



## Research Article

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# On the existence of canonical multi-phase Brakke flows

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**Abstract:** This paper establishes the global-in-time existence of a multi-phase mean curvature flow, evolving from an arbitrary closed rectifiable initial datum, which is a Brakke flow and a BV solution at the same time. In particular, we prove the validity of an explicit identity concerning the change of volume of the evolving grains, showing that their boundaries move according to the generalized mean curvature vector of the Brakke flow. As a consequence of the results recently established in [J. Fischer, S. Hensel, T. Laux and T. M. Simon, The local structure of the energy landscape in multiphase mean curvature flow: Weak-strong uniqueness and stability of evolutions, preprint (2020), <https://arxiv.org/abs/2003.05478>], under suitable assumptions on the initial datum, such additional property resolves the non-uniqueness issue of Brakke flows.

**Keywords:** Mean curvature flow, motion of grain boundaries, integral varifolds

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## 1 Introduction

Arising as the gradient flow of the area functional, the *mean curvature flow* (henceforth abbreviated as MCF) is arguably the most fundamental geometric flow involving extrinsic curvatures. The unknown of MCF is a one-parameter family  $\{\Gamma(t)\}_{t \geq 0}$  of surfaces in the Euclidean space (or in an ambient Riemannian manifold) such that the normal velocity of the flow equals the mean curvature vector at each point for every time  $t$ . The initial value problem for MCF starting with a smooth closed surface  $\Gamma(0) = \Gamma_0$  is locally well-posed in time, until the appearance of singularities such as shrinking or neck pinching. Numerous frameworks of generalized solutions past singularities have been proposed: we mention, among others, the Brakke flows [6], level set flows [8, 12], BV solutions [23, 25] and  $L^2$  flows [5, 29]. Existence of these possibly different generalized solutions to the MCF as well as their relations have been studied intensively in the past 40 years or so.

The aim of the present paper is to establish the global-in-time existence of a *canonical multi-phase Brakke flow* evolving from an arbitrary rectifiable initial datum. The attribute *multi-phase* here refers to the fact that the evolving surfaces are, in fact, *boundaries* of finitely many, but at least two, labelled open subsets of  $\mathbb{R}^{n+1}$  (henceforth referred to also as *grains* or *phases*). The MCF evolution of such objects is strongly motivated by materials science, as it describes the motion and growth of crystallites in polycrystalline materials; see, e.g., [30]. While the literature concerning the two-phase MCF is rich, fewer works have been dedicated to the more general case of multi-phase MCF with at least three grains, despite its relevance in the modeling of physical processes governed by surface tension type energies.

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In the present paper, we work with an arbitrary (but finite) number of grains. The solution we construct consists of two objects: the flow of the evolving grains and a Brakke flow, intertwined as follows. The Brakke flow – a measure-theoretic generalization of MCF, particularly suited to describe the evolution of surfaces through singularities (see Definition 2.1) – is essentially supported on the topological boundary of the grains, and it keeps track of multiplicities. Additionally, the mean curvature of the Brakke flow determines the distributional velocity at which the reduced boundary of each grain moves. As a result of the latter property, the change of volume of each grain between two instants of time can be recovered by integrating the mean curvature over the reduced boundary, a property certainly expected for a smooth MCF but quite non-trivial in a context where singularities and multiplicities occur. The attribute *canonical* refers to this very precise interplay between the Brakke flow and the evolution of the grains. Note that Brakke flows are non-unique in general due to the nature of the formulation, but the existence of the grains prevents redundant non-uniqueness such as sudden vanishing, for example. In the absence of higher multiplicities of the Brakke flow, we show that the collection of the grains (or, more precisely, the collection of their indicator functions) constitutes a *BV solution* of the MCF (see Definition 2.4). In this case, the grain boundaries are, in fact, a smooth MCF almost everywhere in space and time by Brakke’s partial regularity theory [6, 20, 38].

In certain instances, the additional BV characterization may lead to the uniqueness of the canonical Brakke flow. For instance, in ambient dimension  $n + 1 = 2$ , the recent work of Fischer, Hensel, Laux and Simon [13] shows that, as soon as a *strong solution* of the network flow exists (see [13, Definition 16] for the definition of strong solution), any BV solution must coincide with it at least for all times until the first topology changes occur. One conclusion derived from [13] and the present paper is then that, if  $n = 1$  and if a regular network flow starting from the given initial datum exists, then the canonical Brakke flow constructed in the present paper from the same initial datum necessarily coincides with that regular flow until the first topology changes; see [13, Theorem 19] for the precise statement (also see [17] for a similar uniqueness result in  $n = 2$ ). In fact, the work [13] inspired the study carried out in the present paper.

In more precise and technical terms, the highlight of the main results of the present paper may be stated as follows (see the complete statements in Section 2.3).

**Theorem A.** *Let  $E_{0,1}, \dots, E_{0,N} \subset \mathbb{R}^{n+1}$  be mutually disjoint non-empty open sets with  $N \geq 2$  such that  $\Gamma_0 := \mathbb{R}^{n+1} \setminus \bigcup_{i=1}^N E_{0,i}$  is countably  $n$ -rectifiable. Assume that the  $n$ -dimensional Hausdorff measure of  $\Gamma_0$  is finite or grows at most exponentially fast at infinity. Then there exist a Brakke flow  $\{V_t\}_{t \geq 0}$  (see Definition 2.1 below) as well as one-parameter families  $\{E_i(t)\}_{t \geq 0}$  ( $i \in \{1, \dots, N\}$ ) of open sets, with  $\{E_1(t), \dots, E_N(t)\}$  mutually disjoint for each  $t \geq 0$ , such that*

$$\|V_0\| = \mathcal{H}^n \llcorner_{\Gamma_0}, \quad E_i(0) = E_{0,i} \quad \text{for every } i = 1, \dots, N,$$

and satisfying the following properties, writing  $\Gamma(t) := \mathbb{R}^{n+1} \setminus \bigcup_{i=1}^N E_i(t)$ :

- (i)  $\mathcal{H}^{n-1+\delta}(\Gamma(t) \Delta \text{spt}\|V_t\|) = 0$  for any  $\delta > 0$  and for a.e.  $t \geq 0$ .
- (ii) For each  $i = 1, \dots, N$  and for any arbitrary test function  $\phi = \phi(x, t)$ , we have, in the sense of distributions on  $[0, \infty)$ , that

$$\frac{d}{dt} \int_{E_i(t)} \phi \, dx = \int_{\partial^* E_i(t)} \phi h \cdot \nu_i \, d\mathcal{H}^n + \int_{E_i(t)} \frac{\partial \phi}{\partial t} \, dx. \quad (1.1)$$

- (iii) If the Brakke flow is locally a unit density flow, then, locally, we have

$$\mathcal{H}^n \left( \Gamma(t) \Delta \bigcup_{i=1}^N \partial^* E_i(t) \right) = 0 \quad \text{and} \quad \|V_t\| = \mathcal{H}^n \llcorner_{\bigcup_{i=1}^N \partial^* E_i(t)}$$

for a.e.  $t$ .

In the above statement,  $A \Delta B$  denotes the symmetric difference of two sets  $A$  and  $B$ , and  $\text{spt}\|V_t\|$  is the support of the weight measure  $\|V_t\|$  of the varifold  $V_t$ . The symbol  $h$  denotes the generalized mean curvature vector of  $V_t$ , and  $\nu_i$  is the outer unit normal vector field to the reduced boundary  $\partial^* E_i(t)$  of  $E_i(t)$ . Since  $\Gamma(t) = \bigcup_{i=1}^N \partial^* E_i(t)$  for all  $t > 0$  (see Theorem 2.11 (iii)), claim (i) shows that the support of the Brakke flow coincides – up to a lower-dimensional set – with the union of the topological boundaries of the grains for

a.e.  $t > 0$ . Claim (ii) states that each reduced boundary  $\partial^* E_i(t)$  is a solution to the MCF in the integral sense specified in (1.1): that is, the generalized velocity of  $\partial^* E_i(t)$ , defined as the distributional time derivative of the indicator function of  $E_i(t)$ , is precisely  $h \cdot \nu_i \mathcal{H}^n \llcorner_{\partial^* E_i(t)}$ .

When integrated, formula (1.1) provides, as a byproduct, the change of the  $(n + 1)$ -dimensional volume of each grain  $E_i(t)$  in any bounded open set  $U$ :

$$\mathcal{L}^{n+1}(U \cap E_i(t_2)) - \mathcal{L}^{n+1}(U \cap E_i(t_1)) = \int_{t_1}^{t_2} \int_{U \cap \partial^* E_i(t)} h \cdot \nu_i d\mathcal{H}^n dt. \quad (1.2)$$

We emphasize the following point in particular: formulae (1.1) and (1.2) hold true even if there is a “higher multiplicity portion” of  $\|V_t\|$  on  $\partial^* E_i(t)$ , or some “interior boundary”  $\partial E_i(t) \setminus \partial^* E_i(t)$ . As far as the authors are aware of, for generalized MCF, (1.2) had never been established prior to the present paper, even for the two-phase MCF. It is worth mentioning that, in the latter context, the existence of a square-integrable generalized velocity advecting the common boundary of the two phases had been proved before, in the setting of sharp interface limits of minimizers of the Allen–Cahn action functional in [29], and of solutions to the Allen–Cahn equation in [16]. A fundamental new achievement of the present paper is, besides the multi-phase setting, the fact that the generalized velocity advecting each phase is precisely the dot product of the generalized mean curvature of the underlying varifold with the appropriate unit normal. Even though we have  $\|V_0\| = \mathcal{H}^n \llcorner_{\Gamma_0}$ , and thus the unit density condition is satisfied at the initial time of the Brakke flow, it is not possible to exclude, in the very general framework under consideration, the occurrence of higher multiplicities at a later time. Despite all those possible singular behaviors, (1.1) and (1.2) are guaranteed time-globally. Claim (iii) states that, if the higher multiplicity of  $\|V_t\|$  does not occur for  $\mathcal{H}^n$ -a.e.  $x$  and a.e.  $t$  locally in space-time, then the reduced boundary measure and the Brakke flow may be identified with one another in that region, and we may say that the  $N$ -tuple  $\chi = (\chi_{E_1}, \dots, \chi_{E_N})$  is a BV solution to MCF (see Definition 2.4). We can guarantee the existence of a unit density flow for some initial time interval  $[0, T_0)$  if we additionally assume a suitable density ratio upper bound on  $\Gamma_0$  (see Theorem 2.13). Such assumption would still allow for an initial datum  $\Gamma_0$  which consists of a union of Lipschitz curves joined by triple junctions in  $n = 1$  and Lipschitz bubble clusters with tetrahedral singularities in  $n = 2$ , for example.

For general Brakke flows, there is no clear pathway leading from the characterization of Brakke flow, which consists of a variational inequality dictating an upper bound on the rate of change of the mass of the evolving surfaces, to formula (1.1), even under the unit density assumption. In fact, as mentioned already, by the partial regularity theorem for unit density Brakke flows [6, 20, 38], in this latter case it is known that  $\Gamma(t)$  is a  $C^\infty$  MCF in a space-time neighborhood of  $(x_0, t_0)$  for a.e.  $t_0$  and for  $\mathcal{H}^n$ -a.e.  $x_0 \in \Gamma(t_0)$ : nonetheless, this alone is not sufficient to guarantee that  $\chi = (\chi_{E_1}, \dots, \chi_{E_N})$  is a BV solution. The same remark goes for the opposite implication, i.e., from BV solution to Brakke flow. Since there is no known partial regularity theory for general BV solutions, these two notions appear far from being equivalent in any case. In the present paper, instead, the Brakke flow arises as the limit of a suitable time-discrete approximation scheme, analogous to that introduced by Kim and the second-named author in [21], and we prove (1.1) by showing that an analogous identity holds approximately true for the approximating flows, with vanishing errors in the limit. In order to gain enough control on the change of volumes in the approximation scheme and consequently obtain good estimates on the error terms, we will need to implement an appropriate modification to the construction of the time-discrete approximate flows devised in [21]: the details of such modification will be explained thoroughly later; see Section 3.1 and Section A.

Next, we discuss closely related works, particularly on the aspect of existence of generalized MCF. For two-phase MCF, the level-set method [8, 12] provides a general existence and uniqueness result even past the time after singularities appear. On the other hand, the level-set may develop a non-trivial interior, a phenomenon called “fattening”, due to the singular behavior of the MCF. Also, the uniqueness of the level-set solutions depends essentially on the maximum principle and it cannot handle general multi-phase MCF of more than two phases.

For the general multi-phase problem, it is natural to consider an initial datum  $\Gamma_0$  with singularities to start with. For example, in dimension  $n = 1$ , a typical  $\Gamma_0$  in a three-phase problem is a union of curves meeting at

triple junctions. In the parametric setting, Bronsard and Reitich [7] first showed the short-time existence of a unique solution for  $C^{2,\alpha}$  initial datum. Since then, there have been numerous studies (mostly for  $n = 1$ , but also for higher dimensions [9, 14]), and we refer the reader to the survey [27] for the references on the parametric approaches. Due to the nature of the solutions and the need to heavily employ PDE techniques, these existence results do not extend beyond the time of topological changes. With a non-parametric approach and for the existence of MCF with regular triple junctions, one can adopt the elliptic regularization [19] for the class of flat chains with coefficients in a finite group; see [32].

Luckhaus and Sturzenhecker [25] introduced the formulation of BV solution of the two-phase MCF, which can be extended naturally to the multi-phase MCF. Their existence result is conditional, in the sense that a BV solution is shown to exist under the assumption that the time-discrete approximate solutions converge to their limit without loss of surface energy. Laux and Otto [23] proved that a sequence arising from the thresholding scheme of Merriman, Bence and Osher converges conditionally to a BV solution using the interpretation in terms of minimizing movements due to Esedoğlu and Otto [10], again under an assumption similar to [25] (see also [24] for a similar convergence result of the parabolic Allen–Cahn system). The BV solution of [25] was partly motivated by the minimizing movements scheme of Almgren, Taylor and Wang [2], and the multi-phase version has been studied recently by Bellettini and Kholmatov [4].

On the side of Brakke flows, Ilmanen [18] proved the existence of a rectifiable Brakke flow arising as a limit of solutions to a parabolic Allen–Cahn equation, and the second-named author proved the integrality of the Brakke flow [37]. These results are for two-phase MCF, but the relation to the BV solution as formulated in [25] remained obscure. In a different but related problem – the Allen–Cahn action functional –, Mugnai and Röger [29] introduced a notion of  $L^2$  flow to describe a weak formulation of MCF with additional  $L^2$  forcing term for  $n = 1, 2$ . The existence of the  $L^2$  flow depends on the result of Röger and Schätzle [31] which solved one of De Giorgi’s conjectures. The work [29] essentially contains the result that the limit phase boundary of the parabolic Allen–Cahn equation satisfies an analogous equation to (1.1) (see [29, Proposition 4.5]). The solution constructed in the present paper is, in fact, also an  $L^2$  flow in the sense of Mugnai and Röger, and, even though the approach leading to (1.1) is different, some properties of generalized velocities of  $L^2$  flows established in [29] are used in the present paper as well.

Finally, we mention again that a global-in-time existence result of a multi-phase Brakke flow which is equipped with moving grain boundaries was given by Kim and the second-named author in [21], reworking the pioneering paper by Brakke [6] within a different formulation. The grains in [21] move continuously with respect to the Lebesgue measure, but the problem concerning the validity of an exact identity involving the volume change was not addressed in there. Previous works by the authors of the present paper (see [34, 35]), in which certain Brakke flows are constructed with an approximation scheme analogous to that introduced in [21], could be reworked so that the additional conclusions concerning the interplay between the flow of the grains and the Brakke flow can be drawn in those contexts as well: in particular, it is possible to have the Brakke flow with prescribed boundary constructed in [35] satisfy formulae (1.1) and (1.2) (see Section 7.2).

## 2 Notation and main results

### 2.1 Basic notation

We shall use the same notation adopted in [21, Section 2]. In particular, the ambient space we will be working in is the Euclidean space  $\mathbb{R}^{n+1}$ , and  $\mathbb{R}^+$  will denote the interval  $[0, \infty)$ . Coordinates  $(x, t)$  are set in the product space  $\mathbb{R}^{n+1} \times \mathbb{R}^+$ , and  $t$  will be thought of and referred to as “time”. For a subset  $A$  of the Euclidean space,  $\text{clos } A$ ,  $\text{int } A$ ,  $\partial A$  and  $\text{conv } A$  will denote the closure, interior, boundary and convex hull of  $A$ , respectively. If  $A \subset \mathbb{R}^{n+1}$  is (Borel) measurable,  $\mathcal{L}^{n+1}(A)$  or  $|A|$  will denote the Lebesgue measure of  $A$ , whereas  $\mathcal{H}^k(A)$  denotes the  $k$ -dimensional Hausdorff measure of  $A$ . When  $x \in \mathbb{R}^{n+1}$  and  $r > 0$ , then  $U_r(x)$  and  $B_r(x)$  denote the open ball and the closed ball centered at  $x$  with radius  $r$ , respectively. More generally, if  $k$  is an integer, then  $U_r^k(x)$  and  $B_r^k(x)$  will denote open and closed balls in  $\mathbb{R}^k$ , respectively, and  $\omega_k := \mathcal{L}^k(U_1^k(0))$ .

A positive Radon measure  $\mu$  on  $\mathbb{R}^{n+1}$  (or in “space-time”  $\mathbb{R}^{n+1} \times \mathbb{R}^+$ ) is always also regarded as a positive linear functional on the space  $C_c(\mathbb{R}^{n+1})$  of continuous and compactly supported functions on  $\mathbb{R}^{n+1}$ , with the pairing denoted by  $\mu(\phi)$  for  $\phi \in C_c(\mathbb{R}^{n+1})$ . The restriction of  $\mu$  to a Borel set  $A$  is denoted by  $\mu \llcorner_A$ , so that  $(\mu \llcorner_A)(E) := \mu(A \cap E)$  for any  $E \subset \mathbb{R}^{n+1}$ . The support of  $\mu$  is denoted by  $\text{spt } \mu$ , and it is the closed set defined by

$$\text{spt } \mu := \{x \in \mathbb{R}^{n+1} : \mu(B_r(x)) > 0 \text{ for every } r > 0\}.$$

The upper and lower  $k$ -dimensional densities of a Radon measure  $\mu$  at  $x \in \mathbb{R}^{n+1}$  are

$$\Theta^{*k}(\mu, x) := \limsup_{r \rightarrow 0^+} \frac{\mu(B_r(x))}{\omega_k r^k}, \quad \Theta_*^k(\mu, x) := \liminf_{r \rightarrow 0^+} \frac{\mu(B_r(x))}{\omega_k r^k},$$

respectively. If  $\Theta^{*k}(\mu, x) = \Theta_*^k(\mu, x)$ , then the common value is denoted by  $\Theta^k(\mu, x)$  and is called the  $k$ -dimensional density of  $\mu$  at  $x$ . For  $1 \leq p \leq \infty$ , the space of  $p$ -integrable (resp. locally  $p$ -integrable) functions with respect to  $\mu$  is denoted by  $L^p(\mu)$  (resp.  $L_{\text{loc}}^p(\mu)$ ). If  $U \subset \mathbb{R}^{n+1}$  is an open set,  $L^p(\mathcal{L}^{n+1} \llcorner_U)$  and  $L_{\text{loc}}^p(\mathcal{L}^{n+1} \llcorner_U)$  are simply written  $L^p(U)$  and  $L_{\text{loc}}^p(U)$ . For a signed or vector-valued measure  $\mu$ ,  $|\mu|$  denotes its total variation.

Given an open set  $U \subset \mathbb{R}^{n+1}$ , we say that a function  $f \in L^1(U)$  has bounded variation in  $U$ , written  $f \in \text{BV}(U)$ , if

$$\sup \left\{ \int_U f \operatorname{div} g \, dx : g \in C_c^1(U; \mathbb{R}^{n+1}) \text{ with } \|g\|_{C^0} \leq 1 \right\} < \infty.$$

If  $f \in \text{BV}(U)$ , then there exists an  $\mathbb{R}^{n+1}$ -valued Radon measure on  $U$ , which we will call the measure derivative of  $f$  and denote by  $\nabla f$ , such that

$$\int_U f \operatorname{div} g \, dx = - \int_U g \cdot d\nabla f \quad \text{for all } g \in C_c^1(U; \mathbb{R}^{n+1}).$$

We say that  $f \in \text{BV}_{\text{loc}}(U)$  if  $f \in \text{BV}(U')$  for all  $U' \Subset U$ .

For a set  $E \subset \mathbb{R}^{n+1}$ ,  $\chi_E$  is the characteristic (or indicator) function of  $E$ , defined by  $\chi_E(x) = 1$  if  $x \in E$ , and  $\chi_E(x) = 0$  otherwise. We say that  $E$  has locally finite perimeter in  $\mathbb{R}^{n+1}$  if  $\chi_E \in \text{BV}_{\text{loc}}(\mathbb{R}^{n+1})$ . When  $E$  is a set of locally finite perimeter, then the measure derivative  $\nabla \chi_E$  is the associated Gauss–Green measure, and its total variation  $|\nabla \chi_E|$  is the perimeter measure; by De Giorgi’s structure theorem,  $|\nabla \chi_E| = \mathcal{H}^n \llcorner_{\partial^* E}$ , where  $\partial^* E$  is the reduced boundary of  $E$ , and  $\nabla \chi_E = -\nu_E |\nabla \chi_E| = -\nu_E \mathcal{H}^n \llcorner_{\partial^* E}$ , where  $\nu_E$  is the outer pointing unit normal vector field to  $\partial^* E$ .

A subset  $\Gamma \subset \mathbb{R}^{n+1}$  is countably  $k$ -rectifiable if it is  $\mathcal{H}^k$ -measurable and it admits a covering

$$\Gamma \subset Z \cup \bigcup_{h \in \mathbb{N}} f_h(\mathbb{R}^k),$$

where  $\mathcal{H}^k(Z) = 0$  and  $f_h : \mathbb{R}^k \rightarrow \mathbb{R}^{n+1}$  is Lipschitz. A countably  $k$ -rectifiable set  $\Gamma$  is (locally)  $\mathcal{H}^k$ -rectifiable if, moreover,  $\mathcal{H}^k(\Gamma)$  is (locally) finite. Countably  $k$ -rectifiable sets  $\Gamma$  are characterized by the existence of approximate tangent planes  $\mathcal{H}^k$ -almost everywhere (see [33, Theorem 11.6]). In other words,  $\Gamma$  is countably  $k$ -rectifiable if and only if there exists a positive function  $g \in L_{\text{loc}}^1(\mathcal{H}^k \llcorner_\Gamma)$  such that the following holds: for  $\mathcal{H}^k$ -a.e.  $x \in \Gamma$  there exists a  $k$ -dimensional linear subspace of  $\mathbb{R}^{n+1}$ , denoted by  $T_x \Gamma$  or  $\text{Tan}(\Gamma, x)$  and referred to as the (approximate) tangent plane to  $\Gamma$  at  $x$ , such that

$$g(x+r \cdot) \mathcal{H}^k \llcorner_{\frac{\Gamma - [x]}{r}} \xrightarrow{*} g(x) \mathcal{H}^k \llcorner_{T_x \Gamma} \quad \text{in the sense of measures, as } r \rightarrow 0^+.$$

A (positive) measure  $\mu$  on  $\mathbb{R}^{n+1}$  is said to be  $k$ -rectifiable if there are a countably  $k$ -rectifiable set  $\Gamma$  and a positive function  $g \in L_{\text{loc}}^1(\mathcal{H}^k \llcorner_\Gamma)$  such that  $\mu = g \mathcal{H}^k \llcorner_\Gamma$ . If  $\mu$  is  $k$ -rectifiable, i.e.,  $\mu = g \mathcal{H}^k \llcorner_\Gamma$ , then for  $\mu$ -a.e.  $x$  the measures  $\mu_{x,r}$  defined, for  $r > 0$ , by  $\mu_{x,r}(A) := r^{-k} \mu(x+rA)$  satisfy

$$\mu_{x,r} \xrightarrow{*} g(x) \mathcal{H}^k \llcorner_{T_x \Gamma} \quad \text{as } r \rightarrow 0^+,$$

that is,  $g(x) \mathcal{H}^k \llcorner_{T_x \Gamma}$  is the tangent measure of  $\mu$  at  $x$ . In this case, the notation  $T_x \mu$  may be used interchangeably with  $T_x \Gamma$  to denote the approximate tangent plane to the  $k$ -rectifiable measure  $\mu$  at  $x$  for  $\mu$ -a.e.  $x$ . More

generally, given a Radon measure  $\mu$  on  $\mathbb{R}^{n+1}$  and  $x \in \mathbb{R}^{n+1}$ , we say that  $\mu$  has an approximate tangent  $k$ -plane at  $x$  if there exist  $g(x) \in (0, \infty)$  and a  $k$ -dimensional linear subspace  $\pi \subset \mathbb{R}^{n+1}$  such that

$$\mu_{x,r} \xrightarrow{*} g(x)\mathcal{H}^k \llcorner_{\pi} \quad \text{as } r \rightarrow 0^+.$$

When this happens, the plane  $\pi$  is unique, and it is denoted by  $T_x\mu$ .

A  $k$ -dimensional varifold in  $\mathbb{R}^{n+1}$  (see [1, 33]) is defined as a positive Radon measure  $V$  on the space  $\mathbb{R}^{n+1} \times \mathbf{G}(n+1, k)$ , where  $\mathbf{G}(n+1, k)$  is the Grassmannian of (unoriented)  $k$ -dimensional linear subspaces of  $\mathbb{R}^{n+1}$ . If  $V$  is a  $k$ -varifold in  $\mathbb{R}^{n+1}$ , we write  $V \in \mathbf{V}_k(\mathbb{R}^{n+1})$ , and we let  $\|V\|$  and  $\delta V$  denote its weight and first variation, respectively. When  $\delta V$  is locally bounded and absolutely continuous with respect to  $\|V\|$ , we let  $h(\cdot, V) \in L^1_{\text{loc}}(\|V\|; \mathbb{R}^{n+1})$  denote the generalized mean curvature vector of  $V$ , so that  $\delta V = -h(\cdot, V)\|V\|$  in the sense of  $\mathbb{R}^{n+1}$ -valued measures on  $\mathbb{R}^{n+1}$ . If  $\Gamma$  is countably  $k$ -rectifiable, and  $\theta \in L^1_{\text{loc}}(\mathcal{H}^k \llcorner_{\Gamma})$  is positive and integer-valued, we let  $\mathbf{var}(\Gamma, \theta)$  denote the varifold  $\mathbf{var}(\Gamma, \theta) = \theta \mathcal{H}^k \llcorner_{\Gamma} \otimes \delta_{T_{\Gamma}}$ . When  $V$  admits a representation  $V = \mathbf{var}(\Gamma, \theta)$  as above, we say that  $V$  is an integral  $k$ -varifold, and we write  $V \in \mathbf{IV}_k(\mathbb{R}^{n+1})$ . All above notions concerning measures (and varifolds) in the Euclidean space  $\mathbb{R}^{n+1}$  can be immediately localized to open sets  $U \subset \mathbb{R}^{n+1}$ .

## 2.2 Three weak notions of MCF

As anticipated in Section 1, in the last few decades several alternative notions of weak solution to the MCF have been proposed. In this subsection, we briefly define and comment upon the three of interest in the present paper: Brakke flows,  $L^2$  flows and BV flows. We begin with the notion of Brakke flow, introduced by Brakke in [6].

**Definition 2.1** (Brakke flow). Let  $0 < T \leq \infty$ , and let  $U \subset \mathbb{R}^{n+1}$  be an open set. A  $k$ -dimensional (integral) Brakke flow in  $U$  is a one-parameter family of varifolds  $\{V_t\}_{t \in [0, T]}$  in  $U$  such that all of the following conditions hold:

- (i) For a.e.  $t \in [0, T]$ ,  $V_t \in \mathbf{IV}_k(U)$ .
- (ii) For a.e.  $t \in [0, T]$ ,  $\delta V_t$  is locally bounded and absolutely continuous with respect to  $\|V_t\|$ .
- (iii) The generalized mean curvature  $h(\cdot, V_t)$  (which exists for a.e.  $t$  by (ii)) satisfies  $h(\cdot, V_t) \in L^2_{\text{loc}}(\|V_t\|; \mathbb{R}^{n+1})$ , and for every compact set  $K \subset U$  and for every  $t < T$  it holds  $\sup_{s \in [0, t]} \|V_s\|(K) < \infty$ .
- (iv) For all  $0 \leq t_1 < t_2 < T$  and  $\phi \in C^1_c(U \times [0, T]; \mathbb{R}^+)$ , it holds

$$\begin{aligned} & \|V_{t_2}\|(\phi(\cdot, t_2)) - \|V_{t_1}\|(\phi(\cdot, t_1)) \\ & \leq \int_{t_1}^{t_2} \int_U \left\{ -\phi(x, t) |h(x, V_t)|^2 + \nabla \phi(x, t) \cdot h(x, V_t) + \frac{\partial \phi}{\partial t}(x, t) \right\} d\|V_t\|(x) dt. \end{aligned} \quad (2.1)$$

The inequality in (2.1) is typically referred to as *Brakke's inequality*. It is not difficult to show that if  $\{\Gamma(t)\}_{t \in [0, T]}$  is a flow of smooth submanifolds with mean curvature  $h(x, t) = h(x, \Gamma(t))$  and normal velocity  $\nu(x, t)$ , then one has, for any  $0 \leq t_1 < t_2 < T$  and for every  $\phi \in C^1_c(U \times [t_1, t_2])$ , the identity

$$\int_{\Gamma(t)} \phi(x, t) d\mathcal{H}^k \Big|_{t=t_1}^{t_2} = \int_{t_1}^{t_2} \int_{\Gamma(t)} \left\{ -\phi \nu \cdot h + \nabla \phi \cdot \nu + \frac{\partial \phi}{\partial t} \right\} d\mathcal{H}^k dt. \quad (2.2)$$

In particular, if  $\{\Gamma(t)\}_{t \in [0, T]}$  is a smooth MCF, setting  $V_t := \mathbf{var}(\Gamma(t), 1)$  defines a Brakke flow for which (2.1) is satisfied with an equality. Conversely, if  $V_t = \mathbf{var}(\Gamma(t), 1)$  with  $\Gamma(t)$  smooth, then inequality (2.1) is sufficient to guarantee that  $\{\Gamma(t)\}_{t \in [0, T]}$  is a classical solution to the MCF. For further details on the definition, the reader can consult the original work by Brakke in [6] or the more recent monograph [39]. Next, we define the notion of unit density flow.

**Definition 2.2.** A Brakke flow is said to be a *unit density flow* in  $U \times [t_1, t_2]$  if  $\Theta^k(\|V_t\|, x) = 1$  for  $\|V_t\|$ -a.e.  $x \in U$  and  $\mathcal{L}^1$ -a.e.  $t \in [t_1, t_2]$ . If  $U = \mathbb{R}^{n+1}$ , we may simply say that  $\{V_t\}_{t \in [t_1, t_2]}$  is a unit density Brakke flow.

The following definition of  $L^2$  flow has been given by Mugnai and Röger in [29].

**Definition 2.3** ( $L^2$  flow). Let  $0 < T < \infty$ , and let  $U \subset \mathbb{R}^{n+1}$  be an open and bounded set. A one-parameter family  $\{V_t\}_{t \in [0, T]}$  of varifolds in  $U$  is a  $k$ -dimensional  $L^2$  flow if it satisfies (i)–(ii) in Definition 2.1 as well as the following conditions:

(iii') The generalized mean curvature  $h(\cdot, V_t)$  (which exists for a.e.  $t \in [0, T]$  by (ii)) satisfies

$$h(\cdot, V_t) \in L^2(\|V_t\|; \mathbb{R}^{n+1}),$$

and  $d\mu := d\|V_t\|dt$  is a Radon measure on  $U \times (0, T)$ .

(iv') There exist a vector field  $\nu \in L^2(\mu; \mathbb{R}^{n+1})$  and a positive constant  $C$  such that

(iv'1)  $\nu(x, t) \perp T_x\|V_t\|$  for  $\mu$ -a.e.  $(x, t) \in U \times (0, T)$ .

(iv'2) For every  $\phi \in C_c^1(U \times (0, T))$ , it holds

$$\left| \int_0^T \int_U \frac{\partial \phi}{\partial t}(x, t) + \nabla \phi(x, t) \cdot \nu(x, t) d\|V_t\|(x) dt \right| \leq C \|\phi\|_{C^0}. \quad (2.3)$$

Any function  $\nu \in L^2(\mu; \mathbb{R}^{n+1})$  satisfying (iv') above is called a *generalized velocity vector* for the flow.

The definition can be easily motivated by considering (2.2) once again: the latter, indeed, implies (2.3) if both  $h$  and  $\nu$  are in  $L^2(\mu; \mathbb{R}^{n+1})$ . Then  $L^2$  flows can be described as flows of generalized surfaces with generalized mean curvature and velocity vectors in  $L^2$ .

Finally, the following definition of BV flow is related to a motion of *hypersurfaces* which are the boundaries of a finite family of sets of locally finite perimeter; see [23, 25]. Given  $N \geq 2$ , we say that  $\{E_1, \dots, E_N\}$  is an  $\mathcal{L}^{n+1}$ -partition of  $\mathbb{R}^{n+1}$  if  $E_i \subset \mathbb{R}^{n+1}$  for every  $i$ , they are pairwise disjoint, and  $\mathcal{L}^{n+1}(\mathbb{R}^{n+1} \setminus \bigcup_{i=1}^N E_i) = 0$ .

**Definition 2.4** (BV flow). Suppose  $N \geq 2$  is an integer, and let  $0 < T < \infty$ . Then  $N$  one-parameter families  $\{E_i(t)\}_{t \in [0, T]}$  ( $i = 1, \dots, N$ ) identify a BV solution for multi-phase MCF in  $\mathbb{R}^{n+1}$  if all of the following assertions hold:

(i'') For a.e.  $t \in [0, T]$ ,  $\{E_1(t), \dots, E_N(t)\}$  is an  $\mathcal{L}^{n+1}$ -partition of  $\mathbb{R}^{n+1}$ ,  $E_i(t)$  is a set of locally finite perimeter, and, setting  $I_{i,j}(t) := \partial^* E_i(t) \cap \partial^* E_j(t)$  for  $i \neq j$ ,

$$\operatorname{ess\,sup}_{t \in [0, T]} \sum_{i,j=1, i \neq j}^N \mathcal{H}^n(I_{i,j}(t)) < \infty. \quad (2.4)$$

(ii'') There exist scalar functions  $\nu_1, \dots, \nu_N$  such that

$$\int_0^T \int_{\partial^* E_i(t)} |\nu_i(x, t)|^2 d\mathcal{H}^n(x) dt < \infty \quad \text{for every } i, \quad (2.5)$$

and with the property that

$$\int_{E_i(t)} \phi(x, t) dx \Big|_{t=t_1}^{t_2} = \int_{t_1}^{t_2} \int_{E_i(t)} \frac{\partial \phi}{\partial t}(x, t) dx dt + \int_{t_1}^{t_2} \int_{\partial^* E_i(t)} \phi(x, t) \nu_i(x, t) d\mathcal{H}^n(x) dt \quad (2.6)$$

for a.e.  $0 \leq t_1 < t_2 < T$  and for all  $\phi \in C_c^1(\mathbb{R}^{n+1} \times [0, T])$ .

(iii'') Setting  $\nu_i(x, t) = \nu_{E_i(t)}(x)$  for the outer unit normal to the reduced boundary of  $E_i(t)$  at  $x$ , it holds

$$\nu_i(\cdot, t) \nu_i(\cdot, t) = \nu_j(\cdot, t) \nu_j(\cdot, t) \quad \mathcal{H}^n\text{-a.e. on } I_{i,j}(t), \quad \text{for a.e. } 0 \leq t < T.$$

(iv'') The functions  $\nu_i$  further satisfy

$$\sum_{i \neq j} \int_0^T \int_{I_{i,j}(t)} \operatorname{div} g - (\nu_i \otimes \nu_i) \cdot \nabla g d\mathcal{H}^n dt = - \sum_{i \neq j} \int_0^T \int_{I_{i,j}(t)} \nu_i \nu_i \cdot g d\mathcal{H}^n dt \quad (2.7)$$

for all vector fields  $g \in C_c^1(\mathbb{R}^{n+1} \times [0, T]; \mathbb{R}^{n+1})$ .

(v) The following inequality holds for a.e.  $0 \leq t < T$ :

$$\sum_{i,j=1, i \neq j}^N \mathcal{H}^n(I_{i,j}(t)) + \sum_{i,j=1, i \neq j}^N \int_0^t \int_{I_{i,j}(s)} |\nu_i(x, s)|^2 d\mathcal{H}^n(x) ds \leq \sum_{i,j=1, i \neq j}^N \mathcal{H}^n(I_{i,j}(0)). \quad (2.8)$$

Equation (2.6) characterizes  $\nu_i(\cdot, t)$  as the velocity of  $\partial^* E_i(t)$ , as anticipated in Section 1. By [26, Proposition 29.4], for each  $i = 1, \dots, N$ , we have

$$\mathcal{H}^n\left(\partial^* E_i(t) \setminus \bigcup_{j=1, j \neq i}^N I_{i,j}(t)\right) = 0 \quad \text{and} \quad \mathcal{H}^n(I_{i,j}(t) \cap I_{i,j'}(t)) = 0 \quad \text{for } j \neq j', \quad (2.9)$$

and thus (2.7) formally characterizes  $\nu_i v_i$  as the mean curvature vector of  $\bigcup_{i=1}^N \partial^* E_i(t)$  on  $I_{i,j}(t)$ . Since

$$\mathcal{H}^n\left(\bigcup_{i=1}^N \partial^* E_i(t)\right) = \frac{1}{2} \sum_{i,j=1, i \neq j}^N \mathcal{H}^n(I_{i,j}(t)), \quad (2.10)$$

(v) corresponds precisely to the energy dissipation inequality for the hypersurface measures of the MCF.

## 2.3 Main results

**Definition 2.5.** We will denote by  $\Omega$  a function in  $C^2(\mathbb{R}^{n+1})$  such that

$$0 < \Omega(x) \leq 1, \quad |\nabla \Omega(x)| \leq c_1 \Omega(x), \quad \|\nabla^2 \Omega(x)\| \leq c_1 \Omega(x)$$

for all  $x \in \mathbb{R}^{n+1}$ , where  $c_1 \geq 0$  is a constant and  $\|\nabla^2 \Omega(x)\|$  is the Hilbert–Schmidt norm of the Hessian matrix  $\nabla^2 \Omega(x)$ .

The function  $\Omega$  is introduced as a weight function to treat unbounded MCF, which may have infinite  $n$ -dimensional Hausdorff measure in  $\mathbb{R}^{n+1}$ . A typical choice of  $\Omega$  in this case can be  $\Omega(x) = \exp(-\sqrt{1 + |x|^2})$  with a suitable choice of  $c_1$ . If one is interested in MCF with finite measure, one can choose  $\Omega \equiv 1$ , with  $c_1 = 0$  in this case. With a function  $\Omega$  as specified above, we consider an initial datum  $\Gamma_0$  satisfying the following assumption.

**Assumption 2.6.** Suppose that  $\Gamma_0 \subset \mathbb{R}^{n+1}$  is a closed, countably  $n$ -rectifiable set such that

$$\mathcal{H}^n \llcorner_{\Omega} (\Gamma_0) := \int_{\Gamma_0} \Omega(x) d\mathcal{H}^n(x) < \infty. \quad (2.11)$$

Moreover, assume that there are  $N \geq 2$  mutually disjoint non-empty open sets  $E_{0,1}, \dots, E_{0,N}$  such that  $\Gamma_0 = \mathbb{R}^{n+1} \setminus \bigcup_{i=1}^N E_{0,i}$ . In particular,  $\{E_{0,1}, \dots, E_{0,N}\}$  is an  $\mathcal{L}^{n+1}$ -partition of  $\mathbb{R}^{n+1}$ .

By (2.11) and  $\Omega > 0$ ,  $\Gamma_0$  has locally finite  $\mathcal{H}^n$ -measure, and thus  $\Gamma_0$  has no interior points. In particular, we have

$$\Gamma_0 = \bigcup_{i=1}^N \partial E_{0,i}.$$

For a given  $\Gamma_0$  as in Assumption 2.6, the assignment of the partition  $\mathbb{R}^{n+1} \setminus \Gamma_0 = \bigcup_{i=1}^N E_{0,i}$  is certainly non-unique. Each  $E_{0,i}$  may not be connected, for example, and the different choice may result in different MCF. In general,  $E_{0,i}$  has locally finite perimeter, and  $\partial^* E_{0,i} \subset \text{spt}|\nabla \chi_{E_{0,i}}| \subset \partial E_{0,i}$  for each  $i = 1, \dots, N$ .

The following Theorems 2.7–2.12 all hold under Assumption 2.6. First, we claim the existence of a Brakke flow starting with  $\Gamma_0$  which is also an  $L^2$  flow in any bounded domain of  $\mathbb{R}^{n+1}$ , and whose generalized velocity vector coincides with the generalized mean curvature vector of the evolving varifolds.



**Theorem 2.7.** *There exists an  $n$ -dimensional Brakke flow  $\{V_t\}_{t \geq 0}$  in  $\mathbb{R}^{n+1}$  such that the following assertions hold:*

- (i)  $\|V_0\| = \mathcal{H}^n \llcorner_{\Gamma_0}$ .
- (ii) *If  $\mathcal{H}^n(\bigcup_{i=1}^N (\partial E_{0,i} \setminus \partial^* E_{0,i})) = 0$ , then  $\lim_{t \rightarrow 0^+} \|V_t\| = \|V_0\|$ .*
- (iii)  $\|V_t\|(\Omega) \leq \mathcal{H}^n \llcorner_{\Omega}(\Gamma_0) \exp(c_1^2 t/2)$  and

$$\int_0^t \int_{\mathbb{R}^{n+1}} |h(\cdot, V_s)|^2 \Omega d\|V_s\| ds < \infty$$

for all  $t > 0$ .

- (iv) *If  $\mathcal{H}^n(\Gamma_0) < \infty$ , and thus if one can choose  $\Omega \equiv 1$  in Assumption 2.6, then*

$$\|V_t\|(\mathbb{R}^{n+1}) + \int_0^t \int_{\mathbb{R}^{n+1}} |h(\cdot, V_s)|^2 d\|V_s\| ds \leq \mathcal{H}^n(\Gamma_0) \quad \text{for all } t > 0.$$

- (v) *For any  $0 < T < \infty$  and for any open and bounded set  $U \subset \mathbb{R}^{n+1}$ , the one-parameter family  $\{V_t \llcorner_U\}_{t \in [0, T]}$  (where we regard  $V_t \llcorner_U$  as a varifold in  $U$ ) is an  $n$ -dimensional  $L^2$  flow with generalized velocity vector  $v(x, t) = h(x, V_t)$  on  $U \times (0, T)$ .*

**Remark 2.8.** If  $n = 1$ , the above Brakke flow satisfies the additional regularity properties obtained in [22]: for  $\mathcal{L}^1$ -a.e.  $t > 0$ ,  $\text{spt}\|V_t\|$  is locally the union of a finite number of  $W^{2,2}$  curves meeting at junctions with angles of either 0, 60 or 120 degrees for  $N \geq 3$ , and only 0 degree (no transverse crossing) for  $N = 2$ ; see [22, Theorems 2.2 and 2.3] for further details.

**Definition 2.9.** With  $\{V_t\}_{t \geq 0}$  as in Theorem 2.7, suppose  $\mu$  is the Radon measure on  $\mathbb{R}^{n+1} \times \mathbb{R}^+$  given by  $d\mu = d\|V_t\|dt$ , and for  $t \in \mathbb{R}^+$  define the closed set

$$(\text{spt } \mu)_t := \{x \in \mathbb{R}^{n+1} : (x, t) \in \text{spt } \mu\}.$$

The following Theorem 2.10 is satisfied in general for Brakke flows, and thus it holds, in particular, for the flow produced in Theorem 2.7.

**Theorem 2.10.** *The Radon measure  $\mu$  and the Brakke flow  $\{V_t\}_{t \geq 0}$  are related as follows:*

- (i)  $\text{spt}\|V_t\| \subset (\text{spt } \mu)_t$  and  $\mathcal{H}^n(B_r \cap (\text{spt } \mu)_t) < \infty$  for all  $t > 0$  and  $r > 0$ .
- (ii)  $\mathcal{H}^{n-1+\delta}((\text{spt } \mu)_t \setminus \text{spt}\|V_t\|) = 0$  for every  $\delta > 0$  and for  $\mathcal{L}^1$ -a.e.  $t \in \mathbb{R}^+$ .
- (iii)  $\text{spt}\|V_t\|$  is countably  $n$ -rectifiable for  $\mathcal{L}^1$ -a.e.  $t \in \mathbb{R}^+$ .
- (iv)  $V_t = \mathbf{var}(\text{spt}\|V_t\|, \theta_t)$  with  $\theta_t(x) = \Theta^n(\|V_t\|, x)$  ( $\|V_t\|$ -a.e.  $x$ ) for  $\mathcal{L}^1$ -a.e.  $t \in \mathbb{R}^+$ .

The following theorem shows that, in addition to the Brakke flow of Theorem 2.7, there are evolving domains  $\{E_i(t)\}_{t \geq 0}$  starting from  $E_{0,i}$  defining a (generalized) BV solution for multi-phase MCF in  $\mathbb{R}^{n+1}$ .

**Theorem 2.11.** *For each  $i = 1, \dots, N$ , there exists a family of open sets  $\{E_i(t)\}_{t \geq 0}$  such that, setting*

$$\Gamma(t) := \mathbb{R}^{n+1} \setminus \bigcup_{i=1}^N E_i(t),$$

the following assertions hold:

- (i)  $E_i(0) = E_{0,i}$  for  $i = 1, \dots, N$ .
- (ii)  $E_1(t), \dots, E_N(t)$  are pairwise disjoint for  $t \in \mathbb{R}^+$ .
- (iii)  $(\text{spt } \mu)_t = \Gamma(t) = \bigcup_{i=1}^N \partial E_i(t)$  for all  $t > 0$ .
- (iv) For all  $t \in \mathbb{R}^+$ ,  $\|V_t\| \geq |\nabla \chi_{E_i(t)}|$  for every  $i = 1, \dots, N$ , and  $2\|V_t\| \geq \sum_{i=1}^N |\nabla \chi_{E_i(t)}|$ .
- (v)  $S(i) := \{(x, t) : x \in E_i(t), t \in \mathbb{R}^+\}$  is open in  $\mathbb{R}^{n+1} \times \mathbb{R}^+$  for  $i = 1, \dots, N$ .
- (vi) For every  $0 < T < \infty$ , the families  $\{E_i(t)\}_{t \in [0, T]}$  define a generalized BV solution for multi-phase MCF in the following sense: referring to Definition 2.4, (i'') holds when  $\mathcal{H}^n \llcorner_{\Omega}$  replaces  $\mathcal{H}^n$  in (2.4); (ii'') holds when  $\mathcal{H}^n \llcorner_{\Omega}$  replaces  $\mathcal{H}^n$  in (2.5); (iii'') holds. In fact, the scalar velocities  $v_i$  are precisely

$$v_i(x, t) = h(x, V_t) \cdot v_i(x, t),$$

so that (2.6) reads as follows: for every  $i \in \{1, \dots, N\}$ ,

$$\int_{E_i(t)} \phi(x, t) dx \Big|_{t=t_1}^{t_2} = \int_{t_1}^{t_2} \left( \int_{\partial^* E_i(t)} \phi h \cdot \nu_i d\mathcal{H}^n + \int_{E_i(t)} \frac{\partial \phi}{\partial t} dx \right) dt \quad (2.12)$$

for any  $0 \leq t_1 < t_2 < \infty$  and  $\phi \in C_c^1(\mathbb{R}^{n+1} \times \mathbb{R}^+)$ .

(vii) If  $N \geq 3$ , then, for  $\mathcal{L}^1$ -a.e.  $t \in \mathbb{R}^+$  and  $\mathcal{H}^n$ -a.e.  $x \in \Gamma(t)$ ,  $\theta_t(x) = 1$  implies  $x \in \bigcup_{i=1}^N \partial^* E_i(t)$ .

(viii) If  $N = 2$ , then, for  $\mathcal{L}^1$ -a.e.  $t \in \mathbb{R}^+$  and  $\mathcal{H}^n$ -a.e.  $x \in \Gamma(t)$ ,

$$\theta_t(x) = \begin{cases} \text{odd integer} & \text{for } x \in \partial^* E_1(t) (= \partial^* E_2(t)), \\ \text{even integer} & \text{for } x \in \Gamma(t) \setminus \partial^* E_1(t). \end{cases}$$

Notice that in (vi) we speak about *generalized* BV flow because we cannot guarantee, in general, the validity of (2.7). We will comment further on this point in Section 7.1. We anticipate, nonetheless, that further information on the flow, including the validity of (2.7), can be inferred when the Brakke flow is *unit density*. Even though the result follows immediately from Theorem 2.11 (vii), we state it separately.

**Theorem 2.12.** *Suppose that, for  $0 \leq t_1 < t_2 < \infty$  and for an open set  $U$ , the Brakke flow in Theorem 2.7 is a unit density flow in  $U \times (t_1, t_2)$ . Then, for  $\mathcal{L}^1$ -a.e.  $t \in (t_1, t_2)$ ,*

$$\|V_t\|_{\llcorner U} = \mathcal{H}^n \llcorner_{U \cap \bigcup_{i=1}^N \partial^* E_i(t)}. \quad (2.13)$$

Furthermore, (2.7) holds true with  $v_i = h \cdot \nu_i$  for all vector fields  $g \in C_c^1(U \times [t_1, t_2]; \mathbb{R}^{n+1})$ .

If we assume the following additional conditions on  $\Gamma_0$ , we can guarantee that the resulting Brakke flow  $\{V_t\}_{t \geq 0}$  as above is unit density for short time; see also [36, Theorem 2.2 (4)] for a similar statement valid in the context of mean curvature flows with a transport term.

**Theorem 2.13.** *Suppose that  $\mathcal{H}^n(\Gamma_0) < \infty$  and there exist  $r_0 > 0$  and  $\delta_0 > 0$  such that*

$$\sup_{x \in \mathbb{R}^{n+1}, 0 < r < r_0} \frac{\mathcal{H}^n(\Gamma_0 \cap B_r(x))}{\omega_n r^n} < 2 - \delta_0.$$

Then there exists  $T_0 = T_0(n, r_0, \delta_0, \mathcal{H}^n(\Gamma_0)) \in (0, \infty)$  such that  $\{V_t\}_{t \in [0, T_0]}$  in Theorem 2.7 is a unit density Brakke flow and  $\{\chi_{E_1(t)}, \dots, \chi_{E_N(t)}\}_{t \in [0, T_0]}$  in Theorem 2.11 is a BV solution of MCF.

If we set “the maximal existence time” of unit density Brakke flow as

$$\hat{T} := \sup \left\{ t \geq 0 : \int_0^t \|V_s\|(\{x : \theta_s(x) \geq 2\}) ds = 0 \text{ and } \|V_t\| \neq 0 \right\},$$

under the assumption of Theorem 2.13, either  $\|V_t\| = 0$  before  $T_0$ , or we have  $\hat{T} \geq T_0$  and  $V_t$  is a non-trivial unit density flow on  $[0, \hat{T})$  and

$$\{\chi_{E_1(t)}, \dots, \chi_{E_N(t)}\}_{t \in [0, \hat{T})}$$

is also a BV solution of MCF.

Finally, the validity of identity (2.12) allows to employ a simple argument to deduce a lower bound on the *extinction time* for  $V_t$ , namely on the quantity

$$T_* := \sup \{t \in \mathbb{R}^+ : \|V_t\| \neq 0\}.$$

Before stating the result, let us notice that if  $\mathcal{H}^n(\Gamma_0) < \infty$ , then, by an argument using the relative isoperimetric inequality, there is only one  $i_0 \in \{1, \dots, N\}$  such that  $|E_{0, i_0}| = \infty$ , and we can let  $i_0 = N$  without loss of generality. We then set  $E(t) := \bigcup_{i=1}^{N-1} E_i(t)$ .

**Theorem 2.14.** *If  $\mathcal{H}^n(\Gamma_0) < \infty$ , then the extinction time  $T_*$  satisfies*

$$T_* \geq 2 \left( \frac{|E(0)|}{\mathcal{H}^n(\Gamma_0)} \right)^2. \quad (2.14)$$

Observe that if  $\Gamma_0$  is bounded, then  $T_*$  must necessarily be finite, as one can see using the avoidance lemma of Brakke flows (see, for example, [19, 10.6 and 10.7]) and a comparison with a shrinking sphere. Estimate (2.14) was first proved by Giga and Yama-uchi in [15] for two-phase MCF for the solution by level-set method, and it is sharp. In contrast, as far as the authors are aware of, such sharp lower bound had never been established before in the context of multi-phase MCF. Theorem 2.14 will be proved in Section 7.3.

## 2.4 Outline of the proofs and plan of the paper

In what follows, we assume to have fixed the following:

- A function  $\Omega$  as in Definition 2.5.
- A set  $\Gamma_0$  and domains  $\{E_{0,i}\}_{i=1}^N$  as in Assumption 2.6.

The strategy towards the proof of the existence of the Brakke flow  $\{V_t\}_{t \geq 0}$  and of the one-parameter families  $\{E_i(t)\}_{t \geq 0}$  of open sets for  $i \in \{1, \dots, N\}$  from Theorems 2.7 and 2.11, respectively, is analogous to that employed by Kim and the second-named author in [21], with an important technical modification which is crucial to gain enough control on the change of volume of the grains and conclude identity (2.12). Let us explain this point in further detail. The scheme introduced in [21] can be roughly summarized as follows. One constructs, starting from  $\{E_{0,i}\}_{i=1}^N$ , a sequence (indexed by  $j \in \mathbb{N}$ ) of piecewise constant-in-time flows of *open partitions* of  $\mathbb{R}^{n+1}$  of  $N$  elements (see Section 2.5): more precisely, for each  $j$  the corresponding flow  $\{\mathcal{E}_j(t)\}_{t \in [0,j]}$  consists of constant open partitions  $\mathcal{E}_j(t) = \mathcal{E}_{j,k} = \{E_{j,k,i}\}_{i=1}^N$  for  $t$  in intervals (*epochs*)  $((k-1)\Delta t_j, k\Delta t_j)$  of length  $\Delta t_j \rightarrow 0^+$ . The goal is then to show that if the partition  $\mathcal{E}_{j,k+1}$  is constructed from the partition  $\mathcal{E}_{j,k}$  appropriately, then, along a suitable subsequence  $j_\ell \rightarrow \infty$ , the (varifolds associated to) the boundaries  $\partial \mathcal{E}_{j_\ell}(t)$  converge to the desired Brakke flow  $V_t$ .

The open partition  $\mathcal{E}_{j,k+1}$  at a given epoch is constructed from the open partition  $\mathcal{E}_{j,k}$  at the previous epoch by applying two operations, which we call *steps*. The first step is a small *Lipschitz deformation* of partitions with the effect of regularizing singularities by locally minimizing the area of the boundary of partitions at a suitably small scale; the second step consists of flowing the boundary of partitions by an appropriately defined *approximate mean curvature vector*, obtained by smoothing the surfaces' first variation via convolution with a localized heat kernel.

The only difference between the scheme employed in [21] and the one devised in the present paper is in the choice of the Lipschitz deformations in the first step. While in [21] one only requires that the change of volumes of the grains due to Lipschitz deformation is small (for a certain smallness scale), in the present paper we shall require that the change of volume is small *compared to the reduction in surface measure*. We define such new class of *volume-controlled Lipschitz deformations* in Section 3.1, and then we claim that the construction of [21] can be carried over using volume-controlled deformations, as outlined in Section 3.2: by the results of [21], this completes the proof of Theorem 2.7 (i)–(iv) (with some additional remarks), Theorem 2.10 (i) and Theorem 2.11 (i)–(v). There are technical details for verifying that the modifications to the volume-controlled deformations do not pose any difficulties, and we defer it to Section A.

In Section 4, the main result is Theorem 2.11 (vi), namely identity (2.12). For that, we first prove that any Brakke flow is  $L^2$  flow in Section 4.1, which is Theorem 2.7 (v). This fact seems to be first noted in [5], but we include the proof for completeness. Next, Section 4.2 is the main part of the proof, showing the existence of measure-theoretic velocities. The proof consists of calculating explicitly the rate of change of integrals of test functions across different epochs in the approximating flows. We will prove the validity of an approximate identity for the sets  $E_{j_\ell,i}(t)$ , and the use of volume-controlled Lipschitz deformations will be crucial to conclude that the errors vanish in the limit as  $\ell \rightarrow \infty$ . Section 4.3 shows the existence of tangent space of  $\mu$  on the reduced boundary of grains (seen as a set in space-time) and concludes the proof of Theorem 2.11 (vi).

In Section 5, we prove Theorem 2.10 (ii)–(iv), which, in particular, implies that the support  $\text{spt}\|V_t\|$  of the evolving varifolds is  $\mathcal{H}^n$ -equivalent to the boundary of partition  $\Gamma(t) = \bigcup_{i=1}^N \partial E_i(t)$ . This result is used in Section 6. The argument we follow was suggested by Ilmanen in [18, Section 7.1], and we include it for the sake of completeness. It is based on the so-called *clearing out lemma* (see Lemma 5.1), a very robust result, which in turn follows from Huisken's monotonicity formula, stating roughly that if the localized density of  $\|V_t\|$  at

some point  $y$  is too small at a scale  $r > 0$ , then necessarily the point  $(y, t + r^2)$  does not belong to the support of the space-time measure  $\mu$ .

Section 6 contains the proofs of Theorem 2.11 (vii) and (viii). They are improved versions of the integrality theorem [21, Theorem 8.6] in that the behaviors of approximating flows and their grains are tracked more in detail. A characterization in [22, Section 4] of limiting behavior within a length scale of  $o(1/j^2)$ , where measure minimizing property dominates, is essentially used. At the end, we describe the proofs of Theorems 2.12 and 2.13.

Finally, Section 7 contains some final remarks on the notion of generalized BV solutions introduced in Theorem 2.11 (vi) and on the construction of canonical multi-phase Brakke flows with fixed boundary conditions in the spirit of [35], as well as the proof of Theorem 2.14.

## 2.5 Further notation

We collect here some further notation and results which will be extensively used throughout the paper. We begin with the notion of open partitions of  $\mathbb{R}^{n+1}$  of  $N$  elements and corresponding admissible maps.

**Definition 2.15.** Let  $N \geq 2$  be an integer, and let  $\Omega$  be as in Definition 2.5. A collection  $\mathcal{E} = \{E_1, \dots, E_N\}$  of subsets  $E_i \subset \mathbb{R}^{n+1}$  is called an  $\Omega$ -finite open partition of  $N$  elements if the following conditions hold:

- (i)  $E_1, \dots, E_N$  are open and mutually disjoint.
- (ii) It holds

$$\int_{\mathbb{R}^{n+1} \setminus \bigcup_{i=1}^N E_i} \Omega(x) d\mathcal{H}^n(x) < \infty.$$

- (iii) The set  $\bigcup_{i=1}^N \partial E_i$  is countably  $n$ -rectifiable.

The set of all  $\Omega$ -finite open partitions of  $N$  elements is denoted by  $\mathcal{OP}_\Omega^N$ .

Note that it is allowed for some  $E_i$  to be the empty set  $\emptyset$ . Since  $\Omega > 0$  everywhere, property (ii) implies that the closed set  $\mathbb{R}^{n+1} \setminus \bigcup_{i=1}^N E_i$  has locally finite  $\mathcal{H}^n$ -measure, and thus no interior point. In particular, it holds

$$\mathbb{R}^{n+1} \setminus \bigcup_{i=1}^N E_i = \bigcup_{i=1}^N \partial E_i.$$

We define

$$\partial \mathcal{E} := \bigcup_{i=1}^N \partial E_i,$$

and with a slight abuse of notation we use the same symbol to denote the varifold

$$\mathbf{var} \left( \bigcup_{i=1}^N \partial E_i, 1 \right) \in \mathbf{IV}_n(\mathbb{R}^{n+1}),$$

namely the unit density varifold induced from the countably  $n$ -rectifiable set  $\partial \mathcal{E}$ .

**Definition 2.16.** Given  $\mathcal{E} = \{E_i\}_{i=1}^N \in \mathcal{OP}_\Omega^N$ , a function  $f: \mathbb{R}^{n+1} \rightarrow \mathbb{R}^{n+1}$  is  $\mathcal{E}$ -admissible if it is Lipschitz and if it satisfies the following conditions, where we set  $\tilde{E}_i := \text{int}(f(E_i))$  for every  $i$ :

- (i)  $\tilde{E}_1, \dots, \tilde{E}_N$  are pairwise disjoint.
- (ii) It holds

$$\mathbb{R}^{n+1} \setminus \bigcup_{i=1}^N \tilde{E}_i \subset f \left( \bigcup_{i=1}^N \partial E_i \right).$$

- (iii)  $\sup_{x \in \mathbb{R}^{n+1}} |f(x) - x| < \infty$ .

The following lemma is [21, Lemma 4.4].

**Lemma 2.17.** Let  $\mathcal{E} = \{E_i\}_{i=1}^N \in \mathcal{OP}_\Omega^N$ , and let  $f$  be  $\mathcal{E}$ -admissible. Set  $\tilde{\mathcal{E}} := \{\tilde{E}_i\}_{i=1}^N$ , where  $\tilde{E}_i = \text{int}(f(E_i))$ . Then  $\tilde{\mathcal{E}} \in \mathcal{OP}_\Omega^N$ . We will call  $\tilde{\mathcal{E}}$  the push-forward of  $\mathcal{E}$  through  $f$ , denoted by  $\tilde{\mathcal{E}} := f_* \mathcal{E}$ .

Next, we define a class of test functions with good properties. For  $j \in \mathbb{N}$ , we set

$$\mathcal{A}_j := \{\phi \in C^2(\mathbb{R}^{n+1}; \mathbb{R}^+): \phi(x) \leq \Omega(x), |\nabla\phi(x)| \leq j\phi(x), \|\nabla^2\phi(x)\| \leq j\phi(x) \text{ for every } x \in \mathbb{R}^{n+1}\}.$$

Note that  $\Omega \in \mathcal{A}_j$  for all  $j \geq c_1$ .

Finally, we give the notion of smoothed mean curvature vector of a varifold. Let  $\psi \in C^\infty(\mathbb{R}^{n+1})$  be a radially symmetric cut-off function such that

$$\begin{aligned} \psi(x) &= 1 && \text{for } |x| \leq \frac{1}{2}, \\ \psi(x) &= 0 && \text{for } |x| \geq 1, \\ 0 \leq \psi(x) \leq 1, \quad |\nabla\psi(x)| \leq 3, \quad \|\nabla^2\psi(x)\| \leq 9 && \text{for all } x \in \mathbb{R}^{n+1}. \end{aligned}$$

Then, for every  $\varepsilon \in (0, 1)$ , we define

$$\hat{\Phi}_\varepsilon(x) := \frac{1}{(2\pi\varepsilon^2)^{\frac{n+1}{2}}} \exp\left(-\frac{|x|^2}{2\varepsilon^2}\right), \quad \Phi_\varepsilon(x) := c(\varepsilon)\psi(x)\hat{\Phi}_\varepsilon(x),$$

where  $1 < c(\varepsilon) \leq c(n)$  is a normalization constant chosen in such a way that

$$\int_{\mathbb{R}^{n+1}} \Phi_\varepsilon(x) dx = 1.$$

We shall call  $\Phi_\varepsilon$  the smoothing kernel at scale  $\varepsilon$ . For a varifold  $V \in \mathbf{V}_n(\mathbb{R}^{n+1})$ , we then define the  $\varepsilon$ -smoothed mean curvature vector of  $V$  to be the vector field  $h_\varepsilon(\cdot, V) \in C^\infty(\mathbb{R}^{n+1}; \mathbb{R}^{n+1})$  defined by

$$h_\varepsilon(\cdot, V) := -\Phi_\varepsilon * \left( \frac{\Phi_\varepsilon * \delta V}{\Phi_\varepsilon * \|V\| + \varepsilon\Omega^{-1}} \right).$$

In the above formula,  $\Phi_\varepsilon * \|V\|$  is the measure on  $\mathbb{R}^{n+1}$  defined by

$$(\Phi_\varepsilon * \|V\|)(\phi) := \|V\|(\Phi_\varepsilon * \phi) = \int_{\mathbb{R}^{n+1}} \int_{\mathbb{R}^{n+1}} \Phi_\varepsilon(x-y)\phi(y) dy d\|V\|(x)$$

for all  $\phi \in C_c(\mathbb{R}^{n+1})$ , identified with the smooth function

$$(\Phi_\varepsilon * \|V\|)(x) := \int_{\mathbb{R}^{n+1}} \Phi_\varepsilon(y-x) d\|V\|(y)$$

by means of the identity

$$(\Phi_\varepsilon * \|V\|)(\phi) = \langle \Phi_\varepsilon * \|V\|, \phi \rangle_{L^2(\mathbb{R}^{n+1})}.$$

Analogously,  $\Phi_\varepsilon * \delta V$  is the  $\mathbb{R}^{n+1}$ -valued measure on  $\mathbb{R}^{n+1}$  defined by

$$(\Phi_\varepsilon * \delta V)(g) := \delta V(\Phi_\varepsilon * g) = \int_{\mathbb{R}^{n+1}} g(y) \cdot \int_{\mathbb{R}^{n+1} \times \mathbf{G}(n+1, n)} S(\nabla\Phi_\varepsilon(x-y)) dV(x, S) dy$$

for all  $g \in C_c(\mathbb{R}^{n+1}; \mathbb{R}^{n+1})$ , identified with the smooth vector field

$$(\Phi_\varepsilon * \delta V)(x) := \int_{\mathbb{R}^{n+1} \times \mathbf{G}(n+1, n)} S(\nabla\Phi_\varepsilon(y-x)) dV(y, S).$$

We state the following lemma concerning the smoothed mean curvature vector to be used in the subsequent sections. For the proof, the reader can consult [21, Lemma 5.1].

**Lemma 2.18.** *For every  $M > 0$ , there exists a constant  $\varepsilon_1 \in (0, 1)$ , depending only on  $n, c_1$  and  $M$ , such that the following holds. Let  $V \in \mathbf{V}_n(\mathbb{R}^{n+1})$  be an  $n$ -dimensional varifold in  $\mathbb{R}^{n+1}$  such that  $\|V\|(\Omega) \leq M$ , and for every  $\varepsilon \in (0, \varepsilon_1)$  let  $h_\varepsilon(\cdot, V)$  be its smoothed mean curvature vector. Then*

$$|h_\varepsilon(x, V)| \leq 2\varepsilon^{-2}, \tag{2.15}$$

$$\|\nabla h_\varepsilon(x, V)\| \leq 2\varepsilon^{-4}. \tag{2.16}$$

### 3 Existence of multi-phase Brakke flow

#### 3.1 Volume-controlled Lipschitz deformations

In this subsection, we introduce the modified class of Lipschitz deformations used in the present paper to gain improved control on the volume change of partitions. For  $\mathcal{E} \in \mathcal{OP}_\Omega^N$  and  $j \in \mathbb{N}$ , the class is denoted by  $\mathbf{E}^{\text{vc}}(\mathcal{E}, j)$  (where vc indicates “volume controlled”), and it replaces the class  $\mathbf{E}(\mathcal{E}, j)$  defined in [21, Definition 4.8].

**Definition 3.1.** For  $\mathcal{E} = \{E_i\}_{i=1}^N \in \mathcal{OP}_\Omega^N$  and  $c_1 \leq j \in \mathbb{N}$ , define  $\mathbf{E}^{\text{vc}}(\mathcal{E}, j)$  to be the set of all  $\mathcal{E}$ -admissible functions  $f: \mathbb{R}^{n+1} \rightarrow \mathbb{R}^{n+1}$  such that, writing  $\{\tilde{E}_i\}_{i=1}^N := f_*\mathcal{E}$ , the following conditions hold:

- (i)  $|f(x) - x| \leq 1/j^2$  for all  $x \in \mathbb{R}^{n+1}$ .
- (ii) It holds

$$\mathcal{L}^{n+1}(\tilde{E}_i \Delta E_i) \leq \frac{\{\|\partial \mathcal{E}\|(\Omega) - \|\partial f_* \mathcal{E}\|(\Omega)\}}{j} \quad \text{for all } i = 1, \dots, N.$$

- (iii)  $\|\partial f_* \mathcal{E}\|(\phi) \leq \|\partial \mathcal{E}\|(\phi)$  for all  $\phi \in \mathcal{A}_j$ .

The difference between the above class  $\mathbf{E}^{\text{vc}}(\mathcal{E}, j)$  and the class  $\mathbf{E}(\mathcal{E}, j)$  in [21, Definition 4.8] lies in condition (ii), which in [21] was simply  $\mathcal{L}^{n+1}(\tilde{E}_i \Delta E_i) \leq 1/j$ . Since  $\Omega \in \mathcal{A}_j$  for all  $j \geq c_1$ , (iii) implies

$$\|\partial \mathcal{E}\|(\Omega) \geq \|\partial f_* \mathcal{E}\|(\Omega),$$

and thus the right-hand side of (ii) is non-negative. In particular, the identity map  $f(x) = x$  belongs to  $\mathbf{E}^{\text{vc}}(\mathcal{E}, j)$  for  $j \geq c_1$ . We similarly modify the definitions of  $\Delta_j \|\partial \mathcal{E}\|(\Omega)$ ,  $\mathbf{E}(\mathcal{E}, C, j)$  and  $\Delta_j \|\partial \mathcal{E}\|(C)$  in [21, (4.11)–(4.13)] by introducing their volume-controlled counterparts as follows.

**Definition 3.2.** For  $\mathcal{E} \in \mathcal{OP}_\Omega^N$  and  $c_1 \leq j \in \mathbb{N}$ , define

$$\Delta_j^{\text{vc}} \|\partial \mathcal{E}\|(\Omega) := \inf_{f \in \mathbf{E}^{\text{vc}}(\mathcal{E}, j)} \{\|\partial f_* \mathcal{E}\|(\Omega) - \|\partial \mathcal{E}\|(\Omega)\} \leq 0, \quad (3.1)$$

and for a compact set  $C \subset \mathbb{R}^{n+1}$ ,

$$\begin{aligned} \mathbf{E}^{\text{vc}}(\mathcal{E}, C, j) &:= \{f \in \mathbf{E}^{\text{vc}}(\mathcal{E}, j) : \{x : f(x) \neq x\} \cup \{f(x) : f(x) \neq x\} \subset C\}, \\ \Delta_j^{\text{vc}} \|\partial \mathcal{E}\|(C) &:= \inf_{f \in \mathbf{E}^{\text{vc}}(\mathcal{E}, C, j)} \{\|\partial f_* \mathcal{E}\|(C) - \|\partial \mathcal{E}\|(C)\}. \end{aligned} \quad (3.2)$$

Even with this modification, the claims in [21, Section 4] remain essentially the same.

**Lemma 3.3.** For compact sets  $C \subset \tilde{C}$ , we have

$$\Delta_j^{\text{vc}} \|\partial \mathcal{E}\|(\tilde{C}) \leq \Delta_j^{\text{vc}} \|\partial \mathcal{E}\|(C)$$

and

$$\Delta_j^{\text{vc}} \|\partial \mathcal{E}\|(\Omega) \leq (\max_C \Omega) \{\Delta_j^{\text{vc}} \|\partial \mathcal{E}\|(C) + (1 - \exp(-c_1 \text{diam } C)) \|\partial \mathcal{E}\|(C)\}.$$

**Lemma 3.4.** Suppose that  $\{C_l\}_{l=1}^\infty$  is a sequence of compact sets which are mutually disjoint and suppose that  $C$  is a compact set with  $\bigcup_{l=1}^\infty C_l \subset C$ . Then

$$\Delta_j^{\text{vc}} \|\partial \mathcal{E}\|(C) \leq \sum_{l=1}^\infty \Delta_j^{\text{vc}} \|\partial \mathcal{E}\|(C_l). \quad (3.3)$$

We remark that the corresponding statement in [21, Lemma 4.11] contains the additional assumption  $\mathcal{L}^{n+1}(C) < 1/j$ , which we do not need to assume in the present setting. For completeness, we provide the proof.

*Proof.* By (3.2),

$$\Delta_j^{\text{vc}} \|\partial \mathcal{E}\|(C) \geq -\|\partial \mathcal{E}\|(C) > -\infty$$

for any compact set  $C$ . Let  $m \in \mathbb{N}$  and  $\varepsilon \in (0, 1)$  be arbitrary. For all  $l \leq m$ , choose  $f_l \in \mathbf{E}^{\text{vc}}(\mathcal{E}, C_l, j)$  such that

$$\Delta_j^{\text{vc}} \|\partial \mathcal{E}\|(C_l) + \varepsilon \geq \|\partial(f_l)_* \mathcal{E}\|(C_l) - \|\partial \mathcal{E}\|(C_l).$$

We define a map  $f : \mathbb{R}^{n+1} \rightarrow \mathbb{R}^{n+1}$  by setting  $f \llcorner_{C_l} (x) = (f_l) \llcorner_{C_l} (x)$  for  $l = 1, \dots, m$ , and  $f \llcorner_{\mathbb{R}^{n+1} \setminus \bigcup_{l=1}^m C_l} (x) = x$ . The  $\mathcal{E}$ -admissibility of  $f$  follows from that of  $f_l$  and from the fact that  $\{C_l\}$  are mutually disjoint. To prove  $f \in \mathbf{E}^{\text{vc}}(\mathcal{E}, j)$ , we need to check Definition 3.1 (i)–(iii) and (i) follows immediately. Writing  $\{\tilde{E}_i\}_{i=1}^N := f_* \mathcal{E}$ , we have  $\tilde{E}_i \Delta E_i = \bigcup_{l=1}^m C_l \cap (\tilde{E}_i \Delta E_i)$ , and

$$\begin{aligned} \mathcal{L}^{n+1}(\tilde{E}_i \Delta E_i) &= \sum_{l=1}^m \mathcal{L}^{n+1}(C_l \cap (\tilde{E}_i \Delta E_i)) \\ &\leq \sum_{l=1}^m \frac{\{\|\partial \mathcal{E}\|(\Omega) - \|\partial(f_l)_* \mathcal{E}\|(\Omega)\}}{j} \\ &= \sum_{l=1}^m \frac{\{\|\partial \mathcal{E}\| \llcorner_{C_l}(\Omega) - \|\partial(f_l)_* \mathcal{E}\| \llcorner_{C_l}(\Omega)\}}{j} \\ &= \frac{\{\|\partial \mathcal{E}\|(\Omega) - \|\partial f_* \mathcal{E}\|(\Omega)\}}{j}, \end{aligned}$$

where we used (ii) for  $f_l \in \mathbf{E}^{\text{vc}}(\mathcal{E}, C_l, j)$  to conclude (ii) for  $f$ . Condition (iii) can be checked similarly. These show that  $f \in \mathbf{E}^{\text{vc}}(\mathcal{E}, j)$ , and in fact  $f \in \mathbf{E}^{\text{vc}}(\mathcal{E}, C, j)$  by construction. By the definition of  $\Delta_j^{\text{vc}} \|\partial \mathcal{E}\|(C)$ , we have

$$\begin{aligned} \Delta_j^{\text{vc}} \|\partial \mathcal{E}\|(C) &\leq \|\partial f_* \mathcal{E}\|(C) - \|\partial \mathcal{E}\|(C) \\ &= \sum_{l=1}^m (\|\partial(f_l)_* \mathcal{E}\|(C_l) - \|\partial \mathcal{E}\|(C_l)) \\ &\leq m\varepsilon + \sum_{l=1}^m \Delta_j^{\text{vc}} \|\partial \mathcal{E}\|(C_l). \end{aligned}$$

By letting  $\varepsilon \rightarrow 0^+$  first and then  $m \rightarrow \infty$ , we obtain (3.3).  $\square$

The following lemma is similar to [21, Lemma 4.12] with a minor change. The proof is identical.

**Lemma 3.5.** *Suppose that  $\mathcal{E} = \{E_i\}_{i=1}^N \in \mathcal{O}\mathcal{P}_\Omega^N$ ,  $c_1 \leq j \in \mathbb{N}$ ,  $C$  is a compact subset of  $\mathbb{R}^{n+1}$ ,  $f : \mathbb{R}^{n+1} \rightarrow \mathbb{R}^{n+1}$  is an  $\mathcal{E}$ -admissible function such that, writing  $\{\tilde{E}_i\}_{i=1}^N := f_* \mathcal{E}$ , the following conditions hold:*

- (i)  $\{x : f(x) \neq x\} \cup \{f(x) : f(x) \neq x\} \subset C$ .
- (ii)  $|f(x) - x| \leq 1/j^2$  for all  $x \in \mathbb{R}^{n+1}$ .
- (iii)  $\mathcal{L}^{n+1}(\tilde{E}_i \Delta E_i) \leq \{\|\partial \mathcal{E}\|(\Omega) - \|\partial f_* \mathcal{E}\|(\Omega)\}/j$  for all  $i = 1, \dots, N$ .
- (iv)  $\|\partial f_* \mathcal{E}\|(C) \leq \exp(-j \text{diam } C) \|\partial \mathcal{E}\|(C)$ .

Then we have  $f \in \mathbf{E}^{\text{vc}}(\mathcal{E}, C, j)$ .

### 3.2 The constructive scheme

In this subsection, we provide the detailed construction of the sequence of piecewise constant-in-time approximating flows of open partitions leading to the existence result of a multi-phase Brakke flow. We let the weight function  $\Omega$  be as in Definition 2.5, and we consider an initial rectifiable set  $\Gamma_0$  with a corresponding  $\Omega$ -finite open partition of  $N$  elements  $\mathcal{E}_0$  as in Assumption 2.6. For every natural number  $j \geq c_1$ , and for times  $t \in [0, j]$ , we define open partitions  $\mathcal{E}_j(t) = \{E_{j,1}(t), \dots, E_{j,N}(t)\}$  according to the following rule:

$$\mathcal{E}_j(0) = \mathcal{E}_0, \tag{3.4}$$

$$\mathcal{E}_j(t) = \mathcal{E}_{j,k} \quad \text{for all } t \in ((k-1)\Delta t_j, k\Delta t_j]. \tag{3.5}$$

In (3.5), the epoch length is  $\Delta t_j = 2^{-p_j}$  for some  $p_j \in \mathbb{N}$ , and  $k \in \{1, \dots, j2^{p_j}\}$ . For each  $k$ , the open partition  $\mathcal{E}_{j,k}$  is obtained from the open partition  $\mathcal{E}_{j,k-1}$  (with the convention  $\mathcal{E}_{j,0} = \mathcal{E}_0$ ) through successive modifi-

cations, encoded in the following two-step algorithm:

- (1) First, one chooses  $f_1 \in \mathbf{E}^{\text{vc}}(\mathcal{E}_{j,k-1}, j)$  with the property that

$$\|\partial(f_1)_* \mathcal{E}_{j,k-1}\|(\Omega) - \|\partial \mathcal{E}_{j,k-1}\|(\Omega) \leq (1 - j^{-5}) \Delta_j^{\text{vc}} \|\partial \mathcal{E}_{j,k-1}\|(\Omega),$$

and sets

$$\mathcal{E}_{j,k}^* := (f_1)_*(\mathcal{E}_{j,k-1}).$$

Thus, in particular,

$$E_{j,k,i}^* := \text{int}(f_1(E_{j,k-1,i})) \quad \text{for every } i \in \{1, \dots, N\}.$$

- (2) Next, one defines the map

$$f_2(x) := x + \Delta t_j h_{\varepsilon_j}(x, \partial \mathcal{E}_{j,k}^*),$$

where  $\varepsilon_j \in (0, 1)$  and  $h_{\varepsilon_j}(\cdot, \partial \mathcal{E}_{j,k}^*)$  is the  $\varepsilon_j$ -smoothed mean curvature vector of the multiplicity one varifold on  $\partial \mathcal{E}_{j,k}^*$ . Notice that  $f_2$  is a diffeomorphism of  $\mathbb{R}^{n+1}$  due to Lemma 2.18 as soon as  $\Delta t_j \ll \varepsilon_j^4$ . We set

$$\mathcal{E}_{j,k} := (f_2)_* \mathcal{E}_{j,k}^*,$$

and thus

$$E_{j,k,i} := f_2(E_{j,k,i}^*) \quad \text{for every } i \in \{1, \dots, N\}.$$

Notice that the scheme just defined differs from that adopted in [21] only in step (1) of the algorithm, where volume-controlled Lipschitz deformations are used. In spite of such modification, we claim that the proof from [21] can be essentially carried over to this framework, and thus leading to the following theorem.

**Theorem 3.6.** *There is a constant  $c_2 = c_2(n) \gg 1$  with the following property. Let  $\Omega, \Gamma_0$  and  $\mathcal{E}_0 \in \mathcal{OP}_\Omega^N$  be as in Definition 2.5 and Assumption 2.6. Then there exist*

- a subsequence  $j_\ell$  of  $\mathbb{N}$ ,
- reals  $\varepsilon_{j_\ell} \in (0, j_\ell^{-6})$  with  $\lim_{\ell \rightarrow \infty} \varepsilon_{j_\ell} = 0$ ,
- integers  $p_{j_\ell} \in \mathbb{N}$  with  $\Delta t_{j_\ell} = 2^{-p_{j_\ell}} \in (2^{-1} \varepsilon_{j_\ell}^{c_2}, \varepsilon_{j_\ell}^{c_2}]$ ,
- a family  $\{\mu_t\}_{t \in \mathbb{R}^+}$  of Radon measures on  $\mathbb{R}^{n+1}$ ,
- a family  $\mathcal{E}(t) = \{E_1(t), \dots, E_N(t)\}_{t \geq 0}$  of open sets

such that the approximating flow of open partitions  $\mathcal{E}_{j_\ell}(t)$  defined by (3.4) and (3.5) satisfies for all  $T < \infty$ ,

$$\limsup_{\ell \rightarrow \infty} \sup_{t \in [0, T]} \|\partial \mathcal{E}_{j_\ell}(t)\|(\Omega) \leq \|\partial \mathcal{E}_0\|(\Omega) \exp\left(\frac{c_1^2 T}{2}\right), \quad (3.6)$$

$$\limsup_{\ell \rightarrow \infty} \int_0^T \left( \int_{\mathbb{R}^{n+1}} \frac{|\Phi_{\mathcal{E}_{j_\ell}} * \delta(\partial \mathcal{E}_{j_\ell}(t))|^2 \Omega}{\Phi_{\mathcal{E}_{j_\ell}} * \|\partial \mathcal{E}_{j_\ell}(t)\| + \varepsilon_{j_\ell} \Omega^{-1}} dx - \frac{1}{\Delta t_{j_\ell}} \Delta_{j_\ell}^{\text{vc}} \|\partial \mathcal{E}_{j_\ell}(t)\|(\Omega) \right) dt < \infty, \quad (3.7)$$

$$\lim_{\ell \rightarrow \infty} j_\ell^{2(n+1)} \Delta_{j_\ell}^{\text{vc}} \|\partial \mathcal{E}_{j_\ell}(t)\|(\Omega) = 0 \quad \text{for a.e. } t \in \mathbb{R}^+, \quad (3.8)$$

$$\lim_{\ell \rightarrow \infty} \|\partial \mathcal{E}_{j_\ell}(t)\|(\phi) = \mu_t(\phi) \quad \text{for all } \phi \in C_c(\mathbb{R}^{n+1}) \text{ and any } t \in \mathbb{R}^+, \quad (3.9)$$

$$\chi_{E_{j_\ell,i}(t)} \rightarrow \chi_{E_i(t)} \quad \text{in } L^1_{\text{loc}}(\mathbb{R}^{n+1}) \text{ as } \ell \rightarrow \infty \text{ for every } i \in \{1, \dots, N\} \text{ and for every } t \in \mathbb{R}^+. \quad (3.10)$$

Furthermore, the following assertions hold:

- (i) There exists a subset  $Z \subset \mathbb{R}^+$  with  $\mathcal{L}^1(Z) = 0$  such that, for every  $t \in \mathbb{R}^+ \setminus Z$ ,  $\mu_t$  is integral: that is, there exists  $V_t \in \mathbf{IV}_n(\mathbb{R}^{n+1})$  such that  $\|V_t\| = \mu_t$ .
- (ii) If  $V_t$  is defined to be an arbitrary varifold in  $\mathbf{V}_n(\mathbb{R}^{n+1})$  with  $\|V_t\| = \mu_t$  also for  $t \in Z$ , then the family  $\{V_t\}_{t \in \mathbb{R}^+}$  is an  $n$ -dimensional Brakke flow in  $\mathbb{R}^{n+1}$  satisfying the conclusions of Theorem 2.7 (i)–(iv) and Theorem 2.10 (i).
- (iii) The flow of grains  $E_i(t)$  satisfies the conclusions of Theorem 2.11 (i)–(v).

The proofs of the claims contained in the statement of Theorem 3.6 are analogous to the corresponding ones outlined in [21], modulo a few technical modifications in consequence of the use of volume-controlled



Lipschitz deformations. More precisely, the following assertions hold:

- The conclusions (3.6) to (3.9) are contained in [21, Proposition 6.1, Proposition 6.4].
- The existence of the flow of grains  $E_i(t)$ , the convergence in (3.10), and the conclusion (iii) is [21, Theorem 3.5].
- The conclusion (i) is [21, Lemma 9.1].
- The conclusion (ii) is [21, Theorem 3.2, Proposition 3.4], except that Theorem 2.7 (ii) follows from the argument in [35, Proposition 6.10] and Theorem 2.7 (iv) follows from Brakke's inequality and Theorem 2.7 (iii) with  $\Omega = 1$ : Fix  $\phi \in C_c^\infty(\mathbb{R}^{n+1}; [0, 1])$  with  $\phi(x) = 1$  on  $B_1$  and  $\phi(x) = 0$  on  $\mathbb{R}^{n+1} \setminus B_2$ , and for  $k \in \mathbb{N}$ , set  $\phi_k(x) := \phi(x/k)$ . Use  $\phi_k$  in (2.1) with  $t_1 = 0$  and arbitrary  $t = t_2 > 0$  and let  $k \rightarrow \infty$ . In doing so,

$$\int_0^t \int |\nabla \phi_k| |h| d\|V_s\| ds \leq \left( \int_0^t \int |\nabla \phi_k|^2 d\|V_s\| ds \right)^{\frac{1}{2}} \left( \int_0^t \int |h|^2 d\|V_s\| ds \right)^{\frac{1}{2}} \rightarrow 0$$

as  $k \rightarrow \infty$ , due to  $|\nabla \phi_k| = |\nabla \phi|/k$  and uniform bounds from Theorem 2.7 (iii). Then one can see that Theorem 2.7 (iv) holds true.

We will not repeat the proofs of the above results, but we will detail the aforementioned changes due to volume-controlled Lipschitz deformations in Section A. For the time being, we will assume the validity of Theorem 3.6, and we will proceed with the derivation of all remaining results claimed in Section 2.

## 4 BV flow: Proof of Theorem 2.11 (vi)

The main result of this section is the proof of Theorem 2.11 (vi), which we isolate as the following theorem.

**Theorem 4.1.** *The one-parameter family  $\{E_i(t)\}_{t \in \mathbb{R}^+}$  of open partitions defined in Theorem 3.6 is a generalized BV solution to multi-phase MCF with scalar velocities  $v_i = h \cdot v_i$ . More precisely, for every  $i \in \{1, \dots, N\}$  it holds*

$$\int_{E_i(t)} \phi(x, t) dx \Big|_{t=t_1}^{t_2} = \int_{t_1}^{t_2} \int_{E_i(t)} \frac{\partial \phi}{\partial t}(x, t) dx dt + \int_{t_1}^{t_2} \int_{\partial^* E_i(t)} \phi(x, t) h(x, V_t) \cdot v_{E_i(t)}(x) d\mathcal{H}^n(x) dt \quad (4.1)$$

for every  $0 \leq t_1 < t_2 < \infty$  and all test functions  $\phi \in C_c^1(\mathbb{R}^{n+1} \times \mathbb{R}^+)$ .

**Remark 4.2.** Introducing the notation  $\chi_i$  for the indicator function  $\chi_i(x, t) := \chi_{E_i(t)}(x)$ , and recalling that  $\nabla \chi_{E_i(t)} = -v_{E_i(t)} \mathcal{H}^n \llcorner_{\partial^* E_i(t)}$  as  $\mathbb{R}^{n+1}$ -valued Radon measures on  $\mathbb{R}^{n+1}$ , we see that the identity in (4.1) can be rephrased as

$$\int_{\mathbb{R}^{n+1}} \phi(x, t) \chi_i(x, t) dx \Big|_{t=t_1}^{t_2} = \int_{t_1}^{t_2} \int_{\mathbb{R}^{n+1}} \frac{\partial \phi}{\partial t}(x, t) \chi_i(x, t) dx dt - \int_{t_1}^{t_2} \int_{\mathbb{R}^{n+1}} \phi(x, t) h(x, V_t) \cdot d\nabla \chi_{E_i(t)}(x) dt.$$

This implies, in particular, that  $\chi_i \in \text{BV}_{\text{loc}}(\mathbb{R}^{n+1} \times \mathbb{R}^+)$  and its (measure) derivative is

$$\begin{aligned} \nabla' \chi_i(x, t) &= (\nabla \chi_{E_i(t)}(x), -h(x, V_t) \cdot \nabla \chi_{E_i(t)}(x)) dt \\ &= (-v_i(x, t), h(x, V_t) \cdot v_i(x, t)) d\mathcal{H}^n \llcorner_{\partial^* E_i(t)} dt, \end{aligned} \quad (4.2)$$

where  $\nabla' = (\nabla, \partial_t)$  and the identity holds in the sense of  $(\mathbb{R}^{n+1} \times \mathbb{R})$ -valued Radon measures on  $\mathbb{R}^{n+1} \times \mathbb{R}^+$ .

The proof of Theorem 4.1 will be obtained in three main steps, which are the content of Sections 4.1–4.3, respectively. First, we check that Brakke flow implies  $L^2$  flow and recall the important observation Corollary 4.4 due to Mugnai and Röger [29]. Second, we will prove that  $\chi_i \in \text{BV}_{\text{loc}}(\mathbb{R}^{n+1} \times \mathbb{R}^+)$  for each  $i \in \{1, \dots, N\}$ ; see Proposition 4.5. Then we will characterize the measure-theoretic time-derivative of  $\chi_i$  to show that (4.2) holds.

## 4.1 Characterization as $L^2$ flow

In this subsection, we first prove Theorem 2.7 (iv), which we isolate as the following theorem.

**Theorem 4.3.** *Let  $\{V_t\}_{t \in \mathbb{R}^+}$  be the Brakke flow defined in Theorem 3.6. Then, for every  $0 < T < \infty$  and for every open and bounded  $U \subset \mathbb{R}^{n+1}$ , the varifolds  $V_t \llcorner_{(U \times \mathbb{G}(n+1, n))}$  ( $t \in [0, T]$ ) are an  $n$ -dimensional  $L^2$  flow with generalized velocity vector  $v(\cdot, t) = h(\cdot, V_t)$ .*

*Proof.* We verify the requirements of Definition 2.3. Conditions (i) and (ii) are satisfied by  $V_t$  in  $\mathbb{R}^{n+1}$ , and thus they are trivially satisfied when the varifolds are restricted to the open set  $U$ . Concerning (iii)', we have immediately that

$$\int_0^T \int_U |h(\cdot, V_t)|^2 d\|V_t\| dt \leq (\max_{\text{clos } U} \Omega^{-1}) \int_0^T \int_{\mathbb{R}^{n+1}} |h(\cdot, V_t)|^2 \Omega d\|V_t\| dt < \infty,$$

so that  $h(\cdot, V_t) \in L^2(\|V_t\| \llcorner_U; \mathbb{R}^{n+1})$  for a.e.  $t \in [0, T]$ . Analogously,  $d\|V_t\| dt$  is a Radon measure on  $U \times (0, T)$ , and in fact we have

$$\left| \int_0^T \int_U \phi(x, t) d\|V_t\|(x) dt \right| \leq \|\phi\|_{C^0} (\max_{\text{clos } U} \Omega^{-1}) \mathcal{H}^n \llcorner_{\Omega} (\Gamma_0) \int_0^T \exp\left(\frac{c_1^2 t}{2}\right) dt < \infty$$

for every  $\phi \in C_c(U \times (0, T))$ . To complete the proof, we are then only left with checking that (2.3) holds with  $v(\cdot, t) = h(\cdot, V_t)$ : with this choice, indeed, the condition in (d'1) is automatically satisfied due to the perpendicularity of mean curvature (see [6, Chapter 5]). Consider first a test function  $\phi \in C_c^1(\mathbb{R}^{n+1} \times (0, T]; \mathbb{R}^+)$ . Brakke's inequality (2.1) then implies that

$$\int_0^T \int_{\mathbb{R}^{n+1}} \frac{\partial \phi}{\partial t}(x, t) + h(x, V_t) \cdot \nabla \phi(x, t) d\|V_t\|(x) dt \geq \int_0^T \int_{\mathbb{R}^{n+1}} \phi(x, t) |h(x, V_t)|^2 d\|V_t\|(x) dt \geq 0.$$

In particular, the assignment

$$\phi \mapsto L\phi := \int_0^T \int_{\mathbb{R}^{n+1}} \frac{\partial \phi}{\partial t}(x, t) + h(x, V_t) \cdot \nabla \phi(x, t) d\|V_t\|(x) dt$$

defines a positive linear functional on  $C_c^1(\mathbb{R}^{n+1} \times (0, T])$ : hence,  $L$  is monotone, that is,  $L\phi_1 \leq L\phi_2$  whenever  $\phi_1 \leq \phi_2$  everywhere. For every  $\varepsilon \in (0, 1)$ , let  $\psi_{U, \varepsilon} \in C_c^1(\mathbb{R}^{n+1} \times (0, T])$  be the cut-off function

$$\psi_{U, \varepsilon}(x, t) = \psi_U(x) \psi_\varepsilon(t)$$

defined according to the following prescriptions:

- (i)  $0 \leq \psi_U \leq 1$  and  $0 \leq \psi_\varepsilon \leq 1$ .
- (ii)  $\psi_U \equiv 1$  on  $\text{clos } U$ , and  $\psi_U \equiv 0$  on  $\text{dist}(x, \text{clos } U) \geq 1$ .
- (iii)  $\psi_\varepsilon \equiv 1$  on  $[\varepsilon, T]$ , and  $\psi_\varepsilon \equiv 0$  on  $(0, \varepsilon/2]$ .
- (iv)  $\|\nabla \psi_U\|_{C^0} \leq C$  and  $\|\psi'_\varepsilon\|_{C^0} \leq C/\varepsilon$  for a geometric constant  $C$ .

Let now  $\phi \in C_c^1(U \times (0, T])$  be a non-zero function such that  $\text{spt}(\phi) \subset U \times [\varepsilon, T]$ . For such a function, by the definition of  $\psi_{U, \varepsilon}$ , it holds

$$-\psi_{U, \varepsilon} \leq \frac{\phi}{\|\phi\|_{C^0}} \leq \psi_{U, \varepsilon},$$

so that the linearity and monotonicity of  $L$  yield

$$|L\phi| \leq L\psi_{U, \varepsilon} \|\phi\|_{C^0}.$$

Notice that for such a  $\phi$  the space integration can be restricted to  $U$  (as the – continuous – derivatives of  $\phi$  are necessarily zero on  $U^c$  for every  $t$ ), and thus the above argument shows that whenever  $\phi \in C_c^1(U \times (0, T))$  is supported on  $U \times [\varepsilon, T]$ , it holds

$$\left| \int_0^T \int_U \frac{\partial \phi}{\partial t}(x, t) + h(x, V_t) \cdot \nabla \phi(x, t) d\|V_t\|(x) dt \right| \leq L\psi_{U, \varepsilon} \|\phi\|_{C^0}. \quad (4.3)$$

We next proceed to estimate  $L\psi_{U, \varepsilon}$ . We have, setting  $U_1 := \{\text{dist}(x, \text{clos } U) < 1\}$ ,

$$\begin{aligned} L\psi_{U, \varepsilon} &\leq \frac{C}{\varepsilon} \int_{\frac{\varepsilon}{2}}^{\varepsilon} \|V_t\|(U_1) dt + \int_0^T \int_{\mathbb{R}^{n+1}} |h(\cdot, V_t)| |\nabla \psi_U| d\|V_t\| dt \\ &\leq C \left( \max_{\text{clos } U_1} \Omega^{-1} \right) \left( \mathcal{H}^n \llcorner_{\Omega} (\Gamma_0) + (T\mathcal{H}^n \llcorner_{\Omega} (\Gamma_0))^{\frac{1}{2}} \left( \int_0^T \int_{\mathbb{R}^{n+1}} |h(\cdot, V_t)|^2 \Omega d\|V_t\| dt \right)^{\frac{1}{2}} \right). \end{aligned}$$

We see then that  $\sup_{\varepsilon > 0} L\psi_{U, \varepsilon} < \infty$ : in particular, thanks to (4.3), we conclude that inequality (2.3) holds with  $v(\cdot, t) = h(\cdot, V_t)$  for every  $\phi \in C_c^1(U \times (0, T))$ , and thus completing the proof.  $\square$

The following is a simple corollary of Theorem 4.3 and [29, Proposition 3.3].

**Corollary 4.4.** *Let  $\{V_t\}_{t \in \mathbb{R}^+}$  be the Brakke flow defined in Theorem 3.6, and let  $\mu$  be the space-time measure  $d\mu = d\|V_t\| dt$ . Then*

$$\left( \begin{array}{c} h(x_0, V_{t_0}) \\ 1 \end{array} \right) \in T_{(x_0, t_0)} \mu \quad (4.4)$$

at  $\mu$ -a.e.  $(x_0, t_0)$  such that the tangent space  $T_{(x_0, t_0)} \mu$  exists.

## 4.2 Existence of measure-theoretic velocities

We have the following proposition.

**Proposition 4.5.** *Let  $\{\mathcal{E}(t)\}_{t \in \mathbb{R}^+}$  and  $\{V_t\}_{t \in \mathbb{R}^+}$  be as in Theorem 3.6, and let  $\mu \llcorner_{\Omega}$  denote the Radon measure  $\mu \llcorner_{\Omega} := \Omega d\|V_t\| dt$ . Also, for every  $i \in \{1, \dots, N\}$ , set*

$$S(i) := \{(x, t) \in \mathbb{R}^{n+1} \times \mathbb{R}^+ : x \in E_i(t)\}.$$

Then, for every  $i$ , there exists a function  $u_i = u_i(x, t) \in L^2(\mu \llcorner_{\Omega})$  (on  $\mathbb{R}^{n+1} \times [0, T]$  for arbitrary  $T > 0$ ) with  $\text{spt}(u_i) \subset \partial S(i)$  and such that

$$\int_{\mathbb{R}^{n+1}} \phi(x, t) \chi_i(x, t) dx \Big|_{t=t_1}^{t_2} = \int_{t_1}^{t_2} \int_{\mathbb{R}^{n+1}} \frac{\partial \phi}{\partial t}(x, t) \chi_i(x, t) dx dt + \int_{t_1}^{t_2} \int_{\mathbb{R}^{n+1}} \phi(x, t) u_i(x, t) d\|V_t\| dt \quad (4.5)$$

for every  $0 \leq t_1 < t_2 < \infty$  and all test functions  $\phi \in C_c^1(\mathbb{R}^{n+1} \times \mathbb{R}^+)$ .

Proposition 4.5 readily implies the following corollary.

**Corollary 4.6.** *For every  $i \in \{1, \dots, N\}$ ,*

$$\chi_i \in \text{BV}_{\text{loc}}(\mathbb{R}^{n+1} \times \mathbb{R}^+) \quad \text{and} \quad \nabla^! \chi_i(x, t) = (\nabla \chi_{E_i(t)} dt, u_i(x, t) d\|V_t\| dt).$$

In particular, since  $\chi_i$  is the indicator function of  $S(i)$ , the latter is a set of locally finite perimeter in  $\mathbb{R}^{n+1} \times \mathbb{R}^+$ .

*Proof of Proposition 4.5.* We shall divide the proof into several steps. At first, we will drop the dependence of the test function on time, which will be introduced again at a later step. The idea of the proof is to obtain an evolution identity for the approximating flow  $\partial \mathcal{E}_{j_\ell}(t)$  defined in Section 3.2 (where  $j_\ell$  is the sequence of Theorem 3.6), and then to prove that, as  $\ell \rightarrow \infty$ , such identity converges to (4.5). Notice that we can assume without loss of generality that  $t_1 = 0$ , since then the seemingly more general identity can be retrieved by simply taking differences. We will then also rename  $t_2 = T \in (0, \infty)$ .

**Step one: preliminary reductions.** By density, it is evidently sufficient to show that identity (4.5) holds when  $\phi = \phi(x)$  is a function in  $C_c^2(\mathbb{R}^{n+1})$ . We may assume without loss of generality that  $|\phi| \leq \Omega$ . Consider the approximating flow  $\mathcal{E}_{j_\ell}(t)$ , and fix  $\ell$  so large that the flow is defined on the interval  $[0, T]$ . We will deduce the validity of an approximate identity for the approximating flow, with vanishing errors in the limit as  $\ell \rightarrow \infty$ . We fix the index  $i \in \{1, \dots, N\}$ , and, for the sake of simplicity in the notation, we drop the corresponding subscripts, so to write  $\mathcal{E}(t)$  in place of  $\mathcal{E}_{j_\ell}(t)$  and  $E(t)$  in place of  $E_{j_\ell, i}(t)$ . Recalling the construction of  $\mathcal{E}(t)$ , we let  $k_T$  be the integer in  $\{1, \dots, j_\ell 2^{j_\ell}\}$  such that  $T \in ((k_T - 1)\Delta t, k_T \Delta t]$  (with  $\Delta t = \Delta t_{j_\ell}$ ), so that  $E(T) = E(k_T \Delta t) = E_{k_T} := E_{j_\ell, k_T, i}$ . We then have the discretization

$$\int_{E(T)} \phi(x) dx - \int_{E_0} \phi(x) dx = \sum_{k=0}^{k_T-1} \left\{ \int_{E_{k+1}} \phi(x) dx - \int_{E_k} \phi(x) dx \right\}, \quad (4.6)$$

and we can further decompose each summand on the right-hand side of (4.6) as

$$\int_{E_{k+1}} \phi(x) dx - \int_{E_k} \phi(x) dx = D_1 + D_2, \quad (4.7)$$

where

$$D_1 := \int_{E_{k+1}^*} \phi(x) dx - \int_{E_k} \phi(x) dx,$$

$$D_2 := \int_{E_{k+1}} \phi(x) dx - \int_{E_{k+1}^*} \phi(x) dx.$$

Here,  $E_{k+1}^* = \text{int}(f_1(E_k))$  for some Lipschitz function  $f_1 \in \mathbf{E}^{\text{vc}}(\mathcal{E}_k, j_\ell)$  satisfying the almost-optimality condition

$$\|\partial(f_1)_* \mathcal{E}_k\|(\Omega) - \|\partial \mathcal{E}_k\|(\Omega) \leq (1 - j_\ell^{-5}) \Delta^{\text{vc}} \|\partial \mathcal{E}_k\|(\Omega),$$

where  $\Delta^{\text{vc}} \|\partial \mathcal{E}_k\|(\Omega) := \Delta_{j_\ell}^{\text{vc}} \|\partial \mathcal{E}_k\|(\Omega)$ , and  $E_{k+1} = f_2(E_{k+1}^*)$ , with  $f_2(x) = x + \Delta t h_\varepsilon(x, \partial \mathcal{E}_{k+1}^*)$  ( $\varepsilon = \varepsilon_{j_\ell}$ ). We will now proceed evaluating  $D_1$  and  $D_2$  separately.

**Step two: evaluation of  $D_1$  and  $D_2$ .** For  $D_1$ , we simply observe that

$$D_1 = \int_{E_{k+1}^* \setminus E_k} \phi(x) dx - \int_{E_k \setminus E_{k+1}^*} \phi(x) dx,$$

so that, using Definition 3.1 (ii) and (3.1), it holds

$$|D_1| \leq 2 \|\phi\|_{C^0 \mathcal{L}^{n+1}}(E_k \Delta E_{k+1}^*) \leq -2 \|\phi\|_{C^0} \frac{\Delta^{\text{vc}} \|\partial \mathcal{E}_k\|(\Omega) \Delta t}{\Delta t j_\ell}. \quad (4.8)$$

We then proceed with  $D_2$ , and in order to further ease the notation we set  $f(x) := f_2(x)$ ,  $F(x) = f(x) - x$ , as well as  $g := f^{-1}$  and  $G(x) := g(x) - x$ . We also simply write

$$E := E_{k+1}, \quad E^* := E_{k+1}^* = g(E).$$

Using that  $g$  is a diffeomorphism and changing variable in the second integral in  $D_2$ , we have

$$D_2 = \int_E \phi(x) dx - \int_E \phi(g(x)) \mathbf{J}g(x) dx$$

$$= \int_E \{\phi(x) - \phi(g(x))\} dx + \int_E \phi(x) \{1 - \mathbf{J}g(x)\} dx + \int_E (\phi(x) - \phi(g(x))) (\mathbf{J}g(x) - 1) dx, \quad (4.9)$$

where  $\mathbf{J}g$  denotes the Jacobian determinant of  $g$ . Using that  $G(x) = -F(g(x))$  and that

$$F(y) = \Delta t h_\varepsilon(y), \quad h_\varepsilon(\cdot) = h_\varepsilon(\cdot, \partial \mathcal{E}_{k+1}^*),$$

together with (2.15), we have that if  $(\text{spt } \phi)_1 := \{\text{dist}(x, \text{spt } \phi) \leq 1\}$ , then

$$|\phi(g(x)) - \phi(x)| \leq \|\nabla \phi\|_{C^0} |G(x)| \chi_{(\text{spt } \phi)_1}(x) \leq \Delta t \varepsilon^{-3} \chi_{(\text{spt } \phi)_1}(x), \quad (4.10)$$

$$|\phi(g(x)) - \phi(x) - \nabla \phi(x) \cdot G(x)| \leq \|\nabla^2 \phi\|_{C^0} |G(x)|^2 \chi_{(\text{spt } \phi)_1}(x) \leq \Delta t \varepsilon^{c_2-6} \chi_{(\text{spt } \phi)_1}(x). \quad (4.11)$$

Notice that, in order to apply estimate (2.15), we are using that  $\|\partial \mathcal{E}_{k+1}^*\|(\Omega) \leq \|\partial \mathcal{E}_k\|(\Omega)$  and we are assuming that  $\varepsilon = \varepsilon_{j_\ell}$  is smaller than the  $\varepsilon_1$  given by Lemma 2.18 corresponding to the choice

$$M = \sup_{t \in [0, T]} \|\partial \mathcal{E}_{j_\ell}(t)\|(\Omega),$$

which is bounded by a quantity depending only on  $T$ , the initial datum and  $c_1$  due to (3.6). In deducing (4.10) and (4.11), we have also used that, by the definition of  $g$  and (2.15), and for all  $\ell$  large enough, if  $x \notin (\text{spt } \phi)_1$ , then  $g(x) \notin \text{spt } \phi$ , and we have used that  $\varepsilon$  can be assumed sufficiently small, so that  $\varepsilon \|\nabla \phi\|_{C^0}$  and  $\varepsilon \|\nabla^2 \phi\|_{C^0}$  are both bounded by 1. Next, we also estimate

$$|\mathbb{J}g(x) - 1| \leq c(n) \|\nabla G(x)\| \leq c(n) \Delta t \varepsilon^{-4}, \quad (4.12)$$

$$|\mathbb{J}g(x) - 1 - \text{div}(G(x))| \leq c(n) \|\nabla G(x)\|^2 \leq \Delta t \varepsilon^{c_2-9}, \quad (4.13)$$

where we have used that

$$\nabla G = -[(\nabla F) \circ g] \nabla g = -[(\nabla F) \circ g][(\nabla f)^{-1} \circ g],$$

that  $\nabla F = \Delta t \nabla h_\varepsilon$ , and estimate (2.16). We can then conclude from (4.11) and (4.13) that the sum of the first two integrals in (4.9) is

$$= - \int_E \{\nabla \phi(x) \cdot G(x) + \phi(x) \text{div}(G(x))\} dx + \text{Err}_1,$$

where

$$|\text{Err}_1| \leq \Delta t \varepsilon^{c_2-10} \quad (4.14)$$

as soon as  $\varepsilon$  is small enough to absorb the constants depending on  $\mathcal{L}^{n+1}((\text{spt } \phi)_1)$ . On the other hand, using that

$$\nabla \phi(x) \cdot G(x) + \phi(x) \text{div}(G(x)) = \text{div}(\phi(x)G(x))$$

and the divergence theorem, we have

$$\begin{aligned} - \int_E \{\nabla \phi(x) \cdot G(x) + \phi(x) \text{div}(G(x))\} dx &= - \int_{\partial^* E} \phi(x) G(x) \cdot \nu_E(x) d\mathcal{H}^n(x) \\ &= \Delta t \int_{\partial^* E} \phi(x) h_\varepsilon(g(x)) \cdot \nu_E(x) d\mathcal{H}^n(x). \end{aligned} \quad (4.15)$$

Recall that, in the right-hand side of (4.15),  $h_\varepsilon(\cdot) = h_\varepsilon(\cdot, \partial \mathcal{E}_{k+1}^*)$ . We then continue the chain of identities in (4.15) as

$$\Delta t \int_{\partial^* E} \phi(x) h_\varepsilon(x, \partial \mathcal{E}_{k+1}) \cdot \nu_E(x) d\mathcal{H}^n(x) + \text{Err}_2,$$

where

$$\text{Err}_2 := \Delta t \int_{\partial^* E} \phi(x) \nu_E(x) \cdot (h_\varepsilon(g(x), \partial \mathcal{E}_{k+1}^*) - h_\varepsilon(x, \partial \mathcal{E}_{k+1})) d\mathcal{H}^n(x).$$

Since  $\mathcal{E}_{k+1} = f_* \mathcal{E}_{k+1}^*$ , and  $f$  is a diffeomorphism, we have that  $\partial \mathcal{E}_{k+1} = f_\# \partial \mathcal{E}_{k+1}^*$ , where  $f_\#$  denotes the push-forward operator on integral varifolds through  $f$ . Setting, for simplicity,

$$V = \partial \mathcal{E}_{k+1}^* \quad \text{and} \quad \hat{V} = \partial \mathcal{E}_{k+1} = f_\# V,$$

we can write

$$h_\varepsilon(x, \hat{V}) - h_\varepsilon(g(x), V) = [h_\varepsilon(x, \hat{V}) - h_\varepsilon(g(x), \hat{V})] + [h_\varepsilon(g(x), \hat{V}) - h_\varepsilon(g(x), V)]. \quad (4.16)$$

Recall now that the  $\varepsilon$ -smoothed mean curvature vector  $h_\varepsilon(\cdot, V)$  is defined by

$$h_\varepsilon(\cdot, V) = -\Phi_\varepsilon * \frac{\Phi_\varepsilon * \delta V}{\Phi_\varepsilon * \|V\| + \varepsilon \Omega^{-1}}.$$

In particular, using [21, (5.74) and Lemma 4.17], it is easy to estimate the second summand on the right-hand side of (4.16) by

$$|h_\varepsilon(g(x), \hat{V}) - h_\varepsilon(g(x), V)| \leq \varepsilon^{c_2-2n-14} (\|V\|(\Omega) + \|V\|(\Omega)^2).$$

For the first summand on the right-hand side of (4.16), instead,

$$|h_\varepsilon(x, \hat{V}) - h_\varepsilon(g(x), \hat{V})| \leq |g(x) - x| \|\nabla h_\varepsilon\|_{C^0} \leq \Delta t \|h_\varepsilon\|_{C^0} \|\nabla h_\varepsilon\|_{C^0} \leq 4\varepsilon^{c_2-6}$$

by Lemma 2.18. Thus, we can finally estimate

$$\begin{aligned} |\text{Err}_2| &\leq \Delta t \varepsilon^{c_2-2n-14} \|\hat{V}\|(\Omega) (\|V\|(\Omega) + \|V\|(\Omega)^2 + \varepsilon^{2n+7}) \\ &\leq \Delta t \varepsilon^{c_2-2n-14} \|\hat{V}\|(\Omega) (\|\hat{V}'\|(\Omega) + \|\hat{V}'\|(\Omega)^2 + \varepsilon^{2n+7}), \end{aligned} \quad (4.17)$$

where  $\hat{V}' = \partial \mathcal{E}_k$  and we used  $\|V\|(\Omega) = \|\partial(f_1)_* \mathcal{E}_k\|(\Omega) \leq \|\partial \mathcal{E}_k\|(\Omega)$ . Concerning the third integral in (4.9), instead, we use (4.10) and (4.12) to estimate

$$\text{Err}_3 := \int_E (\phi(x) - \phi(g(x))) (\mathbf{J}g(x) - 1) dx$$

by

$$|\text{Err}_3| \leq \Delta t \varepsilon^{c_2-8} \quad (4.18)$$

for all  $\varepsilon$  sufficiently small. We have thus proved that

$$\int_{E_{k+1}} \phi(x) dx - \int_{E_k} \phi(x) dx = \Delta t \left( \int_{\partial^* E_{k+1}} \phi(x) \nu_{E_{k+1}} \cdot h_\varepsilon(x, \partial \mathcal{E}_{k+1}) d\mathcal{H}^n(x) + \text{Err}_{k+1} \right), \quad (4.19)$$

where

$$\text{Err}_{k+1} := (\Delta t)^{-1} (D_1 + \text{Err}_1 + \text{Err}_2 + \text{Err}_3)$$

satisfy estimates (4.8), (4.14), (4.17) and (4.18).

Step three: sum of contributions and limit  $\ell \rightarrow \infty$ . Now, we sum the identities (4.19) for  $k = 0, \dots, k_T - 1$ . Introducing back the subscripts  $j_\ell$  and  $i$ , and using that (see (3.5))

$$\partial \mathcal{E}_{j_\ell}(t) = \partial \mathcal{E}_{j_\ell, k+1} \quad \text{for all } t \in (k\Delta t_{j_\ell}, (k+1)\Delta t_{j_\ell}],$$

we obtain from (4.6) that

$$\int_{E_{j_\ell, i}(T)} \phi(x) dx - \int_{E_{0, i}} \phi(x) dx = \int_0^{k_T \Delta t_{j_\ell}} \int_{\mathbb{R}^{n+1}} \phi(x) h_{\varepsilon_{j_\ell}}(x, \partial \mathcal{E}_{j_\ell}(t)) \cdot d\mu_{E_{j_\ell, i}(t)}(x) dt + \text{Err}_{j_\ell}, \quad (4.20)$$

with

$$\mu_{E_{j_\ell, i}(t)} = -\nabla \chi_{E_{j_\ell, i}(t)} = \nu_{E_{j_\ell, i}(t)} \mathcal{H}^n \llcorner_{\partial^* E_{j_\ell, i}(t)}.$$

Moreover, since  $k_T \Delta t_{j_\ell} \leq T + 1$ , we obtain

$$\begin{aligned} |\text{Err}_{j_\ell}| &\leq \frac{1}{j_\ell} \int_0^{T+1} -\frac{\Delta_{j_\ell}^{\text{vc}} \|\partial \mathcal{E}_{j_\ell}(t)\|(\Omega)}{\Delta t_{j_\ell}} dt - \frac{\Delta_{j_\ell}^{\text{vc}} \|\partial \mathcal{E}_0\|(\Omega)}{j_\ell} + \varepsilon_{j_\ell}^{c_2-11} (T+1) \\ &\quad + \varepsilon_{j_\ell}^{c_2-2n-14} (T+1) (M_{j_\ell}^2 + M_{j_\ell}^3 + \varepsilon_{j_\ell}^{2n+7}), \end{aligned} \quad (4.21)$$

where  $M_{j_\ell} := \sup_{t \in [0, T+1]} \|\partial \mathcal{E}_{j_\ell}(t)\|(\Omega)$ . Next, Lemma 2.18 implies that

$$\left| \int_T^{k_T \Delta t_{j_\ell}} \int_{\mathbb{R}^{n+1}} \phi h_{\varepsilon_{j_\ell}}(\cdot, \partial \mathcal{E}_{j_\ell}(t)) \cdot d\mu_{E_{j_\ell, i}(t)} \right| \leq M_{j_\ell} \varepsilon_{j_\ell}^{c_2-3},$$

so that the end-point  $k_T \Delta t_{j_\ell}$  in the time integral of (4.20) can be replaced by  $T$ . Letting  $\ell \rightarrow \infty$  in the identity (4.20), we have that the left-hand side converges to

$$\int_{E_i(T)} \phi(x) dx - \int_{E_{i,0}} \phi(x) dx$$

due to (3.10), whereas  $\text{Err}_{j_\ell} \rightarrow 0$  thanks to (4.21), (3.6) and (3.7). We are then left with studying the limit

$$\lim_{\ell \rightarrow \infty} \int_0^T \int_{\mathbb{R}^{n+1}} \phi(x) h_{\varepsilon_{j_\ell}}(x, \partial \mathcal{E}_{j_\ell}(t)) \cdot d\mu_{E_{j_\ell, i}(t)}(x) dt. \quad (4.22)$$

To this end, we first observe that, since

$$h_\varepsilon(x, V) = -\Phi_\varepsilon * \left( \frac{\Phi_\varepsilon * \delta V}{\Phi_\varepsilon * \|V\| + \varepsilon \Omega^{-1}} \right)(x),$$

and using that, by definition,  $\Omega(x) \leq \Omega(y) \exp(c_1|x-y|)$  for all  $x, y \in \mathbb{R}^{n+1}$  together with the properties of the kernel  $\Phi_\varepsilon$ , we can then estimate

$$\begin{aligned} \int_{\partial^* E_{j_\ell, i}(t)} \Omega |h_{\varepsilon_{j_\ell}}(\cdot, \partial \mathcal{E}_{j_\ell}(t))|^2 d\mathcal{H}^n &\leq C \int_{\mathbb{R}^{n+1}} \frac{|\Phi_{\varepsilon_{j_\ell}} * \delta(\partial \mathcal{E}_{j_\ell}(t))|^2 \Omega(y)}{\Phi_{\varepsilon_{j_\ell}} * \|\partial \mathcal{E}_{j_\ell}(t)\| + \varepsilon_{j_\ell} \Omega^{-1}} \frac{\Phi_{\varepsilon_{j_\ell}} * (\mathcal{H}^n \llcorner_{\partial^* E_{j_\ell, i}(t)})}{\Phi_{\varepsilon_{j_\ell}} * \|\partial \mathcal{E}_{j_\ell}(t)\| + \varepsilon_{j_\ell} \Omega^{-1}} dy \\ &\leq C \int_{\mathbb{R}^{n+1}} \frac{|\Phi_{\varepsilon_{j_\ell}} * \delta(\partial \mathcal{E}_{j_\ell}(t))|^2 \Omega(y)}{\Phi_{\varepsilon_{j_\ell}} * \|\partial \mathcal{E}_{j_\ell}(t)\| + \varepsilon_{j_\ell} \Omega^{-1}} dy. \end{aligned} \quad (4.23)$$

Therefore, for every  $T > 0$  and for every  $\phi \in C_c(\mathbb{R}^{n+1} \times [0, T])$  it holds

$$\begin{aligned} &\left| \int_0^T \int_{\mathbb{R}^{n+1}} \phi(x, t) \Omega(x) |h_{\varepsilon_{j_\ell}}(x, \partial \mathcal{E}_{j_\ell}(t)) \cdot d\mu_{E_{j_\ell, i}(t)}(x)| dt \right| \\ &\leq \left( \int_0^T \int_{\partial^* E_{j_\ell, i}(t)} \Omega |h_{\varepsilon_{j_\ell}}(x, \partial \mathcal{E}_{j_\ell}(t))|^2 d\mathcal{H}^n dt \right)^{\frac{1}{2}} \left( \int_0^T \int_{\partial^* E_{j_\ell, i}(t)} \Omega |\phi(x, t)|^2 d\mathcal{H}^n dt \right)^{\frac{1}{2}} \\ &\leq C \left( \int_0^T \int_{\mathbb{R}^{n+1}} \frac{|\Phi_{\varepsilon_{j_\ell}} * \delta(\partial \mathcal{E}_{j_\ell}(t))|^2 \Omega(y)}{\Phi_{\varepsilon_{j_\ell}} * \|\partial \mathcal{E}_{j_\ell}(t)\| + \varepsilon_{j_\ell} \Omega^{-1}} dy \right)^{\frac{1}{2}} \left( \int_0^T \int_{\partial^* E_{j_\ell, i}(t)} \Omega |\phi(x, t)|^2 d\mathcal{H}^n dt \right)^{\frac{1}{2}}, \end{aligned} \quad (4.24)$$

where the last line follows from (4.23). In particular, using (3.6) and (3.7), for any fixed  $T > 0$ ,

$$\Omega h_{\varepsilon_{j_\ell}}(\cdot, \partial \mathcal{E}_{j_\ell}(t)) \cdot d\mu_{E_{j_\ell, i}(t)} dt$$

are (signed) Radon measures in  $\mathbb{R}^{n+1} \times [0, T]$  with uniformly bounded total variation, and we can let  $\sigma_i$  denote a subsequential limit as  $\ell \rightarrow \infty$ . Since  $\mathcal{H}^n \llcorner_{\partial^* E_{j_\ell, i}(t)} \leq \|\partial \mathcal{E}_{j_\ell}(t)\|$ , and the latter measures converge, as  $\ell \rightarrow \infty$ , to  $\|V_t\|$  for every  $t \in \mathbb{R}^+$ , it is clear from (4.24) that  $\sigma_i$  is absolutely continuous with respect to the measure  $\mu_{\perp \Omega} = \Omega d\|V_t\| dt$ . We will let  $u_i$  denote the Radon–Nikodým derivative of  $\sigma_i$  with respect to  $\mu_{\perp \Omega}$ , so that

$$\sigma_i = u_i \Omega d\|V_t\| dt \quad (4.25)$$

in the sense of measures. Estimate (4.24) also implies that  $u_i \in L^2(\mu_{\perp \Omega})$ , with

$$\|u_i\|_{L^2(\mu_{\perp \Omega})} \leq C \limsup_{\ell \rightarrow \infty} \left( \int_0^T \int_{\mathbb{R}^{n+1}} \frac{|\Phi_{\varepsilon_{j_\ell}} * \delta(\partial \mathcal{E}_{j_\ell}(t))|^2 \Omega(y)}{\Phi_{\varepsilon_{j_\ell}} * \|\partial \mathcal{E}_{j_\ell}(t)\| + \varepsilon_{j_\ell} \Omega^{-1}} dy \right)^{\frac{1}{2}}.$$

Hence, we can now calculate the limit in (4.22) (along the aforementioned subsequence, not relabeled), which gives

$$\lim_{\ell \rightarrow \infty} \int_0^T \int_{\mathbb{R}^{n+1}} (\phi \Omega^{-1}) \Omega h_{\varepsilon_{j_\ell}}(\cdot, \partial \mathcal{E}_{j_\ell}(t)) \cdot d\mu_{E_{j_\ell, i}(t)} dt = \int_0^T \int_{\mathbb{R}^{n+1}} \phi u_i d\|V_t\| dt.$$

We have then concluded the existence of  $u_i \in L^2(\mu \llcorner_\Omega)$  such that

$$\int_{E_i(T)} \phi(x) dx - \int_{E_{i,0}} \phi(x) dx = \int_0^T \int_{\mathbb{R}^{n+1}} \phi(x) u_i(x, t) d\|V_t\|(x) dt$$

for all  $\phi \in C_c(\mathbb{R}^{n+1})$ , that is, we have obtained (4.5) when  $\phi$  does not depend on  $t$ .

Step four: the case of time-dependent  $\phi$ . We now consider the general case of a test function

$$\phi \in C_c^1(\mathbb{R}^{n+1} \times [0, T]).$$

The proof is analogous, with a few minor modifications which take the dependence on  $t$  into account. First, formula (4.6) becomes

$$\int_{E(T)} \phi(x, k_T \Delta t) dx - \int_{E_0} \phi(x, 0) dx = \sum_{k=0}^{k_T-1} \left\{ \int_{E_{k+1}} \phi(x, (k+1)\Delta t) dx - \int_{E_k} \phi(x, k\Delta t) dx \right\},$$

whereas formula (4.7) becomes

$$\int_{E_{k+1}} \phi(x, (k+1)\Delta t) dx - \int_{E_k} \phi(x, k\Delta t) dx = D_1 + D_2 + D_3,$$

where

$$\begin{aligned} D_1 &:= \int_{E_{k+1}^*} \phi(x, k\Delta t) dx - \int_{E_k} \phi(x, k\Delta t) dx, \\ D_2 &:= \int_{E_{k+1}} \phi(x, k\Delta t) dx - \int_{E_{k+1}^*} \phi(x, k\Delta t) dx, \\ D_3 &:= \int_{E_{k+1}} \phi(x, (k+1)\Delta t) dx - \int_{E_{k+1}} \phi(x, k\Delta t) dx. \end{aligned}$$

By the fundamental theorem of calculus and Fubini's theorem, we can immediately calculate

$$D_3 = \int_{k\Delta t}^{(k+1)\Delta t} \int_{E_{k+1}} \frac{\partial \phi}{\partial t}(x, t) dx dt.$$

The summands  $D_1$  and  $D_2$  are, instead, treated as in the time-independent case, with  $\phi$  replaced by  $\phi(\cdot, k\Delta t)$ . Identity (4.19) then becomes

$$\begin{aligned} & \int_{E_{k+1}} \phi(x, (k+1)\Delta t) dx - \int_{E_k} \phi(x, k\Delta t) dx \\ &= \int_{k\Delta t}^{(k+1)\Delta t} \int_{E_{k+1}} \frac{\partial \phi}{\partial t}(x, t) dx dt + \Delta t \left( \int_{\partial^* E_{k+1}} \phi(x, k\Delta t) \nu_{E_{k+1}} \cdot h_\varepsilon(x, \partial \mathcal{E}_{k+1}) d\mathcal{H}^n(x) + \text{Err}_{k+1} \right). \end{aligned}$$

Introducing back the subscripts  $j_\ell$  and  $i$ , we can then write

$$\begin{aligned} & \Delta t \int_{\partial^* E_{k+1}} \phi(x, k\Delta t) \nu_{E_{k+1}} \cdot h_\varepsilon(x, \partial \mathcal{E}_{k+1}) d\mathcal{H}^n(x) \\ &= \int_{k\Delta t_{j_\ell}}^{(k+1)\Delta t_{j_\ell}} \int_{\partial^* E_{j_\ell, i}(t)} \phi(x, t) \nu_{E_{j_\ell, i}(t)} \cdot h_{\varepsilon_{j_\ell}}(x, \partial \mathcal{E}_{j_\ell}(t)) d\mathcal{H}^n(x) dt + \widetilde{\text{Err}}_{k+1}, \end{aligned}$$



where

$$|\widetilde{\text{Err}}_{k+1}| \leq \Delta t_{j_\ell} \|\partial_t \phi\|_{C^0} (\max_{\text{spt} \phi} \Omega^{-1}) \int_{k\Delta t_{j_\ell}}^{(k+1)\Delta t_{j_\ell}} \int_{\partial^* E_{j_\ell, i}(t)} \Omega |h_{\varepsilon_{j_\ell}}(x, \partial \mathcal{E}_{j_\ell}(t))| d\mathcal{H}^n(x) dt.$$

Summing over  $k = 0, \dots, k_T - 1$ , we can then replace (4.20) with

$$\begin{aligned} & \int_{E_{j_\ell, i}(T)} \phi(x, k_T \Delta t_{j_\ell}) dx - \int_{E_{0, i}} \phi(x, 0) dx \\ &= \int_0^{k_T \Delta t_{j_\ell}} \int_{E_{j_\ell, i}(t)} \frac{\partial \phi}{\partial t}(x, t) dx dt + \int_0^{k_T \Delta t_{j_\ell}} \int_{\mathbb{R}^{n+1}} \phi(x, t) h_{\varepsilon_{j_\ell}}(x, \partial \mathcal{E}_{j_\ell}(t)) \cdot d\mu_{E_{j_\ell, i}(t)}(x) dt + \widetilde{\text{Err}}_{j_\ell}, \end{aligned} \quad (4.26)$$

where  $\widetilde{\text{Err}}_{j_\ell}$  contains, with respect to  $\text{Err}_{j_\ell}$ , an additional error term which can be estimated by

$$|\widetilde{\text{Err}}_{j_\ell} - \text{Err}_{j_\ell}| \leq C \varepsilon_{j_\ell}^{c_2 - 2} \|\partial_t \phi\|_{C^0} (\max_{\text{spt} \phi} \Omega^{-1}) M_{j_\ell}(T + 1),$$

where we have used (2.15). In particular, when  $\ell \rightarrow \infty$ , also  $\widetilde{\text{Err}}_{j_\ell} \rightarrow 0$ . Next, also in this case we can replace  $k_T \Delta t_{j_\ell}$  with  $T$  in the integrals on both sides of (4.26), paying an additional error term which we estimate by

$$\left| \int_T^{k_T \Delta t_{j_\ell}} \int_{E_{j_\ell, i}(t)} \frac{\partial \phi}{\partial t} dx dt \right| \leq C \varepsilon_{j_\ell}^{c_2} \|\partial_t \phi\|_{C^0} \mathcal{L}^{n+1}((\text{spt} \phi)_1),$$

and similarly for others, and they all vanish as  $\ell \rightarrow \infty$ . We can then finally conclude that

$$\int_{E_i(T)} \phi(x, T) dx - \int_{E_{i,0}} \phi(x, 0) dx = \int_0^T \int_{E_i(t)} \frac{\partial \phi}{\partial t}(x, t) dx dt + \int_0^T \int_{\mathbb{R}^{n+1}} \phi(x, t) u_i(x, t) d\|V_t\|(x) dt, \quad (4.27)$$

where  $u_i \in L^2(\mu \llcorner_{\Omega})$  is defined by (4.25).

**Step five: support of  $u_i$ .** To conclude the proof of Proposition 4.5, it only remains to show that  $\text{spt}(u_i) \subset \partial S(i)$ , where

$$S(i) = \{(x, t) \in \mathbb{R}^{n+1} \times \mathbb{R}^+ : x \in E_i(t)\}.$$

Notice that  $S(i)$  is open (relatively to  $\mathbb{R}^{n+1} \times \mathbb{R}^+$ ) by [21, Theorem 3.5 (5)]. Suppose now that  $(\hat{x}, \hat{t}) \notin \partial S(i)$ . Then either  $(\hat{x}, \hat{t}) \in S(i)$  or  $(\hat{x}, \hat{t}) \notin \text{clos}(S(i))$ . In the first case, there is a neighborhood  $(\hat{x}, \hat{t}) \in U \subset \mathbb{R}^{n+1} \times \mathbb{R}^+$  such that  $x \in E_i(t)$  for all  $(x, t) \in U$ . In particular,  $(\hat{x}, \hat{t}) \notin \text{spt} \mu \cup (\text{spt} \|V_0\| \times \{0\})$ , and since  $\sigma_i$  is absolutely continuous with respect to  $\mu$ , also  $(\hat{x}, \hat{t}) \notin \text{spt}(\sigma_i) = \text{spt}(u_i)$ .

In the second case, we have that, necessarily,  $\hat{x} \notin \text{clos}(E_i(\hat{t}))$ . Of course, if  $\hat{x} \in E_{i'}(\hat{t})$  for some  $i' \neq i$ , then  $(\hat{x}, \hat{t}) \in S(i')$ , and the above proof implies again that

$$(\hat{x}, \hat{t}) \notin \text{spt} \mu \cup (\text{spt} \|V_0\| \times \{0\}),$$

which then gives  $(\hat{x}, \hat{t}) \notin \text{spt}(u_i)$ . Thus, we can assume that  $\hat{x} \in \Gamma(\hat{t}) \setminus \text{clos}(E_i(\hat{t}))$ . Since  $(\hat{x}, \hat{t}) \notin \text{clos}(S(i))$ , there is an open neighborhood  $(\hat{x}, \hat{t}) \in U \subset \mathbb{R}^{n+1} \times \mathbb{R}^+$  such that  $U \cap \text{clos}(S(i)) = \emptyset$ , and we can choose  $U$  of the form  $U = U_r(\hat{x}) \times [0, r^2]$  if  $\hat{t} = 0$ , or  $U = U_r(\hat{x}) \times (\hat{t} - r^2, \hat{t} + r^2)$  if  $\hat{t} > 0$ . In both cases, if  $(x, t) \in U$ , then  $x \notin E_i(t)$ . For any function  $\phi \in C_c^1(U)$ , identity (4.27) then gives

$$0 = \iint_U \phi(x, t) u_i(x, t) d\|V_t\|(x) dt = \iint_U \phi(x, t) \Omega^{-1}(x) d\sigma_i(x, t).$$

Since  $\phi$  is arbitrary, we deduce then that  $|\sigma_i|(U) = 0$ , and thus that  $(\hat{x}, \hat{t}) \notin \text{spt}(\sigma_i) = \text{spt}(u_i)$ . The proof of the theorem is now complete.  $\square$

### 4.3 Boundaries move by their mean curvature

In this subsection, we complete the proof of Theorem 4.1, by achieving the representation for the measure-theoretic time derivative  $\partial_t \chi_i$  as specified in Remark 4.2. The crucial step is to prove the following lemma, for which the  $L^2$  flow property of  $\{V_t\}$  plays a pivotal role. We shall denote by  $\mathbf{p}$  and  $\mathbf{q}$  the projections of  $\mathbb{R}^{n+1} \times \mathbb{R}$  onto its factors, so that  $\mathbf{p}(x, t) = x$  and  $\mathbf{q}(x, t) = t$ .

**Lemma 4.7.** *For every  $i \in \{1, \dots, N\}$ , there is a set  $G_i \subset \partial^* S(i)$  with  $\mathcal{H}^{n+1}(\partial^* S(i) \setminus G_i) = 0$  such that the following assertions hold for every  $(x, t) \in G_i$ :*

- (i) *The tangent  $T_{(x,t)}\mu$  exists, and  $T_{(x,t)}\mu = T_{(x,t)}(\partial^* S(i))$ .*
- (ii) *Relation (4.4) holds.*
- (iii)  *$x \in \partial^* E_i(t)$  and  $T_x \|V_t\| = T_x(\partial^* E_i(t))$ .*
- (iv)  *$\mathbf{p}(v_{S(i)}(x, t)) \neq 0$  and  $v_{E_i(t)}(x) = |\mathbf{p}(v_{S(i)}(x, t))|^{-1} \mathbf{p}(v_{S(i)}(x, t))$ .*
- (v)  *$T_x(\partial^* E_i(t)) \times \{0\}$  is a linear subspace of  $T_{(x,t)}\mu$ .*

The proof of Lemma 4.7 can be deduced with relatively little effort from arguments already contained in [29], but we include it for the reader's convenience. Before proceeding, we will need some consequences of the celebrated monotonicity formula by Huisken for MCF. Since said consequences will be needed also later on in the paper, we record them here. First, let us set some notation. For  $(y, s) \in \mathbb{R}^{n+1} \times \mathbb{R}^+$ , we define the  $n$ -dimensional backwards heat kernel  $\rho_{(y,s)}$  by

$$\rho_{(y,s)}(x, t) := \frac{1}{(4\pi(s-t))^{\frac{n}{2}}} \exp\left(-\frac{|x-y|^2}{4(s-t)}\right) \quad \text{for all } t < s \text{ and } x \in \mathbb{R}^{n+1}, \quad (4.28)$$

as well as the truncated kernel

$$\hat{\rho}_{(y,s)}^r(x, t) := \eta\left(\frac{x-y}{r}\right) \rho_{(y,s)}(x, t), \quad (4.29)$$

where  $r > 0$  and  $\eta \in C_c^\infty(U_2; \mathbb{R}^+)$  is a radially symmetric function such that  $\eta \equiv 1$  on  $B_1$ ,  $0 \leq \eta \leq 1$ ,  $|\nabla \eta| \leq 2$  and  $\|\nabla^2 \eta\| \leq 4$ . The following lemma is [21, Lemma 10.3], and it is a variant of Huisken's monotonicity formula for MCF.

**Lemma 4.8.** *There exists  $c(n) > 0$  with the following property. For every  $0 \leq t_1 < t_2 < s < \infty$ ,  $y \in \mathbb{R}^{n+1}$  and  $r > 0$ , it holds*

$$\|V_t\|(\hat{\rho}_{(y,s)}^r(\cdot, t))\Big|_{t=t_1}^{t_2} \leq c(n)r^{-2}(t_2 - t_1) \sup_{t \in [t_1, t_2]} r^{-n} \|V_t\|(B_{2r}(y)).$$

As a consequence, one has the following lemma [21, Lemma 10.4], which provides a uniform upper bound on mass density ratios.

**Lemma 4.9.** *For every  $L > 1$ , there exists  $\Lambda = \Lambda(n, L, \Omega, \|\partial \mathcal{E}_0\|(\Omega)) \in (1, \infty)$  such that*

$$\sup\{r^{-n} \|V_t\|(B_r(x)) : r \in (0, 1], x \in B_L(0), t \in [L^{-1}, L]\} \leq \Lambda. \quad (4.30)$$

*Proof of Lemma 4.7.* Fix  $i \in \{1, \dots, N\}$ , and observe that, since  $\chi_i \in \text{BV}_{\text{loc}}(\mathbb{R}^{n+1} \times \mathbb{R}^+)$  is the characteristic function of  $S(i)$ , it holds  $|\nabla' \chi_i| = \mathcal{H}^{n+1} \llcorner_{\partial^* S(i)}$ . We then let  $g_i$  be the Radon–Nikodým derivative of  $\mu$  with respect to  $|\nabla' \chi_i|$ , namely

$$g_i(x, t) = \frac{d\mu}{d|\nabla' \chi_i|}(x, t) := \lim_{r \rightarrow 0^+} \frac{\mu(B_r^{n+2}(x, t))}{|\nabla' \chi_i|(B_r^{n+2}(x, t))}, \quad (4.31)$$

where  $B_r^{n+2}(x, t)$  is the closed ball with radius  $r$  and center  $(x, t)$  in  $\mathbb{R}^{n+1} \times \mathbb{R}$ . By the Lebesgue–Radon–Nikodým theorem, it holds  $g_i(x, t) < \infty$  for  $\mathcal{H}^{n+1}$ -a.e.  $(x, t) \in \partial^* S(i)$ , and

$$\mu = g_i \mathcal{H}^{n+1} \llcorner_{\partial^* S(i)} + \mu \llcorner_{\Sigma_i} \quad \text{for a set } \Sigma_i \text{ with } \mathcal{H}^{n+1}(\partial^* S(i) \cap \Sigma_i) = 0. \quad (4.32)$$

On the other hand, it is not difficult to see that

$$\mu \ll \mathcal{H}^{n+1}. \quad (4.33)$$

Indeed, first notice that, as an immediate corollary of Lemma 4.9, one has

$$\Theta^{*n+1}(\mu, (x, t)) := \limsup_{r \rightarrow 0^+} \frac{\mu(B_r^{n+2}(x, t))}{\omega_{n+1} r^{n+1}} < \infty \quad \text{for every } (x, t) \in \mathbb{R}^{n+1} \times (0, \infty). \quad (4.34)$$

Let then  $A$  be a set with  $\mathcal{H}^{n+1}(A) = 0$ , and set, for  $Q \in \mathbb{N}$ ,

$$D_Q := \{(x, t) \in \mathbb{R}^{n+1} \times (0, \infty) : \Theta^{*n+1}(\mu, (x, t)) \leq Q\}.$$

Then, by [33, Theorem 3.2], one has

$$\mu(D_Q \cap A) \leq 2^{n+1} Q \mathcal{H}^{n+1}(D_Q \cap A) = 0,$$

so that the conclusion  $\mu(A) = 0$  follows because  $\mathbb{R}^{n+1} \times (0, \infty) = \bigcup_{Q \in \mathbb{N}} D_Q$  due to (4.34).

Combining (4.32) with (4.33), we immediately have that

$$\mu \llcorner_{\partial^* S(i)} = g_i \mathcal{H}^{n+1} \llcorner_{\partial^* S(i)}. \quad (4.35)$$

Similarly, by taking the Radon–Nikodým derivative of  $|\nabla' \chi_i|$  with respect to  $\mu$ , we see that

$$\frac{d|\nabla' \chi_i|}{d\mu}(x, t) \quad \text{is finite for } \mu\text{-a.e. } (x, t).$$

Since  $|\nabla' \chi_i| \ll \mu$  by Theorem 2.11 (iv) and Corollary 4.6, this is also finite for  $|\nabla' \chi_i|$ -a.e.  $(x, t)$  and (4.31) shows that this is equal to  $1/g(x, t)$ , so that, in particular,  $g(x, t) > 0$  for  $\mathcal{H}^{n+1}$ -a.e.  $(x, t) \in \partial^* S(i)$ . Together with (4.35), the latter information implies that  $\mu \llcorner_{\partial^* S(i)}$  is an  $(n+1)$ -rectifiable measure, so that  $T_{(x,t)}(\mu \llcorner_{\partial^* S(i)})$  exists and is equal to  $T_{(x,t)}(\partial^* S(i))$  for  $\mathcal{H}^{n+1}$ -a.e.  $(x, t) \in \partial^* S(i)$ . On the other hand, by [33, Theorem 3.5], for  $\mathcal{H}^{n+1}$ -a.e.  $(x, t) \in \partial^* S(i)$  it holds

$$\lim_{r \rightarrow 0^+} \frac{\mu(B_r^{n+2}(x, t) \setminus \partial^* S(i))}{r^{n+1}} = 0. \quad (4.36)$$

If  $(x_0, t_0) \in \partial^* S(i)$  is such that (4.36) holds and  $\phi \in C_c(B_1^{n+2})$  is arbitrary, then

$$\begin{aligned} & \limsup_{r \rightarrow 0^+} \left| \int_{(\mathbb{R}^{n+1} \times \mathbb{R}^+) \setminus \partial^* S(i)} \phi(r^{-1}(x - x_0, t - t_0)) r^{-(n+1)} d\mu(x, t) \right| \\ & \leq \|\phi\|_{C^0} \lim_{r \rightarrow 0^+} \frac{\mu(B_r^{n+2}(x_0, t_0) \setminus \partial^* S(i))}{r^{n+1}} = 0. \end{aligned}$$

This shows that

$$\begin{aligned} \lim_{r \rightarrow 0^+} \int \phi(r^{-1}(x - x_0, t - t_0)) r^{-(n+1)} d\mu(x, t) &= \lim_{r \rightarrow 0^+} \int_{\partial^* S(i)} \phi(r^{-1}(x - x_0, t - t_0)) r^{-(n+1)} d\mu(x, t) \\ &= g_i(x_0, t_0) \int_{T_{(x_0, t_0)}(\partial^* S(i))} \phi(x, t) d\mathcal{H}^{n+1}(x, t) \end{aligned}$$

for every  $\phi \in C_c(\mathbb{R}^{n+1} \times \mathbb{R})$  and for  $\mathcal{H}^{n+1}$ -a.e.  $(x_0, t_0) \in \partial^* S(i)$ . This completes the proof of (i), whereas (ii) is an immediate consequence of (i) and Corollary 4.4, since, on  $\partial^* S(i)$ ,  $\mu$  and  $\mathcal{H}^{n+1}$  have the same null sets by (4.35).

Next, to prove (iii) and (iv), we are going to use the coarea formula for sets of finite perimeter, slicing  $\partial^* S(i)$  according to hyperplanes  $\{\mathbf{q} = t\}$ . Set, for  $t \in \mathbb{R}^+$ ,

$$(\partial^* S(i))_t := \partial^* S(i) \cap \{\mathbf{q} = t\} = \{x : (x, t) \in \partial^* S(i)\}.$$

Then using, e.g., [26, Theorem 18.11] together with the fact that  $S(i) \cap \{\mathbf{q} = t\} = E_i(t)$ , we have that

$$\mathcal{H}^n((\partial^* S(i))_t \Delta \partial^* E_i(t)) = 0 \quad (4.37)$$

for a.e.  $t \in \mathbb{R}^+$ . Moreover, for such  $t$ ,

$$\mathbf{p}(v_{S(i)}(x, t)) \neq 0, \quad (4.38)$$

$$v_{E_i(t)}(x) = \frac{\mathbf{p}(v_{S(i)}(x, t))}{|\mathbf{p}(v_{S(i)}(x, t))|} \quad (4.39)$$

for  $\mathcal{H}^n$ -a.e.  $x \in (\partial^* S(i))_t$ . Let

$$Z := \{t \in \mathbb{R}^+ : (4.37) \text{ fails}\},$$

and for every  $t \in \mathbb{R}^+$  set

$$Z_t := \{x \in (\partial^* S(i))_t : x \notin \partial^* E_i(t) \text{ or } (4.38) \text{ and } (4.39) \text{ fail}\},$$

so that  $\mathcal{L}^1(Z) = 0$  and, for every  $t \notin Z$ ,  $\mathcal{H}^n(Z_t) = 0$ . Consider then the Borel function  $\kappa(x, t) := \chi_{Z_t}(x)$  on  $\mathbb{R}^{n+1} \times \mathbb{R}^+$ . We have

$$\begin{aligned} 0 &= \int_0^\infty \chi_{\mathbb{R}^+ \setminus Z}(t) \mathcal{H}^n(Z_t) dt \\ &= \int_0^\infty \mathcal{H}^n(Z_t) dt \\ &= \int_0^\infty \int_{\partial^* S(i) \cap \{q=t\}} \kappa(x, t) d\mathcal{H}^n(x) dt \\ &= \int_{\partial^* S(i)} \kappa(x, t) |\nabla^{\partial^* S(i)} \mathbf{q}(x, t)| d\mathcal{H}^{n+1}(x, t), \end{aligned}$$

where in the last identity we have used the coarea formula [3, (2.72)] and where  $\nabla^{\partial^* S(i)} \mathbf{q}(x, t)$  is the tangential gradient, along  $\partial^* S(i)$ , of  $\mathbf{q}$  at  $(x, t)$ . Combining now (i) and Corollary 4.4, we see that

$$\begin{pmatrix} h(x, V_t) \\ 1 \end{pmatrix} \in T_{(x,t)}(\partial^* S(i)) \quad \text{at } \mathcal{H}^{n+1}\text{-a.e. } (x, t) \in \partial^* S(i),$$

which readily implies that  $|\nabla^{\partial^* S(i)} \mathbf{q}(x, t)| > 0$  for  $\mathcal{H}^{n+1}$ -a.e.  $(x, t) \in \partial^* S(i)$ . Hence, it must be  $\kappa(x, t) = 0$  for  $\mathcal{H}^{n+1}$ -a.e.  $(x, t) \in \partial^* S(i)$ , thus proving the first parts of (iii) and (iv). At such points, the identity

$$T_x \|V_t\| = T_x(\partial^* E_i(t))$$

is then obtained by repeating the argument in (i) at fixed  $t$ .

Finally, (v) is always true at points satisfying (i)–(iv): indeed, if  $\xi \in T_x(\partial^* E_i(t))$ , then

$$\begin{pmatrix} \xi \\ 0 \end{pmatrix} \cdot v_{S(i)}(x, t) = \xi \cdot \mathbf{p}(v_{S(i)}(x, t)) = |\mathbf{p}(v_{S(i)}(x, t))| \xi \cdot v_{E_i(t)}(x) = 0.$$

This completes the proof.  $\square$

*Proof of Theorem 4.1.* By virtue of Proposition 4.5, we only need to show the validity of equation (4.2). Fix  $i \in \{1, \dots, N\}$ . Using that  $S(i)$  is a set of locally finite perimeter in  $\mathbb{R}^{n+1} \times \mathbb{R}^+$ , for any  $0 \leq t_1 < t_2 < \infty$  and any  $\phi \in C_c^1(\mathbb{R}^{n+1} \times (t_1, t_2))$  we have that

$$\begin{aligned} \int_{\mathbb{R}^{n+1} \times \mathbb{R}^+} \frac{\partial \phi}{\partial t}(x, t) \chi_i(x, t) dx dt &= \int_{S(i)} \frac{\partial \phi}{\partial t}(x, t) dx dt \\ &= \int_{\partial^* S(i)} \phi(x, t) \mathbf{q}(v_{S(i)}(x, t)) d\mathcal{H}^{n+1}(x, t). \end{aligned} \quad (4.40)$$

Let  $G_i$  be the set of Lemma 4.7. For every  $(x, t) \in G_i$ , we have

$$T_{(x,t)}\mu = (T_x(\partial^* E_i(t)) \times \{0\}) \oplus \text{span} \begin{pmatrix} h(x, V_t) \\ 1 \end{pmatrix},$$

and thus

$$v_{S(i)}(x, t) = \frac{1}{\sqrt{1 + |h(x, V_t)|^2}} \begin{pmatrix} v_{E_i(t)}(x) \\ -h(x, V_t) \cdot v_{E_i(t)}(x) \end{pmatrix}, \quad (4.41)$$

where we have used that  $h(x, V_t) \perp T_x \|V_t\| = T_x(\partial^* E_i(t))$ . In particular, since  $\mathcal{H}^{n+1}(\partial^* S(i) \setminus G_i) = 0$ , equation (4.40) yields

$$\int_{\mathbb{R}^{n+1} \times \mathbb{R}^+} \frac{\partial \phi}{\partial t}(x, t) \chi_i(x, t) dx dt = - \int_{G_i} \phi(x, t) h(x, V_t) \cdot v_{E_i(t)}(x) \frac{1}{\sqrt{1 + |h(x, V_t)|^2}} d\mathcal{H}^{n+1}(x, t). \quad (4.42)$$

Due to (4.41), at points  $(x, t) \in G_i$  the coarea factor with respect to the slicing via  $\mathbf{q}$  is precisely

$$|\nabla^{\partial^* S(i)} \mathbf{q}(x, t)| = \frac{1}{\sqrt{1 + |h(x, V_t)|^2}},$$

so that the chain of identities in (4.42) can be continued as

$$- \int_0^\infty \int_{G_i \cap \{\mathbf{q}=t\}} \phi(x, t) h(x, V_t) \cdot v_{E_i(t)}(x) d\mathcal{H}^n(x) dt = - \int_0^\infty \int_{\partial^* E_i(t)} \phi(x, t) h(x, V_t) \cdot v_{E_i(t)}(x) d\mathcal{H}^n(x) dt,$$

again by the coarea formula. This completes the proof.  $\square$

## 5 Ilmanen's density lower bound

This section contains a proof of the following fact (Theorem 5.3 below), from which we may conclude the proofs of Theorem 2.10 (ii)–(iv): if  $\{V_t\}_{t \in \mathbb{R}^+}$  is as in Proposition 3.6, then there exists a threshold  $\theta_0 > 0$  such that, at “most” points (in a sense to be suitably specified) on the support of the evolving varifolds the mass density is not smaller than  $\theta_0$ . Such density lower bound is already stated in the work of Ilmanen [18, Section 7.1], and we include here its proof only for the sake of completeness.

Using Lemma 4.8 and Lemma 4.9, we prove next the following lemma, which is a variant of Brakke's clearing out lemma (cf. [6, Section 6.3], [18, Section 6.1] and [21, Lemma 10.6]). Recalling the notation set in (4.28) and (4.29), we define, for  $\delta > 0$ ,

$$\hat{\rho}_y^{r,\delta}(x) := \hat{\rho}_{(y,t+\delta r^2)}^r(x, t) = \eta\left(\frac{x-y}{r}\right) \frac{1}{(4\pi\delta r^2)^{\frac{n}{2}}} \exp\left(-\frac{|x-y|^2}{4\delta r^2}\right). \quad (5.1)$$

**Lemma 5.1.** *For any  $L > 1$ , there exists*

$$\delta_0 = \delta_0(n, L, \Omega, \|\partial \mathcal{E}_0\|(\Omega)) \in (0, 1)$$

*with the following property: if  $(y, t) \in B_L(0) \times [L^{-1}, L]$  and  $r \in (0, \frac{1}{2})$  are such that*

$$\|V_t\|(\hat{\rho}_y^{r,\delta_0}) < \frac{1}{2}, \quad (5.2)$$

*then  $(y, t + \delta_0 r^2) \notin \text{spt } \mu$ .*

*Proof.* For  $\delta_0 \in (0, 1)$  to be specified later, suppose towards a contradiction that  $(y, t + \delta_0 r^2) \in \text{spt } \mu$ . Then, by [21, Lemma 10.1 (2)], there is a sequence  $(y_i, t_i)$  converging to  $(y, t + \delta_0 r^2)$  such that  $V_{t_i} \in \mathbf{IV}_n(\mathbb{R}^{n+1})$  and  $y_i \in \text{spt} \|V_{t_i}\|$ . Since  $V_{t_i}$  is an integral varifold  $\mathbf{var}(M_{t_i}, \theta_{t_i})$ , in any arbitrarily small neighborhood of a point  $x \in \text{spt} \|V_{t_i}\|$  there is a point  $\tilde{x} \in M_{t_i}$  where  $M_{t_i}$  has an approximate tangent plane  $\text{Tan}(M_{t_i}, \tilde{x})$  and the density

$\Theta_{V_{t_i}}(\bar{x}) = \theta_{t_i}(\bar{x})$  is an integer. Thus, we can assume without loss of generality that  $\text{Tan}(M_{t_i}, y_i)$  exists and  $\Theta_{V_{t_i}}(y_i) \geq 1$ . Assume also without loss of generality that  $t_i > t$  for all  $i$ , and fix  $\varepsilon > 0$ . Then apply Lemma 4.8 with  $t_1 = t$ ,  $t_2 = t_i$ ,  $s = t_i + \varepsilon$  and  $y = y_i$  to get

$$\|V_s\|(\hat{\rho}_{(y_i, t_i + \varepsilon)}^r(\cdot, s))\Big|_{s=t}^{t_i} \leq c(n)r^{-2}(t_i - t) \sup_{s \in [t, t_i]} r^{-n} \|V_s\|(B_{2r}(y_i)).$$

Consider first the term

$$\begin{aligned} \|V_{t_i}\|(\hat{\rho}_{(y_i, t_i + \varepsilon)}^r(\cdot, t_i)) &= \int_{M_{t_i}} \eta\left(\frac{x - y_i}{r}\right) \rho_{(y_i, \varepsilon)}(x, 0) \theta_{t_i}(x) d\mathcal{H}^n(x) \\ &\geq \int_{M_{t_i} \cap B_r(y_i)} \rho_{(y_i, \varepsilon)}(x, 0) \theta_{t_i}(x) d\mathcal{H}^n(x). \end{aligned}$$

By the change of variable  $z = (x - y_i)/\sqrt{\varepsilon}$  in the integral on the right-hand side, it is not difficult to see that, in the limit as  $\varepsilon \rightarrow 0^+$ , the latter converges to

$$\theta_{t_i}(y_i) \int_{\text{Tan}(M_{t_i}, y_i)} \rho_{(0,1)}(z, 0) d\mathcal{H}^n(z) = \theta_{t_i}(y_i) \geq 1.$$

We can then conclude

$$1 \leq \|V_t\|(\hat{\rho}_{(y_i, t_i)}^r(\cdot, t)) + c(n)r^{-2}(t_i - t) \sup_{s \in [t, t_i]} r^{-n} \|V_s\|(B_{2r}(y_i)).$$

We let then  $i \rightarrow \infty$ : using that  $(y_i, t_i) \rightarrow (y, t + \delta_0 r^2)$  and recalling (5.1), from (4.30) we get

$$\begin{aligned} 1 &\leq \|V_t\|(\hat{\rho}_y^{r, \delta_0}) + c(n)\delta_0 \sup_{s \in [t, t + \delta_0 r^2]} r^{-n} \|V_s\|(B_{2r}(y)) \\ &\leq \|V_t\|(\hat{\rho}_y^{r, \delta_0}) + c(n)\delta_0 \Lambda(n, L + 1, \Omega, \|\partial \mathcal{E}_0\|(\Omega)). \end{aligned} \quad (5.3)$$

Choosing  $\delta_0$  such that the second summand in the right-hand side of (5.3) is less than or equal to  $\frac{1}{2}$  leads to a contradiction with (5.2).  $\square$

**Remark 5.2.** Observe that, since

$$\|V_t\|(\hat{\rho}_y^{r, \delta_0}) \leq (4\pi\delta_0)^{-\frac{n}{2}} r^{-n} \|V_t\|(U_{2r}(y)),$$

Lemma 5.1 immediately implies the following: if  $(y, t) \in B_L(0) \times [L^{-1}, L]$  is such that, for some  $r \in (0, 1)$ ,

$$r^{-n} \|V_t\|(U_r(y)) < \theta_0 := \frac{(4\pi\delta_0)^{\frac{n}{2}}}{2^{n+1}}, \quad (5.4)$$

then  $(y, t + 4^{-1}\delta_0 r^2) \notin \text{spt } \mu$ .

**Theorem 5.3.** For  $L > 1$ , let  $\theta_0 = \theta_0(n, L + 1, \Omega, \|\partial \mathcal{E}_0\|(\Omega))$  be the number defined in (5.4), and define, for  $t \geq 0$ , the sets

$$\begin{aligned} \mathcal{Z}^0 &:= \{(y, t) \in \text{spt } \mu \cap (B_L(0) \times [L^{-1}, L]) : \limsup_{r \rightarrow 0^+} r^{-n} \|V_t\|(U_r(y)) < \theta_0\}, \\ \mathcal{Z}_t^0 &:= \mathcal{Z}^0 \cap (\mathbb{R}^{n+1} \times \{t\}). \end{aligned}$$

Then there exists  $G \subset \mathbb{R}^+$  with  $\mathcal{L}^1(G) = 0$  such that  $\mathcal{H}^{n-1+\alpha}(\mathcal{Z}_t^0) = 0$  for every  $\alpha > 0$  and every  $t \in \mathbb{R}^+ \setminus G$ .

*Proof.* For every  $\theta < \theta_0$  and every  $\sigma \in (0, 1)$ , define

$$\mathcal{Z}_{\theta, \sigma}^0 := \{(y, t) \in \text{spt } \mu \cap (B_L(0) \times [L^{-1}, L]) : r^{-n} \|V_t\|(U_r(y)) < \theta \text{ for every } r \in (0, \sigma)\},$$

so that

$$\mathcal{Z}^0 = \bigcup_{\theta < \theta_0, \sigma \in (0, 1)} \mathcal{Z}_{\theta, \sigma}^0. \quad (5.5)$$

Let  $(y, t) \in \mathcal{Z}_{\theta, \sigma}^0$ . For any  $t' \in (t, t + 4^{-2}\delta_0\sigma^2]$ , let  $r > 0$  be such that  $r^2 = 4\delta_0^{-1}(t' - t)$  (so that necessarily  $r \in (0, \sigma/2]$ ), and let  $y' \in B_{\gamma r}(y)$  (with  $\gamma \in (0, 1)$  to be specified) be arbitrary. Then it holds

$$(y', t) \in B_{L+1}(0) \times [(L+1)^{-1}, L+1].$$

Furthermore, since  $U_r(y') \subset U_{(1+\gamma)r}(y)$ , and since  $(1+\gamma)r < 2r < \sigma$ , it holds

$$r^{-n} \|V_t\|(U_r(y')) < (1+\gamma)^n \theta.$$

Hence, for  $\gamma$  small enough (depending on the ratio  $\theta_0/\theta$ ) it holds  $r^{-n} \|V_t\|(U_r(y')) < \theta_0$ , so that Remark 5.2 implies that

$$(y', t + 4^{-1}\delta_0 r^2) = (y', t') \notin \text{spt } \mu.$$

In particular,  $(y', t') \notin \mathcal{Z}_{\theta, \sigma}^0$ . Analogously, if  $t' \in [t - 4^{-2}\delta_0\sigma^2, t)$  and  $y' \in B_{\gamma r}(y)$  for  $r^2 = 4\delta_0^{-1}(t - t')$  and  $\gamma$  small enough, we have that necessarily  $(y', t') \notin \mathcal{Z}_{\theta, \sigma}^0$ . Otherwise, it would be

$$((1+\gamma)r)^{-n} \|V_{t'}\|(U_{(1+\gamma)r}(y')) < \theta,$$

and thus

$$r^{-n} \|V_{t'}\|(U_r(y)) < (1+\gamma)^n \theta < \theta_0,$$

which would then imply  $(y, t' + 4^{-1}\delta_0 r^2) = (y, t) \notin \text{spt } \mu$ , a contradiction.

We have then concluded the following dichotomy:

$$\text{either } (y, t) \notin \mathcal{Z}_{\theta, \sigma}^0 \text{ or } (y', t') \notin \mathcal{Z}_{\theta, \sigma}^0 \text{ whenever } 0 < |t - t'| \leq 4^{-2}\delta_0\sigma^2 \text{ and } |y' - y|^2 \leq 4\gamma^2\delta_0^{-1}|t - t'|.$$

Therefore, if  $(y, t) \in \mathcal{Z}_{\theta, \sigma}^0$ , then the truncated double paraboloid

$$\mathcal{P}(y, t) := \{|y' - y|^2 \leq 4\gamma^2\delta_0^{-1}|t - t'| \leq 4^{-1}\gamma^2\sigma^2\}$$

intersects  $\mathcal{Z}_{\theta, \sigma}^0$  only in  $(y, t)$ . Next, setting  $2\tau := 4^{-1}\gamma^2\sigma^2$ , we consider sets

$$\mathcal{Z}_{\theta, \sigma, y_0, t_0}^0 := \mathcal{Z}_{\theta, \sigma}^0 \cap (B_1(y_0) \times [t_0 - \tau, t_0 + \tau]), \quad (y_0 \in B_L(0), t_0 \in [L^{-1}, L]),$$

so that a countable union of such sets covers  $\mathcal{Z}_{\theta, \sigma}^0$ . Fix any such set, and call it  $\mathcal{Z}'$  for the sake of simplicity: it will suffice to show that, setting  $\mathcal{Z}'_t := \mathcal{Z}' \cap (\mathbb{R}^{n+1} \times \{t\})$ , it holds  $\mathcal{H}^{n-1+\alpha}(\mathcal{Z}'_t) = 0$  for every  $\alpha > 0$  and a.e.  $t \geq 0$ . Notice that if  $(y, t) \in \mathcal{Z}'$ , then, by the definition of  $\tau$ , the set  $\mathcal{Z}' \cap (\{y\} \times \mathbb{R})$  is contained in  $\mathcal{P}(y, t)$ : in particular, for  $y \in B_1(y_0)$  the fiber  $\{y\} \times \mathbb{R}$  intersects  $\mathcal{Z}'$  in at most one point. Let  $\mathbf{p}$  be the coordinate projection  $\mathbf{p}(x, t) = x$ , fix  $\delta > 0$ , and cover the set  $\mathbf{p}(\mathcal{Z}') \subset B_1(y_0)$  by countably many open balls  $U_{r_i}(y_i)$  so that

$$r_i \leq \delta, \quad \sum_i \omega_{n+1} r_i^{n+1} \leq 2\mathcal{L}^{n+1}(B_1(y_0)). \quad (5.6)$$

For every center  $y_i$  of the balls in the covering, let  $t_i$  be the only point such that  $(y_i, t_i) \in \mathcal{Z}'$ , and notice that, as a consequence of the first part of the proof, if  $(y, t) \in \mathcal{Z}'$  with  $y \in U_{r_i}(y_i)$ , then necessarily  $|t - t_i| < 4^{-1}\gamma^{-2}\delta_0 r_i^2$ . In other words, for  $\delta$  suitably small, the cylinders

$$U_{r_i}(y_i) \times (t_i - 4^{-1}\gamma^{-2}\delta_0 r_i^2, t_i + 4^{-1}\gamma^{-2}\delta_0 r_i^2)$$

are a covering of  $\mathcal{Z}'$ . We can then estimate

$$\begin{aligned} \int_{t_0-\tau}^{t_0+\tau} \mathcal{H}_\delta^{n-1+\alpha}(\mathcal{Z}'_t) dt &\leq \int_{t_0-\tau}^{t_0+\tau} \sum_{i: |t-t_i| < 4^{-1}\gamma^{-2}\delta_0 r_i^2} \omega_{n-1+\alpha} r_i^{n-1+\alpha} dt \\ &\leq \sum_i \int_{t_i-4^{-1}\gamma^{-2}\delta_0 r_i^2}^{t_i+4^{-1}\gamma^{-2}\delta_0 r_i^2} \omega_{n-1+\alpha} r_i^{n-1+\alpha} dt \\ &\leq C(n, \alpha) \gamma^{-2} \delta_0 \delta^\alpha, \end{aligned}$$

where we have used (5.6). Letting  $\delta \rightarrow 0^+$ , we find then

$$\int_{t_0-\tau}^{t_0+\tau} \mathcal{H}^{n-1+\alpha}(Z'_t) dt = 0$$

by monotone convergence. Hence, by taking countable unions,

$$\int_0^\infty \mathcal{H}^{n-1+\alpha}((Z_{\theta,\sigma}^0)_t) dt = 0,$$

with the obvious meaning of the symbols and taking into account that  $Z'_t$  is empty when  $t < L^{-1}$  or  $t > L$ . The conclusion follows from (5.5).  $\square$

The following is the immediate corollary of Theorem 5.3, which proves Theorem 2.10 (ii).

**Corollary 5.4.** *There exists  $G \subset \mathbb{R}^+$  with  $\mathcal{L}^1(G) = 0$  such that for every  $t \in \mathbb{R}^+ \setminus G$ ,*

$$\mathcal{H}^{n-1+\alpha}(\{y \in \mathbb{R}^{n+1} : (y, t) \in \text{spt } \mu \text{ and } \lim_{r \rightarrow 0^+} r^{-n} \|V_t\|(U_r(y)) = 0\}) = 0 \quad \text{for all } \alpha > 0. \quad (5.7)$$

In particular, by recalling from Theorem 2.10 (i) and Theorem 2.11 (iii) that  $\text{spt}\|V_t\| \subset \{x : (x, t) \in \text{spt } \mu\} = \Gamma(t)$ , the set

$$\Gamma(t) = \mathbb{R}^{n+1} \setminus \bigcup_{i=1}^N E_i(t) = \bigcup_{i=1}^N \partial E_i(t)$$

is  $\mathcal{H}^n$ -equivalent to  $\text{spt}\|V_t\|$  for a.e.  $t \geq 0$ , and in fact

$$\dim_{\mathcal{H}^n}(\Gamma(t) \setminus \text{spt}\|V_t\|) \leq n - 1 \quad \text{for a.e. } t \geq 0.$$

Since  $V_t \in \mathbf{IV}_n(\mathbb{R}^{n+1})$  for a.e.  $t \geq 0$ , there exists a countably  $n$ -rectifiable set  $\tilde{\Gamma}(t)$  such that  $V_t = \mathbf{var}(\tilde{\Gamma}(t), \theta_t)$  and  $\theta_t(x) = \Theta^n(\|V_t\|, x)$ . By definition, we have  $\mathcal{H}^n(\tilde{\Gamma}(t) \setminus \text{spt}\|V_t\|) = 0$ , and by [33, Theorem 3.5] we have  $\Theta^n(\|V_t\|, x) = 0$  for  $\mathcal{H}^n$ -a.e.  $x \in \text{spt}\|V_t\| \setminus \tilde{\Gamma}(t)$ . The latter claim shows that  $\text{spt}\|V_t\| \setminus \tilde{\Gamma}(t)$  is included in the set appearing in (5.7), and we can conclude that  $\tilde{\Gamma}(t)$  is  $\mathcal{H}^n$ -equivalent to  $\text{spt}\|V_t\|$ . This proves Theorem 2.10 (iii) and (iv).

## 6 Two-sidedness at unit density point

In this section, we prove Theorem 2.11 (vii) and (viii), which are restated in Propositions 6.3 and 6.4, respectively. To do so, we need to analyze the behavior of approximating flows. The first Lemma 6.1 shows that, for a.e.  $t$ , only the reduced boundaries of approximating grains contribute to the limit measure and that the measures coming from “interior boundaries”  $\partial E_{j_\ell, k}(t) \setminus \partial^* E_{j_\ell, k}(t)$  vanish in the limit. Roughly speaking, this is due to the measure minimizing property in the length scale of  $o(1/j^2)$  which has the effect of eliminating the interior boundaries.

**Lemma 6.1.** *For a.e.  $t \in \mathbb{R}^+$  and  $\mathcal{E}_{j_\ell}(t) = \{E_{j_\ell, k}(t)\}_{k=1}^N$  in Theorem 3.6, we have*

$$\lim_{\ell \rightarrow \infty} \sum_{k=1}^N \|\partial^* E_{j_\ell, k}(t)\| = 2\mu_t. \quad (6.1)$$

*Proof.* We fix  $t$  such that

$$\lim_{\ell \rightarrow \infty} \frac{\Delta_{j_\ell}^{\text{vc}} \|\partial \mathcal{E}_{j_\ell}(t)\|(\Omega)}{j_\ell \Delta t_{j_\ell}} = 0, \quad (6.2)$$

which holds for a.e.  $t \in \mathbb{R}^+$  due to (3.7), and we drop  $t$  for simplicity in the following. It is sufficient to prove that

$$\lim_{\ell \rightarrow \infty} \mathcal{H}^n \left( U_R \cap \text{spt}\|\partial \mathcal{E}_{j_\ell}\| \setminus \bigcup_{k=1}^N \partial^* E_{j_\ell, k} \right) = 0$$



for arbitrary  $R \geq 1$  since

$$\begin{aligned} \text{spt}\|\partial\mathcal{E}_{j_\ell}\| &\subset \bigcup_{k=1}^N \partial E_{j_\ell,k}, \\ \mathcal{H}^n\left(\bigcup_{k=1}^N \partial E_{j_\ell,k} \setminus \text{spt}\|\partial\mathcal{E}_{j_\ell}\|\right) &= 0, \\ 2\|\partial\mathcal{E}_{j_\ell}\| &= \sum_{k=1}^N \|\partial^* E_{j_\ell,k}\| + 2\mathcal{H}^n \llcorner_{\text{spt}\|\partial\mathcal{E}_{j_\ell}\| \setminus \bigcup_{k=1}^N \partial^* E_{j_\ell,k}}. \end{aligned}$$

As in [22, Section 4], let  $r_\ell := 1/(j_\ell)^{5/2}$ . Define

$$Z_\ell := \{x \in U_R \cap \text{spt}\|\partial\mathcal{E}_{j_\ell}\| : \|\partial\mathcal{E}_{j_\ell}\|(B_{r_\ell}(x)) \leq c_3 r_\ell^n\} \quad \text{and} \quad Z_\ell^c := U_R \cap \text{spt}\|\partial\mathcal{E}_{j_\ell}\| \setminus Z_\ell,$$

where  $c_3$  is the same constant appearing in [21, Proposition 7.2] and apply it to each ball  $B_{r_\ell}(\hat{x})$  with  $\hat{x} \in Z_\ell$  to estimate  $\|\partial\mathcal{E}_{j_\ell}\|(B_{r_\ell/2}(\hat{x}))$ : there exists  $c_4 = c_4(n)$  as in the claim and an  $\mathcal{E}_{j_\ell}$ -admissible function  $f$  and  $r \in [r_\ell/2, r_\ell]$  such that the following conditions hold:

- (i)  $f(x) = x$  for  $x \in \mathbb{R}^{n+1} \setminus U_r(\hat{x})$ .
- (ii)  $f(x) \in B_r(\hat{x})$  for  $x \in B_r(\hat{x})$ .
- (iii) It holds

$$\|\partial f_* \mathcal{E}_{j_\ell}\|(B_r(\hat{x})) \leq \frac{1}{2} \|\partial\mathcal{E}_{j_\ell}\|(B_r(\hat{x})).$$

- (iv) For all  $k$ ,

$$\mathcal{L}^{n+1}(E_{j_\ell,k} \Delta \tilde{E}_{j_\ell,k}) \leq c_4 (\|\partial\mathcal{E}_{j_\ell}\|(B_r(\hat{x})))^{\frac{n+1}{n}},$$

where  $\{\tilde{E}_{j_\ell,k}\}_{k=1}^N = f_* \mathcal{E}_{j_\ell}$ .

We may use Lemma 3.5 with  $C = B_r(\hat{x})$  and above (i)–(iv) to check that  $f \in \mathbf{E}^{\text{vc}}(\mathcal{E}_{j_\ell}, j_\ell)$  as long as  $j_\ell$  is large enough (actually, if  $\exp(-j_\ell/2r_\ell) = \exp(-j_\ell^{3/2}/2) < \frac{1}{2}$ ). Then, by the definition of  $\Delta_{j_\ell}^{\text{vc}}\|\partial\mathcal{E}_{j_\ell}\|(\Omega)$ , (i) and (iii) as well as  $\max_{B_r(\hat{x})} \Omega \leq \exp(2c_1 r_\ell) \min_{B_r(\hat{x})} \Omega$ , we have

$$\begin{aligned} \Delta_{j_\ell}^{\text{vc}}\|\partial\mathcal{E}_{j_\ell}\|(\Omega) &\leq \|\partial f_* \mathcal{E}_{j_\ell}\|(\Omega) - \|\partial\mathcal{E}_{j_\ell}\|(\Omega) \\ &\leq (\min_{B_r(\hat{x})} \Omega) \{ \exp(2c_1 r_\ell) \|\partial f_* \mathcal{E}_{j_\ell}\|(B_r(\hat{x})) - \|\partial\mathcal{E}_{j_\ell}\|(B_r(\hat{x})) \} \\ &\leq (\min_{B_r(\hat{x})} \Omega) \left( \frac{1}{2} \exp(2c_1 r_\ell) - 1 \right) \|\partial\mathcal{E}_{j_\ell}\|(B_r(\hat{x})) \\ &\leq -\frac{\min_{B_{2R}} \Omega}{4} \|\partial\mathcal{E}_{j_\ell}\|(B_r(\hat{x})) \\ &\leq -\frac{\min_{B_{2R}} \Omega}{4} \|\partial\mathcal{E}_{j_\ell}\|(B_{r_\ell/2}(\hat{x})) \end{aligned} \tag{6.3}$$

for all sufficiently large  $j_\ell$ . By the Besicovitch covering theorem, we have a mutually disjoint set of closed balls  $\{B_{r_\ell/2}(\hat{x}_i)\}_{\hat{x}_i \in Z_\ell}$  (whose number is at most  $c(n)r_\ell^{-n-1}$ ) such that

$$\|\partial\mathcal{E}_{j_\ell}\|(Z_\ell) \leq \mathbf{B}(n) \sum \|\partial\mathcal{E}_{j_\ell}\|(B_{r_\ell/2}(\hat{x}_i)), \tag{6.4}$$

and (6.3) and (6.4) show that

$$\|\partial\mathcal{E}_{j_\ell}\|(Z_\ell) \leq -\frac{c(n)}{r_\ell^{n+1} \min_{B_{2R}} \Omega} \Delta_{j_\ell}^{\text{vc}}\|\partial\mathcal{E}_{j_\ell}\|(\Omega). \tag{6.5}$$

Since  $-\Delta_{j_\ell}^{\text{vc}}\|\partial\mathcal{E}_{j_\ell}\|(\Omega) \ll r_\ell^{n+1}$  due to (6.2), the right-hand side of (6.5) converges to 0 as  $\ell \rightarrow \infty$ . By (6.5), we need to prove

$$\lim_{\ell \rightarrow \infty} \mathcal{H}^n\left(Z_\ell^c \setminus \bigcup_{k=1}^N \partial^* E_{j_\ell,k}\right) = 0. \tag{6.6}$$

By the Besicovitch covering theorem, we have a set of mutually disjoint balls  $\{B_{r_\ell}(x_i)\}$  with

$$x_i \in Z_\ell^c \setminus \bigcup_{k=1}^N \partial^* E_{j_\ell, k}$$

such that

$$\mathcal{H}^n\left(Z_\ell^c \setminus \bigcup_{k=1}^N \partial^* E_{j_\ell, k}\right) \leq \mathbf{B}(n) \sum_i \mathcal{H}^n\left(B_{r_\ell}(x_i) \cap Z_\ell^c \setminus \bigcup_{k=1}^N \partial^* E_{j_\ell, k}\right). \quad (6.7)$$

Because of the lower bound of the measure  $\|\partial \mathcal{E}_{j_\ell}\|(B_{r_\ell}(x_i)) \geq c_3 r_\ell^n$  for  $x_i \in Z_\ell^c$ , the number of disjoint balls is bounded by  $c_3^{-1} r_\ell^{-n} \|\partial \mathcal{E}_{j_\ell}\|(B_{2R})$ . If we prove that

$$\limsup_{\ell \rightarrow \infty} \sum_i r_\ell^{-n} \mathcal{H}^n\left(B_{r_\ell}(x_i) \cap Z_\ell^c \setminus \bigcup_{k=1}^N \partial^* E_{j_\ell, k}\right) = 0, \quad (6.8)$$

combined with (6.7), we would prove (6.6), ending the proof. Assume for a contradiction that (6.8) were not true and we had a subsequence (denoted by the same index)  $x_\ell \in Z_\ell^c$  such that

$$0 < \alpha \leq r_\ell^{-n} \mathcal{H}^n\left(B_{r_\ell}(x_\ell) \cap Z_\ell^c \setminus \bigcup_{k=1}^N \partial^* E_{j_\ell, k}\right). \quad (6.9)$$

Consider a rescaling  $F_\ell : \mathbb{R}^{n+1} \rightarrow \mathbb{R}^{n+1}$  defined by  $F_\ell(x) = (x - x_\ell)/r_\ell$  and consider sequences  $V_\ell := (F_\ell)_\#(\partial \mathcal{E}_{j_\ell})$  and  $F_\ell(E_{j_\ell, k})$  ( $k = 1, \dots, N$ ). This rescaling was discussed in [22, Section 4], and there exist a subsequence (denoted by the same index) and a limit  $V \neq 0$  with the properties stated in [22, Theorem 4.1], which shows that  $V$  is a unit density varifold and  $\text{spt}\|V\|$  is a real-analytic minimal hypersurface away from a closed lower-dimensional singularity. Moreover,  $\text{spt}\|V\|$  is two-sided in the following sense. Let  $E_1, \dots, E_N \subset \mathbb{R}^{n+1}$  be limits of  $F_\ell(E_{j_\ell, 1}), \dots, F_\ell(E_{j_\ell, N})$  (see [22, p. 517]). By the lower-semicontinuity of the BV function, we have  $\|\partial^* E_k\| \leq \|V\|$ , and  $\{E_1, \dots, E_N\}$  can be defined so that they are mutually disjoint open sets such that  $\mathbb{R}^{n+1} \setminus \text{spt}\|V\| = \bigcup_{k=1}^N E_k$ . The two-sidedness means that, at each regular point  $x$  of  $\text{spt}\|V\|$ , there are two distinct indices  $k_1, k_2 \in \{1, \dots, N\}$  such that  $x \in \text{clos } E_{k_1} \cap \text{clos } E_{k_2}$  (see [22, Lemma 4.8]). In particular, this implies that

$$\|V\| = \frac{1}{2} \sum_{k=1}^N \|\partial^* E_k\|. \quad (6.10)$$

On the other hand, (6.9) implies that

$$\begin{aligned} \|V_\ell\|(U_2) &= \|V_\ell\|\left(U_2 \setminus \bigcup_{k=1}^N \partial^*(F_\ell(E_{j_\ell, k}))\right) + \|V_\ell\|\left(U_2 \cap \bigcup_{k=1}^N \partial^*(F_\ell(E_{j_\ell, k}))\right) \\ &\geq r_\ell^{-n} \mathcal{H}^n\left(U_{2r_\ell}(x_\ell) \cap Z_\ell^c \setminus \bigcup_{k=1}^N \partial^* E_{j_\ell, k}\right) + \|V_\ell\|\left(U_2 \cap \bigcup_{k=1}^N \partial^*(F_\ell(E_{j_\ell, k}))\right) \\ &\geq \alpha + \frac{1}{2} \sum_{k=1}^N \|\partial^*(F_\ell(E_{j_\ell, k}))\|(U_2). \end{aligned} \quad (6.11)$$

Since

$$\|\partial^* E_k\|(U_2) \leq \liminf_{\ell \rightarrow \infty} \|\partial^*(F_\ell(E_{j_\ell, k}))\|(U_2) \quad (6.12)$$

for each  $k$ , (6.10)–(6.12) show

$$\|V\|(U_2) \leq \liminf_{\ell \rightarrow \infty} \|V_\ell\|(U_2) - \alpha \leq \|V\|(B_2) - \alpha.$$

Since  $\|V\|(\partial U_2) = 0$ , this is a contradiction. The argument up to this point shows (6.8), which in turn shows the claim (6.1).  $\square$

The next Lemma 6.2 shows that  $\partial \mathcal{E}_{j_\ell}(t)$  is locally and subsequentially close to “ $\theta$ -layered sheets” after appropriate blow-ups, for almost all times and places.

**Lemma 6.2.** For  $\mathcal{L}^1$ -a.e.  $t \in \mathbb{R}^+$  and  $\mathcal{H}^n$ -a.e.  $x \in \text{spt}\|V_t\|$ , there exist  $\theta := \Theta^n(\|V_t\|, x) \in \mathbb{N}$ ,

$$T := \text{Tan}(\|V\|, x) \in \mathbf{G}(n+1, n),$$

$r_\ell \rightarrow 0+$ , a subsequence  $\{j'_\ell\}_{\ell=1}^\infty \subset \{j_\ell\}_{\ell=1}^\infty$  and  $\mathcal{H}^n$ -measurable sets  $W_\ell \subset T \cap B_{r_\ell}$  with the following property (after a change of variable, we may assume that  $x = 0$  in the following). Define  $f_{(r_\ell)}(y) := y/r_\ell$  for  $y \in \mathbb{R}^{n+1}$  and  $\{E_{j'_\ell,1}, \dots, E_{j'_\ell,N}\} := \mathcal{E}_{j'_\ell}(t)$ . Then we have

$$\lim_{\ell \rightarrow \infty} (f_{(r_\ell)})_\# \partial \mathcal{E}_{j'_\ell}(t) = \mathbf{var}(T, \theta) \quad (6.13)$$

as varifolds,

$$\mathcal{H}^0\left(B_{r_\ell} \cap T^{-1}(a) \cap \bigcup_{i=1}^N \partial E_{j'_\ell,i}\right) = \theta \quad (6.14)$$

for all  $a \in W_\ell$ , and

$$\lim_{\ell \rightarrow \infty} \sup_{a \in W_\ell} \left\{ \left| T^{-1}\left(\frac{x}{r_\ell}\right) \right| : x \in B_{r_\ell} \cap T^{-1}(a) \cap \bigcup_{i=1}^N \partial E_{j'_\ell,i} \right\} = 0, \quad (6.15)$$

$$\lim_{\ell \rightarrow \infty} \frac{\mathcal{H}^n(W_\ell)}{\omega_n r_\ell^n} = 1. \quad (6.16)$$

The claims (6.14) and (6.15) also hold with  $\partial^* E_{j'_\ell,i}$  in place of  $\partial E_{j'_\ell,i}$ .

*Proof.* Without loss of generality, assume that  $t \in \mathbb{R}^+$  satisfies

$$\liminf_{\ell \rightarrow \infty} \left( \int_{\mathbb{R}^{n+1}} \frac{|\Phi_{\varepsilon_{j_\ell}} * \delta(\partial \mathcal{E}_{j_\ell}(t))|^2 \Omega}{\Phi_{\varepsilon_{j_\ell}} * \|\partial \mathcal{E}_{j_\ell}(t)\| + \varepsilon_{j_\ell} \Omega^{-1}} dx - \frac{1}{\Delta t_{j_\ell}} \Delta_{j_\ell}^{\text{vc}} \|\partial \mathcal{E}_{j_\ell}(t)\|(\Omega) \right) < \infty, \quad (6.17)$$

which holds for a.e.  $t \in \mathbb{R}^+$  by (3.7) and Fatou's lemma. By the compactness theorem of [21, Theorem 8.6], we may conclude that there exists a converging subsequence in the sense of varifolds  $\{\partial \mathcal{E}_{j_\ell}(t)\}_{\ell=1}^\infty$  (denoted by the same index) and the limit  $V_t \in \mathbf{IV}_n(\mathbb{R}^{n+1})$  with  $\mu_t = \|V_t\|$ . By (3.10), each  $\{E_{j_\ell,i}(t)\}_{\ell=1}^\infty$  also converges to  $E_i(t)$  in  $L^1_{\text{loc}}(\mathbb{R}^{n+1})$  for  $i = 1, \dots, N$ .

By Corollary 5.4, for a.e.  $t \in \mathbb{R}^+$ , we have

$$\theta_t \mathcal{H}^n \llcorner_{\bigcup_{i=1}^N \partial E_i(t)} = \theta_t \mathcal{H}^n \llcorner_{\text{spt}\|V_t\|} = \|V_t\|,$$

where  $\theta_t(x) := \Theta^n(\|V_t\|, x)$  is  $\mathcal{H}^n$ -a.e. integer-valued. Note in particular that  $\text{spt}\|V_t\|$  as well as  $\bigcup_{i=1}^N \partial E_i(t)$  are countably  $n$ -rectifiable. We fix such a generic  $t$  and subsequently drop the dependence of  $t$ .

In the following, we use the same argument in the proof of [21, Theorem 8.6]. Let  $\{\varepsilon_{j_\ell}\}_{\ell=1}^\infty$  be a subsequence (denoted by the same index) such that the quantity in (6.17) is uniformly bounded. Let  $U \subset \mathbb{R}^{n+1}$  be a bounded open set. It is sufficient to prove the claim on  $U$ . As in [21, pp. 112–113], for each  $j, q \in \mathbb{N}$ , let  $A_{j,q}$  be a set consisting of all  $x \in \text{clos } U$  such that

$$\|\delta(\Phi_{\varepsilon_j} * \partial \mathcal{E}_j)\|(B_r(x)) \leq q \|\Phi_{\varepsilon_j} * \partial \mathcal{E}_j\|(B_r(x))$$

for all  $r \in (j^{-2}, 1)$ , and additionally define

$$A_q := \{x \in \text{clos } U : \text{there exist } x_\ell \in A_{j_\ell, q} \text{ for infinitely many } \ell \text{ with } x_\ell \rightarrow x\}.$$

Following the argument in [21, p. 113], one can prove that

$$\|V\| \left( U \setminus \bigcup_{q=1}^\infty A_q \right) = 0.$$

Thus, for  $\mathcal{H}^n$ -a.e.  $x \in \text{spt}\|V\|$ , we have some  $q \in \mathbb{N}$  such that  $x \in A_q$ , and additionally the approximate tangent space exists with multiplicity  $\theta \in \mathbb{N}$ . Without loss of generality, we may assume that  $x = 0$  and write

$T := \text{Tan}(\|V\|, x)$ . Since  $0 \in A_q$ , there exists a further subsequence of  $\{j_\ell\}_{\ell=1}^\infty$  (denoted by the same index) such that  $x_{j_\ell} \in A_{j_\ell, q}$  with  $\lim_{\ell \rightarrow \infty} x_{j_\ell} = 0$ . Set  $r_\ell = \frac{1}{\ell}$  and define  $f_{(r_\ell)}(x) := x/r_\ell$  and

$$V_{j_\ell} := (f_{(r_\ell)})_\# \partial \mathcal{E}_{j_\ell}, \quad \tilde{V}_{j_\ell} := (f_{(r_\ell)})_\# (\Phi_{\mathcal{E}_{j_\ell}} * \partial \mathcal{E}_{j_\ell}), \quad V_{j_\ell}^* := (f_{(r_\ell)})_\# \partial^* \mathcal{E}_{j_\ell},$$

where  $\partial^* \mathcal{E}_{j_\ell}$  denotes the unit density varifold defined from  $\bigcup_{i=1}^N \partial^* E_{j_\ell, i}$ . We may choose a further subsequence with the following properties:

$$\lim_{\ell \rightarrow \infty} V_{j_\ell} = \lim_{\ell \rightarrow \infty} \tilde{V}_{j_\ell} = \mathbf{var}(T, \theta), \quad (6.18)$$

$$\begin{aligned} \lim_{\ell \rightarrow \infty} \frac{x_{j_\ell}}{r_\ell} &= 0, & \lim_{\ell \rightarrow \infty} \frac{j_\ell^{-1}}{r_\ell} &= 0, \\ \lim_{\ell \rightarrow \infty} r_\ell^{-n} \mathcal{H}^n(B_{r_\ell} \cap \partial \mathcal{E}_{j_\ell} \setminus \partial^* \mathcal{E}_{j_\ell}) &= 0. \end{aligned} \quad (6.19)$$

Note that the choice with (6.19) is possible due to (6.1). We then proceed verbatim as in [21, pp. 114–120] with  $\nu = \theta + 1$  and  $d = \theta$ . In particular, we fix  $\lambda \in (1, 2)$  such that  $\lambda^{n+1}\theta < \theta + 1$  (as in [21, (8.111)]) and we use [21, Lemma 8.5]. In summary, with the same notation as in [21], we obtain a sequence of sets  $G_\ell^{**} \subset \partial \mathcal{E}_{j_\ell} \cap B_{(\lambda-1)r_\ell}$  with the following properties for all large enough  $\ell$ :

$$\lim_{\ell \rightarrow \infty} r_\ell^{-n} \|\partial \mathcal{E}_{j_\ell}\|(B_{(\lambda-1)r_\ell} \setminus G_\ell^{**}) = 0, \quad (6.20)$$

$$\lim_{\ell \rightarrow \infty} \sup \left\{ \left| T^\perp \left( \frac{x}{r_\ell} \right) \right| : x \in G_\ell^{**} \right\} = 0, \quad (6.21)$$

$$\sup_{a \in T \cap B_{(\lambda-1)r_\ell}} \mathcal{H}^0(\{x \in G_\ell^{**} : T(x) = a\}) \leq \theta. \quad (6.22)$$

These claims are, respectively, [21, (8.154), (8.156) (stated differently) and (8.159)]. The measurability of  $G_\ell^{**}$  is not stated in [21]. However, since each step to estimate  $\|\partial \mathcal{E}_{j_\ell}\|(B_{(\lambda-1)r_\ell} \setminus G_\ell^{**})$  uses covering arguments, if necessary, we may simply take the complement of these coverings with no change of estimates and obtain a possibly smaller  $G_\ell^{**}$  which is a Borel set. We next prove that, writing  $\tilde{g}_\ell(a) := \mathcal{H}^0(\{x \in G_\ell^{**} : T(x) = a\})$  for  $a \in T$ , we have

$$\lim_{\ell \rightarrow \infty} \frac{\mathcal{H}^n(\{a \in T \cap B_{(\lambda-1)r_\ell} : \tilde{g}_\ell(a) = \theta\})}{\omega_n (\lambda-1)^n r_\ell^n} = 1. \quad (6.23)$$

Note that  $\tilde{g}_\ell(a)$  as above on  $T$  is  $\mathcal{H}^n$ -measurable (see [11, Lemma 5.8]). To see (6.23), first, by (6.18) and (6.20), we have

$$\lim_{\ell \rightarrow \infty} (f_{(r_\ell)})_\# (\partial \mathcal{E}_{j_\ell} \llcorner_{G_\ell^{**} \times \mathbf{G}(n+1, n)}) = \mathbf{var}(T \cap B_{\lambda-1}, \theta) \quad (6.24)$$

as varifolds. We also have

$$\|T_\# \circ (f_{(r_\ell)})_\# (\partial \mathcal{E}_{j_\ell} \llcorner_{G_\ell^{**} \times \mathbf{G}(n+1, n)})\|(B_{\lambda-1}) = (r_\ell)^{-n} \int_T \tilde{g}_\ell(a) d\mathcal{H}^n(a). \quad (6.25)$$

Since  $T_\#$  commutes with  $\lim_{\ell \rightarrow \infty}$  and  $T_\# \mathbf{var}(T \cap B_{\lambda-1}, 1) = \mathbf{var}(T \cap B_{\lambda-1}, 1)$ , (6.24) and (6.25) show that

$$\theta \omega_n (\lambda-1)^n = \lim_{\ell \rightarrow \infty} (r_\ell)^{-n} \int_T \tilde{g}_\ell(a) d\mathcal{H}^n(a). \quad (6.26)$$

Since  $\tilde{g}_\ell \leq \theta$  due to (6.22) (note also  $G_\ell^{**} \subset B_{(\lambda-1)r_\ell}$ ), equation (6.26) shows

$$0 = \lim_{\ell \rightarrow \infty} (r_\ell)^{-n} \int_{T \cap B_{(\lambda-1)r_\ell}} (\theta - \tilde{g}_\ell) d\mathcal{H}^n \geq \lim_{\ell \rightarrow \infty} (r_\ell)^{-n} \mathcal{H}^n(T \cap B_{(\lambda-1)r_\ell} \cap \{\tilde{g}_\ell \leq \theta - 1\}). \quad (6.27)$$

Then (6.22) and (6.27) show (6.23). Finally, we define

$$W_\ell := \{a \in T : \tilde{g}_\ell(a) = \theta\} \setminus (T \cap \partial \mathcal{E}_{j_\ell} \cap B_{(\lambda-1)r_\ell} \setminus G_\ell^{**}) \cup T \cap \partial \mathcal{E}_{j_\ell} \cap B_{(\lambda-1)r_\ell} \setminus \partial^* \mathcal{E}_{j_\ell}. \quad (6.28)$$

Since  $\tilde{g}_\ell$  is  $\mathcal{H}^n$ -measurable, so is  $W_\ell$ . Due to (6.19), (6.20) and (6.23), we can deduce (6.16). For any  $a \in W_\ell$ ,  $T^{-1}(a) \cap \partial \mathcal{E}_{j_\ell} \cap B_{(\lambda-1)r_\ell}$  consists of  $\theta$  points belonging to  $G_\ell^{**} \cap \partial^* \mathcal{E}_{j_\ell}$  by (6.28). This proves (6.14) (both with  $\partial \mathcal{E}_{j_\ell}$  and  $\partial^* \mathcal{E}_{j_\ell}$ ). This combined with (6.21) also proves (6.15), and we may conclude the proof after renaming  $(\lambda-1)r_\ell$  as  $r_\ell$ .  $\square$

**Proposition 6.3.** For  $V_t$  and  $\{E_i(t)\}_{i=1}^N$  in Proposition 3.6, for a.e.  $t \in \mathbb{R}^+$ , we have

$$\mathcal{H}^n\left(\{x : \theta_t(x) = 1\} \setminus \bigcup_{i=1}^N \partial^* E_i(t)\right) = 0. \quad (6.29)$$

*Proof.* We prove (6.29) for a.e.  $t$  such that the conclusion of Lemma 6.2 holds. With such  $t$  fixed, we drop  $t$  and suppose that (6.29) were not true for a contradiction. We may apply the result of Lemma 6.2 and find a point  $x \in \text{spt}\|V\| \setminus \bigcup_{i=1}^N \partial^* E_i$  with  $\Theta^n(\|V\|, x) = 1$  and  $T := \text{Tan}(\|V\|, x)$ . Moreover, by the well-known property of the set of finite perimeter, there exists some  $k \in \{1, \dots, N\}$  such that

$$\lim_{r \rightarrow 0} \frac{\mathcal{L}^{n+1}(E_k \cap B_r(x))}{\omega_{n+1} r^{n+1}} = 1.$$

Without loss of generality, we may assume that  $x = 0$ ,  $T = \{x_{n+1} = 0\}$  and  $k = 1$ . Since  $\chi_{E_{j_\ell, 1}} \rightarrow \chi_{E_1}$  in  $L^1_{\text{loc}}$  as  $\ell \rightarrow \infty$ , in choosing the subsequence (denoted by the same index) in Lemma 6.2, we may additionally arrange the choice so that we have

$$\lim_{\ell \rightarrow \infty} \frac{\mathcal{L}^{n+1}(E_{j_\ell, 1} \cap B_{r_\ell})}{\omega_{n+1} r_\ell^{n+1}} = 1. \quad (6.30)$$

For simplicity, write the union of the measure-theoretic boundaries as  $\partial_* \mathcal{E}_{j_\ell} := \bigcup_{i=1}^N \partial_* E_{j_\ell, i}$ . Since  $\partial \mathcal{E}_{j_\ell}$  is closed, we remind the reader that

$$\partial^* \mathcal{E}_{j_\ell} \subset \partial_* \mathcal{E}_{j_\ell} \subset \partial \mathcal{E}_{j_\ell}. \quad (6.31)$$

We also define the measure-theoretic interior and exterior of  $E_{j_\ell, 1}$  (see [11, Definition 5.13]) by

$$I_\ell := \left\{x \in \mathbb{R}^{n+1} : \lim_{r \rightarrow 0} \frac{\mathcal{L}^{n+1}(B_r(x) \setminus E_{j_\ell, 1})}{r^{n+1}} = 0\right\}$$

and

$$O_\ell := \left\{x \in \mathbb{R}^{n+1} : \lim_{r \rightarrow 0} \frac{\mathcal{L}^{n+1}(B_r(x) \cap E_{j_\ell, 1})}{r^{n+1}} = 0\right\}.$$

We note from the definition that

$$I_\ell \cap \partial_* \mathcal{E}_{j_\ell} = \emptyset. \quad (6.32)$$

We next use some results in the proof of [11, Theorem 5.23] on the property of measure-theoretic interior and exterior. For each  $m, k \in \mathbb{N}$ , define

$$\begin{cases} G_\ell(k) := \left\{x \in \mathbb{R}^{n+1} : \mathcal{L}^{n+1}(B_r(x) \cap O_\ell) \leq \frac{\omega_n r^{n+1}}{3^{n+2}} \text{ for } 0 < r < \frac{3}{k}\right\}, \\ H_\ell(k) := \left\{x \in \mathbb{R}^{n+1} : \mathcal{L}^{n+1}(B_r(x) \cap I_\ell) \leq \frac{\omega_n r^{n+1}}{3^{n+2}} \text{ for } 0 < r < \frac{3}{k}\right\} \end{cases} \quad (6.33)$$

and

$$\begin{cases} G_\ell^\pm(k, m) := G_\ell(k) \cap \left\{x : x \pm s e_{n+1} \in O_\ell \text{ for } 0 < s < \frac{3}{m}\right\}, \\ H_\ell^\pm(k, m) := H_\ell(k) \cap \left\{x : x \pm s e_{n+1} \in I_\ell \text{ for } 0 < s < \frac{3}{m}\right\}. \end{cases} \quad (6.34)$$

Here  $e_{n+1}$  is the unit vector pointing towards the positive direction of the  $x_{n+1}$ -axis. These sets have the property (see [11, step 3 of Theorem 5.23]) that

$$\mathcal{H}^n(T(G_\ell^\pm(k, m))) = \mathcal{H}^n(T(H_\ell^\pm(k, m))) = 0$$

for all  $k, m \in \mathbb{N}$ . Moreover, for all

$$a \in T \setminus \bigcup_{k, m=1}^{\infty} T(G_\ell^+(k, m) \cup G_\ell^-(k, m) \cup H_\ell^+(k, m) \cup H_\ell^-(k, m))$$

and with  $\mathcal{H}^0(T^{-1}(a) \cap \partial_* E_{j_\ell, 1}) < \infty$ , if  $x_1, x_2 \in T^{-1}(a)$  with  $T^\perp(x_1) < T^\perp(x_2)$ ,  $x_1 \in I_\ell$  and  $x_2 \in O_\ell$ , then there exists  $x_3 \in T^{-1}(a) \cap \partial_* E_{j_\ell, 1}$  such that  $T^\perp(x_1) < T^\perp(x_3) < T^\perp(x_2)$  (see [11, step 5 of Theorem 5.23]). Here,  $x_1$  is

in the interior and  $x_2$  is in the exterior of  $E_{j_\ell,1}$  over  $a$ , and the claim is that there must be a “boundary point”  $x_3$  between these two points. The same claim holds if  $x_1 \in O_\ell$  and  $x_2 \in I_\ell$  instead.

Let  $W_\ell$  be the set obtained in Lemma 6.2. By [11, Lemma 5.9], we have  $\mathcal{L}^{n+1}(I_\ell \Delta E_{j_\ell,1}) = 0$ , so with (6.30) we have

$$\lim_{\ell \rightarrow \infty} \frac{\mathcal{L}^{n+1}(I_\ell \cap B_{r_\ell})}{\omega_{n+1} r_\ell^{n+1}} = 1. \quad (6.35)$$

Then, by the Fubini theorem and (6.35), we may choose a sequence  $\{b_\ell\}_{\ell=1}^\infty \subset \mathbb{R}^+$  such that  $b_\ell \in [r_\ell/3, r_\ell/2]$  and so that, writing

$$\begin{aligned} A_\ell^+ &:= B_{r_\ell} \cap \{x_{n+1} = b_\ell\}, \\ A_\ell^- &:= B_{r_\ell} \cap \{x_{n+1} = -b_\ell\}, \end{aligned}$$

we have

$$\lim_{\ell \rightarrow \infty} \frac{\mathcal{H}^n(I_\ell \cap A_\ell^+)}{\mathcal{H}^n(A_\ell^+)} = \lim_{\ell \rightarrow \infty} \frac{\mathcal{H}^n(I_\ell \cap A_\ell^-)}{\mathcal{H}^n(A_\ell^-)} = 1. \quad (6.36)$$

On cylinders  $T(A_\ell^+) \times [-b_\ell, b_\ell] \subset \mathbb{R}^{n+1}$ , by (6.33), (6.34) and the stated property thereafter, for  $\mathcal{H}^n$ -a.e.  $a \in W_\ell$ , we have the following property:

$$\begin{cases} \text{if } (a, s_1) \in I_\ell \text{ and } (a, s_2) \in O_\ell \text{ with } -b_\ell \leq s_1 < s_2 \leq b_\ell, \\ \text{then there exists } \hat{s} \in (s_1, s_2) \text{ such that } (a, \hat{s}) \in \partial_* E_{j_\ell,1}, \end{cases} \quad (6.37)$$

and similarly if  $(a, s_1) \in O_\ell$  and  $(a, s_2) \in I_\ell$ . On the other hand, we know that  $T^{-1}(a) \cap B_{r_\ell} \cap \partial_* \mathcal{E}_{j_\ell}$  is a singleton located close to  $T$  due to (6.14) and (6.15). Here, we used the fact that (6.14) is satisfied for both  $\partial \mathcal{E}_{j_\ell}$  and  $\partial^* \mathcal{E}_{j_\ell}$  as well as (6.31). We use this fact to get

$$a \in W_\ell \cap T(I_\ell \cap A_\ell^+) \cap T(I_\ell \cap A_\ell^-) =: W_\ell^*.$$

Note that  $(a, r_\ell)$  and  $(a, -r_\ell)$  are both in  $I_\ell$ , and  $(\{a\} \times [-r_\ell, r_\ell]) \cap \partial_* \mathcal{E}_{j_\ell}$  is a singleton due to the way  $W_\ell$  is defined. If  $(\{a\} \times [-r_\ell, r_\ell]) \cap O_\ell \neq \emptyset$ , then (6.37) implies that there must be at least two points of  $\partial_* E_{j_\ell,1}$  in  $\{a\} \times [-r_\ell, r_\ell]$ , since both crossings from  $I_\ell$  to  $O_\ell$  and the other way around have to happen. Since  $\partial_* \mathcal{E}_{j_\ell} = \bigcup_{i=1}^N \partial_* E_{j_\ell,i}$ , this is a contradiction. Combined with (6.32), we conclude that for  $\mathcal{H}^n$ -a.e.  $a \in W_\ell^*$ ,  $\{a\} \times [-r_\ell, r_\ell]$  is a disjoint union of one point of  $\partial_* \mathcal{E}_{j_\ell}$  and two line segments included in  $I_\ell$ , with no point of  $O_\ell$ . Because of (6.16) and (6.36), one also sees

$$\lim_{\ell \rightarrow \infty} \frac{\mathcal{H}^n(W_\ell^*)}{\mathcal{H}^n(A_\ell^+)} = 1.$$

In particular,  $W_\ell^*$  has a positive  $\mathcal{H}^n$  measure in  $T \subset \mathbb{R}^n \times \{0\}$  and there must be a Lebesgue point  $a$  of  $W_\ell^*$  such that  $(\{a\} \times [-r_\ell, r_\ell]) \cap \partial_* \mathcal{E}_{j_\ell}$  is a singleton, say,  $\{(a, s)\}$ . Then, by the Fubini theorem and the property of  $W_\ell^*$ ,

$$\begin{aligned} r^{-(n+1)} \mathcal{L}^{n+1}(O_\ell \cap B_r((a, s))) &\leq r^{-(n+1)} \mathcal{L}^{n+1}((B_r^n(a) \setminus W_\ell^*) \times [s-r, s+r]) \\ &\leq 2r^{-n} \mathcal{H}^n(B_r^n(a) \setminus W_\ell^*), \end{aligned}$$

which converges to 0 as  $r \rightarrow 0$  since  $a$  is a Lebesgue point of  $W_\ell^*$  in  $T$ . Since

$$\mathcal{L}^{n+1}(O_\ell \cap B_r(x)) = \mathcal{L}^{n+1}(B_r(x) \setminus E_{j_\ell,1}),$$

this implies that  $(a, s) \in I_\ell$ . On the other hand,  $(a, s) \in \partial_* \mathcal{E}_{j_\ell}$ , a contradiction to (6.32). This concludes the proof.  $\square$

**Proposition 6.4.** *Assume  $N = 2$ . For  $V_t$  and  $\{E_i(t)\}_{i=1}^2$  in Proposition 3.6, for a.e.  $t \in \mathbb{R}^+$ , we have*

$$\theta_t(x) = \begin{cases} \text{odd} & \text{for } \mathcal{H}^n\text{-a.e. } x \in \partial^* E_1(t) (= \partial^* E_2(t)), \\ \text{even} & \text{for } \mathcal{H}^n\text{-a.e. } x \in \text{spt}\|V_t\| \setminus \partial^* E_1(t). \end{cases}$$

*Proof.* The proof proceeds similarly to the proof of Proposition 6.3, except that we need to localize the argument to each layers. Fix a bounded open set  $U \subset \mathbb{R}^{n+1}$ . We may choose a generic  $t \in \mathbb{R}^+$  as before and drop  $t$ . Since  $\partial^* E_1 = \partial^* E_2$  by the definition of the reduced boundary, for  $\mathcal{H}^n$ -a.e.  $x \in \text{spt}\|V\| \setminus \partial^* E_1$ , we have

$$\lim_{r \rightarrow 0} \frac{\mathcal{L}^{n+1}(E_i \cap B_r(x))}{\omega_{n+1} r^{n+1}} = 1 \quad \text{for either } i = 1 \text{ or } 2.$$

On the other hand, for  $\mathcal{H}^n$ -a.e.  $x \in \partial^* E_1$ , there exists a unit outer normal  $\nu$  to  $\partial^* E_1$  such that, letting

$$B_r^{+(-)}(x) := \{y \in B_r(x) : (y - x) \cdot \nu \geq 0 (\text{resp. } \leq 0)\},$$

we have

$$\lim_{r \rightarrow 0} \frac{\mathcal{L}^{n+1}(E_1 \cap B_r^+(x))}{\omega_{n+1} r^{n+1}} = 0 \quad \text{and} \quad \lim_{r \rightarrow 0} \frac{\mathcal{L}^{n+1}(E_1 \cap B_r^-(x))}{\omega_{n+1} r^{n+1}} = \frac{1}{2}.$$

We use Lemma 6.2, and in the proof of Lemma 6.2 we may additionally assume that the chosen subsequence satisfies

$$\lim_{\ell \rightarrow \infty} \frac{\mathcal{L}^{n+1}(E_{j_\ell, i} \cap B_{r_\ell})}{\omega_{n+1} r_\ell^{n+1}} = 1 \quad \text{for either } i = 1 \text{ or } 2 \quad (6.38)$$

if  $0 \in \text{spt}\|V\| \setminus \partial^* E_1$ , and

$$\lim_{\ell \rightarrow \infty} \frac{\mathcal{L}^{n+1}(E_{j_\ell, 1} \cap B_{r_\ell}^+)}{\omega_{n+1} r_\ell^{n+1}} = 0 \quad \text{and} \quad \lim_{\ell \rightarrow \infty} \frac{\mathcal{L}^{n+1}(E_{j_\ell, 1} \cap B_{r_\ell}^-)}{\omega_{n+1} r_\ell^{n+1}} = \frac{1}{2} \quad (6.39)$$

if  $0 \in \partial^* E_1$ . Without loss of generality, we may assume  $i = 1$  in (6.38),  $T = \{x_{n+1} = 0\}$  and  $B_{r_\ell}^+ = B_{r_\ell} \cap \{x_{n+1} \geq 0\}$  in (6.39). By (6.13), we have

$$\lim_{\ell \rightarrow \infty} (r_\ell)^{-n} \int_{B_{2r_\ell}} \|S - T\| d(\partial \mathcal{E}_{j_\ell})(x, S) = 0. \quad (6.40)$$

Set

$$C_\ell := \left\{ x \in \partial \mathcal{E}_{j_\ell} \cap B_{r_\ell} : \|\text{Tan}(\|\partial \mathcal{E}_{j_\ell}\|, x) - T\| \leq \frac{1}{10} \right\}. \quad (6.41)$$

Given any  $0 < \delta < r_\ell$  and  $\mathcal{H}^n$ -a.e.  $x \in \partial \mathcal{E}_{j_\ell}$ , by the rectifiability of  $\partial \mathcal{E}_{j_\ell}$ , there exists  $0 < r < \delta$  such that

$$\frac{1}{2} \leq \frac{1}{\omega_n r^n} \|\partial \mathcal{E}_{j_\ell}\|(B_r(x)) \quad \text{and} \quad \frac{1}{\omega_n r^n} \int_{B_r(x)} \|\text{Tan}(\|\partial \mathcal{E}_{j_\ell}\|, x) - S\| d(\partial \mathcal{E}_{j_\ell}) \leq \frac{1}{40}. \quad (6.42)$$

Then, for  $\mathcal{H}^n$ -a.e.  $x \in \partial \mathcal{E}_{j_\ell} \cap B_{r_\ell} \setminus C_\ell$ , (6.41) and (6.42) show

$$\begin{aligned} \int_{B_r(x)} \|T - S\| d(\partial \mathcal{E}_{j_\ell}) &\geq \|\text{Tan}(\|\partial \mathcal{E}_{j_\ell}\|, x) - T\| \|\partial \mathcal{E}_{j_\ell}\|(B_r(x)) - \frac{\omega_n r^n}{40} \\ &\geq \omega_n r^n \left( \frac{1}{20} - \frac{1}{40} \right) \\ &= \frac{\omega_n r^n}{40}. \end{aligned}$$

We cover  $\partial \mathcal{E}_{j_\ell} \cap B_{r_\ell} \setminus C_\ell$  by such balls and use the Besicovitch covering theorem to show that

$$\mathcal{H}^n(\partial \mathcal{E}_{j_\ell} \cap B_{r_\ell} \setminus C_\ell) \leq 40 \mathbf{B}_{n+1} \int_{B_{2r_\ell}} \|T - S\| d(\partial \mathcal{E}_{j_\ell}), \quad (6.43)$$

where  $\mathbf{B}_{n+1}$  is the Besicovitch constant. Then (6.40) and (6.43) show

$$\lim_{\ell \rightarrow \infty} (r_\ell)^{-n} \mathcal{H}^n(\partial \mathcal{E}_{j_\ell} \cap B_{r_\ell} \setminus C_\ell) = \lim_{\ell \rightarrow \infty} (r_\ell)^{-n} \mathcal{H}^n(T(\partial \mathcal{E}_{j_\ell} \cap B_{r_\ell} \setminus C_\ell)) = 0,$$

so that  $T^{-1}(a) \cap \partial \mathcal{E}_{j_\ell} \cap B_{r_\ell} \subset C_\ell$  for  $a$  in a large portion of  $T \cap B_{r_\ell}$  for large enough  $\ell$ . Now recall the property of  $W_\ell$  in Lemma 6.2. We may redefine  $W_\ell$  by  $W_\ell \setminus T(\partial \mathcal{E}_{j_\ell} \cap B_{r_\ell} \setminus C_\ell)$  and keep the properties (6.14)–(6.16). By this, we additionally have that

$$\|\text{Tan}(\|\partial \mathcal{E}_{j_\ell}\|, x) - T\| \leq \frac{1}{10} \quad \text{for all } x \in T^{-1}(W_\ell) \cap B_{r_\ell} \cap \partial^* \mathcal{E}_{j_\ell}.$$

We now proceed similarly to the previous Proposition 6.3, and choose  $b_\ell$  satisfying (6.36) in the case of (6.38). The case of (6.39) can be handled similarly, so we discuss the former case. For all large  $\ell$ , we may choose a Lebesgue point  $a$  of  $W_\ell$  in  $T$  such that  $(a, -b_\ell)$  and  $(a, b_\ell)$  are also Lebesgue points of  $I_\ell \cap A_\ell^-$  and  $I_\ell \cap A_\ell^+$ , respectively. By (6.14) and (6.15), there are  $-b_\ell := u_0 < u_1 < \dots < u_\theta < u_{\theta+1} := b_\ell$  such that

$$\bigcup_{k=1}^{\theta} \{(a, u_k)\} = T^{-1}(a) \cap B_{r_\ell} \cap \partial^* \mathcal{E}_{j_\ell}.$$

At each point  $(a, u_k)$ , since it is in  $\partial^* E_{j_\ell, 1}$ , the blow-up of  $E_{j_\ell, 1}$  converges to a half-space, with the approximate tangent space having a small slope relative to  $T$  due to (6.41). Then, for sufficiently small

$$0 < \delta < \min_{0 \leq k \leq \theta} \{u_{k+1} - u_k\} \quad \text{and} \quad k = 1, \dots, \theta,$$

we may choose  $b_{\ell, k} \in [\delta/3, \delta/2]$  so that

$$\frac{\mathcal{H}^n(T^{-1}(B_\delta^n(a)) \cap \{x_{n+1} = u_k + b_{\ell, k}\} \cap O_\ell)}{\omega_n \delta^n} \geq 1 - \frac{1}{6\theta}$$

and

$$\frac{\mathcal{H}^n(T^{-1}(B_\delta^n(a)) \cap \{x_{n+1} = u_k - b_{\ell, k}\} \cap I_\ell)}{\omega_n \delta^n} \geq 1 - \frac{1}{6\theta},$$

or the inequalities replacing the role of  $O_\ell$  and  $I_\ell$ . We may also assume that

$$\frac{\mathcal{H}^n(B_\delta^n(a) \cap W_\ell)}{\omega_n \delta^n} \geq \frac{8}{9}$$

since  $a$  is a Lebesgue point of  $W_\ell$ , and similarly

$$\frac{\mathcal{H}^n(T^{-1}(B_\delta^n(a)) \cap I_\ell \cap A_\ell^\pm)}{\omega_n \delta^n} \geq \frac{8}{9}.$$

With these properties, we can make sure that, with respect to  $\mathcal{H}^n$ , one third of  $W_\ell \cap B_\delta^n(a)$  has the property that, if  $\tilde{a}$  is in this set,

$$(\tilde{a}, \pm b_\ell) \in I_\ell, \quad (\tilde{a}, u_k + b_{\ell, k}) \in O_\ell, \quad (\tilde{a}, u_k - b_{\ell, k}) \in I_\ell \text{ or vice-versa for } k = 1, \dots, \theta.$$

By using (6.37), for  $\mathcal{H}^n$ -a.e.  $\tilde{a}$  as above, there exists some  $s_k \in (u_k - b_{\ell, k}, u_k + b_{\ell, k})$  with  $(\tilde{a}, s_k) \in \partial^* E_{j_\ell, 1}$  for each  $k = 1, \dots, \theta$ , and there are no other points of  $\partial^* E_{j_\ell, 1}$  along the line segment connecting  $(\tilde{a}, -b_\ell)$  and  $(\tilde{a}, b_\ell)$ . Looking at this line segment and the intersection of  $O_\ell$  and  $I_\ell$ , since these two endpoints are in  $I_\ell$  and each  $(\tilde{a}, s_k)$  is sided by  $O_\ell$  and  $I_\ell$ ,  $\theta$  has to be necessarily even. This finishes the proof in the case of (6.38). For (6.39), the similar argument results in the situation that  $(\tilde{a}, -b_\ell) \in I_\ell$  and  $(\tilde{a}, b_\ell) \in O_\ell$ , which necessitates that  $\theta$  is odd. This concludes the proof.  $\square$

Finally, we comment on the proofs of Theorem 2.12 and 2.13. If  $V_t$  is a unit density flow in  $U \times (t_1, t_2)$ , then  $\theta_t(x) = 1$  for  $\|V_t\|$ -a.e.  $x \in U$  and a.e.  $t \in (t_1, t_2)$ . By Theorem 2.10 (ii) and (iv), we may assume that  $V_t = \mathbf{var}(\Gamma(t), 1)$ , and by Theorem 2.11 (vii),  $\Gamma(t)$  may be replaced by  $\bigcup_{i=1}^N \partial^* E_i(t)$ . Thus, (2.13) follows immediately. To check that (2.7) holds, since (see (2.9) and (2.10))

$$\sum_{i \neq j} \mathcal{H}^n \llcorner_{I_{i,j}(t)} = 2\mathcal{H}^n \llcorner_{\Gamma(t)} = 2\|V_t\|,$$

the left-hand side of (2.7) is equal to  $2 \int_0^T \delta V_t(g) dt$ . Since  $v_i v_i = (h \cdot v_i) v_i = h$  for  $\mathcal{H}^n$ -a.e.  $x \in I_{i,j}(t)$  due to the perpendicularity of the mean curvature vector, the right-hand side of (2.7) is  $-2 \int_0^T \int h \cdot g d\|V_t\| dt$ . Since the generalized mean curvature vector exists for a.e.  $t > 0$ , they are indeed equal. This proves the claim of Theorem 2.12. For Theorem 2.13, under the assumption, one can show that there exists

$$T_0 = T_0(n, \mathcal{H}^n(\Gamma_0), r_0, \delta_0) > 0$$



such that (recall (4.28))

$$\int_{\Gamma_0} \rho_{(y,s)}(x, 0) d\mathcal{H}^n(x) < 2 - \frac{\delta_0}{2}$$

for all  $y \in \mathbb{R}^{n+1}$  and  $0 < s \leq T_0$ . Then Huisken's monotonicity formula shows that

$$\int_{\mathbb{R}^{n+1}} \rho_{(y,s)}(x, t) d\|V_t\|(x)$$

is non-increasing on  $t \in [0, s]$ , and thus  $< 2 - \delta_0/2$ . For a contradiction, if  $V_t$  is not unit density on  $[0, T_0]$ , there would exist some  $t \in (0, T_0)$  with  $V_t \in \mathbf{IV}_n(\mathbb{R}^{n+1})$ , and  $y \in \text{spt}\|V_t\|$  such that  $\Theta^n(\|V_t\|, y) \geq 2$  and where  $T_y\|V_t\|$  exists. Then one can prove that

$$\lim_{\epsilon \rightarrow 0^+} \int_{\mathbb{R}^{n+1}} \rho_{(y,t+\epsilon)}(x, t) d\|V_t\|(x) = \Theta^n(\|V_t\|, y) \geq 2.$$

Since  $t + \epsilon < T_0$  for all small  $\epsilon > 0$ , this would be a contradiction. Thus,  $V_t$  is a unit density Brakke flow on  $[0, T_0]$ . Once this is proved, by Theorem 2.12, the claim of the BV solution also follows. This is the outline of the proof of Theorem 2.13.

## 7 Final remarks

### 7.1 On generalized BV solutions

As explained in Definition 2.4, a BV flow is classically defined as consisting of two objects:  $N$  families of sets of finite perimeter  $E_i(t)$ , and velocities  $v_i$ . From them, naturally, one can define a unit density varifold

$$V_t = \mathbf{var} \left( \bigcup_{i=1}^N \partial^* E_i(t), 1 \right)$$

and check that (2.7) implies that the generalized mean curvature  $h(\cdot, V_t)$  is equal to  $v_i v_i$  on  $\partial^* E_i(t)$  for  $i = 1, \dots, N$ . The generalized BV flow of Theorem 2.11 (vi) involves the accompanying Brakke flow  $V_t$  in addition to the families of sets of finite perimeter, and one may wonder if the definition makes sense even without the reference to the Brakke flow. In fact, it is interesting to observe that each  $\partial^* E_i(t)$  for a.e.  $t > 0$  is  $C^2$ -rectifiable due to Menne's  $C^2$ -rectifiability theorem [28, Theorem 4.8], and one can define a unique second fundamental form for  $\partial^* E_i(t)$  as well as a mean curvature vector by the  $C^2$ -approximability property, independent of  $V_t$ . The mean curvature vector defined in this sense coincides with  $h(\cdot, V_t) \|V_t\|$ -a.e. on  $\partial^* E_i(t)$ . Thus,  $h \cdot v_i$  on  $\partial^* E_i(t)$  is uniquely defined from the  $C^2$ -rectifiability without reference to  $V_t$ . On the other hand, the summation

$$\tilde{h} := \frac{1}{2} \sum_{i=1}^N (h \cdot v_i) v_i$$

may not correspond, in general, to the generalized mean curvature vector of  $\mathbf{var}(\bigcup_{i=1}^N \partial^* E_i(t), 1)$  if there is some non-trivial higher multiplicity portion of  $V_t$ . For example on  $\mathbb{R}^2$ , define

$$E_+ := \{(x, y) : y > 0 \text{ if } x \leq 0, y > x^2 \text{ if } x > 0\} \quad \text{and} \quad E_- := \{(x, y) : y < 0 \text{ if } x \leq 0, y < -x^2 \text{ if } x > 0\}.$$

Then  $V := \mathbf{var}(\partial E_+, 1) + \mathbf{var}(\partial E_-, 1)$  has a bounded generalized mean curvature, while  $\mathbf{var}(\partial^* E_+ \cup \partial^* E_-, 1)$  has a singular first variation at the origin. Note that  $V$  has multiplicity = 2 on the negative  $x$ -axis. In this sense, formula (2.7) does not hold in general. Note that (2.8) is relevant only when  $\mathcal{H}^n(\Gamma_0)$  is finite, and it follows from Theorem 2.7 (iv) with  $v_i = h \cdot v_i$ . Overall, for the generalized BV solution, it makes sense to consider the pair of sets of finite perimeter and Brakke flow together, unlike the original BV solutions discussed in Definition 2.4.

## 7.2 MCF with fixed boundary conditions

In [35], given a strictly convex bounded domain  $U \subset \mathbb{R}^{n+1}$  with  $C^2$  boundary  $\partial U$ , a countably  $n$ -rectifiable set  $\Gamma_0 \subset U$  with  $\mathcal{H}^n(\Gamma_0) < \infty$  and an open partition  $E_{0,1}, \dots, E_{0,N}$  of  $U$  such that  $\Gamma_0 = U \setminus \bigcup_{i=1}^N E_{0,i}$ , existence of a Brakke flow and a family of open partitions with fixed boundary condition is established for the given initial datum. The construction method is along the lines of [21], and we may also carry it out using the volume-controlled Lipschitz maps. If one compares the construction in [35] with that in [21], one sees that differences occur only near the boundary  $\partial U$ : more precisely, the approximate smoothed mean curvature vector is damped near the portion of  $\Gamma_0$  close to  $\partial U$ , and there is another step in each epoch – a Lipschitz retraction step (see [35, Section 2.6]). Hence, the proof of the present paper works with no essential change away from  $\partial U$ , and (2.12) holds for  $\phi \in C_c^1(U \times \mathbb{R}^+)$ ; since the formula does not involve  $\nabla \phi$ , by approximation, the same formula holds even for  $\phi \in C^1(\text{clos } U \times [0, T])$  for arbitrary  $T > 0$ . Since the existence results in [34] are based on [35], the same applies to the solutions discussed in [34].

## 7.3 A lower bound estimate for extinction time

*Proof of Theorem 2.14.* Suppose that  $\mathcal{H}^n(\Gamma_0) < \infty$ , and assume without loss of generality that  $N$  is the index of the only grain  $E_{0,i}$  with infinite volume. Define then the open set  $E(t) := \bigcup_{i=1}^{N-1} E_i(t)$ . Since  $v_i \cdot h = -v_j \cdot h$  on  $\partial^* E_i(t) \cap \partial^* E_j(t)$  for  $i \neq j$   $\mathcal{H}^n$ -a.e., after summing over  $i = 1, \dots, N-1$ , formula (2.12) gives

$$|E(t)| - |E(0)| = \int_0^t \int_{\partial^* E(s)} v \cdot h \, d\mathcal{H}^n$$

for all  $0 < t < \infty$ , where  $v$  is the outer unit normal of  $\partial^* E(s)$ . In particular, if we set  $v(t) := |E(t)|$ , then we have

$$v'(t) = \int_{\partial^* E(t)} v \cdot h \, d\mathcal{H}^n \quad \text{for a.e. } t \in \mathbb{R}^+. \quad (7.1)$$

Next, set  $a(t) := \|V_t\|(\mathbb{R}^{n+1})$ . By Brakke's inequality (2.1), the upper derivative  $a'_+(t)$  of  $a(t)$  satisfies

$$-a'_+(t) \geq \int |h|^2 \, d\|V_t\| \geq \int_{\Gamma(t)} |h|^2 \, d\mathcal{H}^n \geq \int_{\partial^* E(t)} |h|^2 \, d\mathcal{H}^n \quad \text{for a.e. } t \in \mathbb{R}^+. \quad (7.2)$$

Combining (7.1) and (7.2) then gives the inequality

$$-v'(t) \leq (\mathcal{H}^n(\partial^* E(t)))^{\frac{1}{2}} \left( \int_{\partial^* E(t)} |h|^2 \, d\mathcal{H}^n \right)^{\frac{1}{2}} \leq (-a(t)a'_+(t))^{\frac{1}{2}} = \left( -\frac{(a^2)'_+(t)}{2} \right)^{\frac{1}{2}}$$

for a.e.  $t \in \mathbb{R}^+$ . Integrating over any interval  $[0, T]$  and using the Cauchy–Schwarz inequality then yields

$$|E(0)| - |E(T)| \leq \sqrt{\frac{T}{2}} (\|V_0\|(\mathbb{R}^{n+1})^2 - \|V_T\|(\mathbb{R}^{n+1})^2)^{\frac{1}{2}} \leq \sqrt{\frac{T}{2}} \mathcal{H}^n(\Gamma_0). \quad (7.3)$$

Since  $V_t \neq 0$  as long as  $E(t) \neq \emptyset$ , the extinction time  $T_*$  is at least equal to the first time when  $E(t)$  becomes the empty set, so that (7.3) implies

$$T_* \geq 2 \left( \frac{|E(0)|}{\mathcal{H}^n(\Gamma_0)} \right)^2,$$

that is, (2.14). □

## A The existence theorem of Kim and Tonegawa revisited

Here we point out places which require a change to  $\mathbf{E}^{\text{vc}}(\mathcal{E}, j)$  from  $\mathbf{E}(\mathcal{E}, j)$  in [21, 22]. It turned out that the proofs require no essential change and the only point to be checked is that the same Lipschitz maps used in the proofs satisfy the condition of Definition 3.1 (ii).

## A.1 Construction of approximate flows

For the construction of discrete approximate sequence in [21, Section 6], we simply replace  $\mathbf{E}(\mathcal{E}_{j,l}, j)$  by  $\mathbf{E}^{\text{vc}}(\mathcal{E}_{j,l}, j)$  and  $\Delta_j \|\partial \mathcal{E}_{j,l}\|(\Omega)$  by  $\Delta_j^{\text{vc}} \|\partial \mathcal{E}_{j,l}\|(\Omega)$  when  $f_1$  is chosen in [21, (6.9)]. As in [21, (6.10)], if we define

$$\begin{aligned} \{E_{j,l,i}\}_{i=1}^N &:= \mathcal{E}_{j,l}, \\ \mathcal{E}_{j,l+1}^* &:= (f_1)_* \mathcal{E}_{j,l}, \\ \{E_{j,l+1,i}^*\}_{i=1}^N &= \mathcal{E}_{j,l+1}^*, \end{aligned}$$

by Definition 3.1 (ii) and (3.1), we have for each  $i = 1, \dots, N$ ,

$$\mathcal{L}^{n+1}(E_{j,l+1,i}^* \Delta E_{j,l,i}) \leq \frac{\{\|\partial \mathcal{E}_{j,l}\|(\Omega) - \|\partial \mathcal{E}_{j,l+1}^*\|(\Omega)\}}{j} \leq -\frac{(\Delta_j^{\text{vc}} \|\partial \mathcal{E}_{j,l}\|(\Omega))}{j}.$$

The change in [21, (6.9)] is also reflected in the estimate [21, (6.4)] and we have

$$\begin{aligned} &\frac{\|\partial \mathcal{E}_{j,l}\|(\Omega) - \|\partial \mathcal{E}_{j,l-1}\|(\Omega)}{\Delta t_j} + \frac{1}{4} \int_{\mathbb{R}^{n+1}} \frac{|\Phi_{\mathcal{E}_j} * \delta(\partial \mathcal{E}_{j,l})|^2 \Omega}{\Phi_{\mathcal{E}_j} * \|\partial \mathcal{E}_{j,l}\| + \varepsilon_j \Omega^{-1}} dx - \frac{(1-j^{-5})}{\Delta t_j} \Delta_j^{\text{vc}} \|\partial \mathcal{E}_{j,l-1}\|(\Omega) \\ &\leq \varepsilon_j^{\frac{1}{8}} + \frac{c_1^2}{2} \|\partial \mathcal{E}_{j,l-1}\|(\Omega). \end{aligned}$$

This leads to estimates (3.7) and (3.8).

## A.2 Proofs of rectifiability and integrality

For the proofs of rectifiability and integrality of  $\mu_t$  for  $\mathcal{L}^1$ -a.e.  $t \in \mathbb{R}^+$ , the smallness of  $\Delta_j \|\partial \mathcal{E}(t)\|$  is essential in [21, Sections 7 and 8]. The general idea is that, whenever  $\Delta_j \|\partial \mathcal{E}(t)\|$  is used in [21], the proofs use contradiction arguments and some appropriate Lipschitz deformations with drastic measure reduction are constructed. Here, “drastic” means that the measure is typically reduced by some factor of the measure itself, so that the reduction is typically much larger than the volume change caused by the deformation. Thus, even if we impose the additional condition, it is satisfied by the same Lipschitz deformations in [21] and we only need to check that it is indeed the case. We point out the following three separate places.

(i) In [21, Proposition 7.2], it is proved that there exists an  $\varepsilon$ -admissible function  $f$  which reduces the measure  $\|\partial \mathcal{E}\|(B_r)$  by the factor of  $\frac{1}{2}$  (see (iii)) for some  $r \in [\frac{R}{2}, R]$  when the measure in  $B_R$  is sufficiently small. Note that (iv) gives the desired estimate on the change of volume of each grain in terms of  $\|\partial \mathcal{E}\|(B_r)$ . Since the radii  $r$  of balls used later are typically  $O(1/j^2)$ , and thus the volume change is  $O(r^{n+1}) = O(r^n/j^2)$ , and  $\|\partial \mathcal{E}\|(B_r) = O(r^n)$ , we can deduce that  $f$  belongs to  $\mathbf{E}^{\text{vc}}(\mathcal{E}, j)$ . Since the claim of [21, Proposition 7.2] is about the existence of an  $\varepsilon$ -admissible function, no change is required in the proof.

(ii) In [21, Theorem 7.3], assumption (iv) should be replaced by the volume-controlled counterpart. In the proof, on [21, pp. 94–95], a Lipschitz map  $f$  is defined with the properties stated in the bottom of [21, p. 94] using [21, Proposition 7.2]. Using [21, (7.40)], which gives

$$(1 - 2^{-\frac{1}{2}}) \|\partial \mathcal{E}_{j,l}\| \llcorner_{\Omega} (B_{r_x}(x)) \leq \|\partial \mathcal{E}_{j,l}\| \llcorner_{\Omega} (B_{r_x}(x)) - \|\partial (f_x)_* \mathcal{E}_{j,l}\| \llcorner_{\Omega} (B_{r_x}(x)),$$

one can proceed in [21, (7.43)] as

$$\begin{aligned} \mathcal{L}^{n+1}(E_i \Delta \tilde{E}_i) &\leq c_4 \sum_{k=1}^{\Lambda} (\|\partial \mathcal{E}_{j,l}\|(B(k)))^{\frac{n+1}{n}} \\ &\leq \frac{c_4 c_3^{\frac{1}{n}}}{2j_l^2} \sum_{k=1}^{\Lambda} \|\partial \mathcal{E}_{j,l}\|(B(k)) \end{aligned}$$

$$\begin{aligned} &\leq \frac{c_4 c_3^{\frac{1}{n}} (\min_{B_3(x_0)} \Omega)^{-1}}{2(1 - 2^{-\frac{1}{2}})j_l^2} \sum_{k=1}^{\Lambda} (\|\partial \mathcal{E}_{j_l}\|_{L_\Omega}(B(k)) - \|\partial f_* \mathcal{E}_{j_l}\|_{L_\Omega}(B(k))) \\ &= \frac{c_4 c_3^{\frac{1}{n}} (\min_{B_3(x_0)} \Omega)^{-1}}{2(1 - 2^{-\frac{1}{2}})j_l^2} (\|\partial \mathcal{E}_{j_l}\|(\Omega) - \|\partial f_* \mathcal{E}_{j_l}\|(\Omega)). \end{aligned}$$

Thus, for all sufficiently large  $l$ , Definition 3.1 (ii) is satisfied. The use of [21, Lemma 4.12] is also justified, and we have  $f \in \mathbf{E}^{\text{vc}}(\mathcal{E}_{j_l}, j_l)$ .

(iii) Throughout [21, Section 8], the only crucial point that needs to be checked is in [21, Lemma 8.1], which involves the actual construction of a measure-reducing Lipschitz deformation. It proves roughly that when  $\partial \mathcal{E}$  is flat and close to being measure-minimizing within a cylinder of size  $O(1/j^2)$ , then the measure has to be an integer multiple of discs. The argument proceeds by assuming the contrary. The intuitive picture is that, if  $\partial \mathcal{E}$  does not have a measure close to a multiple of discs, then one can locate a hole which can be expanded horizontally. This would cause a drastic reduction of the measure and lead to a contradiction to the almost measure-minimizing property. More precisely, besides the change of  $\Delta_j \|\partial \mathcal{E}\|$  to  $\Delta_j^{\text{vc}} \|\partial \mathcal{E}\|$  throughout, near the end of the proof of [21, Lemma 8.1, p. 106], one needs to check that the “expansion map”  $f_a$  is in  $\mathbf{E}^{\text{vc}}(\mathcal{E}, E(r_1, \rho_1), j)$ . We recall that  $Y \subset T^\perp$  is a set of  $\nu$  points with

$$\text{diam } Y < j^{-2} \quad ([21, \text{Lemma 8.1 (3)}]),$$

$$r_1 < R < \frac{j^{-2}}{2} \quad ([21, \text{four lines above (8.7)}] \text{ and } [21, \text{Lemma 8.1 (1)}]),$$

$$\rho_1 = (1 + R^{-1}r_1)\rho < 2\rho < j^{-2} \quad ([21, (8.7)] \text{ and } [21, \text{Lemma 8.1 (1)}]),$$

and, with  $T \in \mathbf{G}(n+1, n)$  fixed,

$$E(r_1, \rho_1) = \{x \in \mathbb{R}^{n+1} : |T(x)| \leq r_1, \text{dist}(T^\perp(x), Y) \leq \rho_1\} \quad ([21, (8.1)]).$$

The map  $f_a$  is defined to be the identity map outside of  $E(r_1, \rho_1)$ , so the change of volume of grains caused by  $f_a$  is at most

$$\mathcal{L}^{n+1}(E(r_1, \rho_1)) \leq 2\omega_n \nu r_1^n \rho_1 < \frac{2\omega_n \nu r_1^n}{j^2}. \quad (\text{A.1})$$

As one can see in [21, (8.67)], the reduction of measure is

$$\|\partial(f_a)_* \mathcal{E}\|(E(r_1, \rho_1)) - \|\partial \mathcal{E}\|(E(r_1, \rho_1)) < -\frac{1}{2}(1 - \zeta)\omega_n r_1^n, \quad (\text{A.2})$$

and we also have from [21, (8.8)] that

$$\|\partial \mathcal{E}\|(E(r_1, \rho_1)) = (\nu - \zeta)\omega_n r_1^n. \quad (\text{A.3})$$

We need to see the difference with the weight  $\Omega$ , and since  $\text{diam } E(r_1, \rho_1) < 4/j^2$ , we have

$$\begin{aligned} &\|\partial(f_a)_* \mathcal{E}\|(\Omega) - \|\partial \mathcal{E}\|(\Omega) \\ &= \|\partial(f_a)_* \mathcal{E}\|_{L_\Omega}(E(r_1, \rho_1)) - \|\partial \mathcal{E}\|_{L_\Omega}(E(r_1, \rho_1)) \\ &\leq \left( \max_{E(r_1, \rho_1)} \Omega \right) \|\partial(f_a)_* \mathcal{E}\|(E(r_1, \rho_1)) - \left( \min_{E(r_1, \rho_1)} \Omega \right) \|\partial \mathcal{E}\|(E(r_1, \rho_1)) \\ &\leq \left( \min_{E(r_1, \rho_1)} \Omega \right) (e^{4c_1} j^2 \|\partial(f_a)_* \mathcal{E}\|(E(r_1, \rho_1)) - \|\partial \mathcal{E}\|(E(r_1, \rho_1))) \\ &\leq \left( \min_{E(r_1, \rho_1)} \Omega \right) \{e^{4c_1/j^2} (\|\partial(f_a)_* \mathcal{E}\|(E(r_1, \rho_1)) - \|\partial \mathcal{E}\|(E(r_1, \rho_1))) + (e^{4c_1/j^2} - 1) \|\partial \mathcal{E}\|(E(r_1, \rho_1))\} \\ &\leq -\frac{1}{2}(1 - \zeta)\omega_n \left( \min_{E(r_1, \rho_1)} \Omega \right) e^{4c_1/j^2} r_1^n + \frac{4c_1}{j^2} e^{4c_1/j^2} (\nu - \zeta)\omega_n r_1^n. \end{aligned} \quad (\text{A.4})$$

In the last line, we used (A.2) and (A.3). Note that the first term of the last line is a negative term of order  $O(r_1^n)$ , while the change of volume expressed in (A.1) is  $O(r_1^n/j^2)$ . Thus, (A.1) and (A.4) give the desired inequality

$$\mathcal{L}^{n+1}(E_i \Delta \tilde{E}_i) \leq \mathcal{L}^{n+1}(E(r_1, \rho_1)) \leq \frac{(\|\partial \mathcal{E}\|(\Omega) - \|\partial(f_a)_* \mathcal{E}\|(\Omega))}{j}$$

for all sufficiently large  $j$ , and we have  $f_a \in \mathbf{E}^{\text{vc}}(\mathcal{E}, E(r_1, \rho_1), j)$ . The rest of the proof is not affected by the change of volume-controlled deformation.

### A.3 Volume change of grains

The motivation of having  $\mathcal{L}^{n+1}(E_i \Delta \tilde{E}_i) < \frac{1}{j}$  in [21] is the use in the proof of [21, Lemma 10.10], and in fact it is the only place that this inequality is essentially used to derive any conclusion. In the proof, see the second line from the bottom of [21, p. 134], it is used to make sure that the volume change of grains is small for each discrete time step and the continuity of the labelling of each grain is derived in the end. The similar smallness of volume change is available with the volume-controlled counterparts since  $\|\partial \mathcal{E}_{j_\ell}(t)\|(\Omega)$  is uniformly bounded for a fixed time interval  $[0, T]$  by (3.6). Thus, the proof can be carried out similarly.

### A.4 Changes in the later paper by Kim and Tonegawa

The results from [22] are used in the present paper and the modifications are needed there as well. On the other hand, similarly, one can check that the change to the volume-controlled counterpart does not cause any difficulties. The part which is relevant to the change is [22, Section 4]. In the proof of [22, Lemma 4.2], a Lipschitz retraction map  $\hat{F}$  is used, with the reduction of measure inside of  $B_{r_\ell R}(z^{(\ell)})$  being  $\beta(r_\ell R)^n$ , while the volume of the ball is  $O((r_\ell R)^{n+1})$  (see [22, (4.5) and (4.6)]). Since  $r_\ell = 1/j_\ell^{5/2}$  (see [22, just after (4.2)]), one can check that  $\hat{F} \in \mathbf{E}^{\text{vc}}(\mathcal{E}_{j_\ell}, j_\ell)$  for all large  $\ell$ . The similar argument can be applied to the proofs of [22, Lemmas 4.3 and 4.5]. The proof of [22, Lemma 4.6] uses [21, Lemma 8.1], with the modifications discussed above in Section A.2 (iii). In the proofs of [22, Lemmas 4.7–4.9], the Lipschitz maps reduce the measure in similar manners, and they belong to the volume-controlled counterparts. In particular, all of the results in [22] hold true even with the modifications.

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