Xenon doping of Liquid Argon in ProtoDUNE Single Phase

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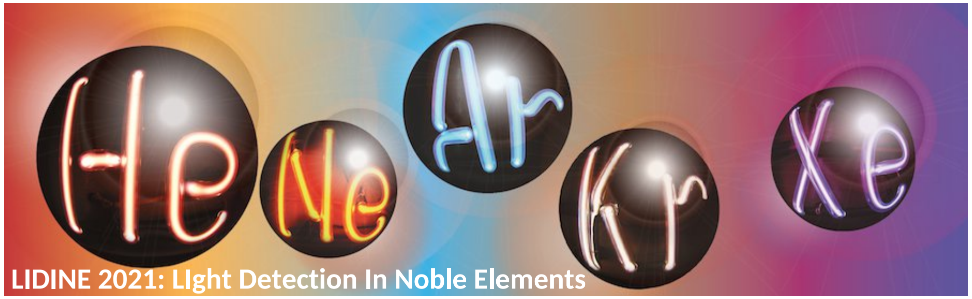

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- Scintillation model
- ProtoDUNE Single Phase
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Motivation of Xe doping (I)

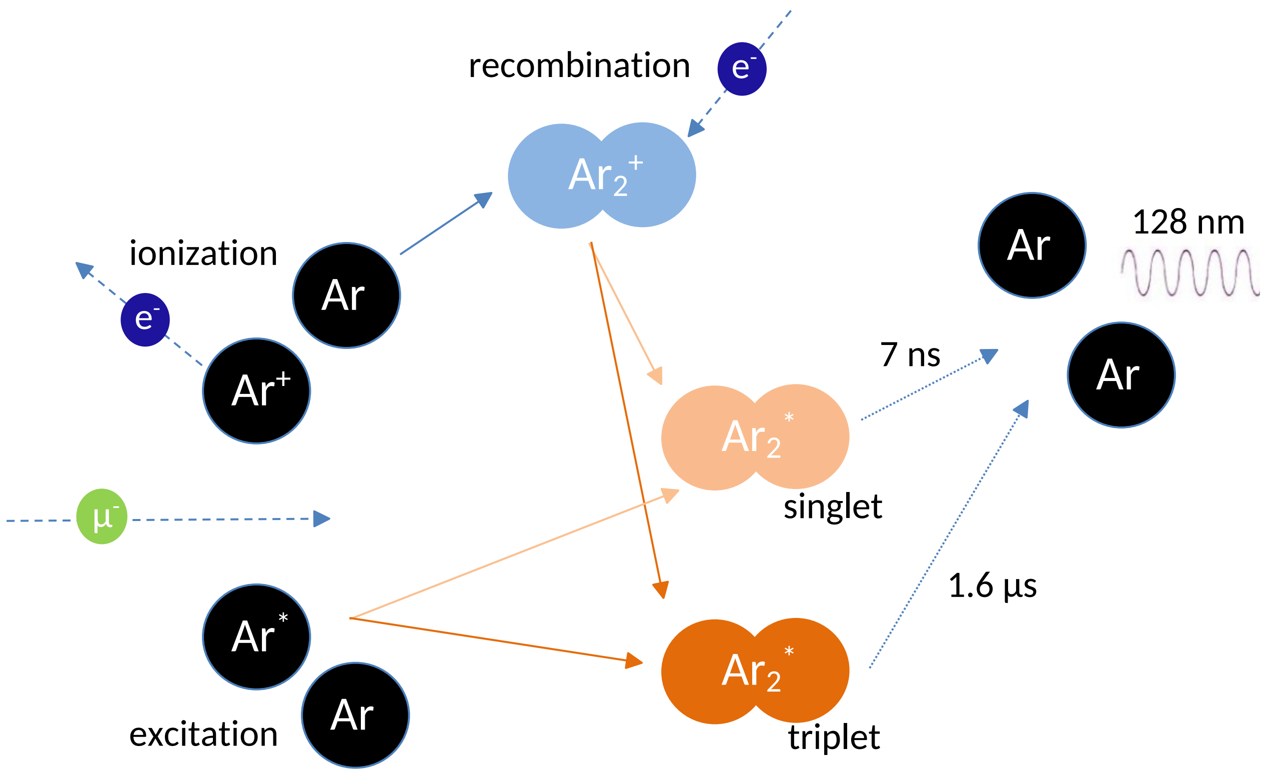
- LAr as a scintillating medium and challenges to use it:
  - Scintillation efficiency comparable with other liquid noble gases
  - Very efficient Pulse Shape Discrimination (PSD) due to the significant difference in relative intensity of the fast and slow components
  - Wavelength of scintillation that lies in the VUV range ($\sim 128\ nm$). A common and convenient solution is the use of wavelength shifters (WLS) that comes with some issues:
    - Low geometrical efficiency
    - Sensitivity to mechanical stress
    - Scattering and re-absorption of the re-emitted light inside the WLS layer
    - Dependence of the WLS efficiency on the coating method
    - Long term stability?

Motivation of Xe doping (II)

- Elegant alternative: volume distributed “WLS” in LAr experiments $\rightarrow$ xenon doping
  - Shift $128\ nm$ wavelength to $178\ nm$
  - Uniform light distribution
  - Larger Rayleigh scattering length @$178\ nm$
  - Increase light yield and detection efficiency far from readout planes
- In literature small scale tests or gas mixture tests so far
  - How about physics, uniformity and stability of large scale Xe doped LAr setups?

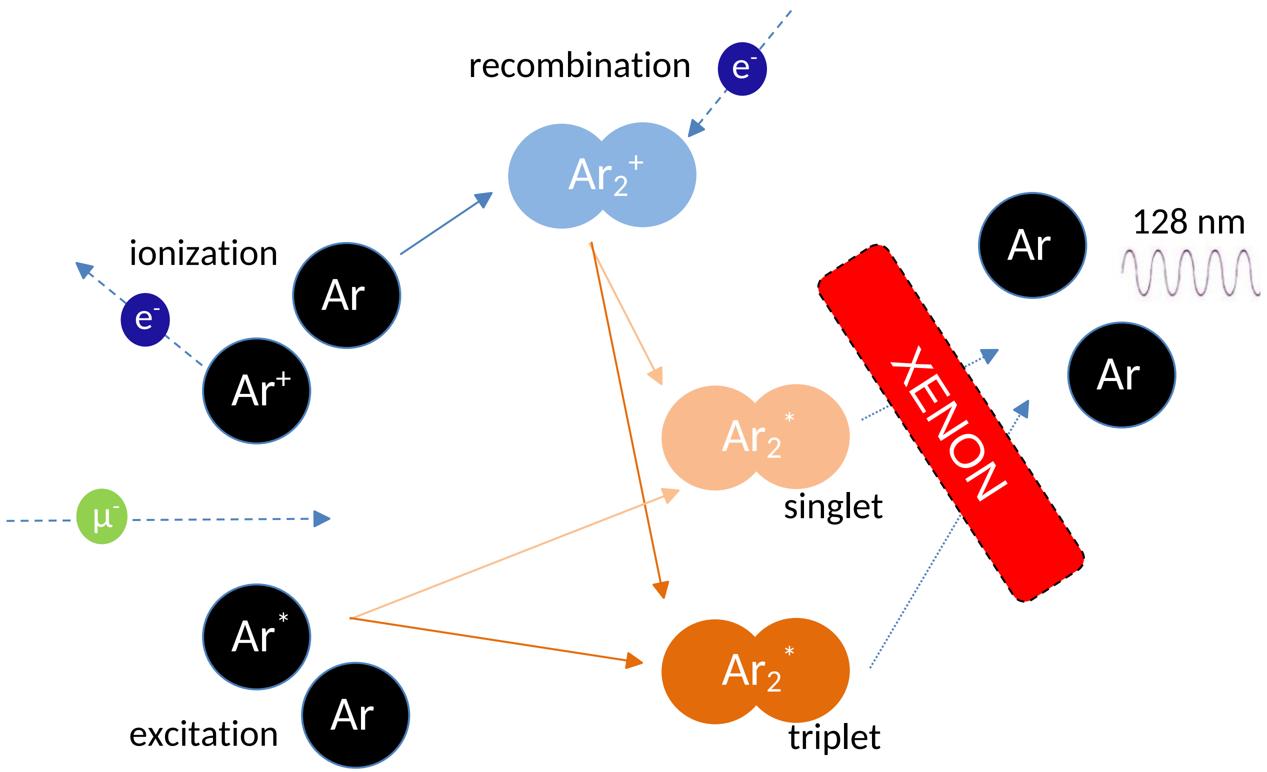
With these in mind, an R&D effort and Xe-doping in ProtoDUNE-SP was performed

LAr scintillation



- An ionizing particle creates liquid argon ionization and excitation
- These states interact with argon creating excited molecules
- Singlet and triplet states are created
- De-excitation emits 128 nm light

LAr scintillation



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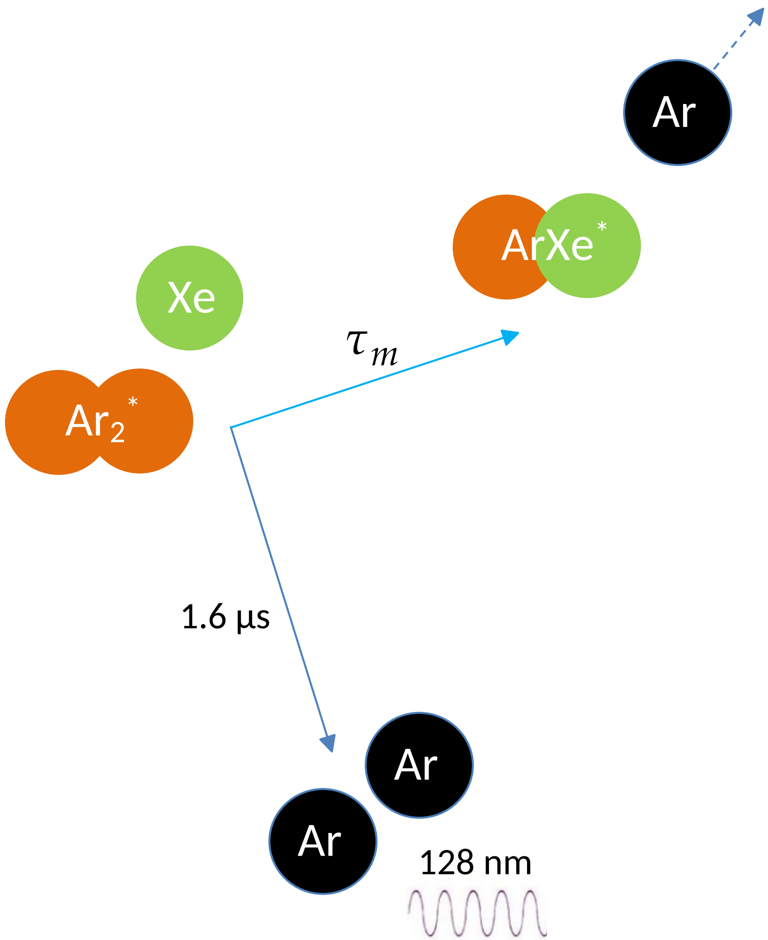
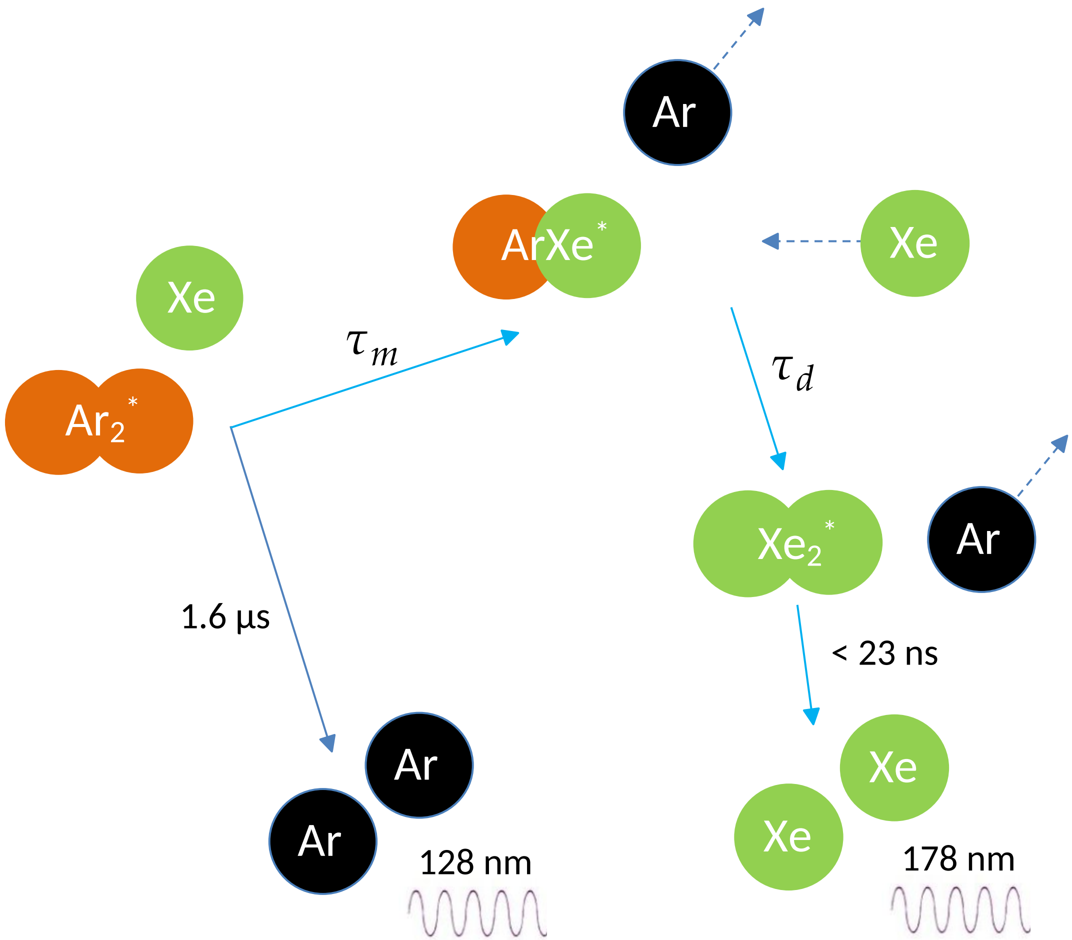
$LAr + Xe$ scintillation



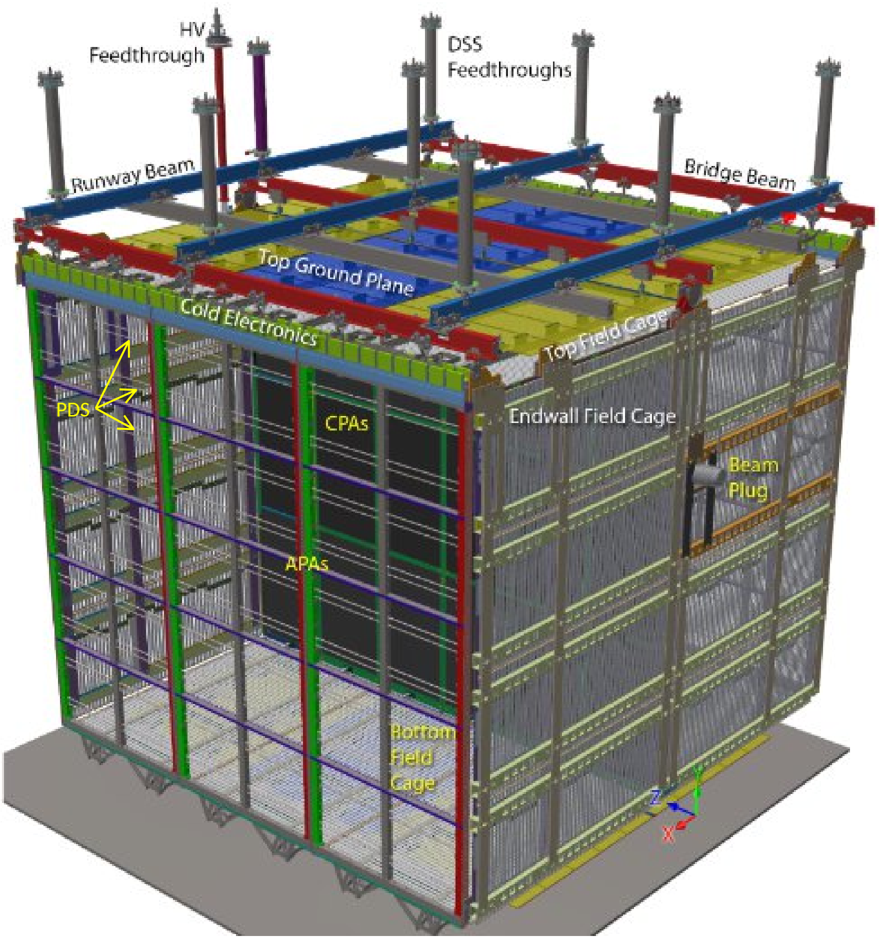
- The excited Ar dimer can interact with xenon
- The result will be an excited state of $ArXe$ molecule
- The time scale of $ArXe^*$ creation τ_m depends on Xenon concentration
- τ_m is smaller at higher concentration making this process more effective

$LAr + Xe$ scintillation



- The excited $ArXe^*$ dimer can interact with Xenon creating a ${Xe_2}^*$
- The time constant of this process is τ_d and it depends on Xenon concentration
- The higher the concentration the more effective the process is
- As final process ${Xe_2}^*$ de-excites (very fast) emitting $178\ nm$ light

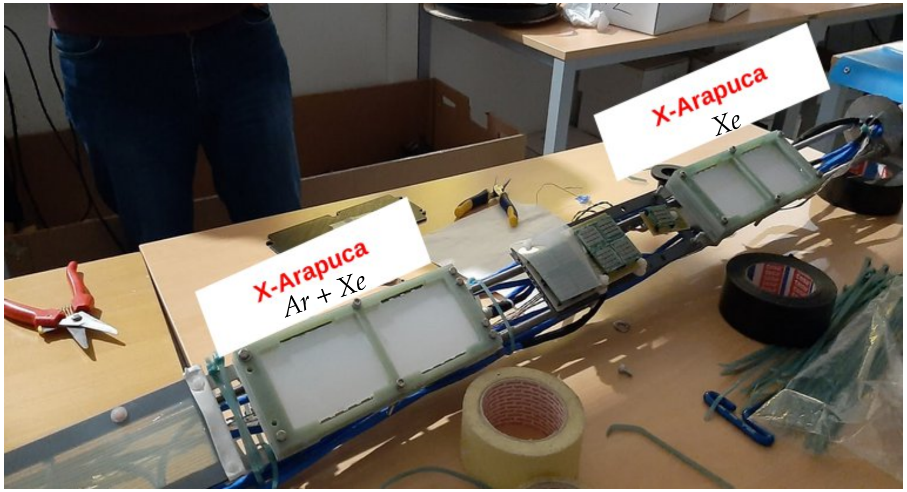
ProtoDUNE Single Phase



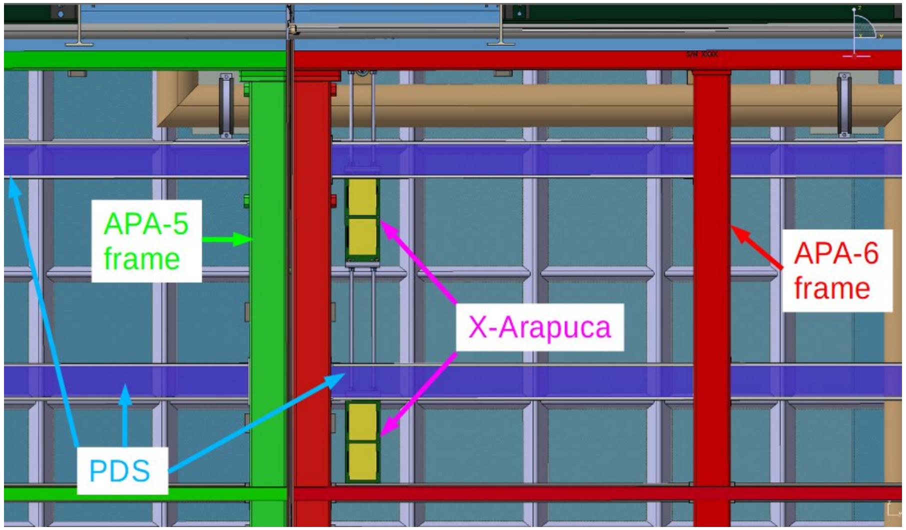
ProtoDUNE-SP is a full scale LAr-TPC prototype for the first module of DUNE far detector located at CERN Neutrino Platform.

- Total LAr mass of 770 t
- Two drift volumes separated by a CPA (Cathode Plane Assembly)
- $500\ V/cm$ electric field to drift ionization charge
- Charge is collected by APA (Anode Plane Assembly) wires
- Photon Detection System (PDS) modules are installed in APA frames
- Ar recirculation pump failure caused a steady contamination of 5.4 ppm of N_2 before xenon doping tests.

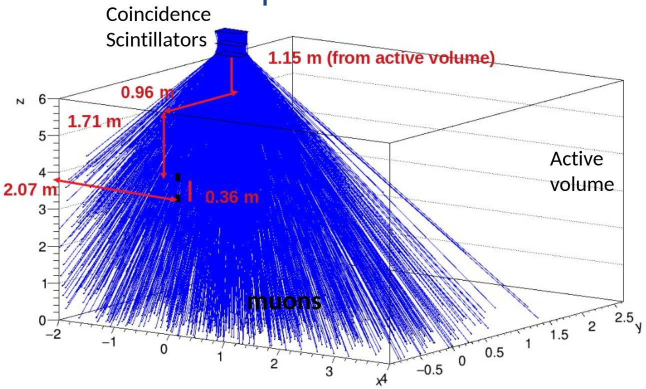
Dedicated X-ARAPUCA setup



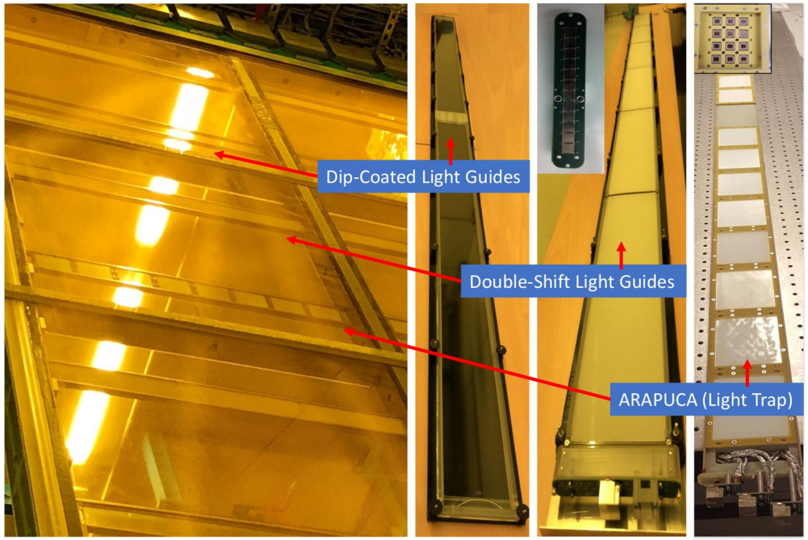
- Installation of xenon scintillation sensitive modules into the cryostat:
  - X-ARAPUCA **equipped with a fused-silica window** that is sensitive to $Xe\ (178\ nm)$ light only "Xe XA"
  - X-ARAPUCA sensitive to $Ar\ (128\ nm) +\ Xe\ (178\ nm)$ light "Ar+Xe XA"



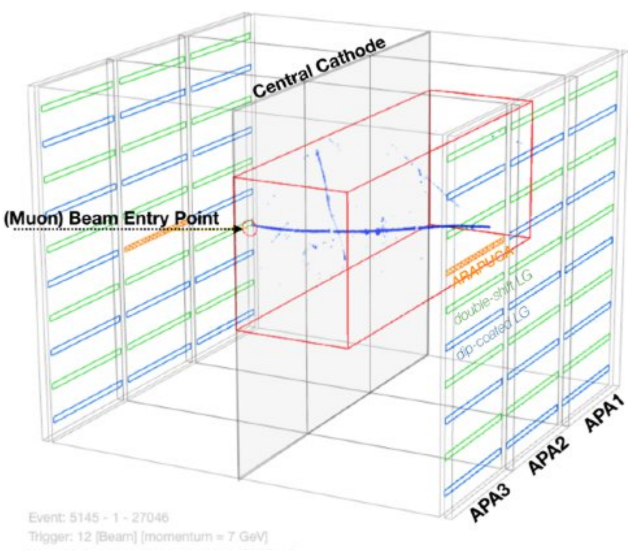
- Sample of vertical cosmic muons, triggered through a standard triple coincidence of $15.5 \times 44\ cm^2$ plastic scintillators.

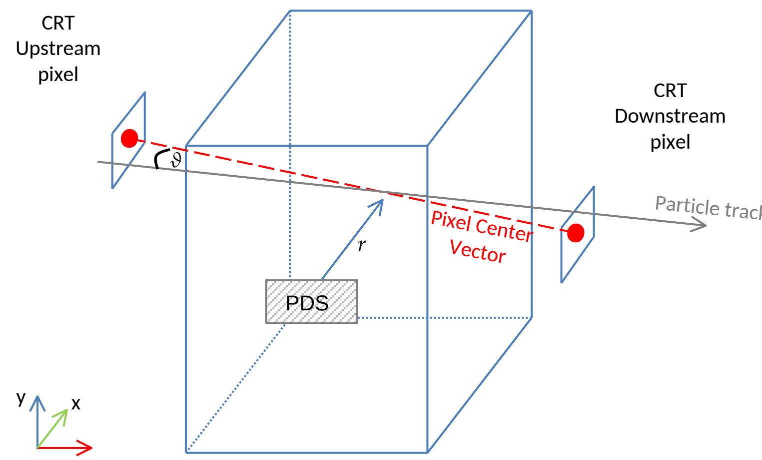


ProtoDUNE-SP PDS

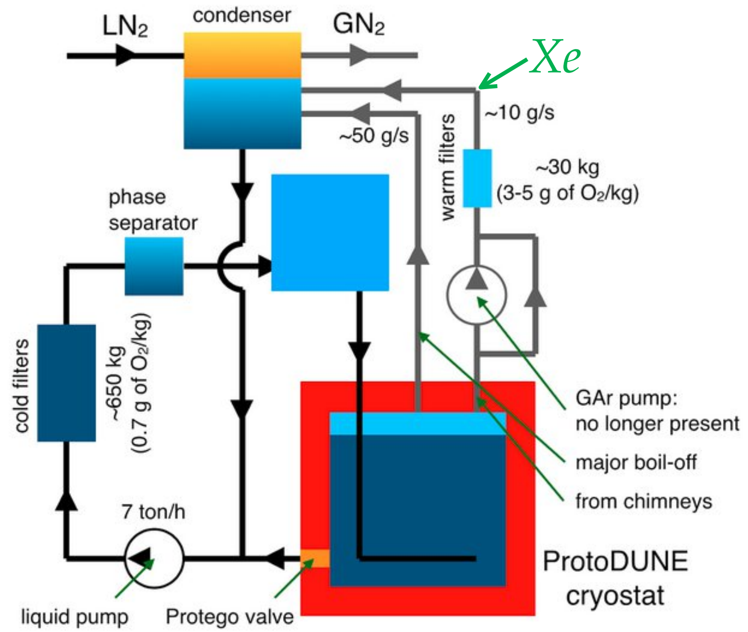


- 10 PDS detectors, regularly spaced along the vertical direction, are inserted into each APA module
- Three different designs: “double-shift light guides”, “dip-coated light guides”, and ARAPUCA light traps
- Sample of horizontal crossing muons, selected through a Cosmic Ray Tagger (CRT)
- The CRT is made of scintillator counters (strips) that enable the estimation of muons tracks position
- (@$500\ V/cm$) If TPC and CRT reconstructed track are compatible $\cos\theta > 0.999$, the radial distance r is computed.





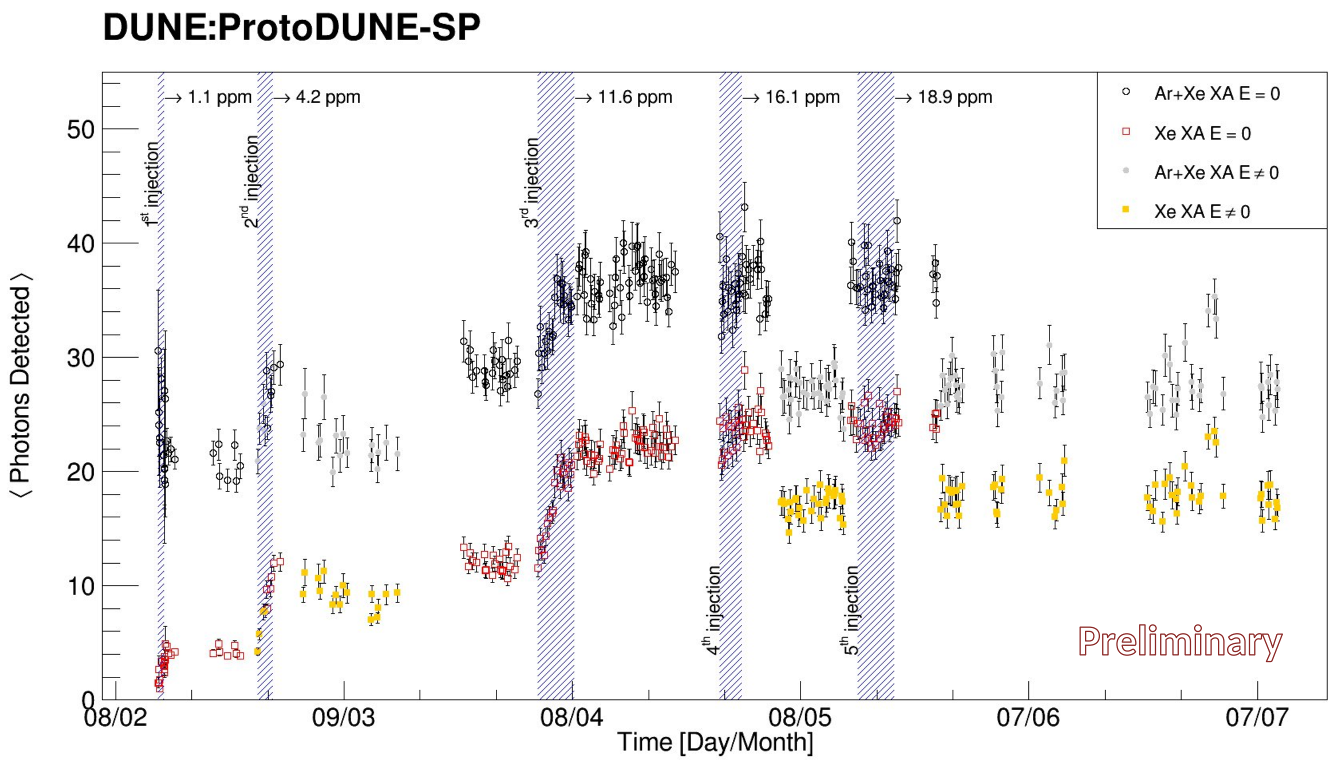
Xenon Injection



- Xenon injection was tested in a small-scale setup with Ar recirculation system
- $\frac{Ar}{Xe} > 10^3$ to avoid freeze-out effect
- Xe is injected in the gas phase far from the LAr condenser at a rate $36\ g/h\ \ [50\ ppb/h]$, this allows full mixing in gas flow
- From numerical (CFD) simulation of LAr flow, Xe is expected to be uniformly distributed within few hours
- 5 different injections were operated, and the detector response was monitored in the meanwhile
- In total 13.5 kg of Xe injected into the cryostat. This is equivalent to 18.8 ppm of Xe in mass, assuming 770 tons of LAr.

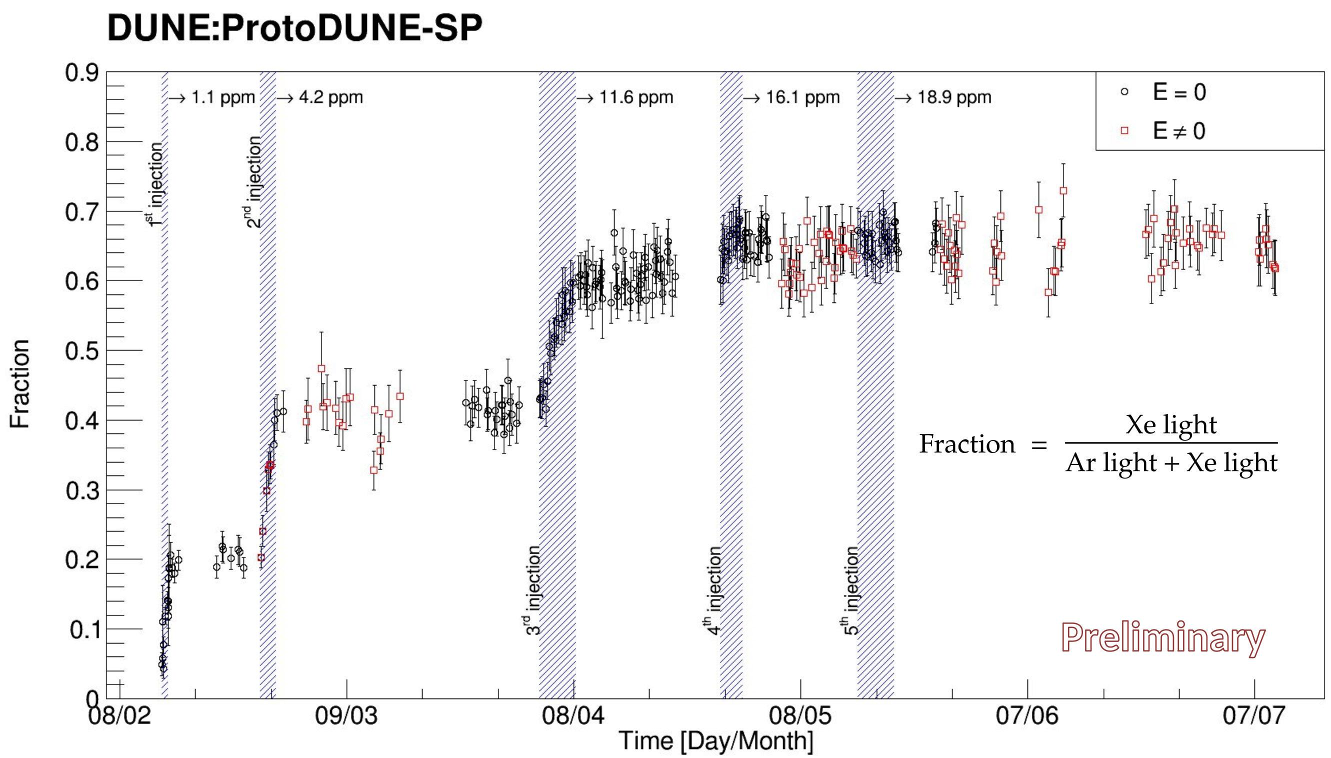
# Injection	Date	Injected Xe [gr]	Injected Xe [ppm]	Cumulative Xe [ppm]
1	13-14 February 2020	776	1.1	1.1
2	26-28 February 2020	2234	3.1	4.2
3	3-8 April 2020	5335	7.4	11.6
4	27-30 April 2020	3192	4.5	16.1
5	15-16 May 2020	400	0.6	16.7
	18-20 May 2020	1584	2.2	18.9

Photons collected



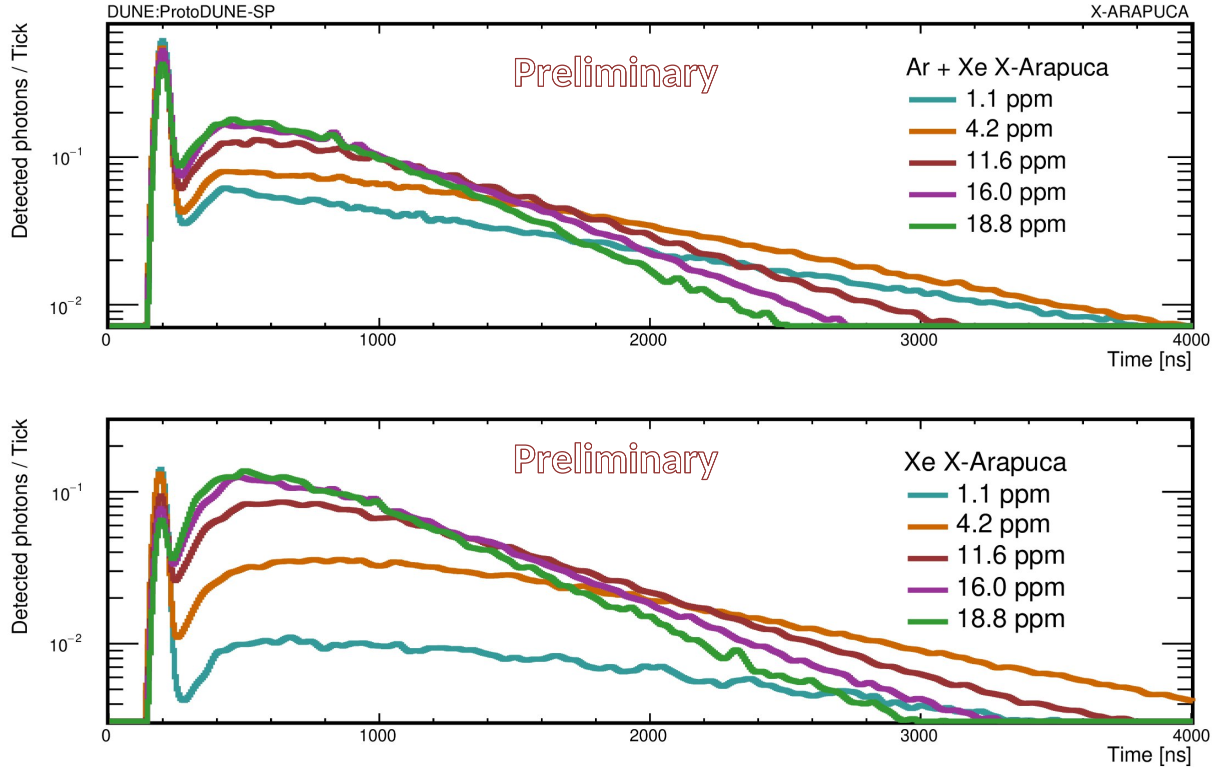
- Light detected by the X-ARAPUCA system as a function of time: number of photons detected increases steadily at each doping. Samples with lower photon yield correspond to periods when TPC electric field was on (lower recombination).

Light Fraction



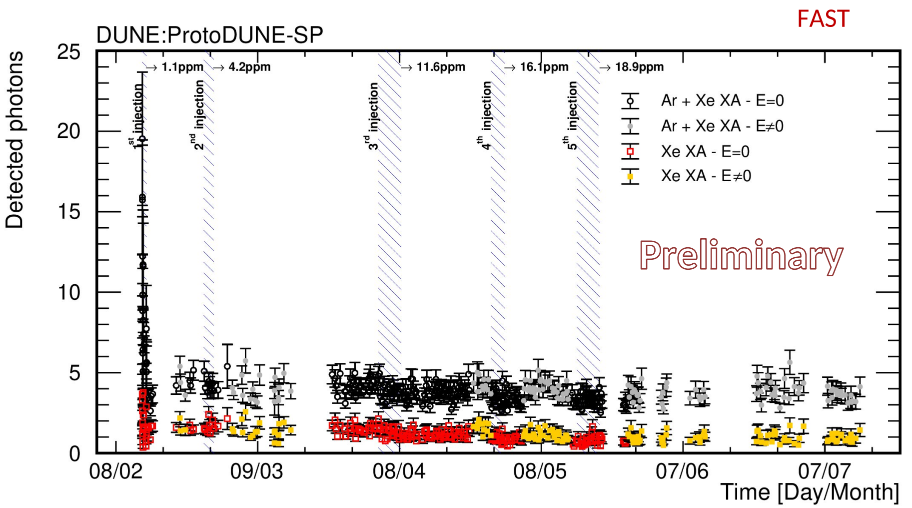
- Fraction of Xe light w.r.t. total light ($Ar + Xe$). The fraction increases with the doping and reaches a plateau around 0.65 for xenon concentration greater than 16.1 ppm.
- The red points correspond to data collected with the nominal TPC electric field, while black points refer to data with no electric field.

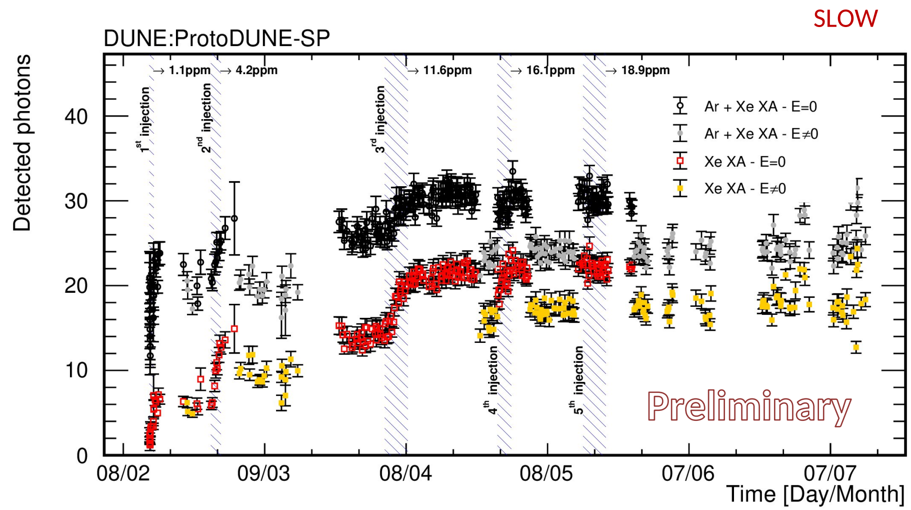
Light time-distribution



- Single PhotoElectron deconvolved waveforms of X-ARAPUCA for different xenon concentrations: $Ar + Xe$ light (top) and Xe light only (bottom). Light increases as a function of Xe concentration, and the distribution becomes shorter in time.

Fast vs Slow components

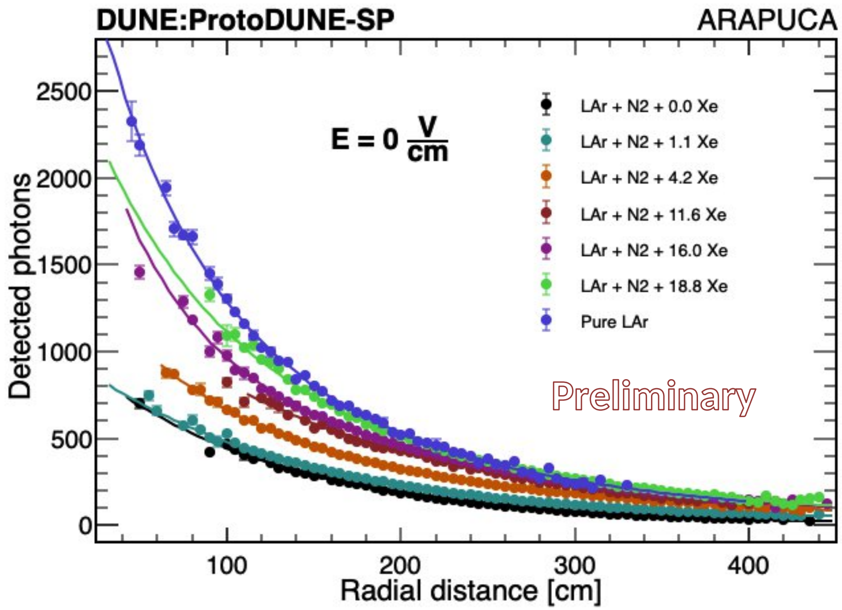


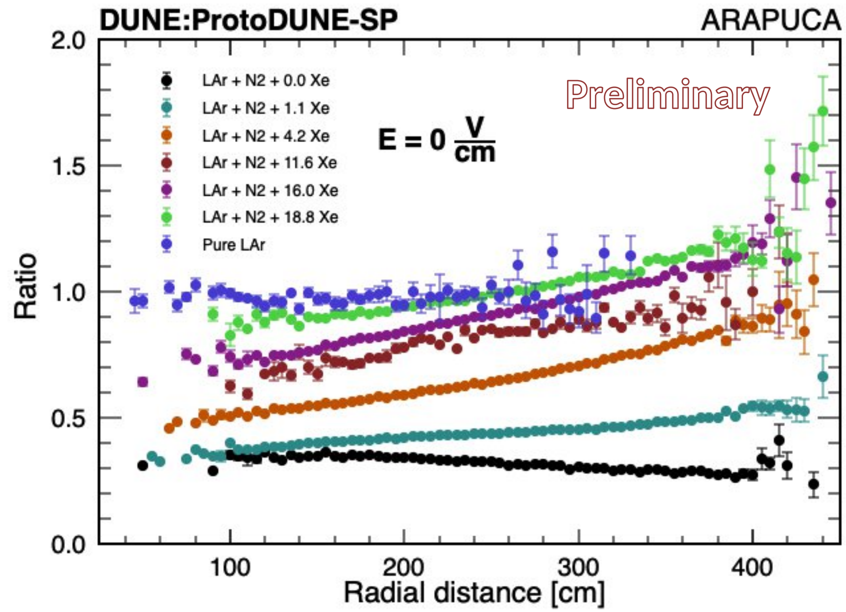


- FAST: integrated light from trigger to $70\ ns$. Unexpected very quick drop during the first doping period, it can be reasonably explained with slight absorption of LAr light from Xe†. Thereafter the light remains constant.
- SLOW: integrated light from $70\ ns$ to the end of the signal. It increases steadily at each doping.

† Neumeier et al., "Attenuation of vacuum ultraviolet light in pure and xenon-doped liquid argon — an approach to an assignment of the near-infrared emission from the mixture", EPL (EurophysicsLetters)111(jul, 2015) 12001, doi:10.1209/0295-5075/111/12001.

Light collection vs distance



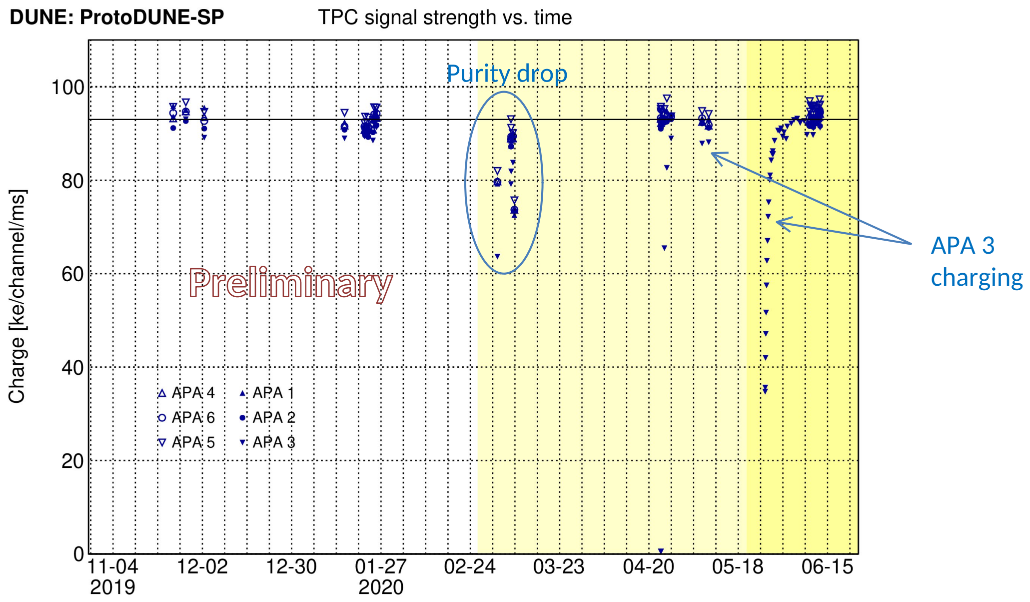


Analysis of ProtoDUNE-SP PDS:

- Light collected by a PDS module as a function of its distance to the track†. N_2 contamination decreases significantly the light collected, while the Xe injection recovers the light.
- Ratio of collected light relative to the pure LAr (no N_2). The light collection uniformity improves as the light collection efficiency far from the APA increases. The trends shown are unaffected by the presence of the TPC electric field.

†Kyle Spurgeon, "Measuring the Rayleigh Scattering Length of Liquid Argon in ProtoDUNE-SP", LIDINE 2021

Charge collection



- Signal strength is used as indicator of charge collection efficiency. It is the average amount of charge collected on the TPC collection wires during a standard run with cosmic rays.
- A straight line indicates the reference value of $93\ ke^{-}/channel/ms$ at $E = 500\ V/cm$
- Sudden drops were due to temporary purity degradation
- The response for APA-3 is always lower for the first few days after high voltage is turned on
- No difference in signal strength after xenon injection.

Conclusion

- First demonstration that a large size ($770\ t$) LAr-TPC can be safely operated with xenon at the level of $\sim 20\ ppm$
  - In total 13.5kg of Xe, 18.8 ppm in mass injected into the cryostat
- $128 \rightarrow 178\ nm$ light shift is effective already at xenon concentrations of a few ppm and it reaches a plateau at $\sim 16\ ppm$
- It helps recovering about 95% of the light originally lost due to N_2 pollution
- The light signal is faster, reducing late light ambiguity
- The profile of the collected light versus the distance is more uniform after the doping, indication of the longer Rayleigh scattering length
- Xenon up to 18.8 ppm does not affect the performance of the charge collection by TPC.

THANK YOU