Doping liquid argon with xenon in ProtoDUNE-SP

Niccolò Gallice

Instrumentation Dept., BNL

April 18, 2024

Fermilab

Neutrino Seminar Series

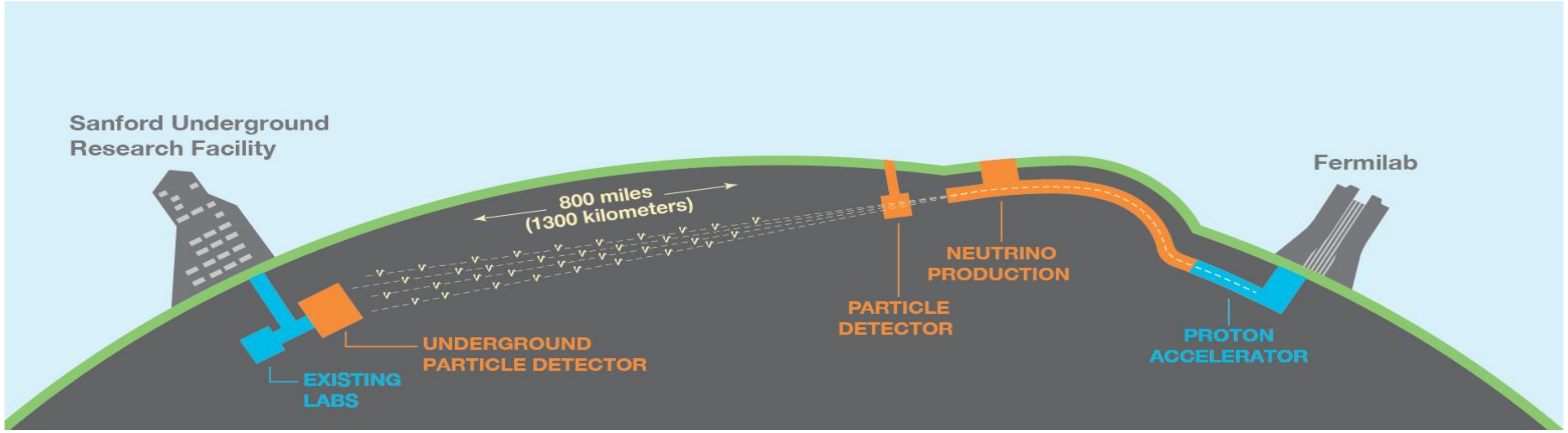
Outline

- Deep Underground Neutrino Experiment (DUNE)
- Liquid Argon Time Projection Chamber (LAr-TPC) technology
- Motivations of xenon doping
- Scintillation mechanism
- Experimental setup:
  - ProtoDUNE-SP
  - Dedicated setup
- Xenon injection procedure
- Results from dedicated setup and ProtoDUNE-SP Photon Detection System
- Charge collection studies
- From scintillation time distribution to microphysics
- Other results and developments

Deep Underground Neutrino Experiment

- **Long baseline oscillation** experiment (~ 1300 km)
- Neutrino and anti-neutrino beam (A 1.2 MW beam upgradeable to 2.4 MW)
- Near detector facility: multi-technology for beam monitoring and physics
- Far detector: 4 Modules (2 + 2) with ~70 kt of liquid argon, 1.5 km underground
- >20 years operation

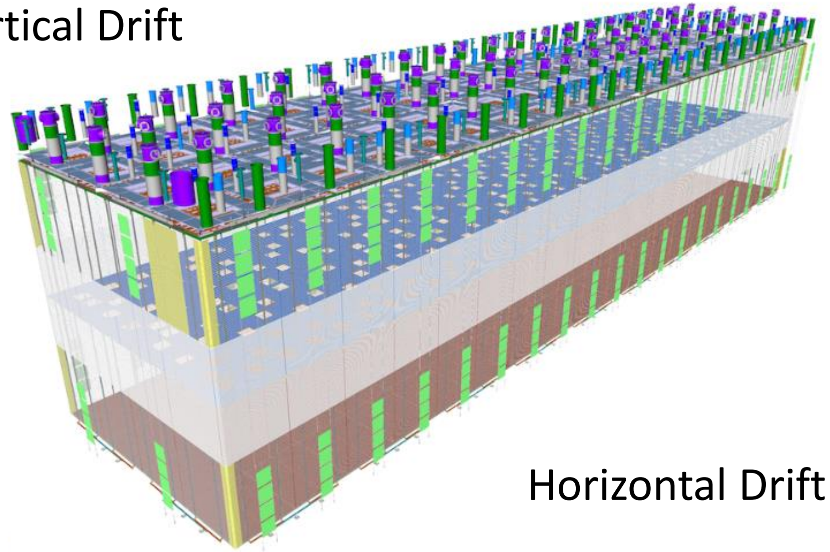
- **Primary physics goals**:
  - 3-neutrino oscillation parameters
  - CP-violation phase δ_{CP}
  - Mass hierarchy
- **Supernova Neutrino Burst**
- **BSM physics:** baryon number violation, sterile neutrinos, non-standard interactions,…



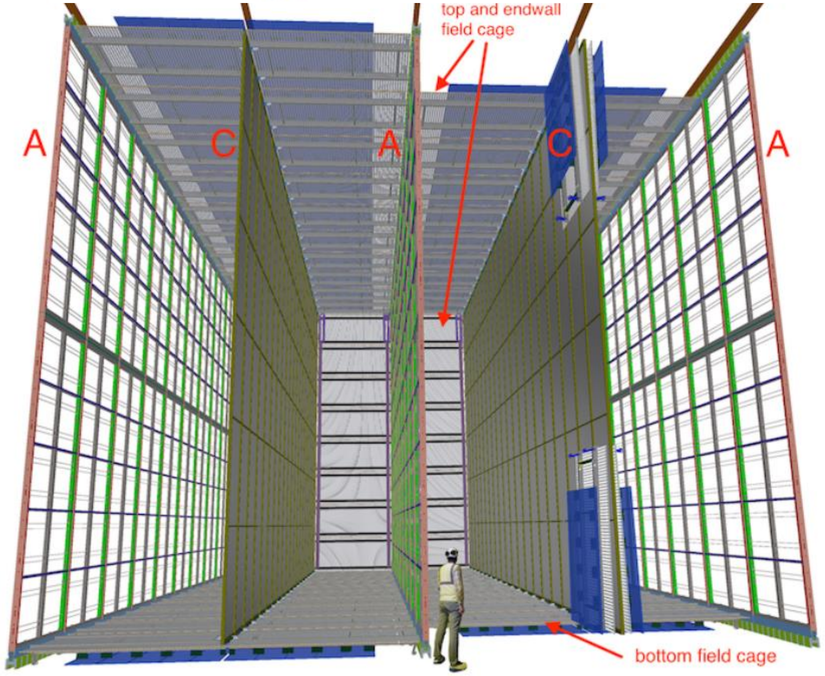
Far detector

- **Highly modular design**, for cryostat and detectors, required by access to SURF caverns through shafts.
- Based on **Liquid Argon Time Projection Chamber** (LAr-TPC) technology, in different flavors
- First module will be a single-phase, **Vertical Drift** Lar-TPC; second module a single-phase, **Horizontal Drift** LAr-TPC

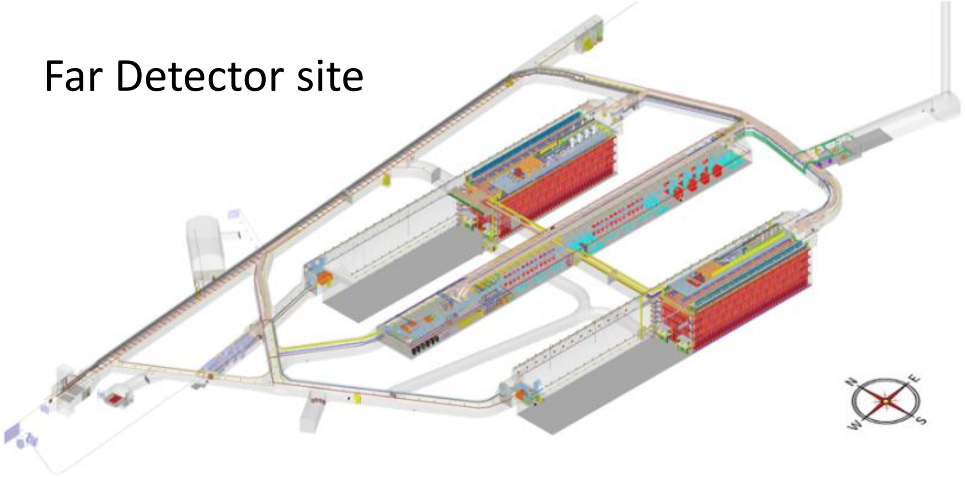
Vertical Drift



Horizontal Drift

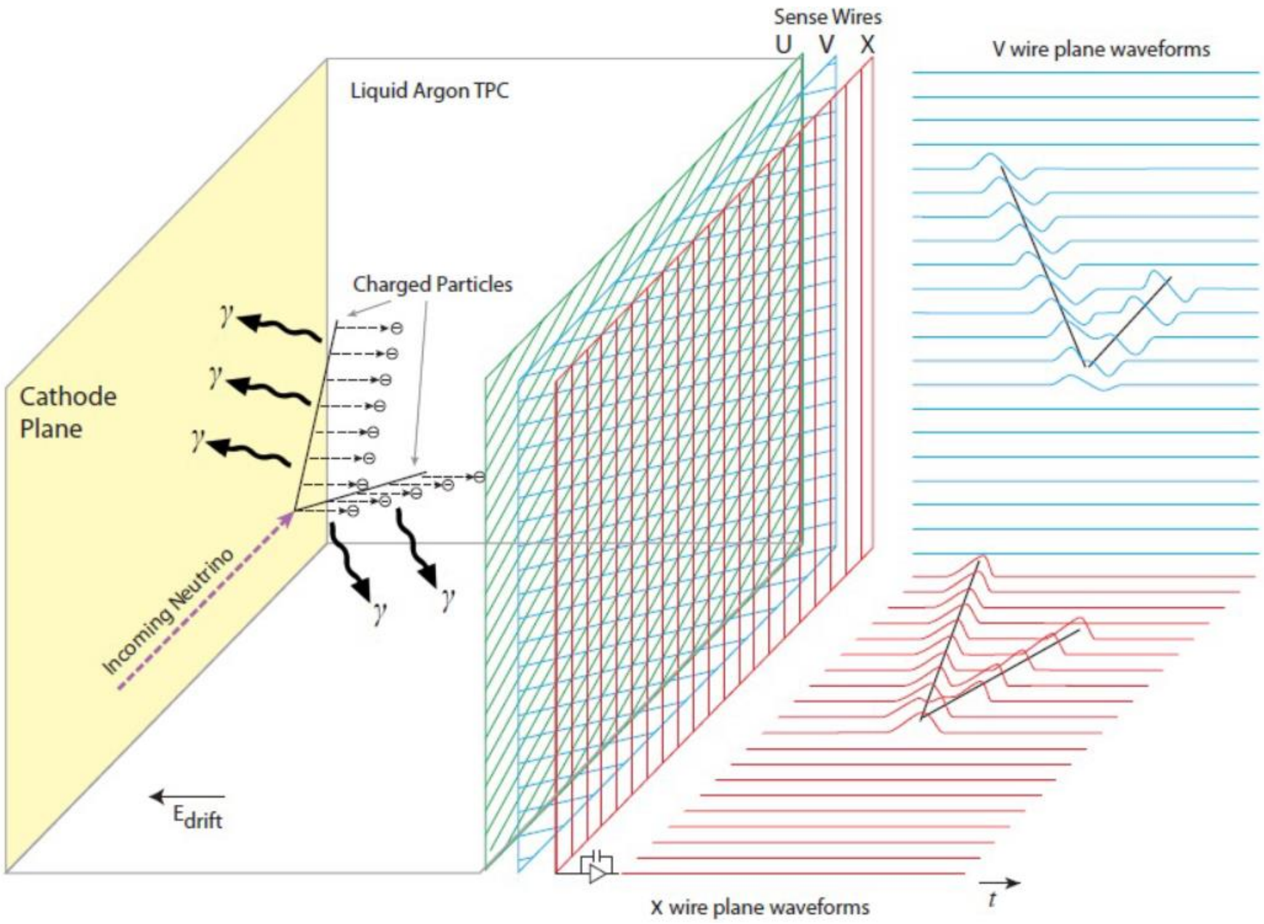


Far Detector site



LAr-TPC

- Charged particles interacting with argon release energy producing ionization and excitation
- An electric field is applied through a Cathode plane $O(100\ kV)$
- Electrons drift to a series of readout planes:
  - U,V → induction planes, record charge passage
  - X → collection plane, collects all the charge generated
  - Precise 2D image reconstruction + calorimetry
- Excitation and electron recombination:
  - Scintillation light (4π, $\lambda = 127\ nm$) provides absolute timing of event
  - Combining with charge readout gives drift space coordinate information
  - Complementary calorimetry
- Complete 3D reconstruction of the event (1 mm precision) and calorimetric information.



Why xenon doping?

- **Liquid Argon is a good scintillator**:
  - Scalable to multi-kton
  - Dense medium good for rare events physics
  - Good electrons mobility for TPC charge readout
  - Light Yield (LY) comparable with other noble liquids (~ 40 000 ph/MeV @$E = 0$ V/cm)
  - Very efficient Pulse Shape Discrimination (PSD)

- **But** light lies in the **Vacuum UltraViolet (VUV)** at 127 nm. **Wavelength shifters** (WLS) are generally deposited **on photosensors**:
  - Low geometrical efficiency (typically 50% of light is lost)
  - Sensitivity to thermal / mechanical stresses
  - Scattering and self-absorption of the emitted light
  - Efficiency dependent on the deposition method

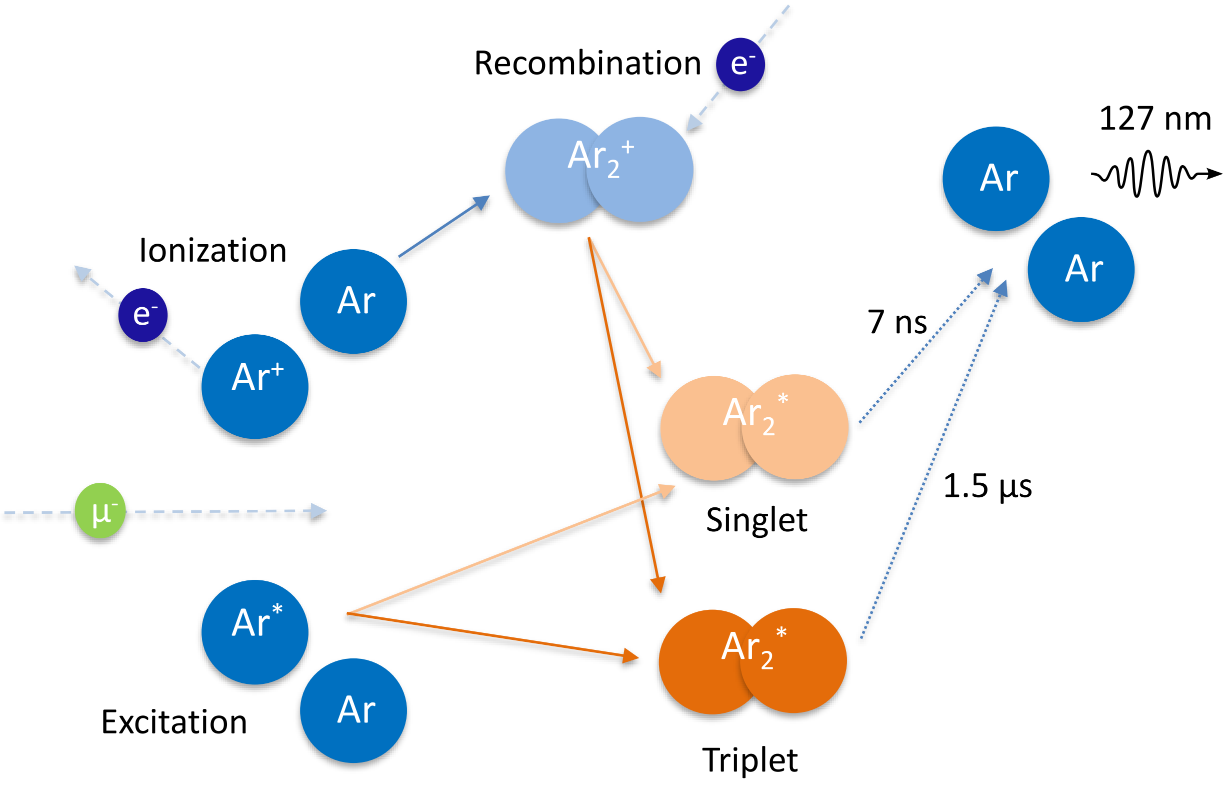
Why xenon doping?

- **Elegant alternative: a volume distributed WLS → Xenon injected into LAr**
  - Shifts 127 nm emission to 175 nm
  - Mitigate WLS coatings 50 % loss
- 175 nm photons have a larger Rayleigh scattering length in LAr:
  - Increase detector uniformity
  - Increase light collection far from the readout plane
- Can recover light quenched by contaminants (N_2)

First large-scale xenon doping of LAr performed in ProtoDUNE-SP

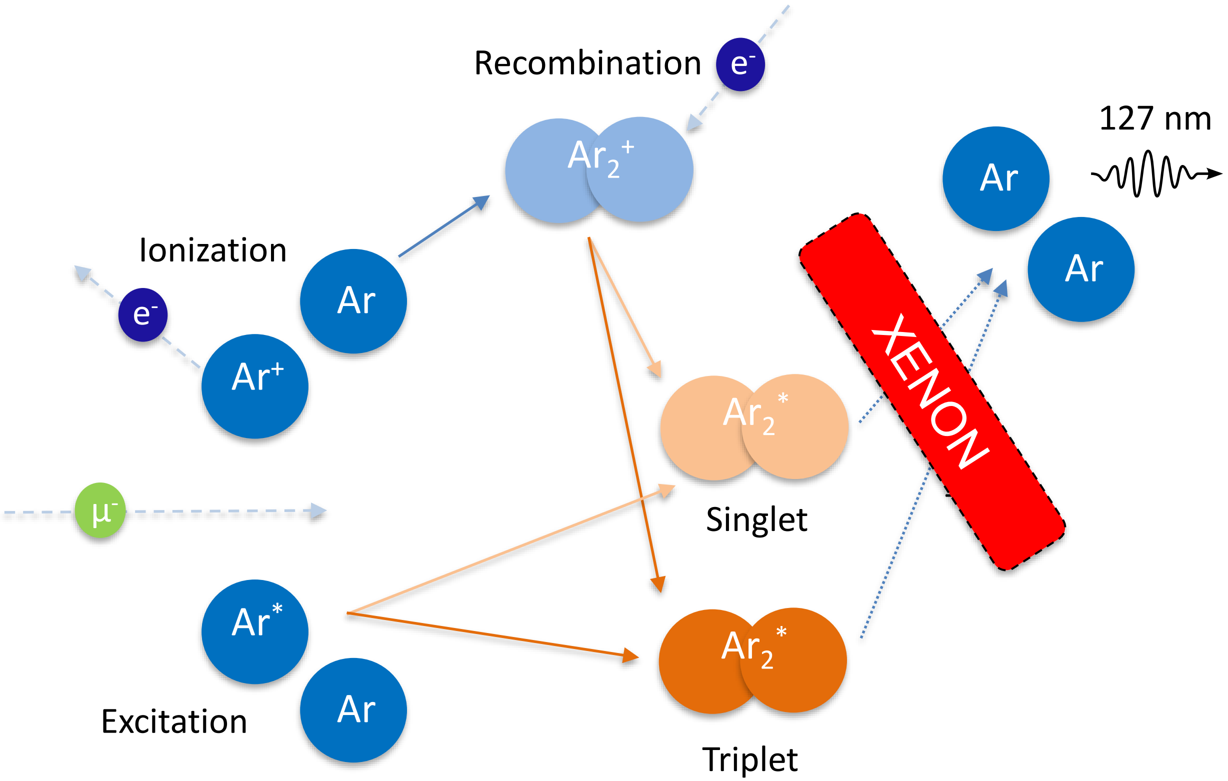
LAr scintillation

- An ionizing particle passing through liquid argon creates ionization and excitation of atoms
- These states interact with argon atoms creating excited molecules
- Singlet and triplet states are created
- De-excitation emits $127\ nm$ light



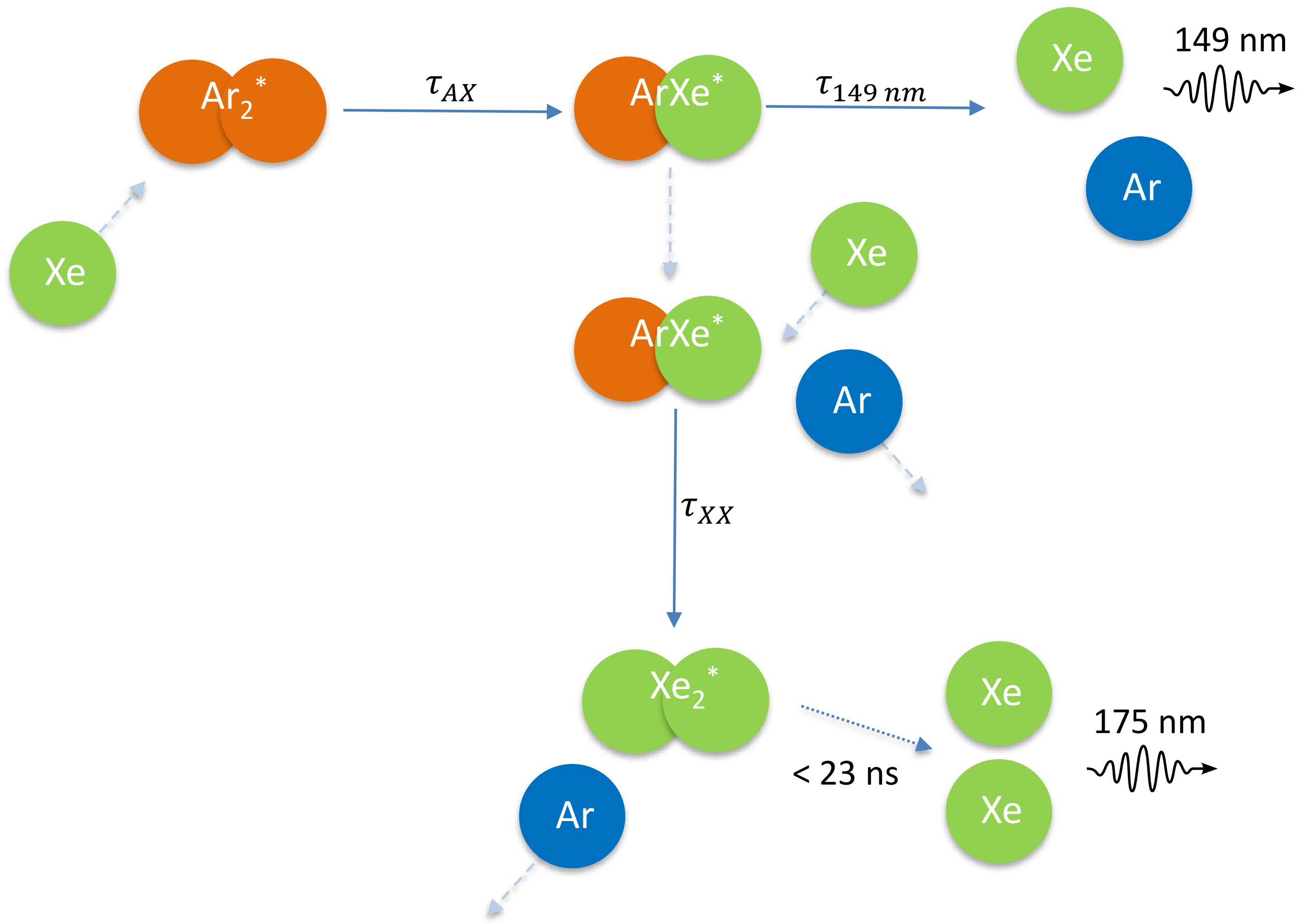
LAr scintillation

- An ionizing particle passing through liquid argon creates ionization and excitation of atoms
- These states interact with argon atoms creating excited molecules
- Singlet and triplet states are created
- De-excitation emits 127 nm light



LAr + Xe scintillation

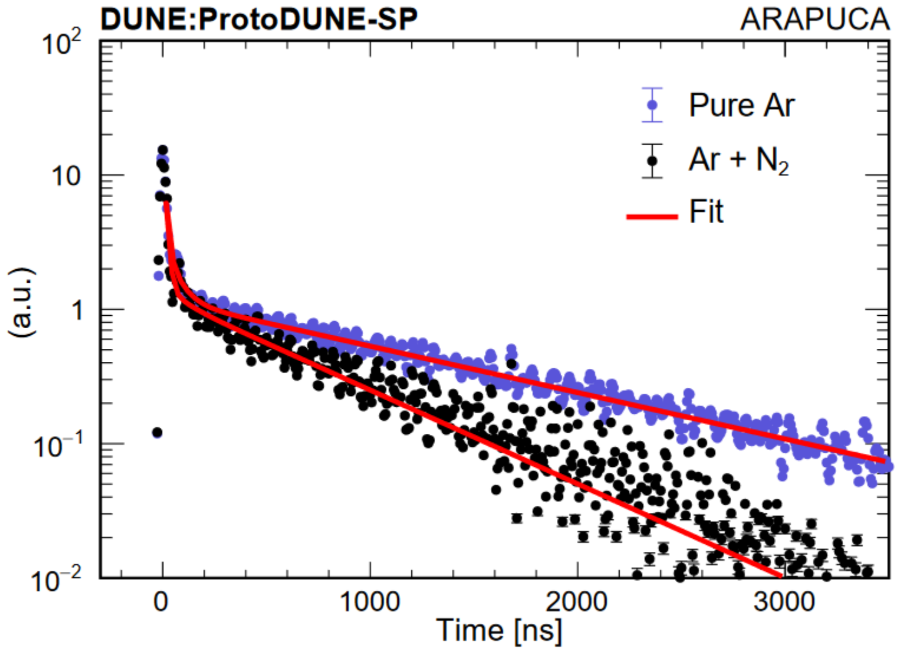
- Argon dimers can interact with xenon creating an ArXe* excimer, this can eventually:
  - De-excite emitting 149 nm photons
  - Interact with Xe and create a Xe_2^* dimer
- The Xe_2^* dimer de-excites quickly emitting 175 nm



Nitrogen contamination in ProtoDUNE-SP

- During the cosmic ray run of ProtoDUNE-SP a sudden failure in the gas recirculation pump occurred, injecting air inside the detector
- Molecules like O_2, CO_2, and H_2O were efficiently removed by the purification system
- The system cannot remove N_2, which remained in the detector until the end of the run
- Measuring the “slow” component of the scintillator light distribution it is possible to quantify the amount of N2 injected

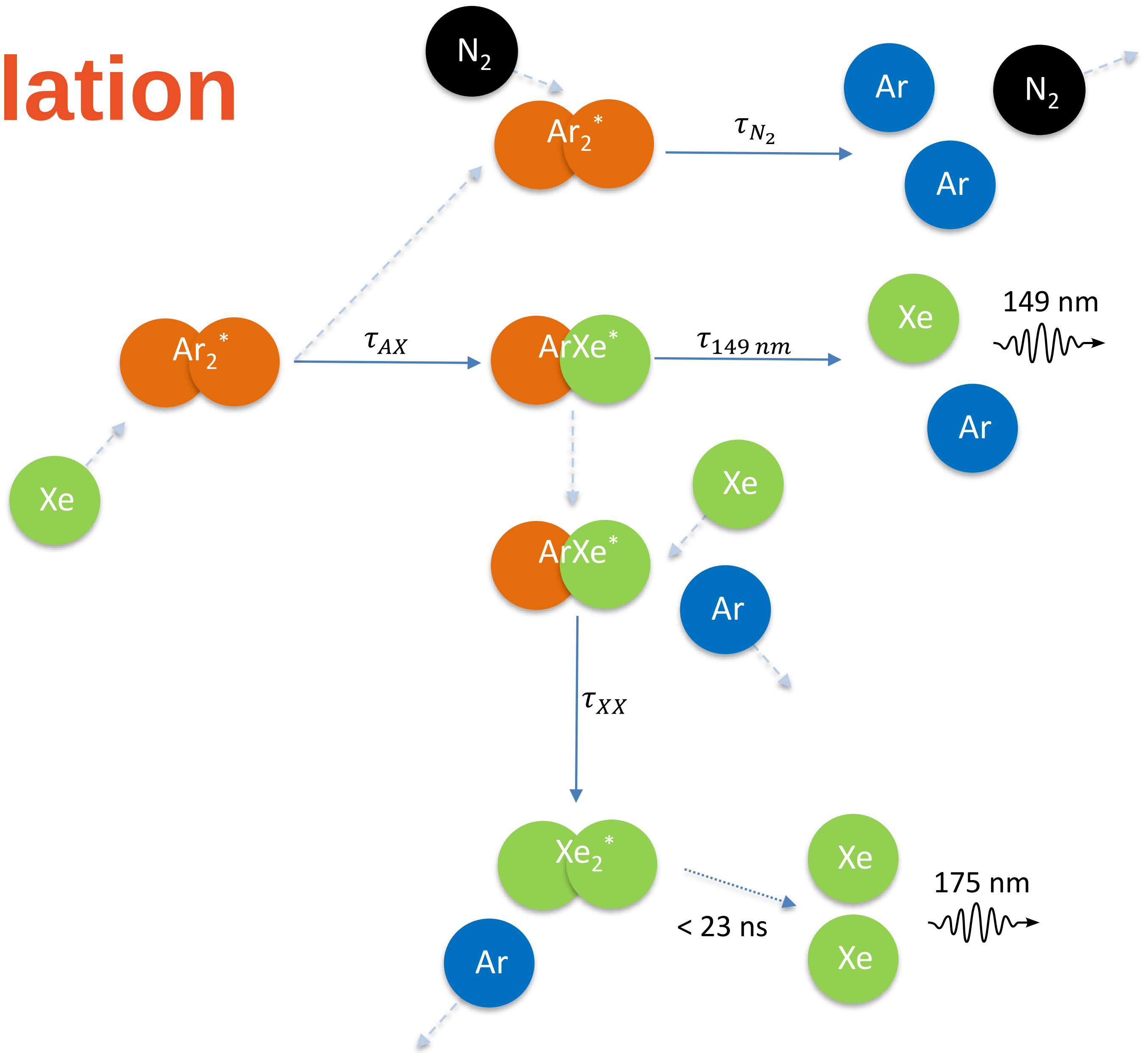
$$\frac{1}{\tau_S}([N_2]) = \frac{1}{\tau_T} + \mathrm{k_Q}[\mathrm{N_2}]$$



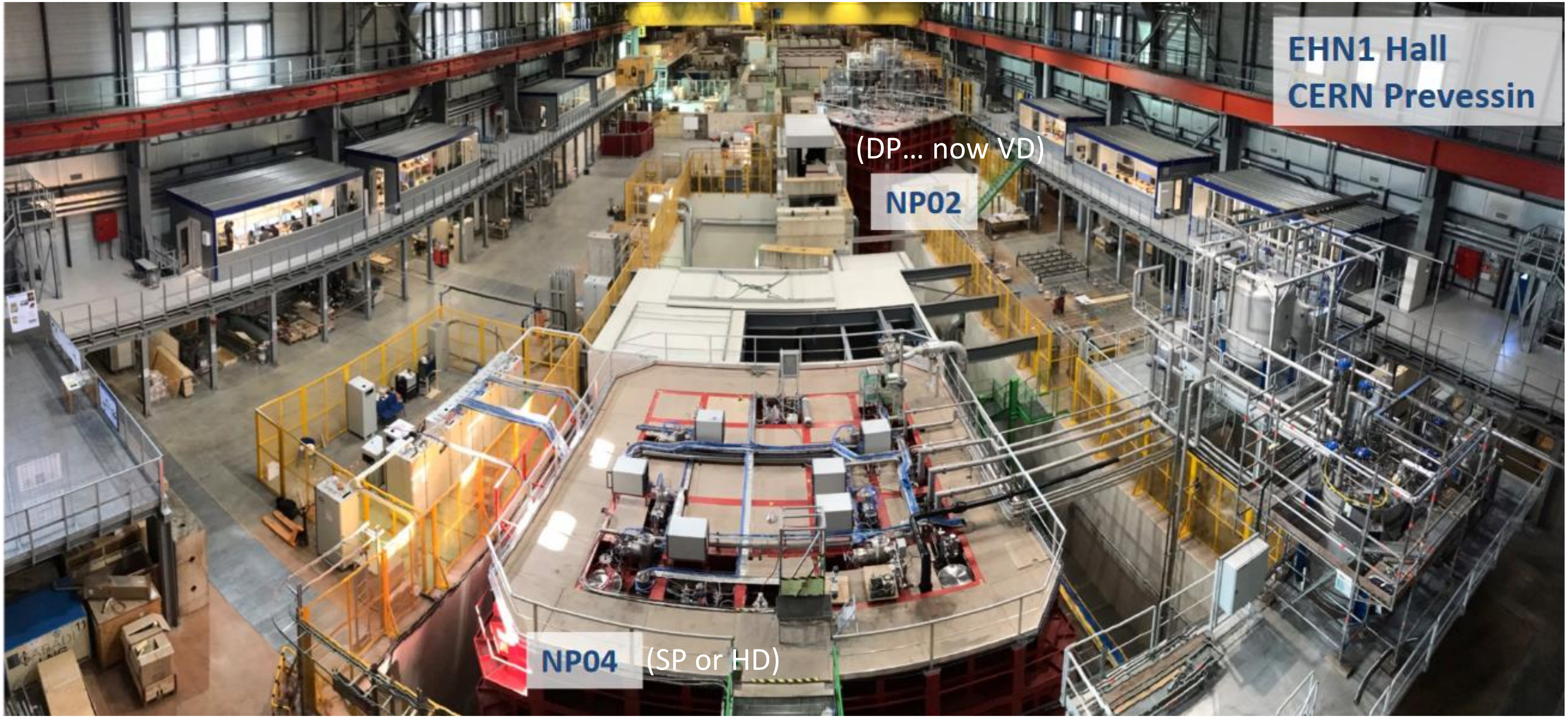
Total amount	$5.4 \pm 0.1\ ppm$
Leaked amount	$5.2 \pm 0.1\ ppm$

LAr + Xe + N_2 scintillation

- Argon dimers can interact with xenon creating an $ArXe^*$ excimer, this can eventually:
  - De-excite emitting 149 nm photons
  - Interact with Xe and create a Xe_2^* dimer
- The Xe_2^* dimer de-excites quickly emitting 175 nm
- If N_2 is present, Ar_2^* can de-excite non-radiatively (quenching)
- $ArXe^*$ creation and N_2 quenching are competing processes



The ProtoDUNE(s)



The ProtoDUNE(s) in a nutshell

- **Two ~1 kt prototypes** with 1:1 dimensional ratio on components wrt DUNE Far Detector
  - Exposed to Very Low Energy (VLE) charged particle beams at CERN
  - Validation of DUNE components design & installation, commissioning, performance and stability studies on **FULL-SCALE** prototypes
- **ProtoDUNE-Single Phase** operated 2018–2020
  - 1 detector, 2 TPCs: 2x 3.6m drift volumes, sharing a common cathode
  - 3-month beam run in late 2018, then cosmics
  - Event reconstruction/identification training
  - R&D site: low-energy calibration (neutron gun), **Xenon doping**, Higher Voltage tests, …
  - Upcoming Phase-II on beam with HD updated design (Filling ongoing right now!!)
- **ProtoDUNE-Dual Phase** operated 2019–2020
  - Development of charge signal amplification, as well as Very High Voltage / large drift (6-12 m) studies
  - Evolved into Vertical Drift -> Phase II
  - Currently equipped with VD technologies and ready for Phase II run.

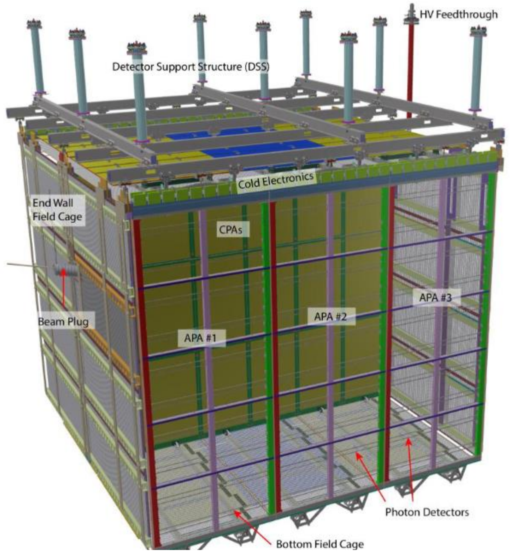
The ProtoDUNE(s) in a nutshell

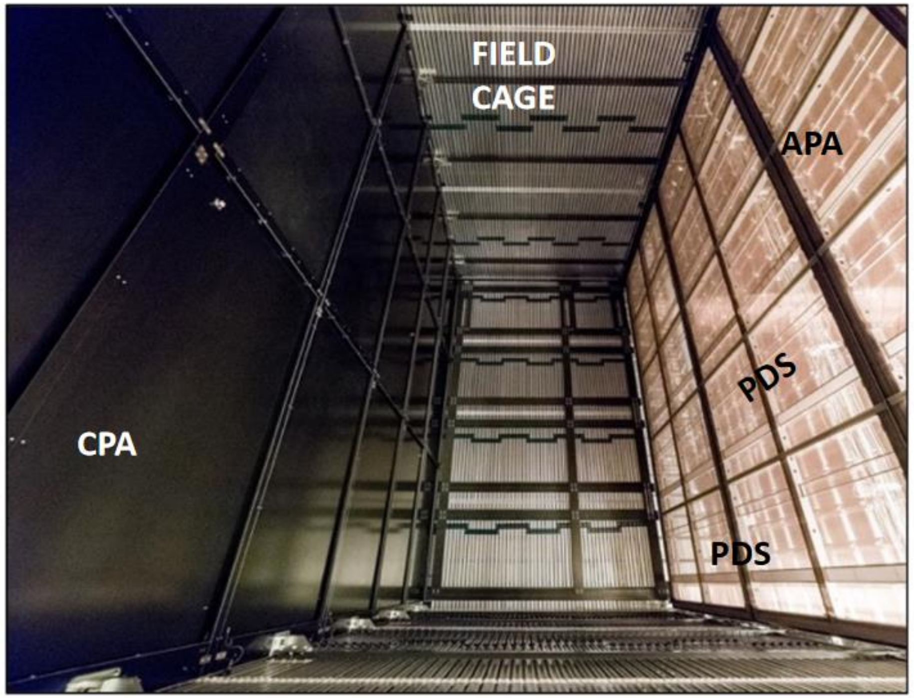
- **Two ~1 kt prototypes** with 1:1 dimensional ratio on components wrt DUNE Far Detector
  - Exposed to Very Low Energy (VLE) charged particle beams at CERN
  - Validation of DUNE components design & installation, commissioning, performance and stability studies on **FULL-SCALE** prototypes
- **ProtoDUNE-Single Phase** operated 2018–2020
  - 1 detector, 2 TPCs: 2x 3.6m drift volumes, sharing a common cathode
  - 3-month beam run in late 2018, then cosmics
  - Event reconstruction/identification training
  - R&D site: low-energy calibration (neutron gun), **Xenon doping**, Higher Voltage tests, …
  - Upcoming Phase-II on beam with HD updated design (Cool Down ongoing right now!!)
- **ProtoDUNE-Dual Phase** operated 2019–2020
  - Development of charge signal amplification, as well as Very High Voltage / large drift (6-12 m) studies
  - Evolved into Vertical Drift -> Phase II
  - Currently equipped with VD technologies and ready for a first Phase II run.

Today focusing on ProtoDUNE Single Phase

Time Projection Chamber (TPC)

- Two drift volumes, each of 1.5 m
- Cathode plane (CPA) made of three 3 mm thick FR4 panels, laminated with Kapton provides up to 180 kV (500 V/cm)
- Field cage of aluminum profiles allows for a uniform electric field in the drift volume
- Anode planes (APA):
  - 6 independent Anode Plane Assemblies (APA) with three active wire planes (15360 channels)
  - 1 Grid; 2x Induction planes (U,V, wrapped wires);1x Collection plane (X) + mesh to isolate Photon Detectors (PDS) inside the frame



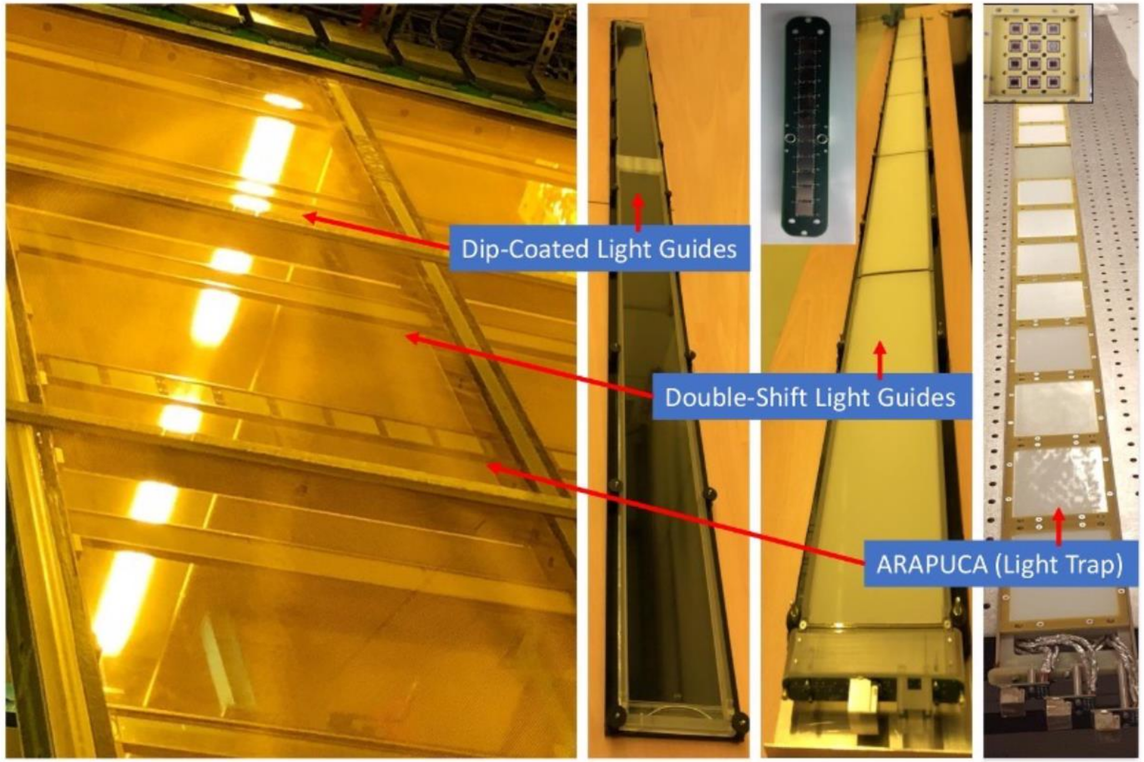


ProtoDUNE SP (HD) : 3.6 m drift (Half detector)

Photon Detection System (PDS)

In the Photon Detection system:

- 3 different technologies read by arrays of 3 or 12 Silicon PhotoMultipliers (SiPMs) from SensL or Hamamatsu
- 10 bars per APA, inside the frame: 207 x 8.6 cm view area into the TPC, per bar
- Metallic mesh to decouple electrically PDs and wire planes

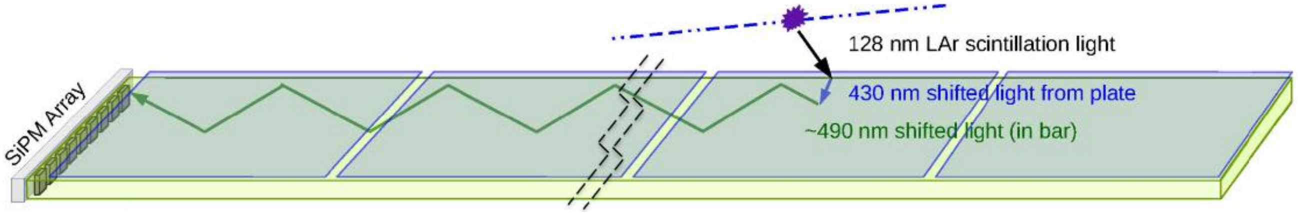


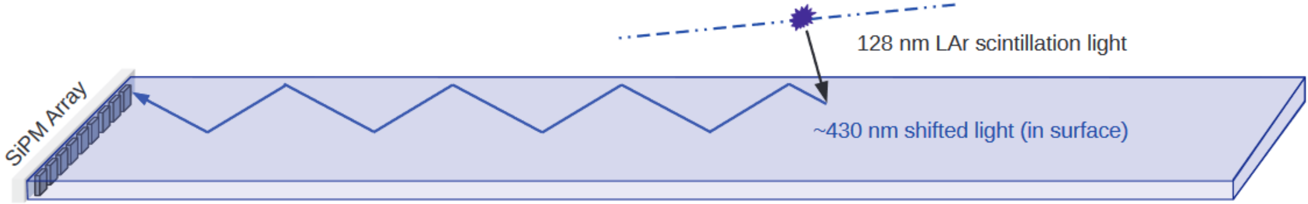
Photon Detection System (PDS)

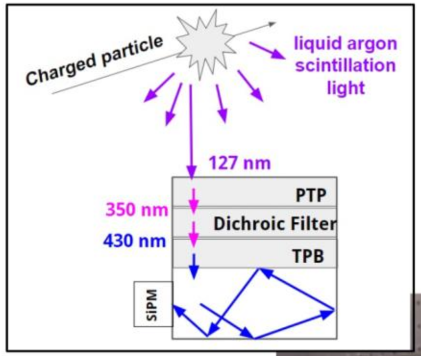
- **Double-shift light guide**
  B. Howard et al. 10.1016/j.nima.2018.06.050
  128nm → 430nm → 490nm
  Wavelength-shifting (WLS) plates + WLS light guide
  Shifted light travels, via total internal reflection, to the readout on one side (four 3-SiPM arrays <-> four read-out channels)

- **Dip-coated light guide**
  L.Bugel, et al 10.1016/j.nima.2011.03.003
  128 nm → 430 nm
  Acrylic dip-coated with TPB+acrylic+toluene solution
  Shifted light travels, via total internal reflection, to the readout on one side (four 3-SiPM arrays ↔ four read-out channels)

- **Arapuca**
  E. Segreto, et al 2018 JINST 13 P08021
  128 nm → 350nm → 430nm
  Light shifted a first time (pTP) crosses a dichroic filter, opaque to higher l, then meets TPB -> second shift. Photons collected promptly or trapped and reflected till they hit one SiPMs (12 cells – read-out channels, each read by 12 SiPM)

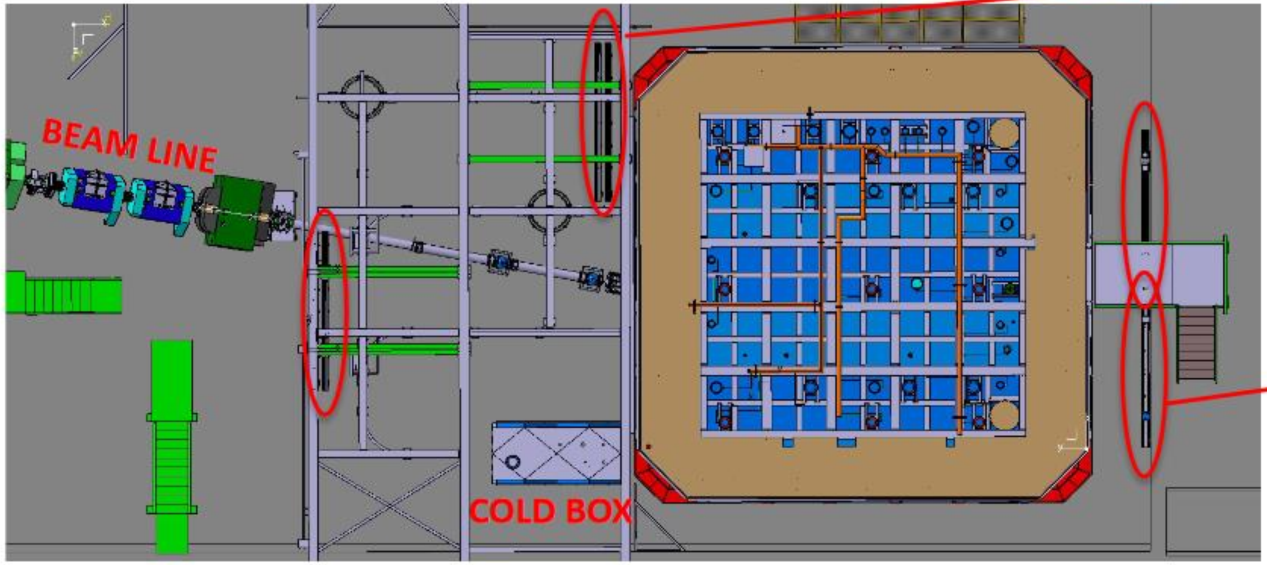


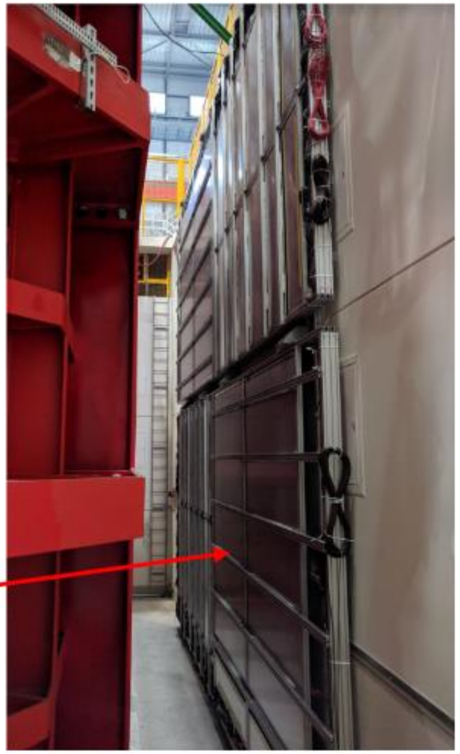




Cosmic Ray Tagger (CRT)

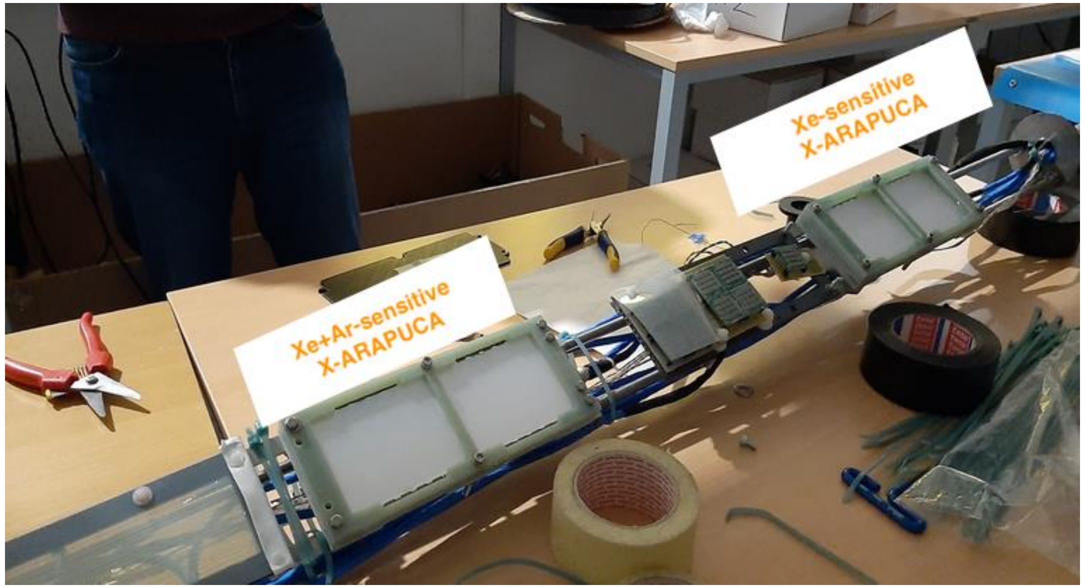
- A Cosmic Ray Tagger (CRT) is installed on the upstream and downstream (w.r.t. to the CERN beam) faces of the detector
- Intercepts and tags muons from cosmic rays crossing the detector
- Each module has 64 scintillator strips (5 cm x 365 cm) read by SiPMs. Rotating two modules by 90˚ → 2D sensitivity.

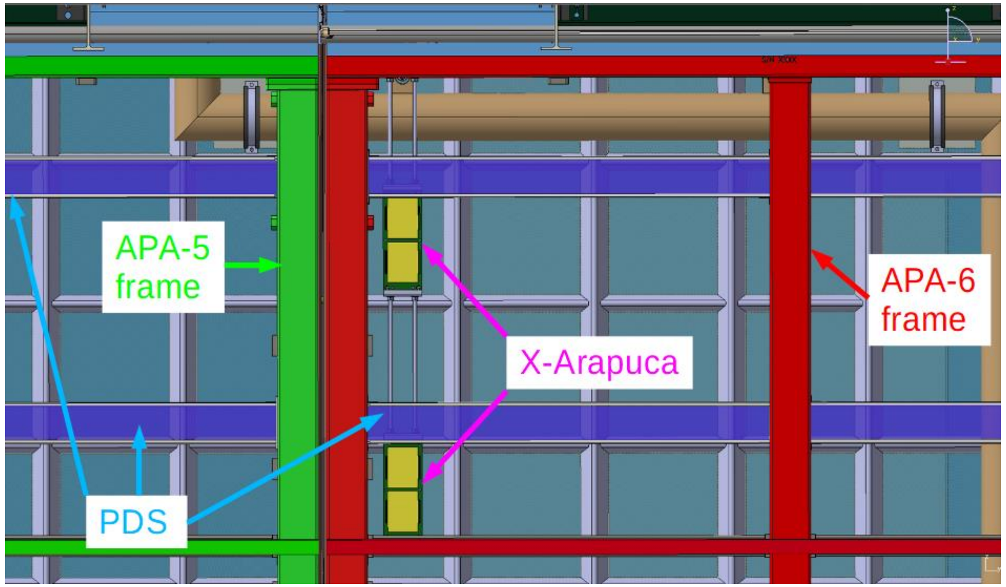




Dedicated X-ARAPUCA setup

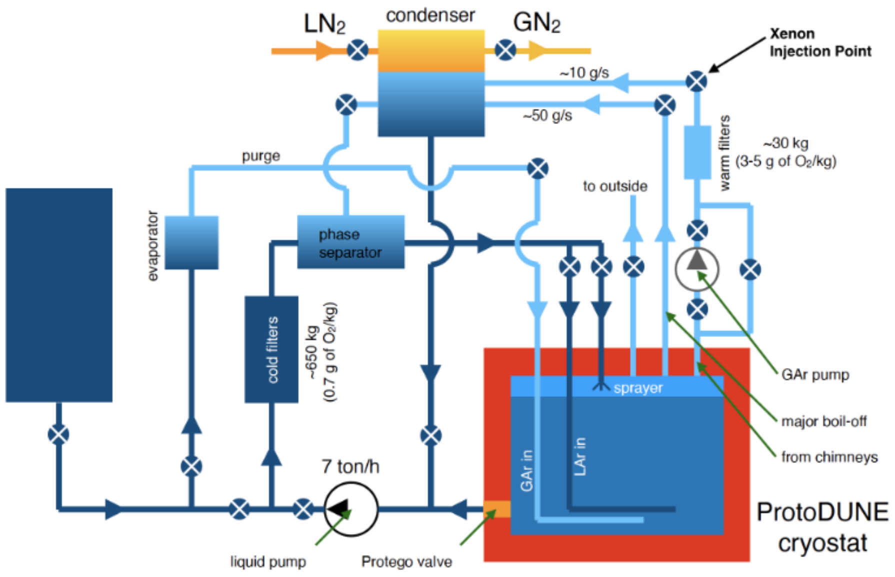
- Installation of modules into the cryostat to disentangle xenon and argon light:
  - X-ARAPUCA **equipped with a fused-silica window** that is sensitive to $Xe\ (175\ nm)$ light only “Xe XA”
  - X-ARAPUCA sensitive to $Xe\ (175\ nm) + Ar\ (128\ nm)$ light “Xe+Ar XA”





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.

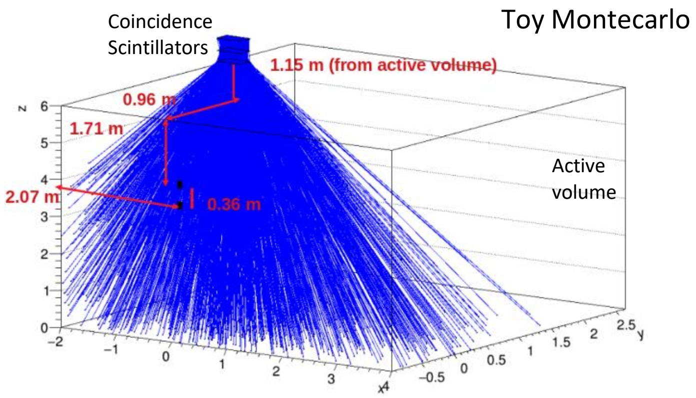


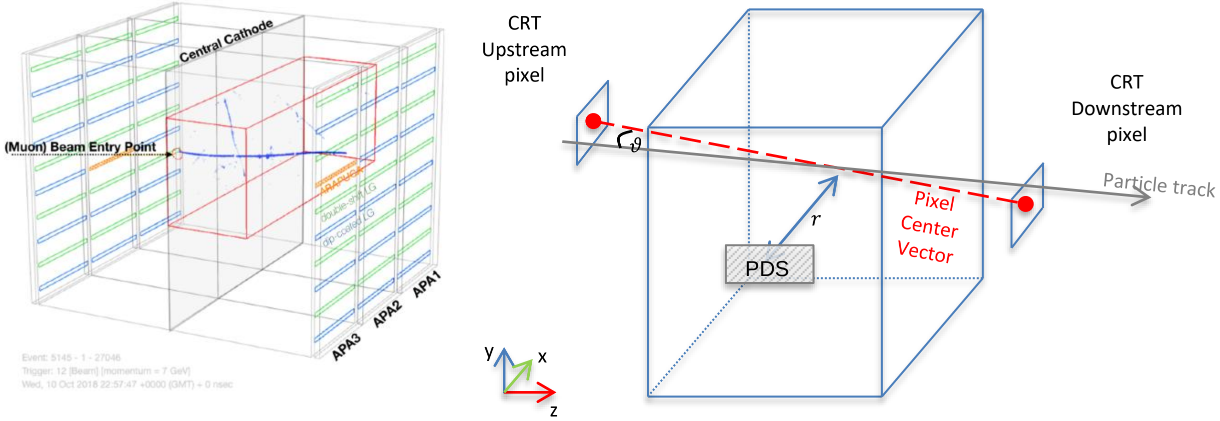
# Injection	Date	Injected Xe [gr]	Injected Xe [ppm]	Cumulative Xe [ppm]
1	13-14 Feb 2020	776	1.1	1.1
2	26-28 Feb 2020	2234	3.1	4.2
3	3-8 Apr 2020	5335	7.4	11.6
4	27-30 Apr 2020	3192	4.5	16.0
5	15-16 May 2020	400	0.6	16.6
	18-20 May 2020	1584	2.2	18.8

DAQ and Data selection

- A muon telescope with standard triple coincidence of $15.5 \times 44\ cm^2$ plastic scintillators was installed on the roof of ProtoDUNE-SP
- It selects vertical muons within a 0.43 sr solid angle
- When a triple coincidence is detected, a trigger for the dedicated setup is issued
- A local DAQ (same electronics of ProtoDUNE-SP) is used to acquire and store data

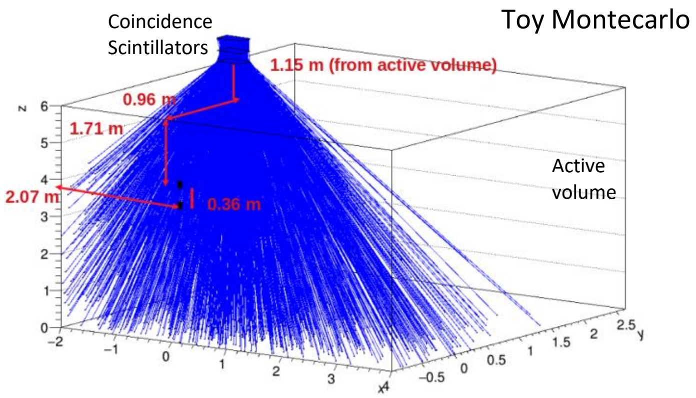
- When ProtoDUNE-SP CRT detects a coincidence between the upstream and downstream module → a trigger is issued
- ProtoDUNE-SP TPC and PDS start data acquisition
- Selection:
  - If TPC track is available: compare TPC reconstructed direction with vector that intersects the strip hits in both triggered CRT modules ($\cos\theta > 0.999$)
  - If $E = 0\ V/cm$: at least two photon detectors in two different APAs within a time coincidence of 13 μs.



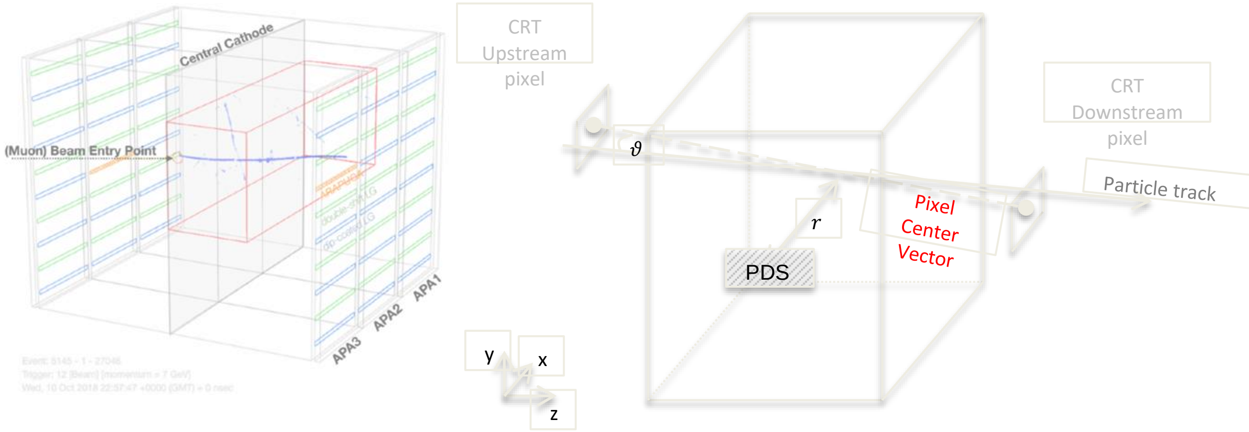


DAQ and Data selection

- A muon telescope with standard triple coincidence of $15.5 \times 44\ cm^2$ plastic scintillators was installed on the roof of ProtoDUNE-SP
- It selects vertical muons within a 0.43 sr solid angle
- When a triple coincidence is detected, a trigger for the dedicated setup is issued
- A local DAQ (same electronics of ProtoDUNE-SP) is used to acquire and store data

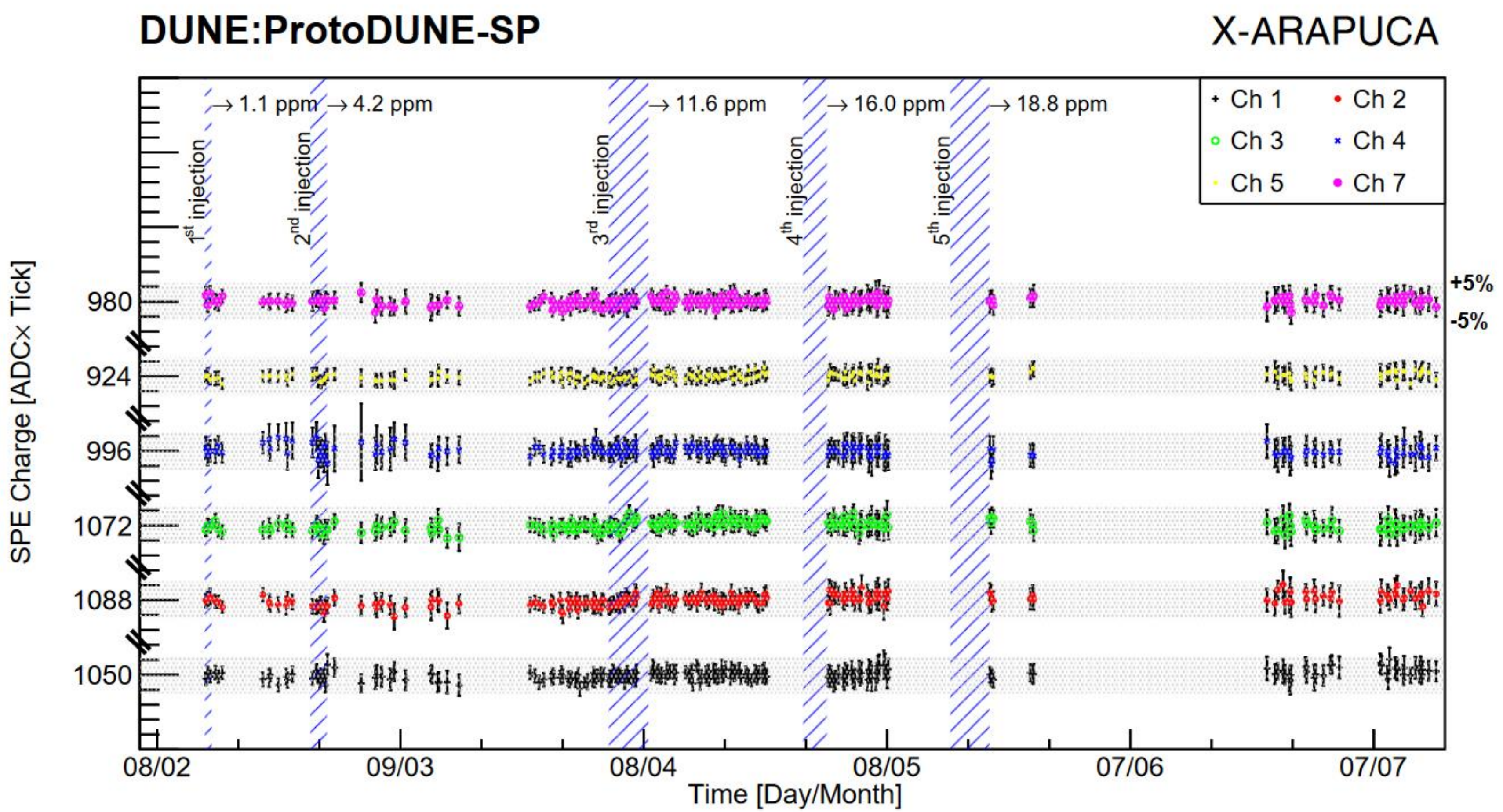


- When ProtoDUNE-SP CRT detects a coincidence between the upstream and downstream module → a trigger is issued
- ProtoDUNE-SP TPC and PDS start data acquisition
- Selection:
  - If TPC track is available: compare TPC reconstructed direction with vector that intersects the strip hits in both triggered CRT modules ($\cos\theta > 0.999$)
  - If $E = 0\ V/cm$: at least two photon detectors in two different APAs within a time coincidence of 13 μs.



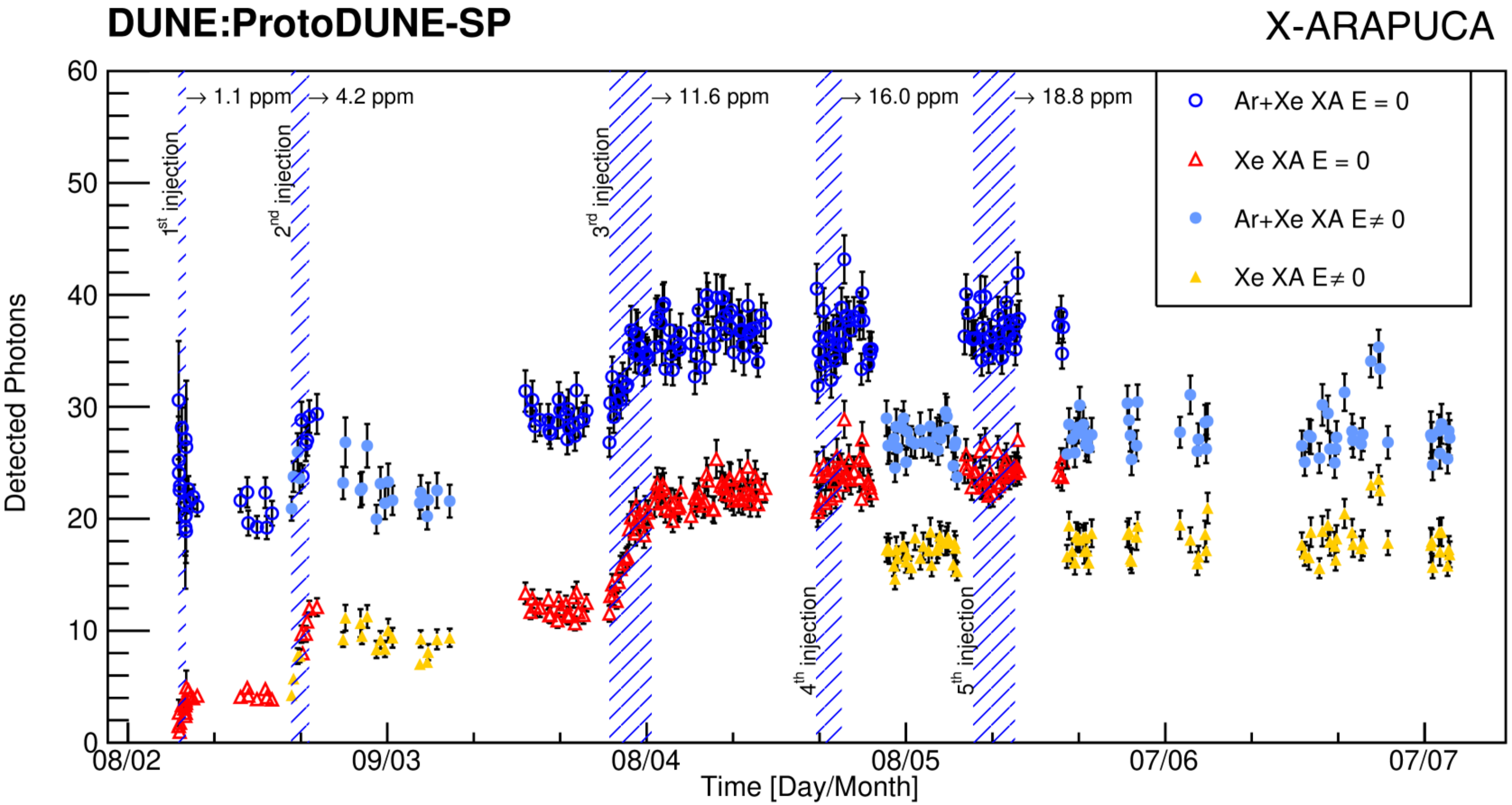
X-ARAPUCA system stability

- Monitoring of sensors and electronics by analyzing the single photoelectron (SPE) response
- A peak finder algorithm searches photoelectron pulses in the tail of each acquired signal
- The charges of these onsets are histogramed
- The first two peaks are fit with two Gaussians and the difference in their mear values is taken as the SPE charge



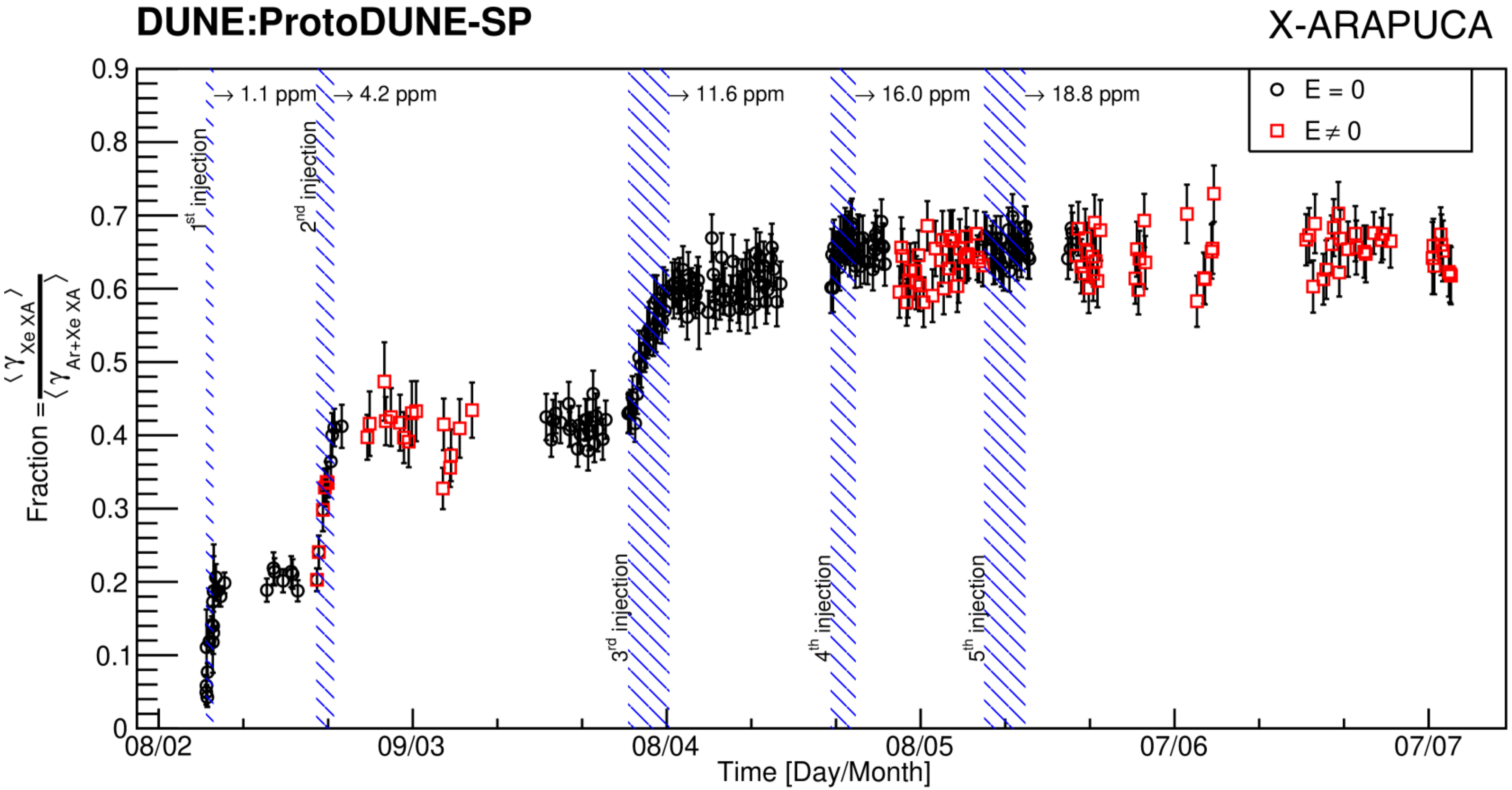
Detected photons

- Light collected by the two X-ARAPUCA modules, in units of detected photons per trigger.
- Shaded areas represent xenon injection periods.



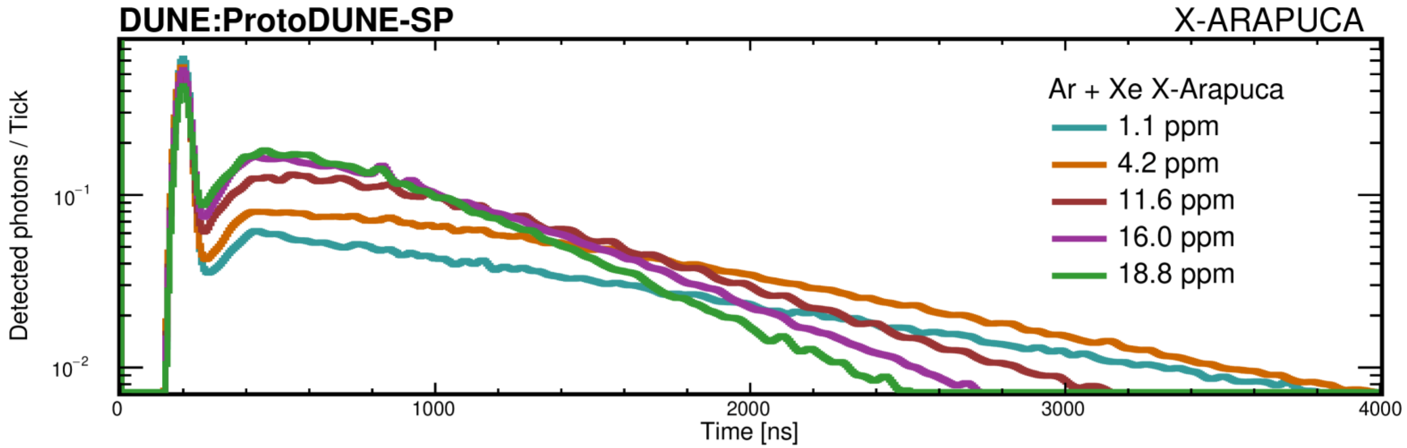
Fraction: $Xe/(Ar + Xe)$

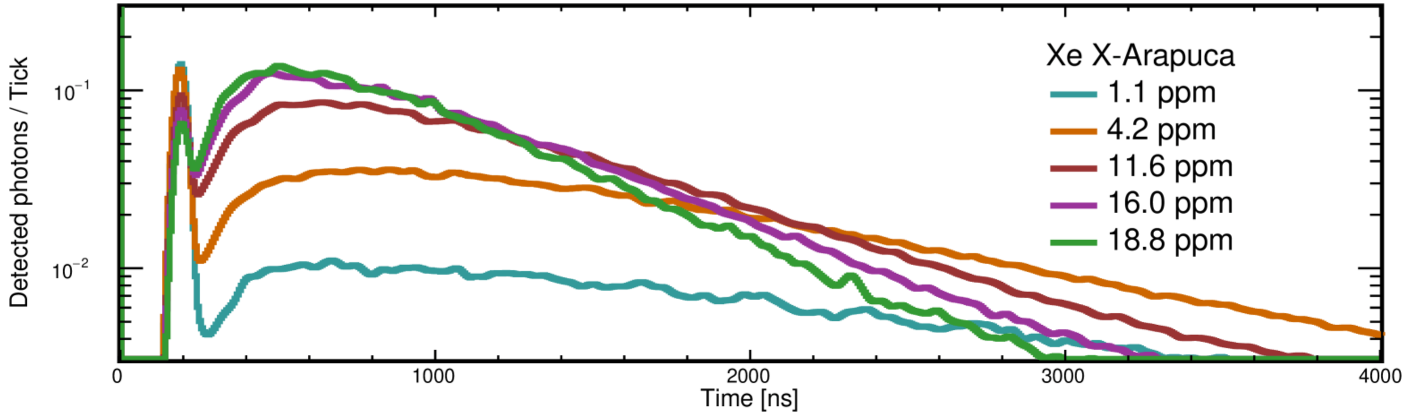
- Fraction of light collected by the xenon-only sensitive X-ARAPUCA.
- Shaded areas represent xenon injection periods.
- The ratio increases with the doping and reaches a plateau around 0.65 for xenon concentration greater than 16.0 ppm.



Scintillation time profile

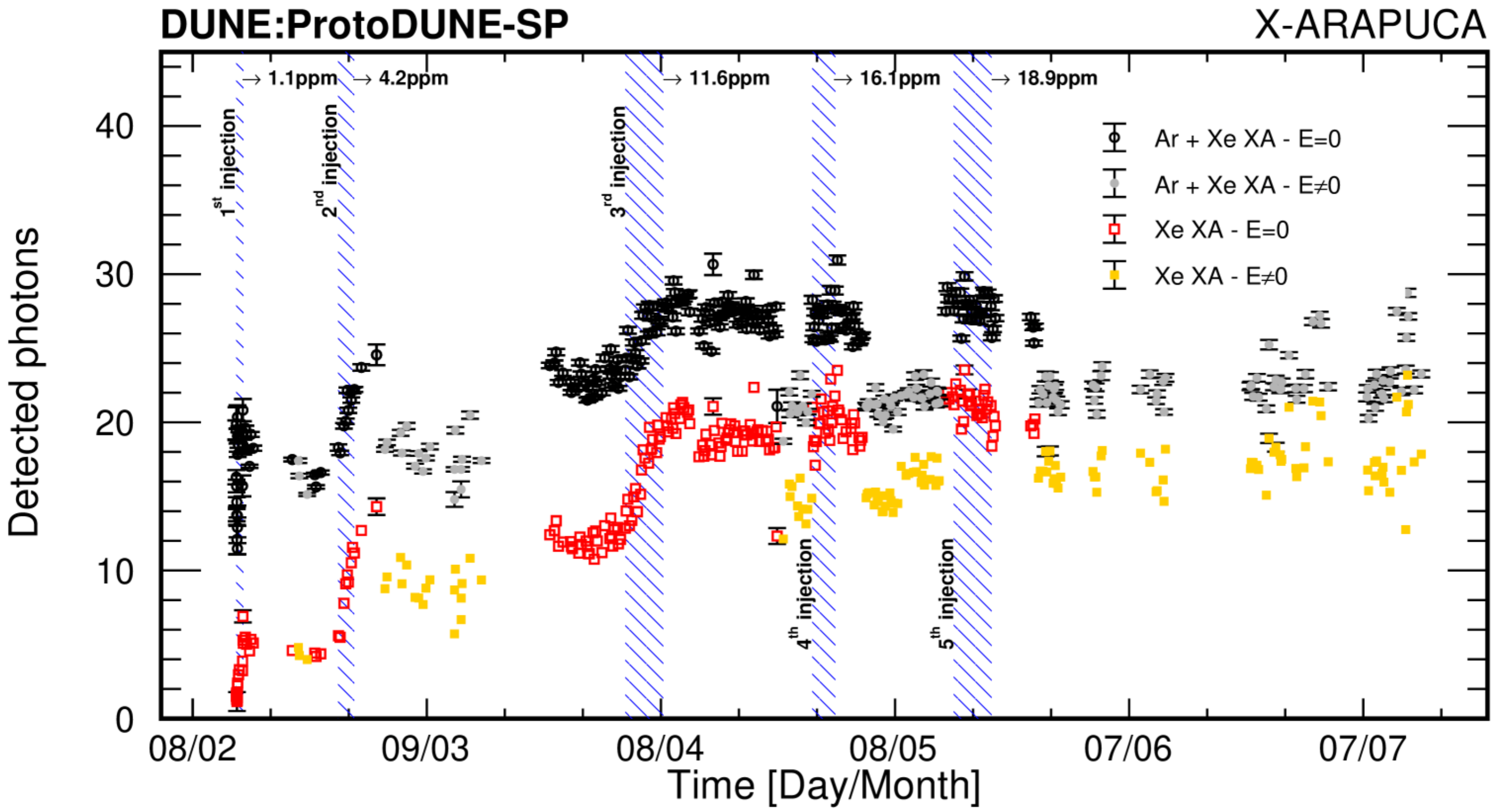
- Averaged scintillation signals are deconvolved by single photoelectron response of the sensor
- Overall light (area under the curve) increases
- Typical bump, due to Ar-Xe creation
- The scintillation profile becomes shorter as xenon get injected





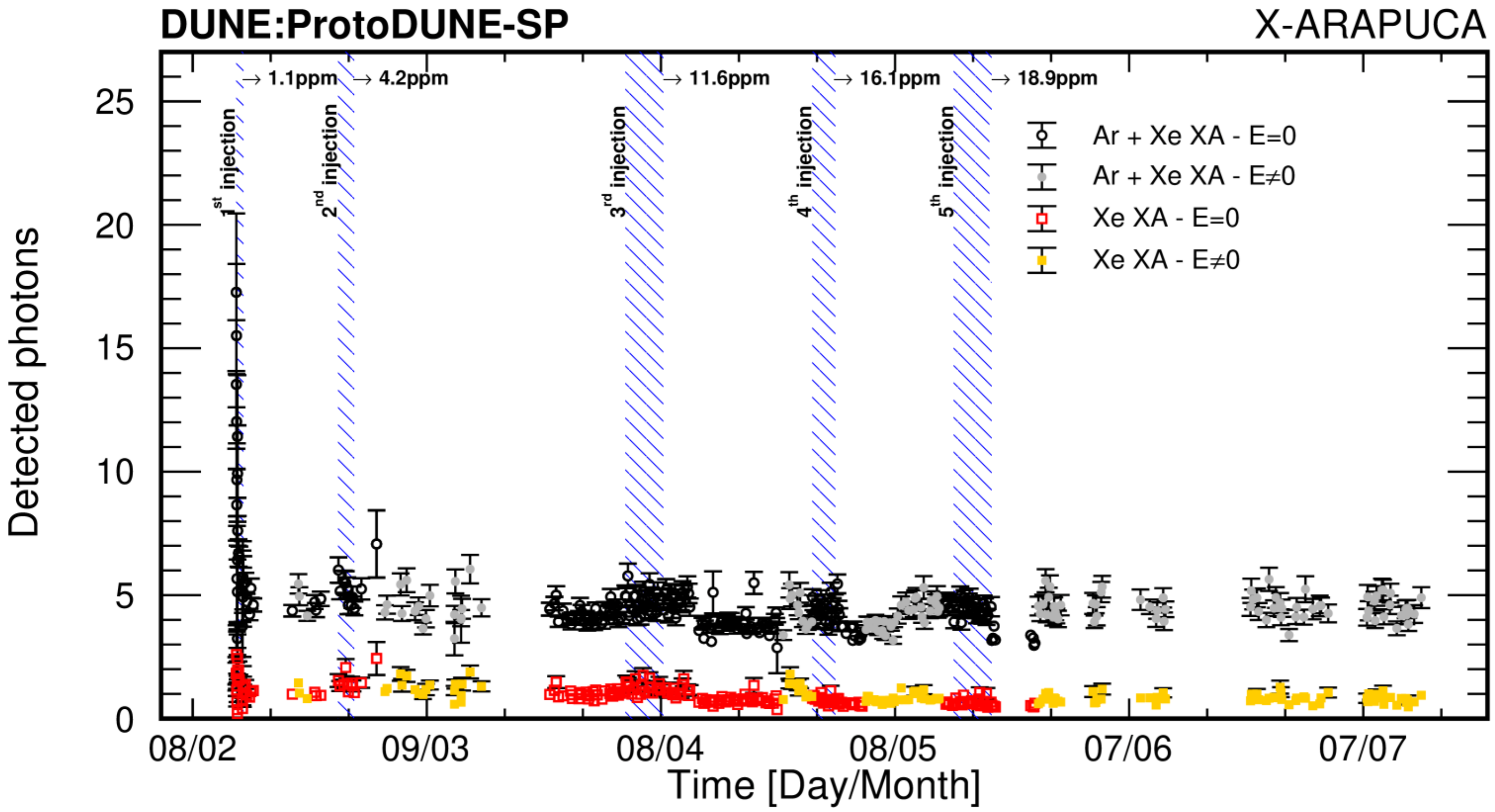
Slow component

- *Slow* light component: detected photons with $t > 74\ ns$ after trigger
- Most affected by xenon doping for low doping concentration
- Same trend as total detected photons (full waveform integral)



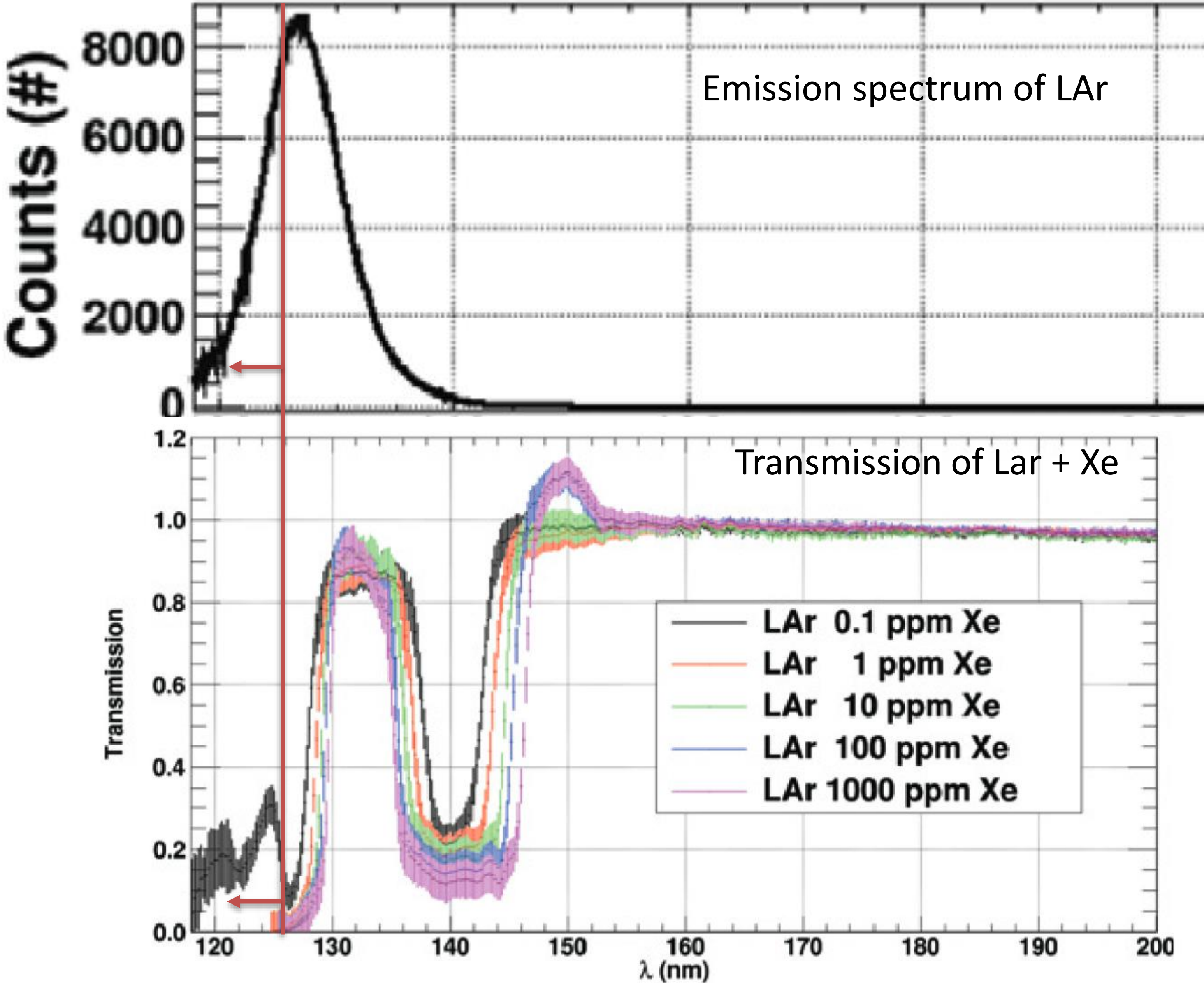
Fast component

- *Fast* light component: detected photons with $t < 74\,ns$ after trigger
- Unexpected reduction of the fast component immediately after the first injection
- Then, stable throughout the doping period



Fast component

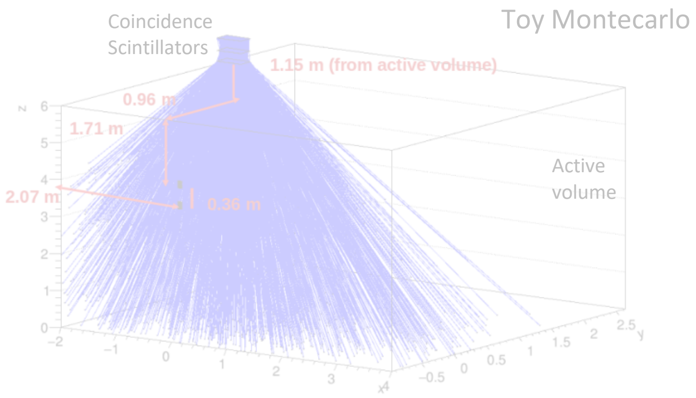
- It cannot be explained by xenon-shifting mechanism: de-excitation time of Ar singlet (~ 6 ns) too quick for energy transfer mechanism
- It is not affected by further xenon injections (collisional processes rates usually $\propto [Xe]$)
- Possible explanation: strong absorption by Ar+Xe mixture overlapping with part of the Ar emission spectrum



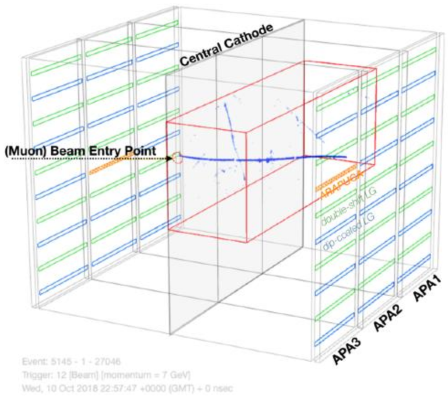
DOI 10.1209/0295-5075/111/12001

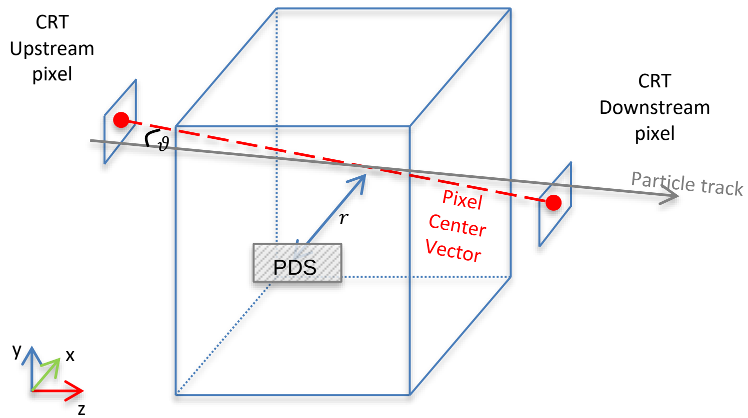
DAQ and Data selection

- A muon telescope with standard triple coincidence of $15.5 \times 44\ cm^2$ plastic scintillators was installed on the roof of ProtoDUNE-SP
- It selects vertical muons within a 0.43 sr solid angle
- When a triple coincidence is detected, a trigger for the dedicated setup is issued
- A local DAQ (same electronics of ProtoDUNE-SP) is used to acquire and store data



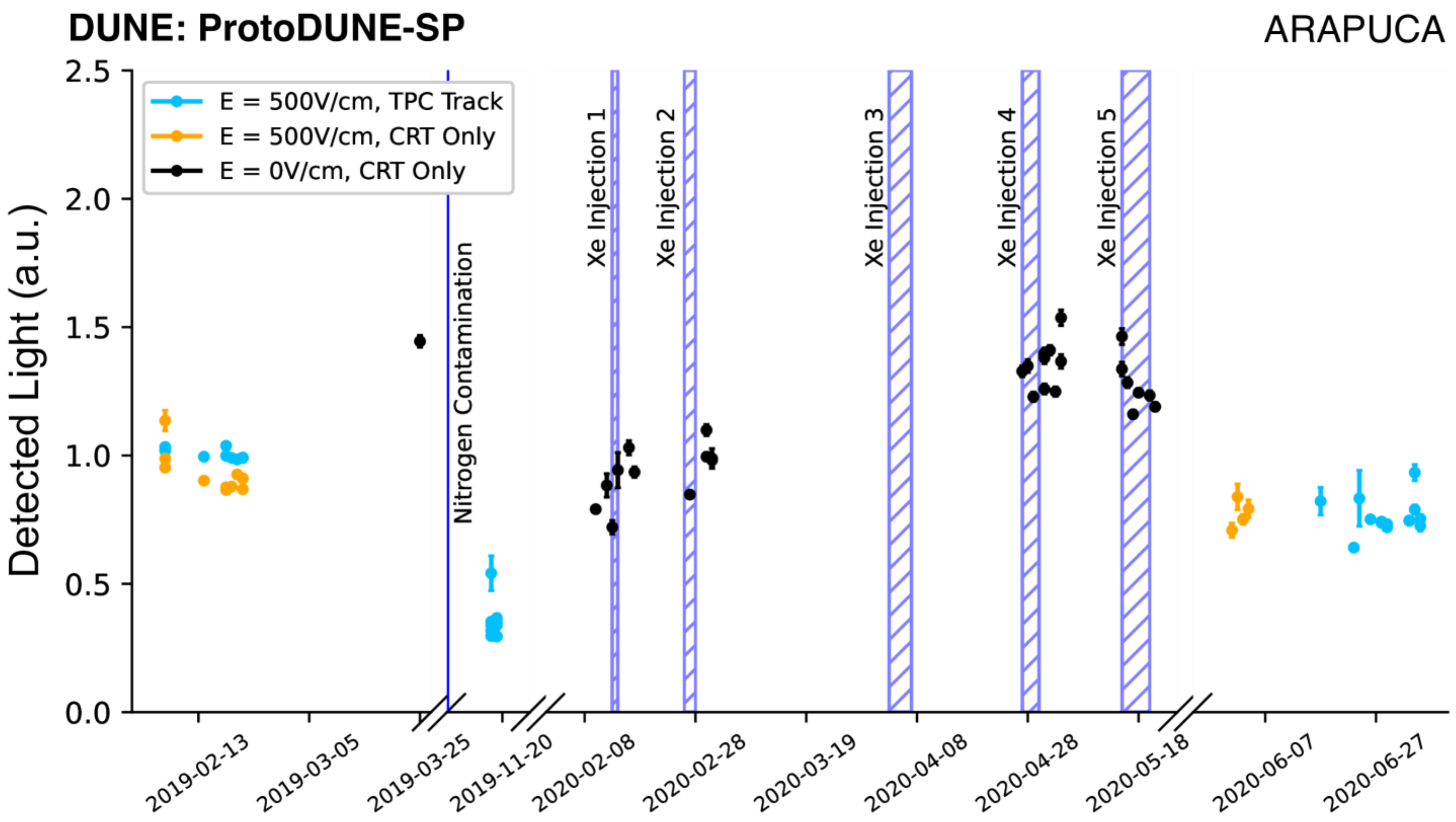
- When ProtoDUNE-SP CRT detects a coincidence between the upstream and downstream module → a trigger is issued
- ProtoDUNE-SP TPC and PDS start data acquisition
- Selection:
  - If TPC track is available: compare TPC reconstructed direction with vector that intersects the strip hits in both triggered CRT modules ($\cos\theta > 0.999$)
  - If $E = 0\ V/cm$: at least two photon detectors in two different APAs within a time coincidence of 13 μs.





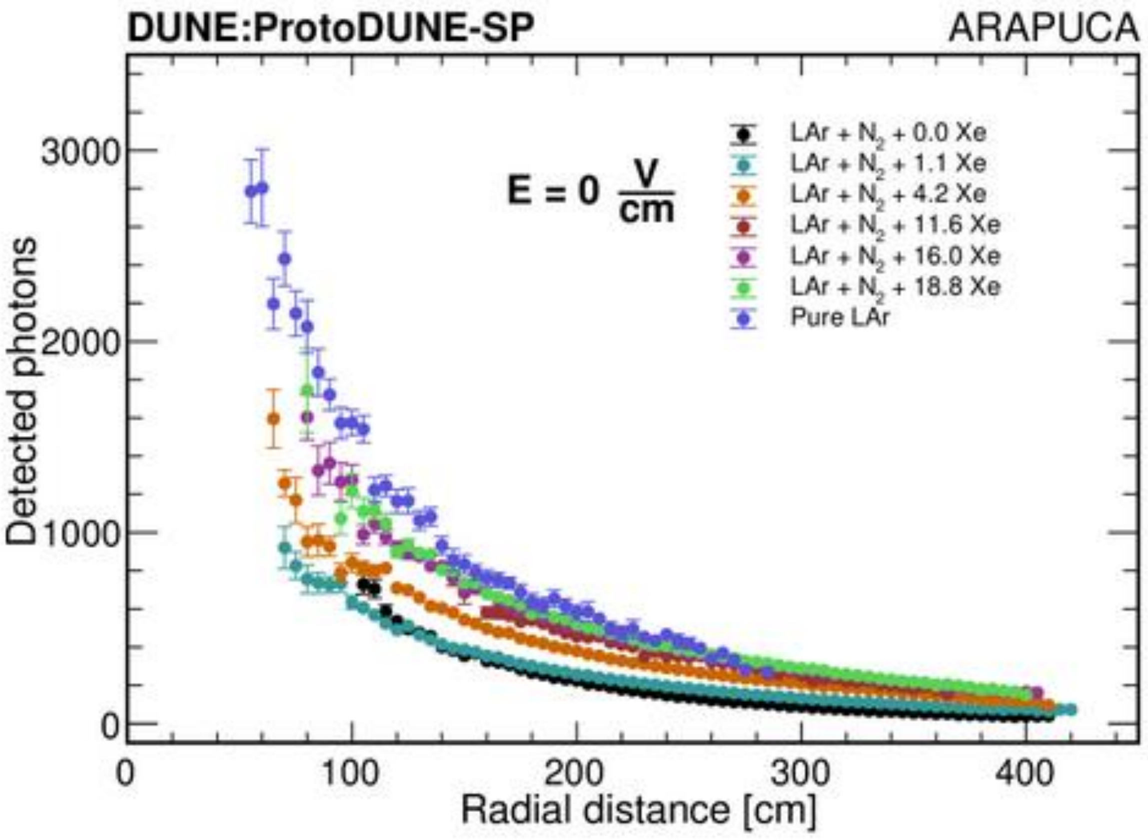
Detected Light

- Average light signal detected by a standard ARAPUCA from PDS
- The average amount of light detected in the ProtoDUNE PDS drops after the nitrogen contamination
- It increases, in steps, with each additional doping with xenon.



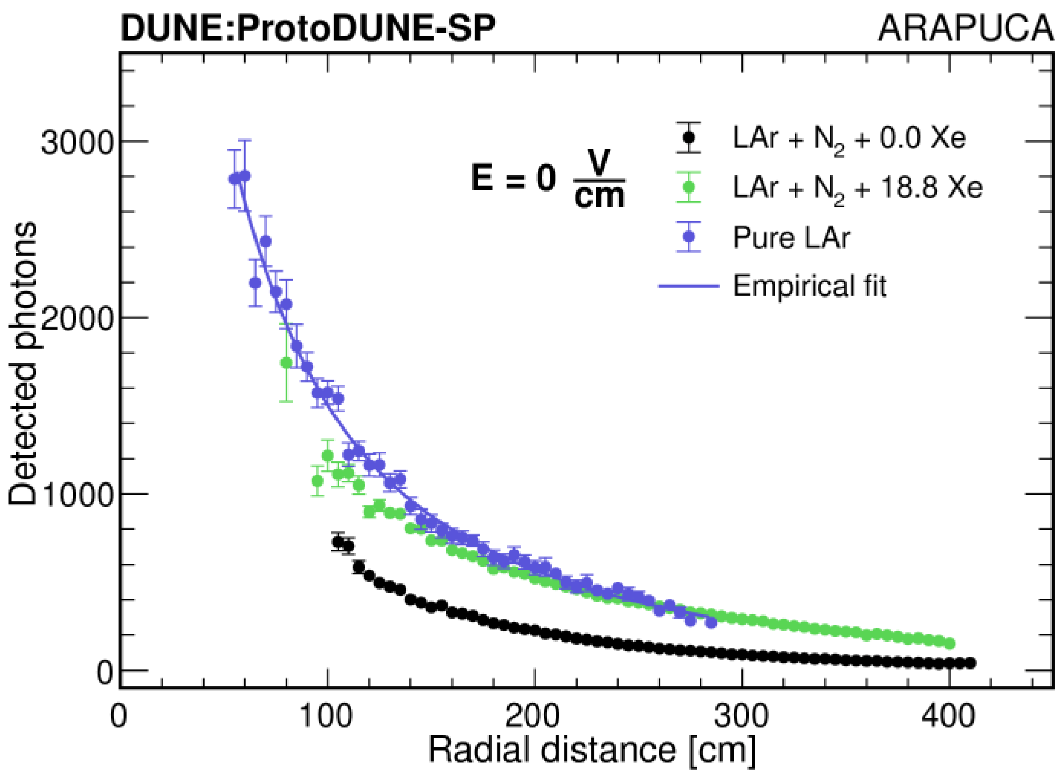
Light collection vs distance

- Average light as a function of the radial distance between the muon track and PDS module
- Nitrogen (black curve) decrease the overall light detected
- Injecting xenon recovers the light overall, but also changes shape...



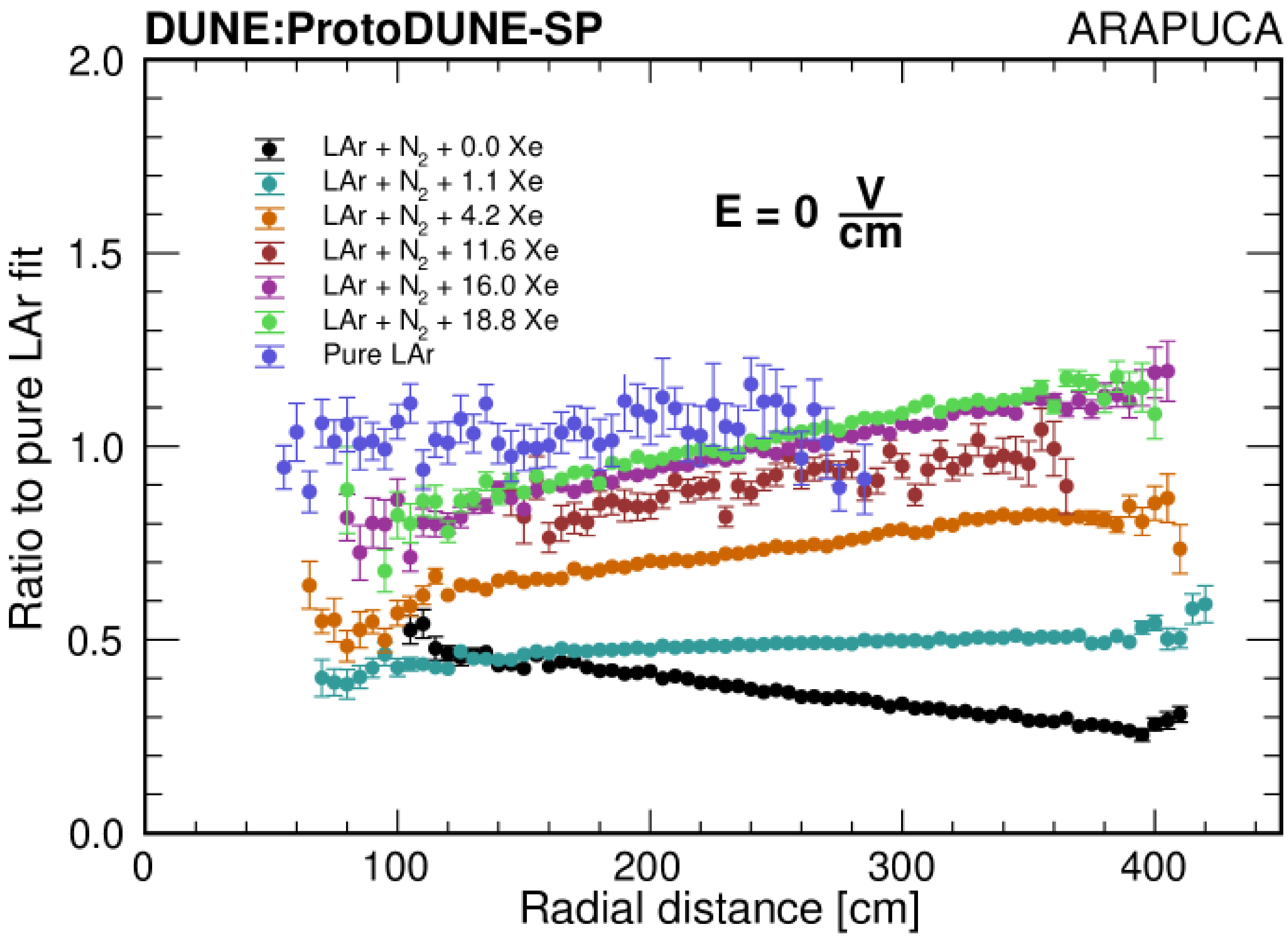
Light collection vs distance

- The Lar “pure” case is fitted with a double exponential $a \exp\left(-\frac{r}{l_1}\right) + b \exp(-\frac{r}{l_2})$
- Data are normalized w.r.t the fit



Light collection vs distance

- The Lar “pure” case is fitted with a double exponential $a \exp\left(-\frac{r}{l_1}\right) + b \exp(-\frac{r}{l_2})$
- Data are normalized w.r.t the fit
- The more xenon is injected, the more the slope increases
- More light is collected far from the readout plane, and less from nearby (w.r.t the LAr “pure” case)
  - More uniform light collection over the drift distance !!

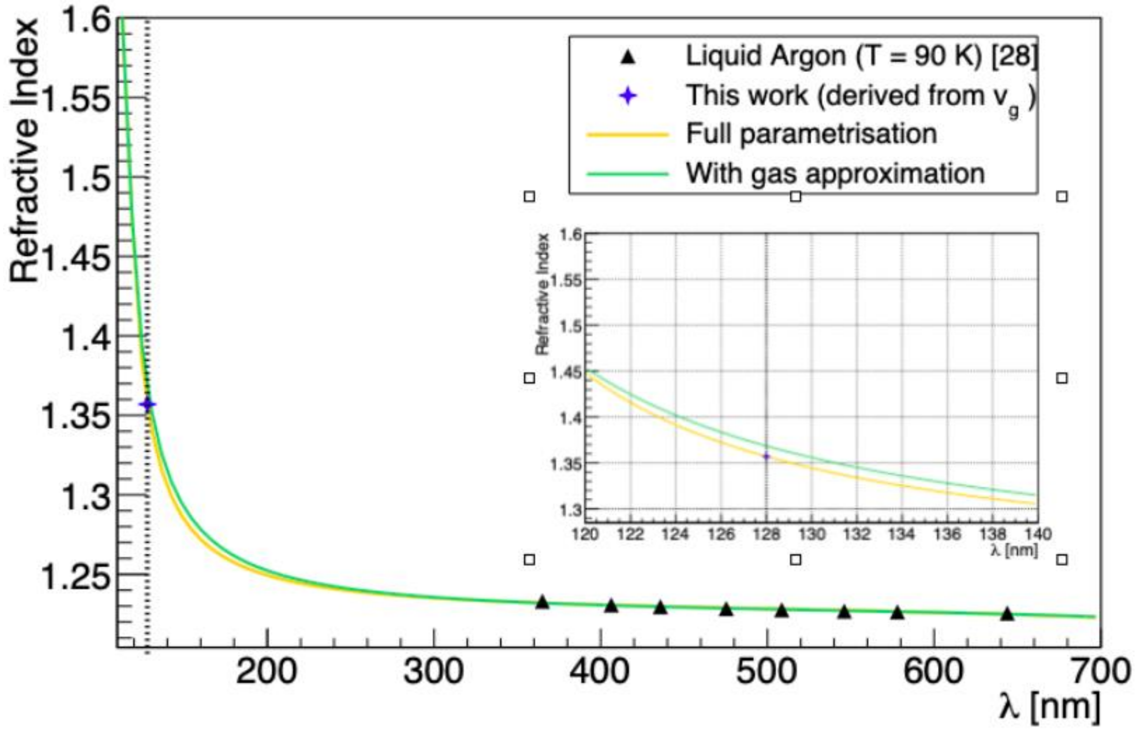


Rayleigh scattering

- In liquid argon the main phenomenon involving light transport is Rayleigh scattering

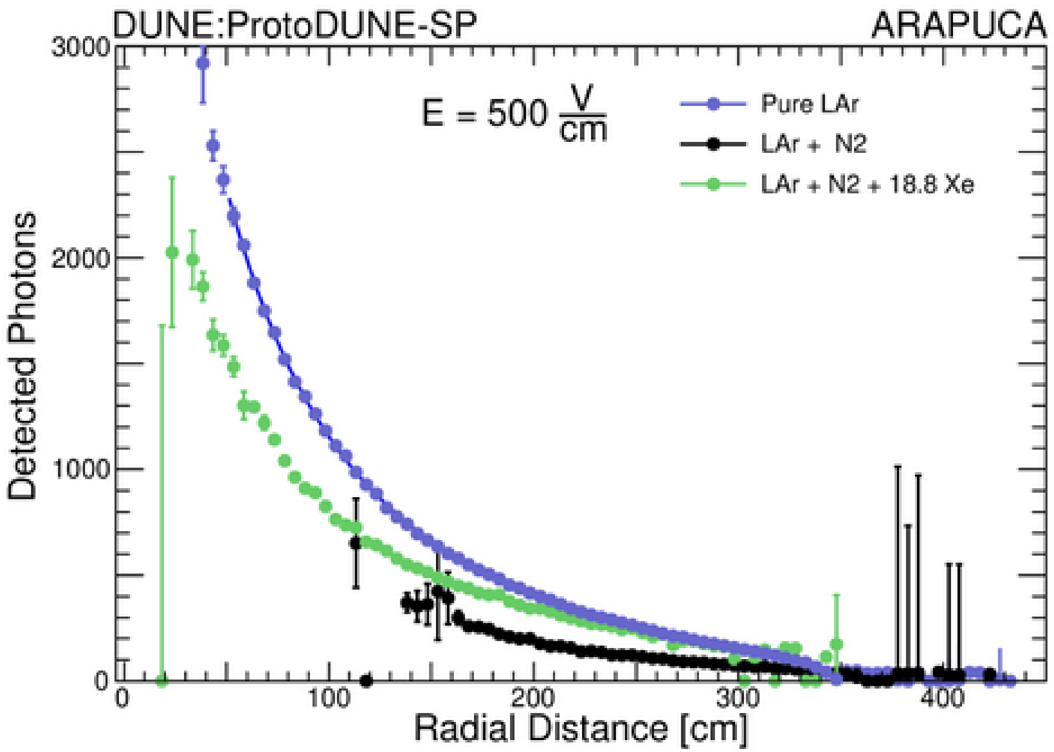
$$\mathcal{L}^{-1} = \frac{16\pi^3}{6\lambda^4}\left[kT\kappa_T\left(\frac{(n_\lambda^2-1)(n_\lambda^2+2)}{3}\right)^2\right]$$

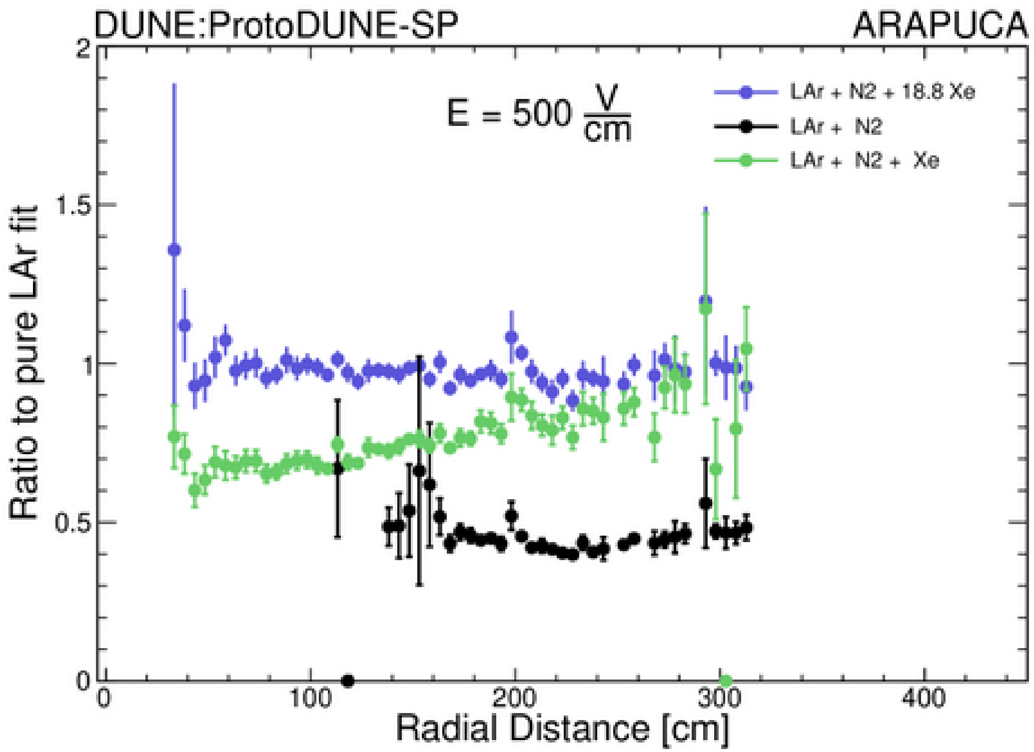
- The scattering length is $\propto \lambda^4$, and strong dependence on n_λ^{-4}
- Increasing the wavelength, the Rayleigh scattering decreases strongly
- Expected Rayleigh scattering lengths:
  - 128 nm → ~91 cm
  - 175 nm → ~7.6 m



DOI 10.1088/1748-0221/15/09/P09009

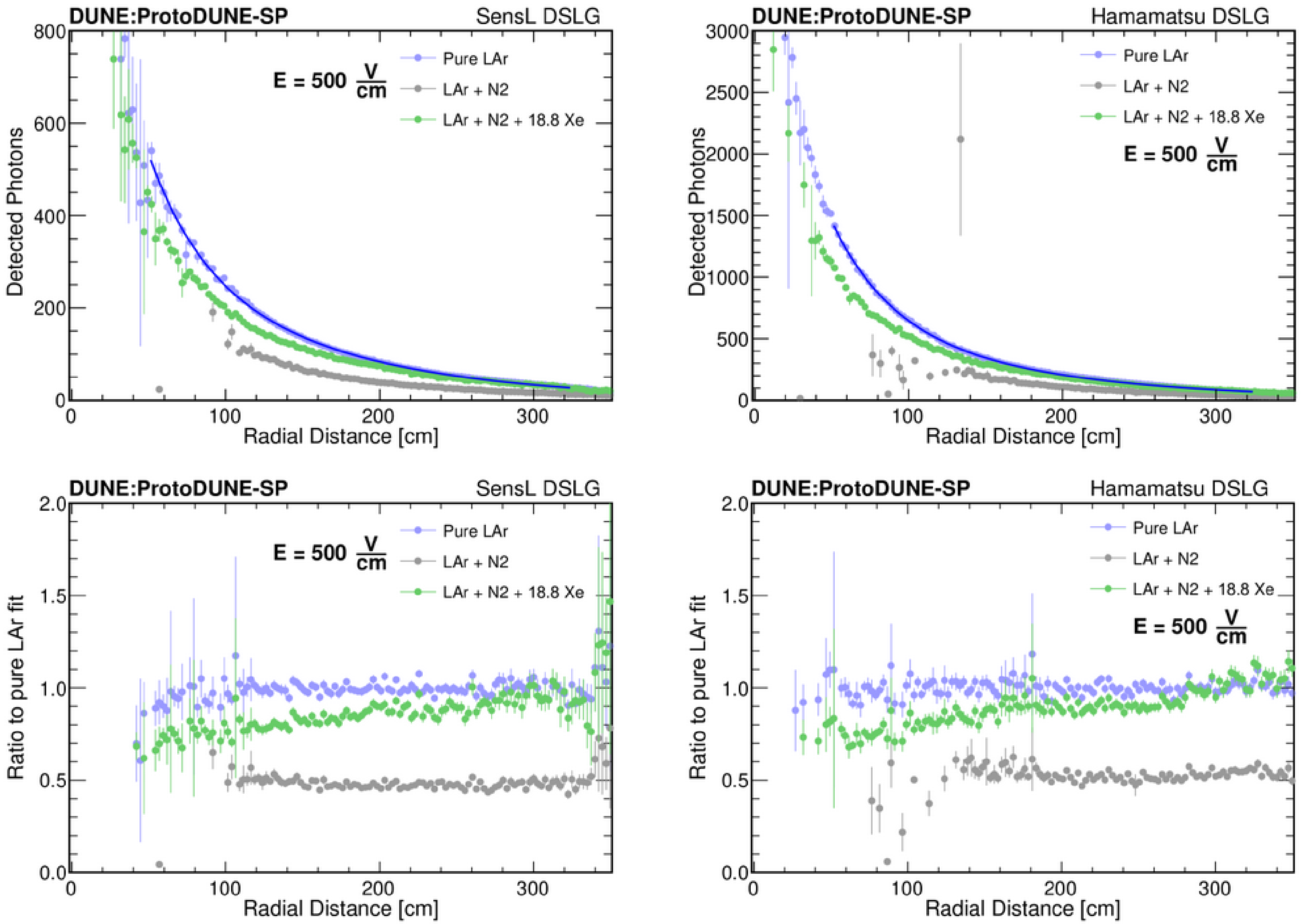
Light collection vs distance (E=500 V/cm)





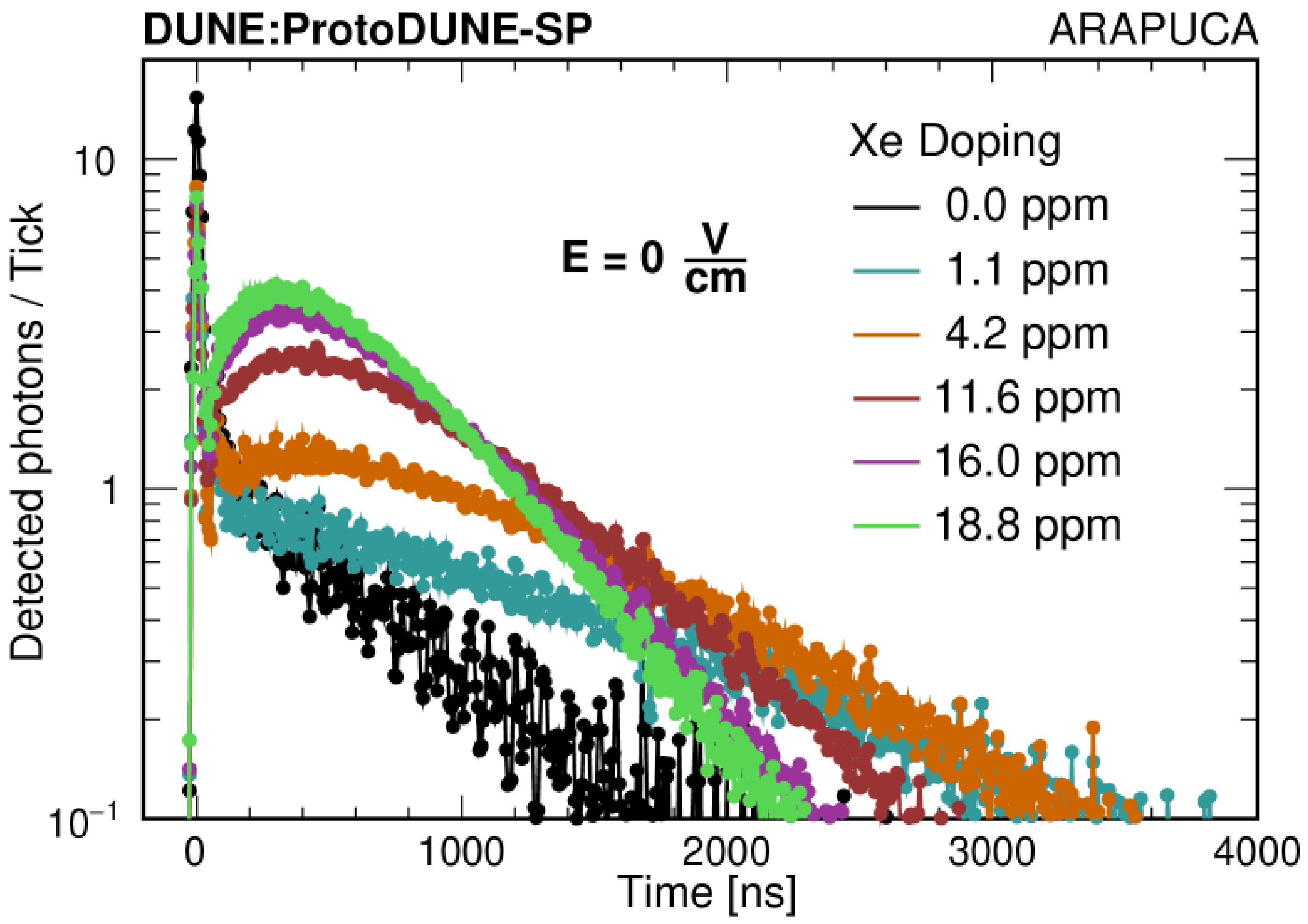
Light collection vs distance

- Trend are checked with other type of sensors (Double Shift Light Guides) with Hamamatsu and SensL SiPM
- Trends compare well to ARAPUCA results



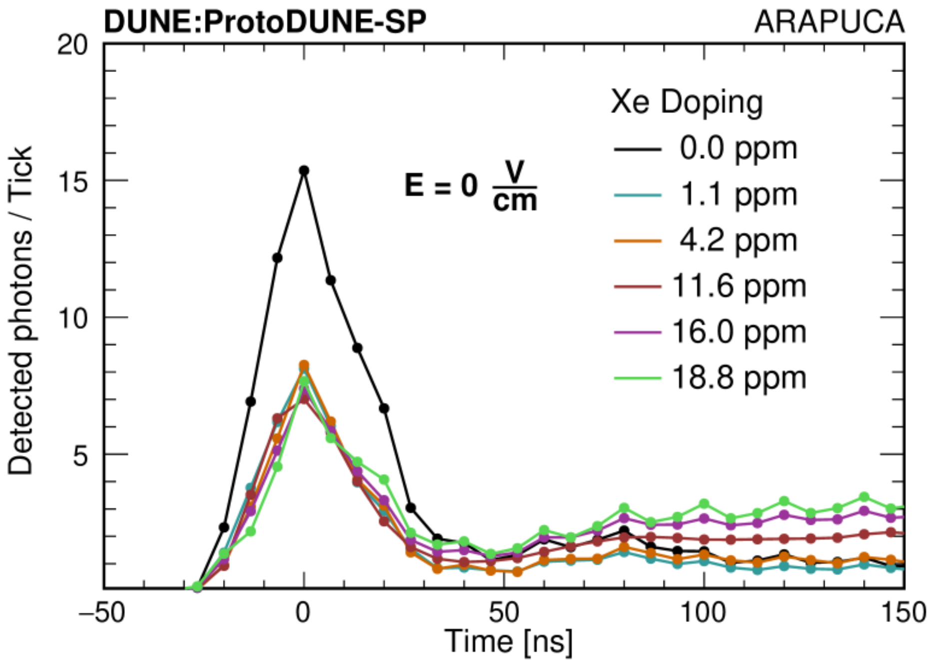
Scintillation time profile

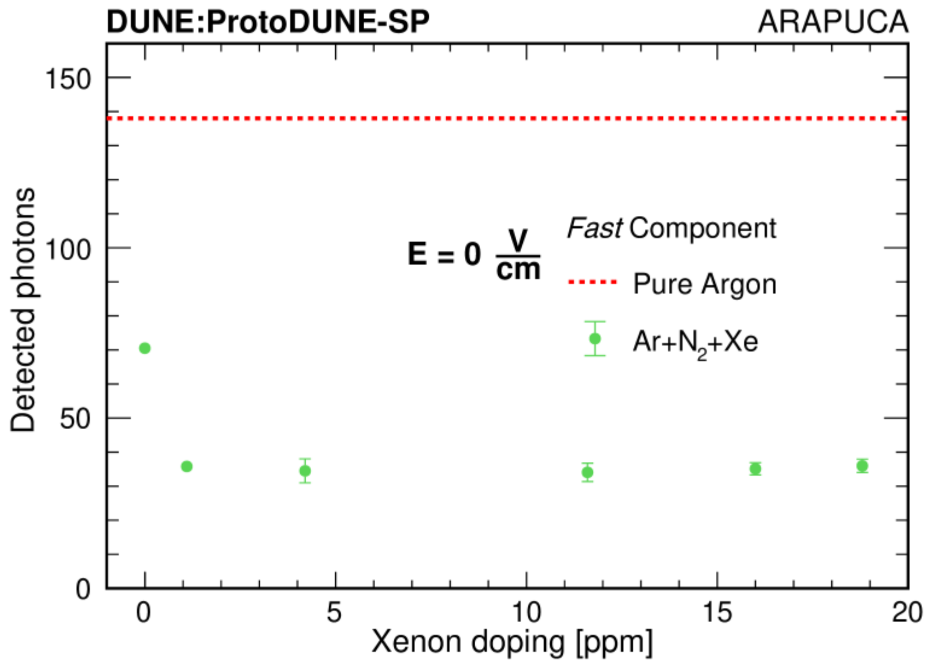
- DUNE PDS can only detect the total light generated (Ar + Xe)
- In good agreement with Ar + Xe X-ARAPUCA in standalone system



Fast component

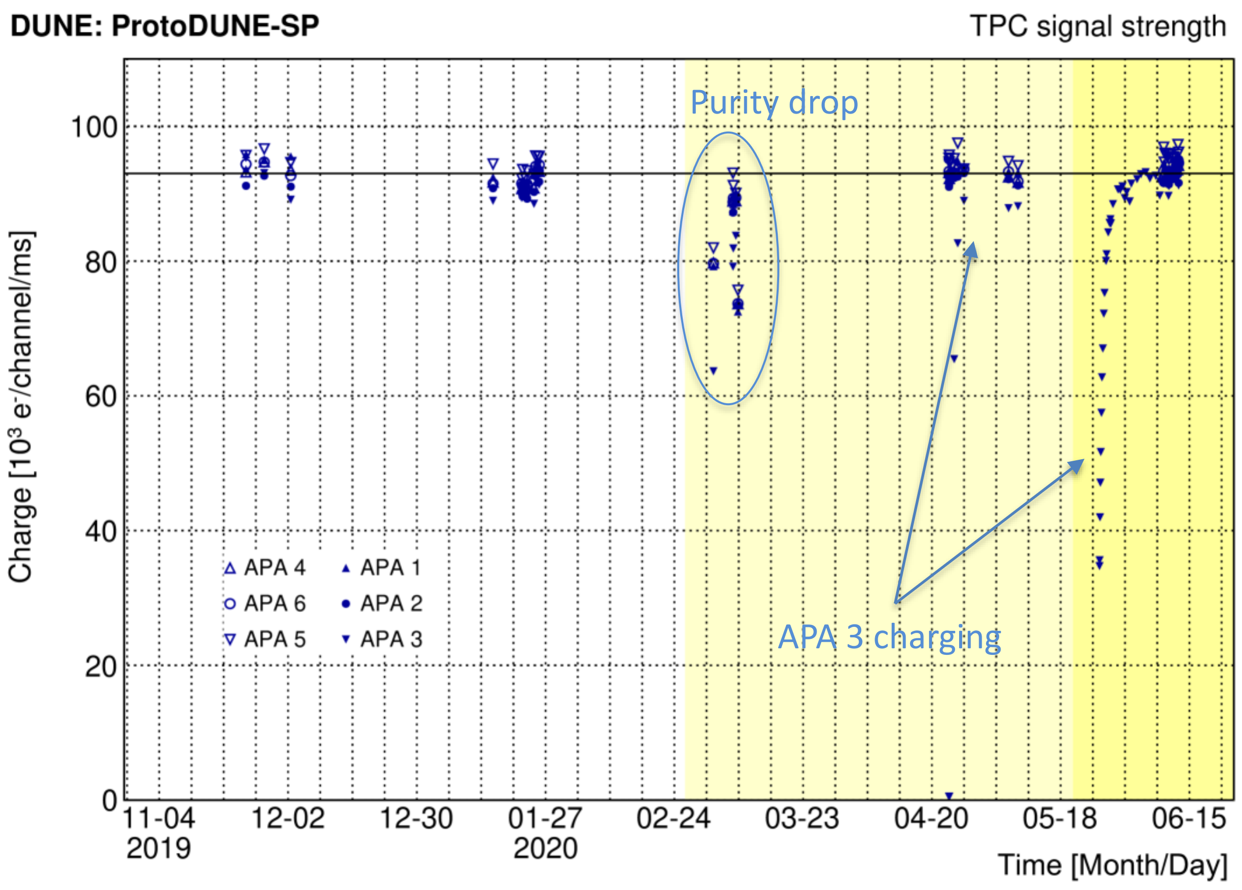
- Fast component reduction confirmed from PDS as well
- Comparison with "Pure" Lar case possible with this setup





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.



Back to …scintillation time profile

PRELIMINARY

- $\frac{dn_{Ar,S}}{dt} = -\lambda_{Ar,S} n_{Ar,S}$
- $\frac{dn_{Ar,T}}{dt} = -(\lambda_{Ar,T} + \lambda_{N_2} + \lambda_{AX}) n_{Ar,T}$
- $\frac{dn_{ArXe^*}}{dt} = \lambda_{AX} n_{Ar,T} - (\lambda_{149\,nm} + \lambda_{XX}) n_{ArXe^*}$
- $\frac{dn_{Xe_2^*}}{dt} = \lambda_{XX} n_{ArXe^*} - \lambda_{Xe} n_{Xe_2^*}$

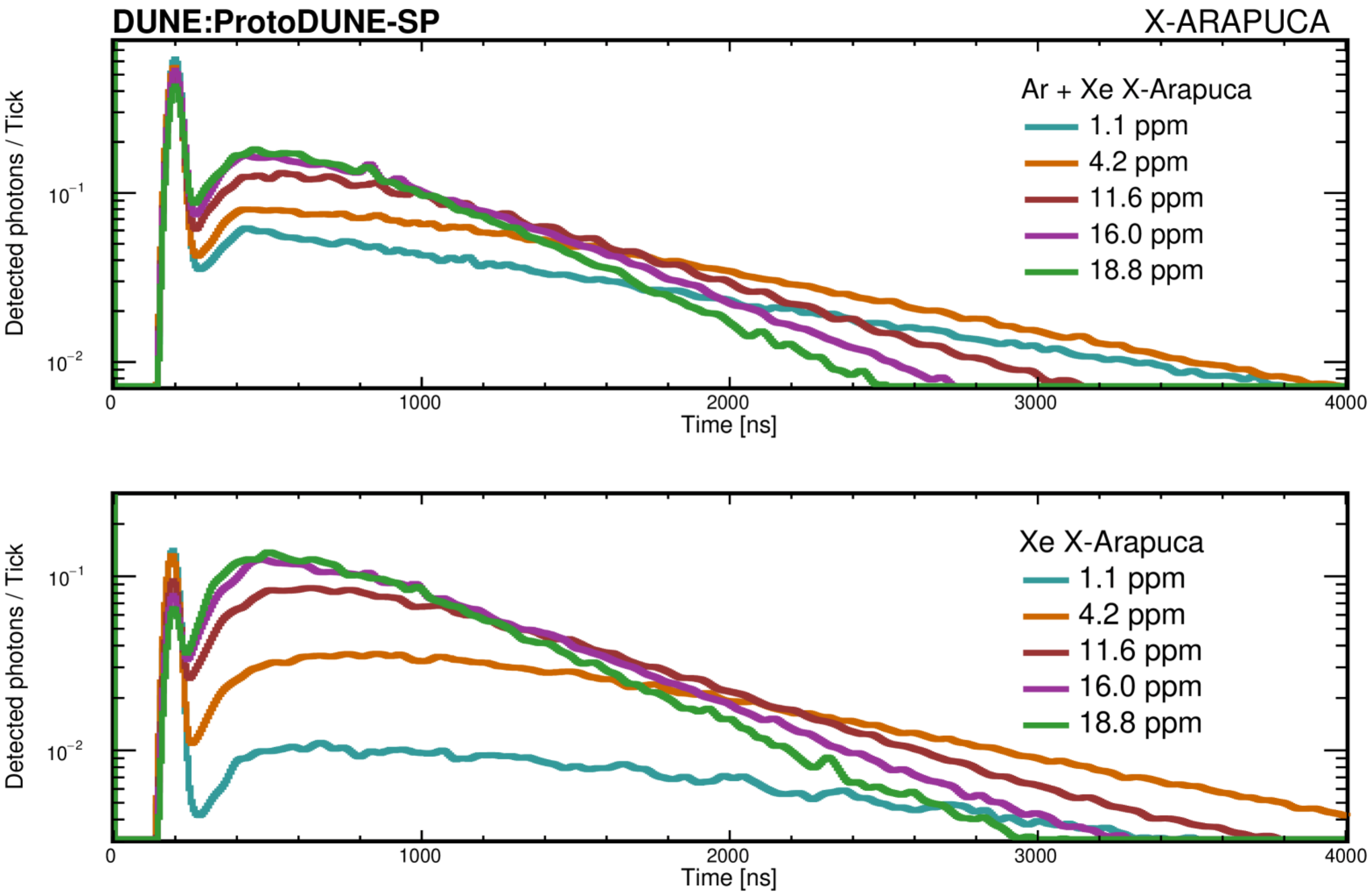
- Intrinsic de-excitation parameters ($\lambda = \tau^{-1}$):
  - $\lambda_{Ar,S}$: Ar singlet radiative emission
  - $\lambda_{Ar,T}$: Ar triplet radiative emission
  - $\lambda_{149\,nm}$: ArXe radiative emission
  - λ_{Xe}: Xe effective radiative emission
- Process parameters dependent on dopant concentration:
  - $\lambda_{N_2} = k_{\mathrm{N}_2}\ [N2]$
  - $\lambda_{AX} = k_{AX}\ [Xe]$
  - $\lambda_{XX} = k_{XX}\ [Xe]$

  where k is the rate constant of the process.

Scintillation time profile

PRELIMINARY

- The time profile can be fitted with three exponentials
- $l(t) = A_f \exp\left(-\frac{t}{\tau_f}\right) + A_i \exp\left(-\frac{t}{\tau_i}\right) + A_s \exp\left(-\frac{t}{\tau_s}\right)$
  - $\tau_i = (\tau_{149\,nm}^{-1} + \mathrm{k_{XX}}[\mathrm{Xe}])^{-1}$
  - $\tau_s = \left(\tau_{Ar,T}^{-1} + \tau_{N_2}^{-1} + k_{AX}[Xe]\right)^{-1}$

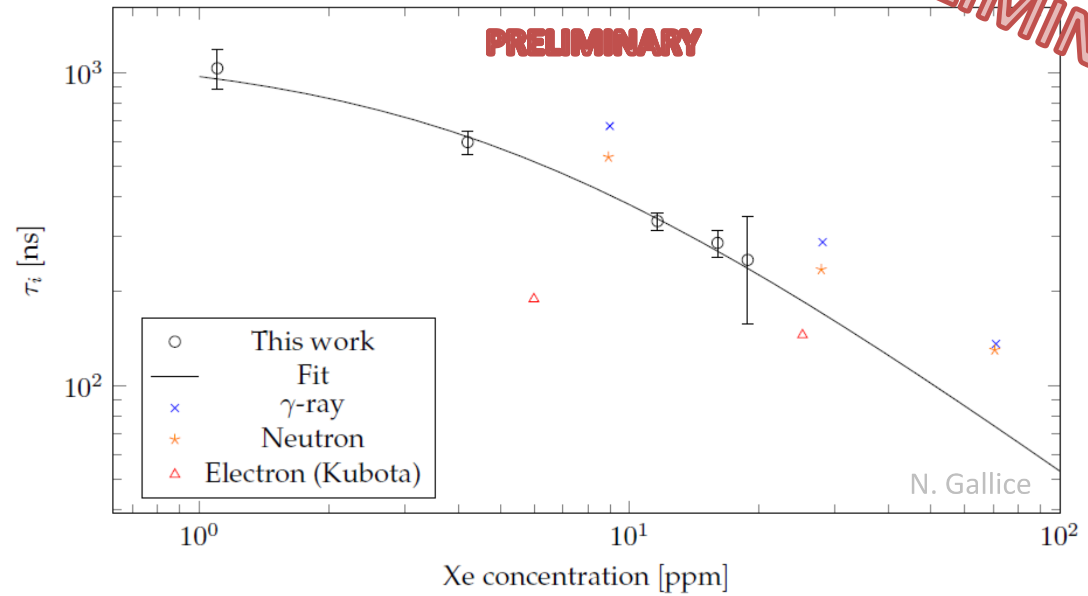


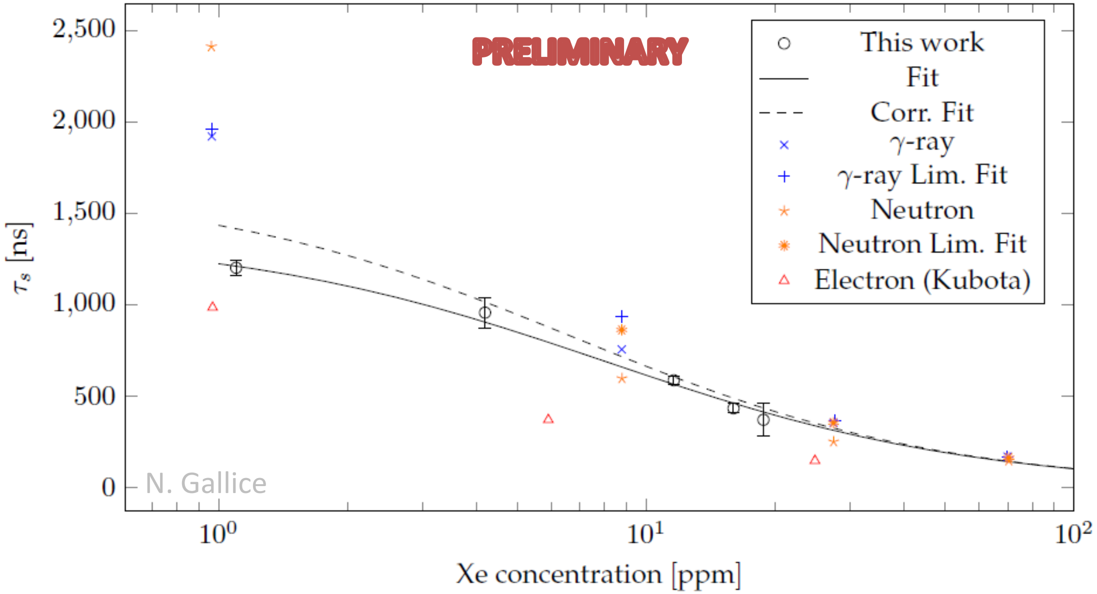
Fitting parameters

- For each xenon concentration the average deconvolved waveform is fitted
- The extracted τ_i and τ_s are plotted as a function of concentration
  - $\tau_i = (\tau_{149\,nm}^{-1} + \mathrm{k_{XX}}[\mathrm{Xe}])^{-1}$
  - $\tau_s = \left(\tau_{Ar,T}^{-1} + \tau_{N_2}^{-1} + k_{AX}[Xe]\right)^{-1}$
- Parametric form is $(a + b[Xe])^{-1}$

Constant	Fit value
k_{AX}	$(8.9 \pm 0.1) \times 10^{-2}\ \mu s^{-1}\ ppm^{-1}$
k_{XX}	$(0.18 \pm 0.01)\ \mu s^{-1}\ ppm^{-1}$
$\tau_{149\,nm}$	$(1.2 \pm 0.1)\ \mu s$

PRELIMINARY

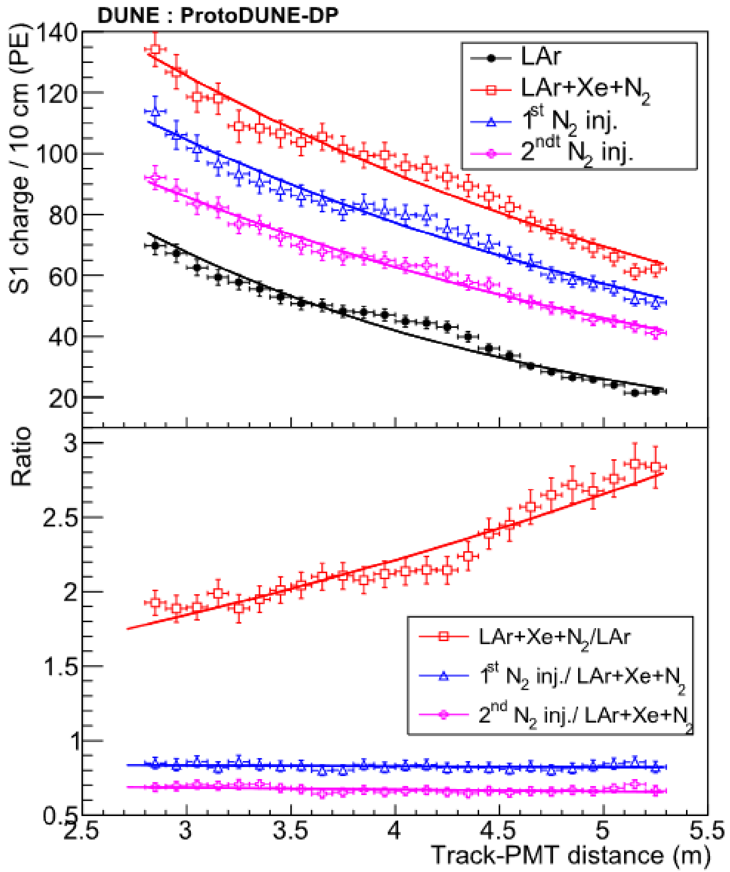


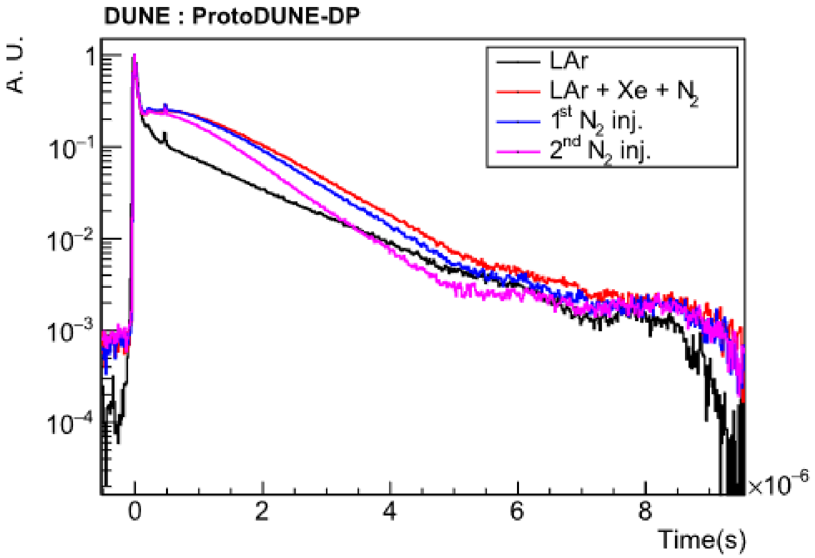


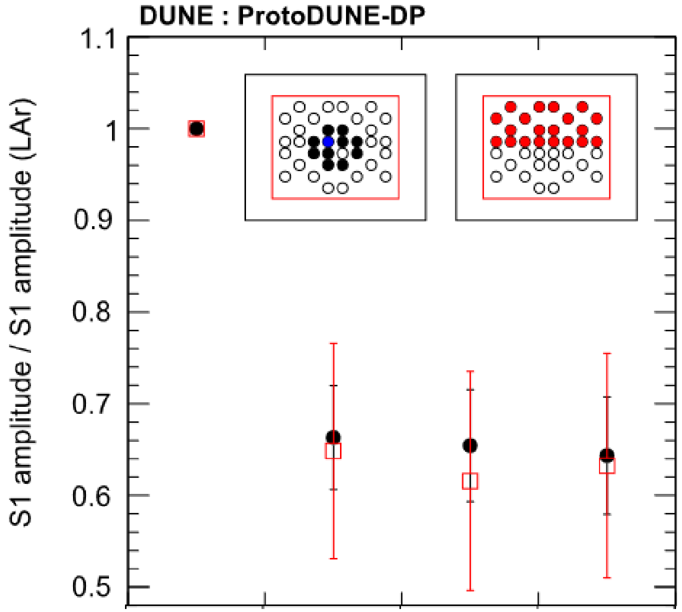
ProtoDUNE-DP

- After the xenon doping run in ProtoDUNE-SP, part of the doped argon was moved to DP detector
- Further injections of N2 were performed

Situation	[Xe](ppm)	[N_2] (ppm)
LAr	0	0
LAr + Xe + N_2	5.8	2.4
1^{st} N_2 inj.	5.8	3.4
2^{nd} N_2 inj.	5.8	5.3





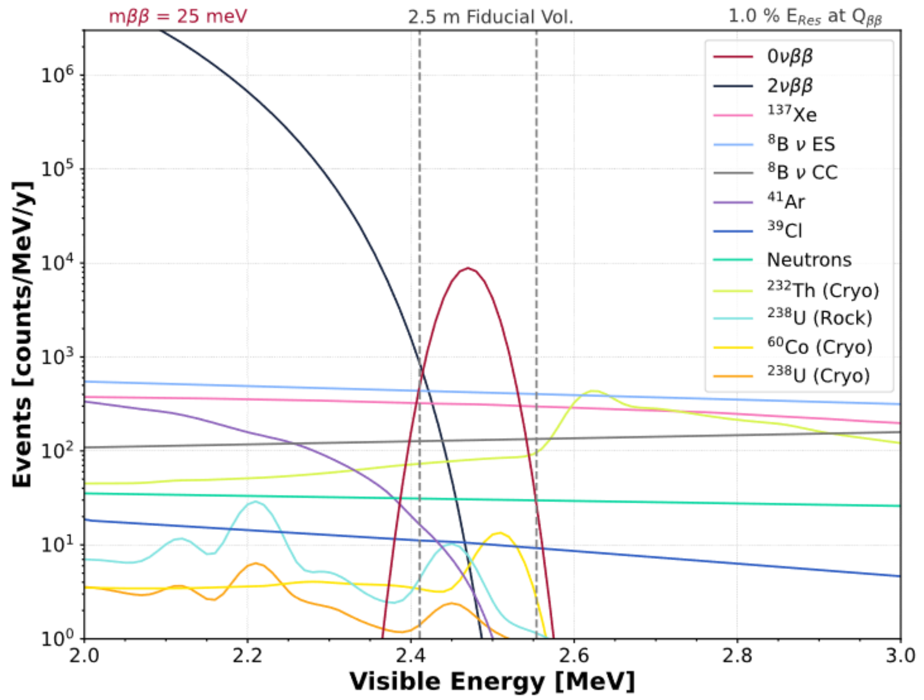


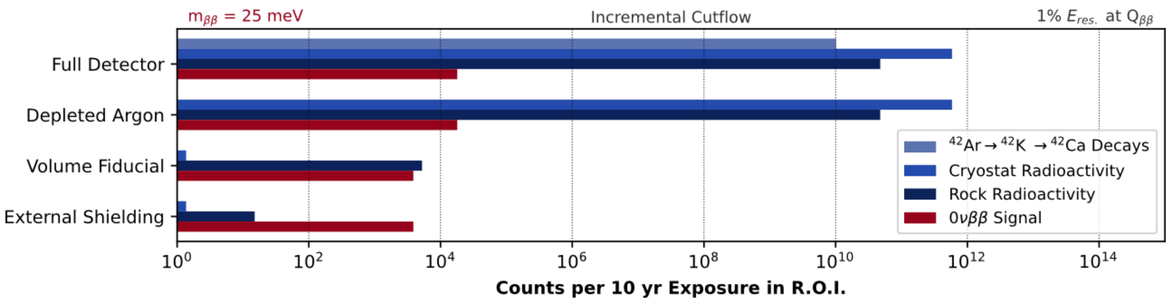
- Similar shape of Ar+Xe waveforms
- Decrease of fast component
- Increase in uniformity

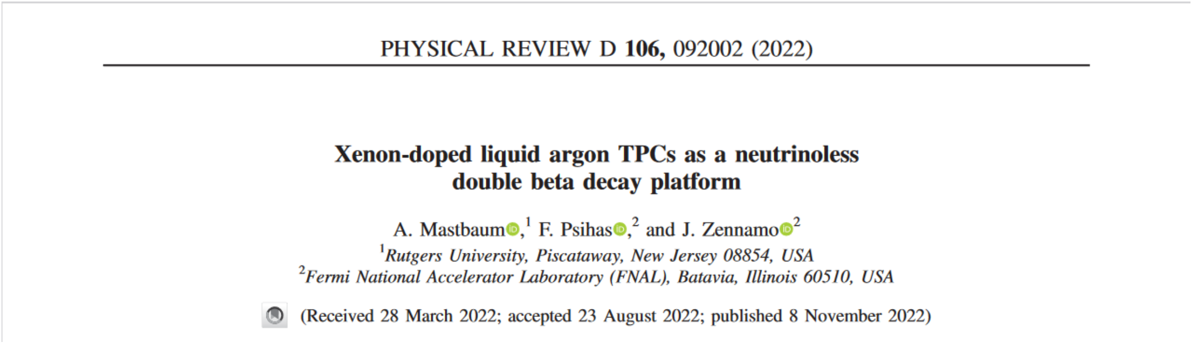
DOI 10.1140/epjc/s10052-022-10549-w

Xenon doping at the next level

- ^{136}Xe candidate for $0\nu\beta\beta$
- Doping DUNE FD at %-level with 90% enriched xenon →~1 kt of xenon
- Next generation $0\nu\beta\beta$ detector
- Techniques and R&D needed for background reduction
- Very challenging! … but appealing






PHYSICAL REVIEW D **106,** 092002 (2022)

Xenon-doped liquid argon TPCs as a neutrinoless double beta decay platform

A. Mastbaum,[1] F. Psihas,[2] and J. Zennamo[2]
[1]*Rutgers University, Piscataway, New Jersey 08854, USA*
[2]*Fermi National Accelerator Laboratory (FNAL), Batavia, Illinois 60510, USA*

(Received 28 March 2022; accepted 23 August 2022; published 8 November 2022)

Conclusions

- First demonstration that a large size (770 t) LAr-TPC can be safely operated with xenon at the level of 18.8 ppm
- 128→178 nm light shift is effective already at xenon concentrations of a few ppm and it reaches a plateau at ~16 ppm
- The light signal is faster as more xenon is injected
- It recovers light lost due to N_2 quenching
- The profile of the collected light versus the distance is more uniform after the doping, indication of the longer Rayleigh scattering length
- Understanding and test of the scintillation underlying physics and model
- Fast component reduction (to be further investigated)
- Xenon up to 18.8 ppm does not affect the performance of the charge collection by TPC

Further developments

- Further understanding of spectral response of Ar+Xe mixtures
  - Direct detection of 149 nm light
  - Proof of 128 nm absorption by xenon
  - Re-emission of absorbed light?
- Investigate feasibility of larger doping ratios for $0\nu\beta\beta$

PREVIEW:

Doping liquid argon with xenon in ProtoDUNE Single-Phase: effects on scintillation light

The DUNE Collaboration https://arxiv.org/abs/2402.01568

Accepted last week with minor revisions by JINST!

THANK YOU!