Xe-doping in ProtoDUNE-SP

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on behalf of
ProtoDUNE-SP Xe-injection team

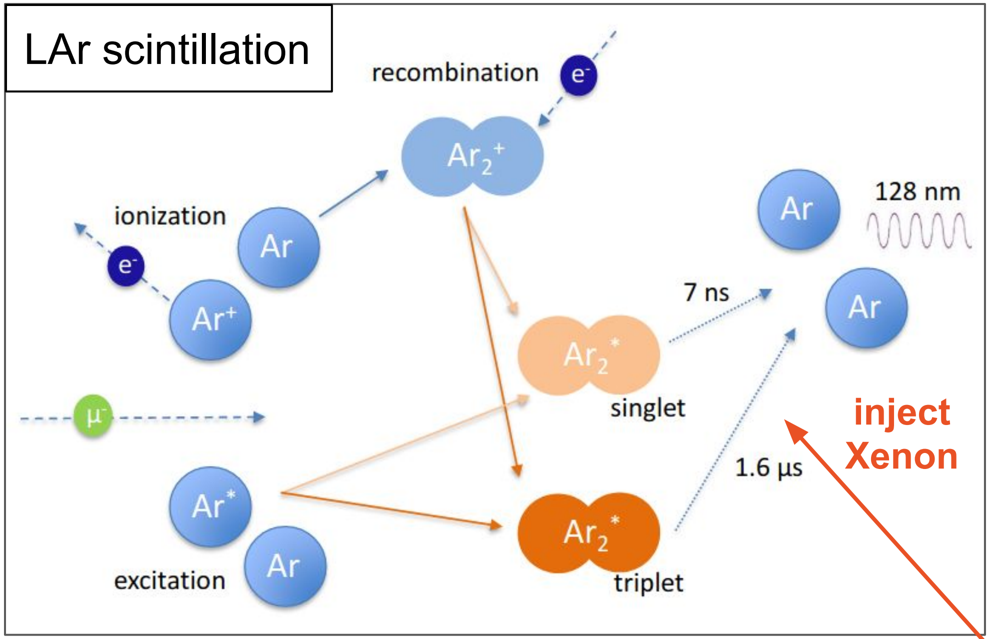
Motivations for Xe-doping in ProtoDUNE-SP

- LAr as a scintillating media and challenges to use it
    - Scintillation efficiency comparable with other liquid noble liquids
    - Very efficient Pulse Shape Discrimination (PSD) due to the significant difference in relative intensities of the fast and slow components
    - Disadvantage comes from the wavelength of scintillation lies in the VUV range (~128nm)
        - A common and convenient solution of this problem is to use wavelength shifters (WLS) but it has some issues as well
            - 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

- Elegant alternative: "volume distributed WLS in LAr experiments" → Xe-doping
    - Shift 128 nm wavelength to 175 nm
    - More uniform light distribution
    - Increase light yield and detection efficiency
    - Possible mitigation for N2 contamination

- In literature, small scale or gas mixture test so far
    - How about physics, uniformity and stability of doped Xe at large scale setups?

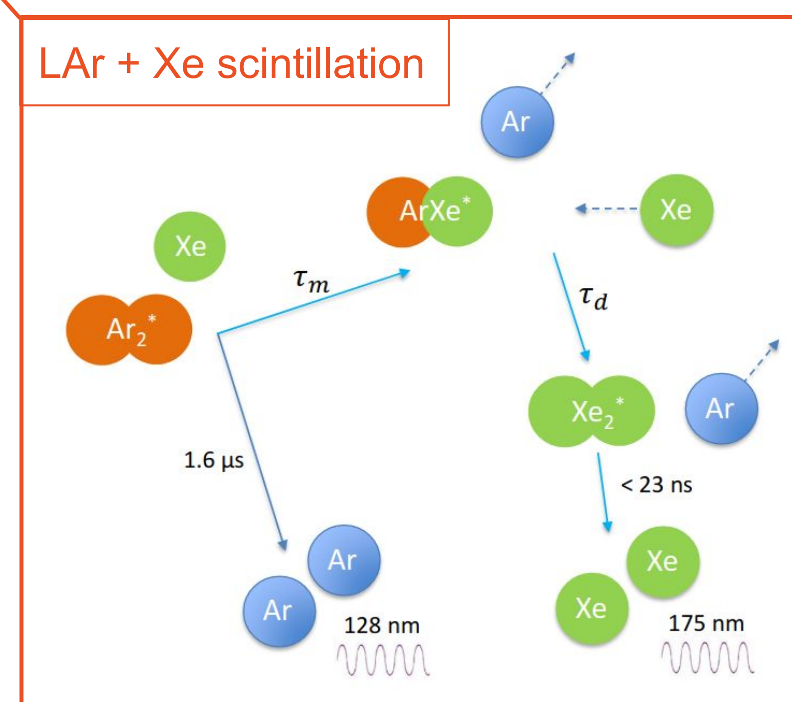
With these in mind, an R&D effort and Xe-doping in ProtoDUNE-SP was performed !!!



- The excited atoms often bond with ground state atoms to form metastable molecules known as excimers that then decay, emitting scintillation at 128 nm
- The ions can recombine with electrons to form excited atoms, in turn producing excimers and then scintillation light at 128 nm

With the presence of Xenon

- The excited Ar dimer may interact with Xe and forms excited ArXe* molecule
- The time scale of ArXe* creation τ_m depends on Xenon concentration
- The excited ArXe* dimer can interact with Xenon creating a Xe_2*. Time scale for this process τ_d depends on Xenon concentration as well
- Eventually, Xe_2* de-excites and creates 175 nm light

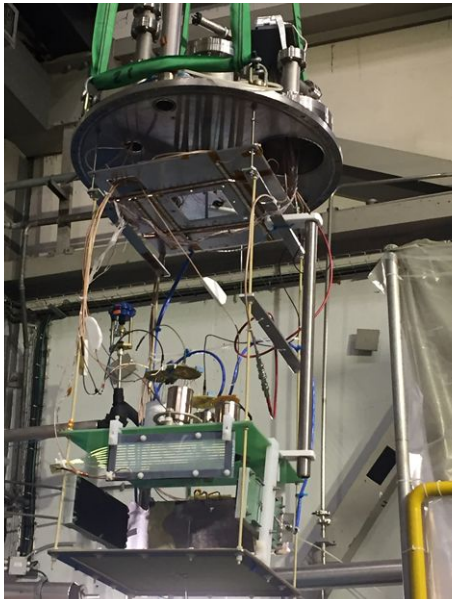


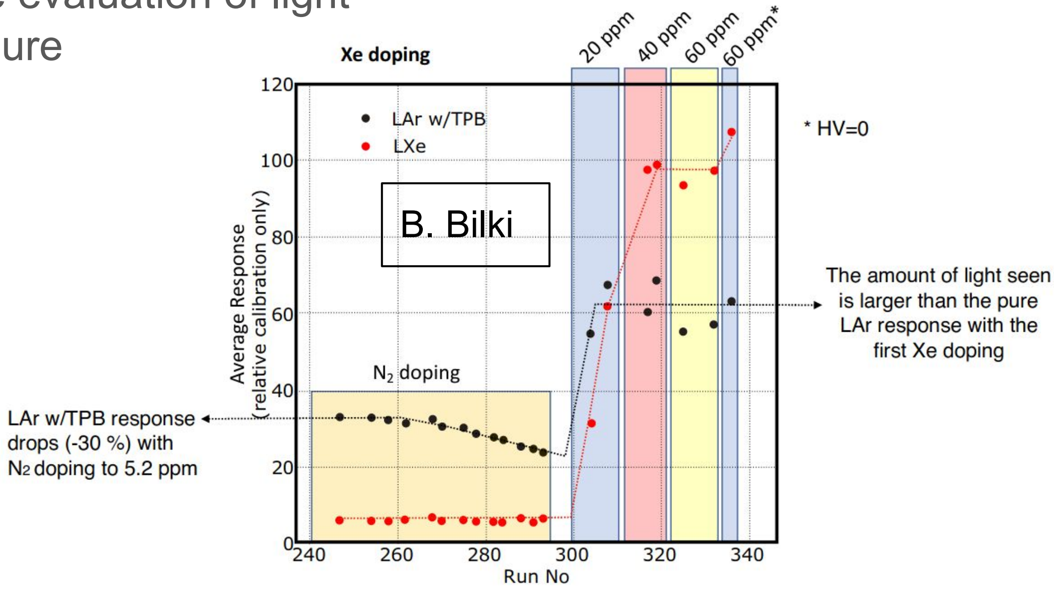
N_2 contamination in ProtoDUNE-SP and R&D on mitigation

- Summer 2019 → gas recirculation pump failure and N_2 contamination in ProtoDUNE
  - 5.7ppm of N2 injected into the cryostat

- Recover the effects of N_2 with Xe-doping in ProtoDUNE-SP?
  - Tests at 50L setup
    - first one with PMTs,
    - second with X-Arapucas, PenFiber and SIPM array)
  - Create ProtoDUNE N_2 conditions
  - Dope with Xe and measure the evaluation of light
  - Bonus: Practise doping procedure

- Small scale test has demonstrated even a small amount of Xe (>5ppm) is enough to cancel out the effects of Nitrogen

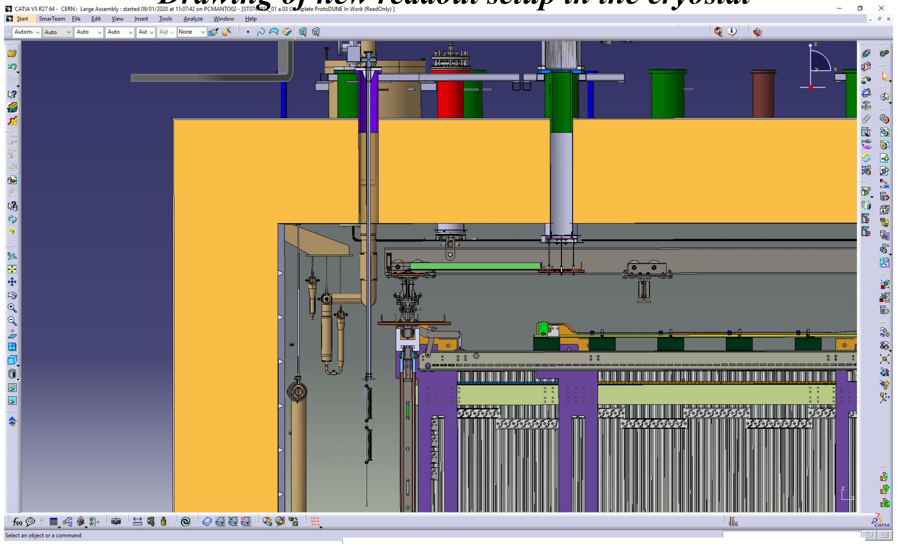




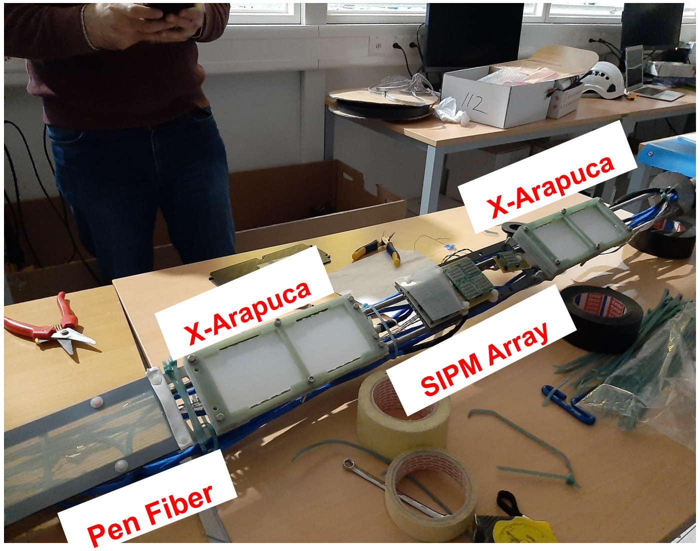
Installation of new PD detectors into the cryostat

- Prepare and install Xe scintillation sensitive PD into the cryostat
  - 1 X-Arapucas with Quartz window, sensitive to Xe scintillation only
  - 1 X-Arapuca without window, sensitive to Xe+LAr scintillation
  - FiberPen module and SIMP array
- Open one of the cryostat openings and insert the mechanical structure holding PDs into the cryostat
- No degradation in lifetime

Drawing of new readout setup in the cryostat



Readout modules



Readout setup assembly

Readout setup insertion

Xe-dopings in ProtoDUNE-SP

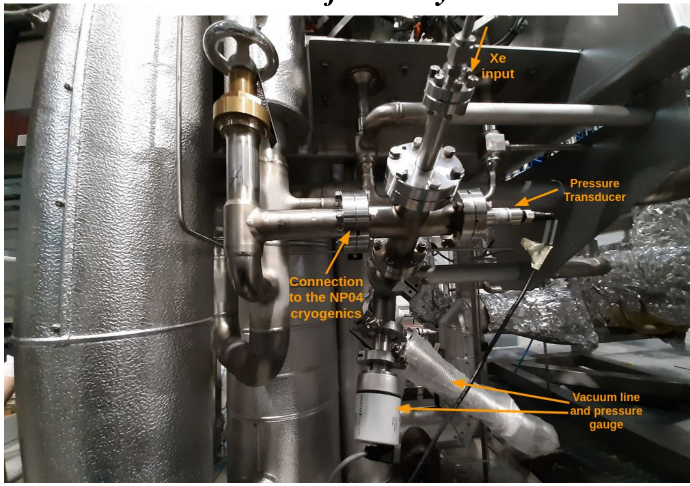
- After all the preparations, Xe-doping was started on Feb 13th and finalized on May 20th

- There were six injections

- In total **13.5kg** of Xe injected into the cryostat. This is equivalent to **18.8 ppm** of Xe in mass, assuming 720 tons of LAr.

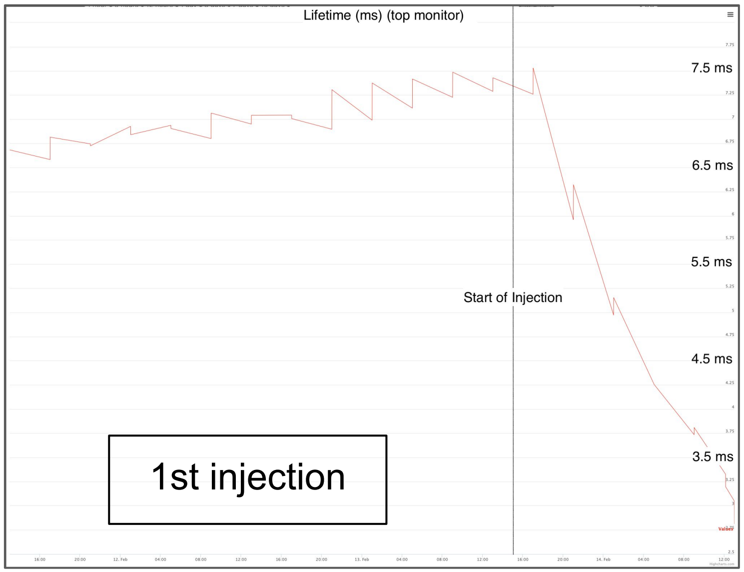
- Regular (almost continues) data taking with ProtoDUNE PD system and newly installed PD detectors (standalone system)

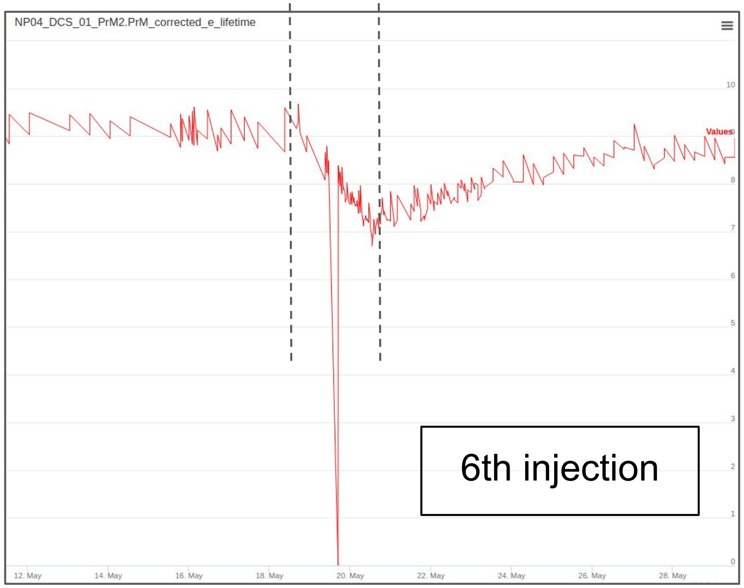
Xe injection system



Difficulties during the Xe-dopings

- We used 3 different Xe bottles for the doping
  - The first bottle from Spanish colleagues
  - The second one borrowed from ATLAS
  - The third one was purchased
- With the first and the third bottle we had reduction in the electron lifetime
  - More drastic decrease with the first bottle (1st injection), 7.5ms→ 3ms: O_2 at 100ppm level and C_2F_6
  - 17ppb of SF_6 in the third bottle (6th injection)
- Smooth operations from 2nd to 5th injection
- Impurities inside the bottle, even at the ppb level, matters!!!





Good news

our filters are able to clean those impurities… add a gether to the injection circuit and clean impurities before injecting Xe into the cryostat

Data taking and analysis campaign for the Xe studies

- Regular, almost continues, data taking during and in between the Xe injections
  - It will continue until the end of ProtoDUNE-SP

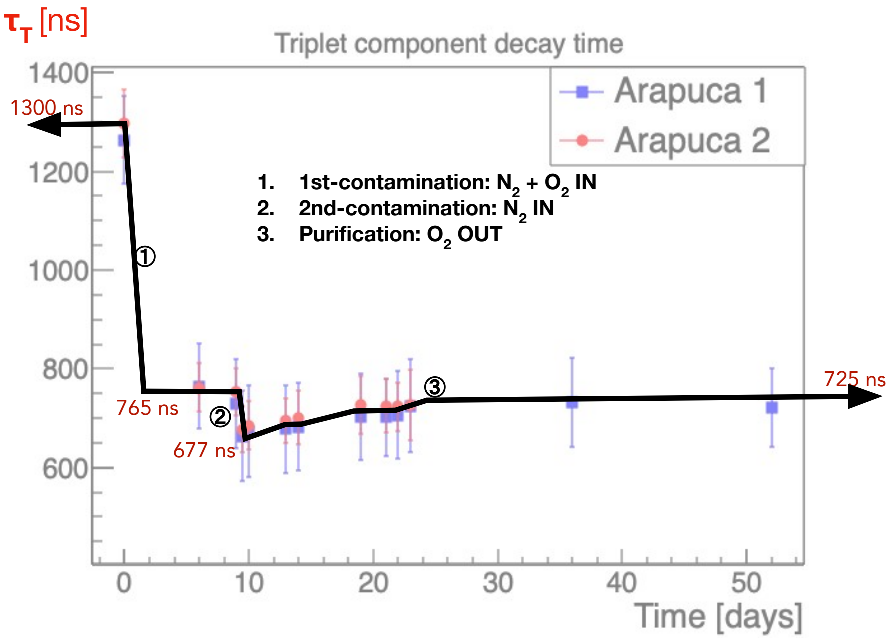
- Data taking
  - ProtoDUNE-SP PD system
    - CRT and time to time hodoscope trigger
    - HV was off most of the time and took some data at 500V/cm as well

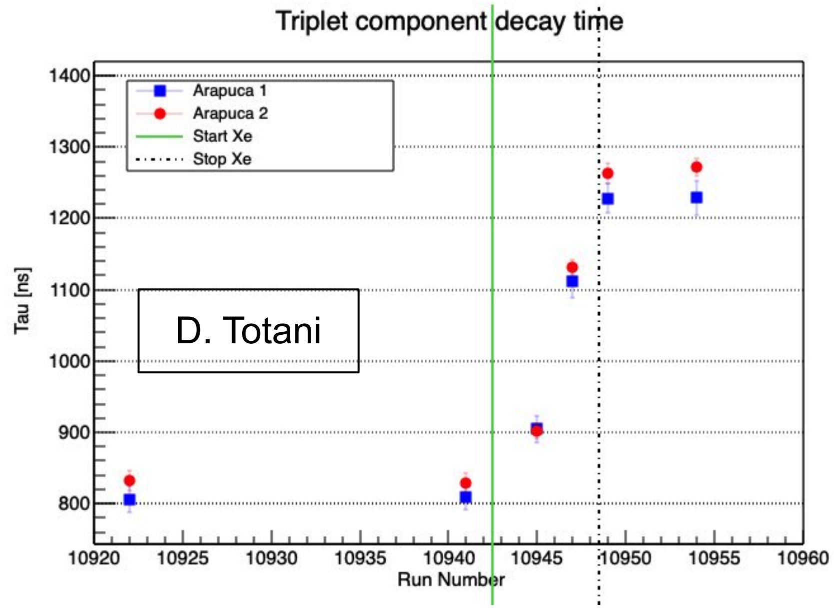
  - Data taking with standalone system
    - External trigger on vertical muons with the hodoscope

- Analysis:
  - Very active and motivated working group with the participation of ~20 colleagues
  - Analysis of the Standalone data:
    - Quick and efficient way to monitor the evolution of light signal inside the cryostat
    - Well advanced with participation of many colleagues

  - Analysis of the ProtoDUNE-SP PDS data:
    - Important for the analysis of stability and uniformity of Xe
    - Recent improvements and speeding up with the analysis

N_2 contamination and mitigation in ProtoDUNE-SP





- The N_2 contamination quenches LAr light reducing the slow components
- Xenon injection recovers the slow component
  - ~ 1ppm was enough in the case of ProtoDUNE-SP

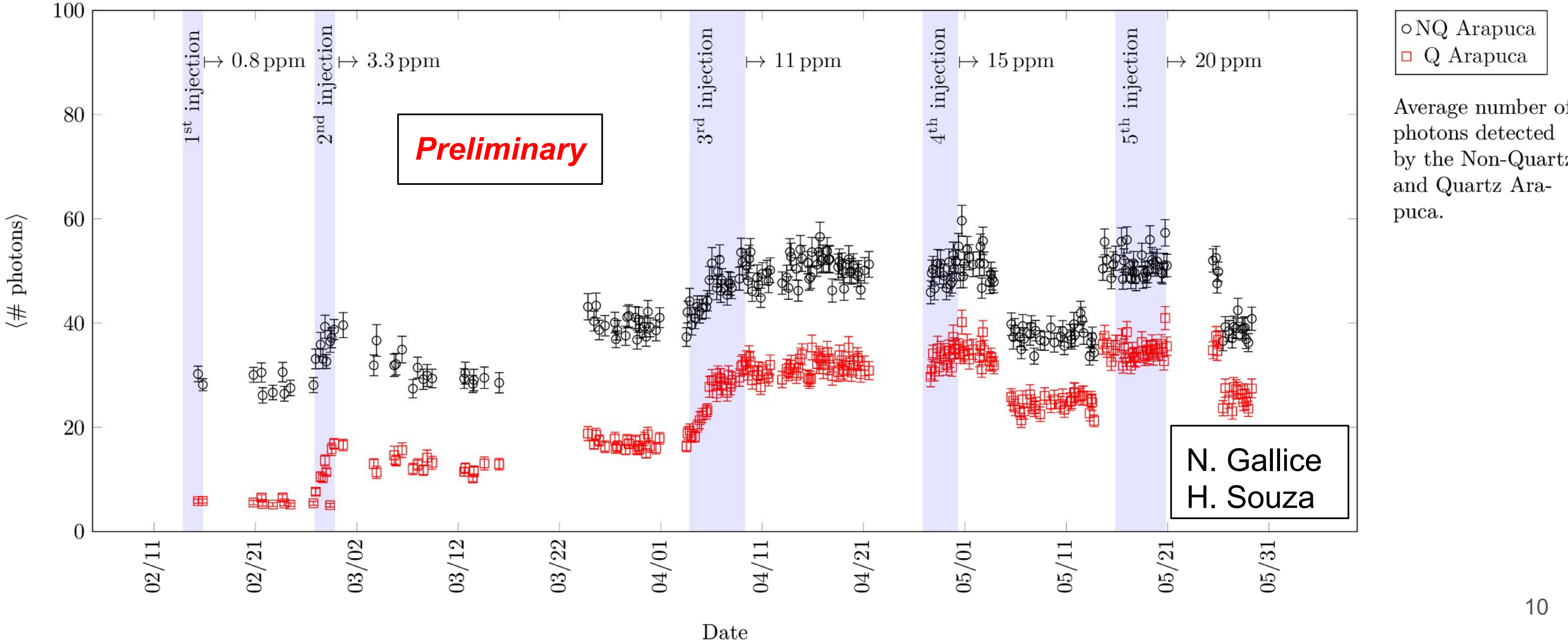
Energy transfer to the xenon-argon dimer effectively prevents the N_2 quenching process

The standalone system data analysis

- Analysis flow:
  - Waveform filtering, noise removal with moving average
  - Baseline subtraction
  - Create average waveform for each channel
  - Apply SPE calibration to each channel

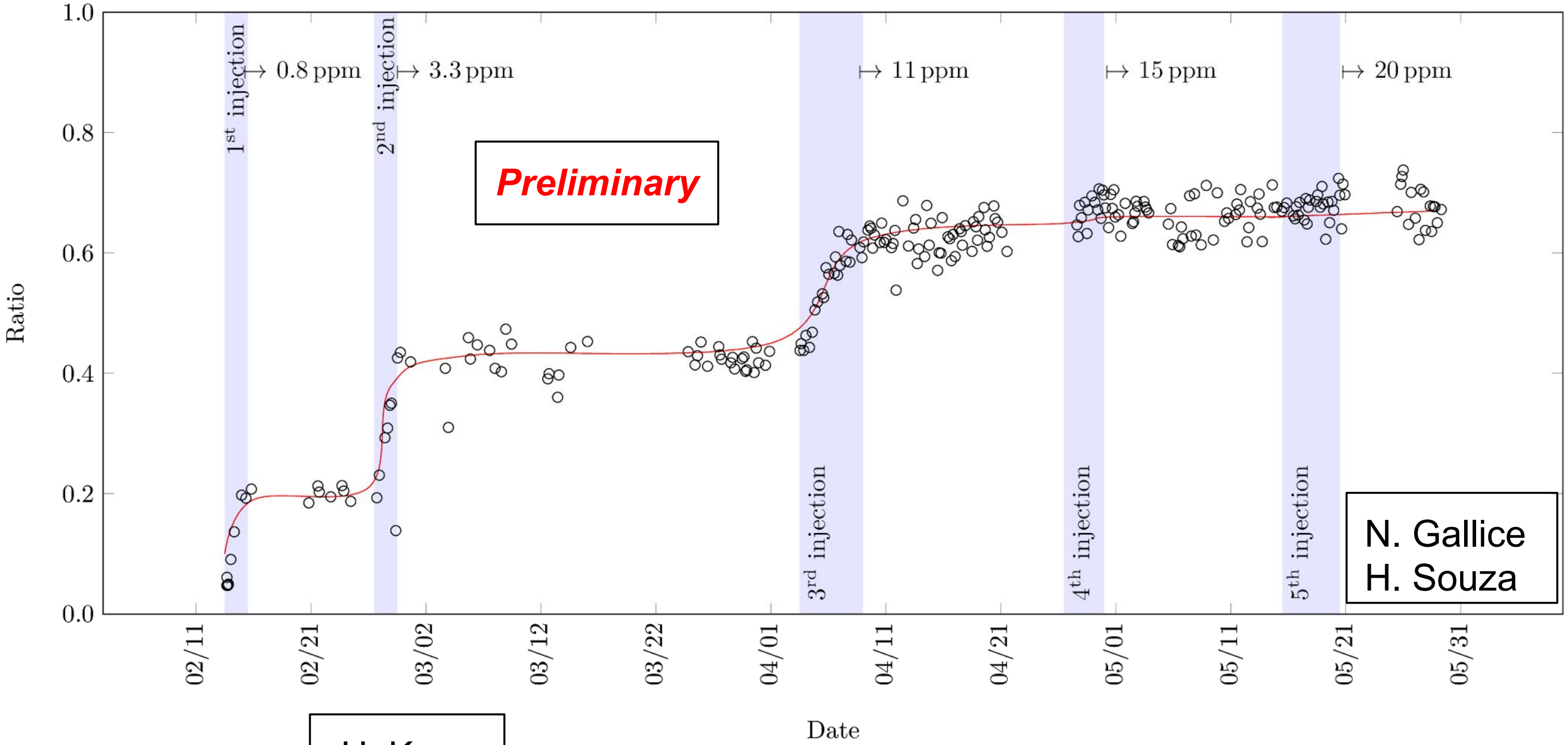
Collected light, light ratios, deconvolve and get tau slow components for Xe+LAr

Collected light



Average number of photons detected by the Non-Quartz and Quartz Arapuca.

The standalone system data analysis - ratios



○ Data
— Qualitative trend

$$\text{Ratio} = \frac{\text{Xe light}}{(\text{Ar} + \text{Xe})\text{ light}}$$

(Ar + Xe) light
↓
ARAPUCA is sensitive to both wavelengths

Xe light
↓
ARAPUCA with a quartz window transparent to Xe light (174 nm) and opaque to Ar light (128 nm)

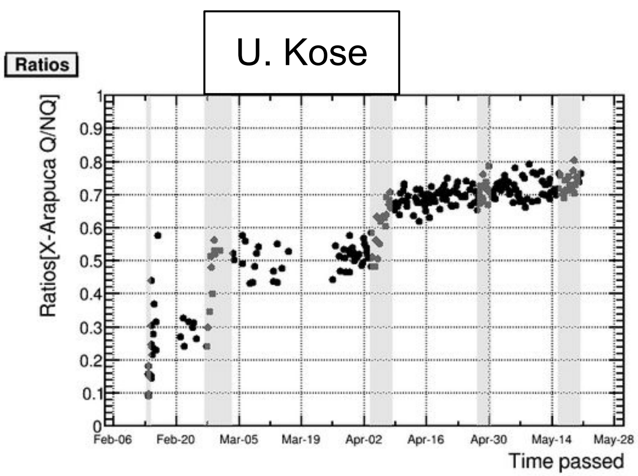
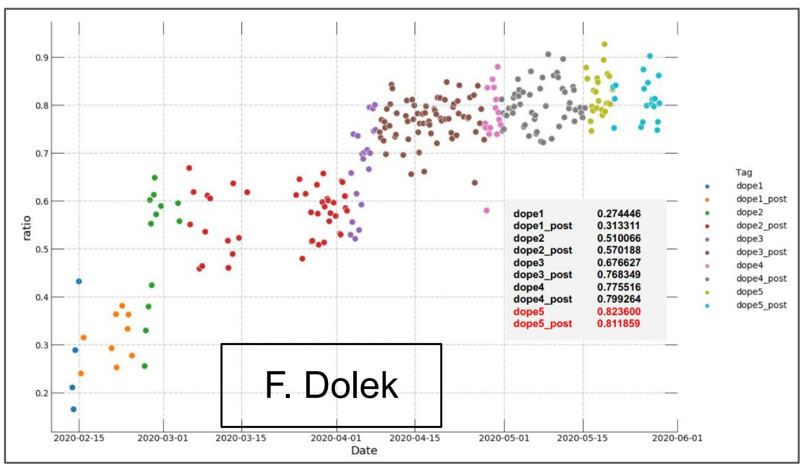
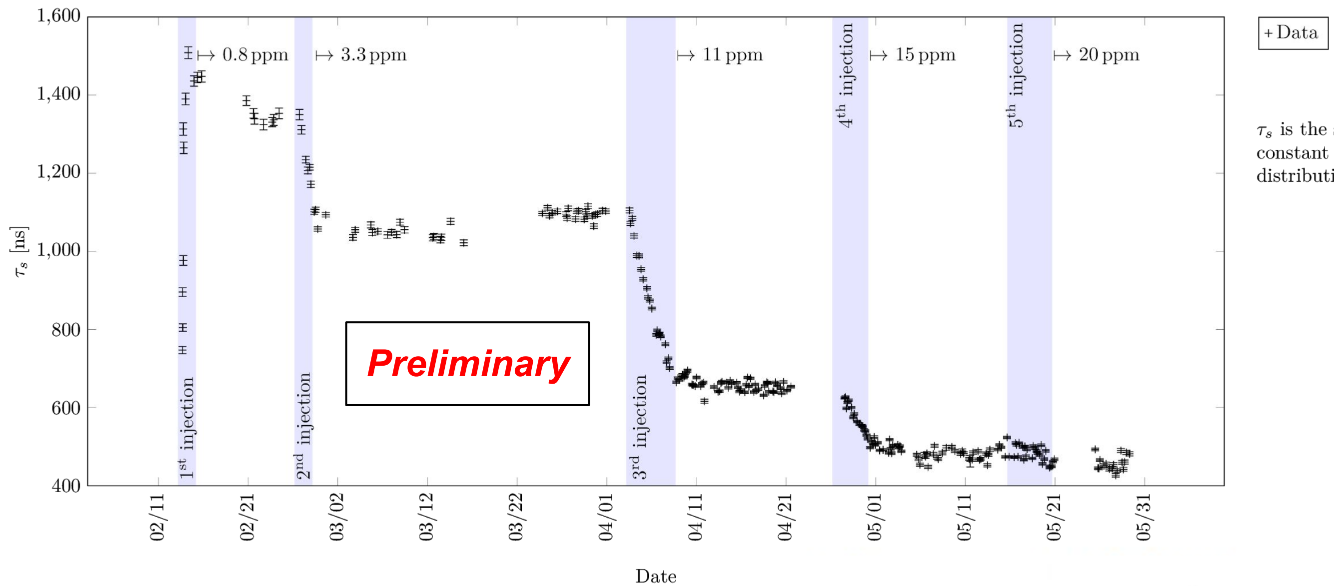


Figure 2: Ratio of X-Arapuca w/o QW to X-Arapuca w/ QW. Doping periods shown in gray box.

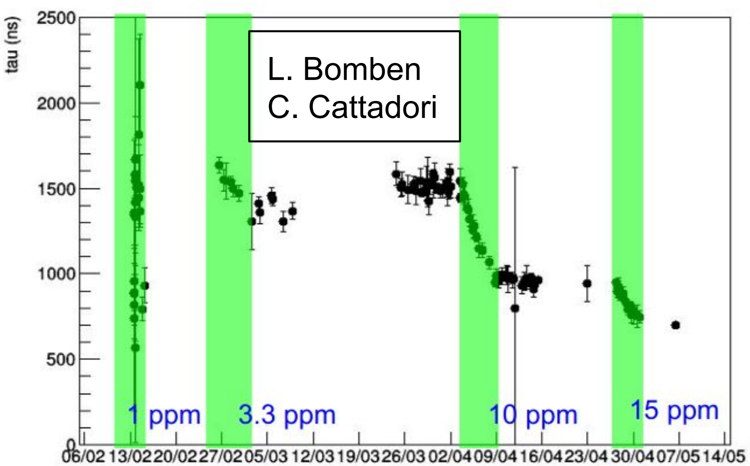


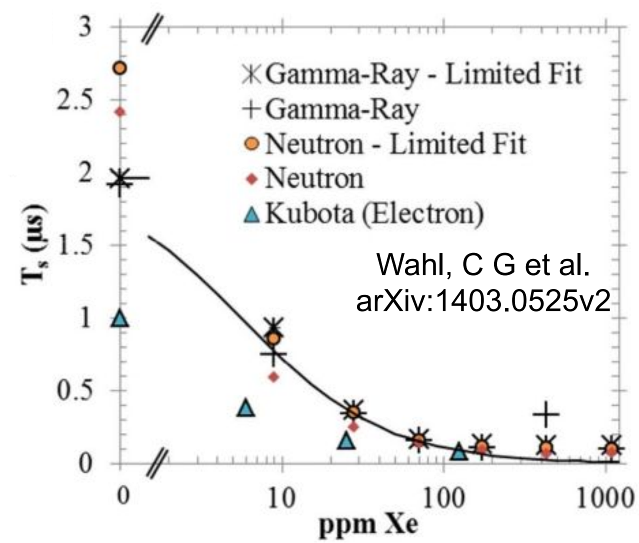
The standalone system data analysis- τ_s



τ_s is the slow time constant of Ar+Xe distribution.

Initial increase and decrease with each doping. The effects of increasing Xe concentration is still visible in the signal duration, which gets shorter as expected



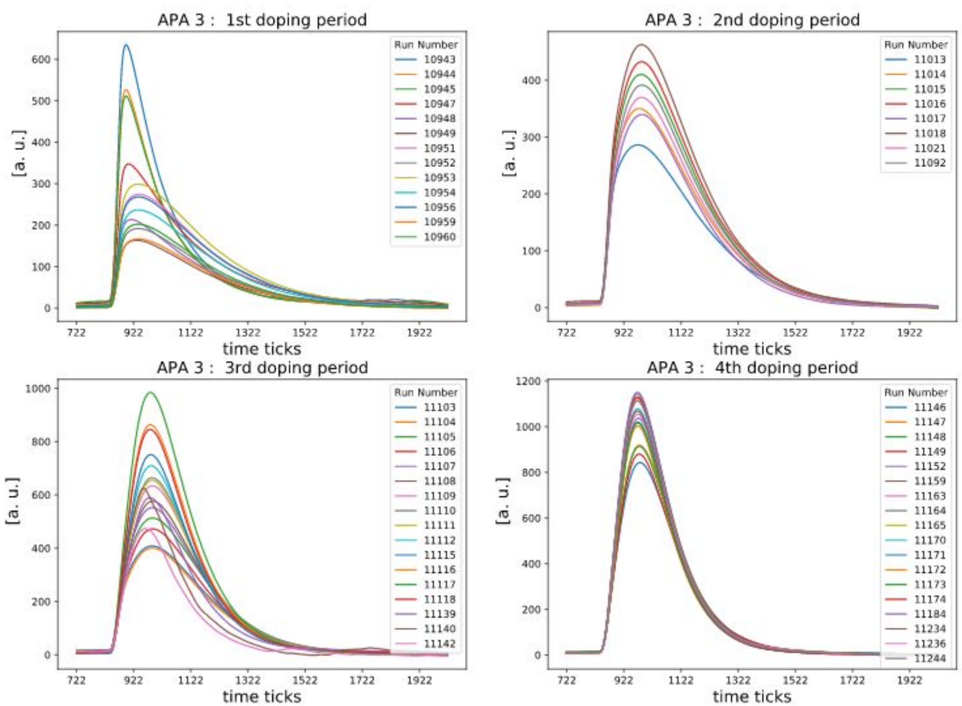


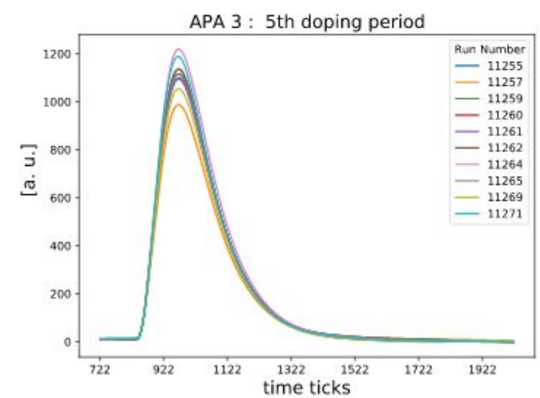
Agreement with the literature

ProtoDUNE-SP PDS data analysis

- Study uniformity and stability of Xe with ProtoDUNE Arapucas
- Analysis flow:
  - LArSoft data conversion→ dump waveforms of standard Arapucas
  - Apply simple event selection on waveforms
  - Waveform filtering, noise removal with moving average
  - Baseline subtraction
  - Create average waveform for each channel
  - Apply SPE calibration to each channel

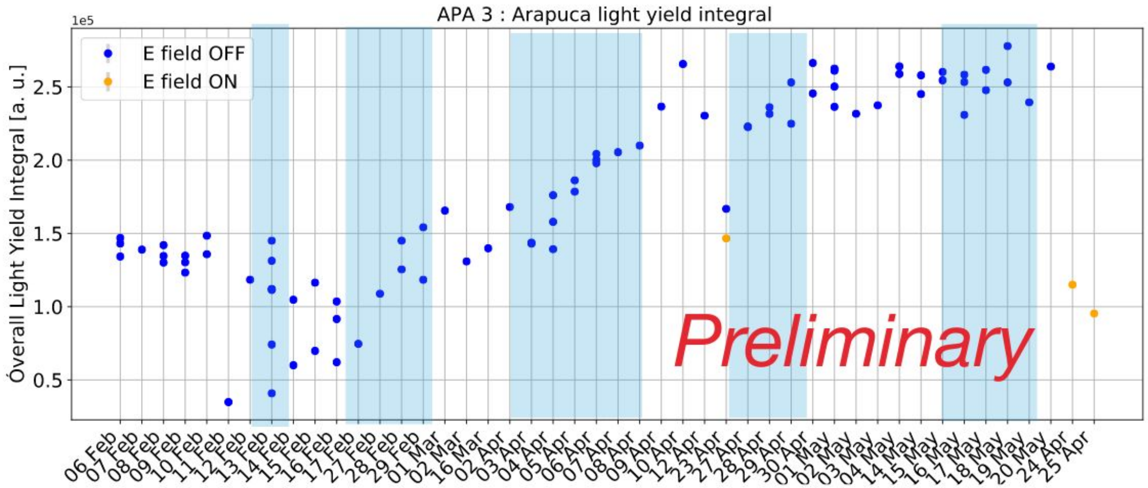
→ Collected light, comparison of APA3 and APA6, compare Arapuca to X-Arapuca ratios

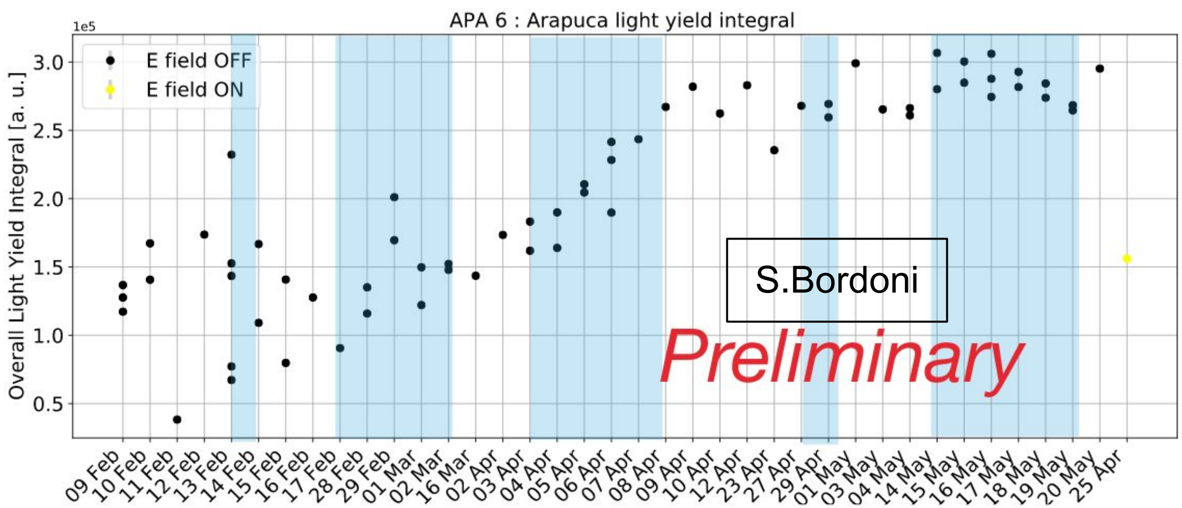




ProtoDUNE-SP PDS data analysis

- APA3 and APA6 light yield integrals:

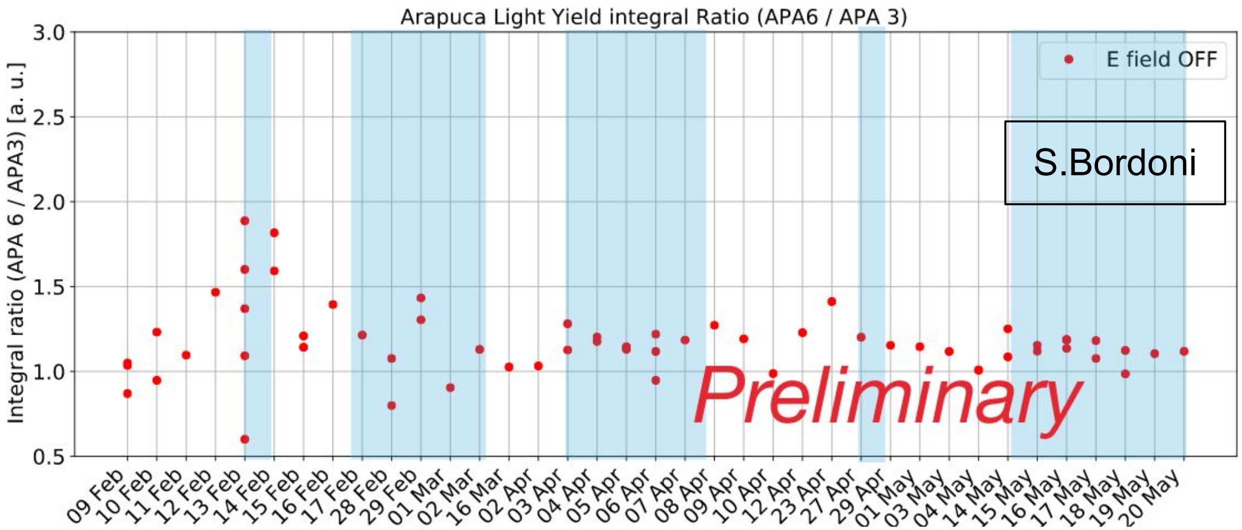


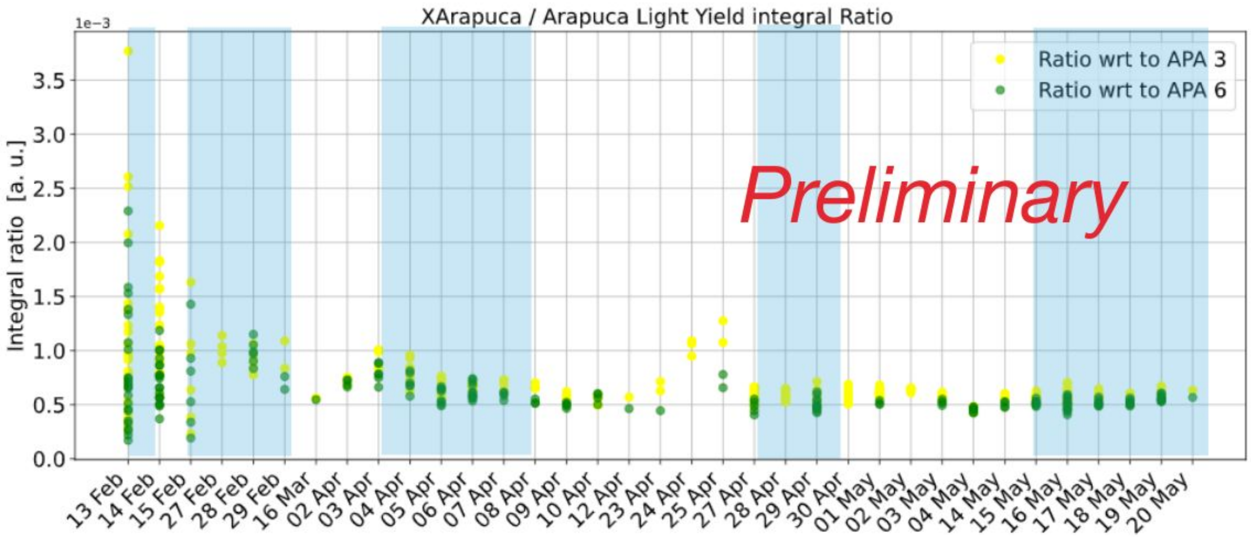


Arapucas confirm the increase of total collected light with increasing Xe concentration mostly ascribed to the full recovery of the N2 quenching with an additional possible contribution of a higher wavelength-shifting efficiency for the xenon-produced 175 nm light

ProtoDUNE-SP PDS data analysis

- APA6 / APA3 light yield ratio:
- X-Arapuca / Arapuca ratio



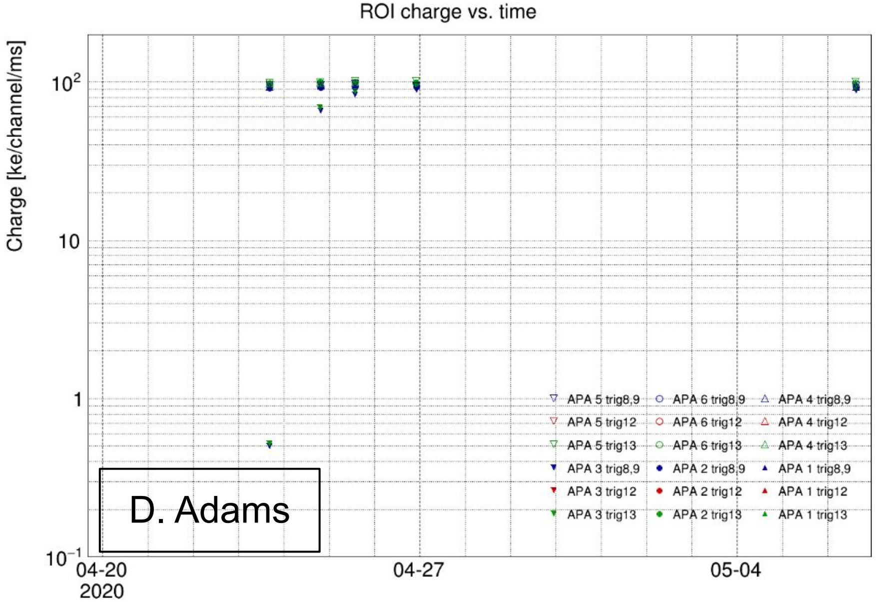


Preliminary analysis suggests Xe dissolves uniformly throughout the detector and remains constant on the timescale of months inside the cryostat

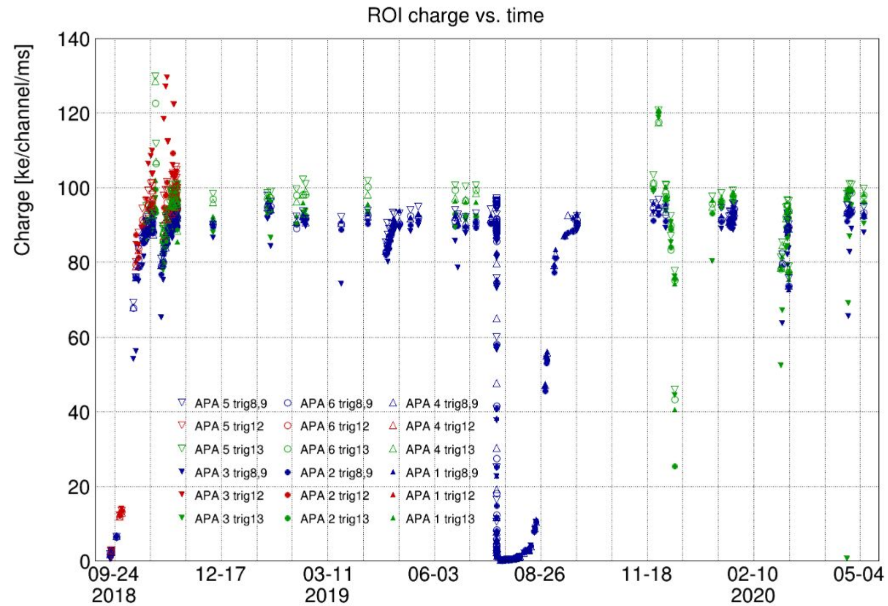
How about the charge signal in the presence of Xe

- Analyze TPC data taken at the presence of Xe inside the cryostat
  - look into the signal strength, charge(ke)/channel/ms
- Xe concentration does not have any visible effect on the collected charge

Recent log scale



Full run linear scale



Next steps ...

- ProtoDUNE-1:
  - Data taking will continue until the middle of July
  - Focus on understanding
    - Effects of Xe on collection efficiency
    - Light collection uniformity in detector volume

- ProtoDUNE-2: It is likely that we will operate ProtoDUNE 2 with xenon doping
  - Significant advantages even with no modifications to X-ARAPUCA baseline
    - Mitigation of nitrogen contamination risk
    - Increase in scattering length (effective improvement in uniformity)
    - Increase in average detection efficiency across detector volume
  - Possible changes to dichroic filter plates and wavelength shifting plates may allow for significant further additions
    - These changes can be implemented late in the module fabrication cycle
    - Studies continuing at UNICAMP, CERN of possible modifications
    - Decision on which modifications, if any, will be taken to the PD baseline at the time of the Final Design Review
    - N.B.: Some changes may result in the X-ARAPUCAs being blind to direct argon scintillation light. Careful consideration required!

Conclusions

- Had successfully finalized Xe-injection in ProtoDUNE-SP
  - In total 13.5 kg of Xe, 18.8 ppm in mass, injected into the cryostat
  - The effects of N_2 contamination has been recovered with a small amount of Xe
  - At ~10 ppm level, LAr slow component has been fully converted into Xe light
  - 1.7 - 2 times increase in the total collected light has been observed

- Data taking and improvement on the analysis will continue

- Planning and R&D for the near future is ongoing
  - Highly likely to run ProtoDUNE 2 with Xe doping
  - Studies continuing at UNICAMP, CERN of possible modifications on the detector components