Towards discovery of hidden sector dark matter with liquid xenon TPCs

P. Sorensen & R. Gibbons
Berkeley Lab

15th International Workshop on the Identification of Dark Matter
L'Aquila, IT
July 8-12, 2024

But first... thanks to the organizers

← Conference co-chair Prof. Ferella in 2006

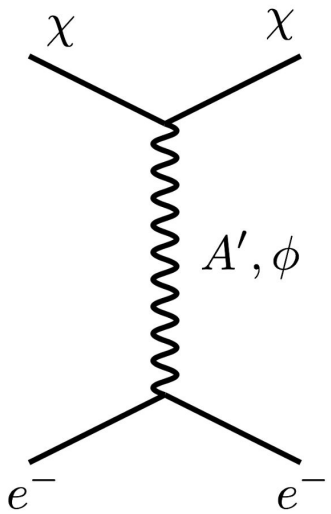
2011: "Direct detection strategies are proposed for sub-GeV mass"

A mild revolution

arXiv:1108.5383 Essig, Mardon, Volansky

Note earlier work e.g.

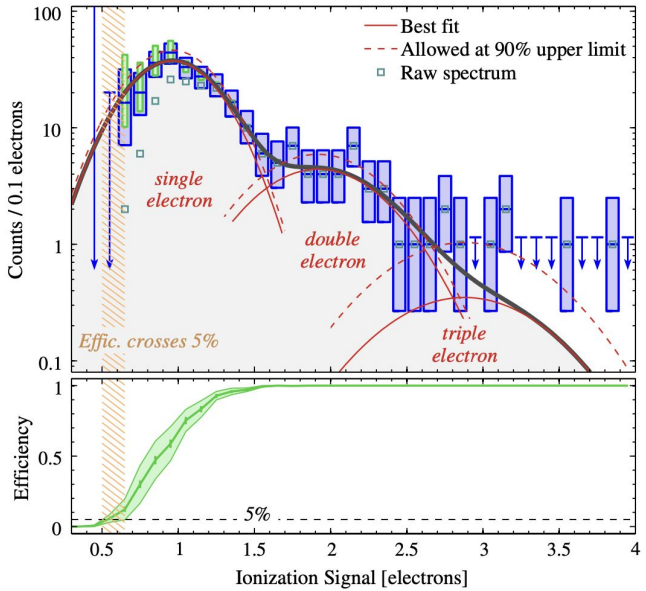
arXiv:0904.2567 Morrissey, Poland, Zurek



$$\overline{\sigma}_e \propto 1/(F_{DM})^2$$

2012: First exclusion limits on sub-GeV dark matter from XENON10

- Beset by an unknown background source of single-to-few electron signals
- In the jargon, (my fault) referred to as “electron trains”
- **The origin of electron trains (“e-trains”) in liquid nobel TPCs has remained elusive!**

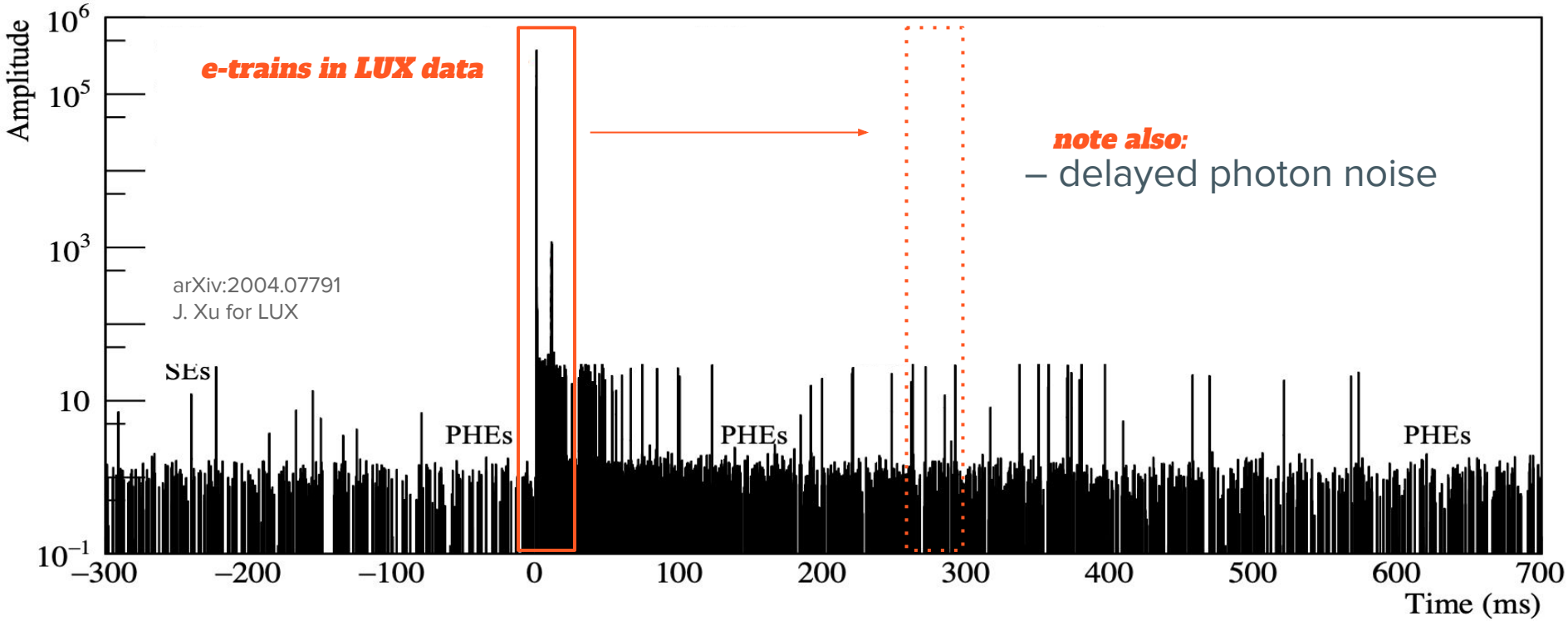


arXiv:1104.3088, P. Sorensen for XENON10
arXiv:1206.2644, Essig, Manalaysay, Mardon, Sorensen, Volansky

What are electron trains?

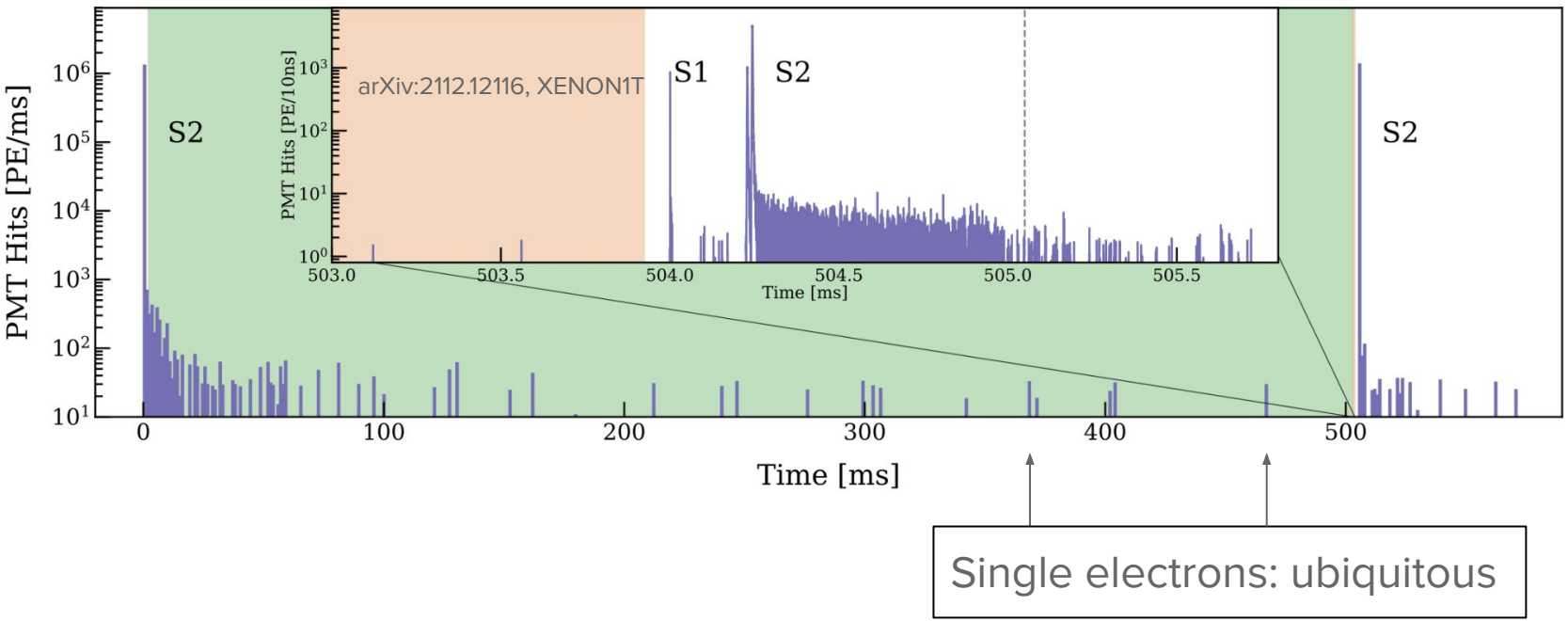
– delayed electron noise

power law decay (!?)



Different instrument, same $#@! problem

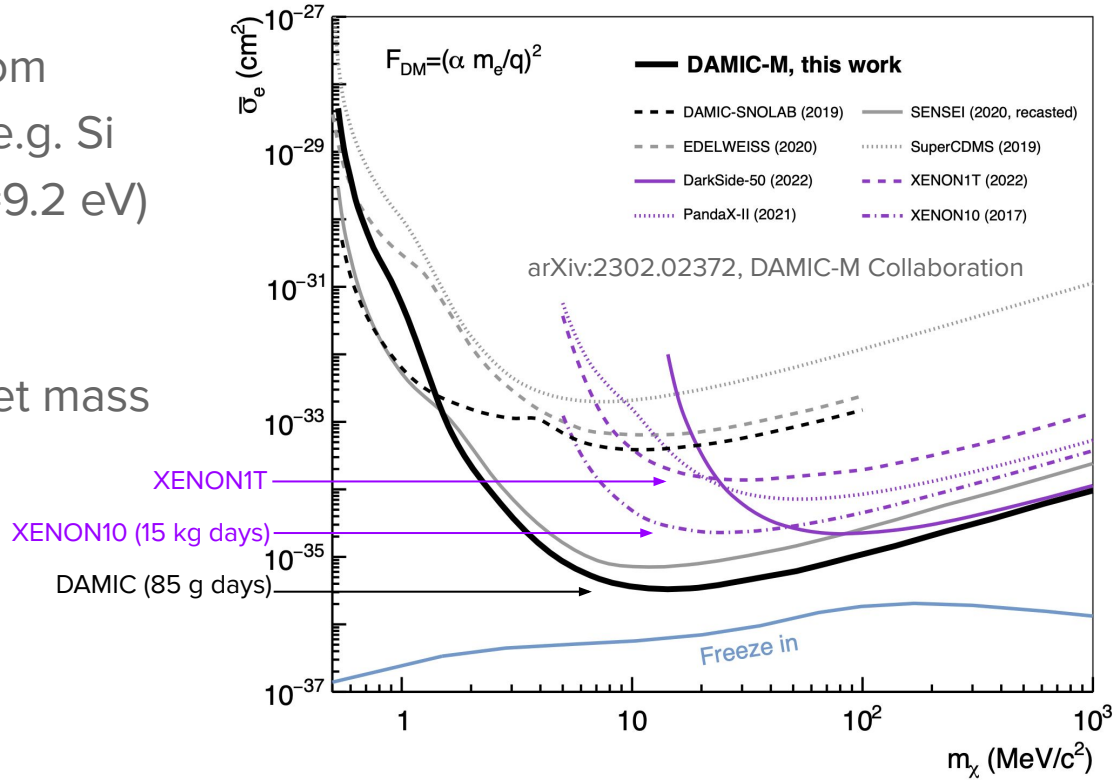
e-trains in XENON1T data



Ideal sub-GeV DM targets are low-bandgap materials

Designing an experiment from scratch, one would choose e.g. Si (ϵ_G=1.1 eV) rather than Xe (ϵ_G=9.2 eV)

But if background-free, target mass improves sensitivity



What causes delayed electron noise?

– photoionization of impurity negative ions by fluorescence photons

Incomplete history below

- 2011–2017: thought to be trapped e- at interface
- 2017–2024: thought to arise from detachment of electrons from electronegative impurity ions (e.g. O_2^-)
  - **Detachment mechanism a source of confusion –** collisional detachment and other mechanisms (e.g. arXiv: 2103.05077 Kopec et al) have a widely recognized issue: why power law, not exponential decay?
  - Sorensen & Kamdin 2017: " … may be due to fluorescence photons which then photoionize impurities in the liquid xenon."
  - Xu (LUX) 2020: "[photons] …. a triggering mechanism for the photoionization [of] negatively charged impurities"

What causes delayed photon noise?

– fluorescence of detector materials, notably PTFE

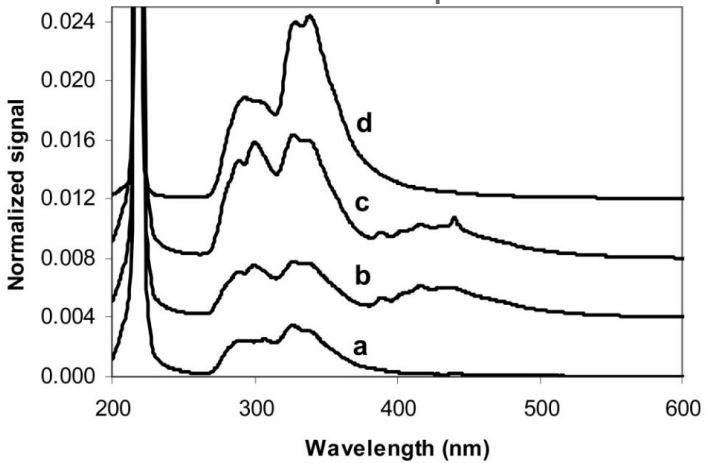
Incomplete history below

- arXiv:1711.07025, Sorensen & Kamdin – hypothesized
- arXiv:2004.07791, Xu for LUX Collaboration – reiterated
- arXiv:1905.03044, Araujo, Pollman, Ulrich – “observed no photoluminescence signal” (!?)

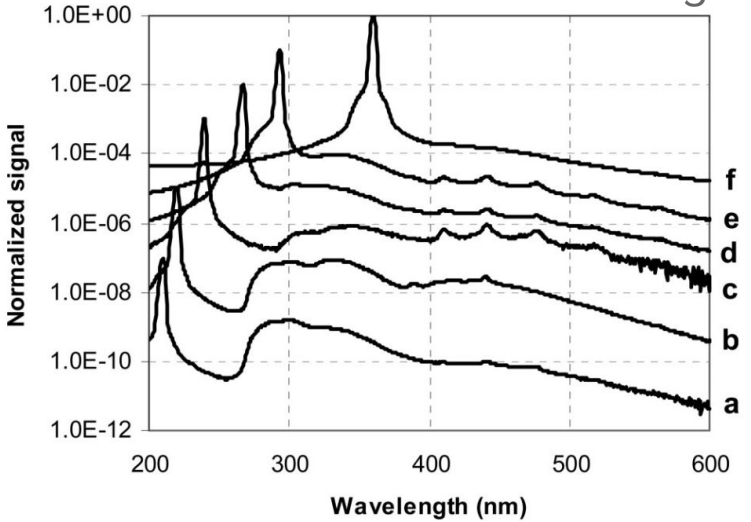
PTFE fluorescence: known

Shaw et al (2007)

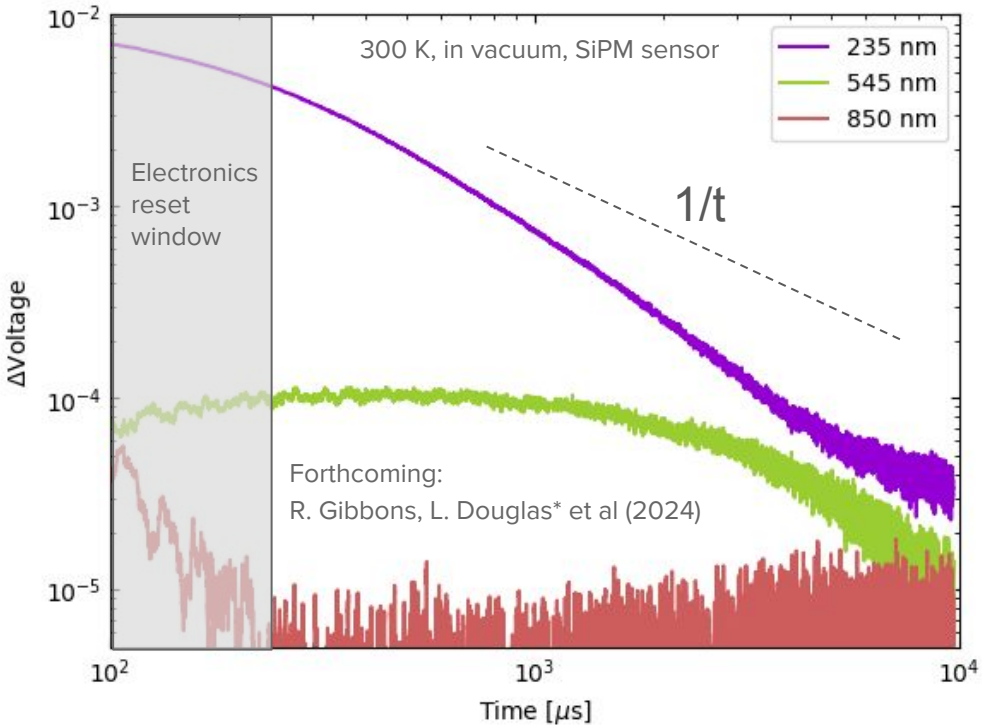
different samples



different excitation wavelength

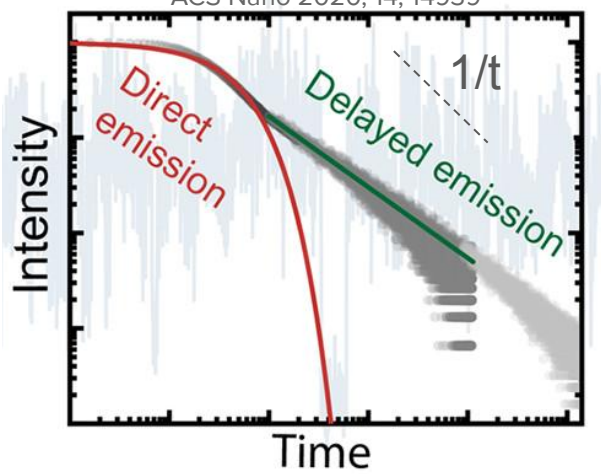


PTFE fluorescence: new!



- Power law fluorescence turns out to be fairly generic

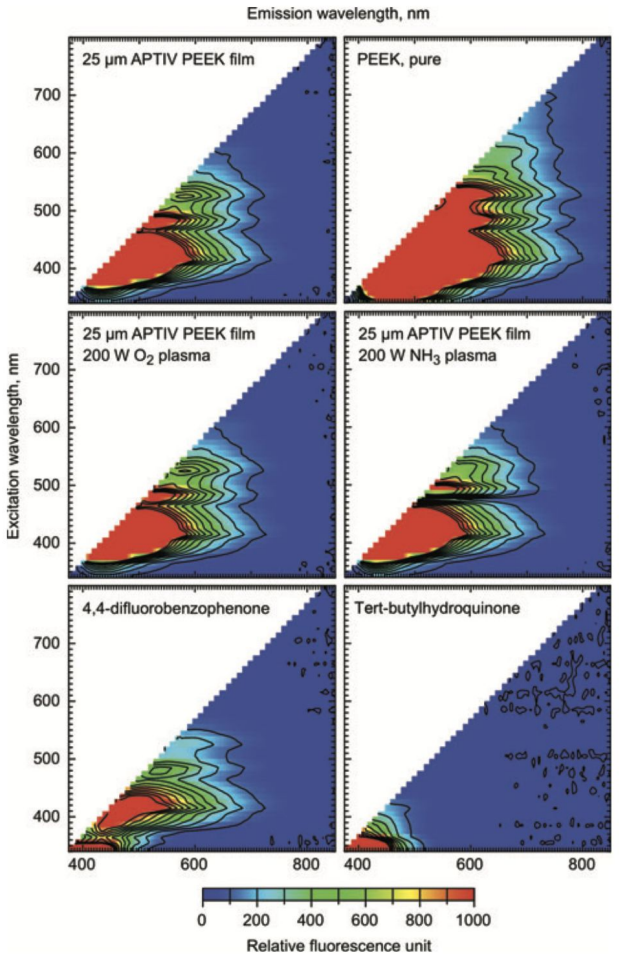
ACS Nano 2020, 14, 14939



by the way...

PEEK also fluoresces

Time domain measurements forthcoming



Althaus et al., Eur. J. Nanomed. 2012;4(1):7–15

My new default

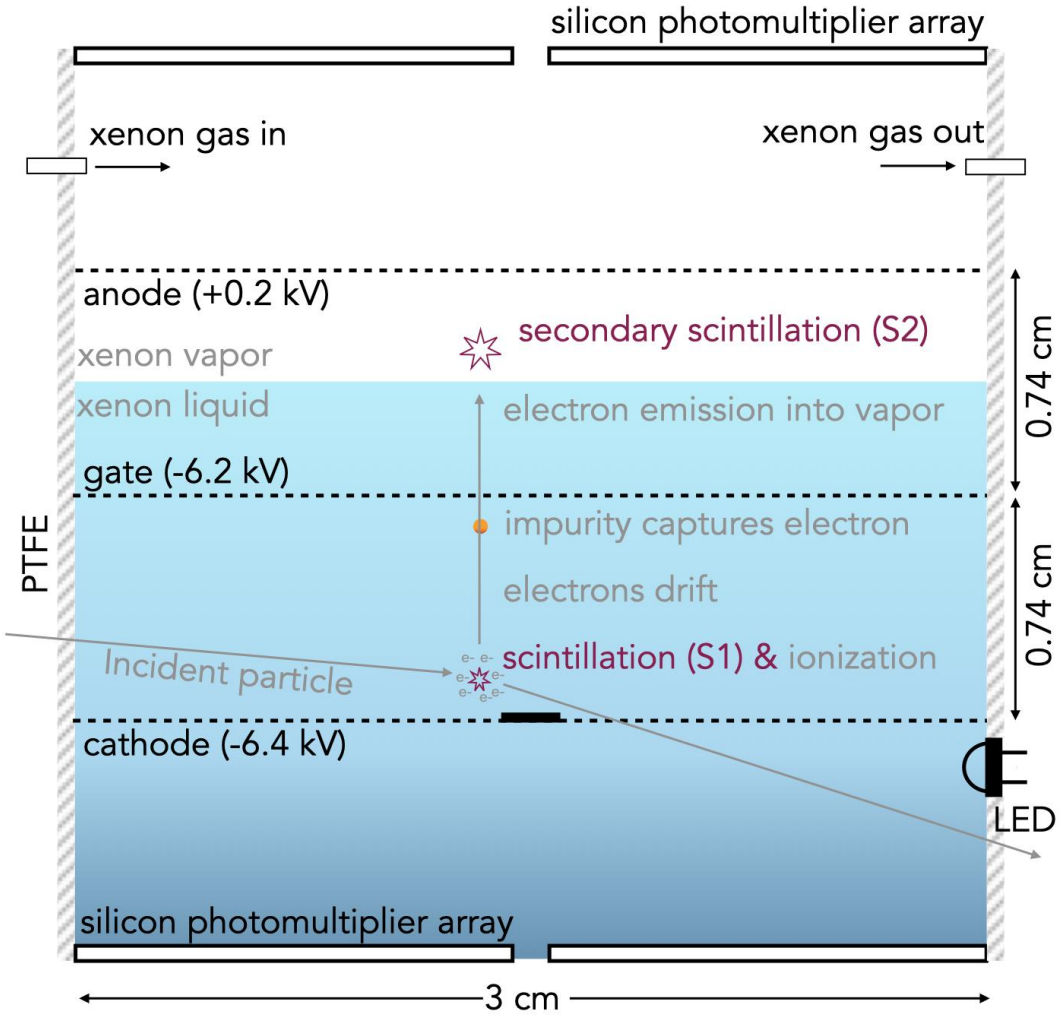
it probably fluoresces*

(until proven otherwise)

*or phosphoresces

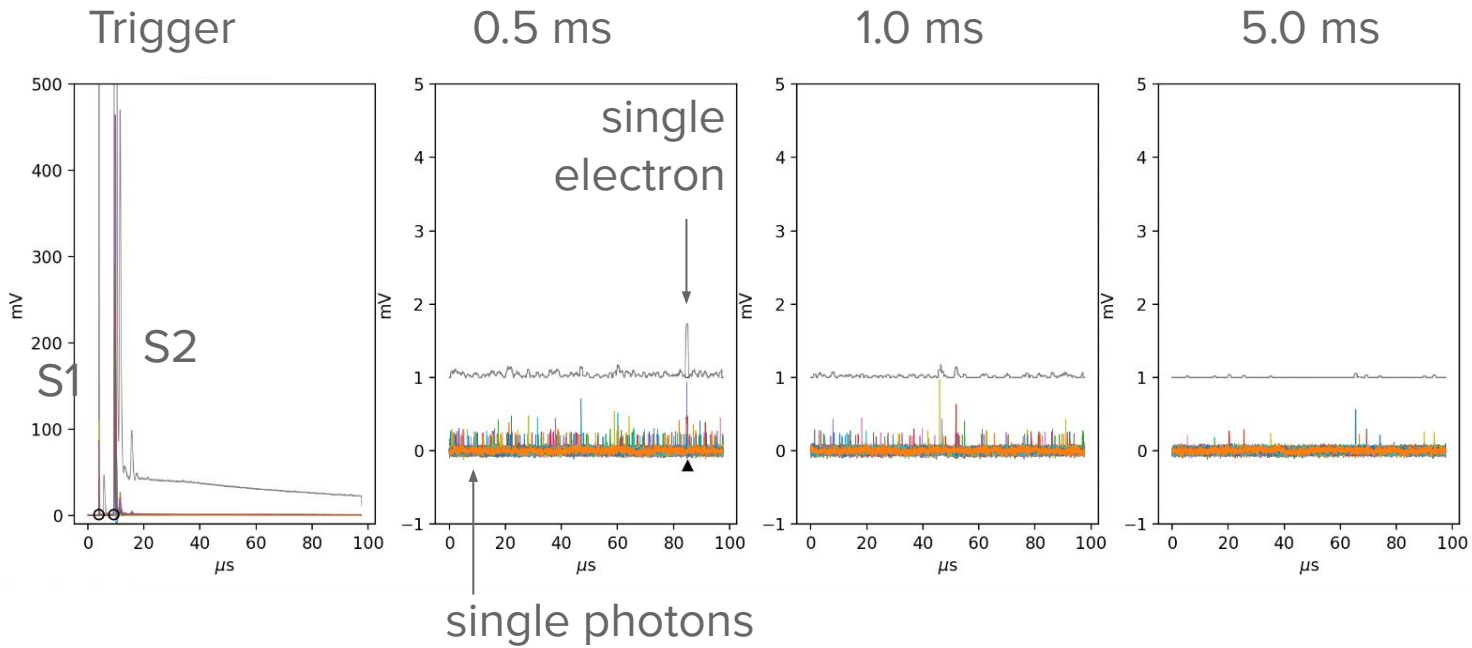
Liquid xenon TPC data

- Usual physical picture @right
- But now also:
  - detector materials fluorescence
  - **fluorescence → photoionization of impurities → e- trains**



Delayed noise in liquid/vapor xenon TPC

Typical data with a cascade trigger on O(100) keV Compton scatters



Zoom on trigger event

S1

S1 photoionization of gate

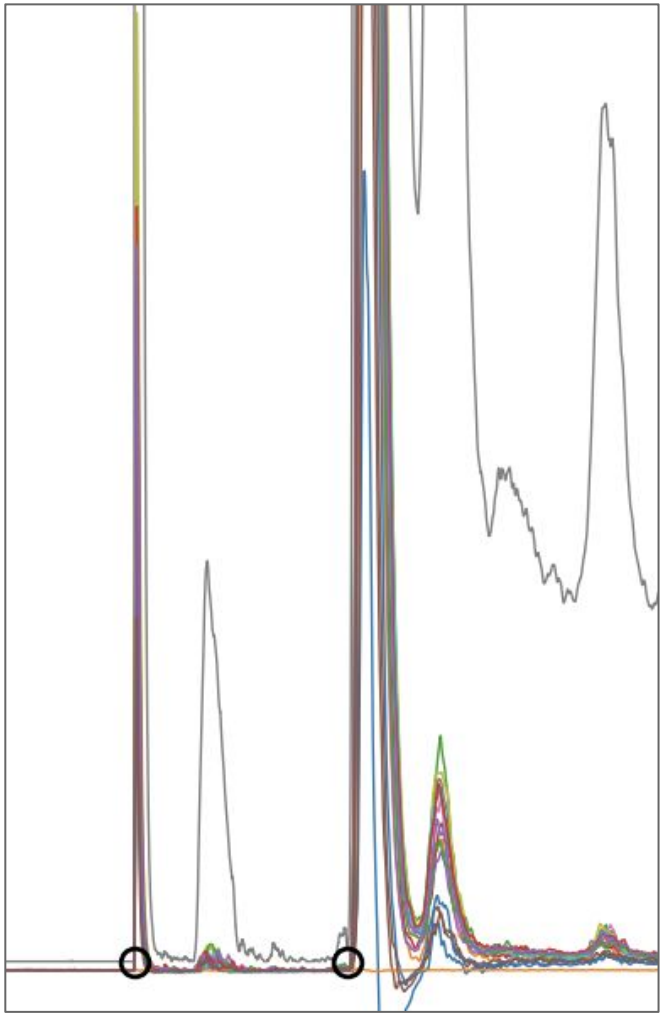
S1 photoionization of bulk impurities

S2

S2 photoionization of gate

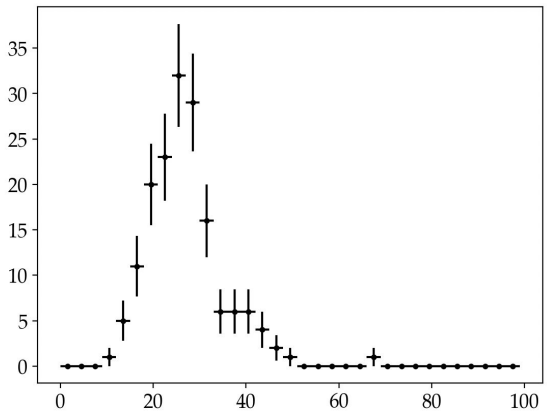
S2 photoionization of cathode

Delayed photons and electrons...

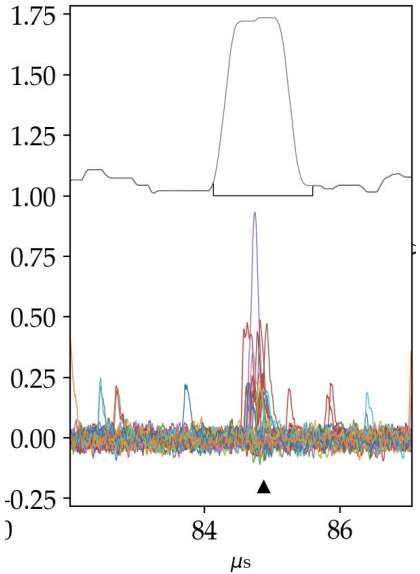


Easy to distinguish single e- from single γ

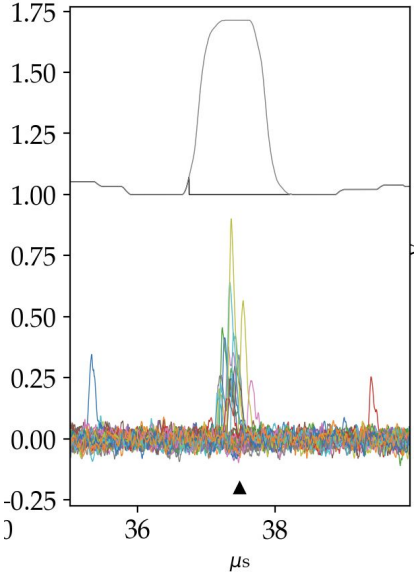
True for unsaturated signals (this analysis)



detected photons/e-



20 photons



24 photons

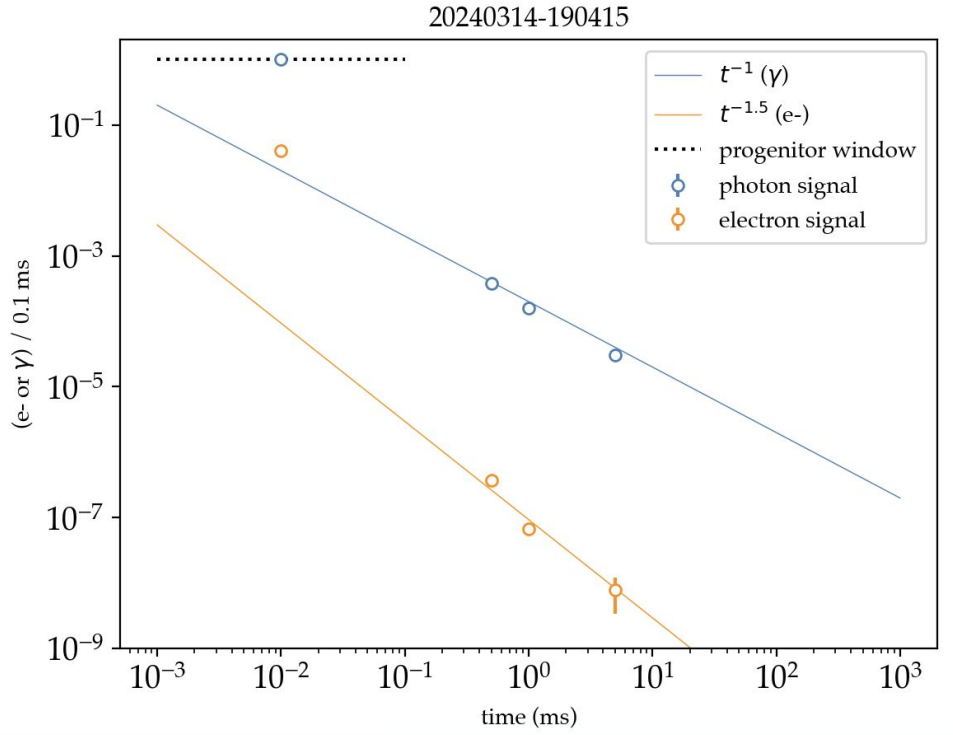
Basic delayed noise measurement

Trigger on O(100) keV Compton scatters from 133Ba source

Count delayed photons and electrons

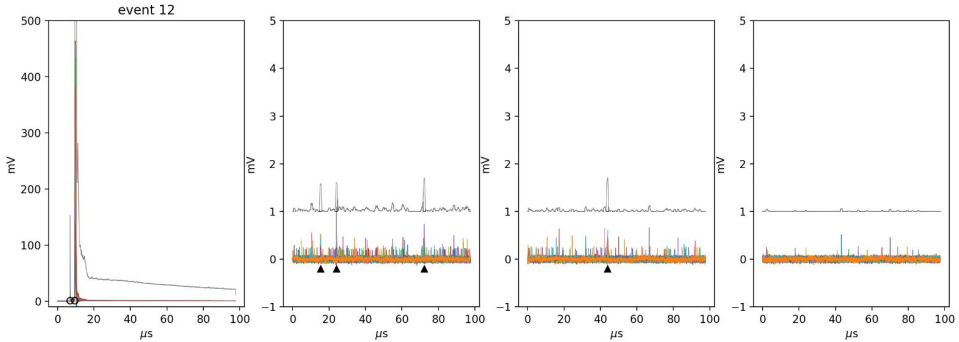
Stack waveforms and normalize to a single detected (S2) photon

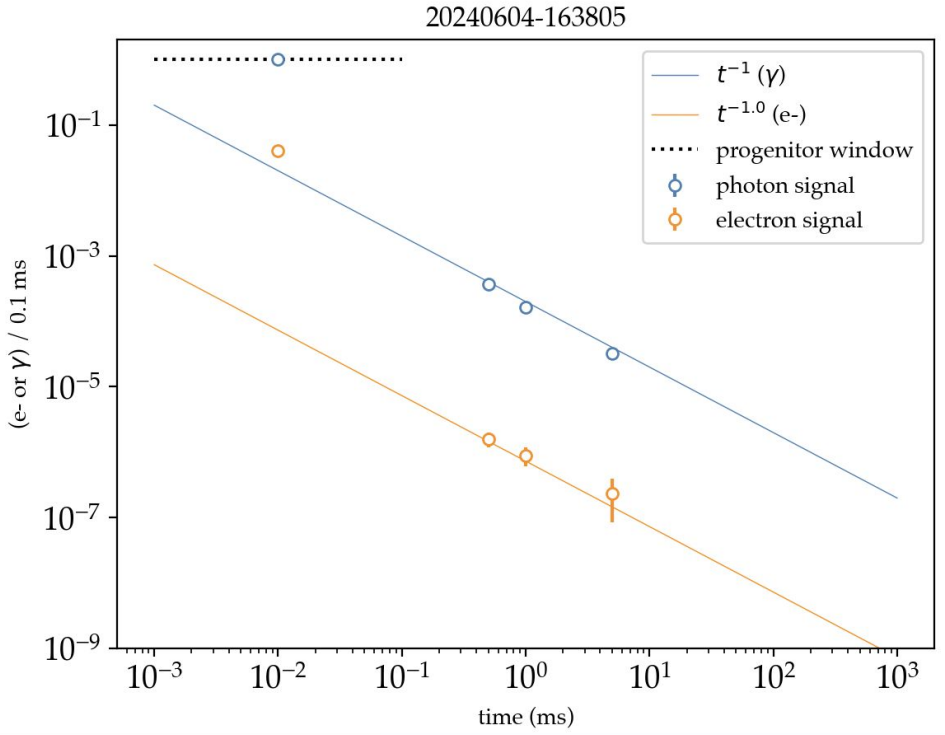
Testbed was “very clean”



Opened TPC to fix a solder connection (dirty work!)

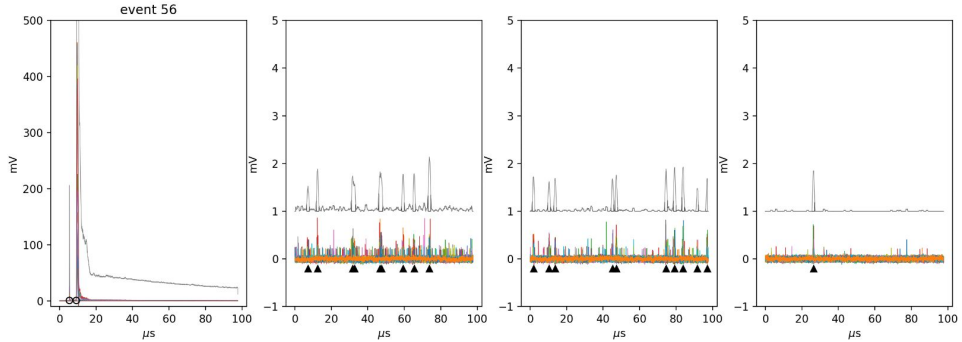
- Delayed photon noise unchanged
- Delayed electron noise increased + change of power law
  - Likely new impurities

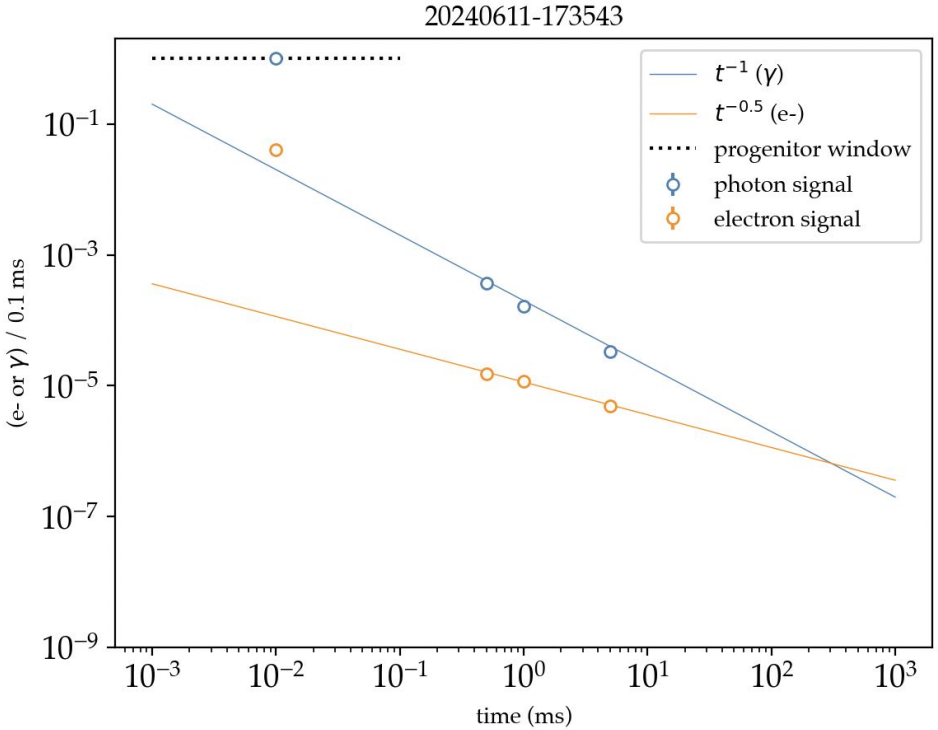




Opened again to install a 235 nm LED (dirtier work?)

- Delayed photon noise unchanged
- Delayed electron noise increased further + further change of power law
  - Maybe additional new impurity species





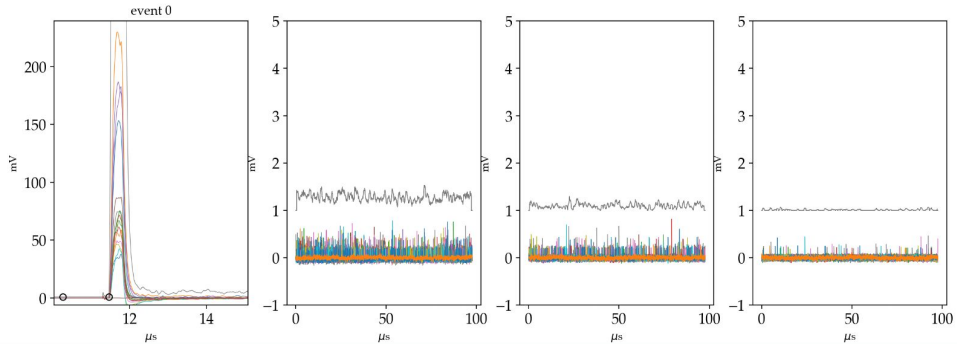
Trigger on 235 nm LED pulse only

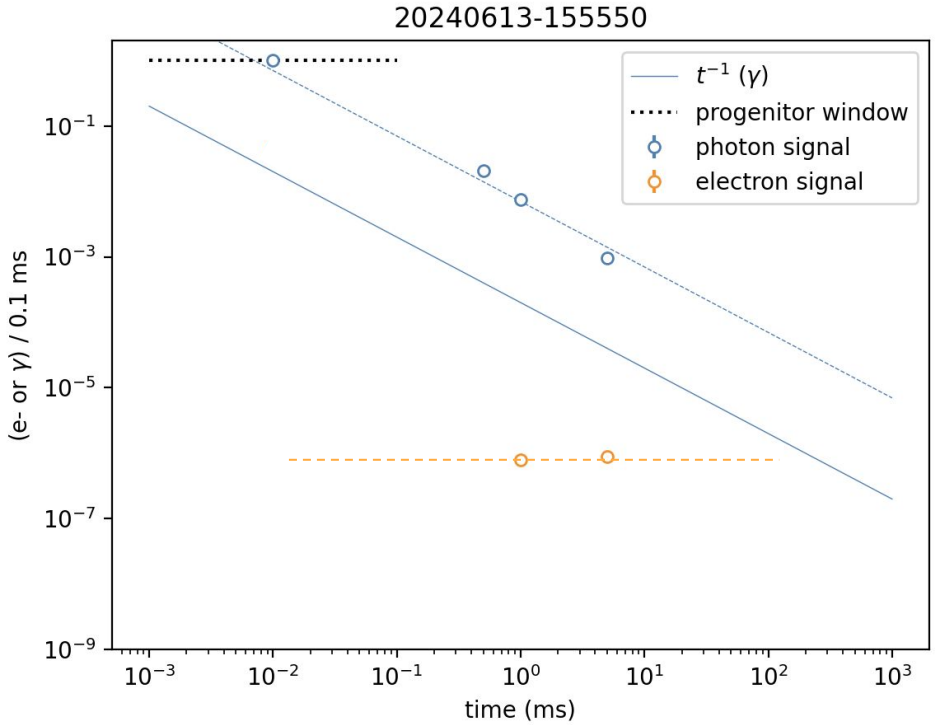
No particle interaction in the trigger

Delayed photon noise increases x35 – **fluorescence!**

Delayed electron noise decreases x5+ (measuring background e- noise)

LED “S2”



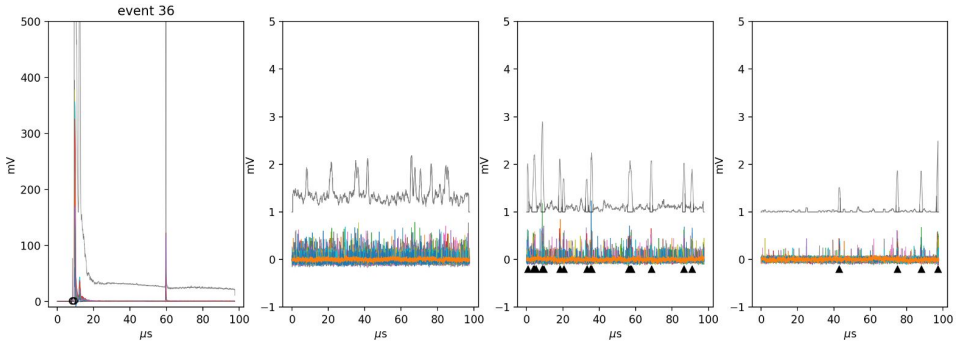


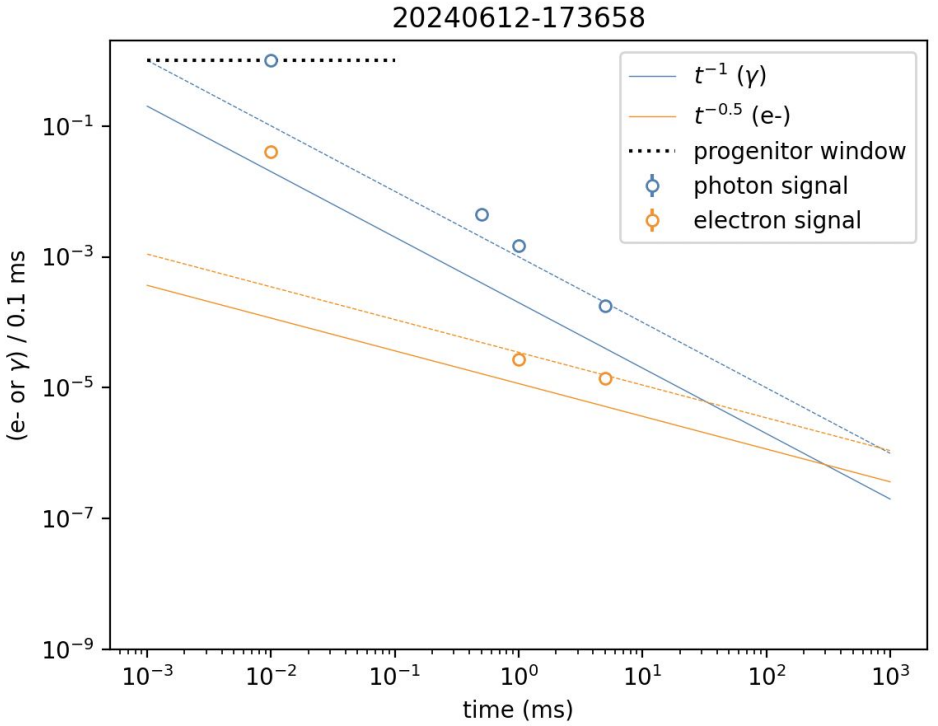
Trigger on particle interaction, chase it with LED pulse

Delayed photon noise increases x5

Delayed electron noise increases x3

235 nm LED pulse





Summary (part i)

- aka: recap of new data
- **PTFE fluoresces with a long, power law tail**
- **Fluorescence photons cause e-trains in liquid xenon TPCs, but only if there are impurity negative ions available in the bulk xenon**
- Our measured factor x¾ (rather than x1) is influenced by systematics:
  - 235 nm LED vs 175 nm xenon scintillation (photoionization cross section)
  - Geometry of LED placement vs S2 location
  - Main point is it is an O(1) effect

Summary (part ii): Implications for XLZD+

- Delayed electron noise is fatal for dark sector searches, but merely annoying for the primary business of LZ, XENONnT (searching for weak-scale dark matter)
- Delayed fluorescence photons, on the other hand, increase the S1 accidental coincidence (AC) background

we've heard alot about AC!

Qing, Henning, Kexin, Ibles (Monday)

Fei (Wednesday)

- Nature has a wry sense of humor

Summary (part ii, addendum)

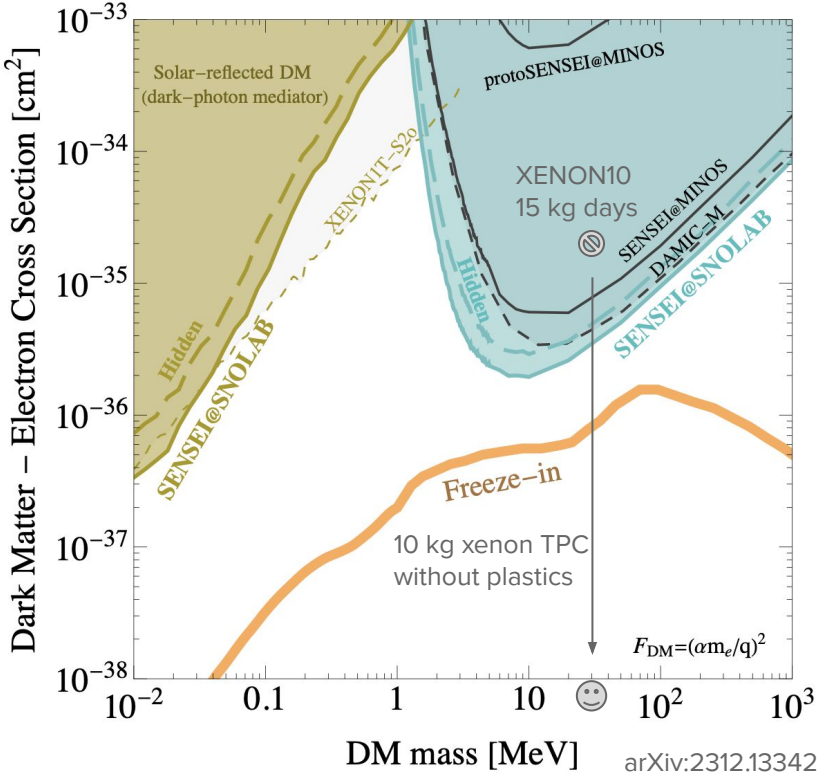
- Note: No mention of fluorescence
  - in the LZ Technical Design Report arXiv:1703.09144
  - in the XENONnT Design article arXiv:2402.10446
  - in the Darkside 20k Design article arXiv:1707.08145
  - in these proceedings in regard to liquid xenon TPC, despite importance of “AC”
- **New fluorescent material screening program likely needed (we have started)**
  - **PTFE almost done**
  - **PEEK next**
  - **Then acrylic, then…**

Summary (part iii)

- A component of the O(1) eV LEE is likely phosphorescence (cousin of fluorescence)
  - Electronic excitation does not require an initial photon, it could be thermal
  - Cf. Strandhagen plenary and several parallel talks

Summary (part iv) + outlook

- A xenon TPC without PTFE, PEEK, etc will have significantly reduced e-train backgrounds
    - Other sources of delayed electrons (e.g. photoionization of electrodes) appear to be sub-dominant
- **Freeze-in region from 5 MeV – 2 GeV should be within reach of a fluorescence-deoptimized 10 kg xenon TPC**



arXiv:2312.13342

Anti-acronym digression

Acronyms, experimentalists love them

But should we?

Parting shot

Planning a new experiment to search for hidden sector dark matter

Without an acronym name!

Instead, an anastrophe:

Stay tuned for the non-fluorescent

“Very Disco”

experiment