Illuminating sub-GeV dark matter with liquid xenon TPCs

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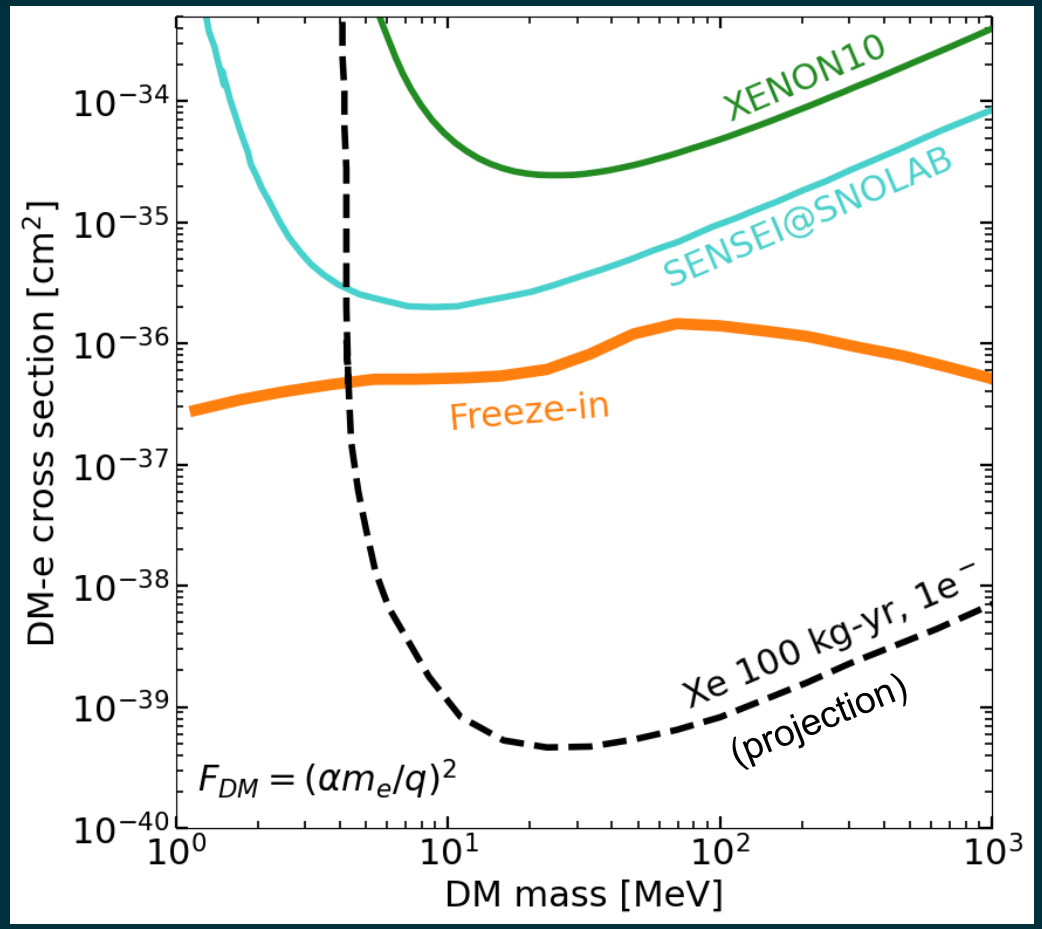
Charge-only signal to search for low-mass dark matter

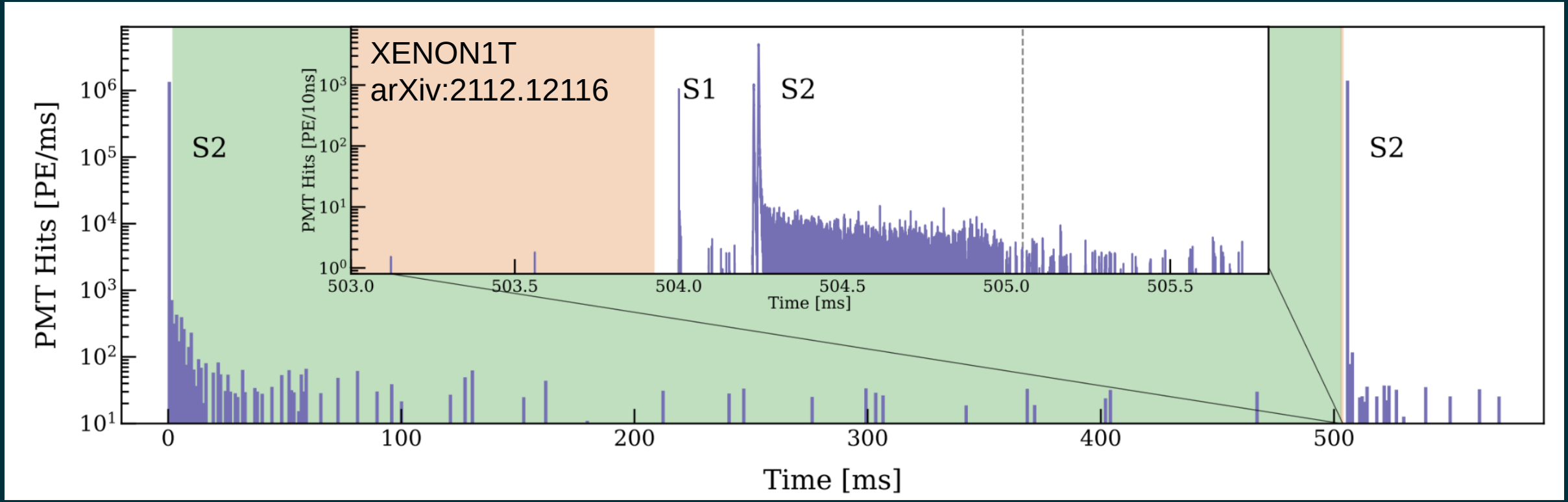
- Min. low-energy threshold, E_g = 9.2 eV
  - Attractive for DM-electron scattering
- No ER/NR discrimination? No problem
  - Neutrino fog dominates over radon
- **~10 kg of xenon to probe freeze-in**
  - Upgrade LZ to perform this search?



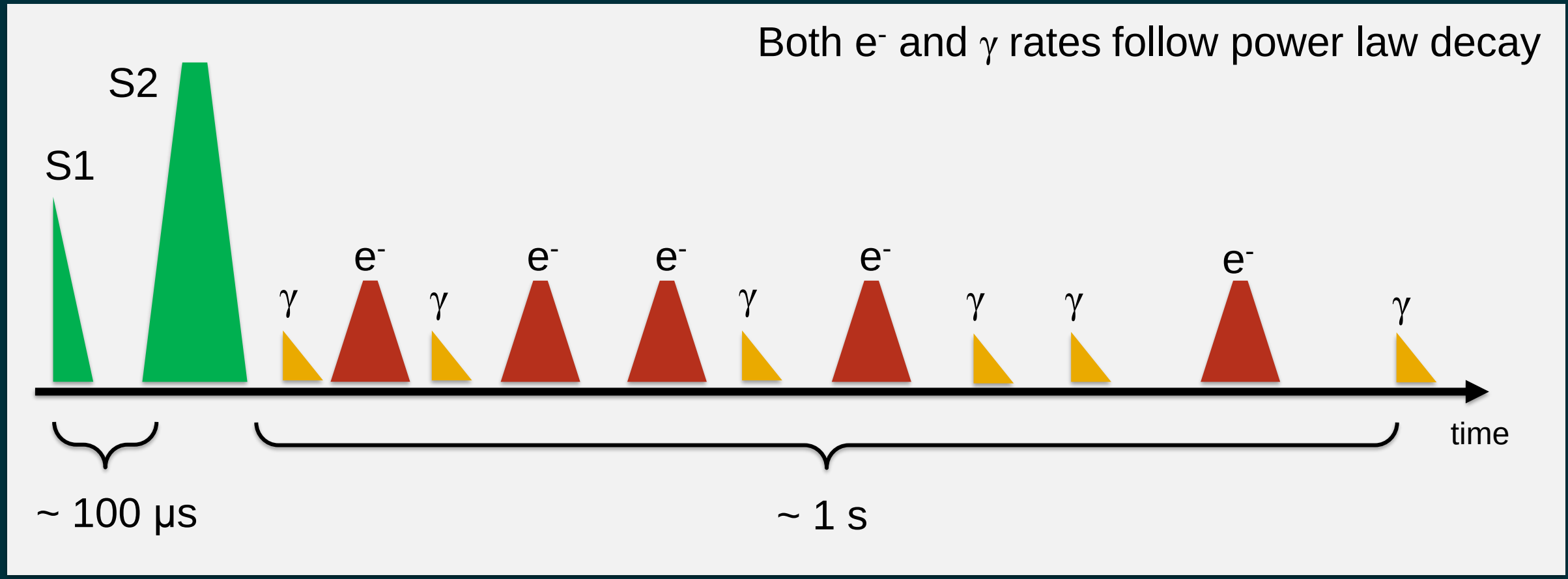
See Matthew Szydagis's talk on LZ!

Dominant background – delayed electron emission ("e-trains")

- Observe elevated rate of single electrons after particle scatters



Delayed emission – electron and photon “trains”



Prior studies (unexhaustive):

- arXiv:1711.07025, Sorensen & Kamdin
- arXiv:2004.07791, Xu for LUX
- arXiv:2112.12116, XENON1T

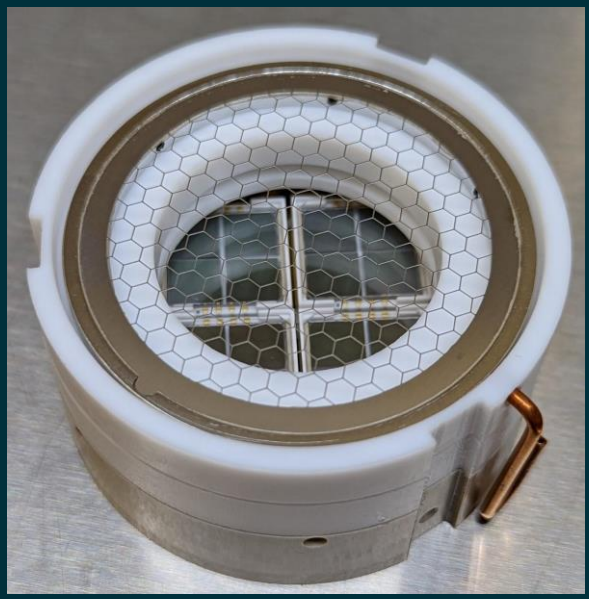
Delayed photons cause delayed electrons

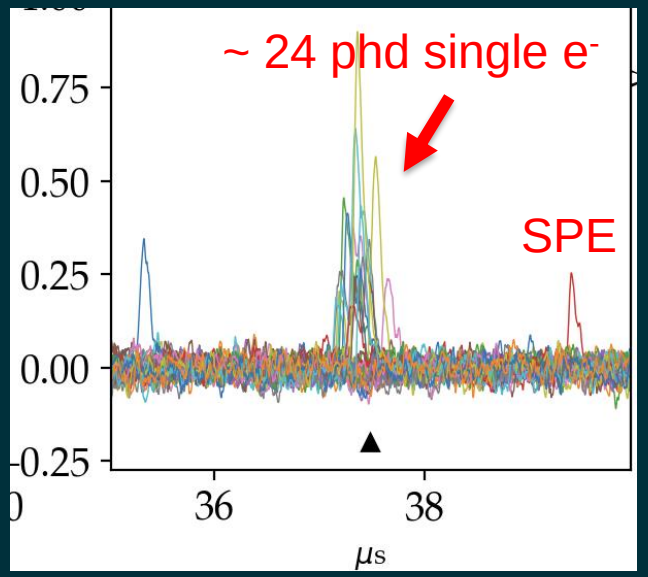
(our conclusion based on recent data)

Mechanism is as follows:
1. Electrons become trapped on impurities in Xe bulk
2. Electrons are released by photoionization from delayed photons

Investigations at LBNL Xenon Lab (formerly *the* TPC Lab)

- ~ 700 g dual-phase xenon TPC
- 32 SiPM channels (later 16 SiPMs + 1 PMT)
- Typical single electron ~ 20-30 phd





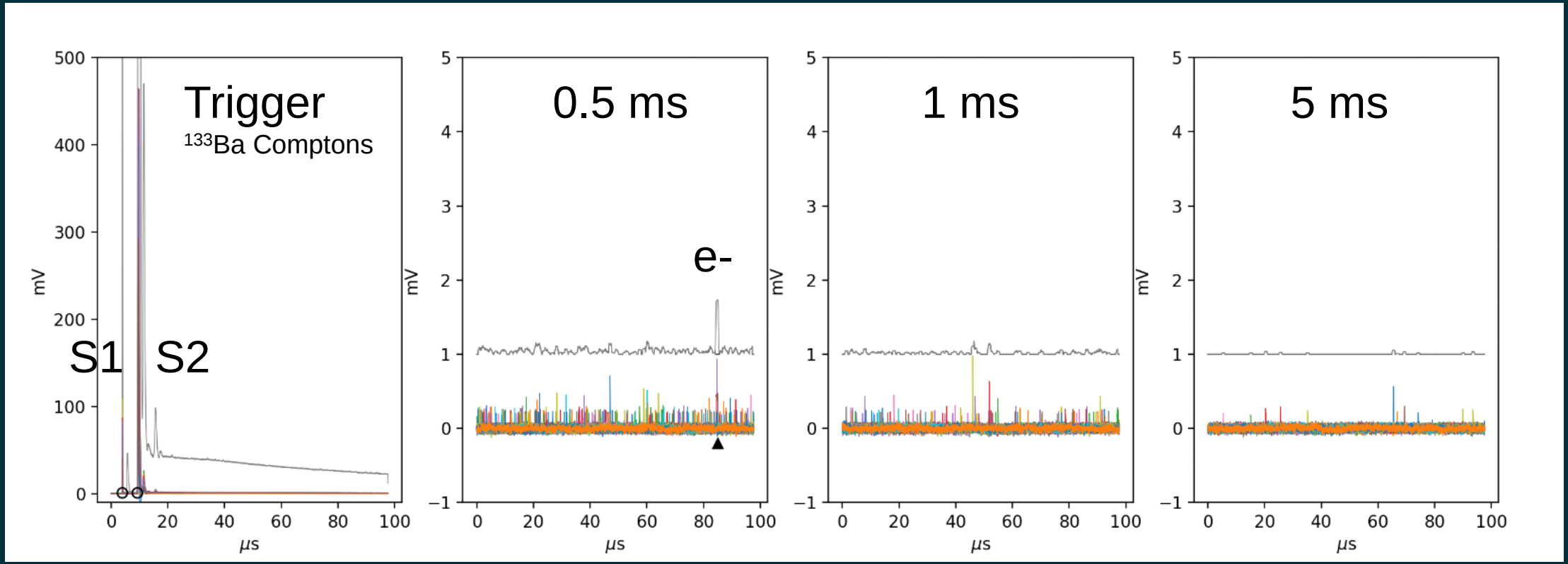
See Scott Kravitz's talk next for crystaLiZe!

More work from this test stand:

- Solid Xe TPC (crystaLiZe): *2312.15082*, *2201.05740*
- H/He-doping Xe (HydroX): *2308.02430*
- SiPM G3 R&D: *2309.07913*

Delayed signal in liquid/vapor xenon TPC

Observe and count delayed electrons and photons

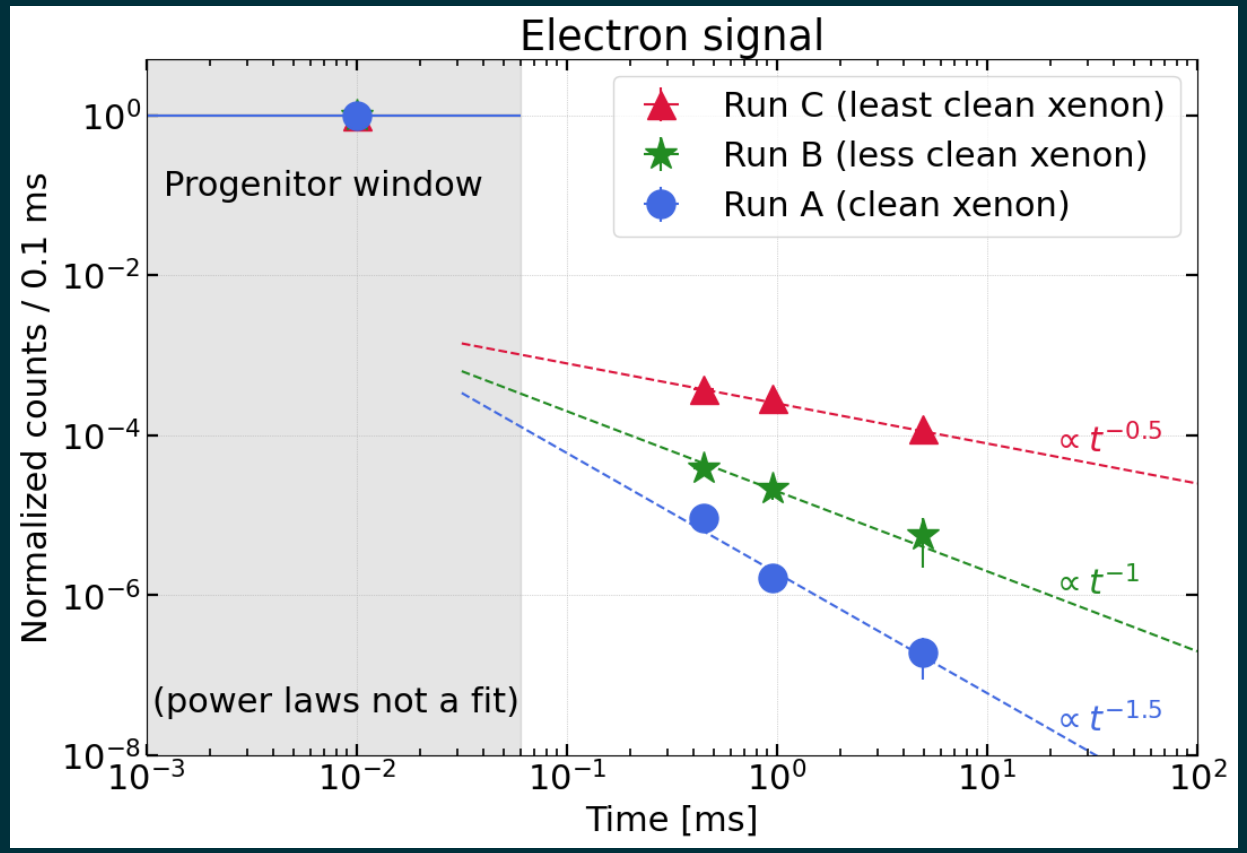


Using “cascade trigger” to sample delayed times

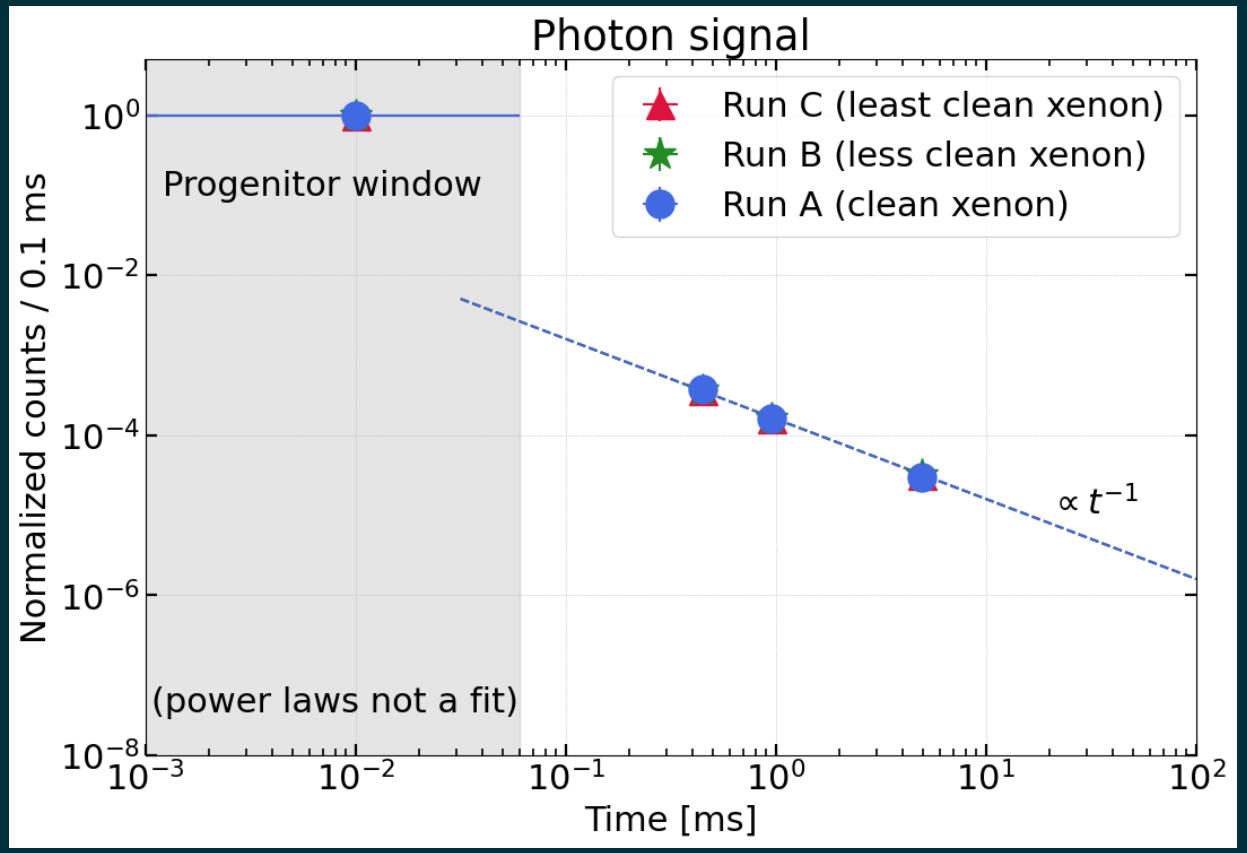
Impurities in xenon bulk

Impurities increase delayed electrons

Seen in prior work e.g., arXiv:1711.07025

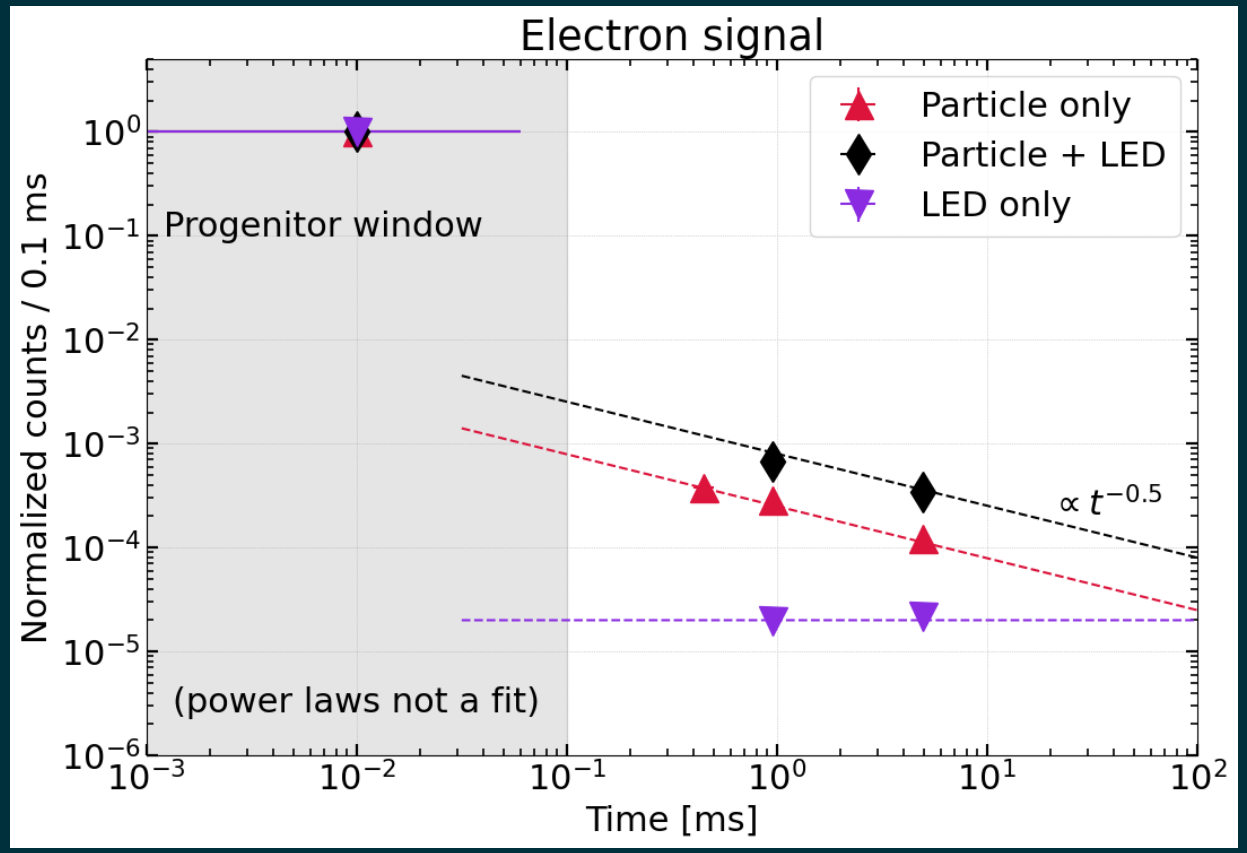


Impurities do no affect delayed photons

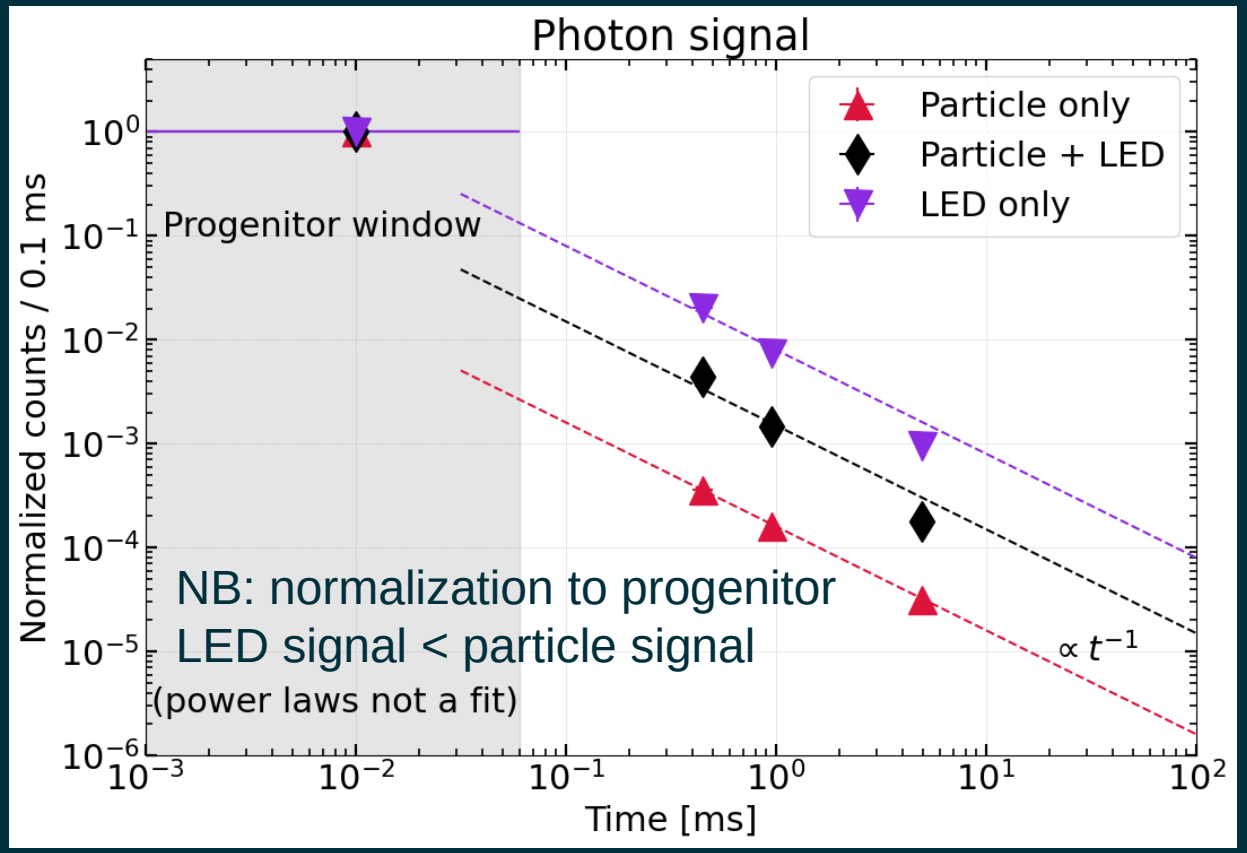


Adding 235 nm LED, 2 µs flash after S2

LED flash increases delayed electrons,
given a particle scatter happened



LED flash induces delayed photons
(from fluorescence of LED itself)

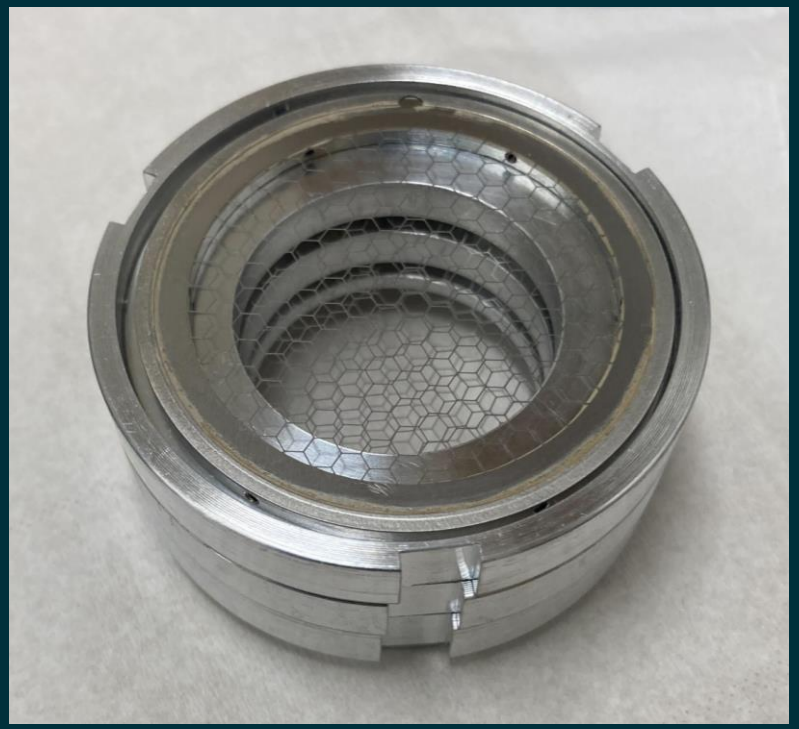


Delayed photons cause delayed electrons

…but what causes delayed photons?

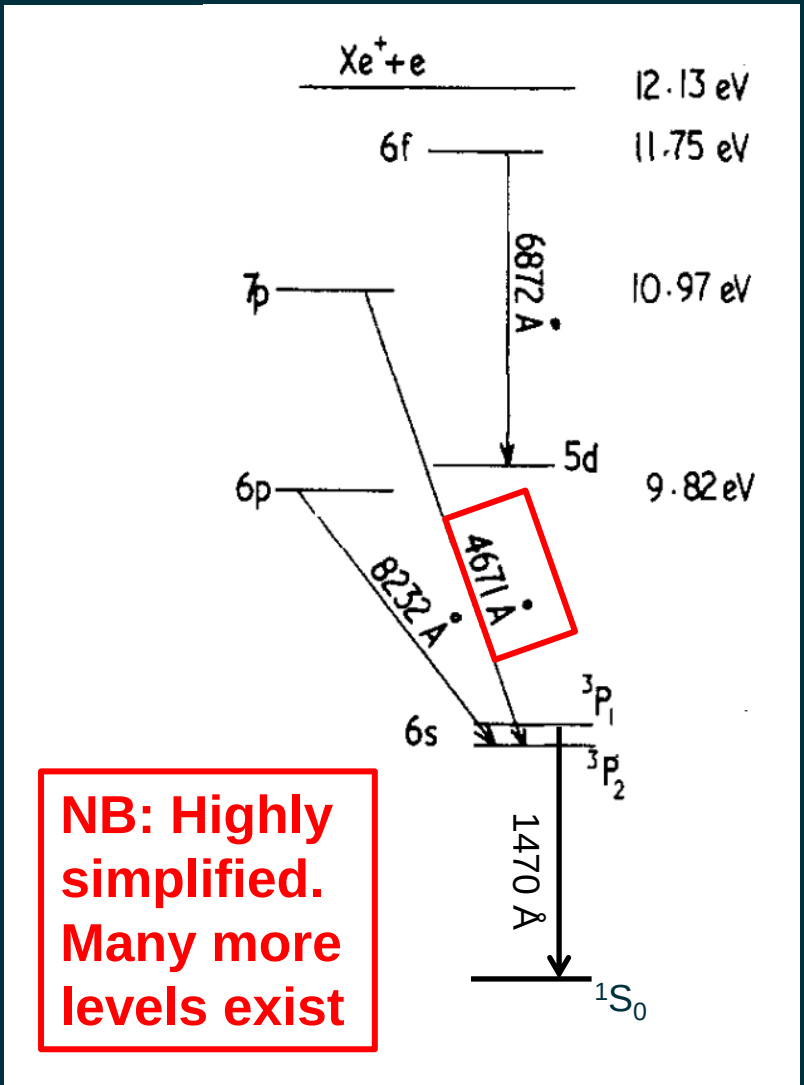
What’s causing delayed photons?

- **Atomic Xe fluorescence/phosphorescence!**
  - Deexcitation of metastable (atomic) Xe
- Based on systematic removal of detector materials
  - Swapped PTFE for Al, delayed photons persist
  - Not from stainless steel electrodes
- Dependency on liquid/gas phase and progenitor



Aluminum TPC frame for 0 V field studies

“Afterglow” well known in plasma/AMO/chemical/applied physics



“Neutral active particles [of xenon] … origin of light emission observed in the afterglow”

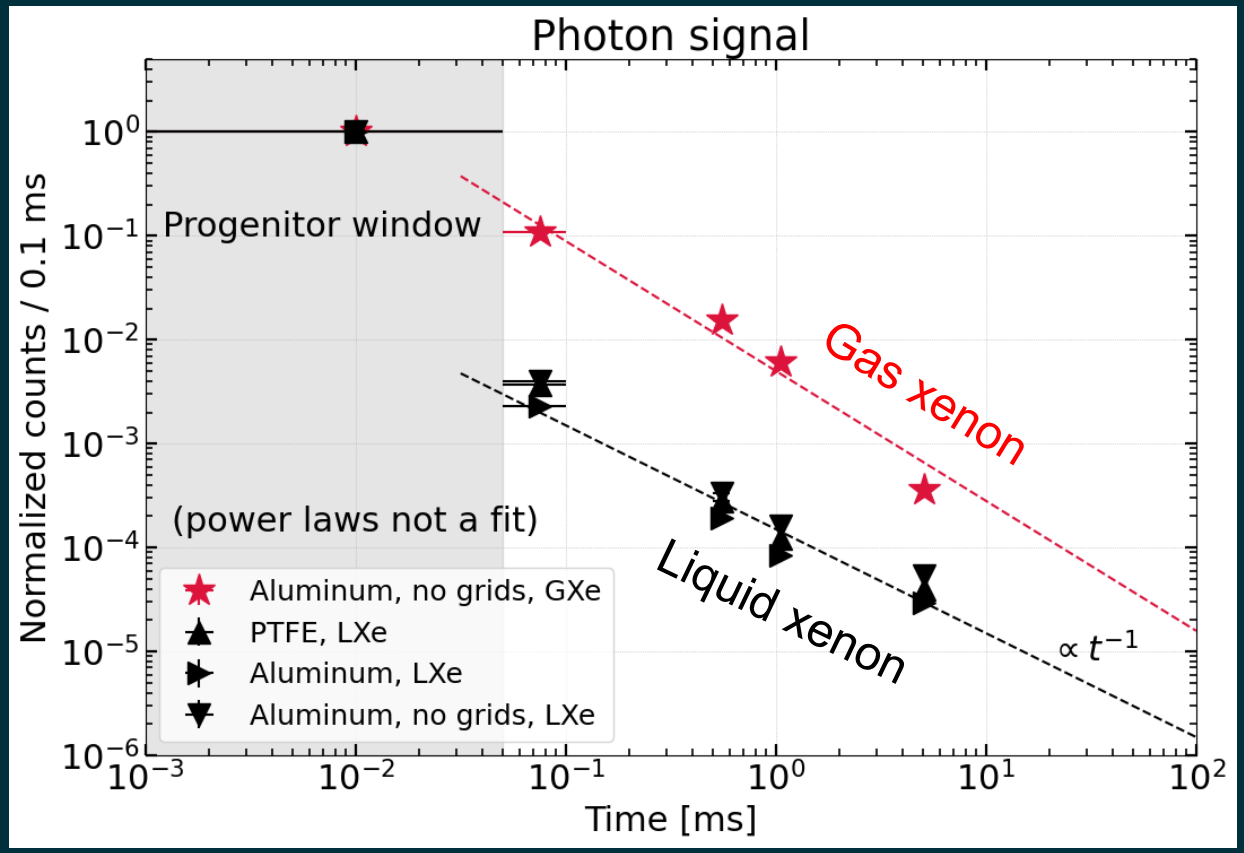
- Pejović, et al., J. Plasma Physics (2013) **79,** part 5, pp. 641–646

Level diagram from A. Barbet, et al, J. Phys. B: Atom. Mol. Phys. 8 1785, 1975

Delayed photons with scintillation-only data

- LXe scintillation (S1) produces same normalized rate of delayed photons as gas electroluminescence (S2)
  - Proportional electroluminescence is *not an ionization process* (only neutral Xe excimers)
- ~x50 more delayed photons in GXe scintillation vs LXe
- Added PMT, lower DPE effect
  - Not all VUV!

Using Rn alphas as progenitor



It appears xenon itself causes delayed photons. Can we stop it?

- Dope xenon with photon absorber such as CO_2 or CH_4?
  - May also help to deexcite the xenon in the first place
  - Need to balance with single electron sensitivity
- Design around it!
  - Block S2 gas signal from entering liquid bulk e.g., opaque electrode/GEM
  - Directly measure charge e.g., G3PIX
- **Currently working to demonstrate both doping and opaque electrode**

Implications for G3 liquid xenon dark matter experiment

- **This problem will persist and worsen for larger detector**
  - Scales with total rate of scatters
- Increased delayed emission will increase accidentals
  - May need to increase S1 PMT coincidence requirement
- **R&D needed: spectrometric photon detection to assist in mitigation**

Summary

- Dual-phase xenon TPCs have sensitivity to sub-GeV dark matter
  - Currently hindered by delayed electron emission
- Delayed photons cause delayed electrons
  - Given impurities in the bulk xenon
- Delayed photons originate from metastable excited xenon states

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Backup

Xenon dimer VUV emission (known knowns)

photon is produced by two mechanisms. One is the direct excitation of Xe atoms that then forms an excited dimer Xe_2^*,

$$Xe^* + Xe + Xe \rightarrow Xe_2^* + Xe,$$
$$Xe_2^* \rightarrow 2Xe + h\nu\ .$$

Scintillation and proportional electroluminescence

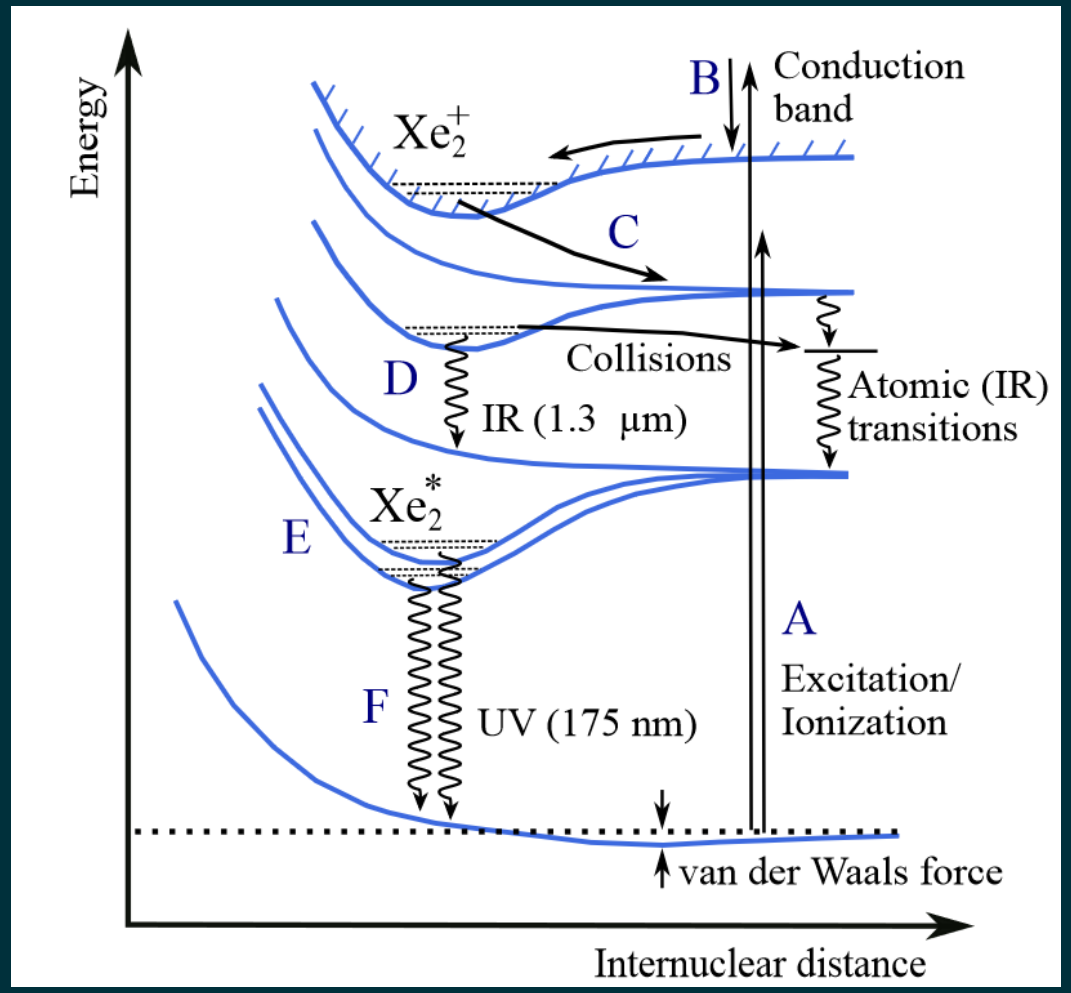
The other process involves the recombination process between electrons and Xe ions

$$Xe^+ + Xe \rightarrow Xe_2^+,$$
$$Xe_2^+ + e^- \rightarrow Xe^{**} + Xe,$$
$$Xe^{**} \rightarrow Xe^* + heat,$$
$$Xe^* + Xe + Xe \rightarrow Xe_2^* + Xe,$$
$$Xe_2^* \rightarrow 2Xe + h\nu\ .$$

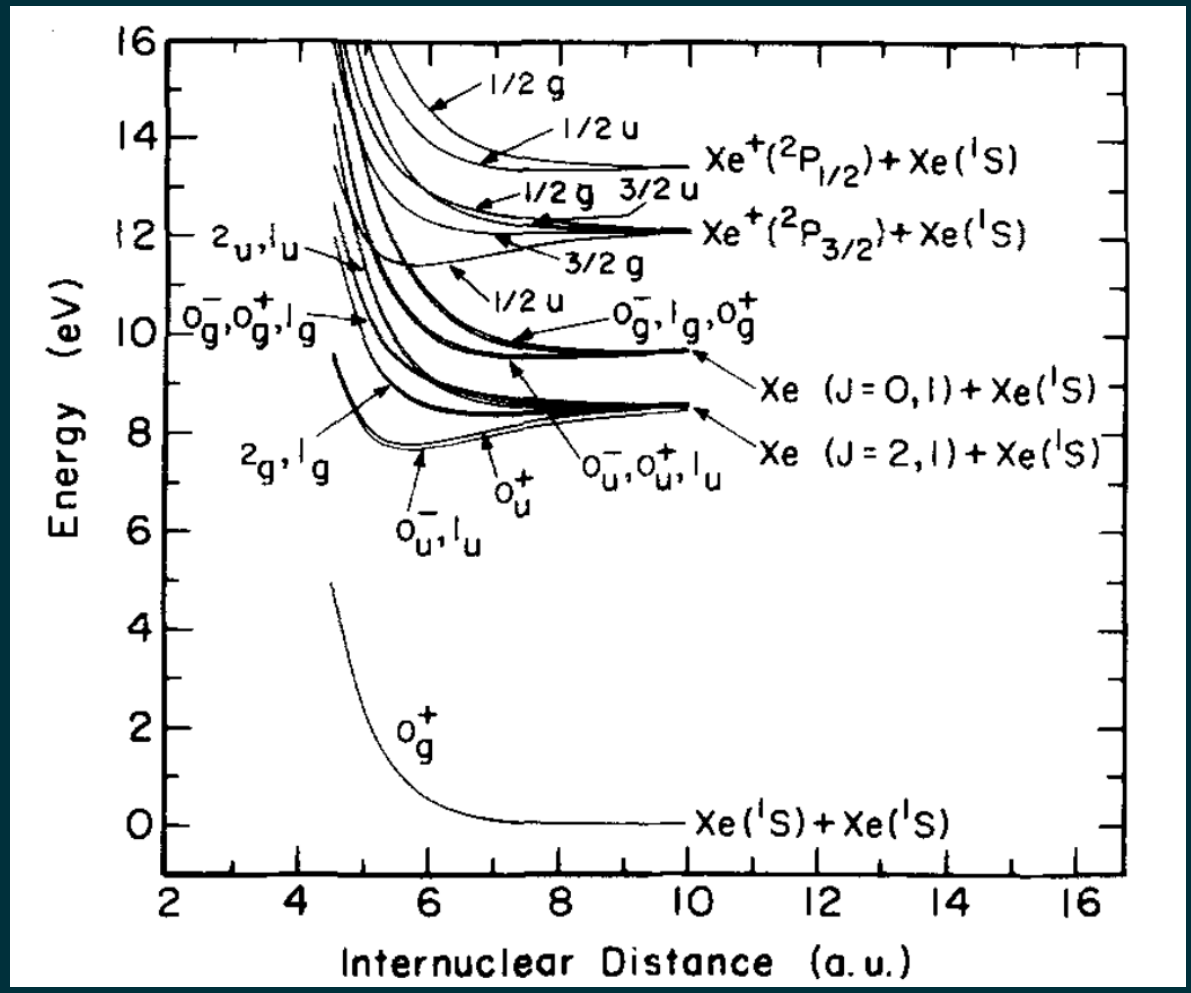
Scintillation

K. Abe, et al. (XMASS), JINST **13** (2018) P12032, arXiv:1809.05988

M. Piotter, et al., Eur. Phys. J. C **83**, 482 (2023)
arXiv:2303.09344



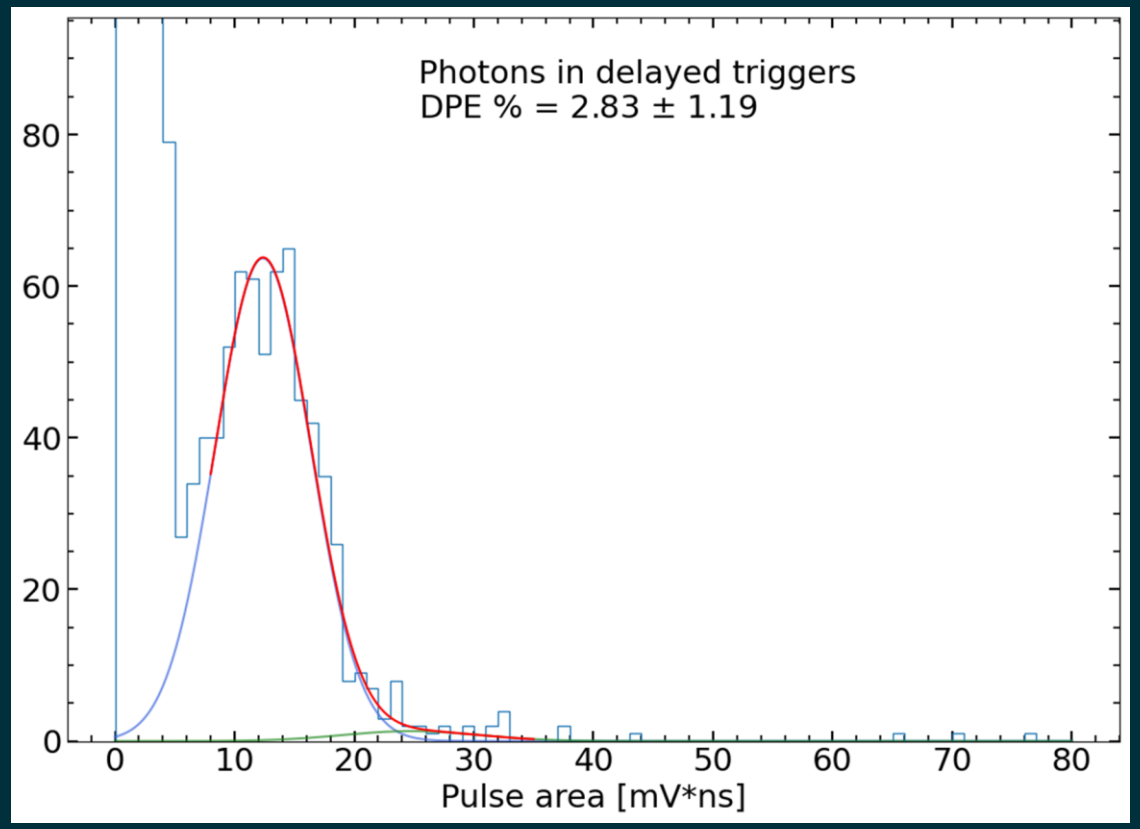
Ermler, et al., J. Chem. Phys. **69**, 976–983 (1978)



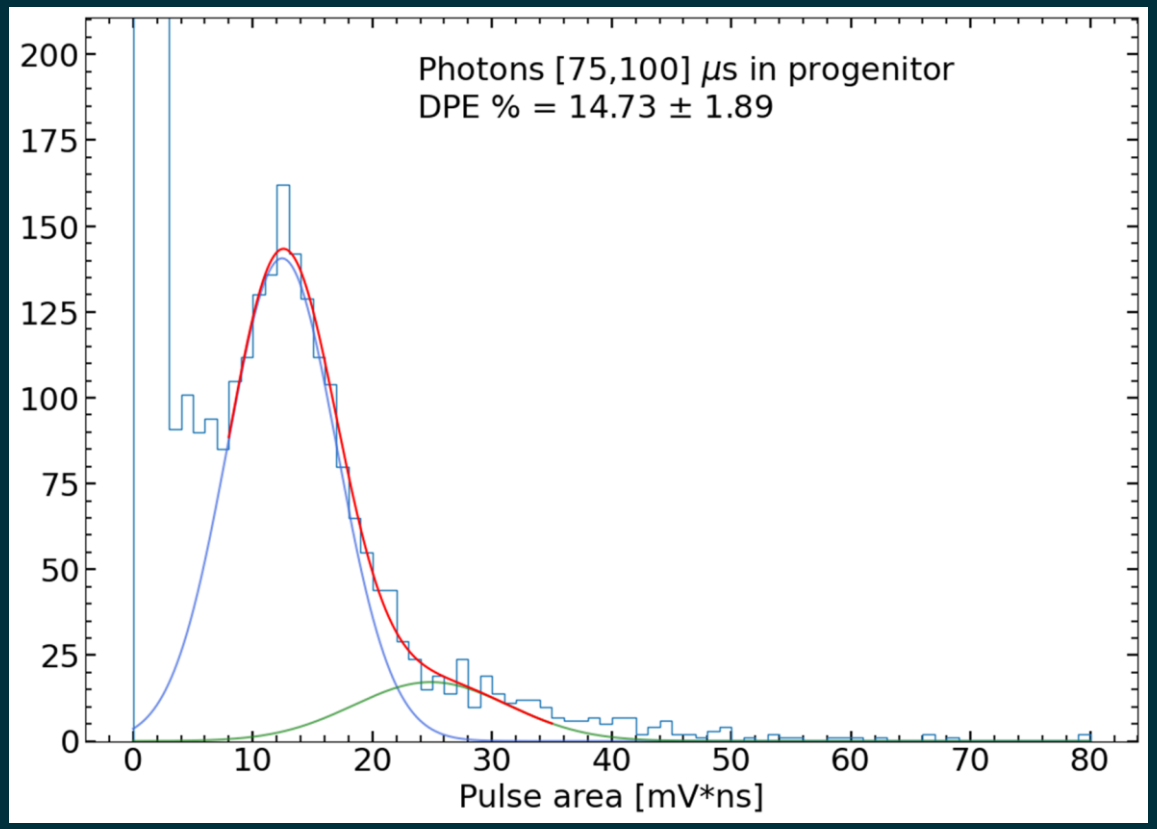
Refined measurements coming soon

Hot off the press: DPE in PMT Data

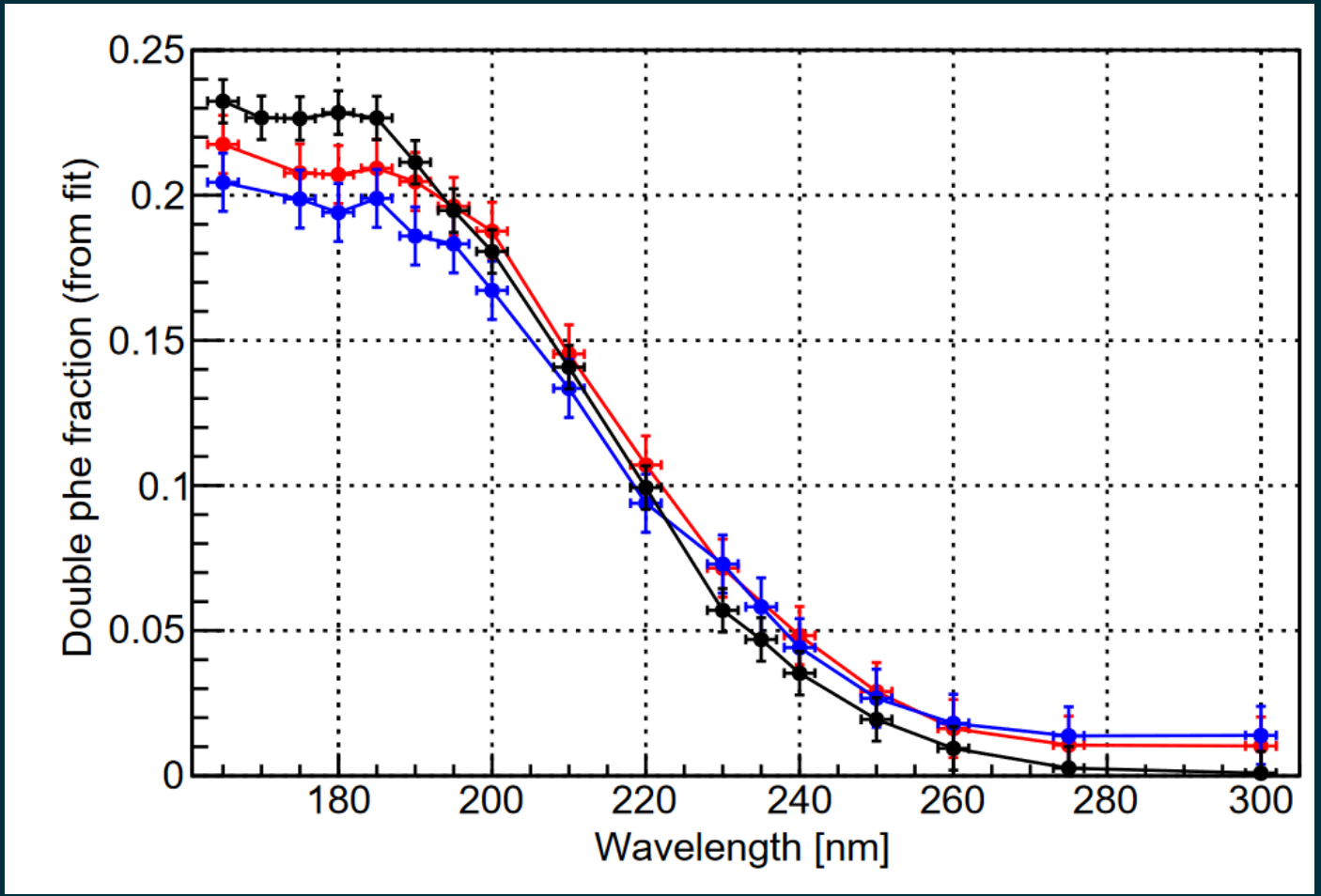
No DPE > 500 us after progenitor



But some at shorter delayed times!



DPE in PMT measurement



C.H. Faham, et al.
JINST **10** (2015) P09010
arXiv:1506.08748