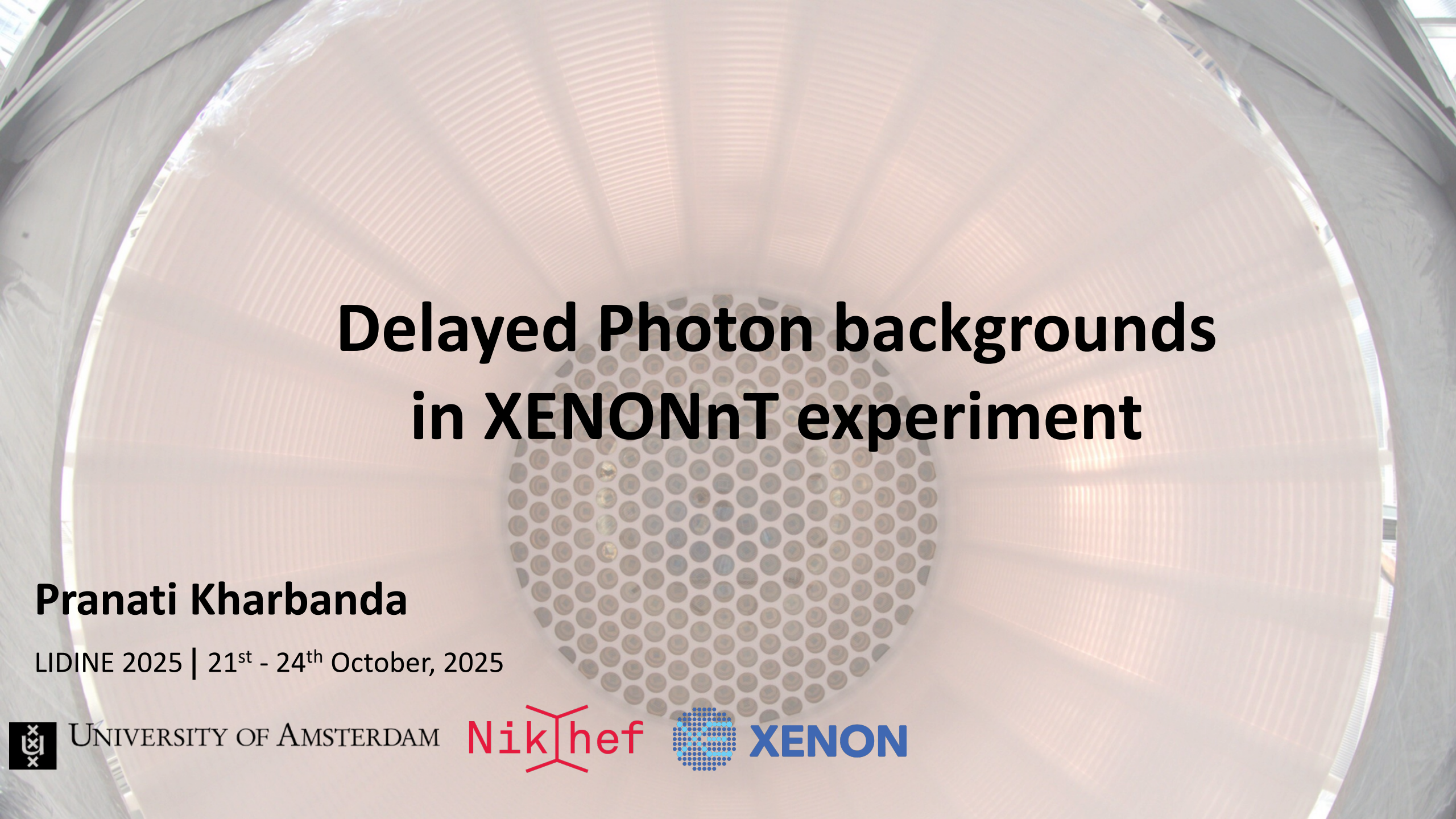


Delayed Photon backgrounds in XENONnT experiment

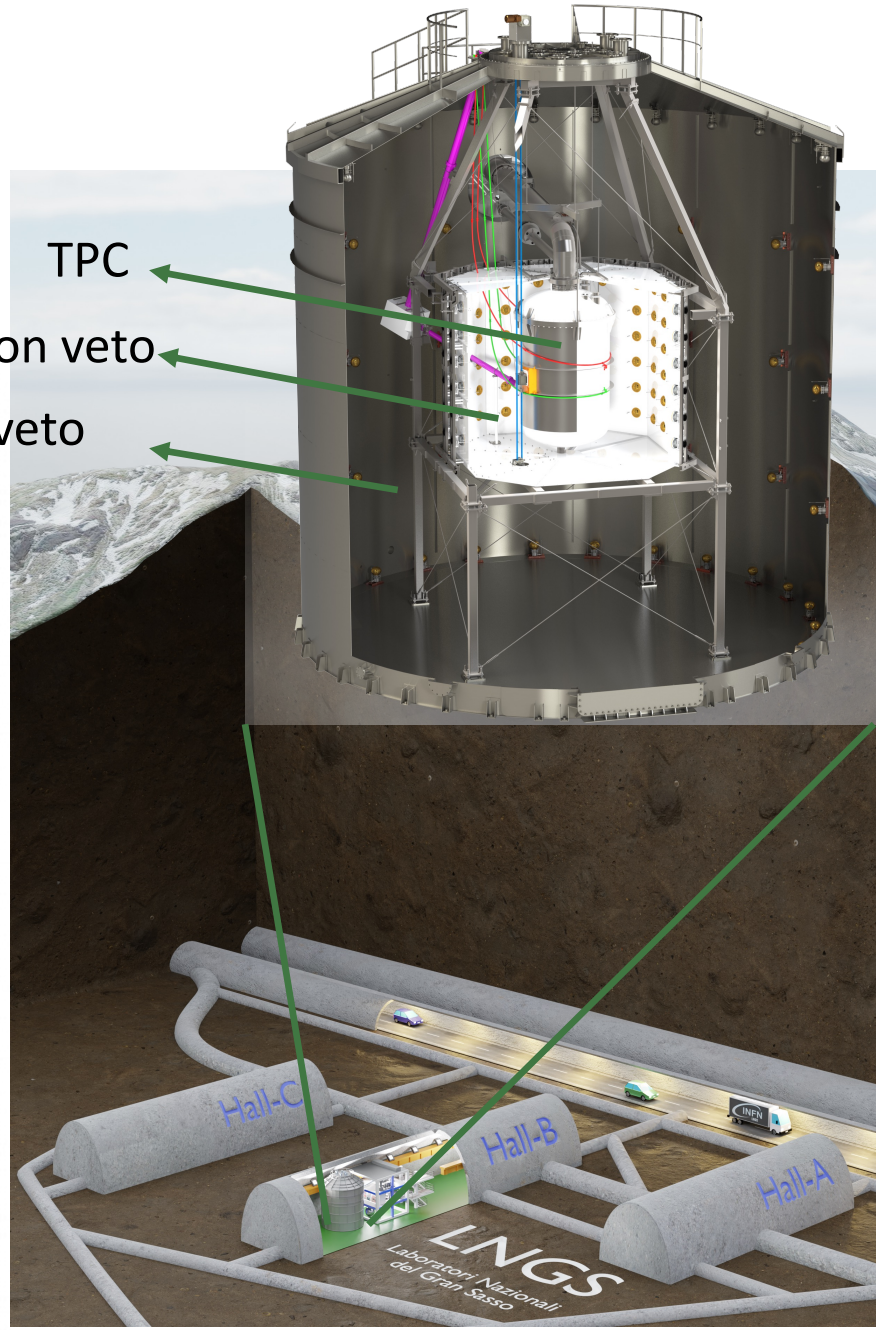
Pranati Kharbanda

LIDINE 2025 | 21st - 24th October, 2025

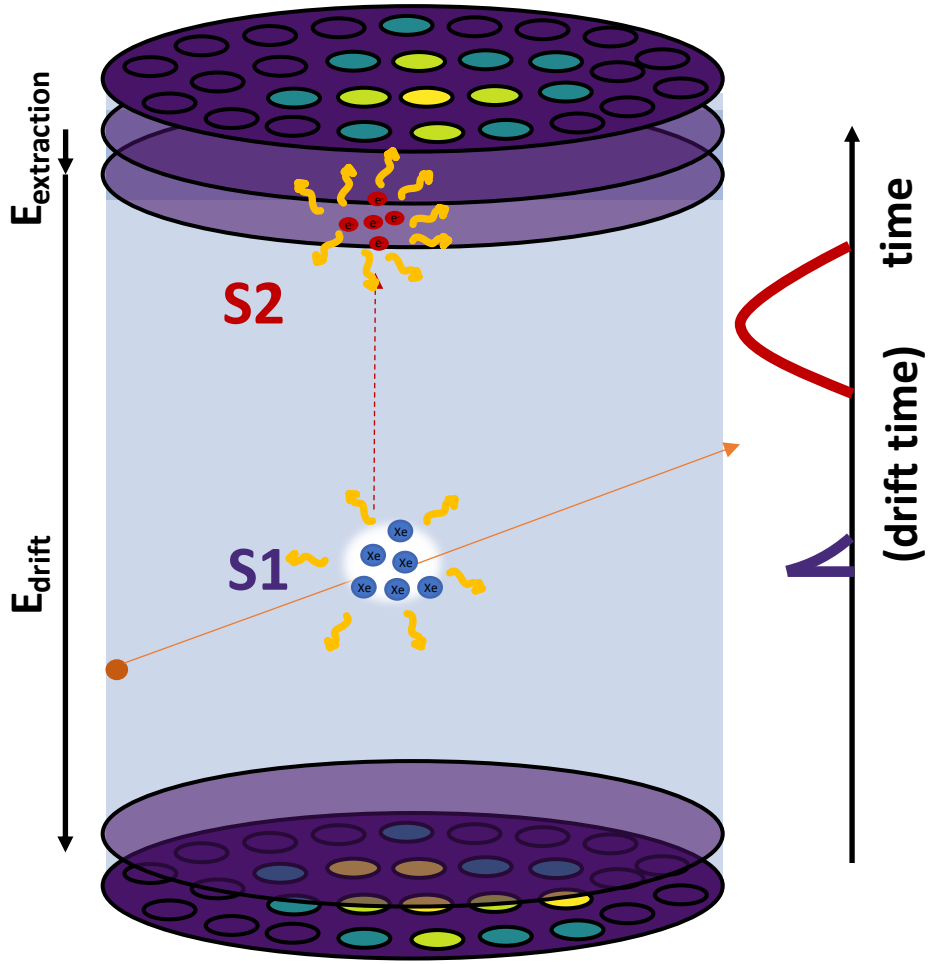
University of Amsterdam Nikhef XENON

XENONnT experiment

- 200+ members
- 30 institutes
- 12 countries



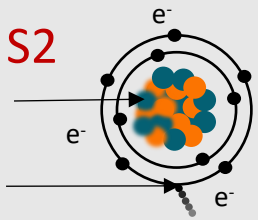
Xenon detector



Dual phase Time Projection Chamber

Main goal: Direct detection of **WIMP dark matter**

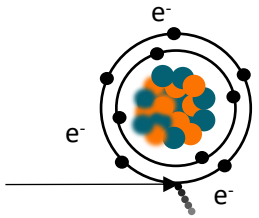
- **S1** prompt scintillation
- **S2** proportional scintillation signal
  - Up to 2.2 ms post S1
- 3D position reconstruction
  - Time difference between S1 and S2
  - PMT hit pattern gives x,y
- Signal discrimination via S2/S1 ratio



Backgrounds for physics searches

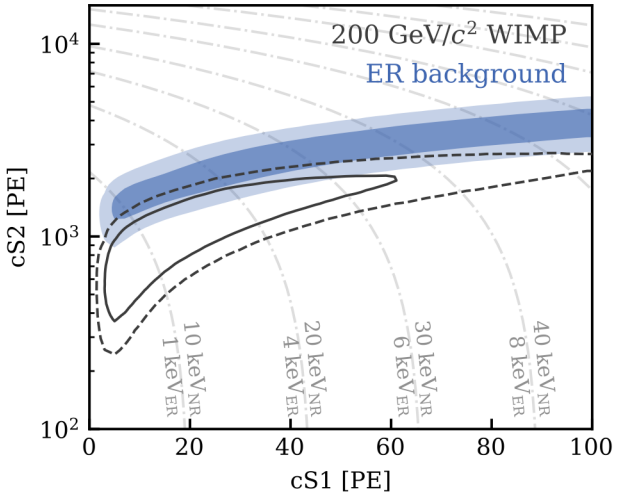
Electronic Recoil (ER)

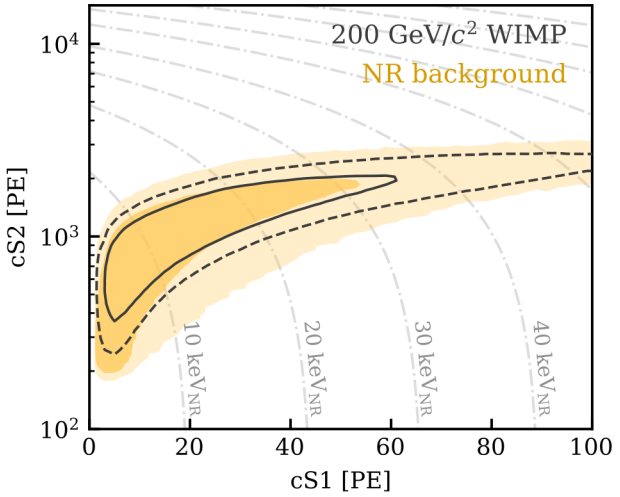
- Dominated by β-decay from ^{214}Pb (^{220}Rn chain)

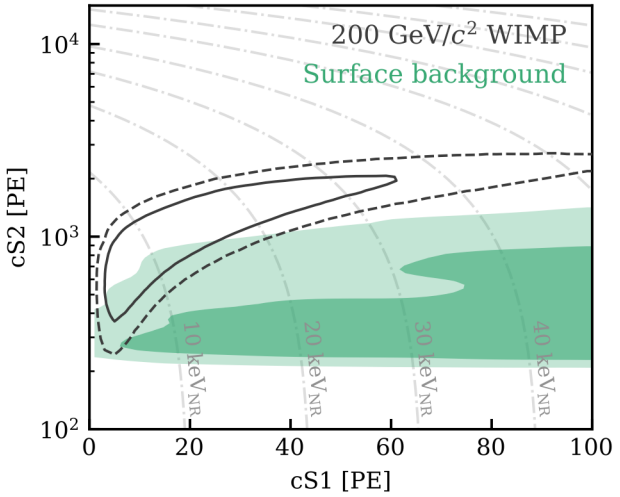


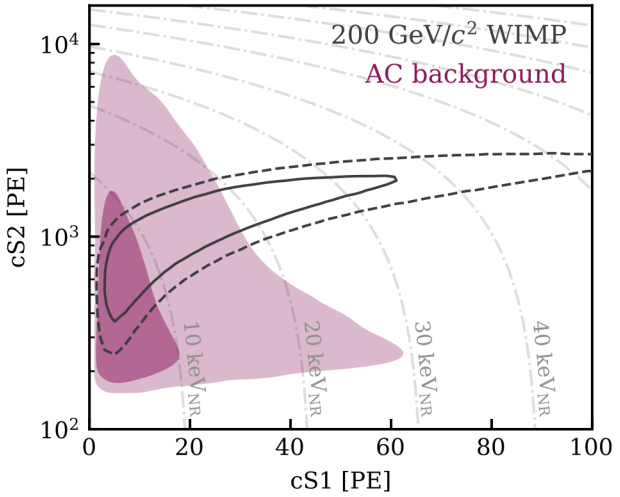
Surface

- ^{210}Pb decays from PTFE wall



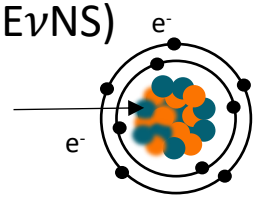






Nuclear Recoil (NR)

- Radiogenic neutrons
- Neutrinos (CEνNS)



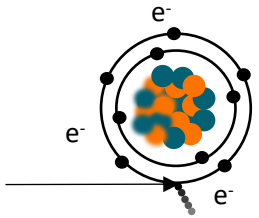
Accidental Coincidences (AC)

- Random pairing of lone S1 and lone S2

Backgrounds for physics searches

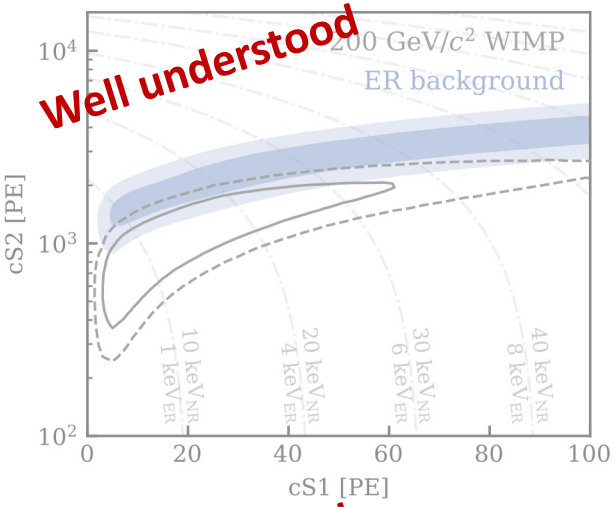
Electronic Recoil (ER)

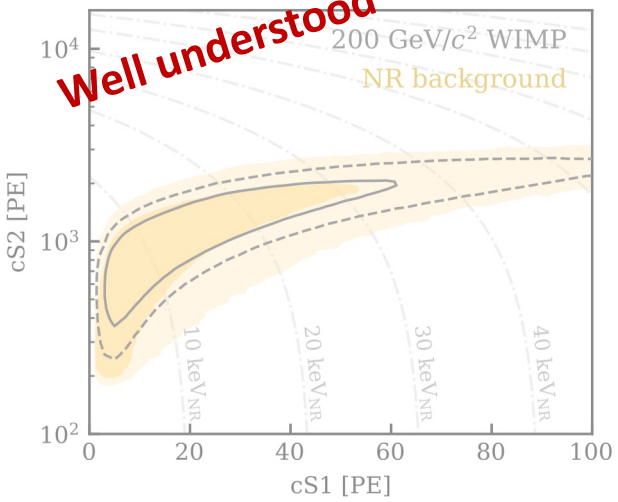
- Dominated by β-decay from ^{214}Pb (^{220}Rn chain)

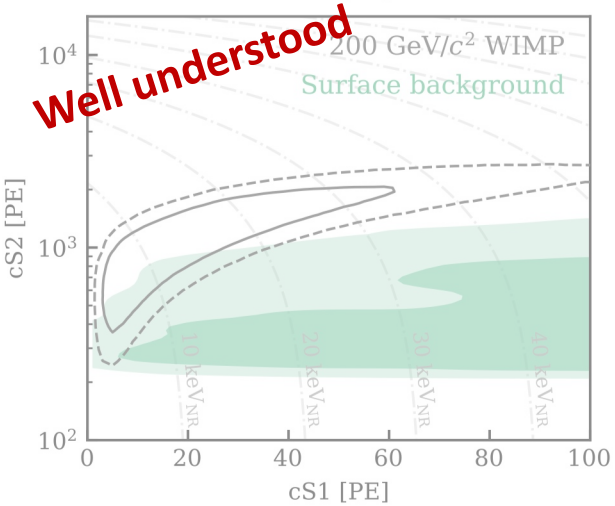


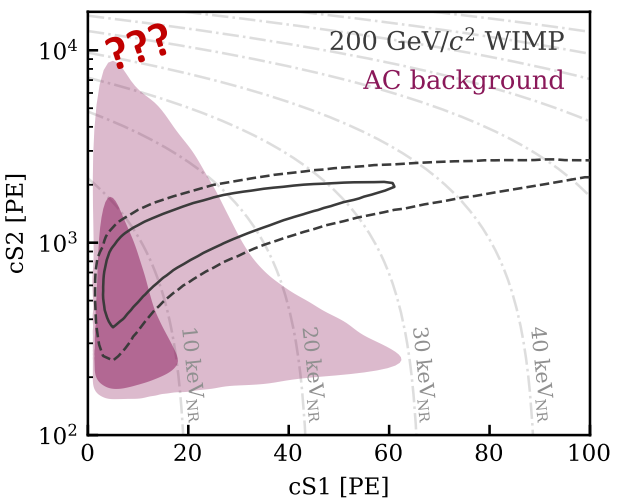
Surface

- ^{210}Pb decays from PTFE wall



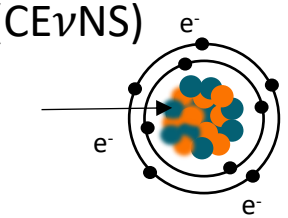






Nuclear Recoil (NR)

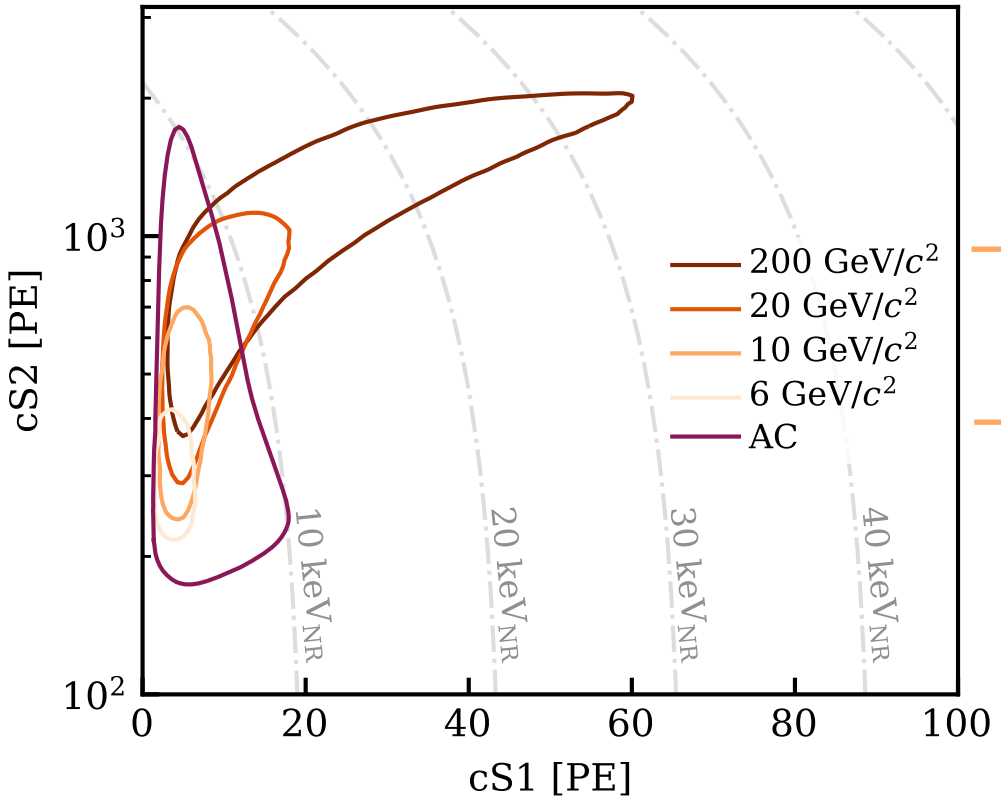
- Radiogenic neutrons
- Neutrinos (CEνNS)

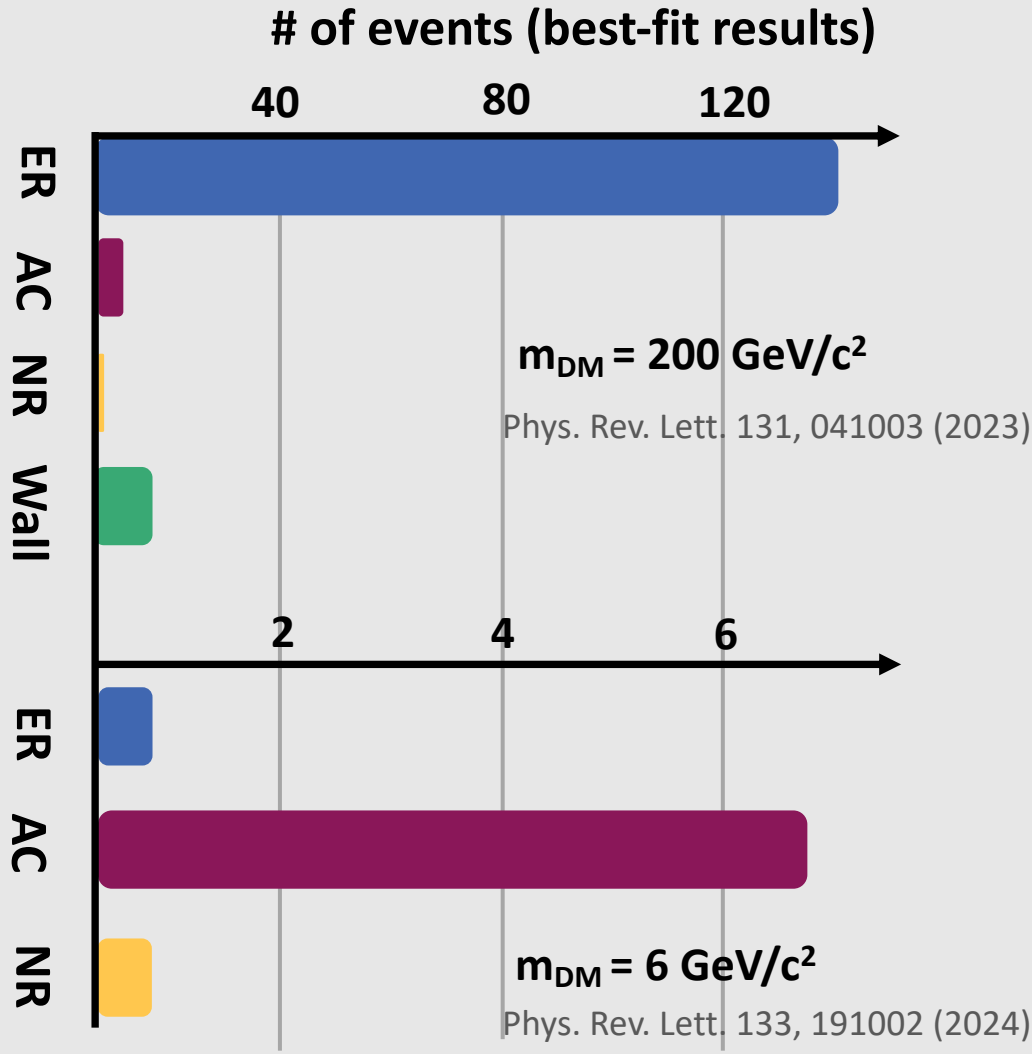


Accidental Coincidences (AC)

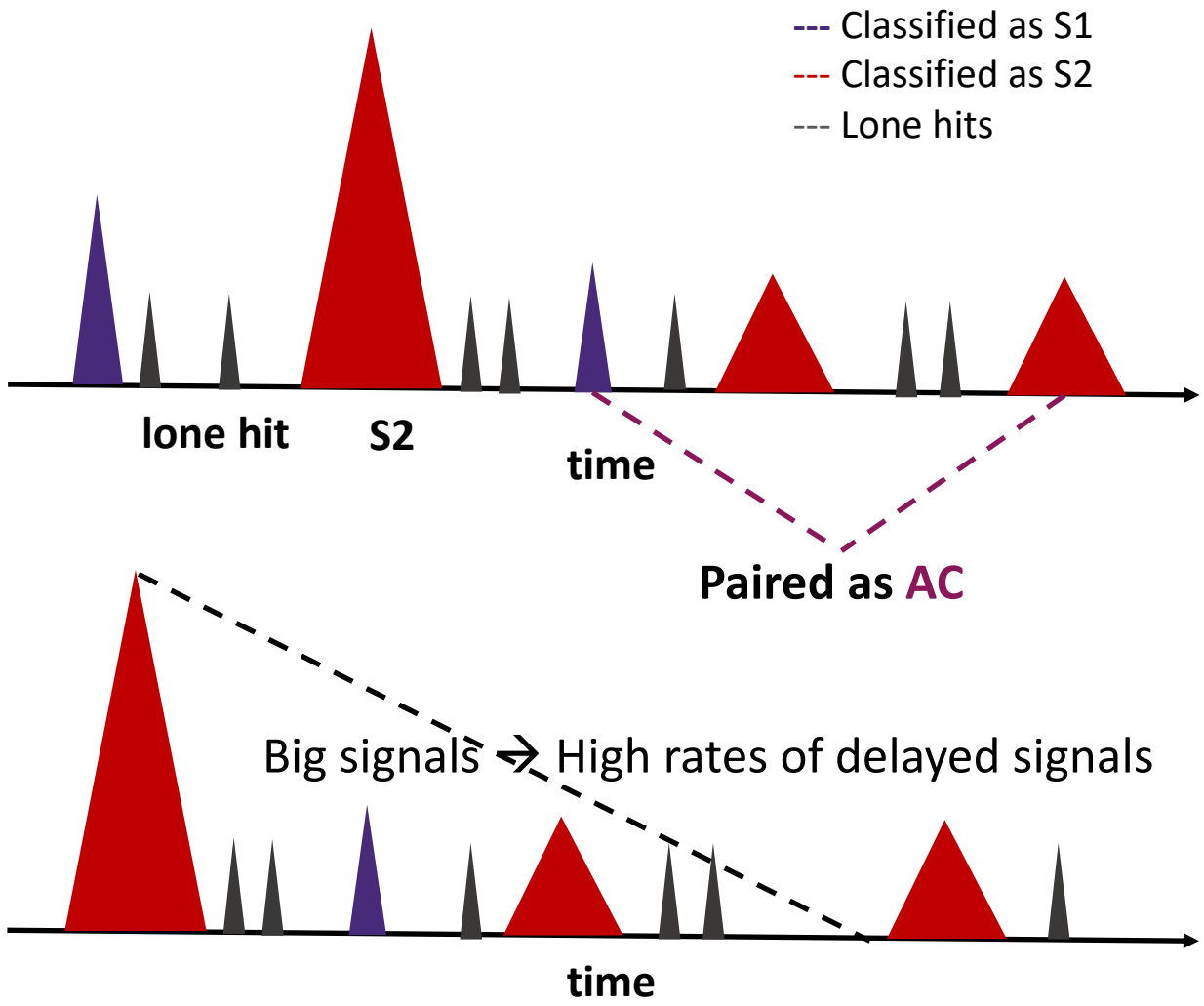
- Random pairing of lone S1 and lone S2

AC: Dominant background for low mass searches





ACs and how they are mitigated

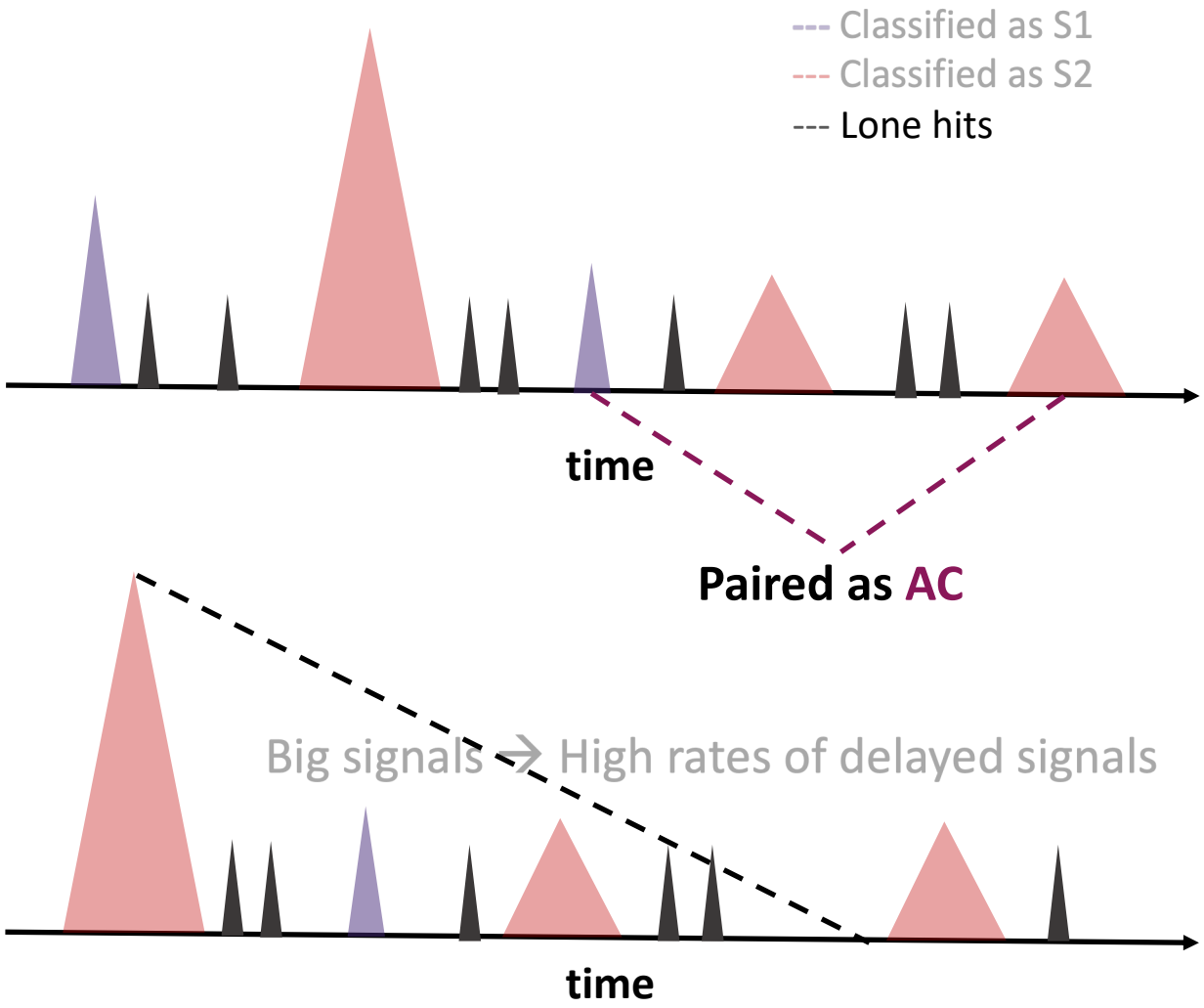


- Random pairing of lone S1 and lone S2

- Lone S1s:
  - Origin: **lone hit pile-ups**, signal misclassification,..
  - Rate = 15 Hz
- Lone S2s:
  - Origin: delayed electrons, electron emissions,..
  - Rate = 150 mHz

- Suppression: **Data driven**
  - Based on width and drift time
  - Spatial and temporal correlation with high energy signals

Focusing on lone hits



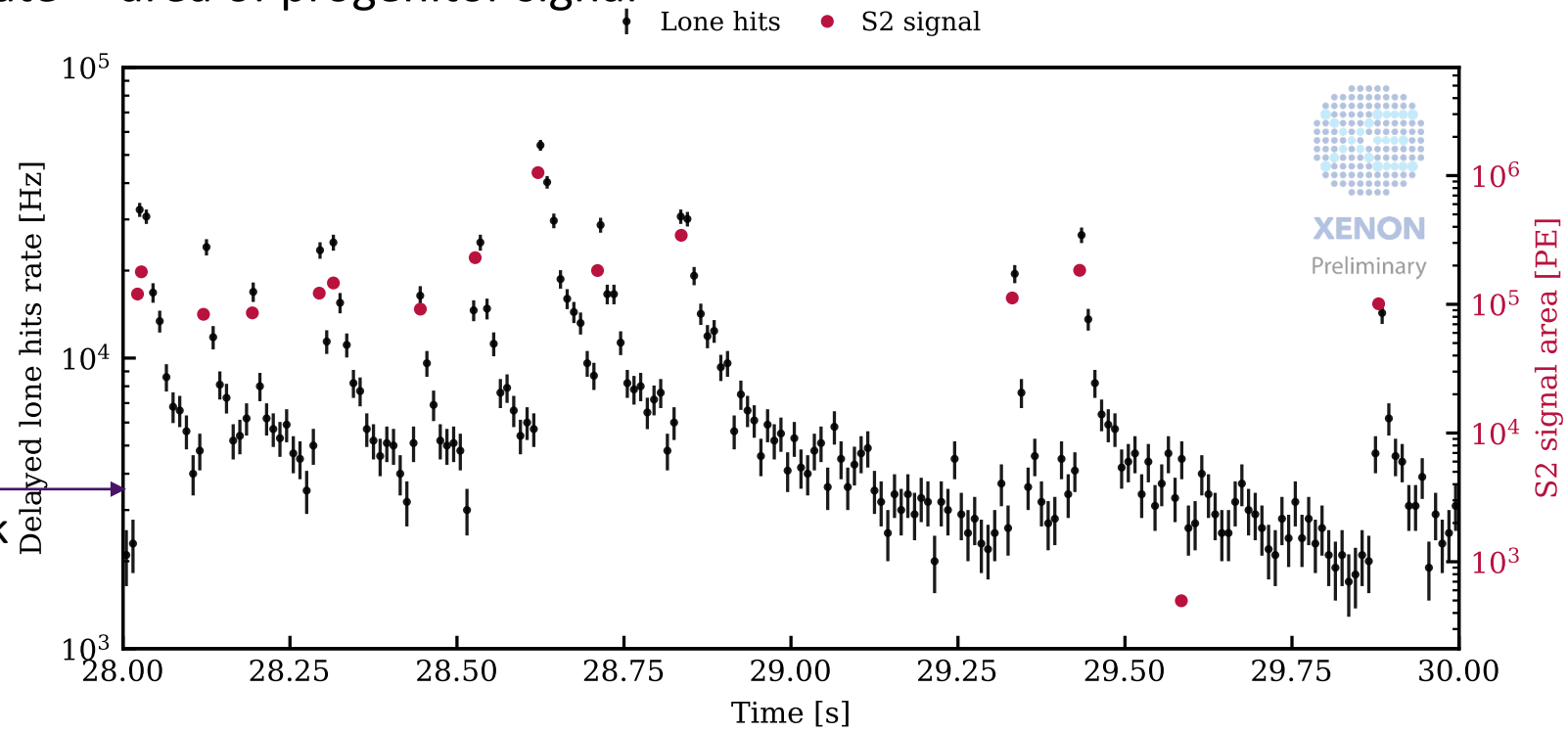
- Random pairing of lone S1 and lone S2

- **Lone S1s:** 1-3 PE hits in PMTs
  - Origin: **lone hit** pile-ups, signal misclassification,..
  - Rate = 15 Hz
- Lone S2s:
  - Origin: delayed electrons, electron emissions,..
  - Rate = 150 mHz

- Suppression: **Data driven**
  - Based on width and drift time
  - Spatial and temporal correlation with high energy signals

Focusing on lone hits

- 2- and 3-fold lone S1 rate dominated by lone hit pileups
- Lone hits rate ∝ area of progenitor signal



Upper limit on total dark counts from all PMTs

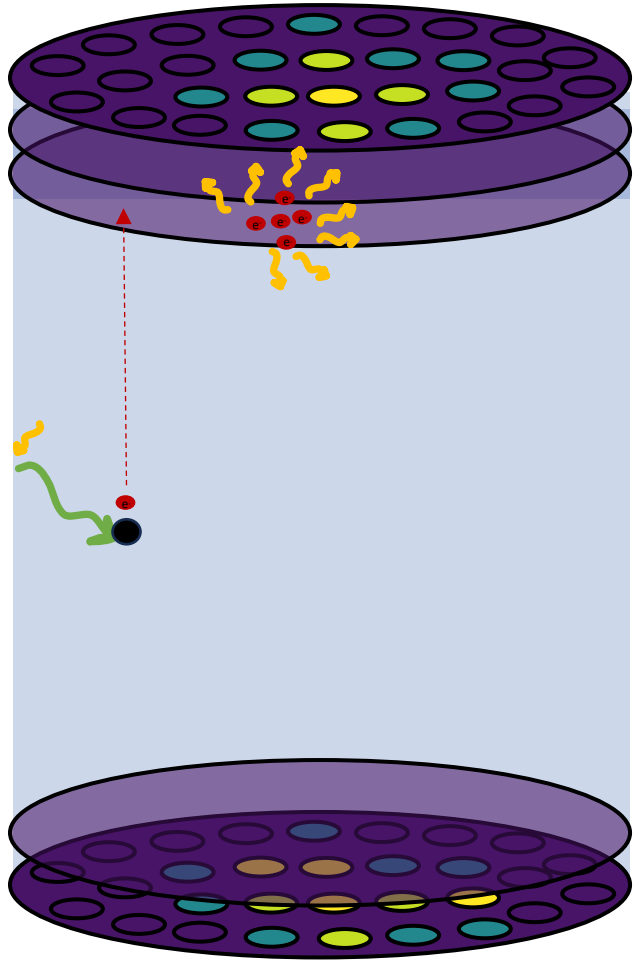
JINST 12 P01024 (2017)

Delayed hits following progenitor S2 in 2 s sample window

What causes these lone hits?

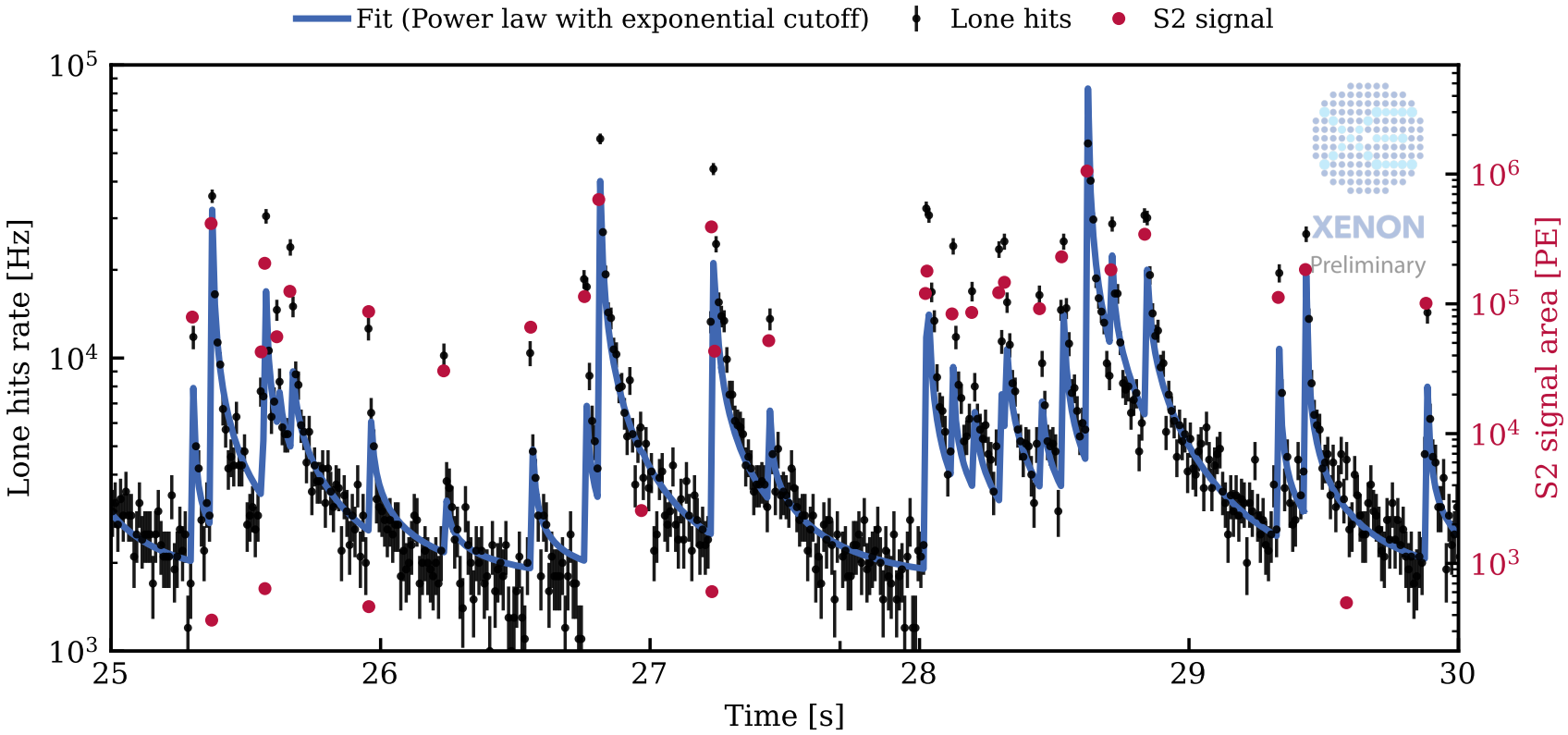
- PMT dark counts
  - < 50 Hz/PMT → Rate too small to be dominant
- PMT afterpulses
  - Characterised, small-time scales
- Photoluminescence of detector materials?
  - Quartz window of PMTs (Phys. Rev. D 112, 052004 (2025))
  - Contaminations in PTFE?
  - …?

- They can also cause delayed electrons!



Time profile of delayed hits

$$R = r_{dc} + \Sigma_{S2}\, \alpha\, A_{S2} \left(\frac{t - t_{S2}}{0.0022\ s}\right)^{k} e^{-\frac{(t - tS_{2\_00}22)}{\tau}}$$

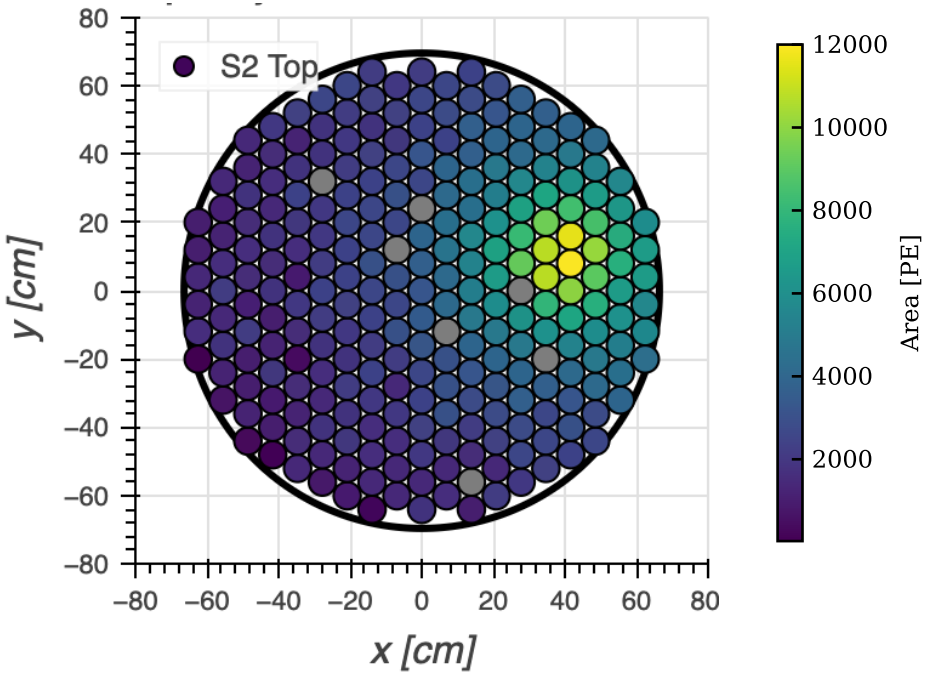


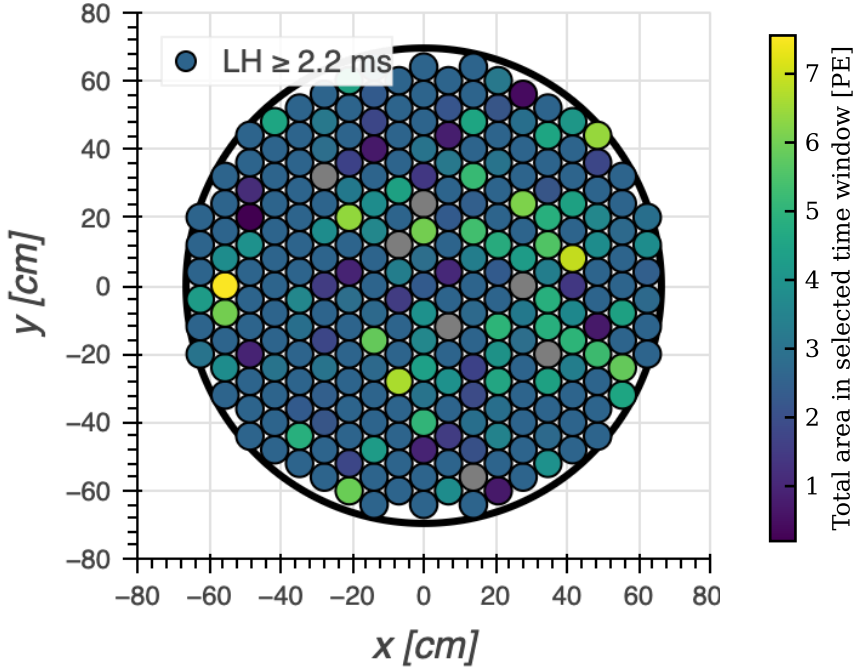
Parameter	Value
r_{dc}	1.8 kHz
α	0.065 PE/Hz
k	-0.65
τ	0.28 s

- Fit late lone hits (> 2.2 ms post S2) over 150 s window
- Resembles Voltz Laustriat model: model of scintillation of aromatic organic compounds

Investigating the hits top PMT pattern

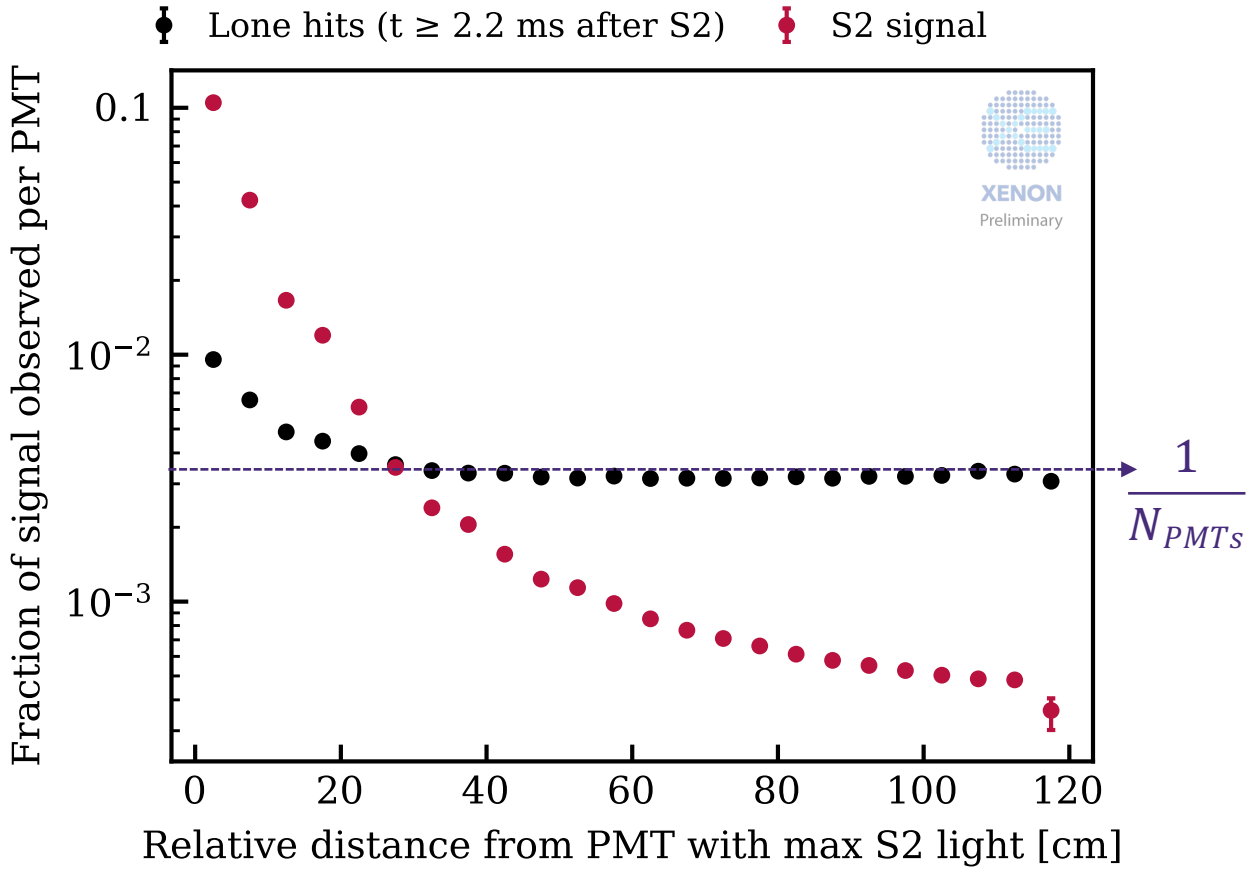
- Photoluminescence of detector materials?
  - **Quartz window of PMTs → does the delayed hits follow the S2 pattern exactly?**
  - Contaminations in PTFE?
  - …?





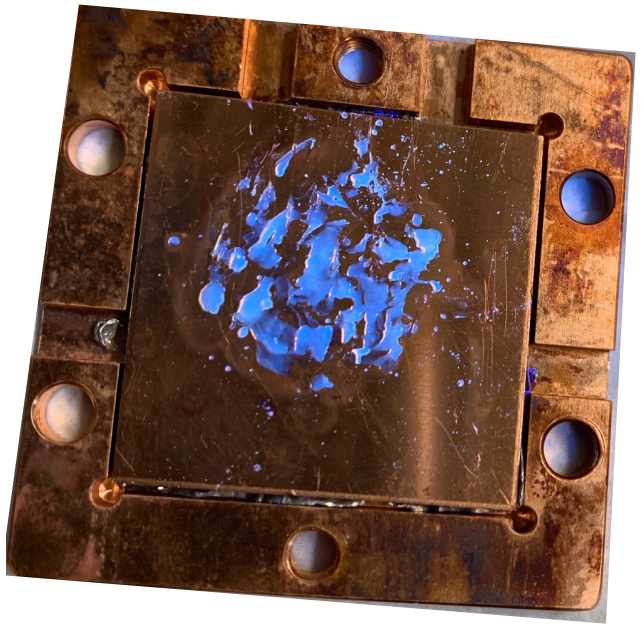
Comparison of lone hits vs S2 top PMT pattern

- Lone hits considered that occur after 2.2 ms and up to 0.2s after an S2, for S2s that come at least 0.2s after the previous event
- Spatial distribution of photons in an S2 signal peaks steeply toward the PMT with most light while only a small fraction of lone hits have spatial correlation to their preceding S2
- ~7 brightest PMTs receive 40 % of the light of an S2 receive only 6% of the lone hits

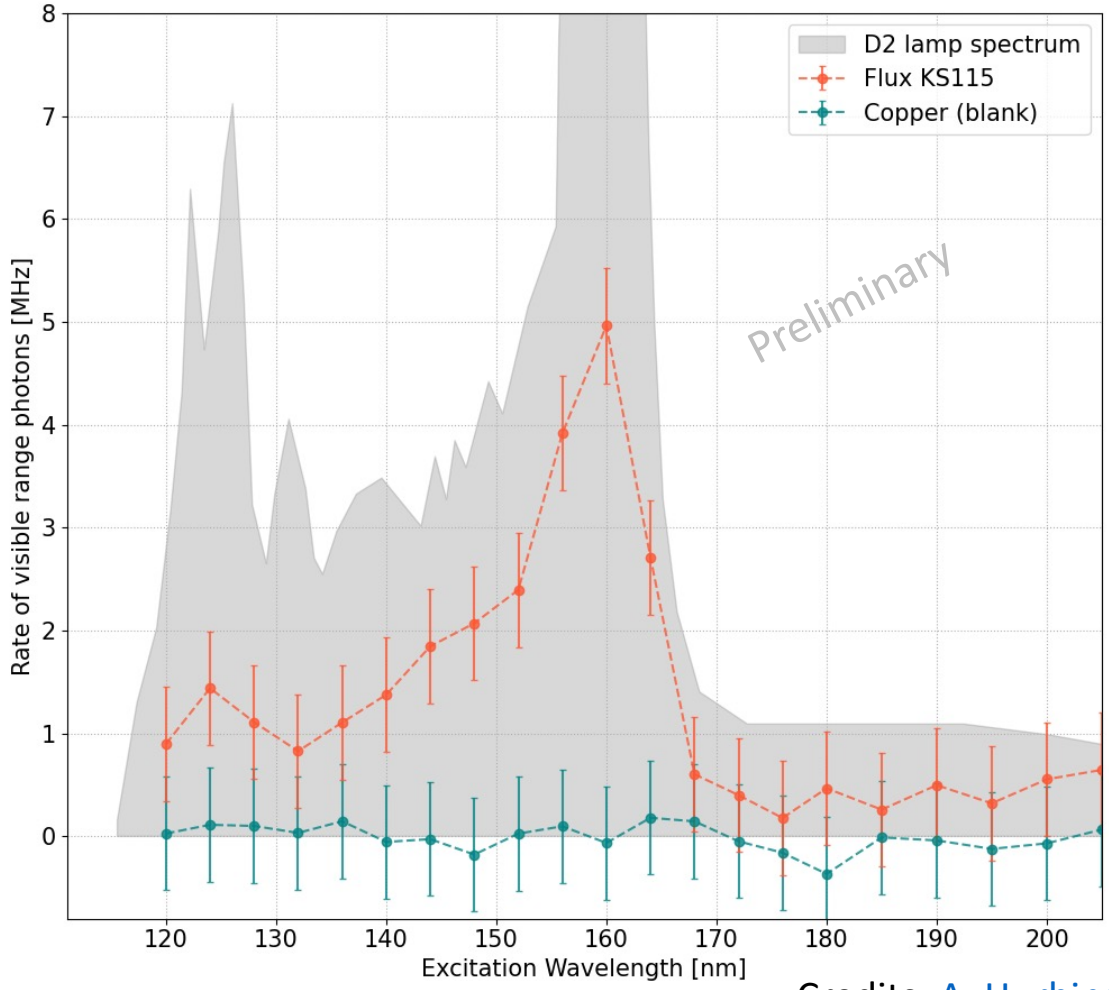


Sensitive measurements of PL yield and decay times of detector materials at Nikhef

- Alternate material that could photoluminesce: **solder flux**
- Ongoing studies to characterise PL yields and time constants of solder flux, PTFE, ….



solder flux under 365 nm light



Credits: A. Hurhina

Summary

- Accidental Coincidences (random pairing of lone S1 and lone S2 signals) are the dominant background for low mass DM searches
- Origin of delayed lone hits is not well understood
- Timing structure and PMT pattern suggest that quartz window photoluminescence is not the sole mechanism of observed delayed photon(-like) signals
- Ex-situ measurements of the PL response of detector materials ongoing @Nikhef

Backup

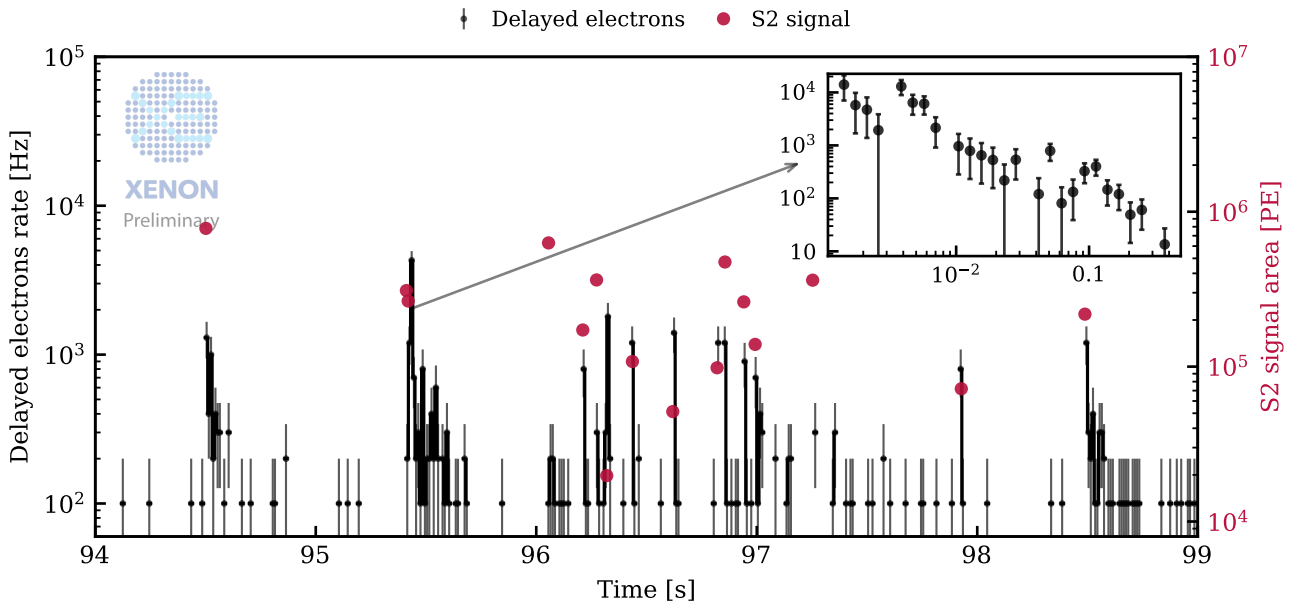
Voltz Laustriat model

$$R = r_{dc} + \Sigma_{S2}\ \alpha\ A_{S2}\ \frac{e^{\frac{-2(t-ts_2)}{\tau_T}}}{1+B\left\{Ei\left(-\frac{t-tS_2\ ta}{\tau_T}+\right)-Ei\left(-\frac{t_a}{\tau_T}\right)\right\}^2\left(1+\frac{t-tS_2}{t_a}\right)}$$

Model	r_{dc} (kHz)	τ (s)	χ_r^2
Exponential	1.7	0.05	11.94
Power	0.013	-	9.72
Power with exp cutoff	1.8	0.28	6.27
Voltz – Laustriat*	1.3	0.04, 26.81	7.97

- Model of scintillation of aromatic organic compounds
- Singlet and triplet states
- Triplet states can be destroyed through triplet-triplet annihilation with timescales related to the diffusion of these dense pockets of ionized species
- After reaching t ≈ τT , the exponential term begins to dominate, cutting off the power-law

Looking closely at delayed electrons



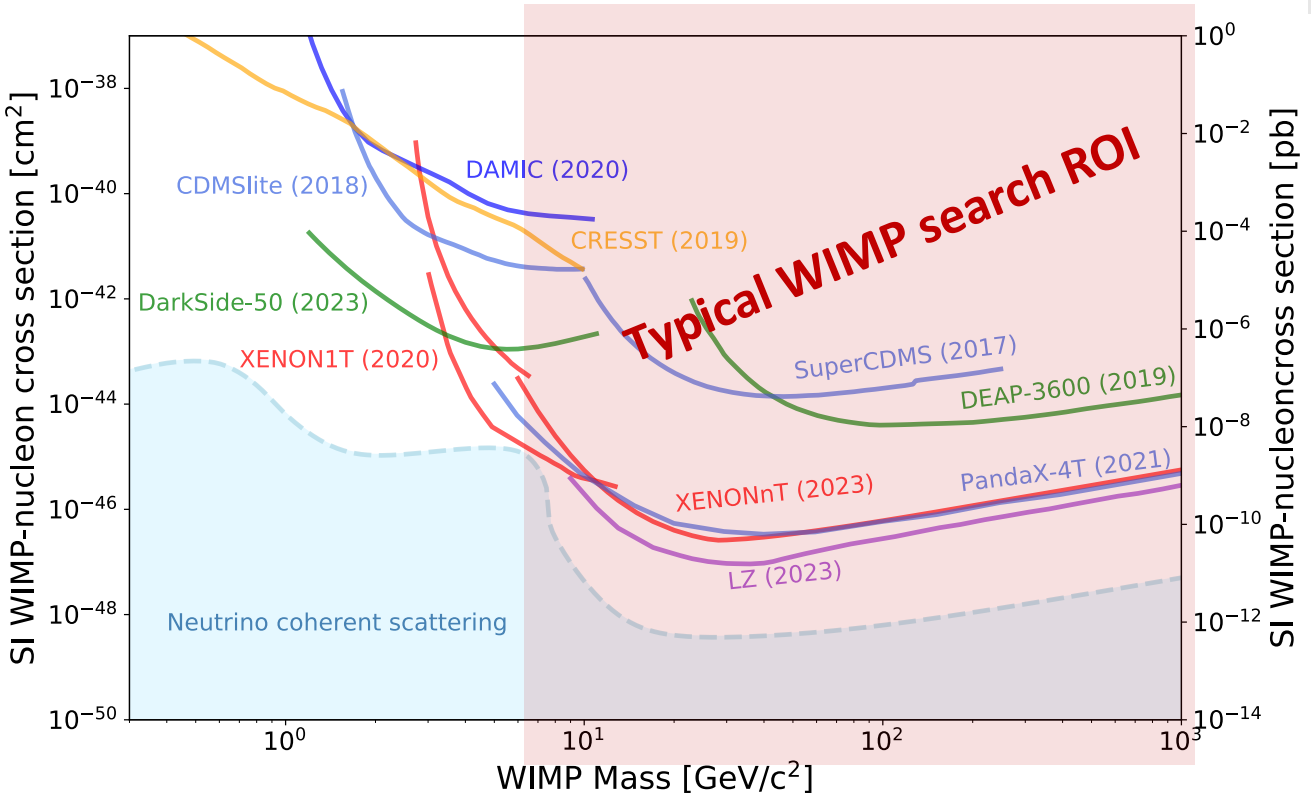
Electrons following progenitor S2 in 5 s sample window

- Random pairing of lone S1 and lone S2

- Lone S1s:
  - lone hit pile-ups, signal misclassification
  - Rate = 15 Hz
- **Lone S2s:**
  - **delayed electrons, electron emissions**
  - **Rate = 150 mHz**

- Originate from
  - release of electrons trapped on impurities, triggered by
    - S2 photons
    - delayed photons?
  - Electron emissions from grids
  - …?

Standard WIMPs... and beyond



Phys. Rev. D **110**, 032001 (2024)

- Light dark matter searches
  - Low S1
  - S2-only
  - Migdal effect
- CEνNS search
- Neutrinoless double-beta decay