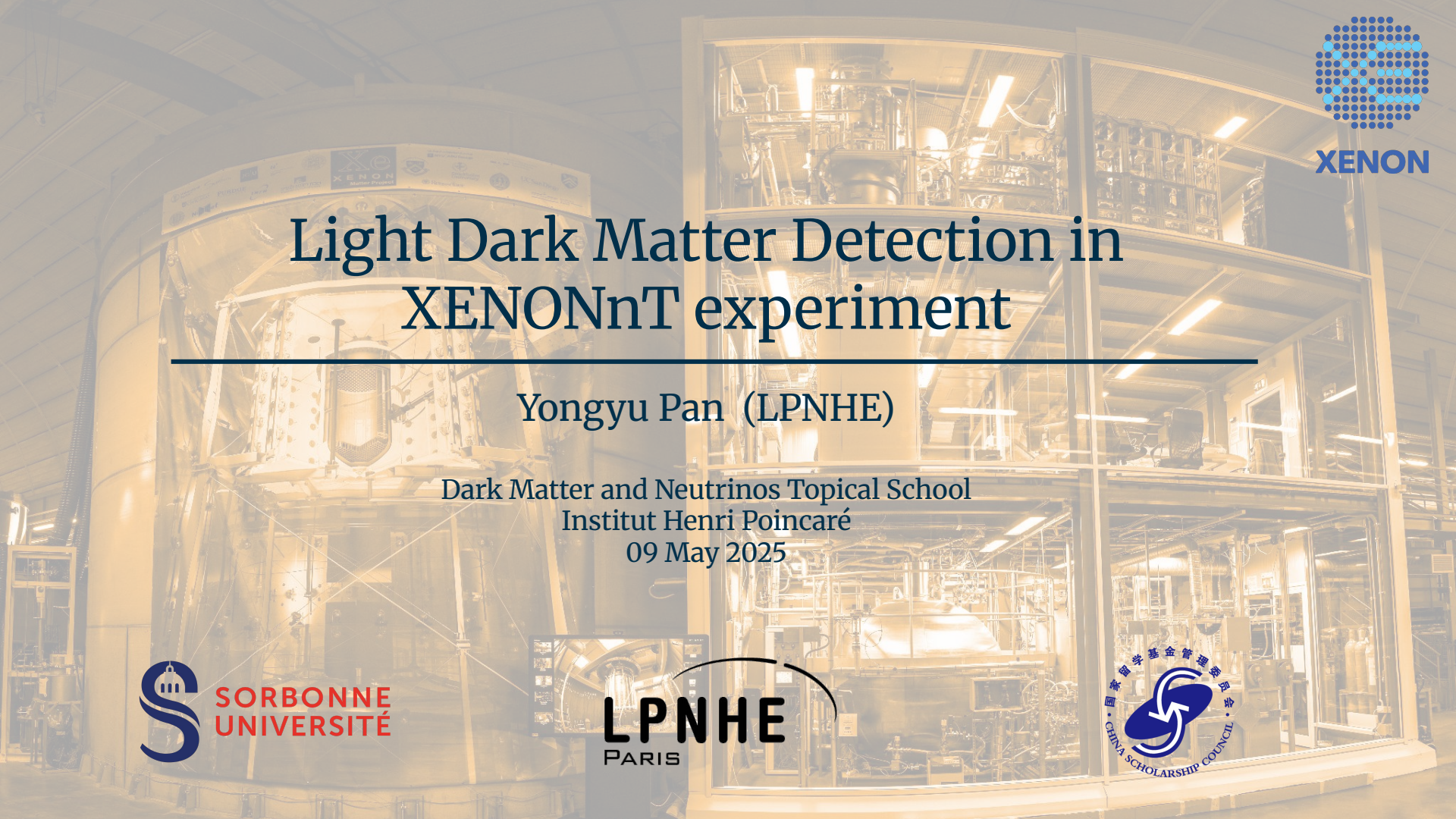

Light Dark Matter Detection in XENONnT experiment

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Dark Matter and Neutrinos Topical School
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09 May 2025

XENON

SORBONNE UNIVERSITÉ

LPNHE PARIS

CHINA SCHOLARSHIP COUNCIL

XENONnT Experiment

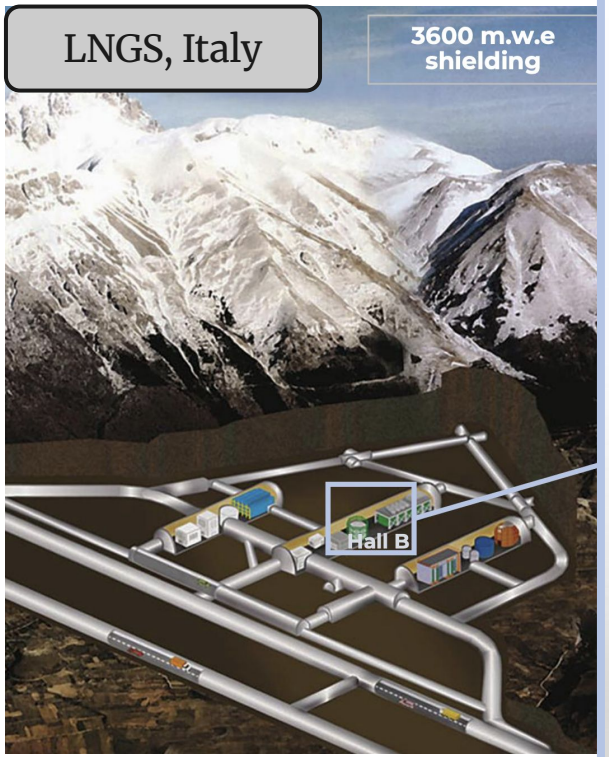
Direct detection of dark matter

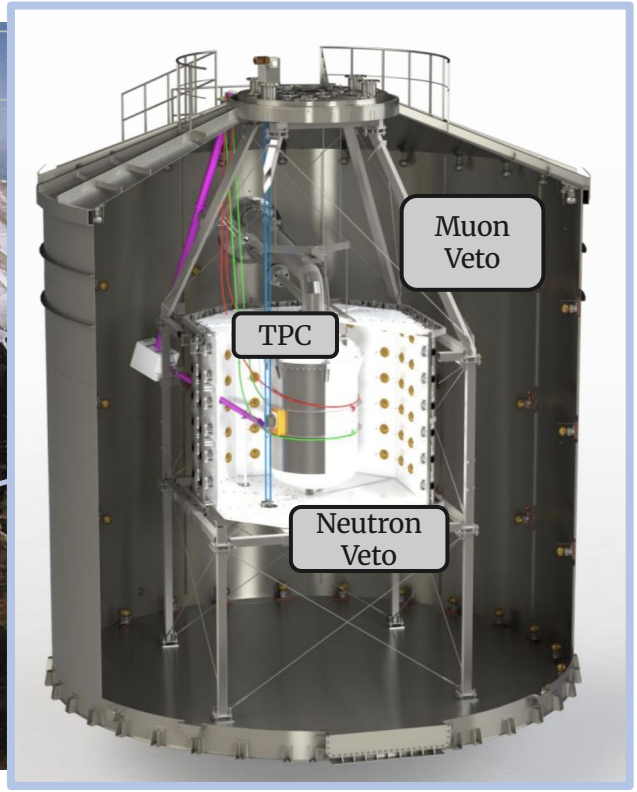
200 + Scientists

30 Institutions

12 Countries

XENON





Main Objective:
Discover Weakly Interacting Massive Particles (WIMPs)

XENON program timeline

XENON10
2005
14 kg

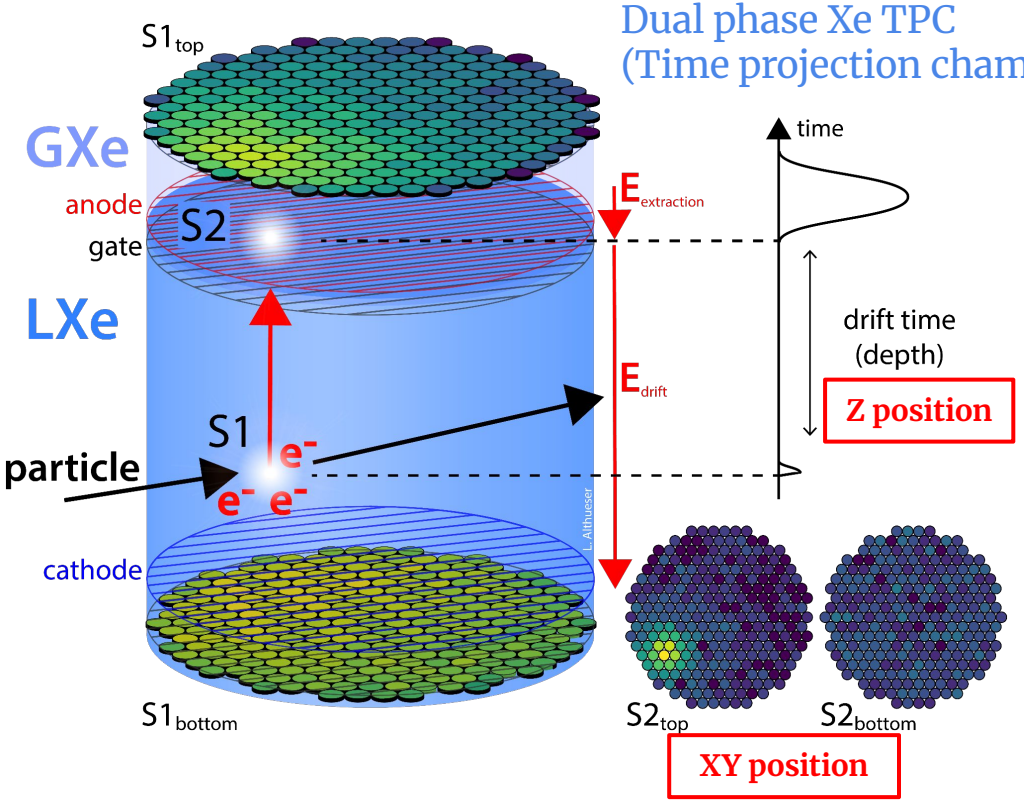
XENON100
2008
62 kg

XENON1T
2016
2 t

XENONnT
2020
6 t

XENONnT Experiment

Direct detection of dark matter



- **S1:** Prompt scintillation light
- **S2:** Secondary scintillation light

induced by ionionized electrons

- **3D Position reconstruction:**
  Drift time + PMT pattern
- **Energy reconstruction:**

$$E = W\left(\frac{cS_1}{g_1} + \frac{cS_2}{g_2}\right)$$

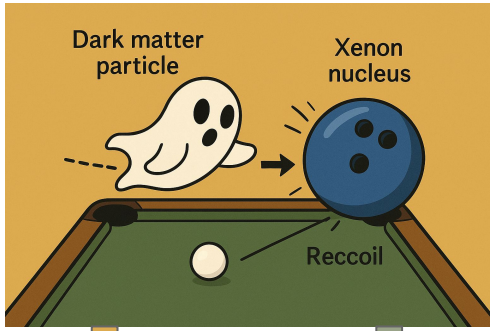
W: Average energy to produce a quanta
cS1, cS2: Corrected area of S1 and S2
g1, g2: Gain of S1 and S2

S2-only analysis

Lower the detection threshold ⇒ Light DM

Why S2-only? Small example:

Q~2.8 keV from Ar37 decay

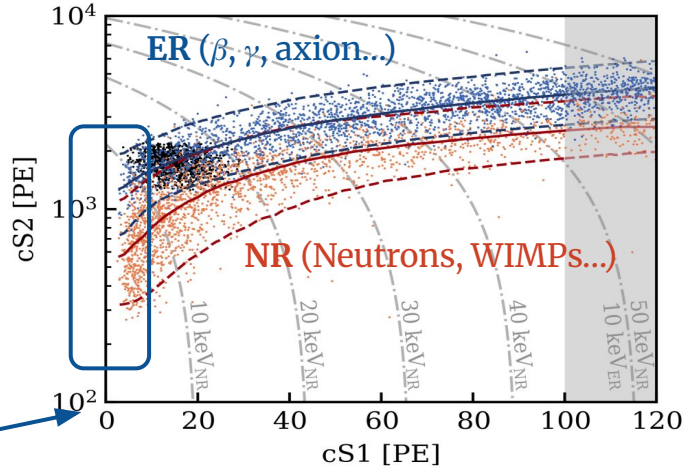


Photon ✖150 e– ✖100

S1 = **15 PE** S2 = **1600 PE**

Detected Photoelectron [PE]

S2 amplified by secondary scintillation

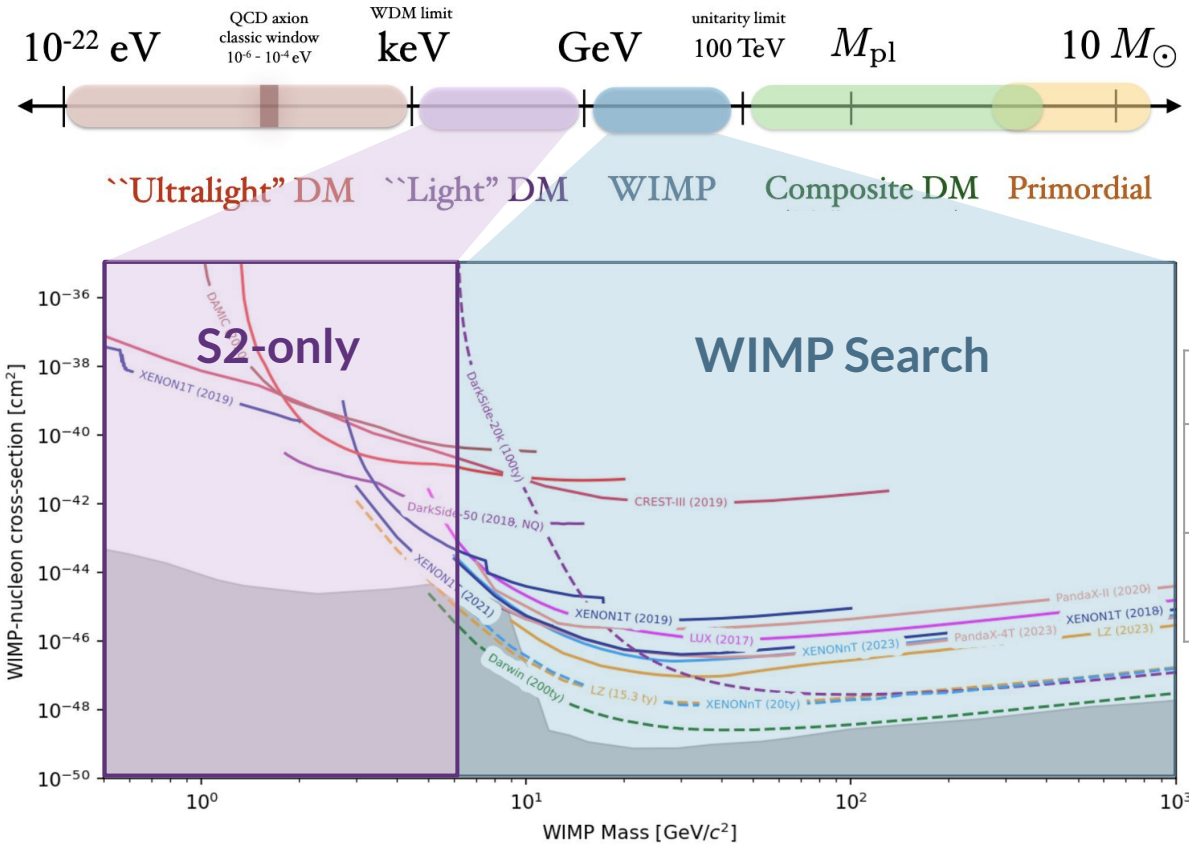


S2 ~ 100 ✖S1
⇒ S1 vanish (<3 PE)
but S2 remain (<500 PE)

NR: Nuclear recoil
ER: Eletronic recoil

S2-only analysis

Lower the detection threshold ⇒ Light DM



S2-only lower the detected recoiled energy:

	S1-S2	S2-only
NR	3.5 keV (6 GeV DM)	0.7 keV (3 GeV DM)
ER	1.2 keV	0.18 keV (0.05-3 GeV DM)

S2-only analysis

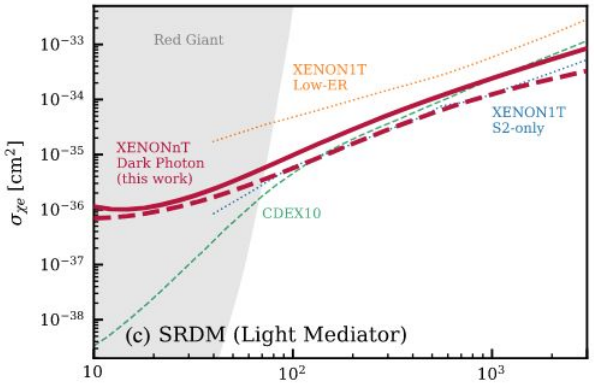
Dark matter model and recent results

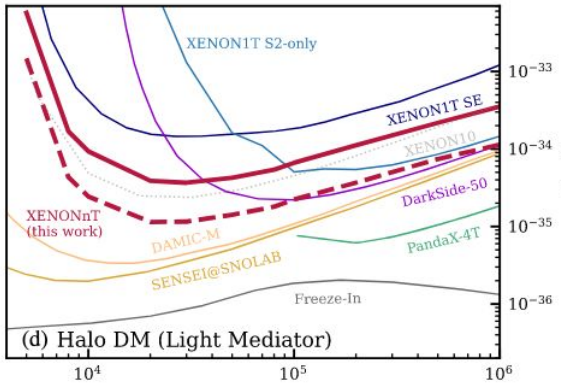
Is done:
- without background model
- < 5 detected electrons

Better results with background model?

SRDM
(Light Mediator)

Solar-Reflected DM
= halo DM upscattered by Sun

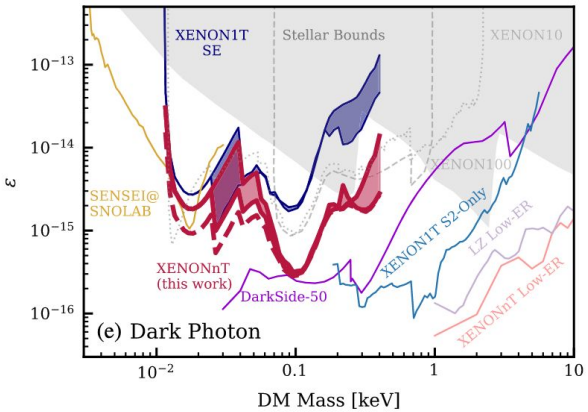


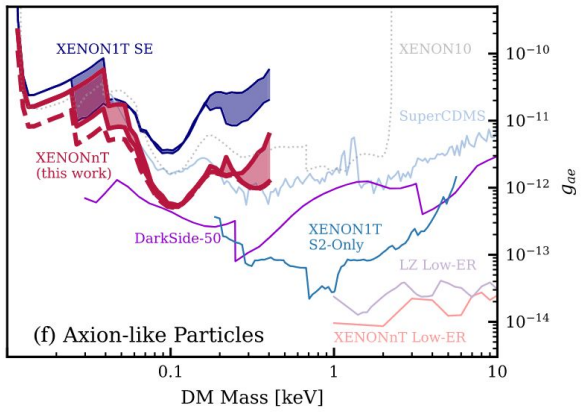


Halo DM
(Light Mediator)

With velocity distribution from standard halo model

Dark photon
(kinetic mixing with SM photon)



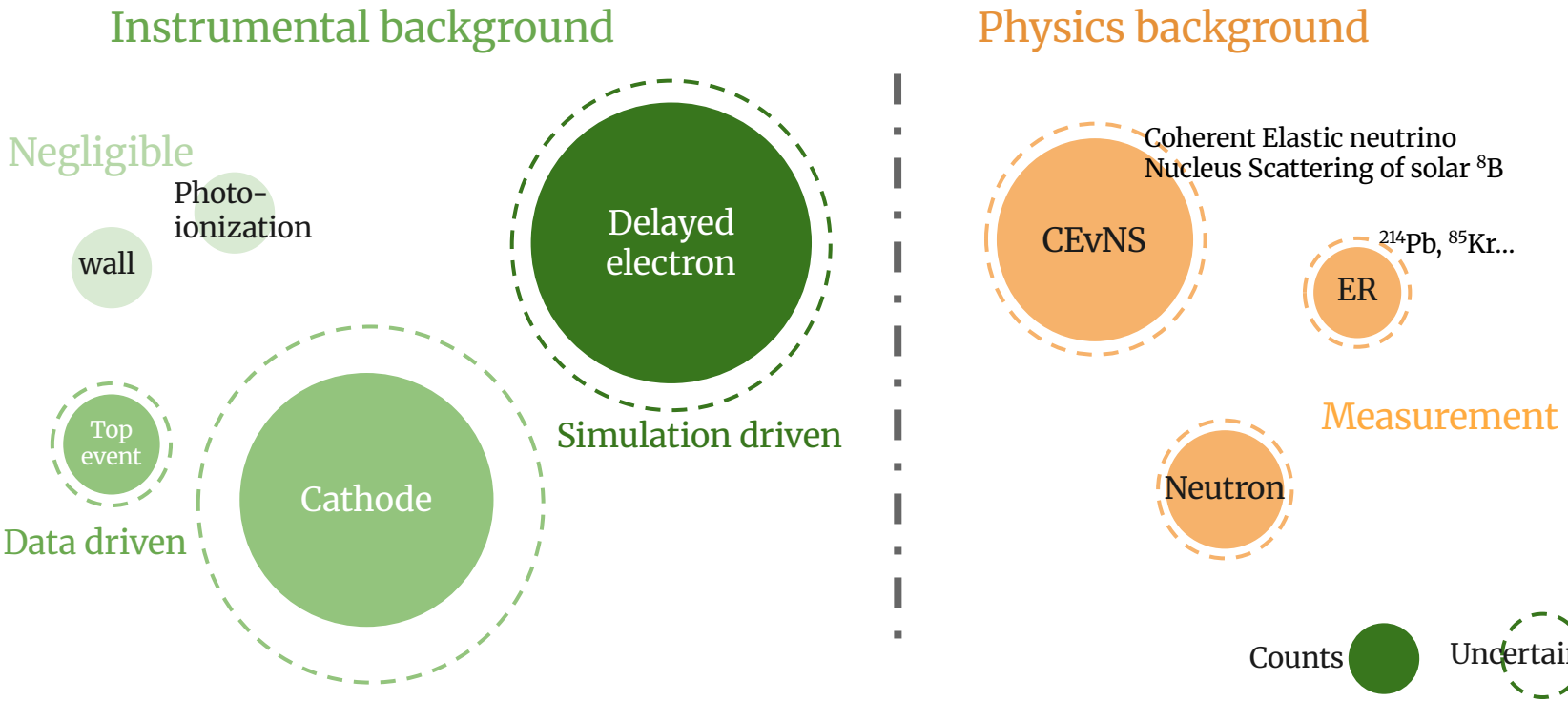


Axion-like particles
(electron coupling)

S2-only analysis (current work)

Major challenge: Background model

Without S1 ⇒ No z-related data selection
Small S2 area ⇒ More sensitive to detector condition



S2-only analysis (current work)

Major challenge: Background model

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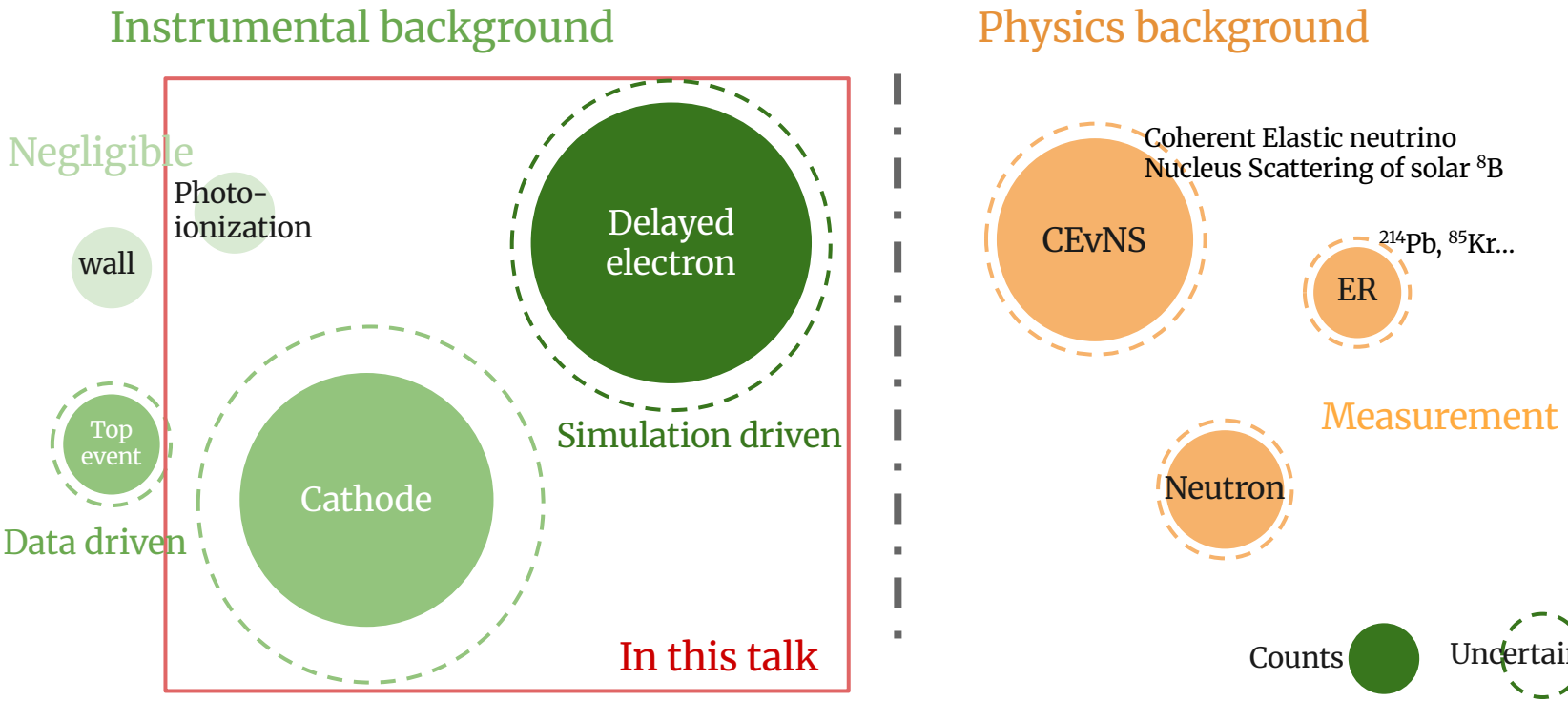
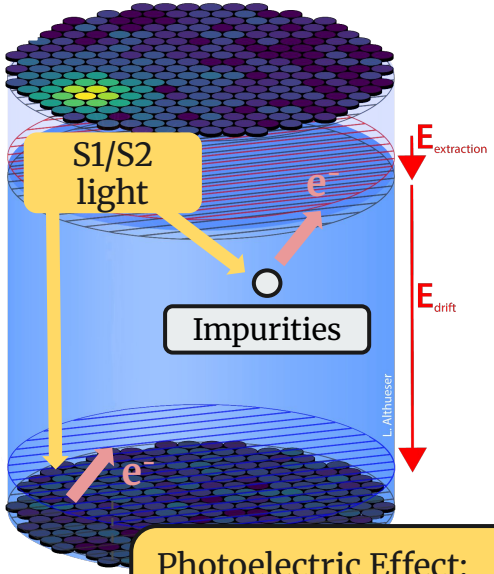


S2-only analysis

Major background: Photoionization vs Delayed electrons

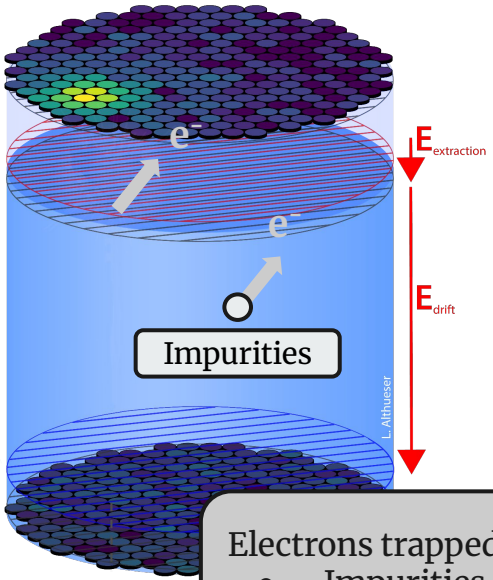
XENON

Photoionization



Photoelectric Effect:
- Impurities in the liquid xenon
- Metal surfaces

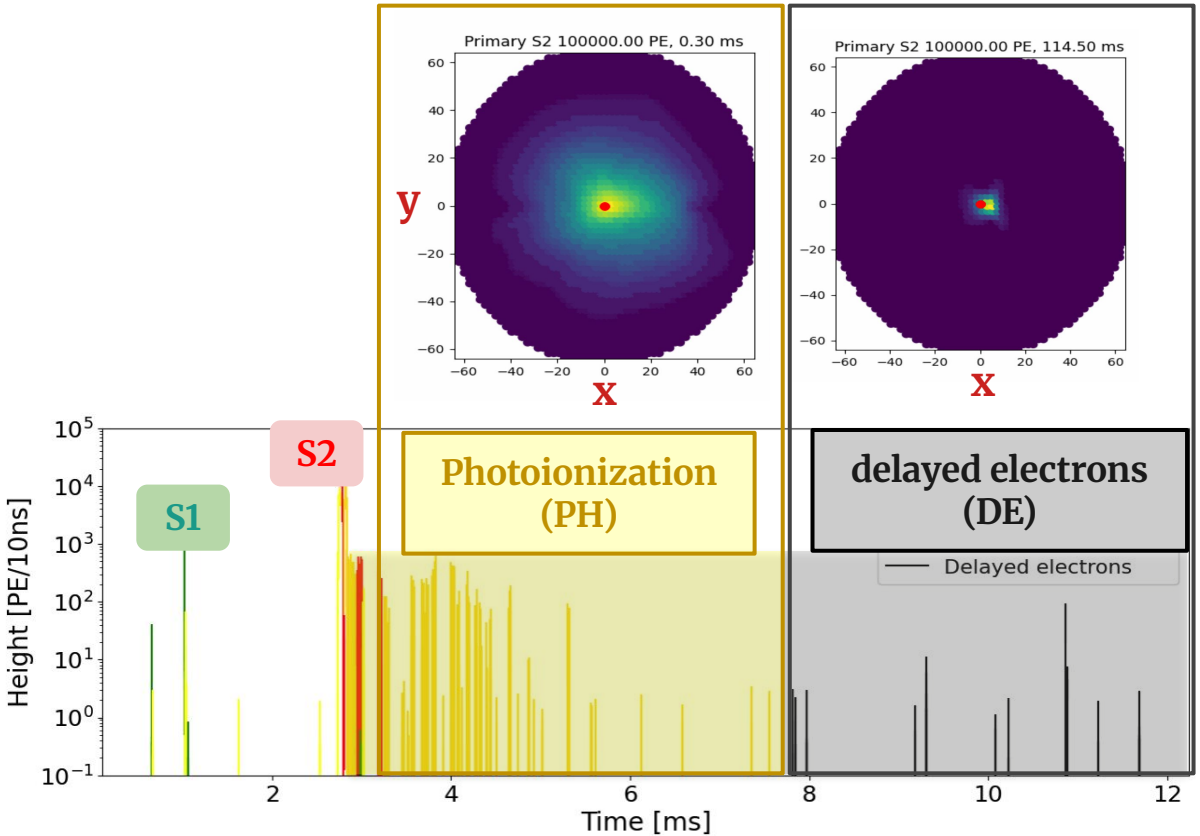
Delayed electrons



Electrons trapped by:
- Impurities
- Liquid-gas interface

S2-only analysis

Major background: Photoionization vs Delayed electrons



Position distribution

PH:
no strongly position correlated with previous S2

DE:
strongly position correlated with previous S2

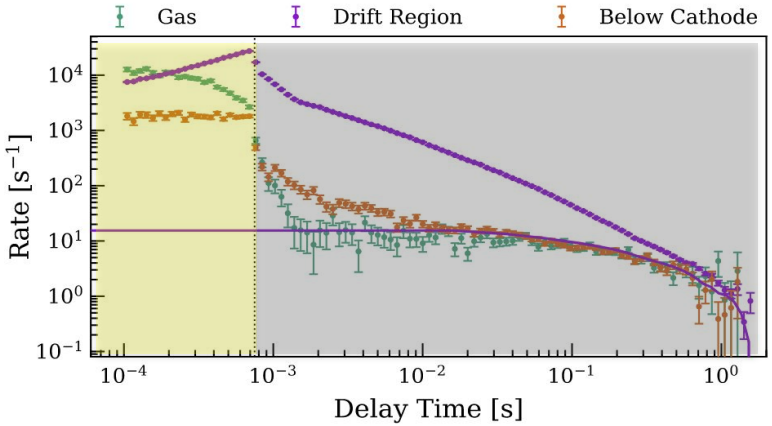
Time distribution

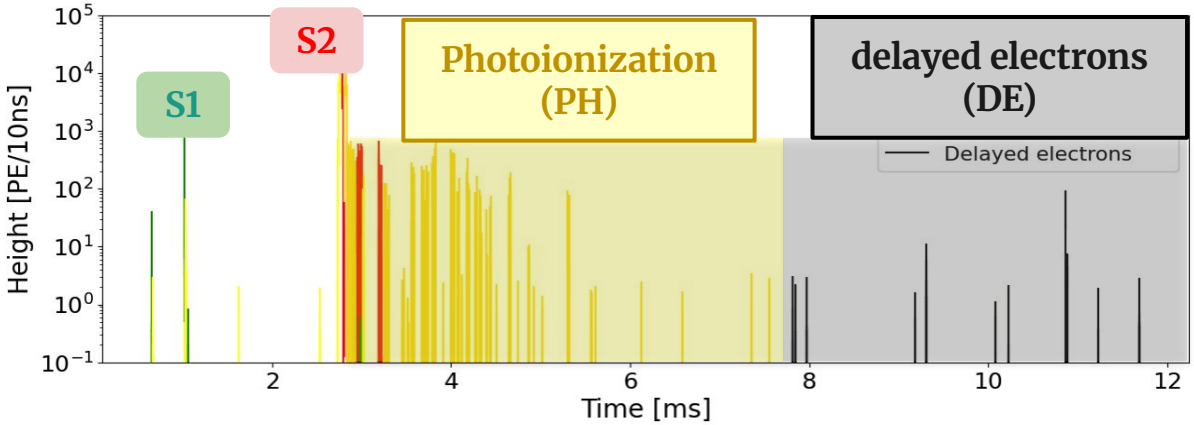
PH:
within 2 * maximum drift time

DE:
outside 2 * maximum drift time

S2-only analysis

Major background: Photoionization vs Delayed electrons





Photoionization:

Can be identified and rejected in time:

- Time veto cut

Delayed electron:

- Simulation-driven modeling

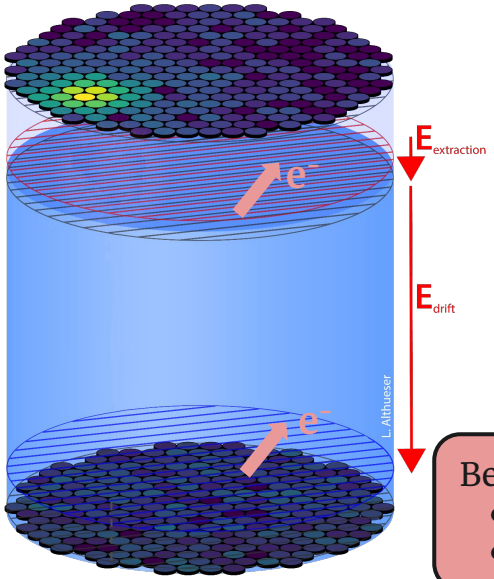
1. Choose large S2
2. Simulate following small S2
   a. Area
   b. Delayed time
   c. Position

S2-only analysis

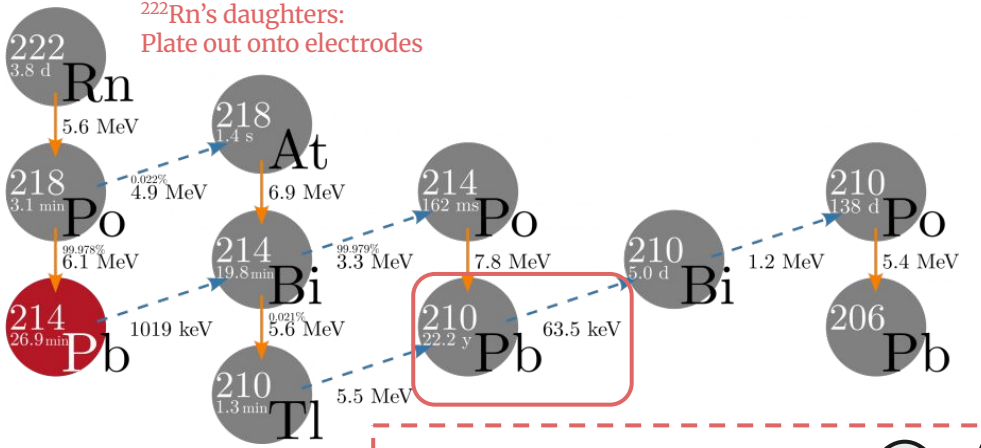
Major background: Cathode events

XENON

Cathode events



^{222}Rn's daughters:
Plate out onto electrodes

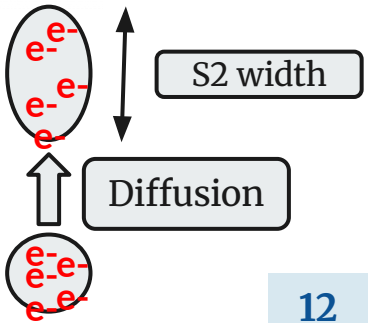


Beta decay from:
- Cathode
- Top electrodes

Can be identified through S2 width

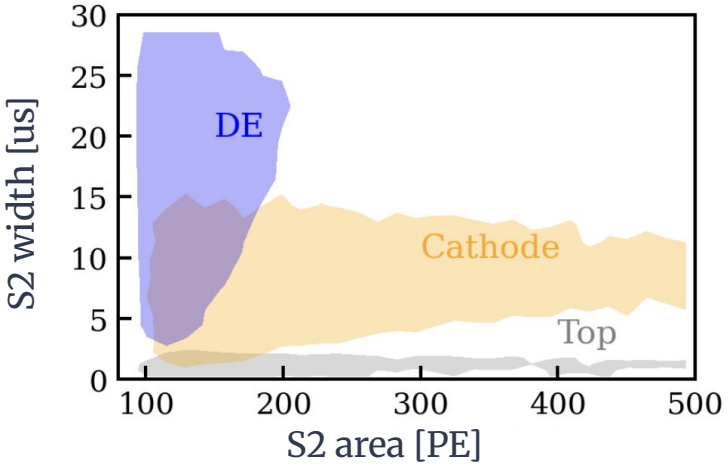
Top events (gate/anode):
- S2 width cut

Bottom events (cathode):
- data-driven modeling



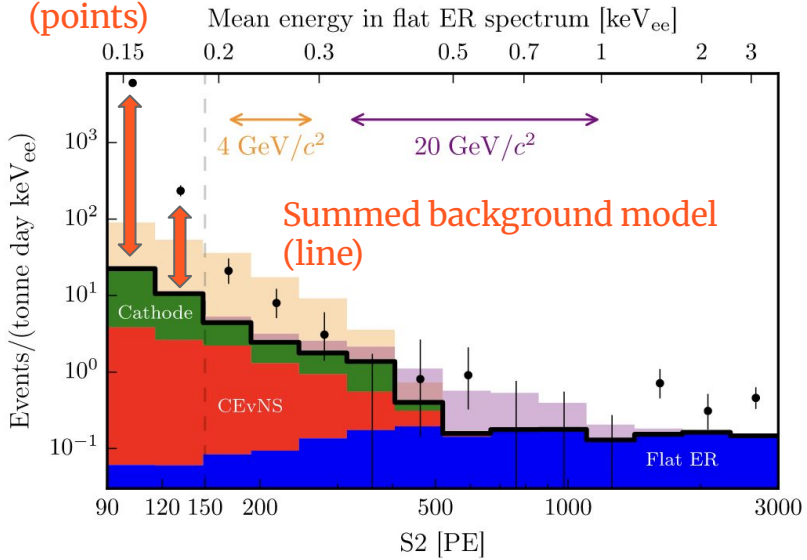
S2-only analysis

Future work: Background Validation



Current instrumental background estimation in XENONnT

Observed data (points)



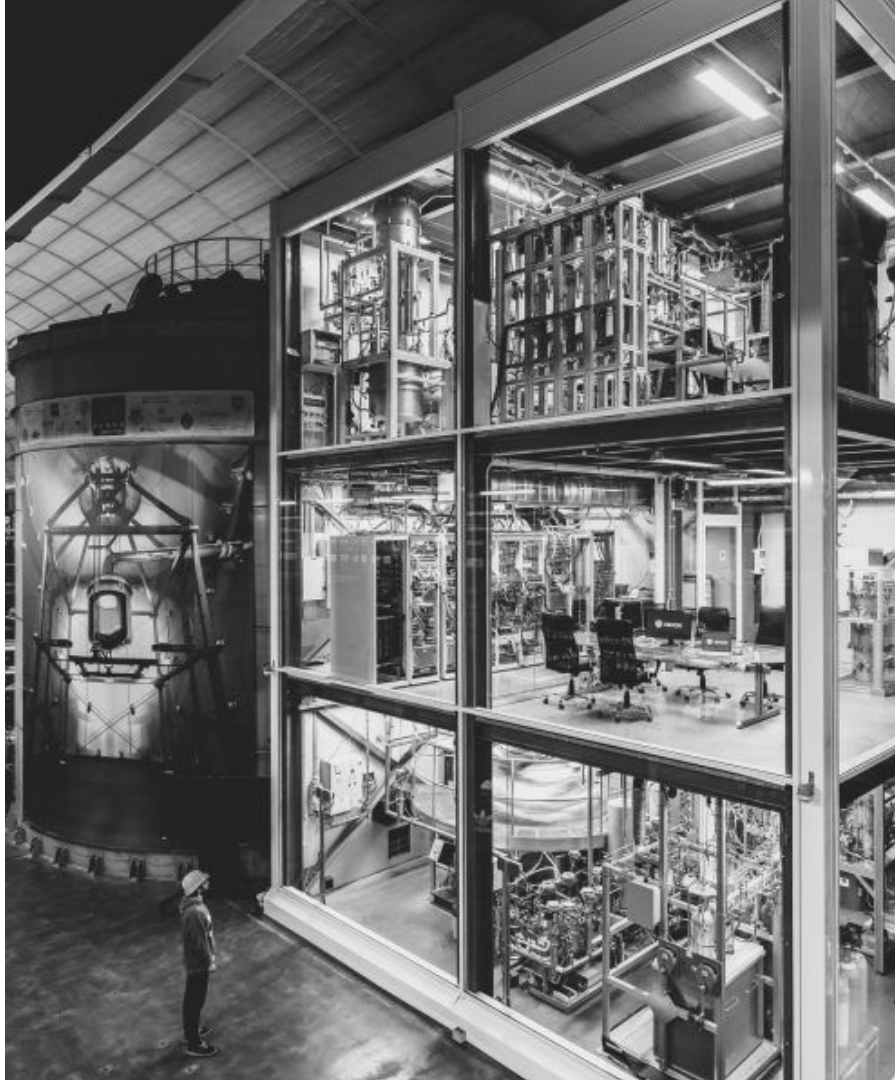
Background validation in XENON1T

Summary

- XENONnT is a dual-phase xenon TPC detector filled with 6 t liquid xenon
- By discarding the S1 signal, the S2-only analysis can lower its recoil-energy threshold by ~7 times
- This enables sensitivity to sub-GeV dark-matter candidates such as dark photons and axion-like particles

- **Dominant instrumental backgrounds**:
  - Delayed electrons
  - Cathode event

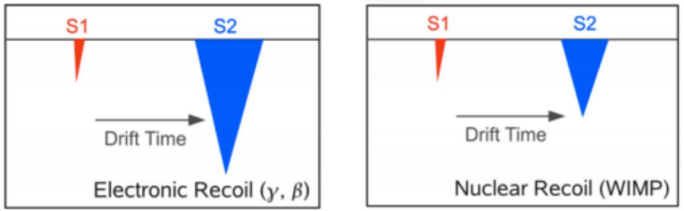
- **Sub-dominant physics backgrounds**:
  - CEνNS
  - Electronic recoils
  - Neutrons

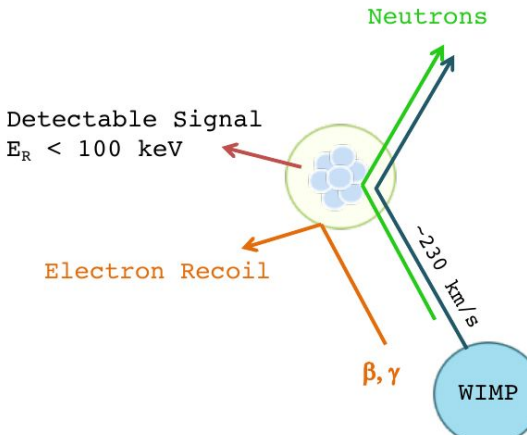


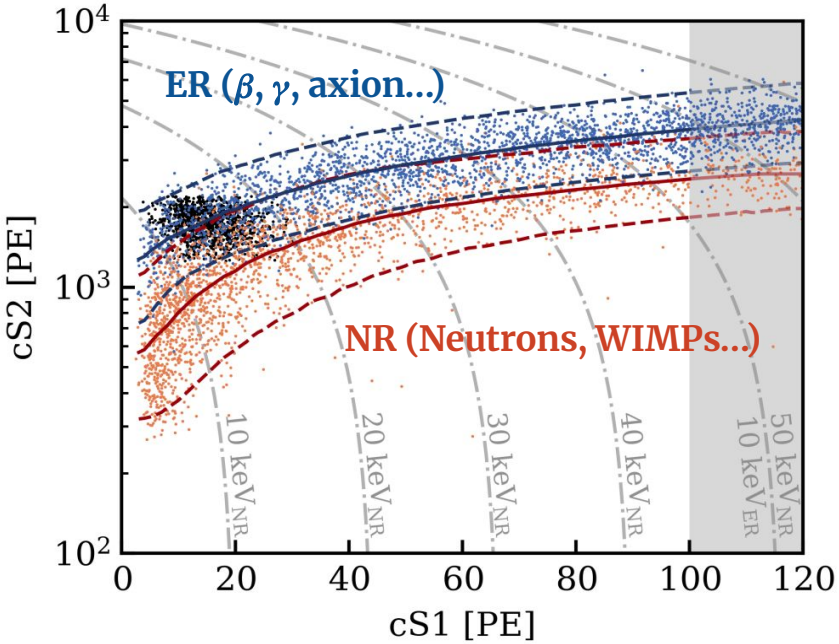
Back-up slides

How to identify NR (nuclear recoil)?

Using S2/S1 to discriminate
electronic recoil (ER) and nuclear recoil (NR)

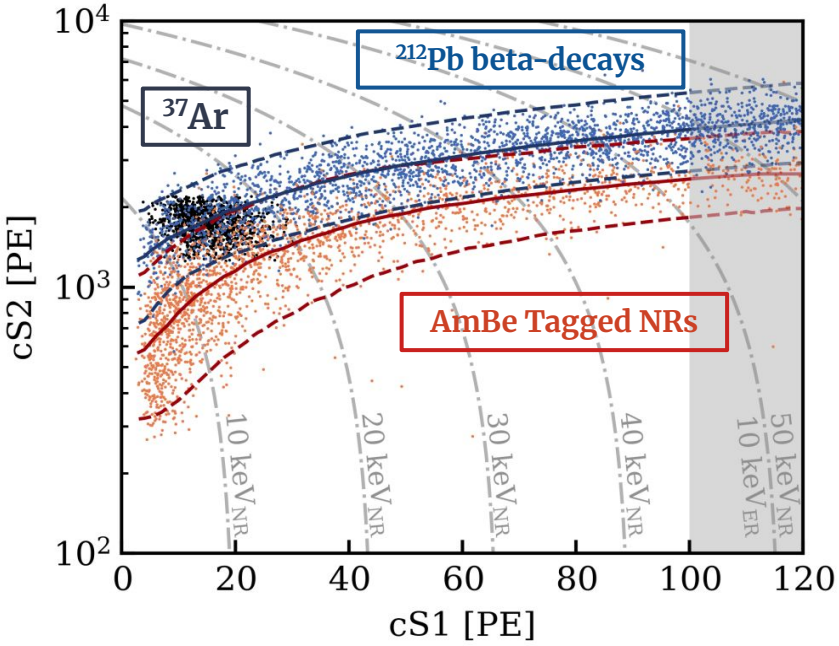






arXiv:2303.14729 [hep-ex]

How to calibrate our detector?



Calibration for ER:

ERs from ^{212}Pb beta-decays from injected gaseous ^{220}Rn:

- Continuous spectrum
- To define cS1 vs cS2 response for ER
- To validate cut acceptance

ERs from injected gaseous ^{37}Ar:

- mono-energetic at 2.8 keV
- To validate the low-energy ER response

Calibration for NR:

NRs from 241 AmBe neutron source:

- Tagged by a coincident gamma captured by neutron veto
- To define cS1 vs cS2 response for NR

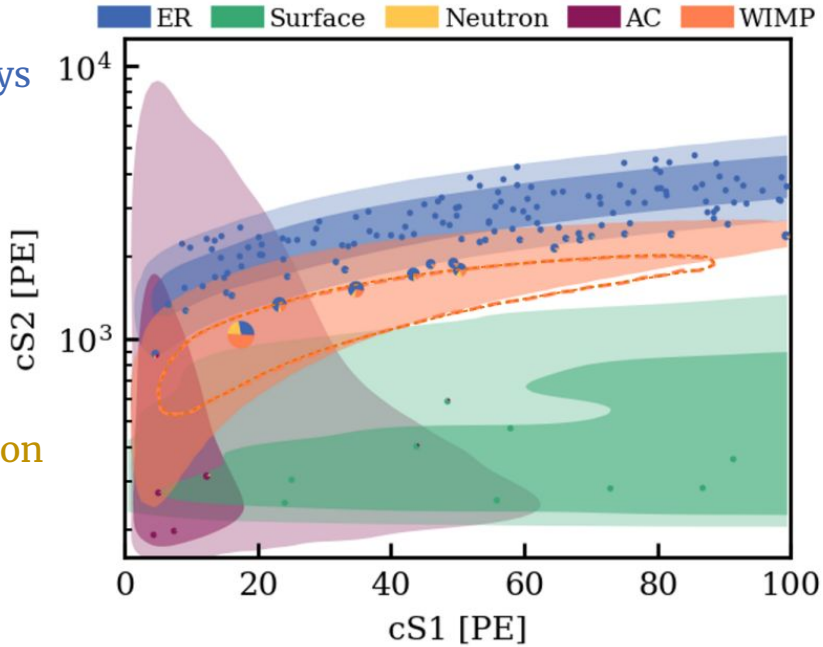
How to identify the background?

ER background:
- Dominated by ^{214}Pb (a daughter of ^{222}Rn) beta-decays

Surface background:
- beta decays of ^{210}Pb from TPC wall
- suppressed by fidicial volume cut

NR (neutron) background:
- Neutrons from spontaneous fission and (α,n) reaction

Accidental coincidence (AC) background:
- Random pairing of S1 and S2 lone signals

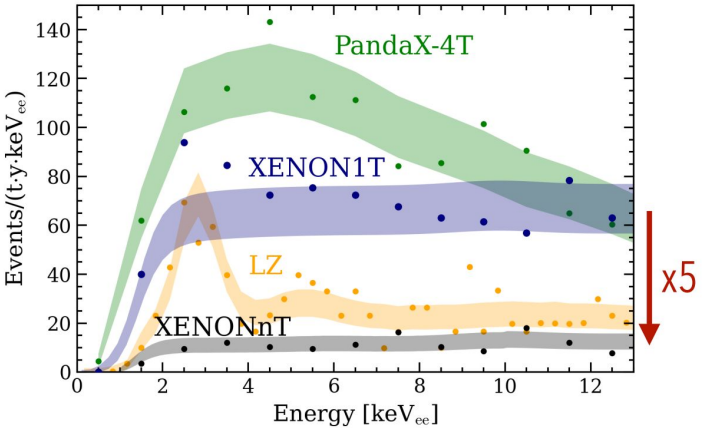


Upgrade from XENON1T to XENONnT

- **Reduction of ER background:**

Major background: β emitter ^{214}Pb, a daughter of ^{222}Rn

Rn distillation column
⇒Reduction of ER background by a factor of ~6



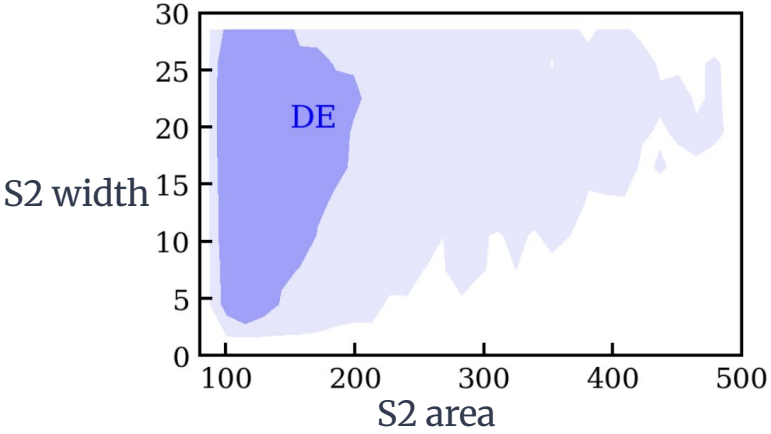
- **New xenon purification system**

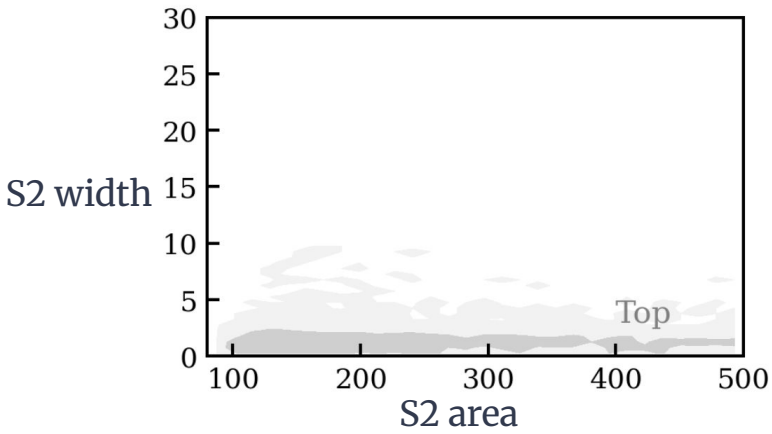
⇒ Higher electron survival rate

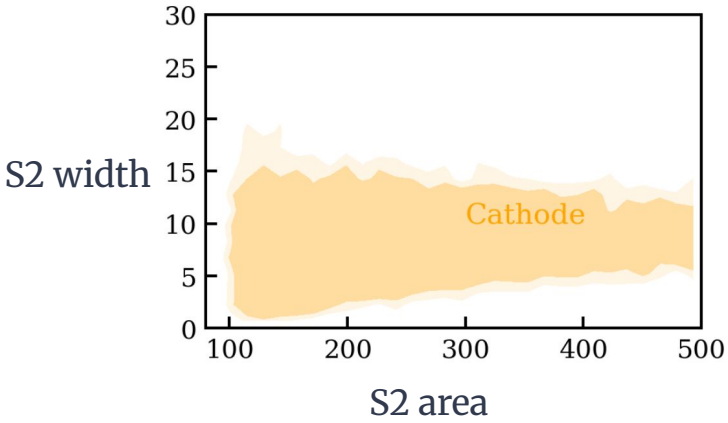
	Full drift time:	Electron lifetime:	Electron survival (@full drift length):
1T	0.67 ms	0.65 ms	30 %
nT	2.2 ms	**~15 ms**	**86 % @ 15 ms**

- **Increased xenon target mass**

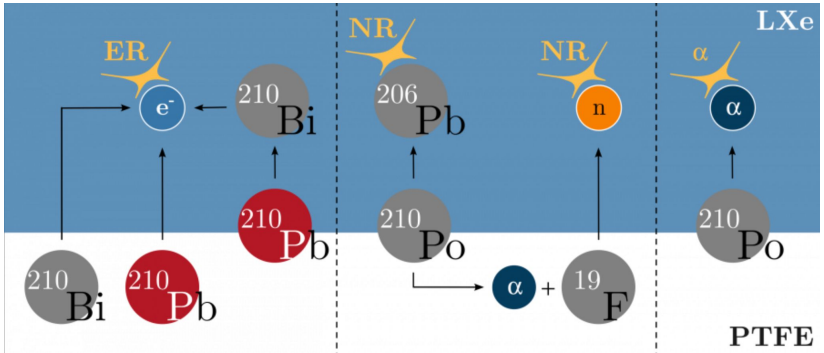
Major instrumental background in S2-only

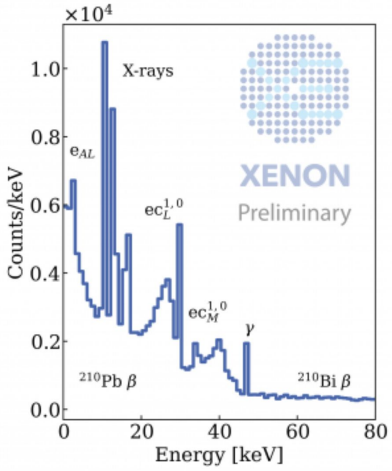


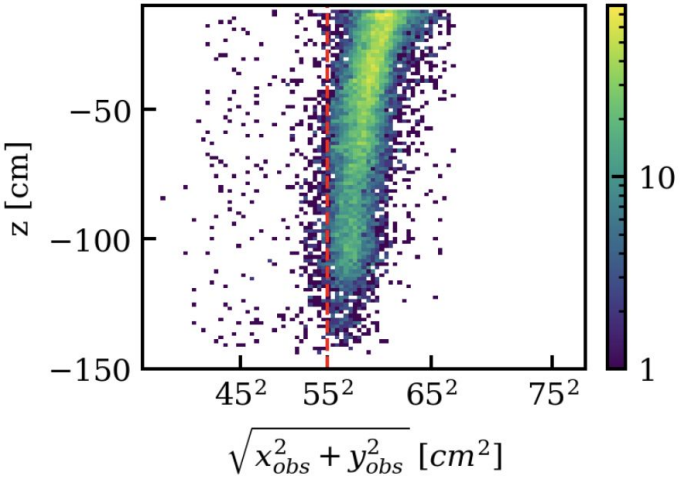


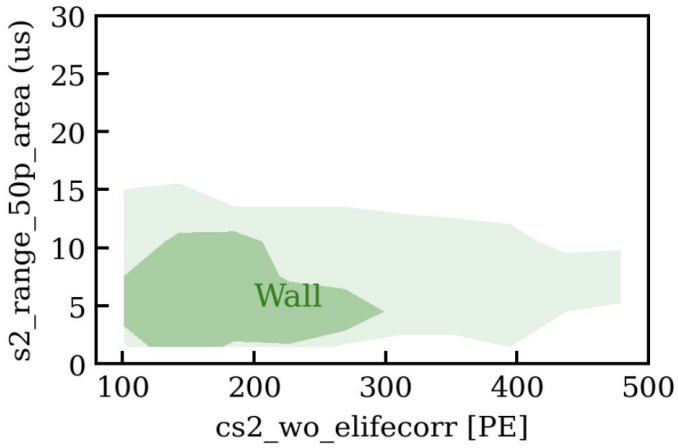


Instrumental background:
Wall



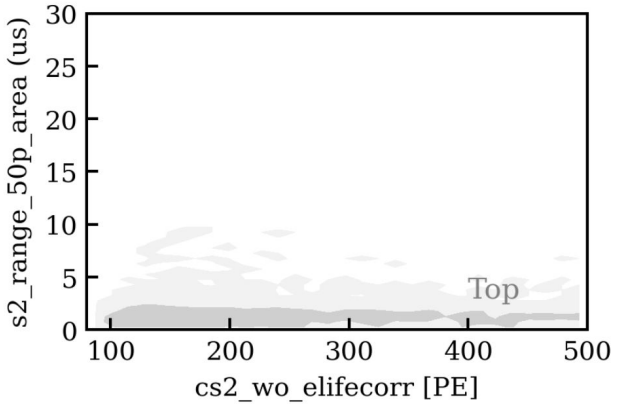


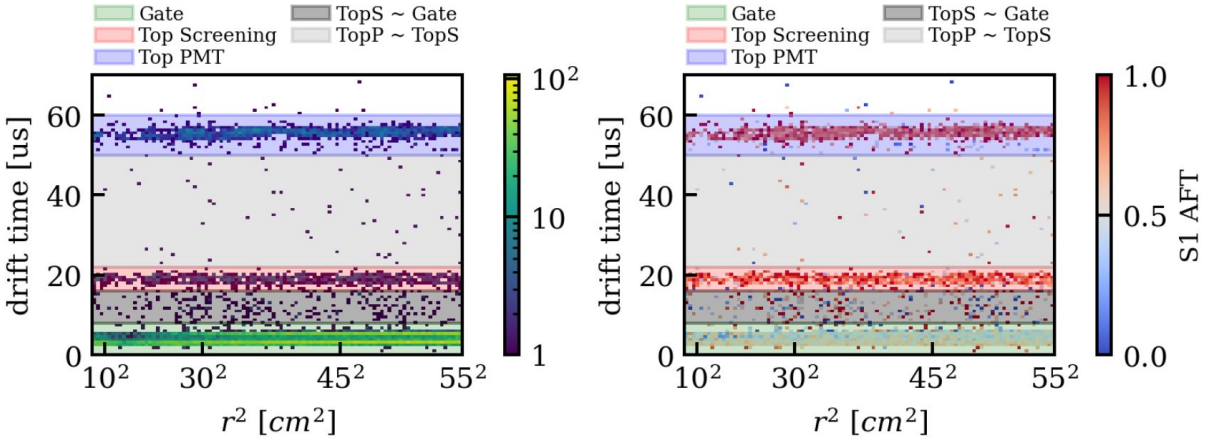




Instrumental background:

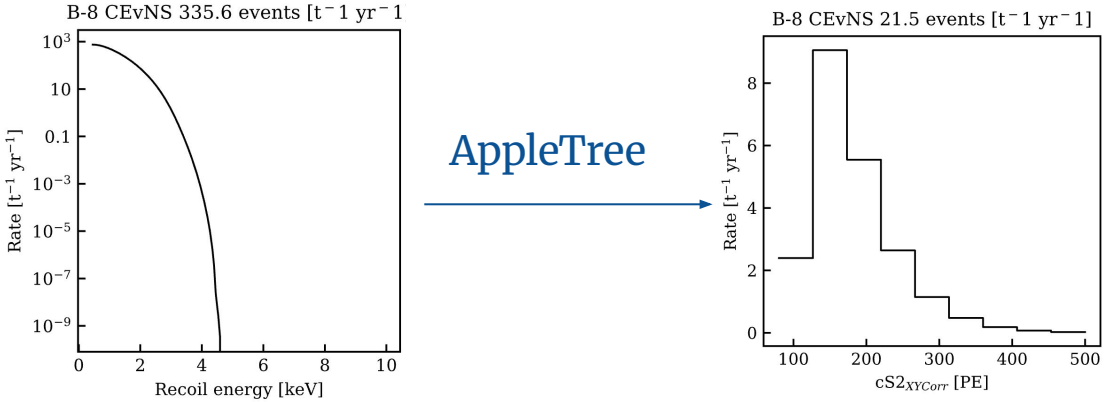
Top electrodes





Physics background: CEvNS

S2-only expected CEvNS events = 10 * 2 fold's



Physics background: ER