Light Dark Matter Detection in XENONnT experiment

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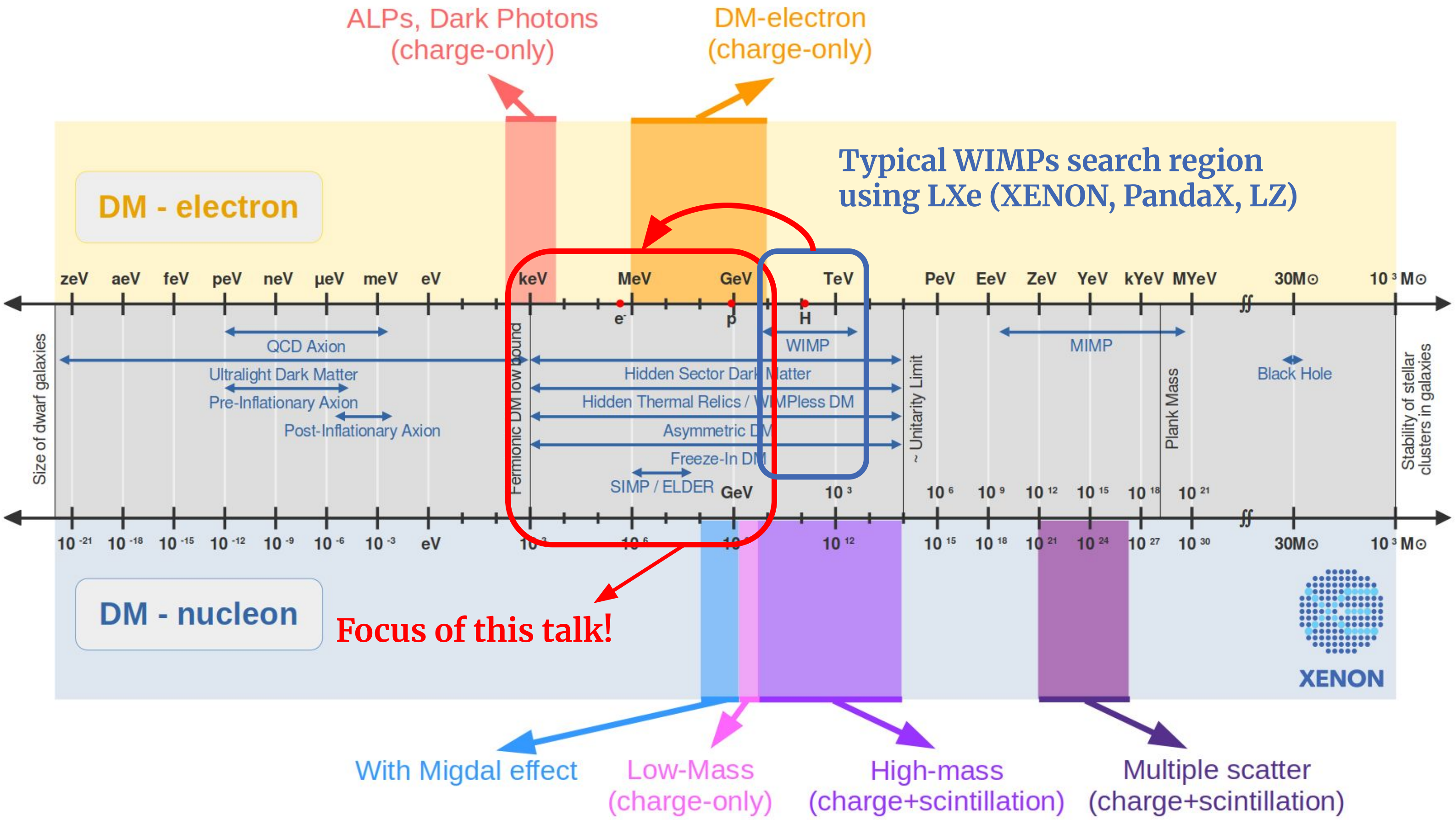
on behalf of XENON Collaboration

PATRAS 2025

22 September 2025

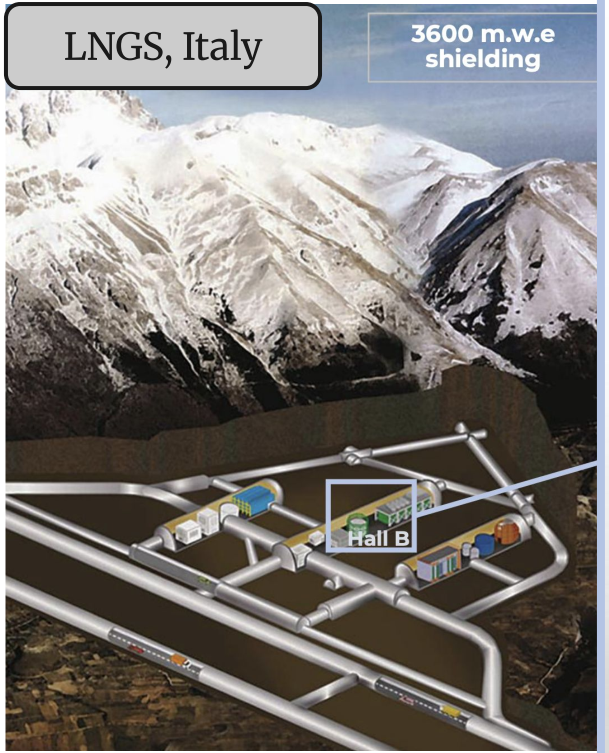
Dark matter search landscape

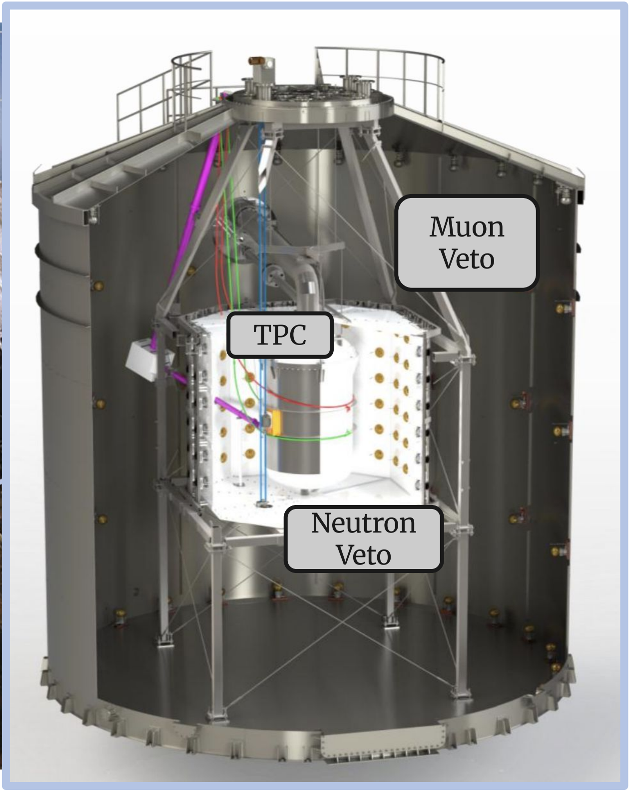


XENONnT Experiment

Direct detection of dark matter

200 + Scientists | 30 Institutions | 12 Countries





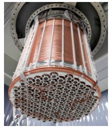
Main Objective:
Discover Weakly Interacting Massive Particles (WIMPs)

XENON program timeline

XENON10
2005
14 kg

XENON100
2008
62 kg

XENON1T
2016
2 t



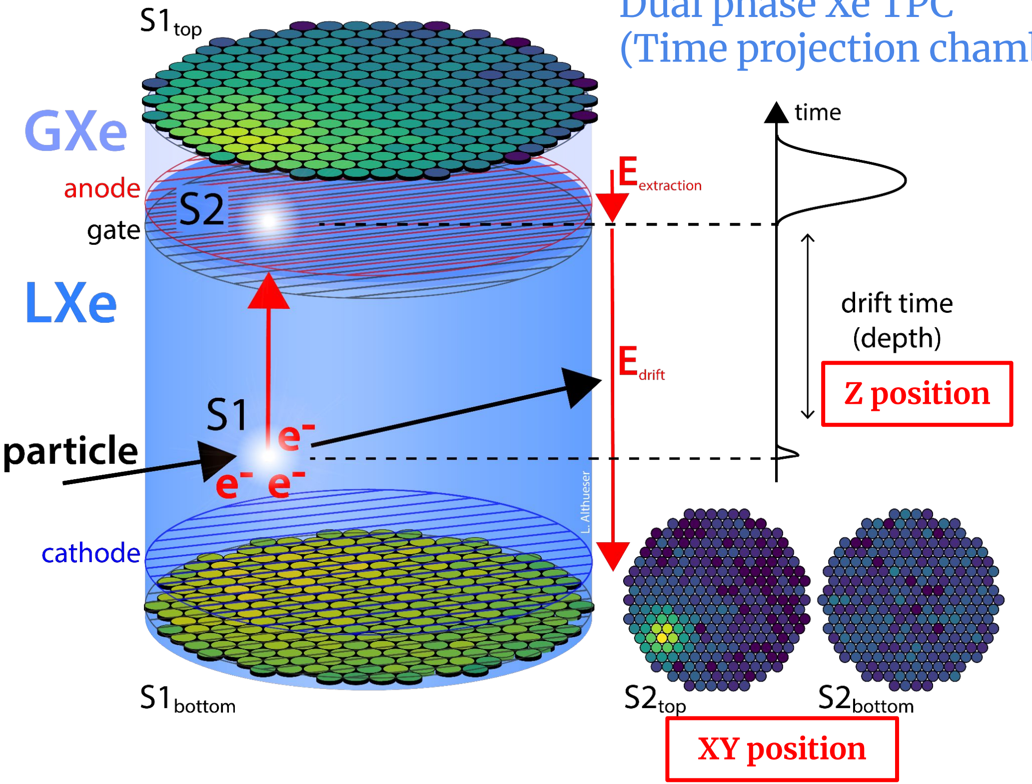
XENONnT
2020
6 t

XENONnT Experiment

Direct detection of dark matter

XENON

Dual phase Xe TPC
(Time projection chamber)



- **S1:** Prompt scintillation light
- **S2:** Secondary scintillation light induced by ionized electrons

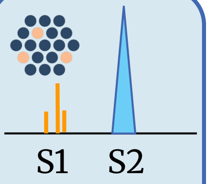
- **3D Position reconstruction:** Drift time + PMT pattern

- **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

Towards lighter Dark Matter



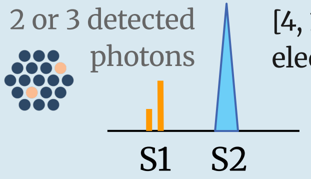
Typical S1–S2

Sensitive to
> 6 GeV/c^2 DM

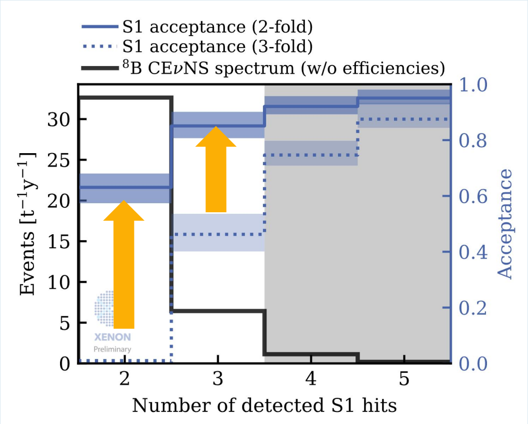
Smaller S1

Low-photon S1 analysis

Phys. Rev. Lett. 134, 111802 (2025)



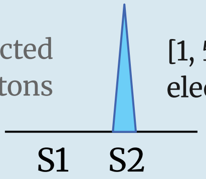
Advantage: Search for light DM [3,12] GeV/c^2
Challenges: Accidental Coincidence, Neutrino fog



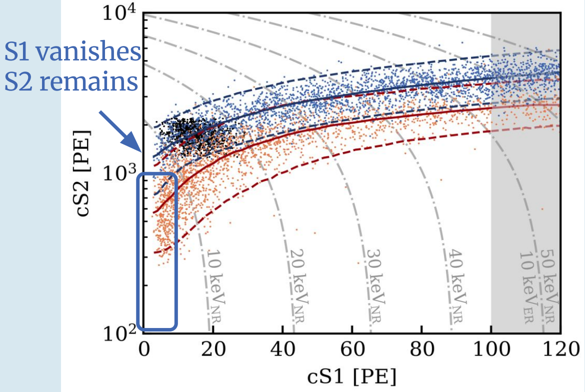
Drop S1

S2-only analysis

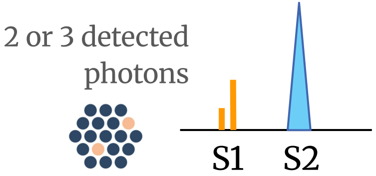
Phys. Rev. Lett. 134, 161004 (2025)



Advantage: Search for lighter DM < 1 GeV/c^2
Challenges: Detector response modeling,
Delayed electron emission



Low-photon S1 analysis
Challenge 1: Neutrino fog

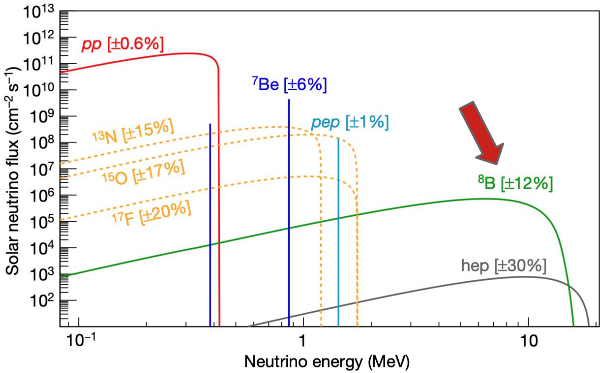


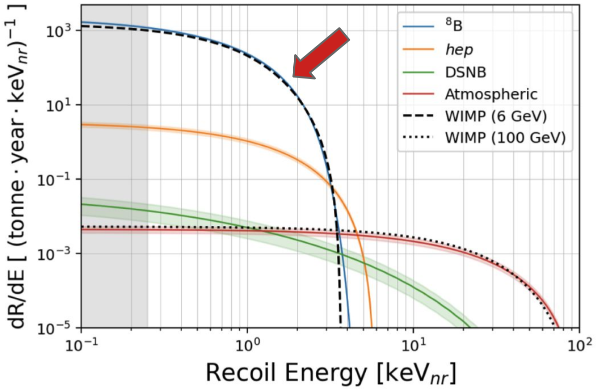
XENON

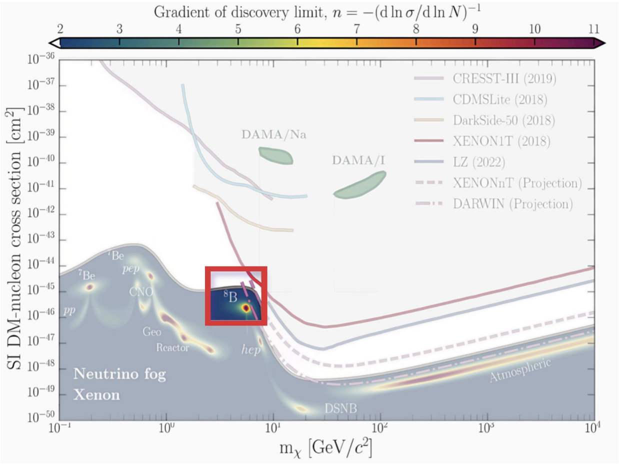
Solar ^{8}B neutrino
Coherent Elastic neutrino (ν) Nucleus Scattering (CEvNS)

Dark matter vs ^{8}B CEvNS:
similar recoil energy spectrum

Neutrino fog:
An "irreducible" background: ~ 300 nuclear recoils/t·yr in [0.5, 5] keV





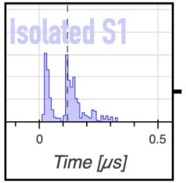


<u>Solution:</u> Measure solar ^{8}B CEvNS with low-energy nuclear recoil calibration (YBe photoneutron source)

Low-photon S1 analysis

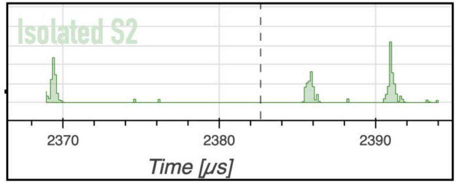
Challenge 2: Accidental coincidence (AC) background

Random pairing of
isolated S1 and isolated S2



NOT physically correlated

"Accidental"



- Photoionization photons
- Lone-hits pile-up

- Delayed electrons trapped in the impurities
- Cathode or gas events losing S1

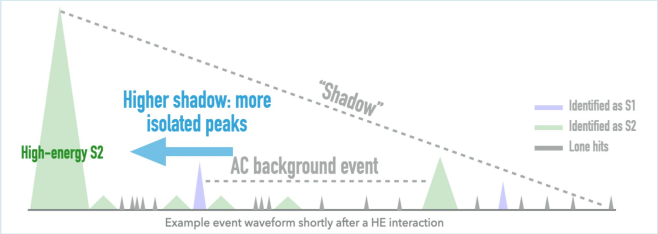
Background Suppression

S1 BDT*:
Signal: Narrow width, DPE** effect
AC: Wider width, no DPE effect

*Boosted Decision Tree
**Double-photoelectron

S2 BDT:
Signal: Drift-time correlated width (diffusion)
AC: Uncorrelated width

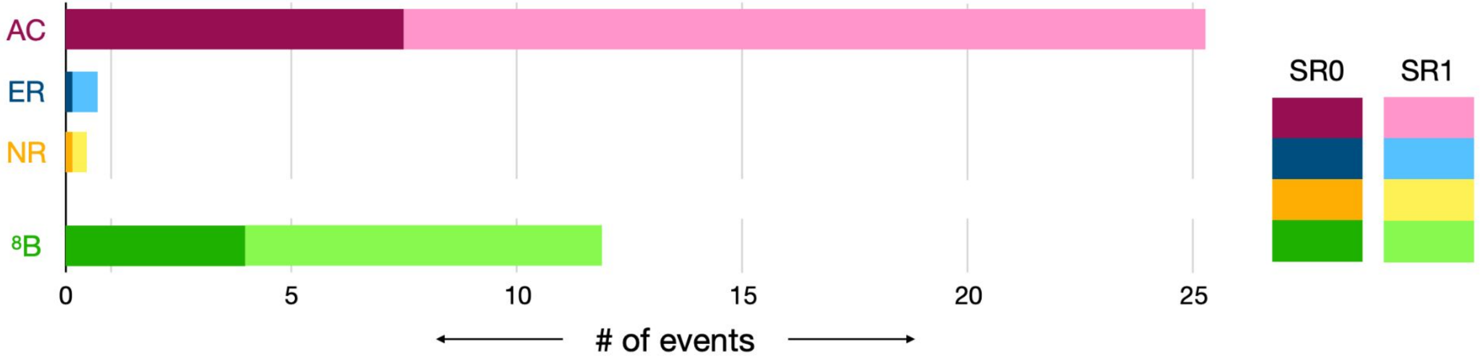
Shadow:
Correlation with previous large S2



Isolated S1 rate: 15 Hz ⇒ 2.3 Hz
Isolated S2 rate: 150 mHz ⇒ 18 mHz

Low-photon S1 analysis

Background summary



AC: Accidental Coincidence background

- Validated by AC-rich sideband
- Uncertainty: 9% (SR0), 6% (SR1)

ER: Electronic Recoil background

- Flat energy spectrum at O(0.1) keV
- 100% conservative uncertainty

^{8}B: CEvNS Signal

- Yields calibrated from YBe Neutron source
- 35% uncertainty from yields and efficiencies

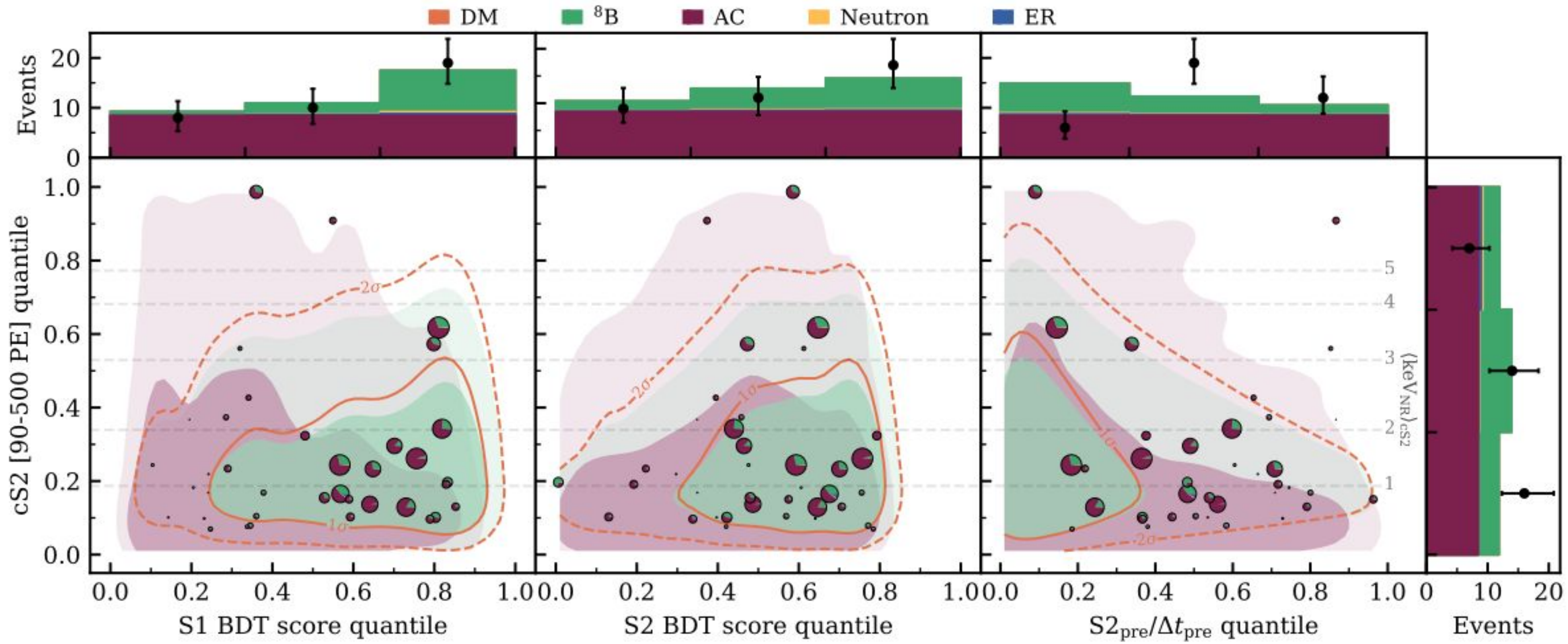
NR: Nuclear Recoil background

- Full chain simulated
- 58% uncertainty from sideband

Background dominated by AC and ^{8}B neutrinos !

Low-photon S1 analysis
Blinded analysis

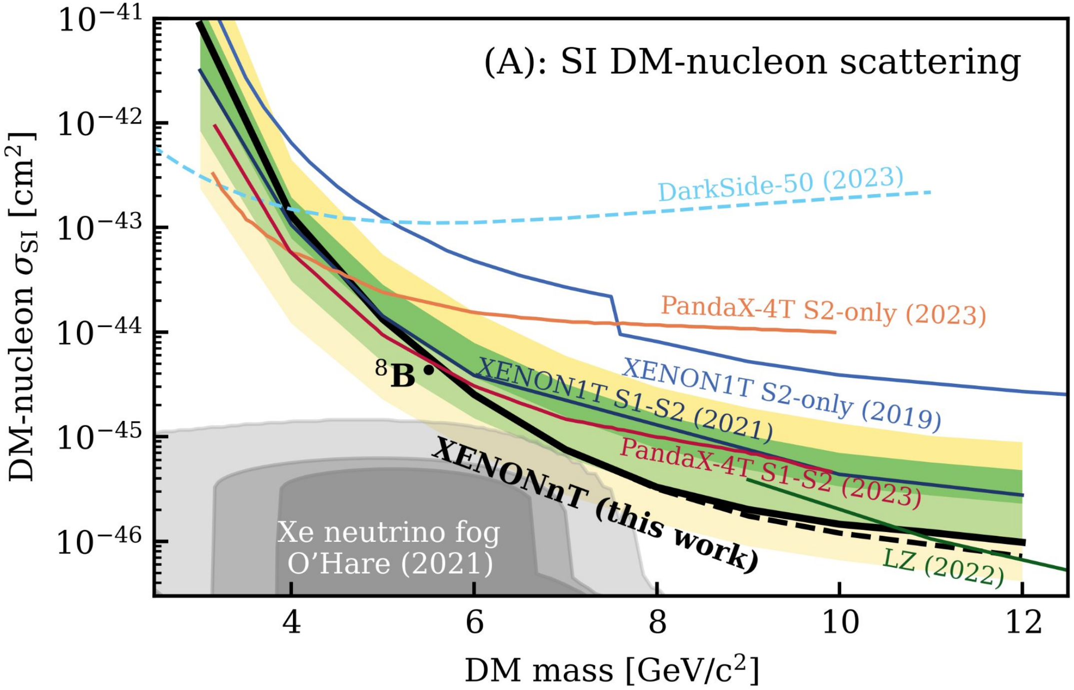
Events distribution through analysis key parameters
Expected background 38.6, observed 37 events



Low-photon S1 analysis

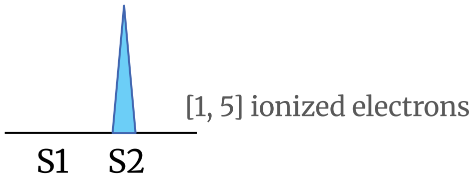
Dark matter limit

- Excludes spin-independent DM-nucleon cross sections above 2.5×10^{-45} cm^2 at 90% confidence level for a 6 GeV/c^2 DM
- DM sensitivity and limit approach the "neutrino fog"



S2-only analysis

Challenge 1: Detector response modeling



XENON

Objective:

Model the detector response to relate true electron number to reconstructed electron number (*Ne,rec*)

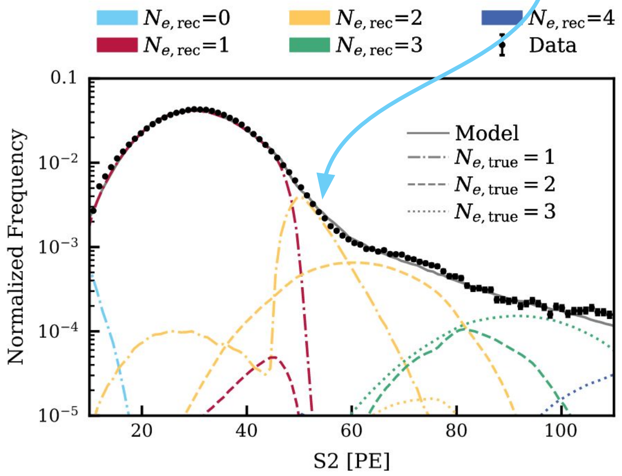
Challenge:

Smearing of the *Ne,rec* due to the detector response fluctuations (diffusion, extraction efficiency, etc)

Approach:

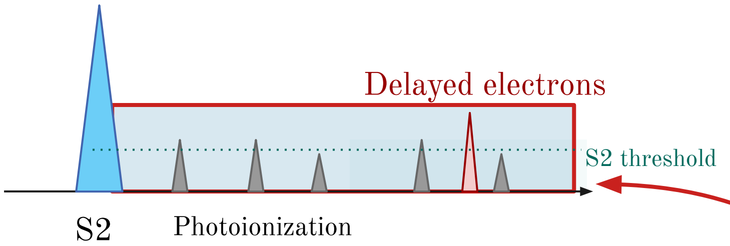
Quantify *Ne,rec* using S2-splitting algorithm, identify the discrepancy with simulation

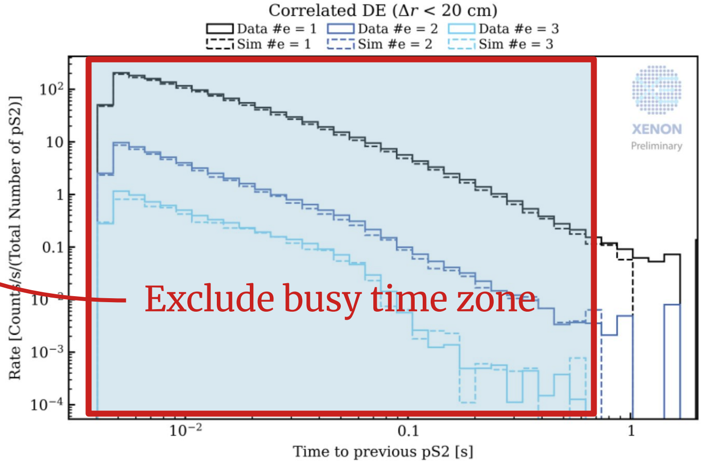
Good agreement between model and data



S2-only analysis

Challenge 2: Delayed electron emission



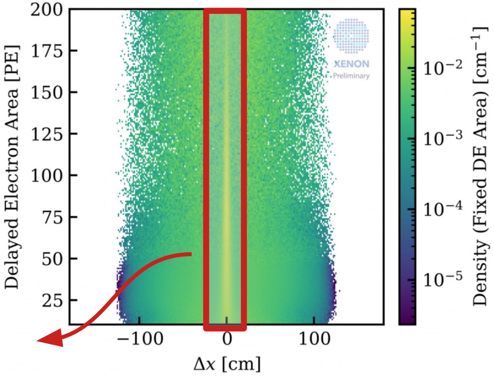


Origin:

Delayed electrons trapped in the impurities

Approach:

1. Pair delayed electrons (small S2) with preceding large S2
2. Characterize their temporal and spatial distribution
3. Exclude the busy temporal / spatial region after large S2



Exclude busy XY regions

S2-only analysis
Unblinding Events

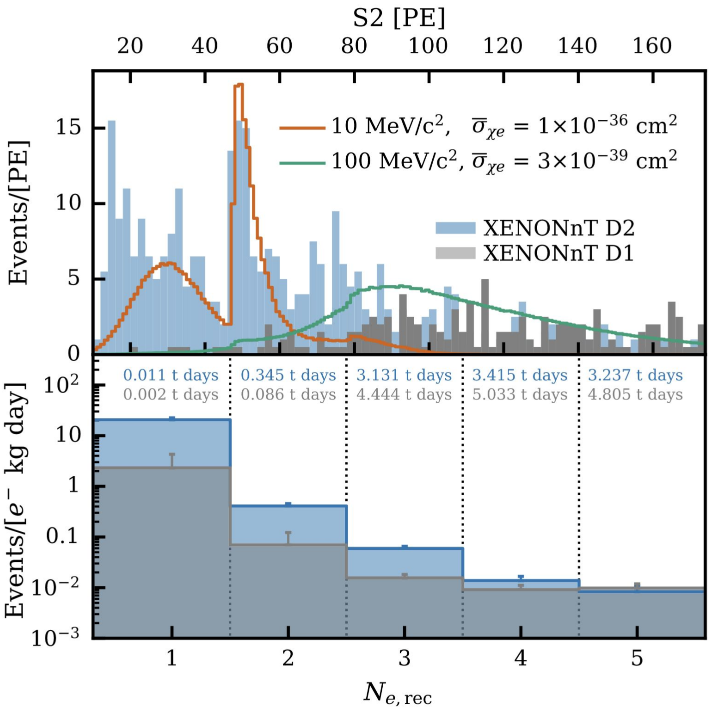
After unblinding:

O(100) S2-only events observed in blinded analysis (blue) and unblinded analysis (gray)

Benchmark models:

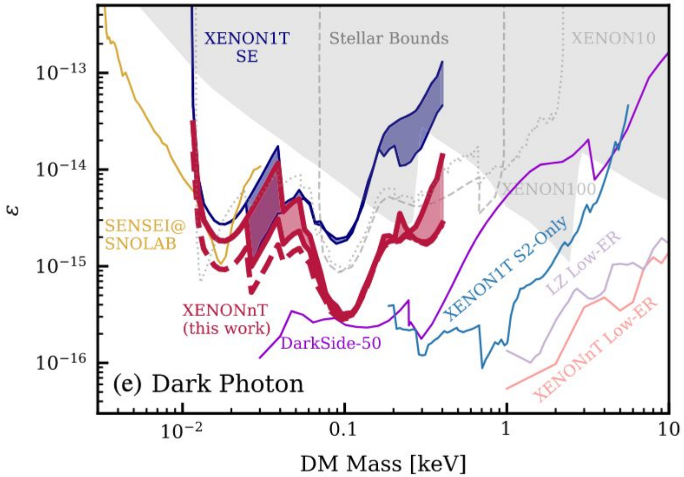
10 MeV/c² & 100 MeV/c² DM-electron scattering (heavy mediator)

Effective livetime increases with electron number since fewer events are removed by the busy-time veto

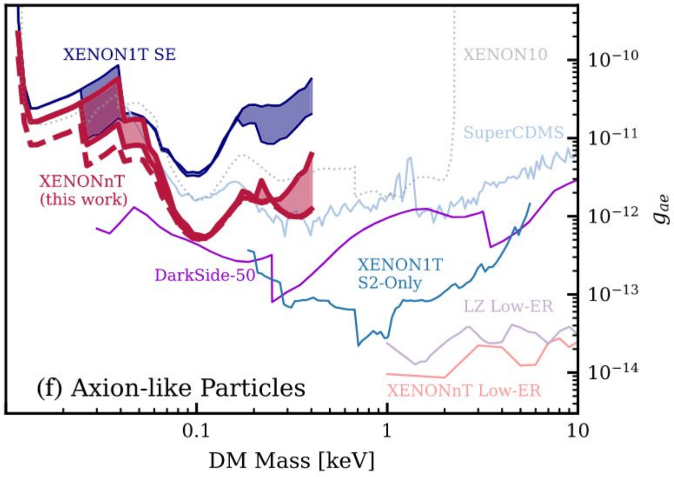


S2-only analysis
Dark matter limits

Dark photon
(kinetic mixing with SM photon)



Axion-like particles
(electron coupling)



Stringent new limits on electron absorption of axion-like particles and dark photons for $m_X < 0.03$ keV/c^2

Summary

Two science searches towards light dark matter in XENONnT:

- Low-photon S1 analysis → sensitive to DM = [3, 12] GeV/c^2
- S2-only analysis → extends reach to sub-GeV DM

Results:

- Spin-independent DM–nucleon cross section down to 2.5 $\times 10^{-45}$ cm^2 at 6 GeV/c^2 DM
- New leading constraints on dark photons and axion-like particles

Please see more details on the papers:

- *Phys. Rev. Lett. 134, 111802 (2025)*
- *Phys. Rev. Lett. 134, 161004 (2025)*

Summary

Two scienc

- Low-
- S2-o

Results:

- Spin
×10⁻
- New
parti

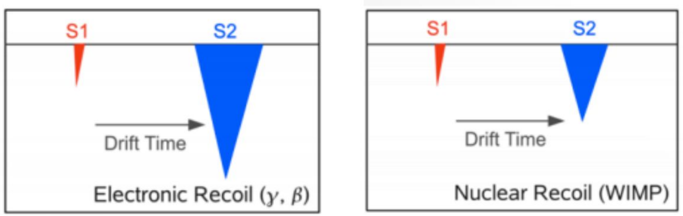
Please see r

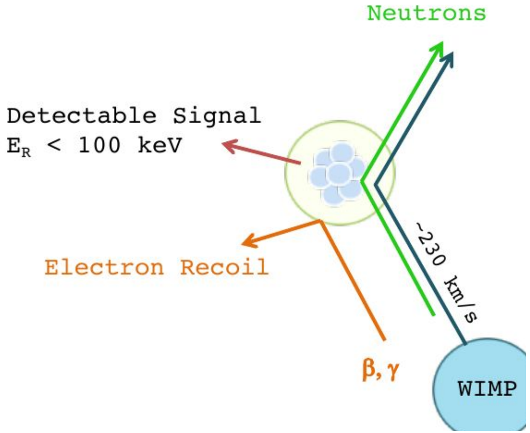
- *Phys.*
- *Phys.*

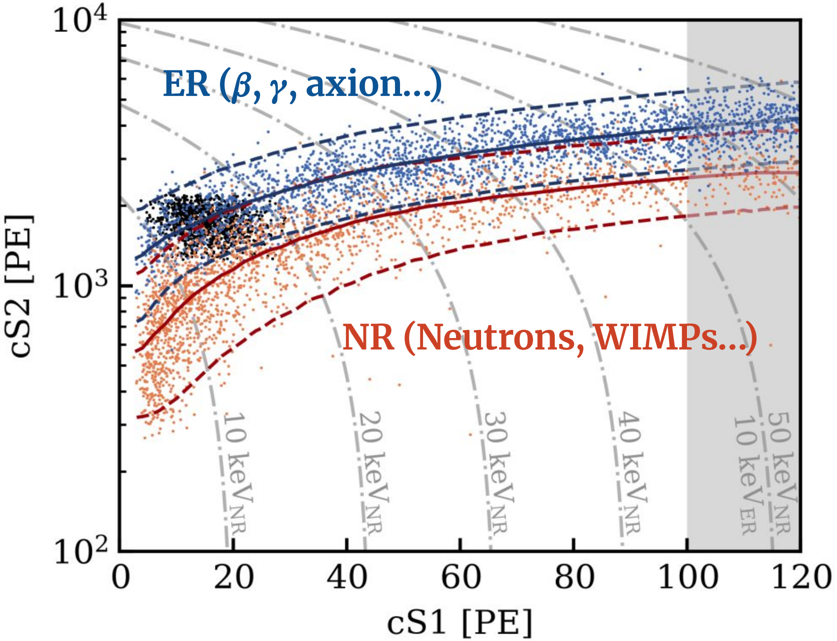
Back-up slides

How to identify NR (nuclear recoil)?

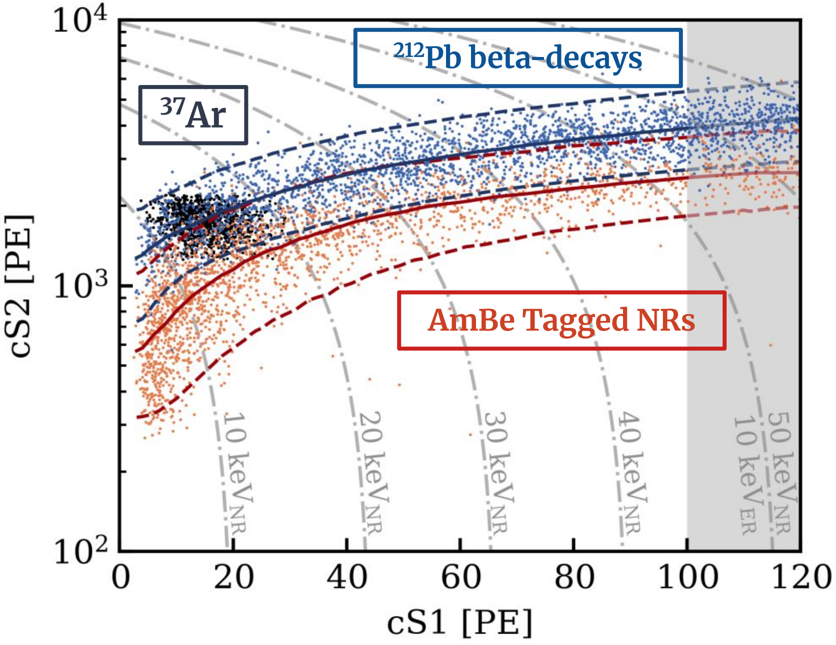
Using S2/S1 to discriminate
electronic recoil (ER) and nuclear recoil (NR)







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

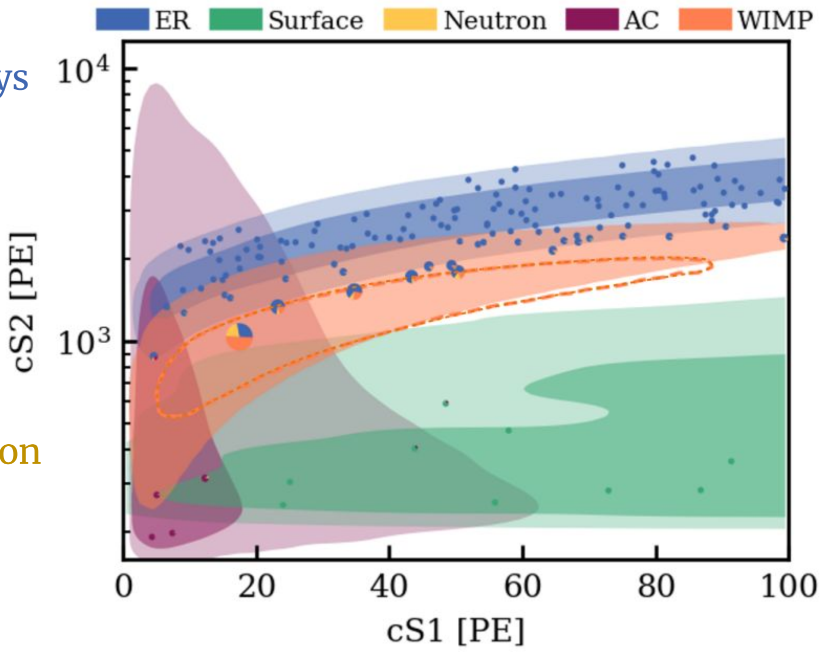
How to identify the background?

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

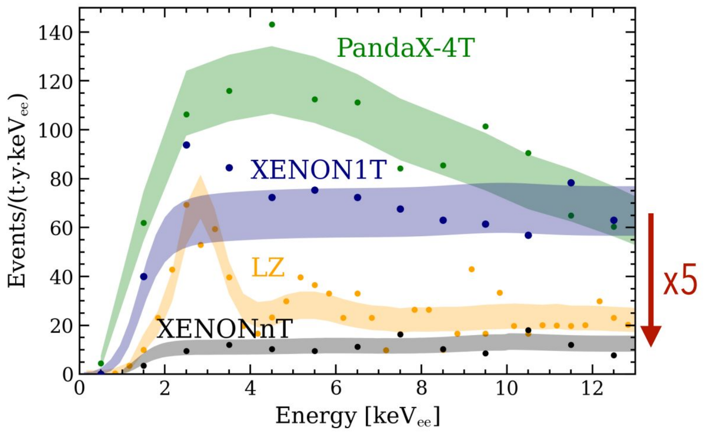
Rn distillation column
⇒Reduction of ER background by a factor of ~6

- **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**



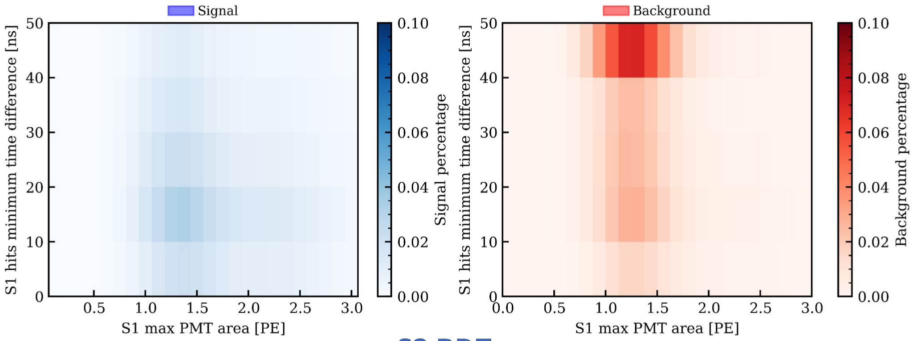
Low-photon S1 analysis
AC background removal

Machine learning AC background suppression

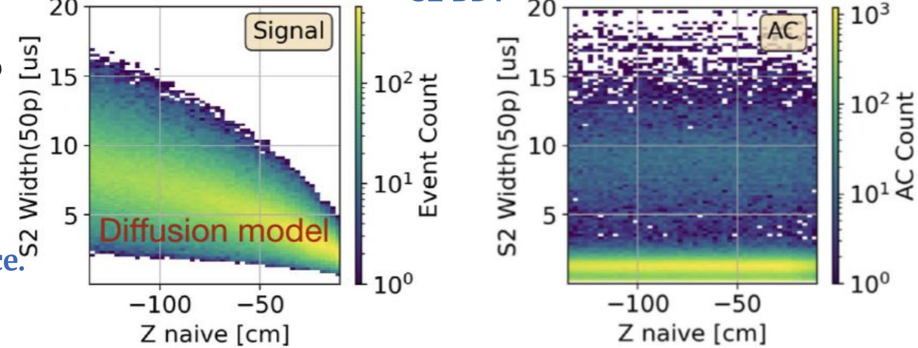
S1 and S2 features can distinguish signal and background using Boosted Decision Tree (BDT).

- **S1 BDT:**
  - Signal: Narrower S1 width, double-photoelectron (DPE) effect.
  - AC: Wider S1 width, no DPE effect.
- **S2 BDT:**
  - Signal: Deeper event ~ wider S2, due to electron diffusion.
  - AC: S2 width uncorrelated with event depth.
- **Both BDT scores are used in the inference.**

S1 BDT

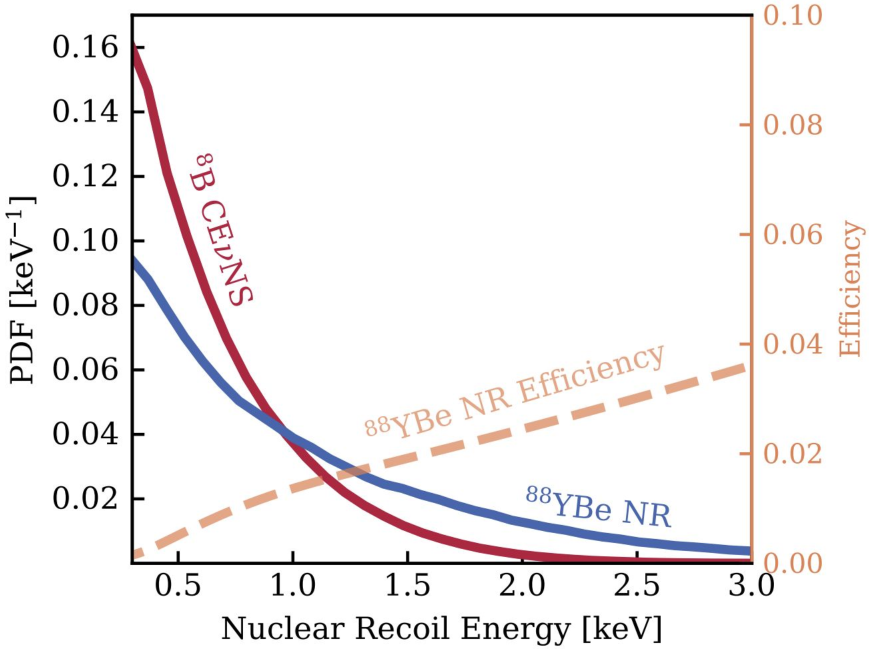


S2 BDT



Low-photon S1 analysis

YBe calibration

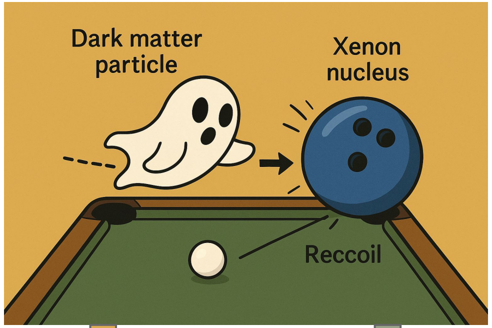


S2-only analysis

Lower the detection threshold ⇒ Light DM

Why S2-only? Small example:

**Q~2.8 keV
from Ar37 decay**



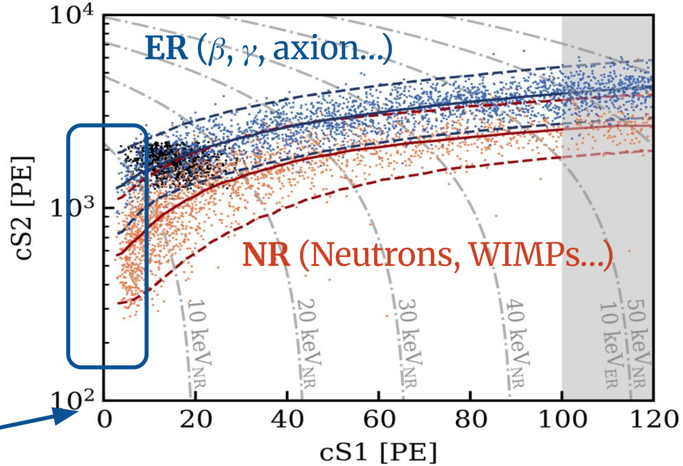
Photon ✖150 → S1 = **15 PE**

e− ✖100 → S2 = **1600 PE**

S2 amplified by secondary scintillation

Detected Photoelectron [PE]

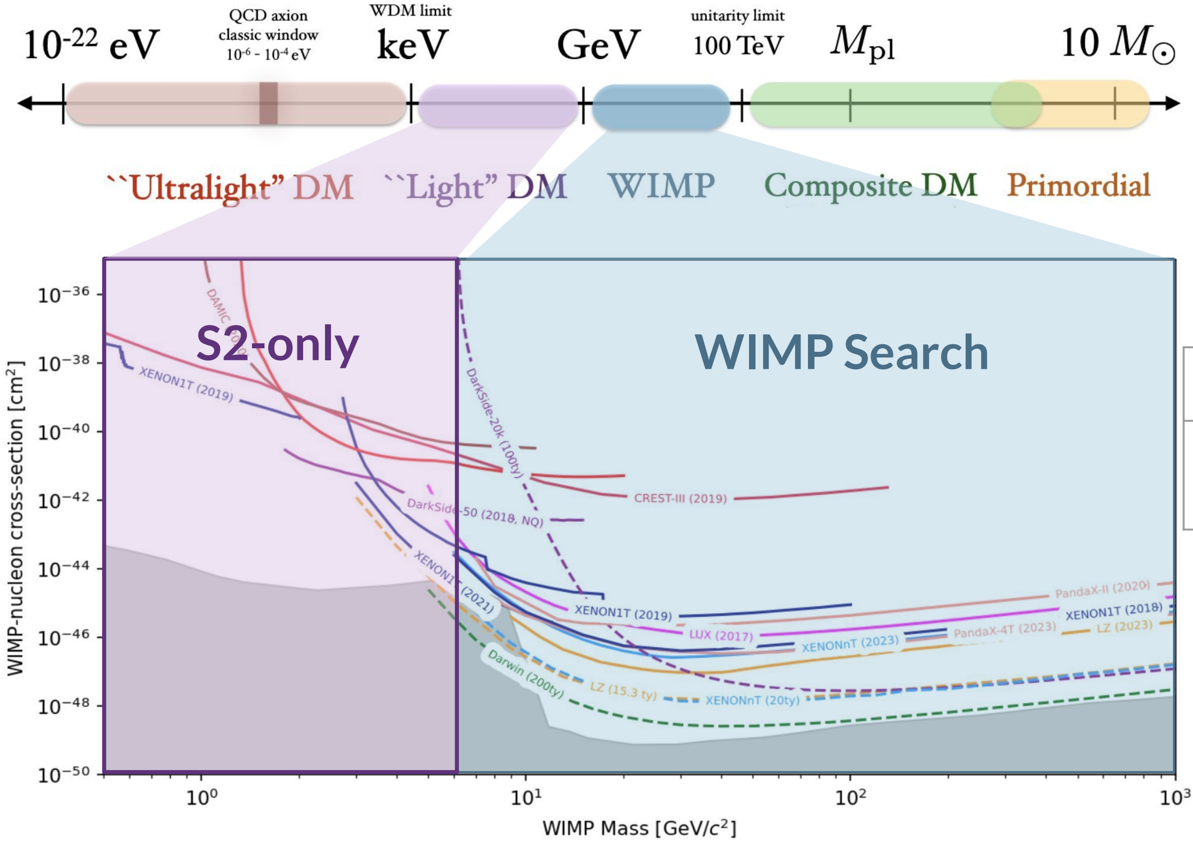
S2 ~ 100 ✖S1
⇒ S1 vanishes (<3 PE)
but S2 remains (<500 PE)



NR: Nuclear recoil
ER: Electronic recoil

S2-only analysis

Lower the detection threshold ⇒ Light DM



S2-only lower the detected recoiled energy:

	S1-S2	S2-only
ER	1.2 keV	13.7 eV (0.05–3 GeV DM)

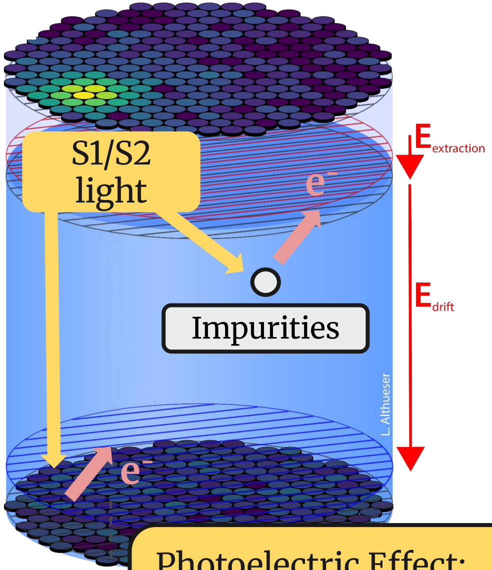
XENON

S2-only analysis

Photoionization vs Delayed electrons

XENON

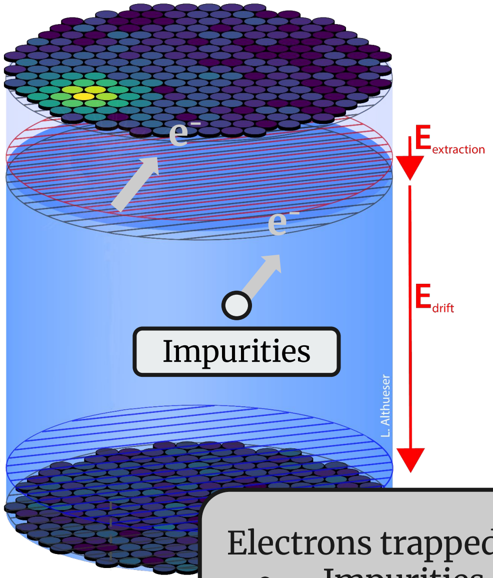
Photoionization



Photoelectric Effect:

- Impurities in the liquid xenon
- Metal surfaces

Delayed electrons



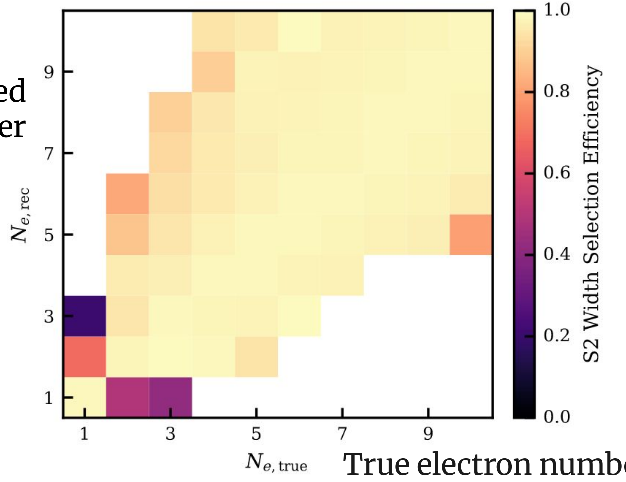
Electrons trapped by:

- Impurities
- Liquid-gas interface

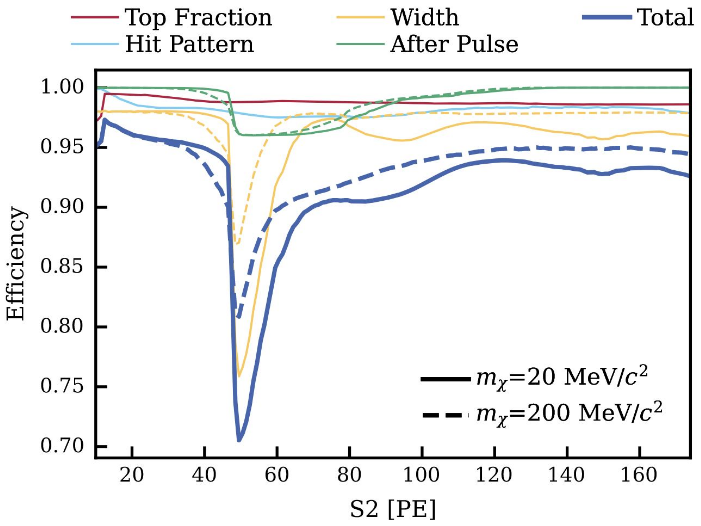
S2-only analysis

S2 width selection efficiency

Reconstructed electron number

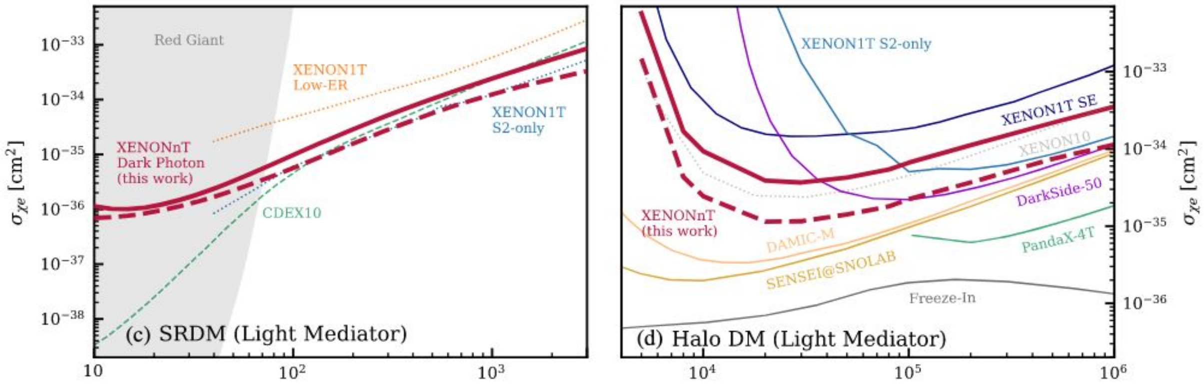


True electron number



S2-only analysis

DM limits



SRDM
(Light Mediator)

Solar-Reflected DM
= halo DM upscattered by Sun

Halo DM
(Light Mediator)

With velocity distribution from standard halo model