Search for WIMPs and light Dark Matter with XENON experiments

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Saint-Jean-de-Monts

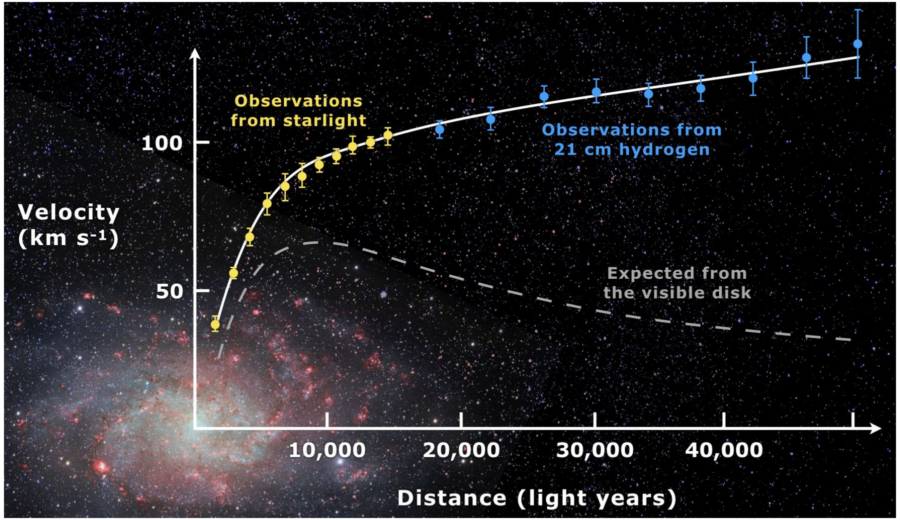
XENON

LPNHE PARIS

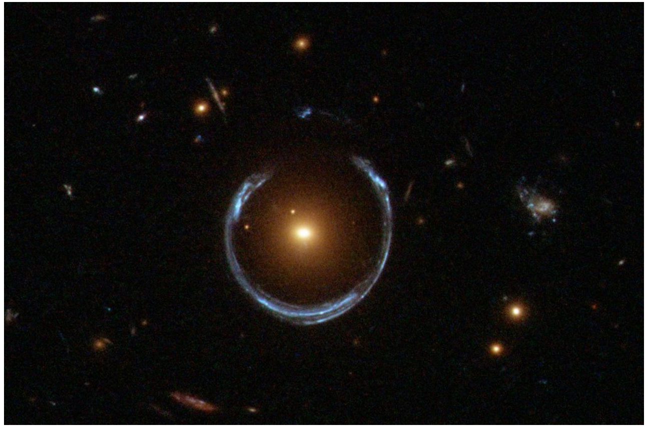
SCIENCES SORBONNE UNIVERSITÉ

Why dark matter?

Galaxy rotation curves



Gravitational lensing



⇒ Makes up of 26.8% of total mass-energy content of the universe

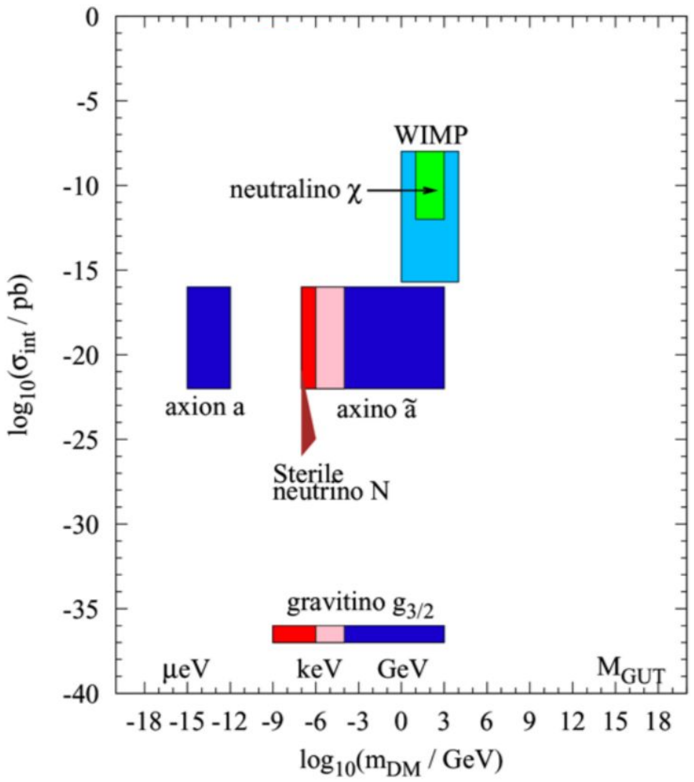
Rubin V C, Ford Jr W K. Rotation of the Andromeda nebula from a spectroscopic survey of emission regions[J]. The Astrophysical Journal, 1970, 159: 379.

What might be Dark Matter?

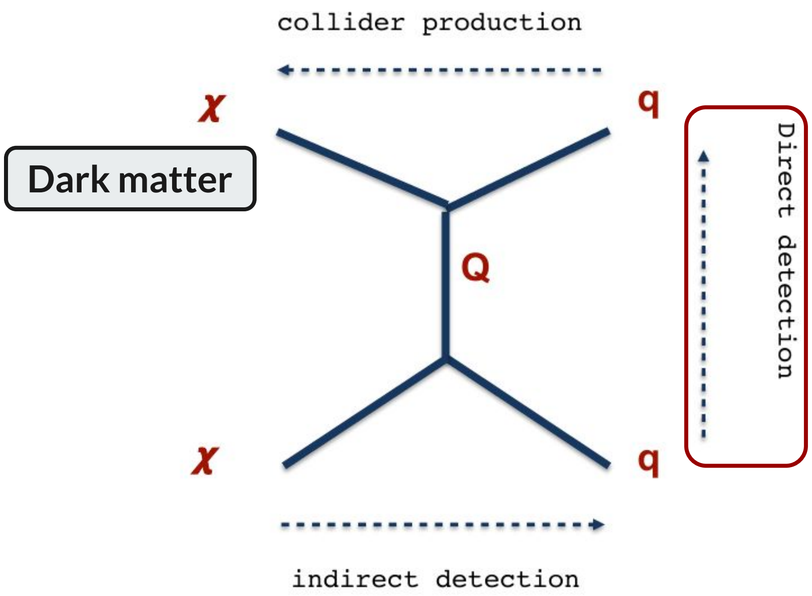
Characteristics of DM:
- BSM particles
- Electrically neutral
- Long-lived

3 mass regimes:
- Hot dark matter: < 1 eV
- Warm dark matter: ~ keV
- Cold dark matter: GeV - TeV

⇒ Small mass particles might show the disagreement with large-scale structure and CMB results
⇒ WIMPs (Weakly interacting massive particles)



How to detect?



- **Colliders production**

Measure missing momentum from $\chi\overline{\chi}$

$$p + p \to \chi\overline{\chi} + X$$

- **Indirect detection**

Detect annihilation SM products

$$\chi\chi \to \gamma\gamma, \gamma \mathrm{Z}, \gamma \mathrm{H}$$

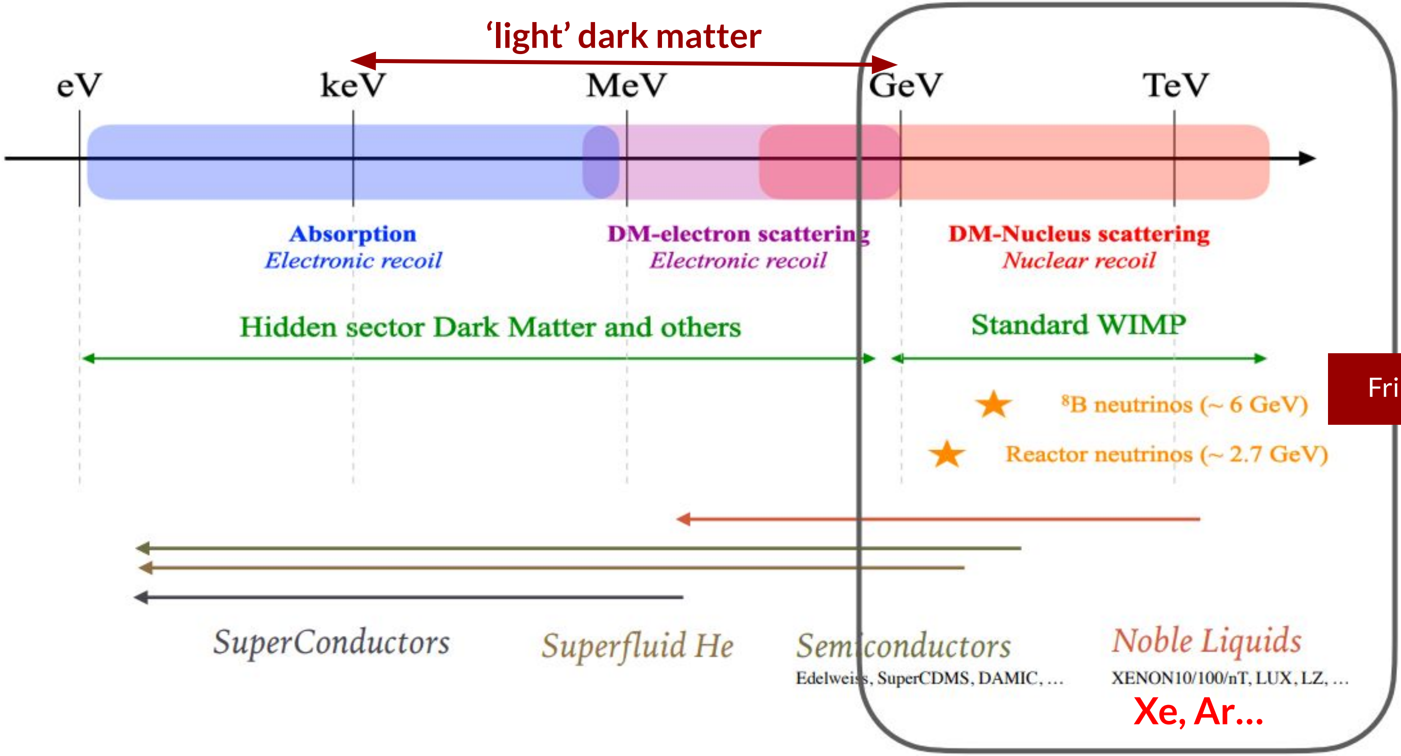
$$\chi\chi \to \mathrm{qq}, \mathrm{W}^{+}\mathrm{W}^{-} \to \mathrm{e} + \mathrm{e}^{-}, \mathrm{p}, \mathrm{v's}$$

- **Direct detection**

Detect the deposited energy of scattering process (light / charge / heat signals)

Direct detection of WIMPs

XENON



Fri 16:30 by Q. Pellegrini

Jodi Cooley, Dark Matter Direct Detection of Classical WIMPs, 2021 Les Houches Summer School lecture manuscript

1. Introduction
2. Overview of XENON & first results
3. S2-only analysis for light DM
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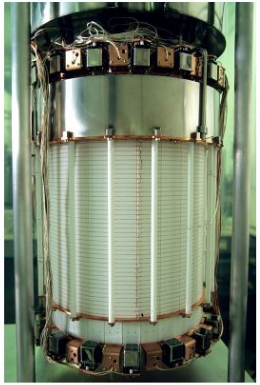
XENON project

@ Gran Sasso National Laboratory (LNGS), Italy

XENON

XENON10

2005-2007
14 kg Xe target
$\sigma_{SI} \sim 9 \times 10^{-44}$ cm^2
(2007)



XENON100

2008-2016
62 kg Xe target
$\sigma_{SI} \sim 10^{-45}$ cm^2
(2016)

XENON1T

2016-2018
2 t Xe target
$\sigma_{SI} \sim 9 \times 10^{-47}$ cm^2
(2018)

XENONnT

2020-2027
5.9 t Xe target
$\sigma_{SI} \sim 2.8 \times 10^{-47}$ cm^2
(2021)

How to detect a particle in our huge xenon tank?

Dual phase TPC (Time projection chamber)

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

induced by ionionized electrons

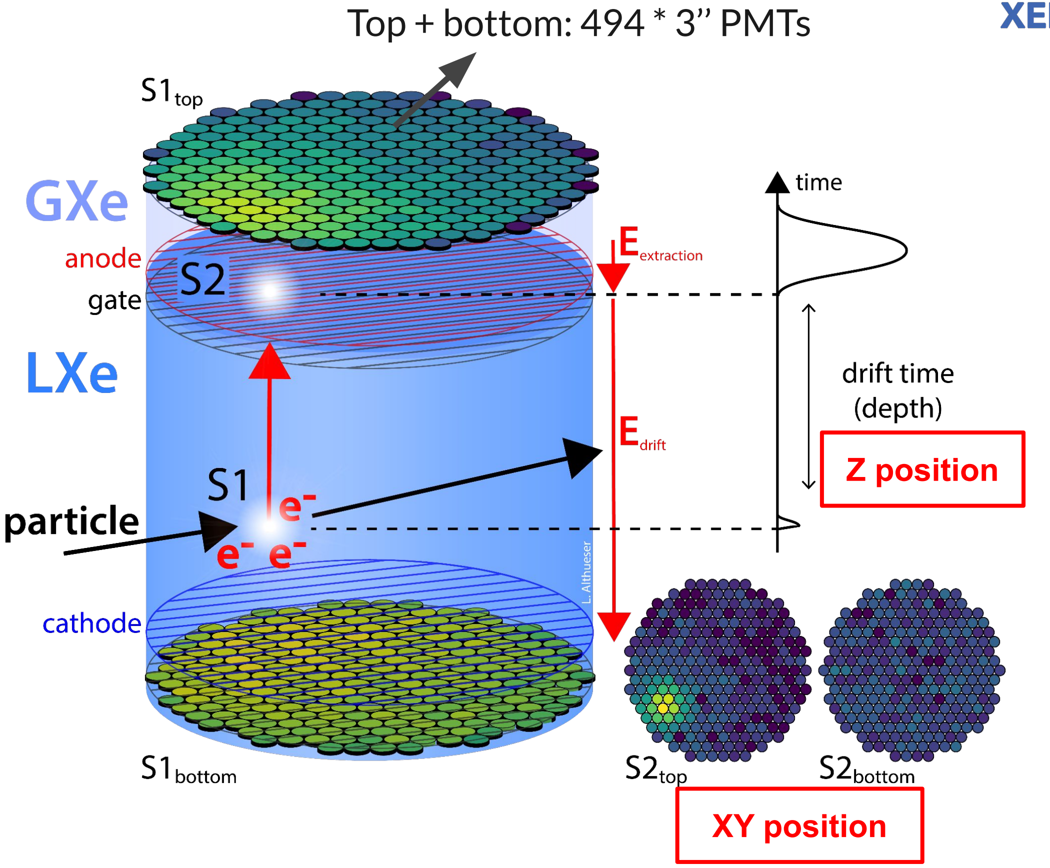
- Position reconstruction:

drift time + PMT pattern

- Energy reconstruction:

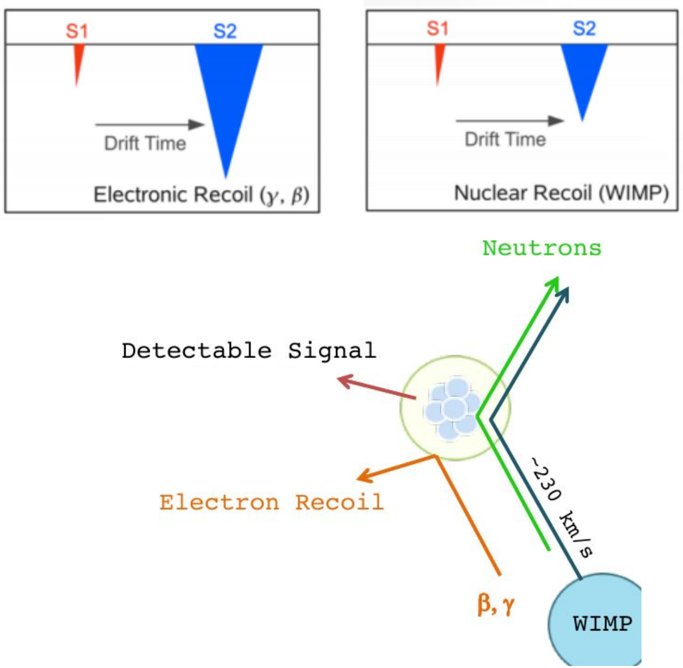
$$E = W\left(\frac{cs_1}{g_1} + \frac{cs_2}{g_2}\right)$$

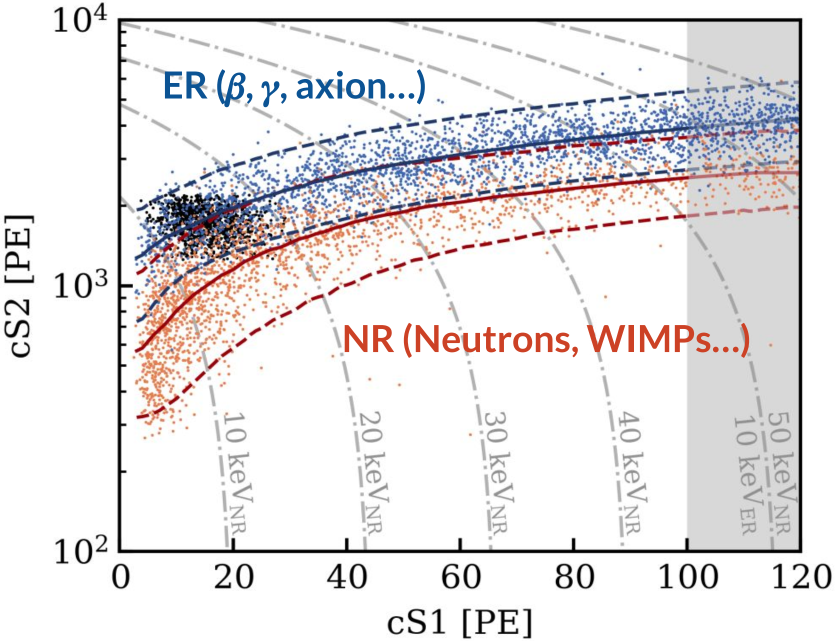
W: average energy to produce a quanta
cS1, cS2: corrected area of S1 and S2
g1, g2: gain of S1 and S2



How to identify WIMPs?

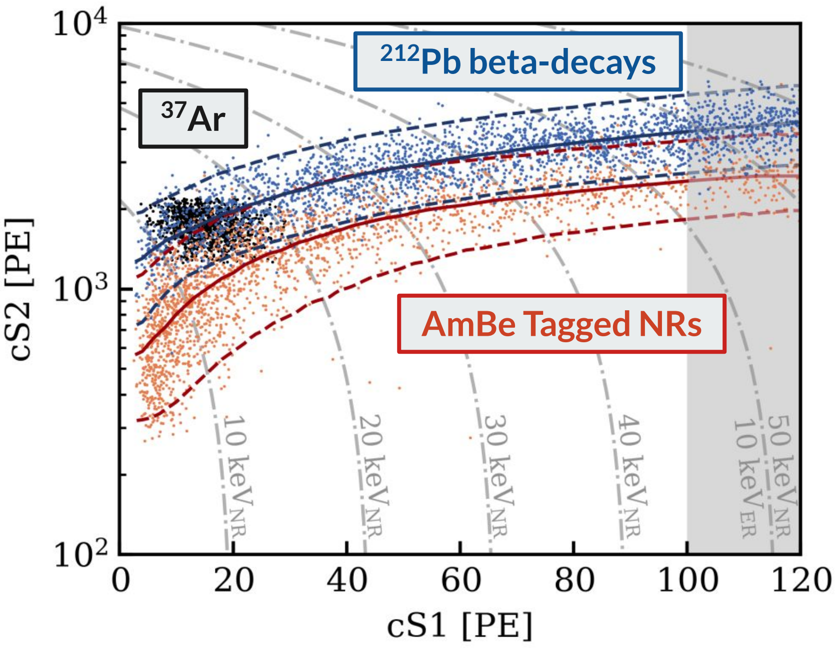
Using S2/S1 to discriminate
electronic recoil (ER) and nuclear recoil (NR)





arXiv:2303.14729 [hep-ex]

How to calibrate our detector?



Calibration for ER:

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

- 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

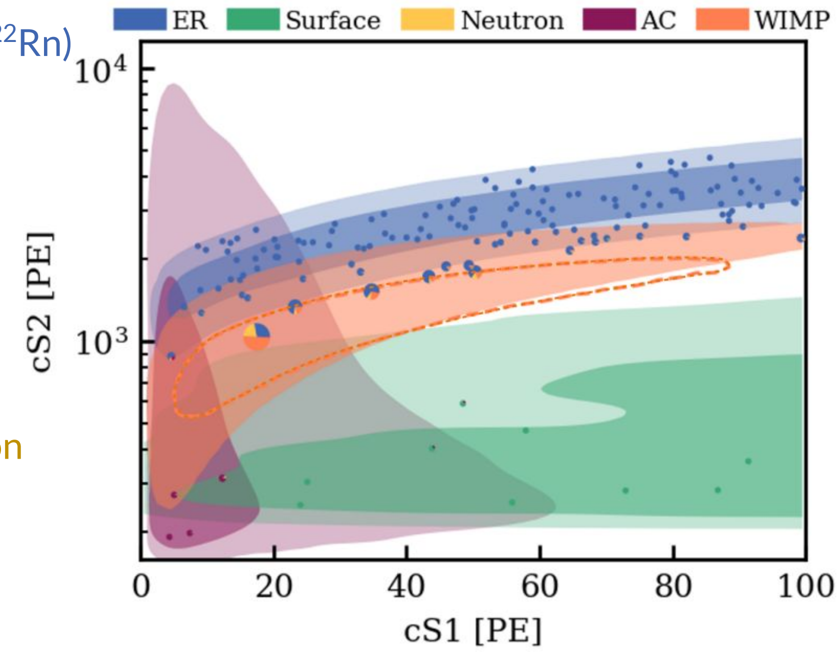
How to identify the background?

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

Surface background:
- beta decays of $^{210}Pb/^{210}Bi$ from TPC wall
- suppressed by fiducial 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



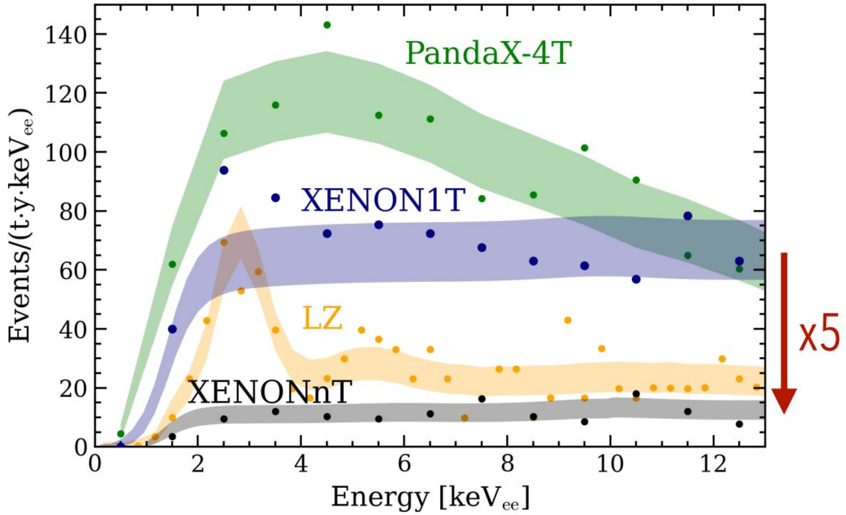
Signal-like region containing 50% of a 200 GeV/c^2 WIMP signal with highest signal-to-noise ratio

Upgrade from XENON1T to XENONnT

XENON

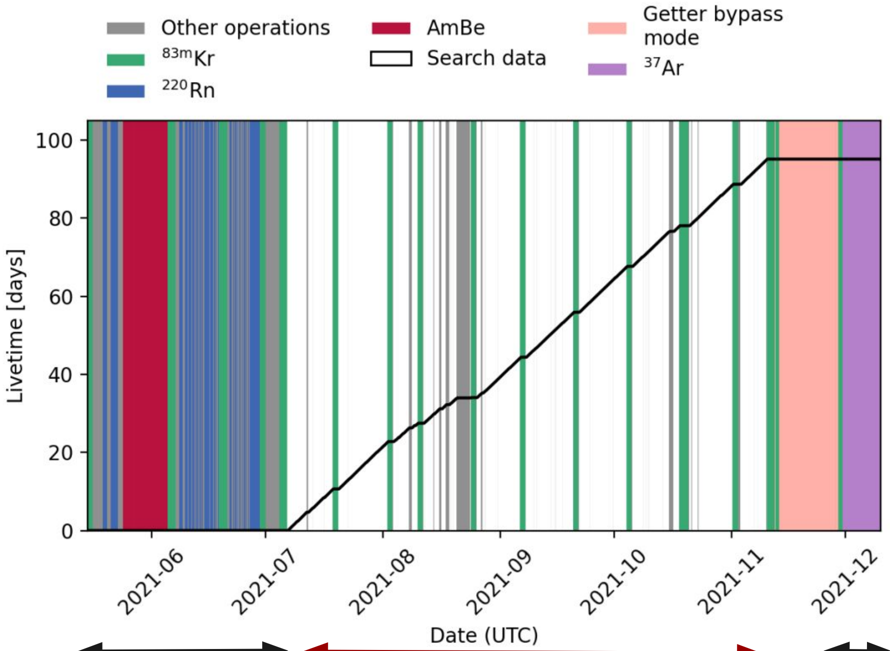
- **Increased xenon target mass**
- **New xenon purification system**
- Reduction of electronegative impurities
  ⇒ Longer electron lifetime
- **Novel Rn distillation column**
- Concentration: 1.8 µbq/kg
- Reduction of ER background by a factor of ~5

	Full drift time (ms)	Electron lifetime (ms)
1T	0.67	0.65
nT	2.2	~15



First results from XENONnT

Used data: SR0 (Science run 0)

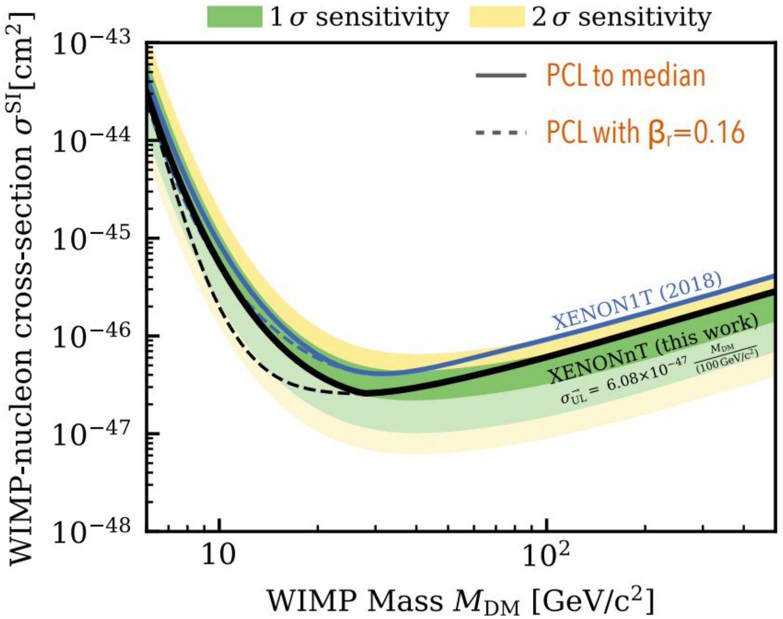


Calibration data

Blinded search data (95.1 live days, 1.1 tonne·year)

Calibration data

Limits on cross-section @ 90% confidence level



16 events in the blinded region
(152 events total in the ROI)

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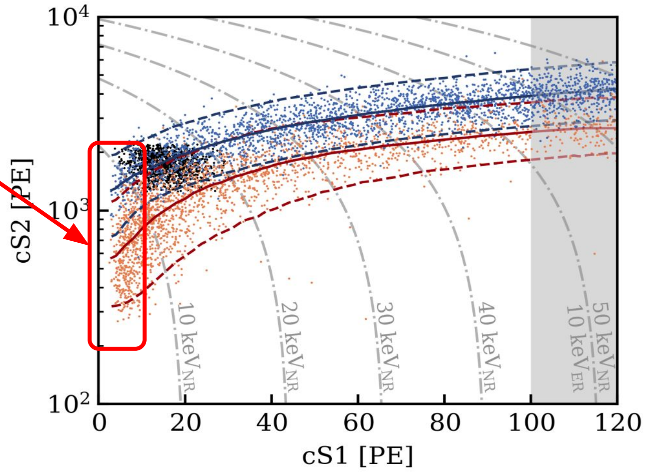
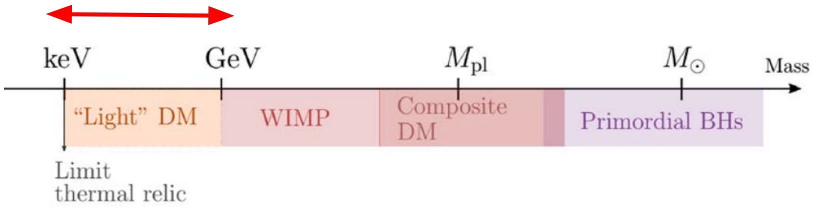
Why only S2 signal?

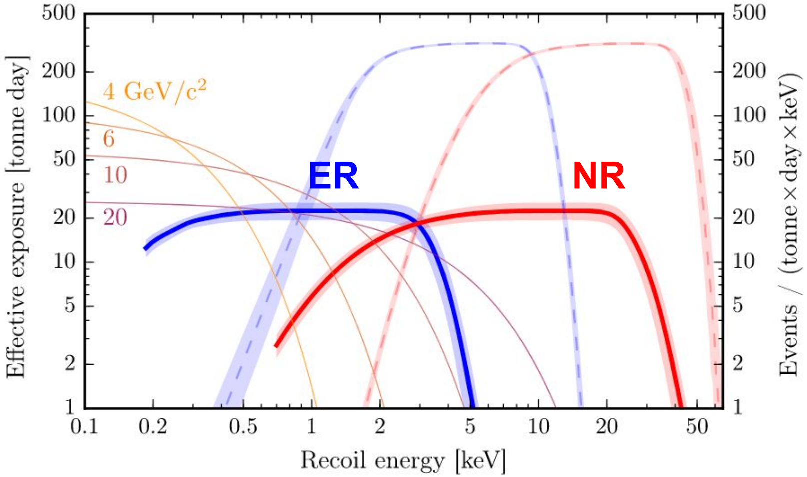
S1 ⇒ ~0 but S2 remains ~ 10^3 PE



With **both S1 (>3 PE) & S2**:
detect events with recoil energy > 3.5 keV
With **only S2 (>150 PE)** :
detect events with recoil energy > 0.7 keV (0.186 keV) for NR (ER)

⇒ S2-only lowers the detectable energy threshold for 'light' dark matter

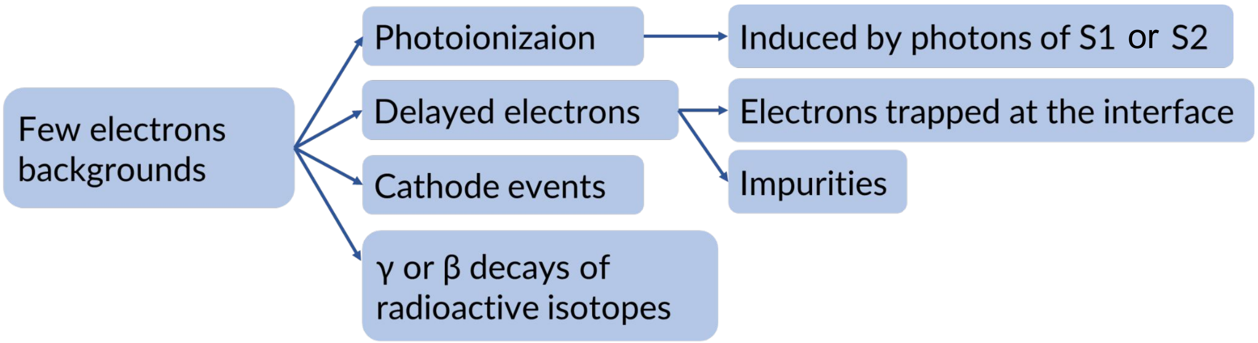




What is the background in S2-only

XENON

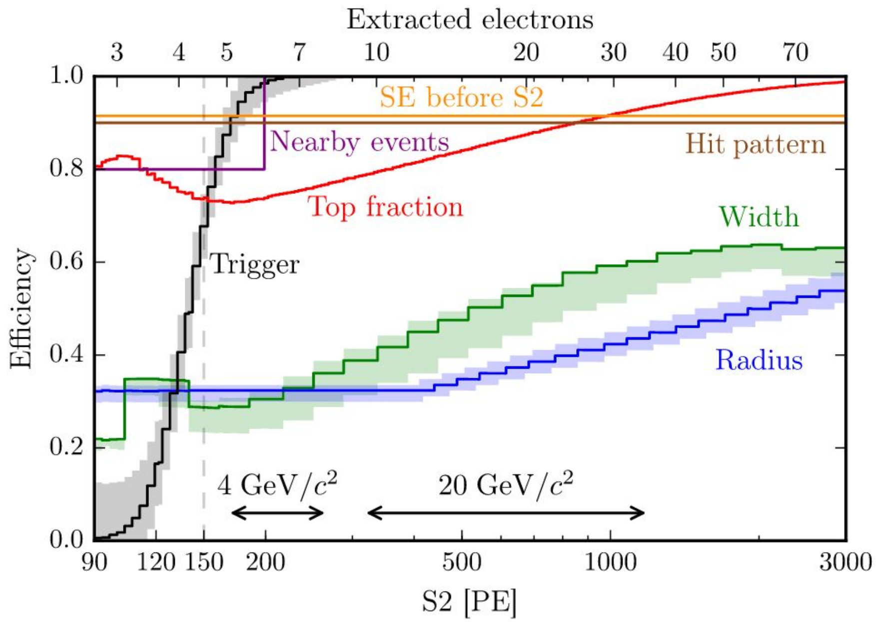
Two main challenges compared to normal S1/S2 analysis:
1. Small signals ⇒ more background, noises…
2. Lack of S1 ⇒ incomplete background model

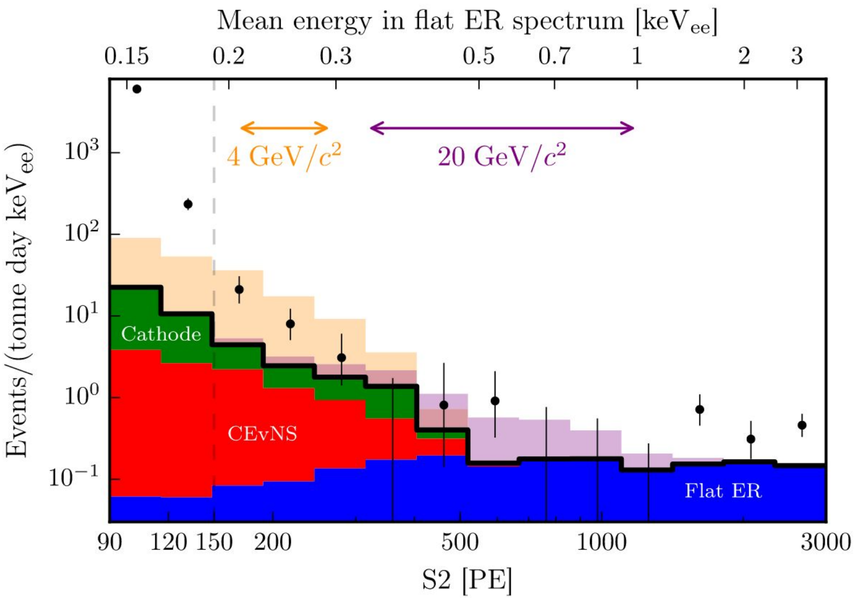


What is the background in S2-only

1. Data selection:
Eliminate unwanted events such as gas events, surface events, pileup of single electrons…

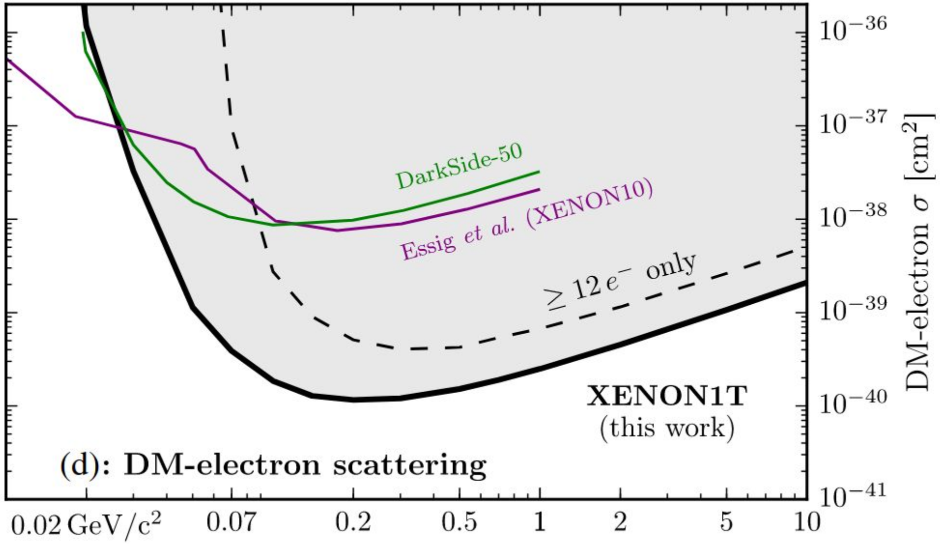
2. Identifying background:
ER background from beta emitter (eg. ^{214}Pb)
CEvNS (coherent nuclear scattering of ^{8}B solar neutrinos) and **cathode events**

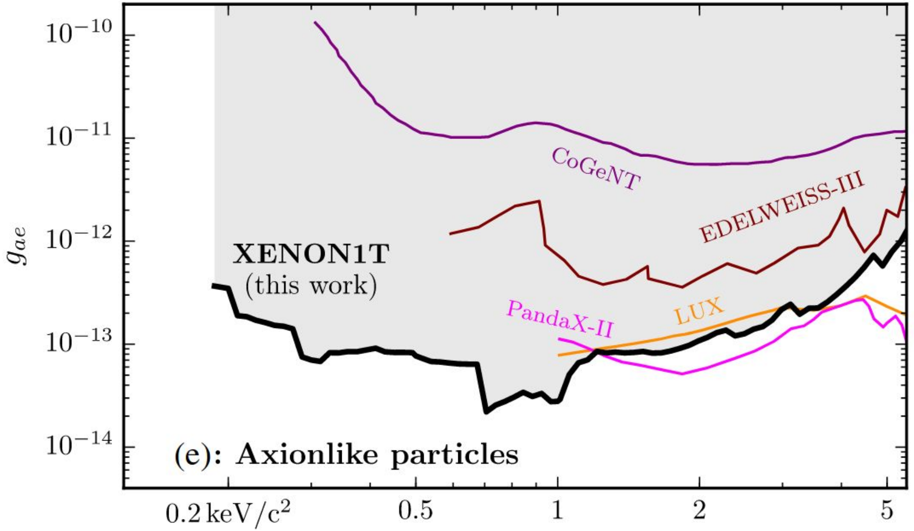




Limits set by S2-only analysis

Results from XENON1T, set upper limits on DM-matter scattering for multiple models @ 90% confidence level





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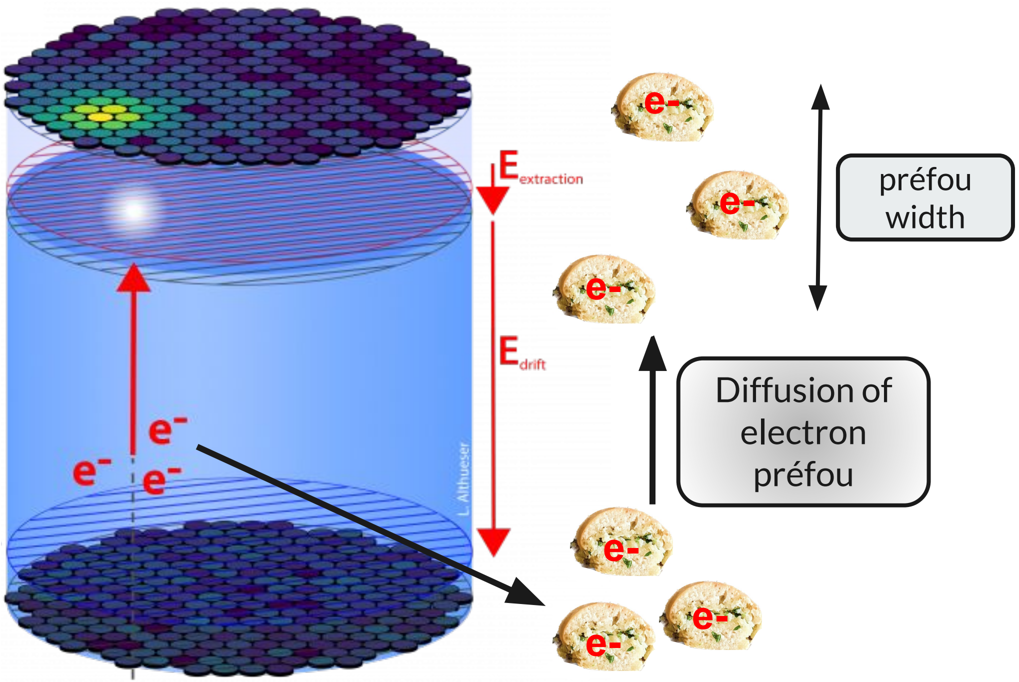
Ongoing analysis on general XENONnT

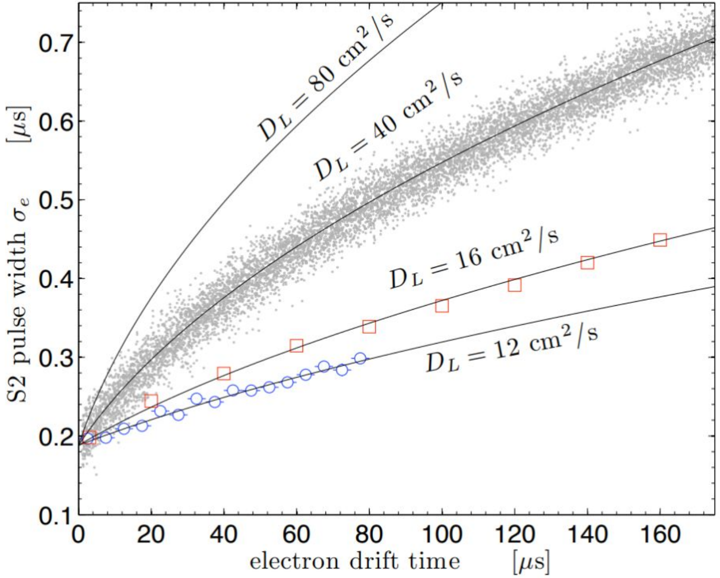
S2 width cut ⇒ reject the events with nonphysical drift time

- General: diffusion model - width ∝ $\sqrt{D^{*}t/v^{2}}$ (diffusion constant, drift time, drift velocity)
- S2-only scale: first principles



Diffusion model to predict S2 width

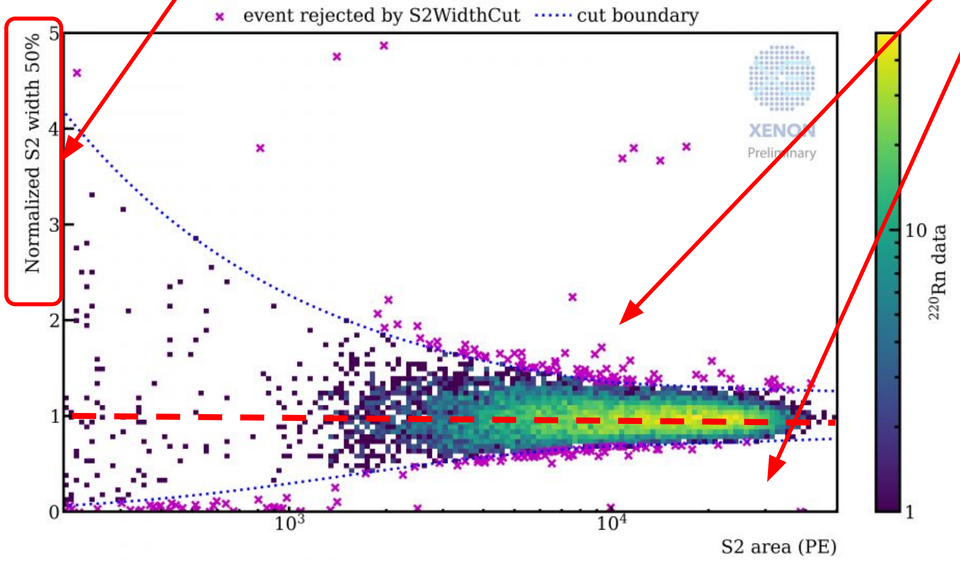
⇒ modeled S2 width

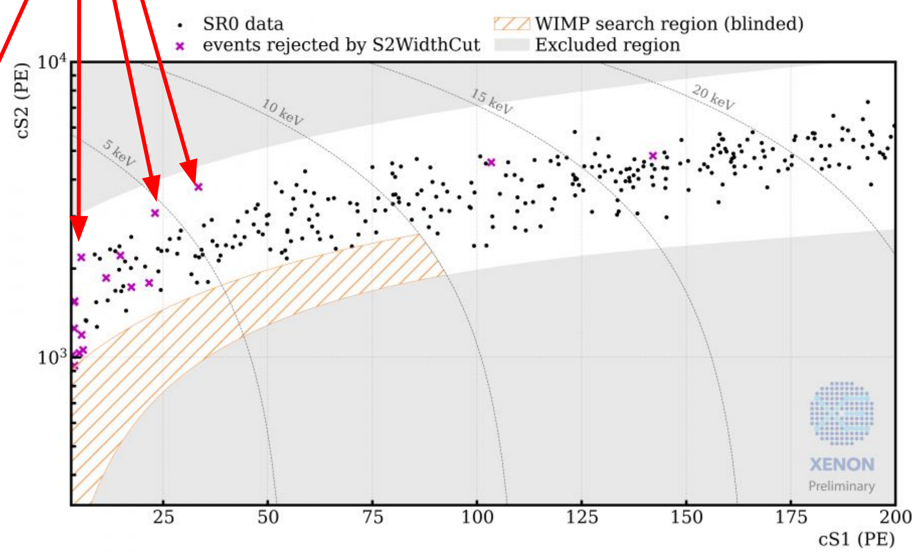


Ongoing analysis on general XENONnT

Normalized S2 width
~ modeled S2 width / measured S2 width

Events rejected by S2 width cut





Ongoing analysis on S2-only

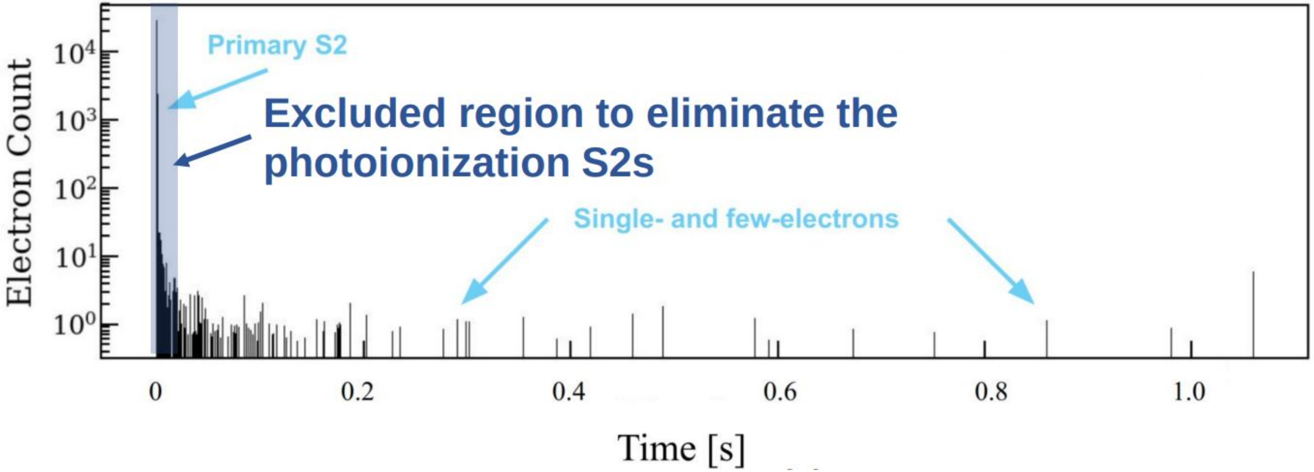
XENON

2. Peak classification algorithm

XENON1T: “Primary S2s” and “delayed electrons”

⇒ identify more categories such as “fake S2”, “photoionization”

⇒ correctly pair primary S2s with their delayed electrons peaks and to register other peaks



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Summary & perspectives

XENON

In conclusion:

- First WIMP search with SR0 data (exposure= 1.1 tonne·year)
- S2-only analysis opens up the possibility of exploring 'light' dark matter particles
- Reduction of ER background (15.8±1.3) events/(t·y·keV) and greater active xenon mass in XENONnT

⇒ more stringent limits on 'light' dark matter set by S2-only analysis

Future works on ongoing analysis:

- Further study on S2 width cut in SR1
- Characterization of different populations classified by new peak classification algorithm in SR1

Thank you for your attention!

Backup - S2 width cut

Definition of S2 width: Time difference between the 0.25 and 0.75-percentile

What affect S2 width: diffusion effect (along z direction, dominent with high amount of e-: >20e-) of electron cloud (dominent with a few e-), drift velocity, z, S2 area

S2 width (50% percentile)

Diffusion coeficient

Drift time

50% percentile range of normal distribution (0,1)

Gate drift time

$$r_{50}^{\text{mod}}(t) = 1.349\sigma = 1.349\sqrt{\frac{2D\cdot(t-t_{\text{gate}})}{v^2} + scw^2}$$

secondary_scintilation_width

Electron drift velocity (average)

= distance (gate - cathode) / (Cathode drift time - Gate drift time)

Use diffusion model (input: drift time) ⇒ predict modeled s2 width

Normalized S2 width:

Mesured / modeled should around 1:

$$r_{50}^{norm}(t) = \frac{\left(r_{50}(t)\right)^2}{\left(r_{50}^{\text{mod}}(t)\right)^2}$$

s2_range_50p_area

Backup - S2 width cut

Aims to remove gas events, accidentally coincidence events, and generally any event with unphysical drift time.

1. Cut based on chi2 distribution:

$$\left(r_{50}^{\text{norm}}\right)^2 \cdot (n_e - 1) = \chi^2(n_e)$$

2. Cut based on percentile: Using WFsim data

$$n_e = \frac{r_{50}^{\text{measured}}}{scg}$$

- Upper boundary:

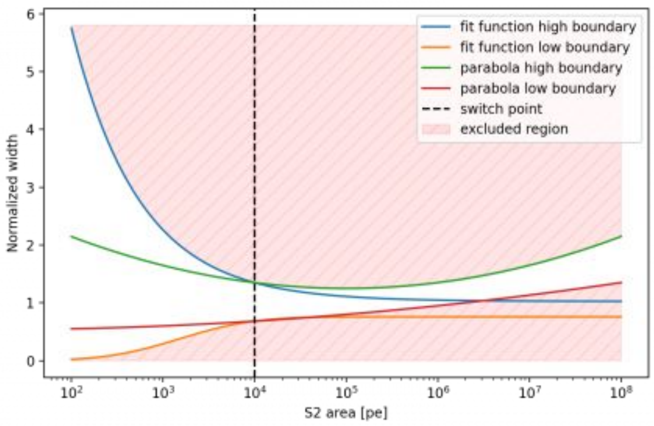
$$f(x)^{UB} = \frac{a_1}{e^{a_2(x-a_3)}} + a_4$$

- Lower boundary:

$$f(x)^{LB} = \frac{b_1}{2} erf\left(\frac{\sqrt{2}\cdot(x-b_2)}{b_3}\right)$$

- Parabola:

$$f(x)^{parab} = p_0 + p_1 + p_2^2$$



Low energy region: statistical fluctuation

switch point: 10^3.8 PE

High energy region: multiple scatter
⇒ parabola founction