Universität Zürich[UZH]

Physik Intitut

Recent results from the XENONnT experiment

CEνNS and light WIMPs

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Dark matter direct detection

Evidences for dark matter:

— Astronomical, astrophysical, cosmological

— 5x more dark matter than baryonic matter

Weakly interacting massive particles (WIMPs)

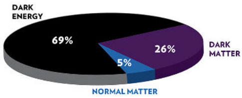
— Mass in the GeV range, interaction strength of the weak scale

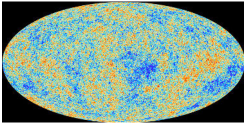
— Many candidates from BSM models

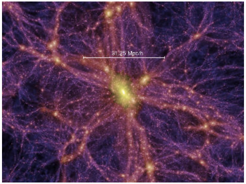
Direct search approach:

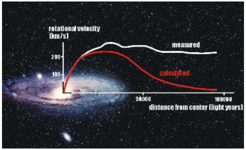
— Earth (and detector) moving through DM halo

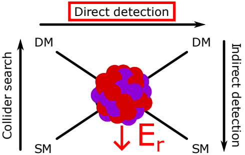
— Can induce „scattering“ event with low recoil energy

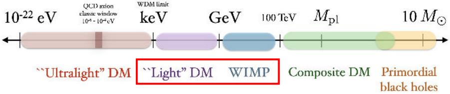












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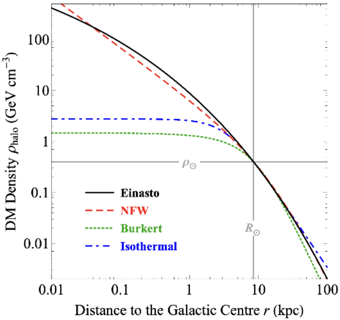
WIMP spectrum and detection efficiency

$$\frac{dR}{dE_{\text{recoil}}} = \frac{M_T}{m_A} \frac{\rho_0}{m_\chi} \int_{v_{\text{min}}}^{v_{\text{esc}}} \epsilon(E_{\text{Recoil}})\, v \cdot f(\vec{v}) \frac{d\sigma_{\chi,N}}{dE_{\text{Recoil}}} dv$$

Astrophysical inputs

- Local DM density $\rho_0 \sim 0.3\mathrm{GeV}/\mathrm{cm}^3$
- DM velocity distribution $f(\vec{v})$



JCAP10(2014)023

— Assumption: DM is collisionless with isotropic velocity distribution

— Isothermal sphere (Maxwell Boltzmann distribution)

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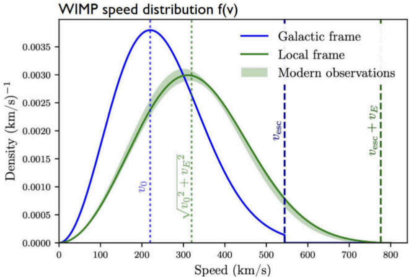

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Particle physics

- WIMP - nucleon cross section $\sigma_{\chi,N}$

$$\frac{d\sigma}{dE_R} = \frac{m_N}{2\mu^2 v^2}\left[\sigma_0^{\text{SI}} F_{\text{SI}}^2 + \sigma_0^{\text{SD}} F_{\text{SD}}^2\right]$$

$$\sigma_0^{\text{SI}} = \frac{4\mu^2}{\pi}\left[Zf_p + (A - Z)f_n\right]^2 \propto A^2$$

— F_{SI} & F_{SD} are nuclear form factors (material specific)

— At low momentum transfer: A^2 scaling due to coherence

WIMP spectrum and detection efficiency

$$\frac{dR}{dE_{\text{recoil}}} = \frac{M_T}{m_A} \frac{\rho_0}{m_\chi} \int_{v_{\min}}^{v_{\text{esc}}} \epsilon(E_{\text{Recoil}})\, v \cdot f(\vec{v})\, \frac{d\sigma_{\chi,N}}{dE_{\text{Recoil}}}\, dv$$

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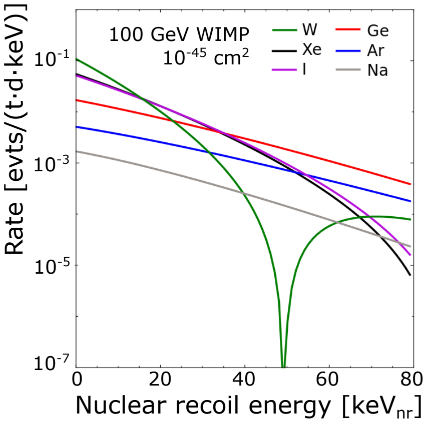
J. Phys. G43 (2016) 013001



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Particle physics

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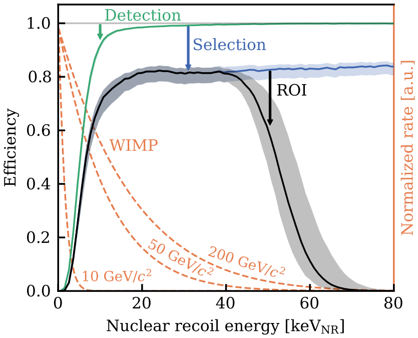
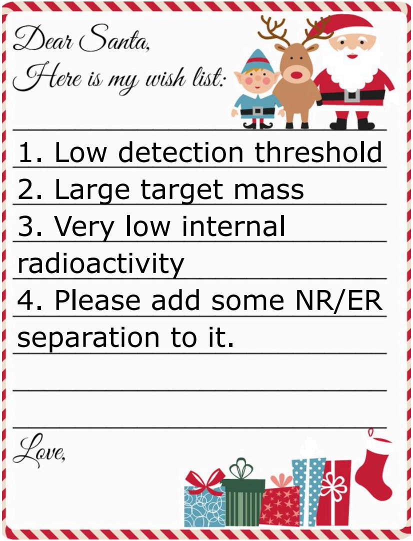
Detector physics

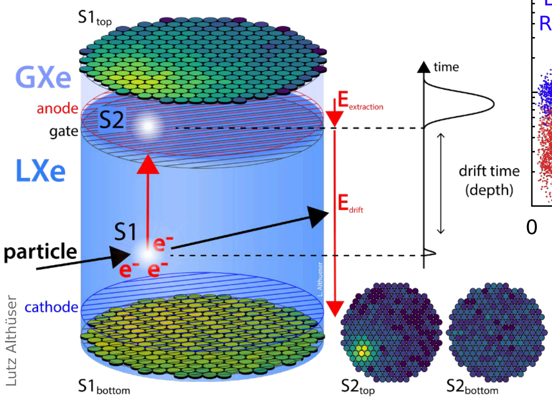
- Target material: atomic mass m_A and total mass M_T
- Energy threshold: $v_{\min}$ and detection efficiency $\epsilon(E_{\text{Recoil}})$

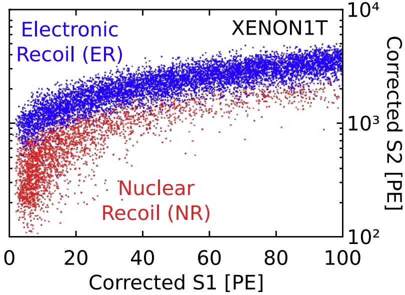
XENONnT: PRL 131, 041003 (2023)

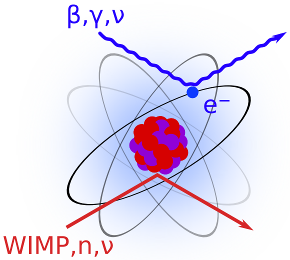



Dear Santa,
Here is my wish list:
1. Low detection threshold
2. Large target mass
3. Very low internal radioactivity
4. Please add some NR/ER separation to it.
Love,

Dual-phase TPC principle







- Electron drift time ⇒ z-position
- Distribution of S2 signal ⇒ x-y-position
- S1/S2 ratio ⇒ signal discrimination

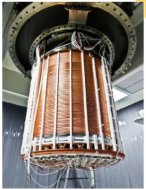
The XENON-family

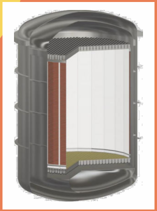
- ∼ 200 scientists
- 29 institutions
- 12 countries

The XENON family-tree

15 kg	161 kg	3.2 t	8.6 t	~50 t
XENON10	XENON100	XENON1T	XENONnT	DARWIN/ XLZD
2005 - 2007	2009 - 2016	2016 - 2018	**Now**	**Future**
0.87 kg × yr	84 kg × yr	1 t × yr	20 t × yr	200 t × yr







Credit: Tim Wolf

The XENON family-tree

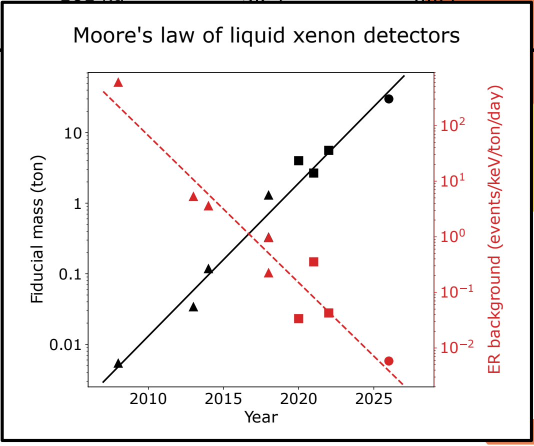
15 kg

XENON10

2005 - 2007

0.87 kg × yr

161 kg   3.2 t   8.6 t

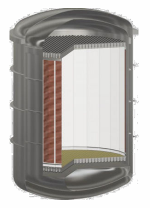


~50 t

DARWIN/ XLZD

Future

200 t × yr



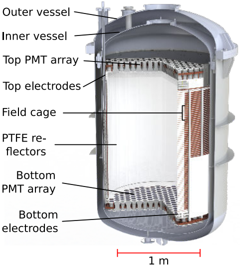
Credit: Tim Wolf

Bigger detector ⇒ less background ⇒ better sensitivity!

Some subsystems of the XENONnT detector

Dual-phase TPC

JCAP11(2020)031 & arXiv: 2007.08796



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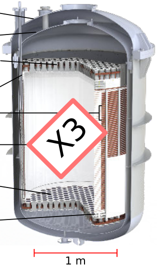
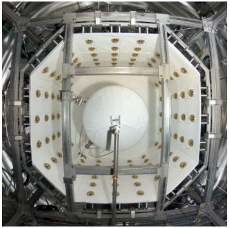


Neutron veto



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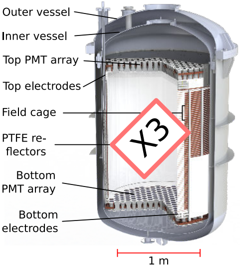
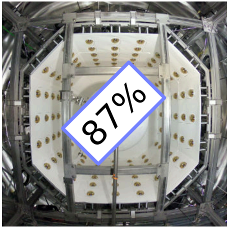


LXe purification

EPJC 82 (2022) 860 arXiv: 2205.07336

Neutron veto



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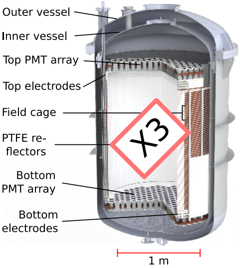

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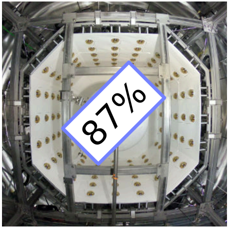
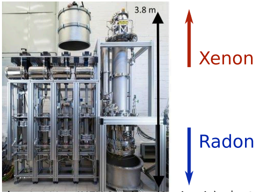


Radon distillation

EPJC82(2022)12,1104 & arXiv:2205.11492



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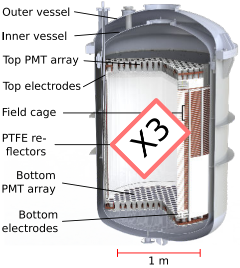

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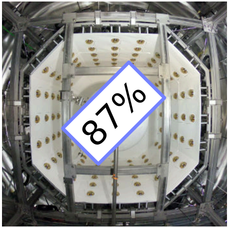

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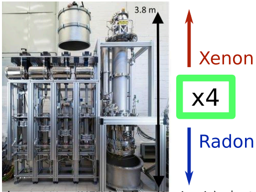
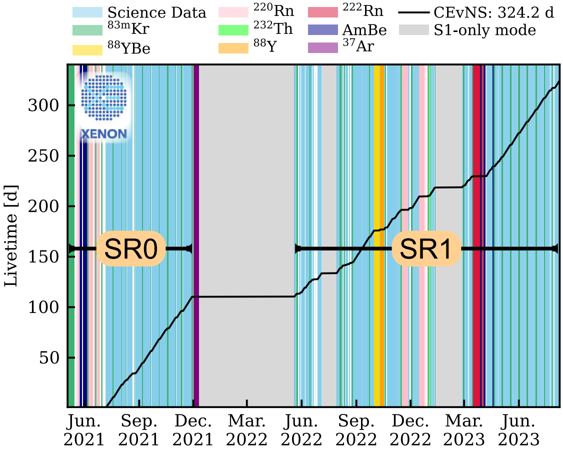
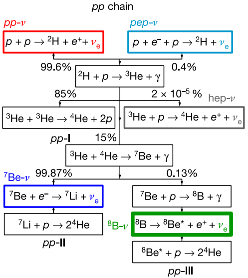


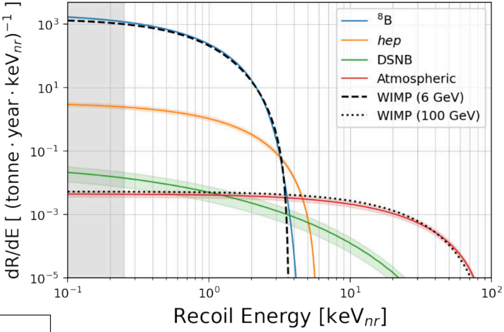
Science Data

- Using data from first two science runs of XENONnT
  - **SR0**: 108.0 days
  - **SR1**: 208.5 days
- Fiducial mass: $\sim$ 4 tonnes
- Exposure: 3.5 tonnes $\times$ years
- Performing the analysis blind

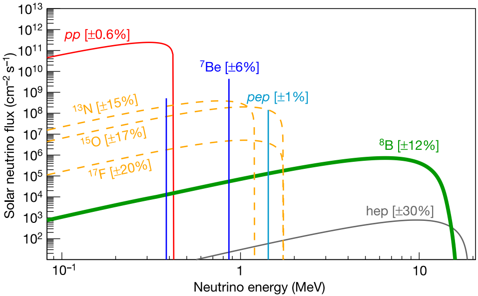


^{8}B Solar neutrinos in XENONnT





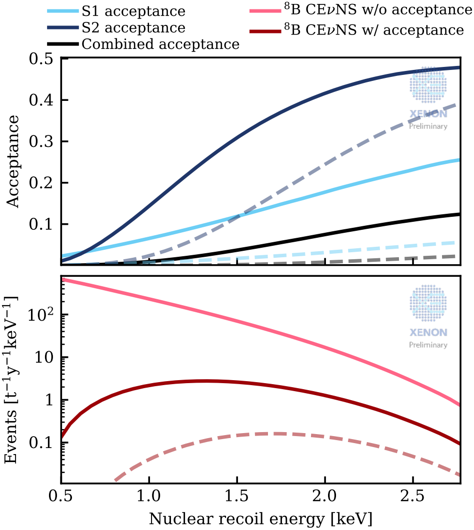
Phys.Rev.D 108 (2023) 2, 022007 & [2304.06142]



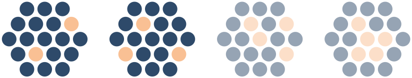
Nature volume 562, pages505–510 (2018)

The ^{8}B spectrum is (almost) identical to the one of 6 GeV/c^2 WIMPs!

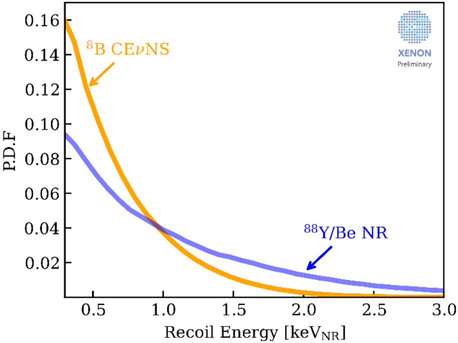
Efficiency to low recoil energies



- ^{8}B spectrum drops steeply below 3 keV!
- Looking only at events with: S1: 2 or 3 PMT hits and S2: Between 120 - 500 PE $\approx$ 4 - 17 electrons.
- $\sim 20\times$ higher CEvNS rate compared to our "standard" analysis (3-fold PMT coincidence, dashed lines)!
- **But:** Higher background, need to calibrate low energy repsonse

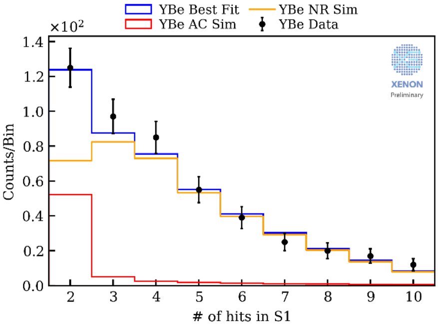


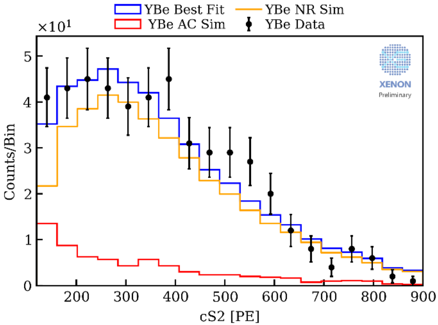
Calibration at lowest energies



- Calibration with an external YBe source
- ^{88}Y emits a high energy gamma: $\gamma + {}^{9}\text{Be} \rightarrow \text{n} + {}^{8}\text{Be}$
- Delivers quasi-monoenergetic low energy neutrons ($\sim$ 152 keV)
- Similar recoil spectrum like ^{8}B neutrinos

Calibration at lowest energies

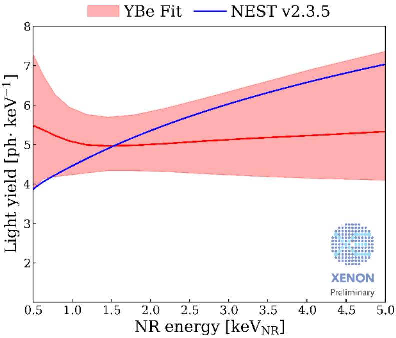


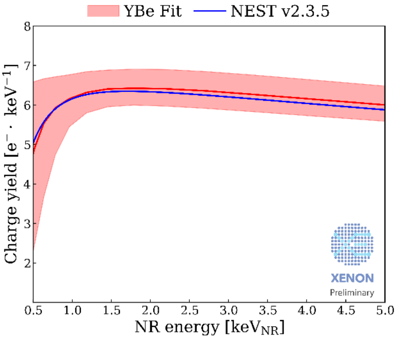


⇒ Constrain of light and charge yield at lowest energies

— Still, the uncertainty is the dominant systematic in the study

Calibration at lowest energies



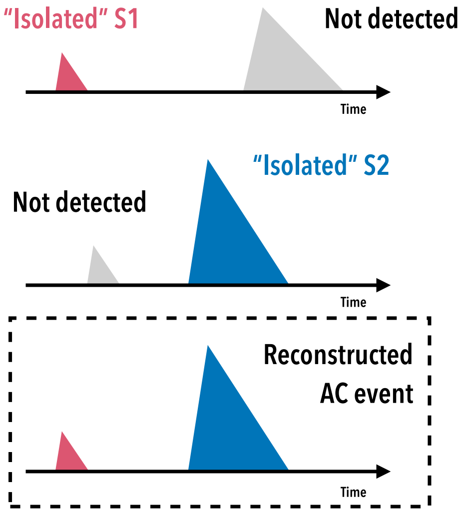


⇒ Constrain of light and charge yield at lowest energies

— Still, the uncertainty is the dominant systematic in the study

Accidental Coincidence (AC) Background

- Dominnant background close to threshold
- Events from incorrectly paired S1 and S2 signals
- Raw AC rate $\sim$ 400 per day
  - "Isolates" S1: $\sim$ 15 Hz
  - "Isolates" S2: $\sim$ 0.15 Hz
- Events are mitigated using:
  - Boosted decision tree using S1 waveform
  - Boosted decision tree using S2 waveform
  - S2 time shadow (see next slide)



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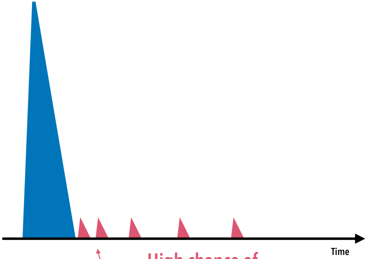
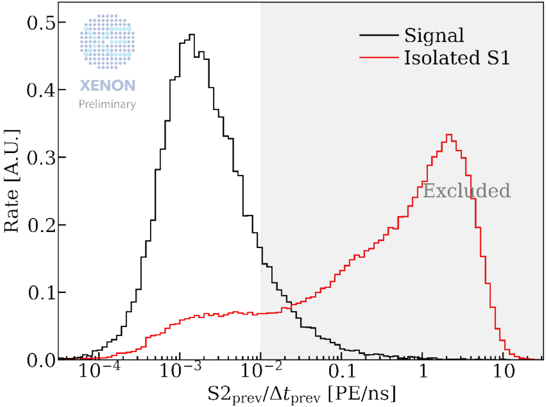




- S2 Time shadow: $S2_{pre}/\Delta t$
- Large value = **close** to a **large** secondary S2

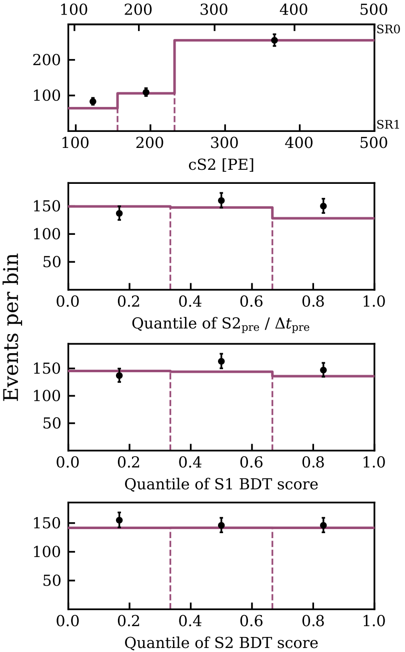
Validation of AC background

- Data driven AC model: Resampling lone S1/S2 pulses into synthetic events
- Dominant background, needs validation!
- Use a **AC sideband** by inversion of anti-AC cuts

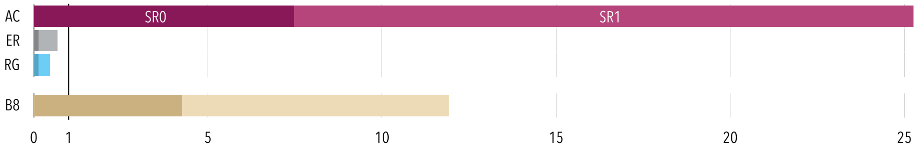
SR0: 121 (122.7)

SR1: 310 (290.0)

- Propagate uncertainties from the sideband into background prediction



Signal and background prediction



Electronic recoils (ER)

- Flat spectrum between 0 and 10 keV
- Conservative assumption of 100%

Radiogenic neutrons (RG)

- 58% uncertainty from side-band unblinding

Surface Background

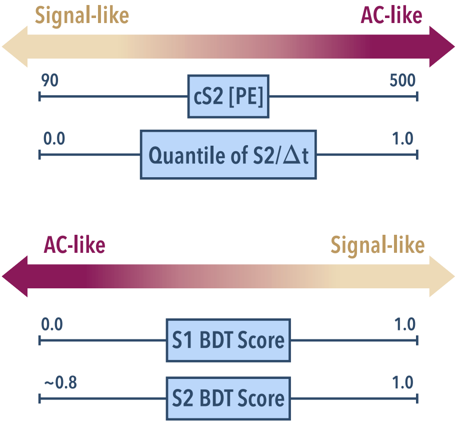
- Fiducial volume chosen to make negligible
- Not included in the likelihood

B8 Signal

- 35% uncertainty due to the yield & efficiency
- Flux is kept as a free parameter

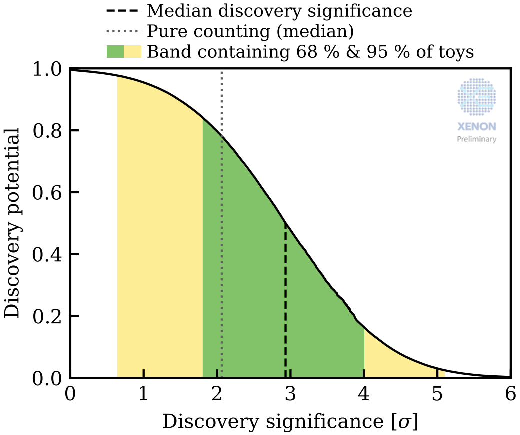
The Likelihood function

- Binned likelihood in 4D parameter space
  - 3 x 3 x 3 x 3 = 81 bins
  - Separate terms for SR0 & SR1
  - Constraints on rates and yields from ancillary measurements
- Data-driven AC background
- Other background and signal models from simulations



Discovery Potential

- Expected background: (26.4 ± 1.5) events
- Expected signal: (11.9 ± 3) events
- Our chances to detect ^{8}B CEνNS:
  - $> 2\sigma$: 80%
  - $> 3\sigma$: 48%



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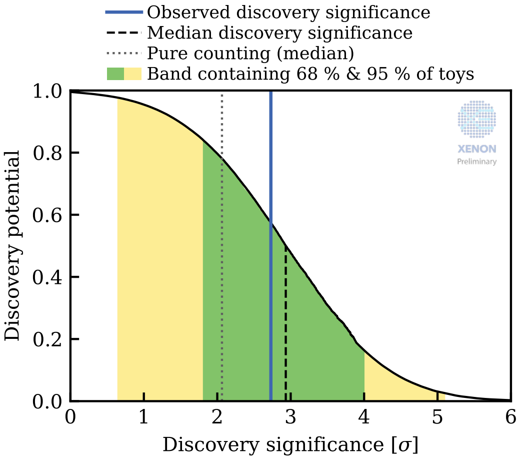


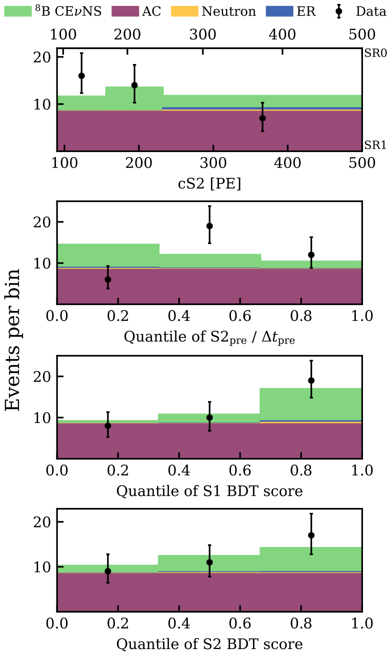
Unblinded dataset

Observed events: 37

Expected events:

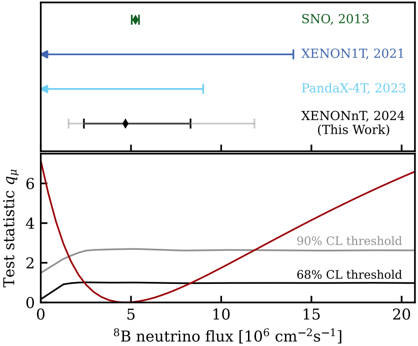
- Background: (26.4 ± 1.4)
- Signal: (11.9 ± 4)

- Goodness of fit (GOF) test performed to check for mismodelling (95% CL)
- $S2_{pre}/\Delta t$ below GOF threshold, but no further sign for issues.
- Note: Removing this dimension from analysis would **increase** the sensitivity to 3.22σ



^{8}B CEνNS Results

- Fix cross-section $\rightarrow$ Measurement of the solar ^{8}B flux: $(4.7^{+3.6}_{-2.3}) \times 10^6\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Compatible with SNO measurement ✓



Almost simultaneous, PandaX: Phys.Rev.Lett. 133 (2024) 19, 191001

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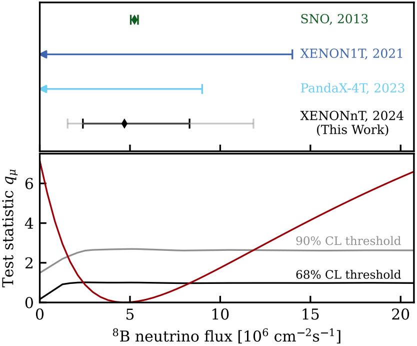

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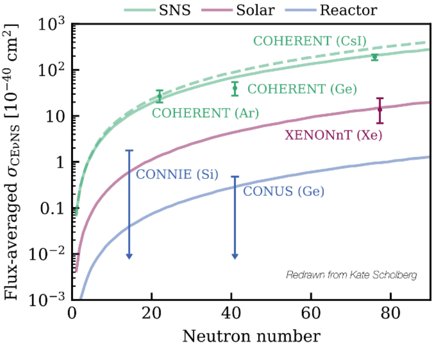
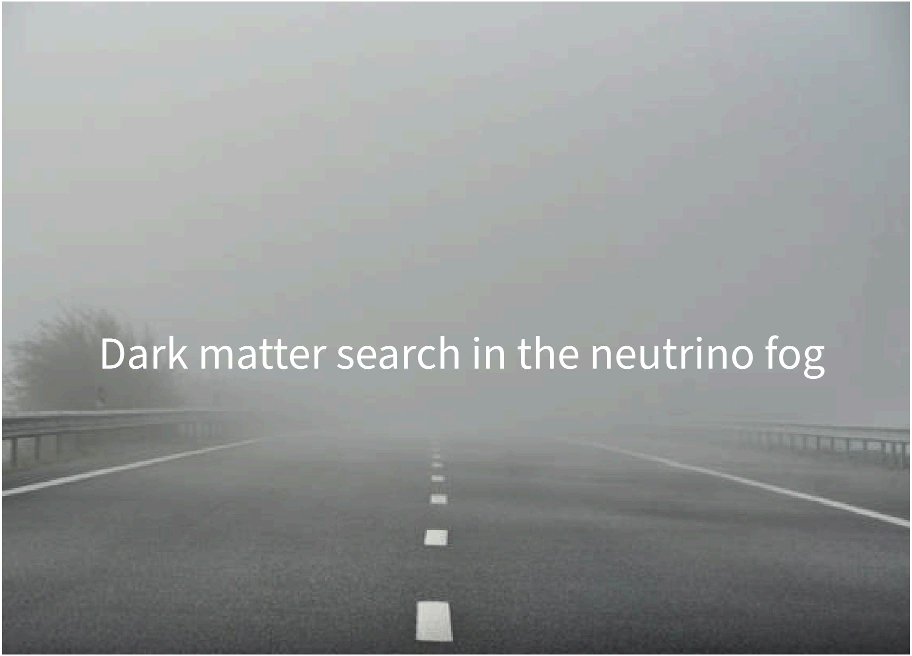
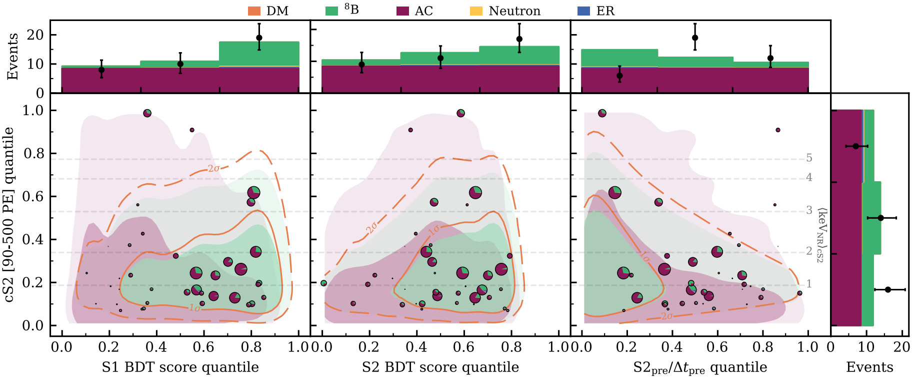


- Fix flux $\rightarrow$ First measurement of the CEνNS cross-section in xenon: $(1.1^{+0.8}_{-0.5}) \times 10^{-39}\,\mathrm{cm}^{2}$
- Compatible with standard model prediction ✓
- $\frac{d\sigma}{dE_R} \sim N^2$

Dark matter search in the neutrino fog



Additional event distributions - Analysis dimensions

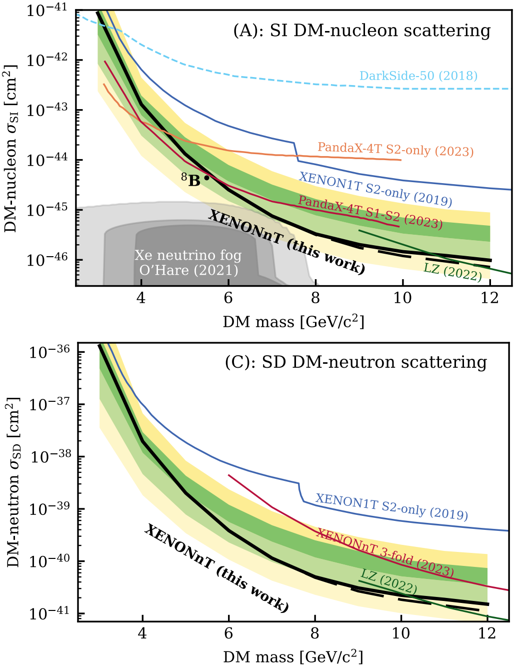


Component	^{8}B-only	4 GeV/c^2	6 GeV/c^2	10 GeV/c^2
SI DM	–	3.2	0.0	0.0
^{8}B CEνNS	$11.4^{+2.0}_{-3.6}$	10.2 ± 2.7	$11.4^{+2.7}_{-2.6}$	$11.4^{+2.7}_{-2.6}$
Total background	$37.7^{+2.5}_{-3.9}$	$36.4\ ^{+3.0}_{-3.0}$	$37.7^{+3.0}_{-2.9}$	$37.7^{+3.0}_{-2.9}$
Observed	37	37	37	37

LightWIMP results

- Upward fluctuation below 5 GeV/c^2
- Downward fluctuation above 5 GeV/c^2
- Apply Power constrain (PCL) to "clip" reported limit at the -1σ sensitivity
- Data & software for re-casting will be released soon!

- Exclude metallic components of "mirror DM", specifically mirror oxygen



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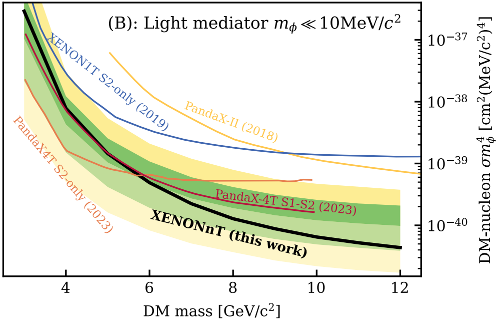
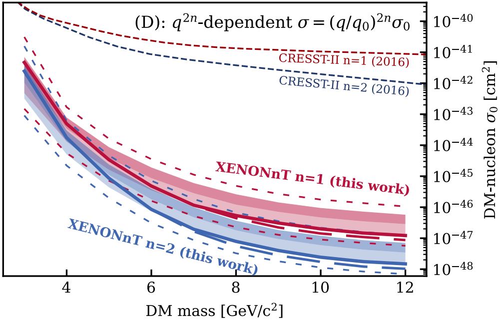
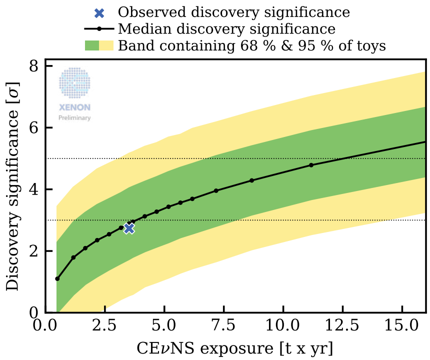
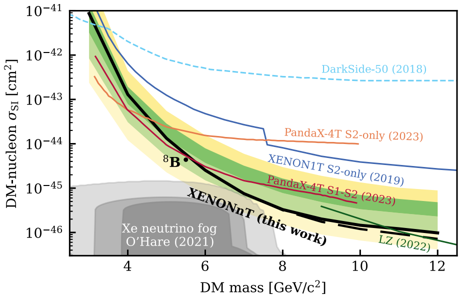




Summary & Outlook

- XENONnT & PandaX-4T are first to measure CEνNS on xenon from astrophysical source
- Measurement of ^{8}B CEνNS at 5σ is in reach within the lifetime of the experiment!



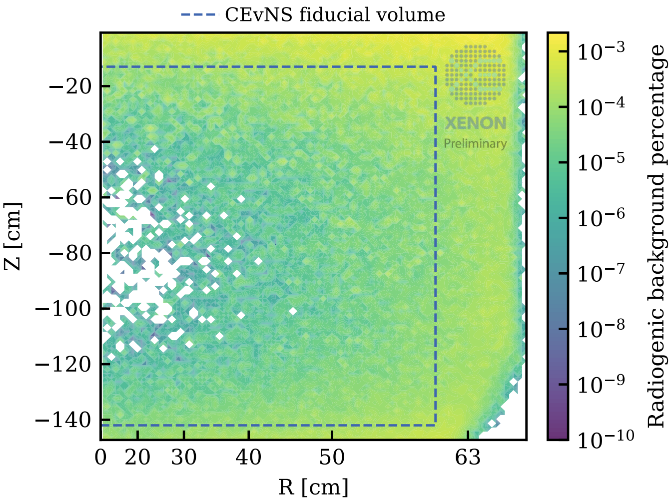


- XENONnT becomes the first to carry out dark matter search in the "neutrino fog"

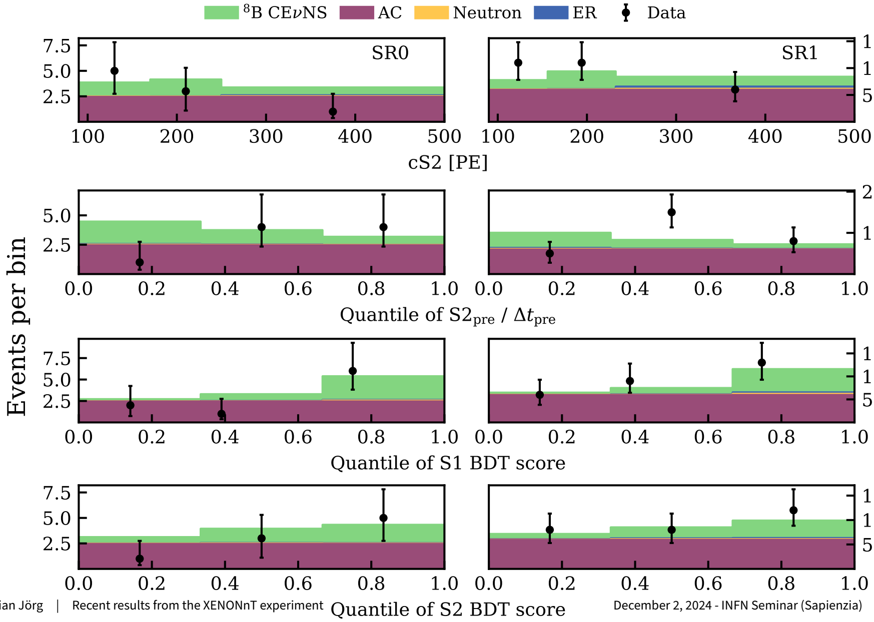
> Thank you very much for your attention!

Backup slides

Neutron background



Additional event distributions - SR0 vs. SR1



Additional event distributions - Event position