Searches for Solar Neutrinos in the XENONnT experiment

Solar Flare X1 from AR2994 in 'Motion' © Miguel Claro

Giovanni Volta

XXI Wokshop on Neutrino Telescope

Sep 30, 2025, Padova

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Max-Planck-Institut für Kernphysik Heidelberg

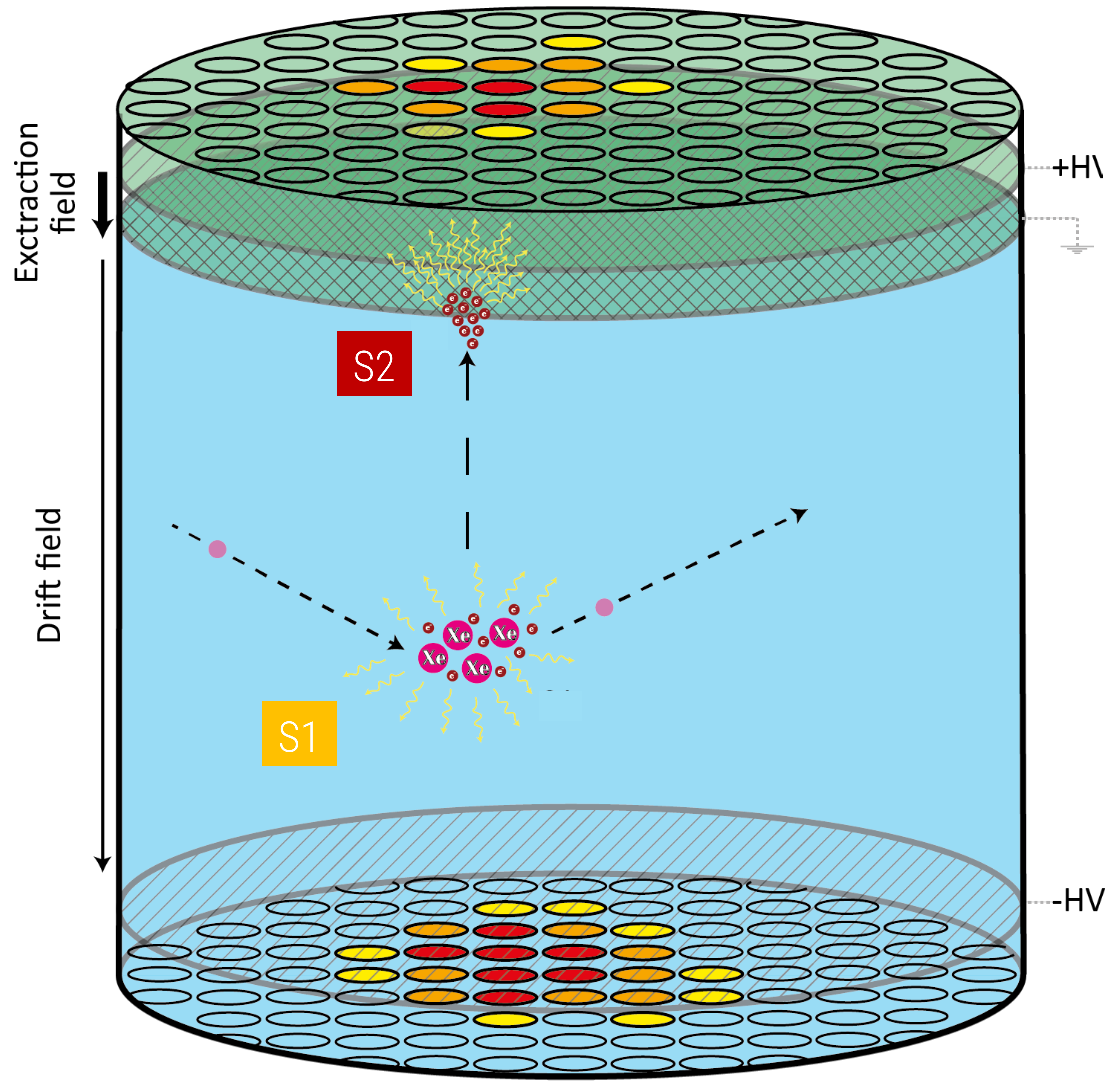
The XENON collaboration

- 180 scientists, 30 institutions, 12 countries
- Laboratori Nazionali del Gran Sasso (LNGS)
- Dual phase liquid-gas xenon time projection chamber
- Primar goals to detect search for dark matter (e.g., Weakly Interactive Massive Particles)

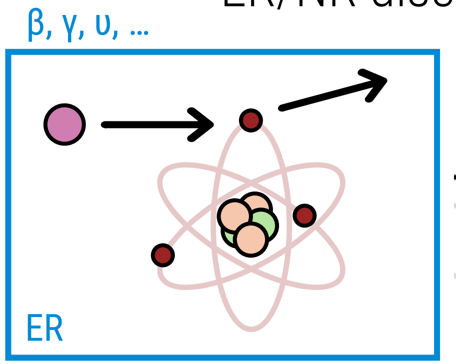
The Daily Business of XENONnT

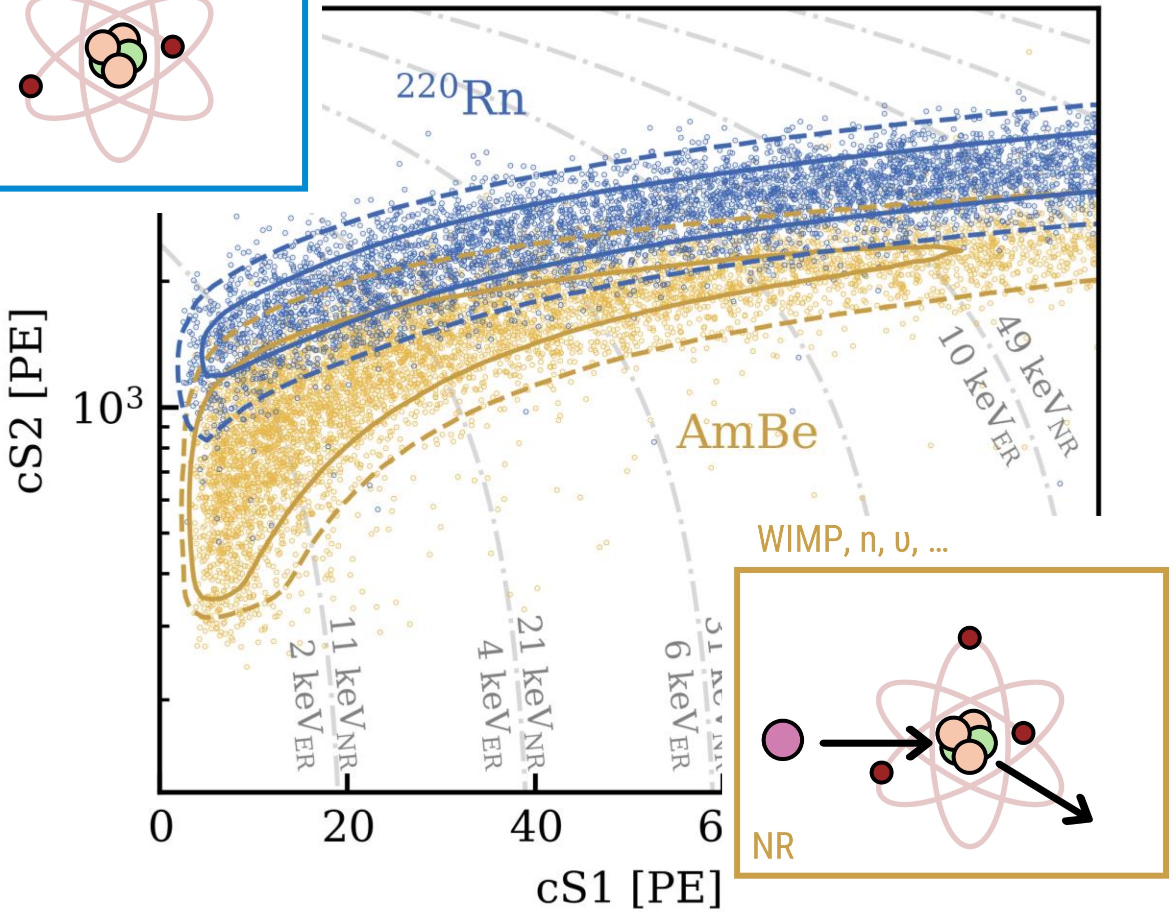
Combination of S1 and S2 signals allows for:

- 3D position reconstruction
- $E_{dep} \propto (n_\gamma + n_{e^-})$
- ER/NR discrimination via the charge-to-light ratio



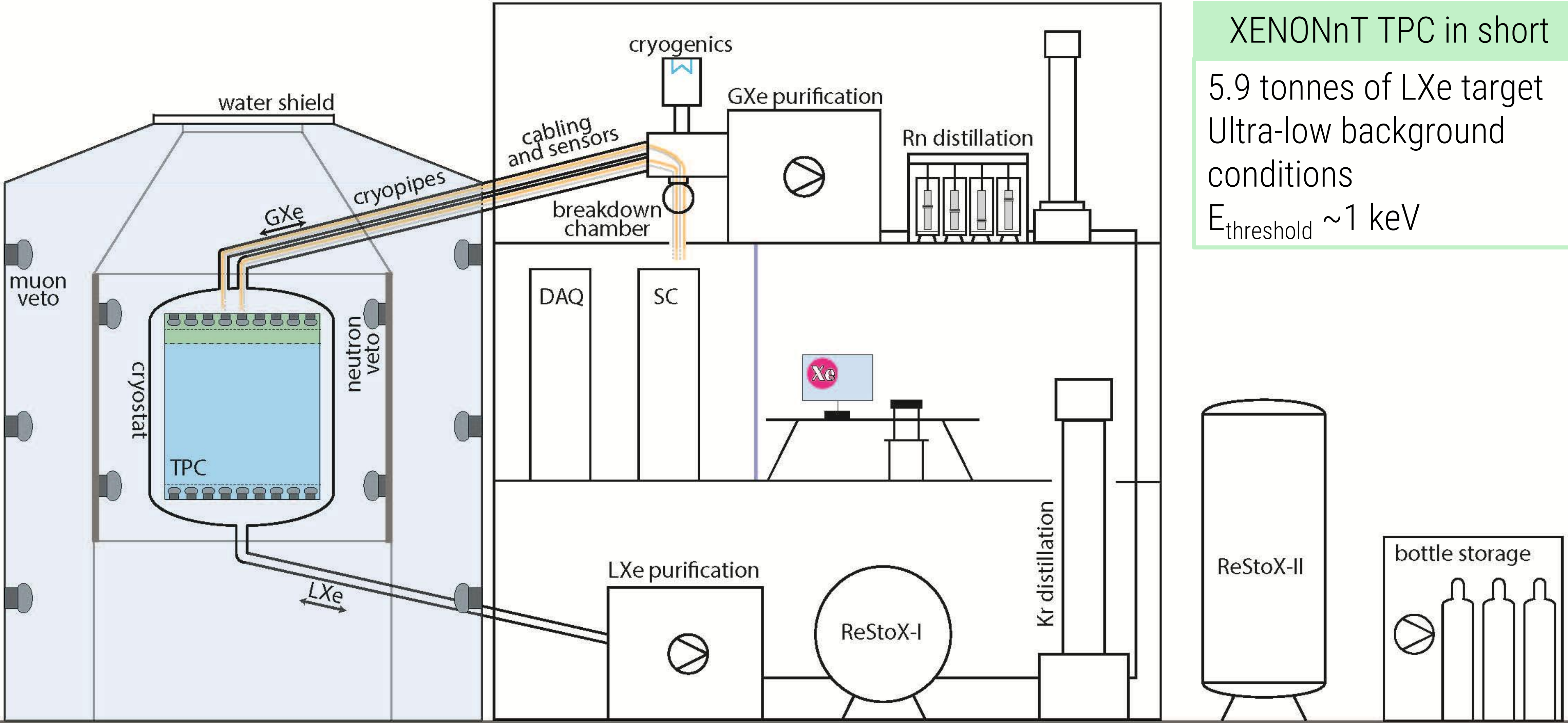
Scintillation photons (S1) and free electrons (∝ S2) are produced from an impinging particle.





The XENONnT experiment

- Depth: 1400 m (3800 m w.e.)
- Three nested detectors (muon veto, neutron veto, TPC) in a ~10 m ×10 m water tank
- Three-floor auxiliary building hosting experiment infrastructure



XENONnT TPC in short

5.9 tonnes of LXe target
Ultra-low background conditions
$E_{threshold}$ ~1 keV

Solar neutrinos – Electron recoils from neutrinos

Grand unified neutrino spectrum at Earth: Sources and spectral components
Low-energy electronic recoil in xenon detectors by solar neutrinos

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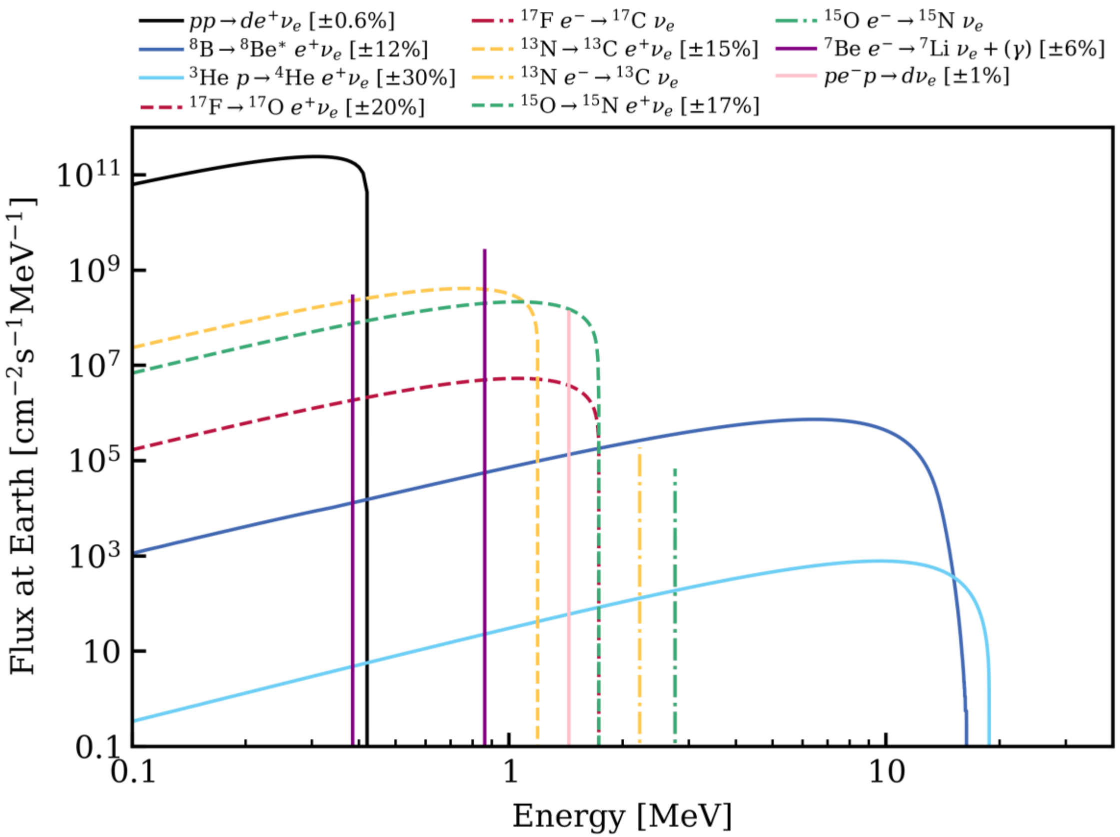
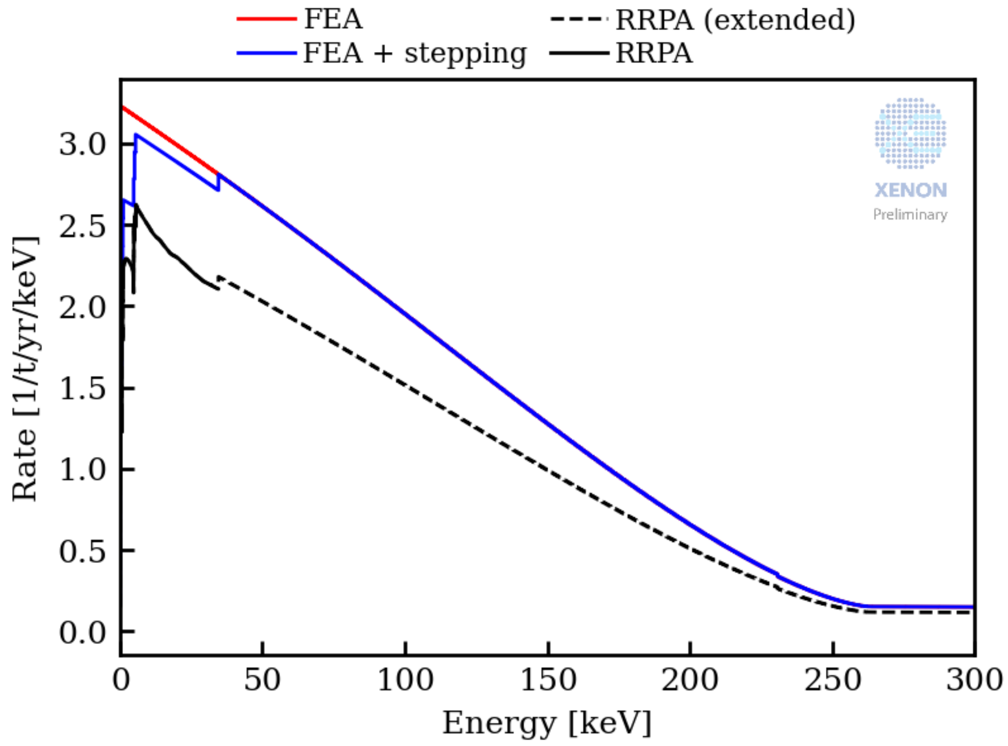
Search for solar-pp elastic electron neutrino scattering

- Dominant in solar neutrino flux (91%)
- Electron recoil signal below 250 keV

- Free electron approximation (FEA) assume electrons are free
- FEA + stepping approximation for accounting for electron binding energy
- Relativistic random phase approximation (RRPA) for calculation of the atomic many-body wave functions



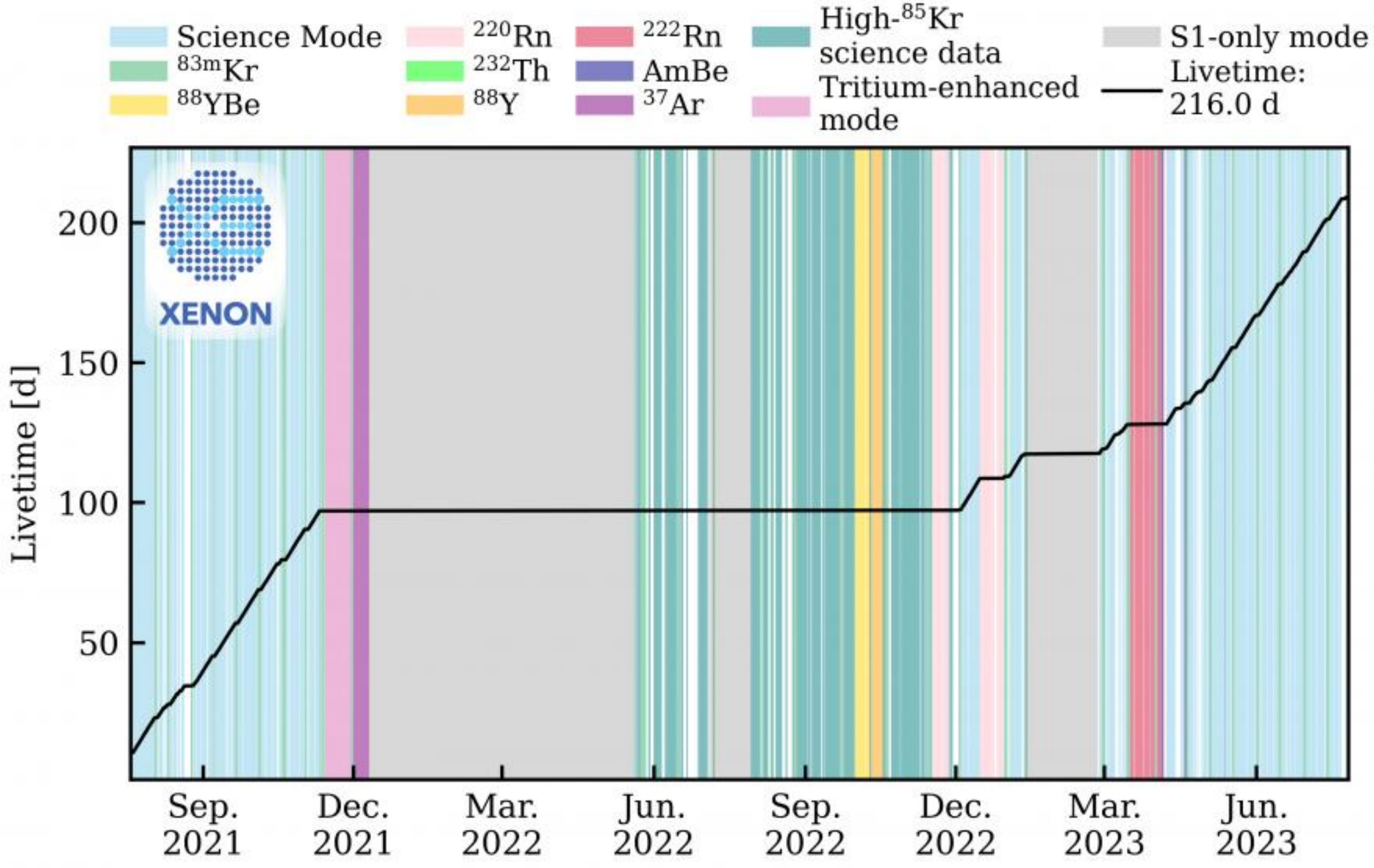


We are in the final stages of this analysis. Today I will discuss our methods and outlook, with final results to be unveiled soon!

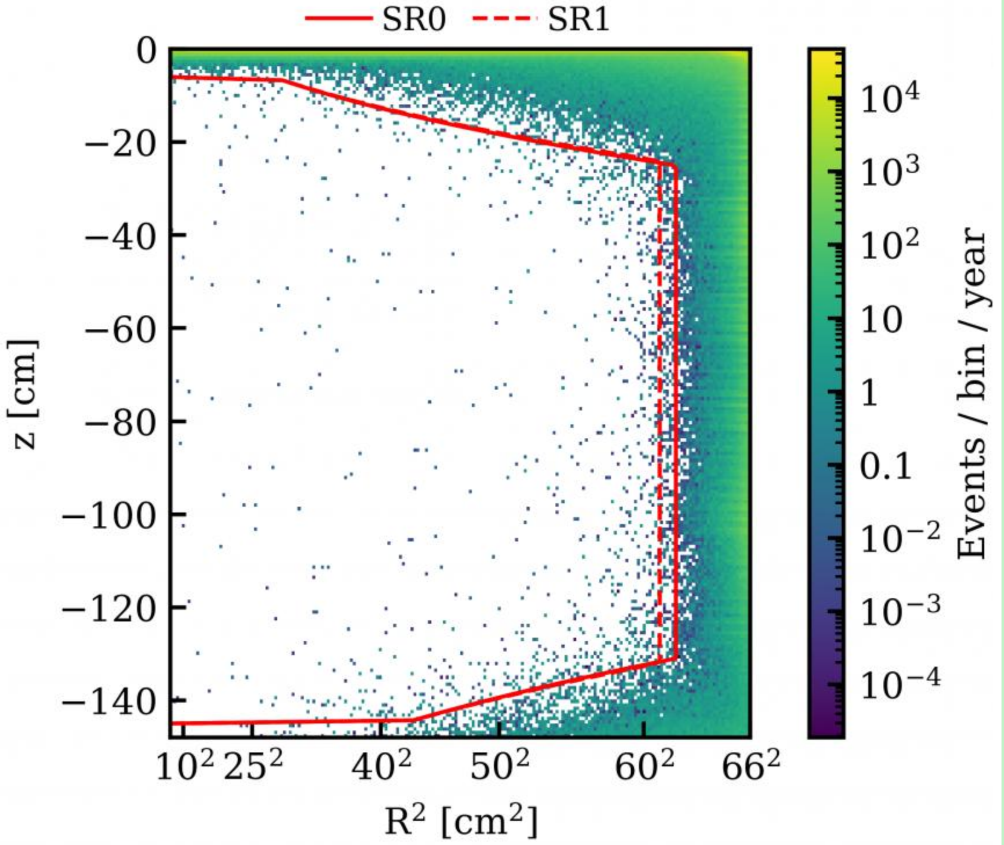
Science data collection

SR0: ~ 97 days

SR1(b): ~ 119 days



ROI: [1, 140] keV
Defining the analysis volume using material radioactivity
SR0 (SR1): ~ 4.13 (4.24) tons



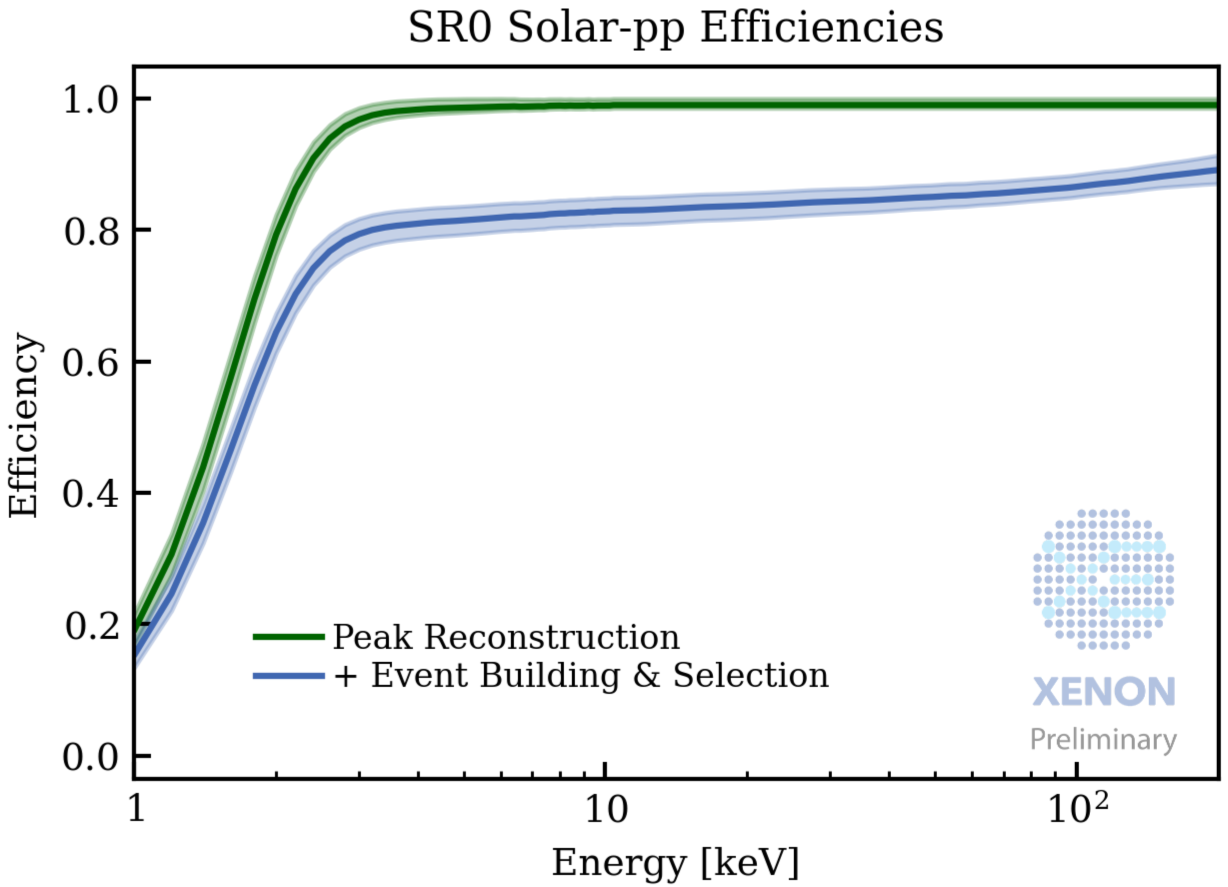
Efficiency & Threshold

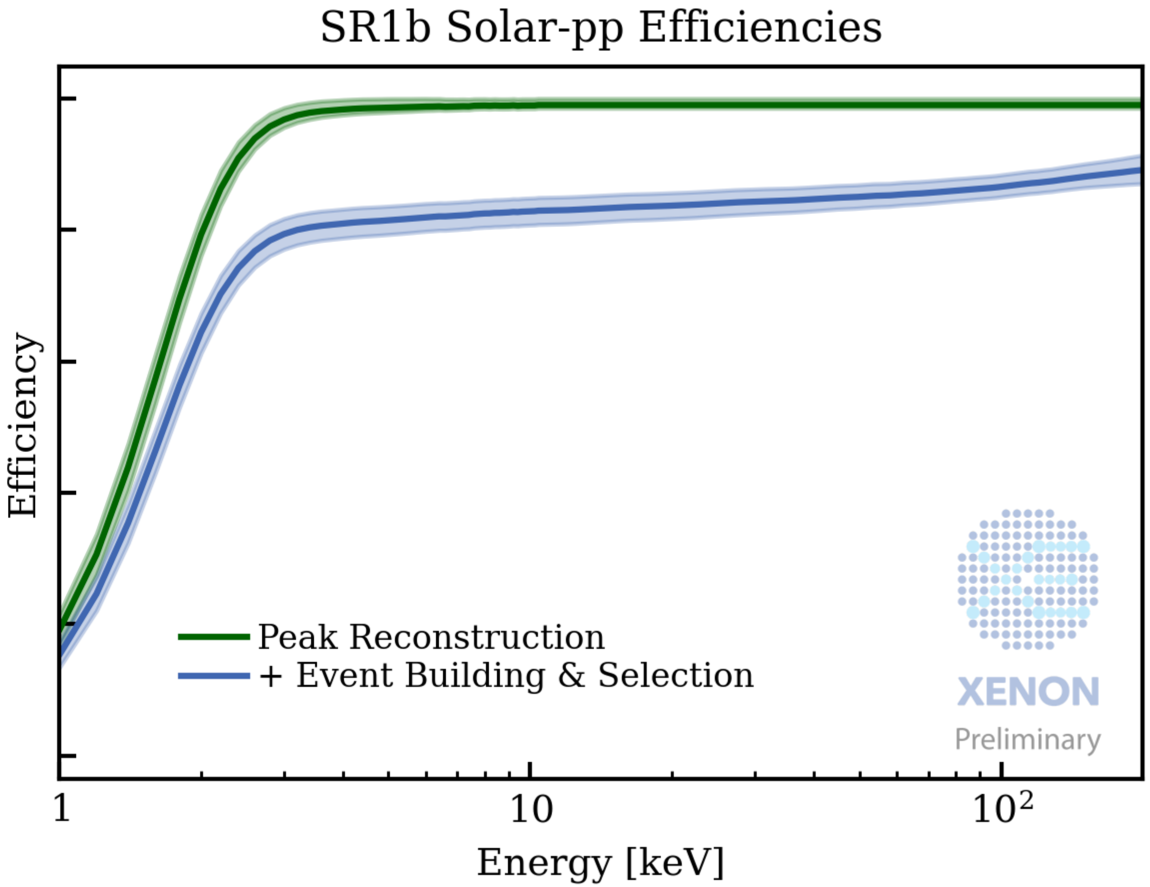
Signal and Event Reconstruction

- How well we reconstruct individual S1 and S2 signals.
- How good we pair S1-S2 signals to construct physical events.
- Achieved 1 keV low-energy threshold.

Selection criteria

- How good we select physical data
- Rejecting unphysical events and improperly reconstructed events
- Fairly flat and ~90% in the ROI





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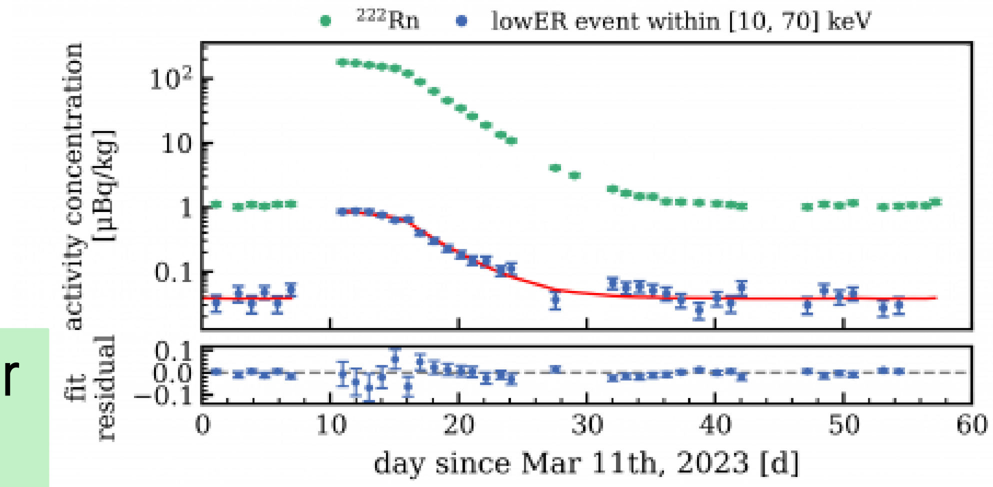
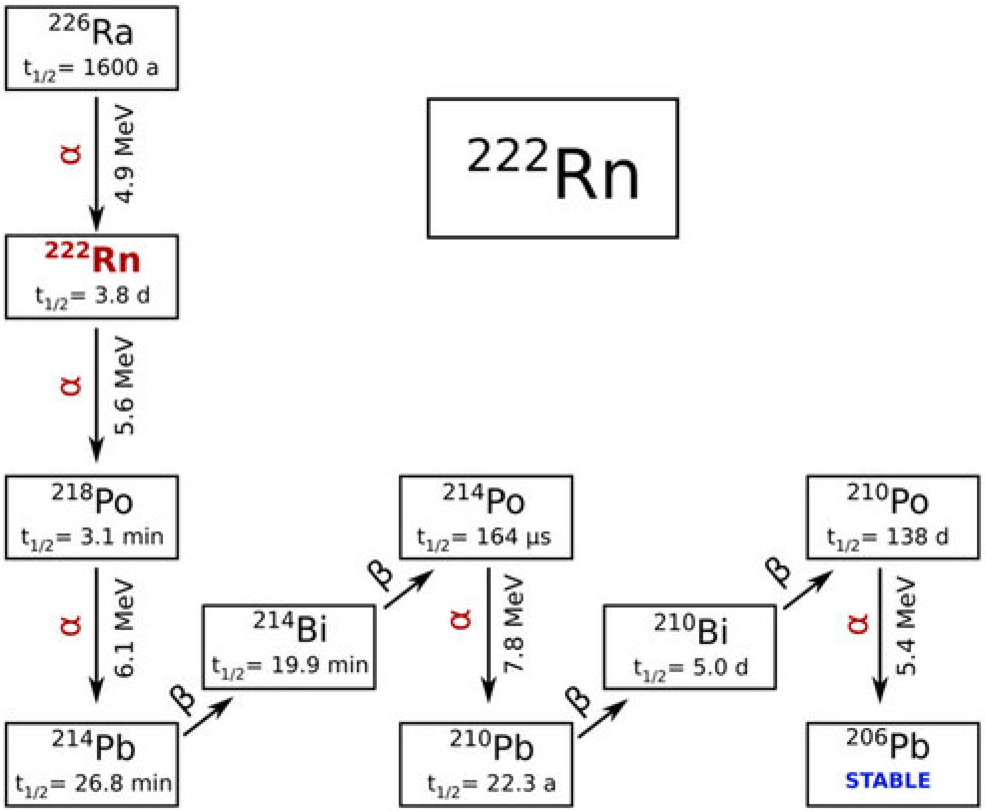
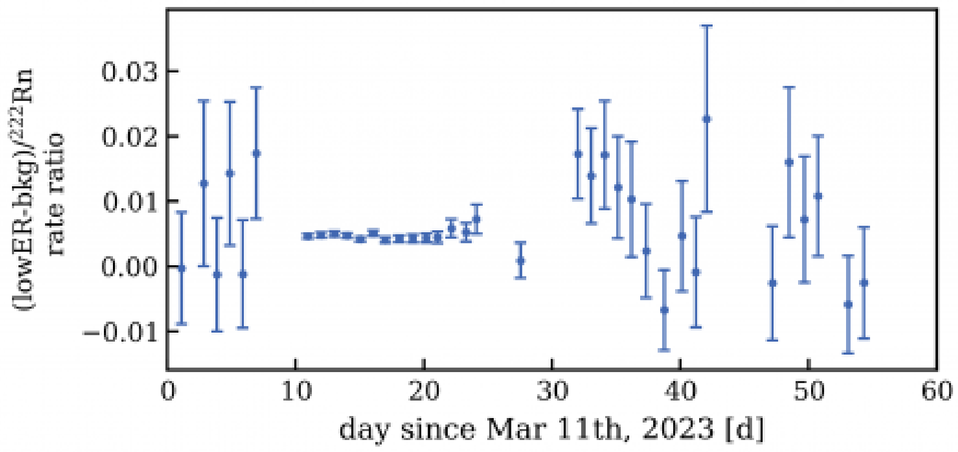
Background contribution: ^{214}Pb

- ^{214}Pb - daughter of ^{222}Rn - contributed via the β decay in the ROI
- Online cryogenic distillation to remove radon based on the difference volatility of Rn and Xe:
  - ^{222}Rn in SR0 ~1.9 μBq/kg
  - ^{222}Rn in SR1 ~0.9 μBq/kg → Comparable level to solar neutrino background!





^{222}Rn



- Dedicated ^{222}Rn calibration in SR1 to estimate the ^{214}Pb/^{222}Rn ratio to constraint ^{214}Pb in science data
- Measure a constant ratio of **0.67 ± 0.03**

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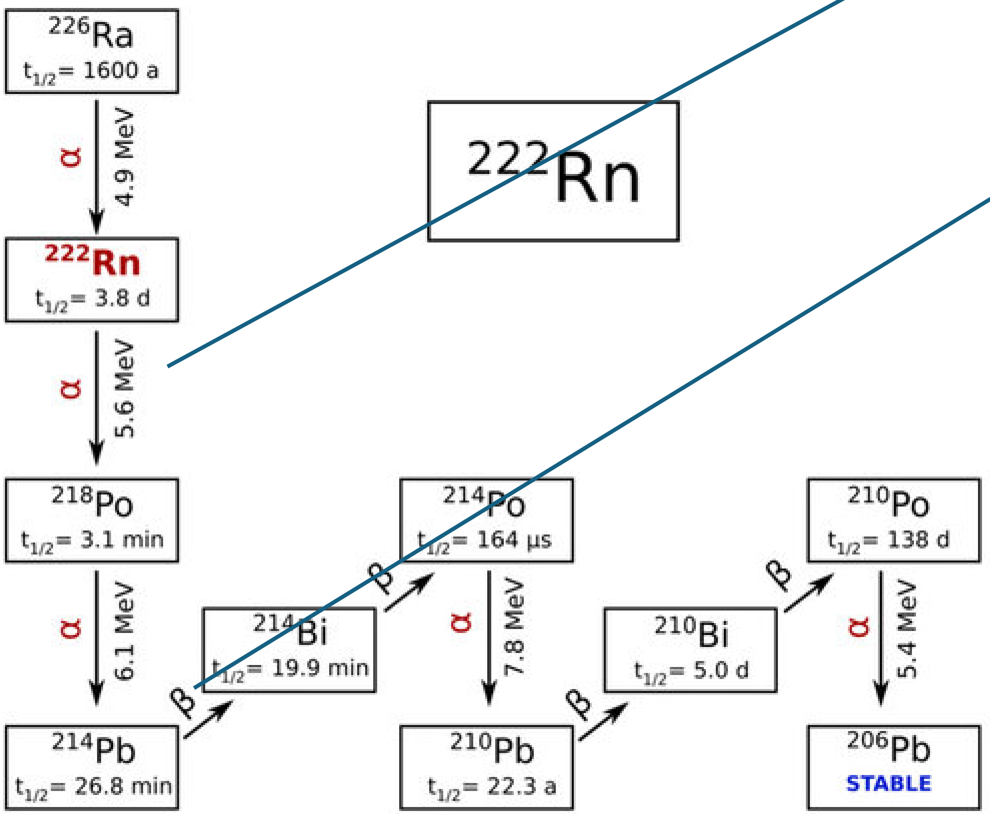
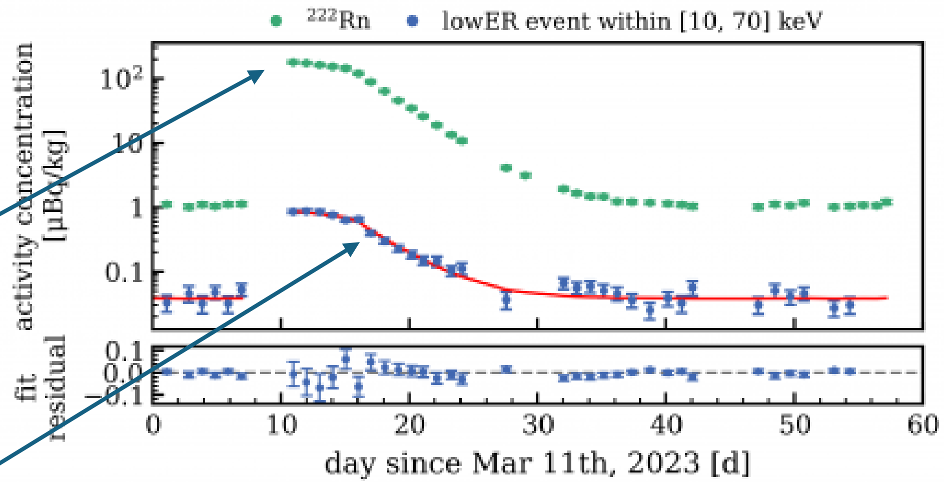
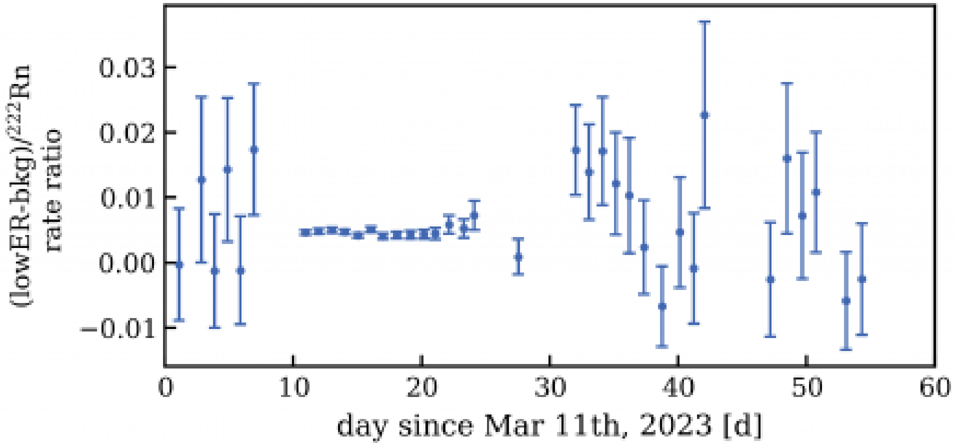




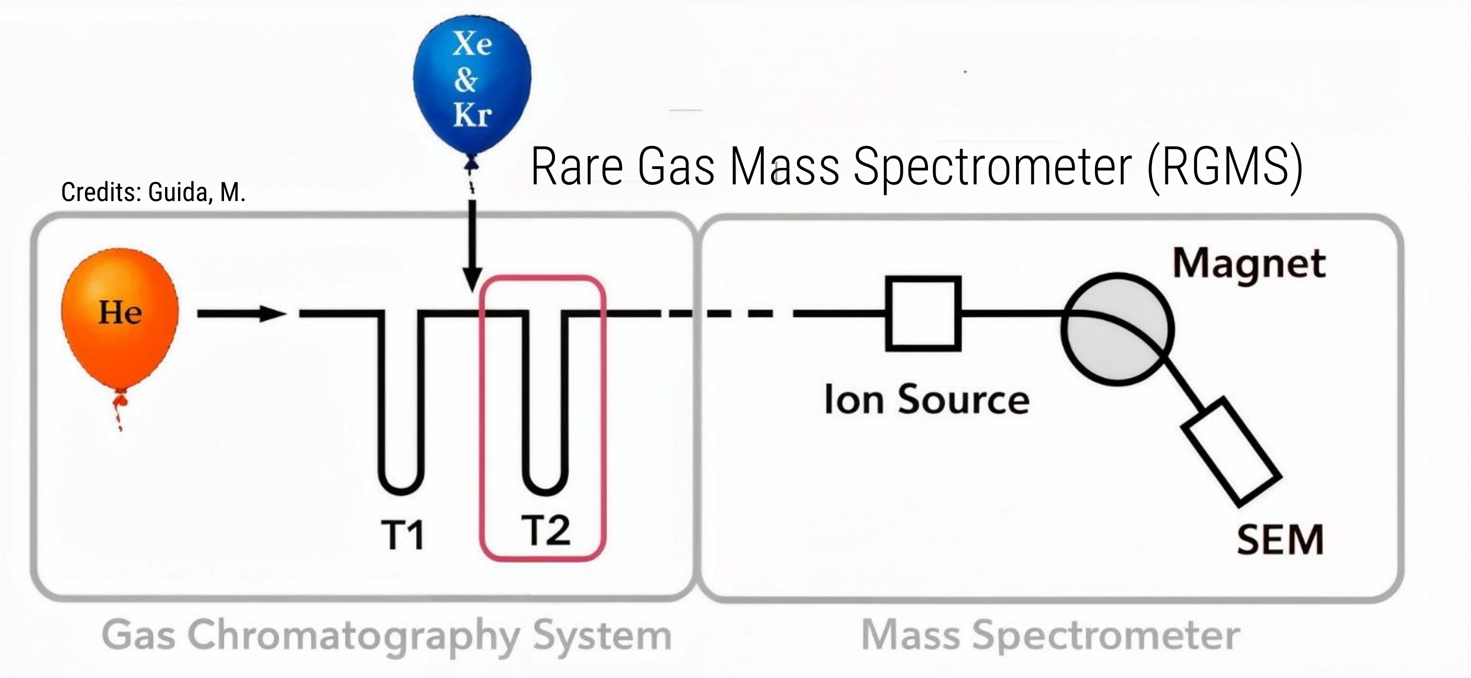


- Dedicated ^{222}Rn calibration in SR1 to estimate the ^{214}Pb/^{222}Rn ratio to constraint ^{214}Pb in science data
- Measure a constant ratio of **0.67 ± 0.03**

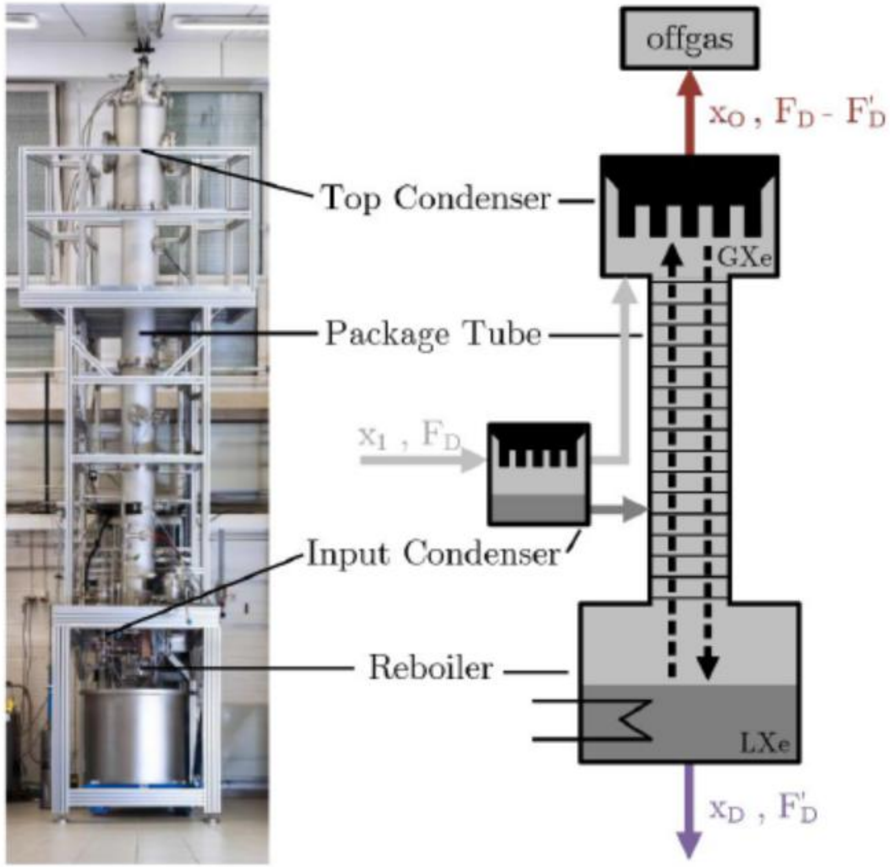
Background contribution: ^{85}Kr

A cryogenic distillation column for the XENON1T experiment
Krypton assay in xenon at the ppq level using a gas chromatographic system and mass spectrometer

- ^{85}Kr internal background in LXe, introduced as a contaminant during xenon's extraction from air:
  β− decay – Q value ~ 687 keV – $T_{1/2}$~10.76 y – ^{85}Kr/^{nat}Kr ~ 2×10^{-11} mol/mol
- Multiple operations by cryogenic distillation column: 10 ppb (10^{-8}) → 60 ppq (6×10^{-14}) ^{nat}Kr/Xe
- Xenon samples from the detector measured at Max-Planck-Institut für Kernphysik in Heidelberg



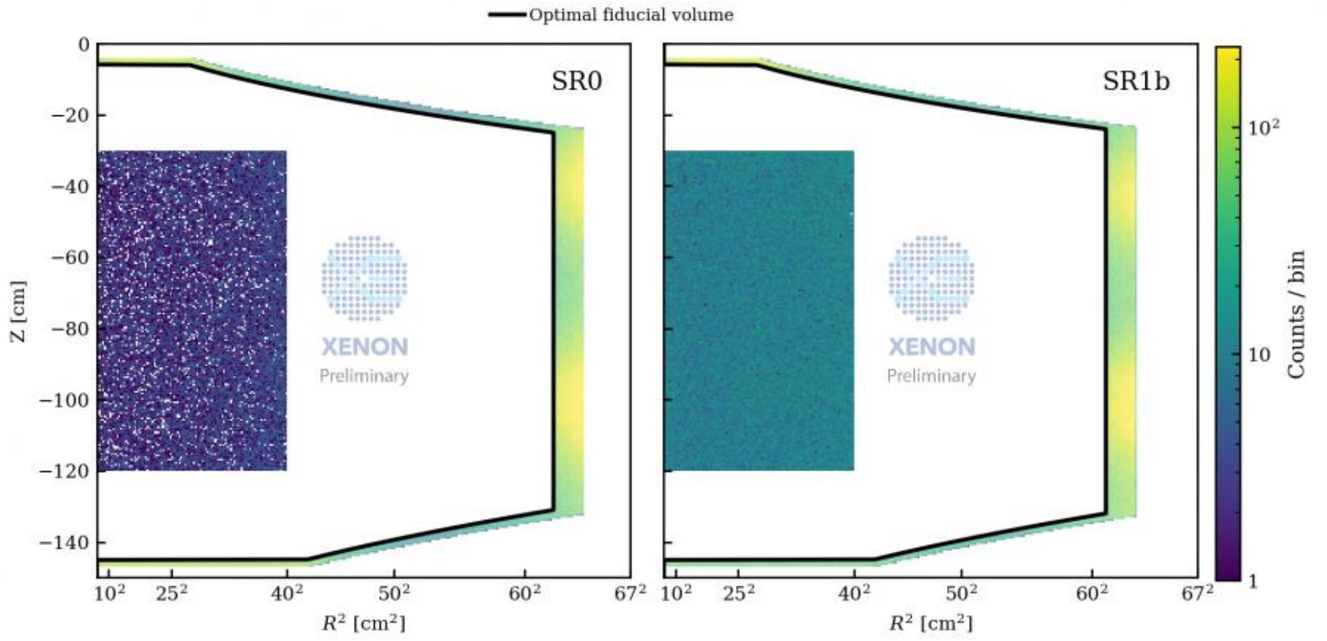
Currently we are validating the RGMS measurements

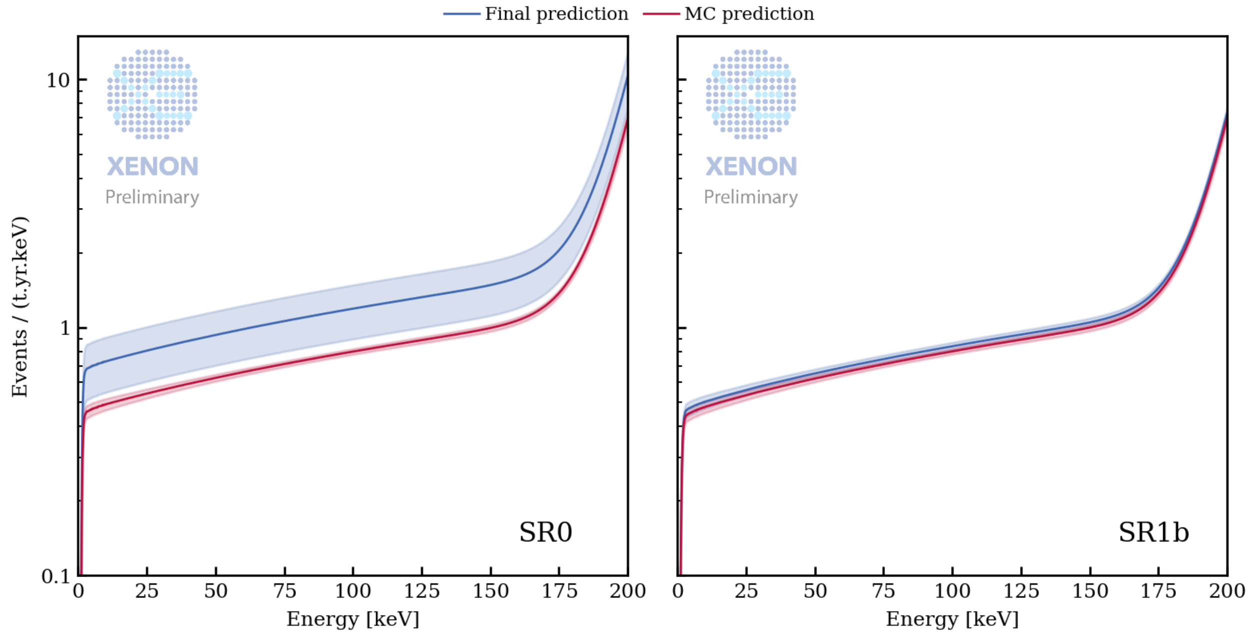


Kr distillation column

Background contribution: radiogenic gamma-ray from materials

- Radiogenic contaminants contribute to the low-energy ER background via Compton scattering of high-energy gamma rays.
- The self-shielding of LXe confines this background primarily to the outer region of the active volume.
- Careful material selection and screening make this a subdominant background.
- Constrained by comparing (subtracted) data and Monte Carlo simulations in an edge volume outside the fiducial volume.





That’s all folks!

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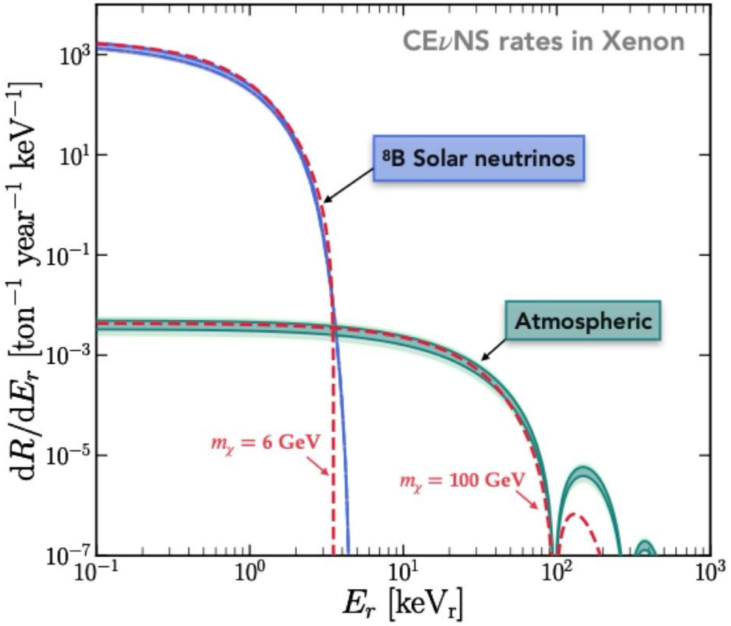
Or maybe not...

Solar neutrinos – Nuclear recoils from neutrinos

[First Indication of Solar ^{8}B Neutrinos via Coherent Elastic Neutrino-Nucleus Scattering with XENONnT]

CEυNS = Coherent Elastic Neutrino-Nucleus Scattering

- Measured by COHERENT (2017) with spallation neutron source
- $\sigma \propto N^2$ and only at low momentum transfer → small recoil energies
- In LXe TPC induce a signal indistinguishable from WIMPs
- Developed a dedicate analysis pipeline to measure ^{8}B solar neutrino via CEυNS



Snapshot of ^{8}B analysis

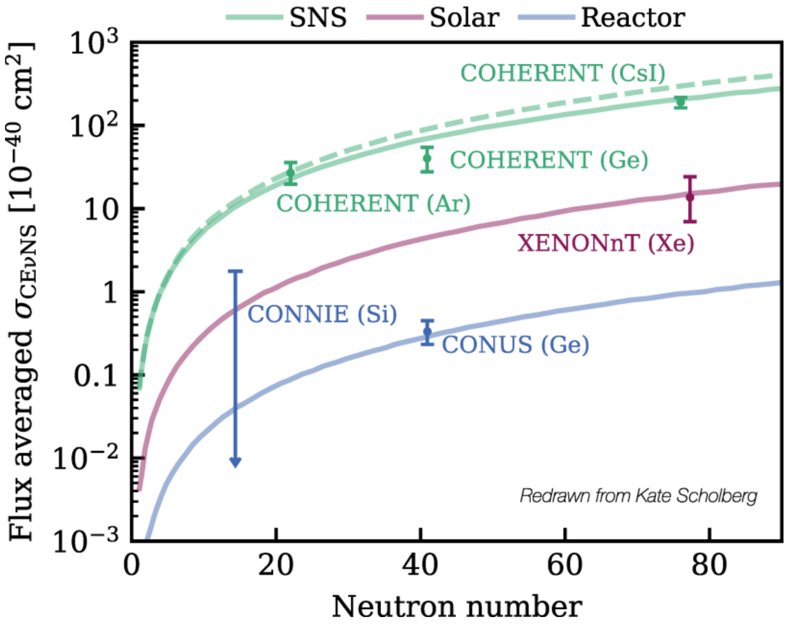
Background-only hypothesis disfavoured at 99.68% ⟶ 2.73σ

Fix cross-section - Measurement of the solar ^{8}B flux:

$$4.7^{+3.6}_{-2.3} \times 10^{6}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

Fix flux - First measurement of the CEυNS cross-section in xenon:

$$1.1^{+0.8}_{-0.5} \times 10^{-39}\ \mathrm{cm}^{-2}$$



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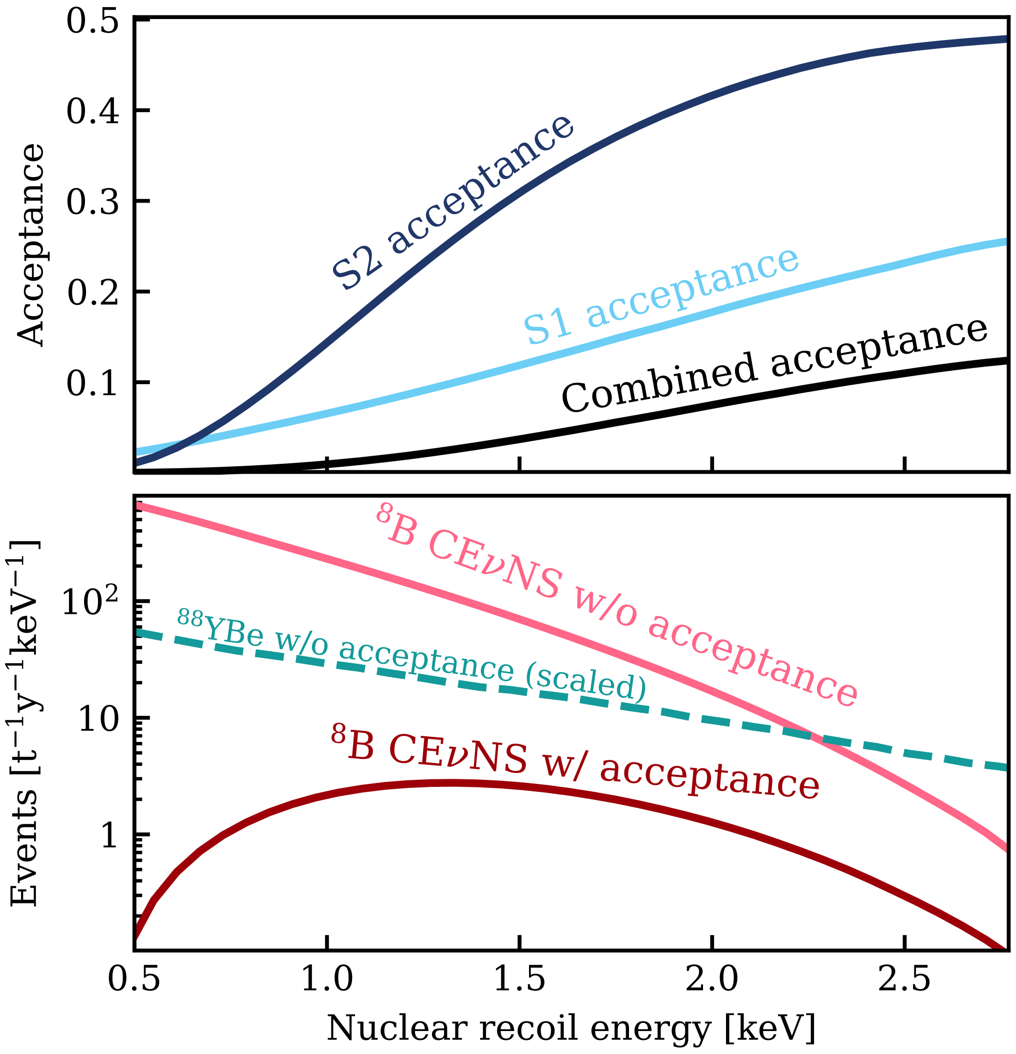
How did we get there?



- Low energy deposited: > 90% of detectable recoils below 2.1 keV
- Decent exposure (~3.5 t × yr) by combining full SR0 and SR1
- Lowering down PMT coincidence for event reconstruction from 3 to 2
- Calibrating the low-energy NR response with 152 keV neutrons from an external ^{88}YBe source
- Enhancing the sensitivity through refined background constraints and a dedicated inference parameter space

Expected Background:
26.4 ± 1.5
Expected Signal:
12 ± 3
Events Observed:
37

Best-fit number of ^{8}B signal events:

$$10.7^{+3.7}_{-4.2}$$

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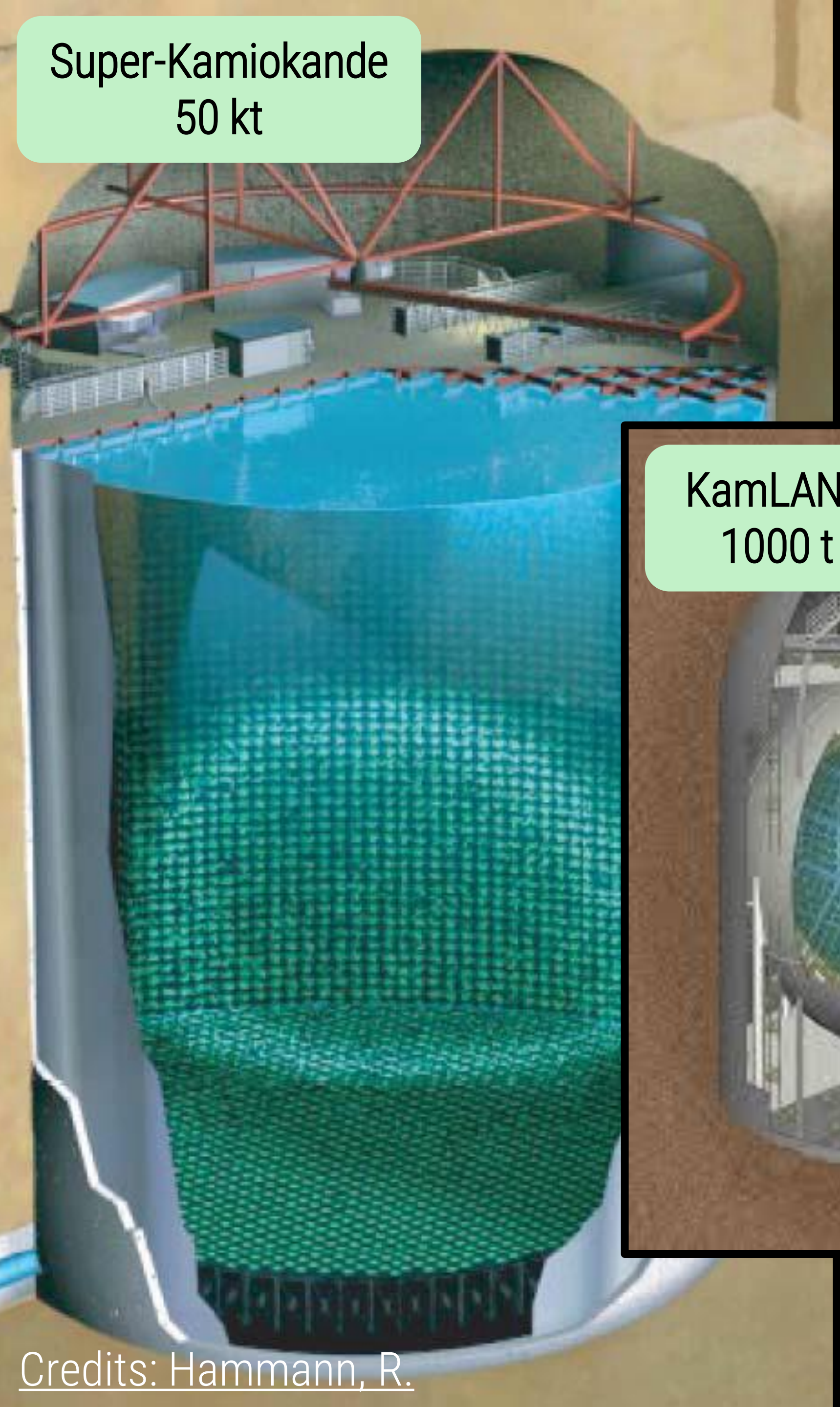
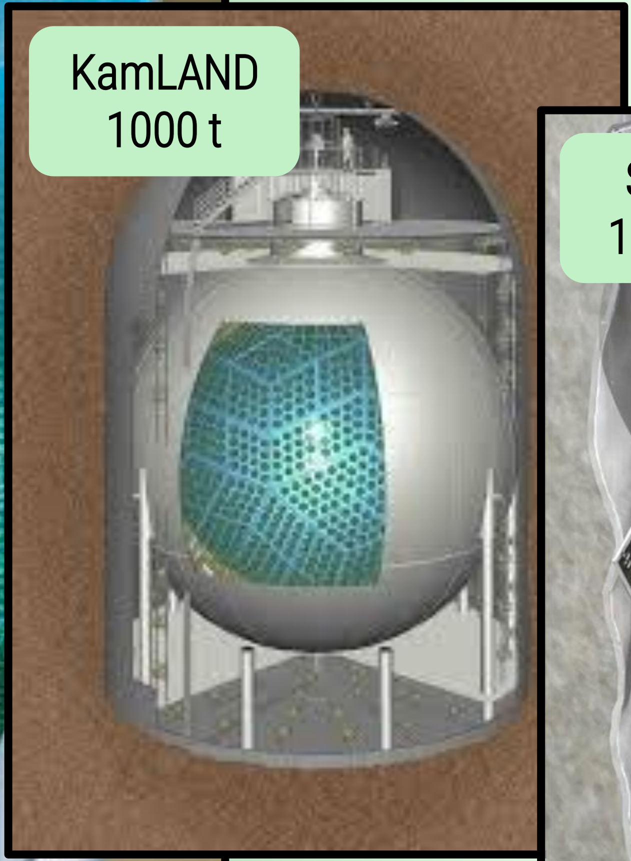
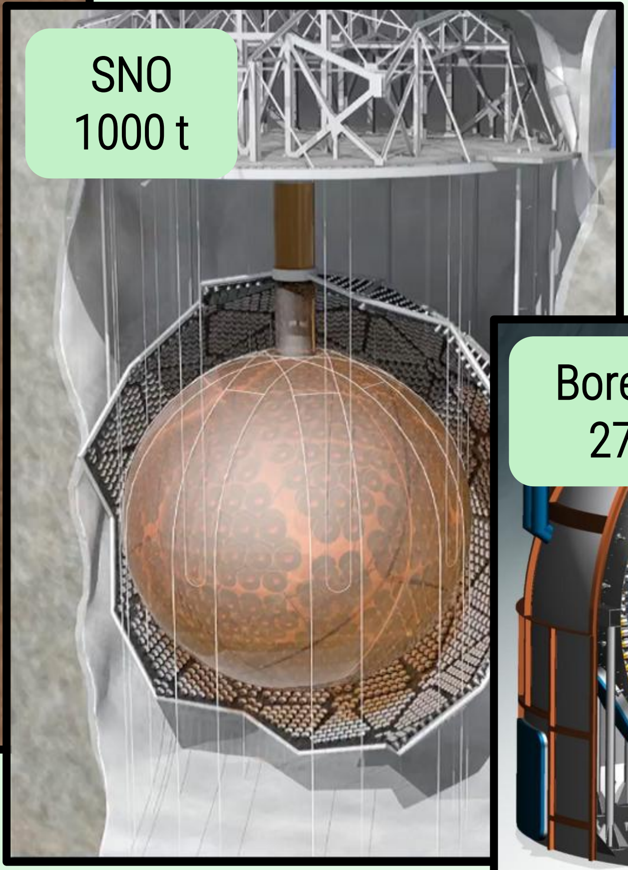
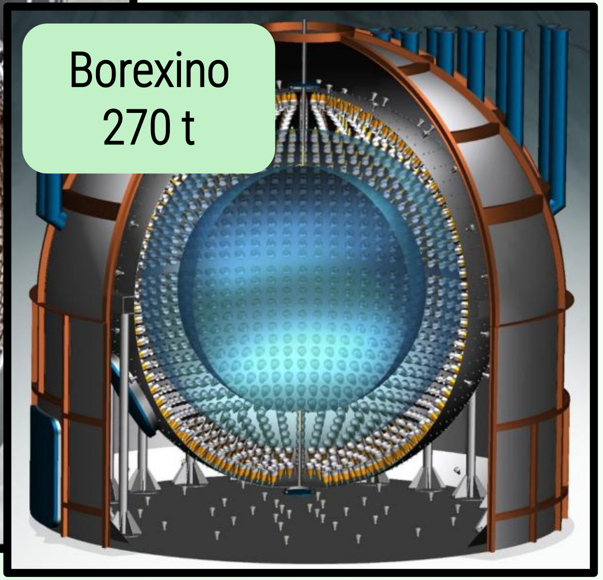
Sitting ~~on the shoulders~~ alongside the giants: XENONnT is the smallest solar neutrino detector









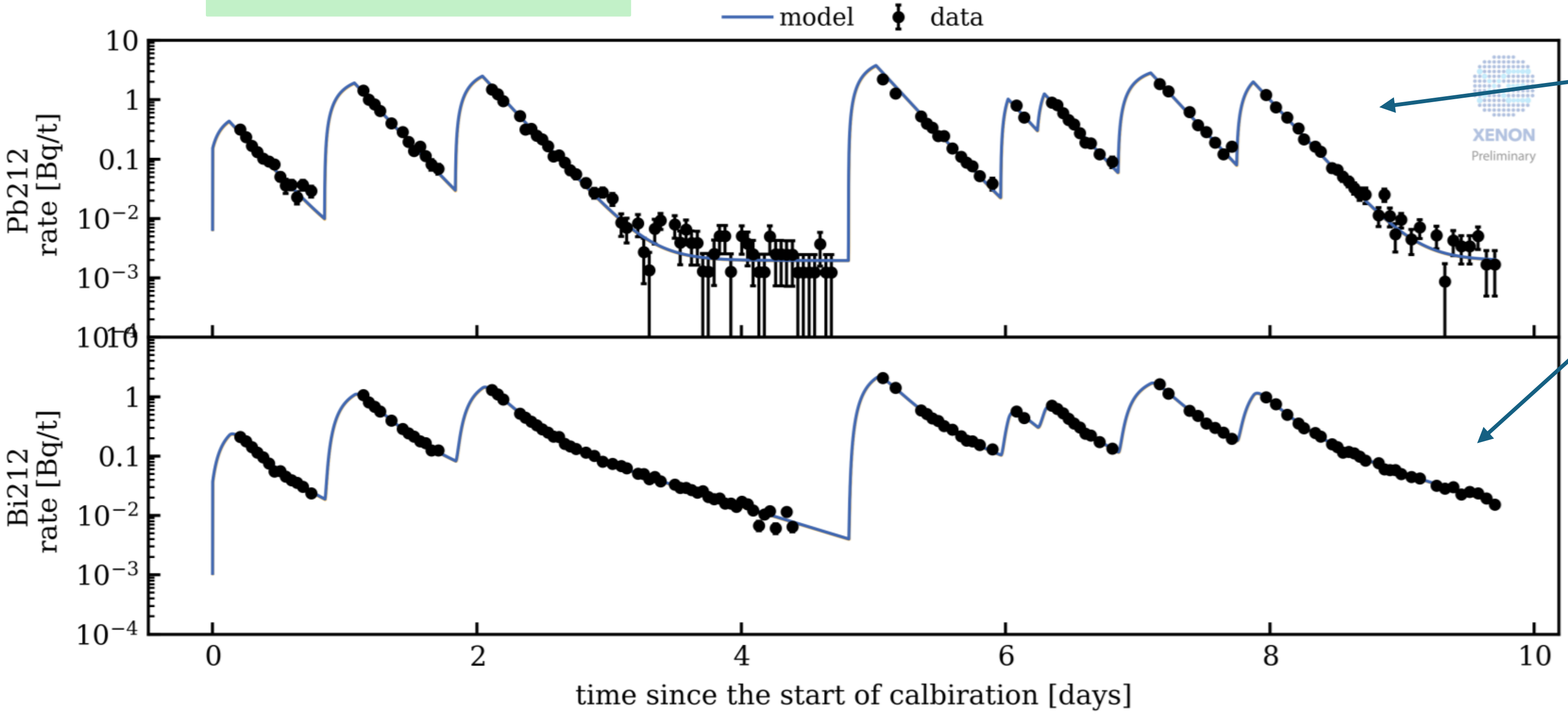
XENONnT
8.5 t

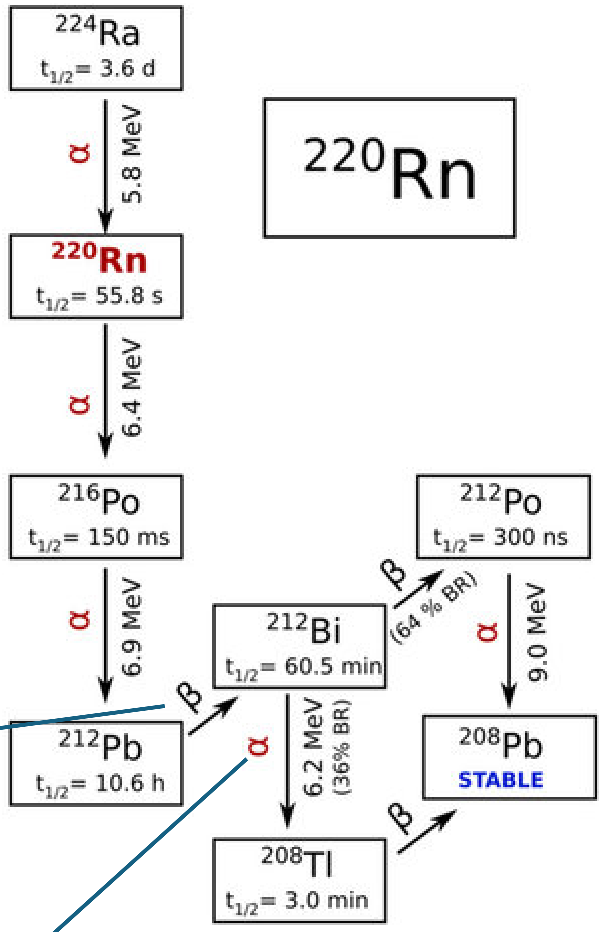
BACK-UP SLIDES

Background contribution: ^{212}Pb

- ^{212}Pb, daughter of ^{220}Rn which is continuously emanated from detector materials contributed via the β decay of in the ROI
- Concentration a factor ×10 smaller compared to ^{222}Rn makes this less problematic
- A plate out model is established using ^{220}Rn calibration data, which allows for constraining the ^{212}Pb background rate using the ^{212}Bi-Po rate that is easy to measure.

SR1 calibration data





Other backgrounds contribution

Intrinsic background

- Xe136: 2υββ decay – constrained from EXO half life and measured isotopic abundance.
- Xe124: 2ECEC decay – possibility to leave it free of constrained using XENON1T measurement.
- Bi214: from Rn222 – high energy gammas from an-instrumented liquid xenon, subdominant.

Possible contamination

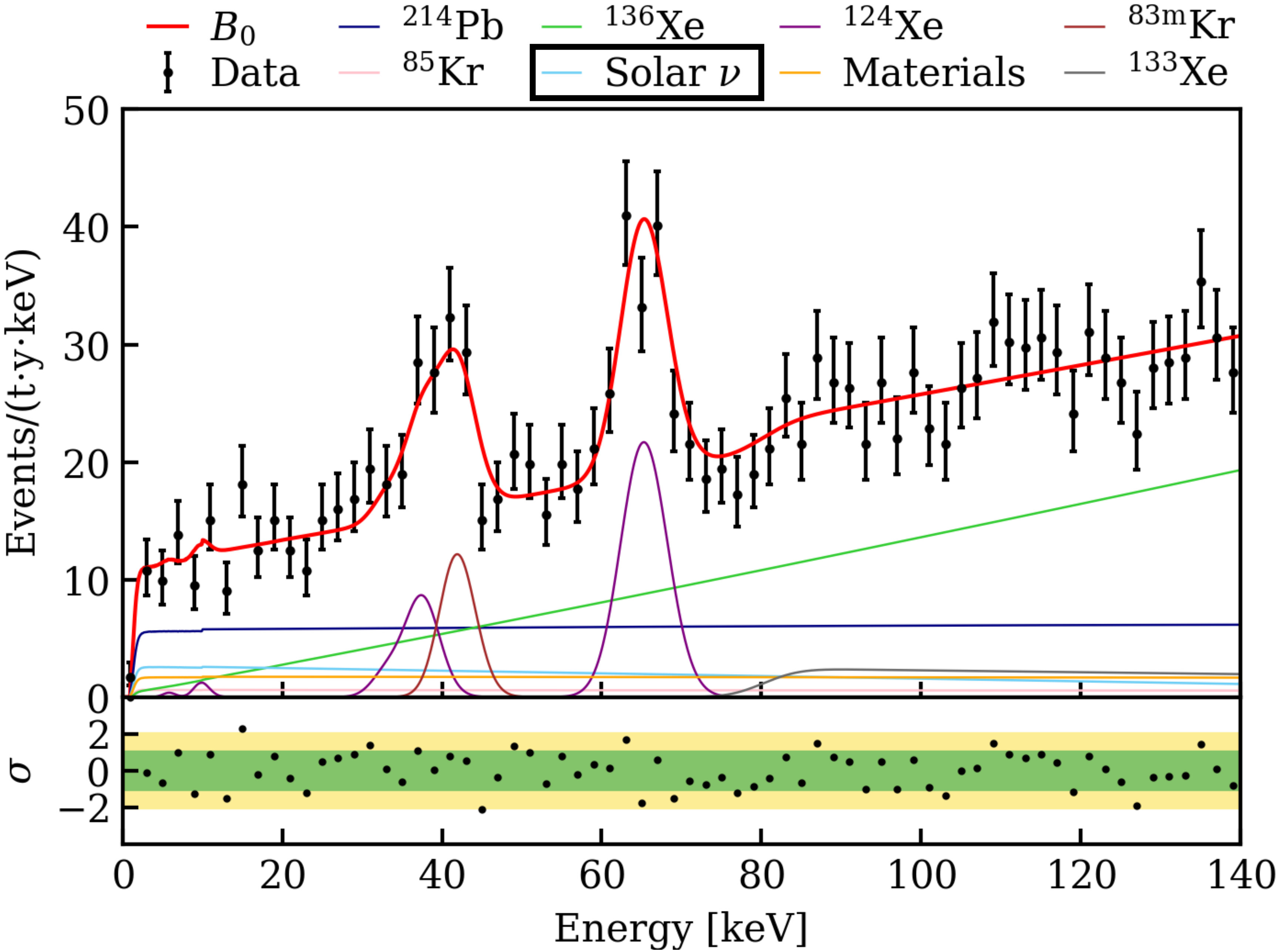
- Kr83m: IC – leftovers from by-weekly calibration campaigns, unharmful.
- H3-like: from SR1 contamination.

Neutron activation

- Xe125 – per-se unharmful however leads to I125. Negligible
- Xe133m: β+γ(81 keV) – left free in the inference
- Xe129m and Xe131m – outside ROI

SR0 low-ER search

Search for New Physics in Electronic Recoil Data from XENONnT



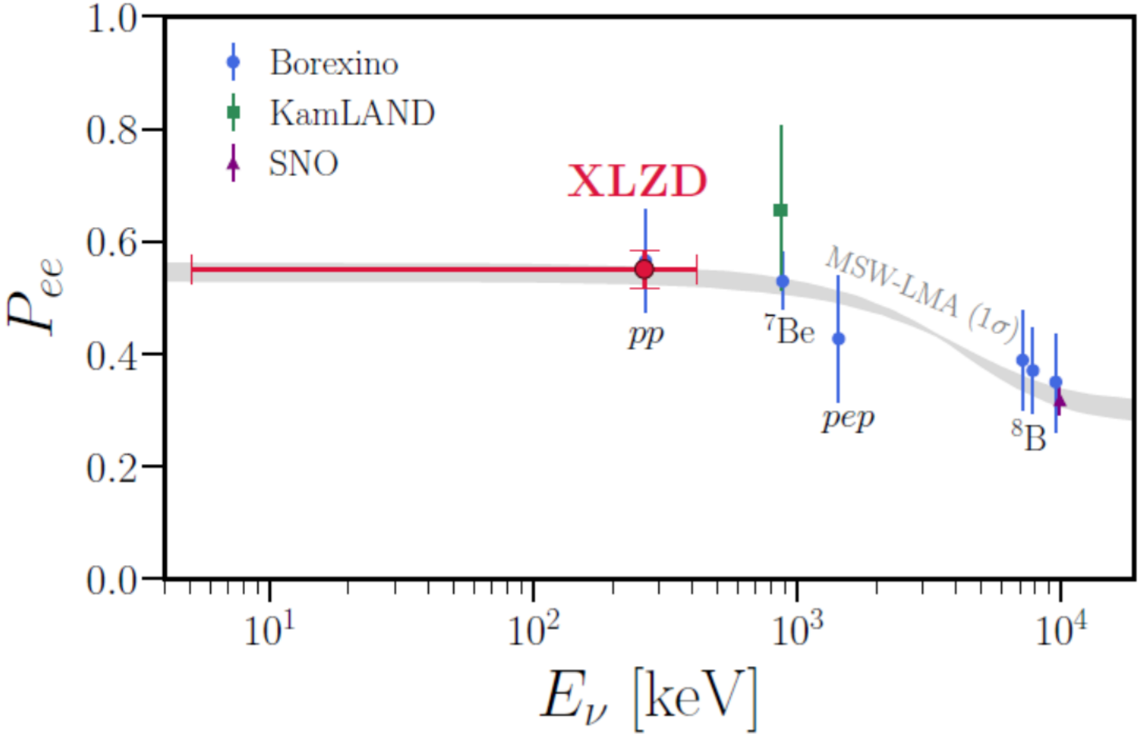
Measurement for the pp neutrino

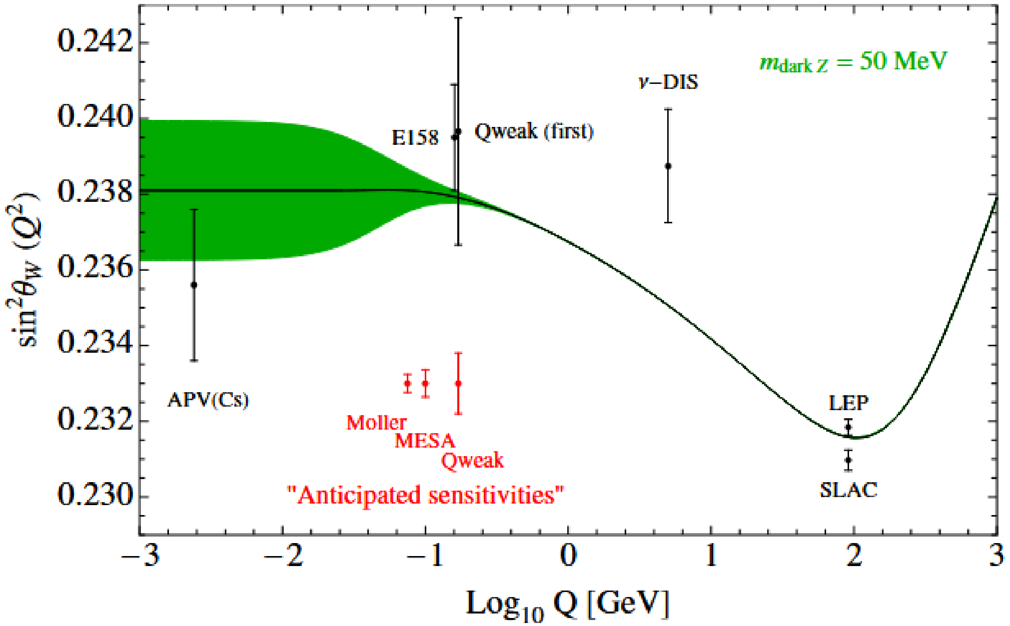
Low-E neutrino physics

- Measurement for ve survival probability (Pe-e)
- Measurement for the Weinberg angle
- Search for exotic neutrino interactions (ex. Magnetic moment)

Goal for XENONnT: Demonstration with 3σ

- Measurement with few % precision expected in future experiment





A next-generation liquid xenon observatory for dark matter and neutrino physics
The XLZD Design Book: Towards the Next-Generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics

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