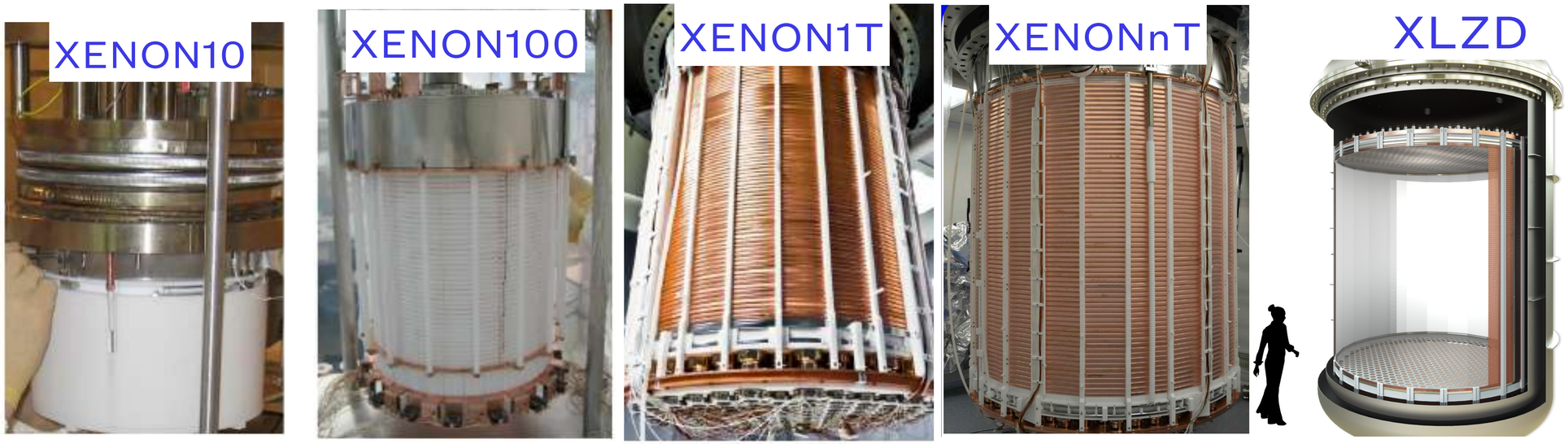


The measurement of low energy solar neutrinos via electron-neutrino scattering with the XENONnT

MASATOSHI KOBAYASHI (ISEE, NAGOYA-U) , 2026/11/11 KMI2026, NAGOYA, JAPAN

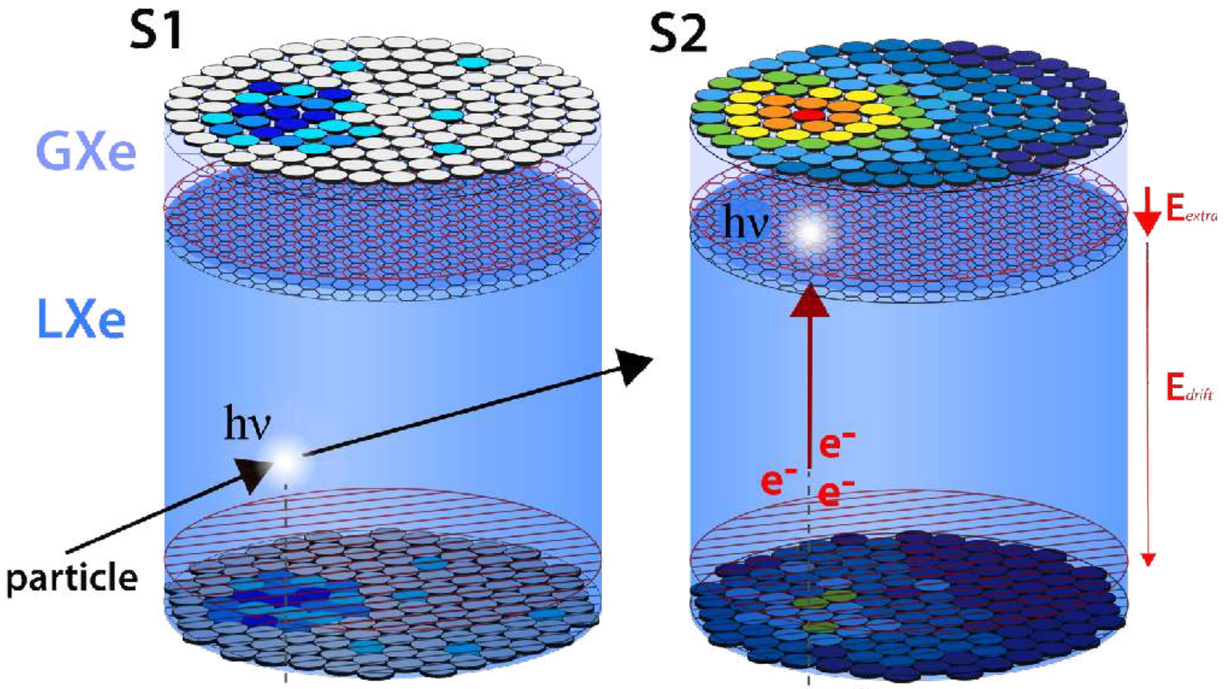
The XENON project

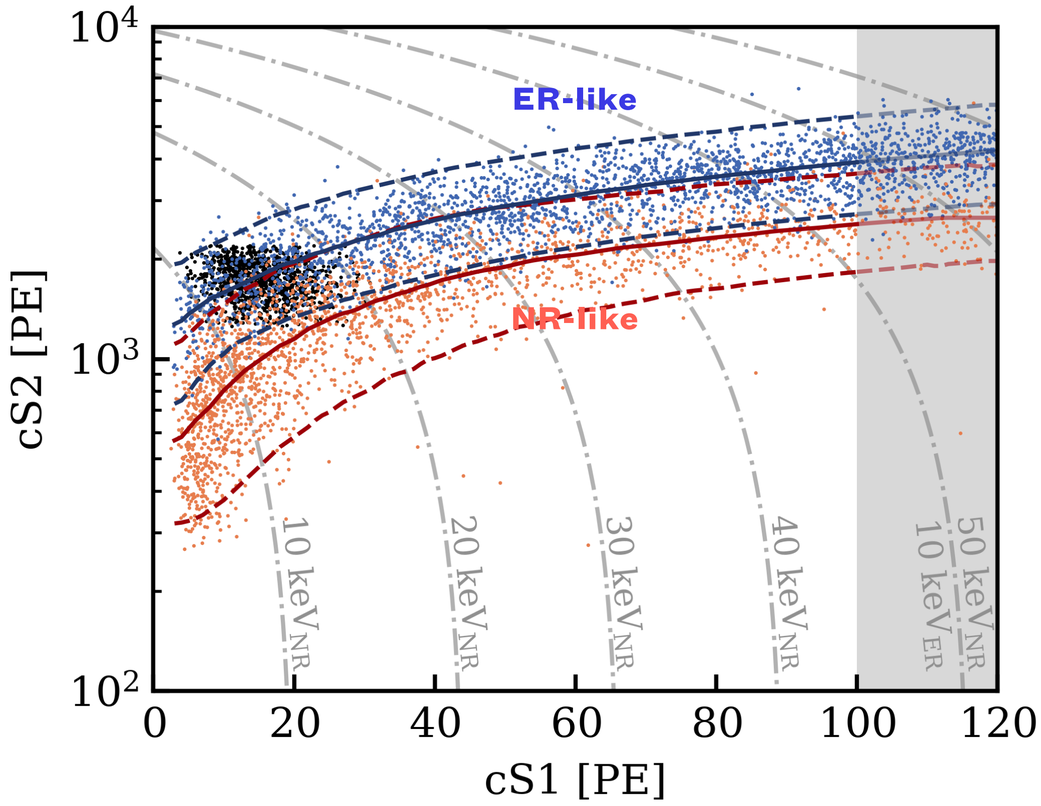
- XENON experiment: Rare event search experiment using liquid xenon detector
  - Dark matter, solar neutrinos, neutrino-less double beta decay,…
- Currently, **XENONnT** experiment is ongoing at LNGS, Italy



Years	2005 - 2007	2008 - 2016	2012 - 2018	2019 - NOW	mid 2030s -
Total Xe mass	25 kg	161 kg	3200 kg	8500 kg	60 - 100 t
WIMPs sensitivity	~10^{-43} cm^2	~10^{-45} cm^2	~10^{-47} cm^2	~10^{-48} cm^2	~10^{-49} cm^2

Liquid Xenon Time Projection Chamber





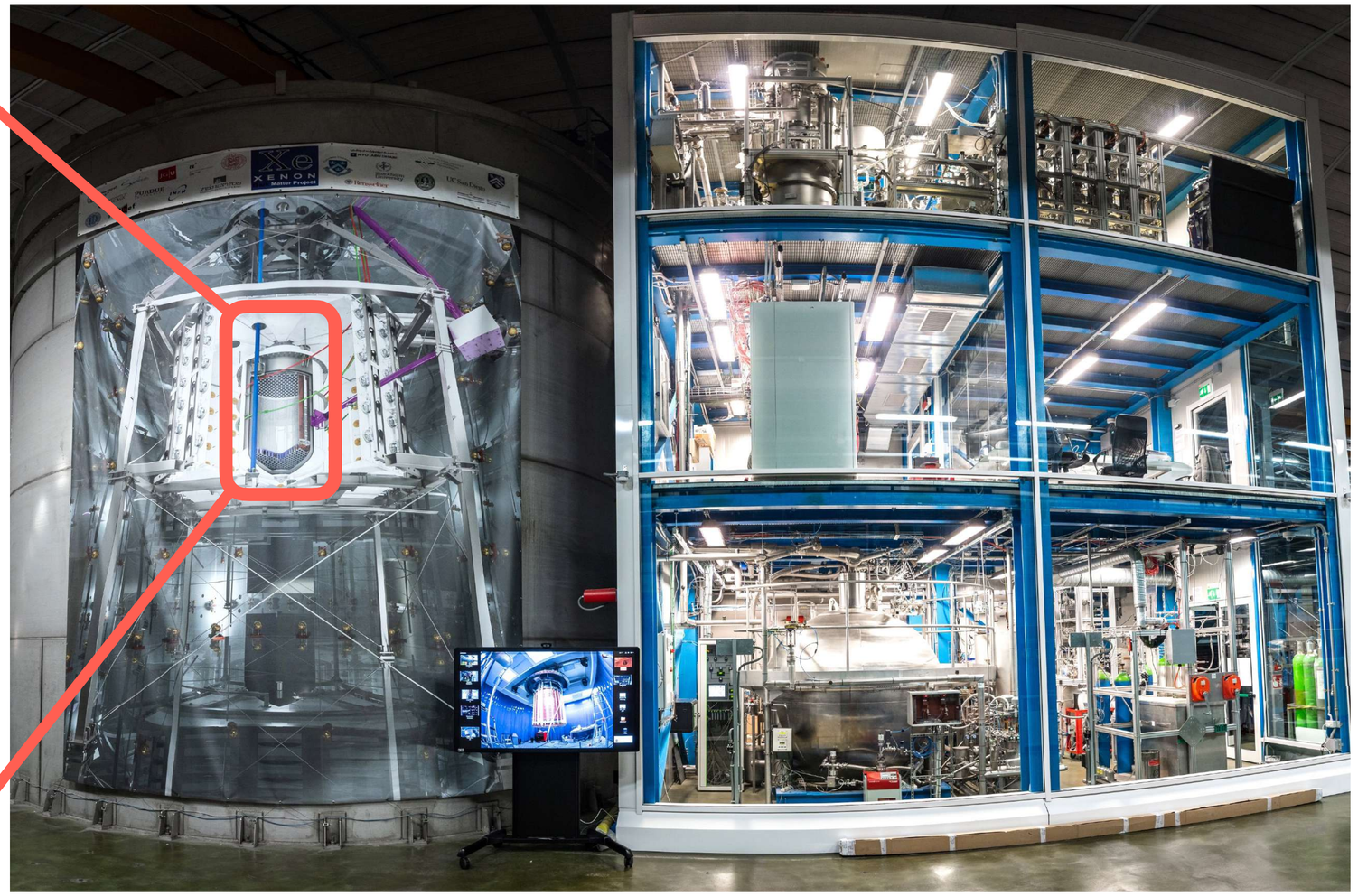
- Dual phase detector: LXe and GXe
- Particles generate signals in LXe
  - S1 signal: Scintillation photon
  - S2 signal: Ionization electrons

- S1/S2 depends on the type of interaction
  - Electronic recoils: lowE-ν, γ ray, β ray, ⋯
  - Nuclear recoils: WIMPs, Neutron,⋯

XENONnT detector

- The XENONnT detector is located at Laboratori Nazionali del Gran Sasso (LNGS), Italy
- Underground area: suppress muon background

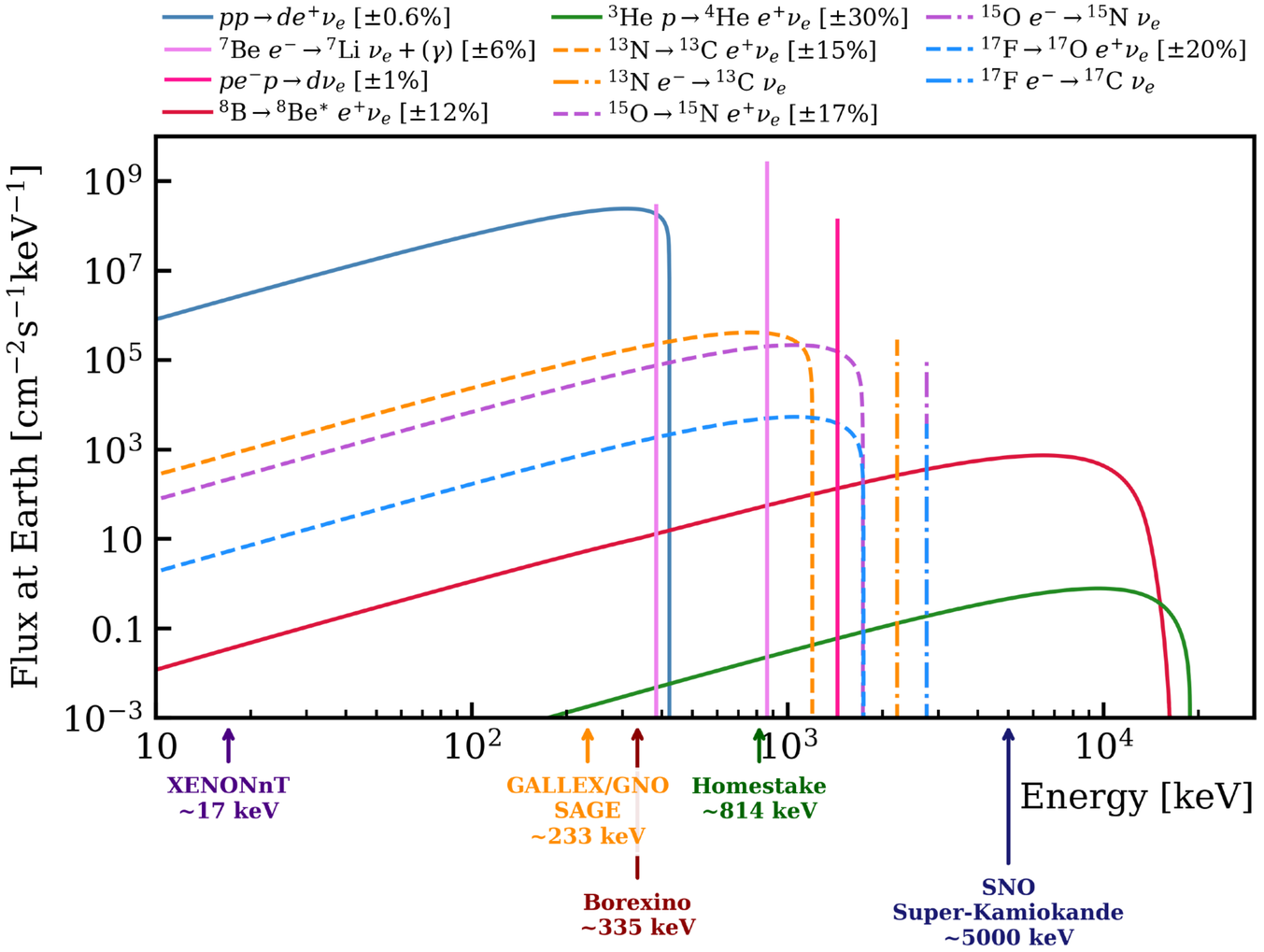




Measuring solar-pp neutrinos in XENONnT

Solar neutrino measurements in XENONnT

- Measurement of solar neutrinos: one of the main target for XENONnT
  - Ultra-low radioactive BG
  - Low threshold
  - Ton-scale mass
- Multiple channels for solar neutrino measurement:
  1. keV scale: via the electronic recoil
     - pp + ^{7}Be
  2. MeV scale: via the nuclear recoil
     - ^{8}B, ⋯ (skipped for this talk)



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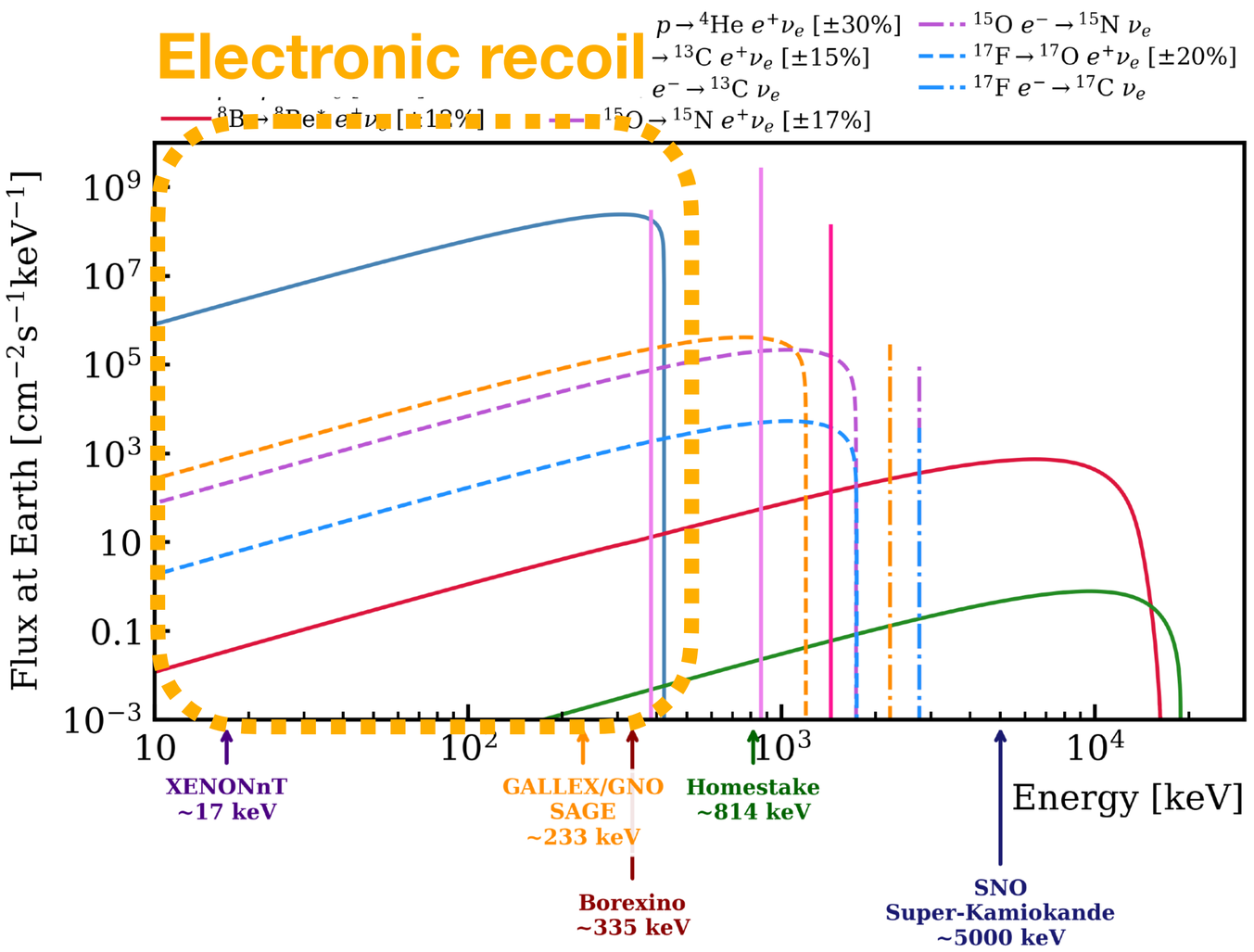
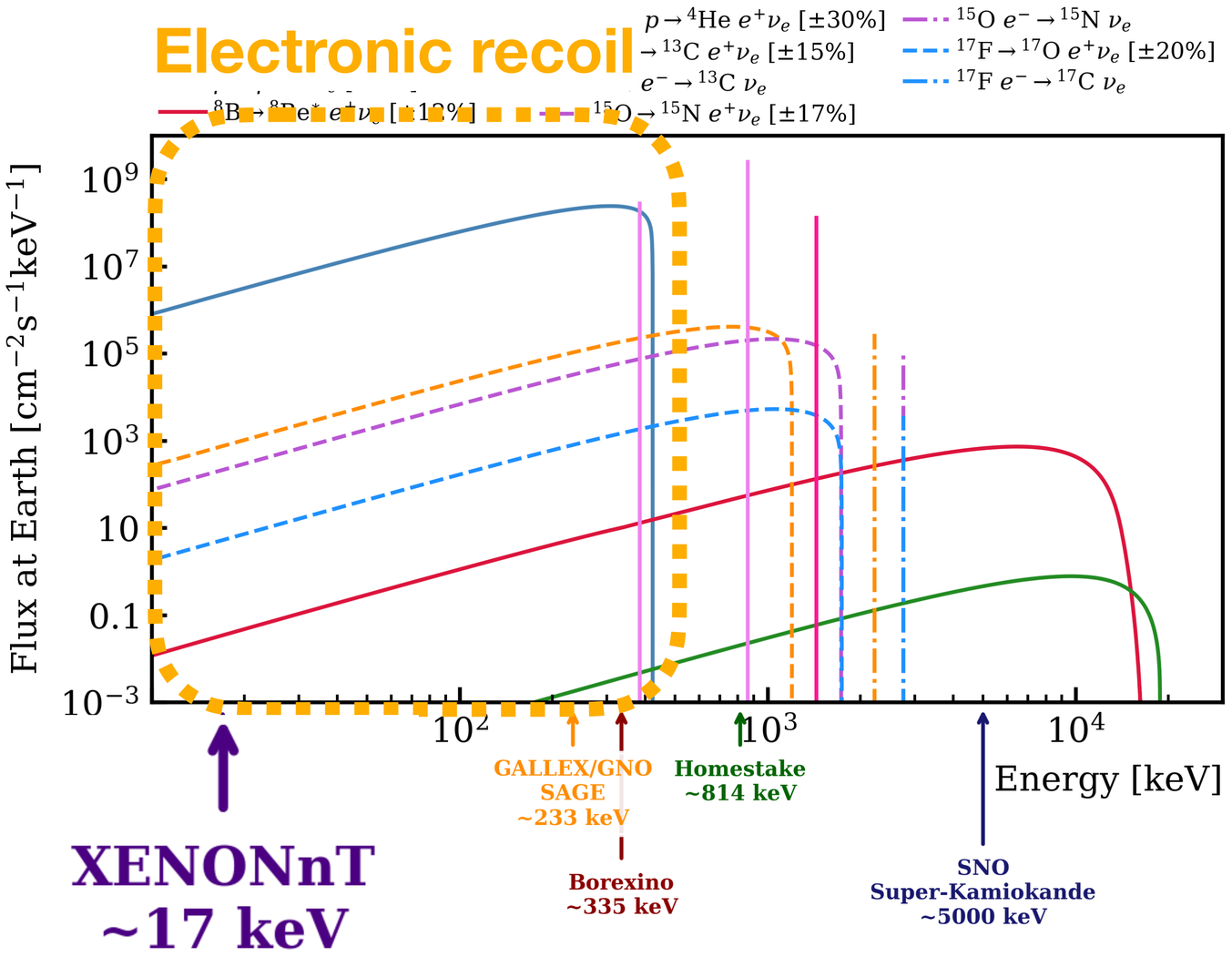


Measuring solar-pp neutrinos in XENONnT

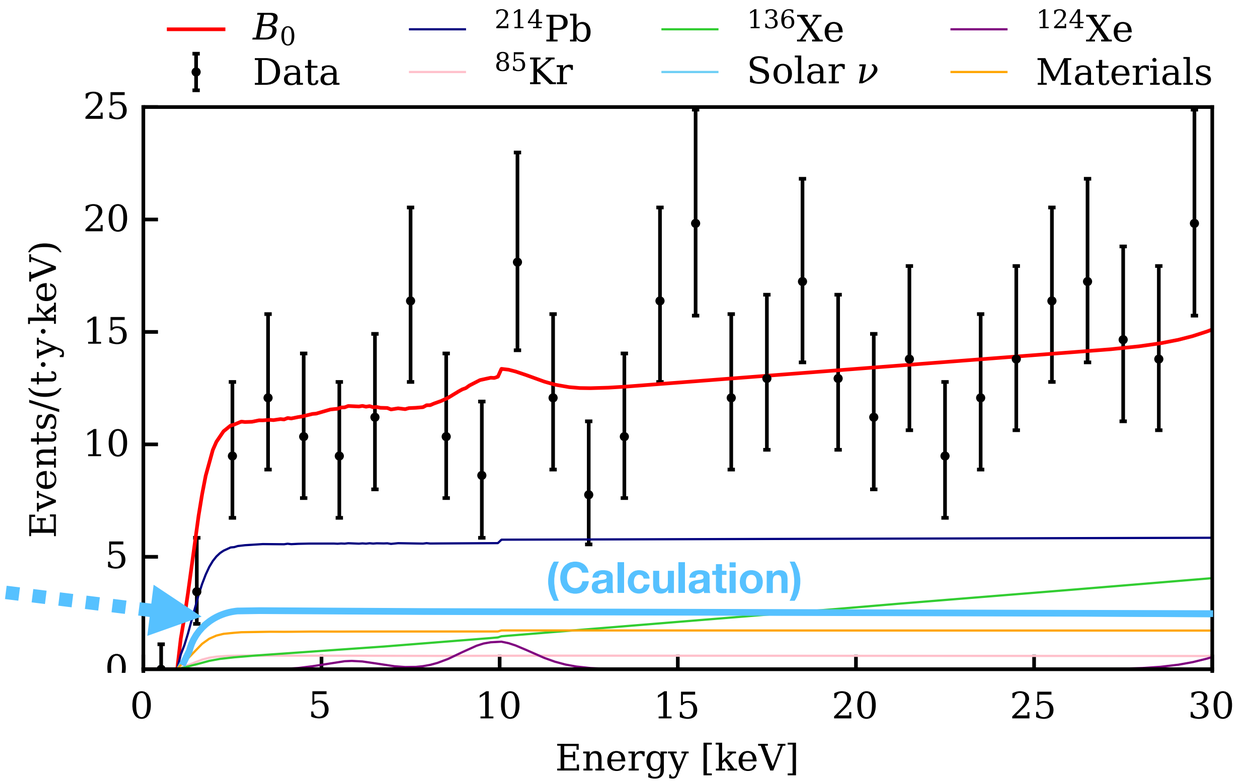
- Measurement via the electronic recoil events:
  - Sensitive for low energy neutrino (pp, ^{7}Be)
- Advantage of XENON: lower threshold
  - XENON detector: ~1keVee
  - Corresponds to ~17keV neutrino



Analysis for XENONnT initial data (SR0, 2022)

- Right: first science run by XENONnT (SR0)
  - Good agreement between **Data** and BG
- Main target for the analysis: peak-like signals
  - “XENON1T Excess”: ex. solar-axions
  - => solar-nu signal was calculated by Borexino’s result

XENONnT SR0 data



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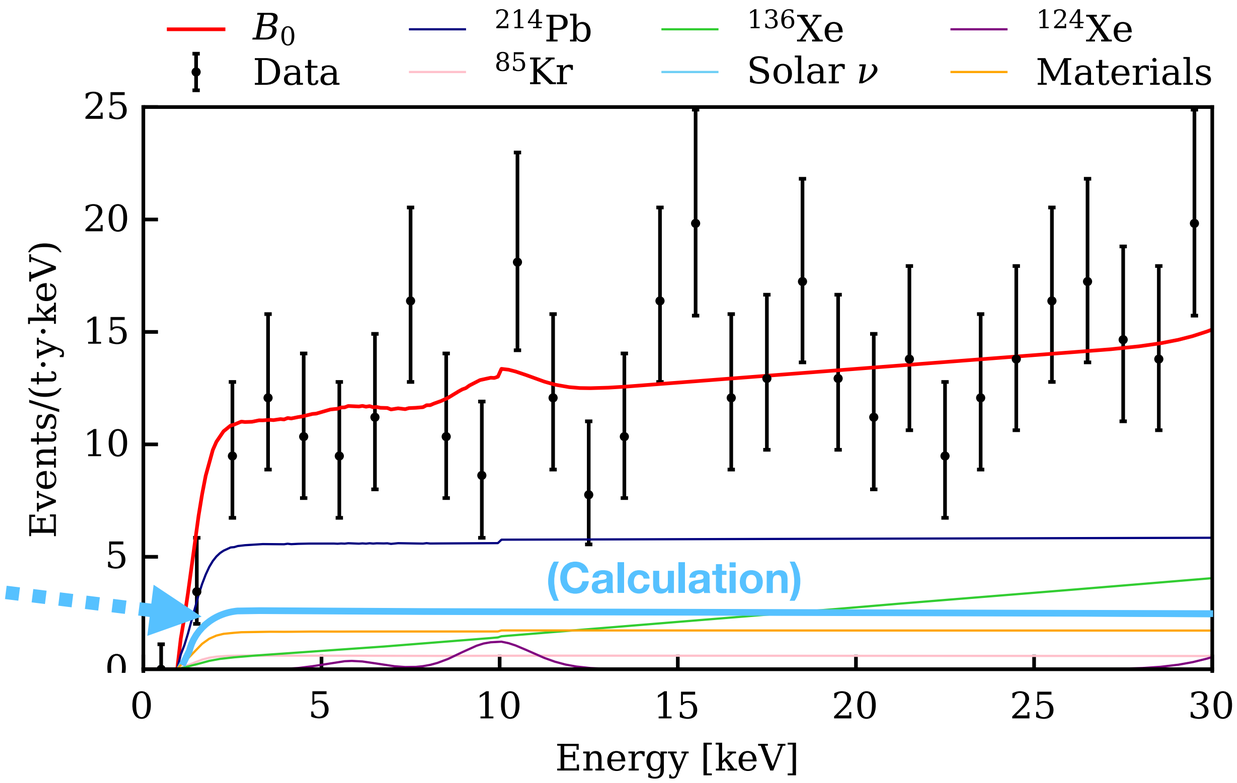
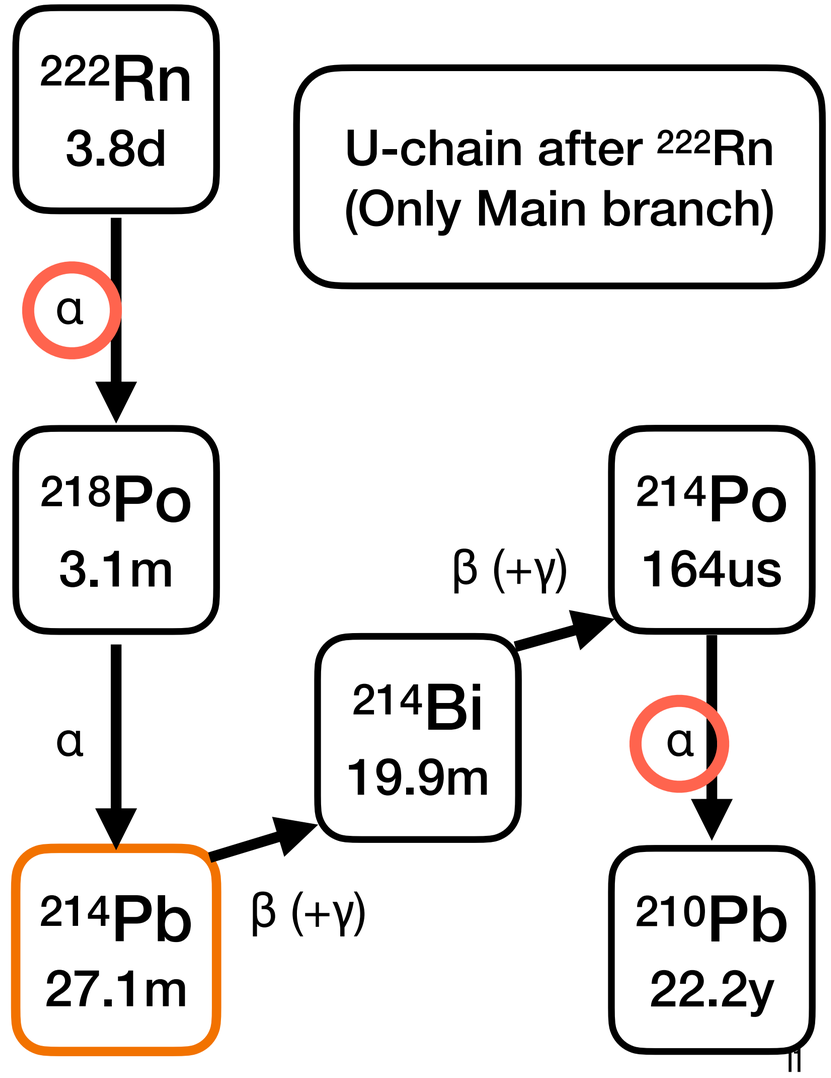
- Main target for the analysis: peak-like signals
  - “XENON1T Excess”: ex. solar-axions
  - => solar-nu signal was calculated by Borexino’s result
- To search for the solar-nu signal, precise understanding of other BG is essential
  - Radon-induced ^{214}Pb, ^{85}Kr, γ-rays,…

XENONnT SR0 data



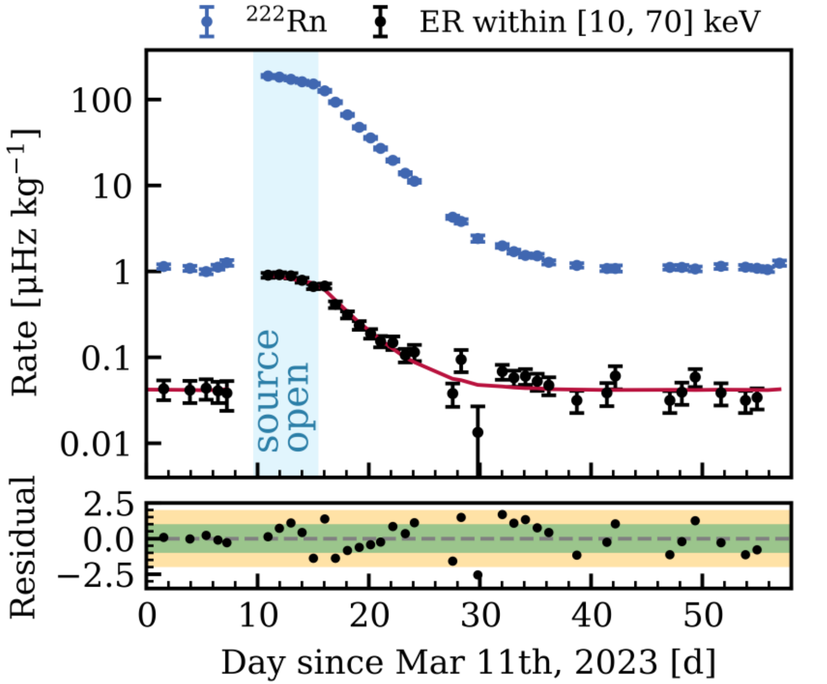
^{214}Pb background

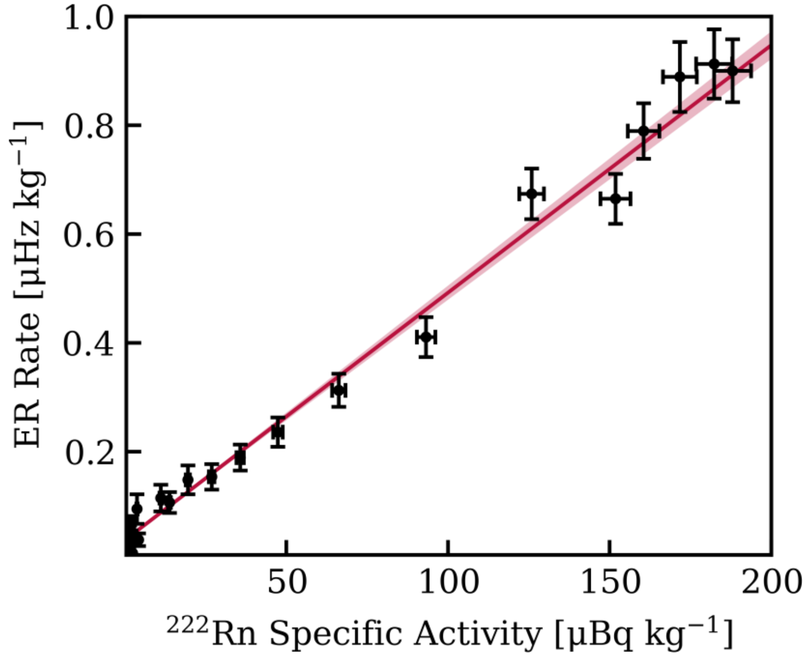
- **Radon-induced ^{214}Pb: largest BG component**
  - Reduced by Radon distillation system
  - β decay of ^{214}Pb creates BG events
  - ^{222}Rn can be counted using α decay; but daughters cannot.
- Ex. in SR0:
  - 1.7 (^{222}Rn) > ^{214}Pb > 0.78 (^{214}Po) [uBq/kg]
- **To search for solar-nu signal, we need to reduce the uncertainty down to ~5% level!**



^{214}Pb background

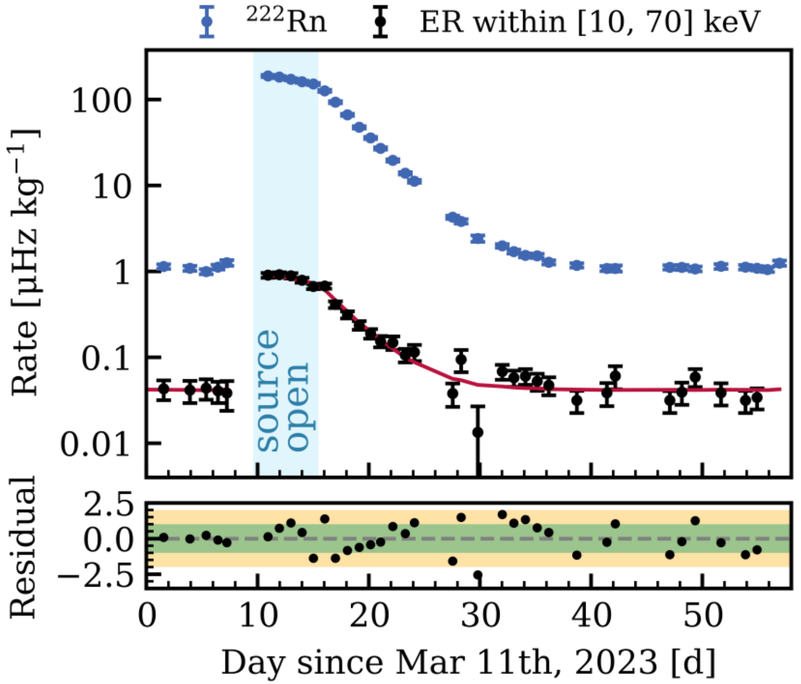
- Result of the ^{222}Rn calibration
- [Rate of α] vs [Rate of ER (10-70keV)]
- ^{214}Pb $\propto$ ^{222}Rn : $\epsilon R_{Pb} = a \cdot R_{Rn} + b$
  - a: Ratio between ^{222}Rn and ^{214}Pb
  - b: BG other than ^{214}Pb
  - ε (calc):correction by branching ratio, efficiency etc

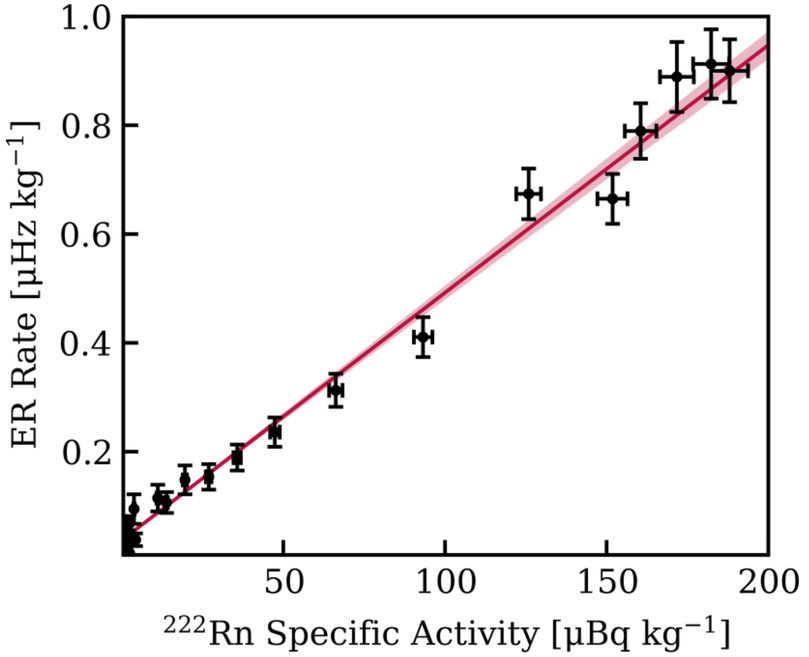




^{214}Pb background

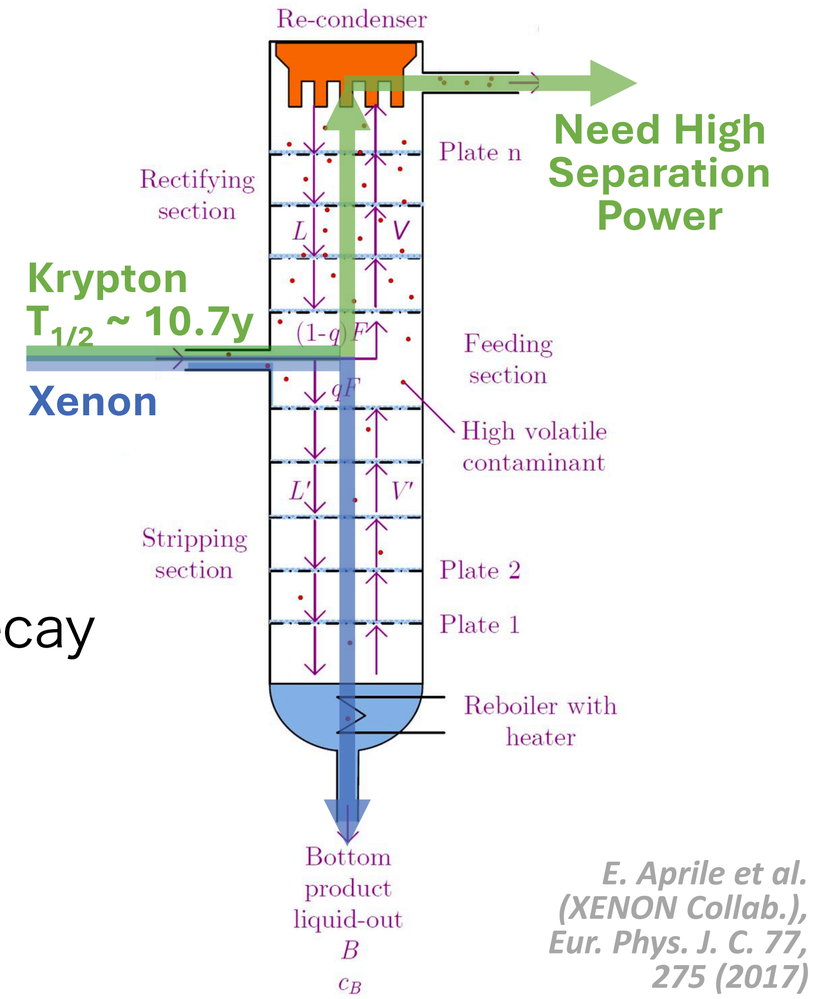
- Fit result:
  - a= **0.66 +/- 0.03 [Bq/Bq]**
- Note:
  - 1 Bq of ^{222}Rn <=> 0.66 Bq of ^{214}Pb
  - Uncertainty reduced to ~4.5% level
  - (i.e. ~40% for previous analysis)
- Estimated specific activity of ^{214}Pb
  - 1.39 ± 0.07 [uBq/kg] for SR0
  - 0.76 ± 0.03 [uBq/kg] for SR1b





Kr-induced background

- **Other major BG : Kr-induced β**
- **Kr-induced β**
  - **β decay of ^{85}Kr (Q=687keV)**
  - Removed by our own distillation (<0.1ppt for Kr)
  - Mass spectrum analysis for sampled gas
  - Confirmed by analytical estimation using rare decay mode of ^{85}Kr
- Estimated concentration of Kr (ppq: 10^{-15})
  - 82 ± 23 [ppq] for SR0
  - 170 ± 70 [ppq] for SR1
- Converted to Kr85 activity with its abundance



E. Aprile et al. (XENON Collab.), Eur. Phys. J. C. 77, 275 (2017)



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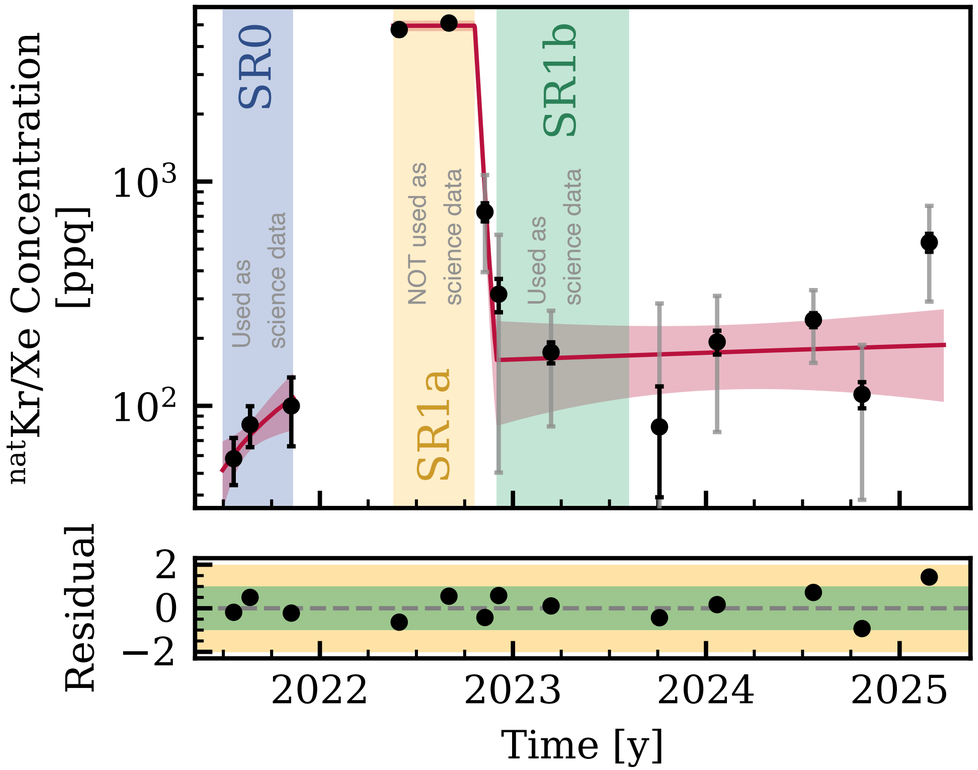
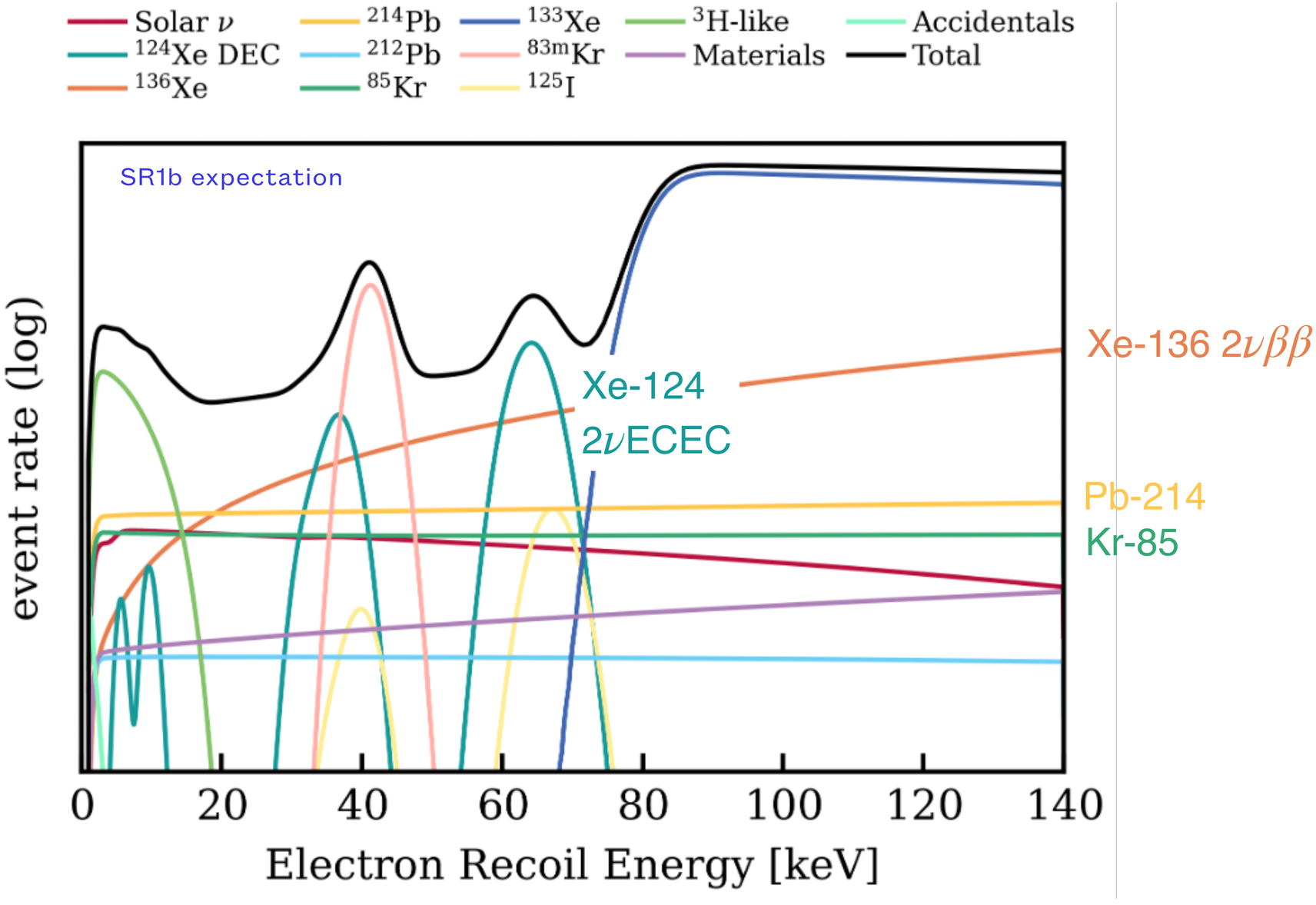
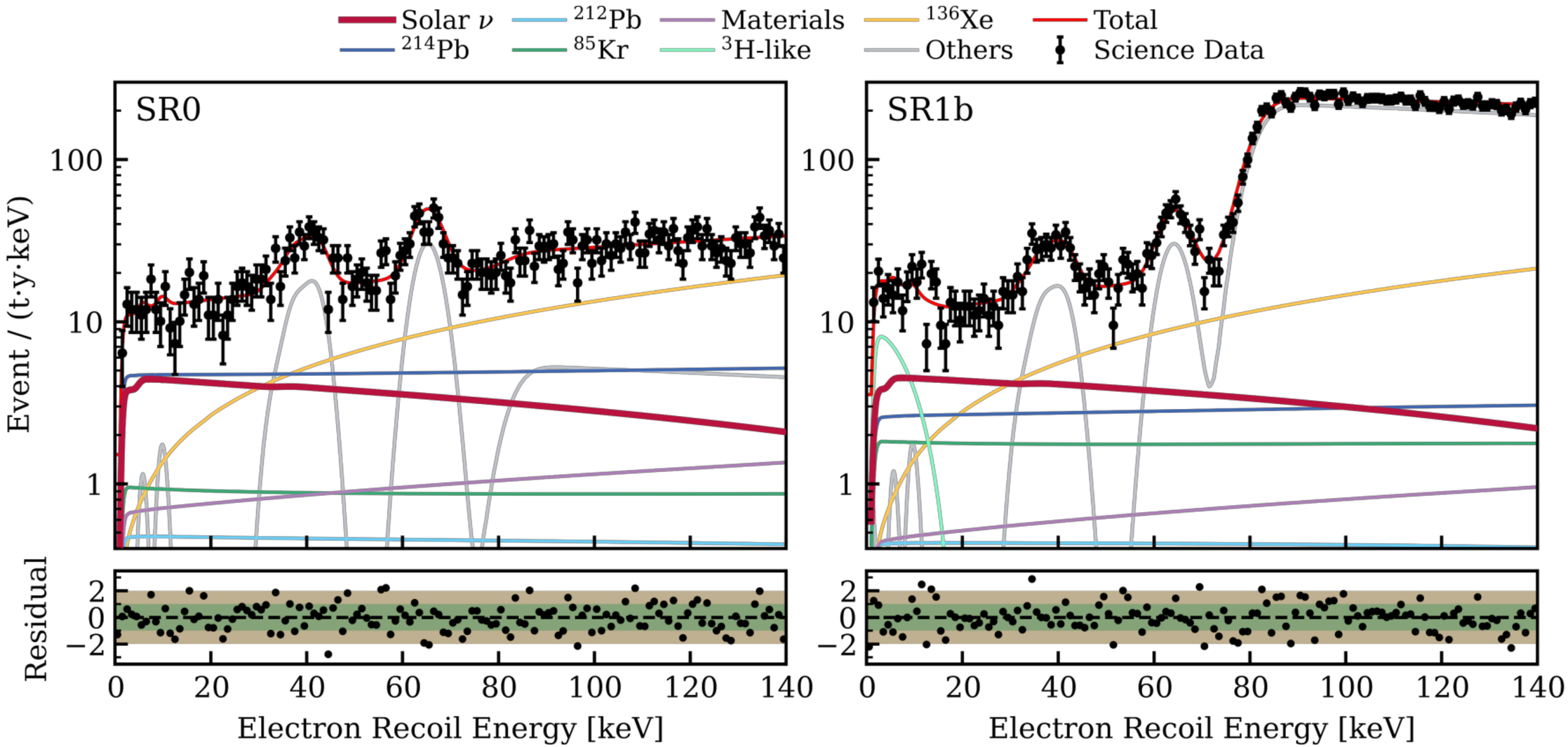


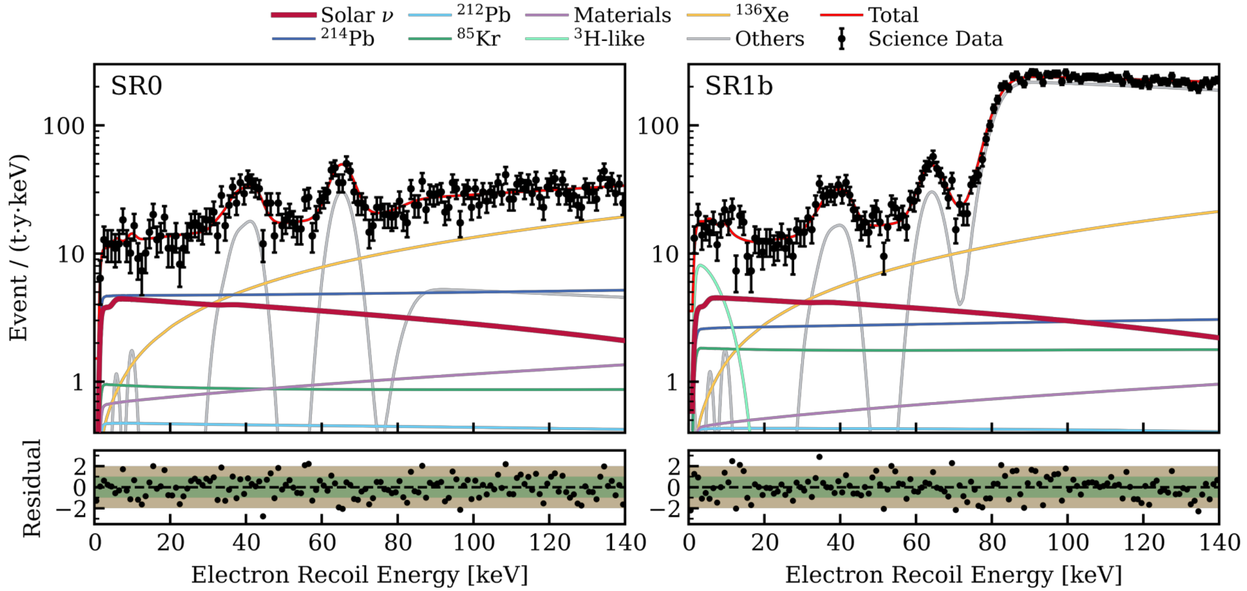
Background model



Fit result


Solar ν
214Pb
212Pb
85Kr
Materials
3H-like
136Xe
Others
Total
Science Data
SR0
SR1b
Event / (t·y·keV)
100
10
1
Residual
2
0
−2
0
20
40
60
80
100
120
140
Electron Recoil Energy [keV]

Result & uncertainty



	SR0	
	Nominal	Best-fit
Solar ν	**295**	**500 ± 70**
^{124}Xe DEC	270	343 ± 22
^{214}Pb	740 ± 40	740 ± 30
^{212}Pb	68 ± 13	68 ± 12
^{85}Kr	130 ± 40	130 ± 30
Materials	160 ± 40	150 ± 30
^{3}H-like	–	–
^{136}Xe	1460 ± 50	1430 ± 40
^{133}Xe	140	310 ± 60
^{83m}Kr	free	98 ± 14
^{125}I	–	–
Accidentals	0.4 ± 0.3	0.5 ± 0.3

	SR1b	
	Nominal	Best-fit
Solar ν	**287**	**660 ± 90**
^{124}Xe DEC	351	445 ± 28
^{214}Pb	538 ± 24	537 ± 23
^{212}Pb	80 ± 10	80 ± 10
^{85}Kr	390 ± 170	330 ± 110
Materials	137 ± 17	136 ± 17
^{3}H-like	233	92 ± 18
^{136}Xe	1990 ± 70	1950 ± 60
^{133}Xe	15937	16740 ± 140
^{83m}Kr	free	111 ± 19
^{125}I	39	0 ± 30
Accidentals	1.3 ± 0.1	1.3 ± 0.1

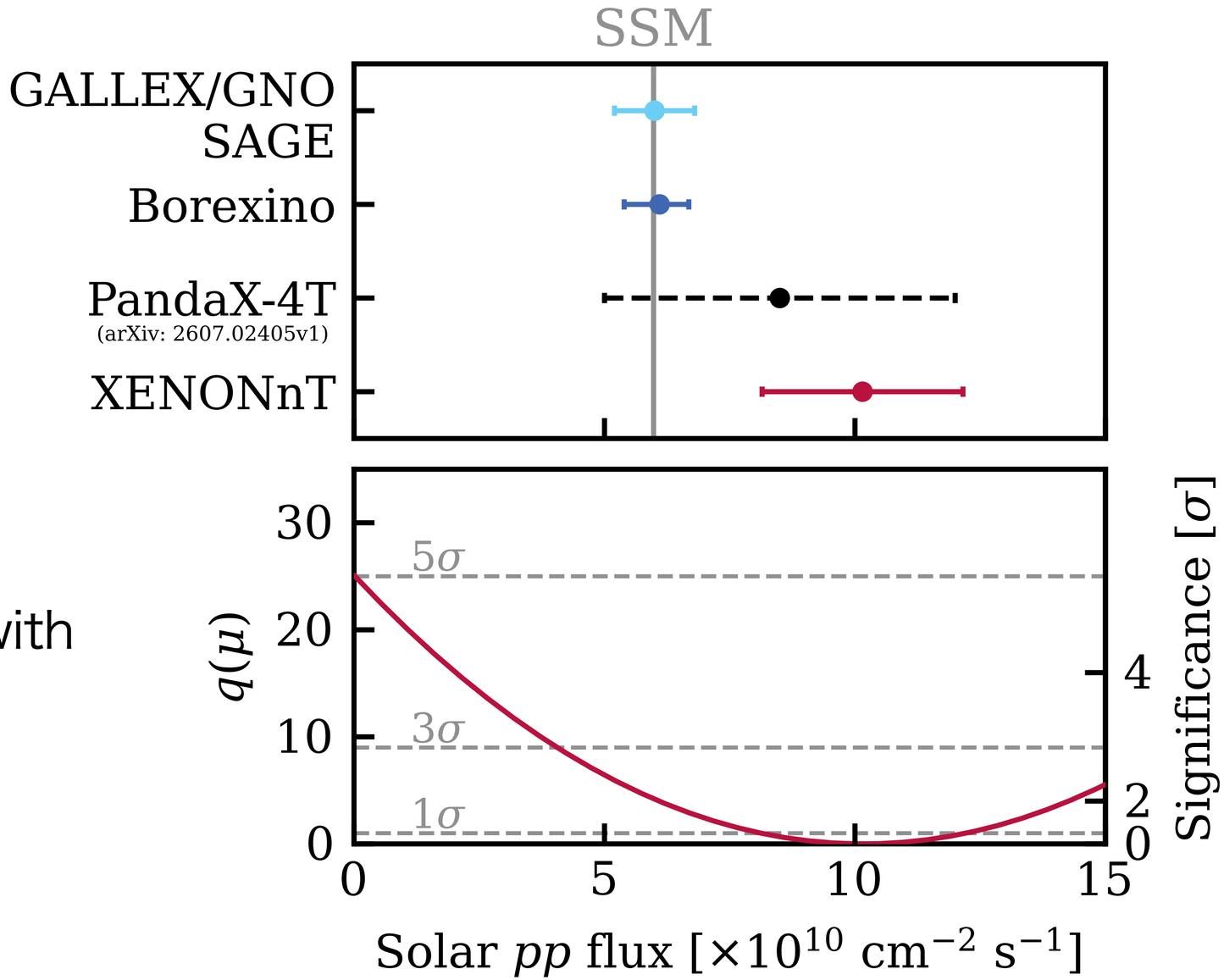
Systematic uncertainties

	σ_- (%)	σ_+ (%)
Fiducial volume	9.7	10
Efficiency	9.0	7.7
Energy bias	2.9	4.1
Energy resolution	1.3	1.4
^{214}Pb correlated uncertainty	4.3	4.1
^{214}Pb spectral shape	1.1	1.1
^{136}Xe spectral shape	1.0	1.0
Systematic uncertainty	14	14
Profile-likelihood uncertainty	14	14
Total	20	20

- Uncertainty from profile-likelihood: 14%
- Non-rate systematic parameters introduces additional 14% systematic uncertainty
- Total uncertainties: **20%**

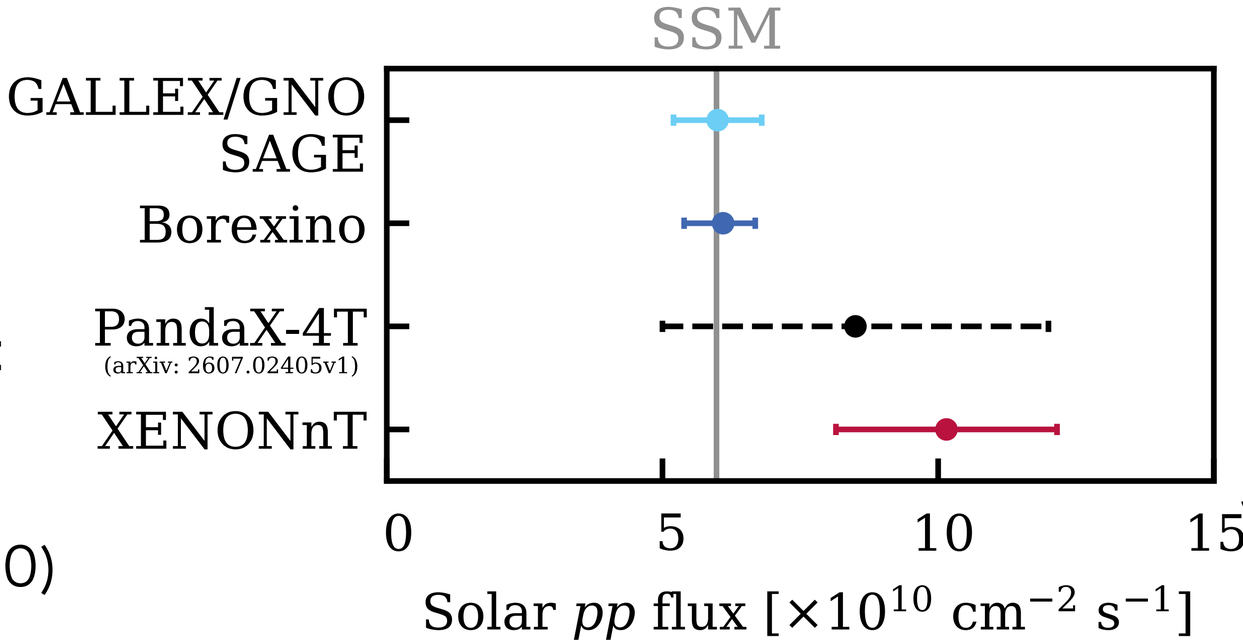
Fit result

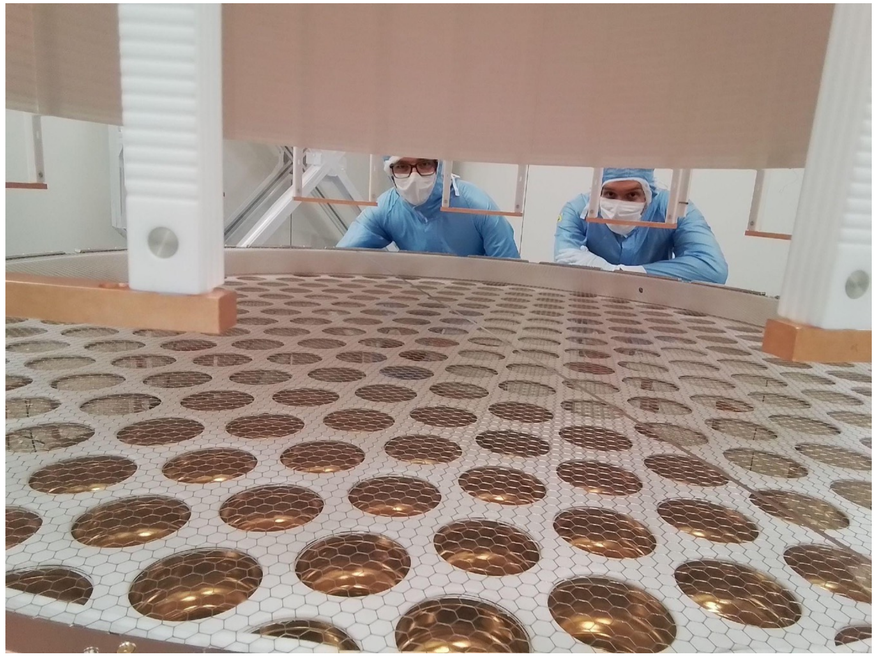
- Best fit flux for pp component:
  - **(10.2 ± 2.0)×10¹⁰ [cm⁻² s⁻¹]**
  - Ratio between the pp and 7Be are fixed
- Measured pp flux is consistent with Borexino result at 1.9 σ
- <u>Reject null-hypothesis by 5.0 σ</u>



Summary

- Measurement of solar neutrinos in XENONnT:
  - **keV-scale (pp + ^{7}Be)** … via ER process
    - Very recently released: (ArXiv: 2608.29450)
    - Reduction of uncertainty for Rn-induced BG to 5%
    - Final result: **(10.2 ± 2.0)×10^{10} [cm^{-2} s^{-1}]**
    - **Reject null-hypothesis by 5.0σ**
  - **MeV-scale (^{8}B)** … via CEvNS NR process
    - PRL. 137, 091807
- **The analysis for more data is ongoing; Stay tuned!**





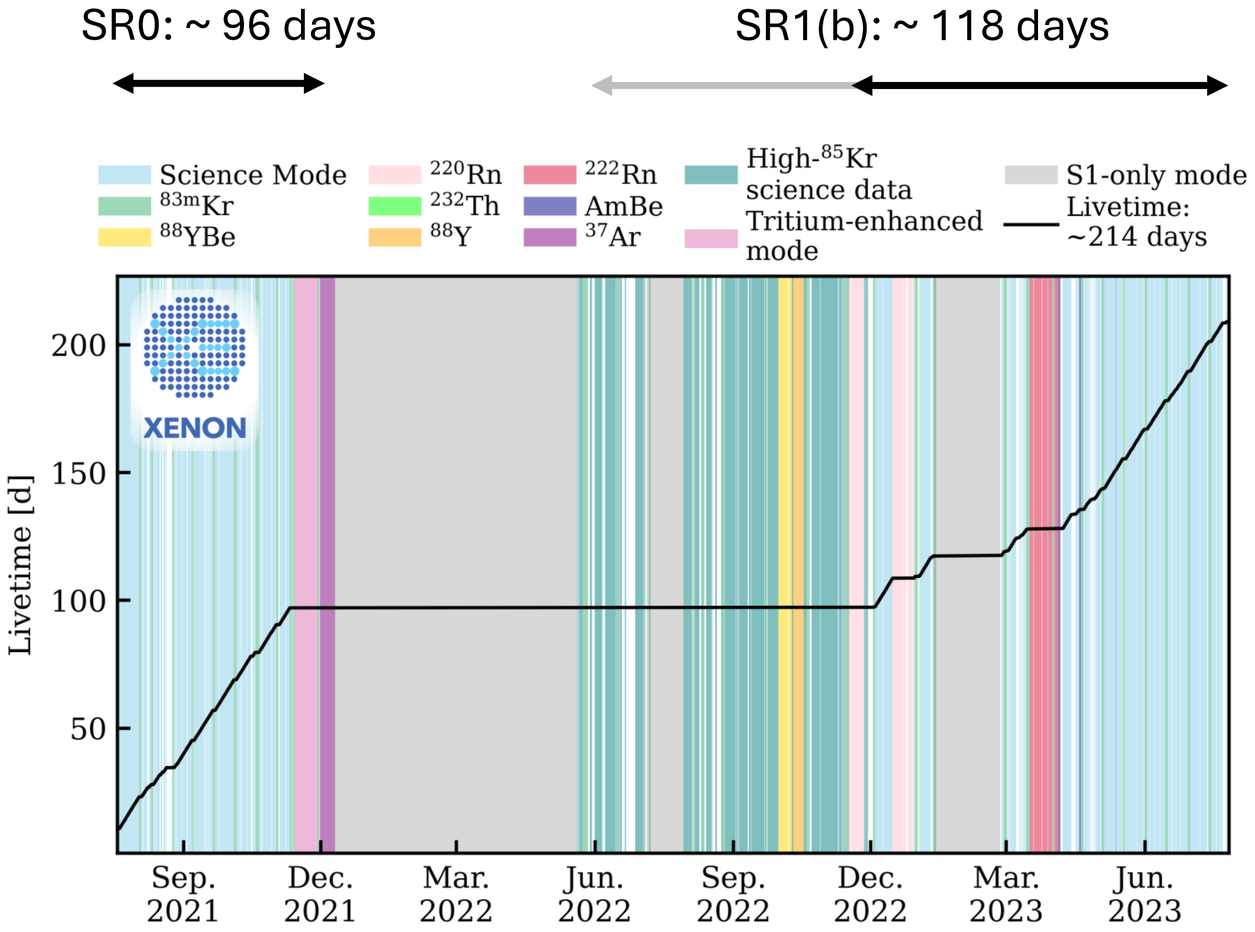
Back Up

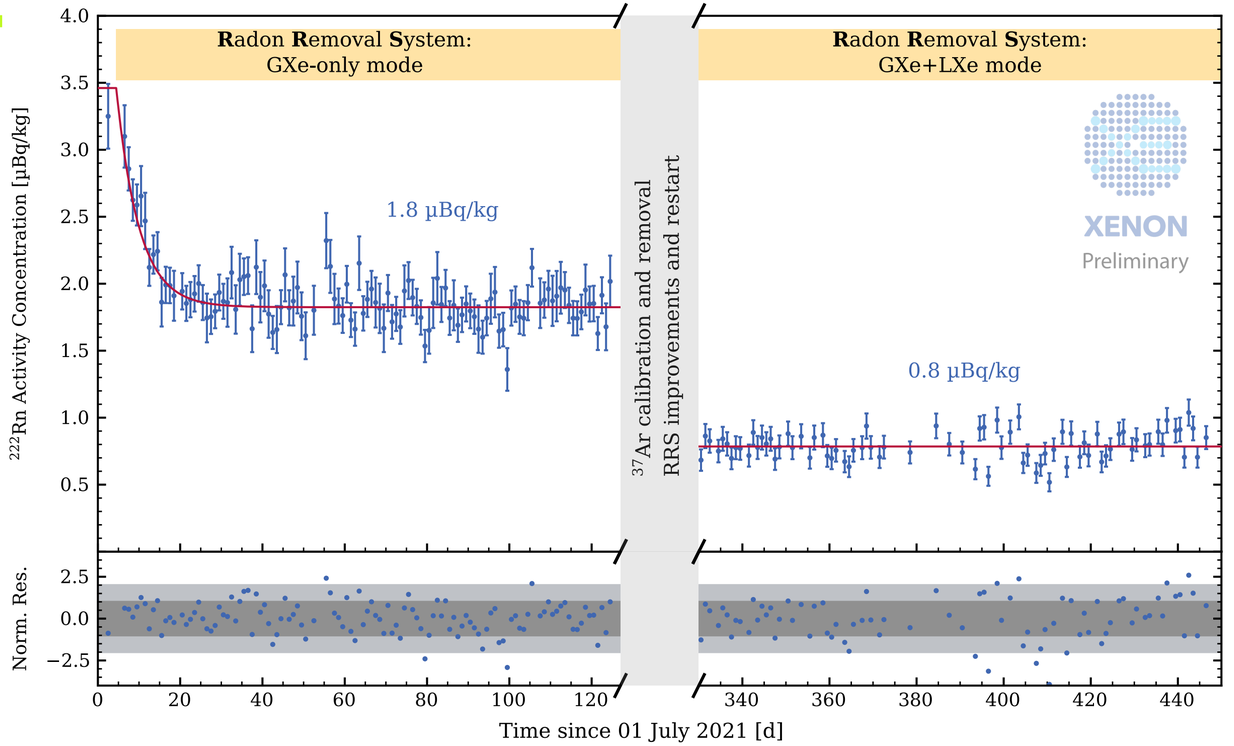
Recent results from XENONnT

- Main focus of this talk:
  - **Measurement of Low energy solar neutrinos in keV scale** **ArXiV: 2608.29450**
- Also analysis for a lot of other physics are ongoing:
  - ^{8}B solar neutrino via CEvNS + search for Low-mass WIMPs **PRL. 137, 091807**
  - Search for Heavy WIMPs **PRL, 133 191002**
  - Search for Magnetic Inelastic DM **ArXiV: 2608.15149**

… and more!

Exposure



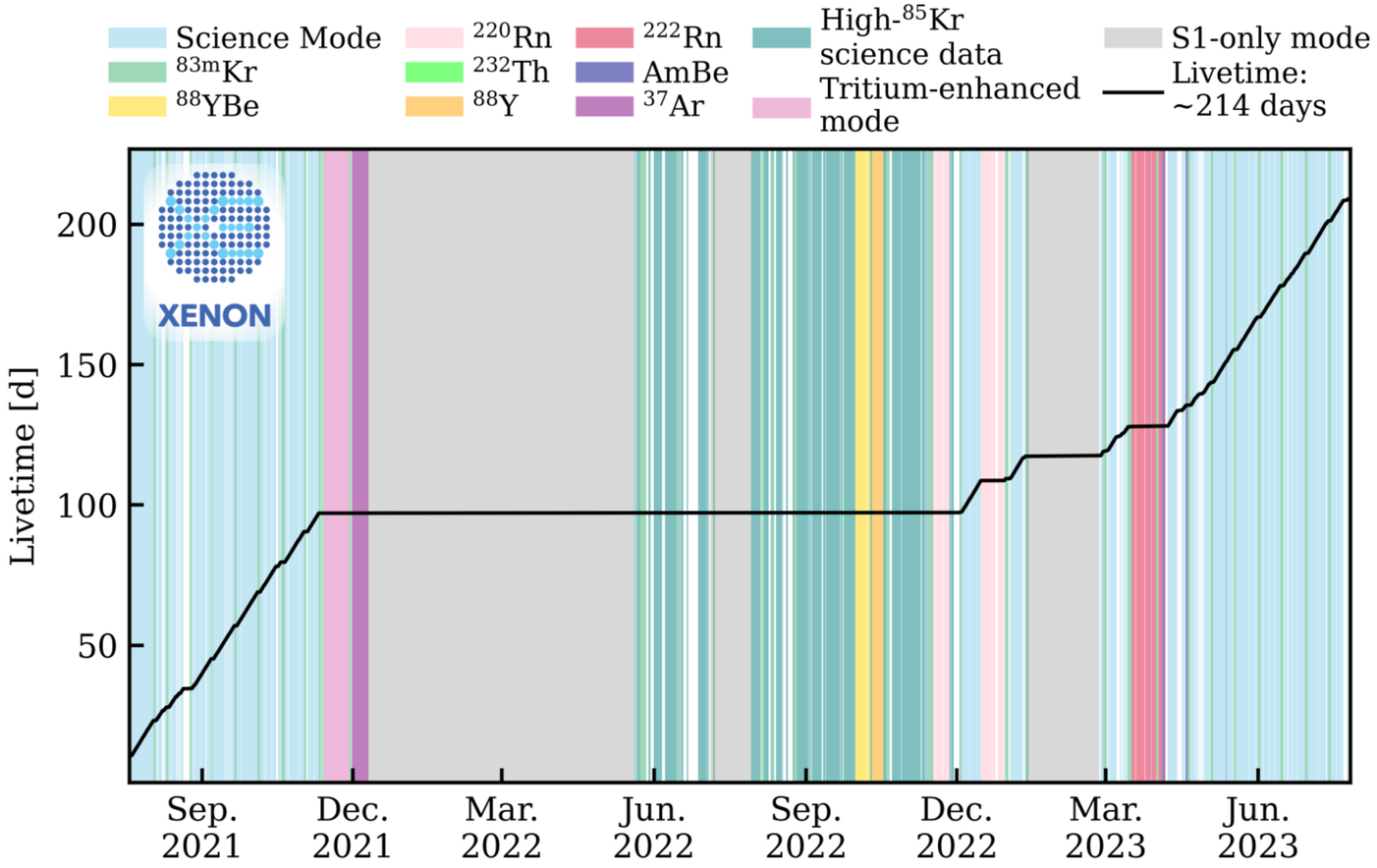


- Exposure:
  - SR0: 0.26 [year] × 4.37 [ton]
  - SR1: 0.51 [year] × 4.00 [ton]
- Between SR0 and SR1, radon removal system was upgraded:
  - 1.8 -> 0.9 [uBq/kg]

Exposure

SR0: ~ 96 days

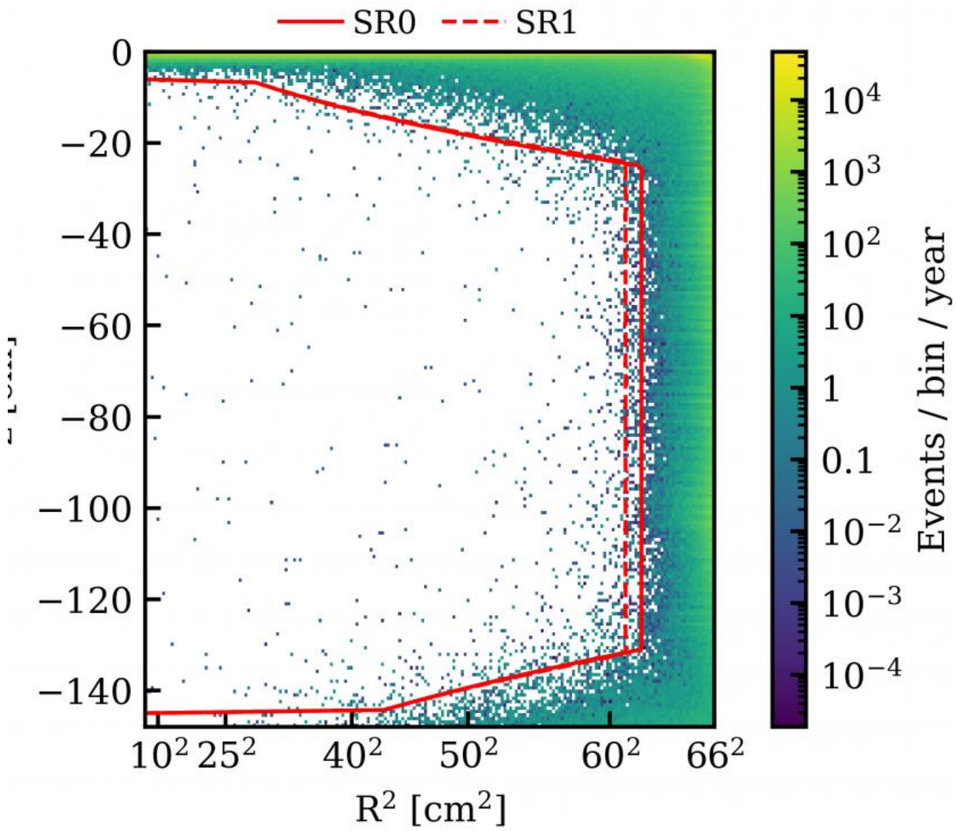
SR1(b): ~ 118 days



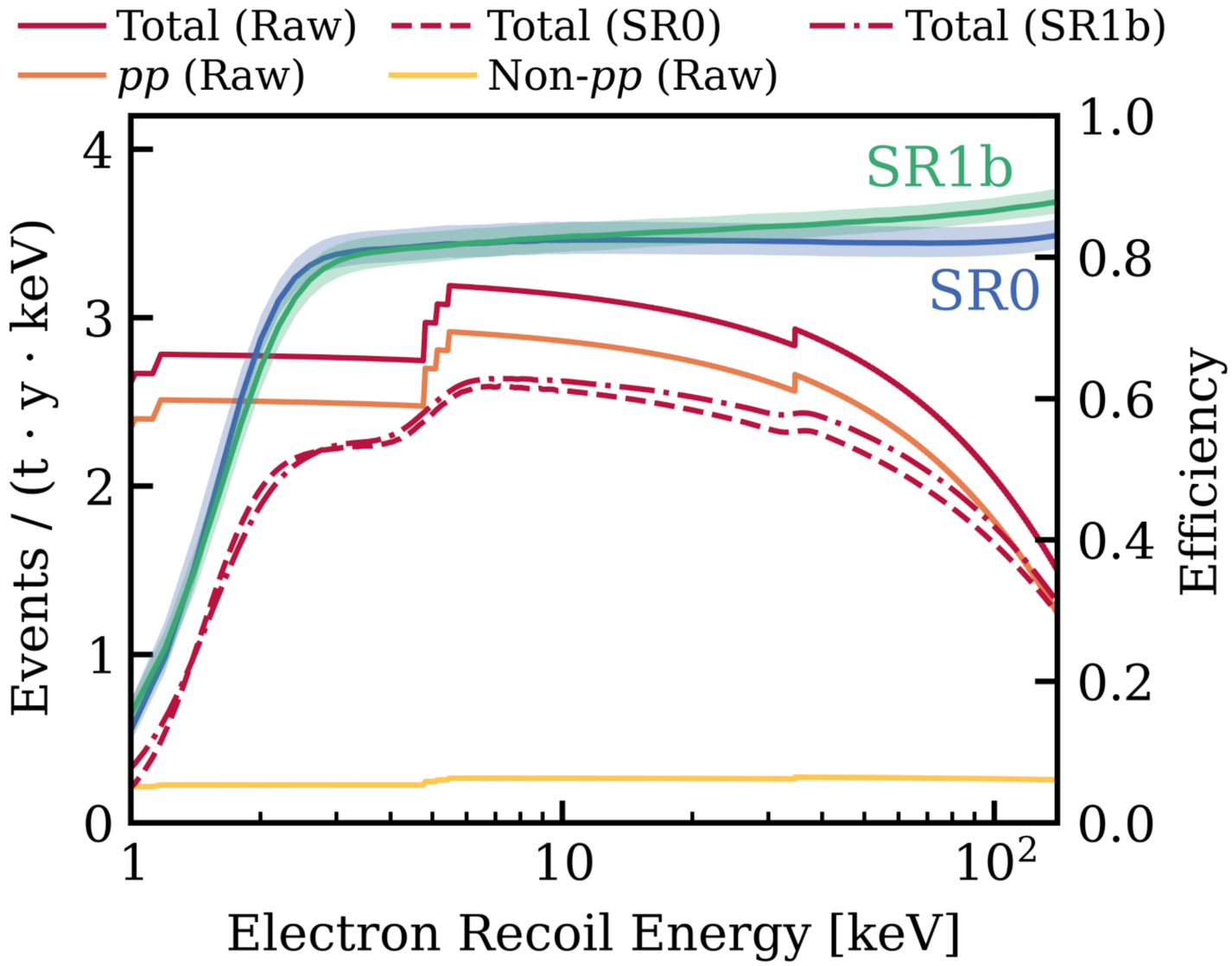
ROI: [1, 140] keV

Optimized base on material radioactivity

SR0 (SR1): ~ 4.13 (4.24) tons



Signal efficiency



Energy Calibration

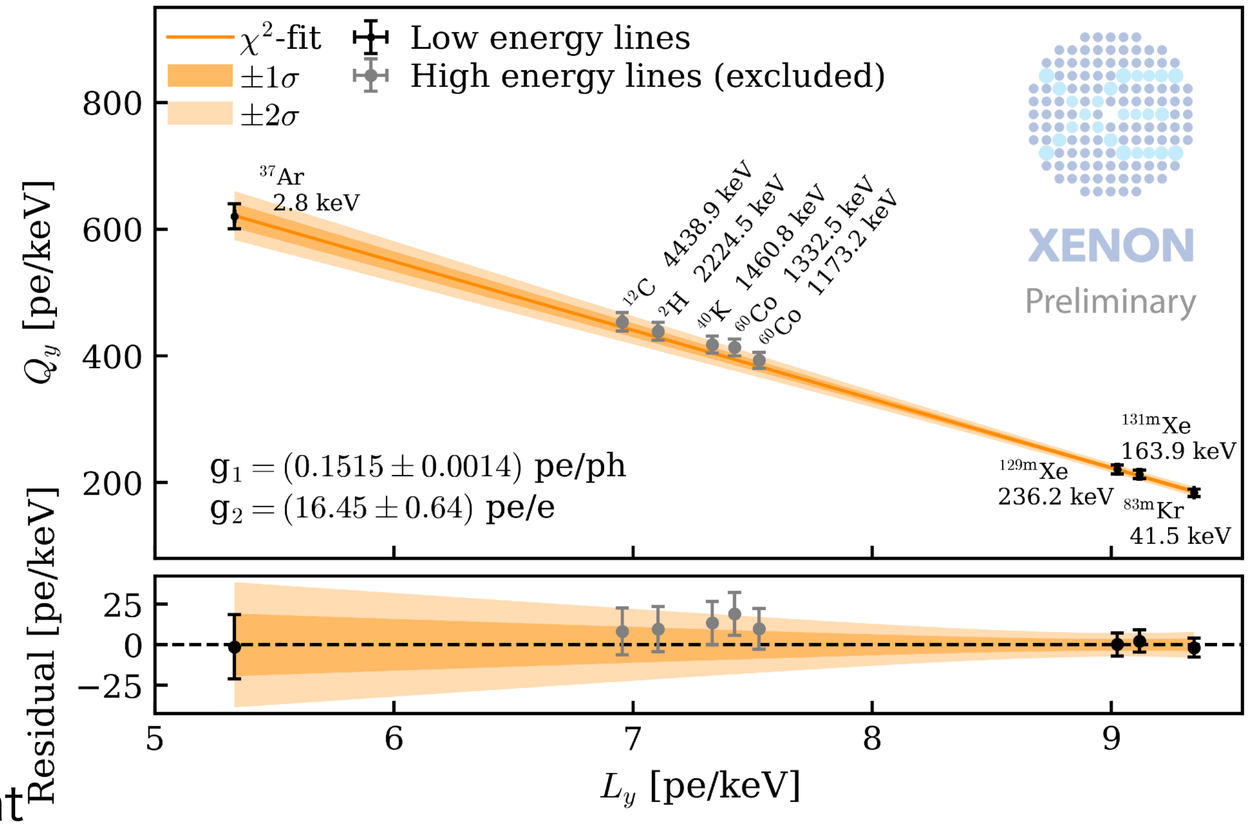
$$E = (n_{ph} + n_e) \cdot W = (\frac{cS1}{g1} + \frac{cS2}{g2}) \cdot 13.7(\text{eV})$$

- cS1, cS2; “corrected” the detector uniformity

- g1 and g2: detector-specific gain constant
  - Extracted from calibration data

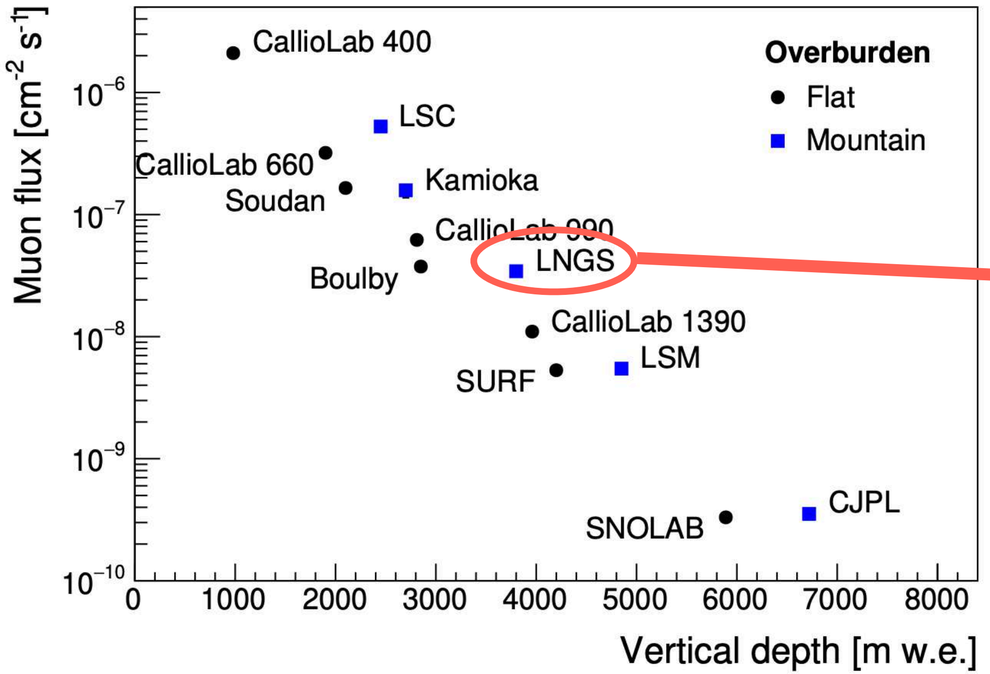
$$Q_y = -\frac{g2}{g1} \cdot L_y + \frac{g2}{W} \quad (Q_y = cS_2/E, \quad L_y = cS_1/E)$$

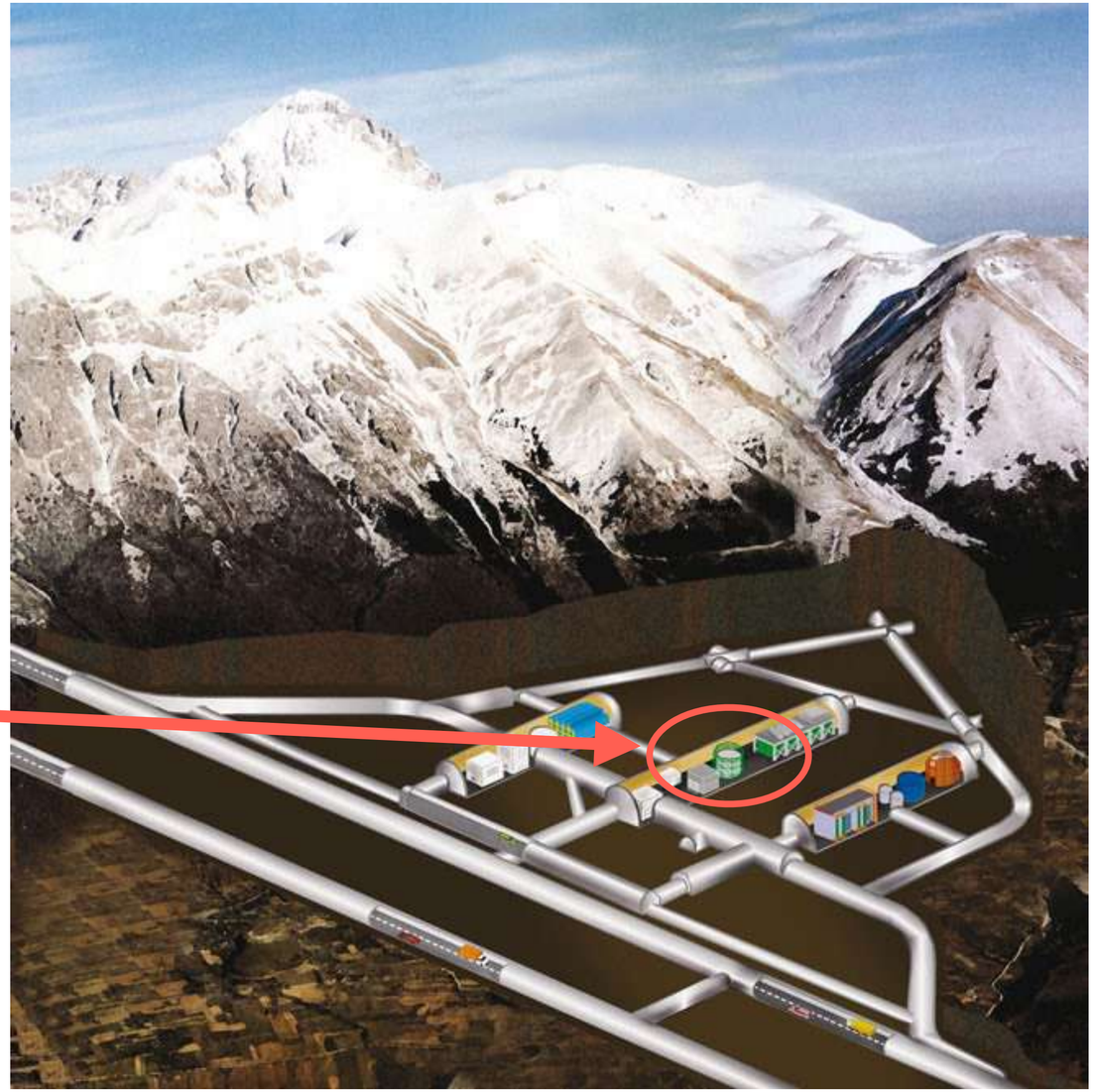
- Using g1 and g2, reconstruct energy of each event



The XENONnT

- The XENONnT detector is located at Laboratori Nazionali del Gran Sasso (LNGS), Italy
- Underground area: suppress muon background
  - 1500 m of rock ~ 3600 m.w.e
  - Suppress muon flux to 10^{-6} of surface area





The XENONnT

Nagoya/JP group contributions

Larger TPC

with 3x active volume

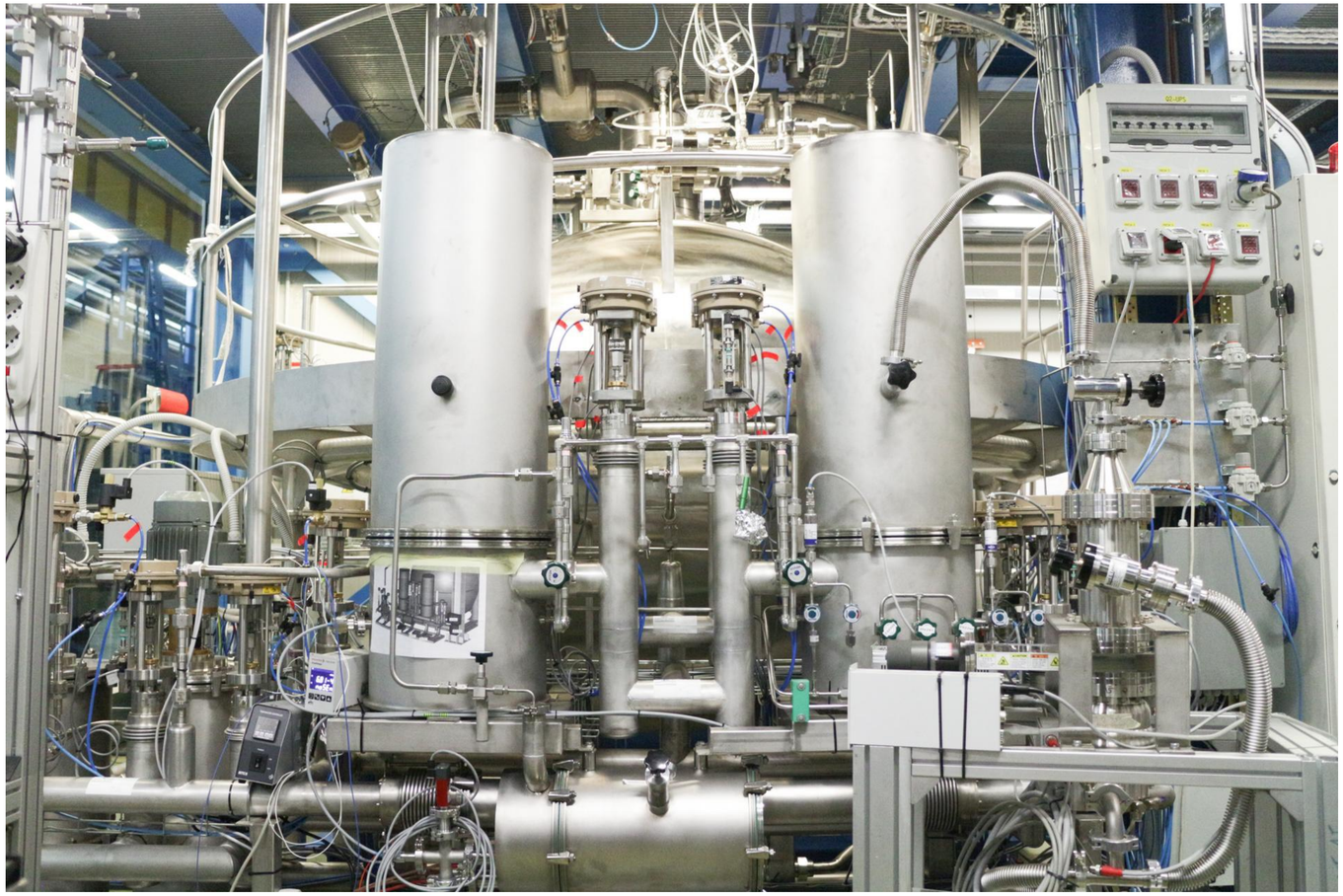
Gd-loaded water Cherenkov neutron veto



Radon distillation column

Liquid xenon purification

LXe Purification



- Liquid purification system
- Direct liquid circulation with cryogenic pump
  - Speed: ~2 LPM with liquid
  - ~x500 of XENON1T system
- Real-time purity measurement with purity monitor

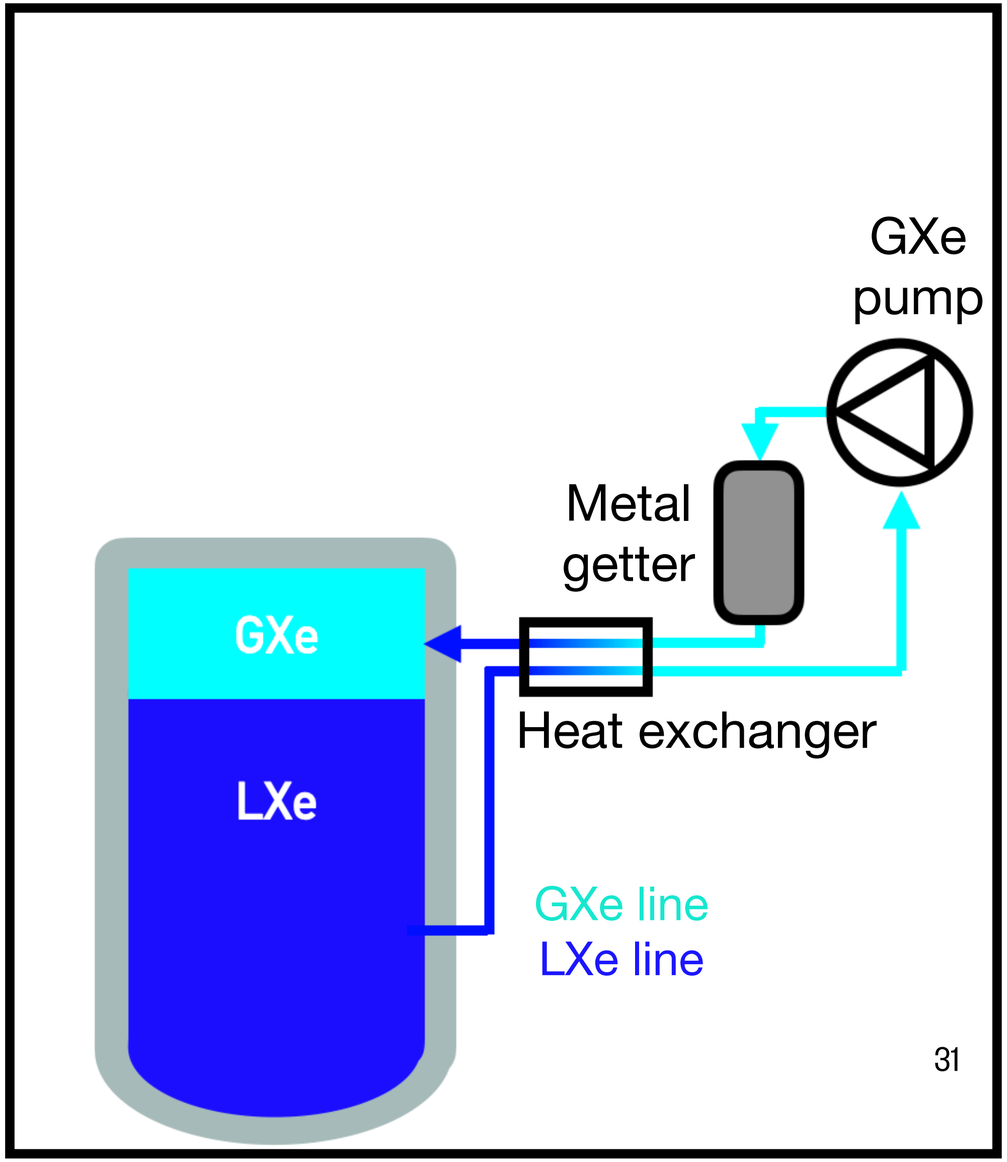
XENON Collaboration

>150 scientists, 29institutions from 12 countries



Radon-induced background

- ^{222}Rn calibration:
  - Compare **[β from ^{214}Pb]** vs **[α from ^{222}Rn]**
- Place the source in the GXe circulation system, and diffuse ^{222}Rn into the detector
  - Source: ^{226}Ra implanted SUS (~2Bq, made by MPIK[1])
  - ^{222}Rn α : ~150 higher than normal run
  - Can be removed by distillation after the calibration



[1] F. Joerg, et al., Applied Radiation and Isotopes, 194, 110666 (2023)

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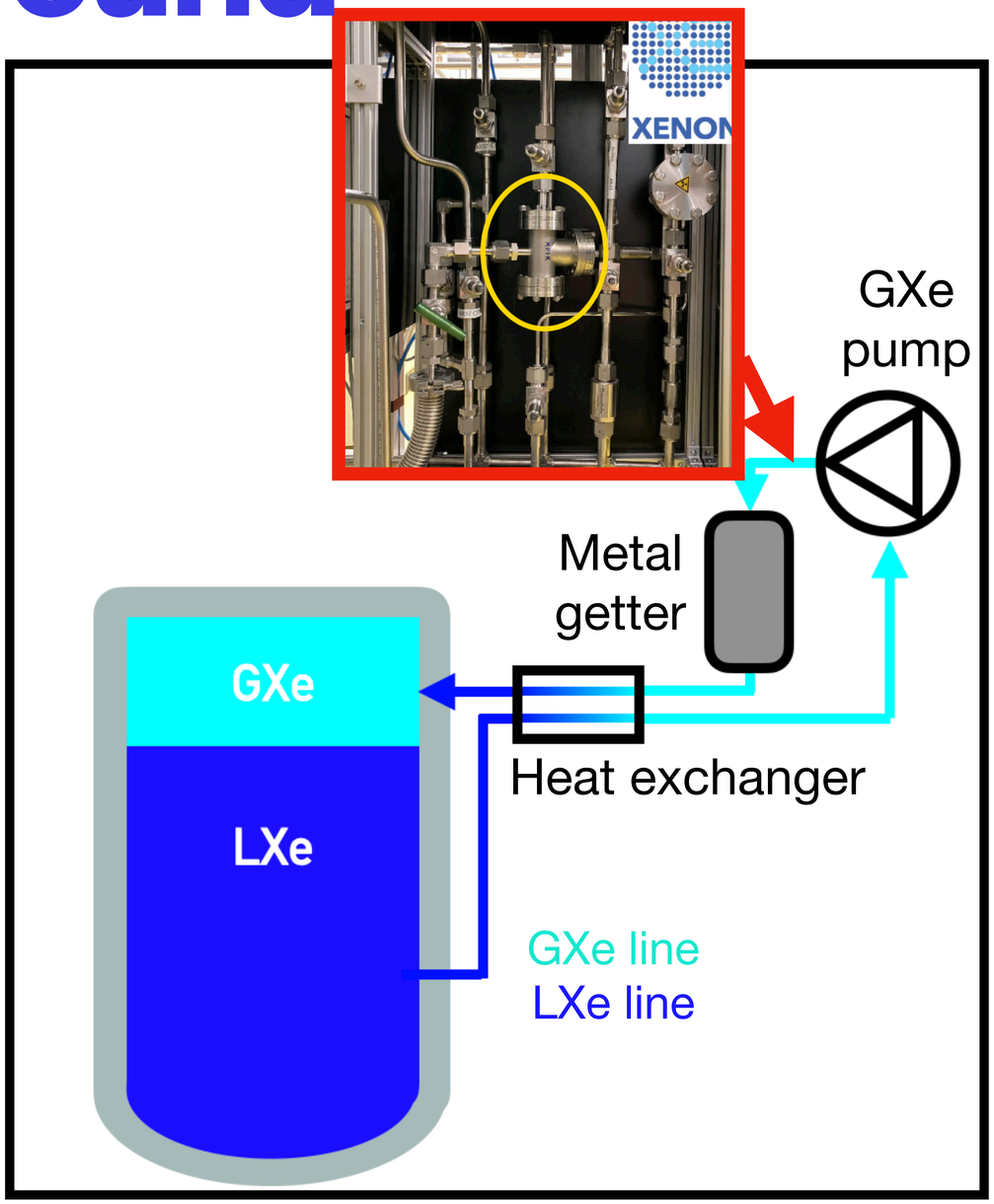

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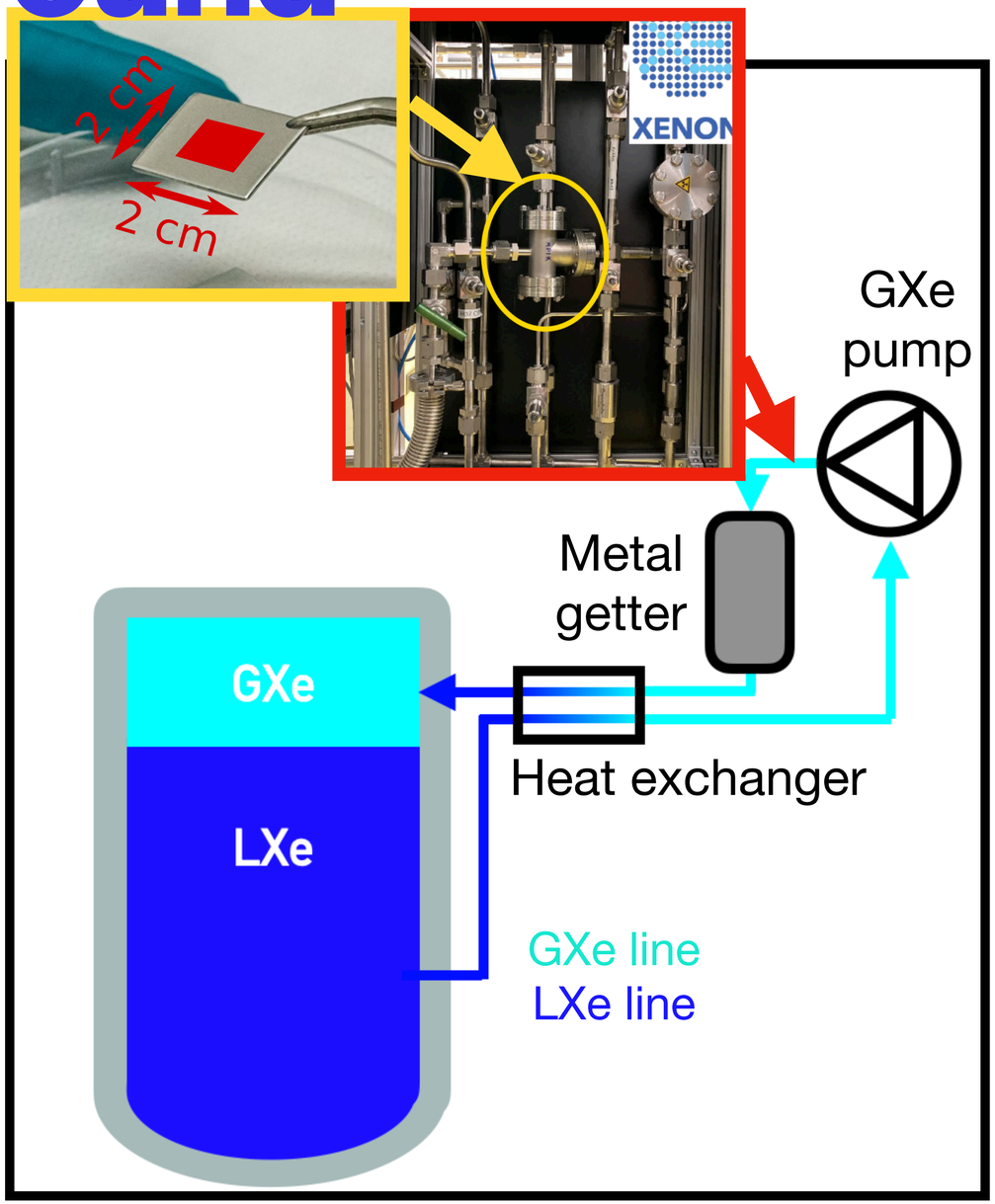
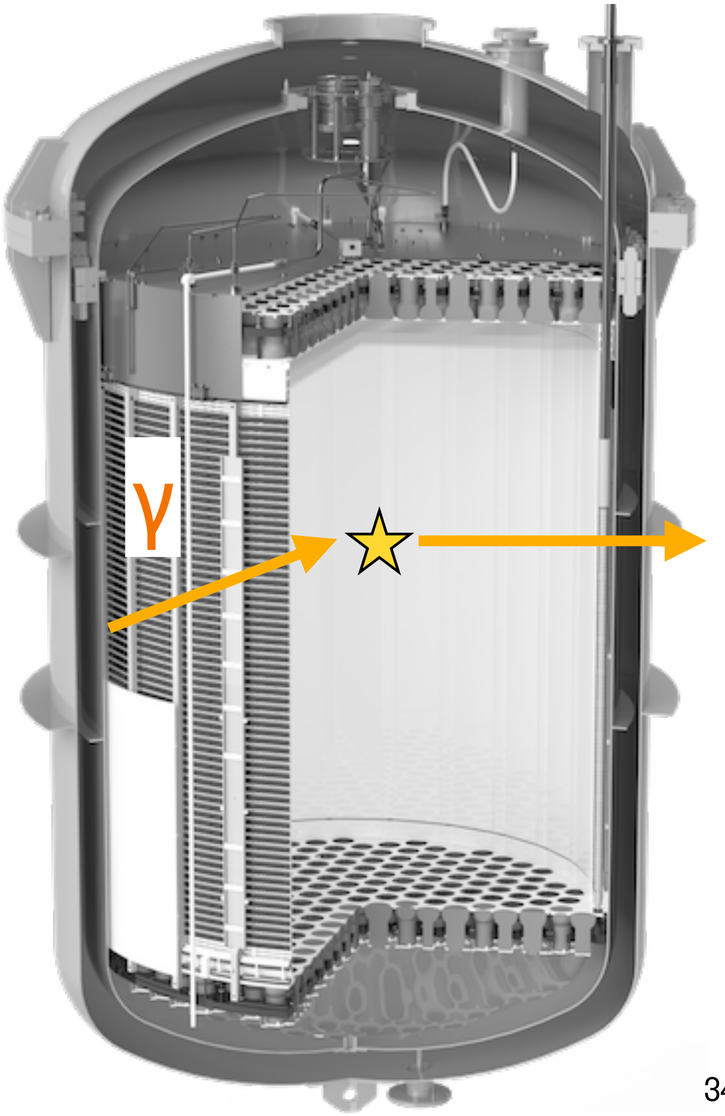


[1] F. Joerg, et al., Applied Radiation and Isotopes, 194, 110666 (2023)

Other backgrounds

- **Other BG : Material γ and Kr-induced**
- **Material γ**
  - **Low energy compton scattering induced by γ from detector materials**
  - Reduced by fiducial cut, estimation by simulation
- **Kr-induced**
  - **β decay of ^{85}Kr (Q=687keV)**
  - Removed by our own distillation (<0.1ppt for Kr)
  - Mass spectrum analysis for sampled gas
  - Also, analytical estimation using rare decay mode of ^{85}Kr



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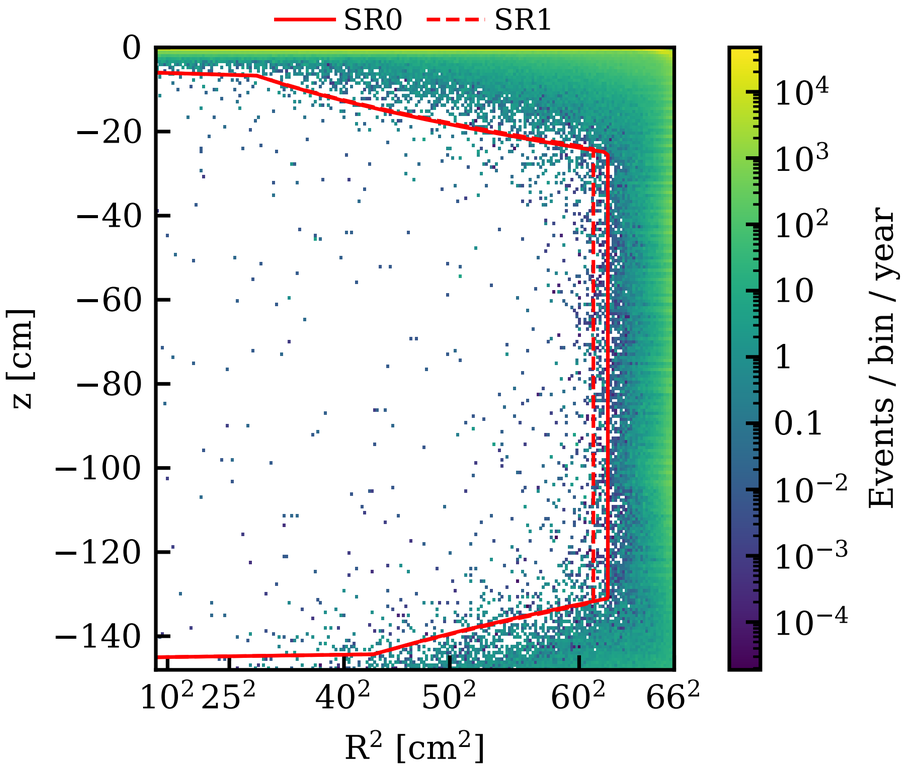


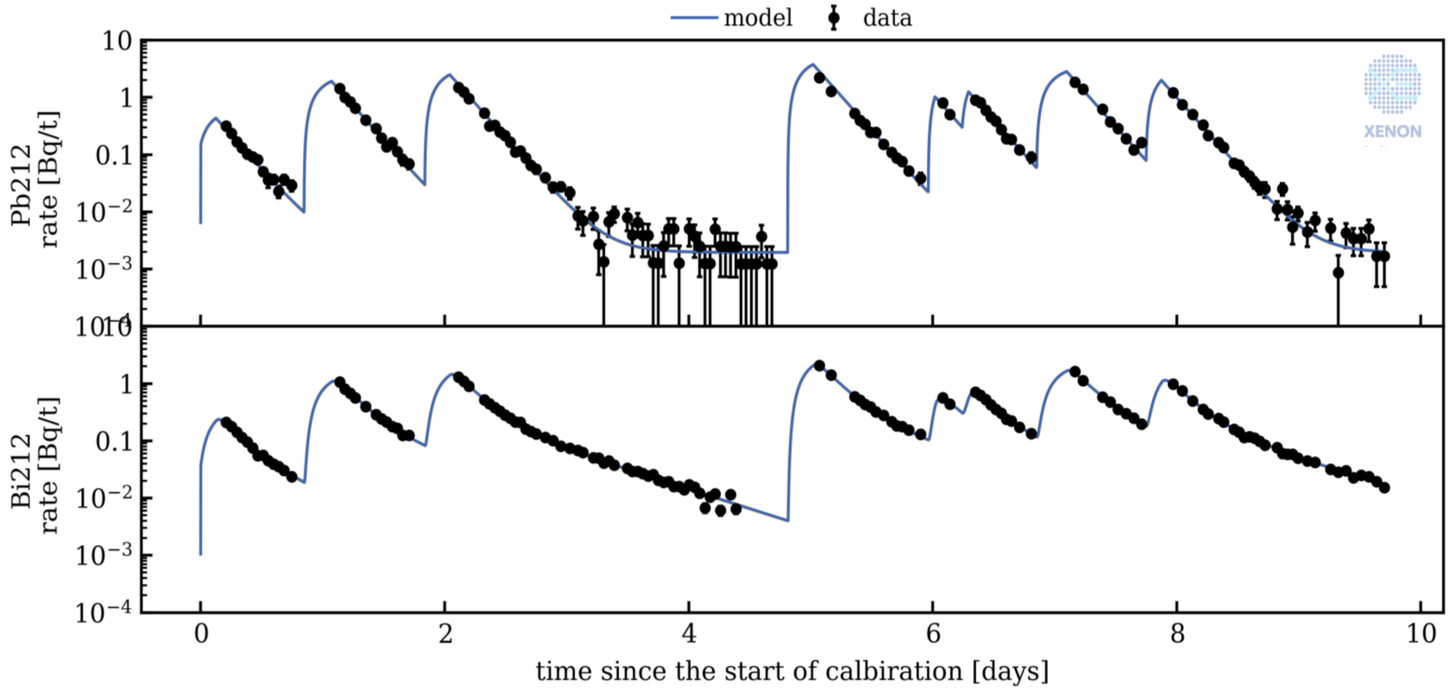
Other backgrounds

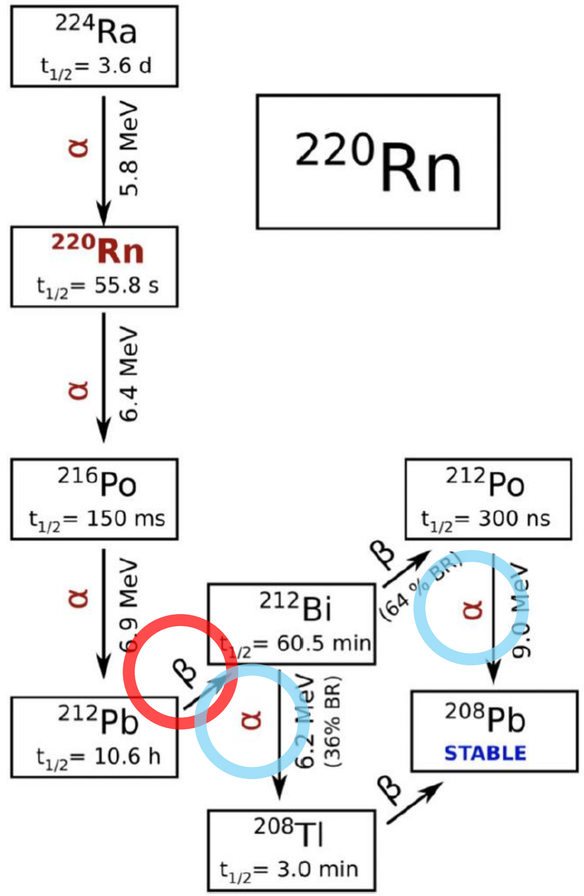
^{212}Pb β decay

Background rate roughly 1/10 of ^{214}Pb

Utilizing ^{220}Rn calibration

- ^{220}Rn and ^{216}Po short half-life => not reaching equilibrium
- Full difference equation modeling required
- Conservative systematic uncertainty: $\approx \mathbf{20}\%$



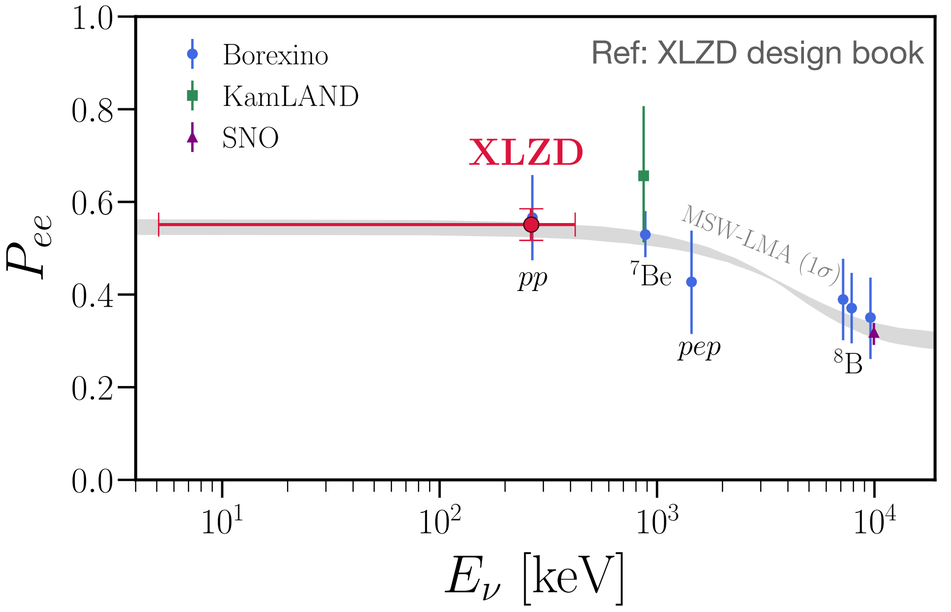


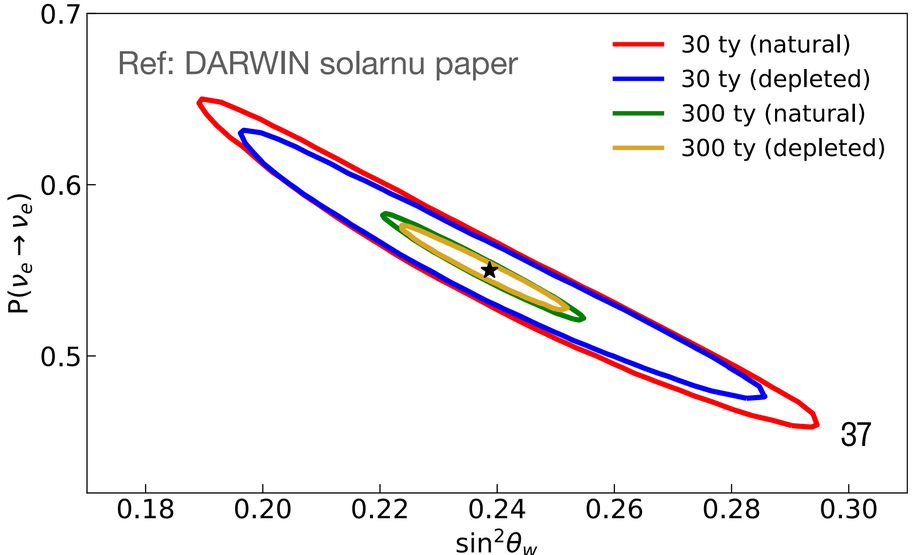
S. Bruenner et al., Eur. Phys. J. C. 81, 343 (2021)

Measurement for the pp neutrino

- **Low-E neutrino physics**
  - Measurement for ν_e survival probability (Pe-e)
  - Measurement for the Weinberg angle
  - Search for exotic neutrino interactions (ex. Magnetic moment)

- **Goal for XENONnT:**
  first observation as demonstration
  - Measurement with few % precision expected in future experiment

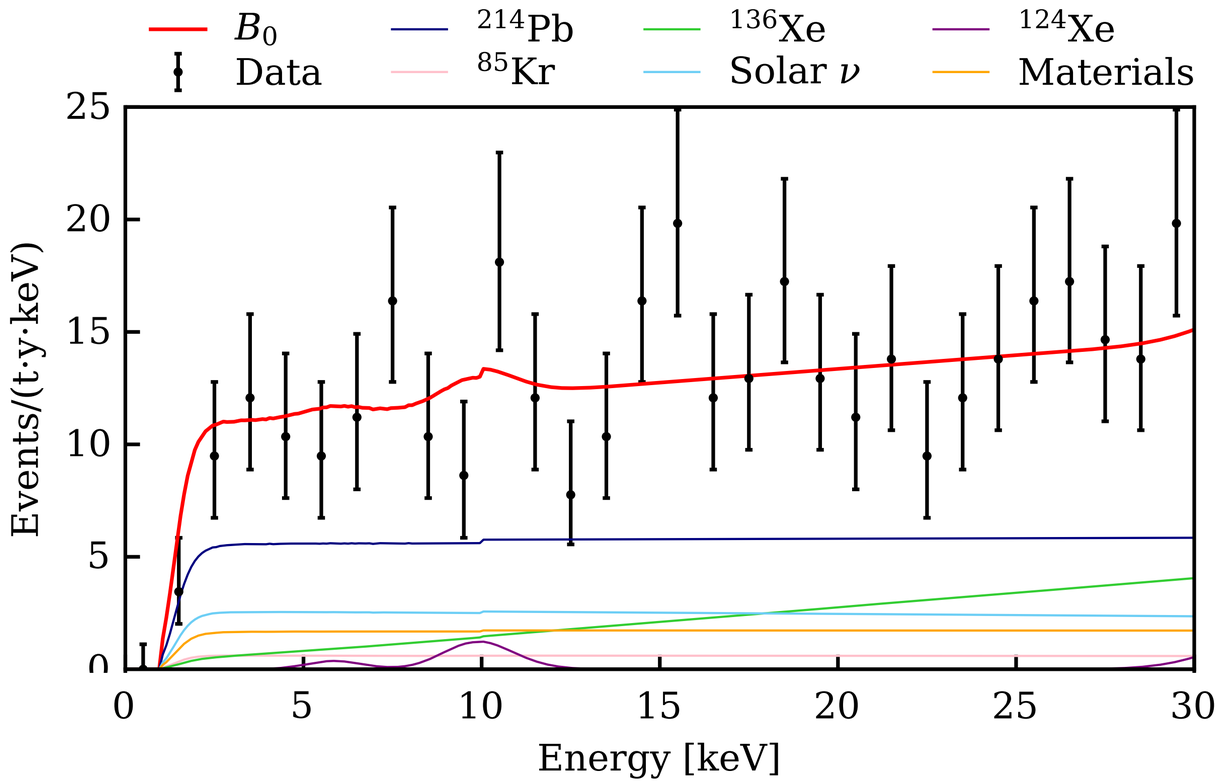




Analysis for XENONnT initial data (SR0)

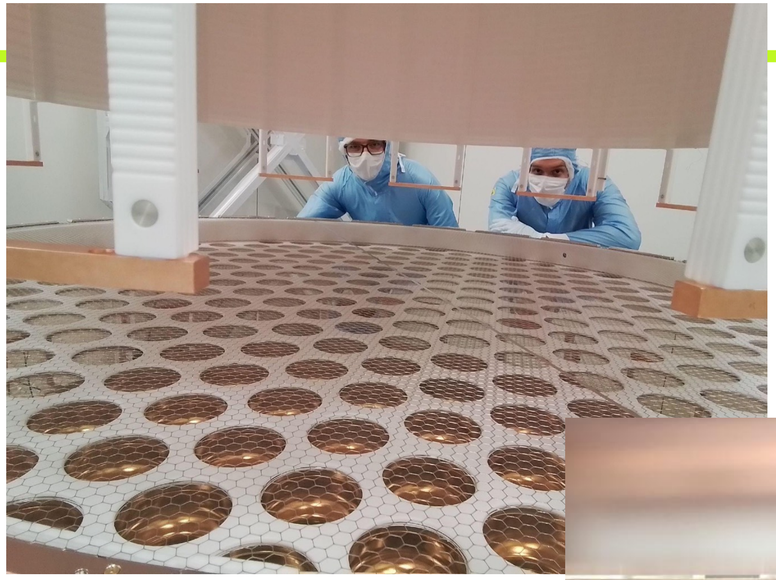
- Right: first science run by XENONnT (SR0)
  - Good agreement between **Data** and BG
- Main target for the analysis: peak-like signals
  - “XENON1T Excess”: ex. solar-axions
  - => solar-nu signal was calculated by Borexino’s result

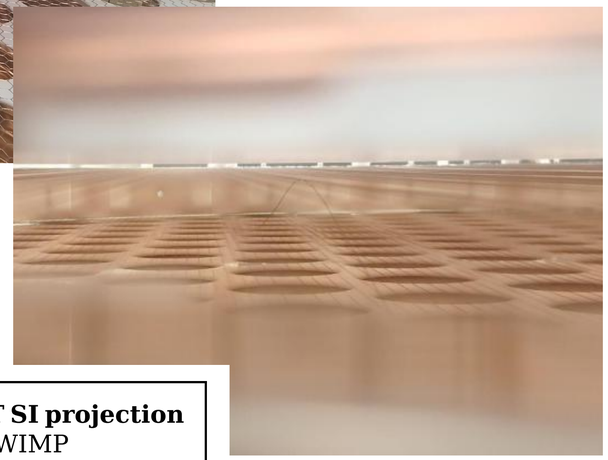
XENONnT SR0 data

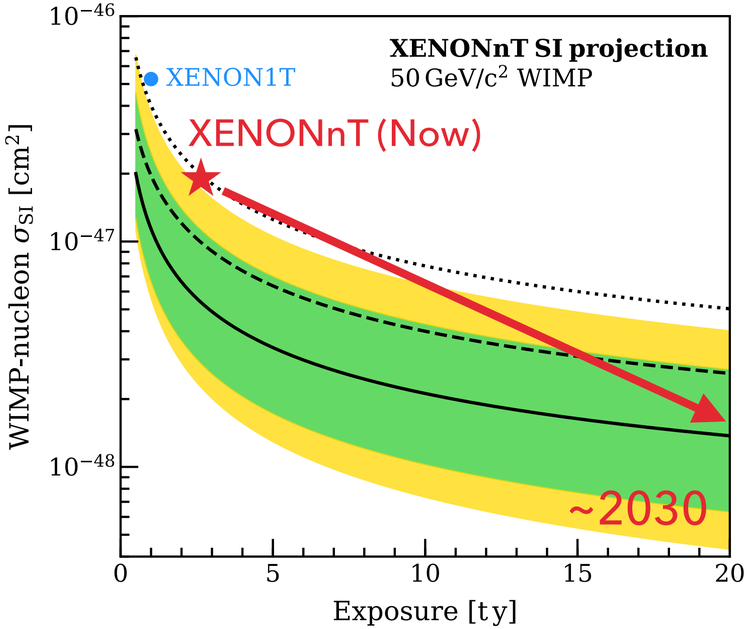


Detector upgrade

- The data taking was stopped at Apr 2025 and stated to upgrade
- In previous detector, there was an issue at the electrode
  - Shortage of cathode electrode and bottom screen electrode
- After replacing problematic electrodes and some PMTs, currently the detector is being commissioned
- Expecting ~x10 better ER/NR discrimination with new electrodes







Cross-checks

Validation Cross-checks

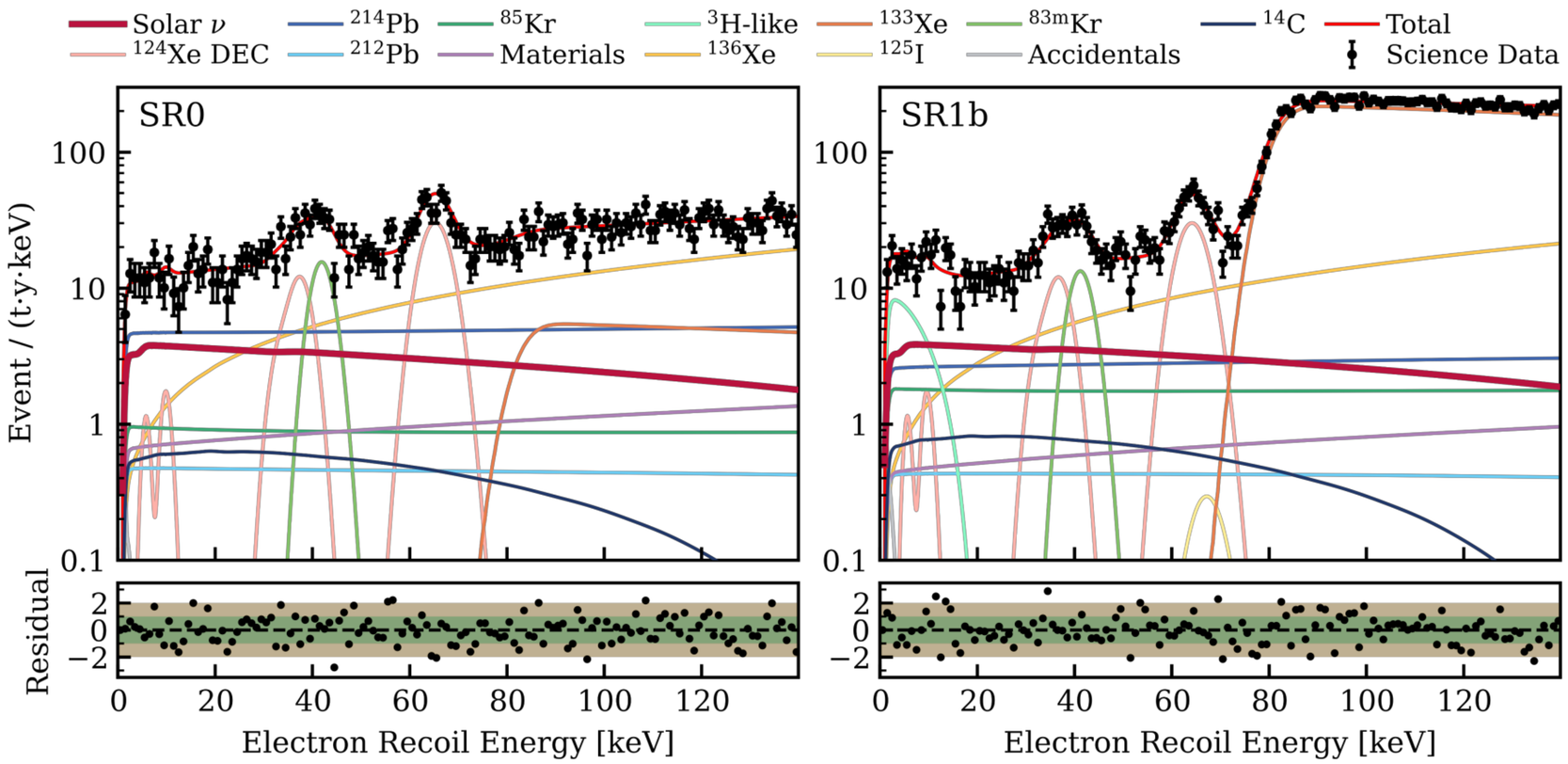
- ✓ different energy intervals
- ✓ inner 2-tonne fiducial volume
- ✓ projection into the [140, 200] keV region

Time Dependence

- ✓ Result checked in multiple data sub-periods
- ✓ Investigated annual signal modulation

Negligible Backgrounds from

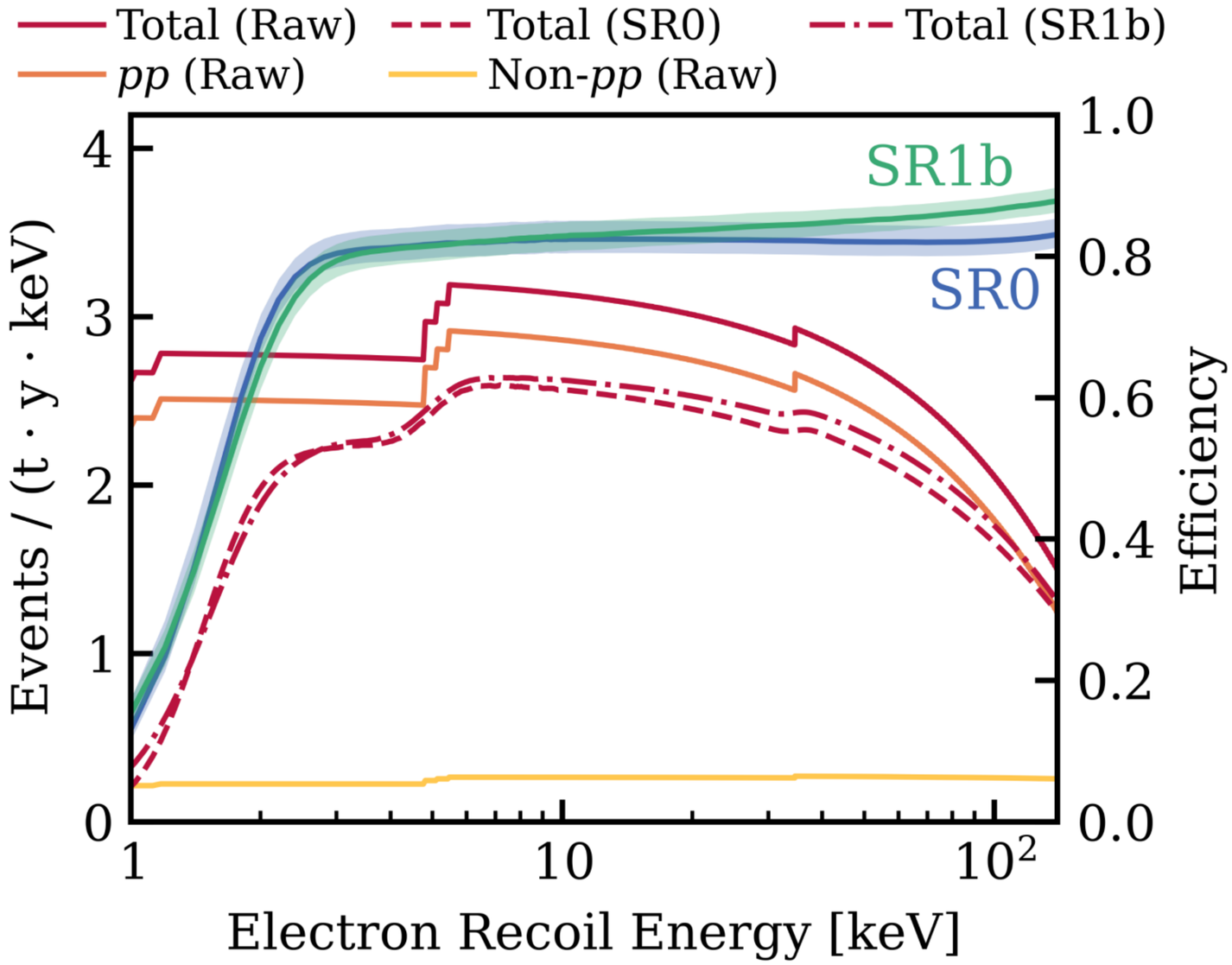
- ✓ ^{39}Ar
- ✓ ^{218}Po β decays
- ✓ ^{134}Xe double-β decay



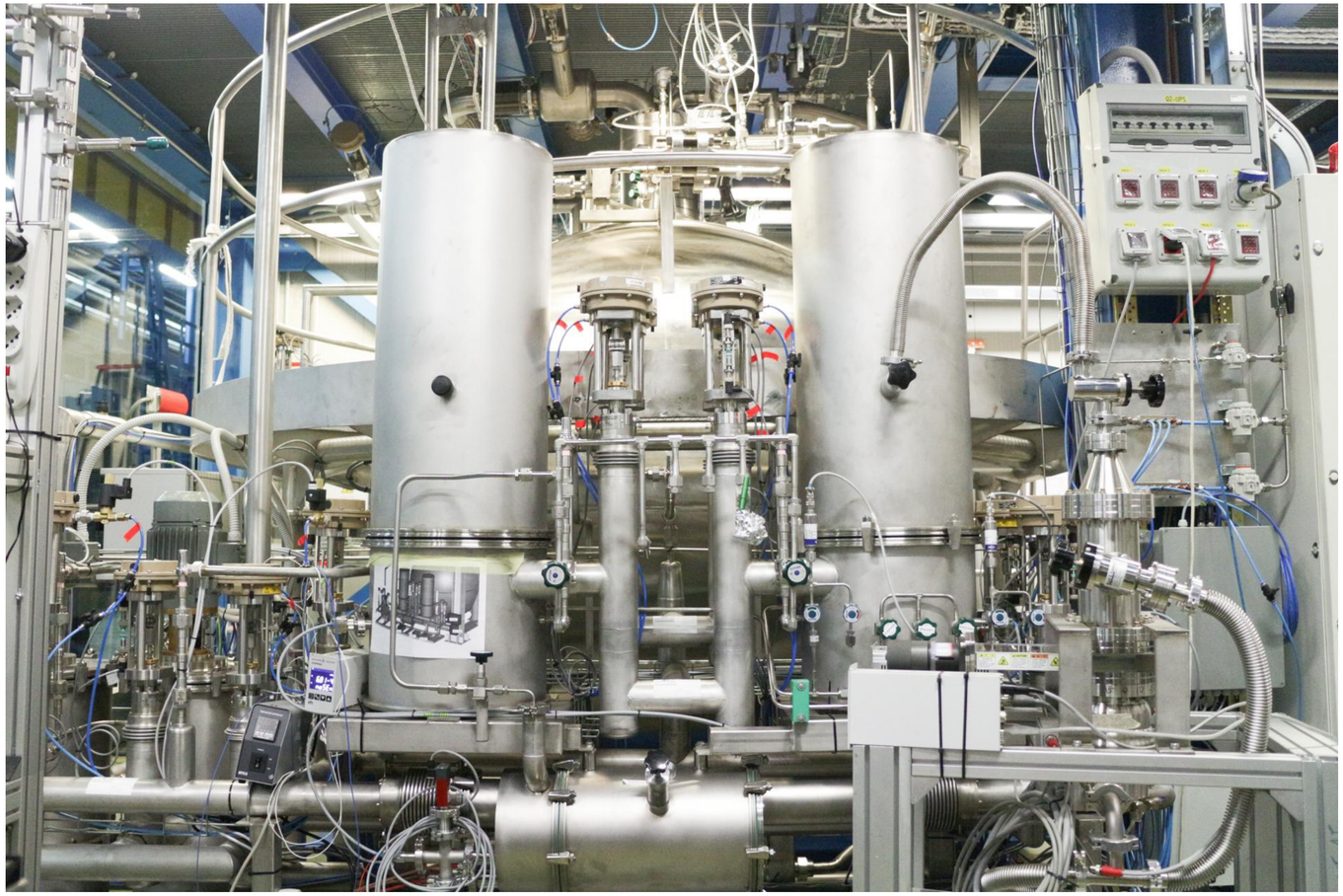
Potential Background

Assuming the maximum conceivable concentration of unmeasured ^{14}C (investigated because its β-spectrum mimics solar neutrinos). The signal significance lowers to 4.3σ, while consistency with Borexino improves to 1.2σ.

Signal efficiency



LXe Purification



- Liquid purification system
- Direct liquid circulation with cryogenic pump
  - Speed: ~2 LPM with liquid
  - ~x500 of XENON1T system
- Real-time purity measurement with purity monitor

Analysis for XENONnT initial data (SR0)

- Right: first science run by XENONnT (SR0)
  - Good agreement between **Data** and BG
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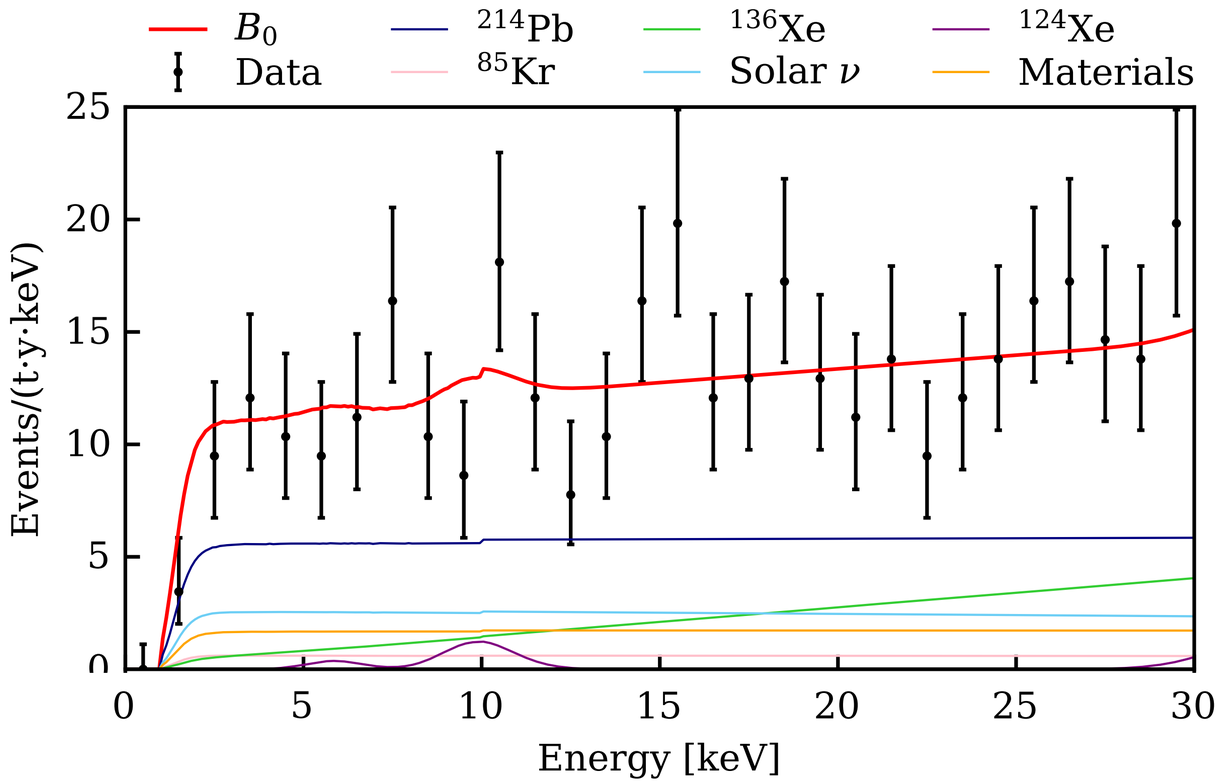
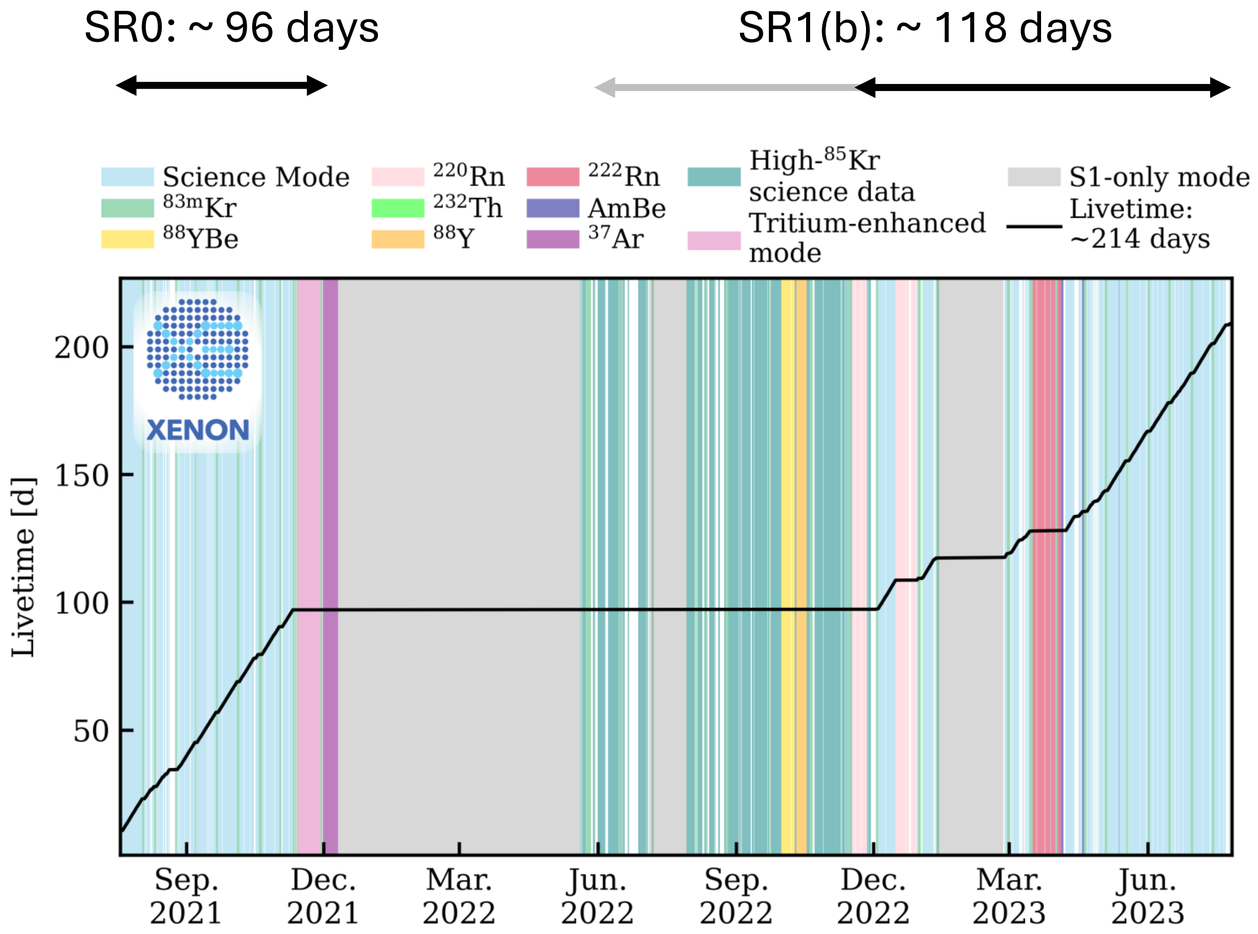
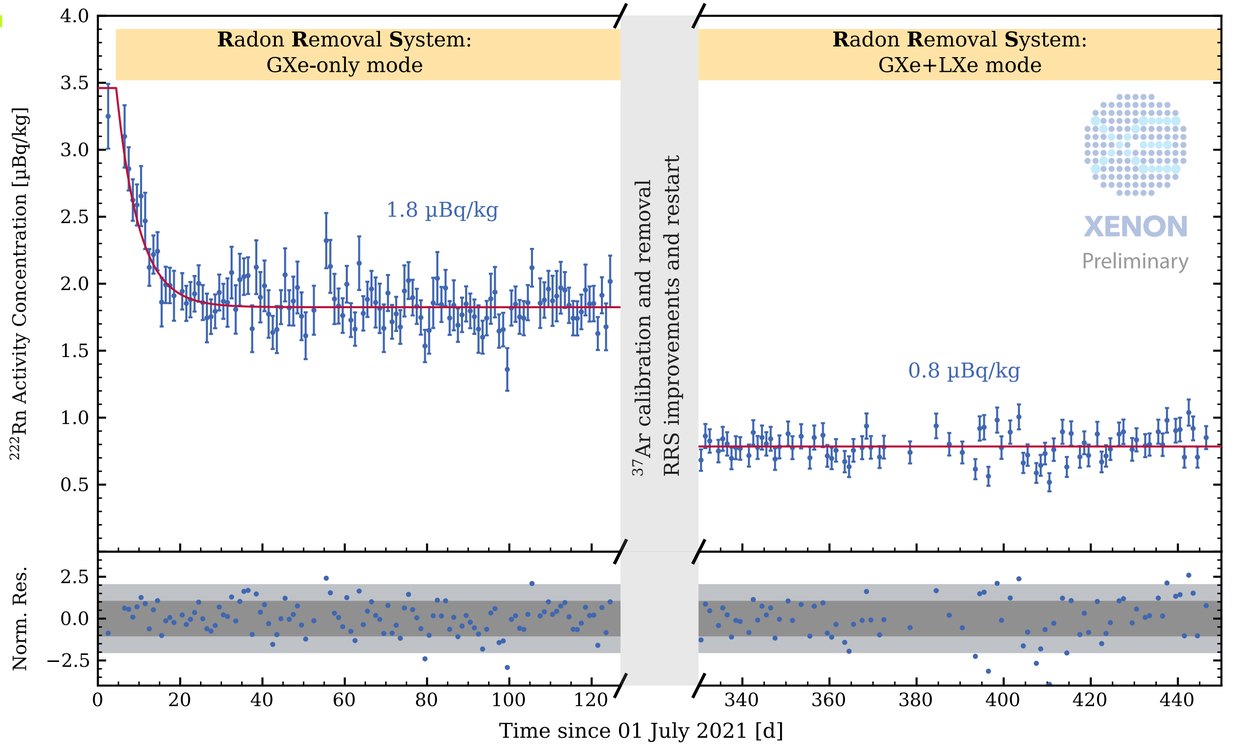
XENONnT SR0 data



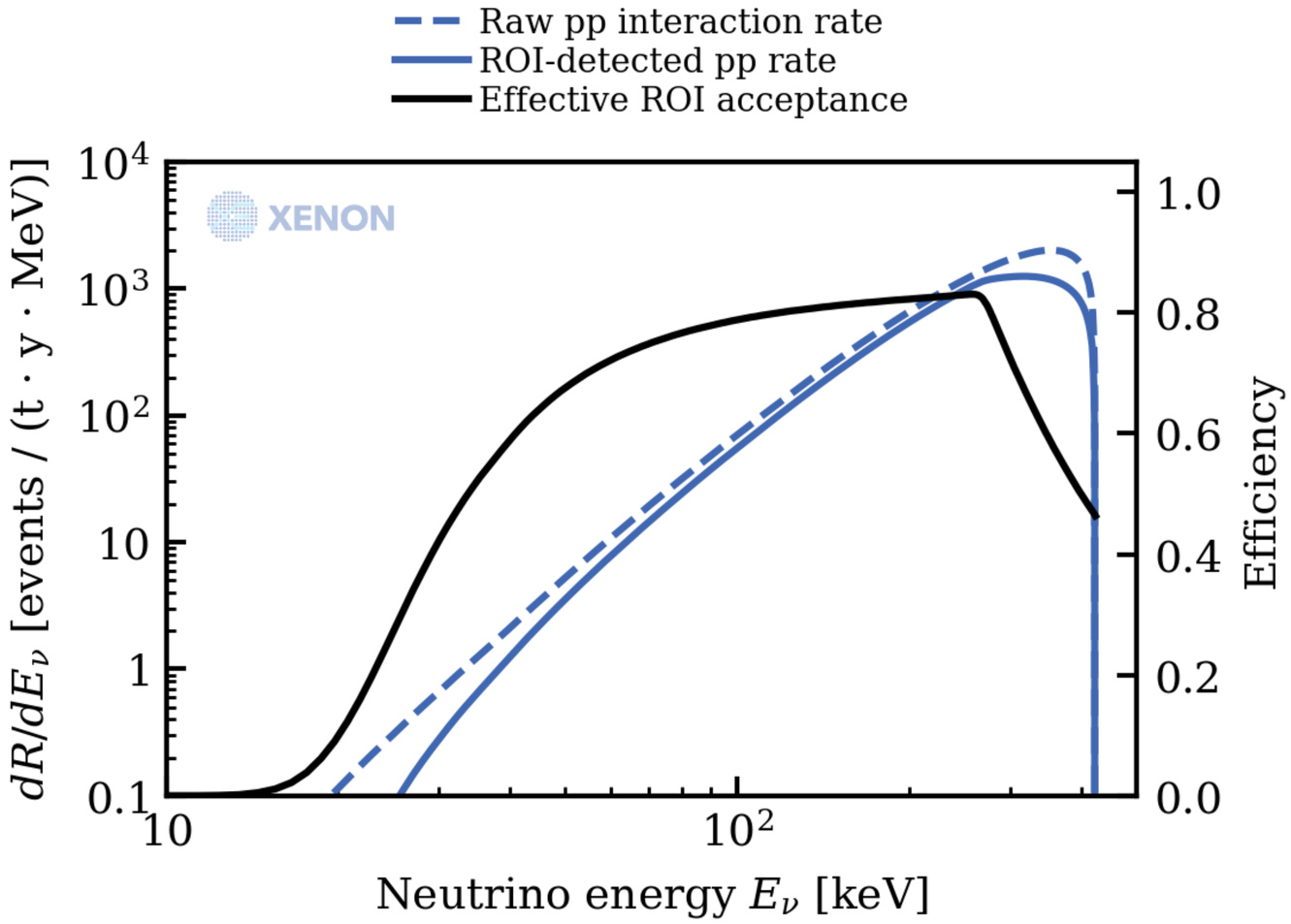
Exposure



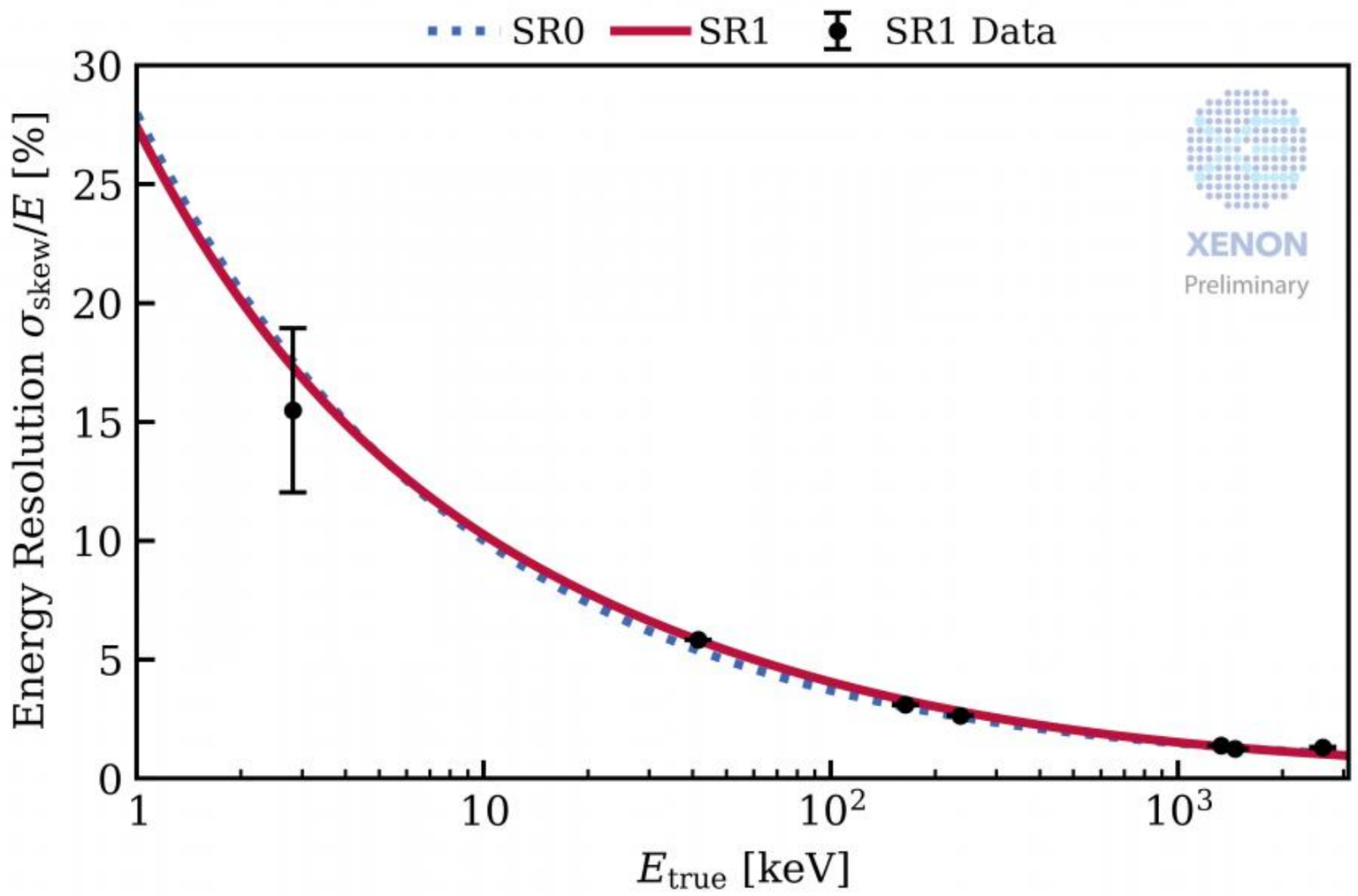


- Exposure:
  - SR0: 0.26 [year] × 4.37 [ton]
  - SR1: 0.51 [year] × 4.00 [ton]
- Between SR0 and SR1, radon removal system was upgraded:
  - 1.8 -> 0.9 [uBq/kg]

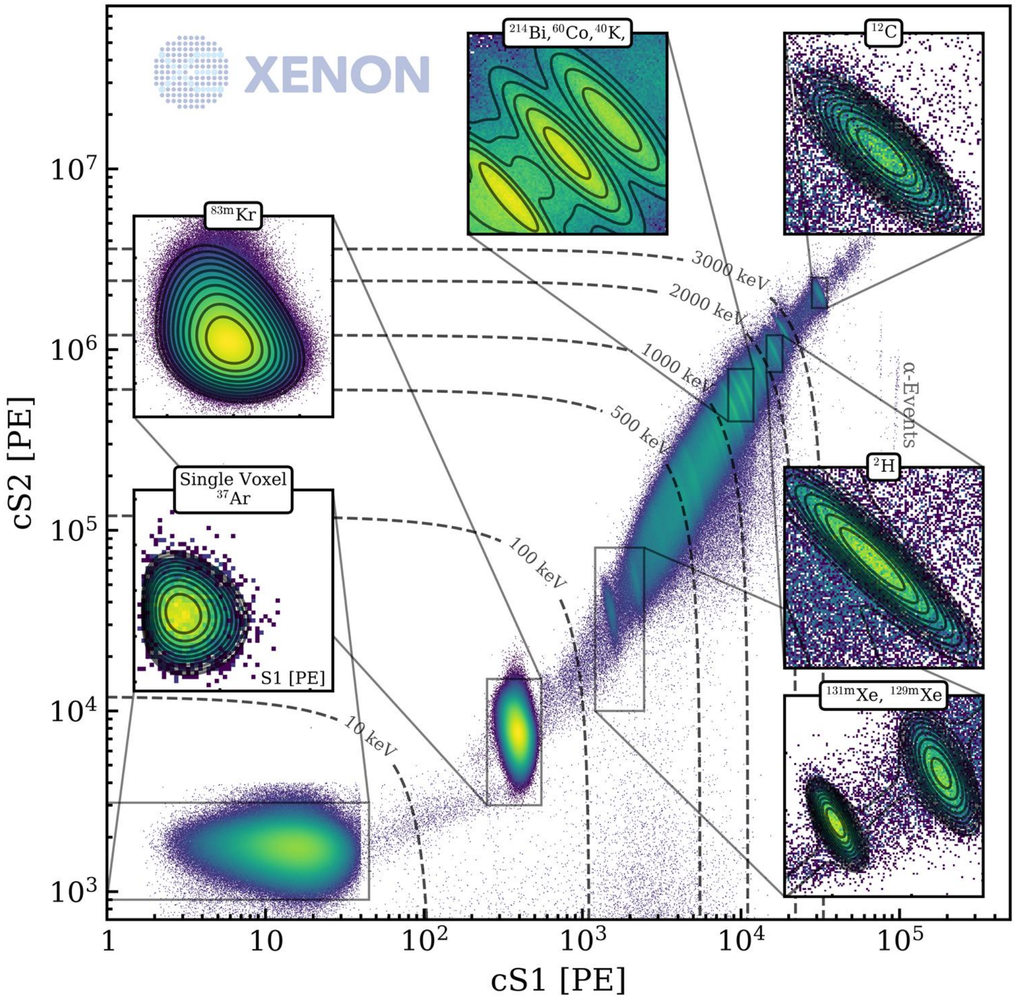
Neutrino energy/recoil electron energy



Energy resolution



Energy reconstruction



$$E_{dep} \propto (n_\gamma + n_{e^-}) \propto \left({}^{\mathrm{cS1}}/_{\mathrm{g1}} + {}^{\mathrm{cS2}}/_{\mathrm{g2}}\right)$$

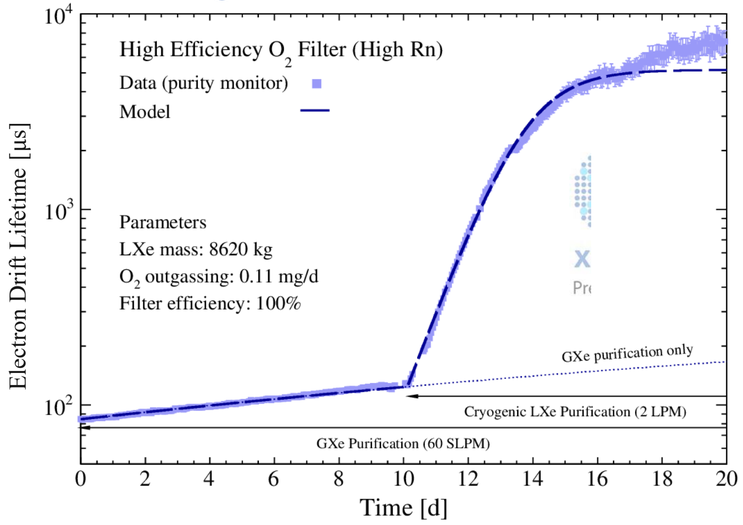
Knowledge of the detector-specific parameters $\boldsymbol{g_1}$ and $\boldsymbol{g_2}$ allows for an precise determination of energy scale, energy resolution and energy bias.

XENON Collab., Phys. Rev. D volume 111, page 062006 (2025)

Purification

Q5 Filter:
Achieved 5 ms electron drift lifetime in 5 days

Q5 Performance



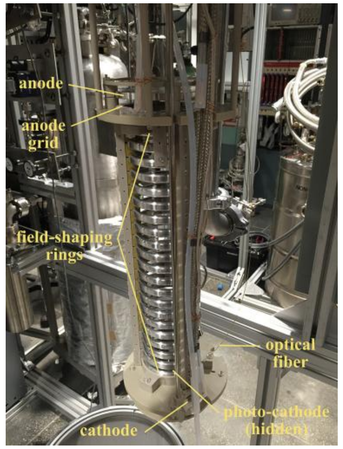
XENONnT Purity Monitor

N. Kato, University of Tokyo (2021), PhD thesis



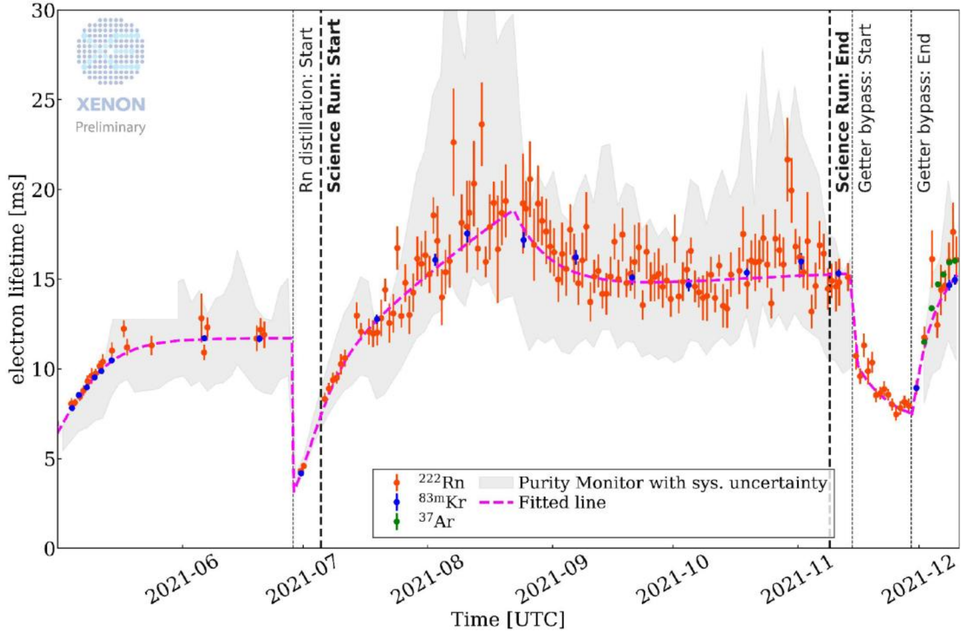
Xeclipse Purity Monitor

G. Plante et al, Eur. Phys. J. C 82, 860 (2022)

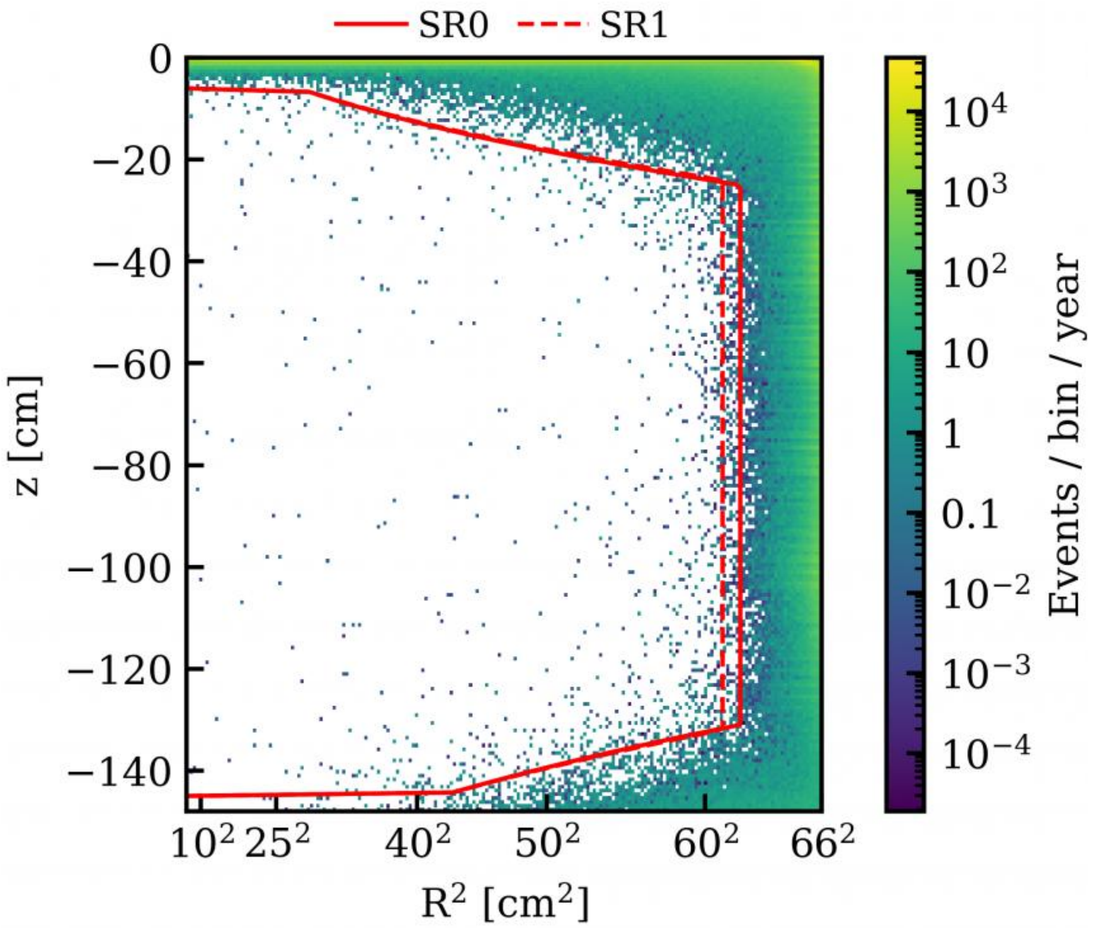


St707 Filter
Maintained a 15 ms electron drift lifetime: approximately 90% of the electrons crossing the entire detector chamber survive.
Also has low radon emanation

St707 Performance

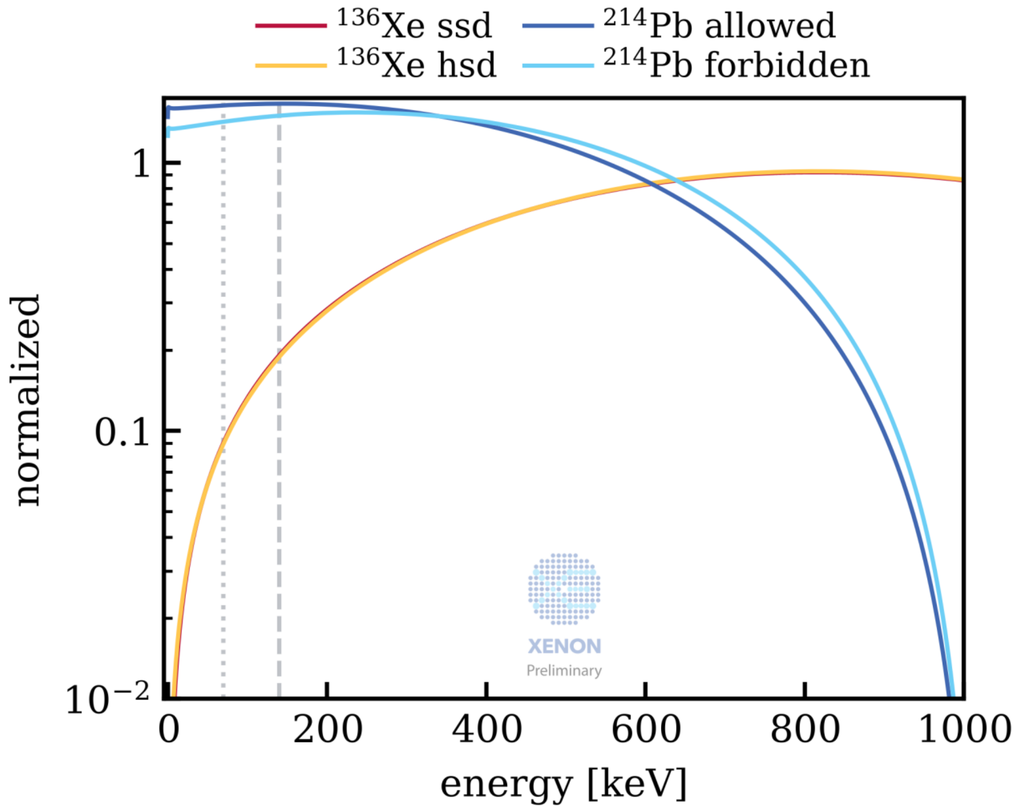


Fiducial volume



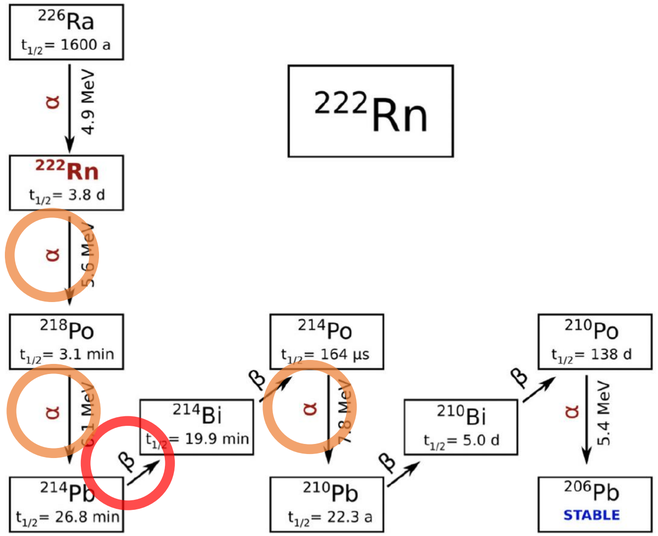
- The fiducial volumen (FV) for this search is largely driven by material backgrounds.
- SR0 and SR1 FV share similar shapes, with the mass as follows:
  - SR0: (4.13 +- 0.12) tonne
  - SR1: (4.24 +- 0.13) tonne
- SR0 and SR1 have different ways to account for the charge-insensitive volume, which makes SR0 FV look ‘larger’.
  - SR0: indirectly in FV mass calculation (about 4% decrease)
  - SR1: directly in position correction

Beta Spectra Models

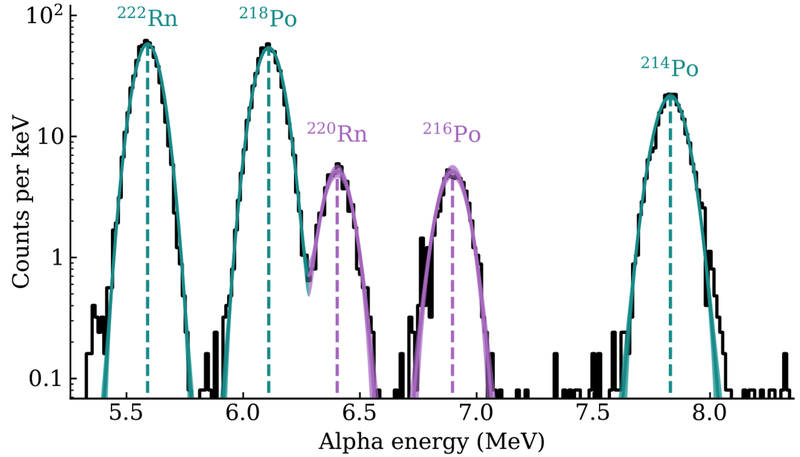


^{222}Rn Tracking

- Tracking the α decays, especially ^{222}Rn
- Following the decay chain to derive the ^{214}Pb β decay rate
- **^{214}Pb is the most dominant background**

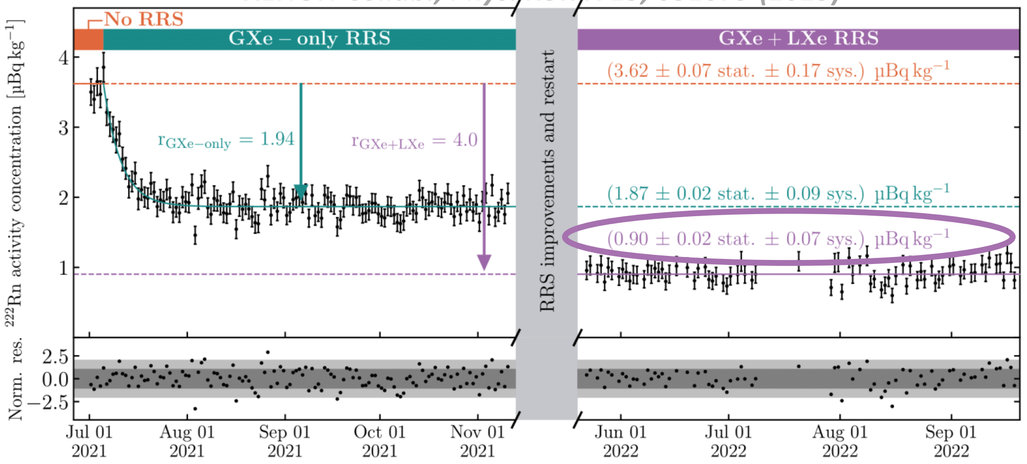


S. Bruenner et al., Eur. Phys. J. C. 81, 343 (2021)



➢ **Reduced ^{222}Rn activity down to 1 µBq/kg level!**

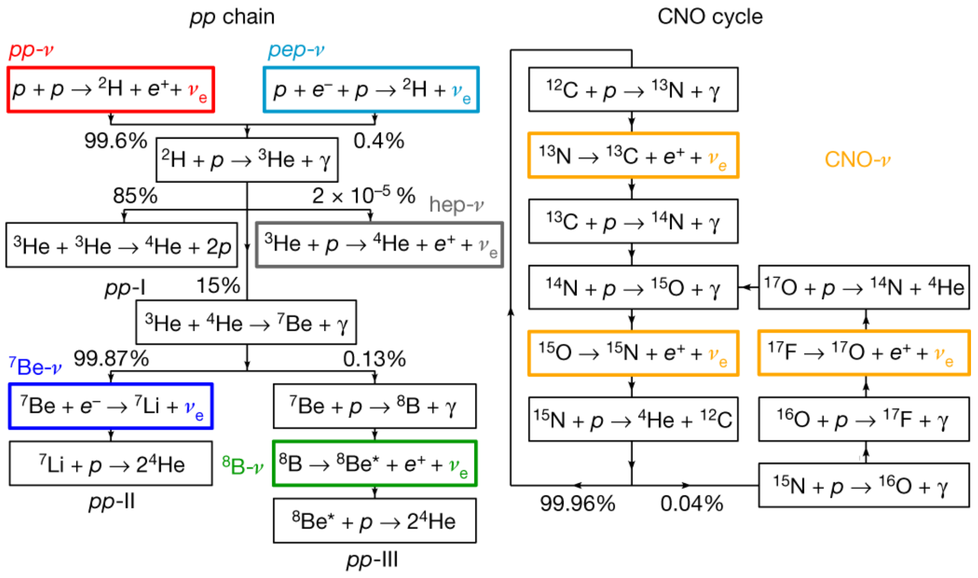
XENON Collab., Phys. Rev. X 15, 031079 (2025)

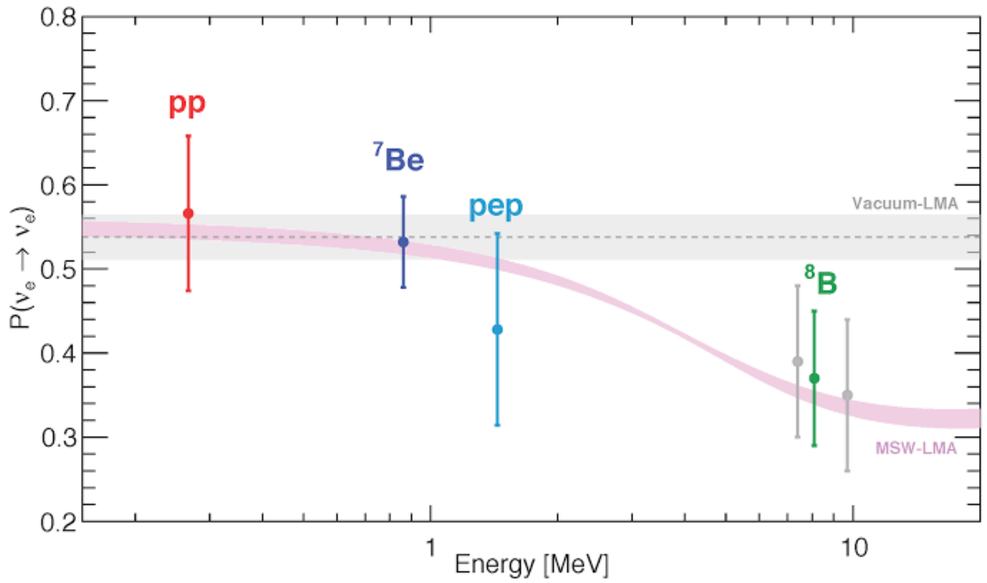


Standard Solar Model and Neutrino Properties

Standard Solar Model (SSM)
Predicts the energy and flux of the electron neutrinos (ν_e) produced in the Sun

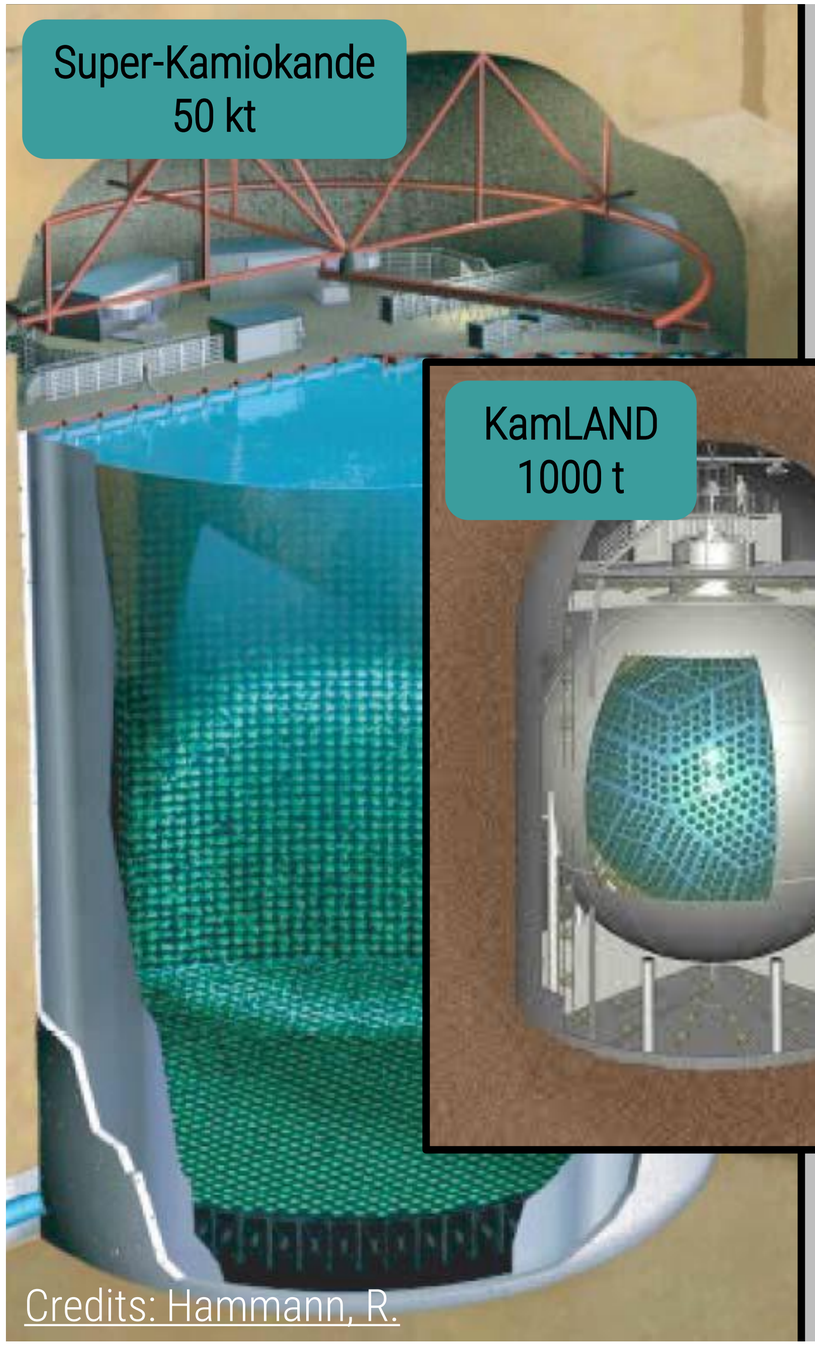
Neutrino Oscillation
Governed by neutrino mass squared difference $\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\ eV^2$ and mixing angle $\sin^2(\theta_{12}) = 0.307 \pm 0.013$;
ν_e experiences an effective matter potential (MSW) when propagating through the Sun, affecting its survival probability

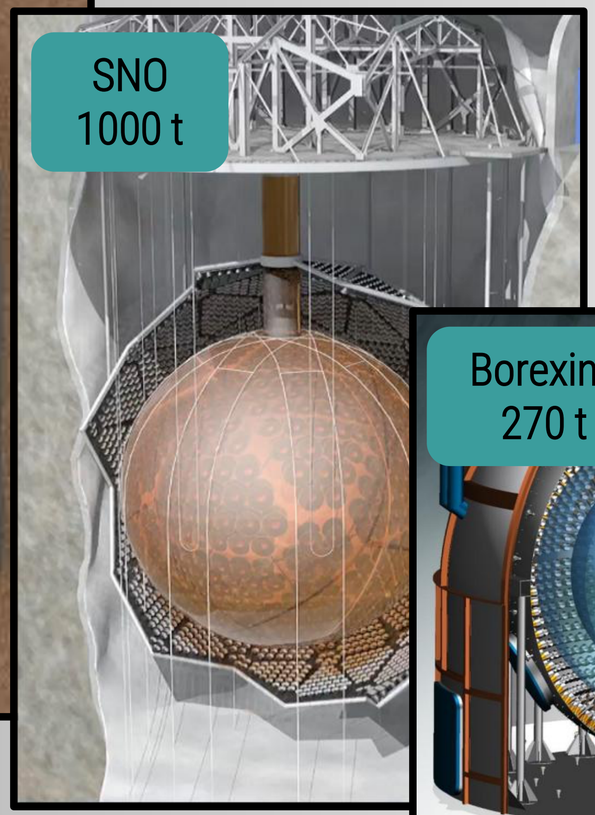


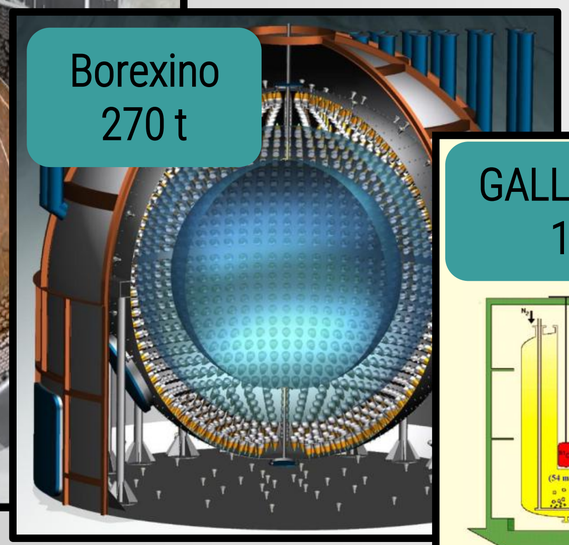


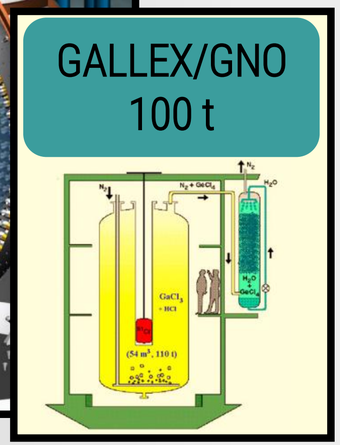
Borexino Collab., Nature volume 562, pages 505–510 (2018)

XENONnT is the smallest solar neutrino detector!









XENONnT
8.5 t



Credits: Hammann, R.