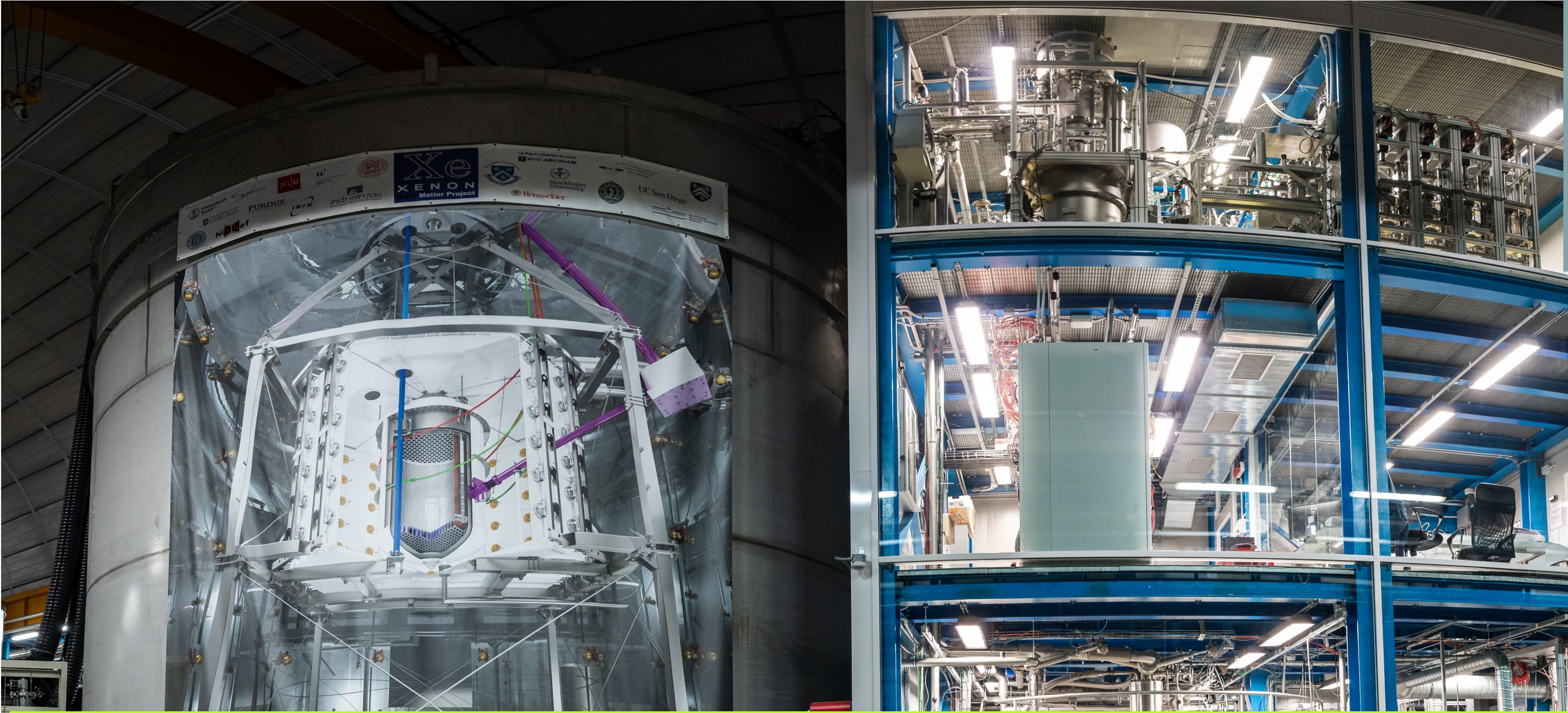
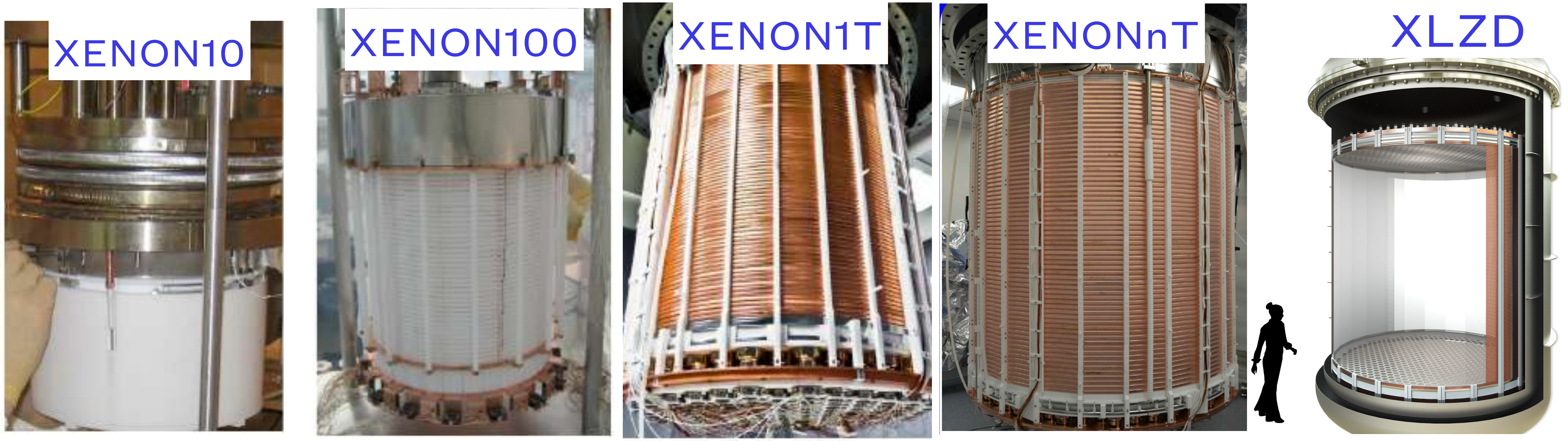


The measurement of low energy solar neutrinos by XENONnT experiment

MASATOSHI KOBAYASHI (KMI, NAGOYA-U) , 02/10/2025 NNN2025, SNOLAB

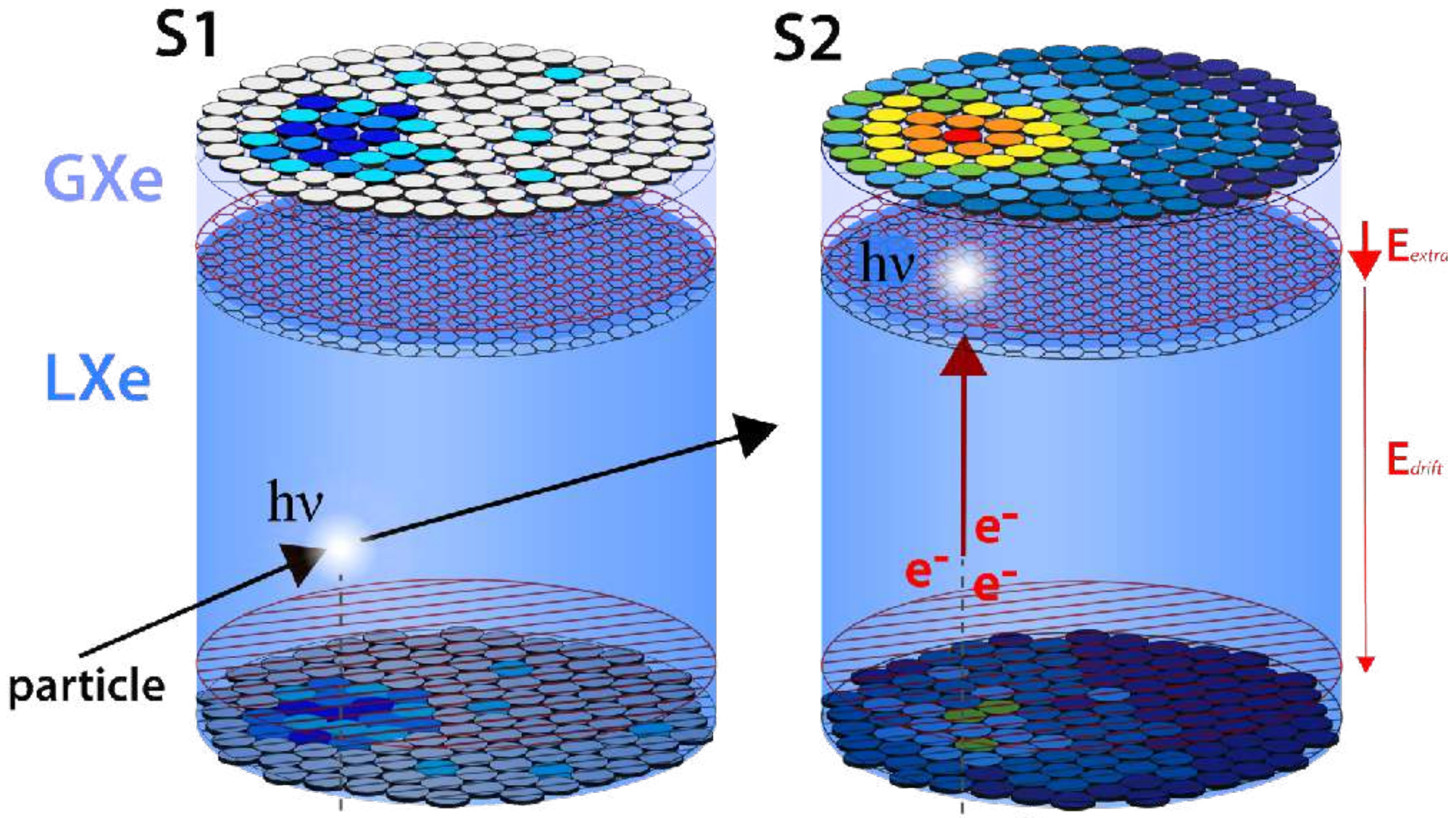
The XENON project

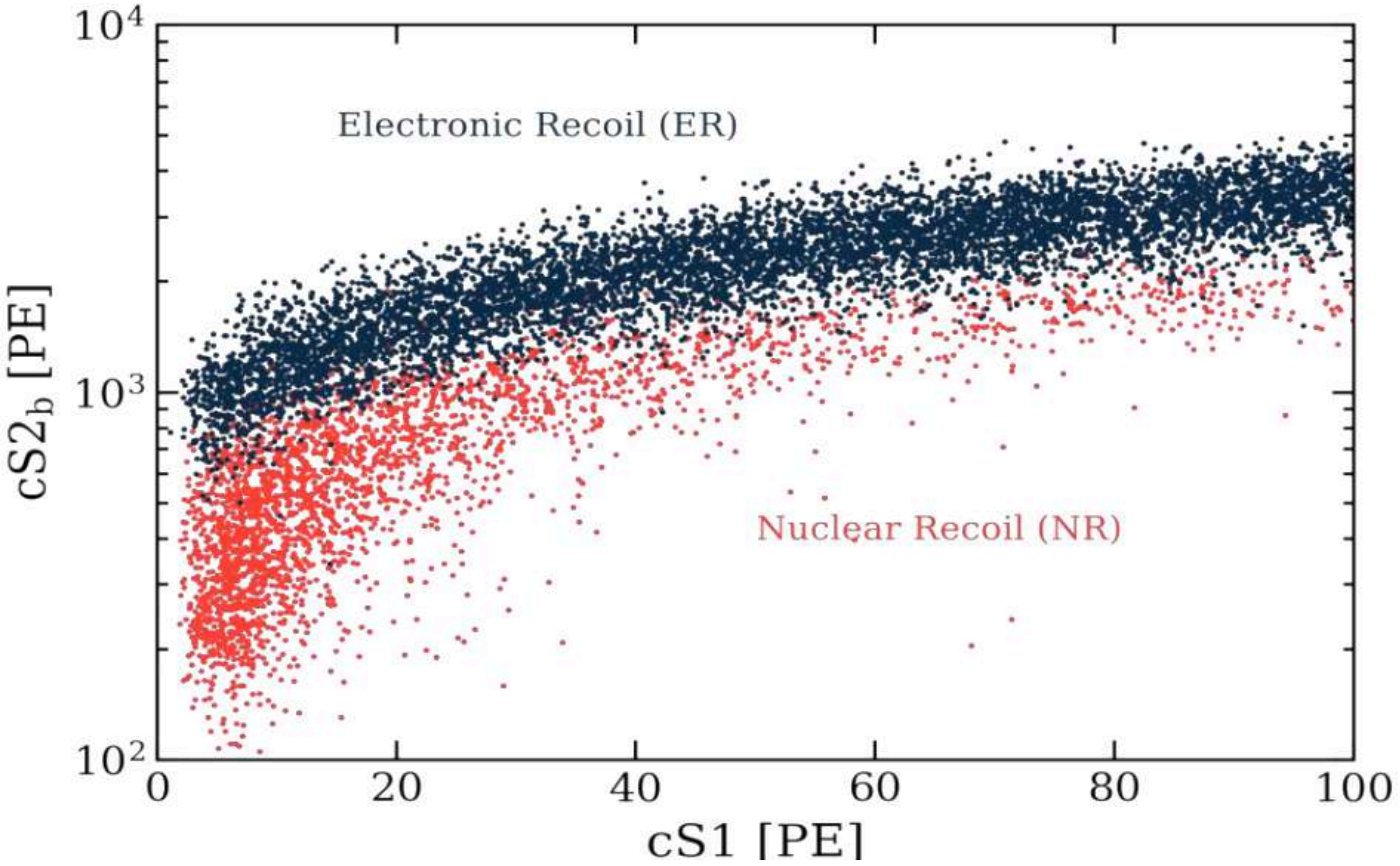
- XENON experiment: Rare event search experiment using liquid xenon detector
  - Dark matter, solar neutrinos, neutrino-less double beta decay,…
- Currently, XENONnT experiment is ongoing at LNGS, Italy
  - XLZD: future project of XENON (+ LZ experiment in US)



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



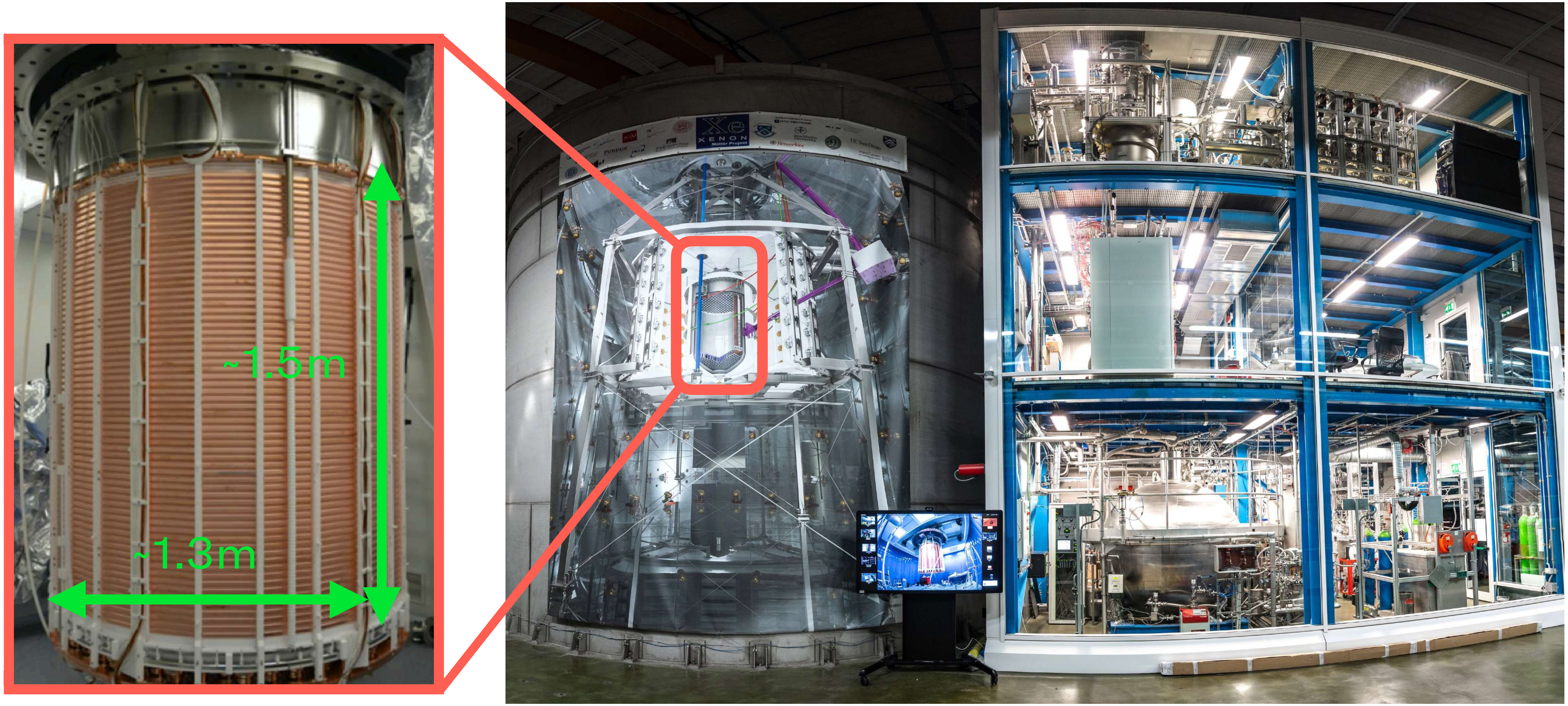


- Dual phase detector: LXe and GXe
  - Using PMTs to detect photons
  - Electric field is applied to drift electrons generated
- DM and BG particles generate signals in LXe
  - S1 signal: Scintillation photon
  - S2 signal: Ionization electrons

- S1/S2 depends on the type of interaction
  - Electronic recoils: γ ray, β ray, Axion,…
  - Nuclear recoils: Neutron, WIMPs,…
- ER events have larger S2 than NR events
  - BG rejection for WIMPs

XENONnT detector

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



Solar neutrino measurements in XENONnT

Solar neutrino measurements in XENONnT

- Measurement of solar neutrinos: one of the 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
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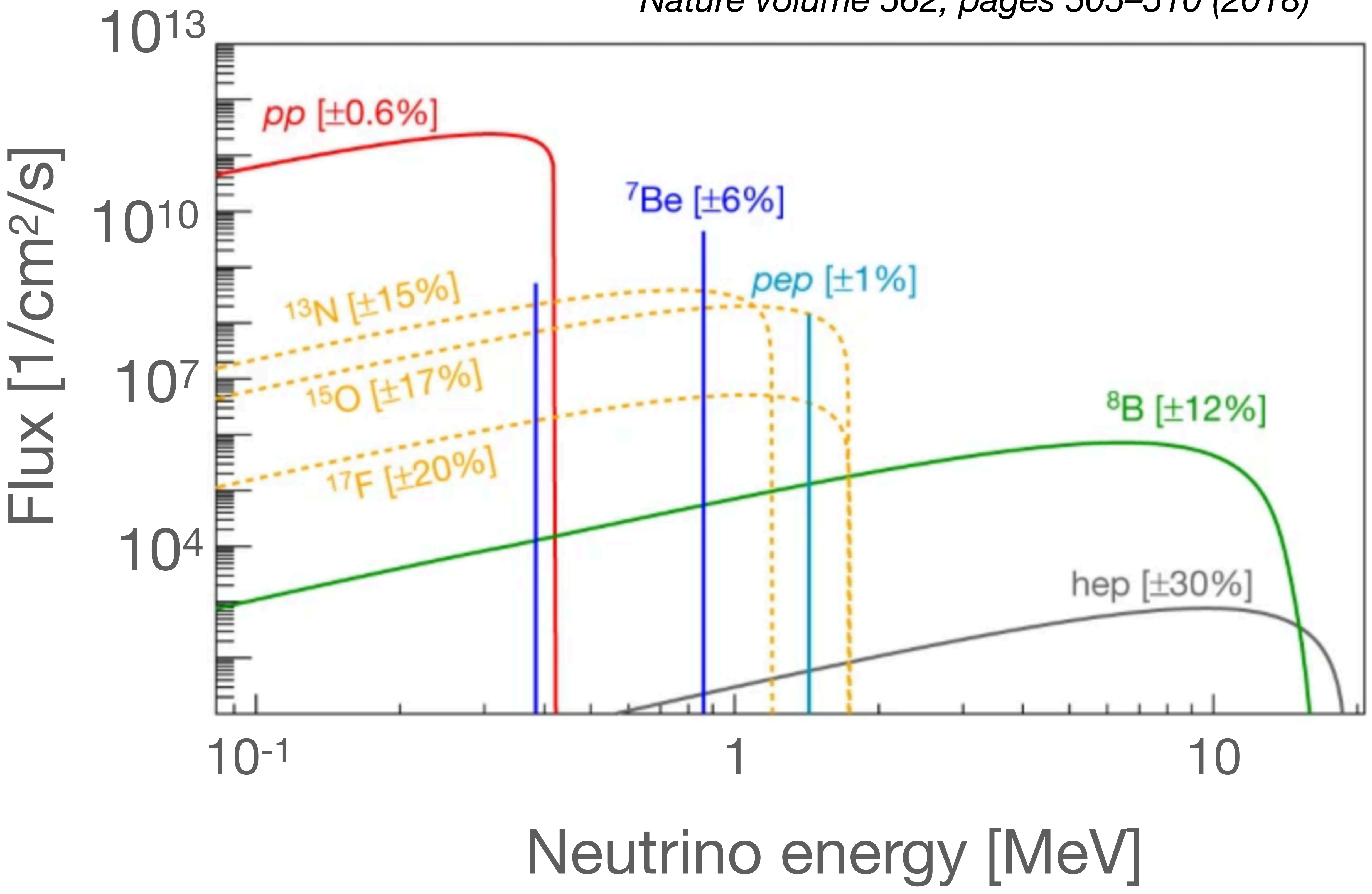
  2. MeV scale: via the nuclear recoil
     - ^{8}B

Nature volume 562, pages 505–510 (2018)



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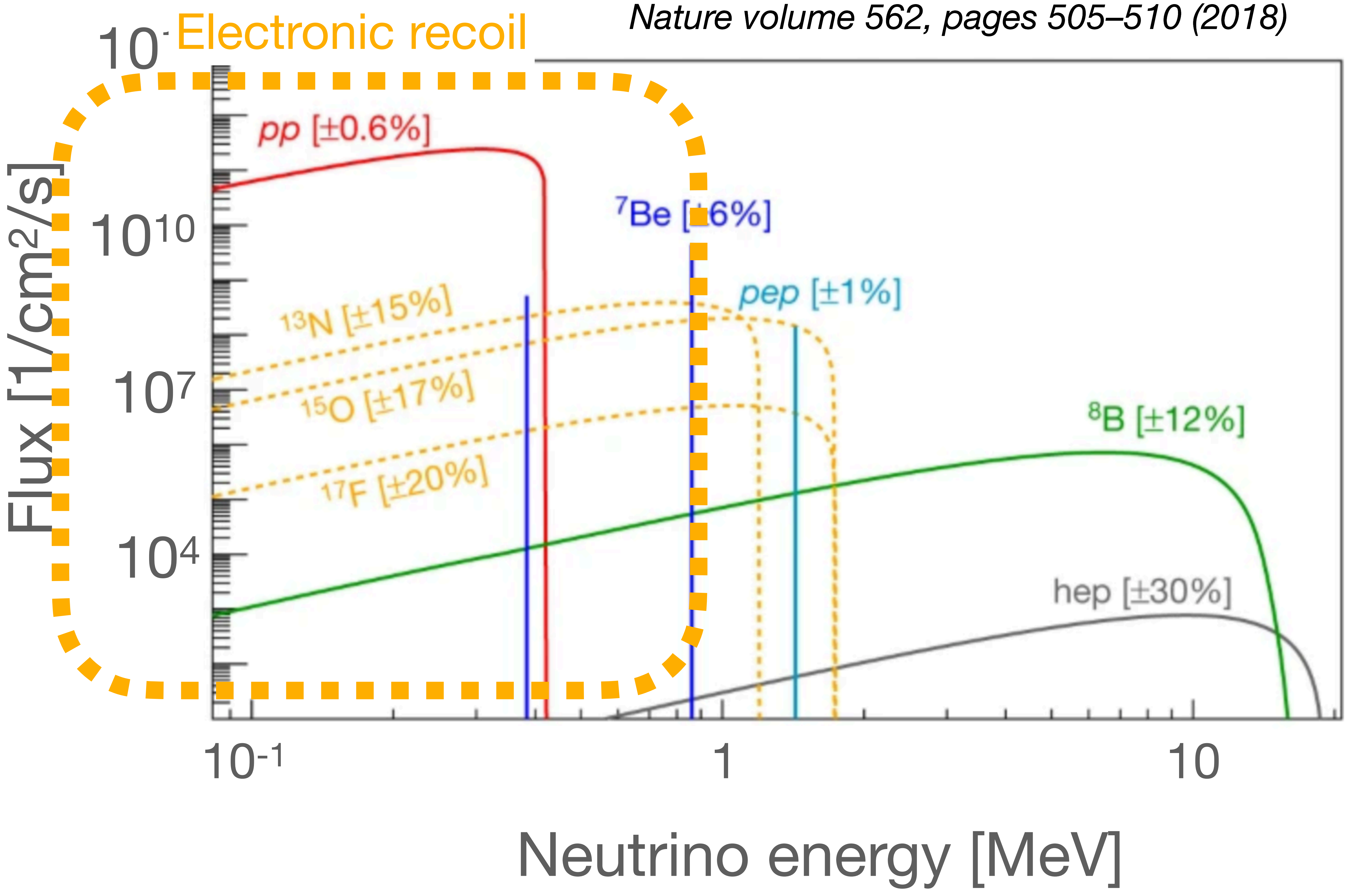

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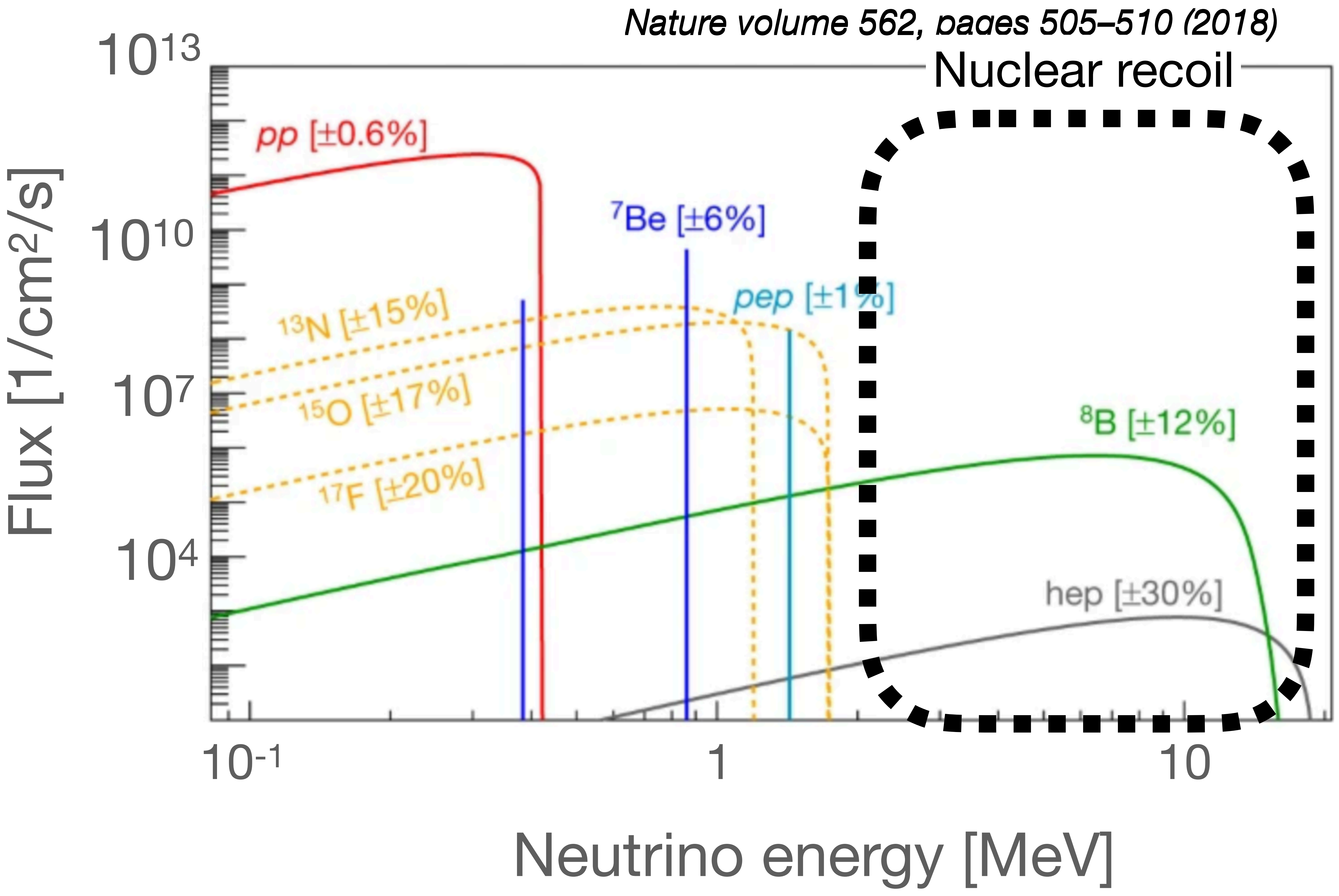

The measurement via electronic recoils

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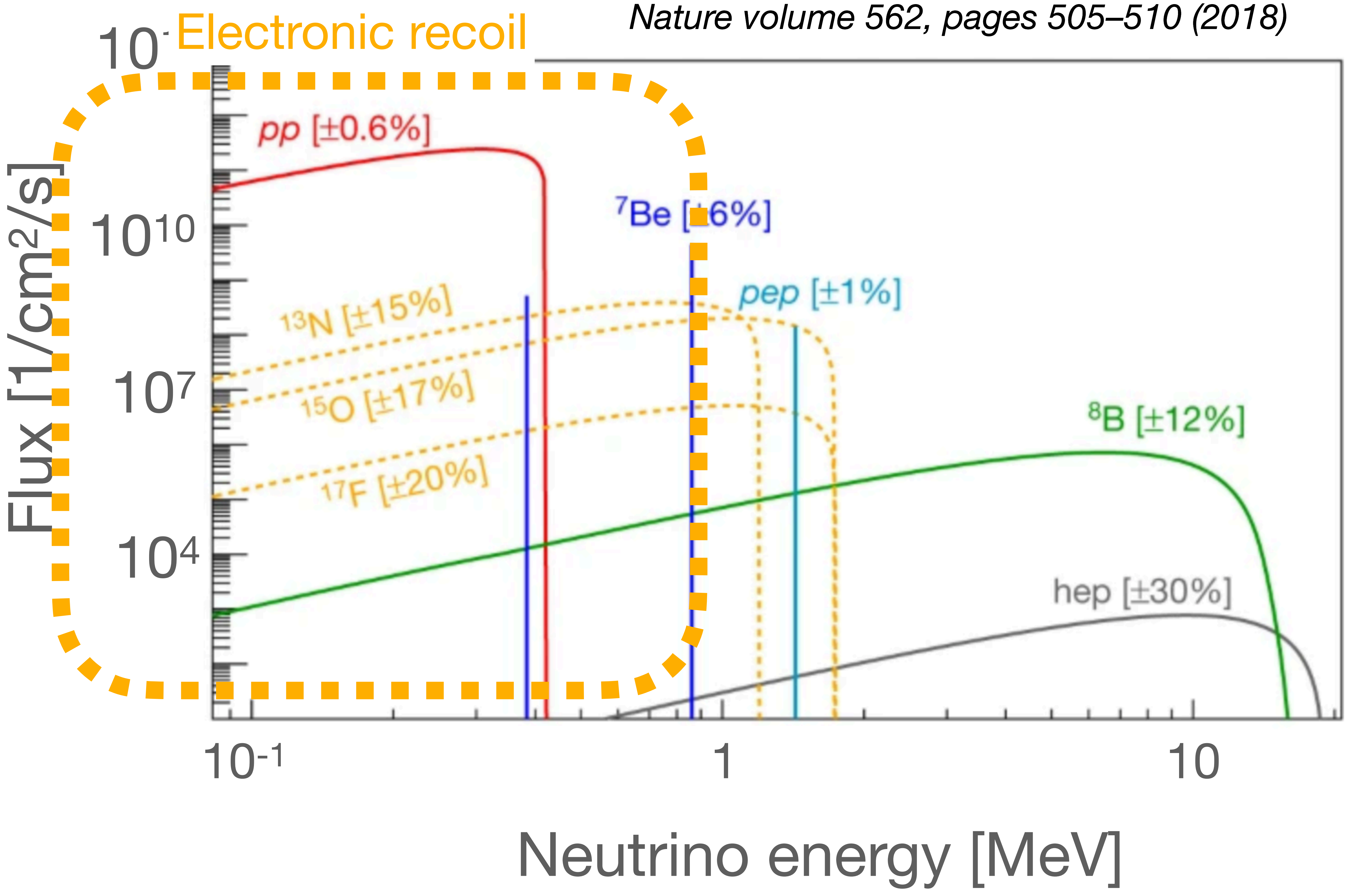
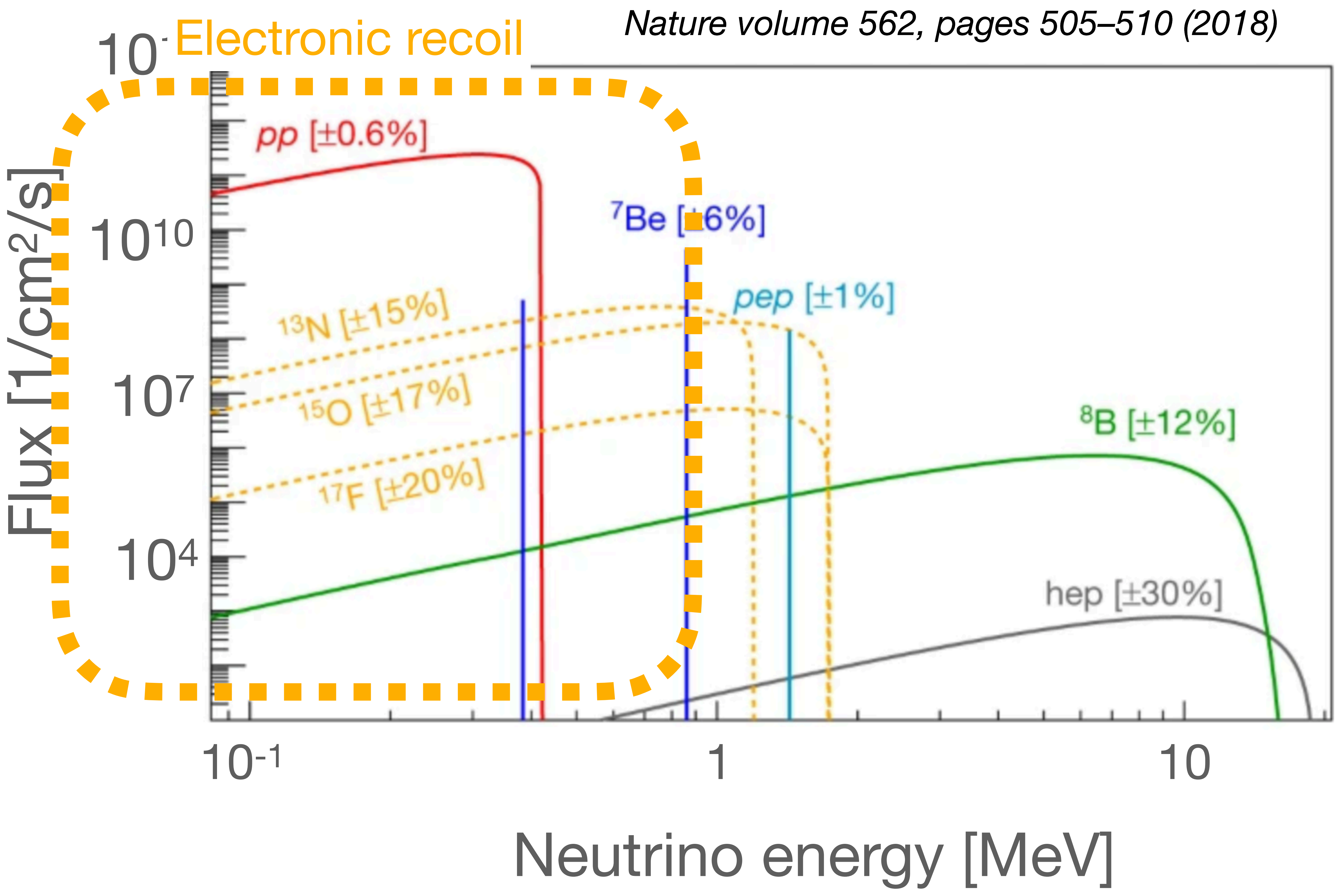


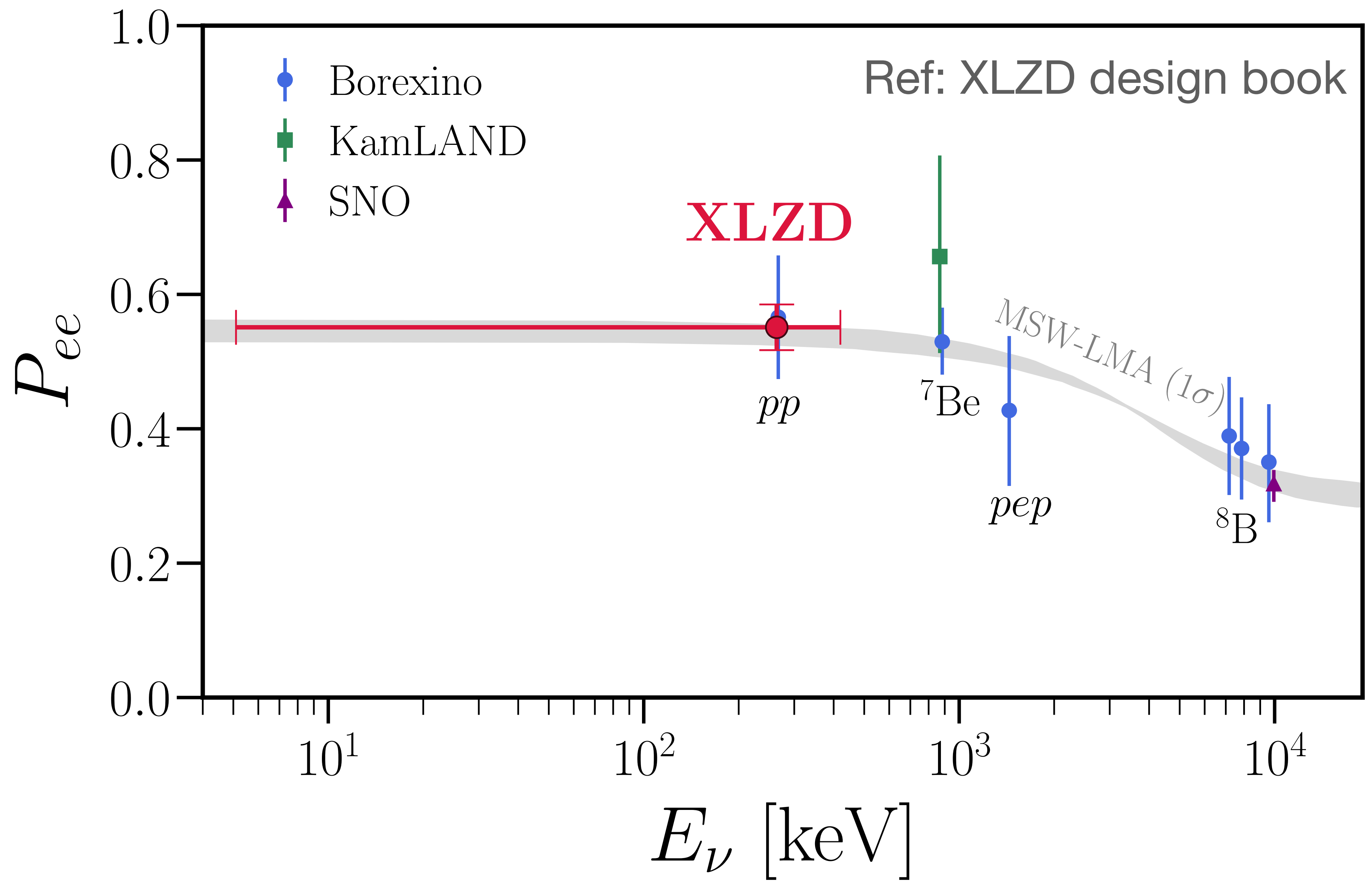
Measurement for the pp neutrino

- Measurement via the electronic recoil events:
  - Sensitive for low energy neutrino (pp, ^{7}Be)
- Advantage of XENON: lower threshold
  - XENON detector: ~1keVee
  - <=> ~160-190keV by Borexino

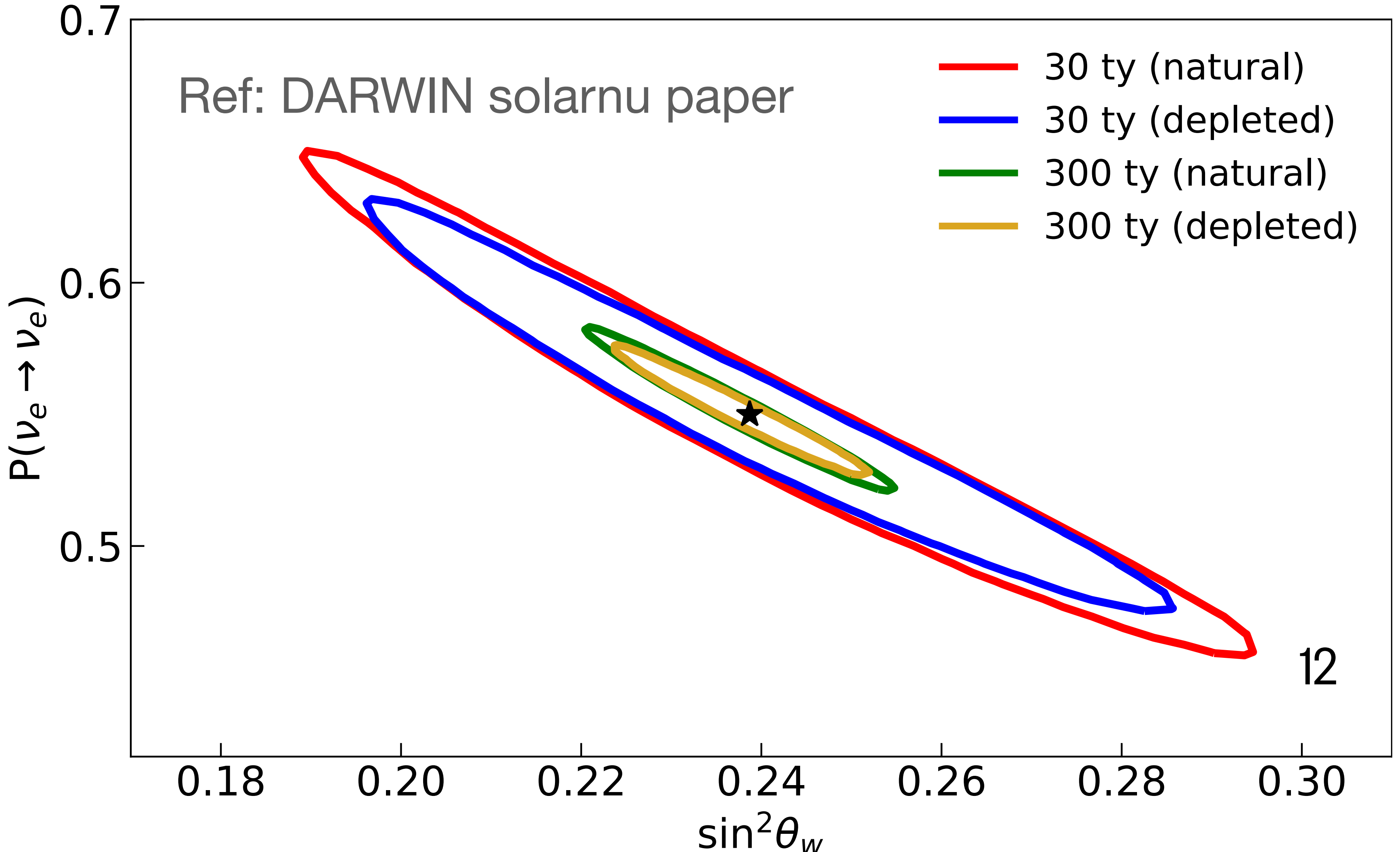


Measurement for the pp neutrino

- **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)



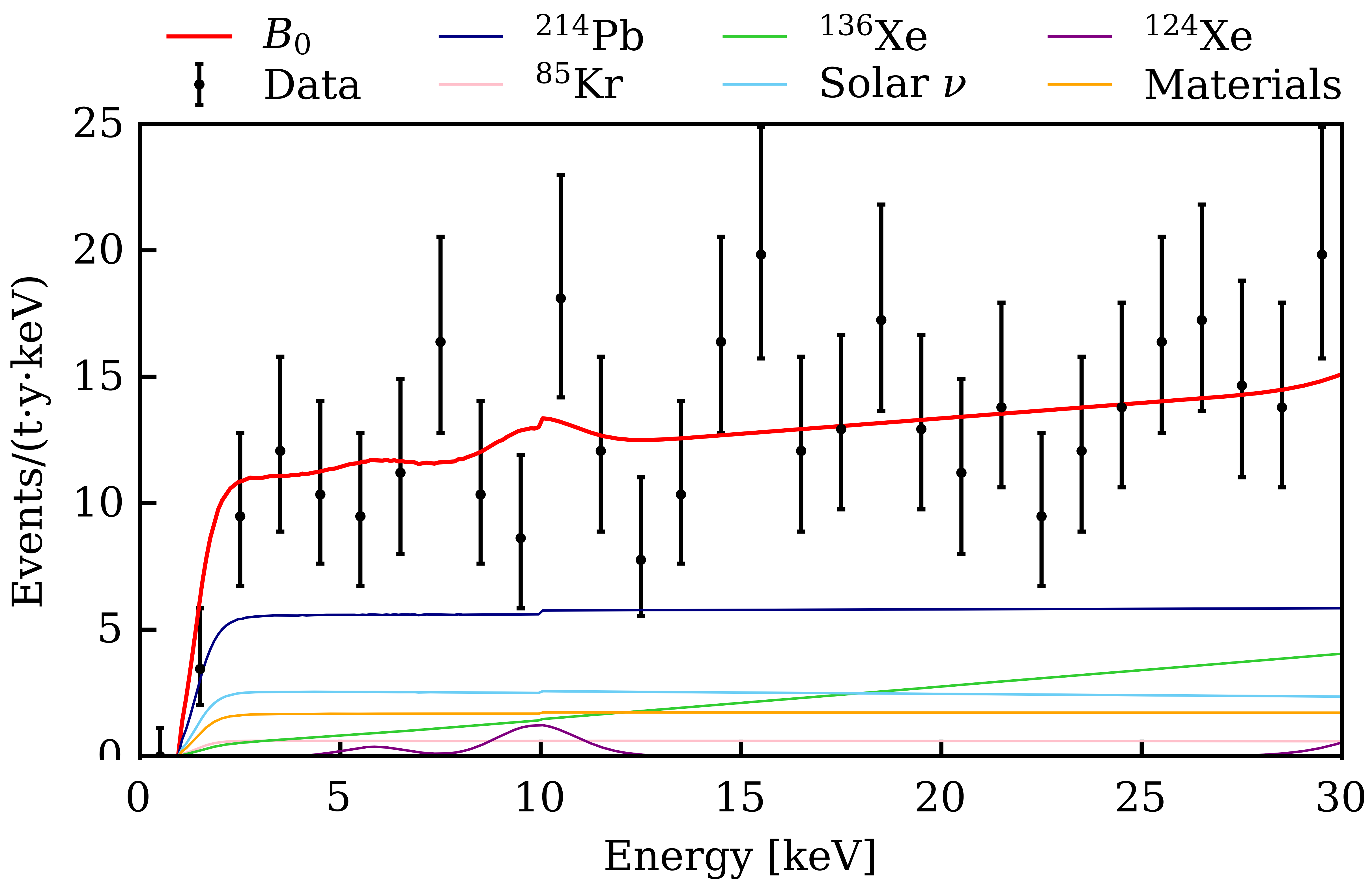
- **Goal for XENONnT: Demonstration with 3σ**
  - Measurement with few % precision expected in future experiment



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



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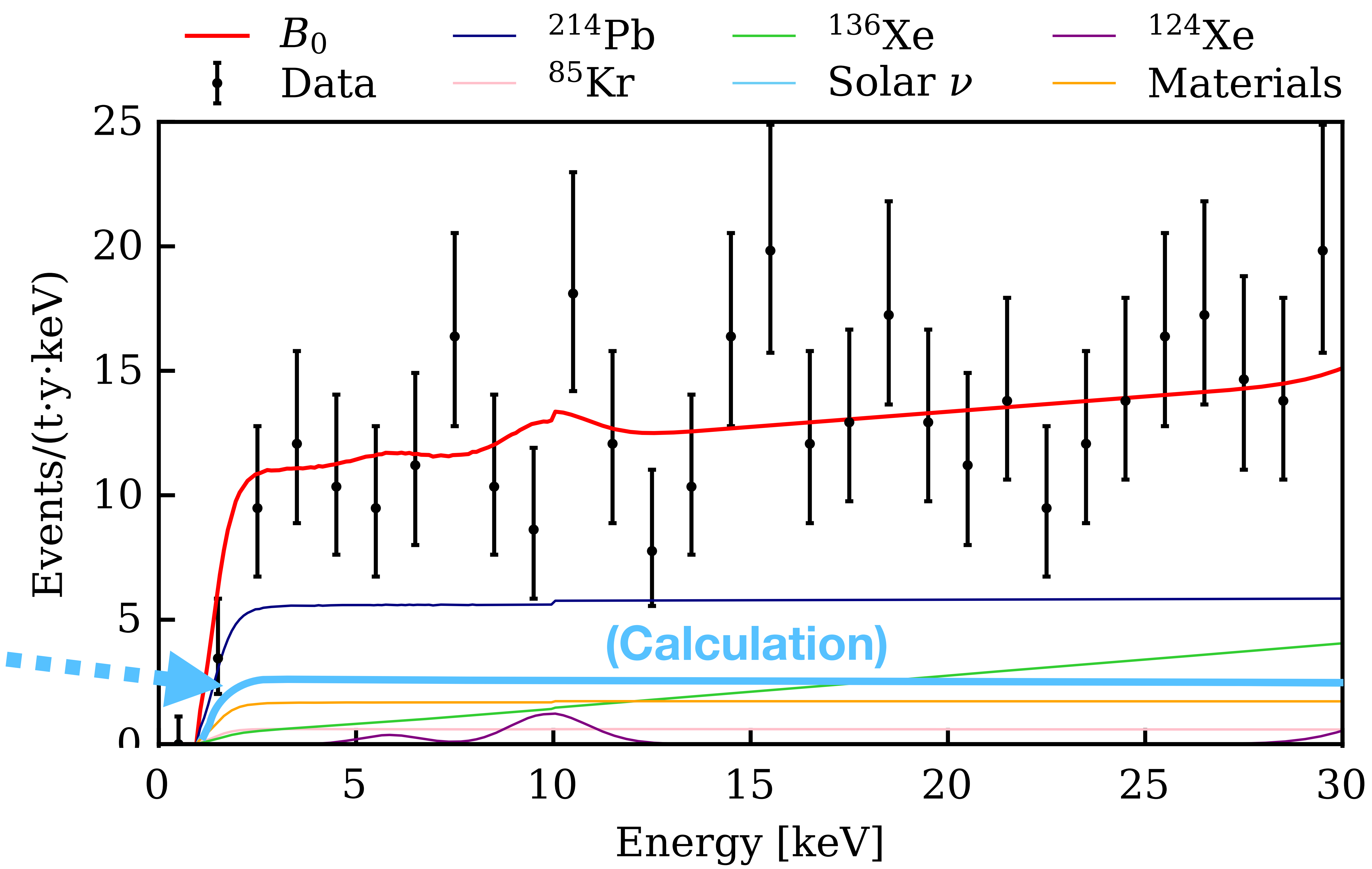

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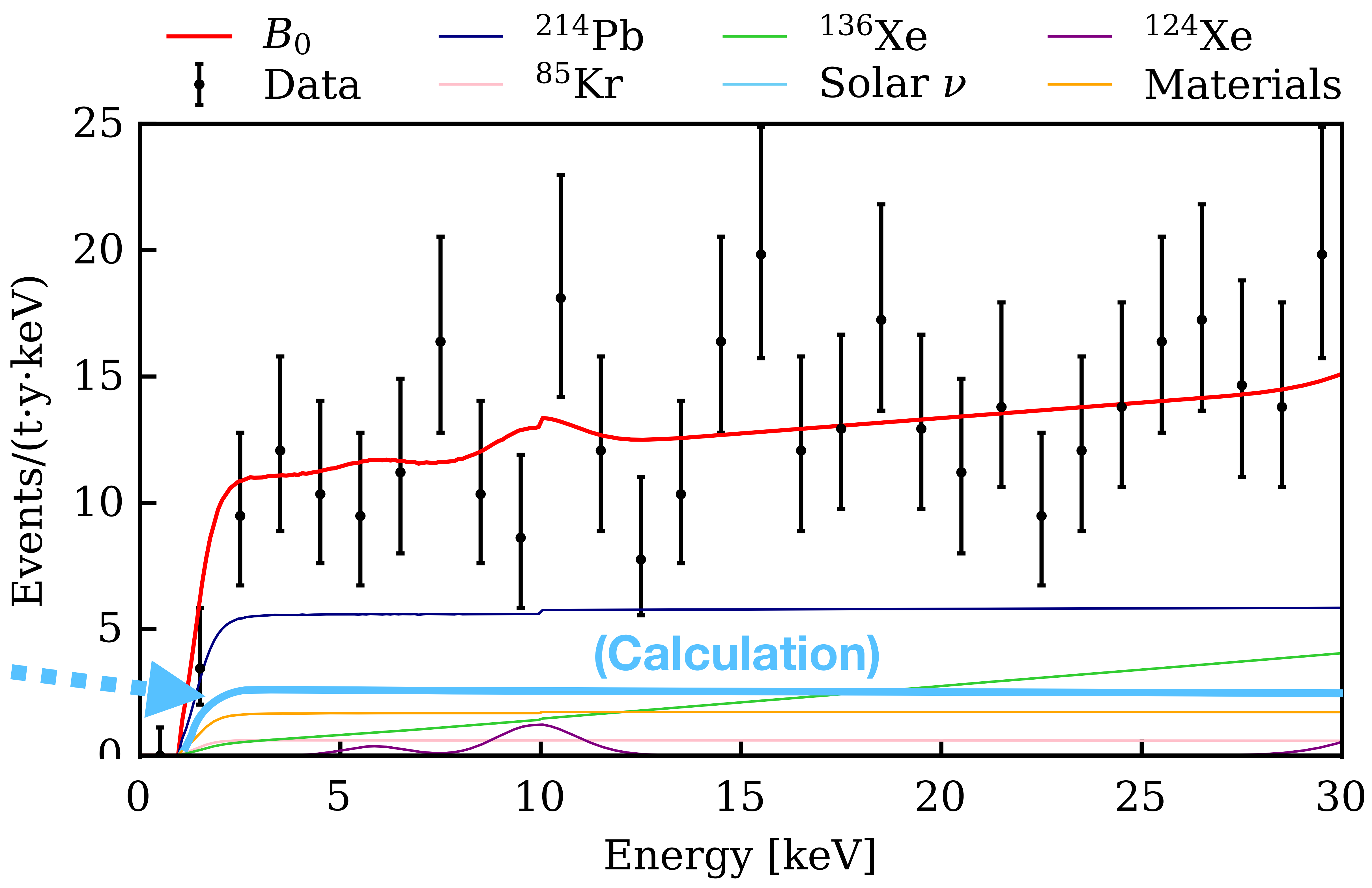
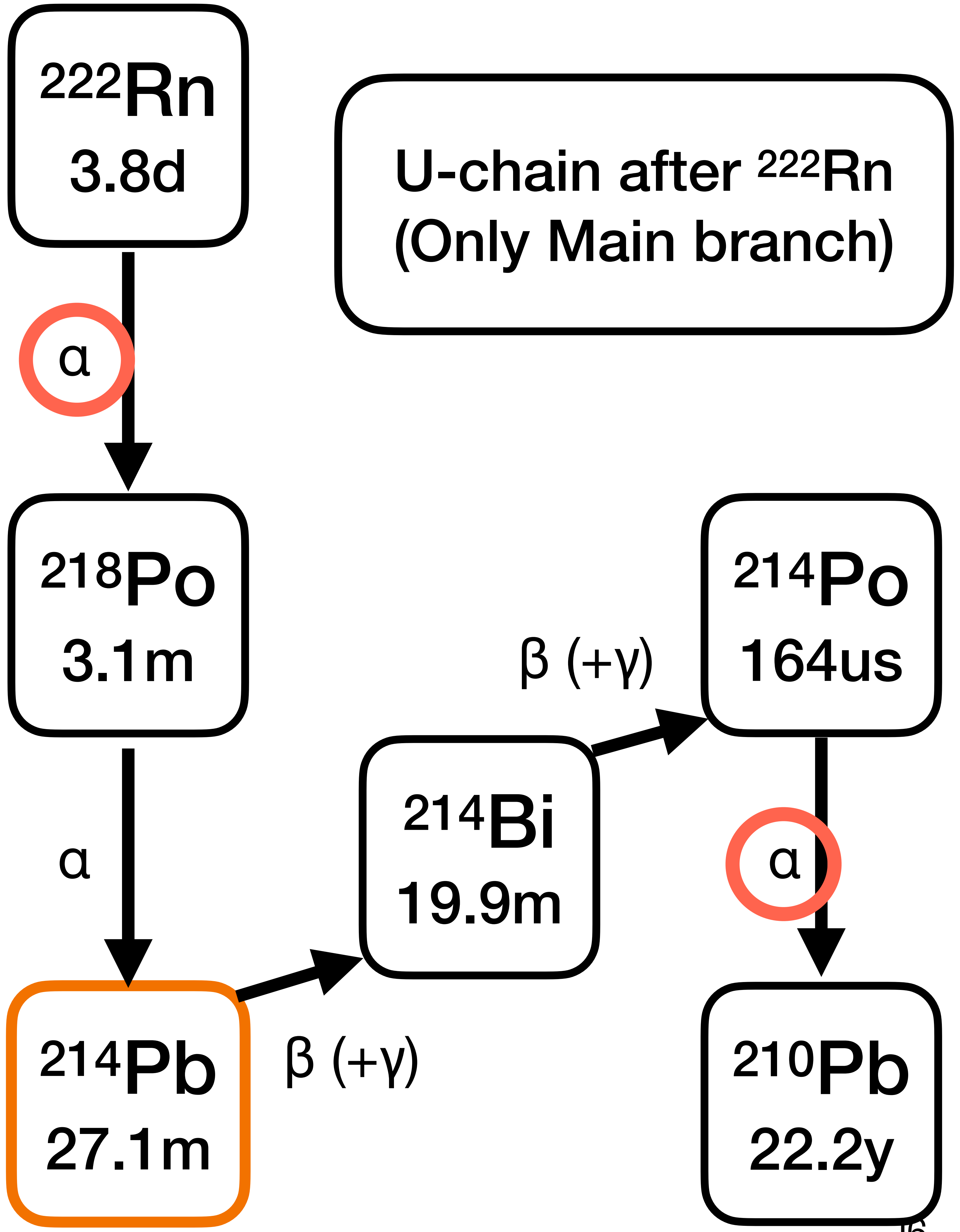
  - "XENON1T Excess": ex. solar-axions
  - => solar-nu signal was calculated by Borexino's result
- To search for the solar-nu signal, precise understanding of other BG is essential
  - Radon-induced ^{214}Pb, ^{85}Kr, γ-rays,⋯

XENONnT SR0 data



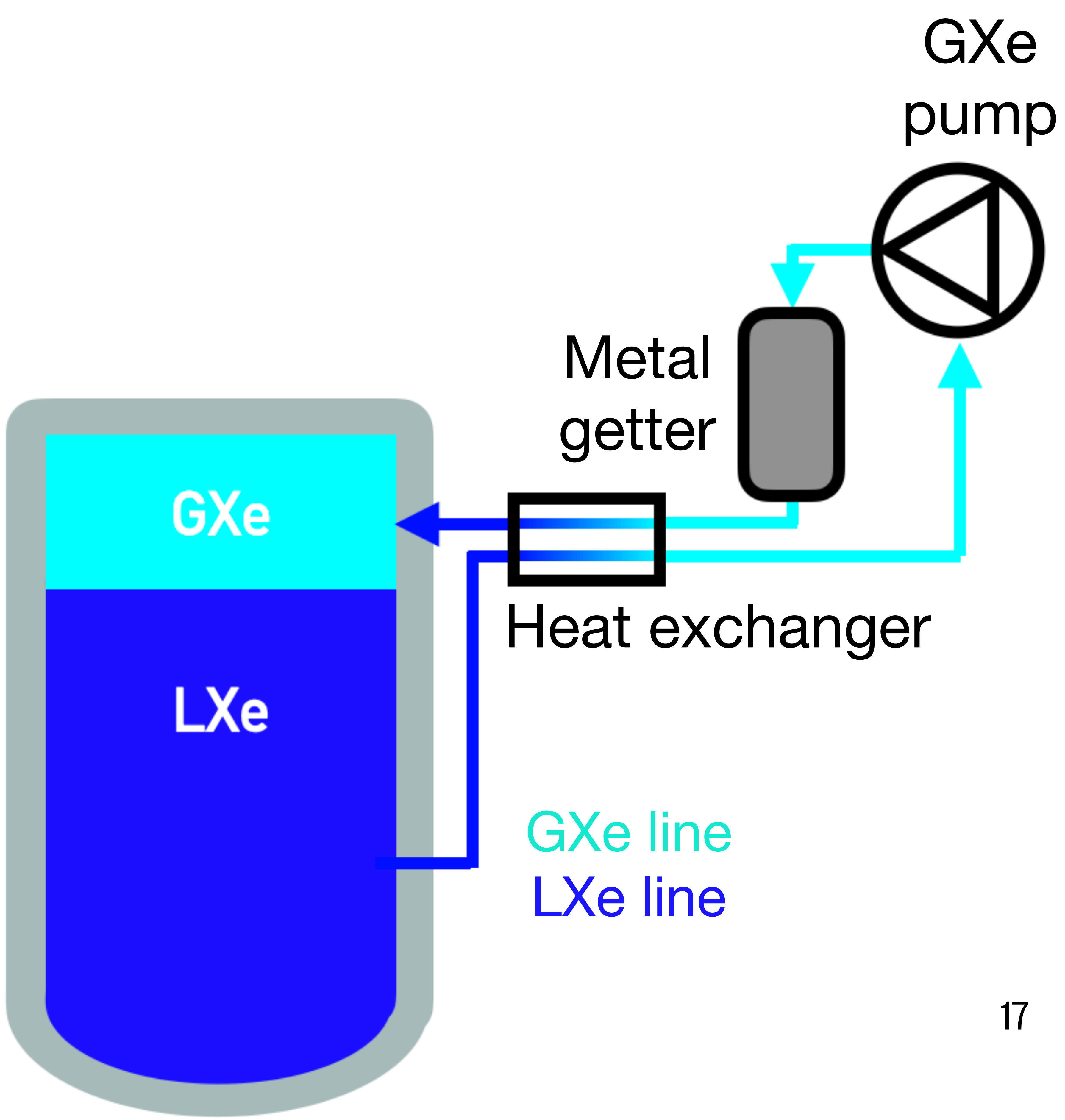
Radon-induced background

- **Radon-induced ^{214}Pb: largest BG component in XENONnT**
  - β decay of ^{214}Pb creates BG events
  - ^{222}Rn can be counted using α decay; but typically daughters have less activities
- Ex. in XENONnT SR0:
  - 1.69 (^{222}Rn) > ^{214}Pb > 0.78 (^{214}Po) [uBq/kg]
  - => ~35% uncertainty for ^{214}Pb activity
- **To search for solar-nu signal, we need to reduce the uncertainty down to ~5% level!**



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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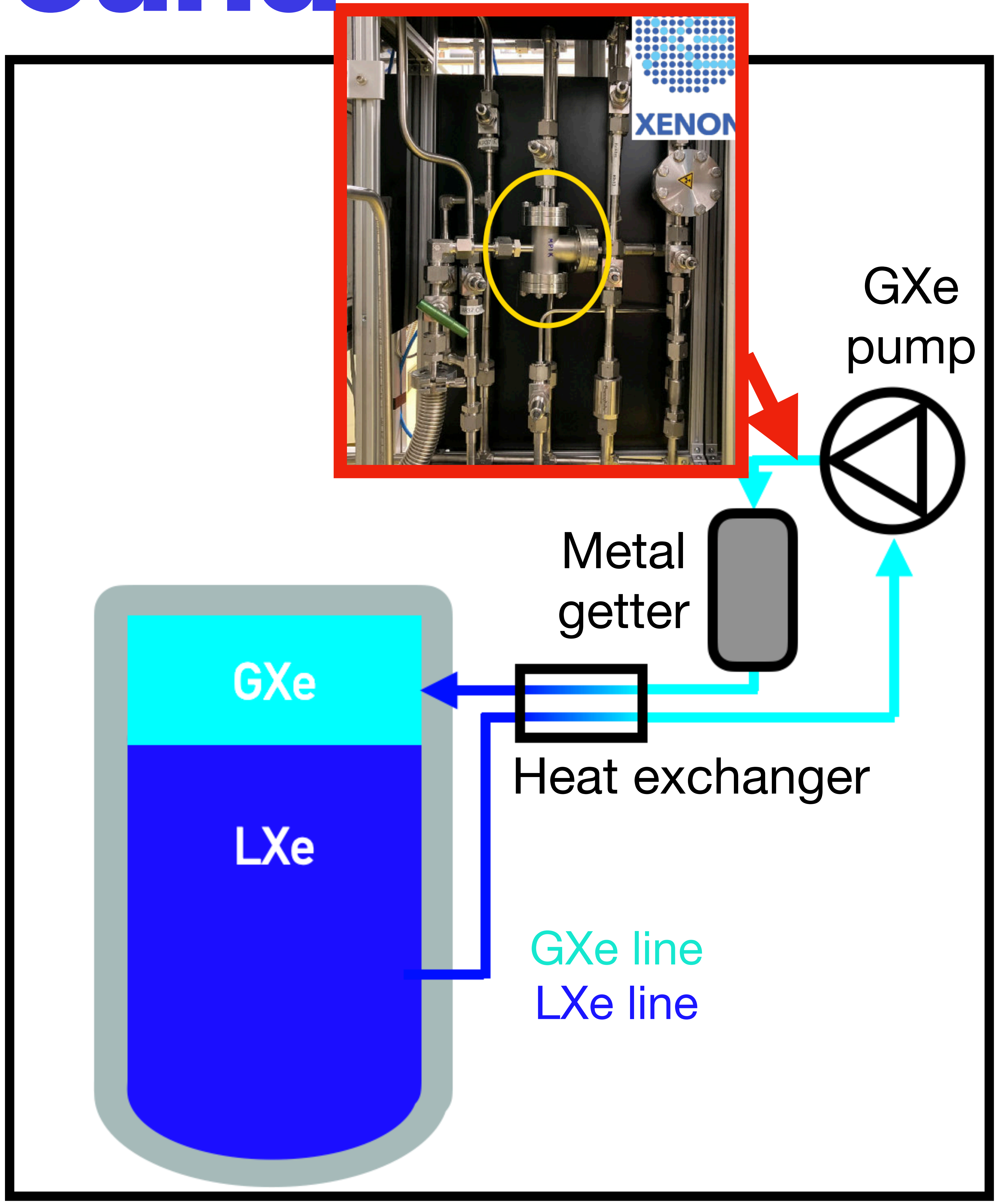

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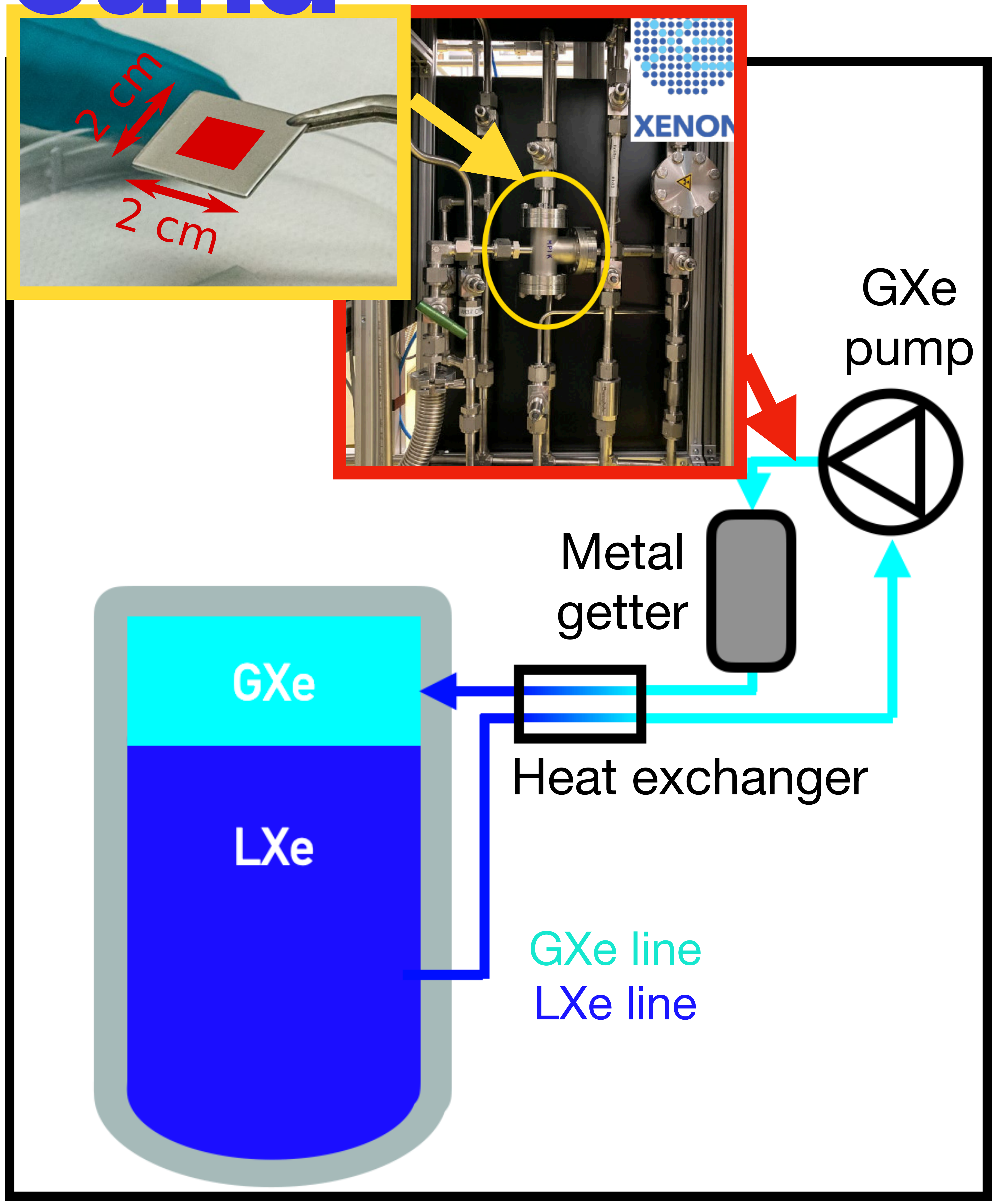

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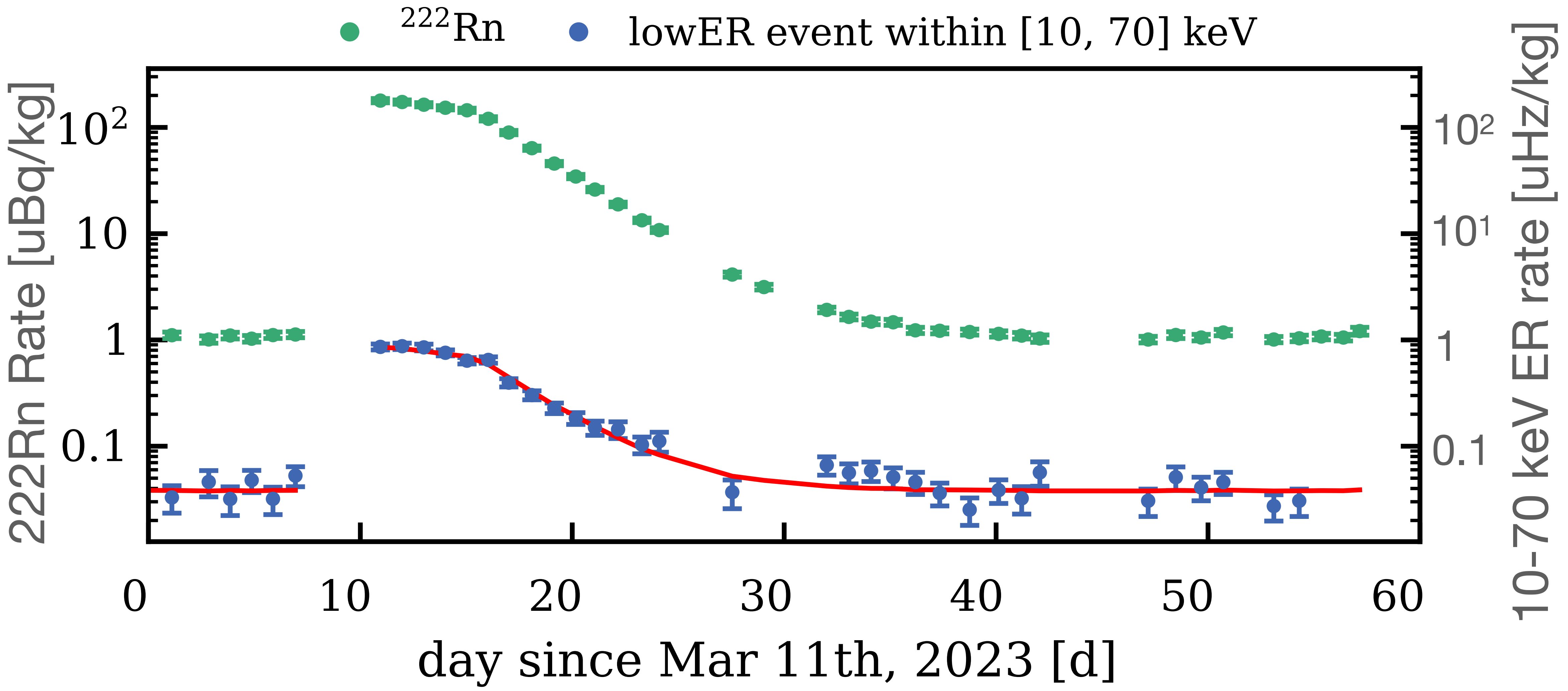
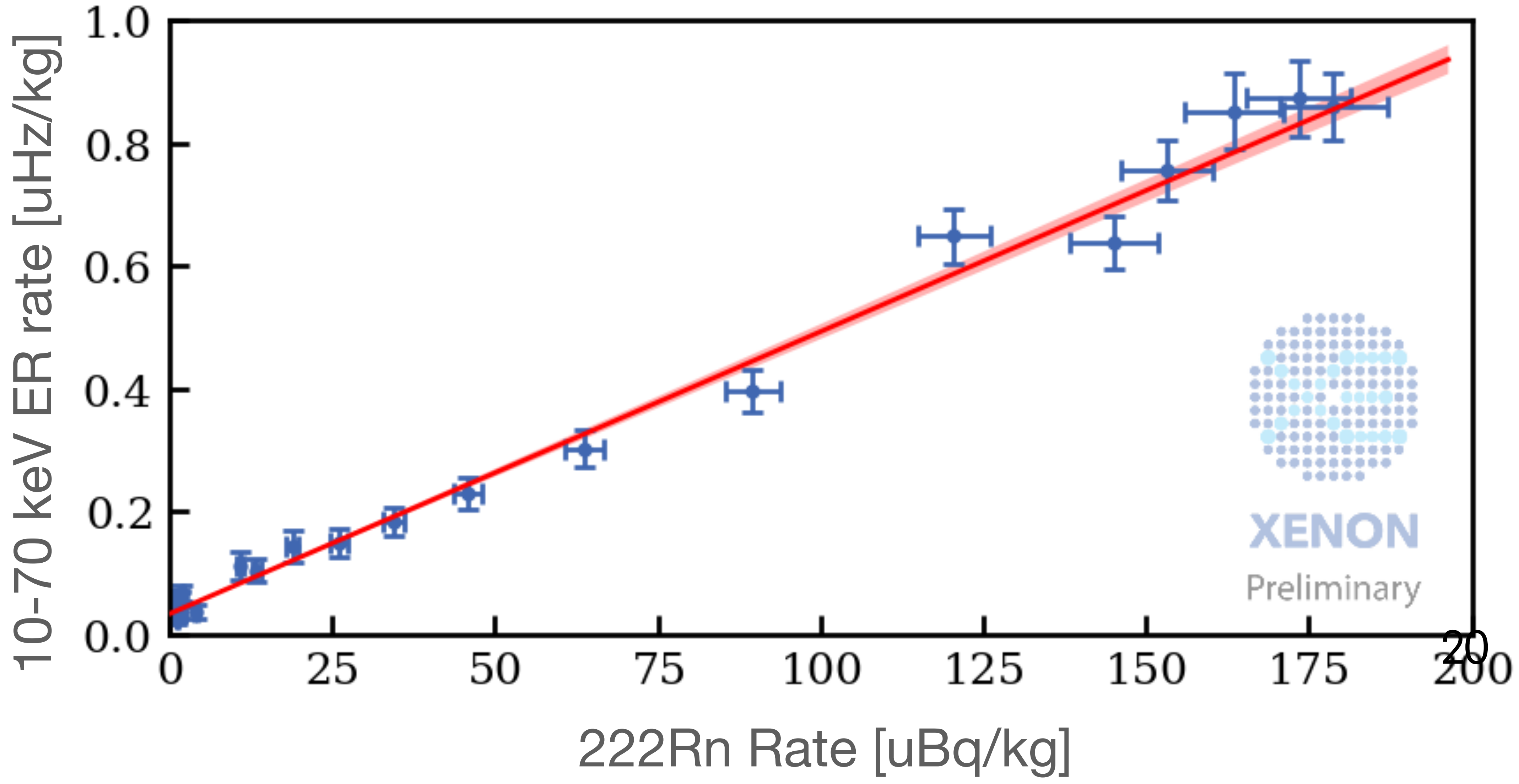
Radon-induced background

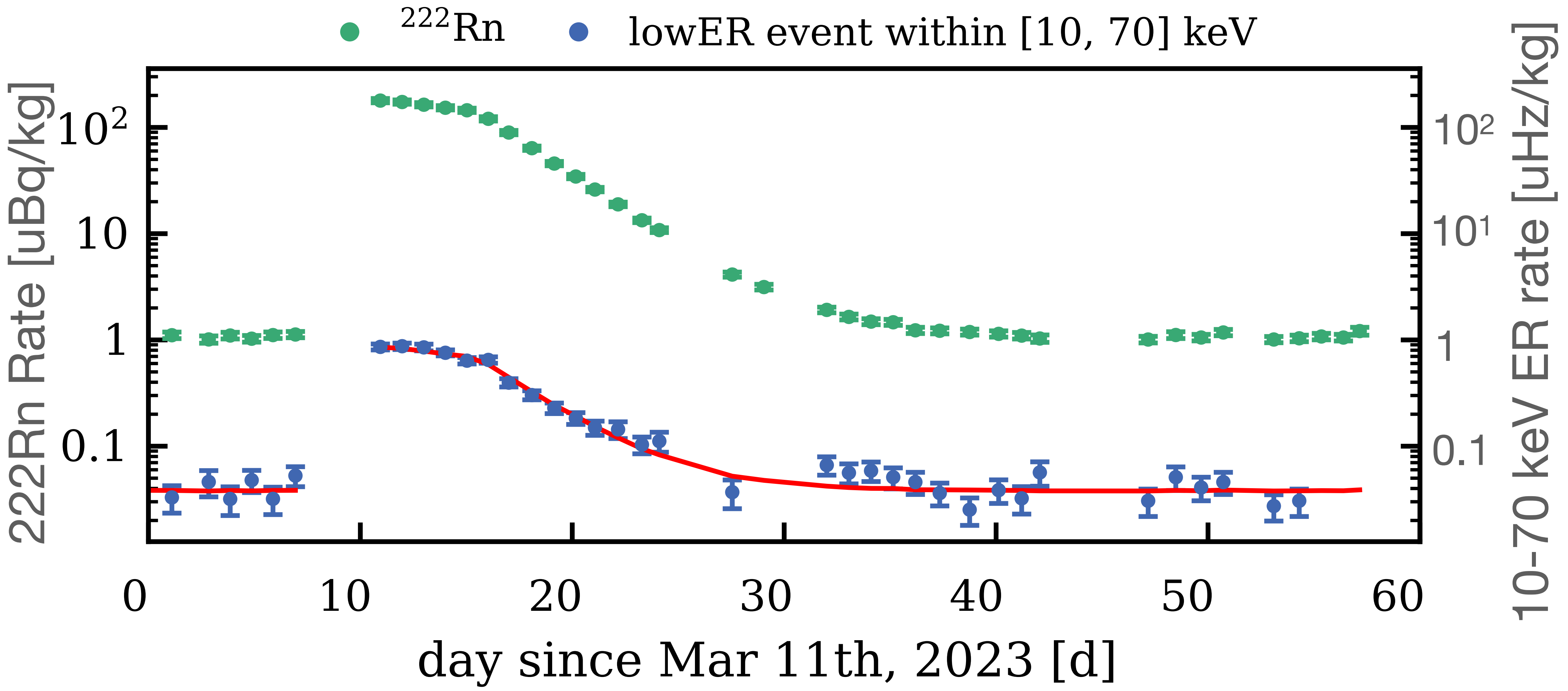
- Result of the calibration
- [Rate of α] vs [Rate of ER (10-70keV)]
- ^{214}Pb ∝ ^{222}Rn： $\epsilon \mathrm{R_{Pb}} = \mathrm{a} \cdot \mathrm{R_{Rn}} + \mathrm{b}$
  - a: Ratio between ^{222}Rn and ^{214}Pb
  - b: BG other than ^{214}Pb
  - ε (calc):correction by branching ratio, efficiency etc

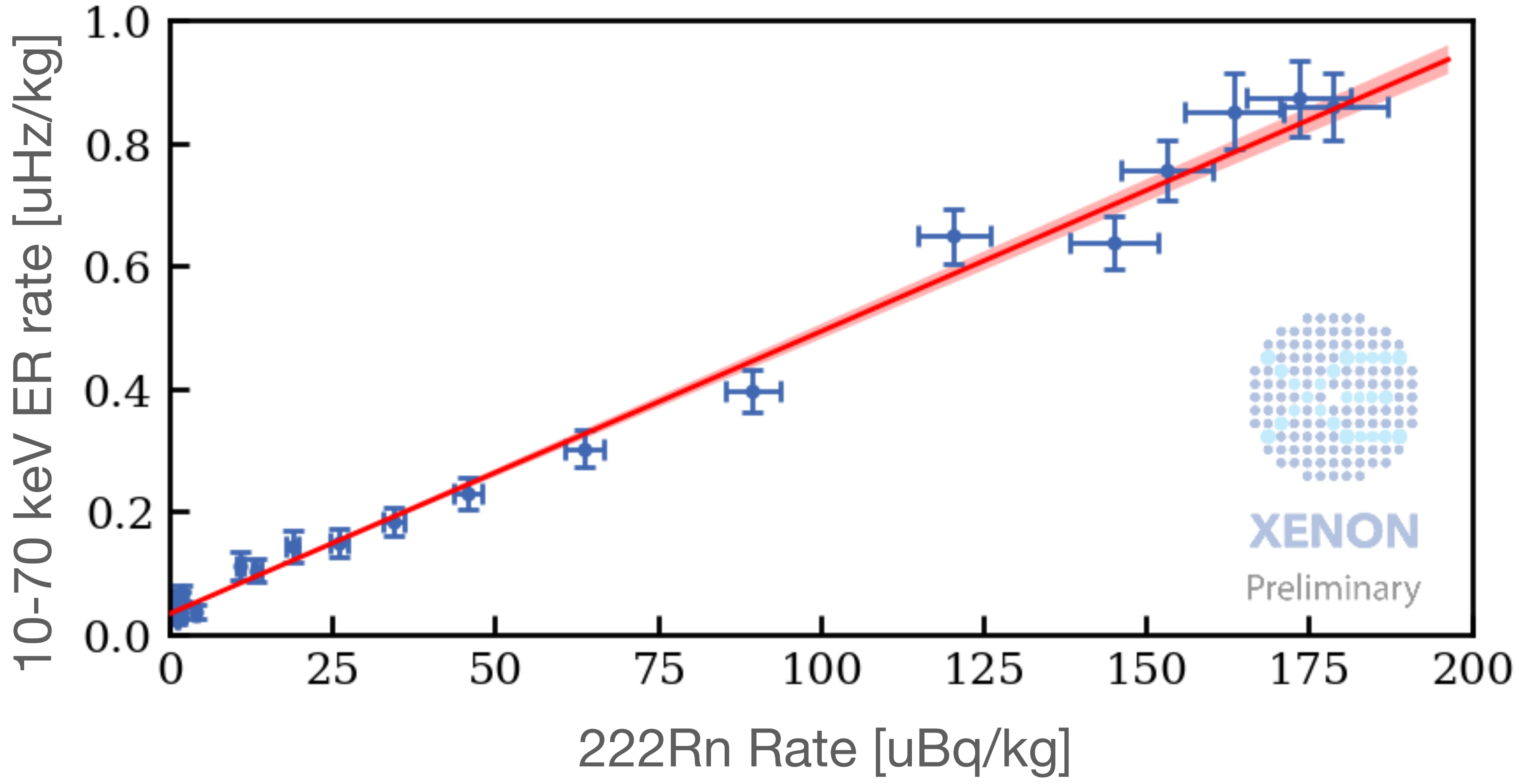




Radon-induced background

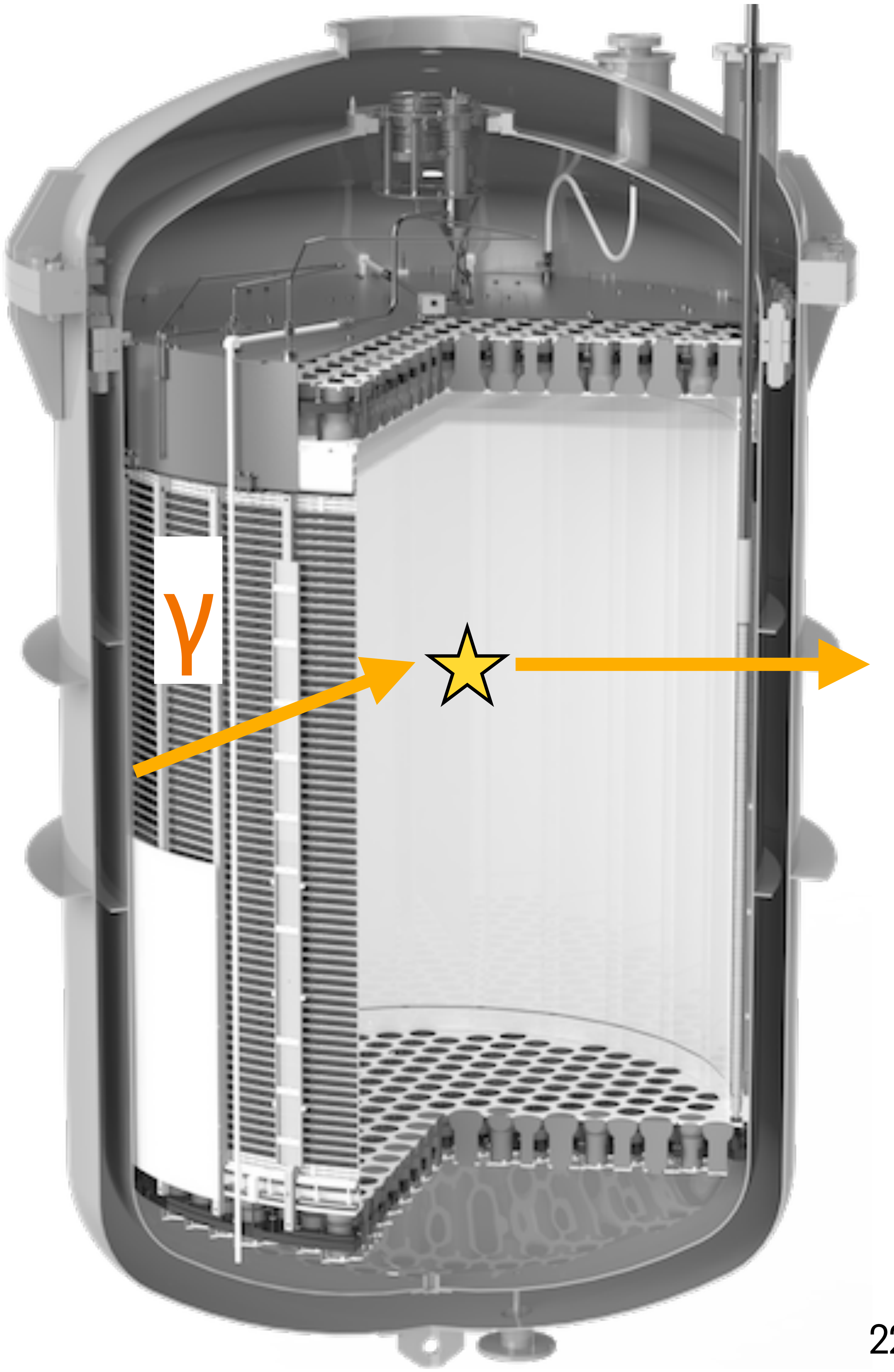
- (preliminary) fit result:
  - a= **0.67 +/- 0.03 [Bq/Bq]**
- Note:
  - 1 Bq of ^{222}Rn <=> 0.67 Bq of ^{214}Pb
  - Uncertainty down to ~4.5% level
- Uncertainty of conversion between calibration and normal runs is under estimation…





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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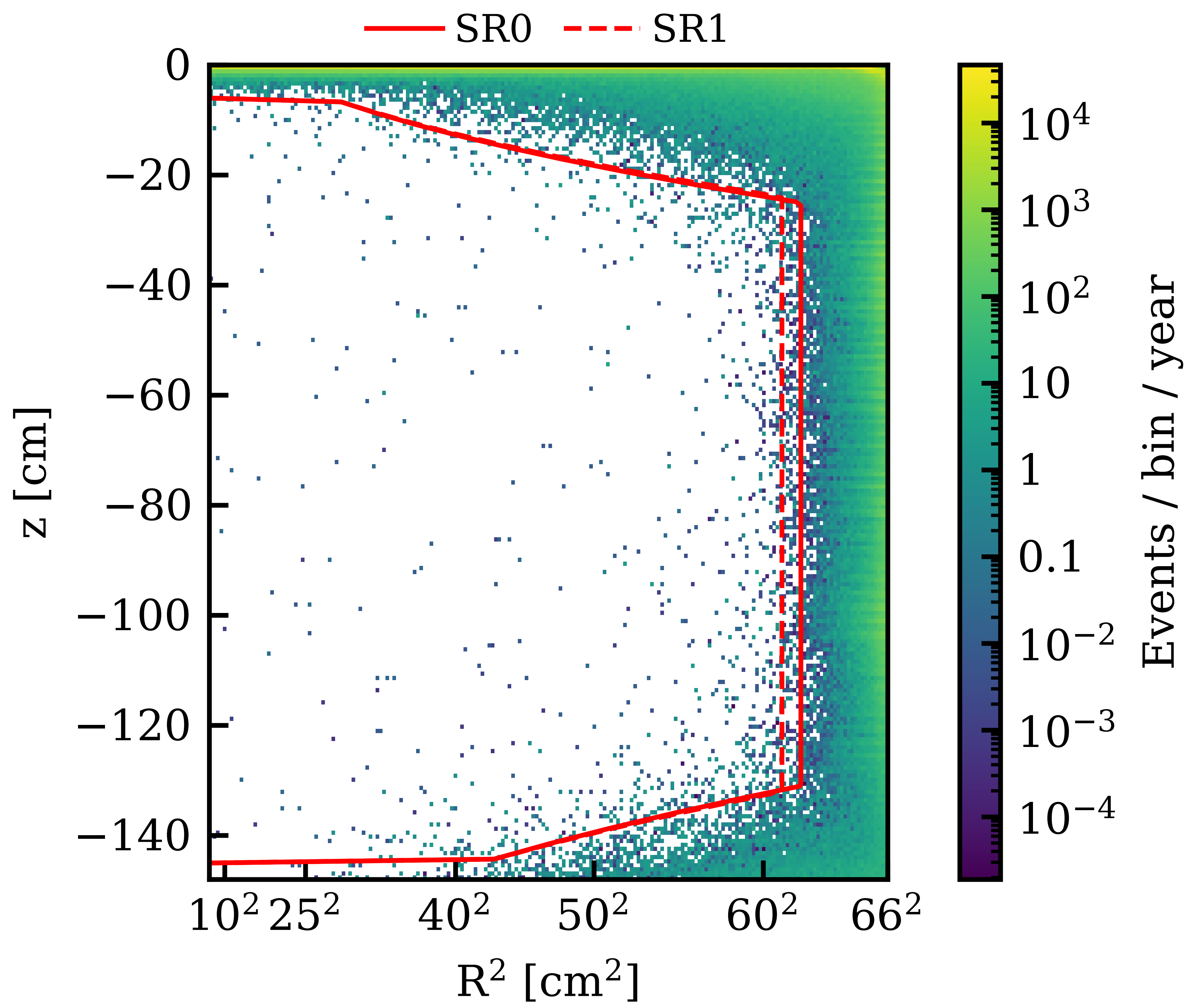

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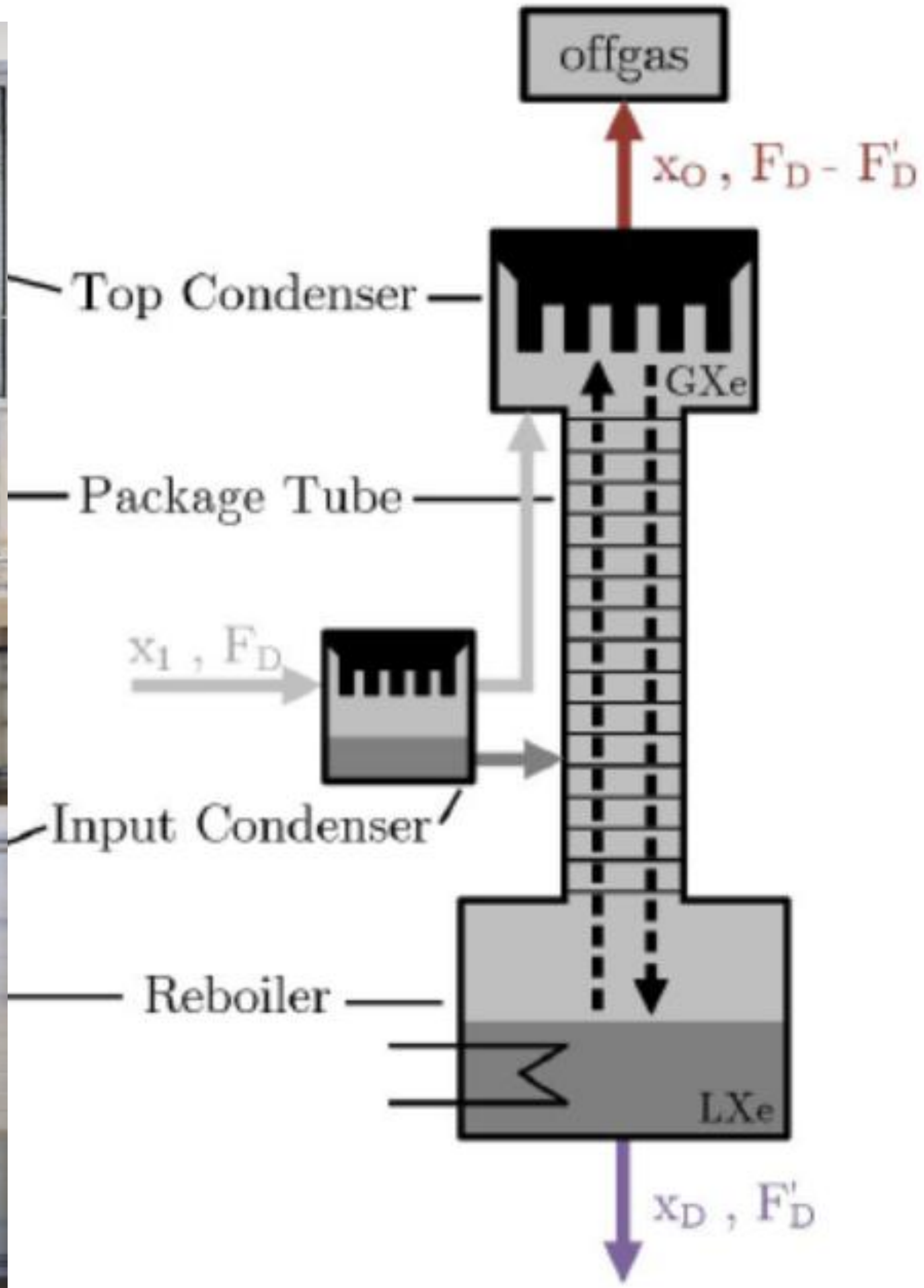

distillation column

The measurement via nuclear recoils

Solar neutrino measurements in XENONnT

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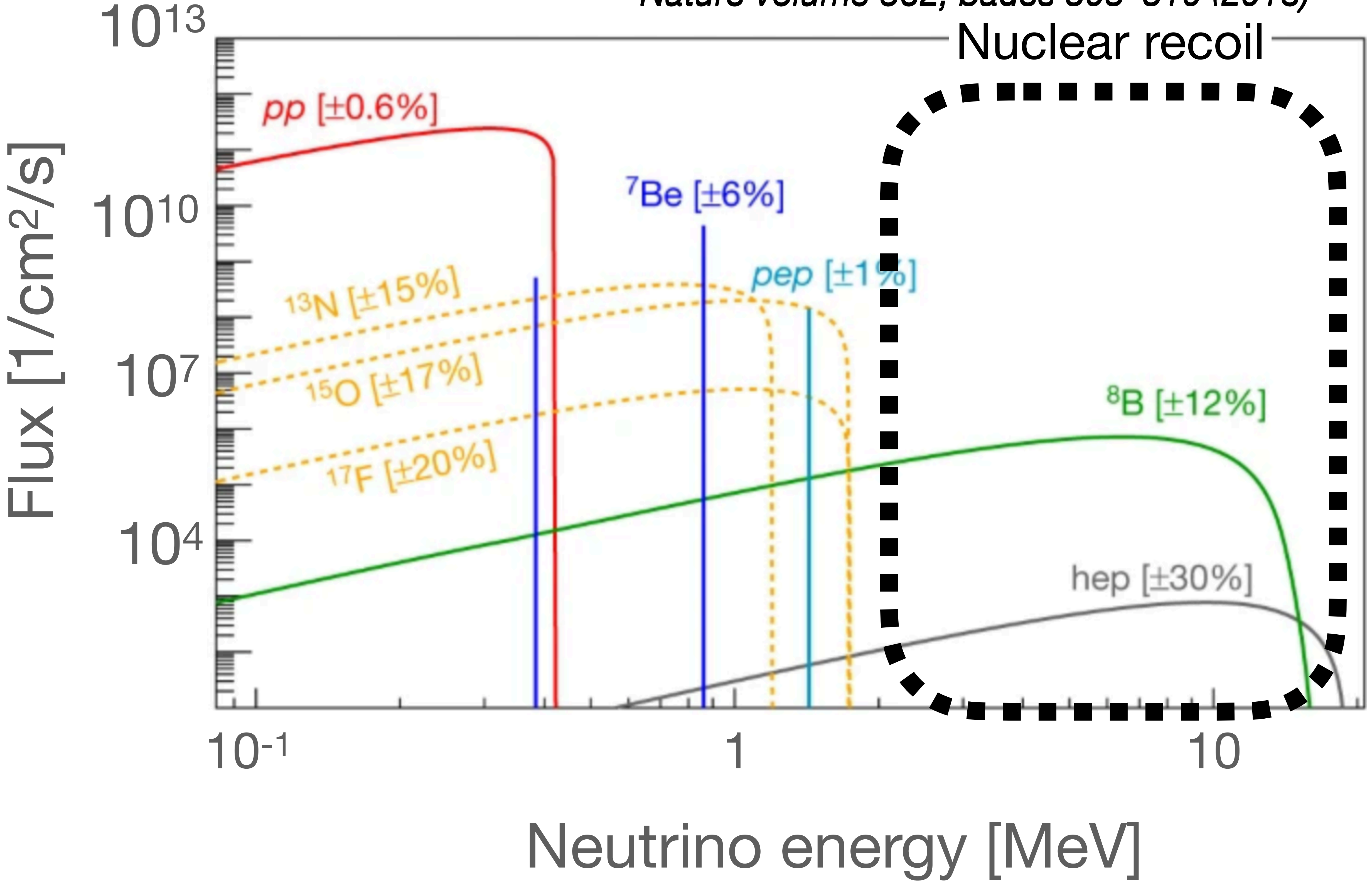
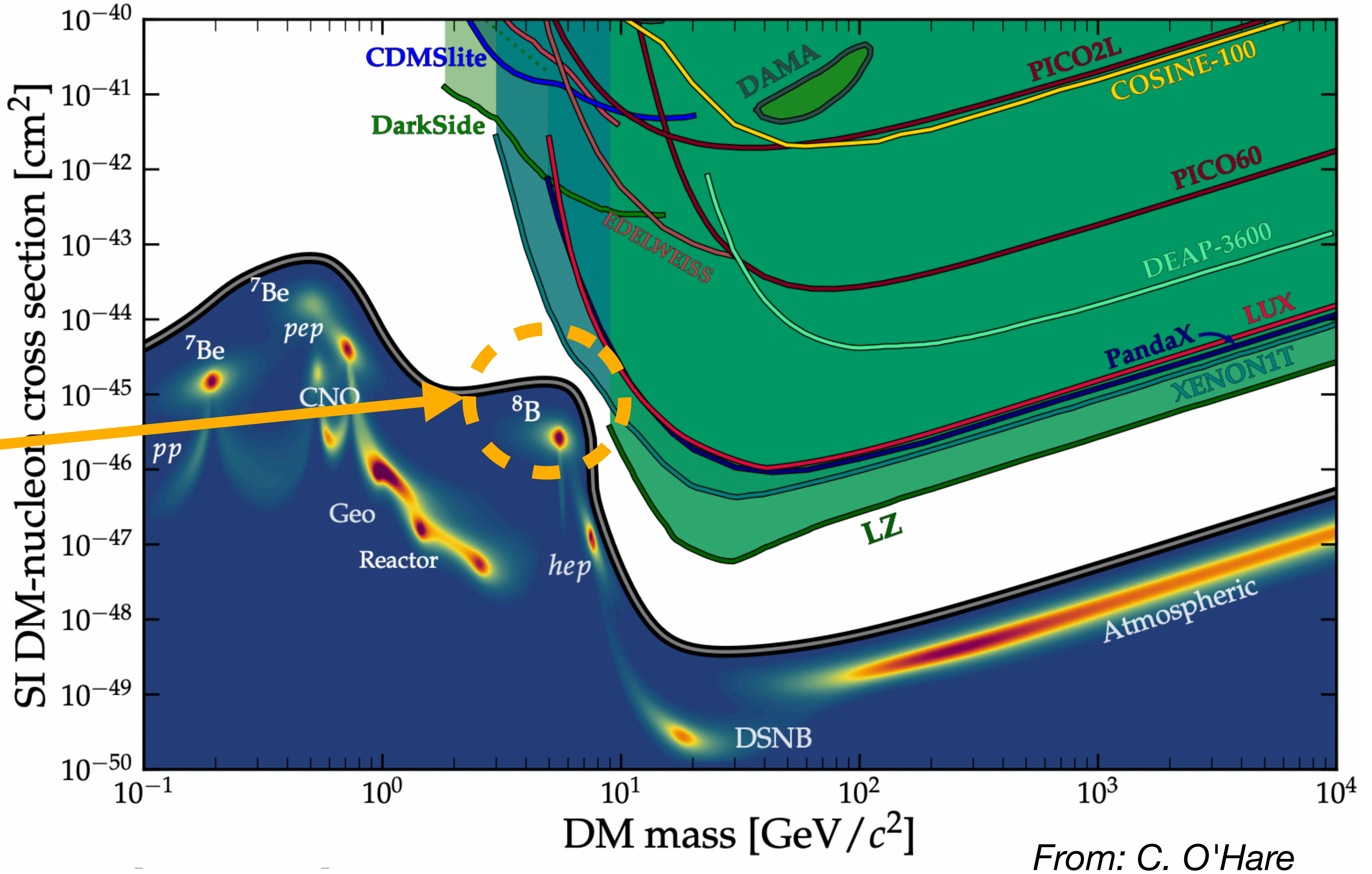


Observing the ^{8}B neutrino signal via CEvNS

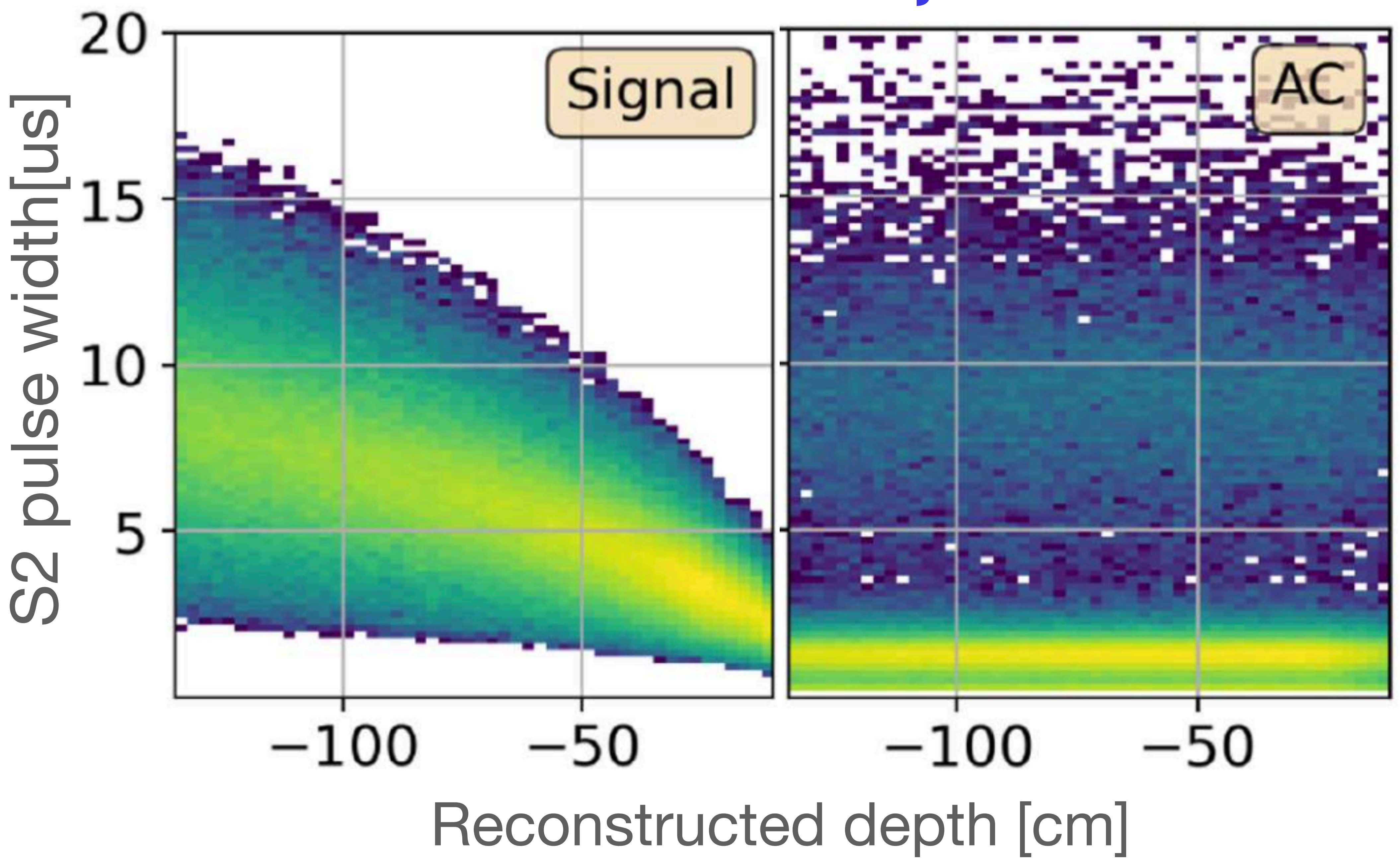
- Measurement of solar ^{8}B ν via CEvNS
  - CEνNS: Coherent Elastic ν-N scattering
  - No observation for natural ν yet
- Shape of recoil spectrum from ^{8}B ν is very similar to DM signal (5.5GeV WIMPs)
  - Important demonstration for DM search
  - In future experiments, atm-ν with higher energy becomes BG: “neutrino fog”

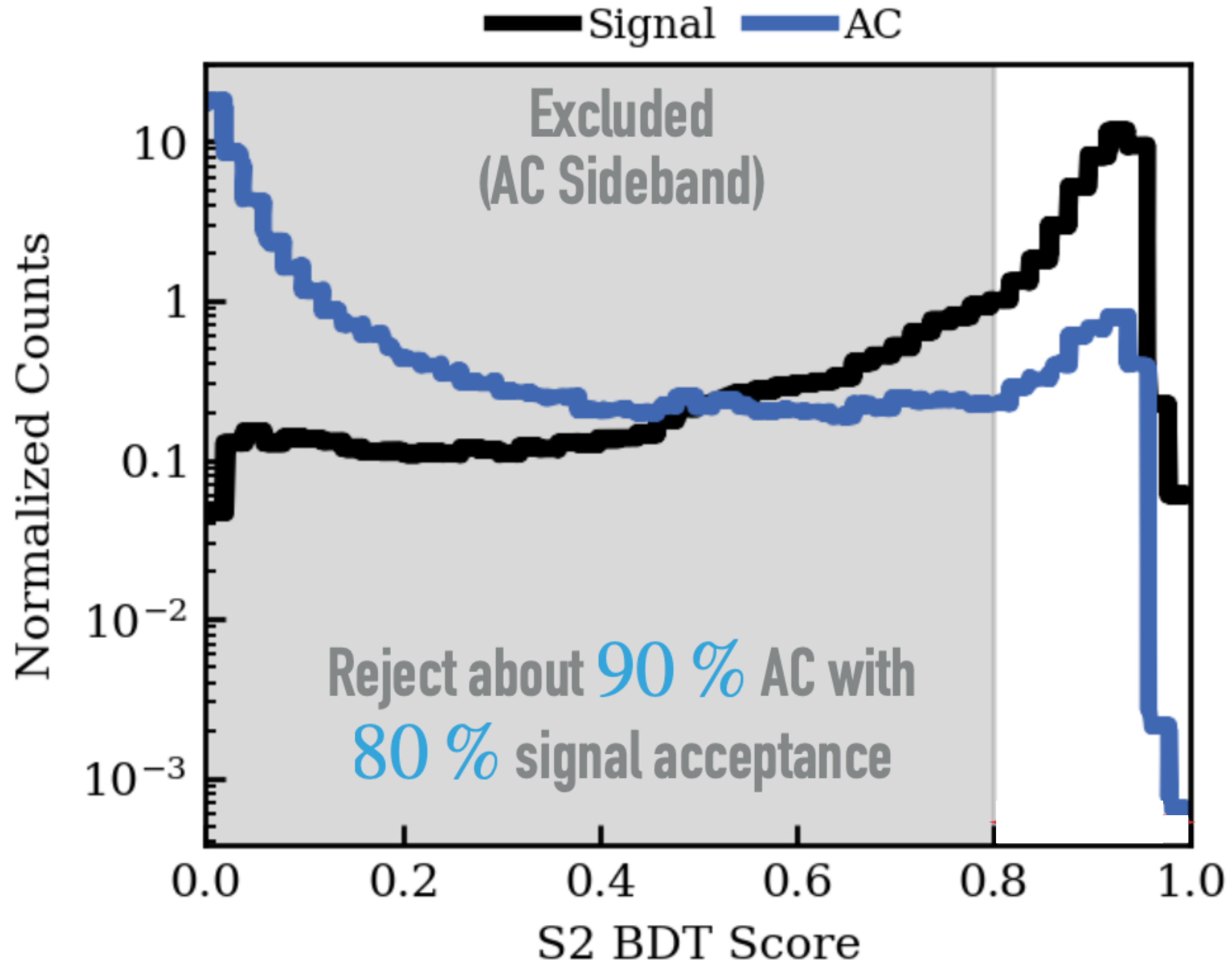


From: C. O'Hare

Accidental Coincidence BG

- Main BG: Accidental Coincidences (AC)
- Random pairing of isolated S1 and isolated S2
  - Exact origin is under investigation, but several parameters can be used to distinguish the signal and BG
  - Ex. timing distribution
- BG suppression via dedicated cuts (including machine learning)
  - The BG model was validated using sideband data





^{8}B neutrino measurement via CEvNS

- Signal expectation: $11.9^{+4.5}_{-4.2}$
- BG expectation: $26.4^{+1.4}_{-1.3}$

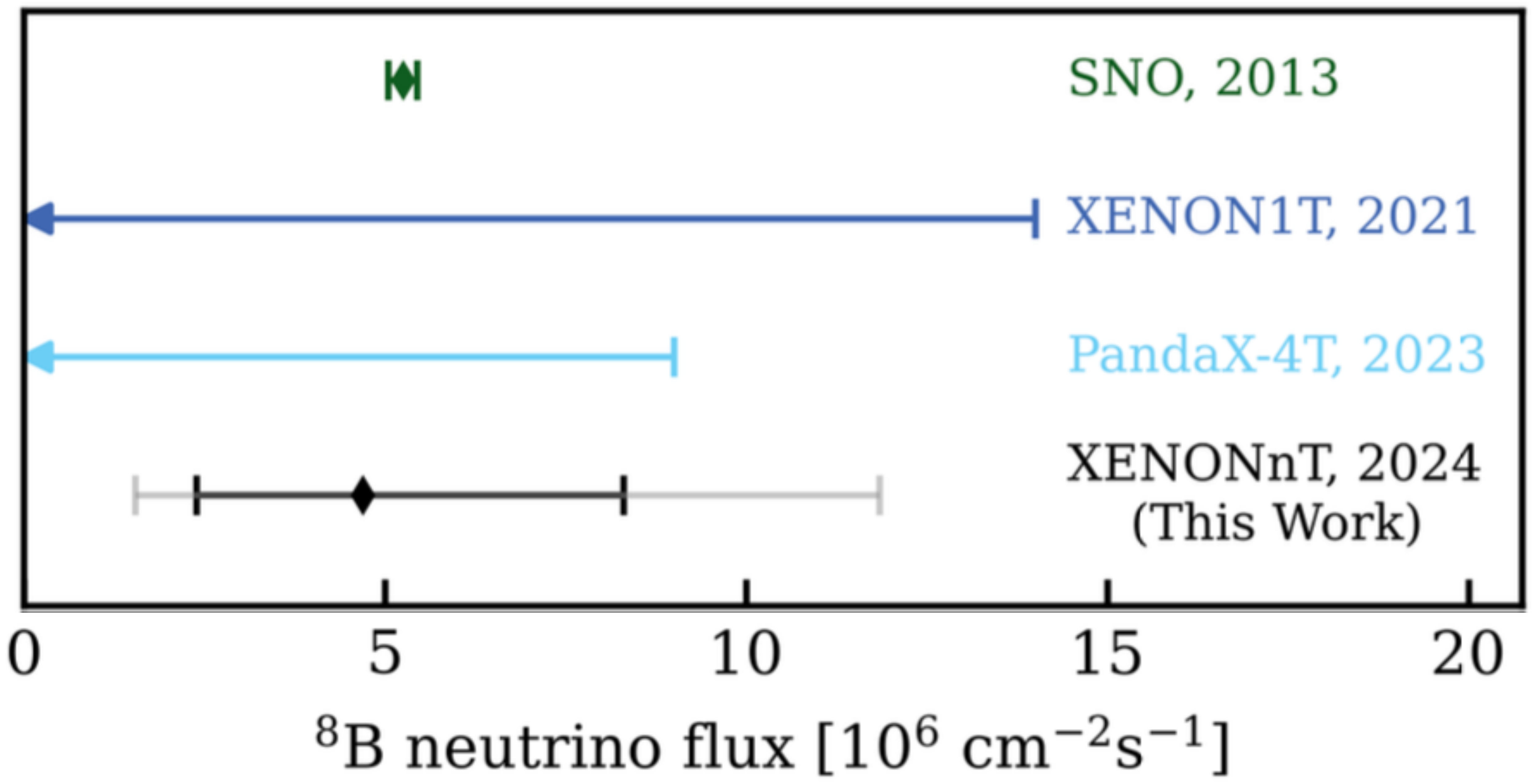
Observed

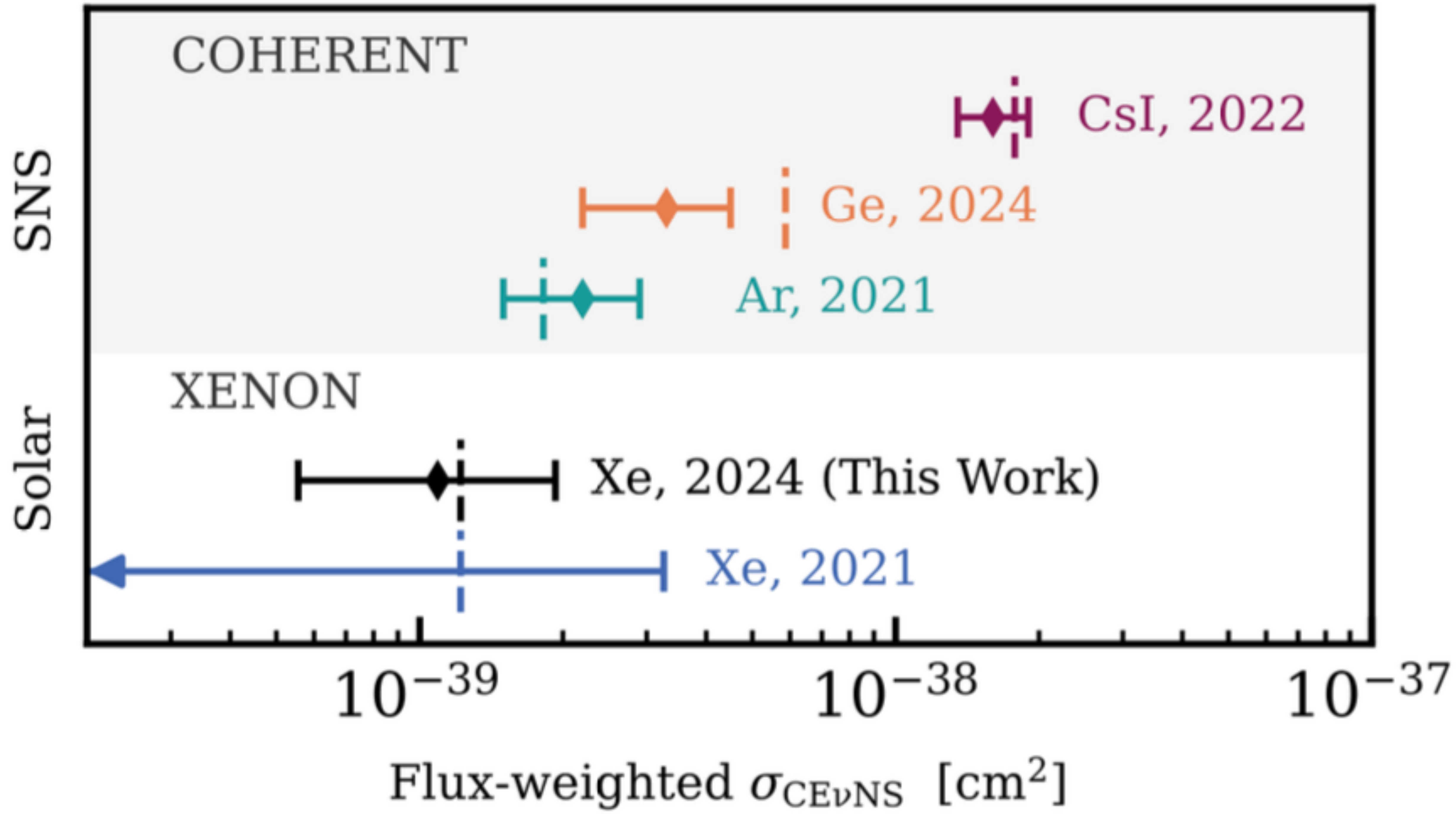
$10.7^{+3.7}_{-4.2}$

$26.3^{+1.4}_{-1.4}$

- Null signal was excluded by **2.73 σ**

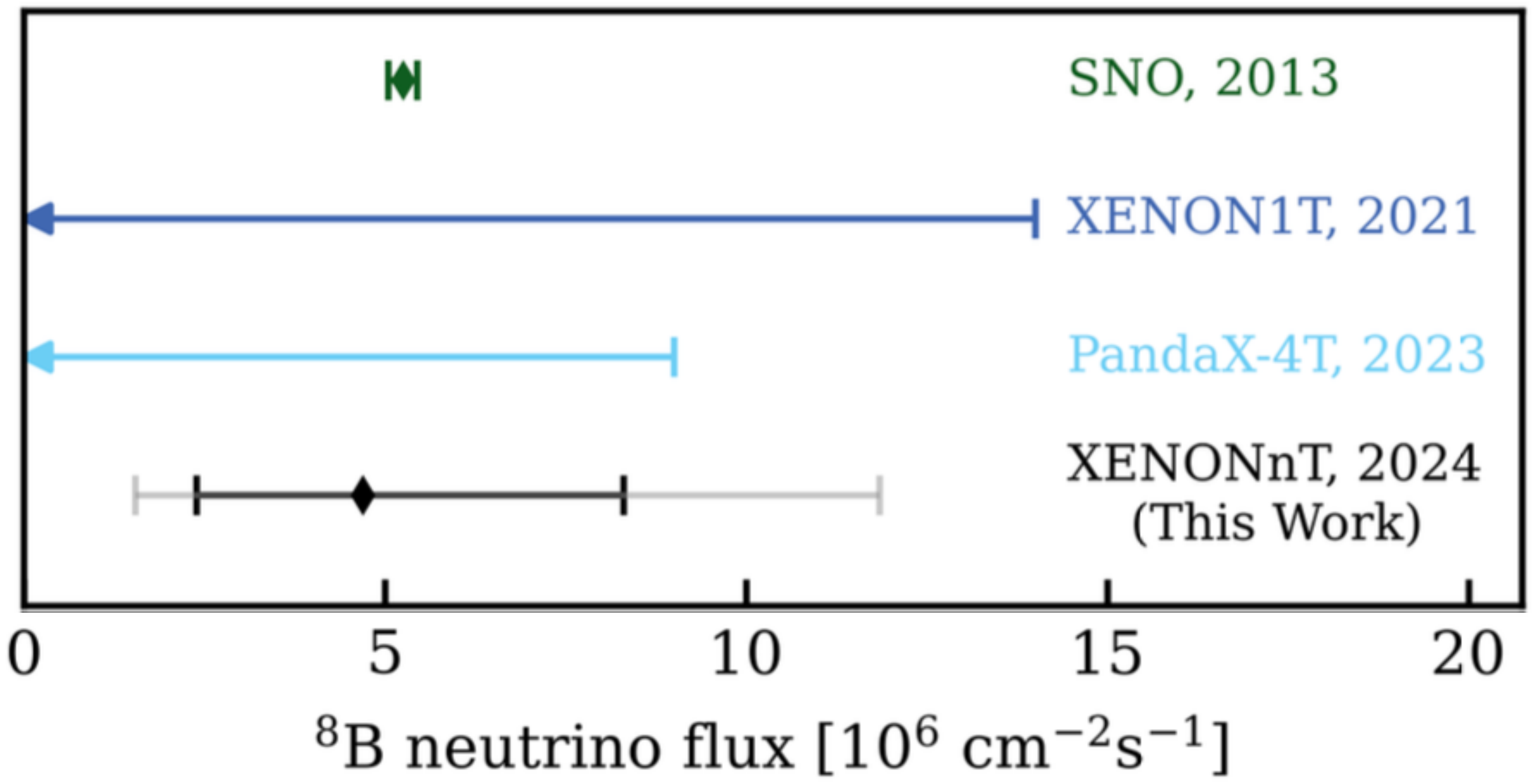
PRL, 133 191002

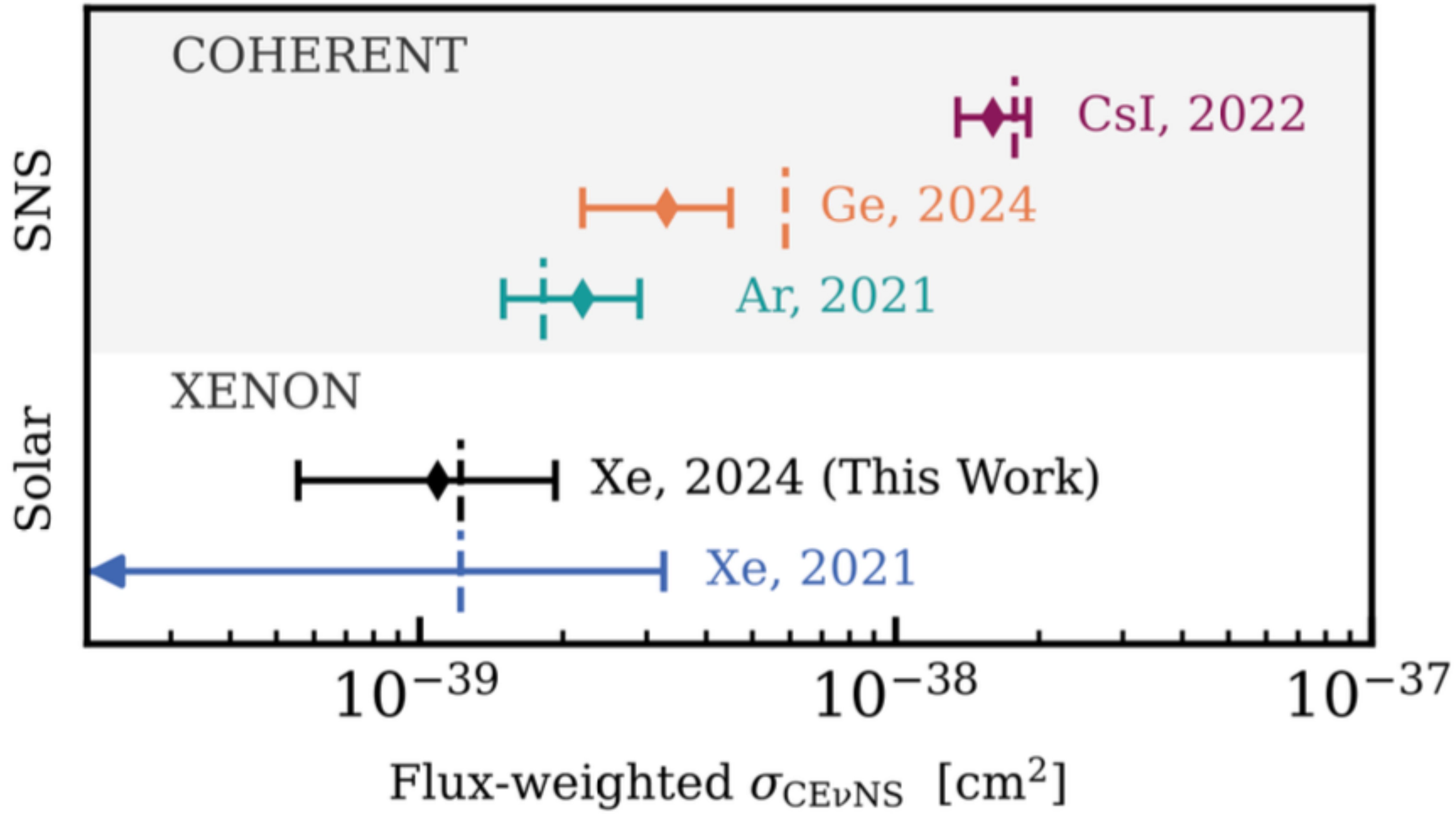




^{8}B neutrino measurement via CEvNS

- Observed cross section is consistent with standard model
- Reported on PRL, 133 191002 (2024)



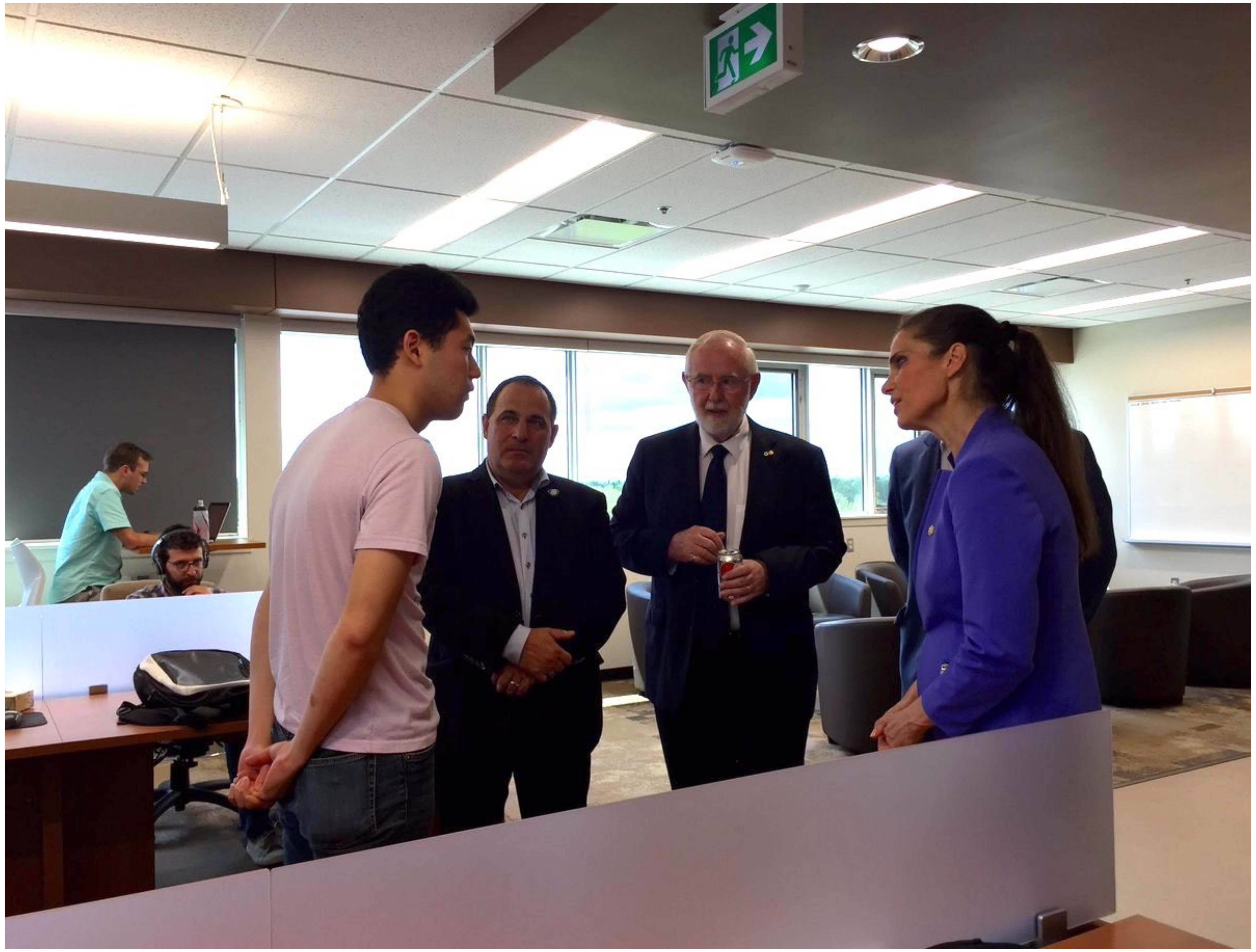


Summary

- **XENONnT**: Astroparticle rare event search experiment in LNGS
  - DM, neutrino physics and other particle physics
- **Neutrino search in XENON**
  - **MeV-scale (^{8}B)**: nuclear recoil… published in 2024
    - Observed CEvNS signal by 2.7 σ
  - **keV-scale (pp, ^{7}Be)**: electronic recoil
    - Reduction of the uncertainty for Rn BG; down to ~5% by calibration
    - Approaching to the final phase of analysis … **Stay tuned!**

Thank you for your attention!

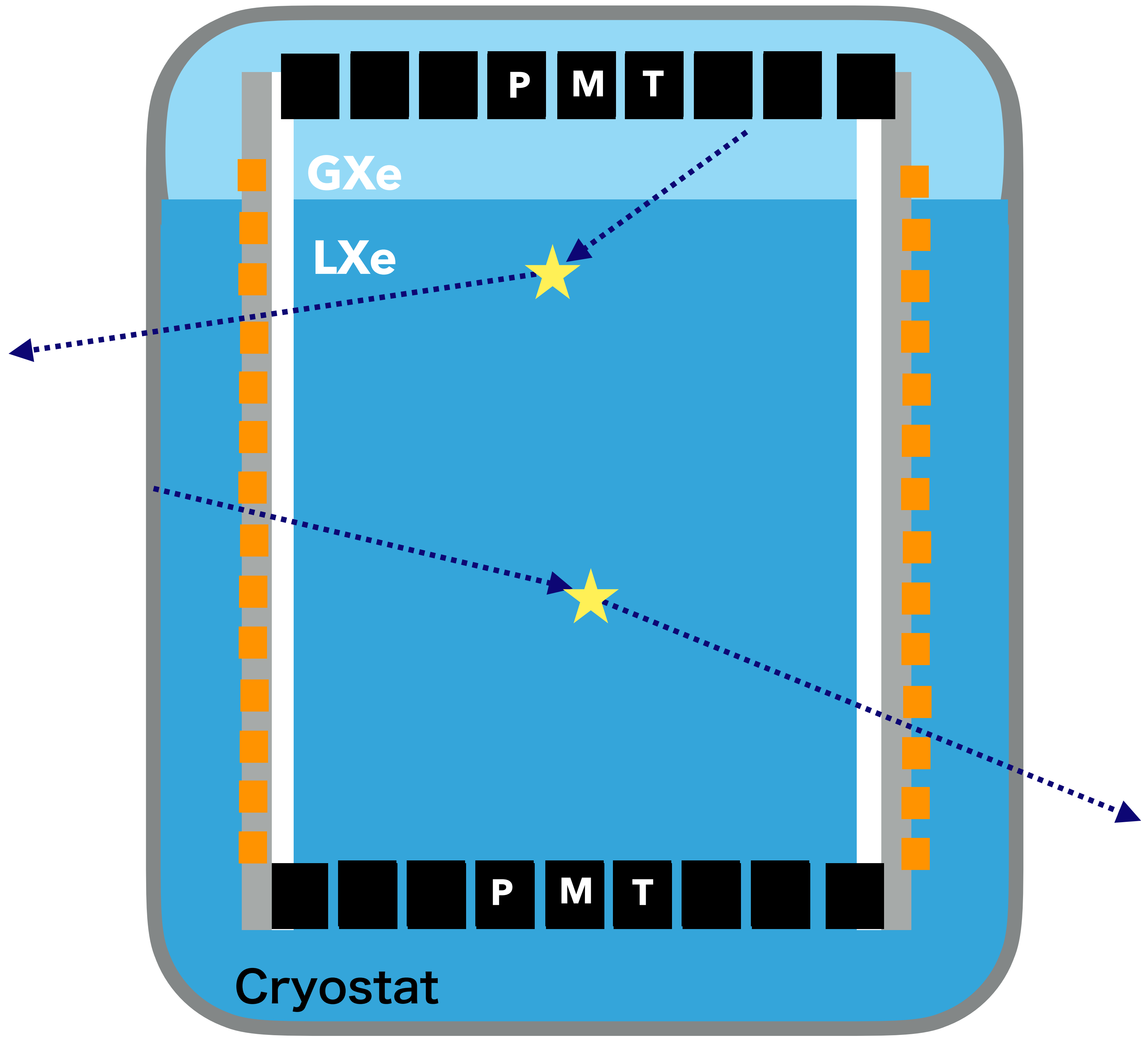
- 9-years ago, as visiting student with Honda-Canada fellowship…



Back Up

Other backgrounds: Material Gamma

- γs from detector material
  - Low-E Compton scattering events induced by γs from U, Th in detector components
  - Reduction by FV cut, and then estimate using simulation



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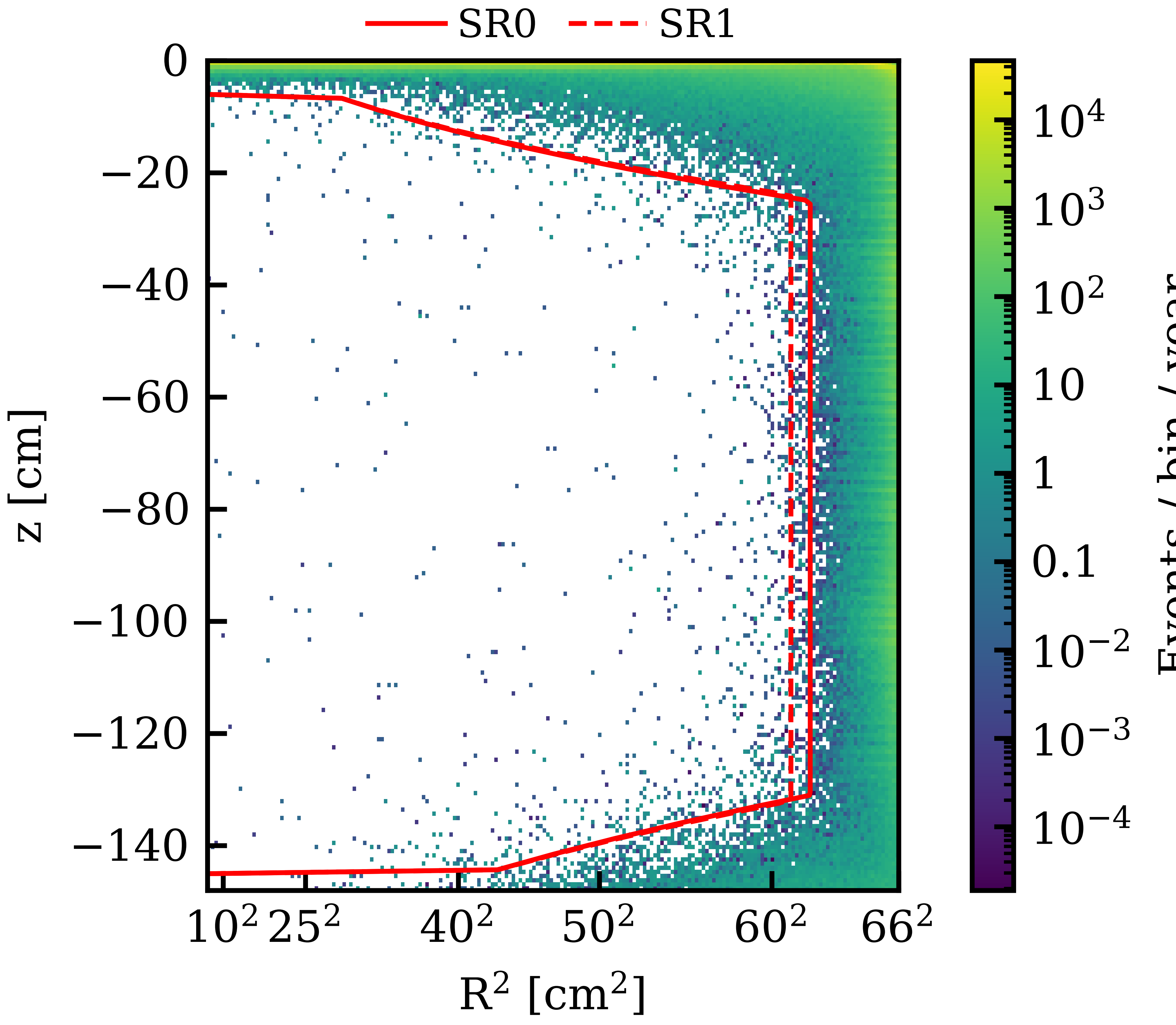

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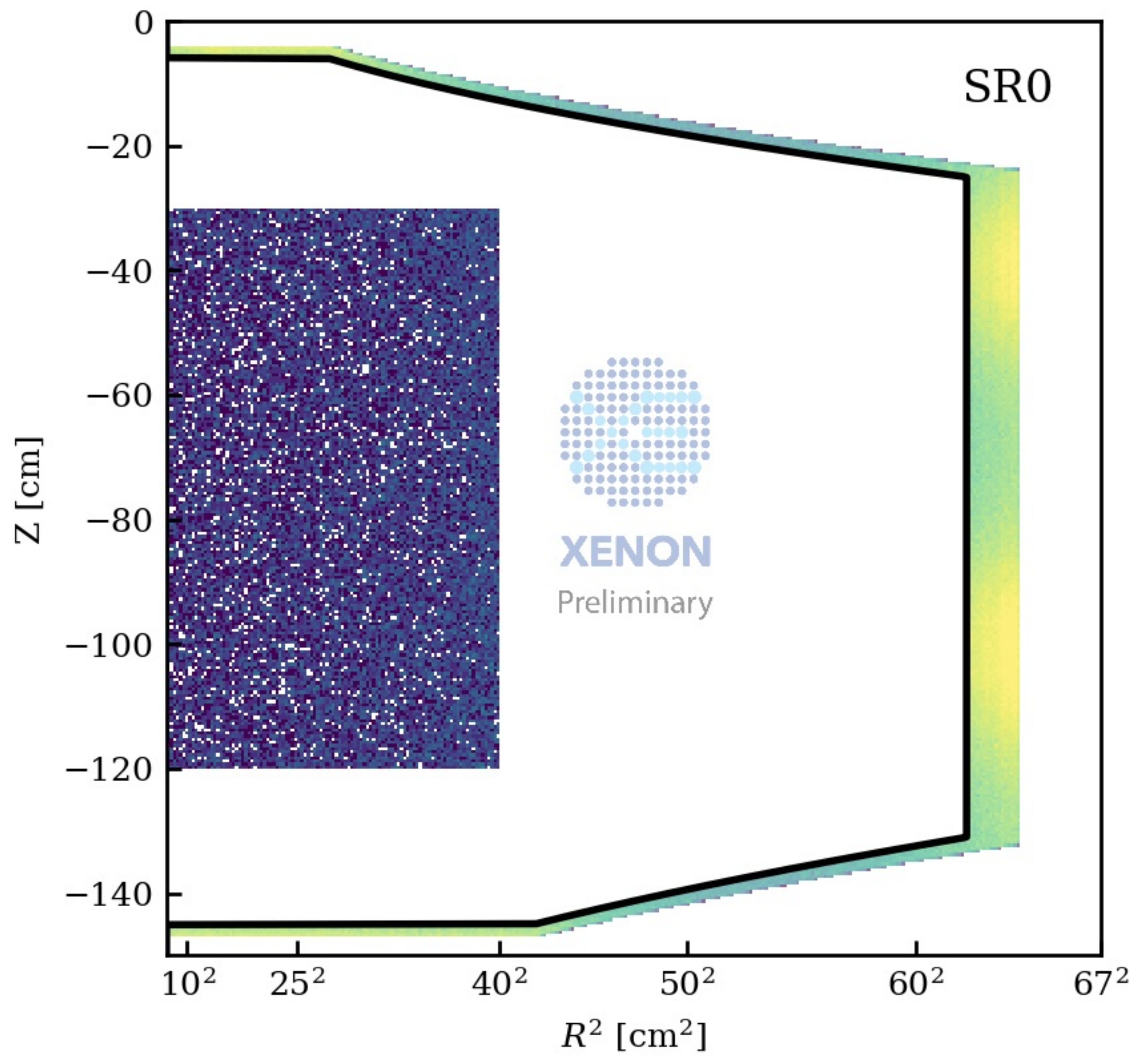
  - Subtract the uniform events using central volume
  - Data/MC = 1.49 (1.05) in SR0 (SR1)
    - MC the MC by the ratio, and take the difference as sys. uncertainty



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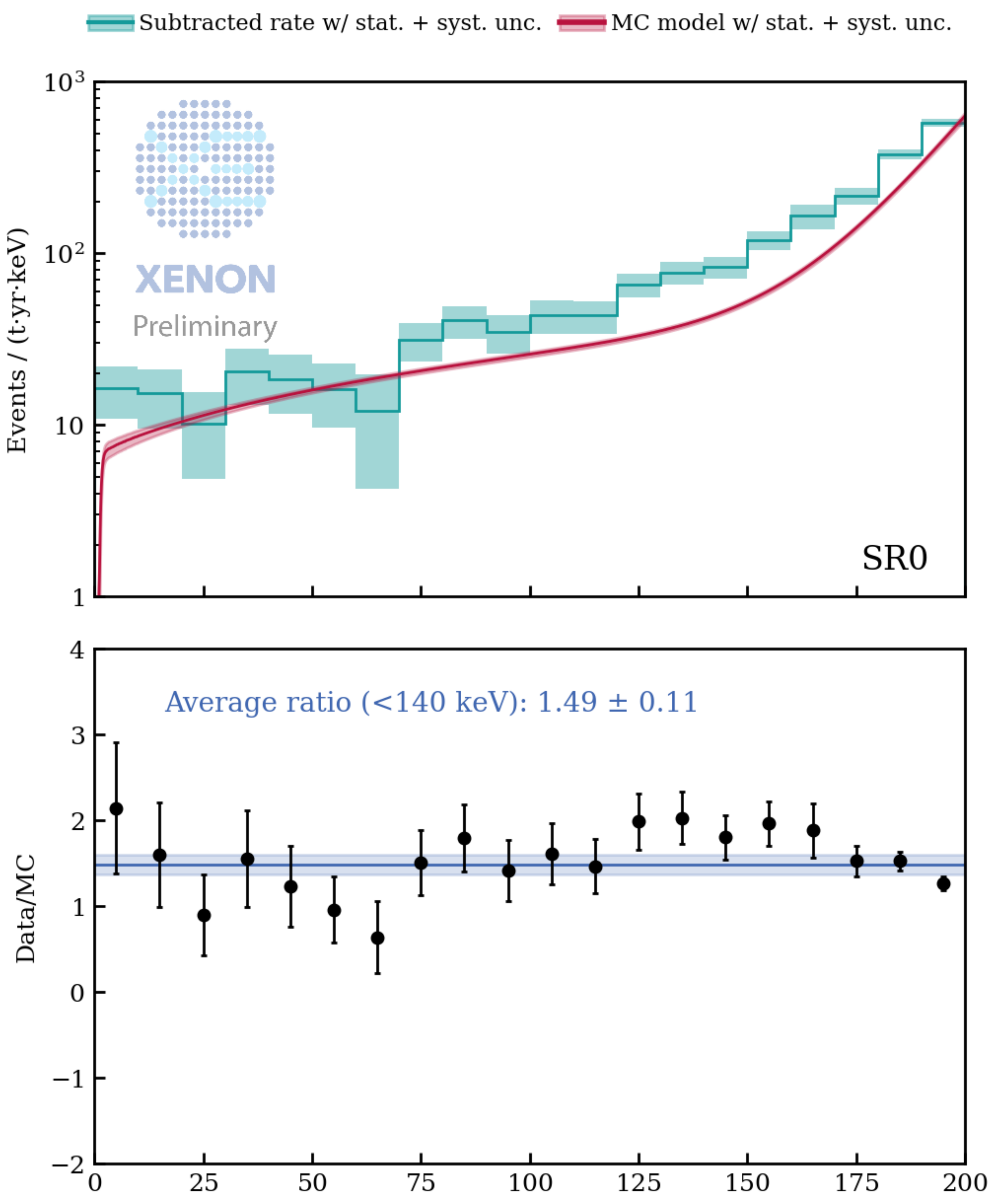
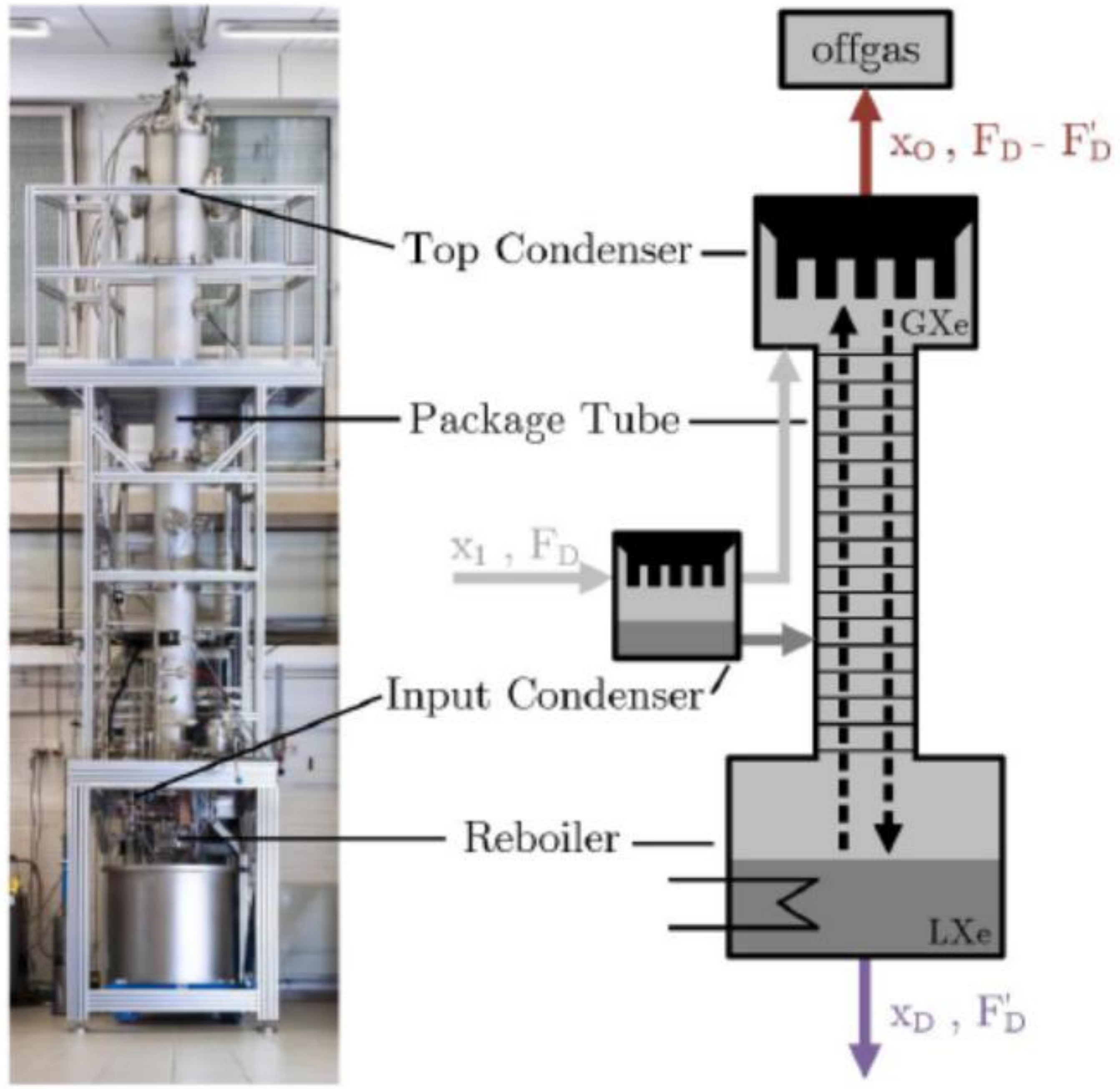


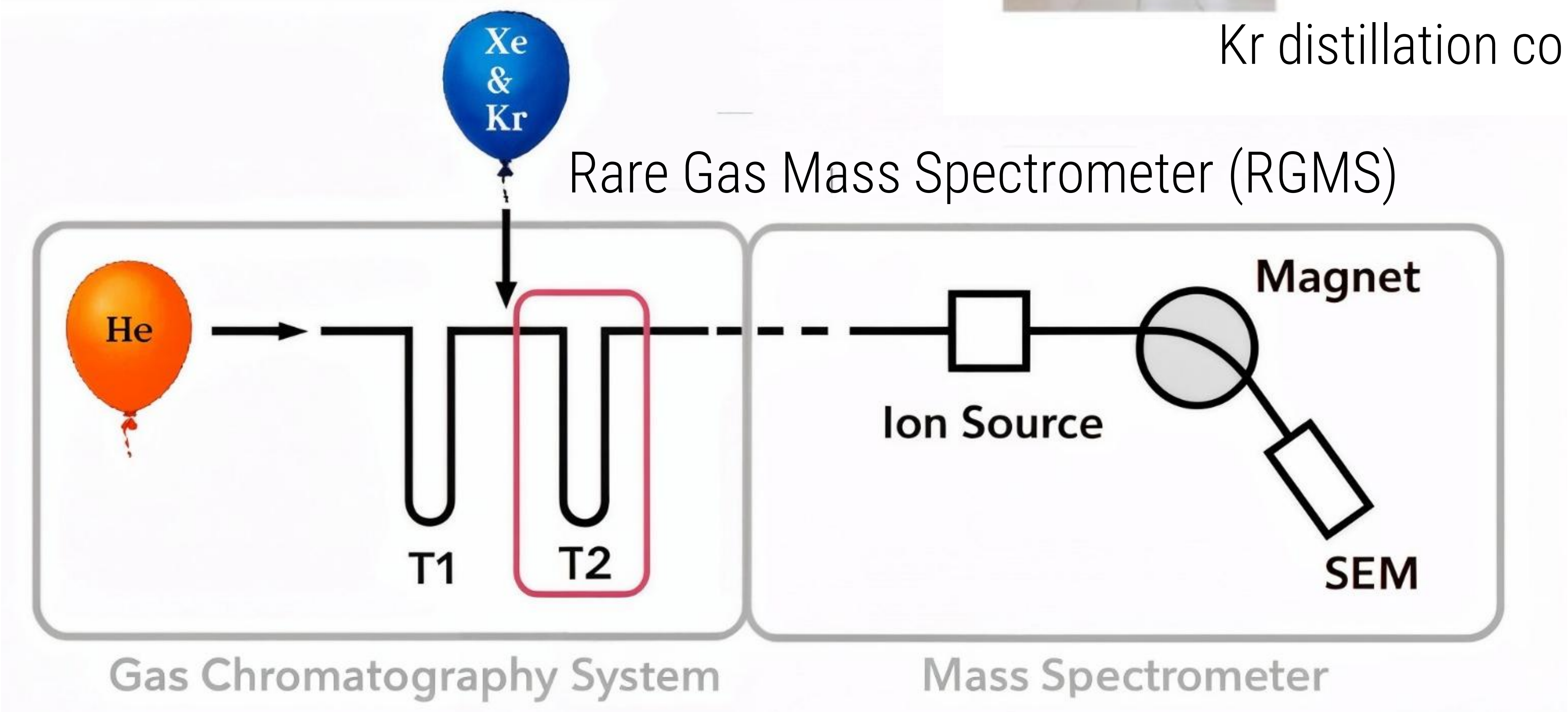
Other backgrounds: Kripton-85

- **Kr : β decay (Q=687keV) by ^{85}Kr**
  - Remove Kr by distillation: <0.1ppt
    - Take gas sample and analysis with mass spectrum



Kr distillation column

  - Also, analytical estimation using rare decay mode of ^{85}Kr
    - Current UL: 0.25ppq @90%CL
    - Limited due to the double-peak selection efficiency
    - Can be improve by ML?



Rare Gas Mass Spectrometer (RGMS)

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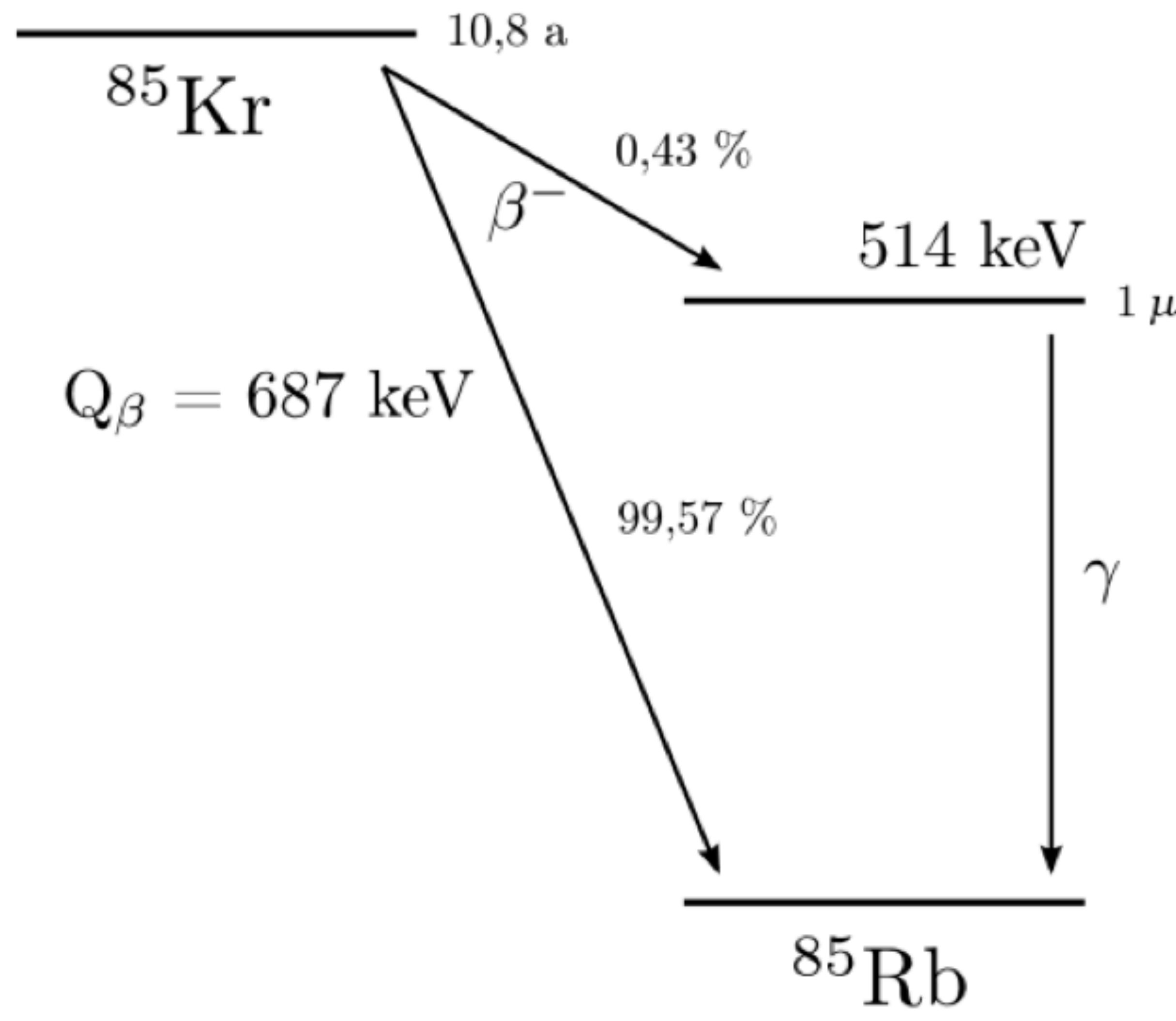
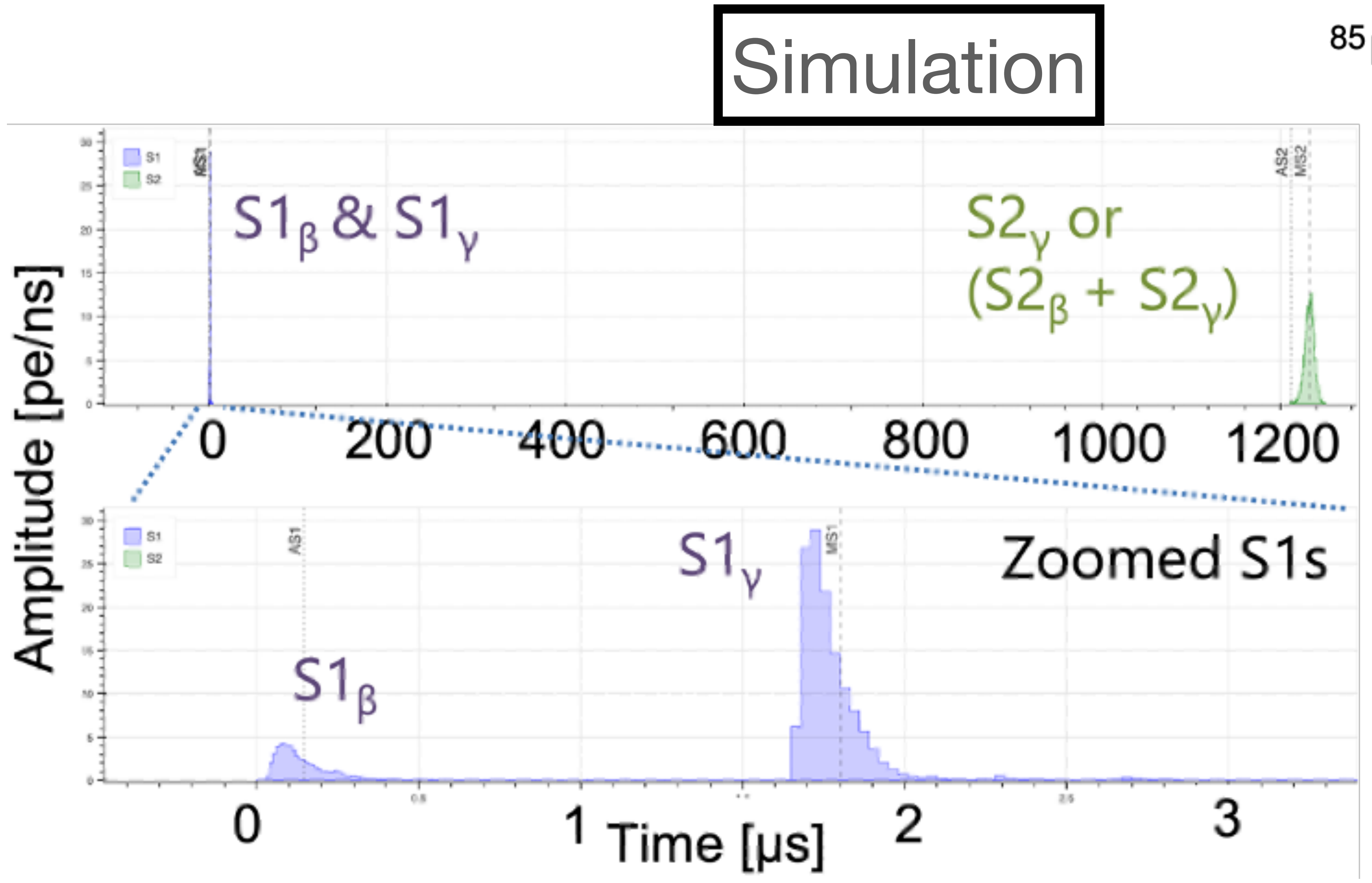
    - Take gas sample and analysis with mass spectrum



^{85}Kr decay scheme

  - Also, analytical estimation using rare decay mode of ^{85}Kr
    - Current UL: 0.25ppq @90%CL
    - Limited due to the double-peak selection efficiency
    - Can be improve by ML?



Result for CEvNS

Component	Expectation	Best-fit
AC (SR0)	7.5 ± 0.7	7.4 ± 0.7
AC (SR1)	17.8 ± 1.0	17.9 ± 1.0
ER	0.7 ± 0.7	$0.5^{+0.7}_{-0.6}$
Neutron	$0.5^{+0.2}_{-0.3}$	0.5 ± 0.3
Total background	$26.4^{+1.4}_{-1.3}$	26.3 ± 1.4
^{8}B	$11.9^{+4.5}_{-4.2}$	$10.7^{+3.7}_{-4.2}$
Observed	37	

- Signal expectation: $11.9^{+4.5}_{-4.2}$
- BG expectation: $26.4^{+1.4}_{-1.3}$

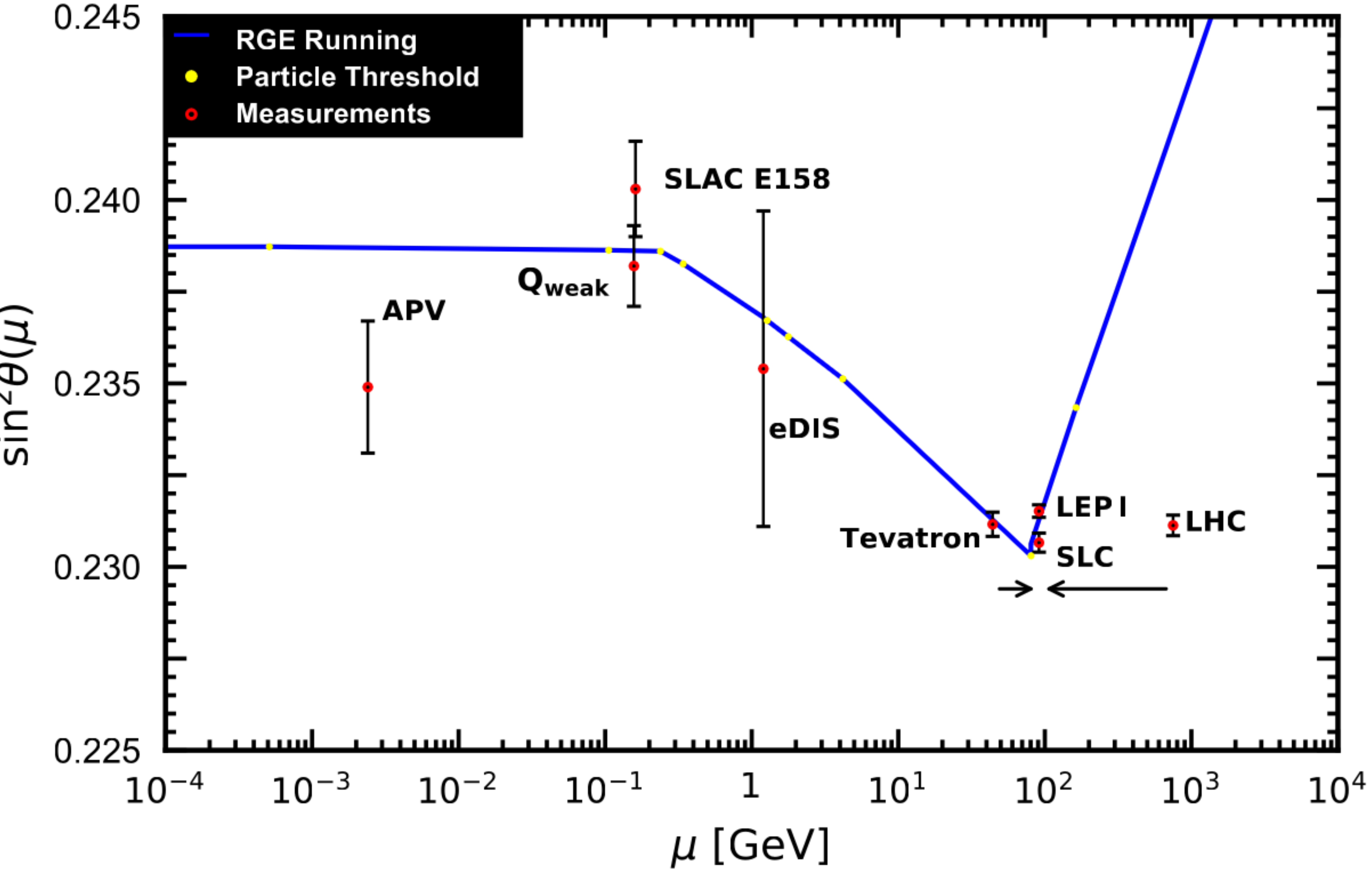
Observed →

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

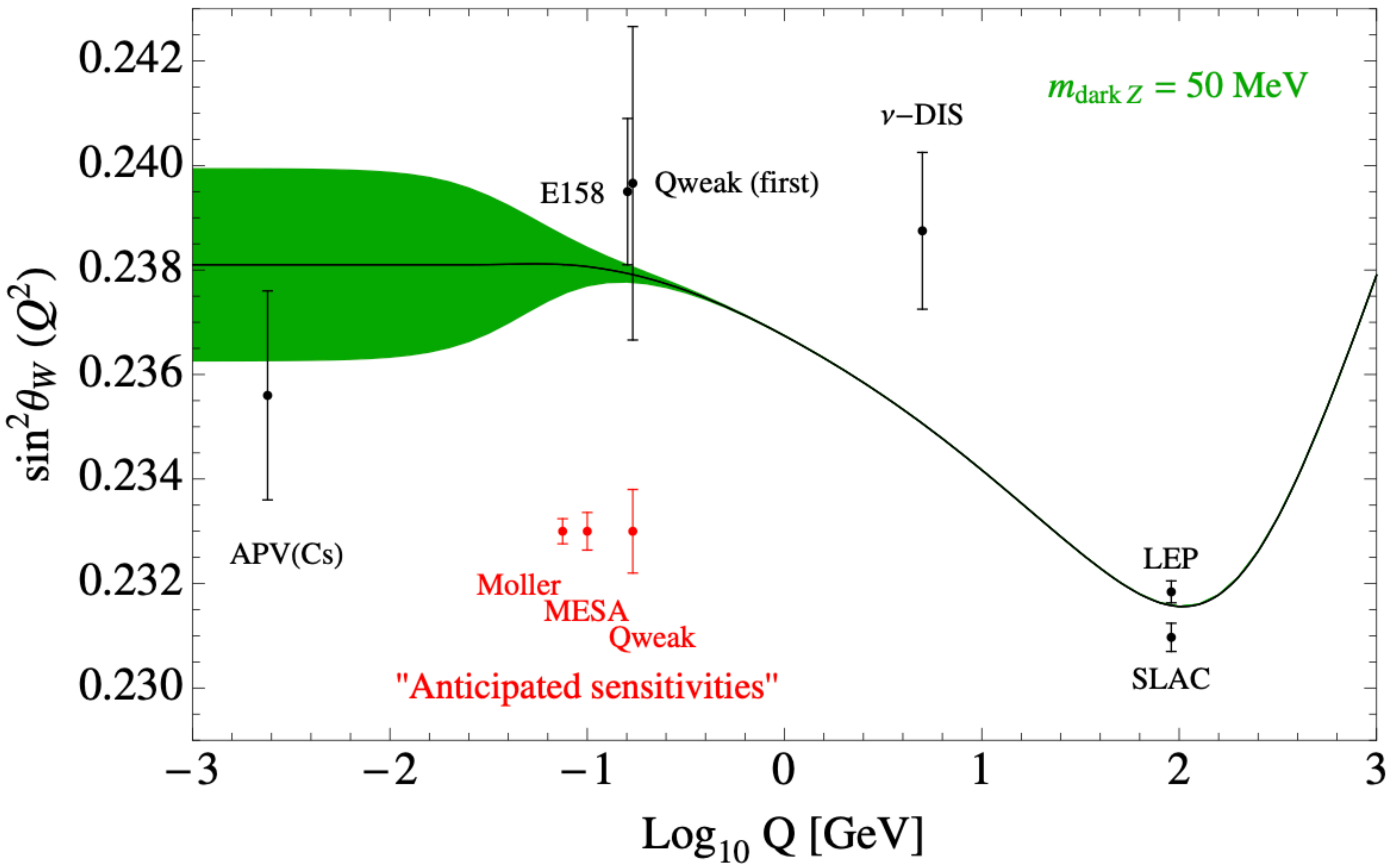
$26.3^{+1.4}_{-1.4}$

Weinberg angle

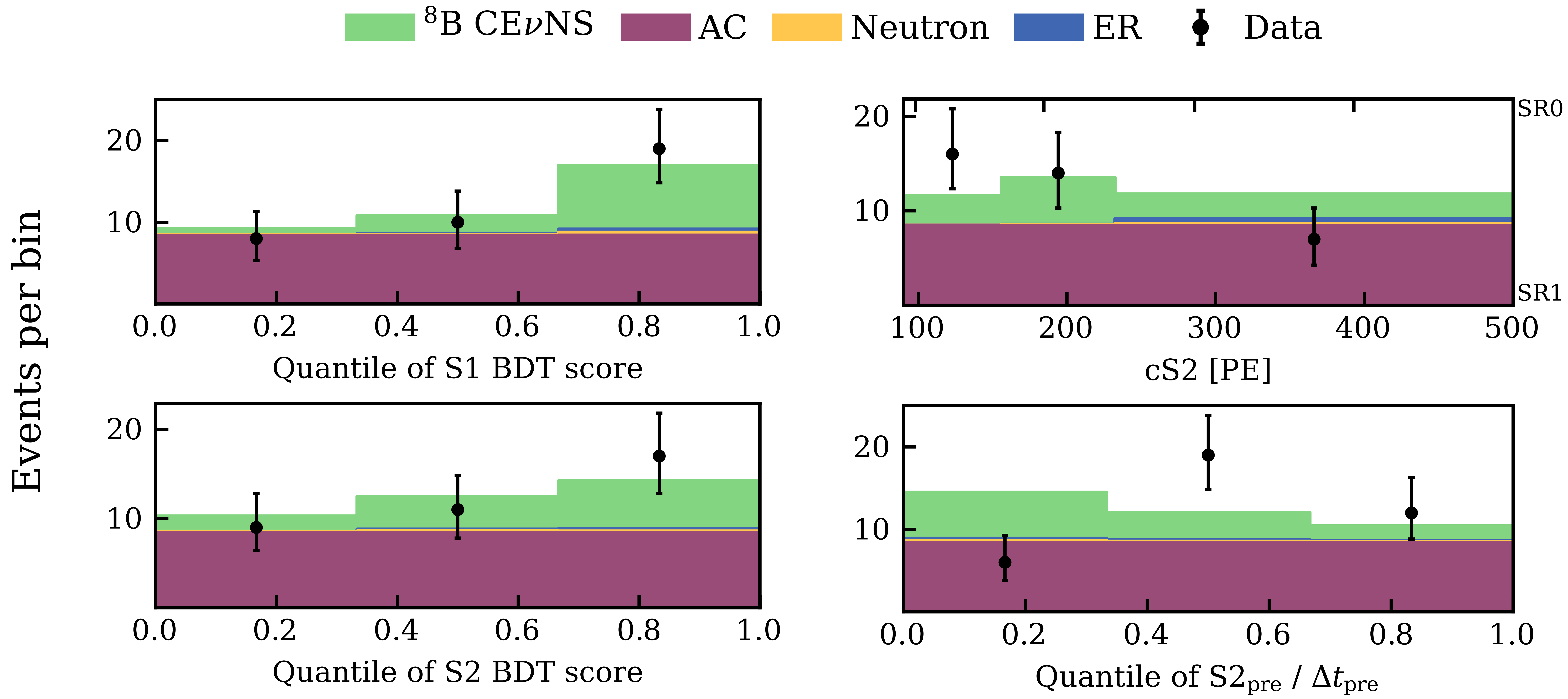
From PDG



PRD 89, 095006 (2014), 1402.3620

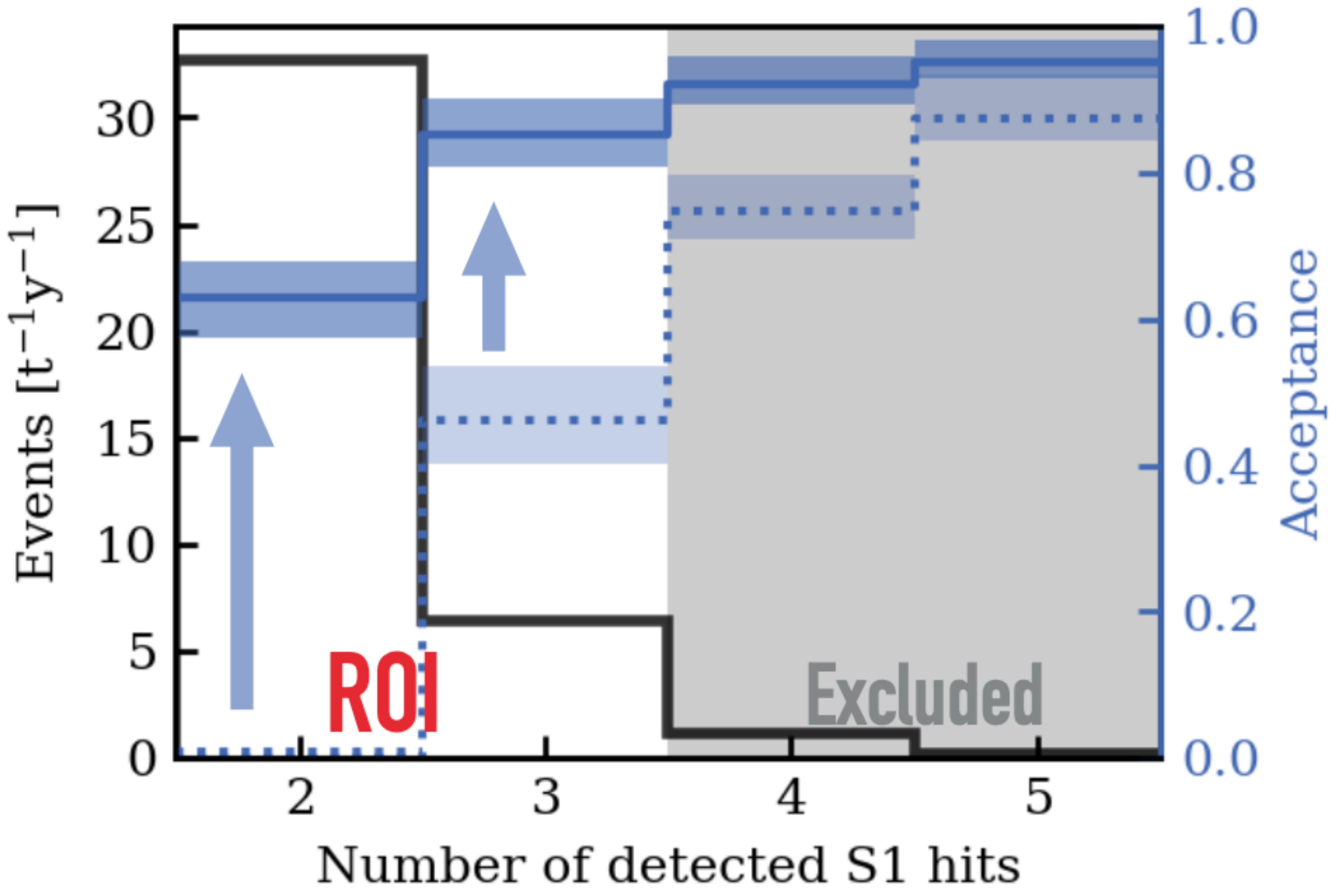


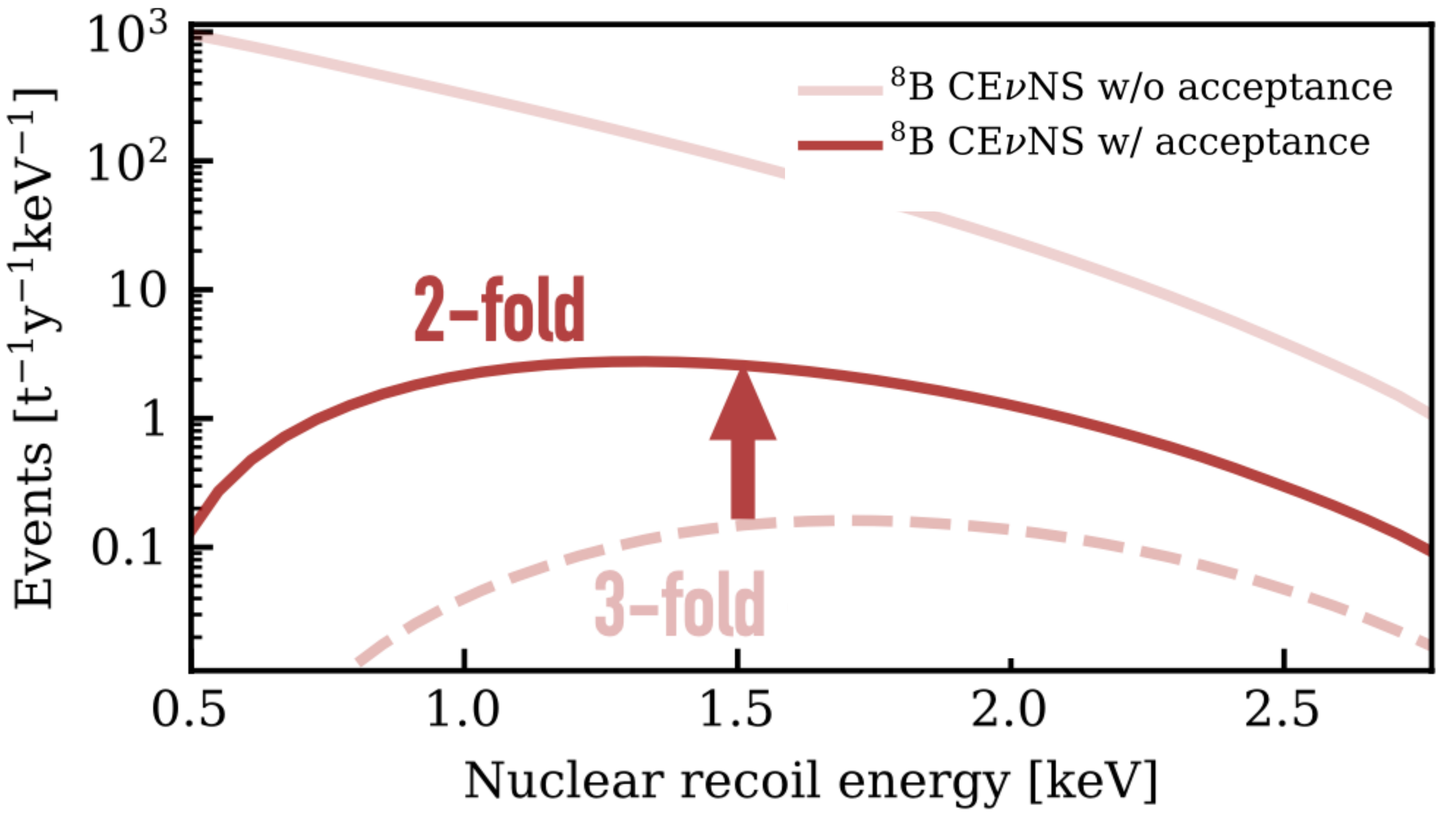
Likelihood for CEvNS / Low mass WIMPs Search



Low threshold analysis

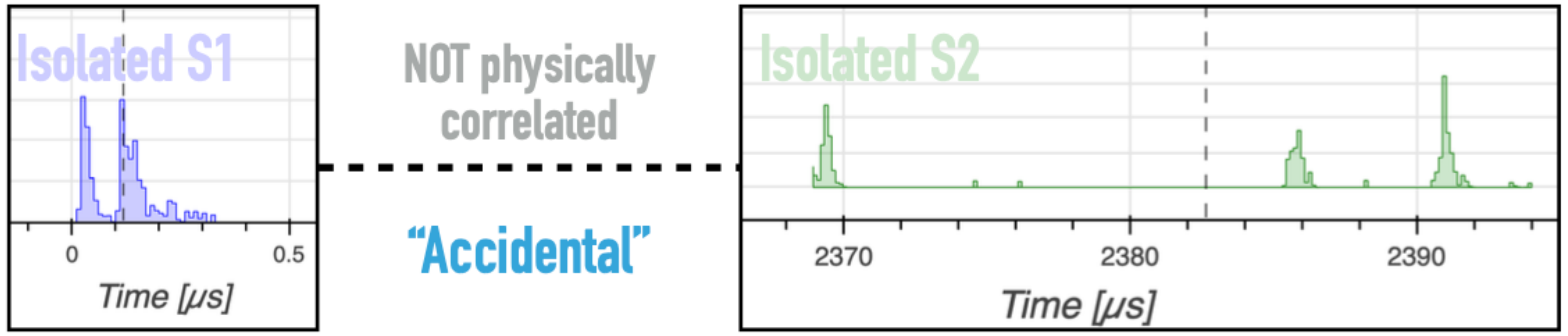
- Due to the small energy deposit from ^8B ν, it is critical to lower the energy threshold
  - The threshold is mainly defined by S1
- Improvement of the acceptance by lowering the threshold by 3 PMT hits -> 2 PMT hits
  - # of signal -> increased by ~17 times!
  - However: BG rate increases as well
    - BG suppression via dedicated cuts (including machine learning)

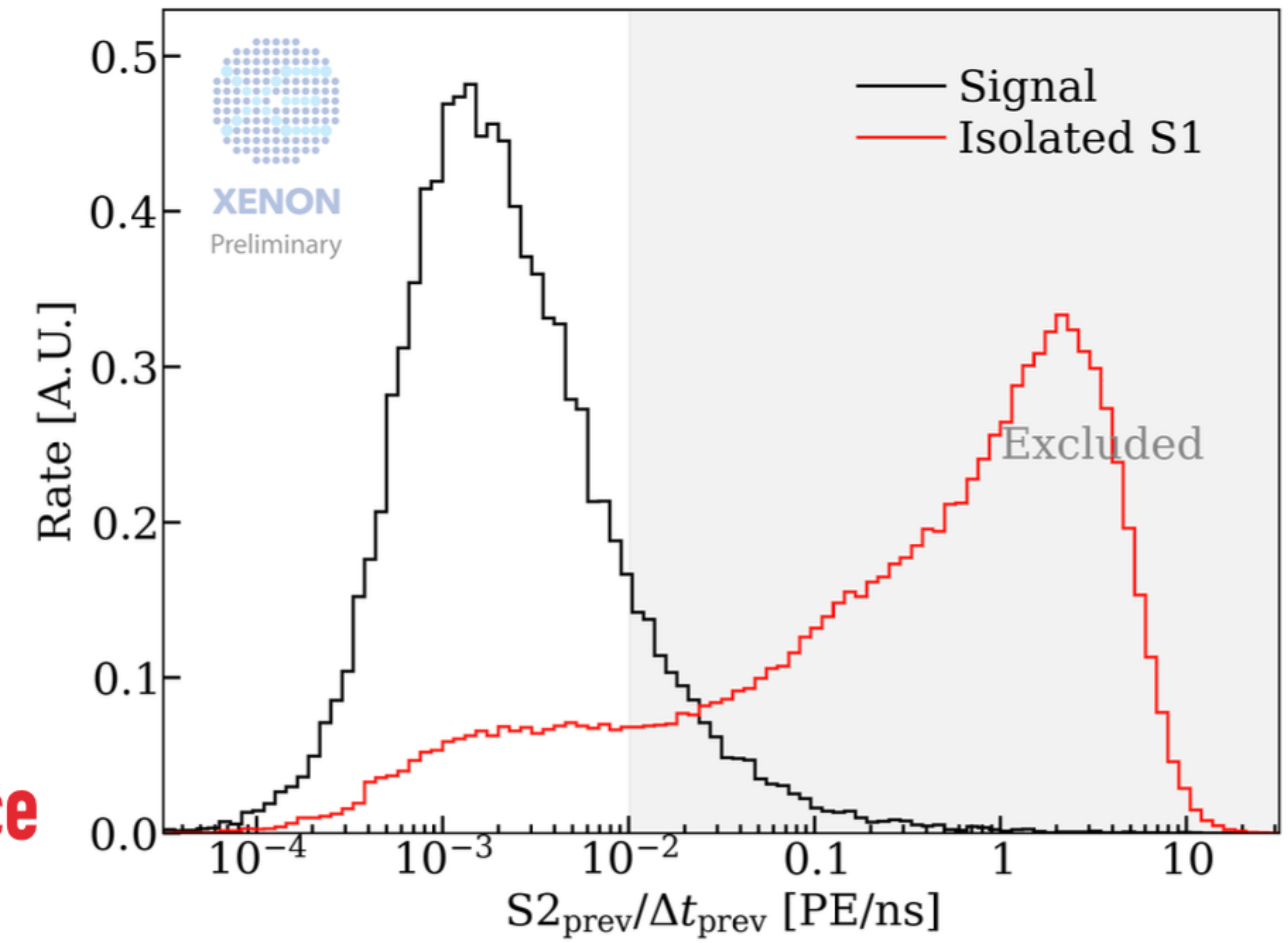




S2 shadow

- **Accidental Coincidence (AC)**: Random unphysical pairing of isolated S1 and isolated S2
  - Isolated peaks are believed to be side products of high energy (HE) interactions
  - Exact physical mechanisms of isolated peaks are under investigation
  - Isolated-S1 Rate before mitigation: 15 Hz
  - Isolated-S2 Rate before mitigation: 150 mHz
- **Mitigated** by utilizing selections based on space&time correlation to previous HE interactions
  - Isolated-S1 rate after mitigation: 2.3 Hz
  - Isolated-S2 rate after mitigation: 25 mHz





eg. TimeShadow selection on Isolated S1s

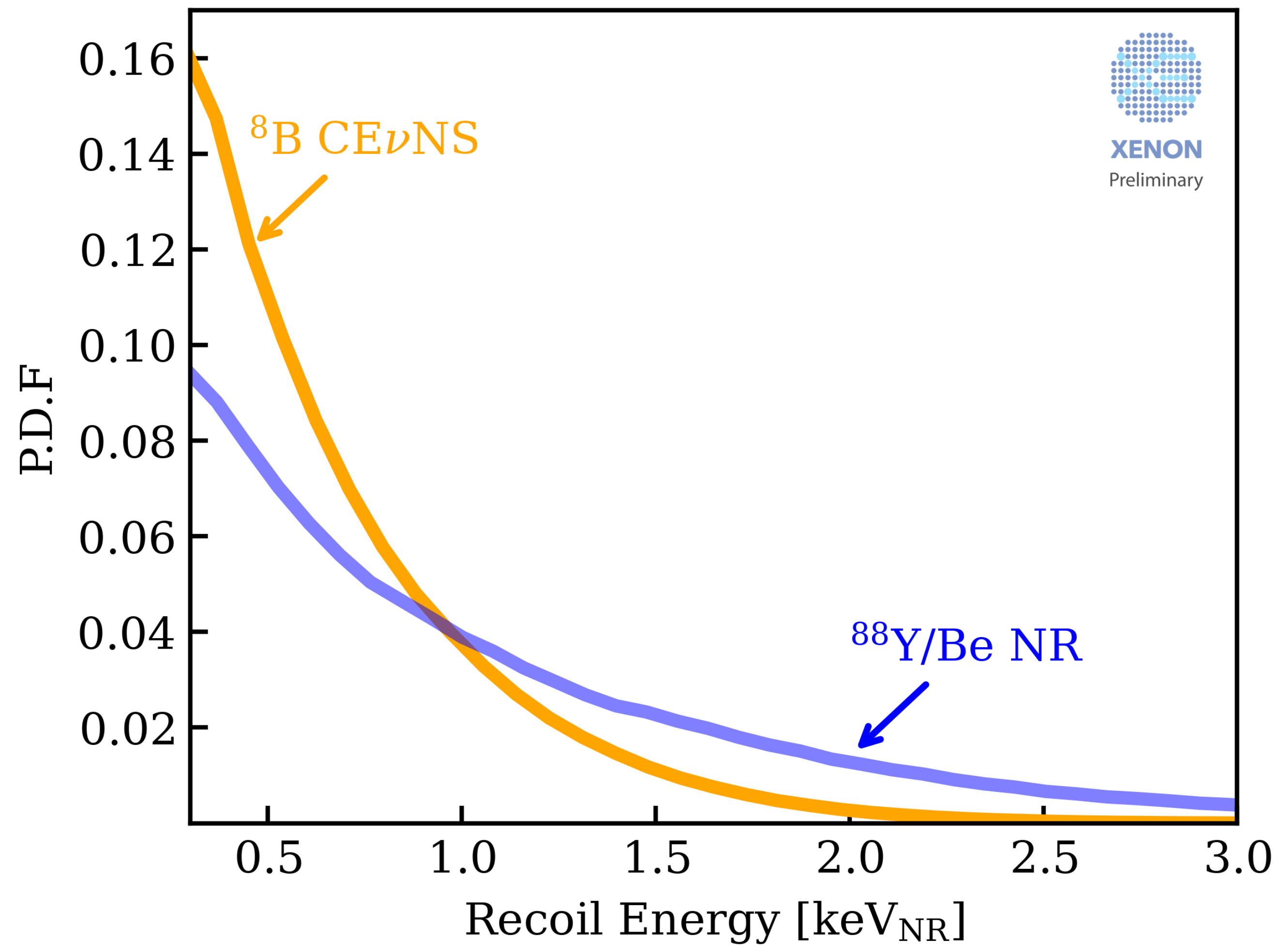
TimeShadow $\equiv \mathrm{Max}(S2_{pre}/\Delta t_{pre})$ used in inference

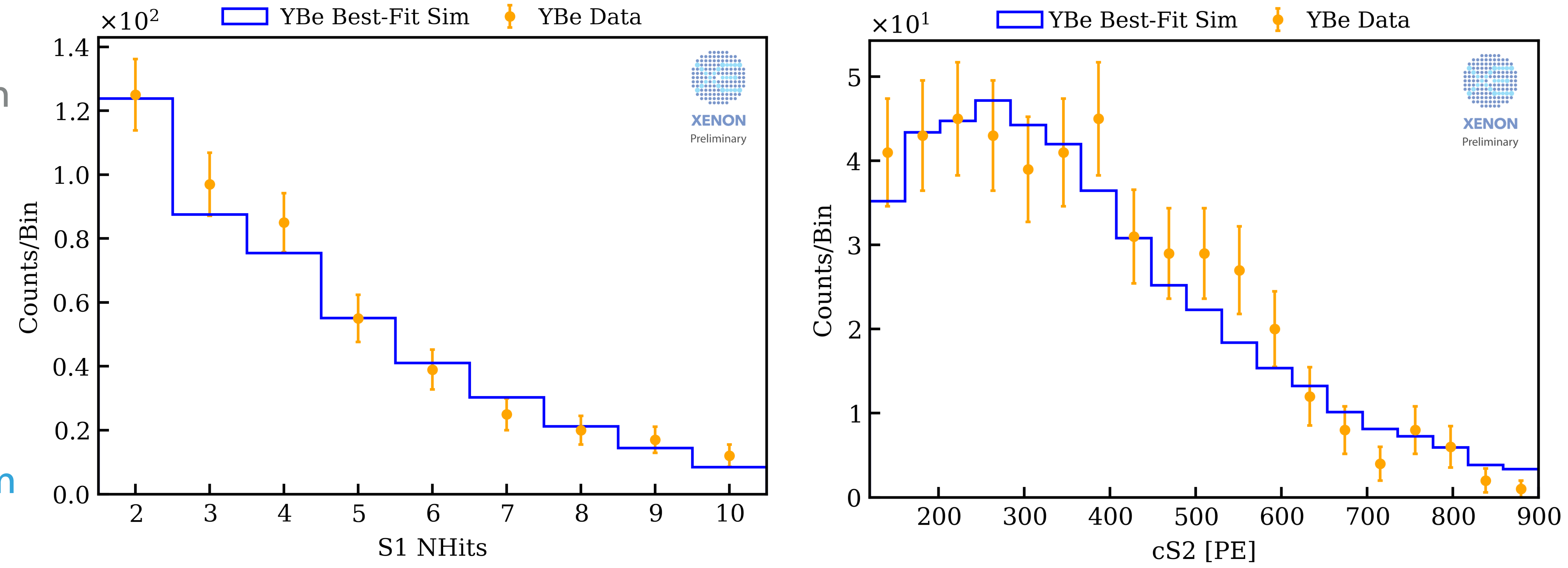
YBe

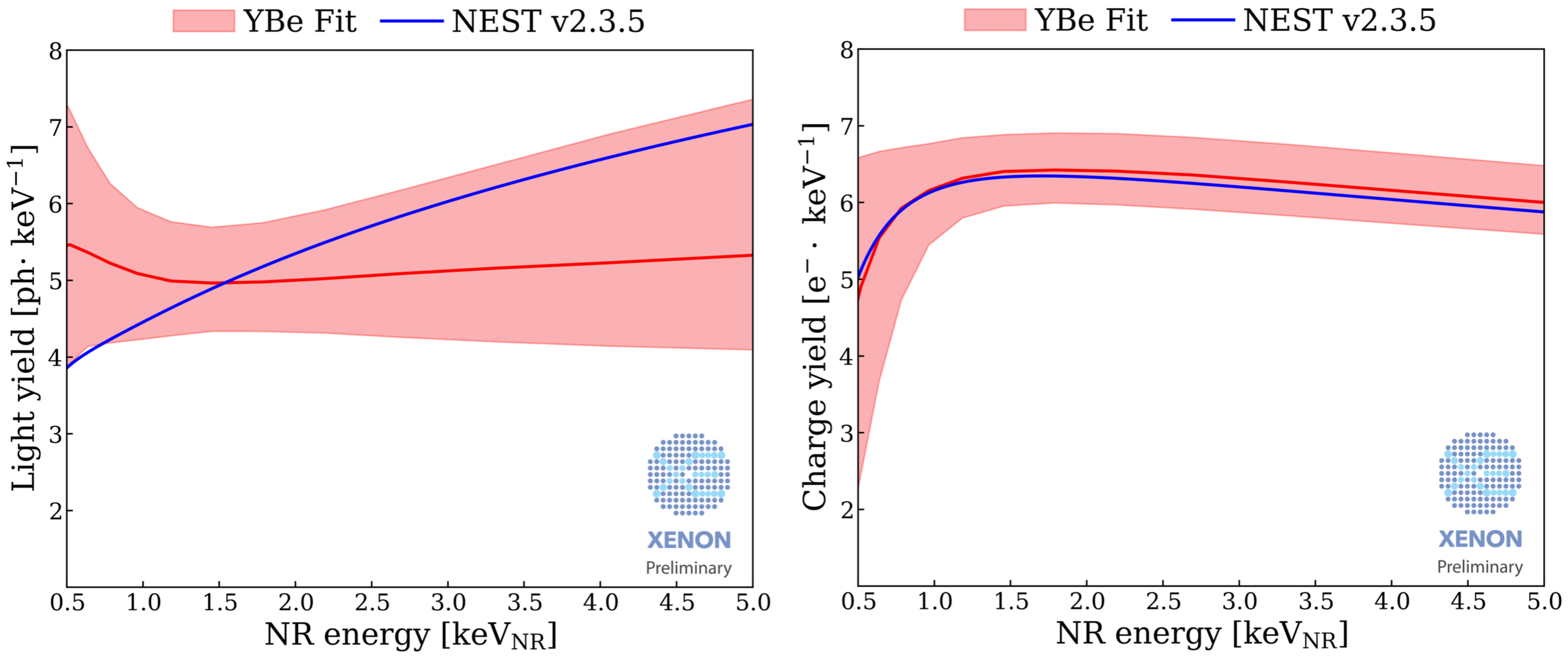
^{88}YBe LOW ENERGY NR CALIBRATION

Publication in preparation

- Low energy NR yield model significantly affects ^{8}B CEνNS detection efficiency
- 152 keV neutrons from photo-disintegration of ^{9}Be by γ-ray of ^{88}Y
  - **Recoil energy spectrum similar to ^{8}B CEνNS**
- Good match between simulation and data
- **Light/charge yield model** are constrained by ^{88}YBe data at 23V/cm
  - Yield model uncertainty leads to ~34% signal rate uncertainty







Validation of AC model with sideband data

- AC background model was validated using the sideband data — events excluded by the S2 score (AC-like events)
- Parameters：
  - S2 size
  - S2size/Δt of event right before
  - S1 ML score
  - S2 ML score

After the High-E events, there are more noisy events

- Difference between data and the model is taken into account as systematic uncertainty
  - 9.0% (SR0), 5.8%(SR1)