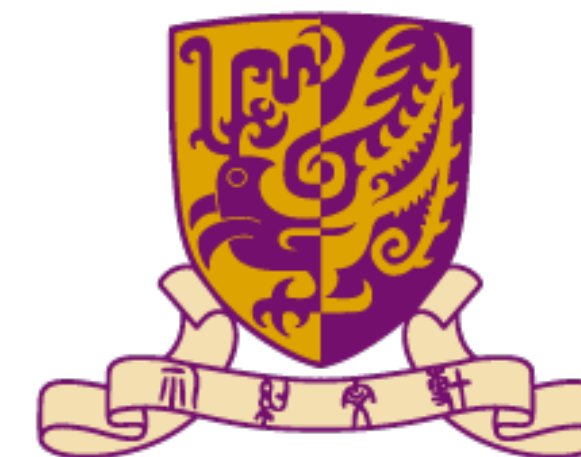




XENON



香港中文大學(深圳)

The Chinese University of Hong Kong, Shenzhen

First Measurement of Solar Neutrinos through Elastic Neutrino-Electron Scattering at the keV Scale

Jingqiang Ye (叶靖强)

yejingqiang@cuhk.edu.cn

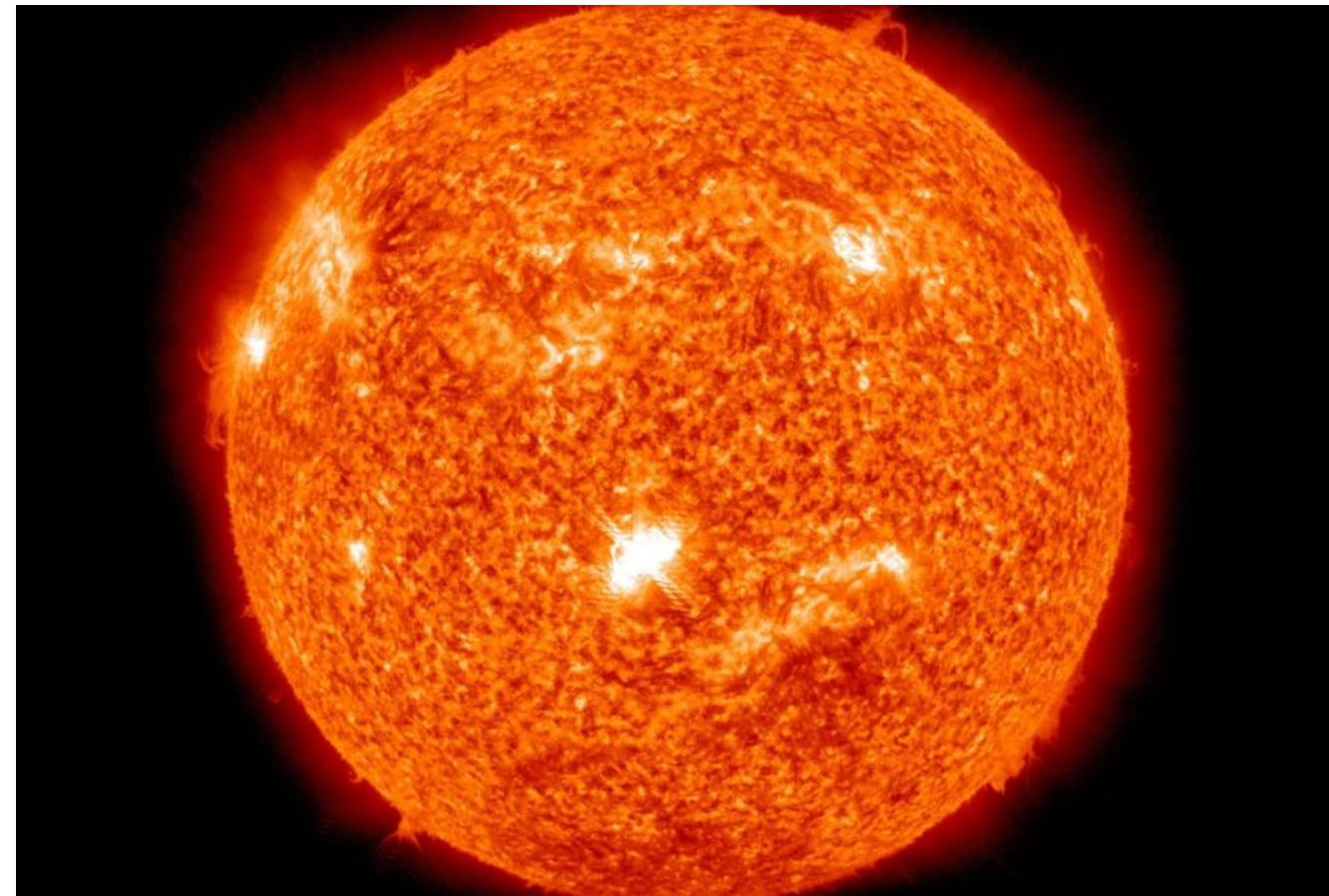
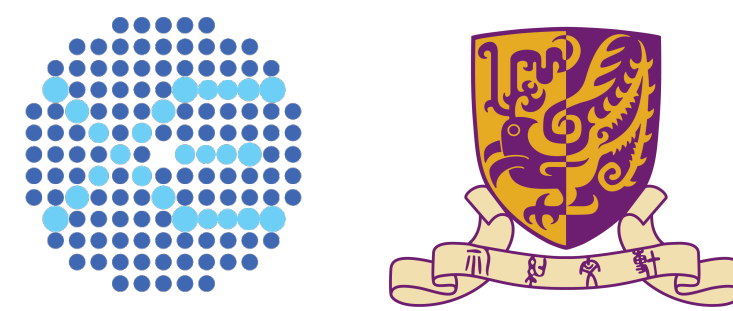
The Chinese University of Hong Kong, Shenzhen

On behalf of the XENON Collaboration

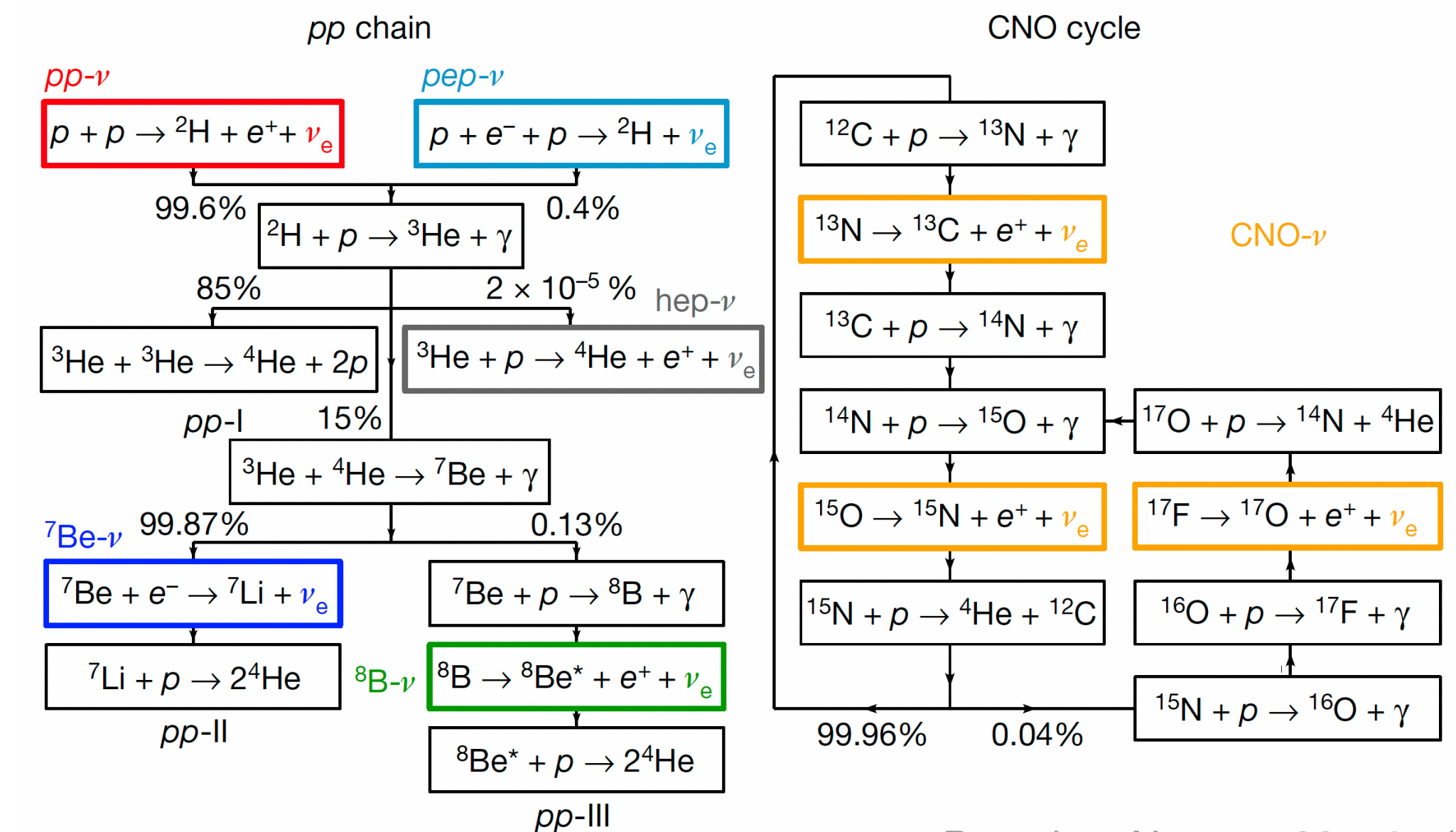
September 1st, 2026

PPC 2026@Sydney

Solar neutrino



Hans Bethe
(1906-2005)

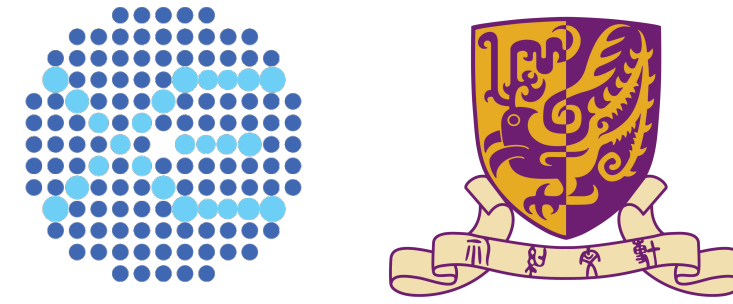


Nuclear fusion in the Sun

Borexino, Nature 562, 505 (2018)

- In 1930s, Hans Bethe pointed out that nuclear fusion powers stars, including the Sun.
- During this process, copious solar neutrinos are emitted.
 - pp: most abundant (~90%)
 - Be-7: second abundant (~10%)
 - B-8: relatively high flux and energy

Solar neutrino detection (incomplete list)

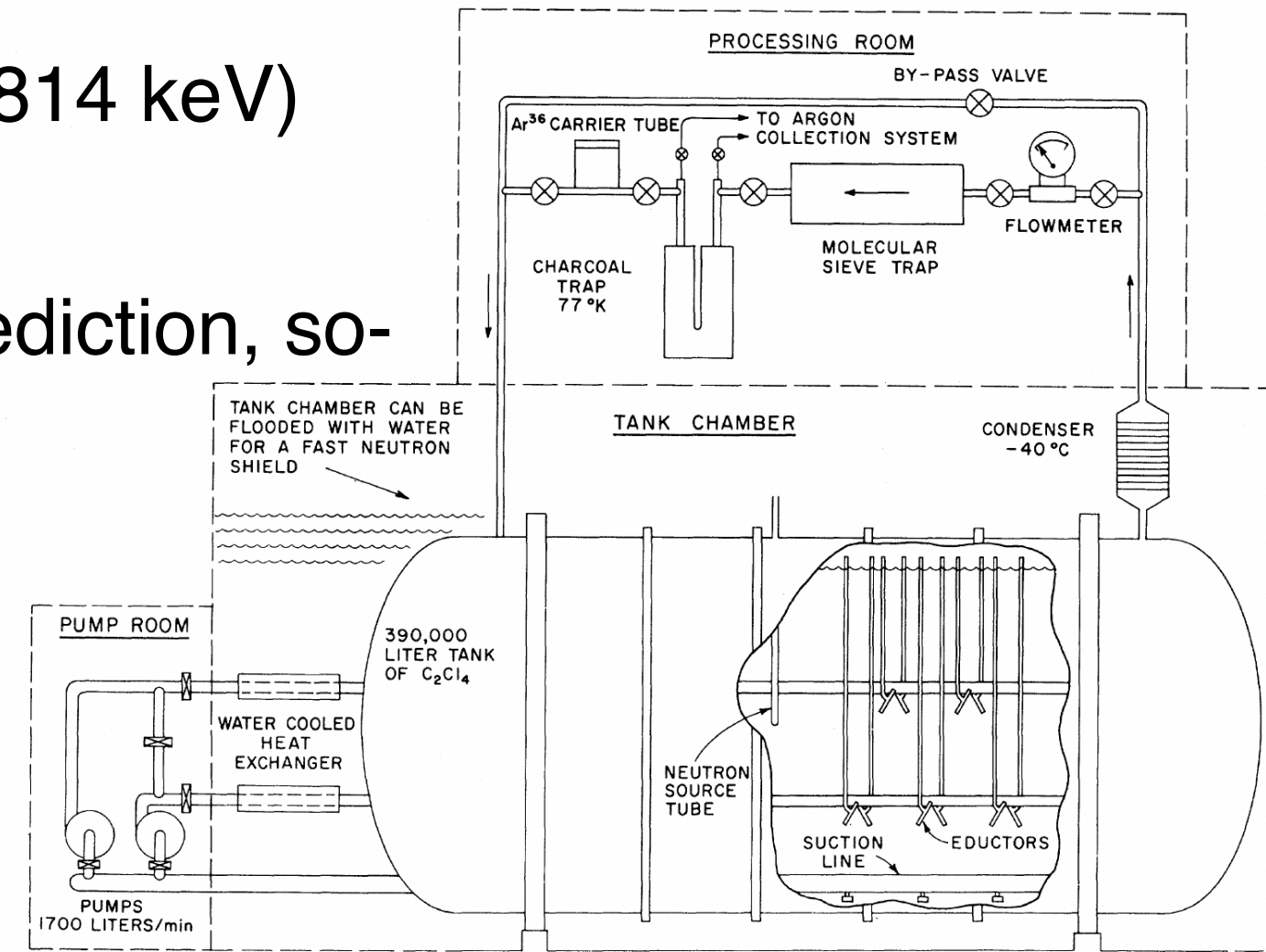


- 1960s-1990s: Homestake experiment
 - ▶ $^{37}\text{Cl} + \nu_e \rightarrow ^{37}\text{Ar} + e^-$ (threshold: 814 keV)
 - ▶ Only sensitive to ν_e
 - ▶ Observed neutrino is only $\sim 1/3$ of prediction, so-called “solar neutrino problem”

Prediction: 7.3 ± 2.3 SNU

Measurement: 2.32 ± 0.22 SNU

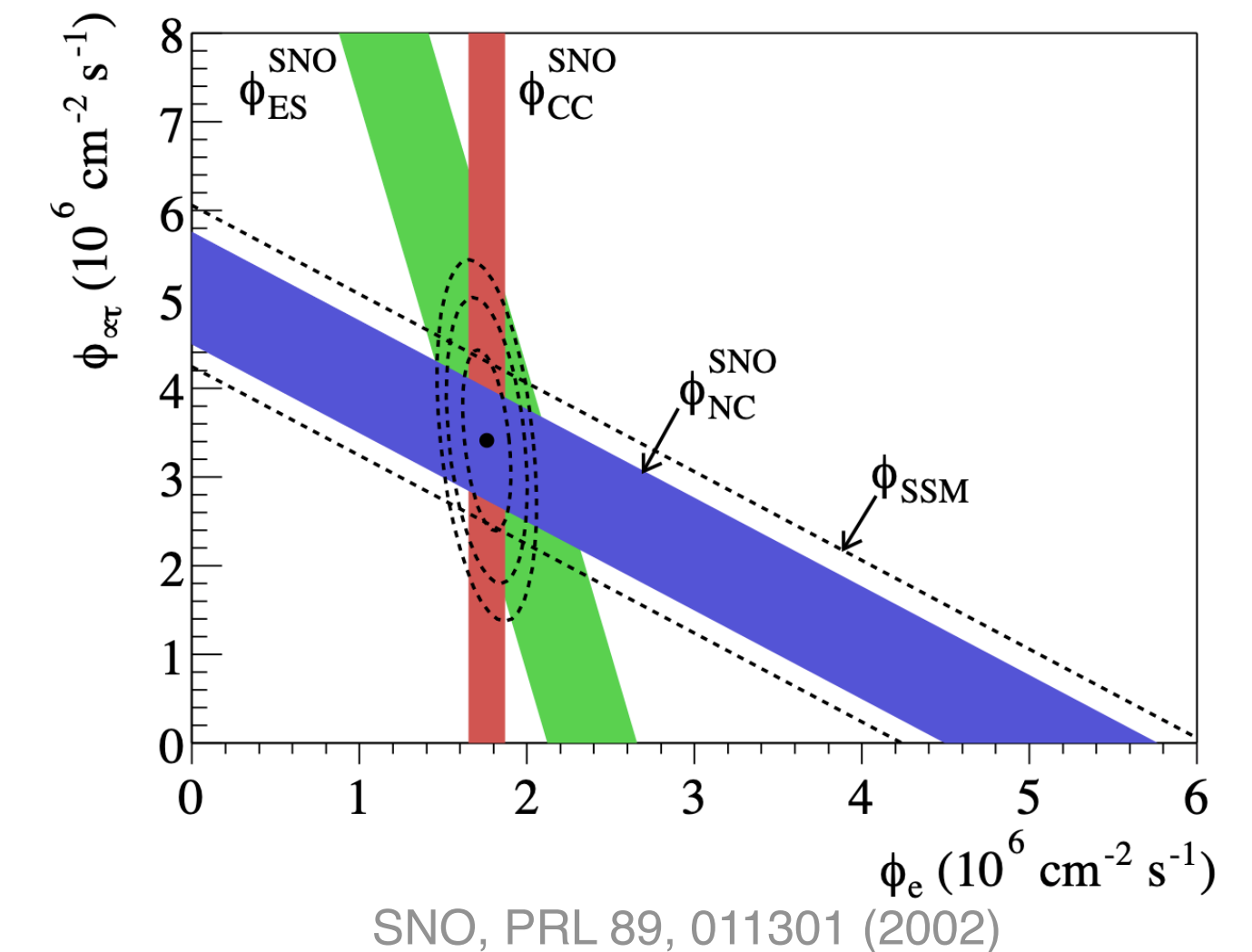
1 Solar Neutrino Unit (SNU) = 1 capture/s/ 10^{36} atoms



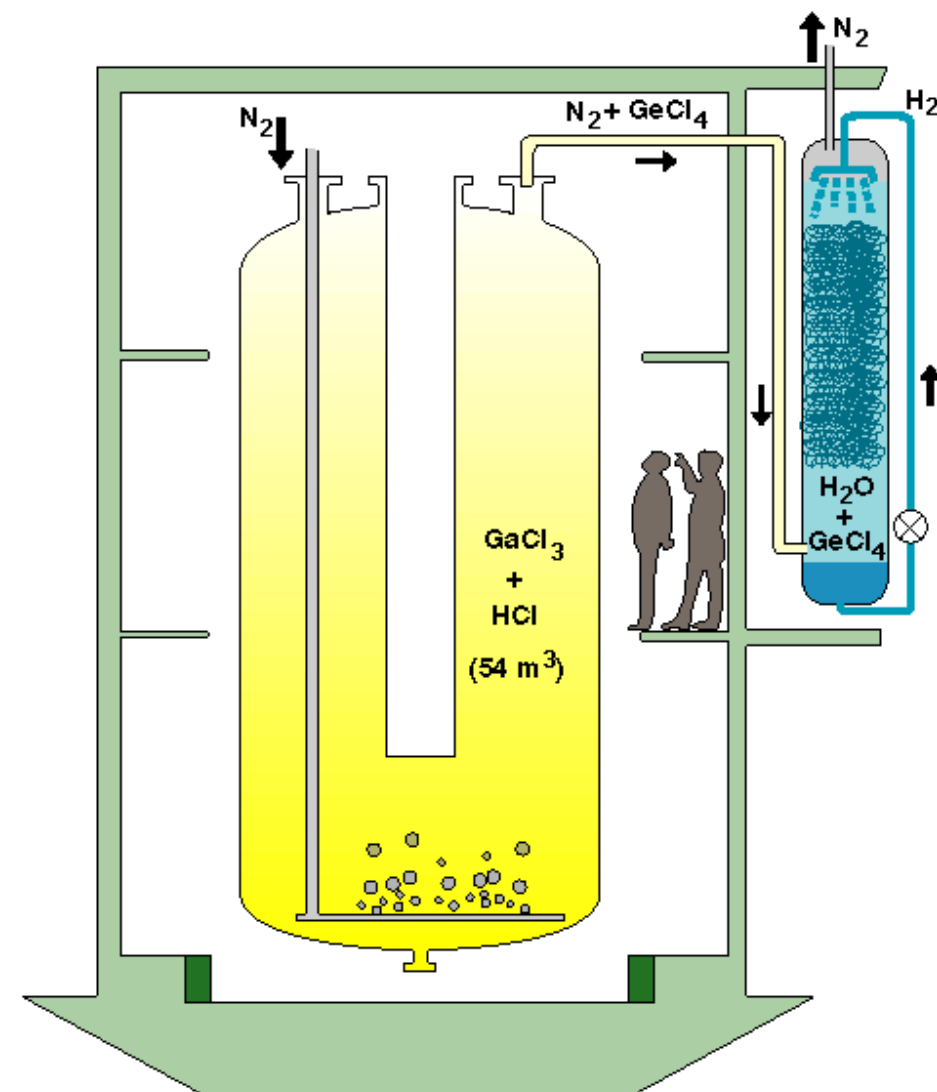
- 2000s: SNO
 - ▶ $\nu_x + d \rightarrow p + n + \nu_x$ (neutral current)
 - ▶ Sensitive to all three flavors with equal weights
 - ▶ Measurement consistent with prediction

Prediction: $\Phi_{SSM} = (5.05^{+1.01}_{-0.81}) \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$

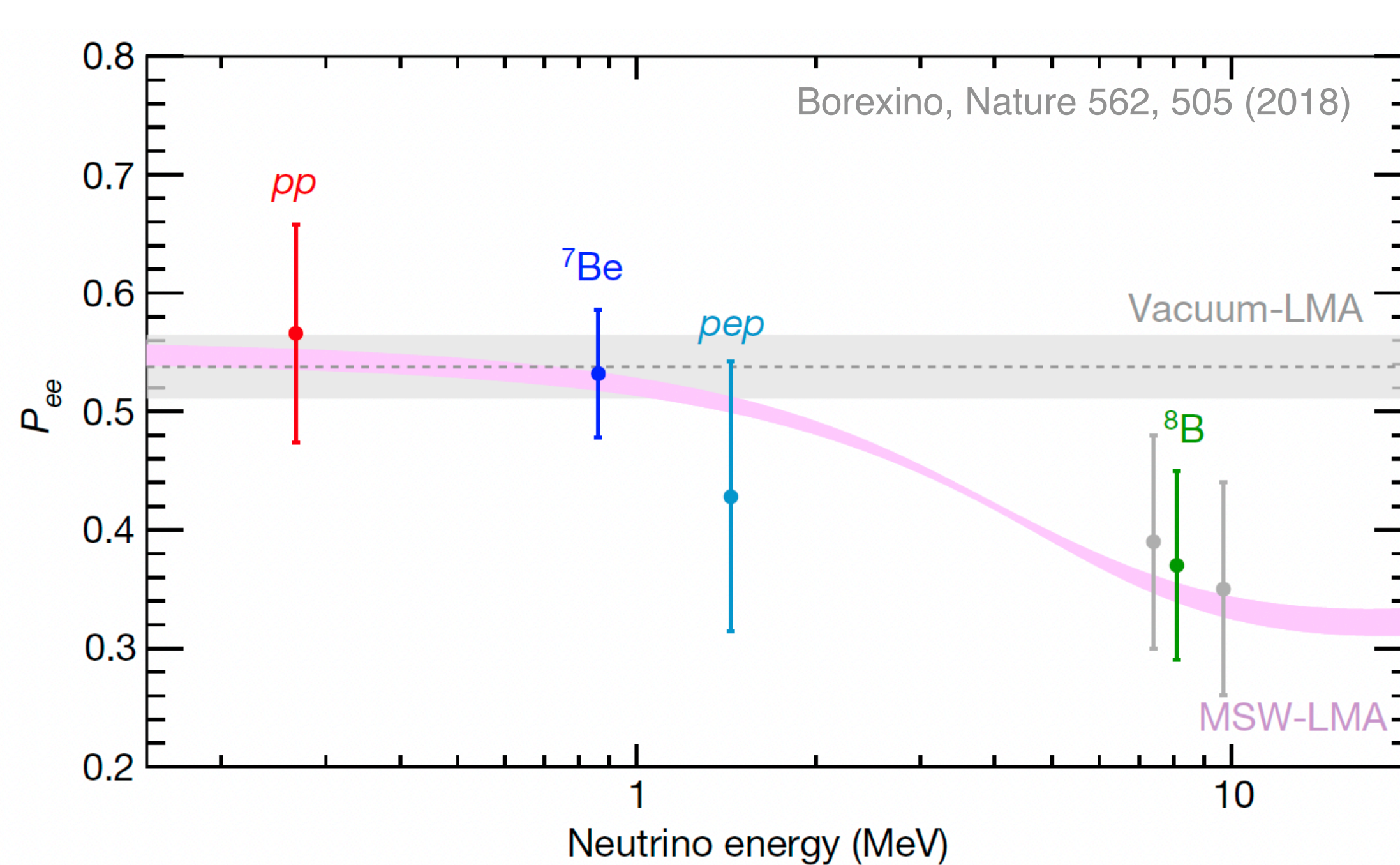
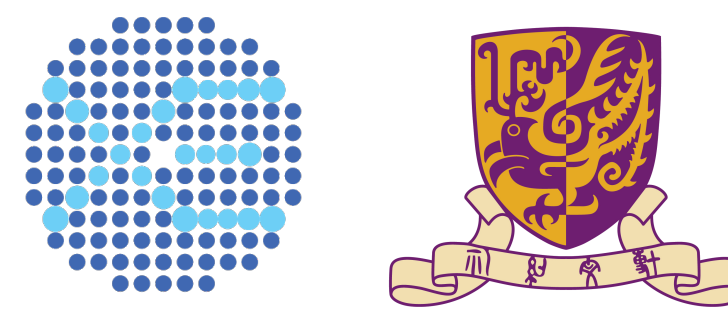
Masurement: $\Phi_{NC} = (5.1 \pm 0.6) \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$



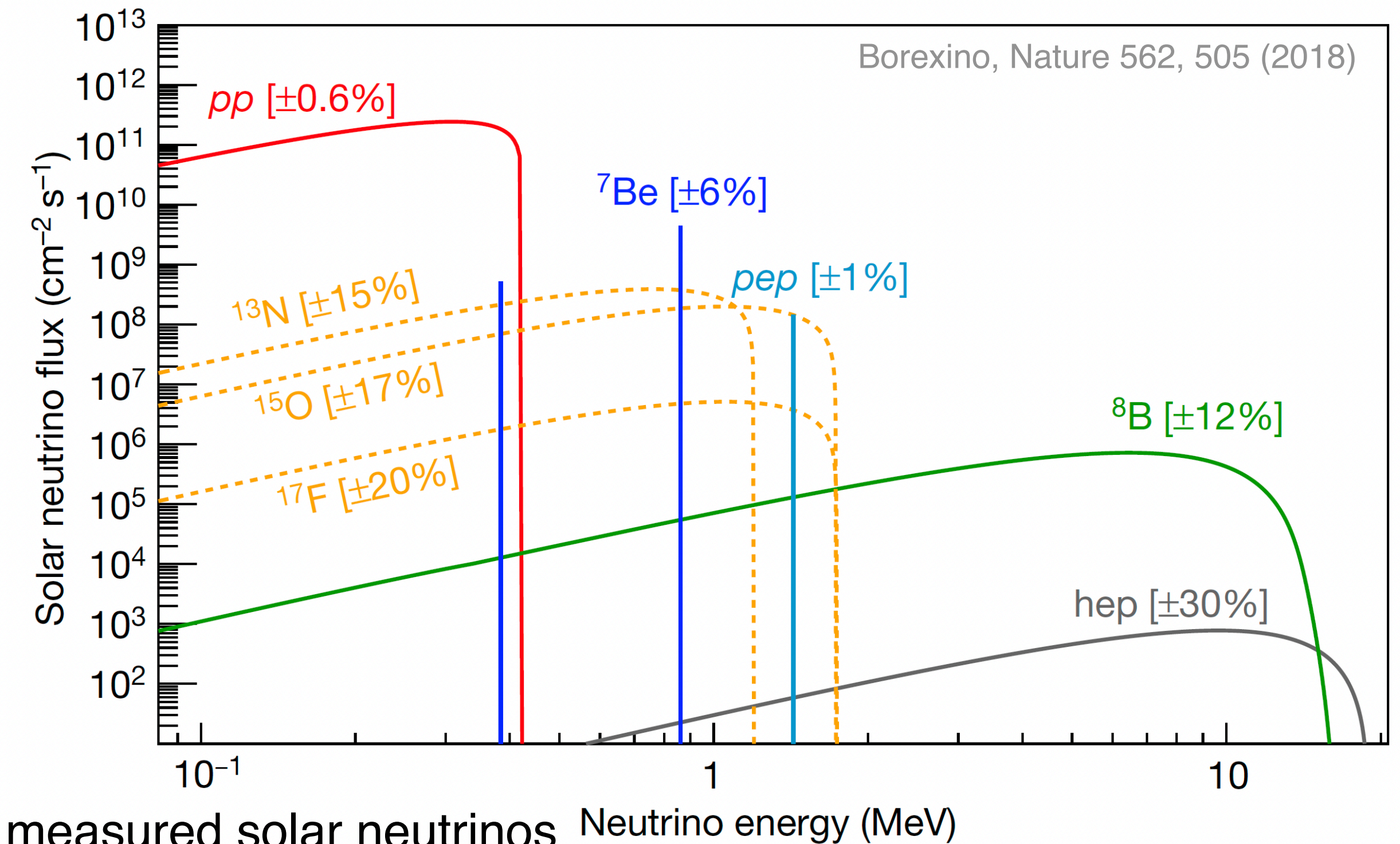
- 1990s-2000s: GALLEX/GNO and SAGE
 - ▶ $^{71}\text{Ga} + \nu_e \rightarrow ^{71}\text{Ge} + e^-$ (threshold: 233 keV)
 - ▶ Only sensitive to ν_e
 - ▶ Observed neutrino: $\sim 60\%$ of prediction



Solar neutrino: useful probe

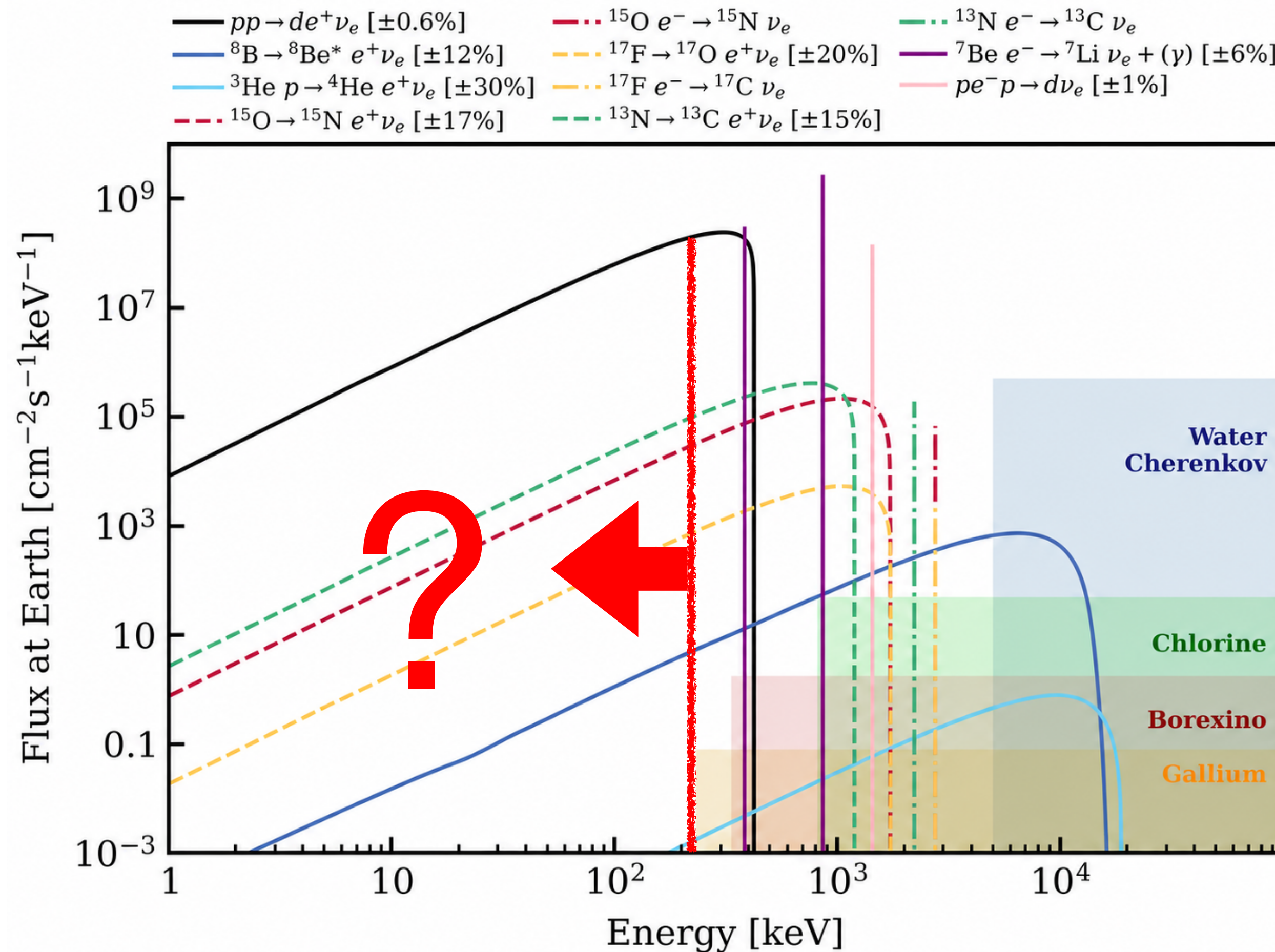
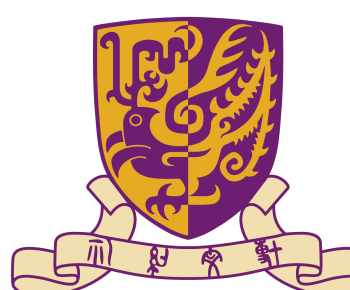
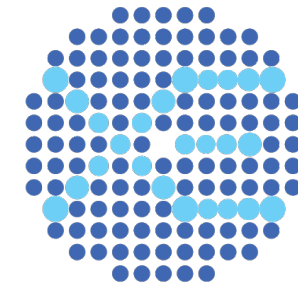


Borexino experiment systematically measured solar neutrinos



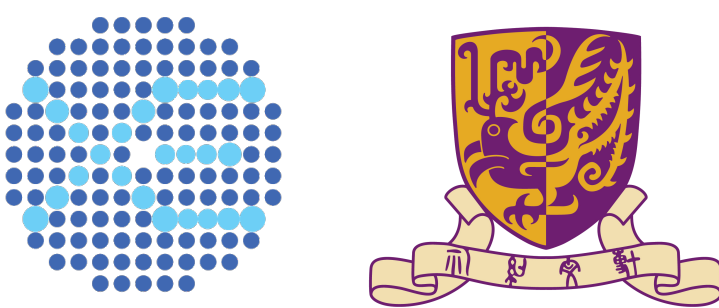
- Solar neutrino as a useful probe for particle physics and astronomy
 - Validated MSW-LMA mechanism of neutrino oscillation and measured mixing parameters
 - Directly confirmed the Standard Solar Model (SSM)

Solar pp neutrino



- Lowest energy threshold so far is 233 keV from Gallium experiments
→ ~34% of solar pp remains unexplored.
- How to explore uncharted solar neutrinos?

XENON Collaboration



31 institutes
~200 scientists



AMERICA

UC San Diego

San Diego

Houston

THE UNIVERSITY OF CHICAGO

Chicago

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

New York City

Bucknell UNIVERSITY

Lewisburg

Zurich

KIT
Karlsruhe Institute of Technology

Karlsruhe

Universität
Münster

Münster

UNI
FREIBURG

Freiburg

JGU

Mainz

MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK
HEIDELBERG

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HEIDELBERG
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Hangzhou

香港中文大學 (深圳)
The Chinese University of Hong Kong, Shenzhen

Shenzhen

東京大学
THE UNIVERSITY OF TOKYO

Tokyo

名古屋大学
NAGOYA UNIVERSITY

Nagoya

KOBE
UNIVERSITY

Kobe

Institute of
SCIENCE
TOKYO

Tokyo

MIDDLE EAST

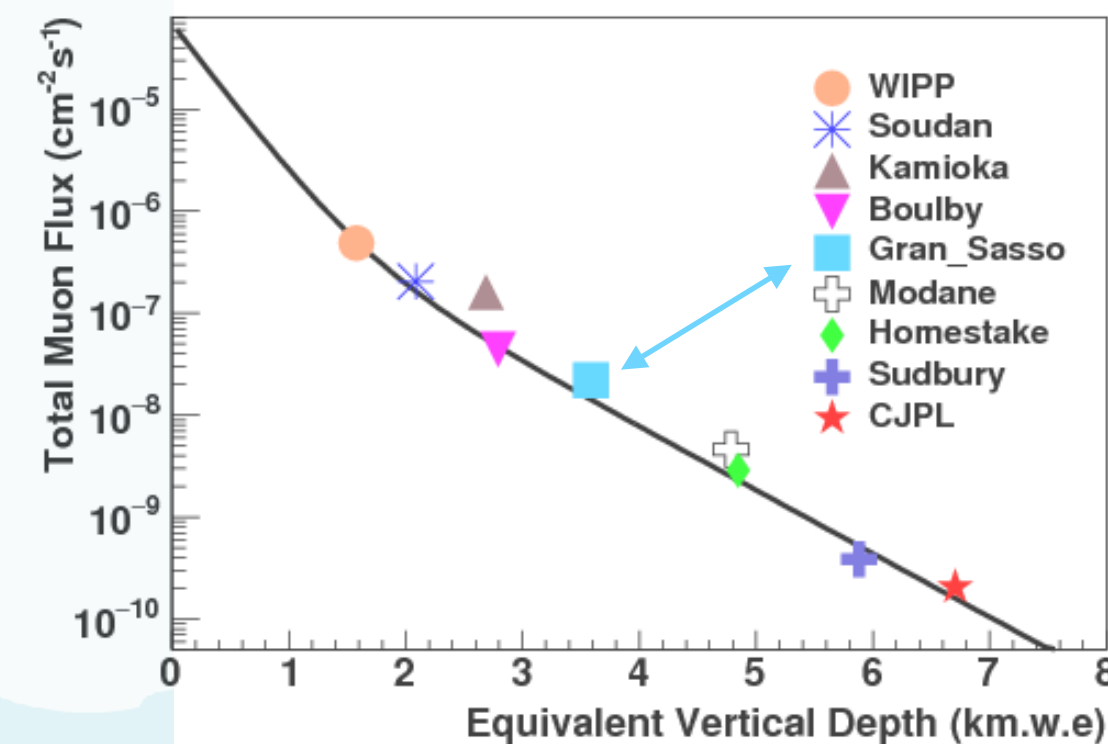
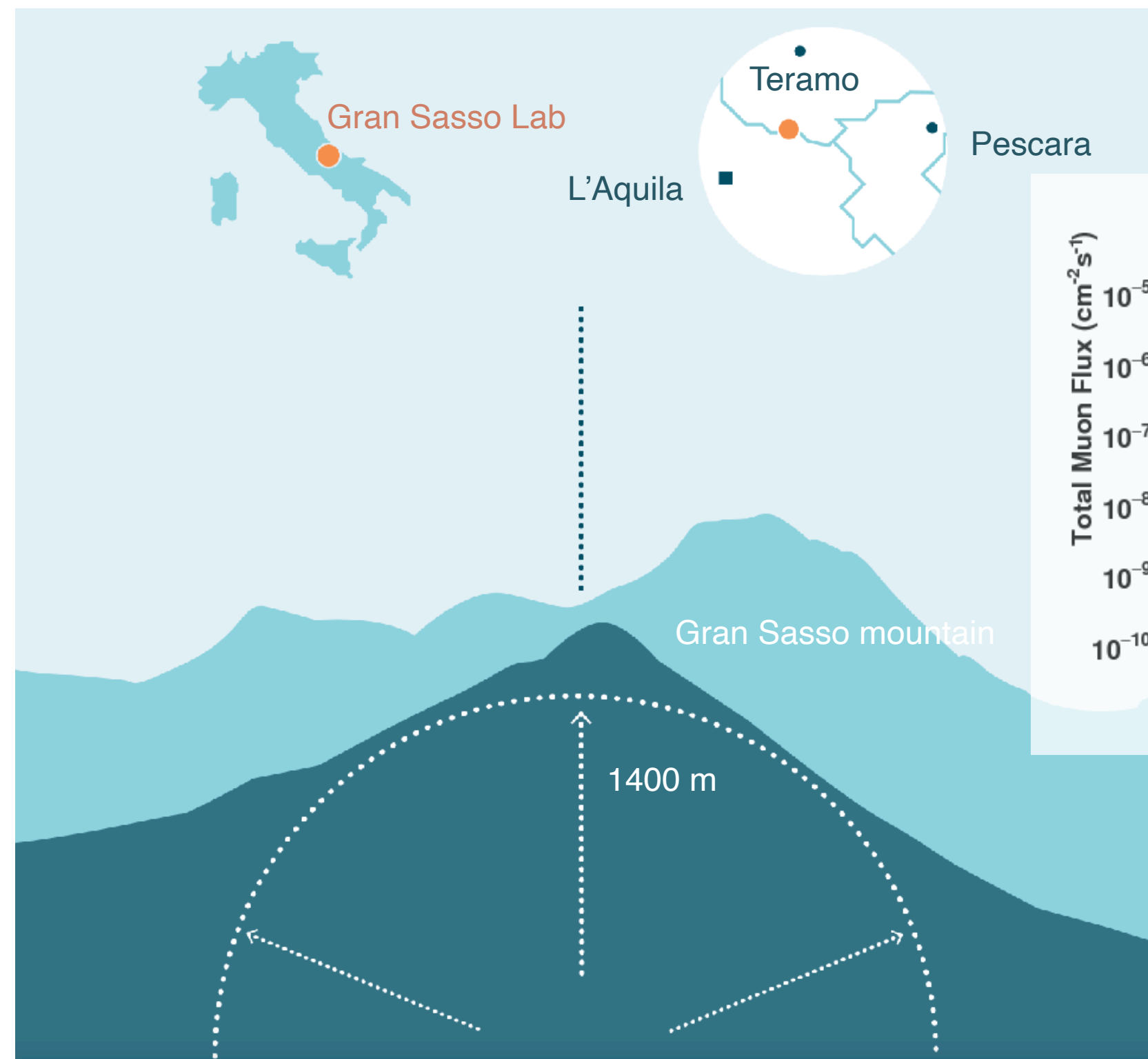
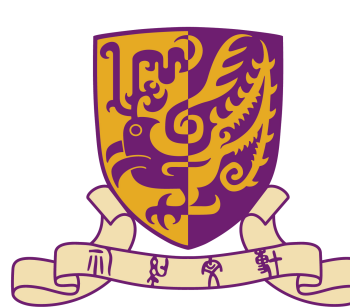
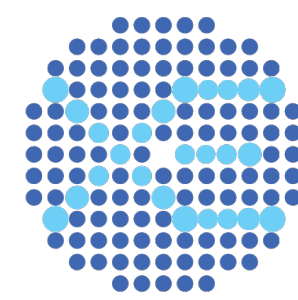
מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

Rehovot

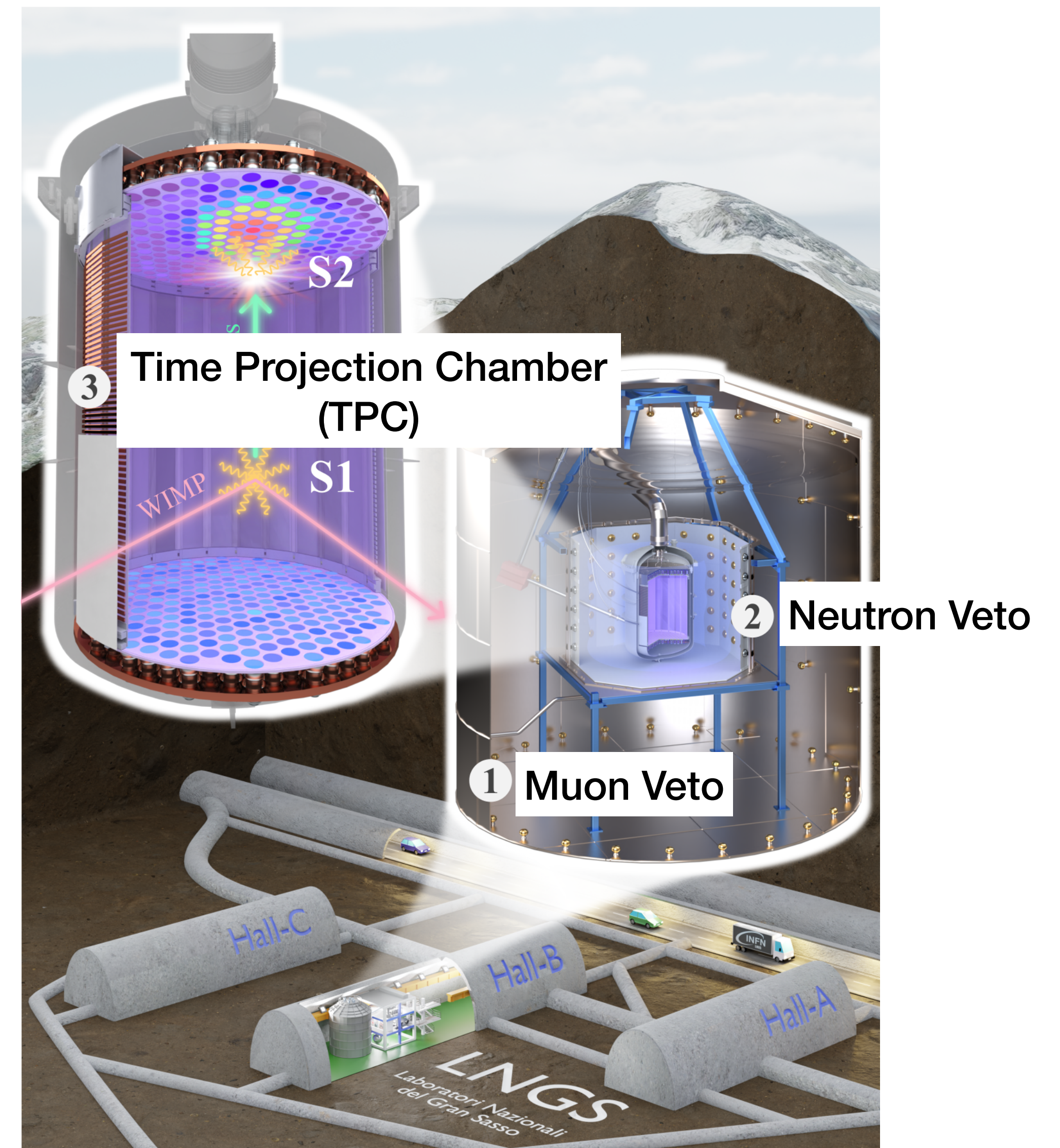
جامعة نيويورك أبوظبي
NYU | ABU DHABI

Abu Dhabi

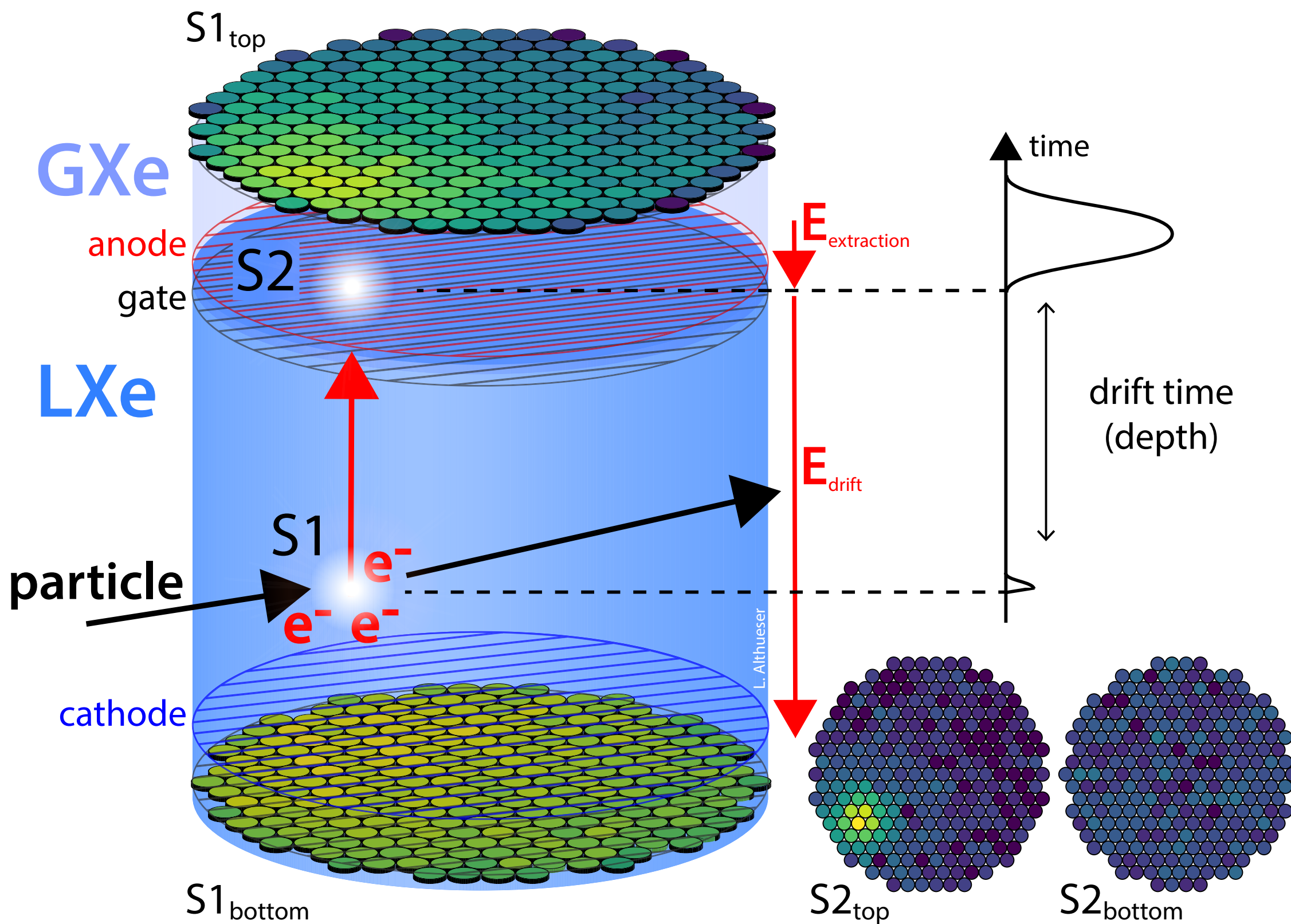
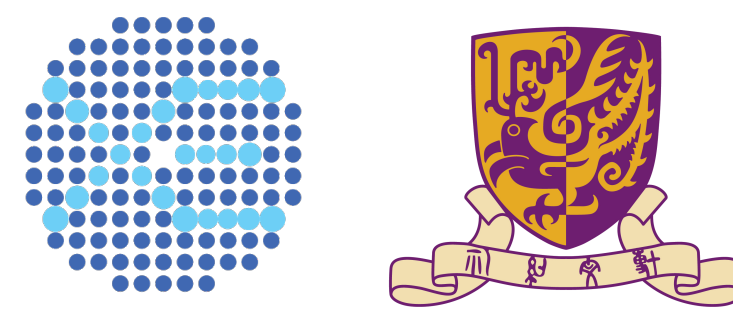
The XENONnT Experiment



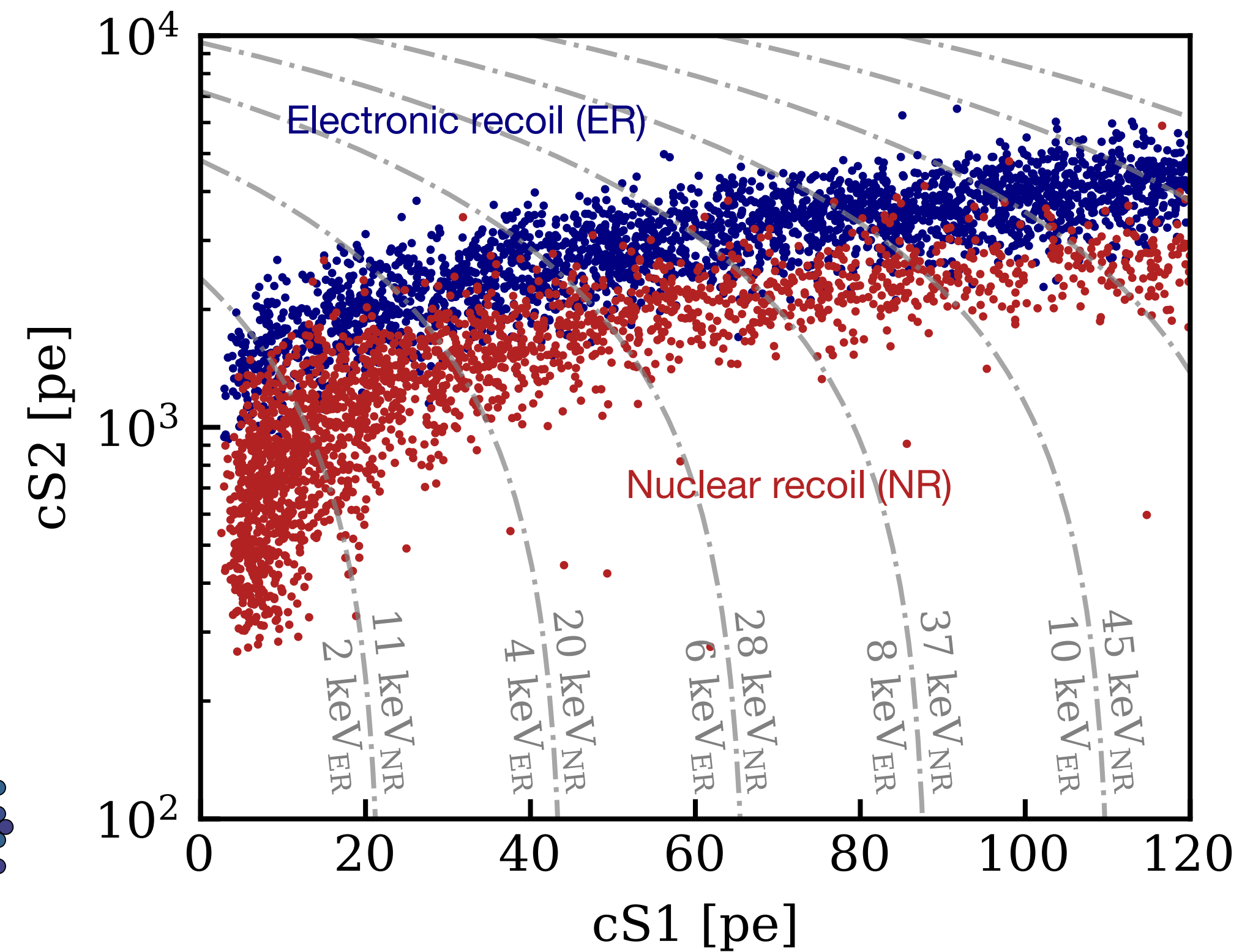
- Located at INFN LNGS
 - Overburden: 1400m (3800m water equivalent)
 - Muon reduction: $\sim 10^{-6}$
- Primary goal: Weakly Interacting Massive Particles (WIMP) search
- 8.5 tonne liquid **xenon** in total
- 5.9 tonne in **Time Projection Chamber (TPC)**



Why TPC?

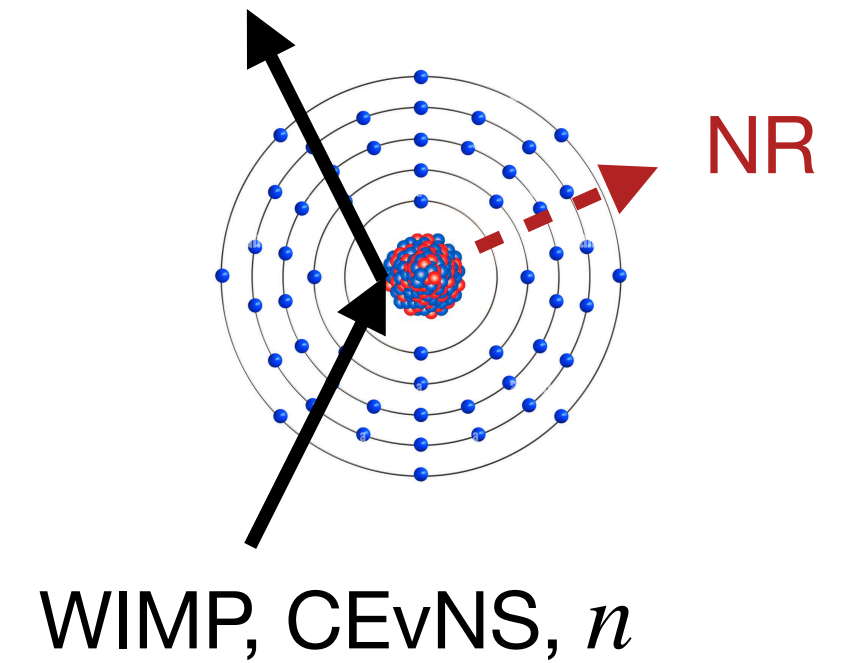


- 3D position reconstruction
- Ability to detect feeble signals

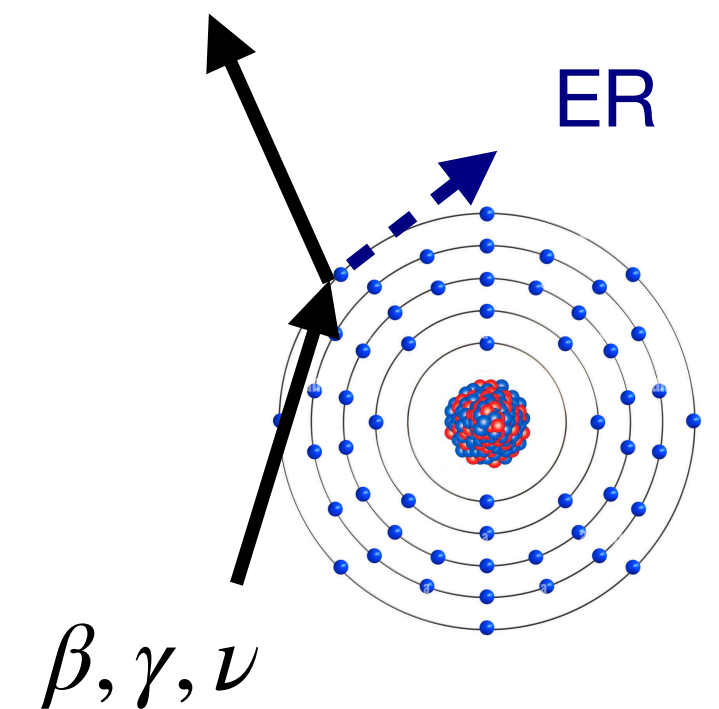


- Particle interaction identification
 - Electronic recoil (ER)
 - Nuclear recoil (NR)

B. Andrieu's Talk



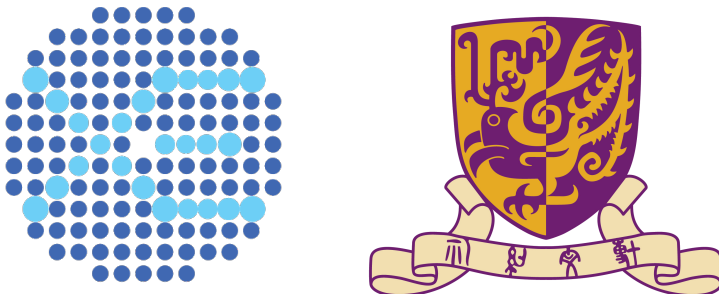
WIMP, CEvNS, n



β, γ, ν

This talk

Why xenon?



Selected Properties of Xe

Property	Value
Atomic Number (Z)	54
Atomic Weight (A)	131.30
Number of Electrons per Energy Level	2,8,18,18,8
Density (STP)	5.894 g/L
Boiling Point	−108.1 °C
Melting Point	−111.8 °C
Volume Ratio	519
Concentration in Air	0.0000087 % by volume

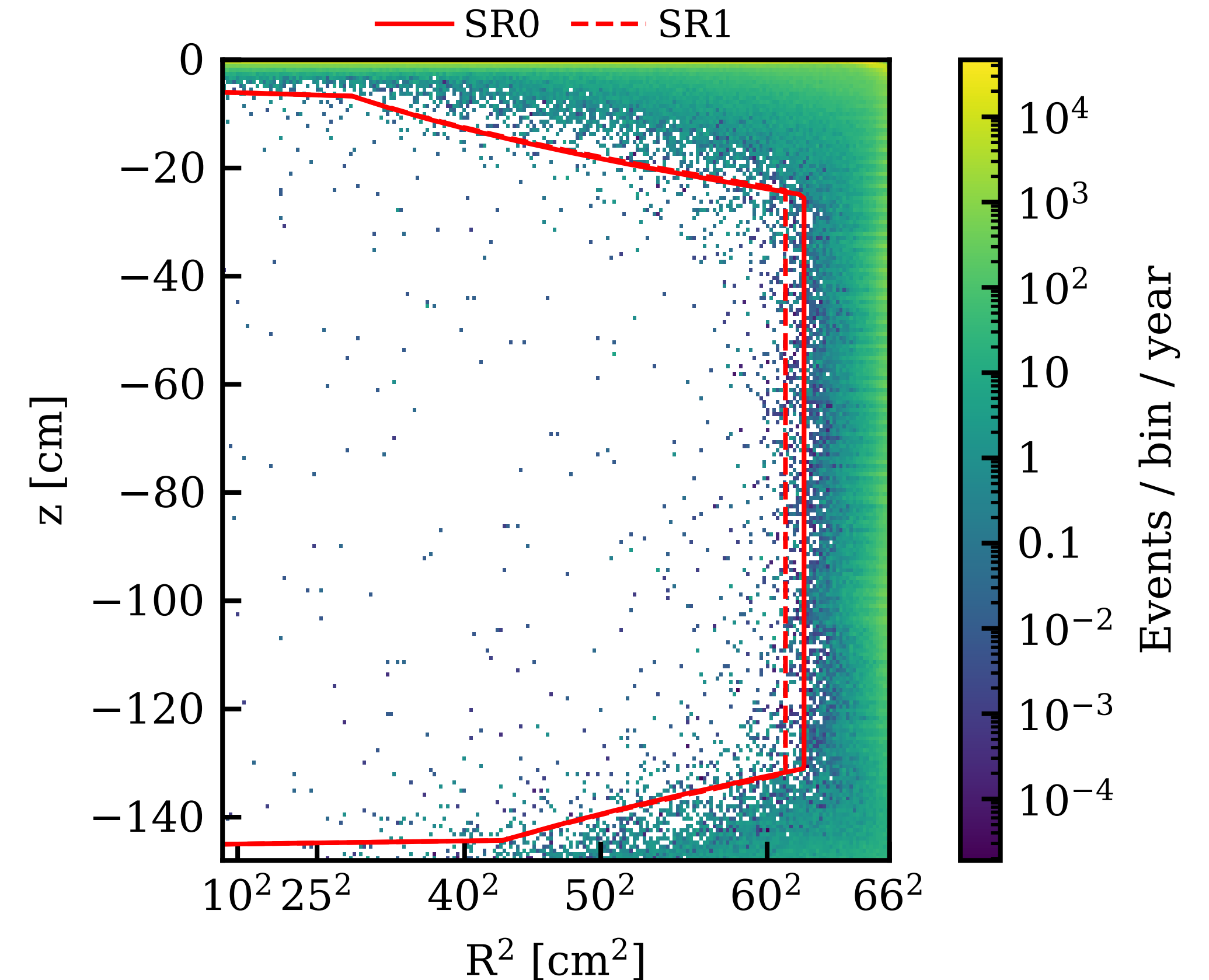
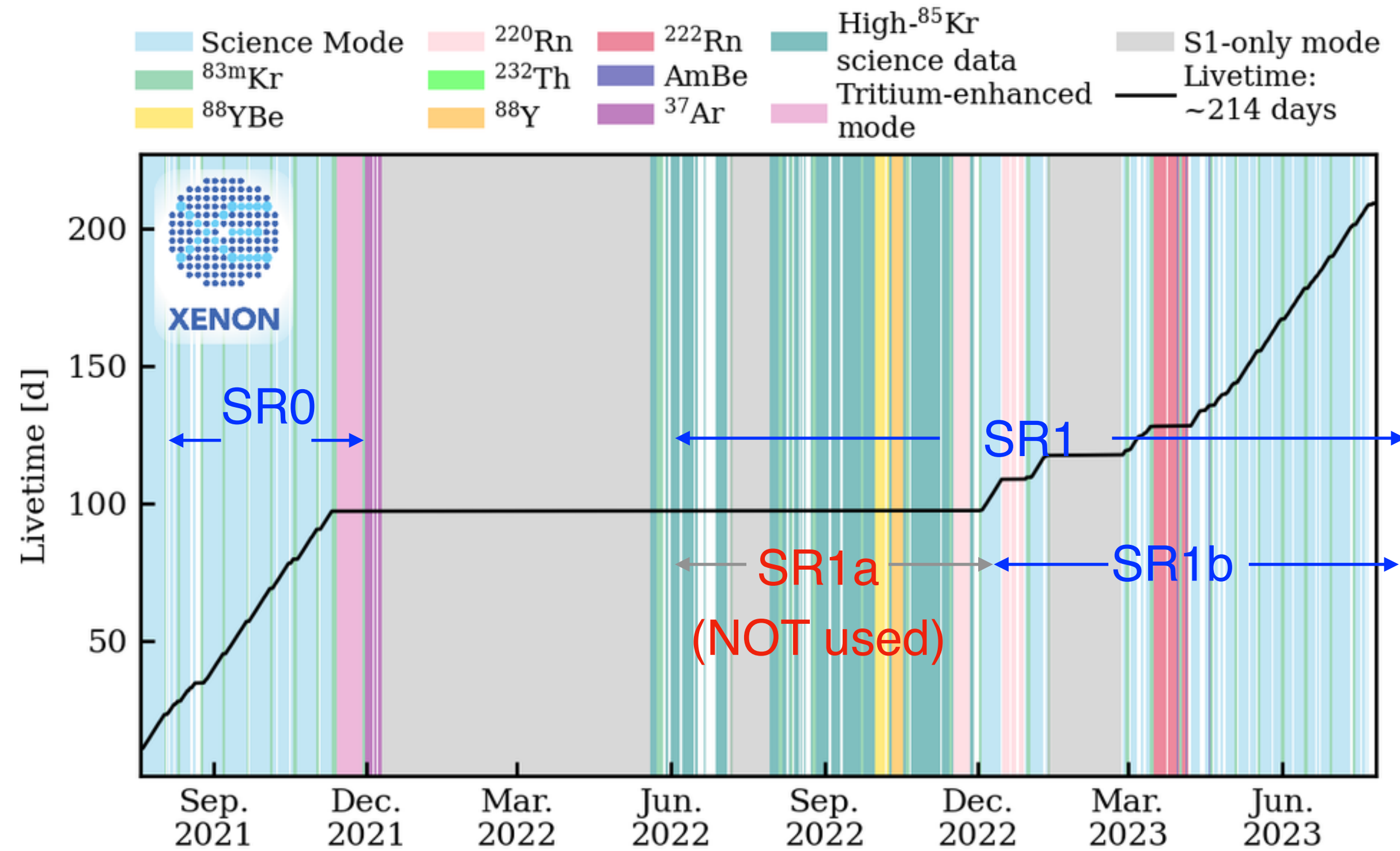
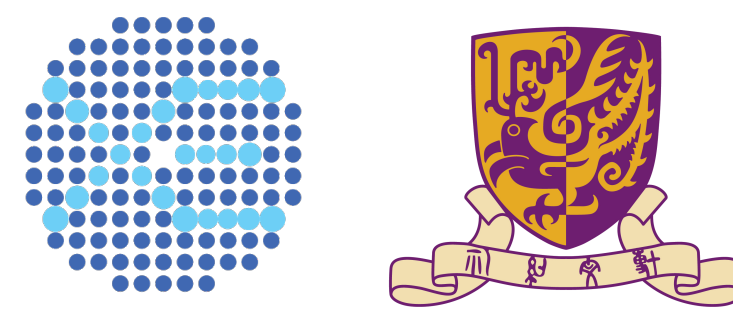
detector threshold

background

exposure

- Low
- Extremely low
- Decent

Exposure



Two science runs (214 live days)

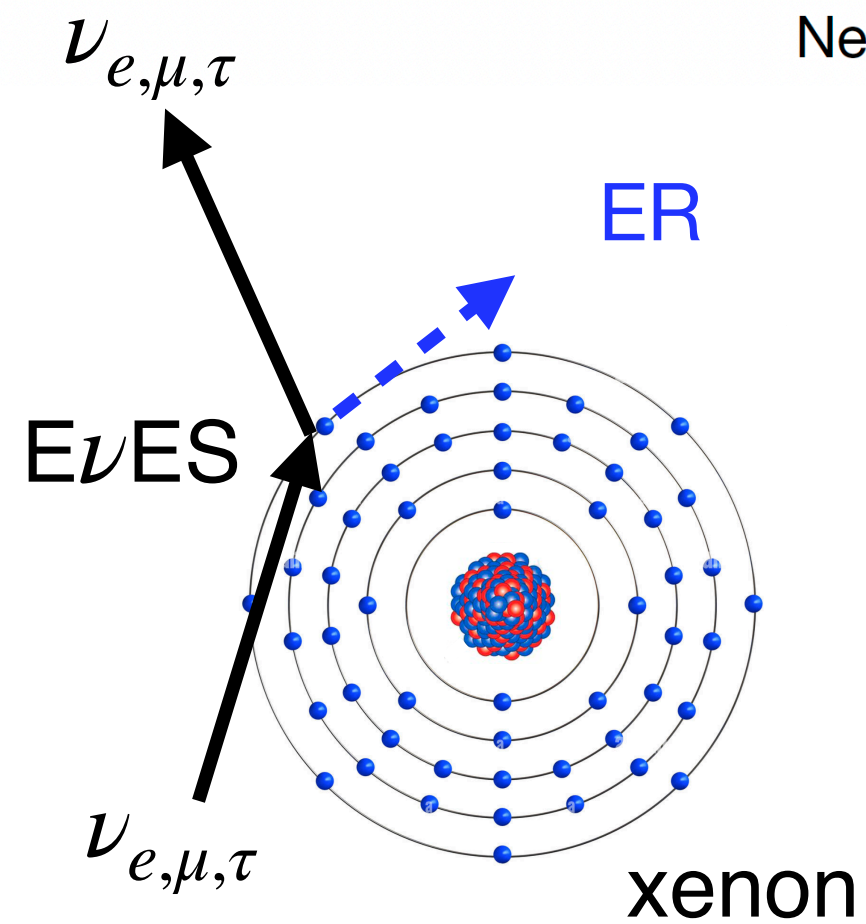
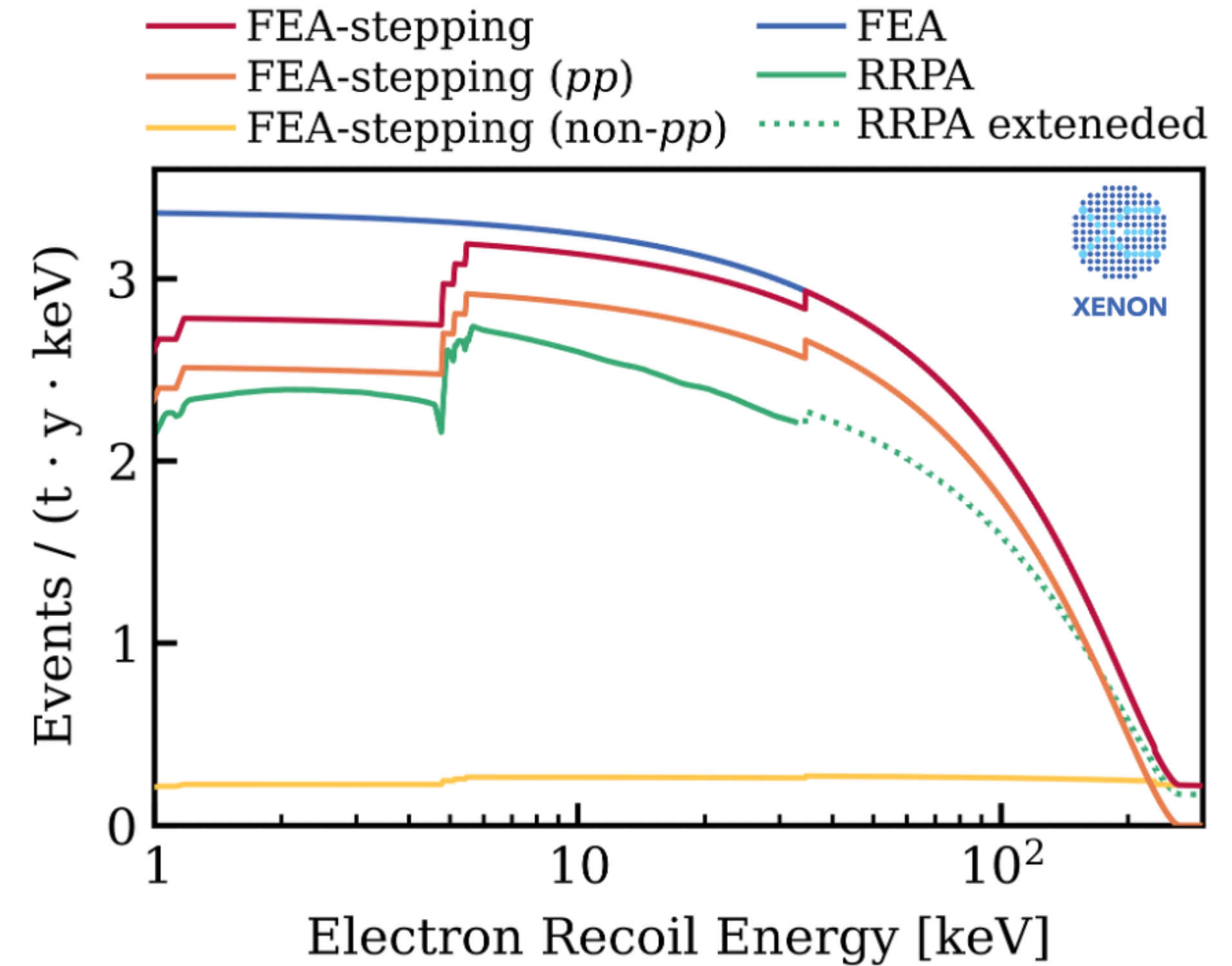
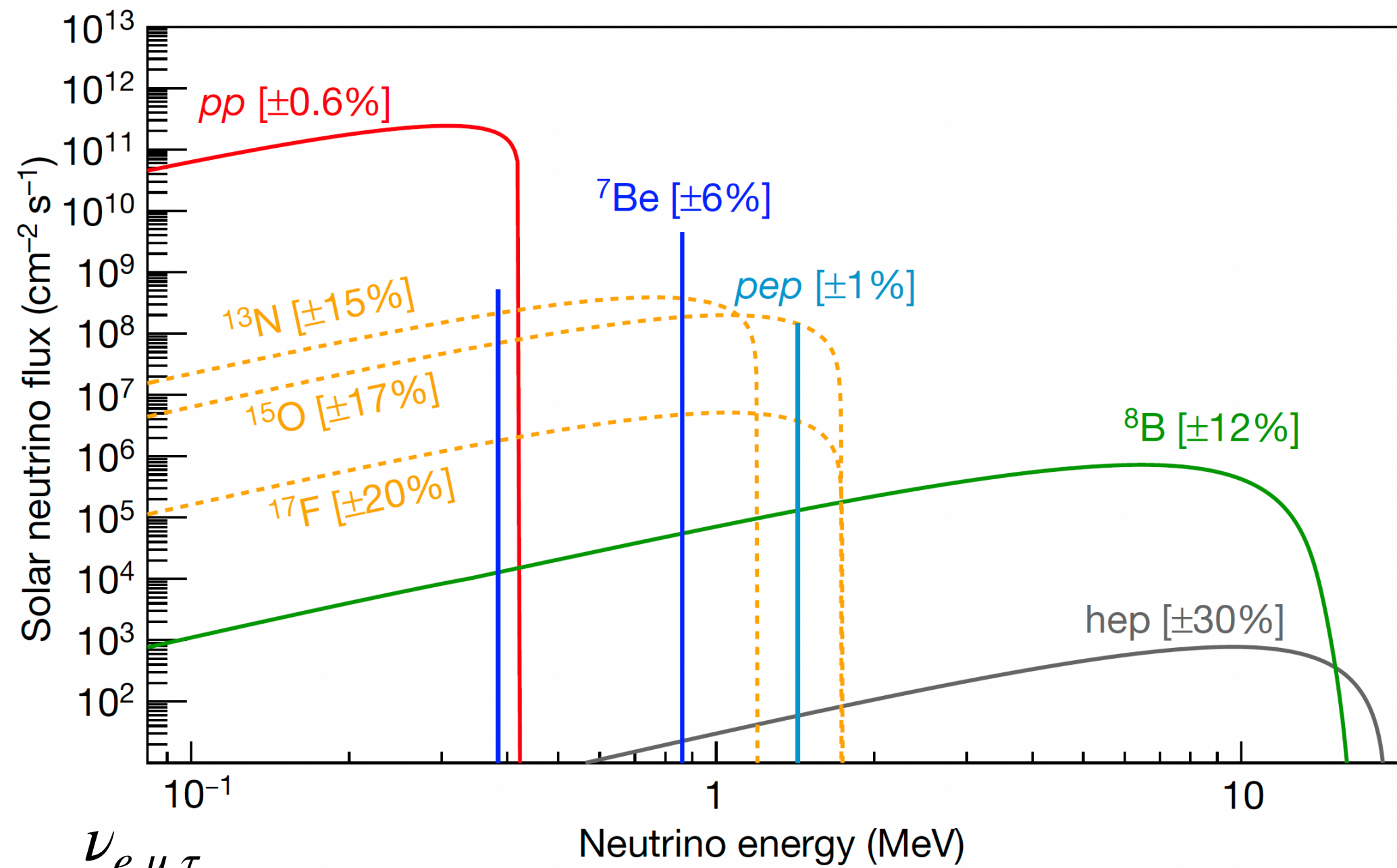
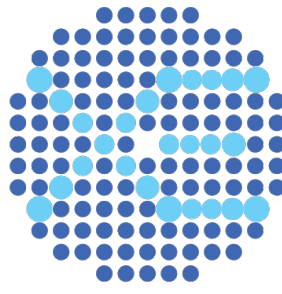
- Science Run 0 (SR0): Jul. 6th, 2021 - Nov. 10th, 2021
- Science Run 1 (SR1): May. 19th, 2022 - Aug. 8th, 2023
 - SR1a NOT used as science data due to higher background level

- Fiducialization helps reduce external backgrounds
- SR0 and SR1 fiducial volume (FV) ~4 tonnes

Time ↙
Mass ↘
Total exposure: **2.46 tonne·year**

exposure

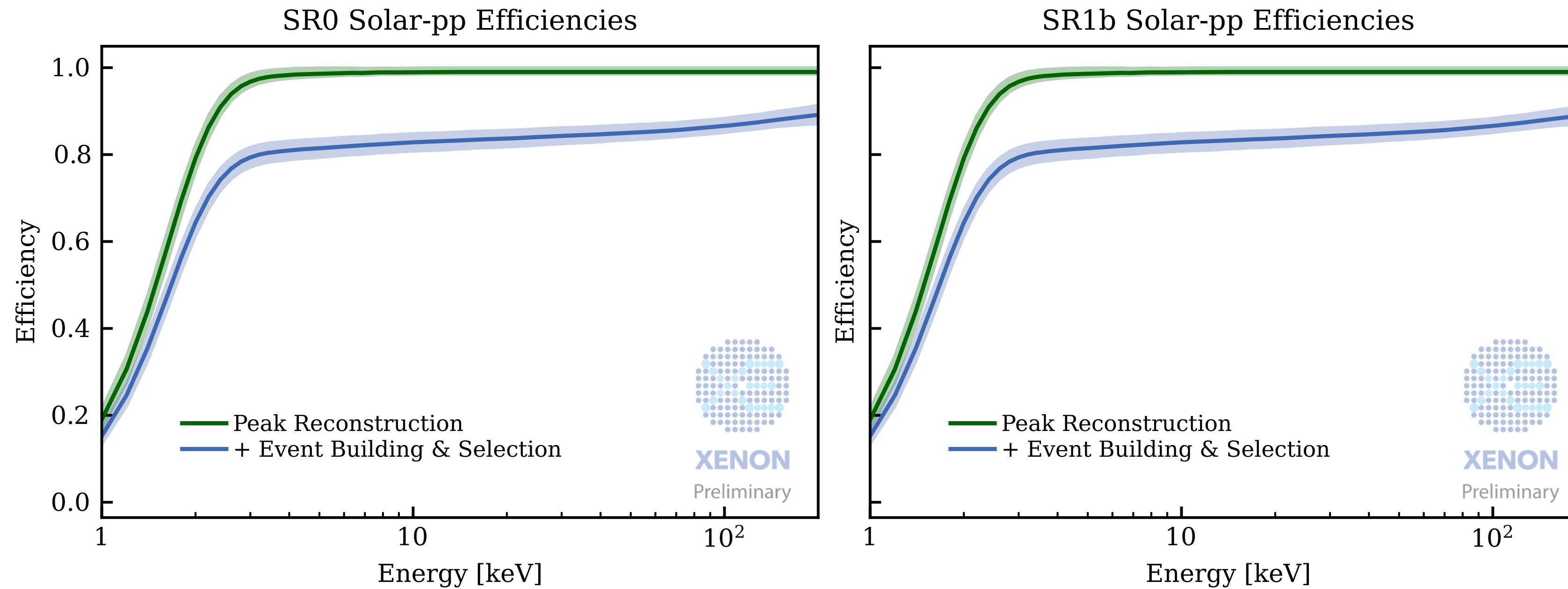
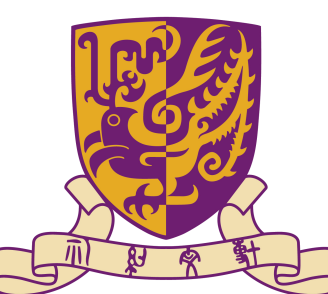
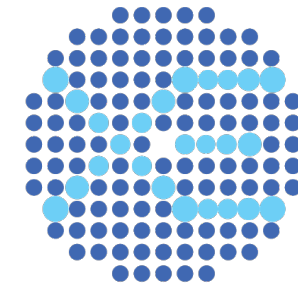
Solar neutrino signal



- Detection channel: $\nu_e + e^- \rightarrow \nu_e + e^-$, elastic neutrino electron scattering (E ν ES)
 - Sensitive to all flavors with different weights ($\sigma_{\mu,\tau}/\sigma_e \approx 1/6$)
 - Contribution: pp ($\sim 90\%$) + Be-7 ($\sim 10\%$)
- Spectrum calculation: Free electron approximation (FEA) + stepping
 - FEA: scattering cross section assuming free electrons
 - Stepping: binding energies of xenon shells

detector threshold

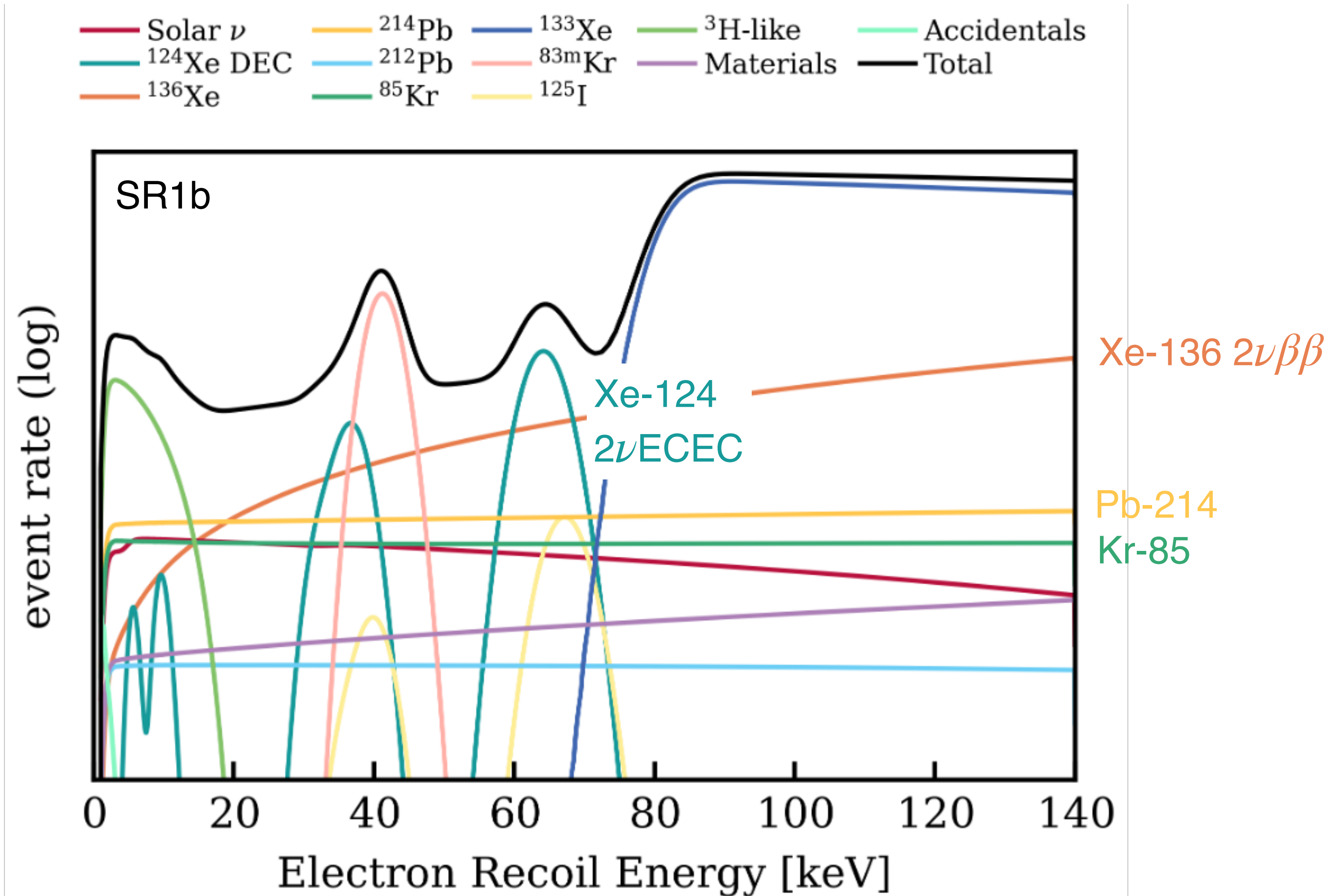
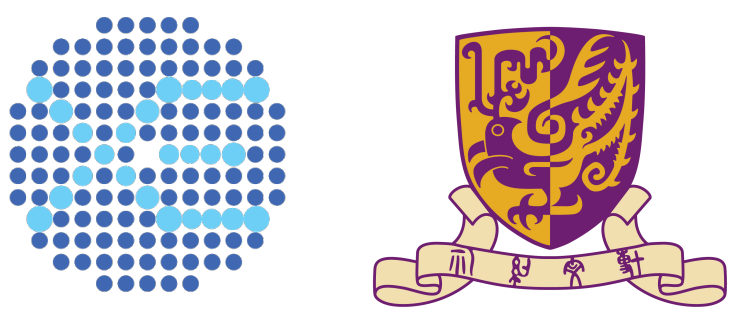
Efficiency and threshold



- Peak reconstruction efficiency: ability to reconstruct S1 or S2 signals
- Total efficiency > 80% after 3 keV
- Threshold:
 - Despoit energy: 1 keV
 - Neutrino energy: 17 keV (lowest to date)

detector threshold

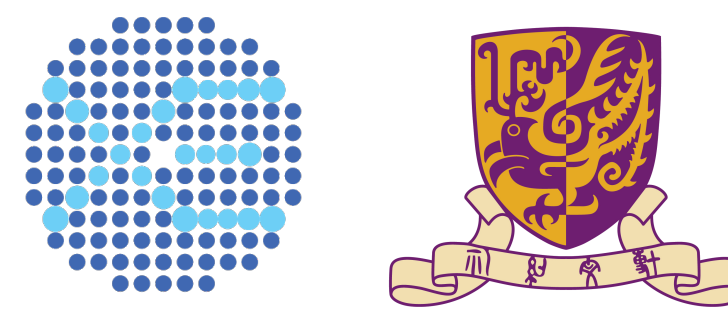
Background



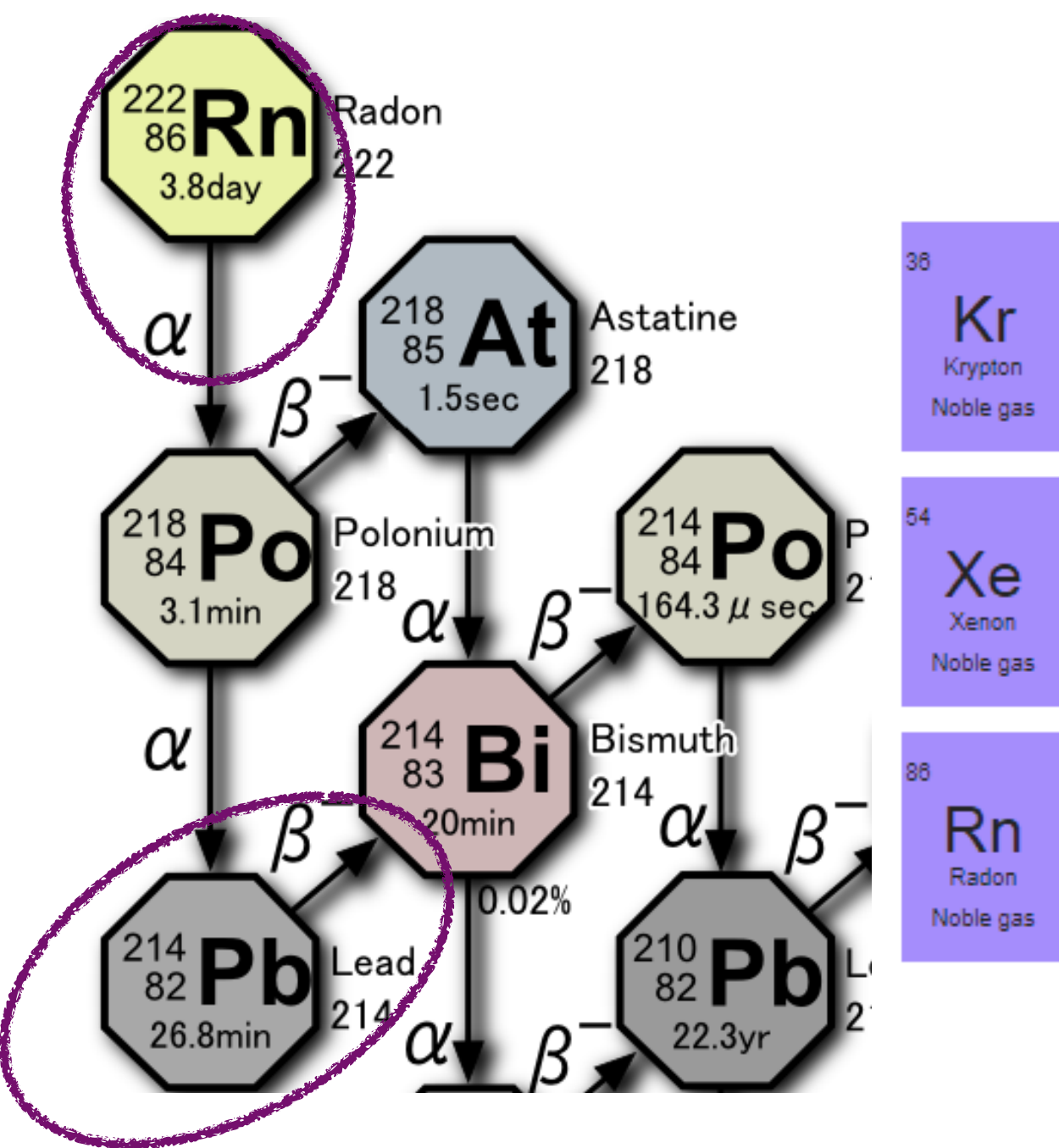
- Natural xenon consists of mostly stable isotopes, with a few exceptions of extremely long-lived isotopes: Xe-136 ($2\nu\beta\beta$) and Xe-124 ($2\nu\text{ECEC}$)

background

Pb214 background - reduction

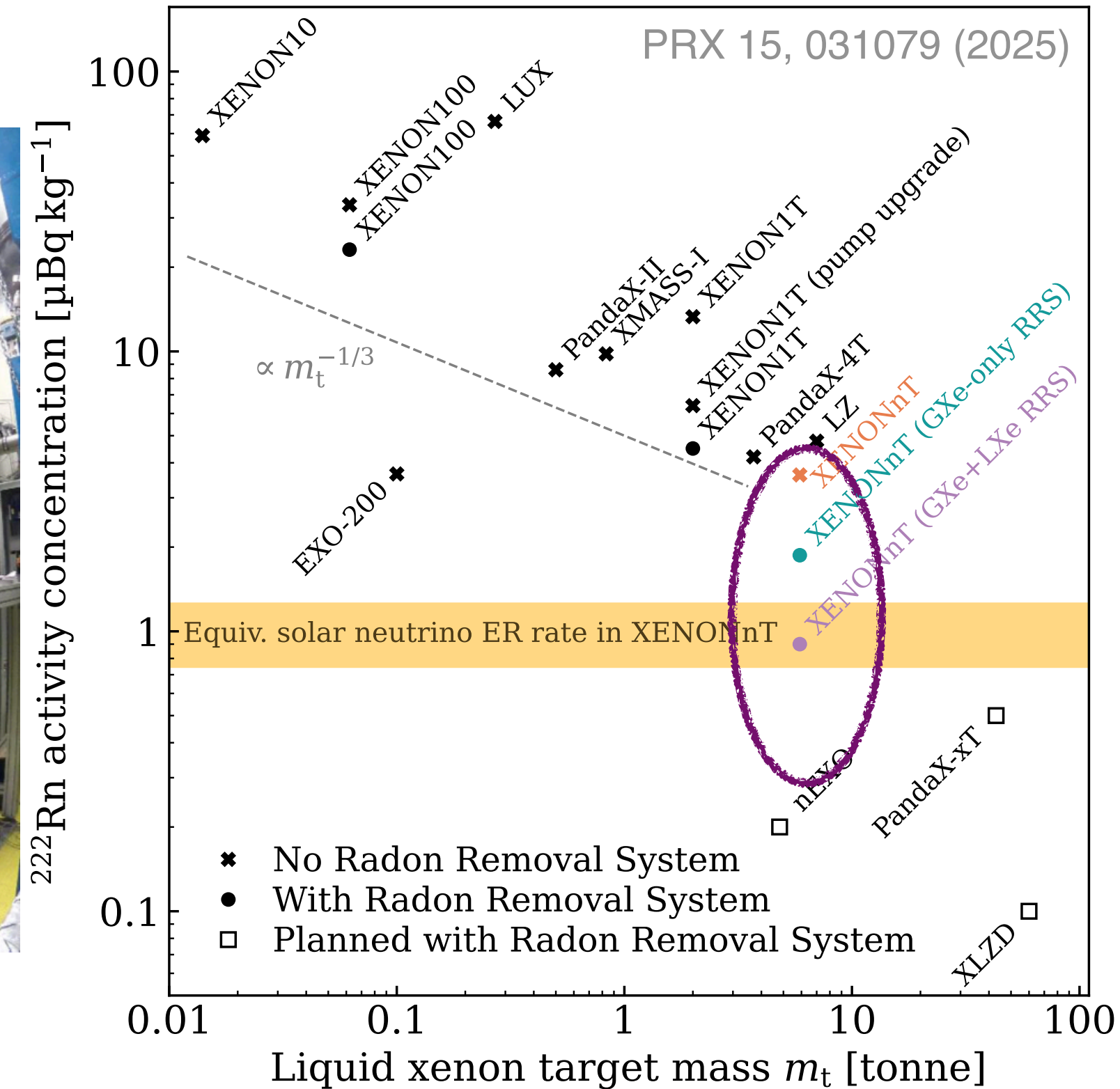


Rn-222 decay chain



Mass	Boiling point	Vapor pressure
84	120 K	
131	165 K	High
222	216 K	Low

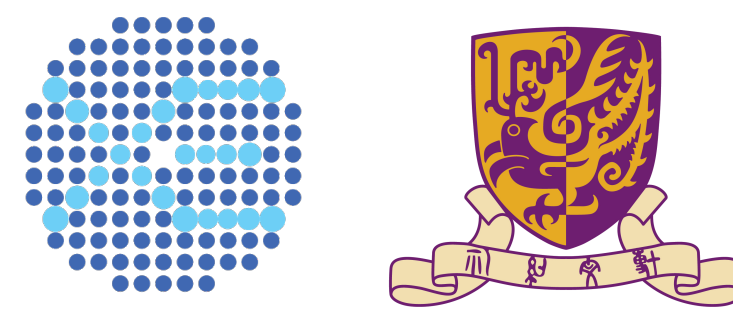
Radon Distillation Column



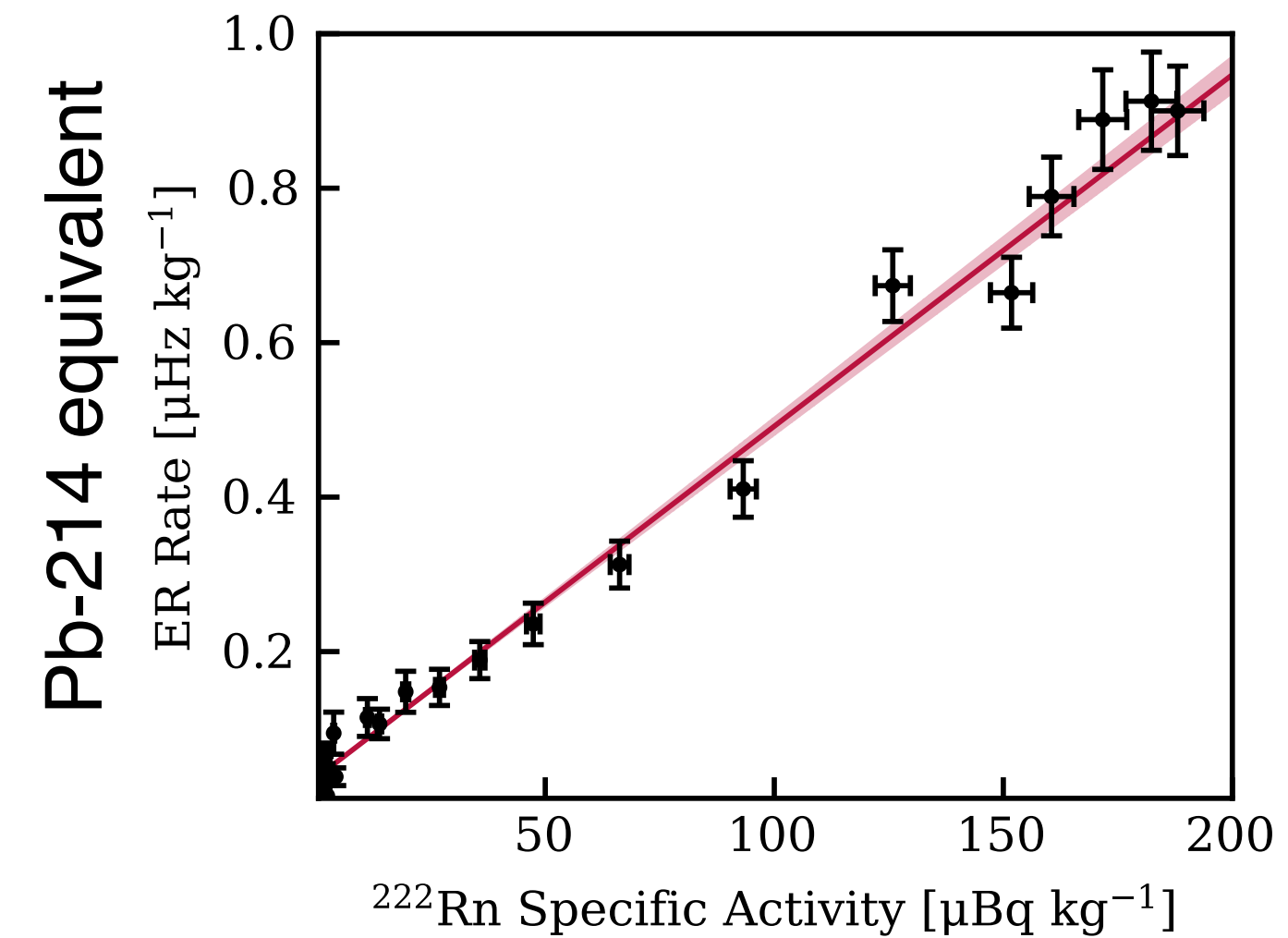
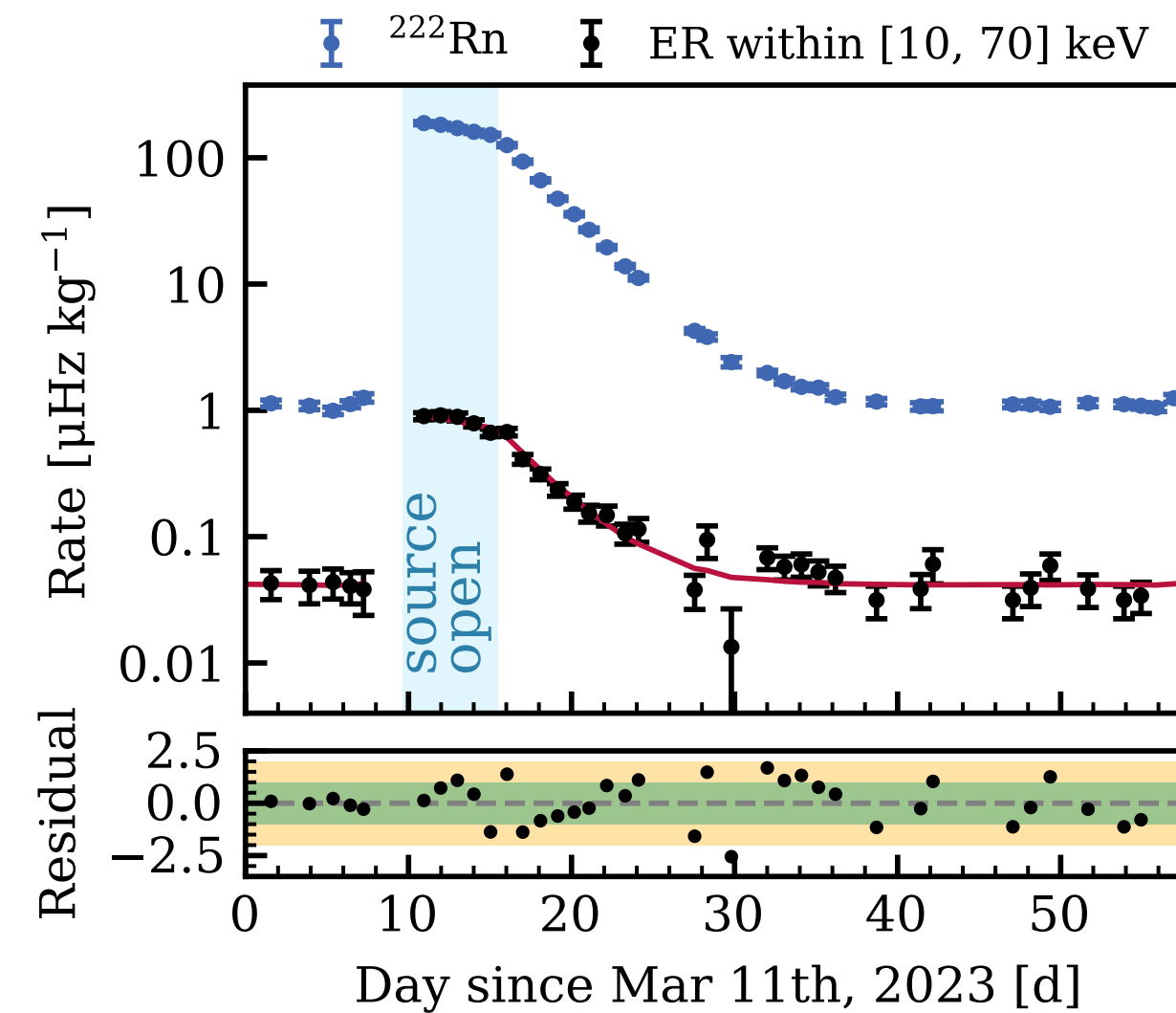
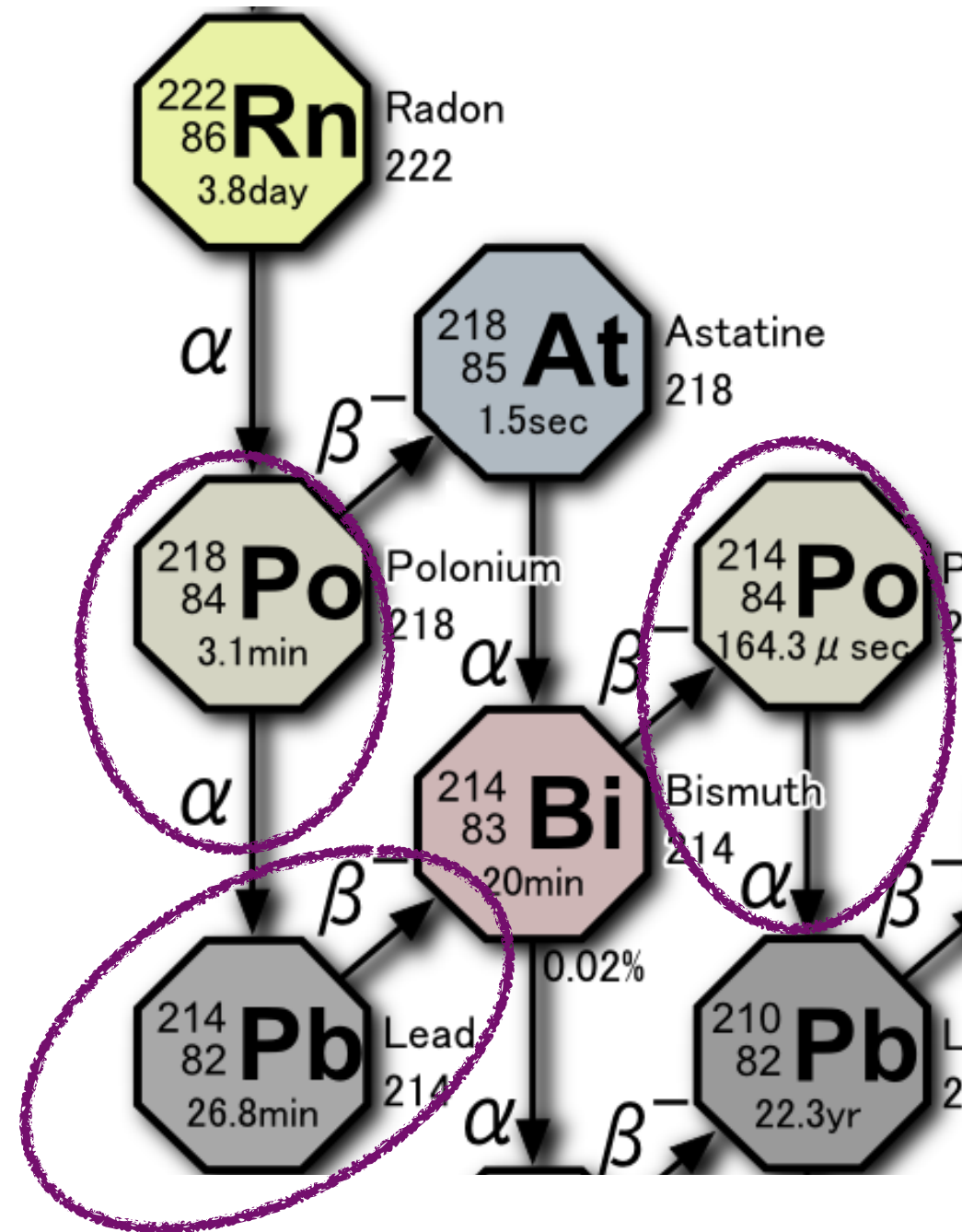
- Pb-214 from the Rn-222 decay chain has a significant contribution to ER backgrounds.
 - Pb-214: beta emitter, Q-value of 1019 keV
- Radon distillation column: reduce Radon exploiting difference in vapor pressure of Xe and Rn
 - SR0: 1.9 $\mu\text{Bq/kg}$
 - SR1: 0.9 $\mu\text{Bq/kg}$. Comparable level to solar neutrino-electron elastic scattering rate.

background

Pb214 background - constraints



Rn-222 decay chain

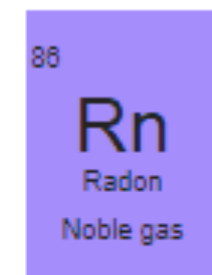
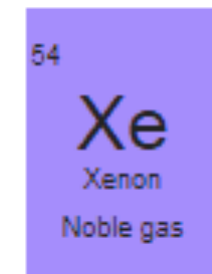
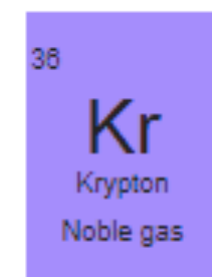
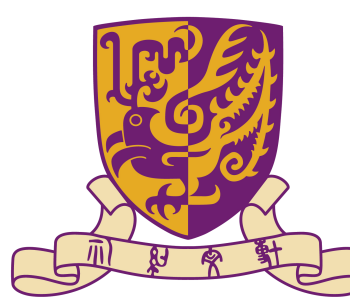
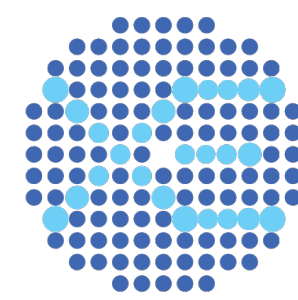


- Alpha rates can be precisely measured, but β rate is not (Pb-214)
- Previous method: bound Pb-214 rate between parent and daughter XENON, PRL 129, 161805 (2022)
 - $0.8 \text{ uBq/kg (Po-214)} < \text{Pb-214} < 1.7 \text{ uBq/kg (Po-218)}$
 - Rel. Unc.: ~40%

- This method: use Rn-222 calibration to constrain Pb-214/Rn-222 ratio
 - Rn-222 alpha rate is already precisely measured
- Measured Pb-214/Rn-222 ratio during calibration: 0.66 ± 0.03
 - Rel. Unc.: 5%

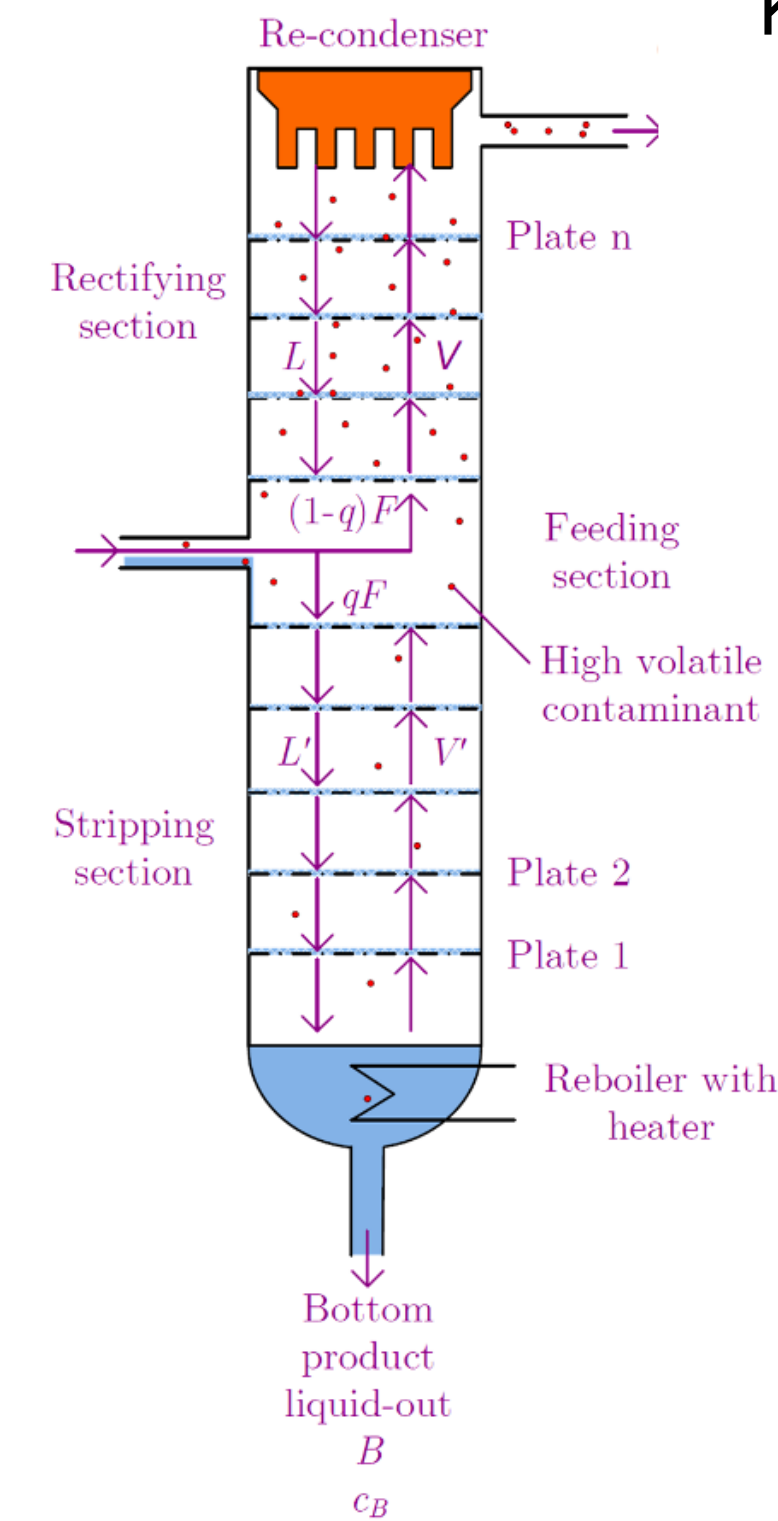
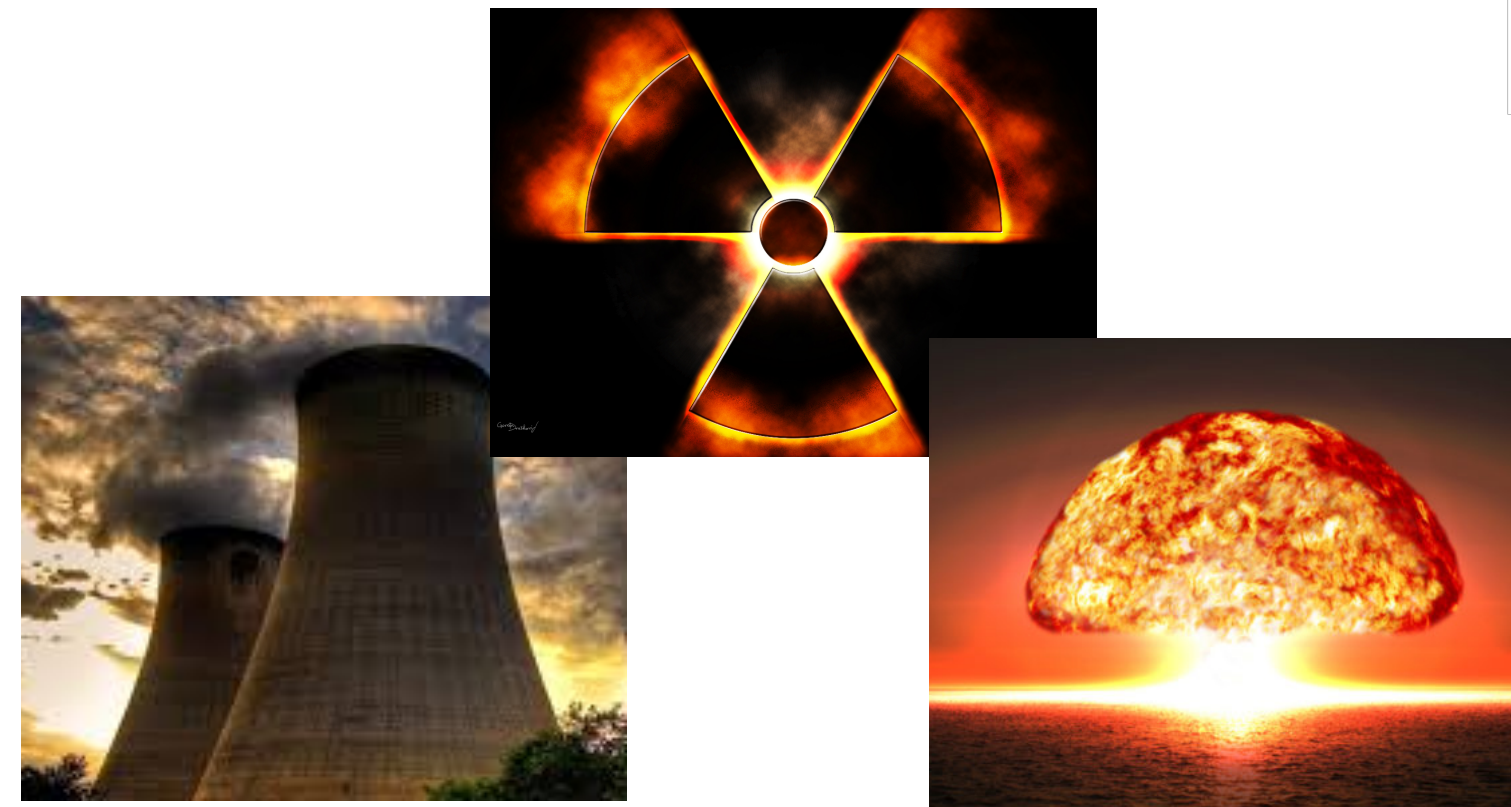
background

Kr85 background - reduction



Mass	Boiling point	Vapor pressure
84	120 K	High
131	165 K	Low
222	216 K	

Kr-85 source



M. Murra, Phd thesis

Krypton Distillation Column

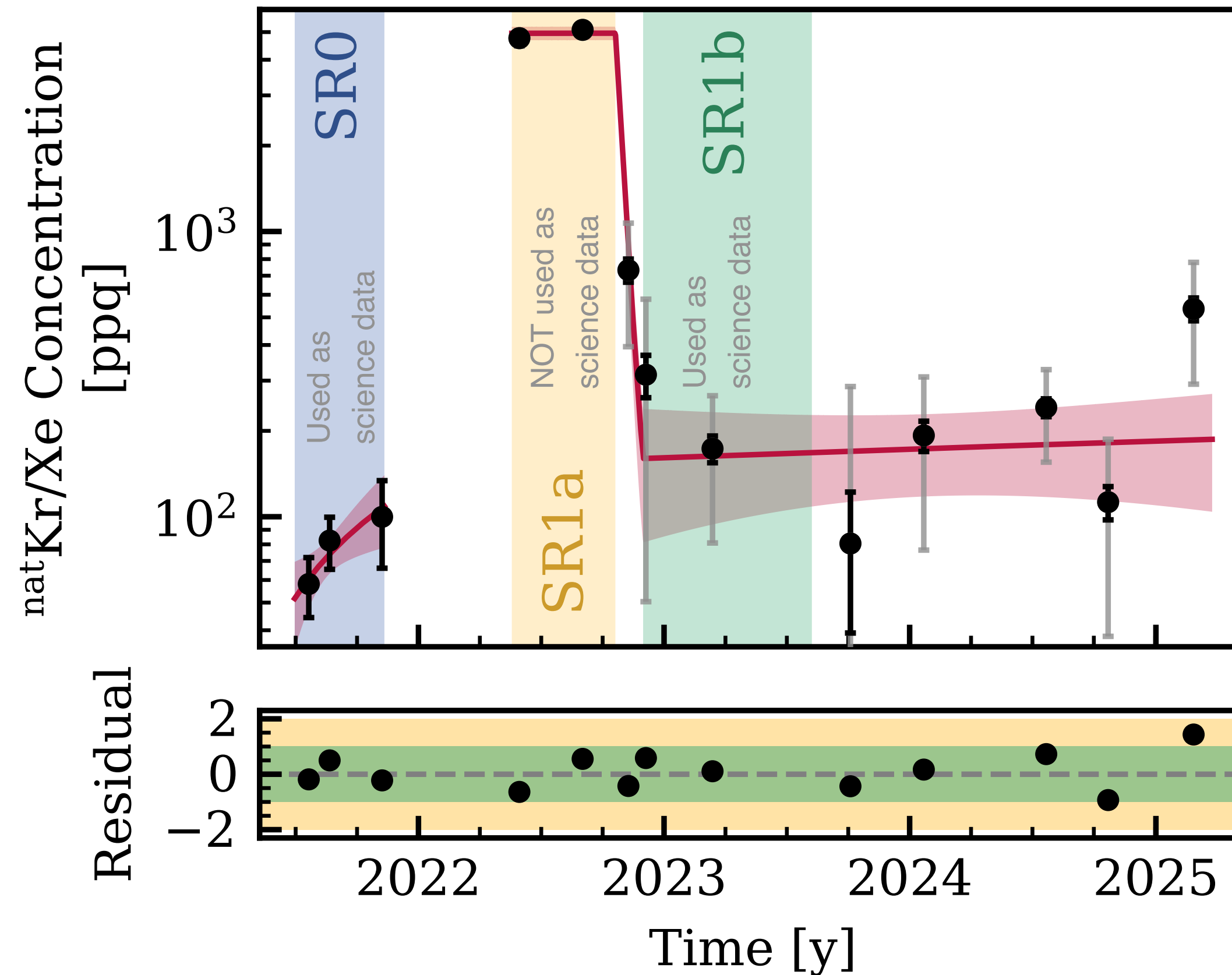
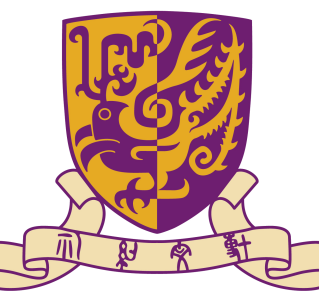
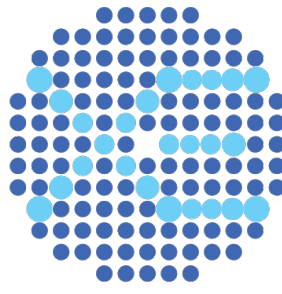


- Kr-85:
 - beta emitter, Q-value of 565 keV
 - Anthropogenic radioactive isotope
- Krypton distillation column: reduce Krypton by utilizing vapor pressure difference between krypton and xenon
 - “Reverse mode” of radon distillation column

XENON, EPJC 77,
275 (2017)

background

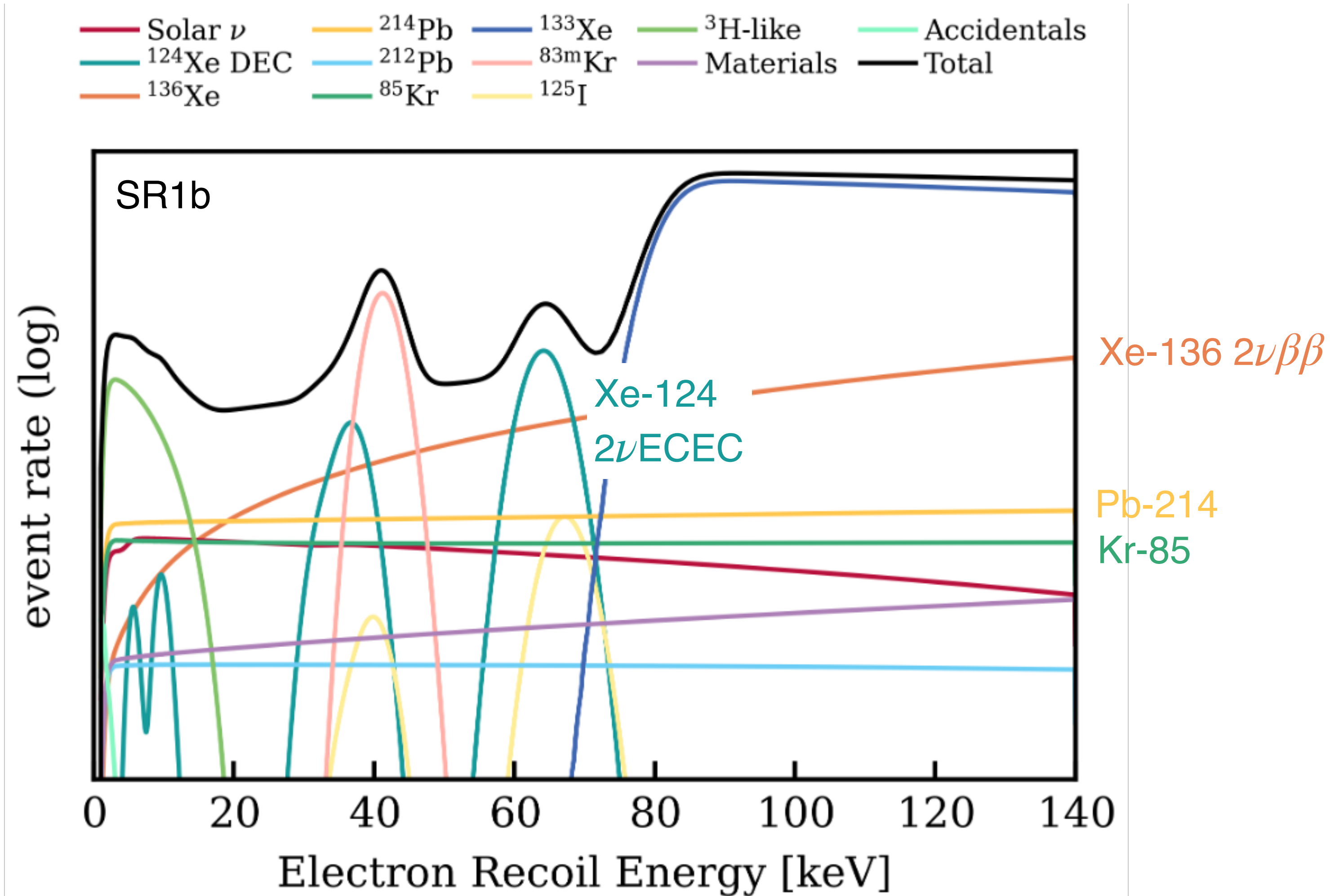
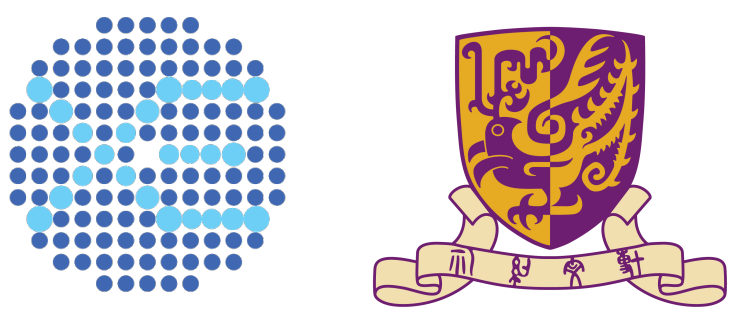
Kr85 background - constraint



- Constraint on Kr-85:
 - Natural Krypton measurement using rare gas mass spectrometer (RGMS)
 - Known abundance of Kr-85
- Conservative uncertainty from two fit modes (30-40%)

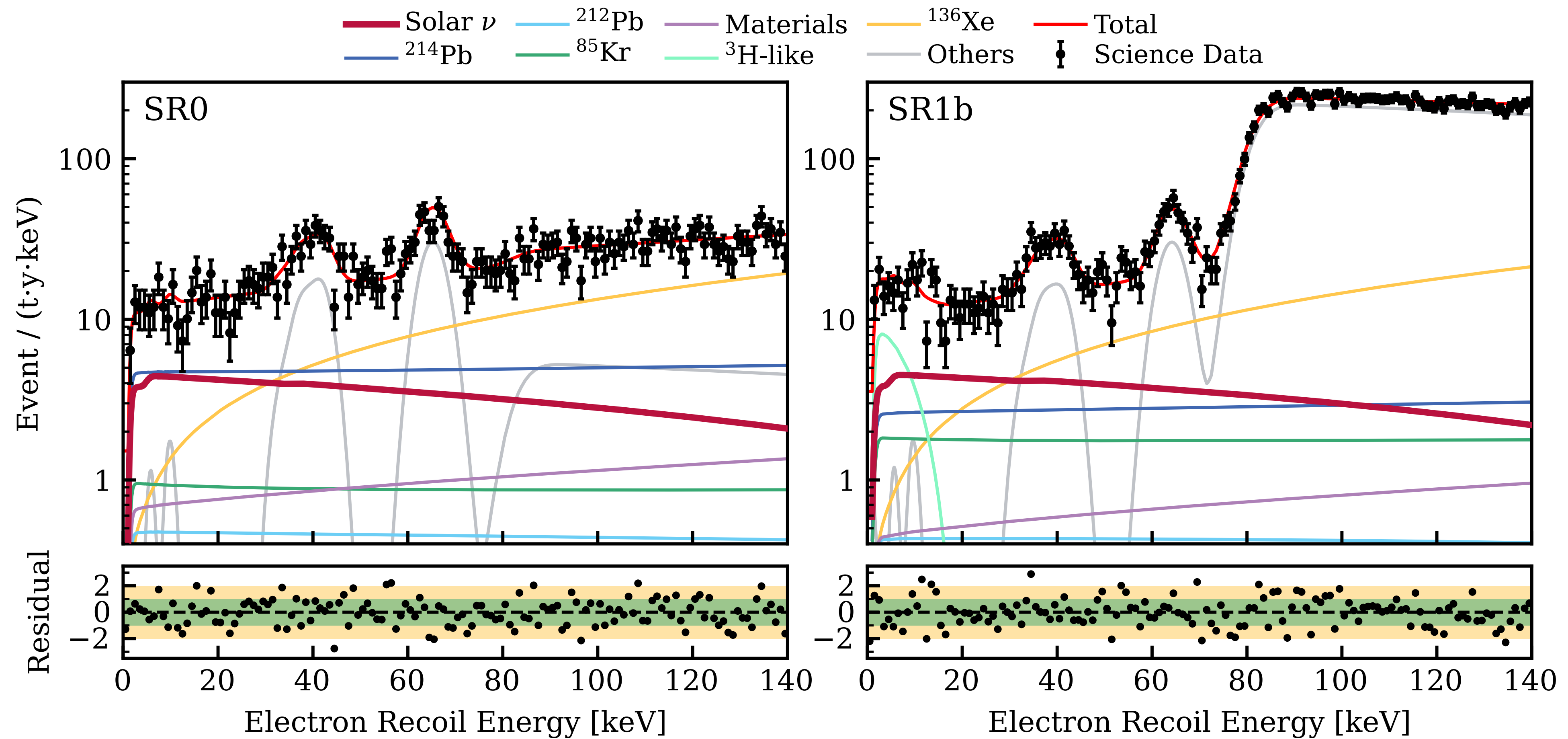
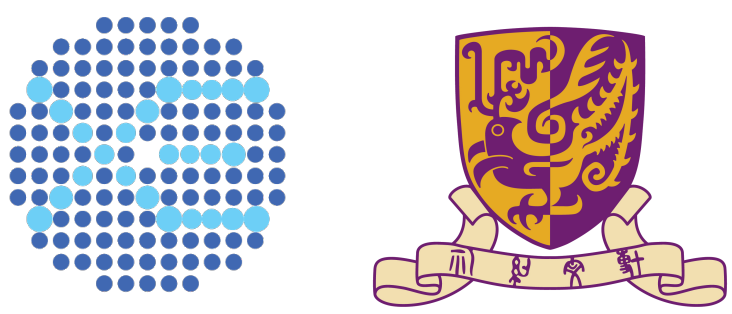
background

Background summary



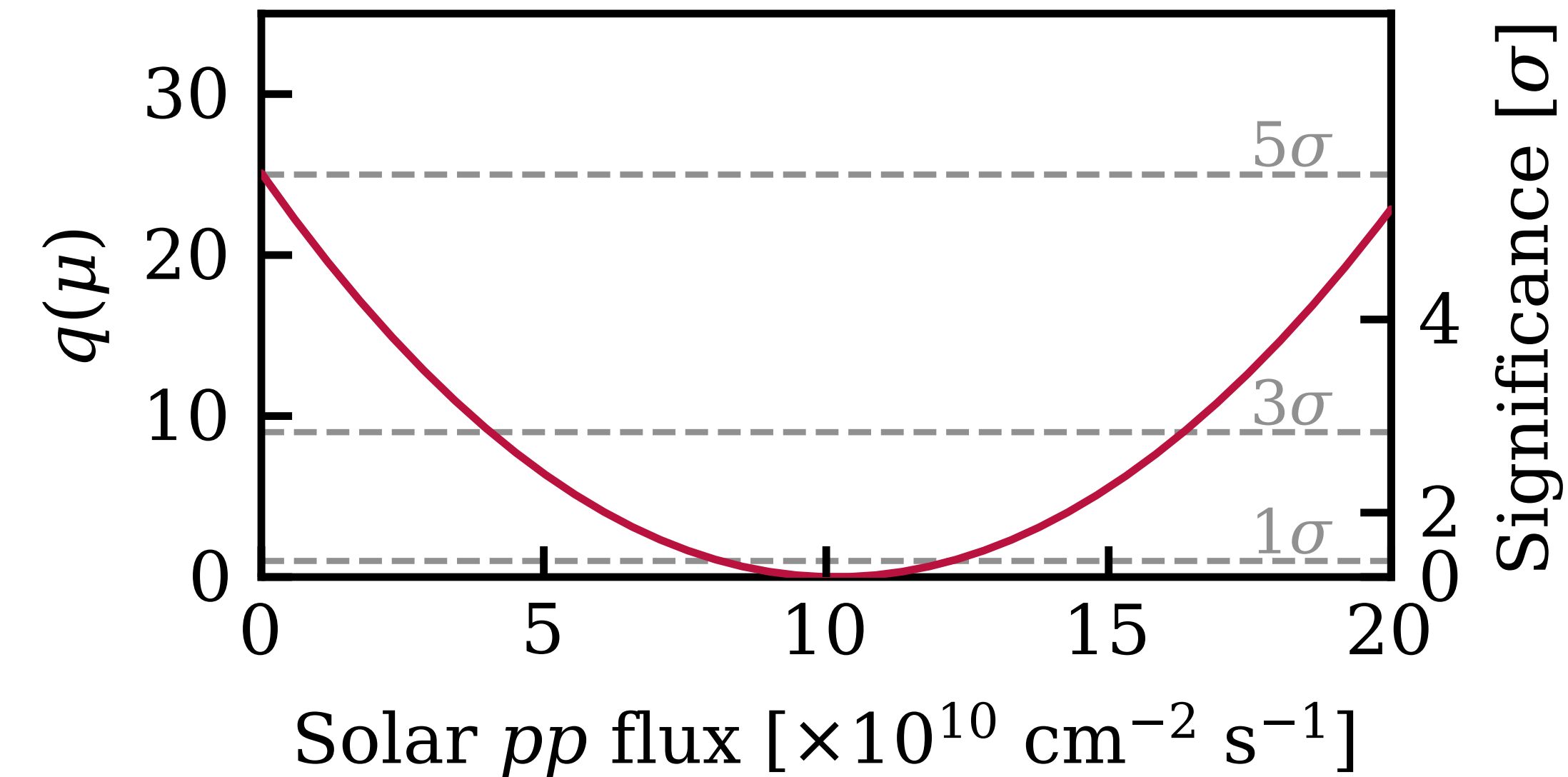
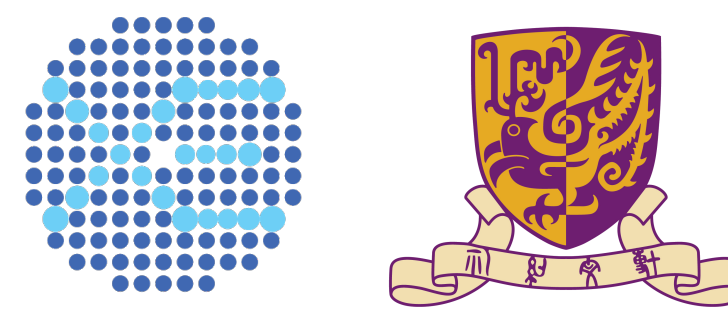
background

Fit to Data

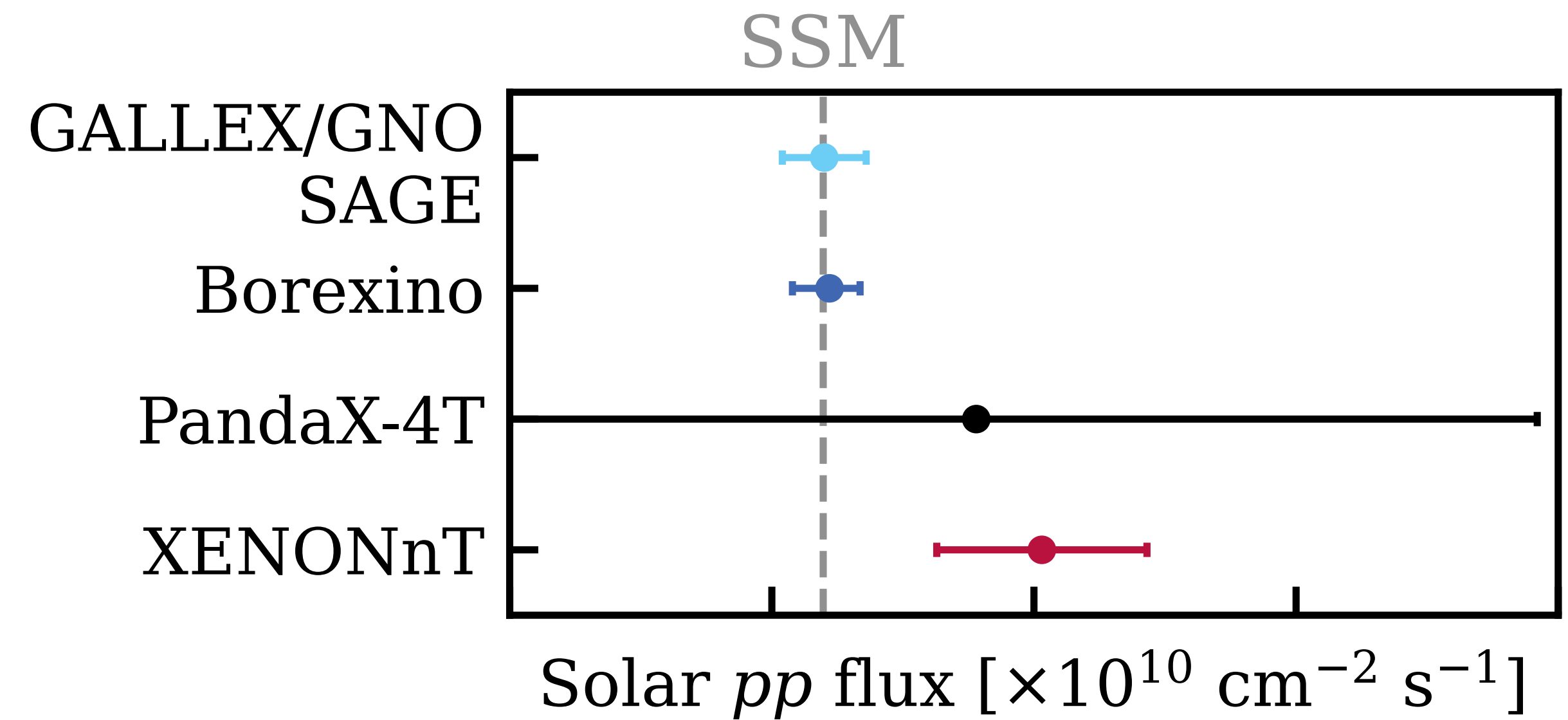


- Shared solar neutrino rate between SR1 and SR1b

Results



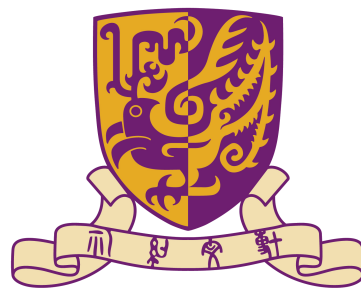
- Absence of solar neutrino-electron scattering is rejected at 5σ



- Measured solar pp flux as $(10.2 \pm 2.0) \times 10^{10} \text{ cm}^{-2} \text{ s}^{-1}$, by fixing ratio of Be-7 and pp neutrinos using HZ B16-GS98 SSM
- Solar pp measurement consistent with Borexino results at 1.9σ

* PandaX-4T submitted a new [pre-print](#) with solar pp flux measured as $(8.5 \pm 3.5) \times 10^{10} \text{ cm}^{-2} \text{ s}^{-1}$

“Solar pp neutrino experiment club”

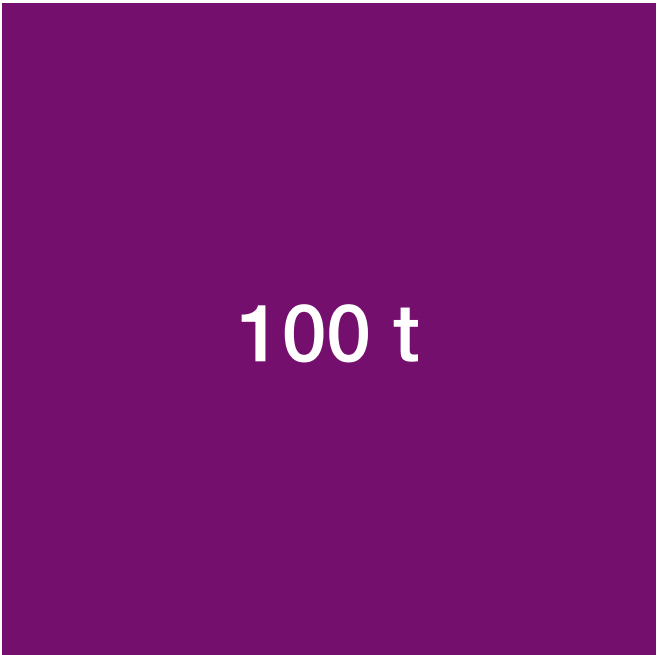
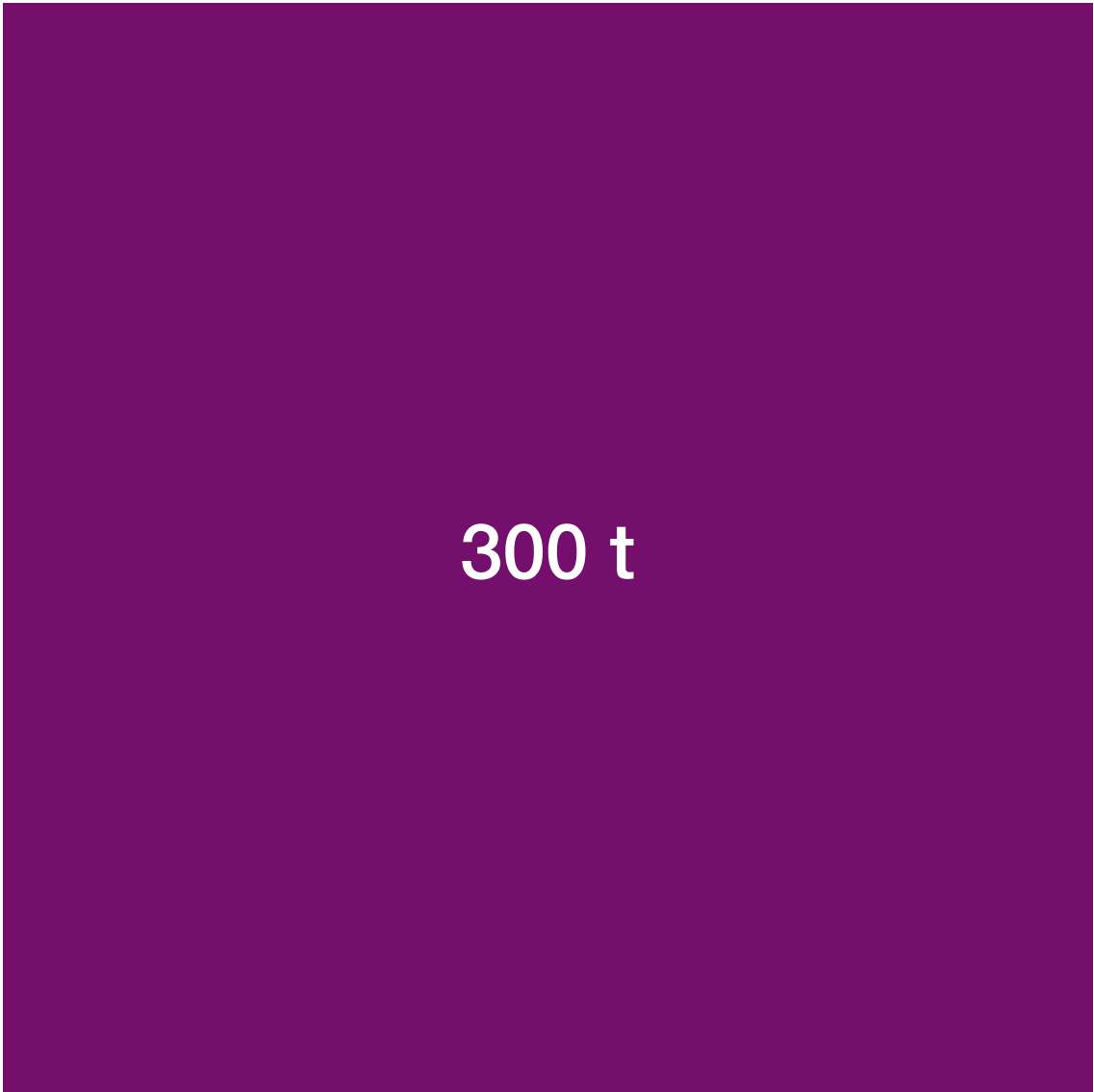


Borexino

GALLEX/GNO

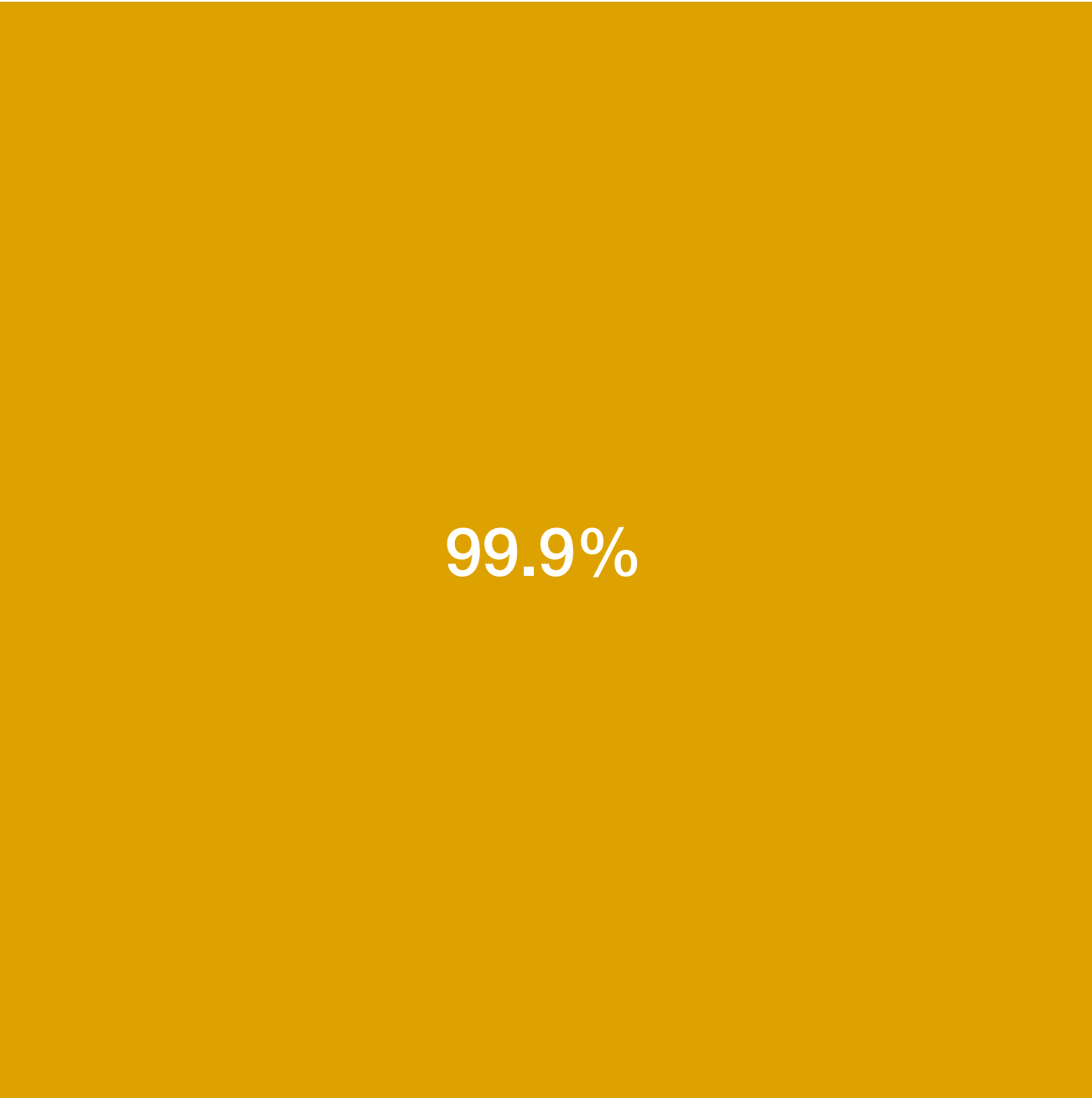
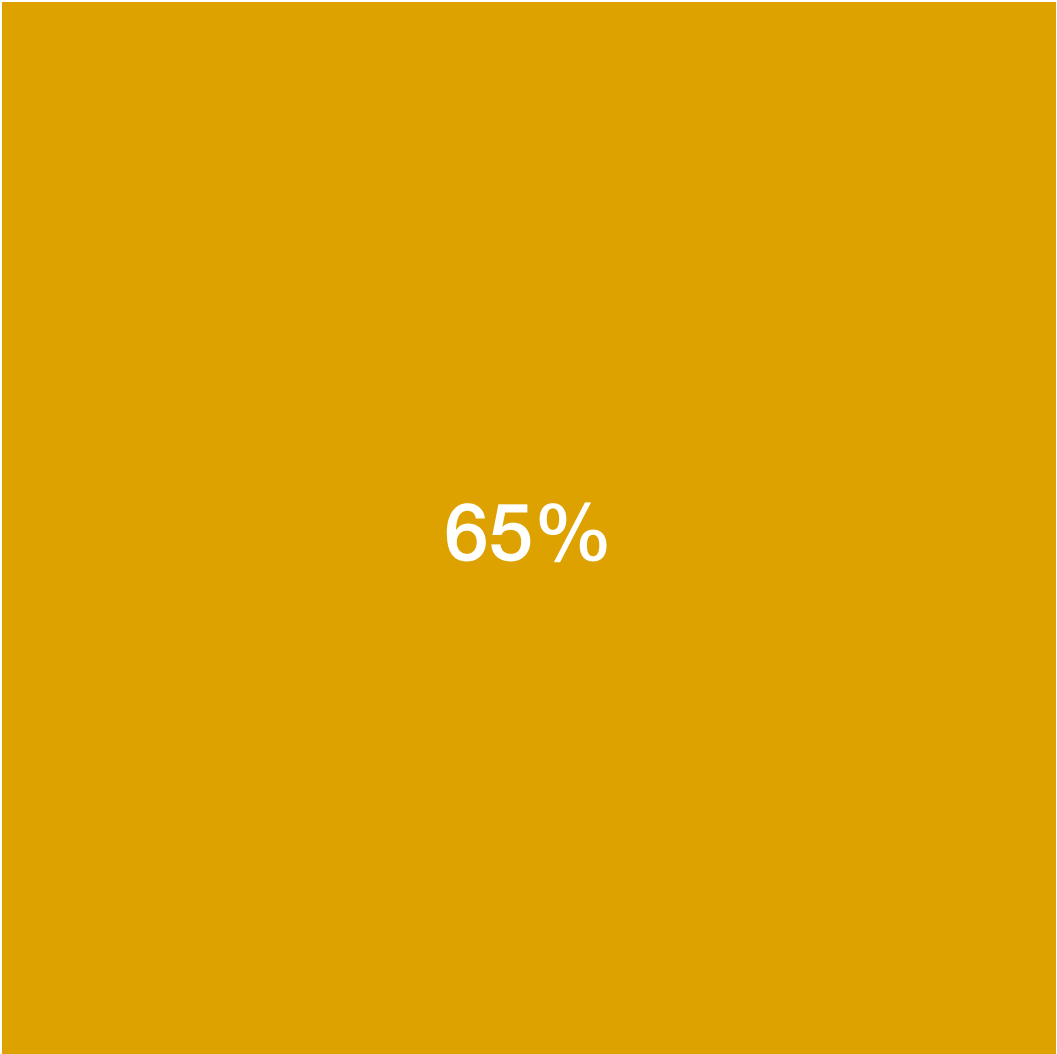
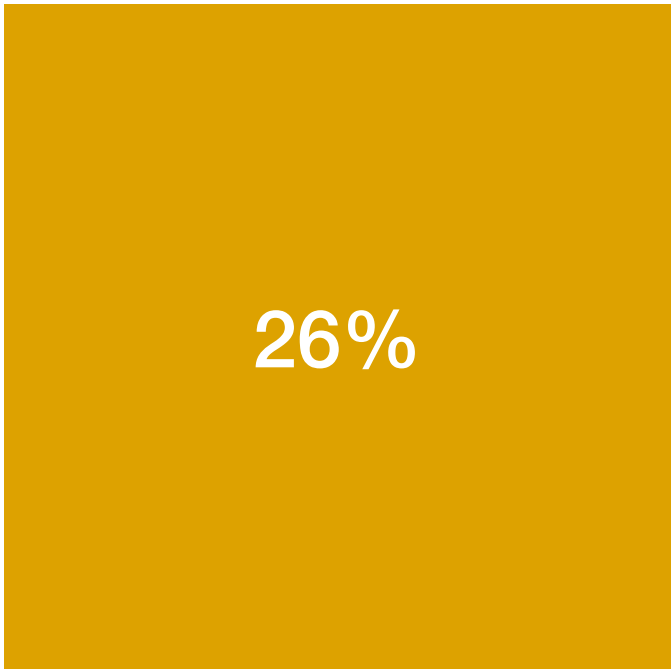
XENONnT

Target
Mass



Less is more

Solar pp
coverage



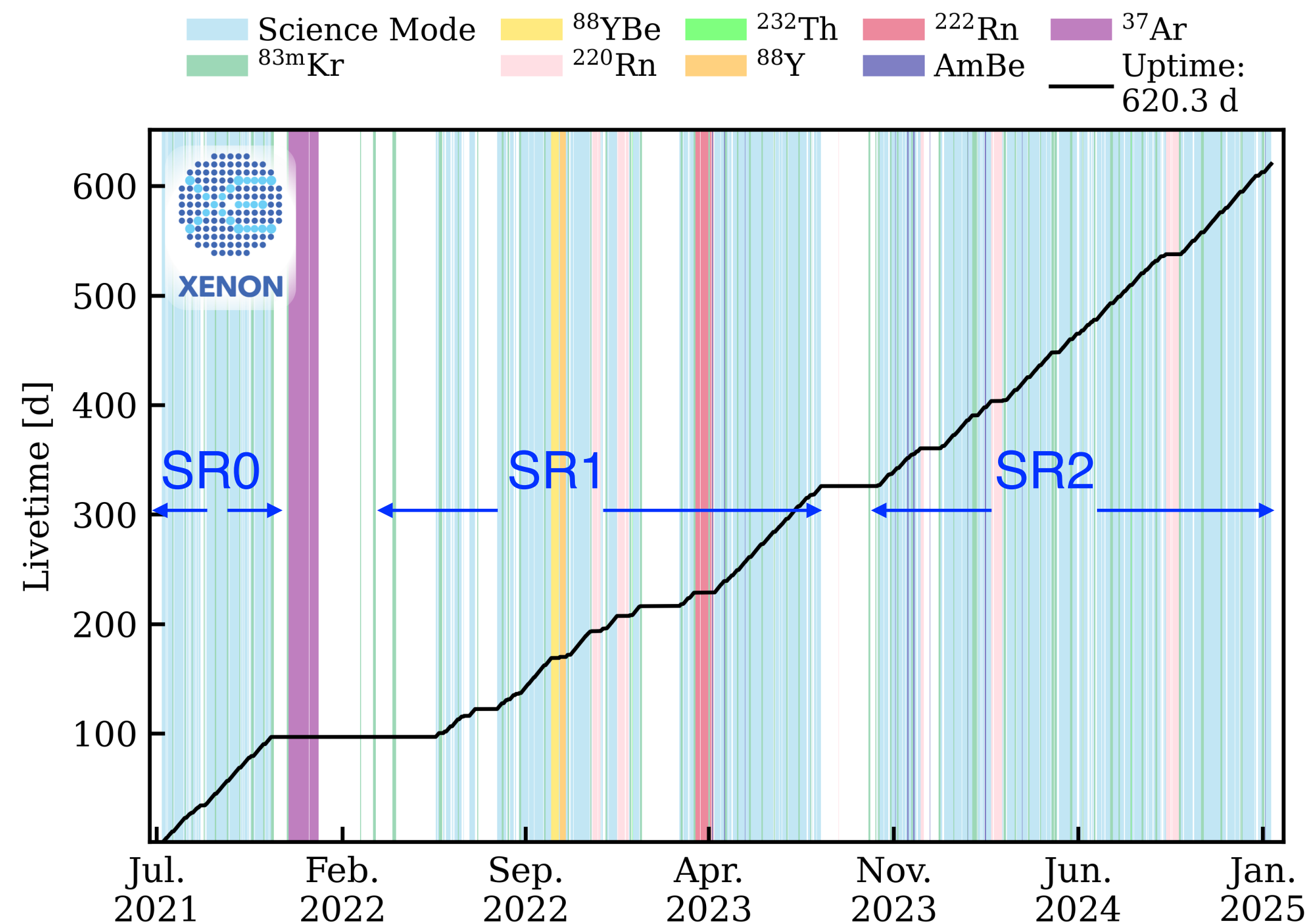
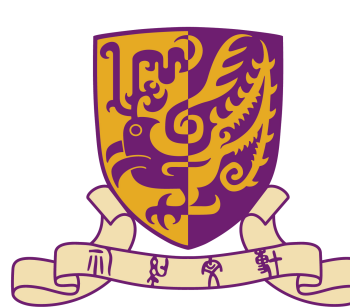
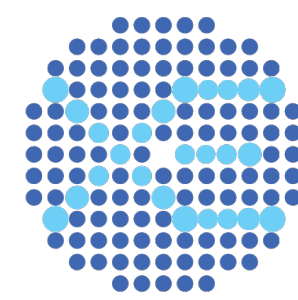
Calculated based on
neutrino energy threshold

335 keV

233 keV

17 keV

Outlook: more data & upgraded detector

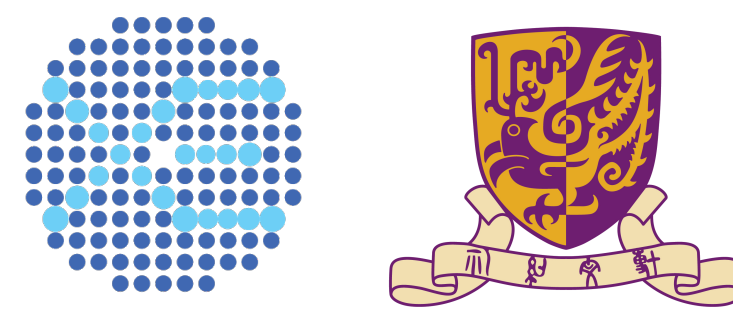


- SR2 is under similar condition of SR1b, and has ~280 days of data



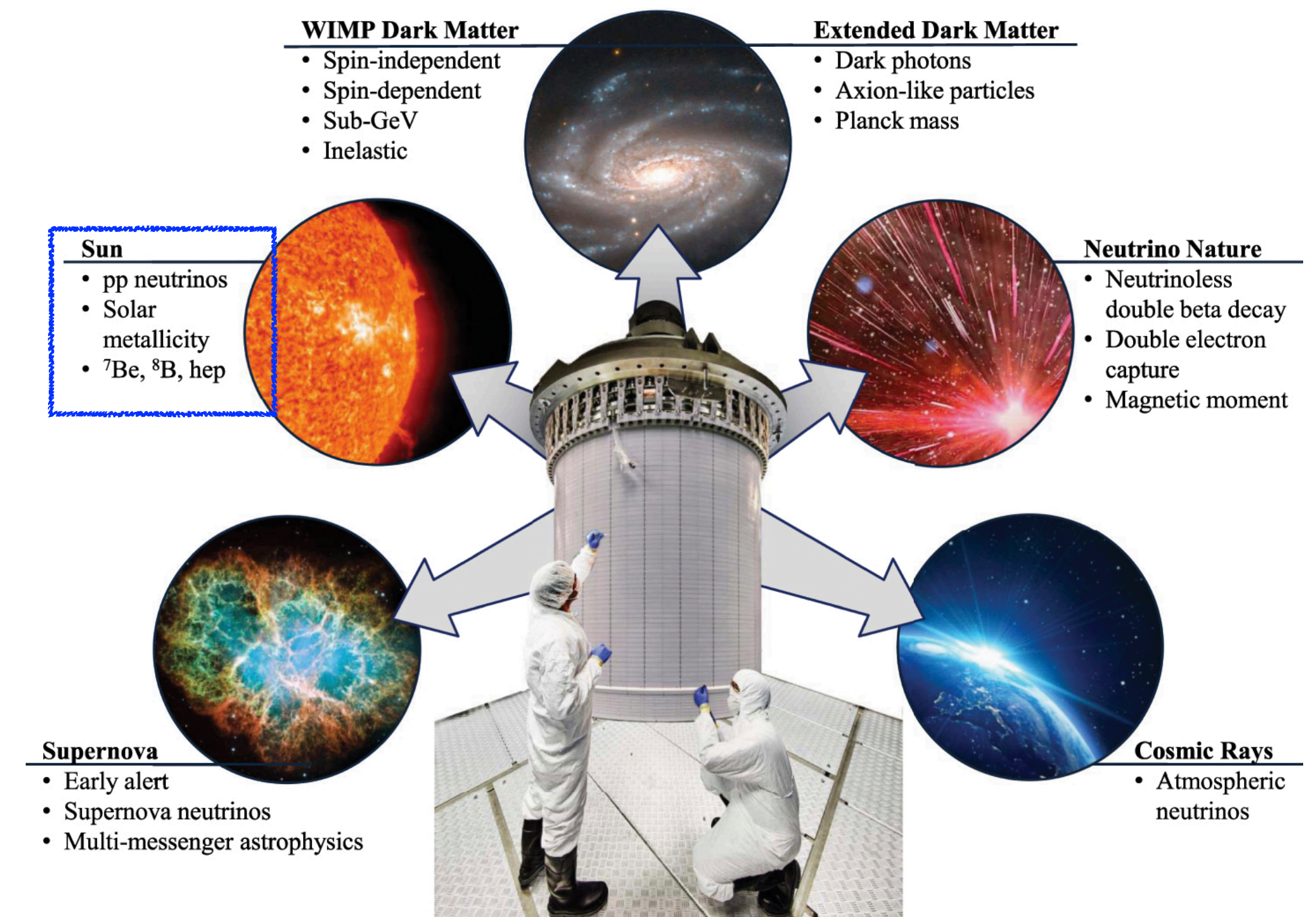
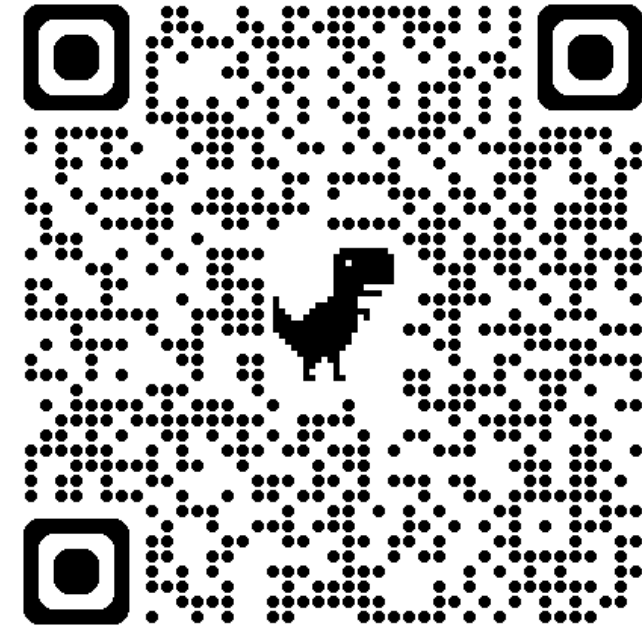
- “XENONnT 2.0” is under commissioning:
 - New electrodes
 - Replaced under performed PMTs
 - Improved stability

Summary



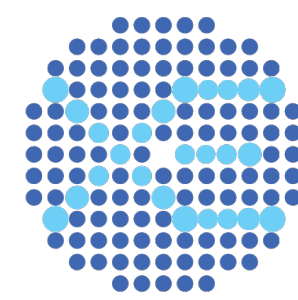
- XENONnT detected solar neutrinos via EvES at 5σ significance
 - The minimum detectable neutrino energy is 17 keV, the lowest to date
 - Measured solar pp flux: $(10.2 \pm 2.0) \times 10^{10} \text{ cm}^{-2} \text{ s}^{-1}$
- This is made possible due to extremely low backgrounds, low threshold, and decent exposure.
 - Particularly the further reduction and improved constraints on the dominant Pb-214 background

- Paper available today on arxiv
 - For now, scan QR code:

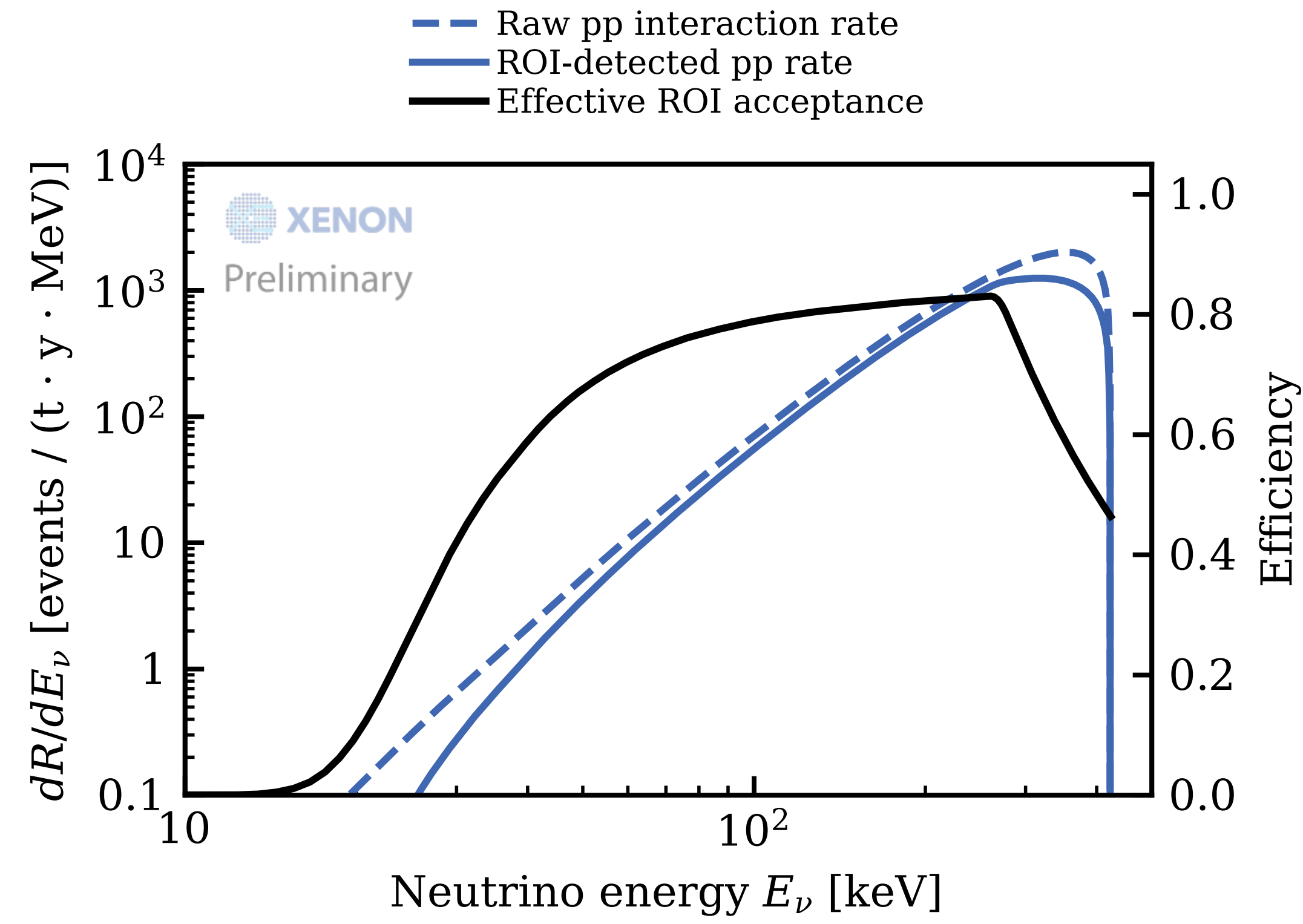
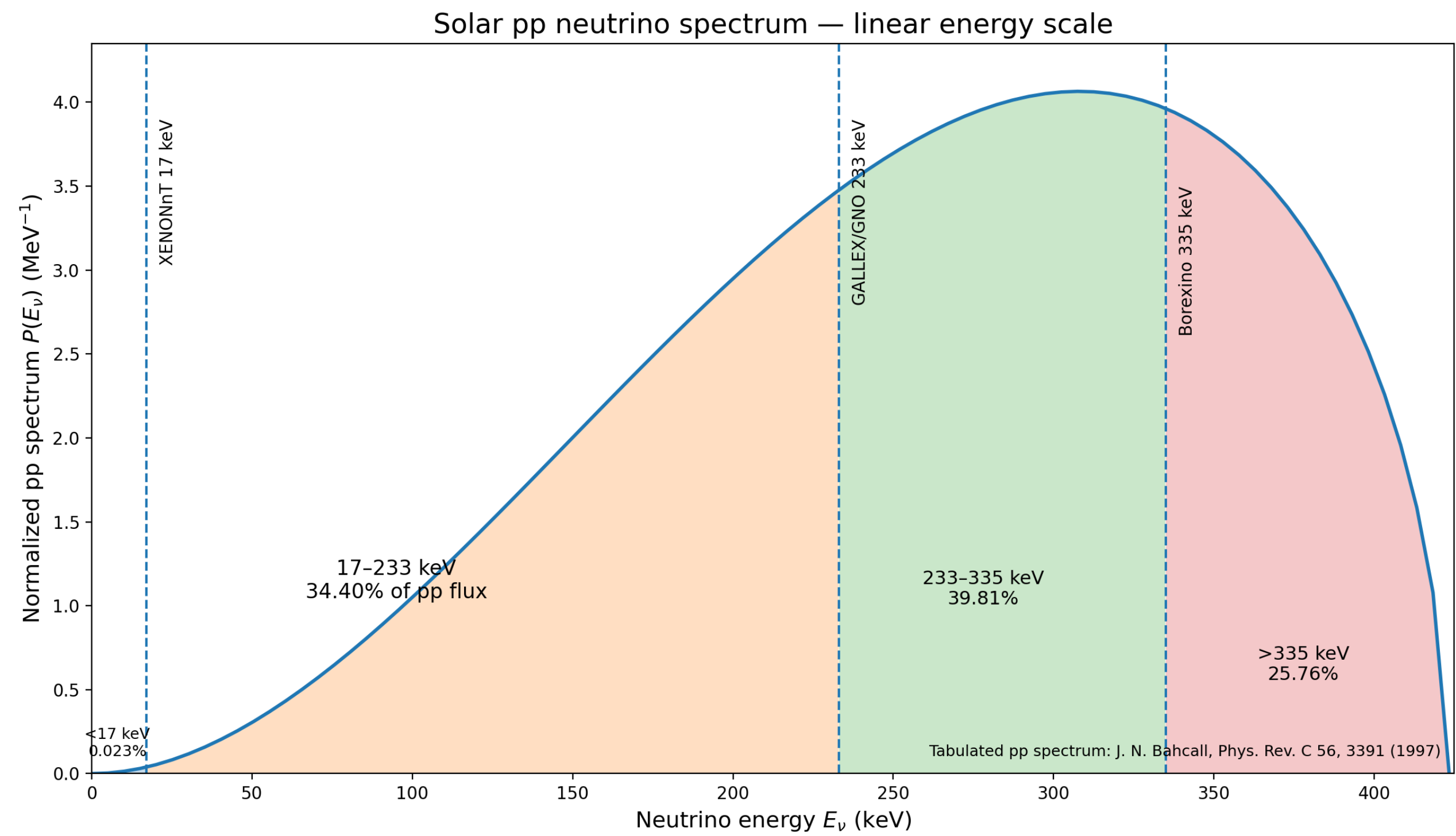
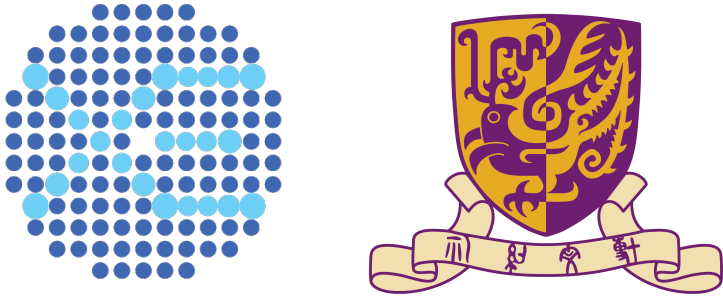


G3 white paper, J. Phys. G 50, 013001 (2023)

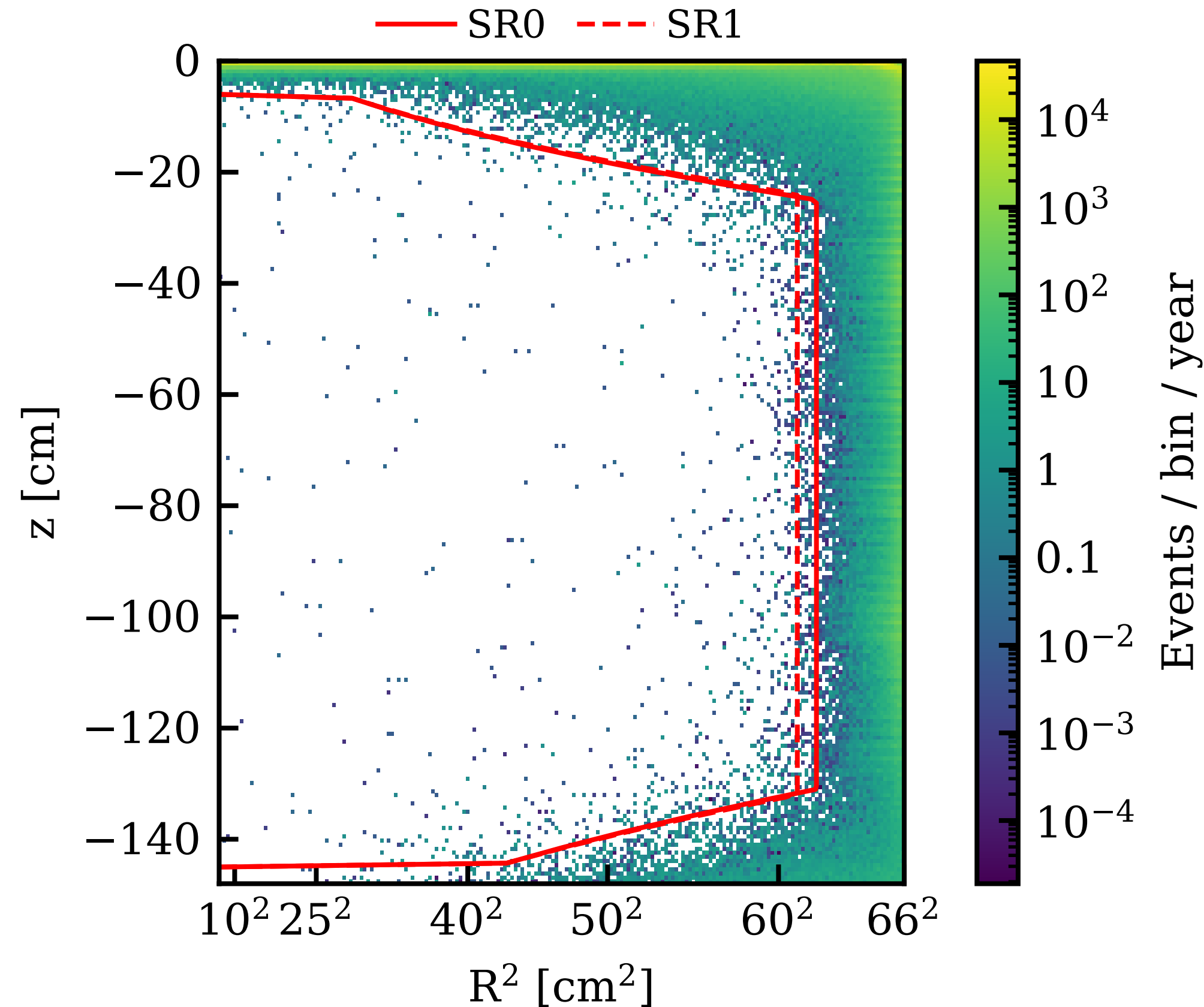
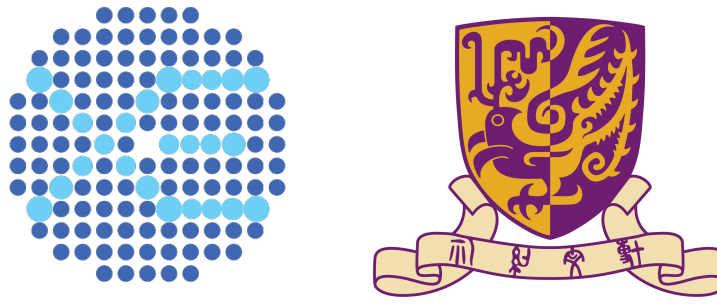
Back up



Solar pp detection

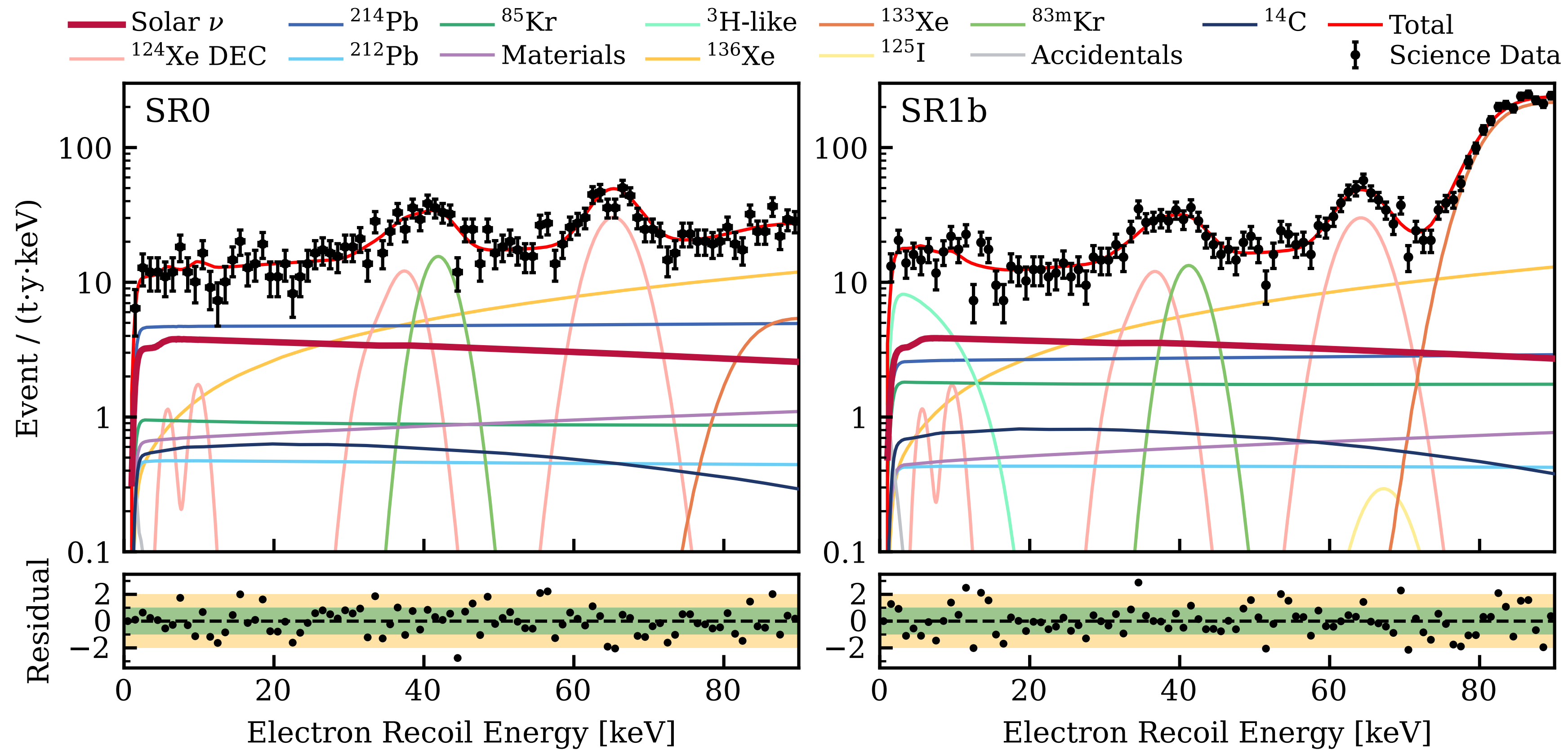
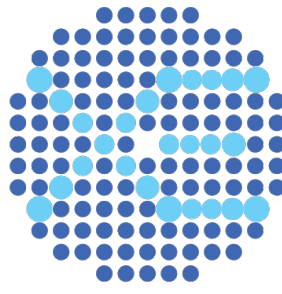


Fiducial volume

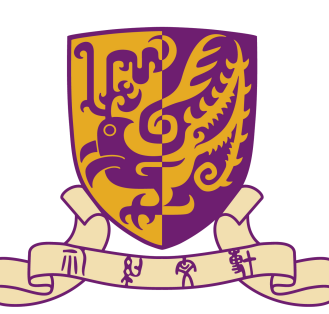


- The fiducial volume (FV) for this search is largely driven by material backgrounds.
- SR0 and SR1 FV share similar shapes, with the mass as follows:
 - SR0: (4.13 ± 0.12) tonne
 - SR1: (4.24 ± 0.13) tonne
- SR0 and SR1 have different ways to account for the charge-insensitive volume, which makes SR0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

C-14 background

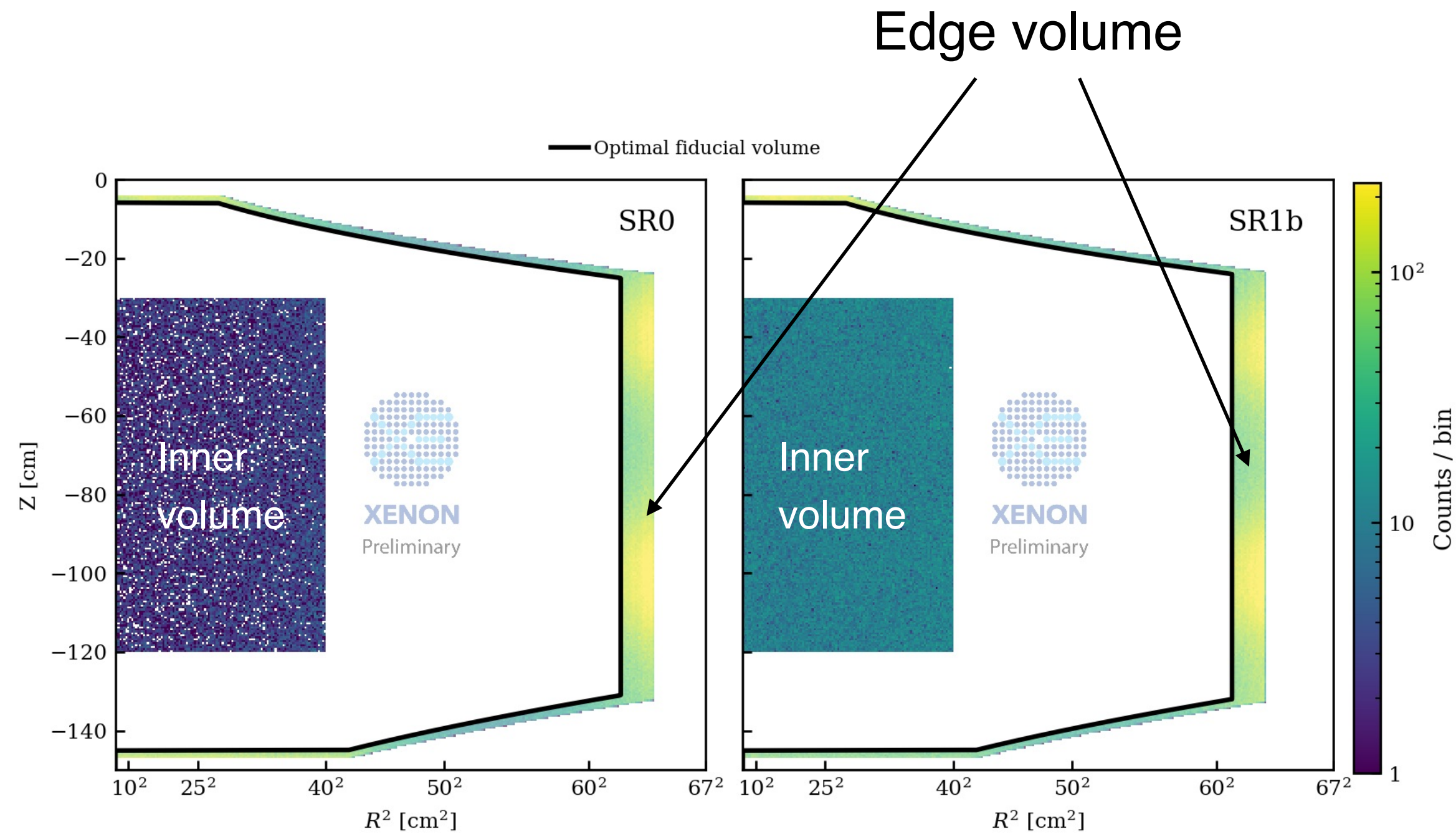
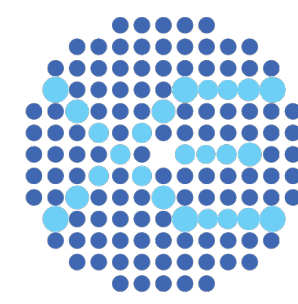


- C-14 beta decay has a Q-value of 156 keV, assumed to be introduced by CO₂ which has the highest conceivable concentration of 100 ppt, as quoted from gaseous purification systems
- Solar neutrino significance: 4.3σ
- Solar pp flux measurement: $(8.7^{+2.8}_{-2.1}) \times 10^{10} \text{ cm}^{-2}\text{s}^{-1}$, consistent with Borexino within 1.2σ

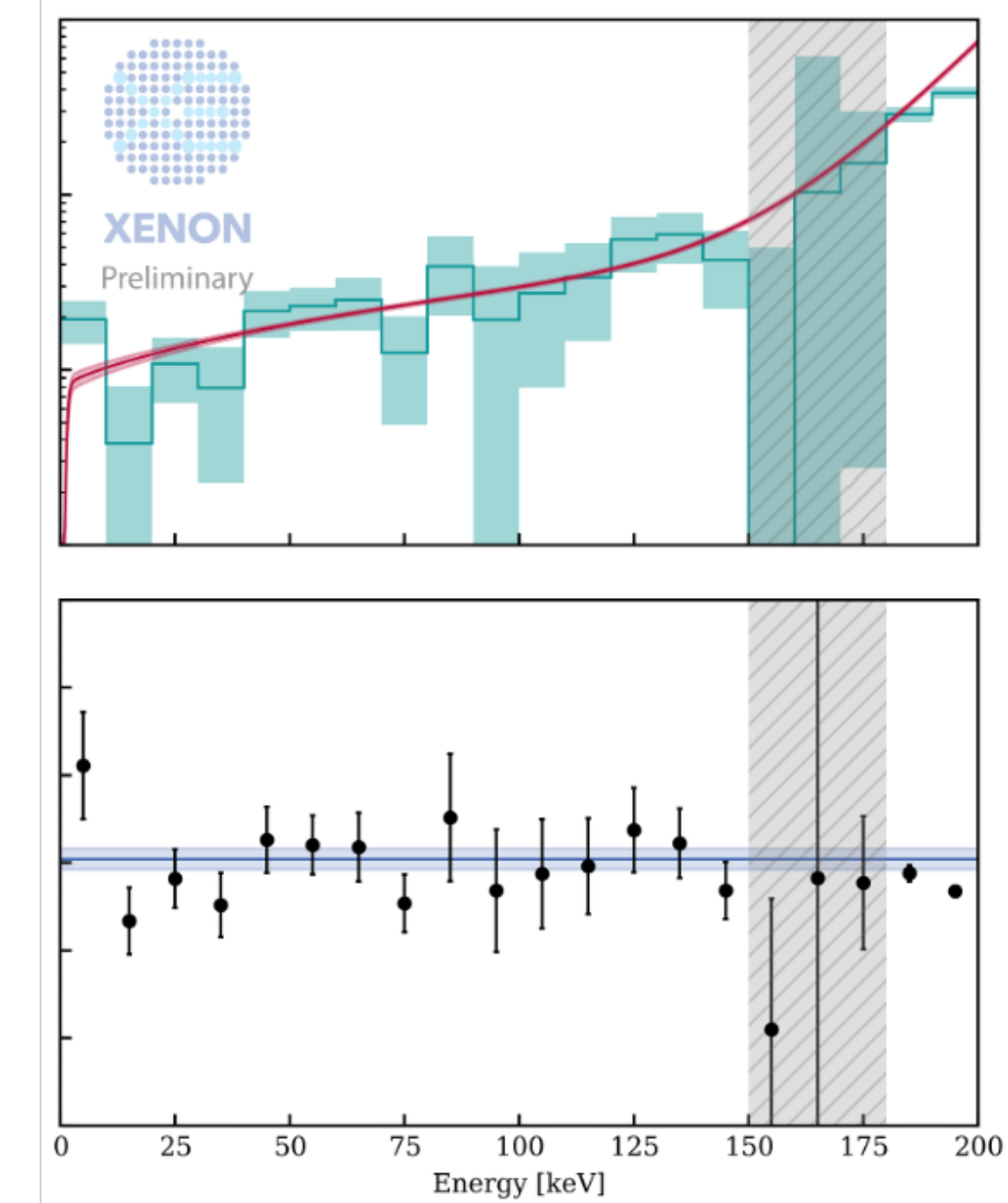


- Beta decay with Q-value of 565 keV
- 47-day Krypton distillation performed before SR1b
- Effective half-life of Ar during krypton distillation is 2.6 days
- Ar39 rate after Krypton distillation is expected to be < 0.1 events/(t y) within ROI (1, 140) keV $\rightarrow$ Negligible

Material background



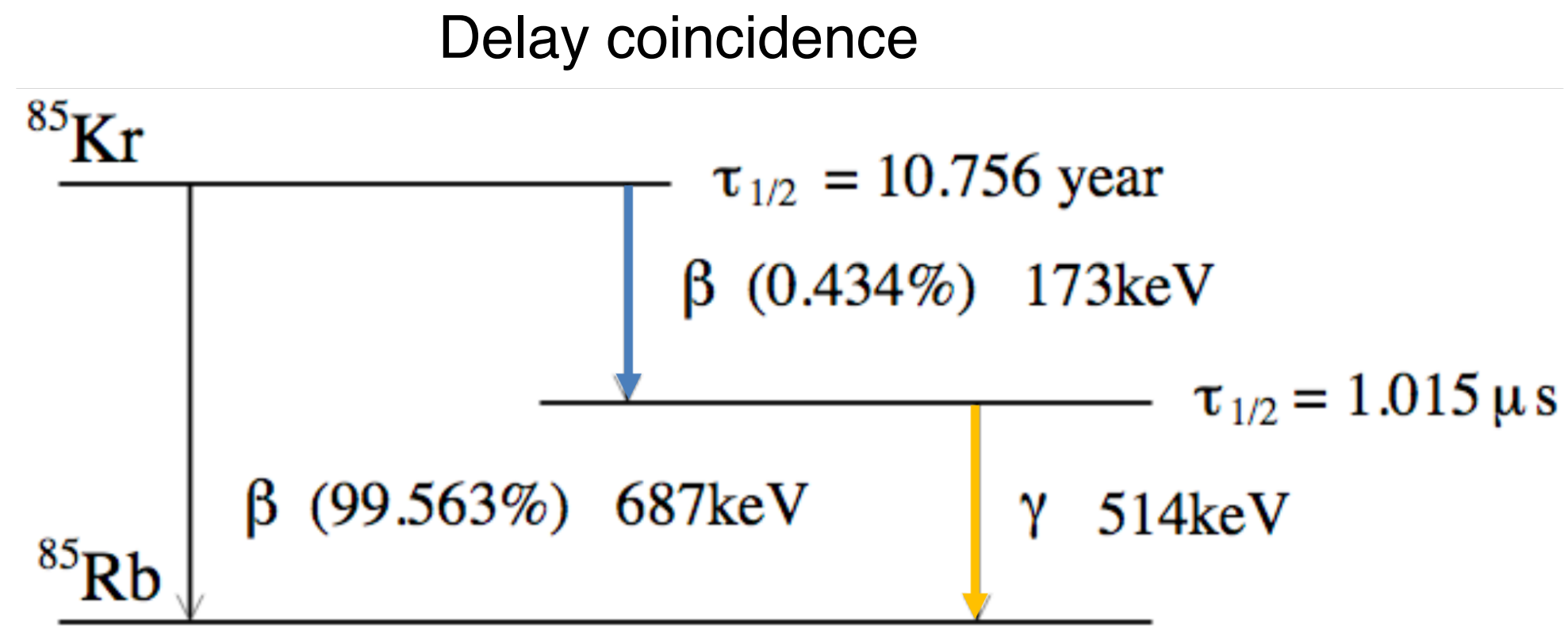
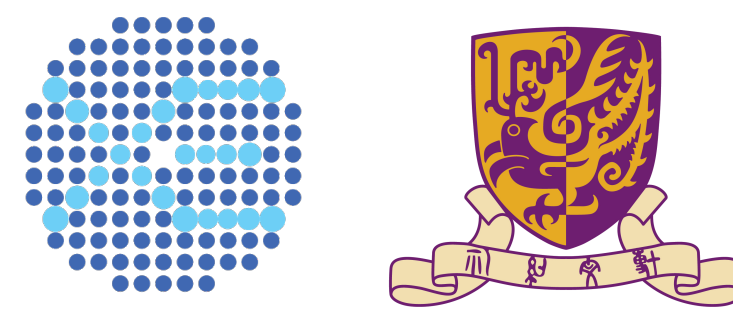
Data-MC comparison in edge volume



- Material backgrounds: Compton scattering of gammas from detector materials
- Reduction: careful material selection and screening [XENON, EPJC 82, 599 (2022)]
- Constraint: Data-MC comparison in the edge volume (2 cm outside FV), uncertainty level 12%
 - MC: simulation using screening inputs
 - Data: edge volume - inner volume

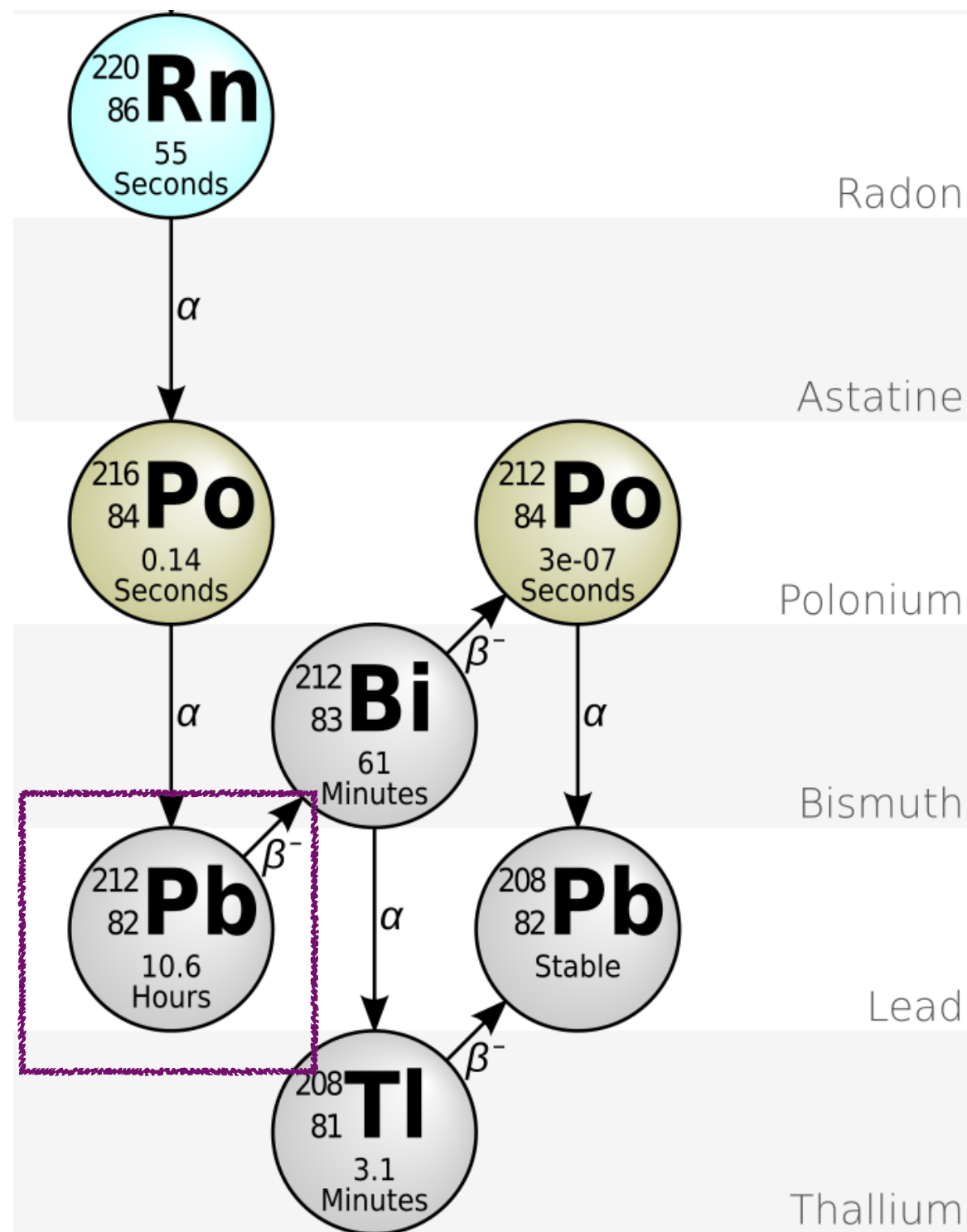
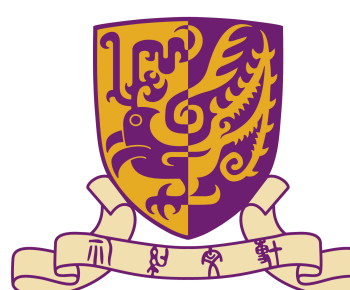
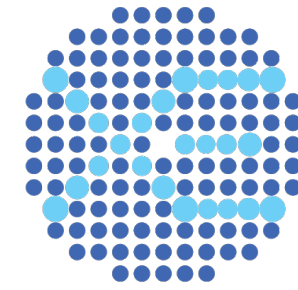
background

Kr85 constraint- delay coincidence

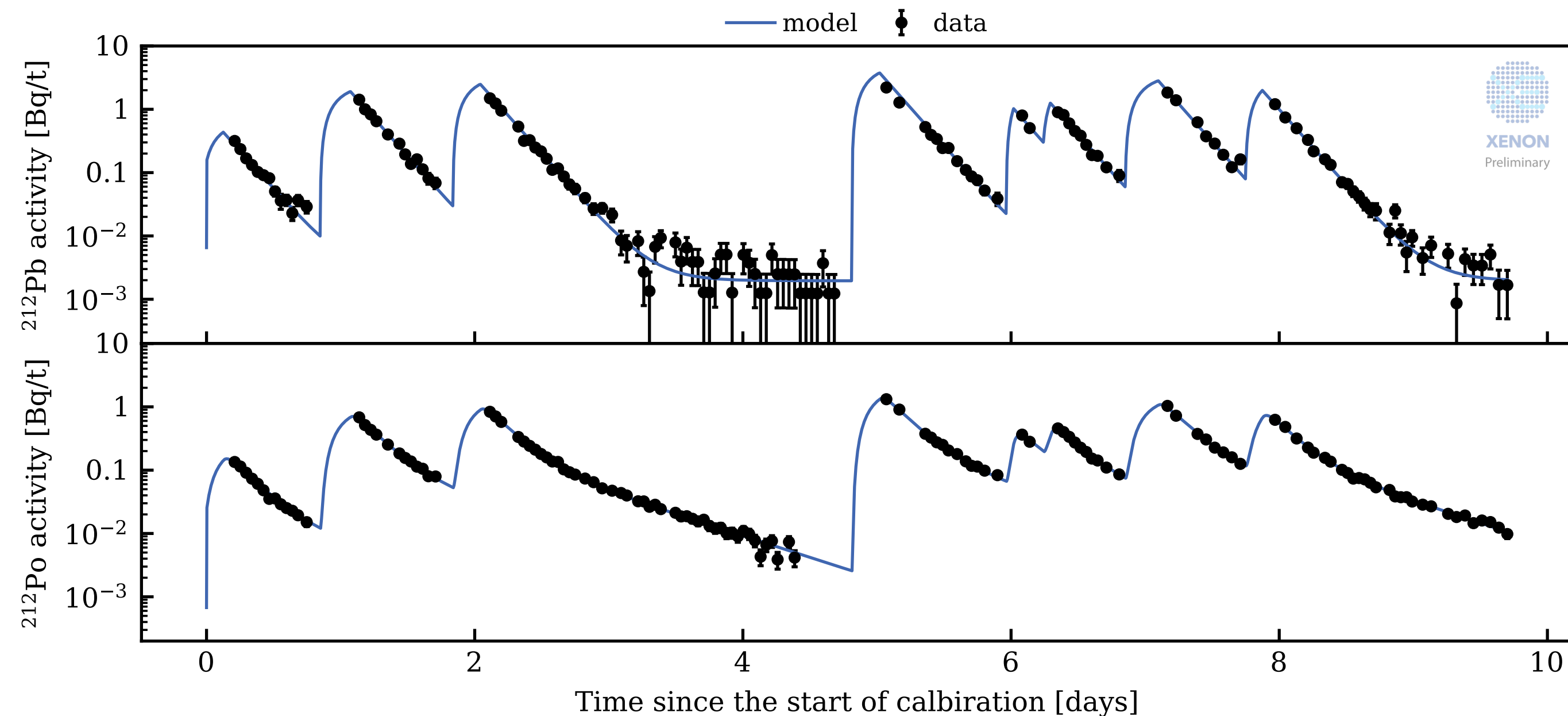


- RMGS Result consistent with delayed coincidence studies: 0.435% of ^{85}Kr decay into nuclear excited state
 - ▶ Y. Kaminaga, ICRR, The University of Tokyo (2024), Msc thesis
 - ▶ H. Schulze Eißing, Universität Münster (2026), PhD thesis

Pb212 background

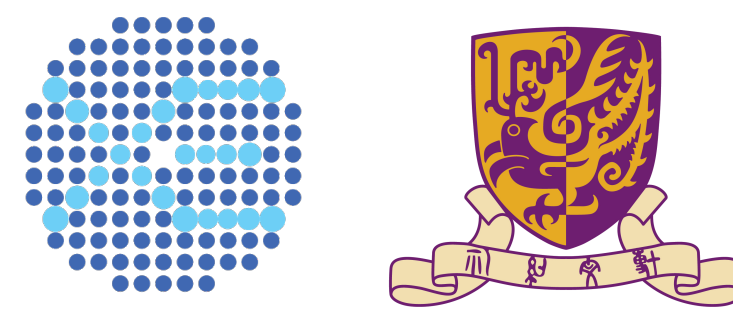


Rn-220 calibration

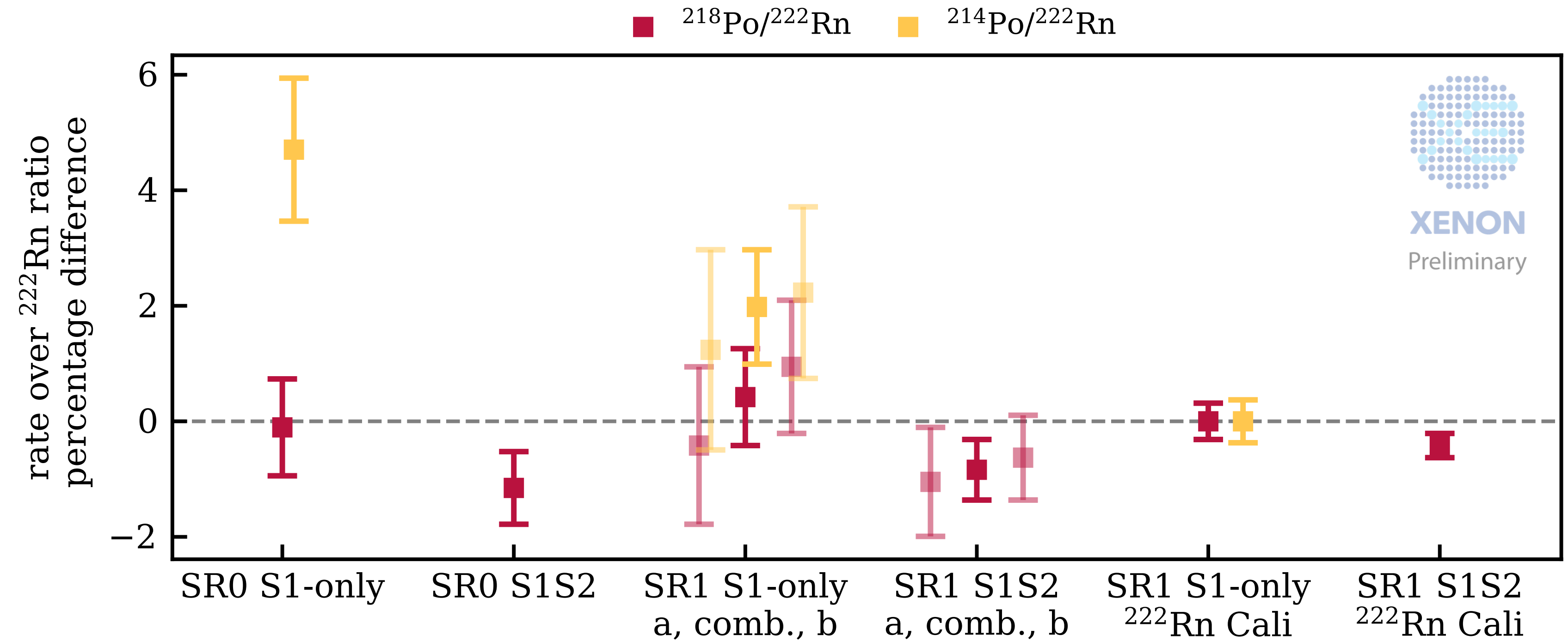
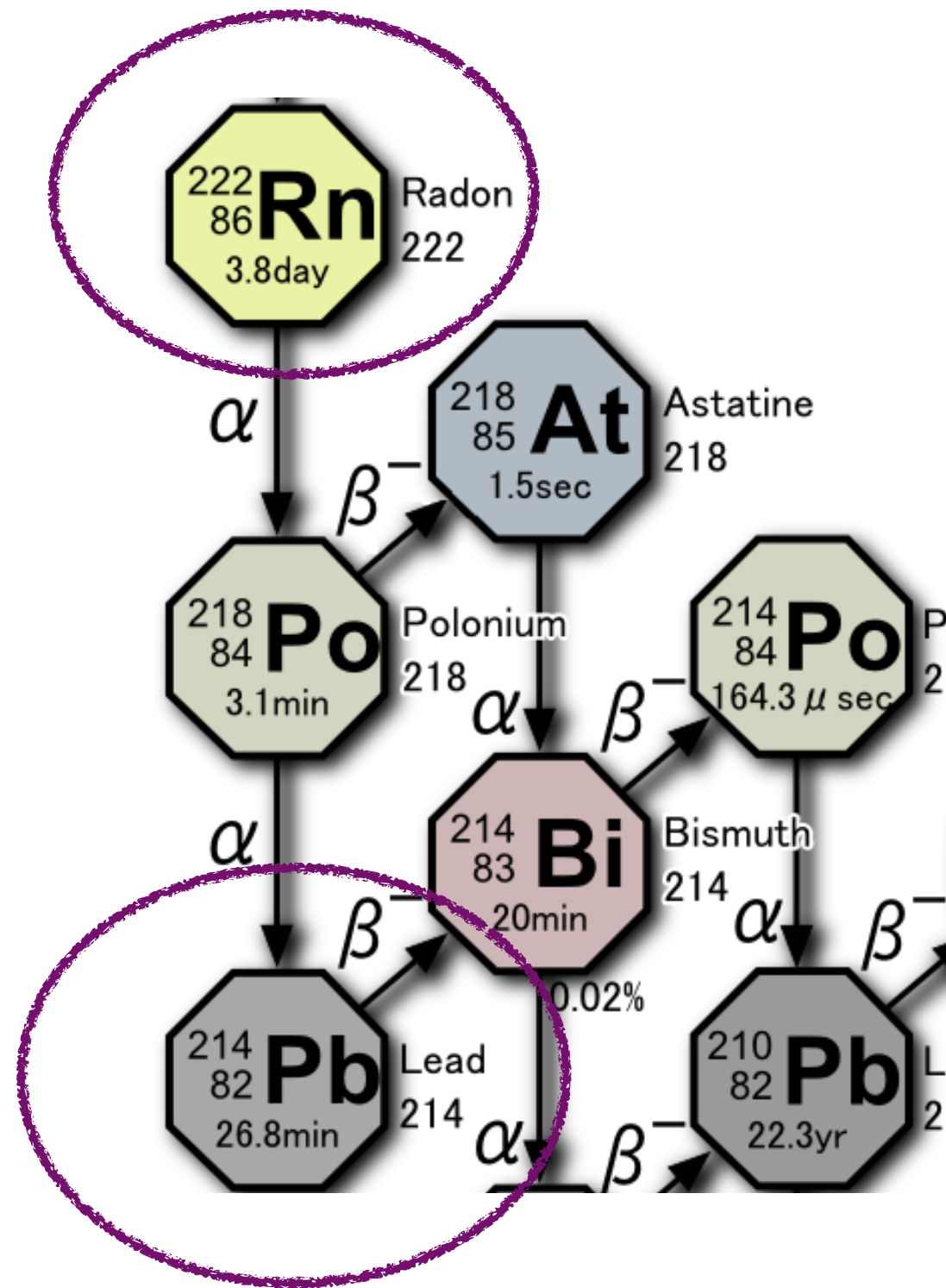


- Beta decay of Pb-212 from the Rn-220 decay chain could also contribute to ER background
- Pb-212 has relatively long half-life (10 hours) and may plate out on detector materials such as PTFE
- A plate out model is established using Rn-220 calibration data, which allows for constraining the Pb-212 background rate using the Rn-220 alpha rate that is easy to measure.

Plateout for Rn222 chain

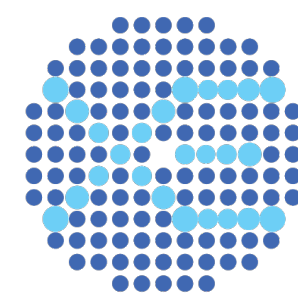


Rn-222 decay chain



- Po-214/Rn-222 ratio is (almost) consistent between SR0, SR1, and Rn-222 calibration in SR1
- Po-218/Rn-222 ratio is not consistent, which may indicate different plateout effects in different periods.

Uncertainty budget



	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