



香港中文大學(深圳)

The Chinese University of Hong Kong, Shenzhen



Status and Prospects of the RELICS Experiment

Jingqiang Ye (叶靖强)

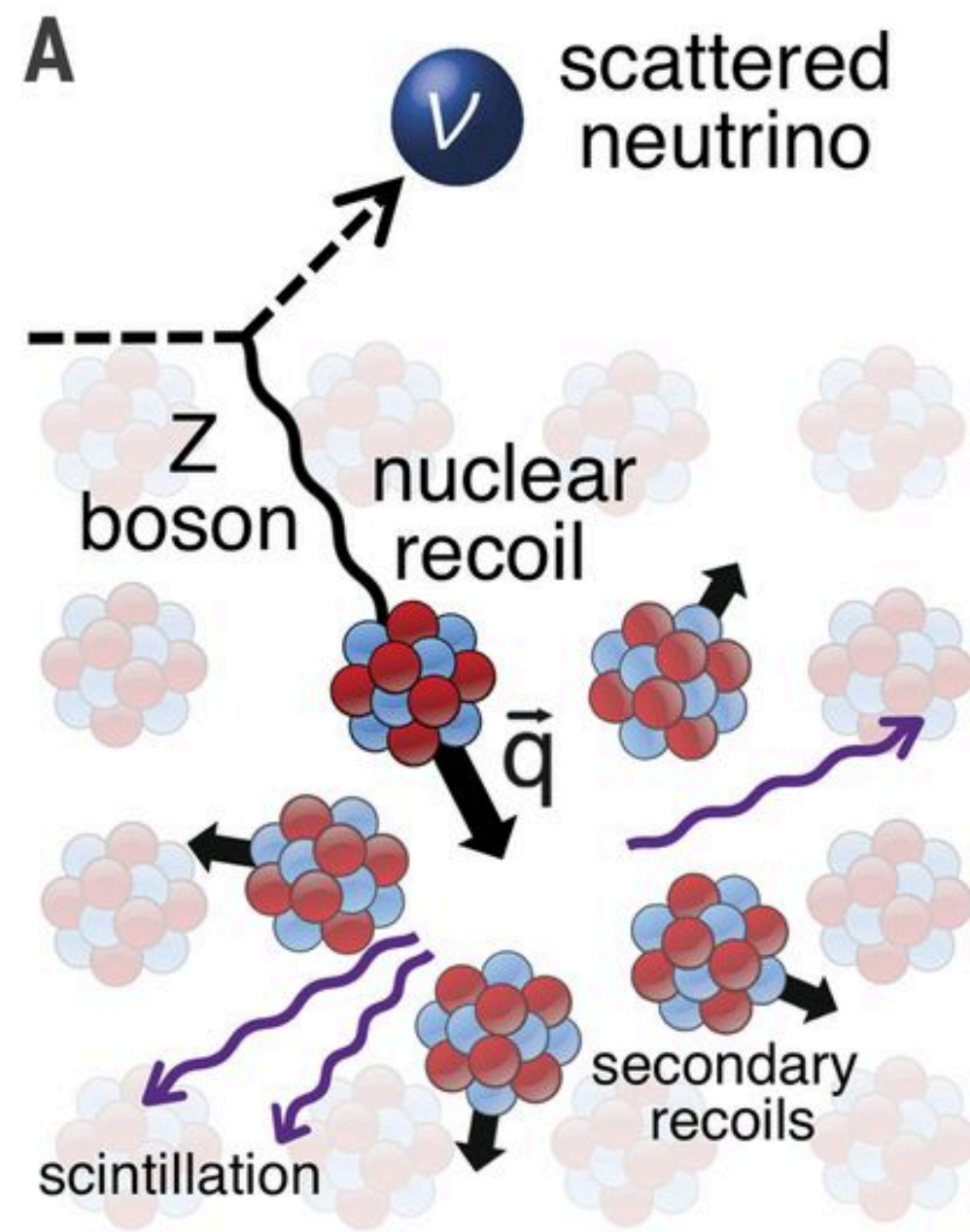
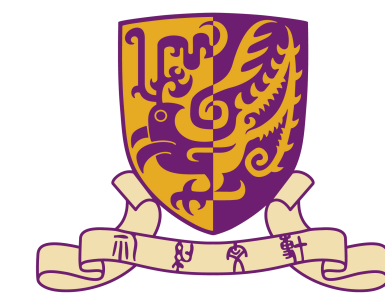
yejingqiang@cuhk.edu.cn

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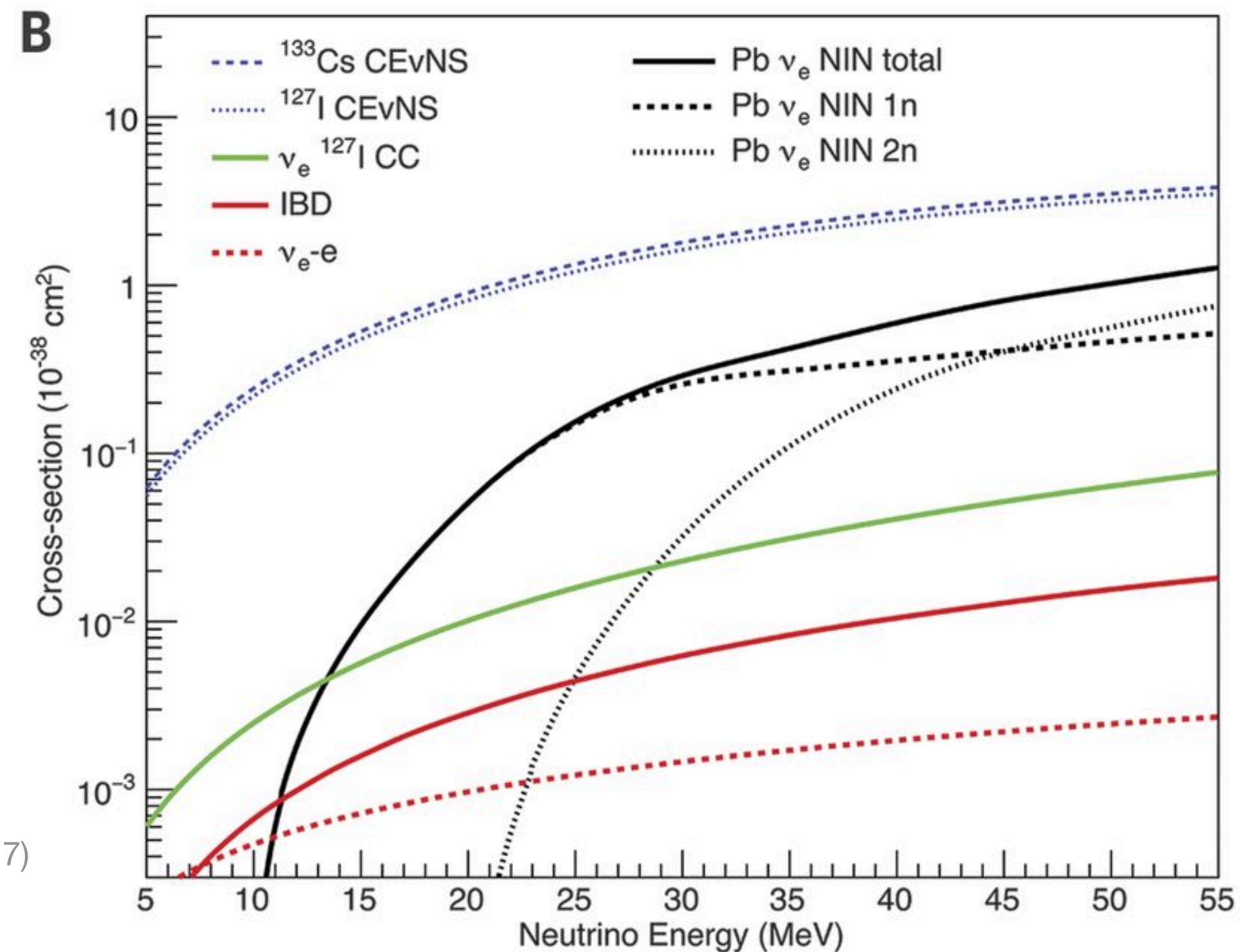
July 6th, 2026

CosPA 2026

Coherent Elastic Neutrino Nucleus Scattering



COHERENT, Science 357, 1123 (2017)



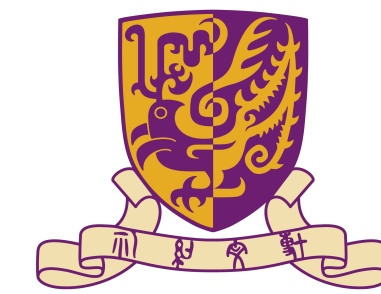
CEvNS

IBD

$\nu_e - e^-$

- Coherent Elastic ν Nucleus Scattering (CEvNS, pronounced 'sevens') is sensitive to all three flavors
- CEvNS happens when the transferred momentum corresponds to a wavelength ($\lambda \sim 1/\Delta p$) of a similar size to the nucleus.
- CEvNS cross-section: 3-4 OM higher than inverse beta decay (IBD) or $\nu_e - e^-$
- Standard Model process

An Act of Hubris



PHYSICAL REVIEW D

VOLUME 9, NUMBER 5

1 MARCH 1974

Coherent effects of a weak neutral current

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(Received 15 October 1973; revised manuscript received 19 November 1973)

If there is a weak neutral current, then the elastic scattering process $\nu + A \rightarrow \nu + A$ should have a sharp coherent forward peak just as $e + A \rightarrow e + A$ does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The experiments are very difficult, although the estimated cross sections (about 10^{-38} cm² on carbon) are favorable. The coherent cross sections (in contrast to incoherent) are almost energy-independent. Therefore, energies as low as 100 MeV may be suitable. Quasi-coherent nuclear excitation processes $\nu + A \rightarrow \nu + A^*$ provide possible tests of the conservation of the weak neutral current. Because of strong coherent effects at very low energies, the nuclear elastic scattering process may be important in inhibiting cooling by neutrino emission in stellar collapse and neutron stars.

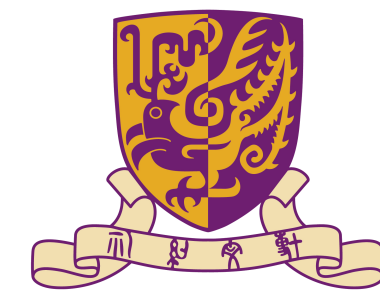
Our suggestion may be an act of hubris, because the inevitable constraints of interaction rate, resolution, and background pose grave experimental difficulties for elastic neutrino-nucleus scattering. We will discuss these problems at the end of this note, but first we wish to present the theoretical ideas relevant to the experiments.



Daniel Freedman (1939 -)

Challenges: low energy threshold and low backgrounds

$CE_{\nu}NS$ as a Probe for Many



- **Particle physics**
 - Weak mixing angle at low momentum transfer
 - Neutrino non-standard interaction (NSI)
 - Neutrino magnetic moment
- **Astrophysics**
 - New approaches to detect solar neutrinos and supernova neutrinos
 - Irreducible backgrounds for dark matter search (“neutrino fog”)
- **Nuclear physics**
 - Nuclear form factor
- **Reactor physics**
 - Minimization for reactor neutrino detector
 - Reactor safeguard

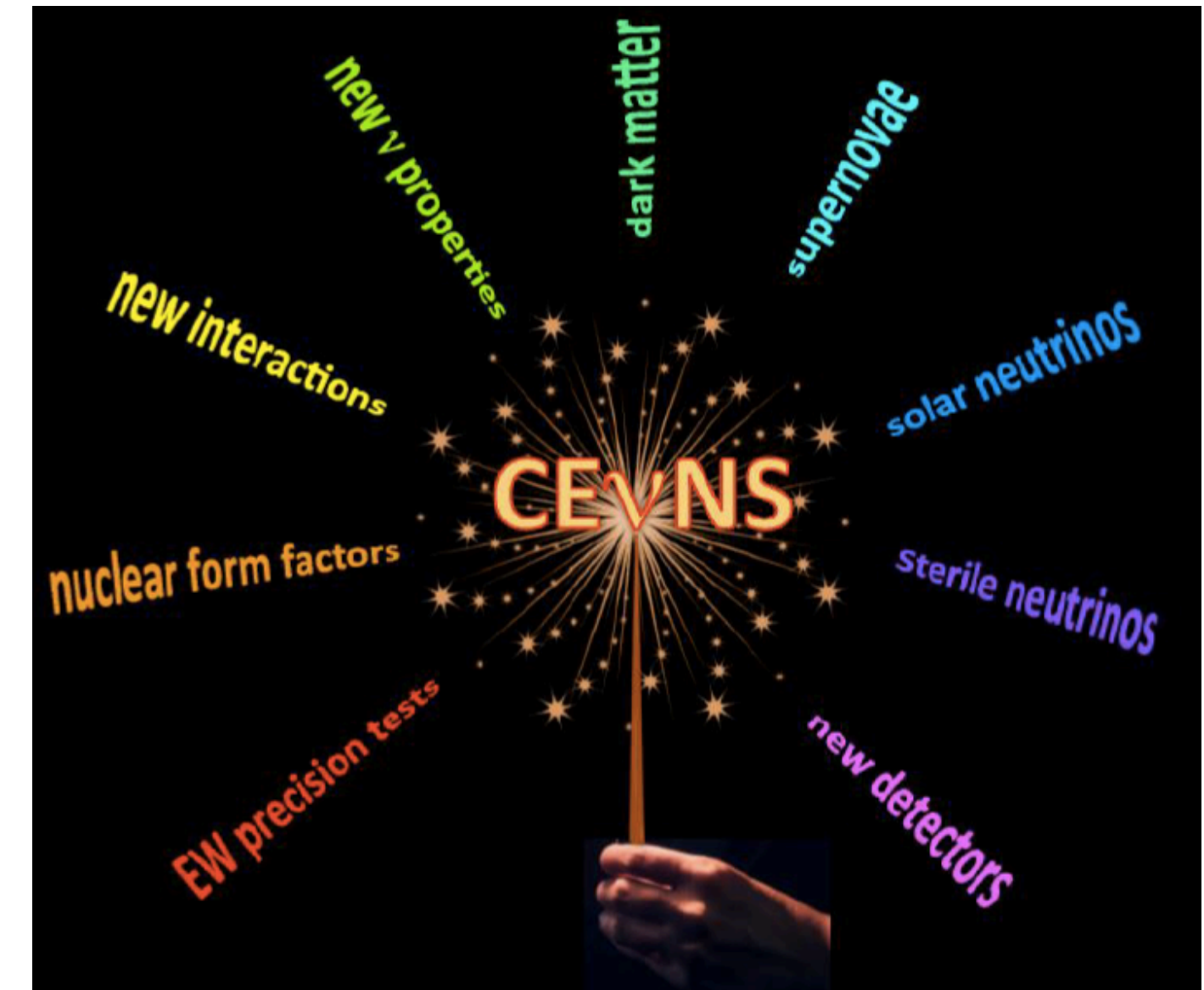
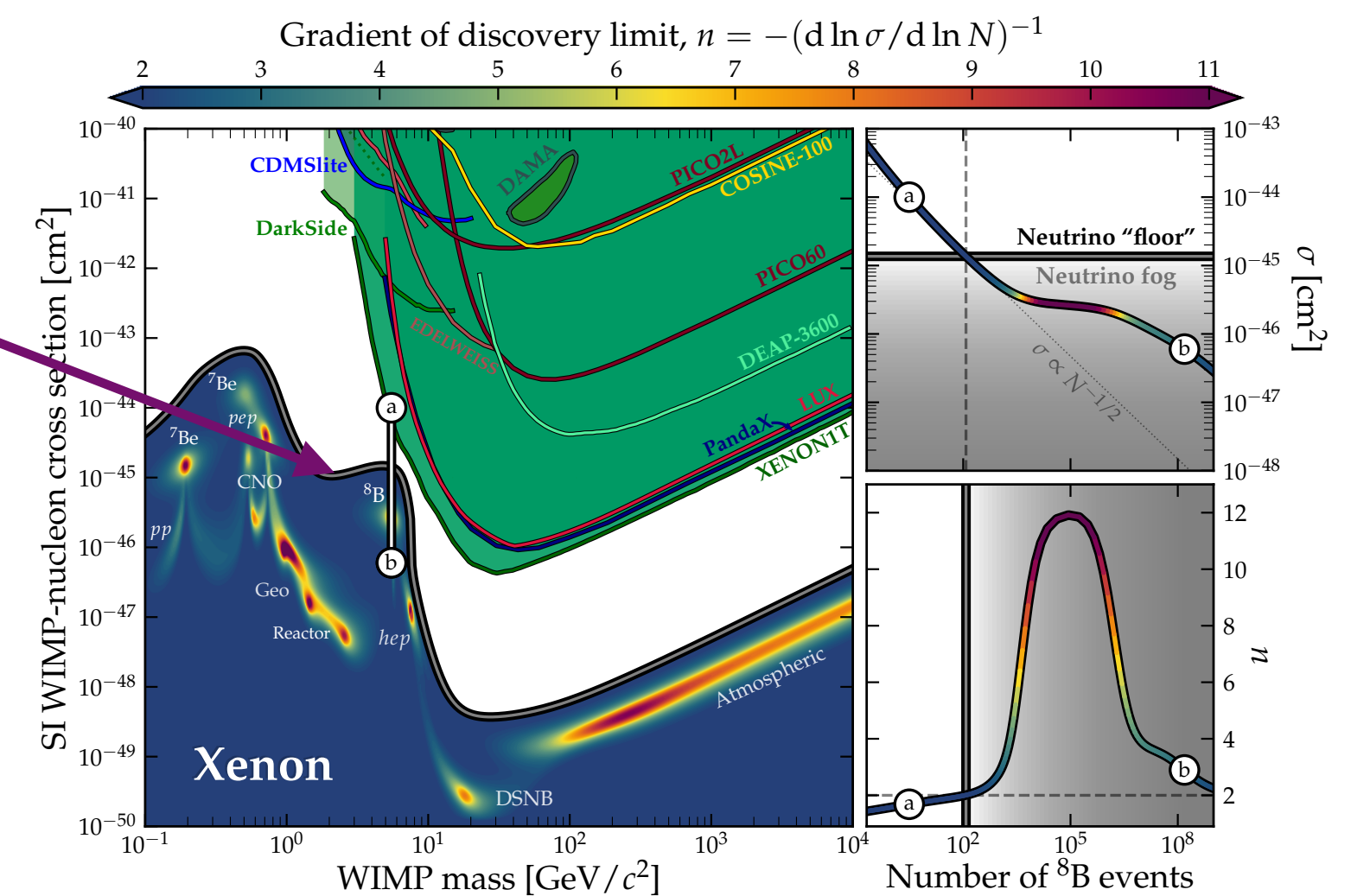


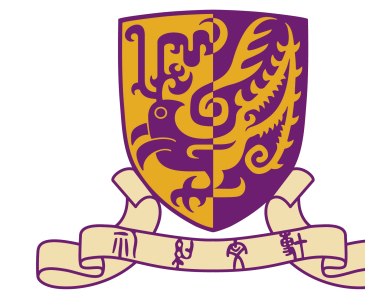
Figure credit: E. Lisi, Neutrino 2018

Neutrino fog

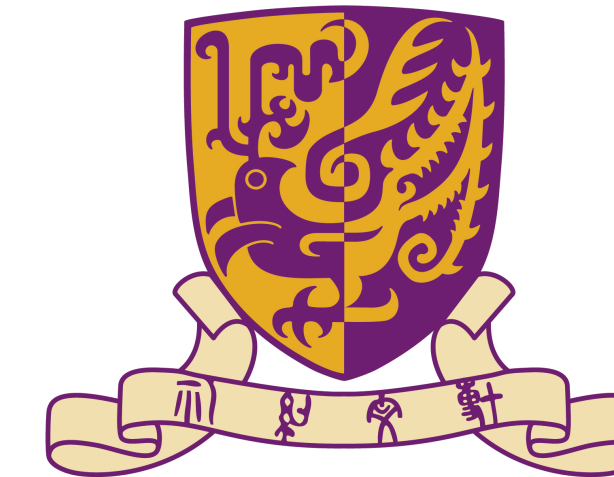
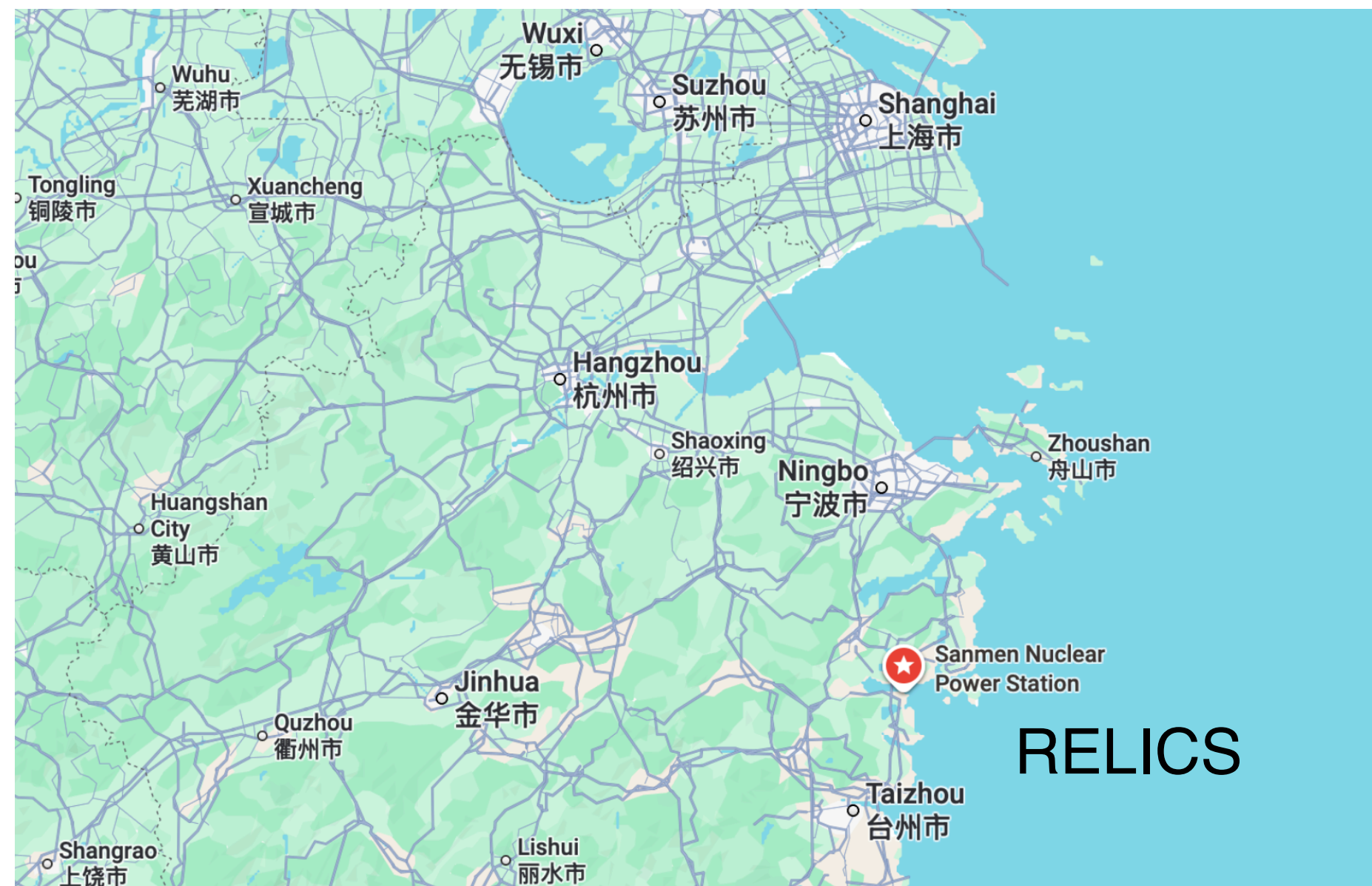


O'Hare, PRL 127, 251802 (2021)

RELICS Program



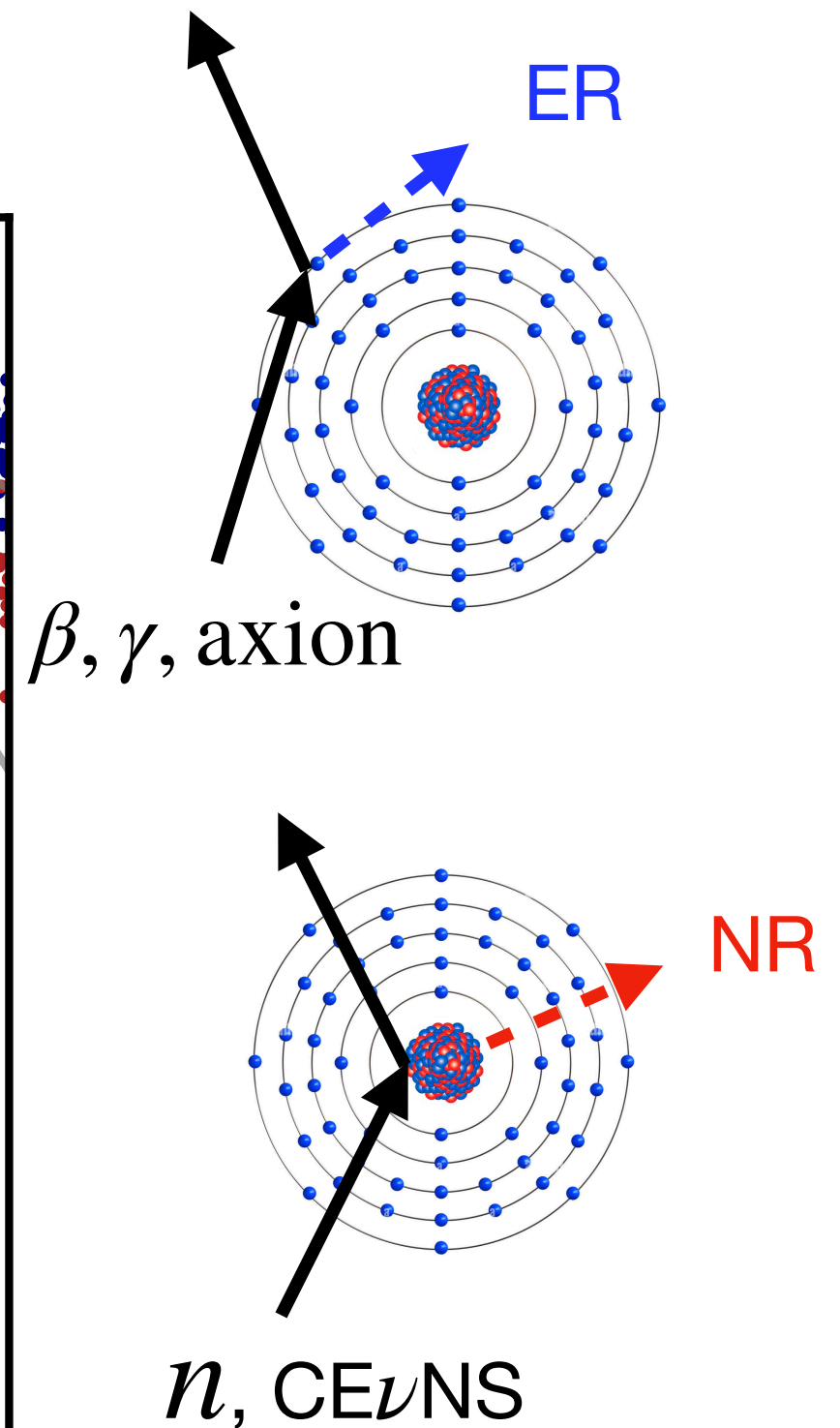
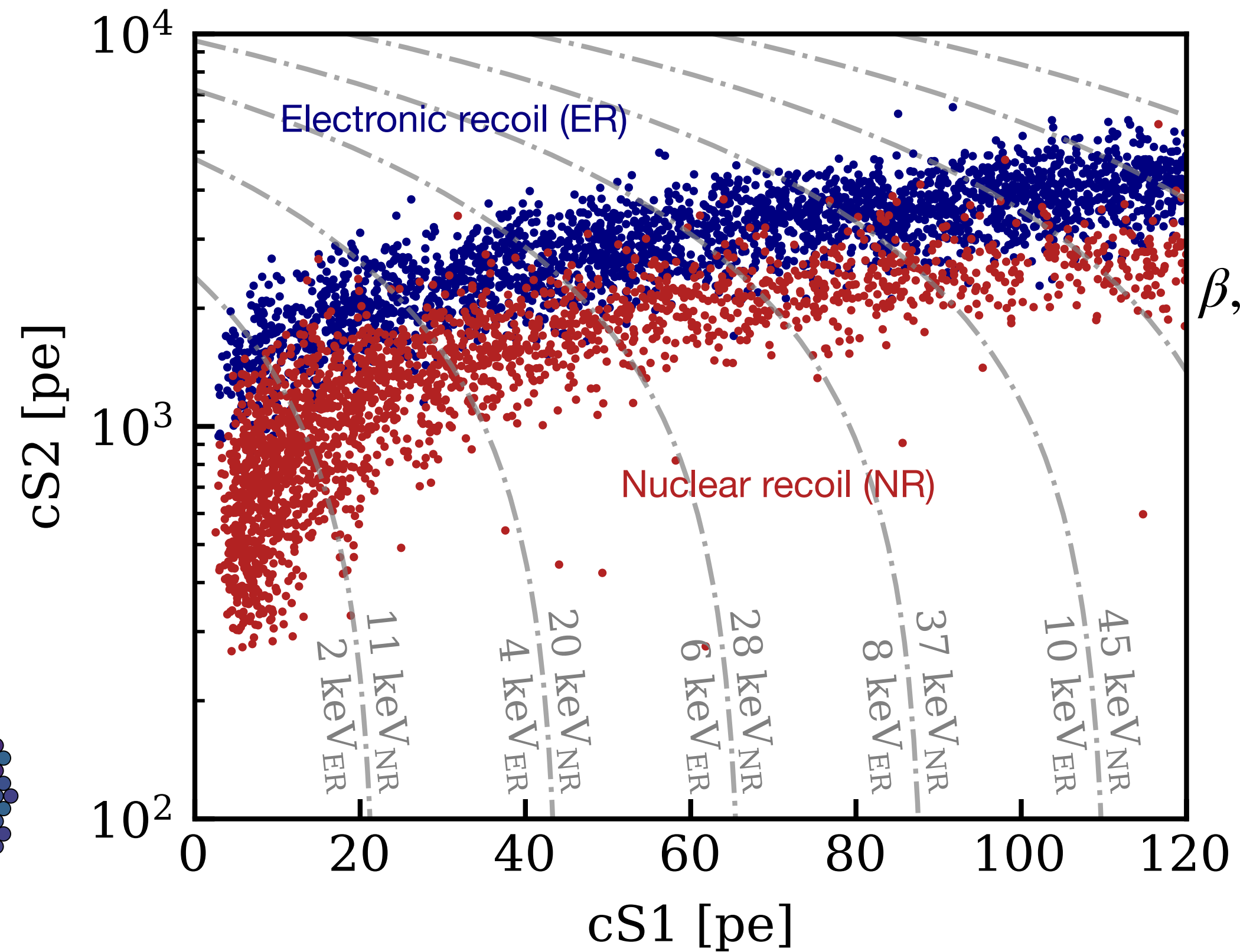
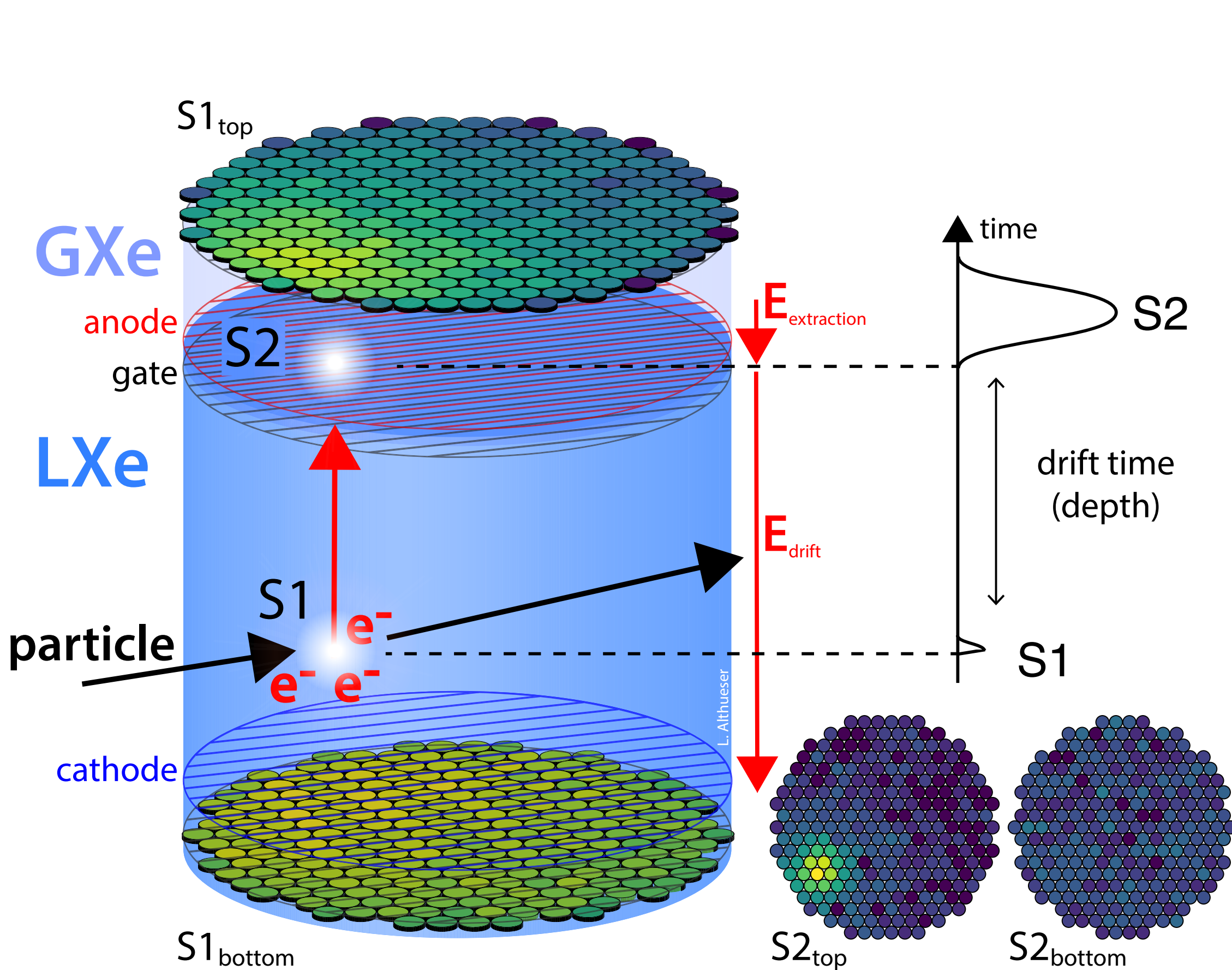
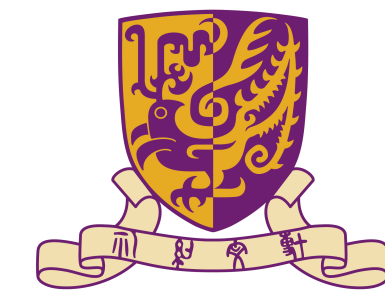
- REactor neutrino LIquid xenon Coherent Scattering (RELICS) program is a staged program, with the goal of deploying detectors at the Sanmen nuclear plant in Taizhou, Zhejiang.
- Reactor: 3.4GW, 22m baseline
- Primary scientific goal: measure $CE\nu NS$ in xenon using reactor ν



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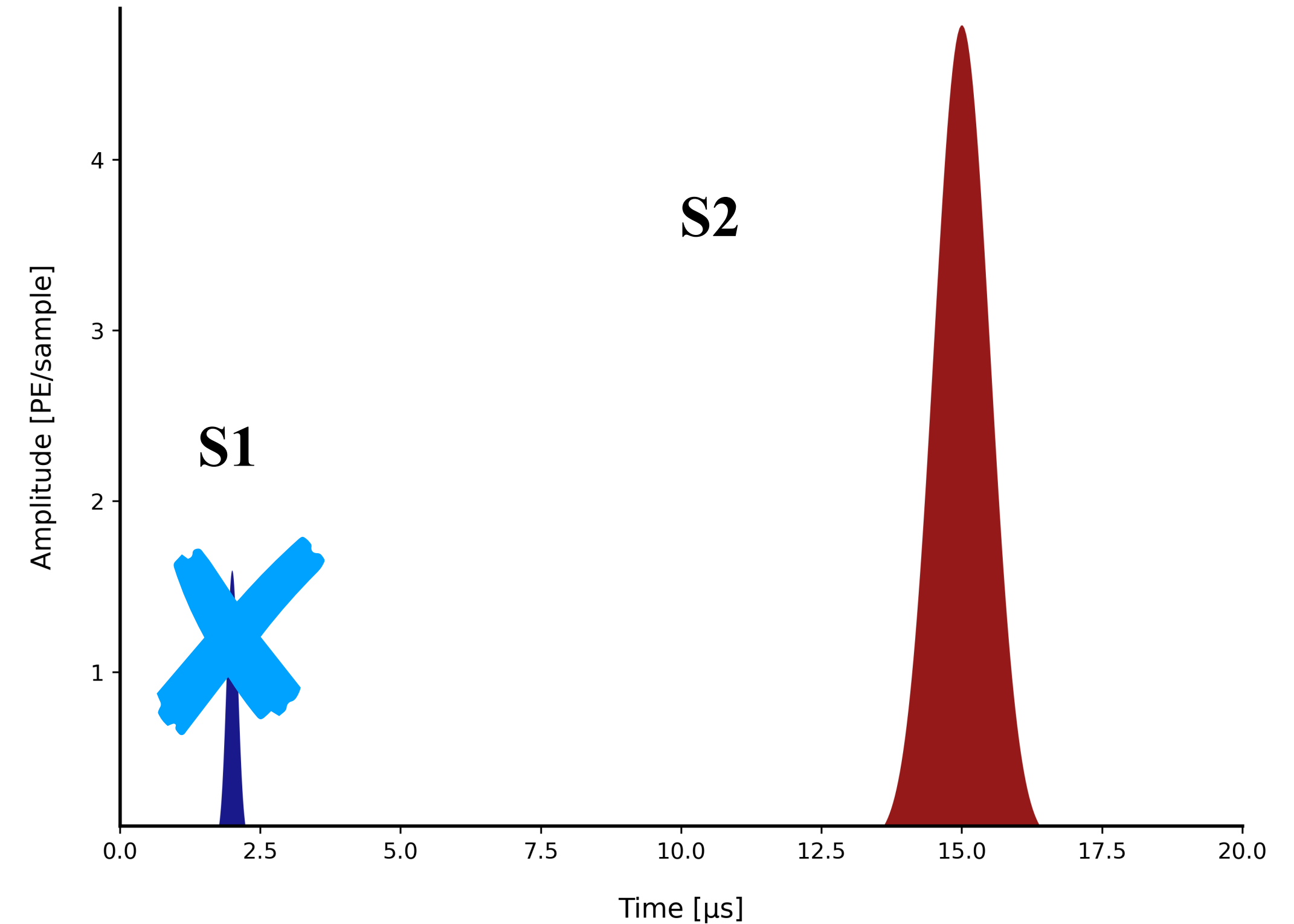
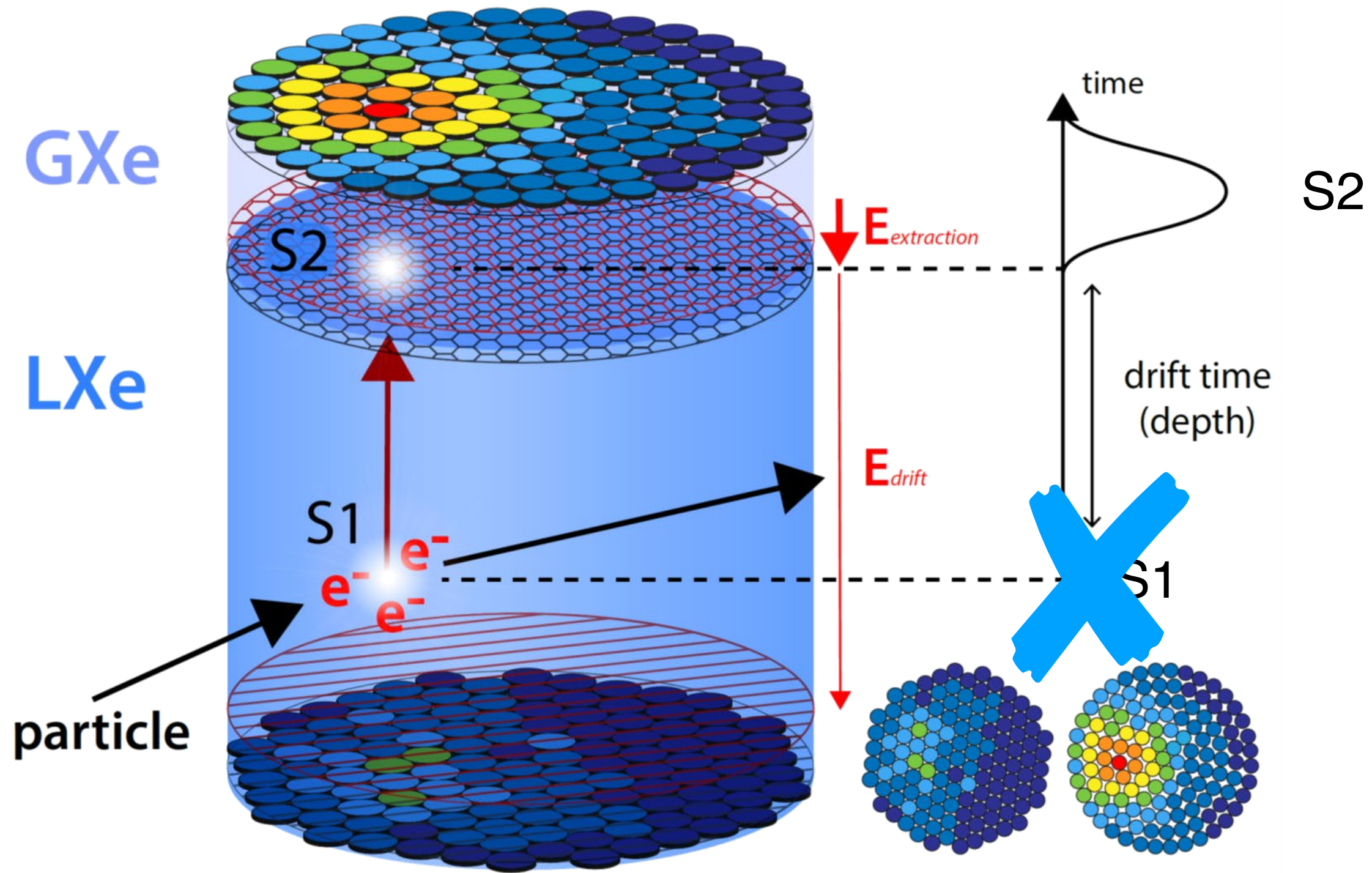
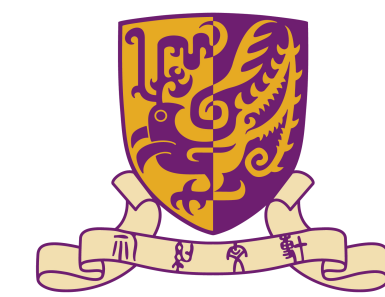
Time Projection Chamber (TPC)



- 3D position reconstruction
- Energy reconstruction

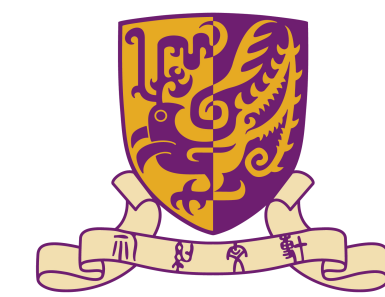
- Particle interaction identification
 - Electronic recoil (ER)
 - Nuclear recoil (NR)

Low Threshold for CE_{ν}NS Search



- **S2 only analysis:** abandon weak S1 signal to lower threshold
- **Energy threshold:** $\text{O}(1) \text{ keV}_{\text{NR}} \rightarrow \text{Sub keV}_{\text{NR}}$
- **Position reconstruction:** $3\text{D } (xyz) \rightarrow 2\text{D } (xy)$

RELICS Program



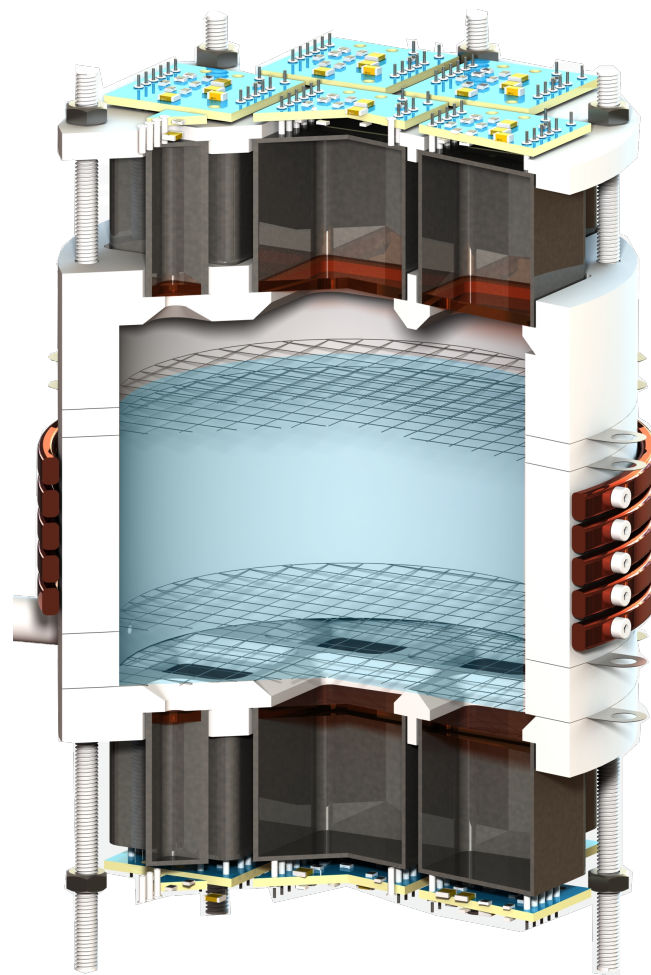
2024

2026

Now

RELICS Prototype:

- No Shielding
- LXe Mass $\sim 0.55\text{kg}$
- PMT Number: 14



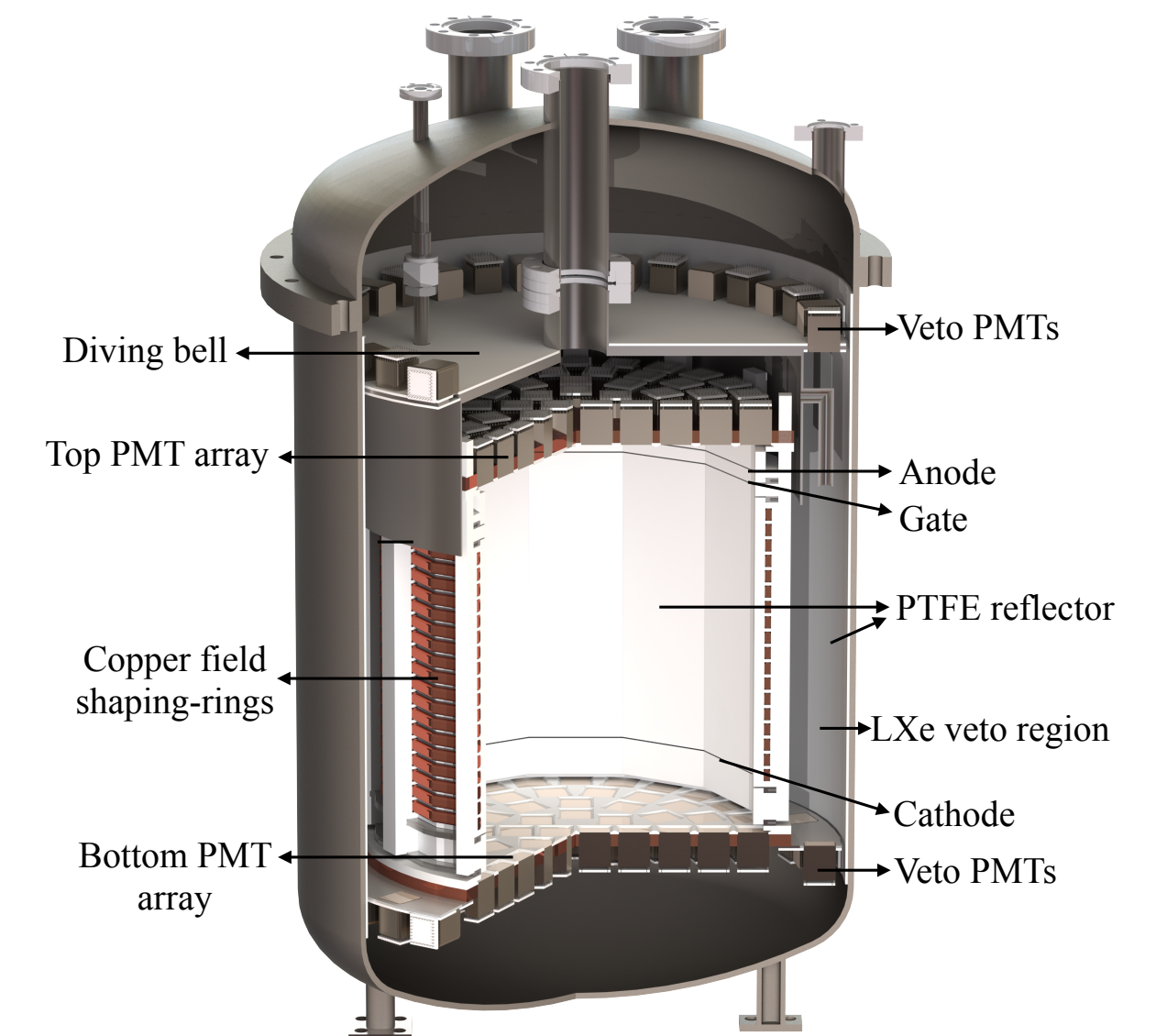
RELICS-10:

- Solid Shielding
- LXe Mass $\sim 10\text{kg}$
- PMT Number ~ 38

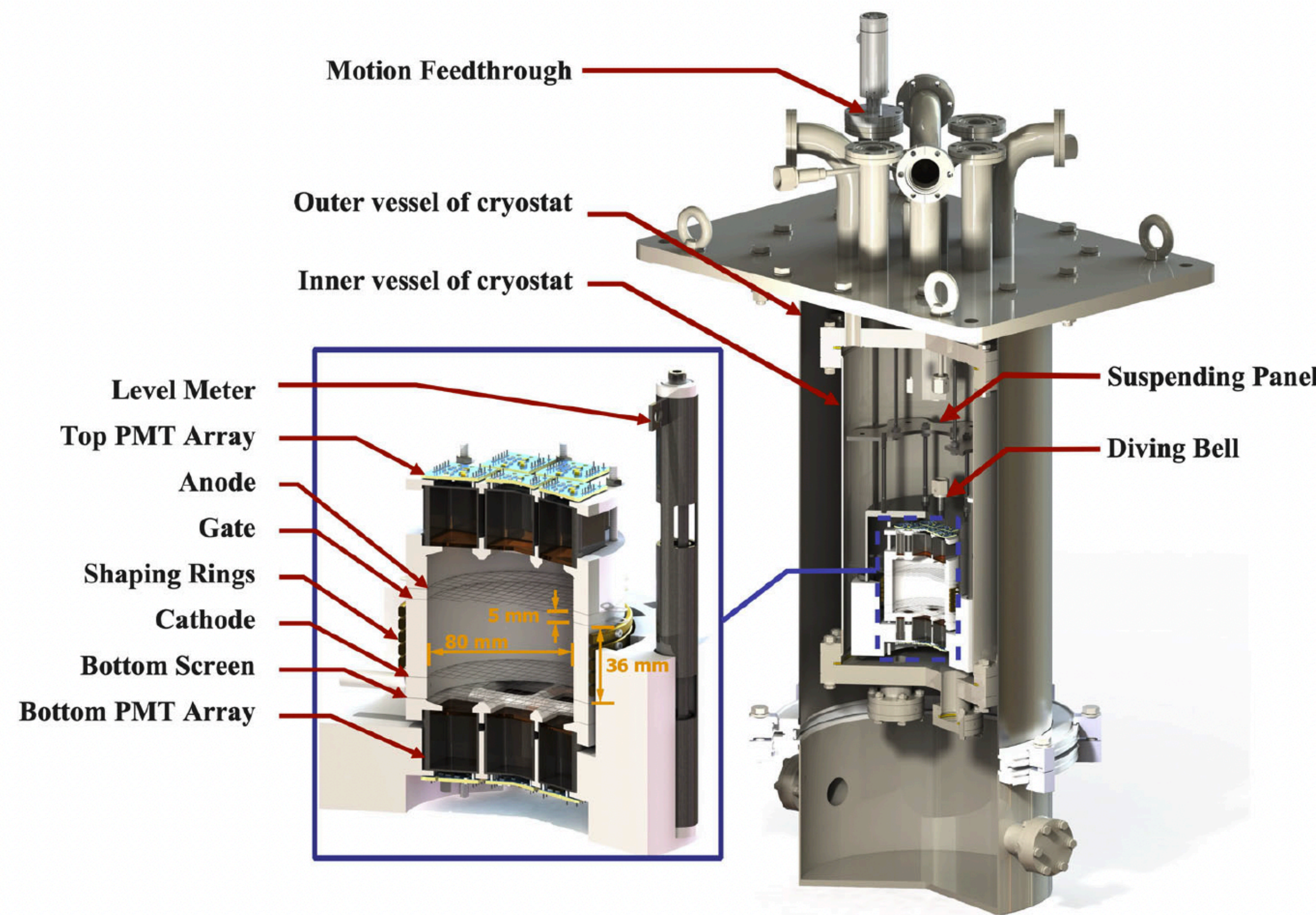
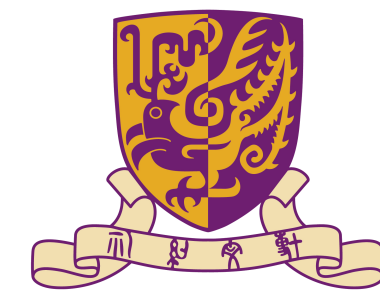


RELICS-50:

- Water Shielding
- LXe Mass $\sim 50\text{kg}$
- PMT Number ~ 128



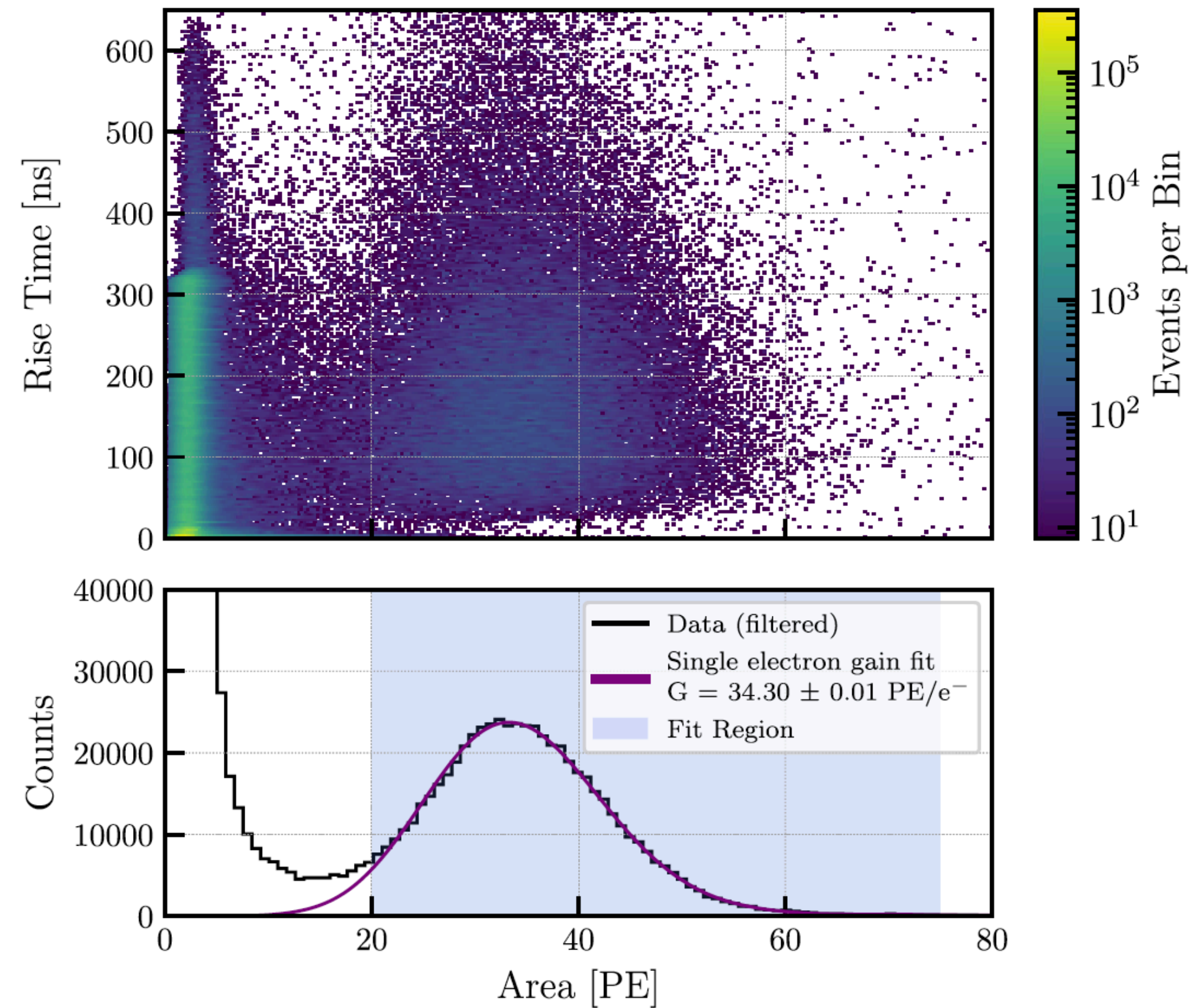
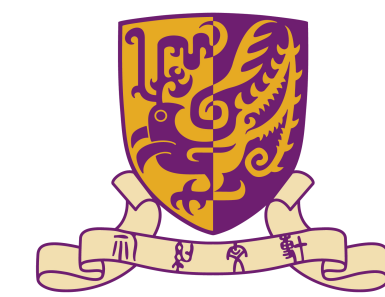
RELICS Prototype



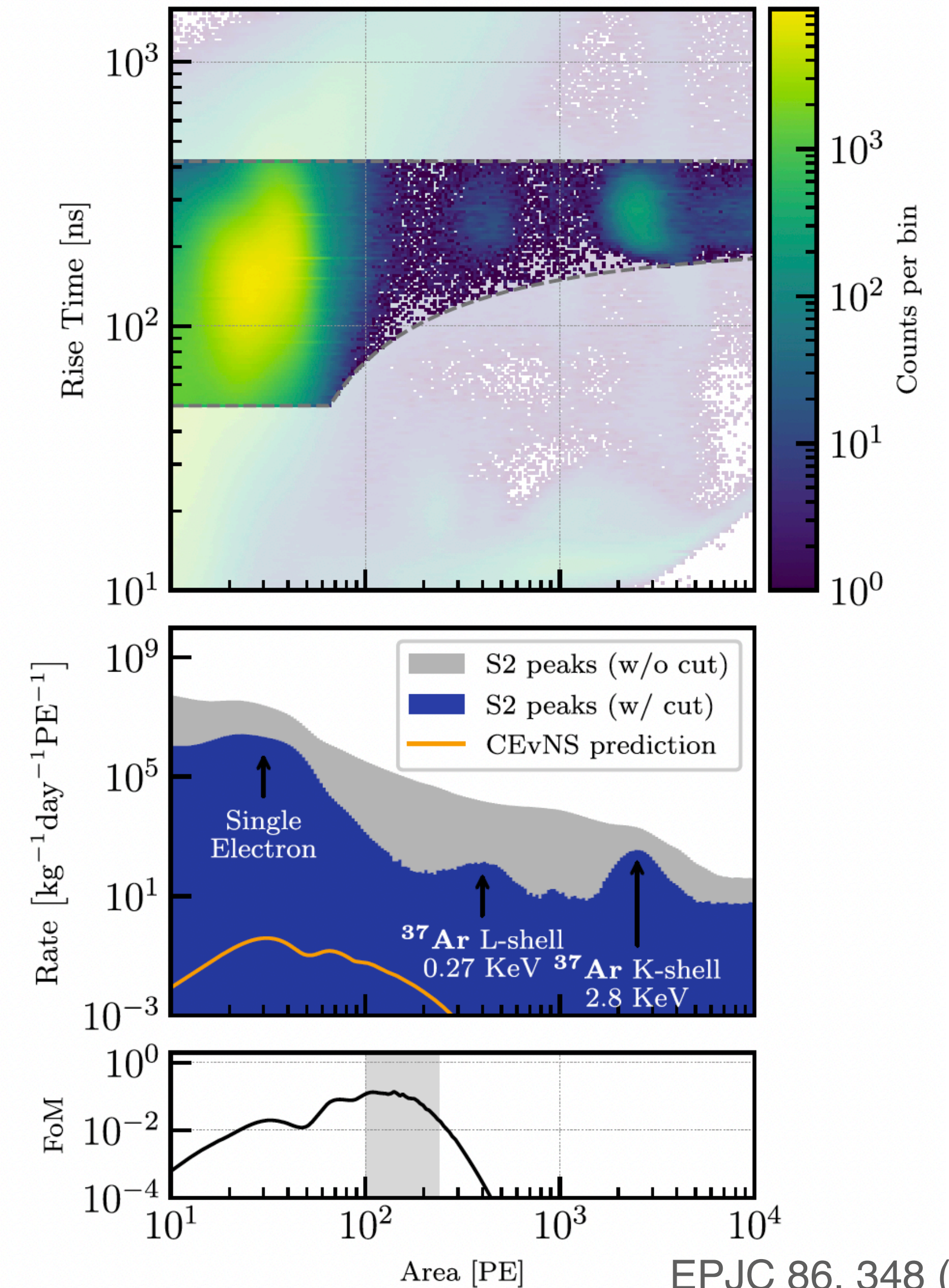
RELICS Prototype:

- No Shielding
- Ar and Kr calibrations
- LXe Mass $\sim 0.55\text{kg}$
- PMT Number ~ 14

Single Electron Gain

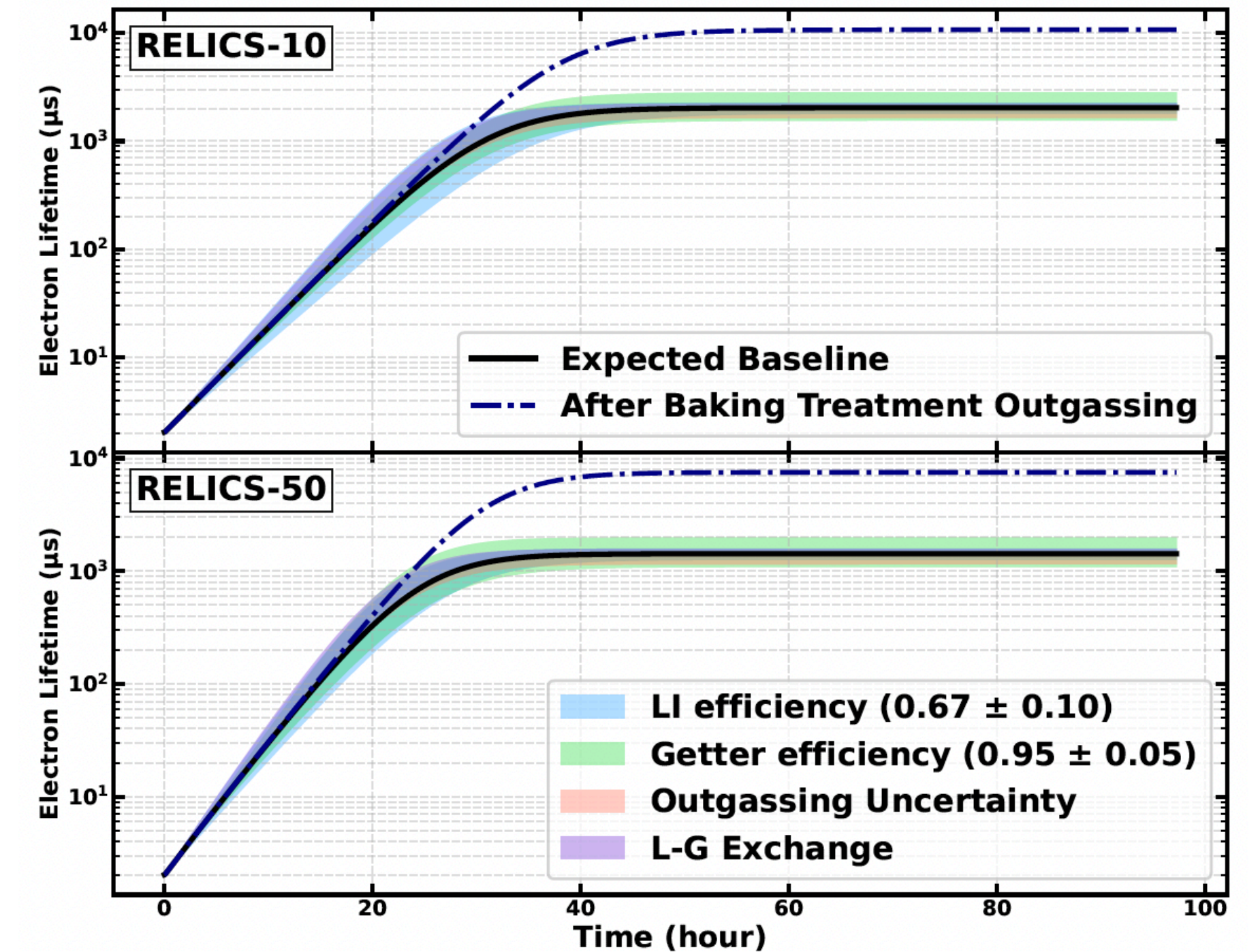
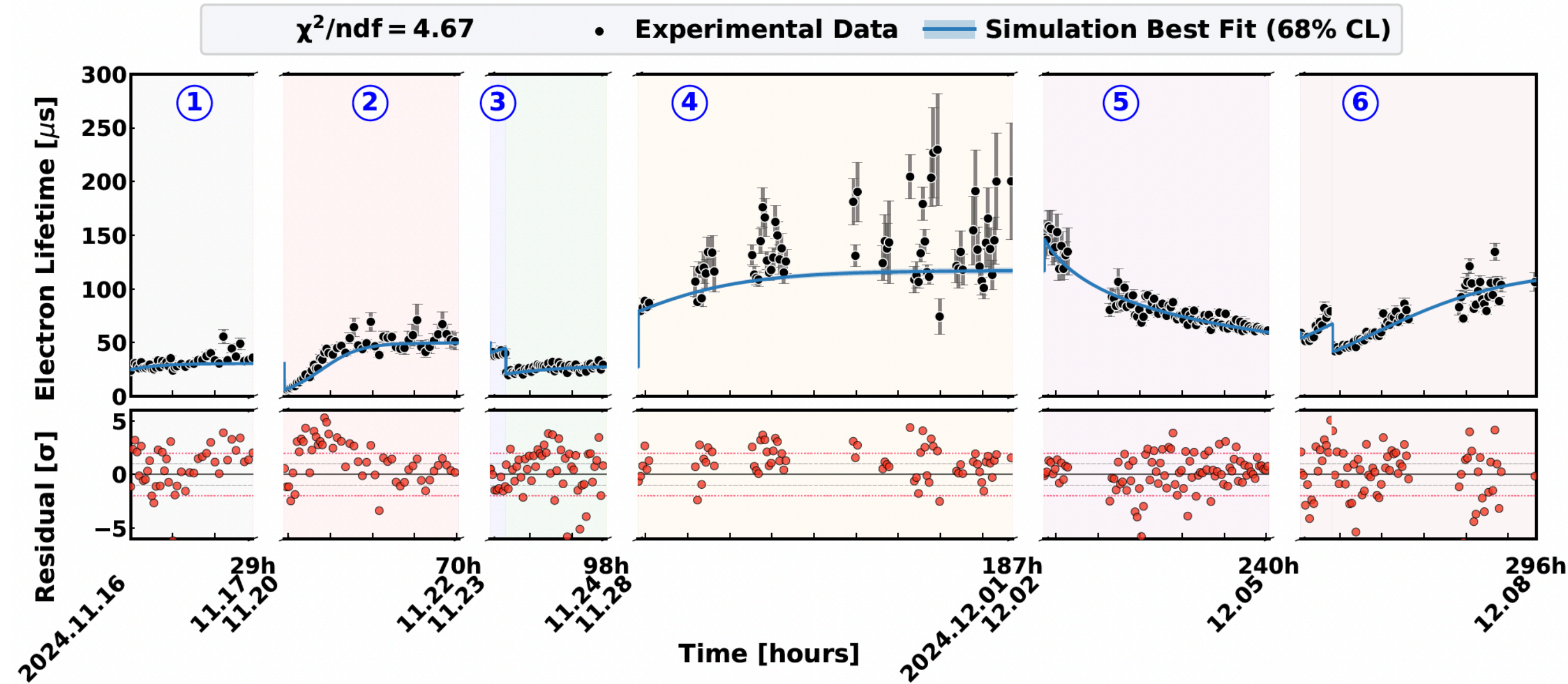
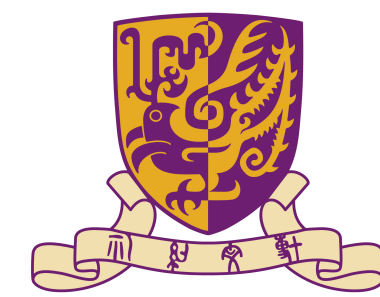


- Single electron gain (SEG) is evaluated to be $\sim 34 \text{ PE/e}^-$
- Achieved sub-keV detection as demonstrated in the Ar37 calibration



EPJC 86, 348 (2026)

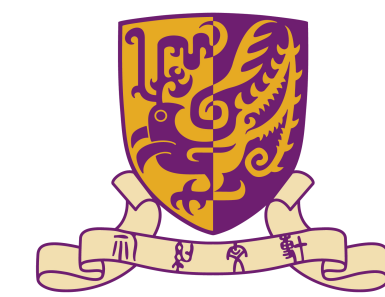
Purification



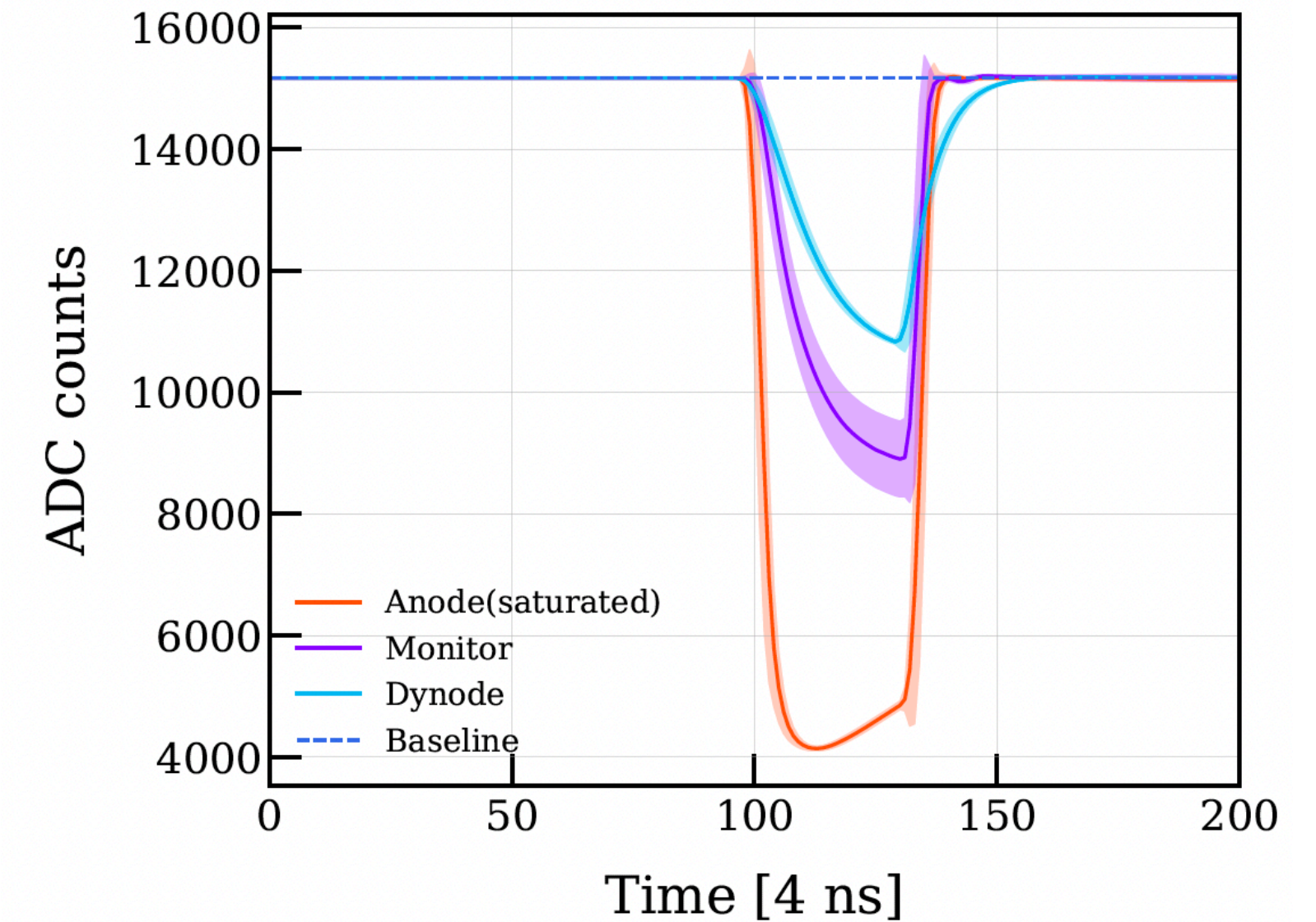
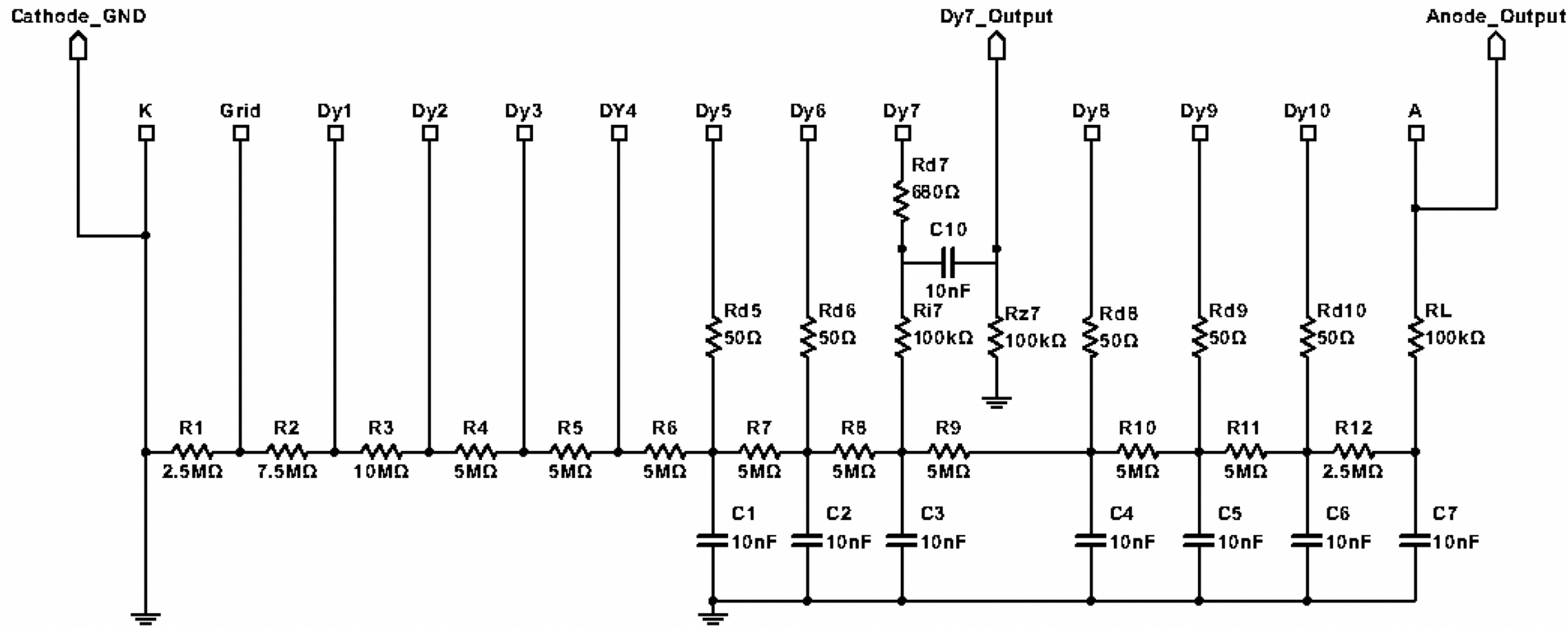
- Low impurity level required for sub-keV nuclear recoil detection (large electron lifetime)
- Purification models constructed and validated by manipulating operations of RELICS prototype
- Getter removal efficiency evaluated to be $\sim 98\%$
- PTFE outgassing rate reduced by a factor of 5 by baking for 2 weeks (and then exposed for 2 days)
- The predicted electron lifetime in RELICS-10 and RELICS-50 > 1 ms based on the purification model
- Further increase by baking detector materials

arXiv: 2604.12572

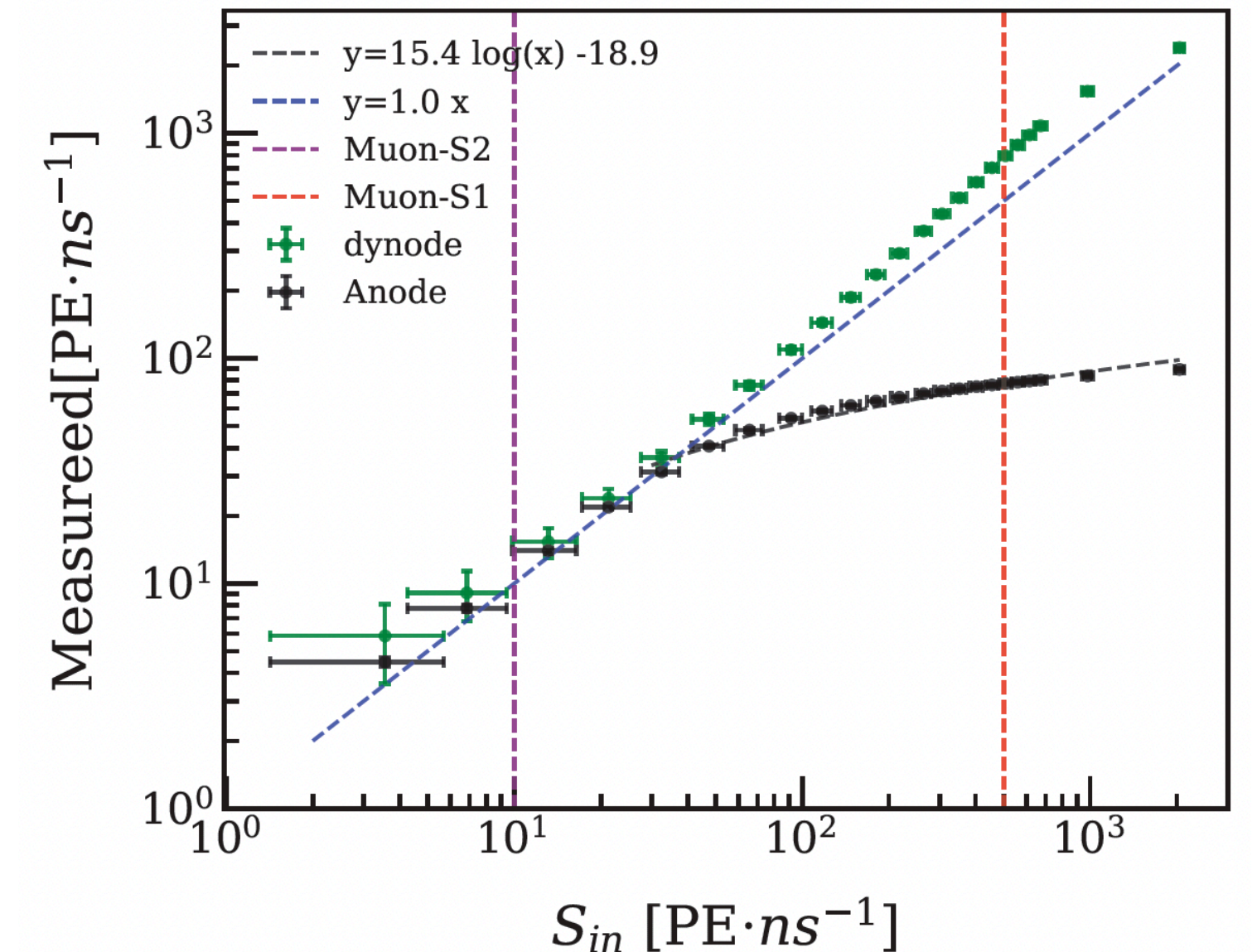
Dual Readout

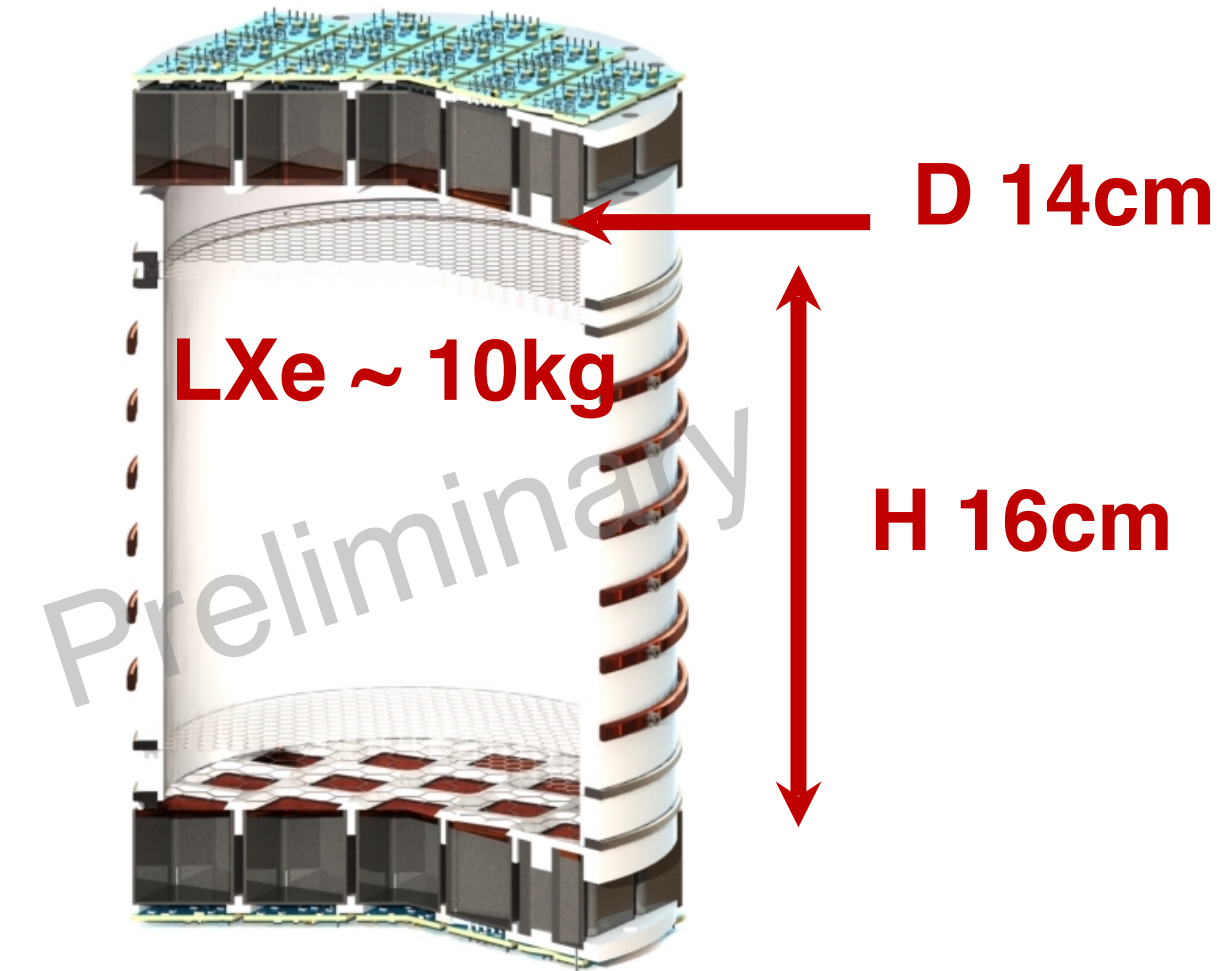
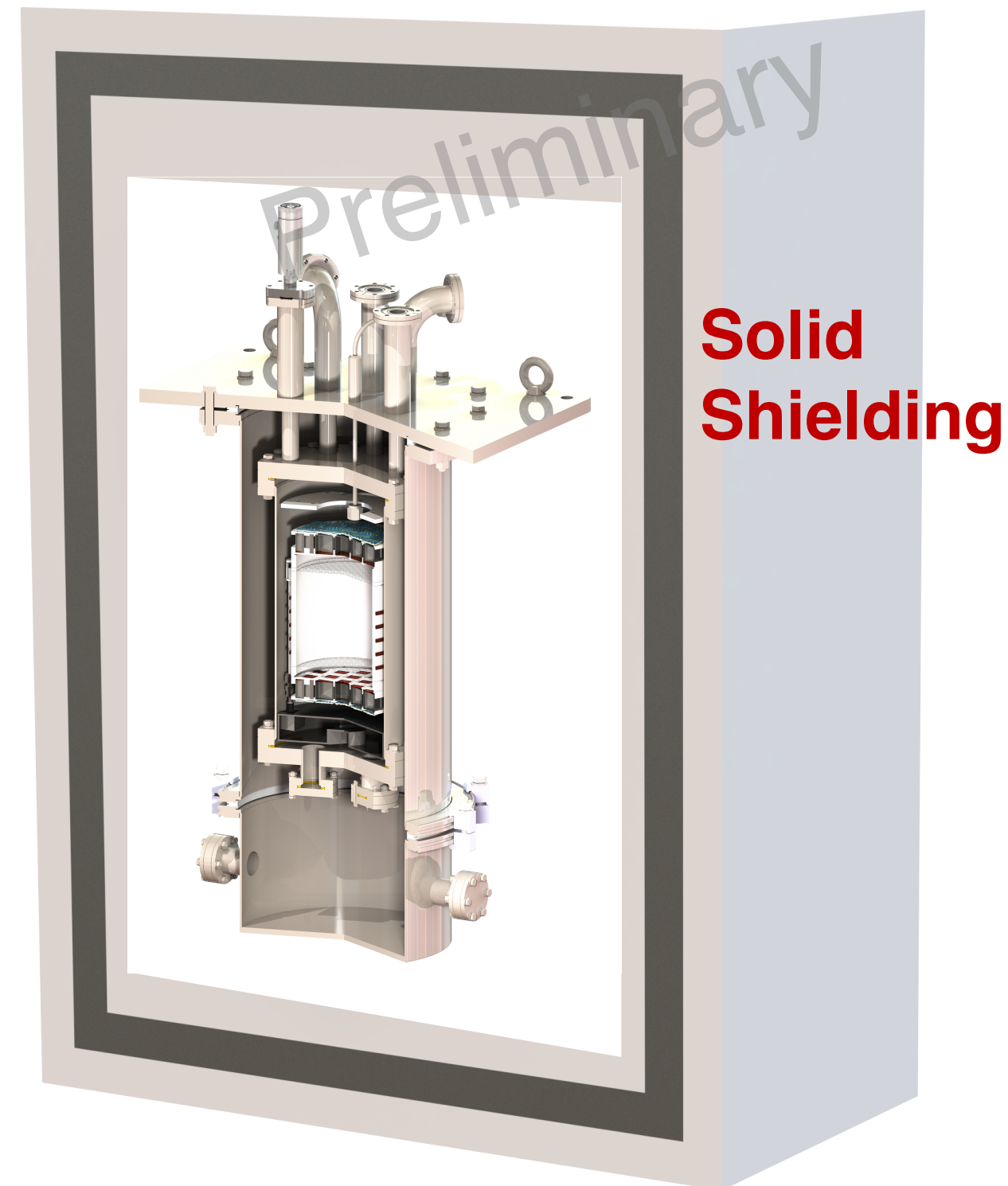


JINST 21, P02039 (2026)



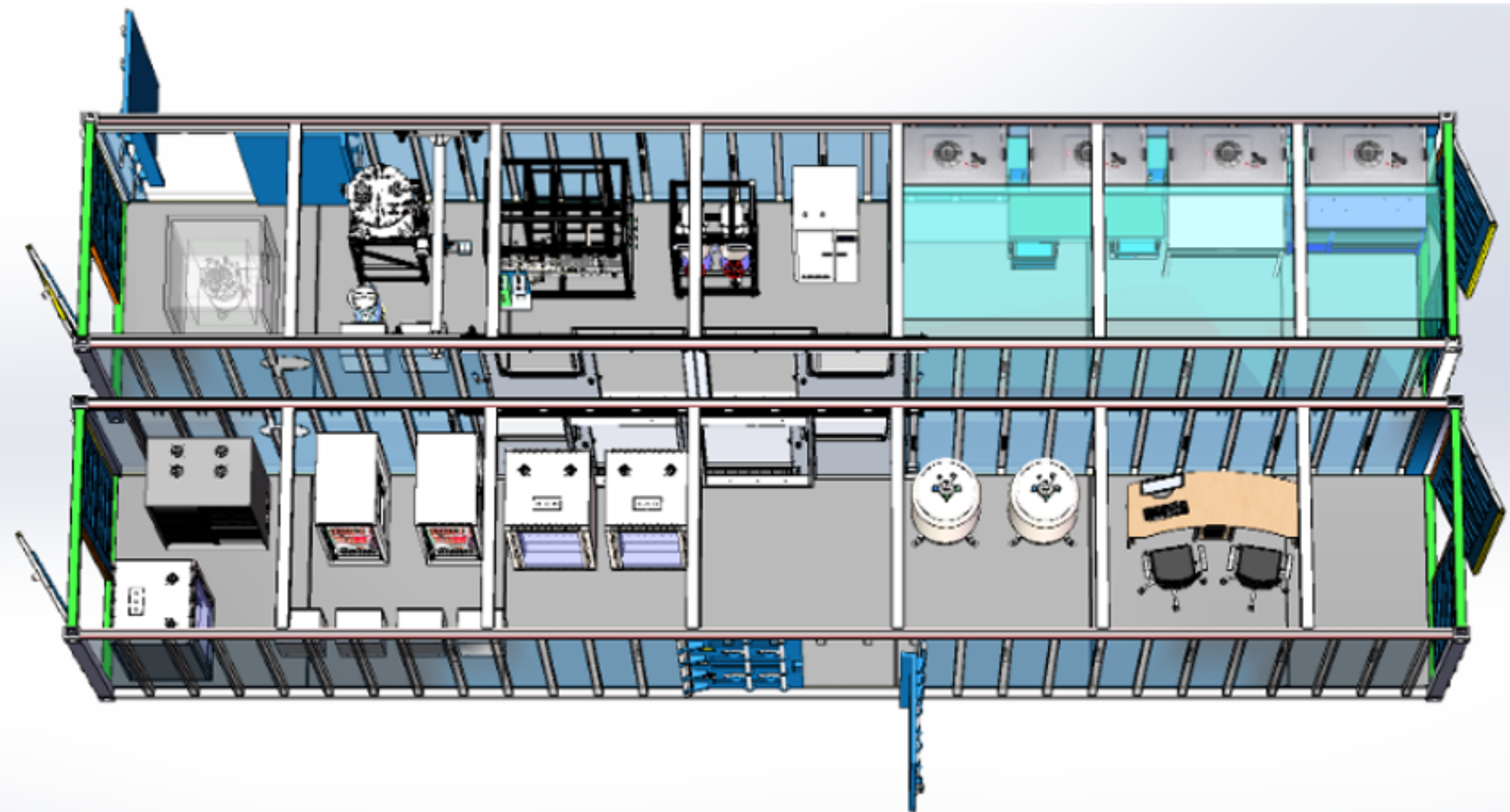
- Requirements on detecting (large) muon events and (small) single electron signals
- Solution: dynode readout for muon and anode readout for single electrons
- PMT8520@800 V, anode saturates ~ 1000 PE, a factor of 50 lower than muon S1.
 - 7th dynode : reduce gain by a factor of ~ 100
- Extend the linear response region by more than 1 OM, while retaining sensitivity to single electrons.



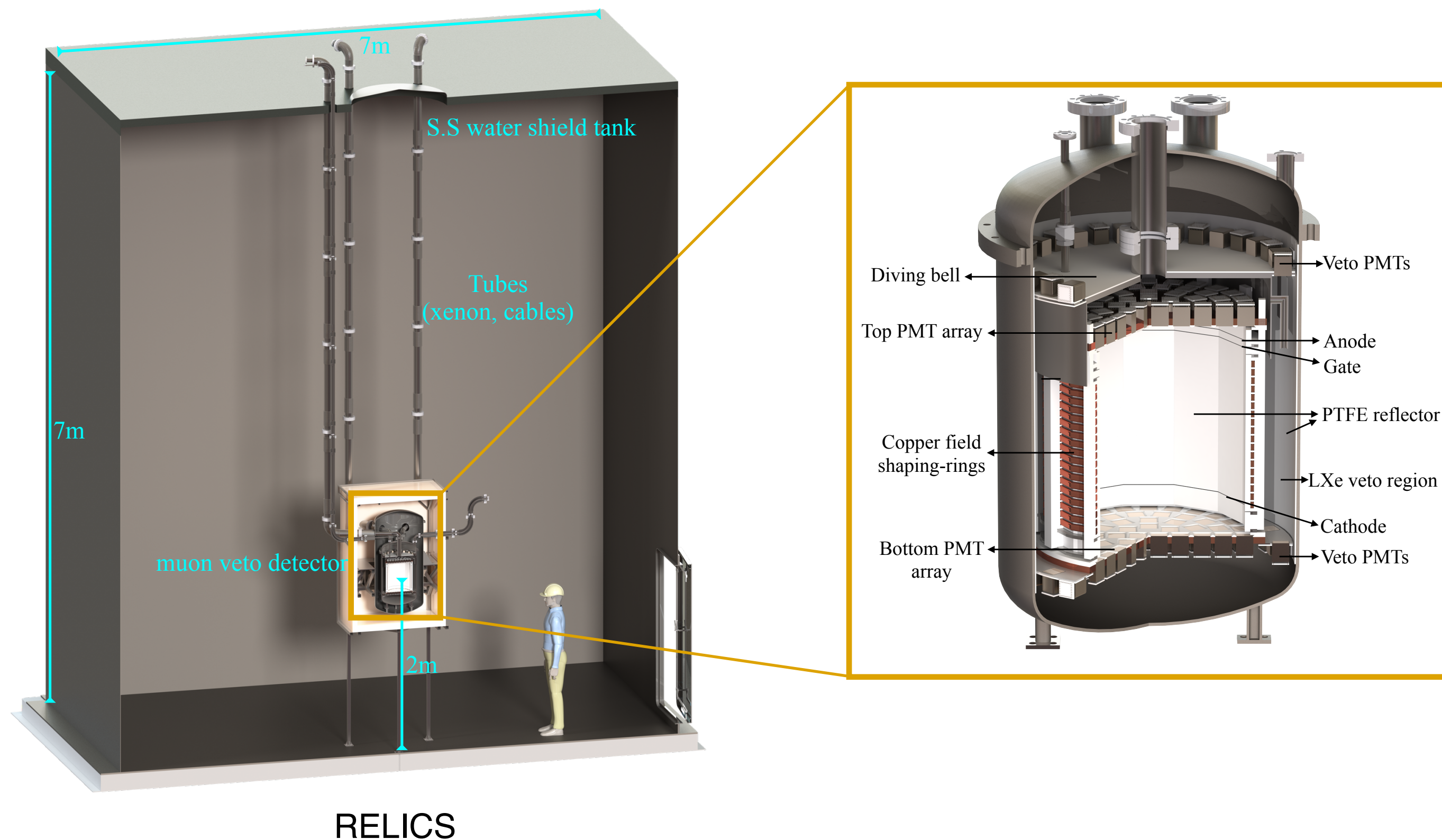


RELICS-10:

- Solid Shielding
- Reactor Neutrino
- 99% Muon Veto
- LXe Mass ~ 10kg
- PMT Number ~ 38



- Use S2-only analysis to achieve an energy threshold to 4 e⁻ (~0.6 keV) with a high efficiency
- Use both **water shielding** and **plastic scintillator** for shielding to reduce cosmic backgrounds.



- Total: 62 kg xenon
- Active: 44 kg
- TPC: 24 cm (H) x 28 cm (D)
- PMT Number: 128 (64+64)

Region of interest (ROI):

- (120, 300) PE
- (4, 10) e⁻
- (0.6, 1.4) keV_{NR}

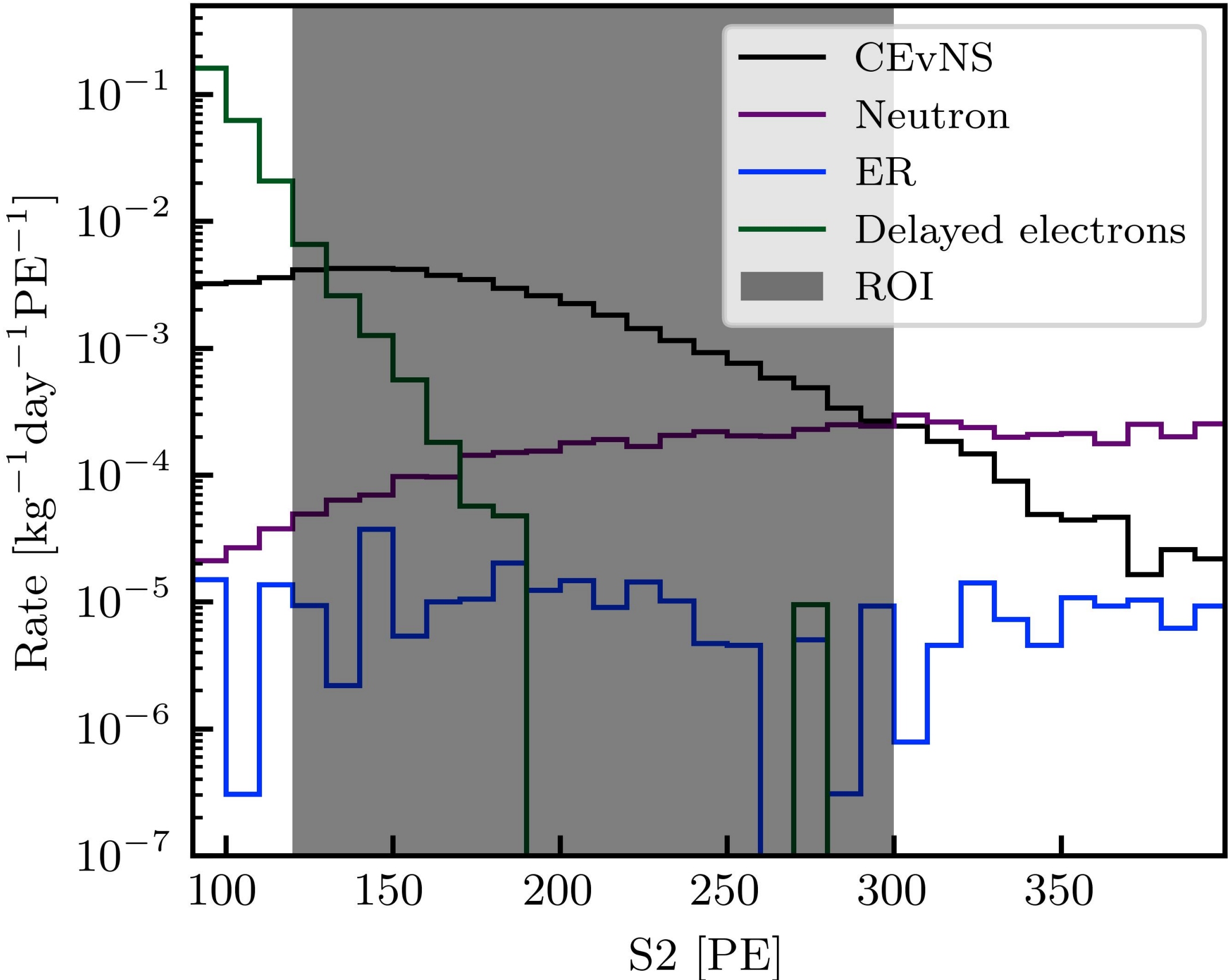
Signal and Background



	Name	Events / (32kg·year)
Signal	CEvNS	4640
Background	Delayed electrons	1325
	Cosmic-ray neutron	340
	Muon-induced neutron	2
	ER	21
	Total	1688

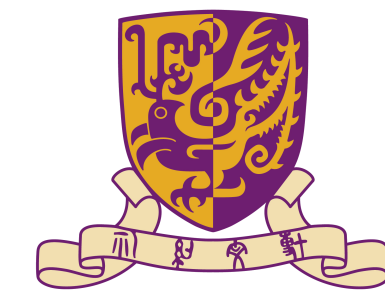
CEvNS ROI: [0.6, 1.4] keV_{NR}

$$\frac{S}{B} \approx 2.7$$

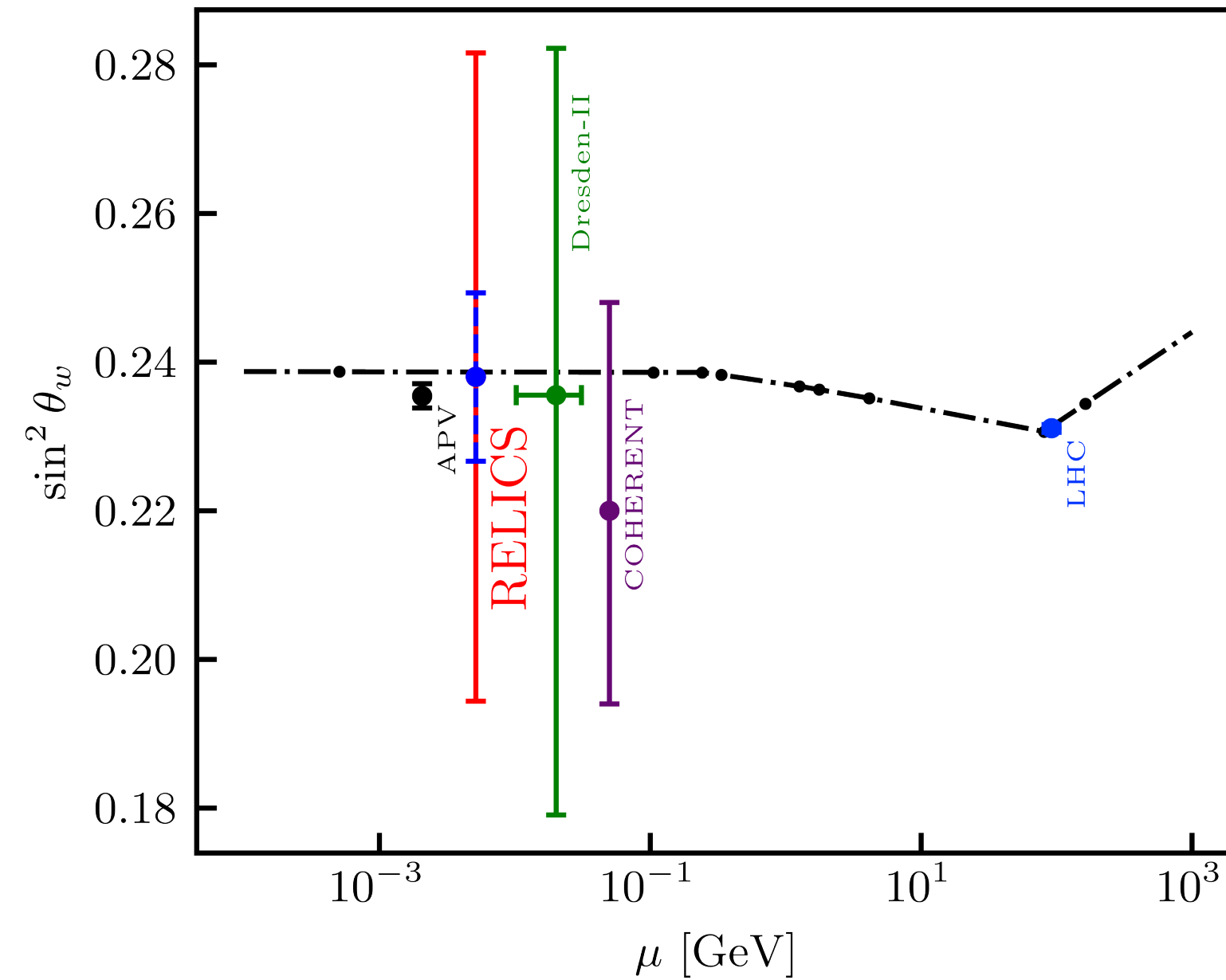
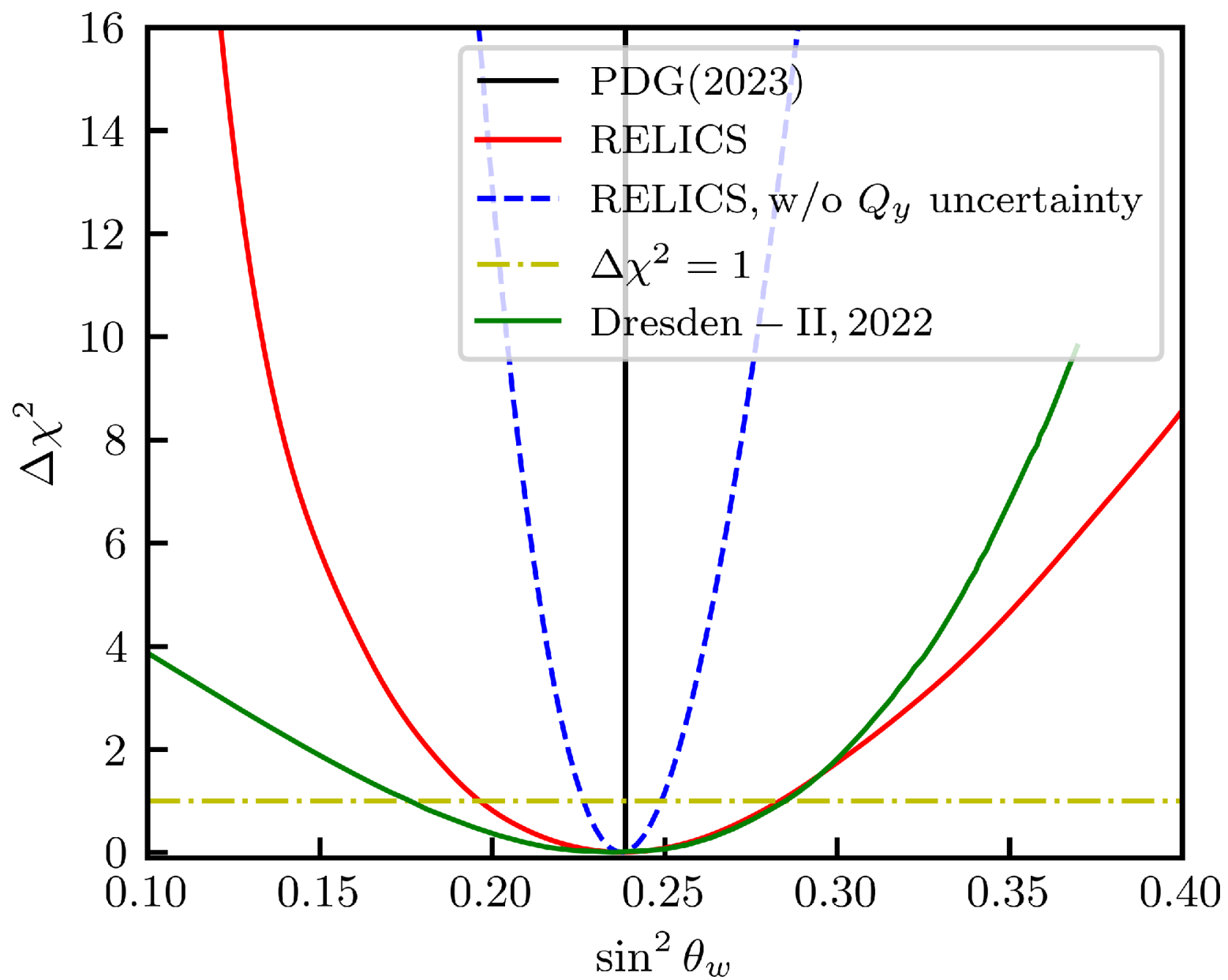


PRD 110, 072011 (2024)

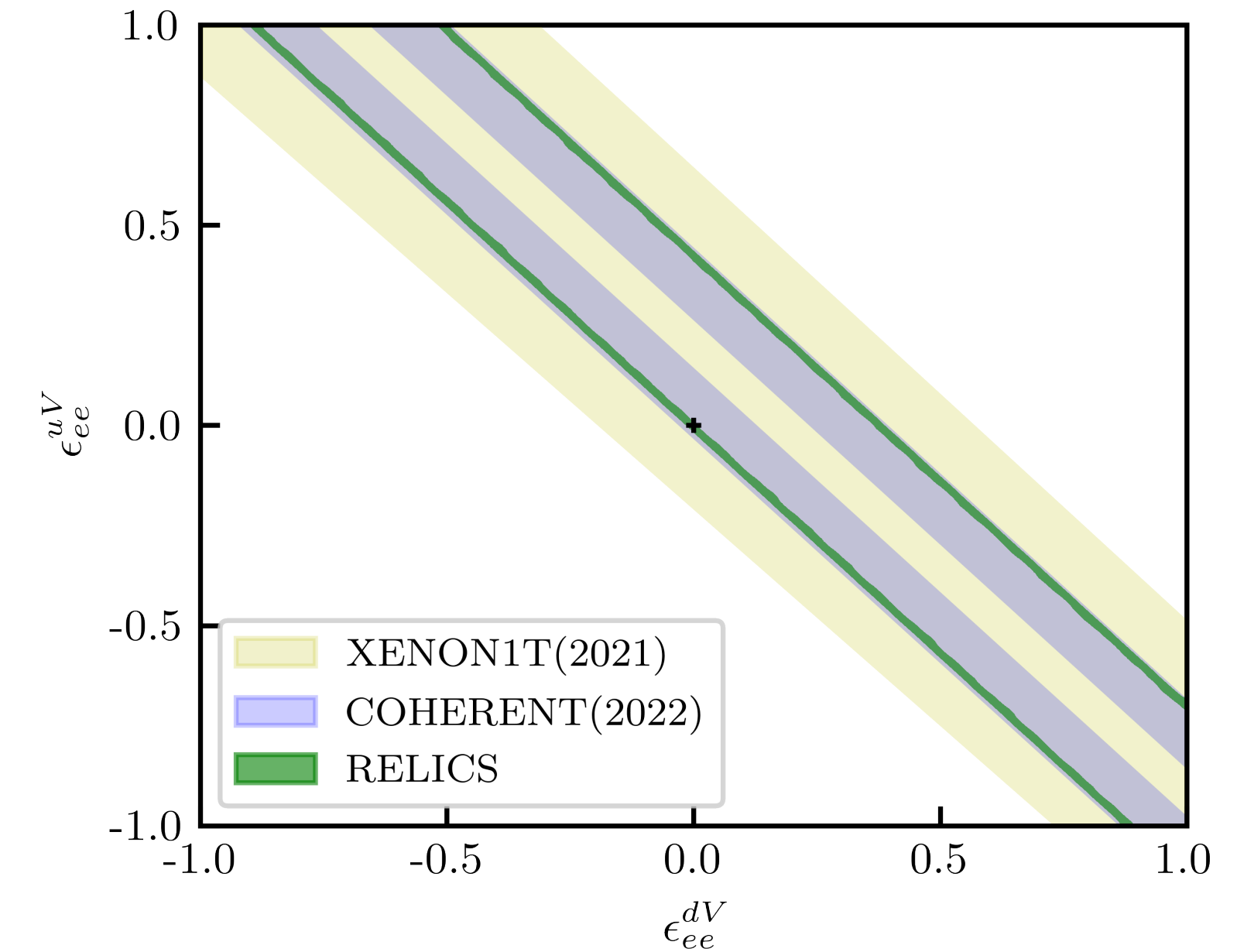
Physics Potential for $\text{CE}\nu\text{NS}$ Search



Weak mixing angle

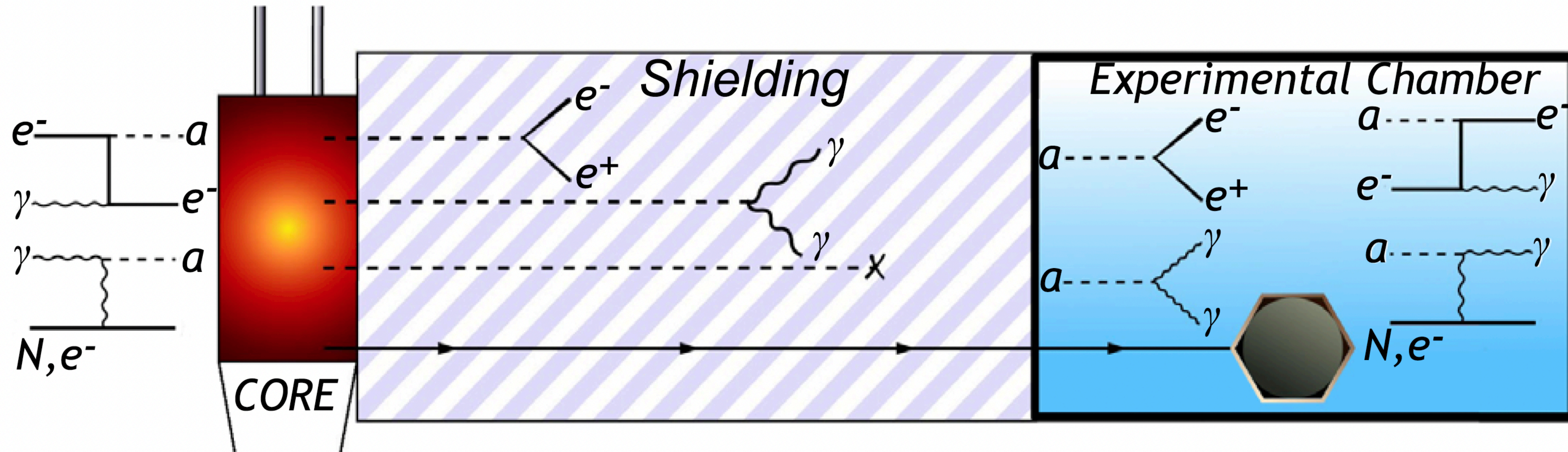
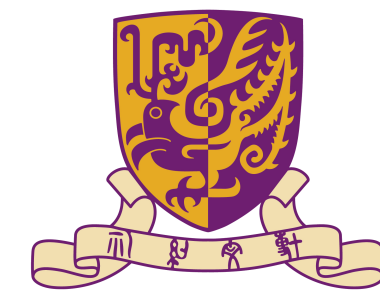


Neutrino non-standard interaction (NSI)



- Assumed exposure: 32 kg · year
- Systematic uncertainty (from charge yield) dominates over statistical uncertainty (expected more than 4000 $\text{CE}\nu\text{NS}$ events)

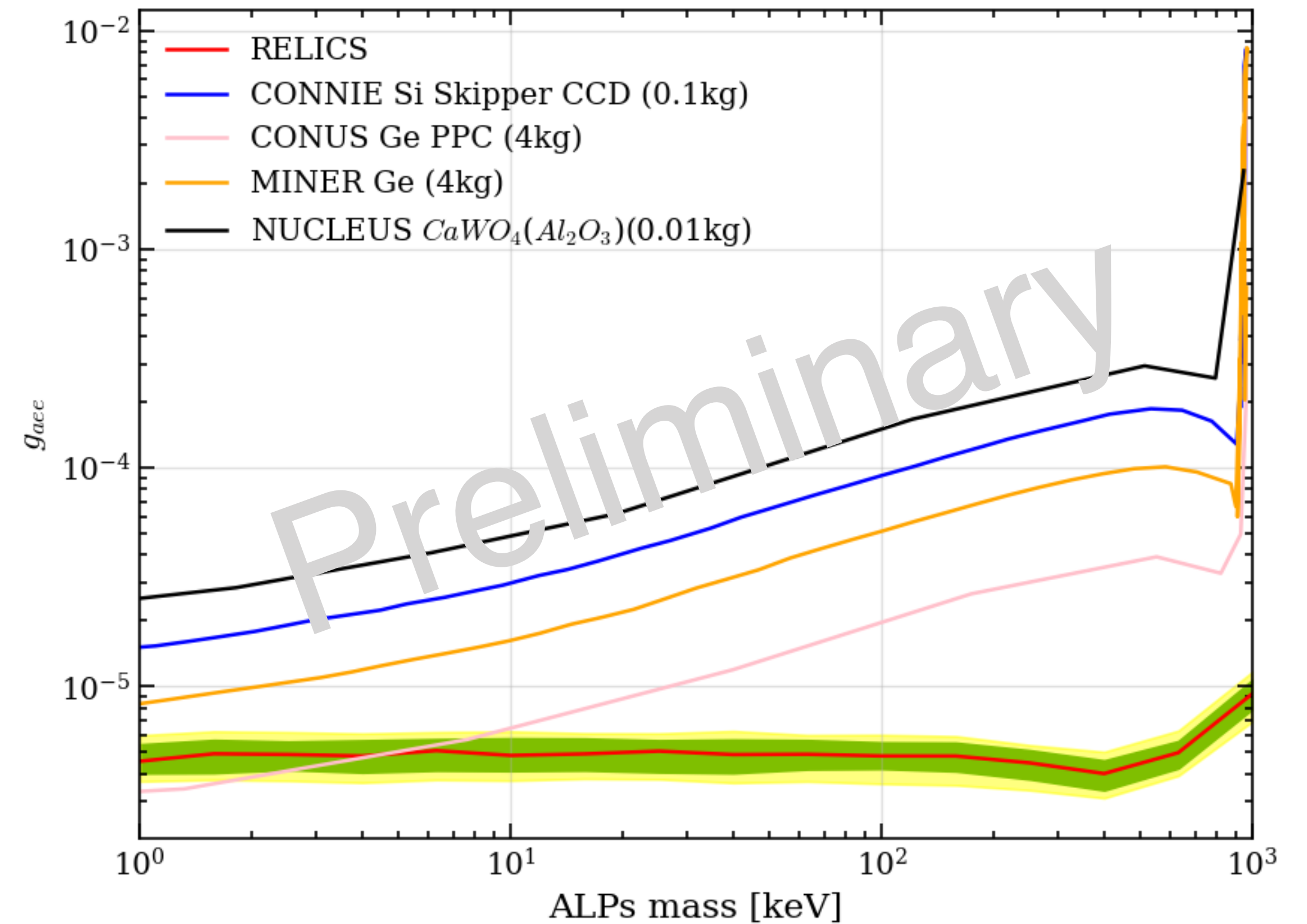
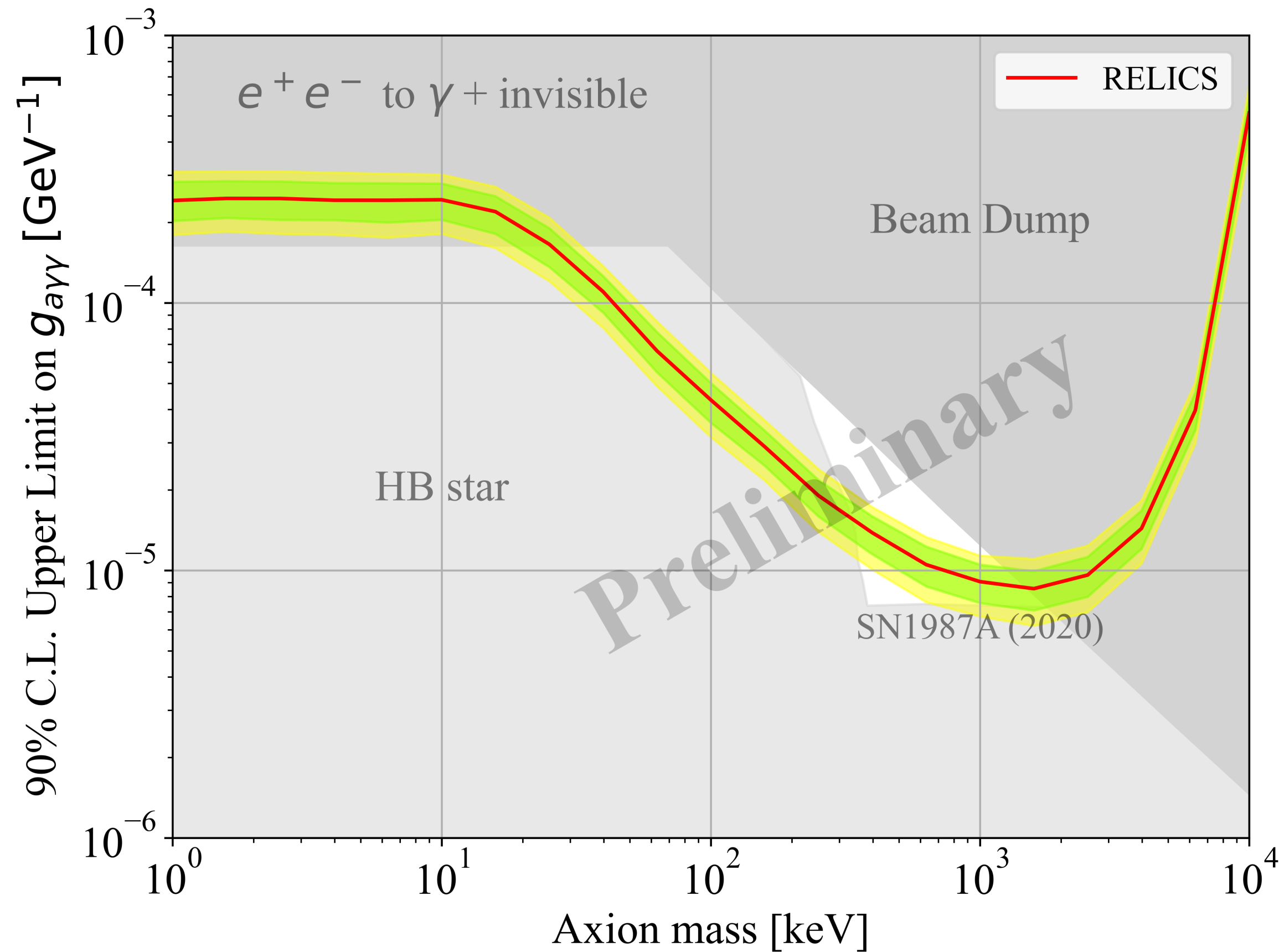
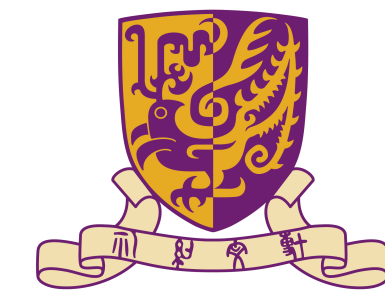
Reactor Axion-like Particles



Dent et al., PRL 124, 211804 (2020)

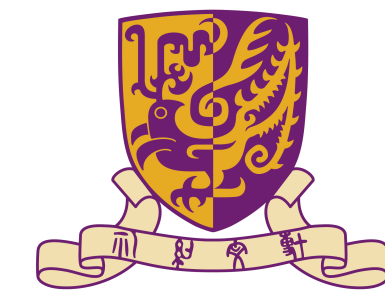
Reactor axion-like particles (ALPs): possible due to copious photons from the fission processes.

RELICS Sensitivity

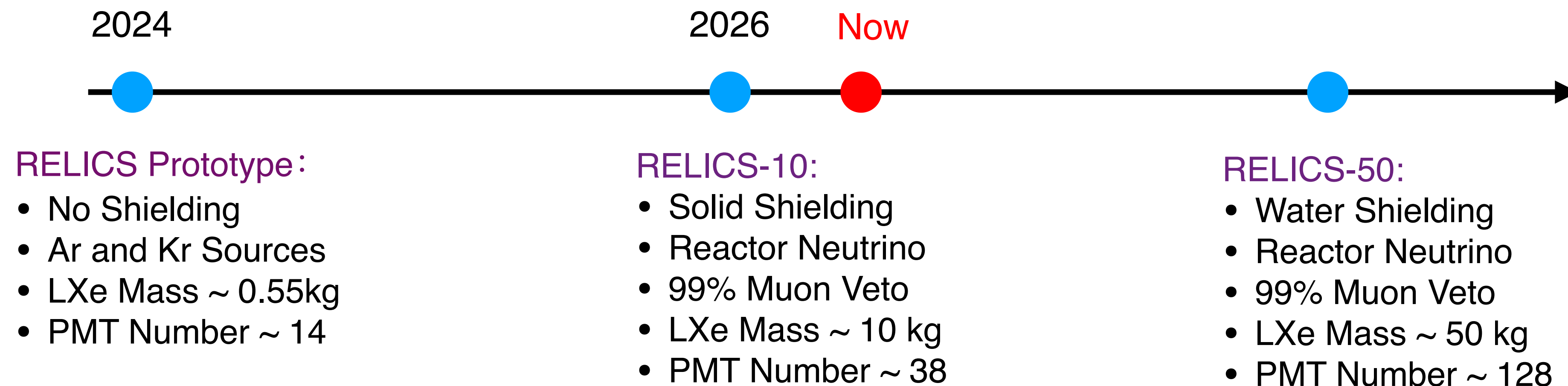


- With 20 kg-year exposure, RELICS is expected to put competitive constraints on axion couplings.

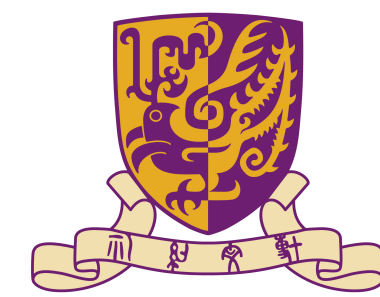
Summary



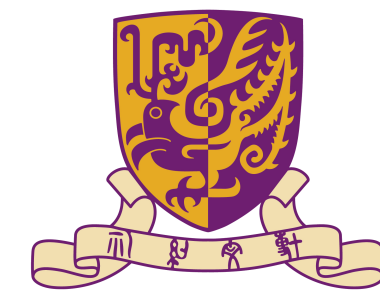
- The staged RELICS program aims to measure $\text{CE}\bar{\nu}\text{NS}$ with reactor neutrinos using LXe TPC
- Energy threshold is $0.6 \text{ keV}_{\text{NR}}$ using S2-only method, and single-electron detectability was demonstrated by RELICS prototype.
- RELICS-10 construction is ongoing
- RELICS-50 expects to observe ~ 4600 $\text{CE}\bar{\nu}\text{NS}$ events per year with pile-up of delayed electrons as the dominant background. Expected S/B ratio of ~ 2.7 .
- Competitive constraints on axion couplings are also expected in RELICS-50.



Back up



Neutrino Energy for CE_νNS



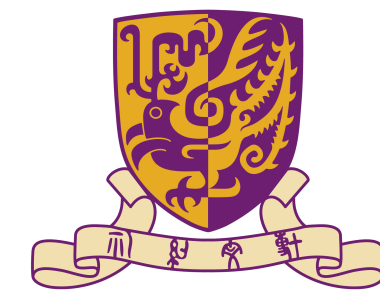
$$\Delta P = m_{\text{Xe}} v_{\text{Xe}} = \frac{2m_{\text{Xe}}m_\nu}{m_{\text{Xe}} + m_\nu} v_\nu \approx 2P_\nu \quad \lambda = \frac{1}{\Delta P} = \frac{1}{2P_\nu} \geq 2R_{\text{Xe}}$$

$$P_\nu \leq \frac{1}{R_{\text{Xe}}} \approx \frac{1}{1.2 \cdot A^{1/3} \text{ fm}} \approx \frac{164}{131^{1/3}} \text{ MeV} \approx 30 \text{ MeV}$$

$$E_r = \frac{\Delta P^2}{2m_{\text{Xe}}} = \frac{2P_\nu^2}{m_{\text{Xe}}} = \frac{2 \times 10^2 \text{ MeV}^2}{131 \text{ GeV}} = 1.5 \text{ keV}$$

- $E_\nu < O(10) \text{ MeV}$ to keep coherence
- $E_\nu > O(1) \text{ MeV}$ to make detectable energy deposit

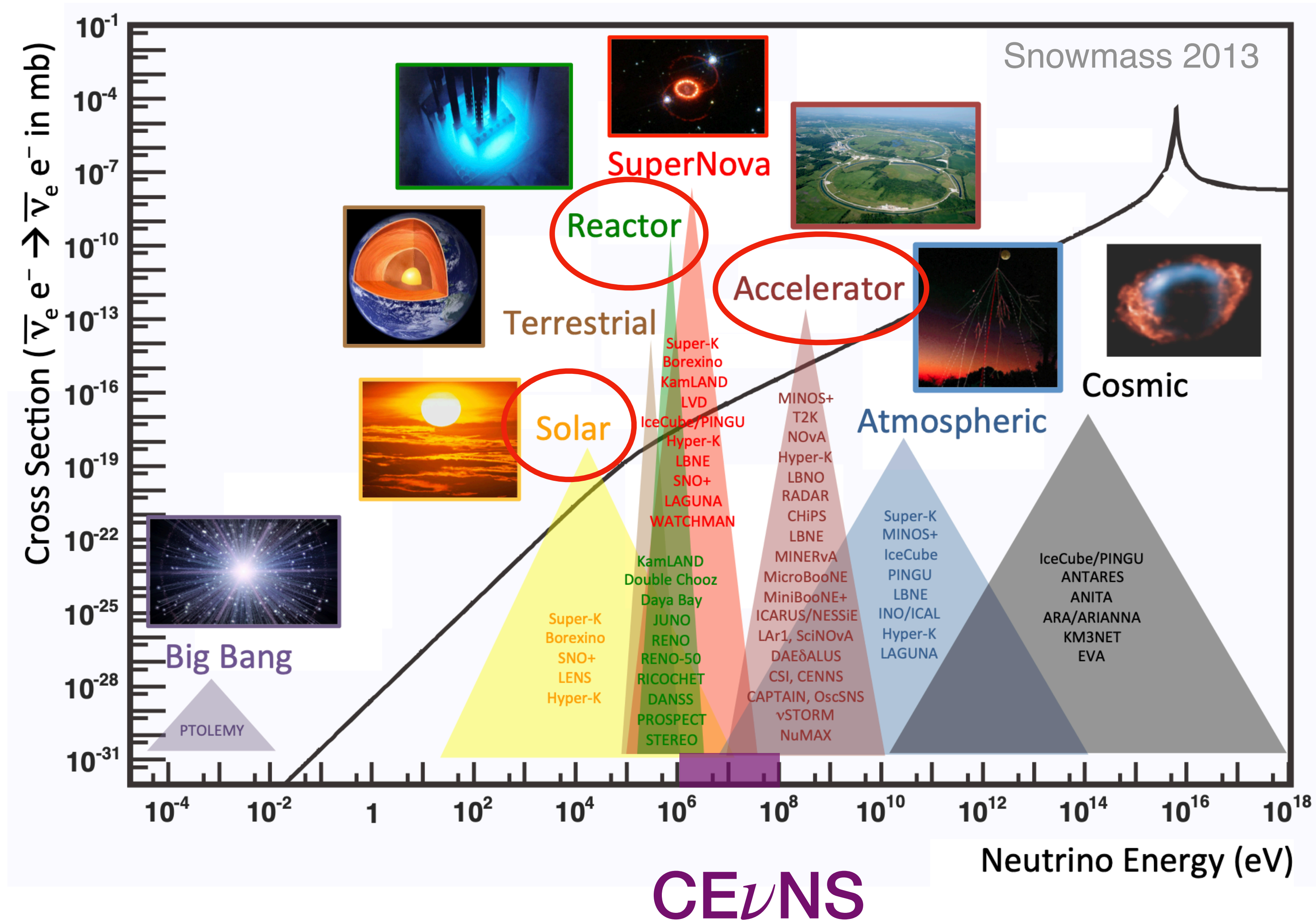
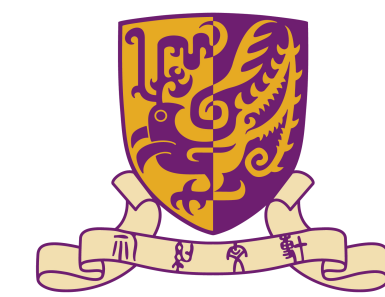
Solar vs. Reactor



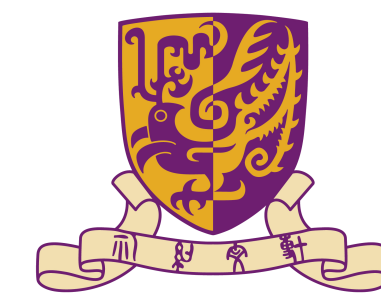
Solar B-8 ν $\Phi_\nu \approx 5 \times 10^6 / (\text{s} \cdot \text{cm}^2)$

Reactor ν $\Phi_\nu \approx 10^{13} / (\text{s} \cdot \text{cm}^2)$

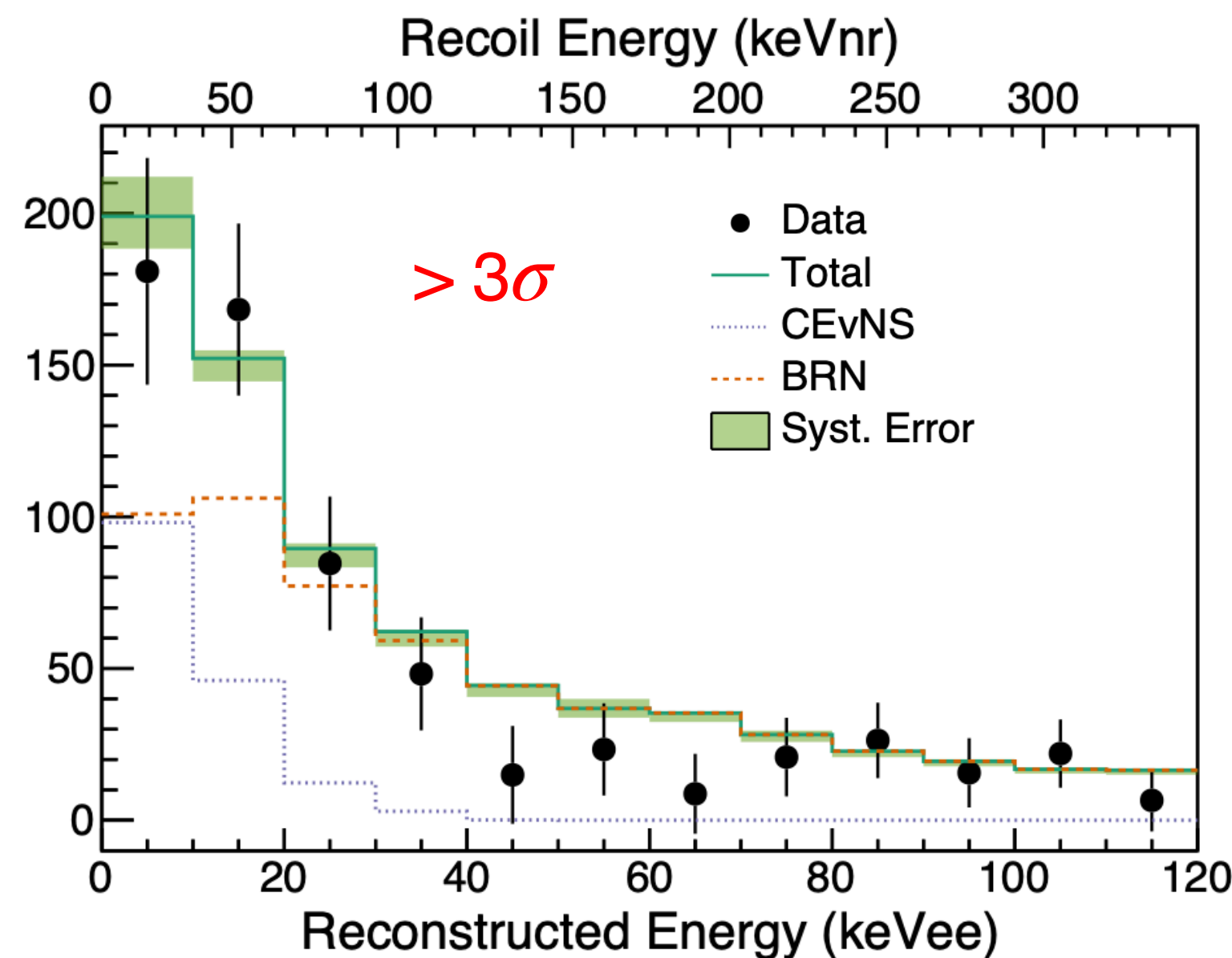
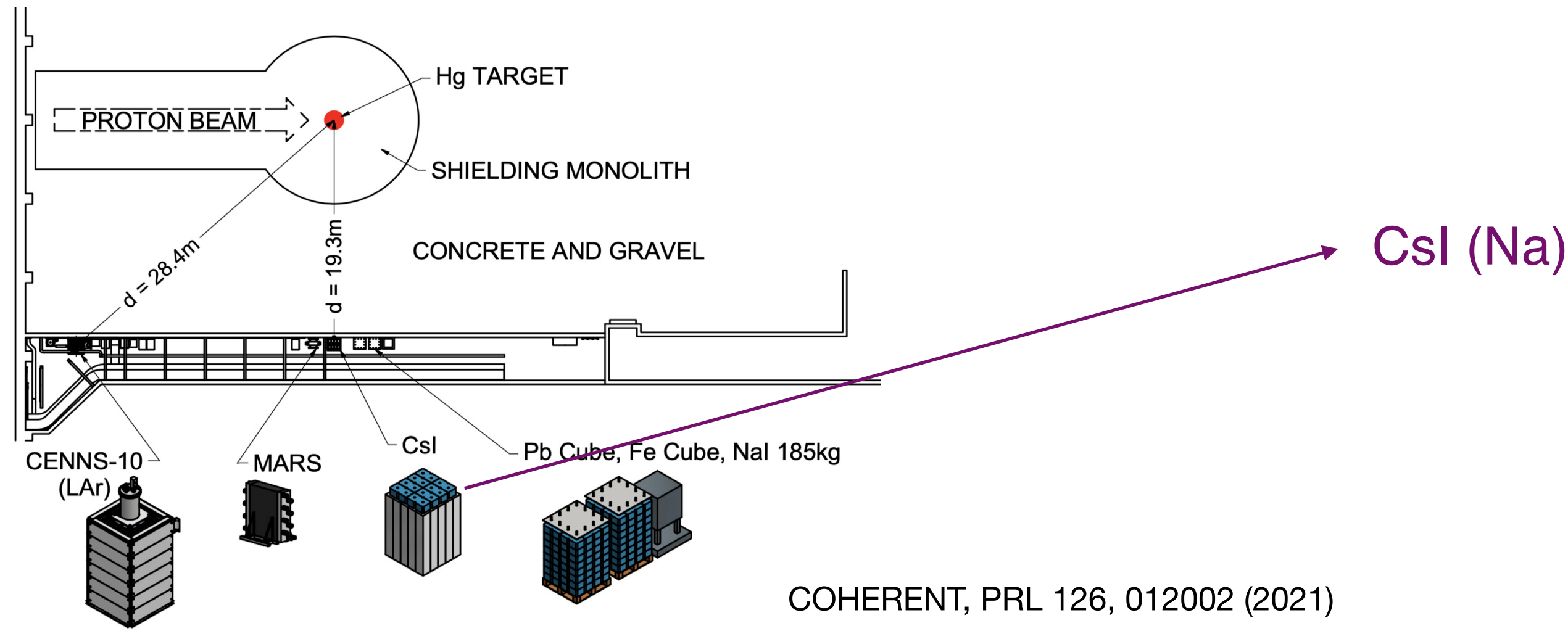
Neutrino Energy for CE_{ν}NS



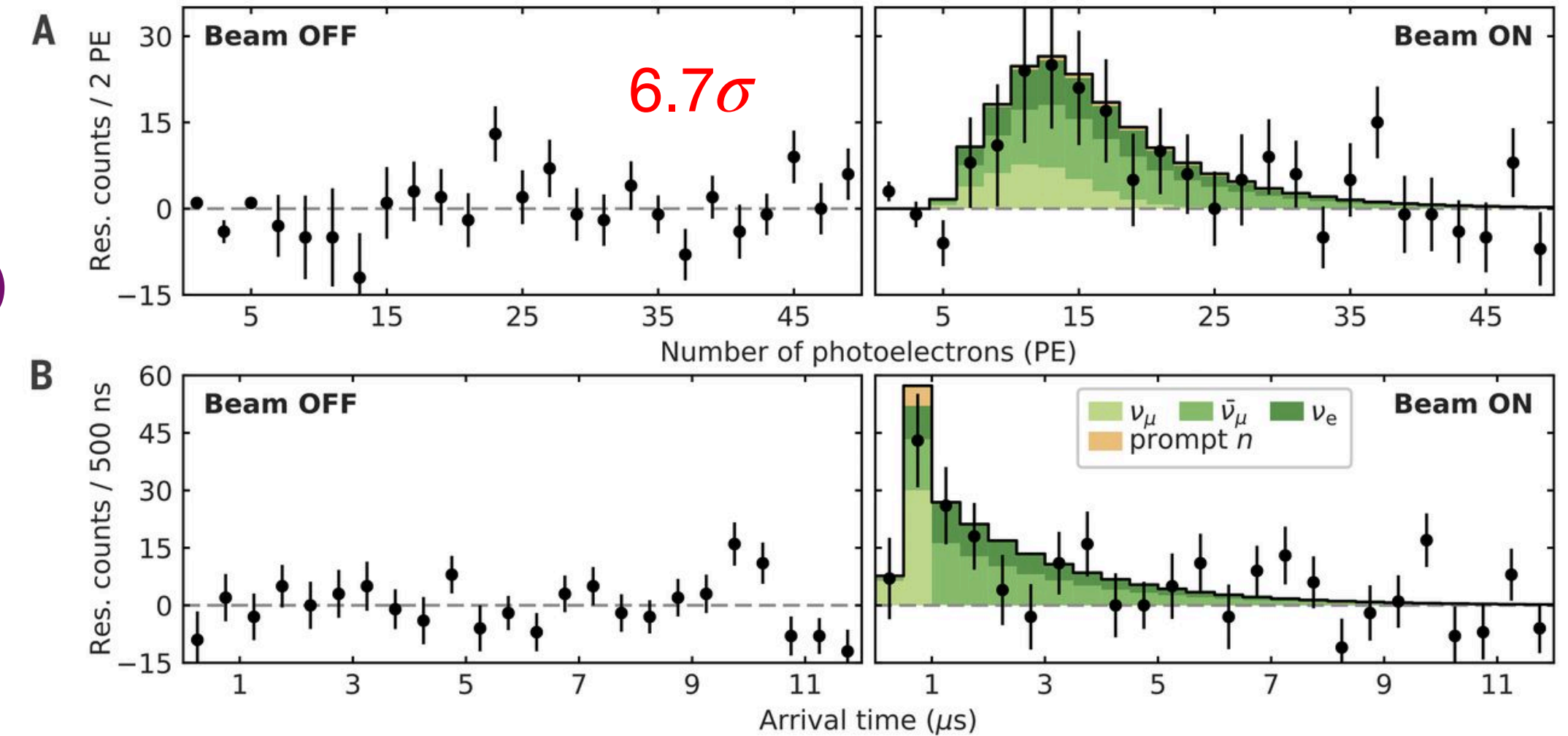
CE ν NS Detection - Accelerator ν



COHERENT @SNS



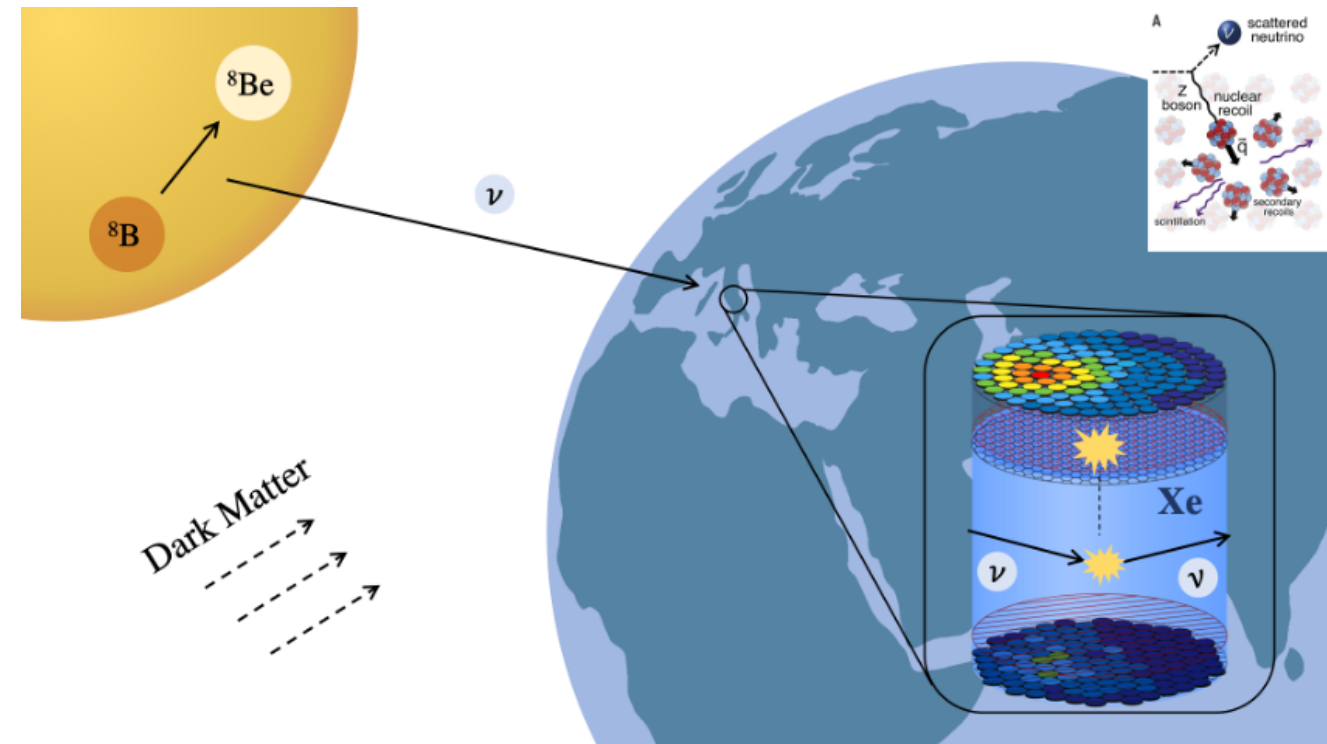
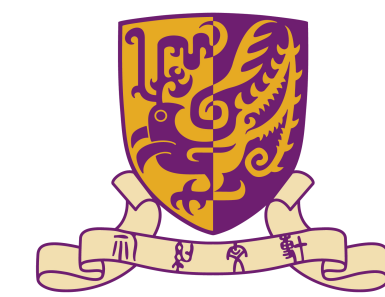
COHERENT, Science 357, 1123 (2017)



- Accelerator ν :
 - Higher energy deposit, $O(10) \text{ keV}_{\text{NR}}$
 - Beam on & off - background control and modeling
 - Timing info - extra signal discrimination over background
- First observed in CsI(Na) by COHERENT in 2017 using accelerator neutrinos from Spallation Neutron Source (SNS)
- Observed in LAr by the same collaboration in 2020

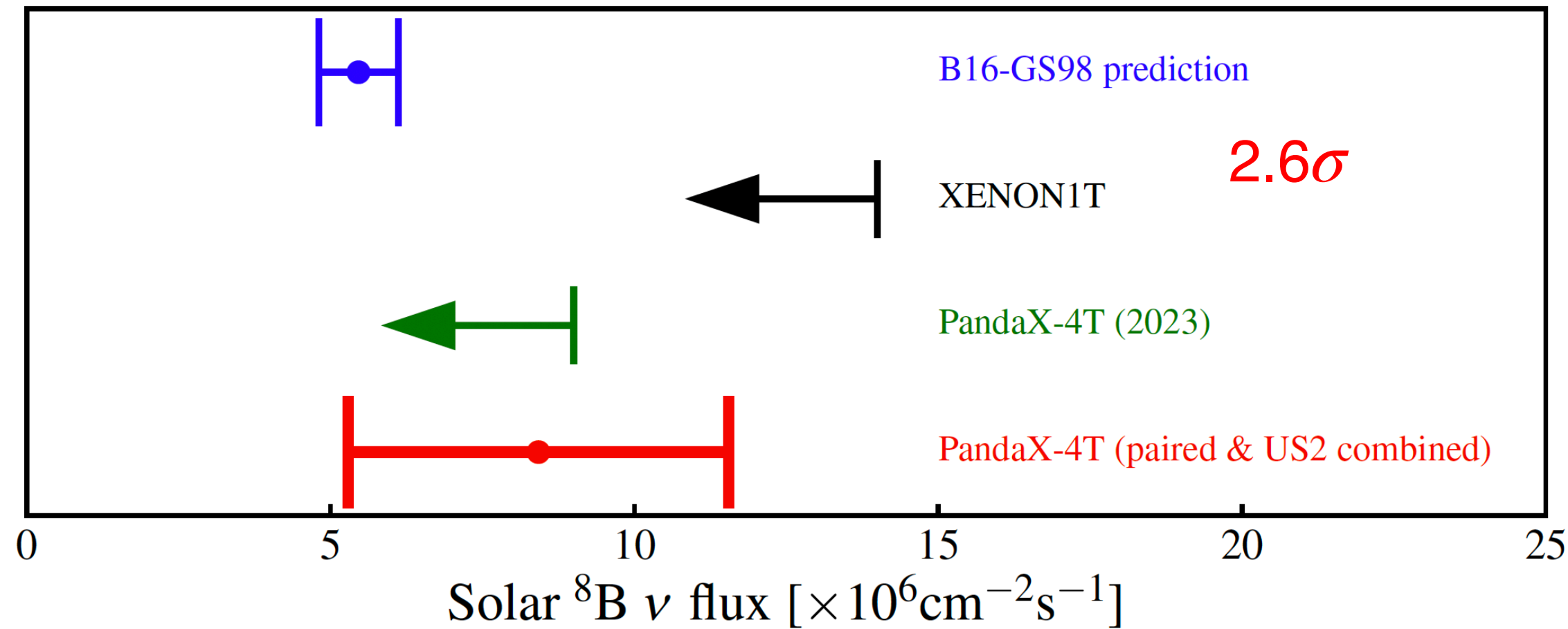


CE ν NS Detection - Solar ν

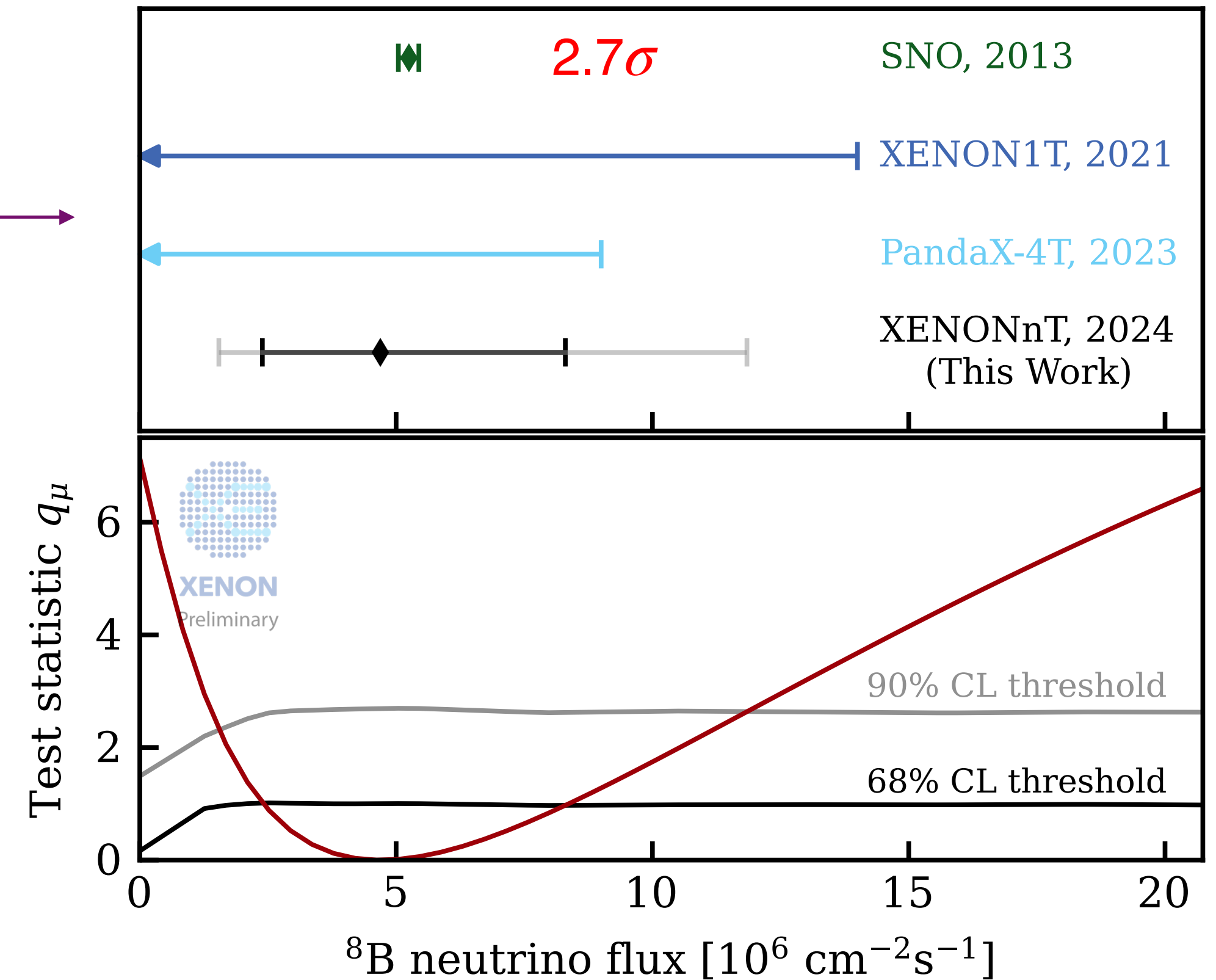


xenon

PandaX-4T, PRL 133, 191001 (2024)

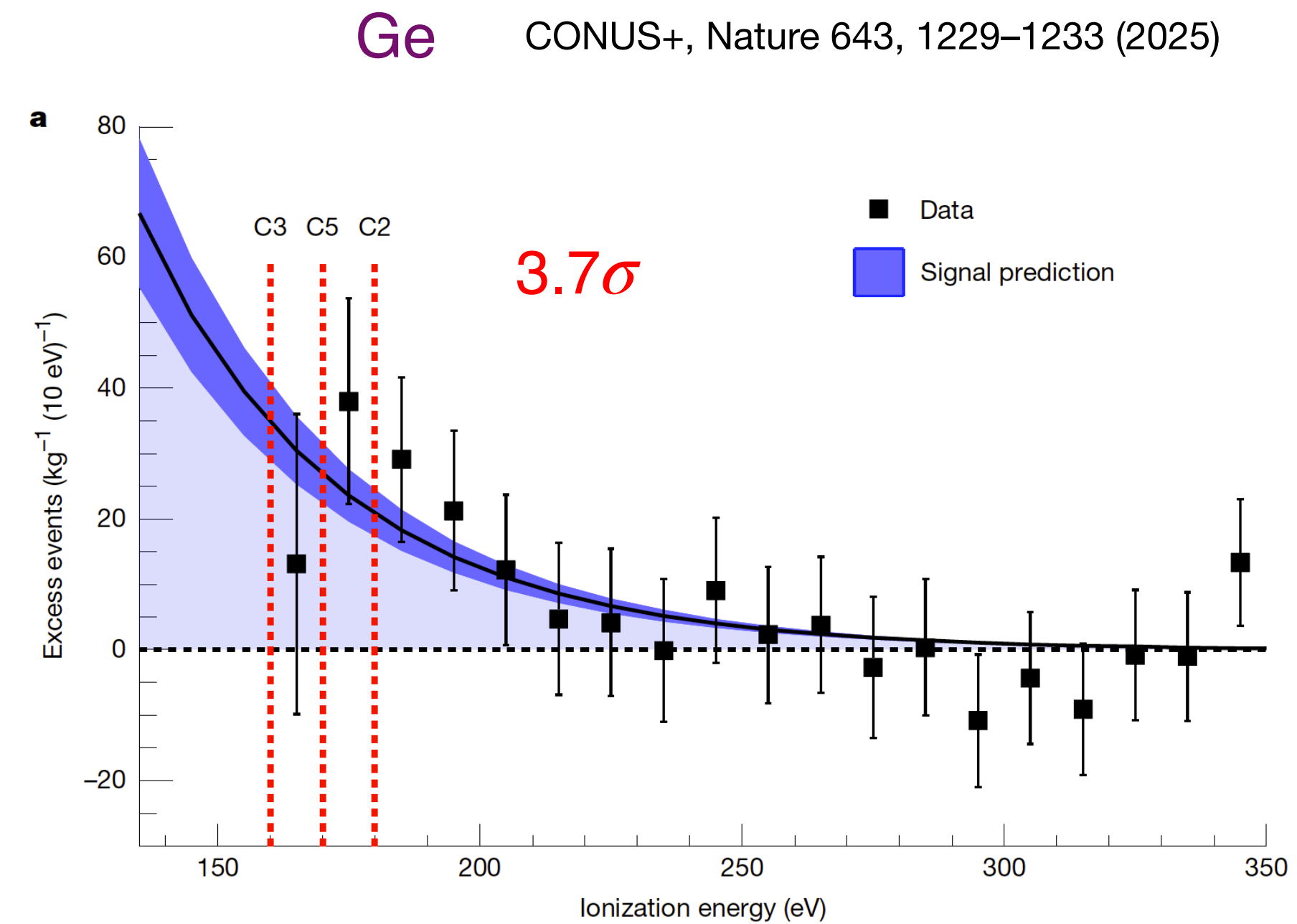
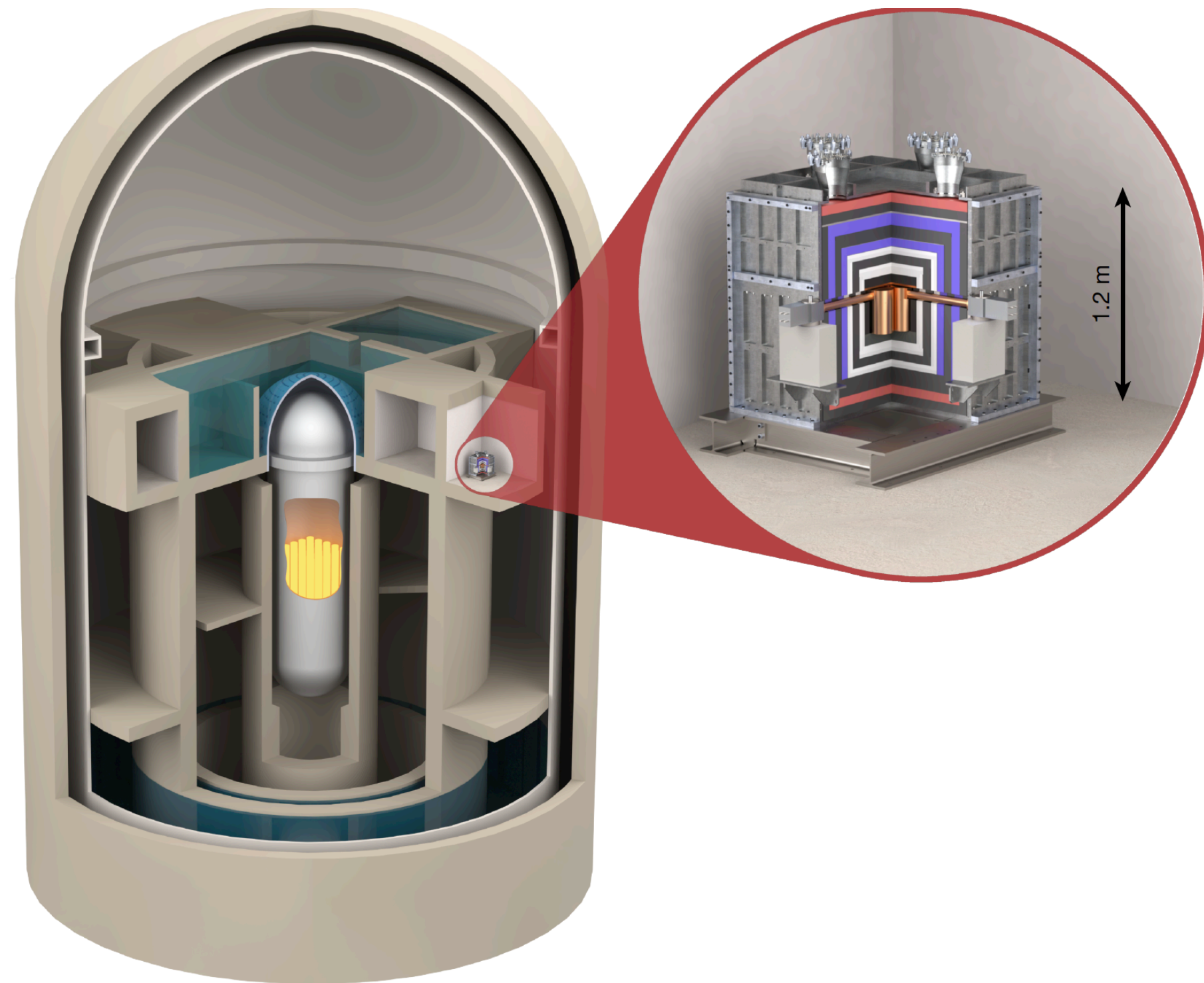
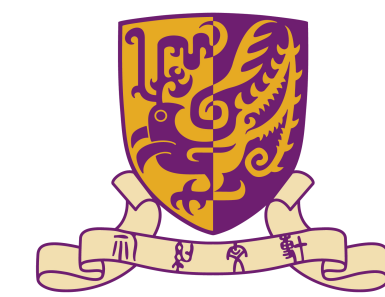


XENONnT, PRL 133, 191002 (2024)



- Solar B-8 neutrinos CE ν NS were detected in **xenon** by PandaX and XENON independently in 2024
- Solar flux measurements consistent with SSM and SNO measurements
- First time with neutrinos from natural sources, and first time in xenon.

CE ν NS Detection - Reactor ν



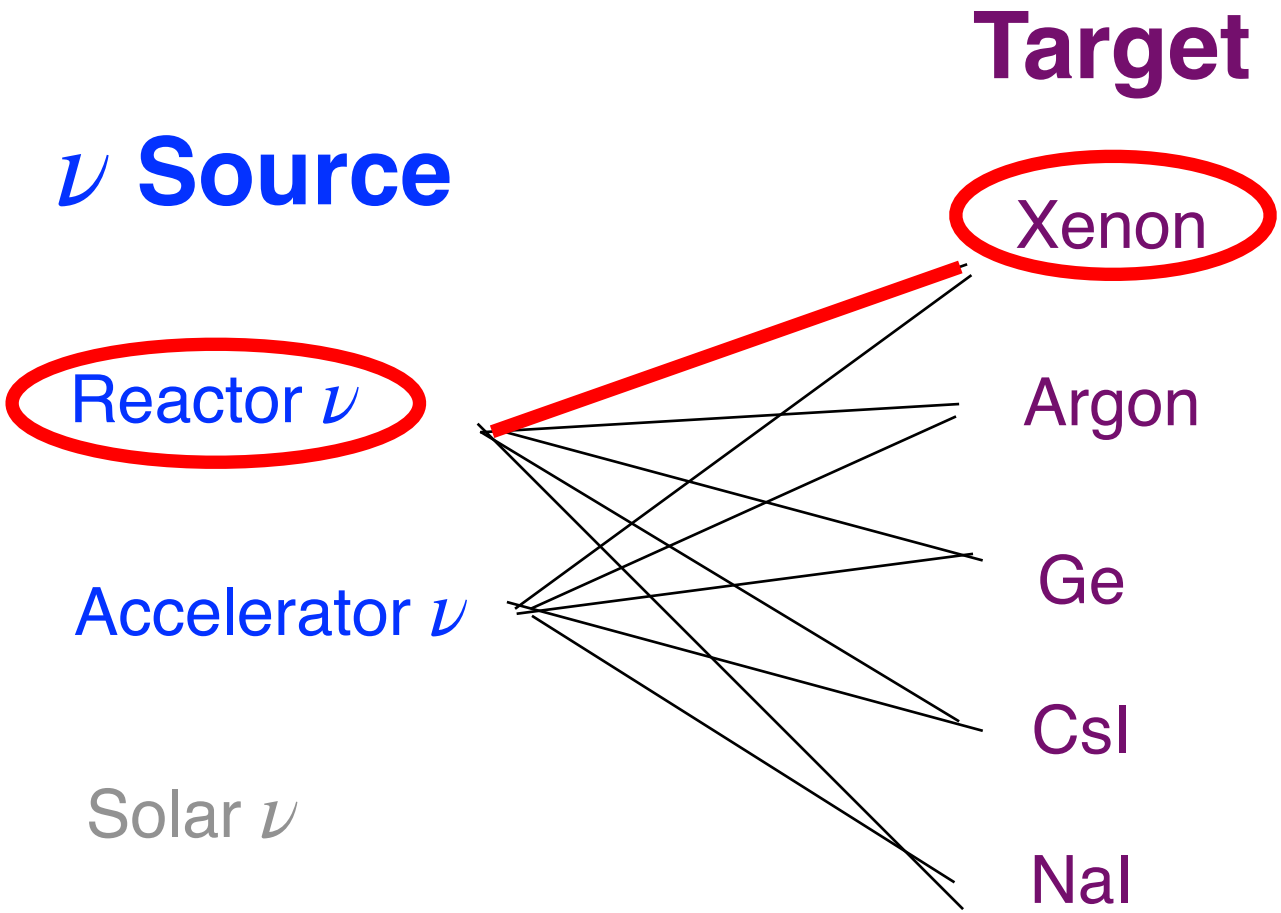
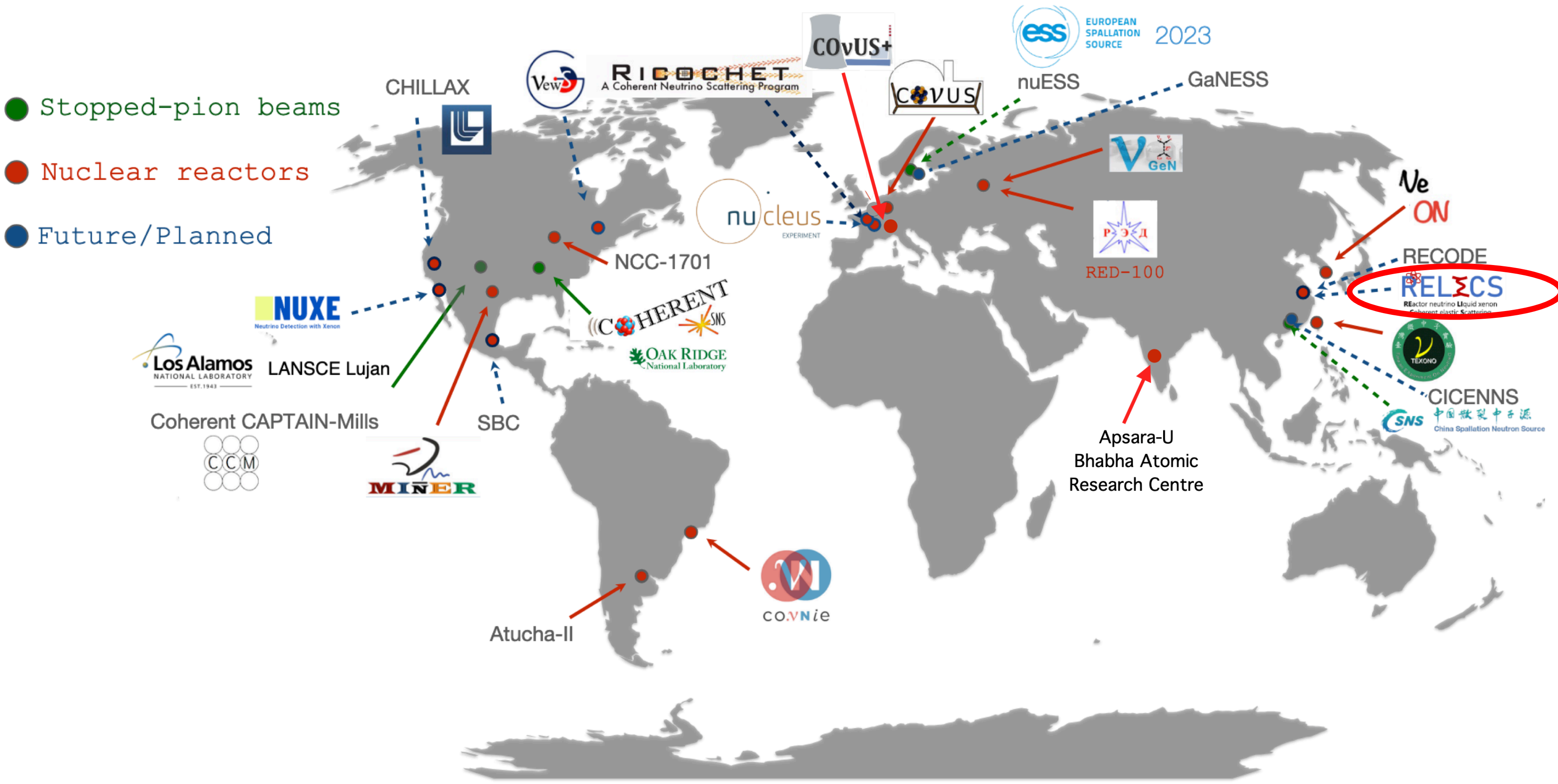
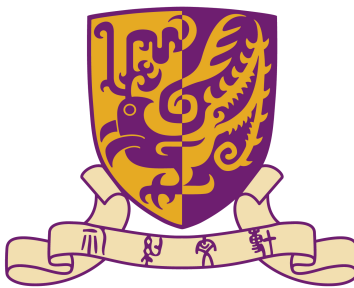
- Reactor ν : large flux, low energy, reactor on-off mode
- CONUS+ observed CE ν NS in High-Purity Germanium (HPGe) using reactor neutrinos in 2025

Reactor ν Experiments



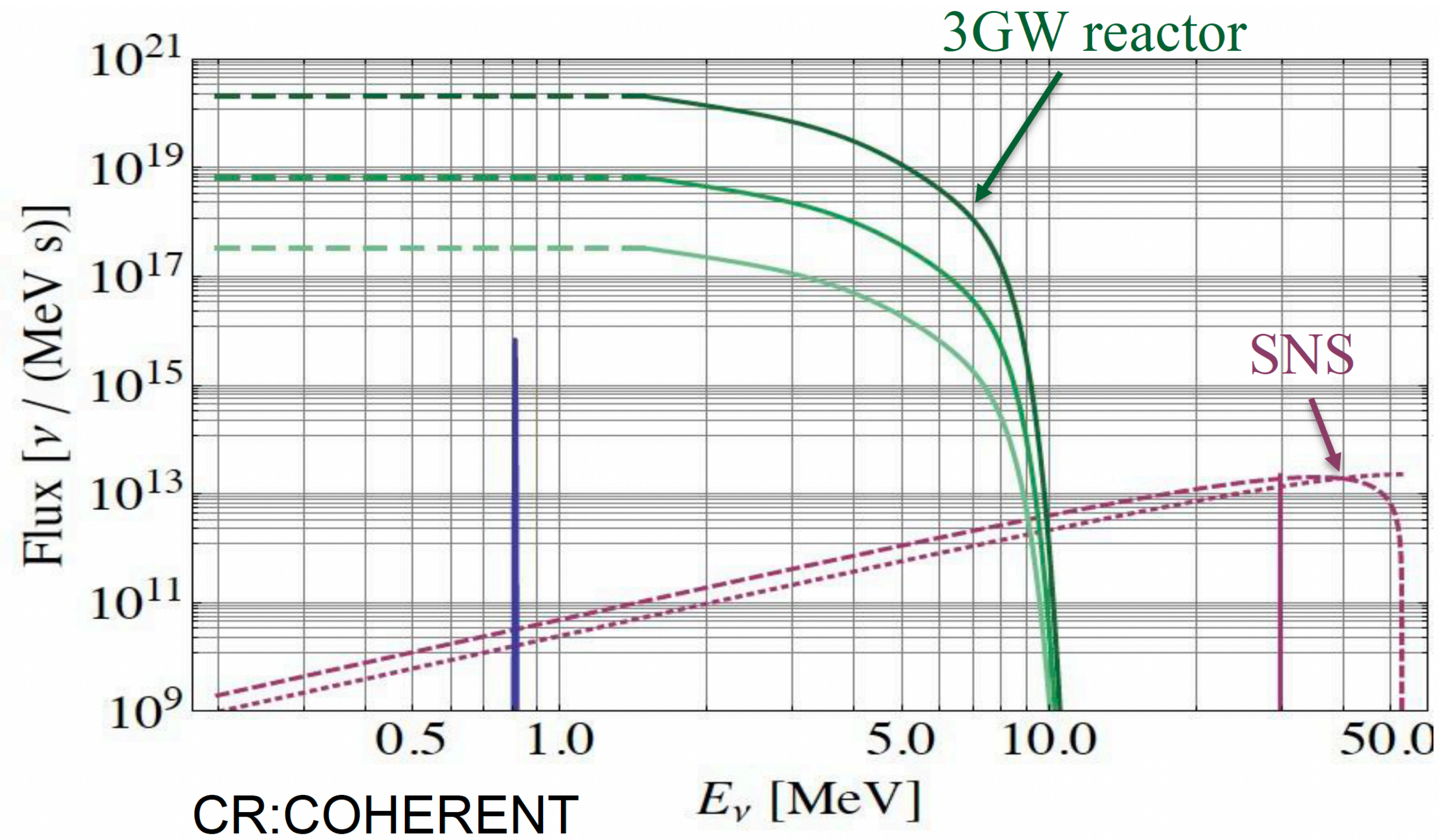
Experiment	Target	Mass	Threshold	Reactor	Distance to Core	Thermal Power	Neutrino flux ($\nu/\text{cm}^2/$	Location
CONNIE	Si CCDs	50 g	~ 40 eVee	Angra 2 reactor	30 m	3.8 GWth	7.8×10^{12}	Brazil
MINER	Ge/Si	4 kg	~ 100 eVnr	TRIGA reactor	2~10 m	1 MWth	$\sim 10^{12}$	USA
RICOCHET	Ge & Zinc	32 g (Ge)	55 eVee	ILL reactor	8 m	58 MWth	1.6×10^{12}	France
CONUS	HPGe	3.74 kg	~ 300 eVee	Kernkraftwerk Brokdorf (KBR)	17 m	3.9 GWth	2×10^{13}	Germany
Nu-Gen	HPGe	1.6 kg	350 eVee	Kalinin NPP	10 m	3.2 GWth	5.4×10^{13}	Russia
TEXONO	HPGe	1 kg	~ 200 eVee	Kuo-Sheng Neutrino Laboratory	28 m	2.9 GWth	6.4×10^{12}	Taiwan, China
RELICS	LXe	50 kg	~ 1 keVnr	Sanmen	22 m	3.4 GW	1.4×10^{13}	China
RECODE	HPGe	10 kg	~ 160 eVee	Sanmen				
	HPGe	1-2 kg	~ 160 eVee	Sanmen	11 m	3.4 GW	5.6×10^{13}	China

Worldwide Efforts for $CE_{\nu}NS$ Search!



A combination question...

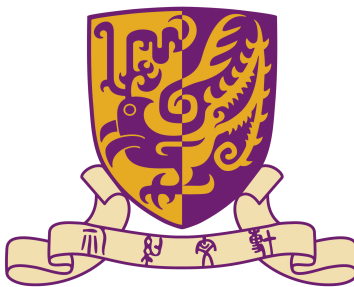
Figure credit: Valentina De Romeri et al.



- High flux
- Low energy deposit, no timing info

$$< 1.5 \text{ keV}_{\text{NR}}$$

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

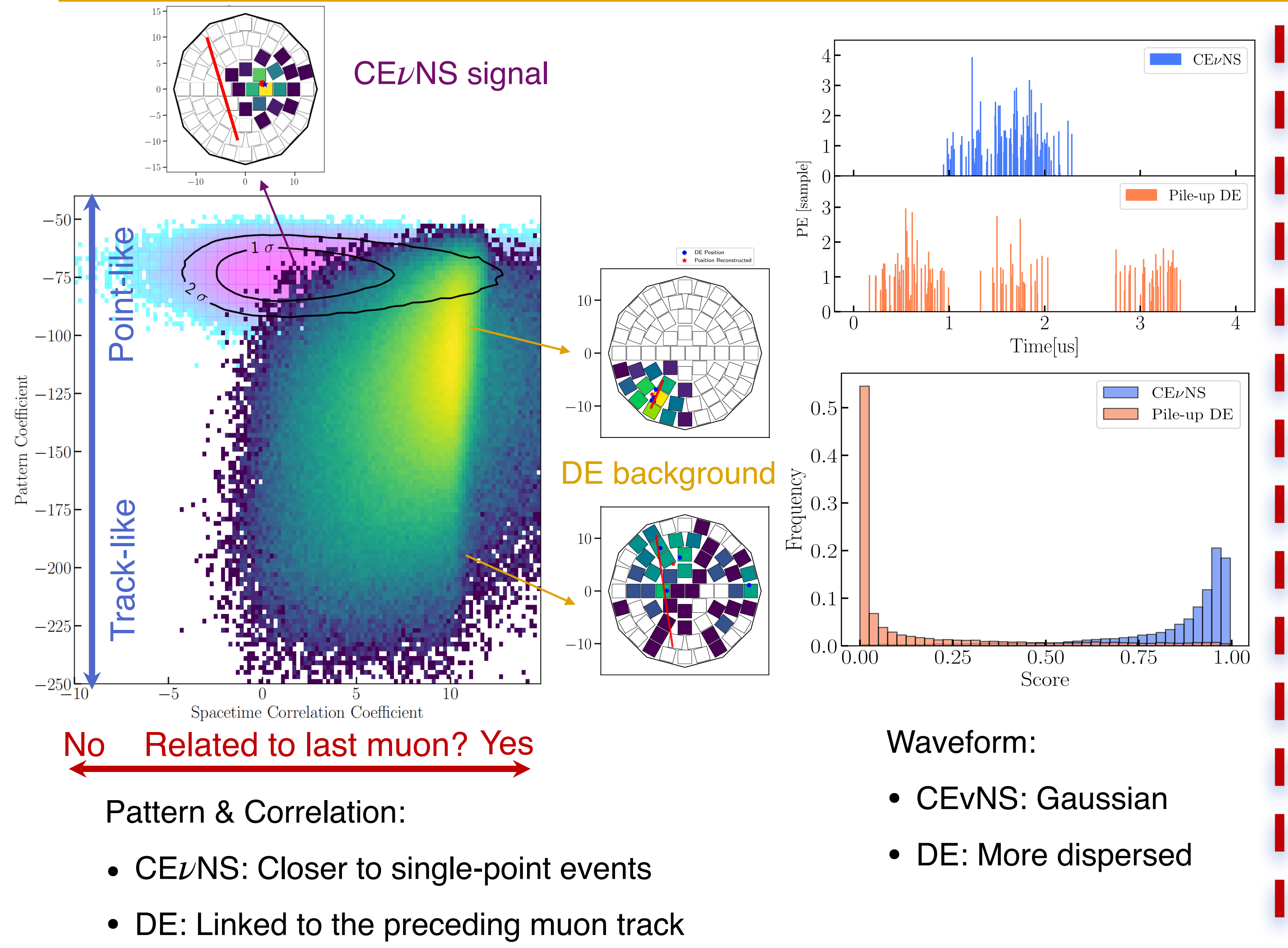
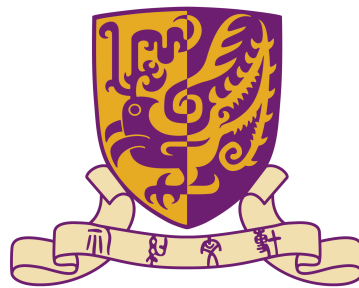
background

detector threshold

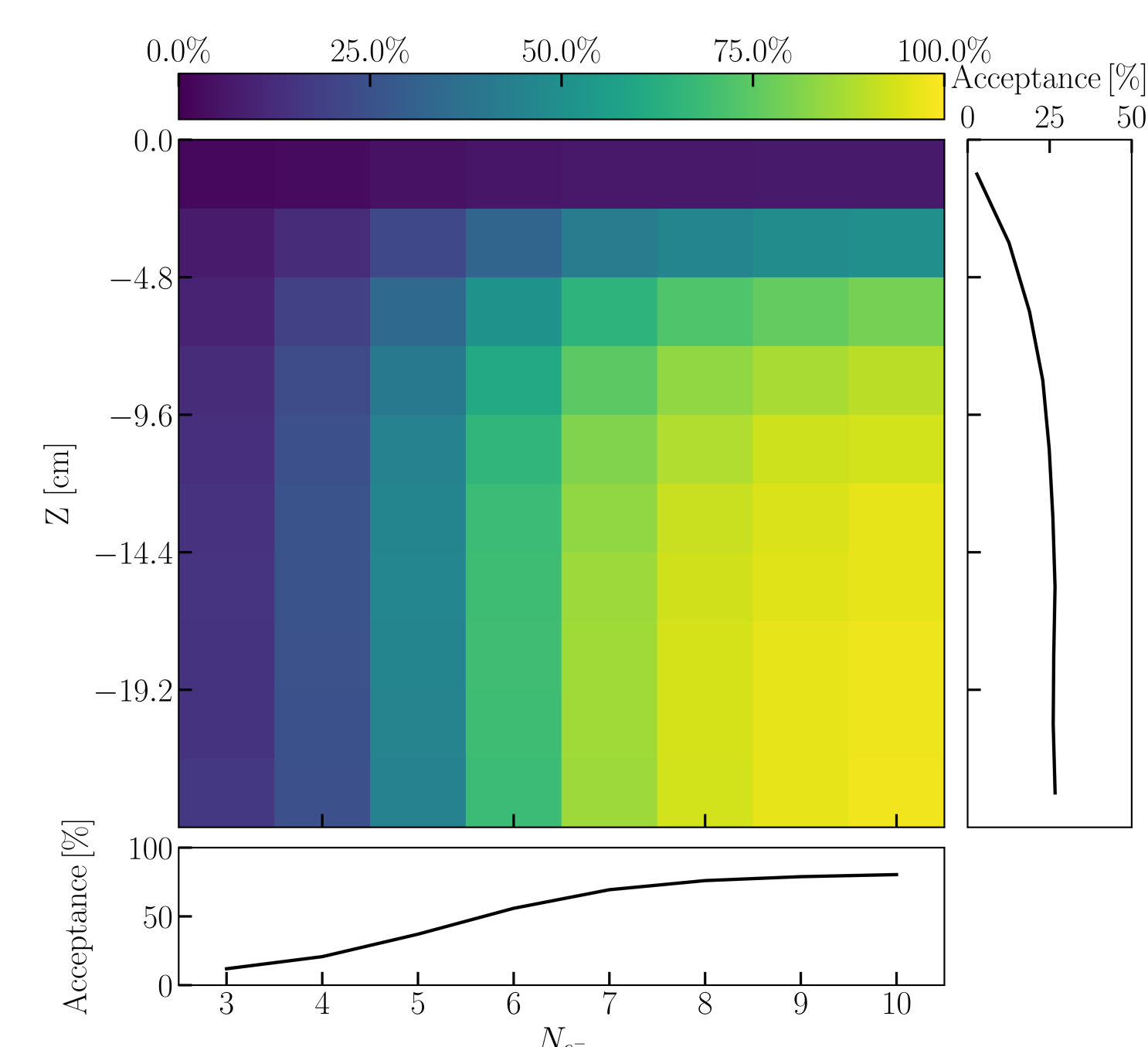
exposure

- Radiopurity
- O(1) keV, sub keV possible
- Scalability & Stability

DE Background Rejection

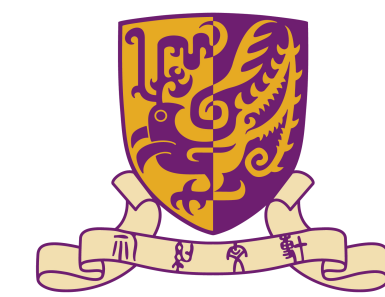


Summary of Signal Acceptance

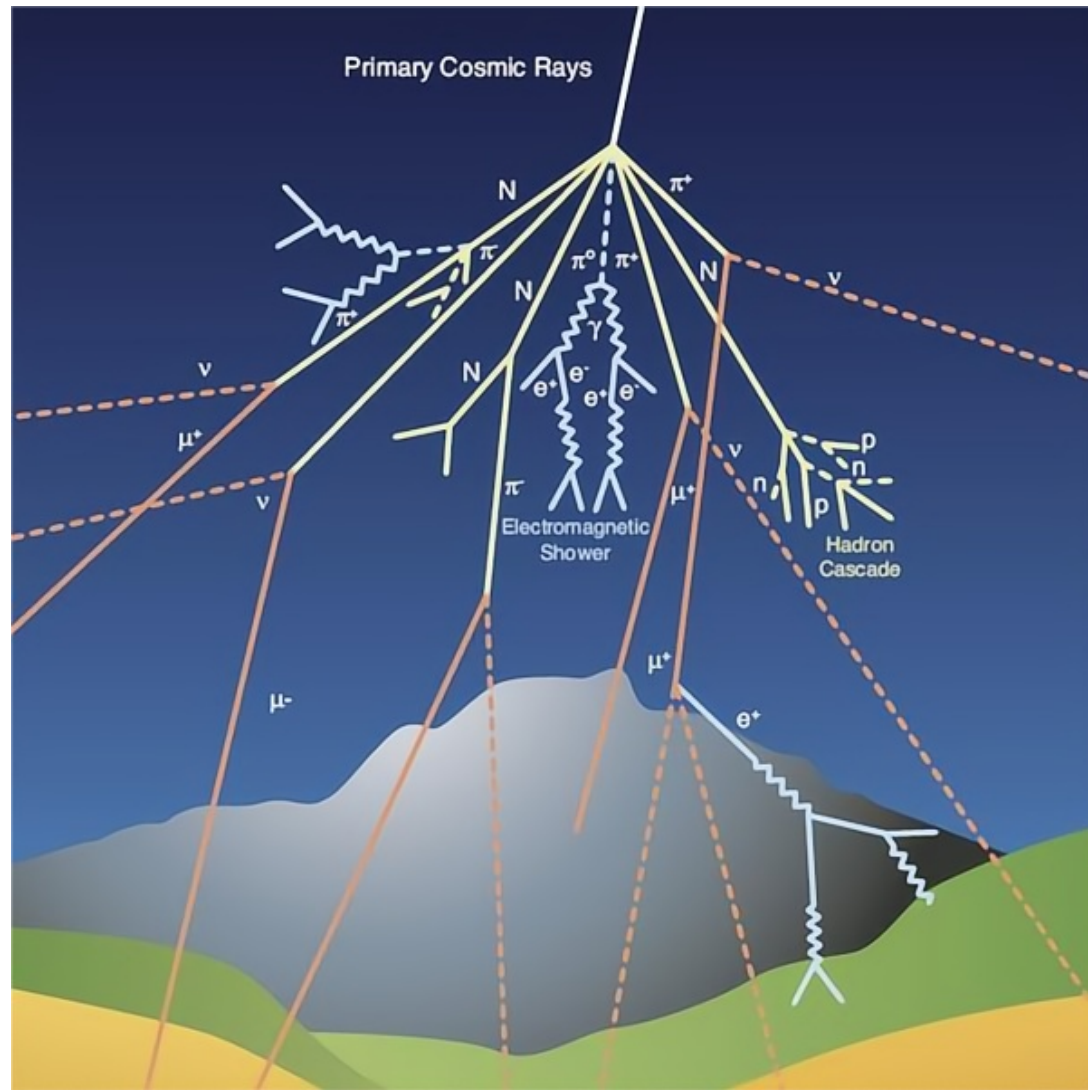


Selection	Signal acceptance	Background rejection
S2 Width	~ 86%	~ 94%
Pattern & Correlation	~ 52%	~99.99%
Waveform	~ 80%	~90%

Background Origins for $CE_{\nu}NS$

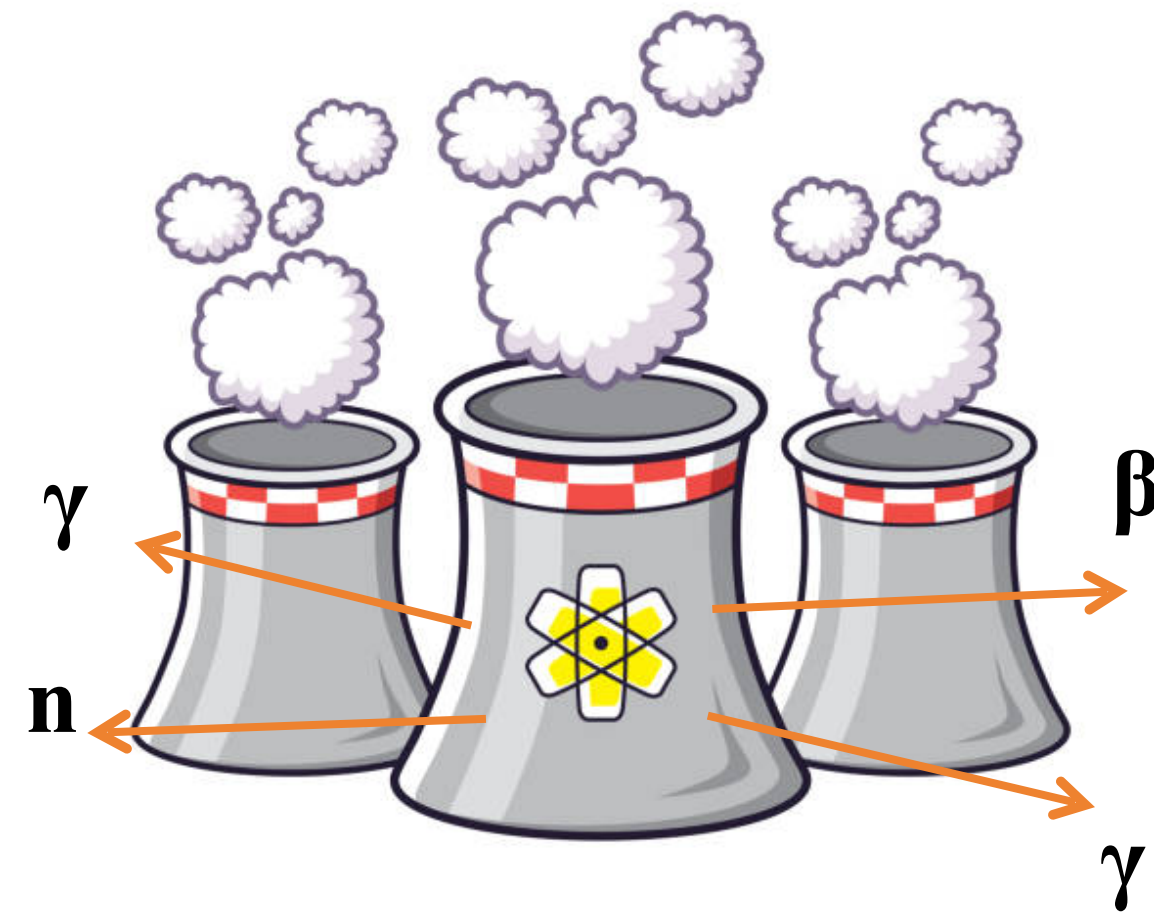


Cosmic



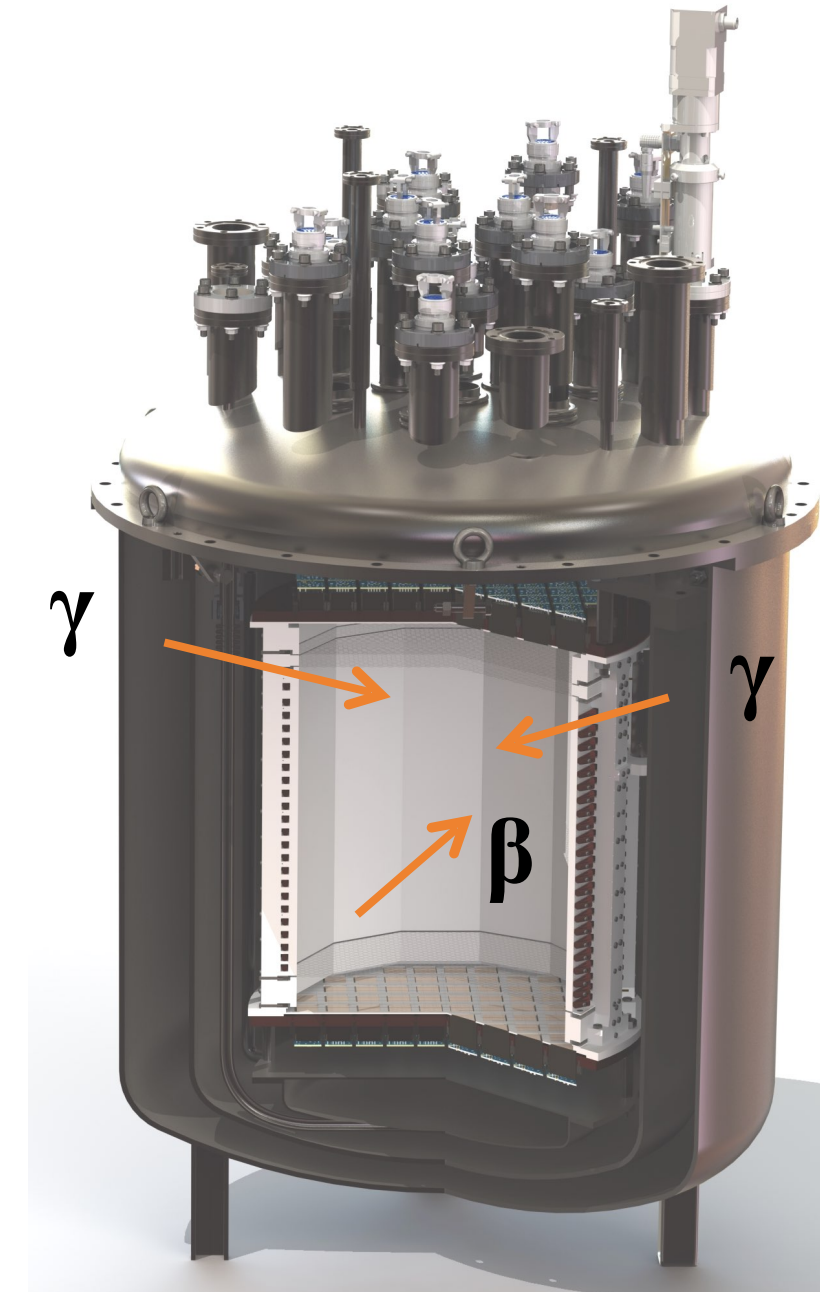
- Cosmic μ
- Cosmic neutron

Reactor



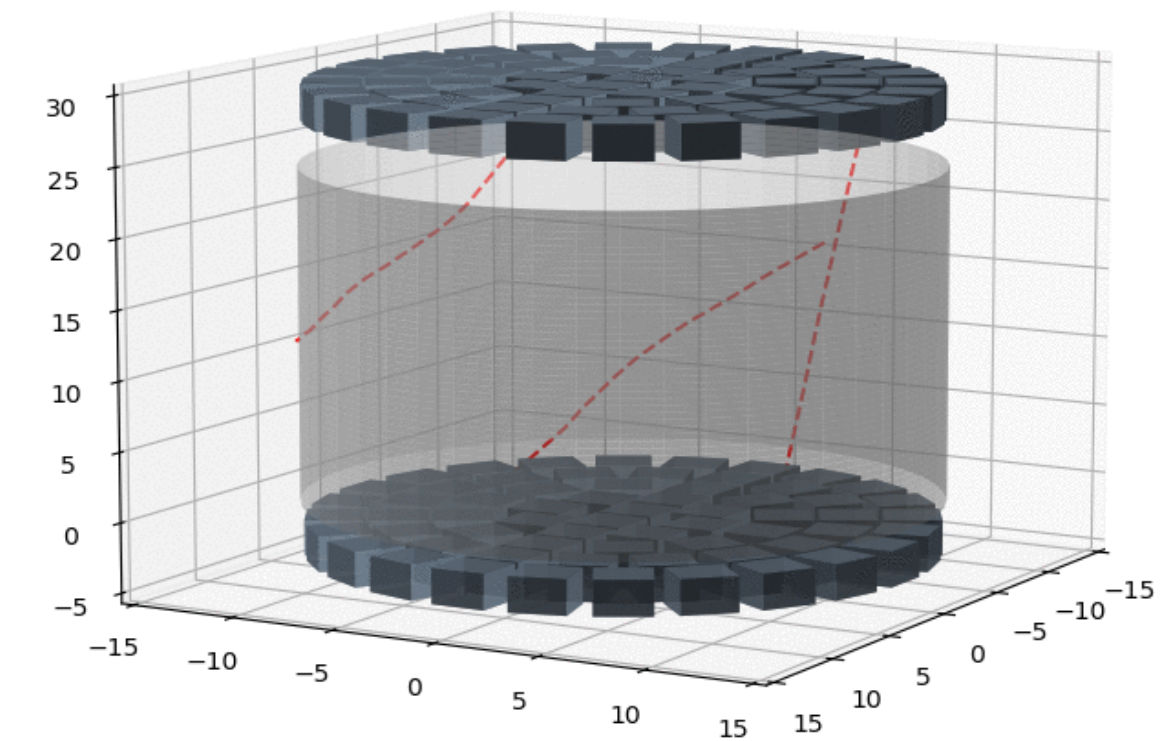
- Reactor Neutron
- Reactor γ

Material



- Material γ, β

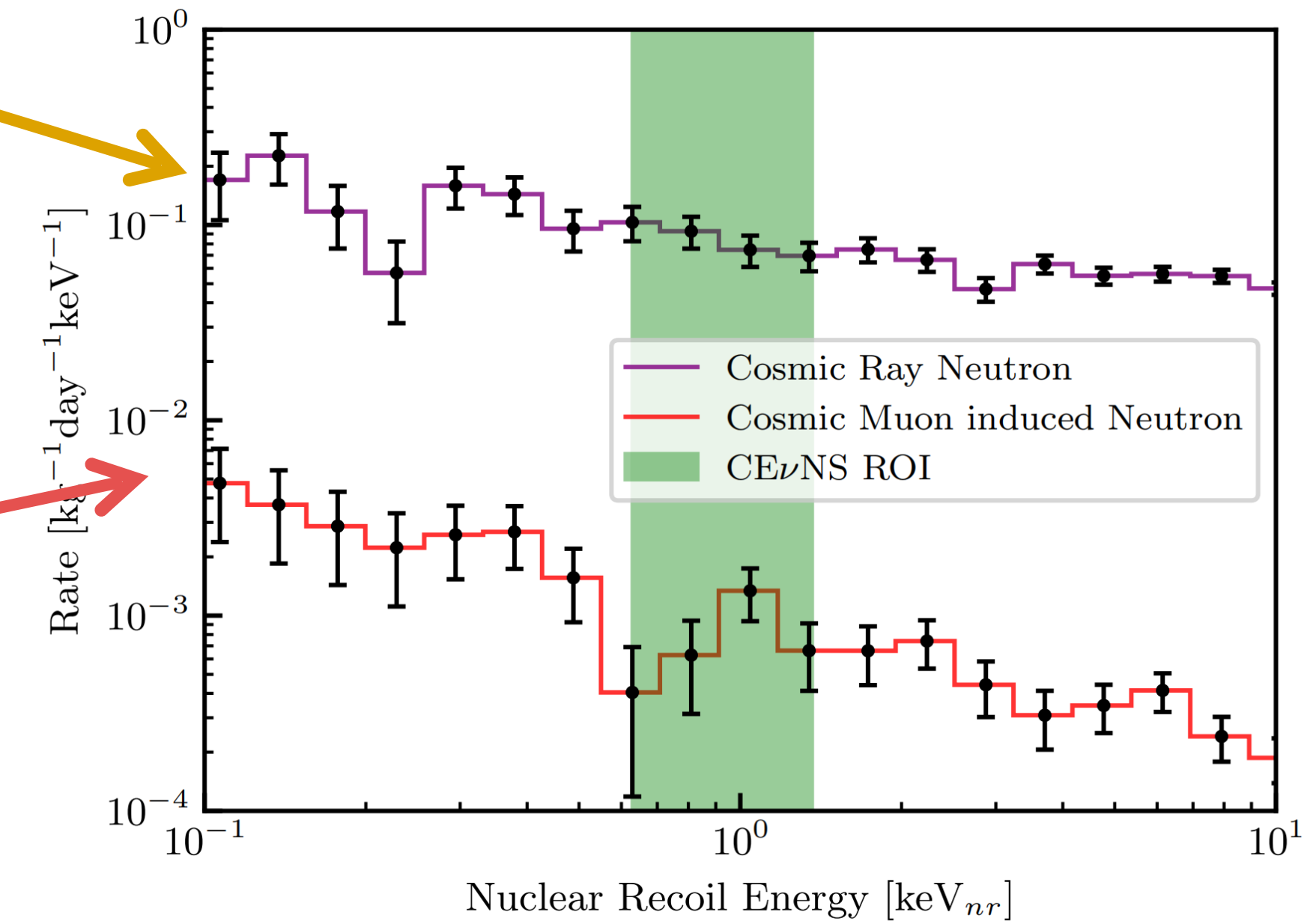
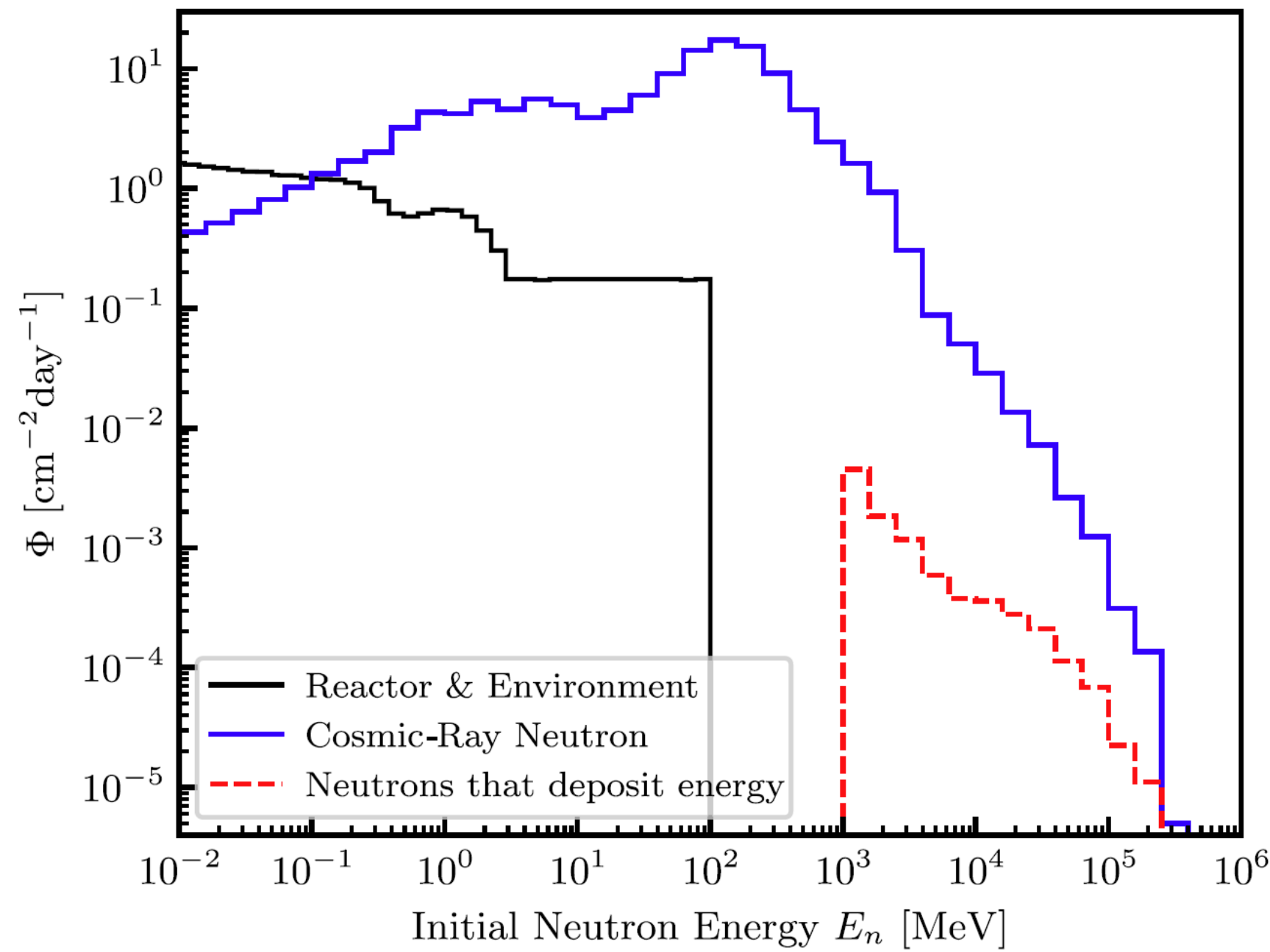
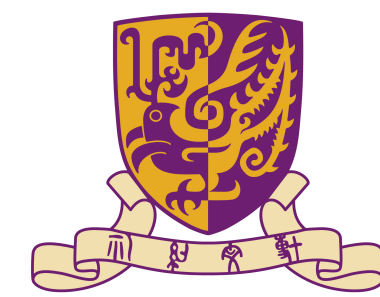
Delayed Electrons



Geant4 Simulation

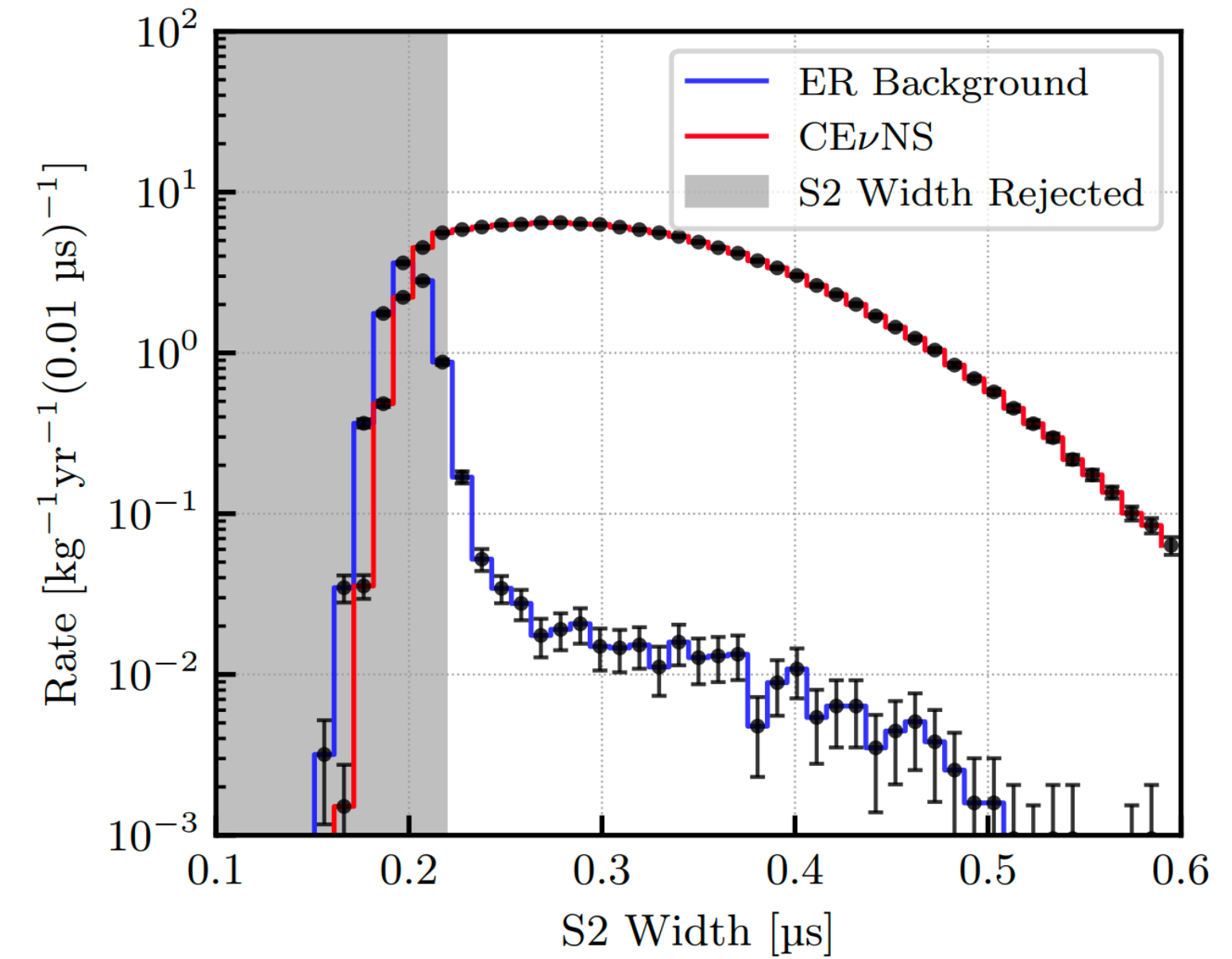
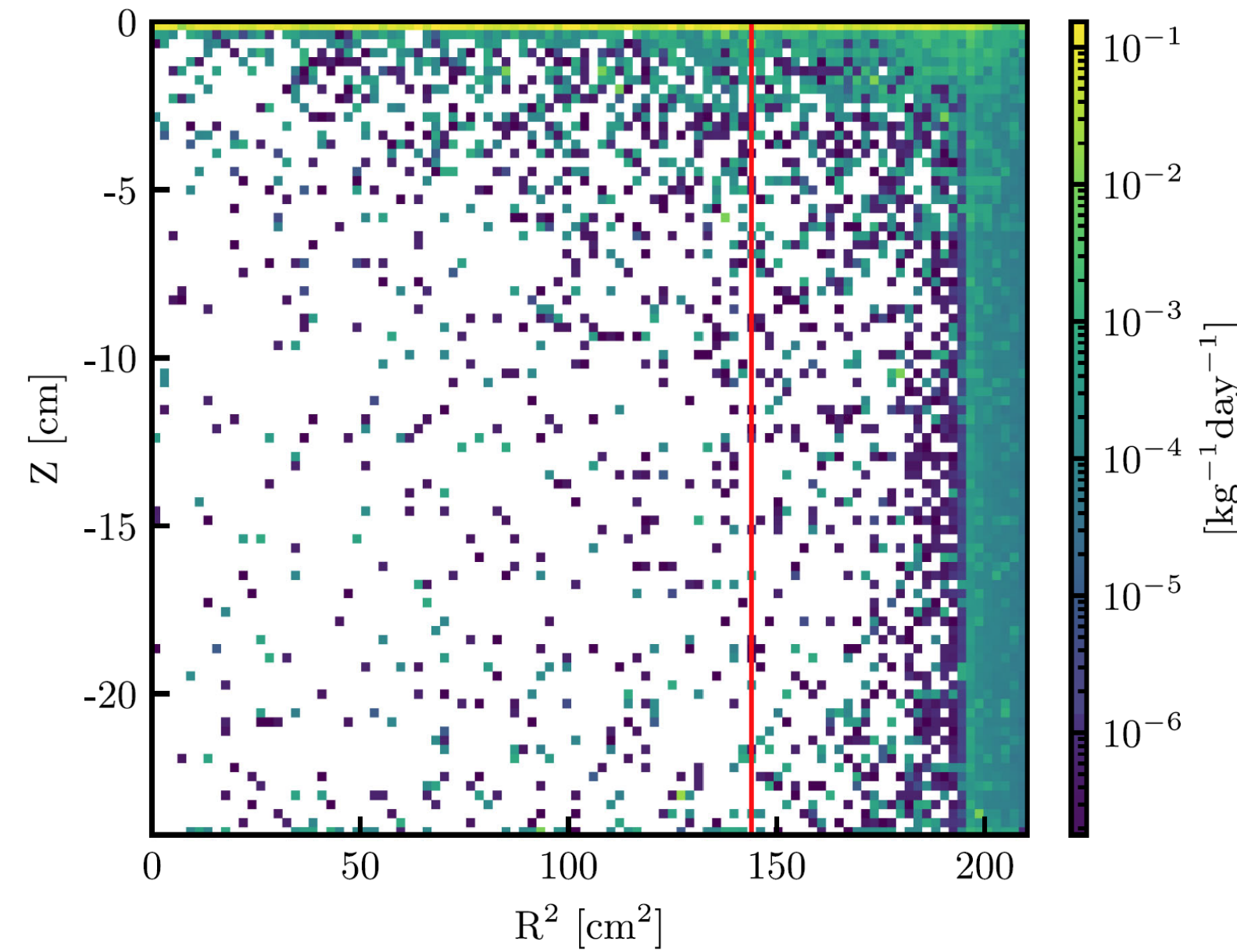
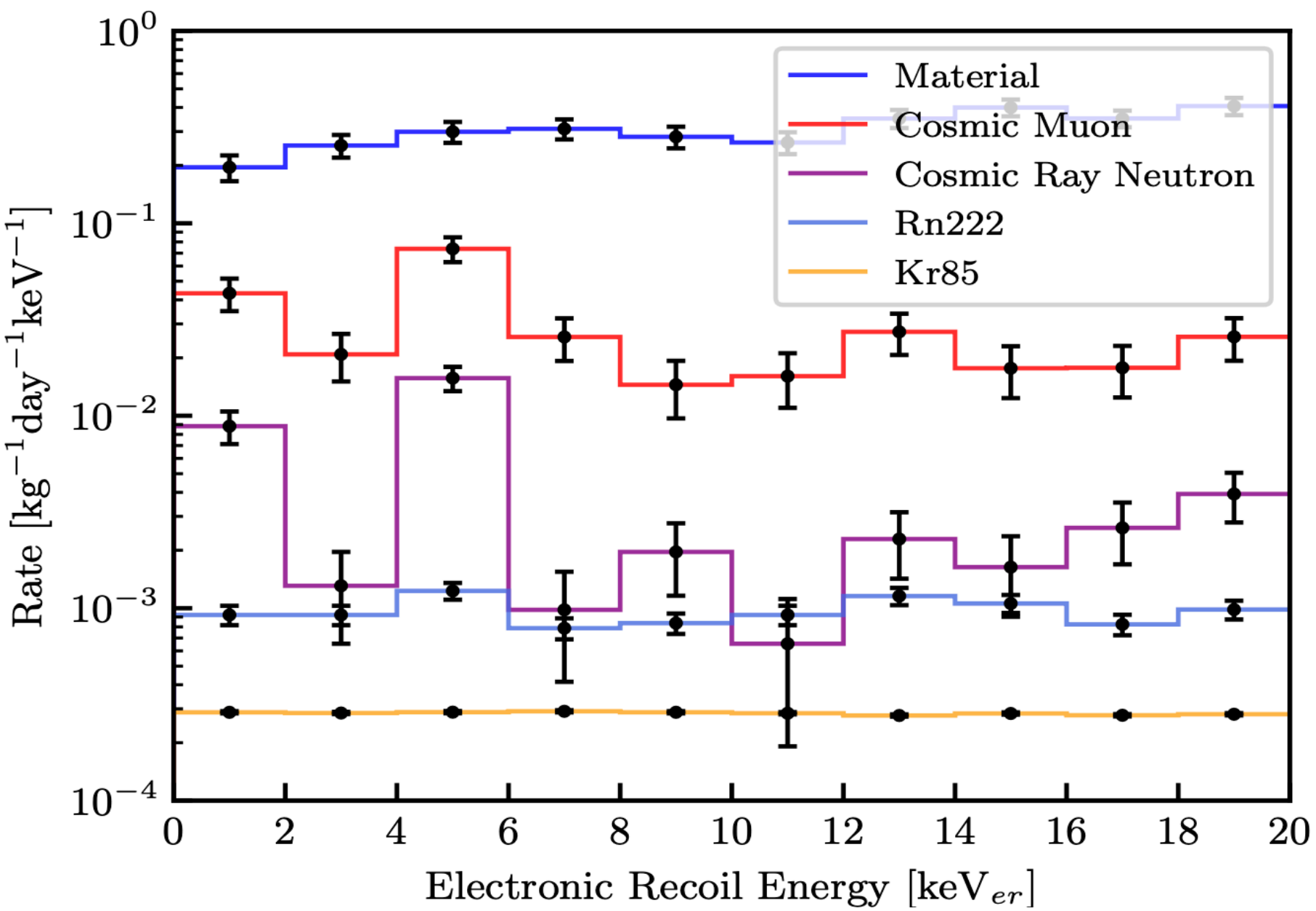
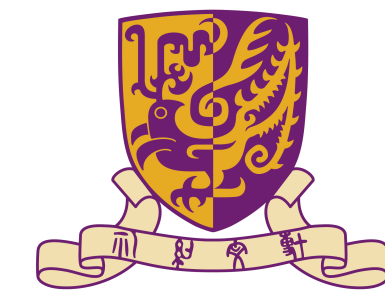
Data-driven Modeling

NR Backgrounds



- Neutron source:
 - Cosmic ray neutron (dominant)
 - Muon-induced neutron
 - Reactor & Environment neutrons
- $(7.7 \pm 0.7) \times 10^{-2} \text{ (kg} \cdot \text{day)}^{-1}$ in (0.6, 1.4) keV_{NR}

ER Backgrounds



Fiducial Volume cut:

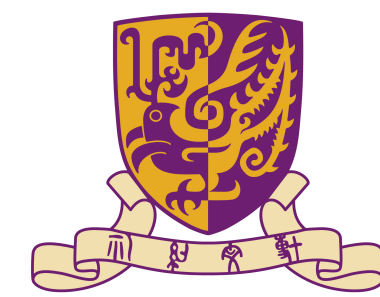
- ER background source:
 - Material
 - Muon-induced ER
 - Cosmic ray neutron-induced
 - Intrinsic
- $(3.1 \pm 0.1) \times 10^{-1} (\text{kg} \cdot \text{day} \cdot \text{keV})^{-1}$ before S2 width cut

- $R < 12 \text{ cm}$
- No Z Position

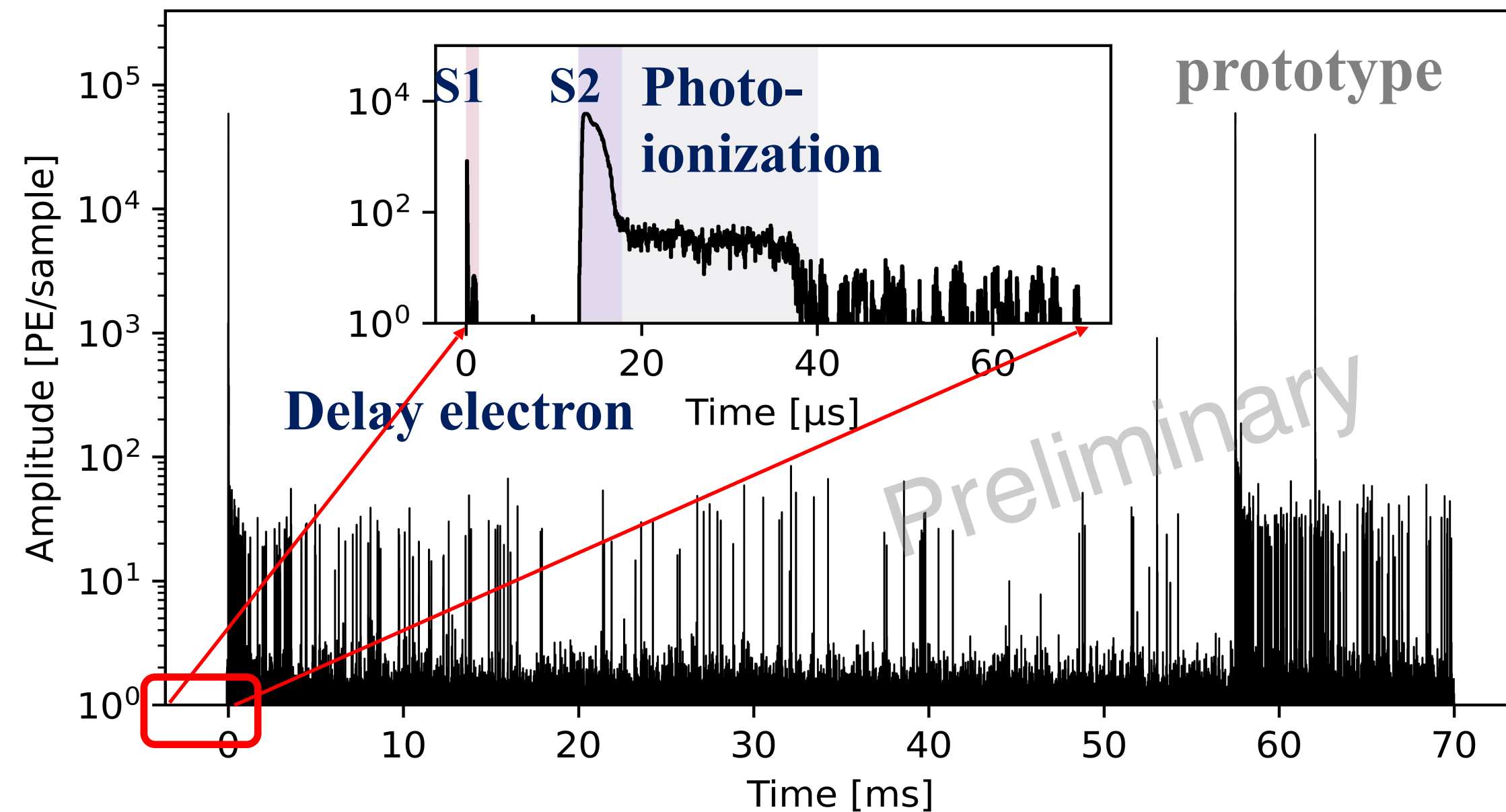
S2 Width selection:

- S2 Width $> 0.22 \mu\text{s}$
- Signal Acceptance $\sim 86\%$
- Rejection Power $\sim 94\%$

Delayed Electrons

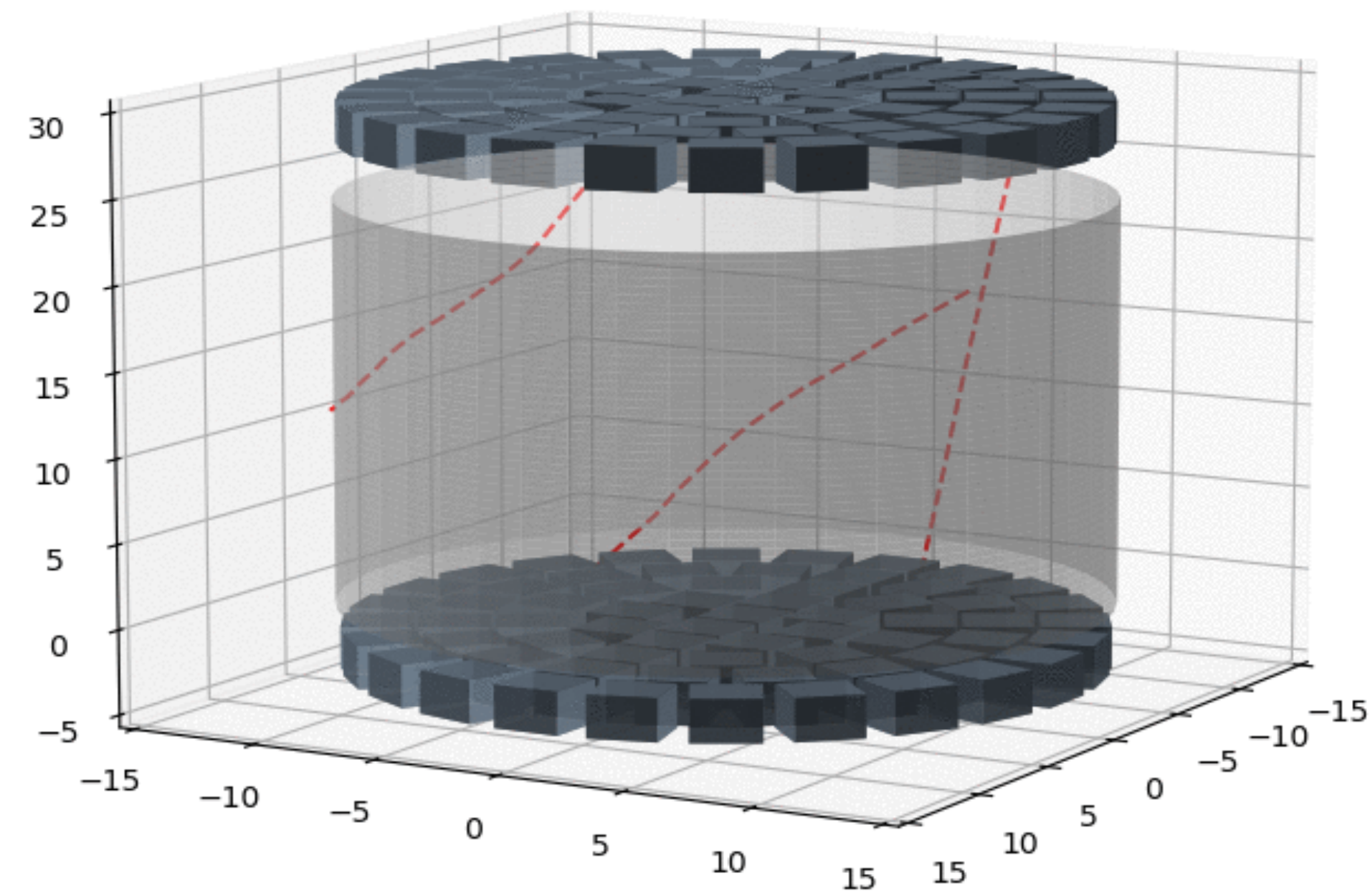
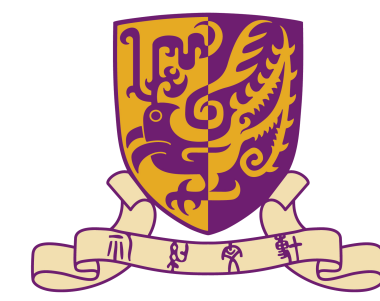


Large Energy deposition

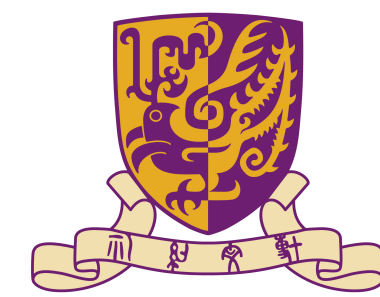


- Observed by large LXe experiments
- Electron emissions following large energy deposition
- Related to muon rate ~ 10 Hz

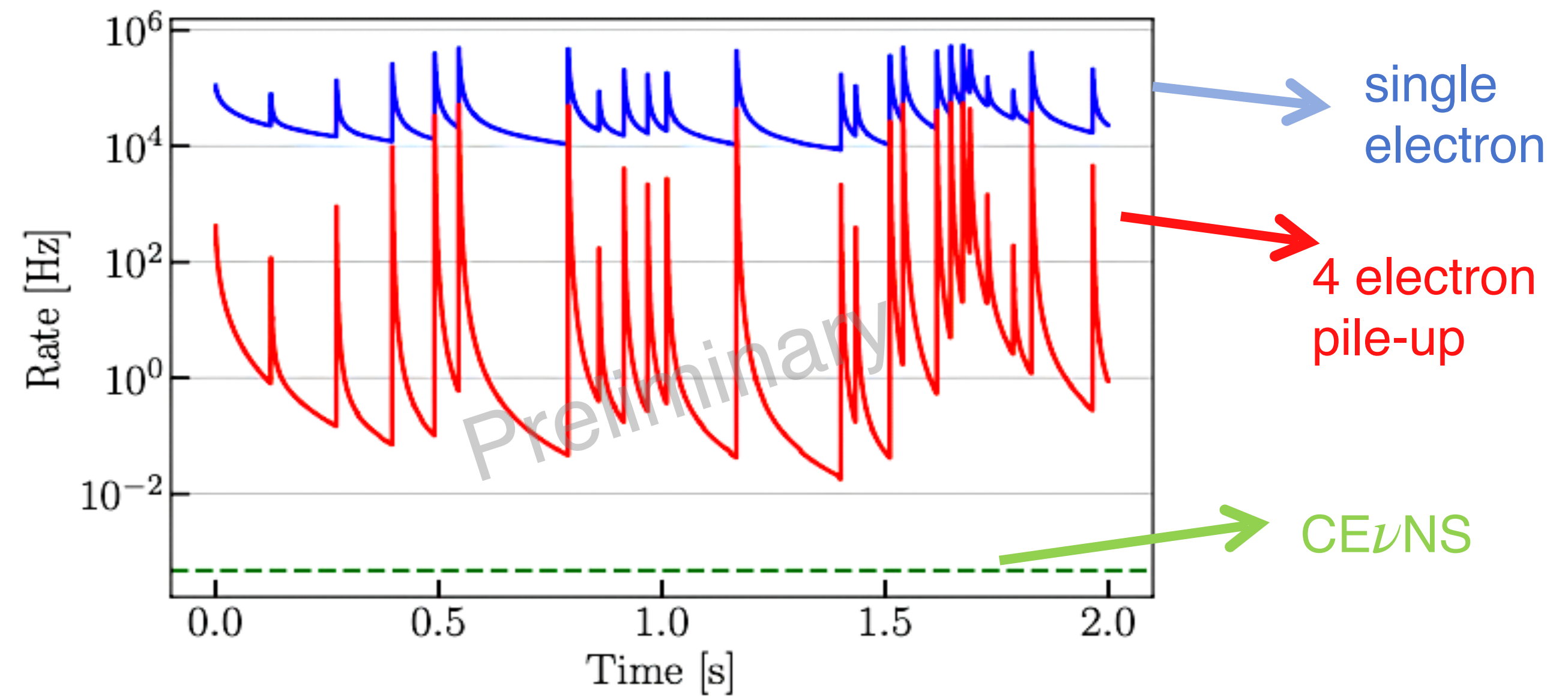
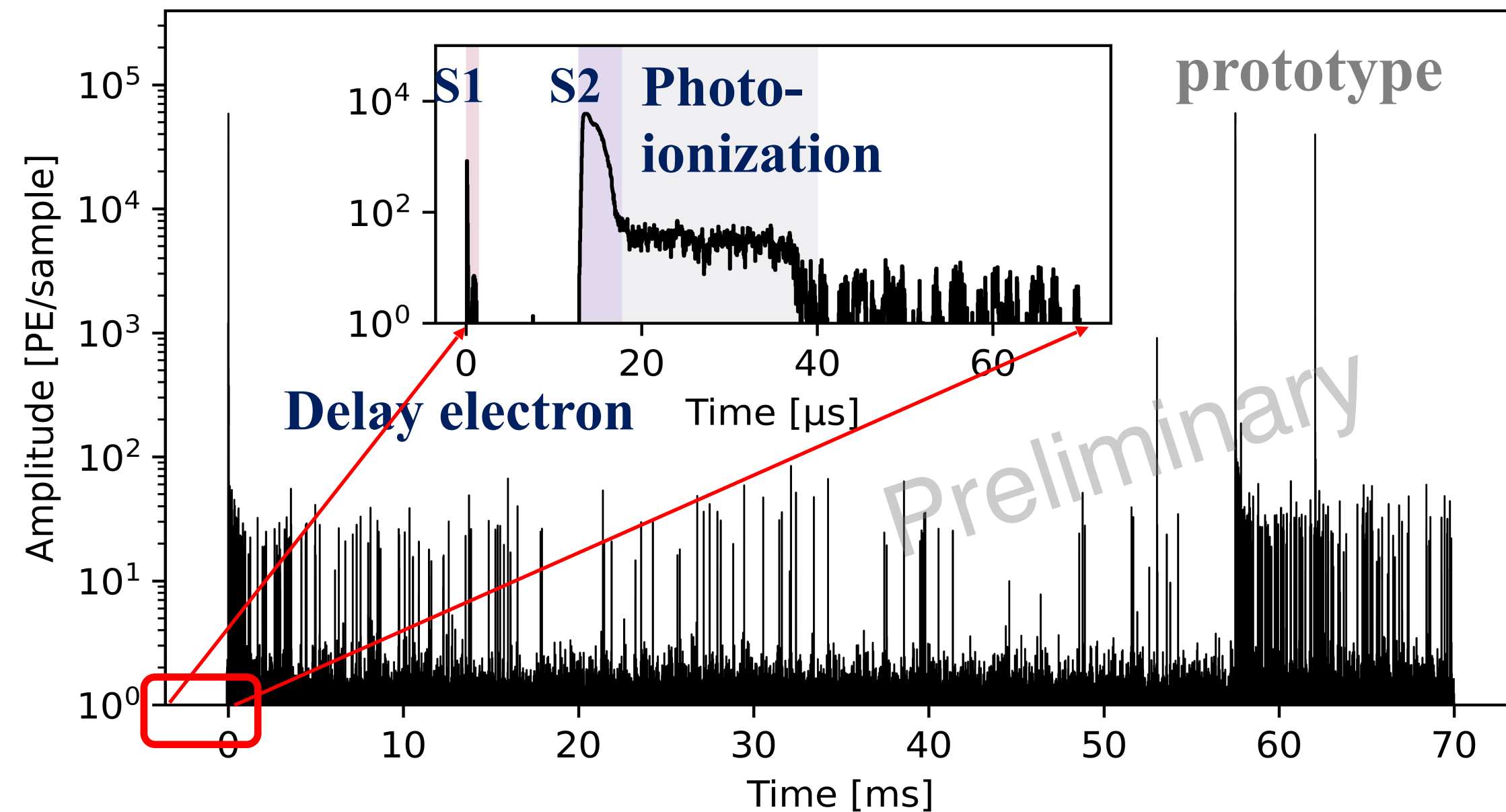
Delayed Electrons



Delayed Electrons



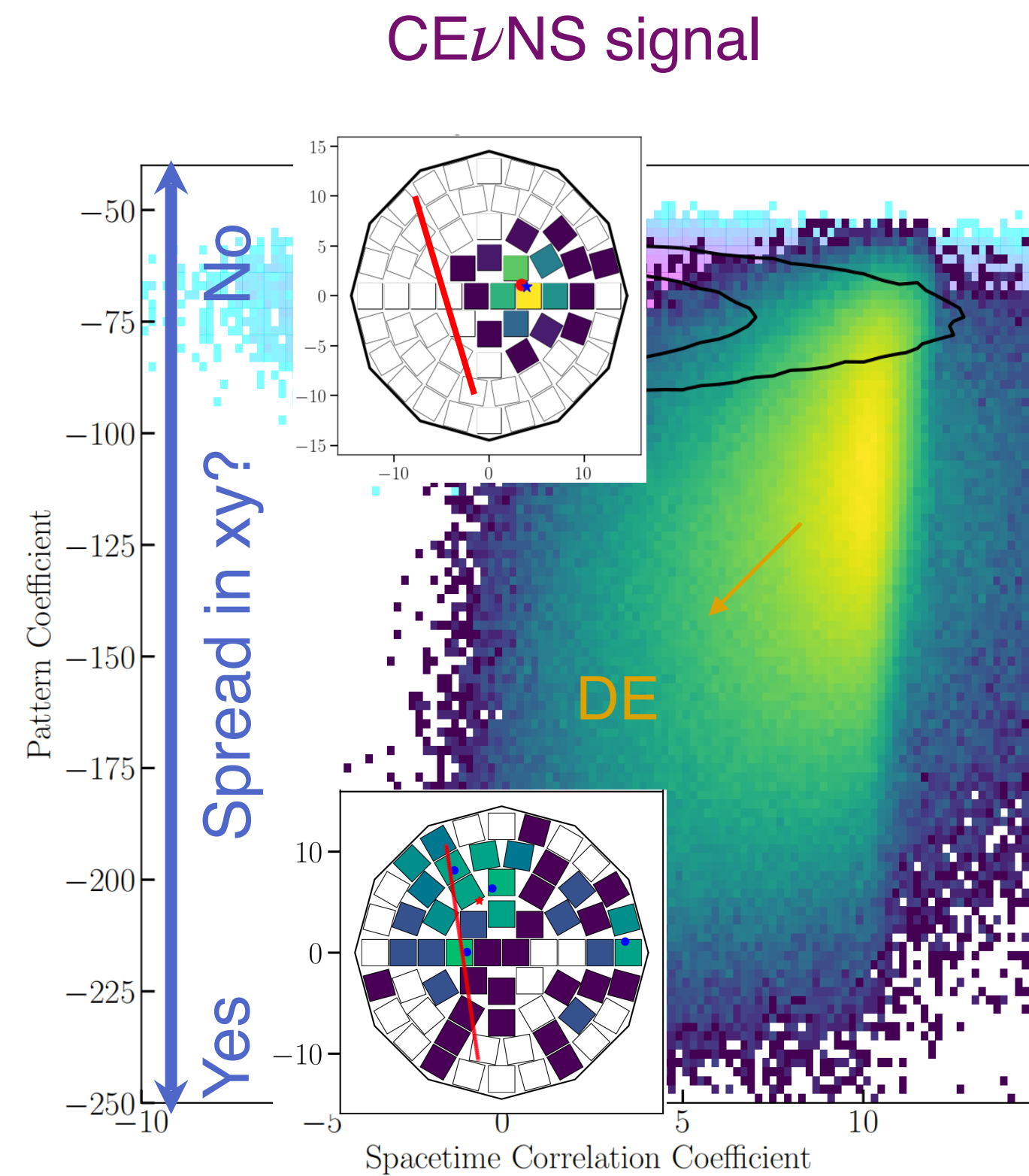
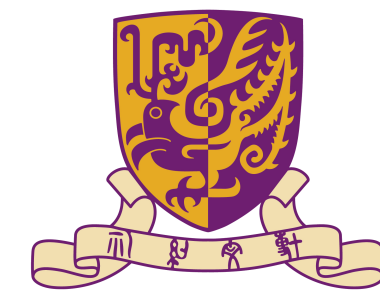
Large Energy deposition



- Observed by large LXe experiments
- Electron emissions following large energy deposition
- Related to muon rate ~ 10 Hz

- Pile-up delayed electron (DE) event rate $\gg$ CE ν NS rate

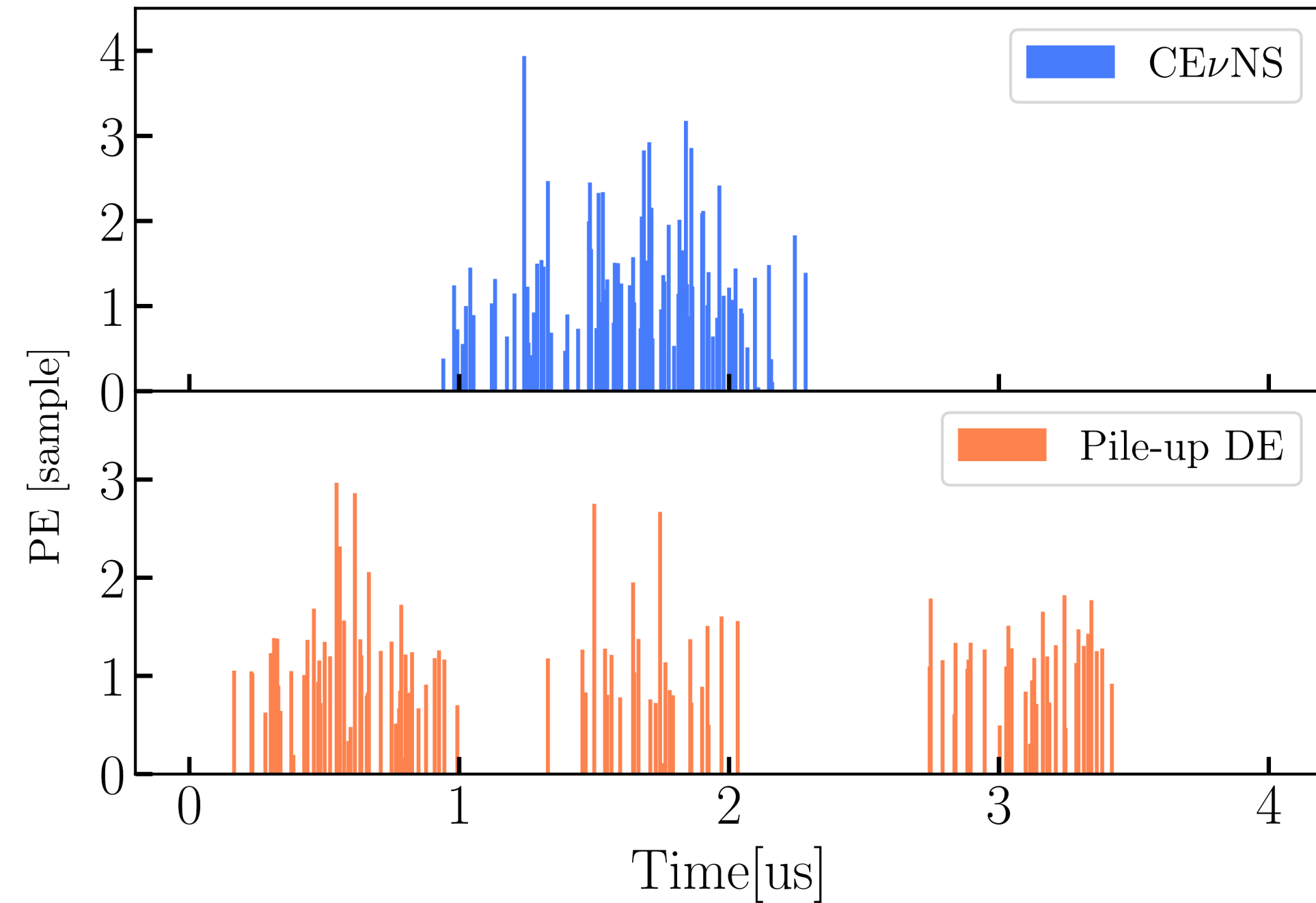
DE Background Rejection



No Related to last muon? Yes

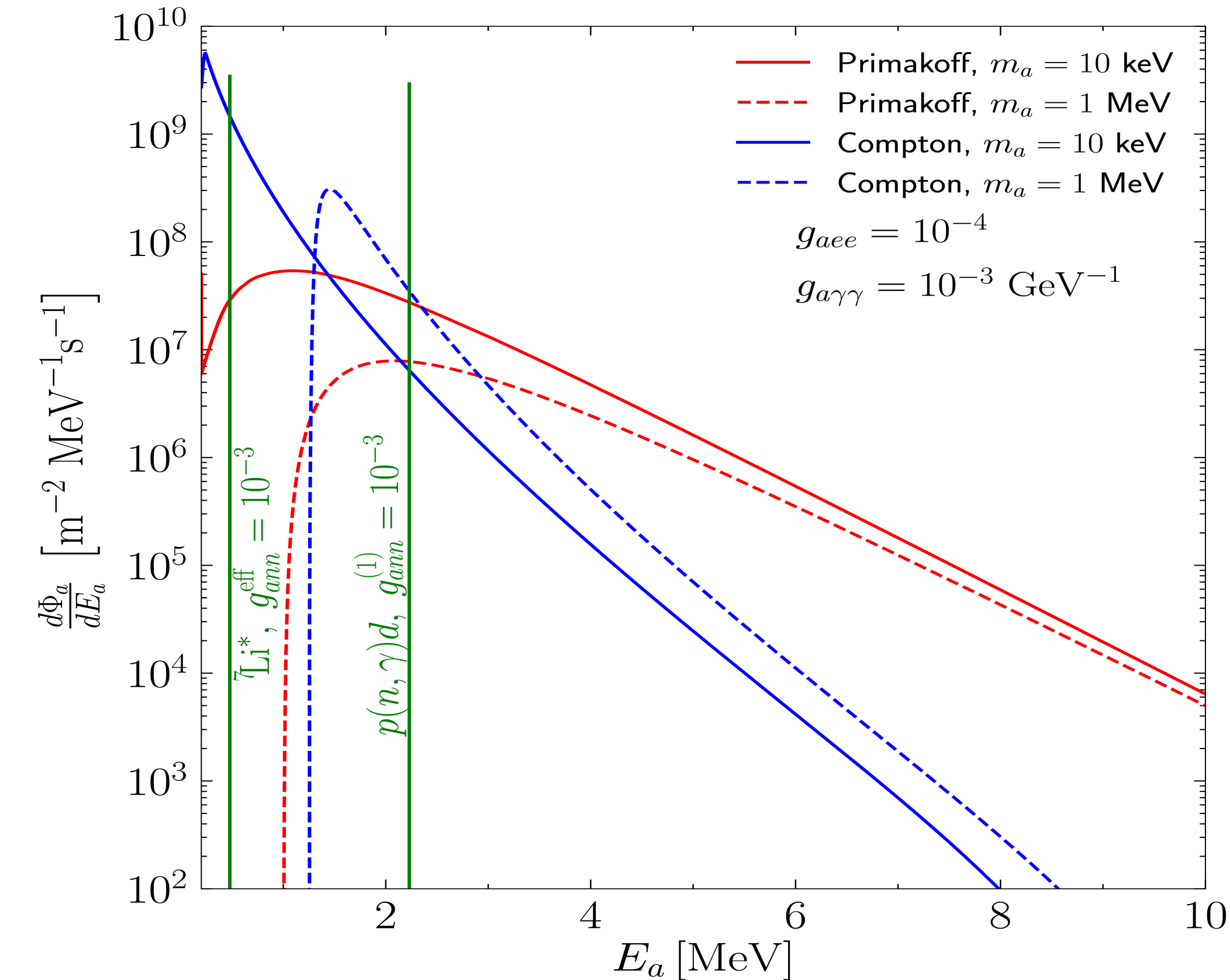
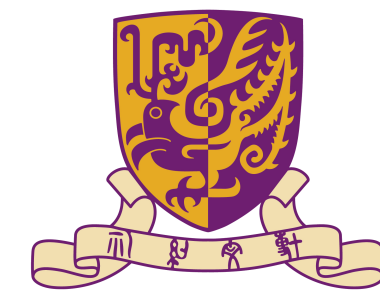
Correlaton with the preceding muon track

Waveform

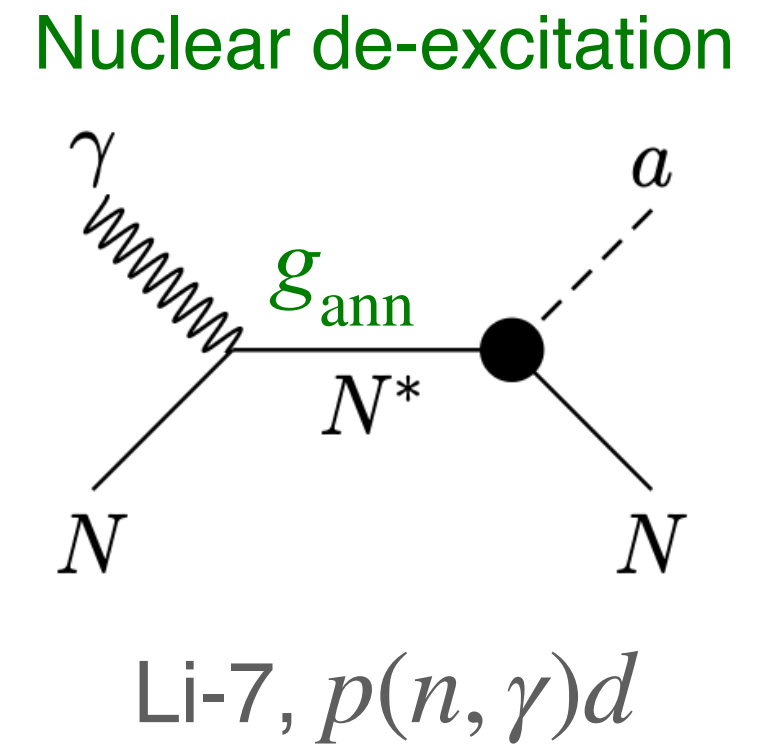
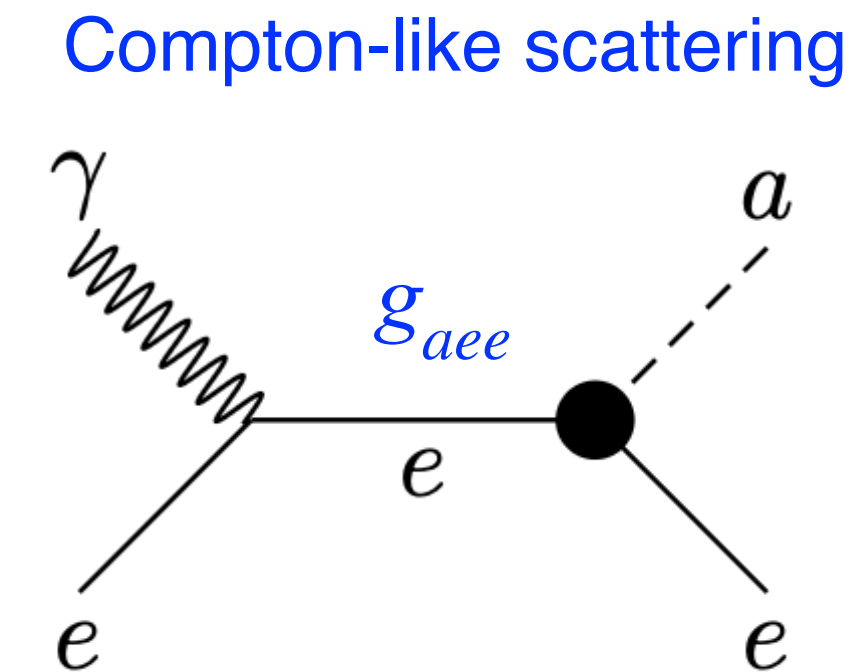
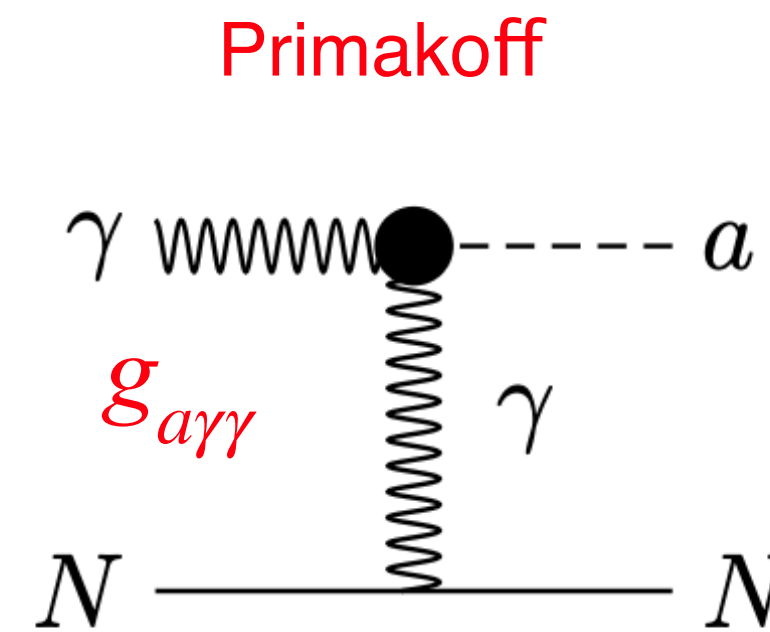


- DE: Spread in space and time
- CE ν NS: clustered

Reactor ALP Production

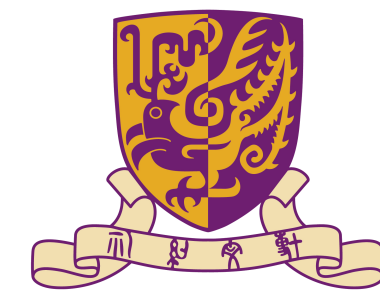


Flux @Sammen site
22 m, 3.4 GW

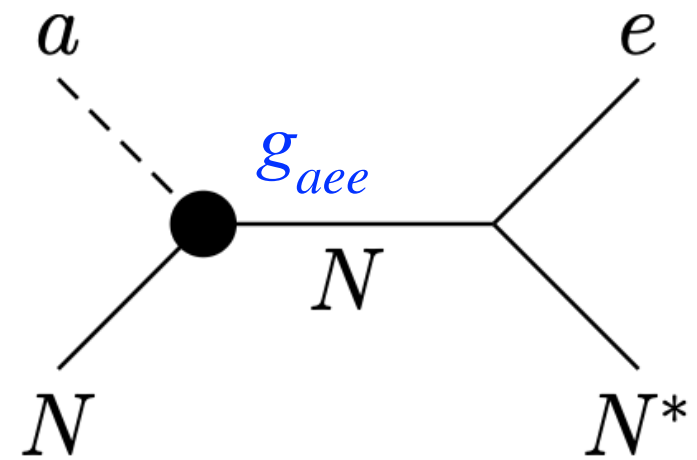


- Reactor ALPs could be shut down when the reactor is off. Reactor on and off data help understand and constrain backgrounds.
- Reactors produce MeV photons (gamma), which allow for probing ALPs with MeV mass!
 - Complementary to the solar ALP search that is at low energies

Reactor ALP Detection in Xenon

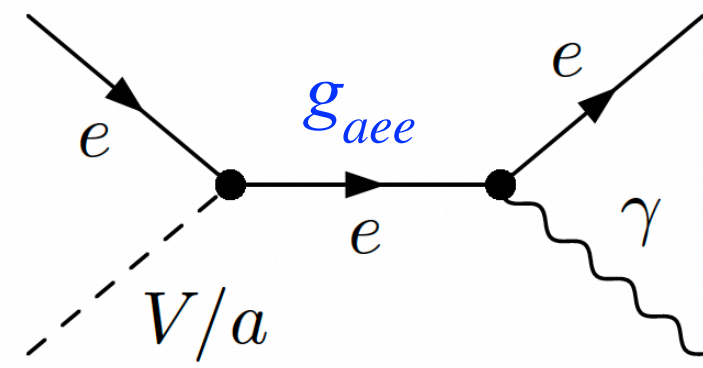


Axio-electric process

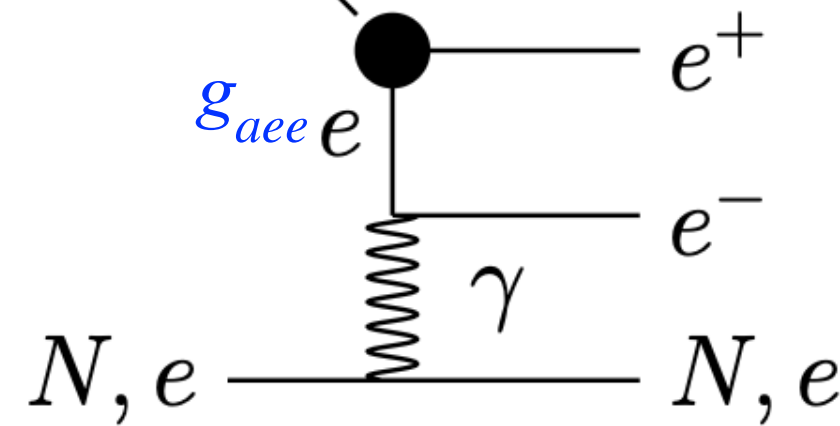


g_{aee}

Inverse Compton-like

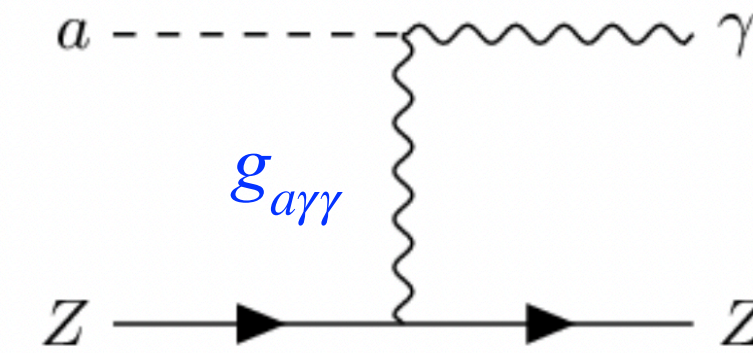


pair production



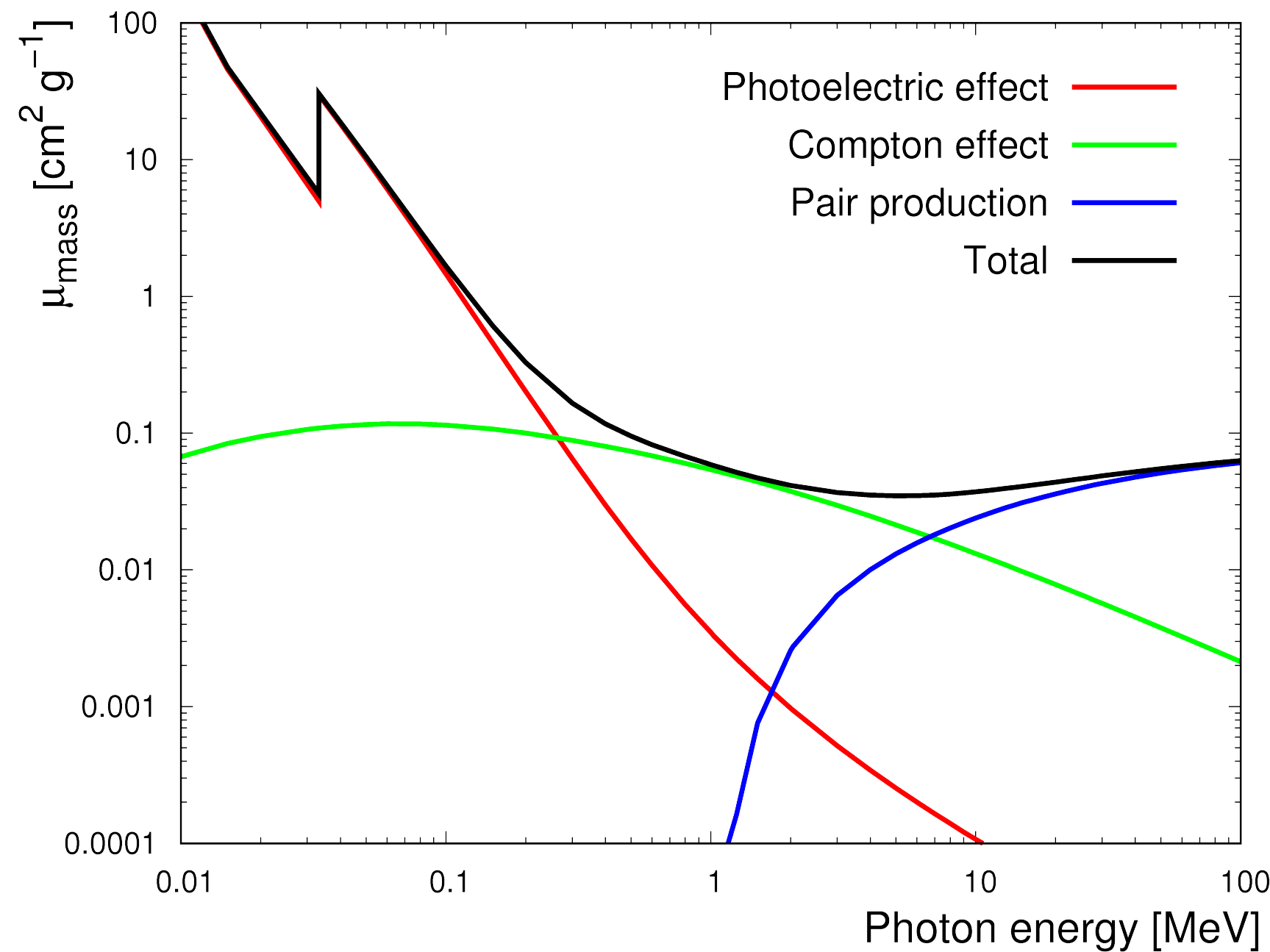
$g_{a\gamma\gamma}$

Inverse Primakoff



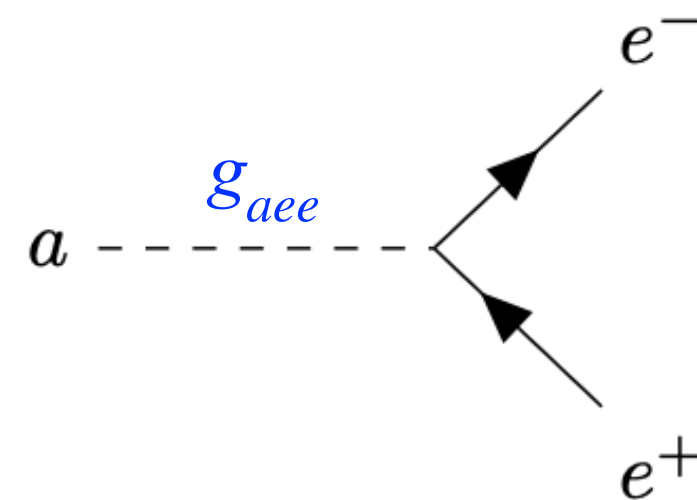
Scattering

Photon interaction in matter

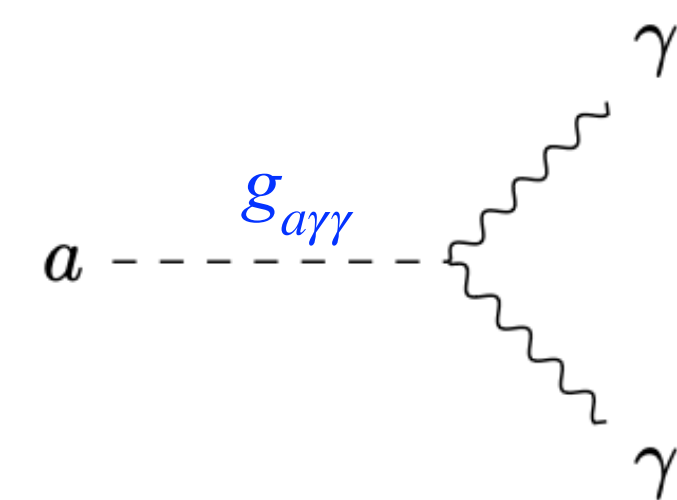


Additional channels

Axion decay - e+e- pairs



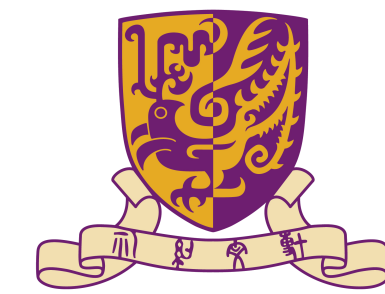
Axion decay - photon



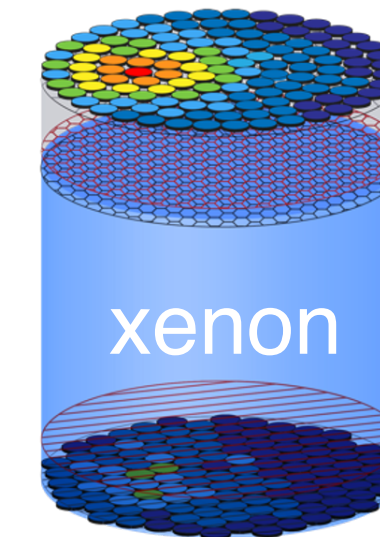
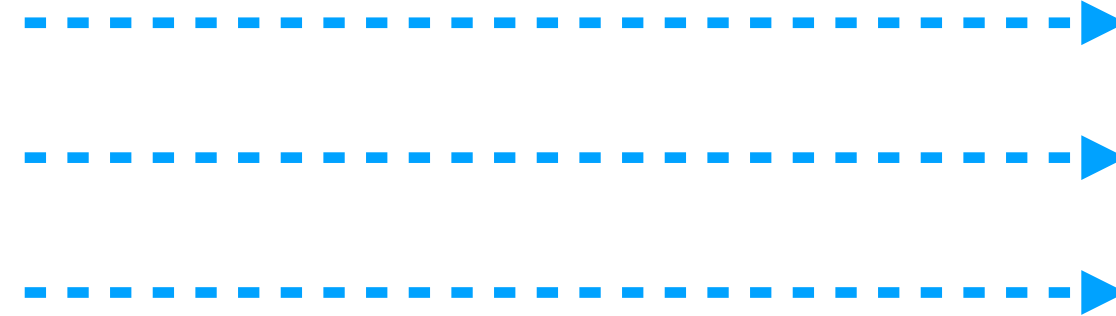
Decay

- Reactor ALP detection has more channels than solar ALPs
 - Additional detection channels due to higher energies
 - Possible to decay

Reactor ALPs Signal Spectrum

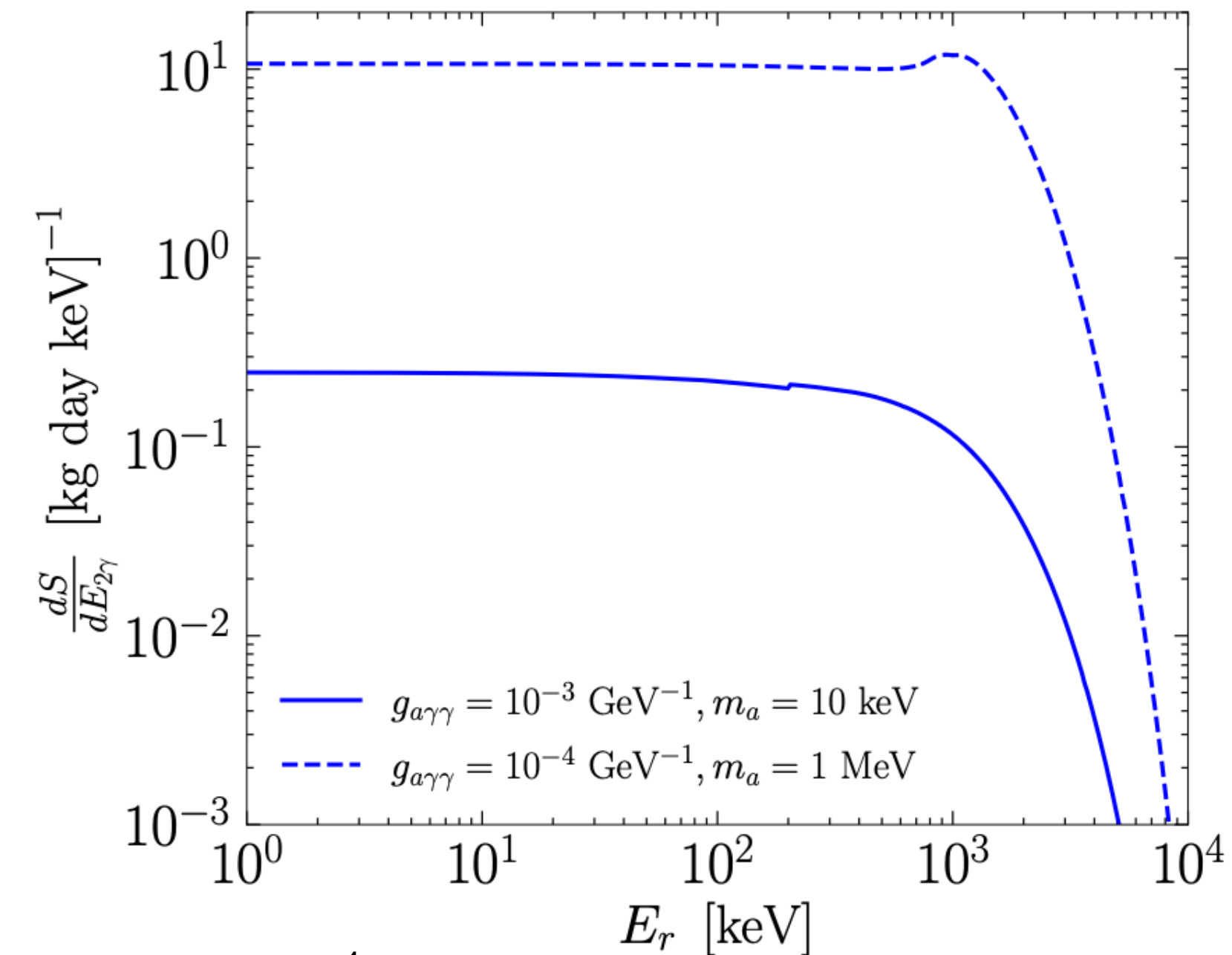
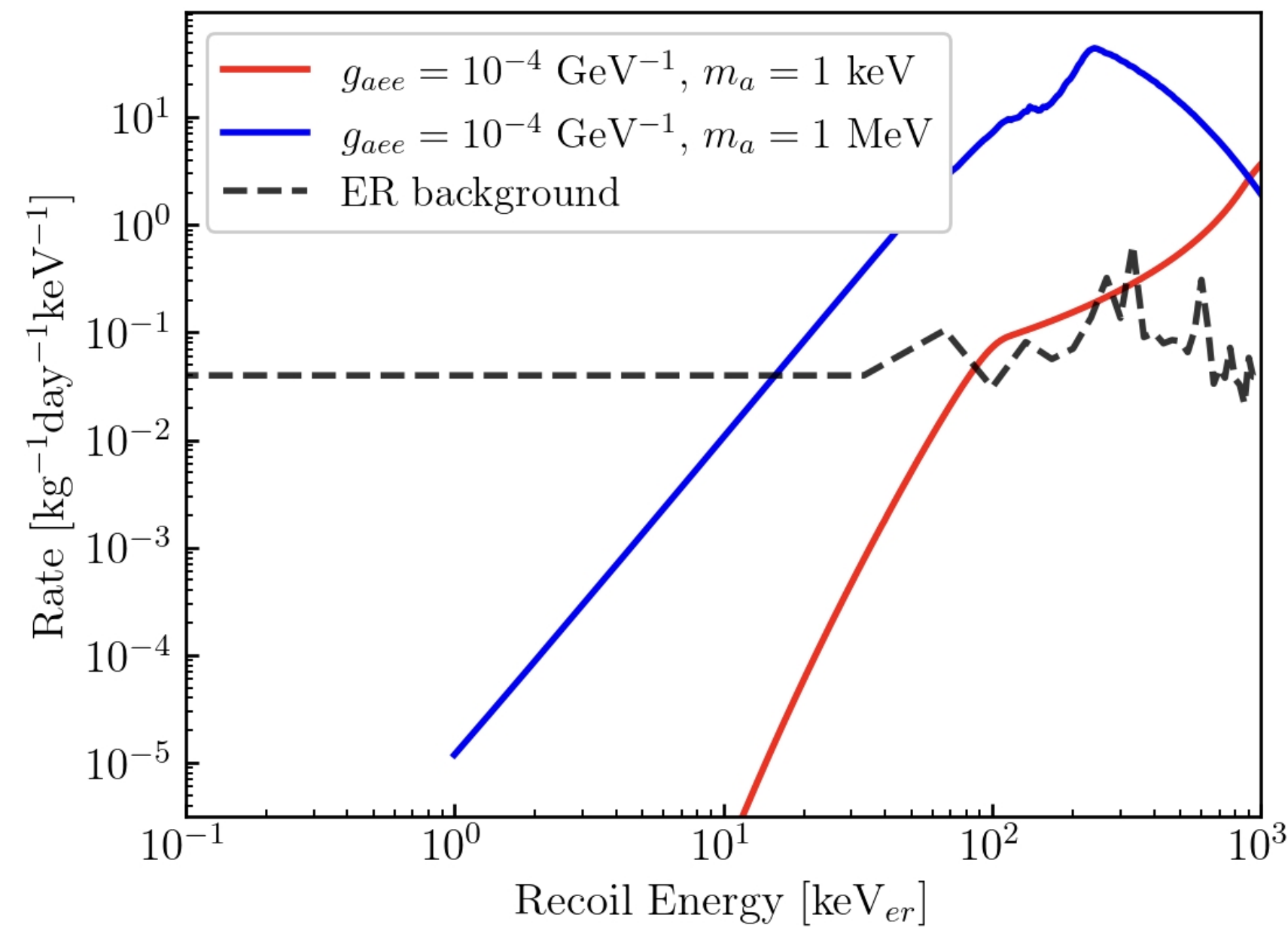


g_{aee}



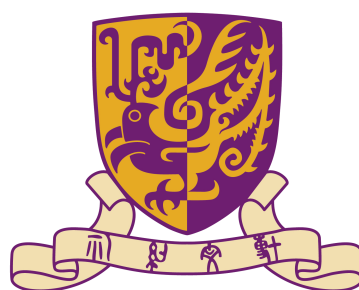
xenon

$g_{a\gamma\gamma}$

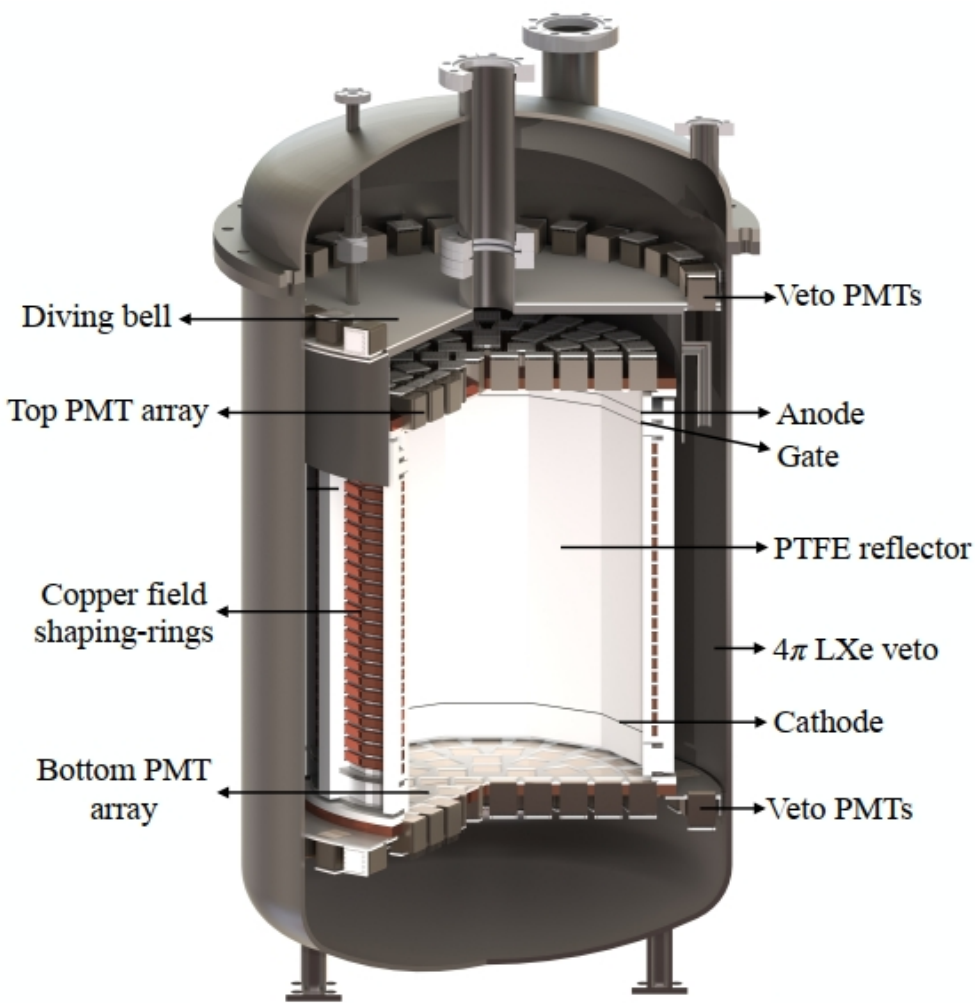


- Reactor ALPs signal rate $\sim g^4$.

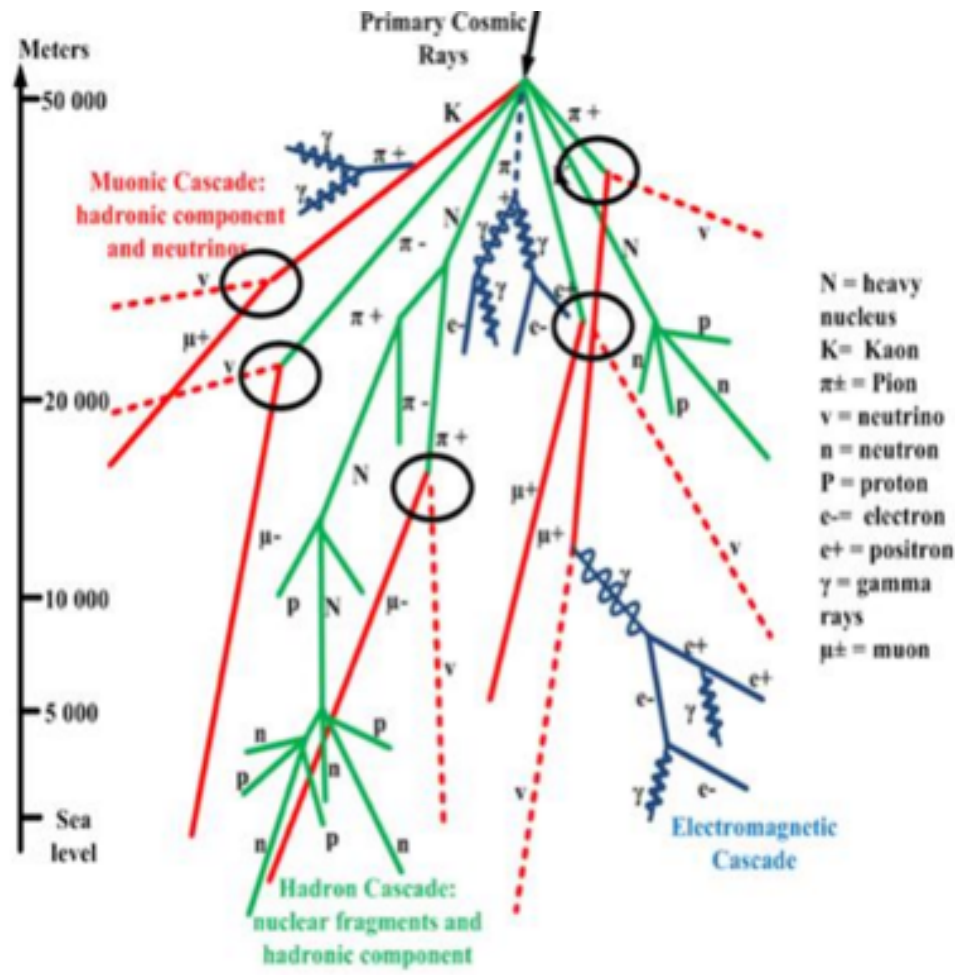
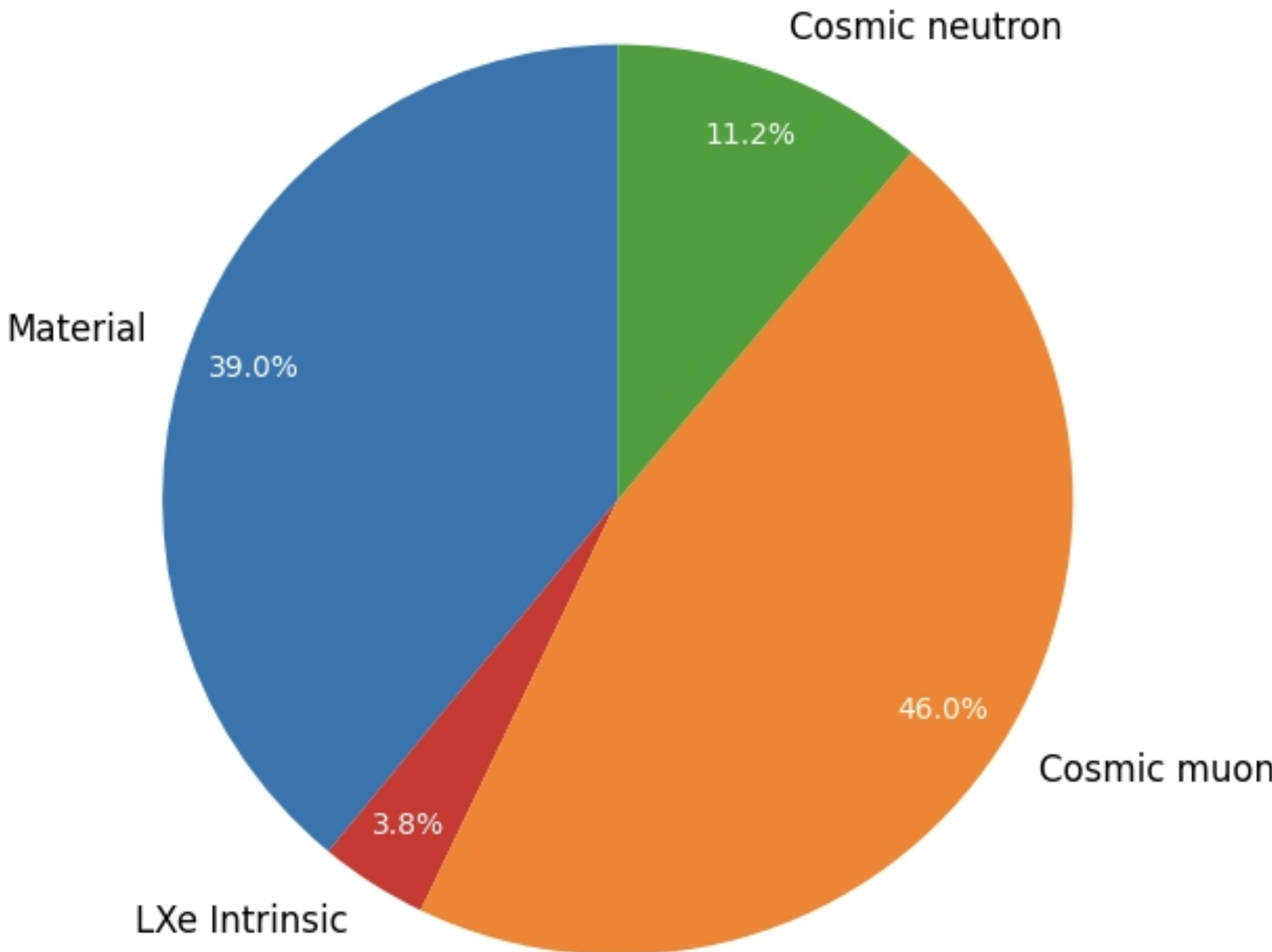
RELICS Background Sources



[0, 20] keV

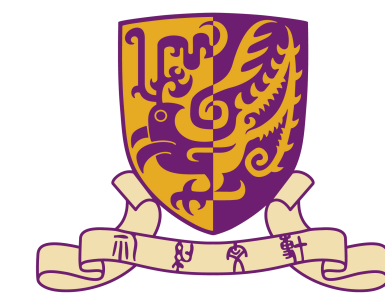


γ from
detector materials

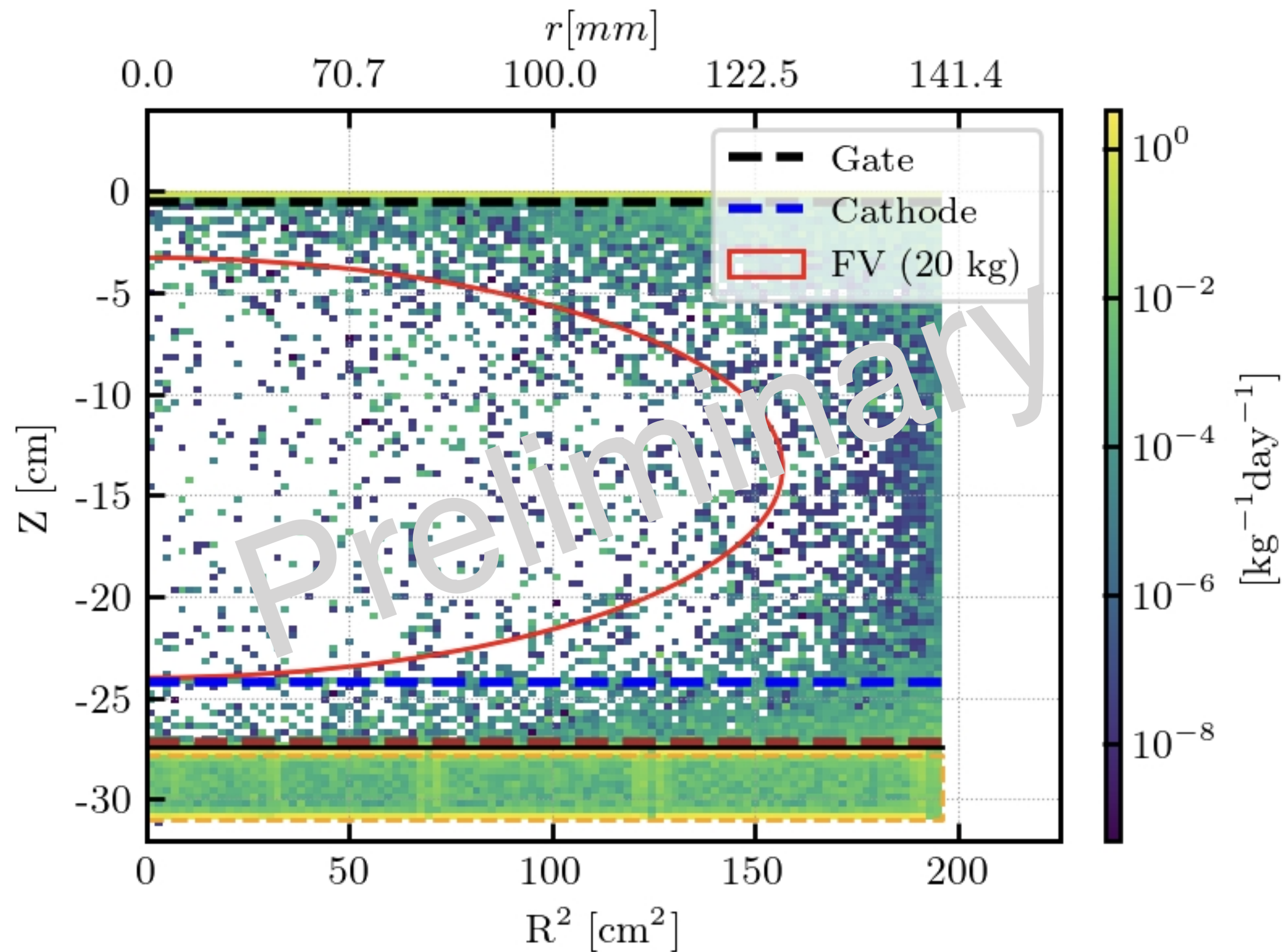


Cosmic muons
Cosmic neutrons

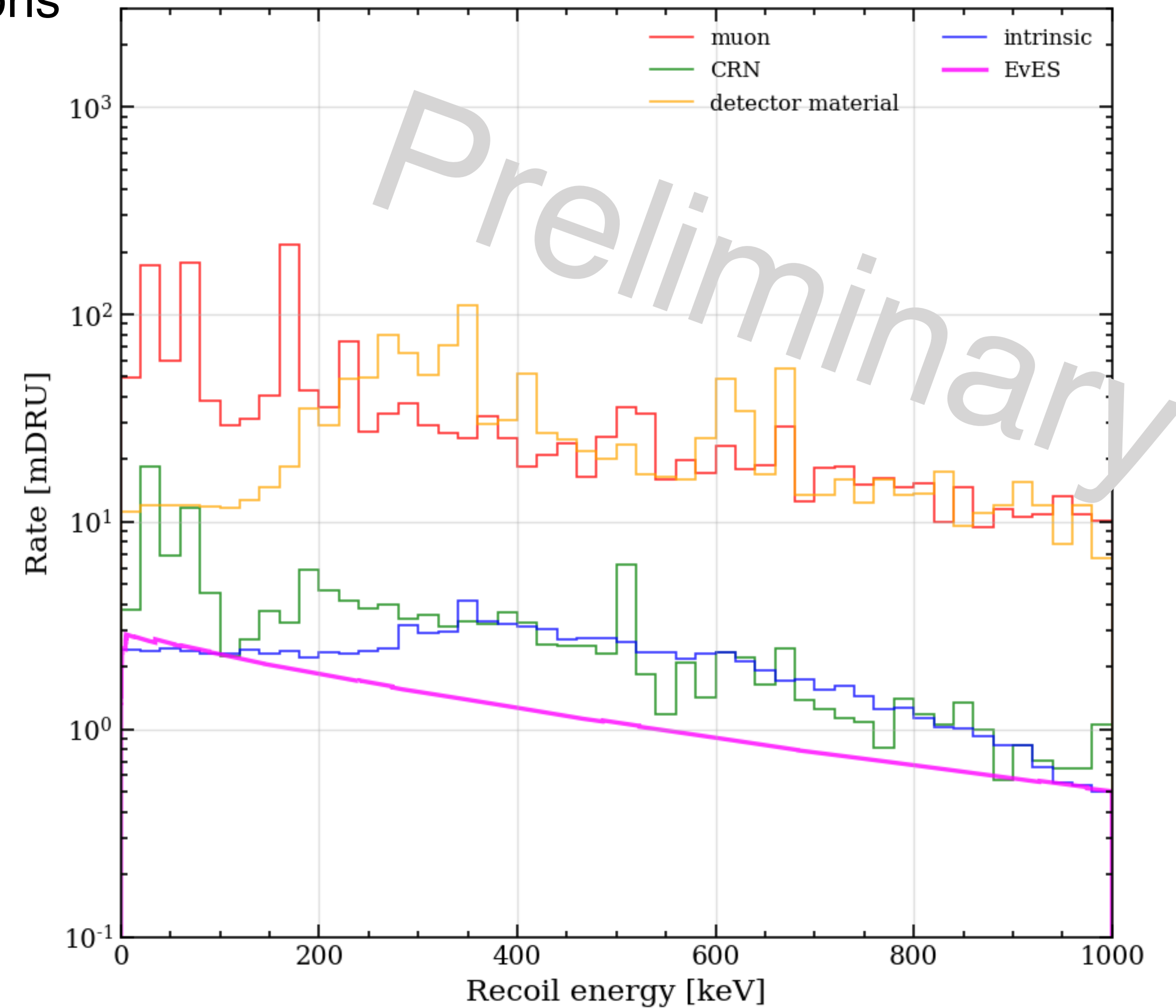
RELICS ER Backgrounds



From Geant4 simulations



S1-S2 analysis enables an optimized FV of 20 kg



ER background: $\sim 7 \times 10^{-2} (\text{kg} \cdot \text{day} \cdot \text{keV})^{-1}$ below 1 MeV