

NEUTRINOLESS DOUBLE BETA DECAY SEARCHES WITH LIQUID SCINTILLATOR DETECTORS

JOSÉ MANEIRA, LIP LISBOA

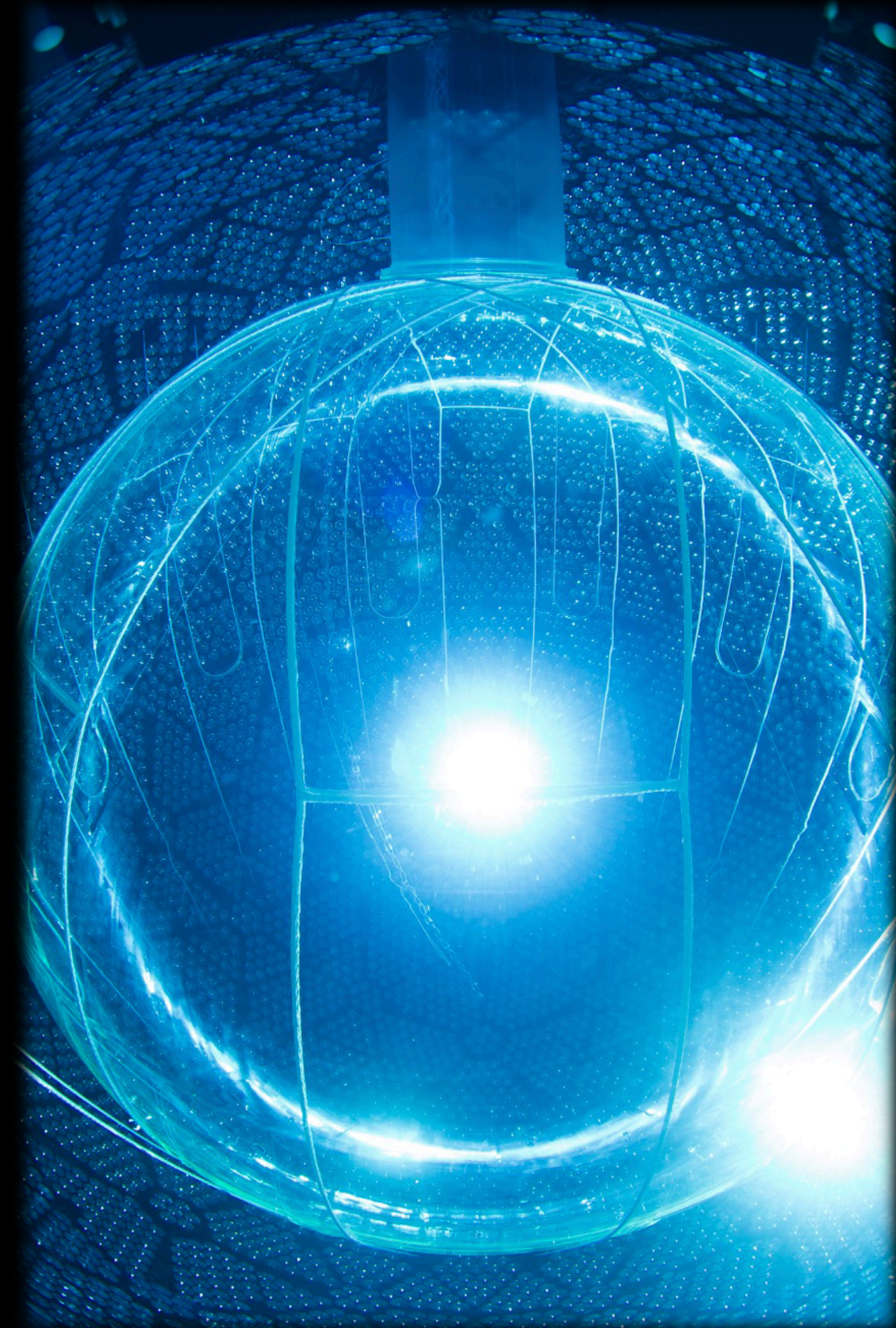
ON BEHALF OF THE SNO+ COLLABORATION

THANKS TO I. SHIMIZU, G. OREBI GANN, S. BILLER

23RD INTERNATIONAL WORKSHOP ON NEXT GENERATION
NUCLEON DECAY AND NEUTRINO DETECTORS (NNN24)

CENTRO BRASILEIRO DE PESQUISA FÍSICAS (CBPF)
RIO DE JANEIRO, BRAZIL

OCTOBER 30, 2024



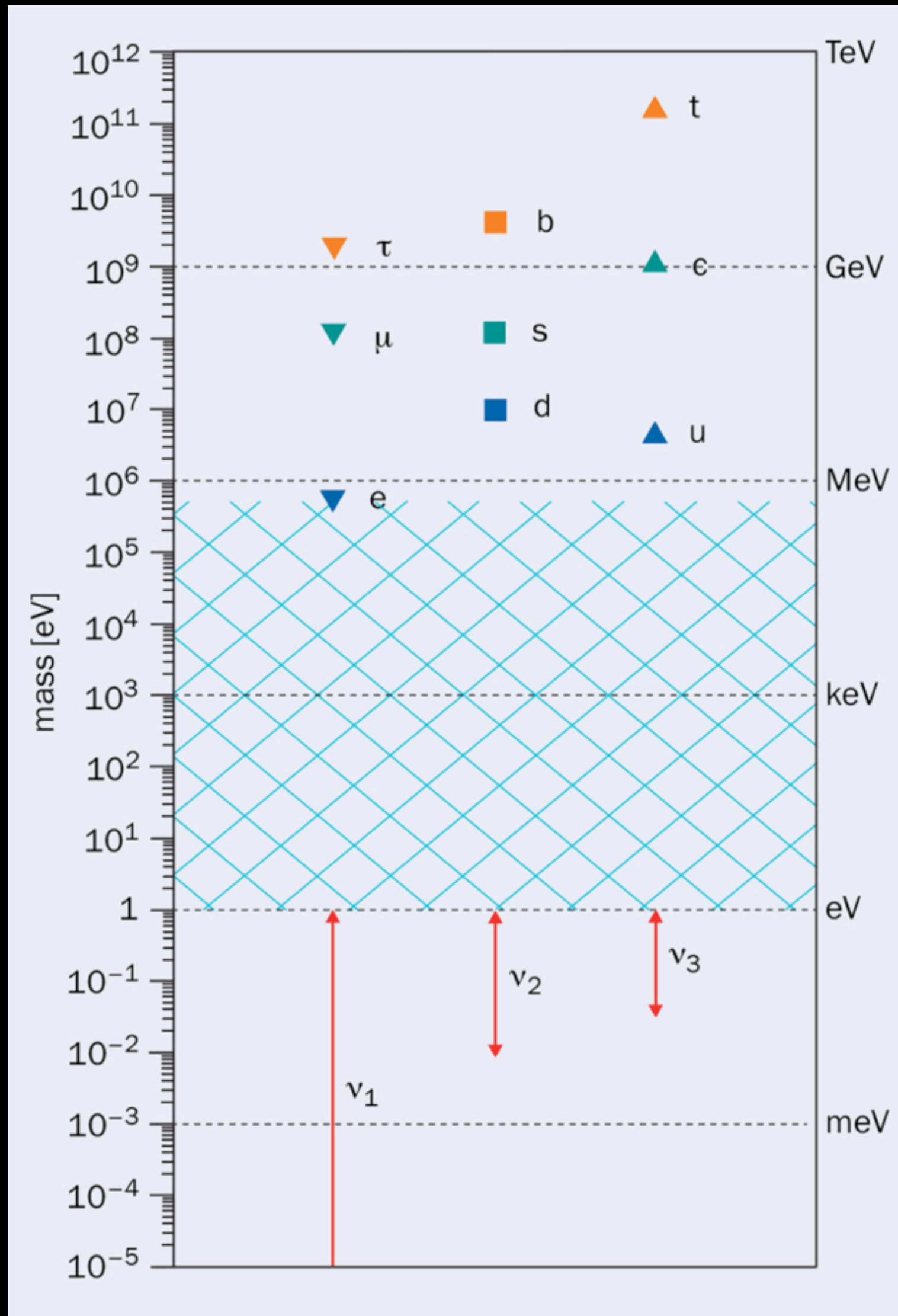
- Introduction
 - Majorana neutrinos
 - Experimental search for neutrinoless double beta decay
- Current $0\nu\beta\beta$ experiments based on liquid scintillator
 - KamLAND-Zen
 - SNO+
- Future Prospects

INTRODUCTION

NEUTRINO MASS, WHY SO TINY?

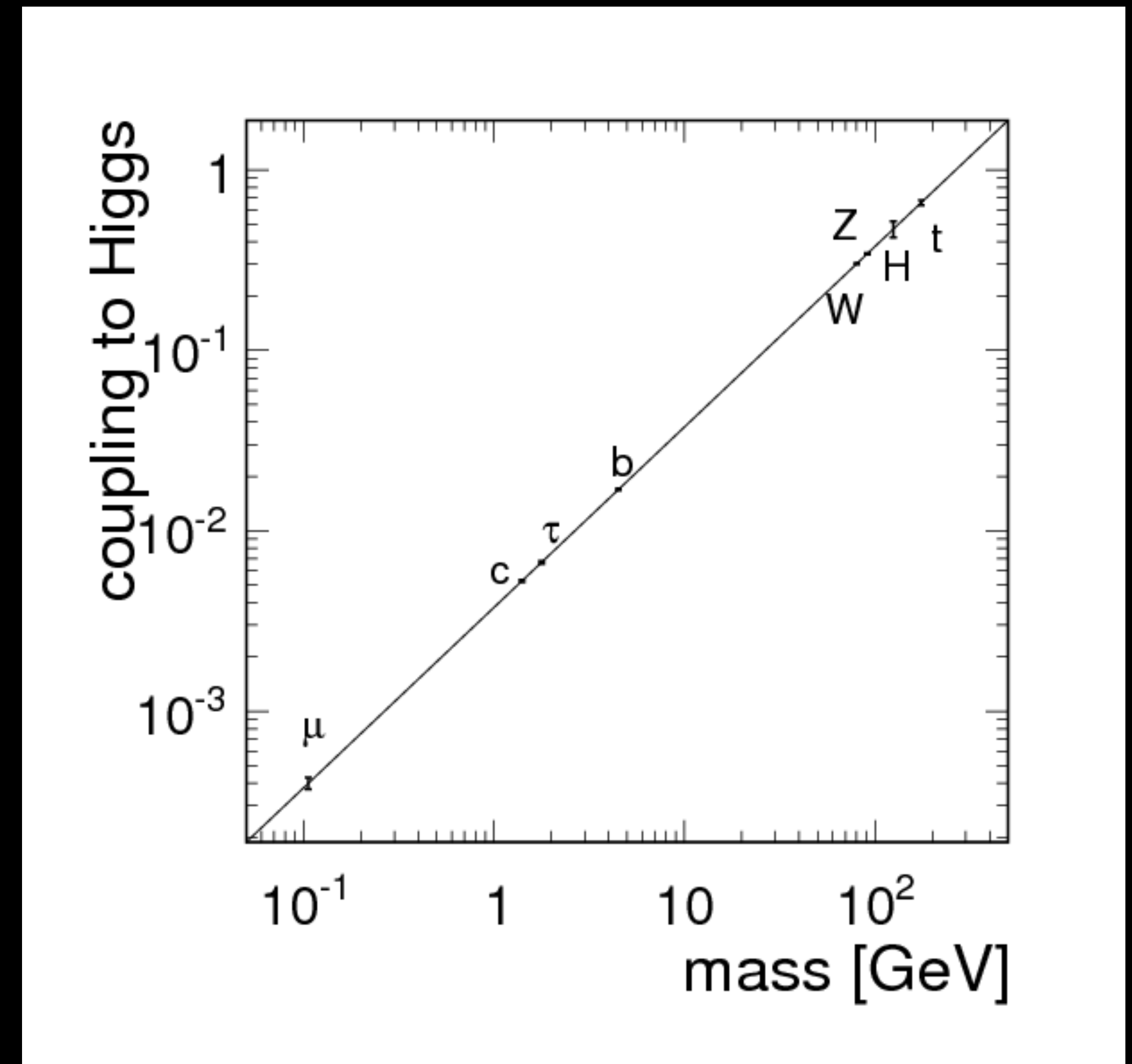


Fermion masses

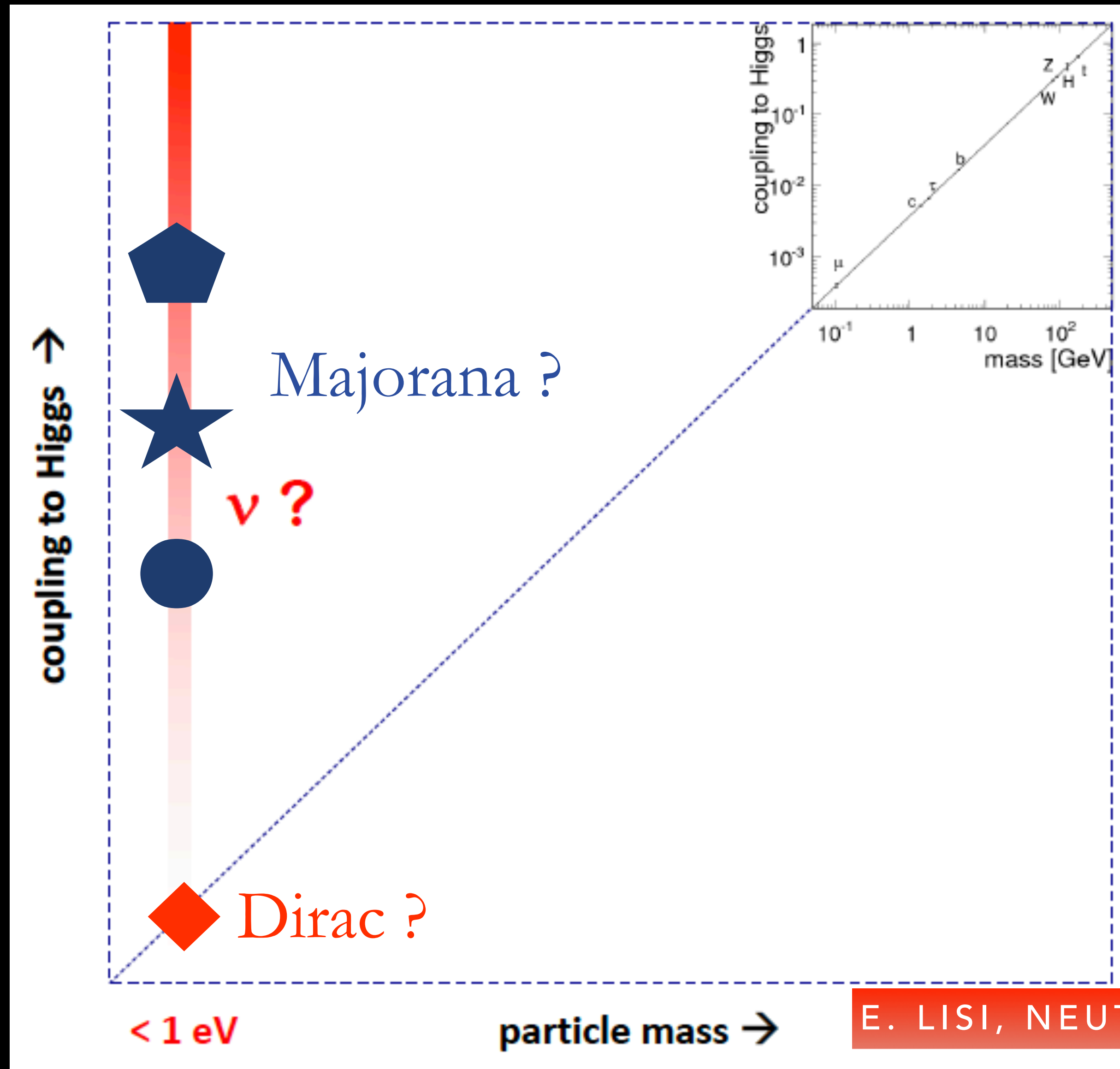


Why this huge gap?

Mass of elementary particles directly related to Higgs interaction



NEUTRINO MASS, WHY SO TINY?



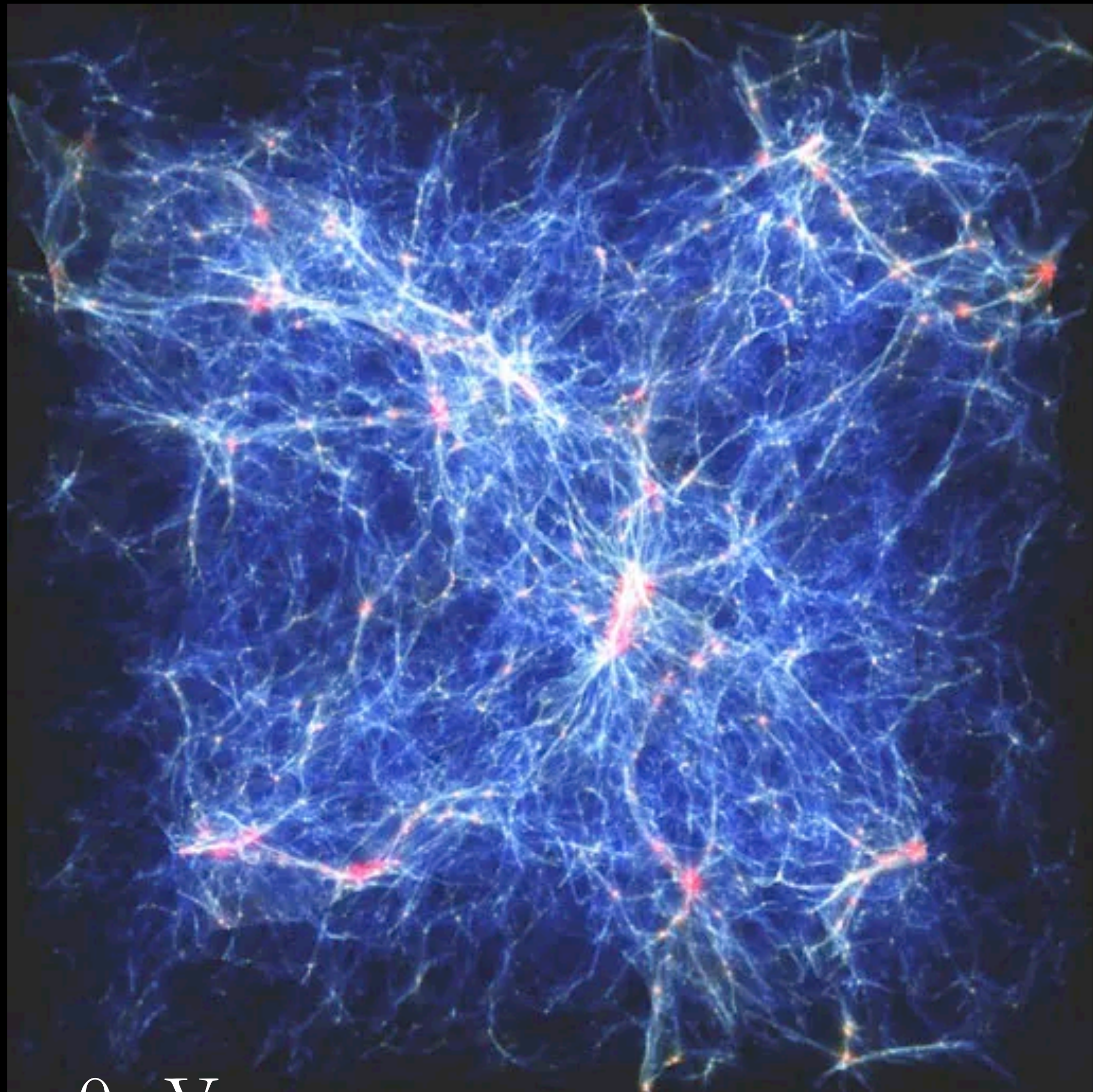
E. LISI, NEUTRINO 2024 (ADAPTED)

Do neutrinos couple to the Higgs in the same way as charged fermions?

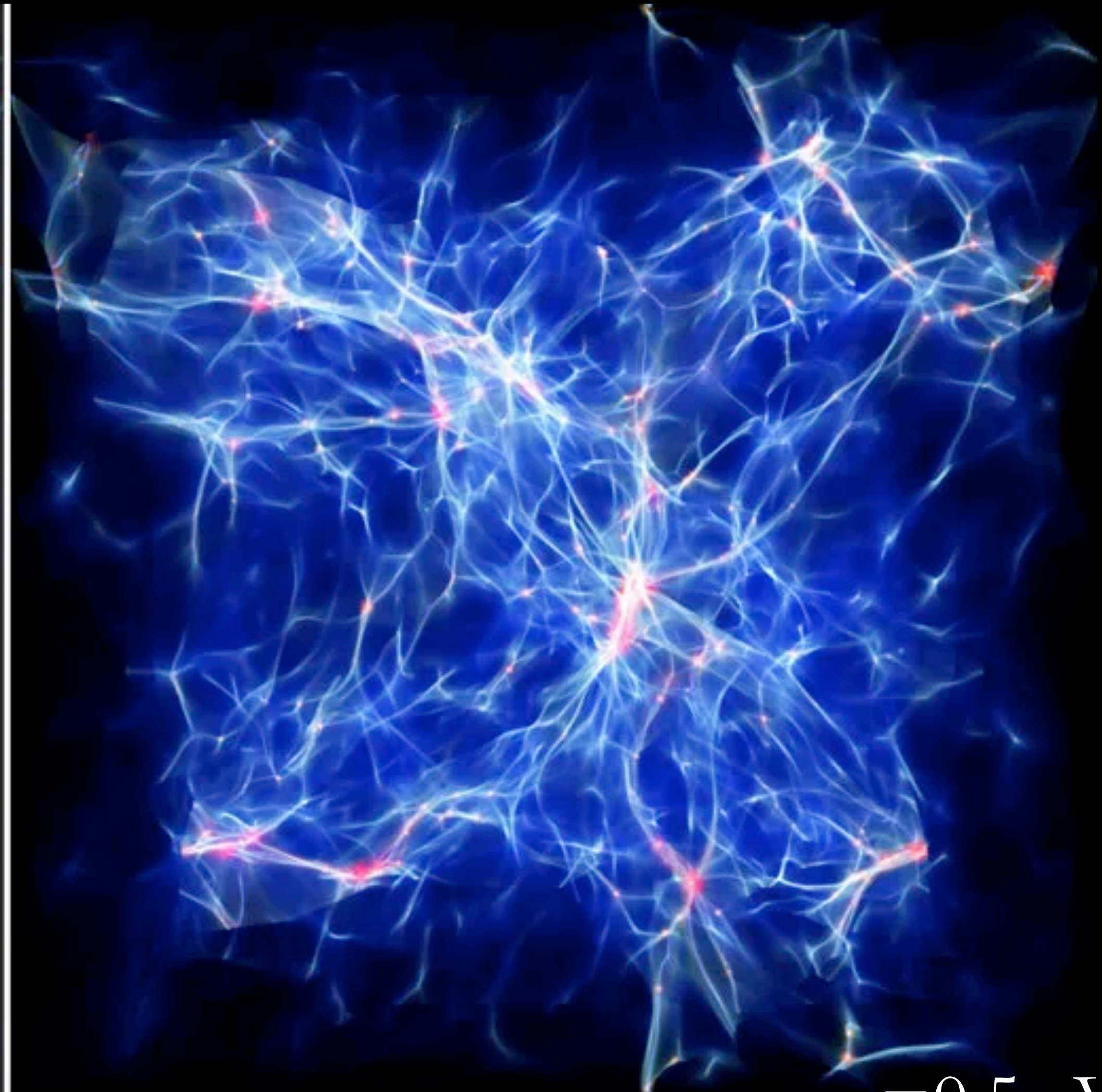
- A test ground for New Physics!
- Possible explanation for matter/antimatter asymmetry.



LARGE SCALE STRUCTURE OF THE UNIVERSE

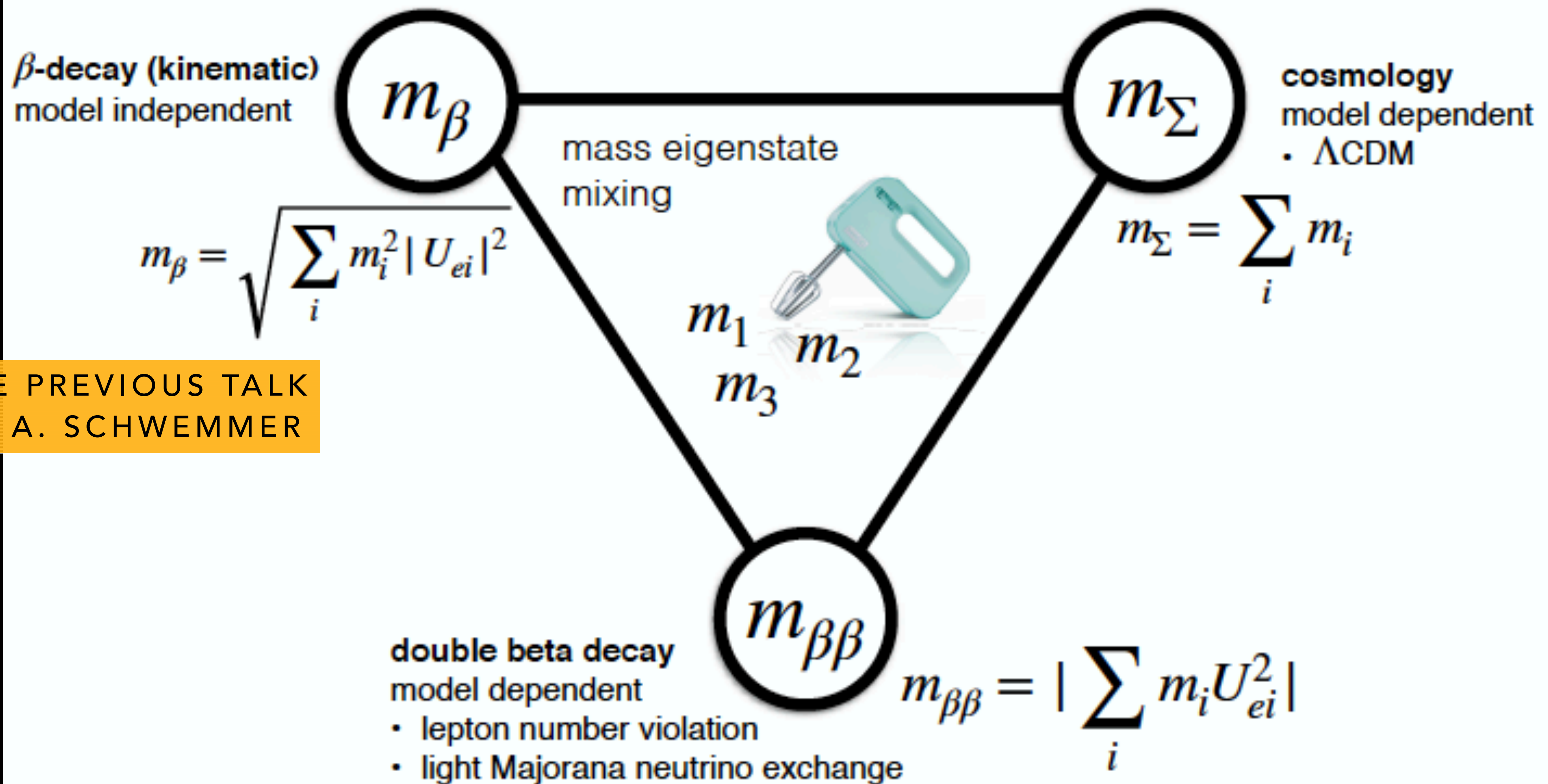


$m_\nu = 0 \text{ eV}$



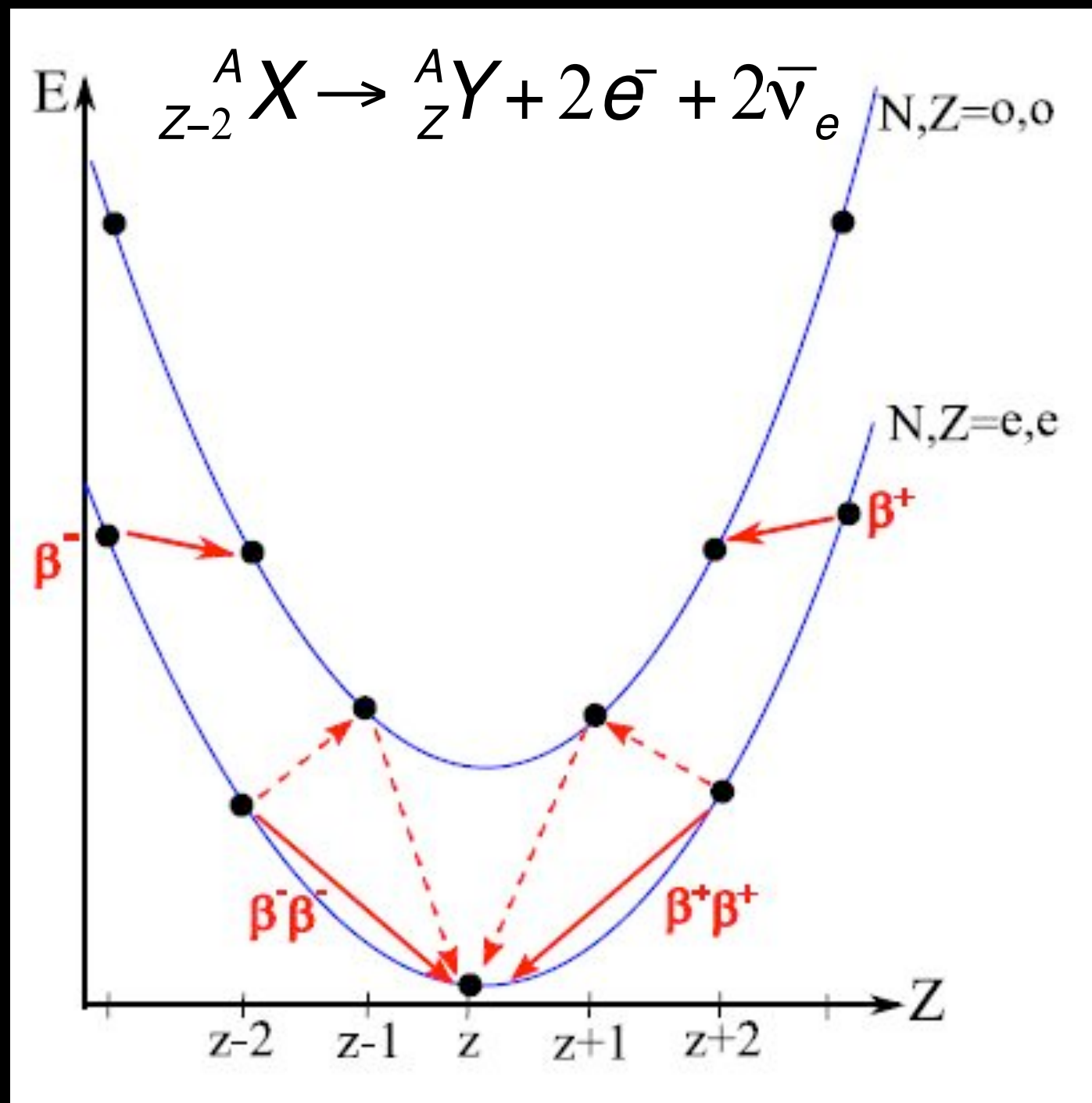
$m_\nu = 0.5 \text{ eV}$

NEUTRINO MASS OBSERVABLES

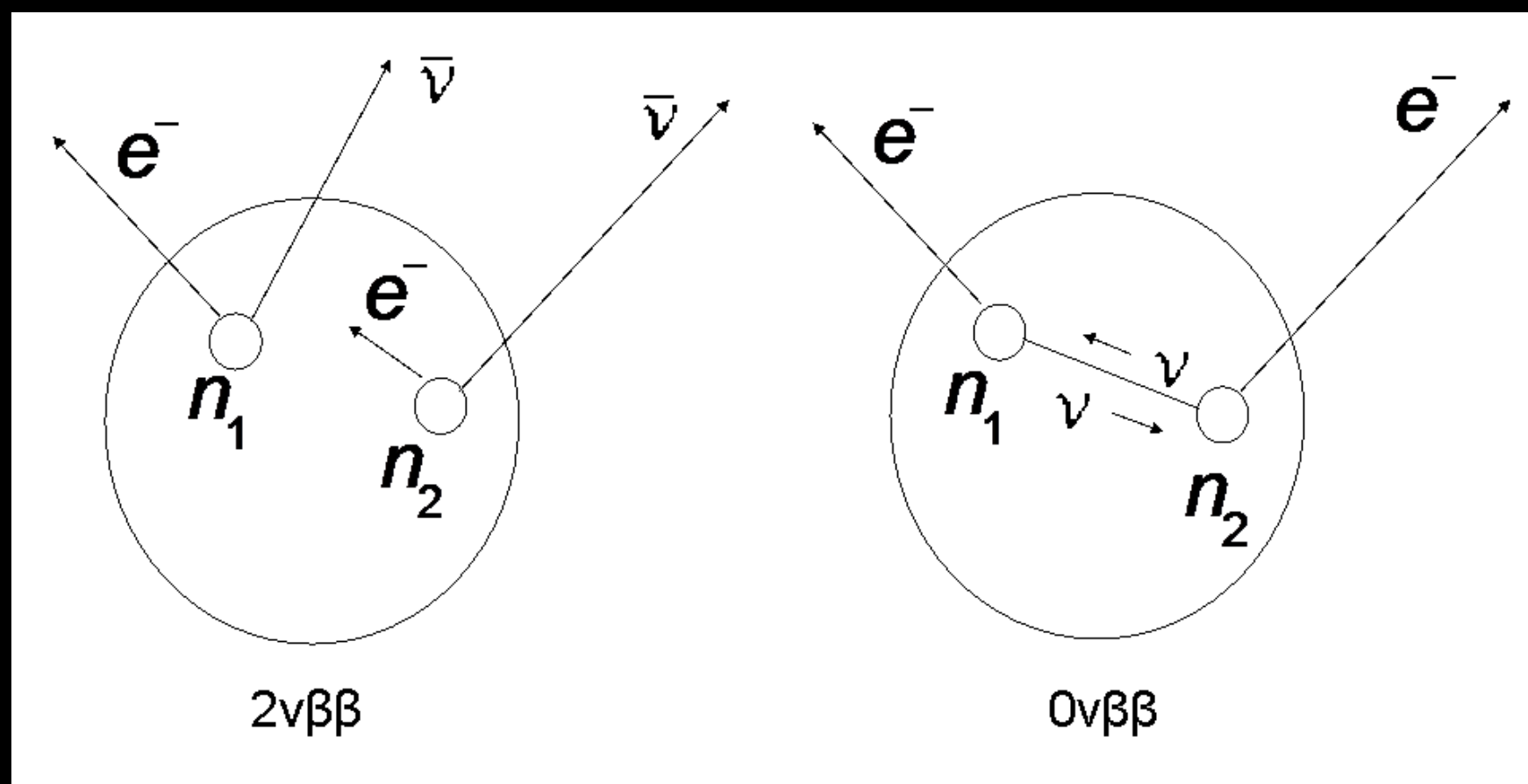


SEE PREVIOUS TALK
BY A. SCHWEMMER

DOUBLE BETA DECAY



- Double beta decay (DBD): in even-even nuclei when beta decay not energetically possible (rare: $T^{1/2} \sim 10^{18} - 10^{21}$ yr)
- Neutrinoless double decay (NLDBD) involves “internal” neutrino annihilation, possible only for Majorana neutrinos
- Large uncertainty in NLDBD nuclear matrix elements

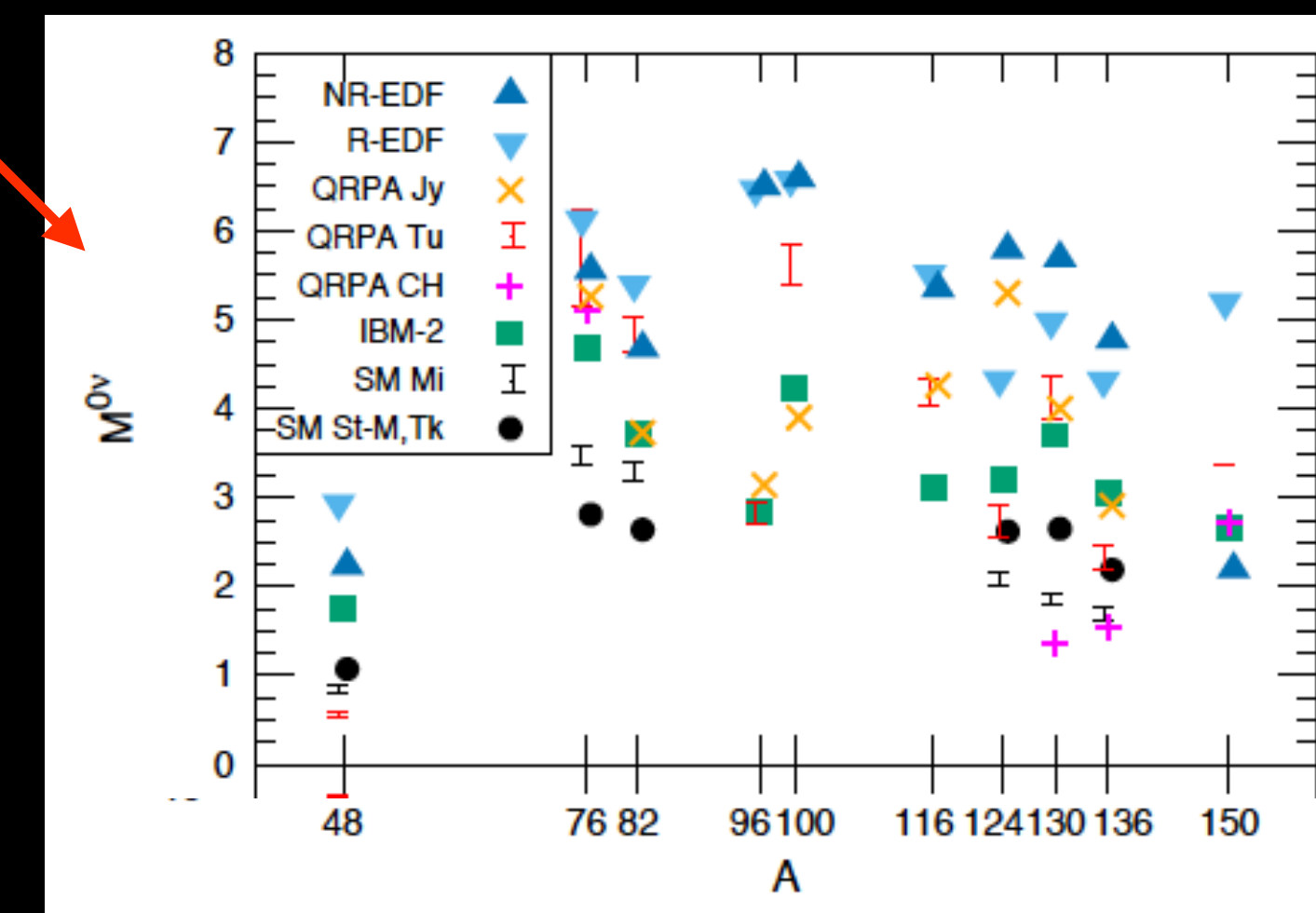


Phase
space

Nuclear matrix
element

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu} |M^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e} \right)^2$$

Effective Majorana mass

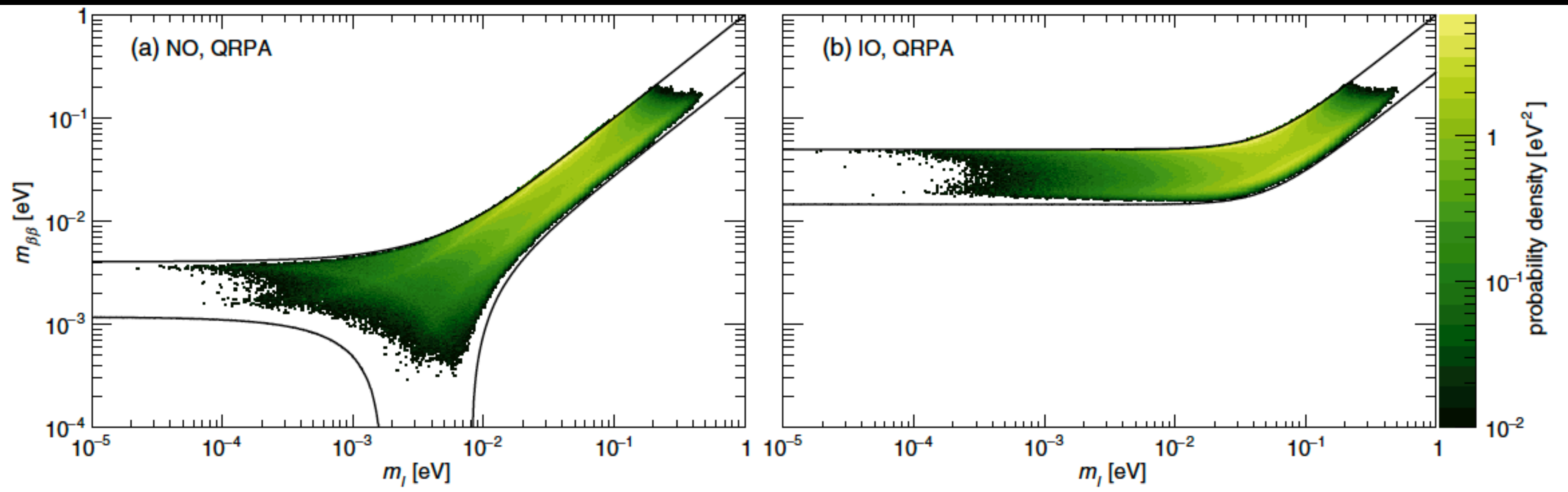


EFFECTIVE MAJORANA MASS

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu} |M^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e} \right)^2$$

$$m_{\beta\beta} = \left| \sum_{k=1}^3 m_k U_{ek}^2 \right| = \left| m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{i(\alpha_2 - \alpha_1)} + m_3 s_{13}^2 e^{i(\alpha_1 - 2\delta_{CP})} \right|$$

- Depends on absolute masses, mixing angles, Dirac and Majorana phases
- Existing neutrino oscillation measurements constrain $m_{\beta\beta}$
- Inverted ordering $m_{\beta\beta} > 20$ meV, normal ordering $m_{\beta\beta} > \sim 1$ meV



- Majorana field: $\phi = \psi + \psi^C$, so $\phi = \phi^C$, i.e. particle = antiparticle
- General Dirac and Majorana mass terms

$$\mathcal{L}^{mass} = \begin{bmatrix} \overline{\nu_L^C} & \overline{N_R} \end{bmatrix} \begin{bmatrix} m_L & m_D \\ m_D & m_R \end{bmatrix} \begin{bmatrix} \nu_L \\ N_R^C \end{bmatrix} + h.c.$$

$$m_{1,2} = \frac{1}{2} \left[(m_L + m_R) \pm \sqrt{(m_L - m_R)^2 + 4m_D^2} \right]$$

- Interesting special case: $m_L = 0$ (no gauge-breaking terms) and $m_R \gg m_D$

$$m_1 = -\frac{m_D^2}{m_R} \qquad m_2 = m_R \left(1 + \frac{m_D^2}{m_R^2} \right) \approx m_R$$

- If $m_D \approx 10^2 GeV$ (EW scale) and $m_R \approx 10^{15} GeV$ (GUT scale), then $m_1 \approx 10 meV$ (scale of ν masses)

SMALLNESS OF NEUTRINO MASSES
EXPLAINED BY EXISTENCE OF
VERY HEAVY NEUTRINOS

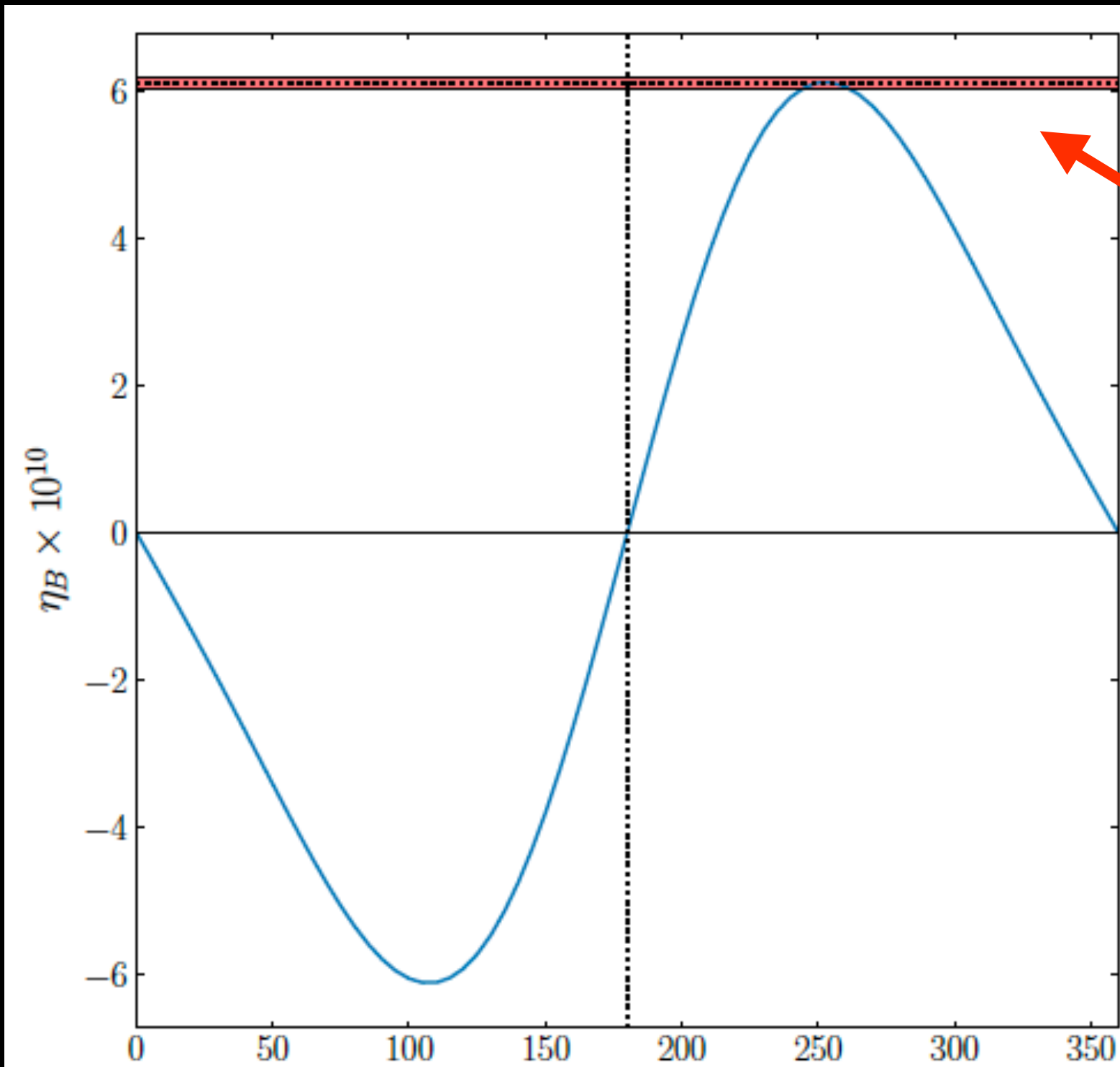
CONNECTION TO LEPTOGENESIS



Leptogenesis possible with CP violation from low energy parameters $\delta_{CP}, \alpha_{21}, \alpha_{31}$

- Model with CP violation only from δ_{CP} , i.e. both Majorana phases = 0
- Model with CP violation only from α_{21} , i.e., $\delta_{CP} = \alpha_{31} = 0$.

BARYON ASYMMETRY

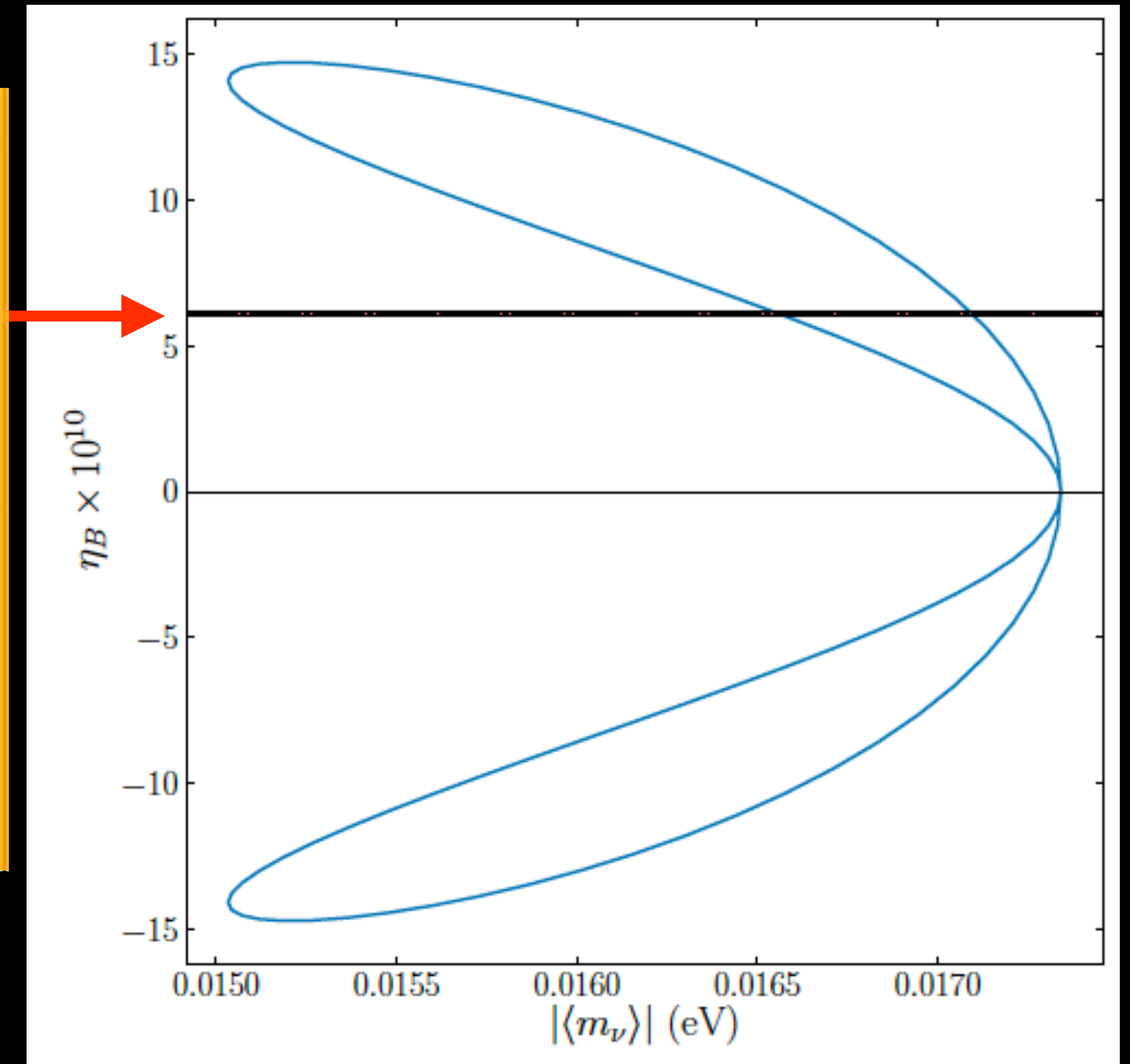


DIRAC CP VIOLATION PHASE

from Big Bang
Nucleosynthesis and
Cosmic Microwave
Background

JHEP (2019) 2019: 34

BARYON ASYMMETRY



MAJORANA MASS

- Both cases NO, high-mass: $M_1 = 3.16 \times 10^{13}$ GeV

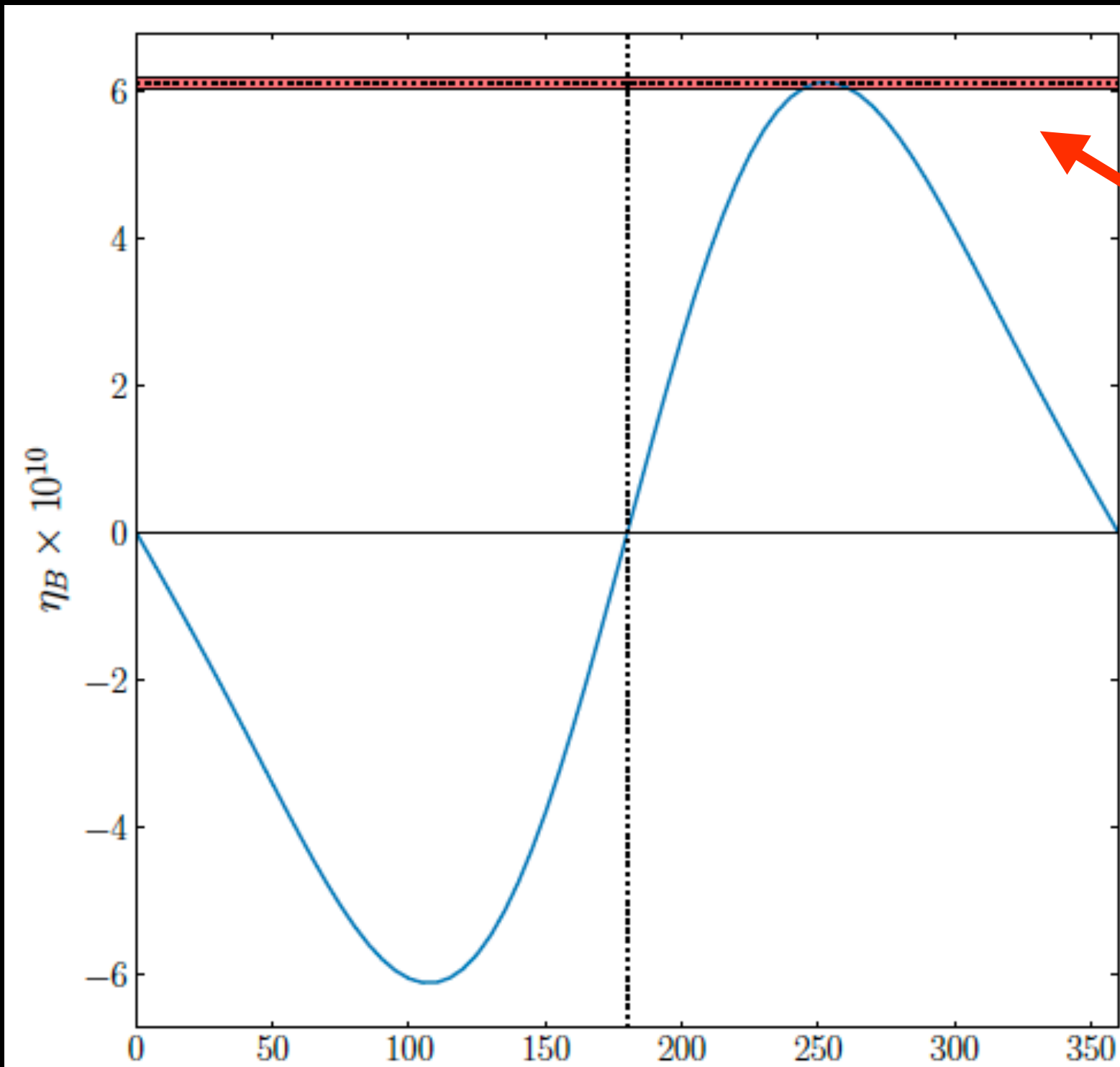
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BARYON ASYMMETRY

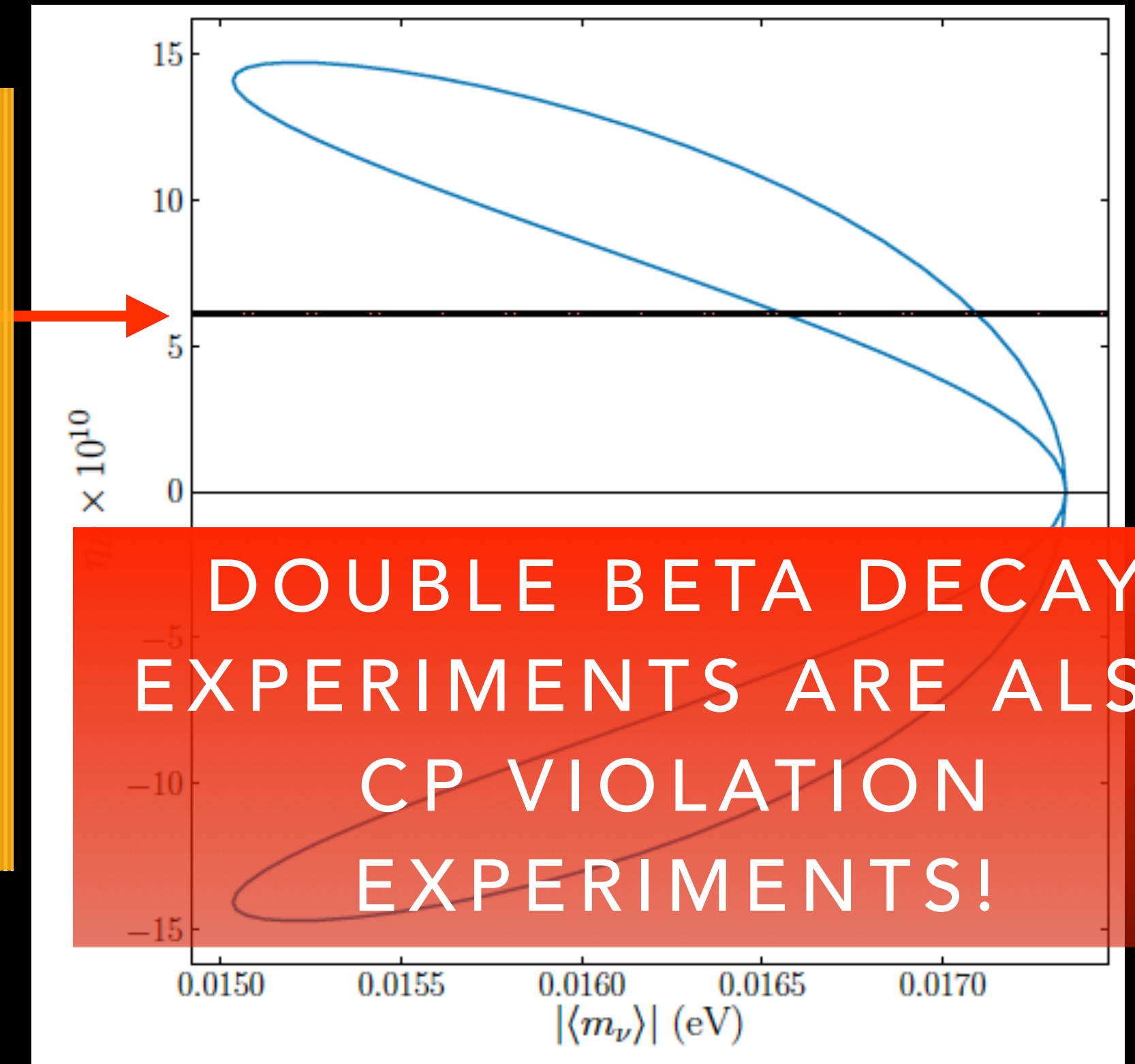


DIRAC CP VIOLATION PHASE

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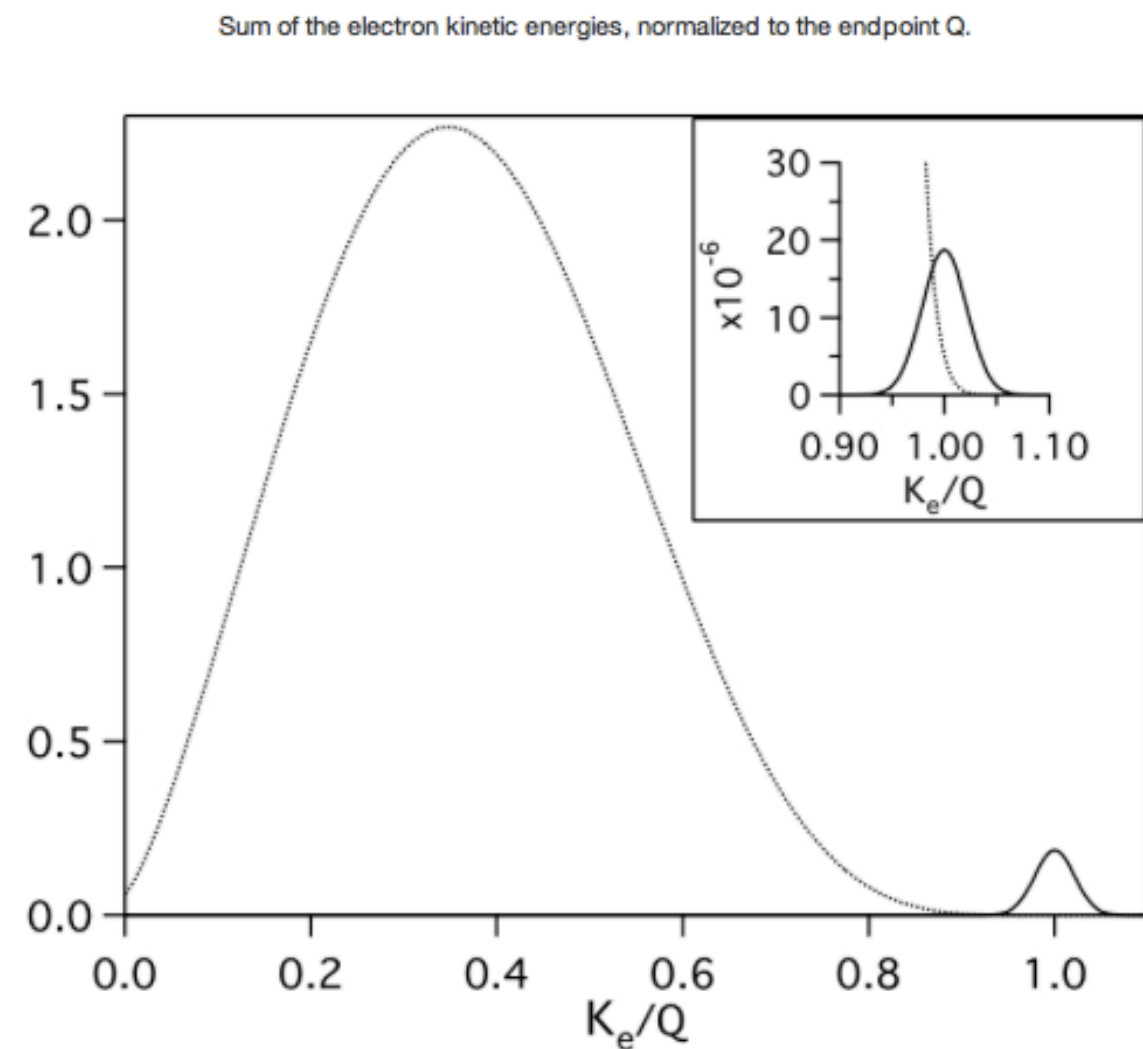
BARYON ASYMMETRY



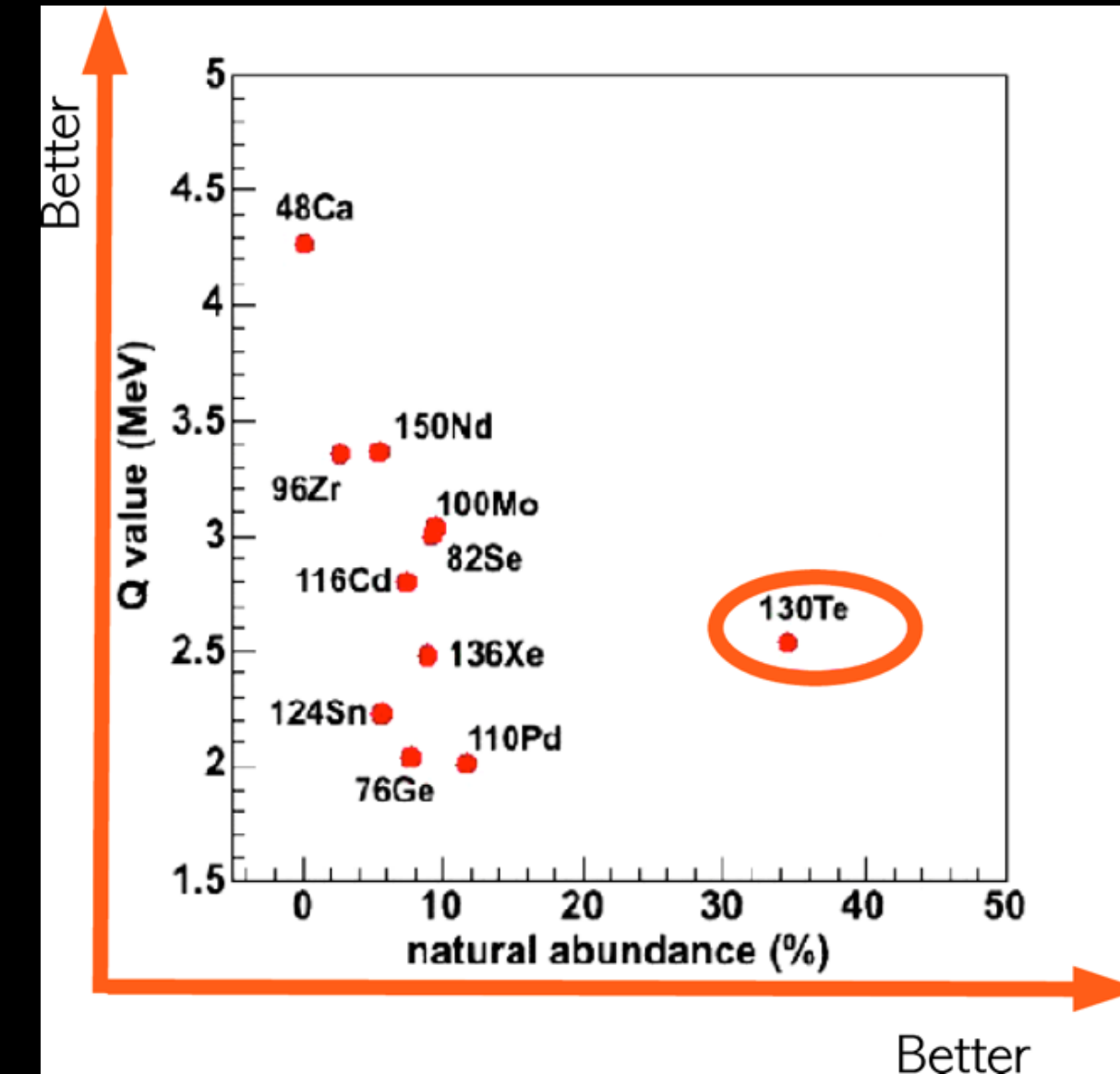
DOUBLE BETA DECAY
EXPERIMENTS ARE ALSO
CP VIOLATION
EXPERIMENTS!

MAJORANA MASS

- Both cases NO, high-mass: $M_1 = 3.16 \times 10^{13}$ GeV

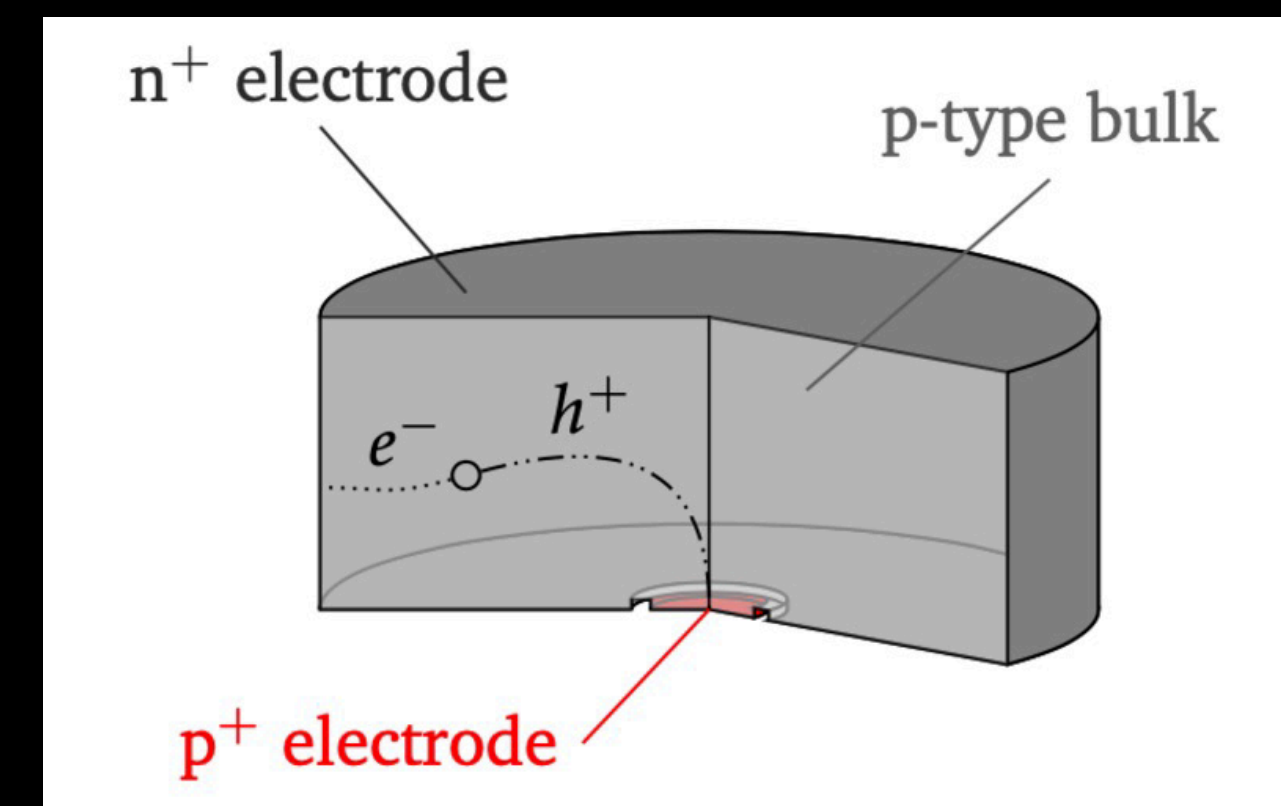


- Choose the isotope: high energy decay, high abundance (or enrich)
- Observe large quantities for a long time
- Detect electron energy sum, reject backgrounds, including DBD



CURRENT LEADING EXPERIMENTAL APPROACHES

1. **Liquid scintillator detectors (Xe/Te).** Poor resolution, but high mass and low background.
2. **Solid state detectors (Ge/Te).** Excellent resolution.
3. **Tracking or topology detectors.** Gas/liquid TPCs. Good BG discrimination, low mass.



CURRENT $0\nu\beta\beta$
EXPERIMENTS BASED
ON LIQUID
SCINTILLATOR



VOLUME 72, NUMBER 10

PHYSICAL REVIEW LETTERS

7 MARCH 1994

New Approach to the Search for Neutrinoless Double Beta Decay

R. S. Raghavan

AT&T Bell Laboratories, Murray Hill, New Jersey 07974

(Received 9 November 1993)

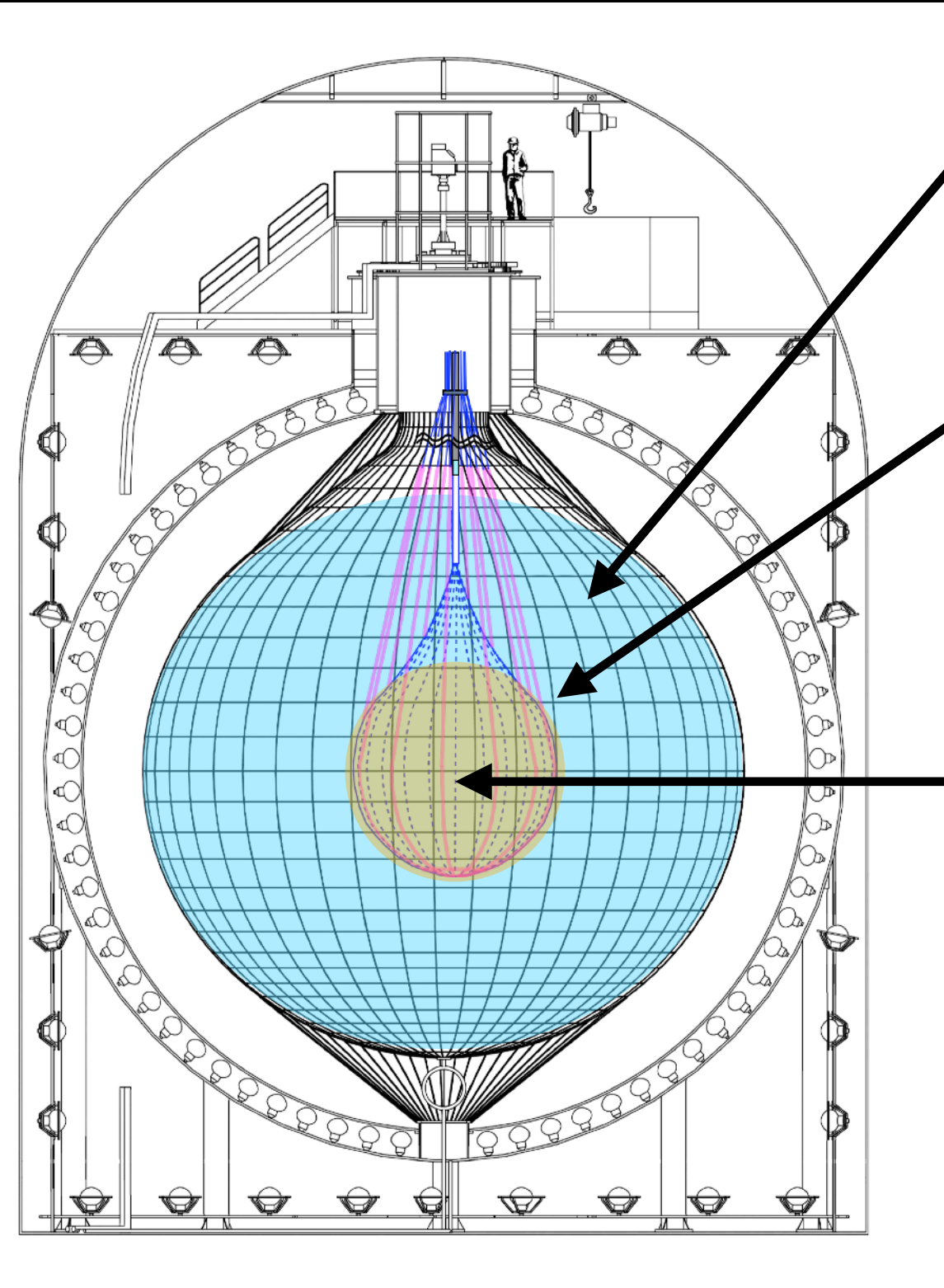
Sub-eV Majorana neutrino masses $\langle m_\nu \rangle$, can be explored by a new approach to neutrinoless double β decay using ^{136}Xe in a Xe gas-loaded, multiton liquid scintillator installed in a very low background detector such as the Kamiokande facility. With enriched ^{136}Xe , a readily implementable, 10 ton detector experiment can establish an $\langle m_\nu \rangle = 0.45$ eV at 3σ in 1 yr (or exclude an $\langle m_\nu \rangle < 0.23$ eV in 2 yr). A 100 ton detector can extend the limit to $\langle m_\nu \rangle < 0.1$ eV, compared with the present limit of $\langle m_\nu \rangle < 1.3$ eV.

- One of the great innovators in our field, Raju was also the first to propose to search for $0\nu\beta\beta$ decays by loading isotope in ultra-pure liquid scintillator detectors

KAMLAND-ZEN

THANKS TO I. SHIMIZU (NEUTRINO 2024)

KAMLAND-ZEN DETECTOR AND PHASES

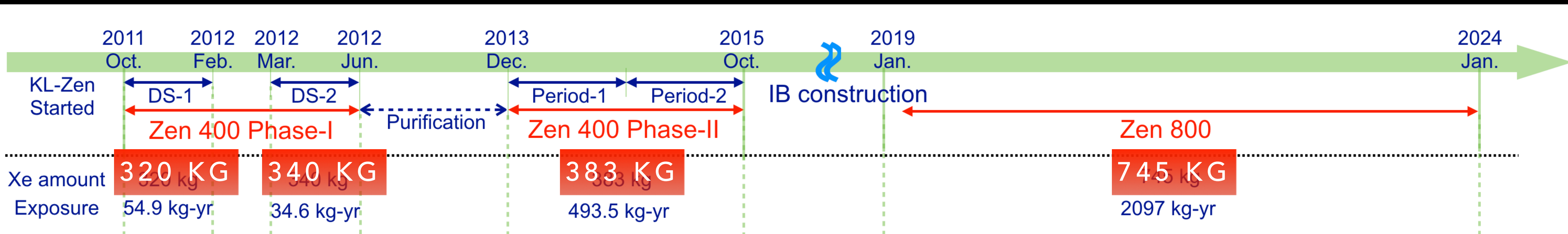


1000 ton pure liquid scintillator

inner balloon

745 kg Xe-loaded liquid scintillator (91% enriched)

- Re-using KamLAND reactor and geo-neutrino detector
- 2011: start of $0\nu\beta\beta$ measurements
- Technique is scalable
 - mass increased from 320 kg to 745 kg
 - scintillator purification
 - balloon replacement
- Highest Xe mass, no external γ backgrounds



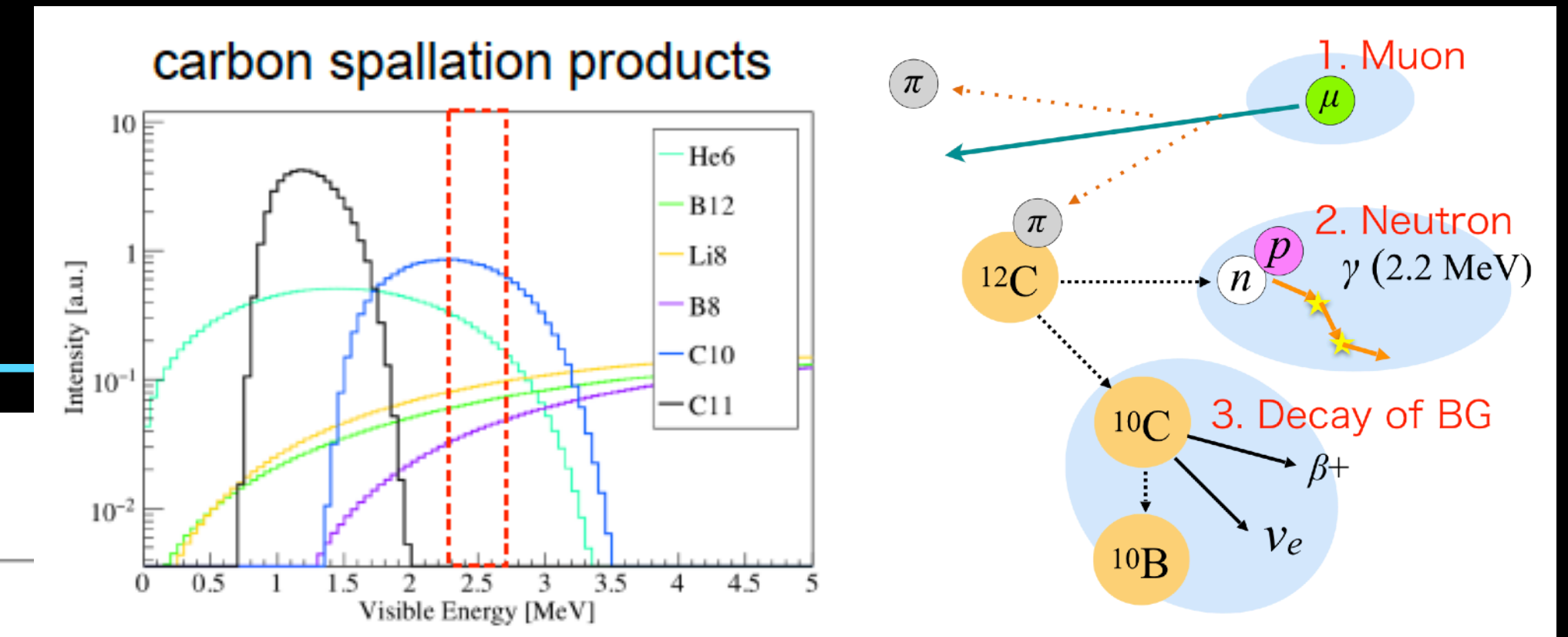
KL-ZEN BACKGROUNDS



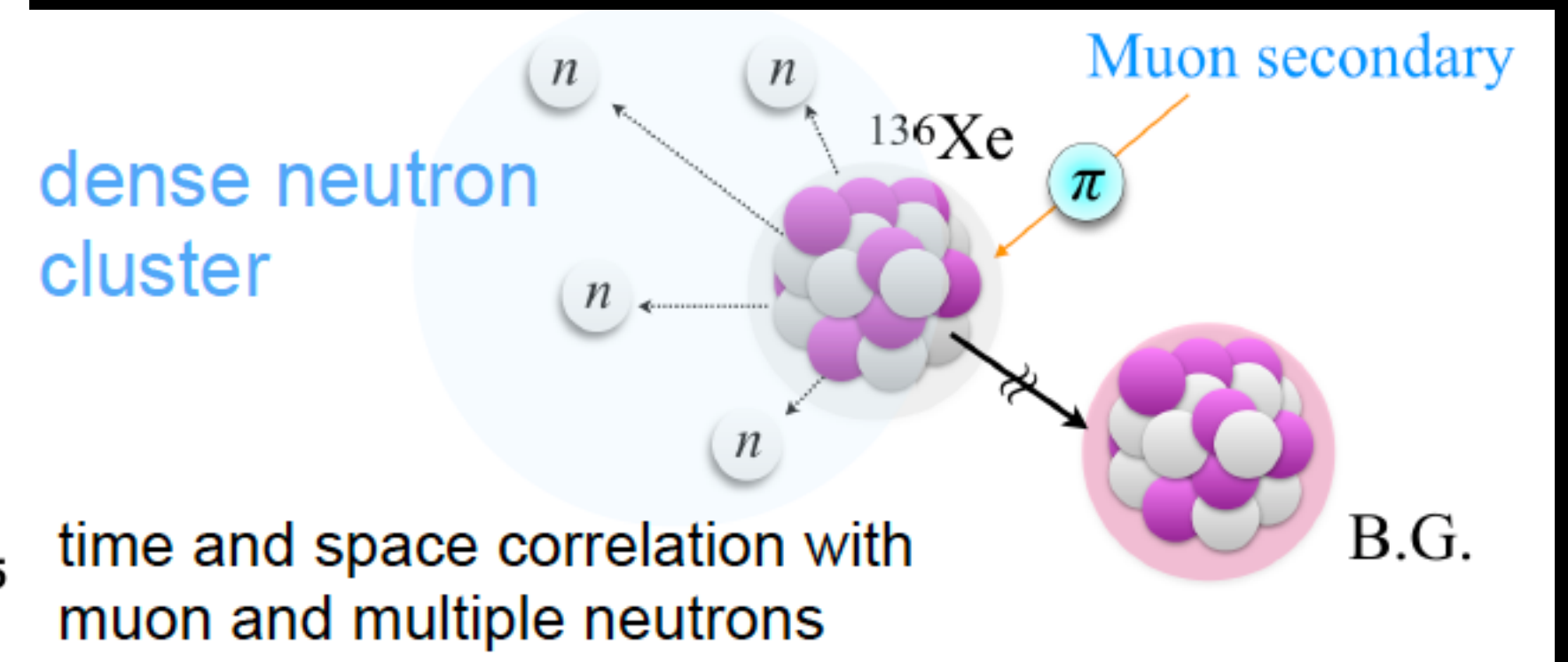
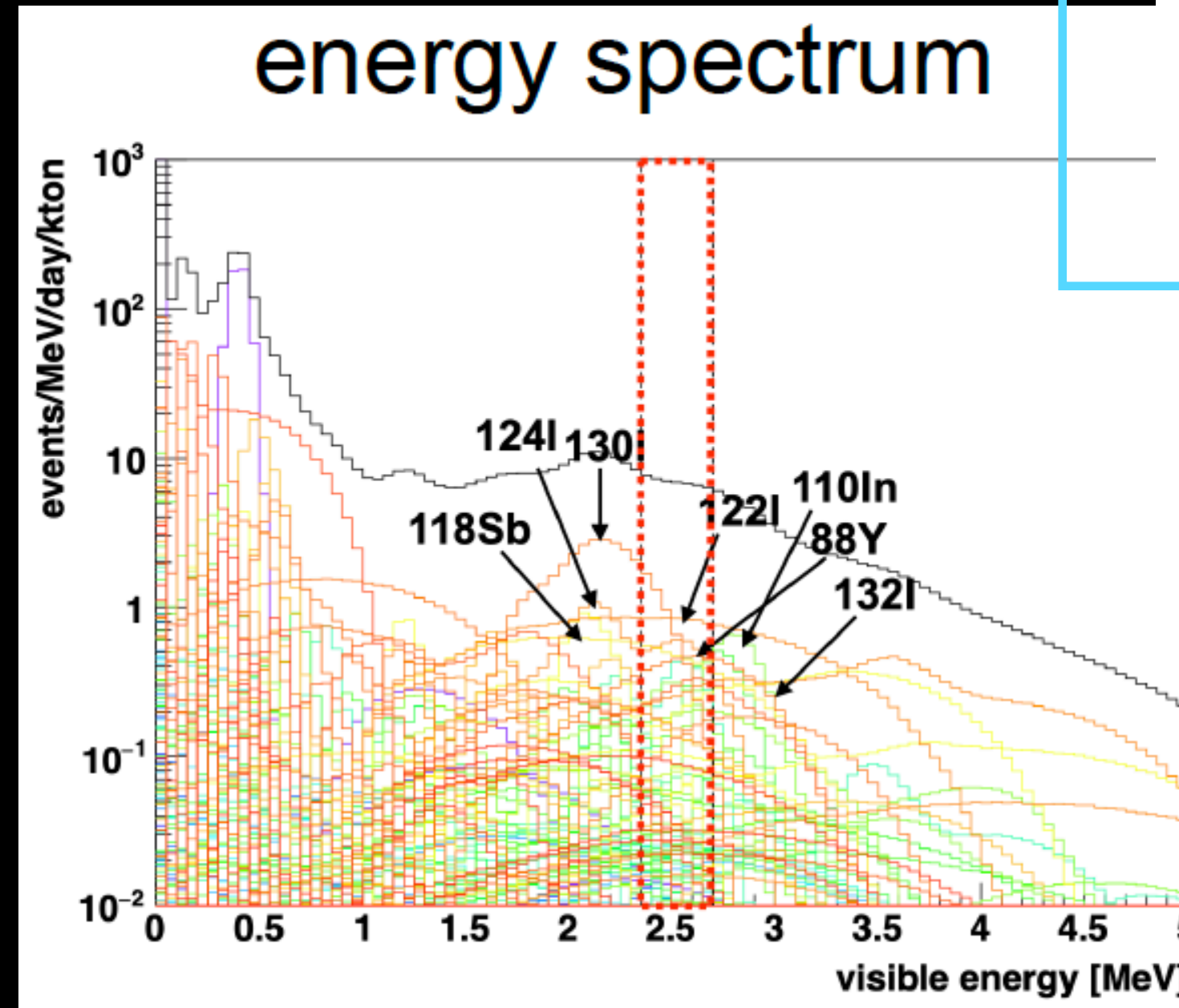
from balloon: increased size, reduced contamination: $> 3\times$ sensitive volume

Zen 400 (R 1.54 m)	Zen 800 (R 1.90 m)
$^{238}\text{U} : 5\times 10^{-11} \text{ g/g}$	$^{238}\text{U} : \sim 4\times 10^{-12} \text{ g/g}$
$^{232}\text{Th} : 3\times 10^{-10} \text{ g/g}$	$^{232}\text{Th} : \sim 2\times 10^{-11} \text{ g/g}$
balloon shape	$\times 10$ reduction of IB ^{214}Bi

short lived carbon-spallation isotopes:
cut all events < 180 s after a muon
95% rejection efficiency



long-lived xenon-spallation isotopes:
simple time-cut would remove all data!
use time and space correlations between muon and multiple neutrons
47% rejection efficiency



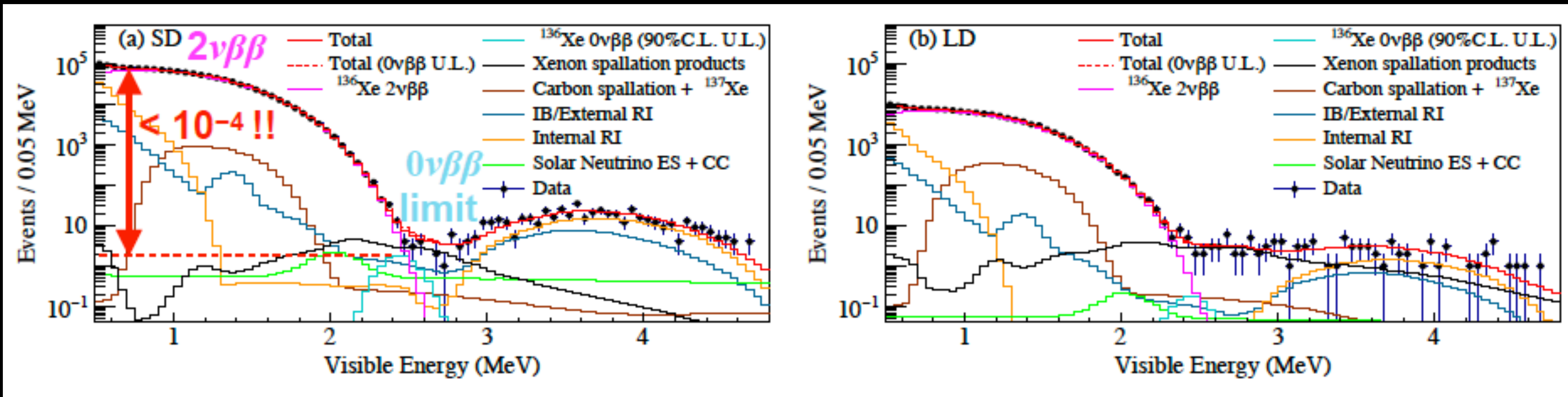
KAMLAND-ZEN 800 ANALYSIS



- Simultaneous fit to energy spectra with/out long-lived background tag ($r < 1.57$ m)

$0\nu\beta\beta$ CANDIDATES
1131 DAYS LIVETIME

LONG-LIVED CANDIDATES
111 DAYS LIVETIME



$0\nu\beta\beta$ BEST FIT: 0 EVENTS
UPPER LIMIT: < 10 EVENTS

LONG-LIVED BG RATE
(2.35-2.70 MeV) MEASURED
 $= 30.2 \pm 4.5 \text{ ev/Xe} - \text{ton/yr}$

KAMLAND-ZEN $0\nu\beta\beta$ RESULTS



^{136}Xe half-live limits (90% C.L.)

KZ 800 $T_{1/2}^{0\nu} > 3.4 \times 10^{26} \text{yr}$

KZ 400 $T_{1/2}^{0\nu} > 0.9 \times 10^{26} \text{yr}$

Combined $T_{1/2}^{0\nu} > 3.8 \times 10^{26} \text{yr}$

ISOTOPE	EXPERIMENT	LIMIT
XE136	KL-ZEN	$3.8 \times 10^{26} \text{ Y}$
GE76	COMBINED	$1.9 \times 10^{26} \text{ Y}$
TE130	CUORE	$4.4 \times 10^{25} \text{ Y}$

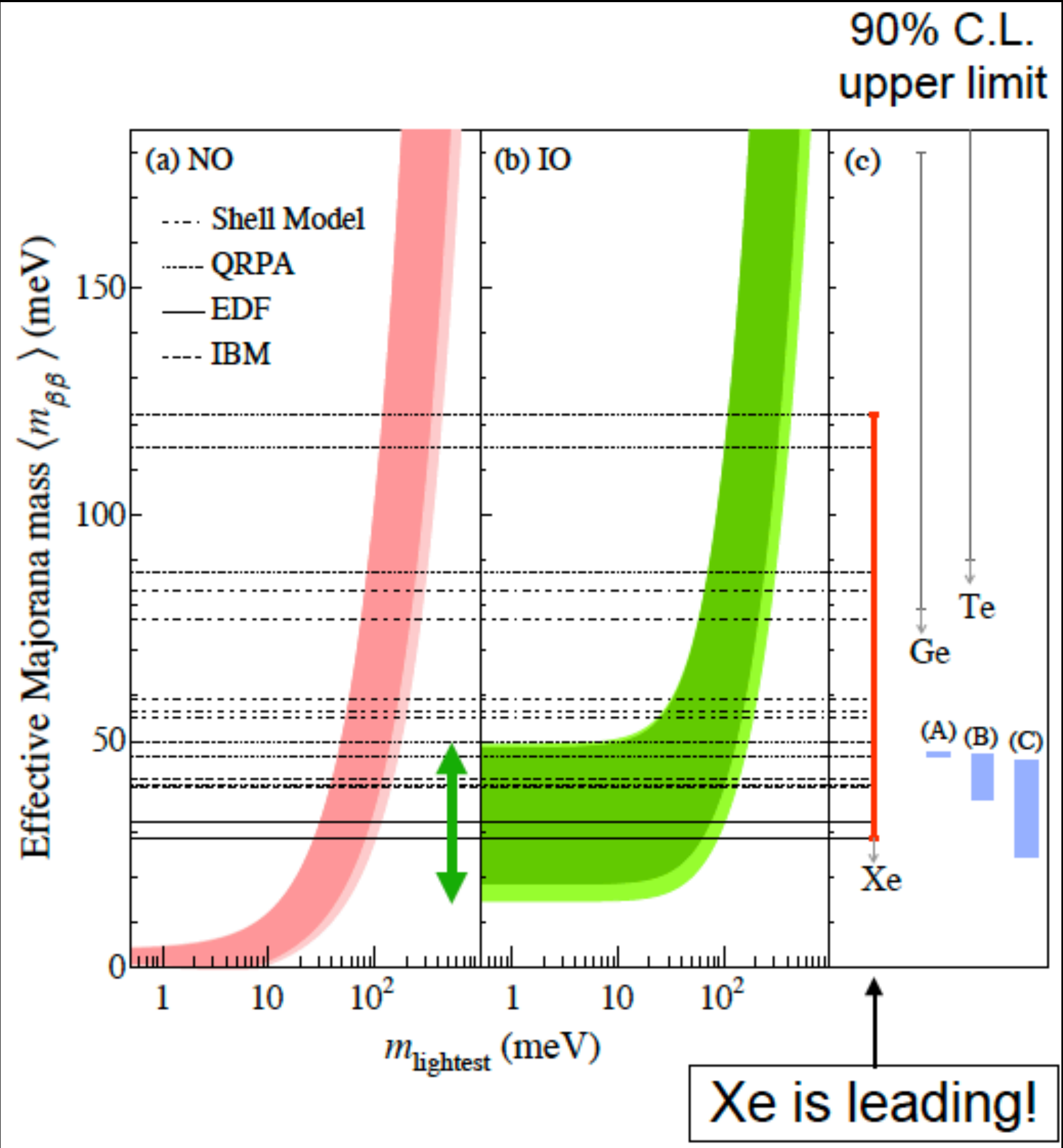
$[T_{1/2}^{0\nu}]^{-1} = G^{0\nu}(Q_{\beta\beta}, Z) |M^{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$

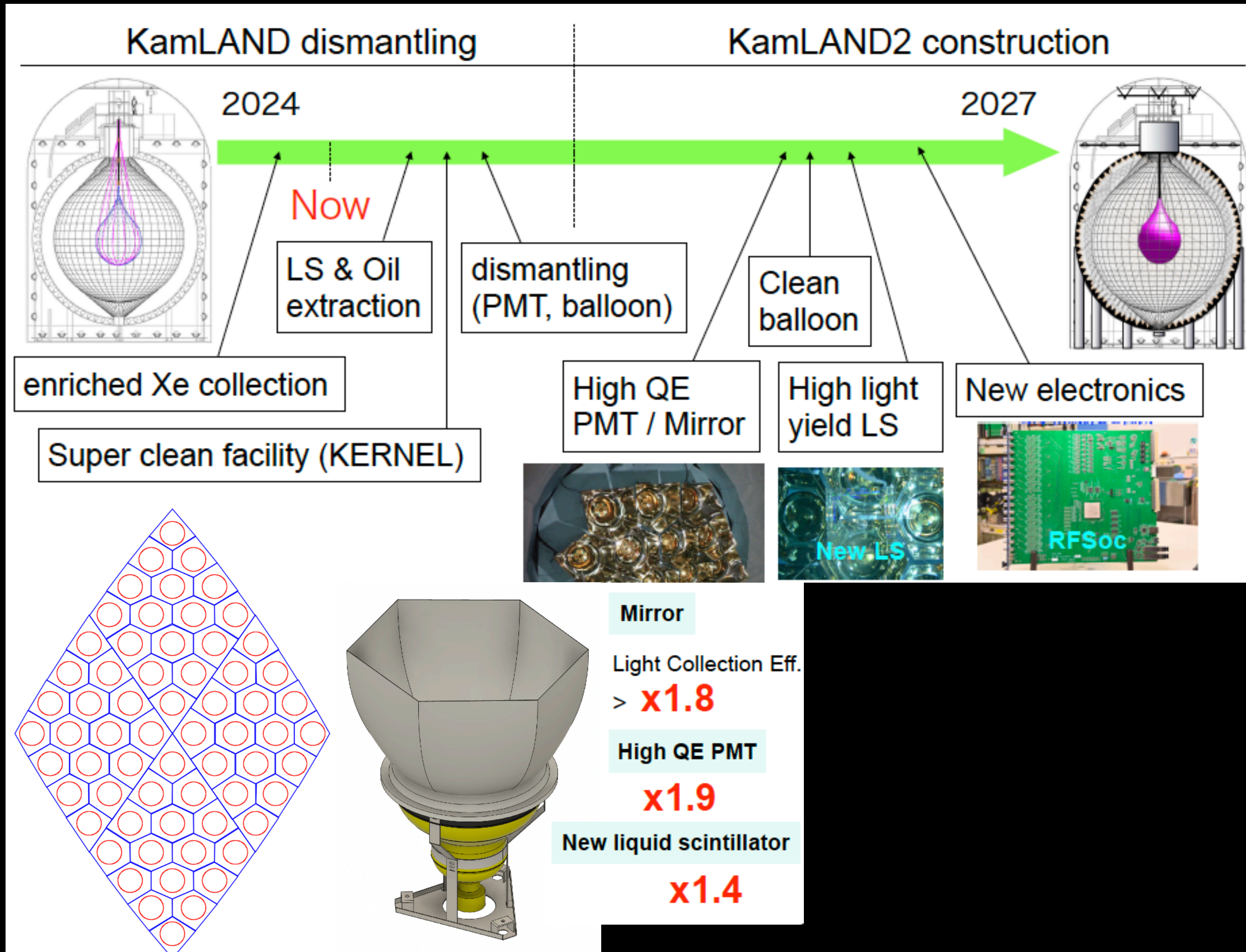
NME for ^{136}Xe : 1.11–4.77

NME calculations assuming $g_A \sim 1.27$			
	Ref.	$M^{0\nu}$	$\langle m_{\beta\beta} \rangle$ (meV)
Shell model	[1]	2.28, 2.45	59.4, 55.3
	[2]	1.63, 1.76	83.1, 77.0
	[3, 4]	2.39	56.7
QRPA	[5]	1.55	87.4
	[6]	2.91	46.6
	[7]	2.71	50.0
	[8]	1.11, 1.18	122, 115
	[9]	3.38	40.1
EDF theory	[10]	4.20	32.3
	[11]	4.77	28.4
	[12]	4.24	32.0
IBM	[13]	3.25	41.7
	[14]	3.40	39.9

reached the IO horizontal band (< 50 meV) with half of the NMEs

Best $m_{\beta\beta}$ limit (Xe)
< 28–122 meV





- Several upgrades targeting the dominant backgrounds
 - $2\nu\beta\beta$: light yield increase: new Liquid scintillator, high QE PMTs, mirrors
 - long-lived isotopes: new electronics for spallation tag
- Expected sensitivity: $1 \times 10^{27} \text{ yr}$, $\sim 20 \text{ meV}$, cover full IO

SNO+

THE SNO+ EXPERIMENT



Repurposing the Sudbury Neutrino Observatory (SNO) detector

2 km underground
~70 muons/day



Rope system
Hold-up and -down
Low Radioactivity

Acrylic Vessel (AV)
12 m diameter

Ultra-Pure
Water

~9300 PMTs

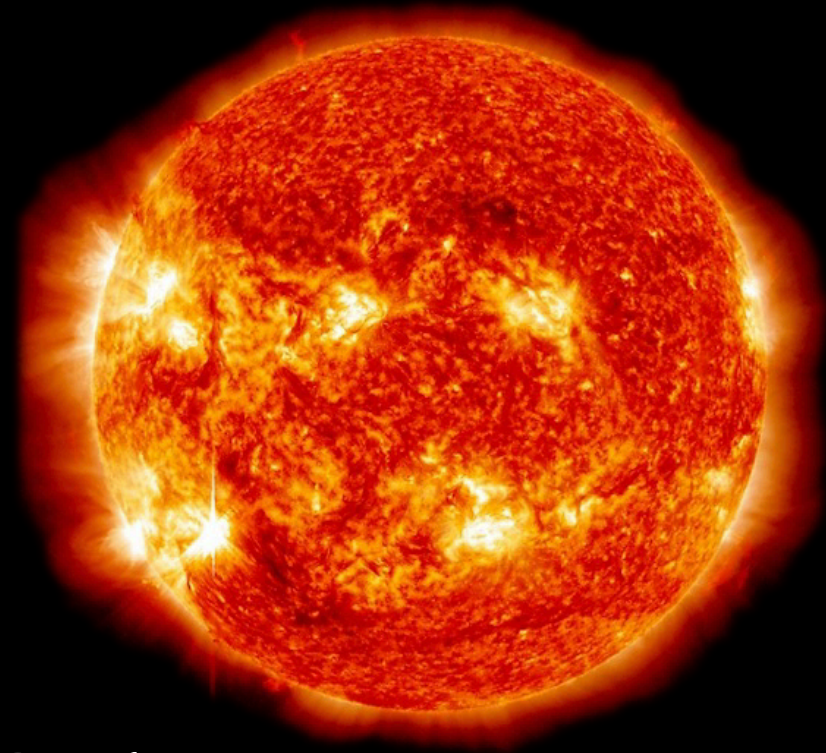
Target Material

1. Water: 905 tonnes
2. LAB Scintillator: 780 tonnes
3. Tellurium loading: +3.9 tonnes



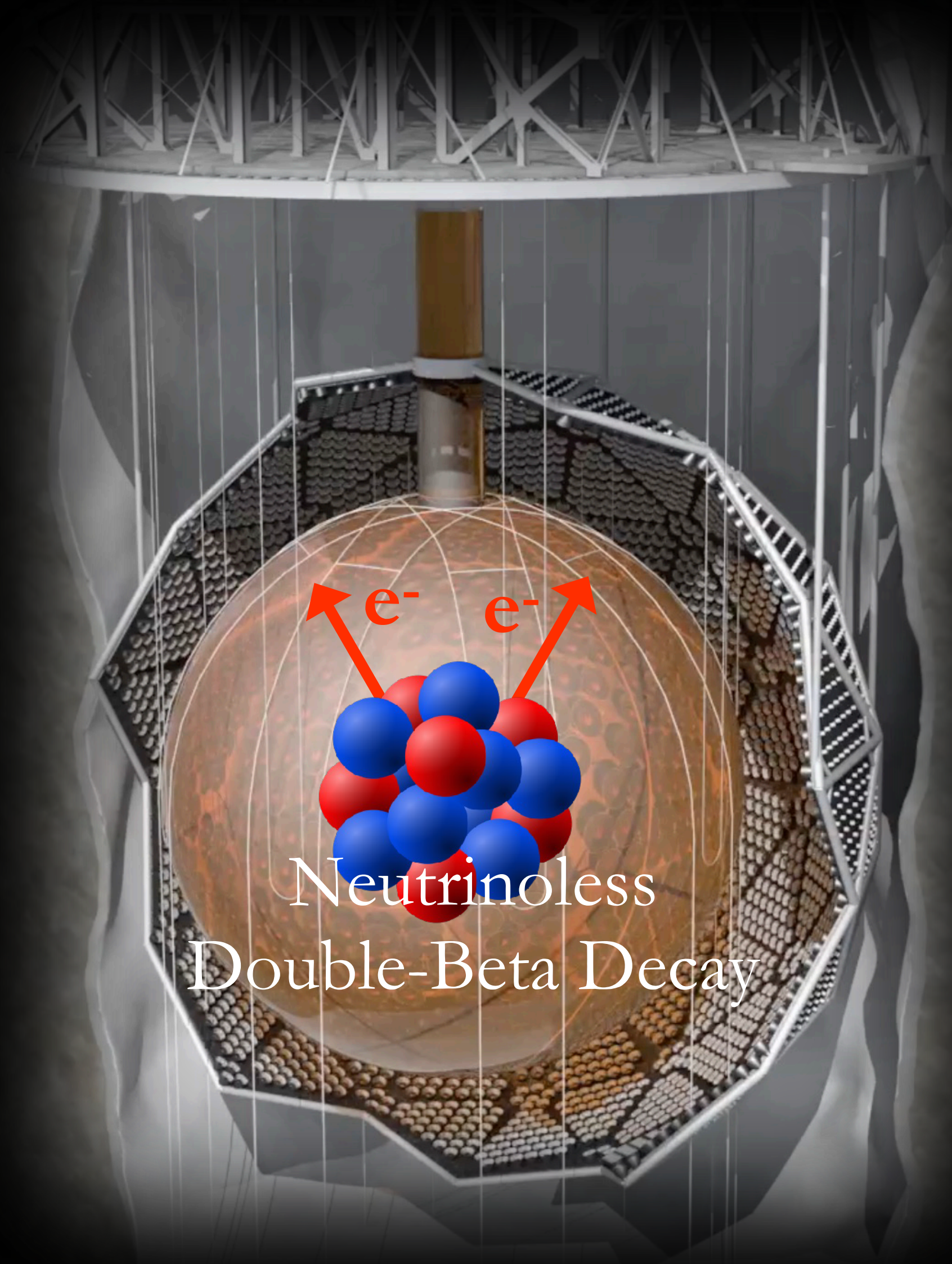
Purification plant

THE SNO+ EXPERIMENT



Solar Neutrinos

Reactor Neutrinos

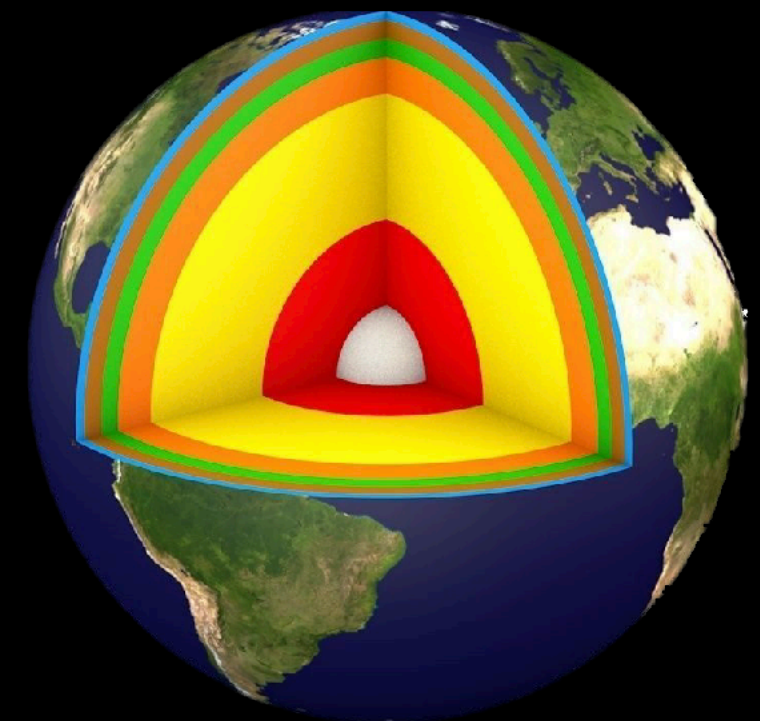


Neutrinoless
Double-Beta Decay

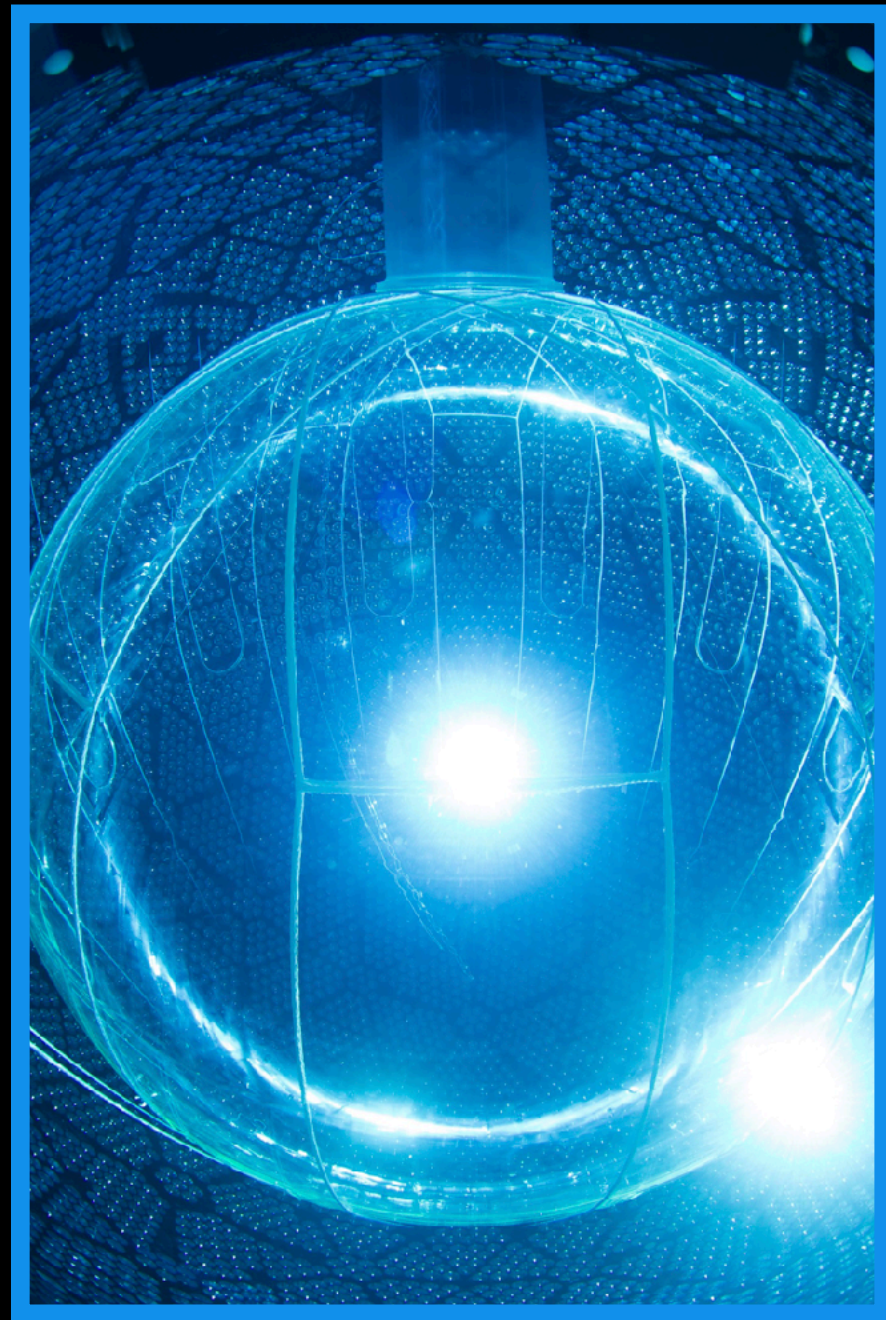


Supernova Neutrinos
+ exotics

Geo-Neutrinos



SNO+ TIMELINE



Water phase

- High Rn
- Low Rn



Partial fill phase

Scintillator over water.
Stop in fill due to Covid.



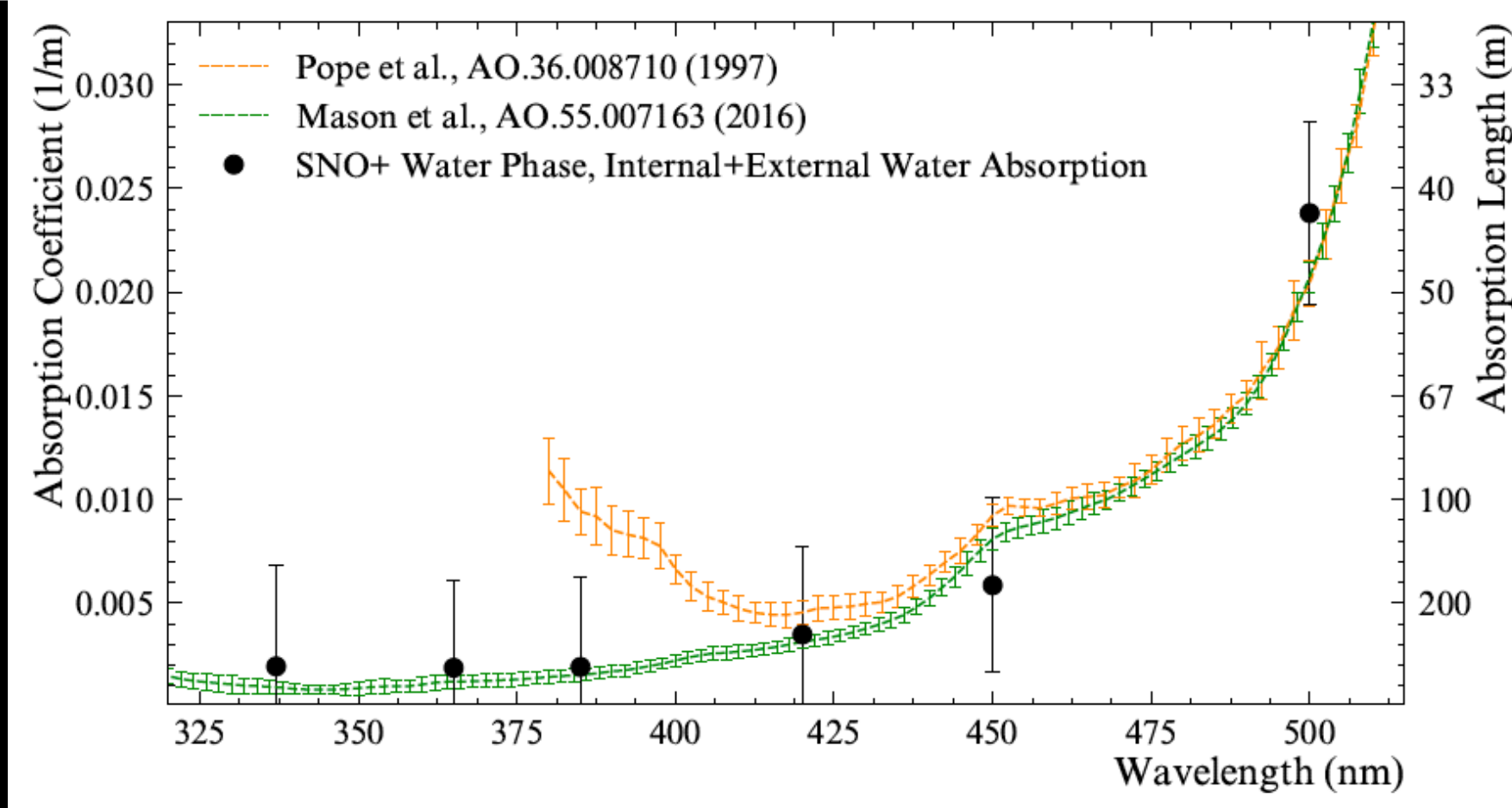
Scintillator phase

- Low PPO
- Nominal PPO
- Added bis-MSB

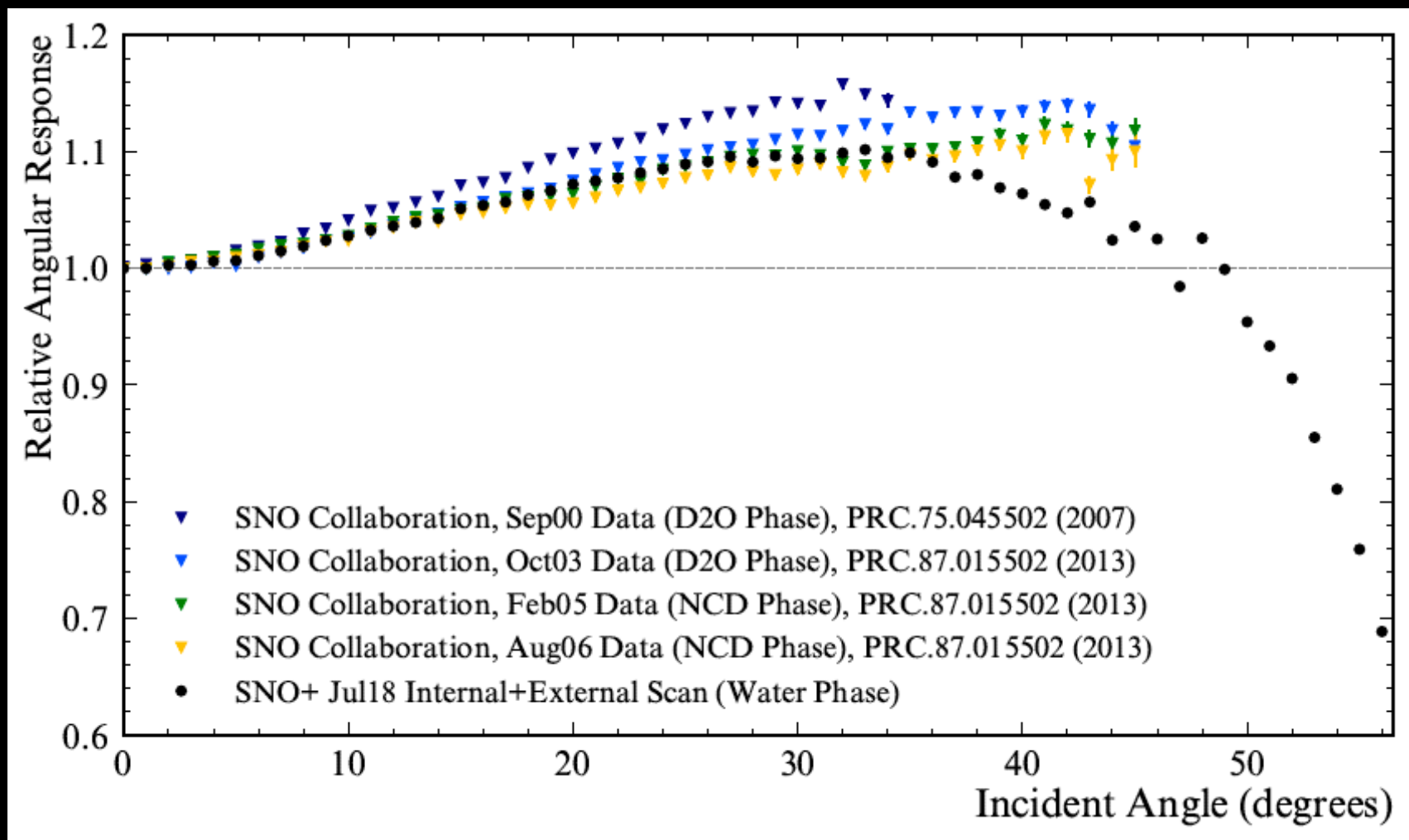


Next:
Tellurium-
loaded phase

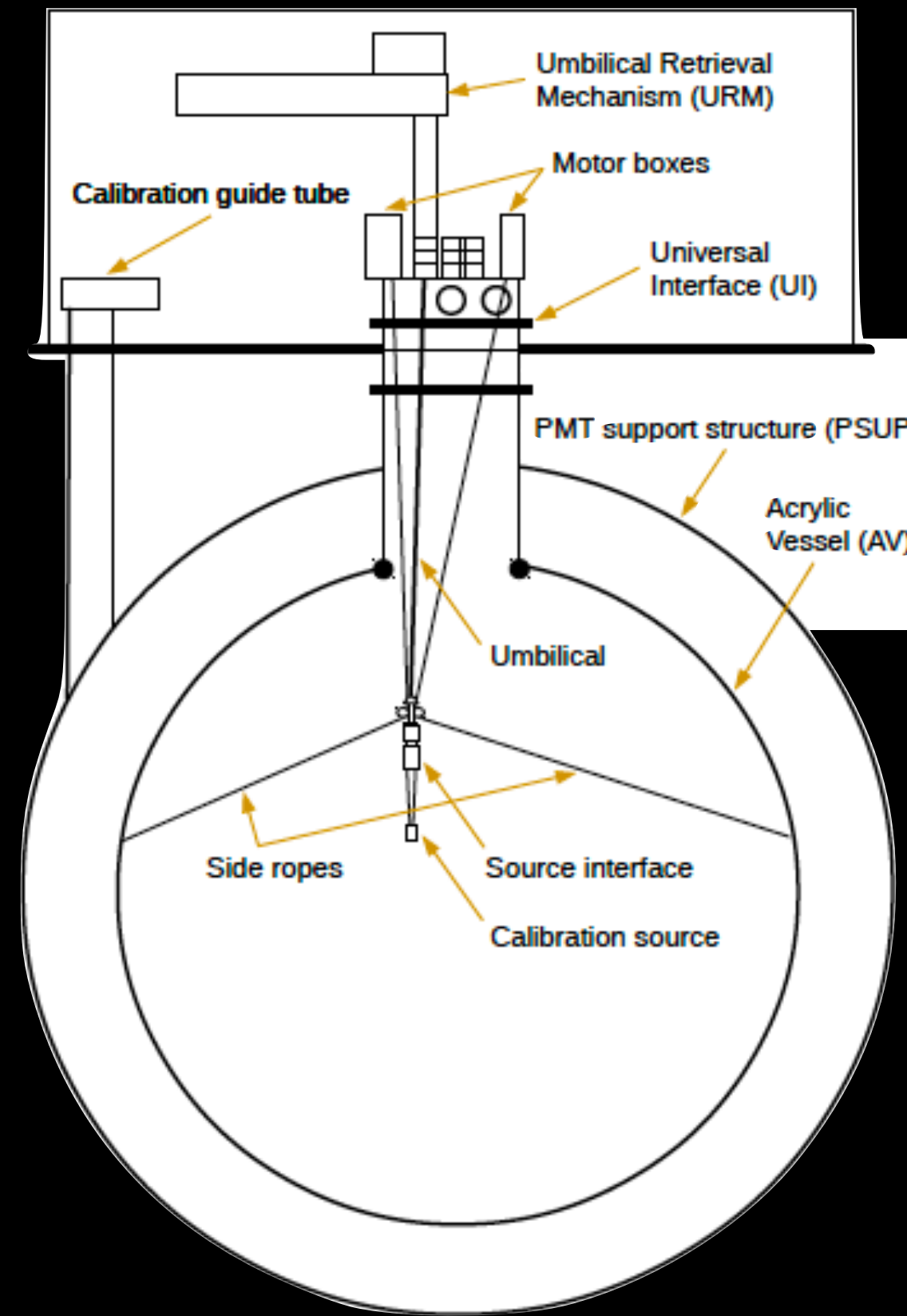
WATER PHASE CALIBRATION



Very long attenuation length of water

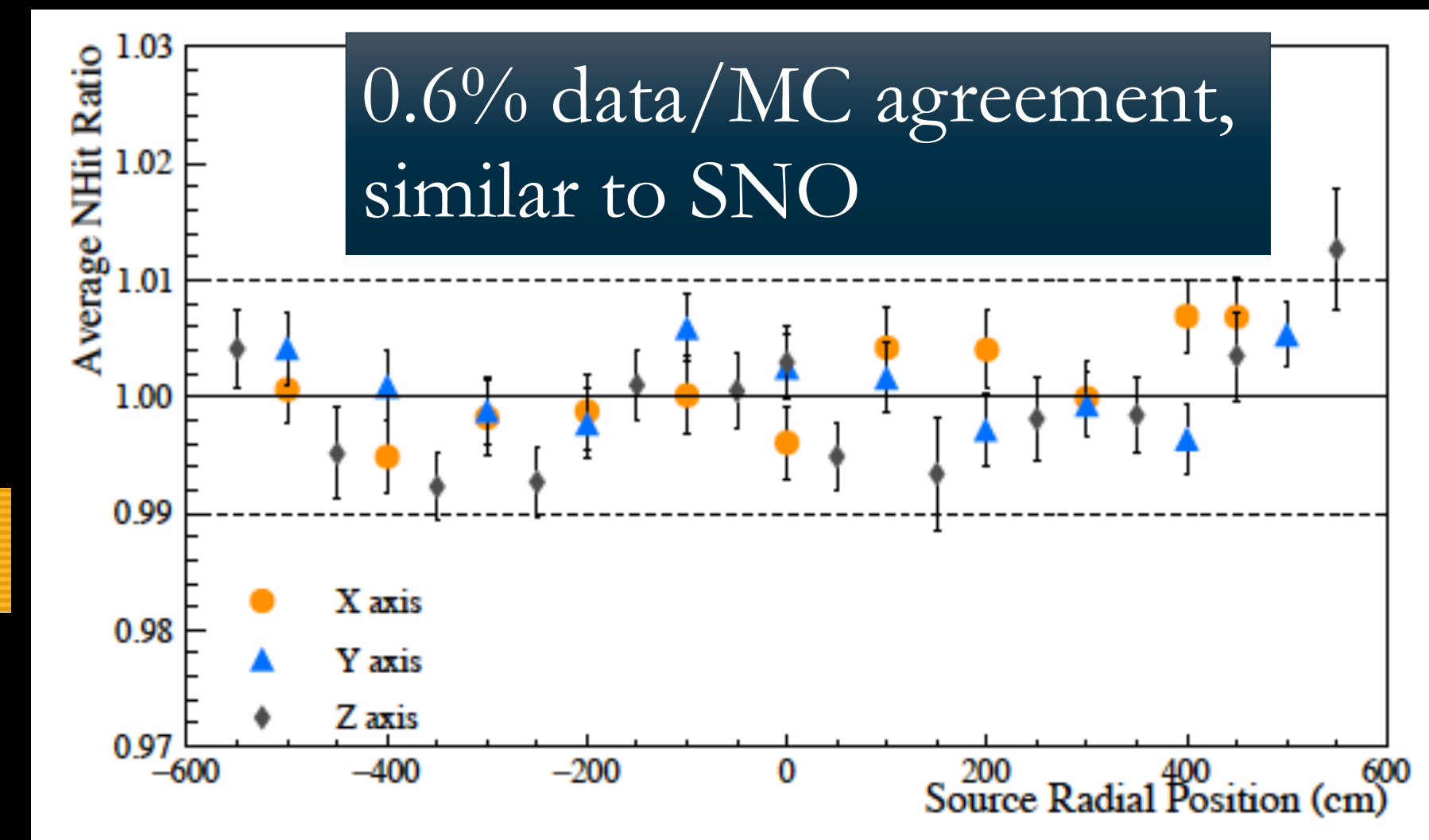


Angular response of PMT + reflectors continuing to decline with time

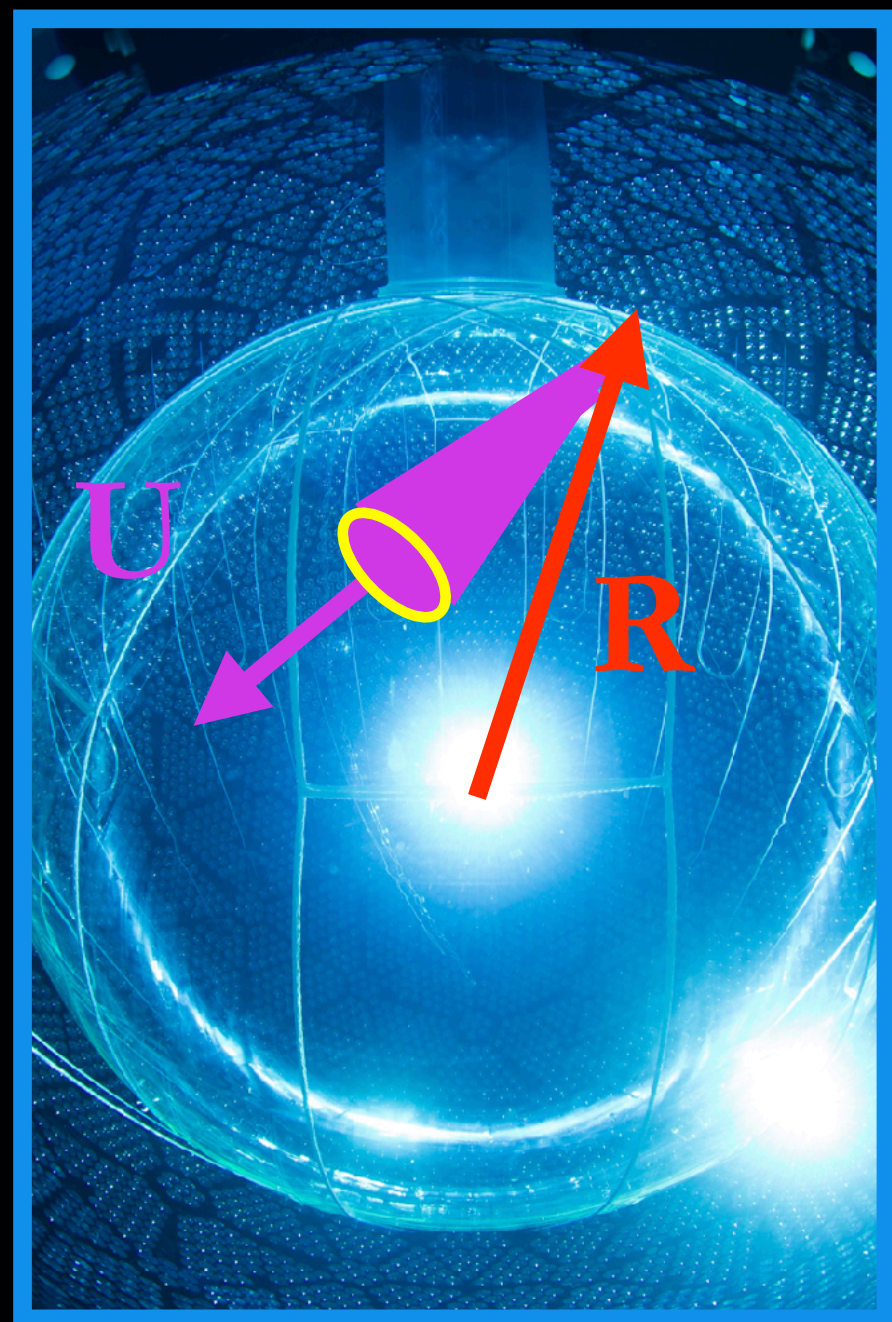


JINST 16 P10021 (2021)

- Internal + external deployment of laserball: full optical calibration of SNO+ in the water phase:
- After using calibration in simulation and reconstructions, excellent data /MC agreement for gamma source



EXTERNAL BACKGROUNDS

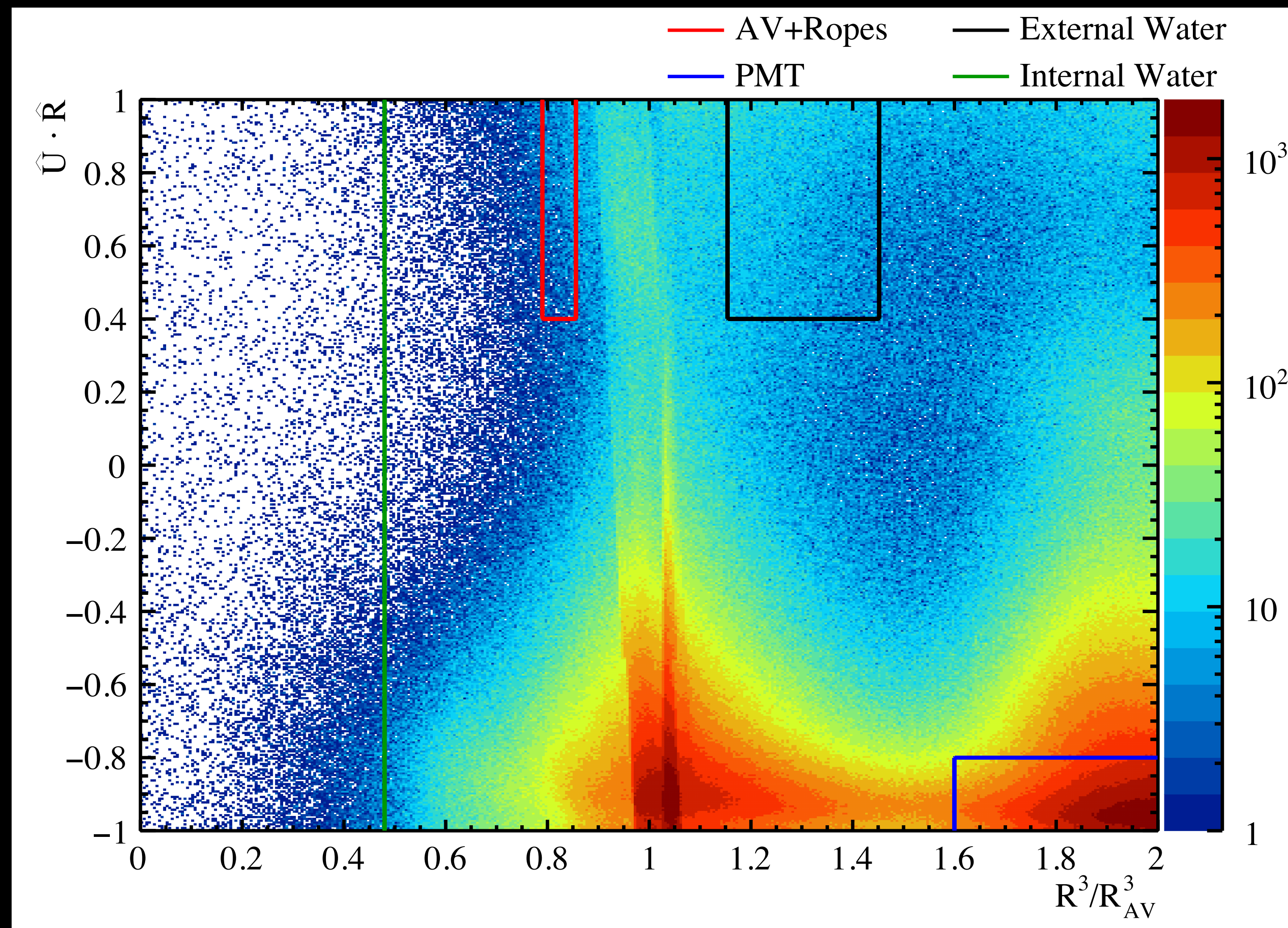


$$U \cdot R$$

>0 outward
 <0 inward

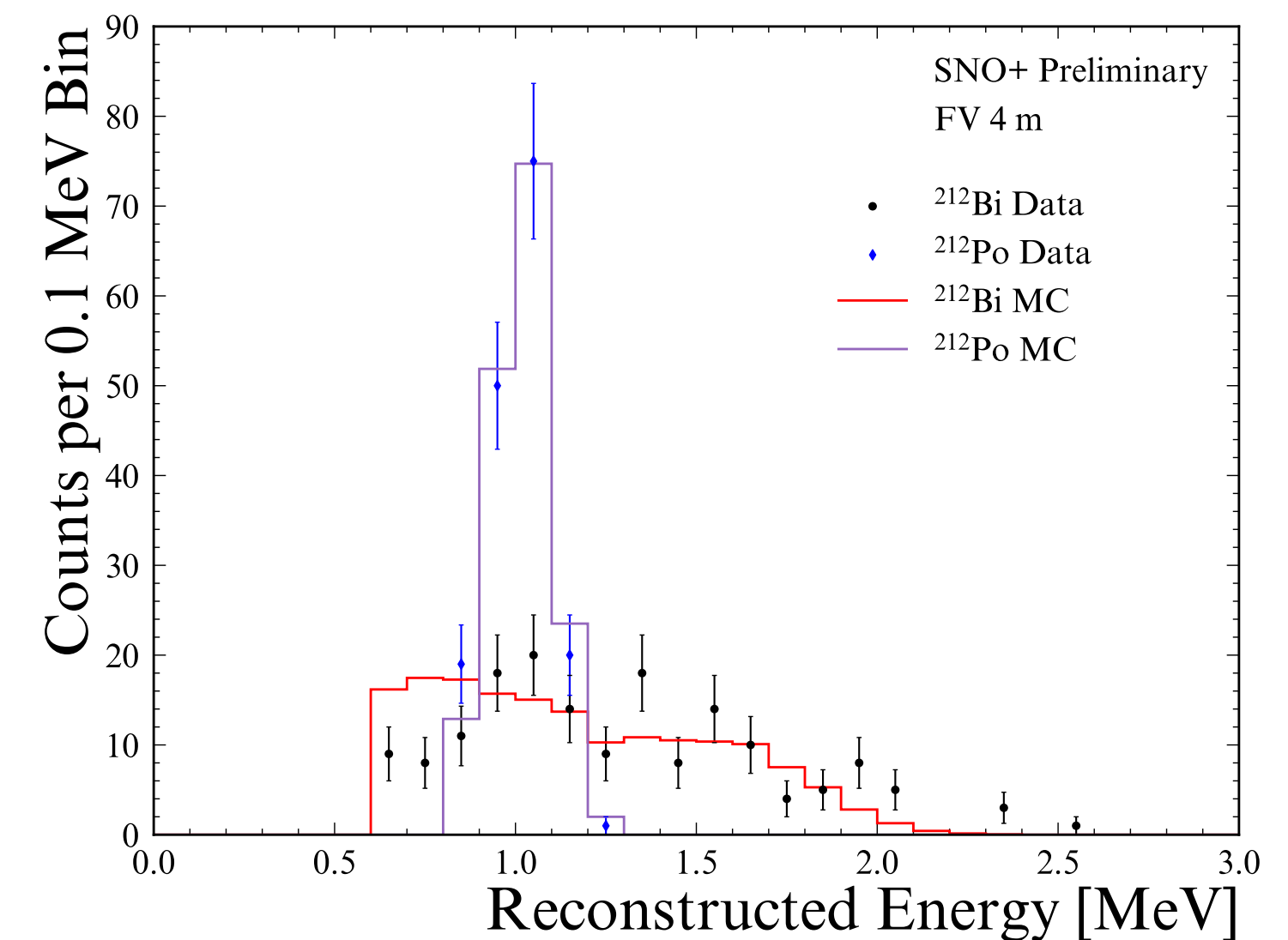
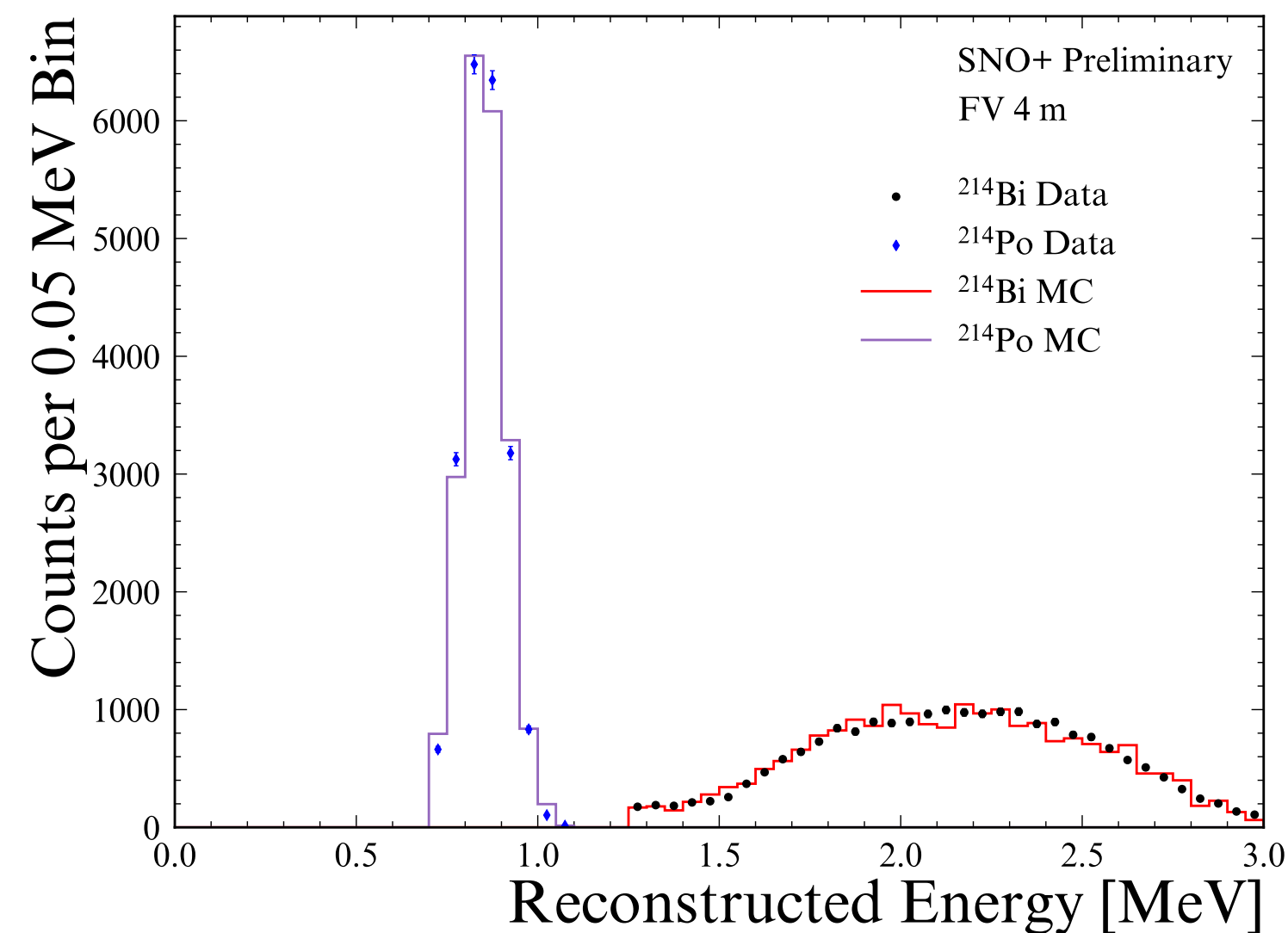
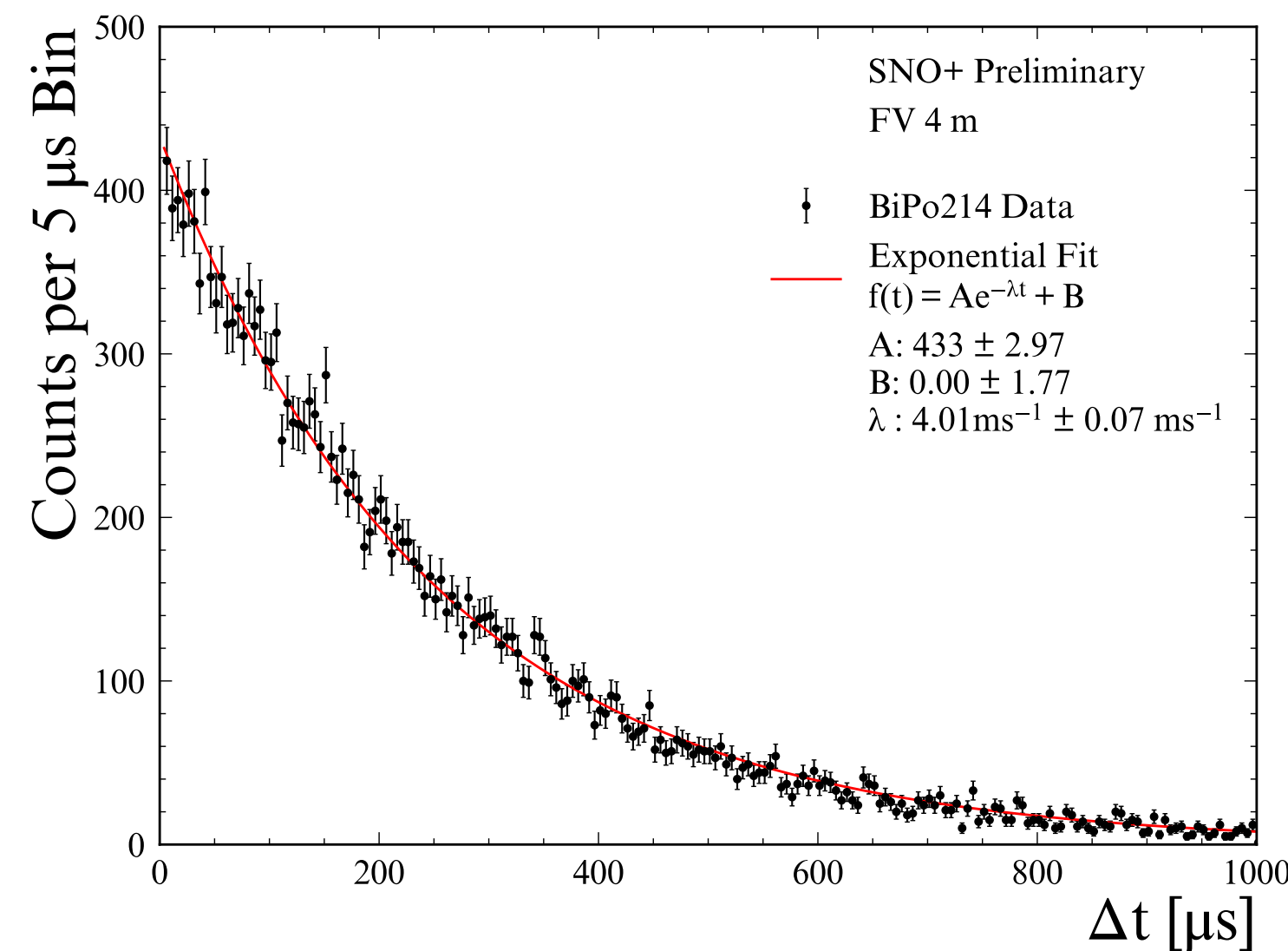
In/Out Direction

- In water phase, directionality helps to constrain external backgrounds
- All at or smaller than nominal



Radial Position

- Short half-lives of Po isotopes: clean identification of the Bi-Po decay sequences
- $$^{214}\text{Bi} \rightarrow ^{214}\text{Po} + e^- + \bar{\nu}_e$$
- $$^{214}\text{Po} \rightarrow ^{210}\text{Pb} + \alpha$$
- $$^{212}\text{Bi} \rightarrow ^{212}\text{Po} + e^- + \bar{\nu}_e$$
- $$^{212}\text{Po} \rightarrow ^{208}\text{Pb} + \alpha$$

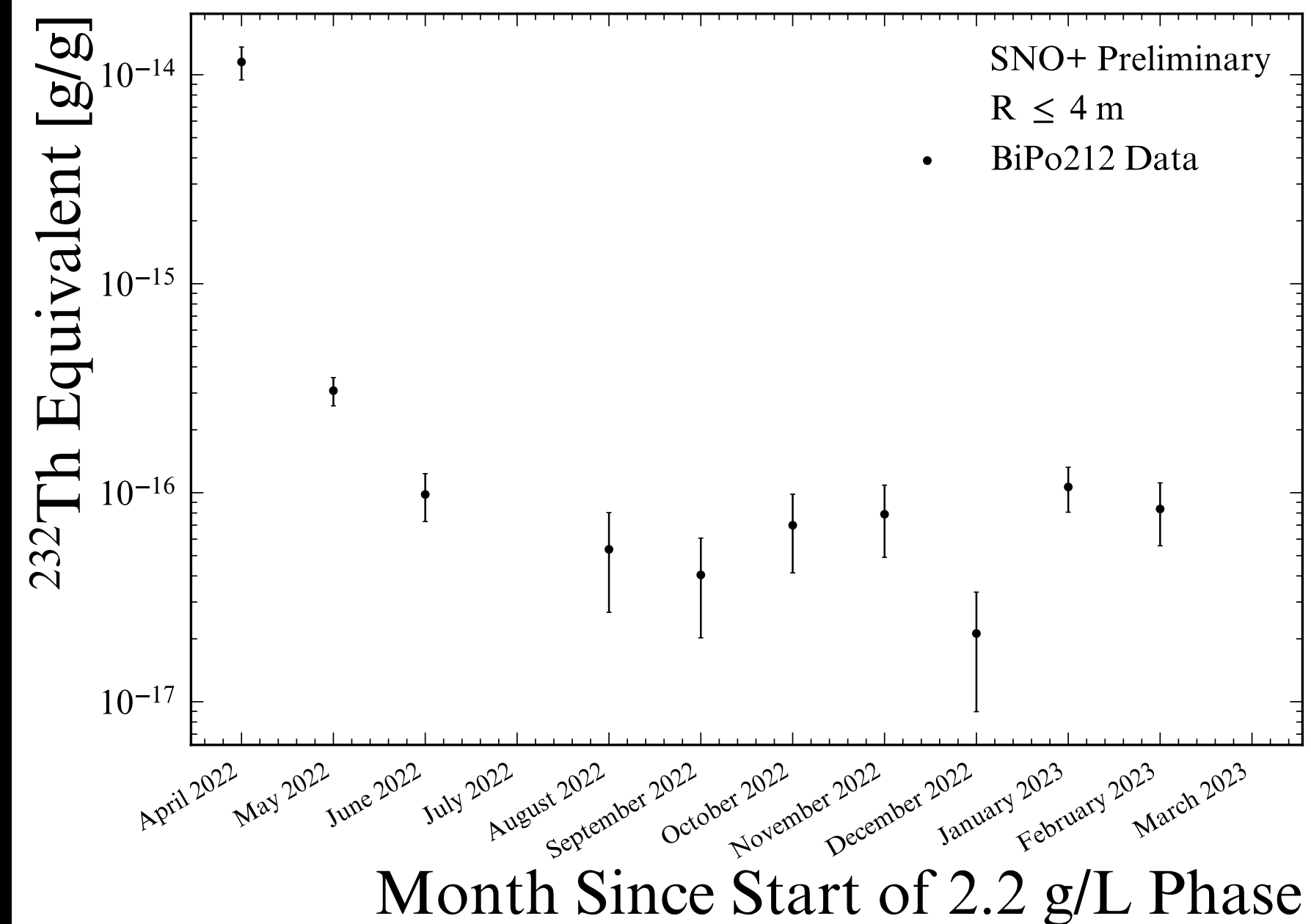
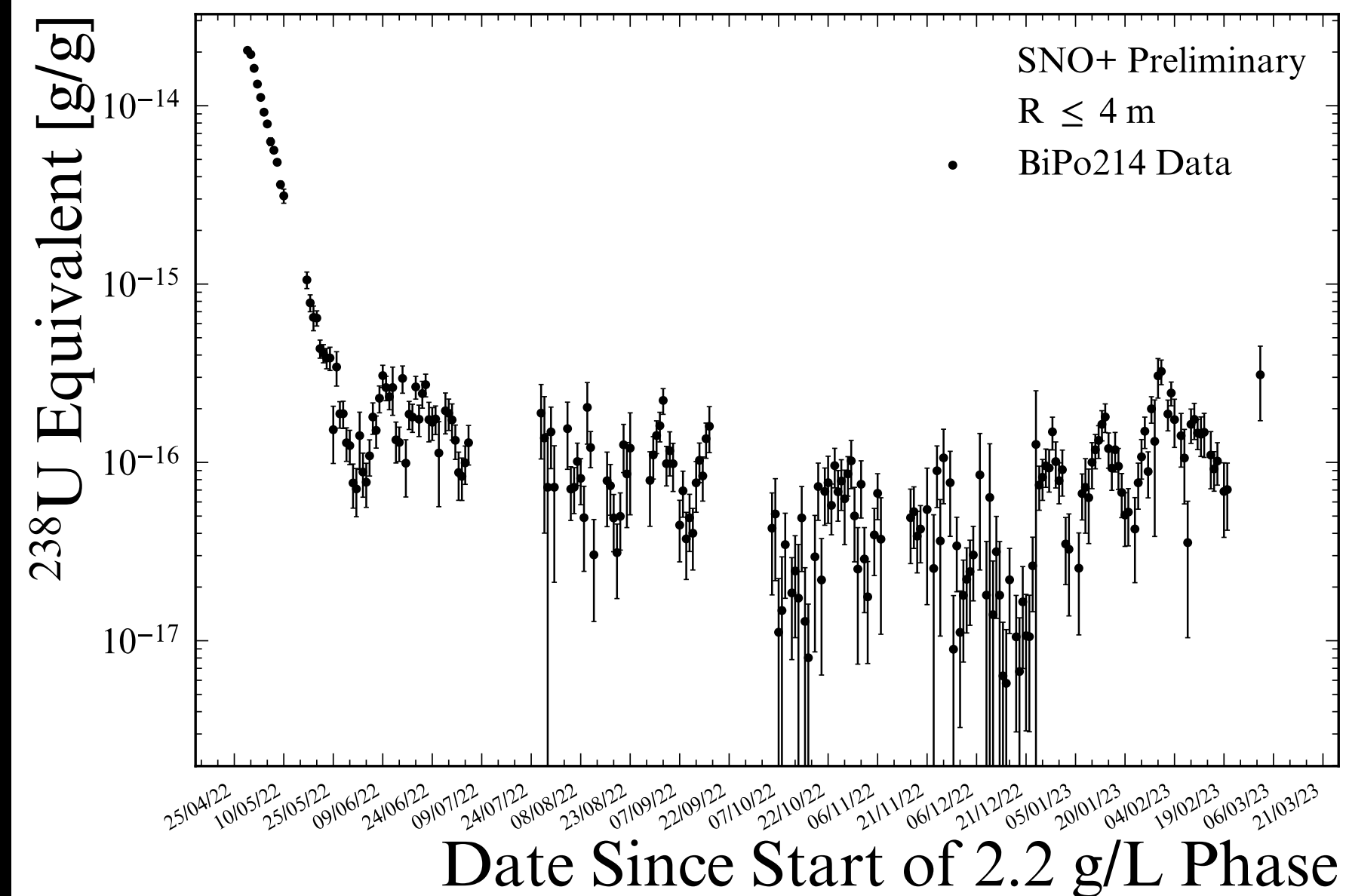


URANIUM AND THORIUM CHAINS



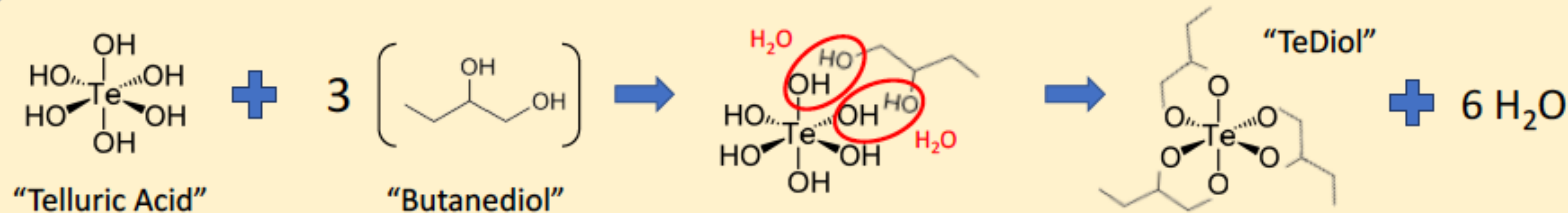
- Scintillator operations cause Radon ingress and breaking of secular equilibrium.
- But half-life is short, so plateau level measures feeding from upper chain by impurities in scintillator.
- Average levels scint phase:
 - Eq. $^{238}\text{U} \sim 4.3 \times 10^{-17} \text{ g/g}$
 - Eq. $^{232}\text{Th} \sim 5.3 \times 10^{-17} \text{ g/g}$

BELOW TARGET LEVELS!

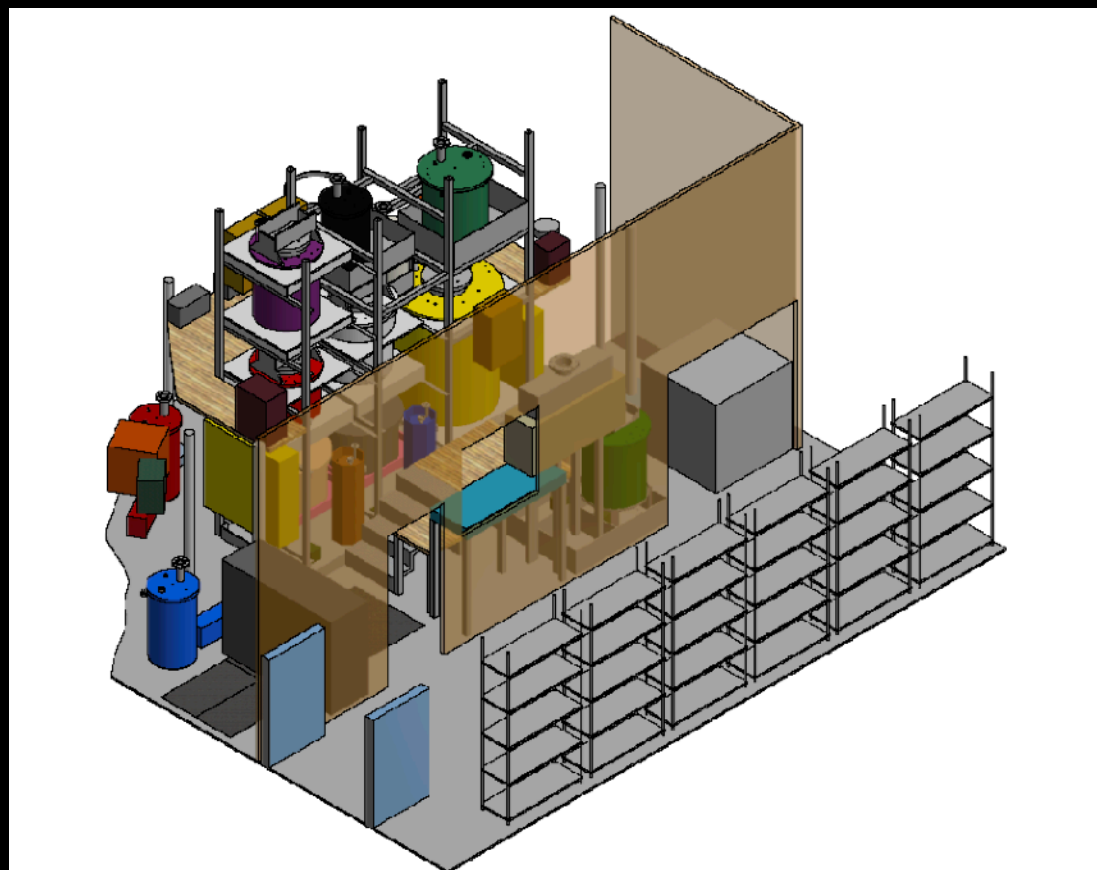


SNO+ WITH TELLURIUM

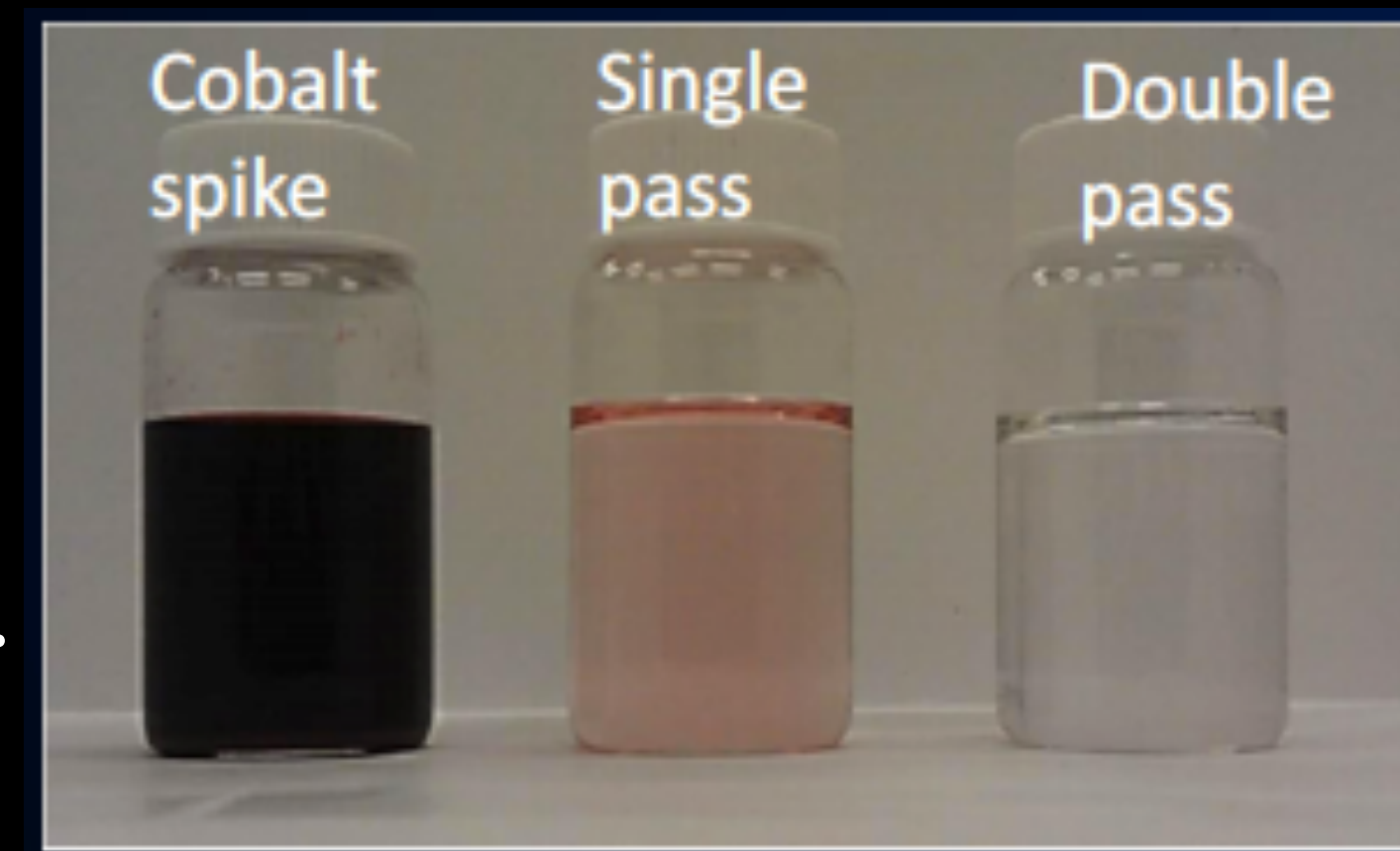
- Why Tellurium?
 - ^{130}Te is the highest natural abundance DBD isotope: 1.3 tons of ^{130}Te at 0.5% loading
- Why scintillator?
 - Purifiable, large detectors and fiducial volume -> high mass and low backgrounds!
- SNO+ developed methods to purify and load Tellurium in liquid scintillator



Tellurium-butanediol complex (TeBD)



- Underground Te acid purification plant:
 - Dissolve in water and force recrystallization
 - Impurities stay in water.

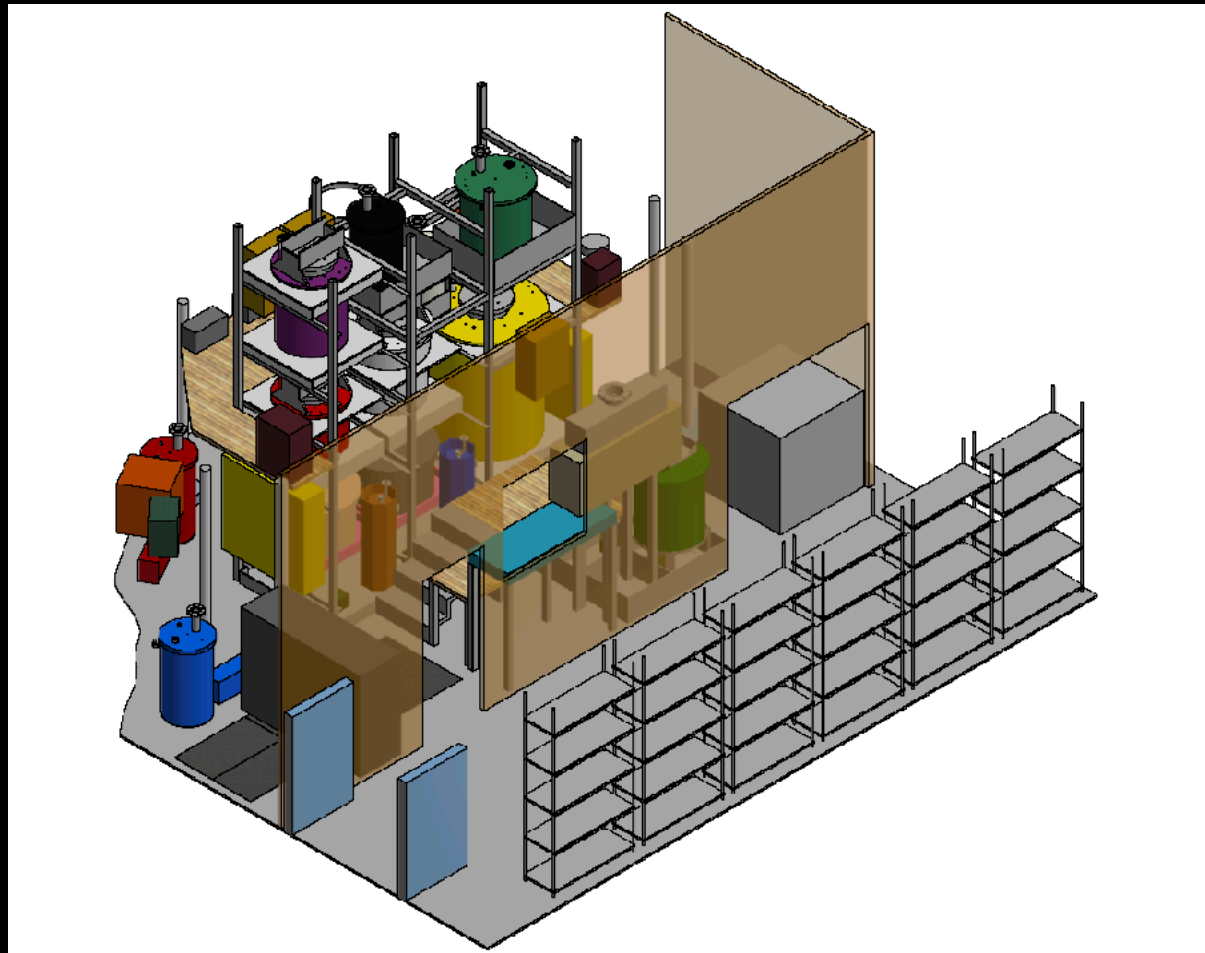


Transparent:
expect
~400 pc/MeV

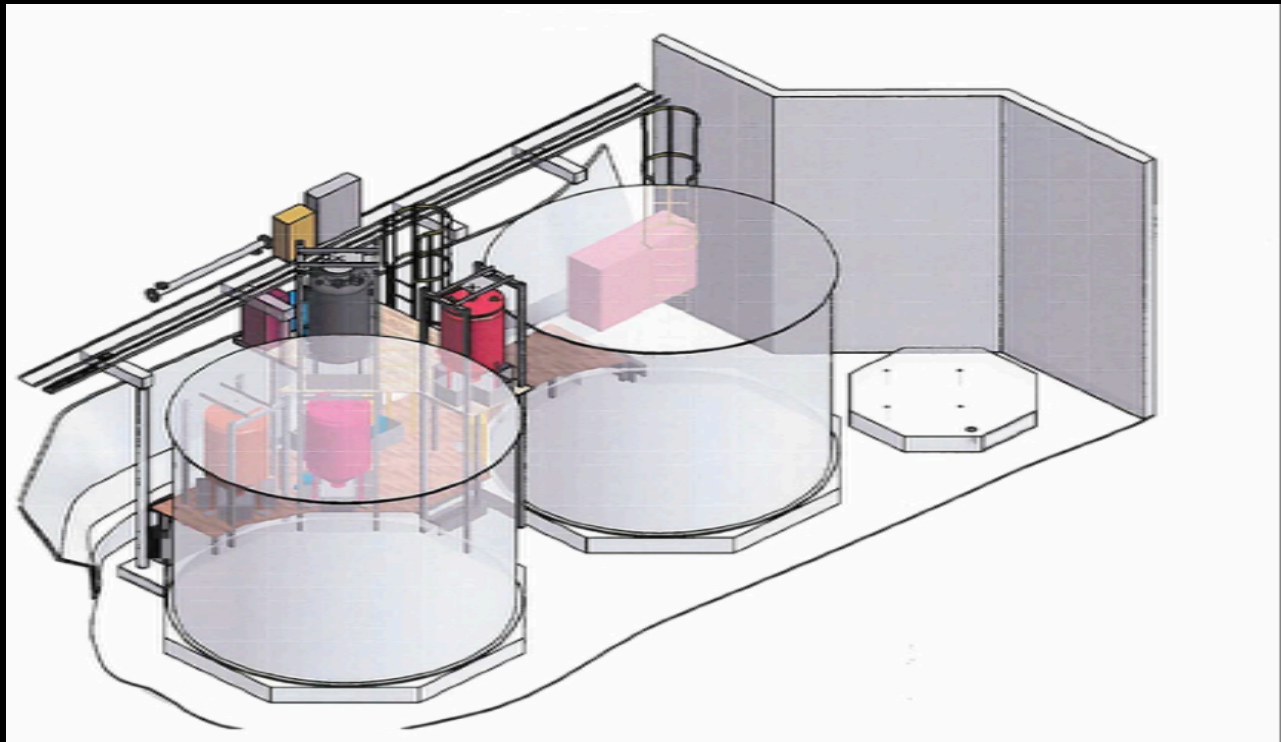
TELLURIUM SYSTEMS



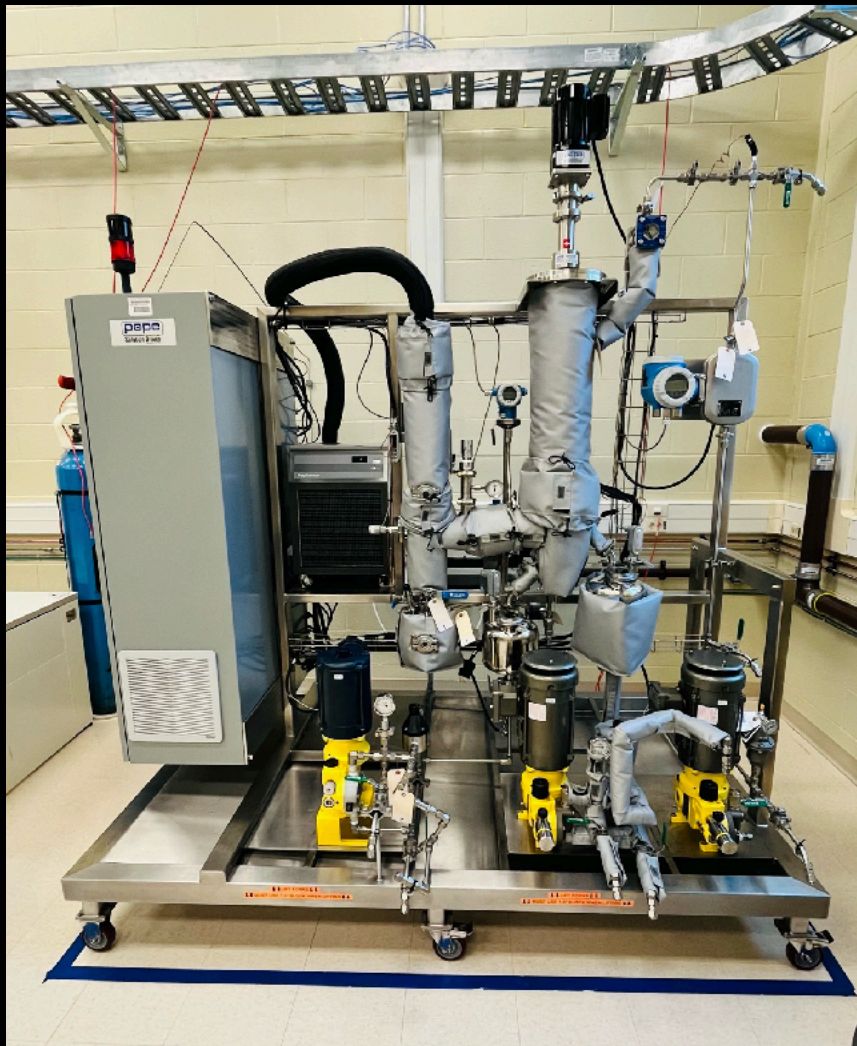
Te acid purification (UG)



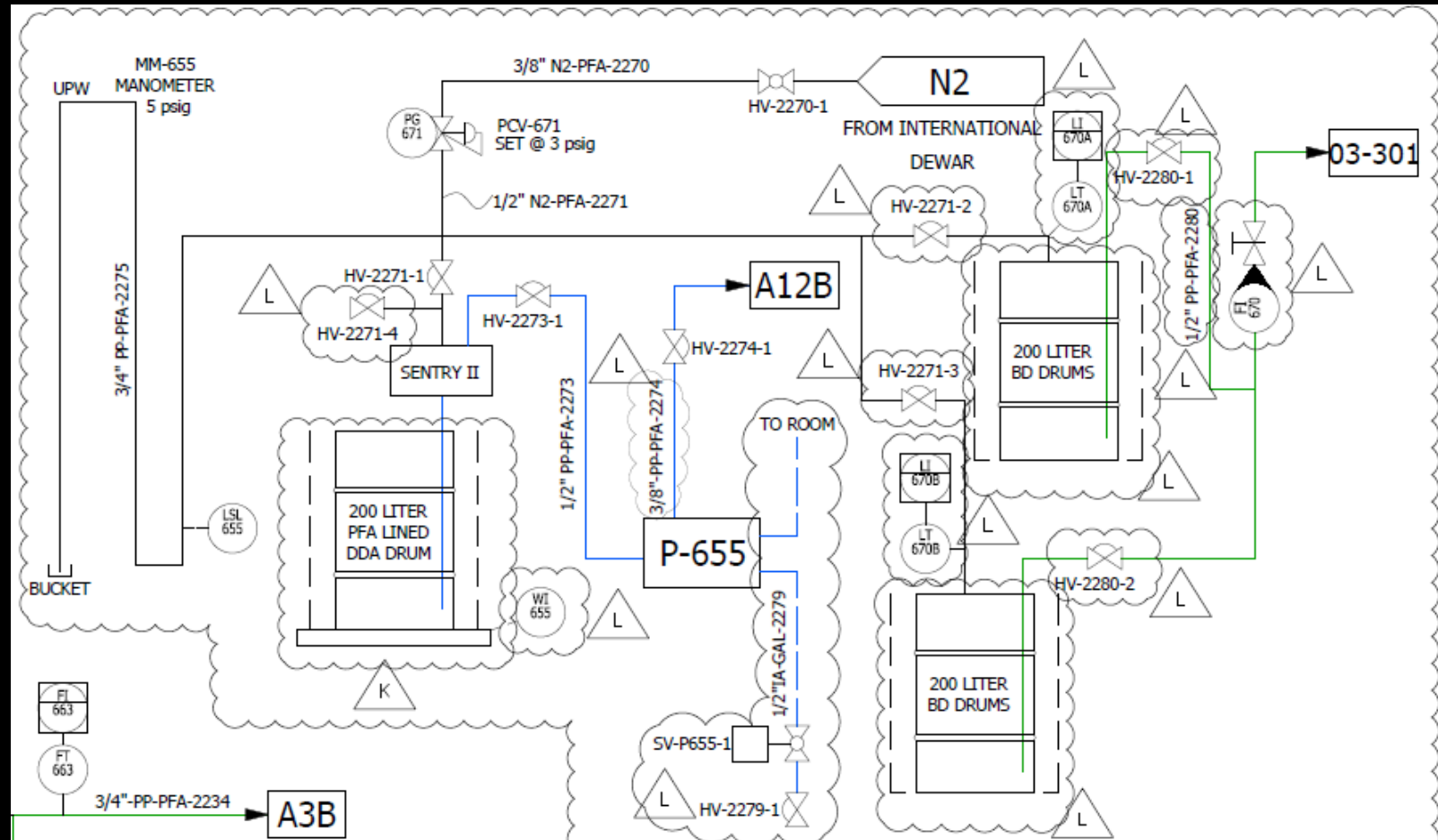
Te diol synthesis (UG)



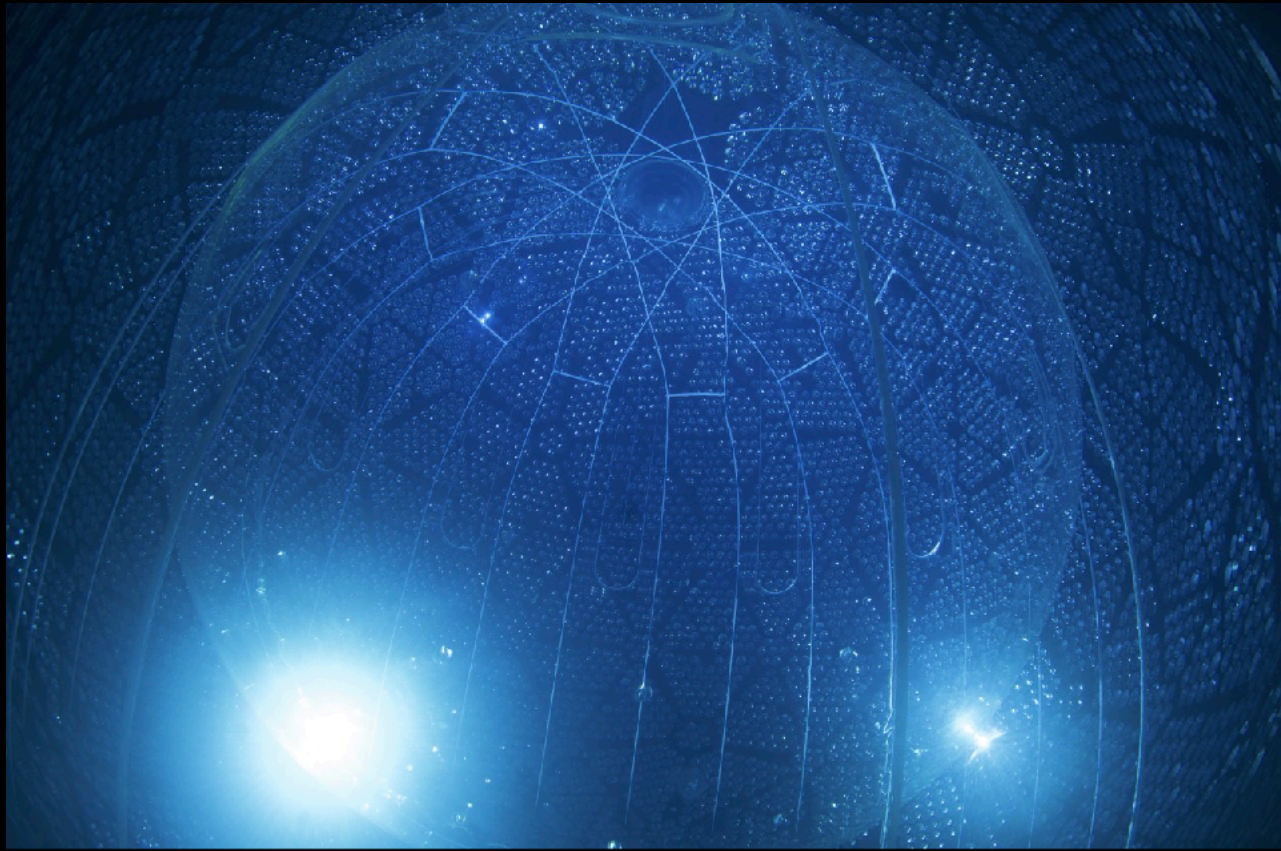
DDA distillation (surface)



DDA surface to UG transfer



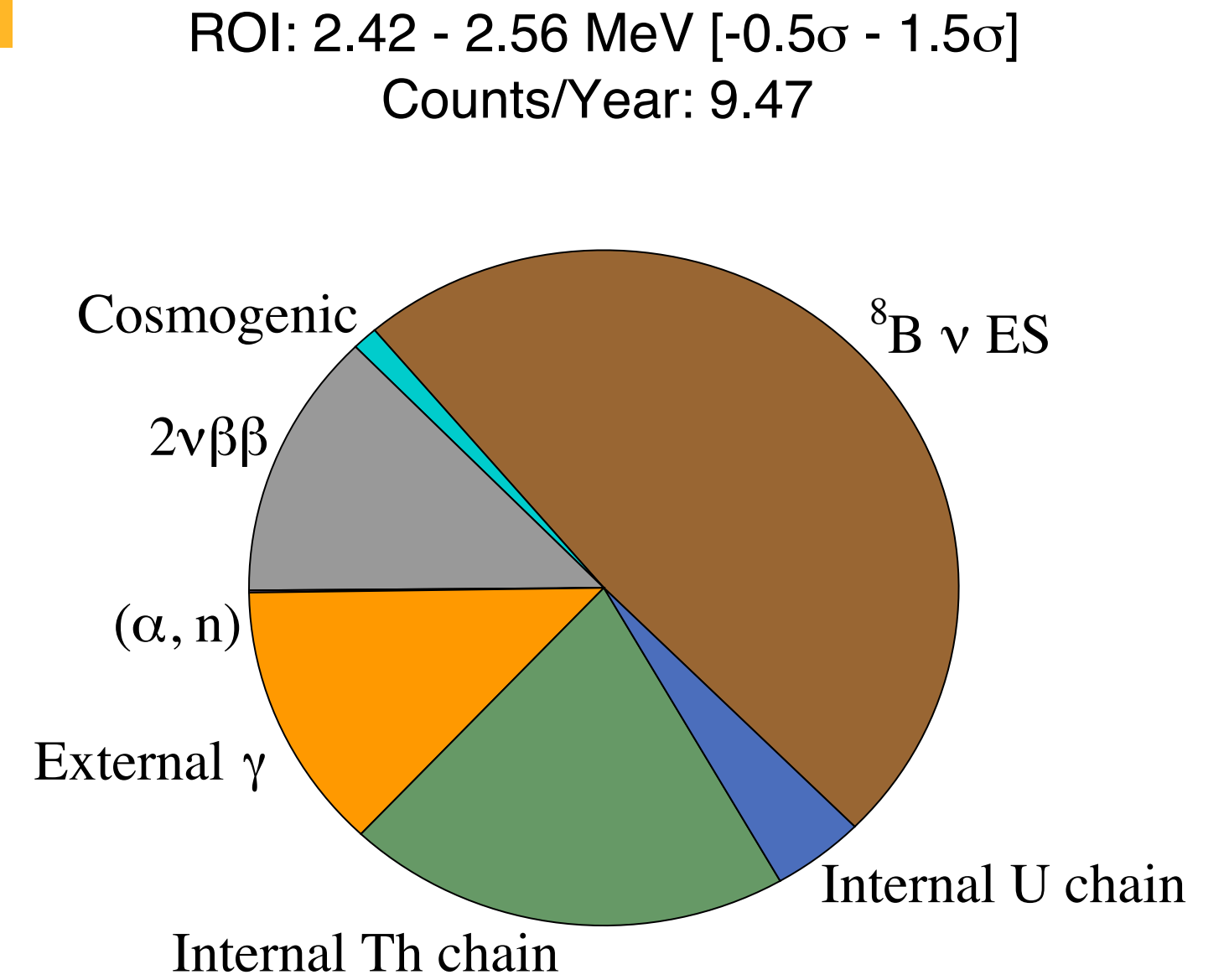
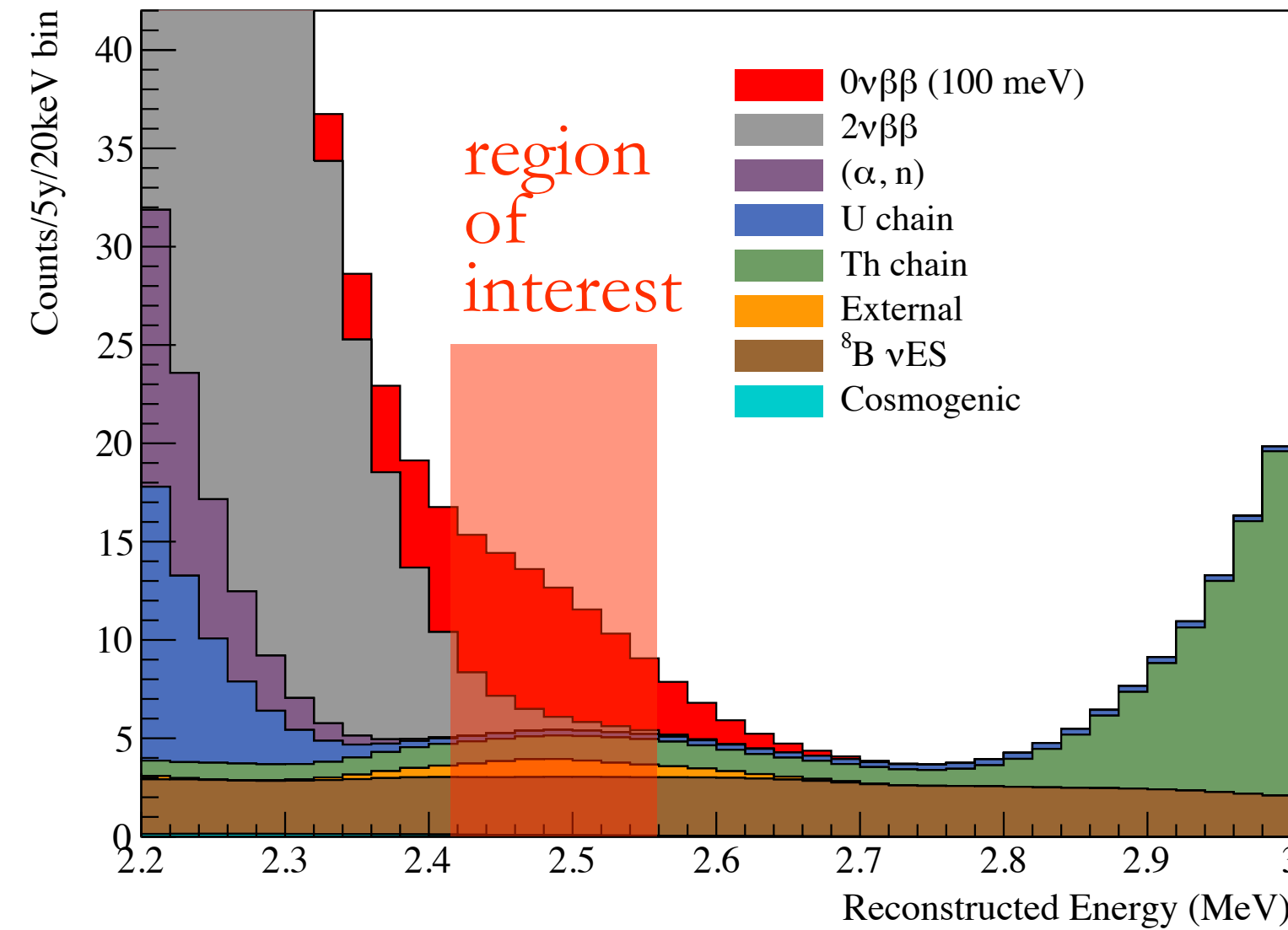
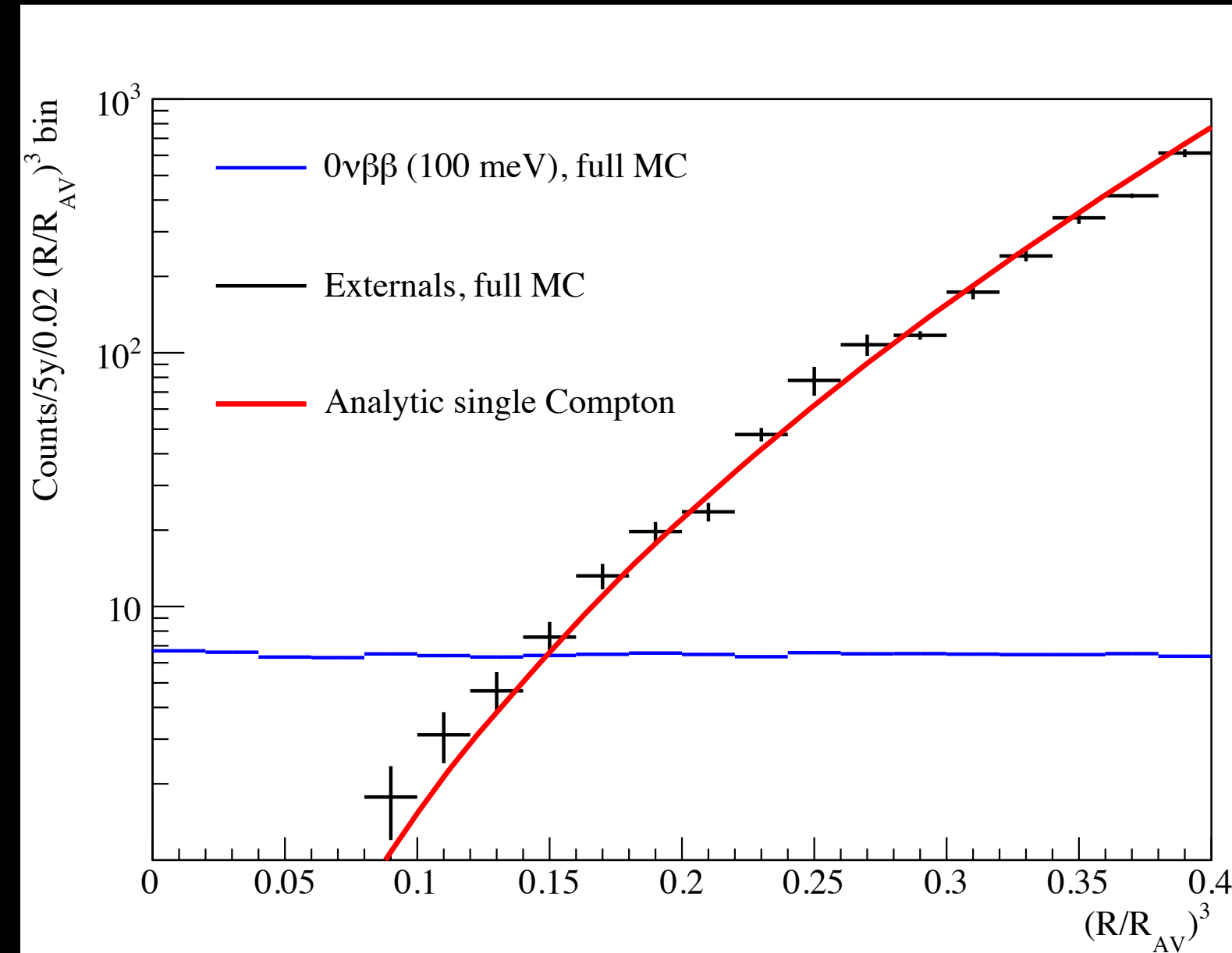
AV



SNO+ DBD SENSITIVITY



PLOTS FOR INITIAL 0.5% LOADING

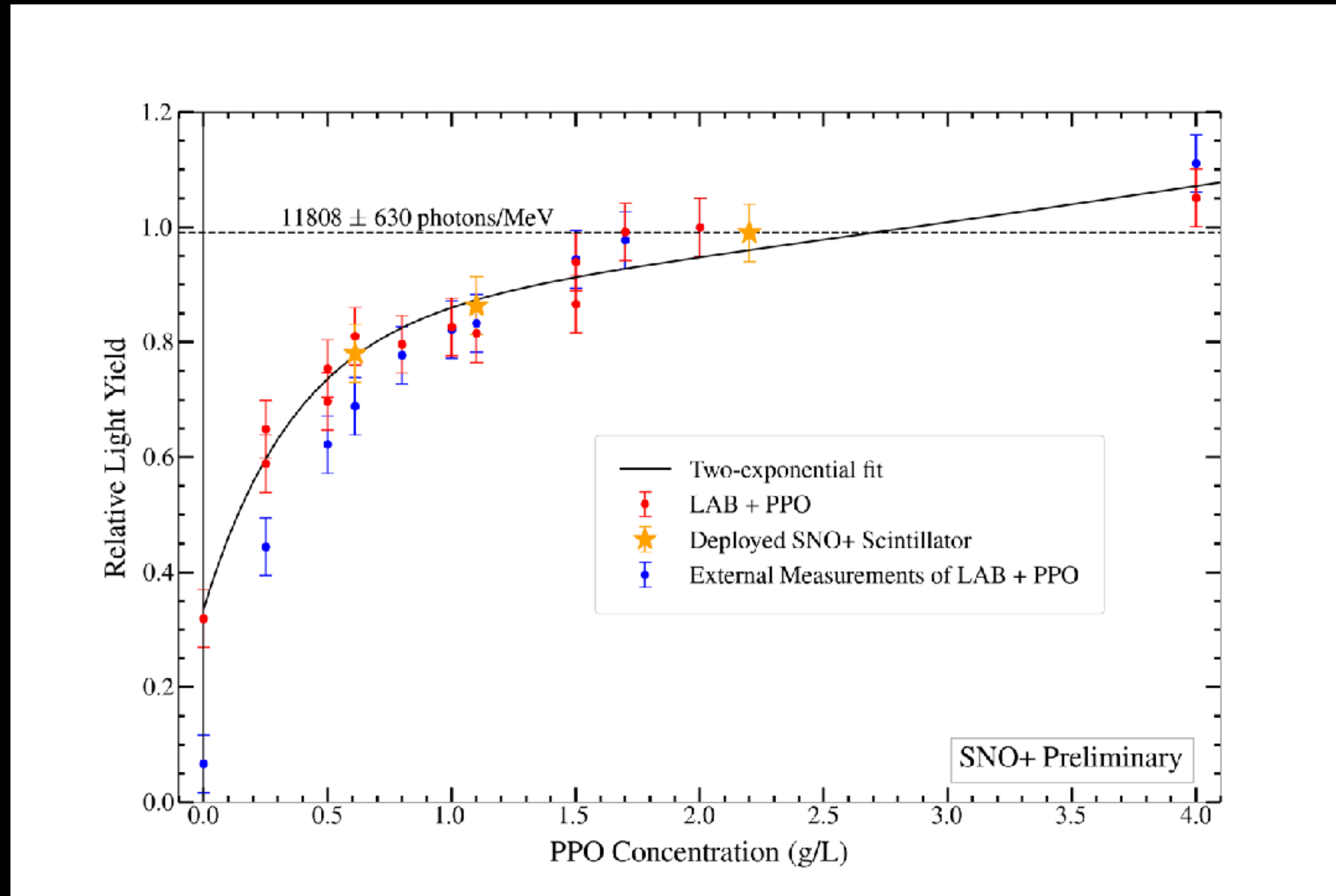


- Water phase constrained external backgrounds
- Scintillator phase constrained several internal backgrounds
- Other expectations based **conservatively** on raw purity and purification factors

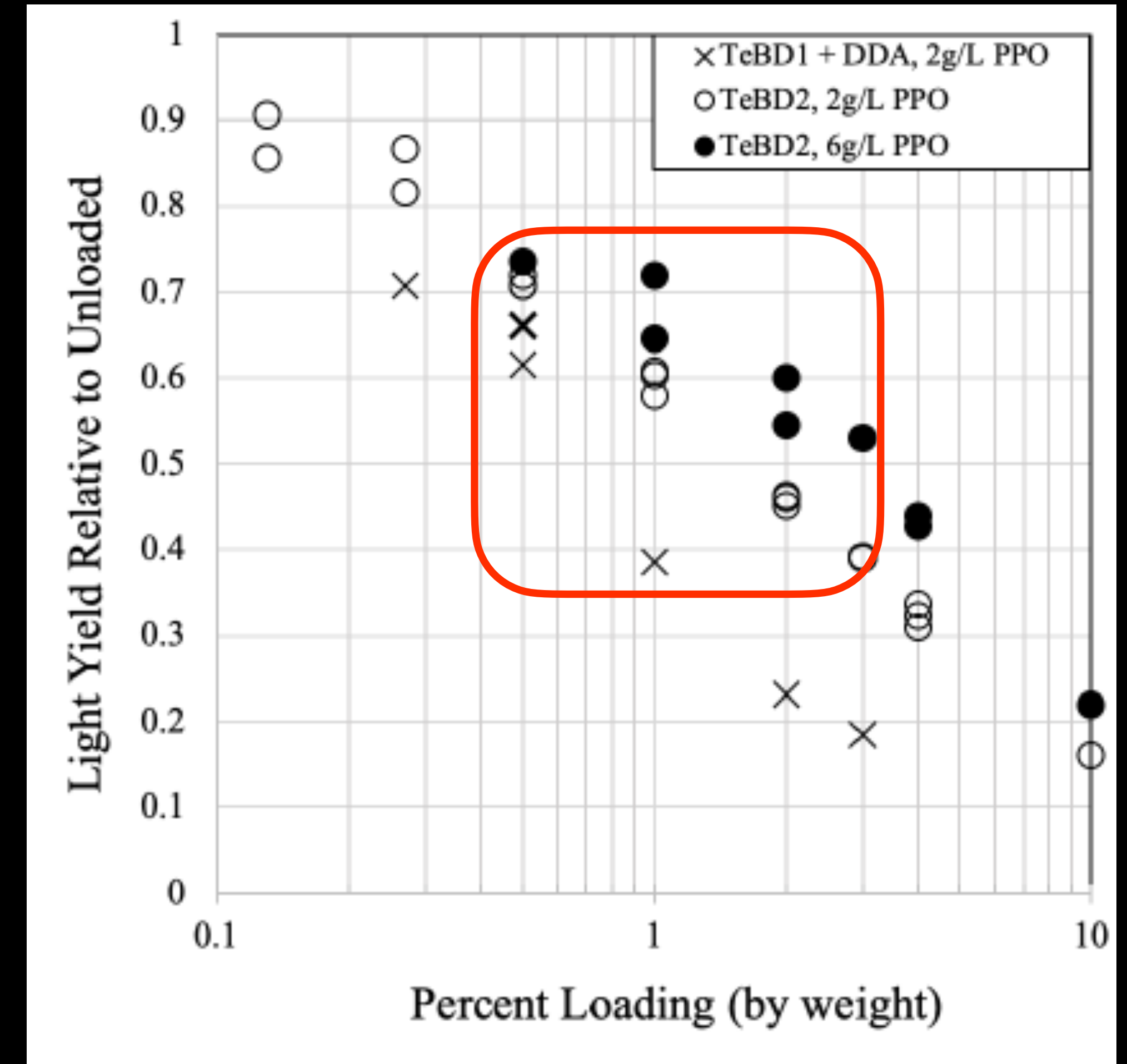
INITIAL 0.5% LOADING: $T_{1/2} > 2 \times 10^{26}$ YRS, 90% C.L., 3 YRS

FUTURE 1.5% LOADING: $T_{1/2} > 7.4 \times 10^{26}$ YRS, 90% C.L., 5 YRS

LIGHT YIELD, HIGHER LOADINGS

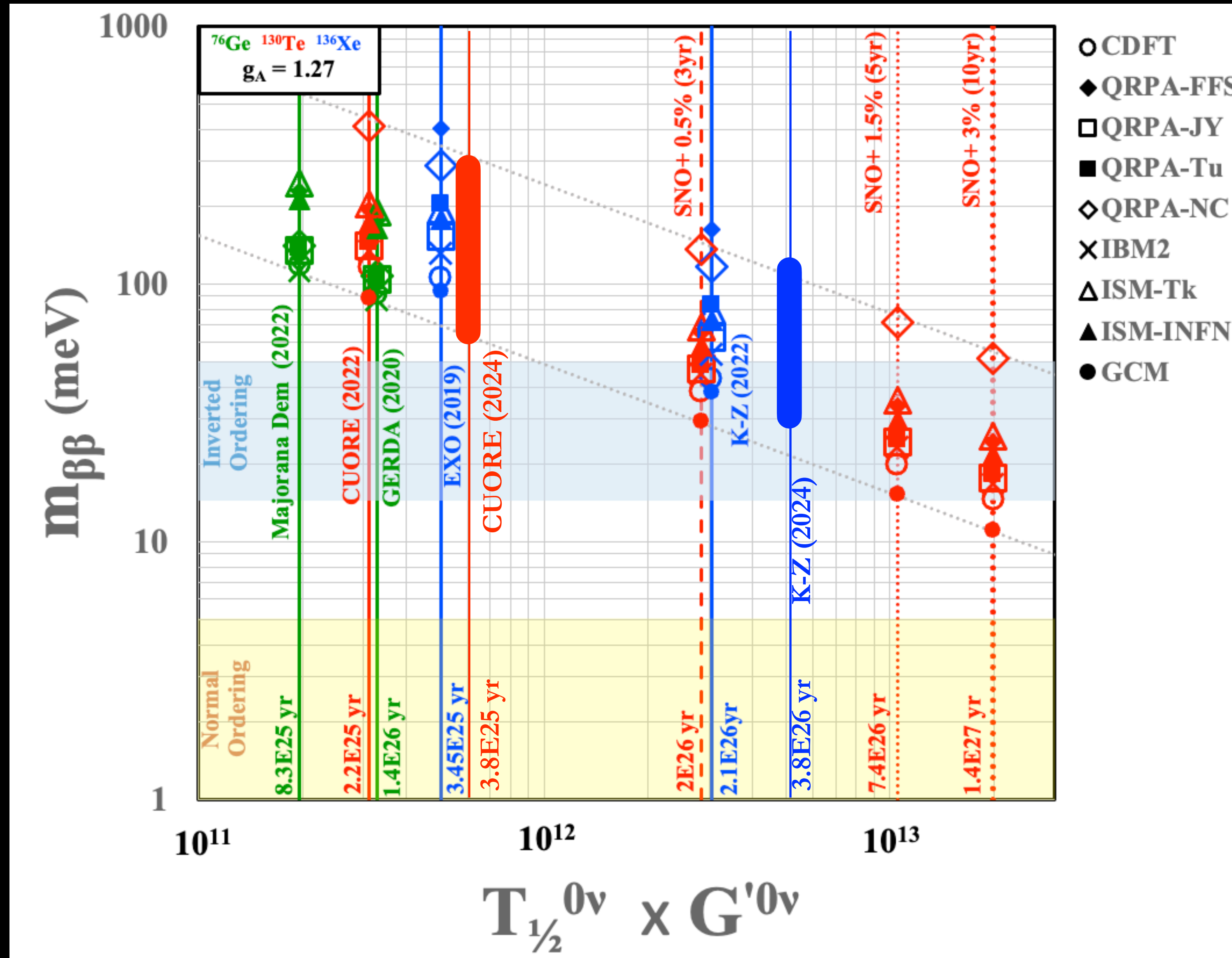


Light yield measured in the detector,
scaling with PPO levels



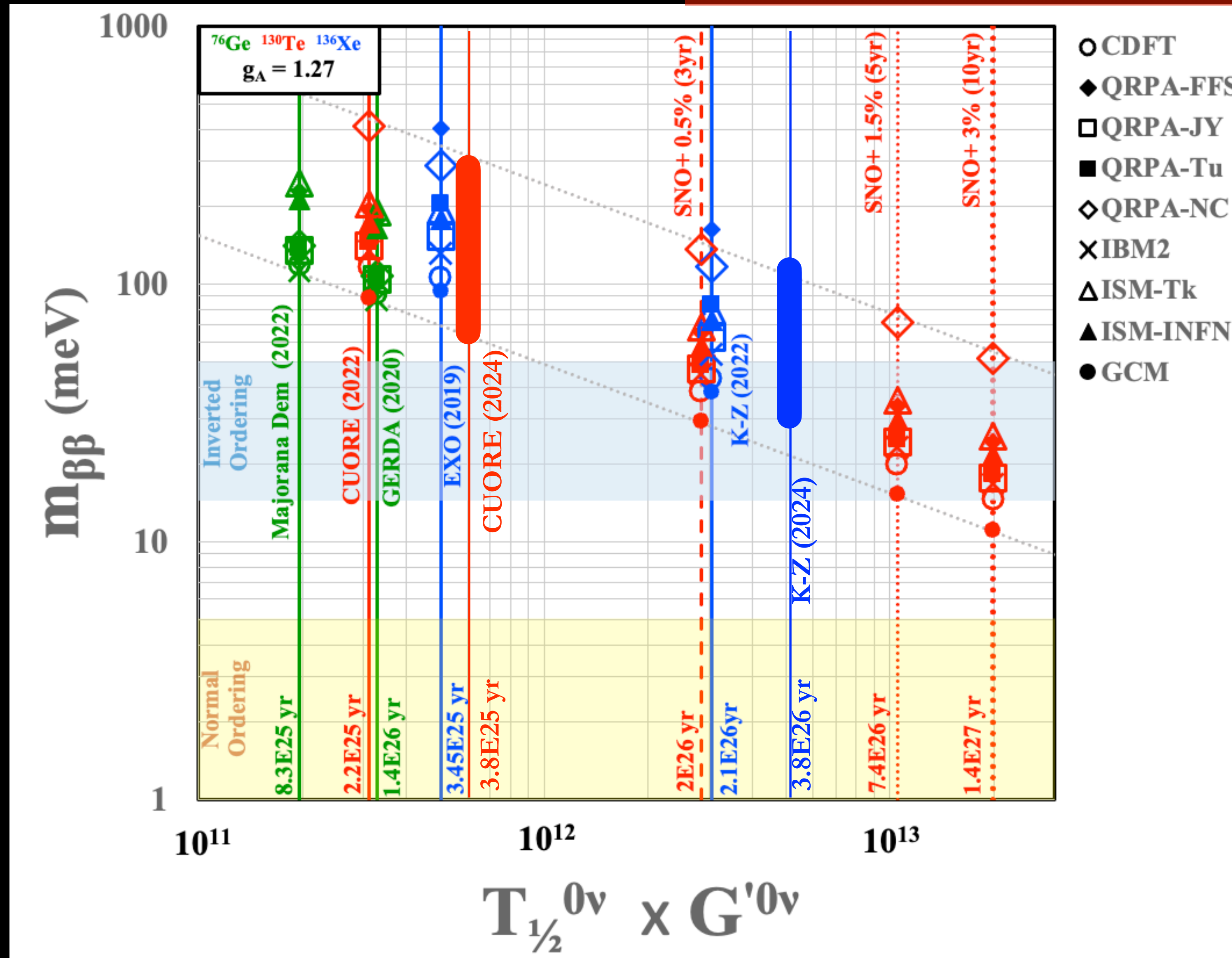
LY can reach 60% of unloaded LS,
even at 2% loading

SNO+ IN CONTEXT



SNO+ IN CONTEXT

AFTER CUORE STOPS, SNO+ WILL
LIKELY ACHIEVE THE WORLD-LEADING
130TE SENSITIVITY

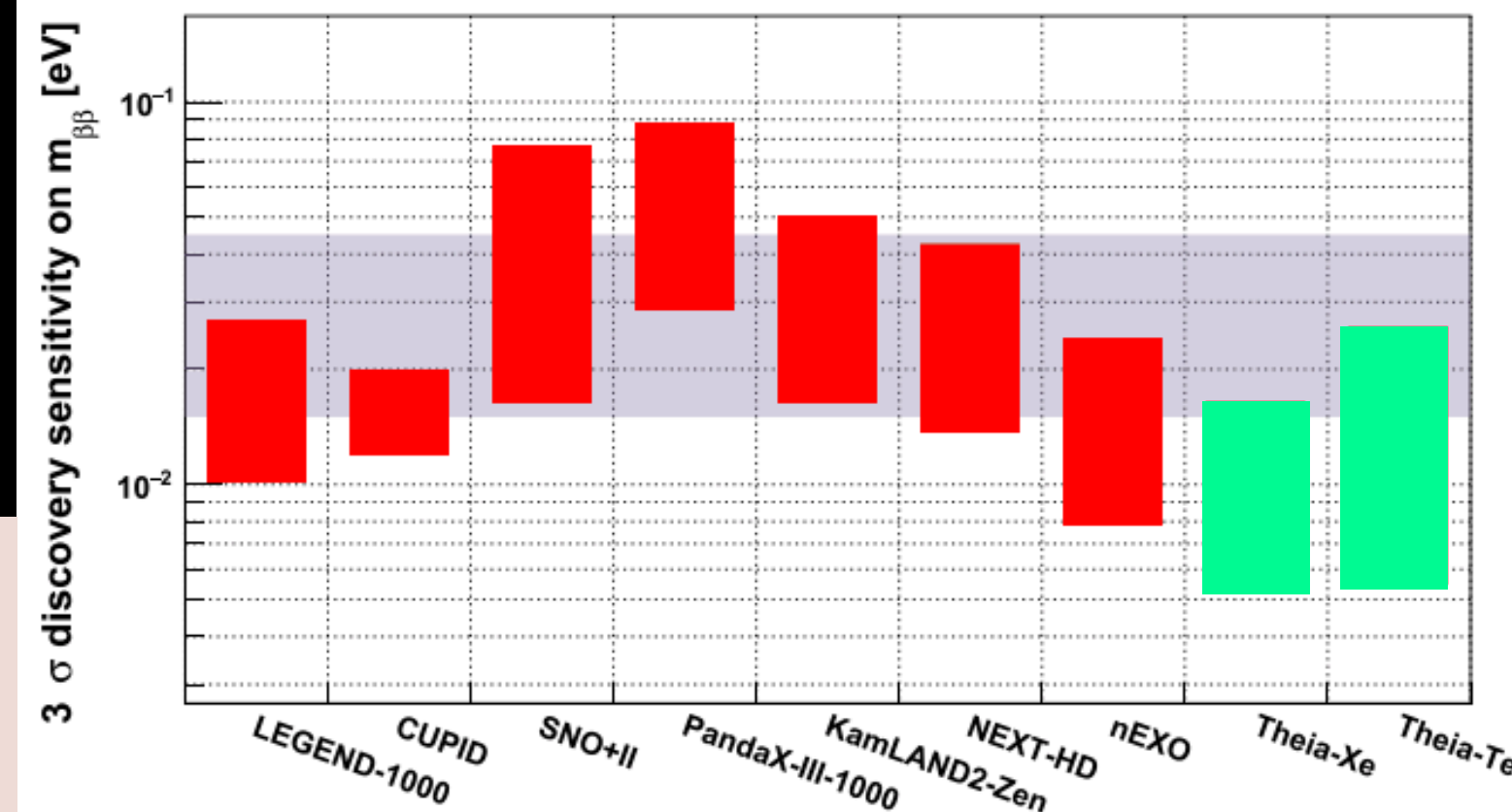
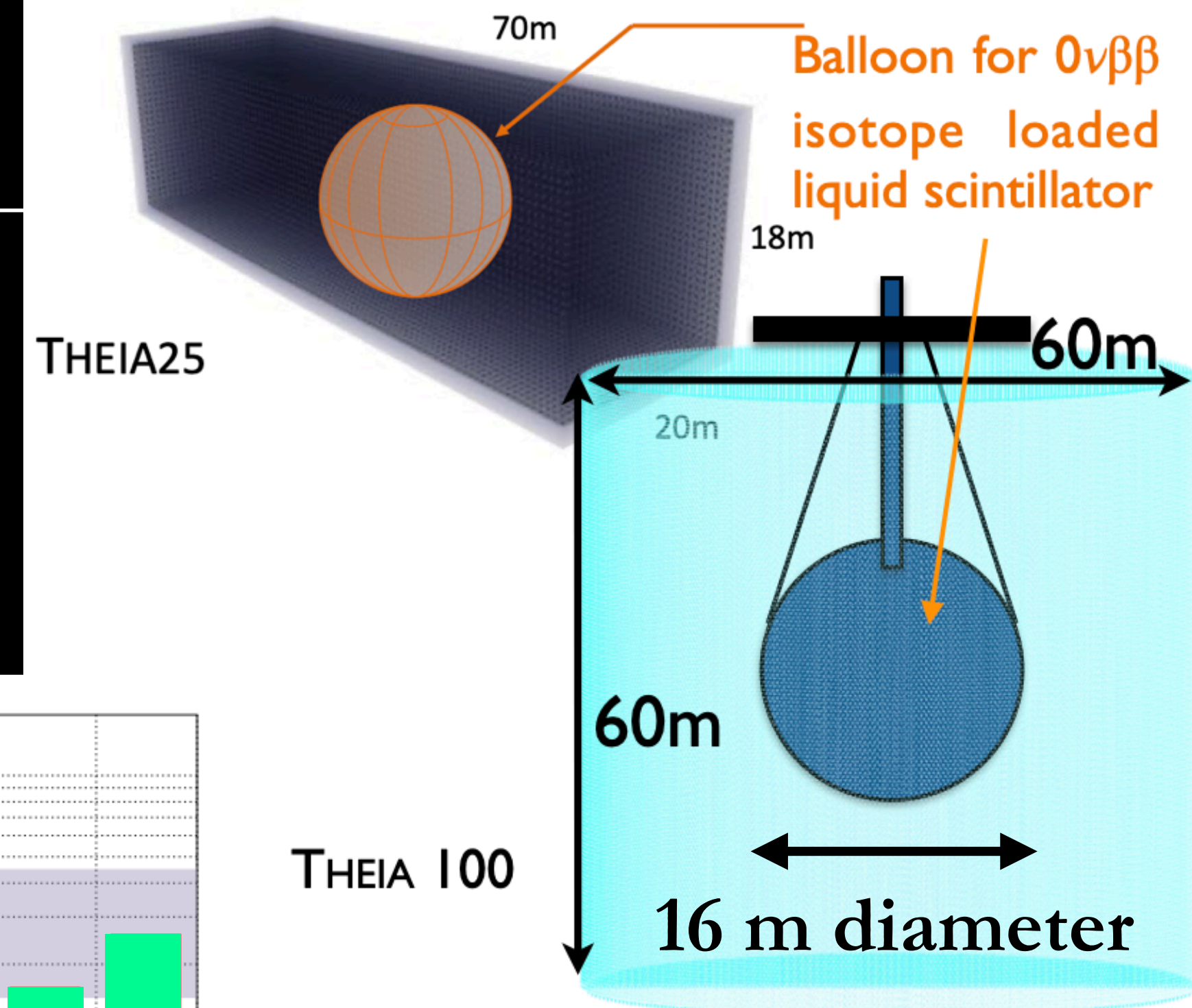


FUTURE PROJECTS

THEIA

THANKS TO G. OREBI GANN

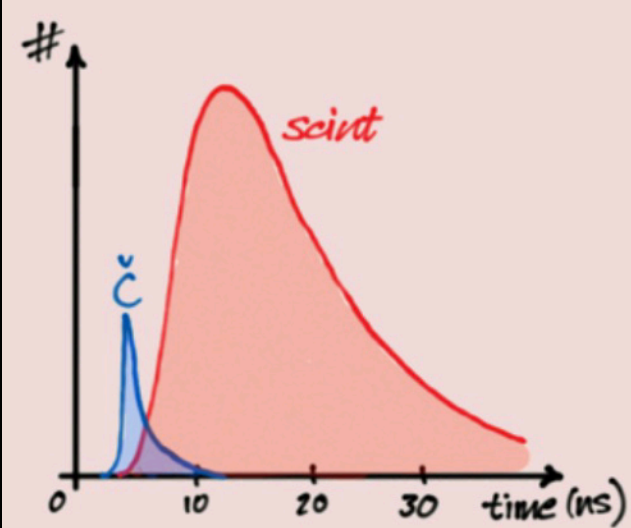
- Scalable Hybrid Cherenkov / scintillation detector
- Ultra-clean + Background rejection via PID, event topology, directionality
- Theia25: 25-kton Theia module at LBNF
- Theia100: 100 kton
- Broad program of other physics



EPJC V.80: 416 (2020)

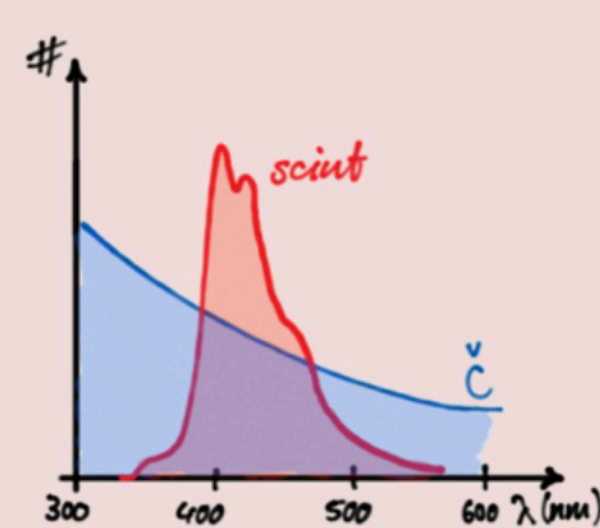
Timing

“instantaneous chertons”
vs. delayed “scintons”
→ ns resolution or better



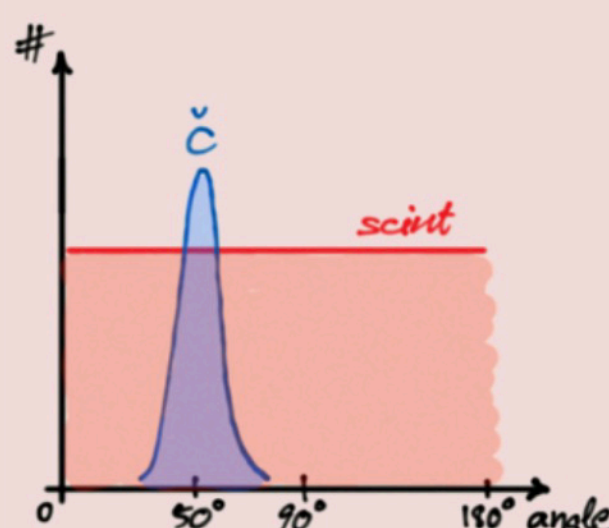
Spectrum

UV/blue scintillation vs.
blue/green Cherenkov
→ wavelength-sensitivity



Angular distribution

increased PMT hit density
under Cherenkov angle
→ sufficient granularity



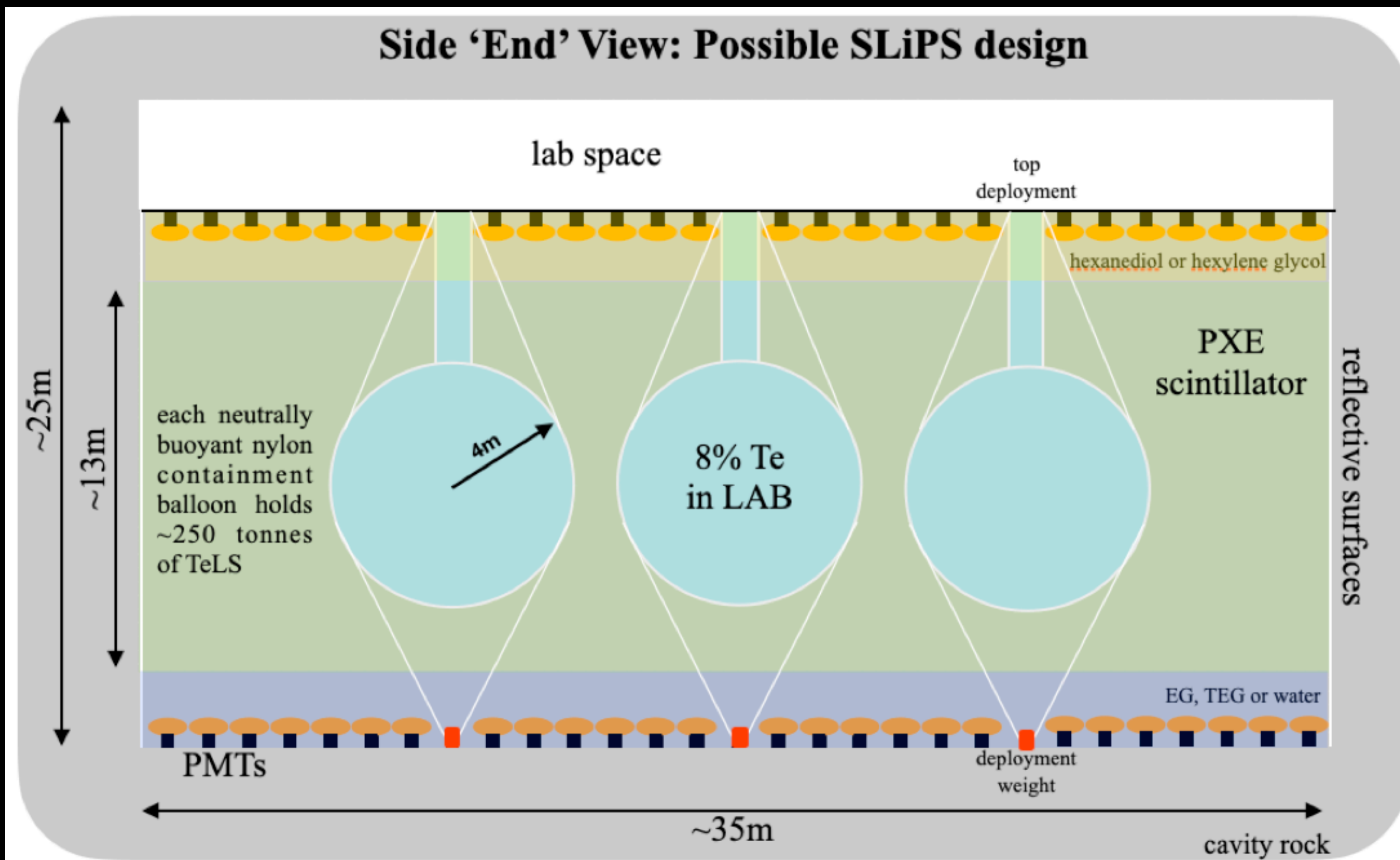
- NLDBD search at Theia100, 10yrs
- Te@5% $T_{1/2}^{0\nu} > 1.1 \times 10^{28} \text{ yr}$
- Xe@3% $T_{1/2}^{0\nu} > 2.0 \times 10^{28} \text{ yr}$
- Mass sensitivity of $\sim 4 - 22 \text{ meV}$:
normal ordering!!

OTHER IDEAS

- Higher loadings of Tellurium in LS
 - cost much lower than Xe or Ge
 - however, light attenuation worsens at higher loadings
- Explore new detector configurations less sensitive to attenuation: SLiPS
- Sensitivity obviously very dependent on total mass. Aiming for $T_{1/2}^{0\nu} > 1 \times 10^{28} \text{yr}$

THANKS TO S. BILLER

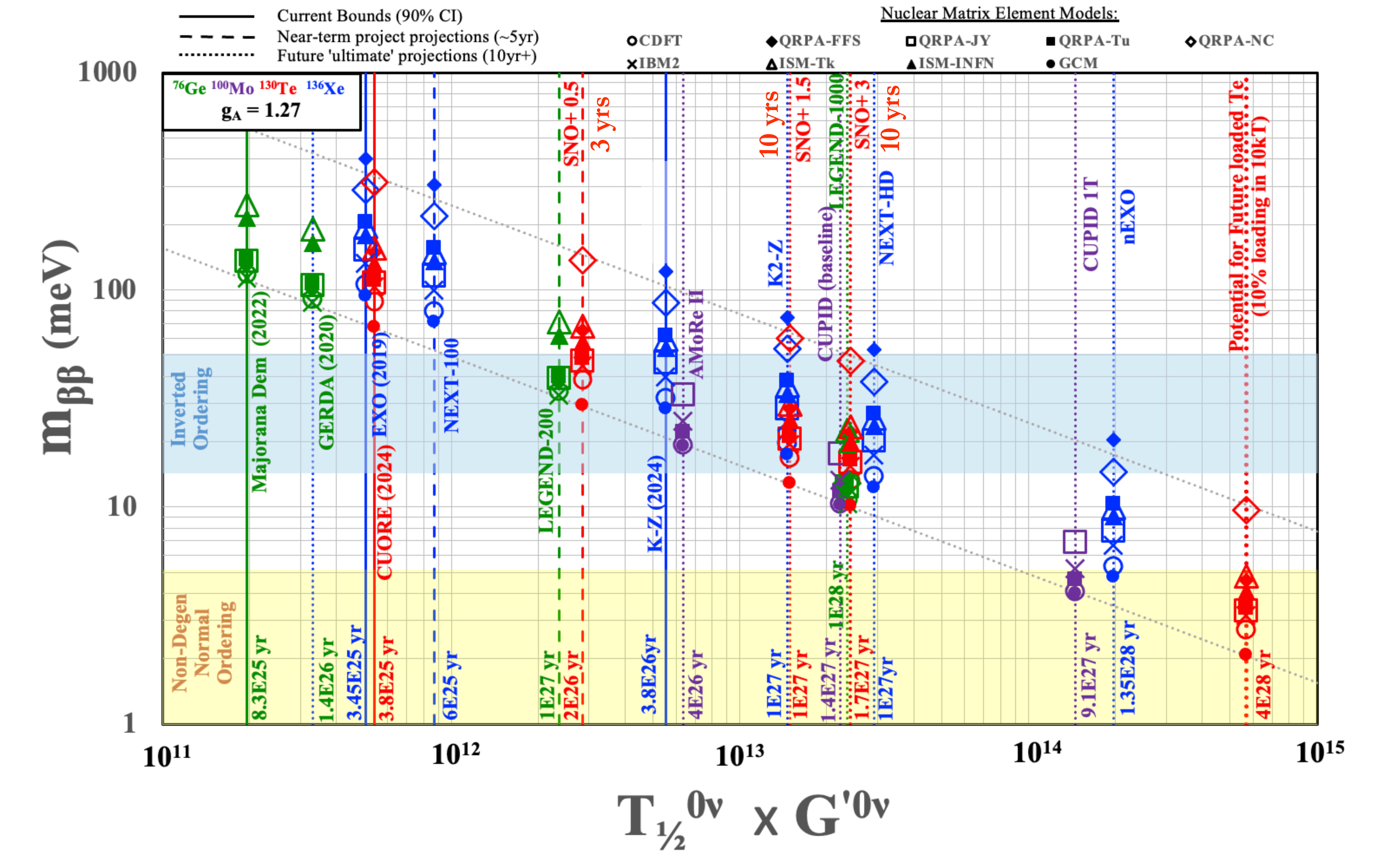
PHYS.REV.D 105 (2022) 7, 072003



More?

SEE NUDOUBT++ TALK
BY S. SCHOPPMAN

A LONG WAY TO GO ...



CONCLUSIONS

- Neutrinoless double beta decay a very high priority search
 - Complementary to CP violation searches in neutrino oscillations
- Liquid scintillator technique has many advantages
 - High mass, low backgrounds, scalability, target-out measurements
 - KamLAND-Zen beautifully demonstrated this, with current leading limit
 - improvements are coming...
- SNO+ is already taking high quality liquid scintillator data
 - soon, will start the DBD phase and reach the best ^{130}Te sensitivity
 - it has developed the LS technique with the highest natural abundance isotope, opening the way for bigger, future detectors

SNO+ COLLABORATION



Supported by FCT, Portugal , project
PTDC/FIS-PAR/2679/2021

EXTRA SLIDES

PREVIOUS RESULTS

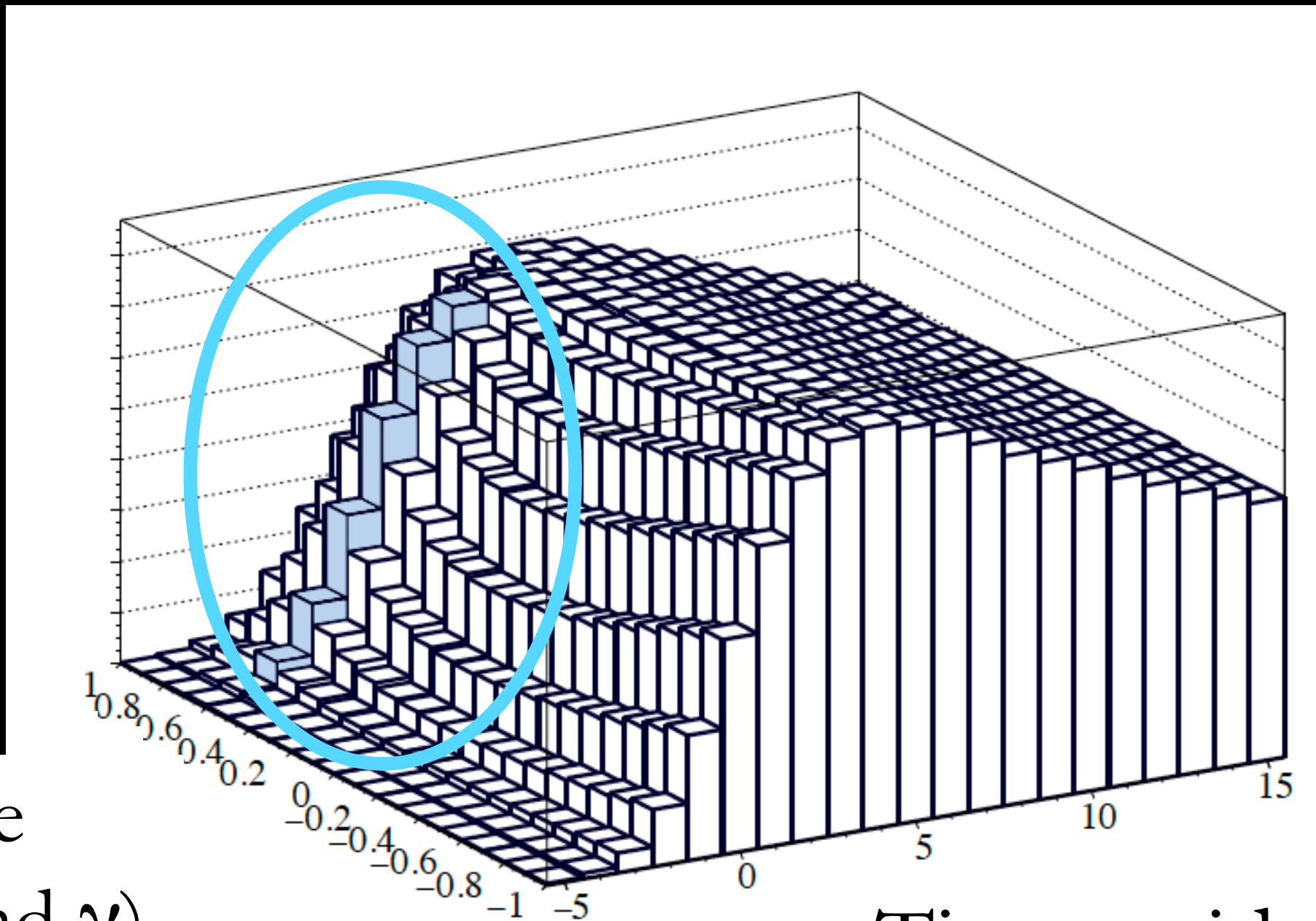
DIRECTIONALITY IN SCINTILLATOR



SNO+ Collab., Phys.Rev.D 109 (2024) 7, 072002

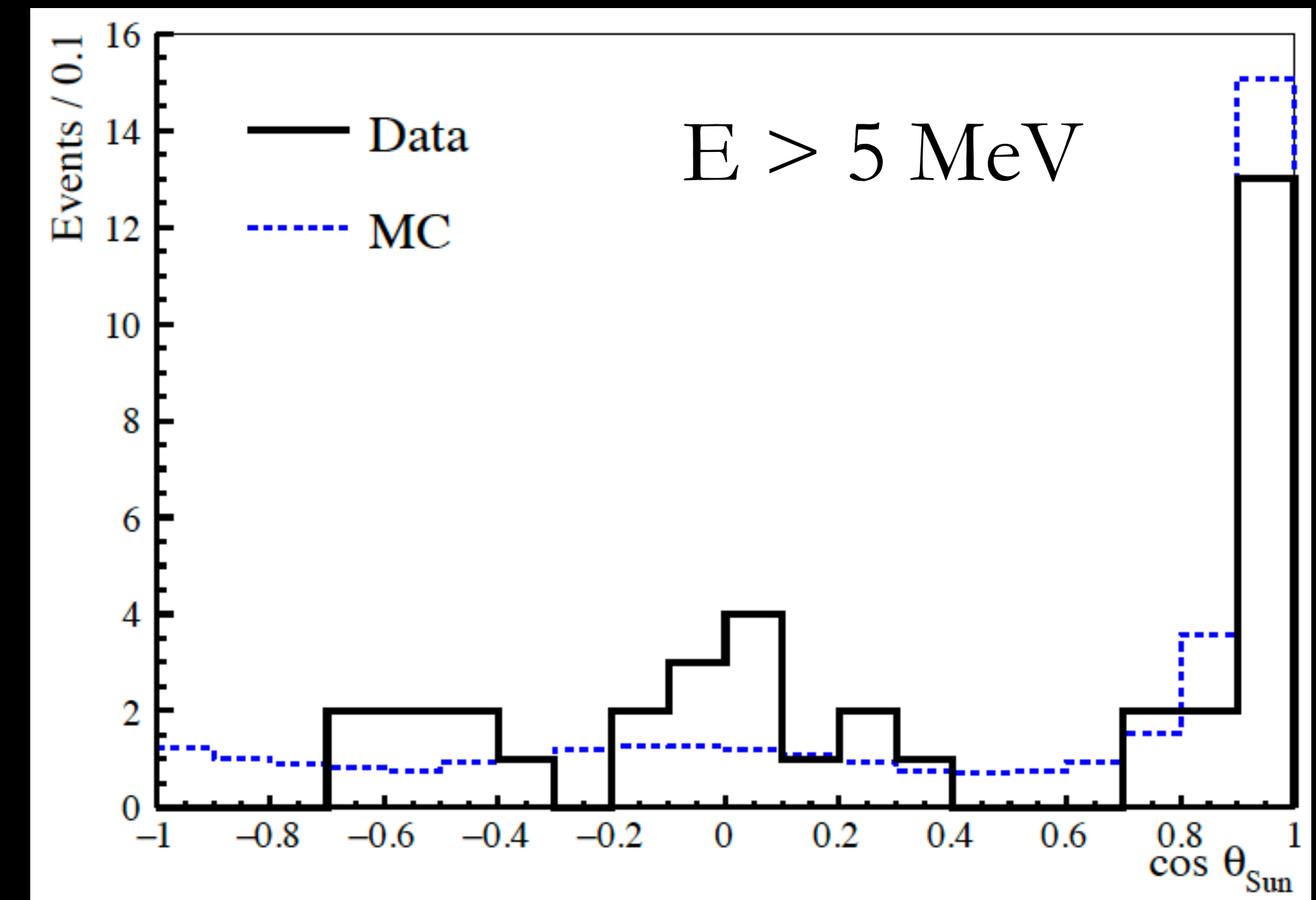
- Slow scintillation leads to good separation between Cherenkov and scintillation photons
- Early data with low PPO (0.6 g/L)
 - Reasonable light yield (300 pe/MeV)
 - Slow timing $\tau = 13.5$ ns (first comp.)

- ^8B solar neutrino analysis
- Data from partial fill and early scint phases (23 and 15 kt-days)



cos (angle
b/w e^- and γ)

Time residual (ns)

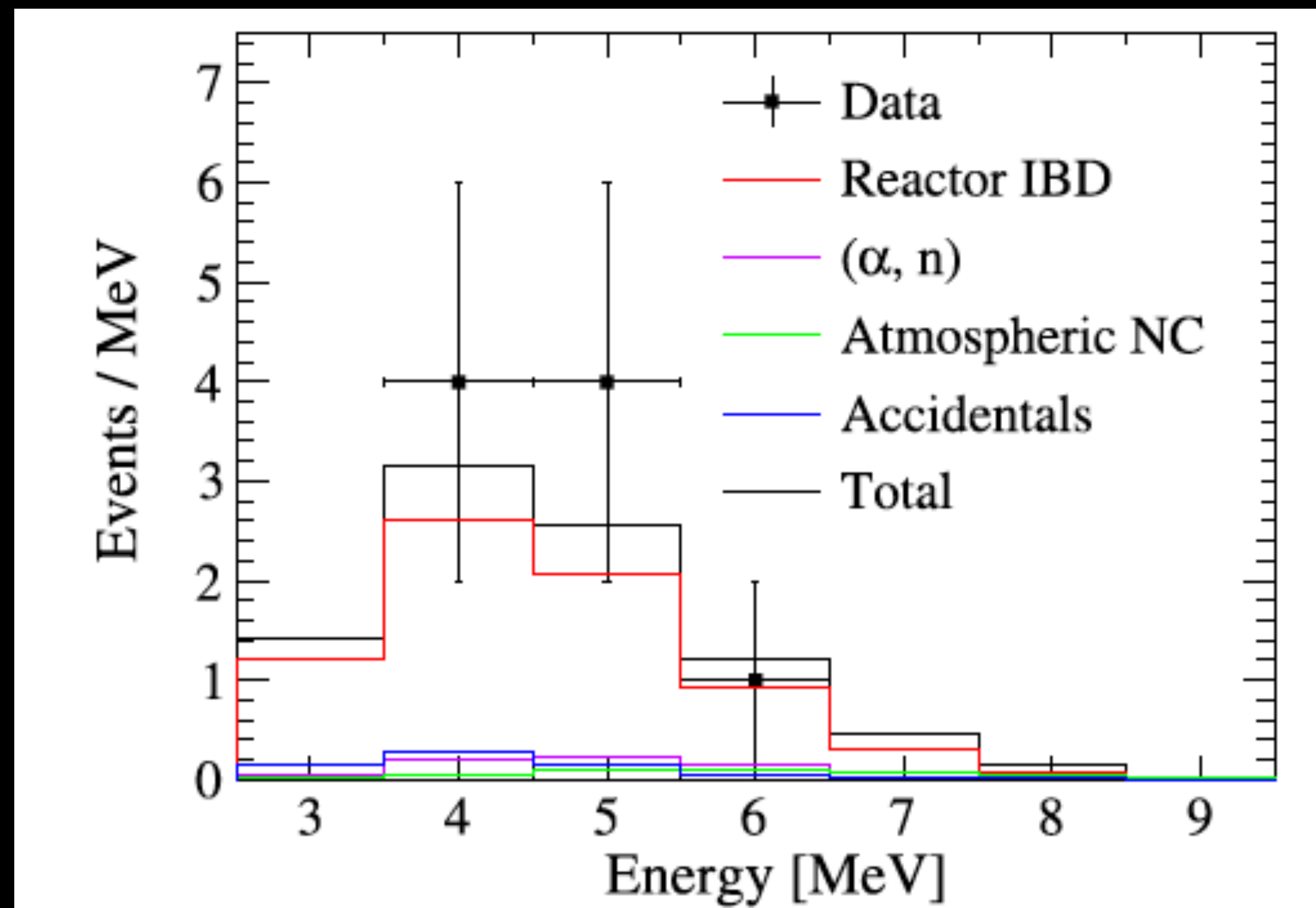


- First event-by-event reconstruction of direction in high light yield scintillator !

REACTOR NEUTRINOS IN WATER



- SNO+ exploited good trigger and light collection performance
- Detected 2.2 MeV gammas from neutron capture, in coincidence with prompt signal. AmBe source calibration showed neutron efficiency of 50%
- First detection of antineutrinos from far reactors with a water Cherenkov detector



Physics ABOUT BROWSE PRESS COLLECTIONS Search articles

Reactor Neutrinos Detected by Water

March 1, 2023 • Physics 16, s28

Researchers have captured the signal of neutrinos from a nuclear reactor using a water-filled neutrino detector, a first for such a device.

SYNOPSIS

PDF Version

Evidence of Antineutrinos from Distant Reactors Using Pure Water at SNO+
A. Allega *et al.* (The SNO+ Collaboration)
Phys. Rev. Lett. **130**, 091801 (2023)
Published March 1, 2023

Recent Articles

A Cleaner Route to Steel Production
Researchers have investigated how pores in a solid change its chemical reactions with other materials. The result could make steel production more environmentally friendly.

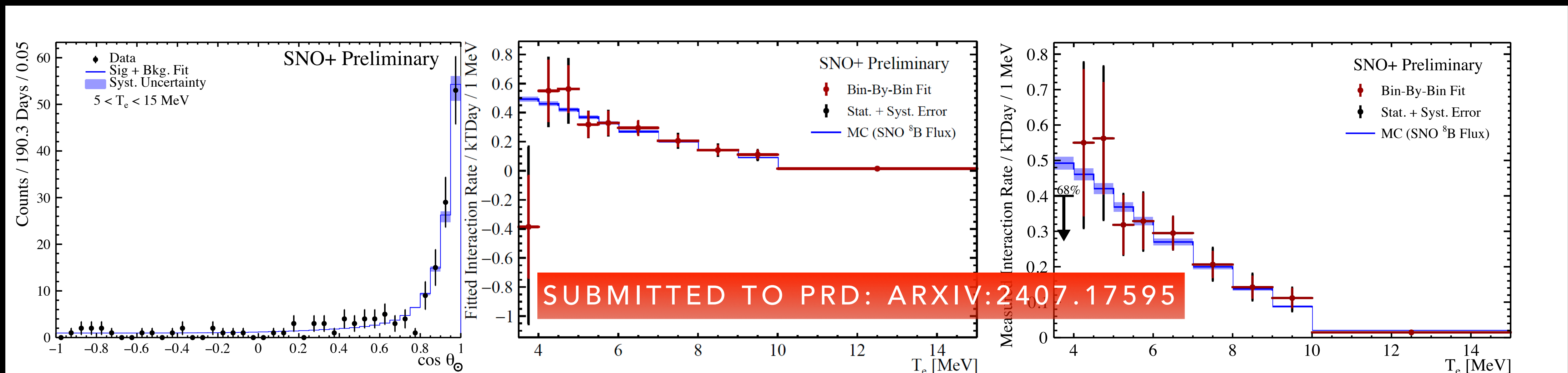
A New Card up Graphene's Sleeve
Graphene is found to exhibit a magnetoresistance dwarfing that of all known materials at room

NEW RESULTS

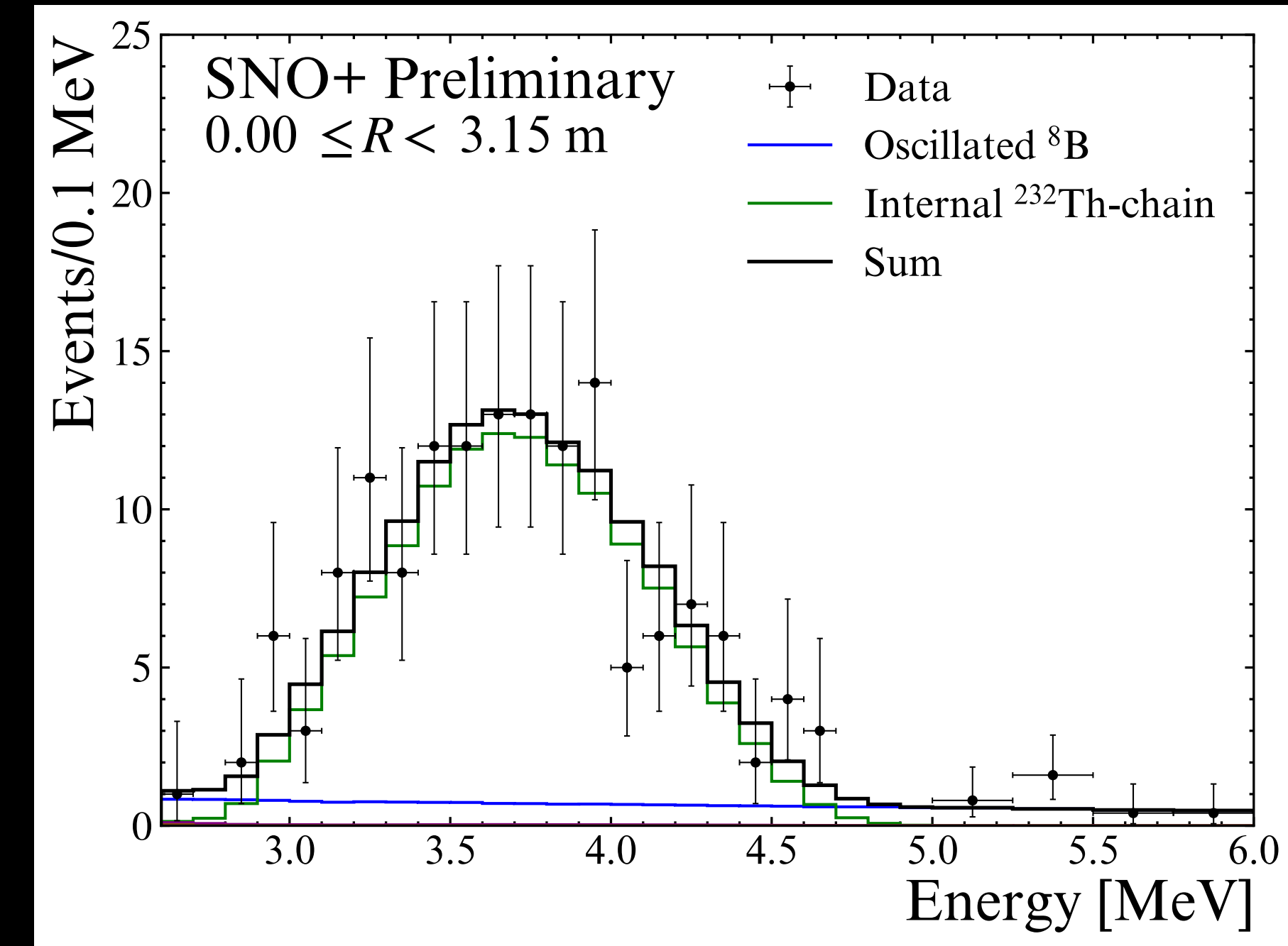
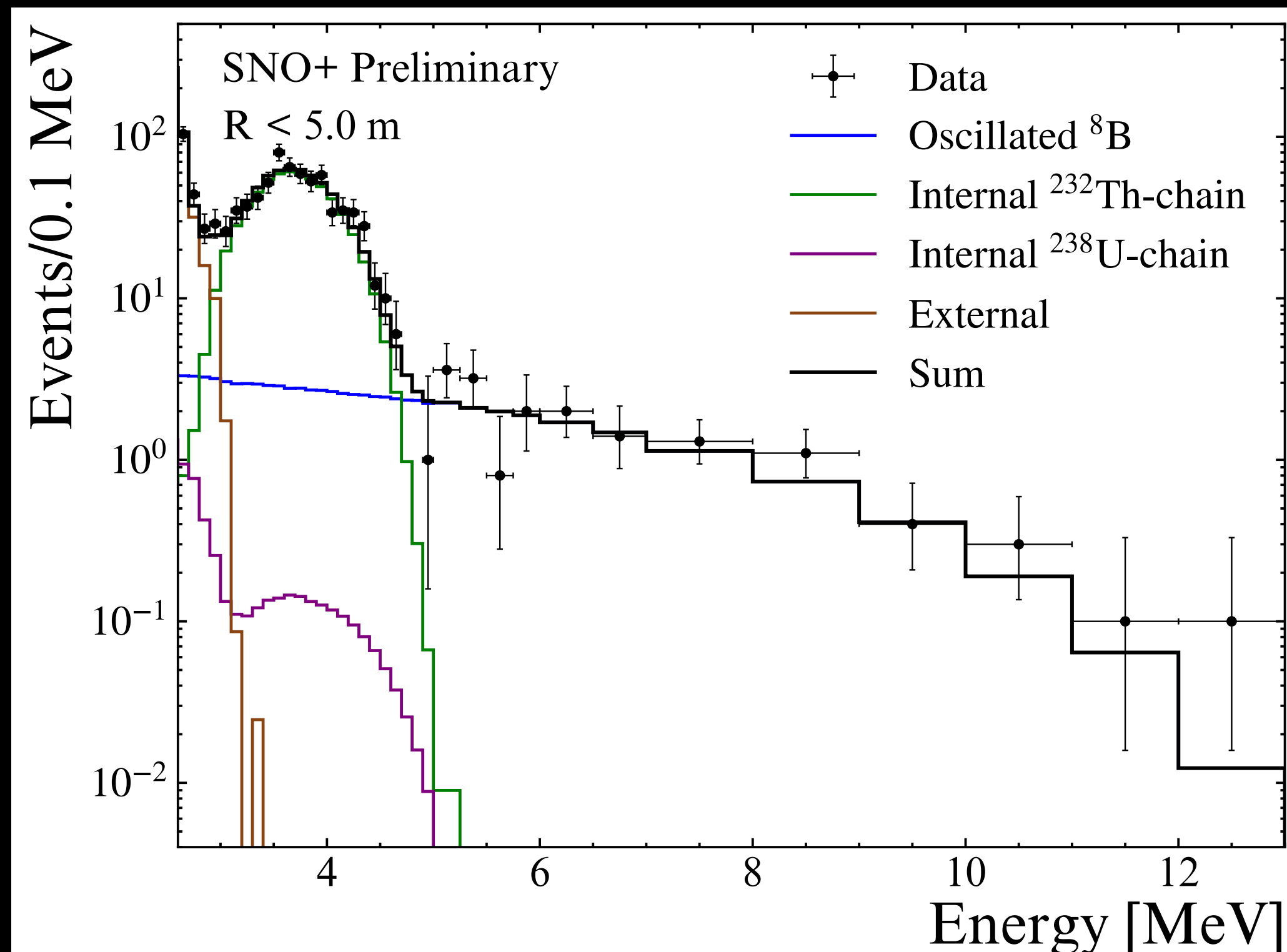
- New analysis of 126.6 kt.days, including 190.3 days of low background data
- Radon in water $\sim 6 \times 10^{-15}$ gU/g
- Lowest background for water Cherenkov detectors > 5 MeV: 0.32 ± 0.07 ev/kt.days

- Results
 - 3.5 MeV threshold, but large uncertainties in first bins
 - Best-fit flux consistent (inc. oscillations) with other experiments, and HZ and LZ solar models

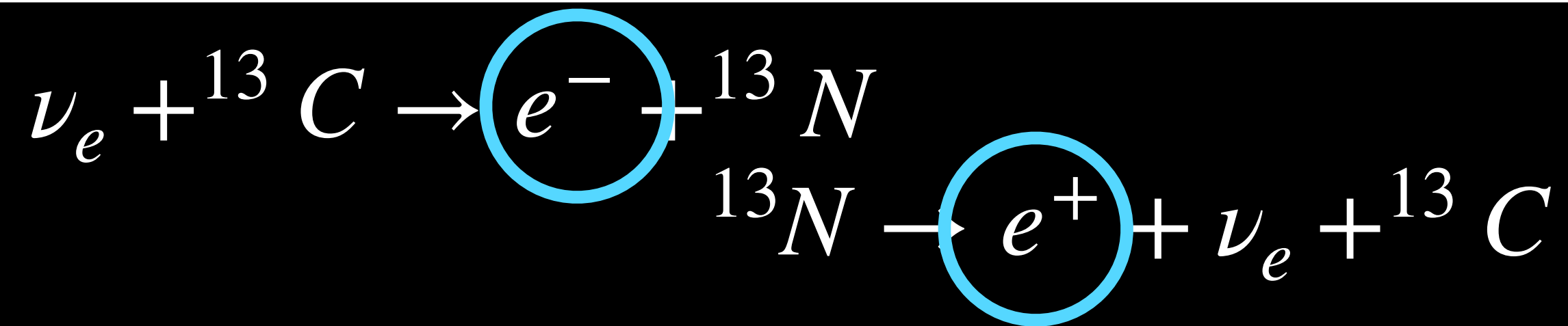
$$\left(5.36^{+0.41}_{-0.39}(\text{stat.})^{+0.17}_{-0.16}(\text{syst.}) \right) \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$$



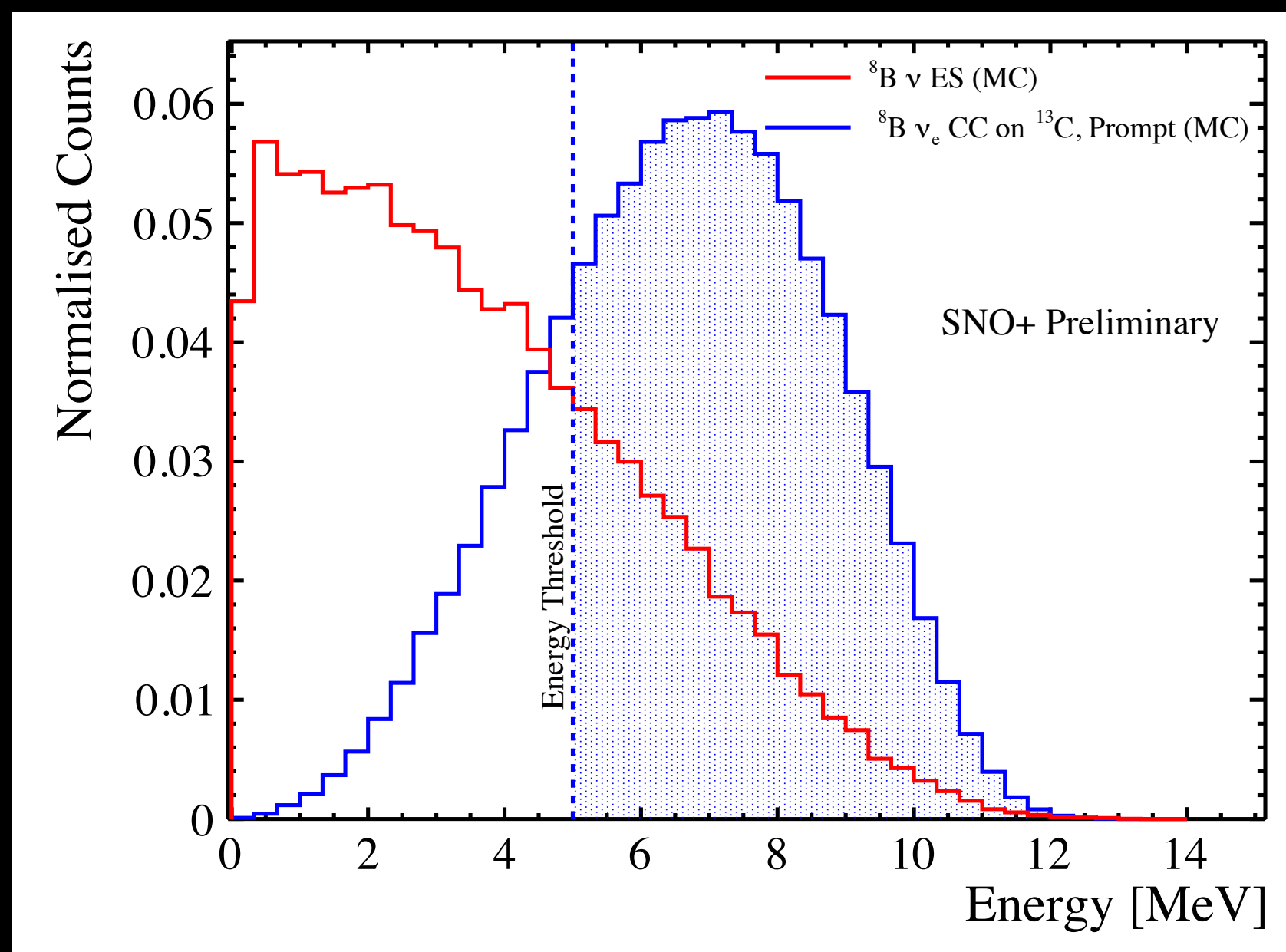
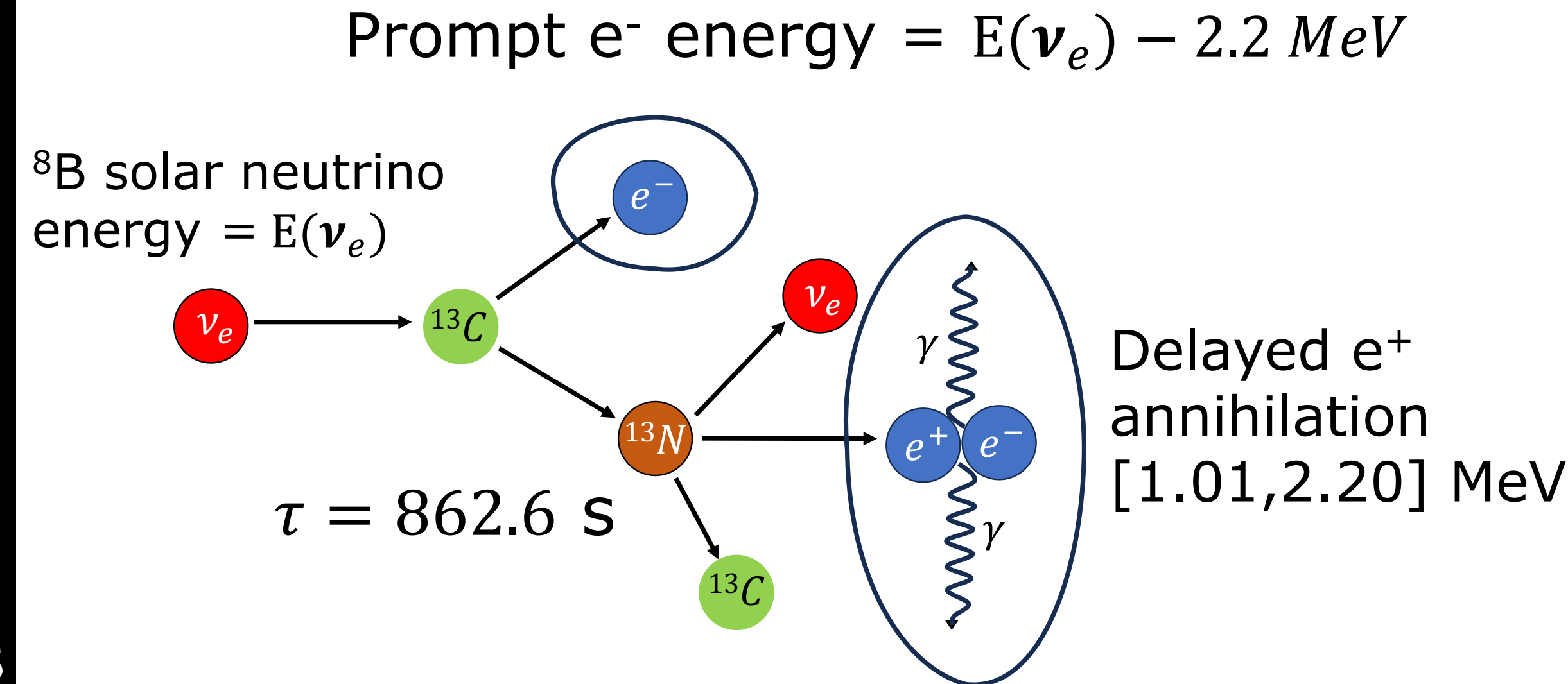
- Analysis of ^8B ES interactions in 138.9 live days of scint. data
- Fitted oscillation parameters compatible with global fits



- Strict fiducial volume cut opens prospects for future sensitivity < 3 MeV !
- ^{232}Th still dominates 3-5 MeV regions, but multisite discriminant will help



- As yet unobserved reaction of electron neutrinos on Carbon-13
- Only 1.1% isotopic abundance, but cross section $\sim 12\times$ higher than ES at ${}^8\text{B}$ ν energies



- Cosmogenic backgrounds from ${}^{11}\text{Be}$: negligible at SNOLAB depth
- Dominant accidental backgrounds determined by data-driven method
- Randomly pick fake prompt, then search for delayed signal candidates

CC ON CARBON-13, RESULTS

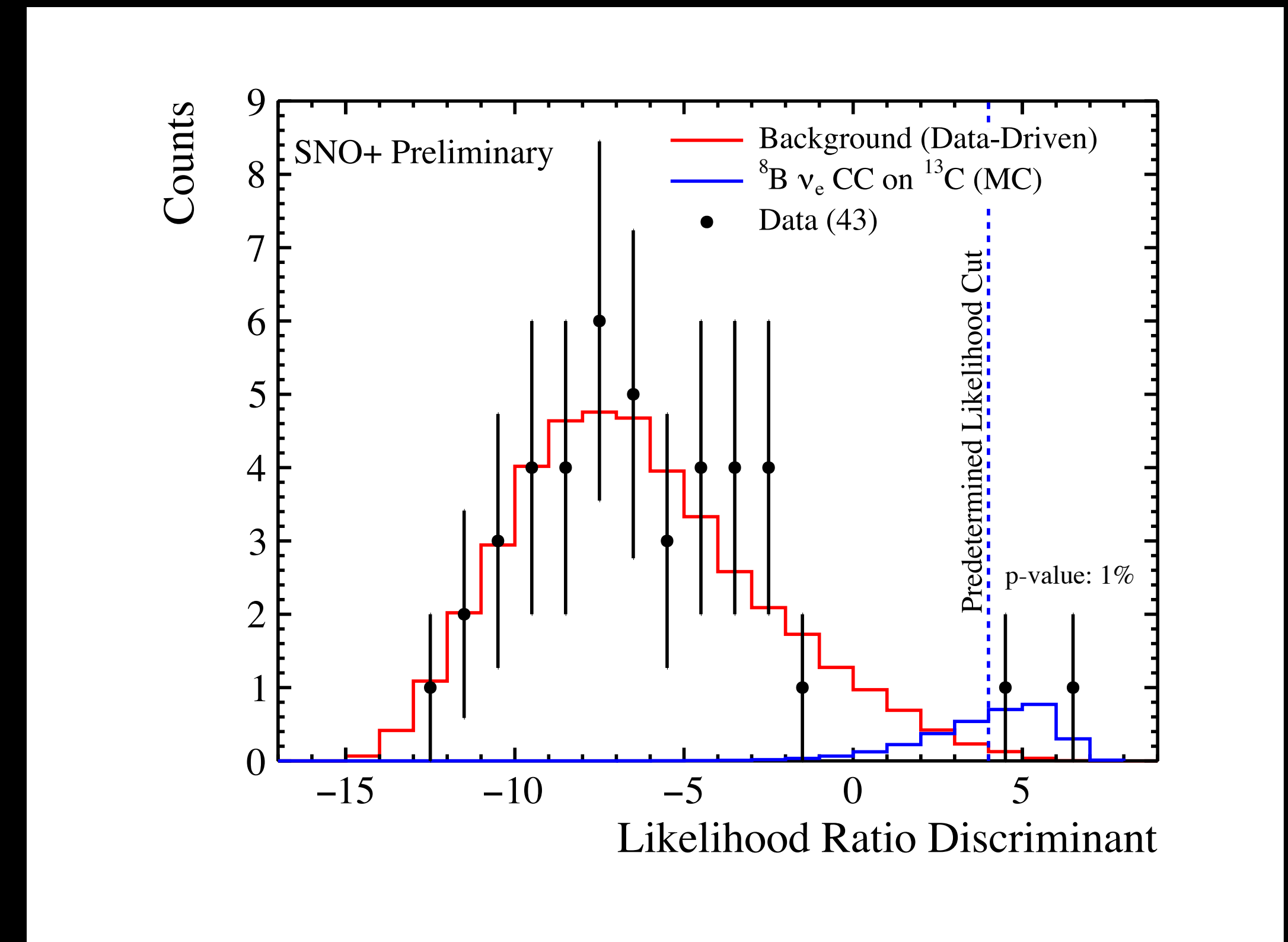


- Cuts optimised prior to “blind box” opening:
 - Fiducial volume: $R < 5.3$ m
 - Prompt energy: $5.0 < E(e^-) < 15.0$ MeV
 - Delayed energy: $1.14 < E(e^+) < 2.2$ MeV
 - $\Delta R < 0.36$ m
 - $0.01 < \Delta T < 24$ min
 - Likelihood ratio analysis
 - Wider cuts on Delayed energy, ΔR , ΔT
 - Likelihood ratio discriminant > 4

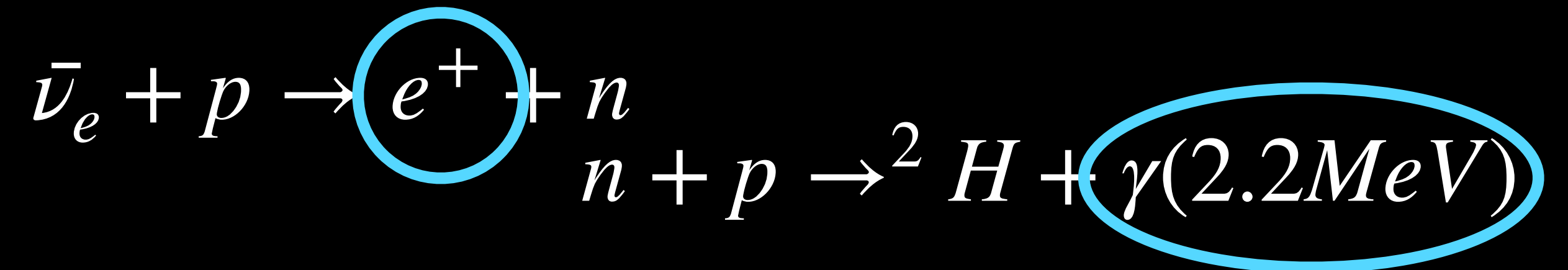
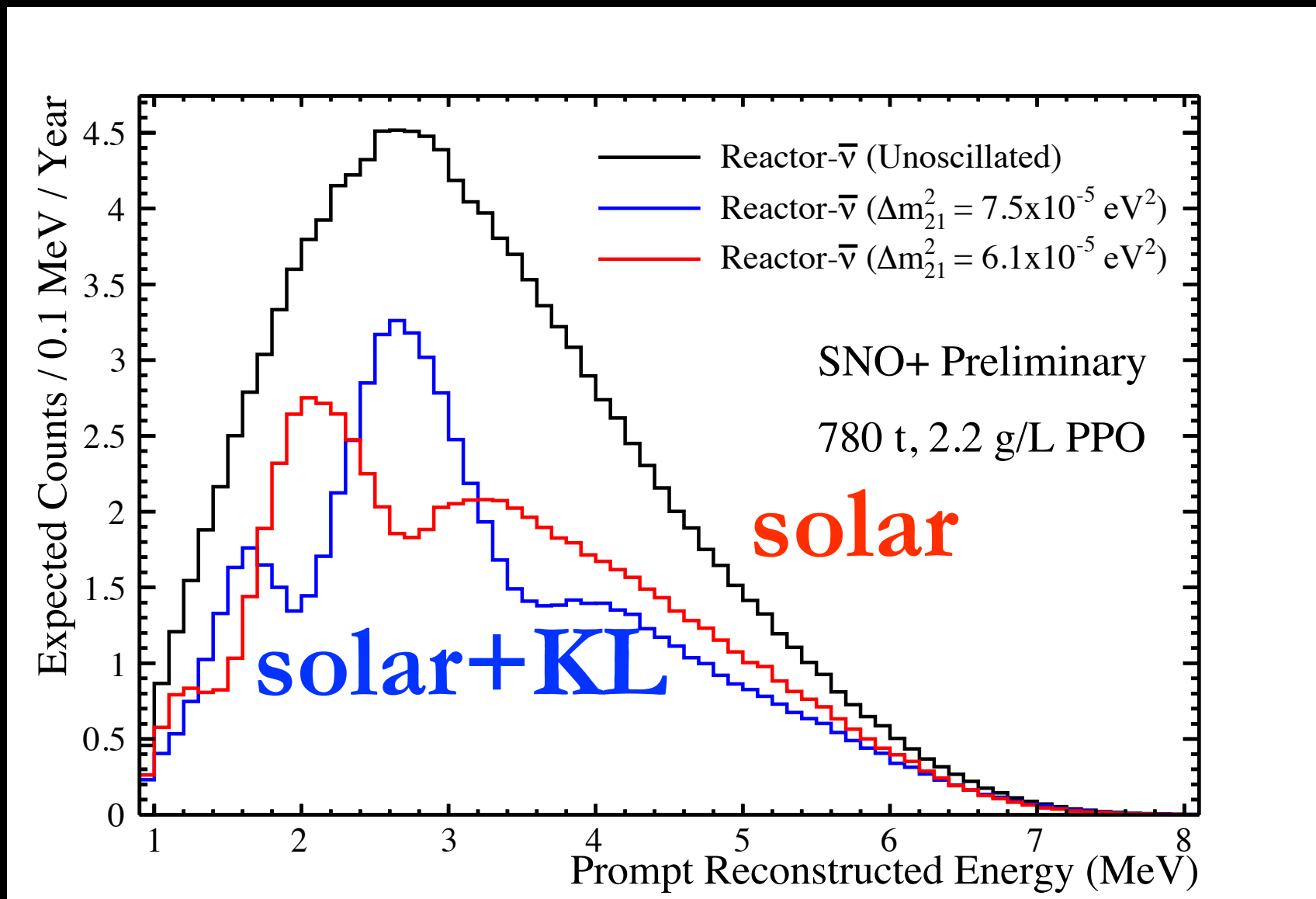
EXPECTED	BOX	LIKELIHOOD
BACKGROUND	0.31	0.17
SIGNAL	1.83	1.79

150.51 live days

2 events found !

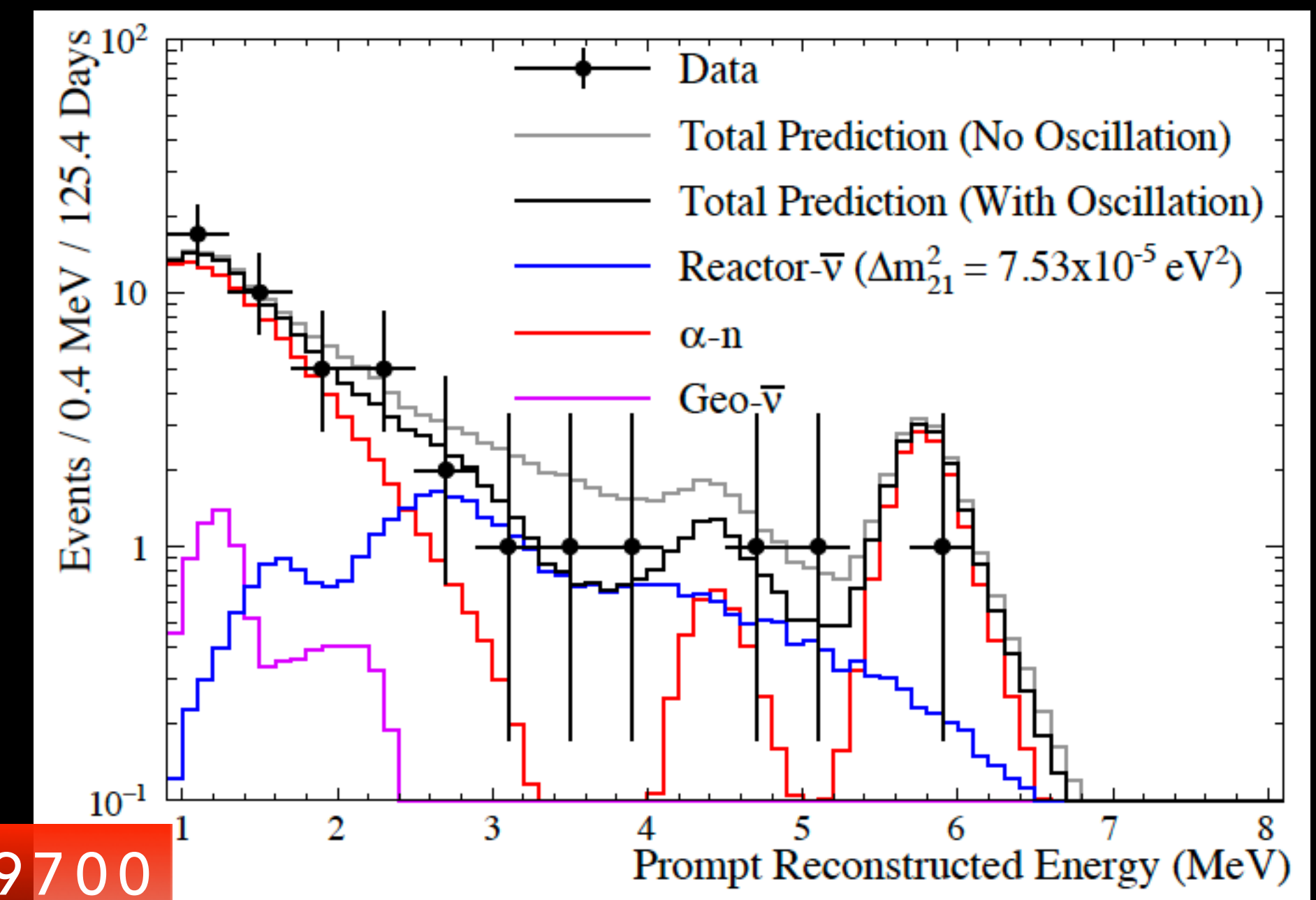


Indicative of a signal from
 ^{13}C CC interactions !



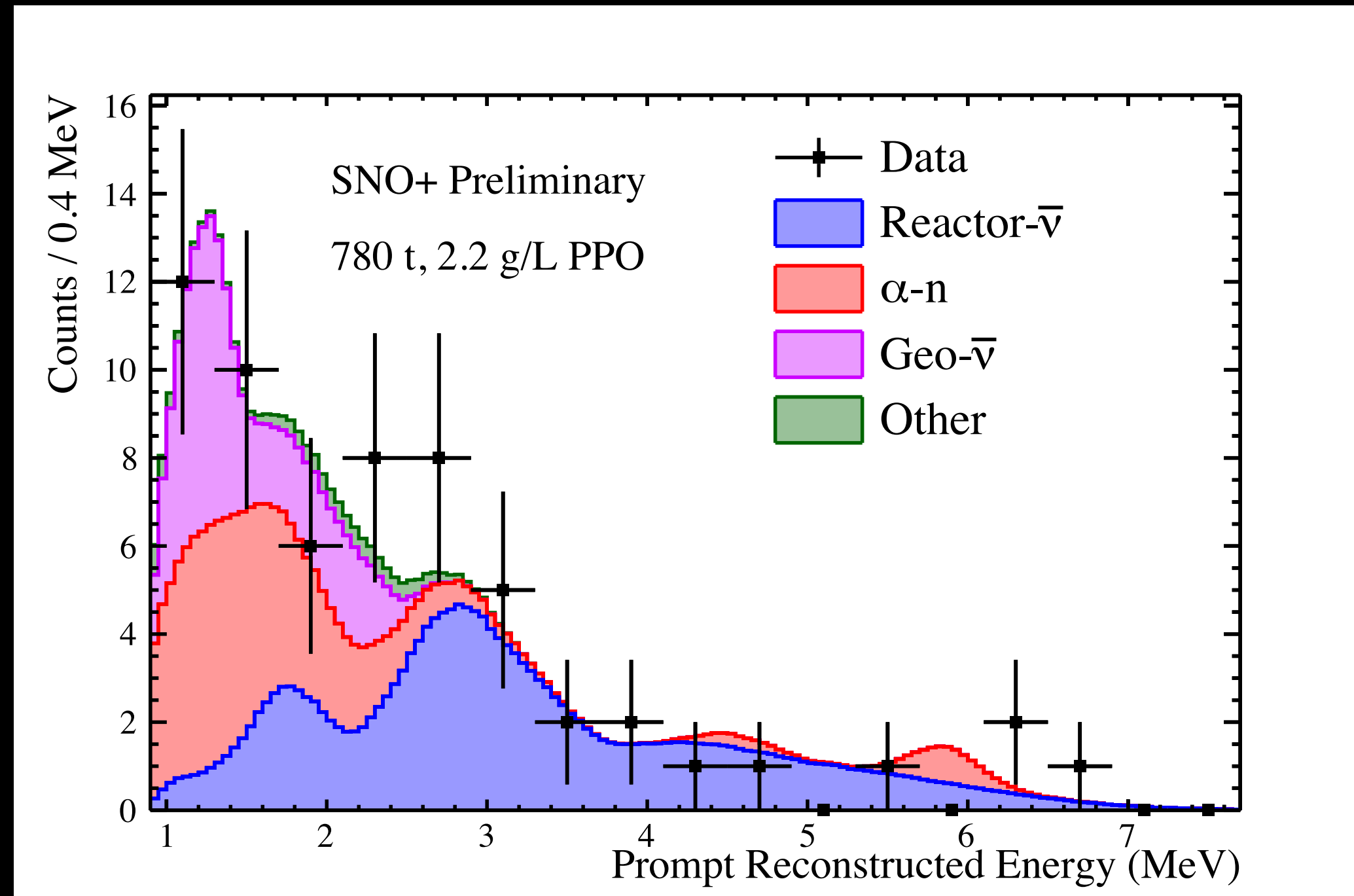
- Prompt spectrum @ SNO+ with sharp features, due to few baselines
- Potential to shed light on solar-KamLAND tension

- Following first detection in a water Cherenkov detector, new results from partial and scint phases
- Main background: (α ,n) reactions on ^{13}C
 - α s from high rate ^{210}Po decays
- Partial fill: 114 t.y exposure, 85 Hz of ^{210}Po
 - Stats and background-limited

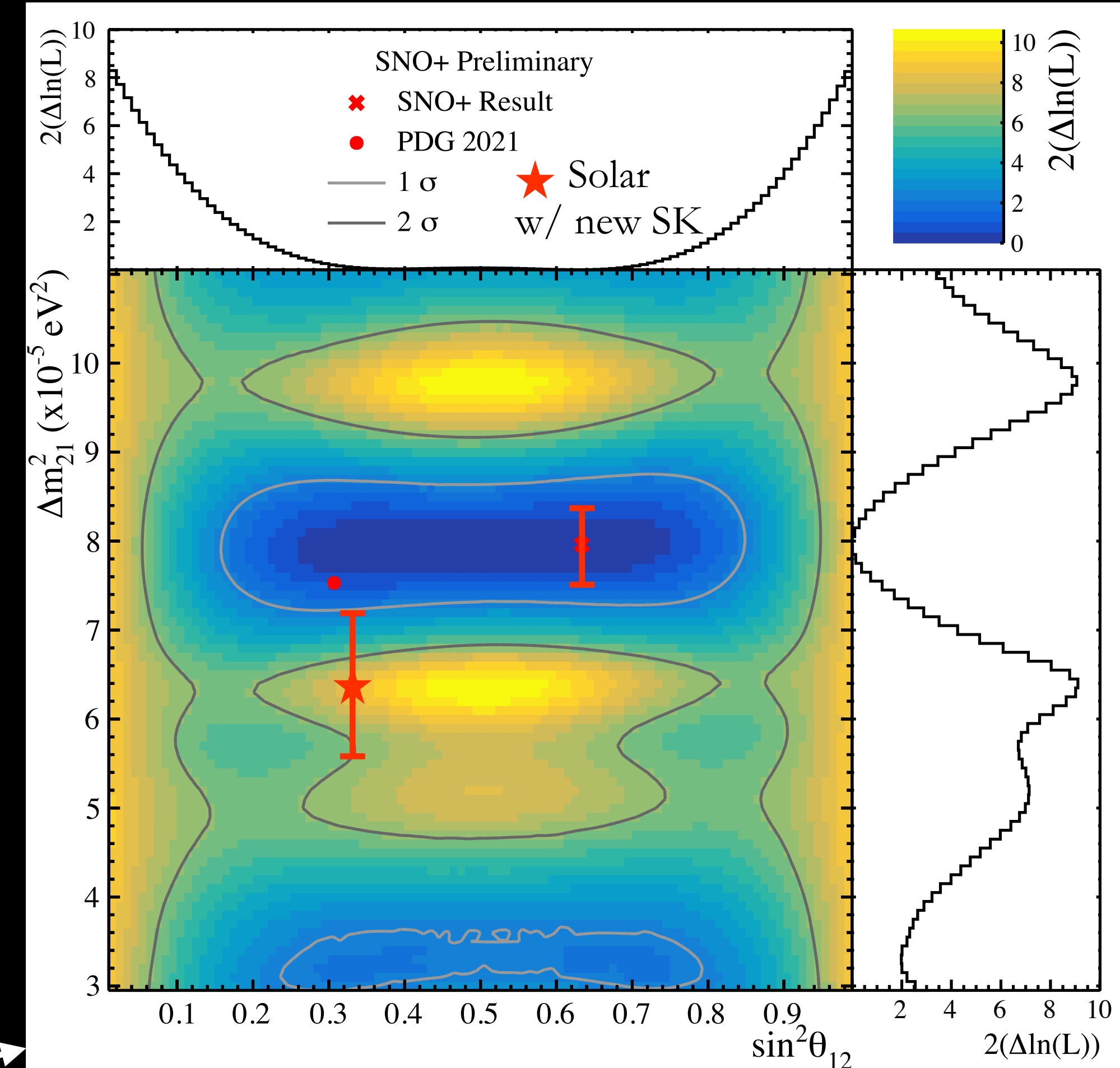


SUBMITTED TO PRD ARXIV:2405.19700

Scint. phase:
286 t.y
exposure,
38 Hz ^{210}Po



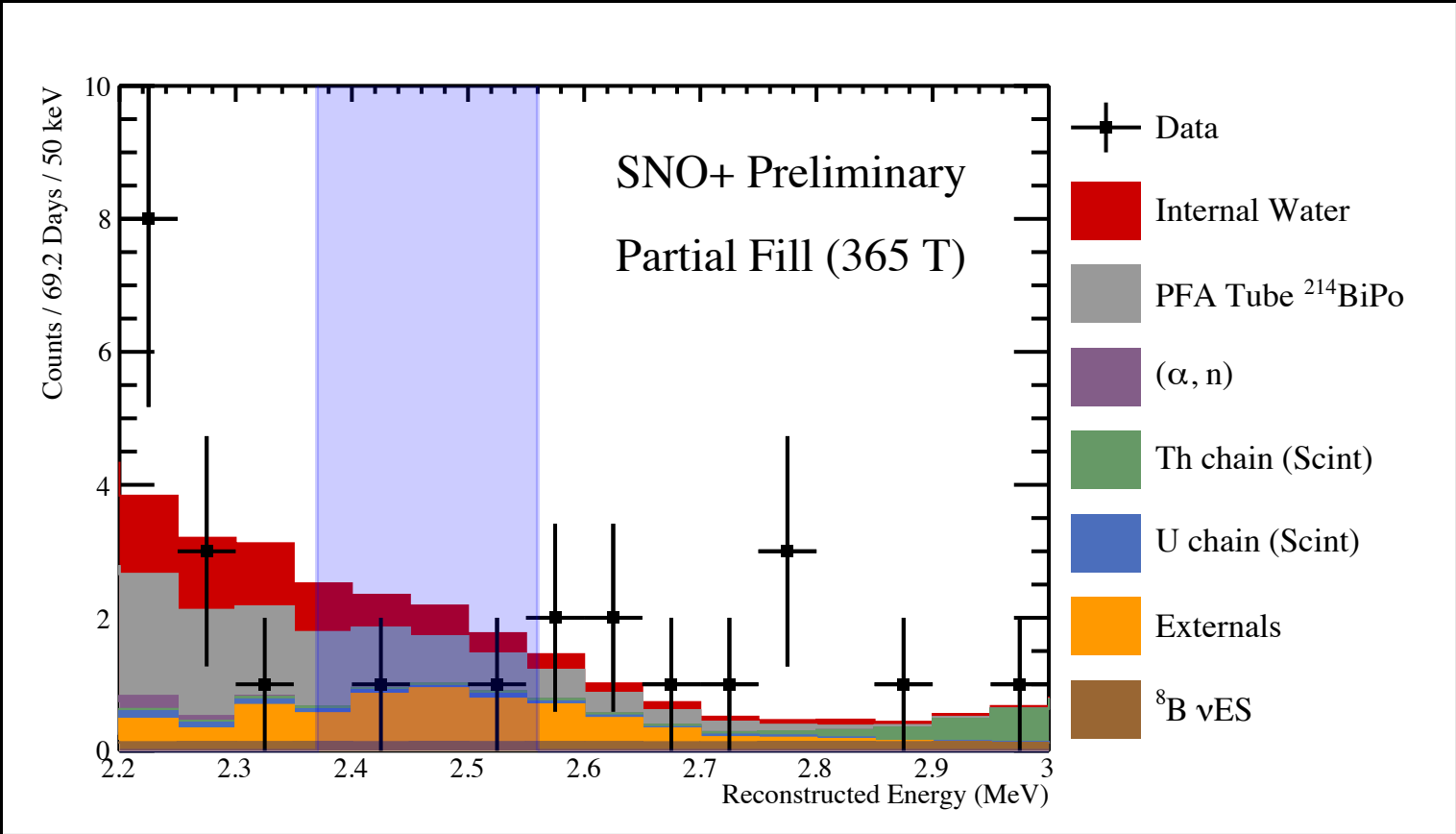
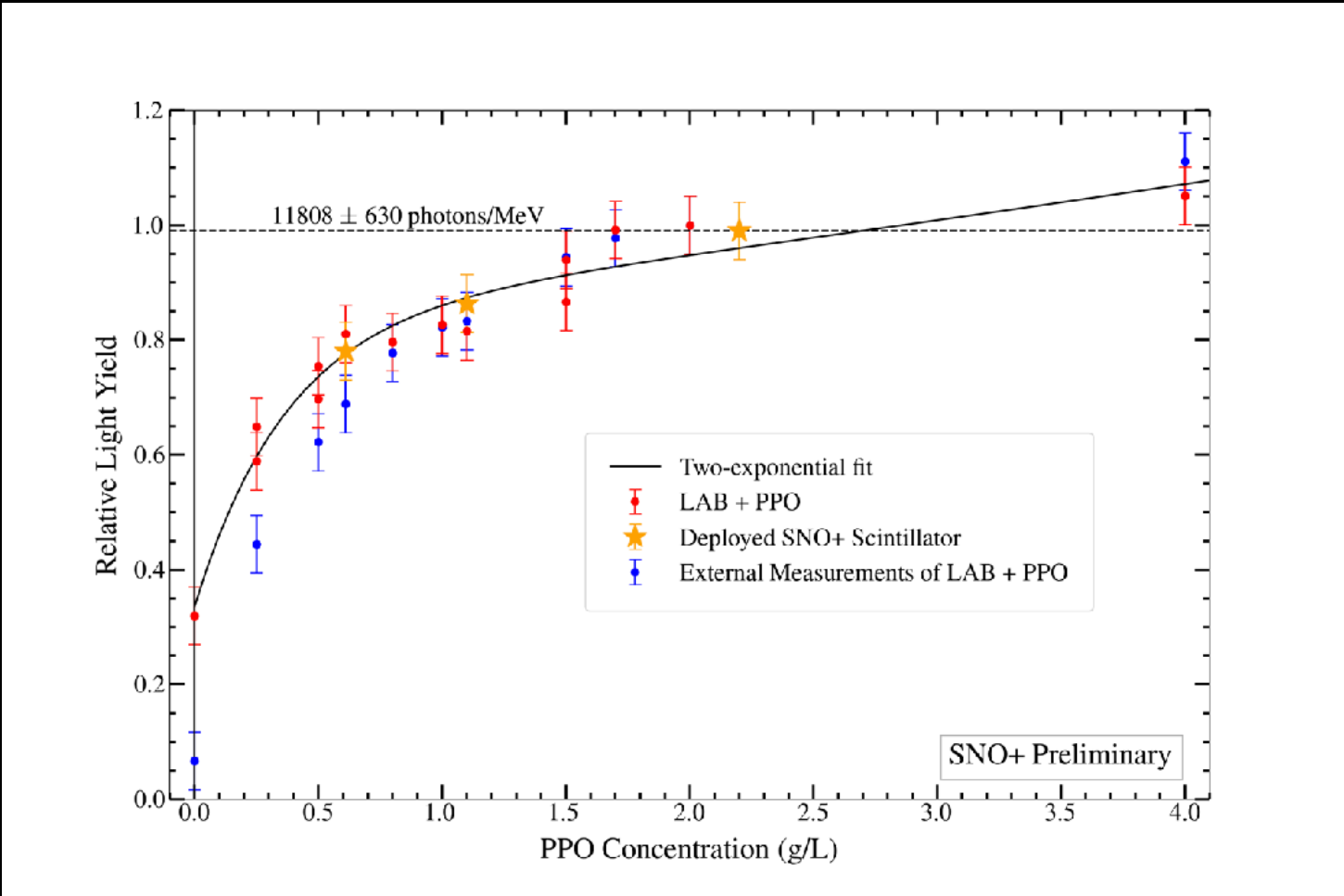
- Still stats limited, but lower (α ,n) background
- Geo-nu 64 ± 44 TNU, will improve soon with (α ,n) classifier
- Unconstrained oscillation fit



$$\Delta m_{21}^2 = 7.96^{+0.48}_{-0.41} \times 10^{-5} \text{ eV}^2$$

- $\sim 1.3\sigma$ from solar only, $< 1\sigma$ from KL

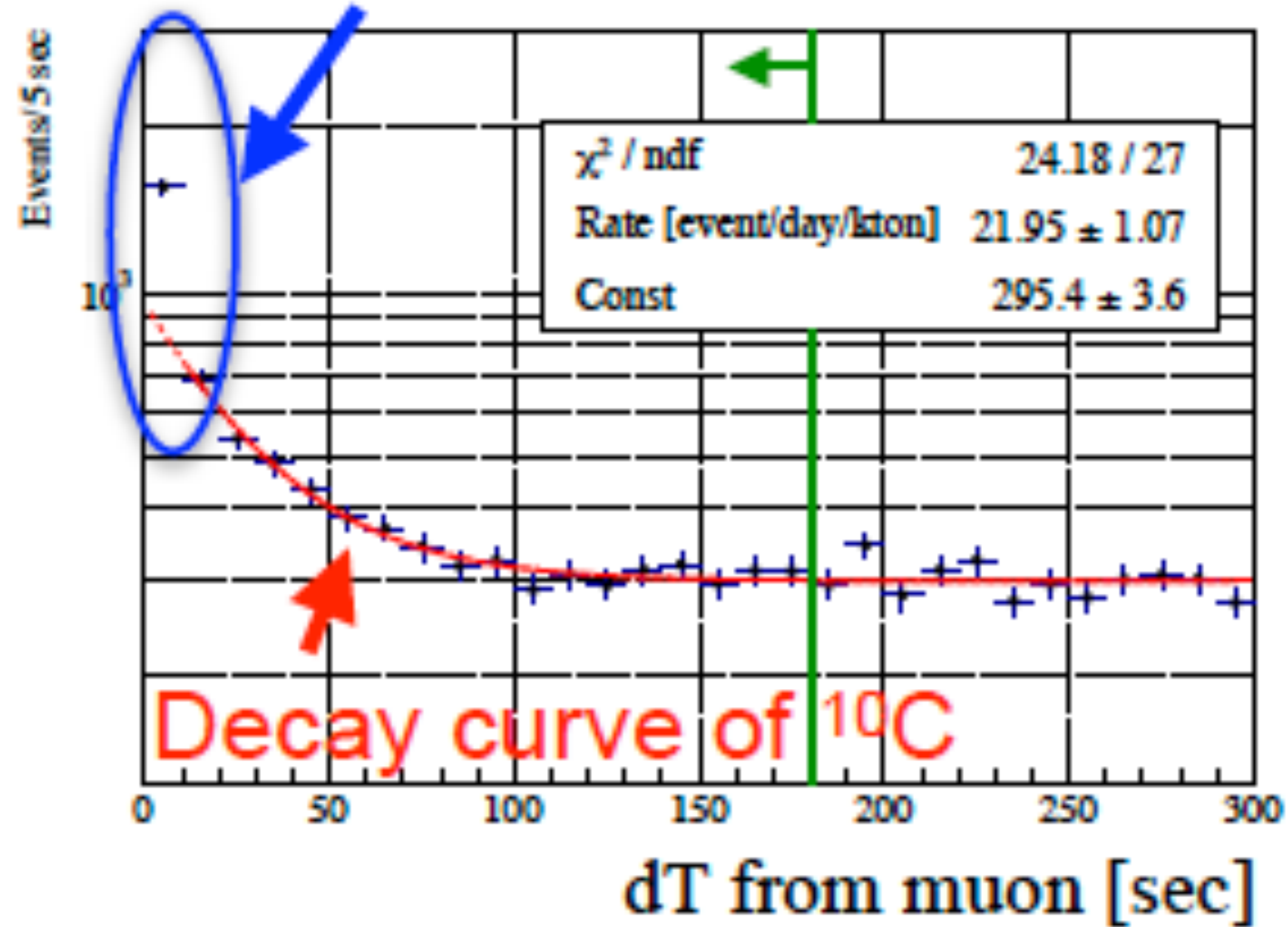
PARTIAL FILL ROI



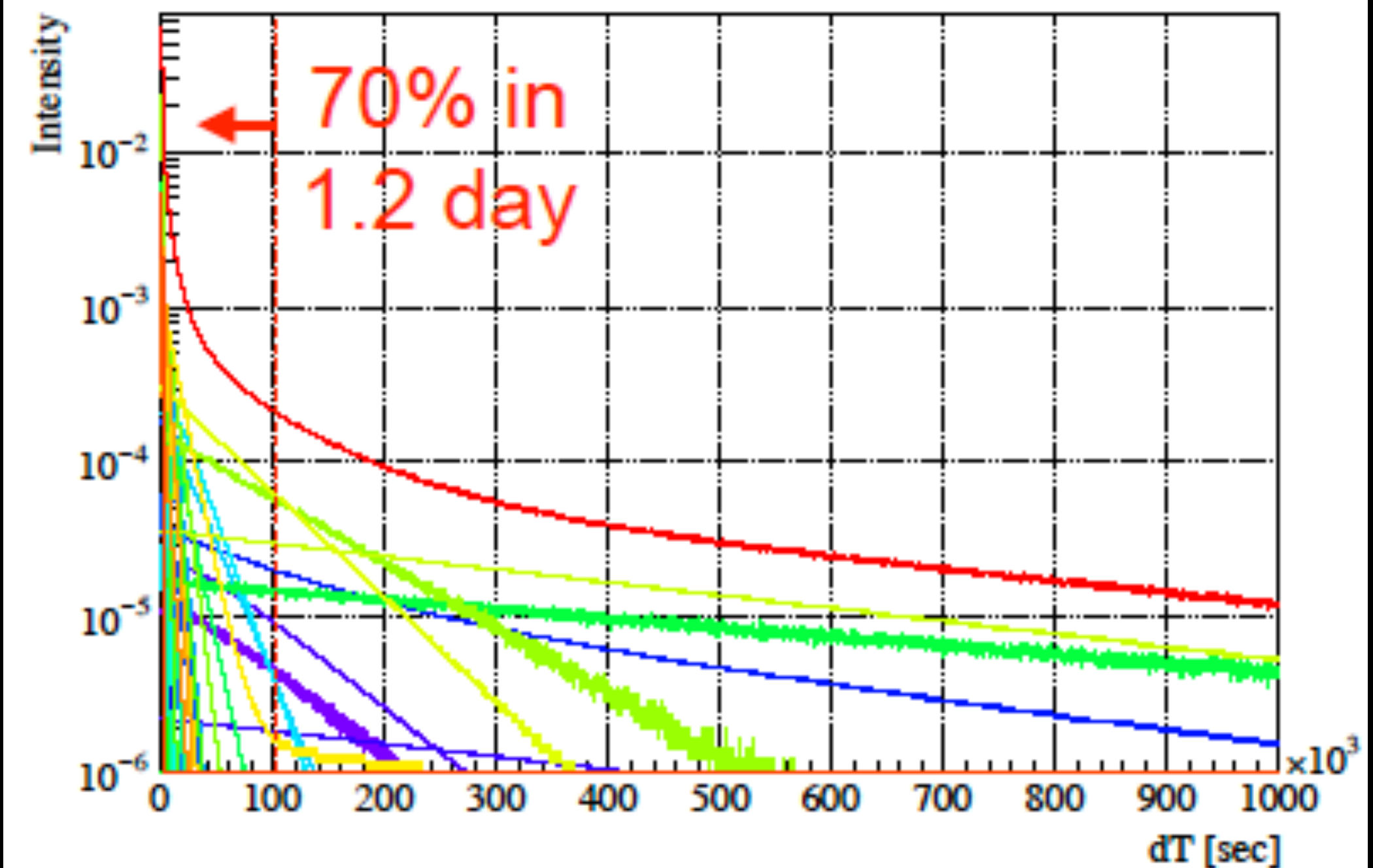
Background	Expected Counts in Partial Fill ROI
Internal Water	1.8
PFA Tube ²¹⁴ BiPo	2.9
Externals	2.5
(α, n)	0
Th Chain (Scint)	0.1
U Chain (Scint)	0.3
⁸ B νES	0.5
Total Backgrounds	8.0

KL-ZEN TIME CUTS

${}^6\text{He}$, ${}^8\text{Li}$, ${}^{12}\text{B}$



time difference from muon

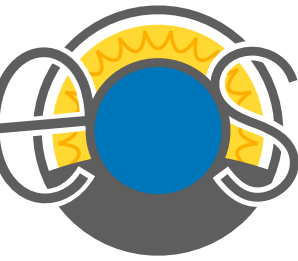


n/yr

need long-time veto



EOS: performance demonstrator

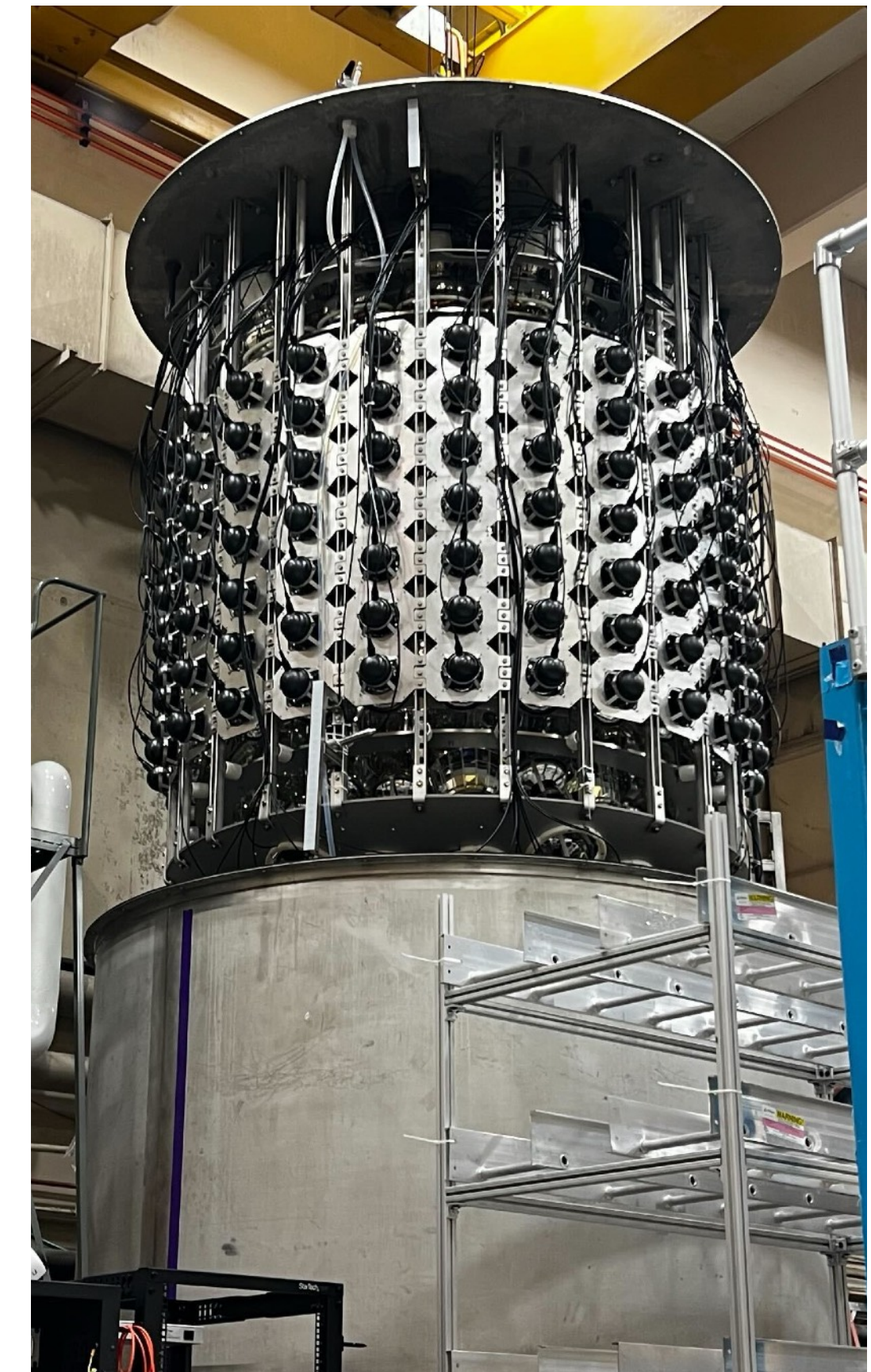
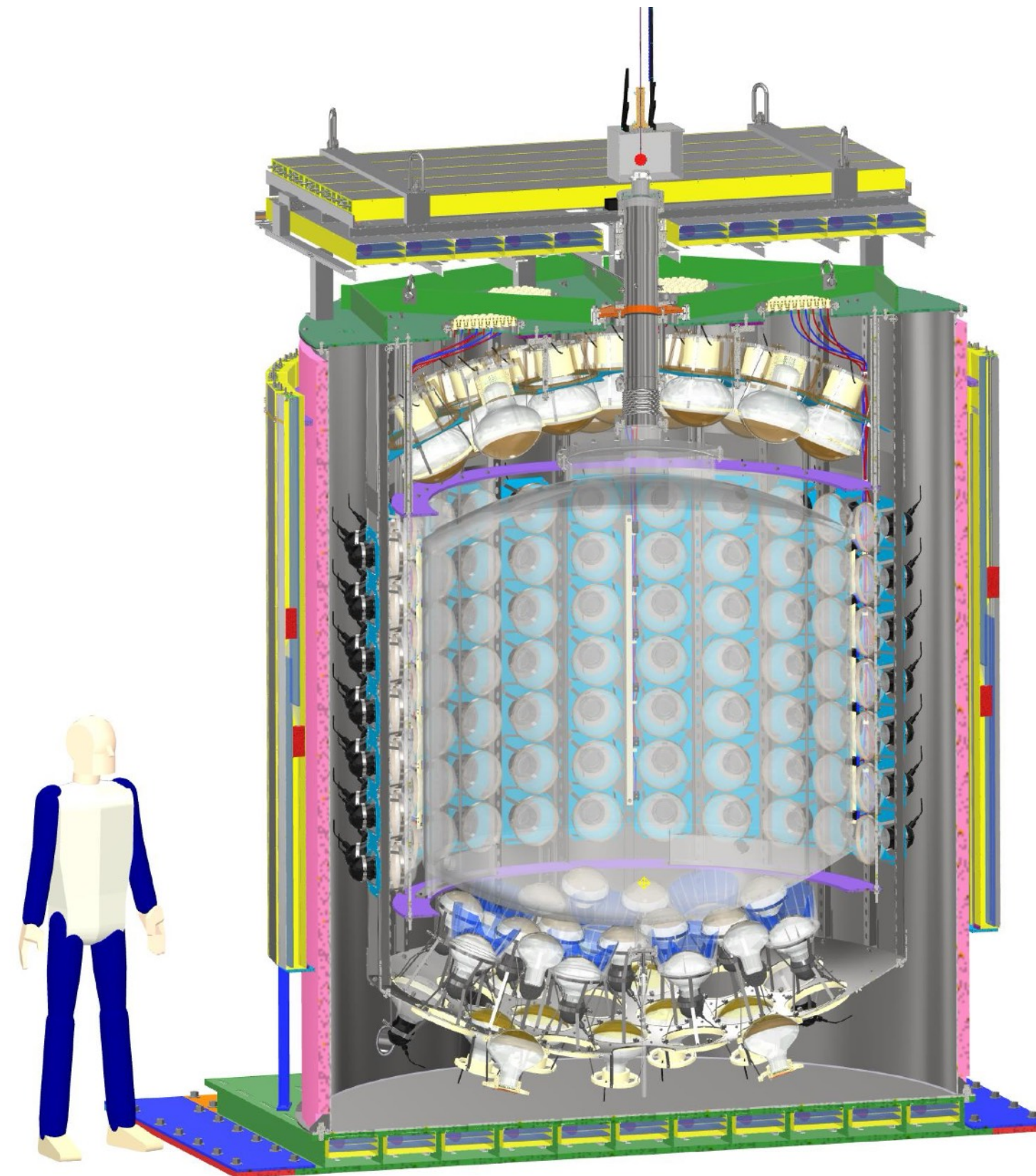


Approach: *design, construct and operate an integrated testbed to demonstrate the performance of novel technology*

Novelty / technology:

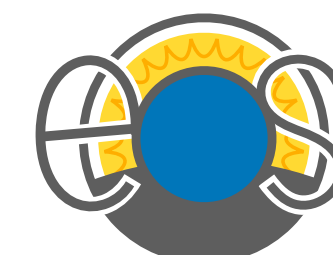
- Novel scintillating liquids — water-based scintillator, slow scintillator
- Ultra-fast photon detectors — novel 8" PMTs (200 8" PMTs: RI4688-100, 900ps FWHM)
- “Quantum chromatic sorting”: dichroicons for spectrally sensitive photon detection
- AI/ML-based analysis techniques
- Deployable sources for studies of vertex, energy, direction reconstruction & PID
- 36-fiber light injection system for optical calibration

Designed for flexible upgrade paths & to be redeployed at a neutrino source
→ *demonstrate viability of future applications*



- Sited on UC Berkeley campus, in Nuclear Engineering (NE) department

EOS concept paper published: *JINST* 18 P02009 (2023),
<https://doi.org/10.1088/1748-0221/18/02/P02009>



The EOS team

Team breakdown:

3 national laboratories
18 top-tier US institutions
8 international collaborating institutions

10 postdoctoral scholars
9 graduate students
18 undergraduate students

USA



University of Colorado
Boulder



Germany



JOHANNES GUTENBERG
UNIVERSITÄT MAINZ



TECHNISCHE
UNIVERSITÄT
MÜNCHEN

Turkey



Portugal



UNIVERSIDADE D
COIMBRA

Finland



Canada

