LABORATÓRIO DE INSTRUMENTAÇÃO E FÍSICA EXPERIMENTAL DE PARTÍCULAS
partículas e tecnologia

UNIVERSIDADE D COIMBRA

The SNO+ Experiment

Nuno Barros, LIP/UC

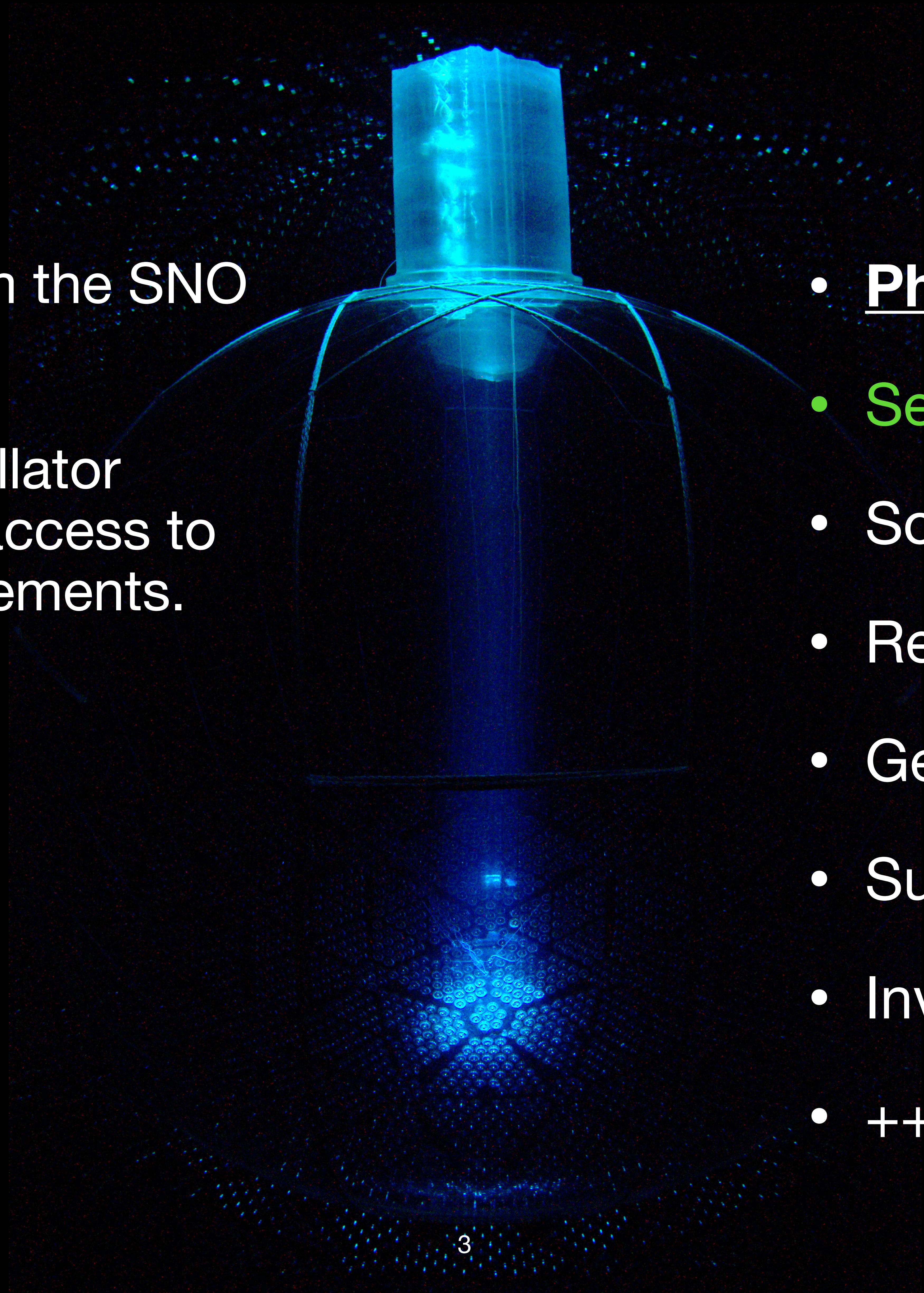
Double Beta Decay: the road to normal hierarchy - ISCTE, June 6-7th 2022

The SNO+ Collaboration

UNIVERSITY OF ALBERTA
BERKELEY LAB
Lawrence Berkeley National Laboratory
UNIVERSITY OF LIVERPOOL
LIP
THE UNIVERSITY OF CHICAGO
KING'S College LONDON
UCDAVIS
UNIVERSITY OF CALIFORNIA
BOSTON UNIVERSITY
Lancaster University
TRIUMF
UNAM
US
University of Sussex
UNIVERSITY OF OXFORD
Queen Mary
University of London
Queen's UNIVERSITY
TECHNISCHE UNIVERSITÄT DRESDEN
Berkeley
UNIVERSITY OF CALIFORNIA
LaurentianUniversity
UniversitéLaurentienne
BROOKHAVEN
NATIONAL LABORATORY
Penn
UNIVERSITY of PENNSYLVANIA
NORWICH UNIVERSITY
SNOLAB

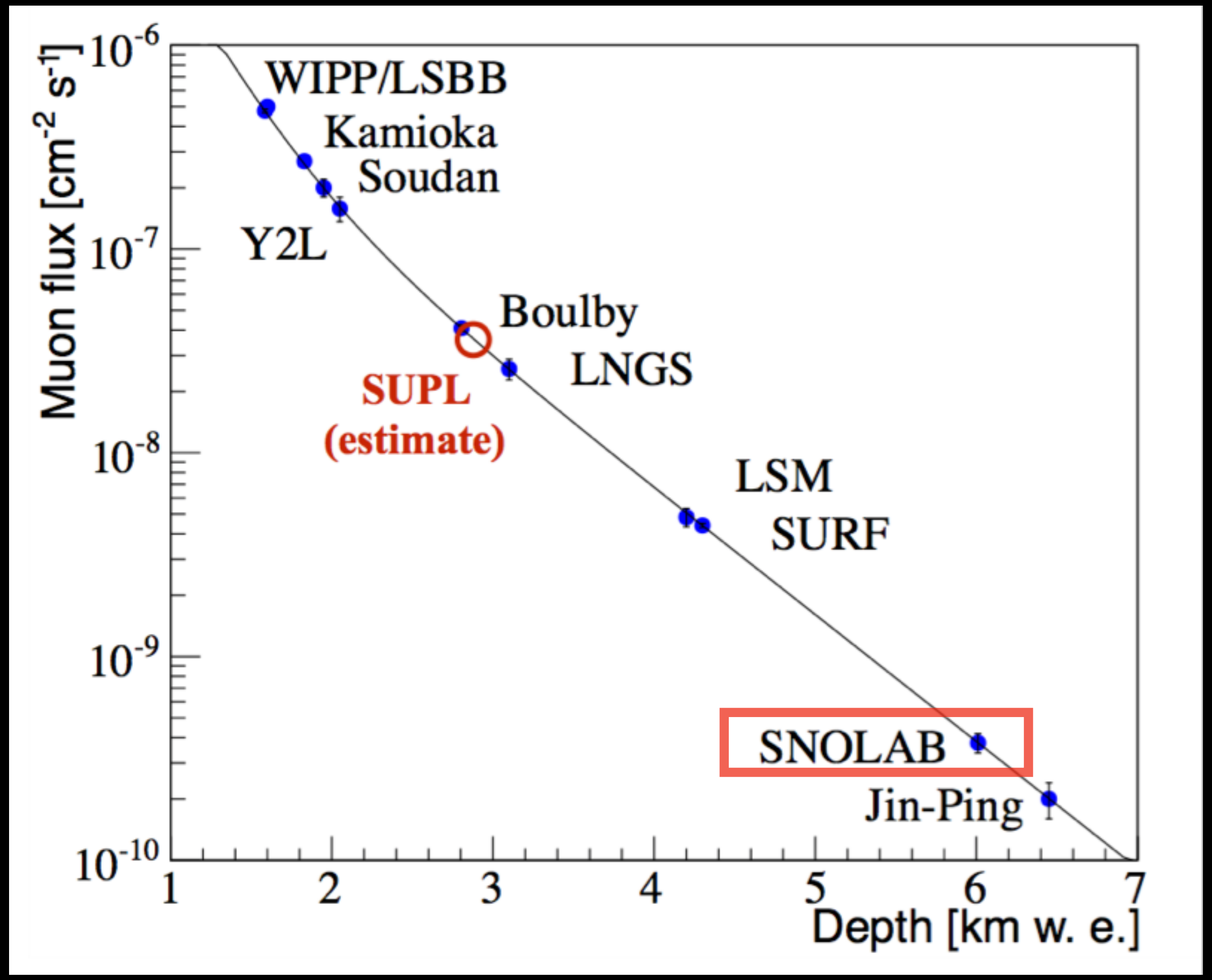
A Multi-purpose Liquid Scintillator Detector

- Infrastructure inherited from the SNO experiment.
- Adapted from D_2O to scintillator detecting medium to give access to low energy (~MeV) measurements.



- **Physics Programme:**
- Search for $0\nu\beta\beta$ in ^{130}Te
- Solar Neutrinos
- Reactor Anti-neutrinos
- Geo-neutrinos
- Supernova bursts
- Invisible nucleon decay
- +++

The SNO+ Detector



780 tons of **liquid scintillator**

loaded with double-beta decay isotope (^{130}Te)

contained in an **acrylic vessel (AV)** 12 m diameter

held-down by **new rope system**

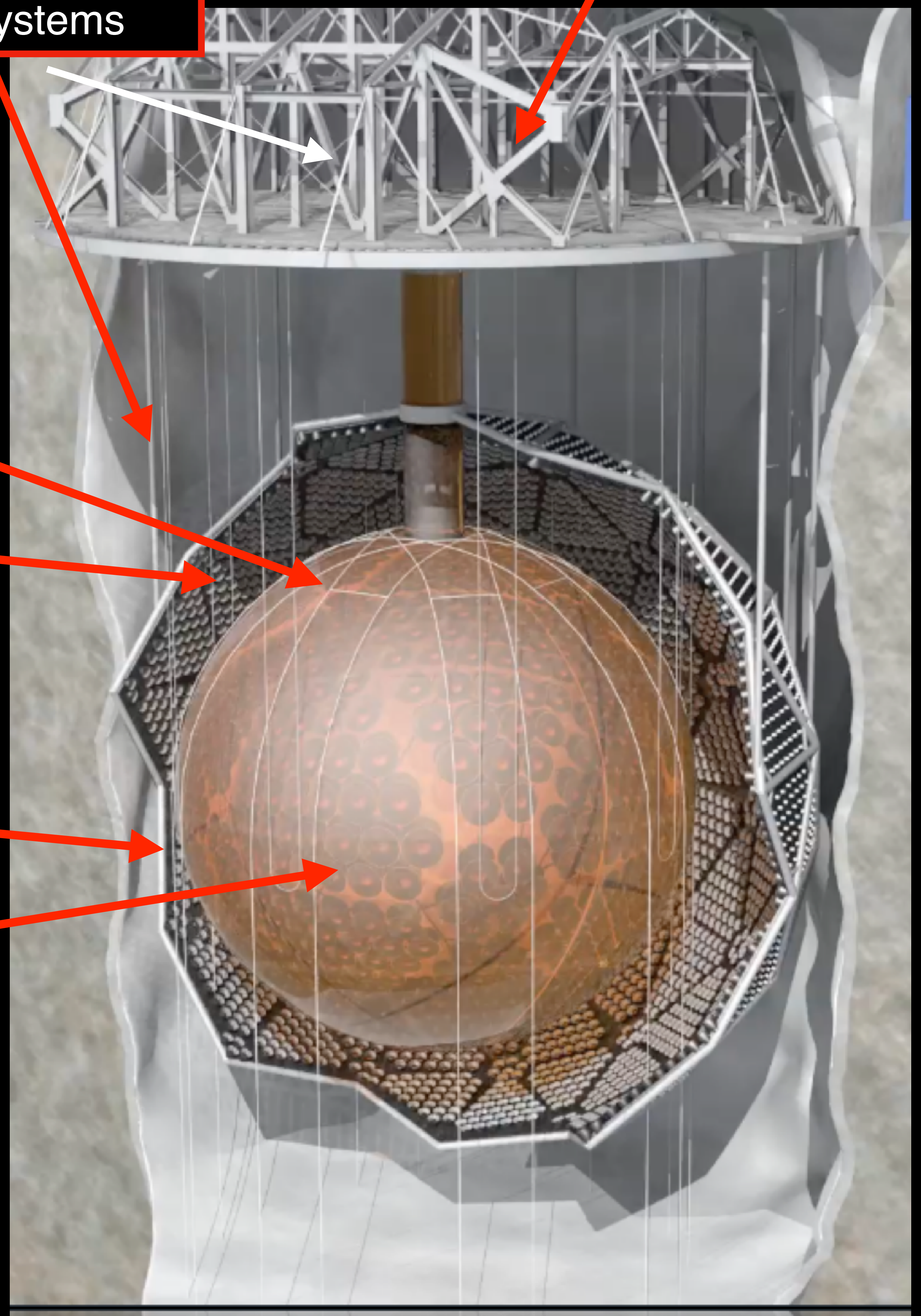
shielded by 7 kt ultra-pure water

viewed by ~ **9300 PMTs** (8”) mounted on 17 m diam. structure

~54% photocathode coverage

new calibration systems

new DAQ and readout cards



μ rate: 0.28 μ d^{-1} m^{-2}

SNO+ Upgrades

Besides ropes and purification plant

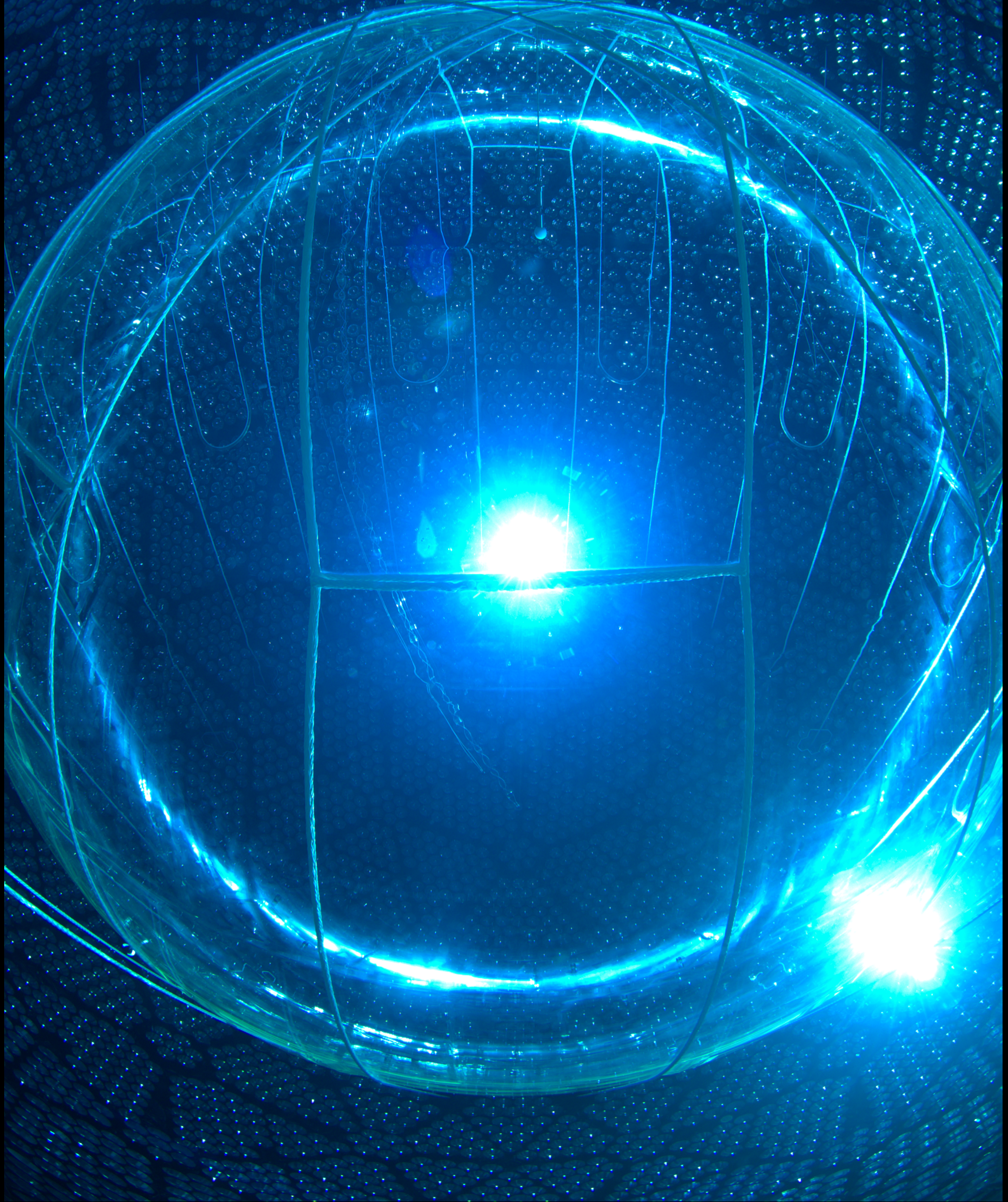
- Refurbishing the electronics
- Repair of many “dead” PMT bases
- All-new DAQ, adapted to the higher trigger rate
- New cover gas system
- New calibration systems capable of deploying in LAB scintillator
- New in-situ injected LED/laser light calibration system
- Calibration system cameras (for photogrammetry)

SNO+ Timeline

2016 2017 2018 2019 2020 2021 2022 2023

- Dec 2016
  Start of Commissioning Data Taking
- May 2017
  Start of Water Phase
- July 2019
  Start of Scintillator Fill
- July 2021
  End of Scintillator Fill
- Tellurium Loading

SNO+ Water Phase



SNO+ Timeline

Water Phase

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Dec 2016
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July 2019
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July 2021
End of
Scintillator Fill

Tellurium
Loading

Acrylic Vessel (AV) filled with 905 tonnes of ultra-pure water (UPW)

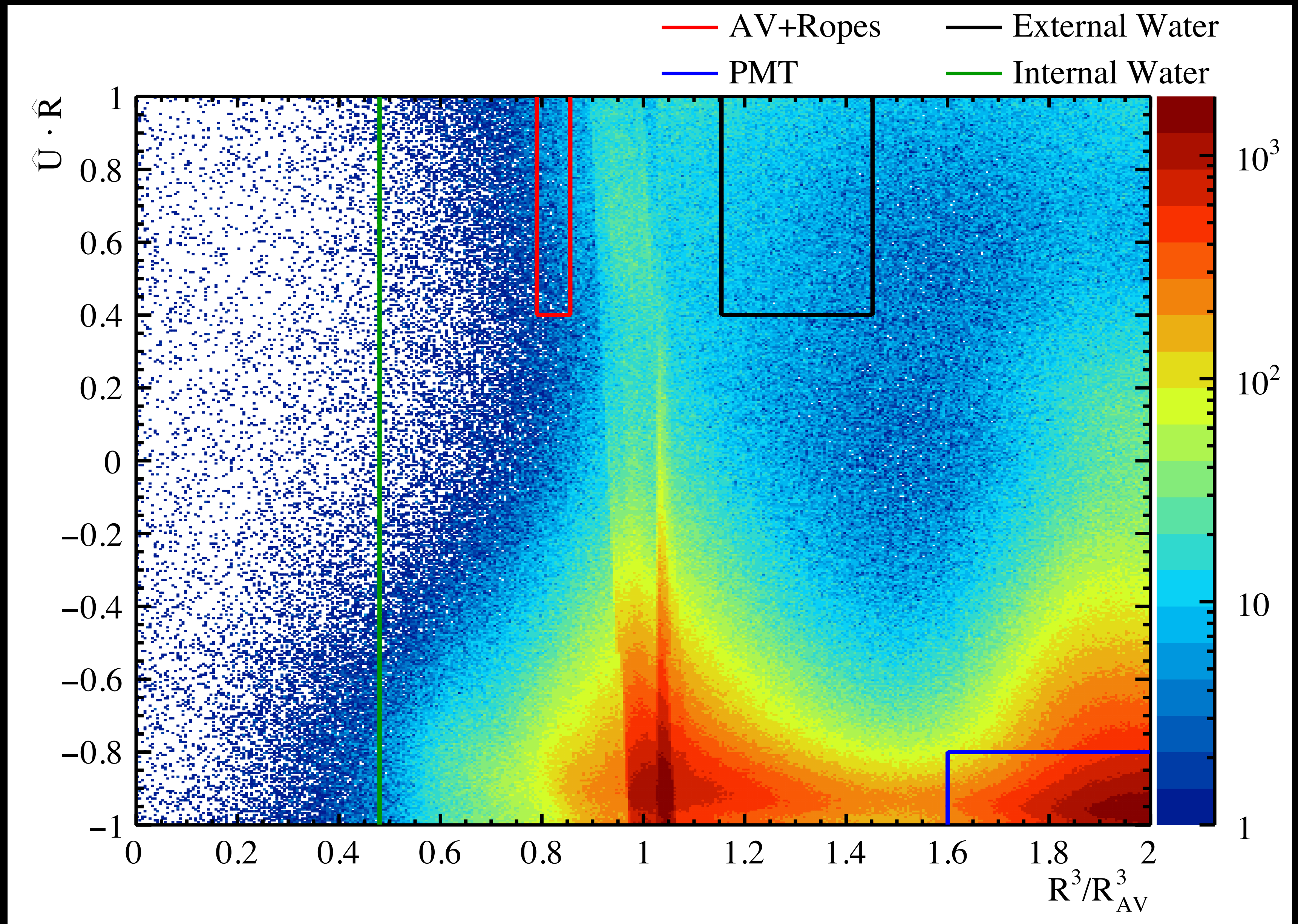
Dataset I: **115 live days**
May 2017 -> December 2017

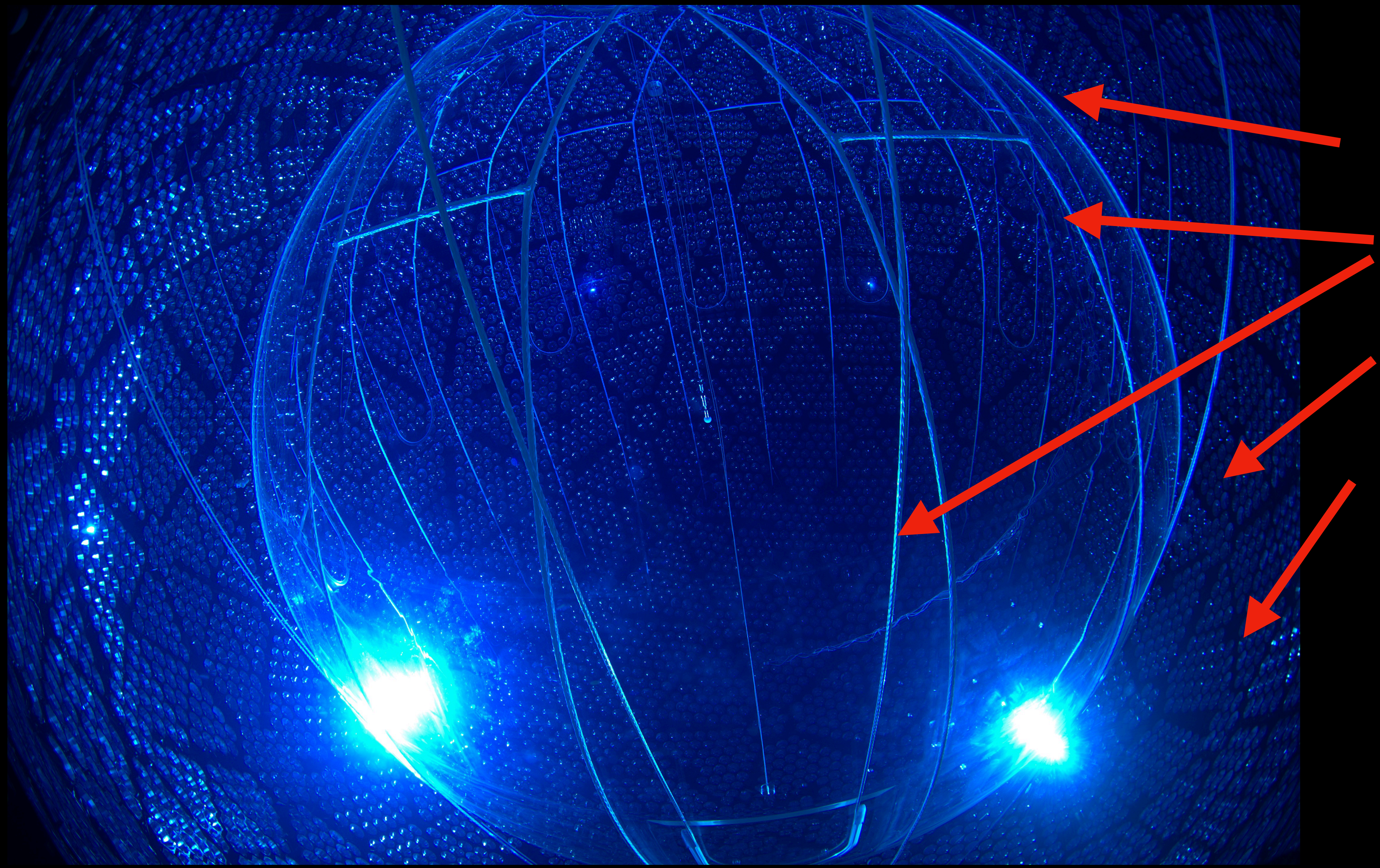
Dataset II: **190 live days**
October 2018 -> July 2019

Water Phase Backgrounds

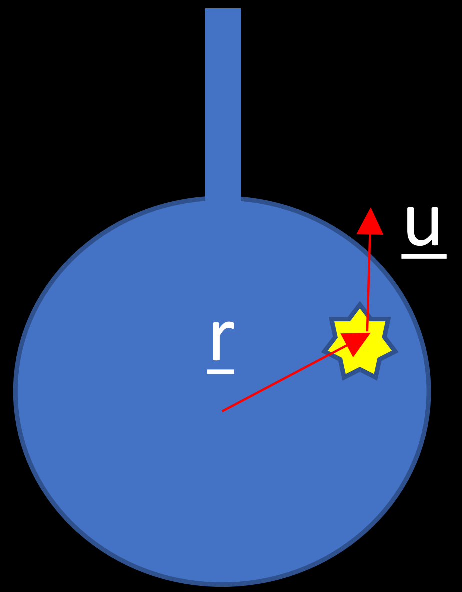
External backgrounds measurement

Simple detector configuration.
Measure components that don't change with detection medium.





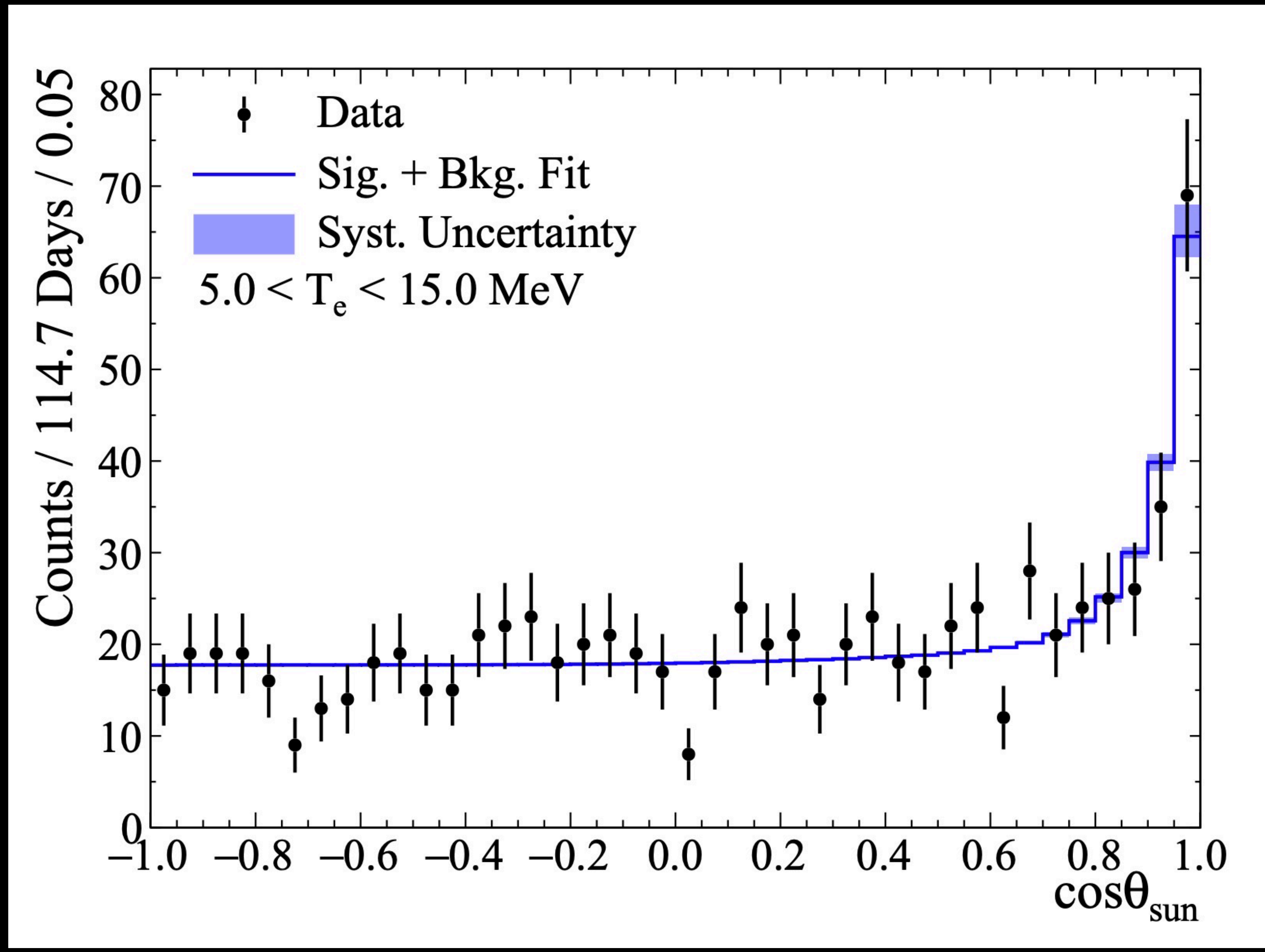
Background	Rate (Fraction of Nominal)
AV+Ropes	$0.52 \pm 0.02^{+0.39}_{-0.28}$
External Water	$0.03 \pm 0.01^{+0.61}_{-0.03}$
PMT	$2.04 \pm 0.04^{+3.69}_{-1.20}$



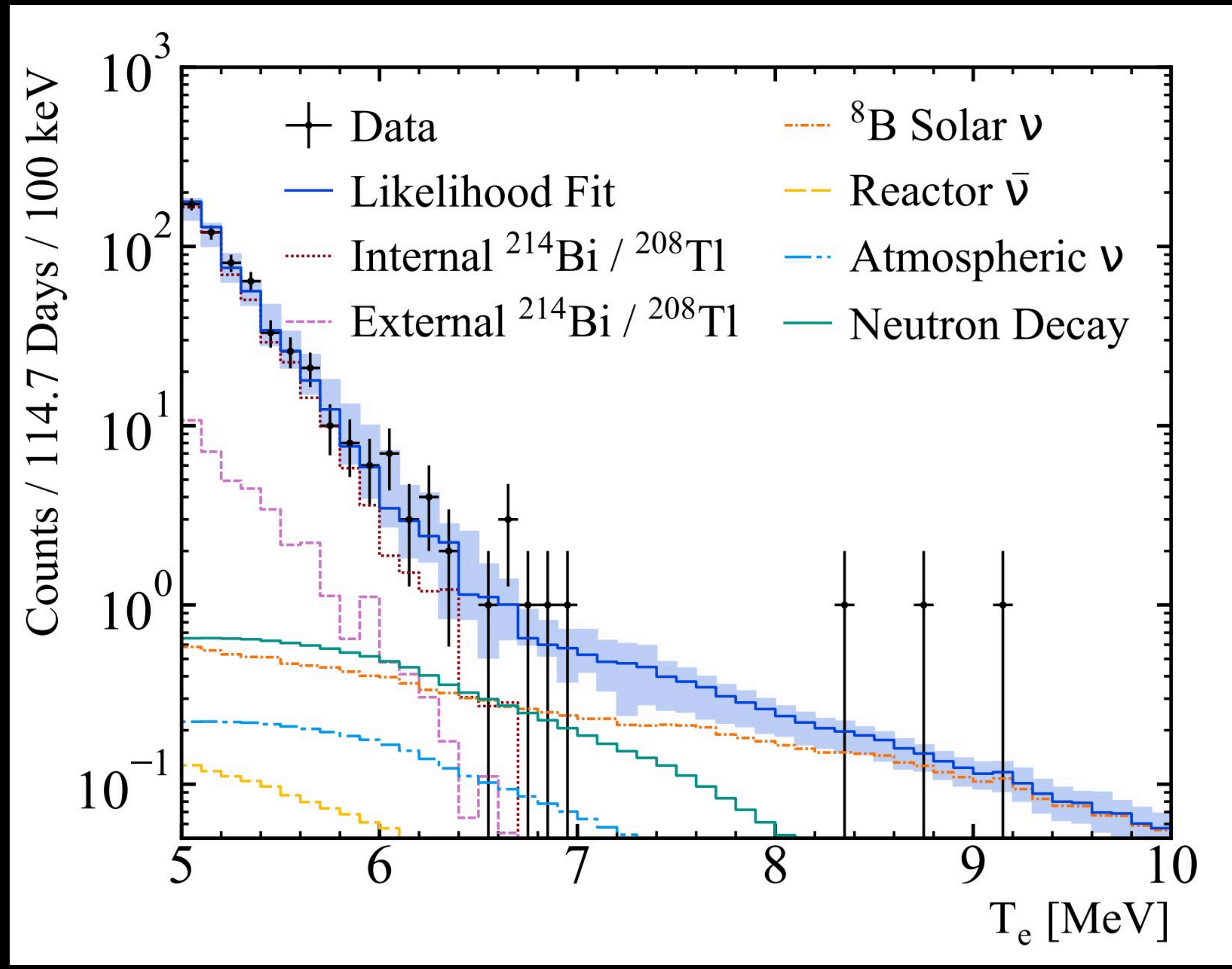
Box analysis performed
Fitted scale factors reduce 0νββ ROI backgrounds from 1.21 to 0.93 events / year
ie >20% below goals

Water Phase Physics Results

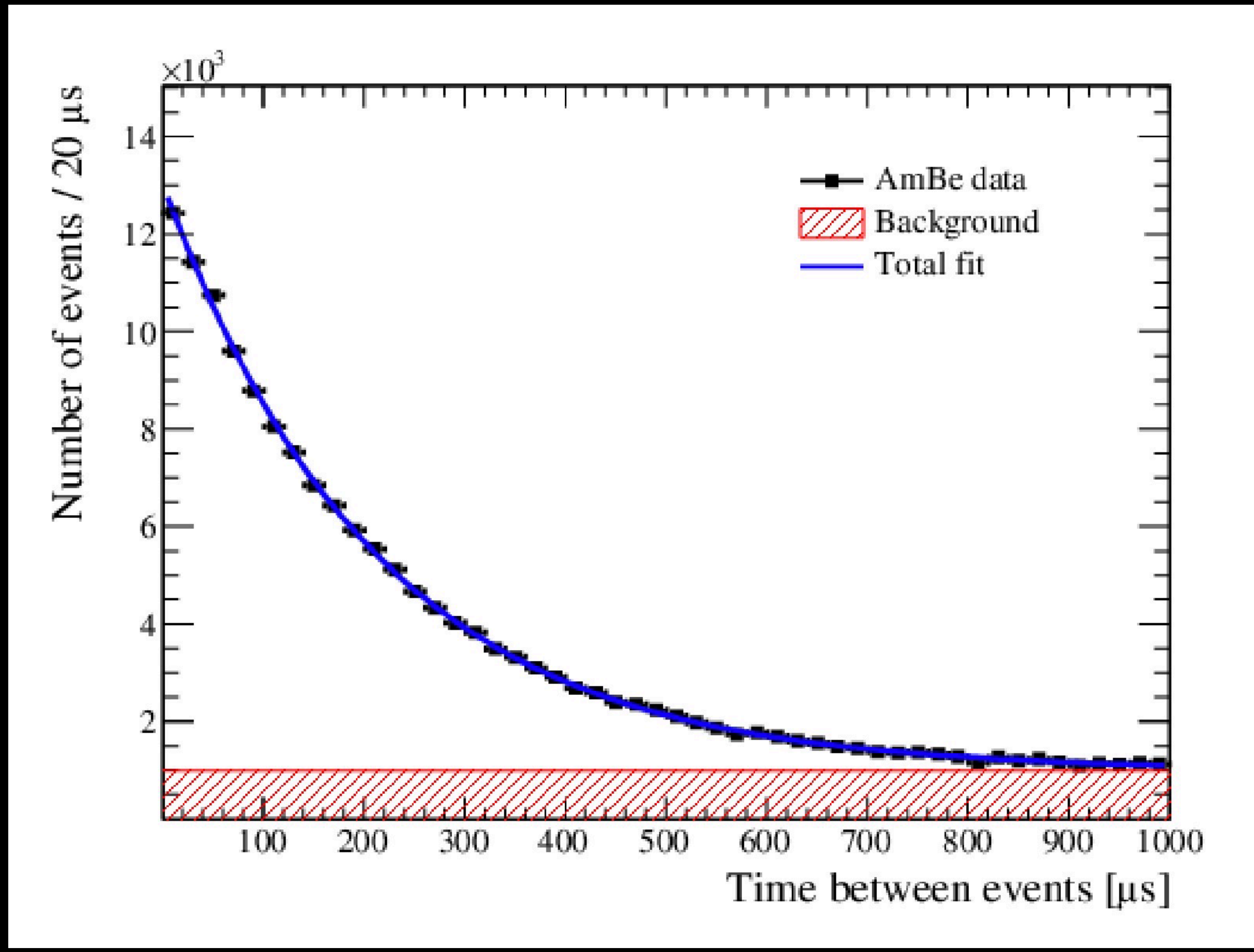
Dataset I (115 days)



^{8}B Solar neutrino flux
Phys. Rev. D 99, 012012 (2019)



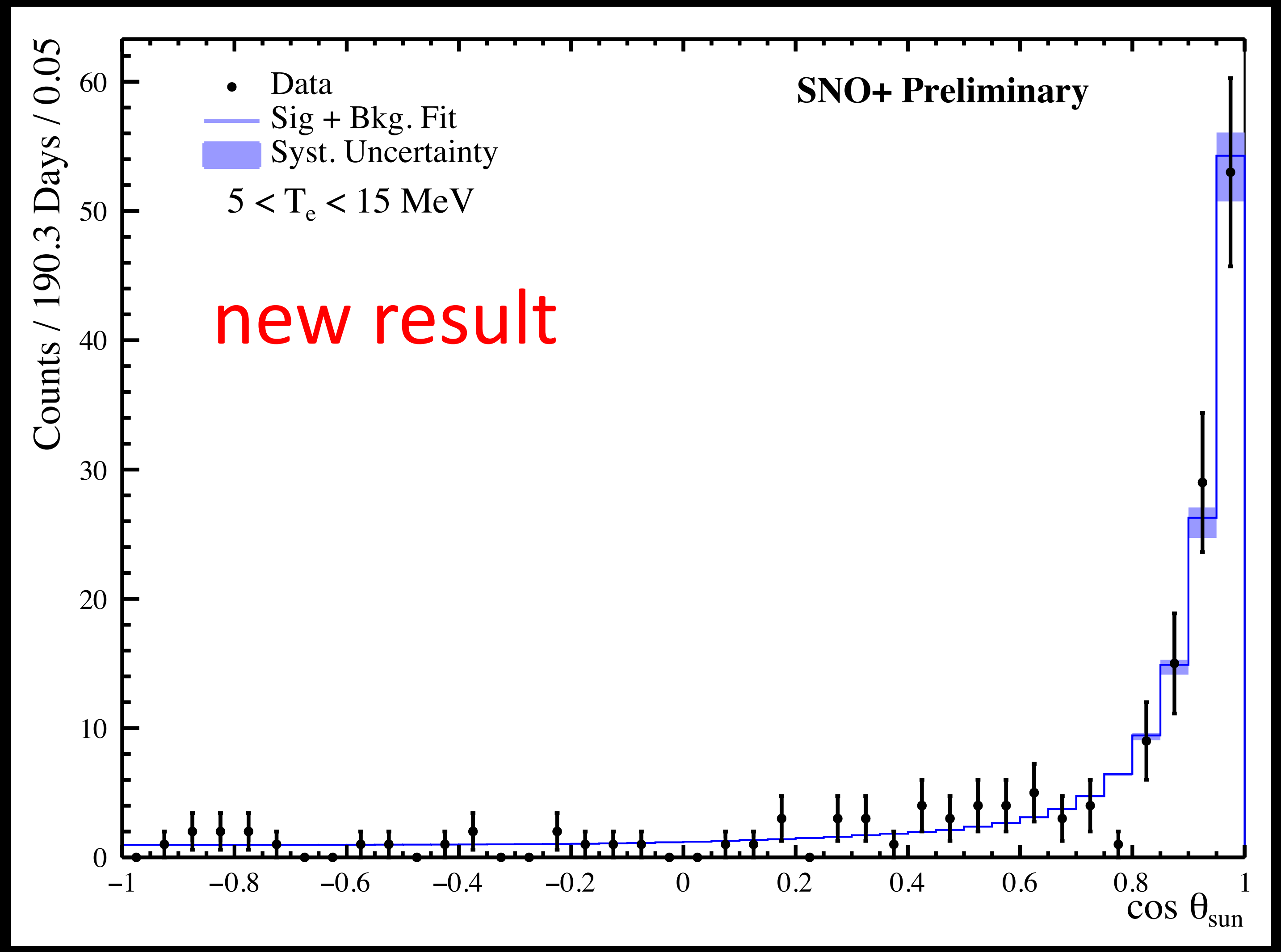
New limits for p, pp and pn invisible nucleon decay modes
Phys. Rev. D 99, 032008 (2019)



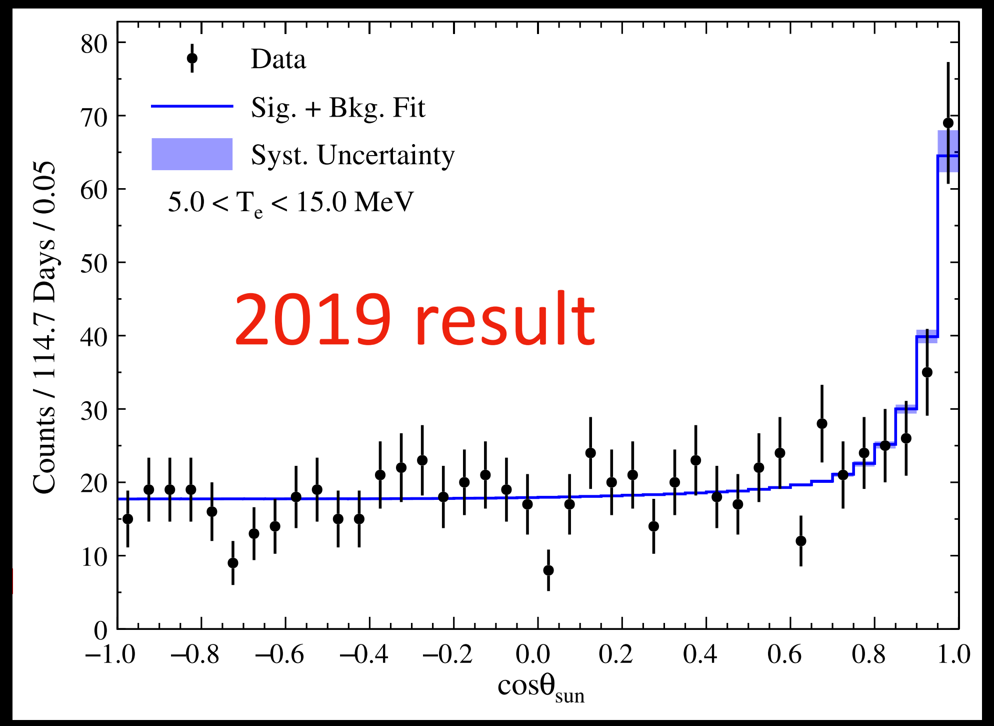
~50% efficiency for triggering on a neutron in pure water
Phys. Rev. C 102, 014002 (2020)

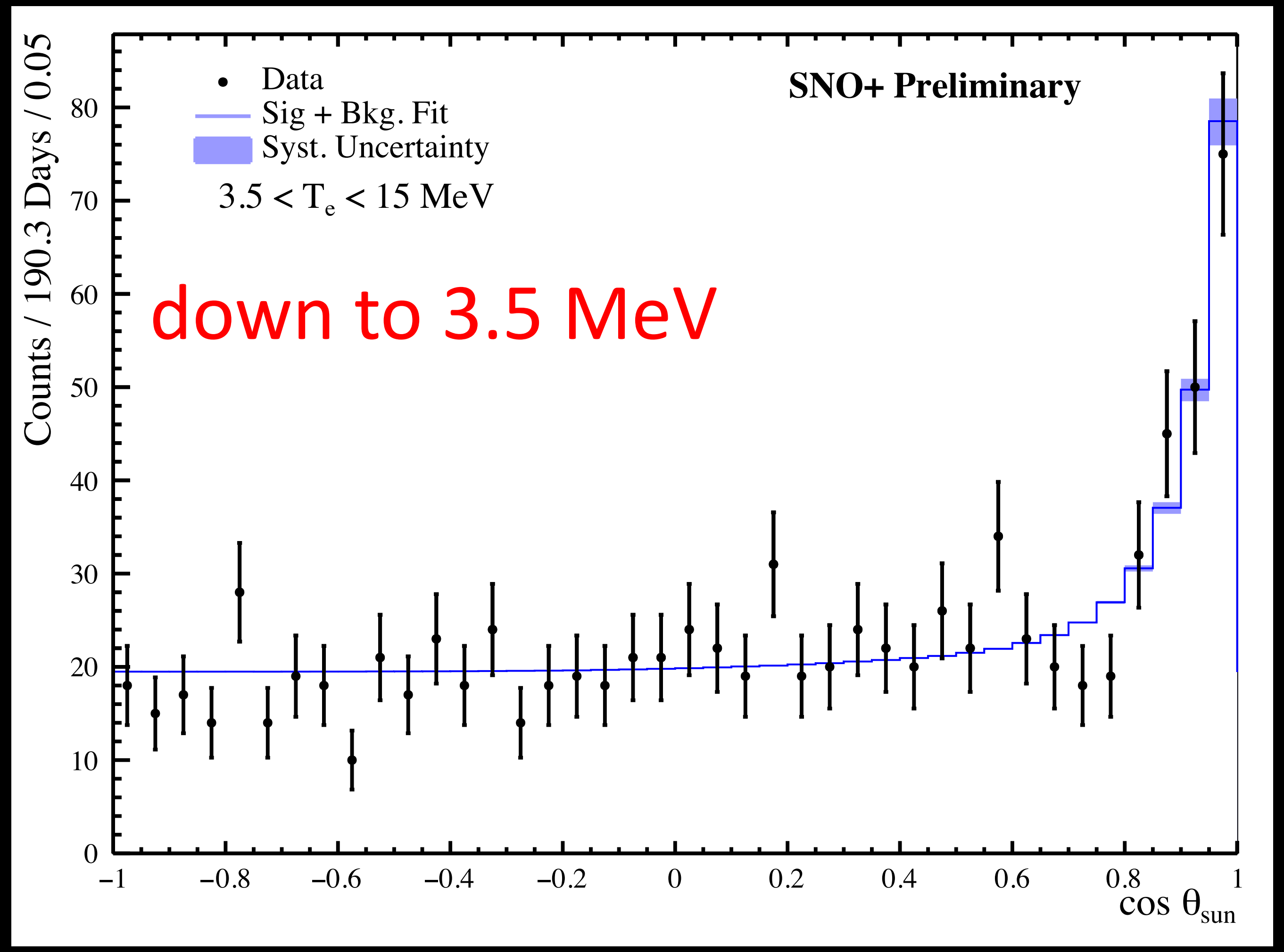
Water Phase Physics Results

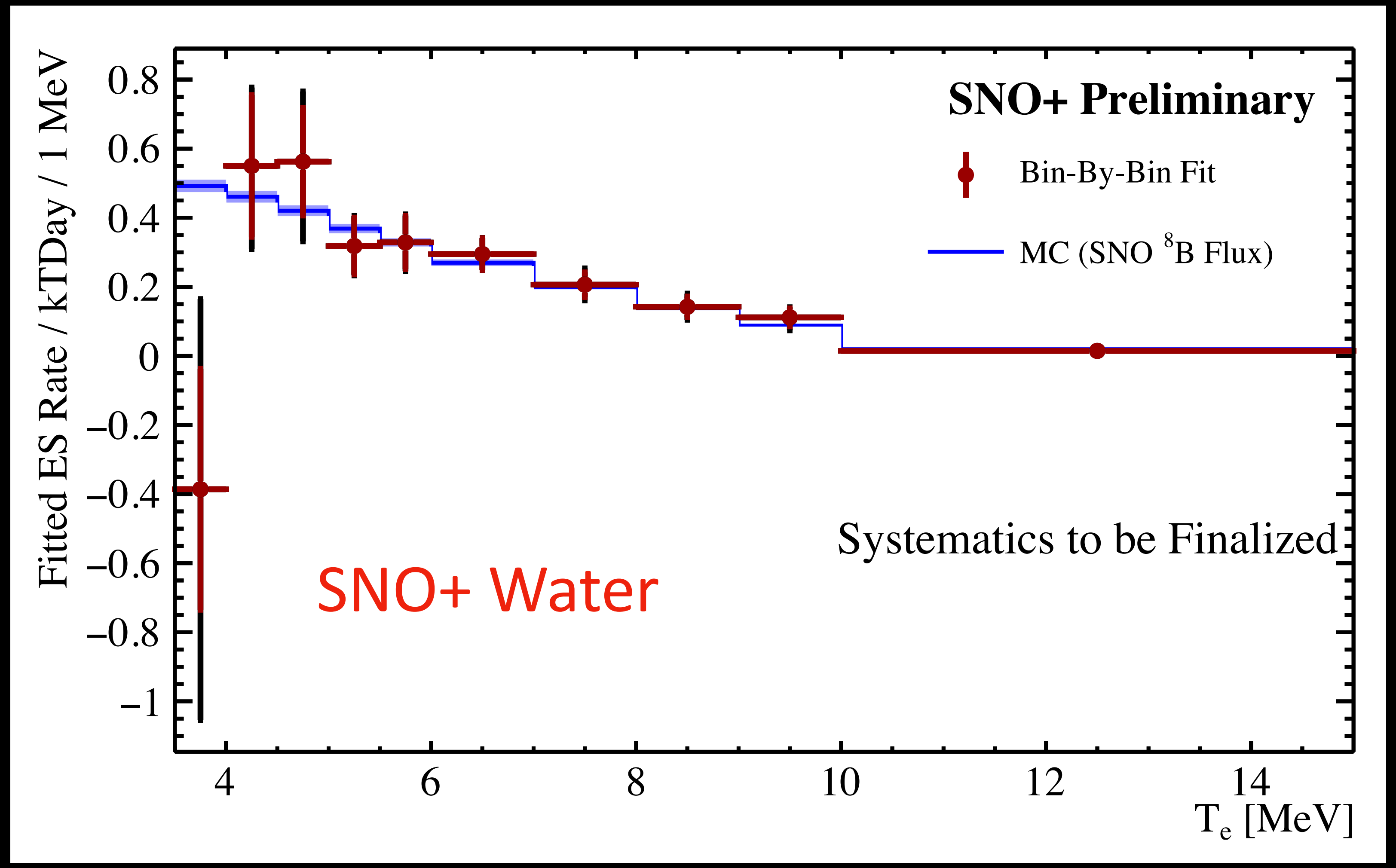
Updated Solar ν results - Dataset II (~190 days)



Same threshold.







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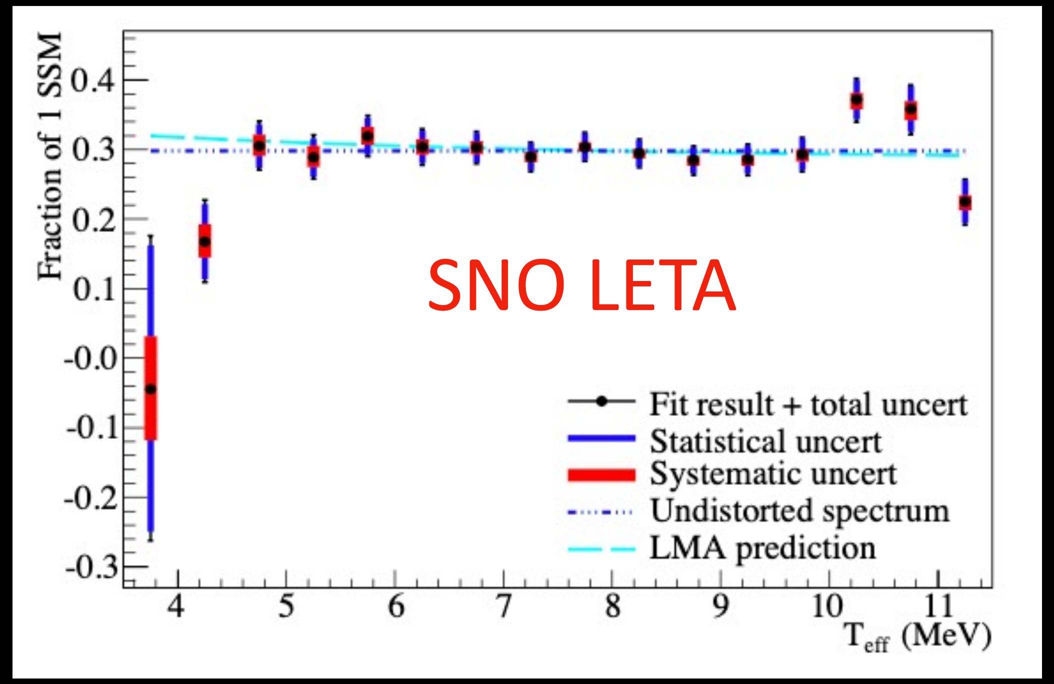
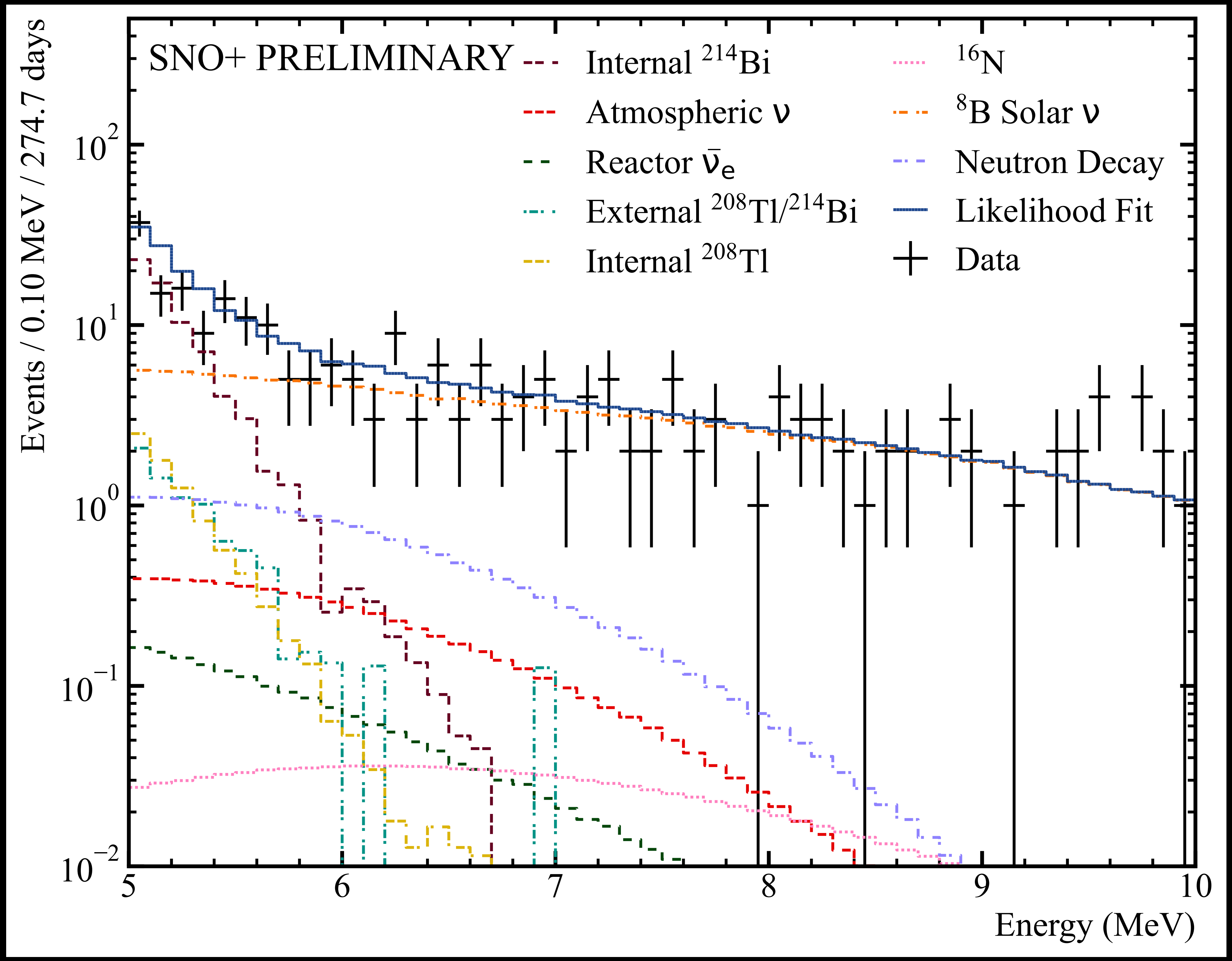


Water Phase Physics Results

Updated Nucleon Decay results - Dataset II (~190 days)

- World's best limits on invisible modes of nucleon decay
  - Recently updated in arXiv:2205.06400
-



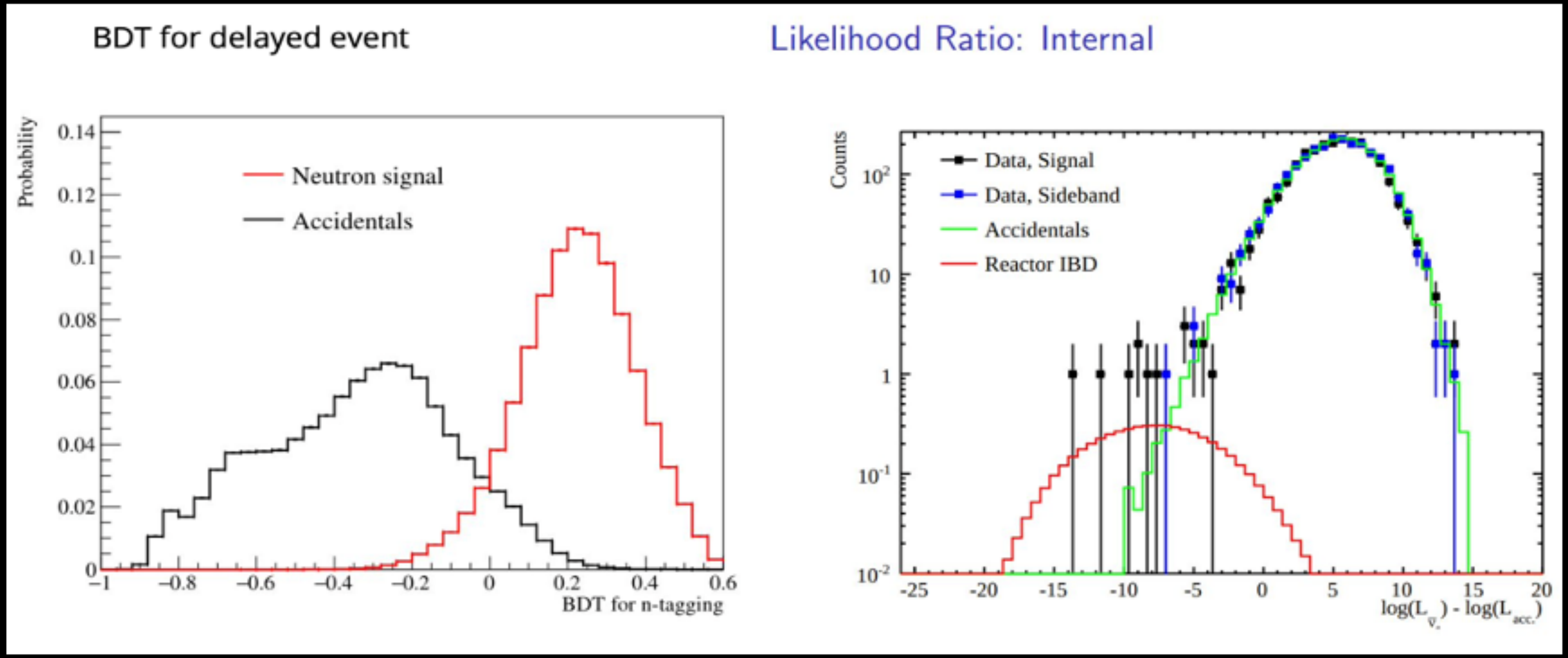
Decay Mode	Partial Lifetime Limit	Existing Limits
n	9.0×10^{29} y	5.8×10^{29} y [5]
p	9.6×10^{29} y	3.6×10^{29} y [6]
pp	1.1×10^{29} y	4.7×10^{28} y [6]
np	6.0×10^{28} y	2.6×10^{28} y [6]
nn	1.5×10^{28} y	1.4×10^{30} y [5]

Improvement of a factor of 3 over existing limits

Water Phase Physics Results

Antineutrino Observation

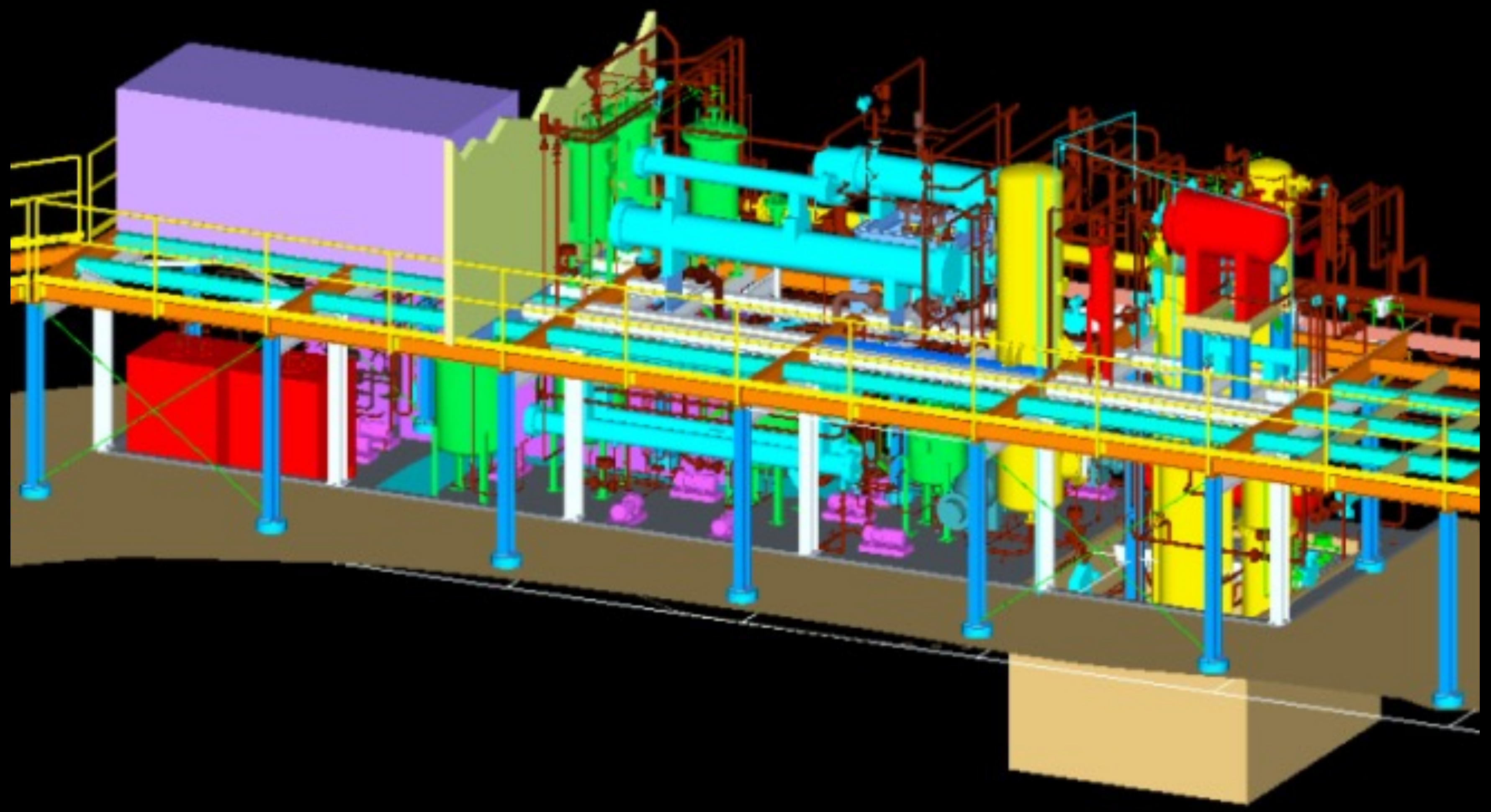
- First observation of reactor $\overline{\nu} + p \rightarrow e^{+} + n$ events using pure water (undoped)
    - publication being prepared; detection of 9 and 10 events in two distinct analyses (BDT and likelihood) with >3 sigma significance
    - made possible by ~50% neutron detection efficiency (highest in a water Cherenkov detector)

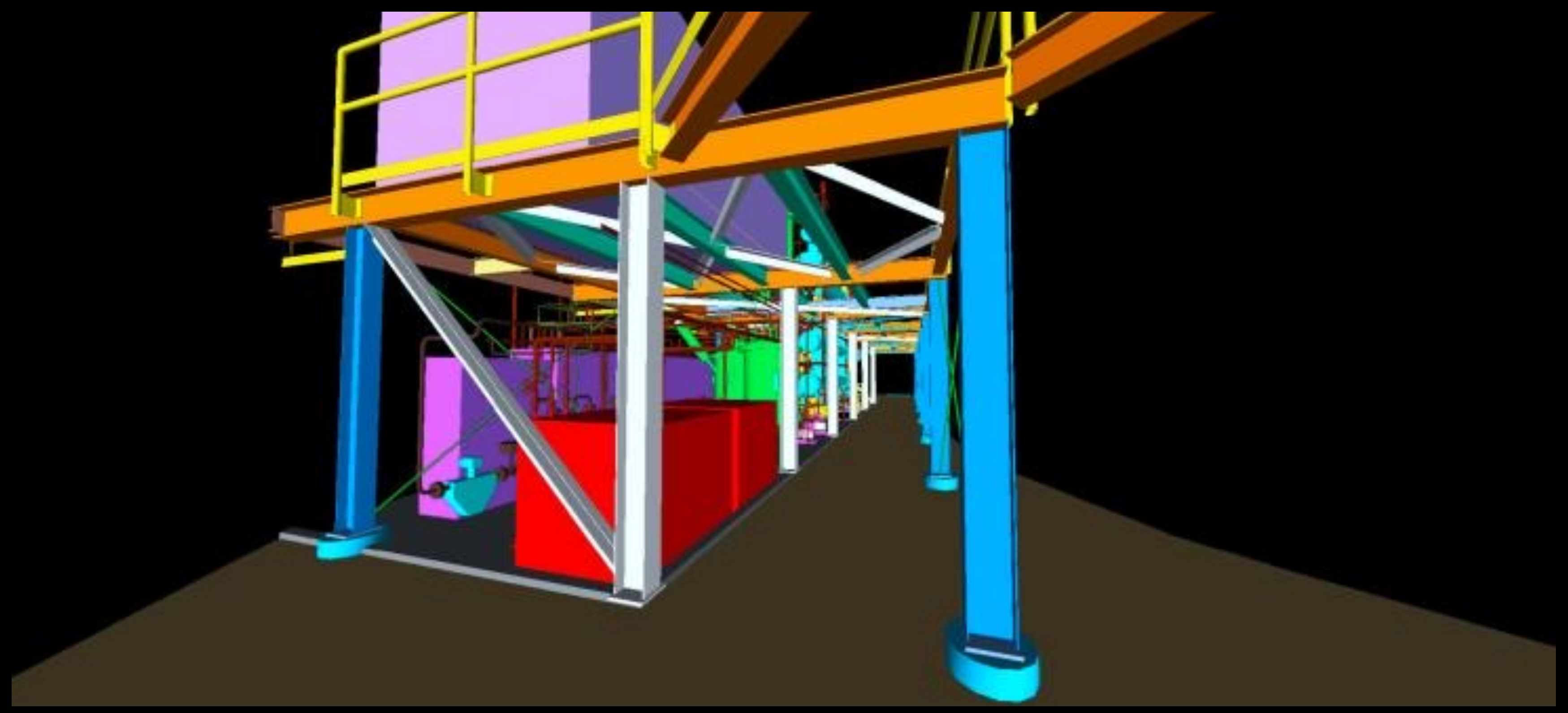


this result does not challenge our understanding of Δm^2_{21}; but does draw attention to upcoming SNO+ measurements with full LS that will

SNO+ Scintillator Purification Plant

- reinforced mezzanine steel
- installed columns, vessels, heat exchangers, tank, pumps, valves, high-grade sanitary piping (orbital- welded, electropolished2012 stainless steel tubing)
- utility plumbing (cooling water, compressed air, vent, boil-off nitrogen)
- process control, wiring, instrumentation, electrical
- firewalls, fire detection and suppression

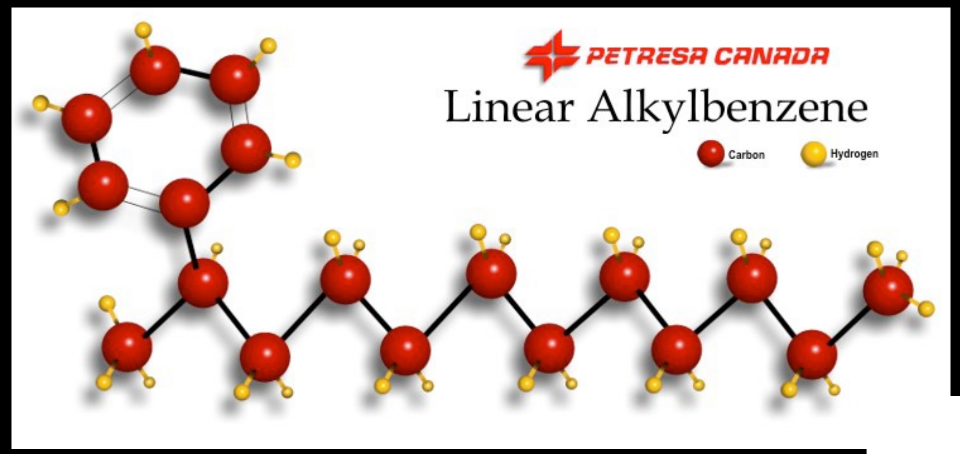




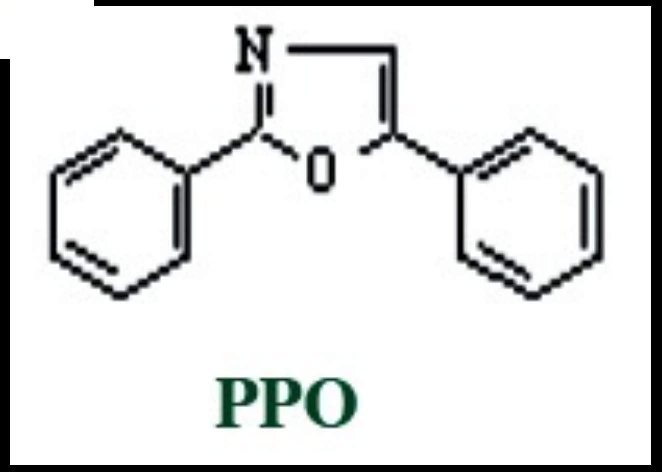
Scintillator Filling

Purification and filling systems underground

Transfer via railcar from surface to underground

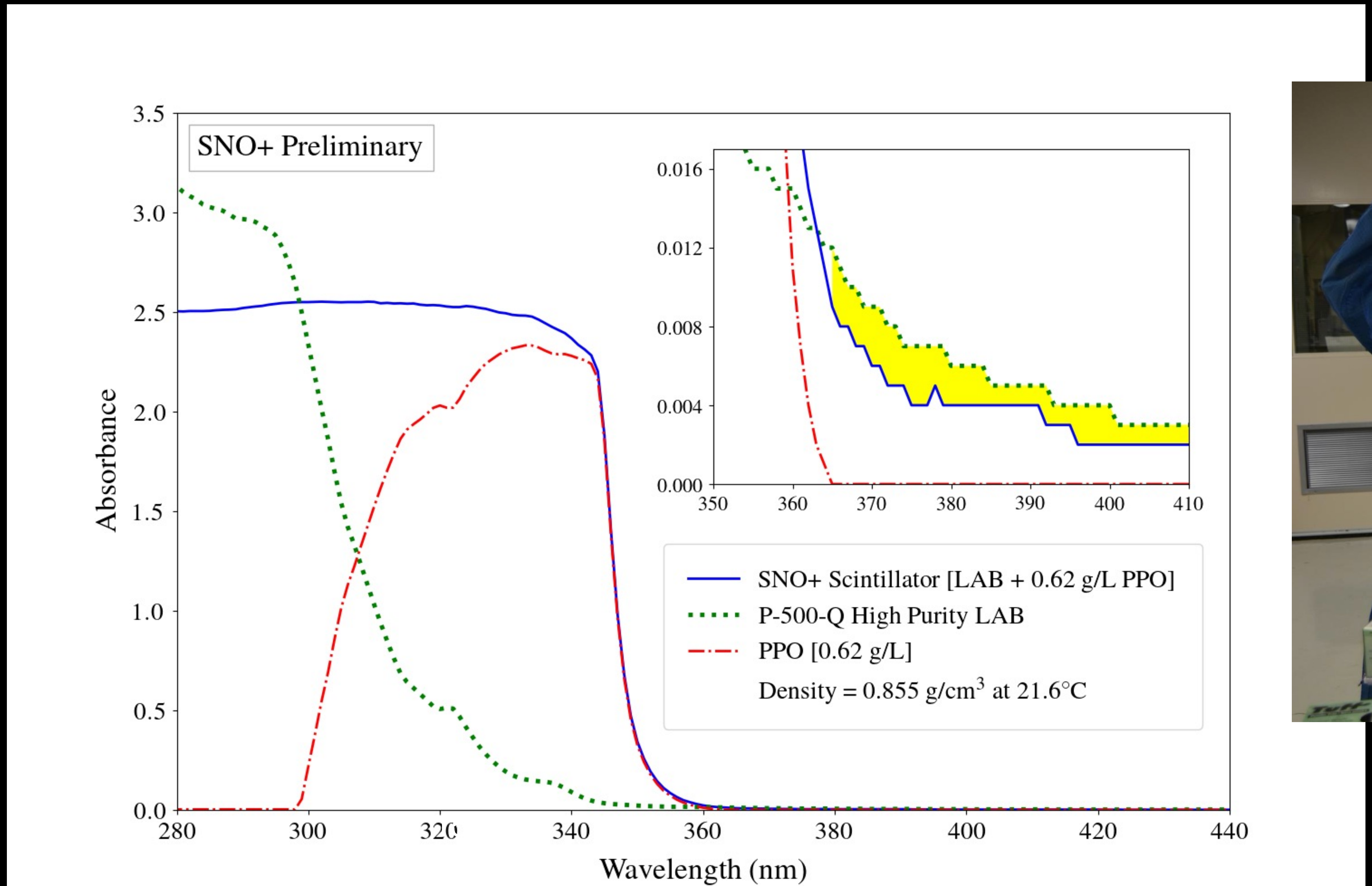


LAB + 2g/L PPO

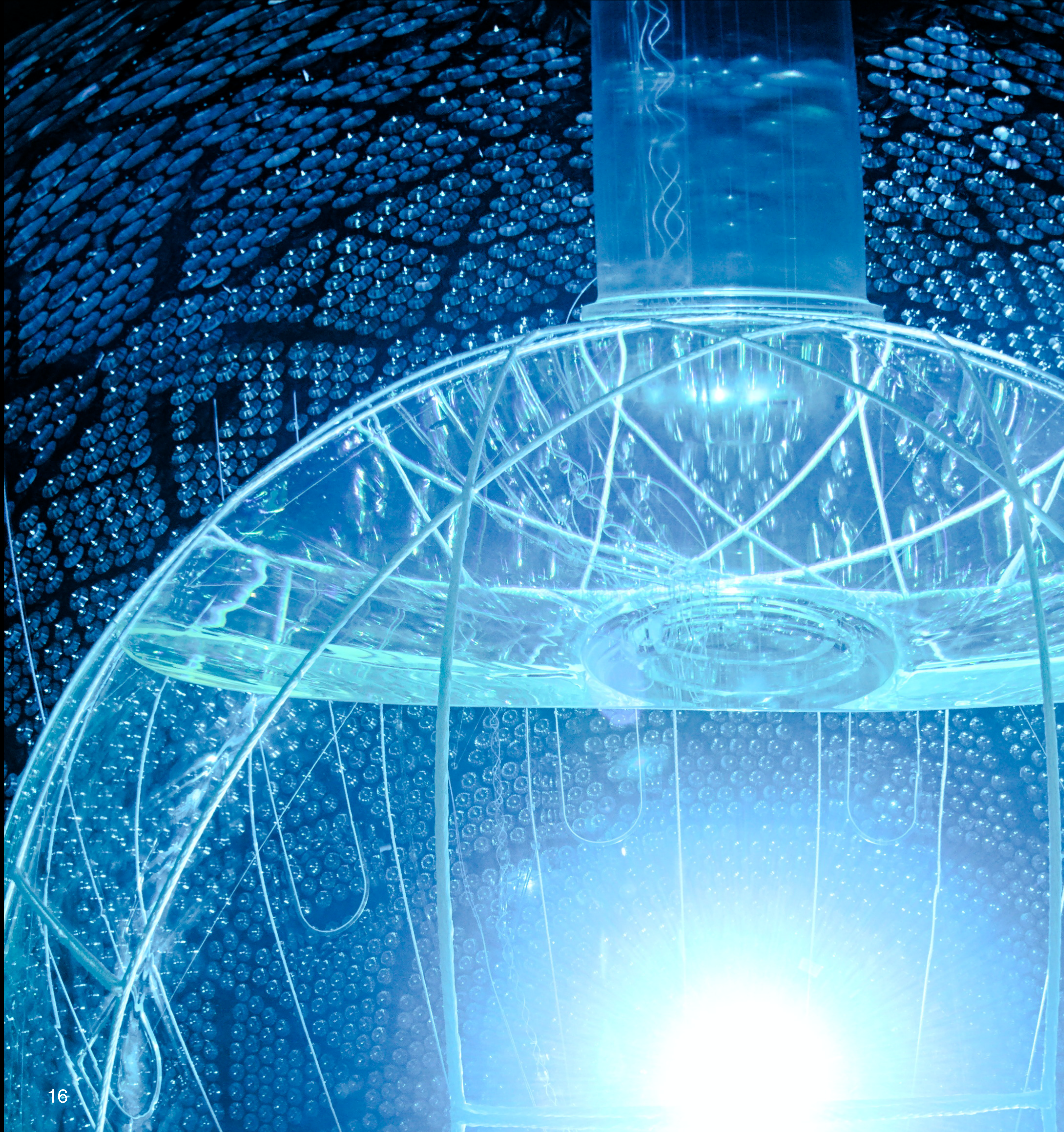


LAB, Master Solution, and final scintillator assessed for quality hourly during purification plant operation and detector filling

- Observe excellent clarity above PPO absorption (UV-Vis spectroscopy)
- Light yield in excess of calibration standards



SNO+ Partial Scintillator-Fill Phase



SNO+ Timeline

Partial Fill Phase

2016 2017 2018 2019 2020 2021 2022 2023

Dec 2016
Start of
Commissioning
Data Taking

May 2017
Start of Water
Phase

July 2019
Start of
Scintillator Fill

July 2021
End of
Scintillator Fill

Tellurium
Loading

Due to Covid Pandemic, paused with

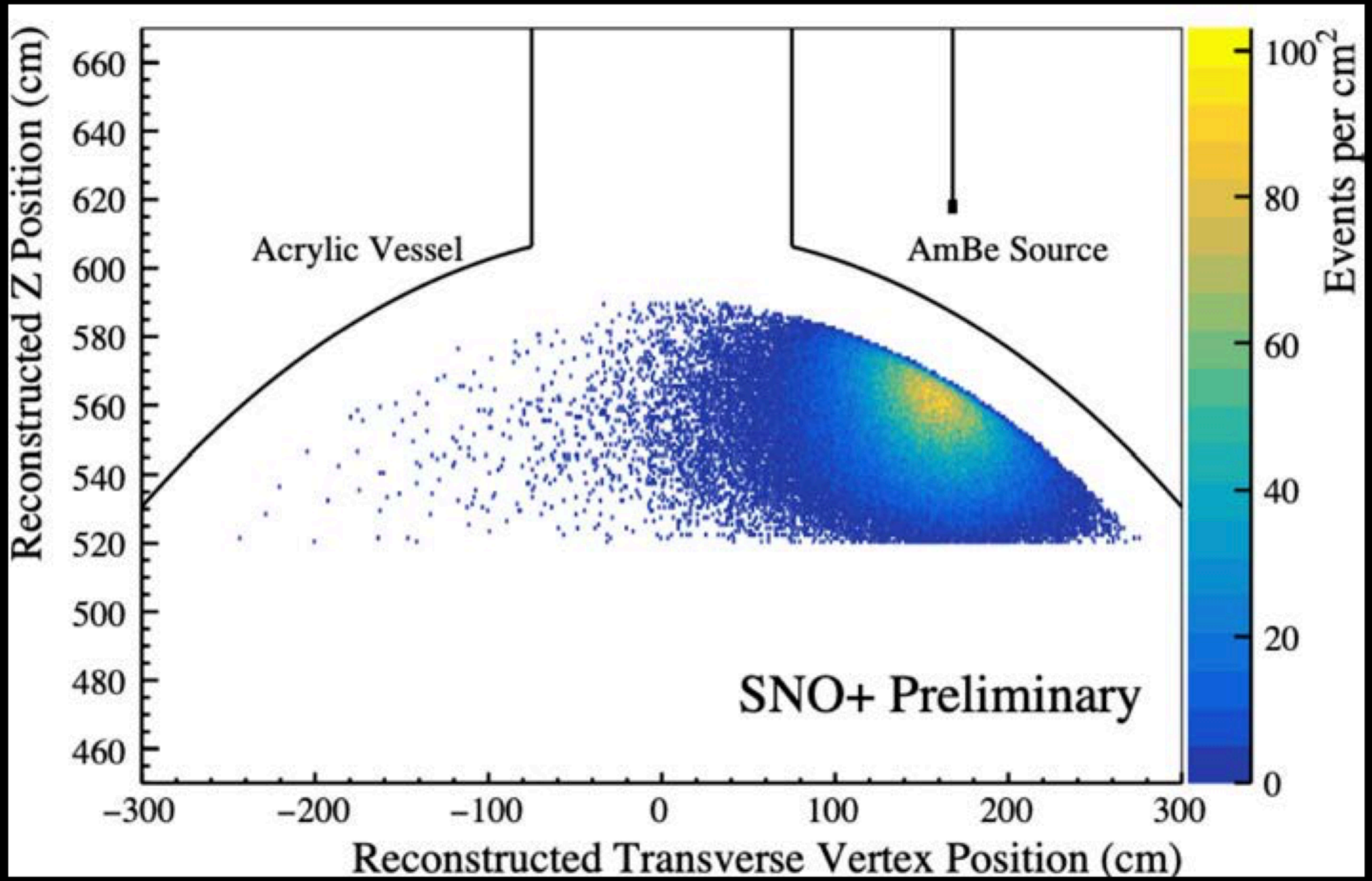
- **365t (47% full) Scintillator**
- **0.5g/L PPO (25% nominal)**
- **for approximately 7 months**

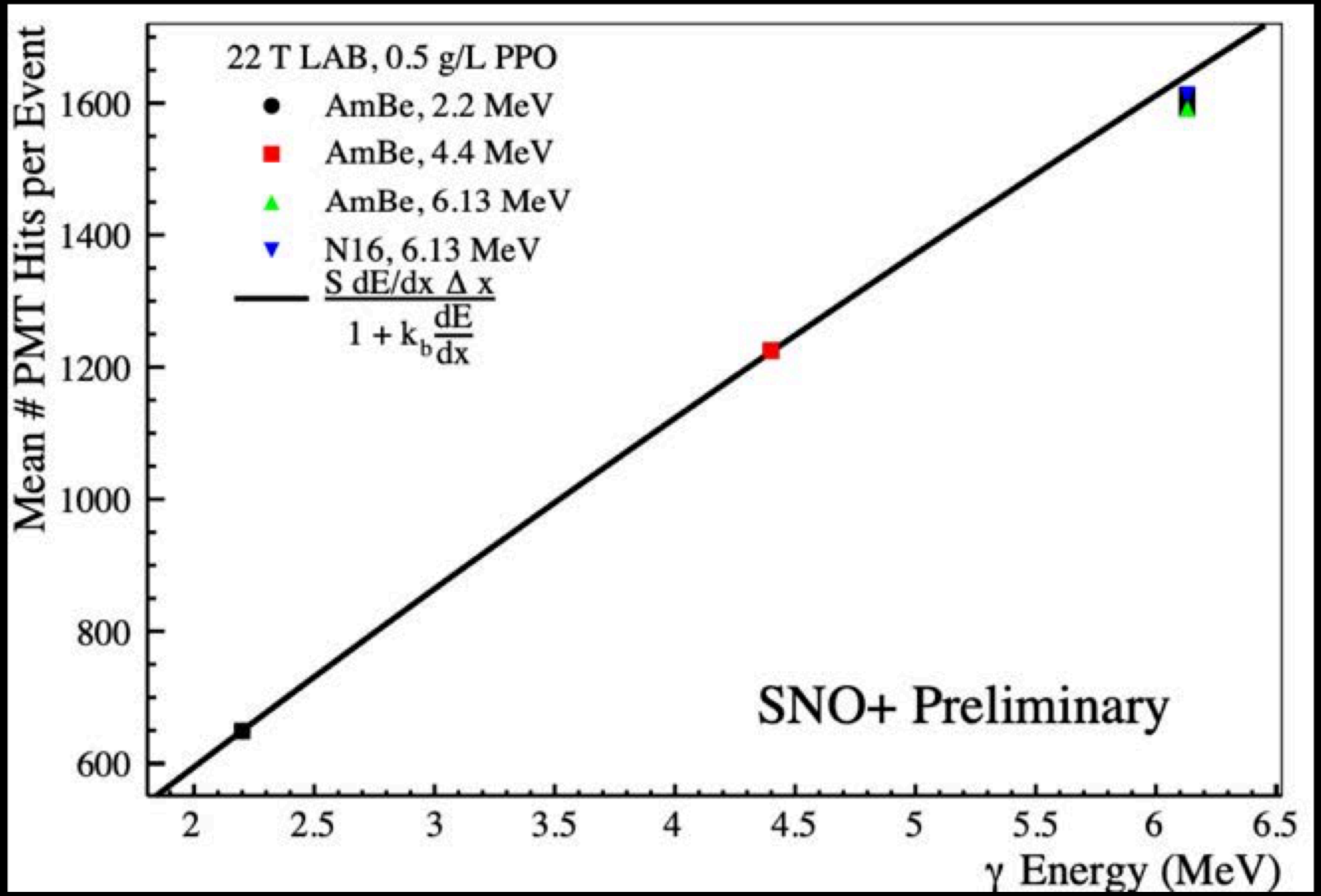
SNO+Partial Fill

Scintillator Light Yield

- Calibration sources (16N, AmBe) deployed through guide tubes into the external water region

- With a PPO concentration of 0.5 g/L (25% of nominal concentration) we saw a LY equivalent of ~300 p.e. / MeV

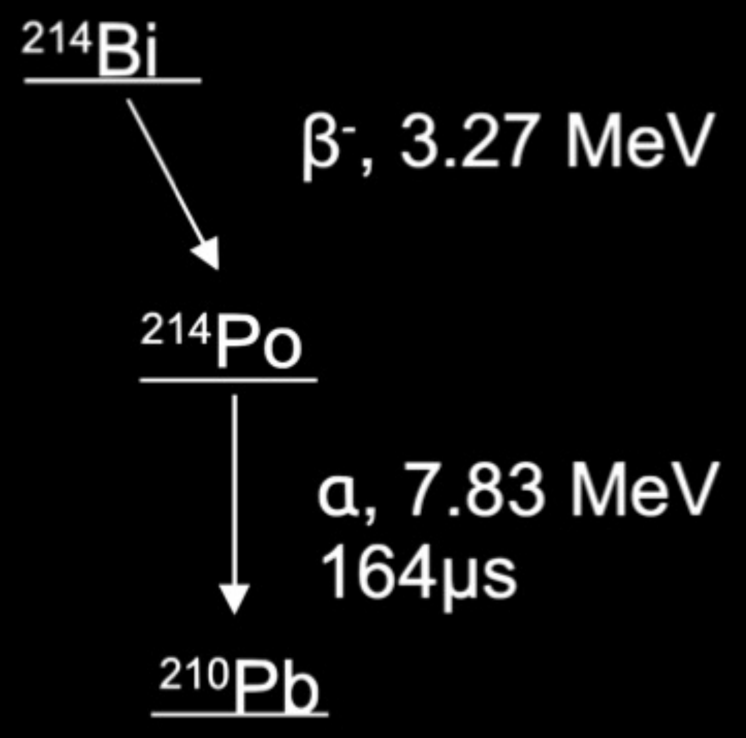




SNO+Partial Fill

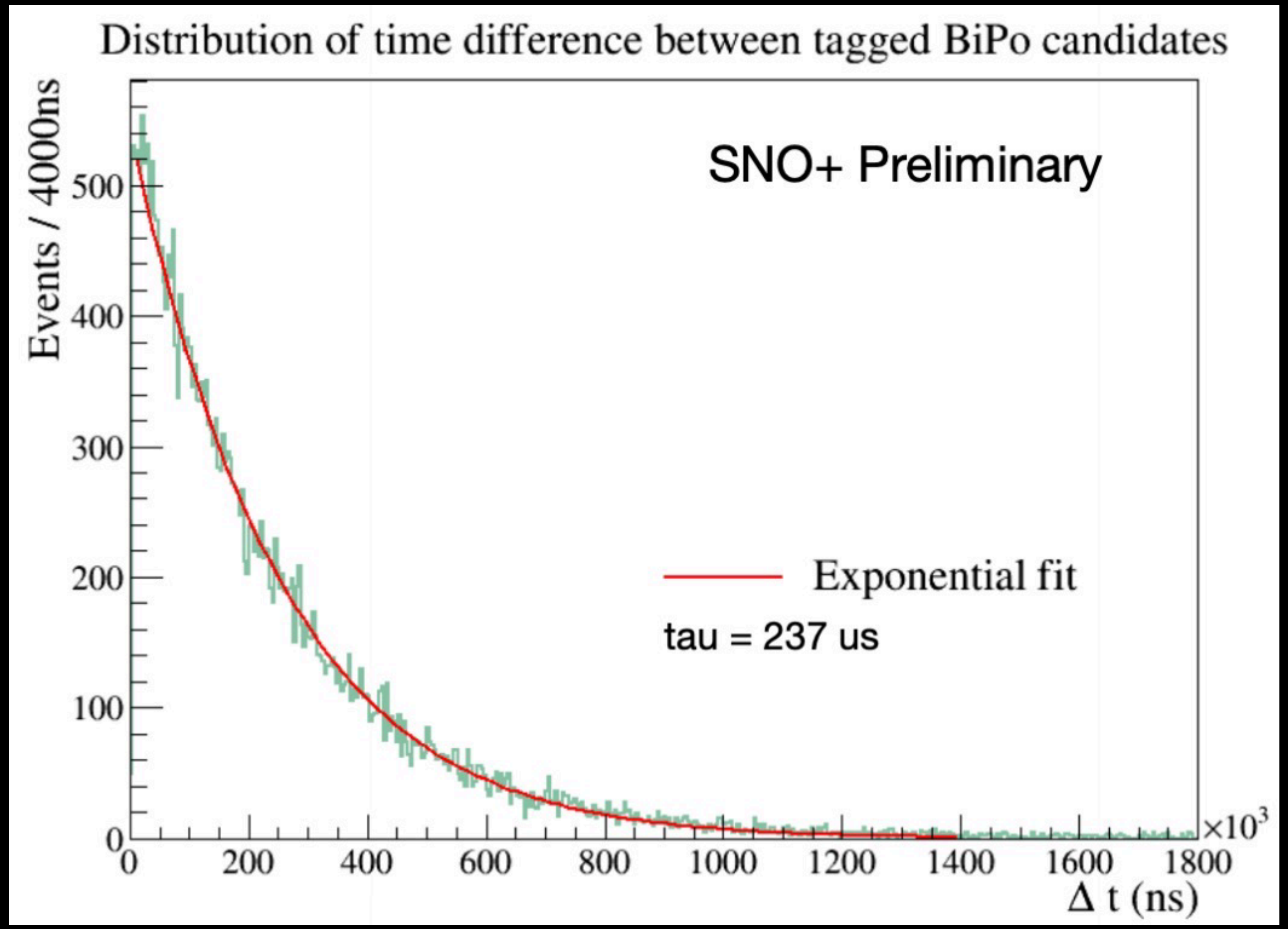
Scintillator Background Measurement

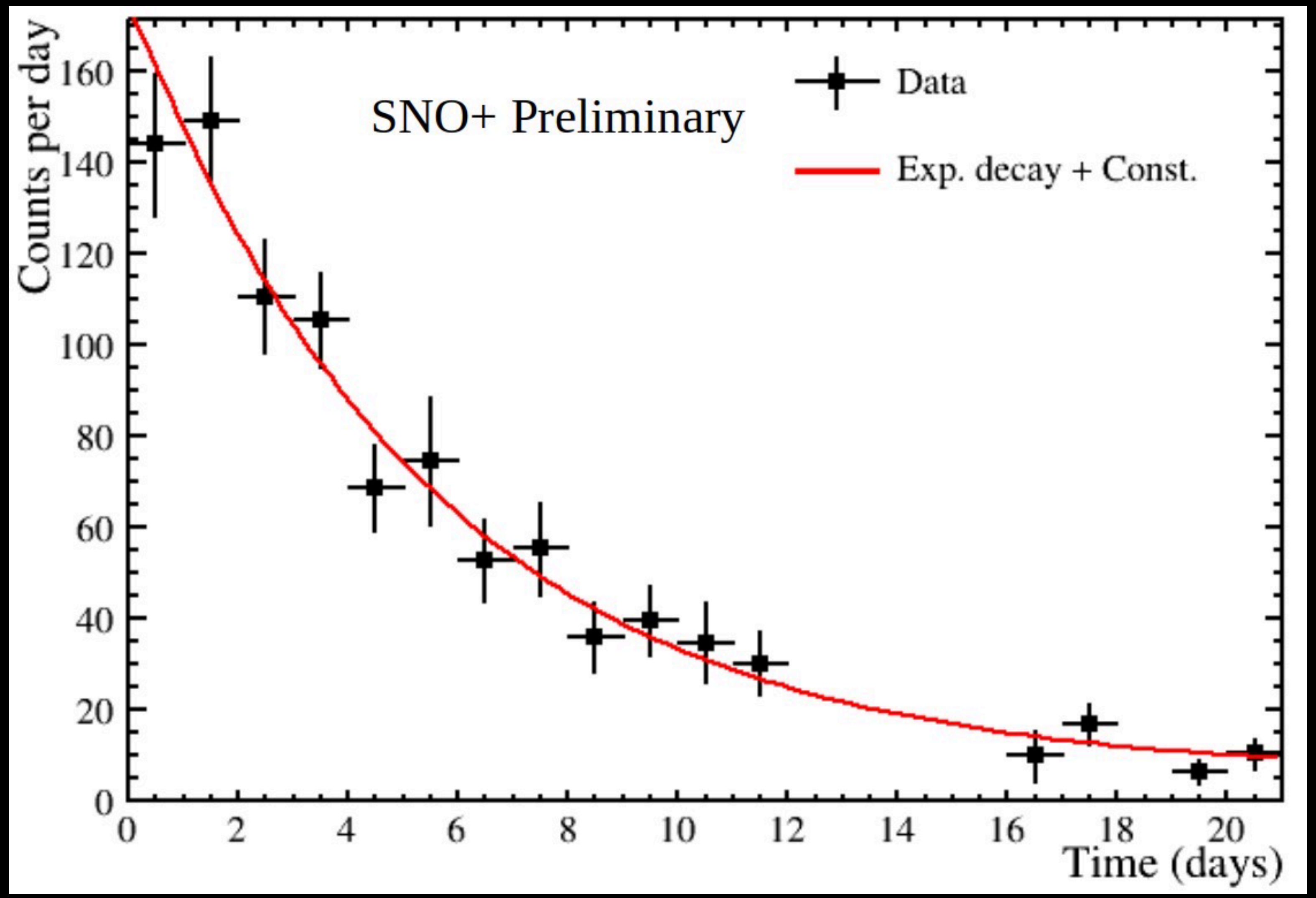
- LS backgrounds measured at
  - ^{214}BiPo delayed coincidences for U chain ($T_{1/2}$ = 164 μs)
    - $(4.7\pm1.2)\times10^{-17}$ g_U/g_{LAB}
  - ^{212}BiPo delayed coincidences for Th chain
    - $(5.3\pm1.5)\times10^{-17}$ g_{Th}/g_{LAB}



Base rate below requirements for 0νββ

- **Opportunity to perform a "target-out" ββ measurement**
  - Test analysis methods
  - Check background model



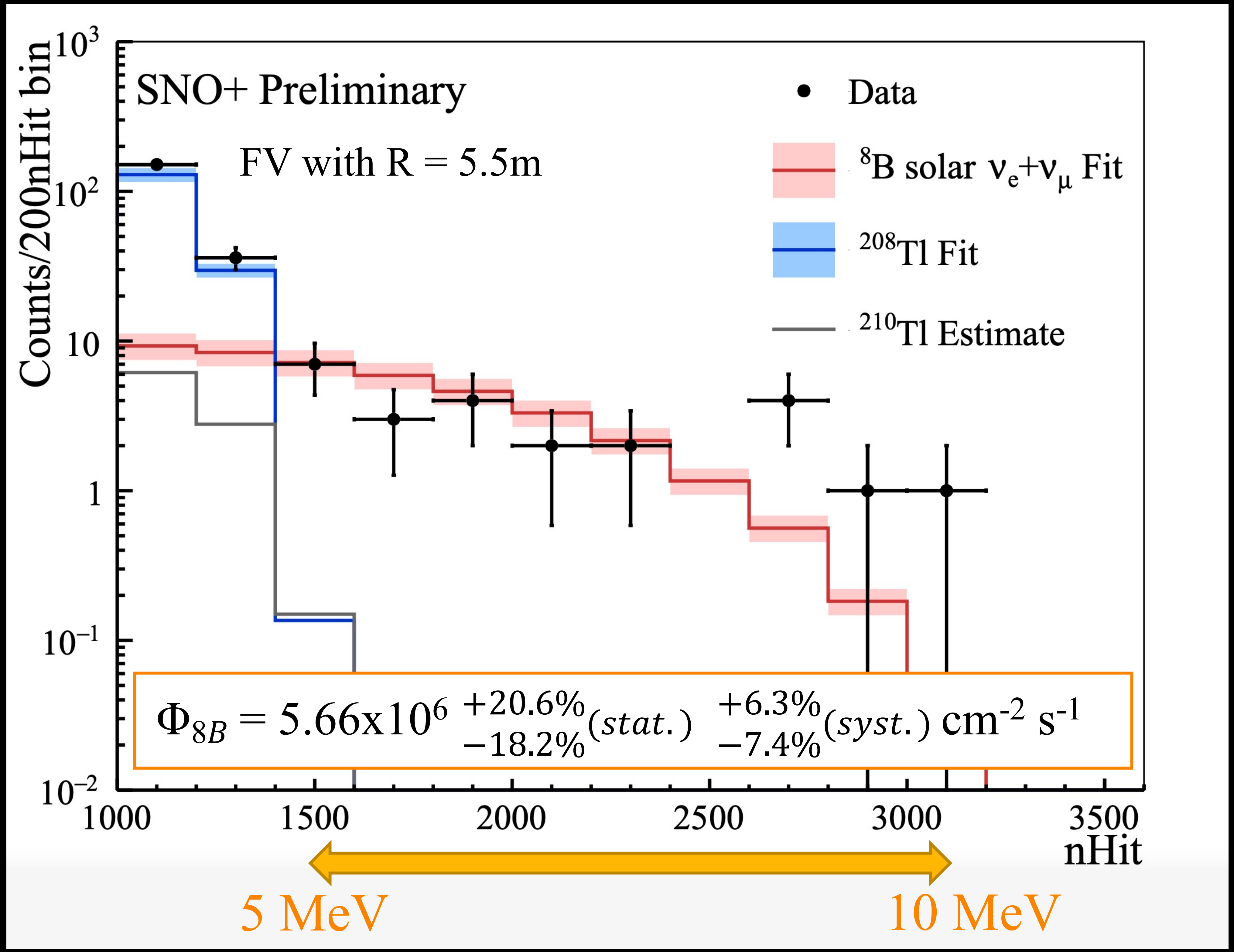


Some Radon (^{222}Rn, $T_{1/2}$ = 3.82 days) introduced with filling that decays away

SNO+Partial Fill

Scintillator Physics

- ^{8}B solar ν + background fit to partial fill data
  - 5.5 m fiducial radius
  - Includes preliminary systematics
  - Flux fitted result compatible with other measurements
- Live for supernova
  - Burst monitoring part of SNEWS-1
  - Pre-supernova monitor enabled (IBD)
- Anti-neutrino measurement
  - Using time coincidence of IBD

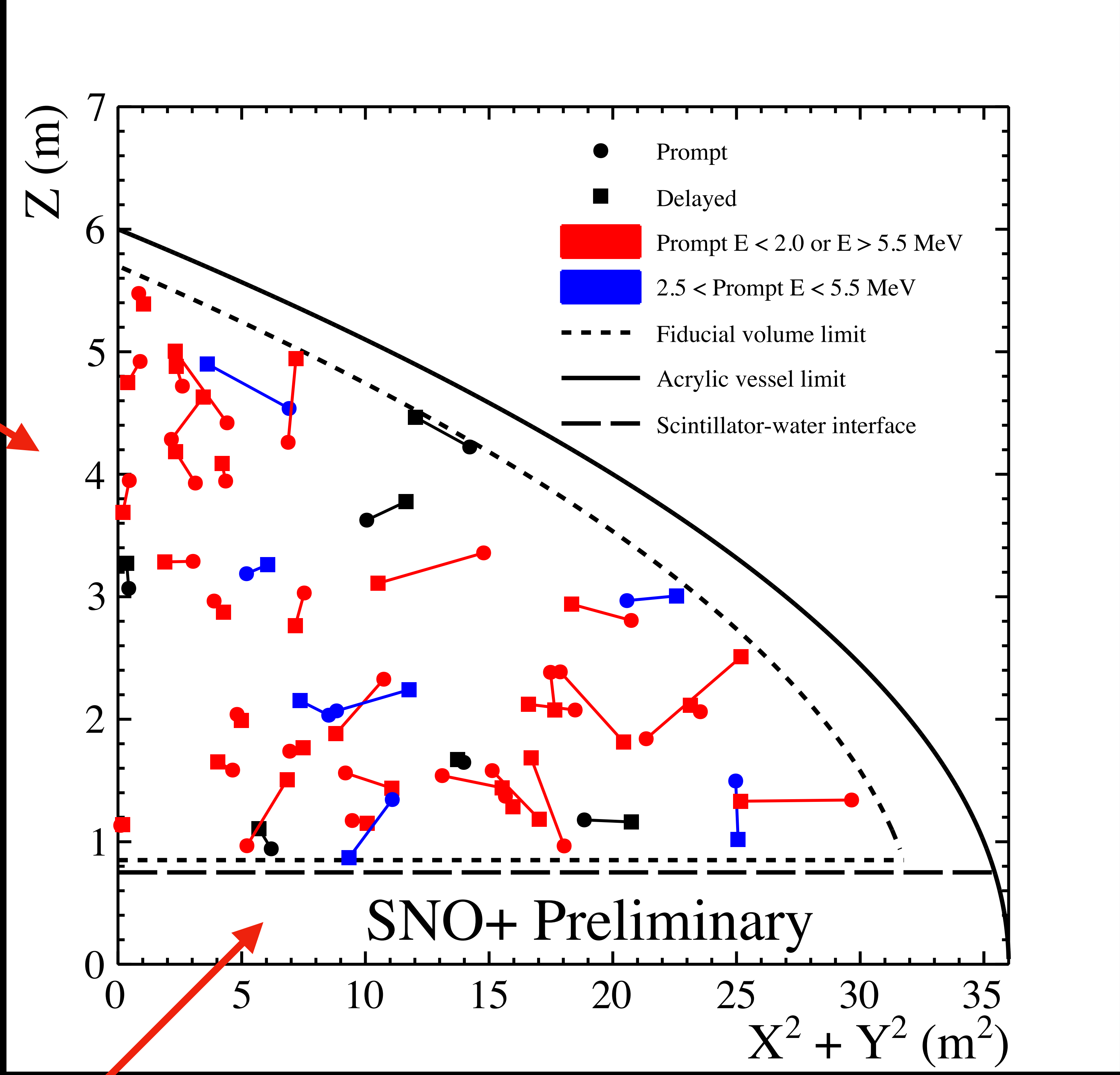


Publication in preparation

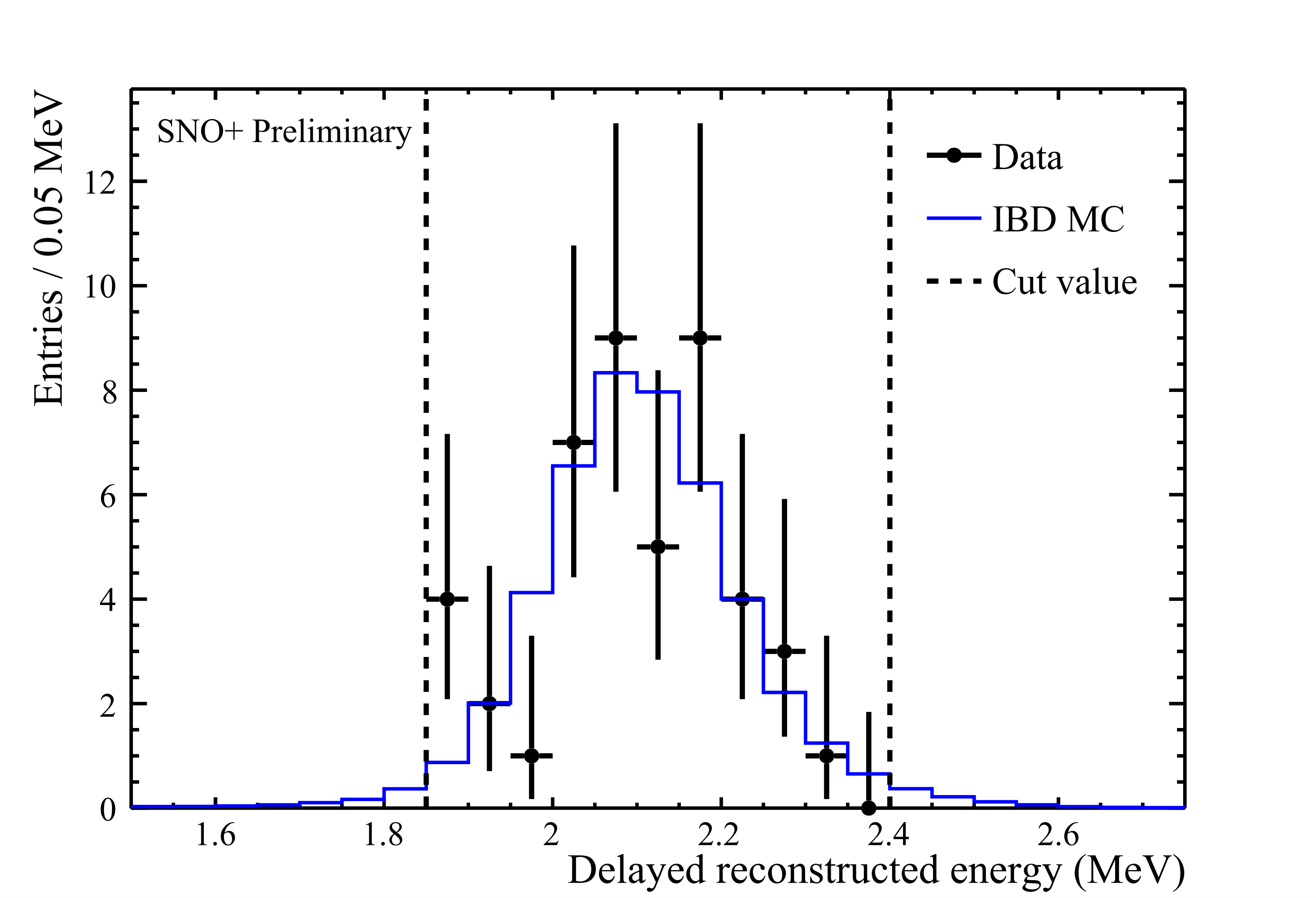
SNO+ reactor antineutrinos

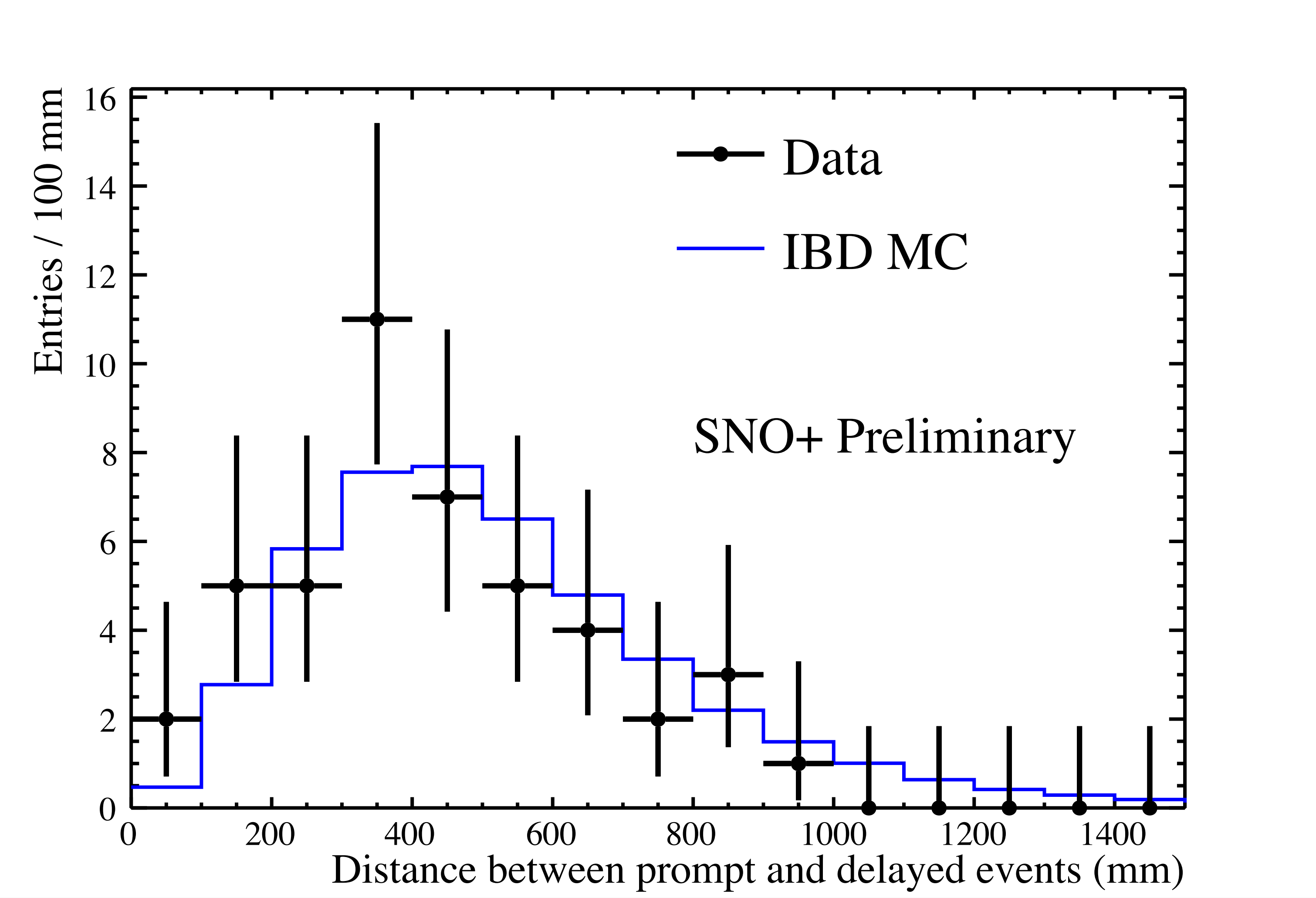
…in partial-fill

Events uniformly distributed in the detector



Fiducialisation to reduce background events from acrylic





S

...in partial-fill

Publication in preparation

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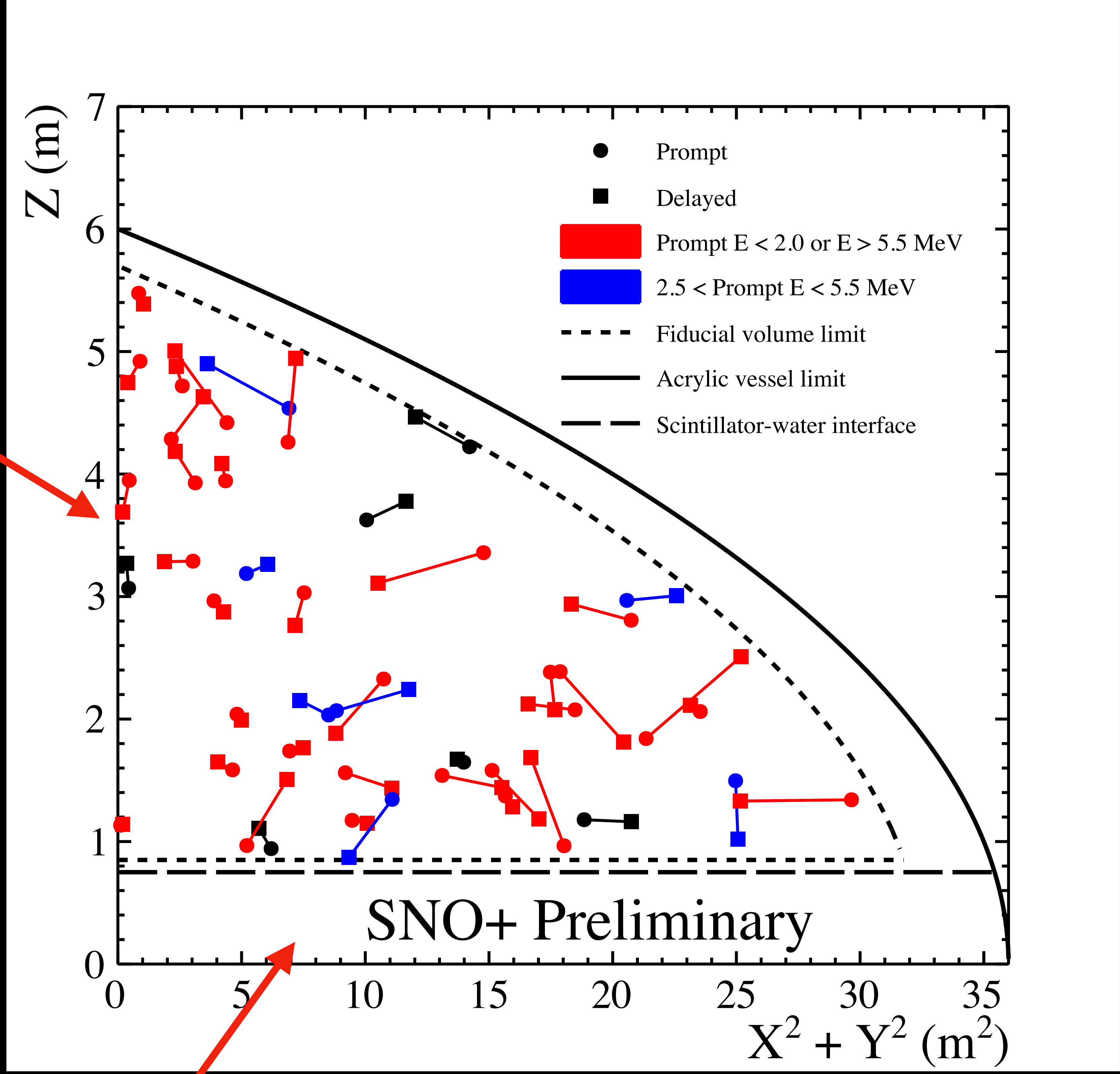

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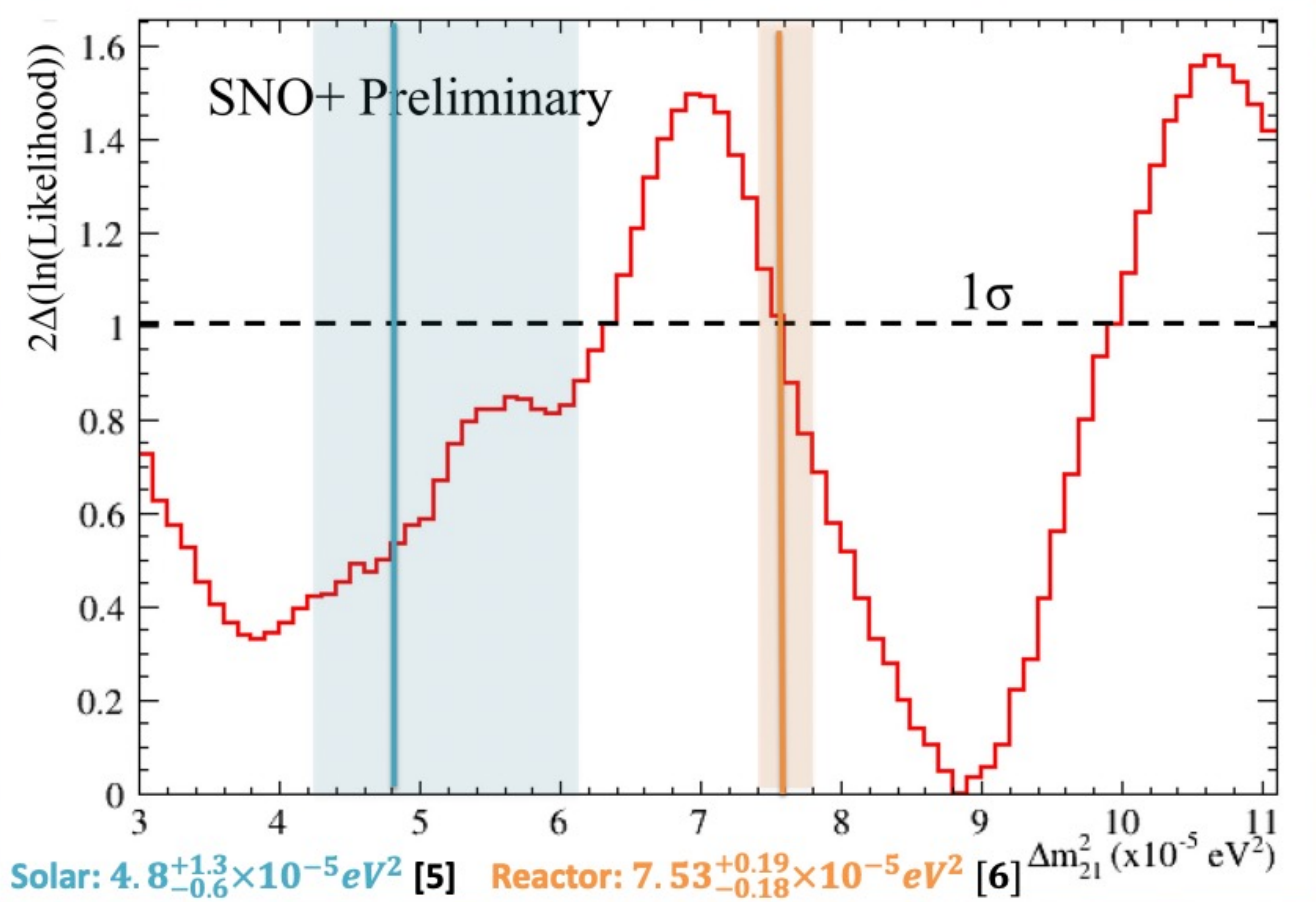


Δm^2_{21} values corresponding to solar and reactor neutrino measurements allowed within 1σ

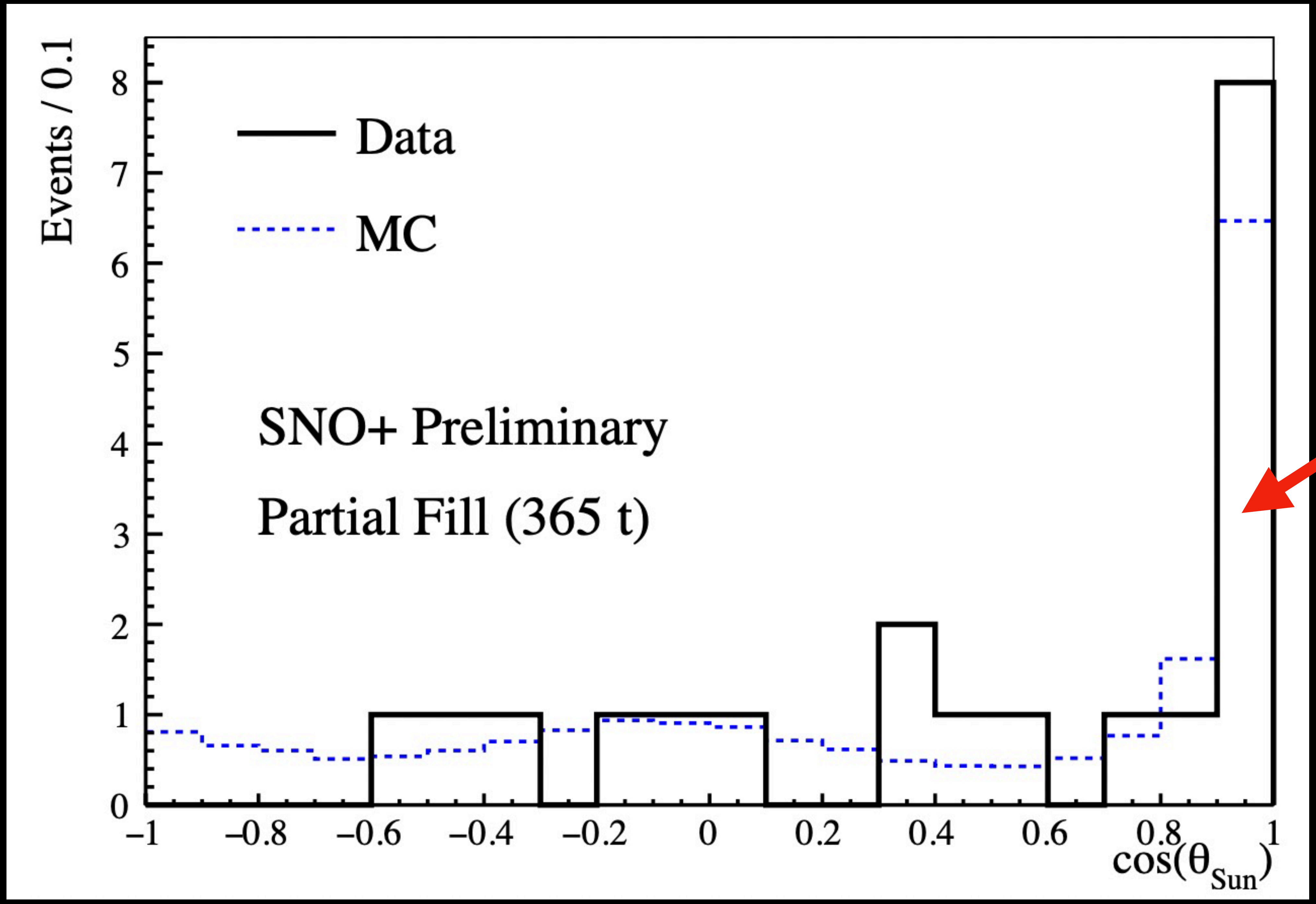
SNO+ Timeline

PPO top-up phase (from 0.5 g/L to 2.2 g/L)

Publication in preparation

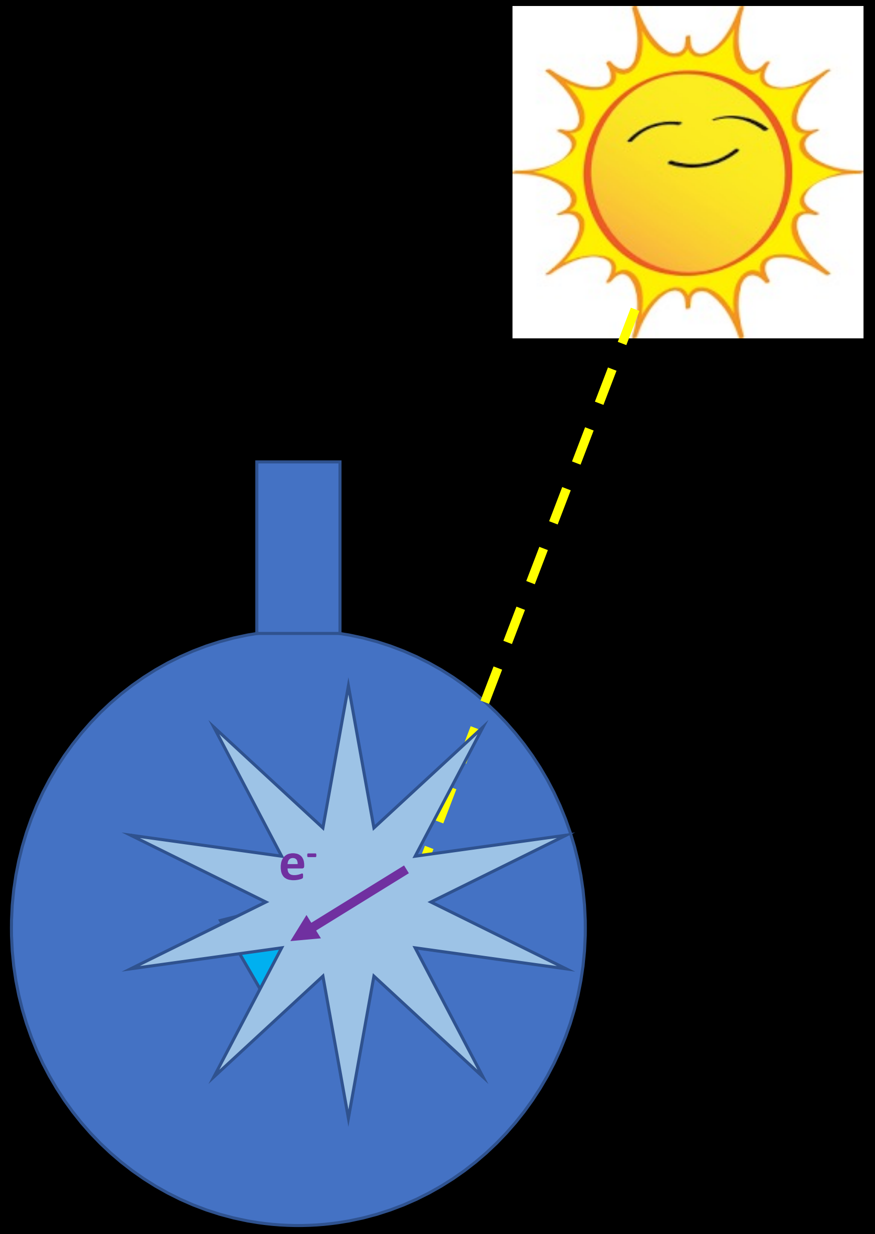
SNO+ direction in scintillation

- Data collected with lower PPO concentration (~0.5 g/L) than nominal (2.2 g/L)
  - Lower LY and slower rise time permits to distinguish early (directional) Cherenkov light



Direction reconstruction from simultaneous Cherenkov + Scintillation fit

Event-by-event direction reconstruction

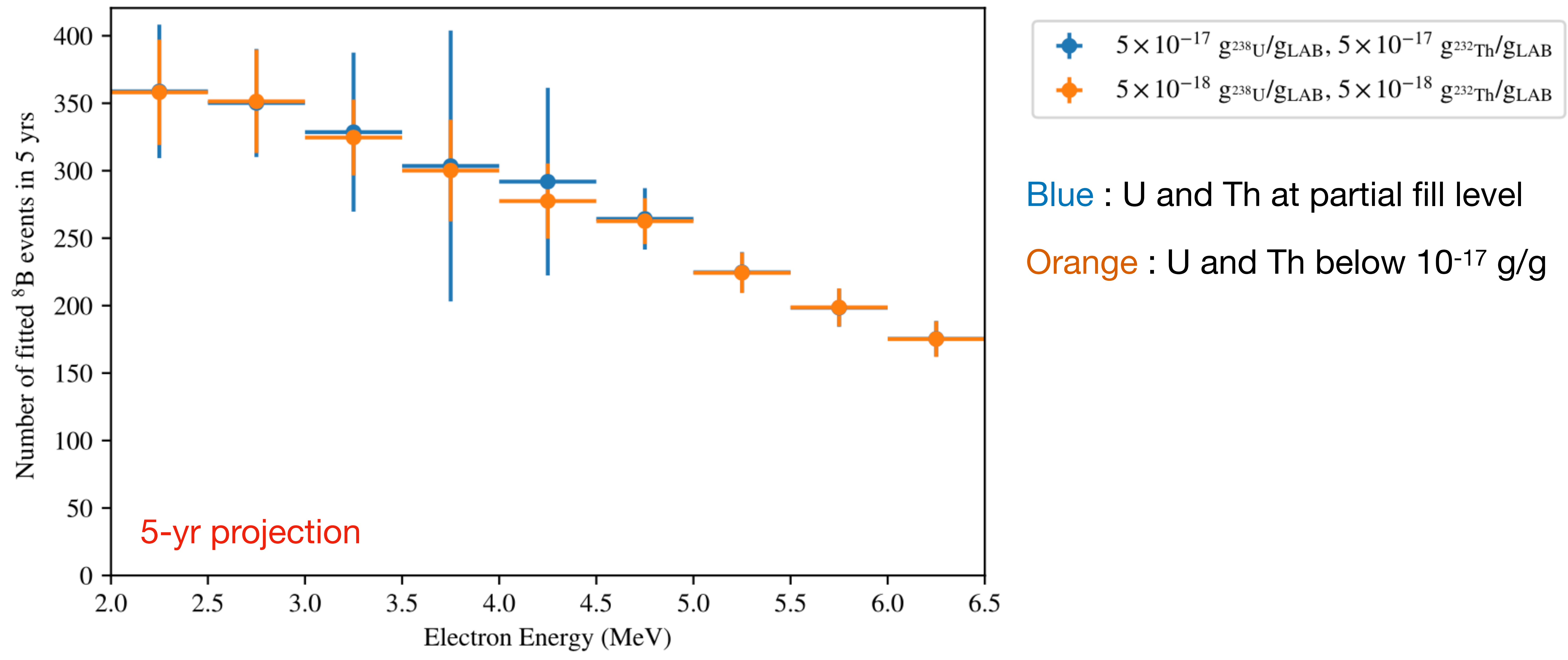


SNO+ Scintillator Phase

Objectives for SNO+ Scintillator Phase

^{8}B Solar ν

- Attempt to measure ^{8}B below 3 MeV
  - Probe into the transition region
  - larger fiducial volume than Borexino
  - cosmogenic backgrounds lower than KamLAND (e.g., no ^{10}C, ^{11}C)



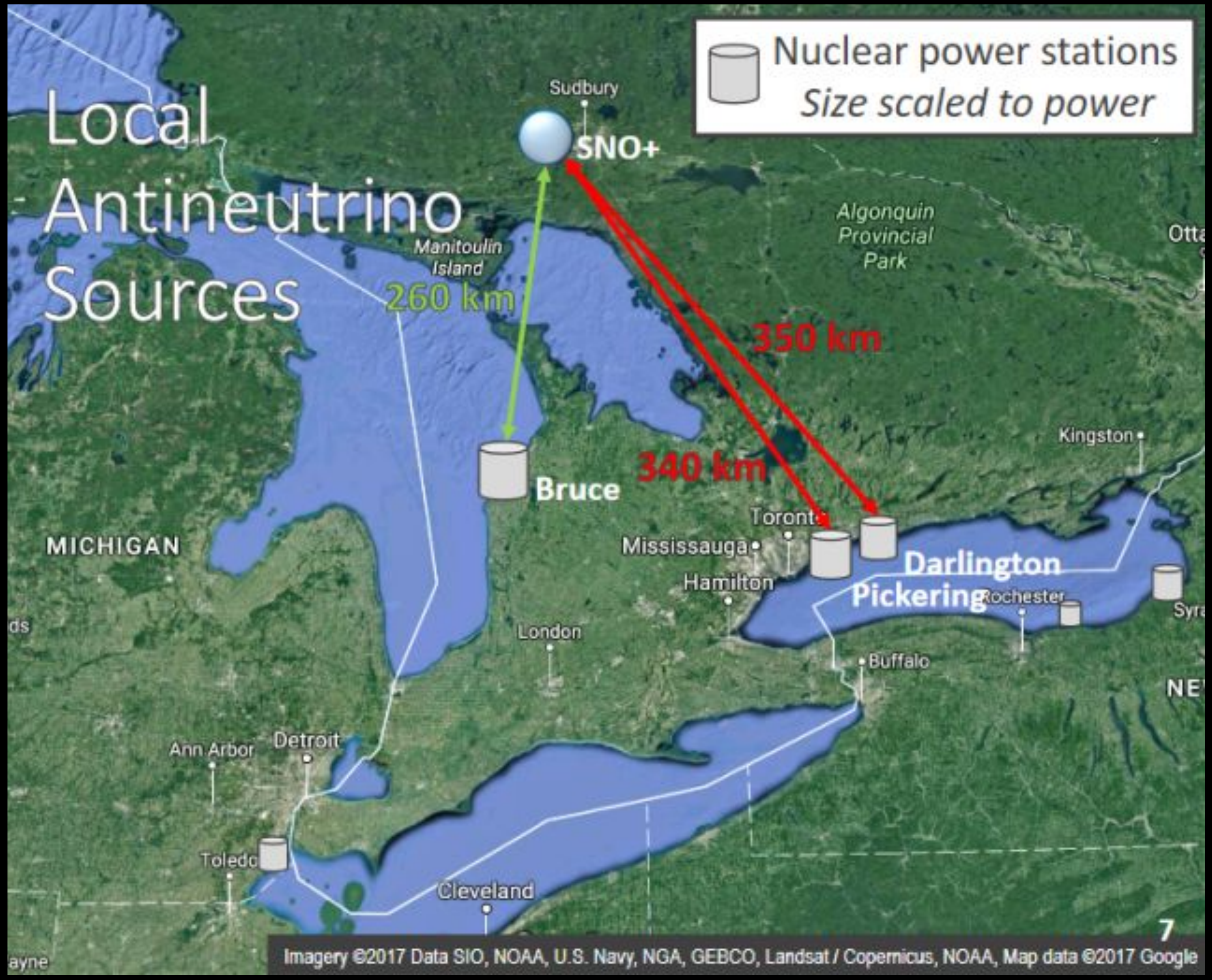
Blue : U and Th at partial fill level

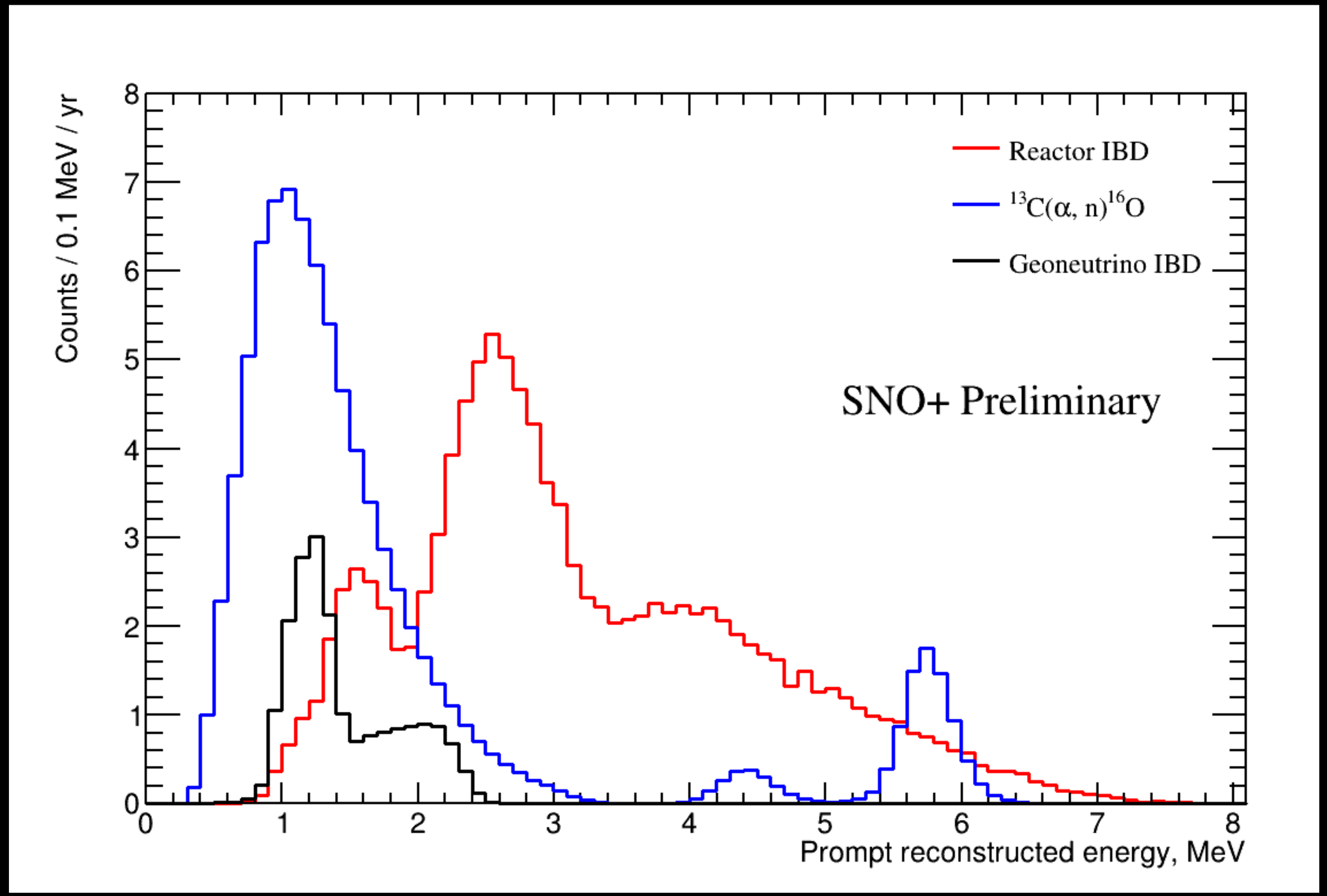
Orange : U and Th below 10^{-17} g/g

Objectives for SNO+ Scintillator Phase

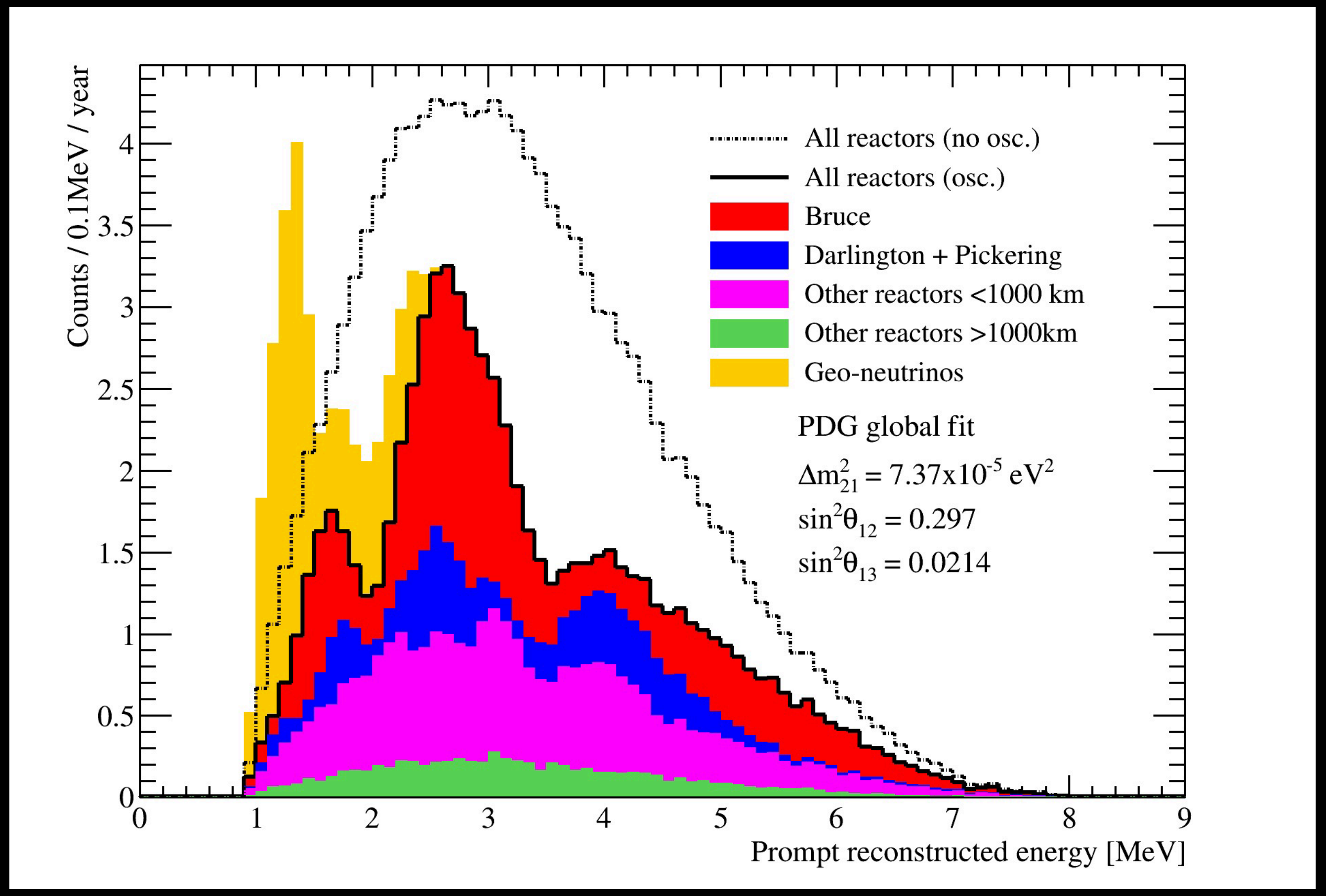
Reactor antineutrinos (Δm^2_{21})

- Sensitivity to probe the tension already after 1 year
  - Shape is more important than rate
- SNO+ location yields only two distinct baselines

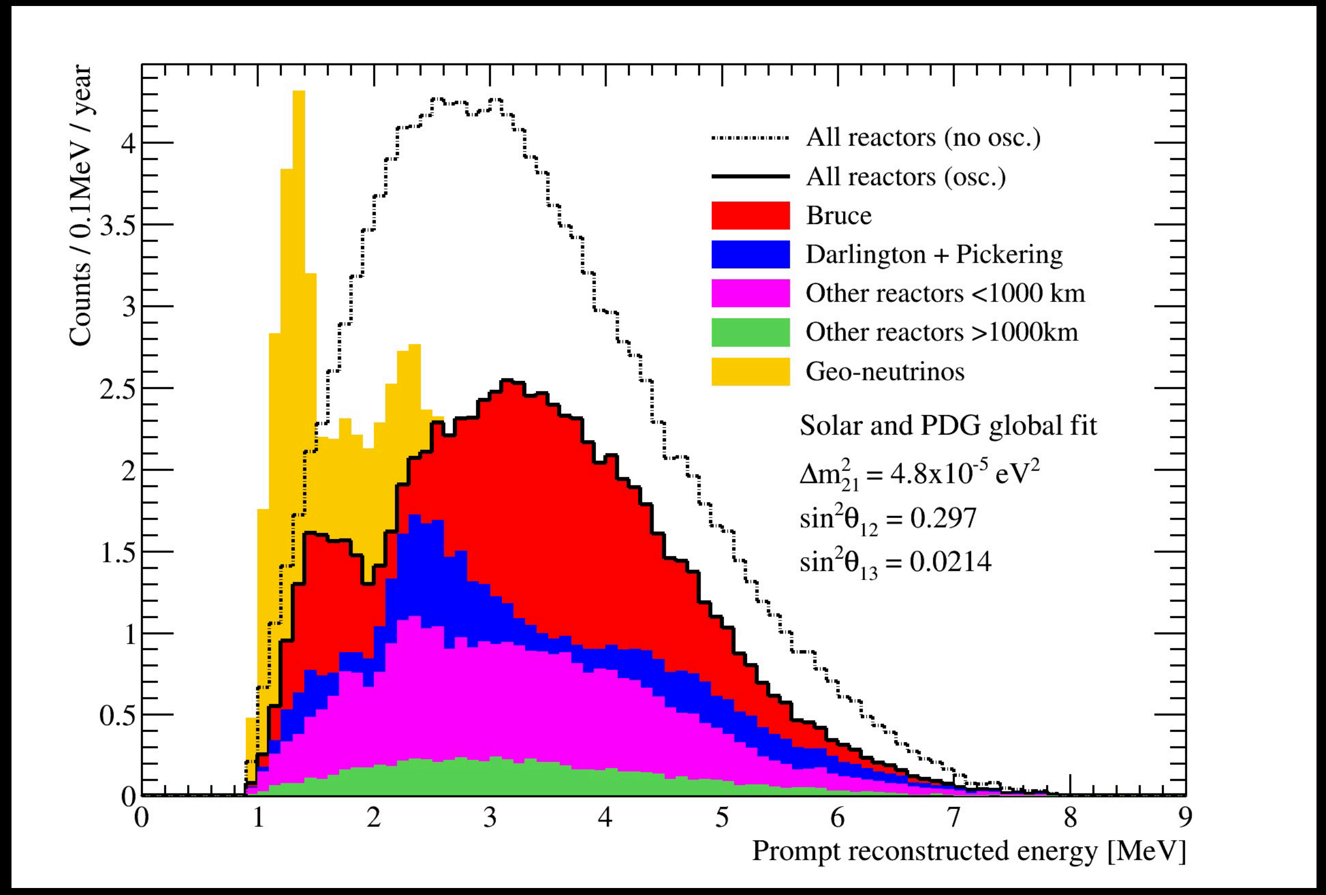




KamLAND (~7x10^{-5} eV^2)



Global (~5x10^{-5} eV^2)



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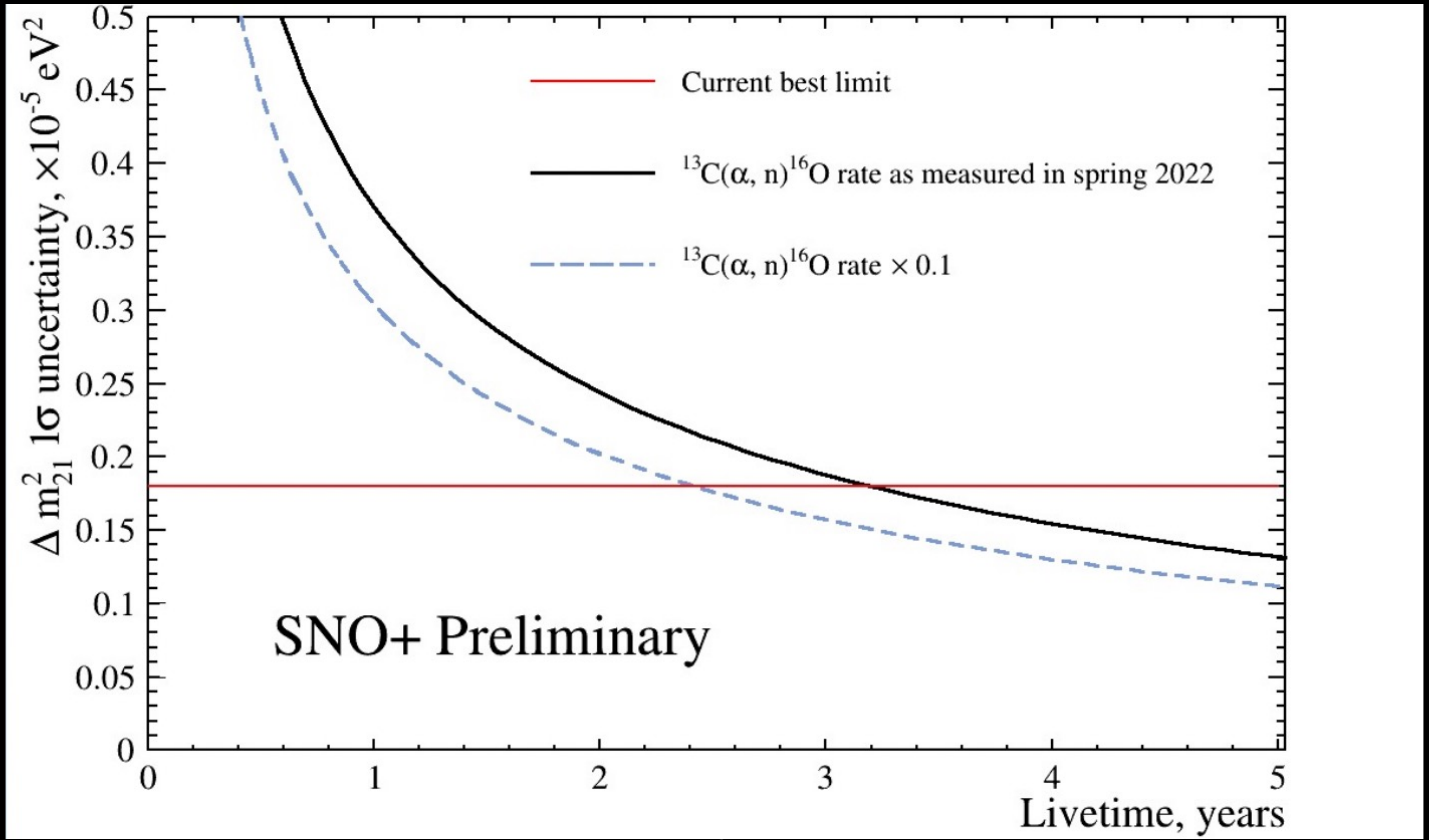
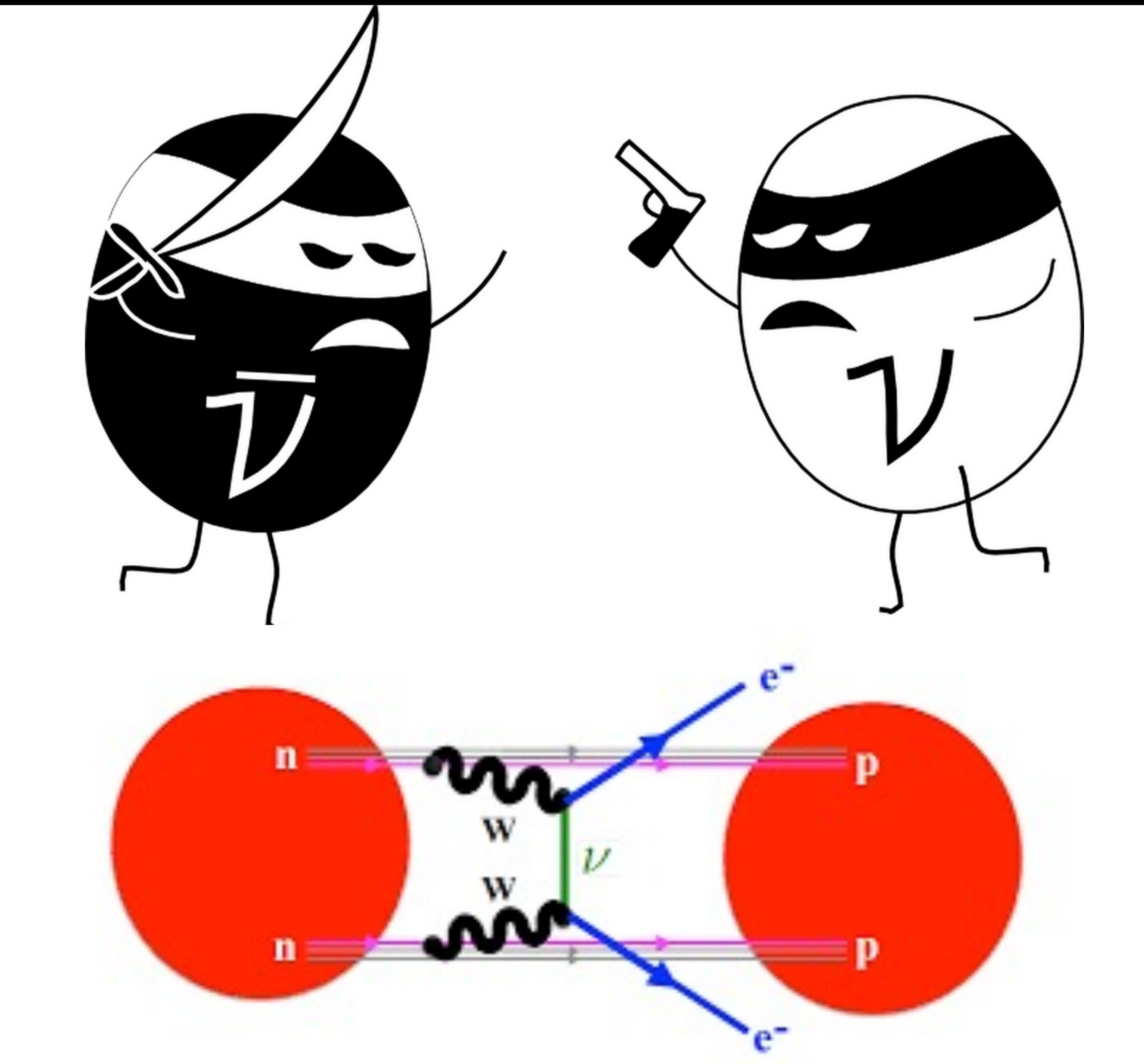


Why is this relevant for SNO+ 0νββ ?

- The advantages of a well-understood detector with low backgrounds are being demonstrated!
- SNO+ has a diverse program of neutrino (and other) physics that is being pursued.
    - The physics themselves are relevant and interesting
    - …better understanding of the detector means better background model
- With the detector performing well; with all background components being measured and constrained (most coming in at or below target levels), it looks promising for the final phase of SNO+…

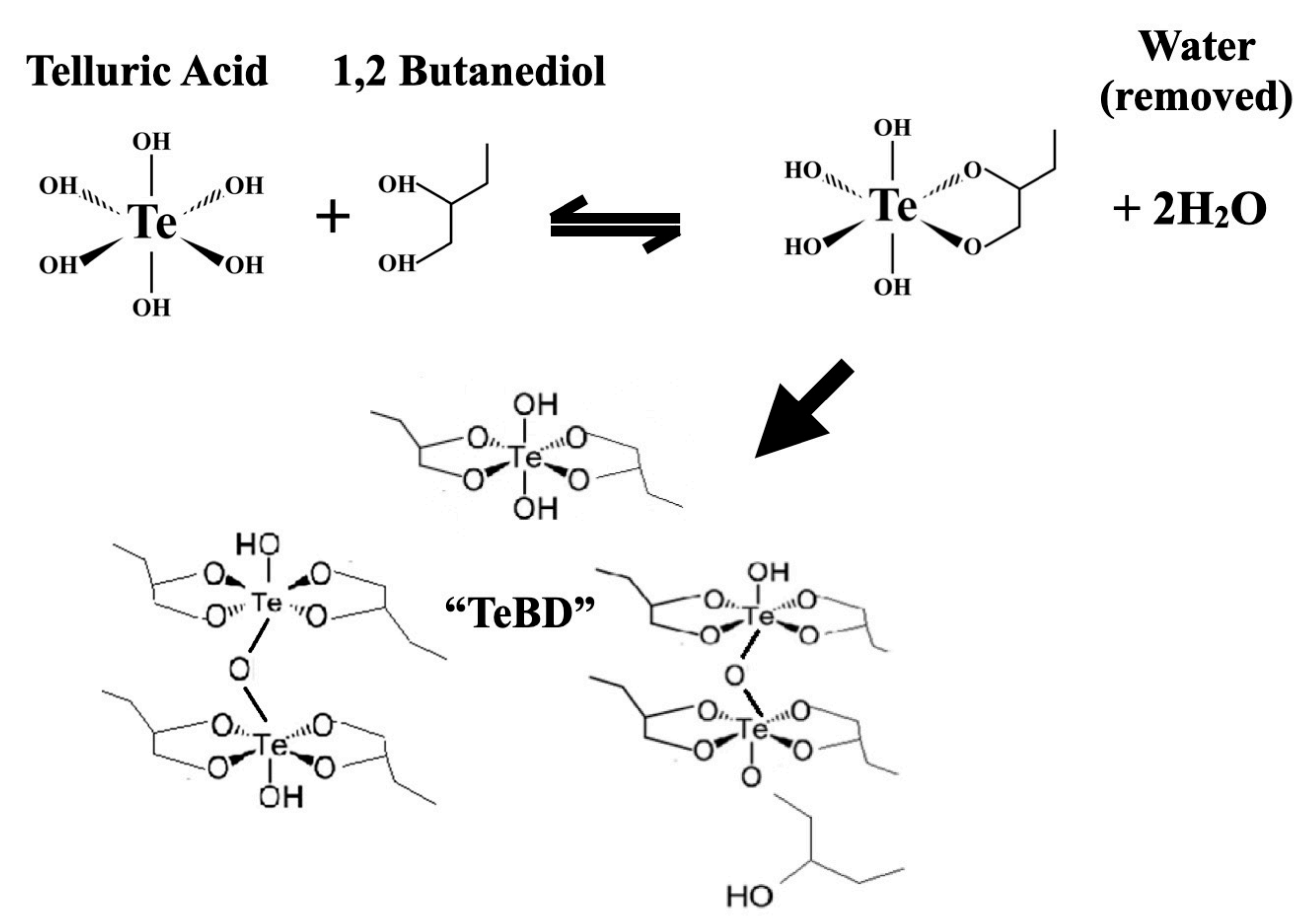
SNO+ Tellurium Double Beta Phase



Neutrinoless Double Beta (0νββ) Decay in SNO+

Strategy of Tellurium-Loaded Liquid Scintillator

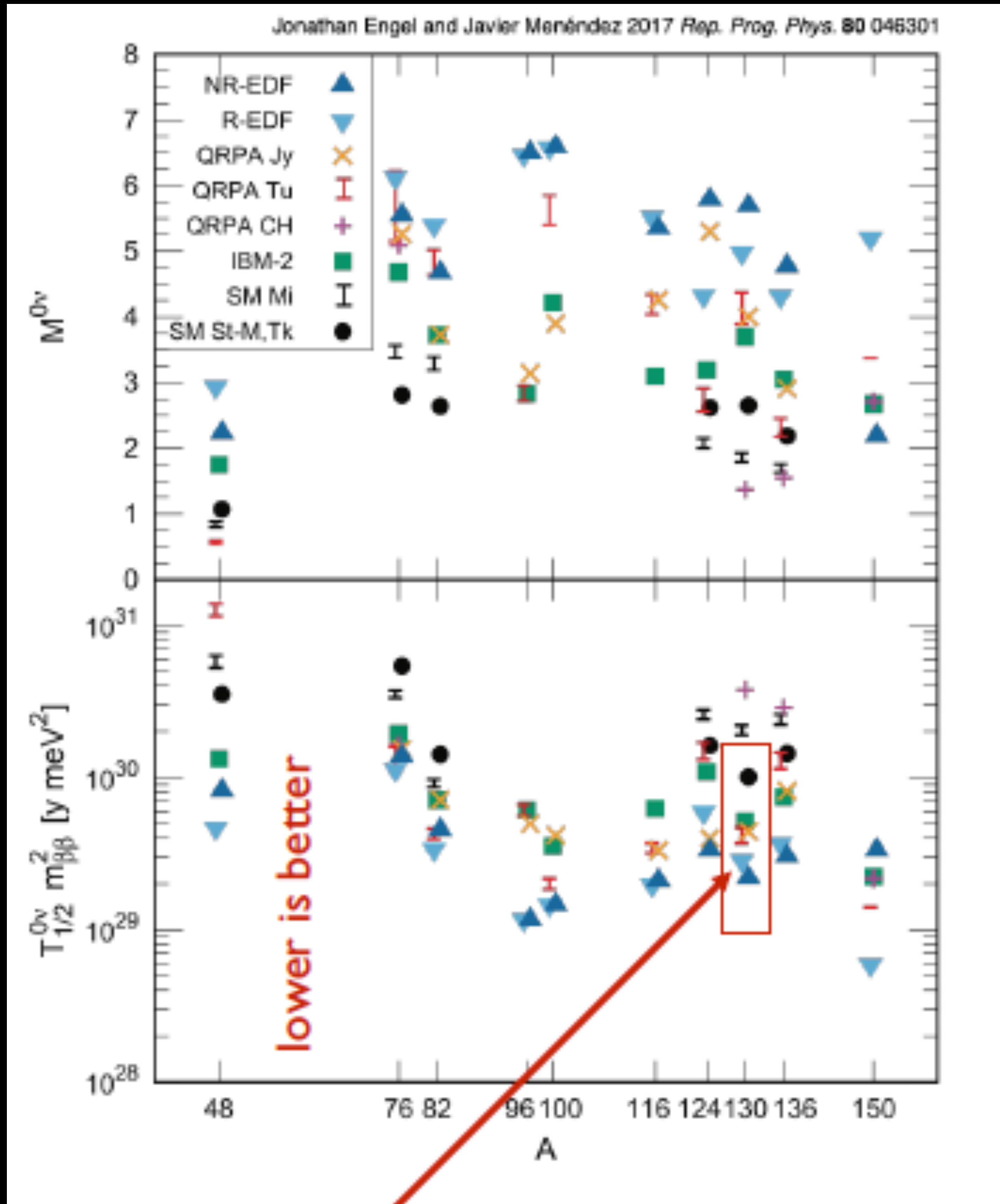
- **Massive Detector:**
    - High statistics
    - Shielding through fiducialisation
- **Liquid Scintillator**
    - Purification methods
    - Scalable loading
    - Homogeneous loading of isotope in detection medium
- **Tellurium-130**
    - Highest natural abundance, no enrichment required, low cost



Tellurium as a DBD candidate

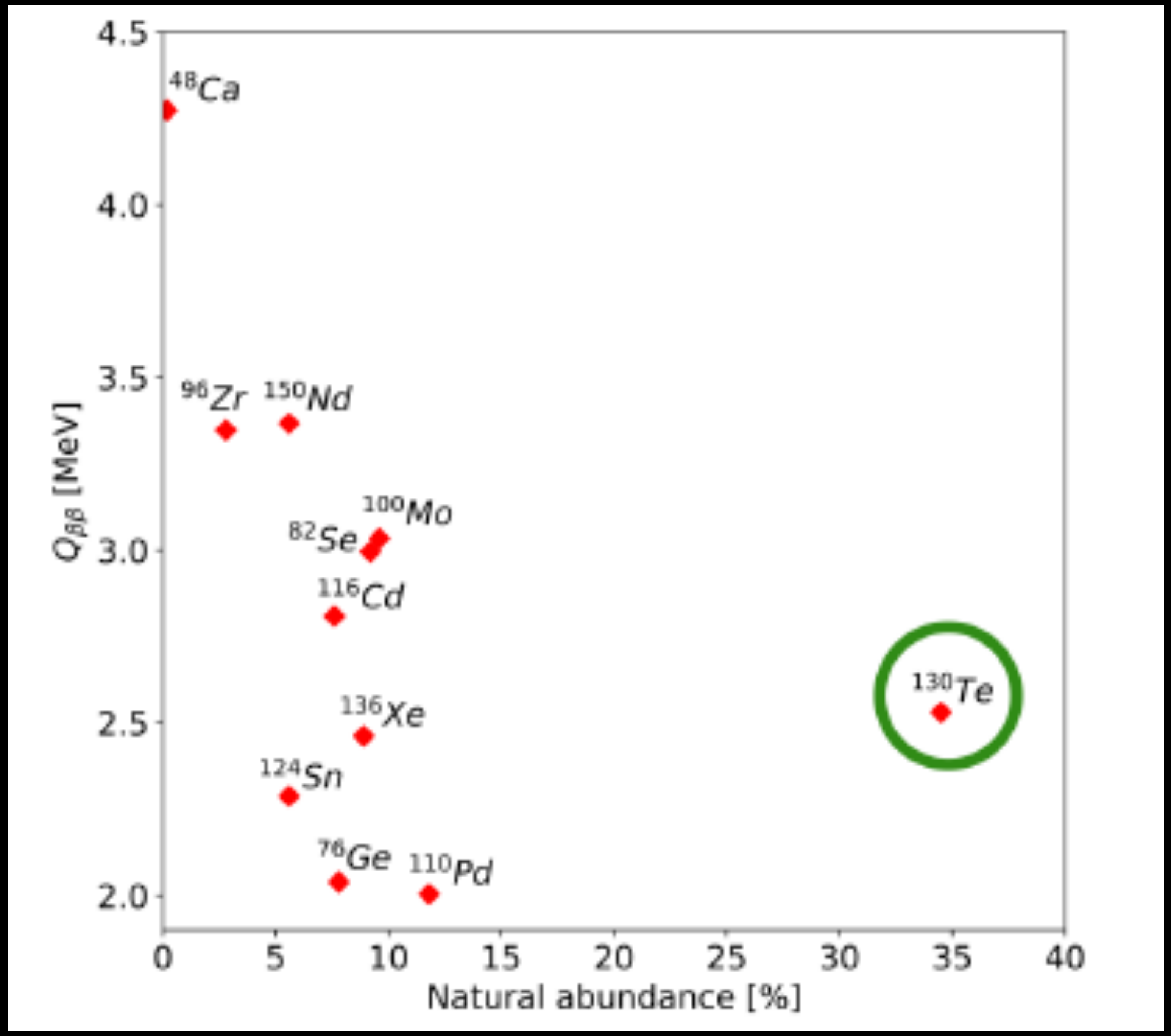
Why Te?

Favourable Phase Space



Favourable $G_{0\nu}(Q,Z)\,|M_{0\nu}|^2$

Very high abundance



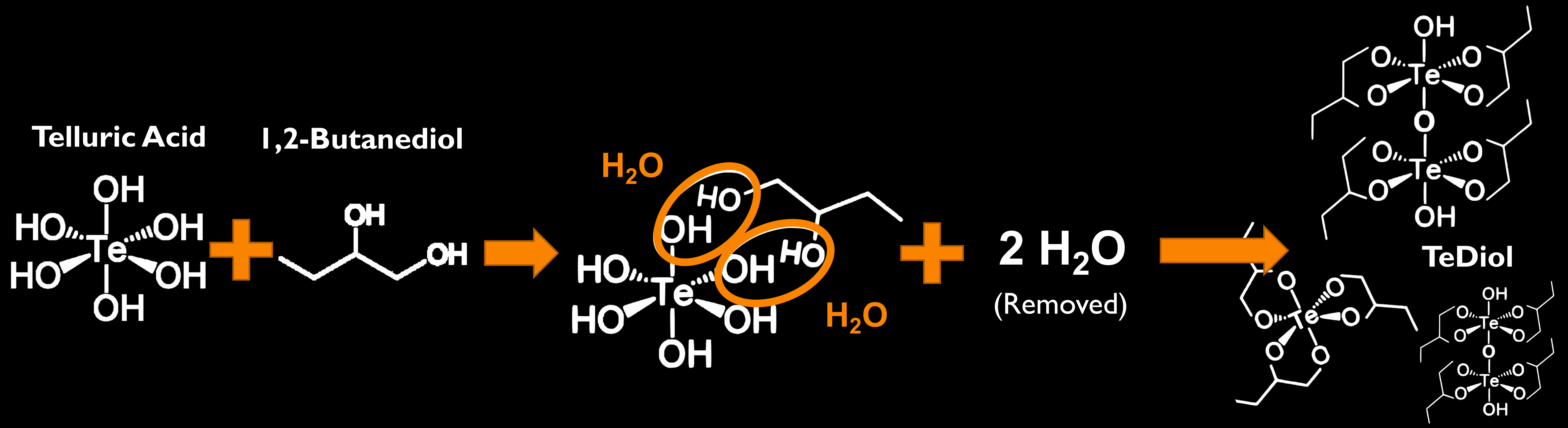
Tellurium loaded LS

Why liquid scintillator?

- Very low backgrounds: 5×10^{-7} counts/keV/$kg_{\text{fiducial detector}}$/yr
- Homogeneous detector volume – reliable background model
- “target out” – ability to measure/constrain backgrounds before isotope added
- “sideband analysis” – not just counts in a bin but distributions in position and energy verify detector response and background model
- liquid detector permits: assays, chemistry; liquid medium can be modified in situ (e.g., adding more Te, more fluor)

The dependence of a putative signal with amount of isotope would be a strong confirmation!

Tellurium Loading



- TeDiol is mixed directly into the LAB+PPO with 15 mg/L bis-MSB and a stabilizer called Dimethyldodecylamine (DDA).

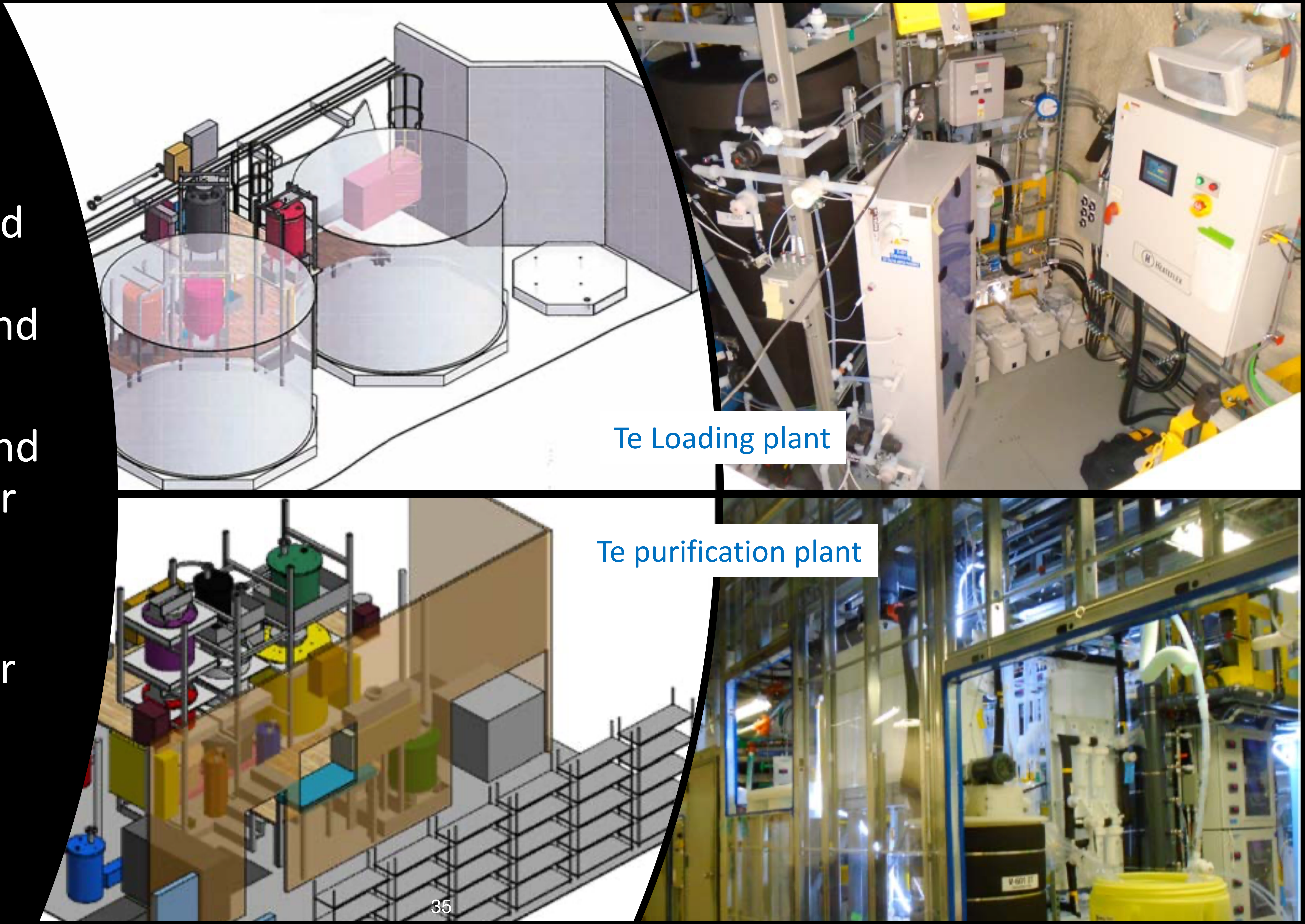
- Final Te-loaded LS cocktail expected to produce ~460 p.e. / MeV in SNO+ for 0.5% Te loading.

Tellurium Plants

- ~8 tons of telluric acid (TeA) has been "cooling" underground for several years.
- Ton-scale underground purification of TeA for further background reduction.
- Target purification for Te cocktail:

  ~ 10^{-15} g/g U

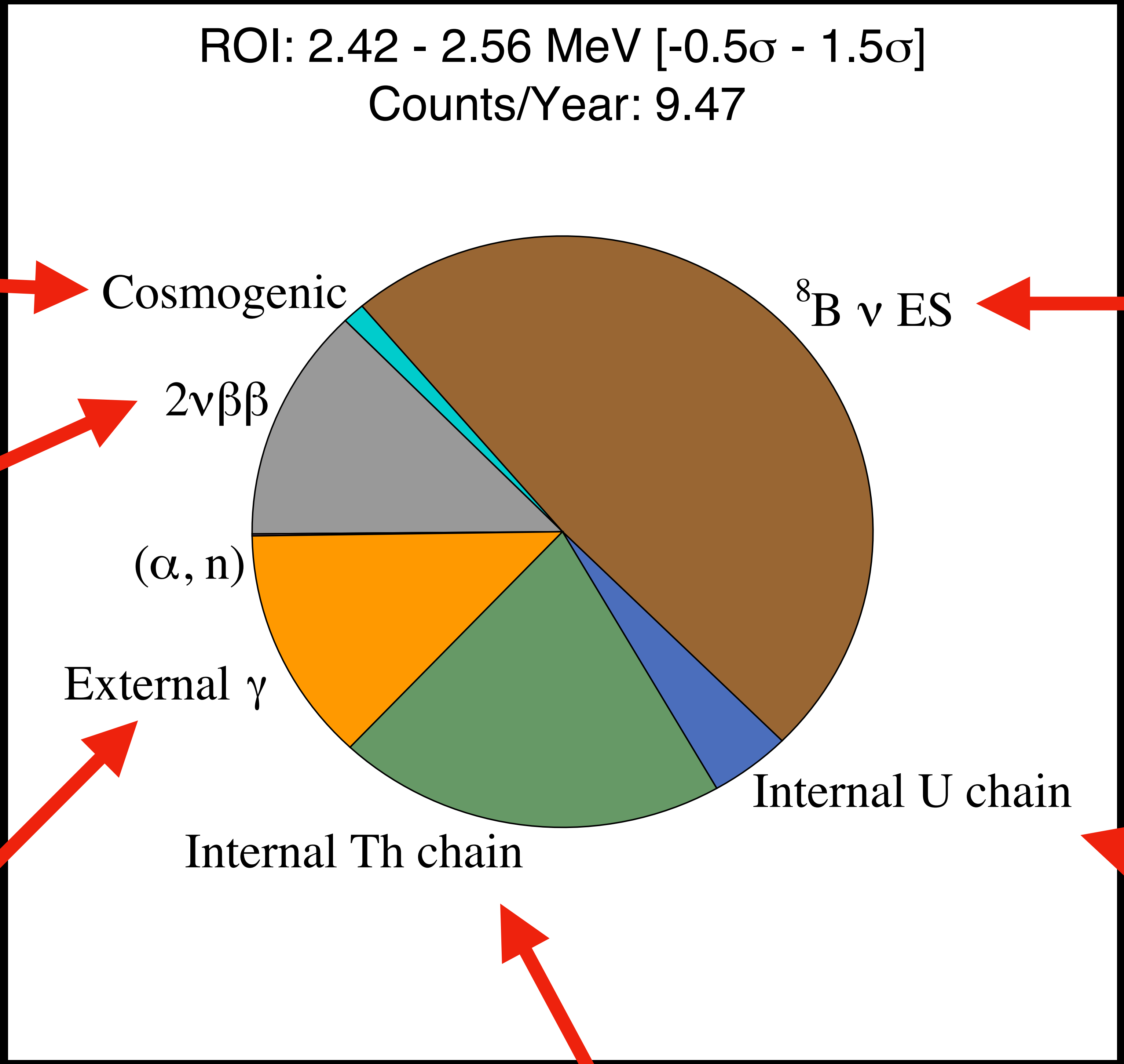
  ~ 10^{-16} g/g Th



SNO+ Te-phase background projections

Major contributions and mitigation strategies

Staged Te-loading allows us to assess Te-backgrounds



Telluric acid has been "cooling" underground for ~8 years
+ Te purification
+ multi-site rejection

Well measured from previous experiments

Suppressed by asymmetric ROI: (assuming ~460 PMT hits/MeV)

U levels already measured below requirements in partial fill ($<10^{-16}$ g/g)

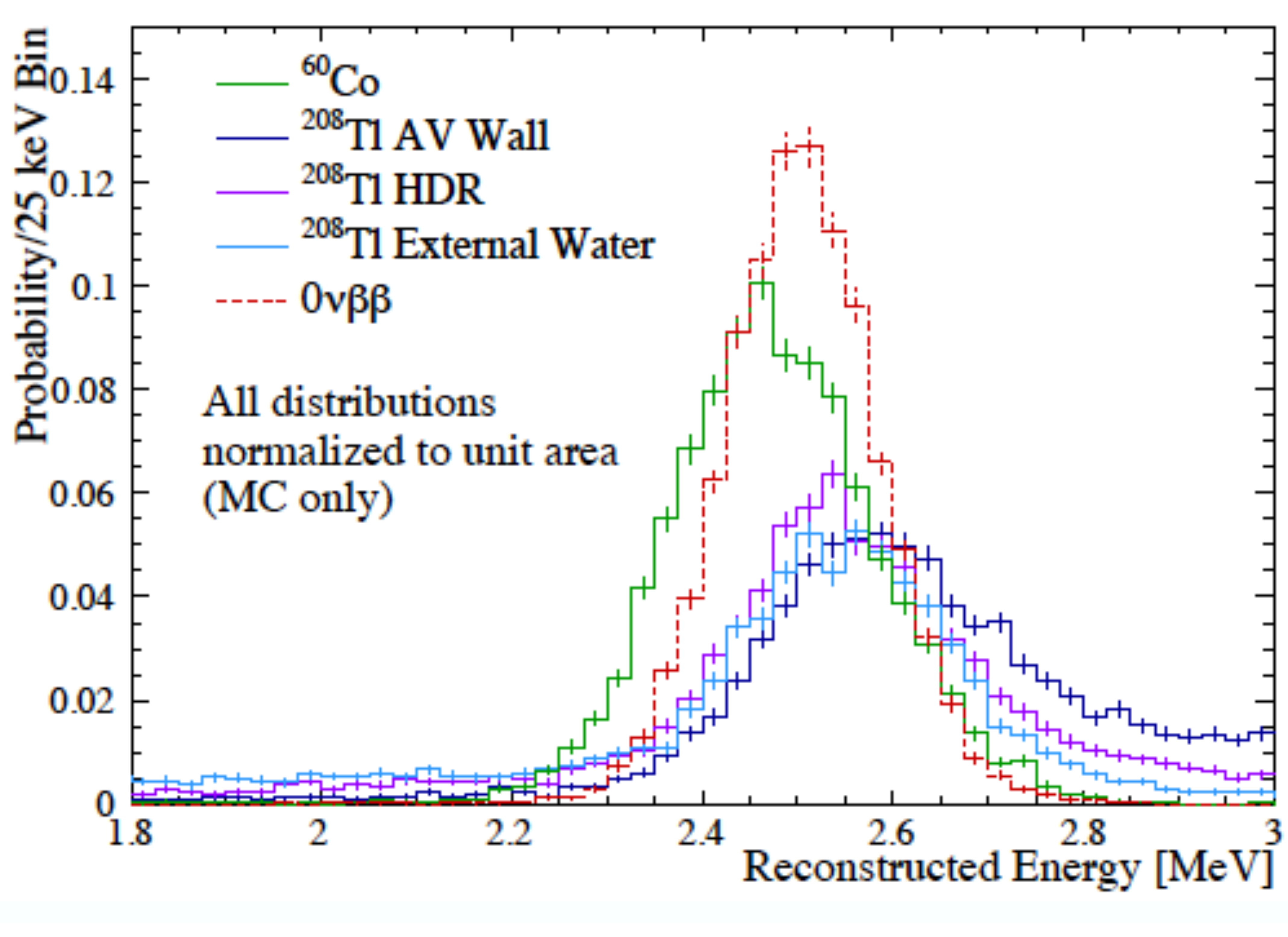
Measured in water data (reduced by 23%)

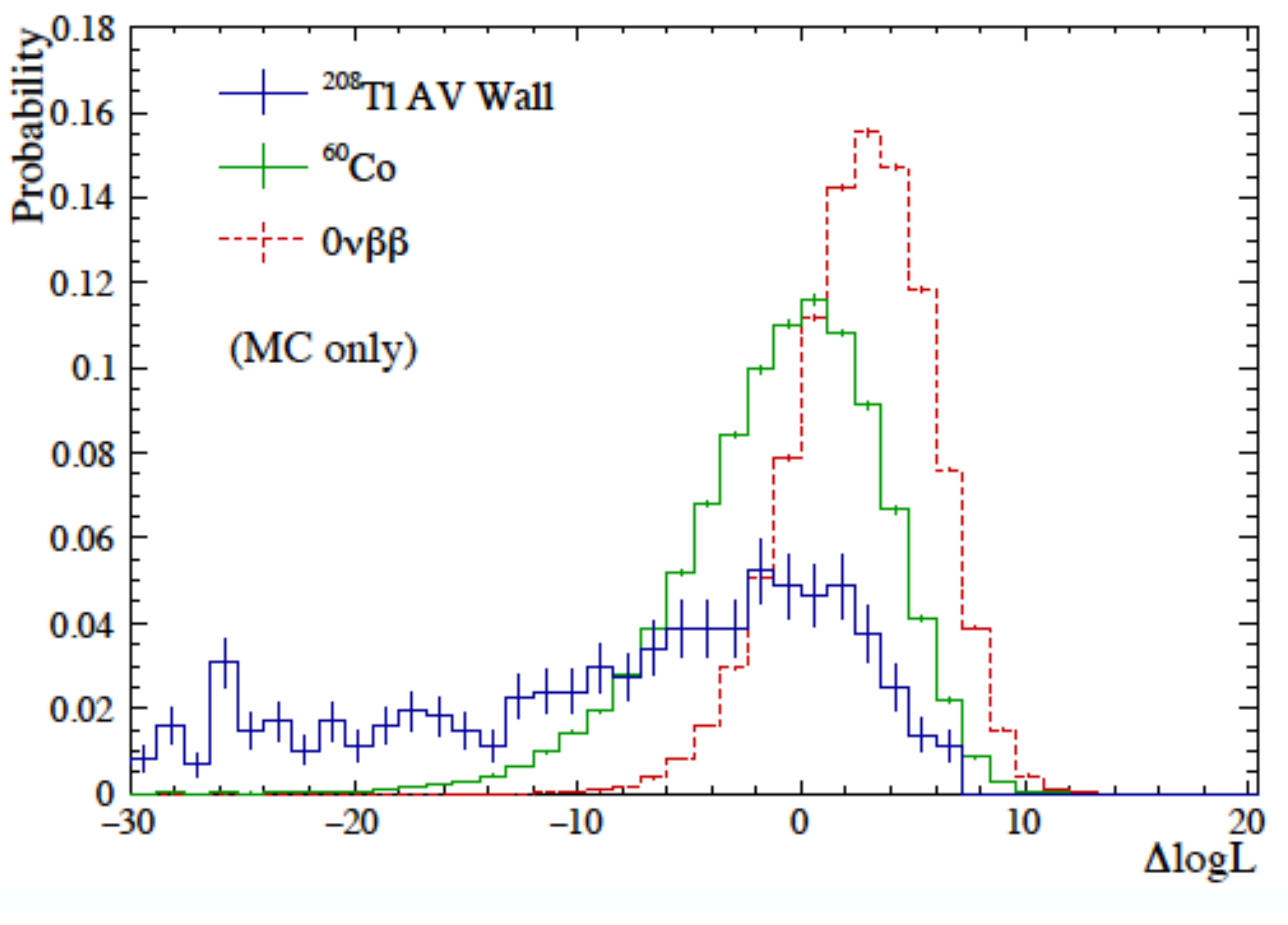
Th levels already measured below requirements in partial fill ($<10^{-16}$ g/g)

SNO+ background suppression

Multi-site background constraint

- Analyses ongoing with promising results



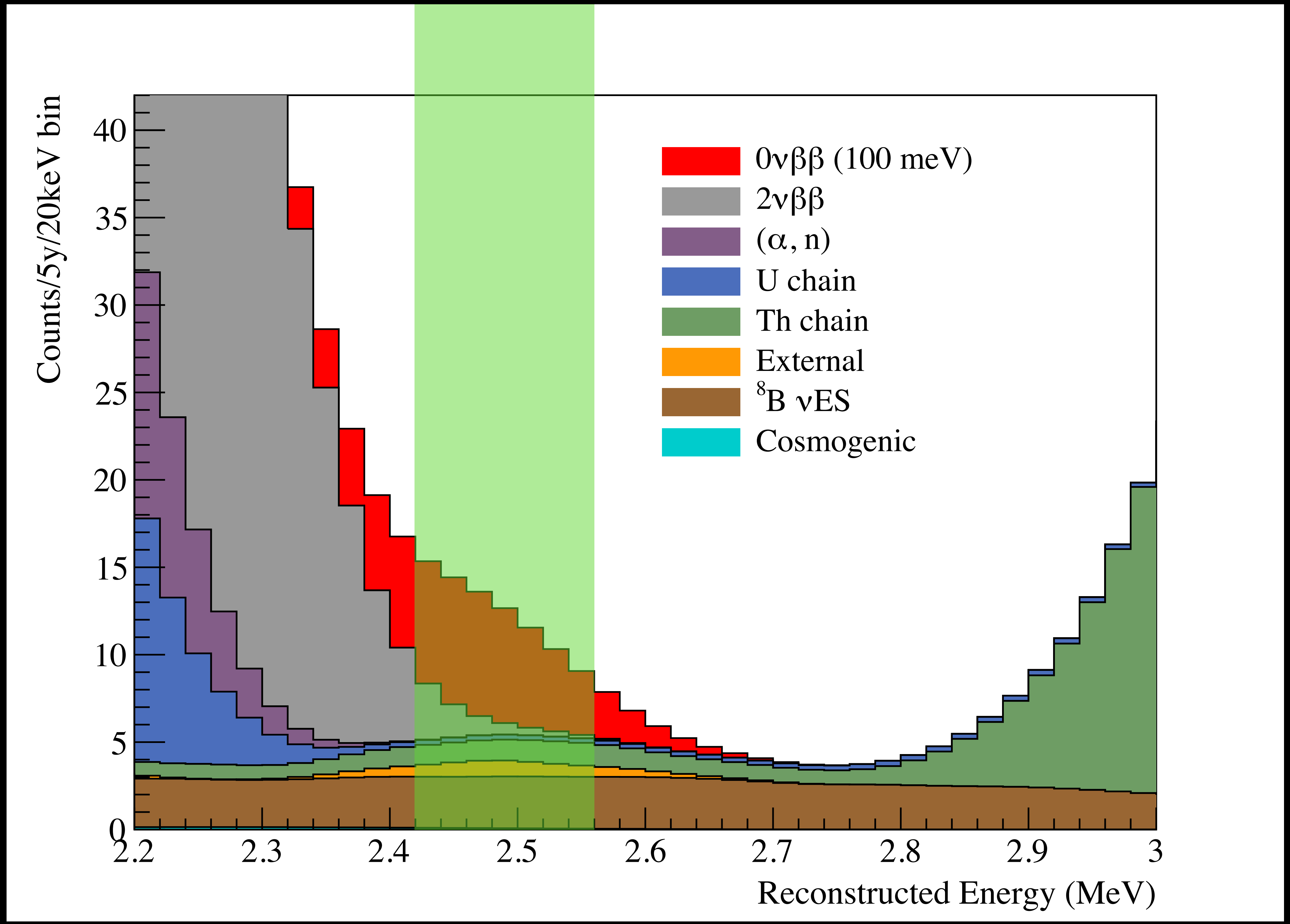


Projected spectrum

Assuming 0.5% loading

- Half-life sensitivity:
  - $T_{1/2} > 2x10^{26}$ years
  - Sensitive to $m_{\beta\beta}$ ~37-89 meV
- Full likelihood analysis using energy, radius and multi-site discriminators achieves this sensitivity with 3 years of data

ROI : 2.42 - 2.56 MeV

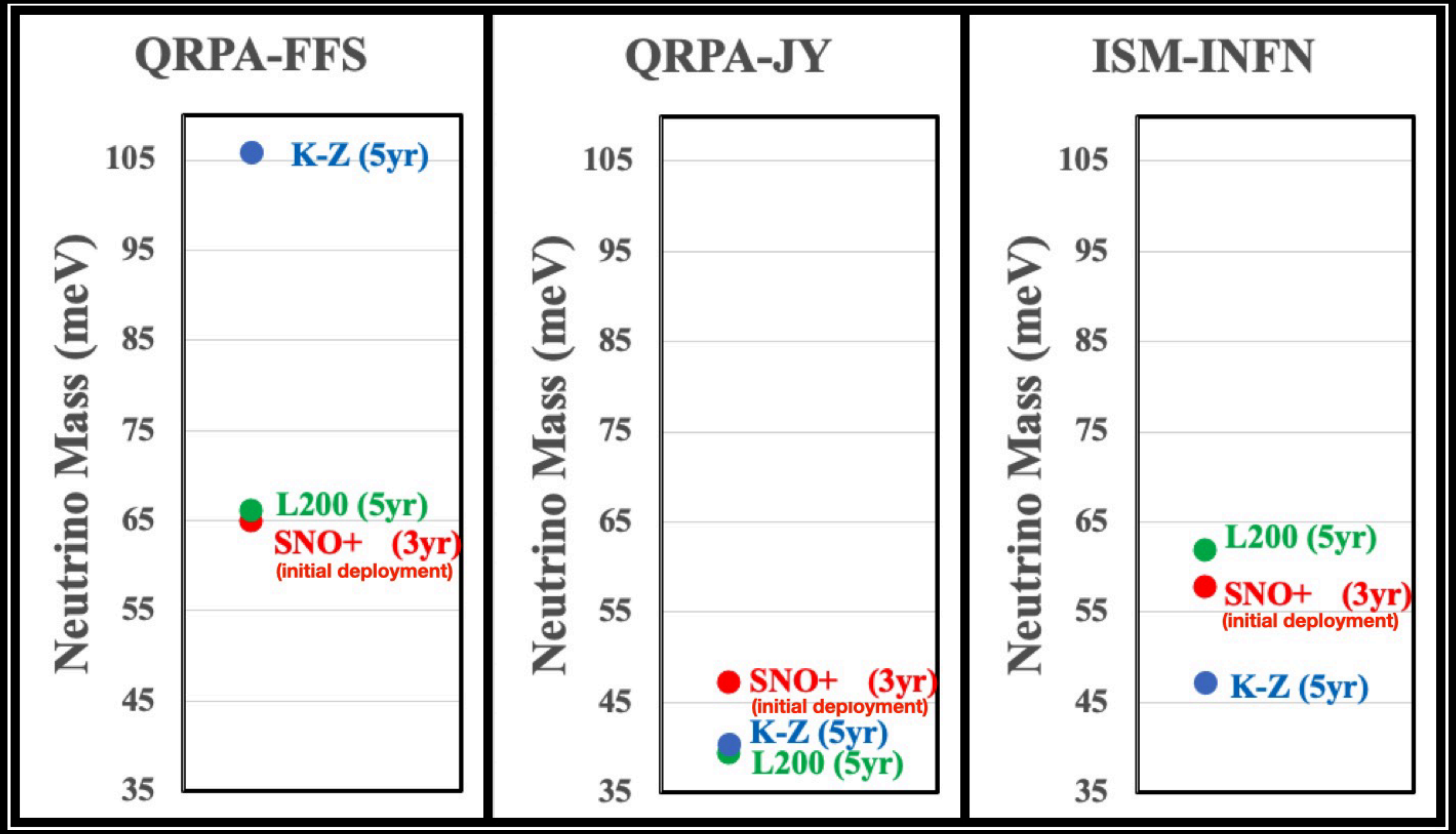


FV of 3.3 m (not optimised)

SNO+ Te-DBD

Additional Considerations

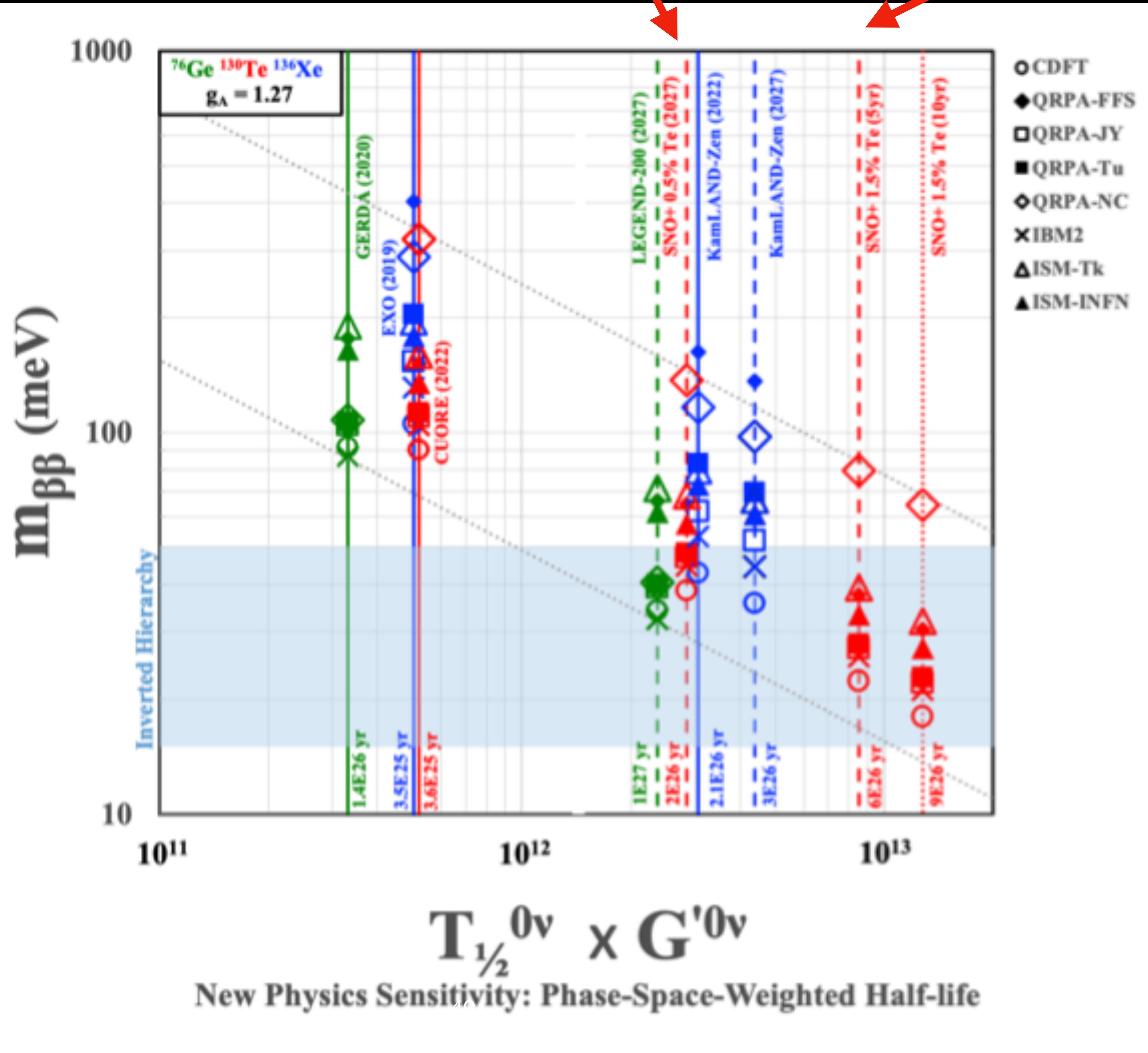
- ^{130}Te DBD is scalable, cost effective, unimpacted by geopolitical events that currently severely affect the availability of isotopic enrichment
- KL-Z 800 has world-leading sensitivity (upper limit 36-156 meV) and highlights the strength of the loaded LS DBD approach
- The competition does not make SNO+ Te DBD less relevant because of complementarity of isotope; NME model dependencies
- higher loading further extends SNO+ sensitivity and “fills the gap”, before larger experiments like nEXO come online
- initial deployment of Te would already be competitive and ready to test any hints of a positive signal
- purification of Te underground is novel technology
- “target out” analysis is a strong and unique feature; all non-Te backgrounds constrained prior to adding any Te
- SNO+ also has single-site/multi-site background constraining power



0νββ sensitivity

2x10^26 yr (0.5% Te)

6x10^26 yr (1.5% Te)



Status of SNO+ Te-DBD

- Tellurium systems are built and ready for operation
  - SNO+ is ready to pursue **full-scale test batches in 2022 and 2023** to purify telluric acid and synthesize tellurium-diol, with SNOLAB assistance in this effort to help retire risks
  - Following demonstration of operations and subsequent approvals, aim to **begin loading Te in the detector in 2024** for the start of the double beta decay phase
  - Meanwhile, the SNO+ project, with endorsement from SNOLAB, is completing R&D to establish the viability and execution plans of Te loading at the 1.5%-2.0% concentration, enabling reaching our goal of DBD sensitivity in the Inverted Mass Ordering region of parameter space

Telluric acid purification

Te-Diol synthesis

Summary

- SNO+ is an operating liquid scintillator neutrino detector filled with LAB + 2.2 g/L PPO and taking data
- Well understood detector from water phase data: backgrounds are low
    - Solar, nucleon decay, neutron capture, anti-neutrino physics
- Early scintillator data (partial fill and low PPO loading) analysed
    - scintillator performance and backgrounds, first scintillator physics measurements
- Diverse Scintillator Physics Program (some already underway)
    - $0\nu\beta\beta$, Solar, reactor-ν, geo-ν, Supernova …
- Already-built underground tellurium plants represent novel technology in the field of low-radioactivity techniques
    - Operating the plants and demonstrating their capabilities is the next step towards preparing to load SNO+ with Te for the $0n\beta\beta$ phase
- Scalable approach of SNO+ has huge potential for extending $0\nu\beta\beta$ sensitivity