The SNO+ Experiment

Lepton Photon 2021 (Jan 22)

KING'S College LONDON

Jeanne Wilson, on behalf of the SNO+ collaboration

SNO+

SNO+ collaboration

These slides contain input from many people

University of Alberta
Berkeley Lab – Lawrence Berkeley National Laboratory
University of Liverpool
LIP
The University of Chicago
King's College London
UC Davis – University of California
Boston University
Lancaster University
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Queen's University
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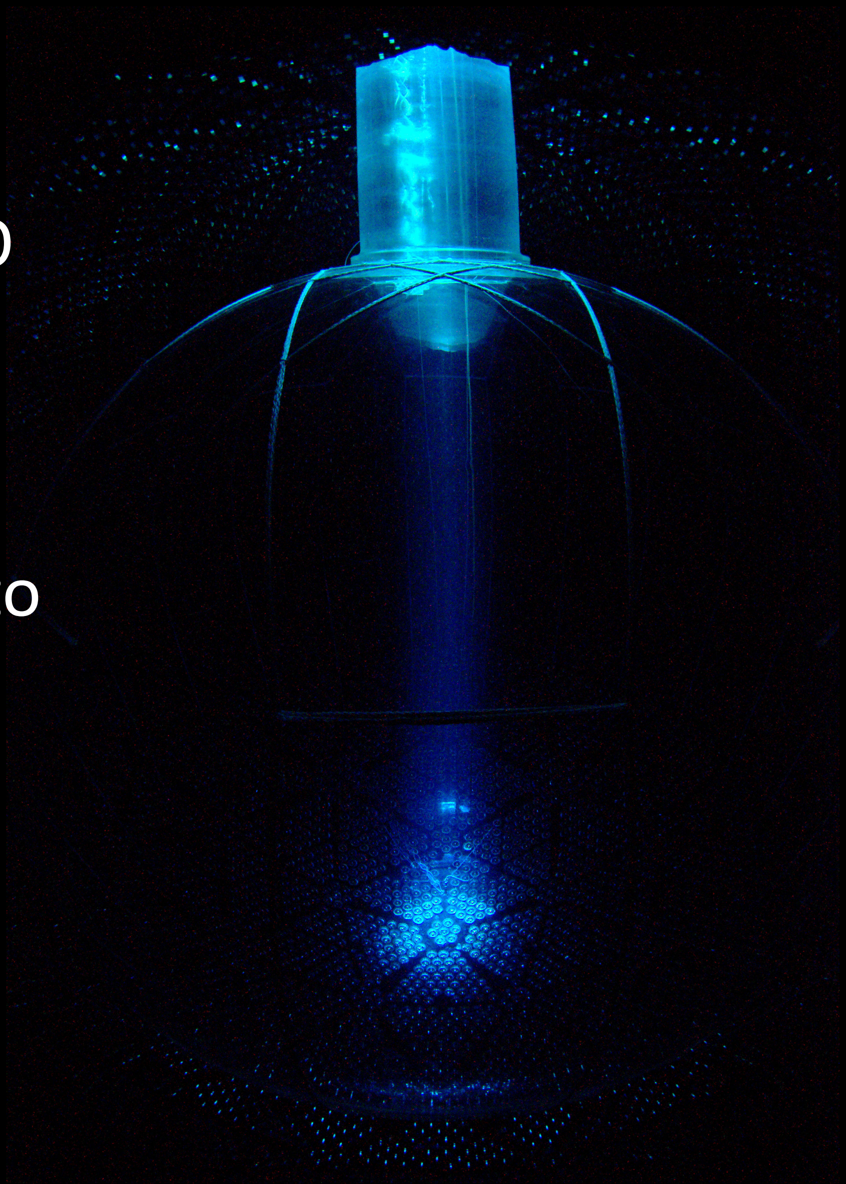
Queen Mary University of London
Technische Universität Dresden
Berkeley – University of California
Laurentian University – Université Laurentienne
Brookhaven National Laboratory
Penn – University of Pennsylvania
Norwich University
SNOLAB

A Multi-purpose Liquid Scintillator Detector

Infrastructure inherited from the successful SNO experiment.

Adapted from D_2O to scintillator detecting medium to give access to low energy (~MeV) measurements.



<u>Physics Programme</u>

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

The SNO+ detector

2km underground in SNOLAB, ~6000 MWE

780 tons of
Liquid scintillator

Loaded with 0.5% double beta decay Isotope (Te130)

Contained in an
Acrylic vessel (AV)
12 m diameter

Held-down by new rope system

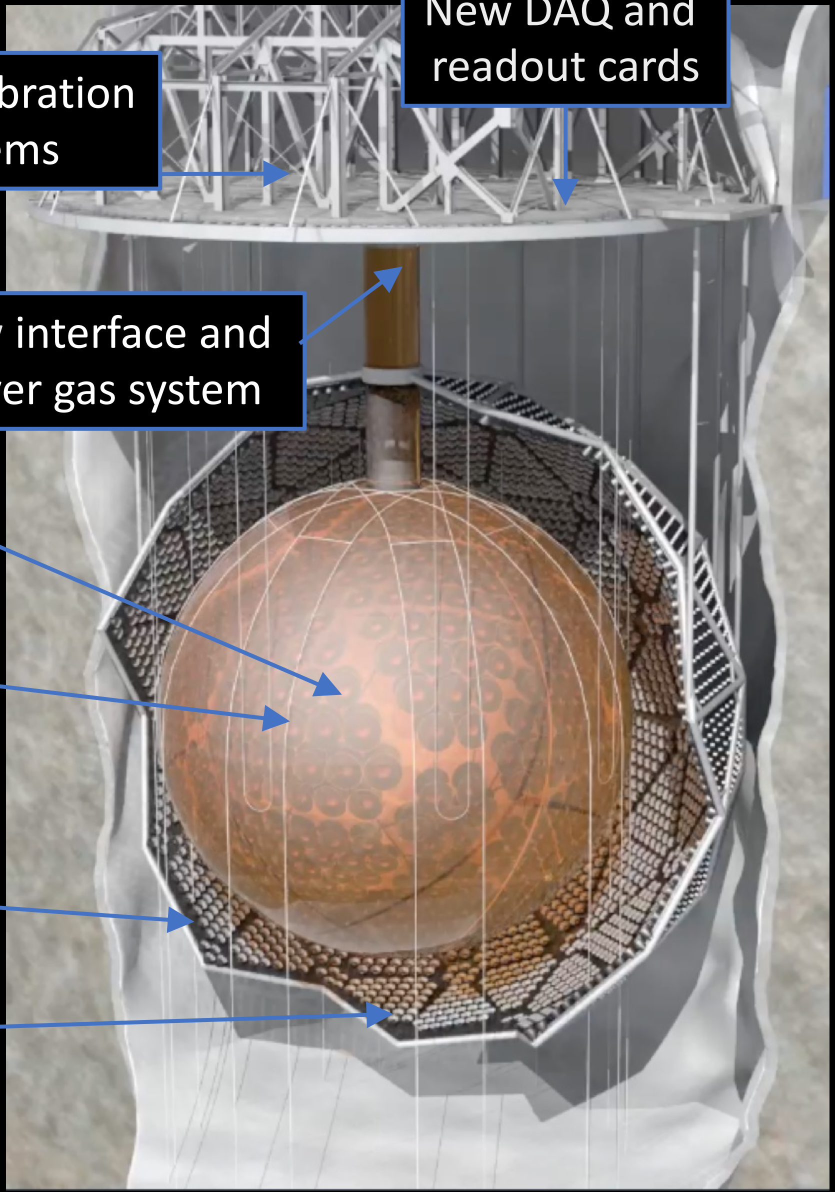
Shielded by 7 kT Ultra-pure water

Viewed by **~9300 PMTs** (8”) mounted on 17 m diam. Structure

New calibration systems

New DAQ and readout cards

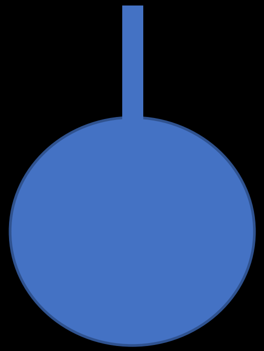
New interface and cover gas system



Timeline

2016 2017 2019 2021 2022 2023

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



Water Phase

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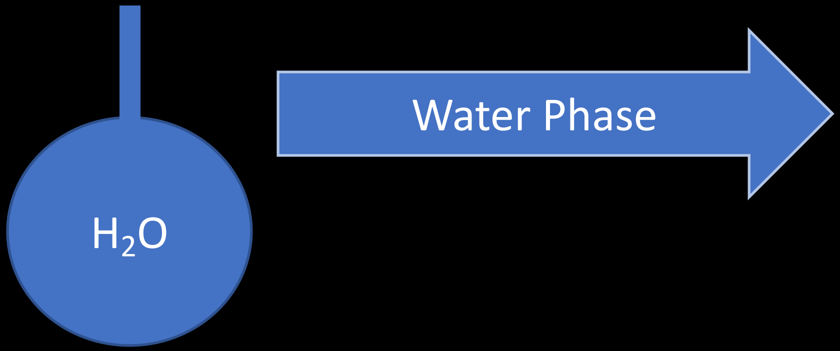


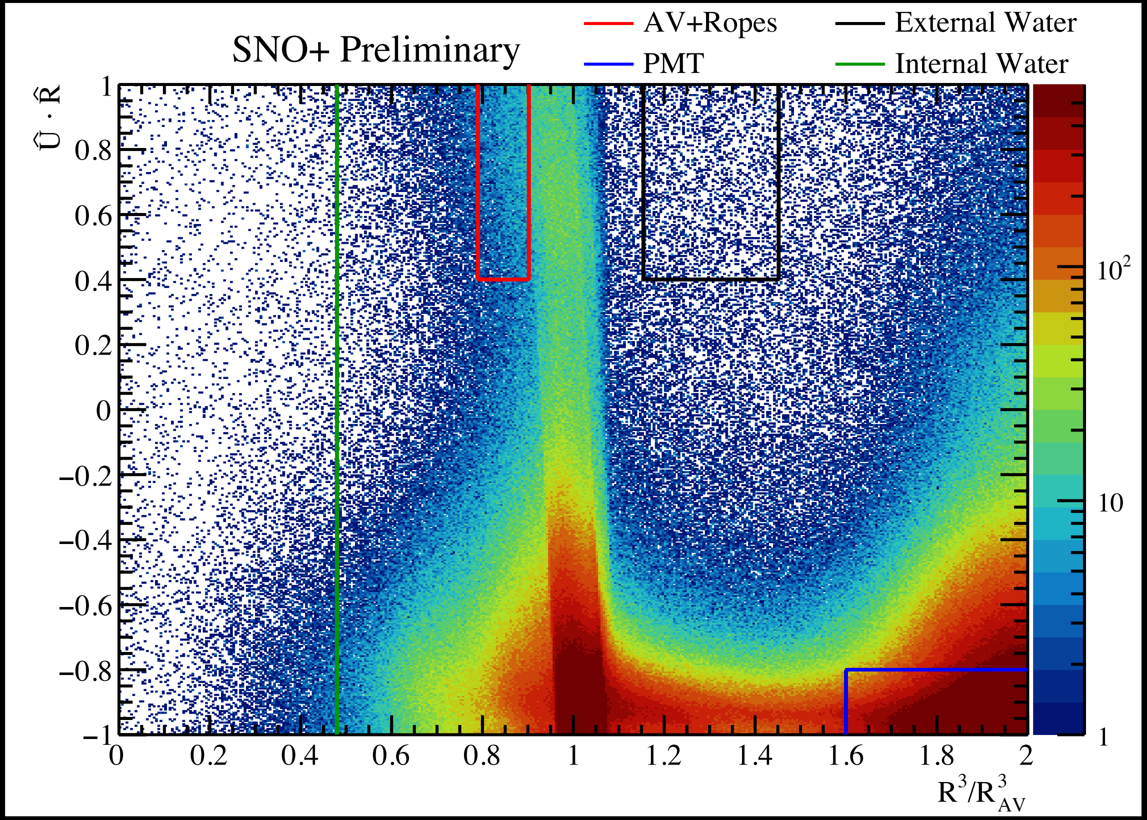
Acrylic Vessel (AV) filled with 905 tonnes of ultra-pure water (UPW)

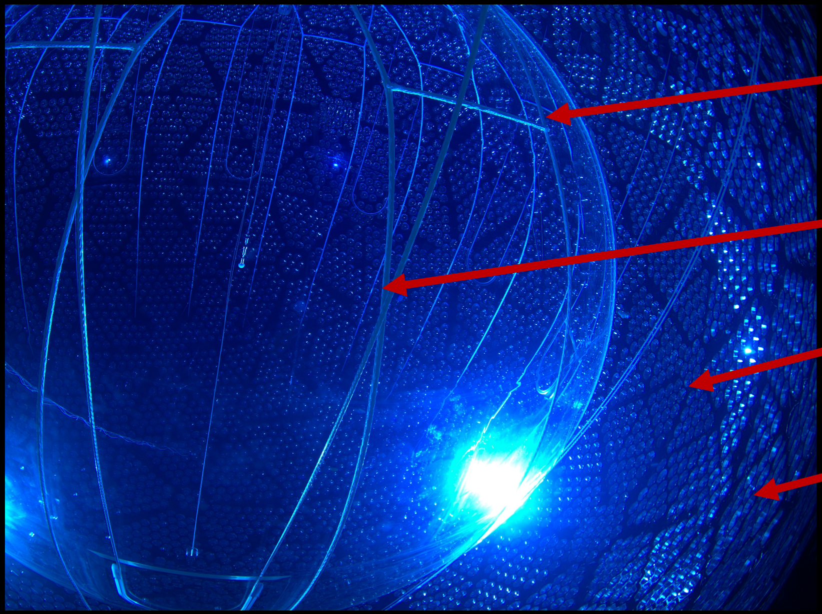
Dataset I: **115 live days**
May 2017 -> December 2017

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

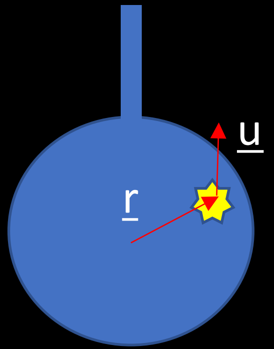
Water Phase Backgrounds

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





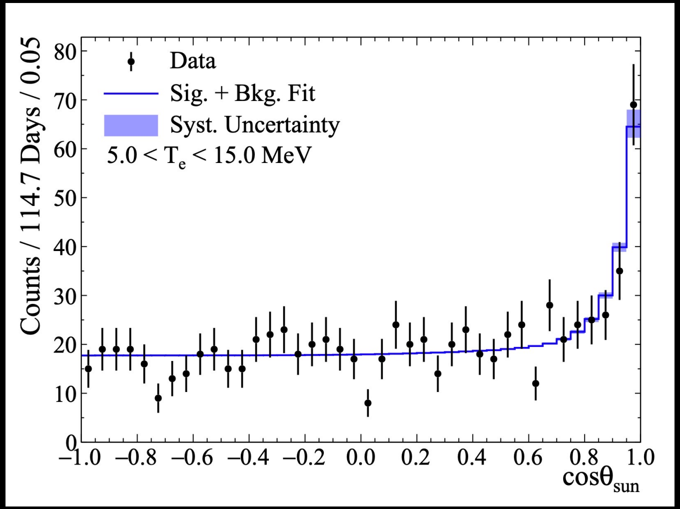
Background	Rate (Fraction of Nominal)
AV+Ropes	$0.52 \pm 0.02^{+0.39}_{-0.28}$
External Water	$0.03 \pm 0.01^{+0.61}_{-0.03}$
PMT	$2.04 \pm 0.04^{+3.69}_{-1.20}$



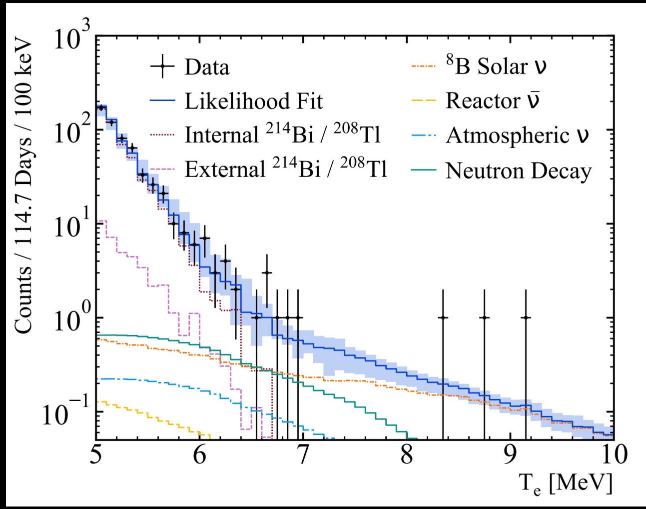
Box analysis performed
Fitted scale factors reduce 0νββ ROI backgrounds from 1.21 to 0.93 events / year
ie >20% below goals

Water Phase Physics Results

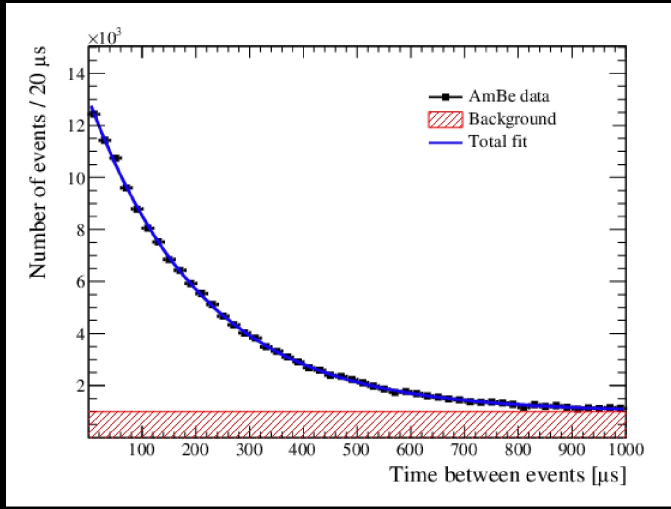
Dataset I (115 days)



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



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



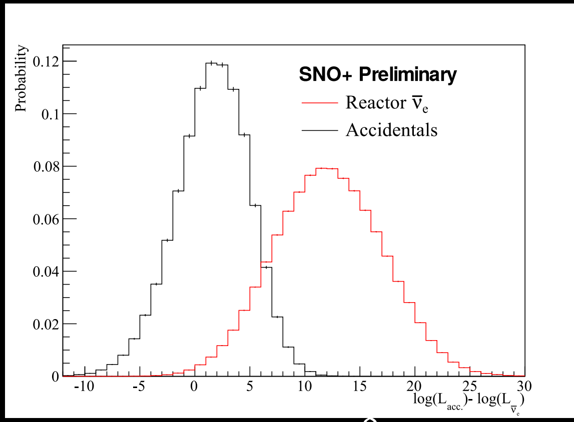
~50% efficiency for triggering on a neutron in pure water
Phys. Rev. C 102, 014002 (2020)

Dataset 2: (+190 days) coming soon

New solar flux and spectrum measurement, lower backgrounds → lower energy threshold

New limits, extra livetime and lower backgrounds → improved sensitivity

Measurement of reactor $\bar{\nu}$ in H_2O detector

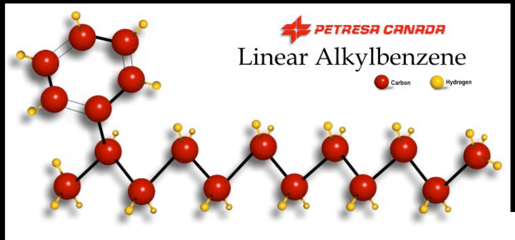


Scintillator filling

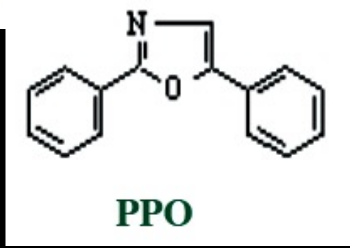
SNO+ and SNOLAB
scientific support

Purification and filling systems underground

Transfer via railcar from surface to underground

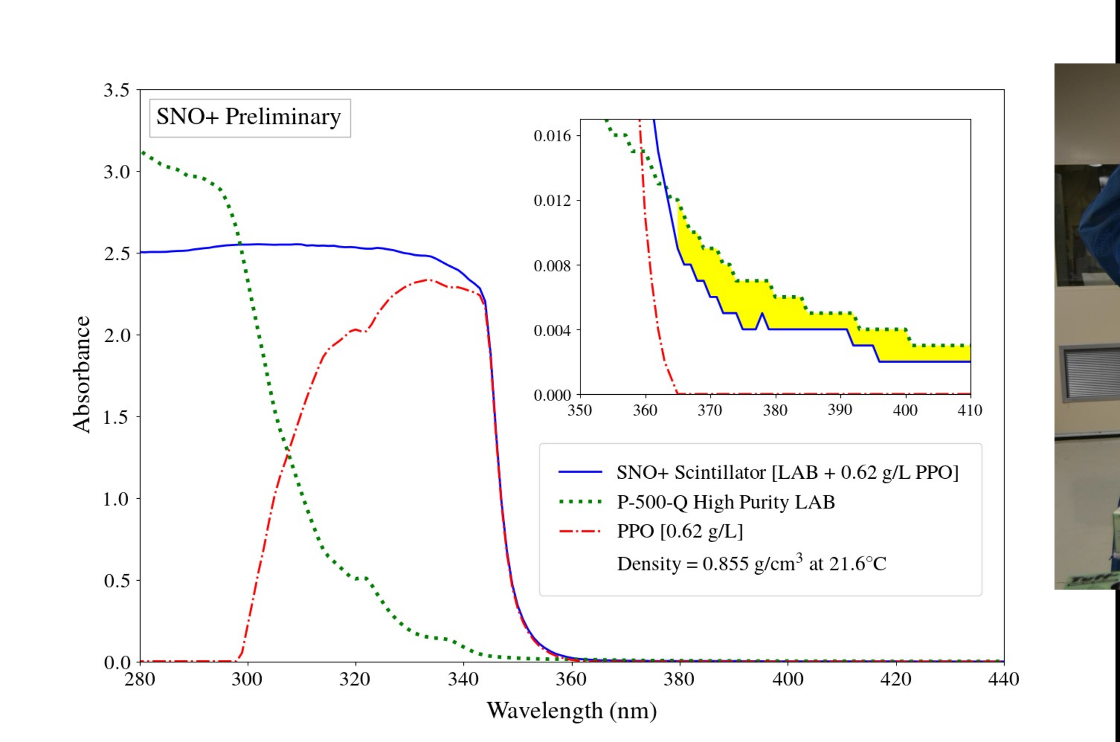


LAB + 2g/L PPO

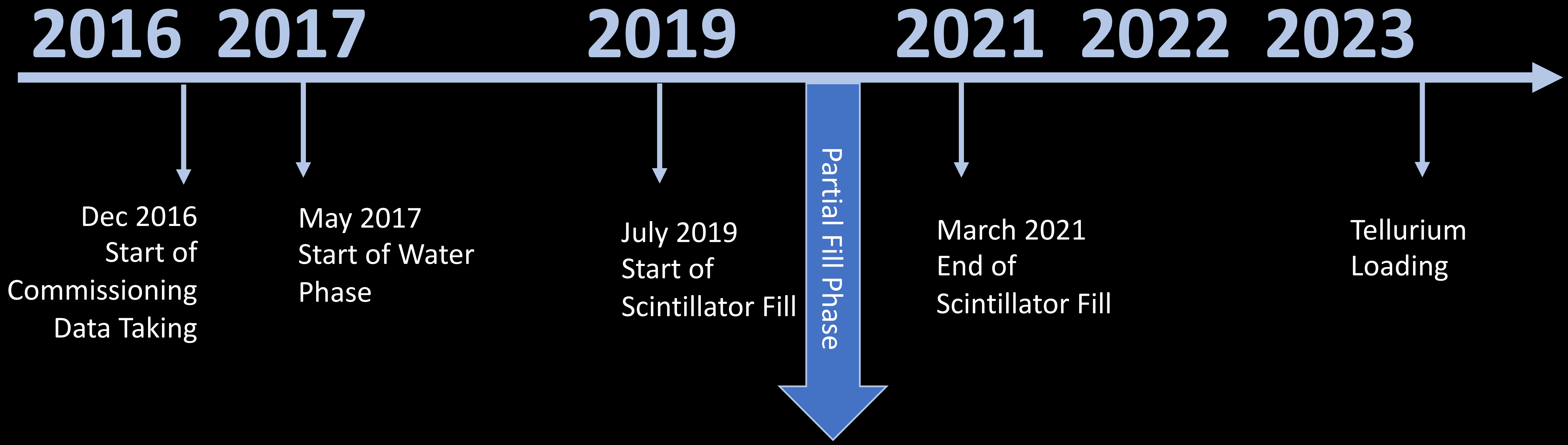


LAB, Master Solution, and final scintillator assessed for quality hourly during purification plant operation and detector filling

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



Partial Fill Phase

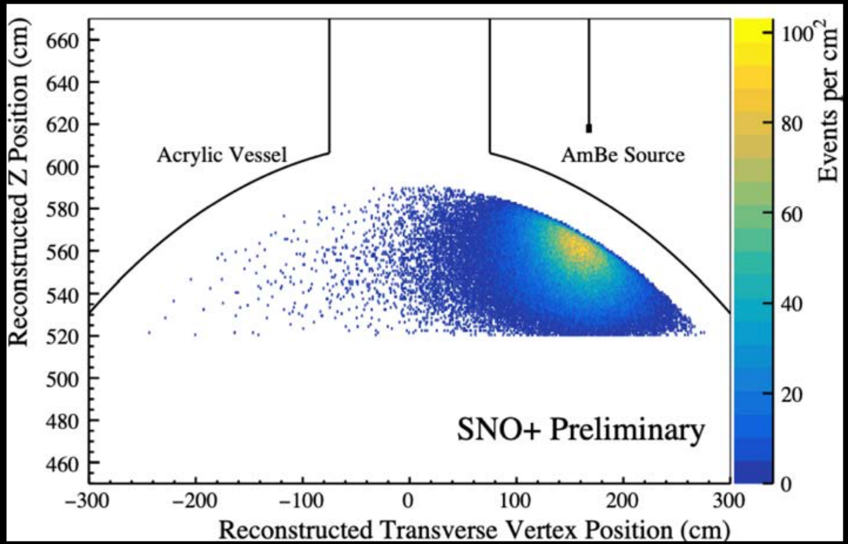


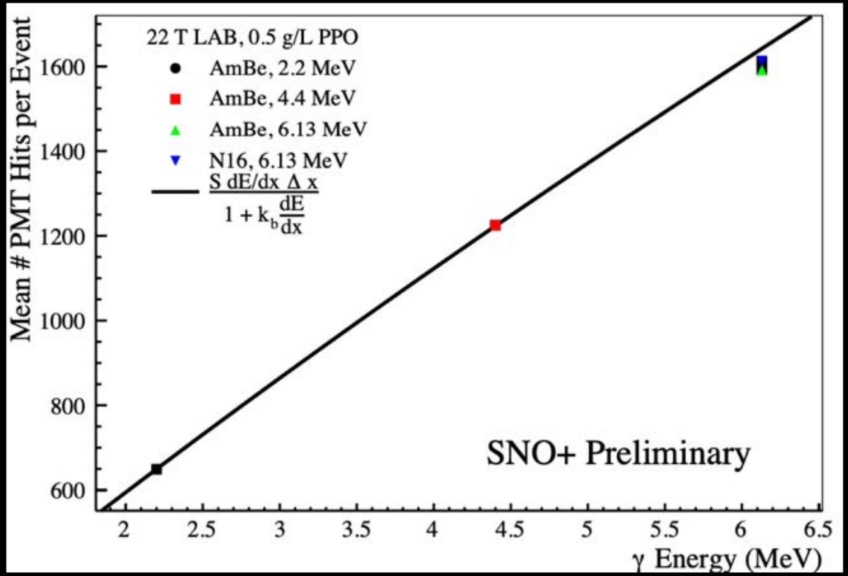
Due to Covid Pandemic, paused with
- **365t (47% full) Scintillator**
- **0.5g/L PPO (25% nominal)**
- **for approximately 7 months**

Scintillator Light Yield

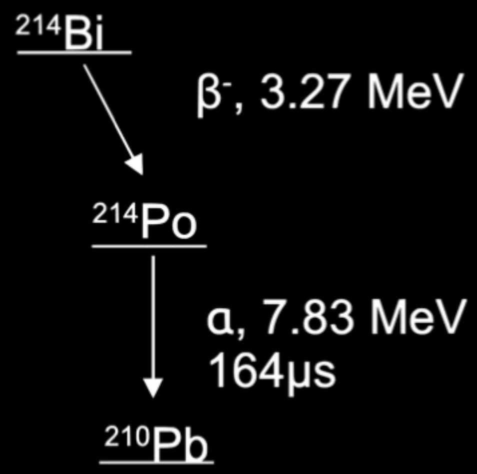
Calibration sources deployed through guide tubes into external (H_2O) region

- With a PPO concentration of only 0.5 g/L (25% of the nominal value) we see a light yield equivalent to ~300 p.e. / MeV





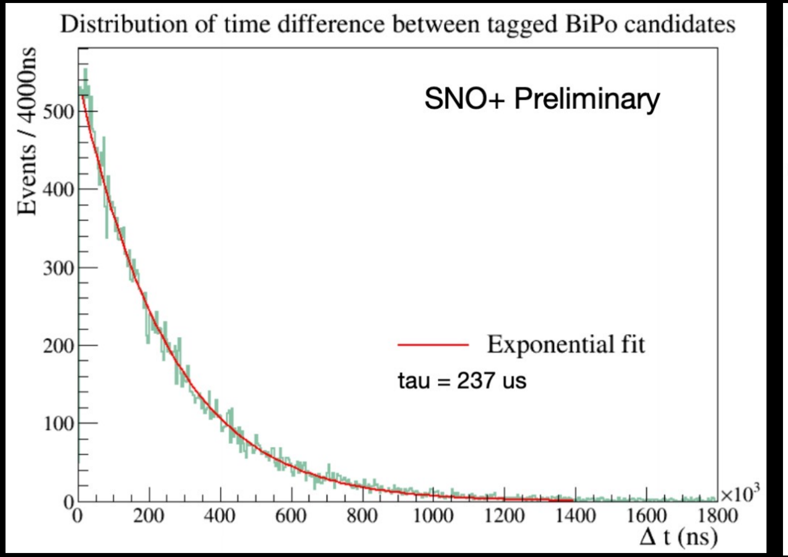
Scintillator Backgrounds

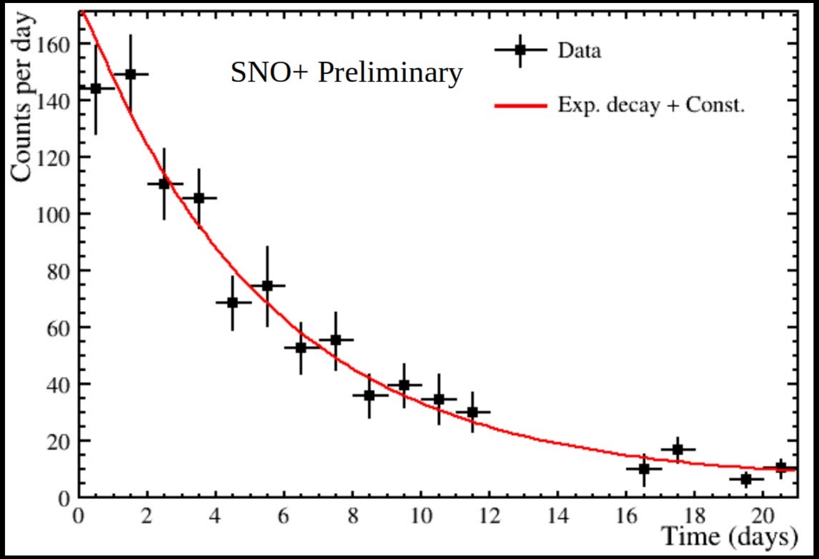


- Measure intrinsic Uranium and Thorium chain contamination through fast time-coincidence β-α events

^{214}Bi-Po (U chain) $T_{1/2}$ = 164μs ^{212}Bi-Po (Th chain) $T_{1/2}$ = 0.30μs

- Some Radon (^{222}Rn half-life = 3.82days) introduced with filling that decays away





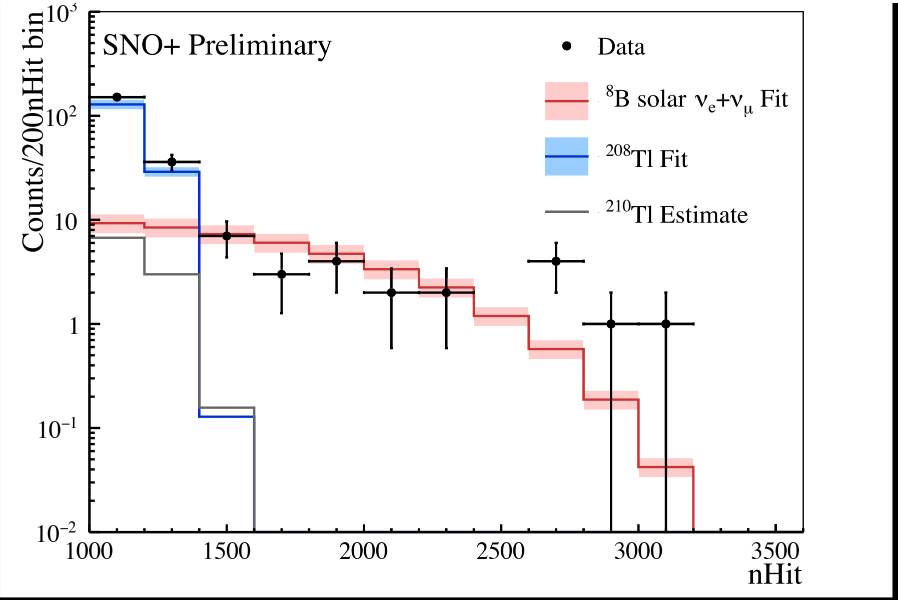
U Rate: 4.7±1.2×10^{-17} gU/gScint
Th Rate: 5.3±1.5×10^{-17} gTh/gScint

Base rate in scintillator below requirements for the 0νββ search

Perform a "target out" $\beta\beta$ analysis
→ prepare/test analysis and techniques using real data
→ determine count rate in the ROI in the absence of Te

Scintillator Physics

$$\Phi_{8B} = 5.66\text{x}10^{6}\ {}^{+20.6\%}_{-18.2\%}(stat.)\ {}^{+6.3\%}_{-7.4\%}(syst.)\ \text{cm}^{-2}\ \text{s}^{-1}$$

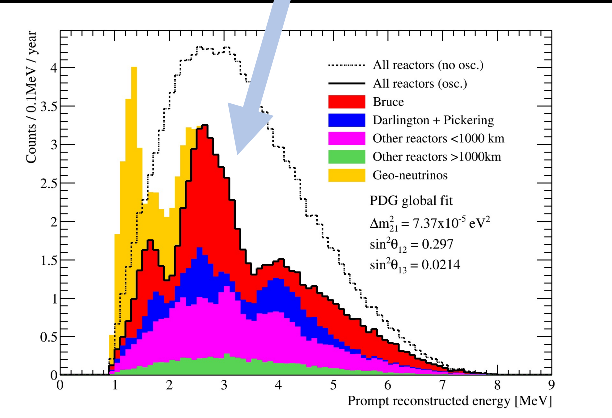


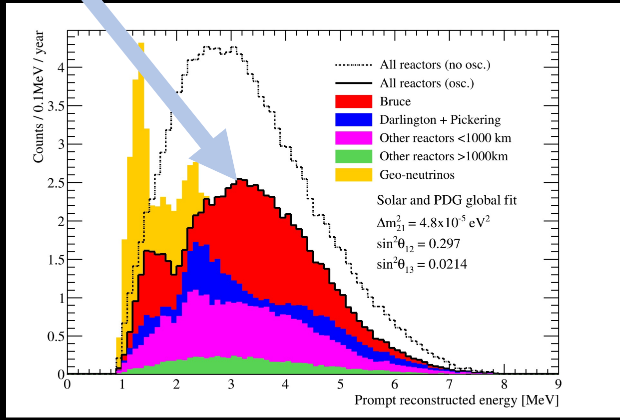
5 – 10 MeV

- ^{8}B solar ν + Bkg fit to the partial fill data,
  - 5.5m fiducial radius
  - including preliminary systematics.
  - Fitted flux compatible with other measurements.

- Anti-neutrino measurement in progress
  - Using time coincidence of inverse beta decay (IBD)
  - Capacity to probe tension in Δm^2_{12}

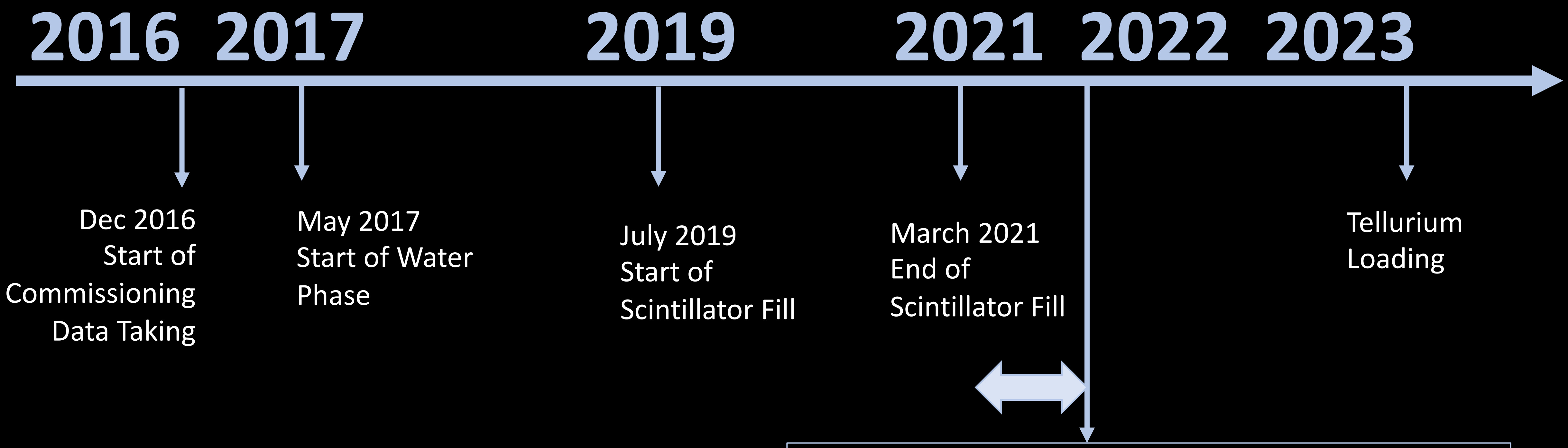
KamLAND vs Solar Global Fit





- Live for supernova
  - Burst monitoring part of SNEWS-1
  - Pre-supernova monitor enabled (IBD)

PPO top-up Phase

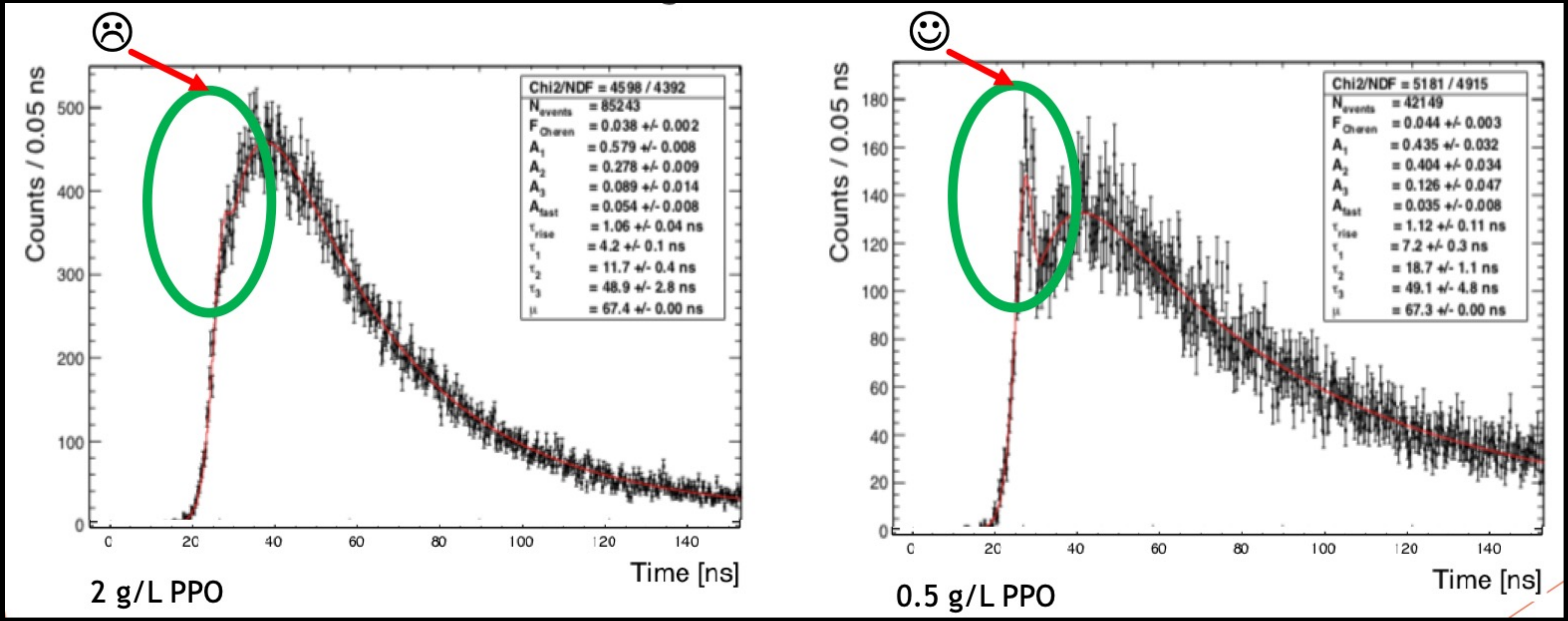


Detector is now full of scintillator

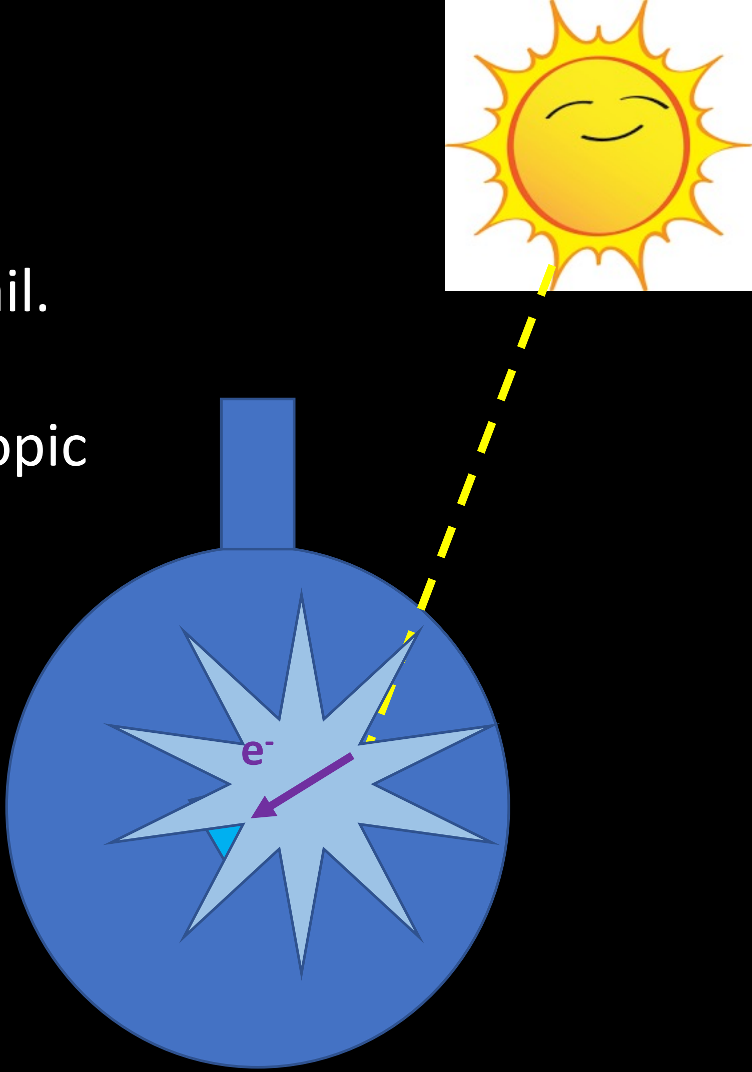
- Circulating scintillator and adding PPO to increase dopant to 2g/L → Completion early 2022

Directionality

Data collected with lower PPO concentrations than our final cocktail. Lower scintillation light yield and slower rise time means we have potential to see initial (directional) Cherenkov light as well as isotropic scintillation light



https://arxiv.org/abs/2001.10825



Holy grail for solar background rejection

Working on proof of principle with partial fill data

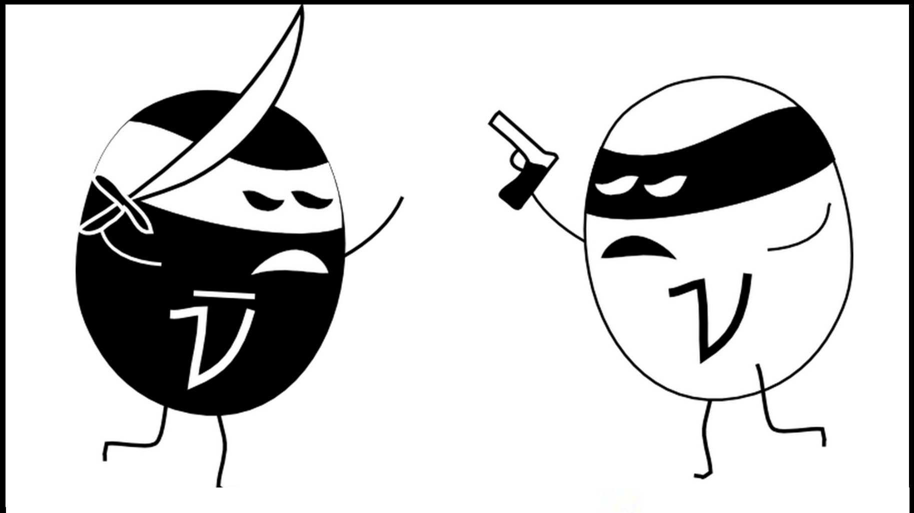
Double Beta Decay

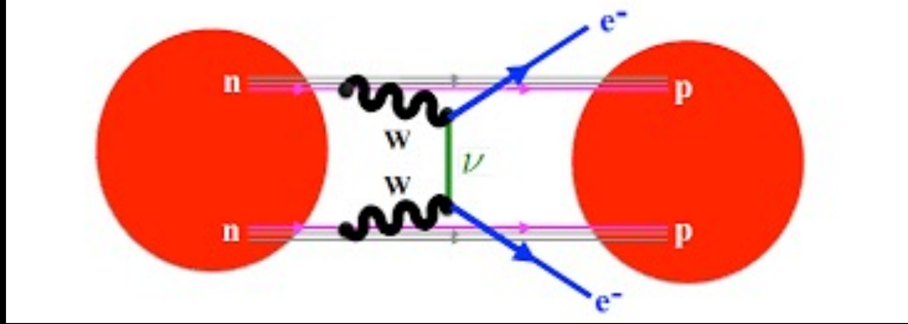
- What is absolute neutrino mass scale?
- Why are neutrinos so light compared to other (Dirac) fundamental particles?
- Are they Majorana particles?

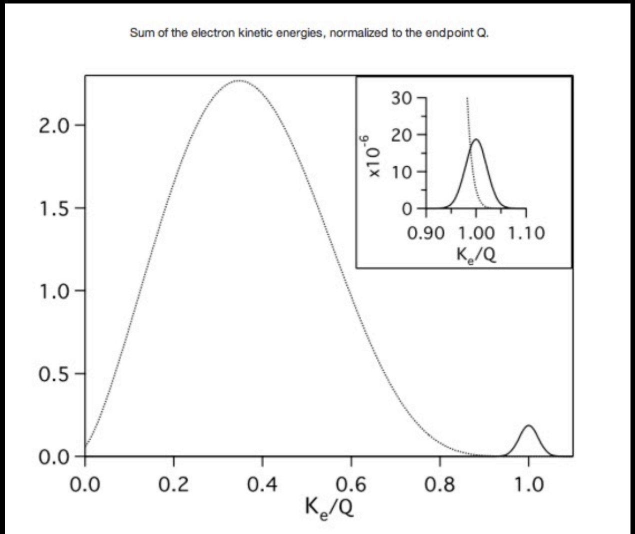
$0\nu\beta\beta$ can only occur for Majorana particles with a rate proportional to the mass

<u>Experimental signature:</u>

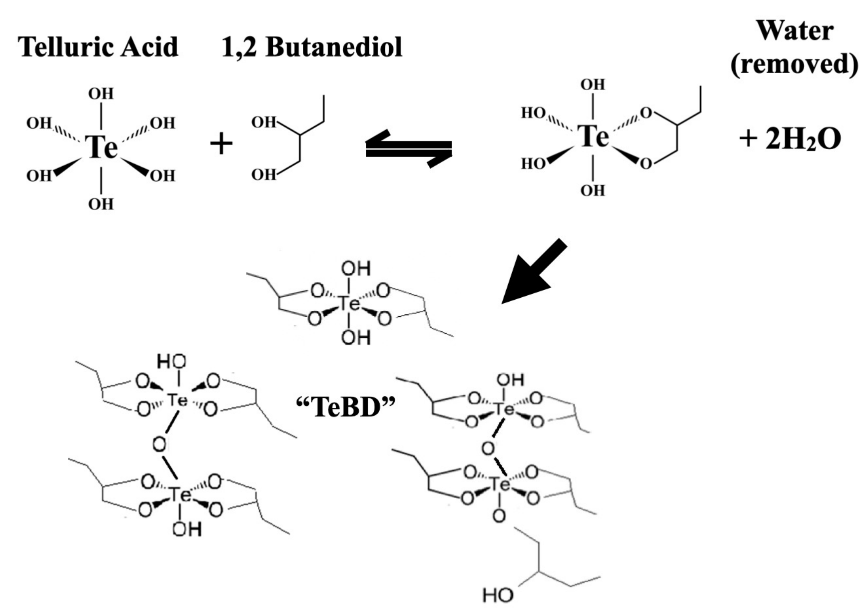
- Emission of 2 electrons at precise Q-value of decay







SNO+ 0νββ strategy



- Massive detector → High statistics
  → Shielding through fiducialisation
- Liquid scintillator → purification methods
  → Loading can be scaled
  → Homogeneous loading of isotope in detection medium

Tellurium-130 → Highest natural abundance (34%), no enrichment required, low cost
→ Q-value at 2.527 MeV – less background from natural radioactivity
→ Load into scintillator with Butanediol

Initial phase loading: 0.5% natural Te by weight = 1333 kg of ^{130}Te.

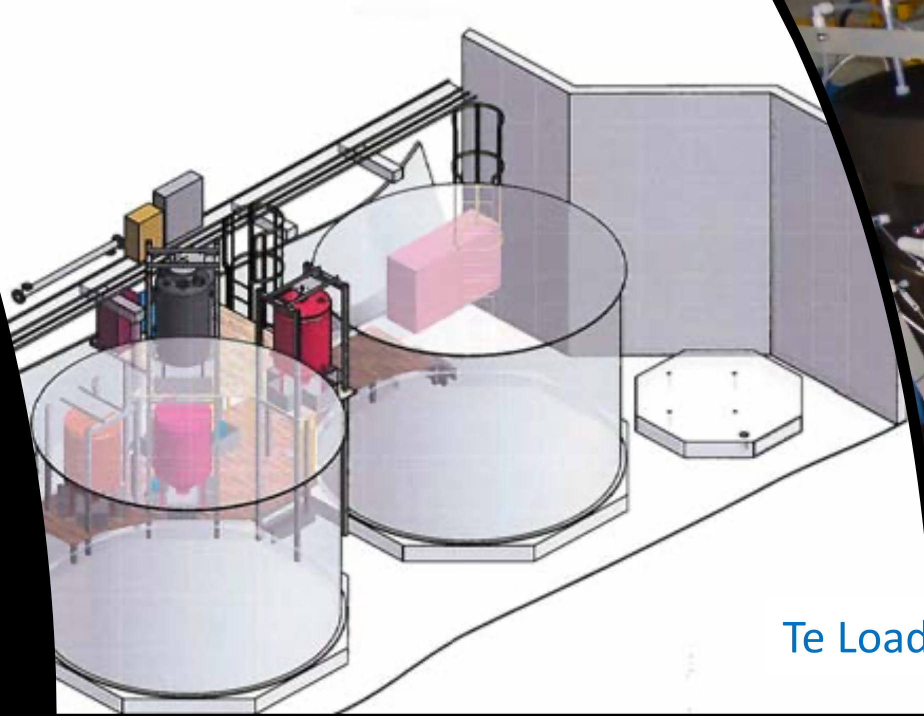
Develop a scalable and affordable approach to push towards the NH in the future

Te loading

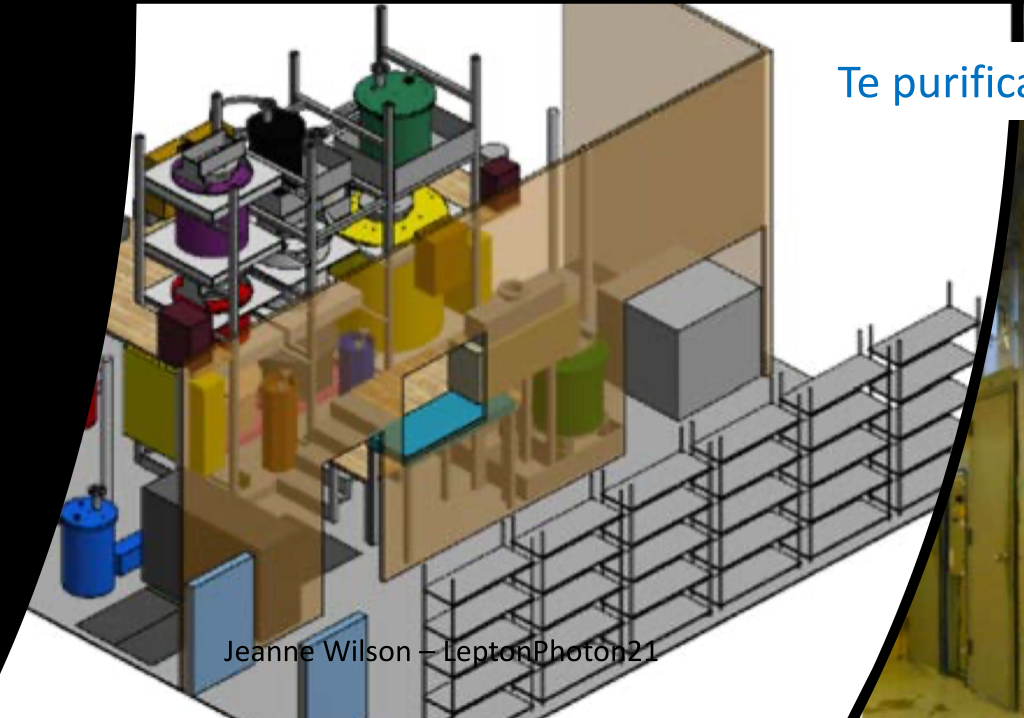
- ~8 tons of telluric acid (TeA) has been "cooling" underground for several years.
- Ton-scale underground purification of TeA for further background reduction.
- Target purification for Te cocktail:

  ~ 10^{-15} g/g U

  ~ 10^{-16} g/g Th



Te Loading plant

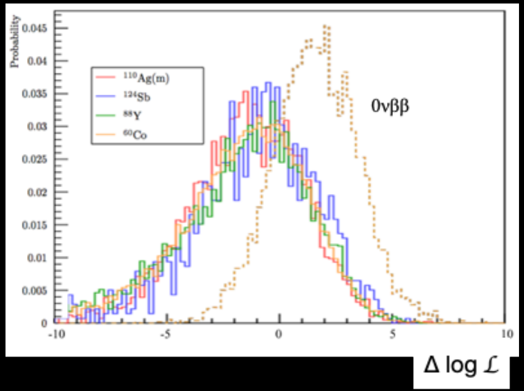


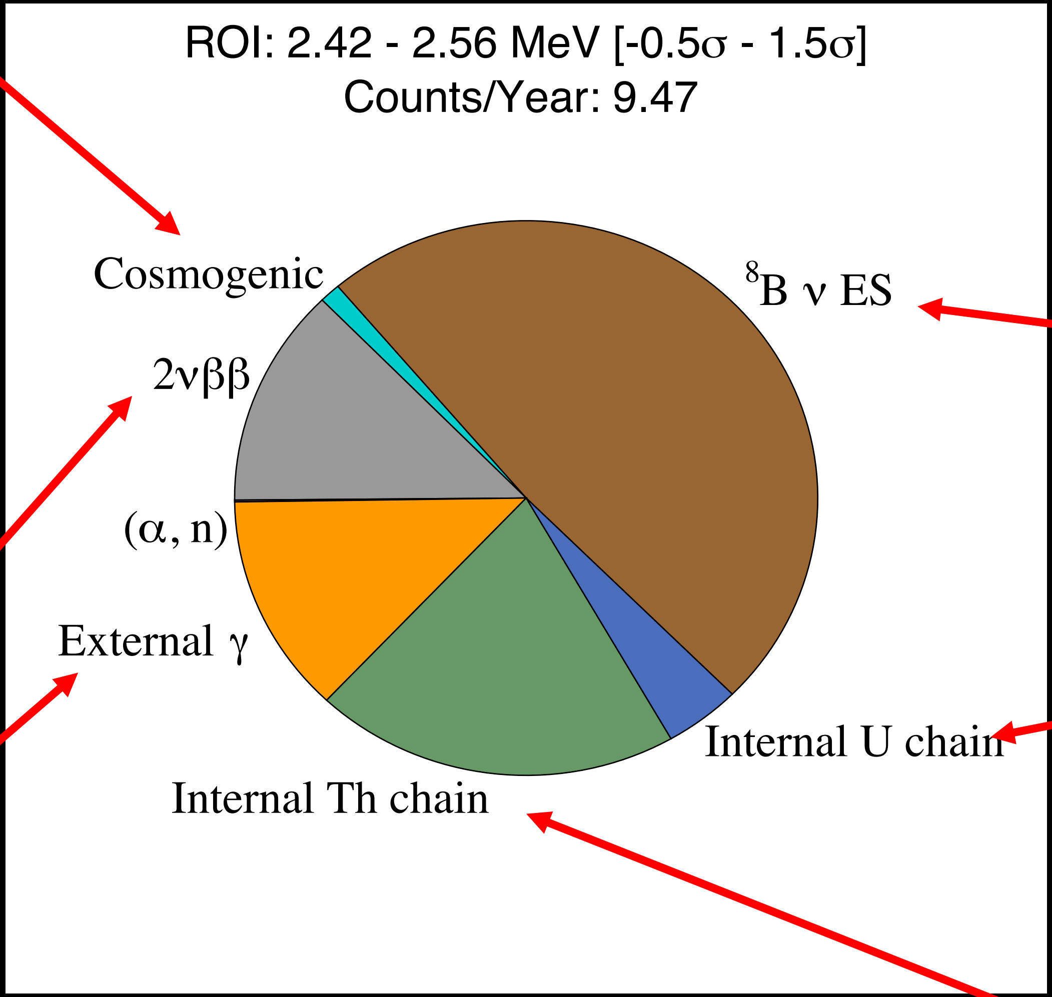
Te purification plant

Te phase background projections

Pure scintillator phase allows "Te-out" measurement to test for any unexpected backgrounds

Our telluric acid has been "cooling" underground for several years.
+ Te purification
+ multi-site rejection *





Staged Te-loading allows us to assess remaining Te-backgrounds

Well measured from previous experiments

Suppressed by asymmetric ROI:
2.42 – 2.56 MeV [-0.5σ- 1.5σ]
Assuming ~460 PMT hits / MeV

Already measured U $<10^{-16}$ g/g in partial fill (pure LAB) below requirements

Measured in water data
Reduce by 23%

Already measured Th $<10^{-16}$ g/g in partial fill (pure LAB) below requirements

* See NIM 943, 162420, 2019 for more details

Projected spectrum: 0.5% loading

Fiducial volume for plot = 3.3m

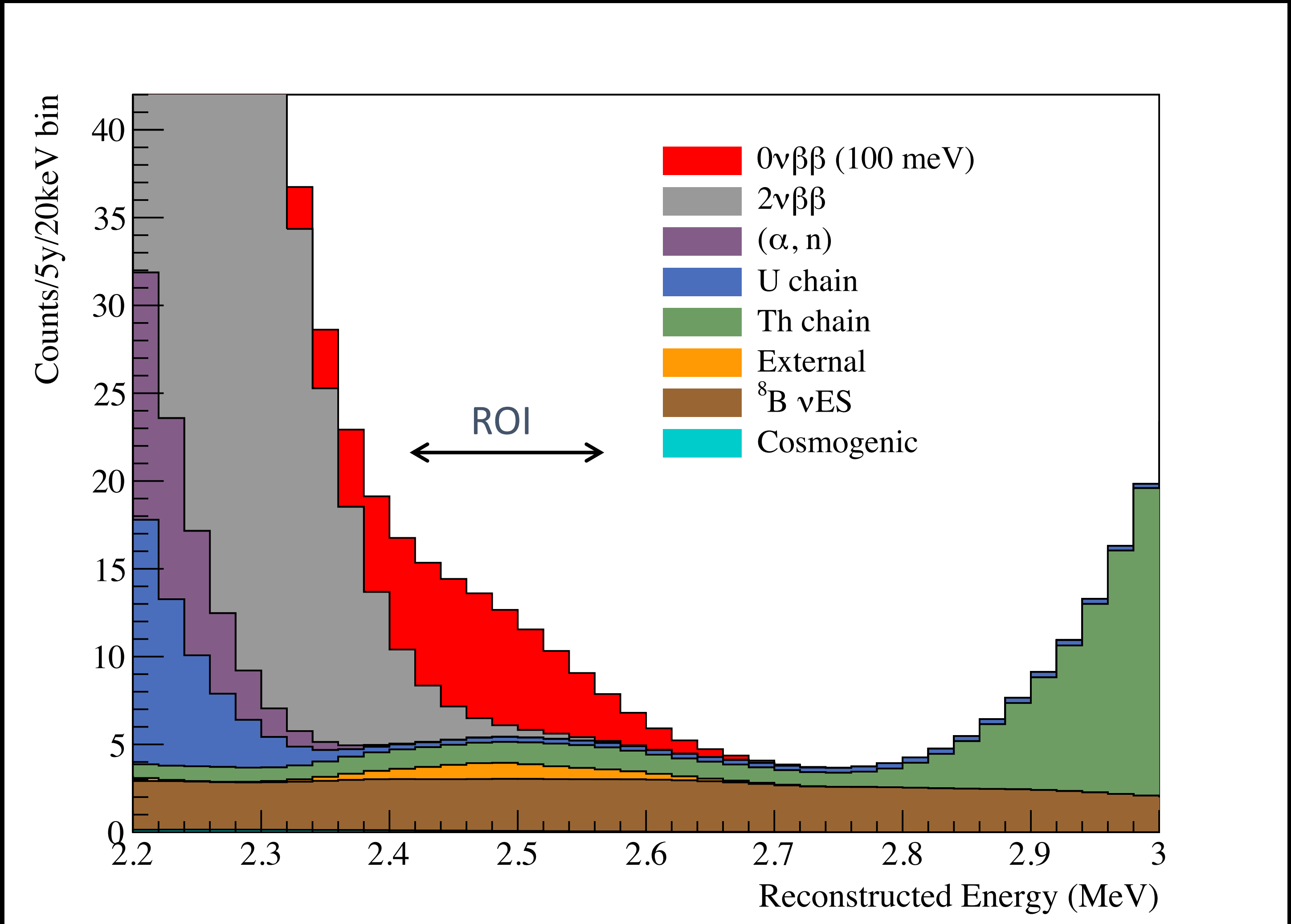
(not optimized)

Half-life sensitivity:

$T_{1/2} > 2\times10^{26}$ years

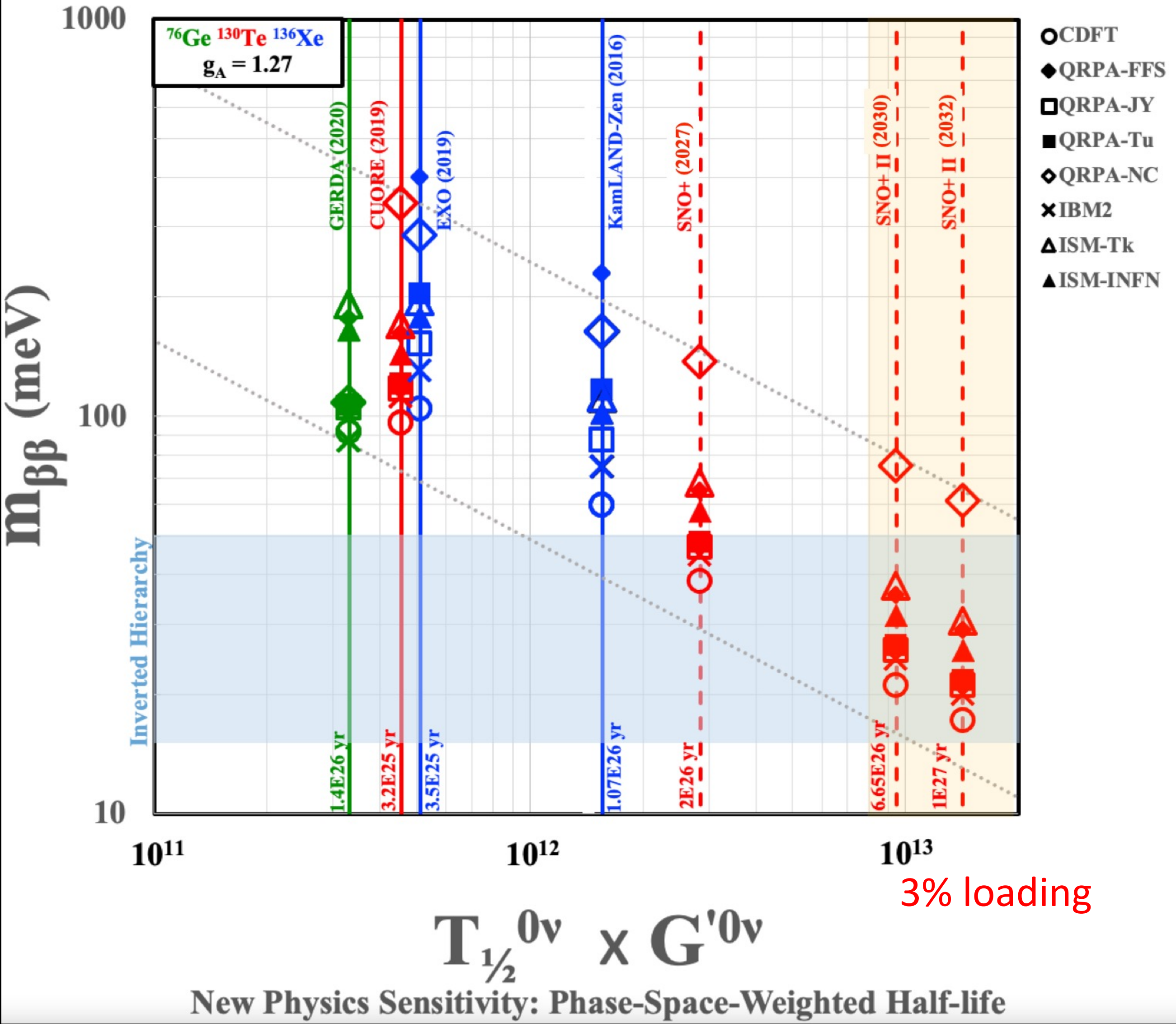
Sensitive to $m_{\beta\beta}$ = 37-89 meV

Full likelihood analysis using Energy, radius and multi-site discriminators achieves this sensitivity with 3 years of data.



Potential future 0νββ sensitivity

- SNO+ approach can be scaled up → SNO+ Phase II
  - Te loading up to several % with good light yield and stability
  - Cost is relatively very low (< $2M per ton of decay isotope)
- Competitive results with different isotopes important given theoretical uncertainties



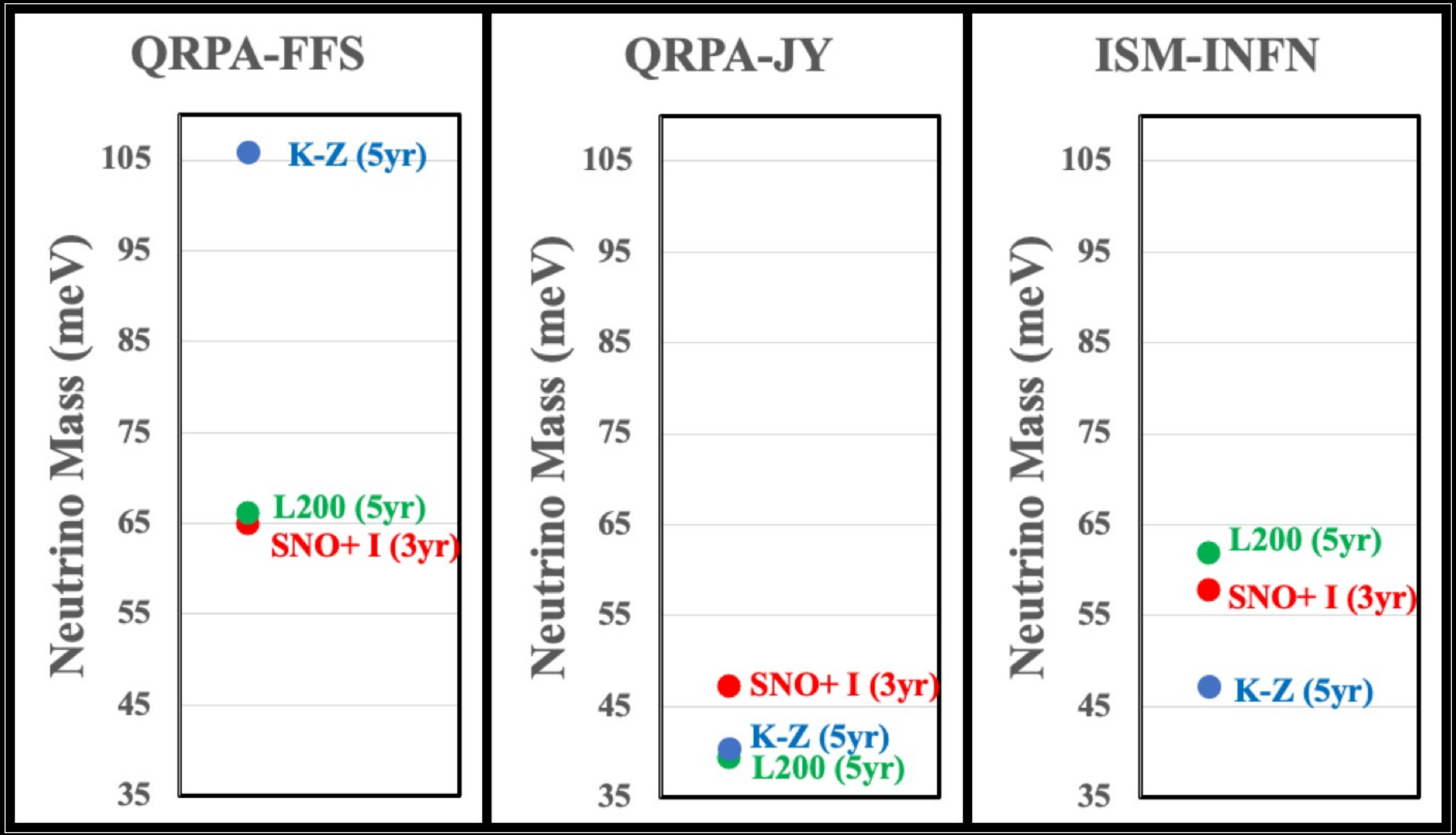
3% loading

Summary

- 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 underway
- Scintillator physics → 0νββ, Solar, reactor-ν, geo-ν, Supernova …
- Te-loading gives competitive 0νββ search with 0.5% loading
- Scalable approach of SNO+ has huge potential for extending 0νββ sensitivity

Backup material

Measuring with different isotopes is very important given theoretical uncertainties



Discovery potential – multidimensional fit

- Fit in E, R and 2 PSD dimensions
- Each point obtained from an Asimov dataset with different strength of signal injected into it (corresponding to different effective Majorana mass)
- Discovery credible interval for 0νββ after 3 years
- Dashed lines indicate 3σ C.I. for analyses with and without PSD