SNO+

Tsinghua University

Seminar on Double Beta Decay
September 16, 2020

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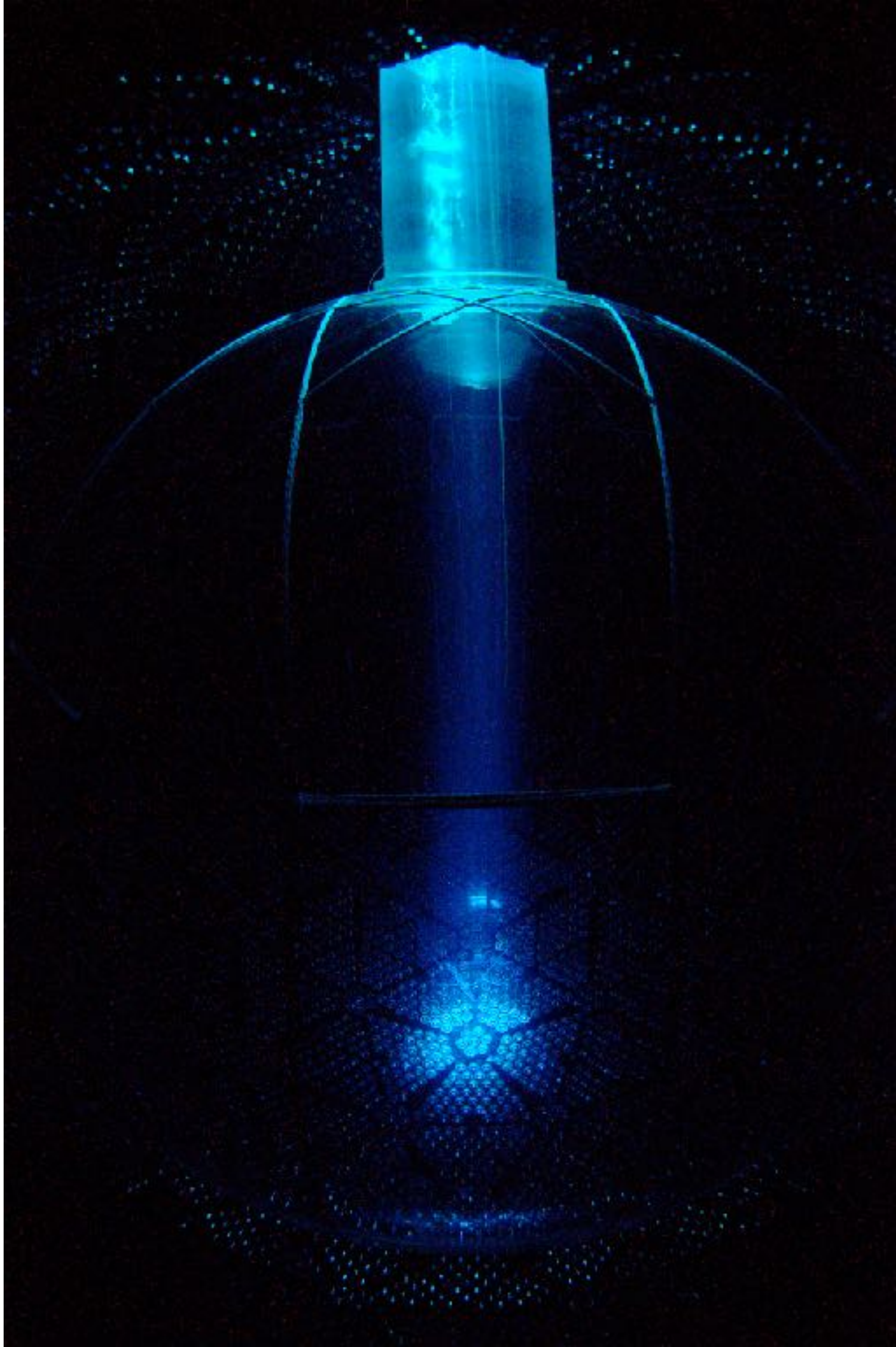
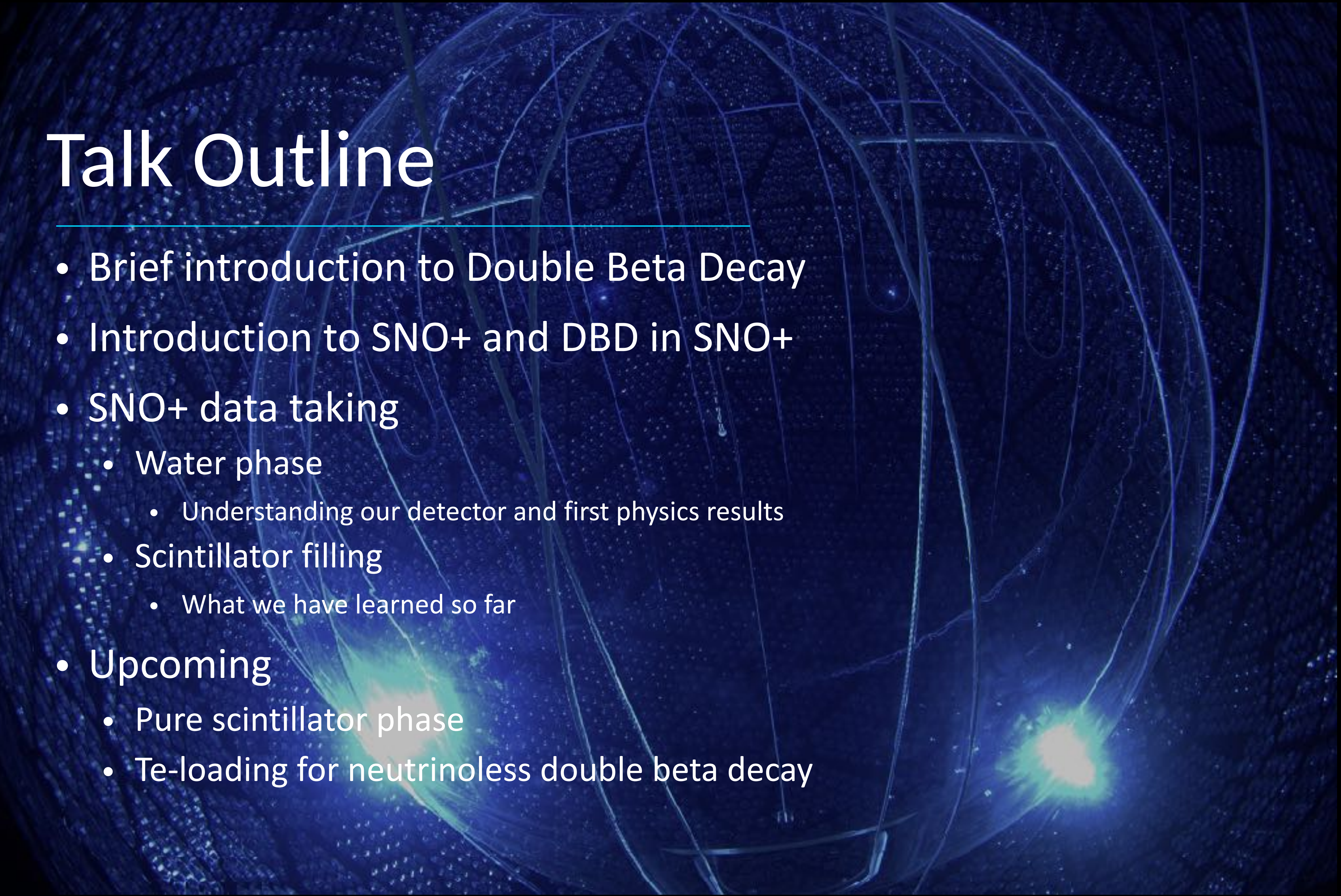
Queen's University
Canadian Institute for Advanced Research

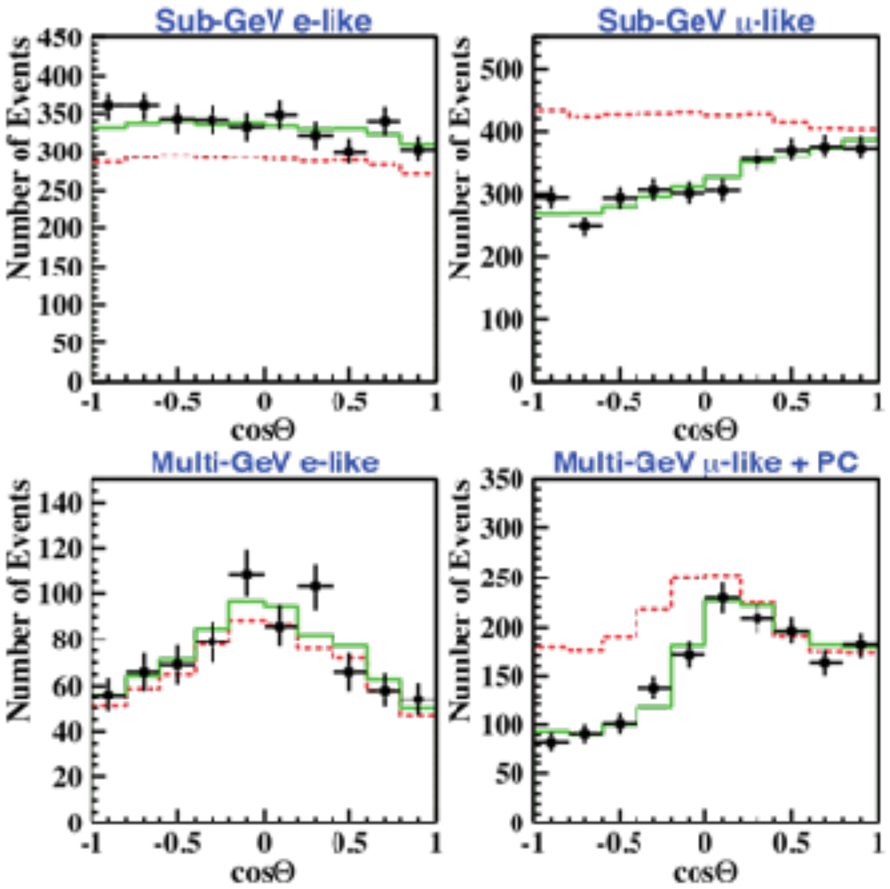


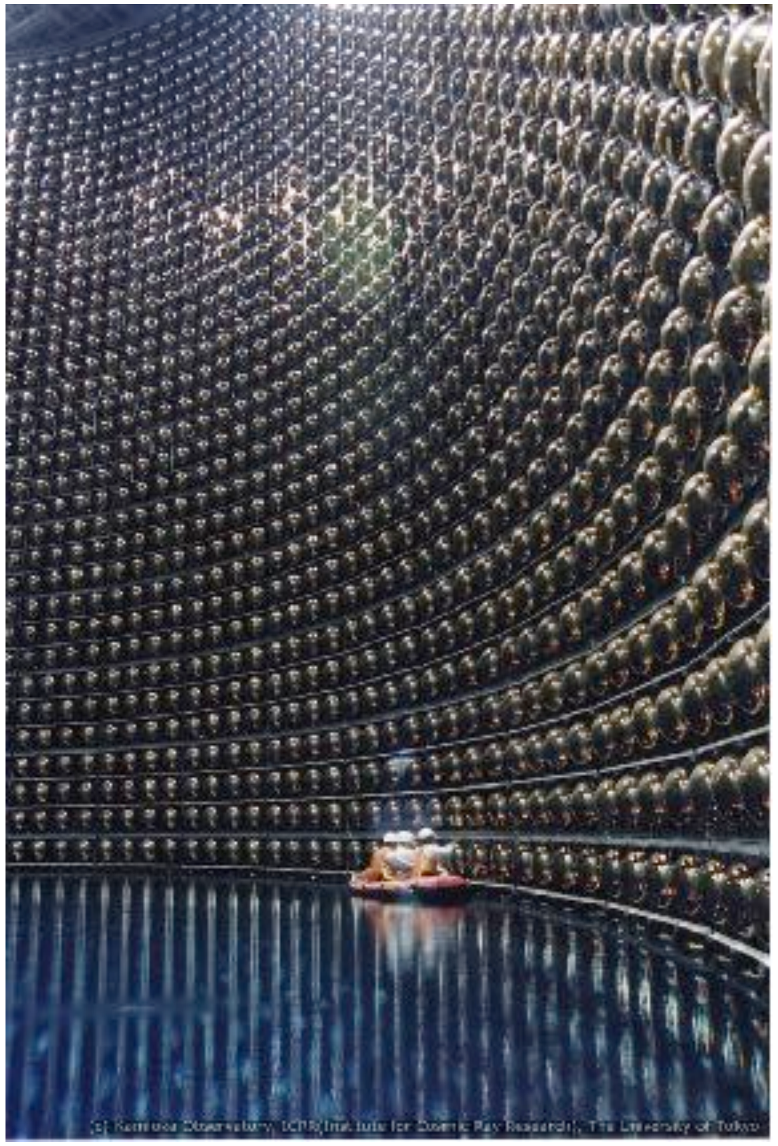


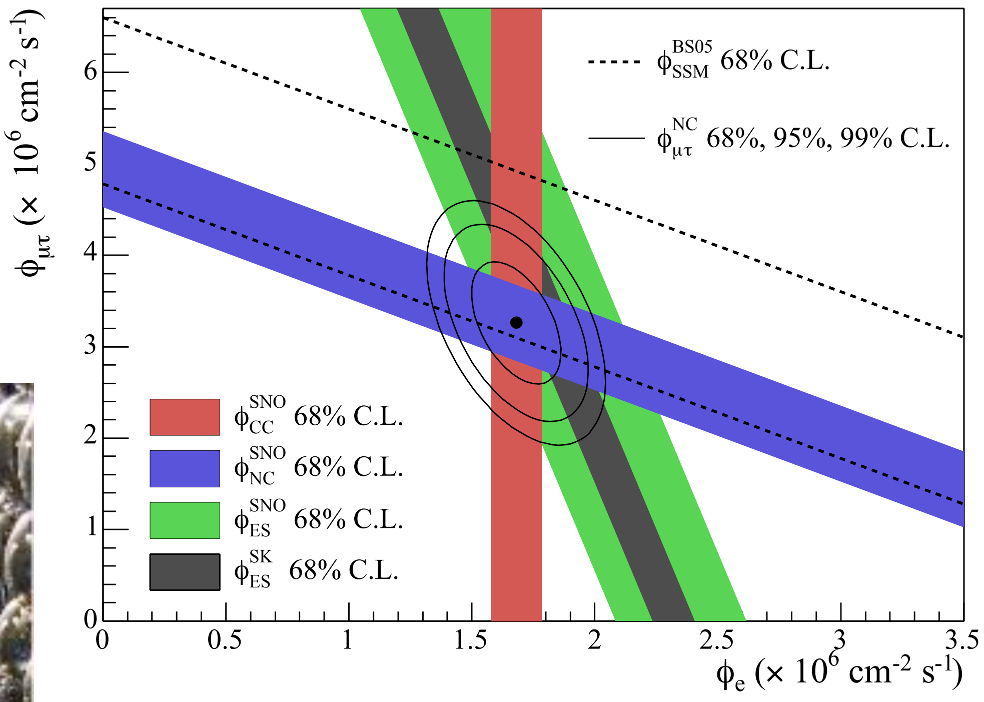
Talk Outline

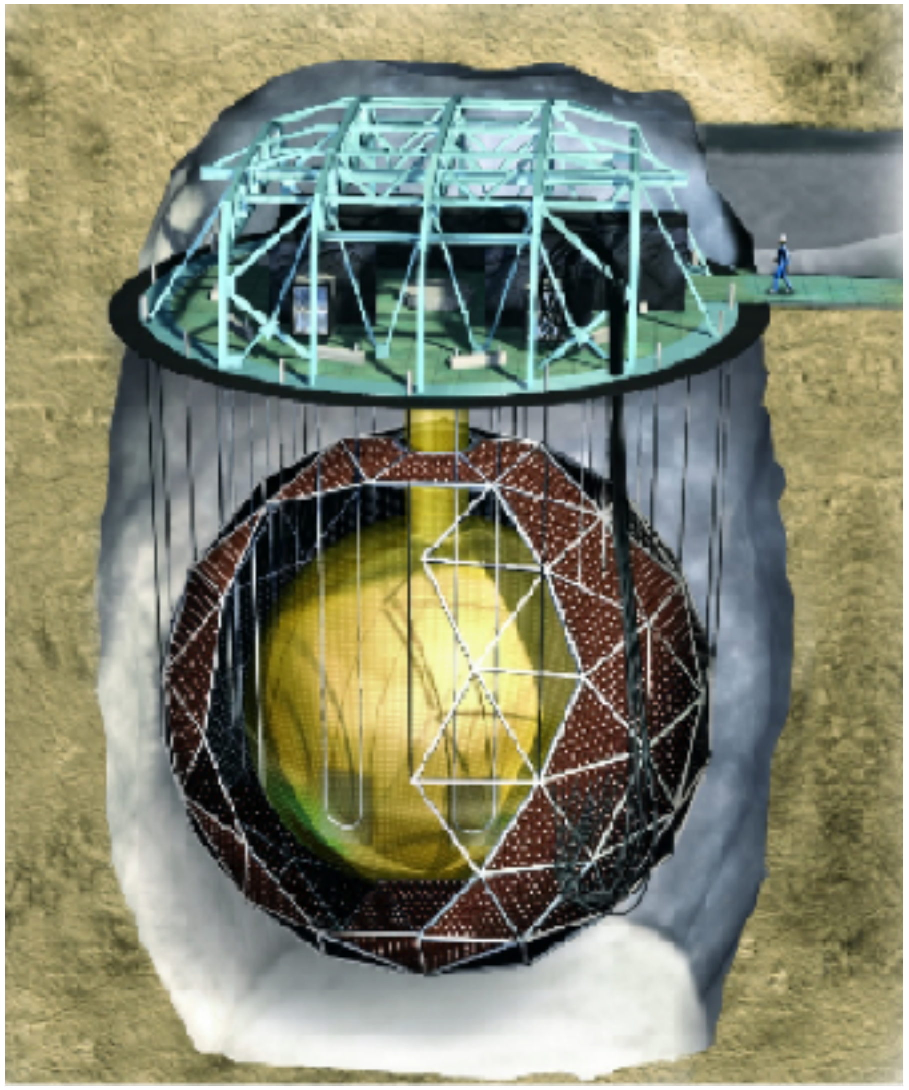
- Brief introduction to Double Beta Decay
- Introduction to SNO+ and DBD in SNO+
- SNO+ data taking
  - Water phase
    - Understanding our detector and first physics results
  - Scintillator filling
    - What we have learned so far
- Upcoming
  - Pure scintillator phase
  - Te-loading for neutrinoless double beta decay

Neutrinos Oscillate
so they have mass









- flux of atmospheric muon neutrinos produced by cosmic rays is not up-down symmetric

- solar neutrinos produced as electron neutrinos in the Sun are detected by SNO as other flavours (ν_μ, ν_τ)

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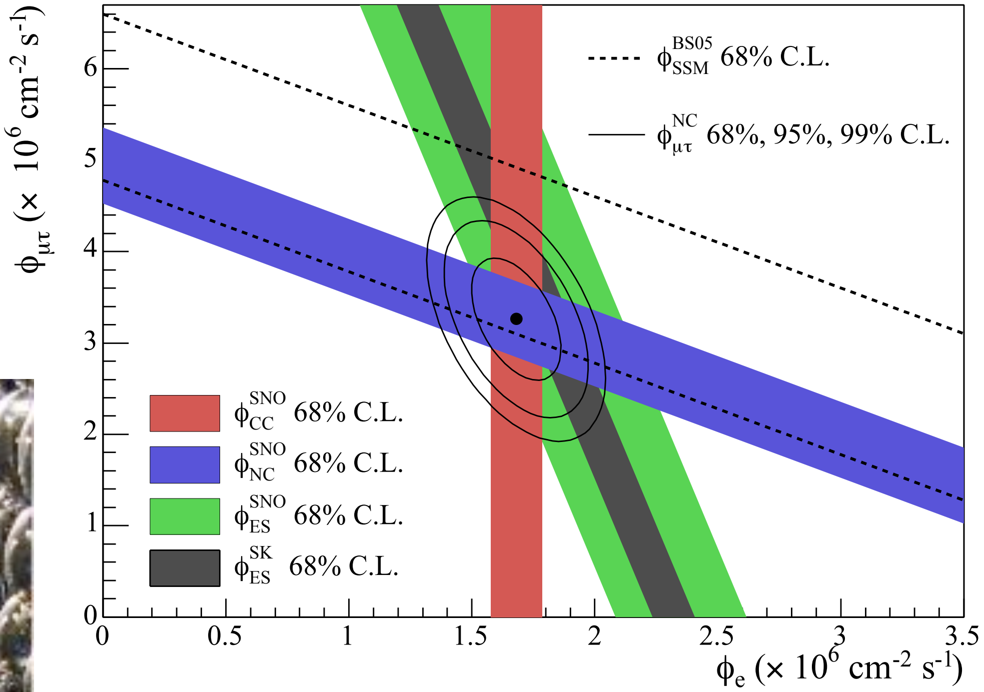

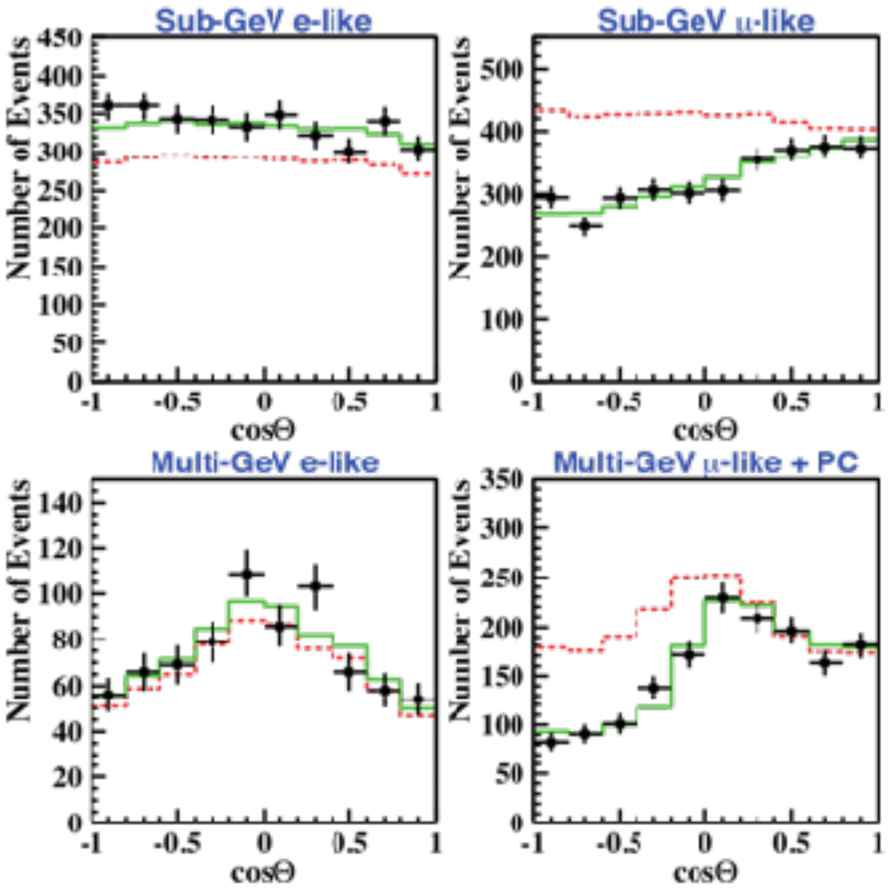

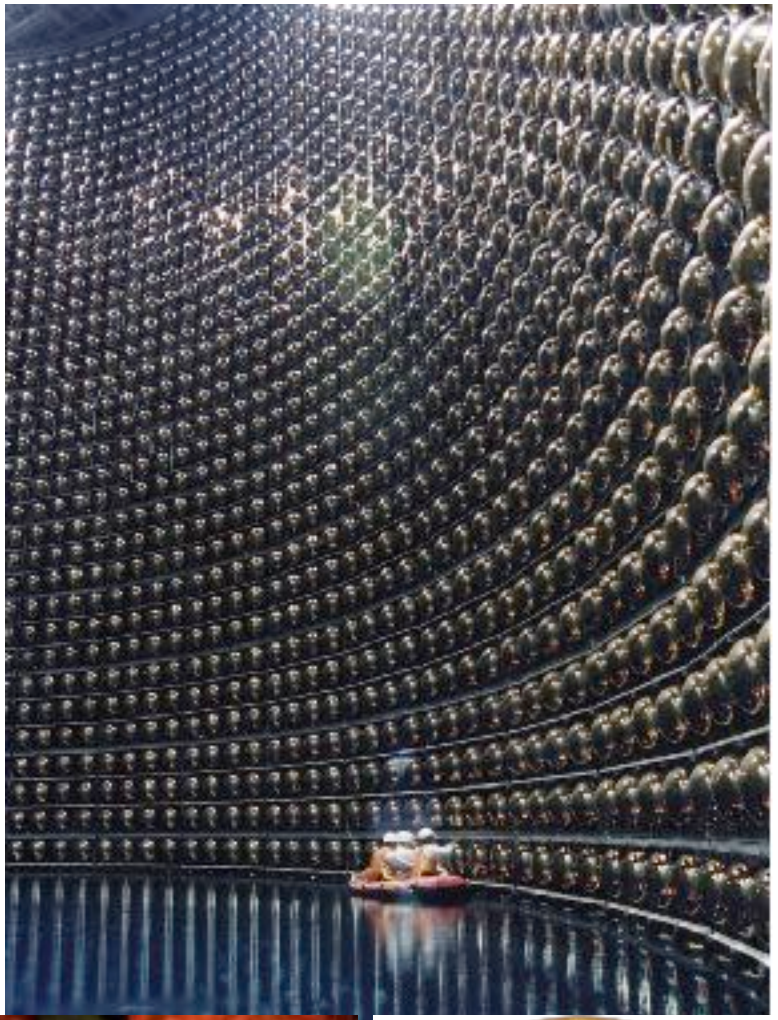

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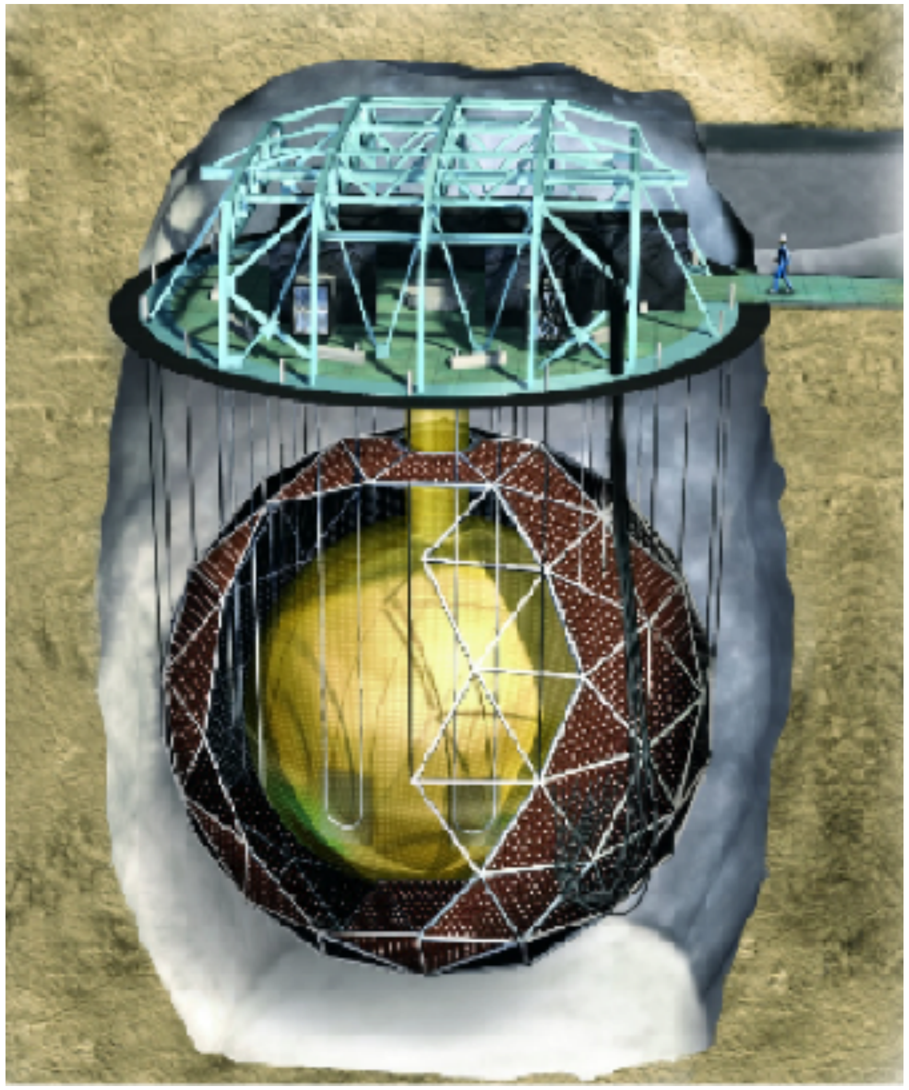


Neutrino Mass

Physics Beyond the Standard Model

Dirac

$$yH\bar{\nu}_R\nu_L \rightarrow m_D\bar{\nu}_R\nu_L$$

why is the Higgs Yukawa coupling so small?
implies new global U(1) symmetry?!
what’s going on with the right-handed fields?

Majorana

neutrinos are their own antiparticles

$$m_M\bar{\nu}^C_L\nu_L$$

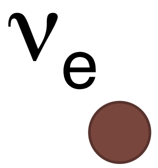
different mass mechanism, not Higgs
small mass could be “natural”

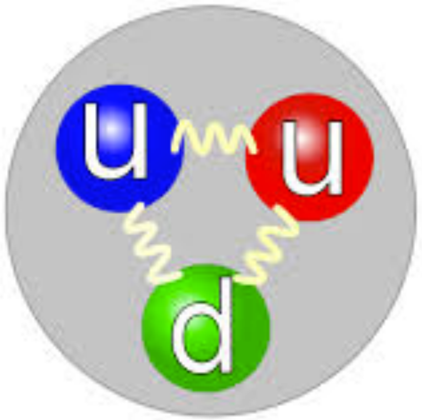
or both

$$\begin{pmatrix}\bar{\nu}_L & \bar{N}^C_L\end{pmatrix}\begin{pmatrix} m & m_D \\ m_D & M\end{pmatrix}\begin{pmatrix}\nu^C_R \\ N_R\end{pmatrix}$$

Are Neutrinos Majorana Fermions?

- they carry no electromagnetic charge, no QCD colour, no moments, no other quantum number
- other than *lepton number*…but what is that?





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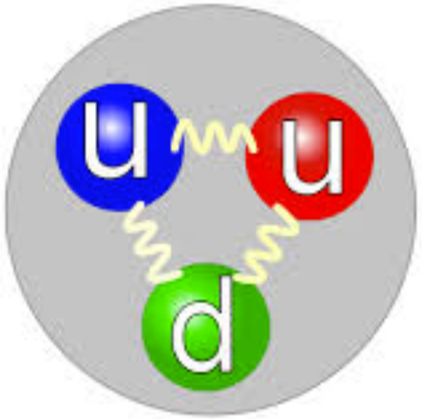

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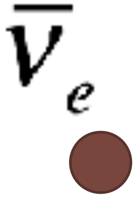

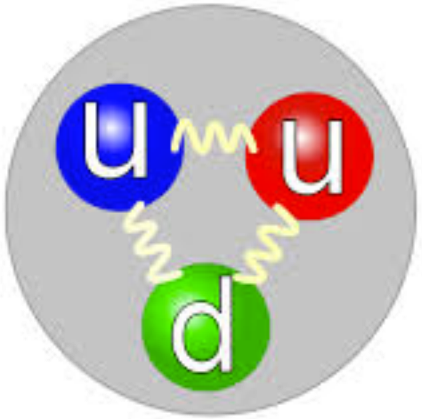

Why does this only happen for the “anti”-neutrino? Does the proton know it was an anti-lepton?

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

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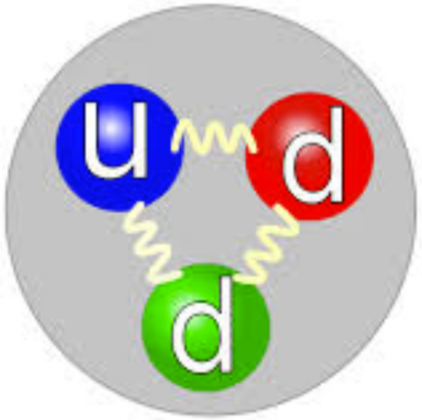

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Answer: Chirality and the Weak Interaction

- the weak interaction distinguishes between left and right chirality and that's why $\bar{\nu}_e + p \rightarrow e^+ + n$

- does the weak interaction *additionally* distinguish between lepton number L = 1 and L = –1? Or is that simply redundant?
  - neutrino and antineutrino: do they carry opposite "weak hypercharge" in addition to opposite chirality?

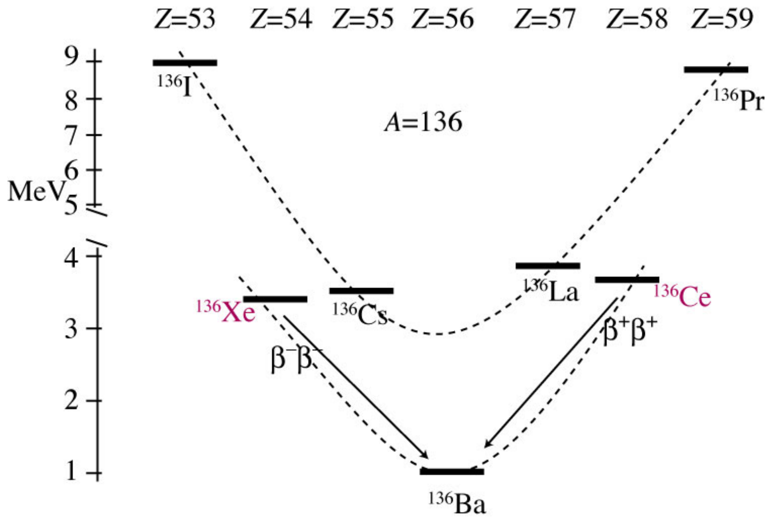
- is lepton number – as global U(1) symmetry – a meaningful quantum number?

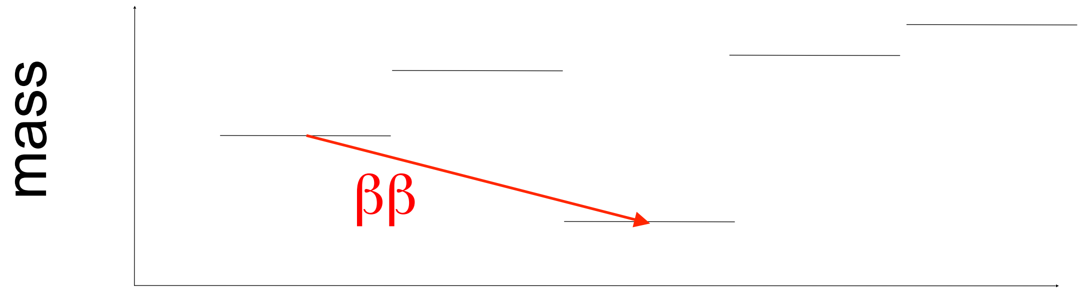
- if one discards lepton number as a meaningful quantity then neutrinos are Majorana fermions…FACT!

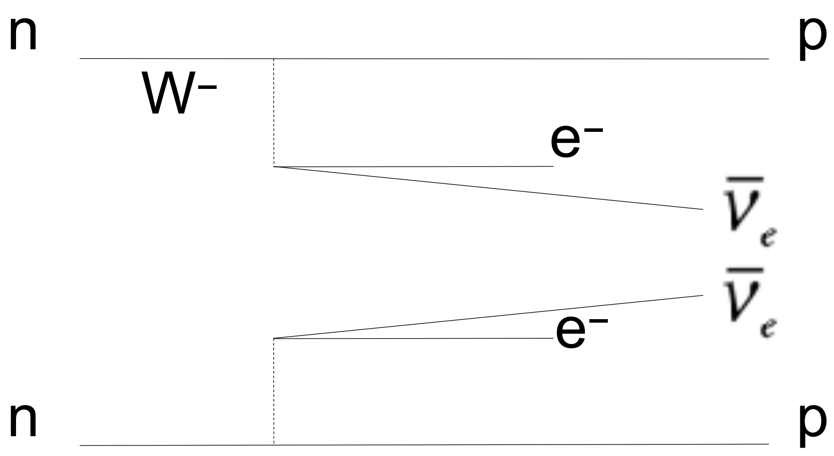
Double Beta Decay

- some even-even nuclei cannot β decay but can undergo double beta decay, a very rare second-order weak process

– e.g. ^{76}Ge has half-life 1.8 × 10^{21} years







2νββ

Double Beta Decay

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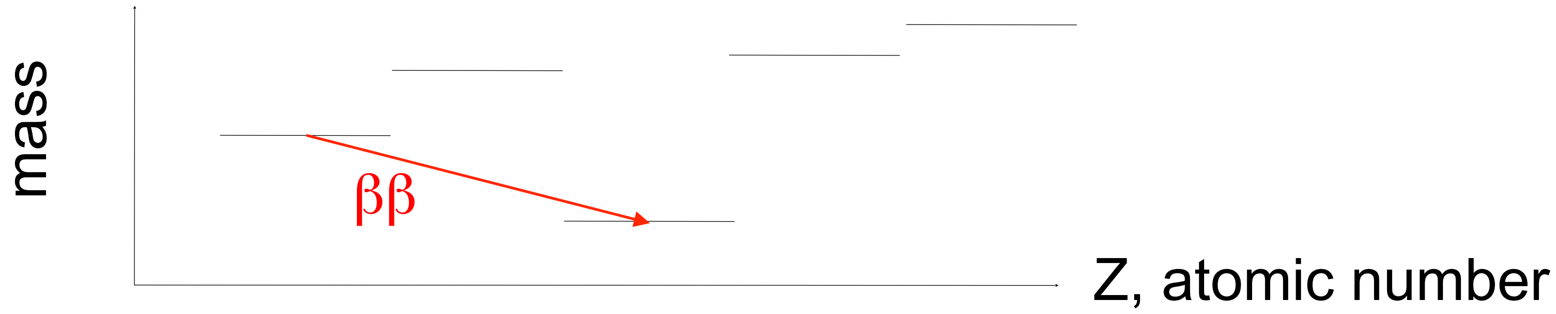
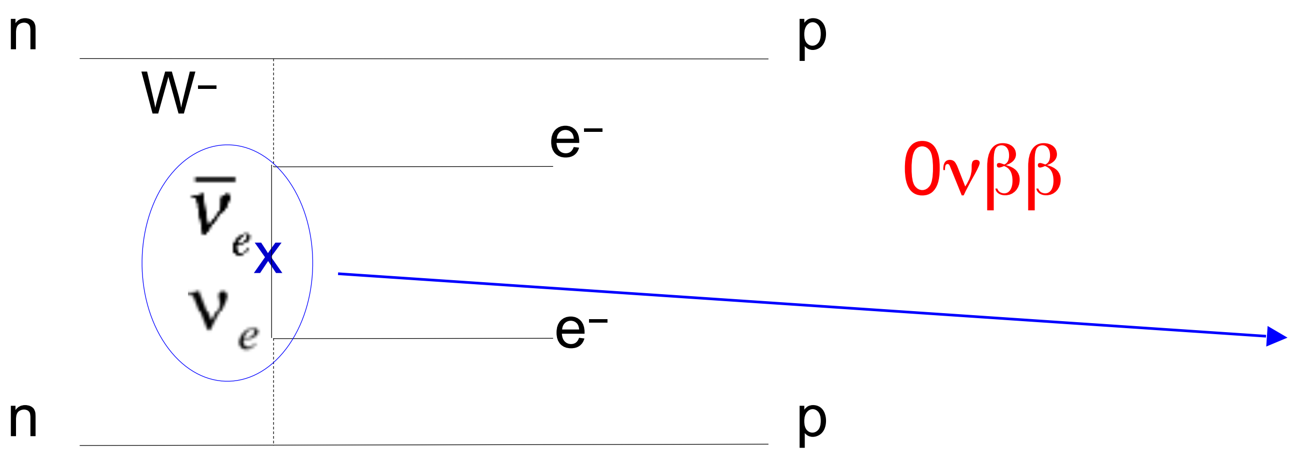


- Q: can this (Beyond the Standard Model) process occur?
  neutrinoless double beta decay

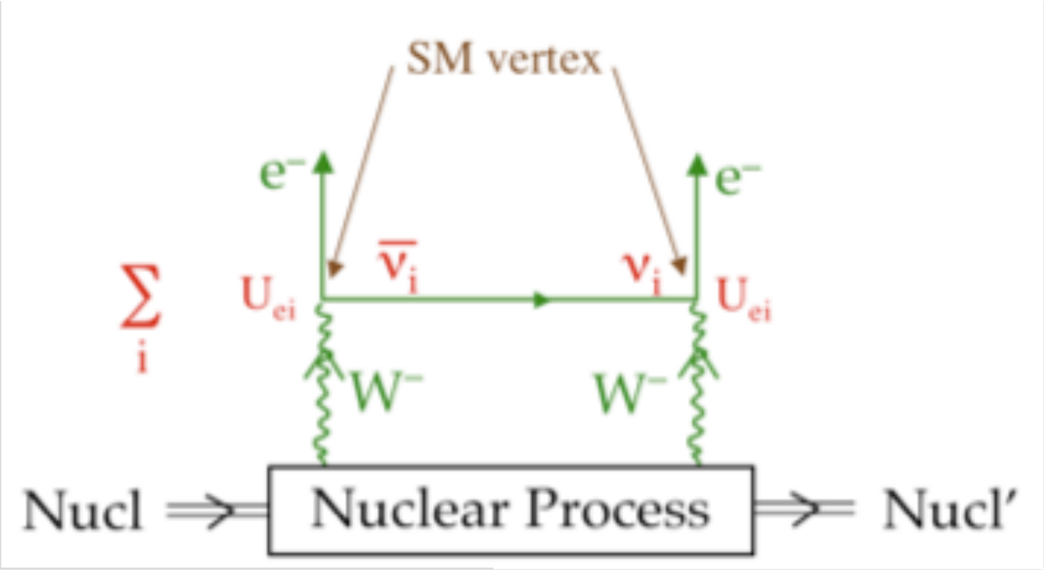


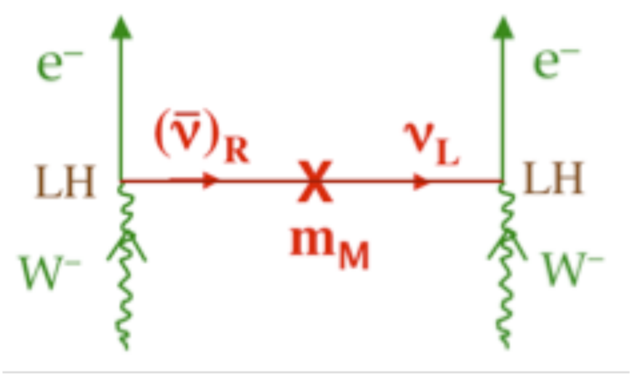
requires neutrinos to be their own antiparticle
– Majorana fermions
as opposed to Dirac fermions

Neutrinoless Double Beta Decay Amplitude

- if and only if Majorana
    - antineutrino = neutrino
- chirality mismatch
    - antineutrino is dominantly right-handed with component m/E that is left-handed
- amplitude

$$\left|\sum_i m_i U_{ei}^2\right| \equiv \langle m_{\beta\beta}\rangle$$





decay rate is amplitude squared, hence

$$\propto \langle m_{\beta\beta}\rangle^2$$

take note: it's the sum of complex-valued U_{ei} with the "Majorana phases"

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \times \mathrm{diag}(1, e^{i\alpha_1}, e^{i\alpha_2})$$

Decay Rate (or Half-Life)

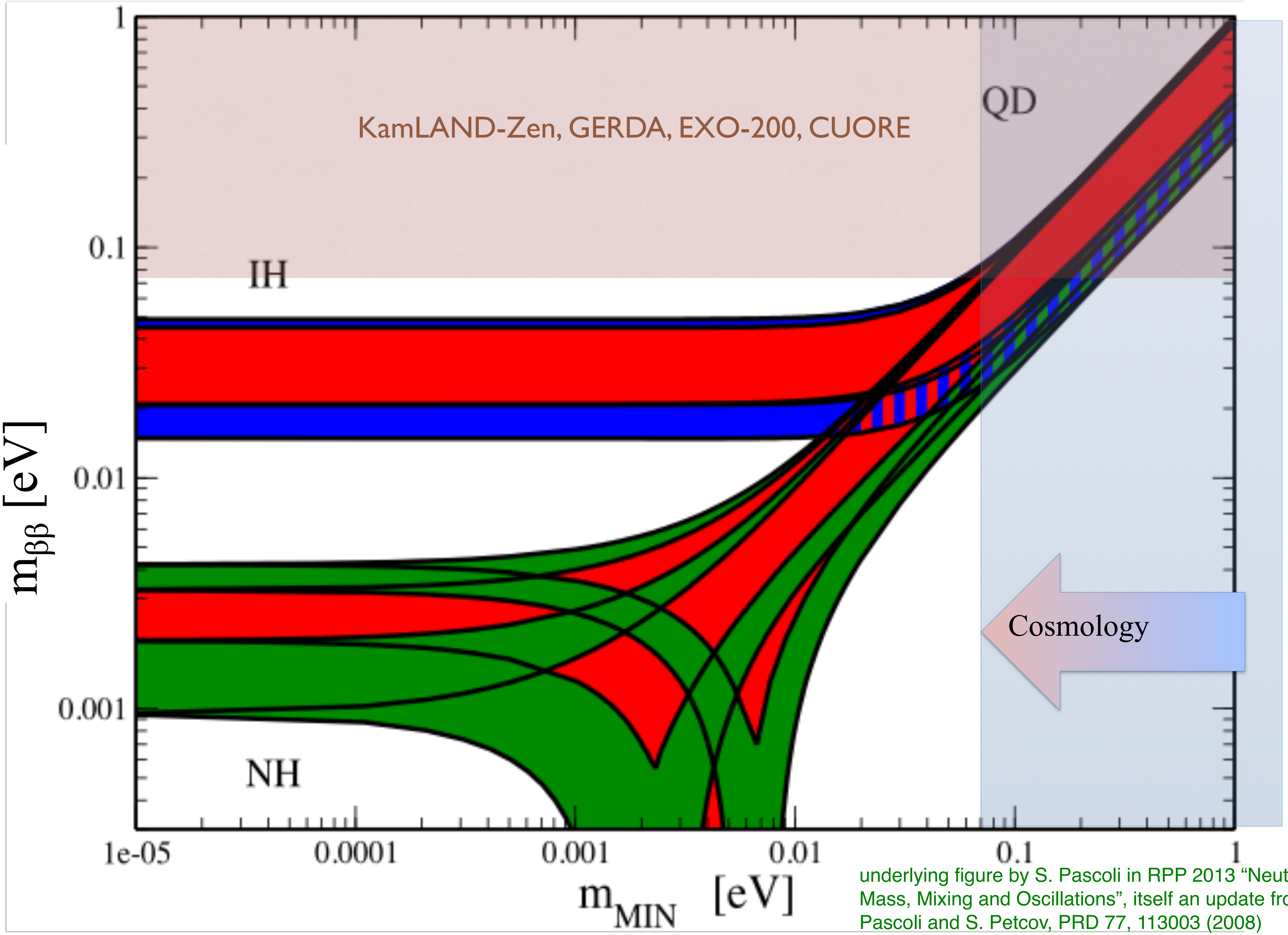
- rate of $0\nu\beta\beta$ decay:

$$\left[T_{1/2}\right]^{-1} = G_{0\nu}\frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}\left|M_{0\nu}\right|^2$$

- $G_{0\nu}$ is the phase space integral (“precisely” calculable)
- $M_{0\nu}$ is the nuclear matrix element
  - challenging to calculate, variety of approaches used, values differ by factors of 2-3
  - rate goes as the NME square (but so does the effective Majorana mass)
- measuring the rate of $0\nu\beta\beta$ decay explores $m_{\beta\beta}$

(assuming light neutrino exchange is the dominant mechanism for this process)

Double Beta Decay Allowed Parameter Space



underlying figure by S. Pascoli in RPP 2013 “Neutrino Mass, Mixing and Oscillations”, itself an update from S. Pascoli and S. Petcov, PRD 77, 113003 (2008)

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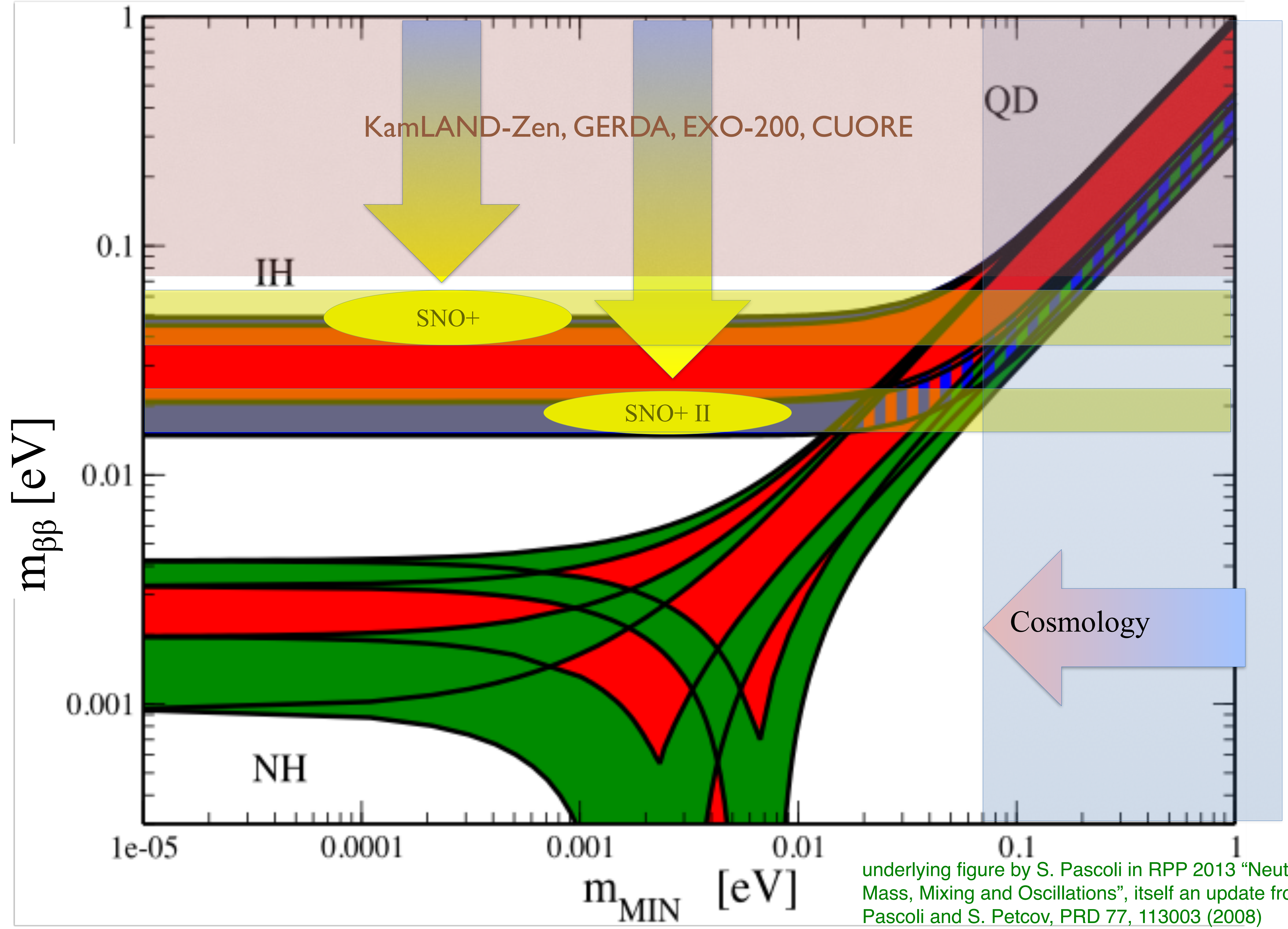

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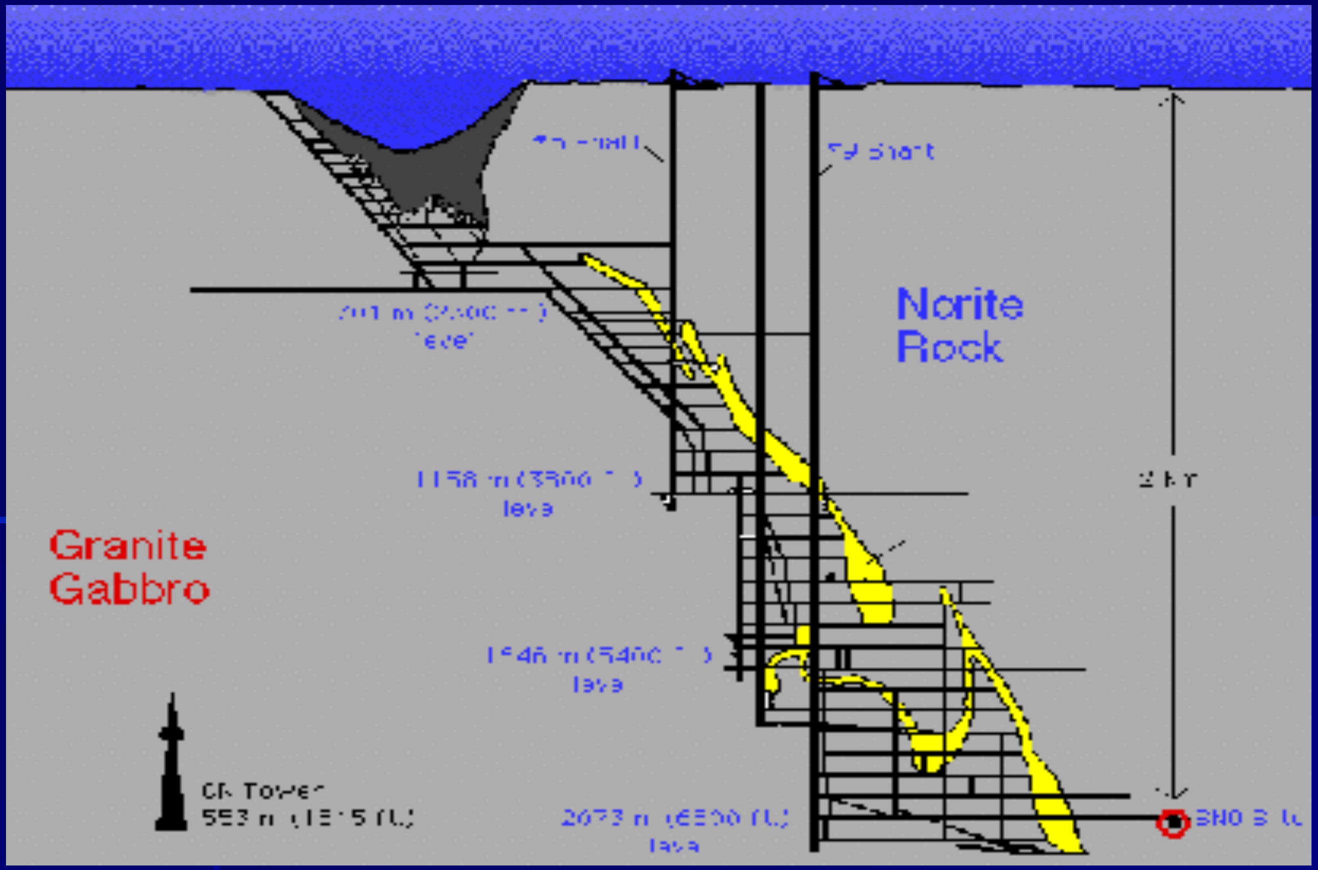
Sudbury Neutrino Observatory

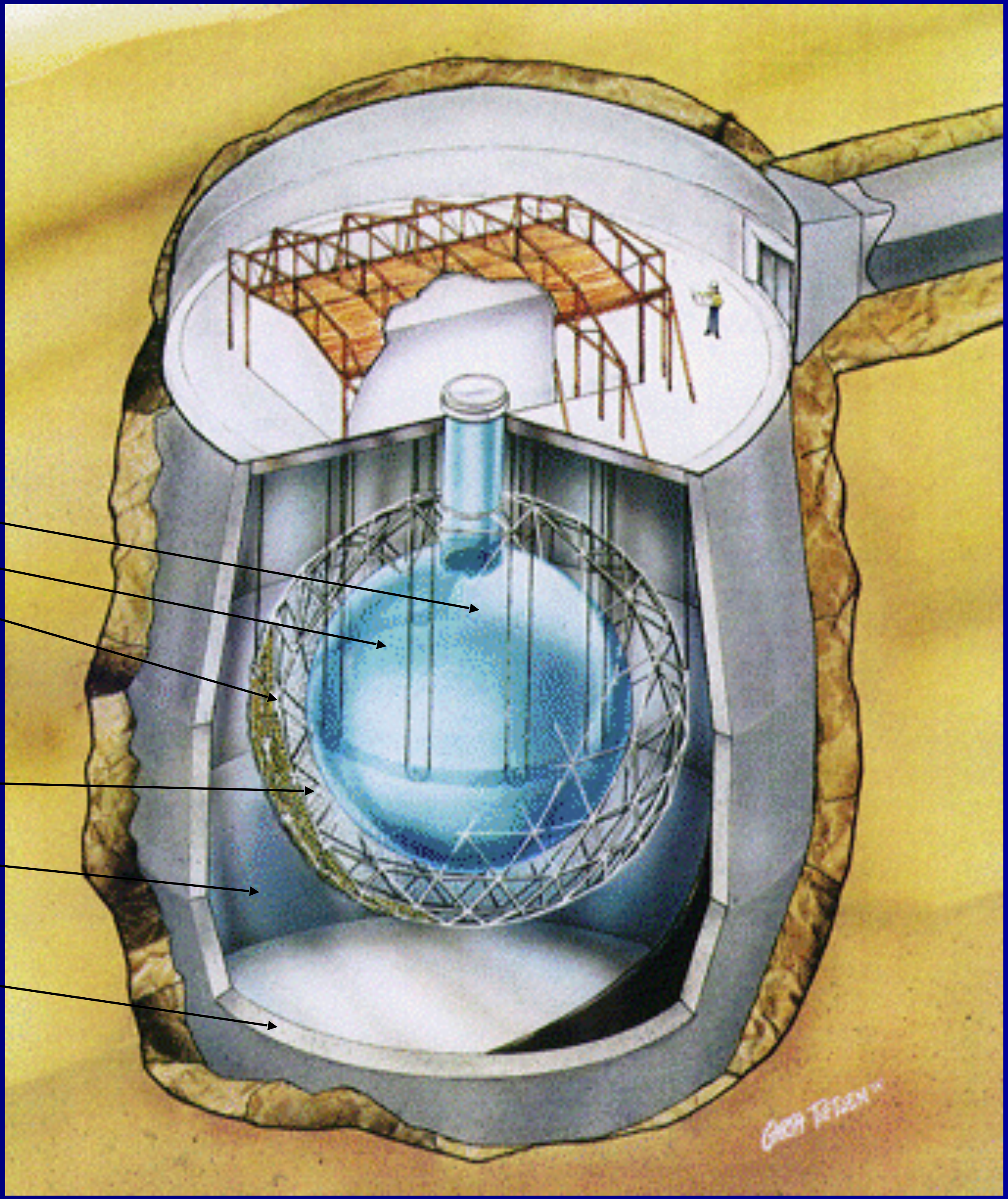


1000 tonnes D_2O

12 m diameter Acrylic Vessel
18 m diameter support structure; 9500 PMTs
(~54% photocathode coverage)

1700 tonnes inner shielding H_2O
5300 tonnes outer shielding H_2O
Urylon liner radon seal

depth: 2092 m (~6010 m.w.e.) ~70 muons/day



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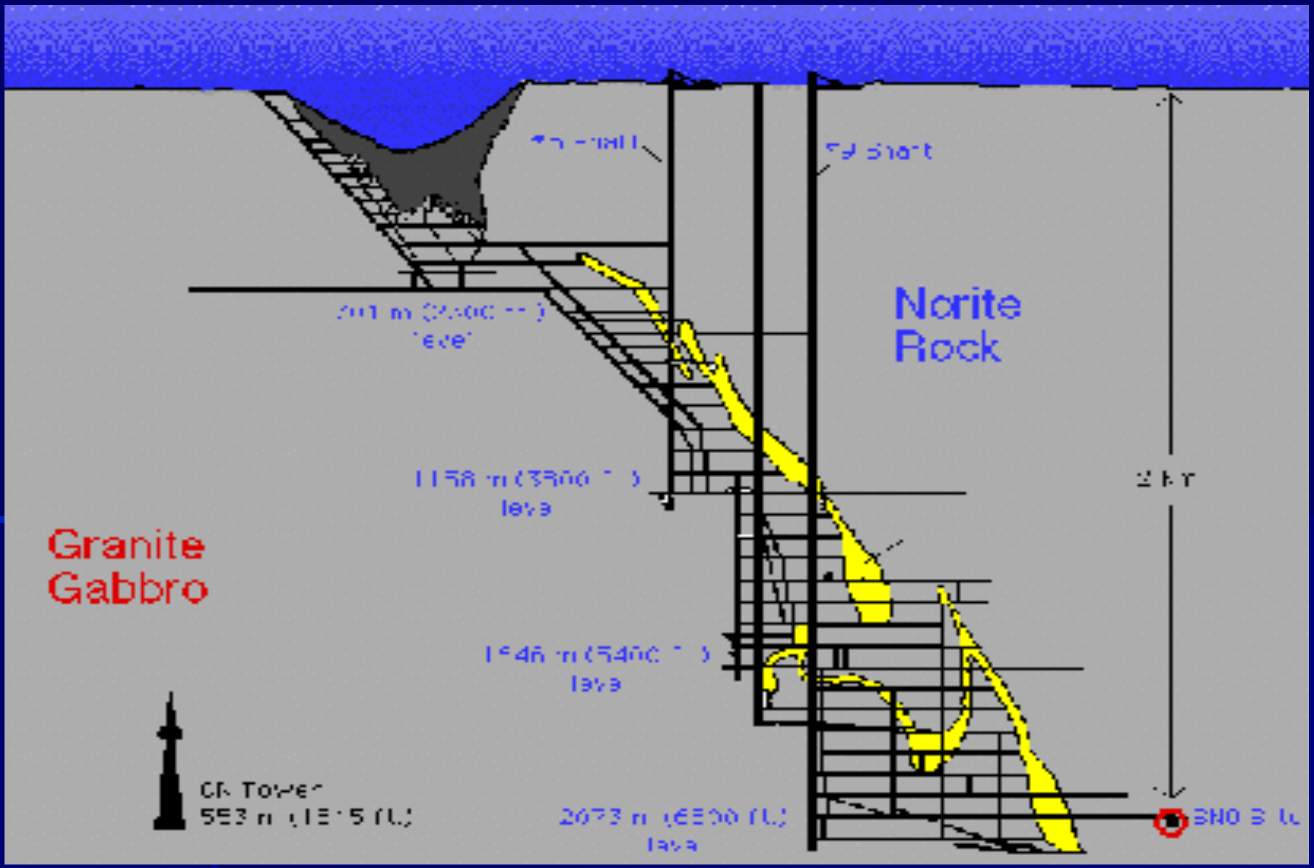

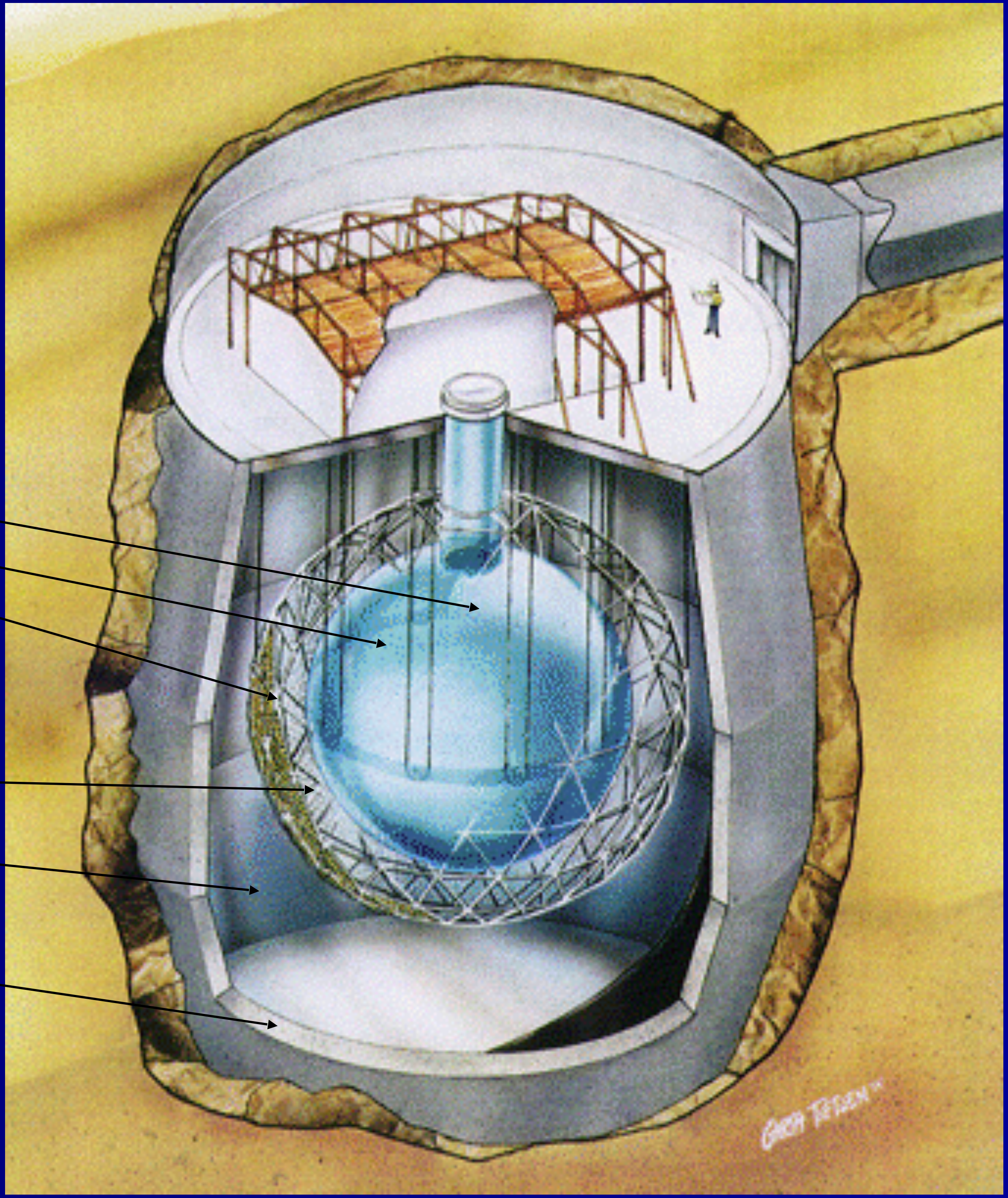

~~1000 tonnes D_2O~~ → **780 tonnes liquid scintillator**

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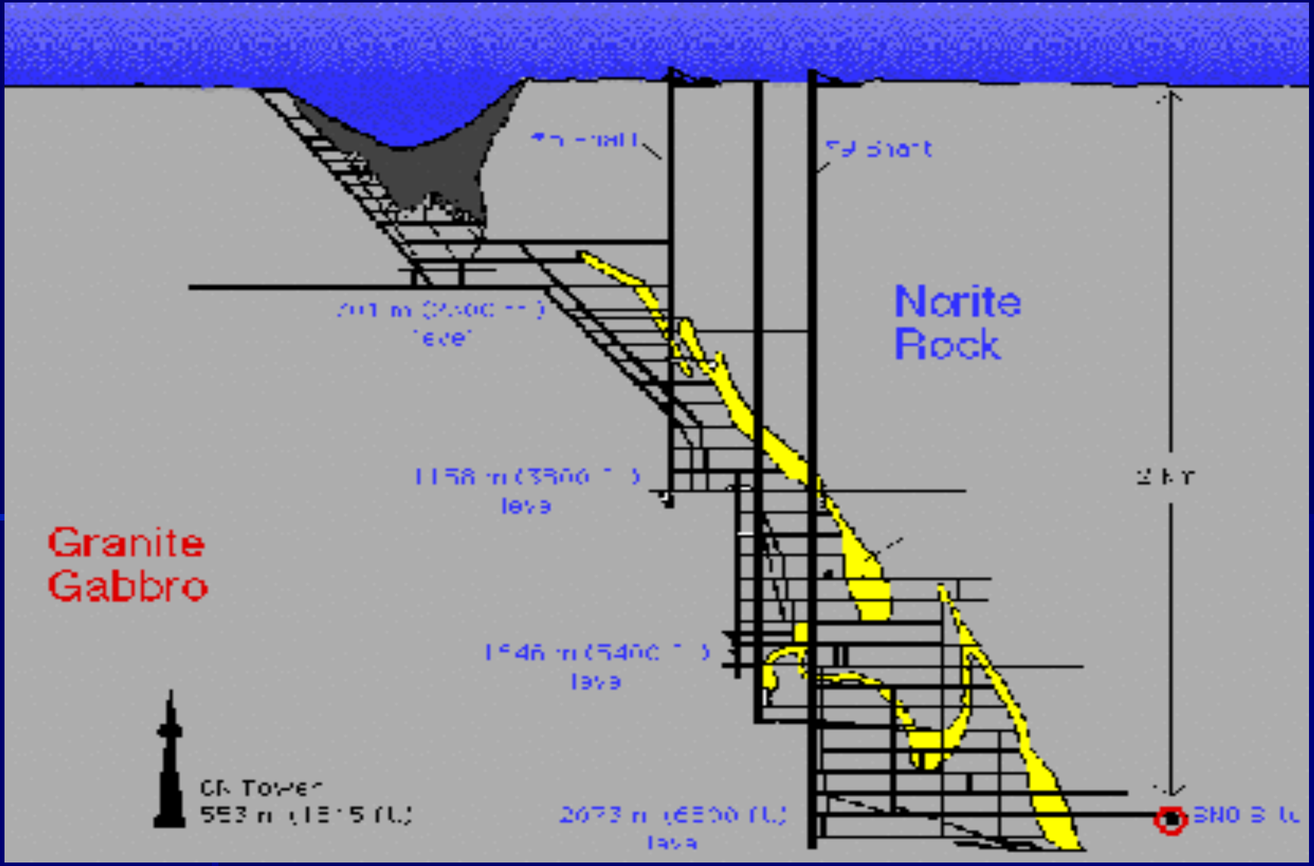

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hold-down rope net

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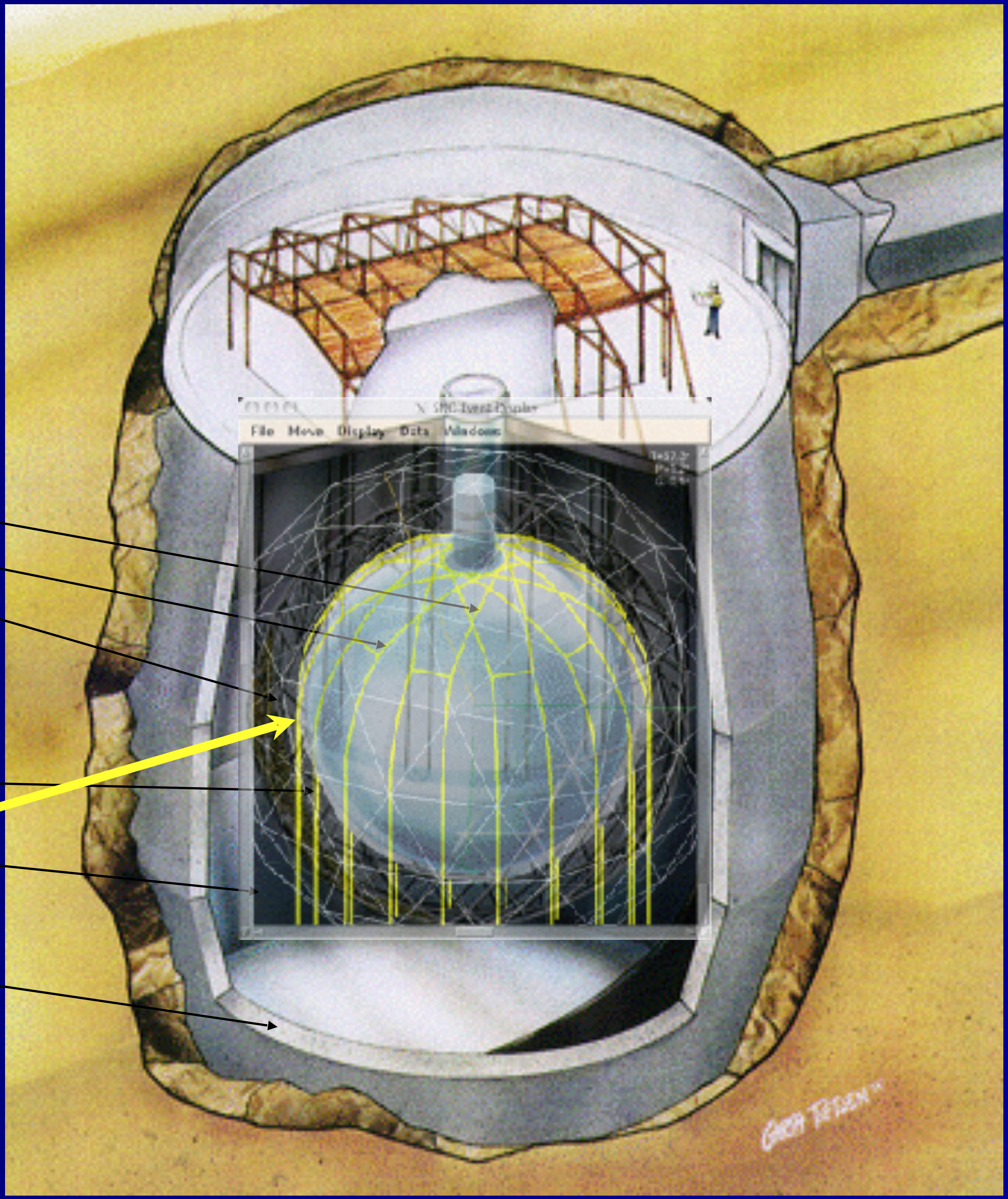

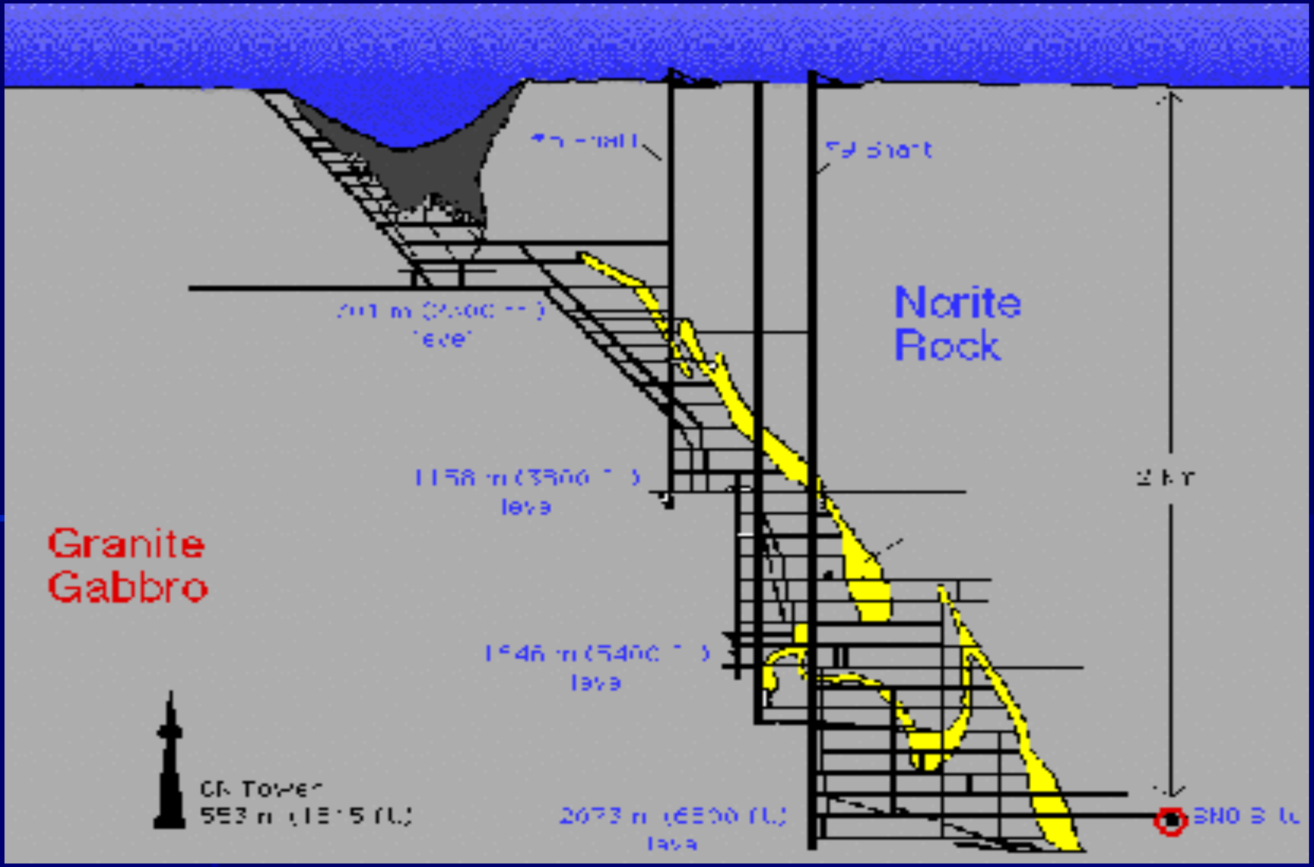

SNO+

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18 m diameter support structure; 9500 PMTs
(~54% photocathode coverage)

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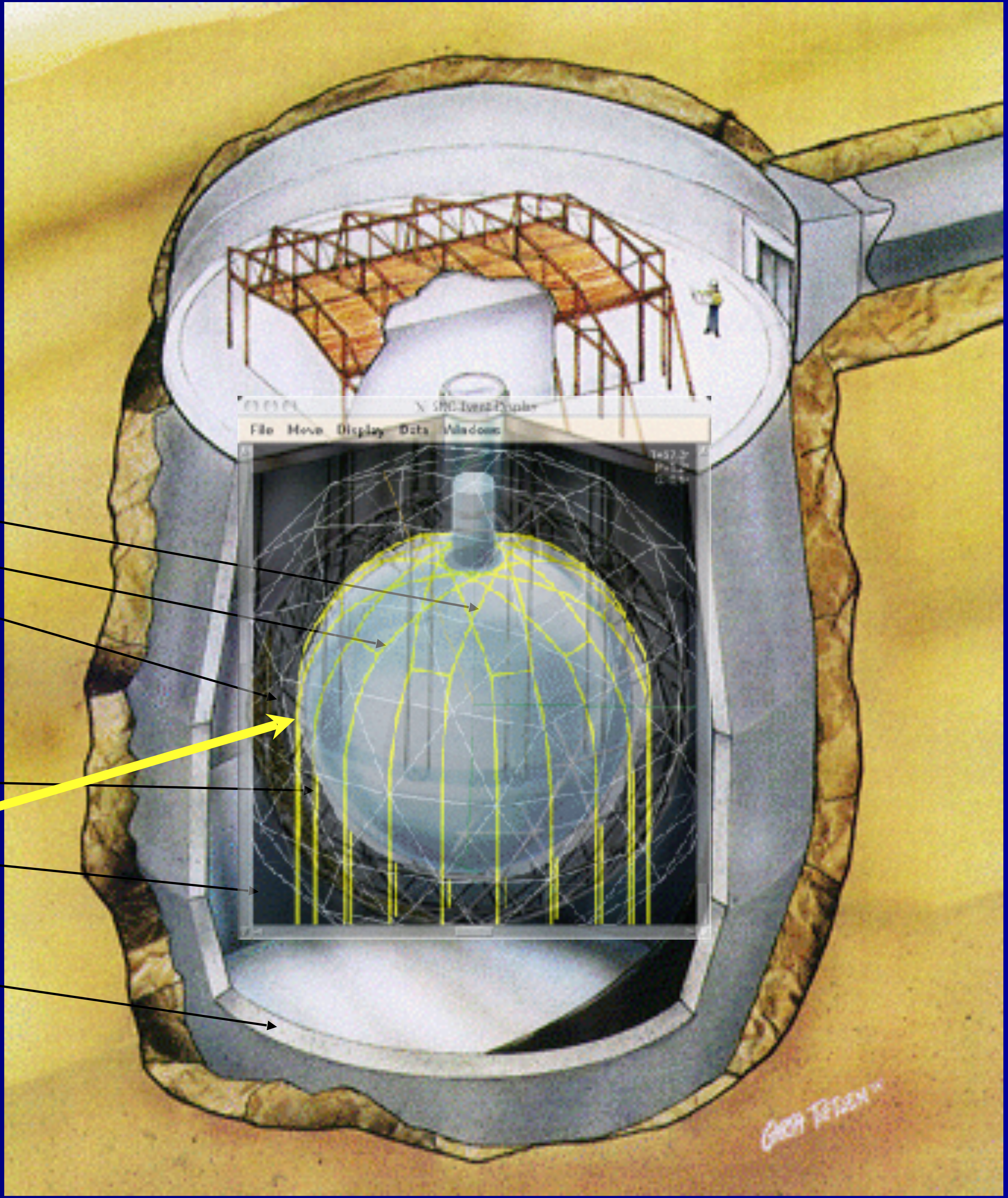
Urylon liner radon seal

hold-down rope net

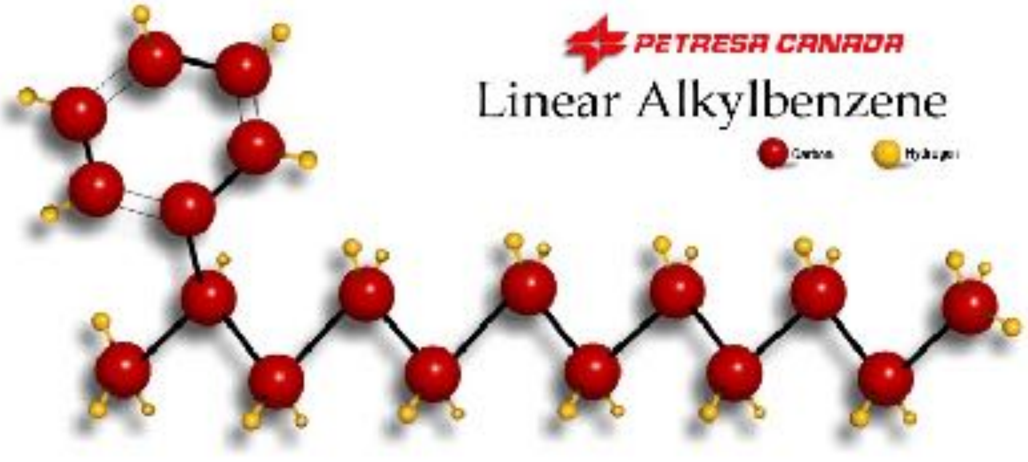
depth: 2092 m (~6010 m.w.e.) ~70 muons/day

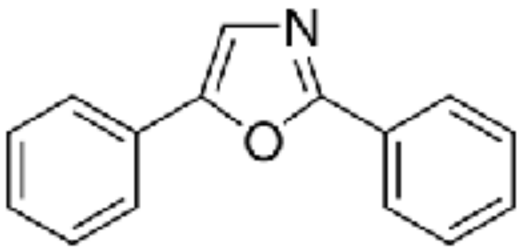


Liquid Scintillator for Neutrino Detection

- >50 times light output compared to water Cherenkov
- organic liquids can be made very radio-pure (e.g. Borexino, KamLAND) – U, Th, K are insoluble in the scintillator
- *enables neutrino physics program <1 MeV to few MeV*

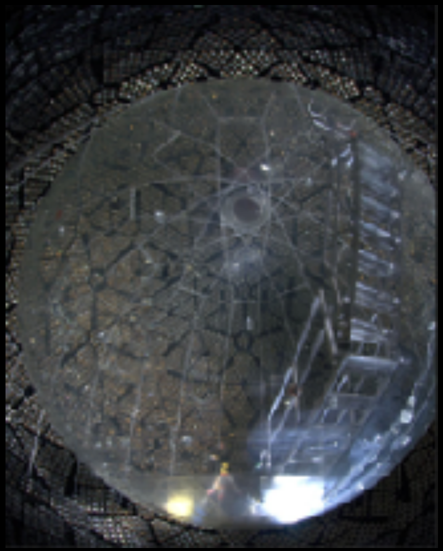
- SNO+ identified linear alkylbenzene as an excellent solvent base for a liquid scintillator neutrino detector
  - long light attenuation length
  - compatible with acrylic
  - safe
  - lower cost





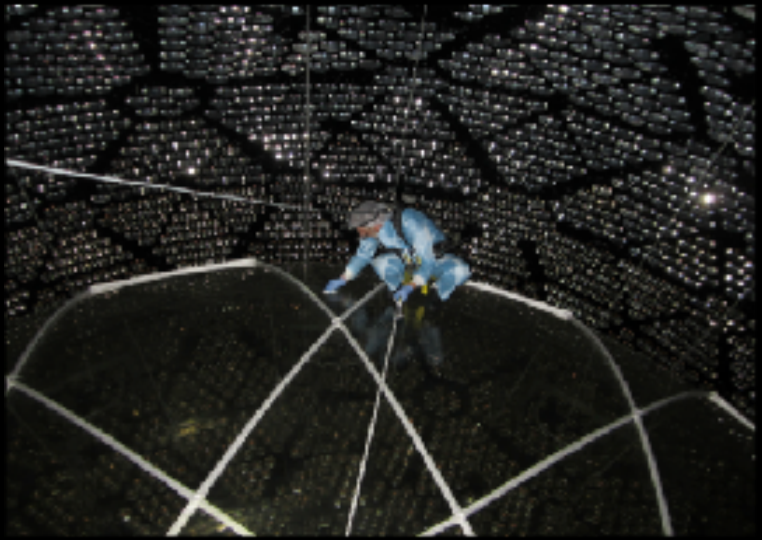
PPO fluor 2 g/L

SNO → SNO+

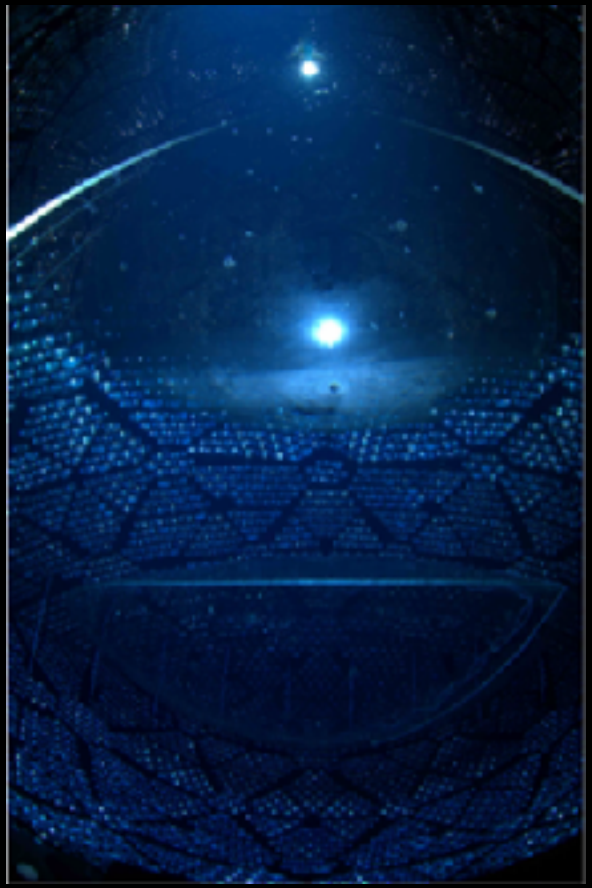


Cleaning the AV

Installed hold-down rope net



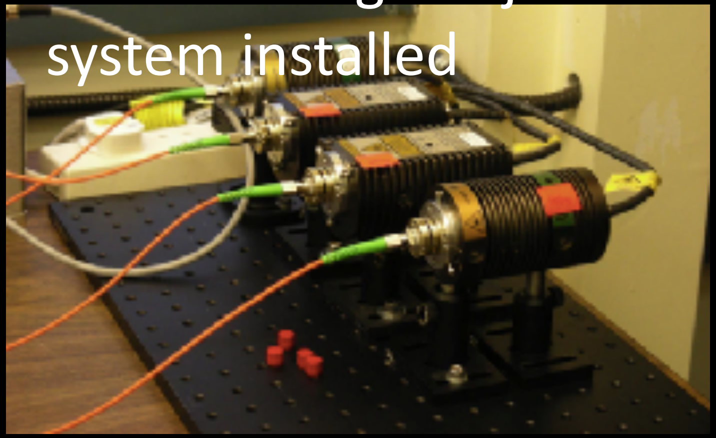
More cleaning



Filling with water

PMT repairs

New calibration hardware: light injection system installed

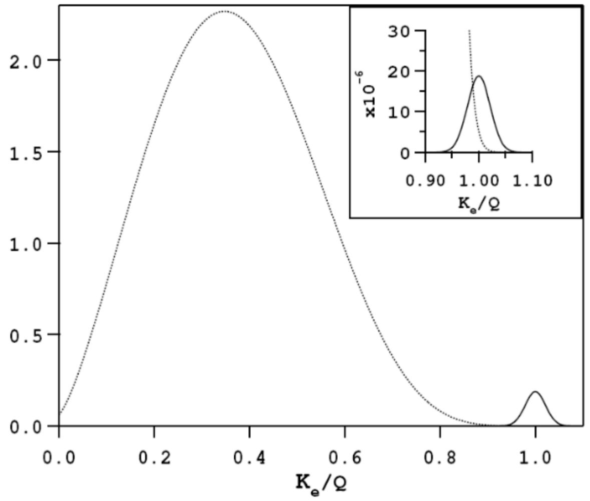


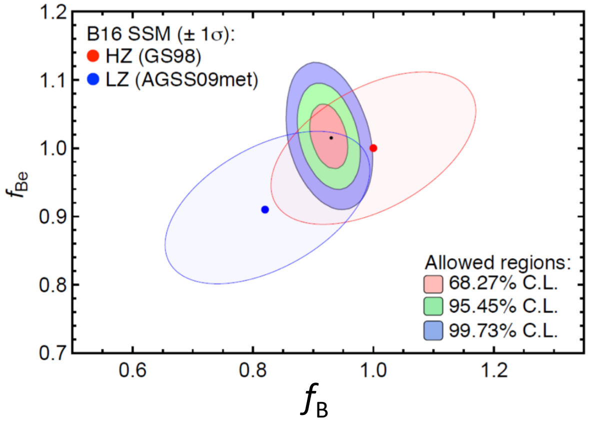
Upgraded trigger electronics and DAQ

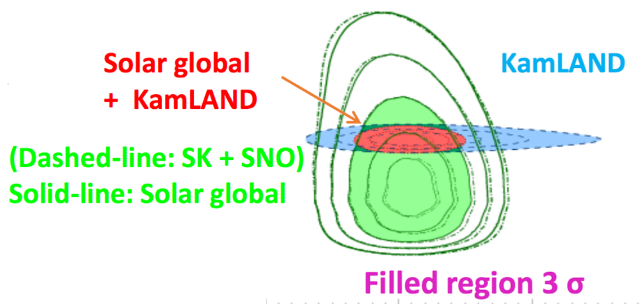
SNO → SNO+ scintillator purification plant

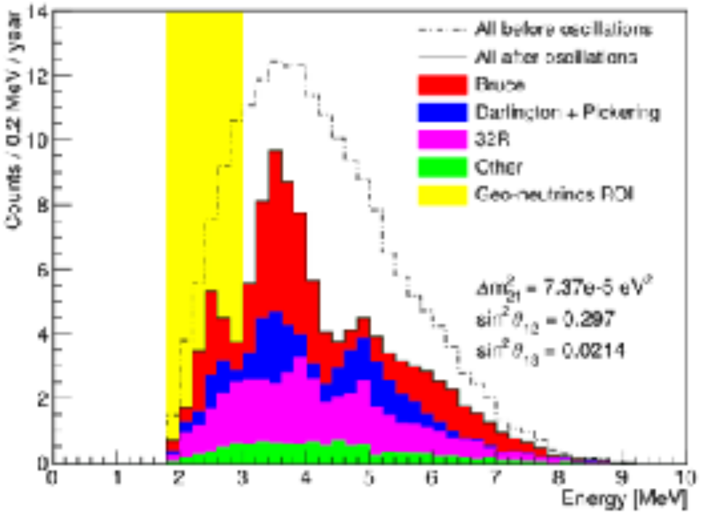
SNO+ Physics Program

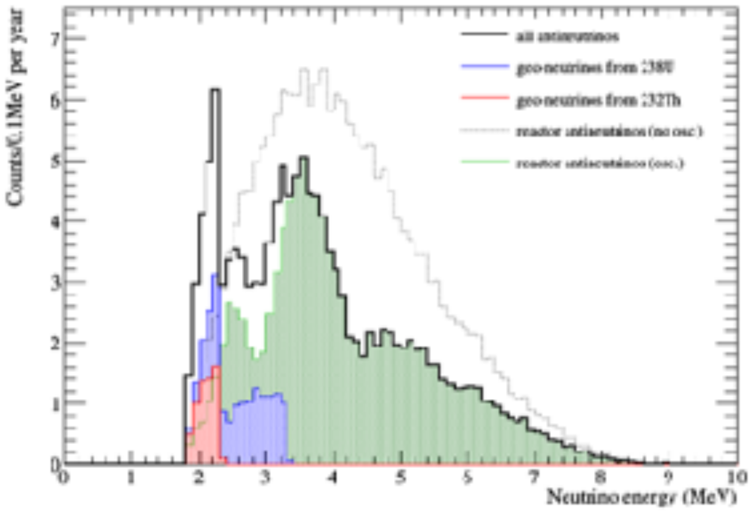
- Neutrinoless double beta decay
- Solar neutrinos
- Reactor antineutrinos
- Geo neutrinos
- Supernova neutrinos
- Nucleon decay

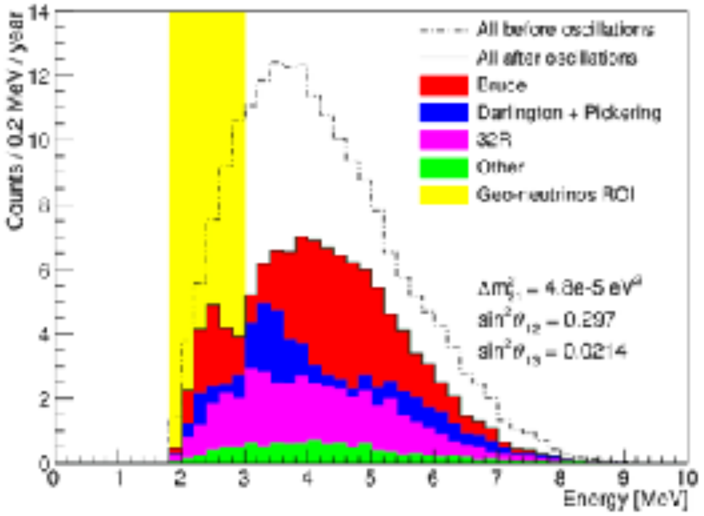


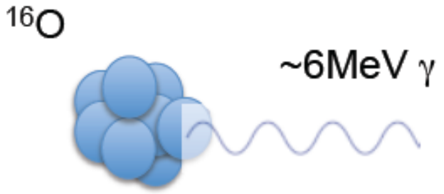






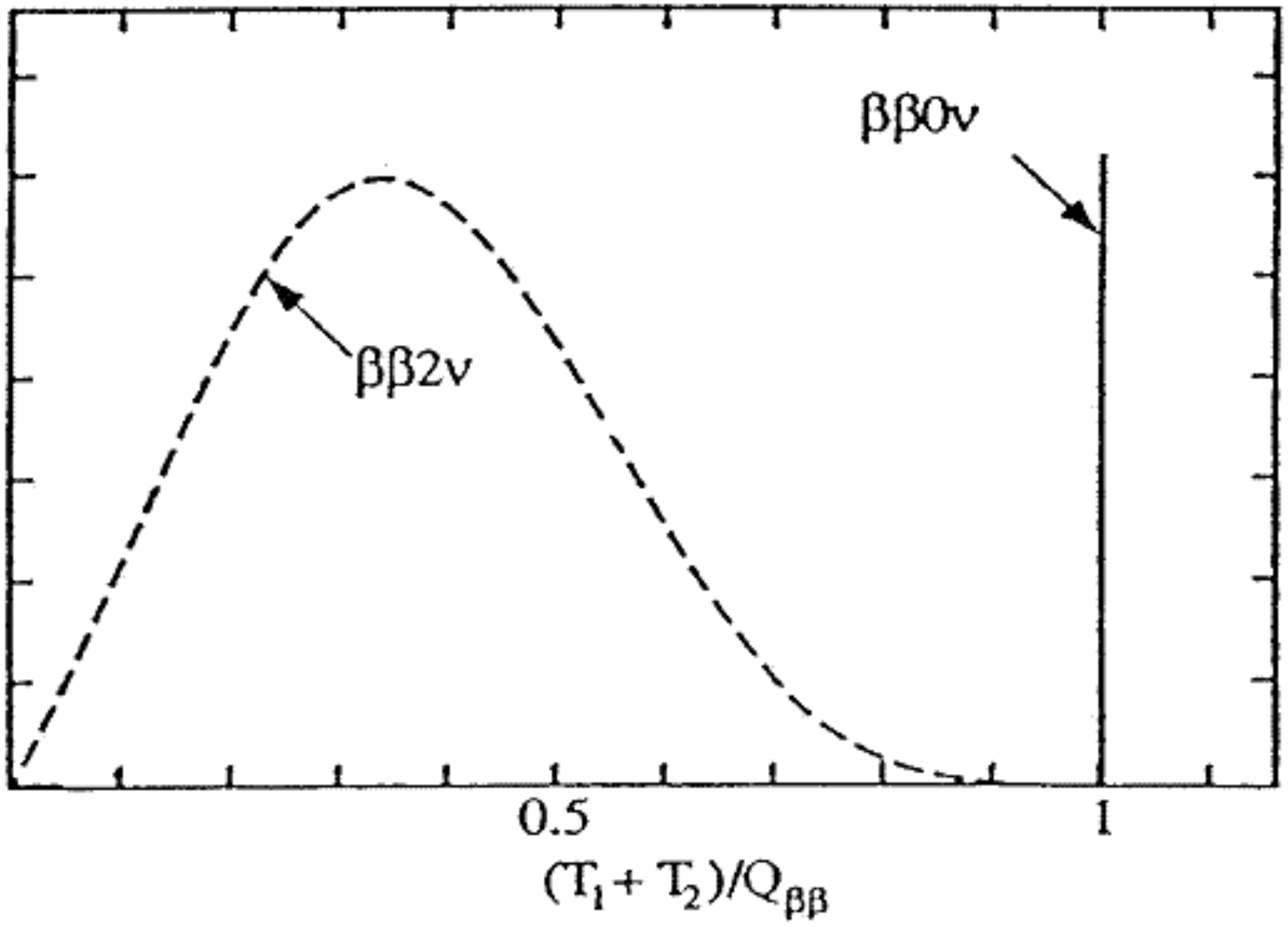






How to Search for 0νββ

- look at sum of energy of both electrons (calorimetry)
- search for a peak at the double beta endpoint



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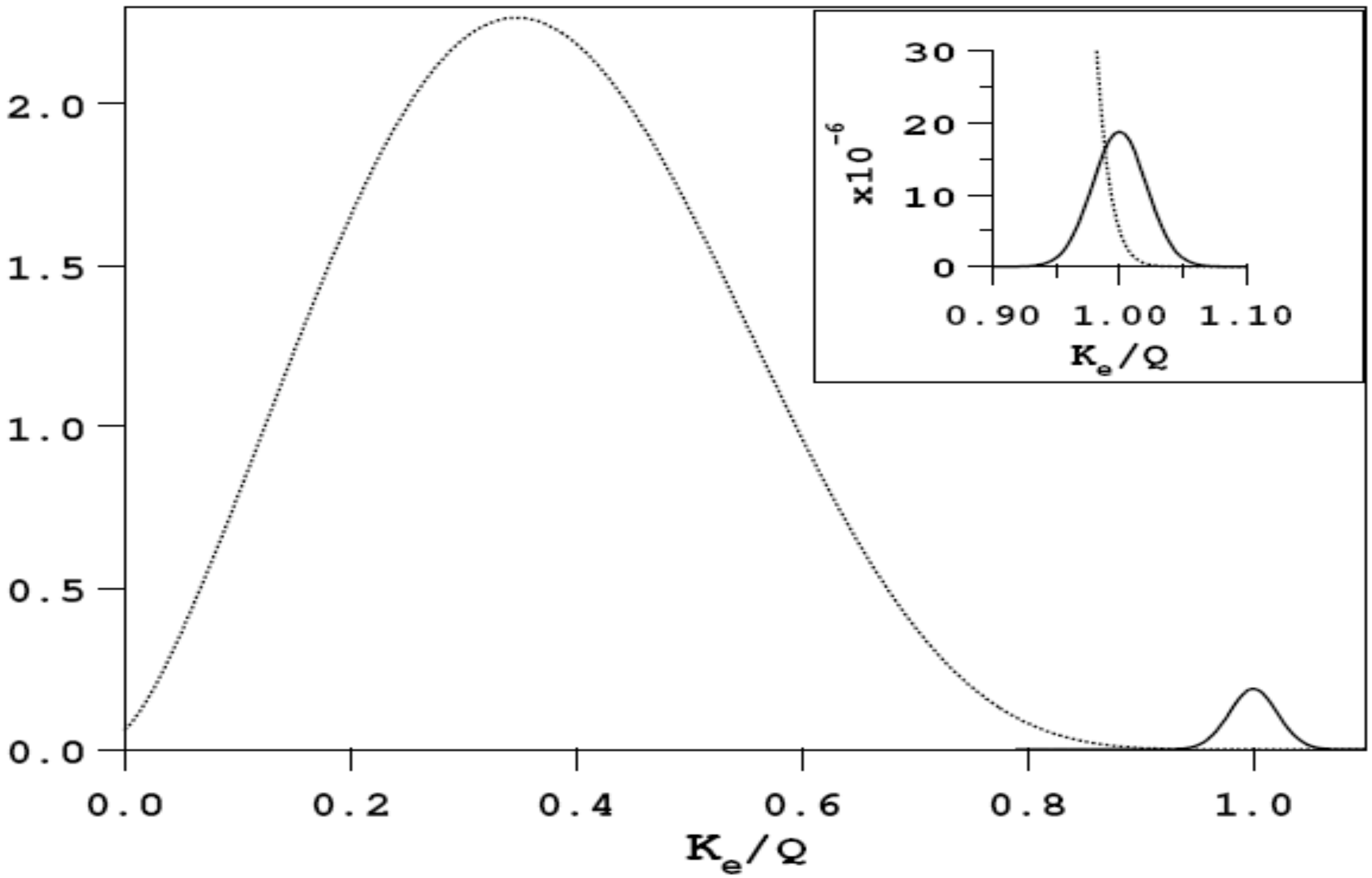
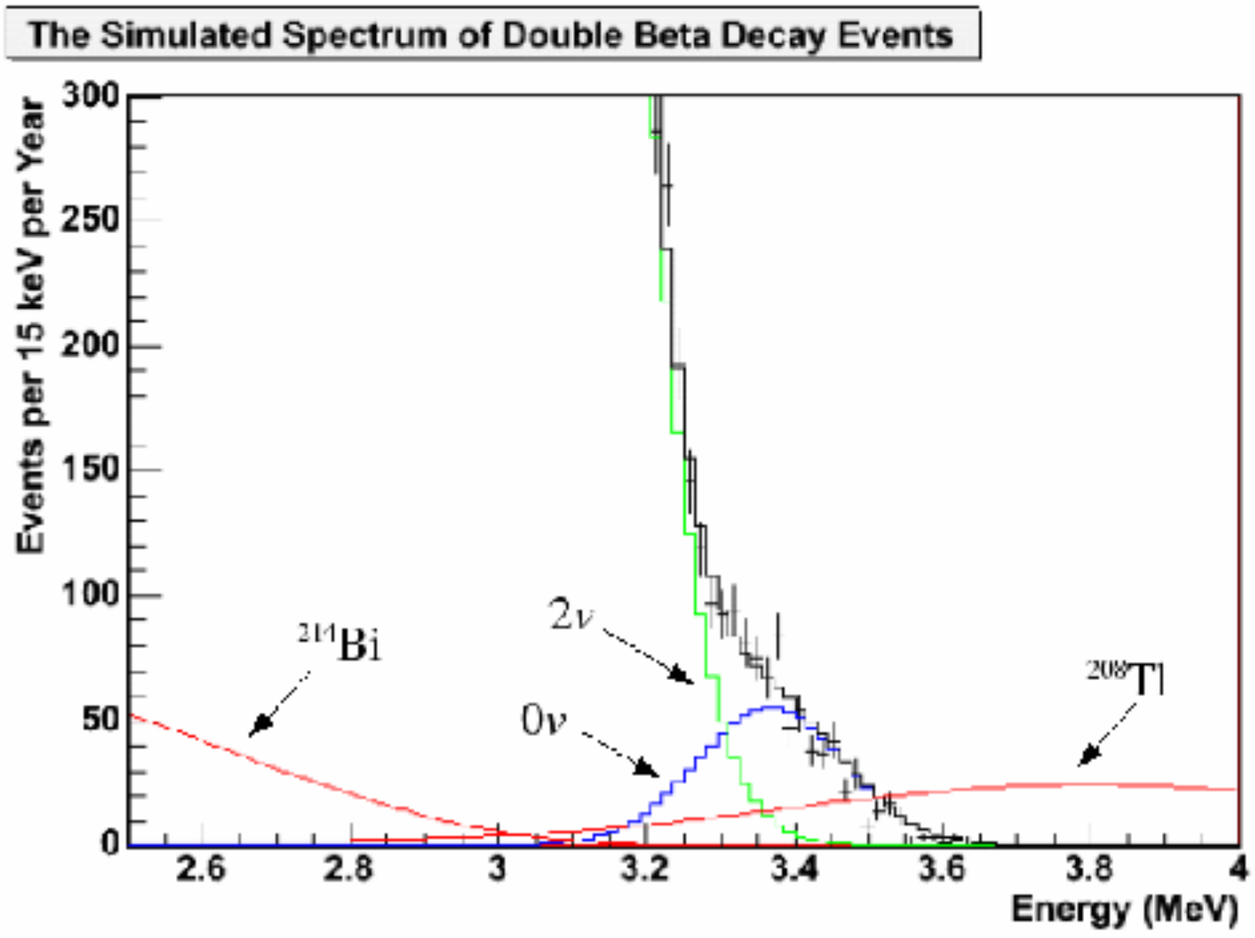


ββ Experiments in Scintillator

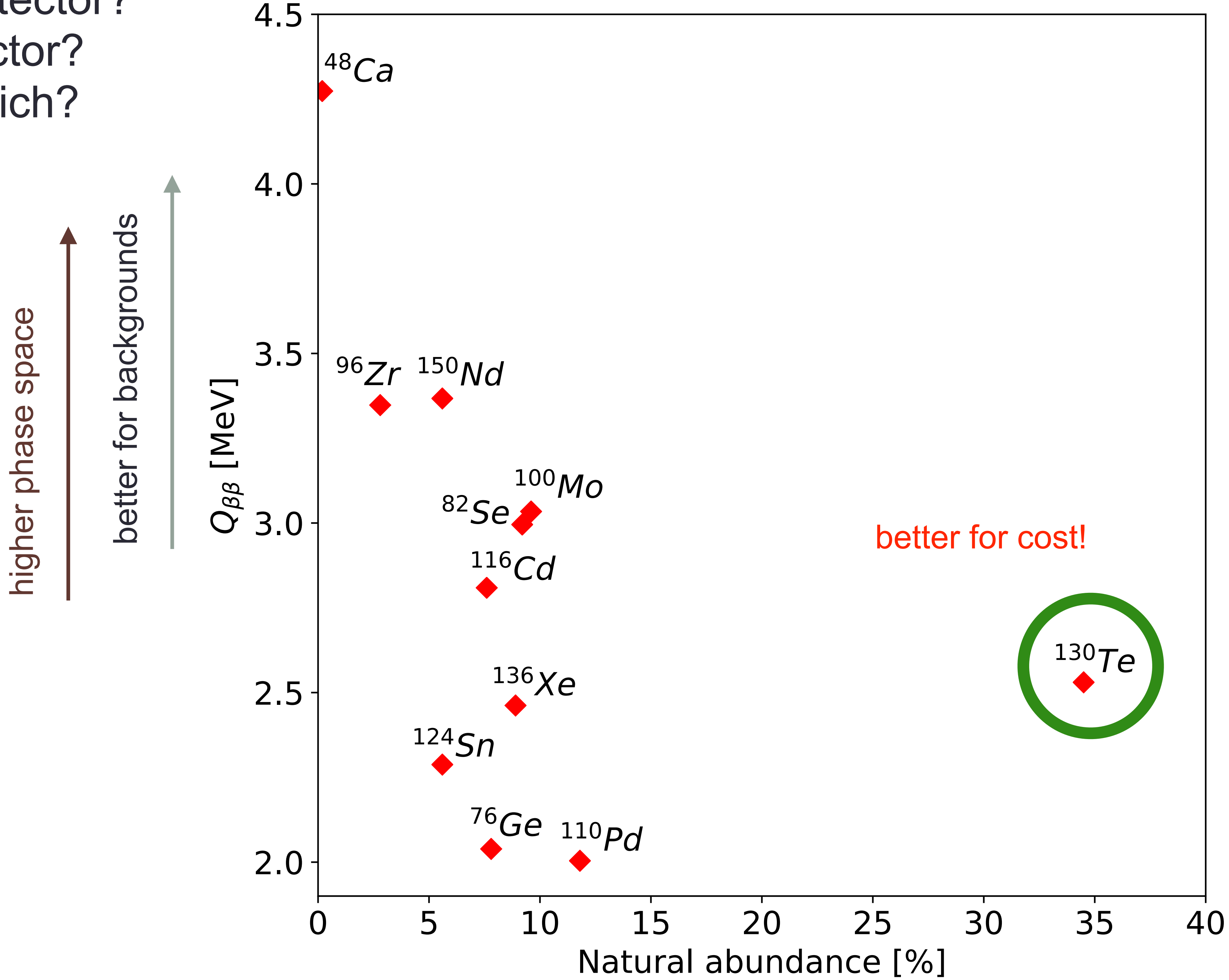
- several double beta isotopes can be made into (or put in) a scintillator
- “economical” way to build a detector with a **large** amount of isotope
- ultra-low background can be achieved (e.g. PMTs far away from the scintillator, self-shielding of fiducial volume)
- homogeneous detector, well-understood background model
- with a liquid scintillator, possibility to purify *in-situ* to further reduce backgrounds

- but with a liquid scintillator, energy resolution is relatively poor
  - but fitting spectrum shapes with high statistics and low background works



Which Isotope?

- can you make into a detector?
- can you put into a detector?
- can you isotopically enrich?



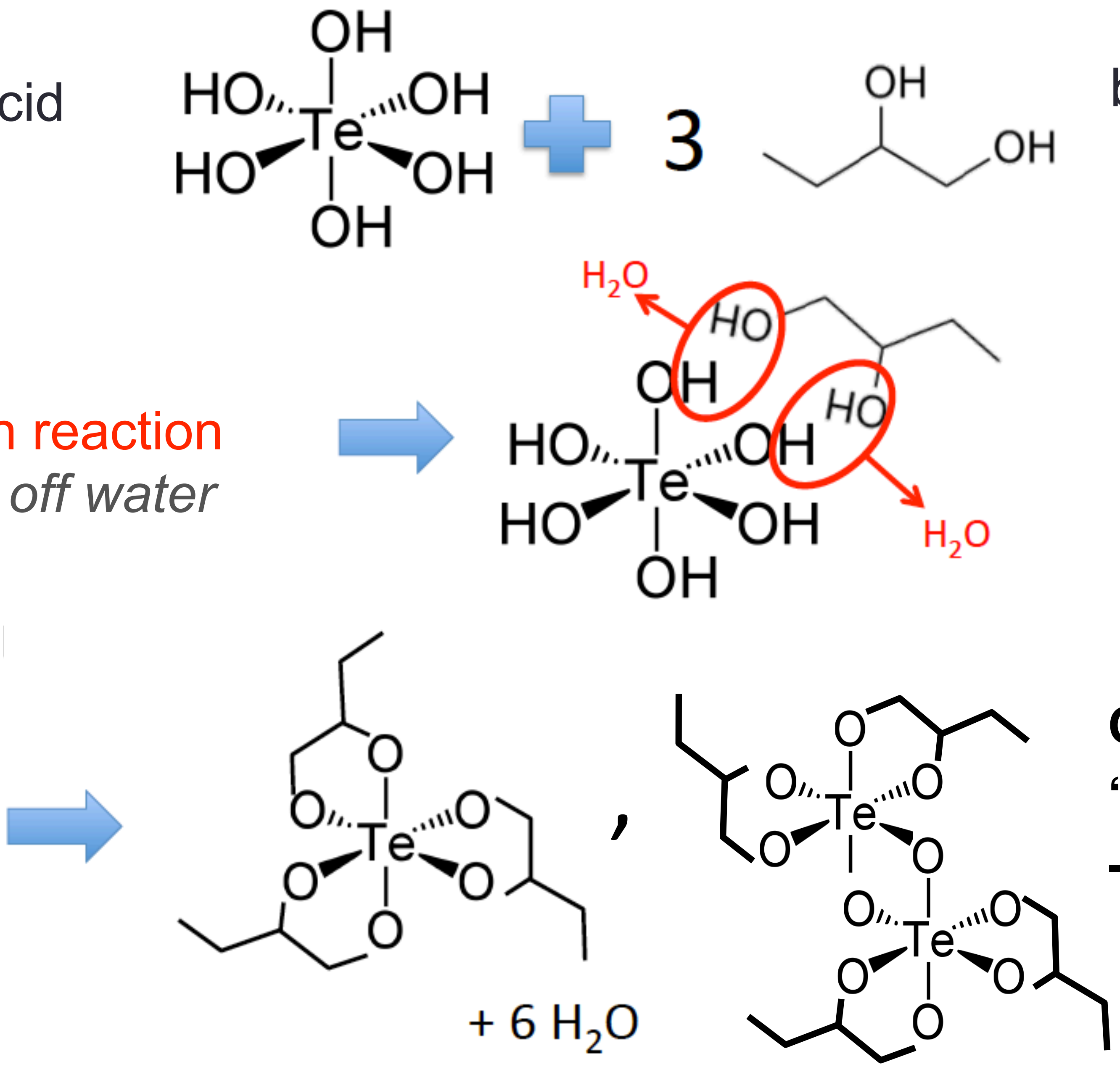
Advantages of Tellurium for Double Beta Decay (in liquid scintillator)

- large natural isotopic abundance 34% for ^{130}Te
  - cost for tonne scale ^{130}Te isotope is ~$2 million because isotopic enrichment is not required
- smallest $2\nu\beta\beta$ background (along with ^{136}Xe)
- in the energy range of the ^{130}Te endpoint, known U chain background (^{214}Bi-^{214}Po) can be rejected by factor >5,000
  - *delayed coincidence used to reject backgrounds*

Tellurium Diol Liquid Scintillator in SNO+

telluric acid
$Te(OH)_6$

butanediol



condensation reaction

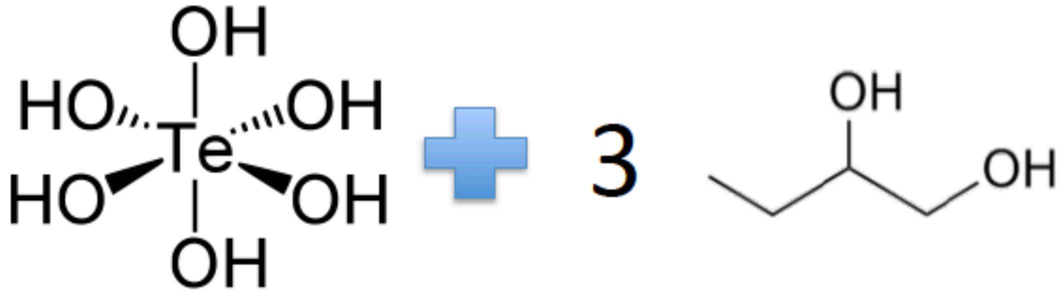
heat to drive off water

CAS #1902158-02-4
“tetrakis[1,2-butanediolato(2-)-κ01,κ02]di-μ-oxodi-tellurium”

organometallic compounds
soluble in LAB

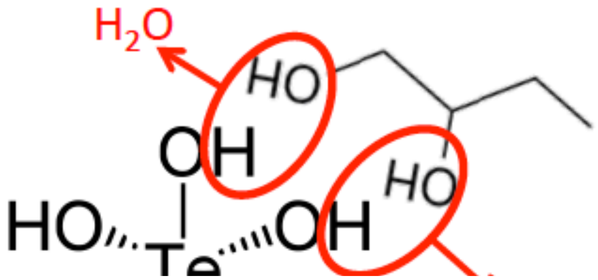
Tellurium Diol Liquid Scintillator in SNO+

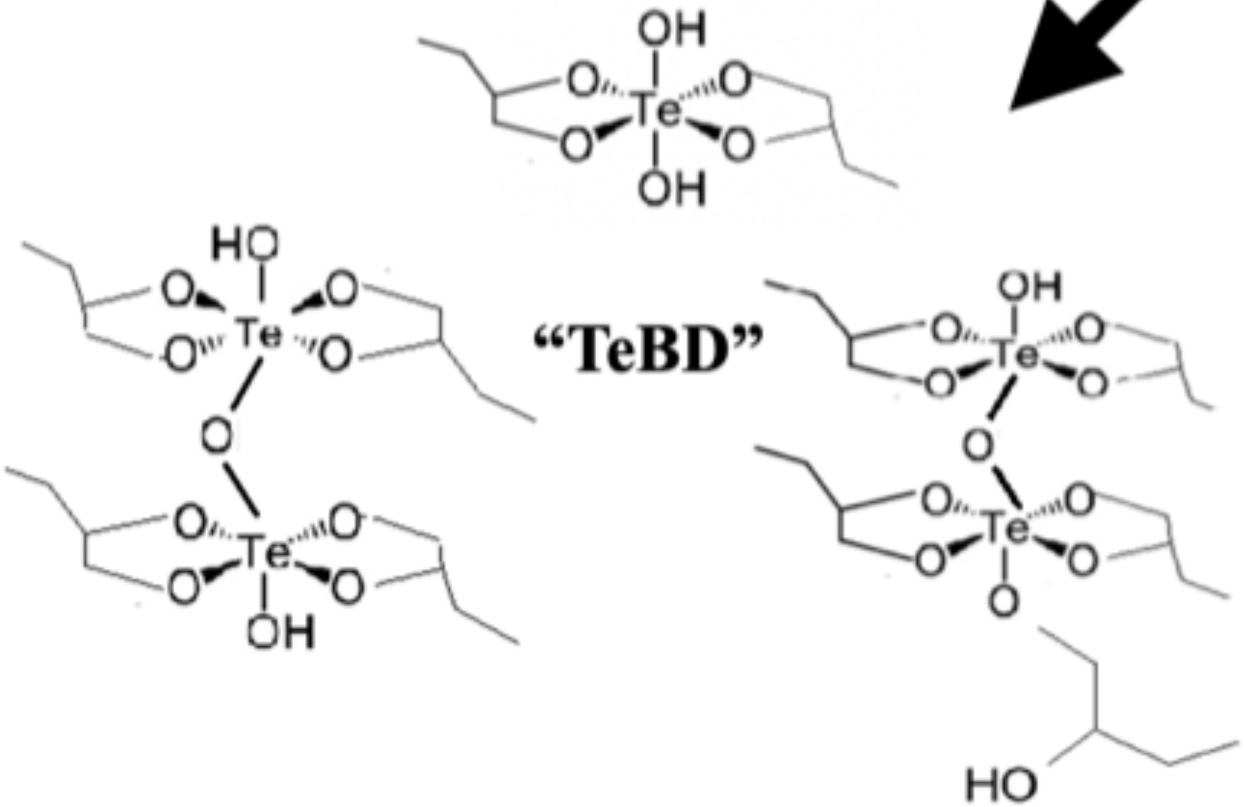
telluric acid
$Te(OH)_6$



butanediol

condensation reaction
heat to drive off wa

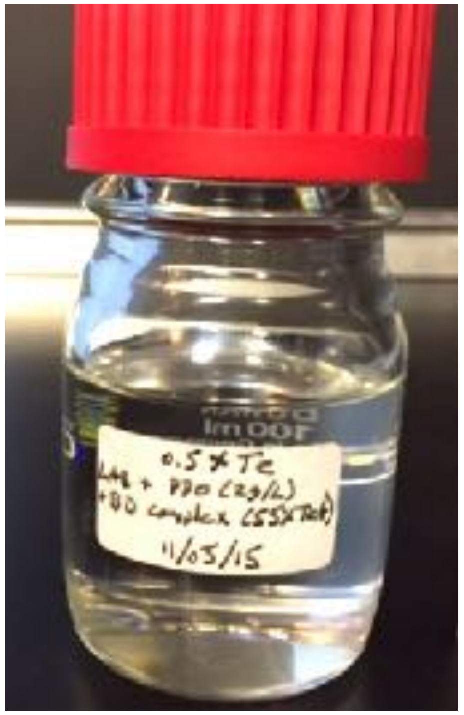



“TeBD”

2-4
tanediolato(2-)
odi-tellurium”

SNO+ Tellurium in Liquid Scintillator

- SNO+ 0.5% Te loading will have 1,330 kg of ^{130}Te ***isotope***



must purify all components of scintillator cocktail to achieve ultra-low backgrounds

  - LAB + PPO
  - telluric acid
  - 1,2-butanediol
  - dimethyldodecylamine stabilizer (DDA)
  - ultra-pure water used in synthesis

- we have tested the purification of all components
  - purification reduction factors of ~100’s-1000’s, up to >10^5 per pass, in our tests

measurements and tests indicate purification targets can be reached for all components of the Te scintillator cocktail

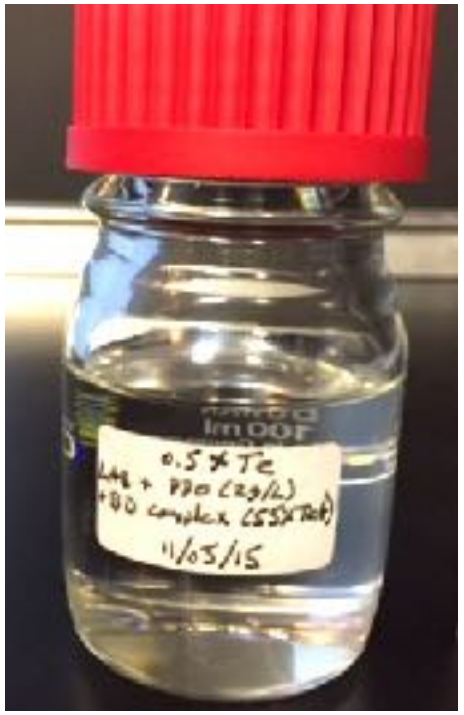
If the TeLS is sufficiently radiopure, the dominant background will be ^{8}B solar neutrinos!

SNO+ Tellurium in Liquid Scintillator

- SNO+ 0.5% Te … f ^{130}Te ***isotope***

must purify all com…
to achieve ultra-low…

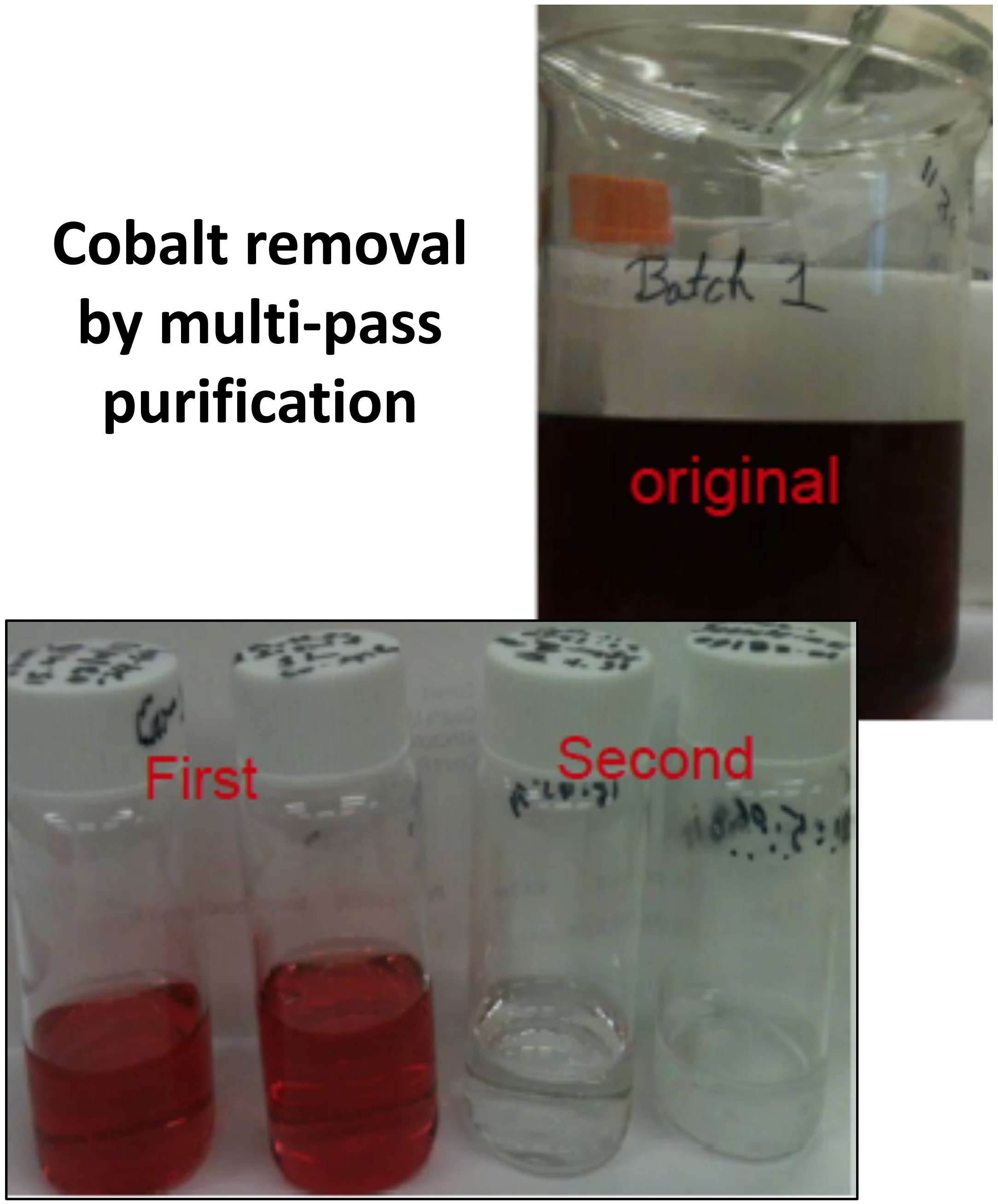
  - LAB + PPO
  - telluric acid
  - 1,2-butanediol
  - dimethyldodecylami…
  - ultra-pure water use…



- we have tested th…
  - purification reductio… …s, in our tests

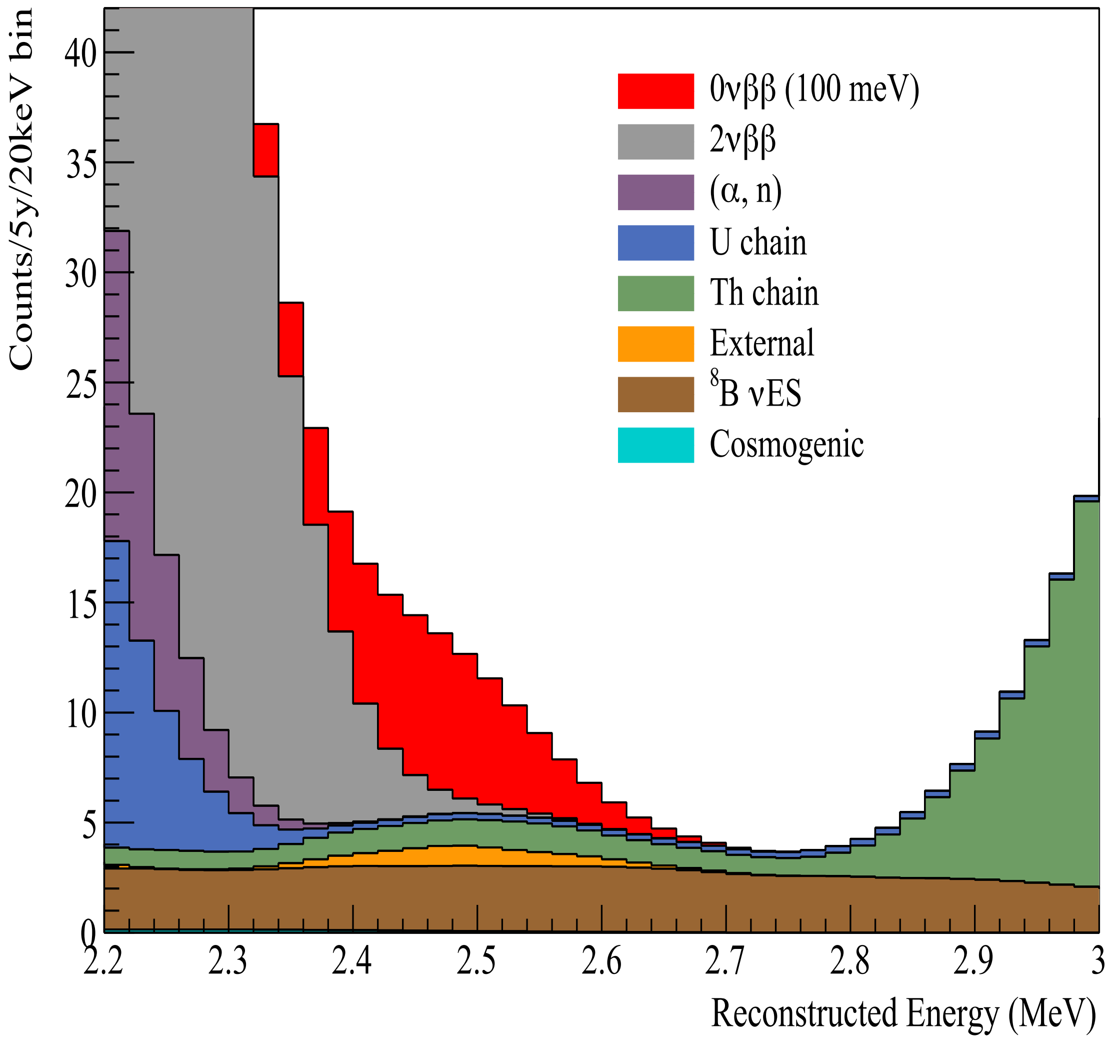
measurements ar… …ts can be reached for all components of the Te scintillator cocktail

Cobalt removal by multi-pass purification



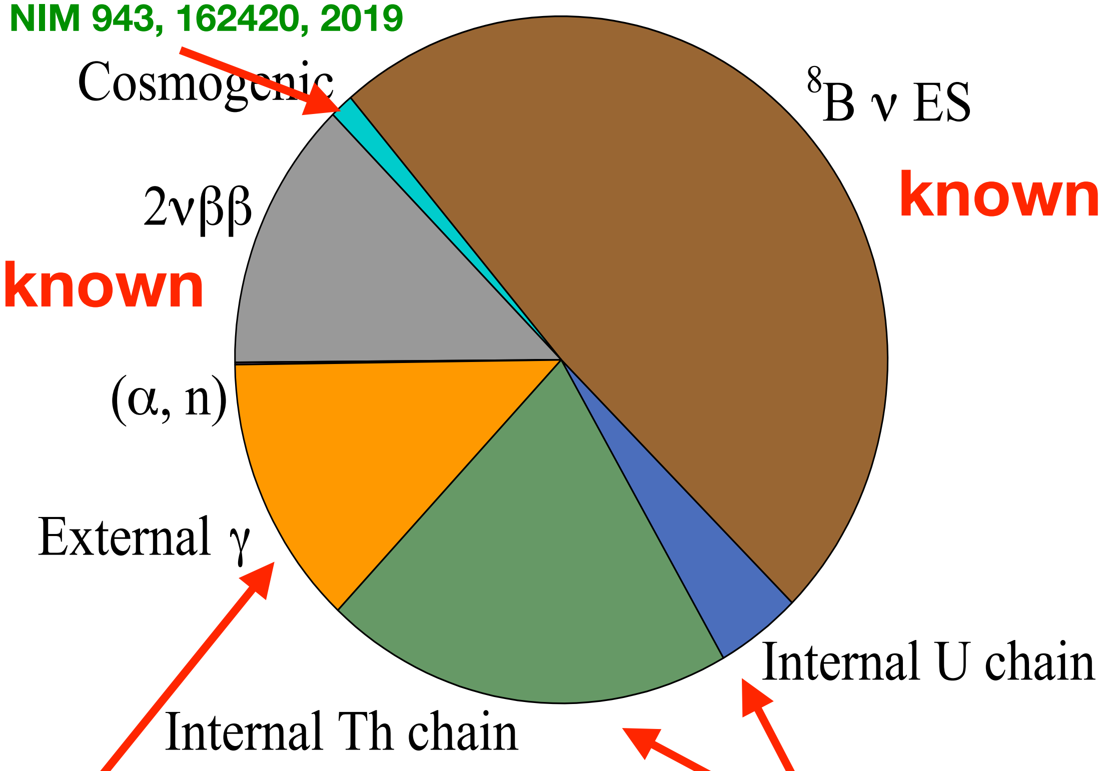
If the TeLS is sufficiently radiopure, the dominant background will be ^{8}B solar neutrinos!

SNO+ Signal/Background – Monte Carlo



Background
9.5 counts/year
in the ROI

ROI: 2.42 - 2.56 MeV [-0.5σ - 1.5σ]
Counts/Year: 9.47



can be verified with multi-site analysis, NIM 943, 162420, 2019

known

known

constrained by water data: target achieved

scint data: target achieved
awaiting Te purification data

Simple counting analysis (5 yrs)
half-life sensitivity: $T_{1/2} > 2.1\times10^{26}$ years
Sensitive to $m_{\beta\beta}$ = 37-89 meV

Water data

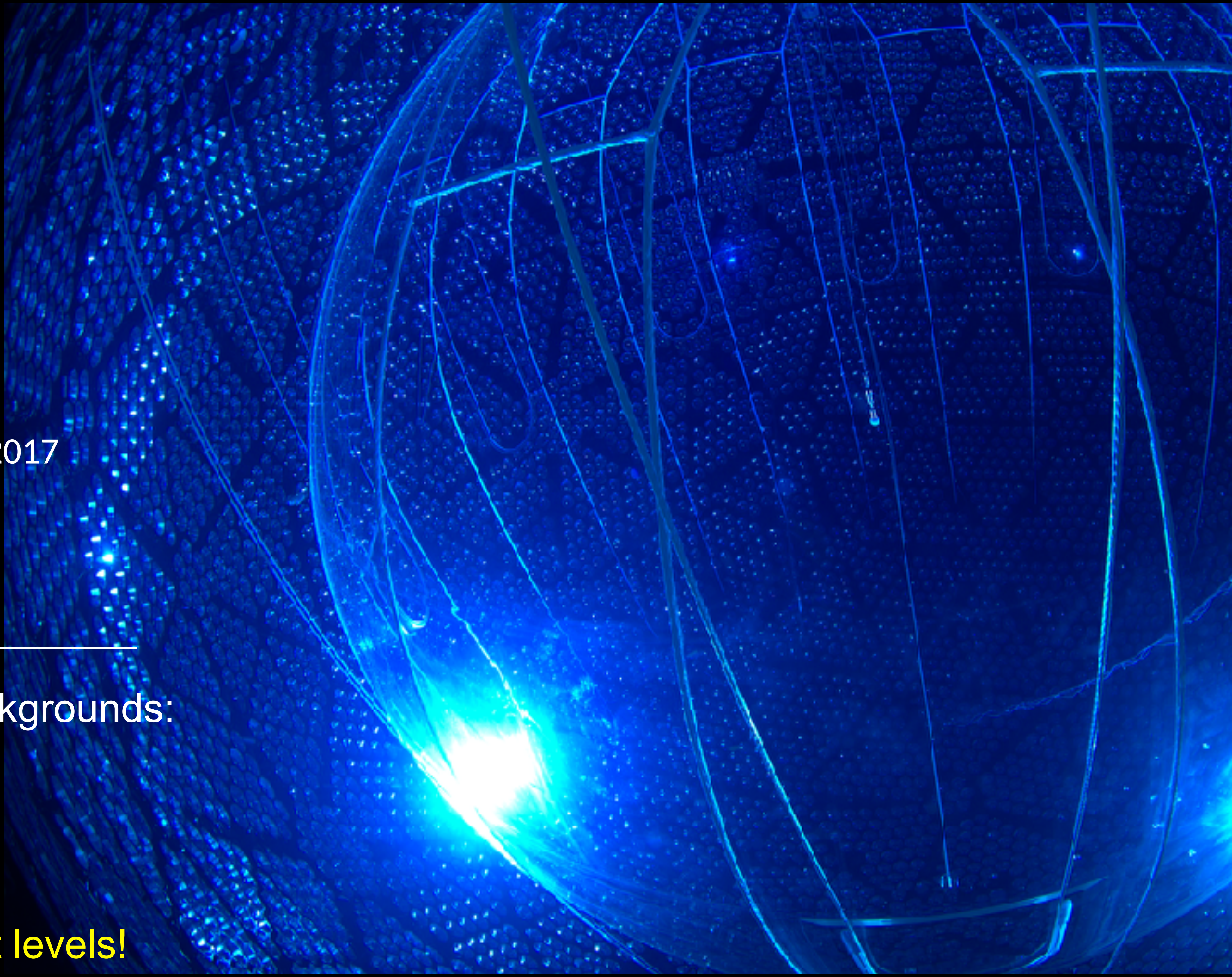
Dataset I: (115 live days)
May 4th 2017 to December 2017

Dataset II: (190 live days)
October 2018 to July 2019

Measured external backgrounds:

- Acrylic Vessel
- Ropes
- Water
- PMTs

→ all at or below target levels!



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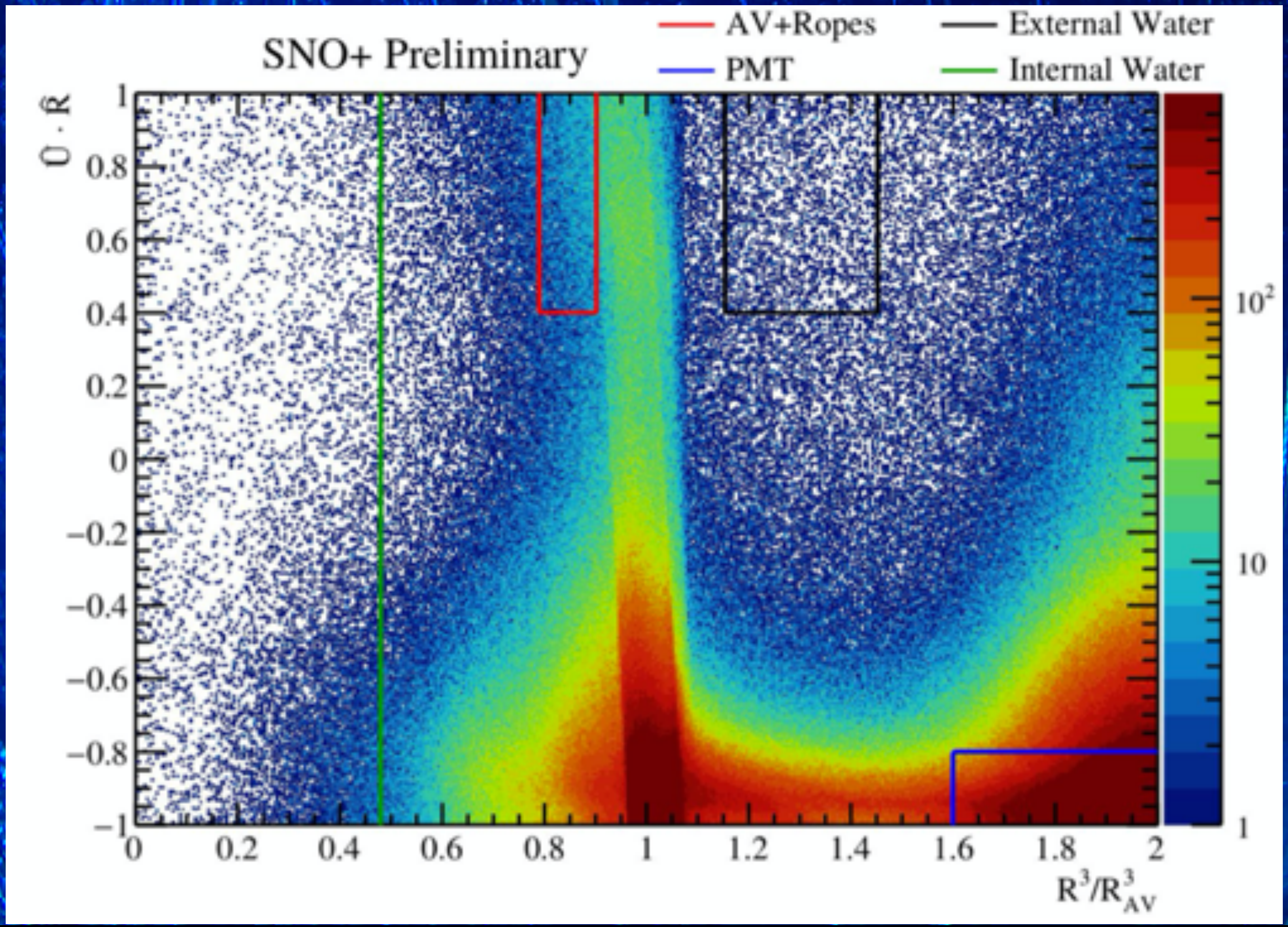
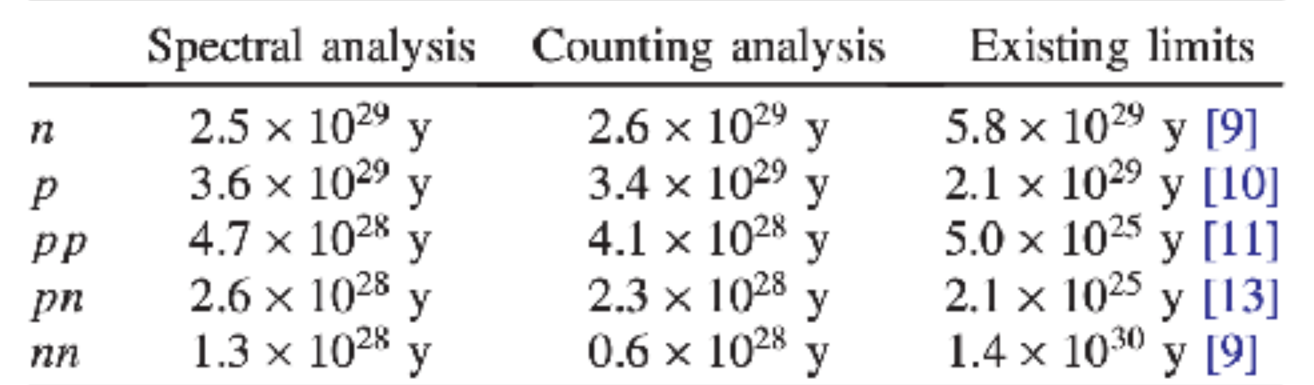


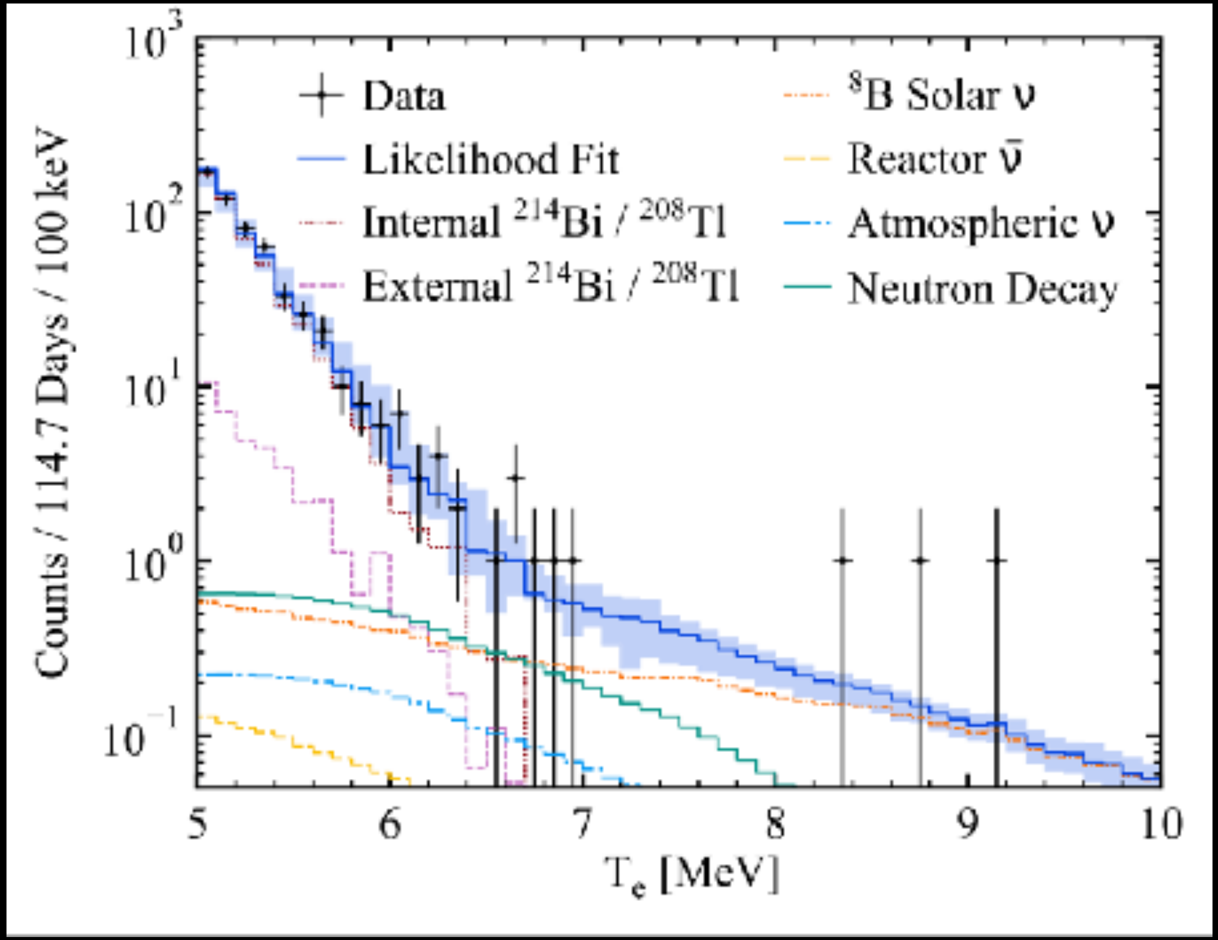
Invisible Nucleon Decay limits
First Data set

Both single and di-nucleon decay modes observable through de-excitation gammas.

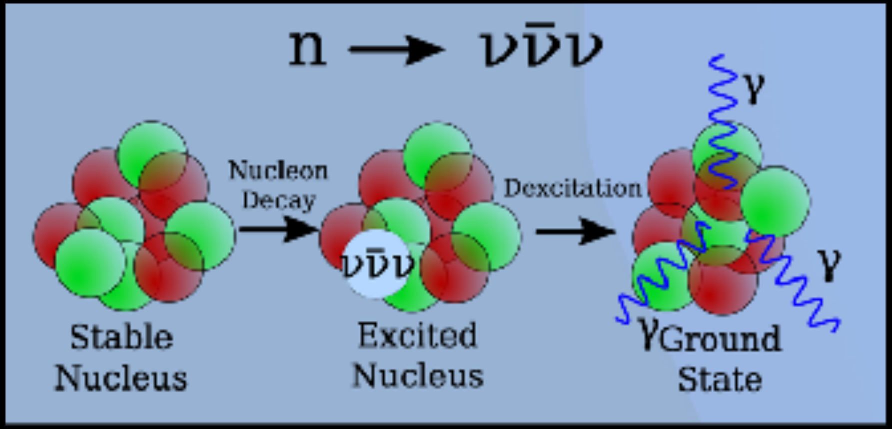
Few backgrounds in energy region of interest (5-10MeV)



	Spectral analysis	Counting analysis	Existing limits
n	2.5×10^{29} y	2.6×10^{29} y	5.8×10^{29} y [9]
p	3.6×10^{29} y	3.4×10^{29} y	2.1×10^{29} y [10]
pp	4.7×10^{28} y	4.1×10^{28} y	5.0×10^{25} y [11]
pn	2.6×10^{28} y	2.3×10^{28} y	2.1×10^{25} y [13]
nn	1.3×10^{28} y	0.6×10^{28} y	1.4×10^{30} y [9]



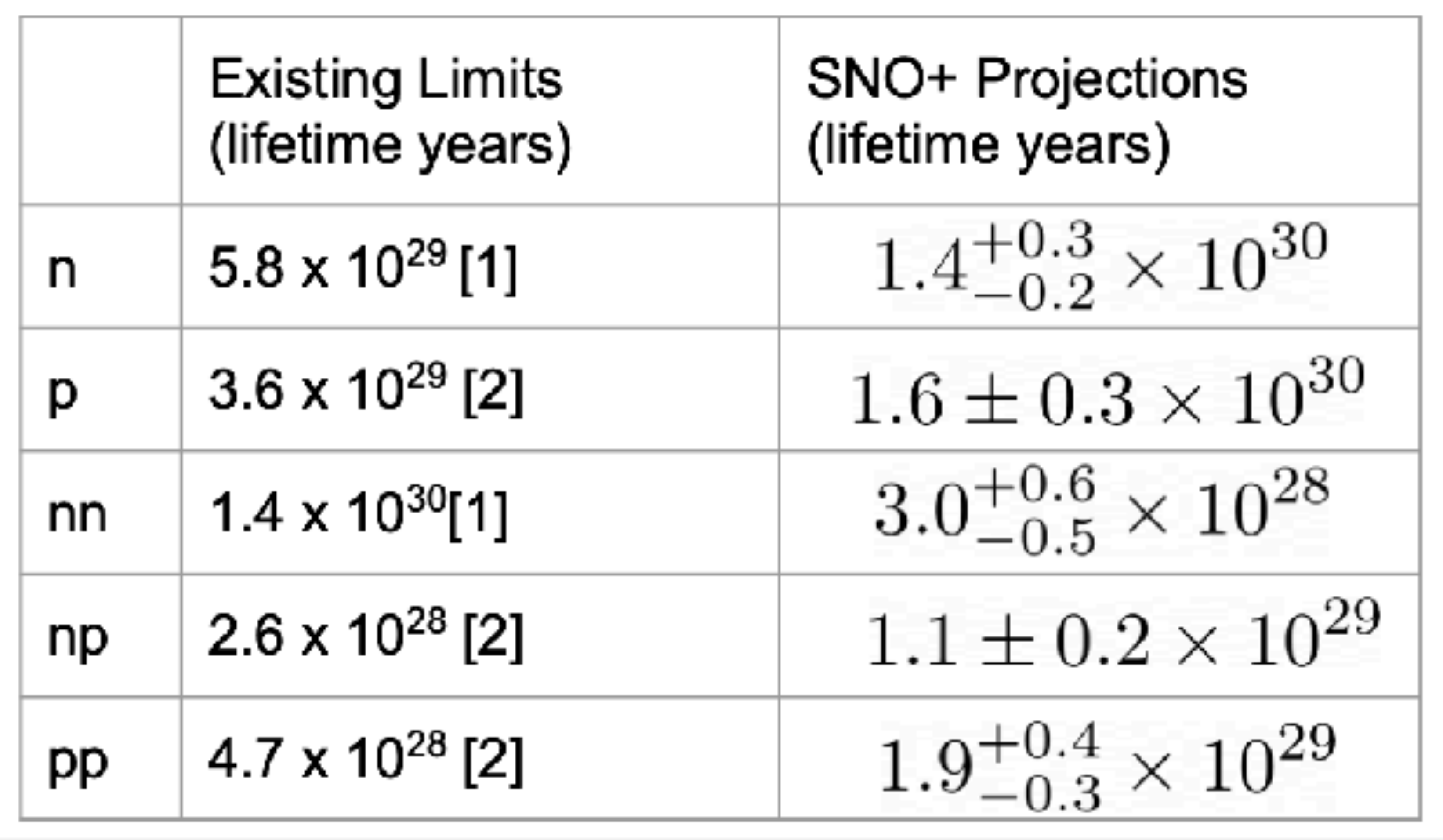
Phys. Rev. D **99**, 032008 (2019)



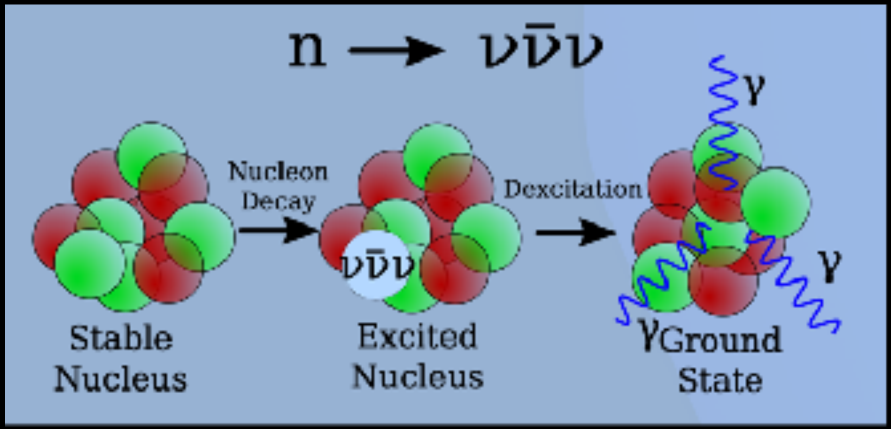
Significant improvements expected

Second data set has more livetime (190 days), significantly lower internal backgrounds and improved optical modelling

New analysis underway



	Existing Limits (lifetime years)	SNO+ Projections (lifetime years)
n	5.8×10^{29} [1]	$1.4^{+0.3}_{-0.2} \times 10^{30}$
p	3.6×10^{29} [2]	$1.6 \pm 0.3 \times 10^{30}$
nn	1.4×10^{30}[1]	$3.0^{+0.6}_{-0.5} \times 10^{28}$
np	2.6×10^{28} [2]	$1.1 \pm 0.2 \times 10^{29}$
pp	4.7×10^{28} [2]	$1.9^{+0.4}_{-0.3} \times 10^{29}$



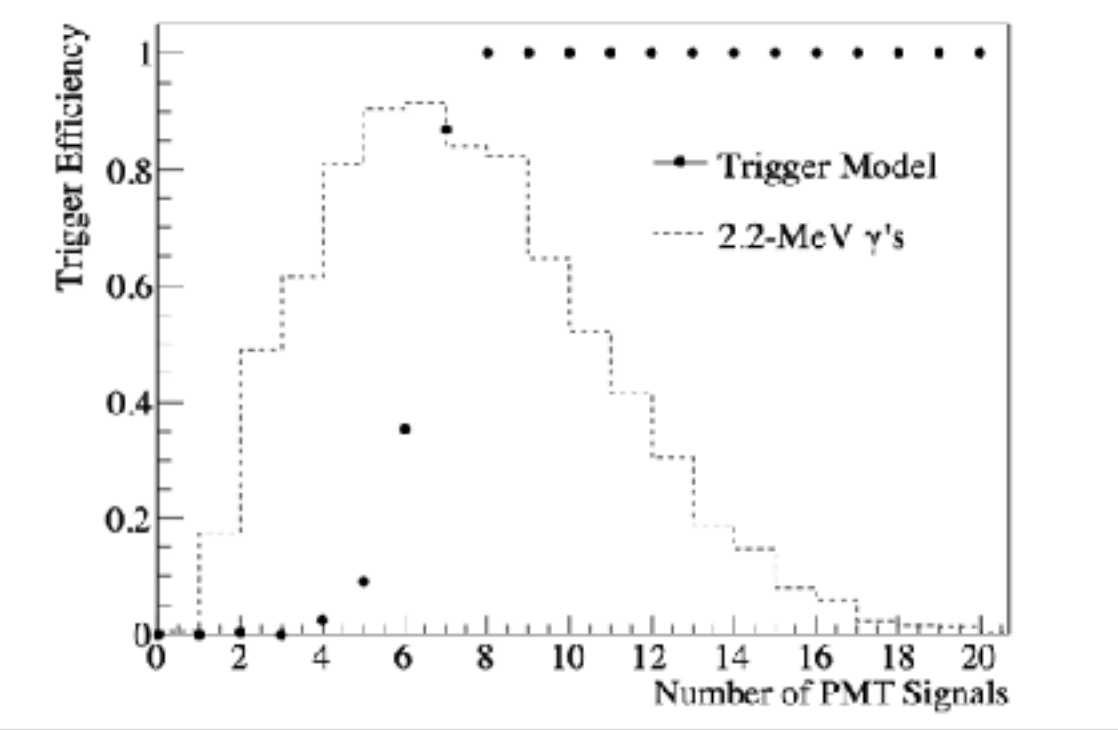
[1] KamLAND
[2] SNO+

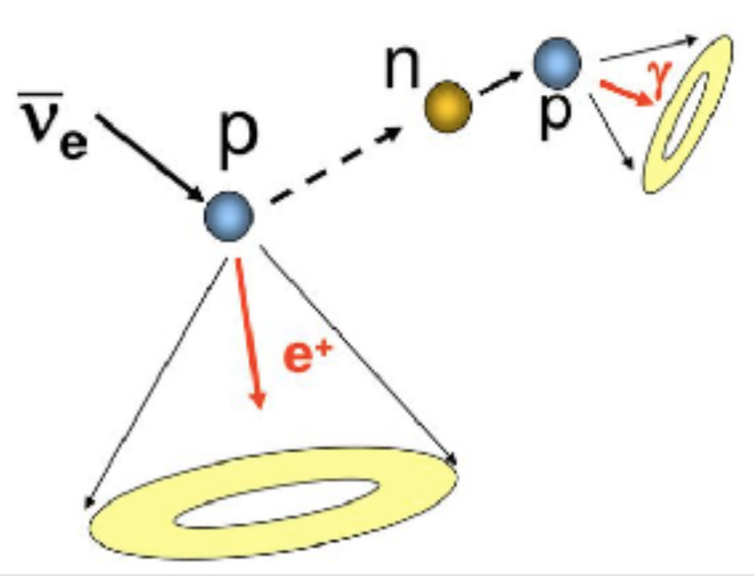
Stable low energy threshold DAQ

Phys. Rev. C **102**, 014002 (2020)

Combination of low detector trigger threshold and low internal background make it possible to look for the neutrons produced in inverse beta decay interactions in pure water.

Simulated trigger efficiency and simulated n-capture gamma signal





n capture on H releases 2.2MeV gamma

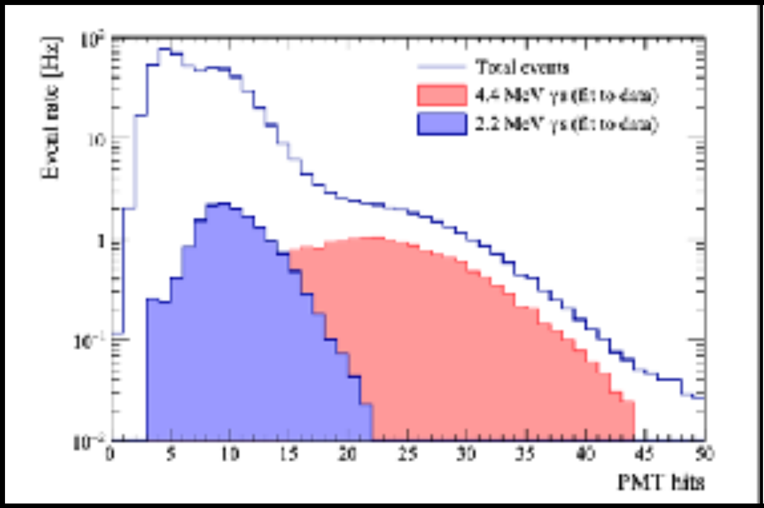
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

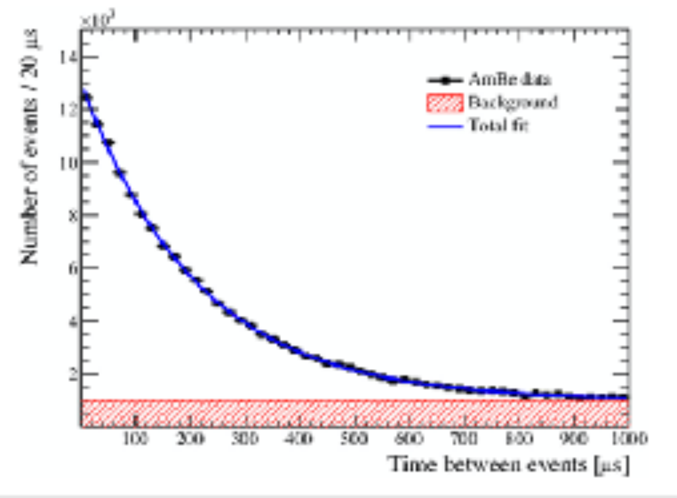
Phys. Rev. C **102**, 014002, 2020

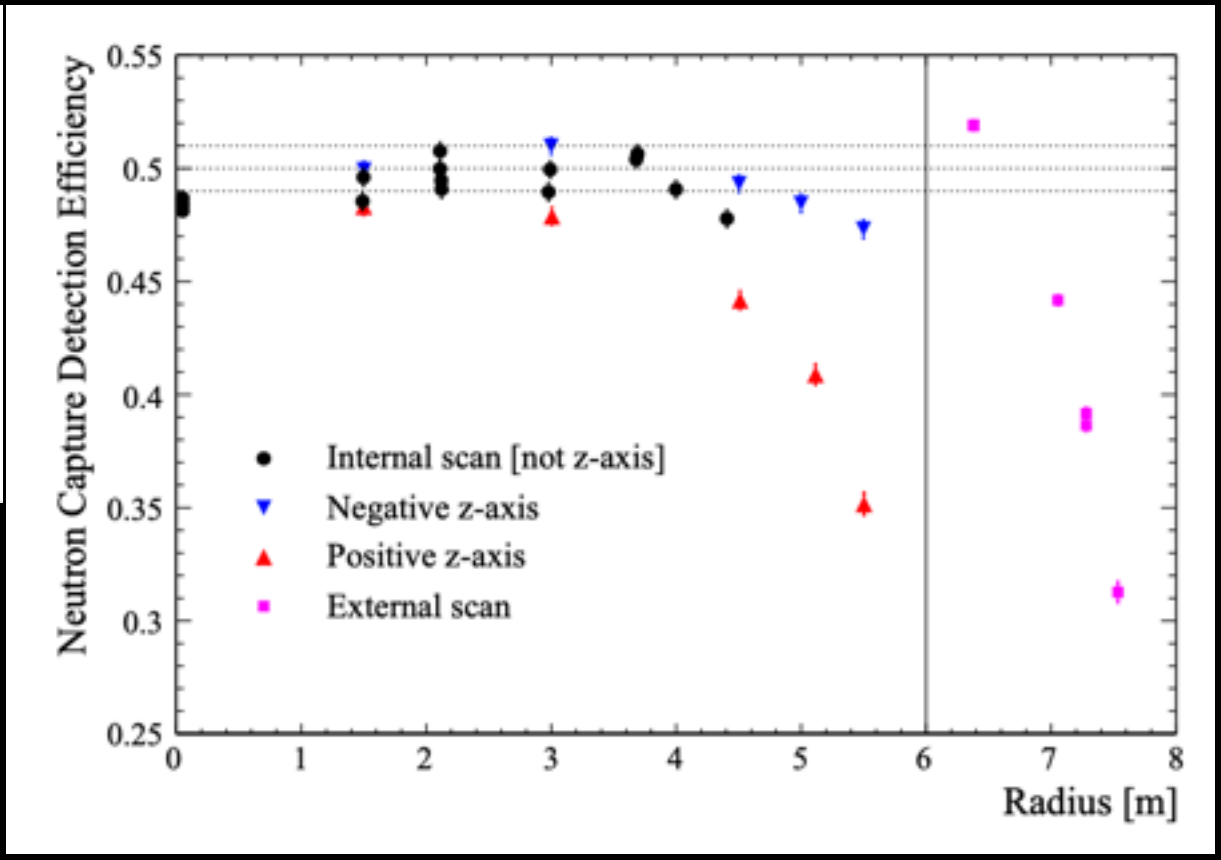
AmBe Calibration – neutron capture

- Internally deployed AmBe neutron source for efficiency of inverse beta decay event detection of antineutrinos
- Coincidence selection applied to source:
  - Prompt: ≥ 17 Nhit for 4.4 MeV γ from $^{12}C^*$
  - Delayed: 7 ≤ Nhit < 17 for 2.2 MeV γ from n-capture on H
  - Δt within 1 ms

Efficiency for tagging neutrons under these conditions is ~50% !



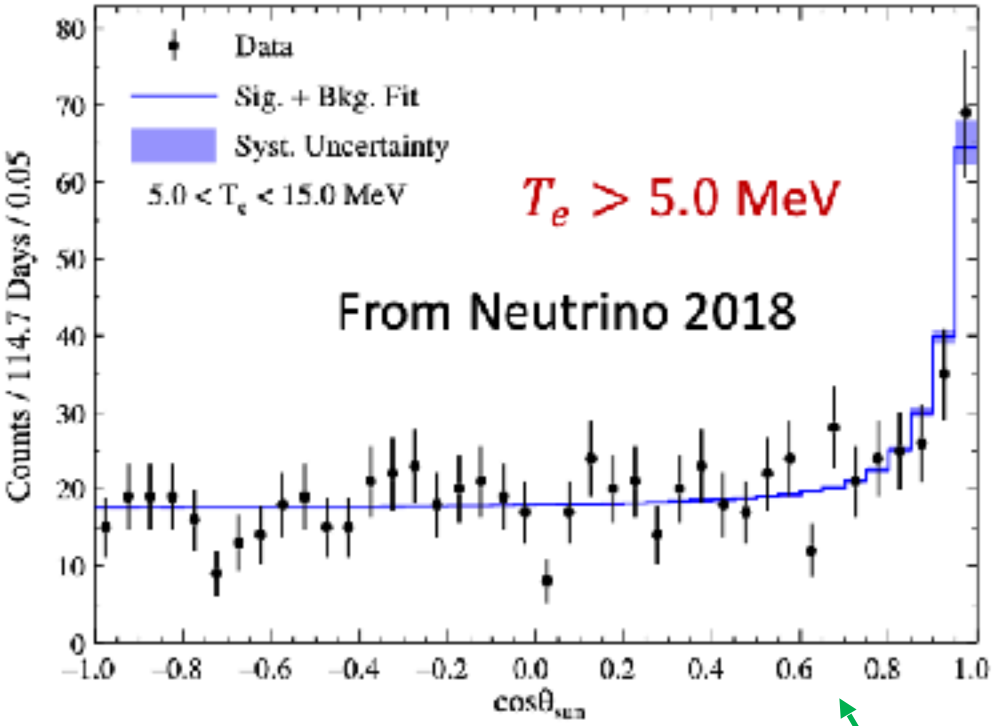




^{8}B SOLAR NEUTRINOS MEASURED BY SNO+ WITH VERY LOW BACKGROUNDS

NOW *EVEN* LOWER BACKGROUNDS!

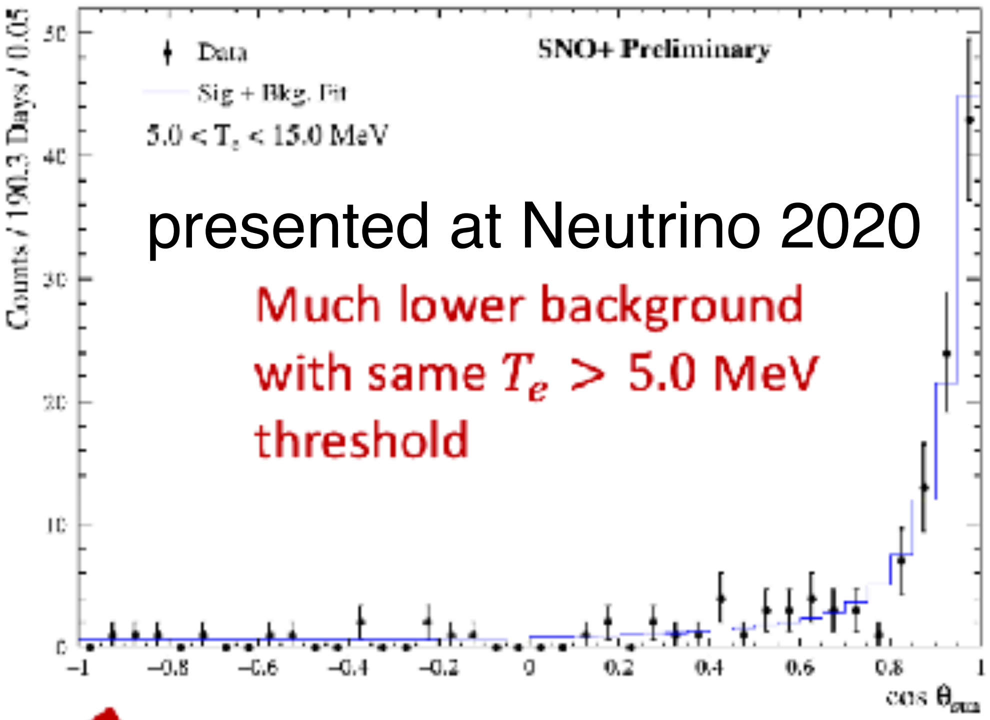
Phys. Rev. D **99**, 012012 (2019)



$T_e > 5.0$ MeV

From Neutrino 2018

NEW

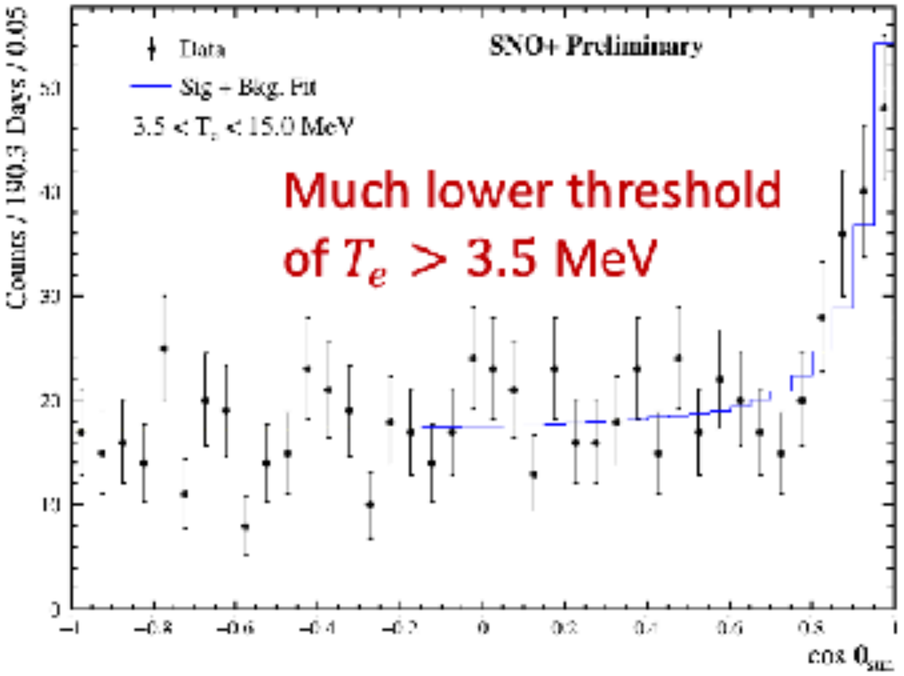


presented at Neutrino 2020

Much lower background with same $T_e > 5.0$ MeV threshold

M. Anderson et al., (SNO+ Collaboration), “Measurement of the ^{8}B solar neutrino flux with very low backgrounds”, Physical Review D **99**, 012012 (2019)

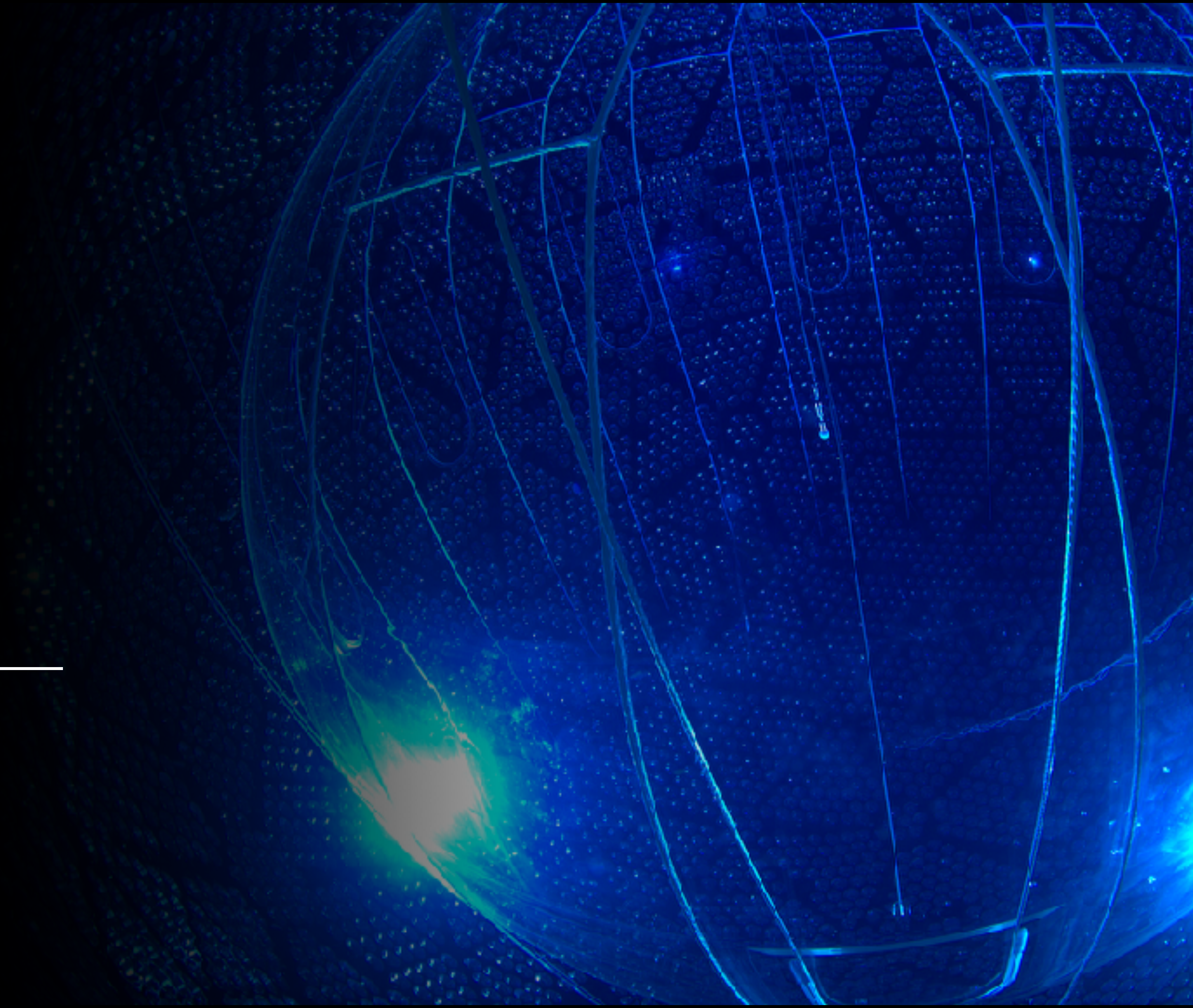
NEW



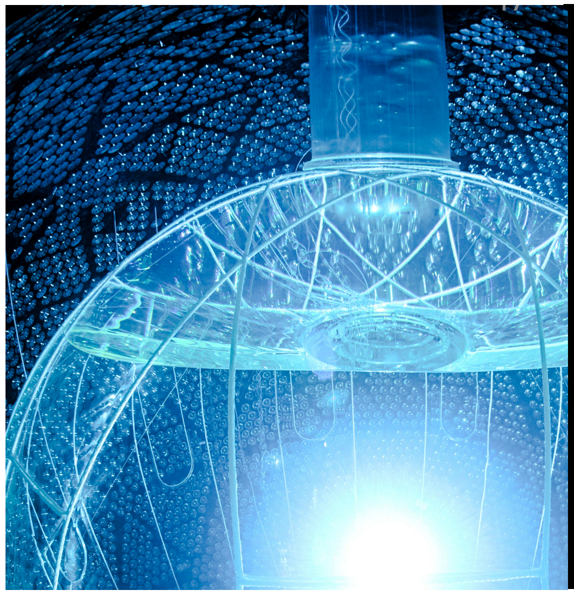
Much lower threshold of $T_e > 3.5$ MeV

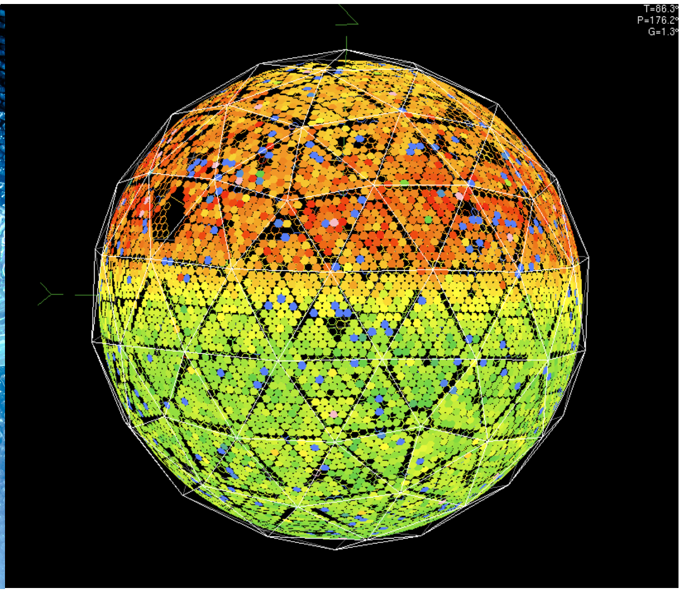
new solar neutrino analysis with lower backgrounds and energy threshold being completed…

Scintillator



Scintillator Fill





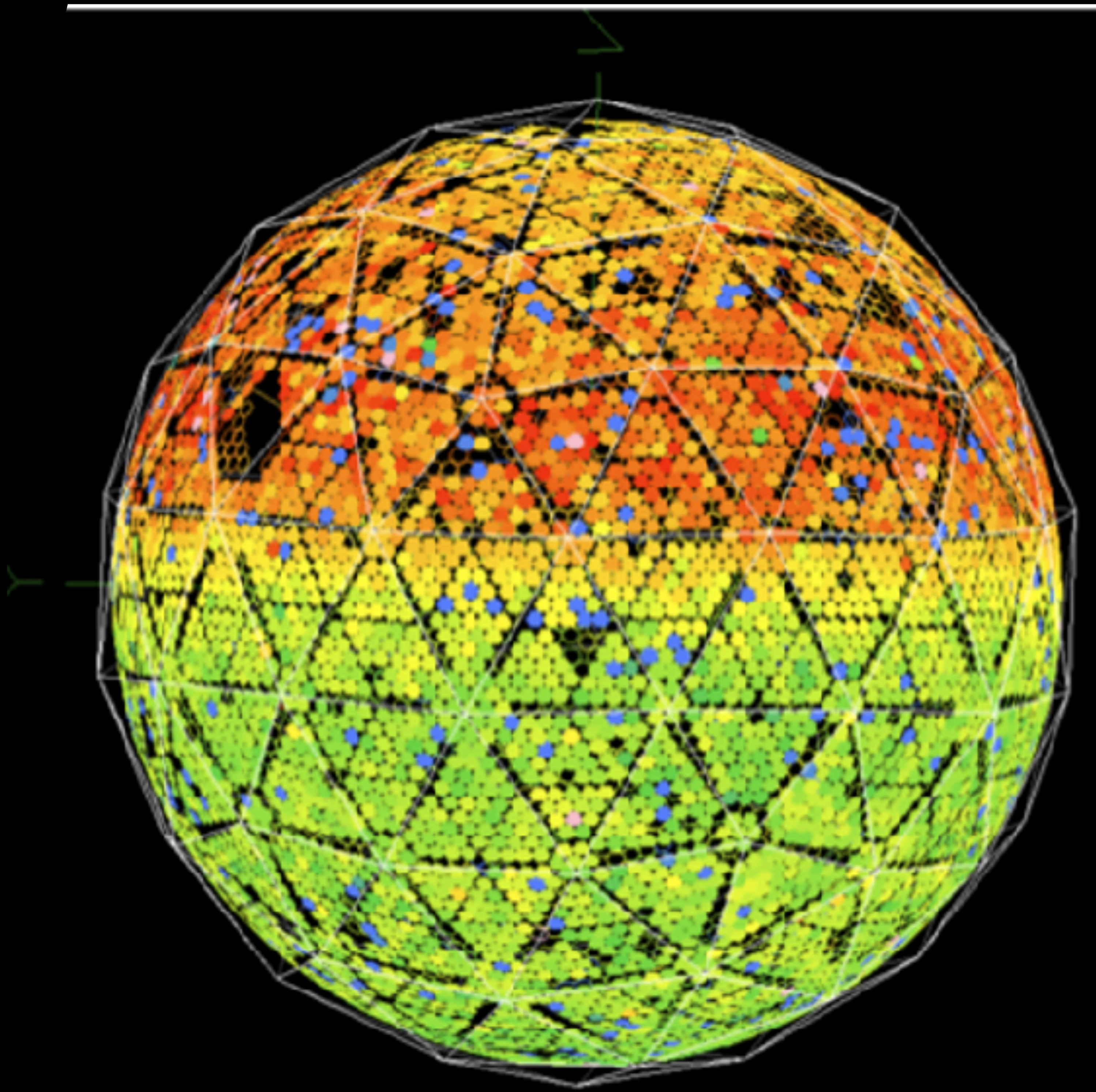
Scintillator fill paused halfway due to COVID-19 pandemic

LS purification and filling was progressing well

Tellurium purification and loading systems completed: undergoing commissioning

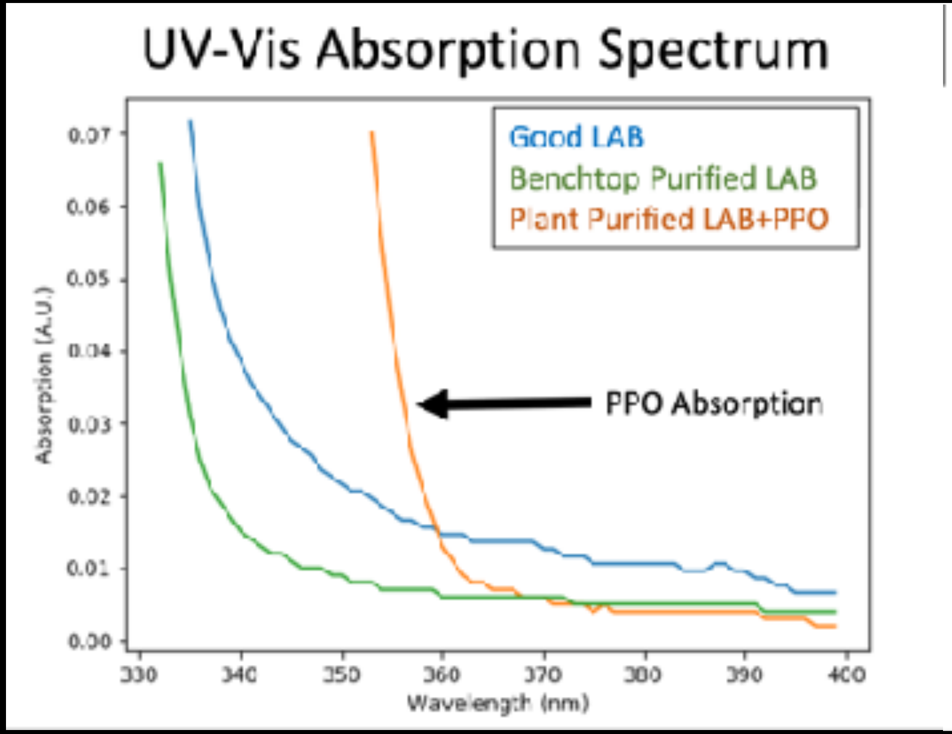
Features of a scintillator detector

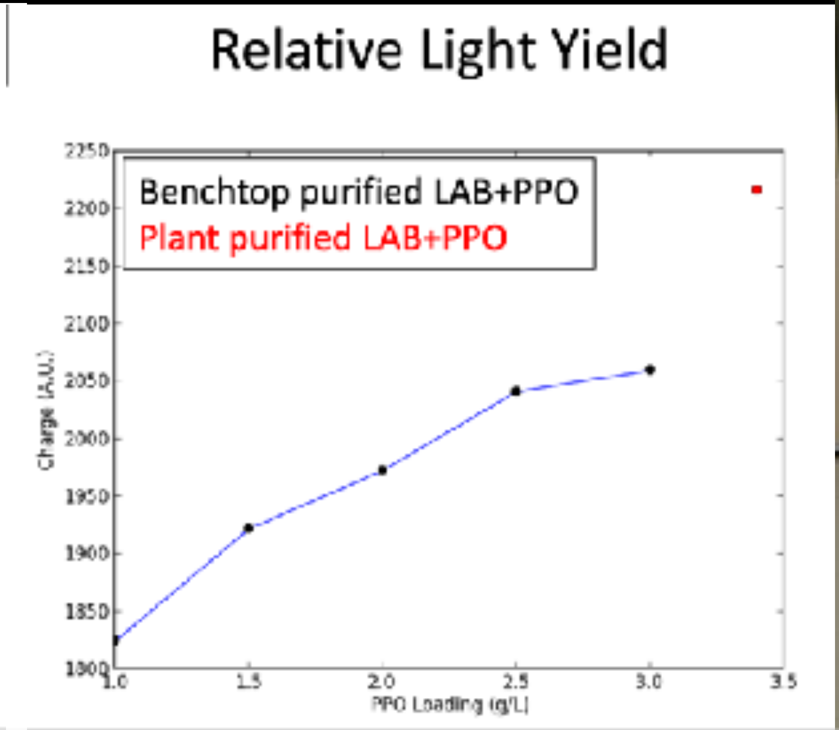
- Thousands of photons per MeV and hundreds of PMT hits / MeV
- Much lower energy threshold: <1 MeV
- Lower radioactivity: easier to purify as U/Th more affinity to water than organic liquids
- Isotropic light – no particle direction information



Hits summed over events
Partial fill

LAB quality


UV-Vis Absorption Spectrum


Relative Light Yield

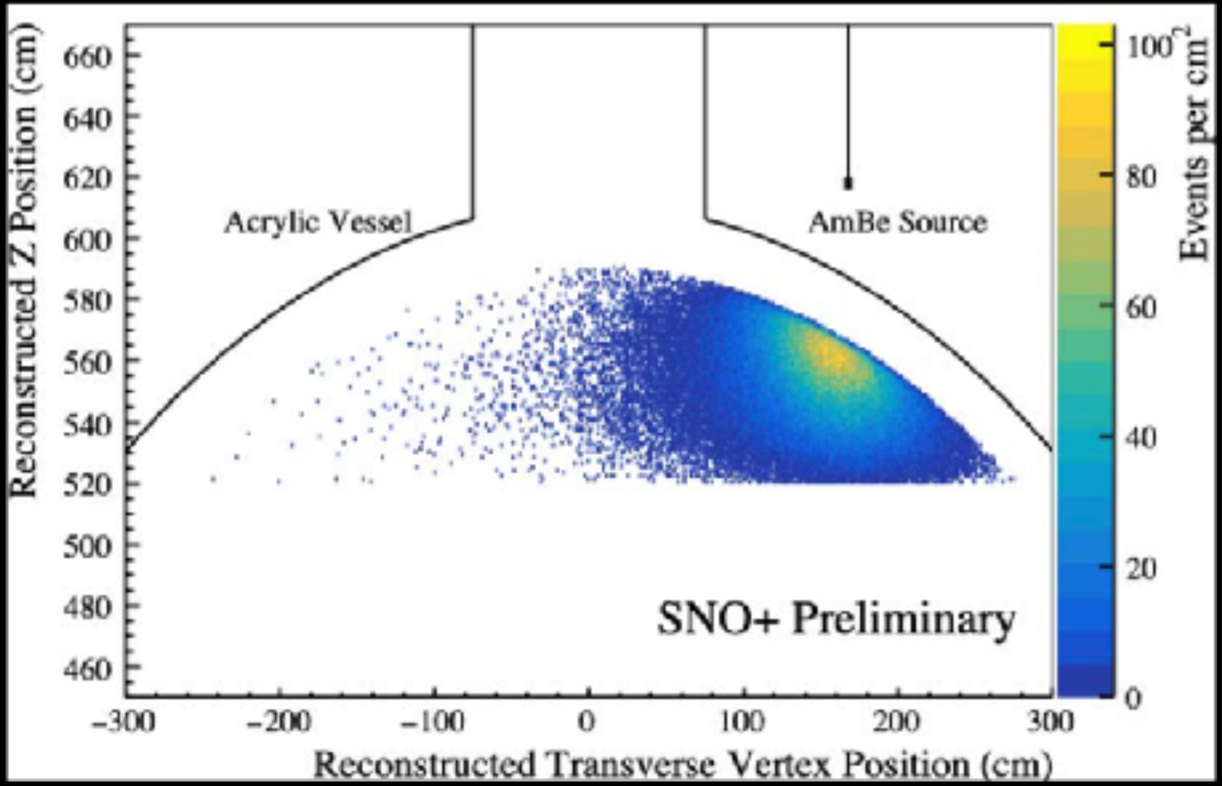
LAB, PPO Master Solution, and final scintillator assessed for quality hourly during purification plant operation and detector filling

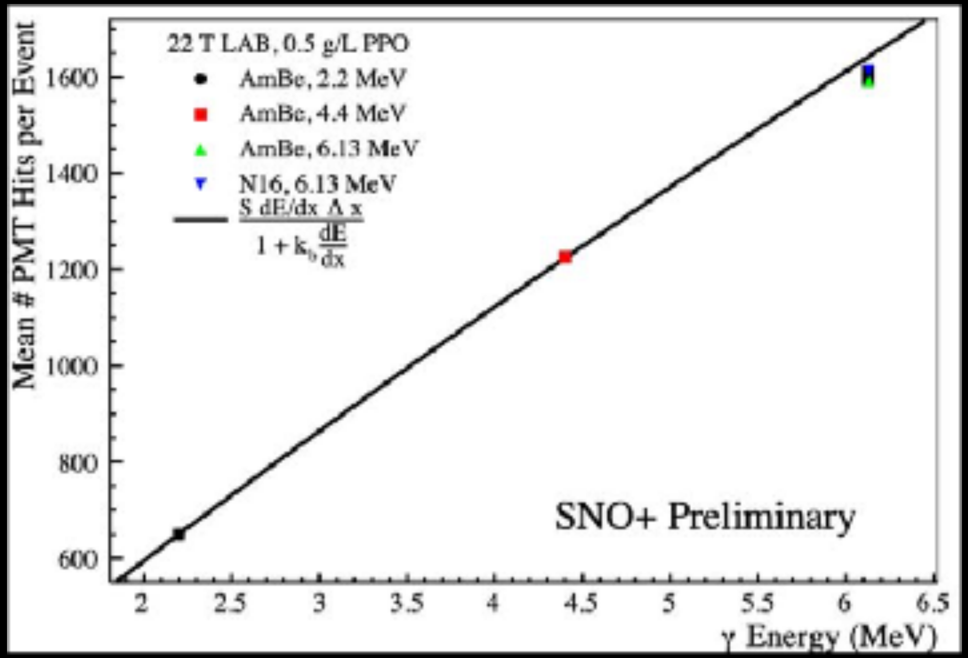
- Observe excellent clarity above PPO absorption (UV-Vis spectroscopy)
- Light yield in excess of calibration standards

Scintillator quality is even better than expected!

Current detector

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



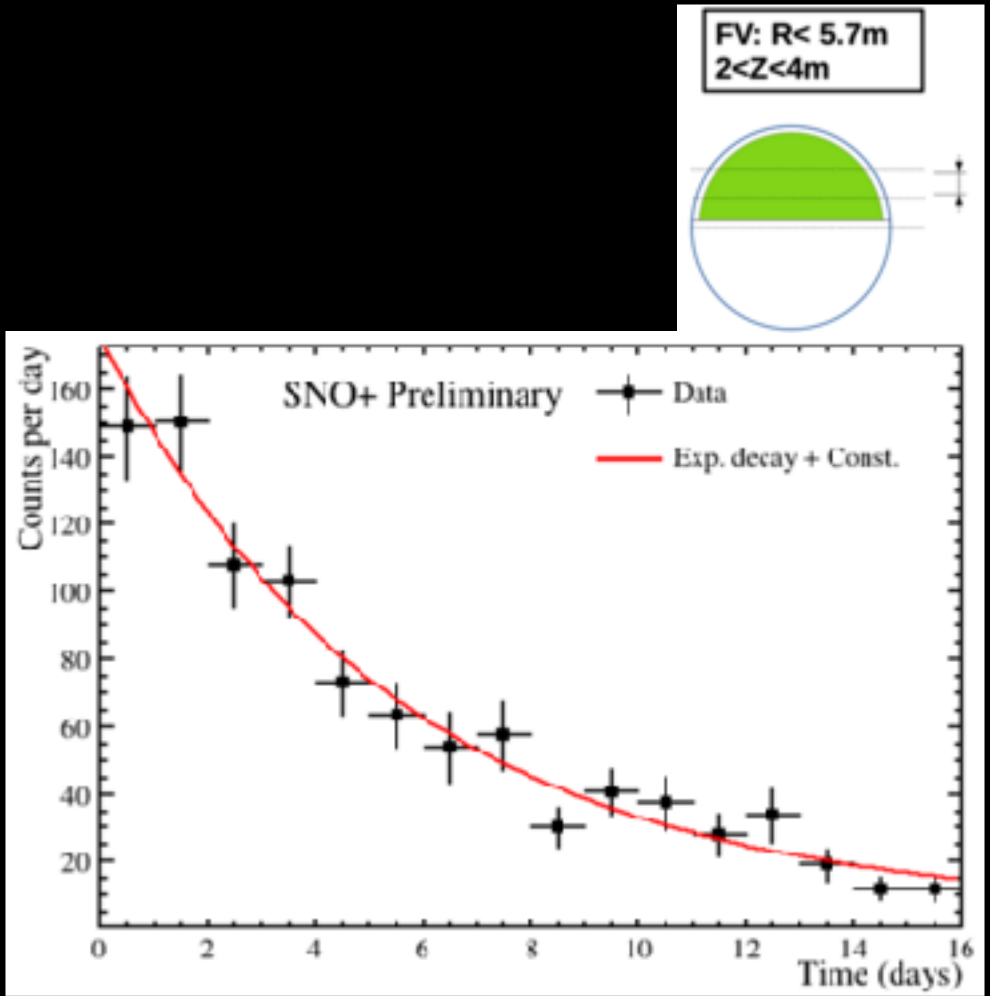


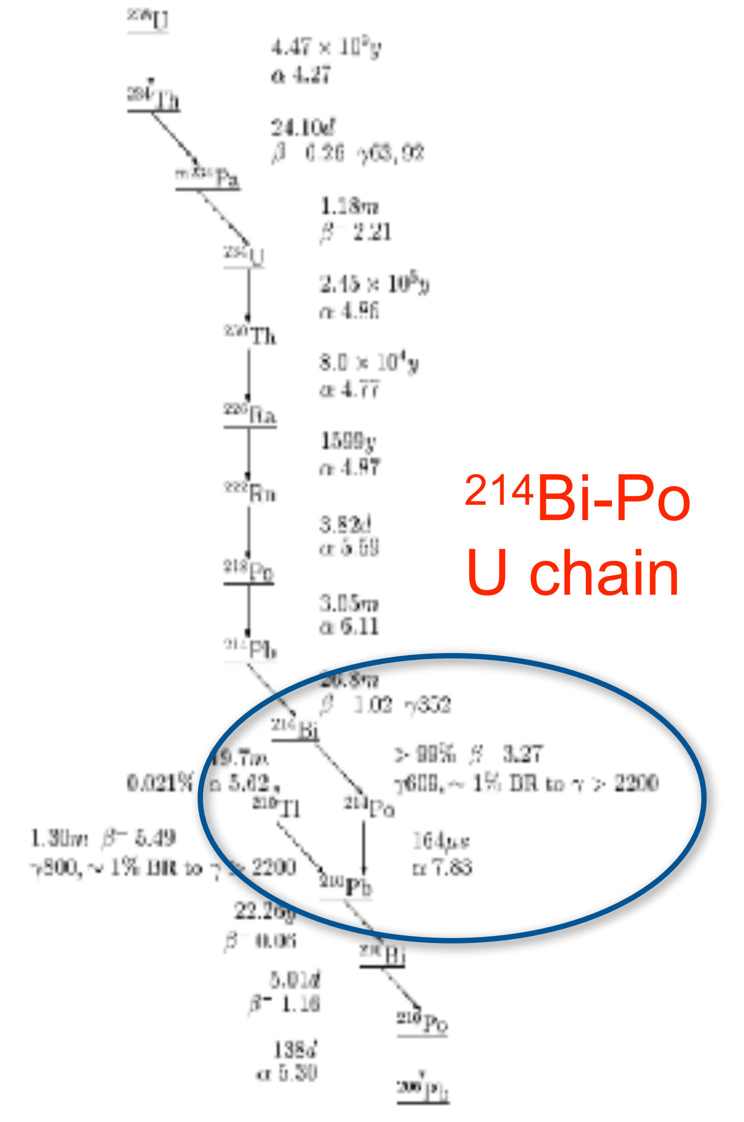
With a PPO concentration of only 0.5 g/L (25% of the nominal value) we see a light yield equivalent to ~300 p.e. / MeV

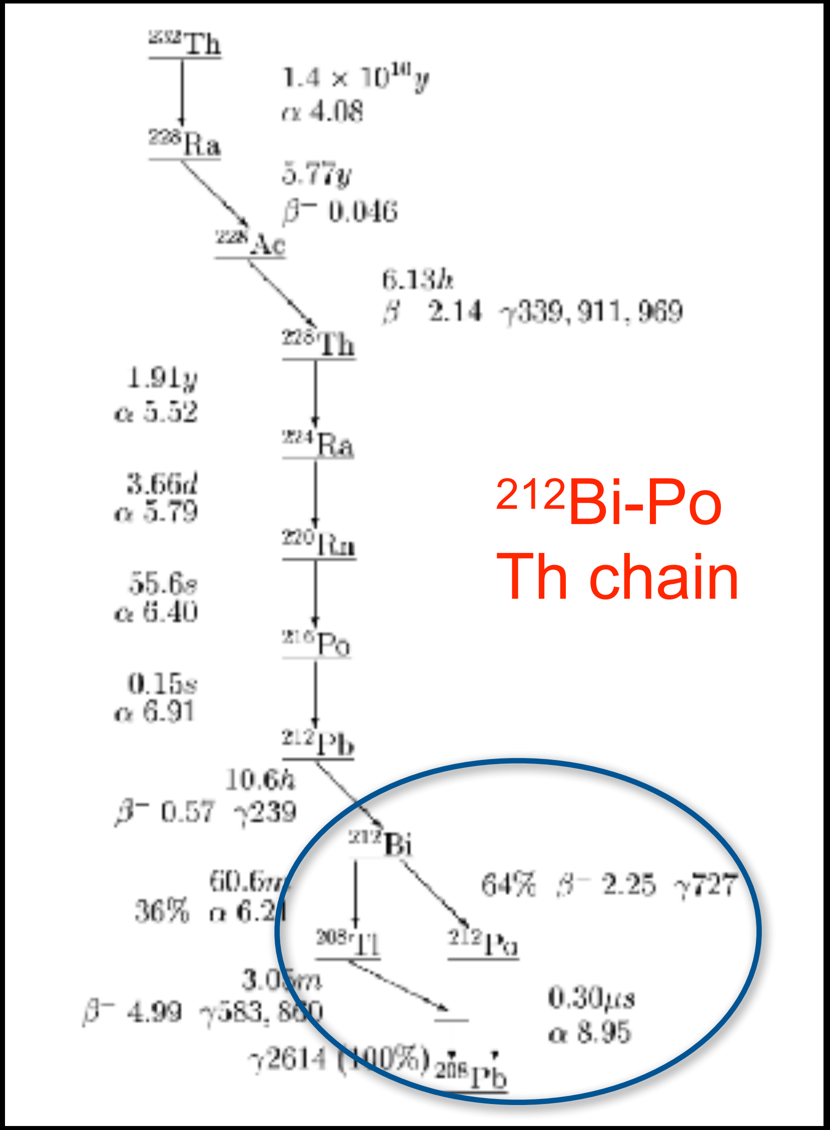
Extrapolates to ~650 p.e. / MeV at 2.0 g/L PPO

Preliminary SNO+ Scintillator Background Measurements

Bi-Po coincidences used to measured supported Rn levels of U and Th equivalent





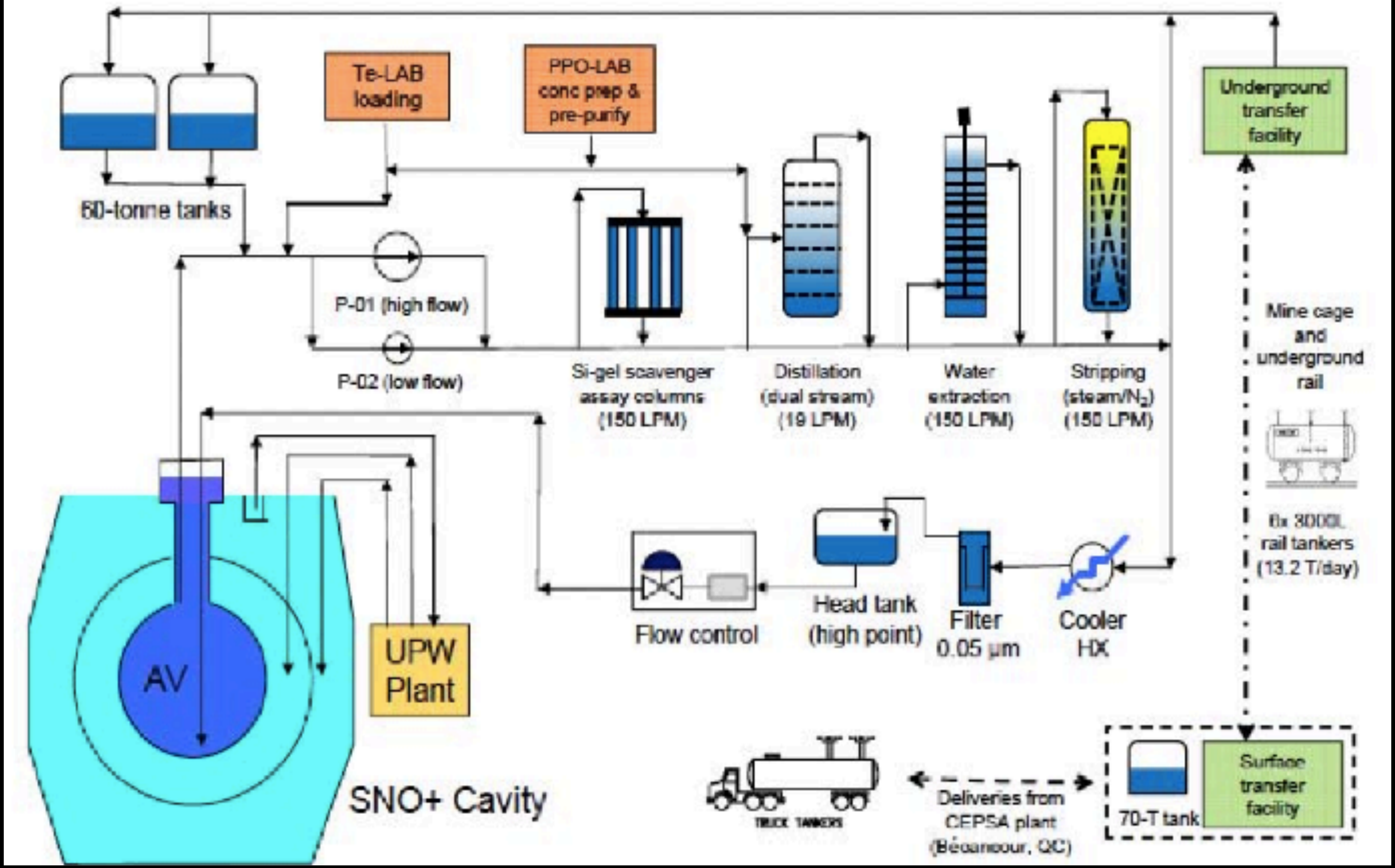


U chain equiv: 4.6 ± 1.9 · 10^{-17} g/g
Th chain equiv: 5 · 10^{-17} g/g
both measured during partial fill

scintillator radiopurity meets DBD required target

Plans to resuming scintillator fill

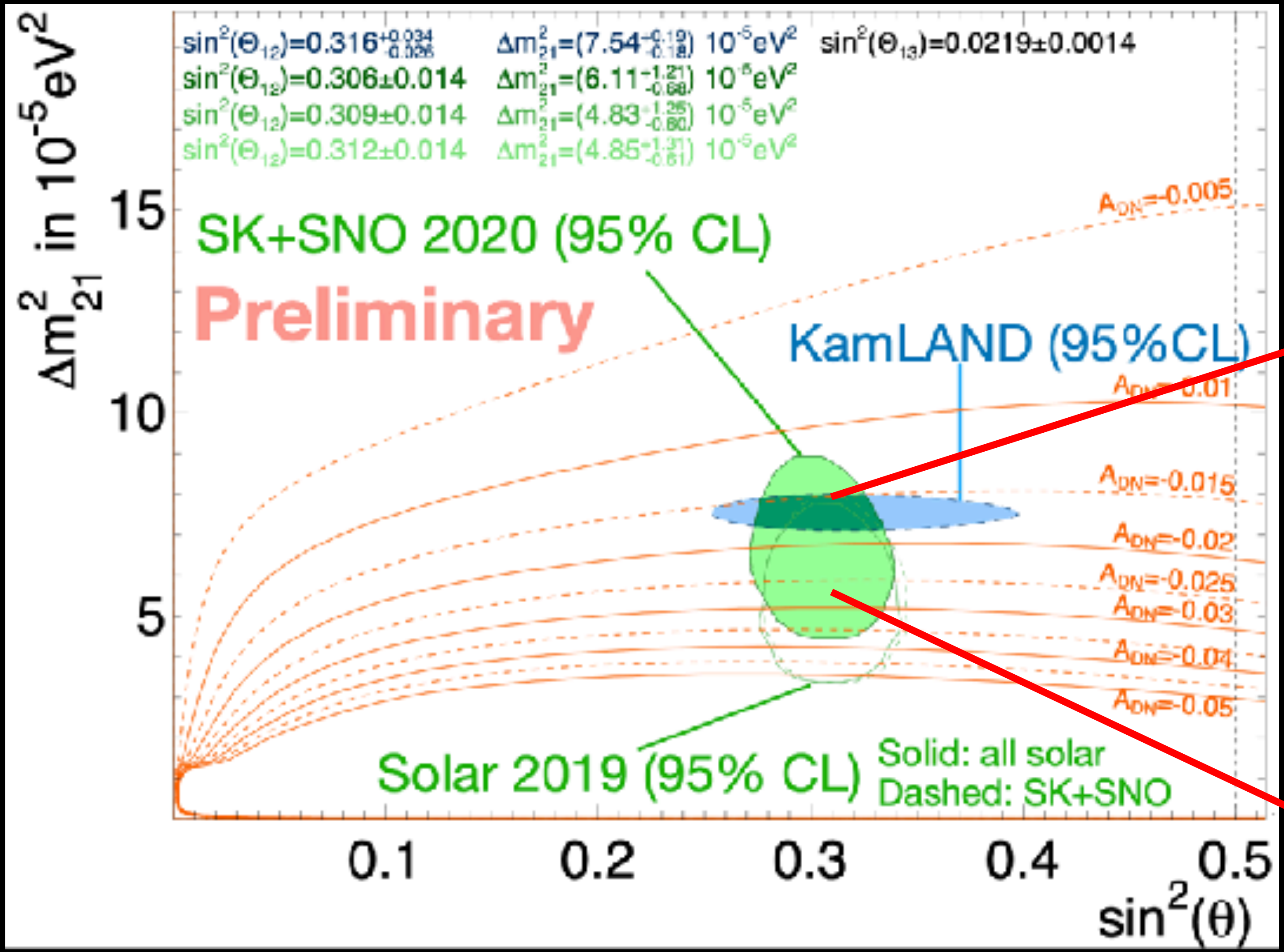
- SNOLAB operations still severely restricted by the pandemic
- Recently started receiving LAB shipments again
- Hope to start underground scintillator purification plant next month…

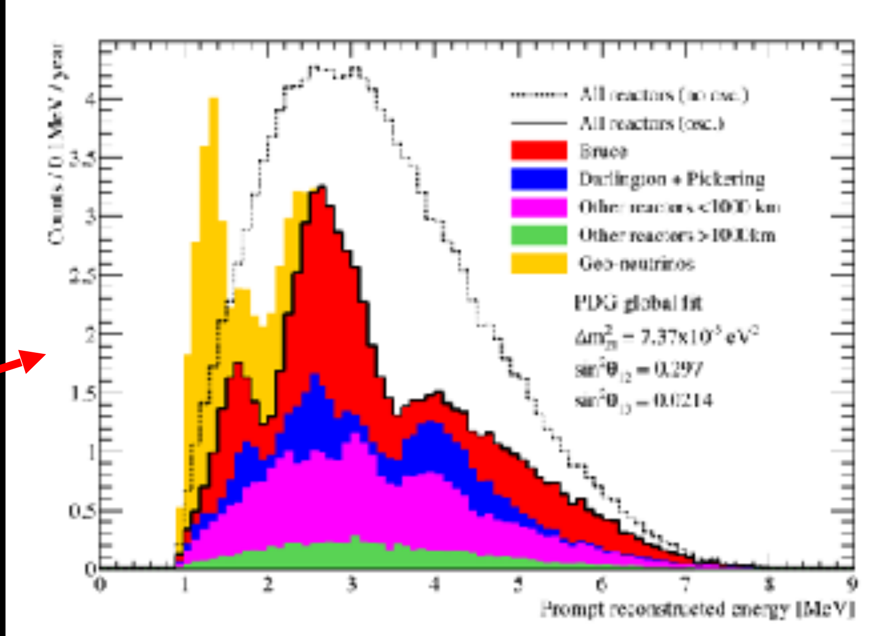


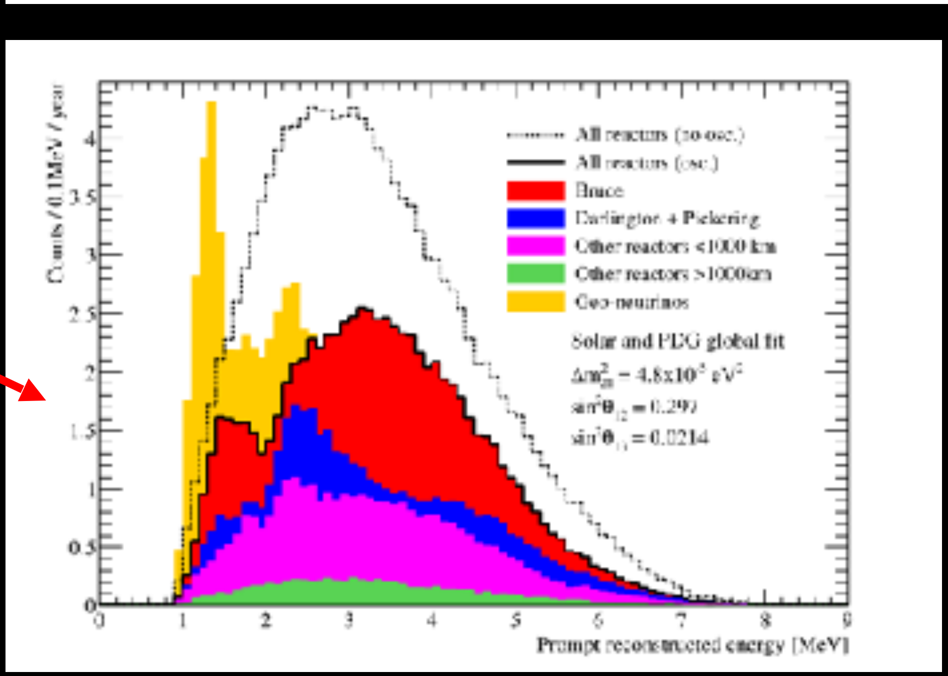
Example

Scintillator Physics Goals: Reactor Antineutrino

Capacity to probe Solar : KamLAND tension in Δm^2_{12}





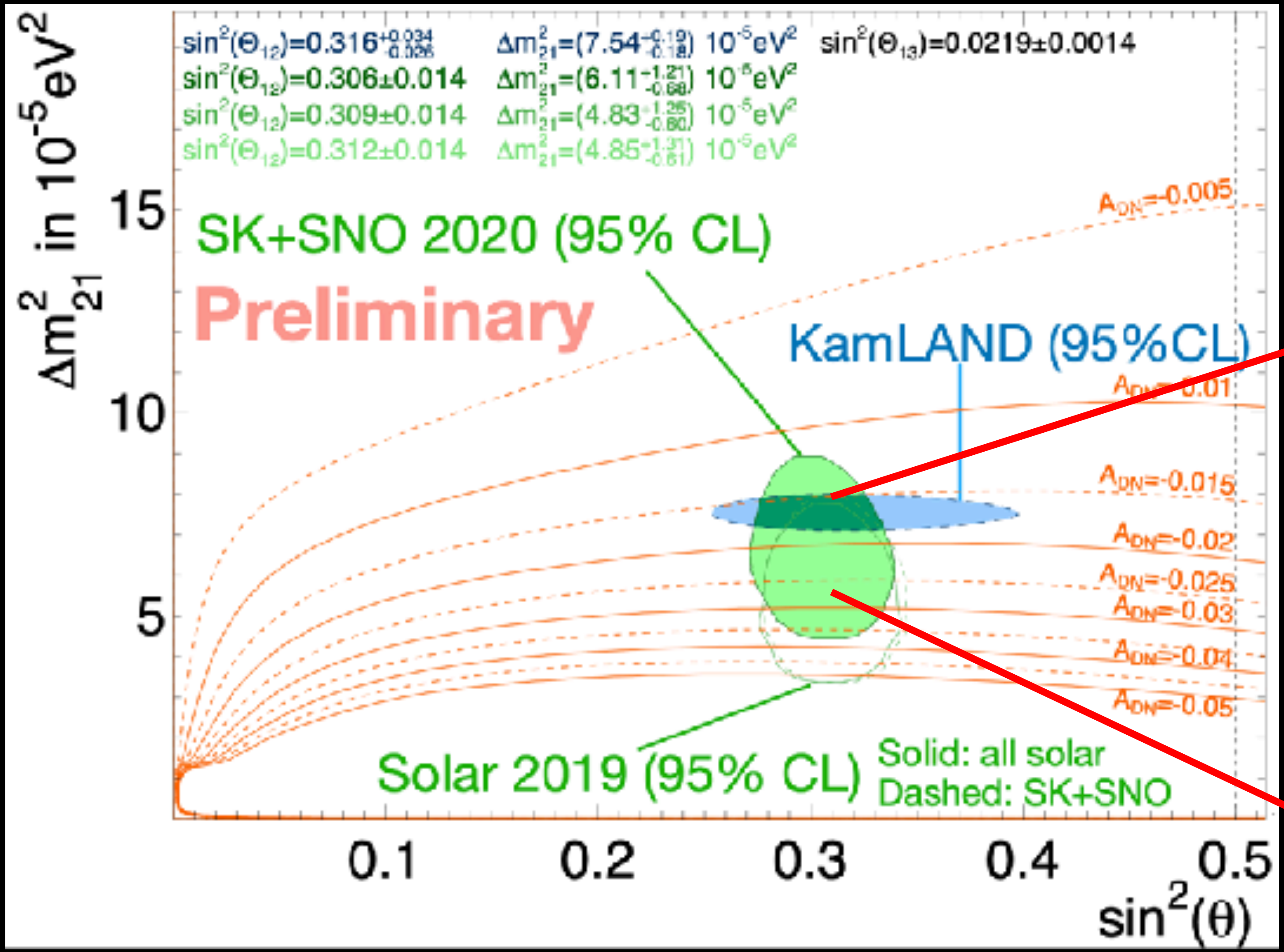


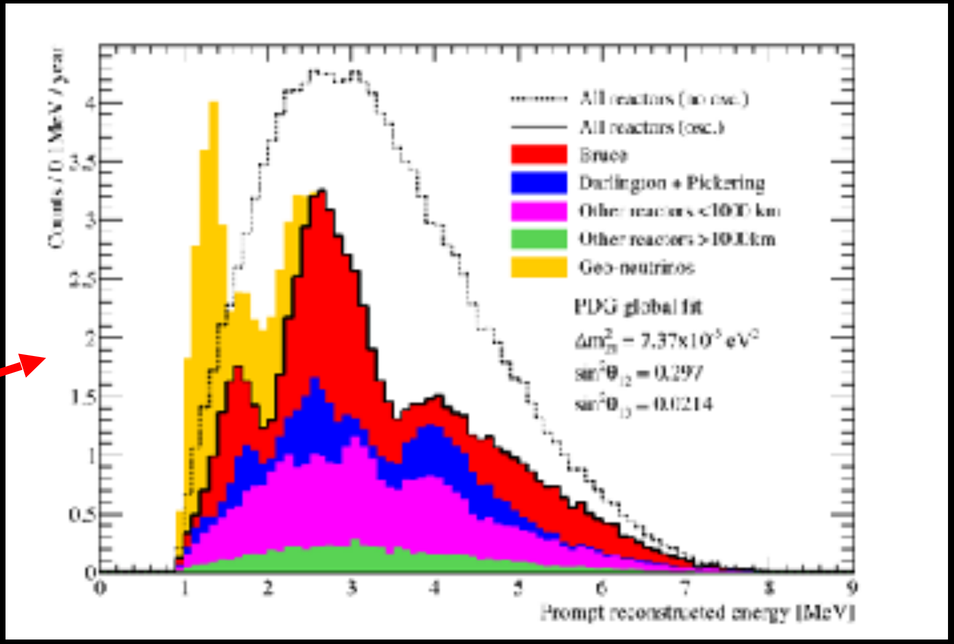
https://indico.fnal.gov/event/43209/contributions/187863/attachments/129474/159089/nakajima_Neutrino2020.pdf

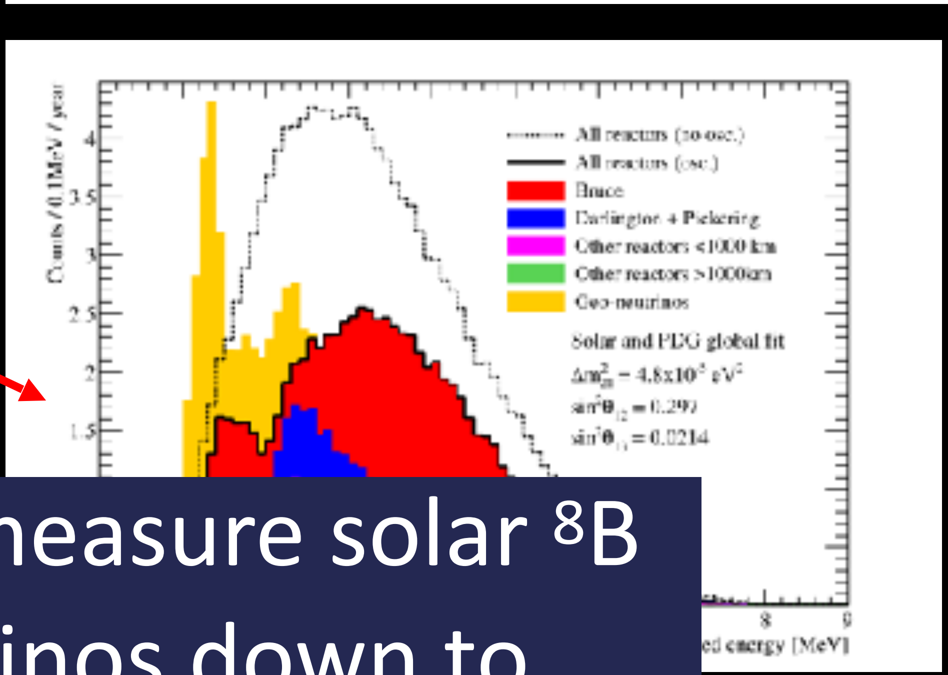
Example

Scintillator Physics Goals: Reactor Antineutrino

Capacity to probe Solar : KamLAND tension in Δm^2_{12}



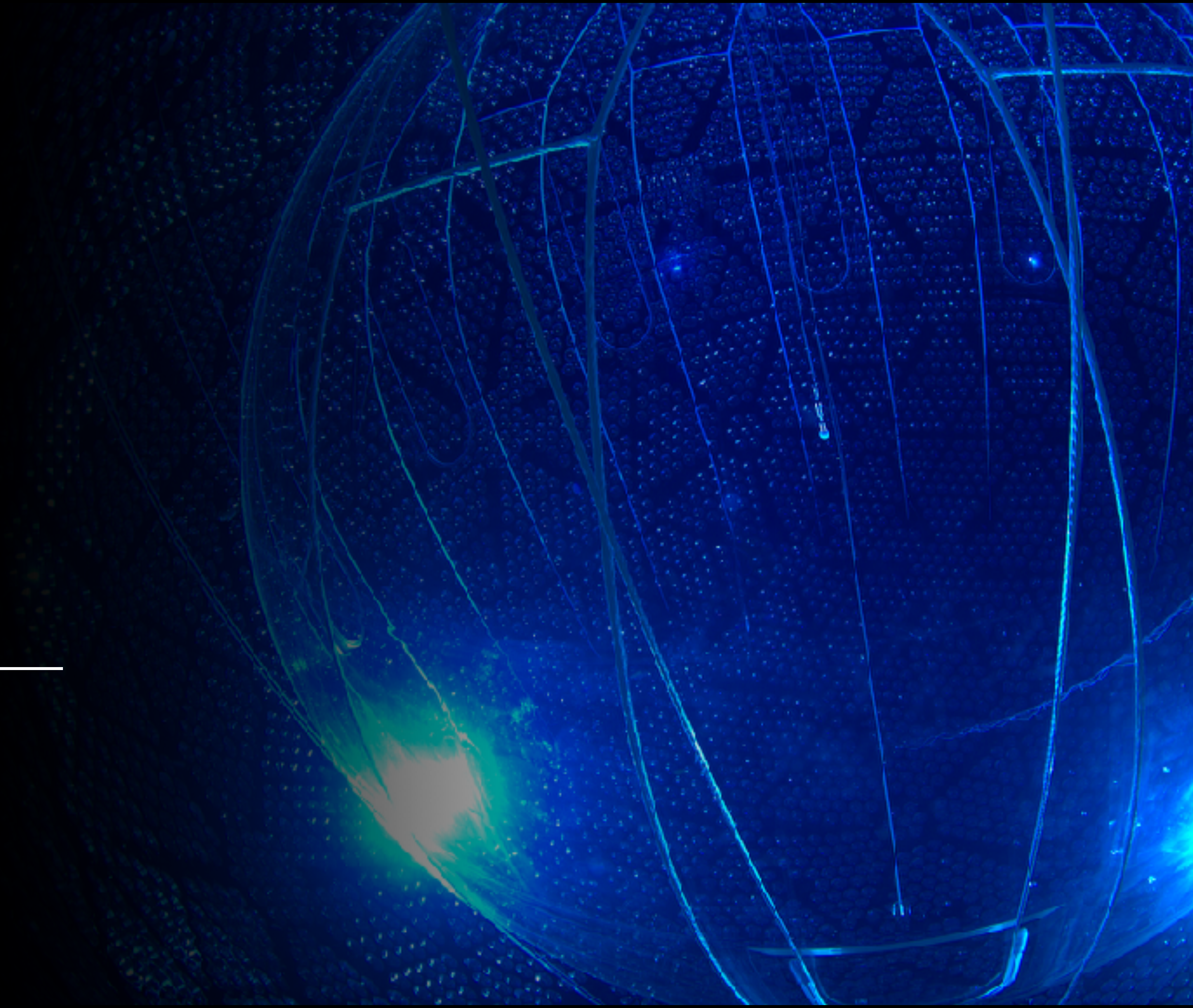




Can measure solar ^8B neutrinos down to ~2.8MeV in same detector

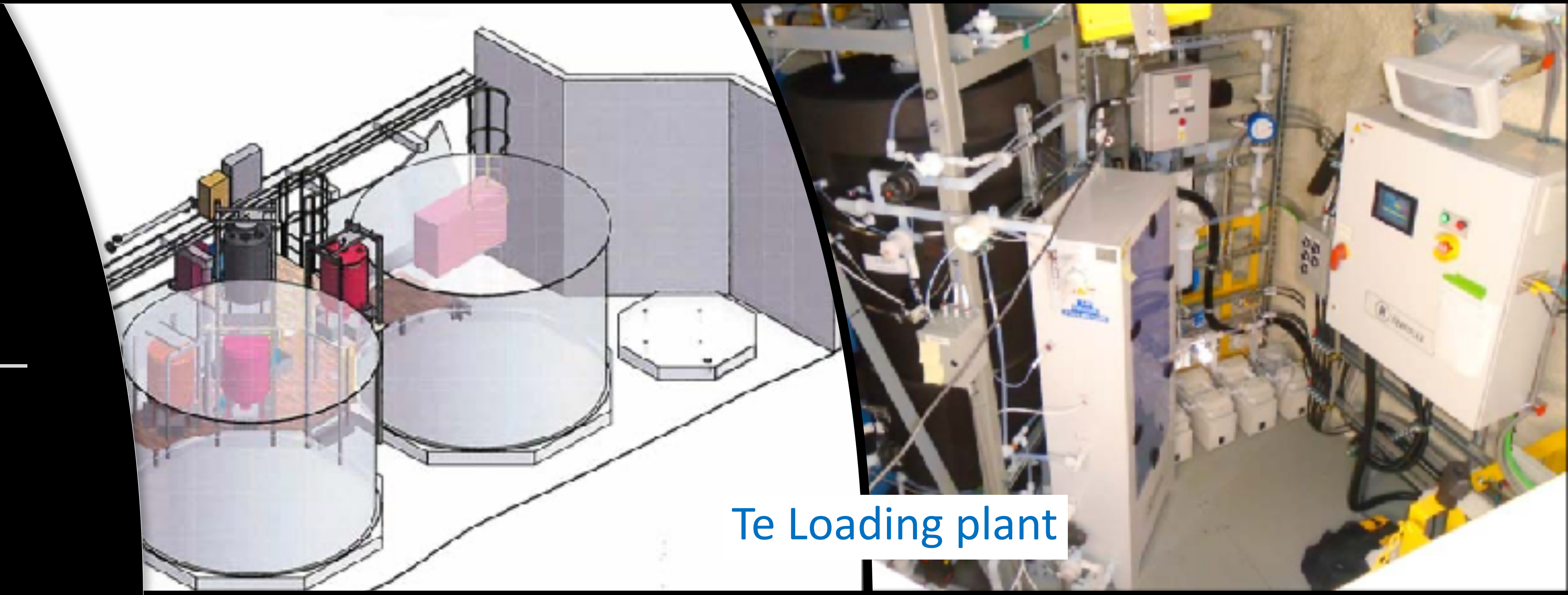
https://indico.fnal.gov/event/43209/contributions/187863/attachments/129474/159089/nakajima_Neutrino2020.pdf

Tellurium

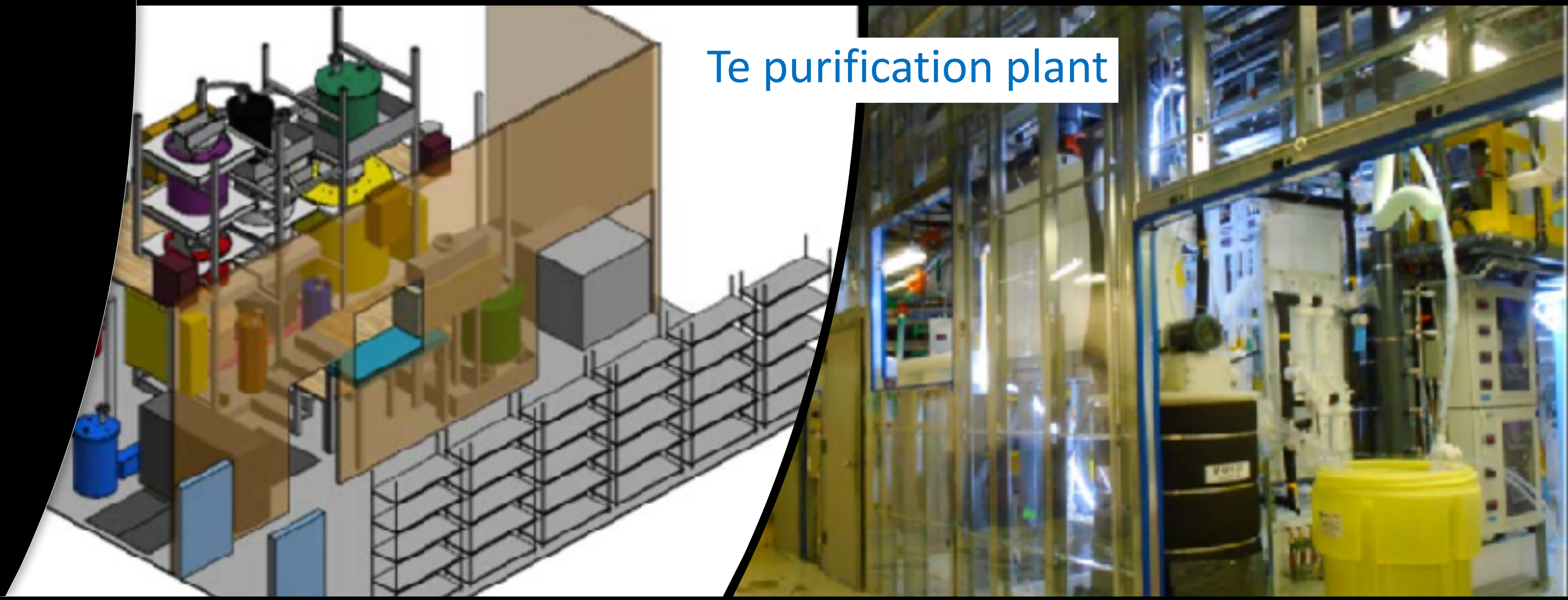


Te loading: status

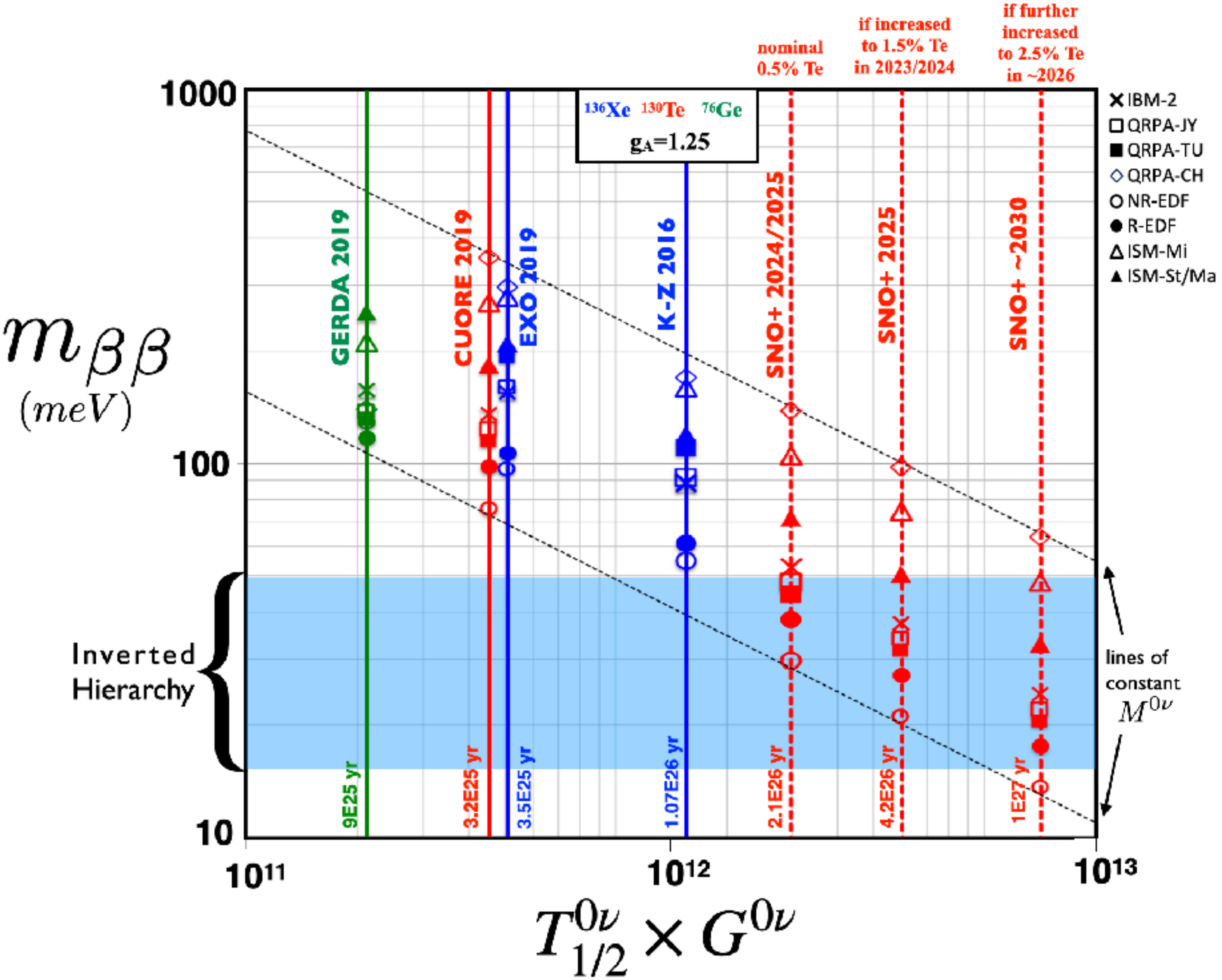
- Construction and installation of the purification and loading plants is finished
- 250 kg batch processing of tellurium underground
- Preparing for the first test batch of Te purification and synthesis when activities resume in the lab



Te Loading plant



Te purification plant

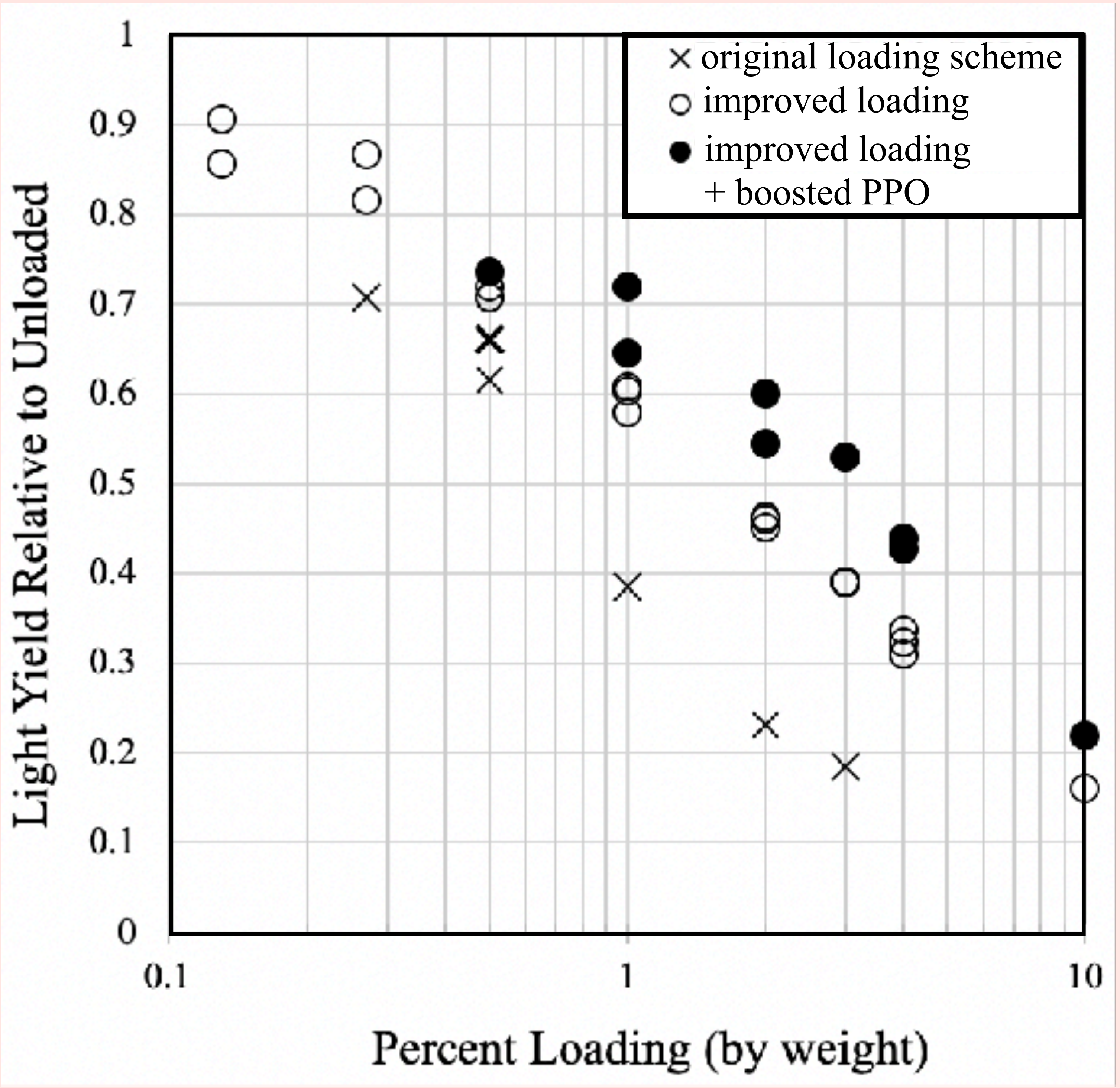


New Physics Sensitivity: Phase-Space Weighted Half-Life

Phase II Progress:

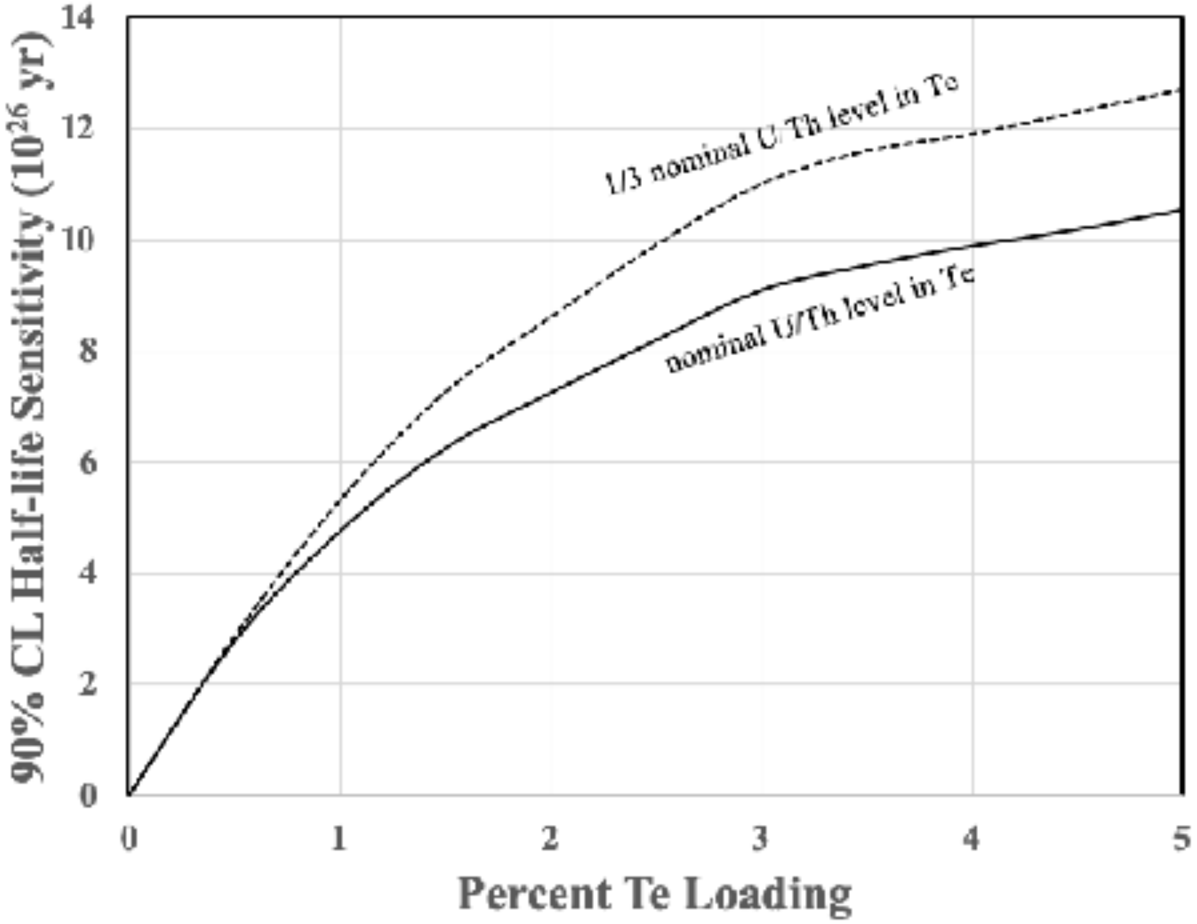
Te-loading technology now achieves levels of several percent with improved light yield - can use existing SNO+ Phase I Te loading systems (now being commissioned)

Scintillator samples with several percent Te are stable on the timescales of years

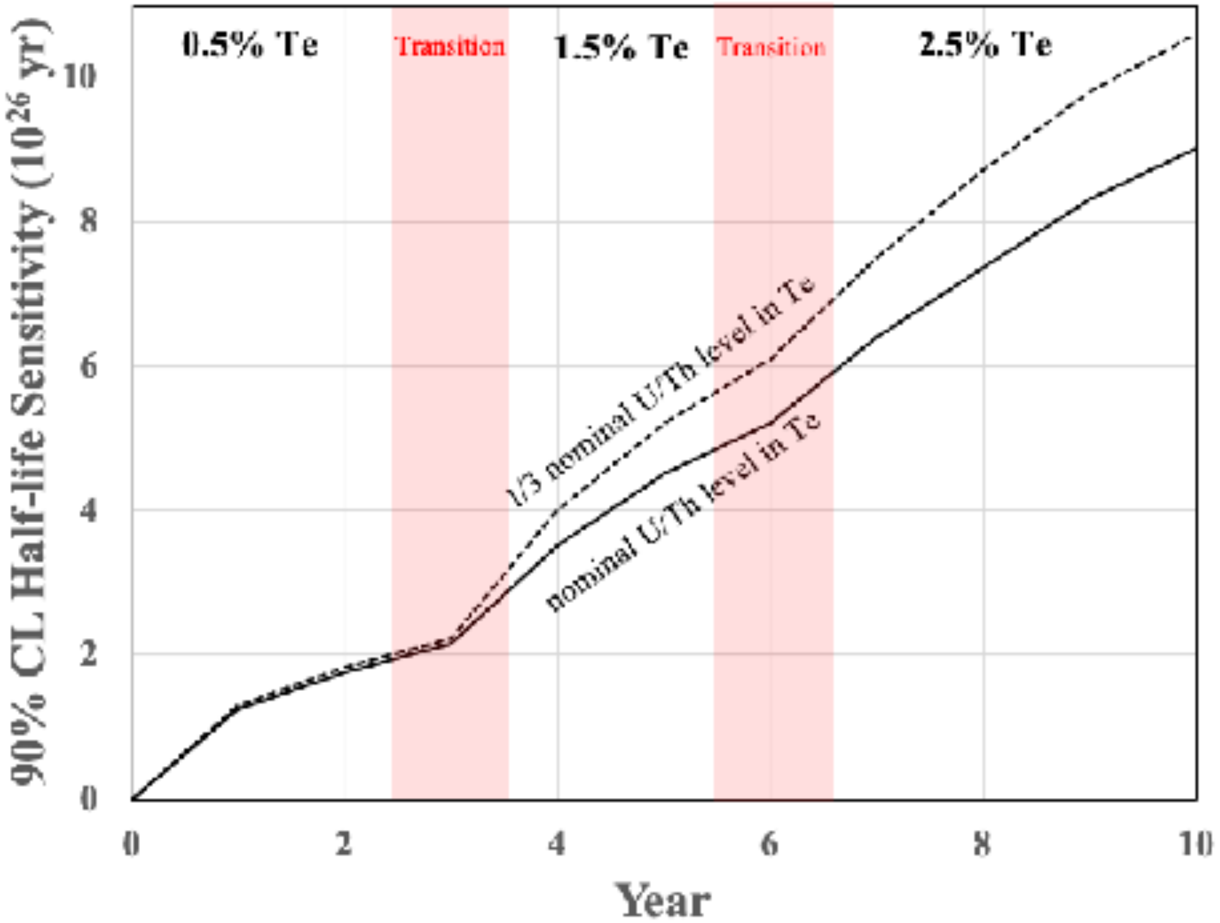


The cost of additional loading is **~$2M per tonne of 0νββ isotope**, which is 1-2 orders of magnitude less expensive than any other approach!

→ Technology looks economically viable for significant scale-up in future experiment to pursue discovery-level sensitivity beyond the Inverted Ordering range of $m_{\beta\beta}$ parameter space



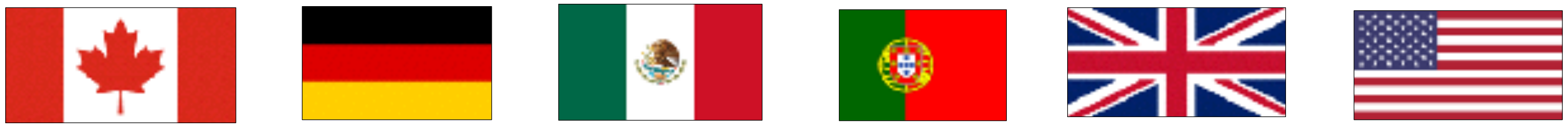
SNO+ Phase II
5yr Half-life Sensitivity vs Loading



SNO+ Phased Loading Plan
(no detector upgrades required)

SNO+ Collaboration

Univ. of Alberta
UC Berkeley / Lawrence Berkeley National Lab
Boston Univ.
Brookhaven National Lab
Univ. of Chicago
UC Davis
Technical Univ. of Dresden
IPP
King’s College London
Lancaster Univ.
Laurentian Univ.
LIP Lisbon and Coimbra
Univ. of Liverpool
UNAM
Univ. of Oxford
Univ. of Pennsylvania
Queen’s Univ.
Queen Mary Univ. of London
SNOLAB
Univ. of Sussex
TRIUMF



SNO+ Collaboration