SNO+: Current Status and Prospects

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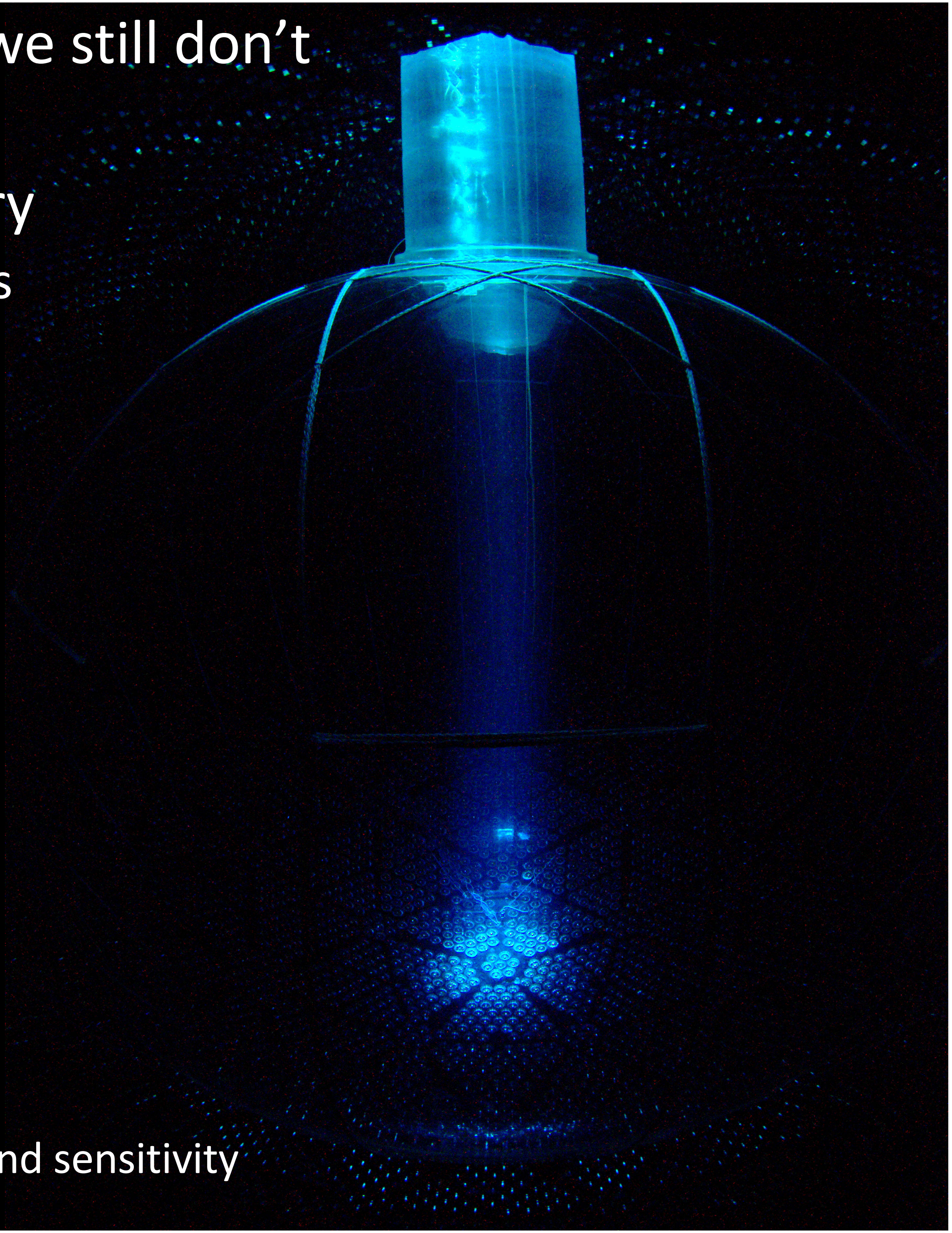
SNO+



- Neutrino theory - what we still don’t know
- Double beta decay theory
  - Experimental approaches
  - The SNO+ approach
- Evolution of SNO+
  - SNO -> SNO+
  - Water phase
    - Invisible nucleon decay
    - Solar spectra
    - Neutron capture
  - Scintillator Fill
    - Solar physics
    - Reactor neutrinos
    - Geo neutrinos
  - Te-loaded Fill
    - Double beta challenges and sensitivity

Neutrino Oscillations

Neutrino flavour states we observe are linear super-positions of neutrino mass states

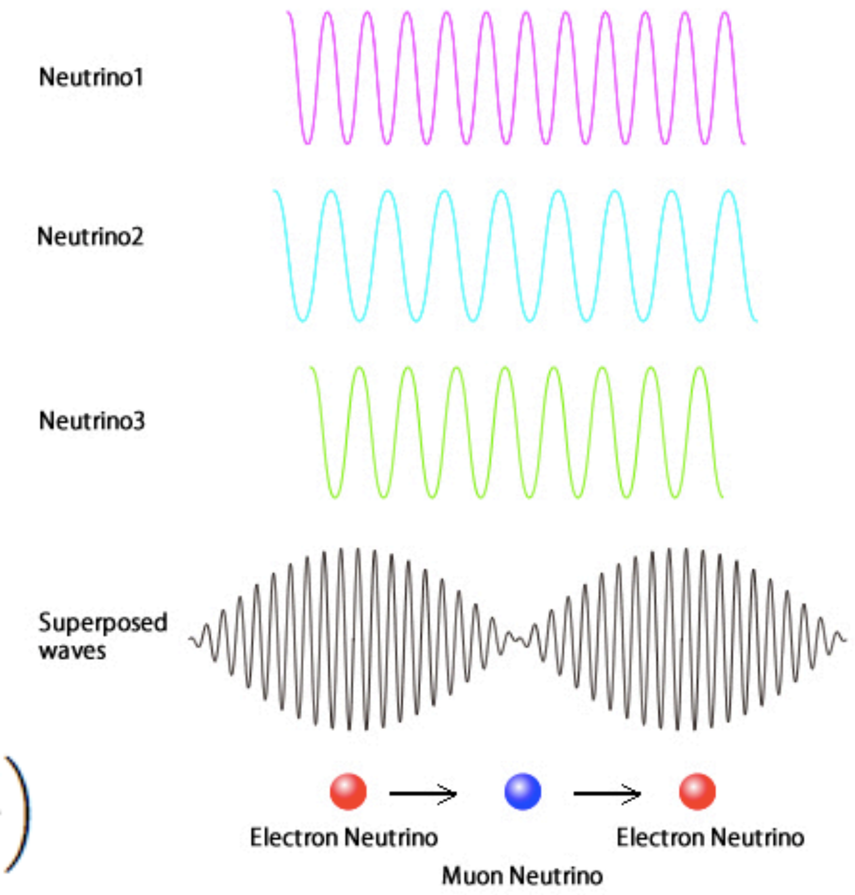
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U_{e1}, U_{e2}, U_{e3}\\ U_{\mu1}, U_{\mu2}, U_{\mu3}\\ U_{\tau1}, U_{\tau2}, U_{\tau3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} = U_{\rm MNS}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$$\begin{aligned} U_{\rm MNS} &= U_{23}U_{13}U_{12} \\ &= \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{+i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\end{aligned}$$

where $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$.

$$P\left(\nu_\alpha \to \nu_\beta\right) = \left|\sum_i U^*_{\alpha i} e^{-im_i^2 \frac{L}{2E}} U_{\beta i}\right|$$

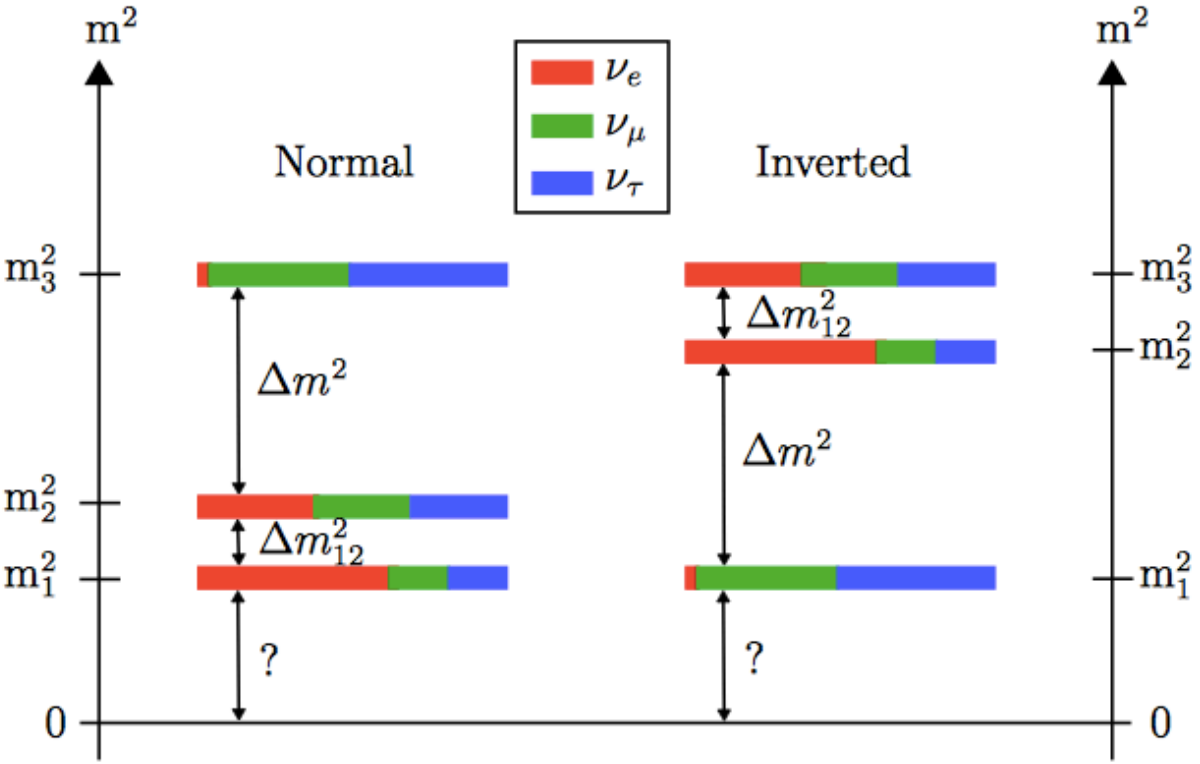
$$P\left(\nu_\alpha \to \nu_\beta\right) = \sin^2(2\theta_{ij})\sin^2\left(\boxed{\Delta m^2_{ij}}\frac{1.27L}{E}\right)$$

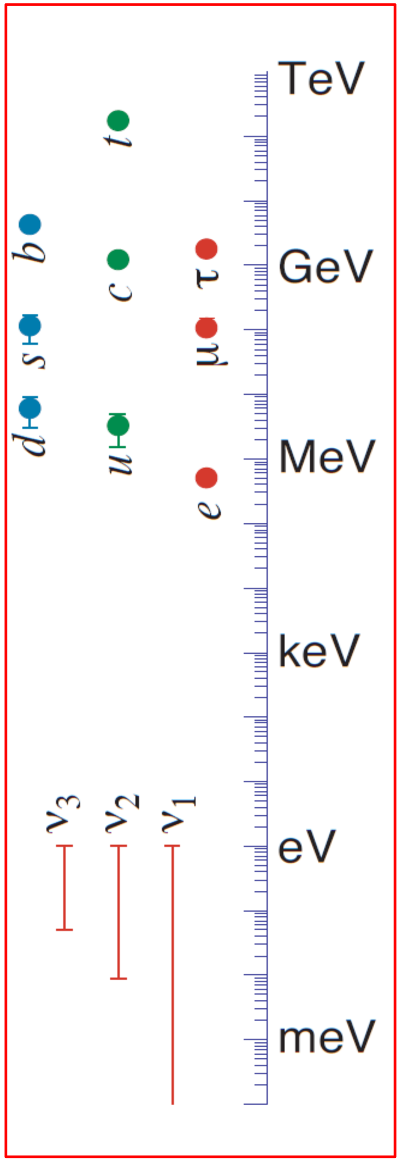


http://www.hyper-k.org/en/img/waves.jpg

Neutrino Masses

- Oscillations probe Δm^2
- Remaining Questions:
  - Why is $m_\nu << m_{quark}$?
  - Mass Ordering – sign of Δm_{23}
  - Absolute Mass Scale

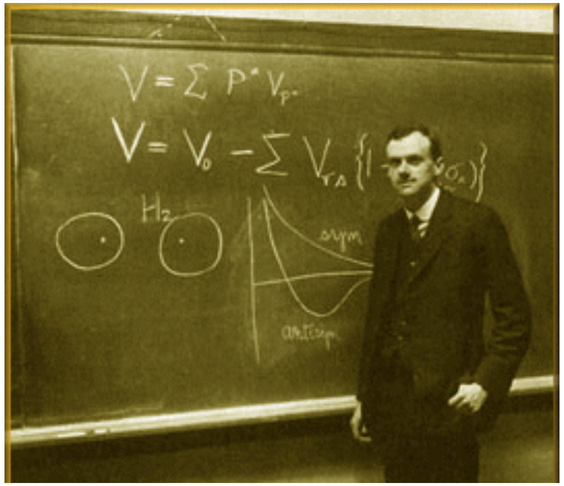




Neutrino Nature

Dirac Particle

- Requires unnaturally small coupling to Higgs field to explain small neutrino masses
- Right handed neutrinos not observed



$$\mathcal{L} = -m_D \bar{\nu}_L \nu_R + h.c.$$

Majorana particle

neutrino = antineutrino

Violates L conservation

- Small masses explained by the see-saw mechanism

$$\mathcal{L} = -m_M \bar{\nu}_R^c \nu_R + h.c.\,,$$

$$\nu_R^c = i\gamma^2 \nu_R^*\,,$$

$$\mathcal{M} = \begin{pmatrix} 0 & m_D \\ m_D & m_M \end{pmatrix}$$

Neutrino Nature

Dirac Particle

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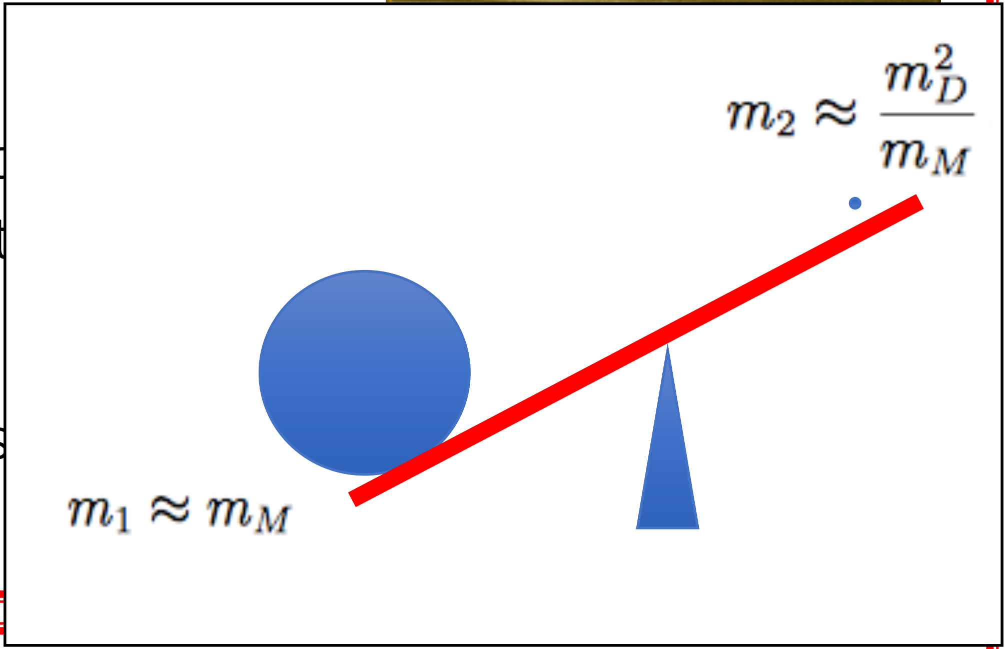

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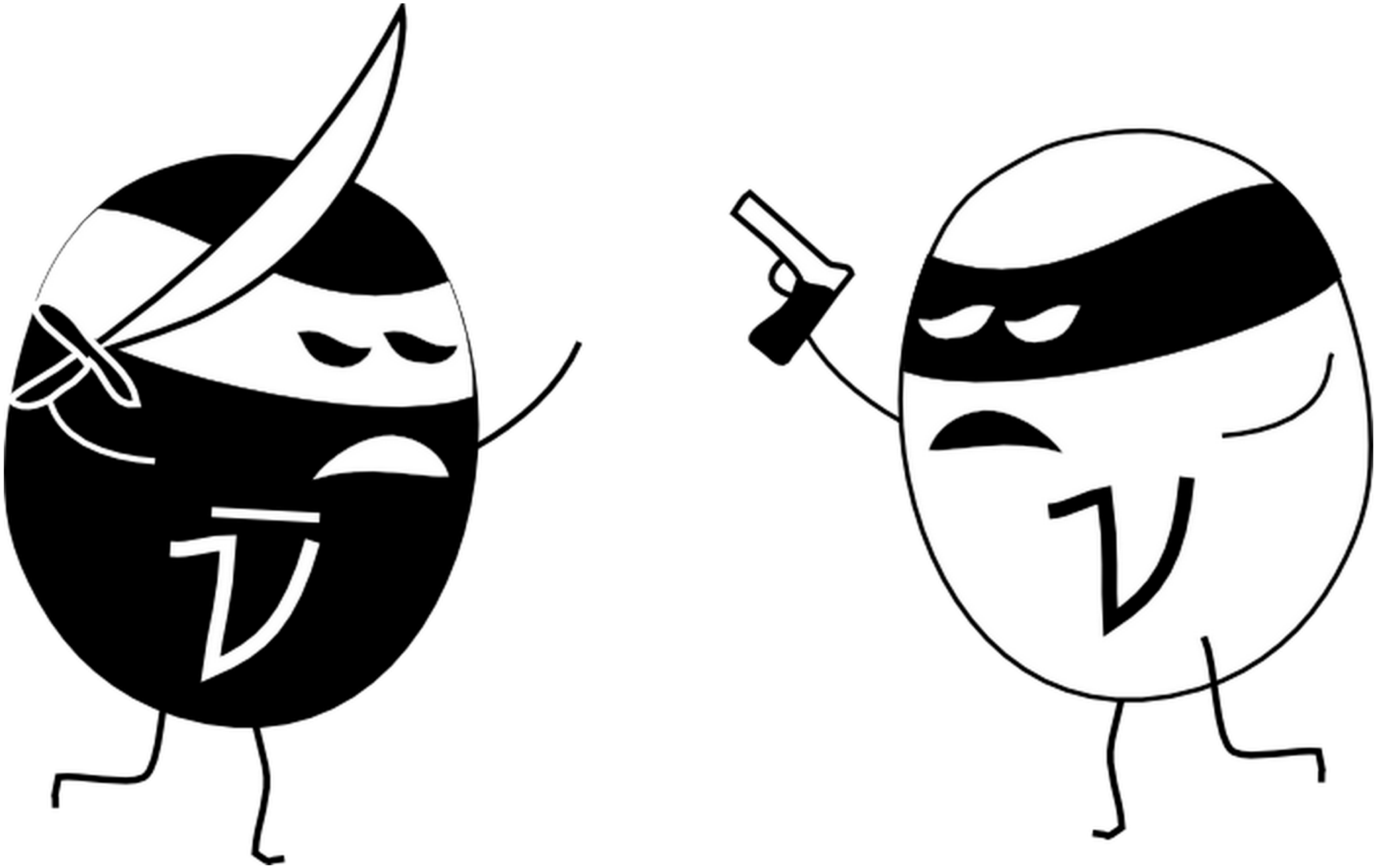
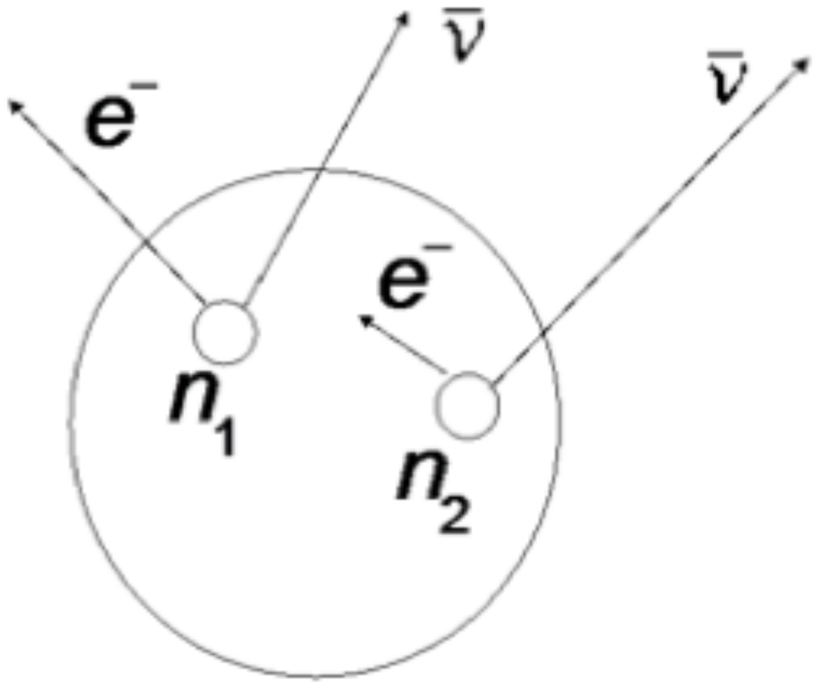
Neutrinoless Double Beta Decay

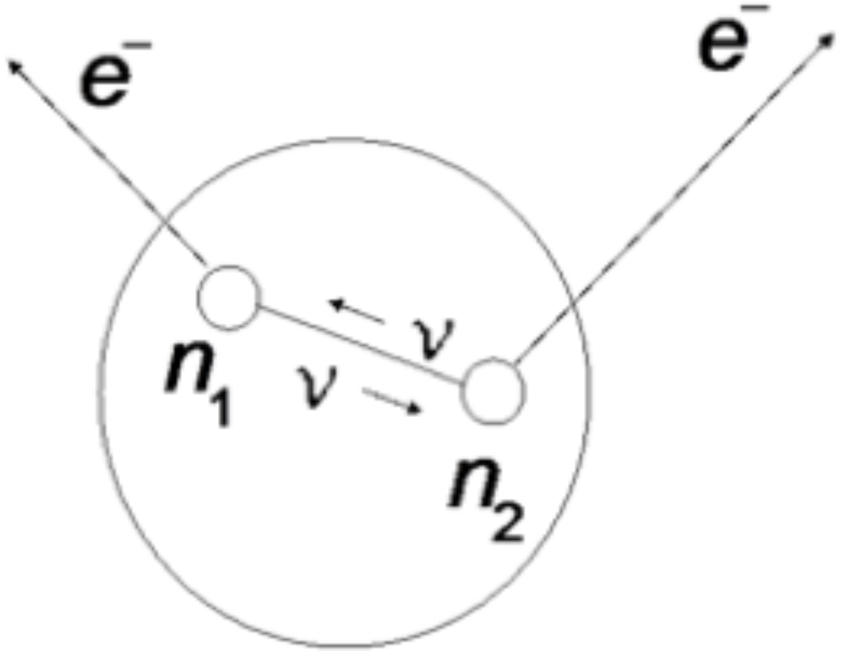


Neutrinoless Double Beta Decay

$(A,Z) \rightarrow (A,Z+2) + 2\,e^- + 2\nu_e$



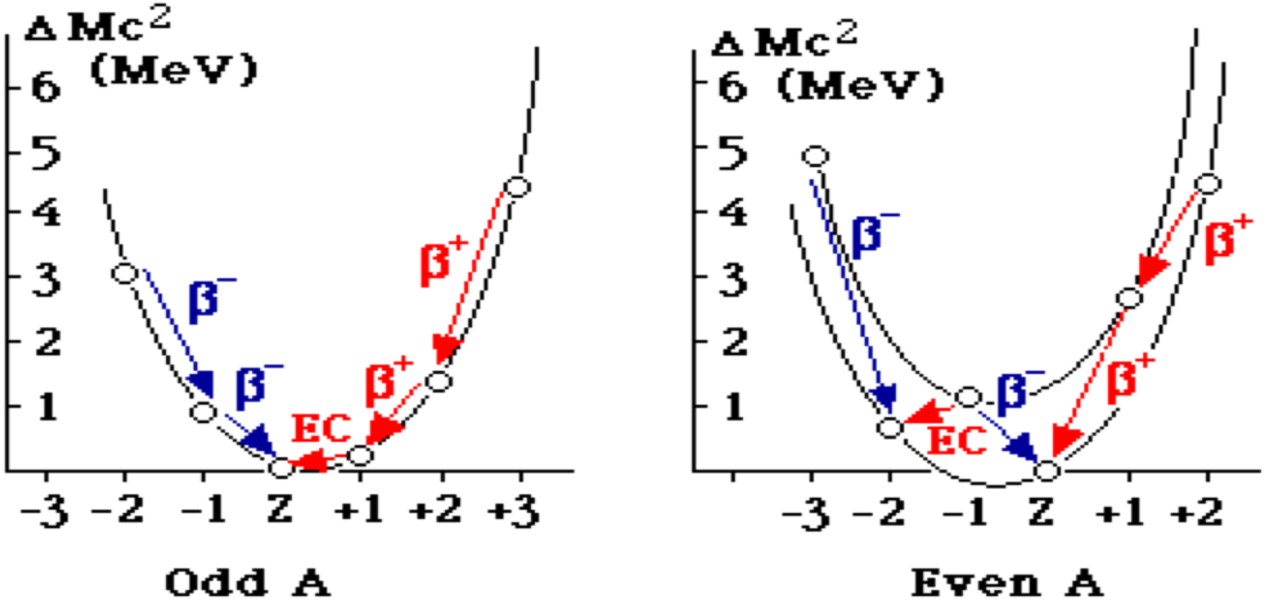
2νββ



0νββ

$(A,Z) \rightarrow (A,Z+2) + 2\,e^-$

Double Beta Decay



Only occurs for 35 known isotopes

$$m = Zm_p + (A - Z)m_n - E_B$$

Semi-empirical mass formula

$$\delta(A,Z) = \begin{cases} +\delta_0 & Z, N \text{even } (A \text{ even}) \\ 0 & \text{A odd} \\ -\delta_0 & Z, N \text{ odd } (A \text{ even}) \end{cases}$$

Binding energy

$$E_B = a_V A - a_S A^{2/3} - a_C \frac{Z(Z-1)}{A^{1/3}} - a_A \frac{(A-2Z)^2}{A} + \delta(A,Z)$$

Volume term

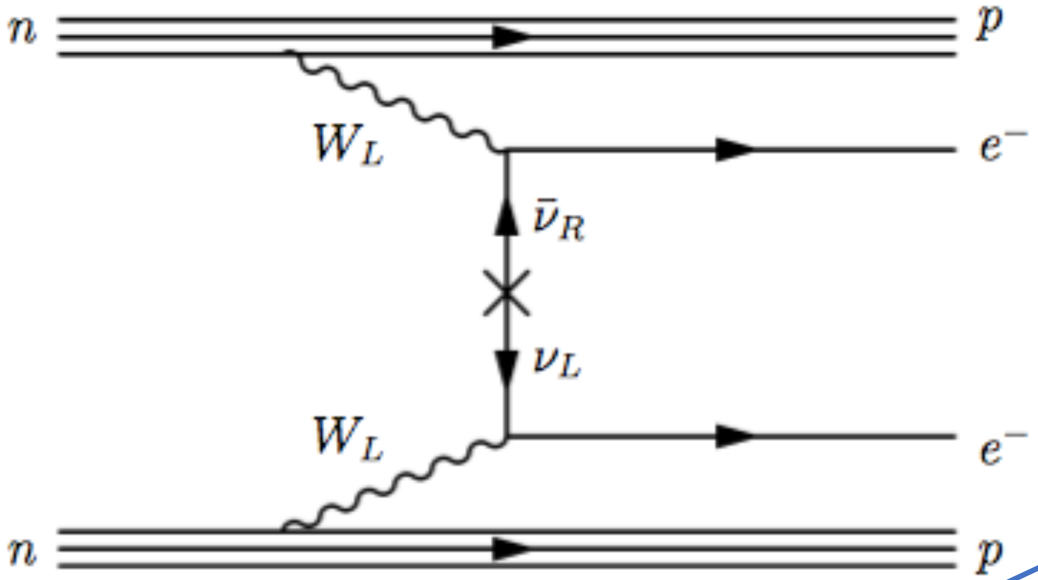
Surface term

Coulomb term

Asymmetry term

Pairing term

Majorana mass



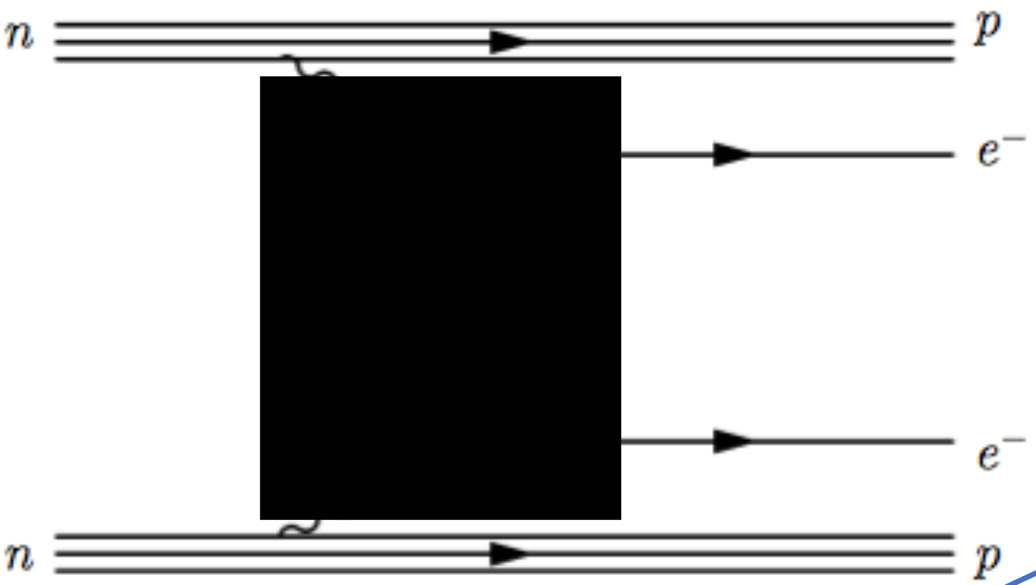
Nuclear Matrix Elements

$$\left(t_{0\nu}^{1/2}\right)^{-1} = G^{0\nu} g_A^4 \left|M^{0\nu}\right|^2 \langle m_{\beta\beta}\rangle^2$$

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

Phase space factor $\propto Q_{\beta\beta}^5$

Majorana mass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Nuclear Matrix Elements

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

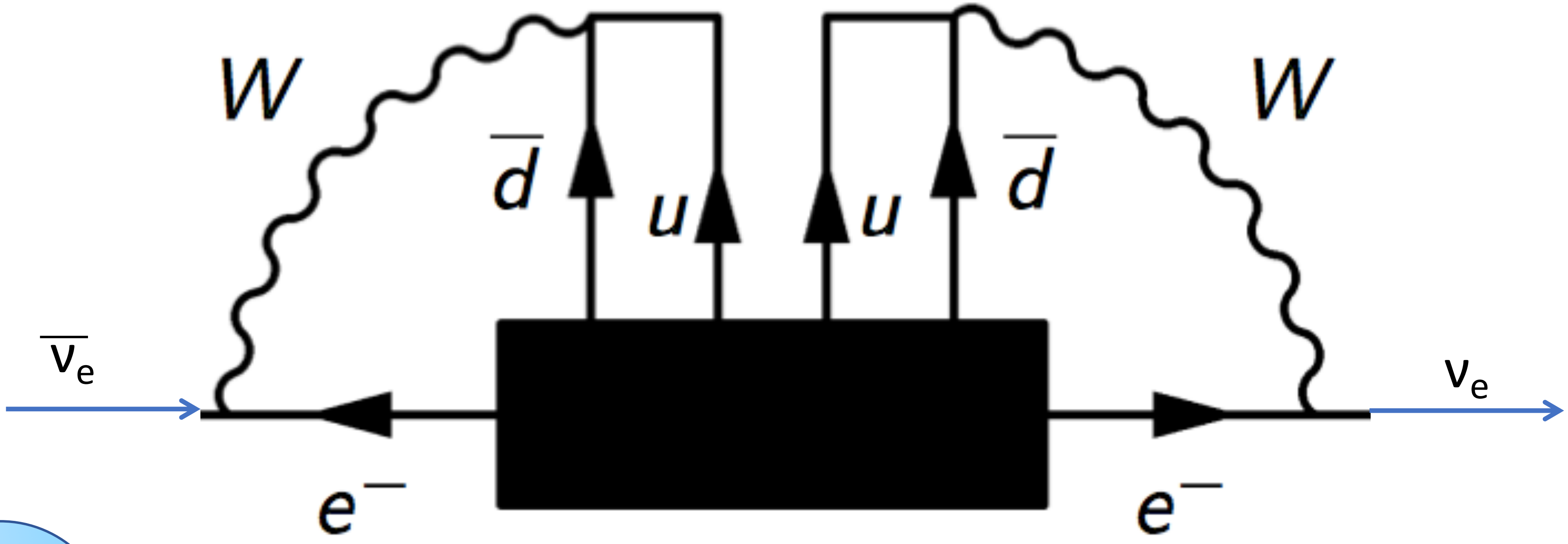
Phase space factor $\propto Q_{\beta\beta}^5$

Other mechanisms for 0νββ

- R-parity violating supersymmetry
- Left-right extensions of standard model

Schechter Valle Theorem

- The existence of any 0νββ mode would imply an effective Majorana mass term



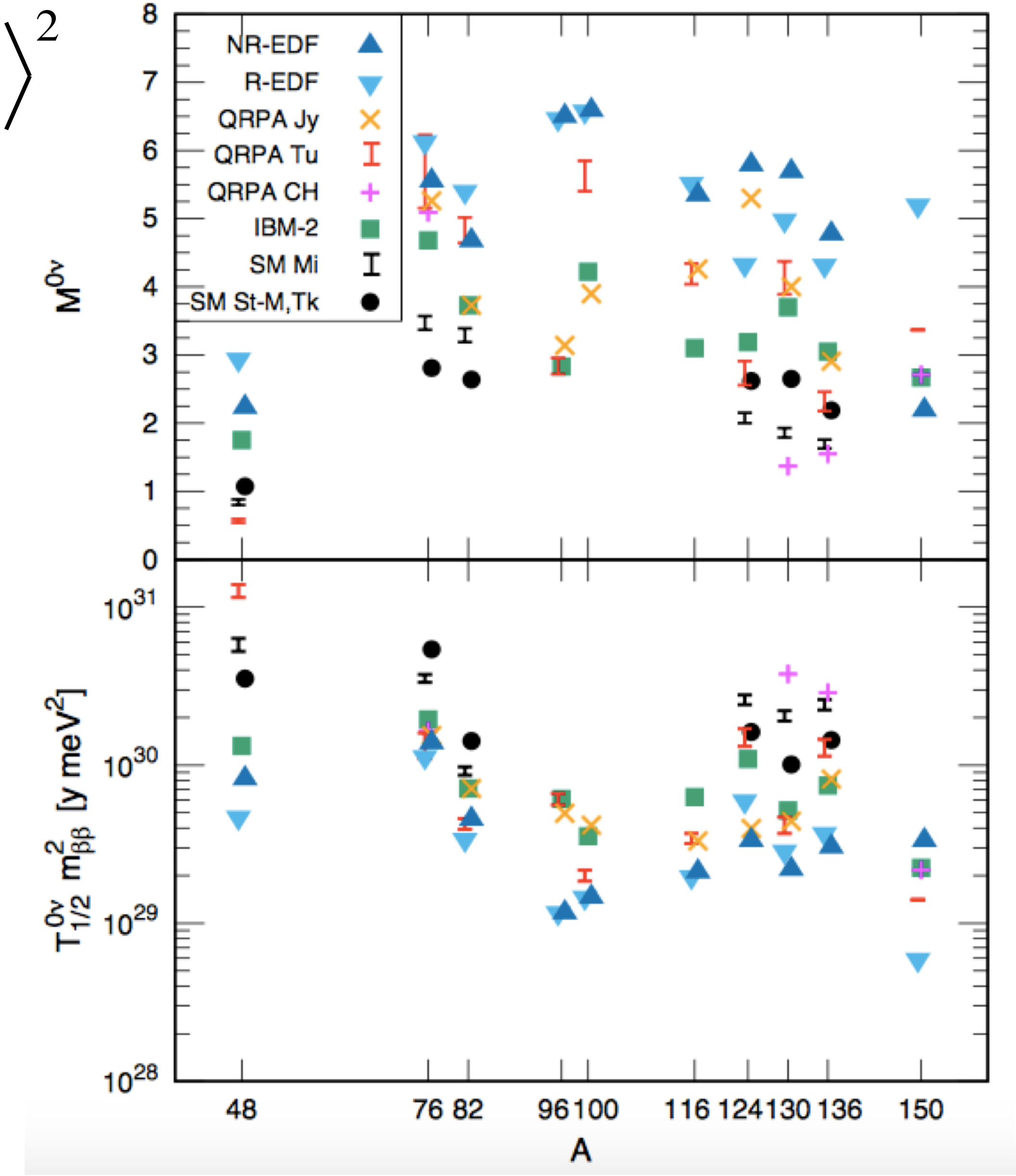
Nuclear matrix elements

$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu} \cdot \left|M^{0\nu}\right|^{2} \cdot \langle m_{\beta\beta} \rangle^{2}$$

Phase space

Nuclear Matrix Element

- Many bodied calculation – relies on models
- Factor 2-3 uncertainty
- Propagates into uncertainty on neutrino mass



[arXiv:1610.06548](https://arxiv.org/abs/1610.06548)

Neutrinoless Double Beta Decay

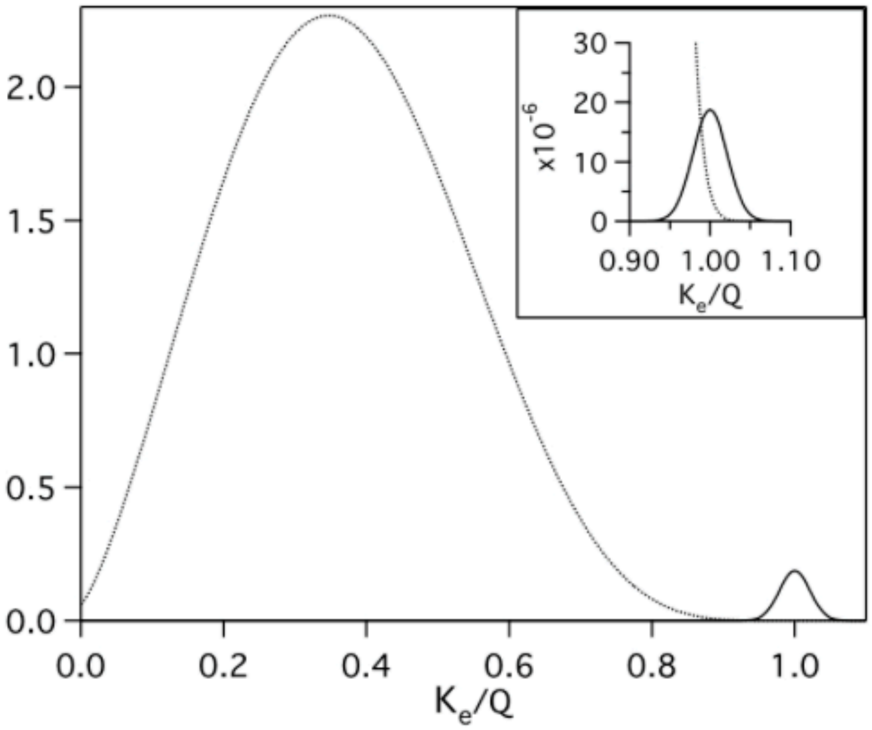
$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu} \cdot \left|M^{0\nu}\right|^2 \cdot \langle m_{\beta\beta} \rangle^2$$

Phase space

Nuclear Matrix Element

$$\langle m_{\beta\beta} \rangle^2 = |\sum_i U_{ei}^2 m_{\nu_i}|^2$$

Sum of the electron kinetic energies, normalized to the endpoint Q.

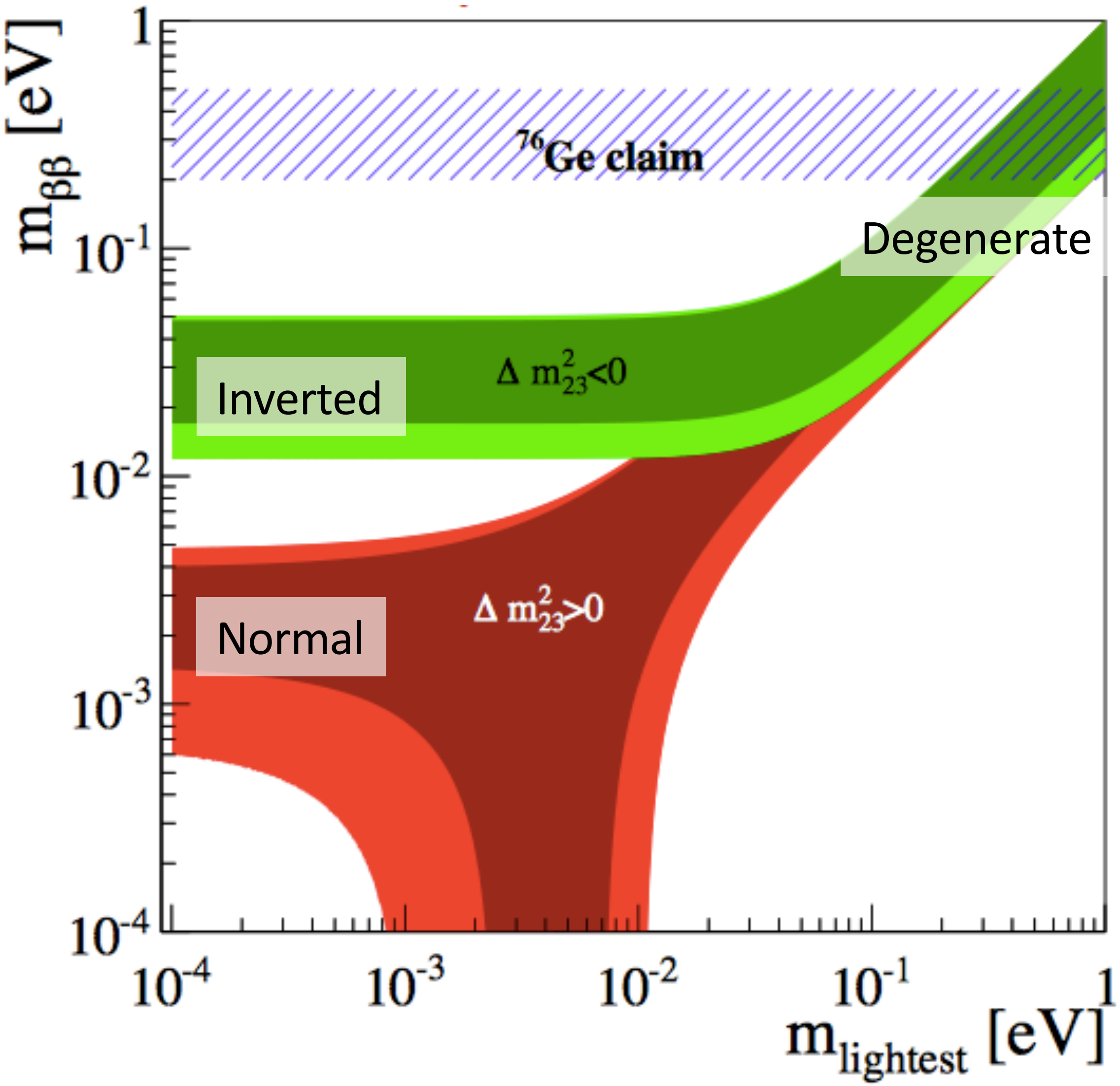


<u>Experiment options</u>

- Select isotopes with favourable **phase space**
- Select isotopes with favourable **matrix elements**
  - Beware large uncertainty / differences between models
- Select isotopes with large **abundance** or good enrichment opportunity
- Good **energy resolution**
- Low **Backgrounds** in region of interest (ROI)

Experimental Sensitivity

0νββ limits



~10kg

~100kg

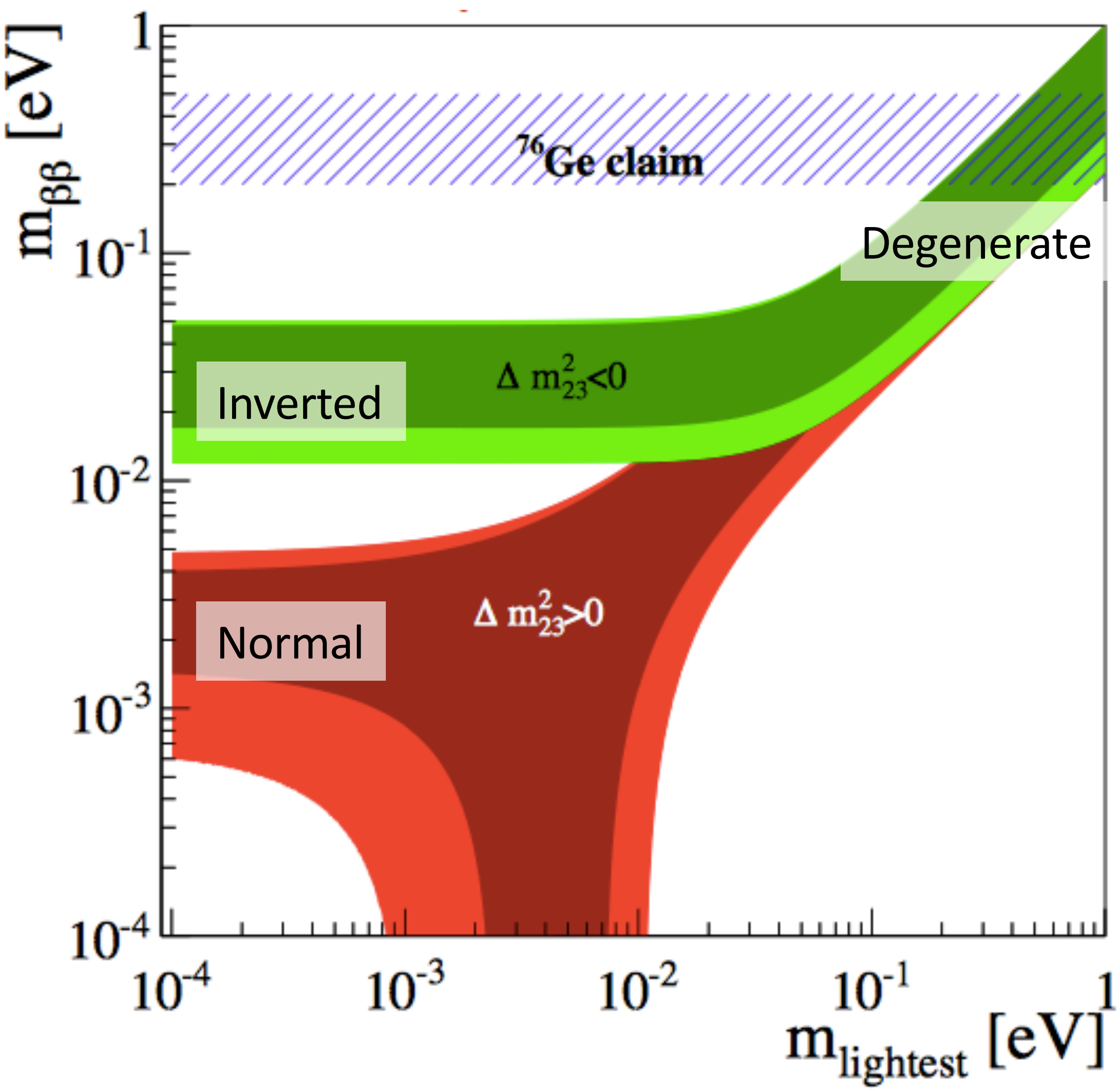
~1000kg

~10000+kg!

$$m_{\beta\beta} = \left|\sum_i m_i \cdot U_{ie}^2\right|$$

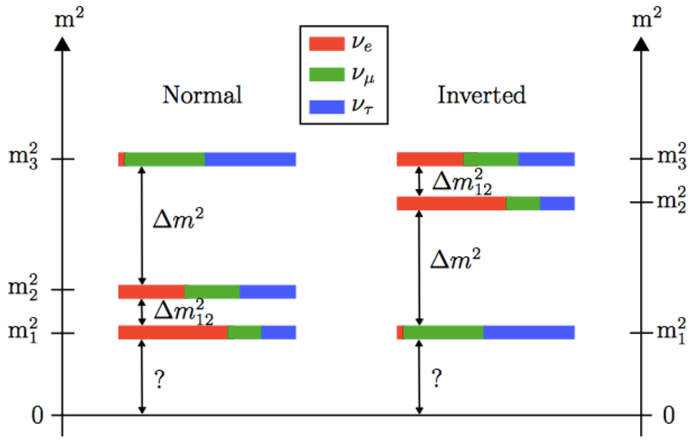
Cosmology

Experimental Sensitivity



~10kg

~100kg



$$m_{\beta\beta} = \left|\sum_i m_i \cdot U_{ie}^2\right|$$

Backgrounds

- Source = Detector
  - Limits ‘passive’ material and associated background contributions
- Source + Detector
  - Ability to swap isotope, overcome technology limitations

$$T_{1/2} \propto a \cdot \epsilon \sqrt{\frac{M \cdot t}{\Delta E \cdot B}}$$

Backgrounds scale with detector mass

$$T_{1/2} \propto a \varepsilon M t$$

Background free

$$\widehat{T^{0\nu\beta\beta}_{1/2}}(n_\sigma) = \frac{\ln 2}{n_\sigma} \cdot N \cdot \epsilon \cdot \frac{\sqrt{t}}{\sqrt{(b \cdot M + c)\delta E}}$$

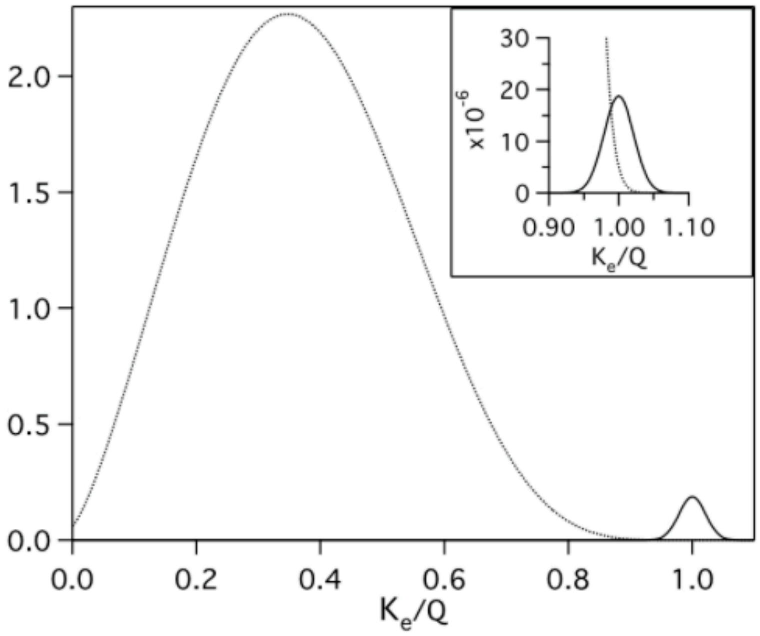
Scaling backgrounds

Constant backgrounds

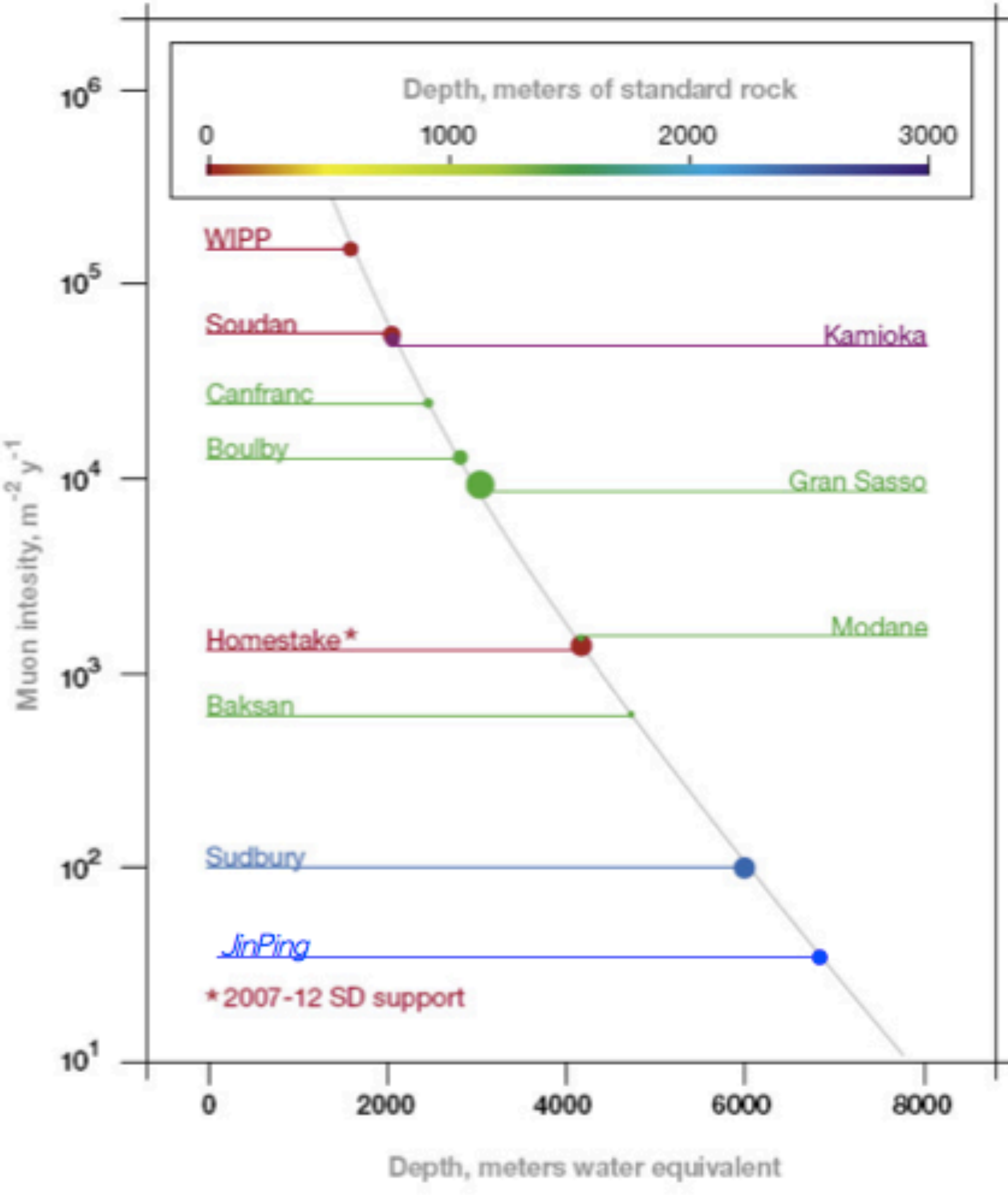
Background sources

- Looking at Q-values ~2-4MeV range
- Intrinsic radioactive isotopes in detector materials
  - ^{238}U and ^{232}Th chains (highest gamma 2.6MeV)
- Cosmogenic isotopes
  - Longer lived isotopes created by muons, p, n
- Solar Neutrinos
- 2νββ
- + specifics

Sum of the electron kinetic energies, normalized to the endpoint Q.



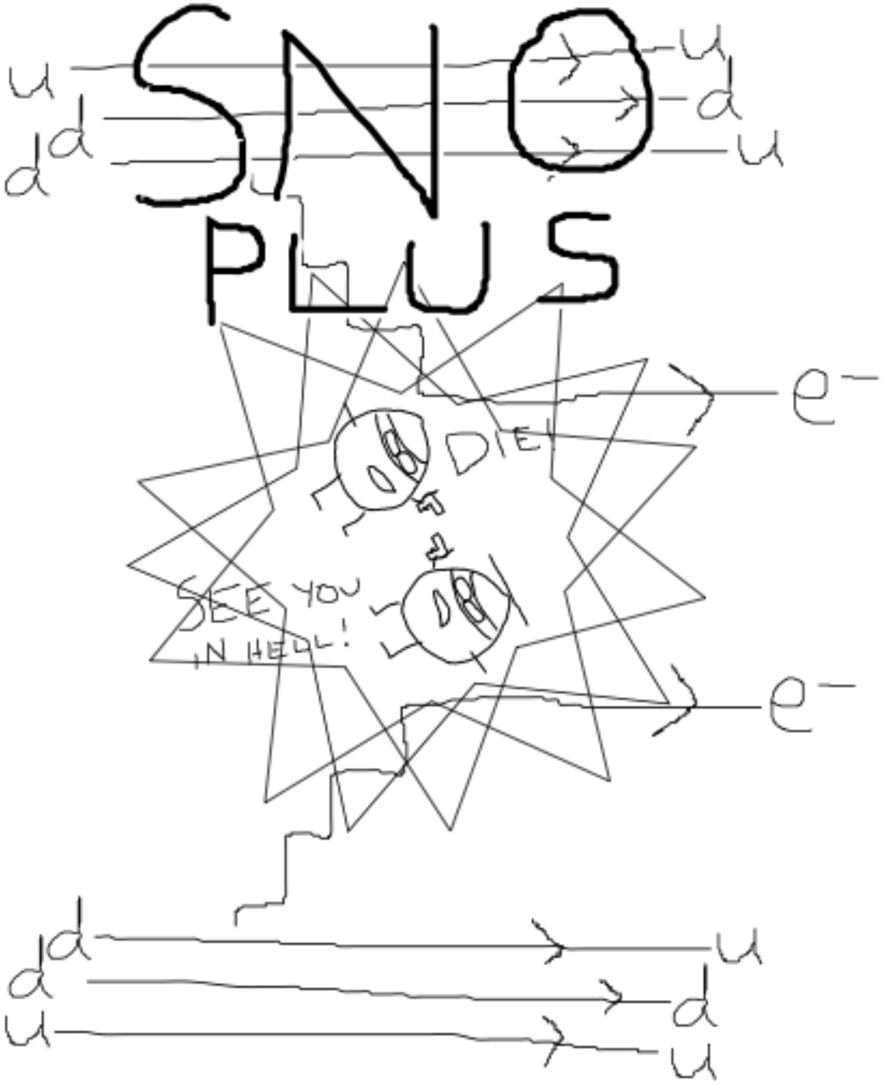
Location



Adapted from http://www.deepscience.org/contents/underground_universe_popup03.shtml

Muon flux = 70 muons/day

Class-2000 clean room lab


SNO
PLUS
u
d
d
u
d
u
DIE!
SEE YOU IN HELL!
e⁻
e⁻
d
d
u
u
d
u

Main goal : 0νββ search

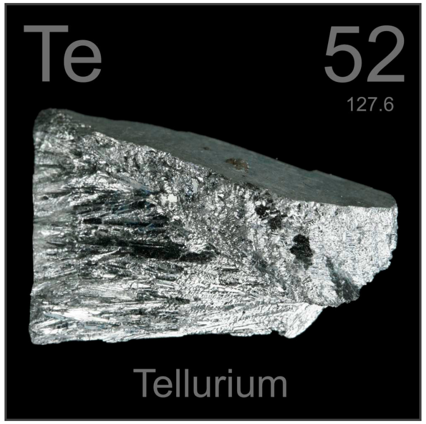
Load large amount of isotope into homogeneous detector

Statistical identification of 0νββ peak over well understood background model

Very low energy background experiment

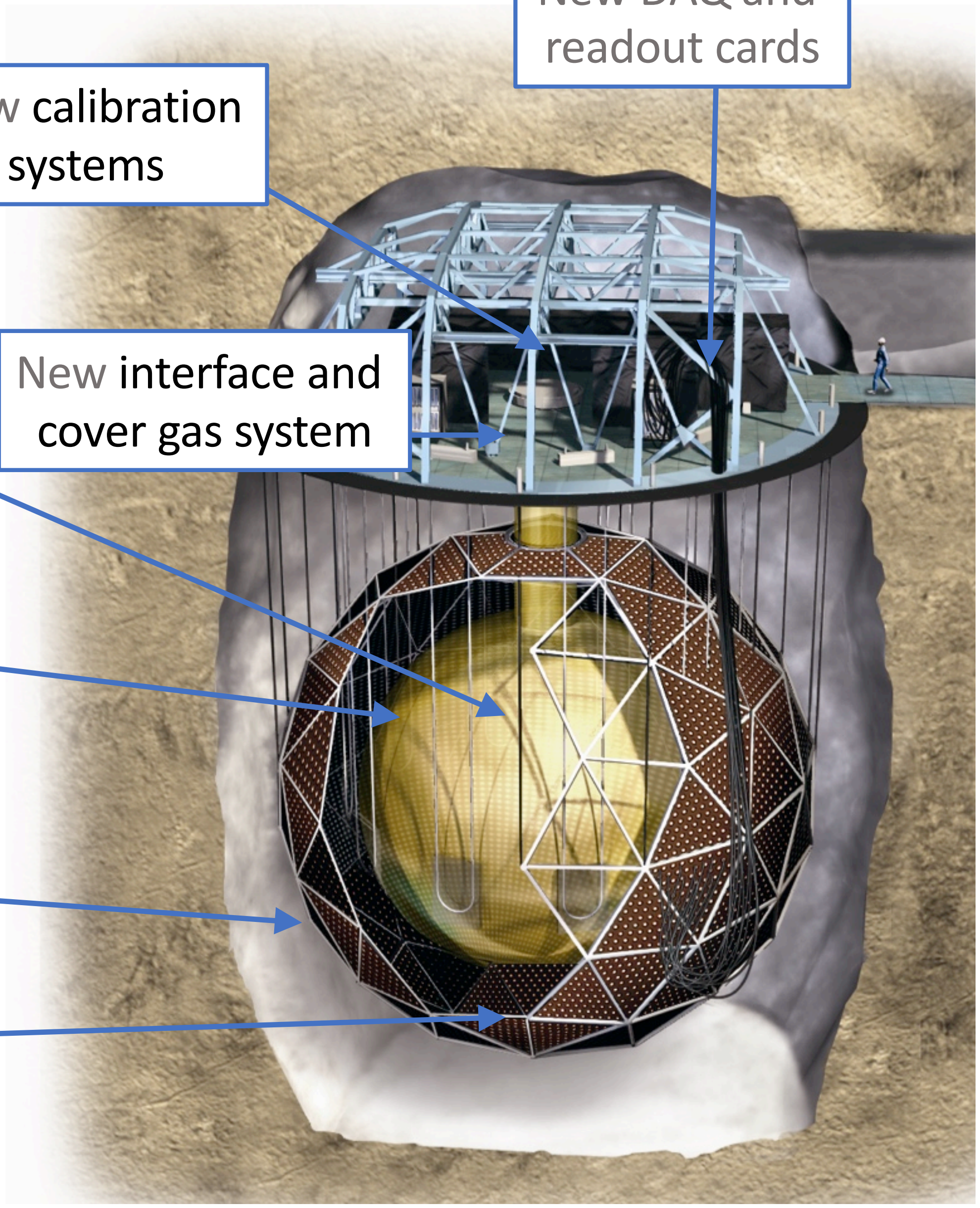
Potential for other physics:

- Solar Neutrinos
- Reactor Neutrinos
- Geo Neutrinos
- SuperNova Neutrinos
- Invisible Nucleon Decay



The SNO+ detector

2km underground in SNOLAB, ~6000 MWE



New DAQ and
readout cards

New calibration
systems

780 tons of
Liquid scintillator

Loaded with 0.5%
double beta decay
Isotope (Te130)

New interface and
cover gas system

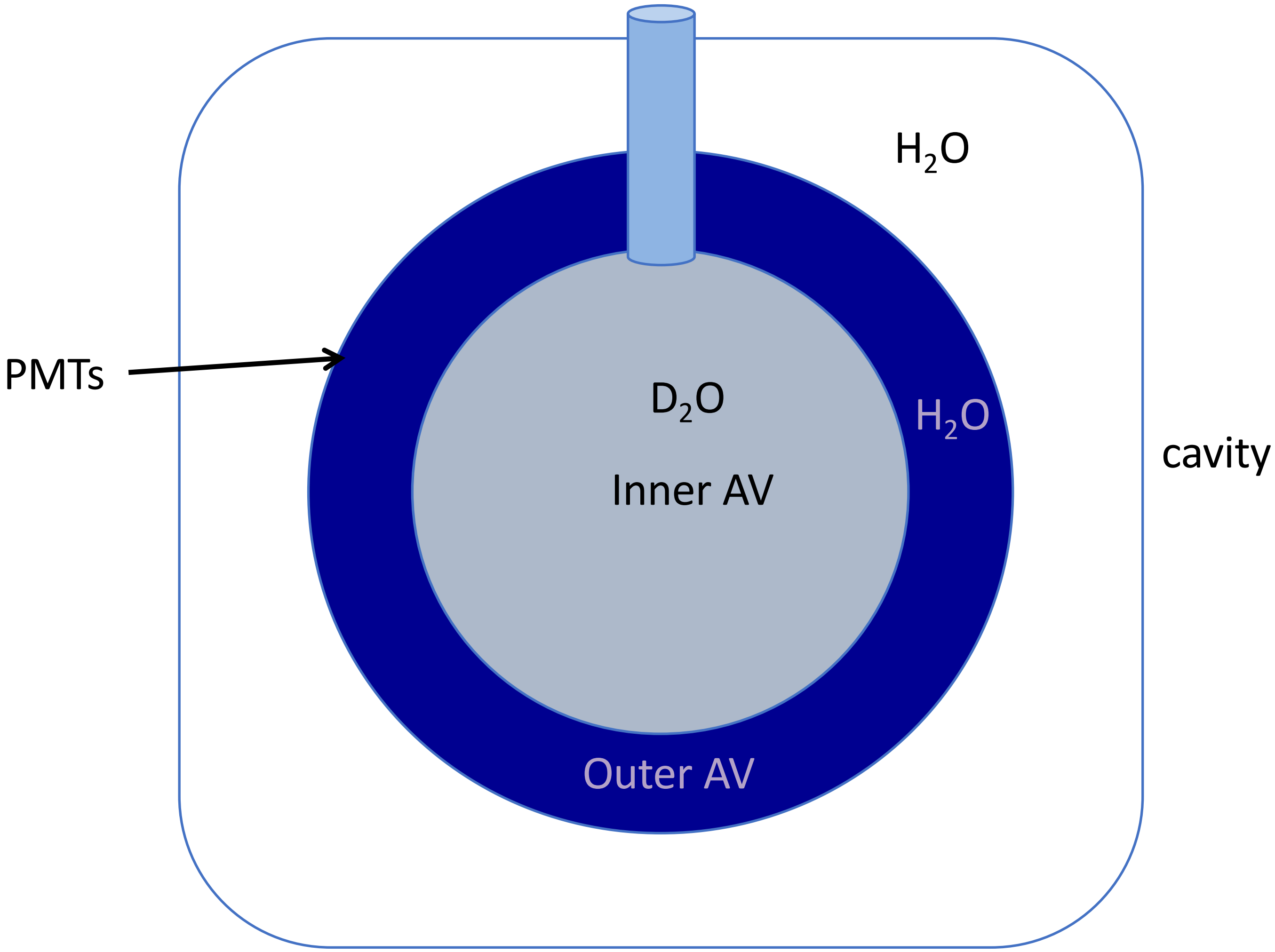
Contained in an
Acrylic vessel (AV)
12 m diameter

Held-down by
new rope system

Shielded by 7 kT
Ultra-pure water

Viewed by **~9500 PMTs** (8”)
mounted on 17 m diam. Structure

SNO



H$_2$O

PMTs

D$_2$O

Inner AV

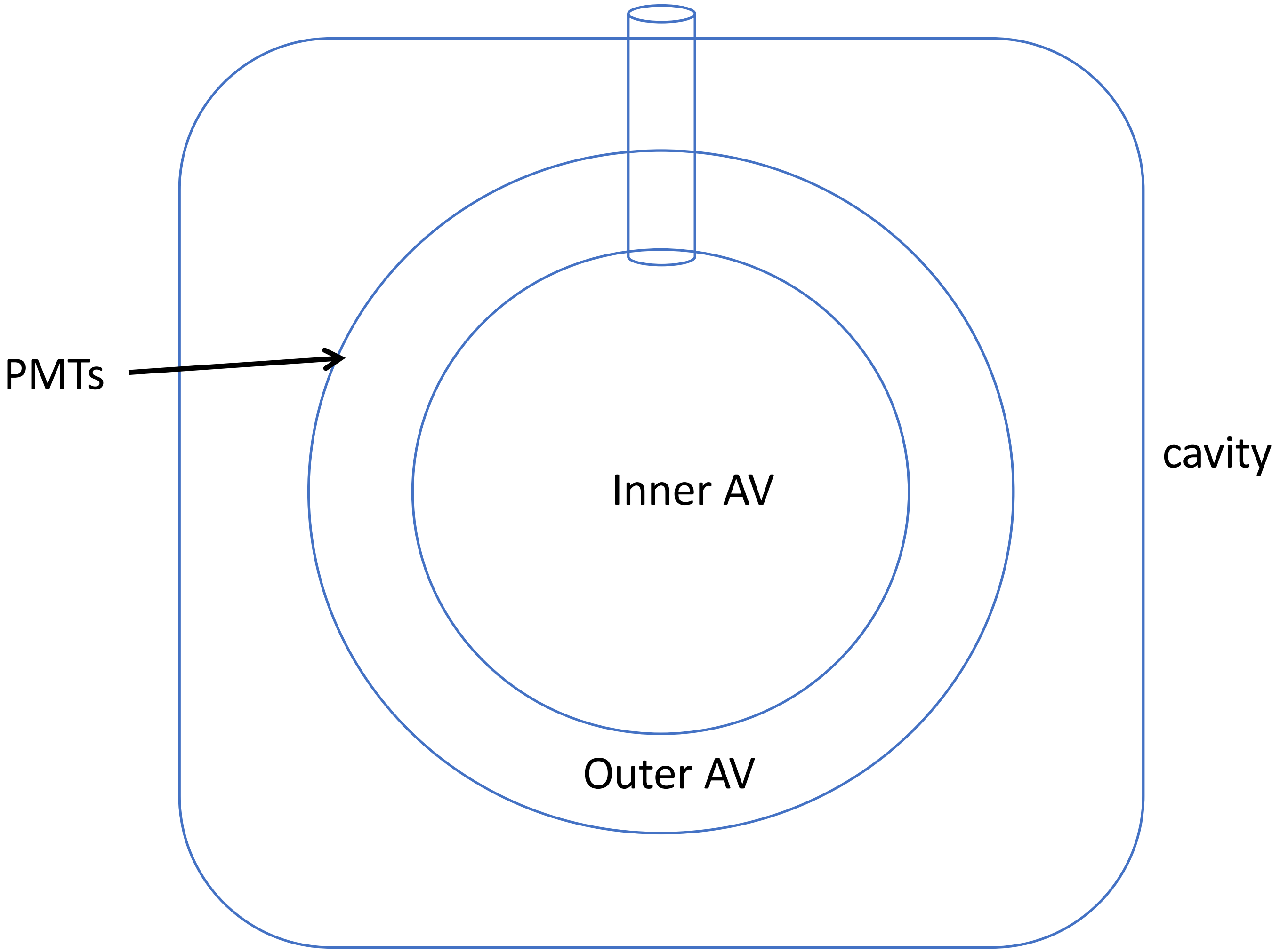
H$_2$O

cavity

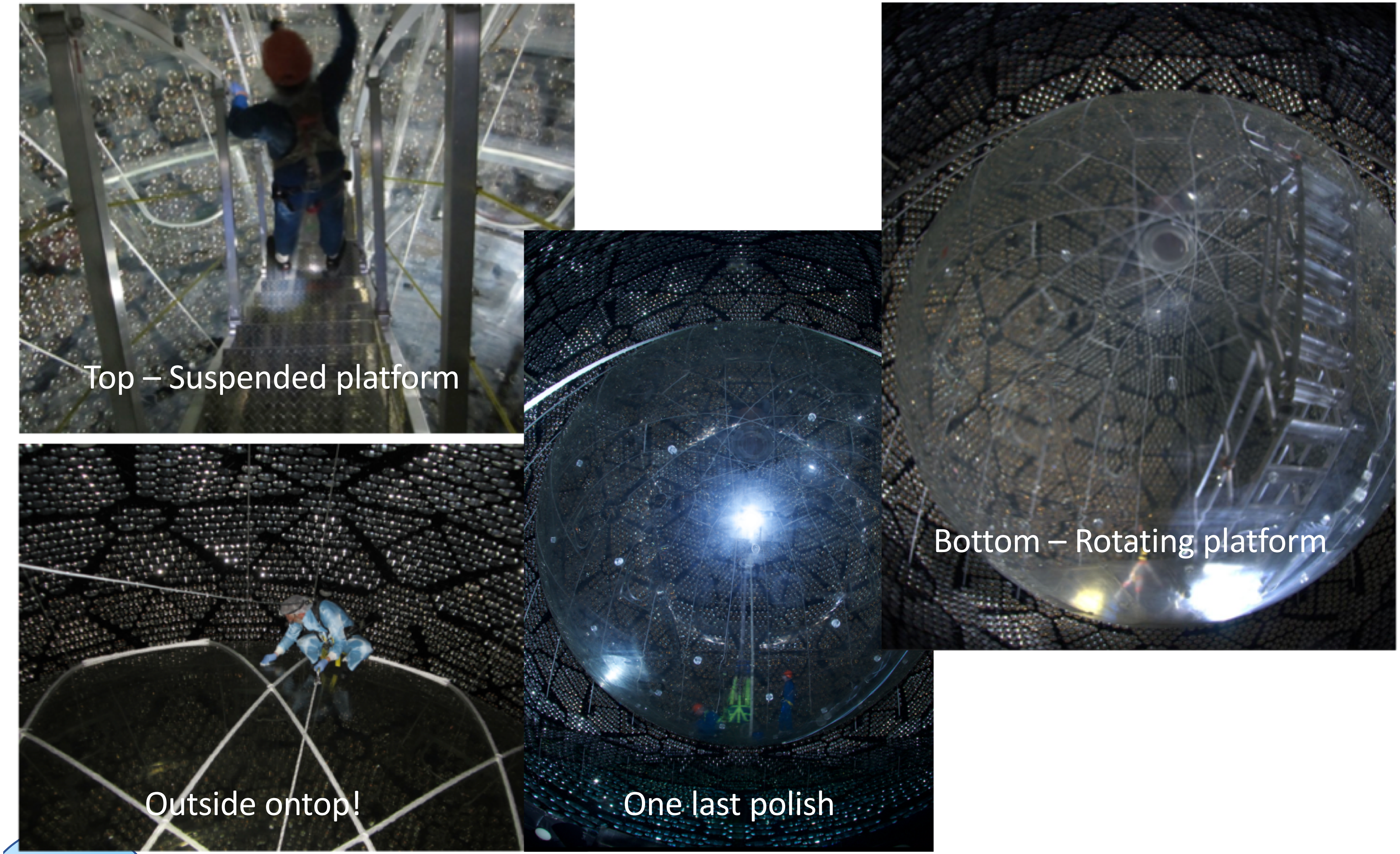
Outer AV

Filling SNO+

- After SNO – empty



AV cleaning



Top – Suspended platform

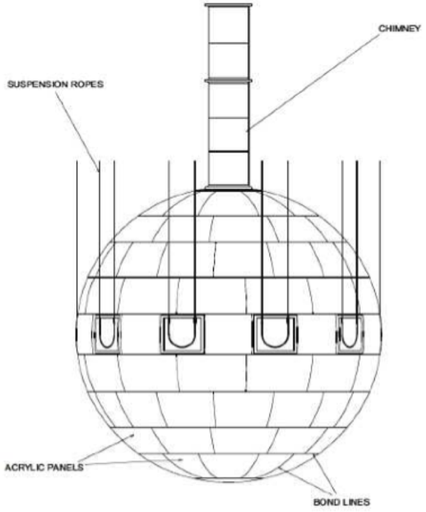
Bottom – Rotating platform

Outside ontop!

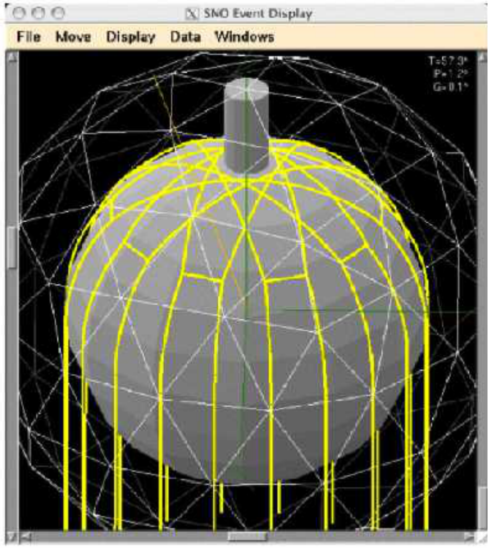
One last polish

New rope system

SNO ropes



SNO+ rope net

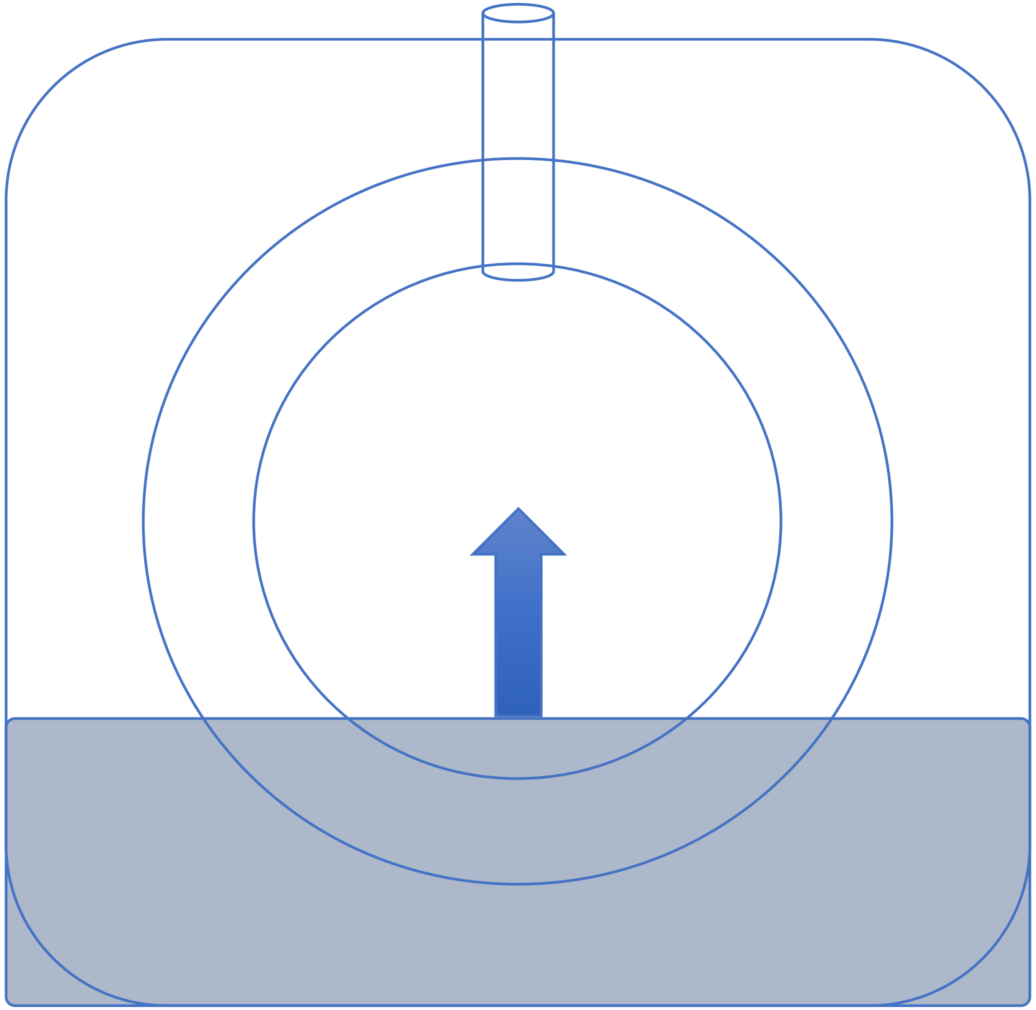


Installed before water fill

Successfully tested the hold-down rope net, by letting cavity water go above level inside AV, applying a 280,000 lb load (127 tons, the full load) to the rope net.

Filling SNO+

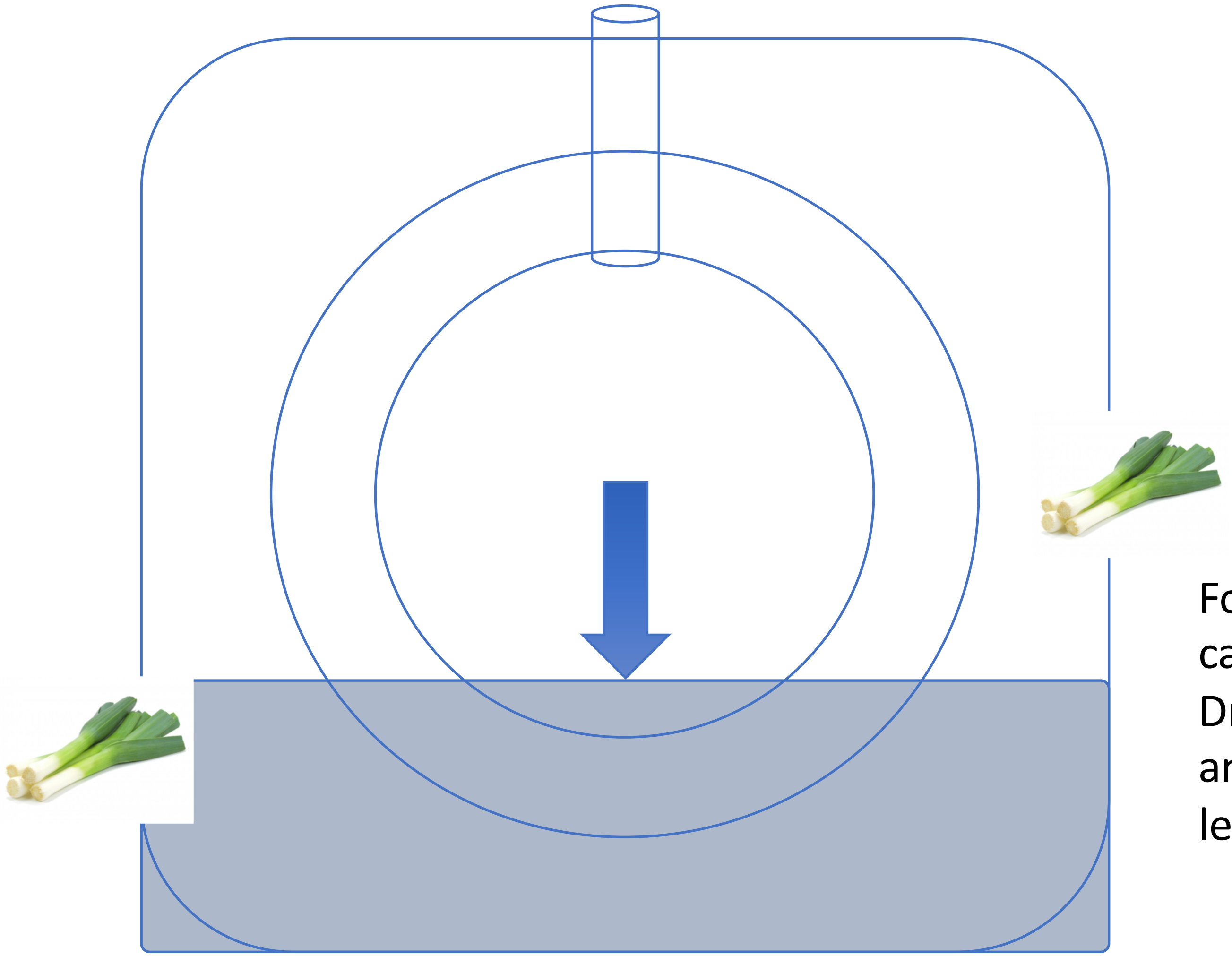
- Phase 0 – water fill



Fill inner and outer Volumes with UPW simultaneously

Filling SNO+

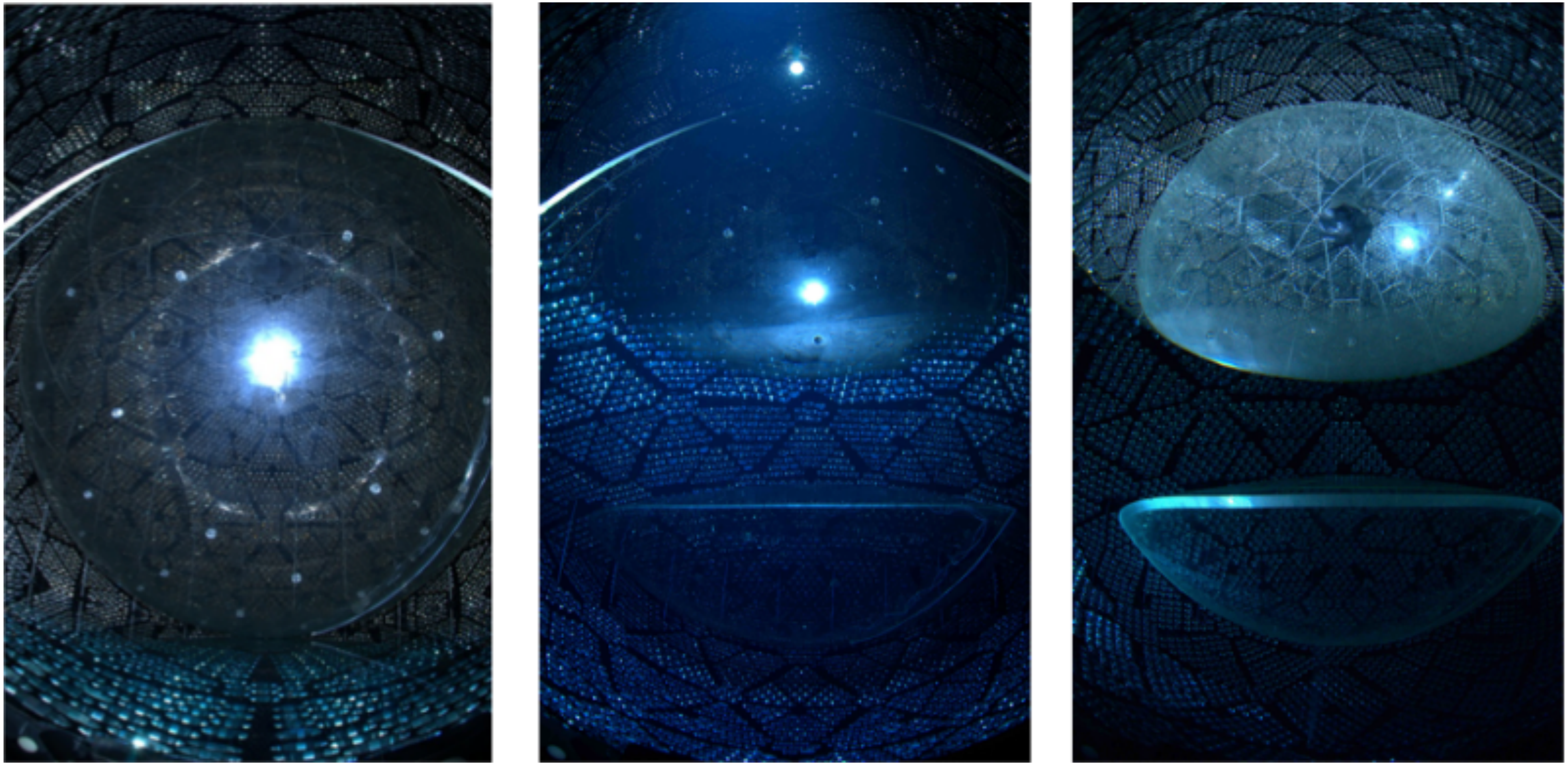
- Phase 0 – water fill



Found leaks in cavity liner ☹
Drain to find and repair leaks

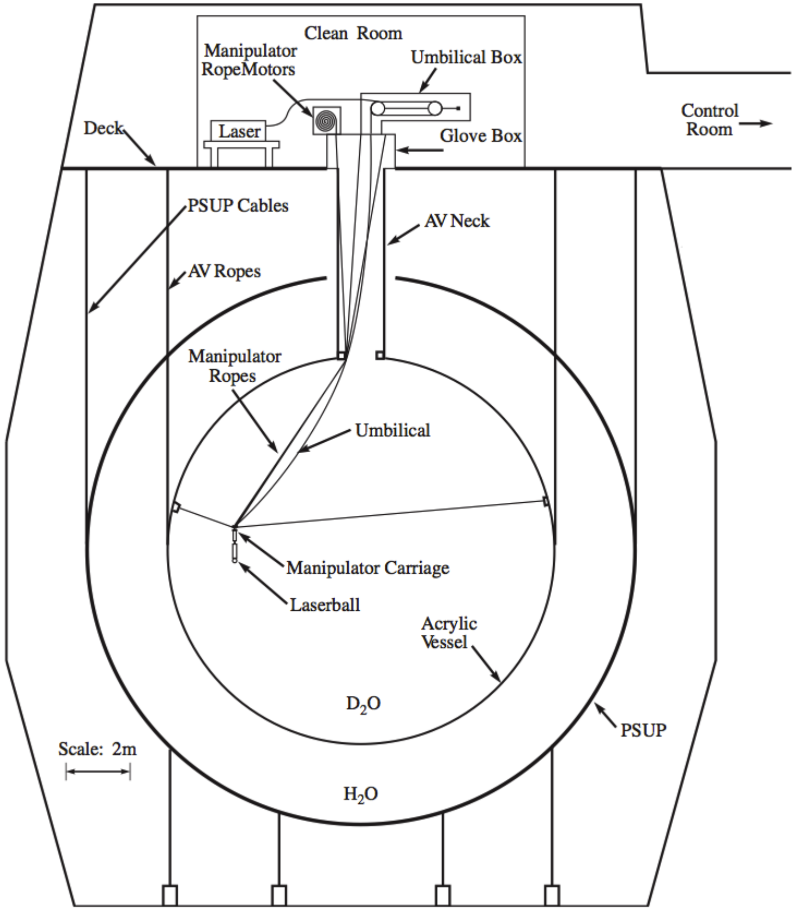
Water Filling

- Boating trips to install new calibration system



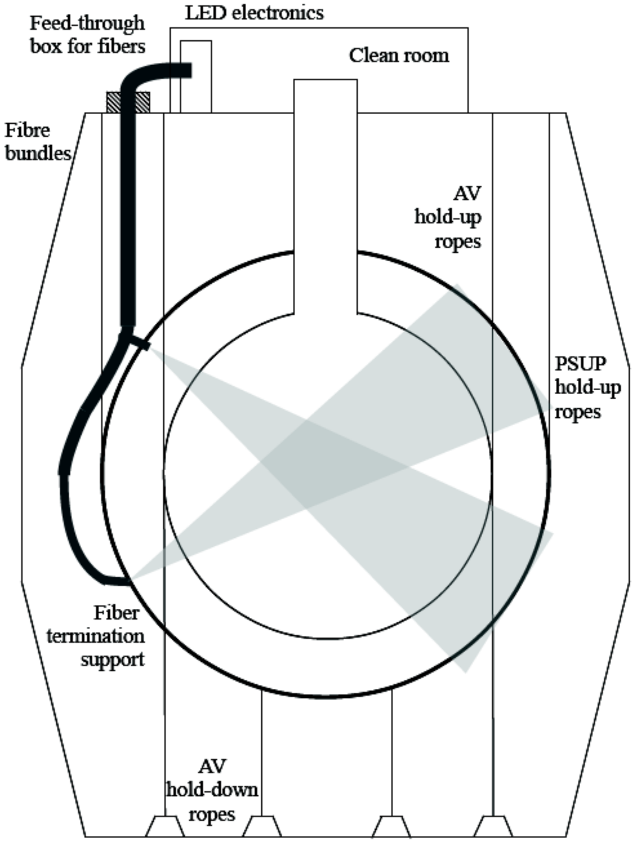
New Calibration systems

SNO: Deployed sources



SNO+: External source

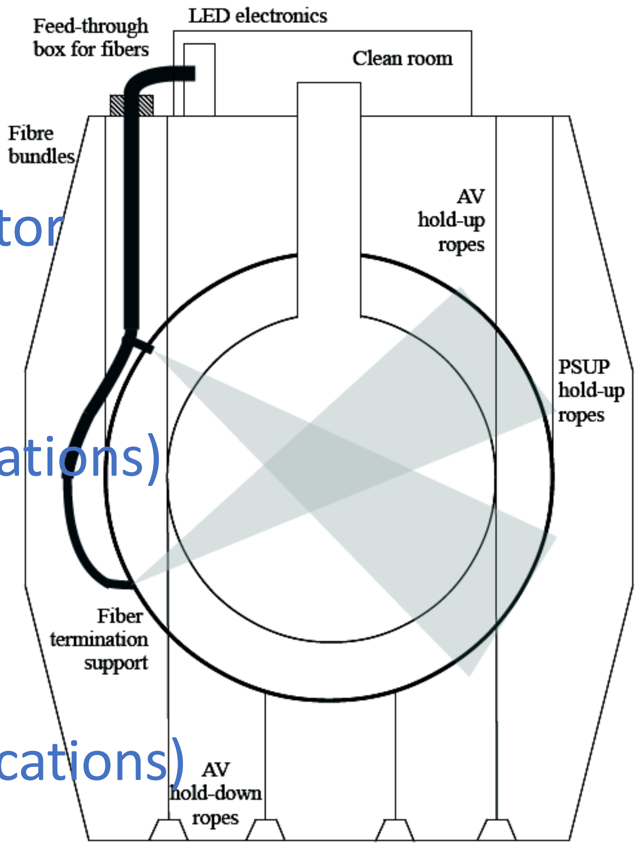
Embedded LED/Laser Light Injection Entity (ELLIE)



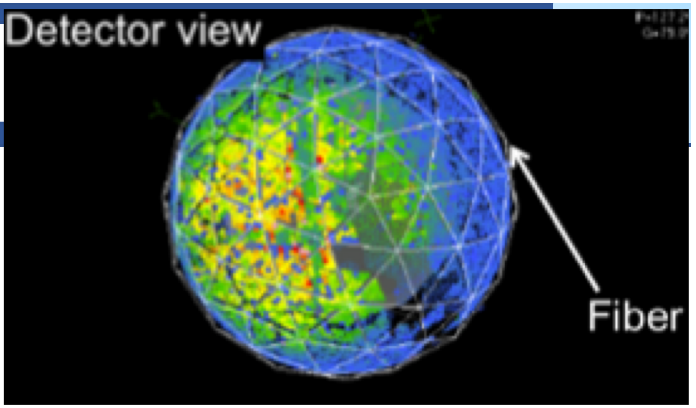
New calibration systems: ELLIE

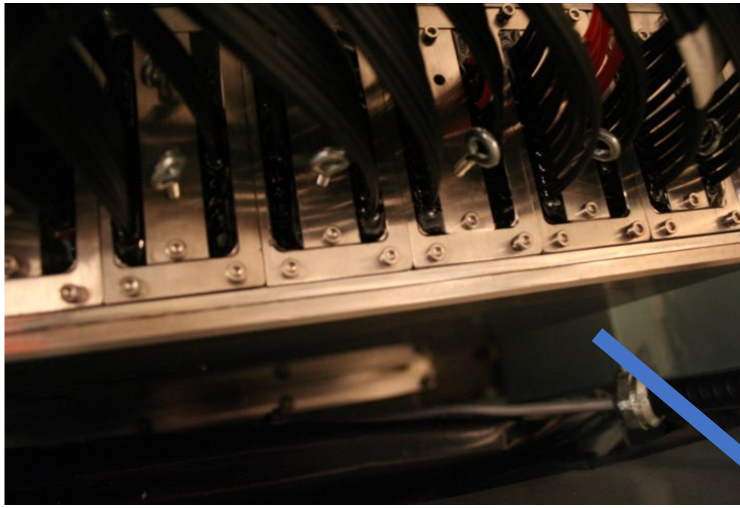
Will provide continuous calibrations throughout SNO+ operation

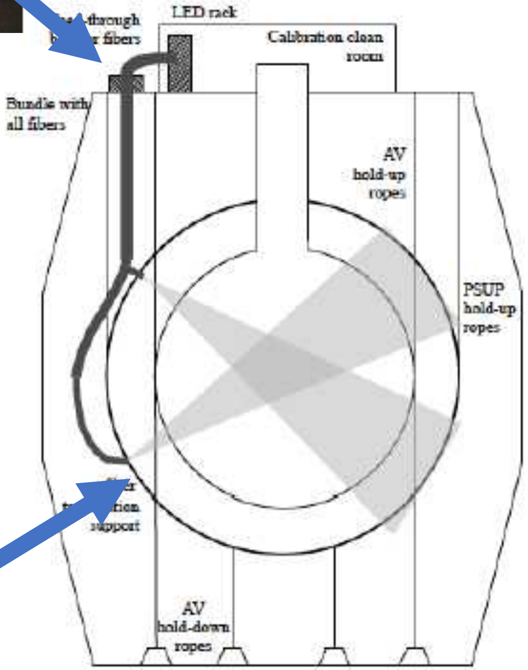
- Timing (T)ELLIE:
  - 91 injection positions
  - Monochromatic (~520nm) from LEDs
  - Light coverage of entire inward-facing detector
- Scattering module (SM)ELLIE
  - 12 injection points (three at each of four locations)
  - Multiple wavelengths from lasers
- Attenuation module (AM)ELLIE
  - Eight injection points (two at each of four locations)
  - Multiple wavelengths (tbc)

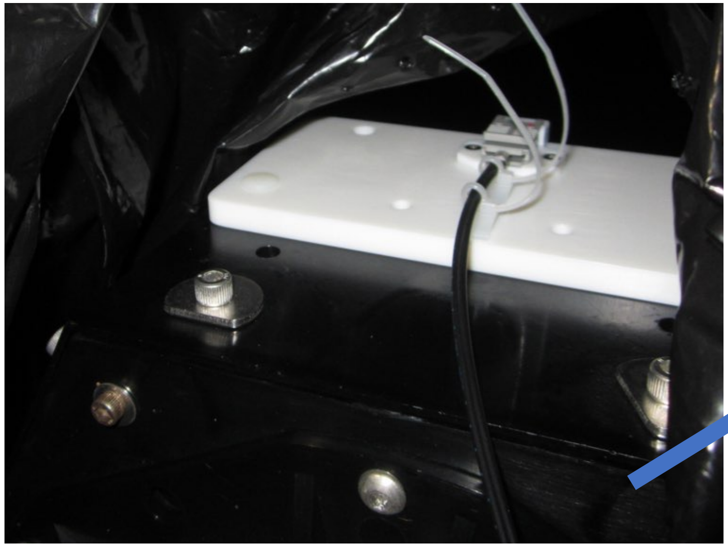


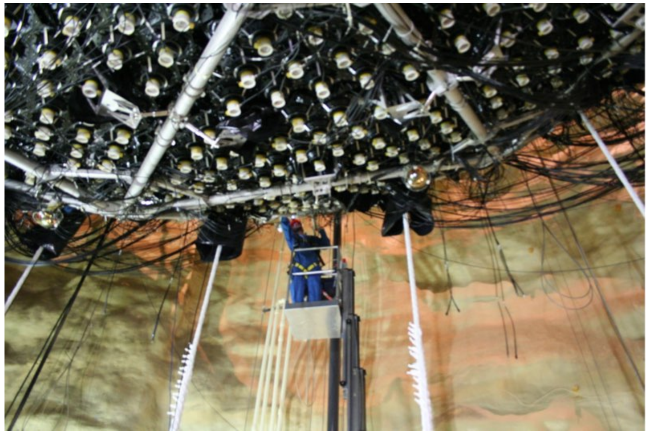
ELLIE Installation





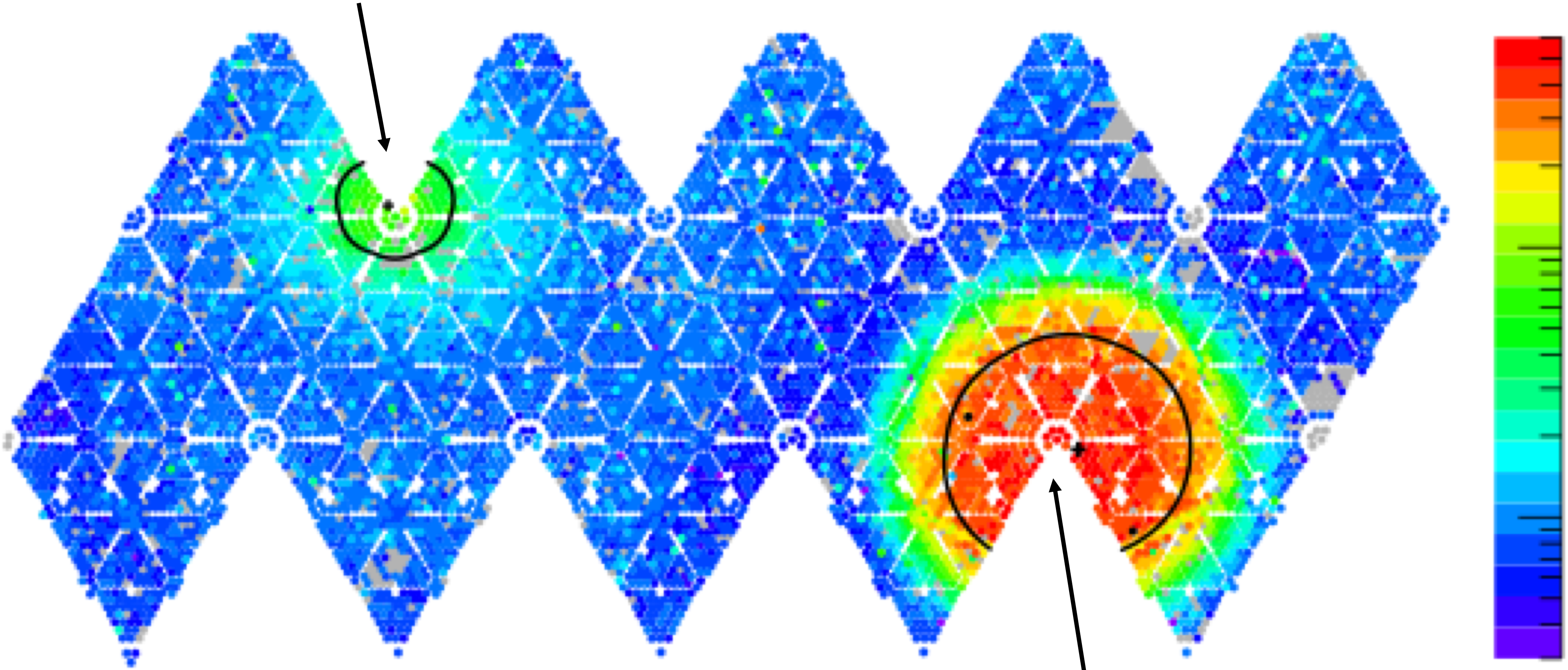






TELLIE data

PMT Occupancy scale
Grey = offline,
purple = <0.03%, red ~6%



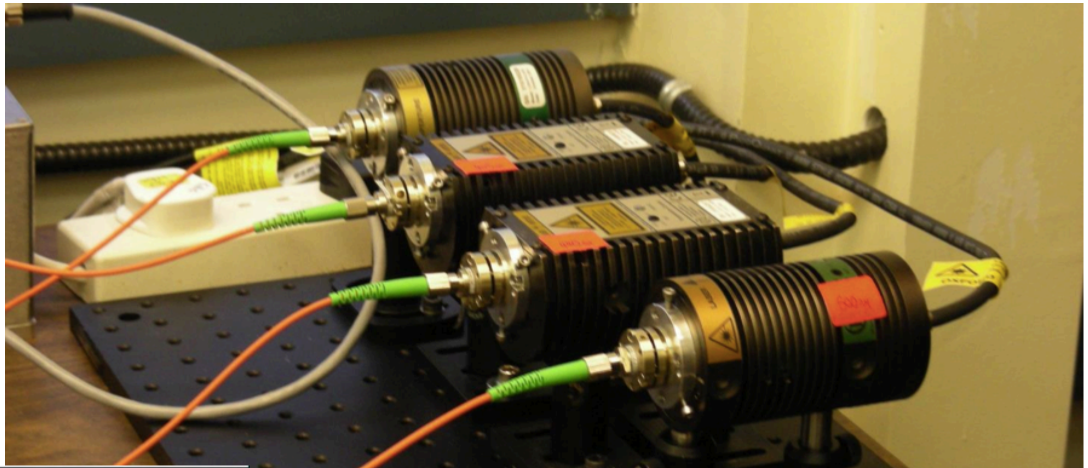
AV reflection

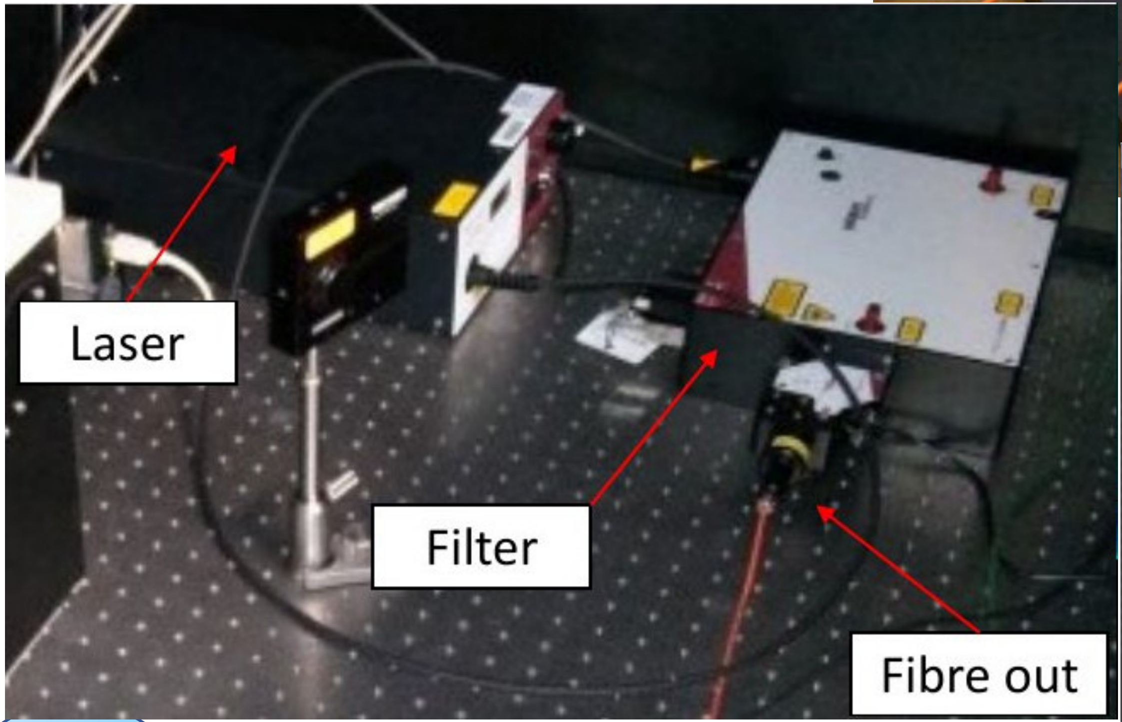
Beam spot – direct light

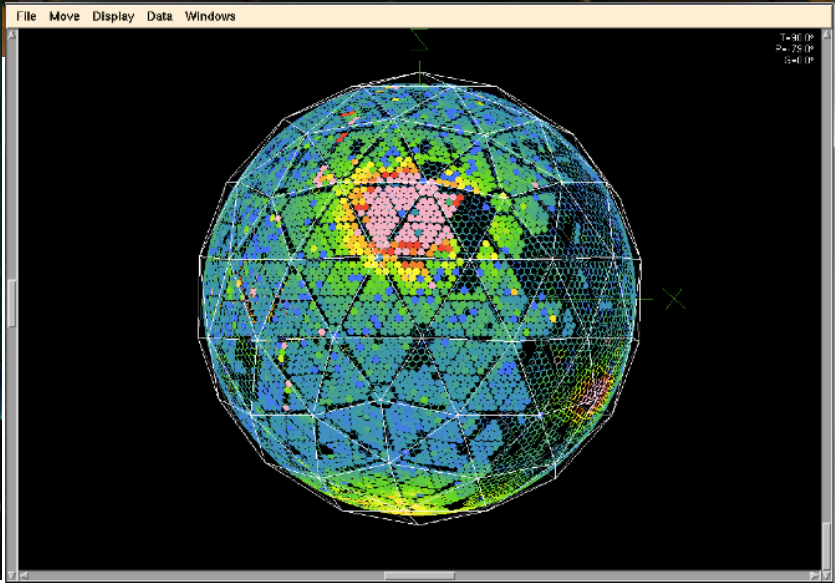
New calibration systems: (SM)ELLIE

4x fixed wavelength laser heads (375nm 407nm, 446nm and 495nm)

One continuously tunable 'supercontinuum' laser with a range from 450 – 800 nm.

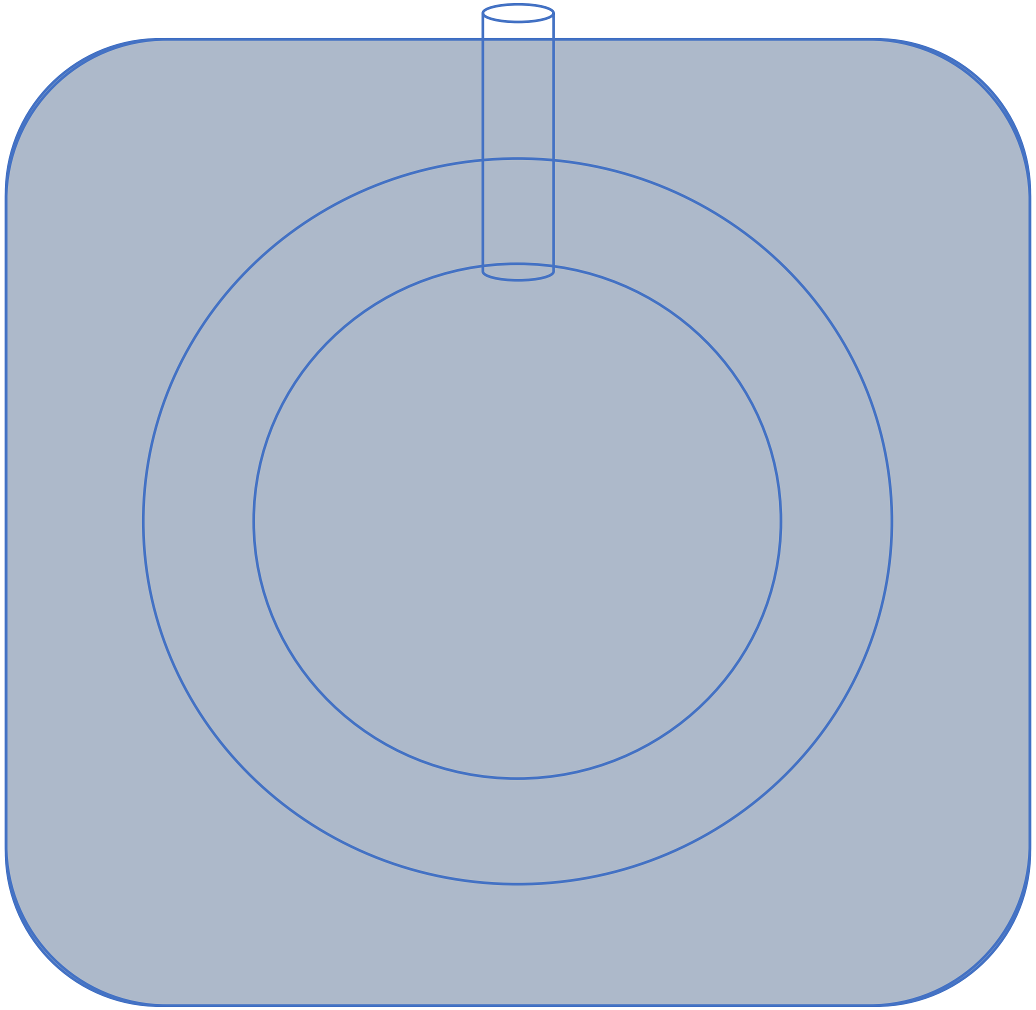


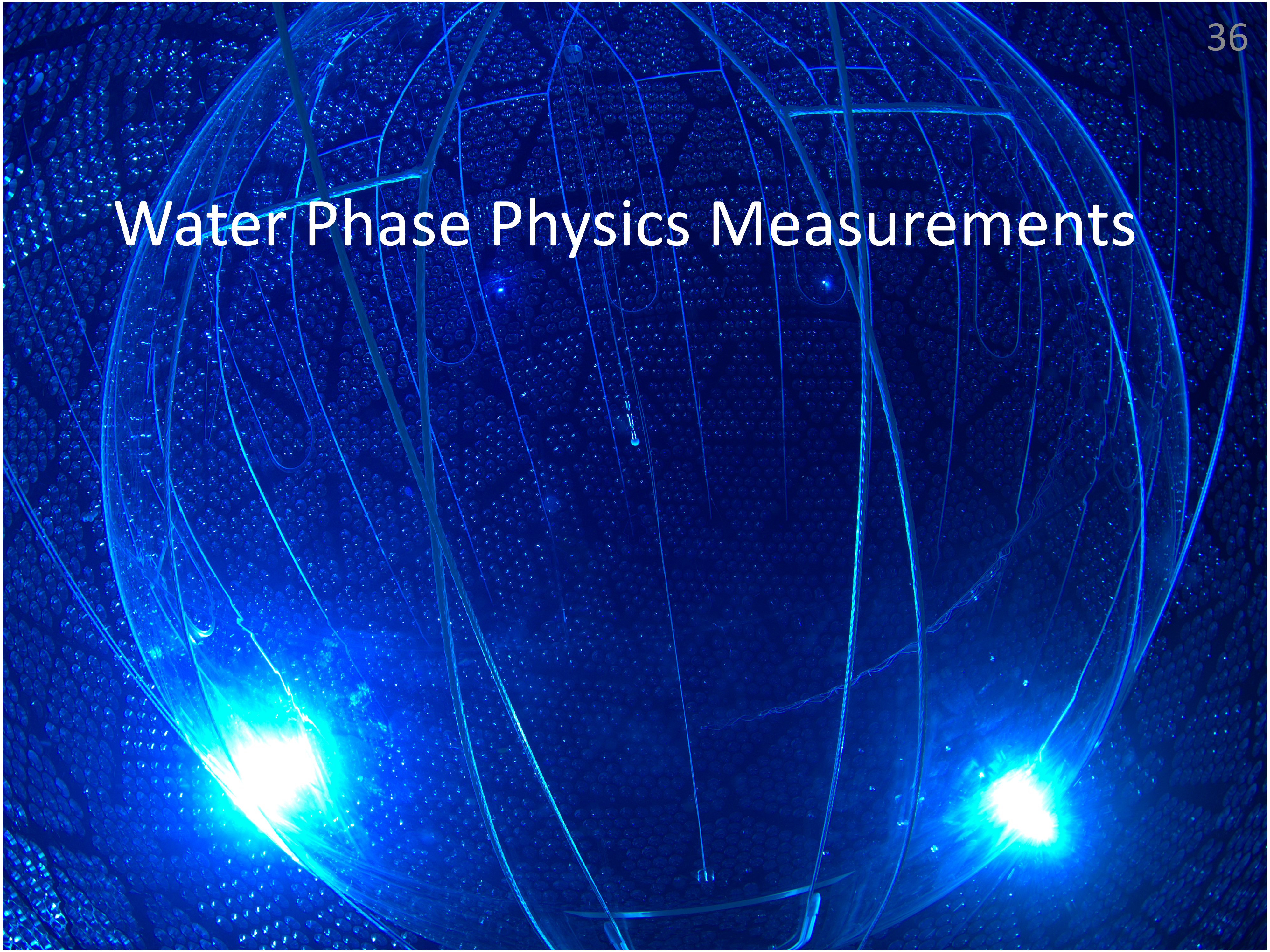




Filling SNO+

- Phase 0 – water fill. May 4th 2017 – Oct 2018



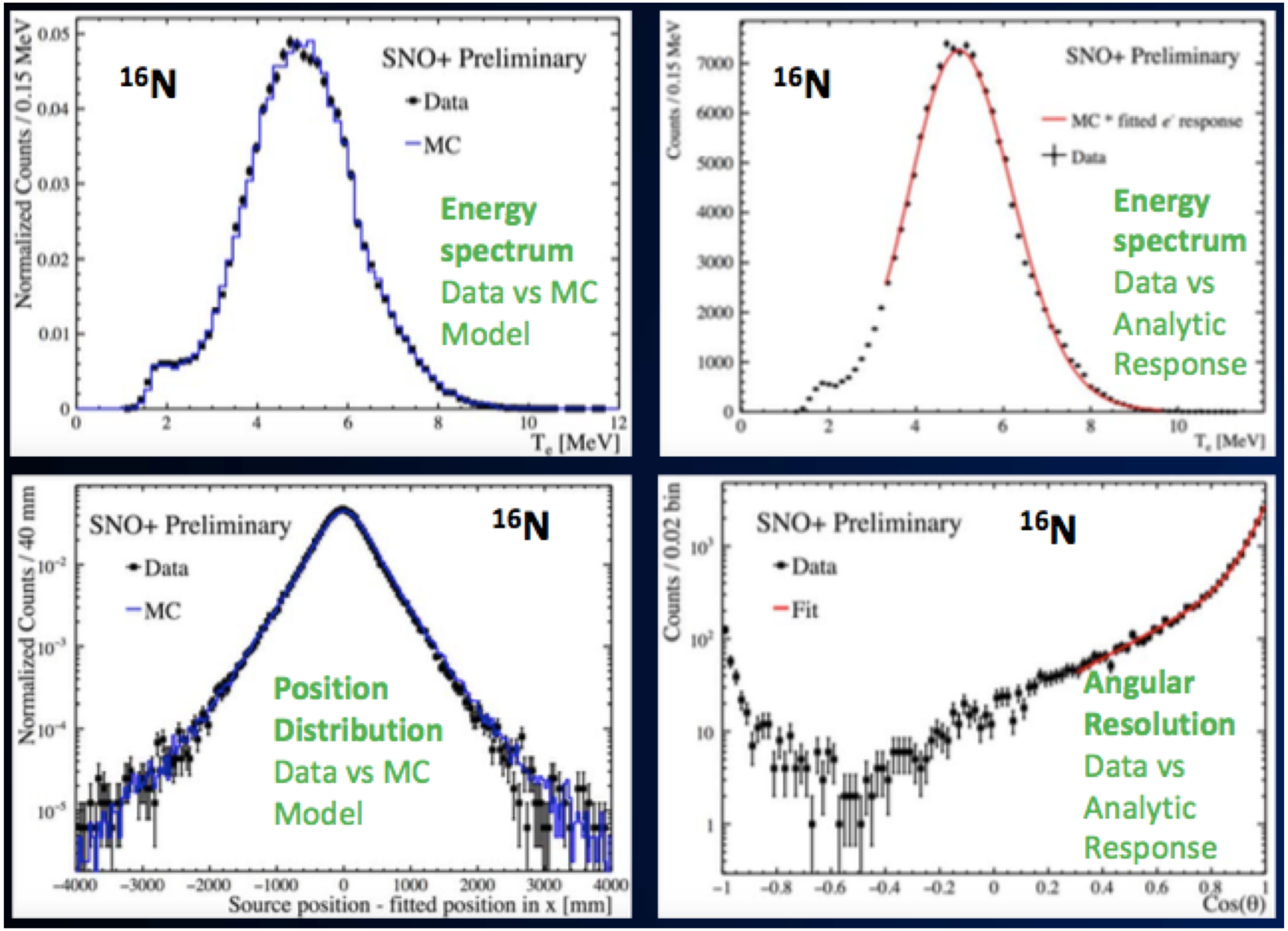


Water Phase Physics Measurements

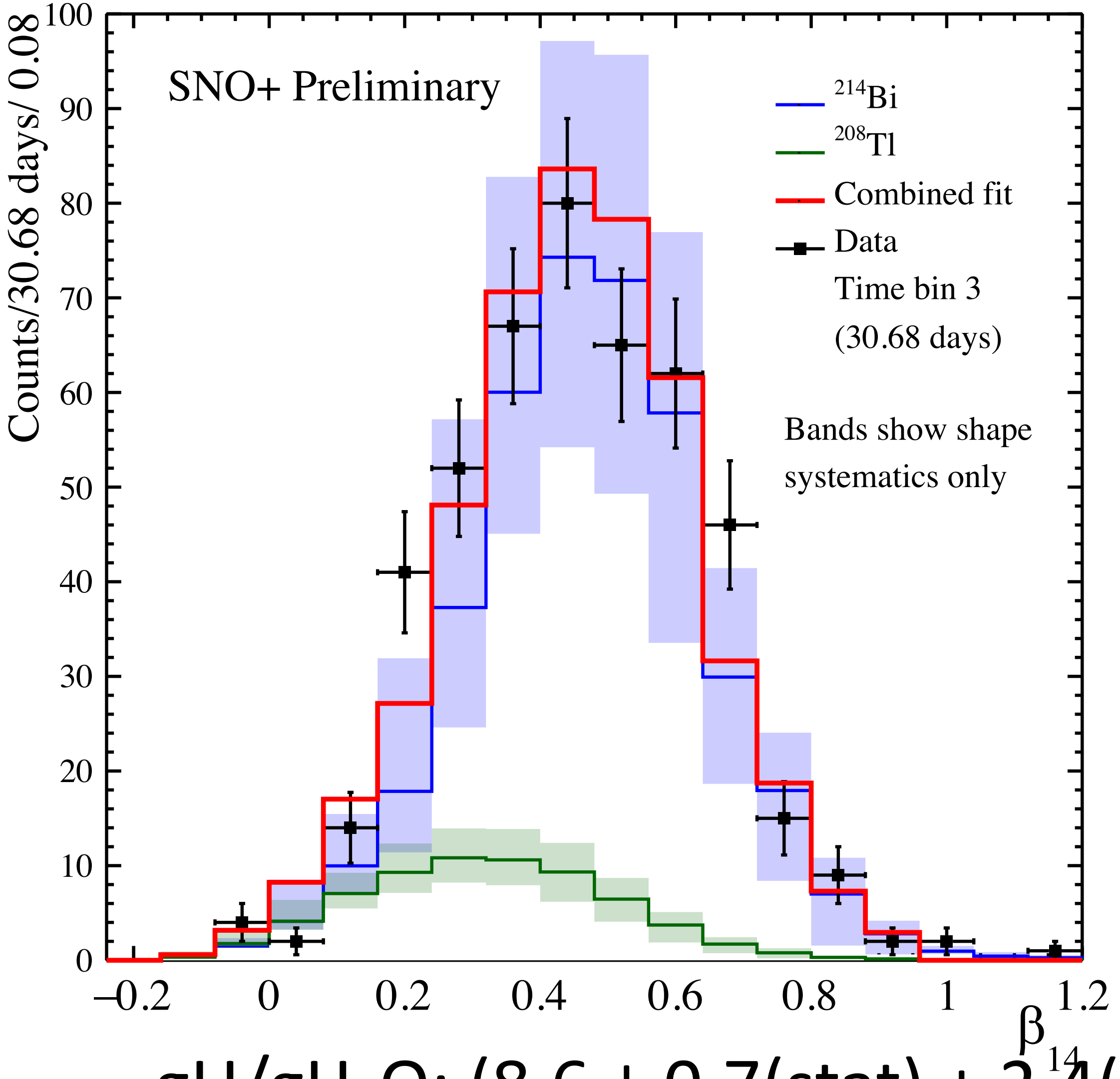
Calibrations – ^{16}N source

Internal ^{16}N calibration source (~6.1 MeV gamma)

Source was deployed along 3 axes throughout the detector volume:



Internal Detector Backgrounds



Measured intrinsic radioactivity of the water inside the AV:

- R < 4.3meters
- 4.0 < E < 5.6MeV

1D fit in isotropy parameter β_{14} for ^{214}Bi and ^{208}Tl components

gU/gH_2O: $(8.6 \pm 0.7(\text{stat}) + 2.4(\text{sys}) - 1.6(\text{sys})) \times 10^{-14}$

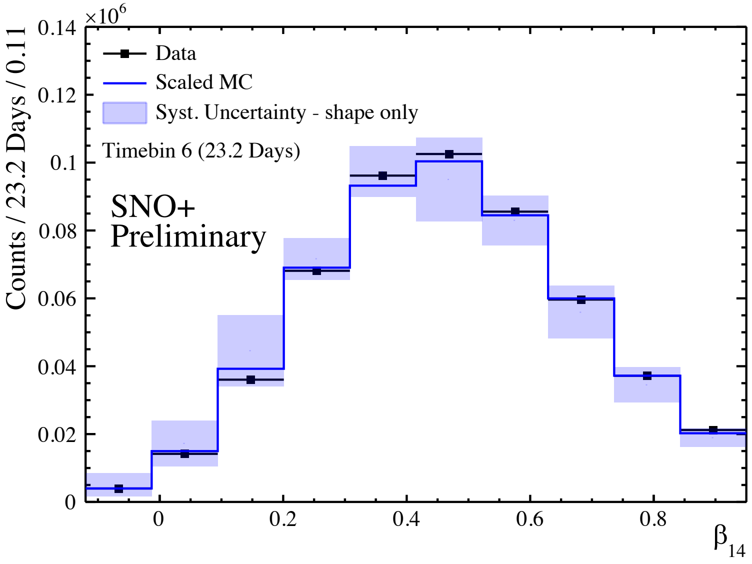
gTh/gH_2O: $< 2.7 \times 10^{-14}$ (95% C.L.)

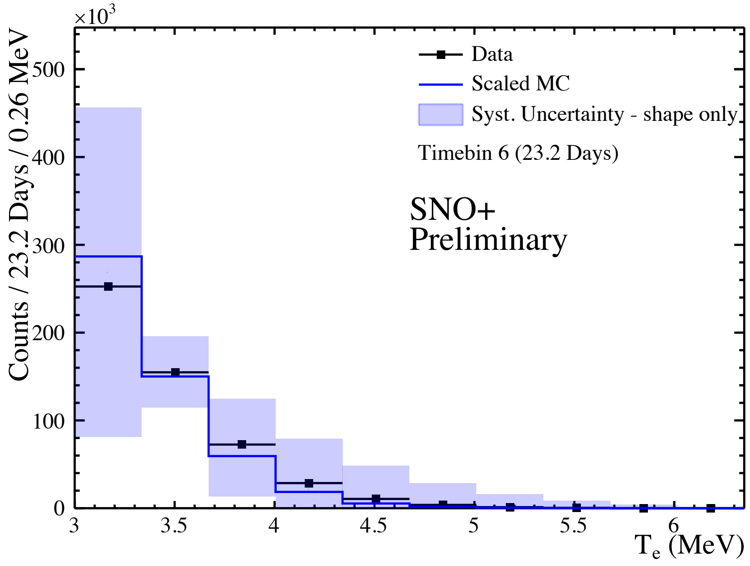
External Detector Backgrounds

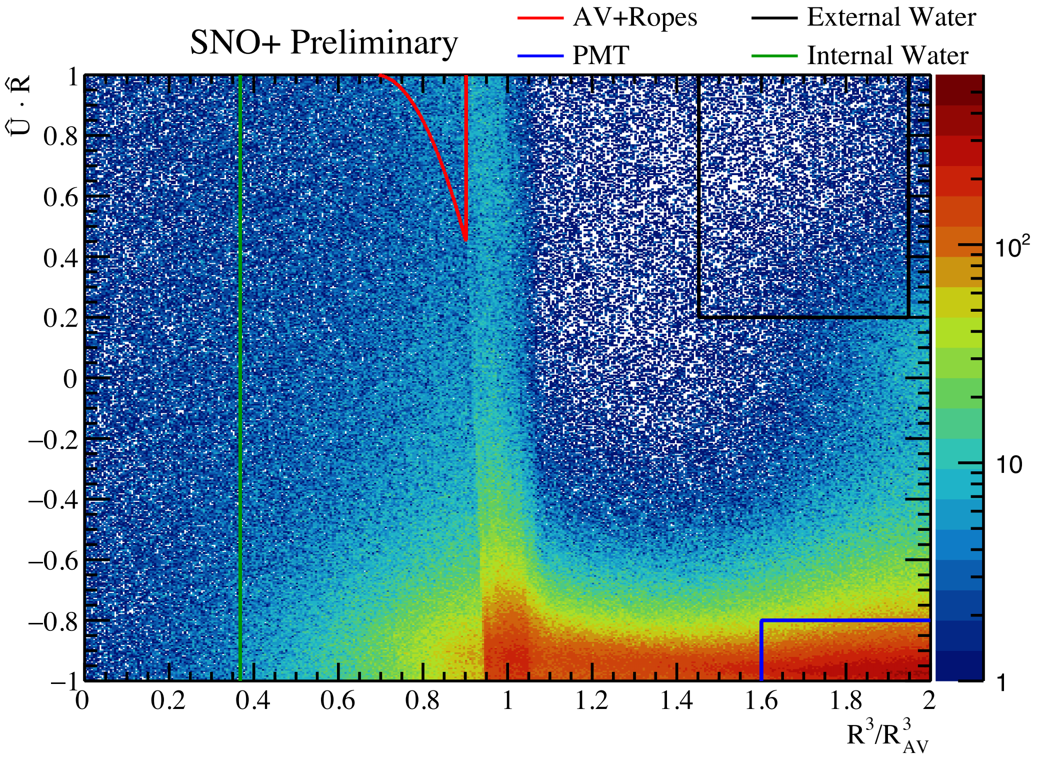
Measure background radioactivity from AV, ropes, external H_2O and PMTs

Box Analysis and Likelihood Fit

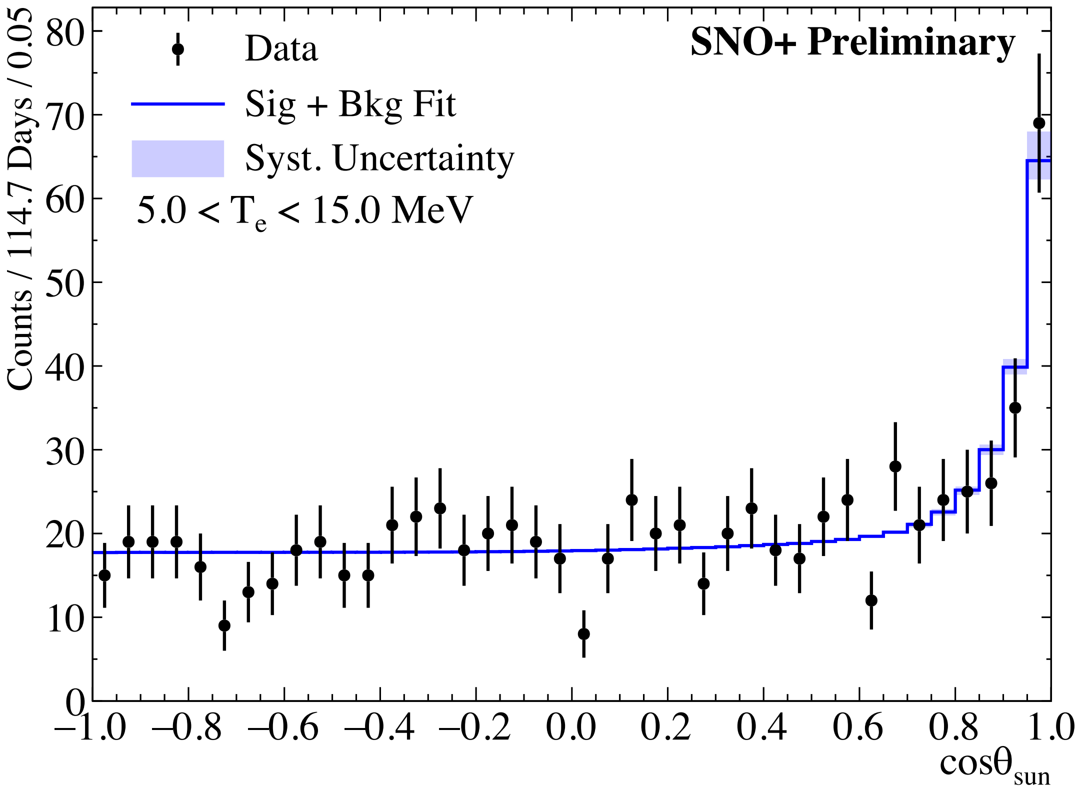
Source	Analysis Method	Results (measured/expectation)
PMTs	Box Analysis	^{208}Tl: $1.16 \pm 0.02(\text{stat})^{+1.09}_{-0.46}\,(\text{syst})$
AV + ropes	Likelihood Fit	^{214}Bi: $1.69 \pm 0.86(\text{stat})^{+3.62}_{-4.10}(\text{syst})$
	Likelihood Fit	^{208}Tl: $0.00 \pm 0.09(\text{stat})^{+0.95}_{-0.21}\,(\text{syst})$

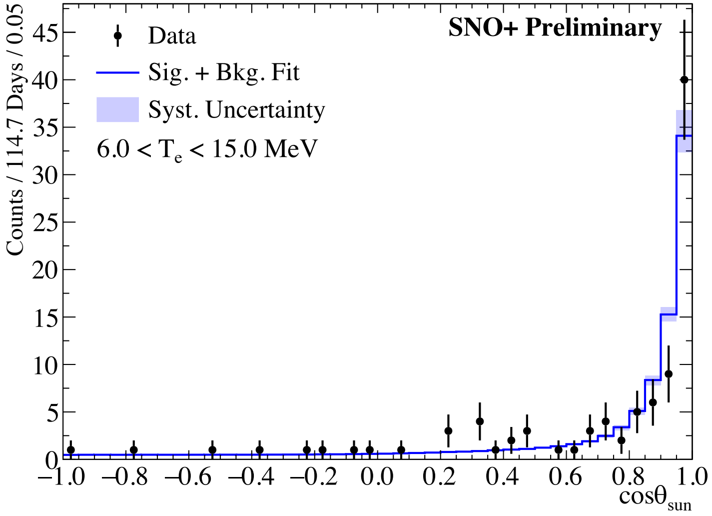


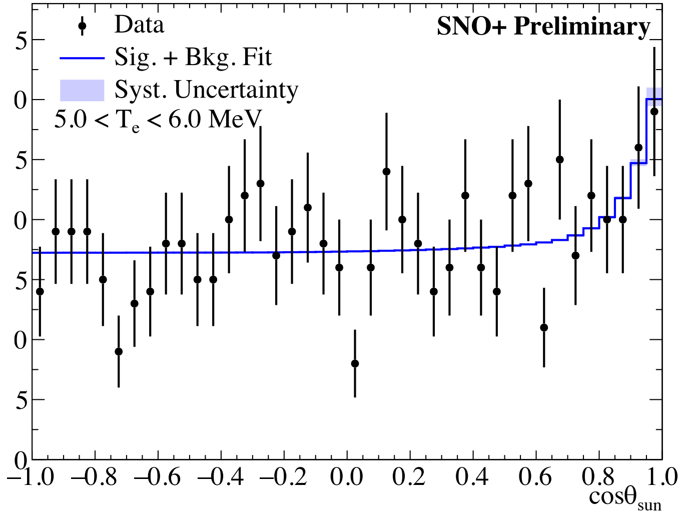




Measurement of ^{8}B Solar Neutrino Flux with very low backgrounds.







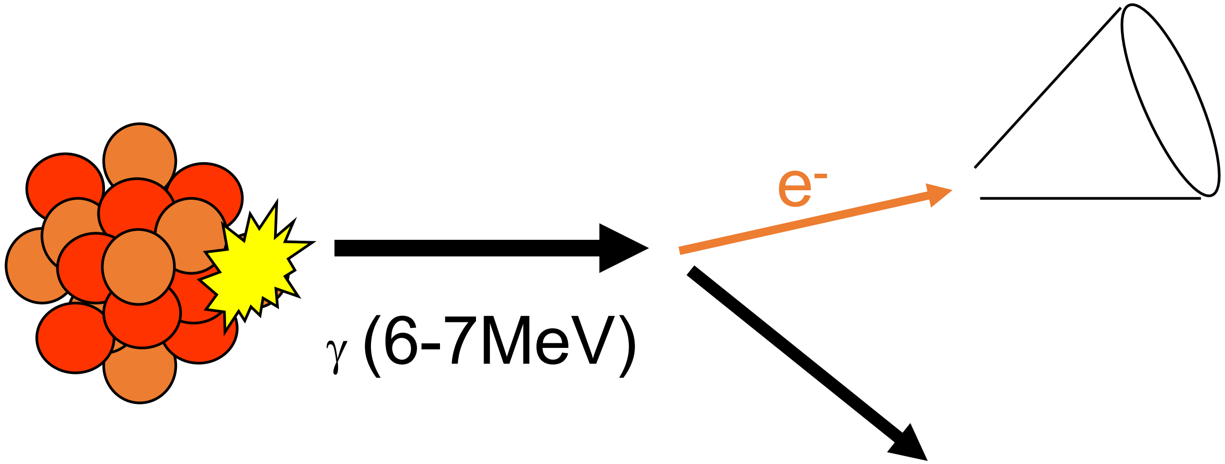
Best signal:background achieved in water to date. Good measurement even with small data set. Spectrum paper in preparation

Invisible Nucleon Decay

- Invisible nucleon decay modes – deposit no visible energy in detector.

  eg. $N \rightarrow 3\nu$

- See γ from de-excitation of residual nucleus.

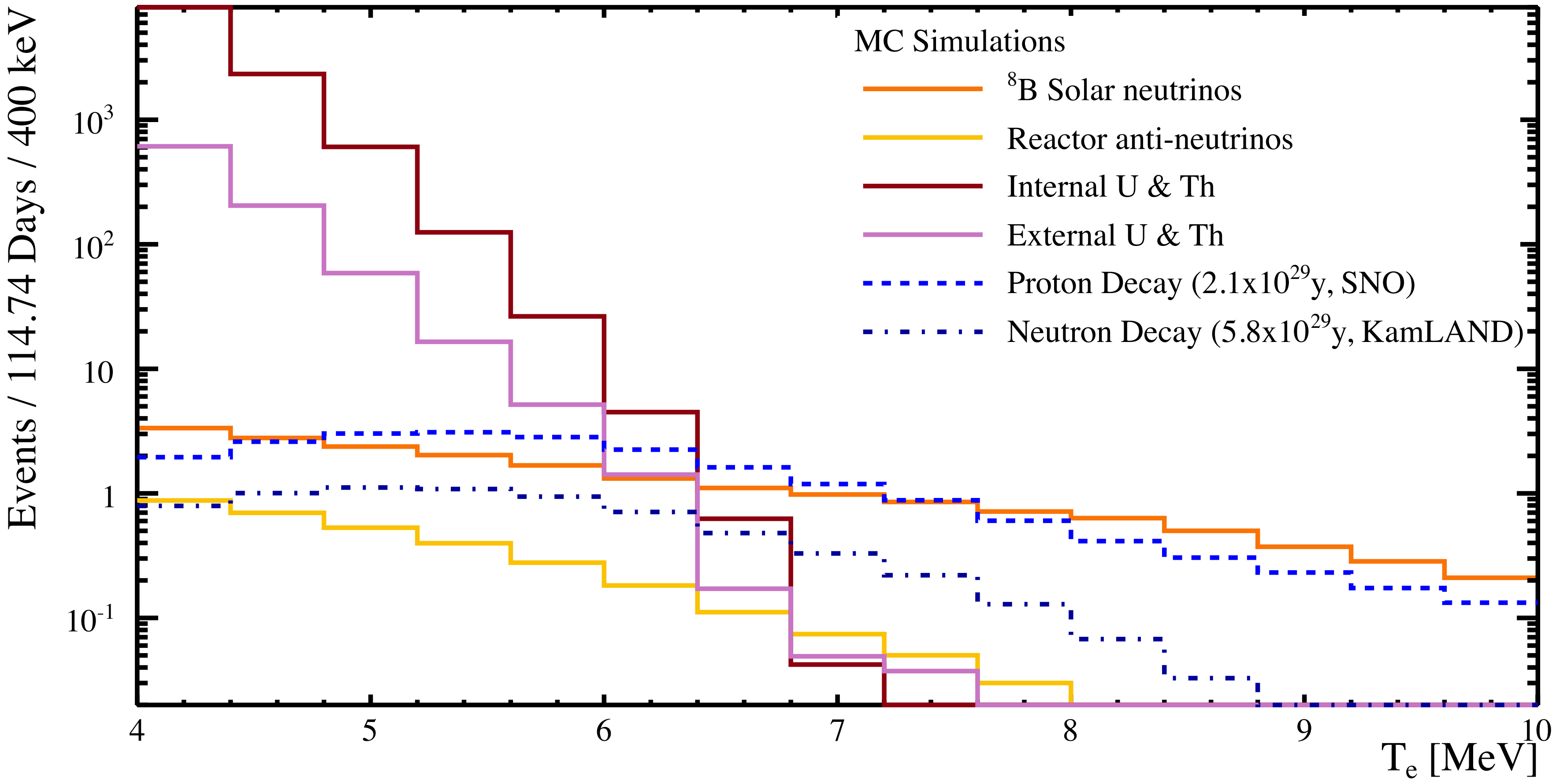


$^{16}\mathbf{O} \rightarrow {}^{15}\mathbf{O}^{*} \rightarrow {}^{15}\mathbf{O} + \gamma$

- Detect γ in SNO+ water phase with good efficiency and very little background

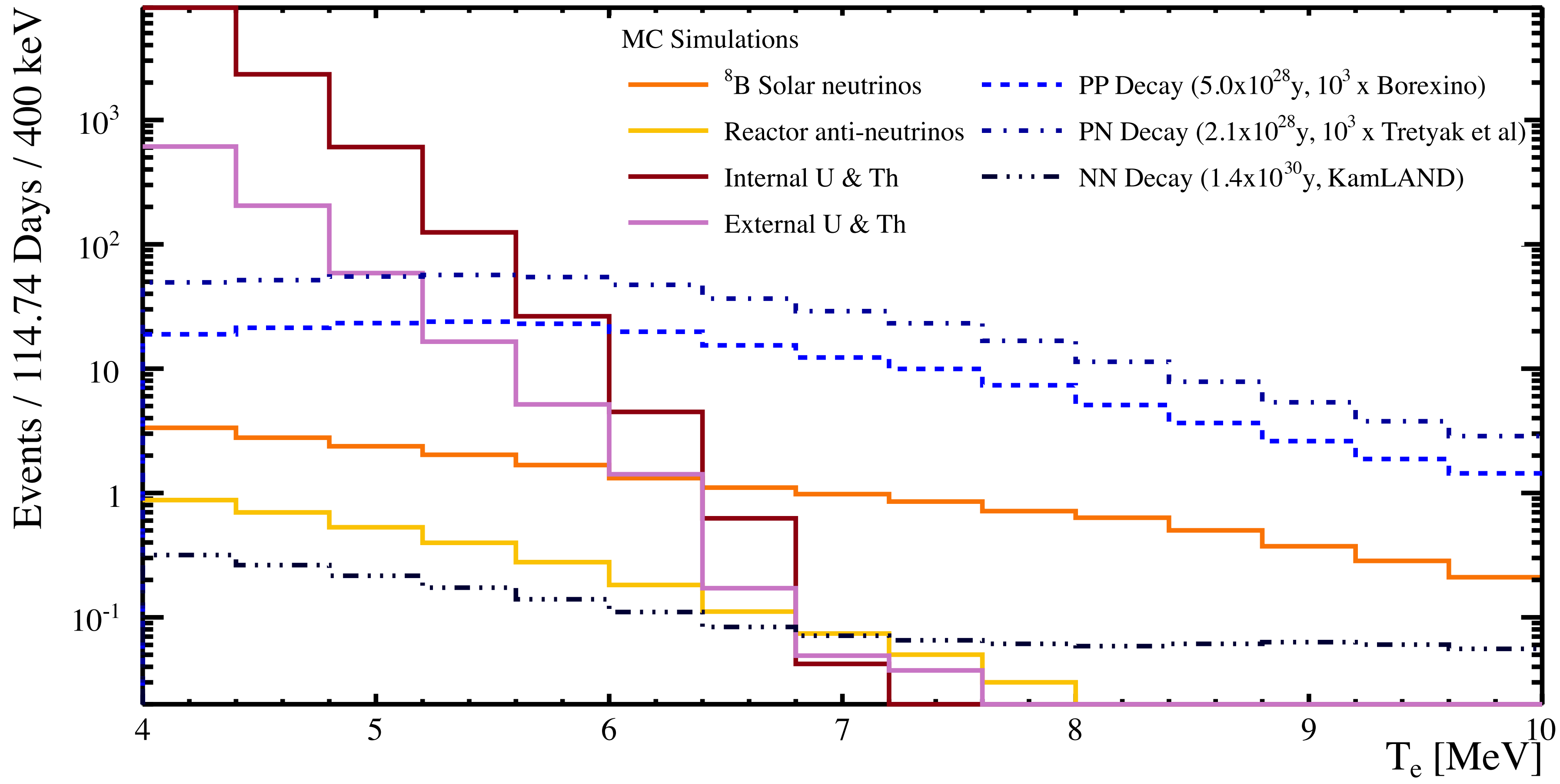
Nucleon Decay Search

- Comparison of signal and background



Nucleon Decay Search

- Comparison of signal and background – dinucleon

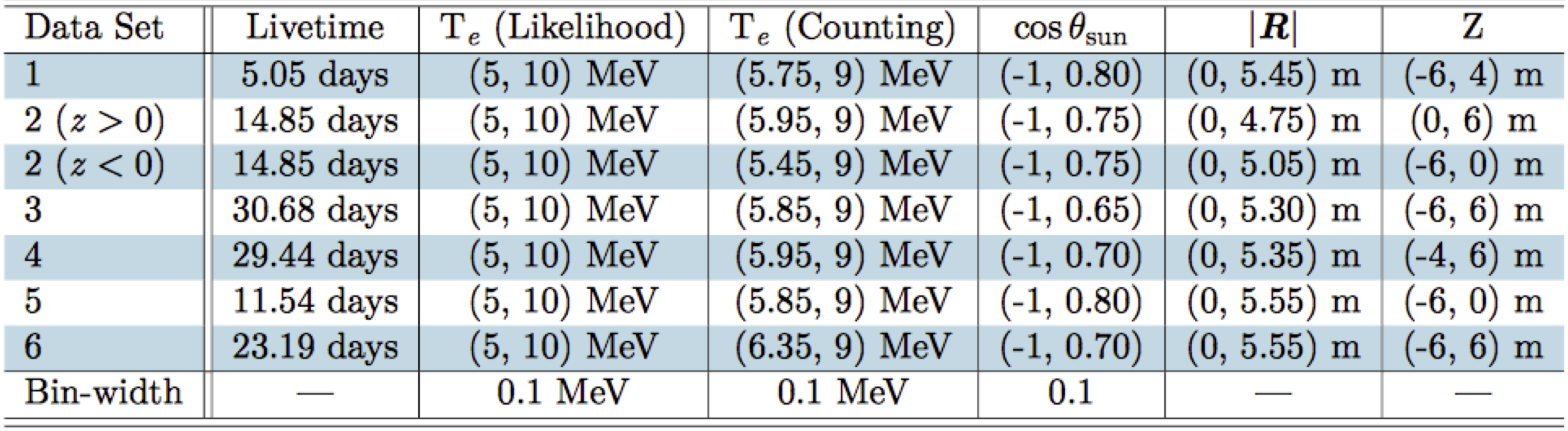


Invisible Nucleon Decay Analysis

- Official data taking began May 2017.
- Data was split into 6 data sets, during each of which the background levels were relatively stable. Each set has its own analysis cuts and background estimates.
- 114.7 days of livetime used for the background and nucleon decay analysis, running through December 2017.
- 2 independent blind analyses conducted.

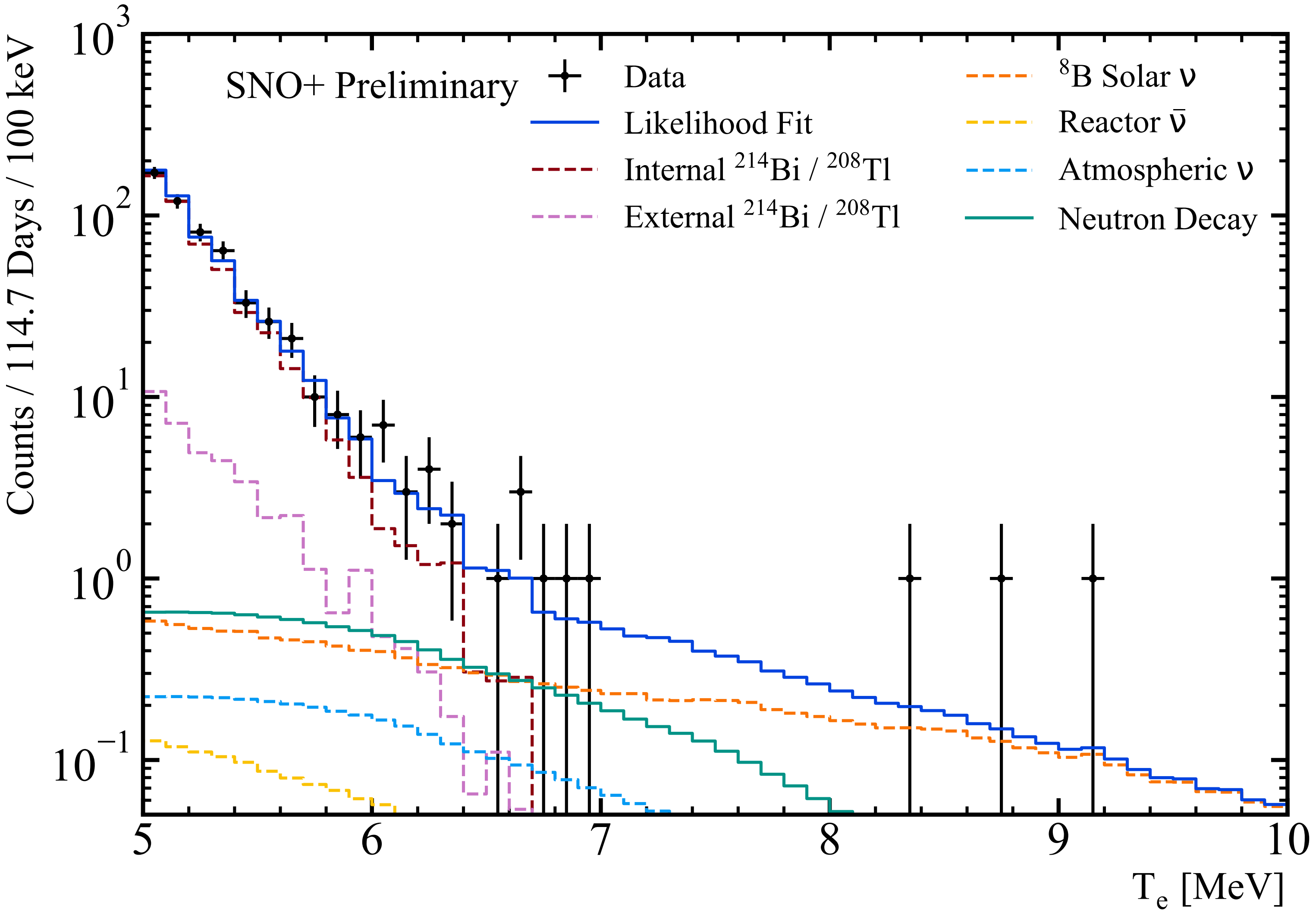
Removes solar neutrinos

Selects lowest bg regions in detector

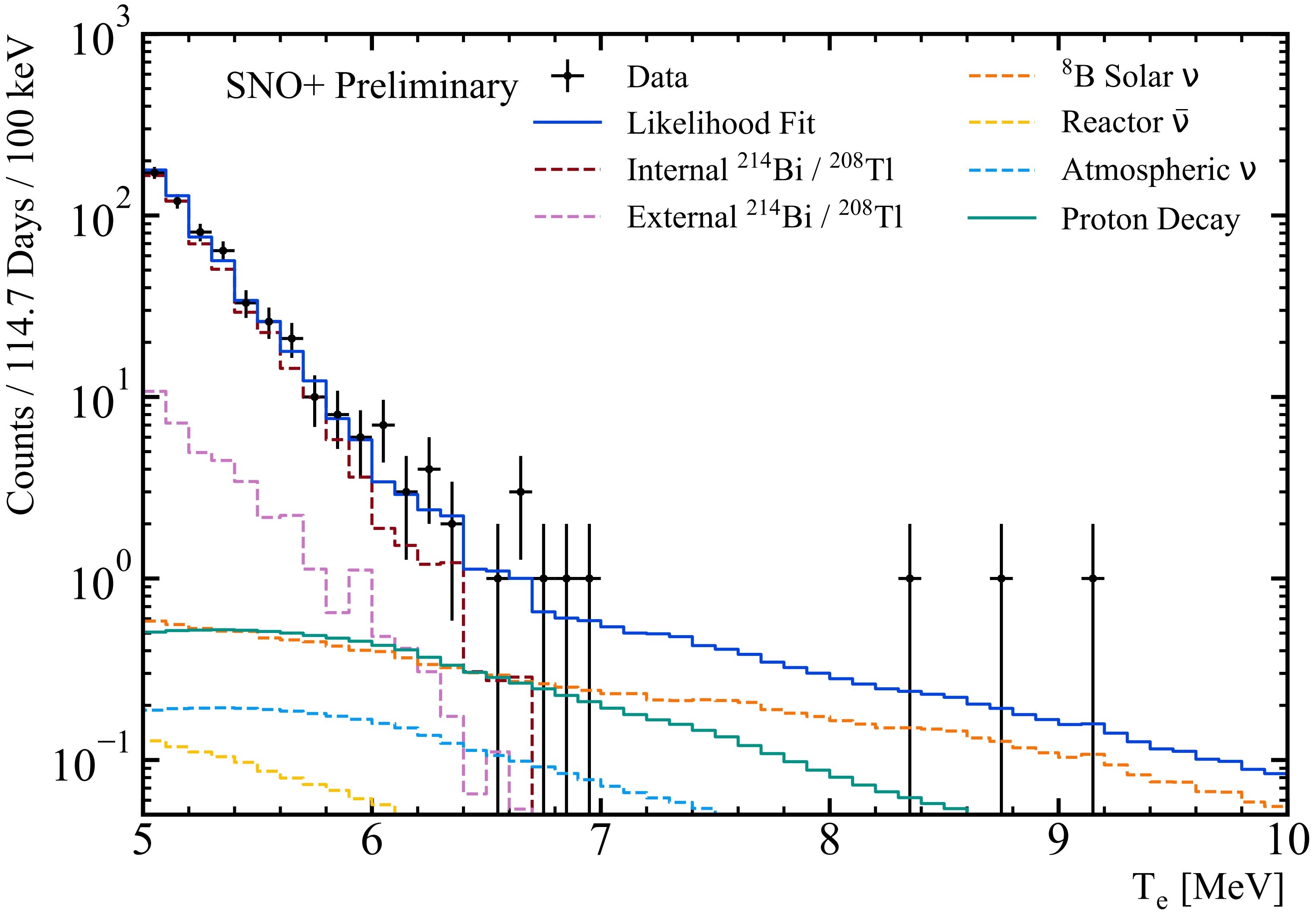


Data Set	Livetime	T_e (Likelihood)	T_e (Counting)	$\cos\theta_{\text{sun}}$	$\lvert\boldsymbol{R}\rvert$	Z
1	5.05 days	(5, 10) MeV	(5.75, 9) MeV	(-1, 0.80)	(0, 5.45) m	(-6, 4) m
2 ($z > 0$)	14.85 days	(5, 10) MeV	(5.95, 9) MeV	(-1, 0.75)	(0, 4.75) m	(0, 6) m
2 ($z < 0$)	14.85 days	(5, 10) MeV	(5.45, 9) MeV	(-1, 0.75)	(0, 5.05) m	(-6, 0) m
3	30.68 days	(5, 10) MeV	(5.85, 9) MeV	(-1, 0.65)	(0, 5.30) m	(-6, 6) m
4	29.44 days	(5, 10) MeV	(5.95, 9) MeV	(-1, 0.70)	(0, 5.35) m	(-4, 6) m
5	11.54 days	(5, 10) MeV	(5.85, 9) MeV	(-1, 0.80)	(0, 5.55) m	(-6, 0) m
6	23.19 days	(5, 10) MeV	(6.35, 9) MeV	(-1, 0.70)	(0, 5.55) m	(-6, 6) m
Bin-width	—	0.1 MeV	0.1 MeV	0.1	—	—

Full Spectral Fit - neutron

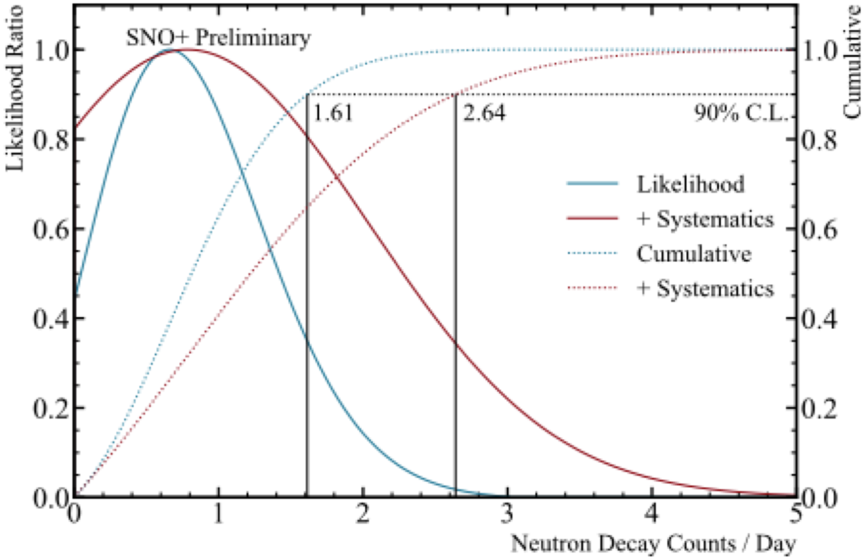


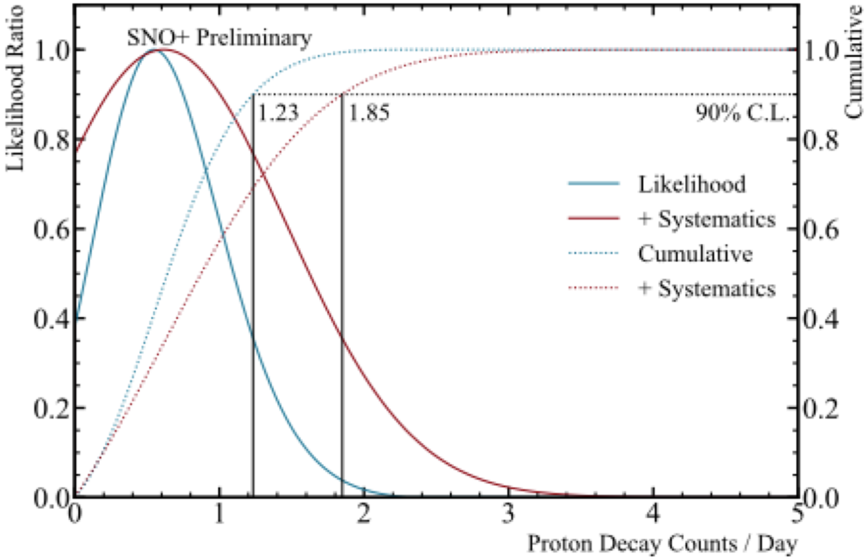
Full Spectral Fit- proton



Results of the Spectral Fit at 90% C.L.

Mode	SNO+ Limits (years)	Current Limits
n	2.49×10^{29}	5.8×10^{29} [KamLAND]
p	3.56×10^{29}	2.1×10^{29} [SNO]
pp	4.68×10^{28}	5.0×10^{25} [Borexino]
pn	2.57×10^{28}	2.1×10^{25} [Tretyak et. al.]
nn	1.25×10^{28}	1.4×10^{30} [KamLAND]

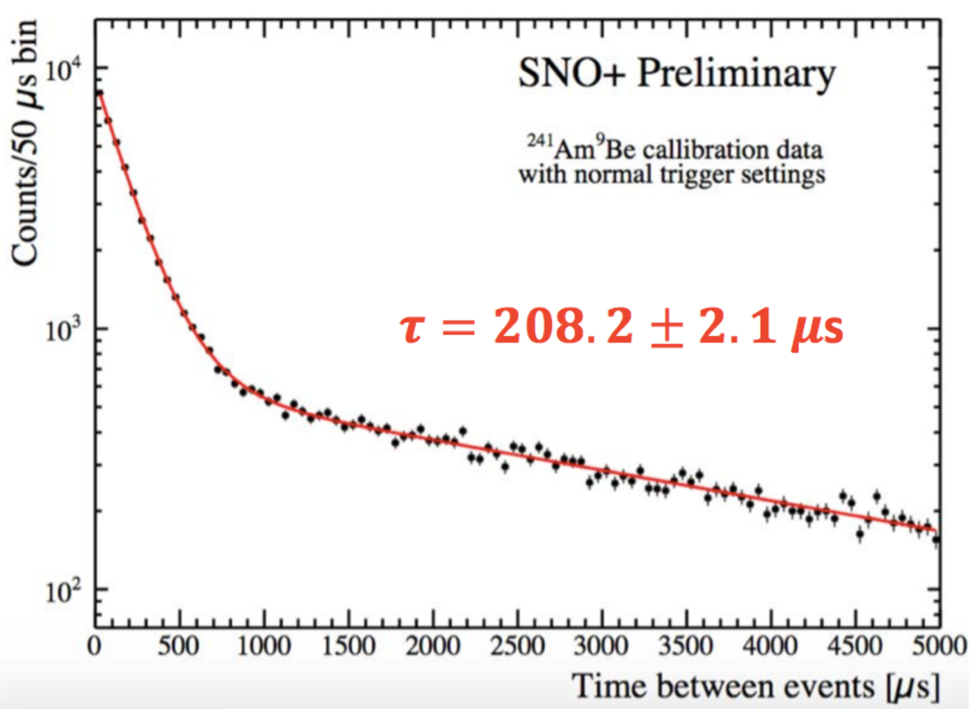


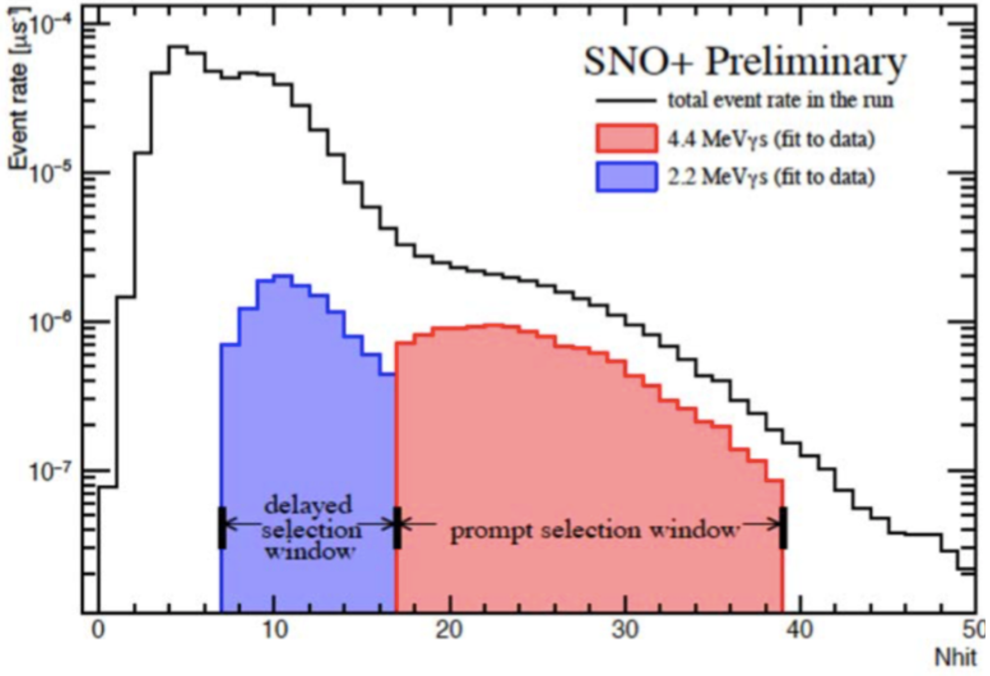


AmBe Calibration – neutron capture

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

Efficiency for tagging neutrons under these conditions is 46%





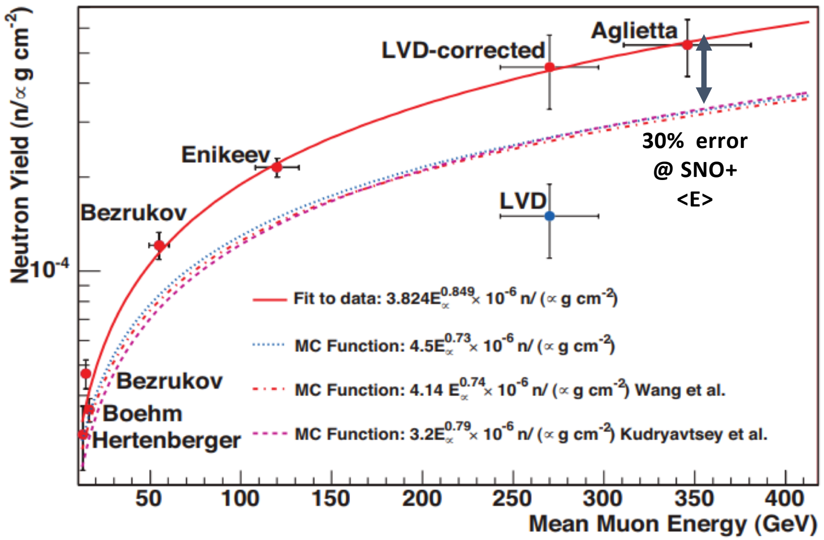
Muon Induced Neutrons

Aim

Measure the multiplicity of neutrons produced by cosmic muons

Why?

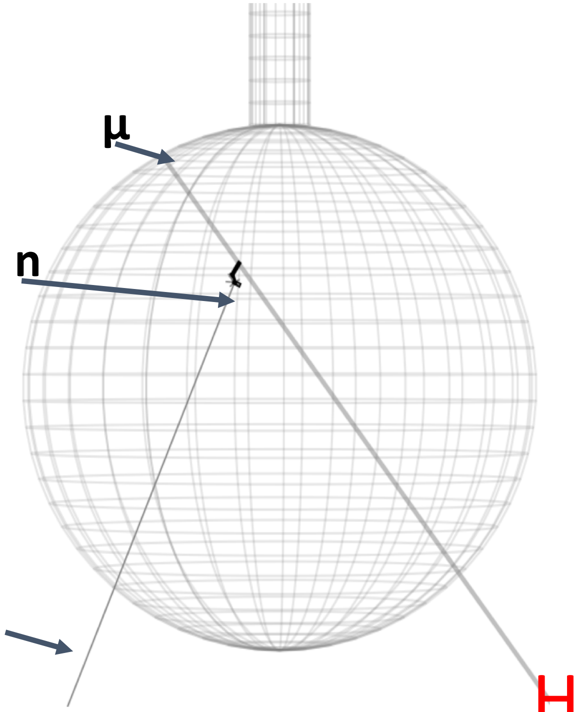
Data vs Theory



Rare signal searches

- Neutron backgrounds constitute a background for various rare single searches e.g. DM searches

What?



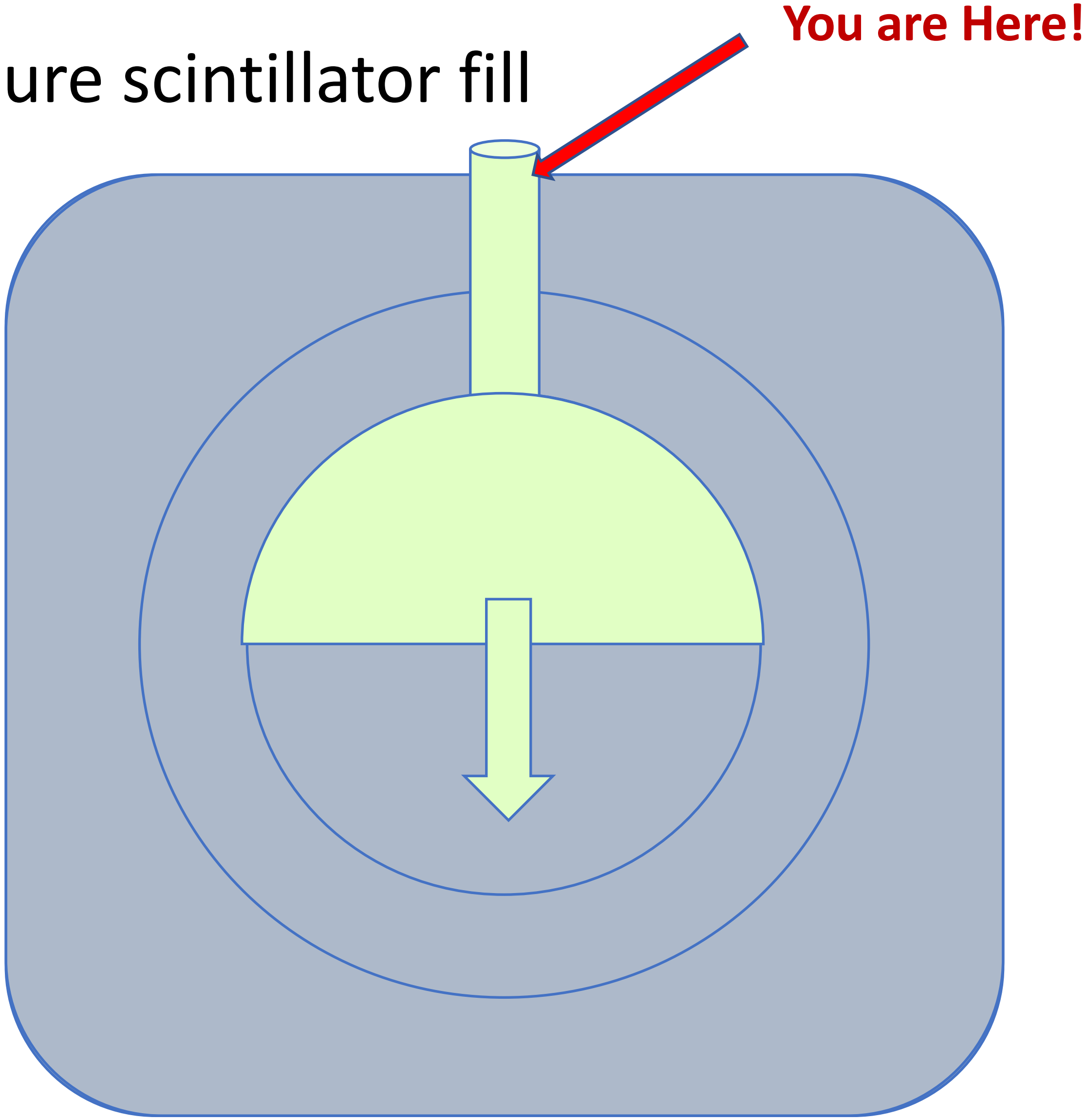
How?

1. Tag and reconstruct muons.
2. Find neutron efficiency for each track via MC.
3. Doped data driven particle selection.
    - Splice random event windows with pruned reconstructed neutron information.
    - Optimise selection.
4. Estimate background rate per track.
5. Carry out Maximum Log Likelihood fits between data and expected multiplicity, given track efficiency and expected background.
6. Produce compatibility of data with models tested.

Filling SNO+

- Phase 1 – pure scintillator fill

24/10/18 ->

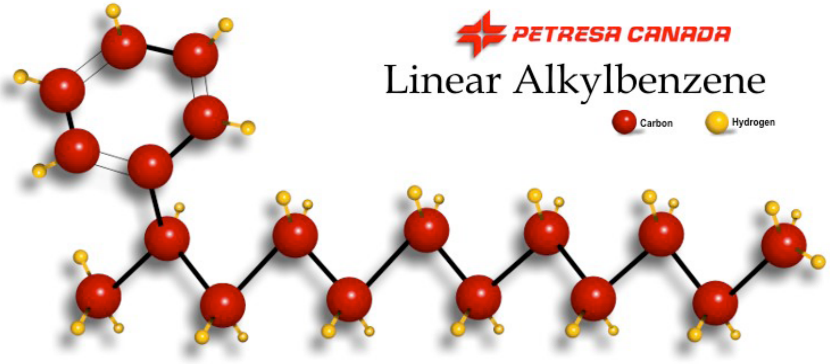


Scintillator is less dense than water.
Fill inner AV from the top, remove H_2O from bottom

Scintillator LAB + PPO

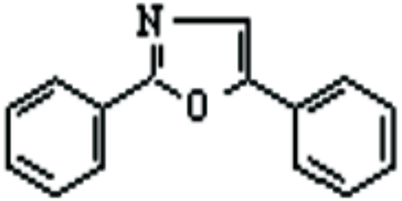
Scintillator of choice Linear Alkylbenzene (LAB)

- Compatible with acrylic
- High light yield
- Optical transparency
- Low scattering
- Fast decay, different for alpha/beta
- High flash point, low toxicity
- Density = 0.78g/cm^3



Properties:

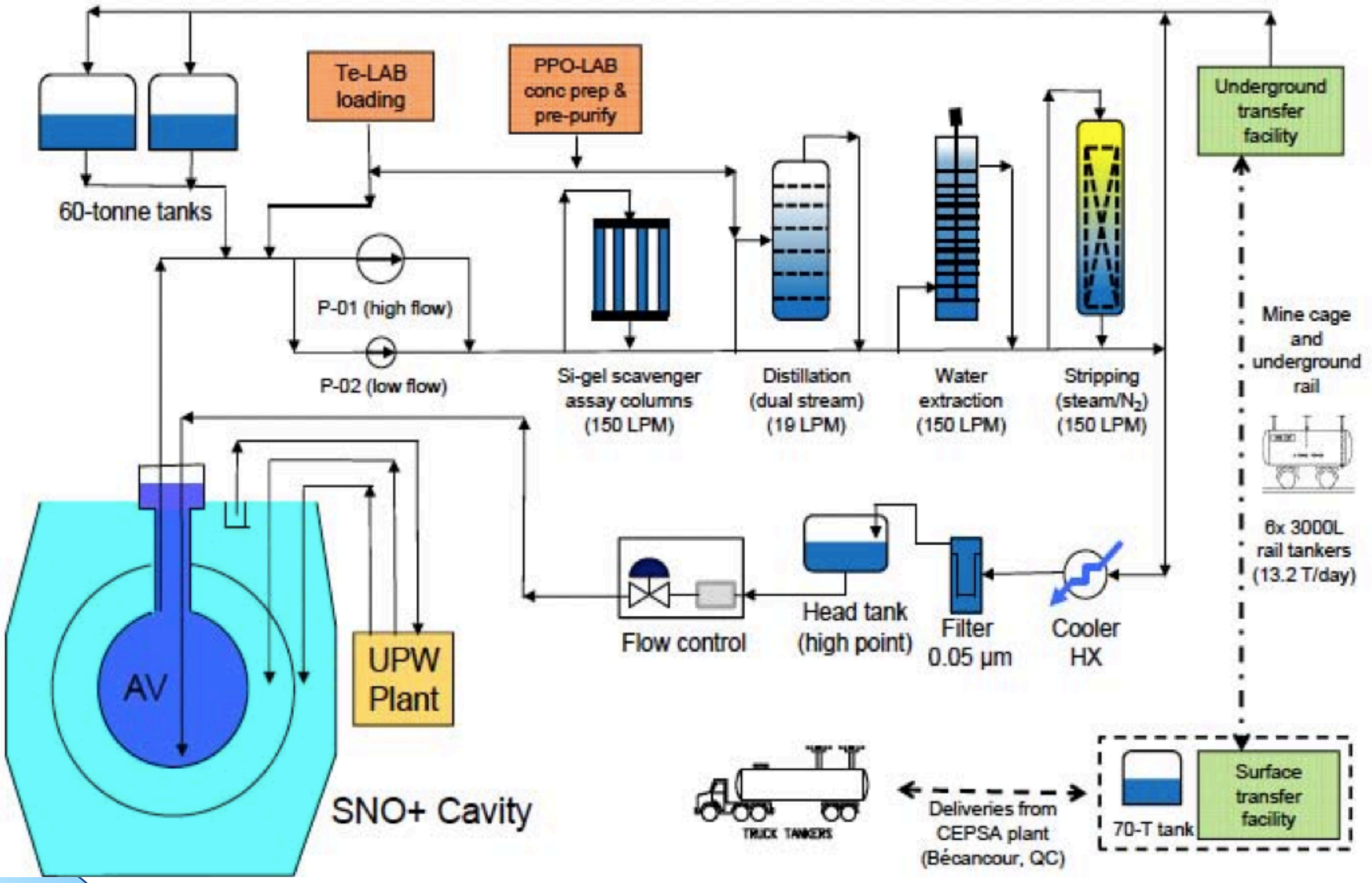
- 450 observed photons per MeV
- Resolution of 5% at 1 MeV
- kB = 71.9±3.9 μm/MeV



PPO

We can observe the difference between αs and βs in scintillator timing response. Allows for Particle ID in observed events.

Scintillator Delivery and Purification



Purification Plant - LABPPO

- Multi-stage distillation
  - Remove heavy metals, improve UV transparency
- Pre-purification of PPO concentrated solution
- Steam/N_2 stripping under vacuum
  - Remove Rn, Kr, Ar, O_2
- Water extraction
  - Remove Ra, K, Bi
- Metal scavengers
  - Remove Bi, Pb
- Microfiltration
  - Remove dust

Target levels:

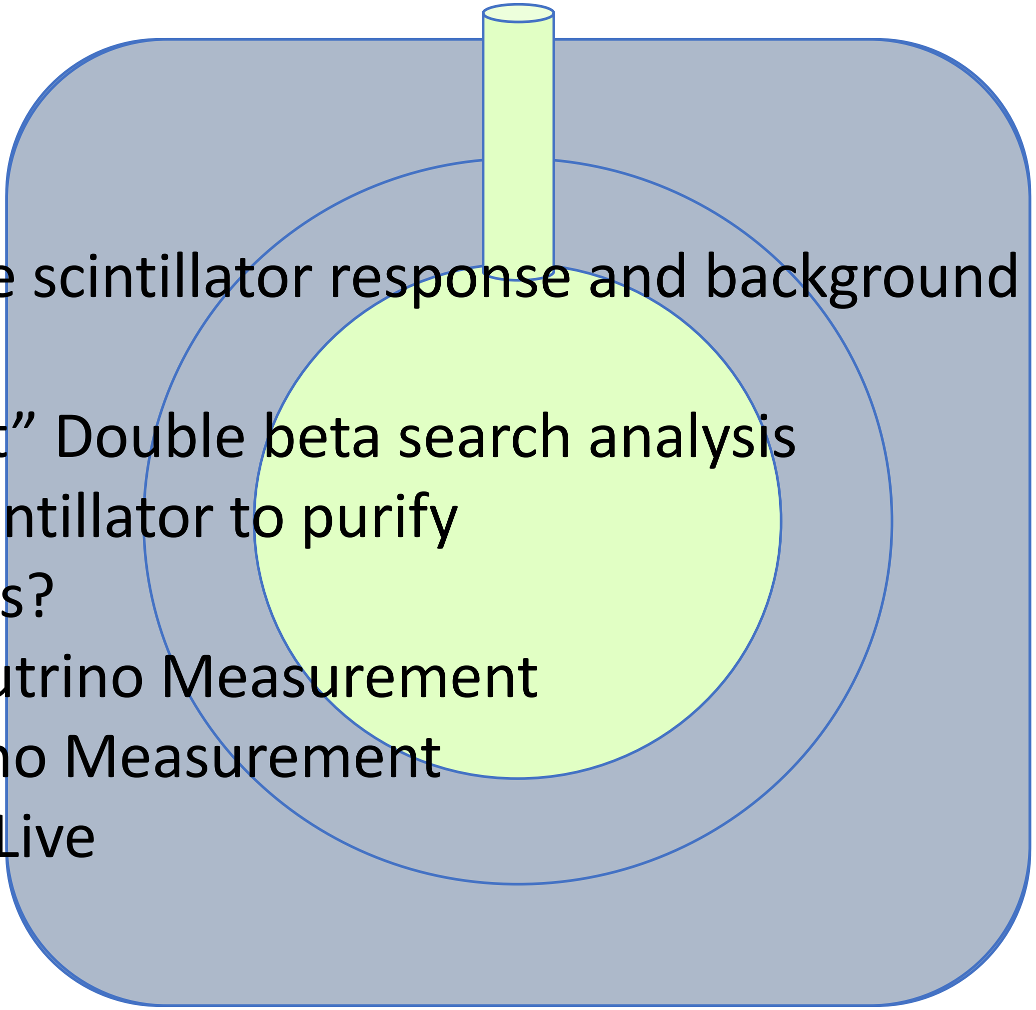
- ^{85}Kr: 10^{-25} g/g
- ^{40}K: 10^{-18} g/g
- ^{39}Ar: 10^{-24} g/g
- U: 10^{-17} g/g
- Th: 10^{-18} g/g


Leak Checked
E-110
Clea
250 lbs

Scintillator delivery

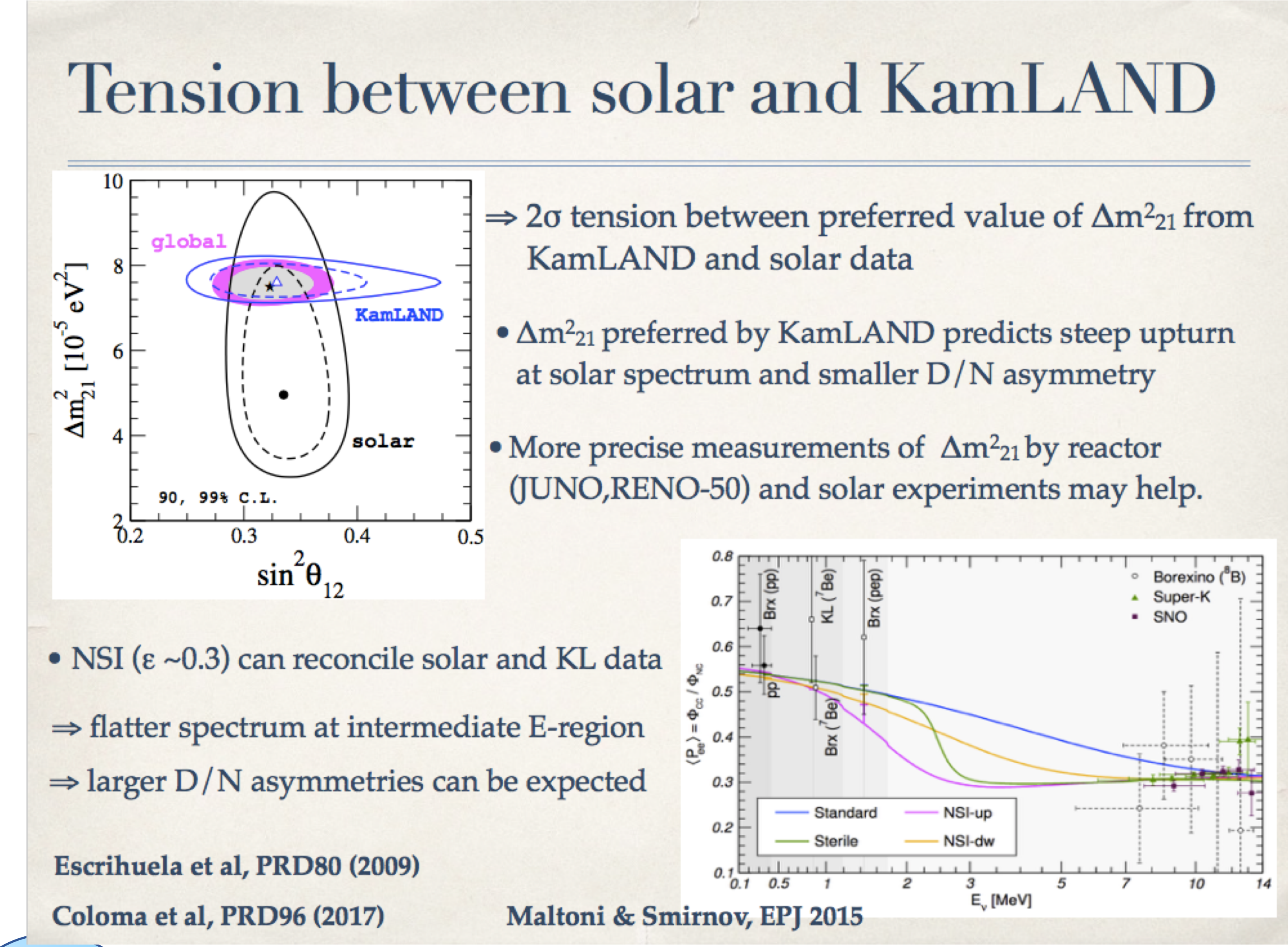
Filling SNO+

- Phase 1 – pure scintillator fill



- Characterise scintillator response and background levels
- “Source Out” Double beta search analysis
- Circulate scintillator to purify
- Solar physics?
- Reactor Neutrino Measurement
- Geo Neutrino Measurement
- SuperNova Live

Reactor Neutrinos – Scintillator Phase



Tension between solar and KamLAND

⇒ 2σ tension between preferred value of Δm^2_{21} from KamLAND and solar data

- Δm^2_{21} preferred by KamLAND predicts steep upturn at solar spectrum and smaller D/N asymmetry
- More precise measurements of Δm^2_{21} by reactor (JUNO,RENO-50) and solar experiments may help.

- NSI (ε ~0.3) can reconcile solar and KL data

⇒ flatter spectrum at intermediate E-region

⇒ larger D/N asymmetries can be expected

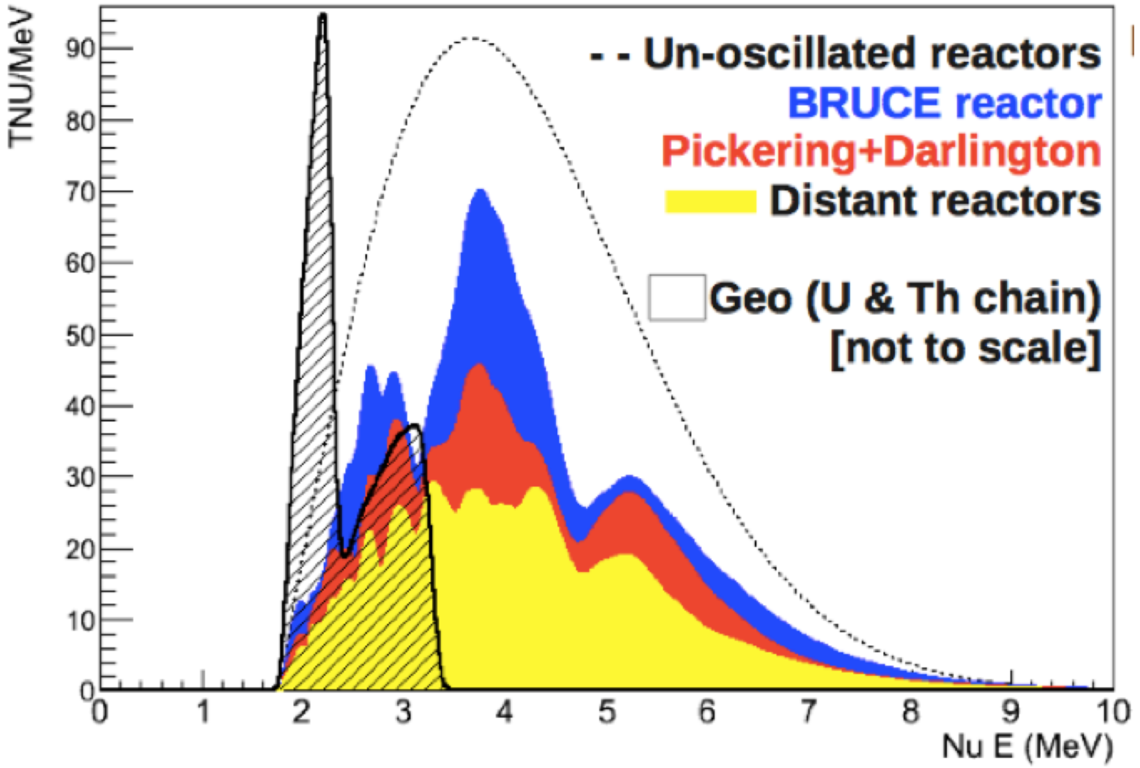
Escrihuela et al, PRD80 (2009)

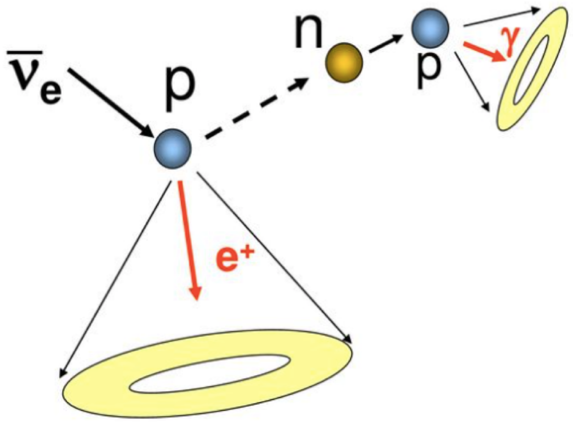
Coloma et al, PRD96 (2017)

Maltoni & Smirnov, EPJ 2015

Tortola, Neutrino2018

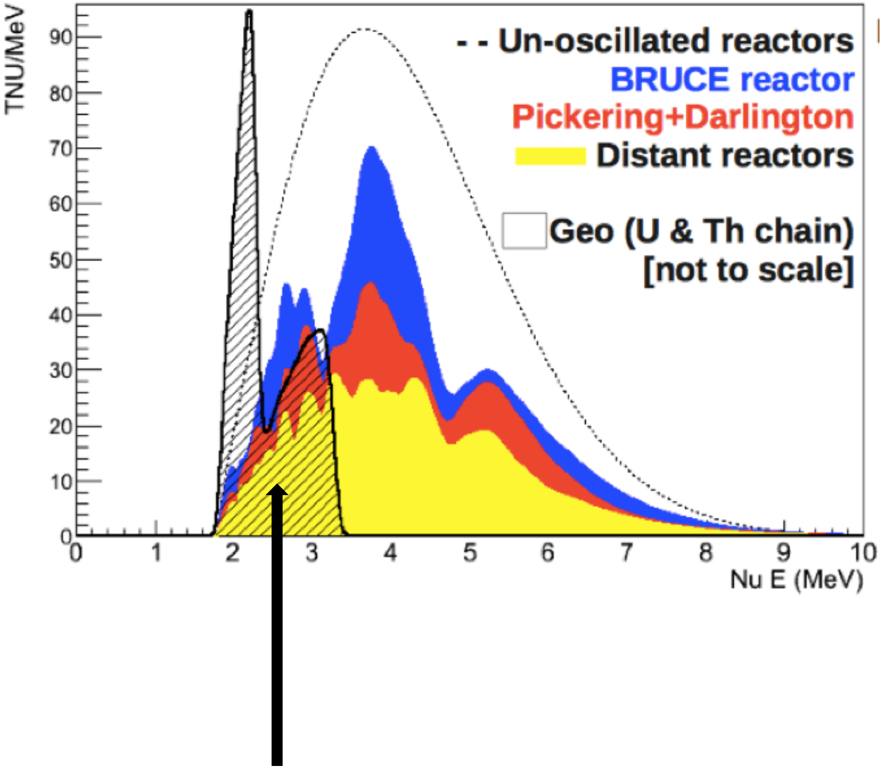
Reactor Neutrinos – Scintillator Phase

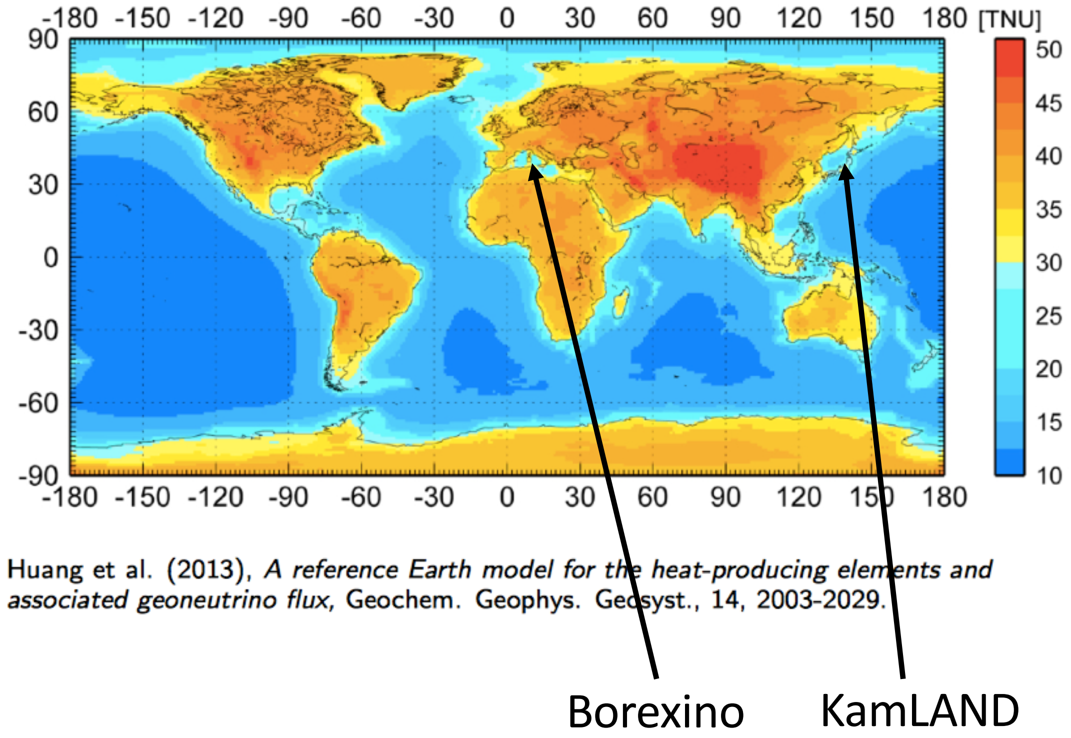




- Inverse beta decay gives clear coincidence signal in scintillator (and Te-loaded Scintillator), low background
- Expect 0.7e^{-5} statistical sensitivity on Δm_{12}^2 with 3 months of data
- SNO+ has potential to resolve KamLAND-Solar tension

Geo Neutrinos – Scintillator Phase



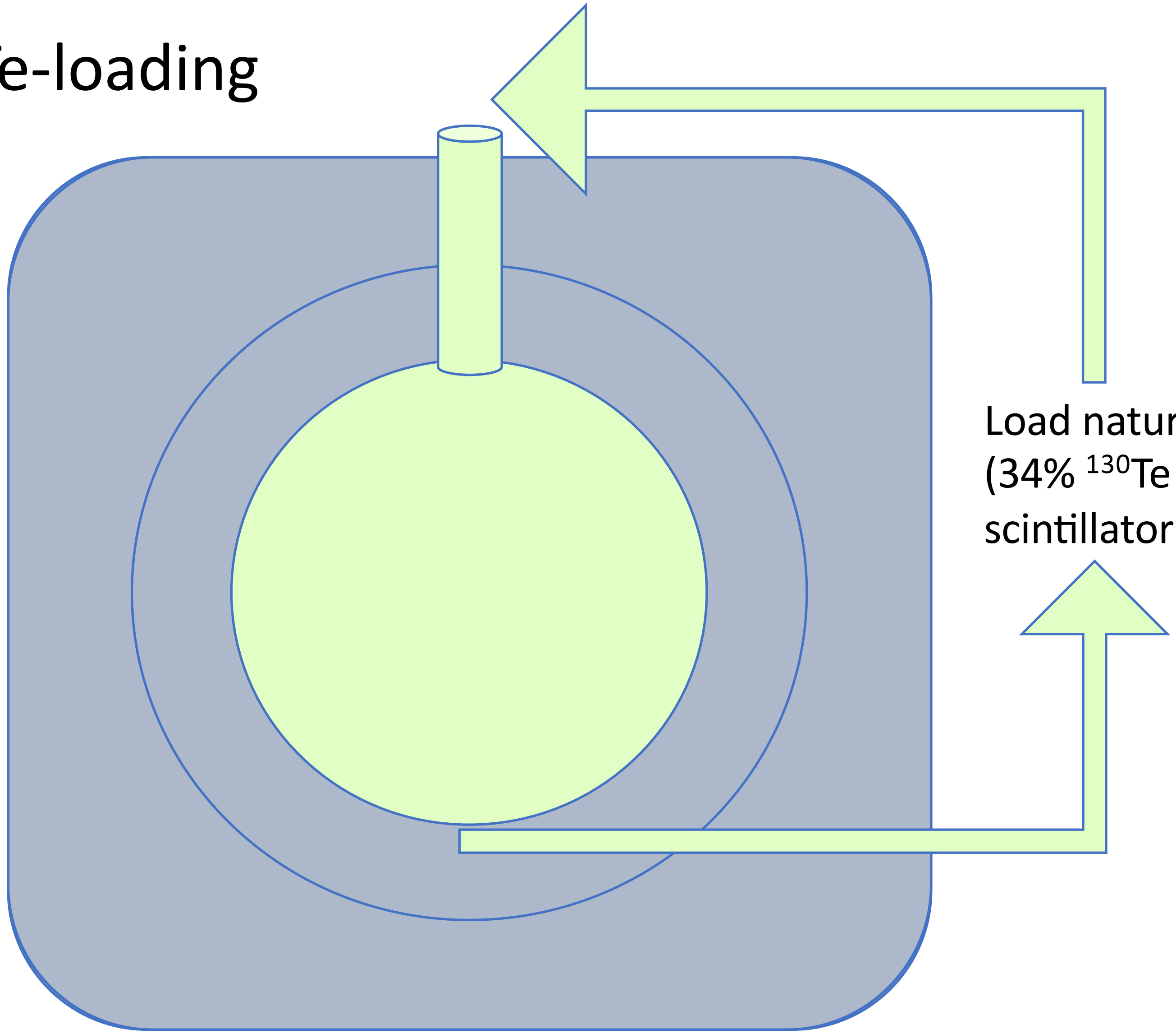


Huang et al. (2013), *A reference Earth model for the heat-producing elements and associated geoneutrino flux*, Geochem. Geophys. Geosyst., 14, 2003-2029.

- Expect 30 geo-ν events per year in SNO+
- 1st measurement in North America
- Results help to distinguish between different geo-physics models

Filling SNO+

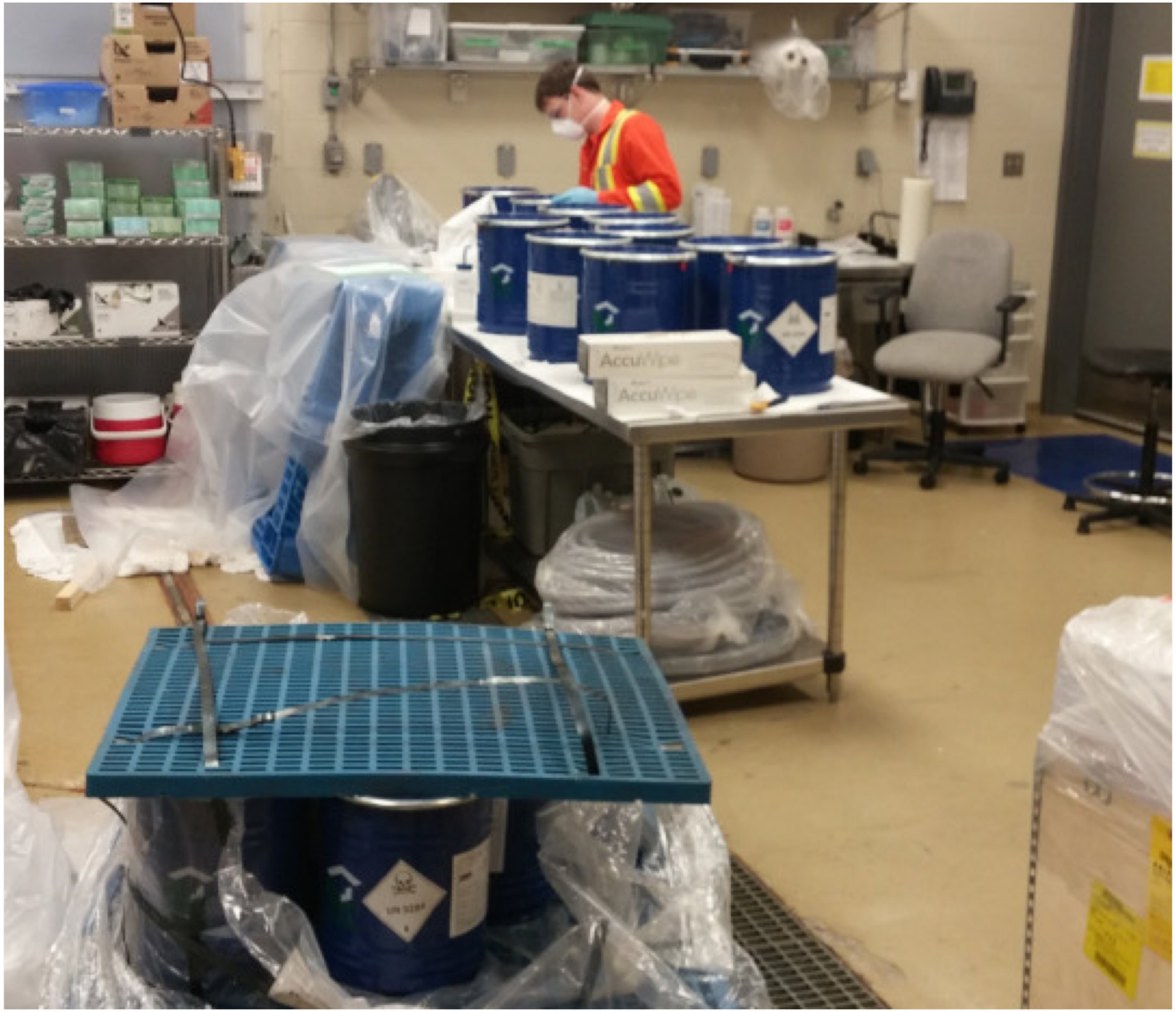
- Phase 2 – Te-loading



Load natural Te (34% ^{130}Te into the scintillator)

First batch in storage underground
Cosmogenic cool-down since January 2015

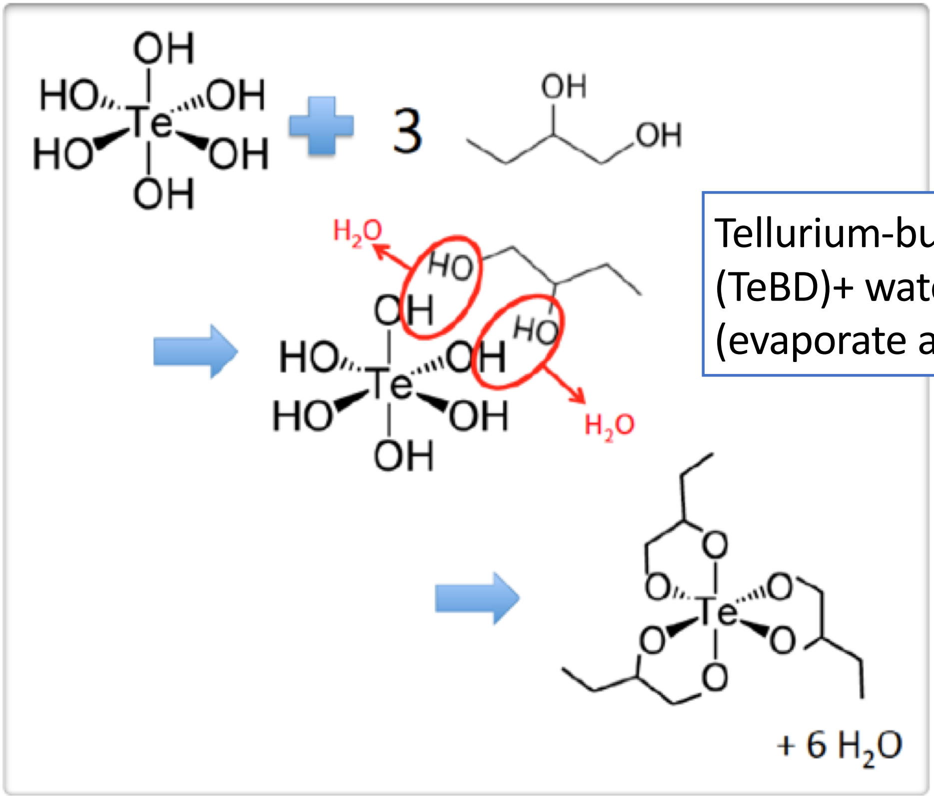
Second Delivery – September 2016



Loading the scintillator

Load Te into scintillator with Butanediol

- TeBD very transparent and soluble in LAB liquid scintillator
- Expect ~400 p.e./MeV



Tellurium-butanediol complex (TeBD)+ water
(evaporate after synthesis)

SNO+ phase 1
loading: 0.5%
=
1333 kg of isotope

Telluric acid purification

<u>0.5% Te target levels:</u>

1.3×10^{-15}g/g ^{234}U

5×10^{-16}g/g ^{232}Th

Cosmogenic reactivation
Lozza & Petzoldt, Cosmogenic activation of a natural tellurium target, Astroparticle Physics. DOI: 10.1016/j.astropartphys.2014.06.008

Need 10^4-10^5 factor reduction for cosmogenically activated ^{60}Co, ^{110m}Ag, ^{126}Sn, ^{88}Zr, ^{88}Y, ^{124}Sb

Purification technique relies on solubility of TeA in water based on pH

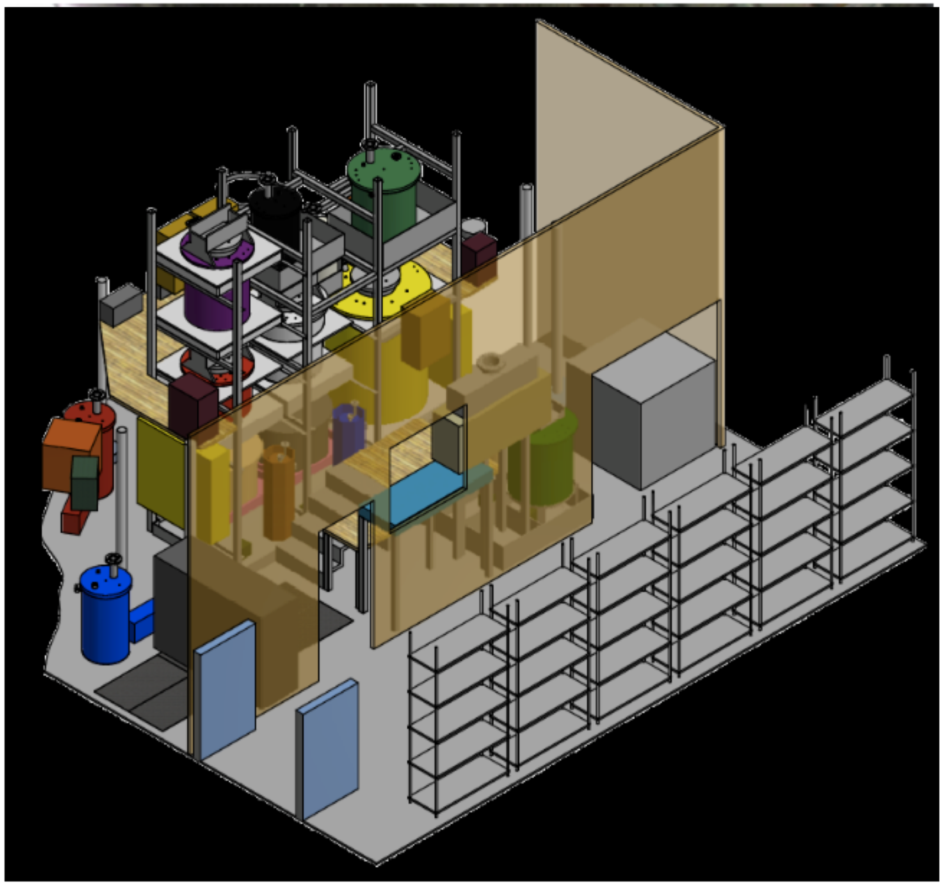
$$Te(OH)_6 \leftrightarrow Te(OH)_5O^- + H^+$$

Insoluble soluble

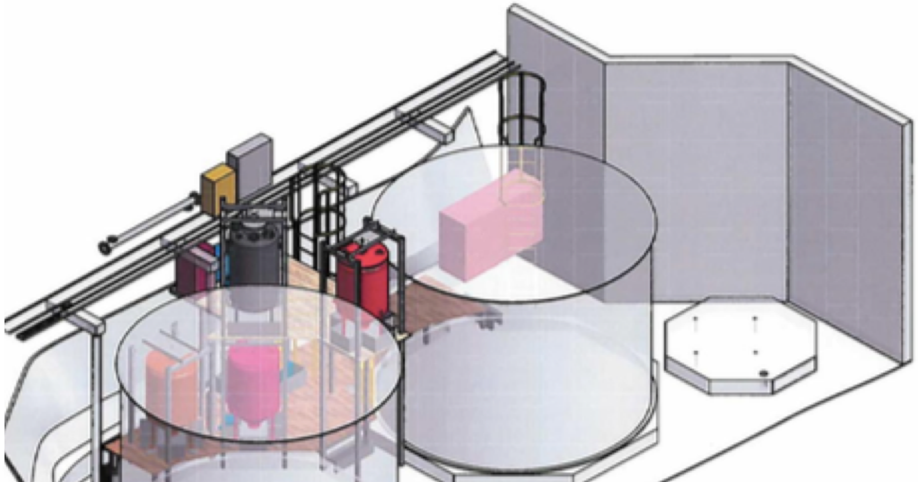
Force TeA to recrystalise by adding Nitric acid, let it precipitate out and drain the ‘dirty’ liquid

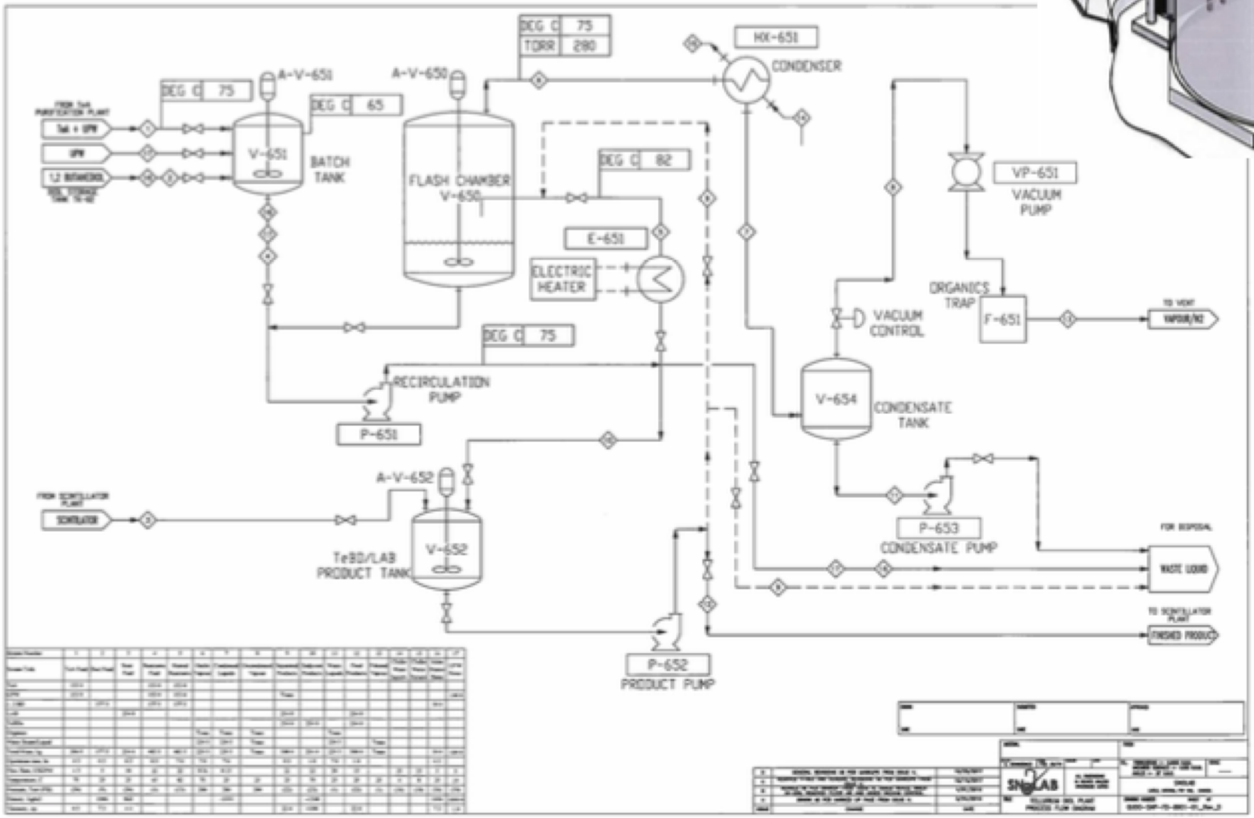
10kg Pilot plant
Successful operation

TeA Plant



Commissioning now underway

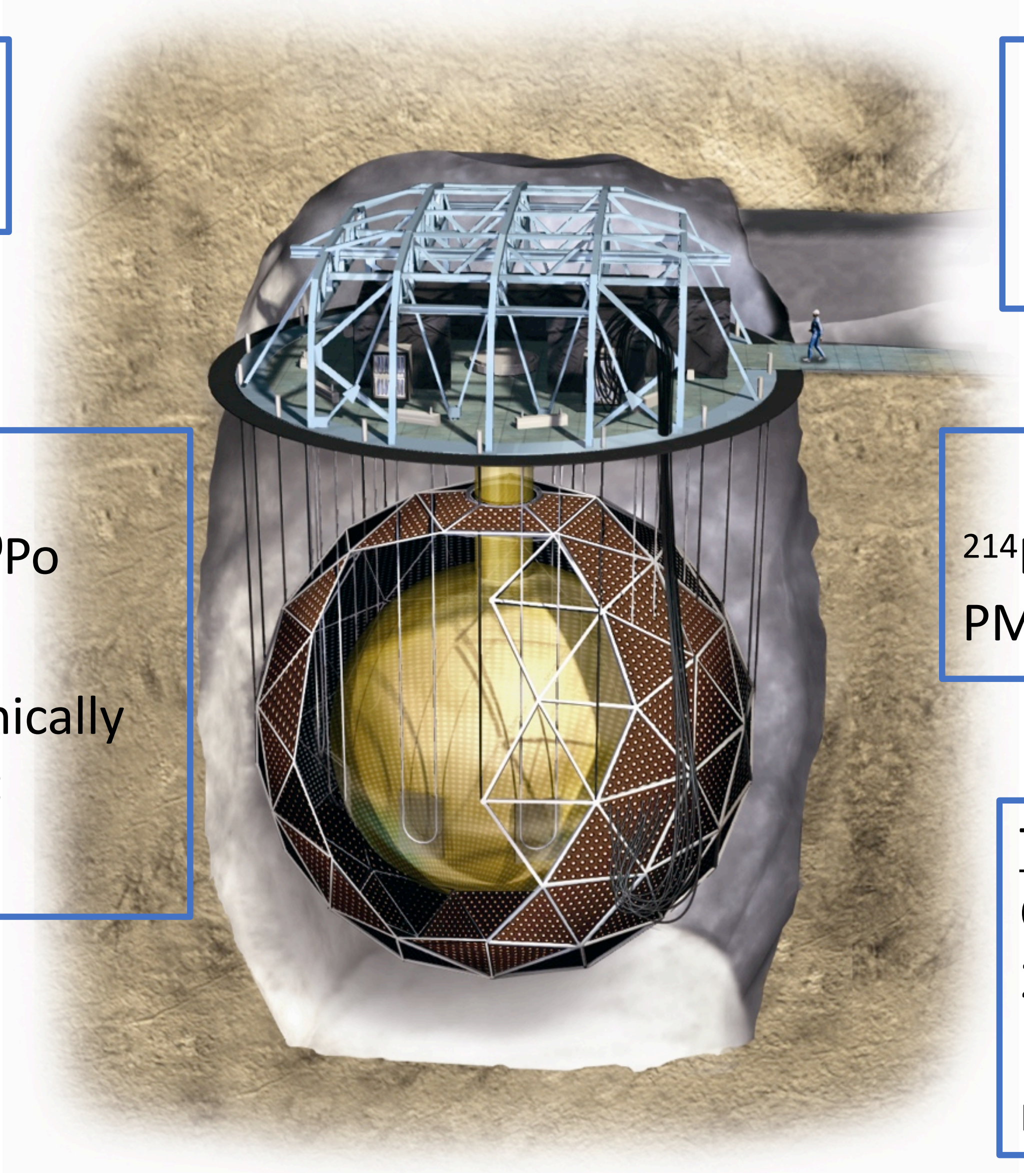




Diol Plant

Note: Space is limited underground!

Backgrounds



LAB-PPO

^{238}U, ^{232}Th, ^{14}C

Solar ^{8}B ν

Tellurium

^{238}U, ^{232}Th, ^{210}Po

2νββ

Residual cosmogenically activated isotopes:

^{60}Co, ^{131}I

Implanted Radon daughters in AV

^{210}Pb, ^{210}Bi, ^{210}Po

Externals:

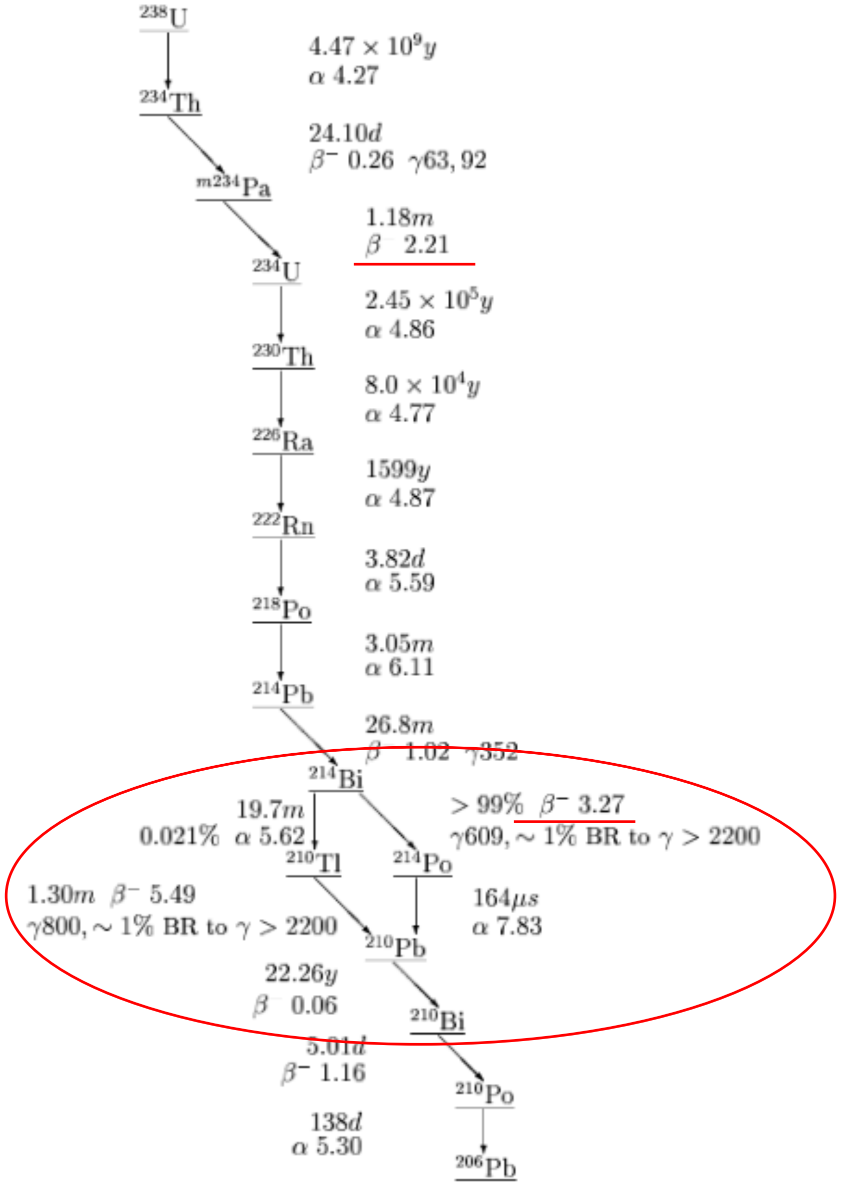
^{214}Bi, ^{208}Tl ϒ from PMTs, AV, Ropes, H_2O

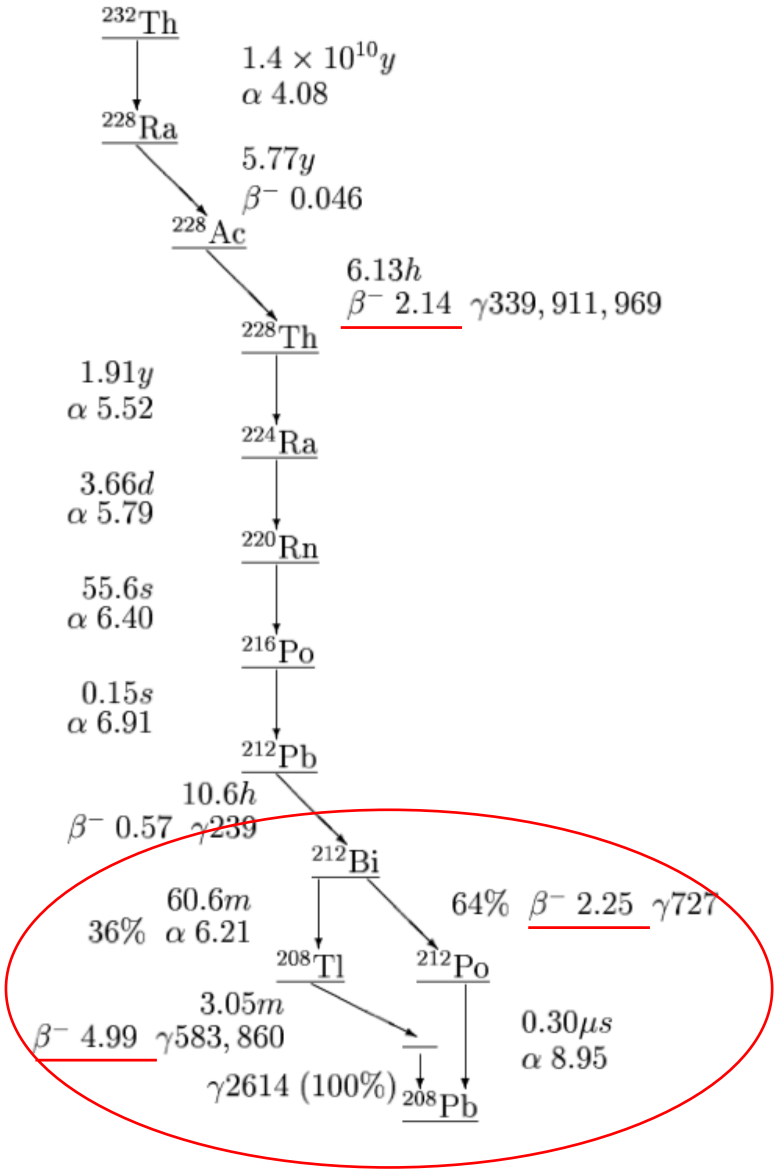
Thermal neutrons:

Capture on H to 2.2MeV ϒ:

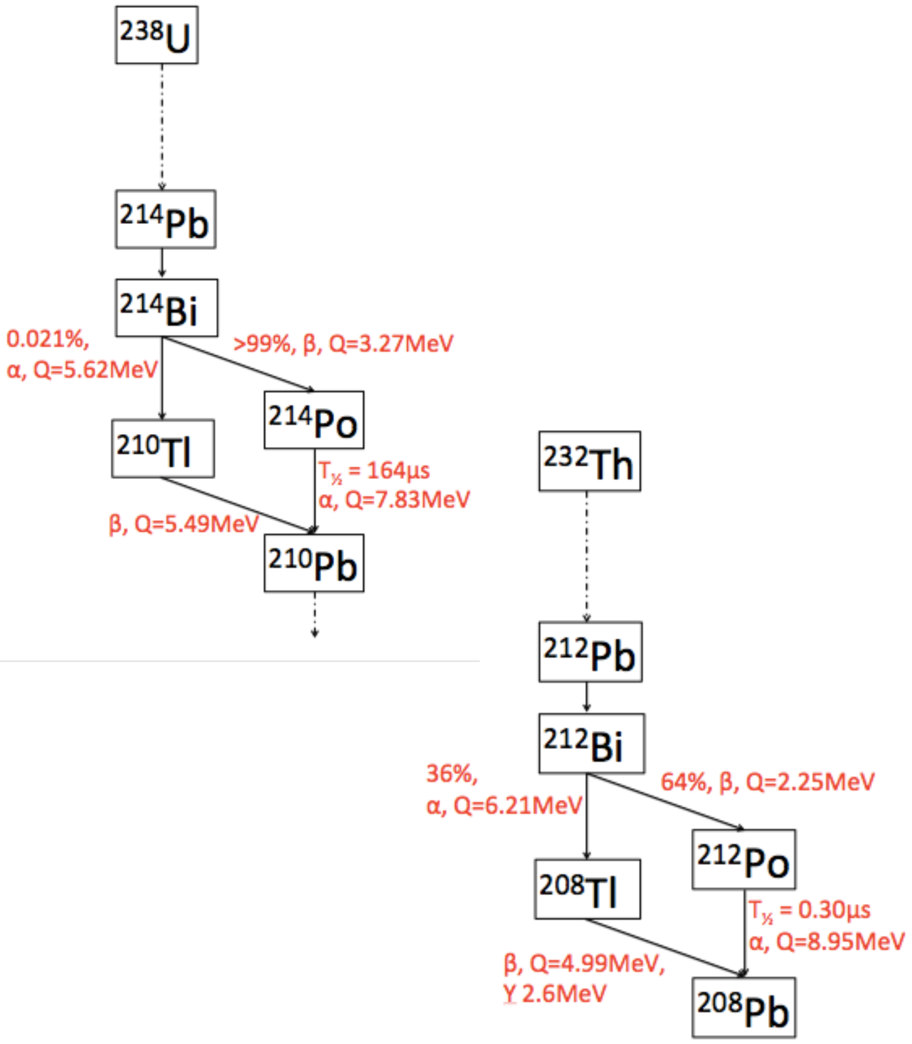
Muon induced neutrons, (α,n)

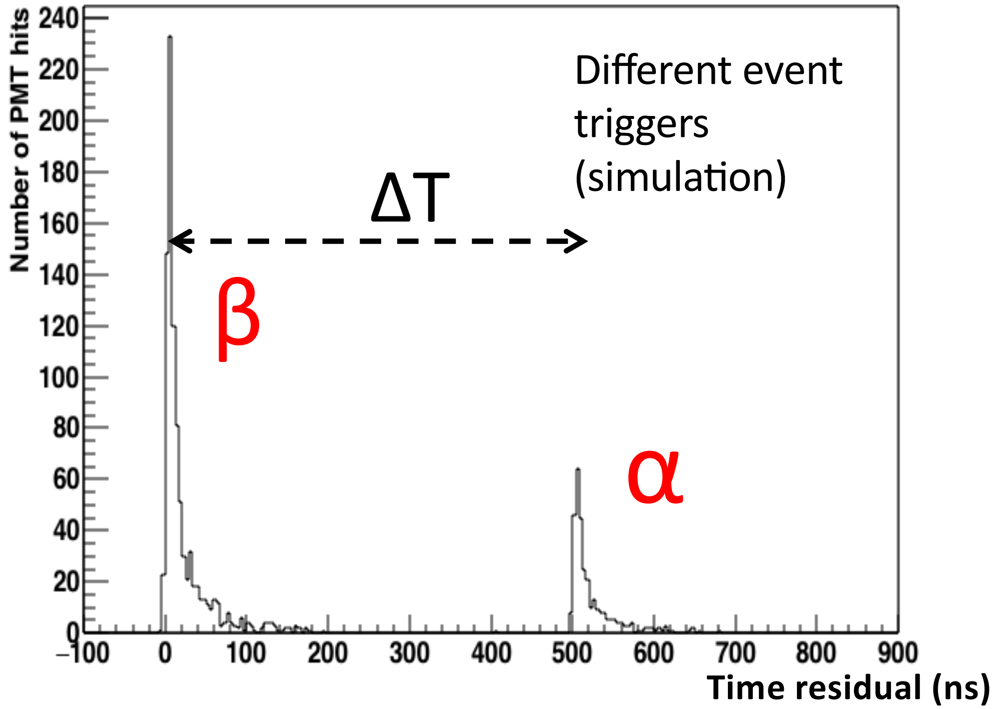
Uranium and Thorium Chain





Bi-Po Rejection 1





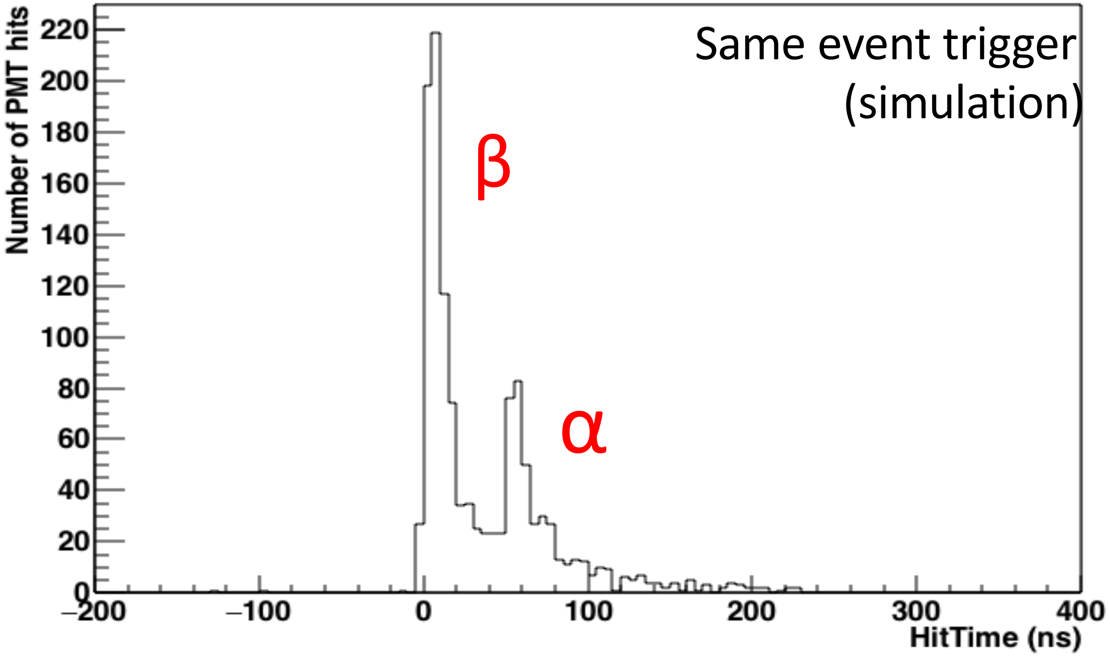
Different event triggers (simulation)

Rejection criteria: $\Delta T(\beta\text{-}\alpha) < 24 \times T_{½}^{214Po}$
Nhits(α) > 50
if(ΔT>500ns), ΔR(β-α) < 1.5m

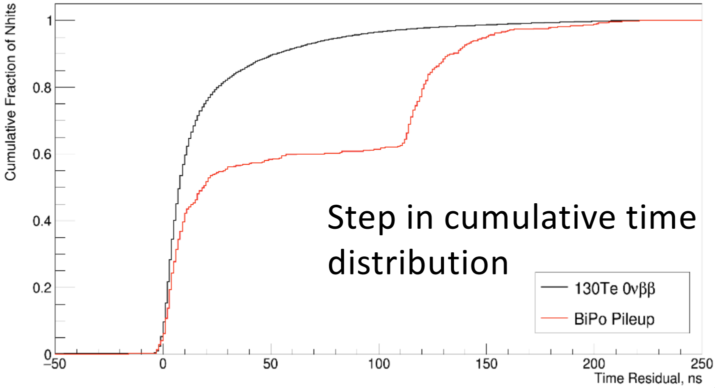
Calculated rejection efficiency (α >400ns after β, R<3.5m):

ε_{214} = 99.9975%, ε_{212} = 99.999%

BiPo Rejection 2

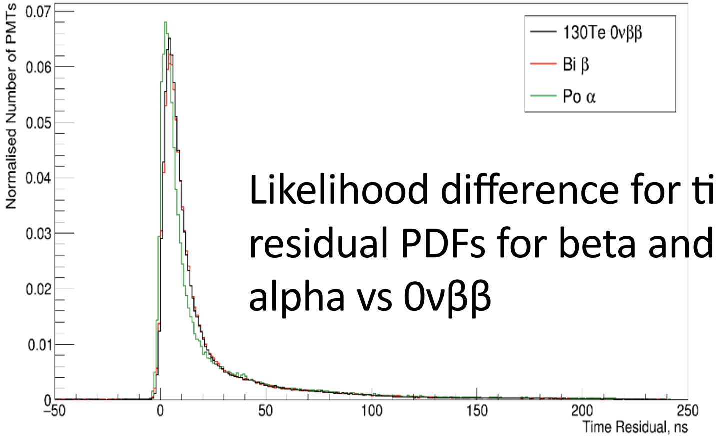


K. Majumdar, DPhil Thesis, University of Oxford, 2015

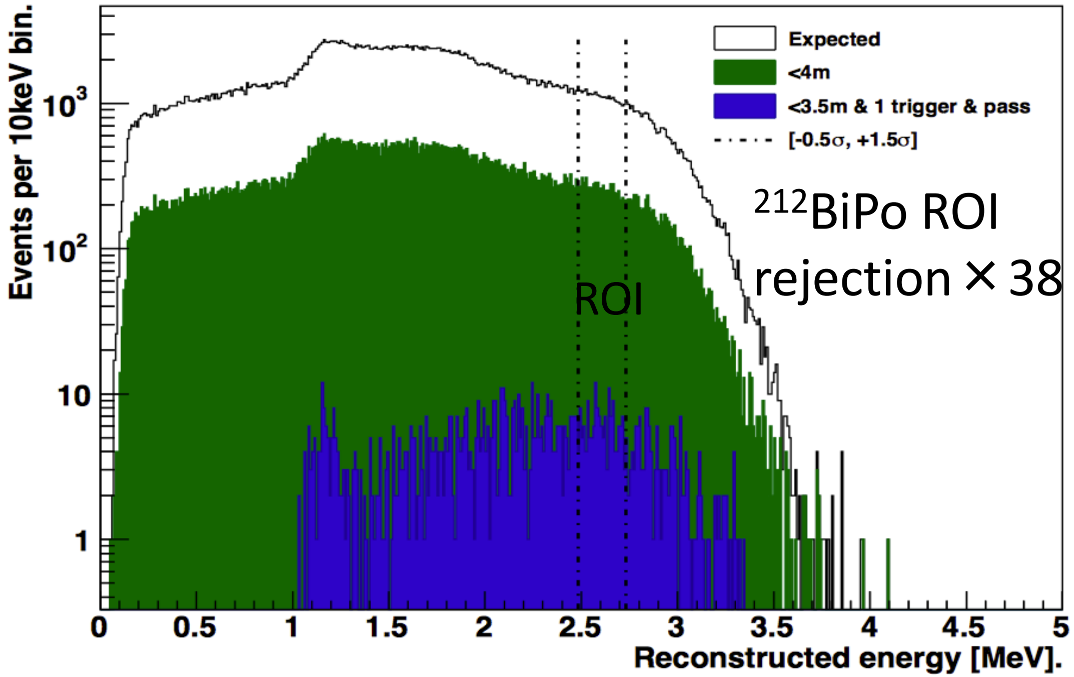


Step in cumulative time distribution

Time residual (ns)



Likelihood difference for time residual PDFs for beta and alpha vs 0νββ

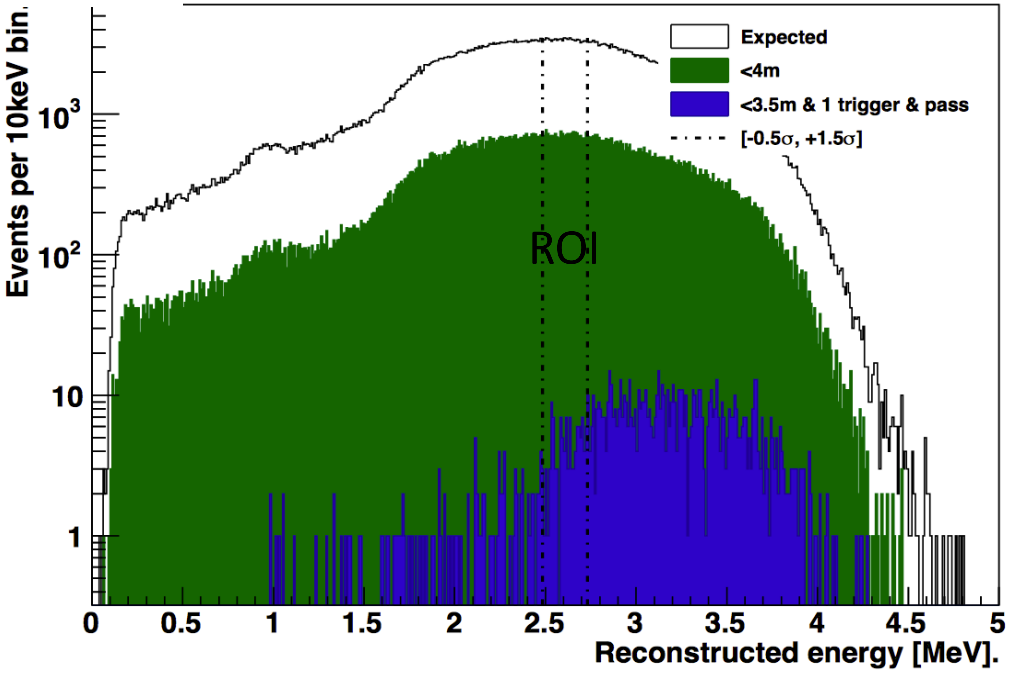


^{212}BiPo ROI

rejection × 38

^{214}BiPo ROI

rejection × 49



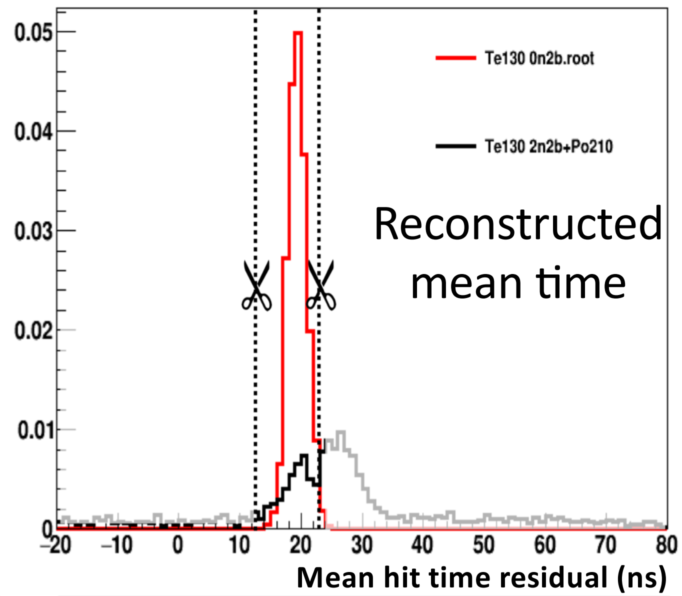
< 4 BiPo total / year in ROI

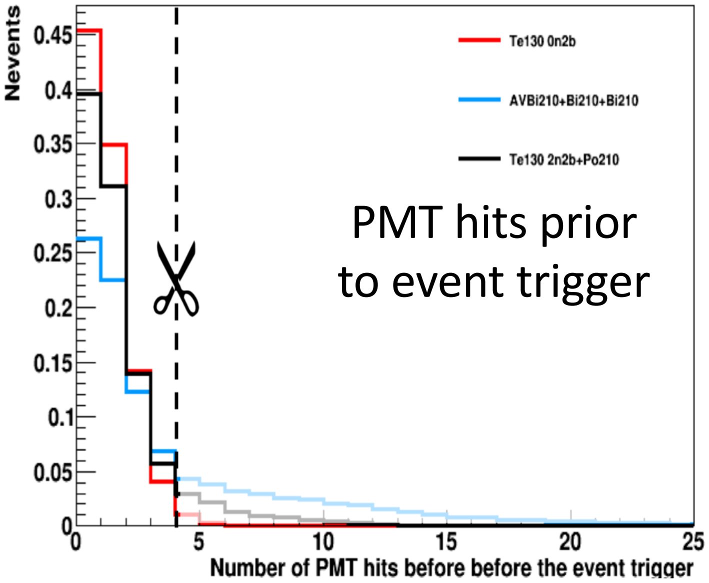
Methods sensitive to scintillator optics:

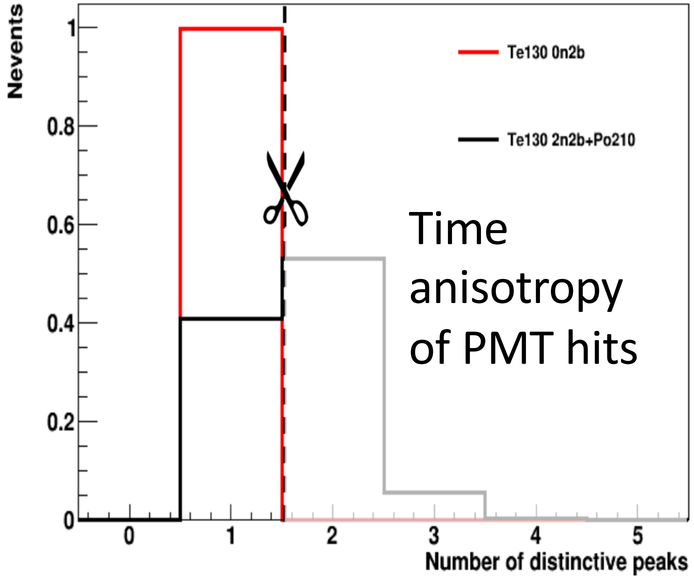
Light yield

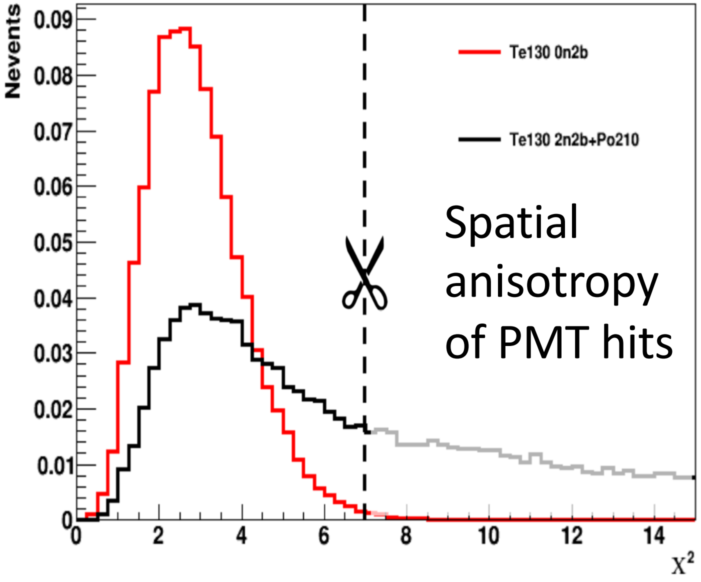
Timing

Random PileUp

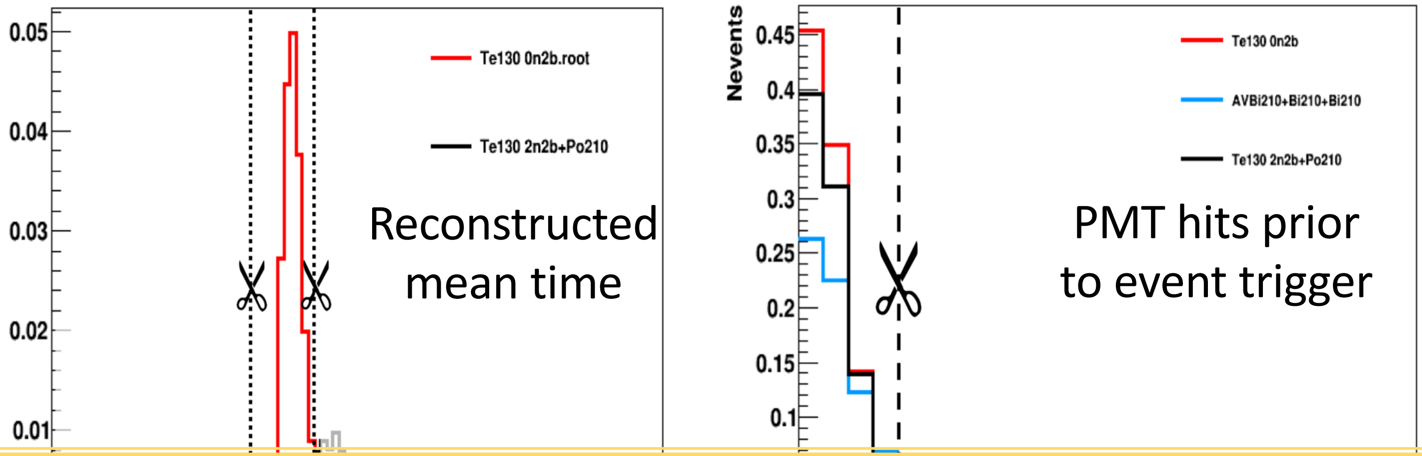








Random PileUp

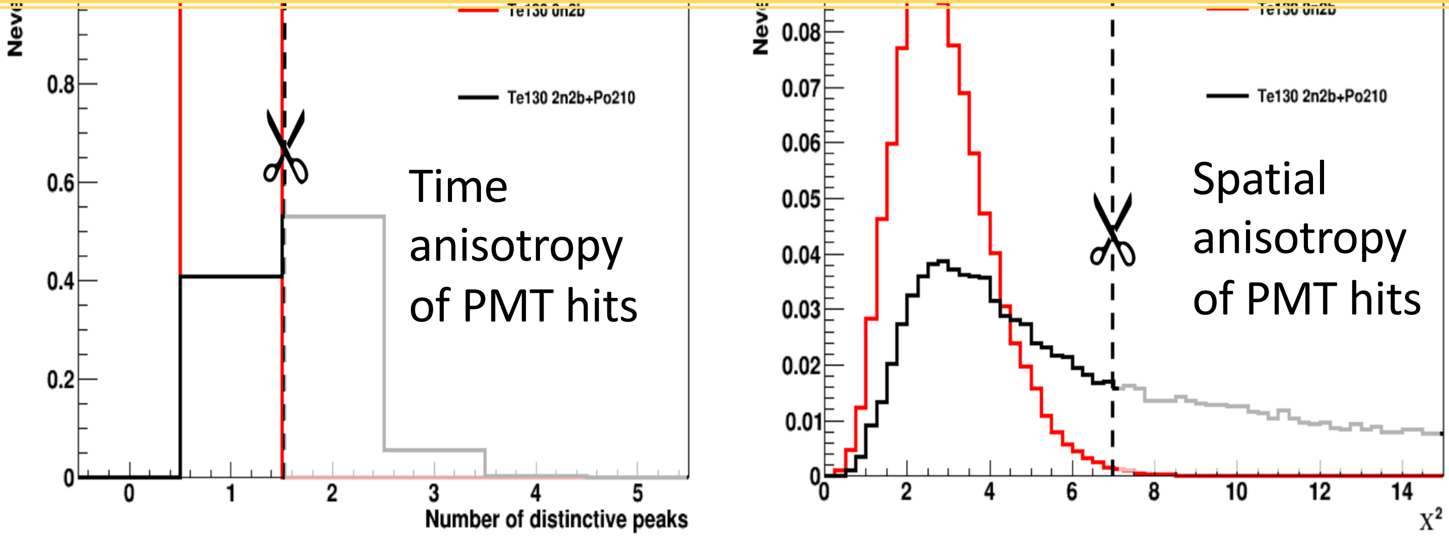


Reconstructed mean time

PMT hits prior to event trigger

Expect 36.3 pileup events / year in 0νββ ROI before rejection

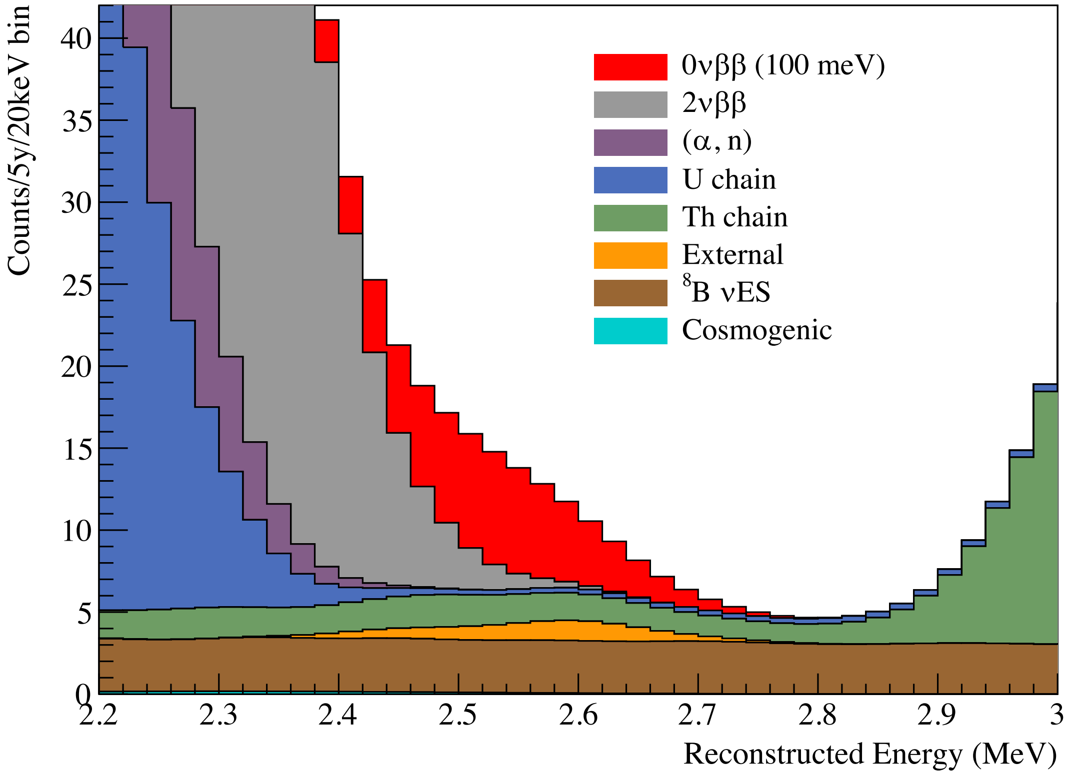
➔ **0.23** events/year after cuts



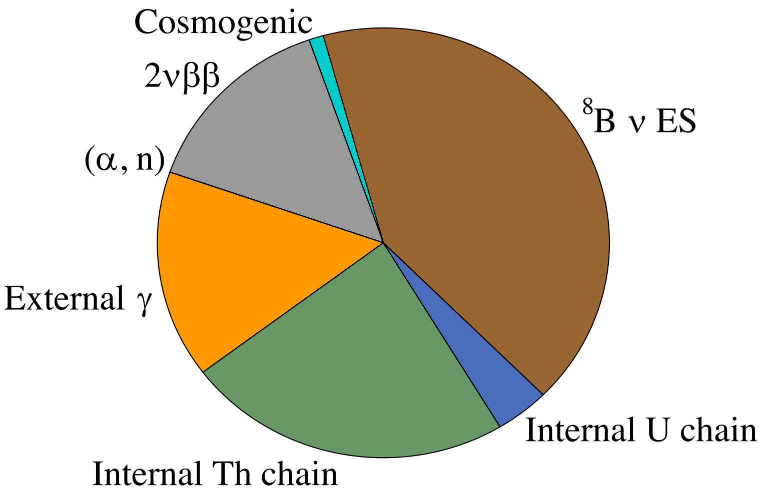
Time anisotropy of PMT hits

Spatial anisotropy of PMT hits

SNO+ Sensitivity



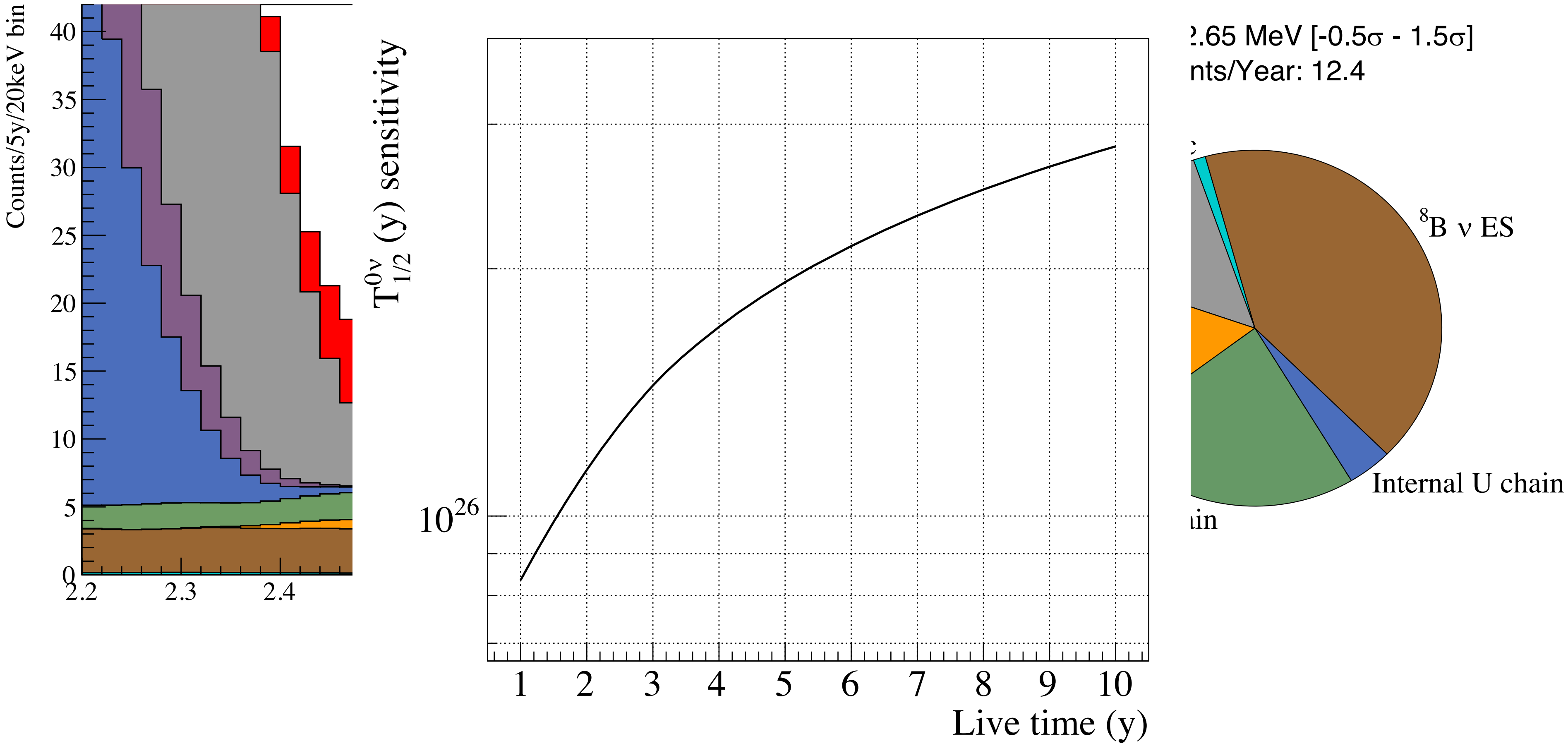
ROI: 2.49 - 2.65 MeV [-0.5σ - 1.5σ]
Counts/Year: 12.4



LAB+PPO+bisMSB+Te(0.5%)+Diol
390 PMT hits / MeV

Sensitivity: $T_{1/2}$>1.9.10^{26} years (5 years)

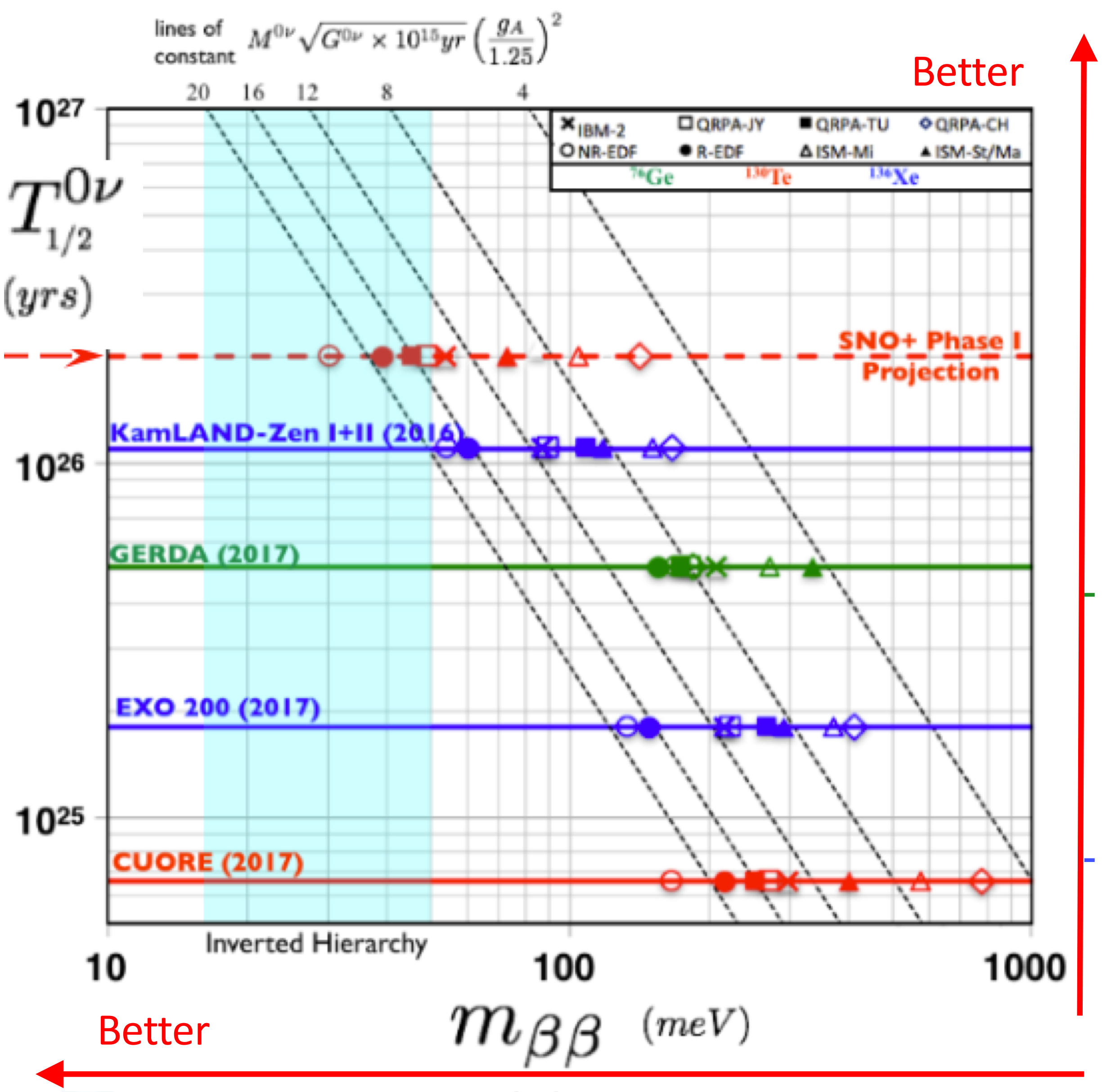
SNO+ Sensitivity



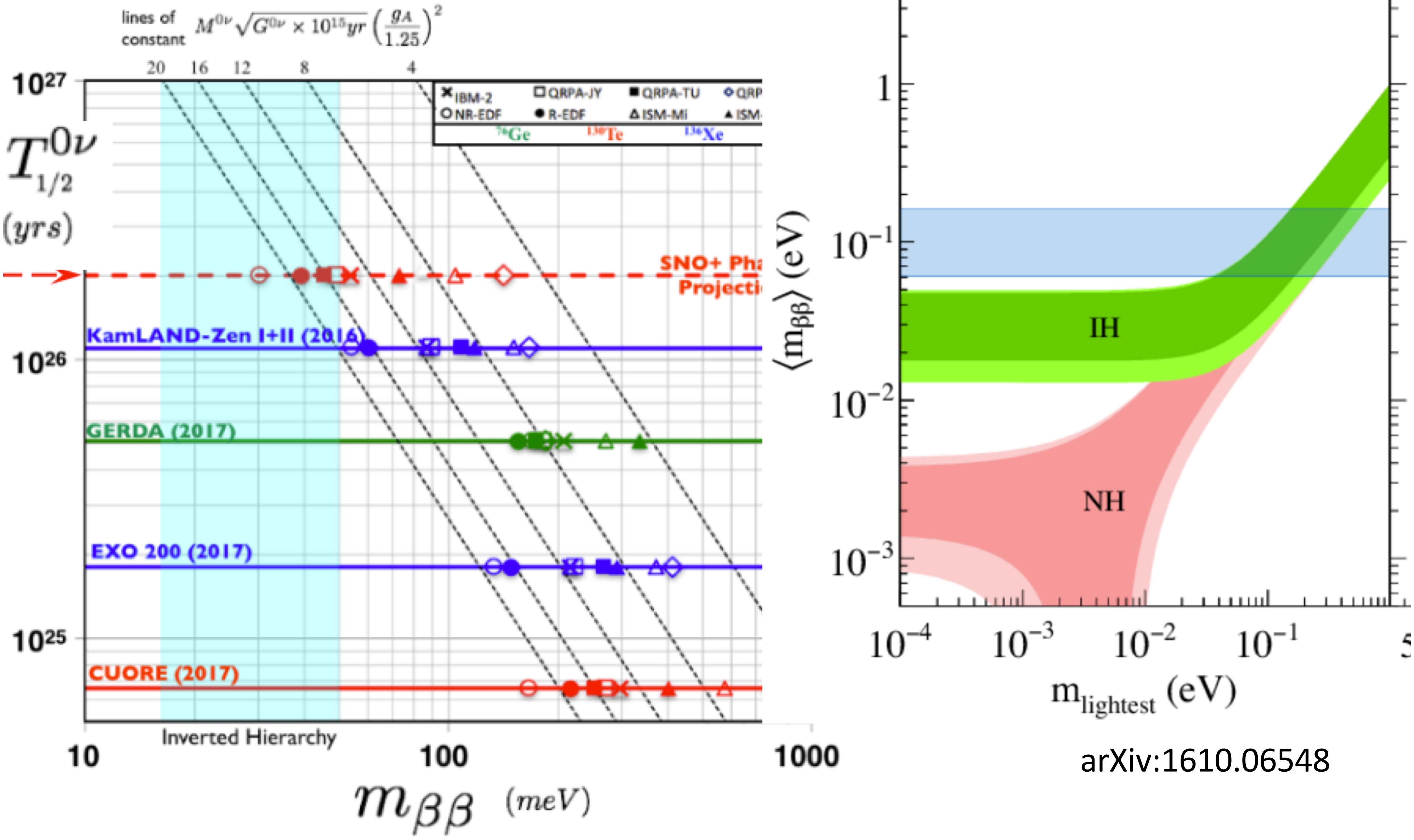
Sensitivity: $T_{1/2}>1.9.10^{26}$ years (5 years)

SNO++ R&D: HQE PMTs, higher Te loading

Sensitivities and Outlook



Sensitivities and Outlook

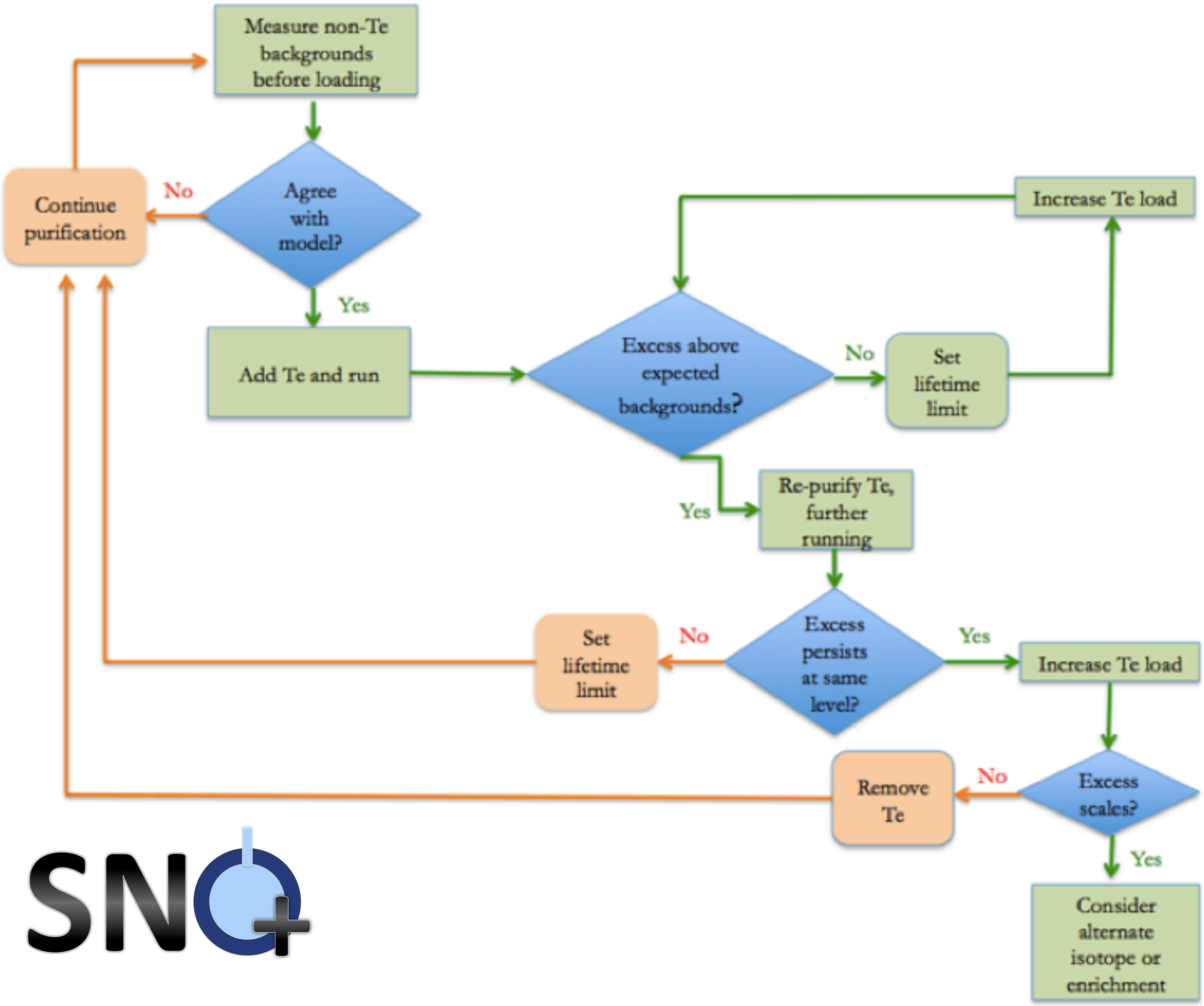


arXiv:1610.06548

What if you see a signal?

- Scrutinize analysis
    - Blind search?
- Rule out all potential backgrounds
- Does it scale with isotope mass? Livetime?
- Is the signal seen with different isotopes? Experiments?

SNO+: What if we see a Bump?



SUMMARY

- SNO+ is running and has produced first (water) physics results
  - Detector operating stably with low backgrounds and well understood response
  - New limits on invisible modes of nucleon decay
  - Publications imminent
- SNO+ is now filling with liquid scintillator
  - Potential to measure reactor m12 and geo-neutrinos in short scintillator run
  - Characterise Source-out backgrounds for…
- ^{130}Te double beta decay search
  - Main physics goal of SNO+