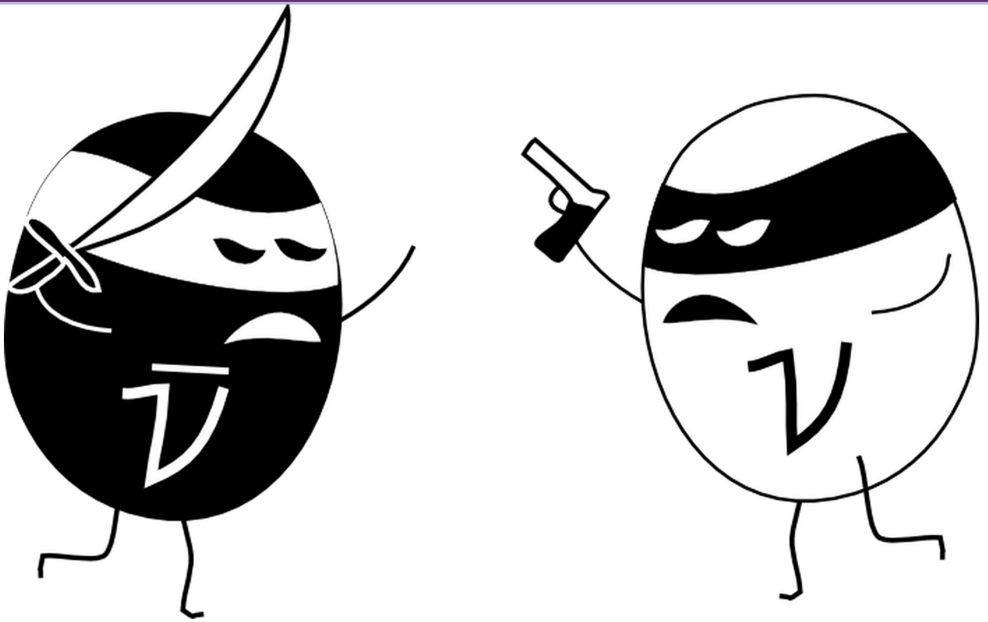
Aims and Current status of the SNO+ Experiment



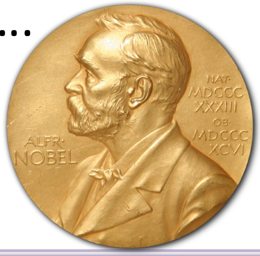
J R Wilson
20/10/2016

Contents

- ★From SNO to SNO+
- ★Phase 0: Water fill
  - ★Invisible nucleon decay
- ★Phase 1: Pure scintillator fill
  - ★Solar physics
- ★Phase 2: Te-loaded scintillator
  - ★Neutrino-less double beta decay
    - ★Backgrounds
    - ★Calibrations
- ★All phases:
  - ★Anti-neutrino physics
  - ★Supernovae

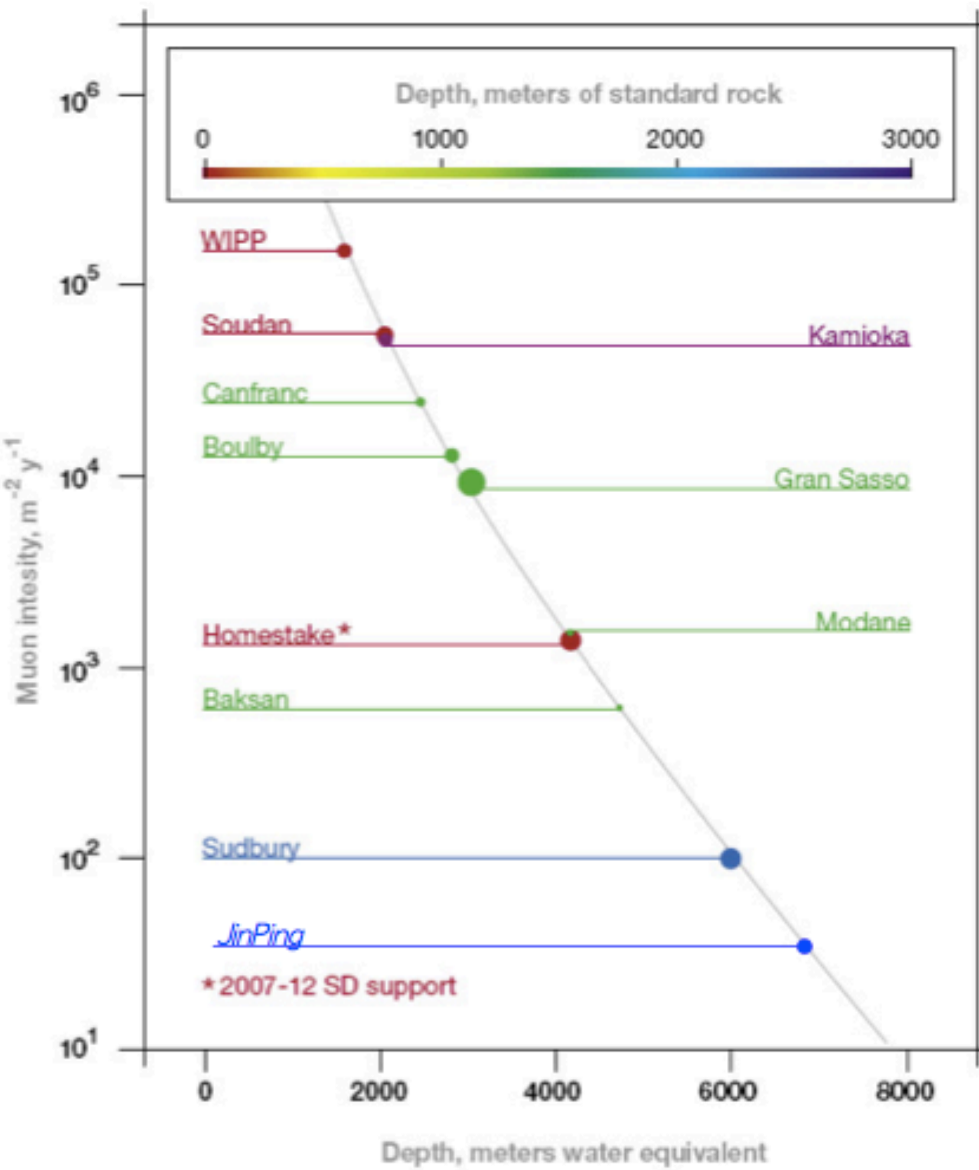
From SNO to SNO+

- Why do we only see 1/3 of the solar neutrinos we expect?
- Measure ν_e and ν_x flux on D_2O target to solve the "solar neutrino problem"
- Proved neutrinos oscillate between flavour states!
(DOI: 10.1103/PhysRevC.88.025501)
- They must have mass….



- How massive are neutrinos?
- How do we explain their tiny masses?
  - Probe the neutrino mass and nature through Neutrinoless double beta decay.
  - Is the neutrino a Majorana particle?
- Sensitivity to low energy interactions in low background liquid scintillator
  - Other precision physics measurements

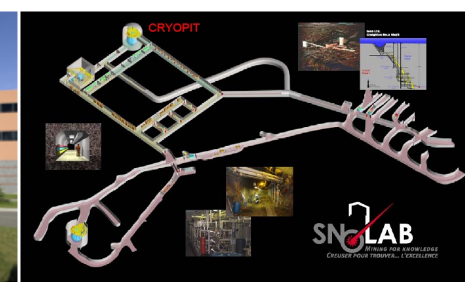
Location



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

Muon flux = 70 muons/day

Class-2000 clean room lab



The SNO detector

1000 tons of **Heavy Water**

Loaded with NaCl In phase 2

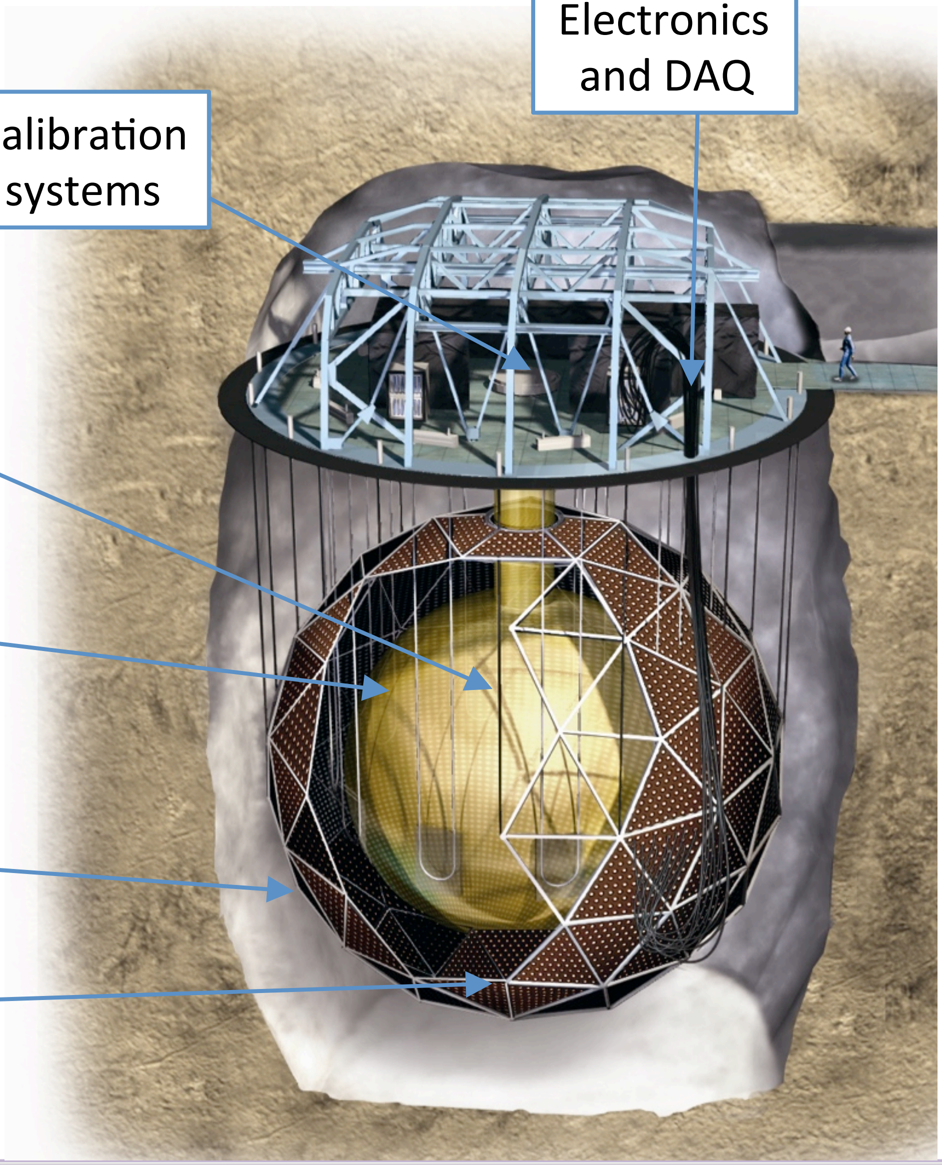
Contained in an **Acrylic vessel (AV)** 12 m diameter

Shielded by 7 kT Ultra-pure water

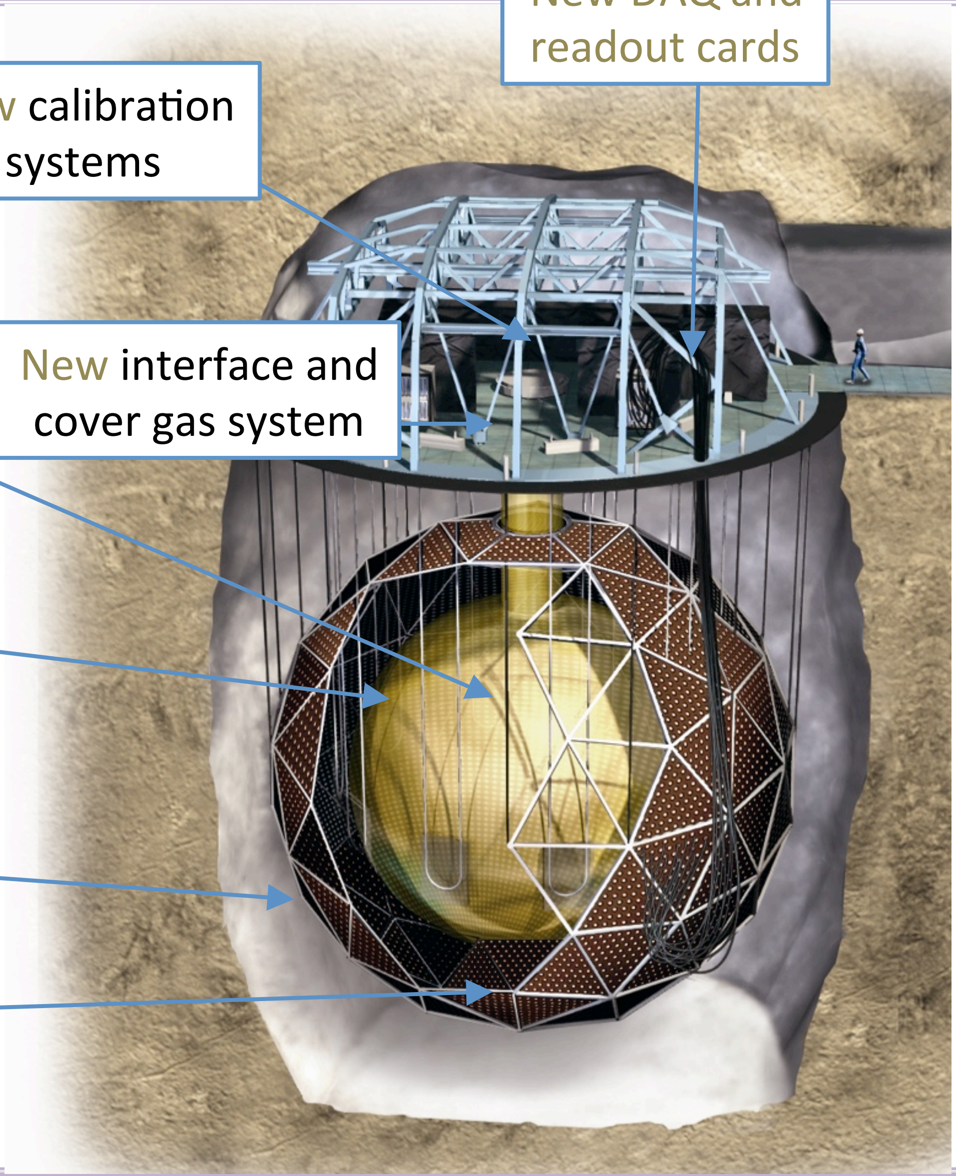
Viewed by **~9500 PMTs** (8”) mounted on 17 m diam. Structure

Calibration systems

Electronics and DAQ



The SNO+ detector



New DAQ and readout cards

New calibration systems

780 tons of **Liquid scintillator**

Loaded with double beta decay Isotope (Te130)

New interface and cover gas system

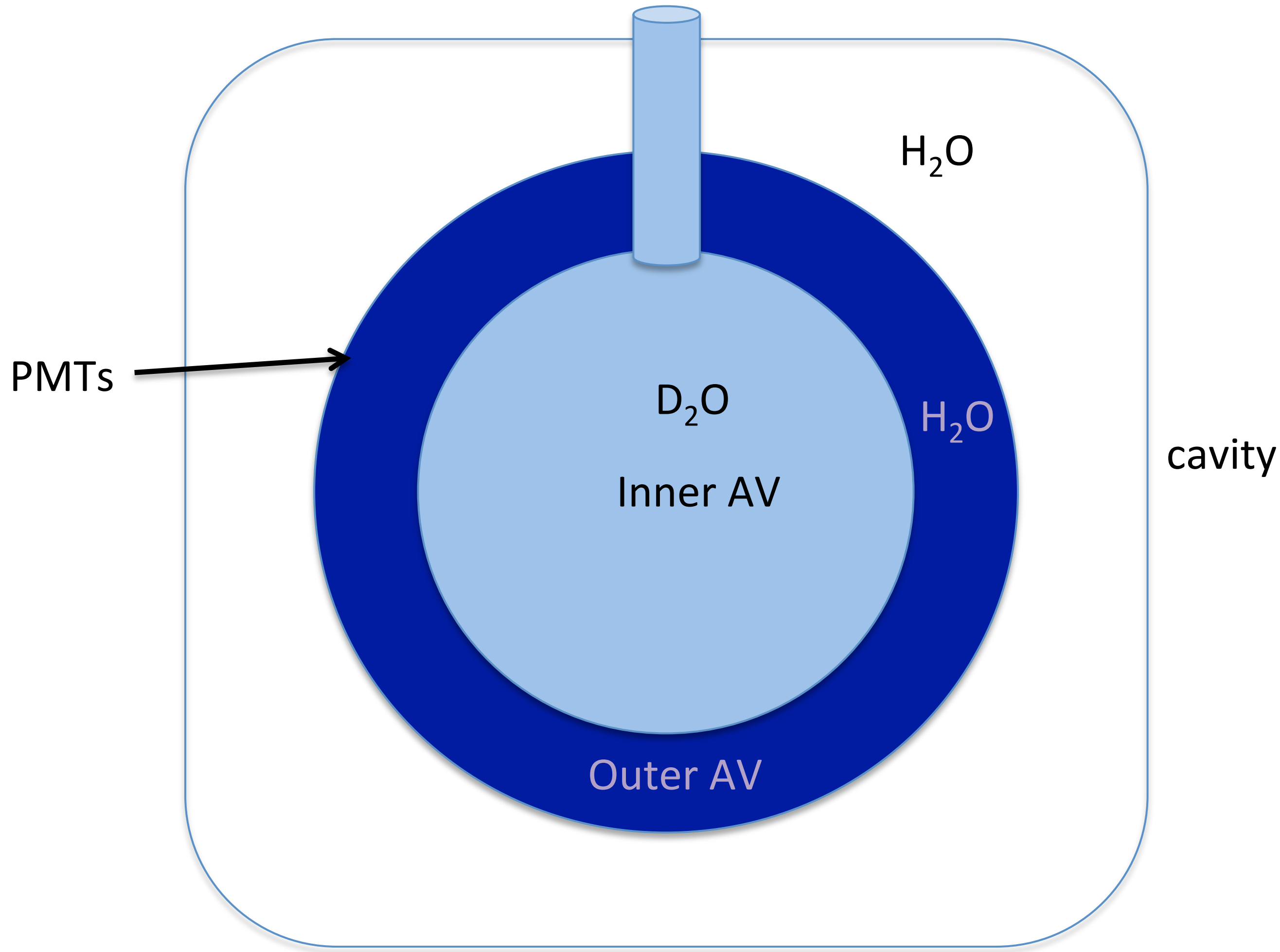
Contained in an **Acrylic vessel (AV)** 12 m diameter

Held-down by new rope system

Shielded by 7 kT Ultra-pure water

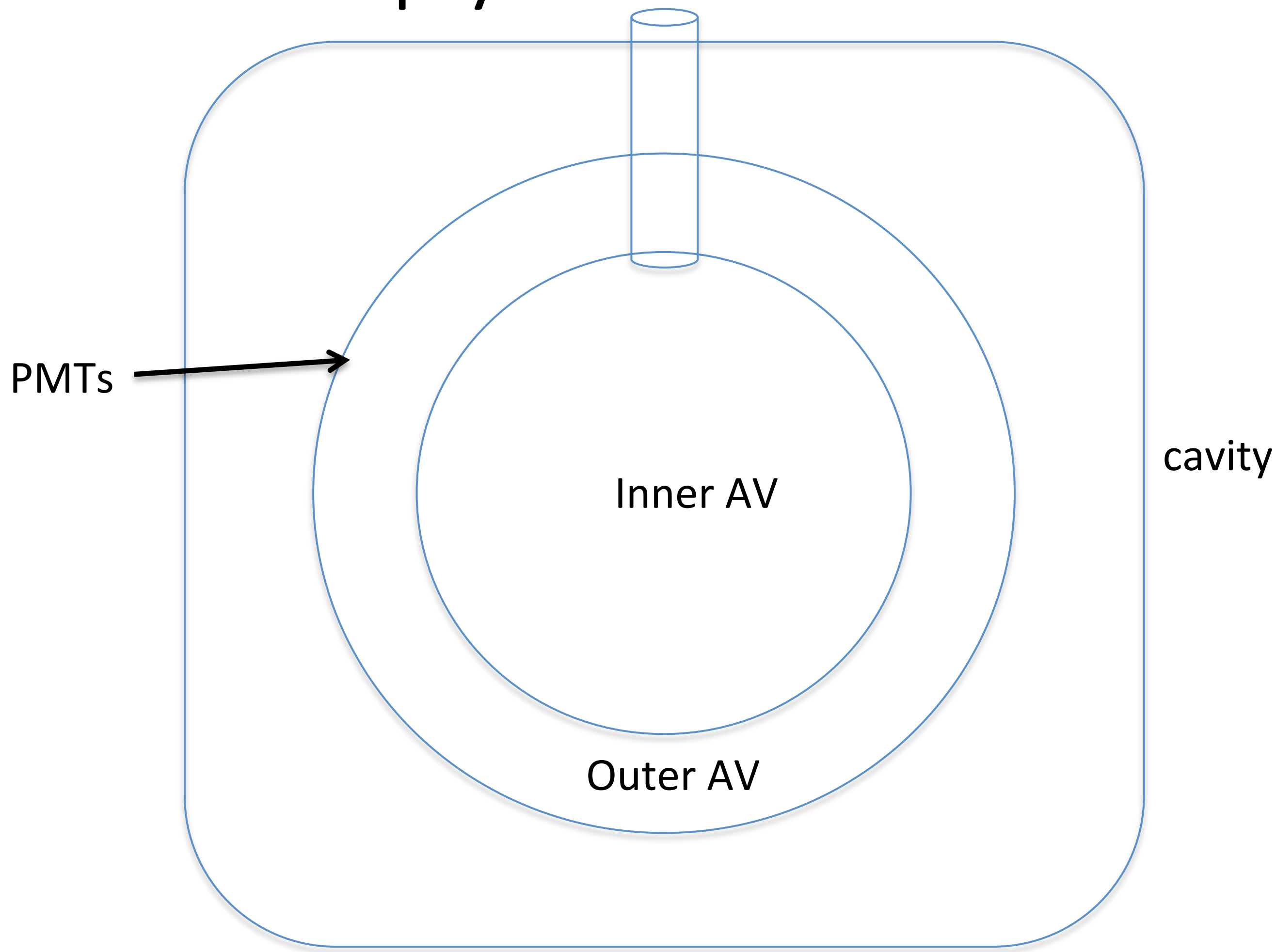
Viewed by **~9500 PMTs** (8”) mounted on 17 m diam. Structure

SNO

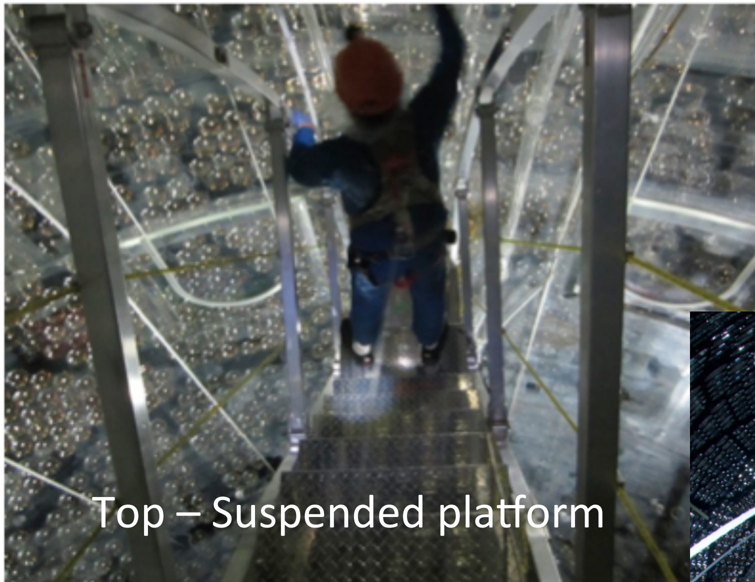


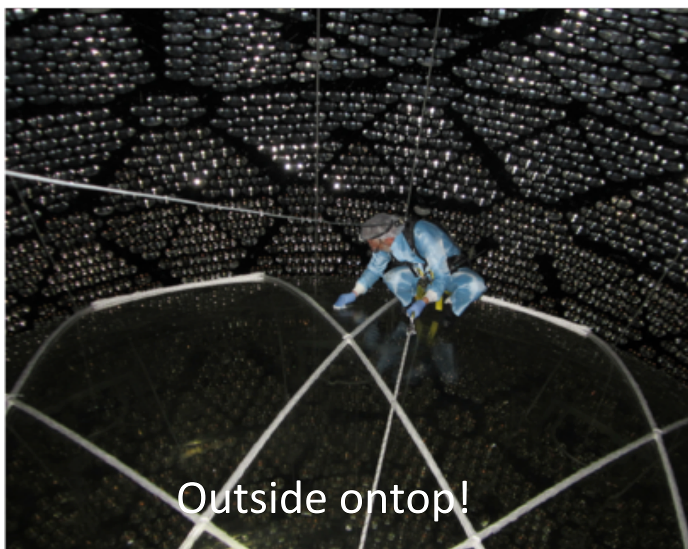
Filling SNO+

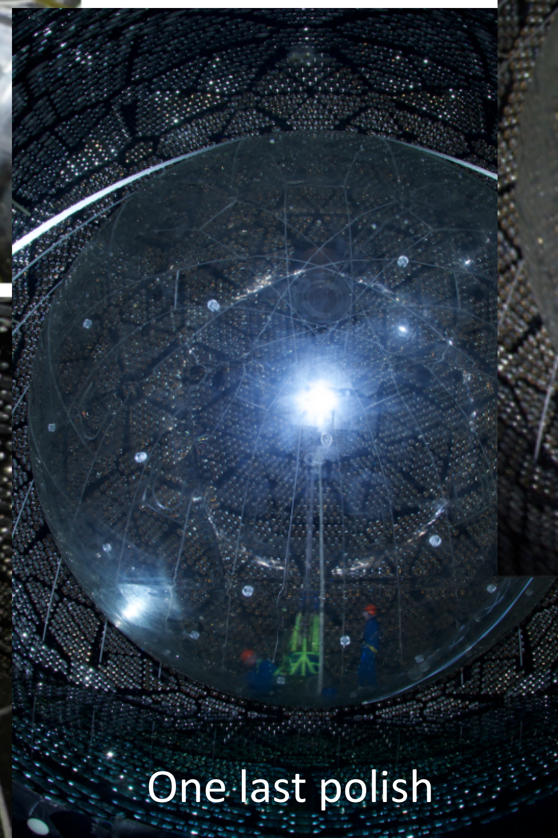
★After SNO – empty

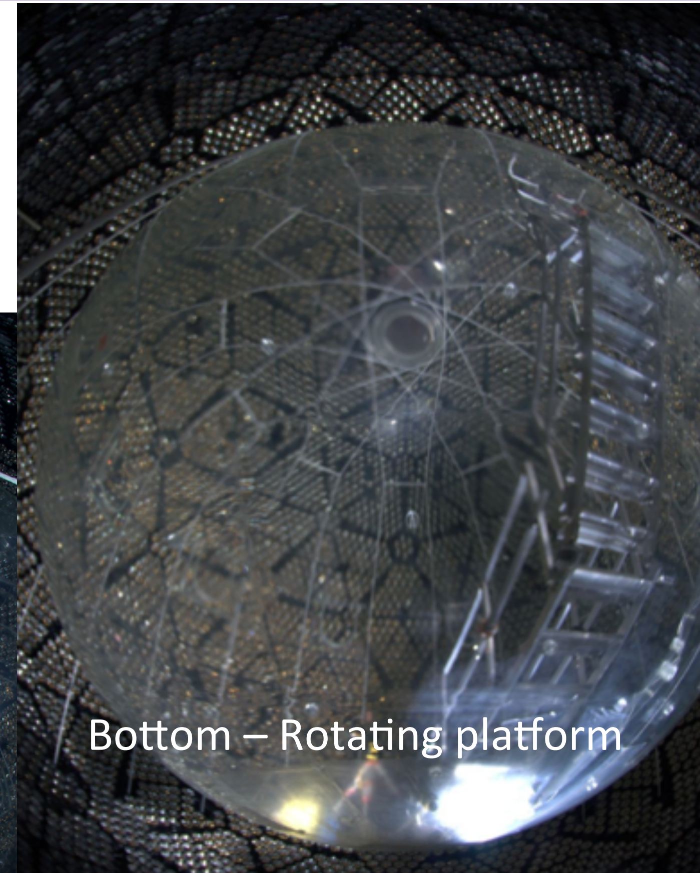


AV cleaning


Top – Suspended platform

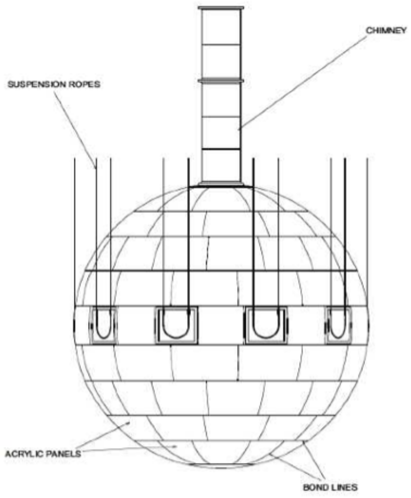

Outside ontop!


One last polish

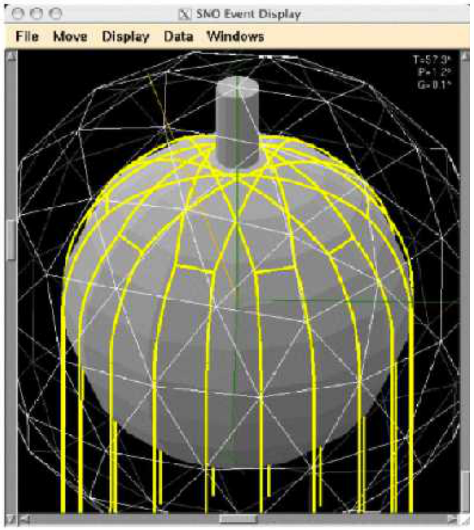

Bottom – Rotating platform

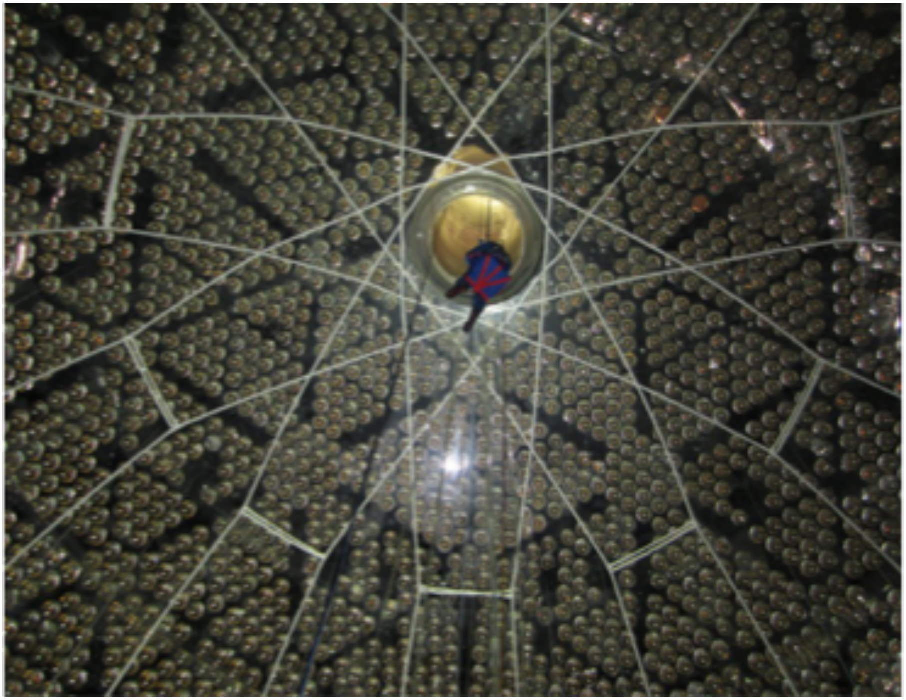
New rope system

SNO ropes



SNO+ rope net



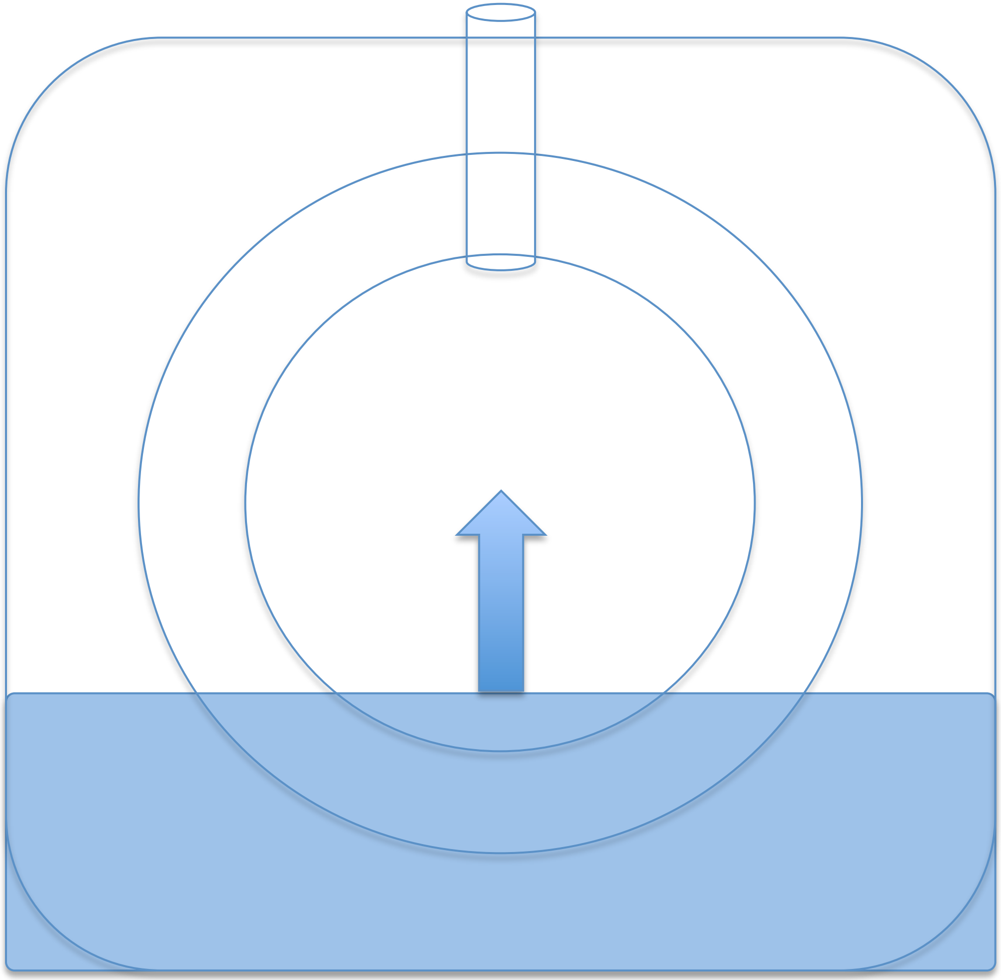


Installed before water fill

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.

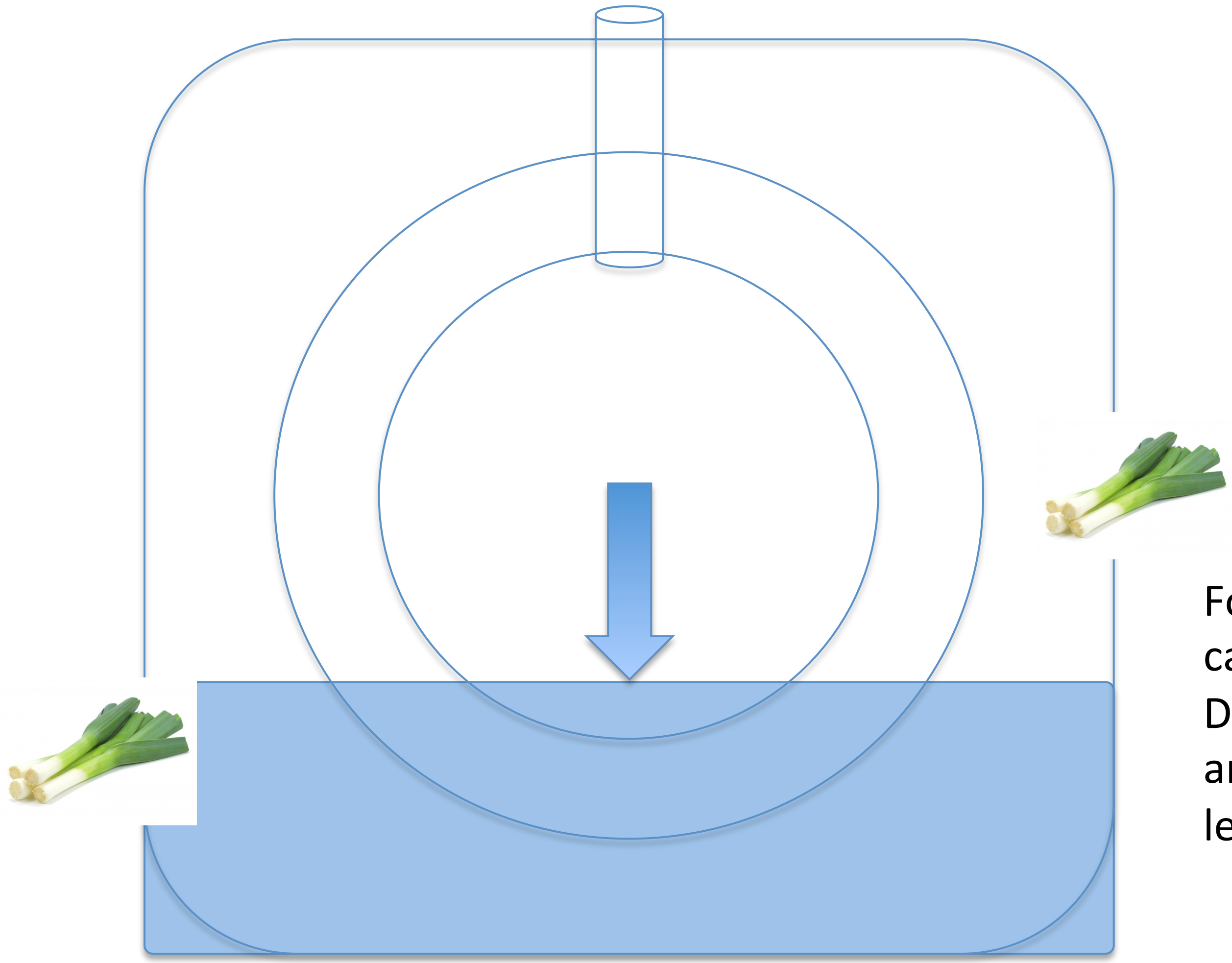
Filling SNO+

★Phase 0 – water fill



Fill inner and outer Volumes with UPW simultaneously

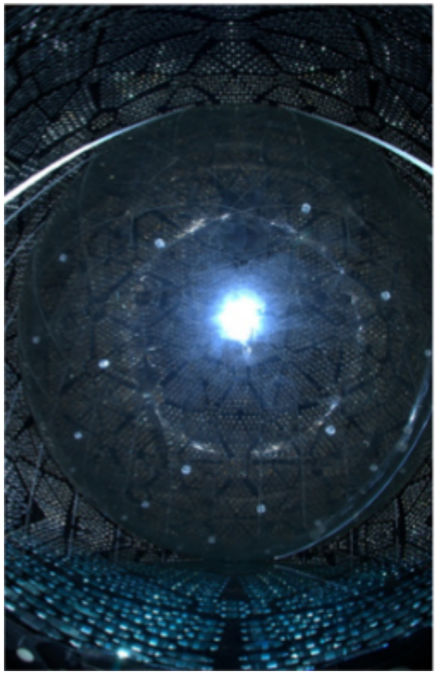
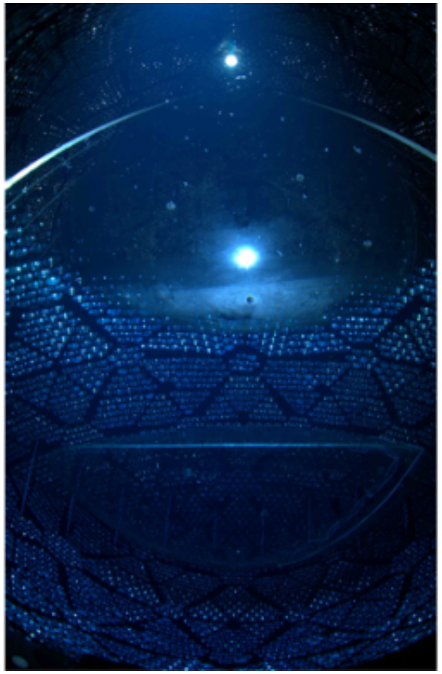
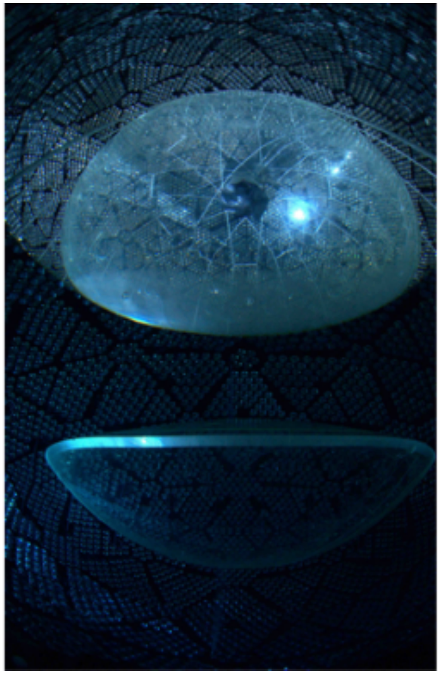
★ Phase 0 – water fill



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

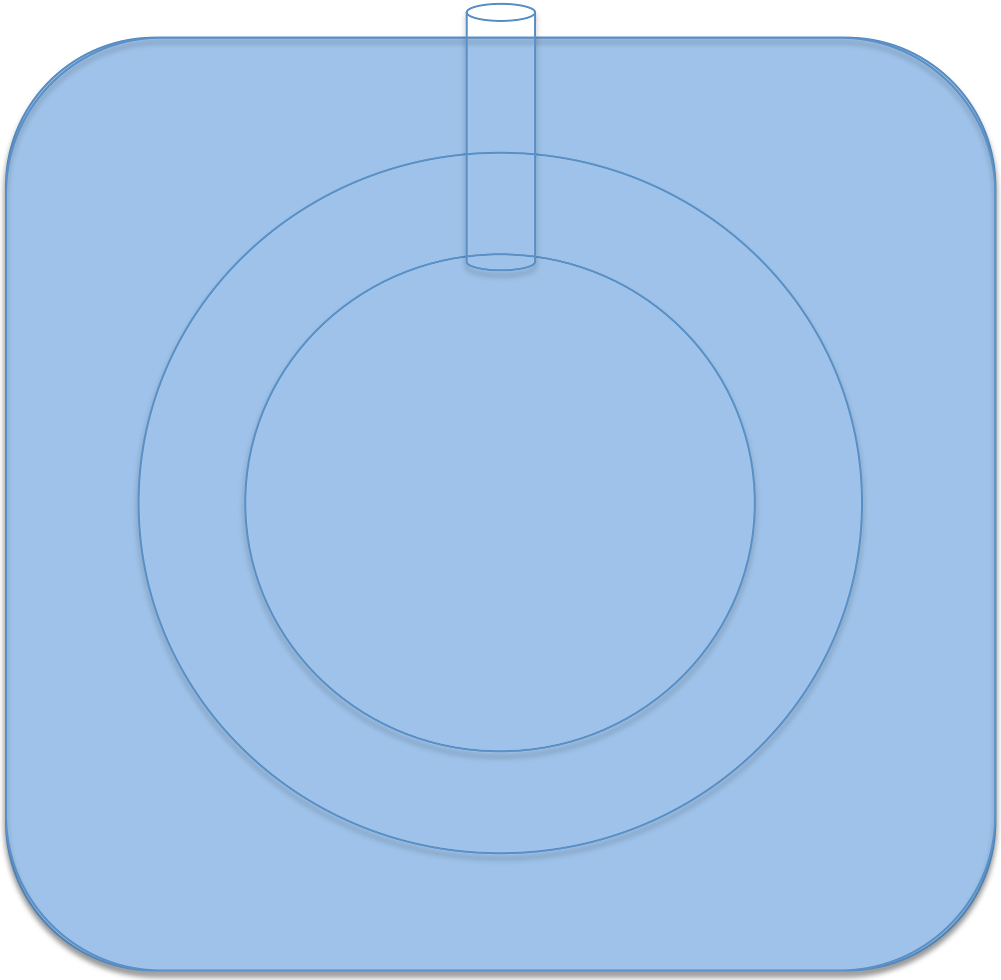
Leaks ☹

- ★ Major effort to find and fix leaks
  - ★ Currently at 46 foot level and filling
    - ★ Last boating trip this week – final fibre installations

Filling SNO+

★ Phase 0 – water fill



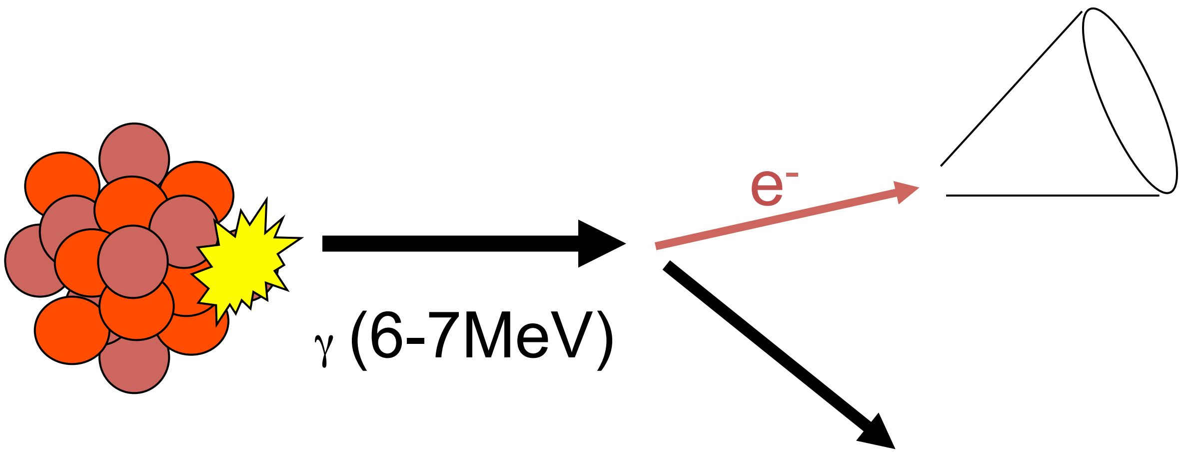
Commission and calibrate with H_2O filled detector.
Soon!

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.

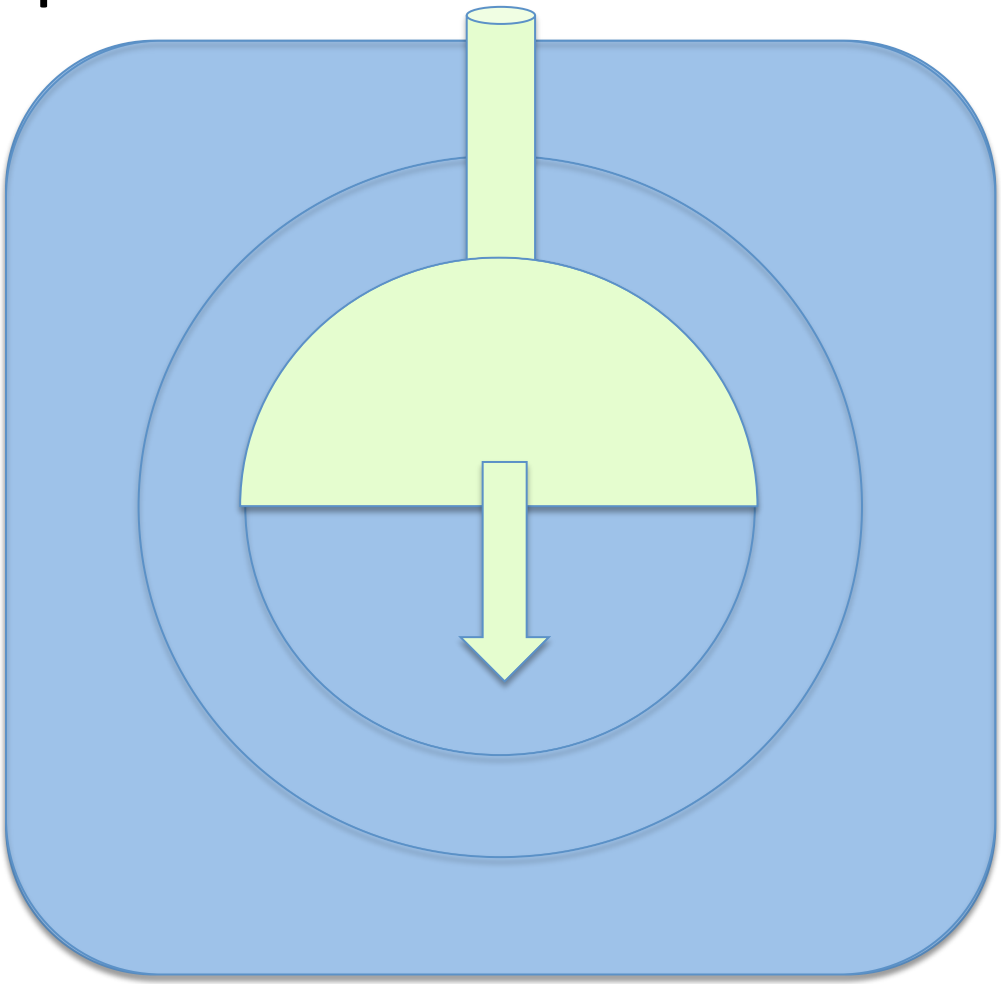


$^{16}O \rightarrow {}^{15}O^* \rightarrow {}^{15}O + \gamma$

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

Filling SNO+

★ Phase 1 – pure scintillator fill

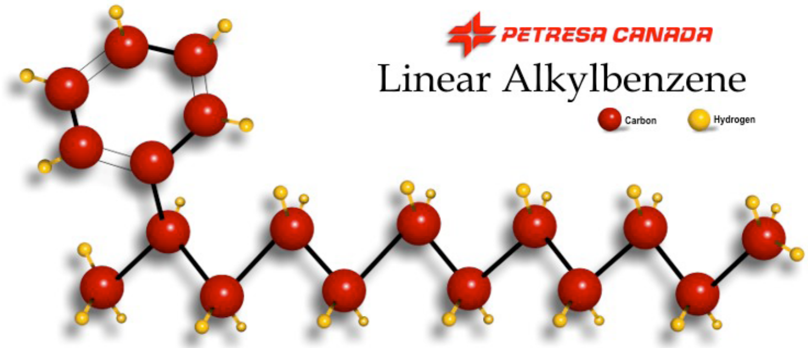


Scintillator is less dense than water.
Fill inner AV from the top, remove H_2O from bottom

Scintillator LAB + PPO

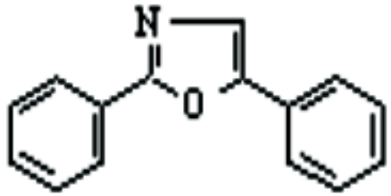
Scintillator of choice Linear Alkylbenzene (LAB)

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



Properties:

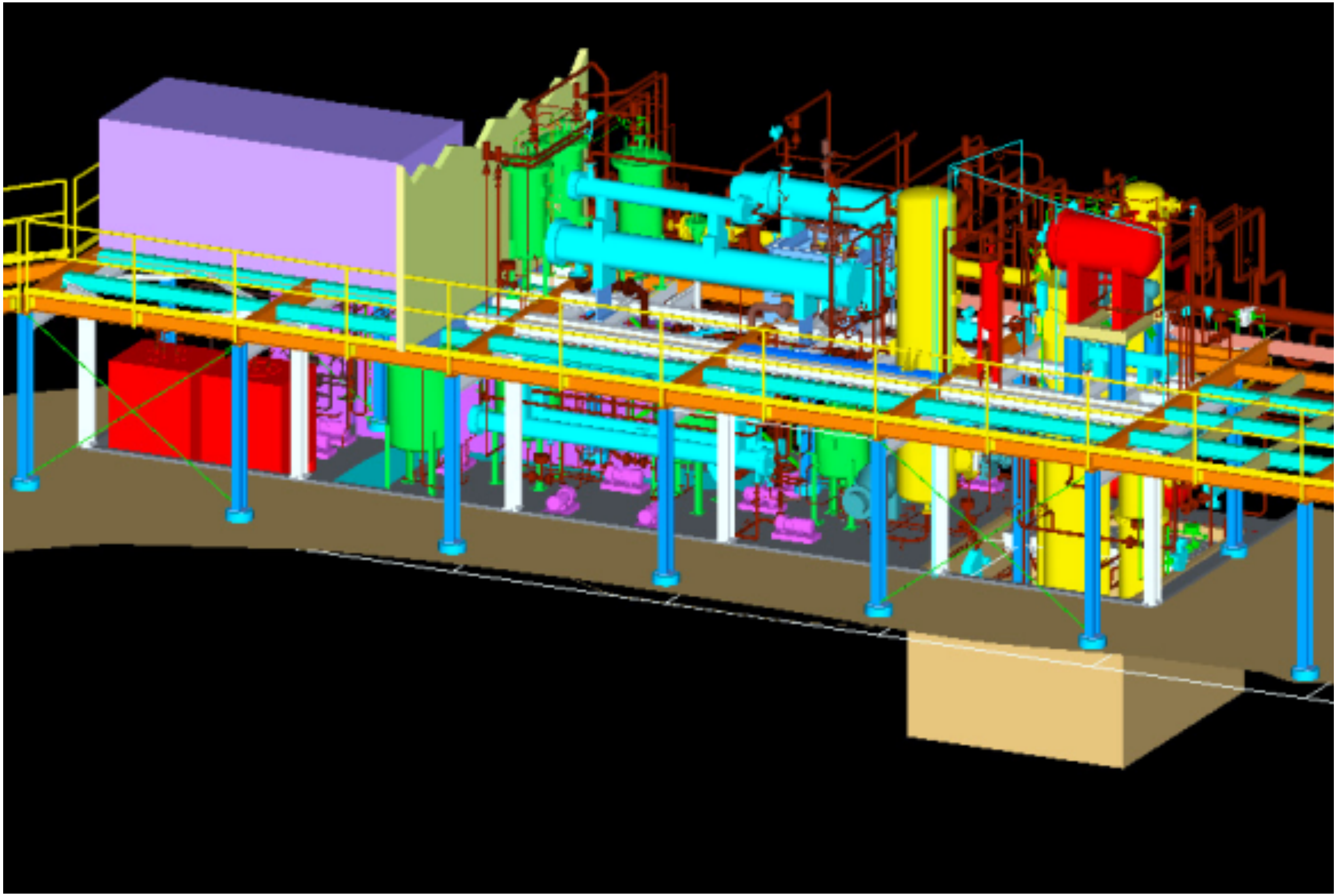
- 450 observed photons per MeV
- Resolution of 5% at 1 MeV
- $kB = 71.9 \pm 3.9$ µm/MeV



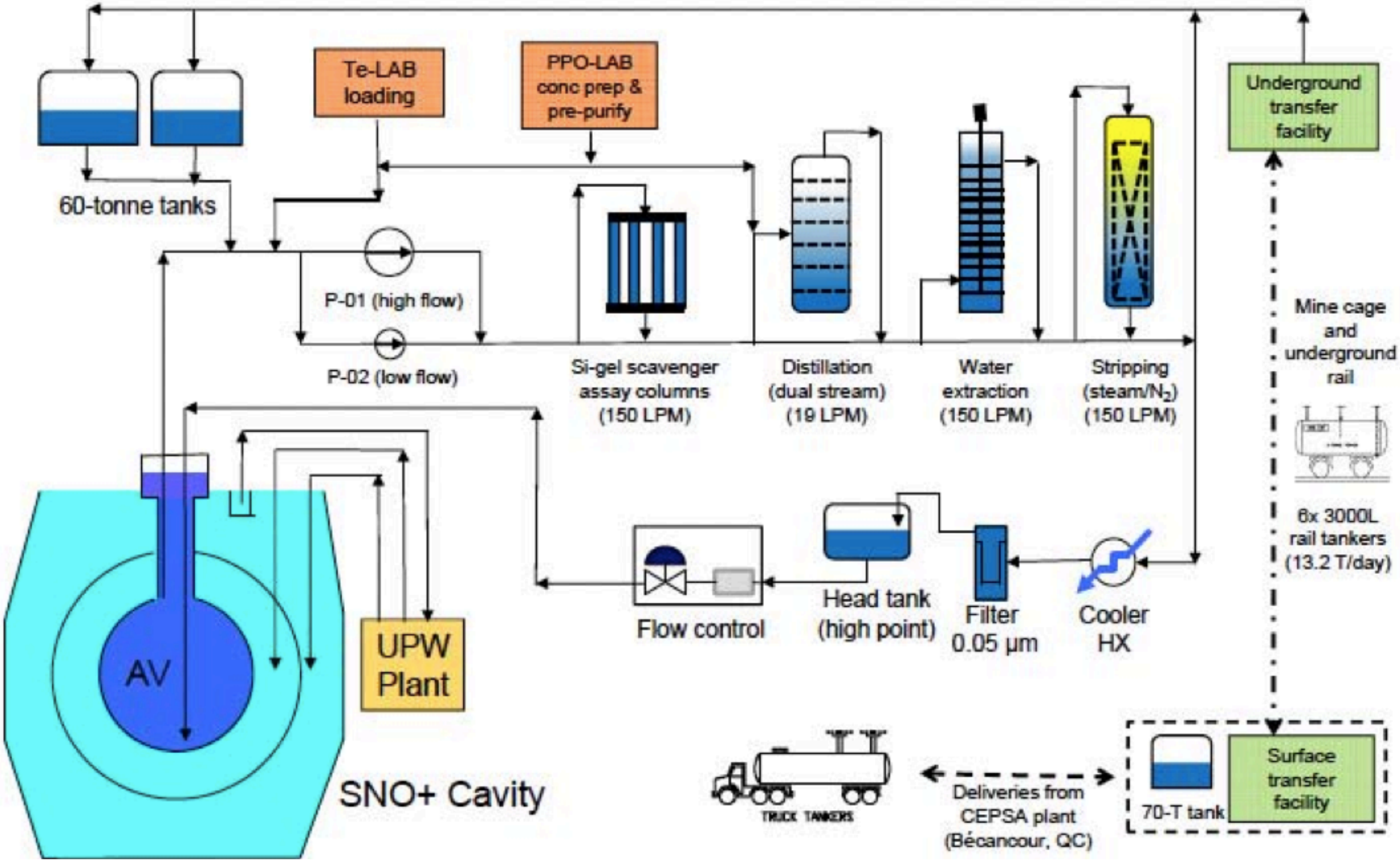
PPO

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

Scintillator Purification Plant



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

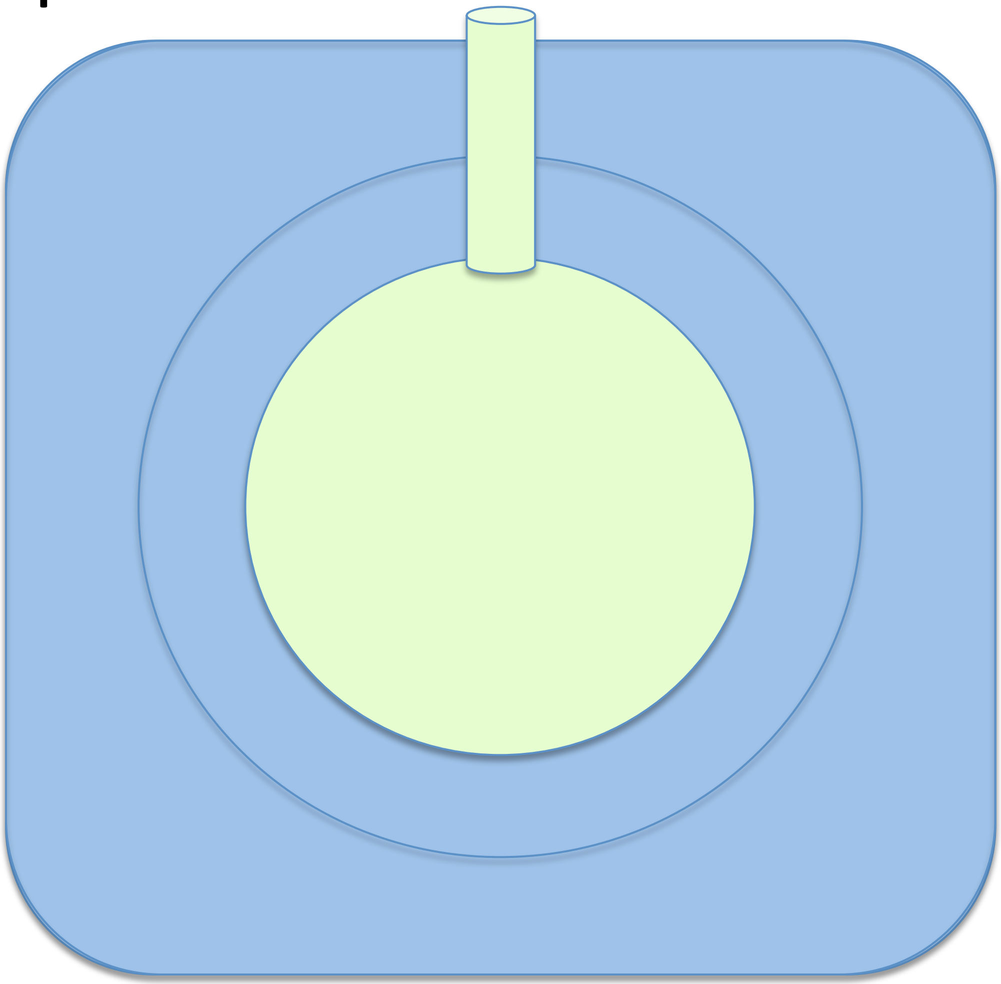
<u>Target levels:</u>

- ^{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


E-110
250 lbs

Filling SNO+

★ Phase 1 – pure scintillator fill



Characterise scintillator response and backgrounds in-situ.

Circulate scintillator to purify

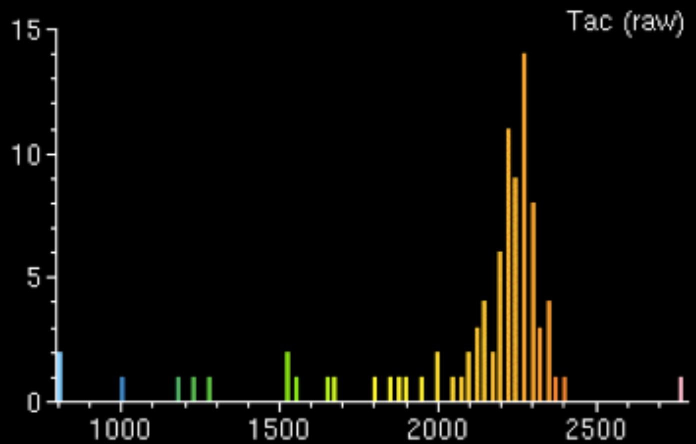
Solar physics?

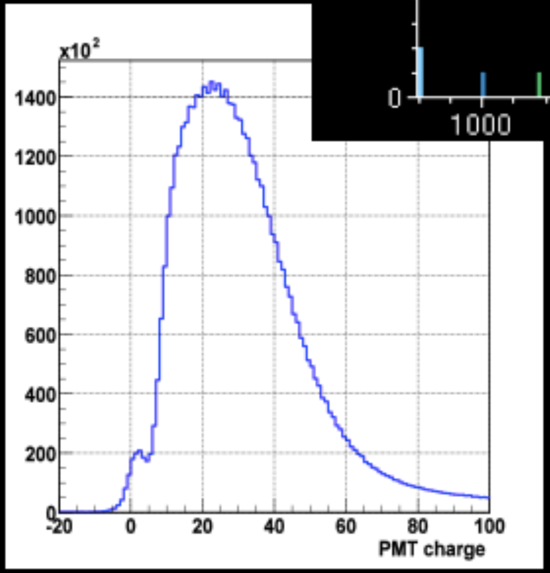
What we measure

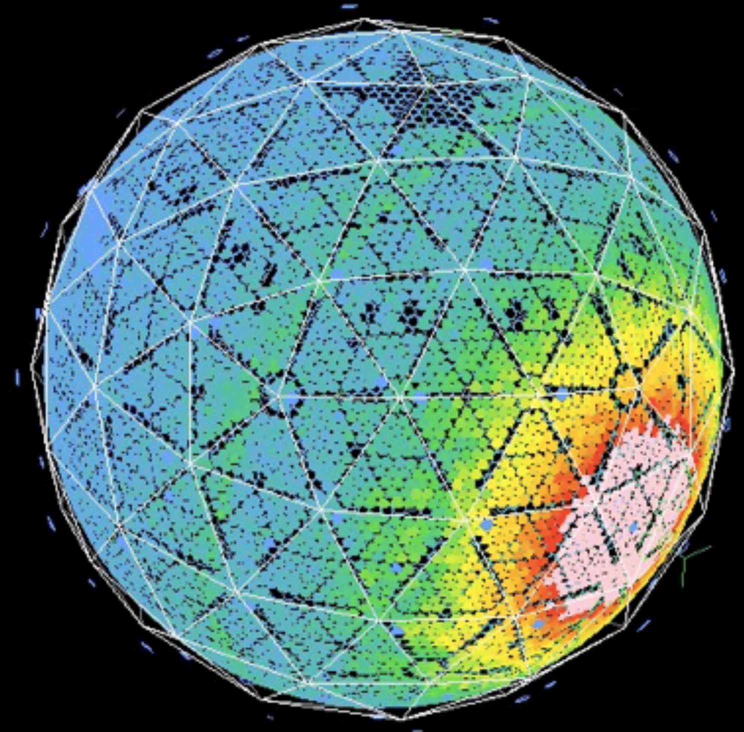
"event": a light pulse seen by SNO+.

For each PMT, we measure:

- PMT charge
- PMT time





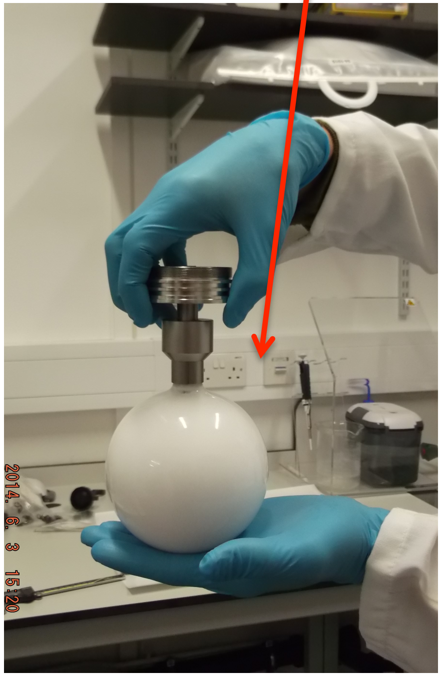


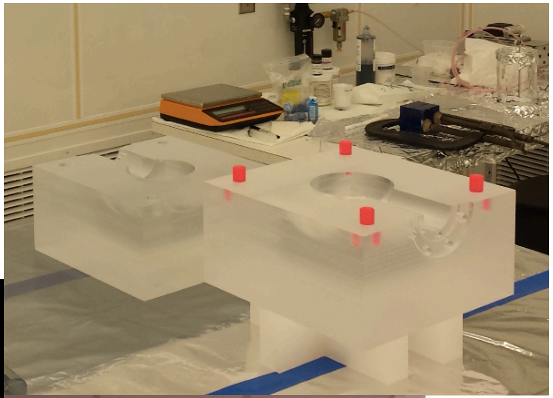
from those, we "reconstruct" the original charged particle

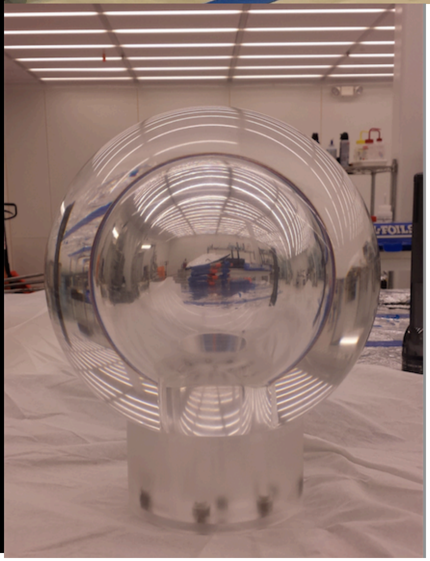
- position
- energy
- type

Calibrations

- ★ Deployed sources:
  - ★ Radioactive: ^{46}Sc, ^{48}Sc, ^{57}Co, ^{24}Na
  - ★ Laserball (optics), Cerenkov source

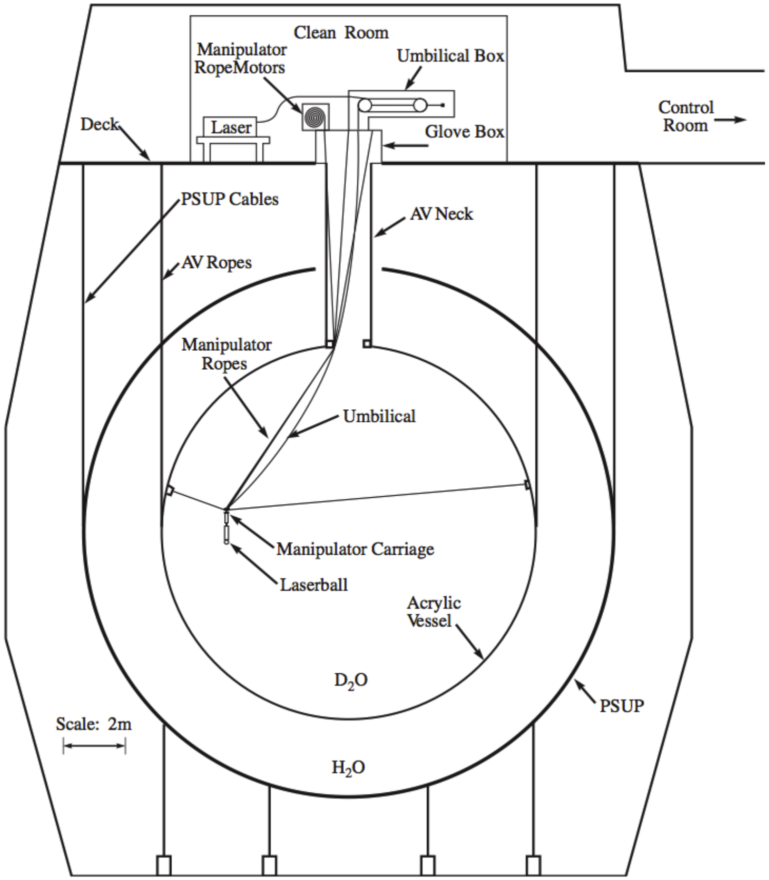






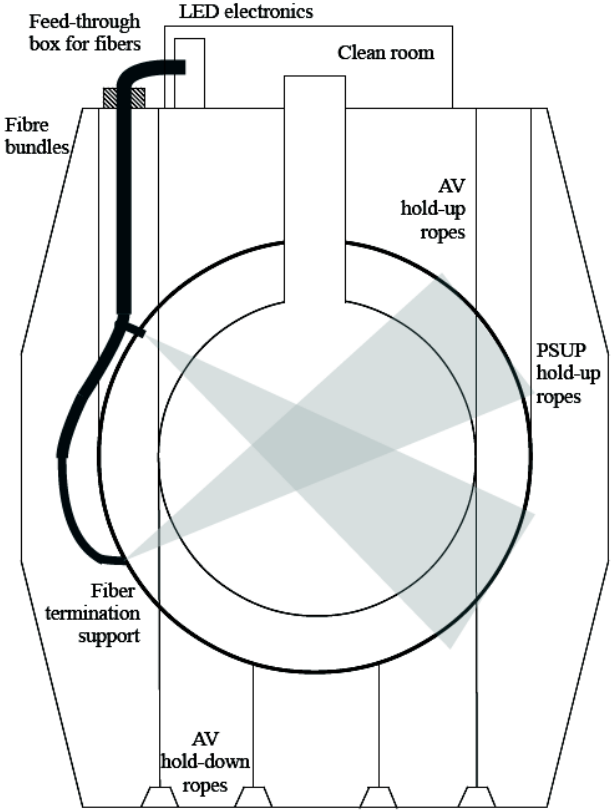
New Calibration systems

SNO: Deployed sources



SNO+: External source

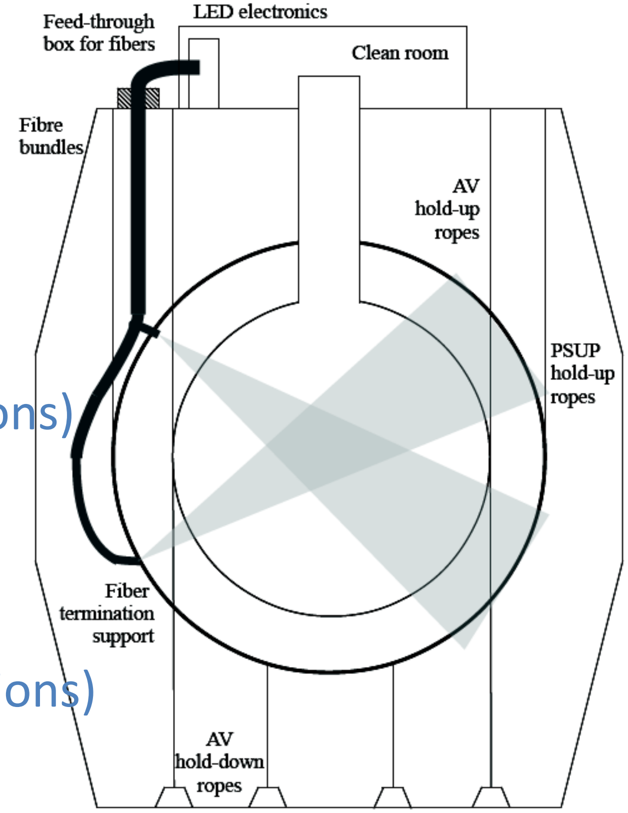
Embedded LED/Laser Light Injection Entity (ELLIE)



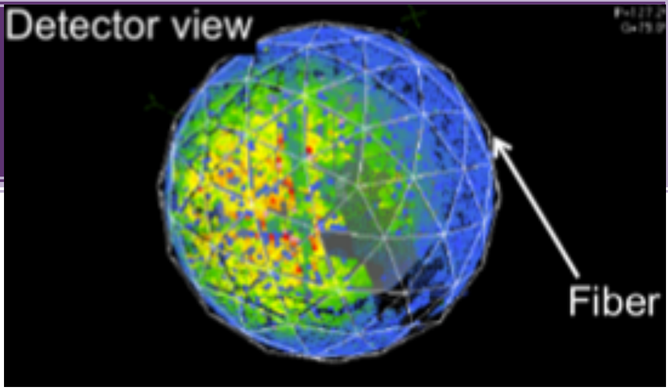
New calibration systems: ELLIE

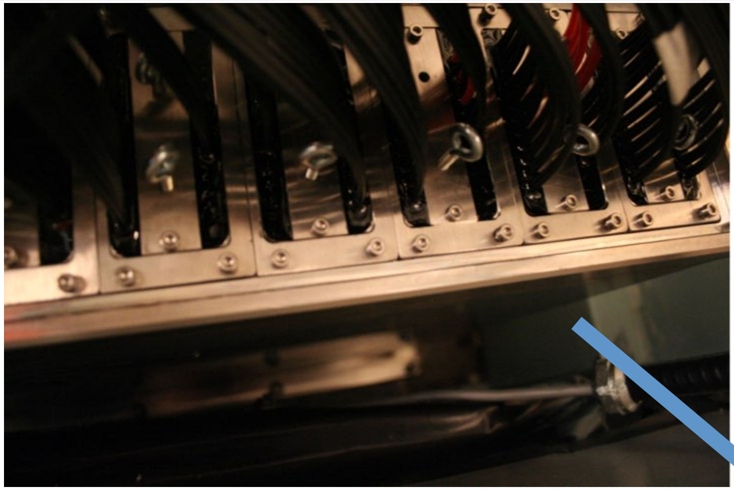
Will provide continuous calibrations throughout SNO+ operation

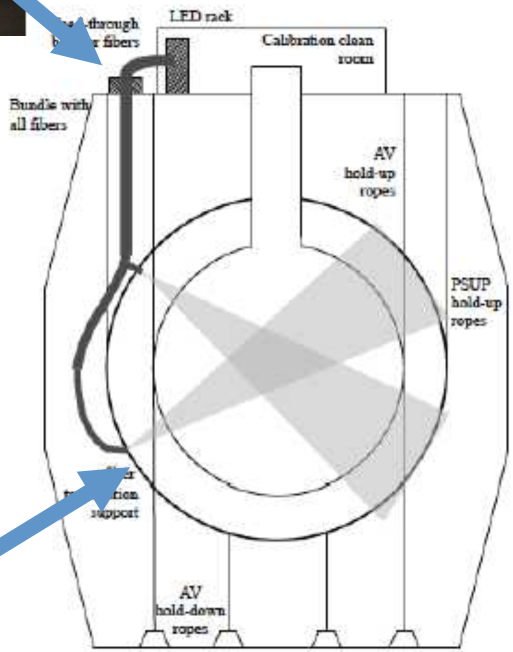
- ★ Timing (T)ELLIE:
  - ★ 91 injection positions
  - ★ Monochromatic (~520nm) from LEDs
  - ★ Light coverage of entire inward-facing detector
- ★ Scattering module (SM)ELLIE
  - ★ 12 injection points (three at each of four locations)
  - ★ Multiple wavelengths from lasers
- ★ Attenuation module (AM)ELLIE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

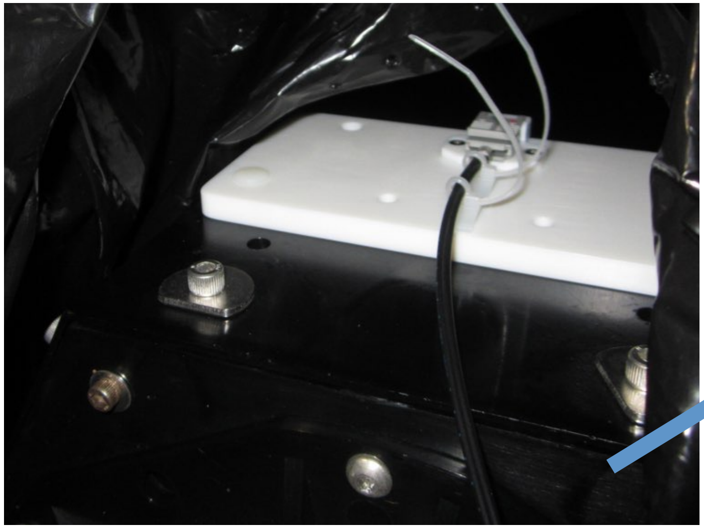


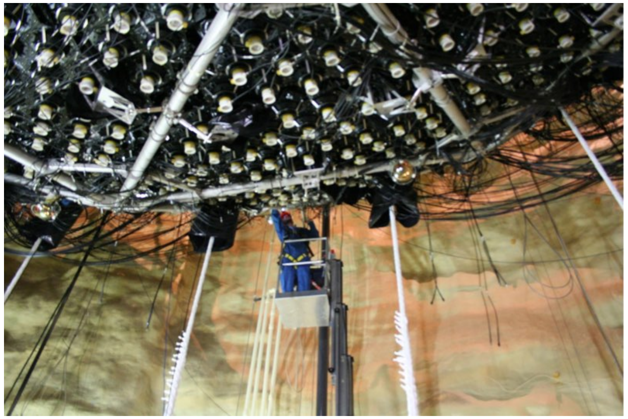
ELLIE Installation







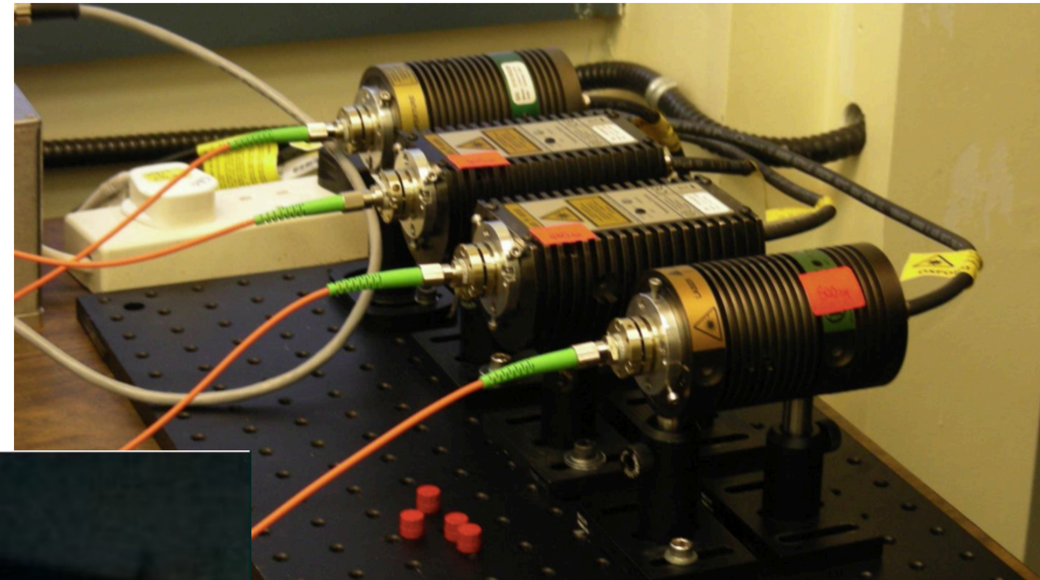


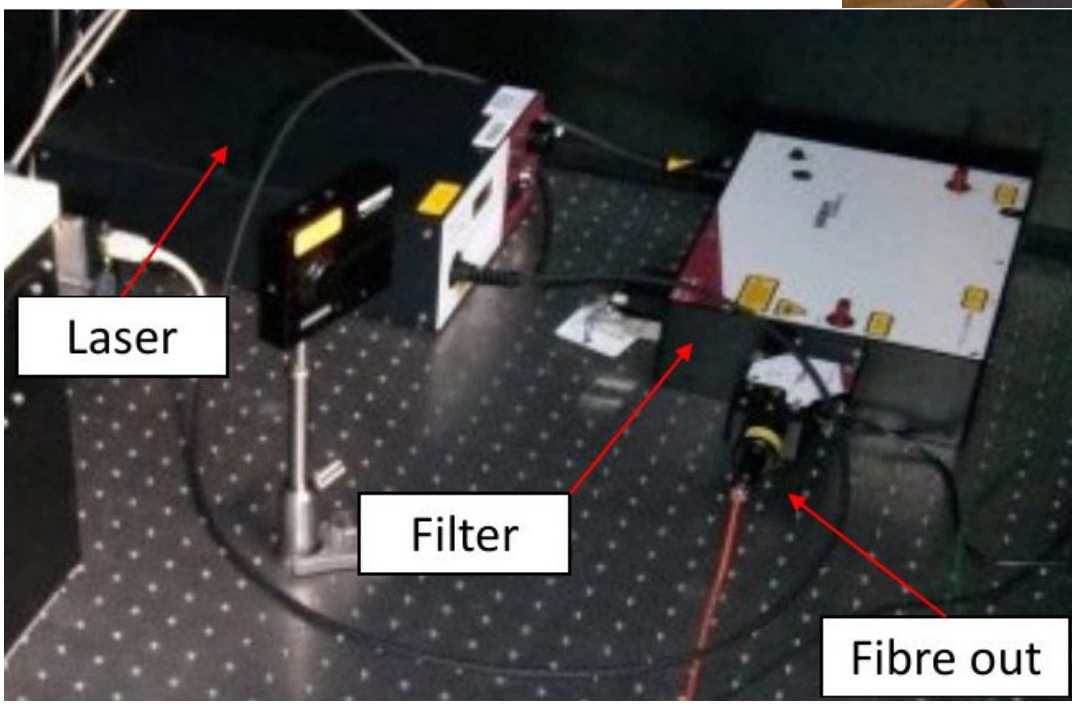


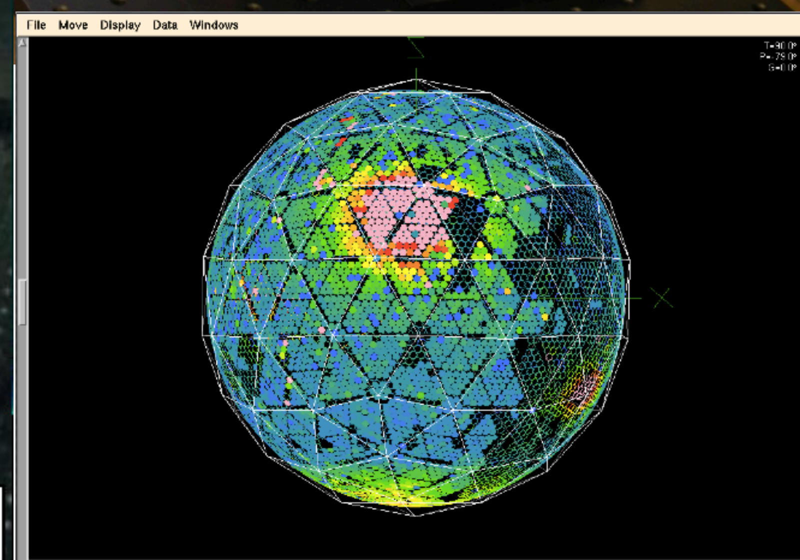
New calibration systems: (SM)ELLIE

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

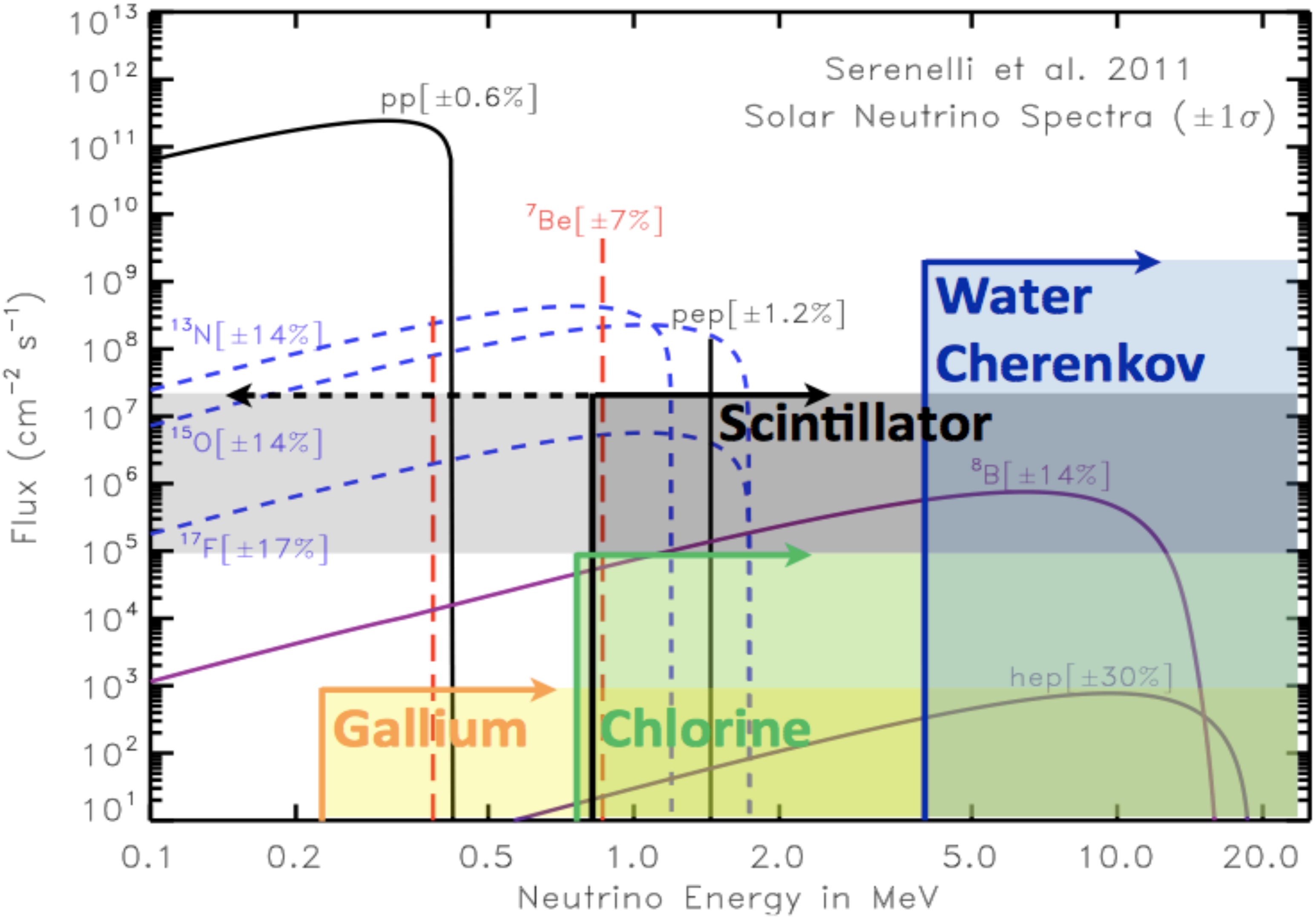
One continuously tunable 'supercontinuum' laser with a range from 450 – 800 nm.





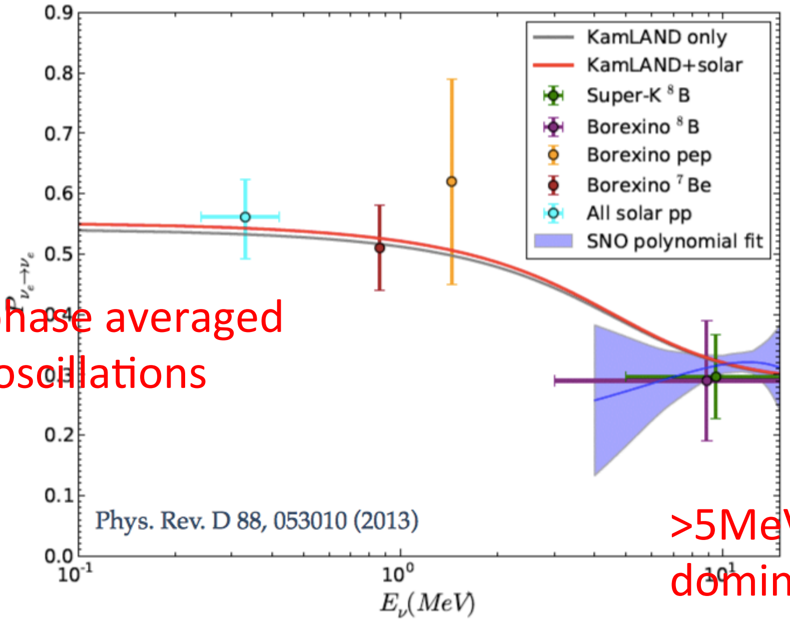


Solar Neutrinos



Solar Neutrino Physics

- ★ What can the Sun tell us about neutrinos?
  - ★ Precision pep flux
  - ★ Low energy ^8B spectrum
  - ★ Day/night asymmetry?



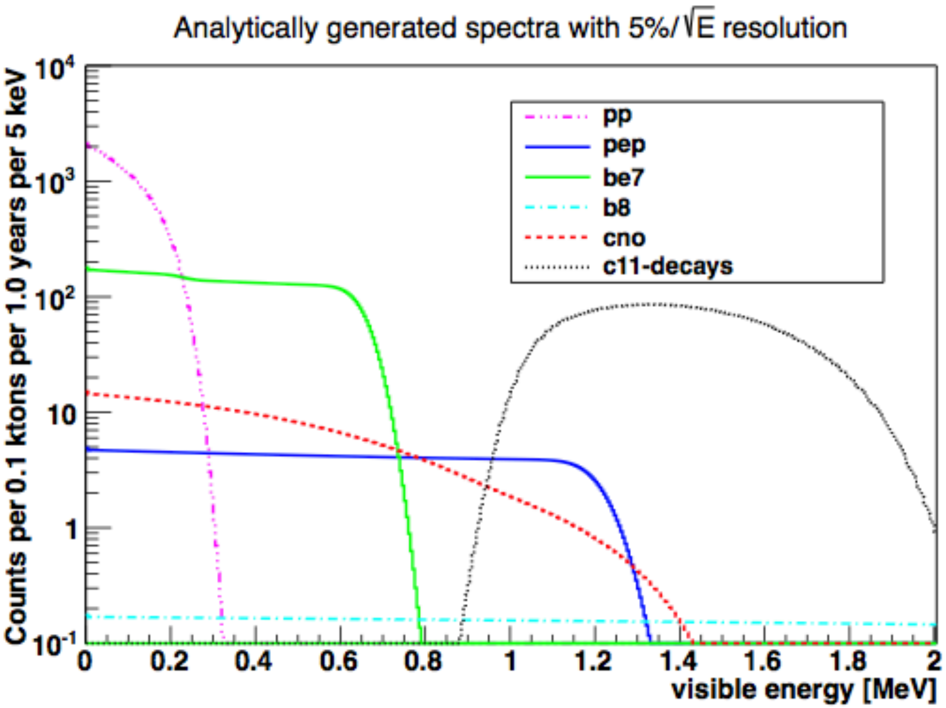
<1MeV phase averaged vacuum oscillations

>5MeV Matter dominated resonant conversion

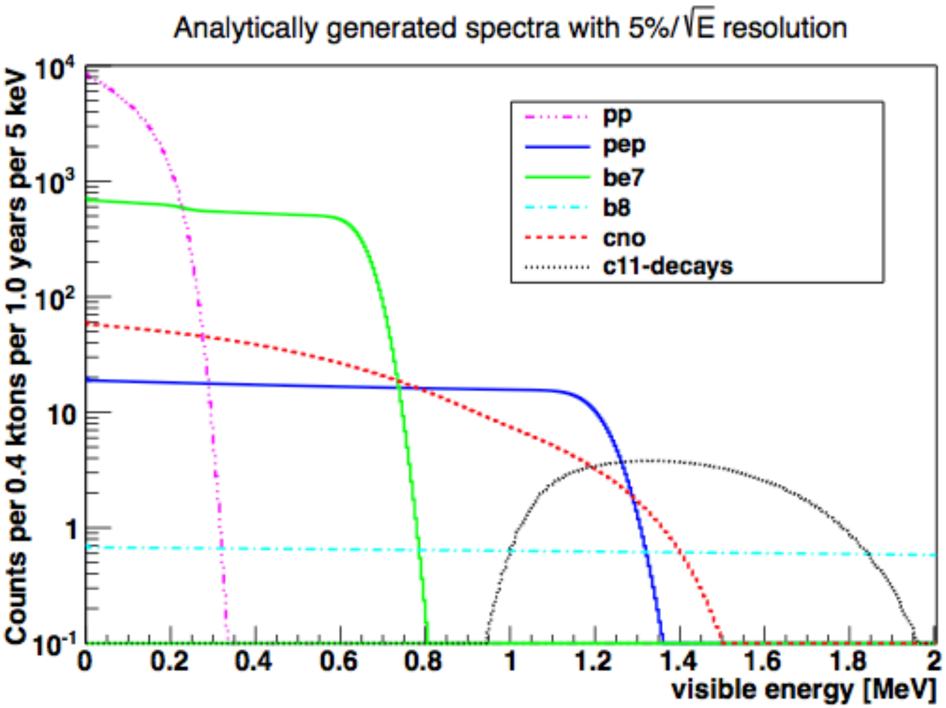
- ★ What can neutrinos tell us about the Sun?
  - ★ CNO flux -> Resolve solar metallicity problem
  - ★ Direct pp measurement -> Luminosity constraint

A matter of depth

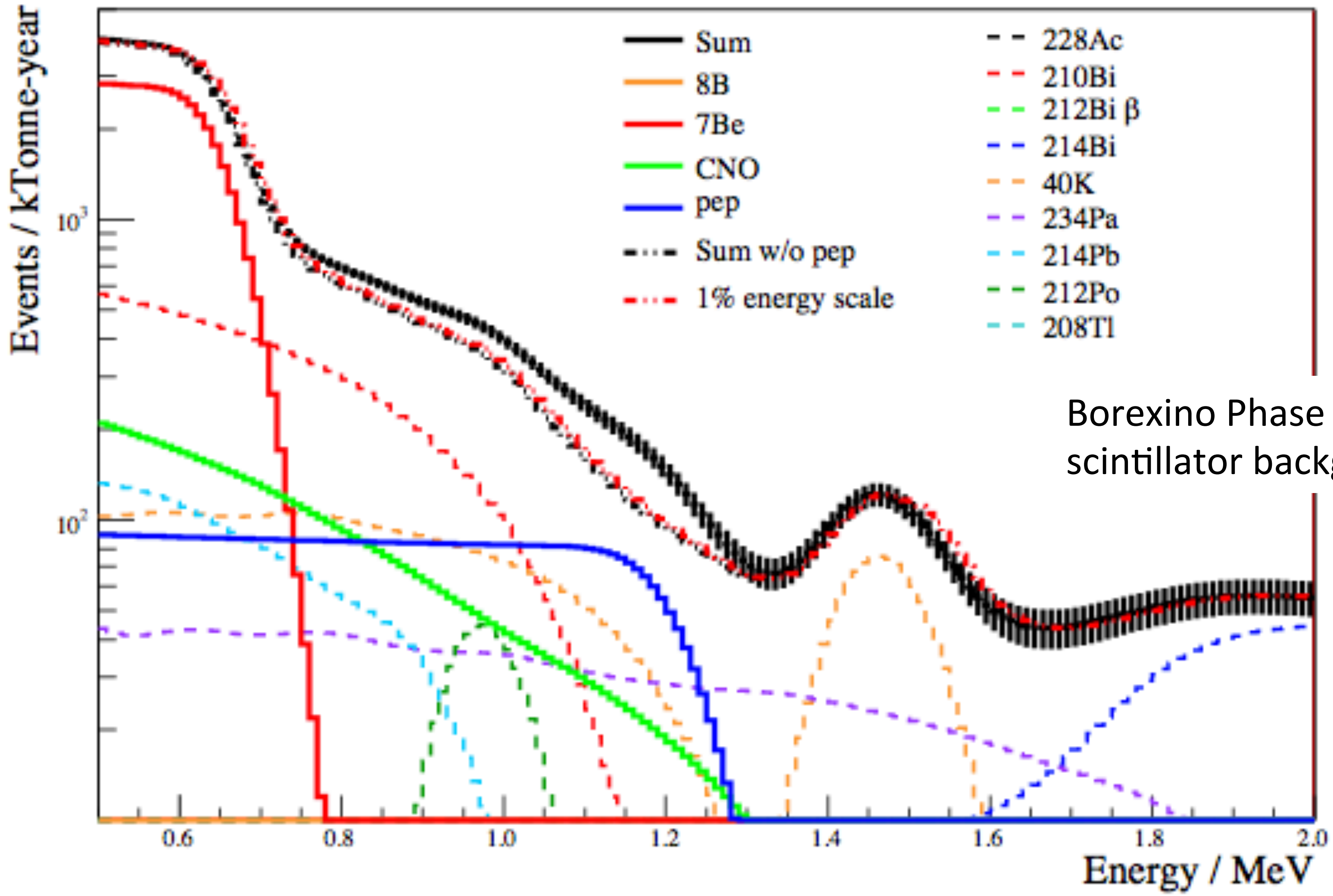
Borexino



SNO+

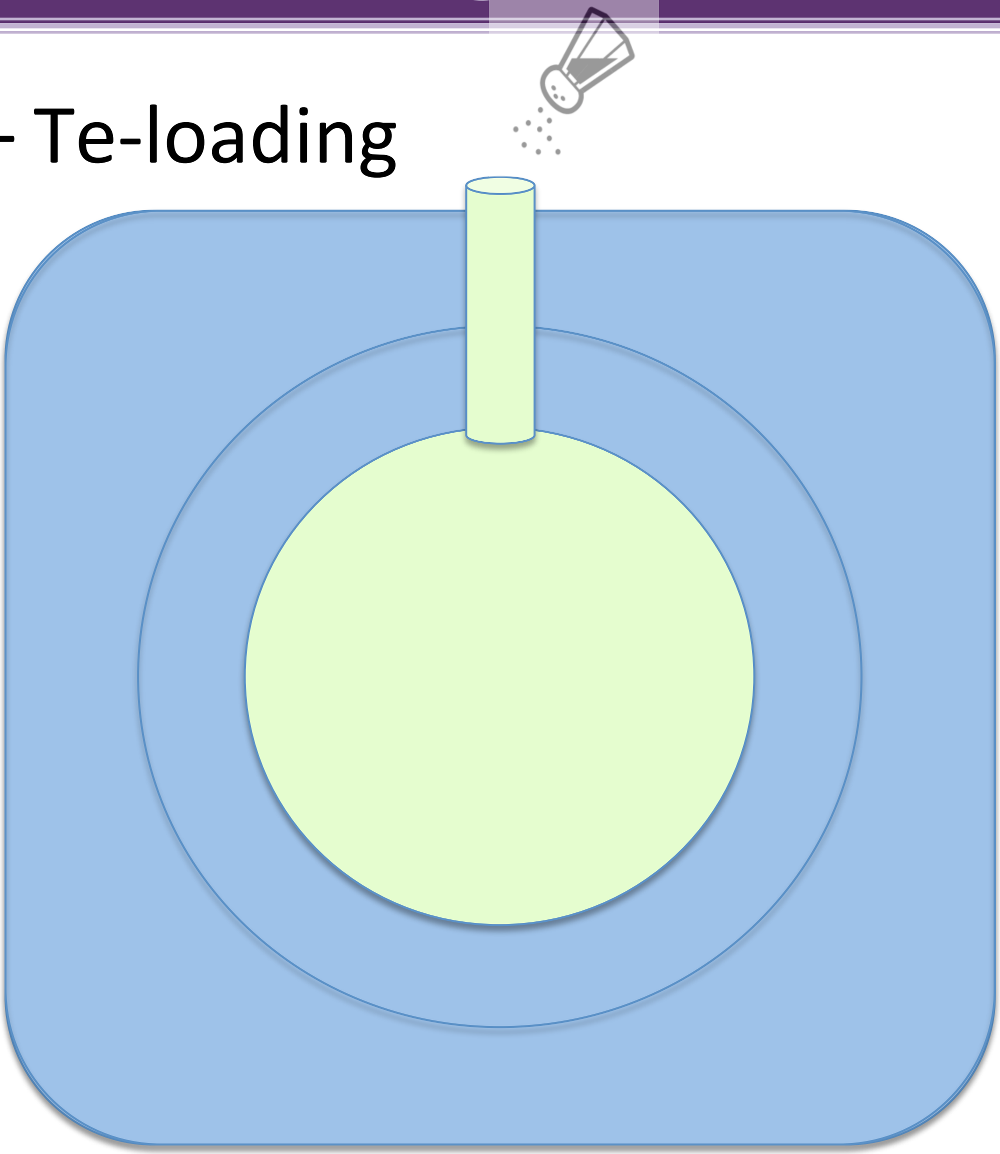


SNO+ solar signals



Borexino Phase 1 scintillator backgrounds

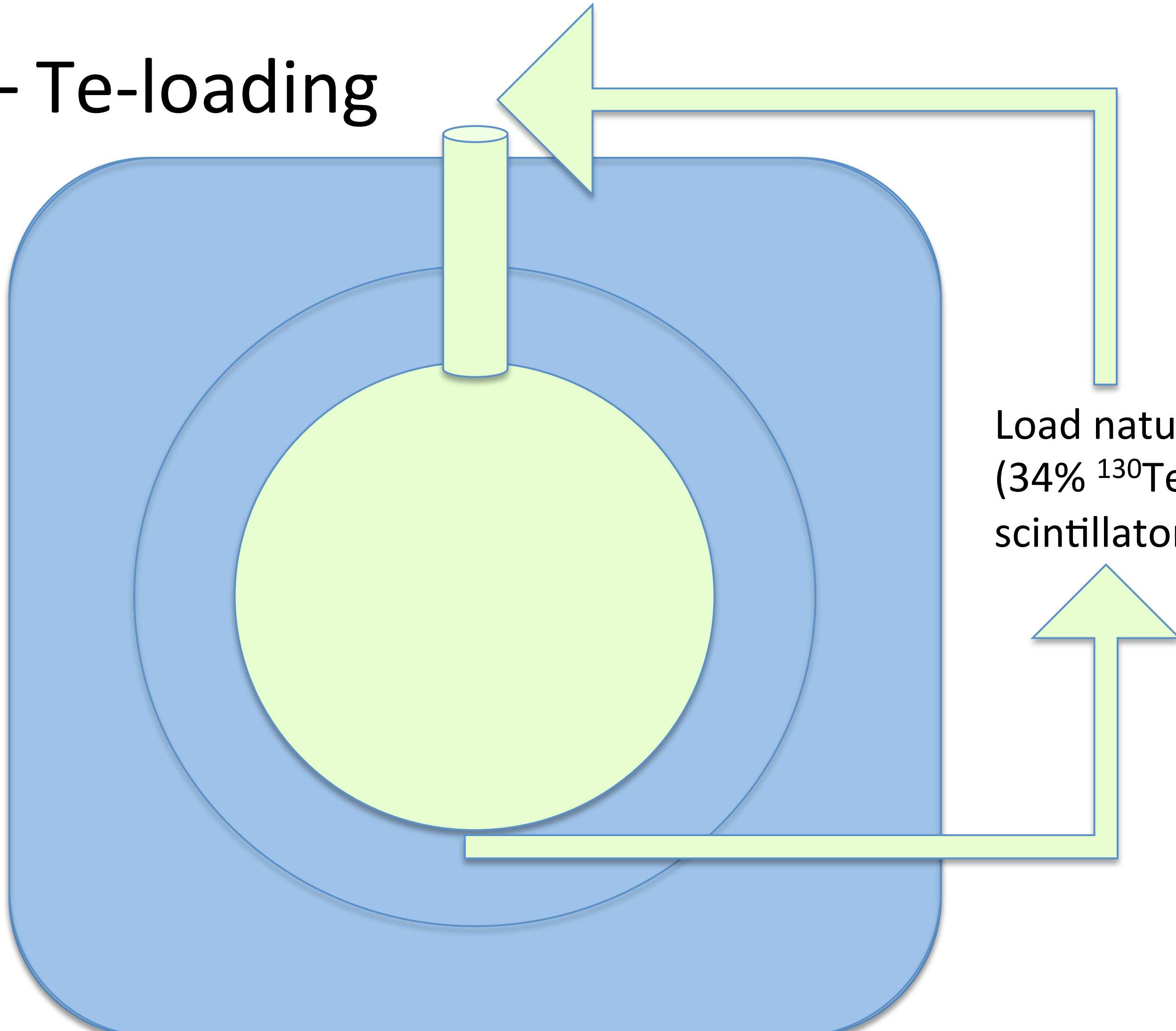
★ Phase 2 – Te-loading



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

Filling SNO+

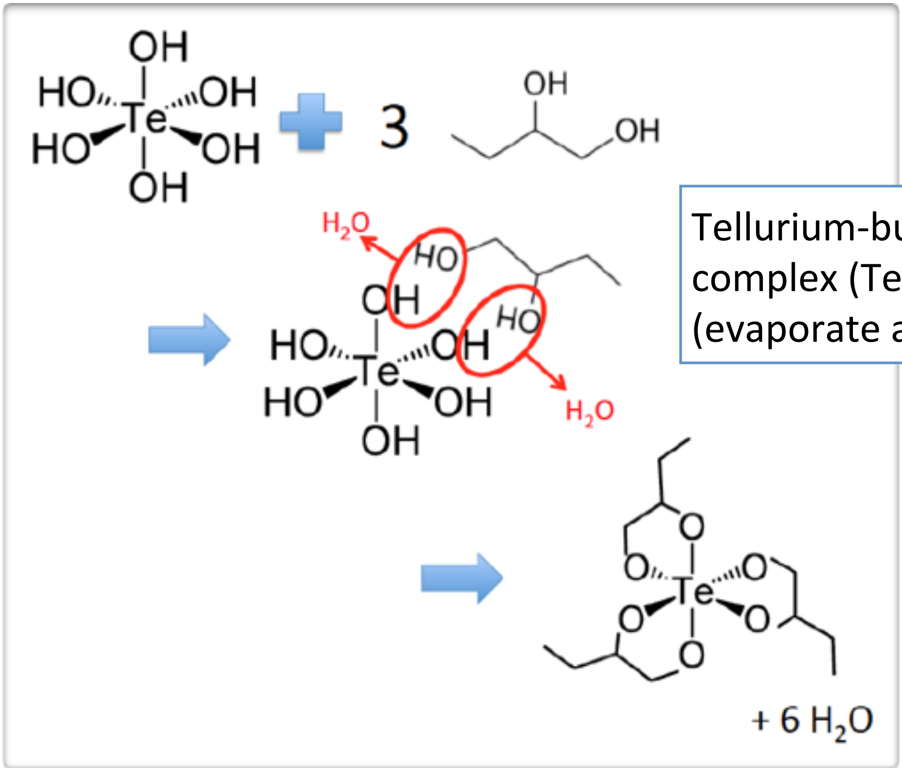
★ Phase 2 – Te-loading



Loading the scintillator

New method has been developed for loading the scintillator!

- 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

Above ground

- Dissolve $Te(OH)_6$ in water
- Re-crystalize using nitric acid
- Rinse with ethanol

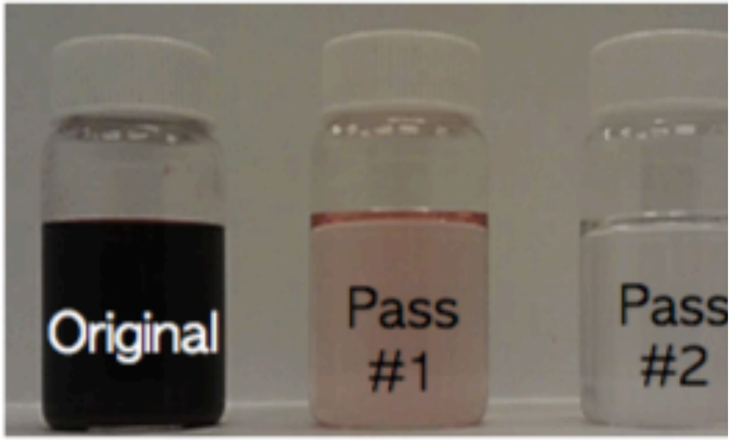
} 10^4 reduction

Below ground

- Dissolve in 80˚C water
- Thermally re-crystalize
- 50% yield

} 10^2

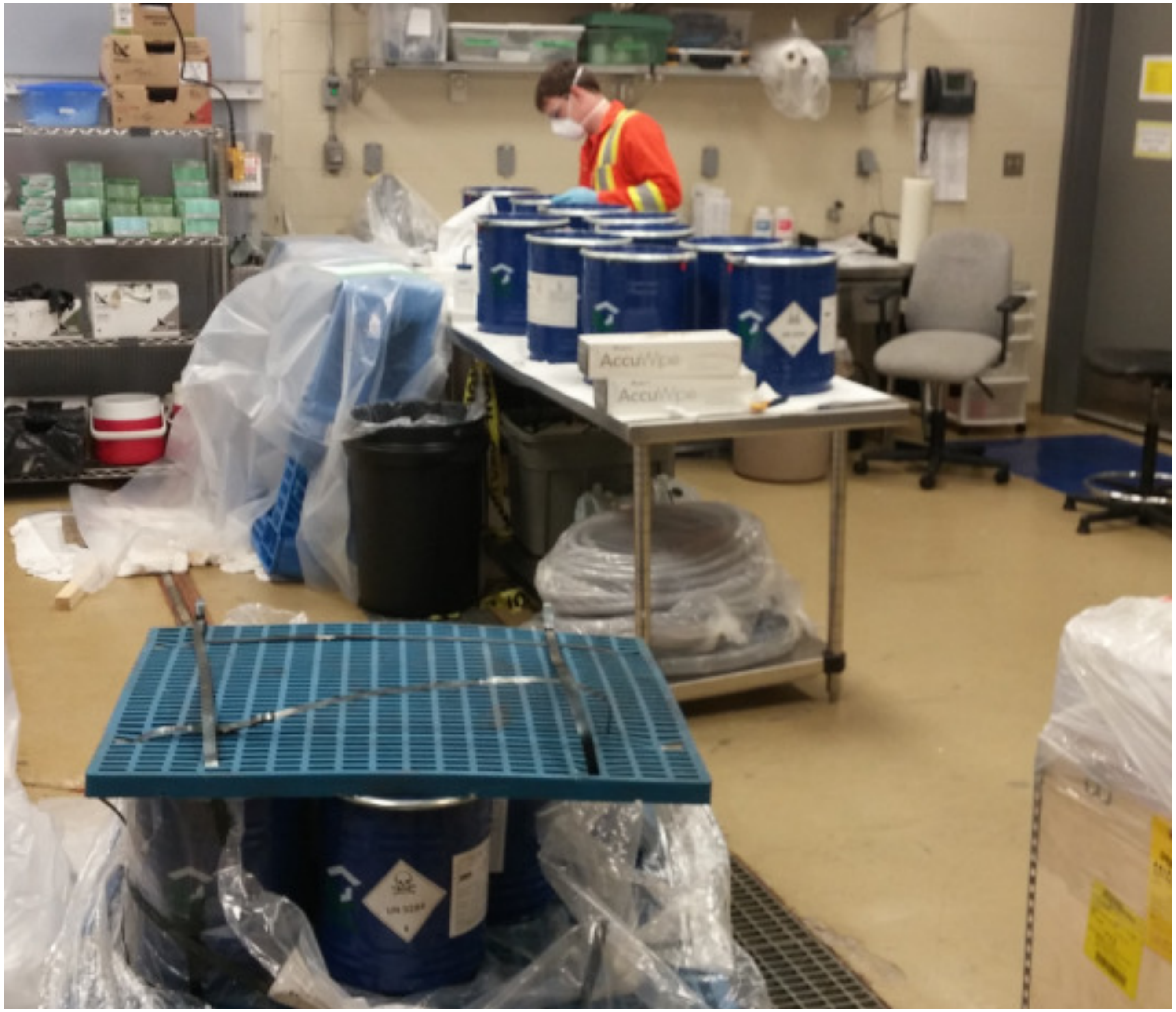
Cosmogenic reactivation
Lozza & Petzoldt, Cosmogenic activation of a natural tellurium target, Astroparticle Physics.
DOI: 10.1016/j.astropartphys.2014.06.008



^{60}Co spike test

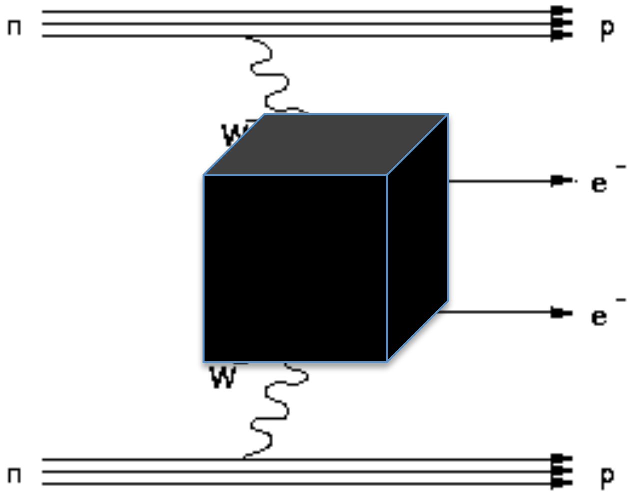
First batch in storage underground
Cosmogenic cool-down since January 2015

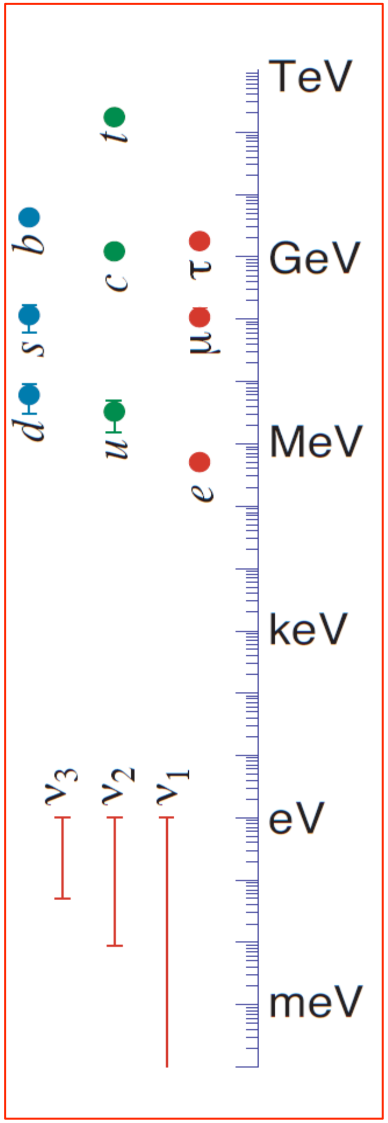
Second Delivery – September 2016



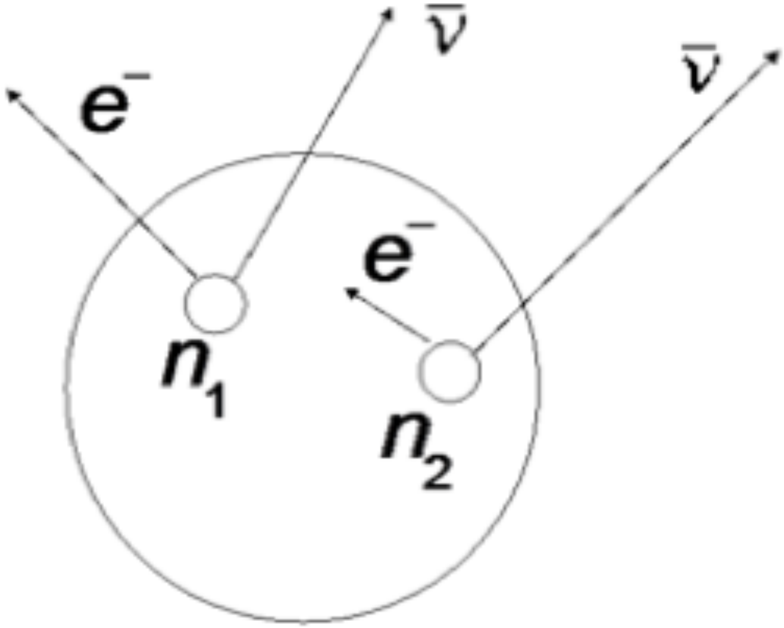
Double Beta Decay

- ★ Hard to explain smallness of neutrino masses with Higgs mechanism
- ★ Most favoured alternative = See-saw mechanism
  - ★ Majorana neutrinos
  - ★ Leptogenesis

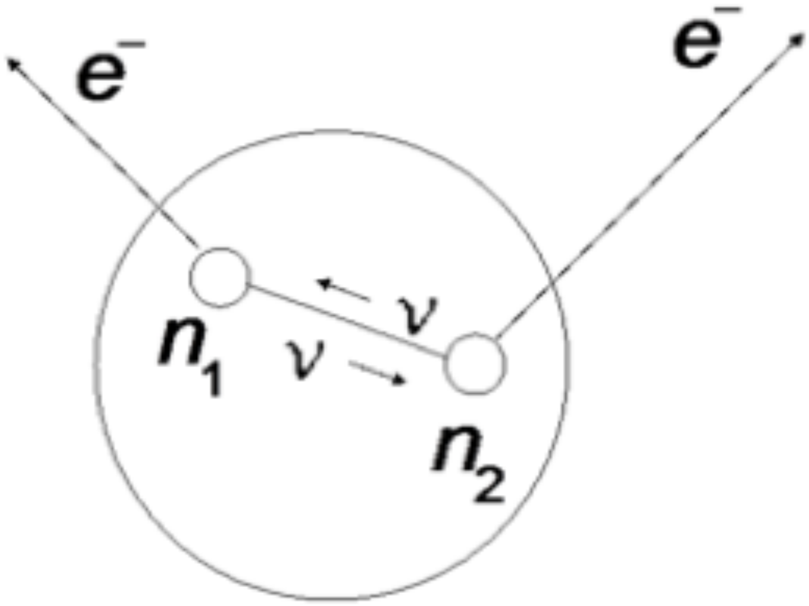




Neutrinoless Double Beta Decay



2νββ



0νββ

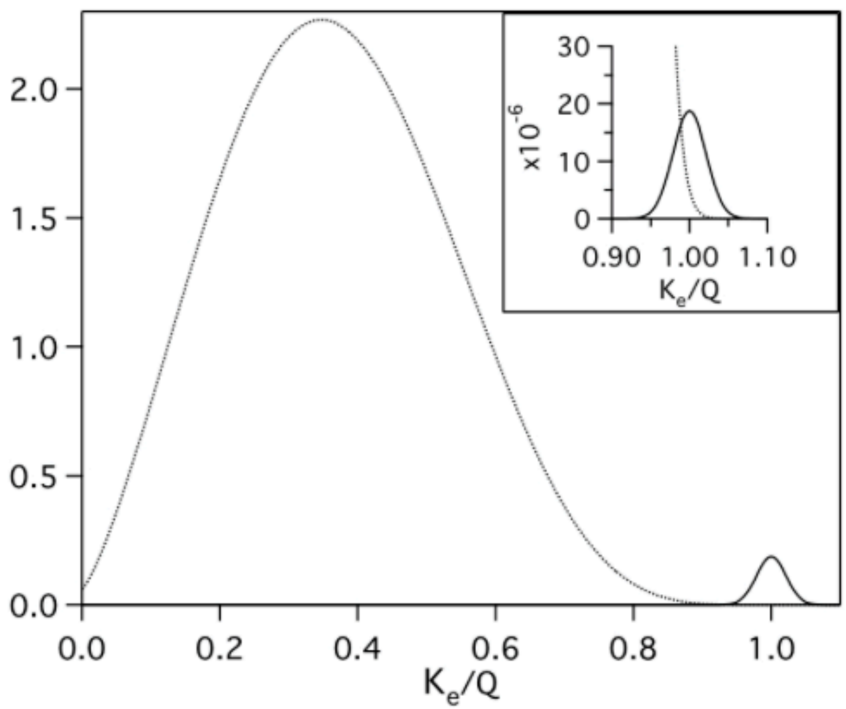
Neutrinoless Double Beta Decay

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

Phase space

Nuclear Matrix Element

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



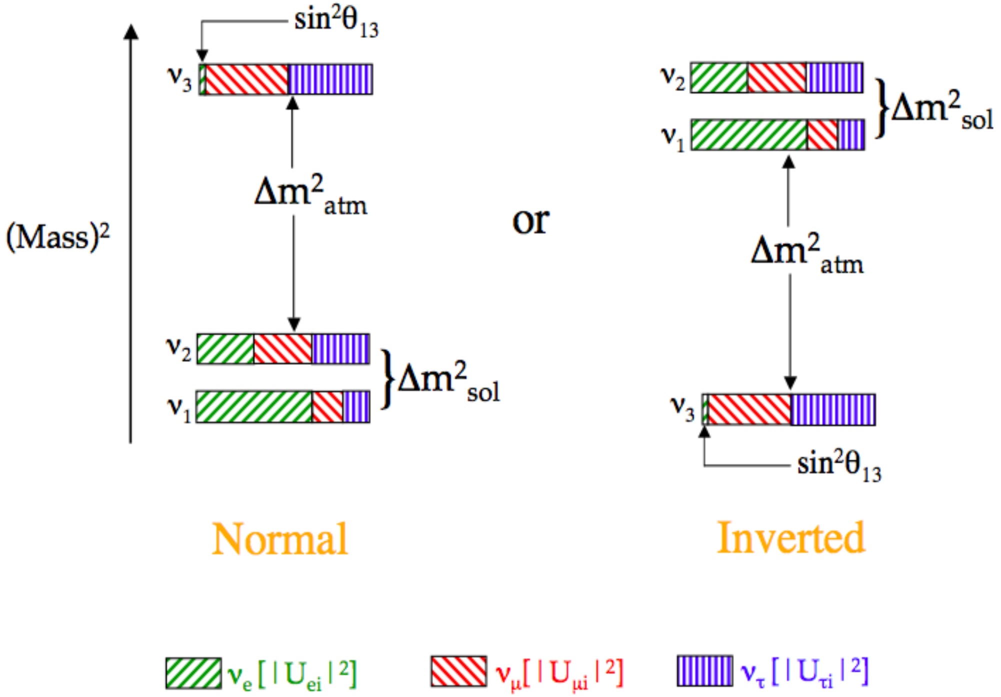
<u>Experiment options</u>

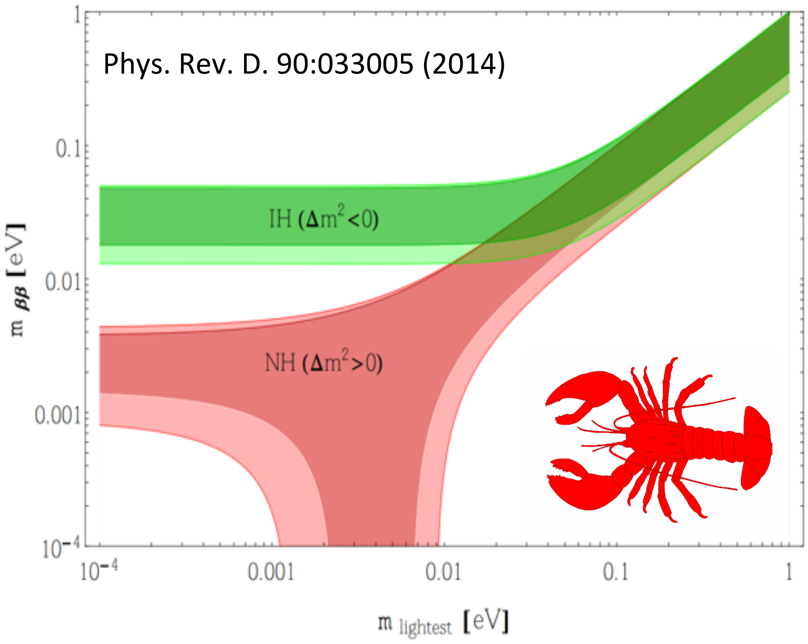
- Select isotopes with favourable phase space
- Select isotopes with favourable matrix elements
  - Beware large uncertainty / differences between models
- Good energy resolution
- Low Backgrounds in region of interest (ROI)

Neutrinoless Double Beta Decay

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

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

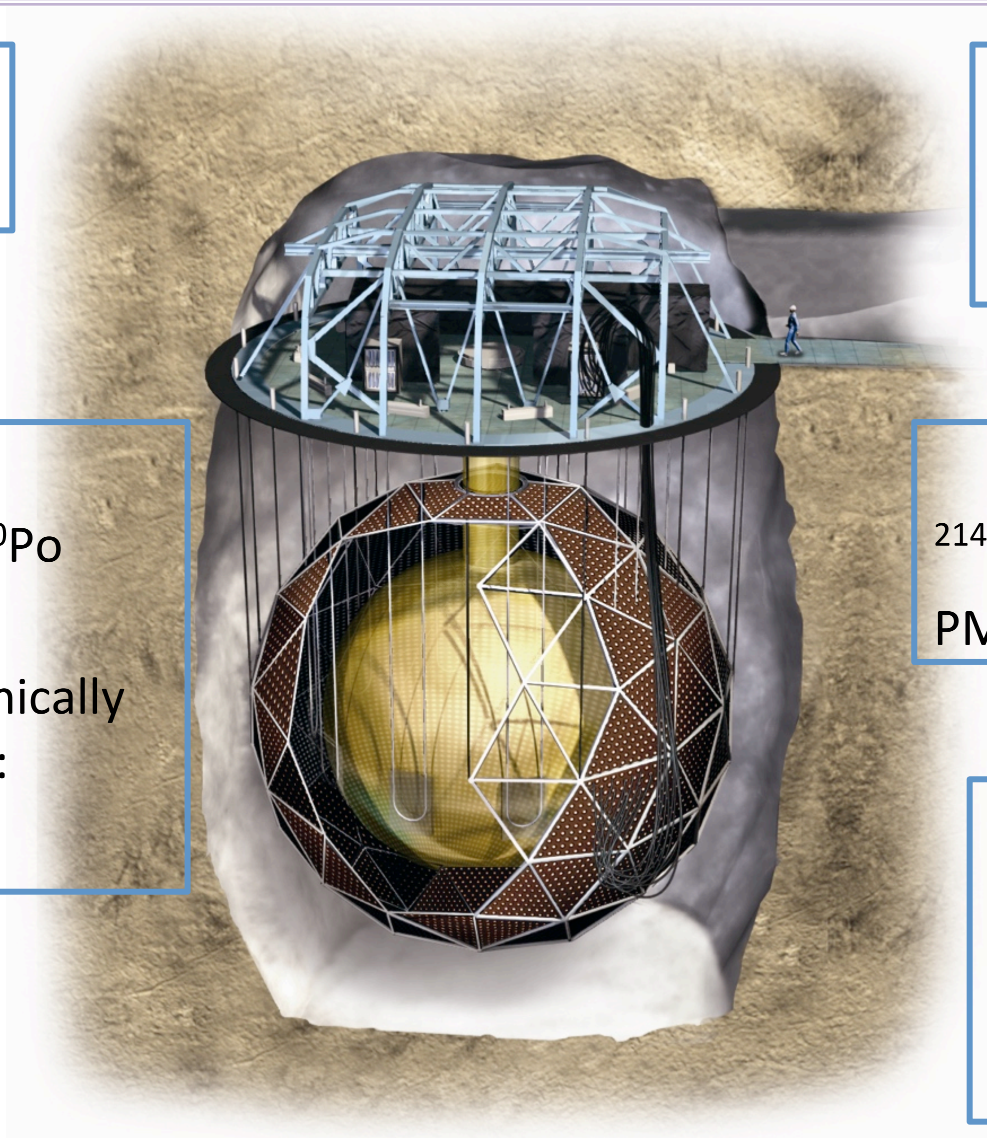




Backgrounds

<u>LAB-PPO</u>
^{238}U, ^{232}Th, ^{14}C
Solar ^{8}B ν

<u>Implanted Radon daughters in AV</u>
^{210}Pb, ^{210}Bi, ^{210}Po

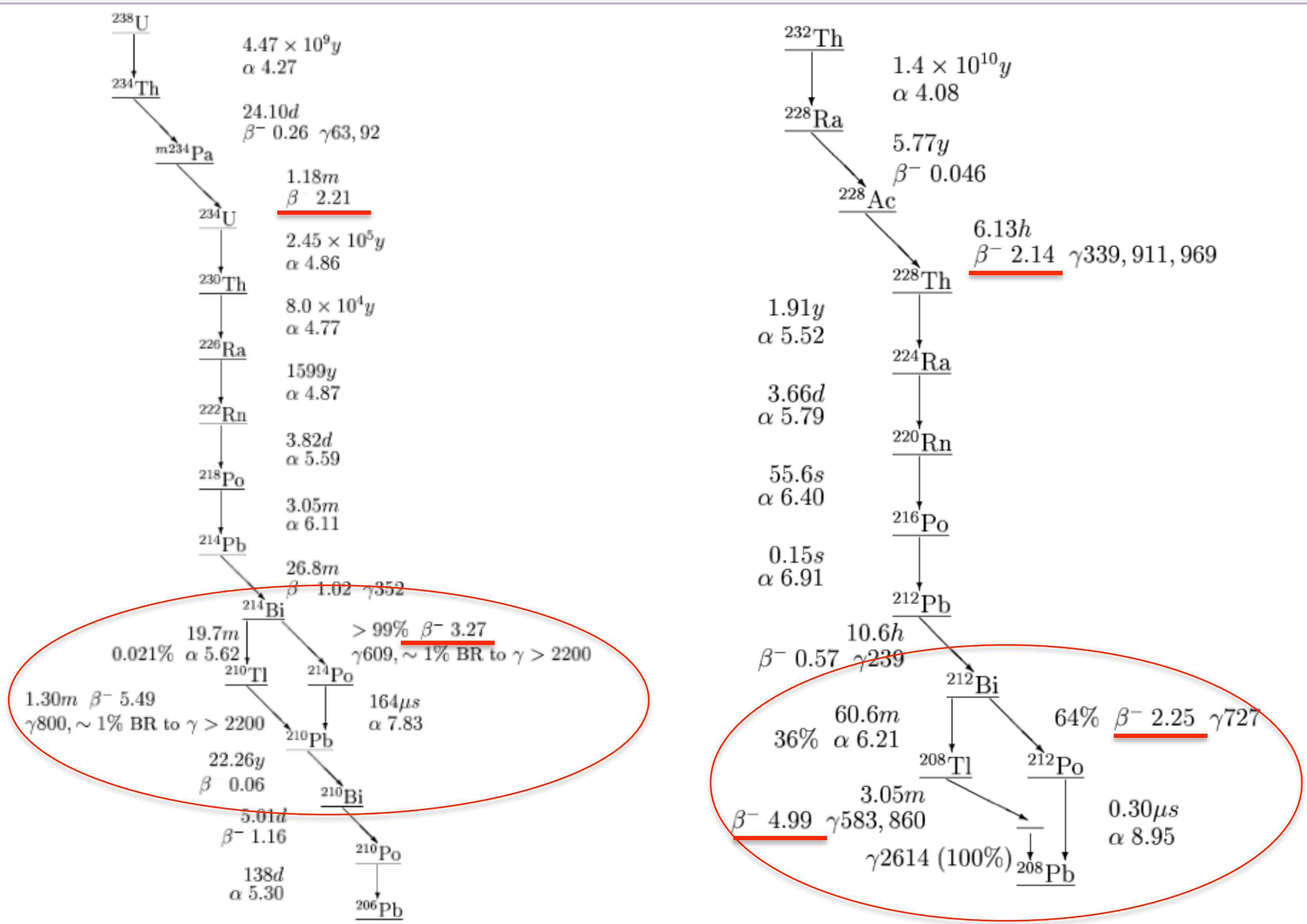


<u>Tellurium</u>
^{238}U, ^{232}Th, ^{210}Po
2νββ
Residual cosmogenically activated isotopes:
^{60}Co, ^{131}I

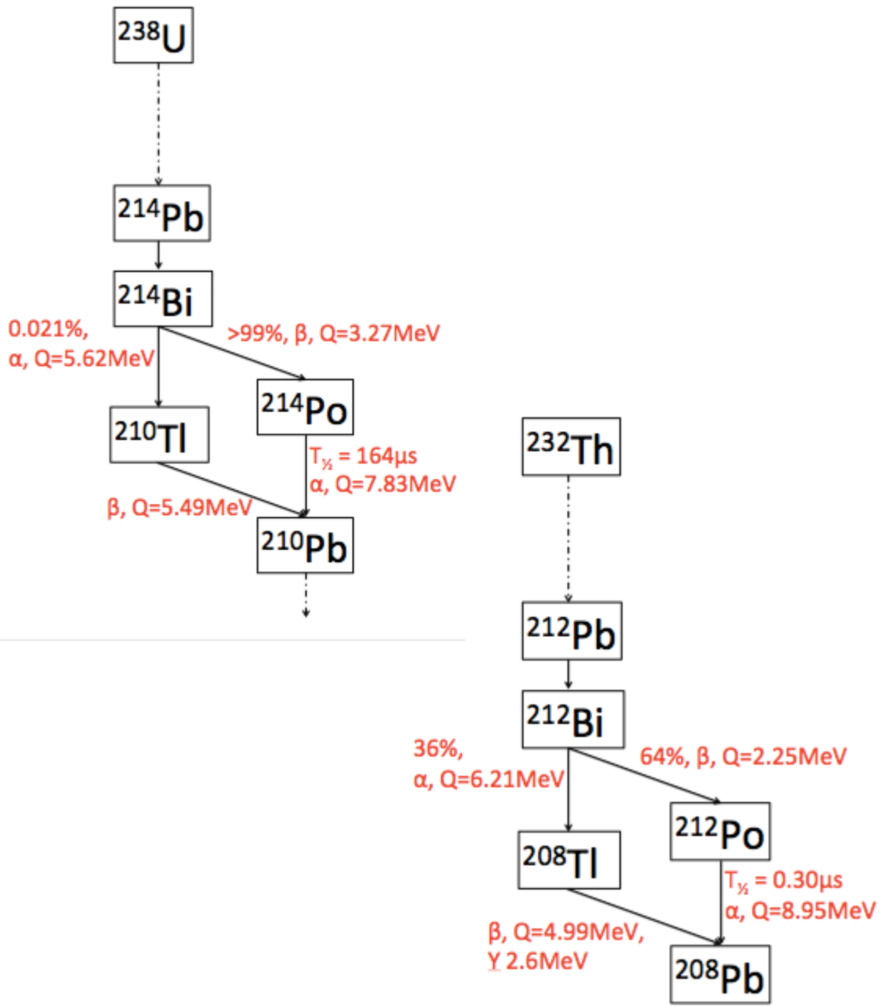
<u>Externals:</u>
^{214}Bi, ^{208}Tl ϒ from
PMTs, AV, Ropes, H_2O

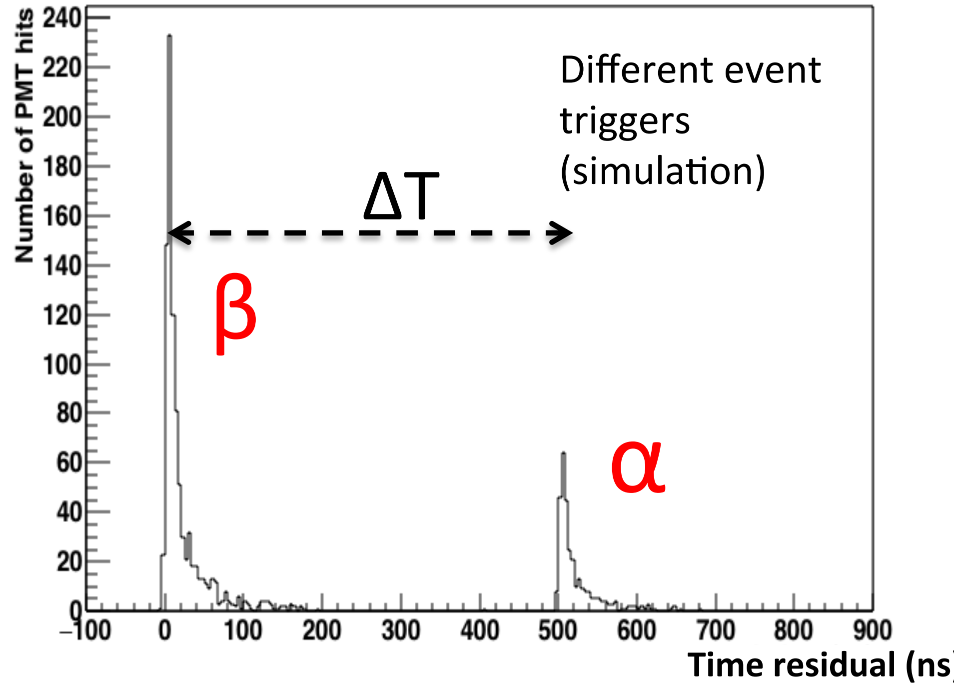
<u>Thermal neutrons:</u>
Capture on H to 2.2MeV ϒ:
Muon induced neutrons, (α,n)

Uranium and Thorium Chain



Bi-Po Rejection 1





Rejection criteria: $\Delta T(\beta-\alpha) < 24 \times T_{1/2}^{214Po}$

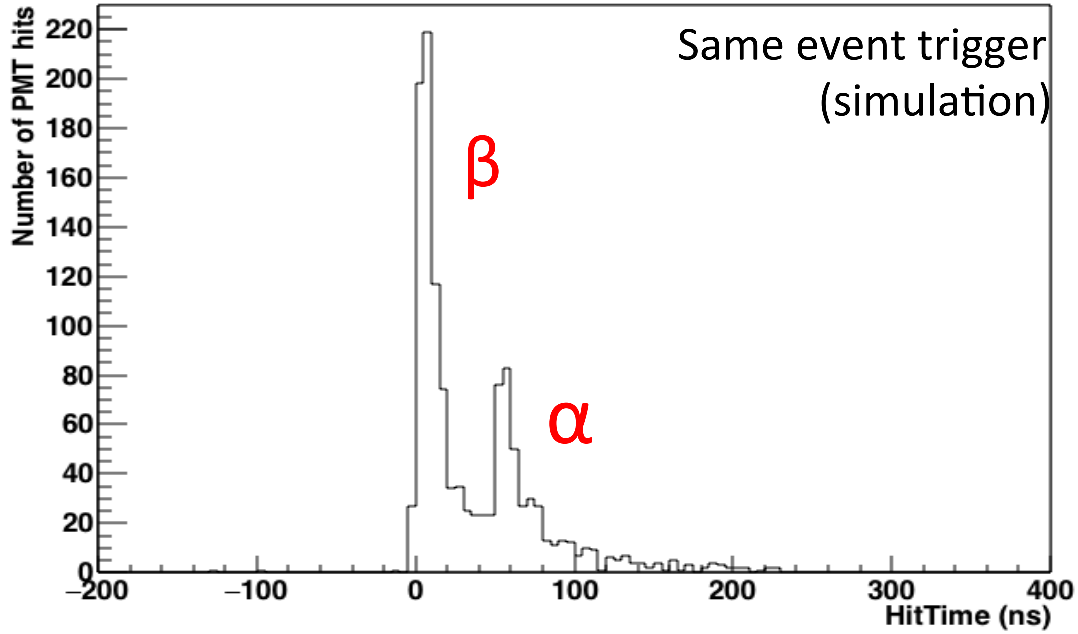
$Nhits(\alpha) > 50$

if(ΔT>500ns), $\Delta R(\beta-\alpha) < 1.5$m

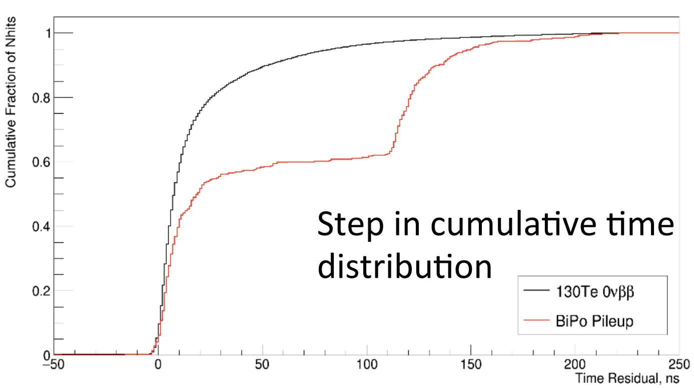
Calculated rejection efficiency (α >400ns after β, R<3.5m):

$\boldsymbol{\varepsilon_{214} = 99.9975\%, \varepsilon_{212} = 99.999\%}$

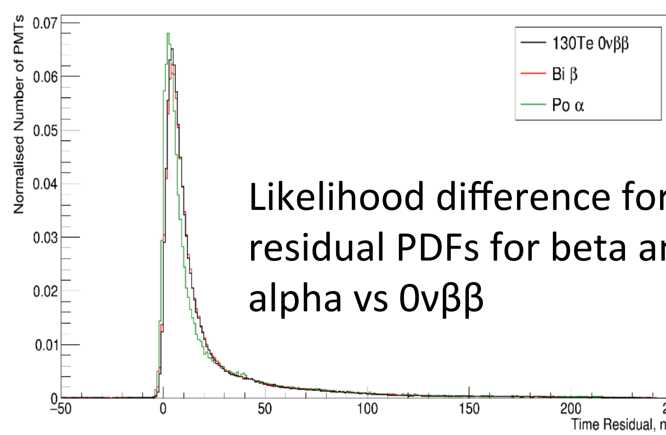
BiPo Rejection 2



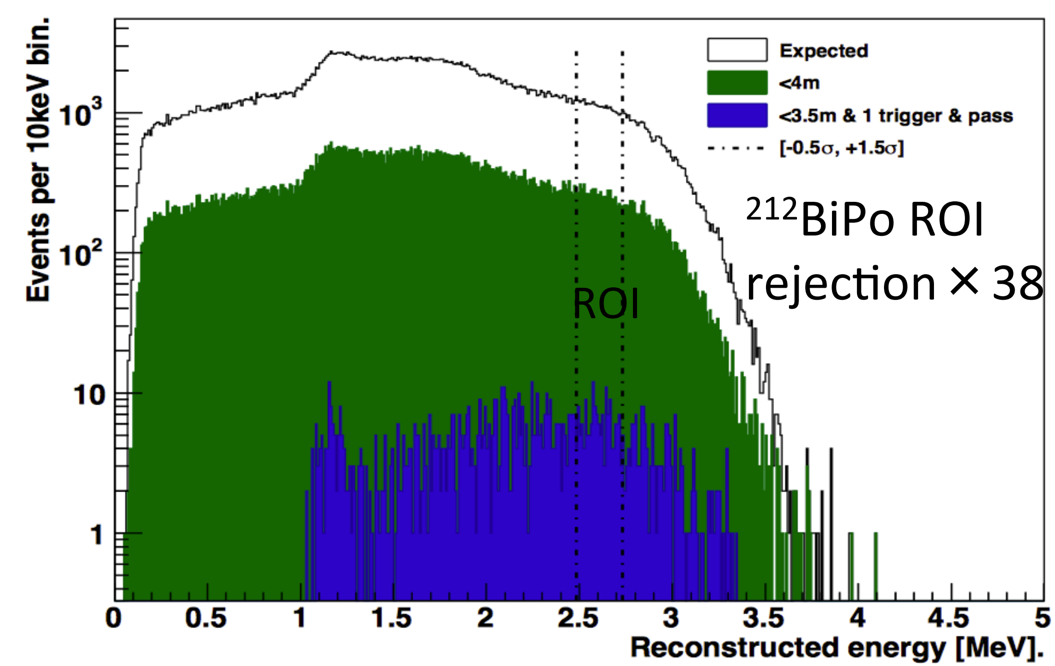
K. Majumdar, DPhil Thesis, University of Oxford, 2015



Time residual (ns)

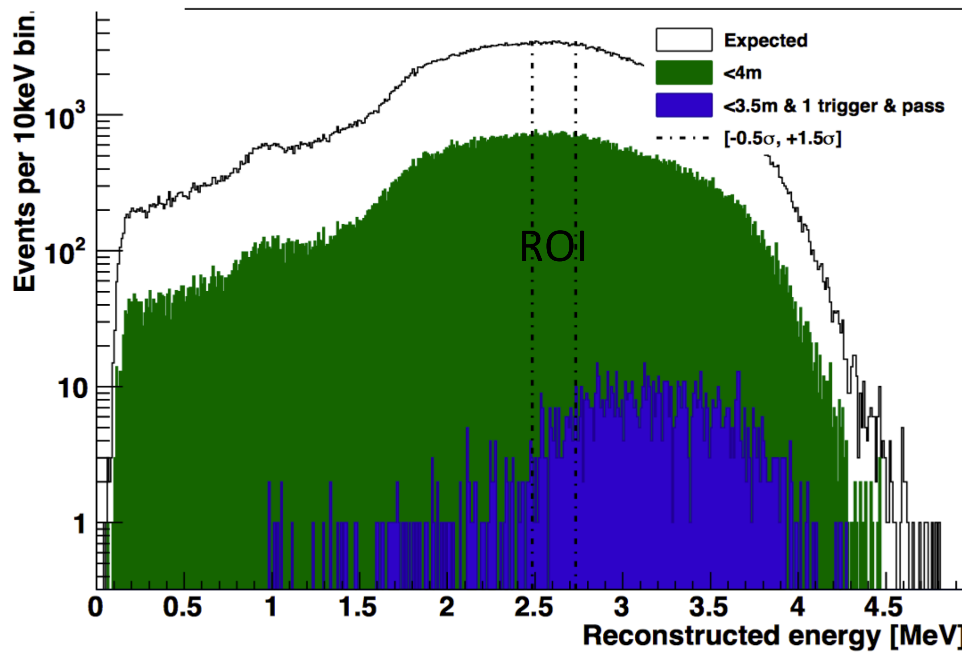


ction 2



^{212}BiPo ROI rejection × 38

^{214}BiPo ROI rejection × 49

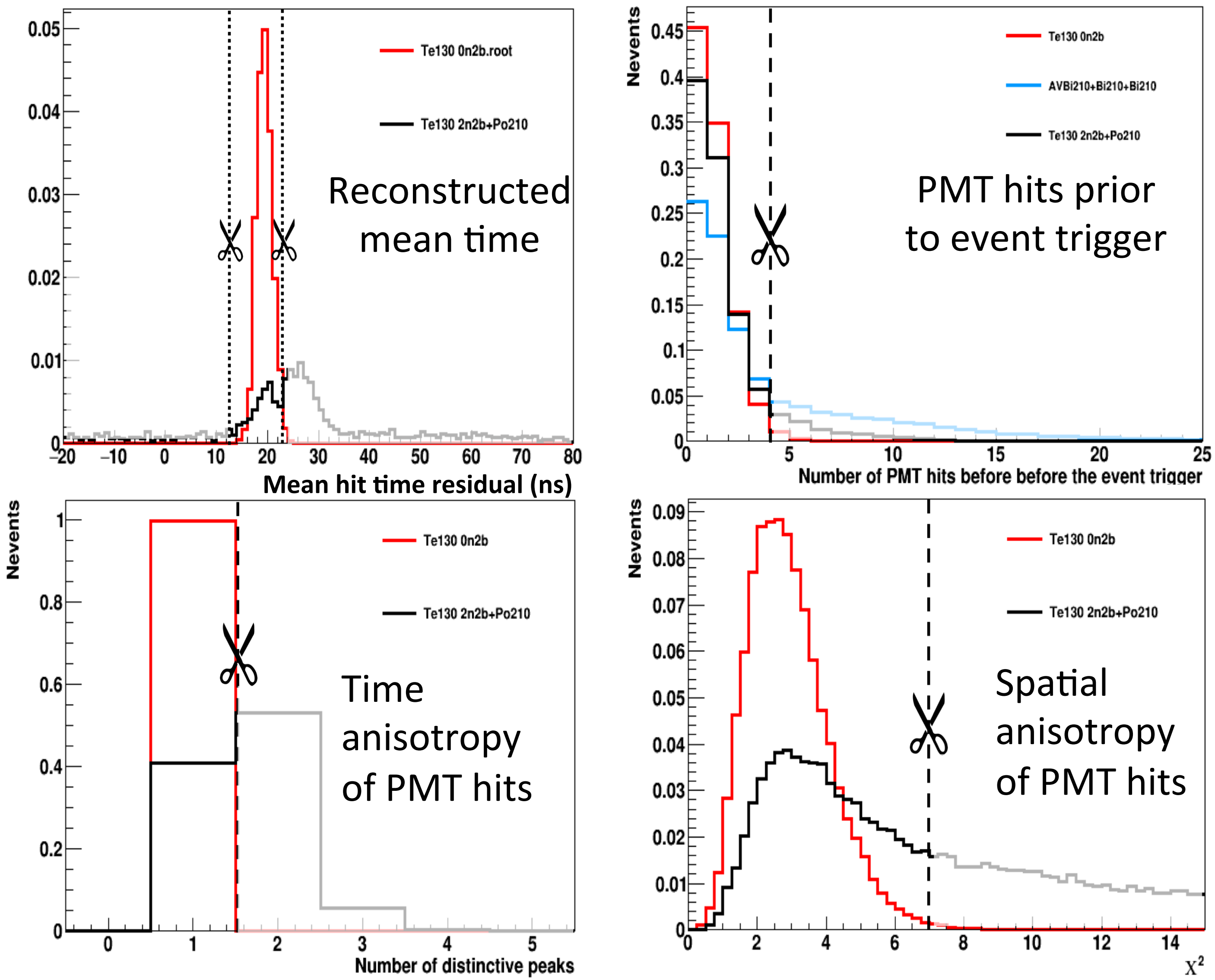


< 4 BiPo total / year in ROI

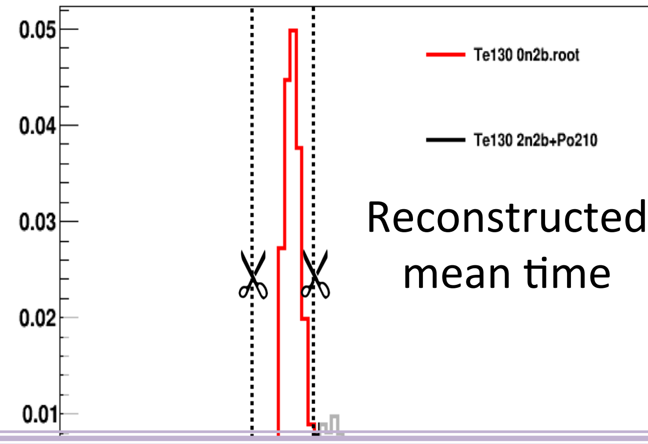
Methods sensitive to scintillator optics:

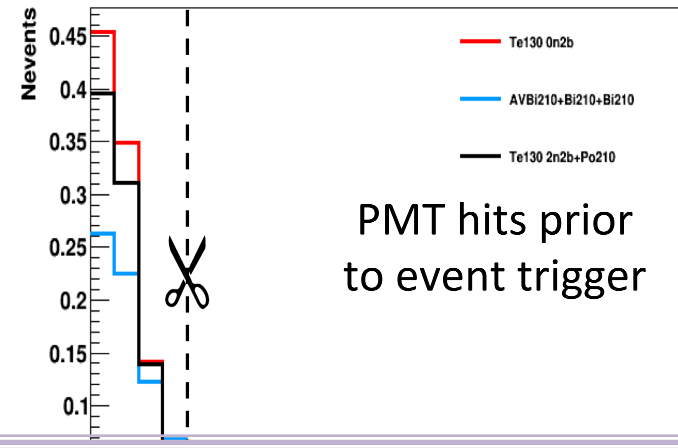
- Light yield
- Timing

Random PileUp

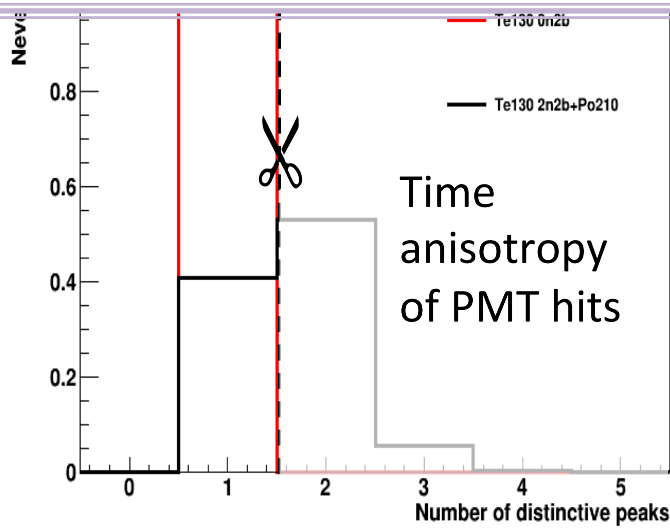


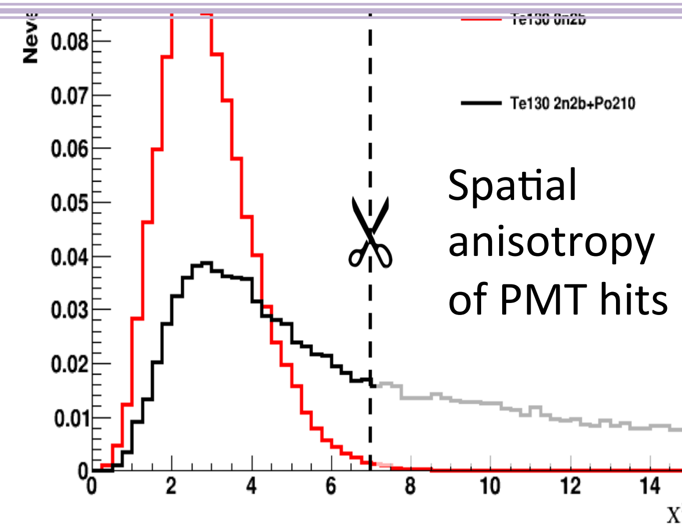
Random PileUp





Expect 36.3 pileup events / year in 0νββ ROI before rejection
➔ **0.23** events/year after cuts





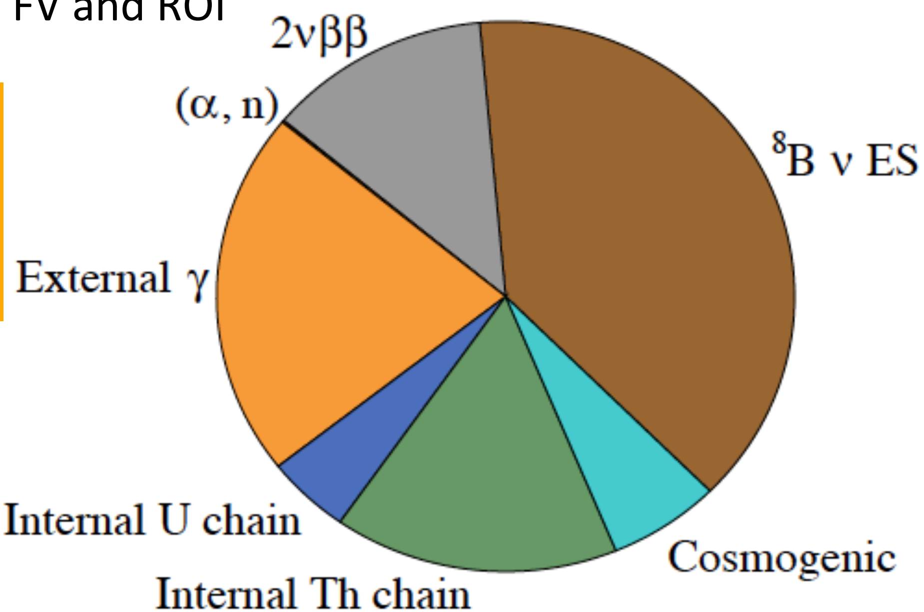
Backgrounds for 0nuBB search

Two neutrino mode 2νββ:
asymmetric ROI around the 0νββ signal
limited by energy resolution

^{8}B solar neutrinos:
- flat spectrum
- constrained by SNO/SK data
- also limited by resolution

14 ev/yr in FV and ROI

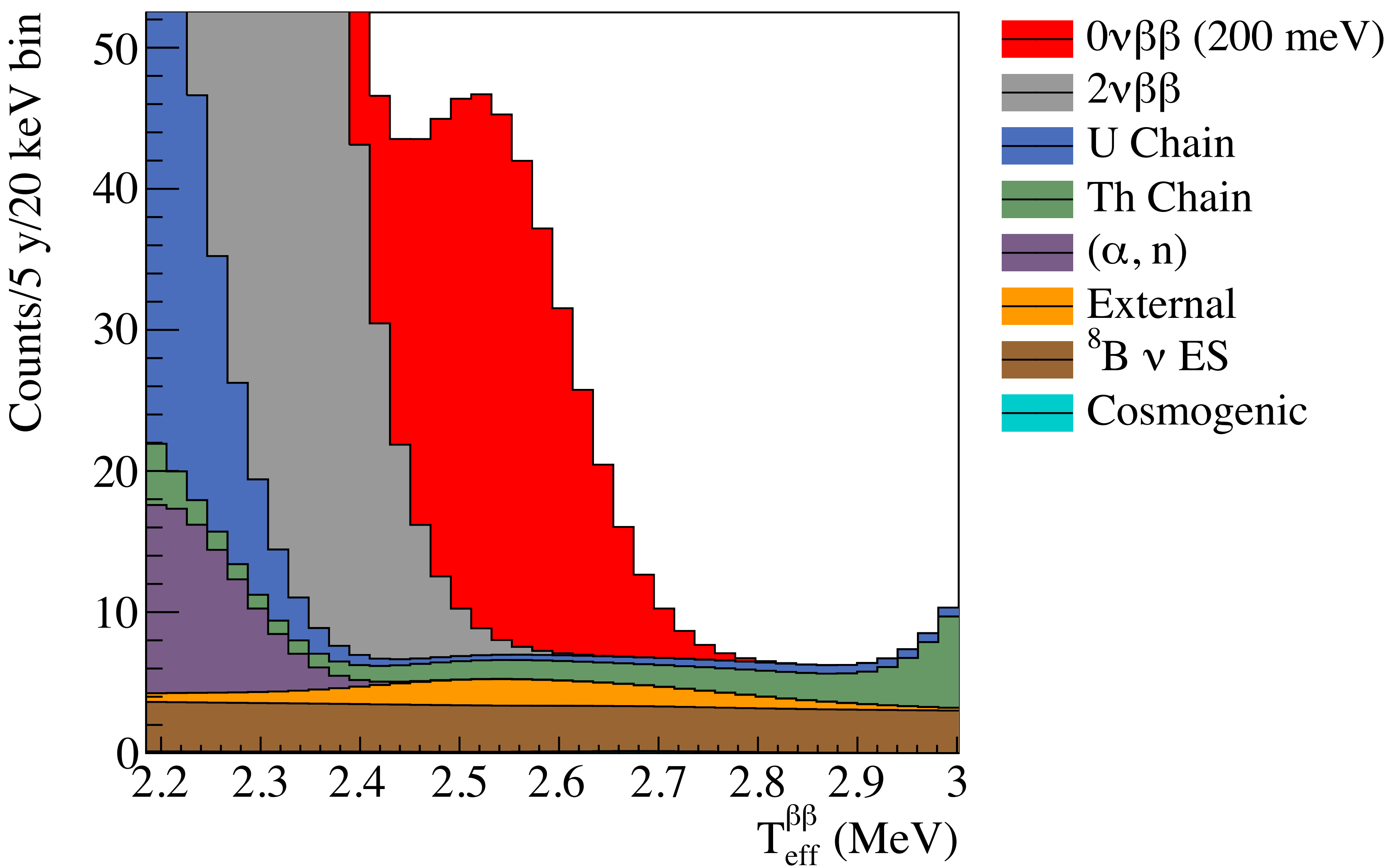
External gammas:
- from AV, ropes, water, PMTs
- fiducial volume (20%) cut
- requires good timing



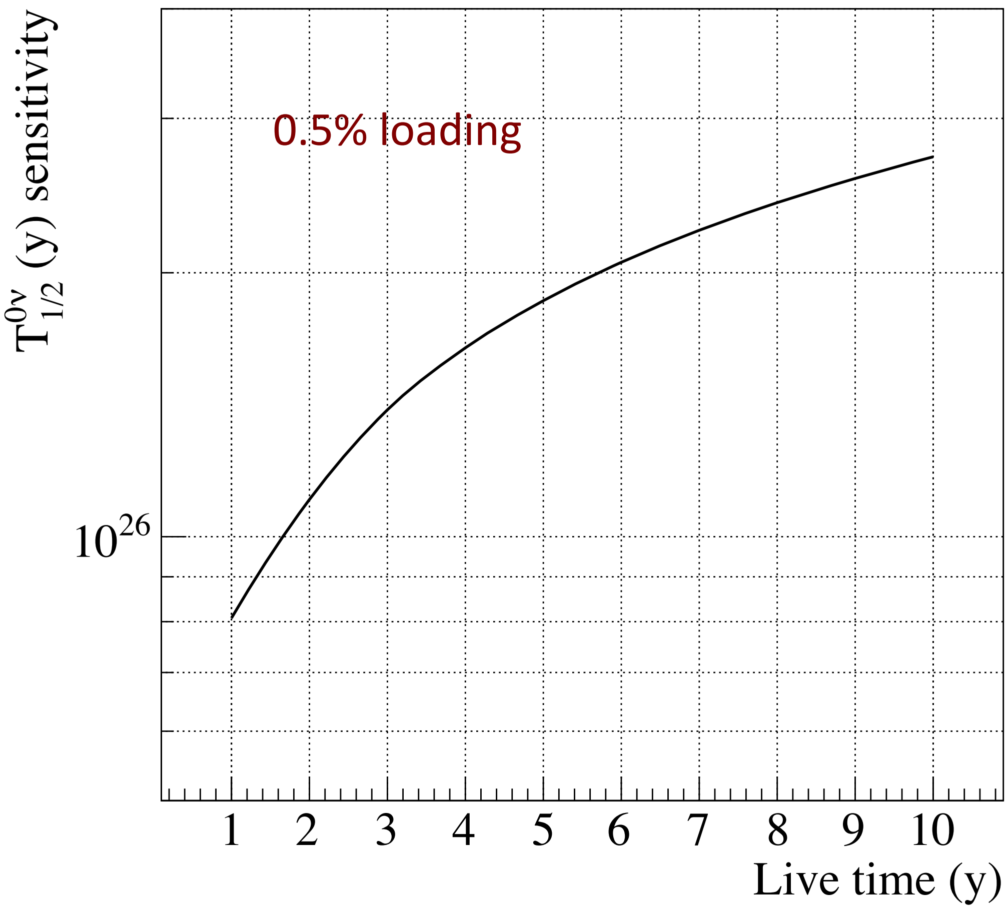
Internal U/Th chain
- betas from ^{214}BiPo, ^{212}BiPo
- tagged with β-α time-correlations
- same trigger window: x50 rejection
- different trigger window: 100% rejection

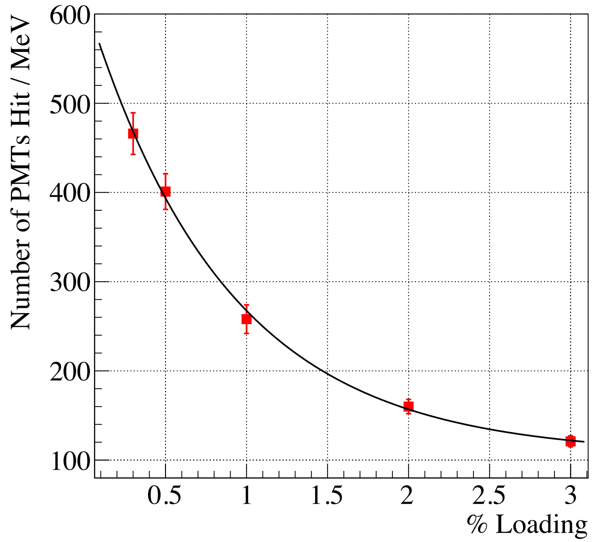
Cosmogenics:
- ^{124}Sb, ^{60}Co, ^{110m}Ag, ^{88}Y, ^{22}Na
- reduced by purification and "cool-down" UG storage
- About 1 ev/yr in ROI/FV

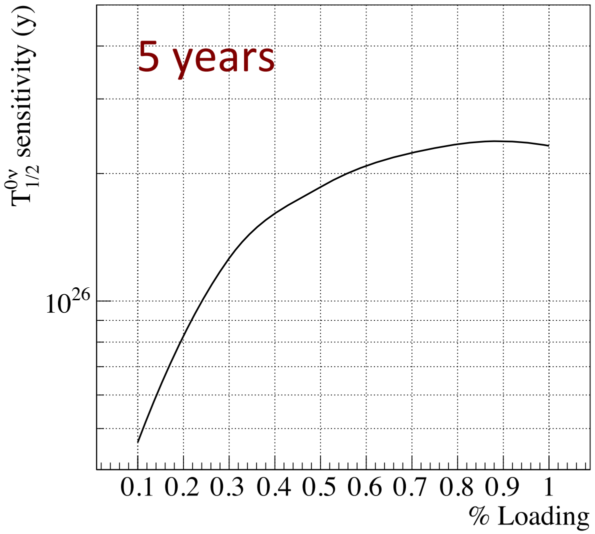
ROI Energy Spectrum



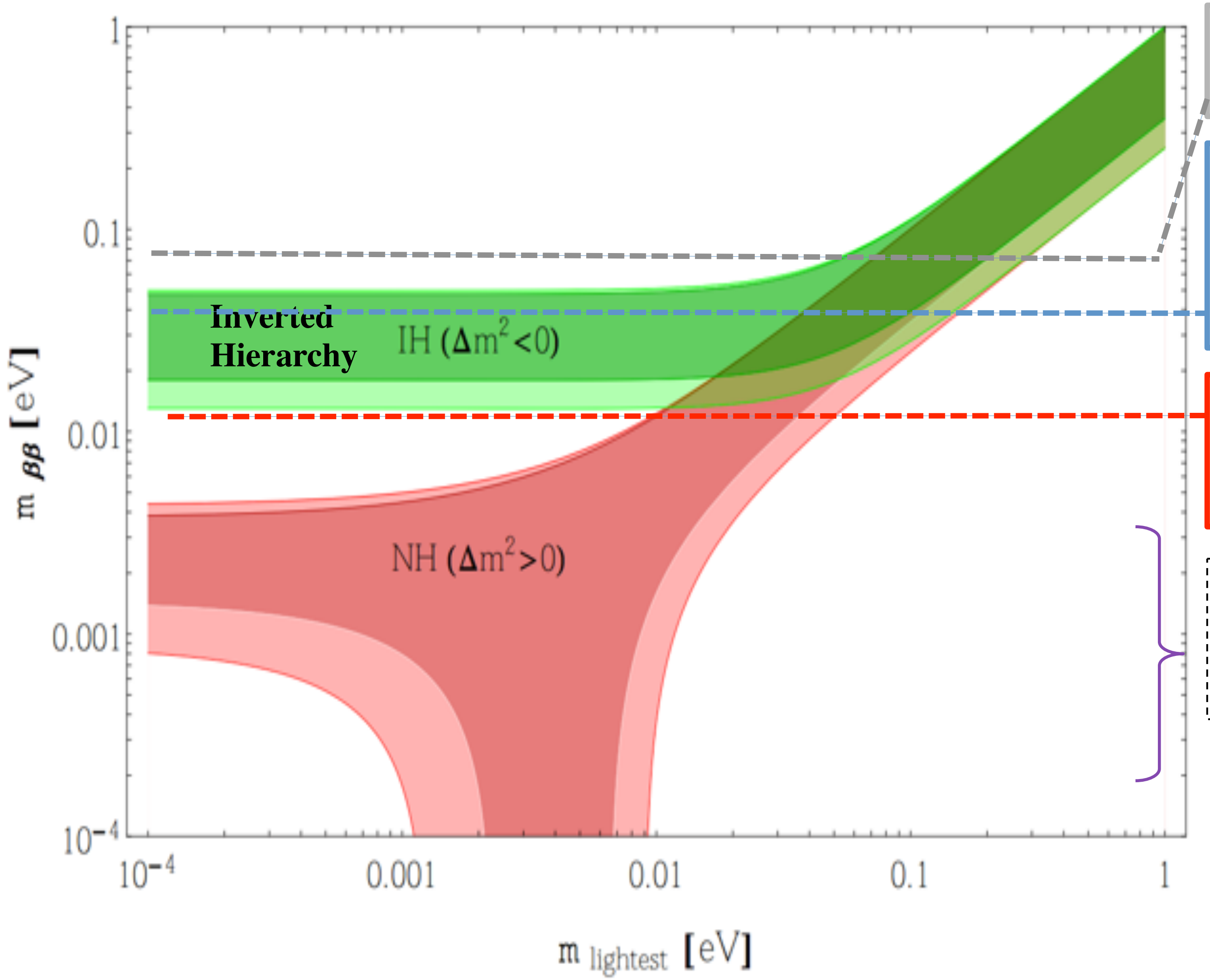
Sensitivity







0vBB Sensitivity



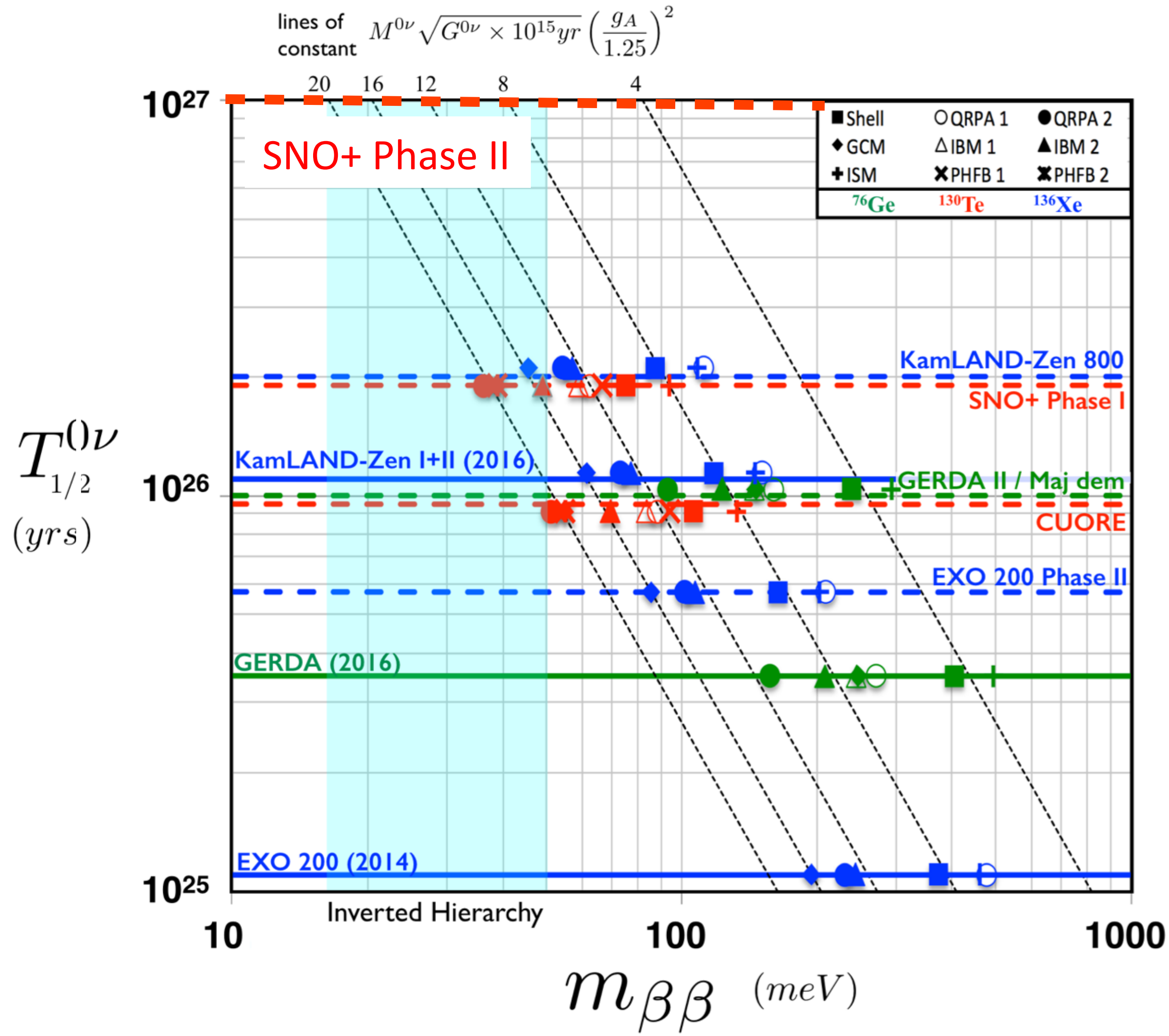
Best Current Limits (EXO, KLZ, Gerda, NEMO-3)

Current Target Level (SNO+ Phase 1, CUORE, EXO+, GERDA+, KLZ+, Full SuperNEMO)

Inverted Hierarchy Explorers (SNO+ Phase 2/3 (?) nEXO (?), Super-KLZ (?))

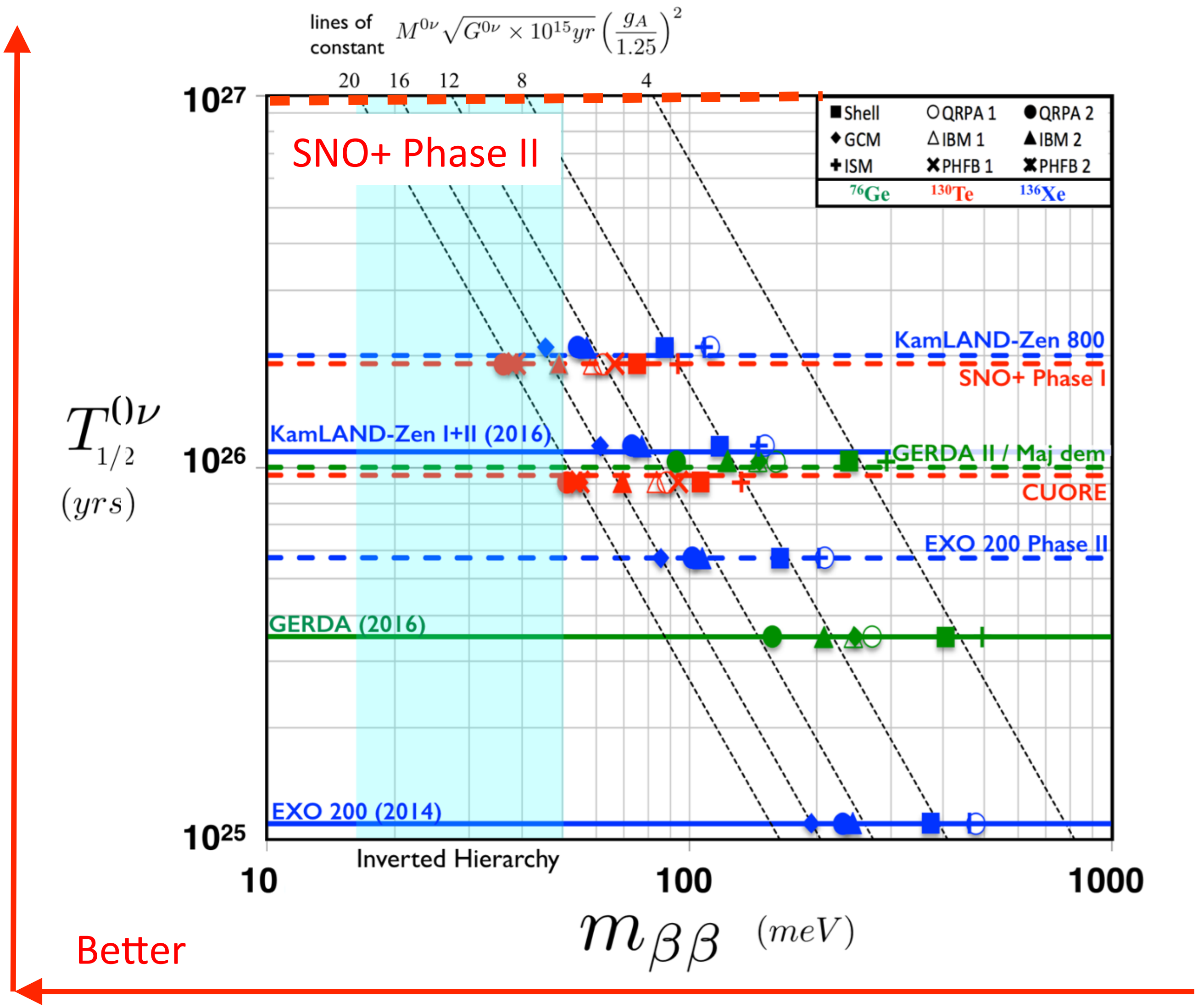
There Be Dragons….. Biller, Physical Review D, 071301R

Comparison with other experiments



Plot by S. Biller

Comparison with other experiments



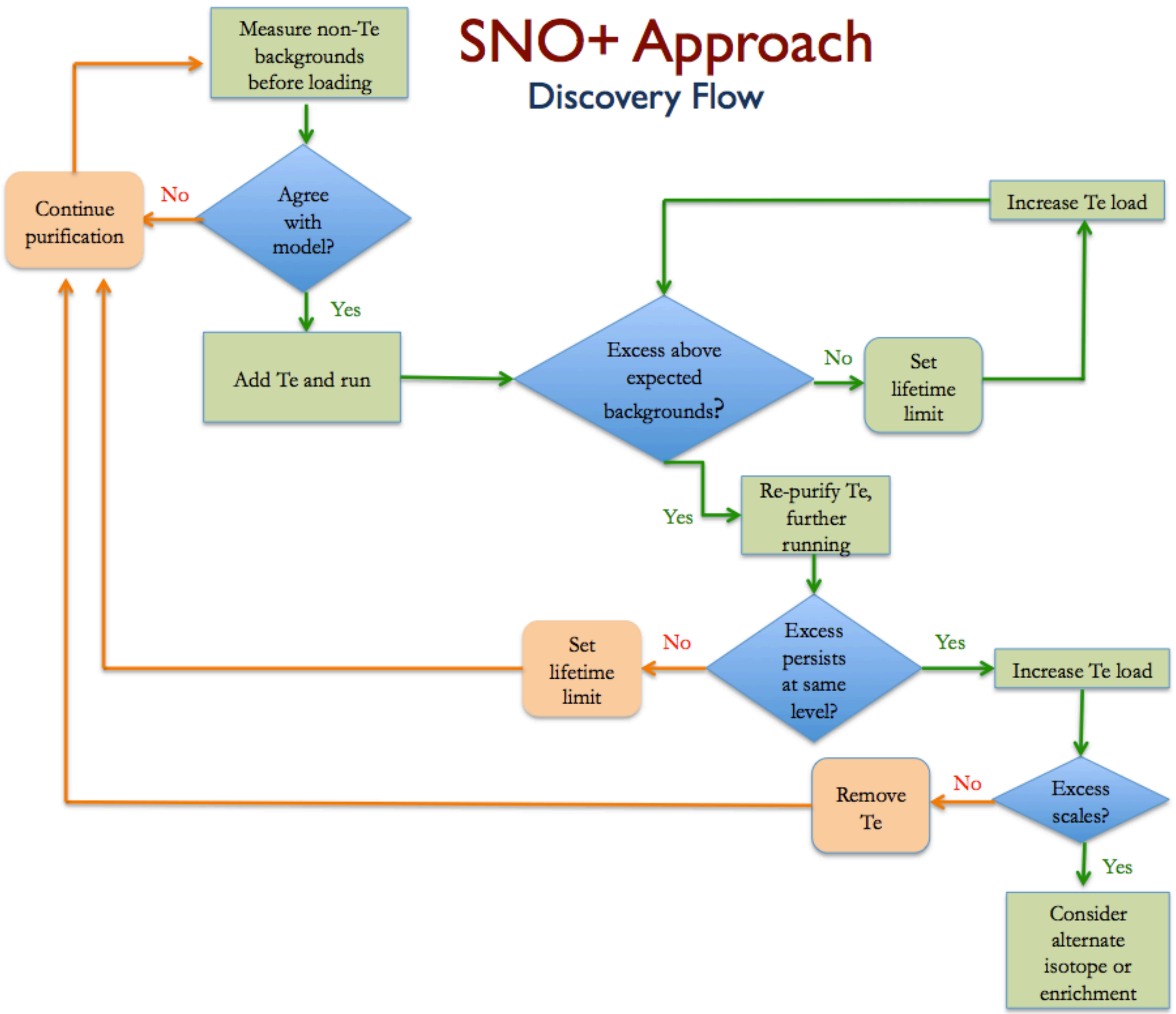
We don't know which of the nuclear models (diagonal lines) is best.

Large uncertainties.

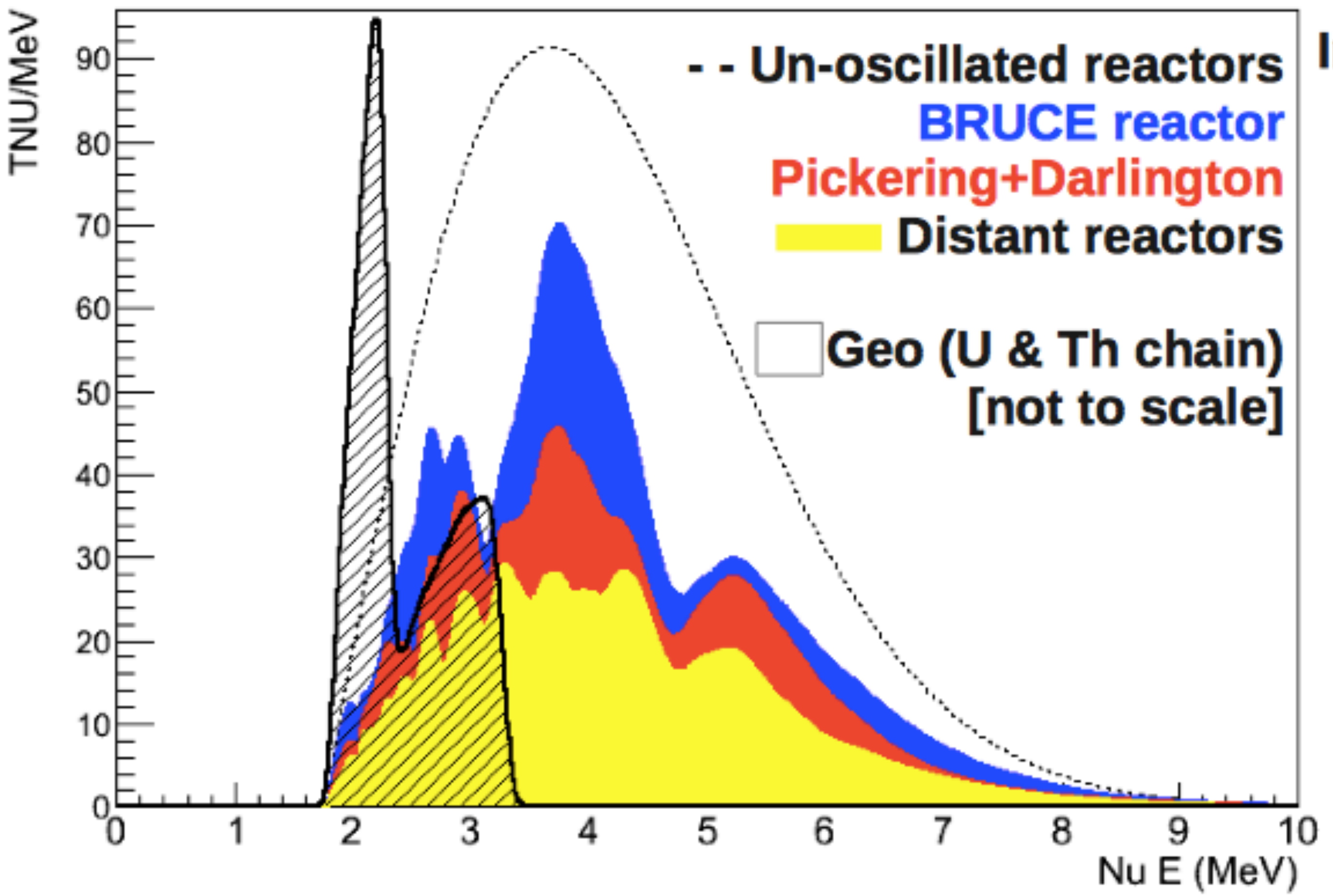
Need experiments with different isotopes!

Plot by S. Biller

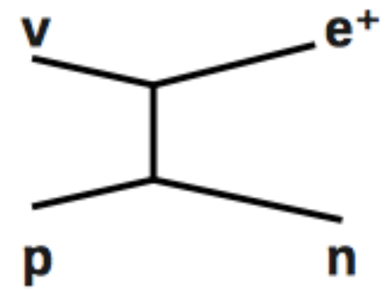
What if we see a bump?



Anti-neutrinos in SNO+



Inverse Beta Decay



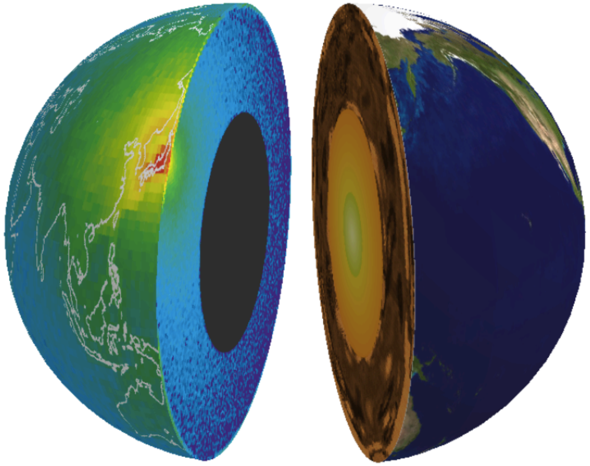
coincidence tag (dT~250 ns)

n+p -> 2.2 MeV γ

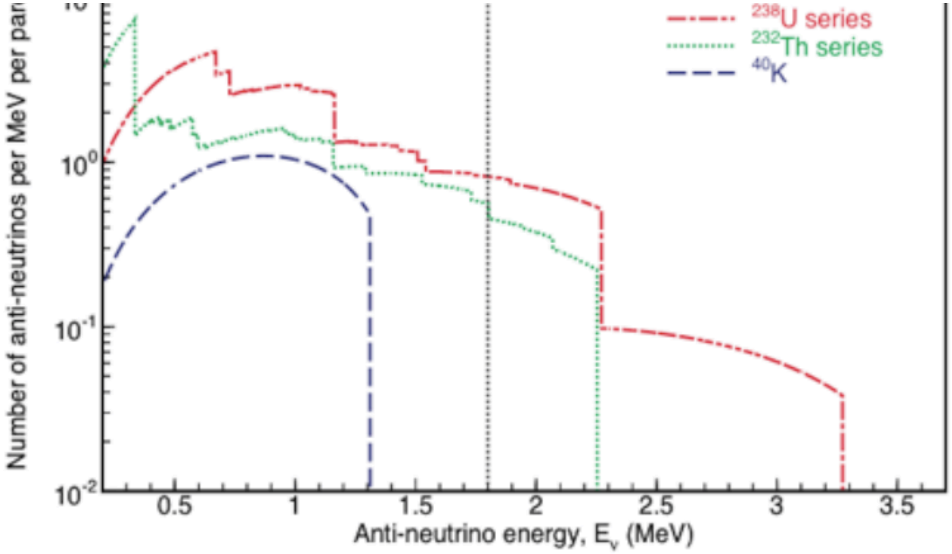
Threshold
Eν > 1.8 MeV

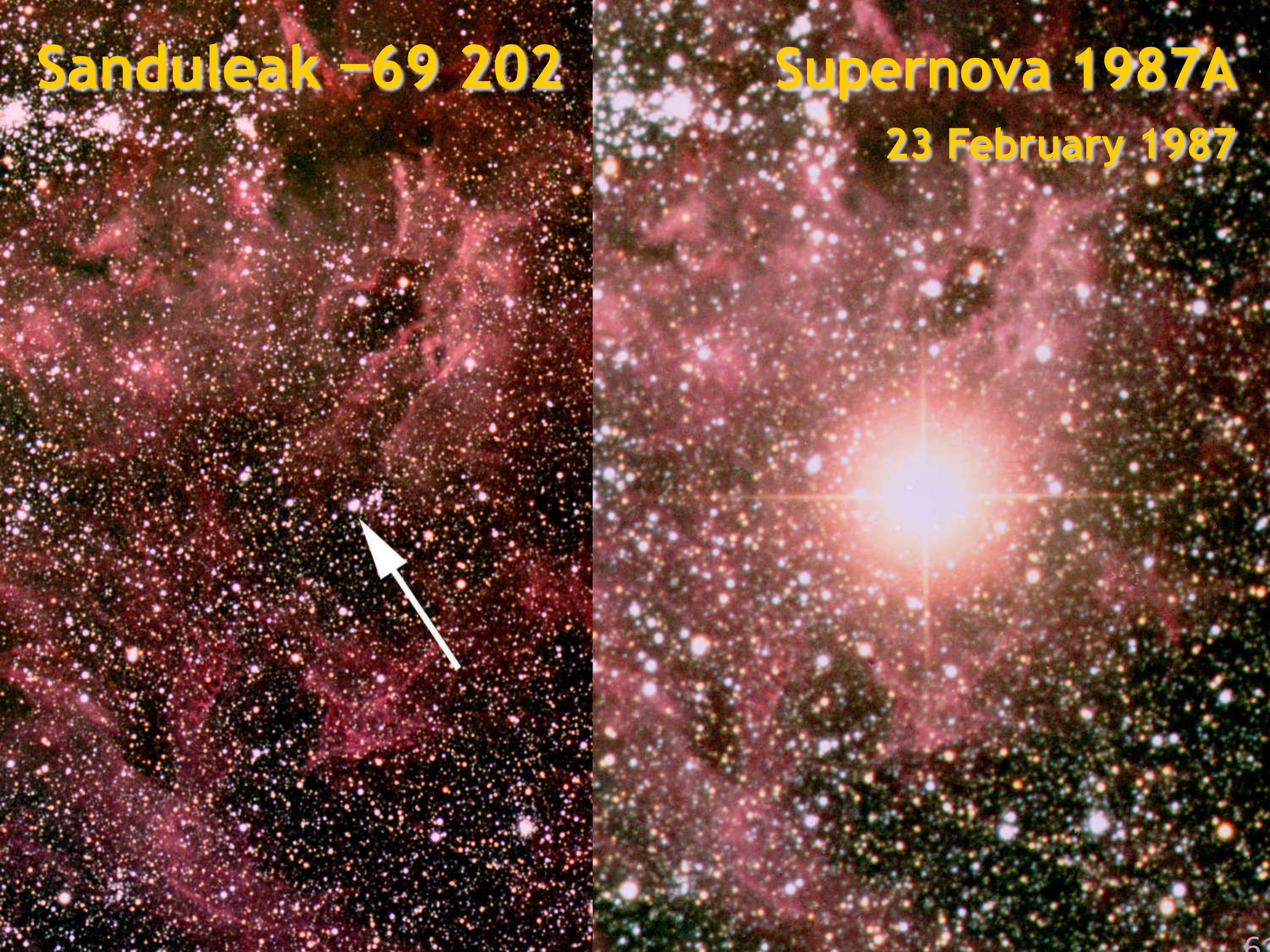
~ 100 events / year; oscillation sensitivity after 3-5 year LAB run
more bkg in low E geo-nu region

Geo-Neutrinos



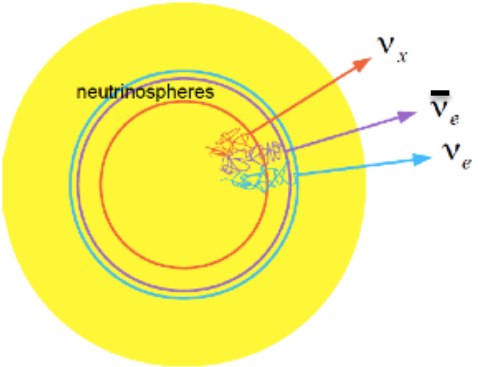
The left half shows the simulated production distribution for the geoneutrinos detectable with KamLAND, and the right half shows the Earth structure.




Sanduleak −69 202
Supernova 1987A
23 February 1987

SuperNova Detection in SNO+

- ★ Core-collapse supernovae: 99% of their gravitational binding energy released in the form of neutrinos (several 10^{53} erg)
- ★ 10MPc SN, interactions in 5.5m FV:



Reaction	Number of Events
NC: $\nu + p \rightarrow \nu + p$	429.1 ± 12.0 [a]
CC: $\bar{\nu}_e + p \rightarrow n + e^+$	194.7 ± 1.0
CC: $\bar{\nu}_e + {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{B}_{g.s.} + \mathrm{e}^+$	7.0 ± 0.7
CC: $\nu_e + {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{N}_{g.s.} + \mathrm{e}^-$	2.7 ± 0.3
NC: $\nu + {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{C}^*(15.1\,\mathrm{MeV}) + \nu'$	43.8 ± 8.7
CC/NC: $\nu + {}^{12}\mathrm{C} \rightarrow {}^{11}\mathrm{C}$ or ${}^{11}\mathrm{B} + \mathrm{X}$	2.4 ± 0.5
ν–electron elastic scattering	13.1[b]

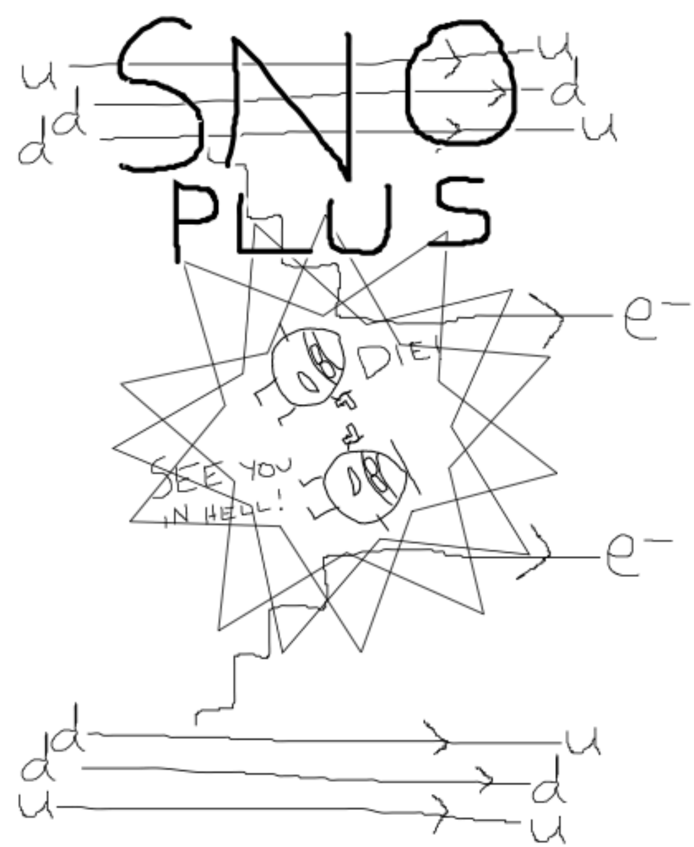
[a] 118.9±3.4 above a trigger threshold of 0.2 MeV visible energy.
[b] The Standard Model cross section uncertainty is < 1%.

- ★ Member of SNEWS

Summary

- ★ SNO+ is a low background, low energy, liquid scintillator detector
  - ★ Lots of work
  - ★ lots of challenges
  - ★ lots of physcis
- ★ Phase-0, water-fill imminent

Thanks for listening !



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Armstrong State University
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University of California, Berkley
University of California, Davis
Lawrence Berkeley National Laboratory
University of Chicago
University of Pennsylvania
University of Washington

TU Dresden

UNAM

Back Up Slides

OnuBB Sensitivity: Assumptions

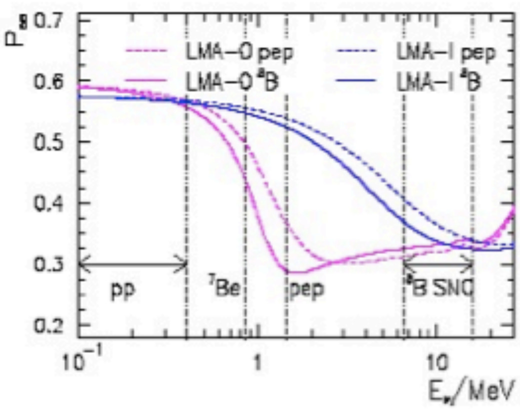
- Scintillator loaded with 0.5% natTe by mass
- $M^{0\nu}$ = 4.03 (IBM-2) [1]
- $G^{0\nu} = 3.69 \times 10^{-14} y^{-1}$ [2]
- R < 3.5 m (FV = 20%)
- > 99.99% (98%) rejection of ^{214}BiPo (^{212}BiPo)
- Light yield 390 NHits/MeV
- Energy resolution is gaussian with width $\sigma(E) = \sqrt{(E\ [MeV]/390)}$

[1] J. Barea, J. Kotila, F. Iachello, Nuclear matrix elements for double-beta decay, Phys. Rev. C 87, 014315 (2013).

[2] J. Kotila, F. Iachello, Phase space factors for double-beta decay Phys,Rev. C 85, 034316 (2012).

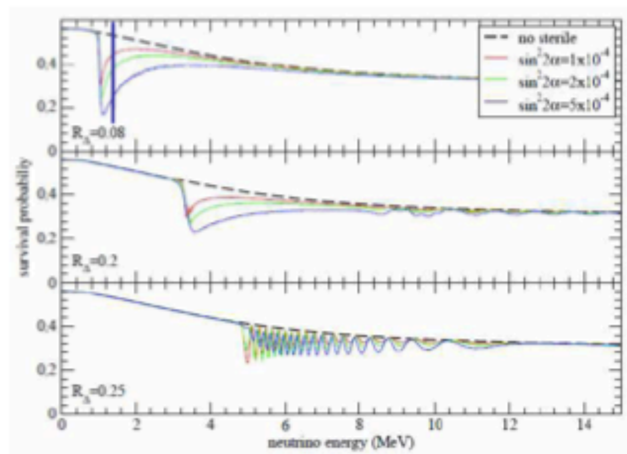
Pep neutrinos – test for new Physics

Non-standard interactions (flavour changing NC)



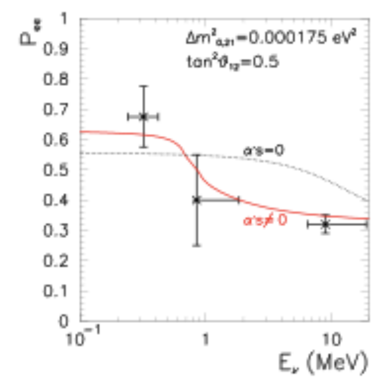
Friedland, Lunardini, Peña-Garay, PLB 594, (2004)

Sterile Neutrinos



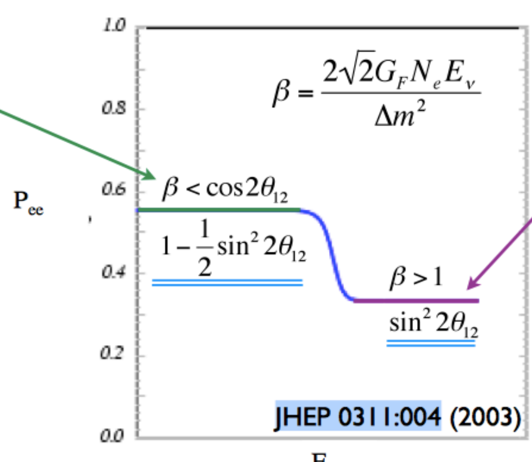
Holanda & Smirnov PRD 83 (2011) 113011

Mass varying neutrinos (MaVaNs)



M.C. Gonzalez-Garcia, M. Maltoni Phys Rept 460:1-129 (2008)

Low energy (<1MeV):
Phase-averaged vacuum oscillations



JHEP 0311:004 (2003)

'High' energy (>5MeV):
Matter-dominated resonant conversion