Queen Mary
University of London

SNO+

European Research Council
Established by the European Commission

Jeanne Wilson

3-2-2015

SNO+ Collaboration

Queen's
Alberta
Laurentian
SNOLAB
TRIUMF

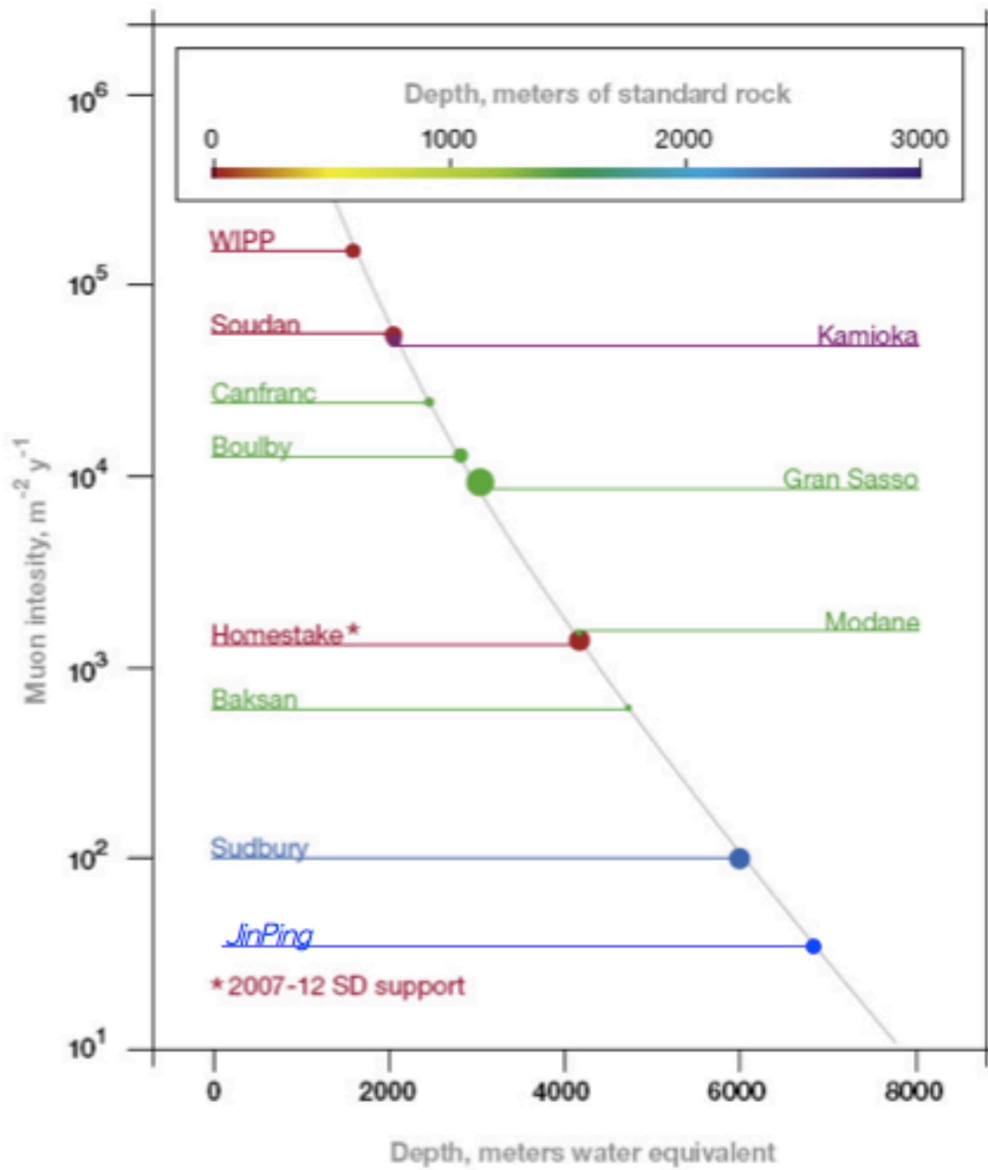
BNL, AASU
U Penn, UNC
U Washington
UC Berkeley/LBNL
Chicago, UC Davis

Oxford
Sussex
QMUL
Liverpool
Lancaster

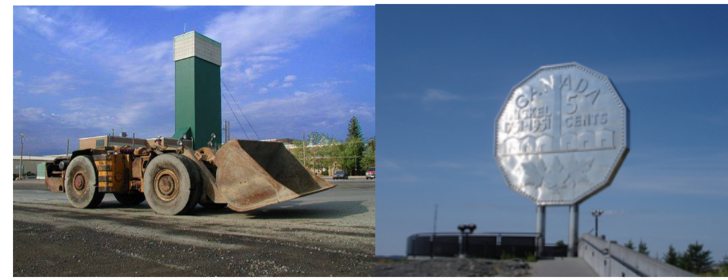
LIP Lisboa
LIP Coimbra

TU Dresden

Location

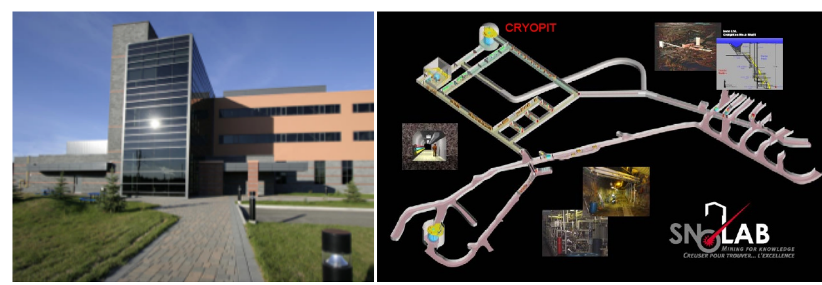


Adapted from http://www.deepscience.org/contents/underground_universe_popup03.shtml



Muon flux = 70 muons/day

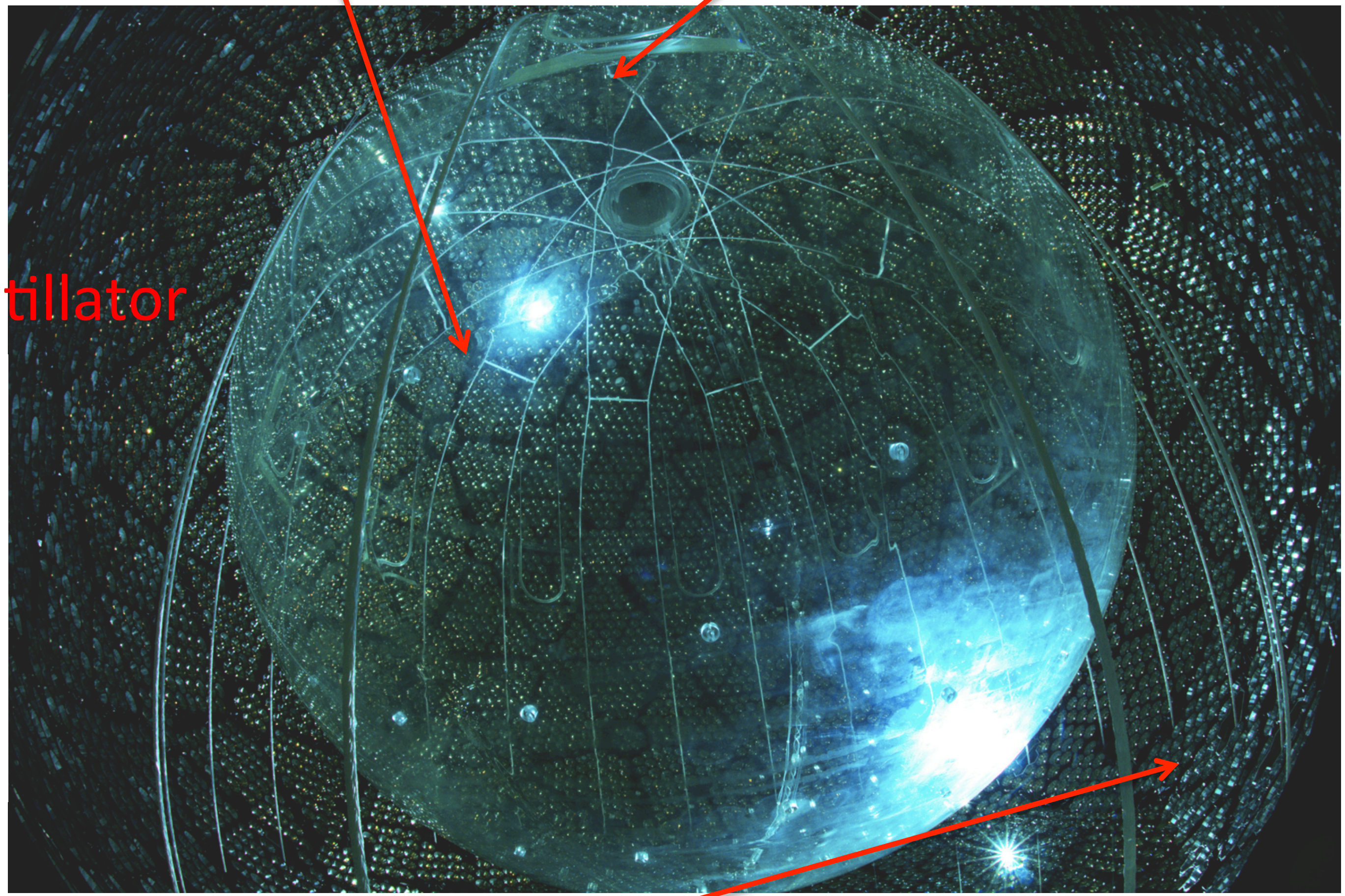
Class-2000 clean room lab



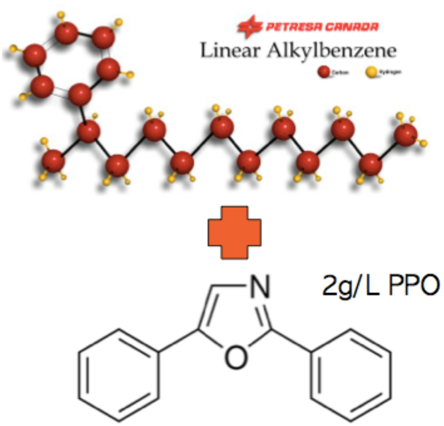
SNO+ Detector

- 12m diameter Acrylic Vessel

Hold down rope net



- 780 tonnes scintillator

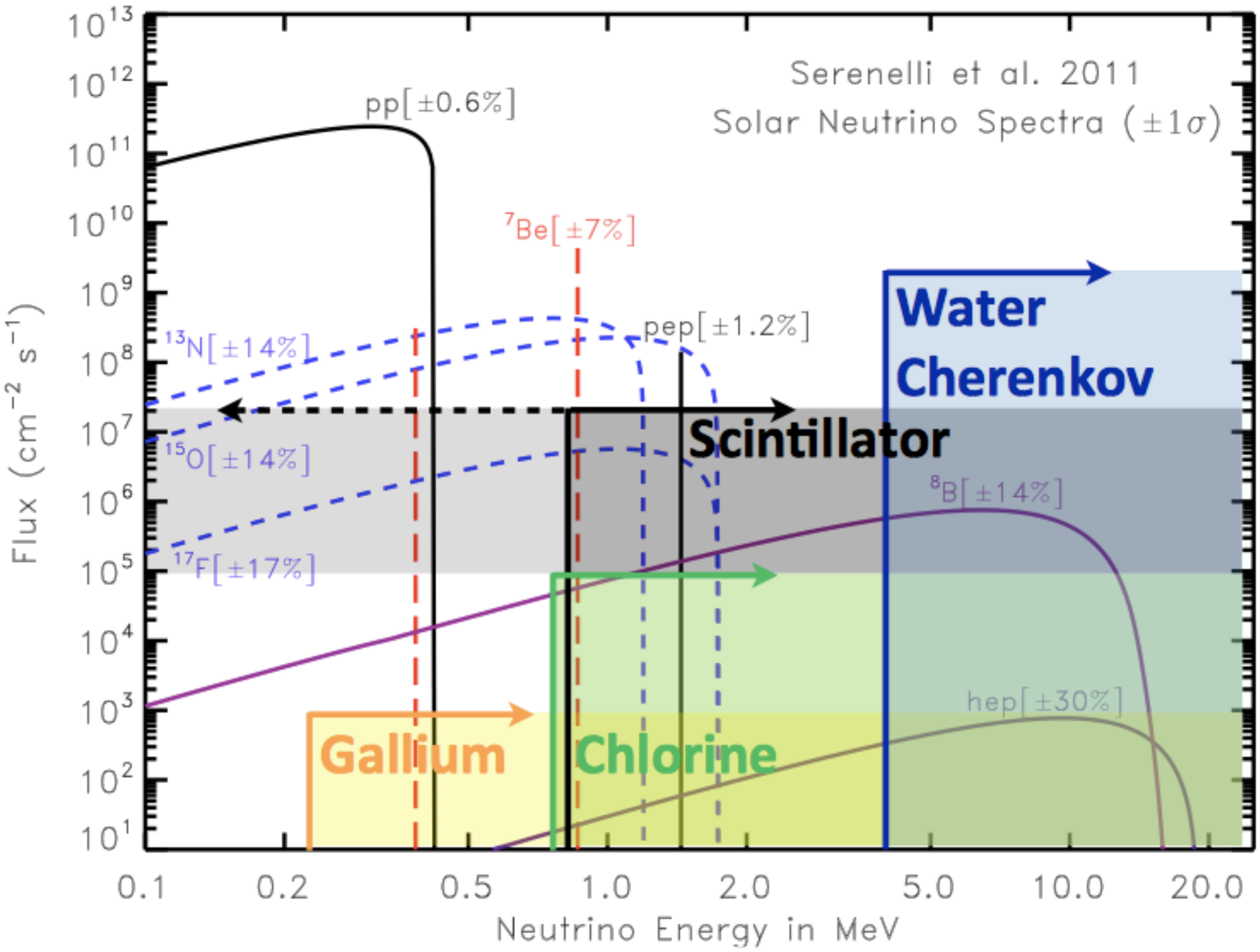


- 7ktonnes water shielding
- ~9500 8inch PMT array

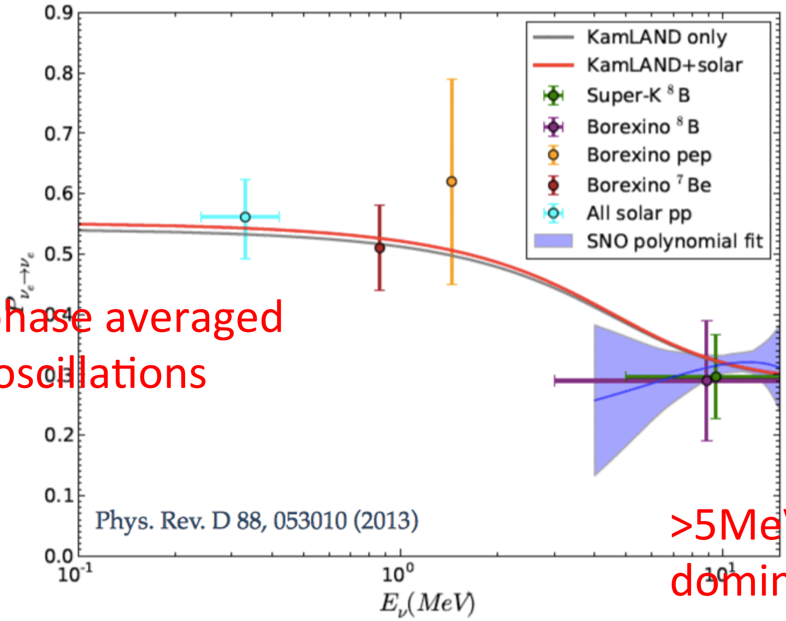
SNO+ Physics Program

- Low Energy Solar Neutrinos
- Supernovae sensitivity
- Reactor Neutrinos
- Geoneutrinos
- Invisible Nucleon Decay (water phase)
- Neutrinoless double beta decay search

Solar Neutrinos



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



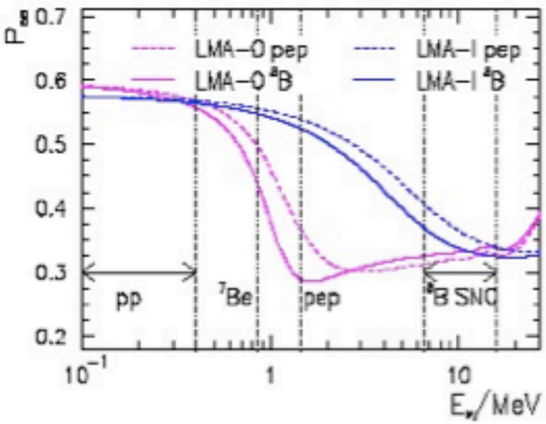
<1MeV phase averaged vacuum oscillations

>5MeV Matter dominated resonant conversion

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

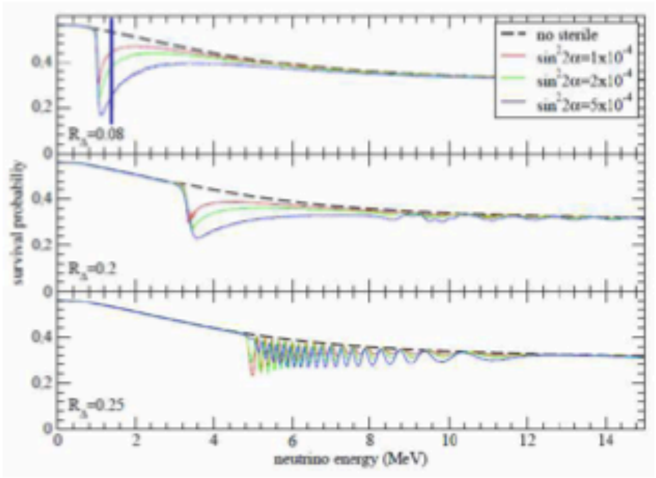
Pep neutrinos – test for new Physics

Non-standard interactions (flavour changing NC)



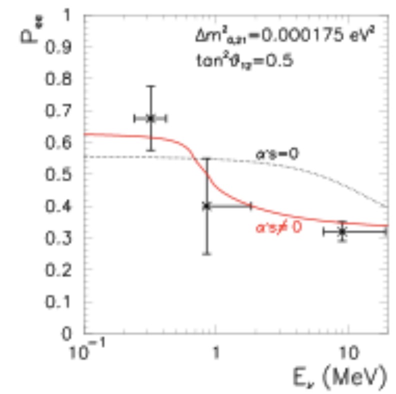
Friedland, Lunardini, Peña-Garay, PLB 594, (2004)

Sterile Neutrinos



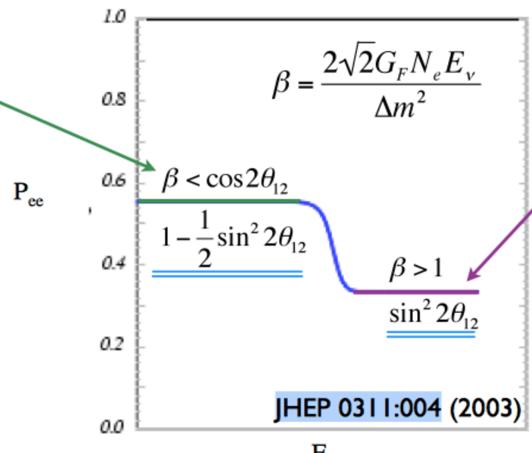
Holanda & Smirnov PRD 83 (2011) 113011

Mass varying neutrinos (MaVaNs)



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

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

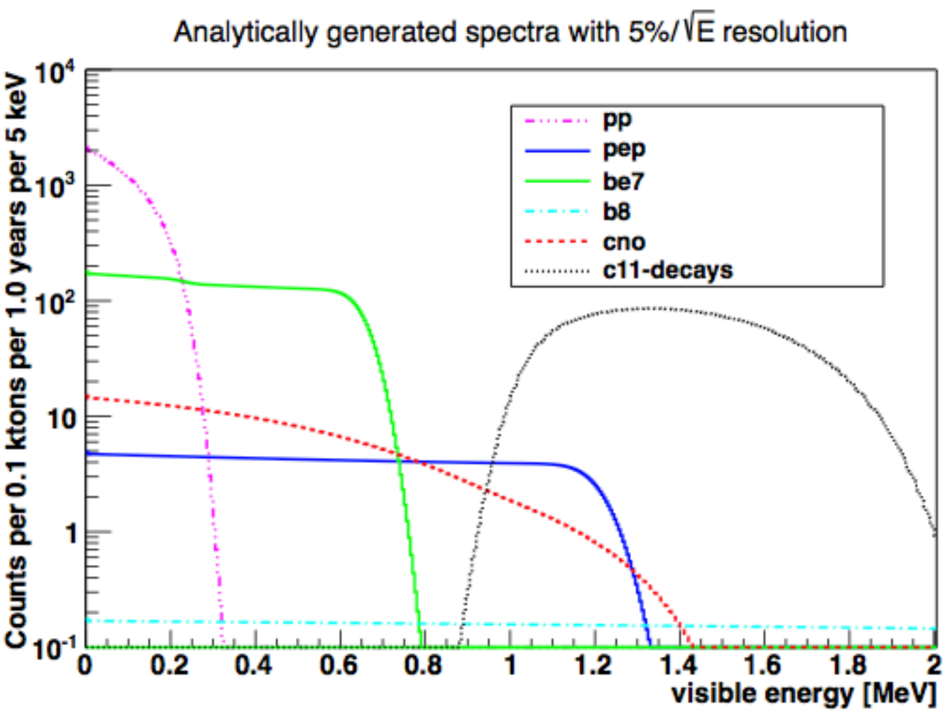


JHEP 0311:004 (2003)

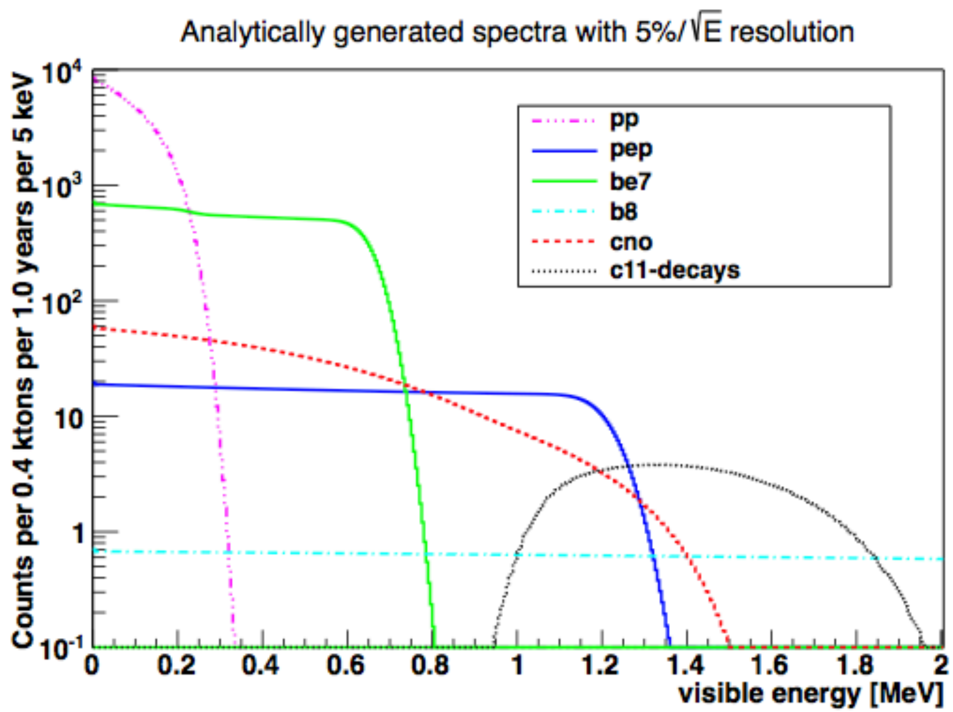
'High' energy (>5MeV): Matter-dominated resonant conversion

A matter of depth

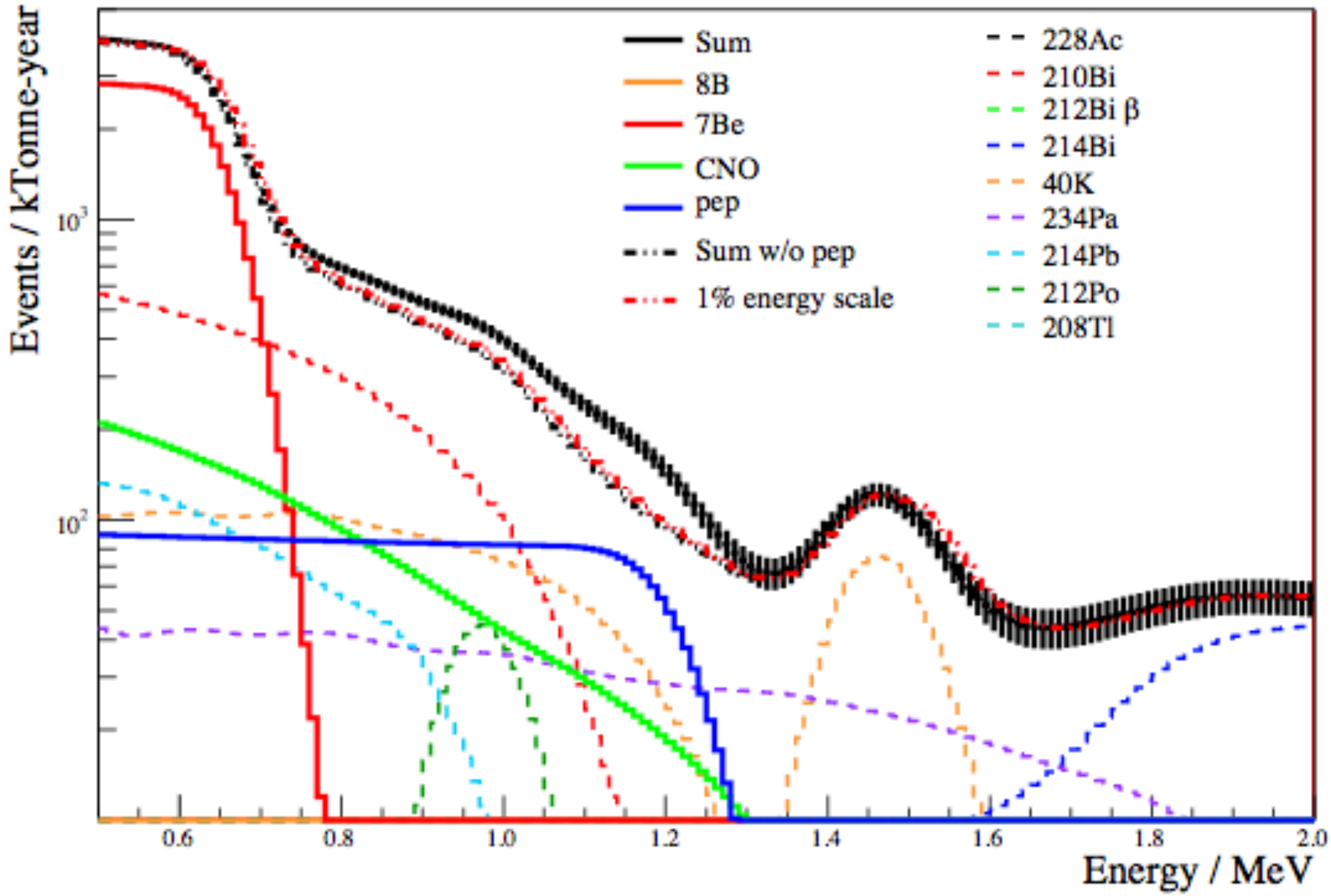
Borexino



SNO+



SNO+ solar signals

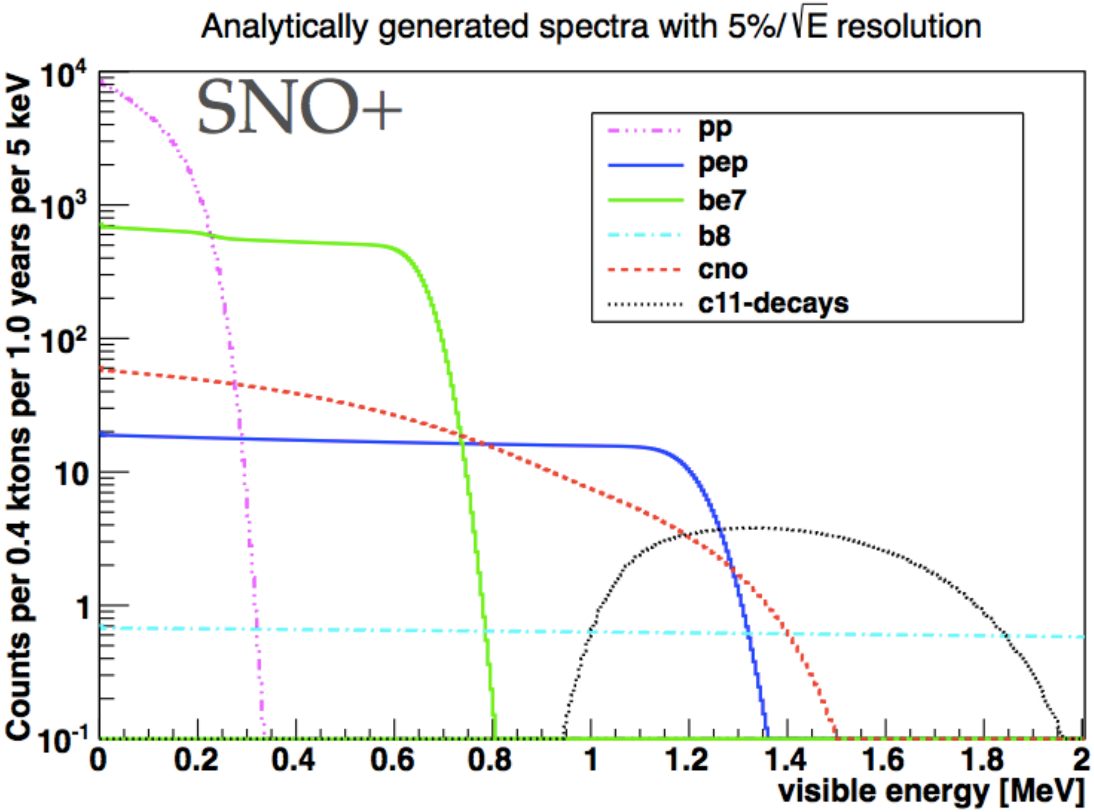


SNO+

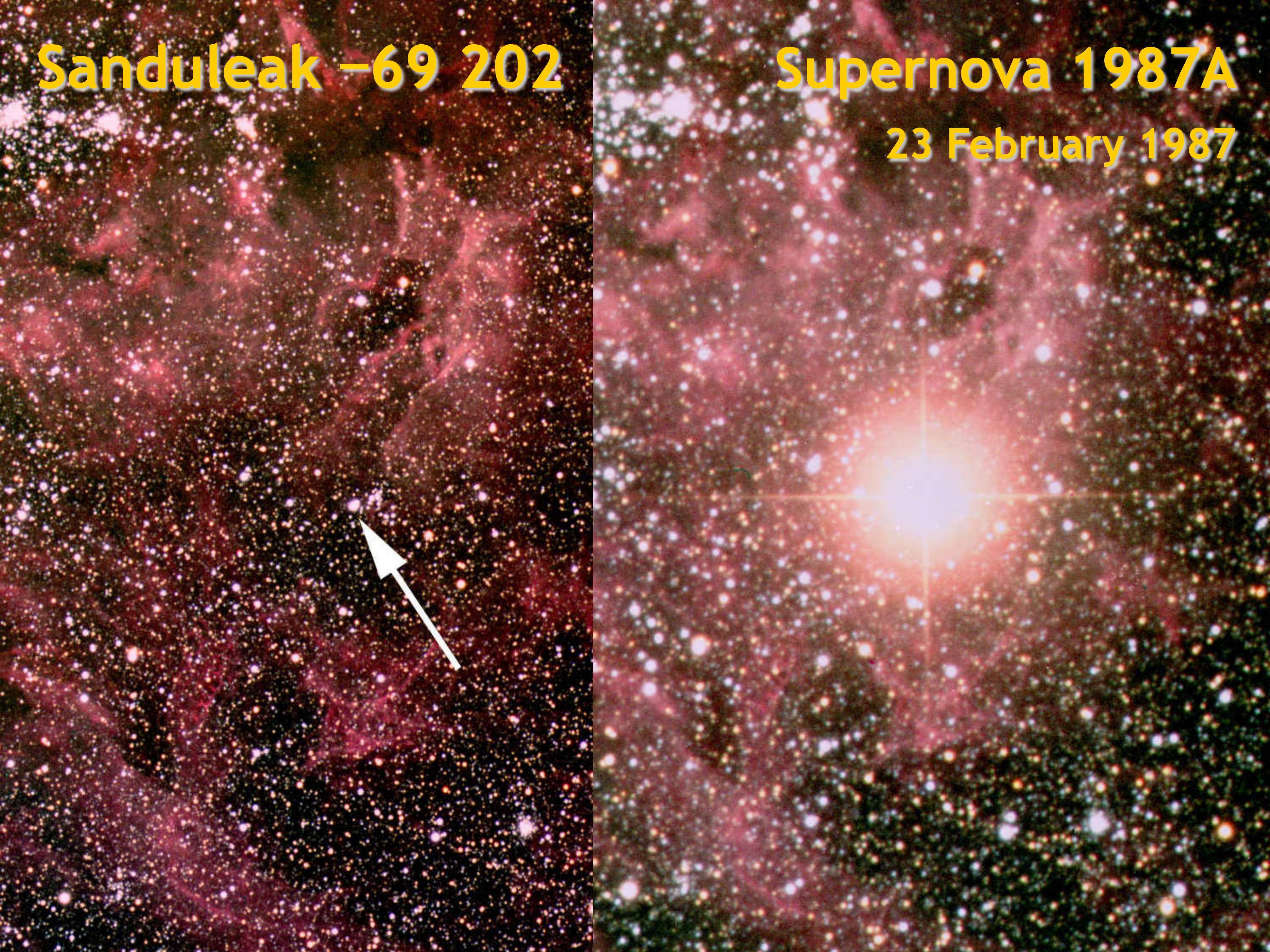
- Assuming Borexino Phase 1 backgrounds
- 1 year livetime
- 50% FV cut to remove external backgrounds

(pp dependent on ^{14}C, ^{85}Kr)

(CNO dependent on ^{210}Bi)



	pep	^8B	^7Be	pp	CNO
1 yr	9%	7.5%	4%	~ a few %	~ 15 %
2 yr	6.5%	5.4%	2.8%		

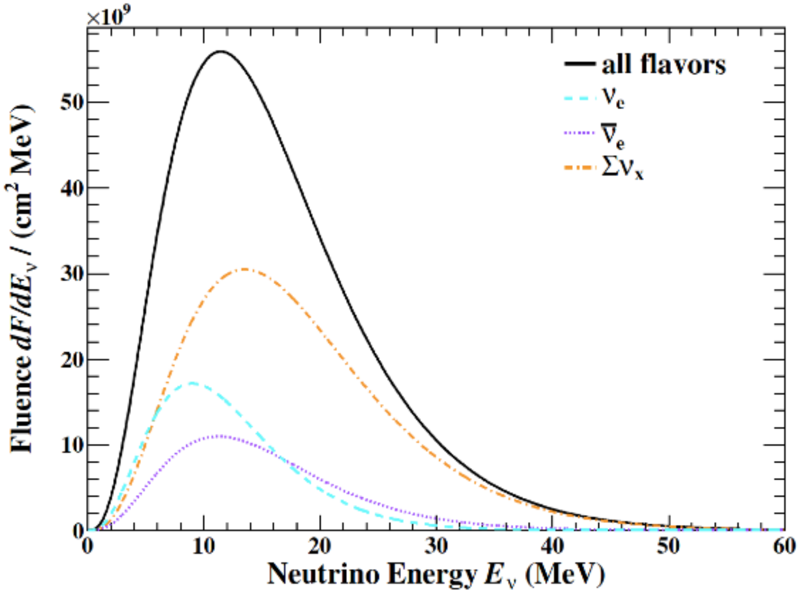

Sanduleak −69 202
Supernova 1987A
23 February 1987

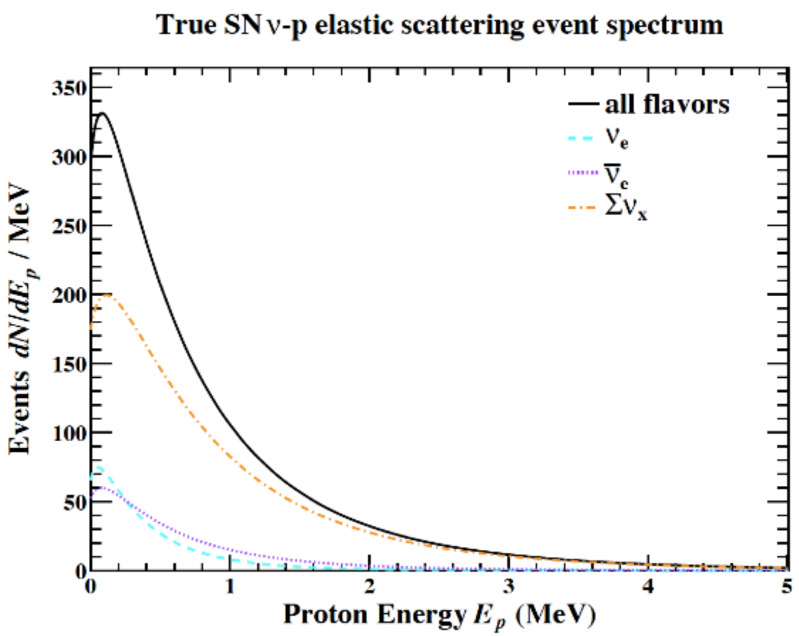
SuperNovae in SNO+

- 99% of the energy release in a core collapse SN ($\sim 10^{53}$ erg) is emitted as νs (all flavours, ν and anti-ν) with typical energies ~O(15MeV)
- Neutrino emission lasts ~10s
- Expect 1-3 SN/century in our Galaxy (~O(10)kpc)
- Expect ~600 ν in SNO+

(Anti)Neutrino Interaction	Expected Number of Events
$\nu_e + e^- \rightarrow \nu_e + e^-$	8
$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$	3
$\nu_{\mu,\tau} + e^- \rightarrow \nu_{\mu,\tau} + e^-$	4
$\bar{\nu}_{\mu,\tau} + e^- \rightarrow \bar{\nu}_{\mu,\tau} + e^-$	2
$\bar{\nu}_e + p \rightarrow n + e^+$	263
$\nu_e + {}^{12}C \rightarrow {}^{12}N + e^-$	27
$\bar{\nu}_e + {}^{12}C \rightarrow {}^{12}B + e^+$	7
$\nu_x + {}^{12}C \rightarrow {}^{12}C^*(15.11MeV) + \nu_x$	58
$\nu_x + p \rightarrow \nu_x + p$	273**

SuperNovae in SNO+

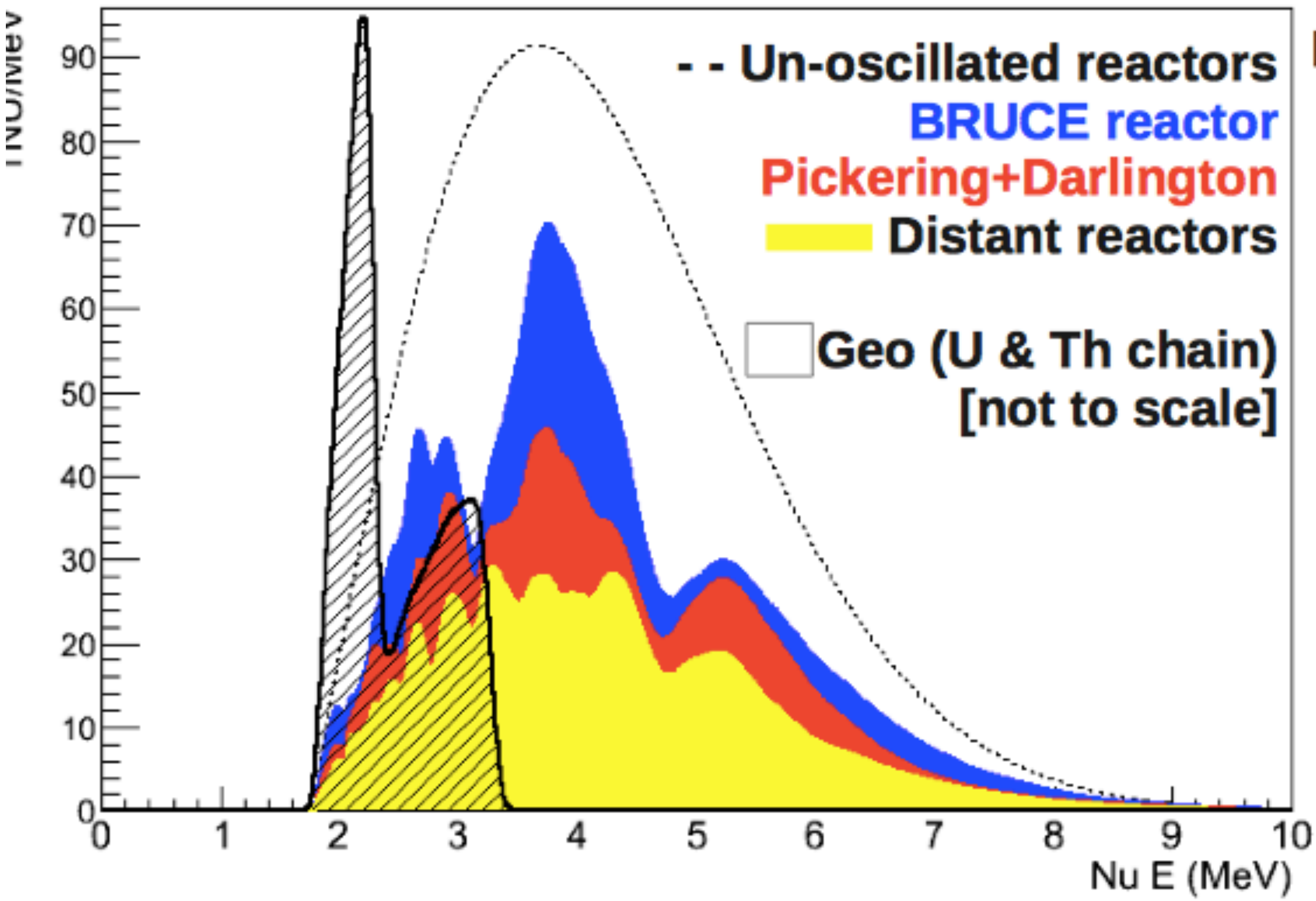




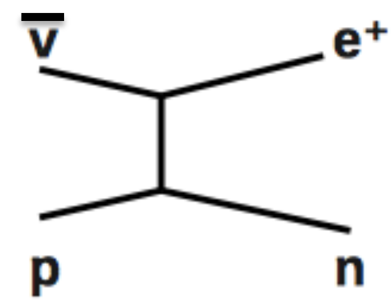
- convolution with $\nu + p \rightarrow \nu + p$ cross-section gives p energy spectrum
- detector response to protons needed

Reactor Neutrinos

AntiNeutrinos in SNO+



Inverse Beta Decay

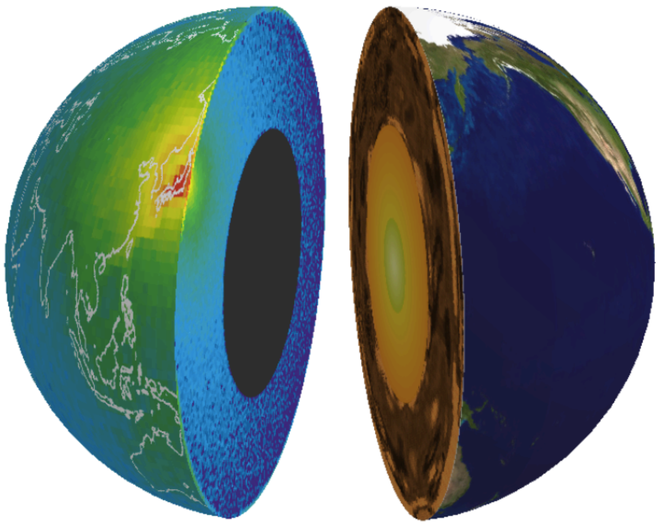


coincidence tag (dT~250 ns)
n+p -> 2.2 MeV γ

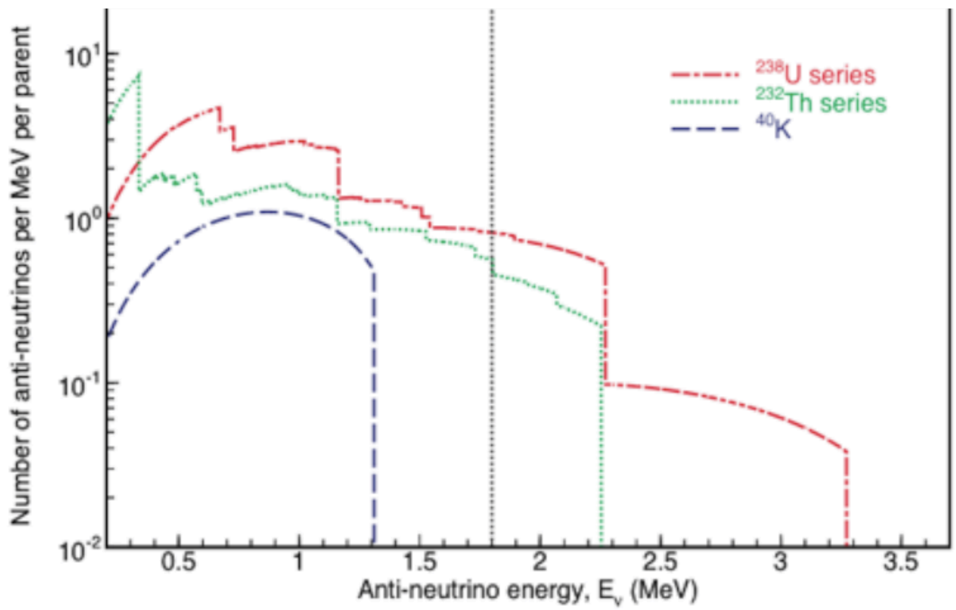
Threshold
Eν > 1.8 MeV

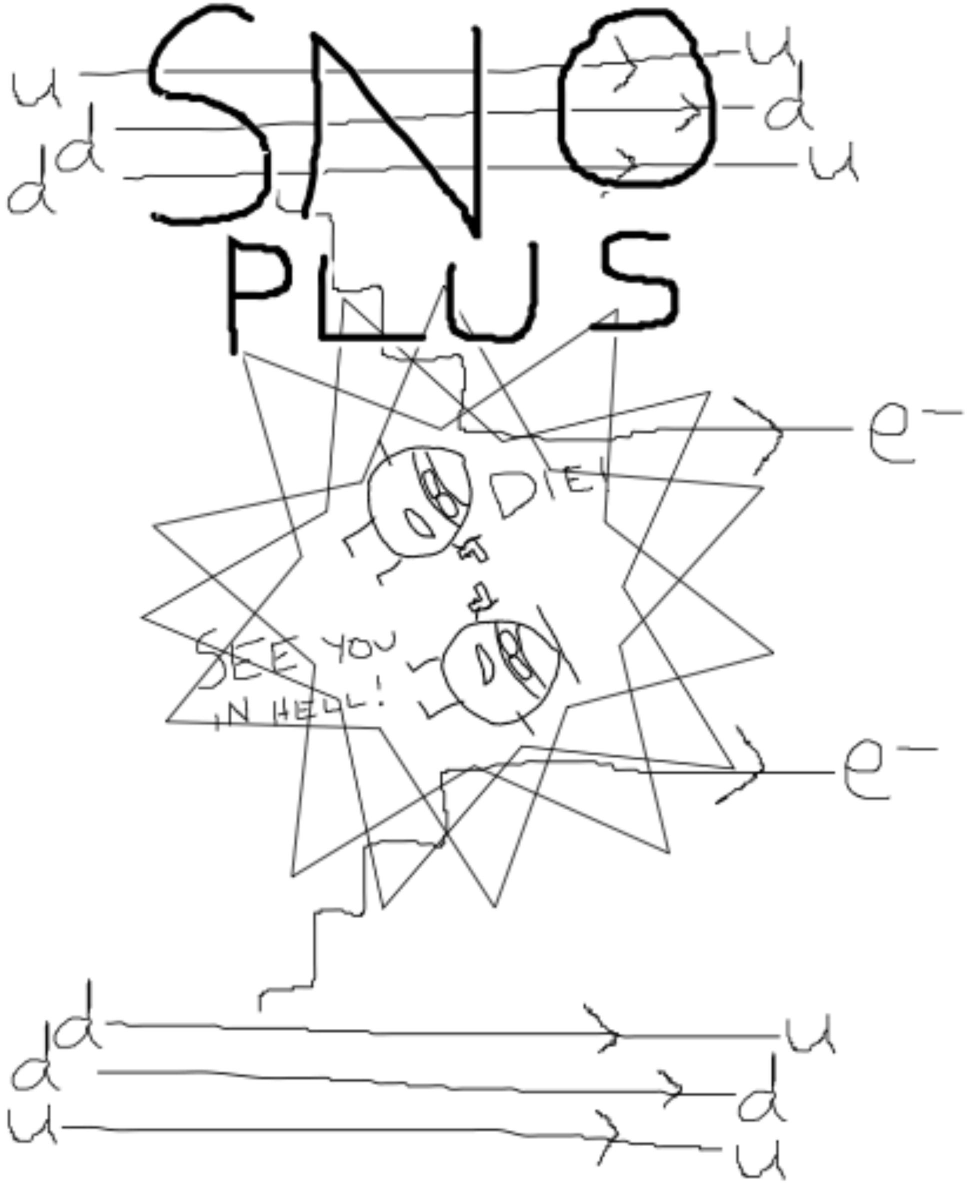
~ 100 events / year; oscillation sensitivity after 3-5 year LAB run
more bkg in low E geo-nu region

GeoNeutrinos



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




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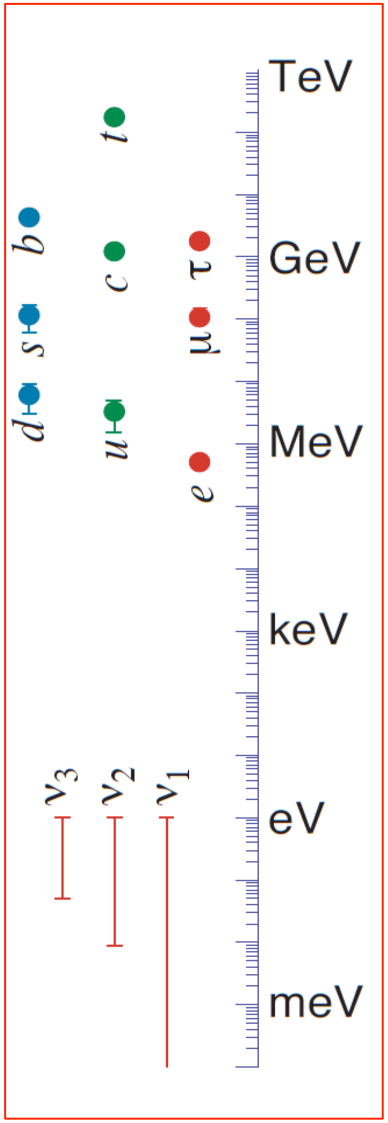
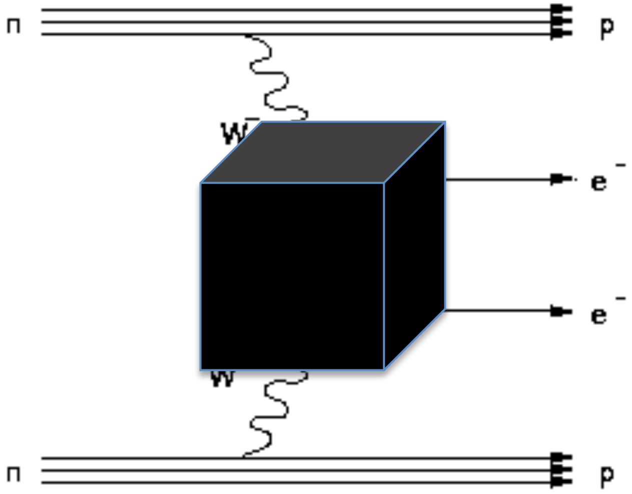
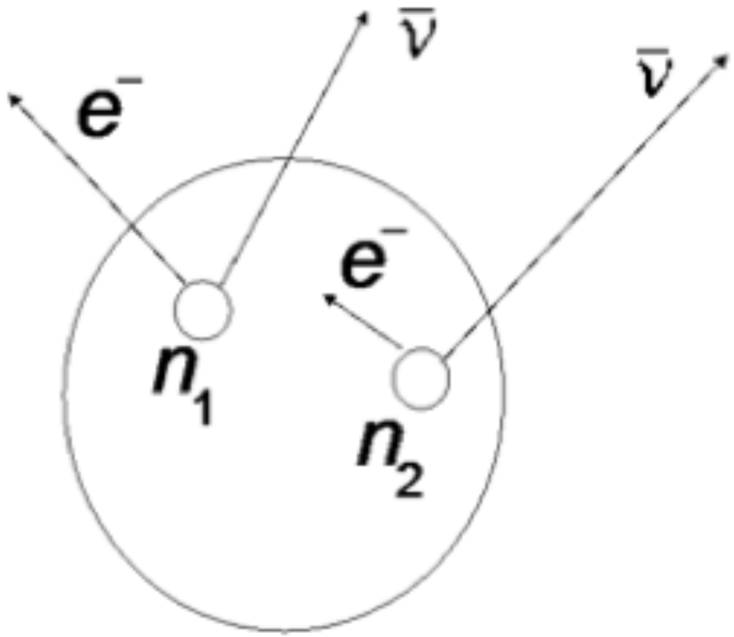
Double Beta Decay

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

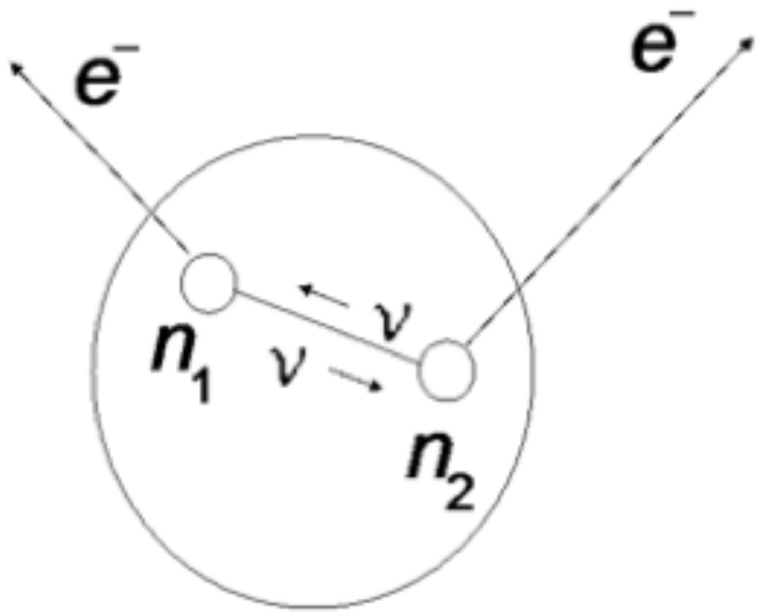




Neutrinoless Double Beta Decay



2νββ



0νββ

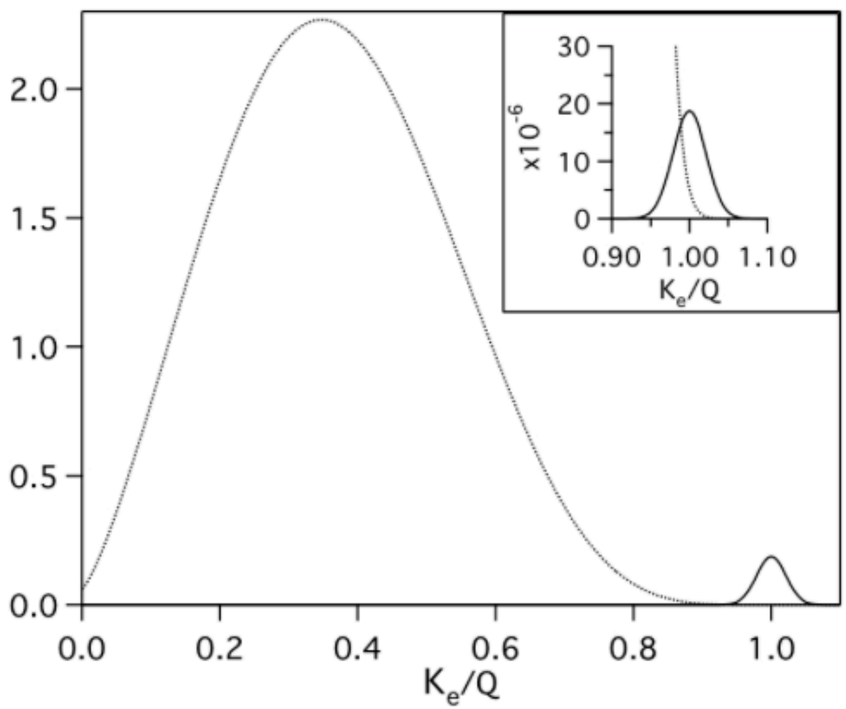
Neutrinoless Double Beta Decay

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

Phase space   Nuclear Matrix Element

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

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



<u>Experiment options</u>

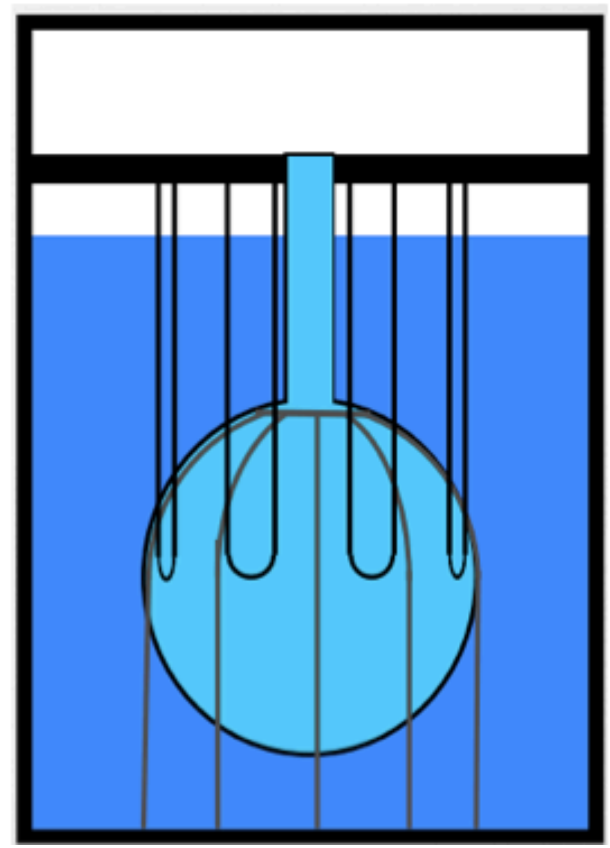
- Select isotopes with favourable phase space
- Select isotopes with favourable matrix elements
  - Beware large uncertainty / differences between models
- Good energy resolution
- Low Backgrounds in region of interest (ROI)

0νββ search – SNO+ approach

- Statistics over energy resolution
- Tellurium – 130
  - Favourable 0νββ : 2νββ phase space ($T_{1/2}^{2\nu\beta\beta} = 7\times10^{20}$ years)
  - 34% natural abundance
  - 2.53MeV endpoint energy
- Large amount of isotope
  - 0.3% loading (by weight) = 2.34tonnes ^{nat}Te = 800kg ^{130}Te = $1.5million
  - Towards tonne-scale 0νββ search at relatively low cost
- Large homogeneous detector, well defined background model
  - Aim to be dominated by solar neutrino background
- Isotope In/Out capability

Stages of SNO+

- Water phase
  - External background analysis
- Scintillator phase
  - Background analysis
- 0.3% Te-Scintillator phase
  - $0\nu\beta\beta$ physics

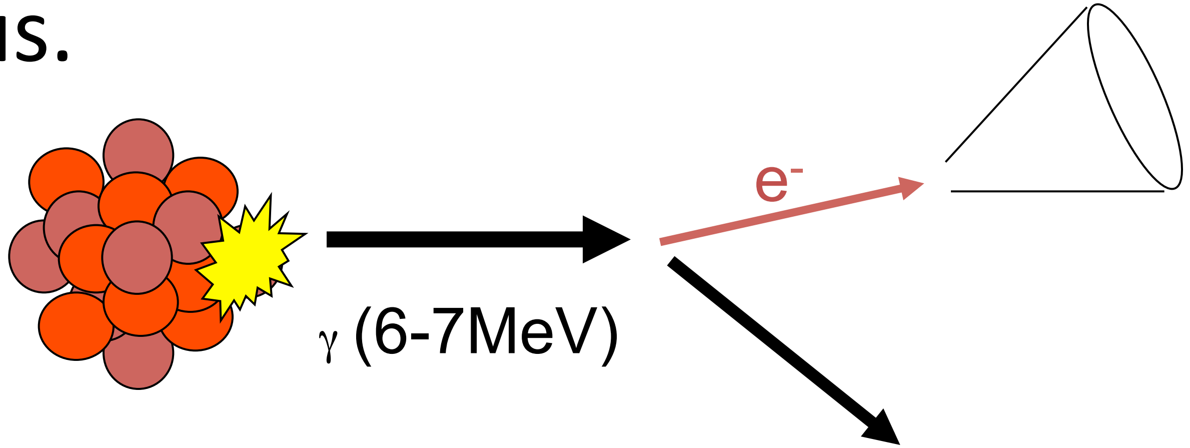


Invisible Nucleon Decay

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

  eg. $N \rightarrow 3\nu$

- See γ from de-excitation of residual nucleus.



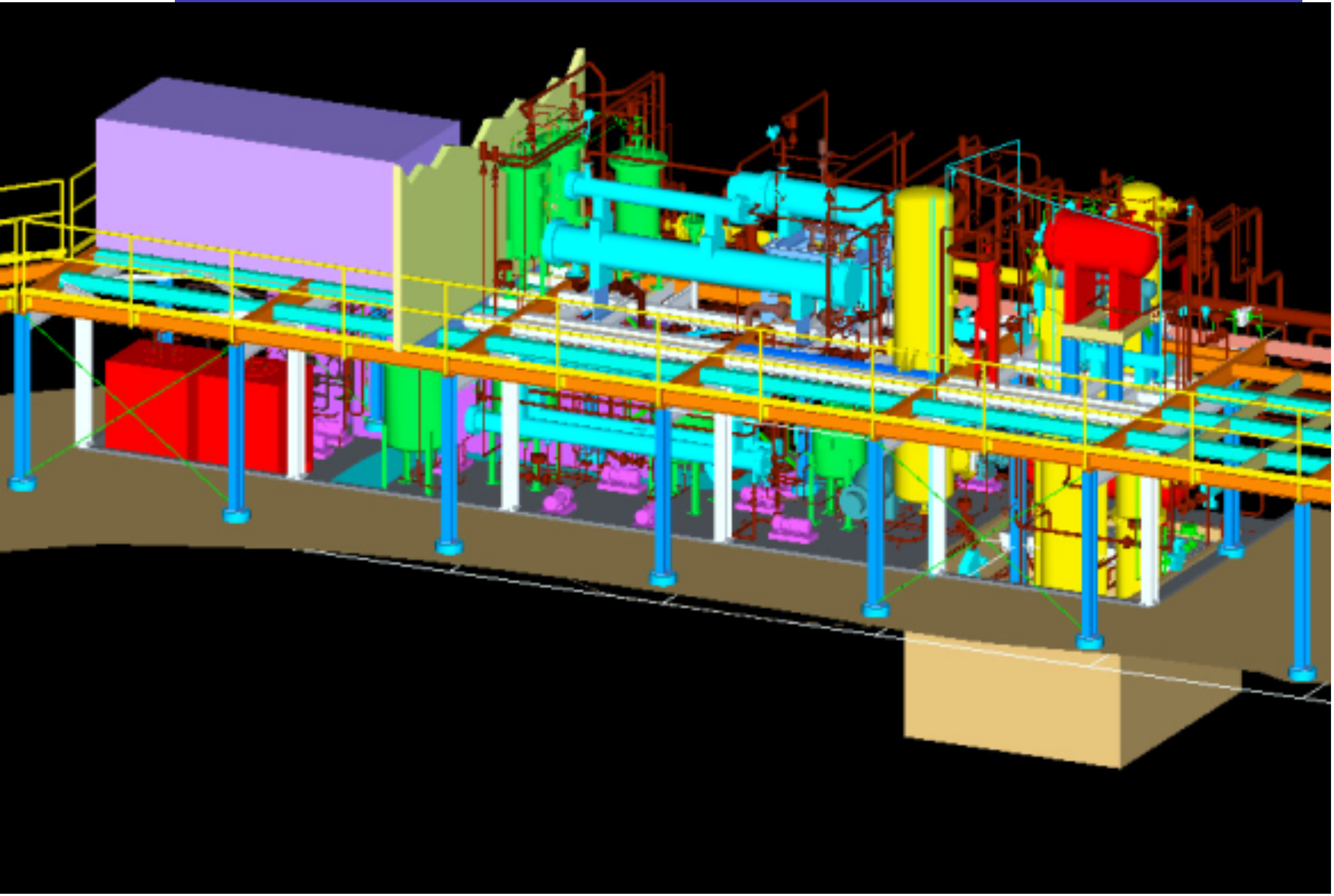
$^{16}O \rightarrow {}^{15}O^* \rightarrow {}^{15}O + \gamma$

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

Status

- Now filling the SNO+ detector with water
- Float-the-boat to demonstrate hold-down rope system operation at full buoyant load
- Water-filled data taking starts soon
  - to study external backgrounds and detector optics
- Completed scintillator purification plant process piping
  - Helium leak checking and passivation
- liquid scintillator fill to start in late 2015
- Installation of tellurium purification skid and Te purification in late 2015
- Addition of Te to SNO+ liquid scintillator and DBD run in 2016

Scintillator purification plant



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:

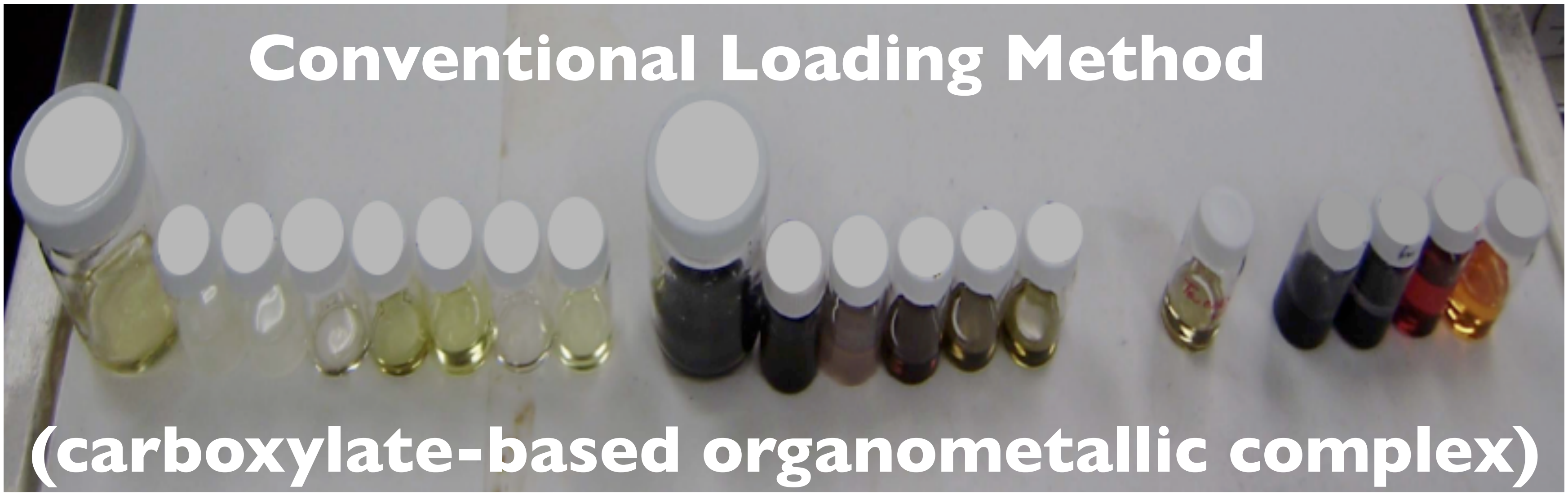
- ^{85}Kr: 10^{-25} g/g
- ^{40}K: 10^{-18} g/g
- ^{39}Ar: 10^{-24} g/g
- U: 10^{-17} g/g
- Th: 10^{-18} g/g

Space is limited underground!

- Helium leak checking all seals and valves
- Cleaning and Passivation

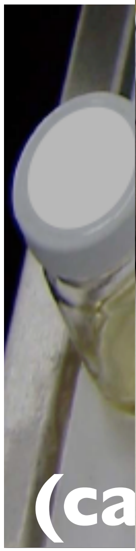
First Attempts at Te-Loaded Scintillator

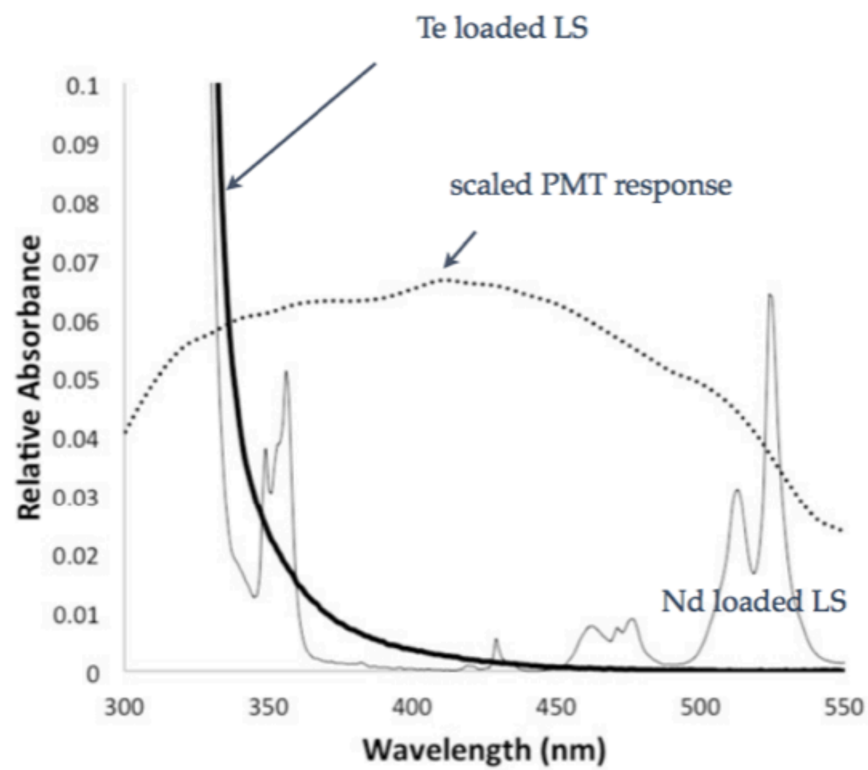
First Attempts at Te-Loaded Scintillator



- …then, breakthrough new approach was developed at BNL, works for loading Te in liquid scintillator

First Attempts at Te-Loaded Scintillator





- … w approacn was d s for loading Te in li

pH Selective Telluric Acid Recrystallisation

- Telluric acid obeys the following equilibrium:

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

Insoluble ($Te(OH)_6$) — Soluble ($Te(OH)_5O^-$)

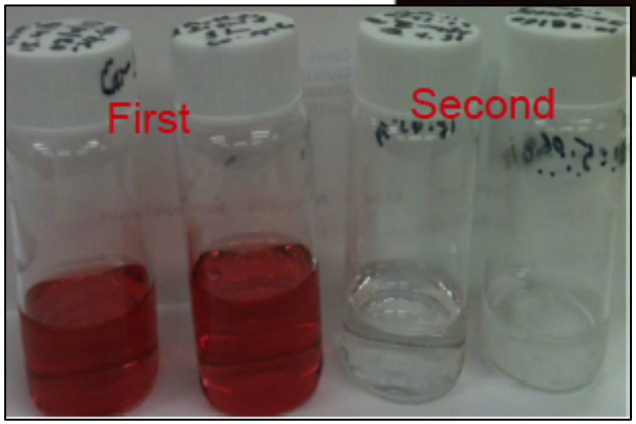
  – pH determines the equilibrium state

1. Dissolve telluric acid in water and filter it
   – Removes insoluble impurities

2. Add nitric acid to force the telluric acid to recrystallize/precipitate, pump away the liquid, rinse with ethanol
   – Removes soluble impurities

- By "tuning" the pH at each step, the process can be quite selective – most elements are removed with high efficiency

Cobalt removal by multi-pass purification



See S. Hans et. al. *Purification of Telluric Acid for SNO+ Neutrinoless Double Beta Decay Search*. In preparation.

Telluric Acid Purification

Above ground

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

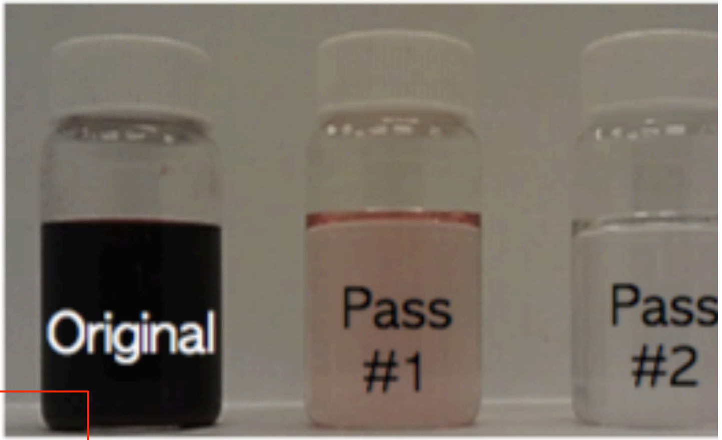
} 10^4 reduction

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

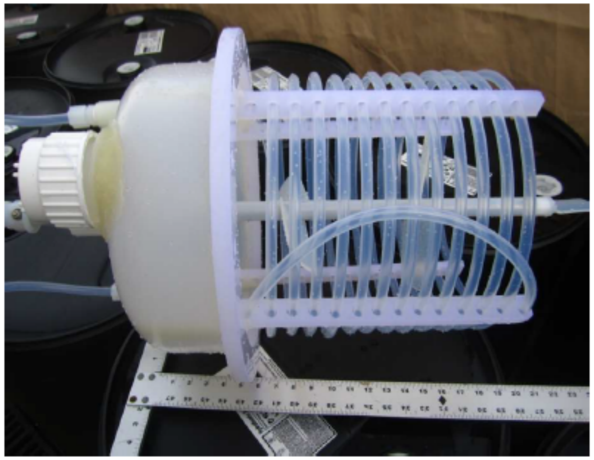
Measured Single Pass Reduction Factors

Element	Reduction Factors From Spike Tests	Non-spiked, before purification	Non-spiked, after purification
Sn	$>1.67\times10^2$	20	<20
Zr	$>2.78\times10^2$	70	<10
Ti		40	<10
Al		<30	<30
Co	$(1.62\pm0.34)\times10^3$	<10	<10
Mn		150	<5
Fe		40	<30
Ag	$>2.78\times10^2$	<10	<10
Y	$>2.78\times10^2$	<10	<10
Sc	$>1.65\times10^2$	<10	<10
Sb	$>2.43\times10^2$	30	<20
^{228}Th	$(3.90\pm0.19)\times10^2$	<0.02	<0.02
^{224}Ra	$(3.97\pm0.20)\times10^2$	1400	<5
^{212}Pb	$(2.99\pm0.22)\times10^2$	440	<3
^{212}Bi	$(3.48\pm0.81)\times10^2$	300	<10
^{238}U	$(3.90\pm0.19)\times10^2$	<0.02	<0.02

	No purification	Purification + 5 hrs re-activation + "polishing" & 6 month cool-down
^{22}Na	15309	0.0947
^{26}Al	0.048	5.724E-7
^{42}K	565	0.0044
^{44}Sc	102	0.0004
^{46}Sc	43568	0.1993
^{56}Co	2629	0.0099
^{58}Co	25194	0.0888
^{60}Co	6906	0.0396
^{68}Ga	37343	0.2201
^{82}Rb	18047	0.0071
^{84}Rb	11850	0.0113
^{88}Y	390620	2.3079
^{90}Y	823	0.0019
^{102}Rh	276189	1.8389
^{102m}Rh	133848	1.0438
^{106}Rh	1534	0.0111
^{110m}Ag	69643	0.4184
^{110}Ag	939	0.0056
^{124}Sb	3101138	9.7353
^{126m}Sb	240	1.205E-5
^{126}Sb	358996	0.0015

Two-pass purification should meet our purity goals.

Scale-Up



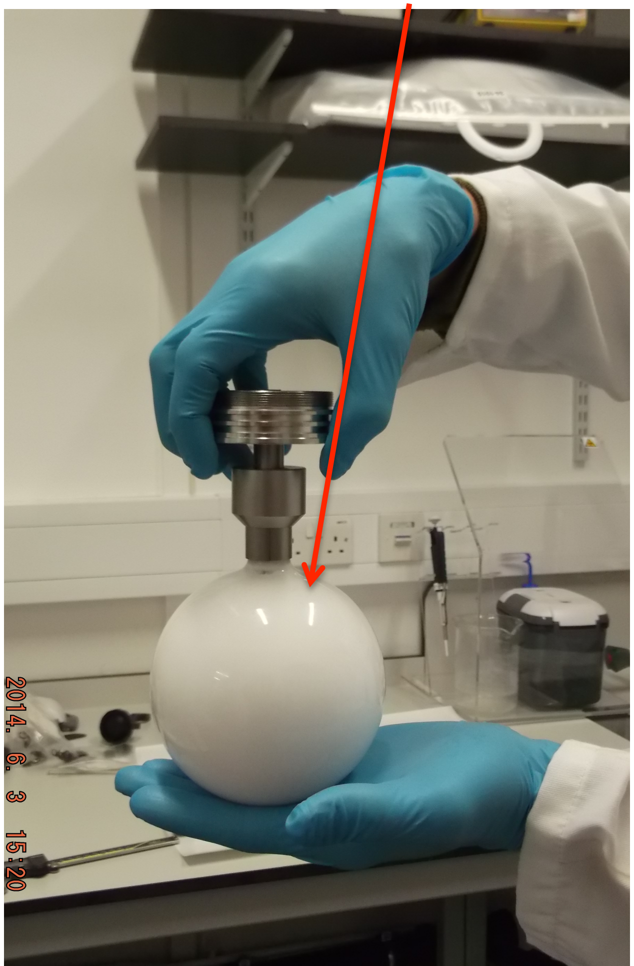
- Working with an industrial partner (SeaStar Chemicals, Sydney, BC) to scale processes up to ~200kg batch size
  - A few months to process the 4 tonnes of telluric acid for 0.3% loading
- Currently operating a 10kg pilot-scale plant
- Working on full-scale design for SNOLAB now

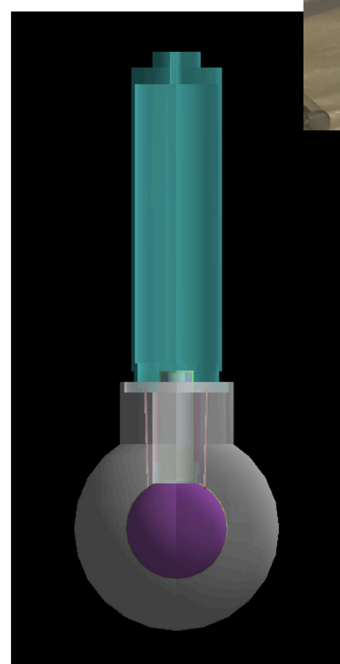
First batch of Telluric Acid

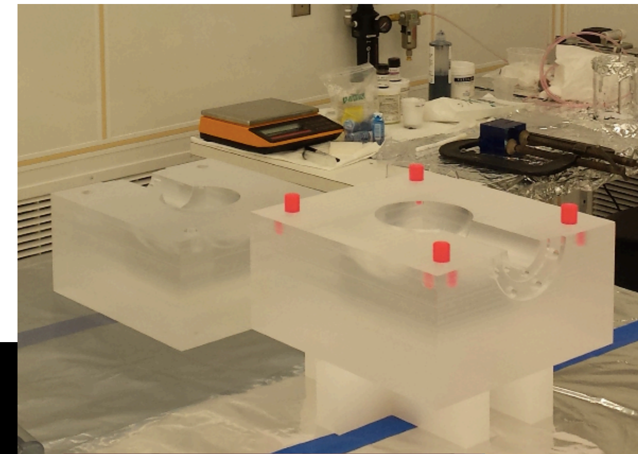
1.8 tonnes, cooling underground at SNOLAB

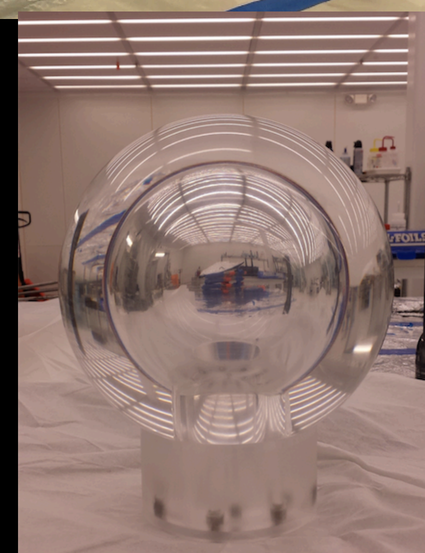
Calibration

- Deployed sources:
  - Laserball (optics), Cerenkov source



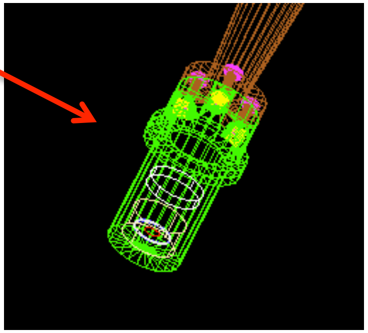


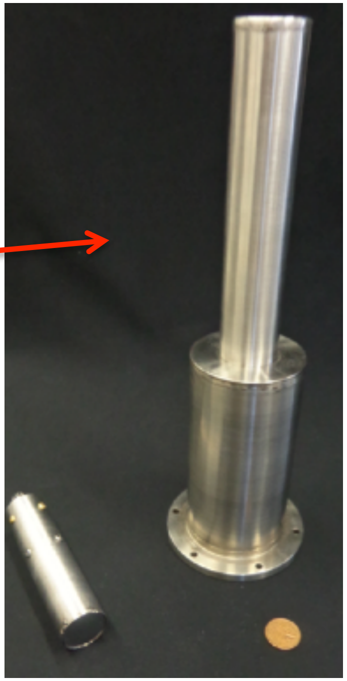


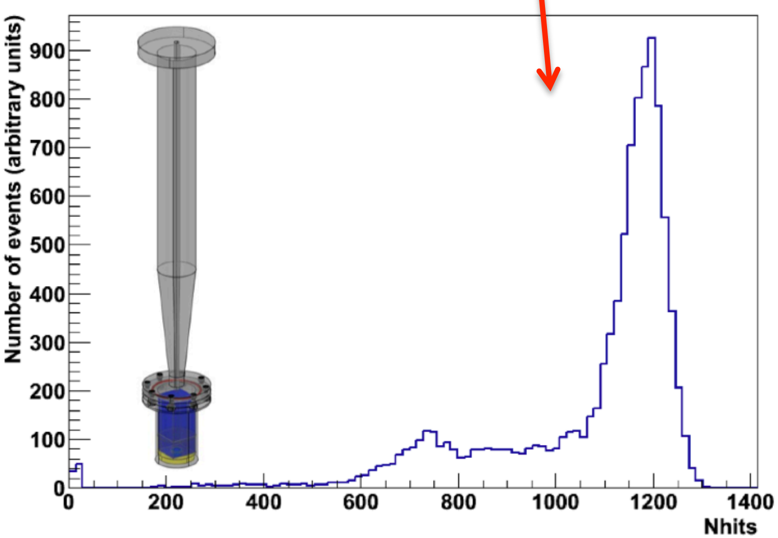


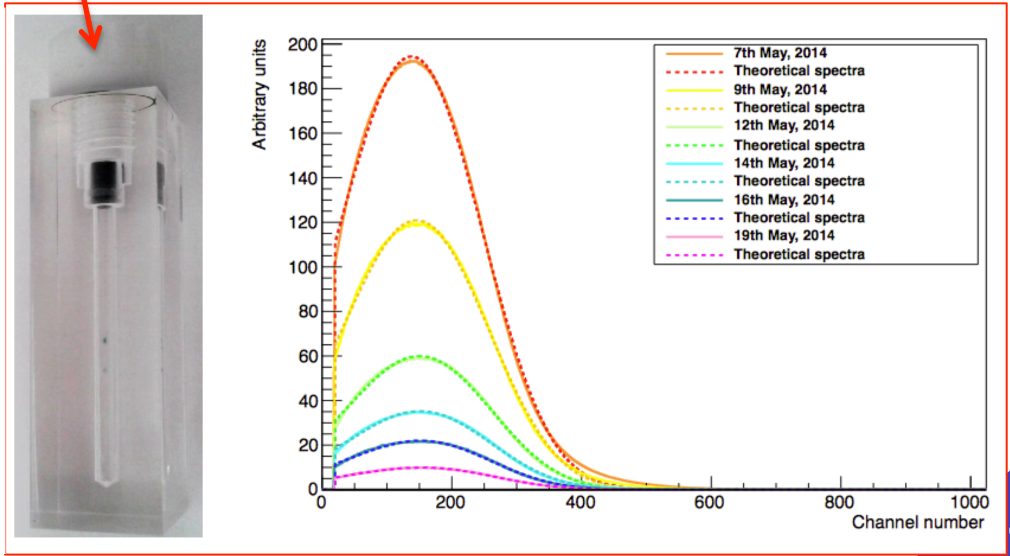
Calibration

- Deployed sources:
  - Laserball (optics), Cerenkov source
  - ^{48}Sc, ^{60}Co, ^{90}Y (beta), ^{57}Co, ^{24}Na



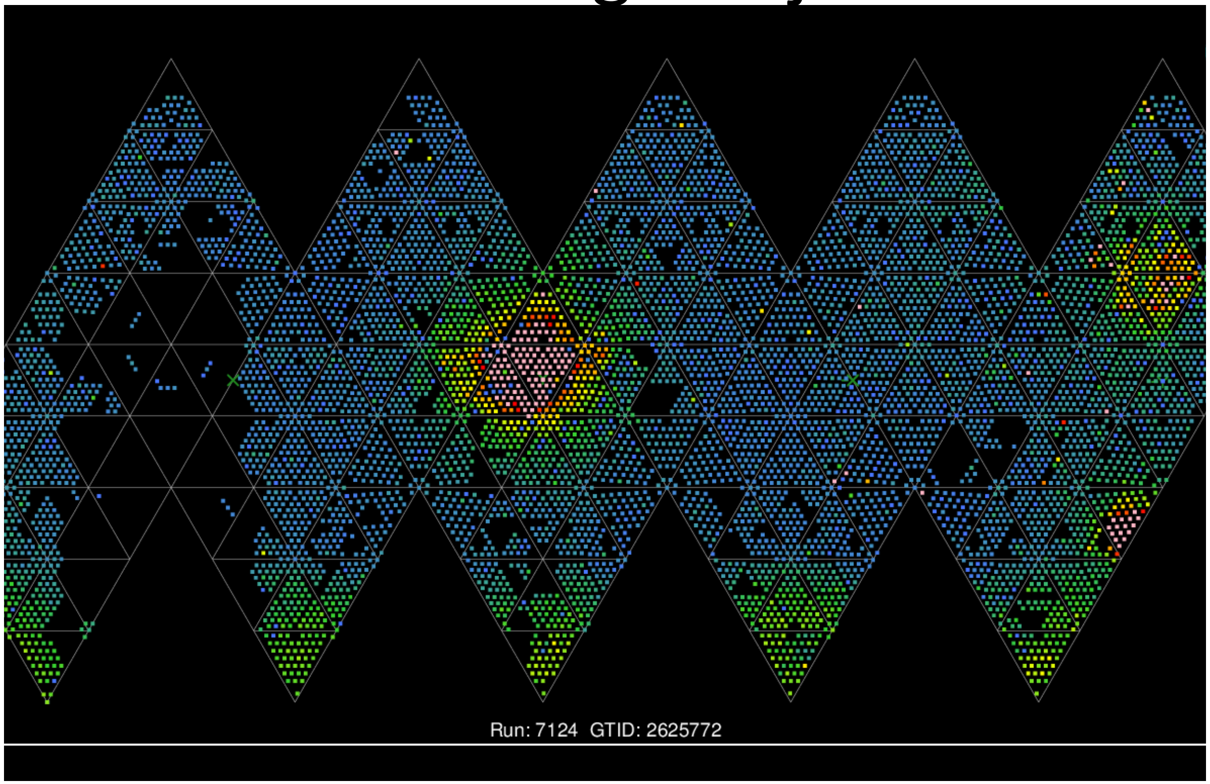






Calibration

- Deployed sources:
  - Laserball (optics), Cerenkov source
  - ^{48}Sc, ^{60}Co, ^{90}Y (beta), ^{57}Co, ^{24}Na
- Embedded light injection fibres



Calibration

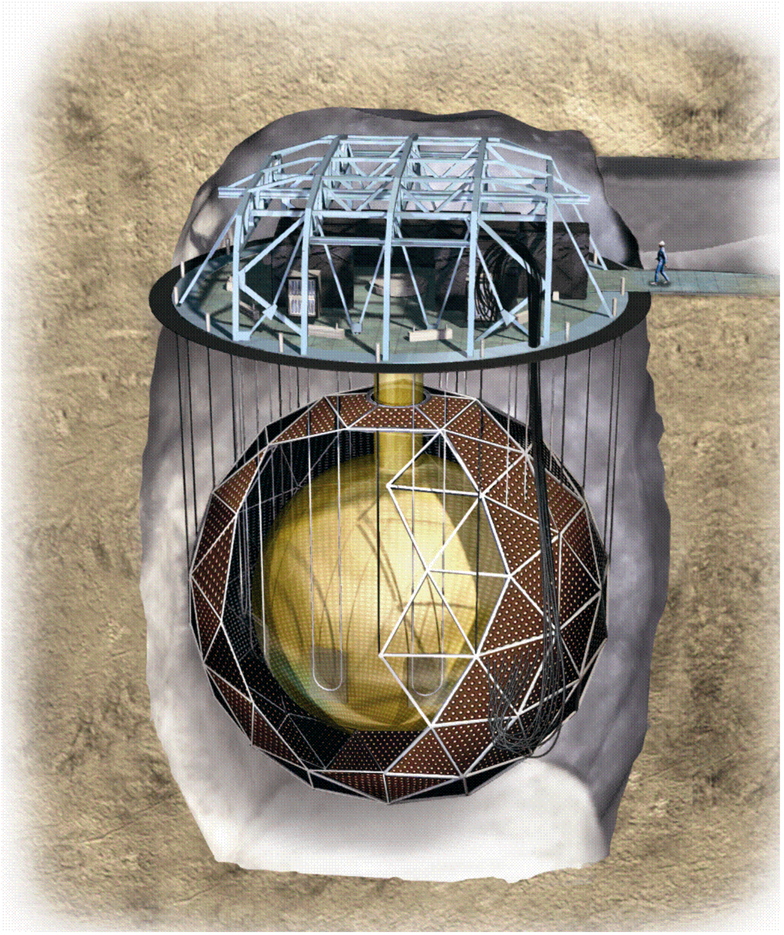
- Deployed sources:
  - Laserball (optics), Cerenkov source
  - ^{48}Sc, ^{60}Co, ^{90}Y (beta), ^{57}Co, ^{24}Na
- Embedded light injection fibres
- Internal sources
  - ^{14}C, ^{210}Bi, ^{210}Po, ^{214}Bi-Po, ^{212}Bi-Po

Backgrounds

LAB-PPO : ^{238}U, ^{232}Th, ^{14}C

Externals:

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



Implanted Radon daughters in AV:

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

Thermal neutrons:

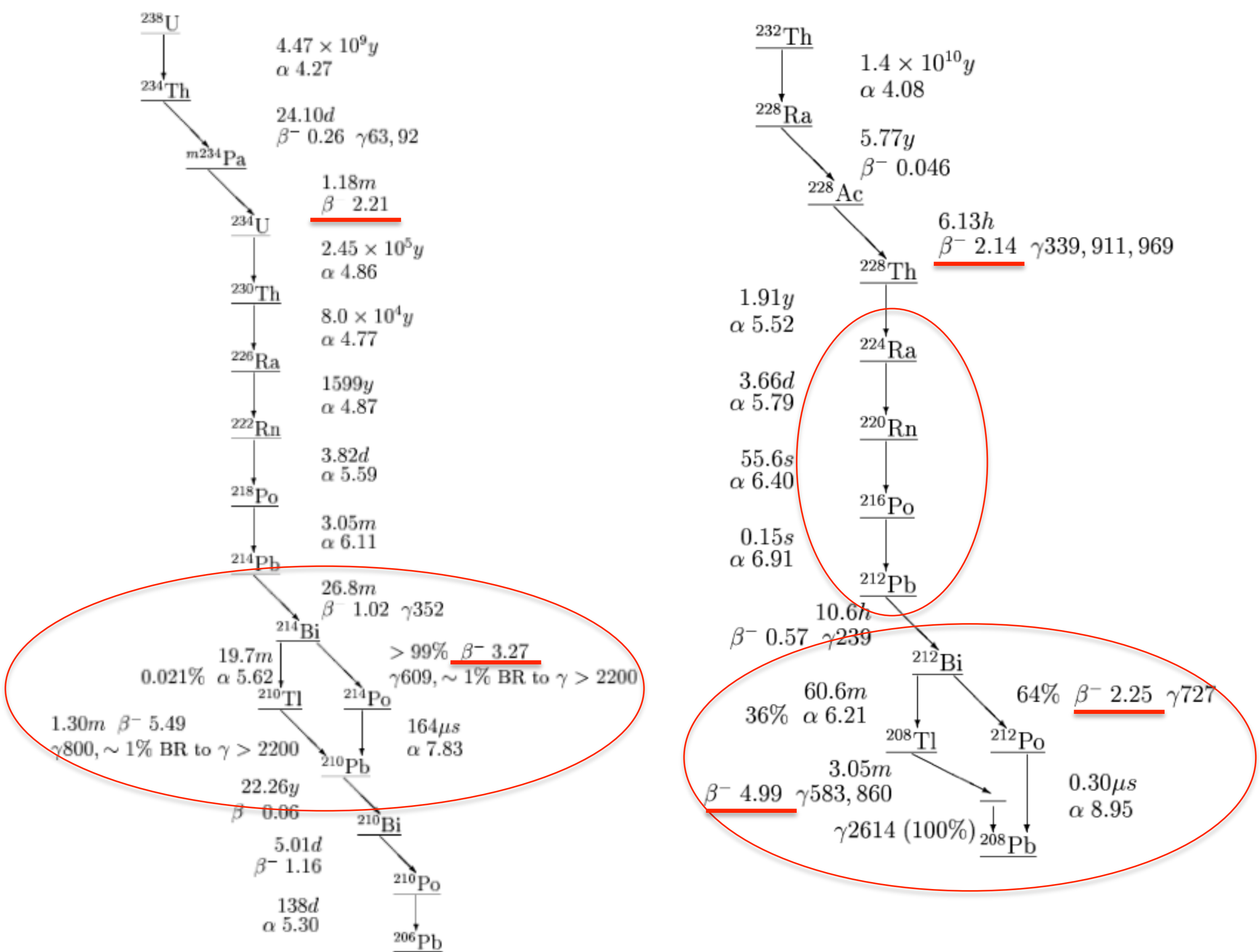
capture on H to 2.2MeV ϒ:

Muon induced neutrons, (α,n)

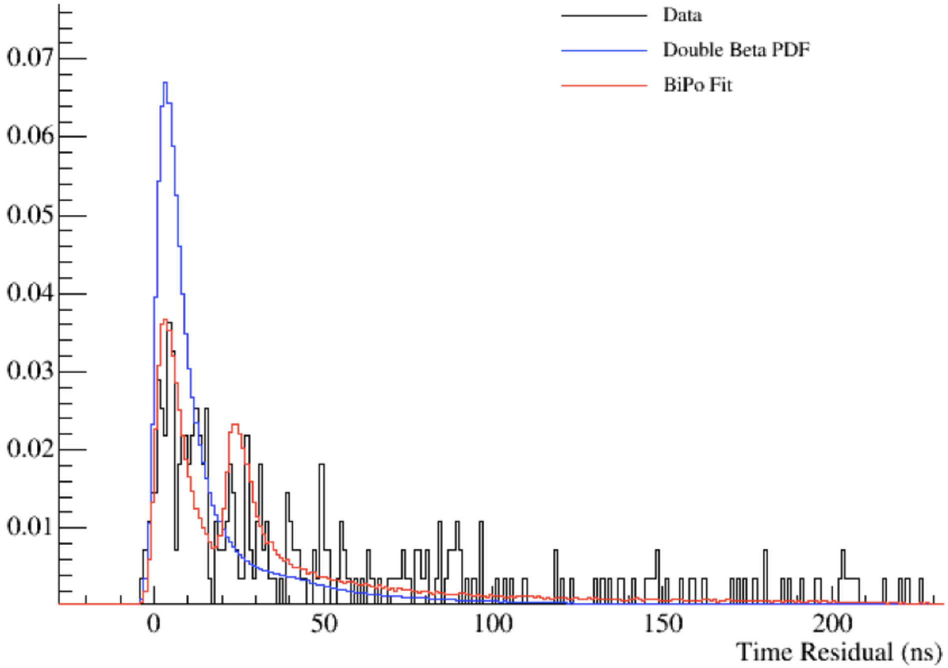
Tellurium : ^{238}U, ^{232}Th, ^{210}Po

Residual cosmogenically activated isotopes: ^{60}Co, ^{131}I

Uranium and Thorium Chain



BiPo rejection

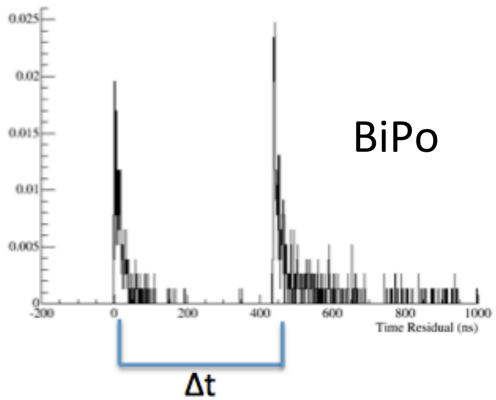


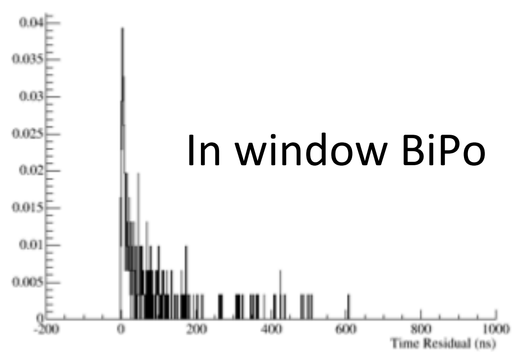
Likelihood ratio cuts to reject in-window BiPo

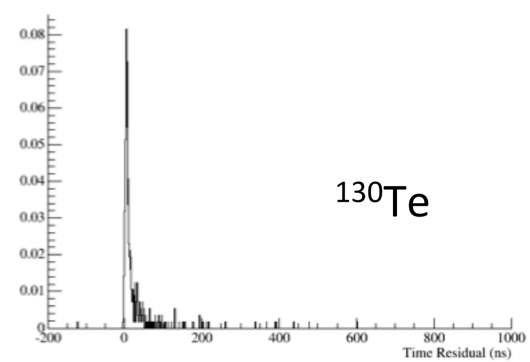
- Timing Residuals
- Beta and alpha energies

Overall
214BiPo factor > 25000 rejection
212BiPo factor > 70 rejection

SNO+ 'RAT' Simulations

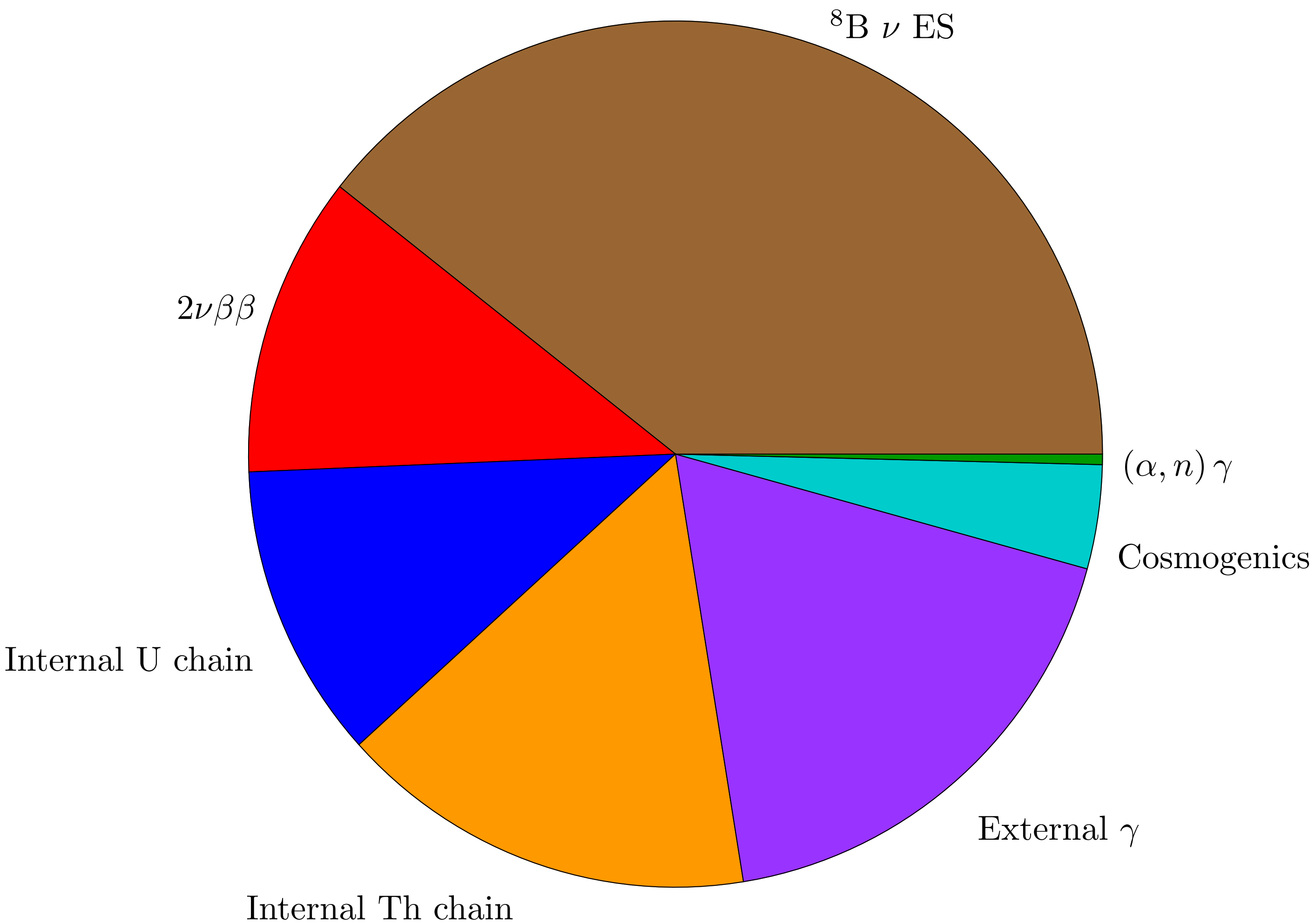




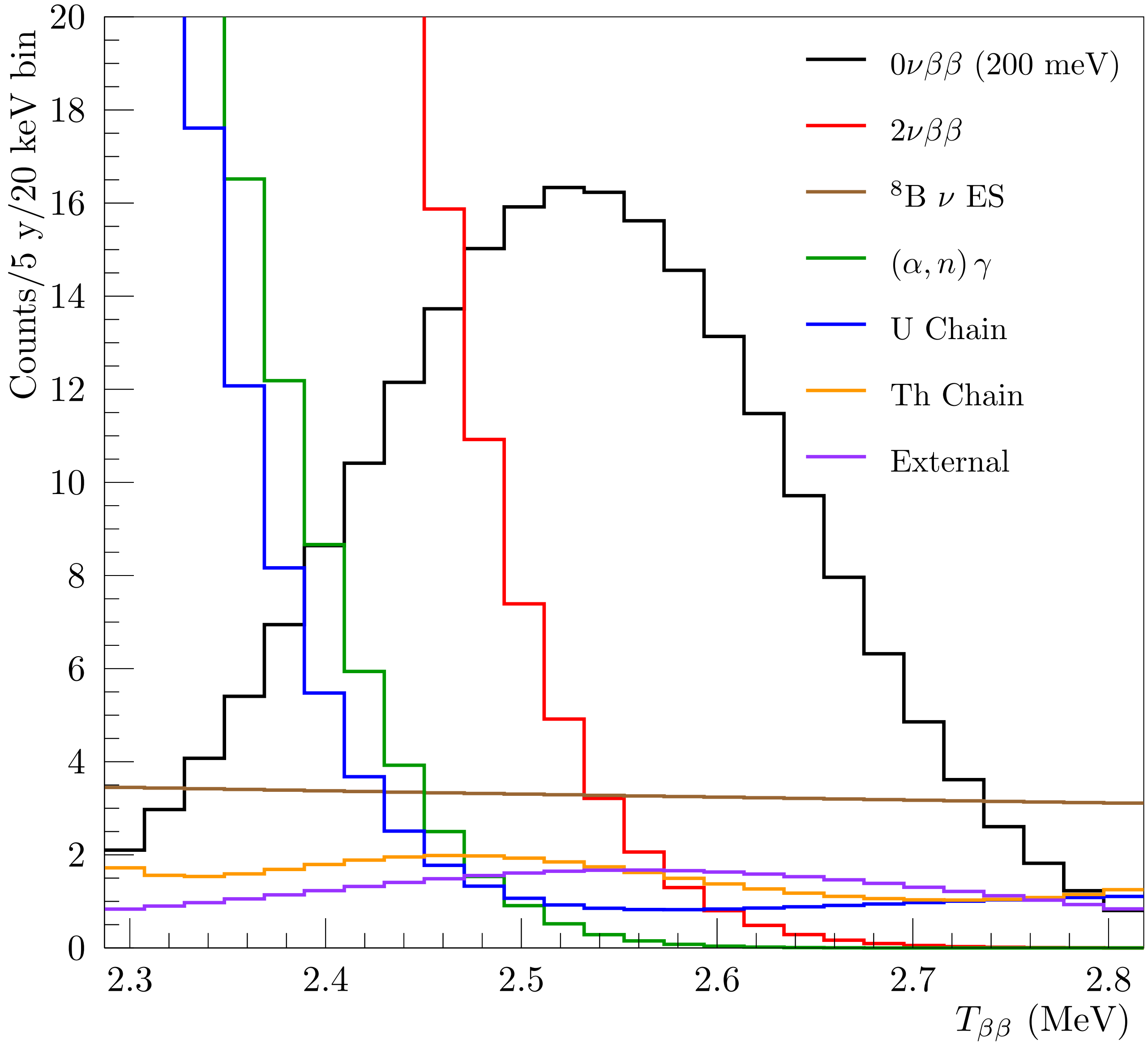


Backgrounds

Optimized ROI: $-0.5\sigma \rightarrow 1.5\sigma$



Predicted Spectrum



Spectrum inputs

- ^{130}Te undergoes double beta decay with nuclear matrix element M = 4.03 (IBM-2) [1] and phase space factor G = 3.69 x 10^{-14} y^{-1}, based on the expression in [2] and g_A = 1.269 [1]
- Scintillator loaded with 0.3% natTe by mass
- Energy resolution is Gaussian with width

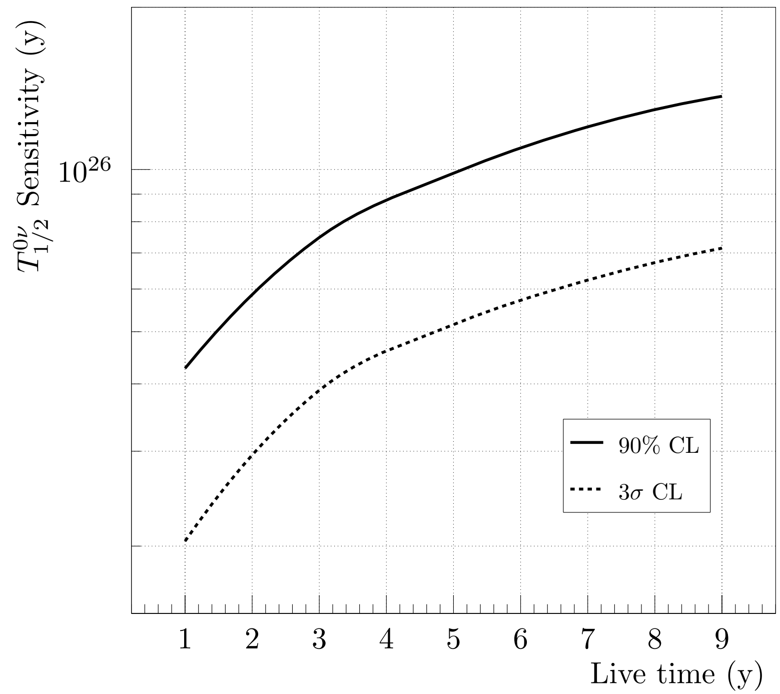
$$\sigma(E) = \sqrt{(E\ [MeV]/200)}$$

- 3.5 m (20%) fiducial volume cut
- 100% efficiency of detection and analysis, including reconstruction
- Tagging techniques which remove all ^{212}BiPo and ^{214}BiPo coincidences in separate trigger windows, and reduce in-window coincidences by a factor of 50

[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).

SNO+

Sensitivity 0.3% loading



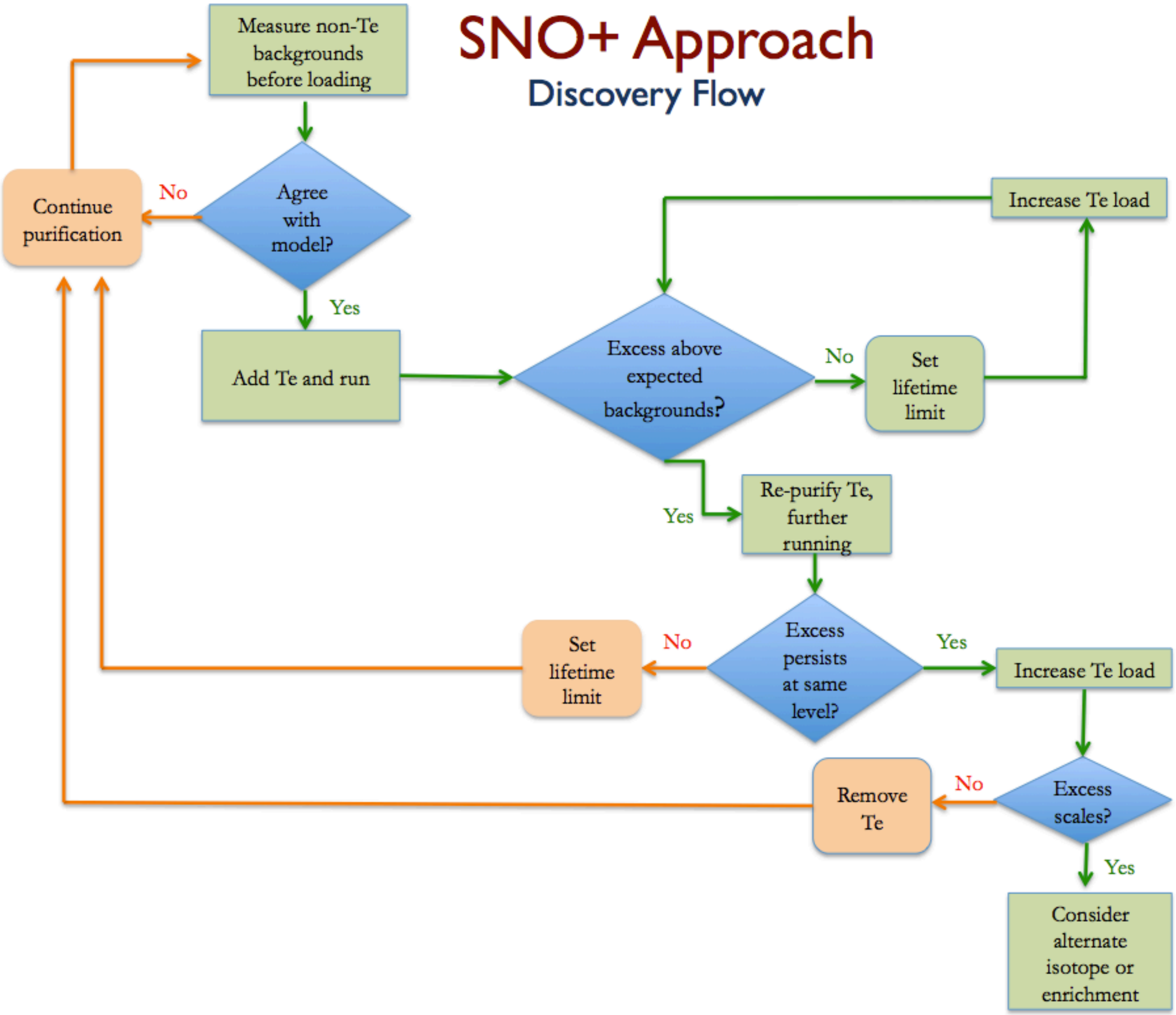
1 year, 18.6counts in ROI, at 0.3% loading -> 4.27×10^{25} years,

5 years at 0.3% loading -> 9.84×10^{25} years, (90% CL)

Cuoricino $T_{1/2}>2.8\times10^{24}$ years at 90% C.L -> <300-710meV, depending on the adopted nuclear matrix element evaluation

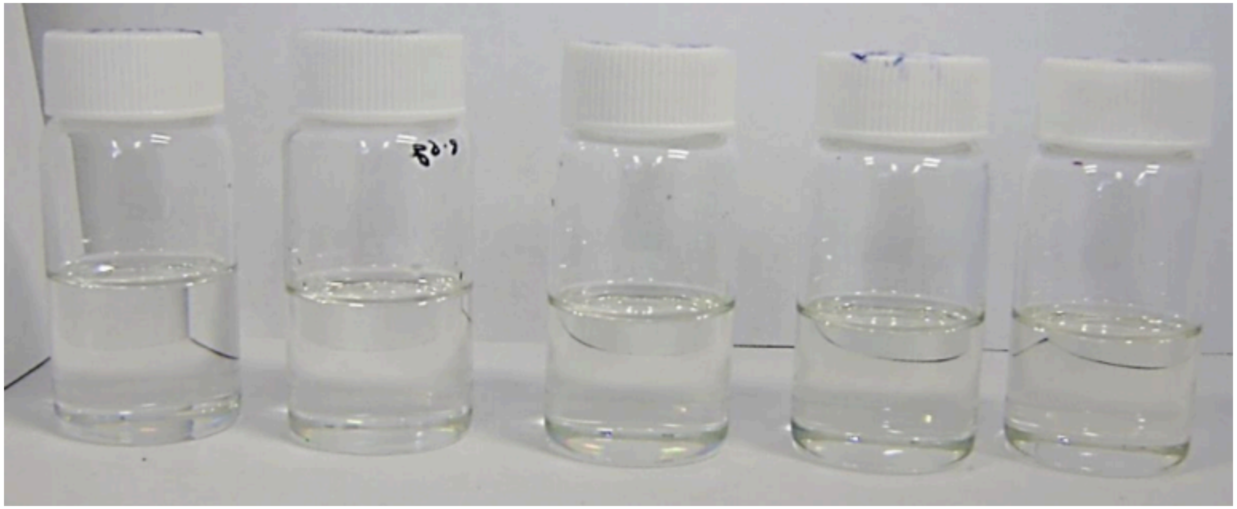
[arXiv:1012.3266 [nucl-ex]]

What if we see a bump?



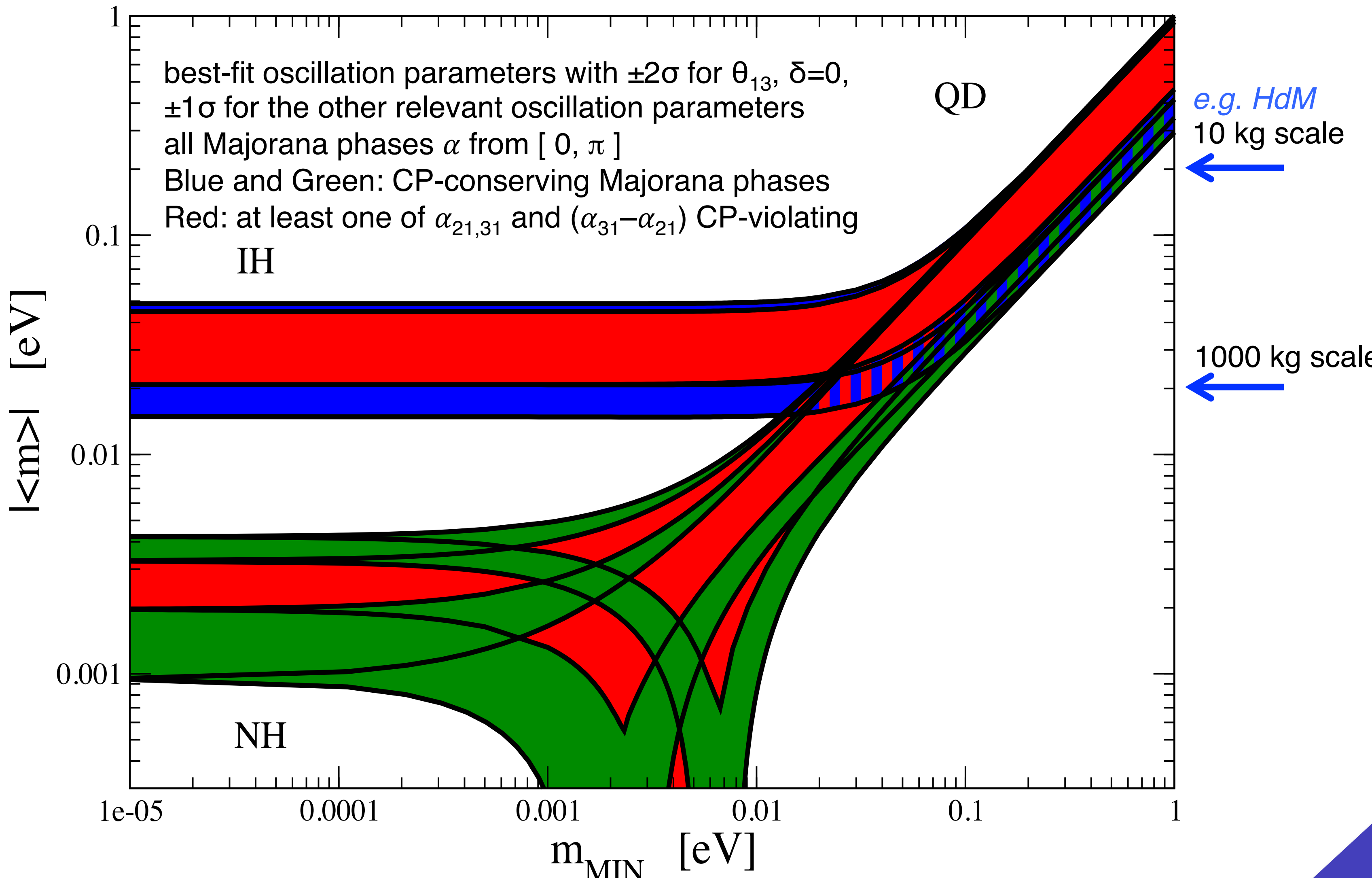
Percent Loading of Te is Feasible

- 0.3%, 0.5%, 1%, 3%, 5% (from left to right)

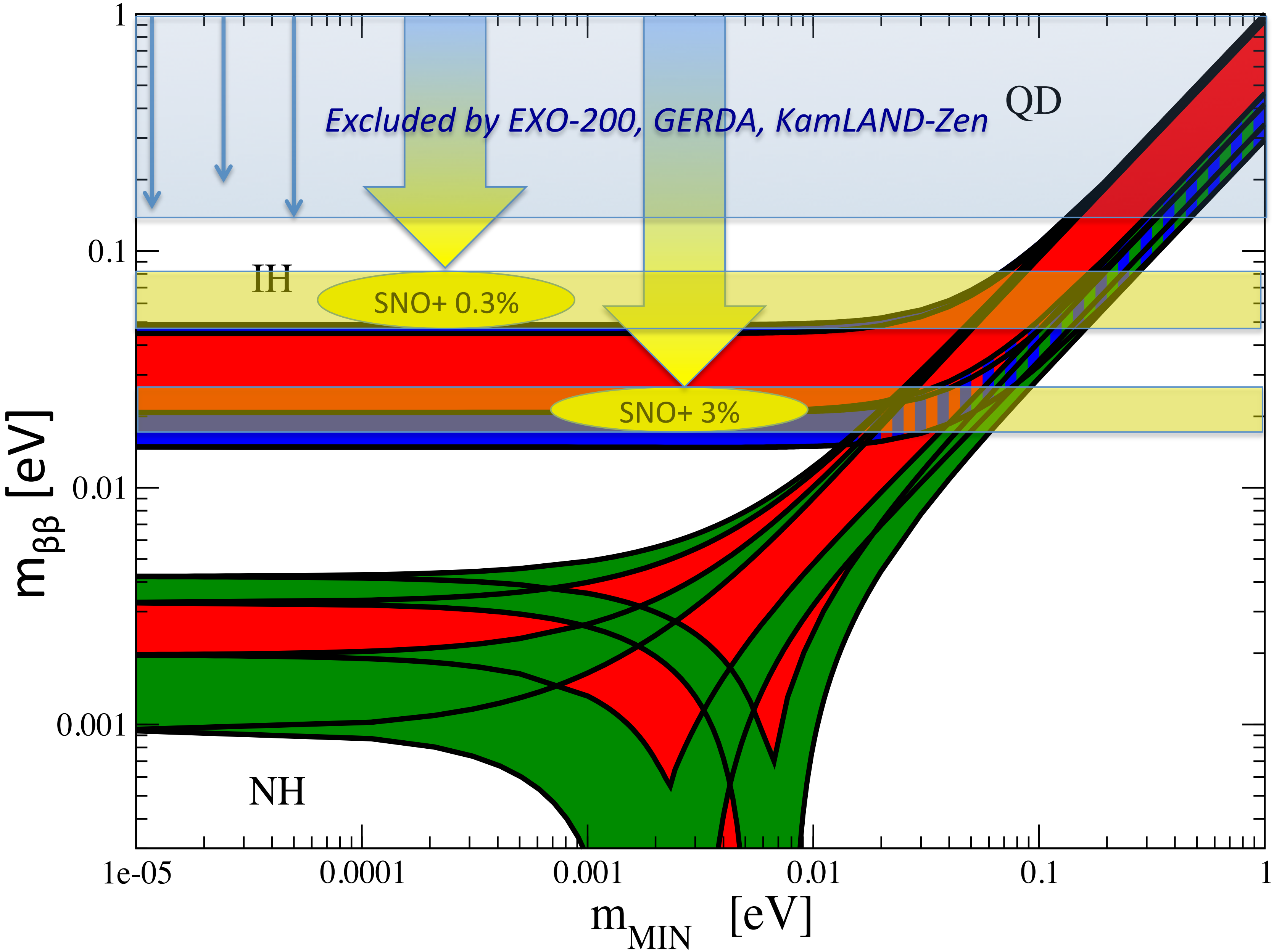


- 3% Te in SNO+ Phase II DBD corresponds to 8 tonnes of ^{130}Te *isotope* (cost for this much tellurium is only ~ $15M)
- Contain isotope within a bag (KamLAND-Zen style)?
- Upgrade SNO+ PMT array – High QE PMTs?

$<m_{\beta\beta}>$ and the Neutrino Mass Hierarchy

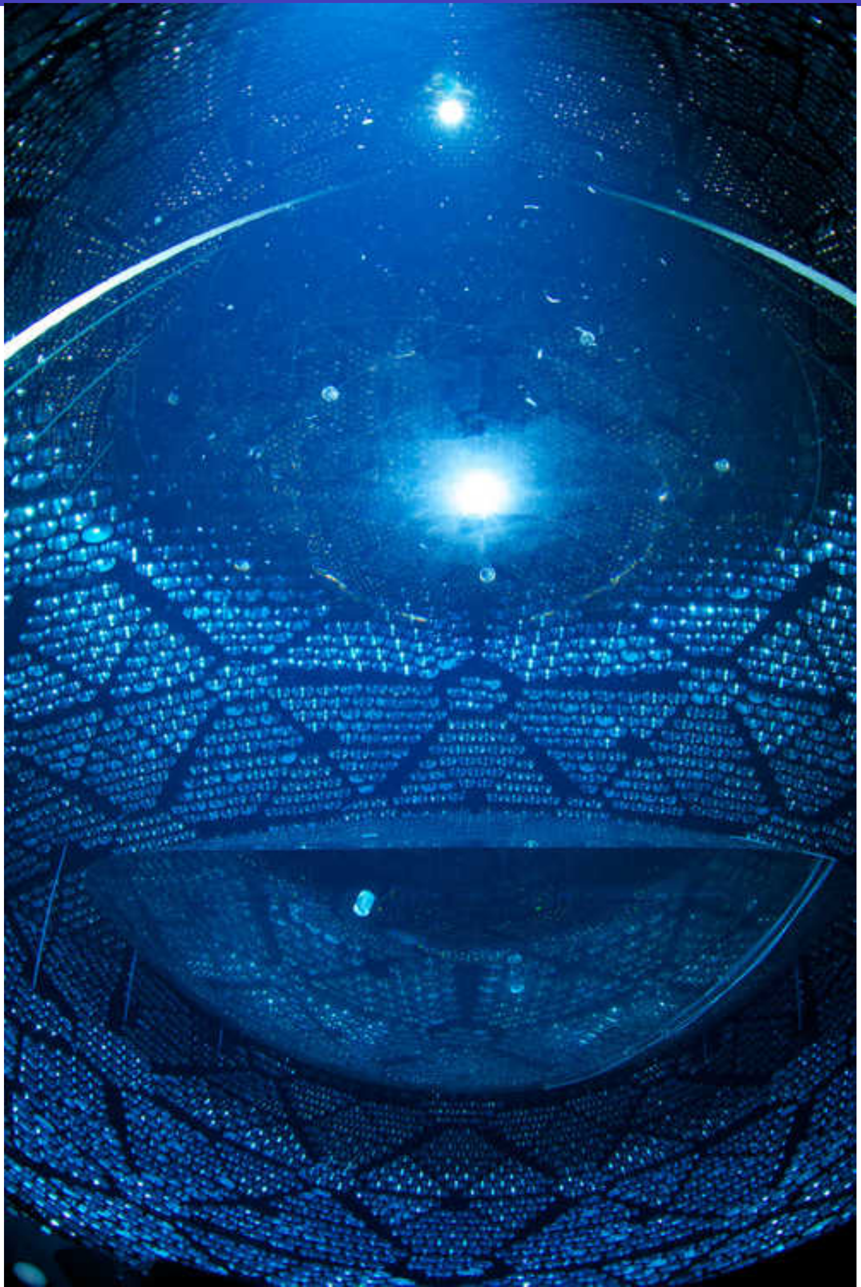


updated figure by S. Pascoli in RPP 2013 "Neutrino Mass, Mixing and Oscillations", originally in S. Pascoli and S. Petcov, PRD 77, 113003 (2008)



1
0.1
0.01
0.001
1e-05
0.0001
0.001
0.01
0.1
1
Excluded by EXO-200, GERDA, KamLAND-Zen
QD
IH
SNO+ 0.3%
SNO+ 3%
NH
$m_{\beta\beta}$ [eV]
m_{MIN} [eV]

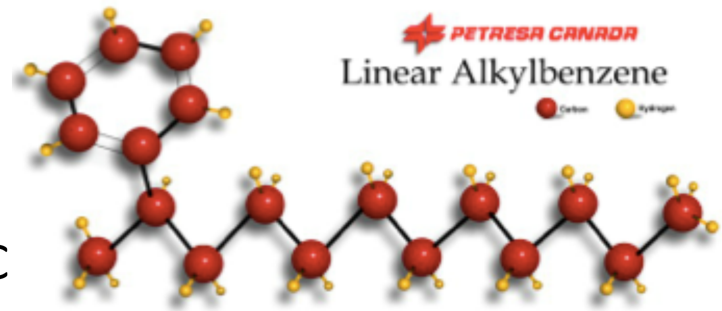
Thank you for Listening!

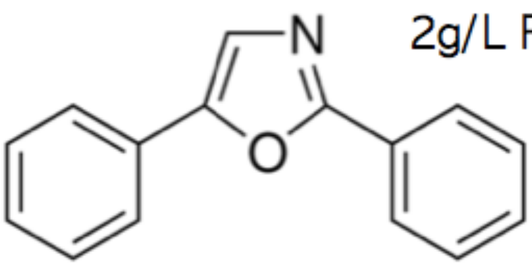


Backup slides

Liquid Scintillator

- Linear alkylbenzene (LAB) + 2g/L fluor 2,5 diphenyloxazole (PPO)
  - Chemical compatibility with acrylic
  - High light yield, high purity
  - Good optical transparency, low scattering
  - Fast decay – β - α separation
  - Low toxicity, environmentally safe
  - High flash point, 140C, boiling point 278-314C
  - Low solubility in water, 0.041 mg/L





2g/L PPO

Status

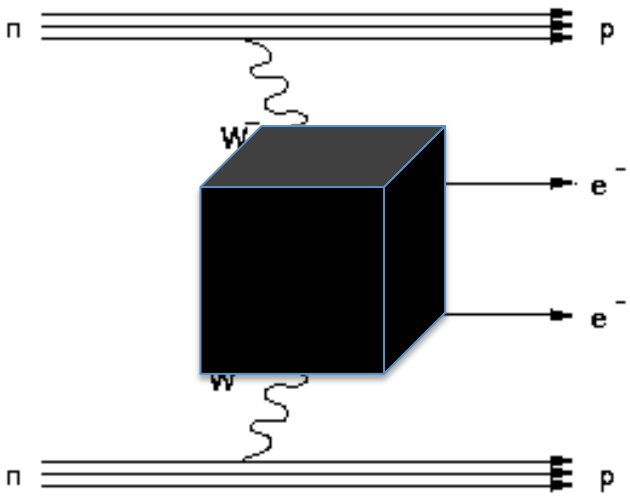
- now filling the SNO+ detector with water
- float-the-boat test in the next few weeks
  - to demonstrate hold-down rope system operation at full buoyant load
- water-filled data taking starts in few months
  - to study external backgrounds and detector optics
- now installing scintillator purification plant process piping
- liquid scintillator fill to start in 2015
- installation of tellurium purification skid and Te purification in late 2015
- addition of Te to SNO+ liquid scintillator and DBD run in 2016

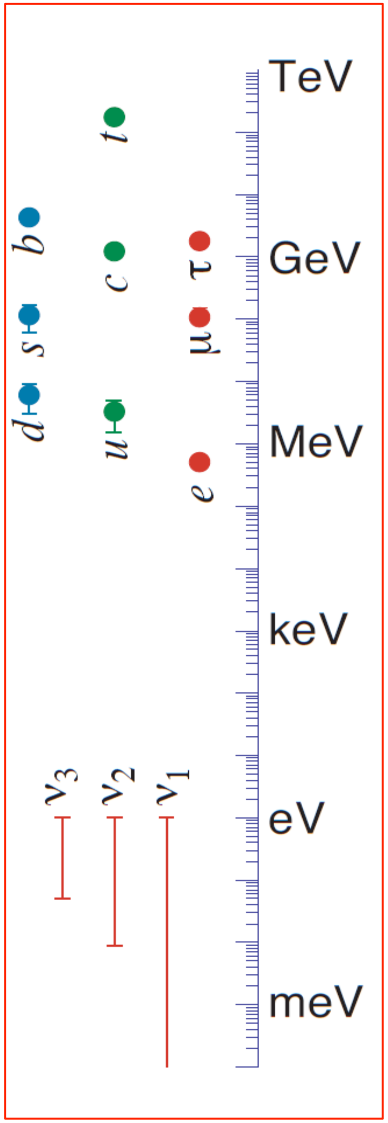
Solar Neutrinos

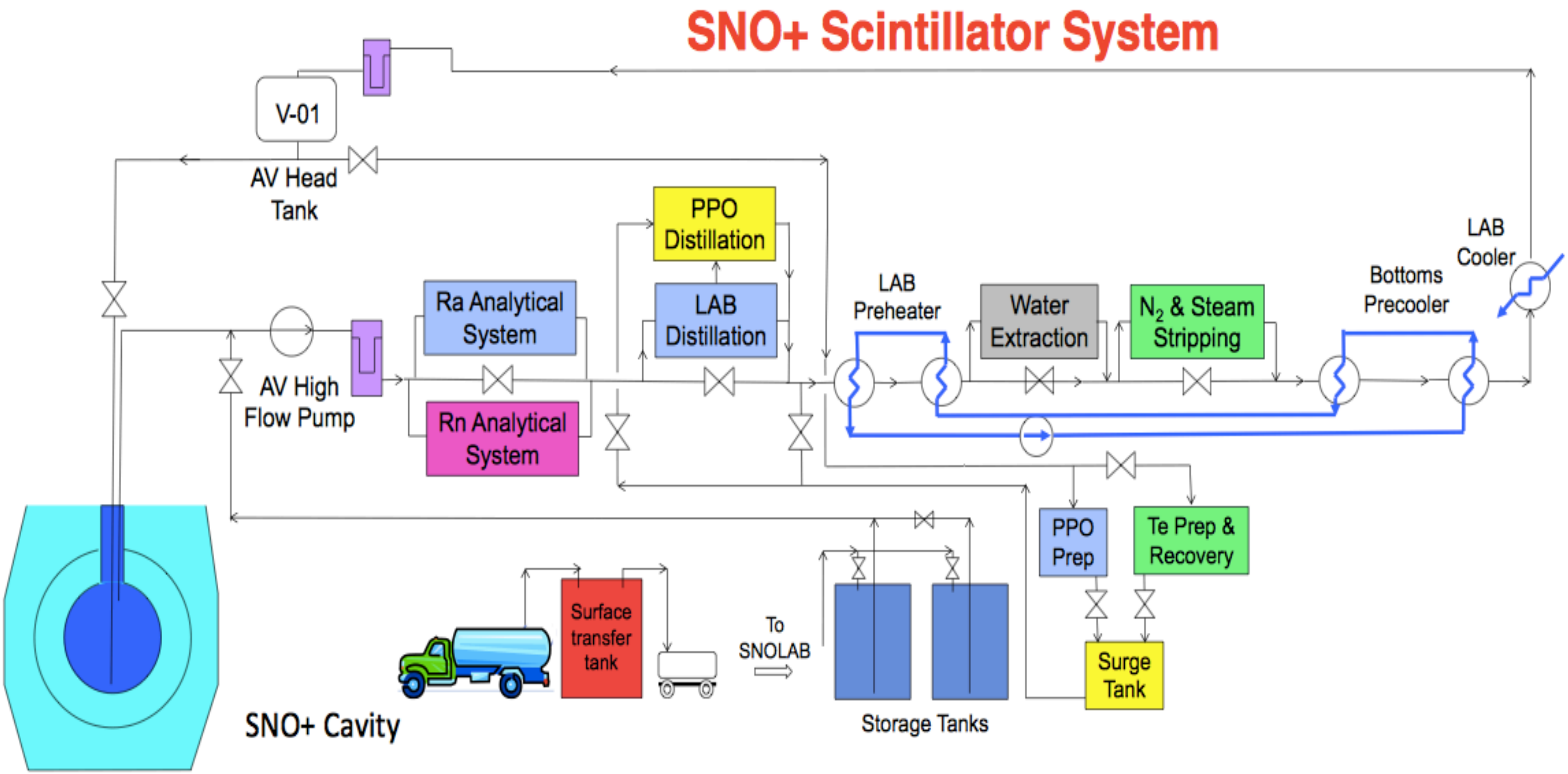
- SNO+ has decided to prioritise $0\nu\beta\beta$
- Radon daughters have accumulated on the surface of the AV over the last few years in a significant way. If these leach into the scintillator, the purification system has the capability to remove them.
- However, depending on the actual leach rate, that removal might be inefficient and the ^{210}Bi levels in the scintillator too high for a pep/CNO solar neutrino measurement without further mitigation.
- Mitigation could include enhancing online scintillator purification, draining the detector and sanding the AV surface to remove radon daughters, or deploying a bag.
- $0\nu\beta\beta$ and low-energy ^{8}B solar neutrino measurements are not affected by these backgrounds

Double Beta Decay

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






SNO+ Scintillator System
V-01
AV Head Tank
PPO Distillation
LAB Distillation
Ra Analytical System
Rn Analytical System
AV High Flow Pump
LAB Preheater
Water Extraction
N_2 & Steam Stripping
Bottoms Precooler
LAB Cooler
PPO Prep
Te Prep & Recovery
Surge Tank
Surface transfer tank
To SNOLAB
Storage Tanks
SNO+ Cavity

Cosmogenics

- Nitric acid recrystallisation process performed on surface for safety
- Cosmogenic isotopes re-develop between the end of purification and moving the Te underground
  - Goal = 5 hour transit time
  - Additional underground polishing step
    - Dissolve in warm water
    - Thermal recrystallisation

	No purification	Purification + 5 hrs re-activation + "polishing" & 6 month cool-down
^{22}Na	15309	0.0947
^{26}Al	0.048	5.724E-7
^{42}K	565	0.0044
^{44}Sc	102	0.0004
^{46}Sc	43568	0.1993
^{56}Co	2629	0.0099
^{58}Co	25194	0.0888
^{60}Co	6906	0.0396
^{68}Ga	37343	0.2201
^{82}Rb	18047	0.0071
^{84}Rb	11850	0.0113
^{88}Y	390620	2.3079
^{90}Y	823	0.0019
^{102}Rh	276189	1.8389
^{102m}Rh	133848	1.0438
^{106}Rh	1534	0.0111
^{110m}Ag	69643	0.4184
^{110}Ag	939	0.0056
^{124}Sb	3101138	9.7353
^{126m}Sb	240	1.205E-5
^{126}Sb	358996	0.0015

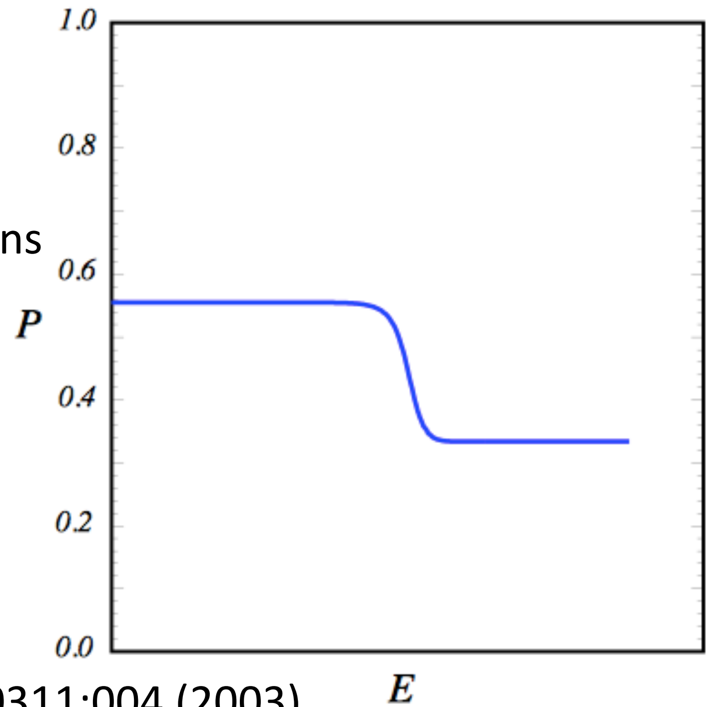
Lozza & Petzoldt, Cosmogenic activation of a natural tellurium target, Astroparticle Physics. DOI: 10.1016/j.astropartphys.2014.06.008

Precision Spectral Measurements

- Accurate measurement of θ_{12} , Δm_{12}^2
  - $\sin^2\theta_{12} = 0.304$, $\Delta m_{12}^2 = 7.5\times10^{-5}$ eV^2
  - Some sensitivity to other angles through global fits
- Energy dependence of ν_e survival probability
  - Confirm MSW effect

$$\beta = \frac{2\sqrt{2}G_F n_e E_\nu}{\Delta m^2}$$

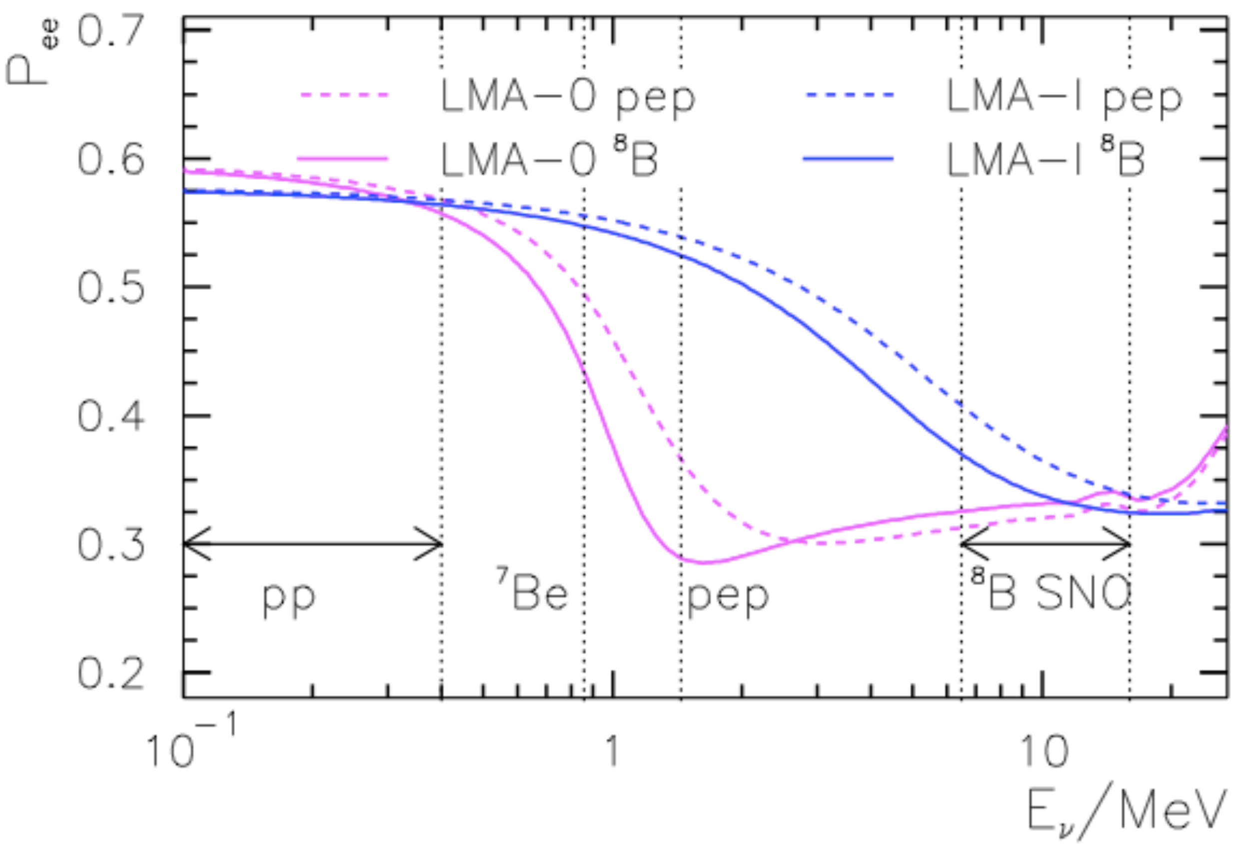
$\beta < \cos2\theta_{12} \approx 0.4$
Vacuum averaged oscillations
$Pee = 1 - \frac{1}{2}\sin^2 2\theta_{12}$



$\beta > 1$
Matter Dominated resonant conversion
$Pee = \sin^2\theta_{12}$

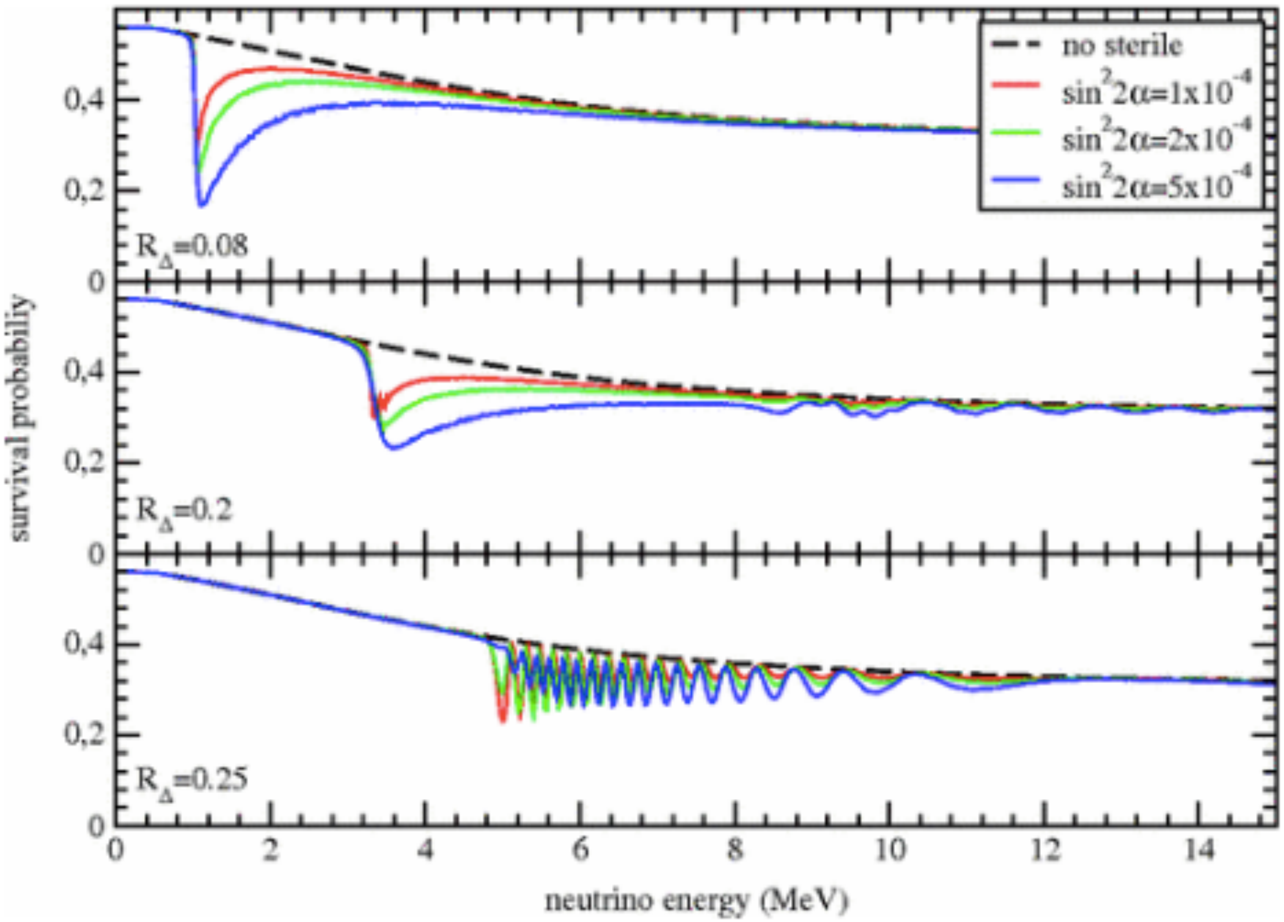
Bahcall, Pena-Garay, JHEP 0311:004 (2003)

New Physics…. Non standard Interactions



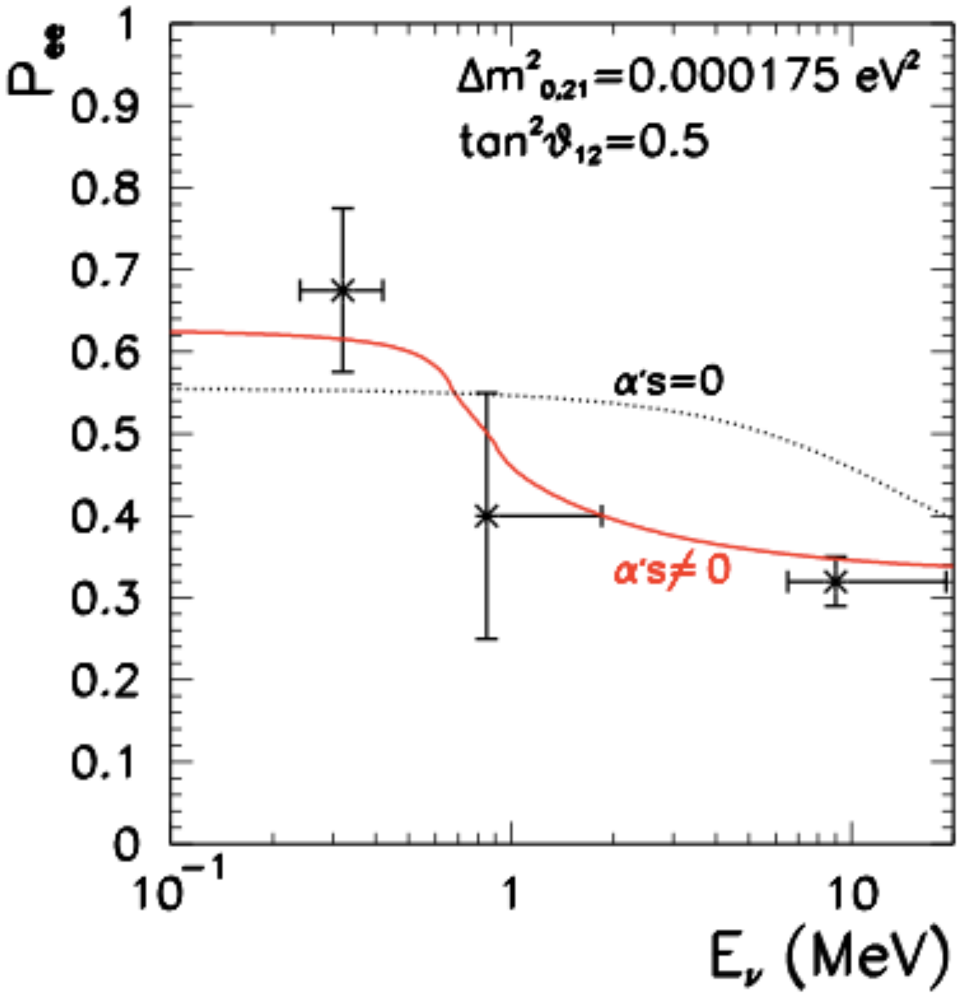
Phys.Lett.B594:347,2004 Friedland, Lunardini, Pena-Garay
Flavour changing interactions at allowed level can modify conversion probability for neutrinos < 6MeV

New Physics… Sterile neutrinos



Phys. Rev. D **83**, 113011 [Holanda and Smirnov]
Additional oscillation to possible sterile neutrino fraction

New Physics… Mass Varying Neutrinos



Phys.Rept.460:1-129,2008 [M.C. Gonzalez-Garcia, Michele Maltoni]
Neutrino mass arises from the interaction with a scalar field, the acceleron, whose effective potential changes as a function of the neutrino density