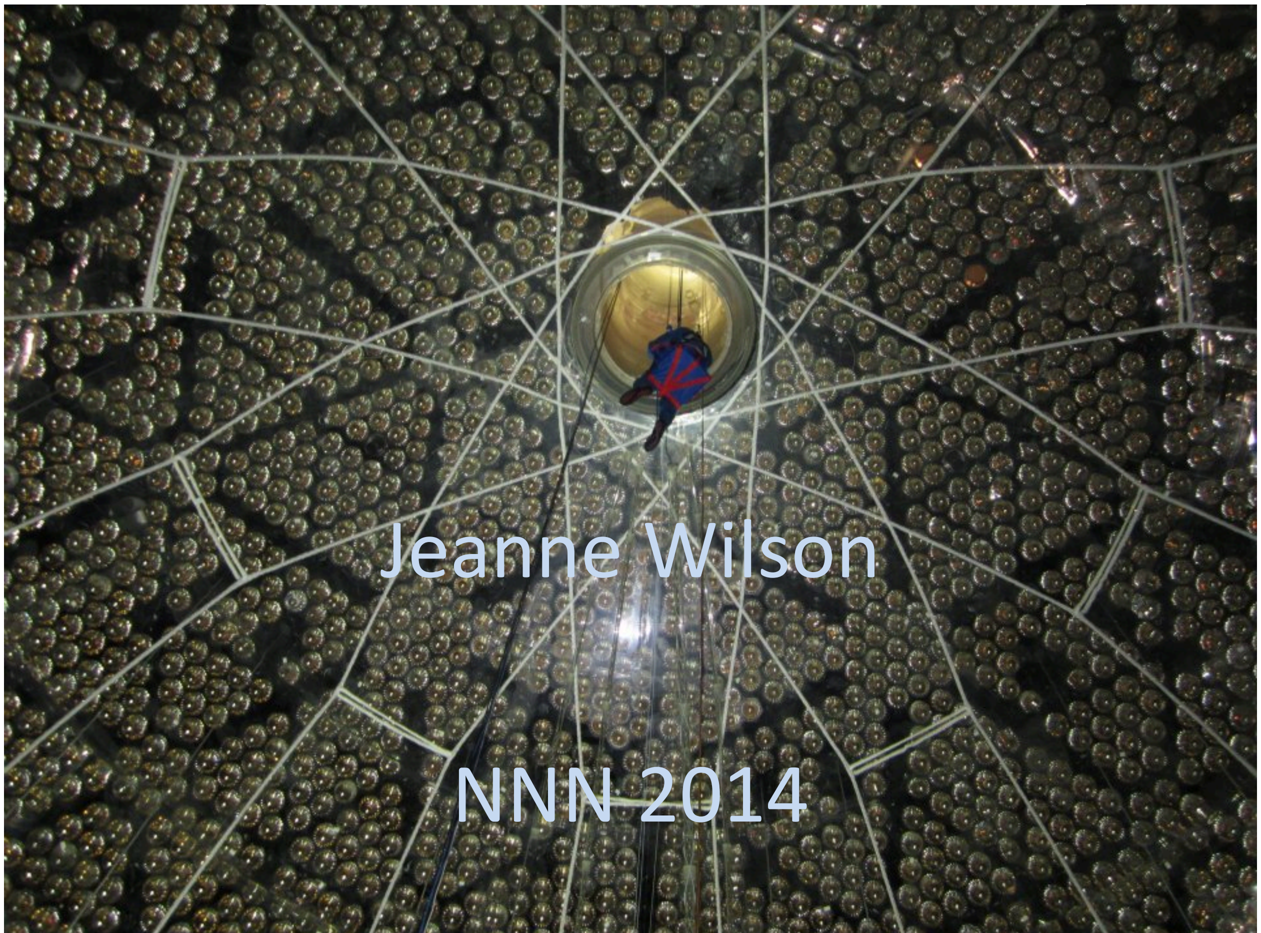
Queen Mary University of London

SNO+

European Research Council
Established by the European Commission



Jeanne Wilson

NNN 2014

SNO+ Collaboration

Queen's
Alberta
Laurentian
SNOLAB
TRIUMF

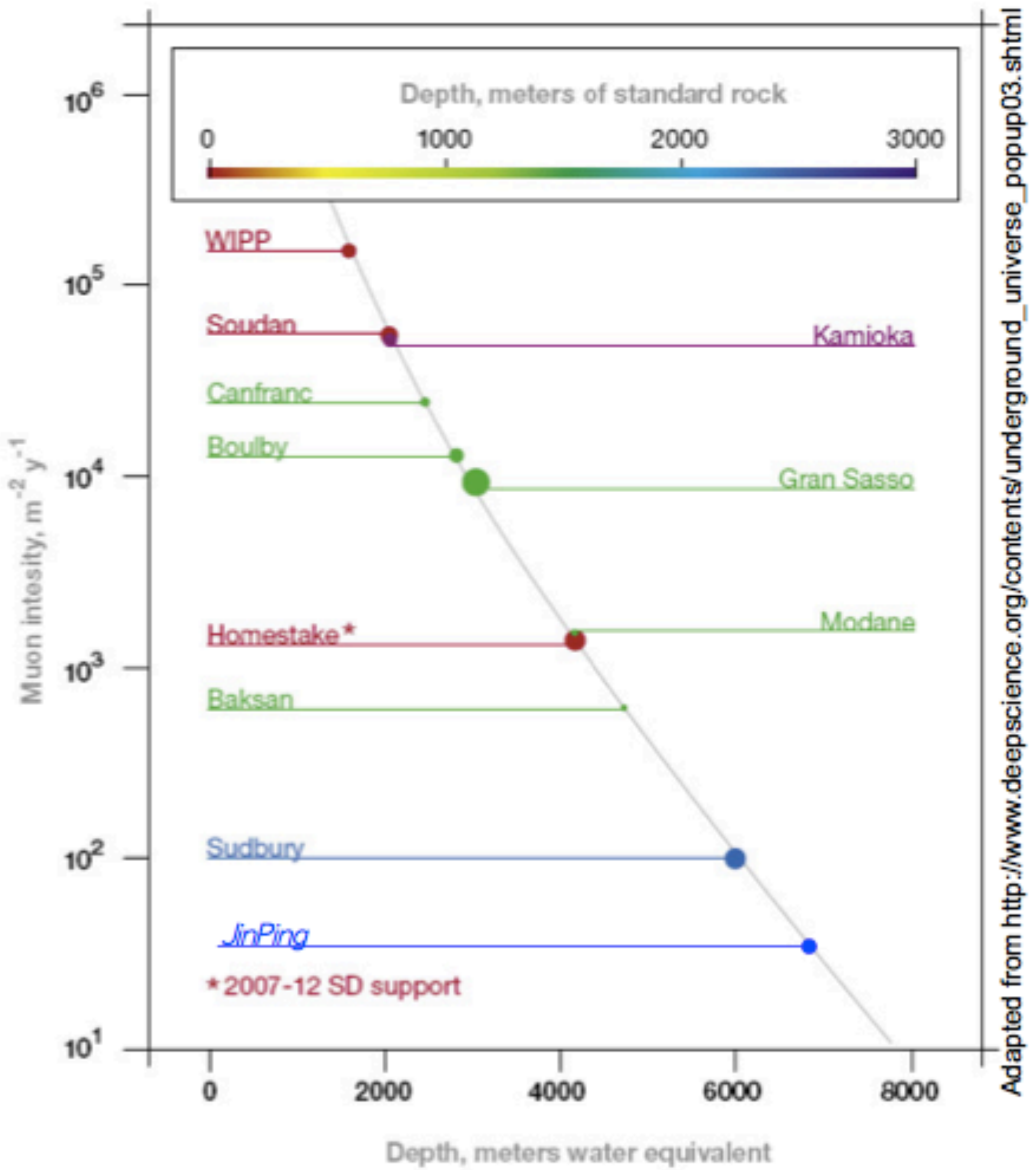
BNL, AASU
U Penn, UNC
U Washington
UC Berkeley/LBNL
Chicago, UC Davis

Oxford
Sussex
QMUL
Liverpool
Lancaster

LIP Lisboa
LIP Coimbra

TU Dresden

Location



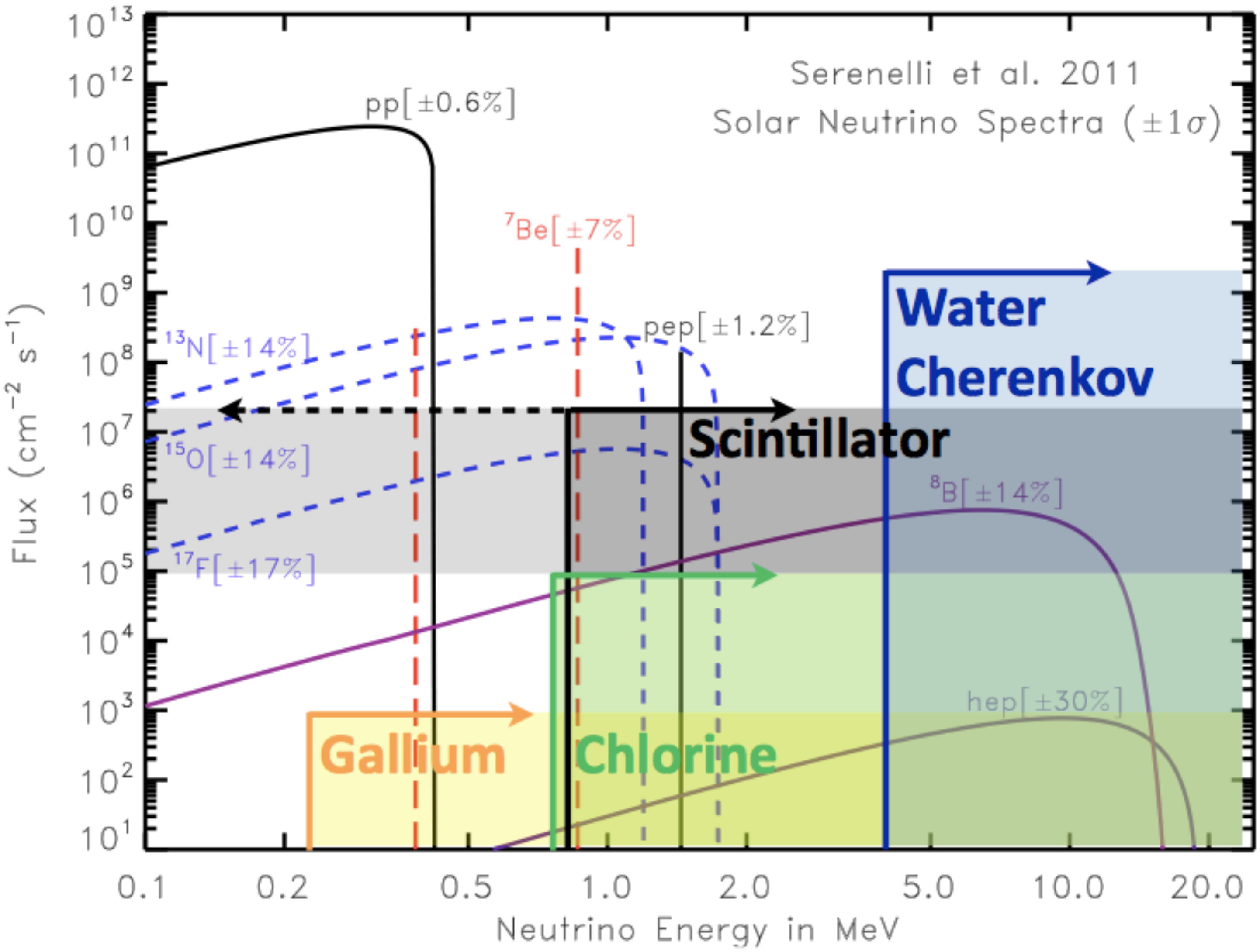
Muon flux = 70 muons/day

Class-2000 clean room lab

SNO+ Physics Program

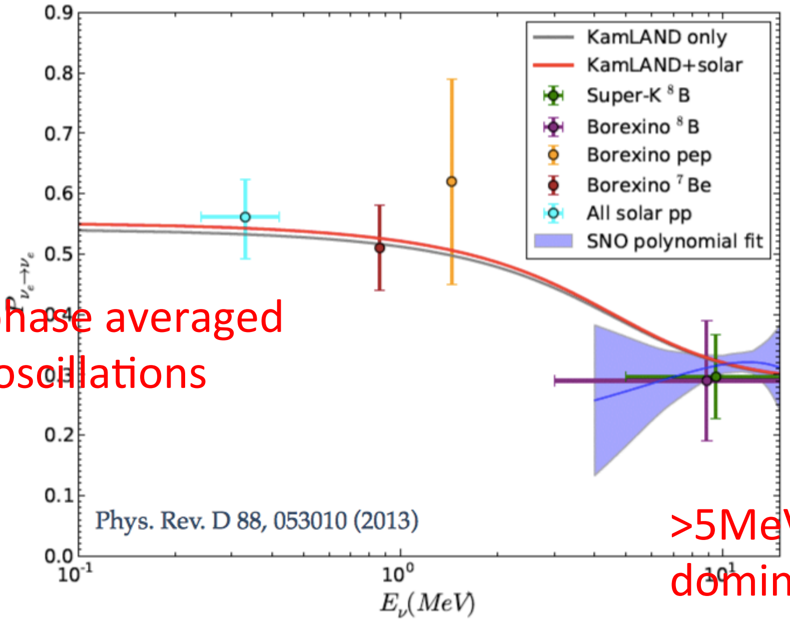
- Low Energy Solar Neutrinos
- Neutrinoless double beta decay search
- Supernovae sensitivity
- Reactor Neutrinos
- Geoneutrinos
- Invisible Nucleon Decay (water phase)

Solar Neutrinos



Solar Neutrino Physics

- 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

Neutrinoless Double Beta Decay

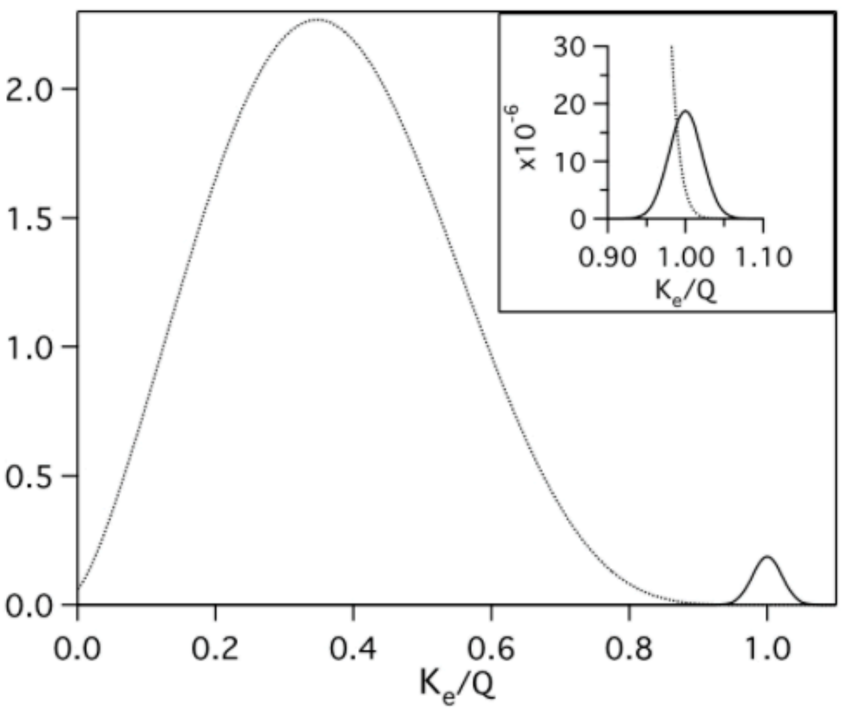
$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu} \cdot \left|M^{0\nu}\right|^2 \cdot \langle m_{\beta\beta} \rangle^2$$

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)

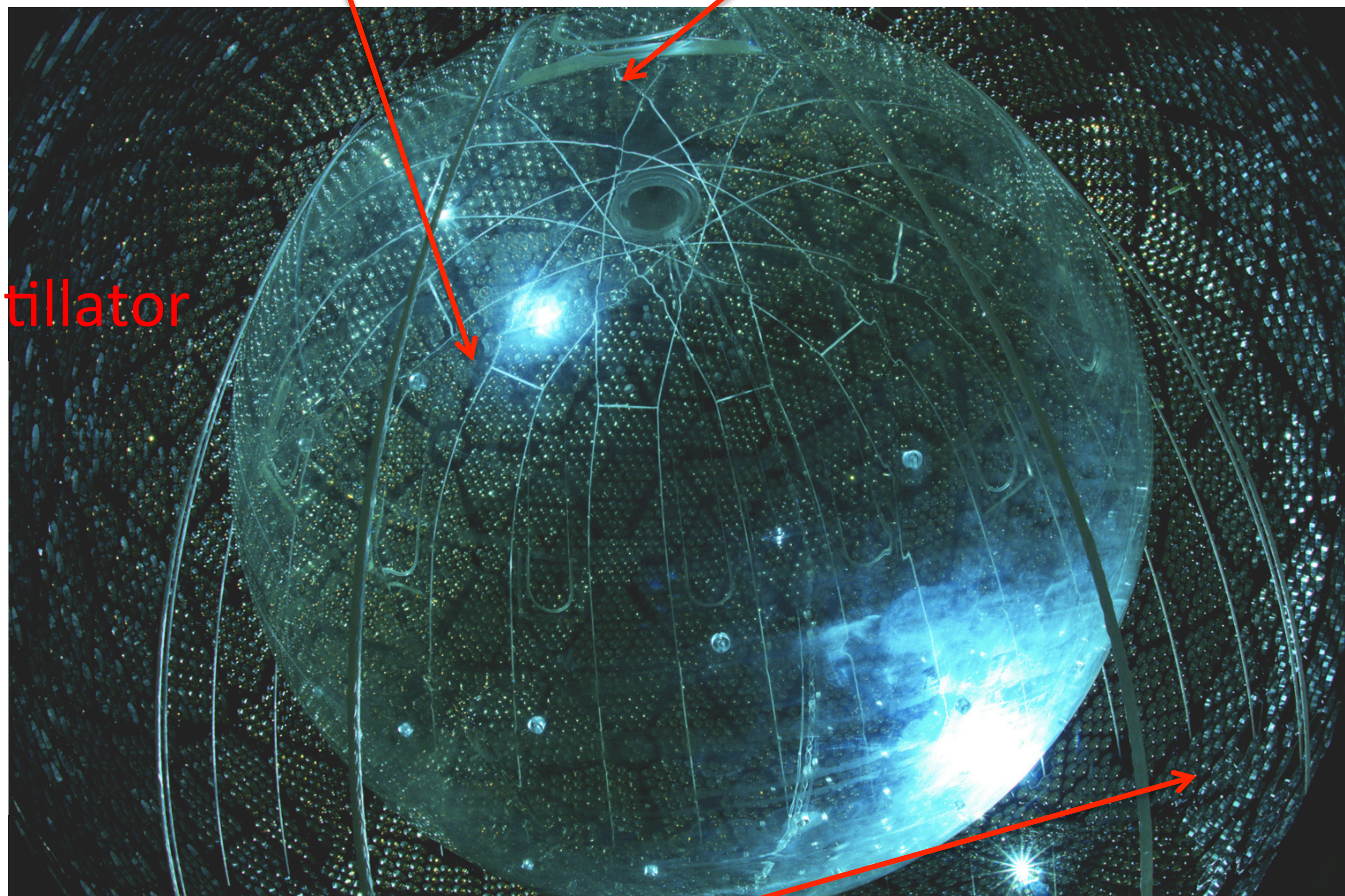
$0\nu\beta\beta$ search – SNO+ approach

- Statistics over energy resolution
- Tellurium – 130
  - Favourable $0\nu\beta\beta$: $2\nu\beta\beta$ 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 $0\nu\beta\beta$ search at relatively low cost
- Large homogeneous detector, well defined background model
  - Aim to be dominated by solar neutrino background
- Isotope In/Out capability

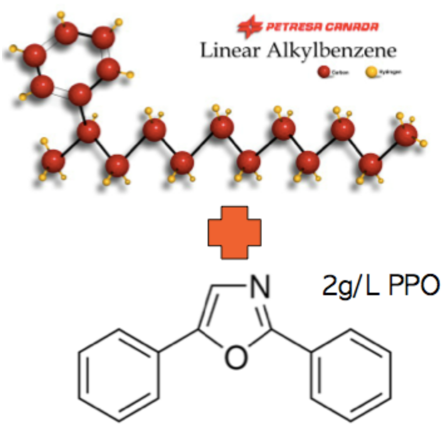
SNO+ Detector

- 12m diameter Acrylic Vessel

Hold down rope net

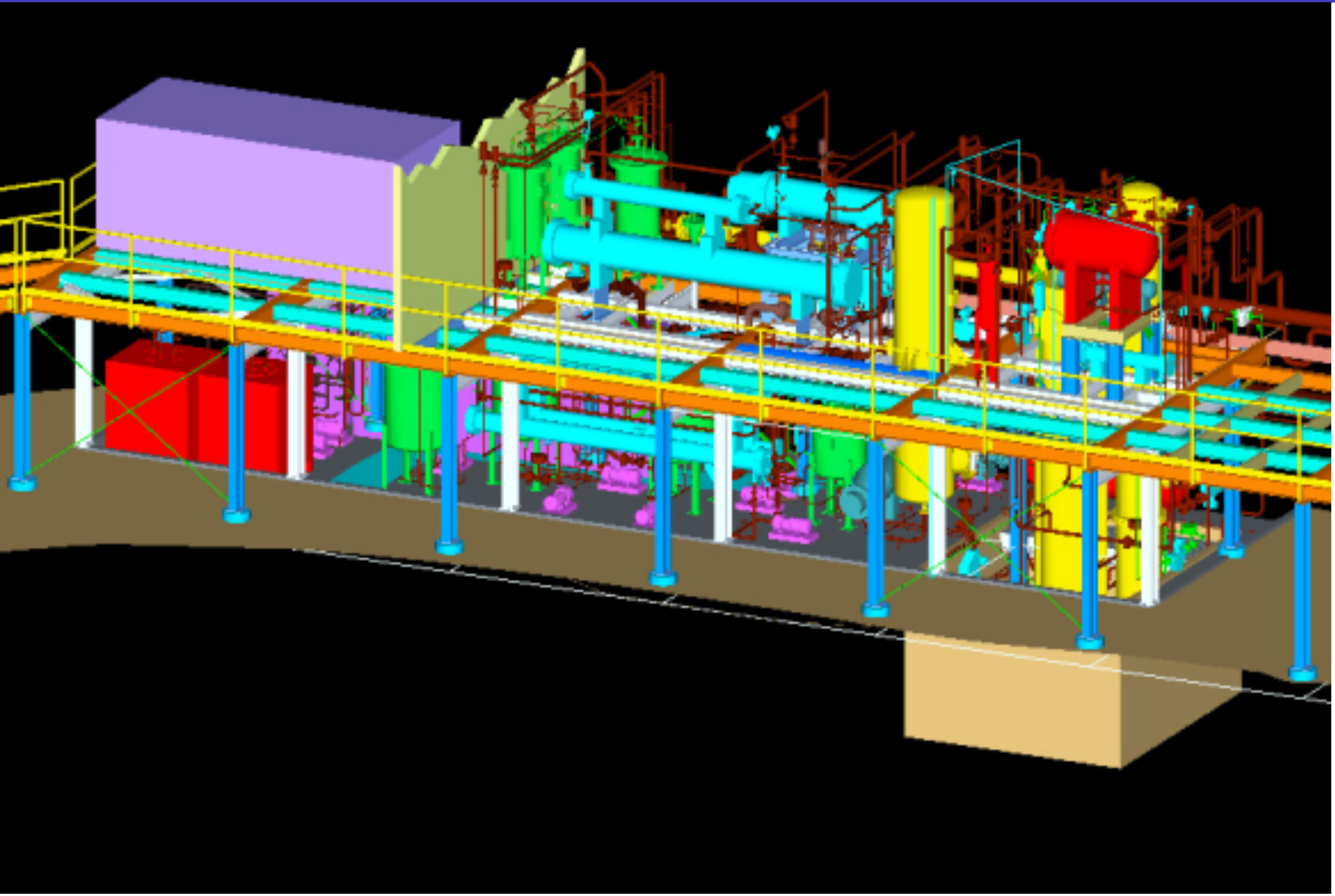


- 780 tonnes scintillator



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

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

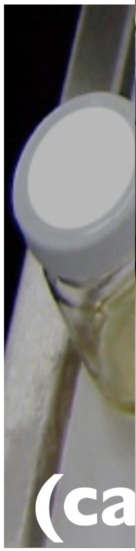


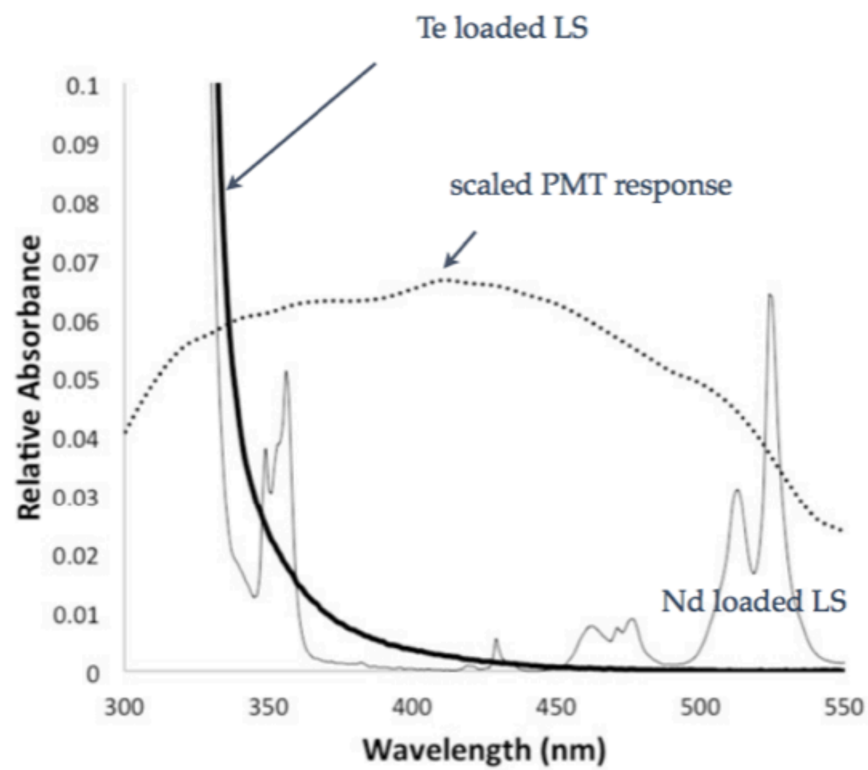

First Attempts at Te-Loaded Scintillator

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





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li

Telluric Acid Purification

Above ground

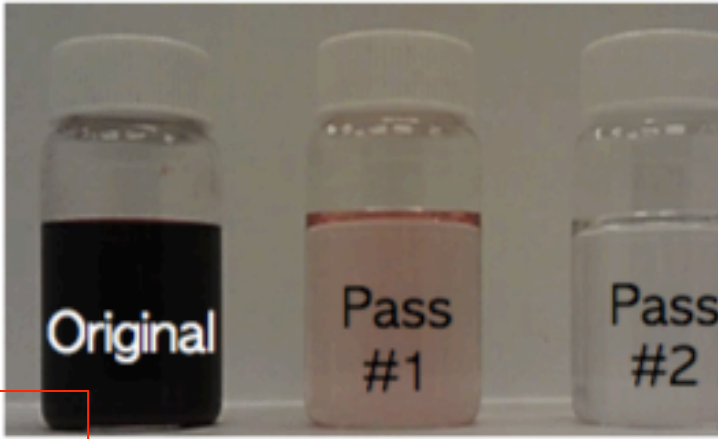
- Dissolve $Te(OH)_6$ in water
- Re-crystalize using nitric acid
- Rinse with ethanol

10^4 reduction

Below ground

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

10^2



^{60}Co spike test

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

Measured Single Pass Reduction Factors

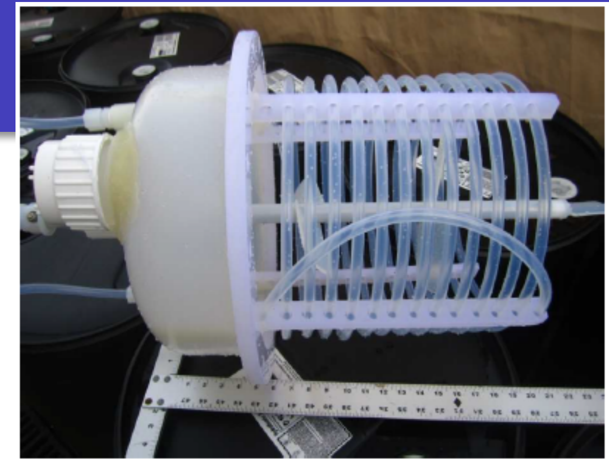
Element	Reduction Factors From Spike Tests	Non-spiked, before purification	Non-spiked, after purification
Sn	$>1.67\times10^2$	20	<20
Zr	$>2.78\times10^2$	70	<10
Ti		40	<10
Al		<30	<30
Co	$(1.62\pm0.34)\times10^3$	<10	<10
Mn		150	<5
Fe		40	<30
Ag	$>2.78\times10^2$	<10	<10
Y	$>2.78\times10^2$	<10	<10
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
- Plan to have the full-scale design for SNOLAB this winter

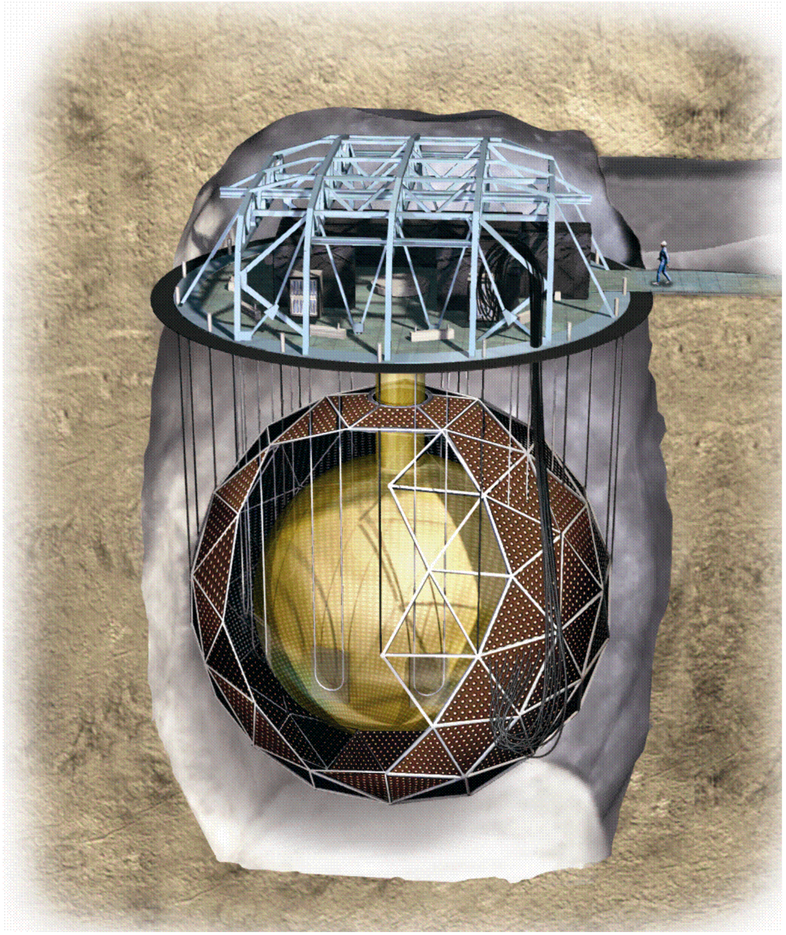


Backgrounds

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:

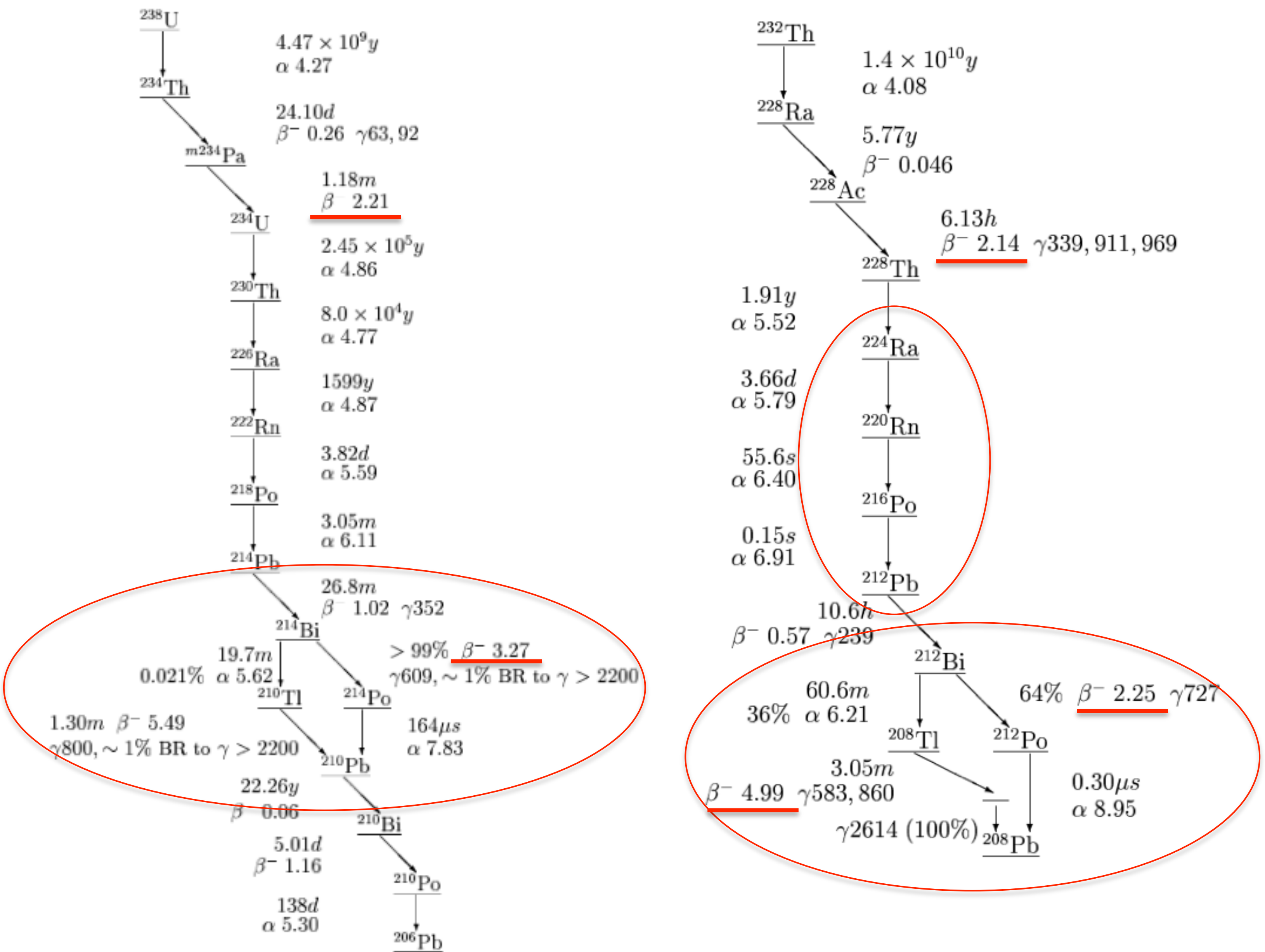
capture on H to 2.2MeV ϒ:

Muon induced neutrons, (α,n)

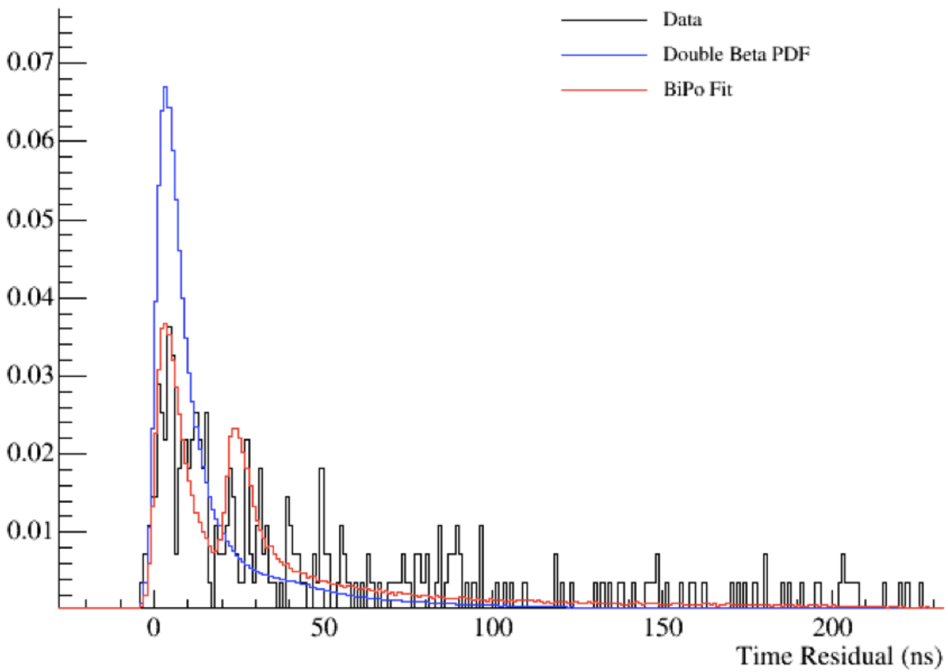
Tellurium : ^{238}U, ^{232}Th, ^{210}Po

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

Uranium and Thorium Chain



BiPo rejection

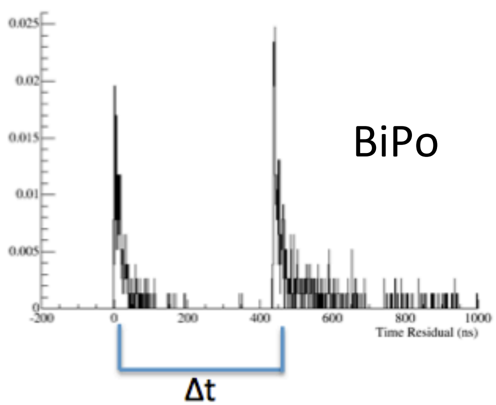


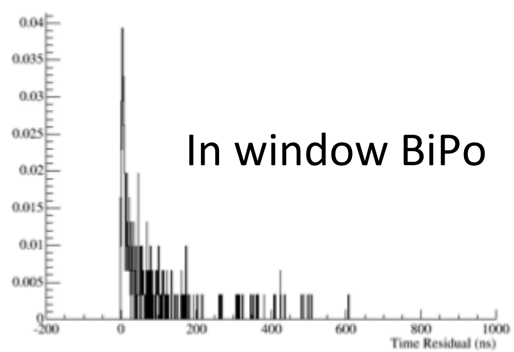
Likelihood ratio cuts to reject in-window BiPo

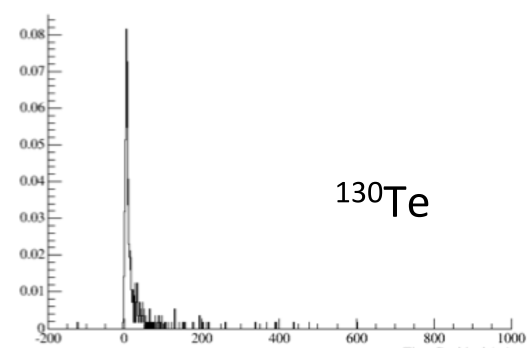
- Timing Residuals
- Beta and alpha energies

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

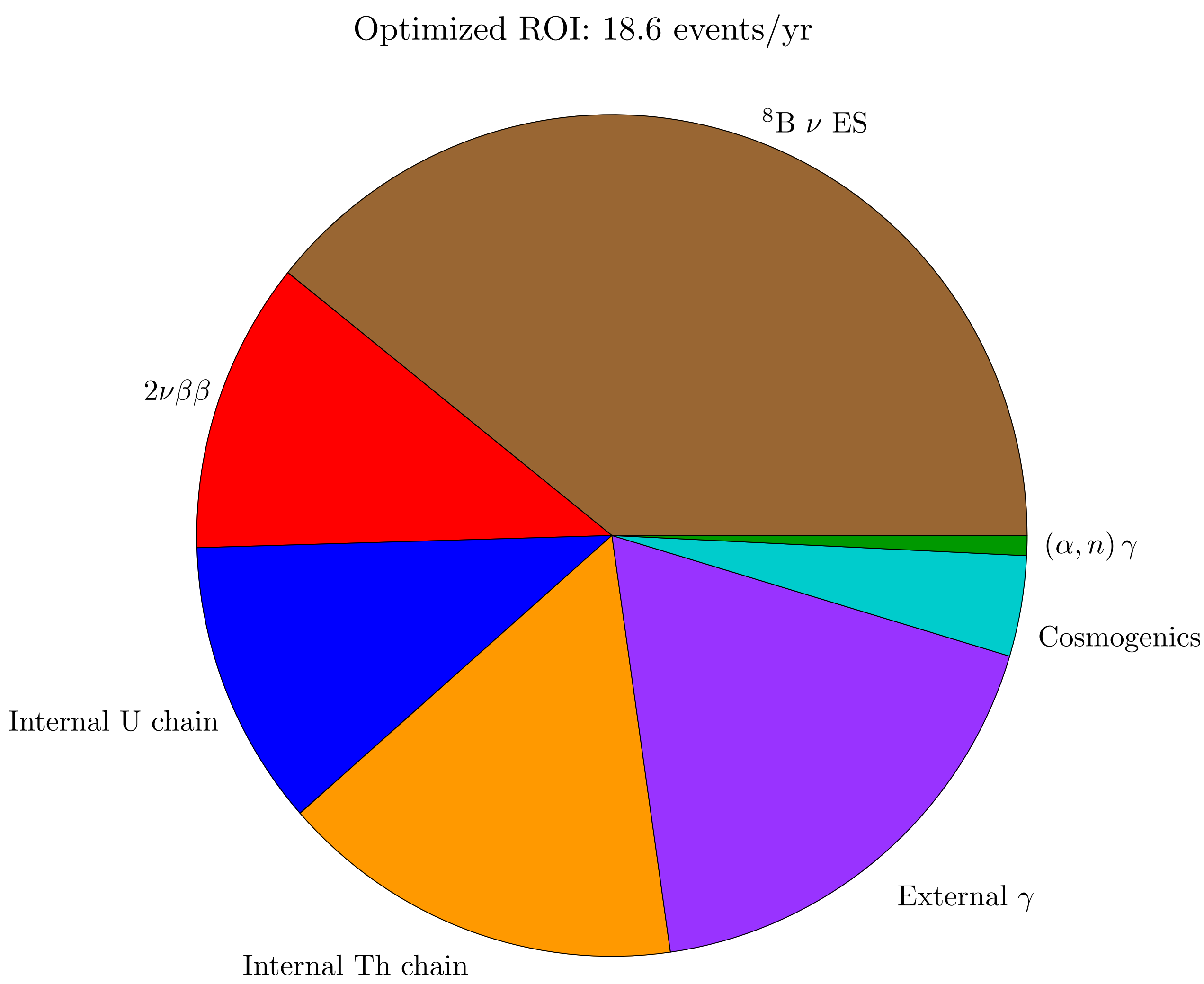
SNO+ 'RAT' Simulations



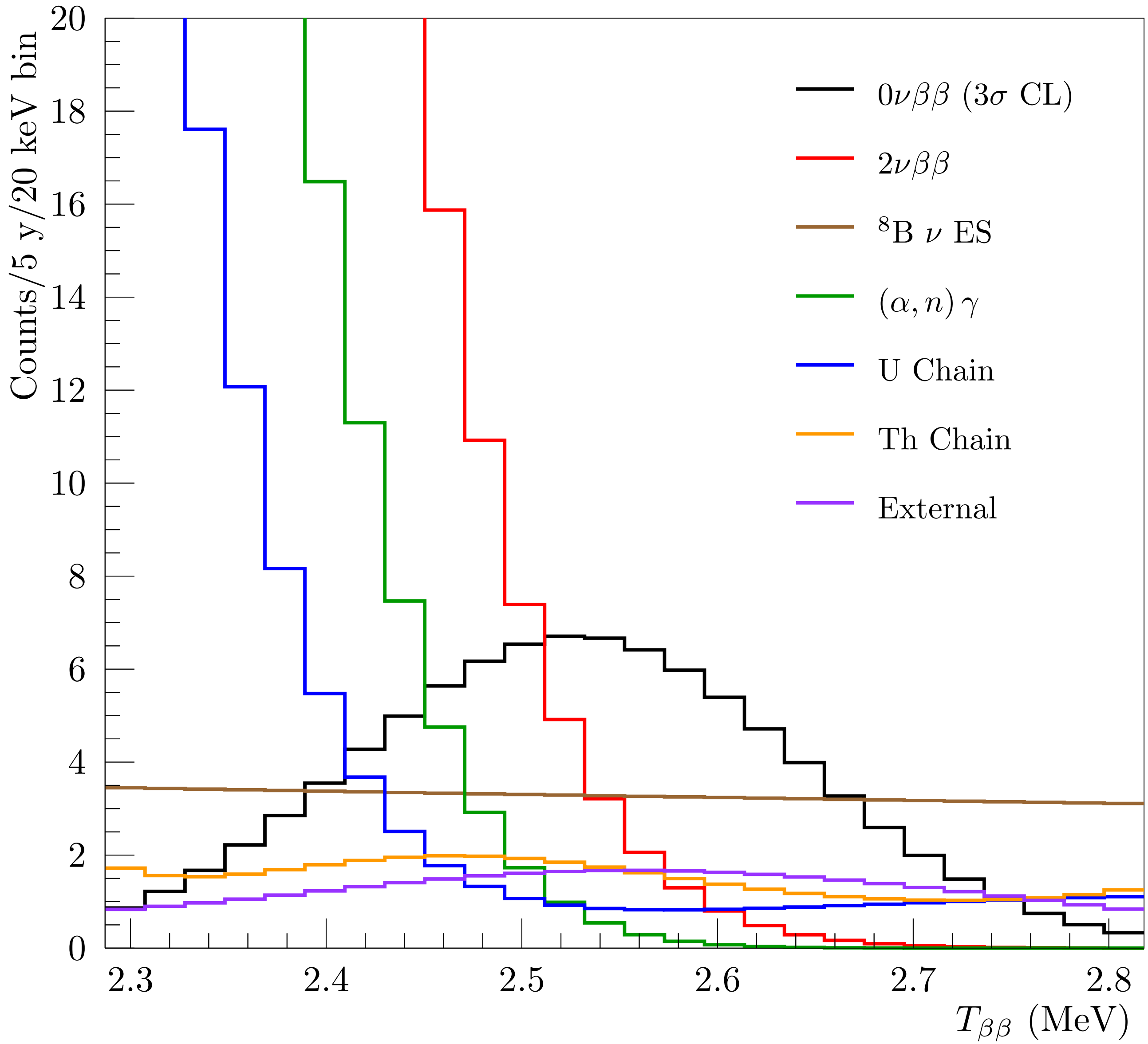




Backgrounds



Spectrum Plot



Spectrum inputs

- ^{130}Te undergoes double beta decay with nuclear matrix element M = 4.03 (IBM-2) [1] and phase space factor G = $3.69 \times 10^{-14}\ y^{-1}$, 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

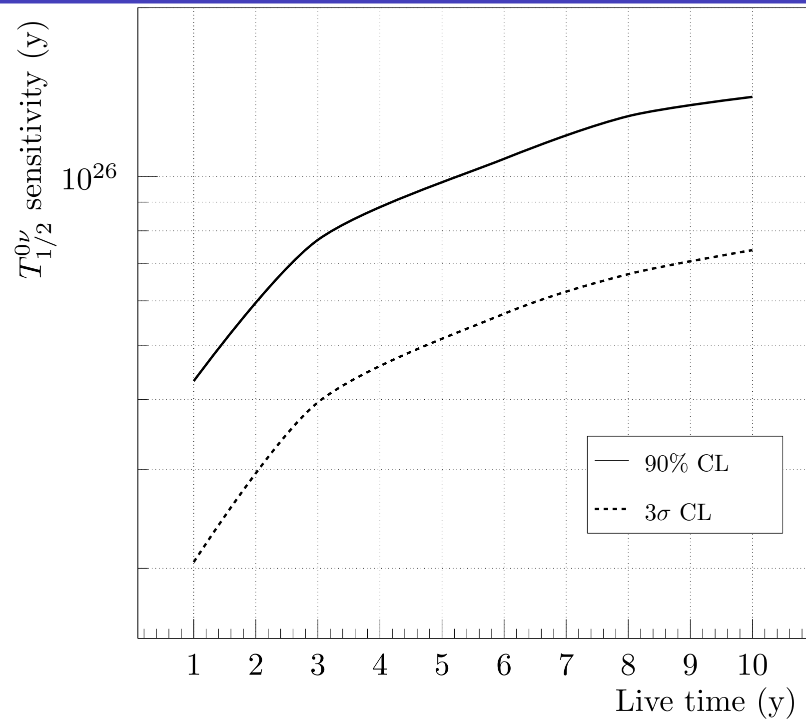
$$\sigma(E) = \sqrt{(E\ [MeV]/200)}$$

- 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).

Sensitivity 0.3% loading



1 year at 0.3% loading -> 4.32×10^{25} years, (~100meV)

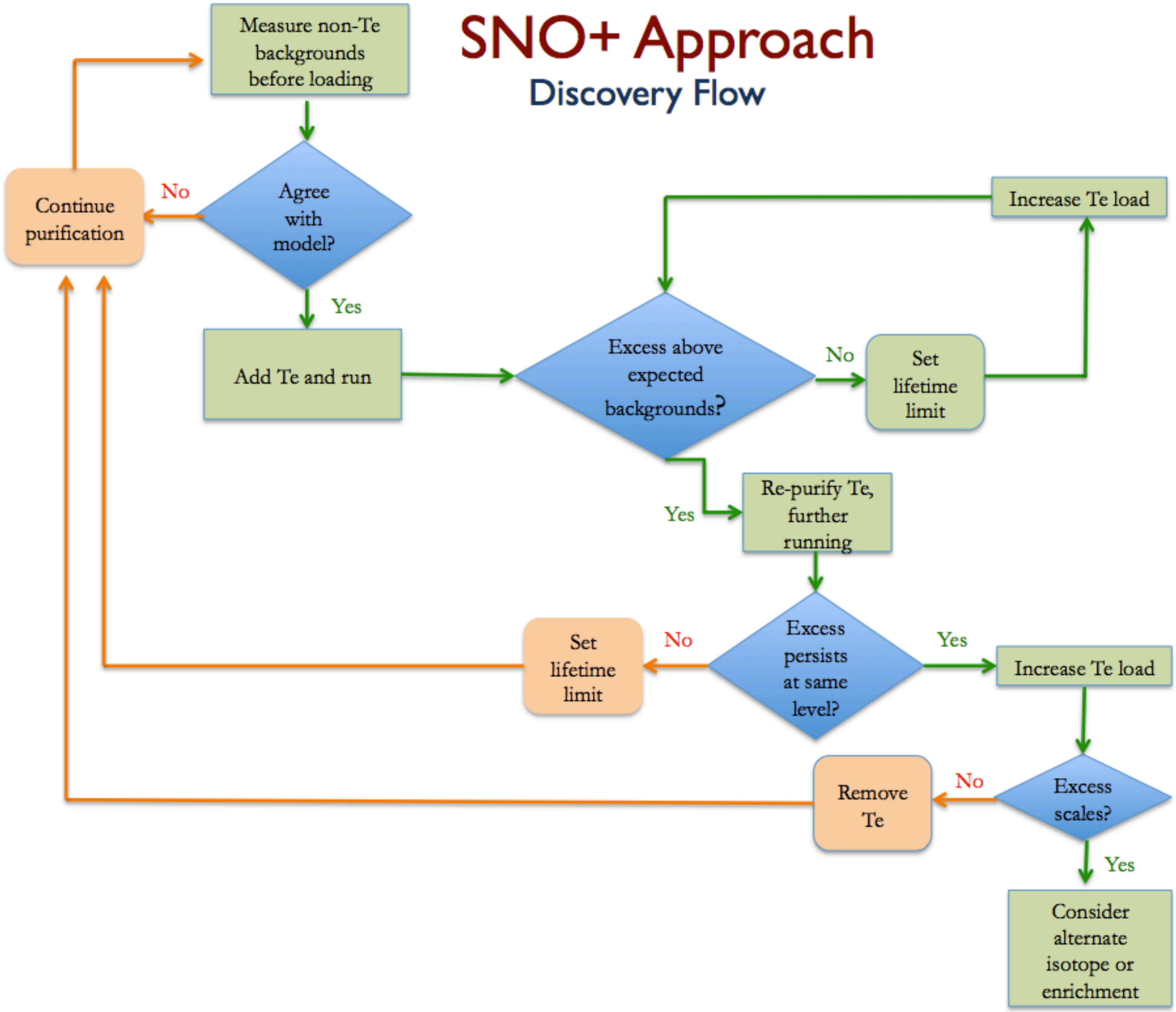
5 years at 0.3% loading -> 9.67×10^{25} years, (~67meV)

(90% CL)

Cuoricino $T_{1/2}$>2.8×10^{24} years at 90% C.L -> <300-710meV, depending on the adopted nuclear matrix element evaluation

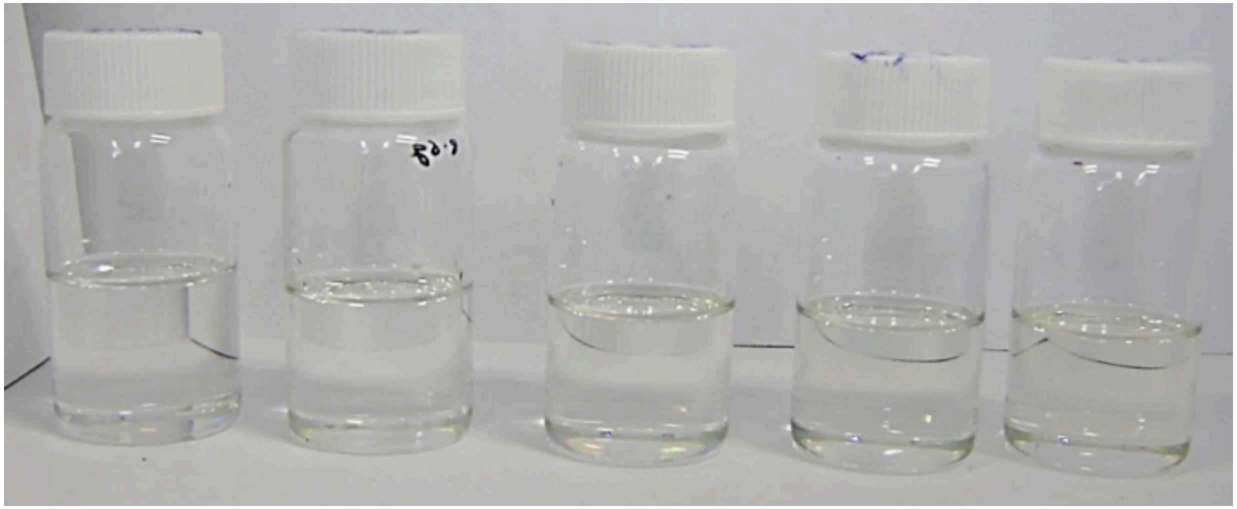
[arXiv:1012.3266 [nucl-ex]]

What if we see a bump?



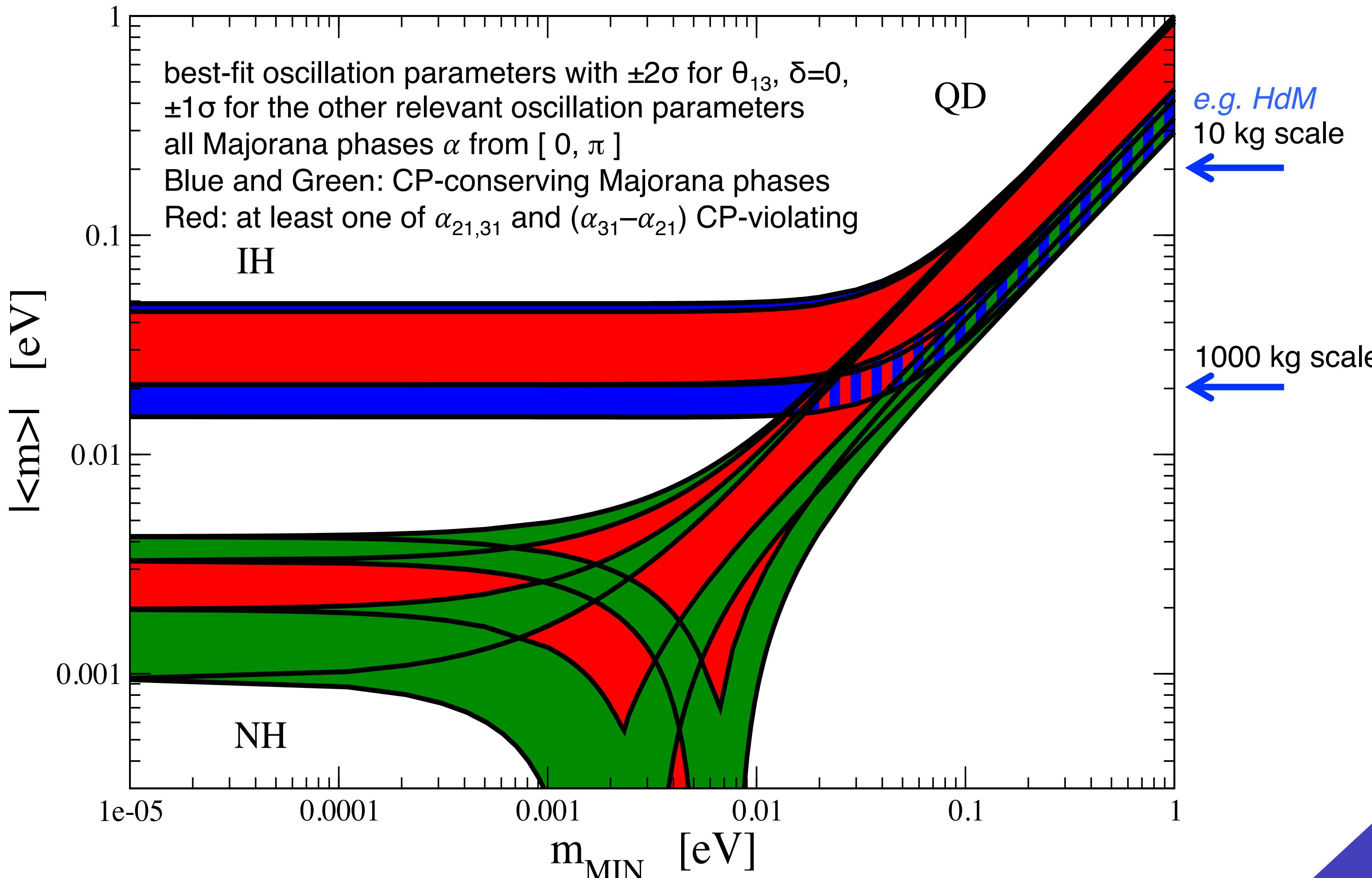
Percent Loading of Tellurium is Feasible

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

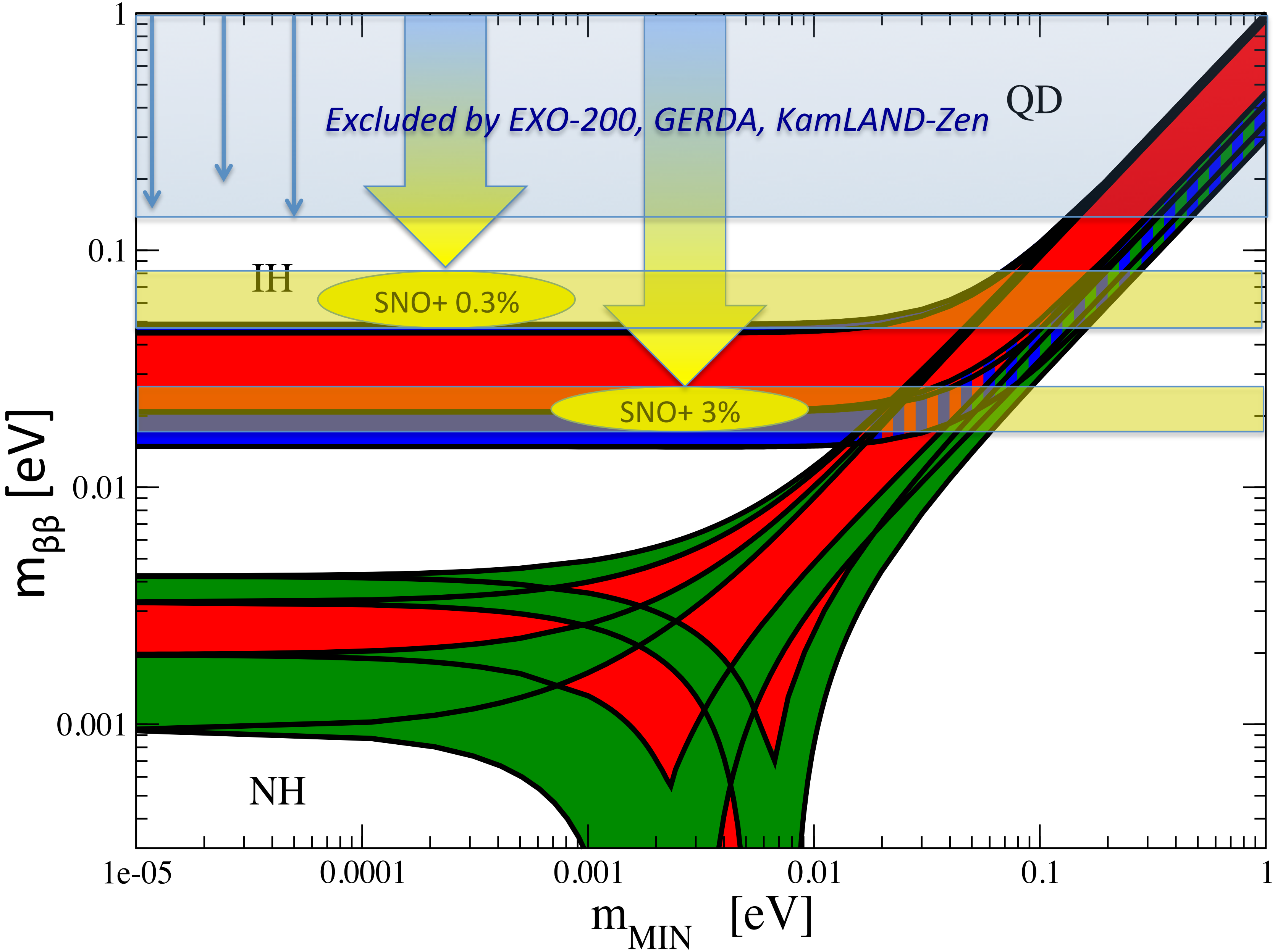


- 3% Te in SNO+ Phase II DBD corresponds to 8 tonnes of ^{130}Te *isotope* (cost for this much tellurium is only ~ $15M)
- Contain isotope within a bag (KamLAND-Zen style)?
- Upgrade SNO+ PMT array – High QE PMTs?

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

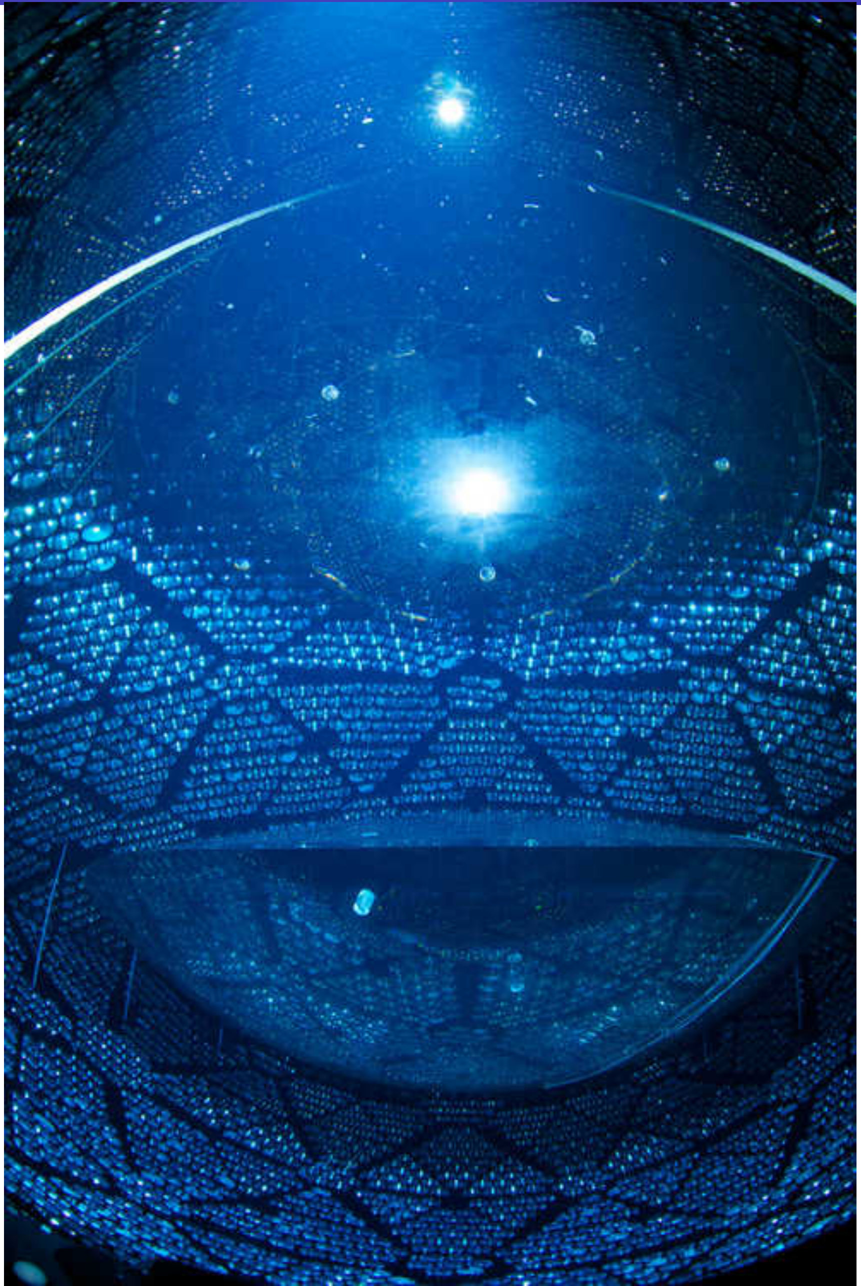


updated figure by S. Pascoli in RPP 2013 "Neutrino Mass, Mixing and Oscillations",
originally in S. Pascoli and S. Petcov, PRD 77, 113003 (2008)



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

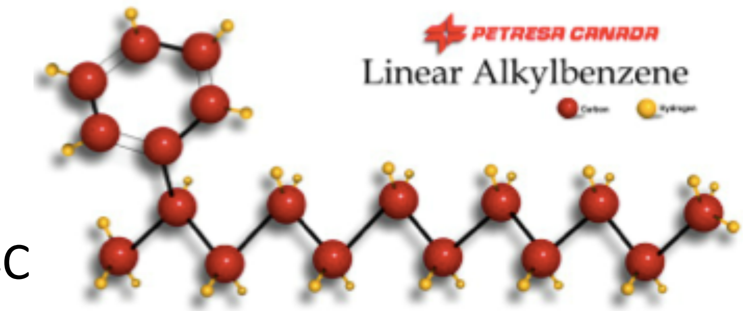
Thankyou for Listening!

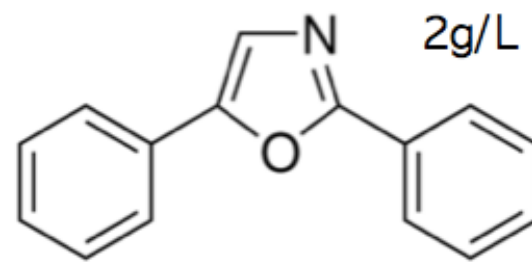


Backup slides

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





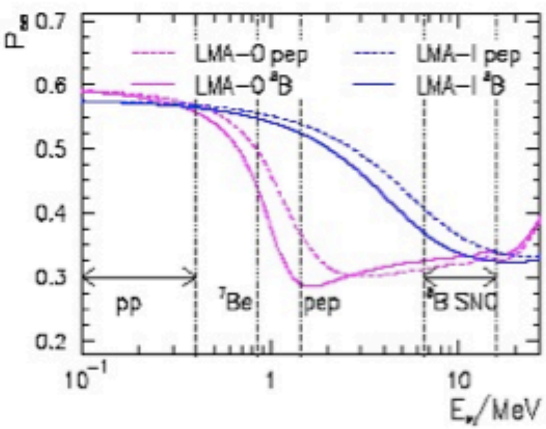
2g/L PPO

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

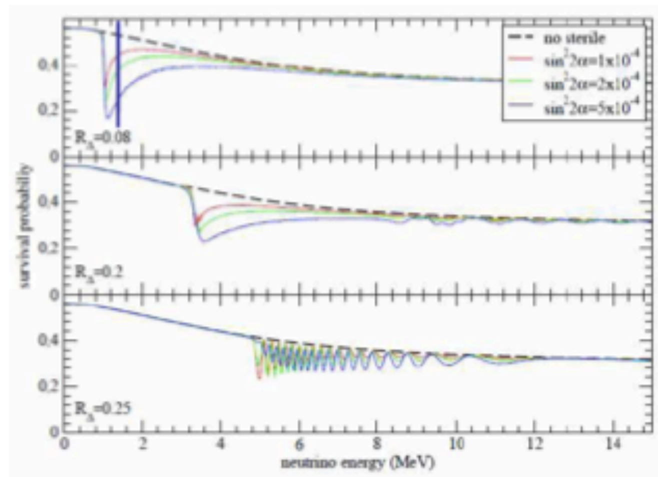
Pep neutrinos – test for new Physics

Non-standard interactions (flavour changing NC)



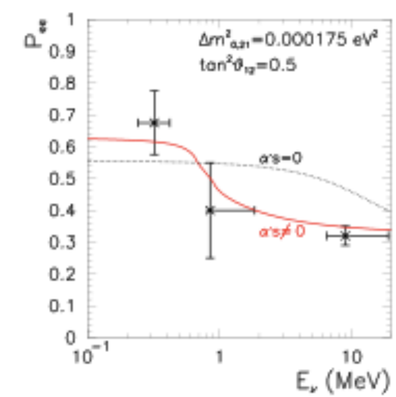
Friedland, Lunardini, Peña-Garay, PLB 594, (2004)

Sterile Neutrinos



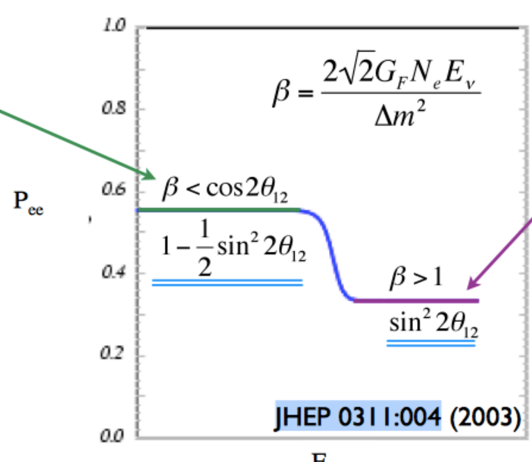
Holanda & Smirnov PRD 83 (2011) 113011

Mass varying neutrinos (MaVaNs)



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

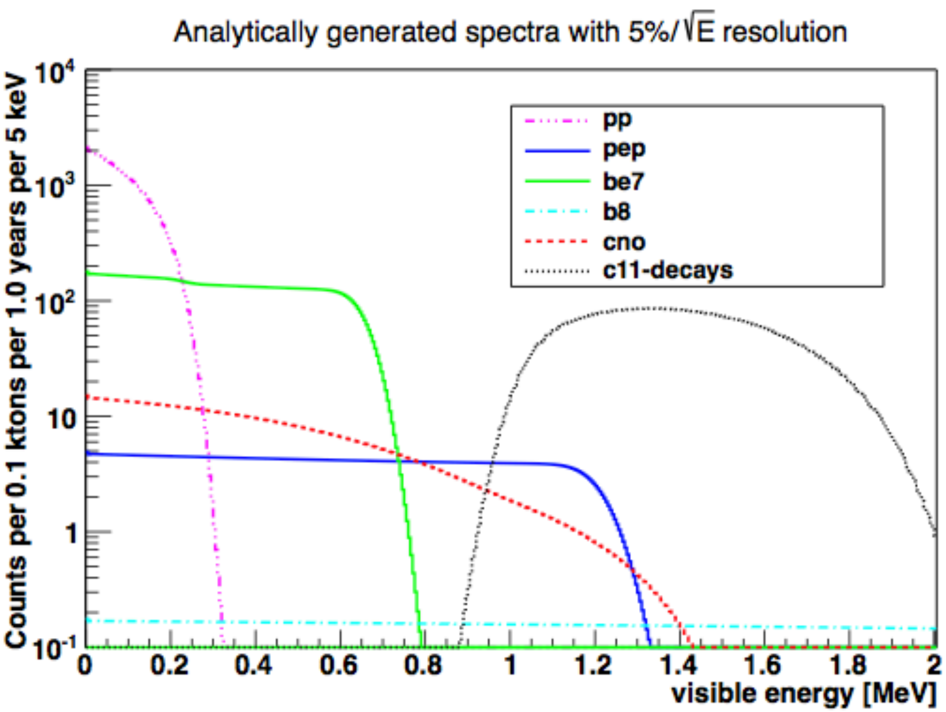
Low energy (<1MeV): Phase-averaged vacuum oscillations



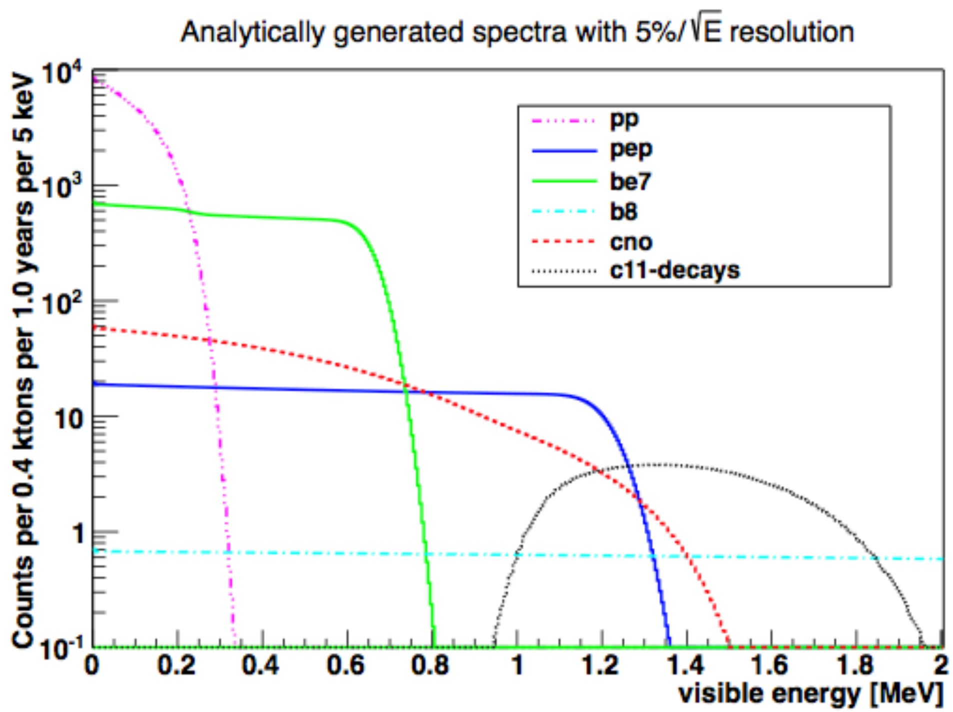
'High' energy (>5MeV): Matter-dominated resonant conversion

A matter of depth

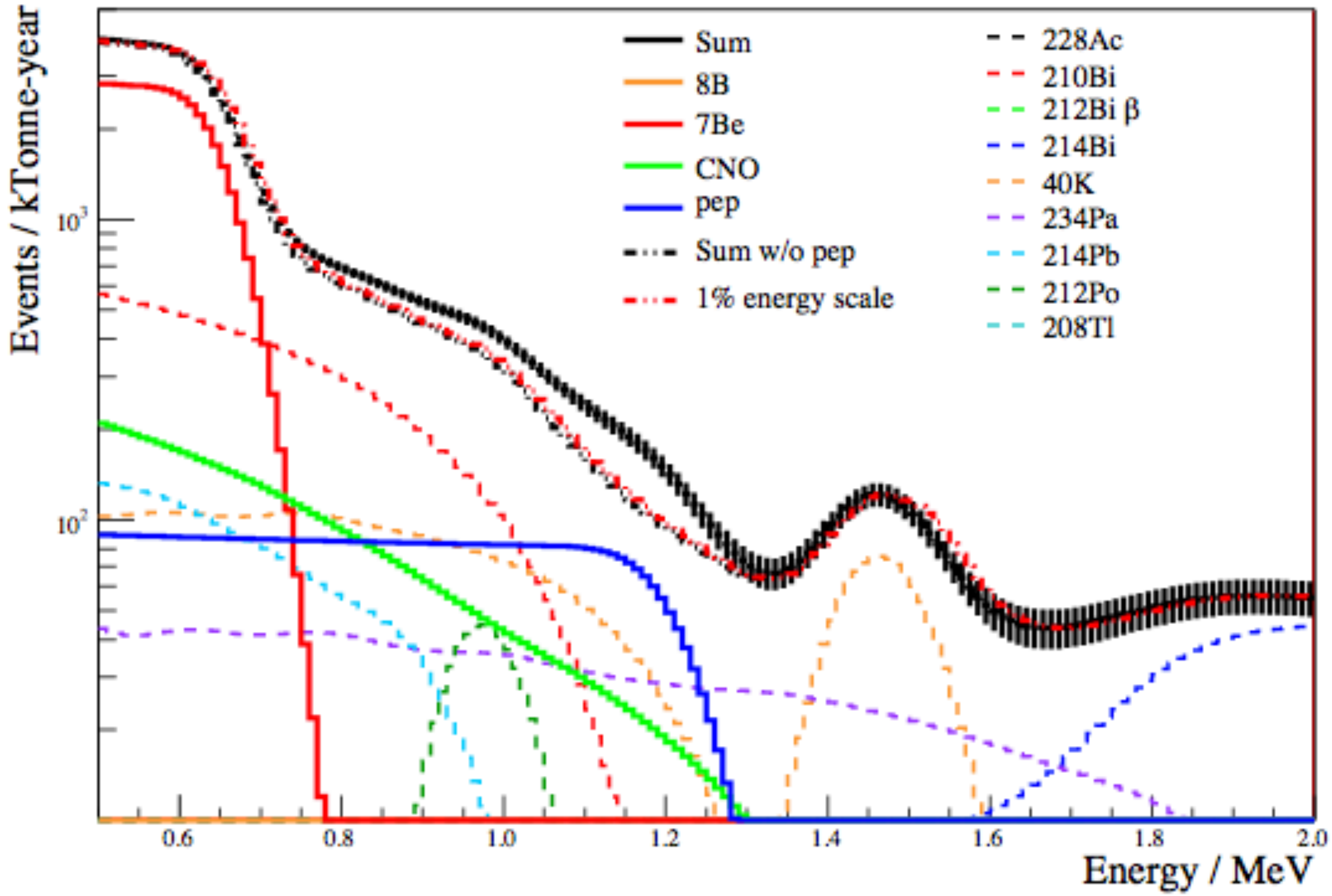
Borexino



SNO+



SNO+ solar signals

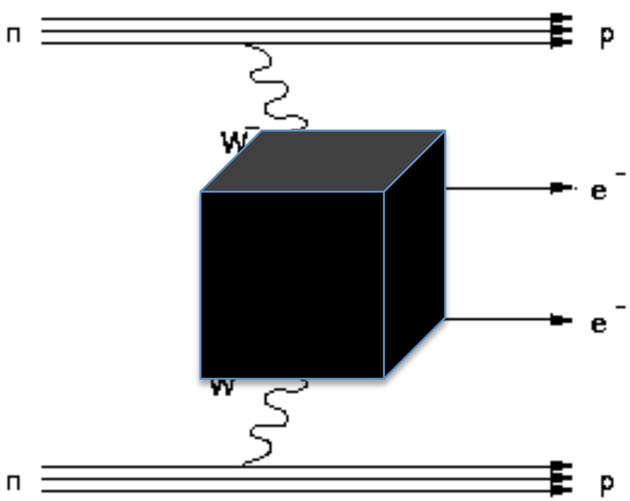


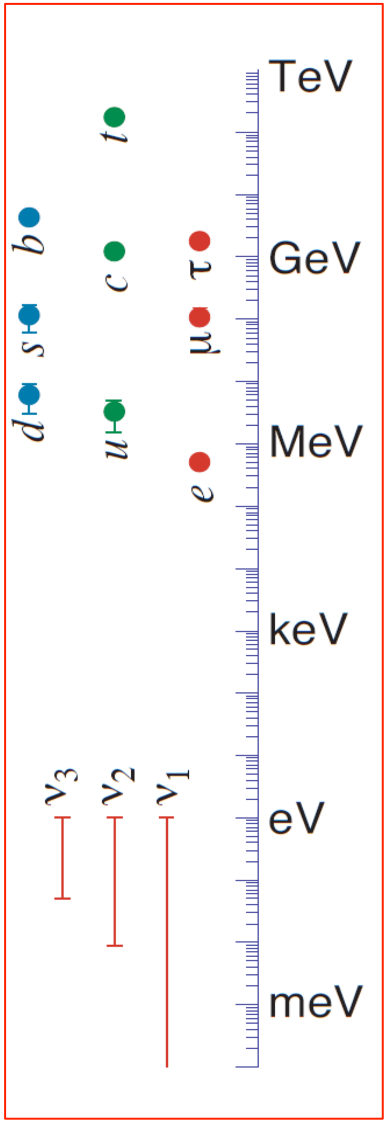
Solar Neutrinos

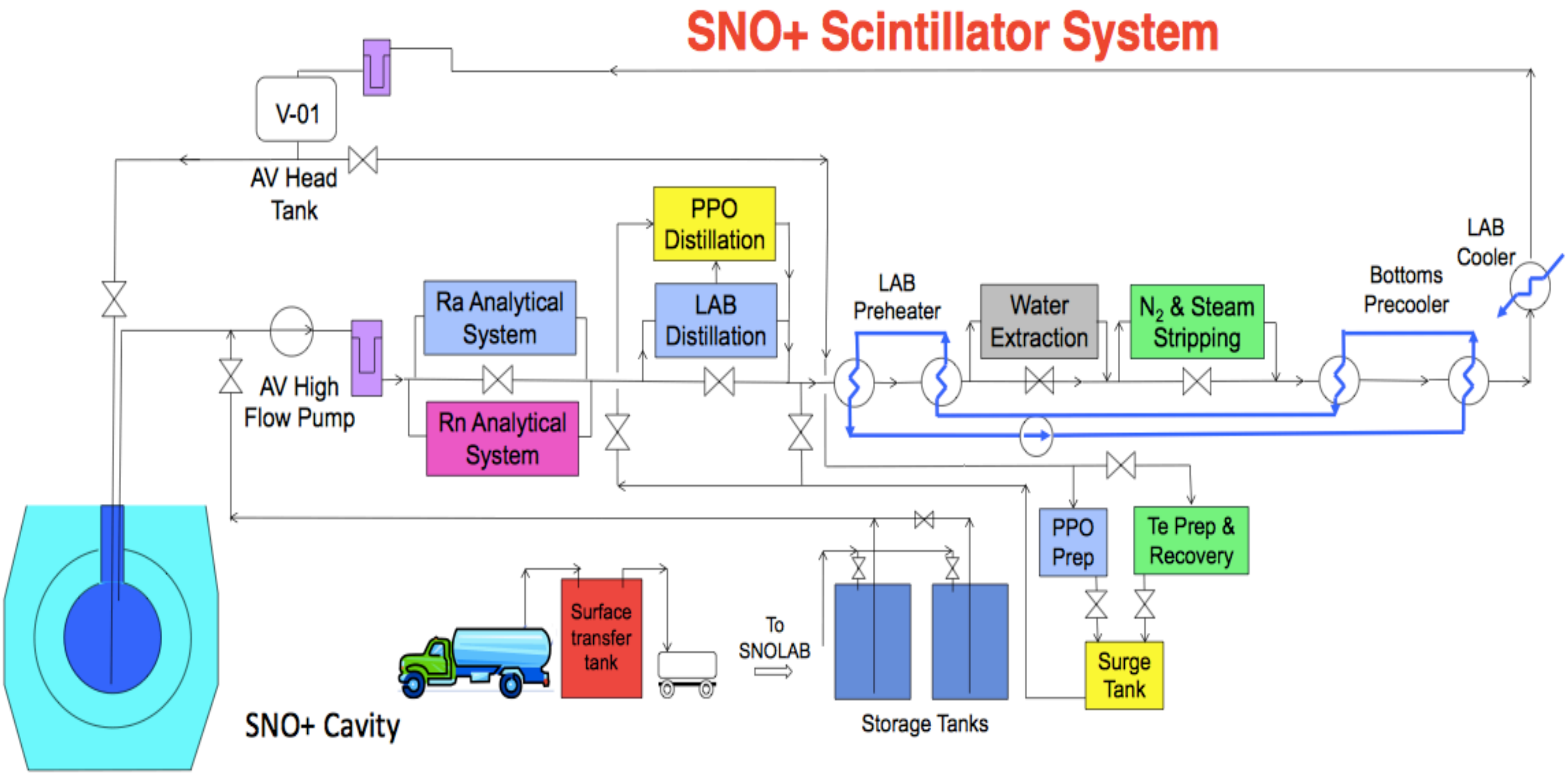
- SNO+ has decided to prioritise $0\nu\beta\beta$
- Radon daughters have accumulated on the surface of the AV over the last few years in a significant way. If these leach into the scintillator, the purification system has the capability to remove them.
- However, depending on the actual leach rate, that 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

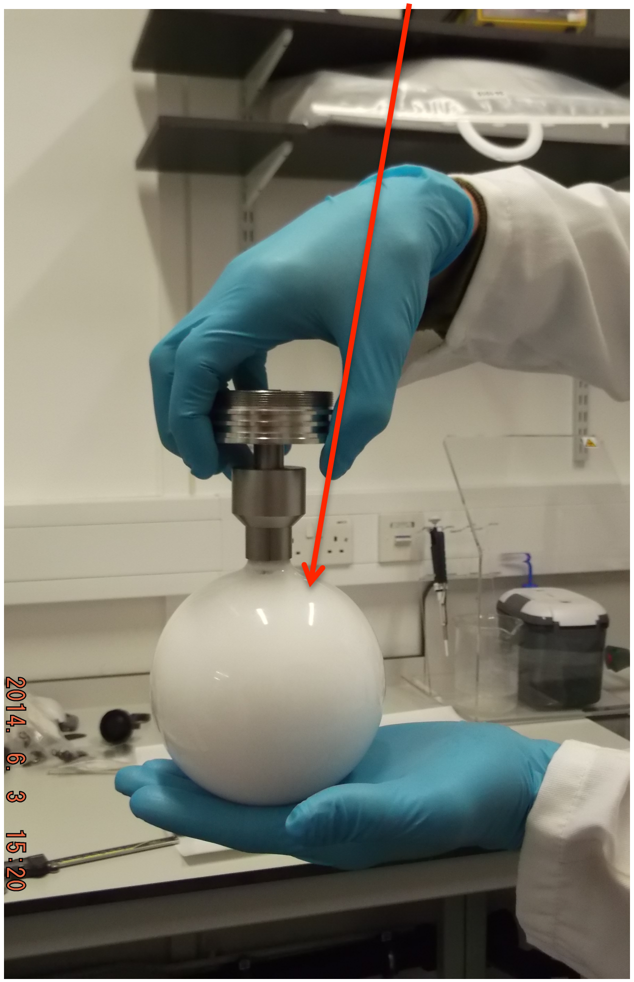


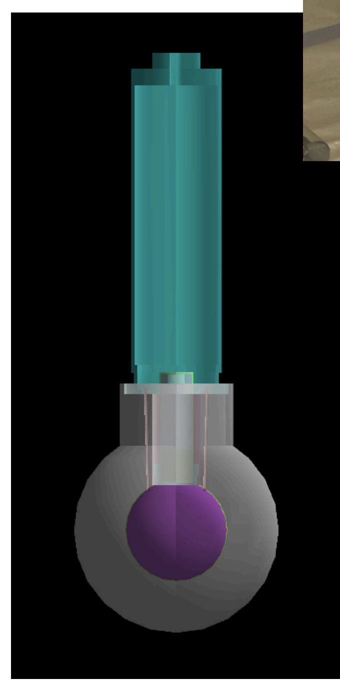


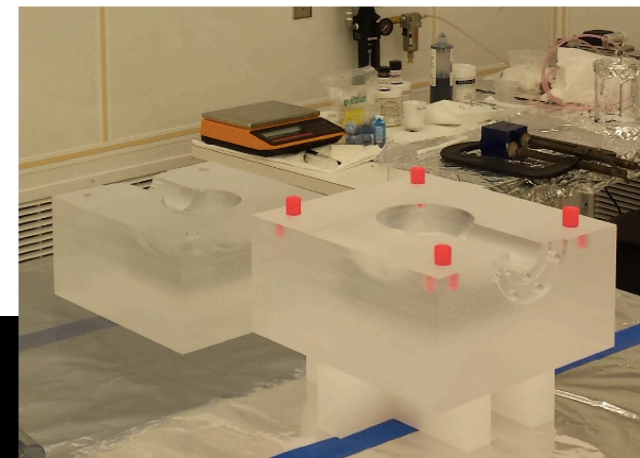

SNO+ Scintillator System
V-01
AV Head Tank
PPO Distillation
LAB Distillation
Ra Analytical System
Rn Analytical System
AV High Flow Pump
LAB Preheater
Water Extraction
N_2 & Steam Stripping
Bottoms Precooler
LAB Cooler
PPO Prep
Te Prep & Recovery
Surge Tank
Surface transfer tank
To SNOLAB
Storage Tanks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

Calibration

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

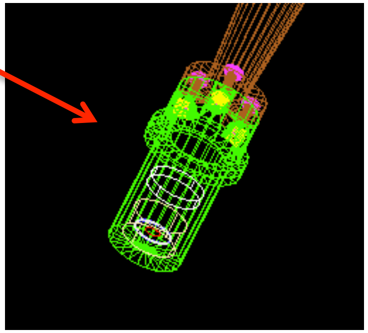


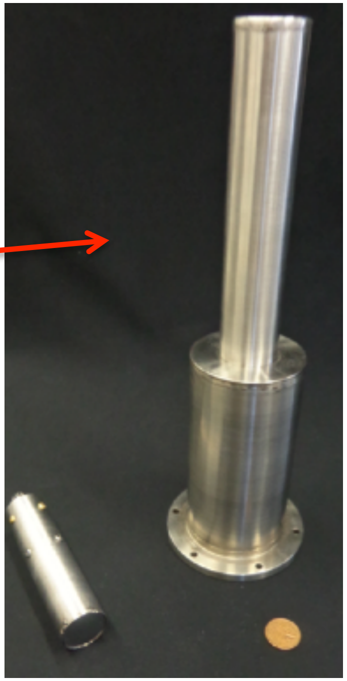


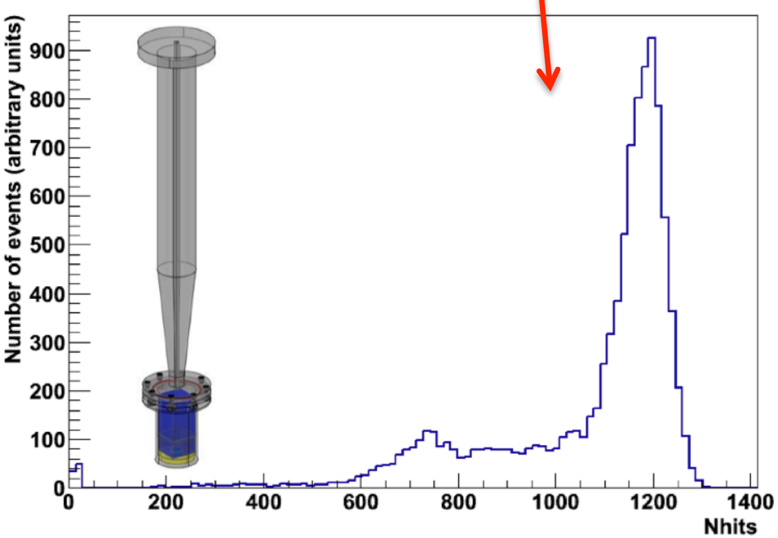


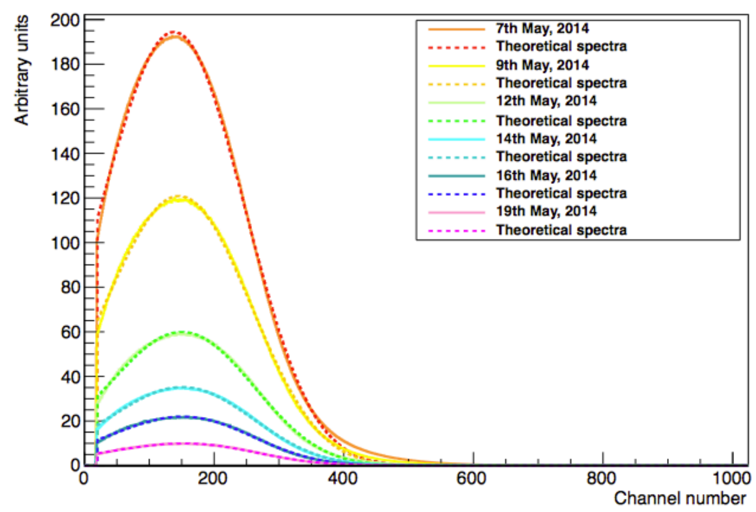
Calibration

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



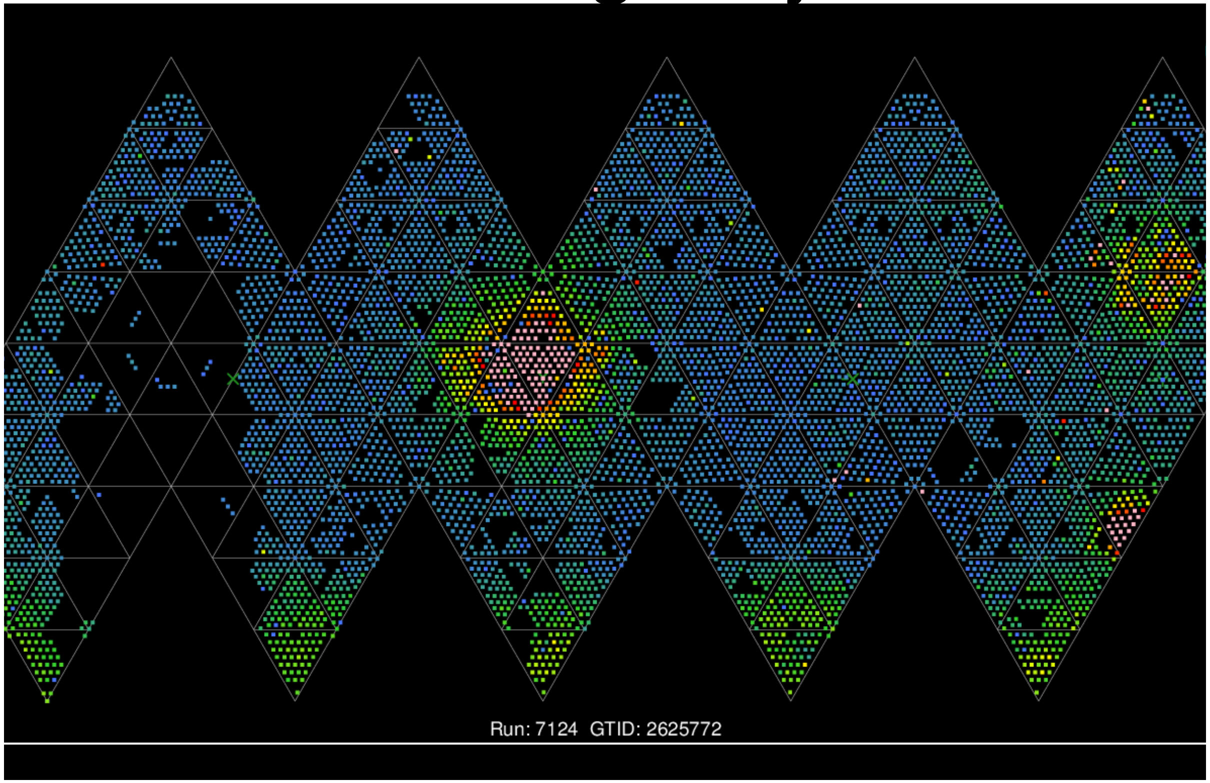






Calibration

- 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

pH Selective Telluric Acid Recrystallisation

- Telluric acid obeys the following equilibrium:

$$\underset{\text{Insoluble}}{Te(OH)_6} \longleftrightarrow \underset{\text{Soluble}}{Te(OH)_5O^-} + H^+$$

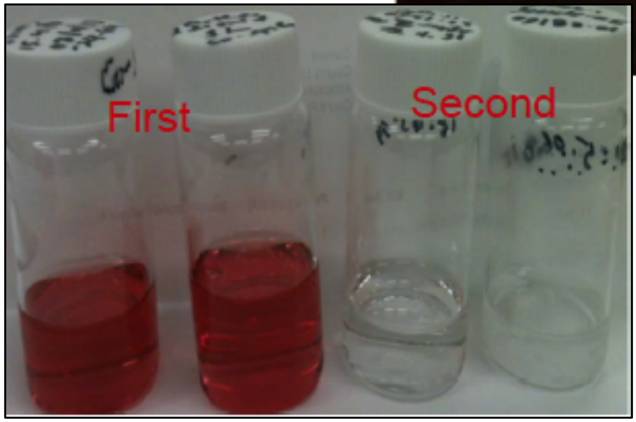
  - pH determines the equilibrium state

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.

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