$0\nu\beta\beta$ experiments and SNO+

Jeanne Wilson

NExT meeting

4/5/11 Southampton

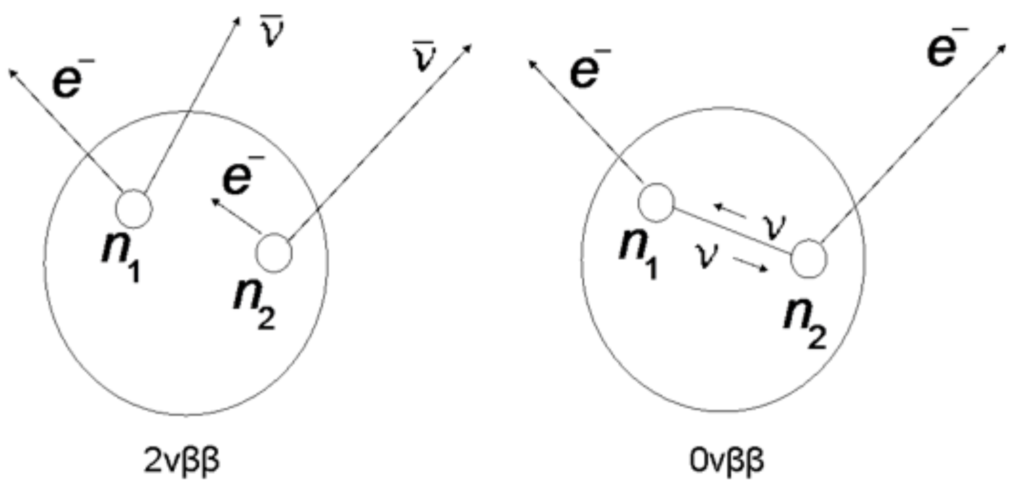
Contents

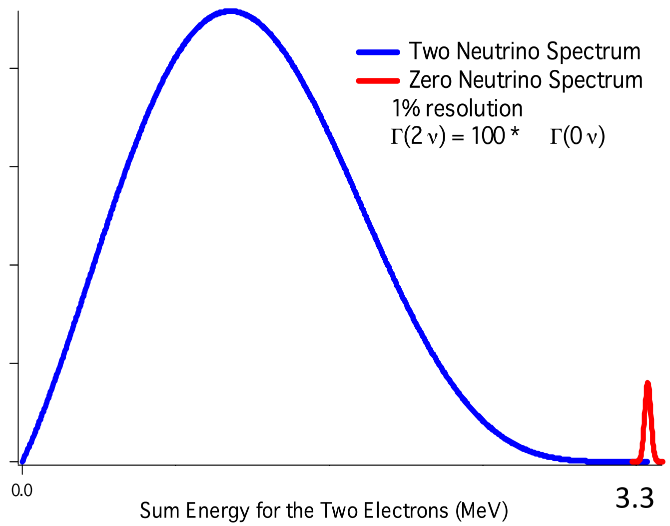
- 0νββ and what it can tell us
- Uncertainties
- Experimental Approaches
- Current Experimental status
- SNO+ 0νββ

Neutrino-less Double Beta Decay

- Is the neutrino a Majorana particle?
- What is the absolute neutrino mass scale?
- Neutrino mass hierarchy

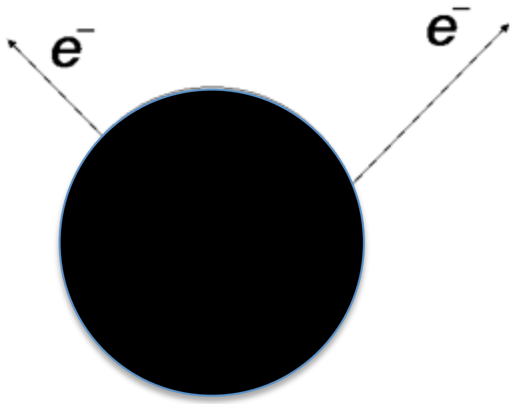
Key inputs to Grand Unified Theories





- Can only occur for 35 known isotopes
- $\Delta L = 2$ units

Uncertainties 1: Mechanism



0νββ

$$\text{Majorana}: \begin{pmatrix} \nu_\uparrow \\ \nu_\downarrow \end{pmatrix} \qquad \textit{Dirac}: \begin{pmatrix} \nu_\uparrow \\ \nu_\downarrow \\ \bar{\nu}_\downarrow \\ \bar{\nu}_\uparrow \end{pmatrix}$$

- Light neutrino exchange

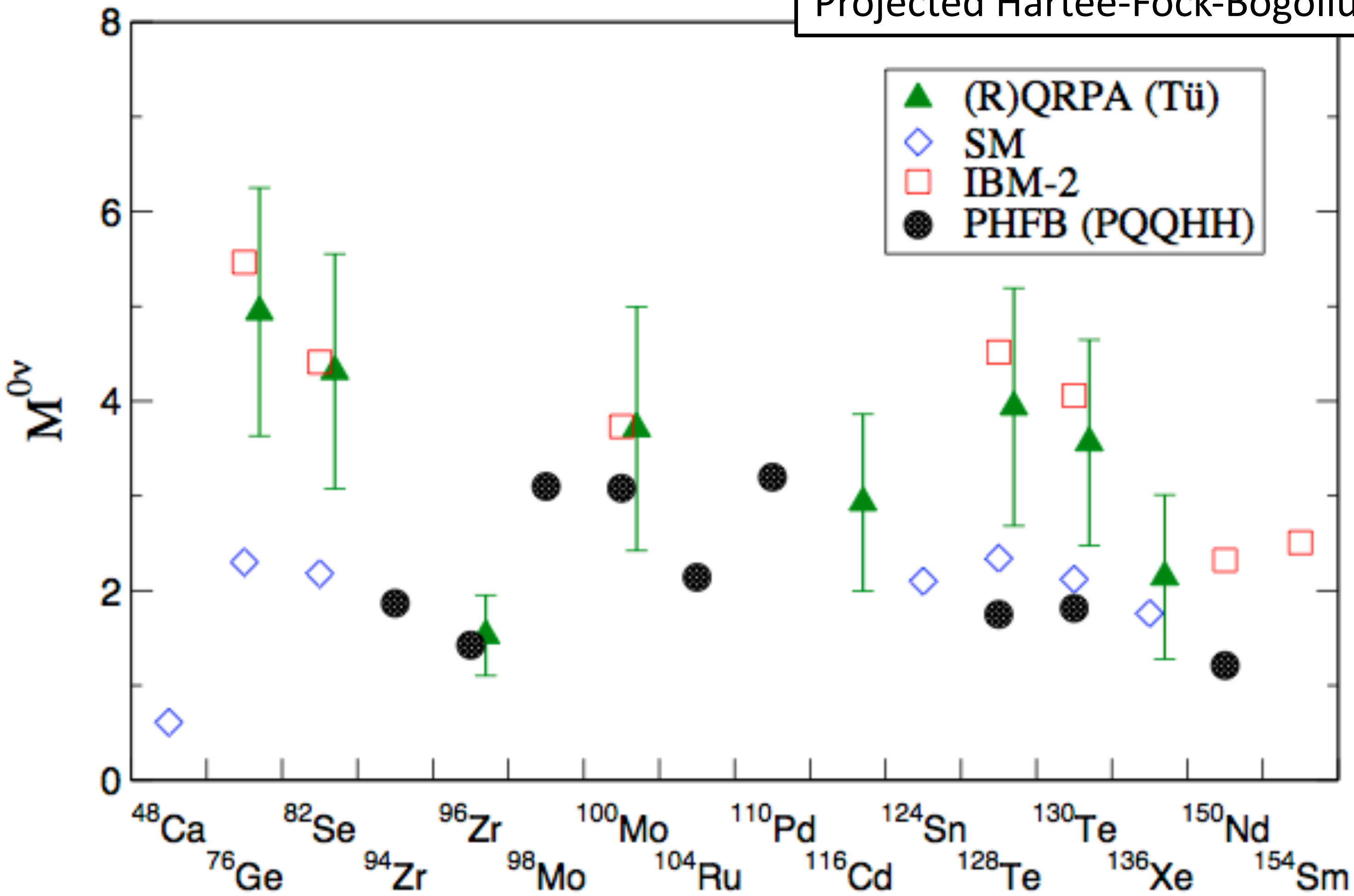
Schechter-Valle theorem:

Any mechanism inducing the 0νββ decay produces an effective Majorana mass for the neutrino, which must therefore contribute to this decay.

Uncertainties 2 : Matrix element

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

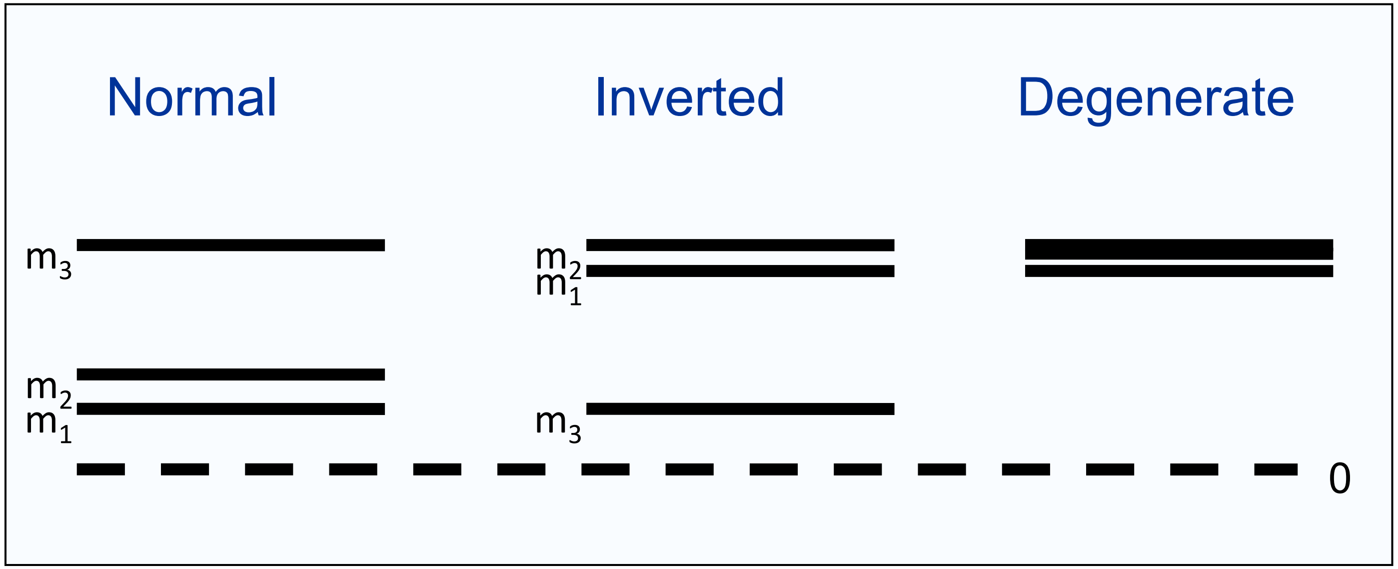
Quasi-particle Random Phase Approximation
Shell Model
Interacting Boson Model
Projected Hartee-Fock-Bogoliubov Approach



Faessler (2011) J. Phys: Conf Ser. 267 012059

Neutrino Mass

- Oscillations $\Delta m_{23} \approx 2.32\ .\ 10^{-3}\ eV^2$ -> ≈50meV



- Tritium decay $m_{ve} < 2.3eV$

$$m_{\nu_e}^2 = \sum_i |U_{ei}|^2 \cdot m_{\nu_i}^2$$

- 0νββ evidence $\langle m_\nu \rangle = 0.2\text{-}0.6\ eV$

$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 \cdot m_{\nu_i} \right|$$

H.V. Klapdor-Kleingrothaus et al., Phys. Lett. B586 (2004) 198-212

Neutrino Masses

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \Rightarrow \frac{m_i^{\ 2}}{2E_\nu} \Rightarrow \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

$$U = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\beta_1} & 0 \\ 0 & 0 & e^{i\beta_2} \end{pmatrix}$$

Solar Atmospheric

Majorana : $U = U_{PMNS}\ \mathrm{diag}(1, e^{i\beta 1}, e^{i\beta 2})$

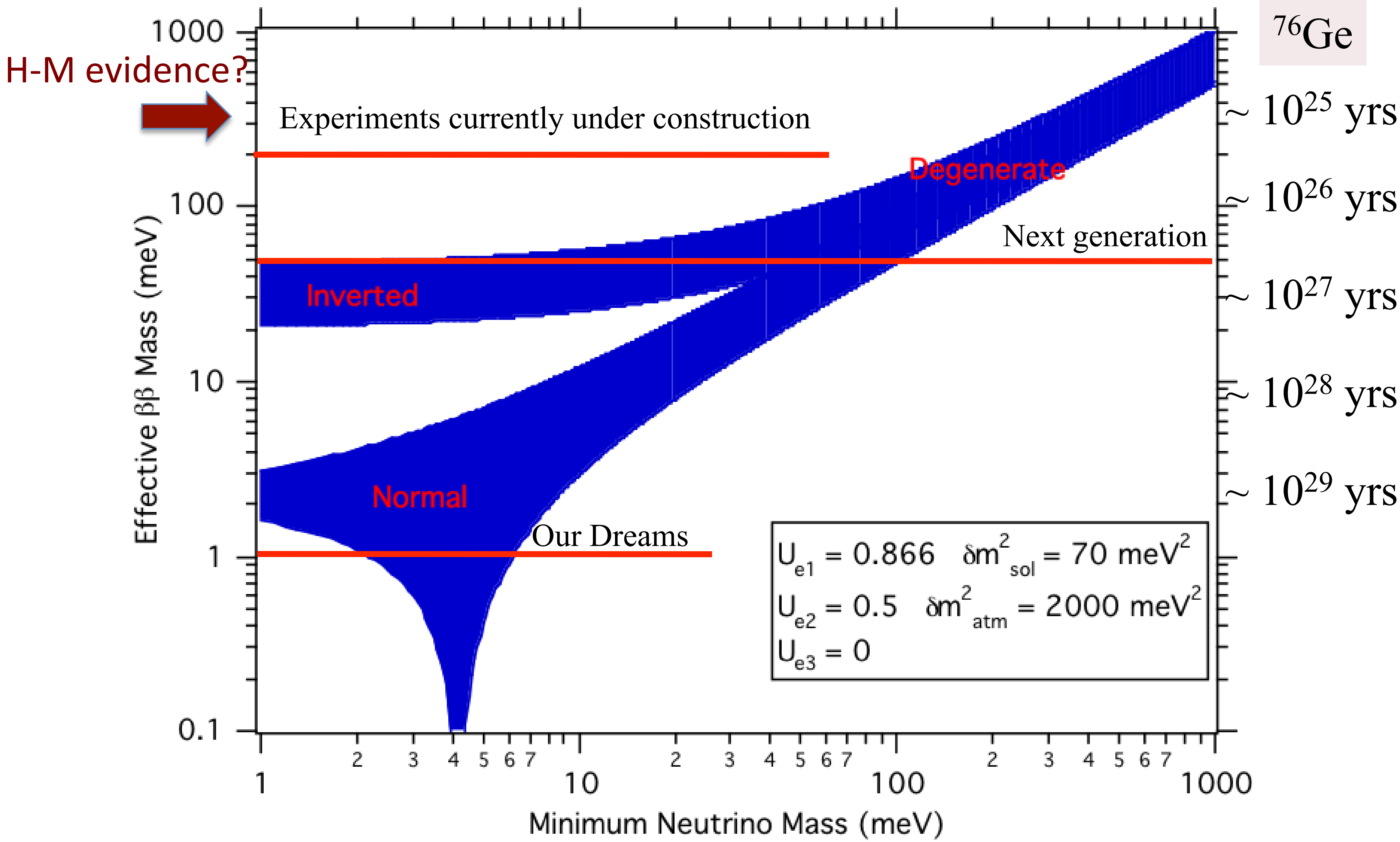
$$\langle m \rangle \equiv m_{ee} = \left| {}_k\ U_{ek}^2 m_k \right| = \left| {}_k\ |U_{ek}|^2 e^{i\ {}_{ek}} m_k \right|$$

$$m_{ee} = U_{e1}^{\ 2} m_1 \pm U_{e2}^{\ 2} m_2 \pm U_{e3}^{\ 2} m_3$$

Neutrino Mass

1) Test KK claim and degenerate heirarchy
   - $m_{\beta\beta}$ < 200meV, ~10s kg isotope
2) Test 50meV range and start probing inverted heirarchy
   - $m_{\beta\beta}$ < 50meV, 100s kg isotope
3) To probe into normal heirarchy region need tonnes of isotope

Allowed phase space



Current 0νββ Limits

Isotope	$T_{1/2}$ (years)	$\langle m_\nu \rangle$ eV	Experiment
^{76}Ge	$> 1.9 \cdot 10^{25}$	< 0.22 – 0.41	HM
	$= 1.2 \cdot 10^{25}$	= 0.28 – 0.52	KK (part HM)
	$= 2.2 \cdot 10^{25}$	= 0.21 – 0.38	KK (part HM)
	$> 1.6 \cdot 10^{25}$	< 0.24 – 0.44	IGEX
^{130}Te	$> 2.8 \cdot 10^{24}$	< 0.35 – 0.59	CUORICINO
^{100}Mo	$> 1.1 \cdot 10^{24}$	< 0.45 – 0.93	NEMO-3
^{82}Se	$> 3.6 \cdot 10^{23}$	< 1.89 – 1.61	NEMO-3
^{116}Cd	$> 1.7 \cdot 10^{23}$	< 1.45 - 2.76	SOLOTVINO

Refs in arXiv: 1101.4502

Experimental Approaches

Maximise candidate isotope mass

Maximise measuring time

$$T_{1/2}^{0\nu} \propto \sqrt{\frac{M \times t}{B \times \Delta E}}$$

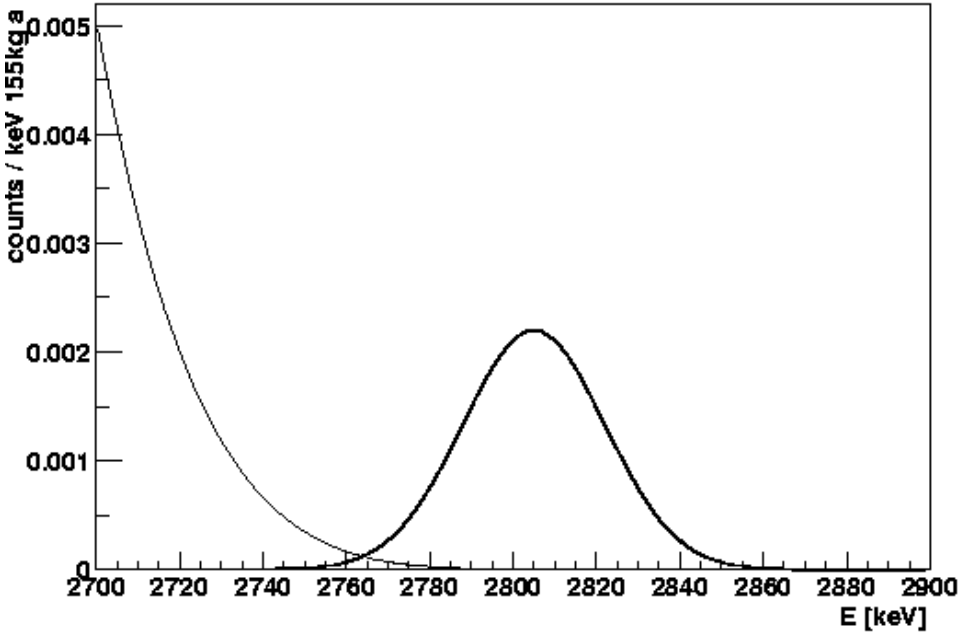
Minimise Background Level

Optimise Energy Resolution

- Large Mass, high isotopic abundance
- High Q value
- Good energy resolution
- Background rejection/Signal identification techniques
- Source = Detector

Common backgrounds: 2νββ Decays

- The ultimate, irreducible background



^{76}Ge (Diode) 0.2%

^{130}Te (Bolometer) 0.4%

^{136}Xe (gaseous TPC) 3.3%

CdZnTe (Semiconductor) 3-4%

Liquid scintillator ~5%

Plastic scintillator ~14%

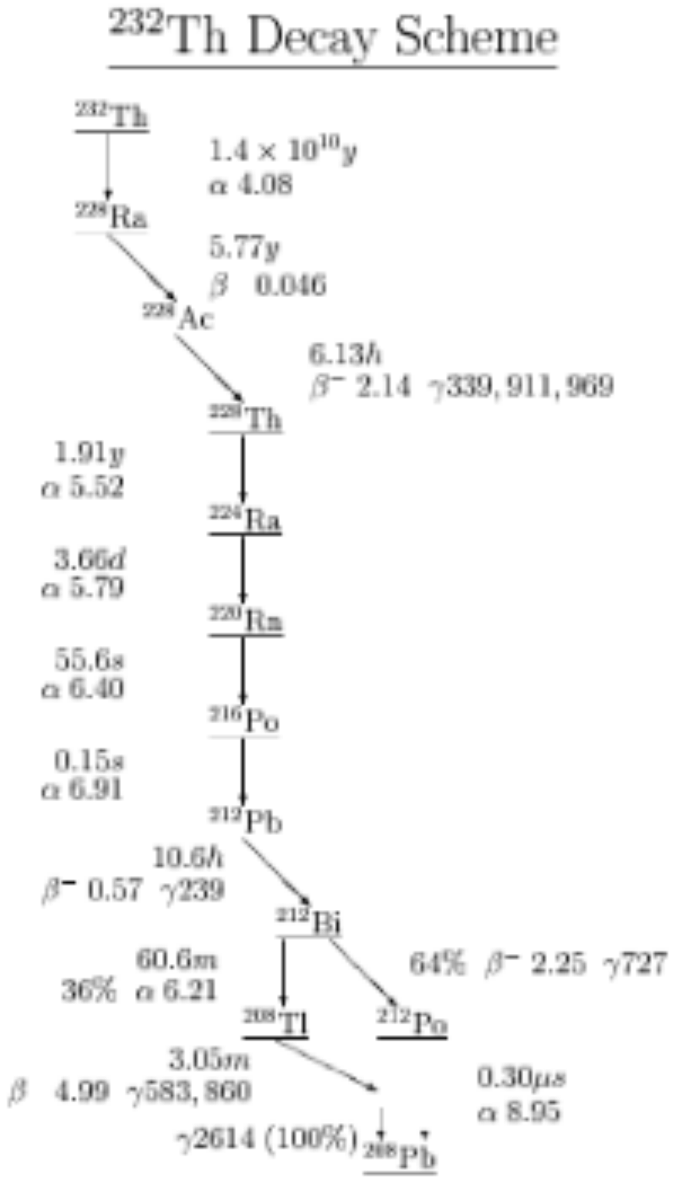
$$F = \frac{8Q(\Delta E / Q)^6}{m_e} = 3.7 * 10^{-10}$$

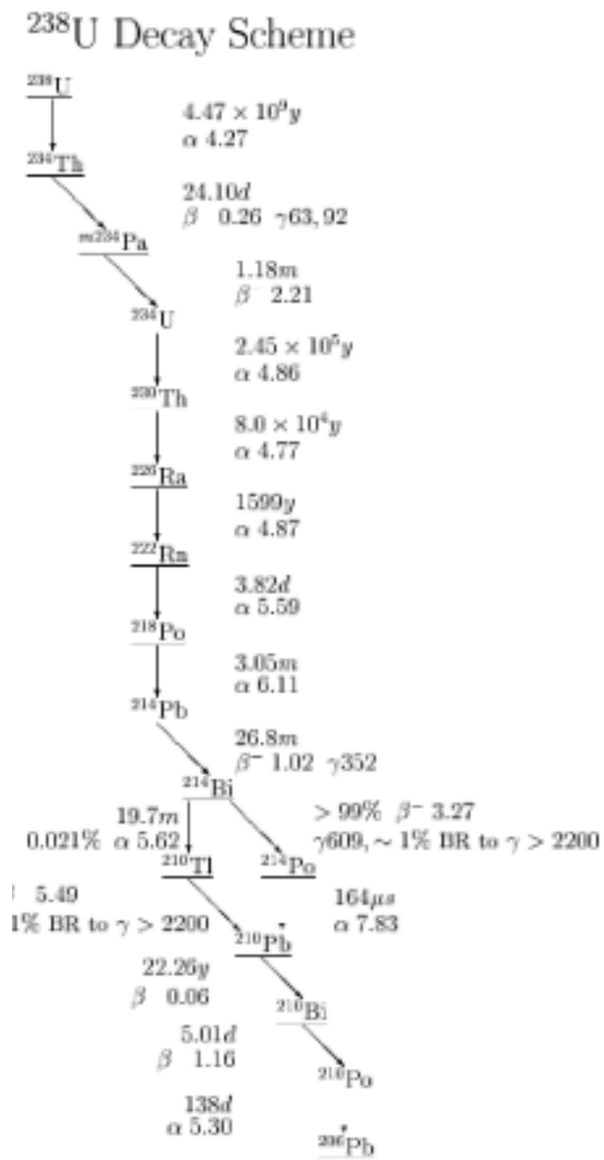
S. Elliott, P. Vogel, Ann. Rev. Nucl. Part. Sci. 2002

Common Backgrounds ++

- Solar neutrinos
- Natural decay chains ^{238}U, ^{228}Th
  - Gammas up to 2.6MeV
  - αs up to 8.9MeV
  - βs up to 3.3MeV
- Cosmic ray muons
- Cosmogenic activation
- ^{235}U, ^{85}Kr

Natural Decay chains: U and Th



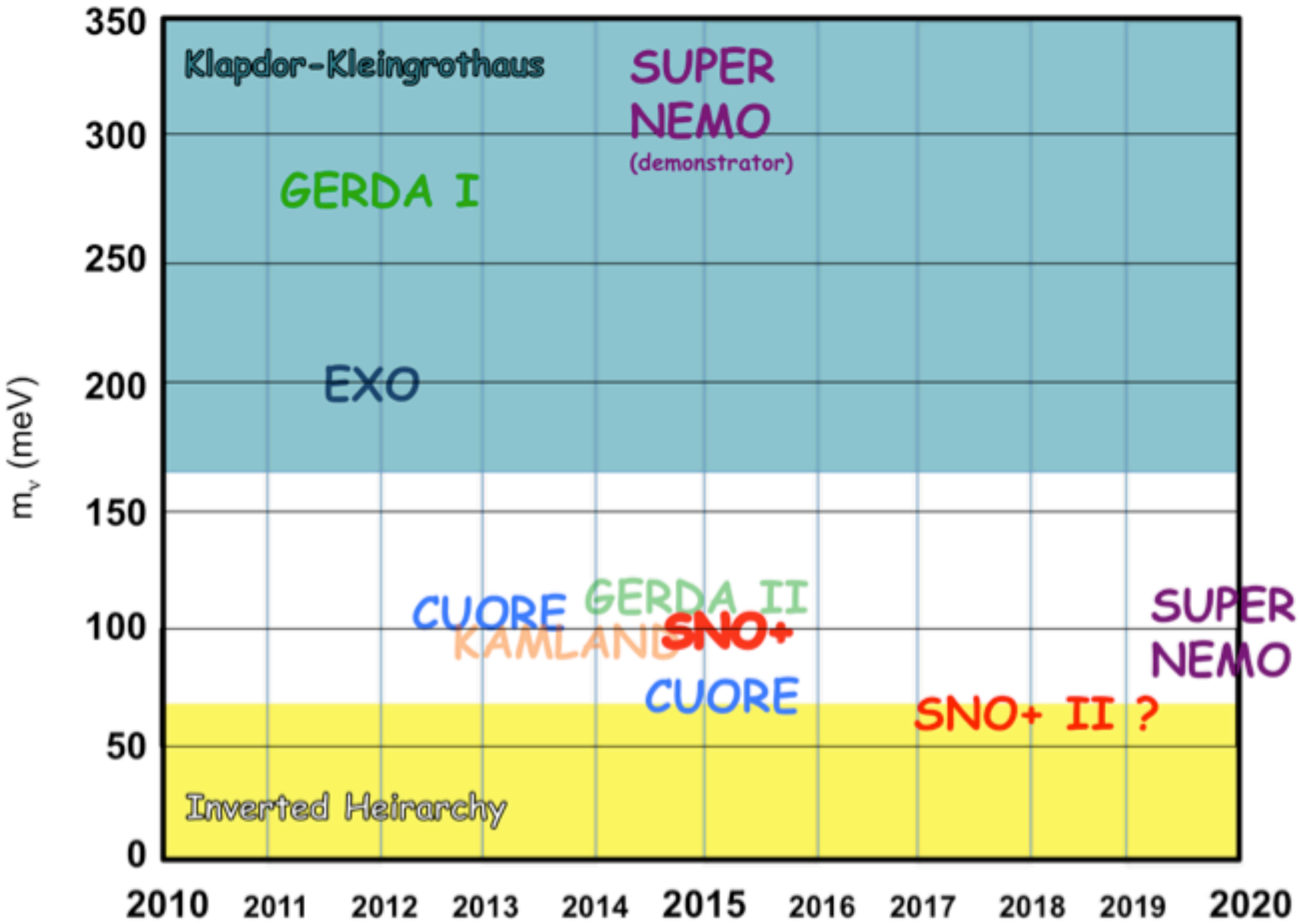


How can you be sure a signal is $0\nu\beta\beta$?

- Two techniques:
  1. Redundancy
  2. Redundancy

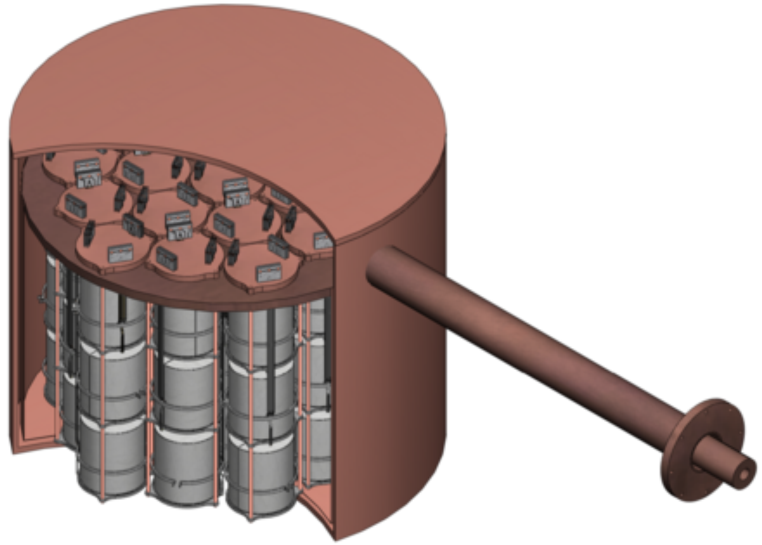
- Different isotopes with signals predicted at different energies, with different backgrounds, and different signal rates that scale correctly with the corresponding matrix elements.

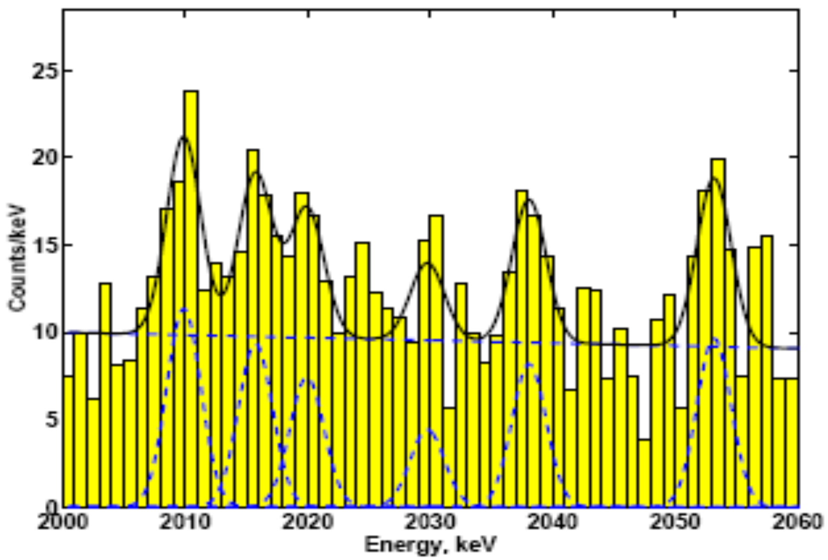
Developing Experiments



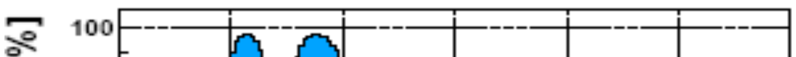
^{76}Ge semiconductors

- Old experiments: H-M, IGEX
- New: GERDA, Majorana
- Source = detector
- Q = 2.039MeV
- Cool to ~70K, ΔE≈0.2%



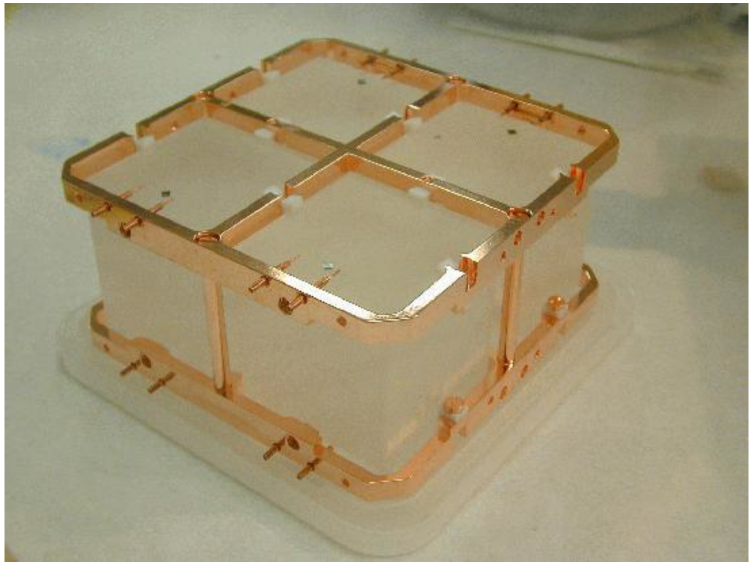


- Increased mass
- Liquid argon shielding
- Segmented detectors
- Improved production



Cuoricino ^{130}Te Bolometers

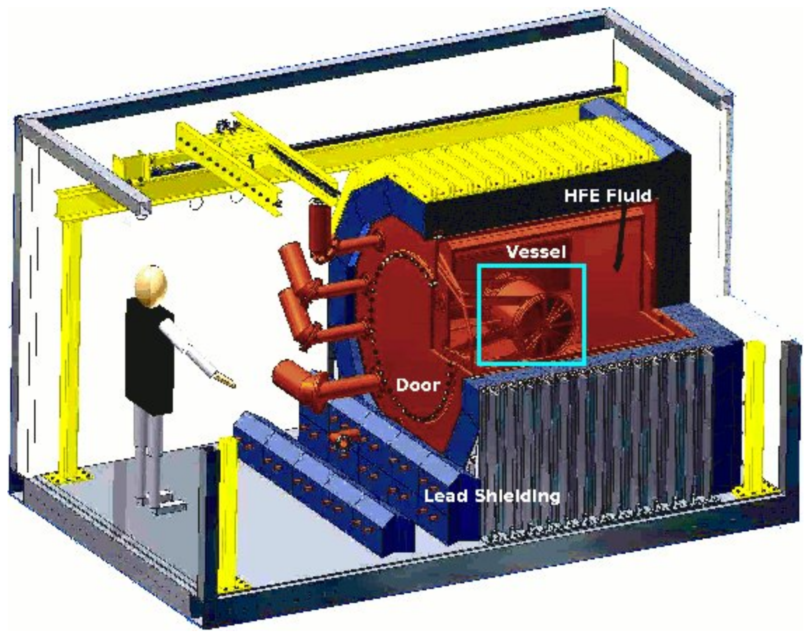
- Sensitivity 0.1-0.5eV
- Tower of enriched TeO_2 bolometers
- Cool to 10mK
- 11kg ^{130}Te isotope
- 30% natural abundance
- Q = 2.528MeV ΔE = 8keV



- Pilot for large scale CUORE experiment

EXO ^{136}Xe TPC

- Liquid Xe TPC in cryostat
  - Primary scintillation light
  - + Ionisation – drift electrons in electric field
- Easily enriched to 80% (Russian Centrifuges)
- Q = 2.48MeV
- 200kg prototype
- Tagging through Ba daughter

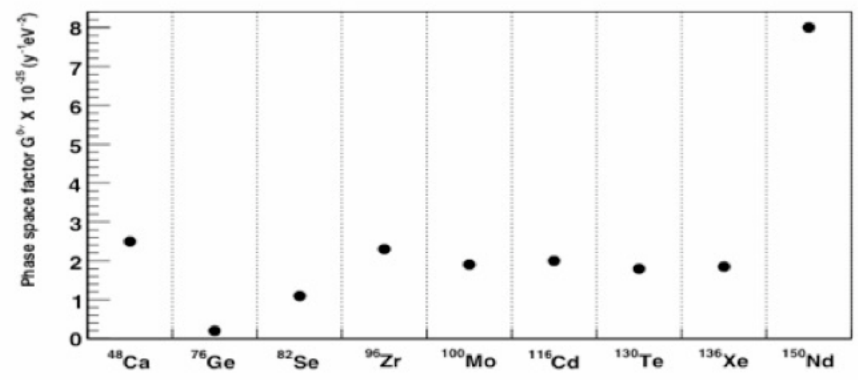


NEMO-3

- Thin films of candidate isotope in
- Wire tracking chamber
- Plastic scintillator calorimeters
- Event ID: 2 e^- tracks
- Poor energy resolution ~14%
- Source ≠ Detector
  - Harder to scale up sensitivity

- Pilot for SuperNEMO experiment
- 100kg ^{82}Se (or ^{150}Nd)

SNO+ Double Beta Decay

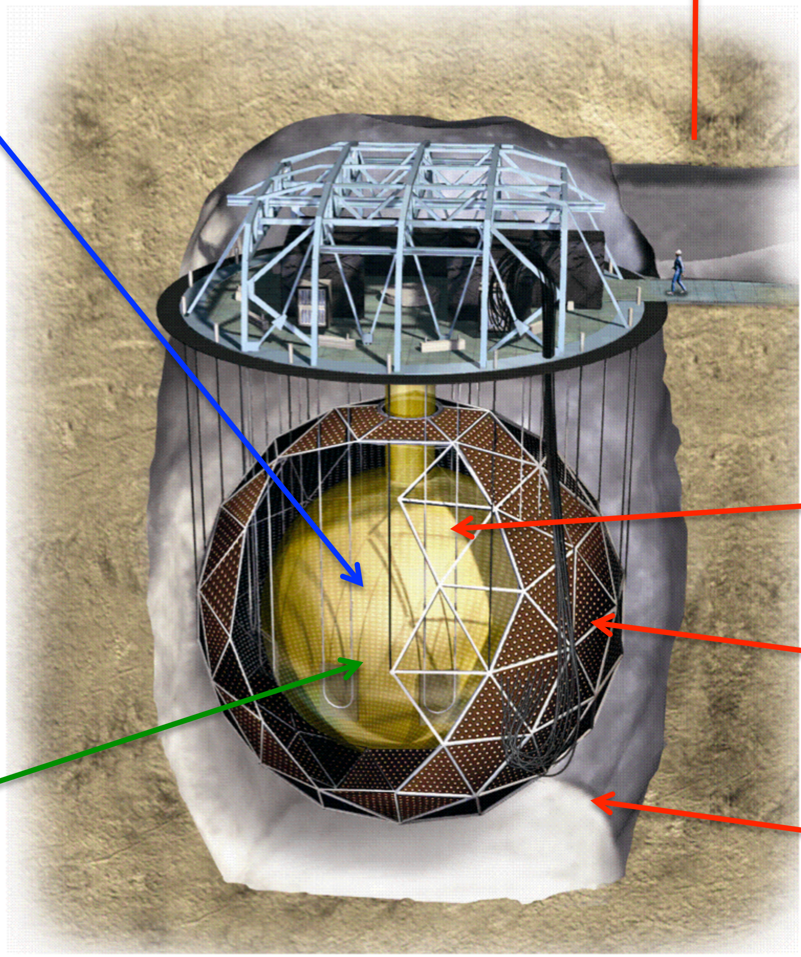


- ^{150}Nd
  - Q = 3.37MeV
  - largest phase space, fast rate
  - 5.6% natural abundance, enrichment possible
- Large, homogeneous liquid scintillator detector leads to well-defined background model
- Source in–source out capability
- ~5% energy resolution but high statistics

SNO+

2km underground, 6000 mwe
Ultra-low CR μ background

780 tonnes linear alkyl benzene (LAB) liquid scintillator
$<10^{-17}$ g/g U and Th



12m diameter acrylic vessel (AV)

~9000 PMTs

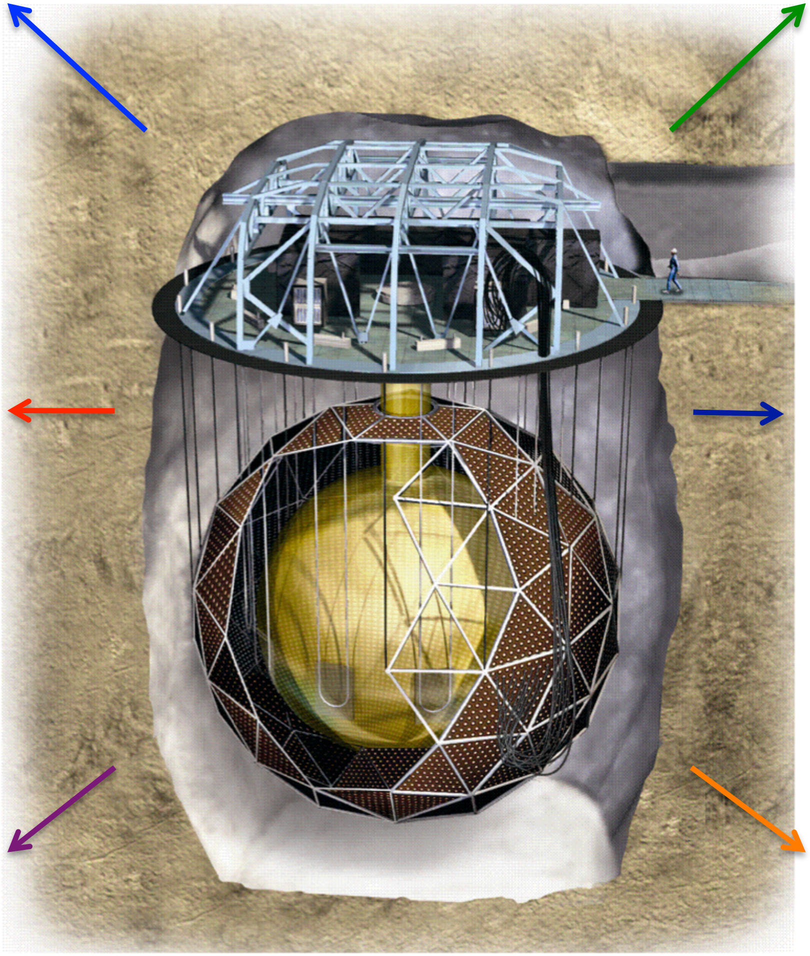
~7 ktonne H_2O shielding

~50kg ^{150}Nd loaded into the LAB
0νββ measurement

SNO+

First solar pep flux measurement.
Test of neutrino oscillation models and new physics

Search for Neutrino-less double beta decay.
Probe neutrino nature and mass.



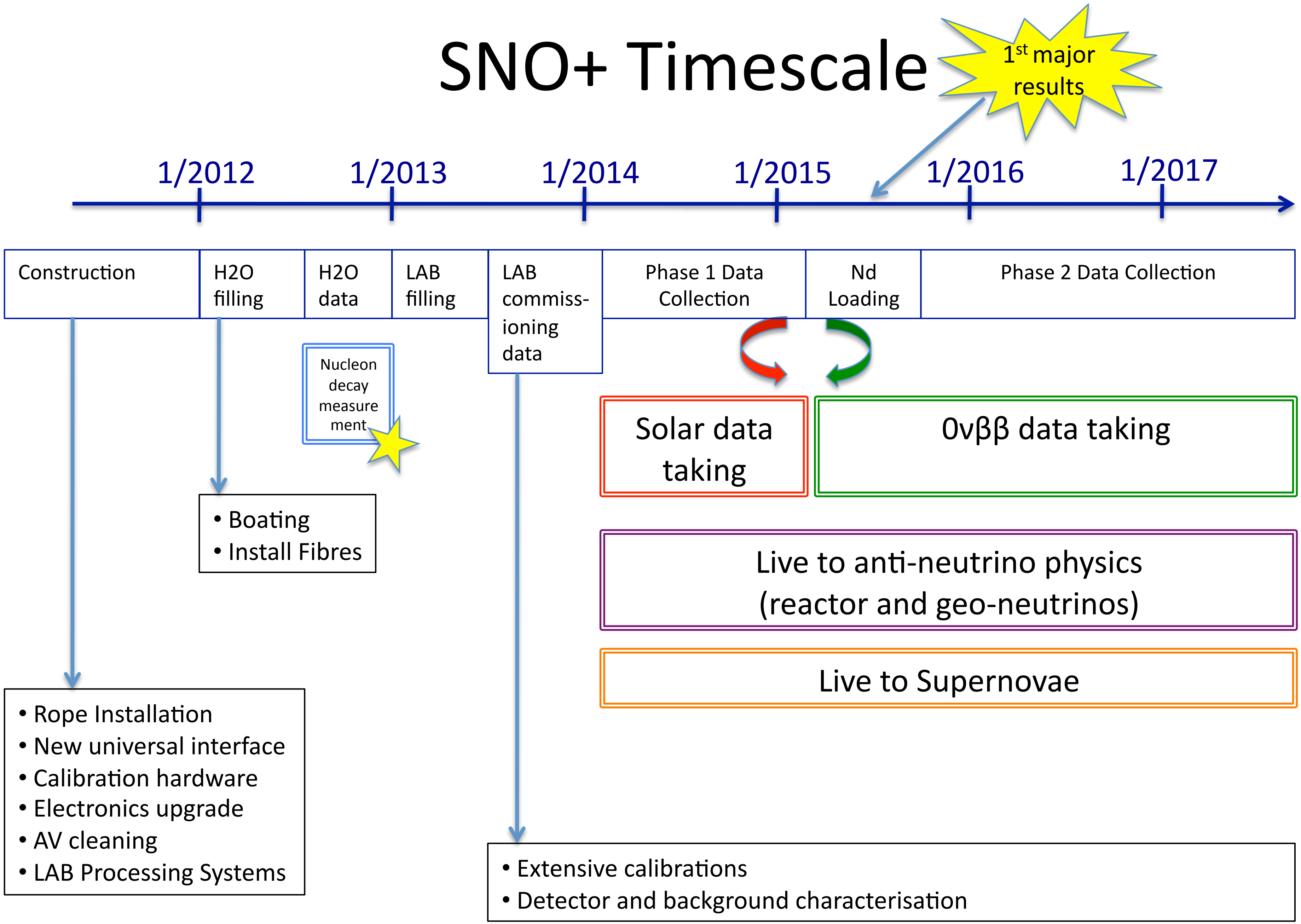
First solar CNO flux measurement.
Understanding of solar models

Inputs to 2νββ models and theory

Unique environment for other low energy physics:
reactor neutrinos,
geo-neutrinos,
supernova detection

Advancing detector technology:
LAB scintillator
Calibration techniques
Purification methods

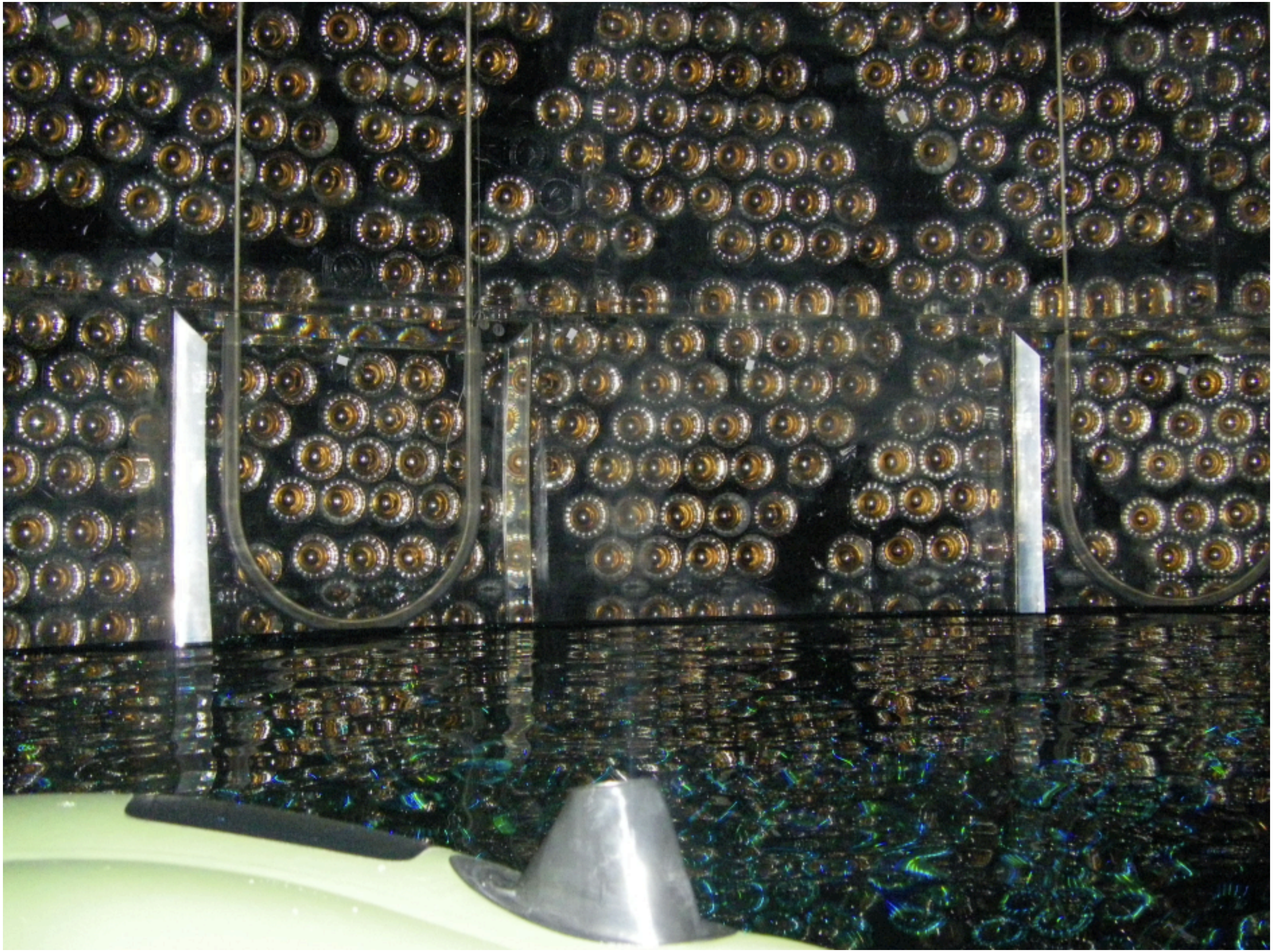
Not just a double beta experiment....

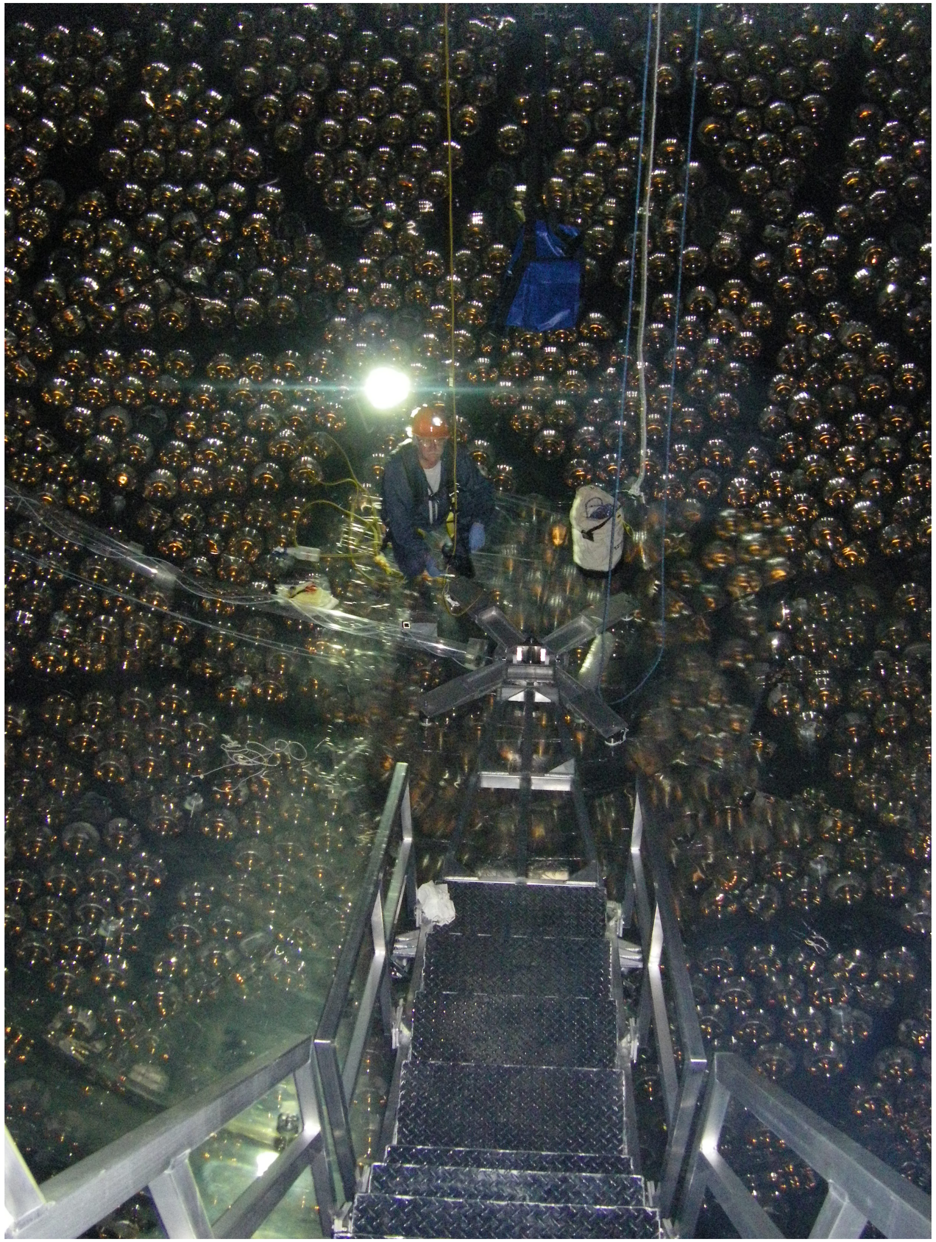


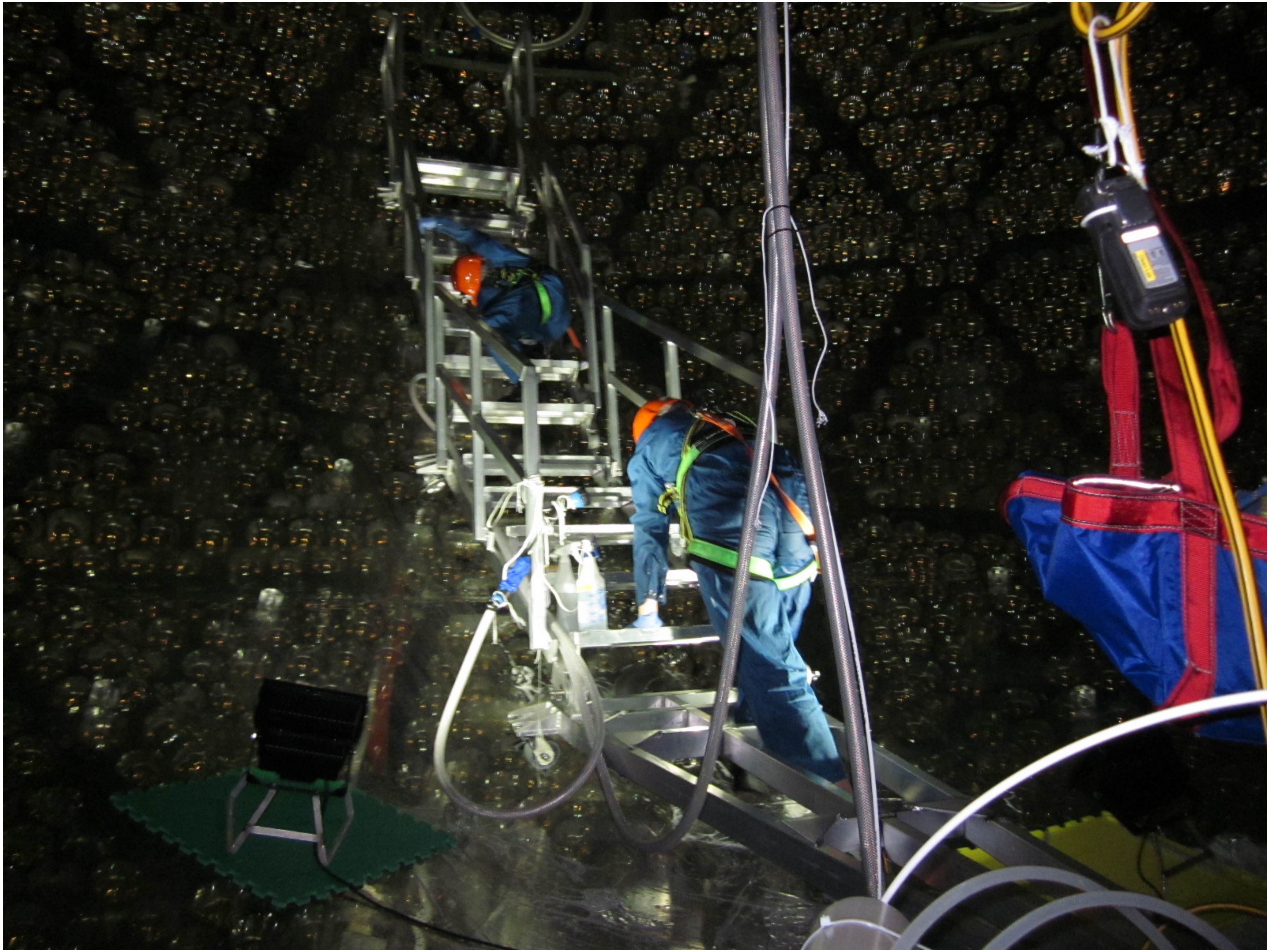
SNO+ Timescale
1st major results
1/2012
1/2013
1/2014
1/2015
1/2016
1/2017
Construction
H2O filling
H2O data
LAB filling
LAB commiss-ioning data
Phase 1 Data Collection
Nd Loading
Phase 2 Data Collection
Nucleon decay measure ment
Solar data taking
0νββ data taking
Live to anti-neutrino physics (reactor and geo-neutrinos)
Live to Supernovae
• Boating
• Install Fibres
• Rope Installation
• New universal interface
• Calibration hardware
• Electronics upgrade
• AV cleaning
• LAB Processing Systems
• Extensive calibrations
• Detector and background characterisation

Converting SNO to SNO+

- Hold-down ropes
- Wear and Tear repairs and surveys
- Upgraded electronics
- Upgraded calibration hardware
- New fluid processing systems

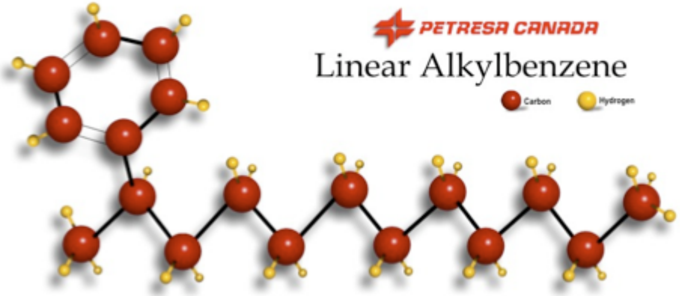




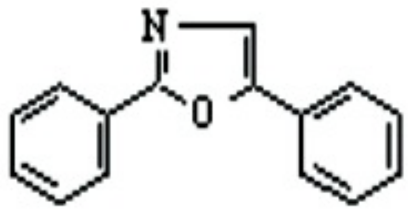


SNO+ Liquid scintillator

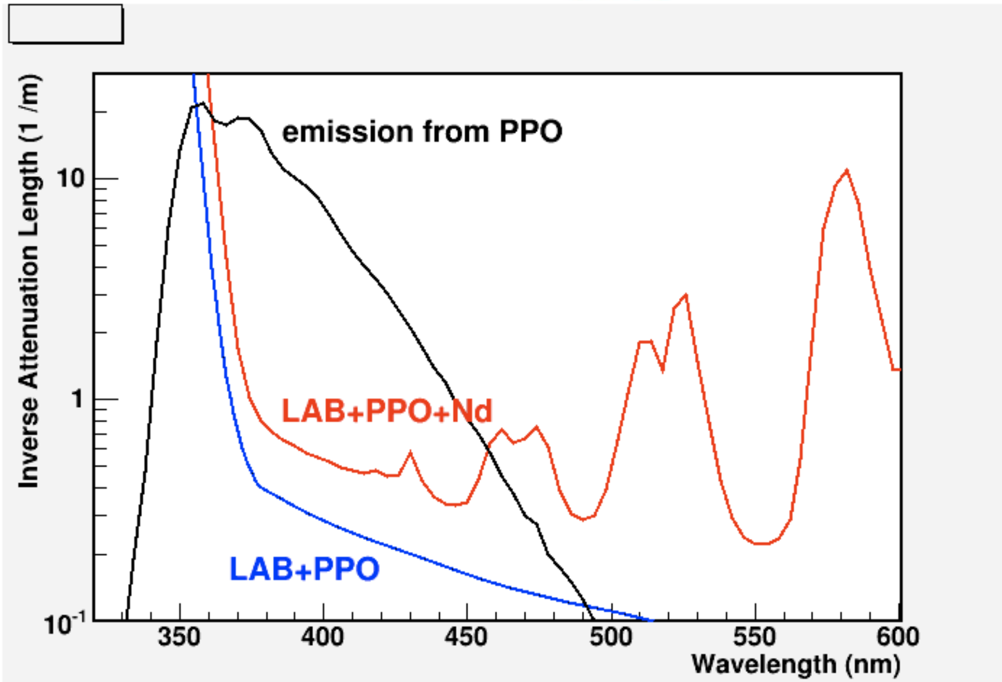
- Cheap
- Safe: high flash point, low toxicity
- Compatible with SNO acrylic
- ~400 hits / MeV, ΔE ≈5%
- Nd-carboxylate solutions have been stable at 0.1% and 1% concentrations for over 3.5 years.



+ PPO



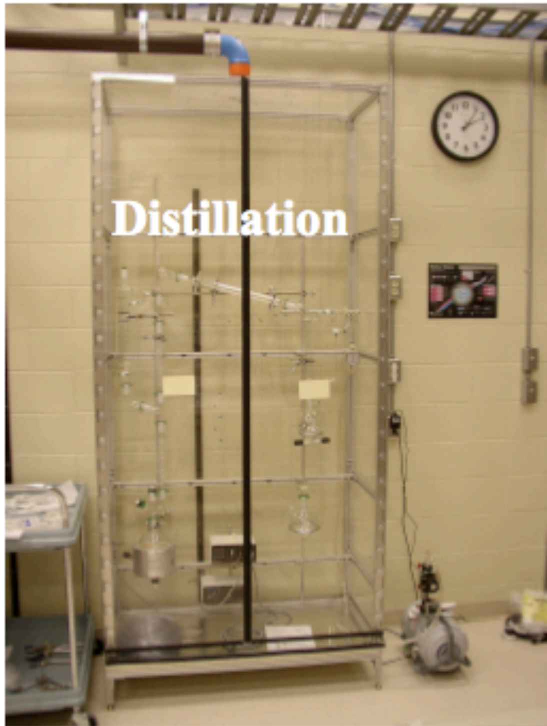
2,5-Diphenyloxazole

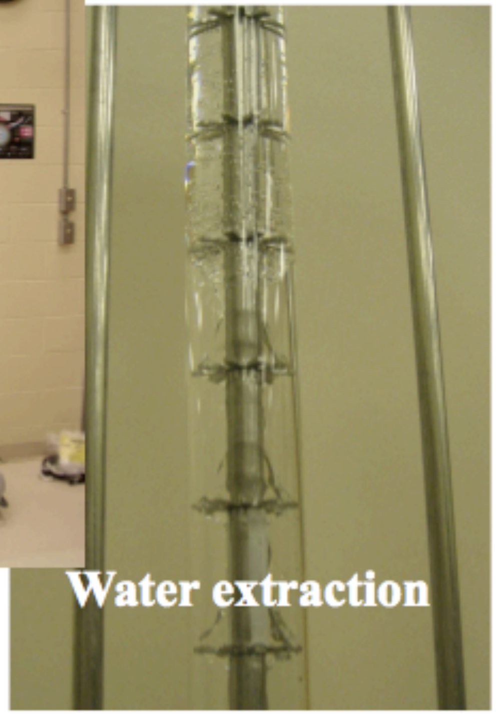


Purification Systems

- Several fluids to handle
  - Light water
  - Bulk scintillator
  - Fluor (PPO) solution
  - Neodymium-loaded compound
- Scintillator plant
  - Distillation
  - Water extraction
  - Gas removal
  - Filtration and ultra-filtration
  - R&d on metal scavenger columns
- Goals
  - Scintillator purity of 1×10^{-17} g/g U/Th
    - Reached by Borexino
    - C-14,Kr-85 not a problem because of low energy, C-11 not a problem because of depth
  - Nd-compound purity of < 1×10^{-14} g/g U/Th
    - Need factor of 10^6 reduction

Test plants at SNOLAB

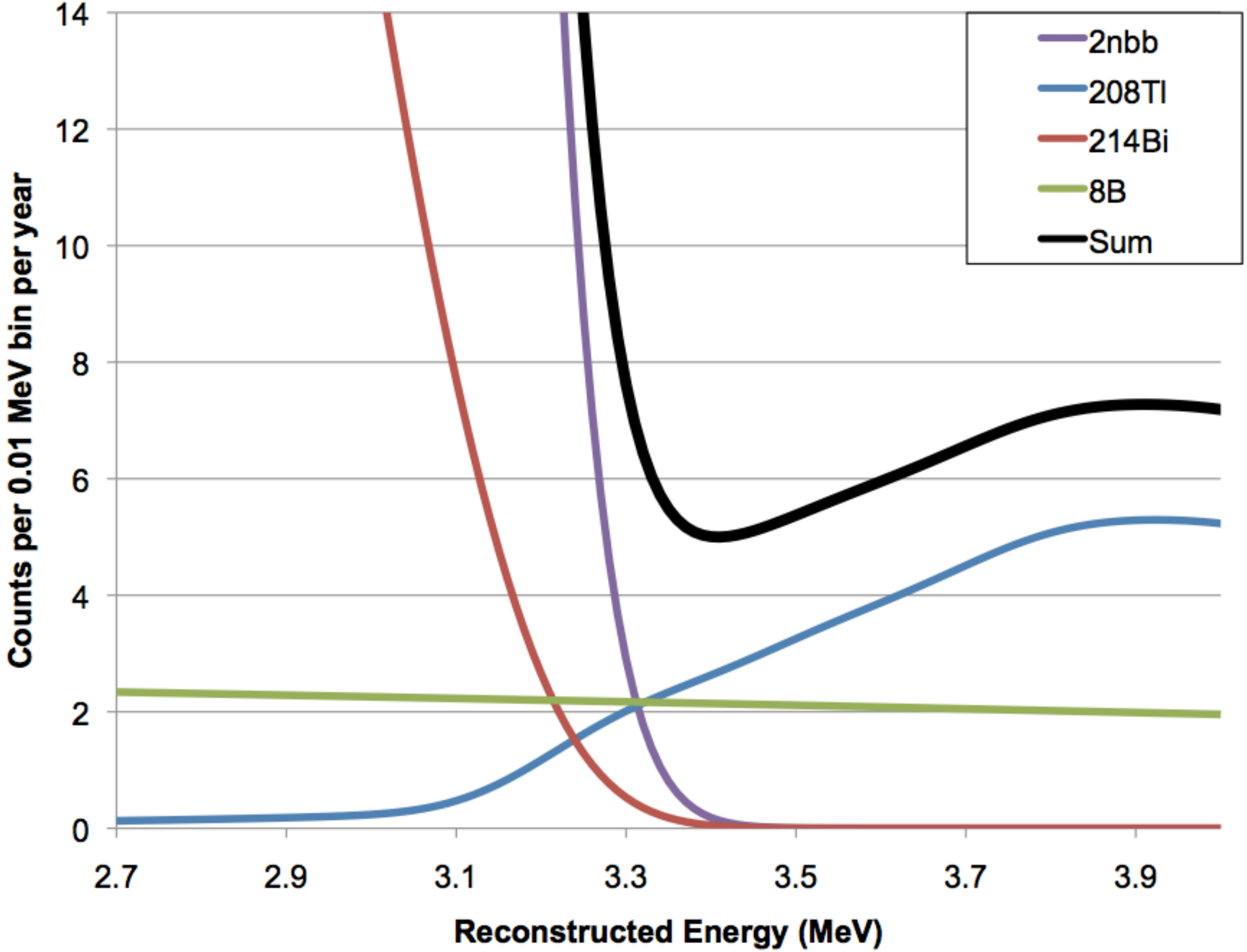




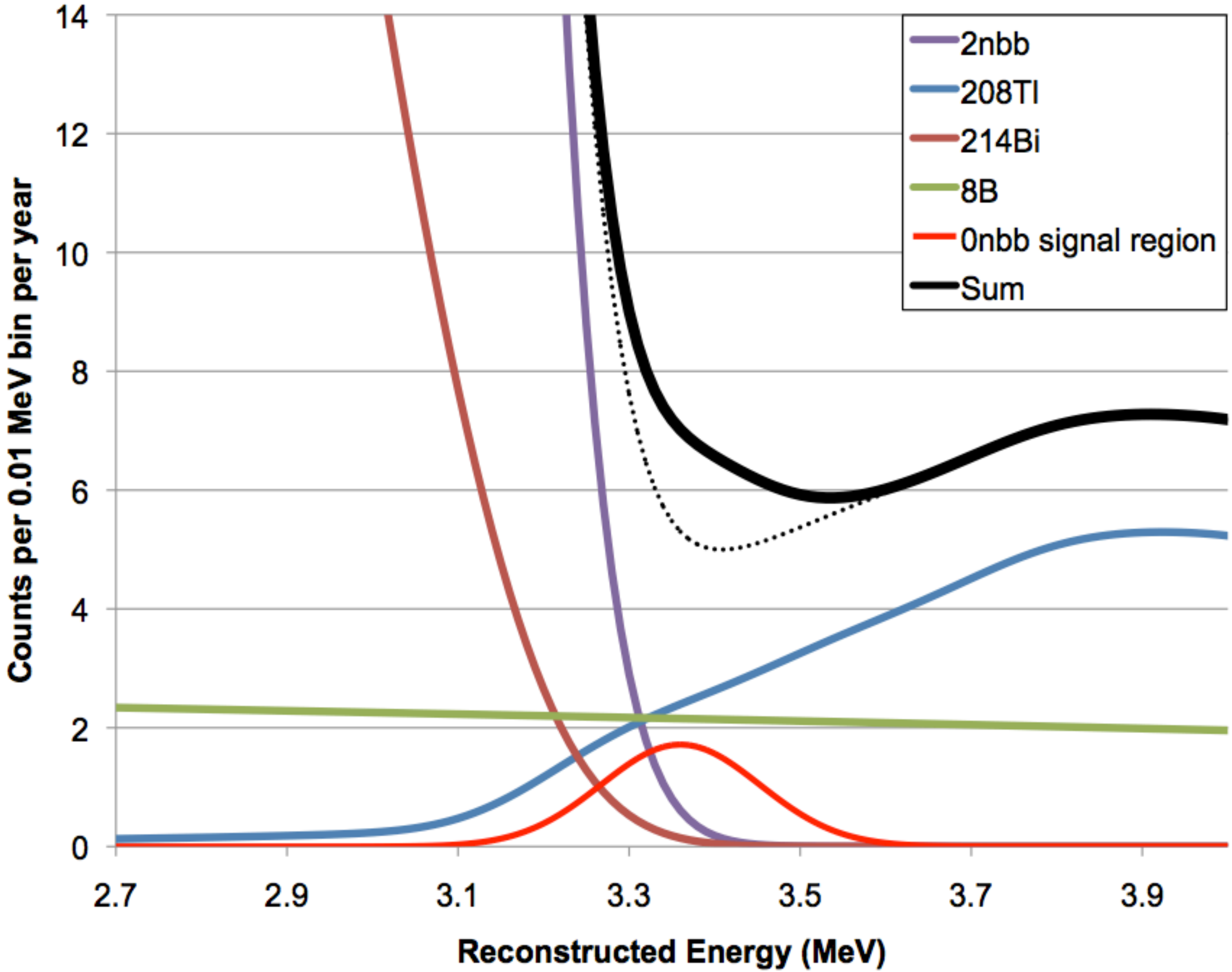
- Status
  - designed
  - pit excavation underway

Self Scavenging

- Lanthanide hydroxide 10 orders of magnitude more soluble in water than $Th(OH)_4$
  - Nd salt dissolved in pure water, pH adjusted using ammonium hydroxide to 6.03 solution
  - stirred for 60 min, followed by gravitational filtration at 20-25 μm
  - Dry and count filtrate
- Th and Bi 100% removed and other lanthanide bgs (eg ^{176}Lu, ^{138}La, Gd, Sm) reduced
- Easily incorporate into Nd processing scheme
- Can buy cheap Nd and purify it ourselves



14
12
10
8
6
4
2
0
Counts per 0.01 MeV bin per year
2.7
2.9
3.1
3.3
3.5
3.7
3.9
Reconstructed Energy (MeV)
2nbb
208Tl
214Bi
8B
Sum



14
12
10
8
6
4
2
0
2.7
2.9
3.1
3.3
3.5
3.7
3.9
Counts per 0.01 MeV bin per year
Reconstructed Energy (MeV)
2nbb
208Tl
214Bi
8B
0nbb signal region
Sum

SNO+ upgrade possibilities

1. Enriched isotope (not necessarily ^{150}Nd)
    - Atomic Vapour Laser Isotope Separation, AVLIS
    - Ion Cyclotron Resonance, ICR
    - Gaseous diffusion
    - Ultra-centrifugation
    - Distillation
    - Crown ethers
2. Nanoparticles
    - Significant less optical absorption while dissolving more isotope
    - Raleigh scattering negligible when particle size < 5 nm

LS technique itself can of course scaled up!

Summary

- SNO+ should be able to test KK signal with ~1year natural ^{150}Nd data
- And sensitivity to ~100meV within 3-5years
- Upgrades possible
- Lots of experiments on the market but redundancy is necessary
- SNO+ is not just a ββ experiment


Back Up

The Neutrino Mass

$$\langle m \rangle \equiv m_{ee} = \left| {}_{k} \; U_{ek}^{2} m_{k} \right| = \left| {}_{k} \; \left| U_{ek} \right|^{2} e^{i \;\; {}_{ek}} m_{k} \right|$$

$$m_{ee} = U_{e1}^{2} m_{1} \pm U_{e2}^{2} m_{2} \pm U_{e3}^{2} m_{3}$$

relative CP phases = ±1

$$m_{e} = \Sigma \; | U_{ek} |^{2} \; m_{k}$$

Natural Nd in SNO+ - sensitivity