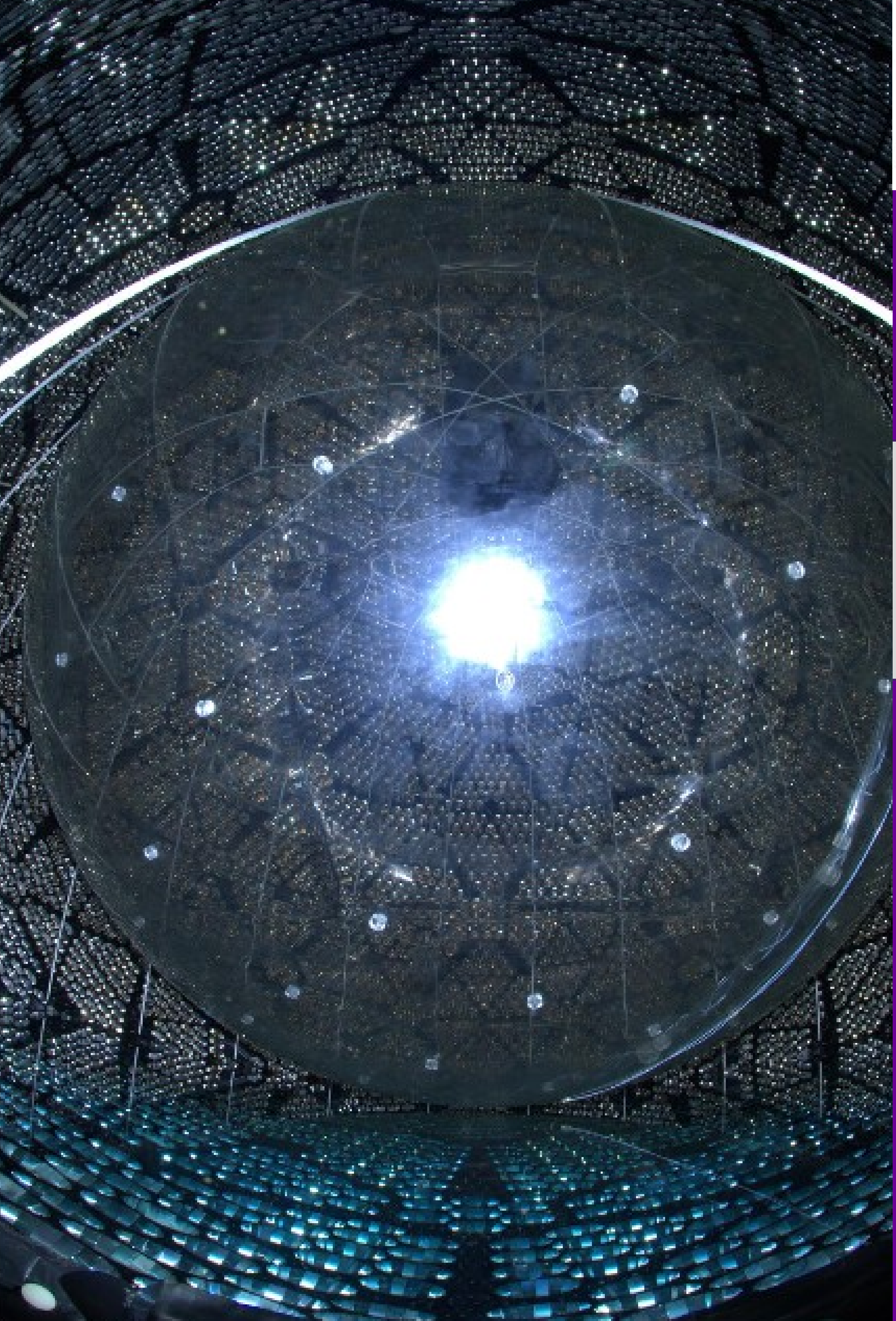


SNO+ EXPERIMENT:
Looking for neutrinos

Laura Segui
University of Oxford

OUTLINE

1. Neutrino Properties
2. Neutrinoless double beta decay
3. SNO+ Experiment
    1. New Te loading and purification technique
    2. Sensitivity & background
    3. Other physics
4. Summary

Neutrino and their Properties

Characteristics

- Electrically neutral leptons
- Three flavours: ν_e, ν_μ, ν_τ
- Spin ½
- Lightest particle in the SM $<0.3\text{eV}/c^2$
- Mass → physics BSM

Unknowns & Importance

- Absolute mass
- Nature: Dirac or Majorana

➔ CP-violation: leptogenesis

➔ Messengers of the Universe

➔ Probe environments that other radiation cannot penetrate

Neutrino and their Properties

In the SM neutrinos are massless, but..

1970 Davis (Chlorine experiment, Homestake) measured the neutrinos coming from the Sun
Only 1/3 of the expected neutrinos were detected ...

1998 Super-Kamiokande (Kamioka) studied the atmospheric neutrinos
(interaction cosmic rays-atmosphere)
ν_μ crossing the Earth seem to disappear …

2001 SNO (SNOLAB) confirms the oscillation of solar neutrinos

2015

More Nobel prizes in
neutrino physics:
1995 Reines
1988 Lederman,
Schwartz, Steinberg
2002 Davis, Koshiba

→ From the experiments of oscillations $m_\nu \neq 0$ → Physics beyond the Standard model

Neutrino Flavour

Neutrino mass and interaction eigenstates are not the same!

- Oscillation is the consequence of neutrino flavour mixing.
- Distinguish between flavour states (ν_i with i = e, μ, τ) and mass eigenstates (ν_l, with mass m_1, m_2, m_3).
  - Interact in weak eigenstates, defined by charged lepton: $\boldsymbol{\nu_e}$ **,** $\boldsymbol{\nu_\mu}$ **,** $\boldsymbol{\nu_\tau}$
  - Propagate in mass eigenstates: $\boldsymbol{\nu_1}$ **,** $\boldsymbol{\nu_2}$ **,** $\boldsymbol{\nu_3}$
- Mapping from weak to mass eigenstates by the PMNS (Pontecorvo-Maki-Nakagawa-Sakata) matrix, *U* (Lepton-sector equivalent of the CKM matrix).

In vacuum:

$$P_{\nu_\alpha\to\nu_\alpha}(L,E)=1-\sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)+\mathit{subleading\ effects}$$

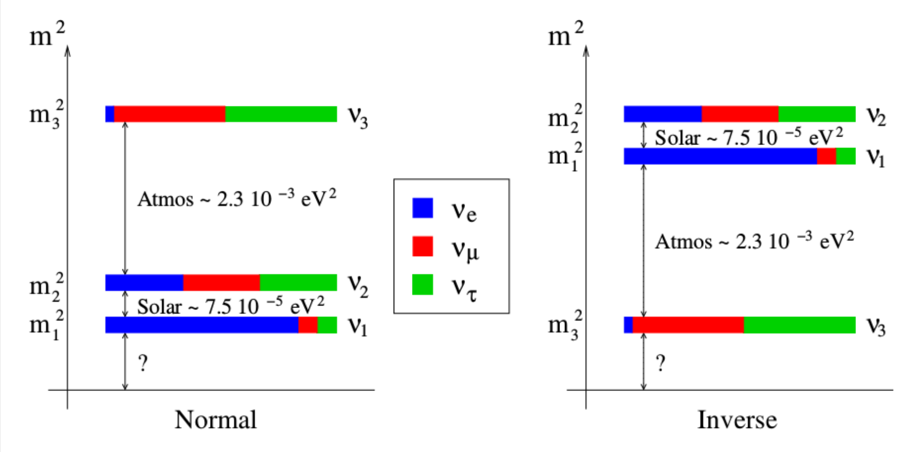
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\underbrace{\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\substack{\text{Solar }\nu\text{'s \& KamLAND}\\ P(\nu_e\to\nu_x)\\ \theta_{12}\sim 33^\circ,\ \Delta m_{12}^2}}\underbrace{\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13}\end{pmatrix}}_{\substack{\text{Reactor }\nu\text{'s}\\ P(\nu_e\to\nu_e)\ \&\ P(\nu_\mu\to\nu_e)\\ \theta_{13}\sim 8.5^\circ,\ \Delta m_{13}^2,\ \delta_{CP}}}\underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}}_{\substack{\text{Atmospheric }\nu\text{'s}\\ P(\nu_\mu\to\nu_\mu)\\ \theta_{23}\sim 45^\circ,\ \Delta m_{23}^2}}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Weak interaction eigenstates

Mass eigenstates

Three mixing angles: θ_{12} , θ_{13} , θ_{23}
One CP-violating phase: δ_{CP}

Neutrino Properties: What do we still don't know?



From oscillation experiments we know:

- Differences in mass
- Angles (although we need better accuracy), first glimpse of δ_{CP}

But...

➔ What are the absolute values of the neutrino masses?

➔ What is the mass hierarchy?
Normal (m1<m2 ≪ m3) or inverted (m3 ≪ m1 <m2)?

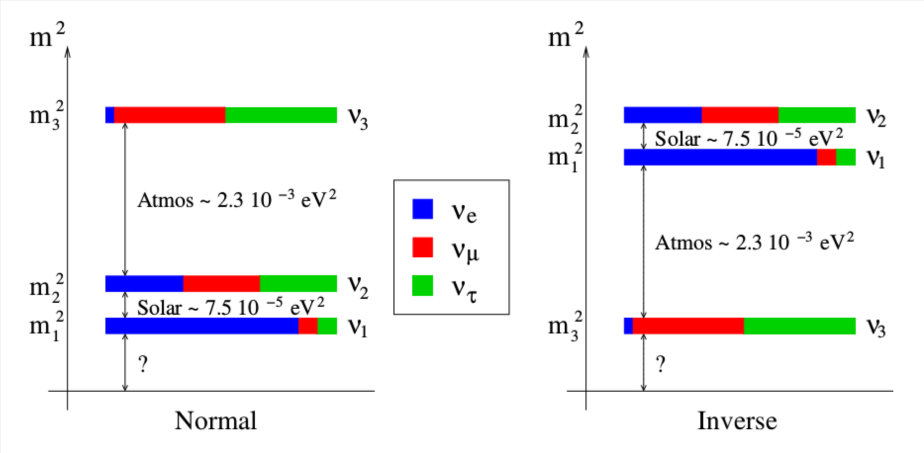
➔ What is neutrinos nature? Dirac or Majorana?
Lepton number violation, neutrinoless double beta decays

➔ What is the mechanism for neutrino masses?
Why neutrino masses are so much smaller than any other fundamental matter particles in the SM?

➔ Is there CP violation in the lepton sector?
What is the value of the Dirac CP-violating phase δ?

➔ Are there only three neutrinos?

Neutrino Properties: What do we still don't know?



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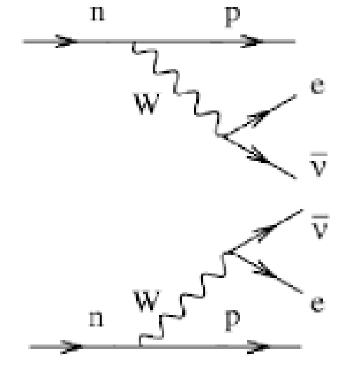
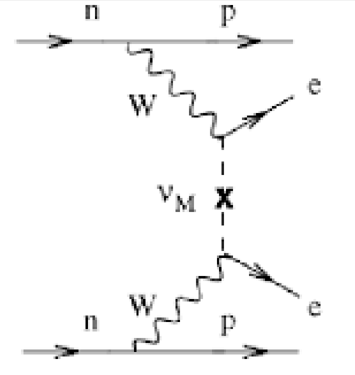
Double beta decay

2νββ

0νββ





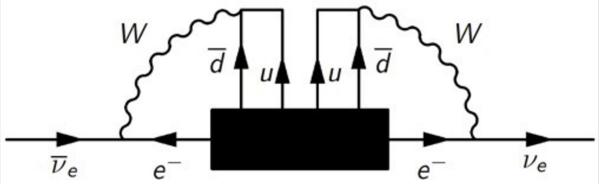
$T^{2\nu}_{1/2} \sim 10^{18} - 10^{21}$ y

$T^{0\nu}_{1/2} > 10^{25}$ y

2νββ: (A, Z) → (A, Z+2) + 2 e- + 2ν $\Delta L = 0$

0νββ: (A, Z) → (A, Z+2) + 2 e- $\Delta L = 2 \longrightarrow \nu = \bar{\nu}$

Physics beyond SM



0νββ process

$$\left(T^{0\nu}_{1/2}\right)^{-1} = \underbrace{G_{0\nu}\left|M^{0\nu}_{GT} - \frac{g_V^2}{g_A^2} M^{0\nu}_{F}\right|^2}_{F_N = \text{Nuclear Factor}} \chi^2$$

Sometimes also written as:

$$F_N = G_{0\nu} M^{0\nu}$$

where χ

$\rightarrow \dfrac{\langle m_\nu \rangle}{m_e}$ **Mass Mechanism**

$$\langle m_\nu \rangle = \sum_i \left(U_{ei}^2 m_i\right)$$

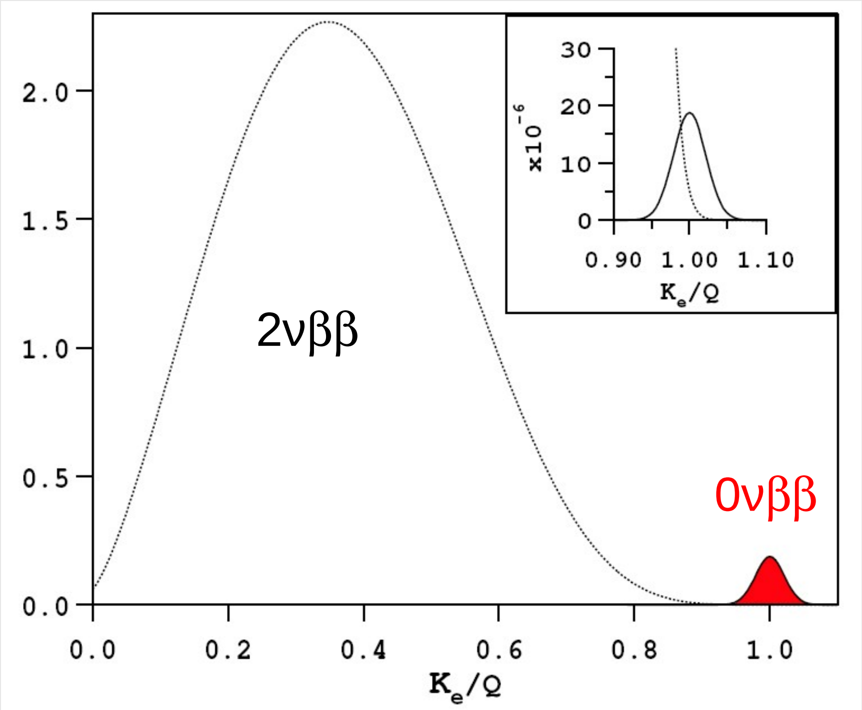
$\rightarrow \langle \lambda \rangle, \langle \eta \rangle$ Right handed currents

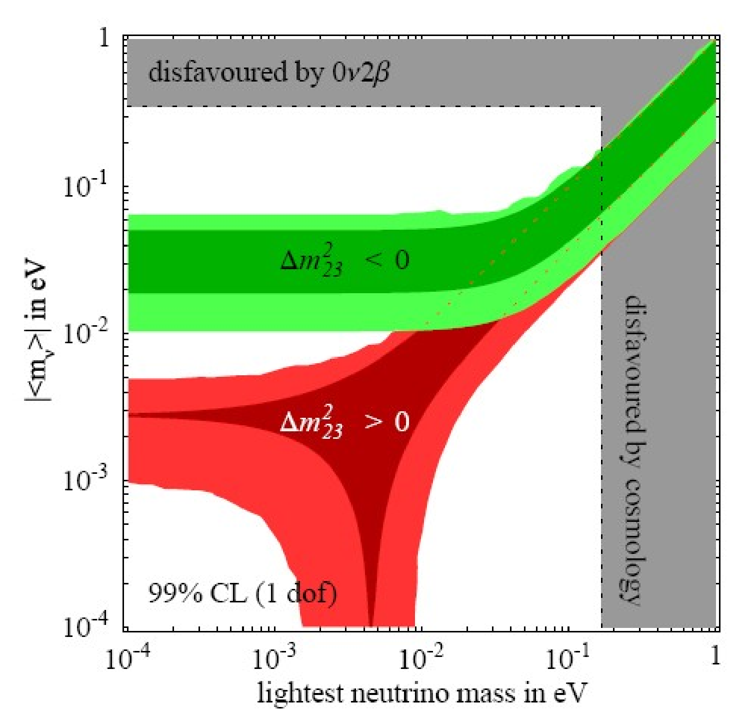
$\rightarrow \langle g_M \rangle$ Majoron emission

……

Experimental Signature

- Supposing the mass mechanism:
  2 electrons sharing all the available transition energy (**$Q_{\beta\beta}$**)





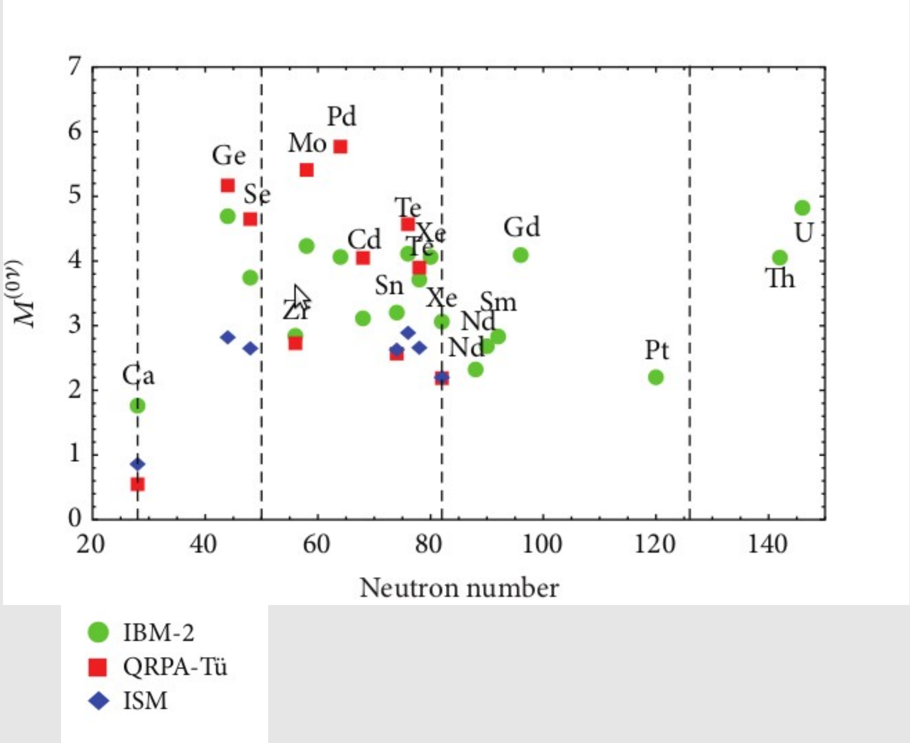
$$\langle m_\nu \rangle = m_e \left(F_N T^{0\nu}_{1/2} \right)^{-1/2} = \sum_i^{n_\nu} U^2_{ei} m_{\nu,i}$$

Theoretical Uncertainties: NME

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G_{0\nu}\underbrace{\left|M^{0\nu}_{GT} - \frac{g_V^2}{g_A^2}M^{0\nu}_{F}\right|}_{M^{0\nu}}^{2}\frac{\langle m_\nu\rangle^2}{m_e^2} = G_{0\nu}M^{0\nu}\frac{\langle m_\nu\rangle^2}{m_e^2}$$

$G_{0\nu}$, phase space factor, is calculable (~7% error).

Nuclear matrix elements (NME) via theory.



- Extracting an effective neutrino mass requires a good understanding of the nuclear matrix elements (NME)
- Agreement between methods doesn't necessarily provide an estimate of theoretical uncertainties or of actual values.
- Measurement of the **0νββ** process for **various isotopes** would reduce the uncertainty.
- The measurement of the **2νββ** mode could provide **useful information** for the NME estimation.

Theoretical Uncertainties: quenching of g_A

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G_{0\nu}\left|M^{0\nu}_{GT} - \frac{g_V^2}{g_A^2} M^{0\nu}_F\right|^2 \frac{\langle m_\nu\rangle^2}{m_e^2} = G_{0\nu} M^{0\nu} \frac{\langle m_\nu\rangle^2}{m_e^2}$$

axial-vector coupling constant

$g_A = 1.269$ measured in weak interactions and decays of nucleons, **renormalized** for nucleons

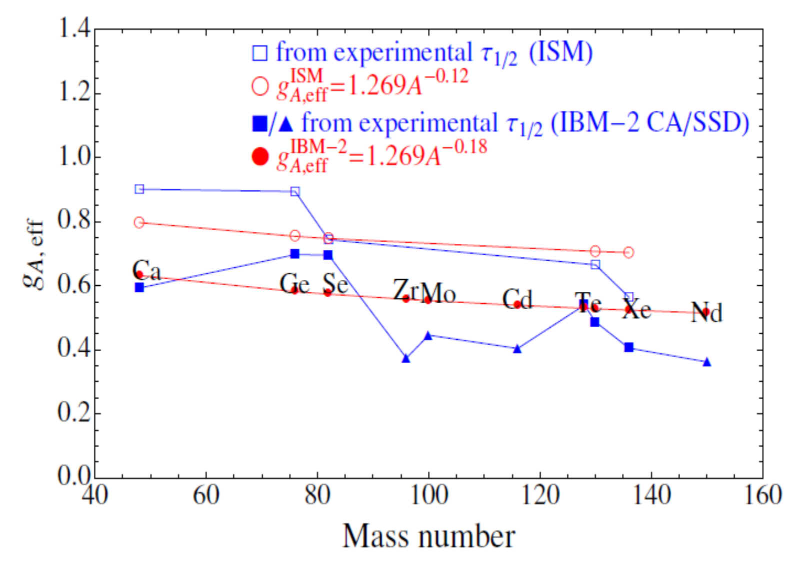
Differences observed between predicted and measured value in 2νββ mode

$$\left(T^{2\nu,\,\exp}_{1/2}\right)^{-1} = G_{2\nu}\left|M^{2\nu}_{eff}\right|^2 \quad \rightarrow \quad \left(M^{X}_{eff}\right)^{-1} = \left(\frac{g_{A,eff}}{g_A}\right)^2 \left|M^{X}\right|$$

Calculated for the *X* isotope according to different models

→ $g_{A,eff}$ is essentially a way to rescale M_{theor}

From 2νββ data



J.Barea, J.Kotila, F.Iachello, Phys. Rev. C87, 014315 (2013)

Similar values found for β−/EC for IBM-2 and for QRPA

(Ejiri, Soukouti and Suhonen, PLB 729, 27(2014))

Three main cases to considered

$g_A = 1.269$	(nucleon)
$g_A = 1$	(quarks)
$g_{phen} = 1.269\ A^{-\gamma}$	(2νββ data)

IBM-2: $\gamma = 0.18$
QRPA: $\gamma = 0.16$
ISM: $\gamma = 0.12$

Different $g_{A,eff}$ can change calculated 0νββ rate by ~20

→ Longer time of measurements, existing values different...

BUT,

Is the re-normalization of g_A the same in 2νββ as in 0νββ?

Experimental sensitivity

The number of background events expected along the experiment lifetime is

$$N_B = b(t) \cdot \Delta E \cdot M \cdot t_{\exp}$$

Two cases depending on the background level:

$$N_B \gg 1 \qquad T_{1/2}^{0\nu} \propto \epsilon \frac{f}{A} \sqrt{\frac{M\, t_{\exp}}{b(t)\, \Delta E}}$$

$$N_B < 1 \qquad T_{1/2}^{0\nu} \propto \epsilon \frac{f}{A} M\, t_{\exp}$$

Zero-background experiments

b = background [c/keV/kg/y]
t_{exp} = measuring or exposure time [y]
M = detector mass [kg]
ε = detector efficiency
f = isotopic abundance
A = atomic number
ΔE = energy resolution [keV]

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The number of background events expected along the experiment lifetime is

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In **SNO+**, not all backgrounds scale with detector mass (for ex. ^{8}B and external backgrounds)
→ a constant factor *C*
(caveat: as long as our light levels are good enough to pin back the 2νββ)

$$N_B = \left(b(t)\cdot M + C\right)\Delta E \cdot t_{\exp}$$

$$T^{0\nu}_{1/2} \propto \epsilon \frac{f}{A}\frac{t_{\exp}}{\sqrt{(b\cdot M + c)\,\Delta E\, t_{\exp}}}$$

Experimental sensitivity

$$T^{0\nu}_{1/2} \propto \epsilon \frac{f}{A}\sqrt{\frac{M\,t_{exp}}{b(t)\,\Delta E}}$$

b = background [c/keV/kg/y] ↓↓

t_{exp} = measuring or exposure time [y] ↑↑

M = detector mass [kg] ↑↑

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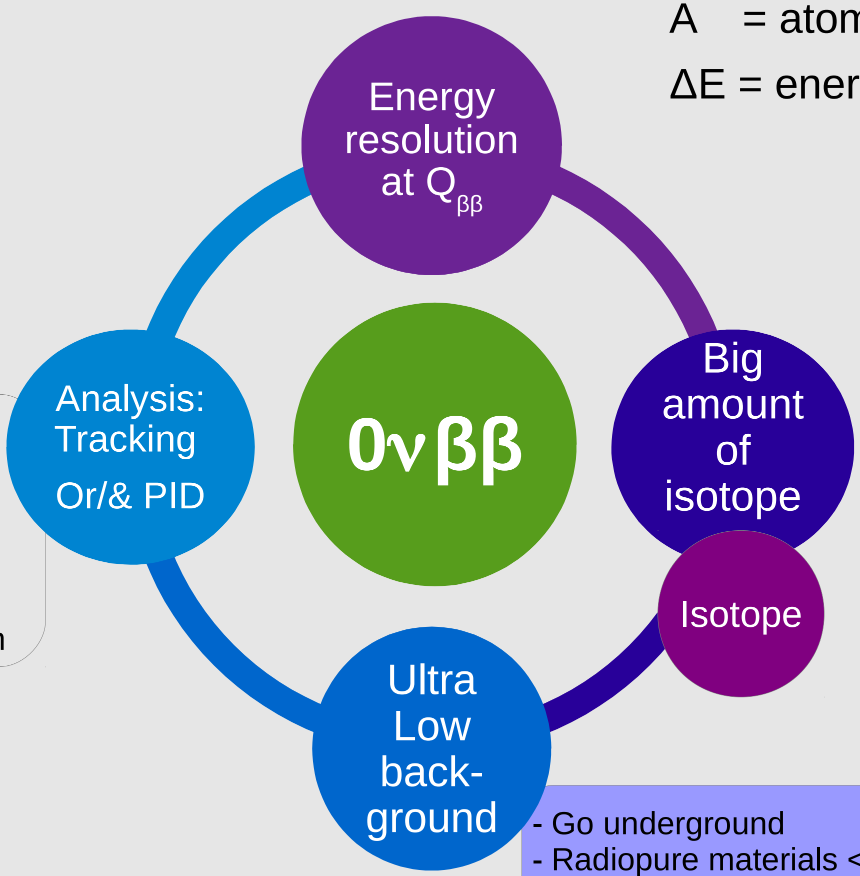
A = atomic number

ΔE = energy resolution [keV] ↓↓



Energy resolution at $Q_{\beta\beta}$

Analysis: Tracking Or/& PID

0νββ

Big amount of isotope

Isotope

Ultra Low back-ground

- Tracking
- Particle ID
- Angular, spatial, time correlations
- Granularity
- PSD
- Ion identification

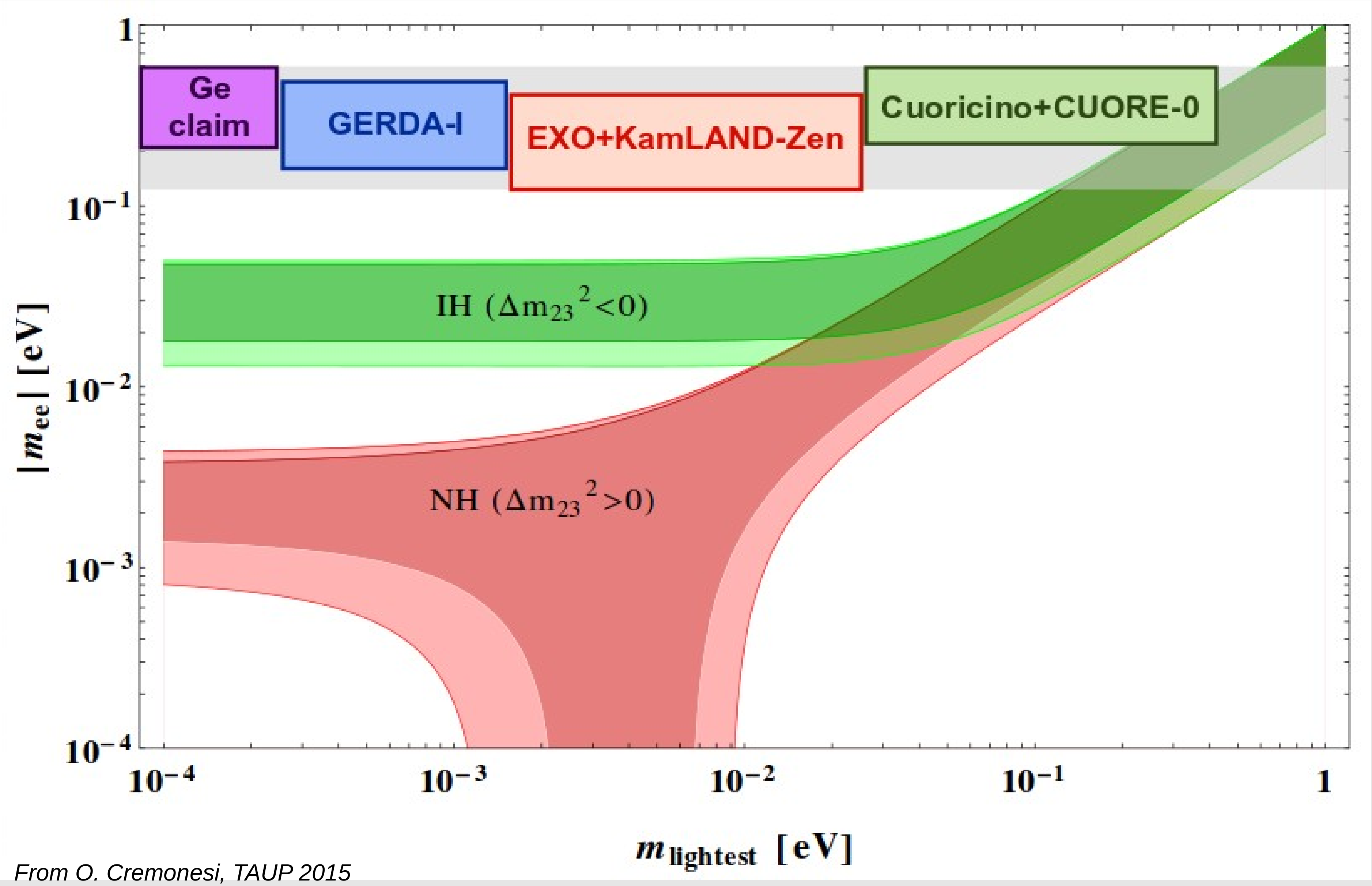
- Go underground
- Radiopure materials << 0.1 mBq/kg
- Shielding
- Analysis

Experimental situation

Past and recent results

Experiment	***Isotope***	***Technique***	***Laboratory***	***Results***		
				$T_{1/2}^{2\nu}$ **(y)**	$T_{1/2}^{0\nu}$ **(y)**	$\langle m_\nu \rangle$ **(eV)**
CUORICINO	^{130}Te	Bolometers	Gran Sasso	-	> 3.0 10^{24}	< 0.19 – 0.68
Heidelberg – Moscow	^{76}Ge	Ge diodes	Gran Sasso	1.6 ± 0.2 10^{21}	> 1.6 10^{25}	< 0.35
Heidelberg – Moscow*	^{76}Ge	Ge diodes	Gran Sasso	1.6 ± 0.2 10^{21}	1.2 10^{25}	0.44
IGEX	^{76}Ge	Ge diodes	Canfranc	-	> 1.6 10^{25}	< 0.33 – 1.35
NEMO - 3	^{100}Mo	Tracking + Calorimetry	Modane	7.2 ± 0.6 10^{18}	> 1.1 10^{24}	< 0.33 – 0.87
EXO	^{136}Xe	LXe TPC	WIPP	2.2 ± 0.1 10^{21}	> 1.1 10^{25}	< 0.14 – 0.38
GERDA	^{76}Ge	Ge diodes	Gran Sasso	1.8 ± 0.1 10^{21}	> 2.1 10^{25}	< 0.2 – 0.4
KamLAND- Zen	^{136}Xe	Liquid Scintillation	Kamioka	2.3 ± 0.1 10^{21}	> 1.1 10^{26}	< 0.06 – 0.16

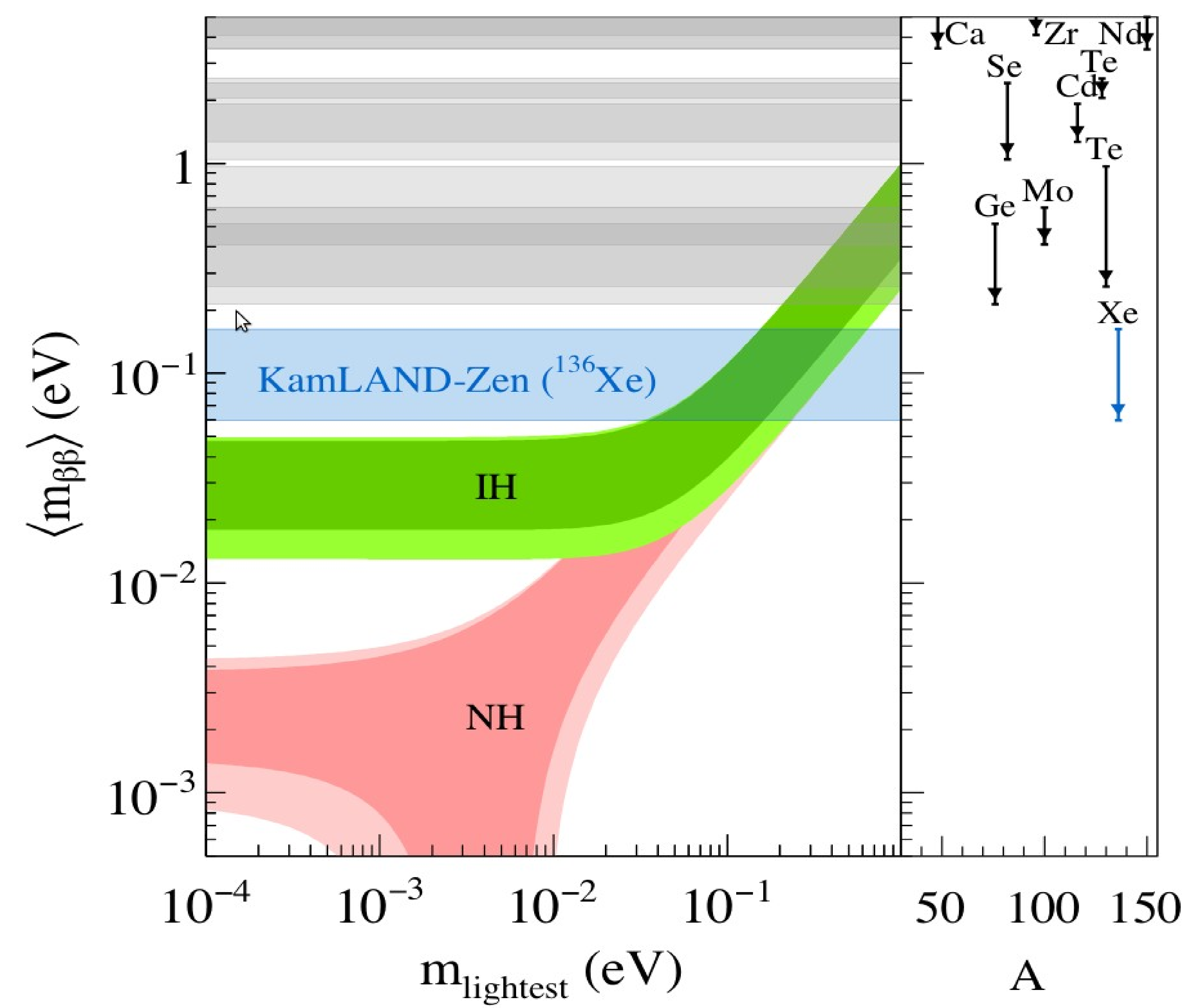
Experimental situation



From O. Cremonesi, TAUP 2015

Experimental situation

New limits from KamLand-Zen: combining Phase I and Phase II → 1.1 x 10^{26} yr (90% CL) → 60-161 meV



10th May 2016, http://arxiv.org/pdf/1605.02889.pdf

Experimental situation

Future (personal selection) of experiments

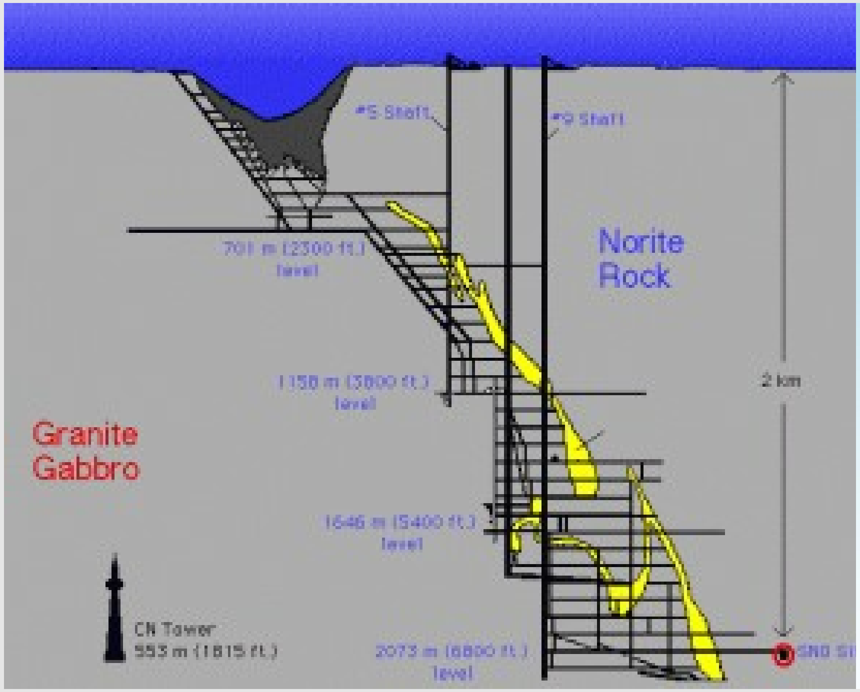
Experiment	***Isotope***	***Technique***	***Main Strength***
CUORE (LNGS)	130Te	Bolometers	Resolution, Efficiency
GERDA II (LNGS)	76Ge	Ge Diodes	Resolution, Efficiency
KamLANDZen (Kamioka)	136Xe	Xe Liquid scintillation	Background, efficiency
MAJORANA (SURF)	76Ge	Ge Diodes	Resolution, Efficiency
NEXT (LSC)	136Xe	Tracking + Calorimetry	Background Rejection, Efficiency
SNO+ (SNOLAB)	130Te	Te Liquid Scintillation	Background, Mass
SUPERNEMO (LSM)	82Se, 150Nd	Tracking + Calorimetry	Bakground Rejection, Isotope Selection
1TGe (GERDA+MJ)	76Ge	Best technology from GERDA, MAJORANA	Resolution, Efficiency
CUPID	130Te	Hybrid bolometers	Background, Resolution
nEXO (WIPP)	136Xe	TPC Ionization + Scintillation	Mass, Efficiency, Final State Signal
AMORE (Y2L)	100Mo	CaMoO4 bolometers	Resolution
CANDLES (Kamioka)	48Ca	CaF2 Scintillation	Background, Efficiency
COBRA (LNGS)	130Te, 116Cd	ZnCdTe Semiconductors	Resolution, Efficiency
LUCIFER (LNGS)	82Se	ZnSe bolometers	Resolution, Background
MOON (UW)	100Mo	Tracking + Scintillation	Compactness, Background

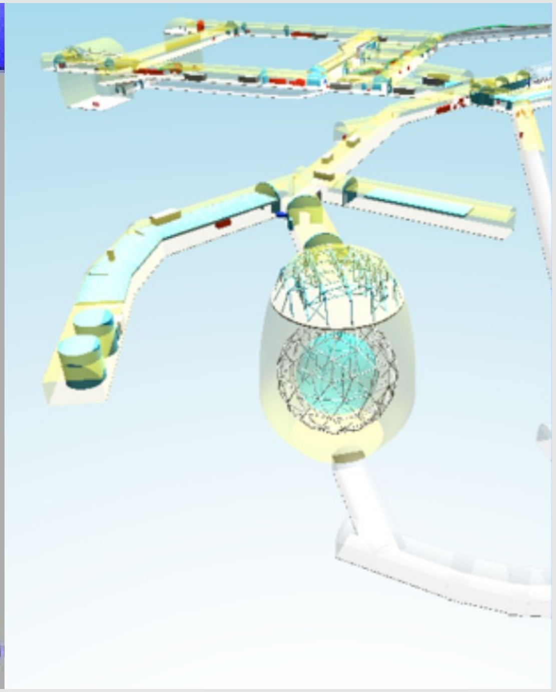
On- going or commissioning
few kg

R&D
~tonne

R&D further

The SNO+ Experiment

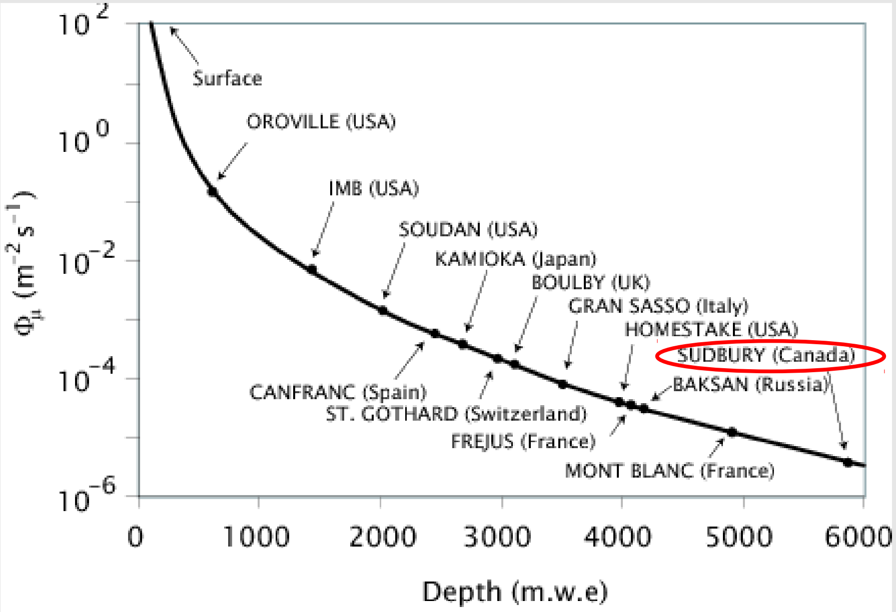




SNOLAB
MINING FOR KNOWLEDGE
CREUSER POUR TROUVER... L'EXCELLENCE

- Located at SNOLAB inside the Creighton mine near Sudbury, Canada.
- SNO+ is the successor to Sudbury Neutrino Observatory (SNO).

- Depth = 2070 m (6000 m.w.e.)
- ~60 muons /day in SNO+
- 10,000 sq ft Class-2000 clean room



The SNO+ Collaboration

LIP Coimbra
LIP Lisbon

SNOLAB
TRIUMF
U. of Alberta
Queens University
Laurentian University

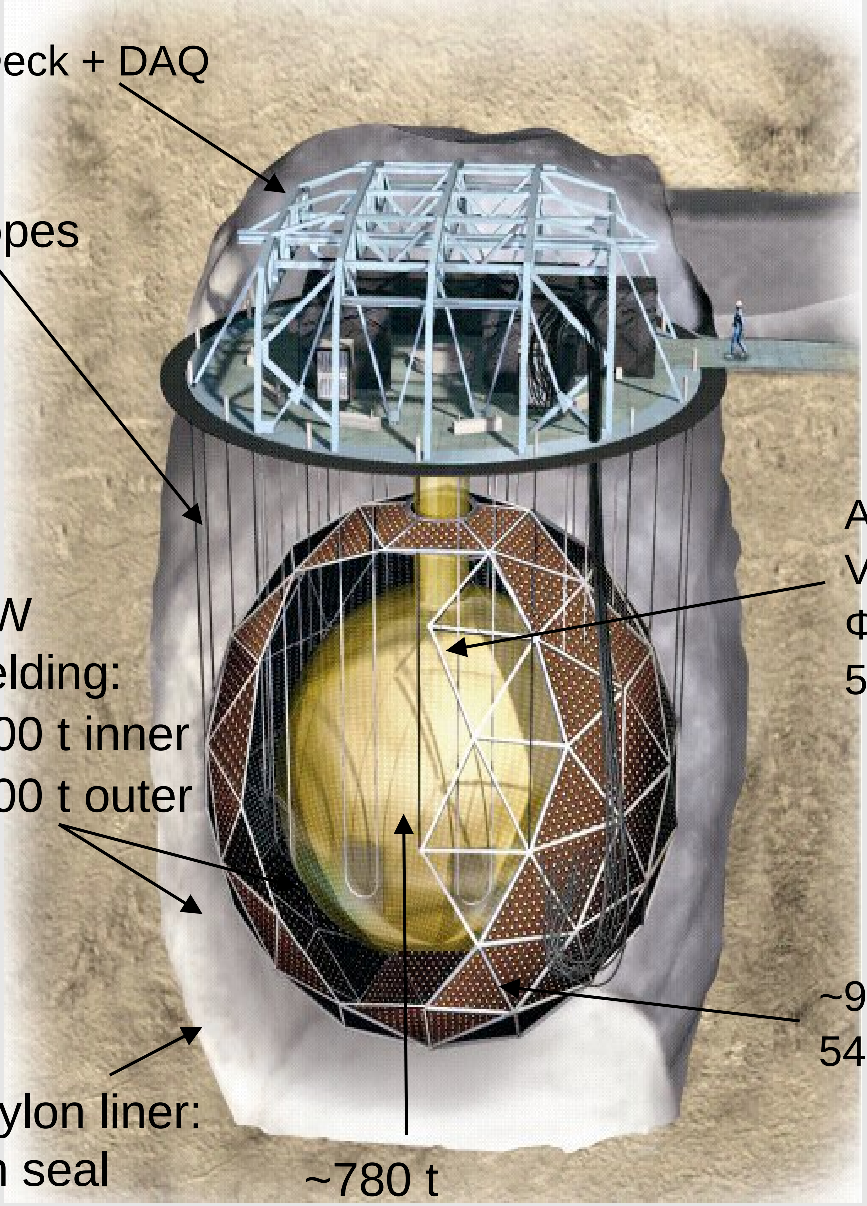
TU Dresden

UNAM

Oxford University
Queen Mary, (U. of London)
U. of Liverpool
U. of Sussex
U. of Lancaster

Armstrong State U.
Brookhaven National Lab.
U. of California, Berkley
U. of California, Davis
Lawrence Berkley National Lab.
U. of Chicago
U. of Pennsilvania
U. of Washington

The SNO+ Detector



Deck + DAQ

Ropes

UPW
shielding:
- 1700 t inner
- 5300 t outer

Urylon liner:
Rn seal

~780 t
Liquid organic
scintillator + PPO

Acrylic
Vessel
Φ 12 m
5 cm thick

~9400 PMTs, 8”
54% coverage

Broad neutrino physics program

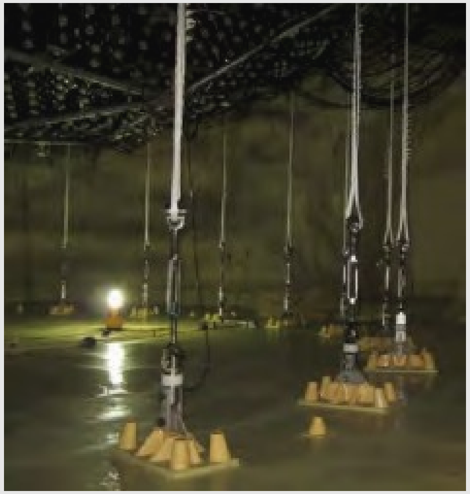
- **Neutrinoless double beta decay of ^{130}Te**
- Reactor anti-neutrinos
- Geo anti-neutrinos
- Supernovae neutrinos
- Nucleon decay and exotic physics
- Solar neutrinos (pep, CNO, low E ^{8}B)

Three Experimental Phases

- Water-Phase
- Liquid scintillator phase
- **Te-loaded liquid scintillator**

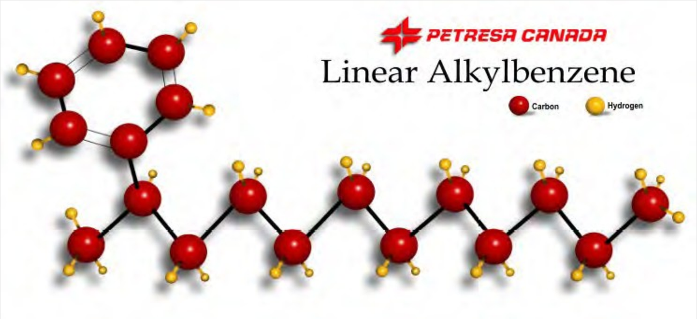
Upgrades since SNO

- New hold-down rope system on the top of the AV anchored to the cavity floor.
  High purity Tensylon ropes.
- New hold-up rope system more radiopure (Tensylon).
- DAQ and trigger system upgraded to cope with the high light yield of scintillator (higher rate, lower threshold).
- ~ 500 defective PMT bases have been repaired.
  Expected ~9400 working PMT at the start of data taking.
  Installed 3 HQE PMTs (test bench for Phase II).
- New calibration system.
  - Optical sources (LED and lasers coupled to fibres).
  - Radioactive sources (gamma, alpha, neutron, beta).
- New cover gas system to limit Rn ingress into the detector
- Scintillator and Te purification plants (discussed later)



Liquid Scintillator

Linear alkylbenzene (LAB) + 2g/L fluor 2,5-diphenyloxazole (PPO)



ρ = 0.86 g/cm^3 @ 12°C

LAB

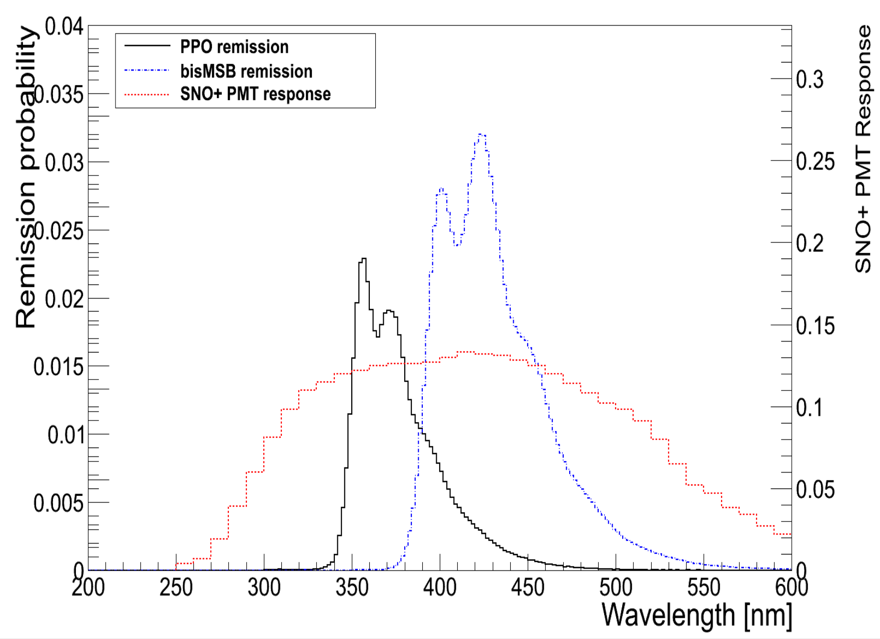
- Long time stability
- Compatibility with acrylic
- High purity levels directly from manufacturer
- Long attenuation and scattering length
- High light yield (~10,000 photons/MeV)
- Low cost, low toxicity, biodegradable, high flash point 130°C
- Metal loading possible
- PID between alpha an betas

PPO

- Common “whitening” or marker dye
- Low toxicity
- Melting point 72°C, boiling point 360°C

bisMSB

- As secondary WLs (at least for the loaded phase)



However, some of the optical properties will change depending on the loading technique of Te-130

R&D in the best way to load it

Double beta decay in SNO+

First phase **0.5% nat. Te = ~ 1300kg of ^{130}Te** deployed into liquid scintillator (LAB+PPO+bisMSB)

➔The ββ isotope and the detector are distinct in SNO+: background runs before deployment

^{130}Te

✔ High abundance (34%) in natural Te

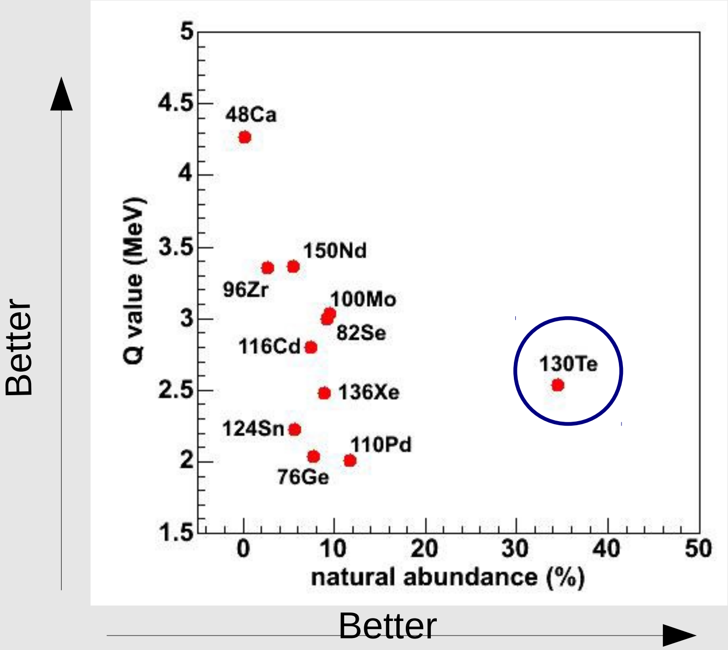
✔ $T_{1/2}^{2\nu\beta\beta}$= 7x10^{20} yr, one of the longest 2νββ (measured by NEMO)

✔ High $Q_{\beta\beta}$ = 2526.97 ± 0.23 keV

✔ High light yield (~9,500 ph/MeV)

✔ Successfully loaded in LAB

✗ Small α -β separation when loaded



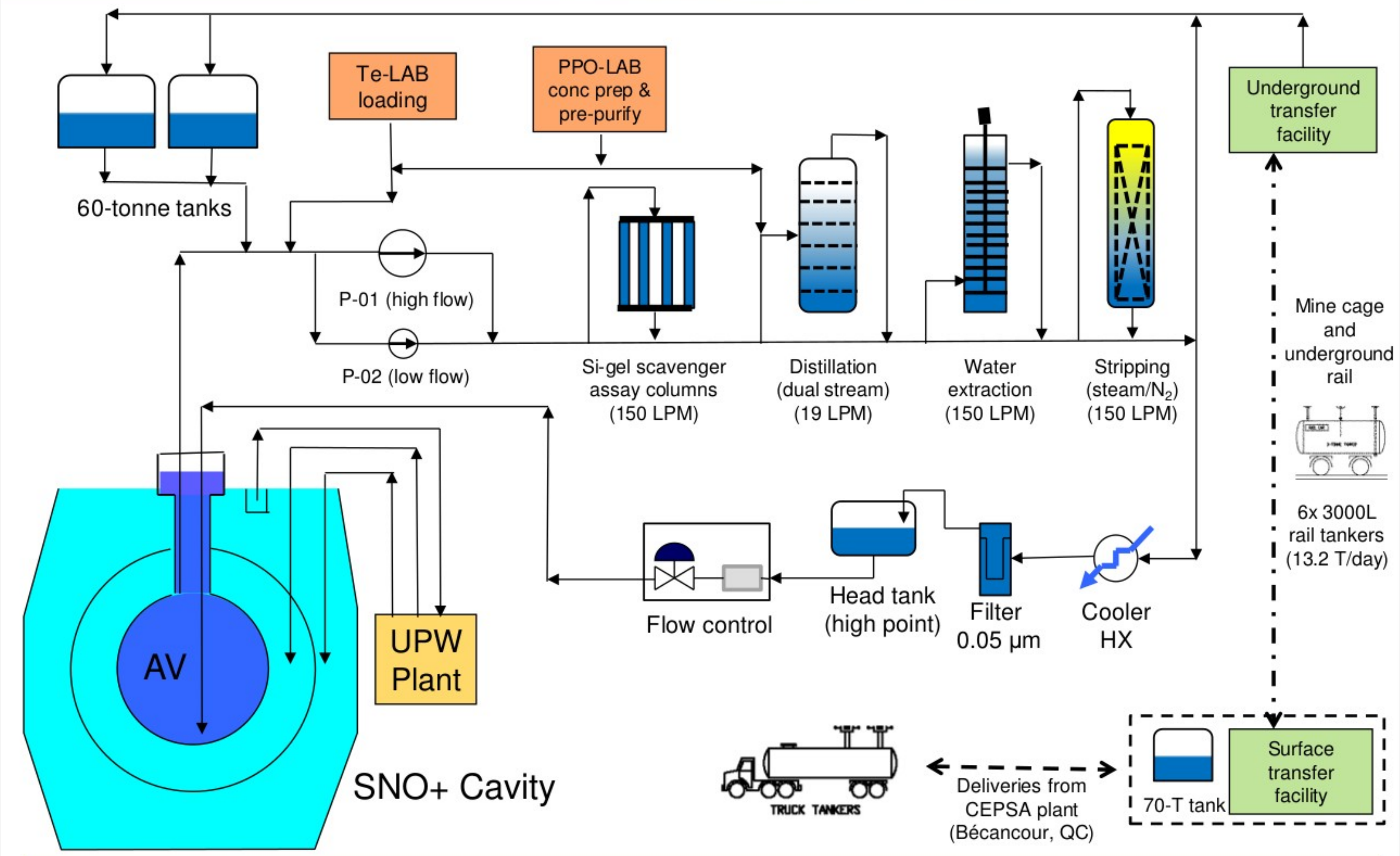
High Q value reduces backgrounds and increases the phase space & decay rate.
Large abundance makes the experiment cheaper.

Scintillator Purification Plant

LS Target Levels

^{85}Kr <10^{-25} g/g
^{40}K <10^{-18} g/g
^{39}Ar: 10^{-24} g/g
^{238}U-chain: 10^{-17} g/g
^{232}Th-chain: 10^{-18} g/g
(~ 9 cpd ^{238}U and 3 cpd ^{232}Th)

Plant under commissioning with water



→ Industrial petrochemical plant built underground

- Multi-stage distillation
- Pre-purification of PPO concentrated solution
- Steam/N2 stripping under vacuum
- Water Extraction
- Metal scavengers
- Microfiltration

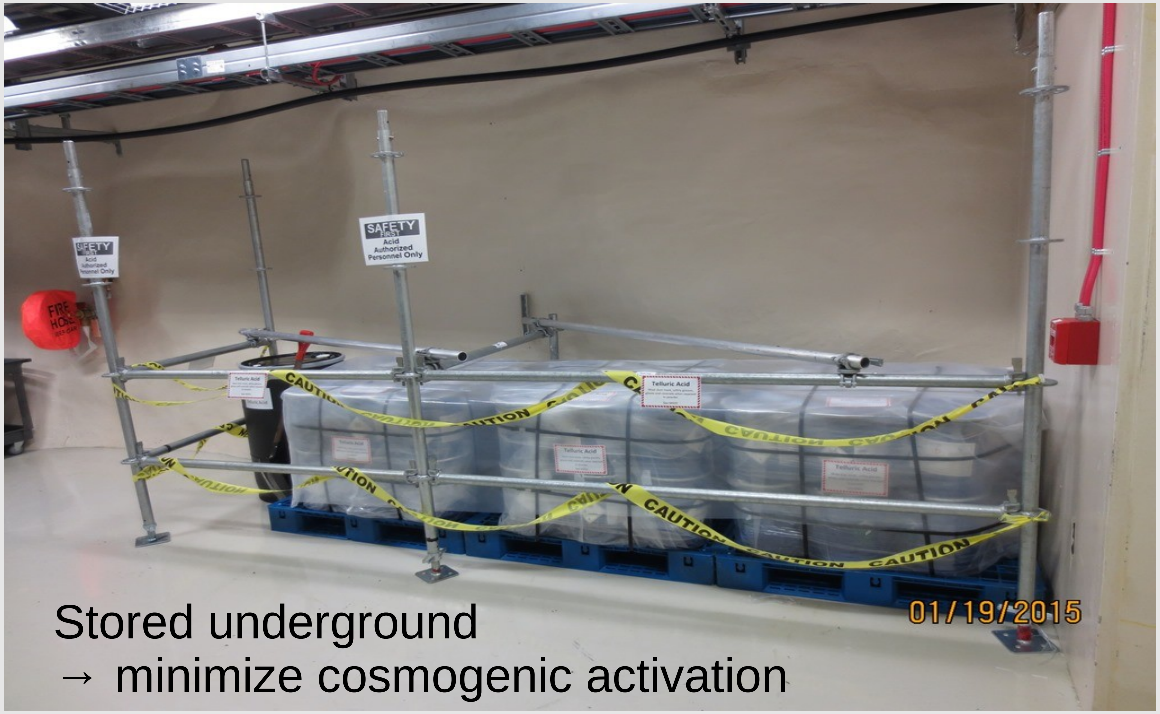
→ Recirculation possible in 4 days

Tellurium production and delivery

- Te extracted from mine (depth ~ 300 m) in April 2014
- Control during the production
  - Visit to the production site prior to start of processing
  - BNL QA/QC tests on samples from each barrel before approval to sent to SNOLAB
- Shipped to SNOLAB (arrived on January 7th 2015)
- Transported underground on January 19th 2015
  - Testing one sample from one of the barrel to cross-check previous results

1.8 tonnes of Te, corresponding to ~1 tonne $Te(OH)_6$, or ~0.13% Te loading


Sample control



Stored underground
→ minimize cosmogenic activation

Tellurium Purification

Tellurium Target levels:

2.5×10^{-15} g/g in ^{238}U (3×10^{-8} Bq/kg)

3×10^{-16}g/g in ^{232}Th (1.2×10^{-9} Bq/kg)

(raw Te ~10^{-11} g/g U/Th, 10^{-4} Bq/kg)

- Te contamination in U/Th
- Also can be cosmogenically activated
  - Main **^{60}Co, ^{110m}Ag, ^{126}Sn, ^{88}Zr, ^{88}Y, ^{124}Sb**
- Rejection of cosmogenic isotopes needed **10^4-10^5** *(V. Lozza and J. Petzoldt, Astropart. Phys. 61, 62-71 (2015))*
- Some of these cosmogenics are not soluble in water

  → can be removed by the scavenging method.

- New technique developed at BNL for Te-loaded scintillators

Tellurium Purification

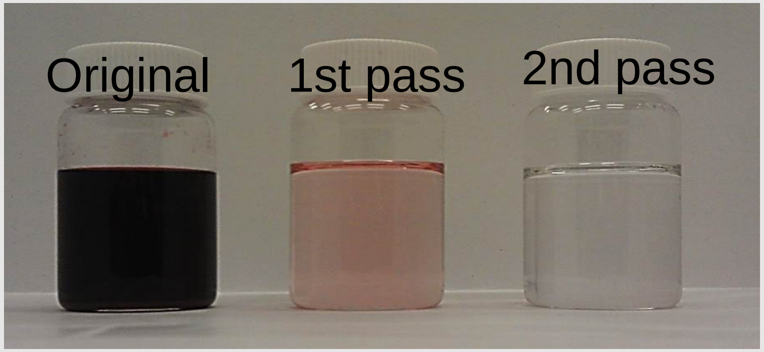
See “S. Hans et. al. *Purification of Telluric Acid for SNO+ Neutrinoless Double Beta Decay Search*. Nim A, Volume795, 21 September 2015, Pages 132–139”

1. Acid-recrystallization (2 passes):
   - Dissolve $Te(OH)_6$ in water
   - Recrystallize using nitric acid
   - Rinse with ethanol

> 10^4 reduction

+ Improvement optical transmission blue region

^{60}Co spike



^{60}Co removed by a factor >10^4 after two passes

Tellurium Purification

See “S. Hans et. al. *Purification of Telluric Acid for SNO+ Neutrinoless Double Beta Decay Search*. Nim A, Volume795, 21 September 2015, Pages 132–139”

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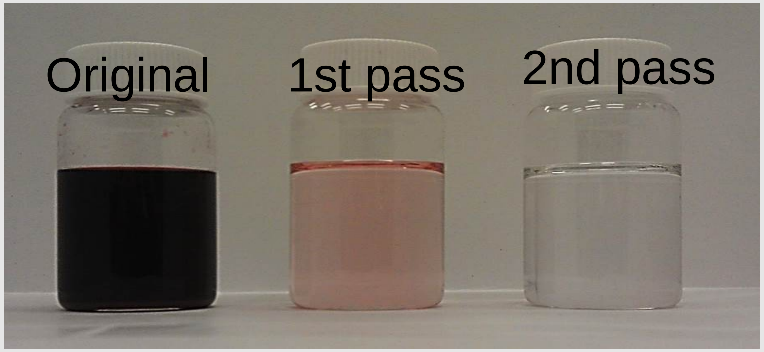


^{60}Co removed by a factor >10^4 after two passes

2. Thermal-recrystallization:
    - Rinse completely nitric acid
    - Dissolve purified $Te(OH)_6$ in warm water (80°C)
    - Cool to recrystallize thermally

> 10^2 reduction

Approx. 70% of telluric acid crystal will be recovered.
The residual 30% repeat process

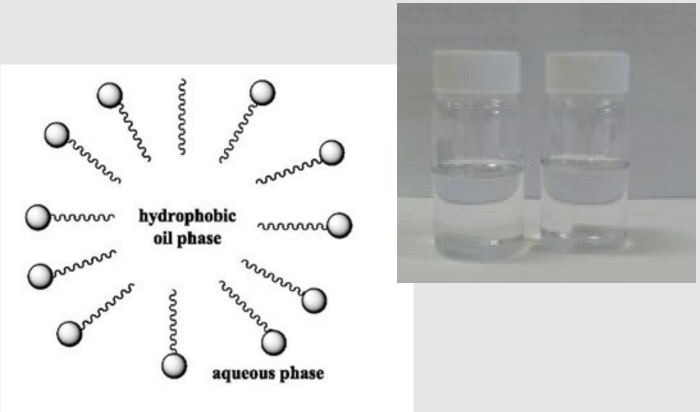
+ storage underground for 6 months →

→ **negligible contribution from cosmogenics**

10kg pilot-scale plant operated successfully
Final design
~200 kg TeA/batch

Tellurium Loading techniques

1. Surfactant + Telluric Acid (aqueous)
    - Surfactant worsens absorption length
    - Need surfactant purification of 10^6
        - Custom underground synthesis of the surfactant
        - Thin-film distillation

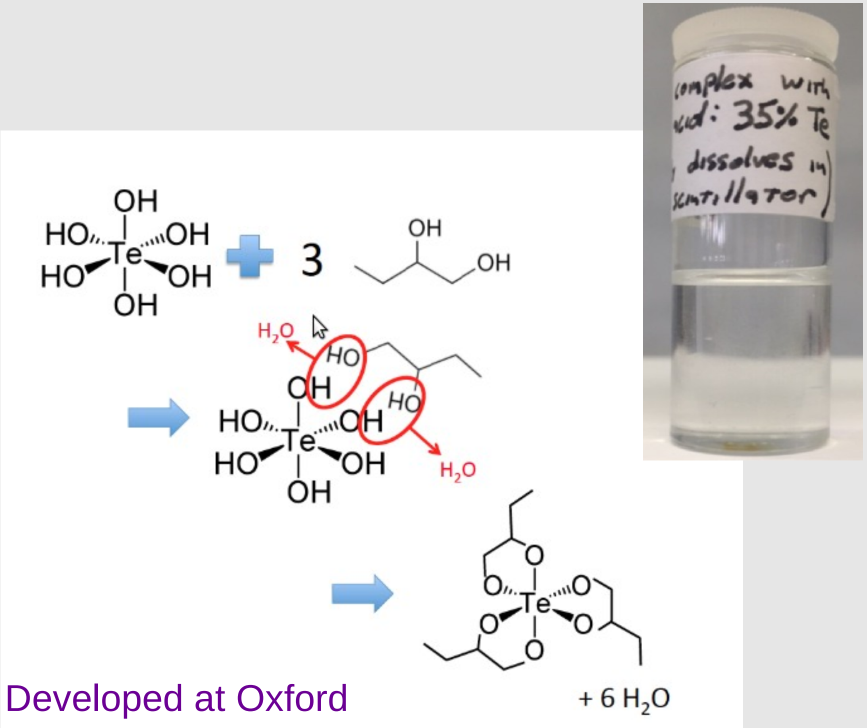


Developed at BNL

2. Organometallic ("Diol") form of Tellurium
   Organotelluric diol complex

    - Higher light yields
    - Don't need surfactant
    - Opens a new R&D line

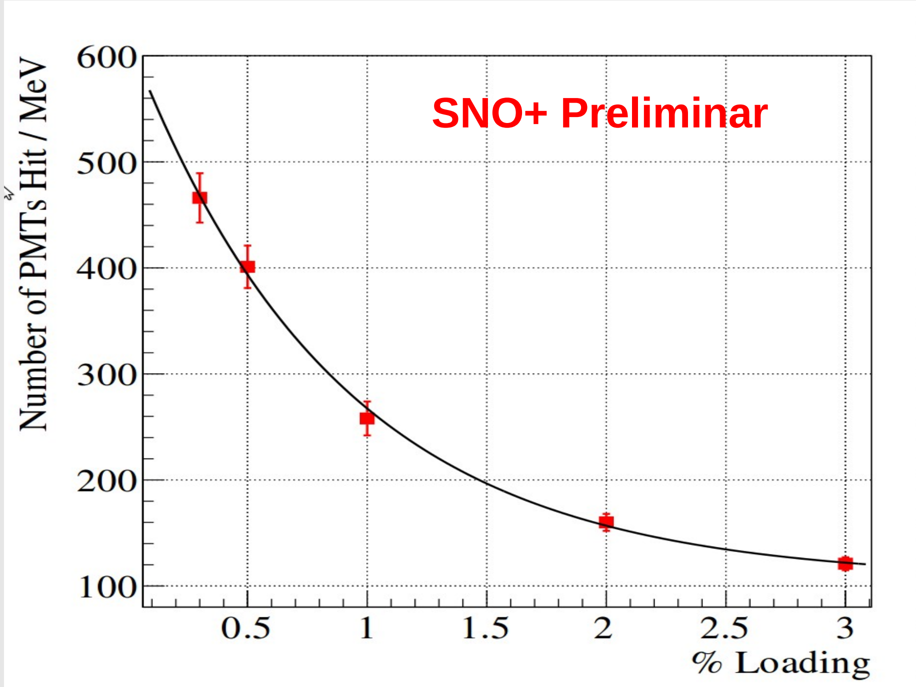
   Not all "diols" works, seems to require 2 OH groups ("diols") that are near each other...
   Best candidate: **1,2- butanediol**



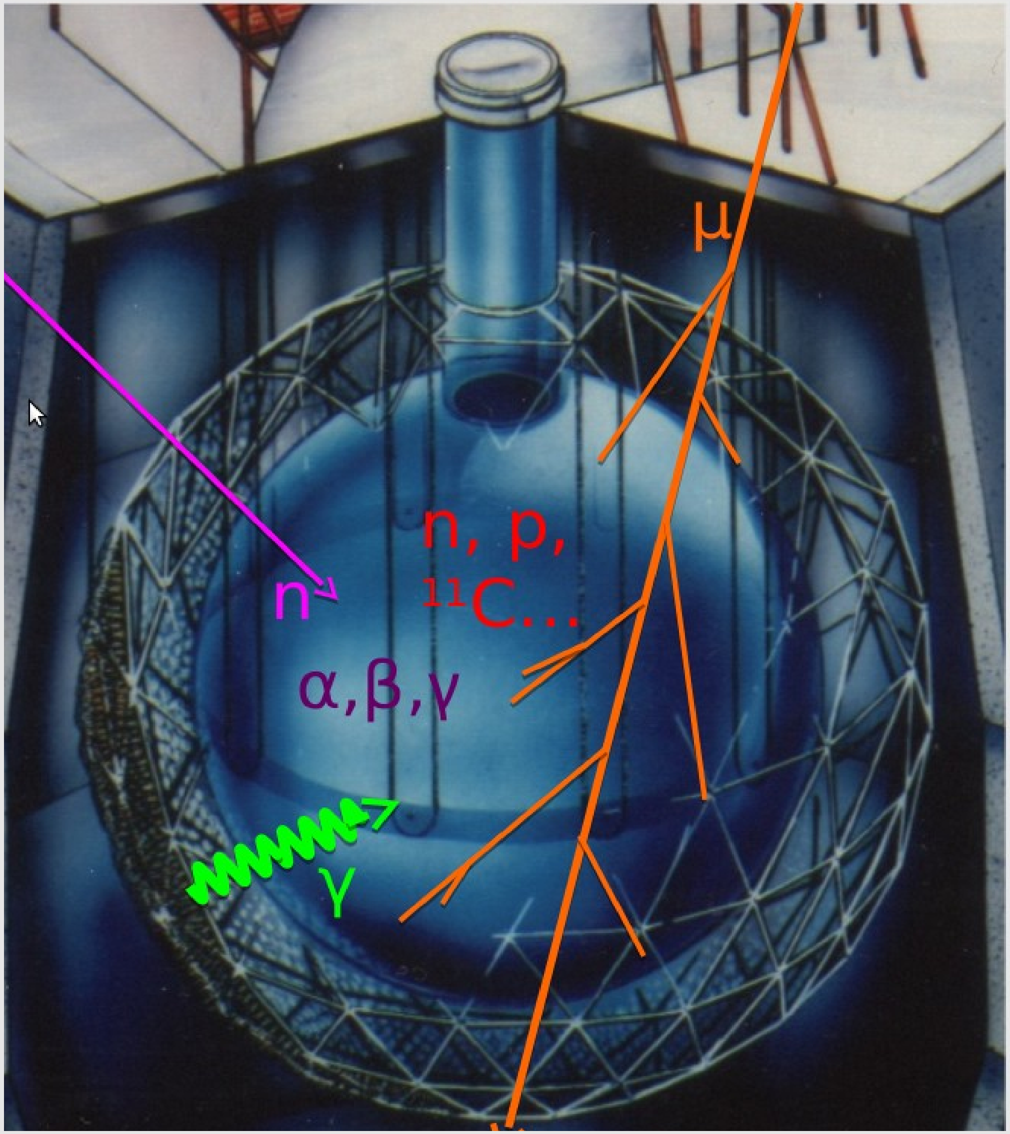
Developed at Oxford

Te-Diol complex and optics

- ✔ Diols are characterized by similar attenuation length than LAB
  - ✔ At 0.5% Te-diol >10 m (above 380 nm)
  - ✔ Optical transparency doesn't change with increasing loading
  - ✔ At 0.5% Te-diol intrinsic quenching no dominant
    - ✔ Expect ~400 Nhits/MeV
  - ✗ Diol is a quencher which needs mitigation to higher loadings
    - - Ways to reduce it under development
- ✔ High purification factor has been achieved
  - ✔ Diol distillation
- ✔ No cosmogenic activation
- ✔ Stable for > year
- ✔ Possible to purify in existing plant



Backgrounds



Internal (Scintillator + Te)
- U/Th chain, ^{40}K
- Neutron capture
- ^{14}C
- Te cosmogenics (^{60}Co,^{88}Y,^{110m}Ag,^{124}Sb)

Externals
- ^{214}Bi and ^{208}Tl gammas from AV and PMT's mainly
- Radon (and radon daughters) from AV surface leaching into scintillator (^{210}Bi, ^{210}Po, ^{210}Pb)

Fast Neutrons
From external muons

Cosmic muons
^{11}C (solar phase), n capture in H_2 2.2MeV

^{8}B solar neutrinos: constrained from SNO

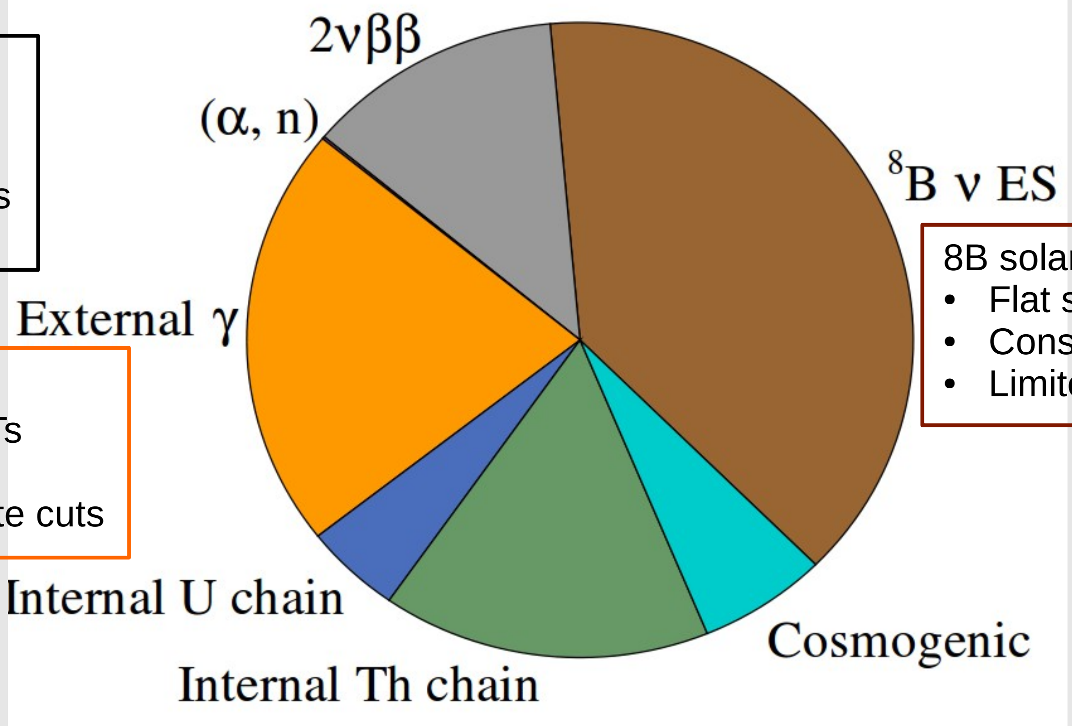
2νββ: slow rate isotope

Background Model

$2\nu\beta\beta$:
- Assymetric RoI
- Limited by energy resolution

(alpha,n)
- Alpha-capture on $^{13}C/^{18}O$
- Neutrons produced
- Capture of thermal neutrons
- Delayed coincidence tag

External γ's:
- From AV, ropes, water, PMTs
- Fiducial volume (20%) cut
- 50% extra rejection multi-site cuts



8B solar neutrinos:
- Flat spectrum
- Constrained by SNO/SK data
- Limited by resolution

Internal U/Th chain:
- 214BiPo, 212BiPo
- β–α delayed coincidence tagging
  - 100% rejection in RoI
  - In-window trigger: x50 rejection

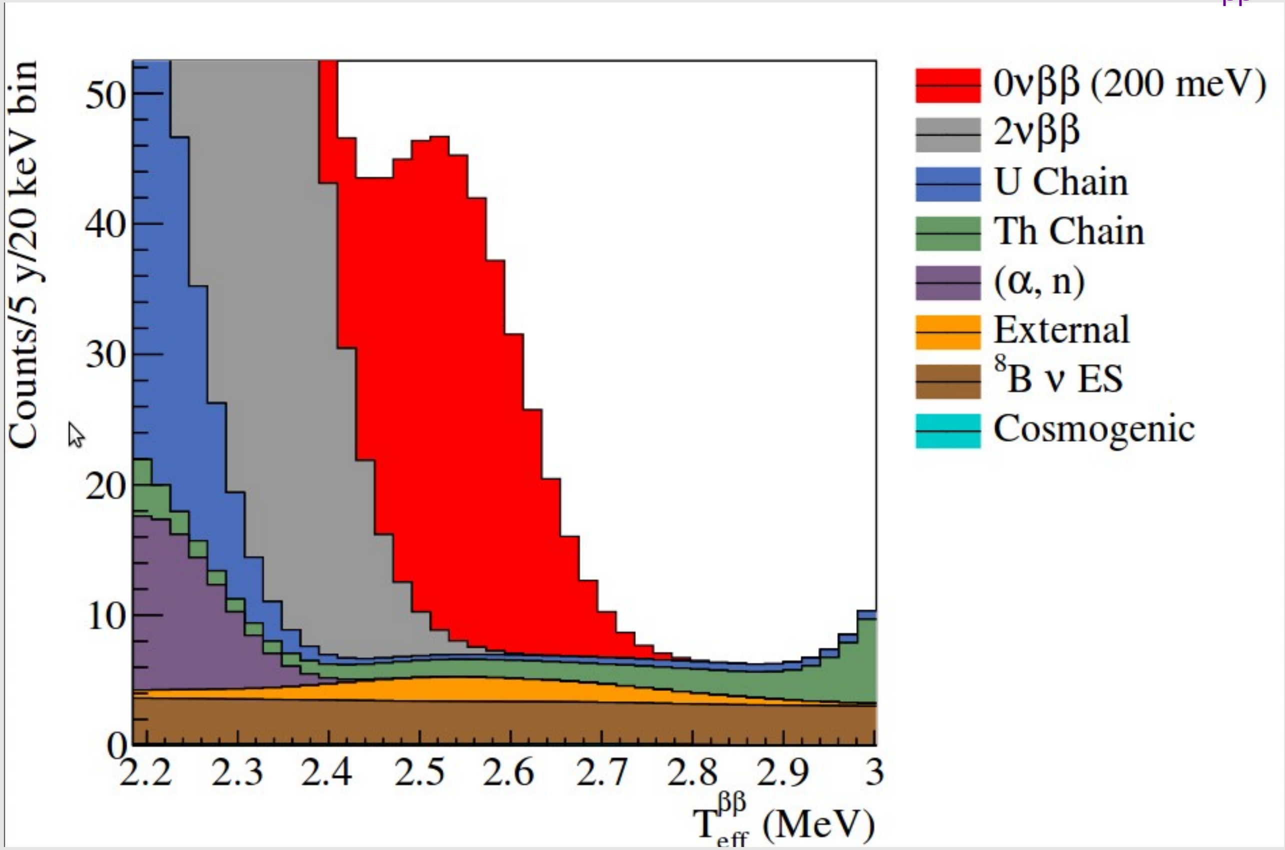
Cosmogenic:
- Mitigation: purification + “cool-down” UG
- <1ev/yr in RoI-FV
- Further reduction if needed: multi-site events

Total = 13.4 c/y

3.16×10^{-4} c/y/kg/keV

Background Model and sensitivity

0.5%Te, 5 yr, assymetric RoI −0.5σ → +1.5σ around $Q_{\beta\beta}$

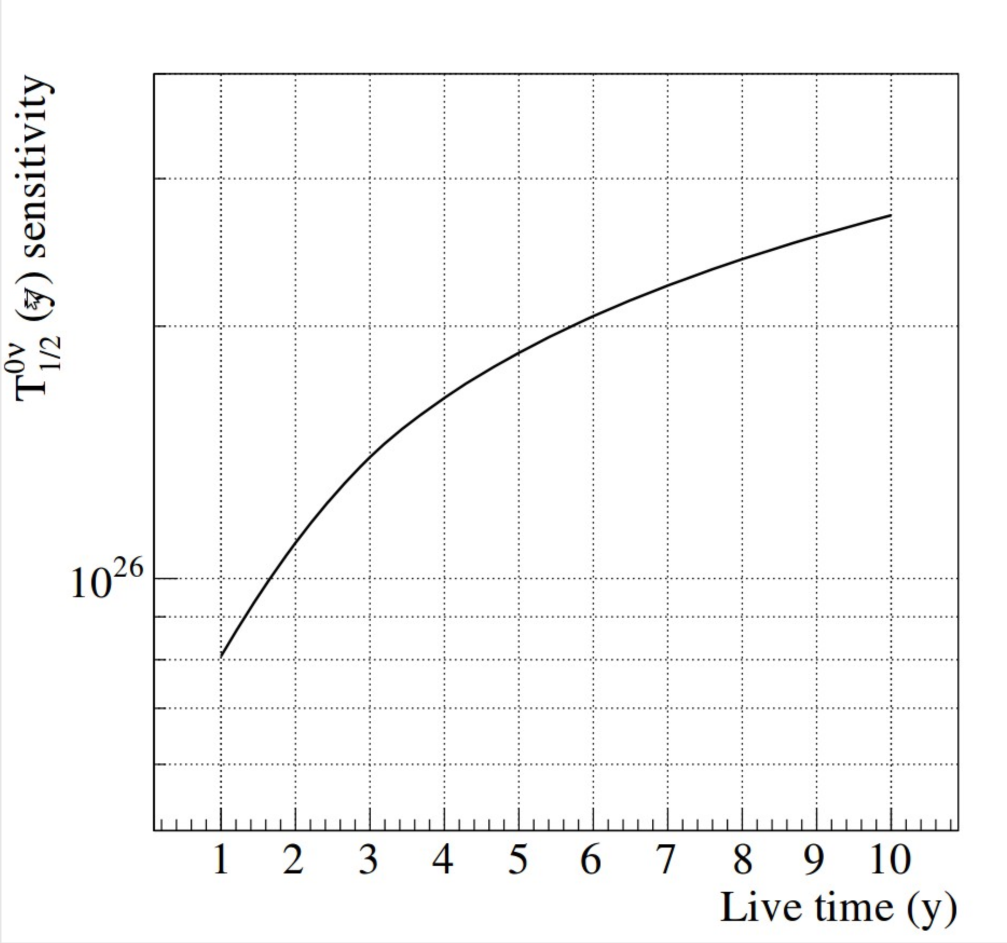


- $m_{0\nu\beta\beta}$ =200 meV*
- 3.5 m (20%) fiducial volume cut
- RoI [2487.3-2650.5] keV
- 1300 kg ^{130}Te
- Efficiency ~ 60%

- 400 Nhits/ MeV(~ 4% ΔE)
- RoI > 99.99% efficient ^{214}BiPo tag
- Factor 50 reduction ^{212}BiPo (pile-up)
- Negligible cosmogenic isotopes

*J. Barea et al. Phys. Rev. C87 (2013) 014315
J. Kotila, F.Iachello. Phys. Rev. C 85 (2012) 034316

Sensitivity



	1 year	5 year
c/y	13.39	63.43
$T_{1/2}$ (10^{26} y)	0.80	**1.96**
$m_{\beta\beta}$ (meV)	75.2	**38 - 92**

90% CL
$M^{0\nu}$ = 4.03 (IBM-2)
$G_{0\nu}$ = 3.69 x 10^{-14} y^{-1}
g_A = 1.269
IBM-2 NME model

Towards a Phase II Experiment

Improve sensitivity by improving

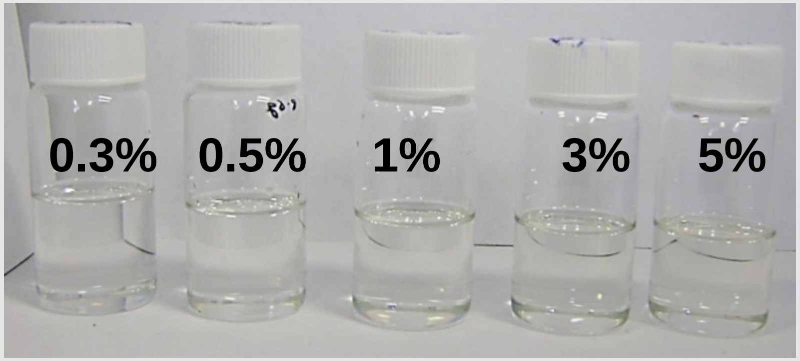
Light yield and going to **higher loading**

- Improve current technique
- New techniques also under development
- Higher QE PMTs
- Improved concentrators → Coverage to 80%
- Using a low background bag for more efficient use of isotope

30L, 0.5% Te-BD in LS

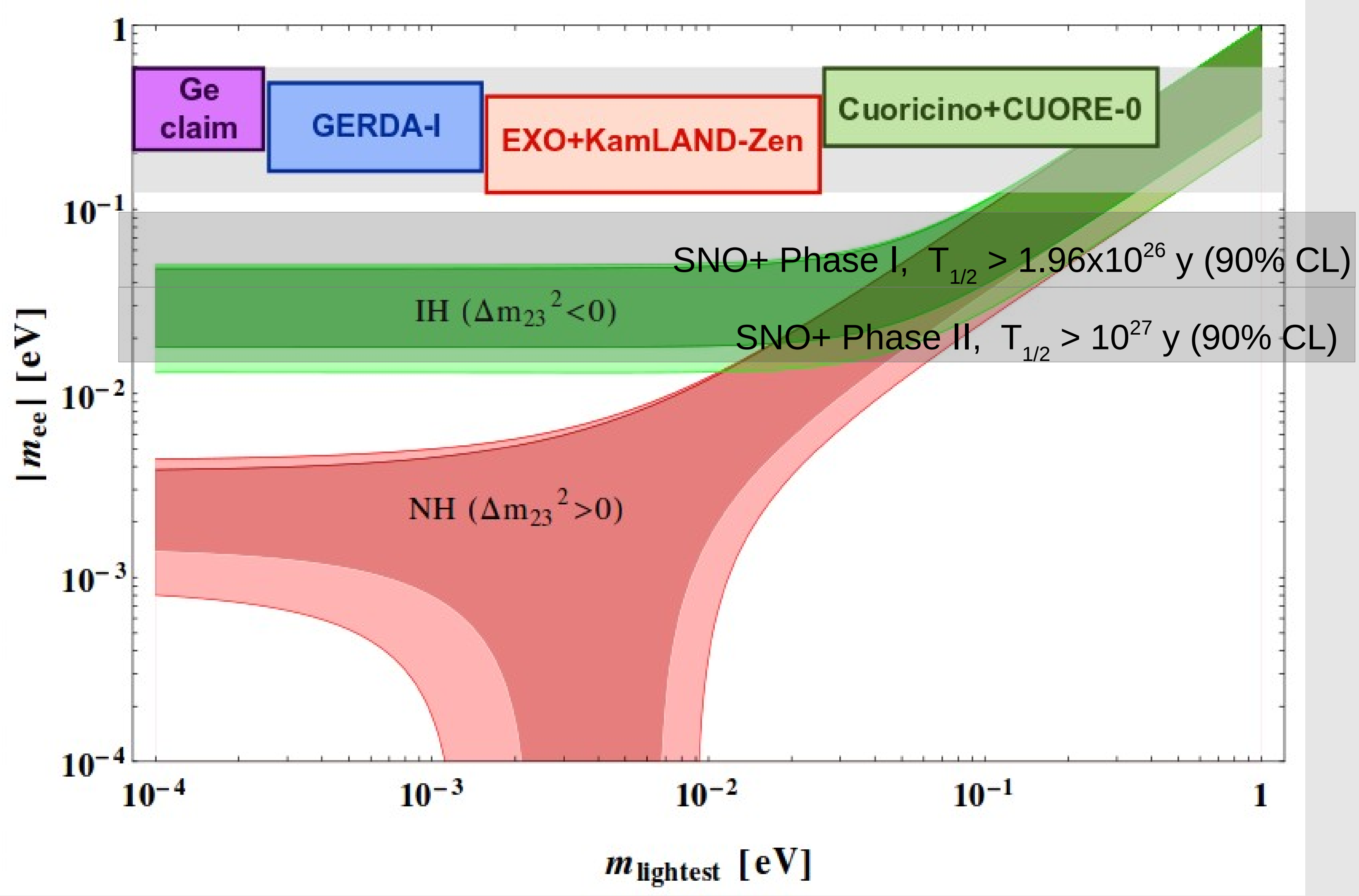
3% nat. Te loading →
~ 8 tonnes ^{130}Te

with no other improvement
$T_{1/2}^{0\nu\beta\beta} \sim 2 \times 10^{26}$ yr
+ Higher QE PMTS
$T_{1/2}^{0\nu\beta\beta} \sim 10^{27}$ yr



Different Te loadings in LAB

Sensitivity



Modified from Oliviero Cremonesi, TAUP 2015

SNO+: Other physics goals – SOLAR NEUTRINOS

SNO+ solar neutrino goal: **pep/CNO and ^{8}B solar neutrino measurement**

- Low ^{11}C background thanks to depth (100 times lower than Borexino)
- Low energy threshold thanks to LAB

➢ Precision measurement of pep solar neutrino and low energy ^{8}B neutrinos

Probe the interactions of neutrinos with matter to search for new physics

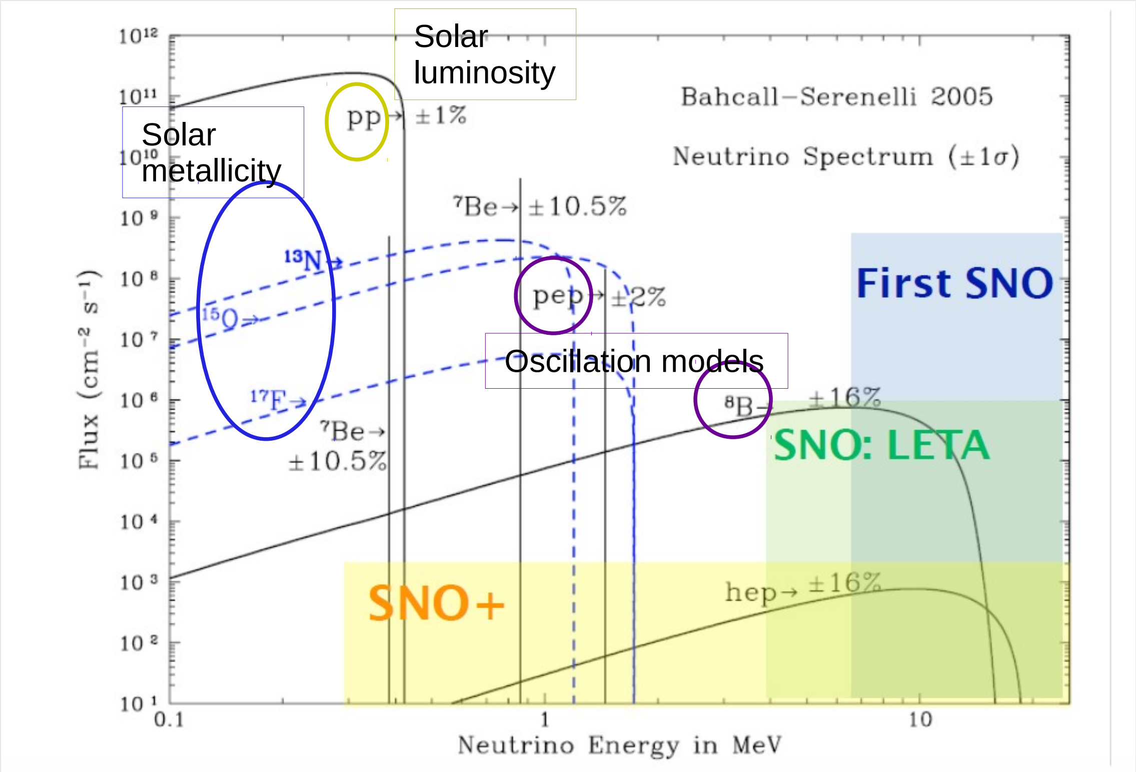
➢ CNO neutrinos: depends linearly on the core metallicity

Constrain metallicity of the solar interior

➢ + day/night asymmetry → MSW effect

- pp neutrinos depend on the ^{14}C and ^{85}Kr levels in pure scintillator
- Pep component is favourable due to:
  - single energy (1.44 MeV)
  - very well predicted flux (1.2 % uncertainty)
- ^{8}B neutrinos are favourable due to:

  the production region closer to solar interior (new physics effects enhanced)

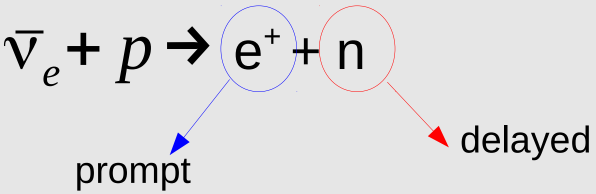


Solar luminosity

Solar metallicity

Oscillation models

SNO+: Other physics goals - ANTINEUTRINOS



$$\bar{\nu}_e + p \rightarrow e^+ + n$$

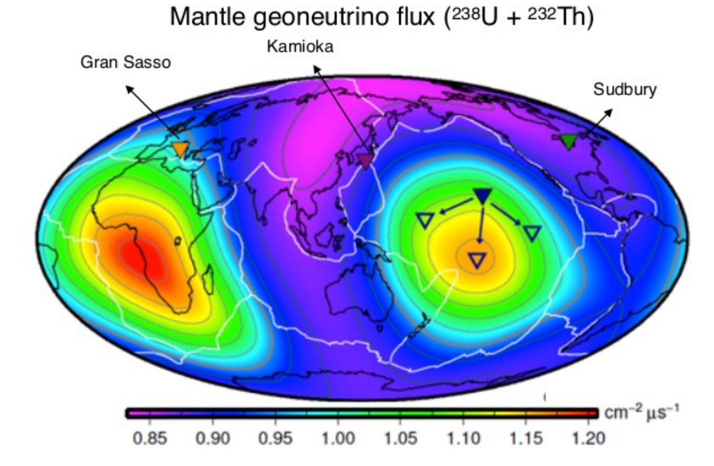
Due to the efficient neutron tagging (2.2 MeV γ) anti-neutrinos can be detected in all SNO+ phases

Reactor anti-neutrinos

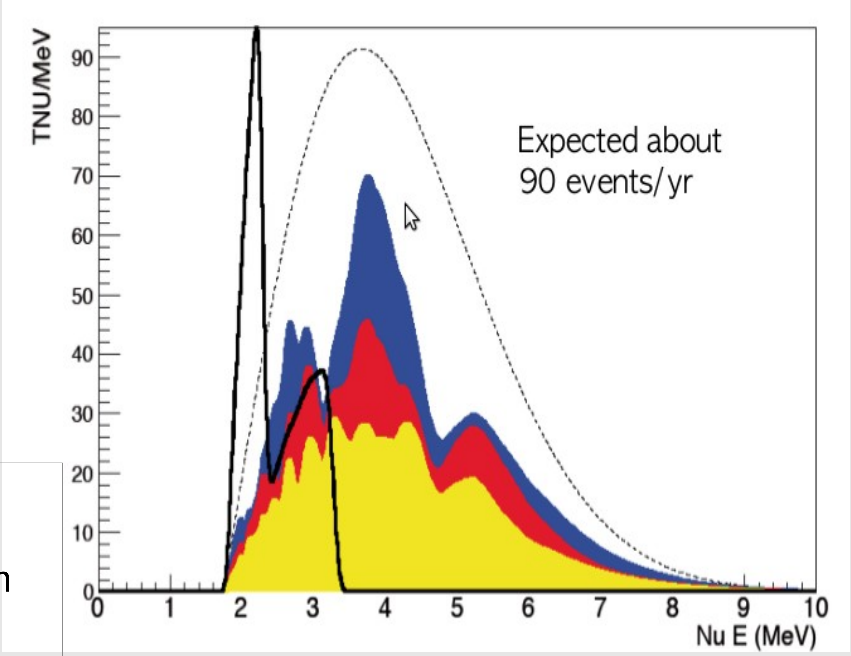
- Oscillation parameters
- 3 nearby reactors dominate flux
- Lower flux (20%) than KamLAND, but very clear oscillation pattern for L/E ~ 100 km / MeV
- All over 700km distance

Geo anti-neutrinos

- Investigate origin of radiogenic heat flow of the Earth
- Half of the anti-neutrinos flux in SNO+
- Up to now measured in KamLAND and Borexino
- Very well known geological structure in Sudbury
- U, Th and K in Earth's crust and mantle



Expected visible antineutrino energy spectrum in SNO+



Expected about 90 events/ yr

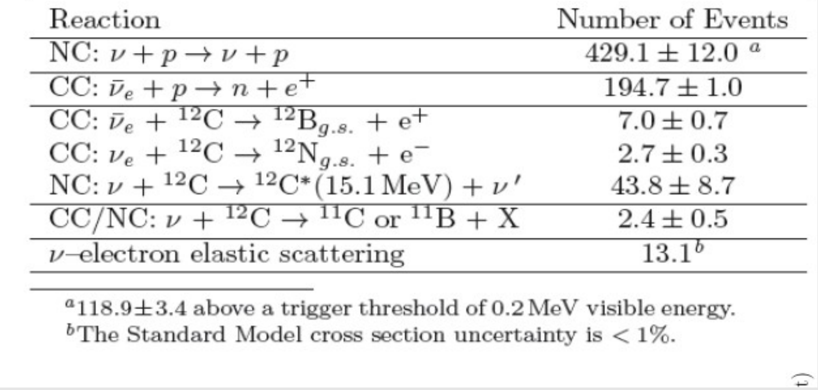
— — nonoscillated reactor spectrum
—— geoneutrino spectrum
🟦 reactor at 240km
🟥 reactors at 350km
🟨 other reactors

SNO+: Other physics goals - SUPERNOVA

- p-ν elastic scattering events (in LAB)
- SNO+ plans to be part of SuperNova Early Warning System (SNEWS)

Core-collapse supernovae: 99% of their gravitational binding energy released in the form of neutrinos (several 10^{53} erg).

Detection ways & expected signal (5.5 m 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]

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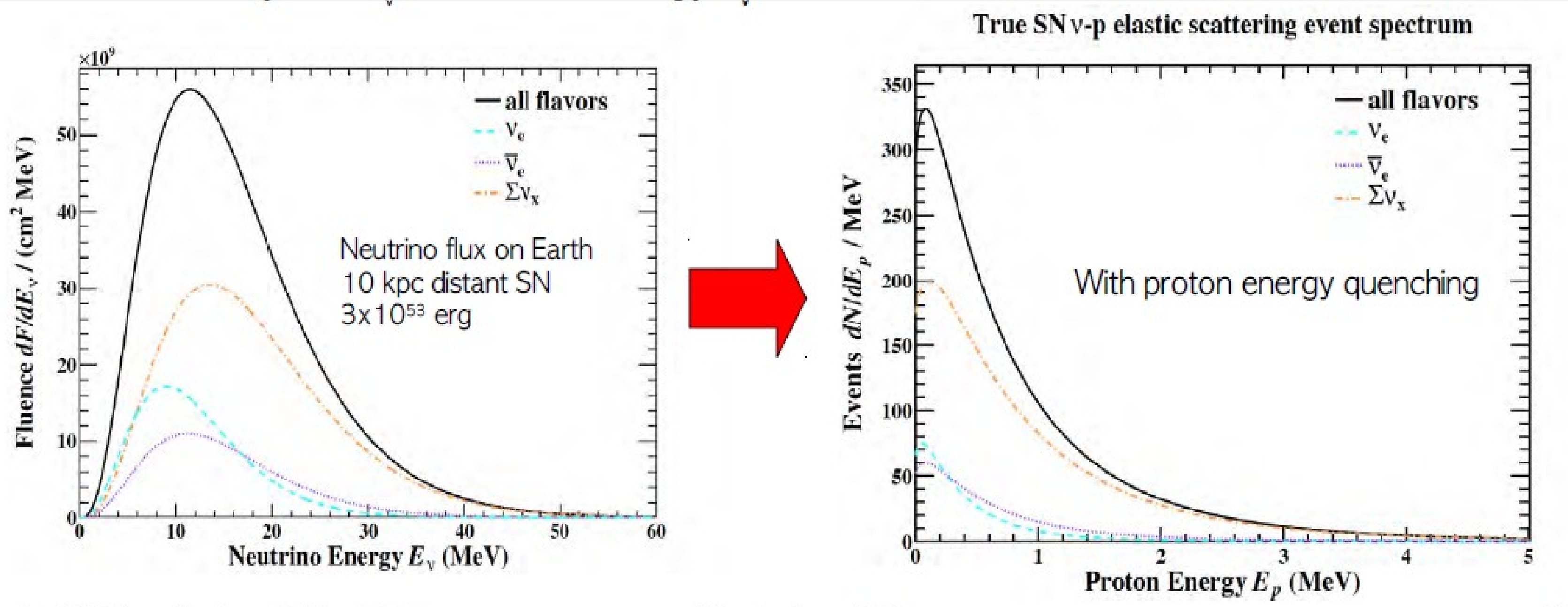
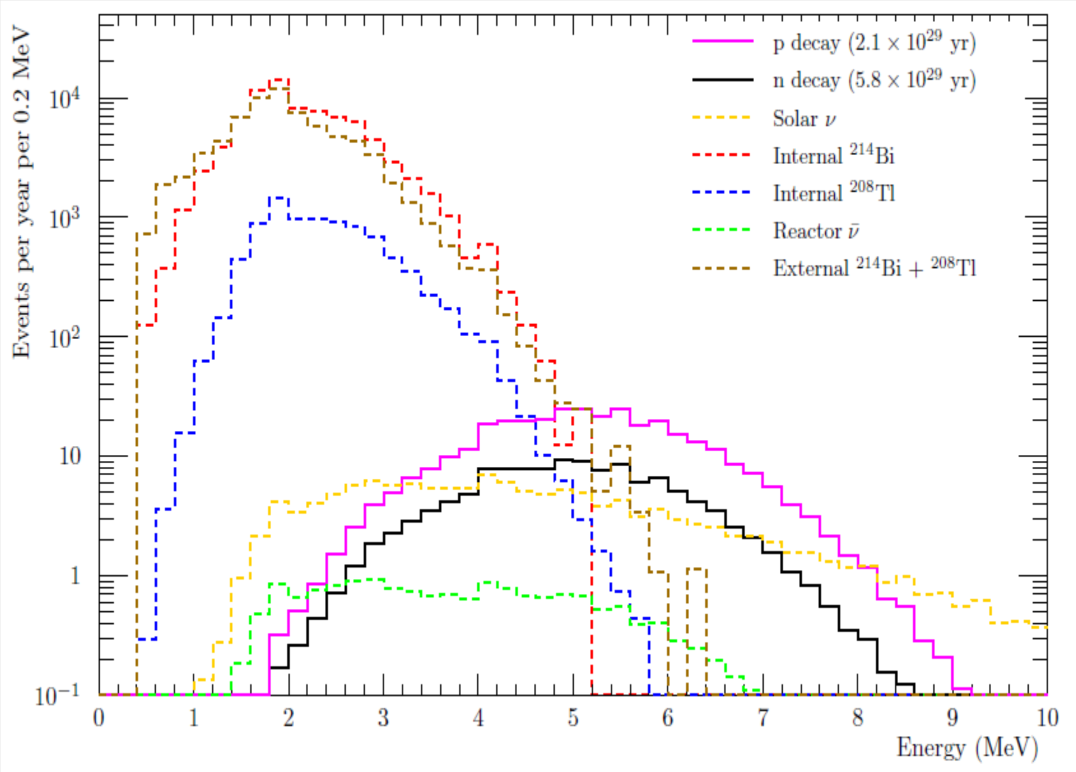
[a] 118.9±3.4 above a trigger threshold of 0.2 MeV visible energy.

[b] The Standard Model cross section uncertainty is < 1%.

SNO+ sensitivity to Ev and total energy



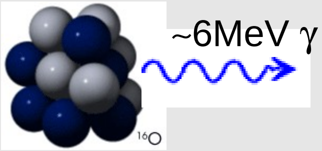
SNO+: Other physics goals – NUCLEON DECAY



Primary mode: n → 3ν

$^{16}\text{O} \rightarrow {}^{15}\text{O}^* \rightarrow {}^{15}\text{O} + \gamma$ (6-7 MeV)

- Detect signal through the de excitation of the remaining nucleus
- Nucleon decay in ^{16}O leaves an excited state, producing 6 MeV gammas around 45% of the time



Assumptions:

- 6 months of water data
- FV = 5.5 m
- Cosθ > 0.8 to solar direction
- ROI = 5.4 – 9 MeV

Proton mode τ > 1.38×10^{30} yrs
Neutron mode τ > 1.25×10^{30} yrs

Current limit 5.8×10^{29} yrs, KL

SNO+ Timescale

- Detector

2016
  - Water fill (July 2016)
  - Commissioning with water
  - Scintillator fill (~ 6 months)

2017
  - Scintillator fill (~ 6 months)
  - Pure scintillator commissioning
  - Mix tellurim in (end 2017)
  - Te loaded phase starts ($0\nu\beta\beta$)

2018
  - $0\nu\beta\beta$ data-taking

2016
- Scintillator plant
  - Commissioning
- Te purification plant

2017
  - Installation complete

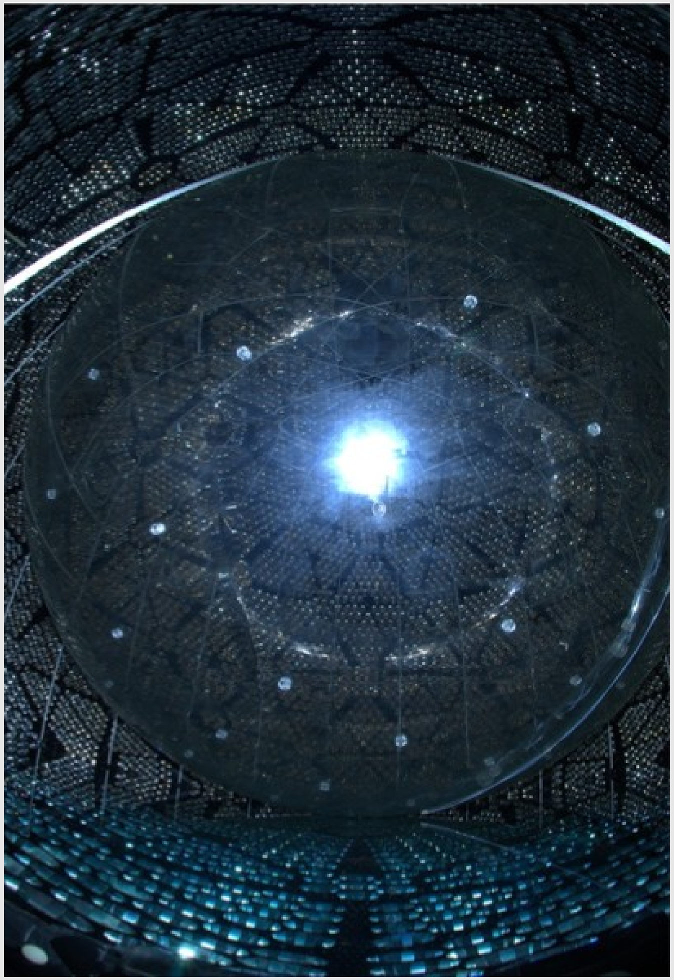
Goal	Water	Pure LS	Te-LS
Neutrinoless double-beta decay			☑
^{8}B solar neutrinos		☑	☑
Low energy solar neutrinos		☑	
Reactor and geo anti-neutrinos		☑	☑
Exotics searches	☑	☑	☑
Supernova	☑	☑	☑

Conclusions and Outlook

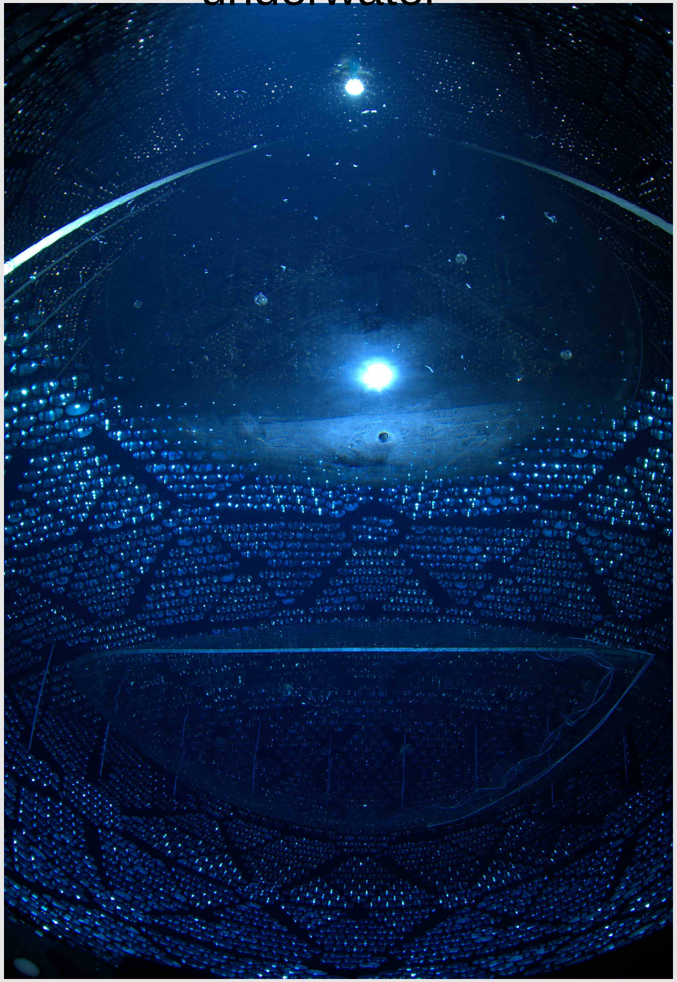
- SNO+ is a multi-purpose neutrino liquid scintillator detector
- First aim is the **neutrinoless double-beta decay** search with **^{130}Te**
- Developed purification and loading techniques for large amount of Te
- Developed background models based on activities and optical properties measured
  - Main backgrounds do not scale with Te loading!
- Initial **0.5%Te** (by mass) loaded → **$T_{1/2}^{0\nu\beta\beta} \sim 2 \times 10^{26}$ yr**
  - Expect to reach top of inverted hierarchy region of masses
- Improvement for phase II in light yield and higher loading will allow to cover all the inverted hierarchy
- Progress on many other fronts as
  - AV rope systems, calibration systems, scintillator plant, ...
- Water-phase data will start summer 2016
- Te-loaded phase will start by the end of 2017

Thank you!

Camera above water



Camera and light underwater



Camera underwater, light above water