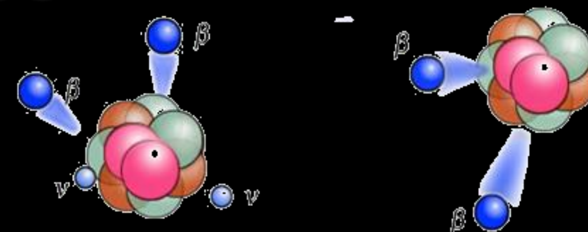
Organic Scintillator and Tellurium Purification Techniques of the SNO+ Double Beta Decay Experiment

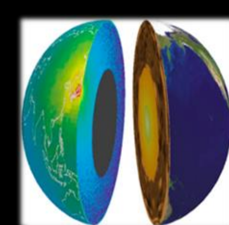
Szymon Manecki, Queen's University
Low Radioactivity Techniques - Korea
Ewha Womans University, May 26th, 2017

SNO+ Physics Goals

- Neutrinoless Double Beta Decay of ^{130}Te
- Low Energy Solar Neutrinos
- Reactor Antineutrinos
- Geo-Neutrinos
- Supernova-ν



- Three stages:
  - Water phase
  - Liquid scintillator phase
  - Te-loaded liquid scintillator



SNOLAB Facility

SNO+ Detector

780t of liquid scintillator
(LAB+PPO)

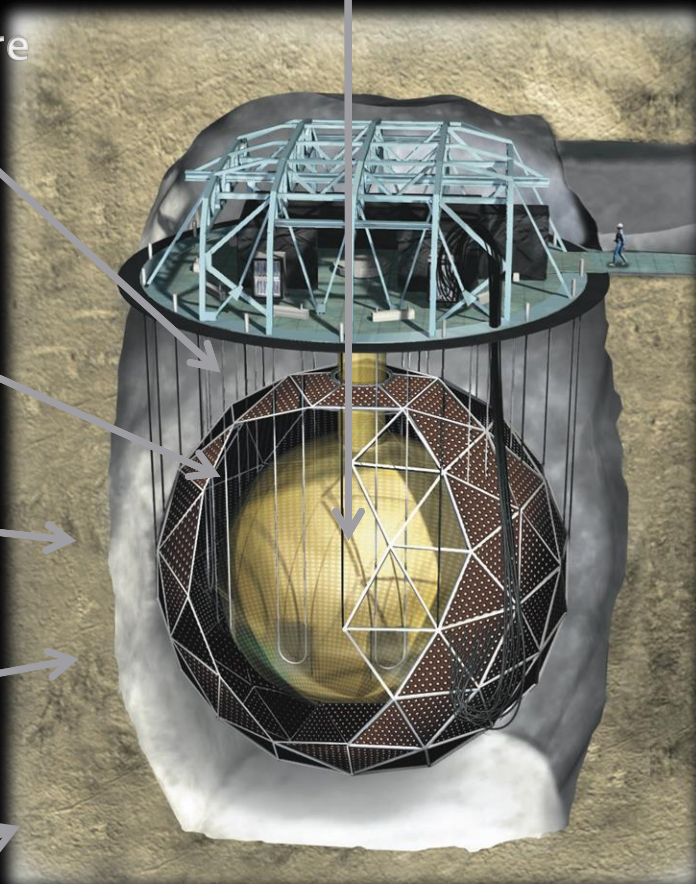
PSUP = PMT Support Structure
~9500 PMT, 54% Coverage

Acrylic Vessel (AV)
Φ=12m, thickness=5cm

Light water (H_2O) shielding
- 1700t internal
- 5300t external

Urylon Liner/Radon Seal

Norite Rock



Low cost
High flash point: 130°C
Low toxicity

Light attenuation length> 20 m at 420 nm

High light yield (~10,000 photons/MeV)

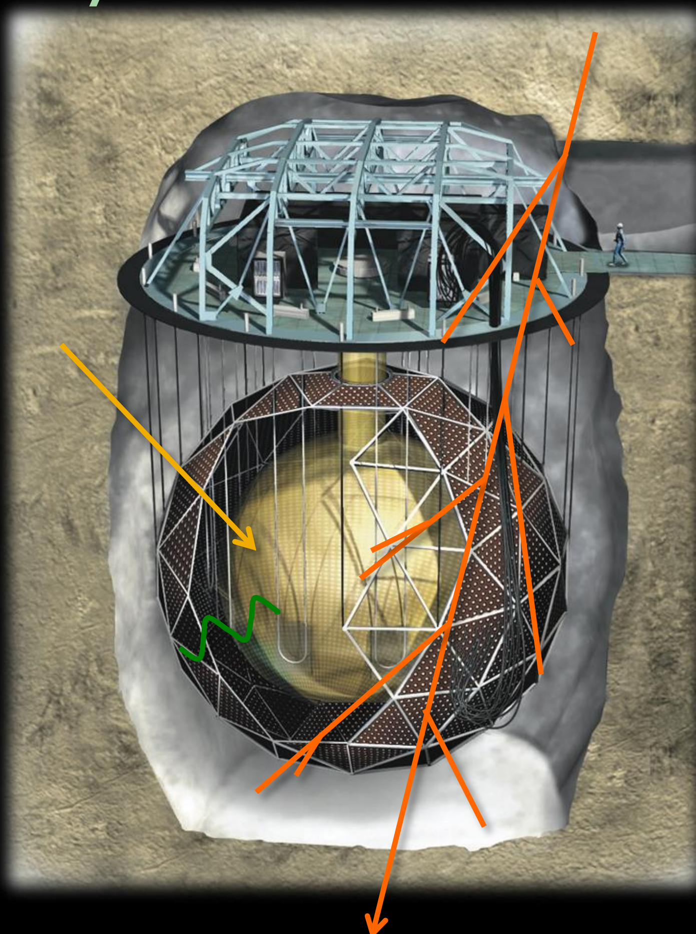
Smallest scattering of all scintillating solvents investigated

SNO+ Detector

Internal Radioactivity
Traces of radioisotopes (U/Th chain, ^{40}K, etc) in the scintillator

External Gammas
from decays in the acrylic, water, PMTs, etc.

Fast Neutron
from external muons



Cosmogenics
Neutrons and radionuclides from spallation and hadronic showers

Cosmic Ray Muons

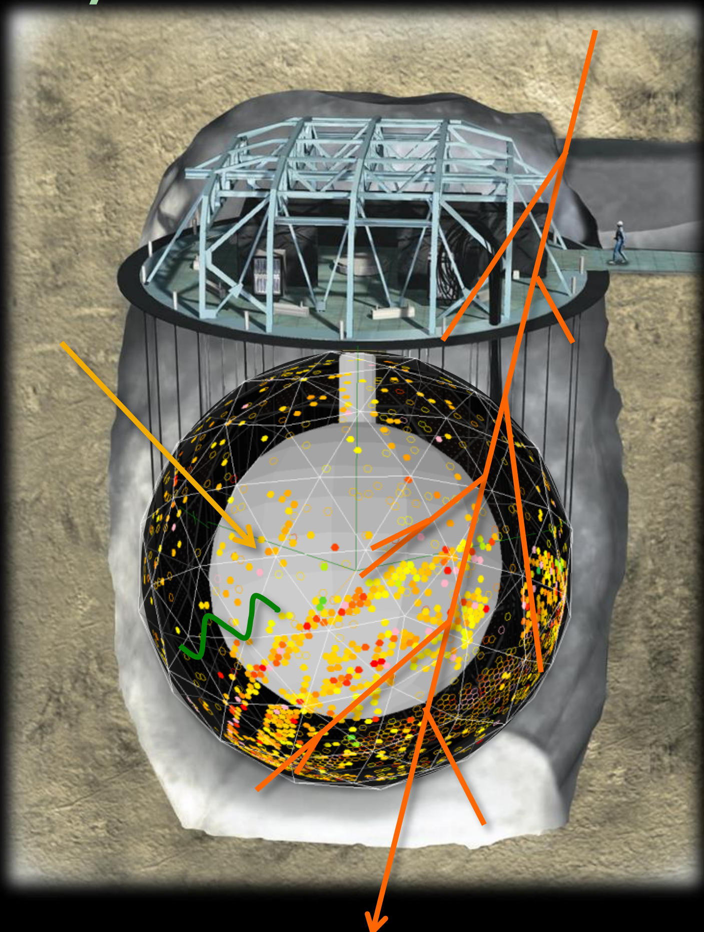
μ n γ α, β
n, p, ^{11}C…

SNO+ Detector

Internal Radioactivity
Traces of radioisotopes
(U/Th chain, ^{40}K, etc)
in the scintillator

External Gammas
from decays
in the acrylic, water,
PMTs, etc.

Fast Neutron
from external muons



Cosmogenics
Neutrons and radionuclides from spallation and hadronic showers

Cosmic Ray Muons

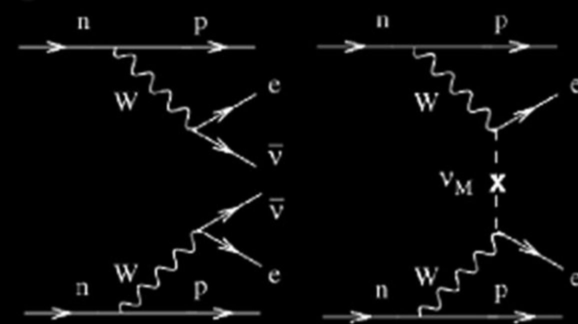
μ n γ α, β
n, p, ^{11}C…

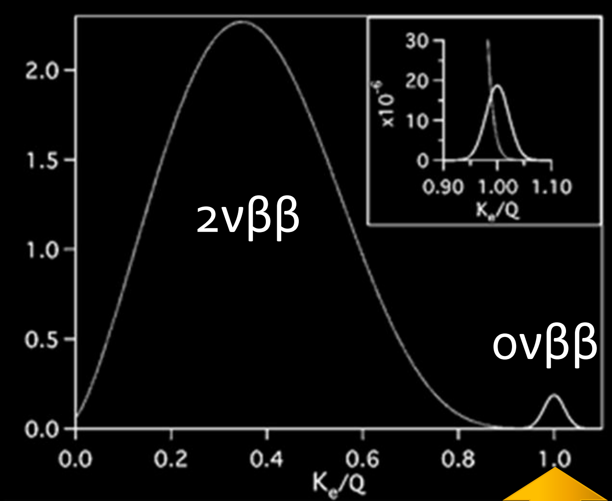
^{130}Te Double Beta Decay

- Are neutrinos their own anti-particles?
  - 2νββ (Dirac)
    $(A, Z) \longrightarrow (A, Z+2) + 2e^- + 2\nu_e$
    ~ 10^{18}-10^{21} years
  - 0νββ (Majorana)
    $(A, Z) \longrightarrow (A, Z+2) + 2e^-$
    > 10^{25} years
  - With the Mass Mechanism:

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

$$\langle m_{\beta\beta}\rangle^2 = |\sum_i U^2_{ei}\, m_{\nu i}|^2$$



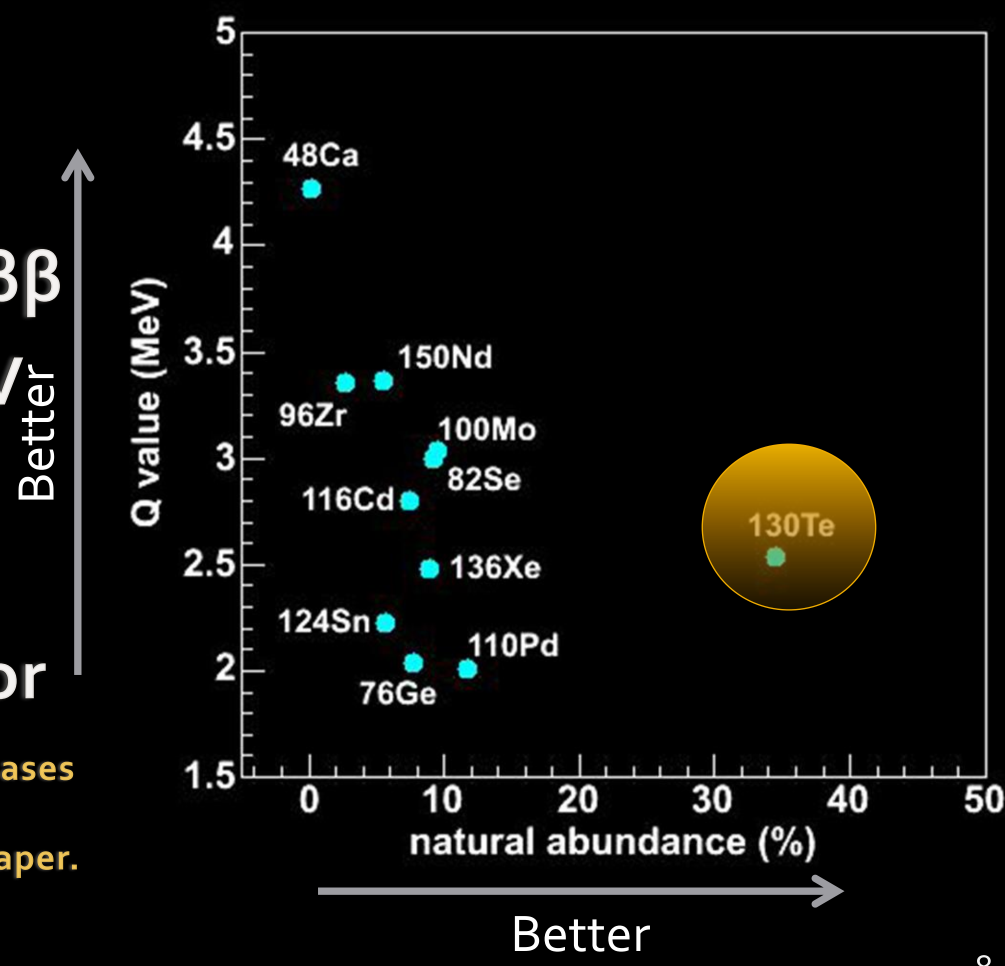


D.B.D. experiments need good energy resolution, low backgrounds, and large amounts of isotope.

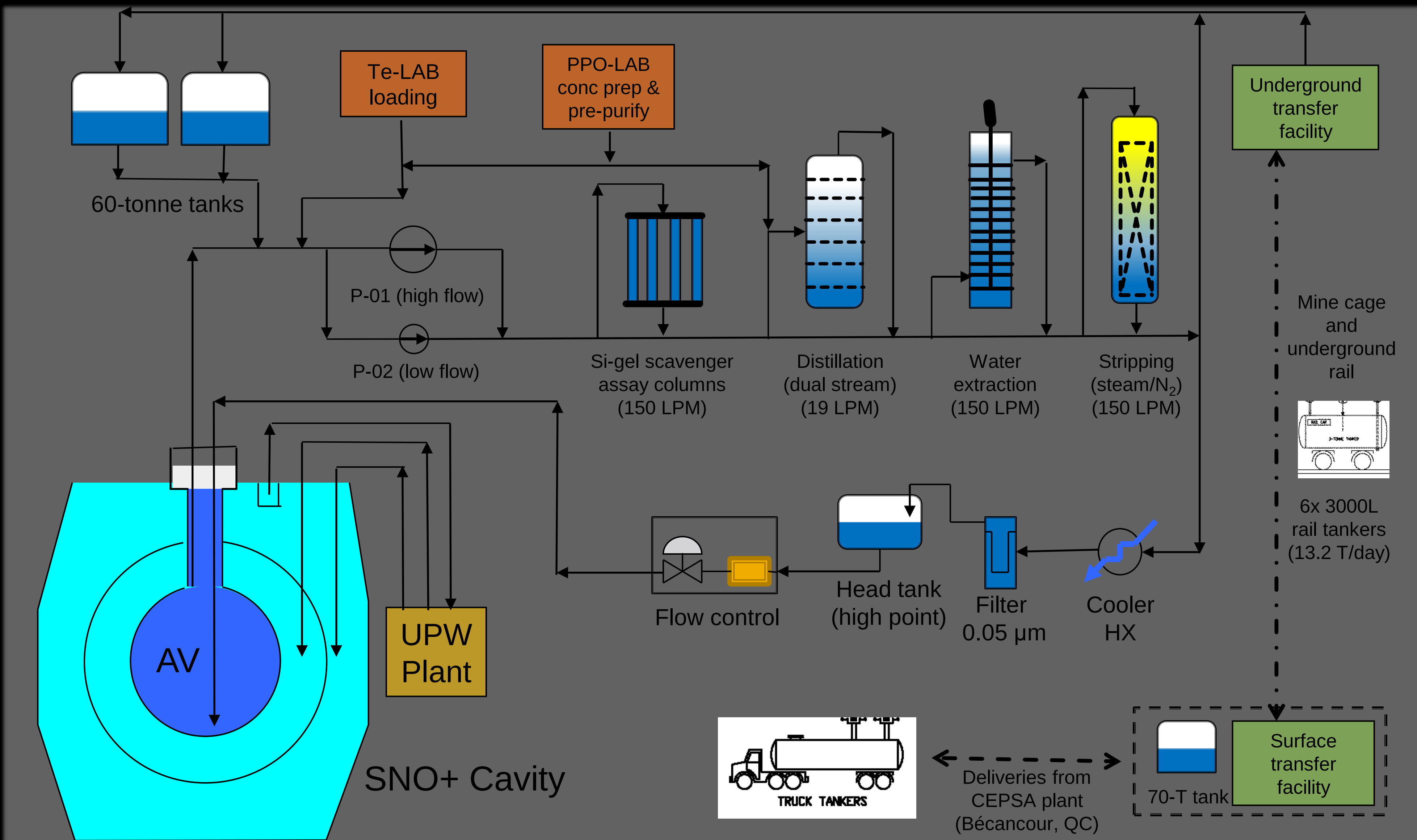
^{130}Te Double Beta Decay

- Selection of the best isotope for SNO+
  - High natural abundance (34%)
  - $T_{1/2}^{2nbb}$= 7x10^{20} years one of the longest 2νββ
  - High $Q_{\beta\beta}$ = 2526.97keV
  - High light yield
  - Successfully loaded in the liquid scintillator

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



Scintillator Purification Plant



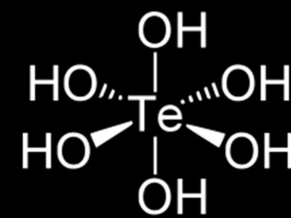
Scintillator Purification Plant

- Multi-stage distillation
  - Dual-stream PPO distillation
  - Removes heavy metals
  - Improves UV transparency
- N_2 / steam stripping
  - Removes Rn, Kr, Ar, O_2
- Water extraction
  - Removes Ra, K, Bi
- Metal scavenging
  - Removes Bi, Pb
- Microfiltration
  - Removes 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

Telluric Acid Production

- Te extracted from mine (depth ~ 300 m) in April 2014



  - Visit to the production site prior to start of processing
  - QA/QC tests on samples from each barrel before approval to send to SNOLAB

3.8 tonnes of $Te(OH)_6$, corresponding to ~2.1 tonnes Te, or ~0.26% Te loading

- Shipped to SNOLAB (January 7th 2015)
  - Transported underground on January 19th 2015
  - Testing one sample from one of the barrels to cross-check previous results

Telluric Acid Purification

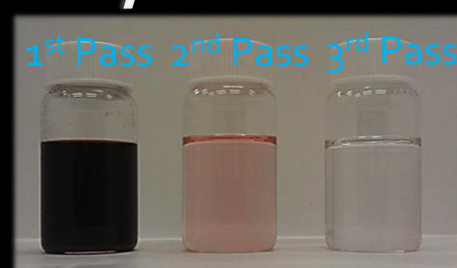
- The purification technique relies on solubility of TeA in water based on pH
  - $Te(OH)_6 \leftrightarrow Te(OH)_5O^- + H^+$
    in-soluble soluble
  - Insoluble contamination
    - Dissolve in water, and filter
  - Soluble contamination
    - Force TeA to recrystallize by adding Nitric Acid, let it precipitate out, and drain the "dirty" liquid
  - The process can be made tellurium selective

Telluric Acid Purification

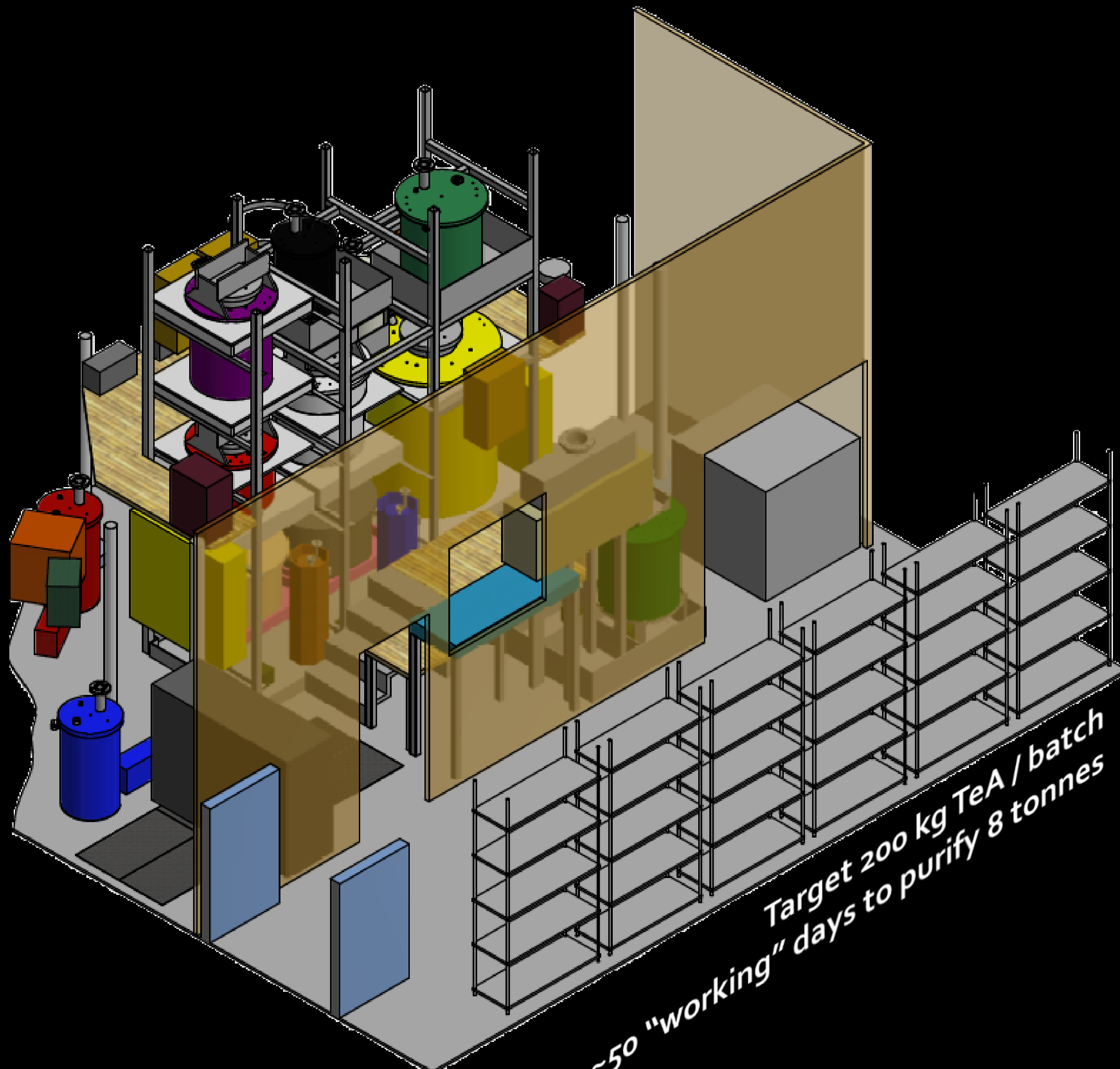
- 0.5% Tellurium Target levels:
  - $1.3\text{x}10^{-15}$ g/g in ^{238}U ($3\text{x}10^{-8}$ Bq/kg)
  - $5\text{x}10^{-16}$g/g in ^{232}Th ($1.2\text{x}10^{-9}$ Bq/kg)
    - (raw Te ~10^{-11} g/g U/Th, 10^{-4} Bq/kg)
- Cosmogenic contamination from activation on Te
  - ^{60}Co, ^{110m}Ag, ^{126}Sn, ^{88}Zr, ^{88}Y, ^{124}Sb
    - Rejection needed 10^4-10^5

Isotope	t_{exp}=1 yr
^{22}Na	15309
^{26}Al	0.048
^{42}K	565
^{44}Sc	102
^{46}Sc	43568
^{56}Co	2629
^{58}Co	25194
^{60}Co	6906
^{68}Ga	37343
^{82}Rb	18047
^{84}Rb	11850
^{88}Y	390620
^{90}Y	823
^{102}Rh	276189
^{102m}Rh	133848
^{106}Rh	1534
^{110m}Ag	69643
^{110}Ag	939
^{124}Sb	3101138
^{126m}Sb	240
^{126}Sb	358996

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



Telluric Acid Purification Plant



Telluric Acid Purification Plant

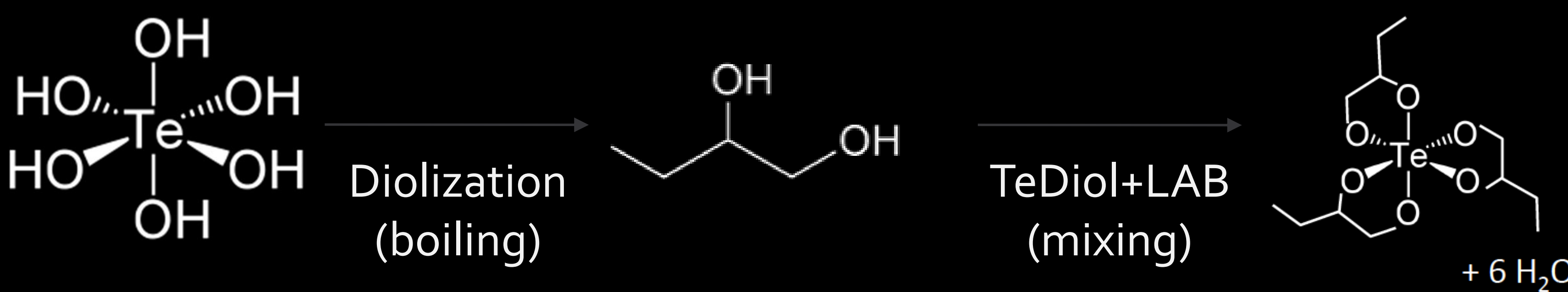
0νββ LS Requirements

- Reach high tellurium concentration
  - 0.5% Te in 780 tonnes of scintillator
- Preserve good optics of the cocktail
  - Transparency, Scattering, Light Yield
- Maintain high purity of the scintillator
  - U/Th reduction factor
  - Cosmogenic activation

The TeDiol Complex

- Tellurium loading in Linear Alkyl Benzene
  - Through direct mixing in of an organometallic complex of Tellurium

- Butane-Diol based Te complex ("TeDiol"):

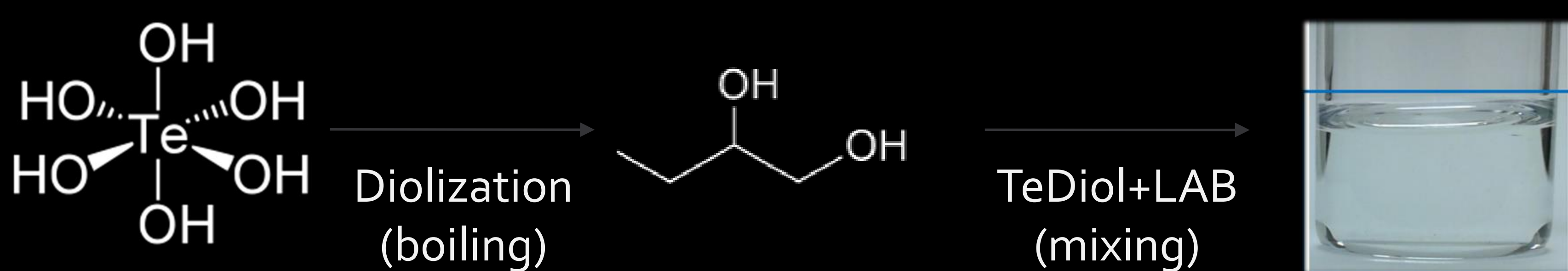


Telluric Acid Butanediol in SNO+

The TeDiol Complex

- Tellurium loading in Linear Alkyl Benzene
  - Through direct mixing in of an organometallic complex of Tellurium

- Butane-Diol based Te complex (“TeDiol”):



Telluric Acid Butanediol in SNO+

The Diol Assay

- Identified distributor in Japan, Kowa-Co.
  - High quality and affordable (8 tonnes needed)
  - $^{14}C/^{12}C$ to confirm its non-biogenic origin
    - Accelerator Mass Spectrometry at uOttawa:
      - Sample #1: $(14.3 \pm 1.2) \times 10^{-16}$ Blank #1: $(26.0 \pm 7.4) \times 10^{-17}$
      - Sample #2: $(4.8 \pm 1.2) \times 10^{-16}$ Blank #1: $(2.5 \pm 1.2) \times 10^{-17}$

The André E. Lalonde AMS Laboratory

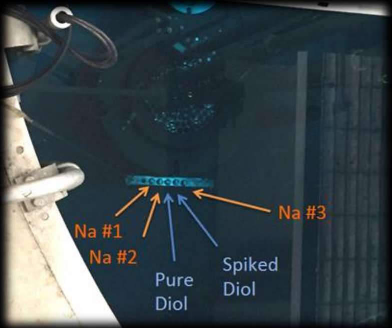
University of Ottawa
25 Templeton Street
Ottawa, ON K1N 6N5
Canada

Radiocarbon@uOttawa.ca

The Diol Assay

- Gamma-ray spectrometry
  - High Purity Ge (HPGe) detector at SNOLAB
    - $^{238}U < 3.13$ ppb
    - $^{232}Th < 0.26$ ppb
    - $^{40}K < 386.56$ ppb

- Neutron Activation Analysis
  - NAA at UC Davis
    - $^{238}U < 0.3$ ppb
    - $^{232}Th < 3.3$ ppb
    - $^{nat}Na \sim$ ppm -> a fraction of which is ^{22}Na

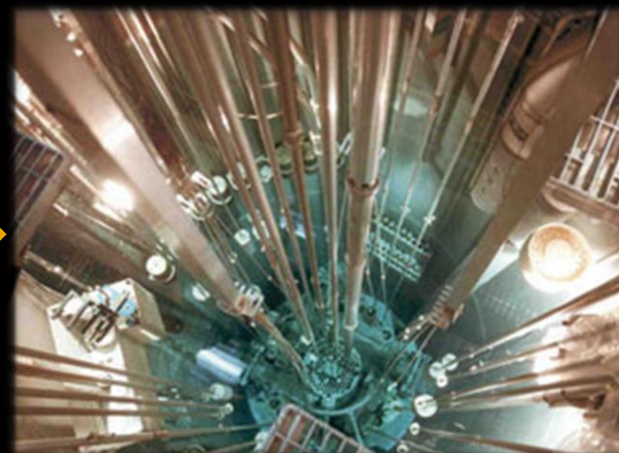


Experiment or Laboratory	Total (2005 - Today)
SNO	11
SNO+	125
SNOLAB	81
EXO	19
MiniCLEAN	56
DEAP	133
HALO	13
PICASSO	9
DM-ICE / DRIFT	23
COUPP / PICO	92
DAMIC	15
NEWS-SNOLAB	1
Total	578
Calibrations & Tests	118

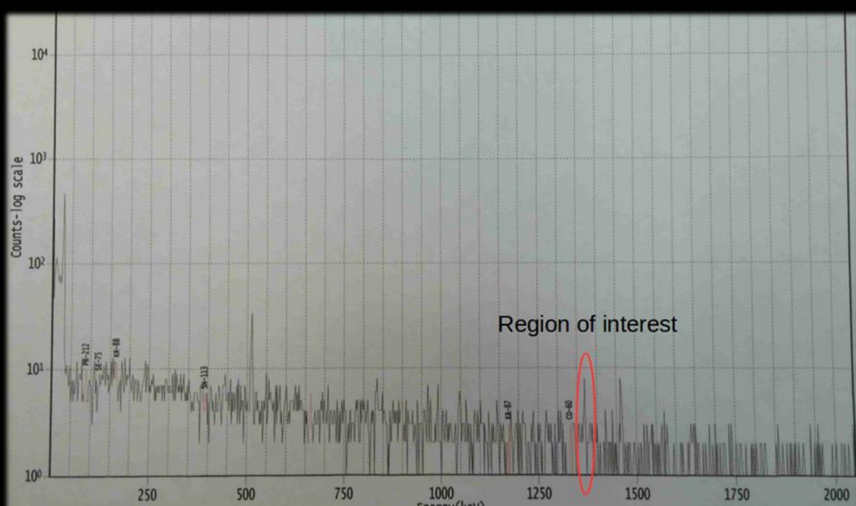
The Diol Assay

- Tracing sodium contamination with NAA



TRIGA-type research reactor in Sacramento, owned and operated by UC Davis



Na (2.2 ± 1.0) ppb

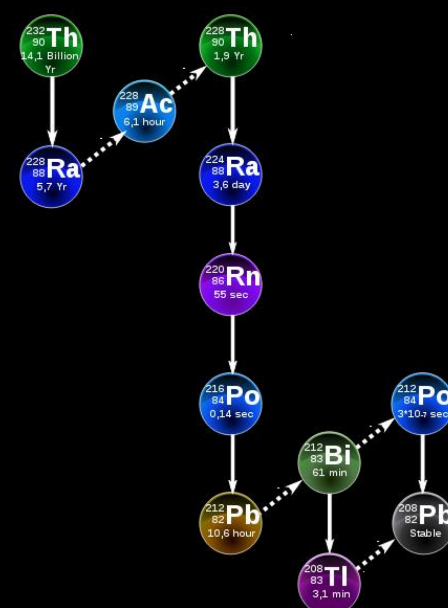
The Diol Purification

- Bench-top distillation with radio spikes
  - ^{228}Th spike in 1,2-Butanediol
    - Low T (70 °C, 80 mTorr)

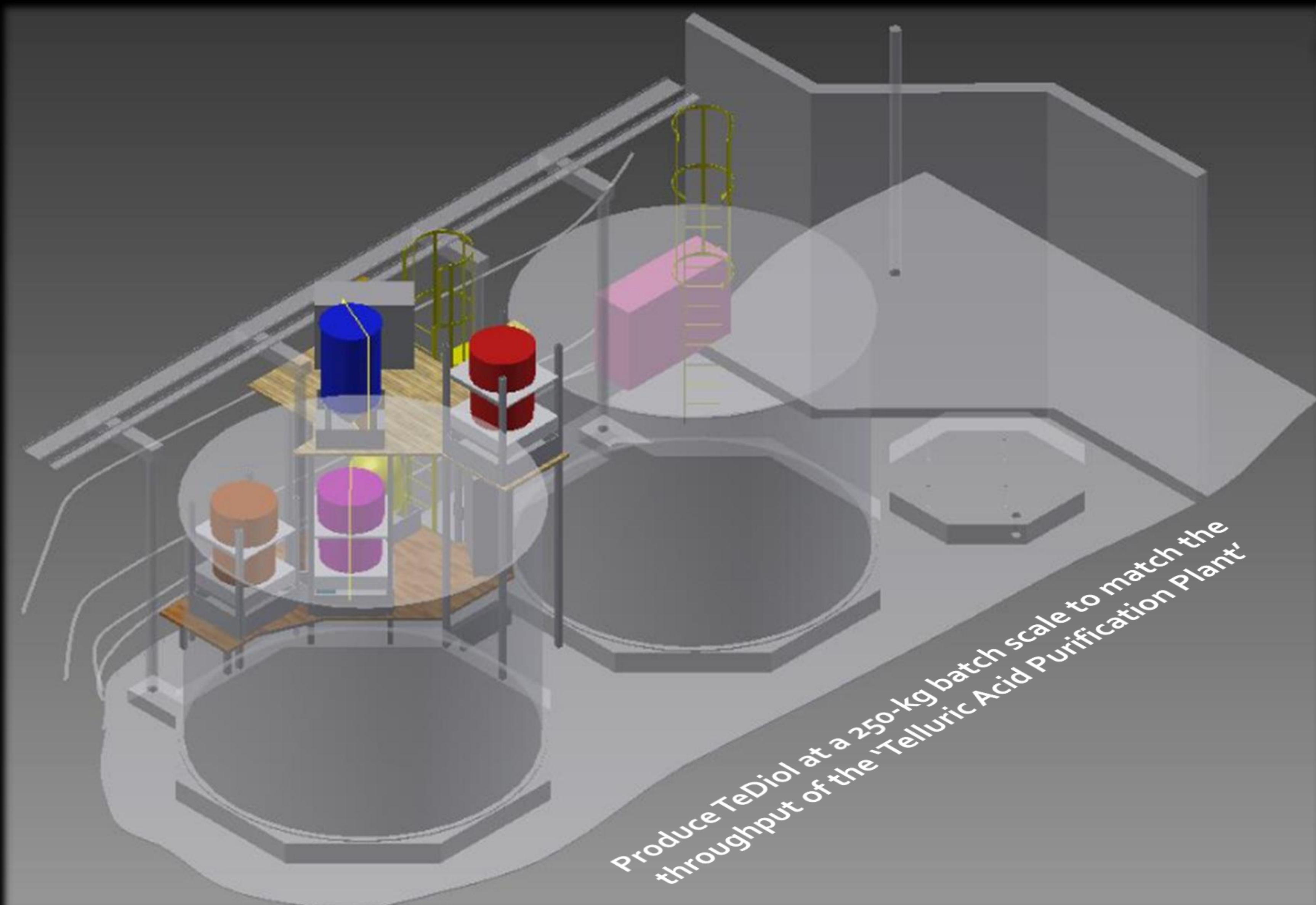
	Initial activity mBq/g	Distillate activity mBq/g	Reduction factor
^{228}Th	72	<0.014	>5100
^{224}Ra	72	<0.013	>5500

    - High T (170 °C, 225 Torr)

	Initial activity Bq/g	Distillate activity µBq/g	Reduction factor
^{228}Th	1.94	7 ± 1	280 000
^{224}Ra	1.94	13 ± 5	150 000



The TeDiol Plant

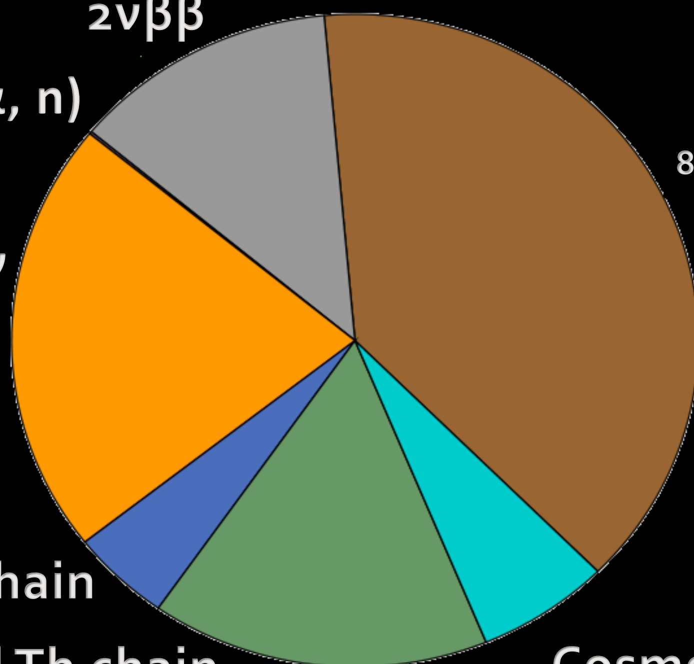


The TeDiol Plant

Backgrounds Budget

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

^{8}B ν ES
^{8}B solar neutrinos:
Flat spectrum
Constrained by SNO/SK data
Limited by resolution



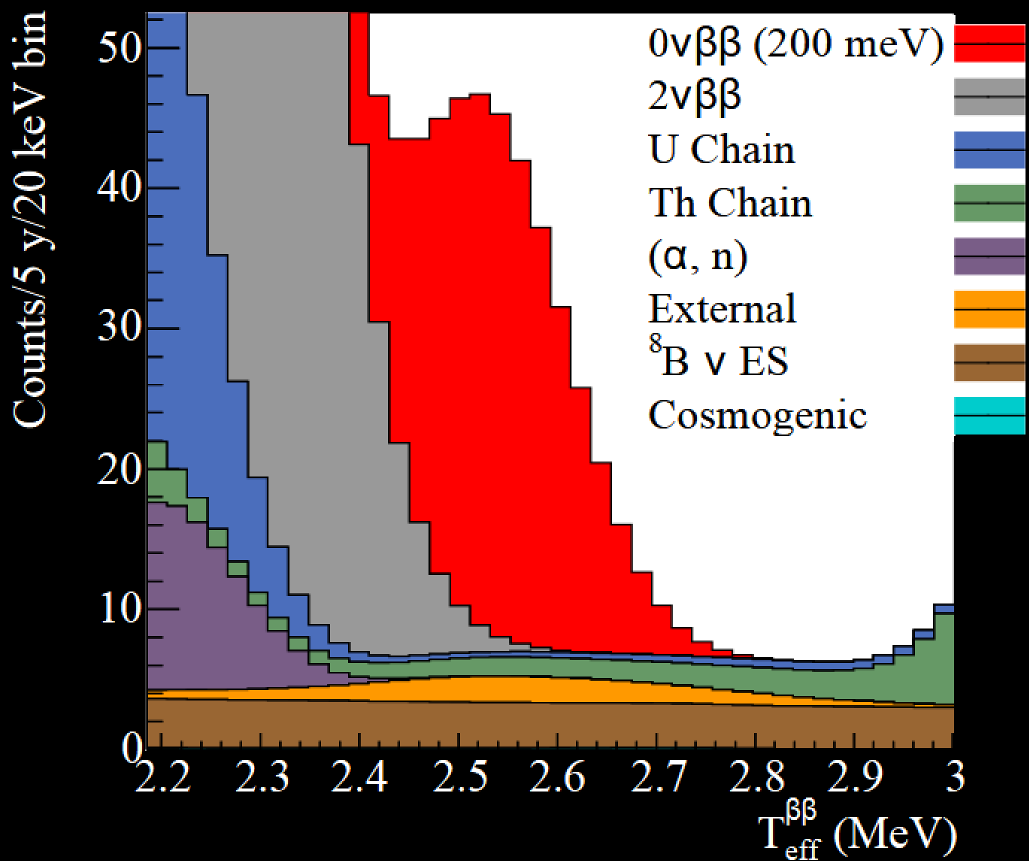
External γ
From AV, ropes, water, PMTs
Fiducial volume (20%) cut
50% extra rejection multi-site cuts

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

Internal U/Th
^{214}BiPo, ^{212}BiPo
B-α delayed coincidence tagging
100% rejection in RoI
In-window trigger: x50 rejection

0νββ Sensitivity

- 1.3 tonnes of ^{130}Te in LAB (at 0.5% ^{nat-}Te)

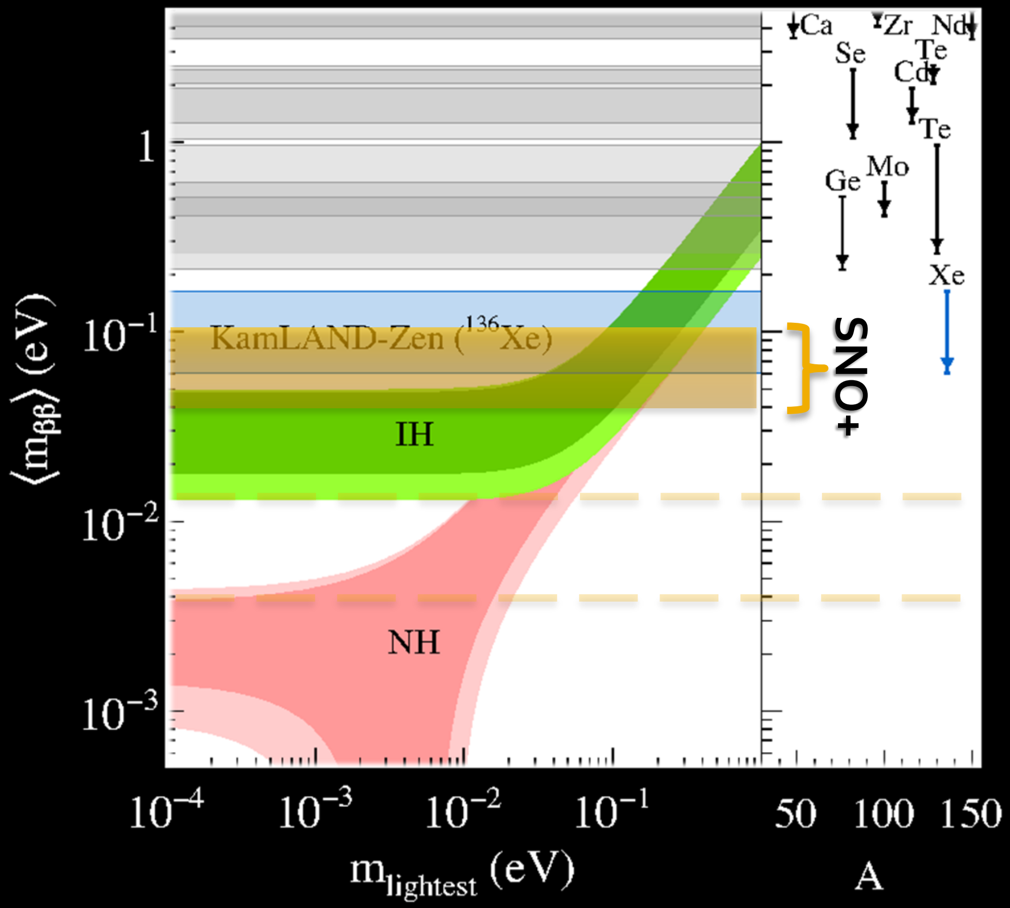


- [-0.5; +1.5] σ around $Q_{\beta\beta}$
- 400 NHits/MeV (~4% ΔE)
- Fiducial Volume: 20% total

	$T_{1/2}$ [yr]	$m_{0\nu\beta\beta}$ [meV]
1 yr	8×10^{25}	75.2
5 yrs	1.96×10^{26}	38 – 92

0νββ Sensitivity

- 1.3 tonnes of ^{130}Te in LAB (at 0.5% ^{nat}Te)



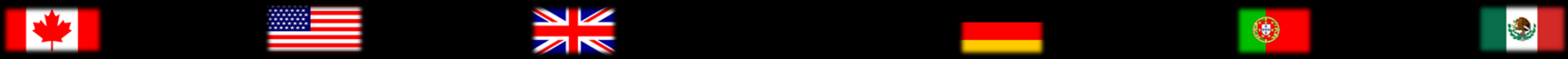
- [-0.5; +1.5] σ around $Q_{\beta\beta}$
- 400 NHits/MeV (~4% ΔE)
- Fiducial Volume: 20% total

	$T_{1/2}$ [yr]	$m_{0\nu\beta\beta}$ [meV]
1 yr	8×10^{25}	75.2
5 yrs	1.96×10^{26}	38 – 92

$0\nu\beta\beta$ Schedule

- 2017-2018
  - Scintillator plant commissioning
  - Scintillator fill
    - Unloaded scintillator phase (short)
    - Evaluation of backgrounds for $0\upsilon\beta\beta$
  - Commissioning of the Tellurium plant(s)
- 2018-2019
  - Tellurium loading
  - Begin $0\upsilon\beta\beta$ phase

SNO+ Collaboration



Backup

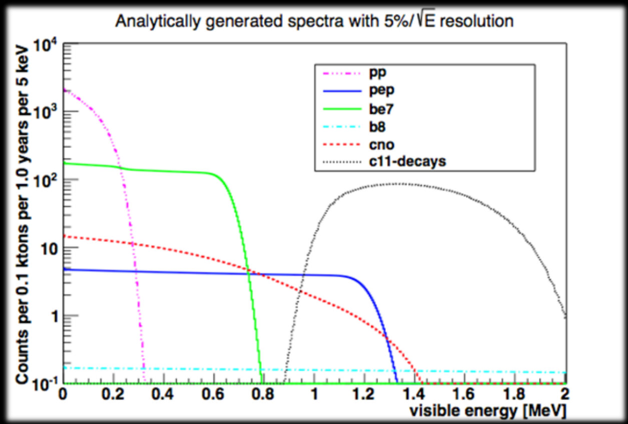
Backgrounds Budget

- Current sensitivity studies assume that in the background budget, solar neutrinos would be the dominant factor
  - $2\nu\beta\beta$ spectrum “leaks” into the ROI [8.5/23.2 c-yr]
    - Improved energy resolution with good optics
  - External backgrounds (^{208}Tl ,^{214}Bi) [3.5/23.2 c-yr]
    - Minimized with proper fiducialisation, and PSD
  - Internal backgrounds and detector response
    - U/Th [3.8/23.2 c-yr] and cosmogenics [0.1/23.2 c-yr] reduced by purification & cooling
    - Bi-Po/(α,n) tagged with space-time coincidence
    - ^{210}Po-$2\nu\beta\beta$/^{210}Bi-$2\nu\beta\beta$ pile-up events reduced based on PMT-hit time distribution
    - Apply the “source-in – source-out ” approach
  - Flat ^{8}B (ES) e^{-} normalized to known flux [7.2/23.2 c-yr]

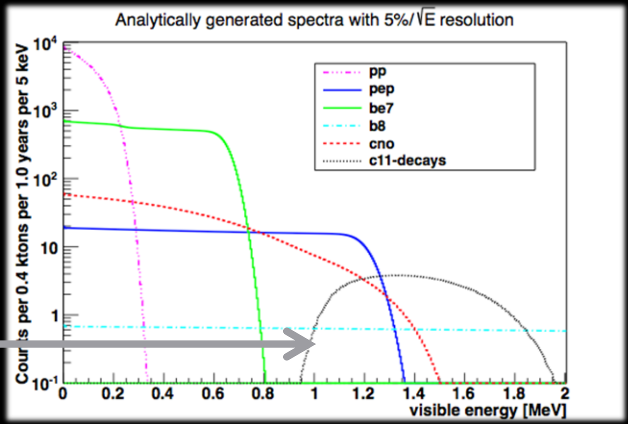
SNOLAB Facility

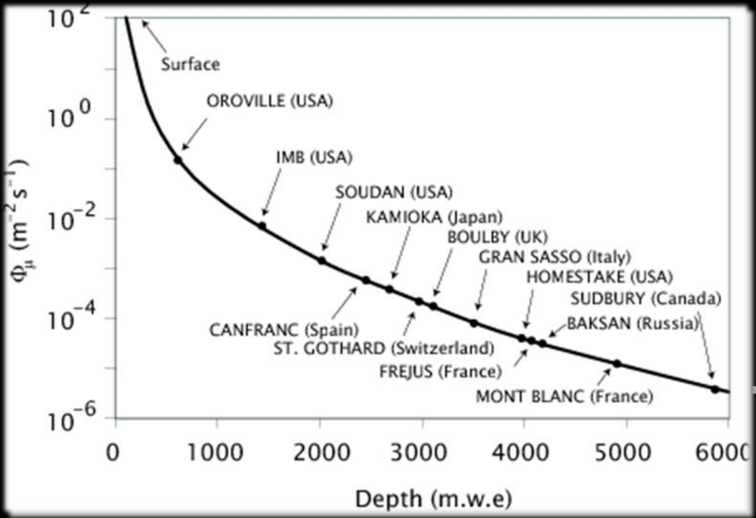
- Depth = 2070 m (6000 m.w.e.)
- 60 muons/day in SNO+
- 10,000 sq ft class-2000 clean room

LNGS



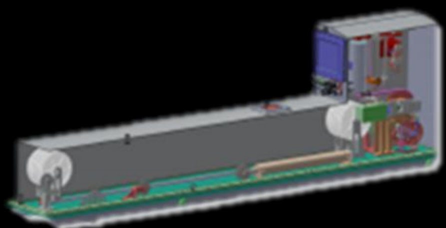
SNOLAB

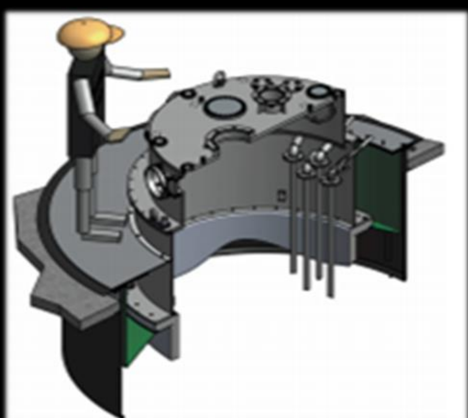


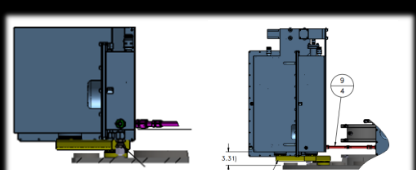


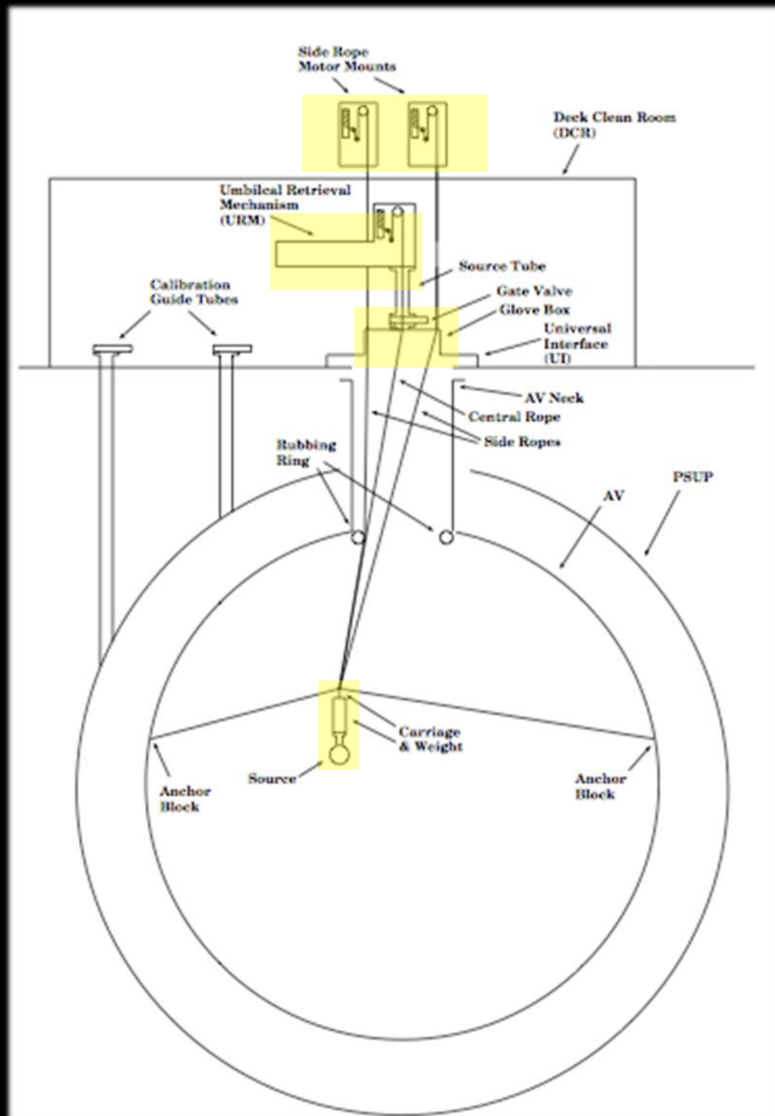
Calibration Hardware

New (Re)Design







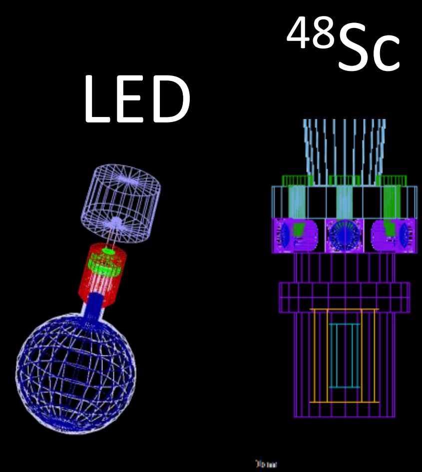


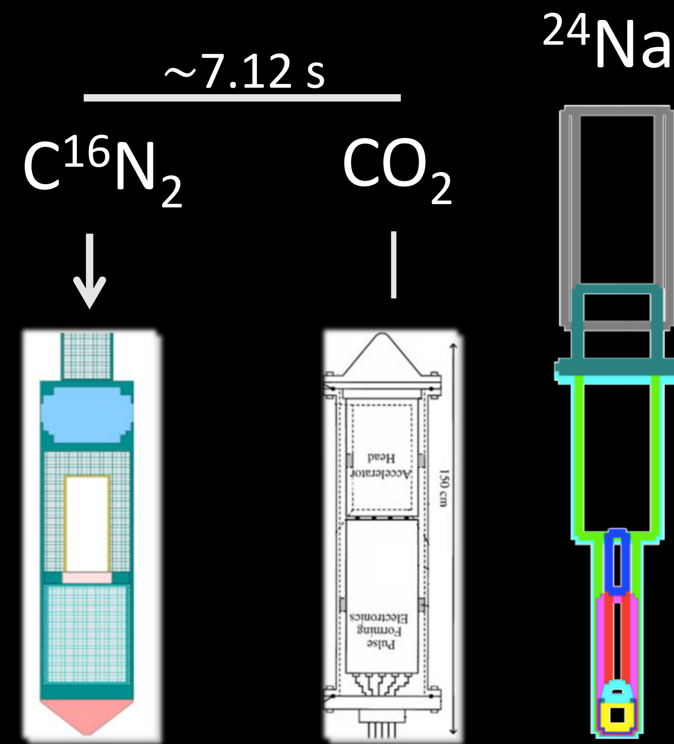
New Technology

Calibration Sources

- **Need Double encapsulation**
  - **Limitation for ^{222}Rn, ^{90}Y**

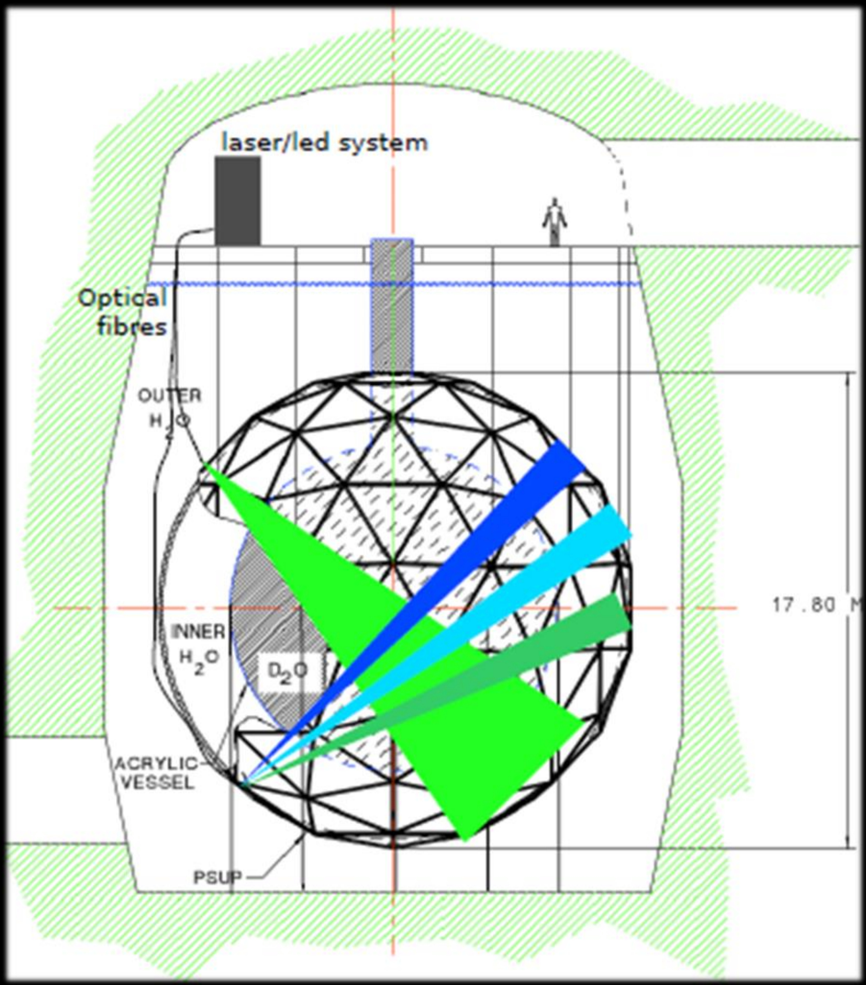
- **Radioactive and optical sources α, β, γ, n, with laser injection laserball and Cherenkov**

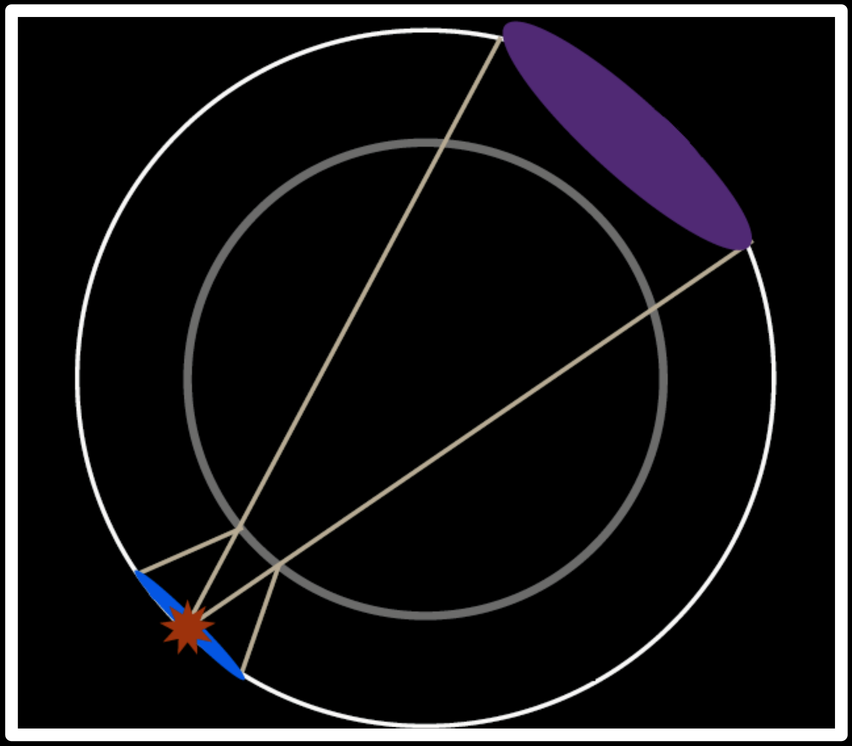




Type	γ					β	α	n		
Src.	^{57}Co	^{60}Co	^{48}Sc	^{24}Na	^{16}N	^{90}Y(?)	^{214}Po(?)	n-p	n-^{12}C	n-Fe
MeV	0.1	2.5 (sum)	3.3 (sum)	4.1 (sum)	6.1	2.3	7.7	2.2	4.9	~7.5

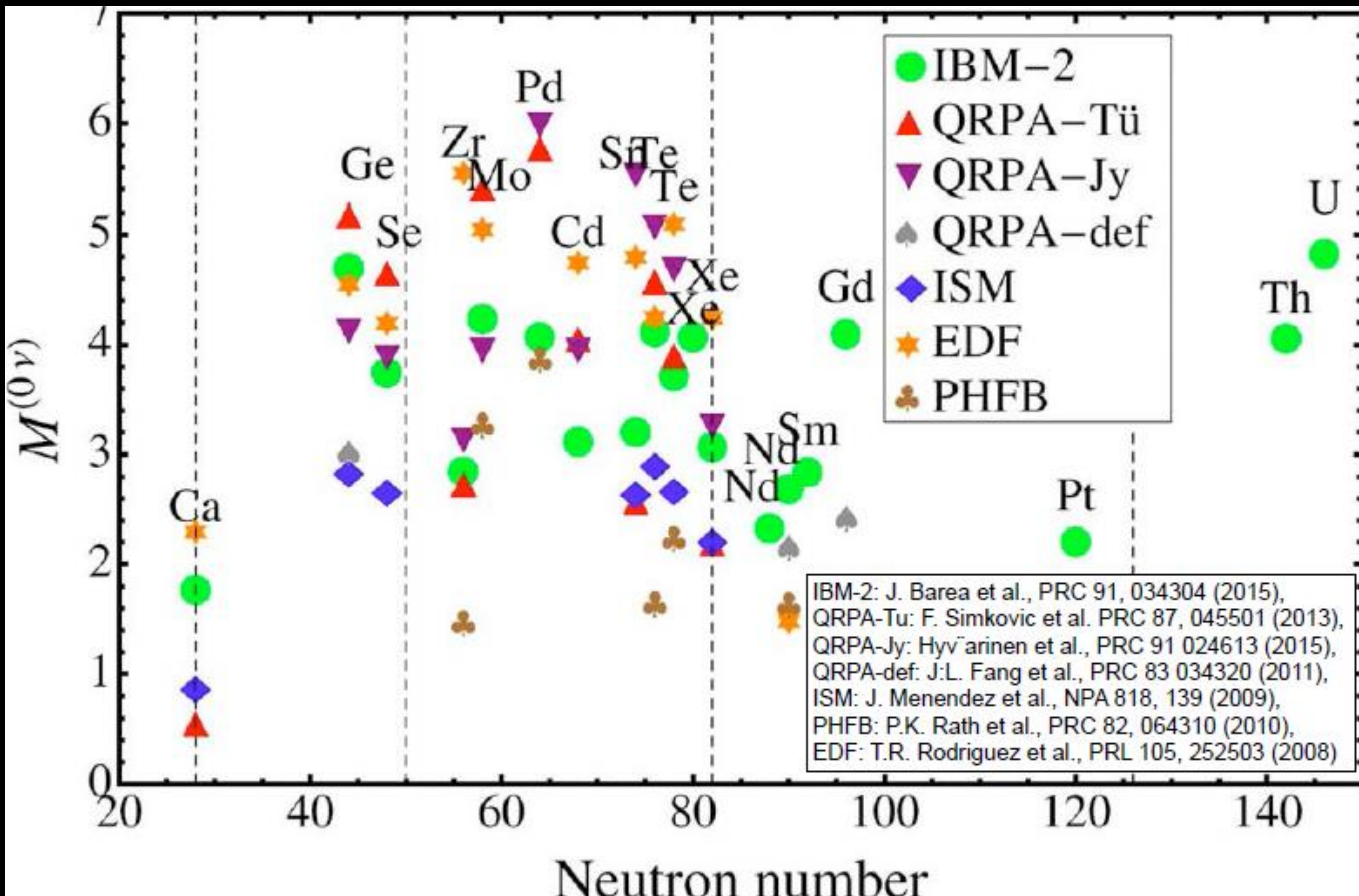
Optical Calibration





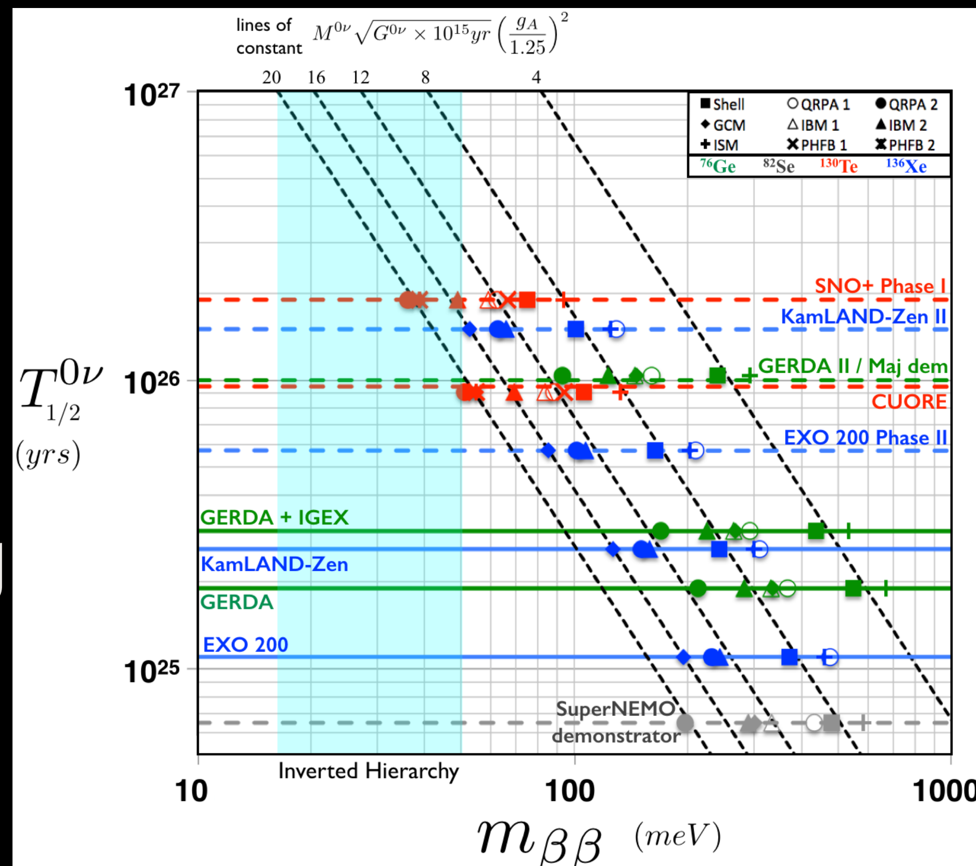
Light emitted from the support structure from 92 fibres installed between PMTs. Each gives 10E3-10E5 photons/pulse.

0νββ Isotope Selection

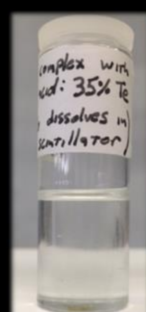


ovββ Sensitivity in Phase II

- Improve sensitivity by improving
  - Light yield and going to higher loading
    - Improve current technique
  - Higher QE PMTs
    - Improved concentrators
      - Coverage to 80%

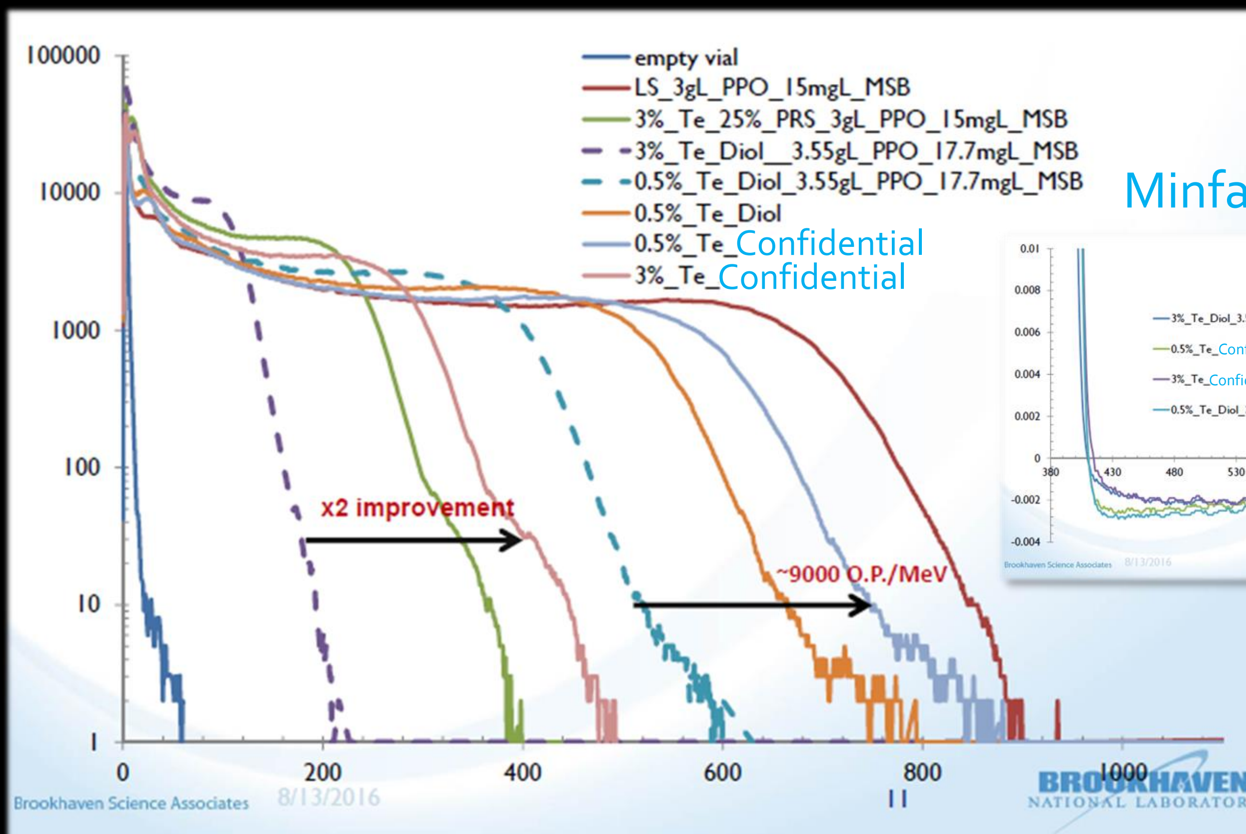


- Goal: 3% nat. Te loading
  - ~ 8 tonnes ^{130}Te
  - Higher QE PMTS
  - $T_{1/2}$ onbb ~ 10^{27} yr



ovββ Phase III R&D

- 2x the Light Yield and same absorption with alternative approach at 3%Te



Courtesy of
Minfang Yeh of BNL