Search for Neutrinoless Double Beta Decay at SNOLAB

Szymon Manecki, March 4th, 2026

Double Beta Decay

- Are neutrinos their own anti-particles?

- $2\nu\beta\beta$ (Dirac)
  $(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\nu_e$
  ~ 10^{18}-10^{21} years

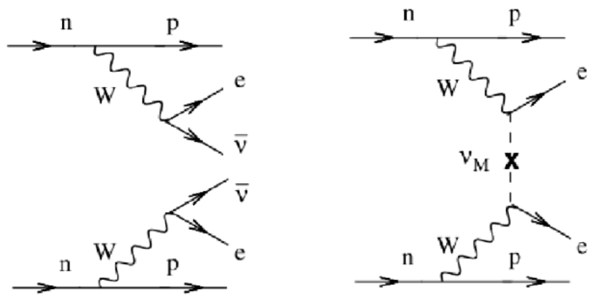
- $0\nu\beta\beta$ (Majorana)
  $(A, Z) \rightarrow (A, Z+2) + 2e^-$
  > 10^{25} years

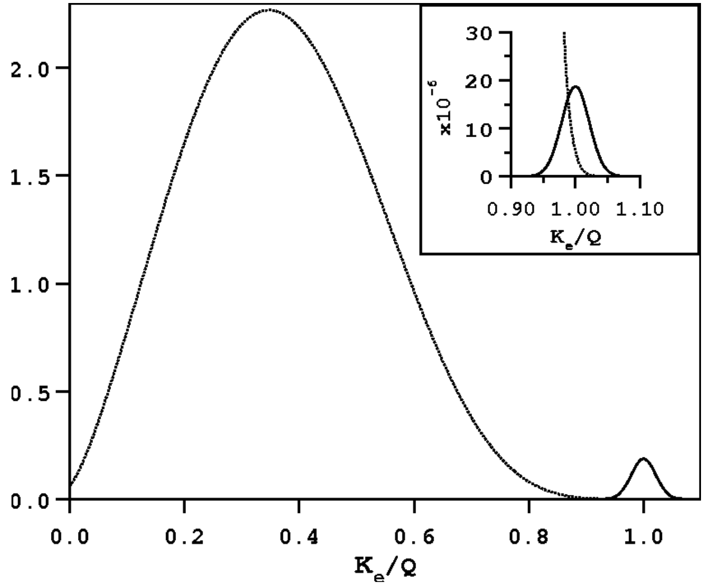
- We measure:

$$\frac{1}{T_{1/2}} = G\, g_A^4\, \mathcal{M}^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

G: Phase space factor

$\mathcal{M}$: Nuclear matrix element





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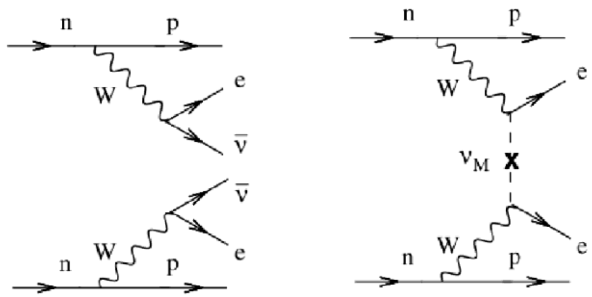
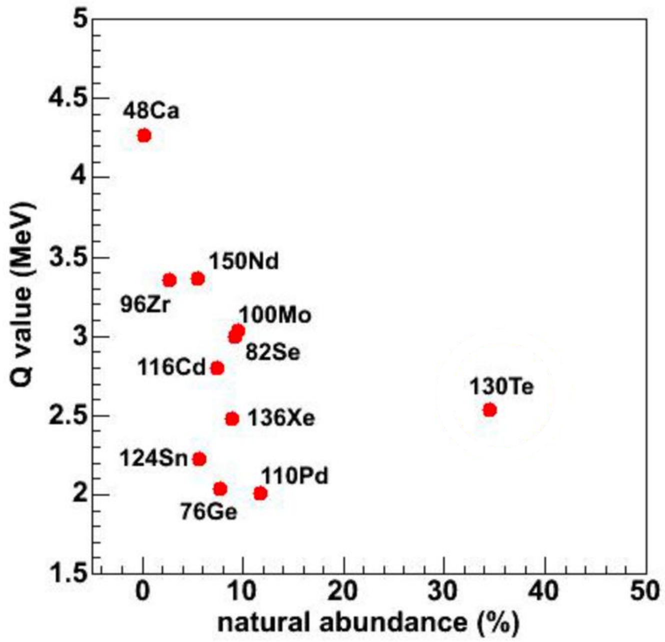
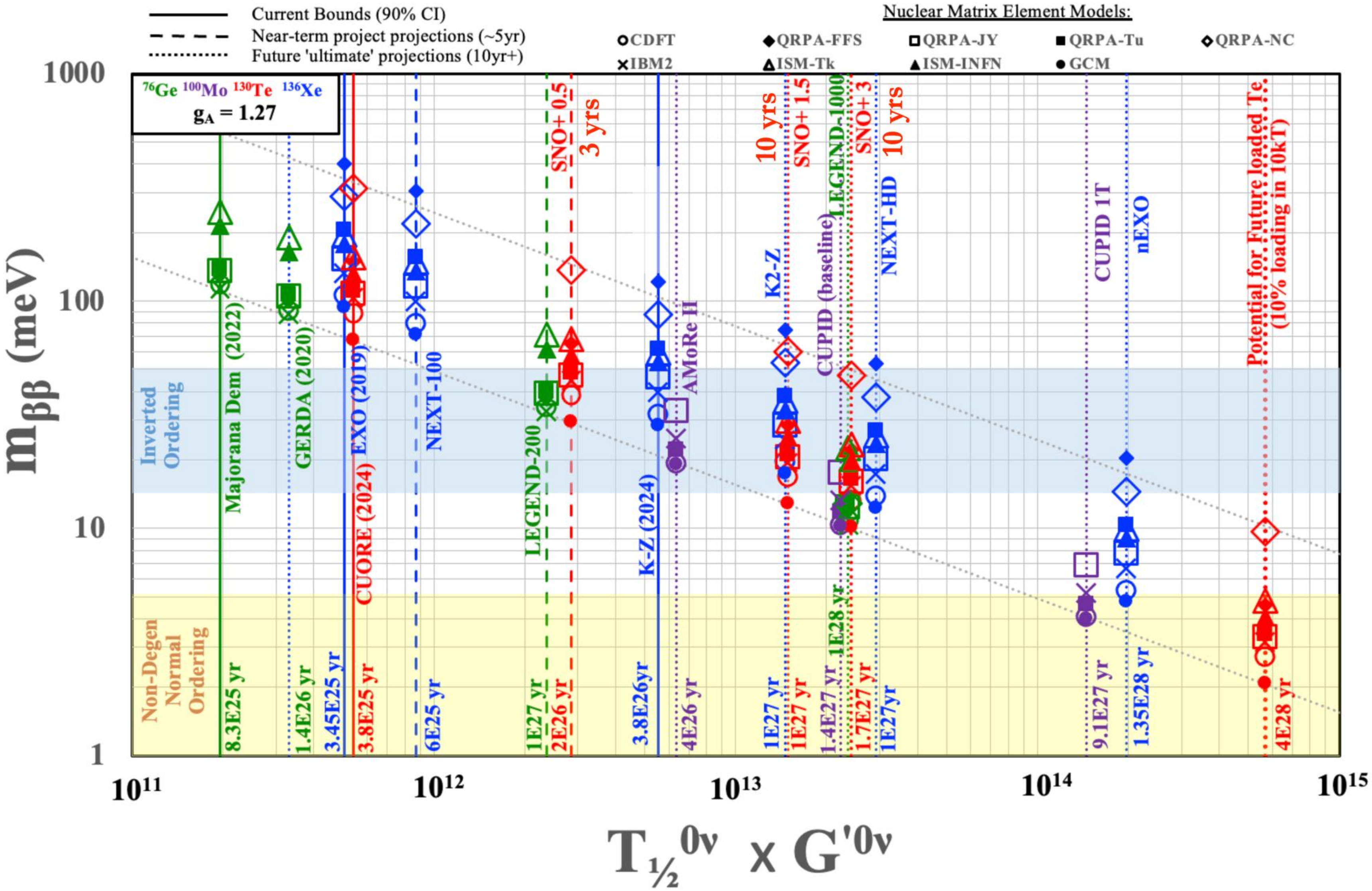
Phase space factor

Nuclear matrix element



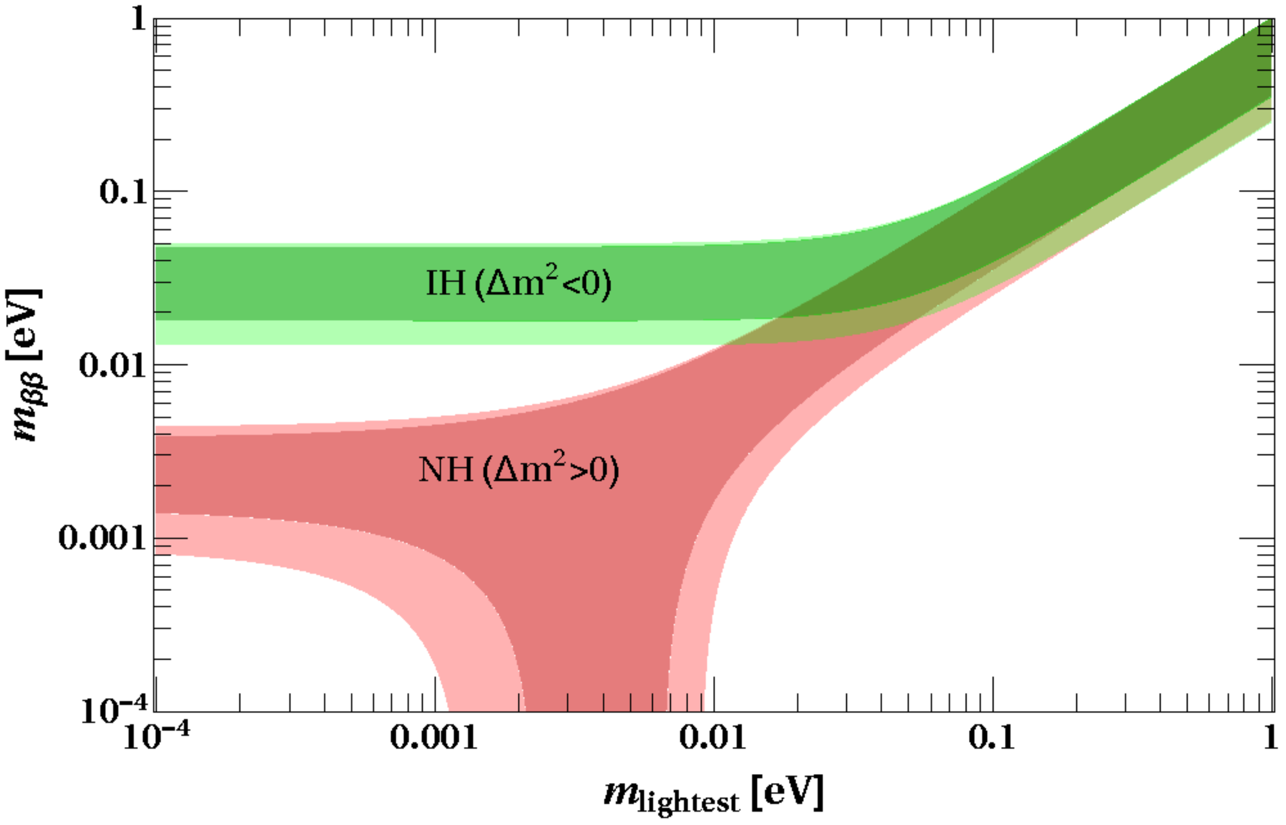


Neutrinoless Double Beta Decay

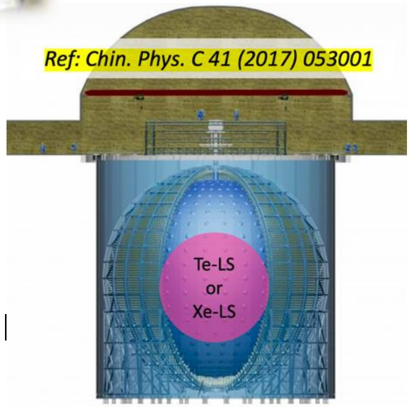


Neutrinoless Double Beta Decay

- Towards the bottom of Normal Hierarchy

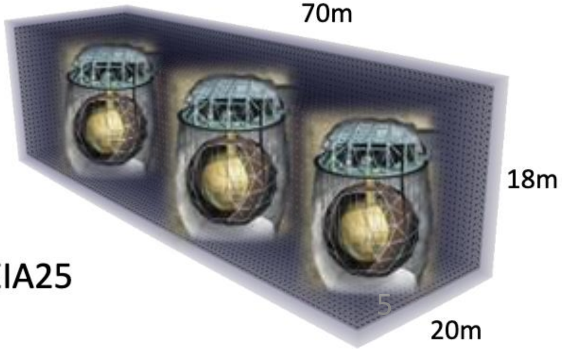


SNO+



JUNO-II

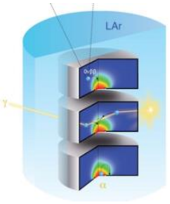
THEIA



THEIA25

Neutrinoless Double Beta Decay

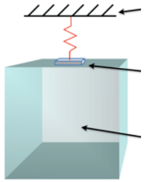
- LEGEND-200
  - 200 kg of ^{enr}Ge HPGe TPC's



- $T^{0\nu}_{1/2}$ lower limits (90% frequentist C.L.)

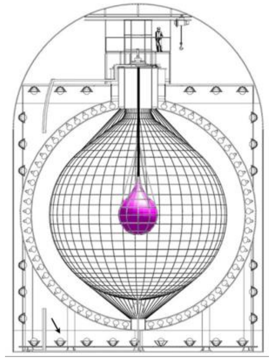
Observed	Sensitivity
$> 1.9 \cdot 10^{26}$ yr	$2.8 \cdot 10^{26}$ yr

- CUORE
  - 750 kg TeO_2 cryogenic calorimeters

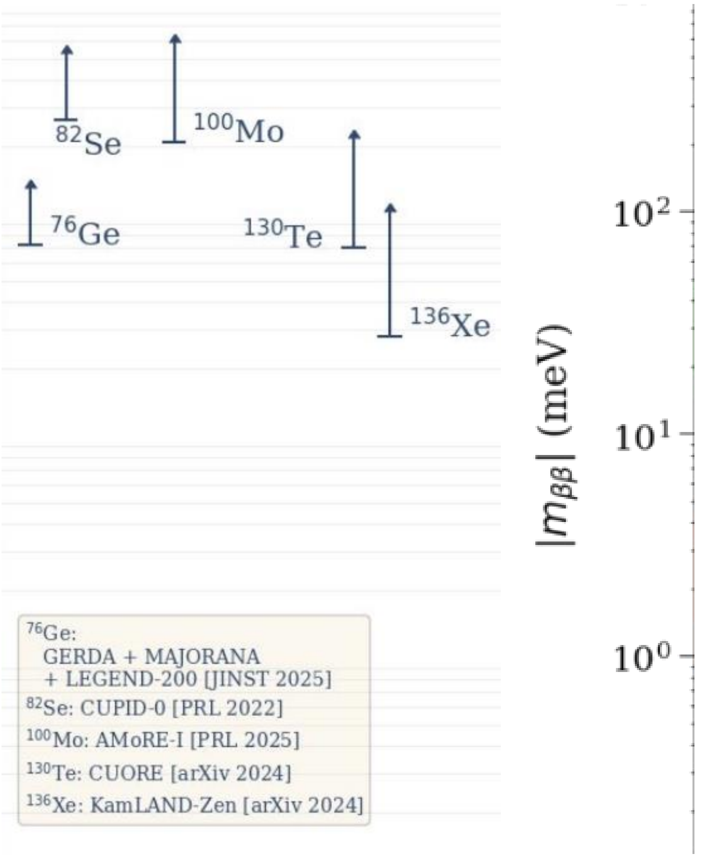


Half-life limit: $T^{0\nu}_{1/2} > 3.8 \times 10^{25}$ yr (90% C.I.)

- KamLAND-Zen
  - 800 kg ^{enr}Xe scintillator based detector

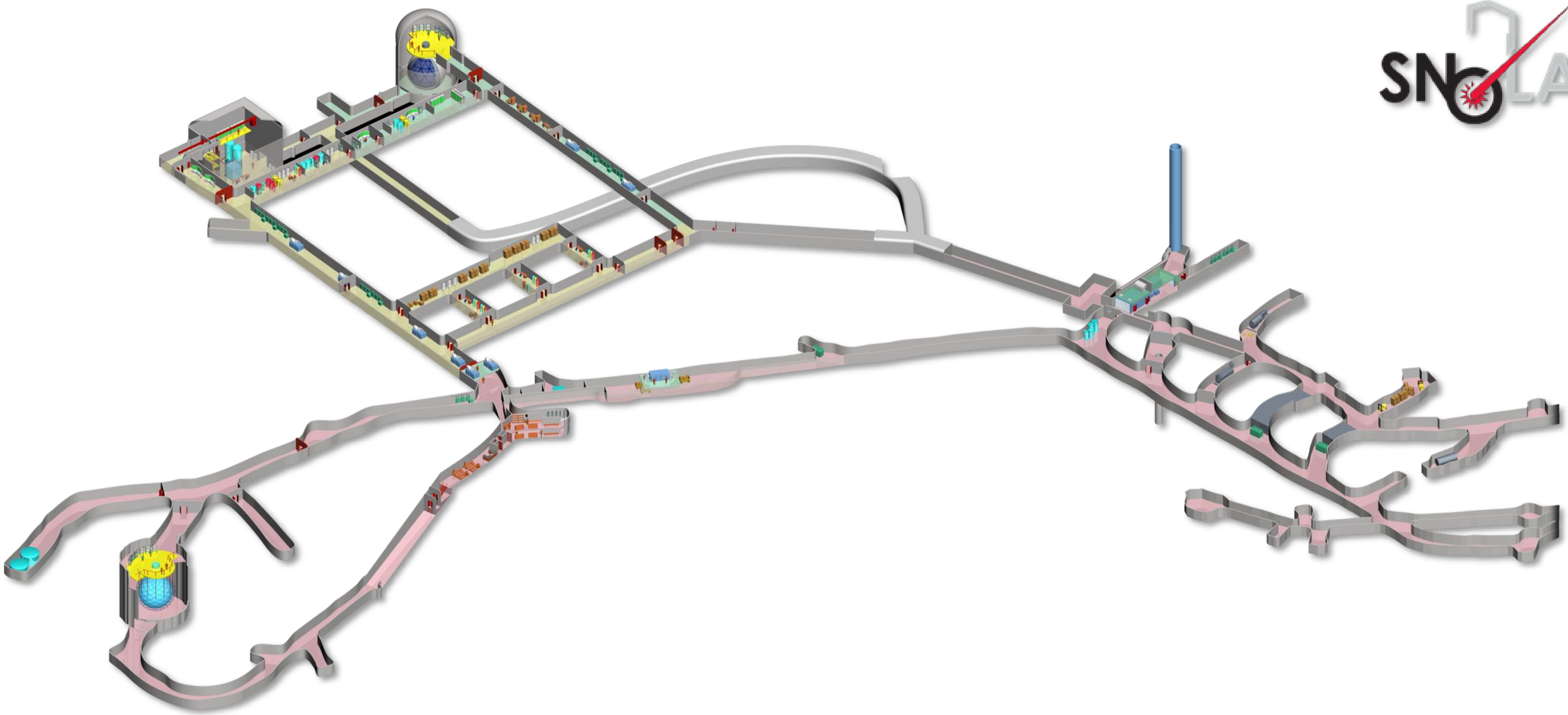


Combined $T^{0\nu}_{1/2} > 3.8 \times 10^{26}$ yr

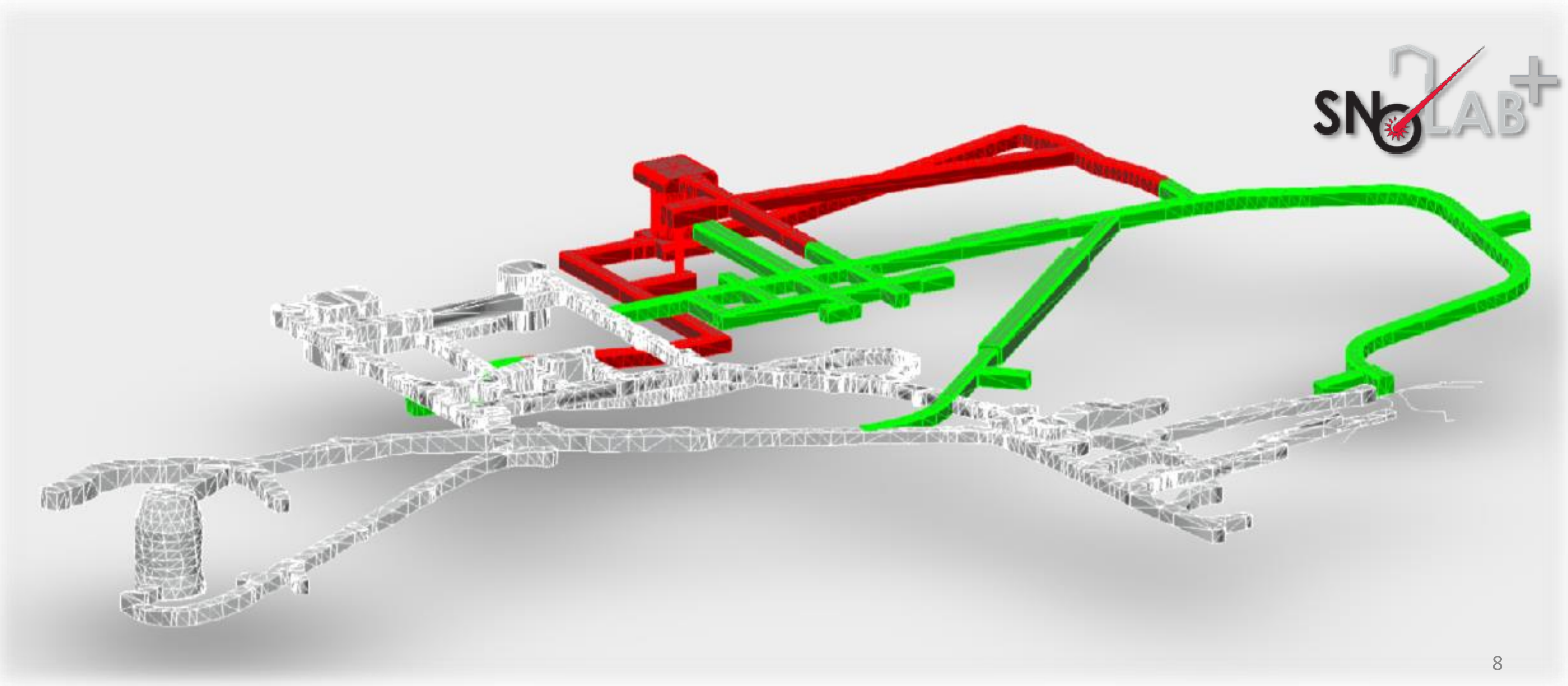


https://agenda.infn.it/event/37867/sessions/29923/#20240618

SNOLAB Map



SNOLAB+ Map

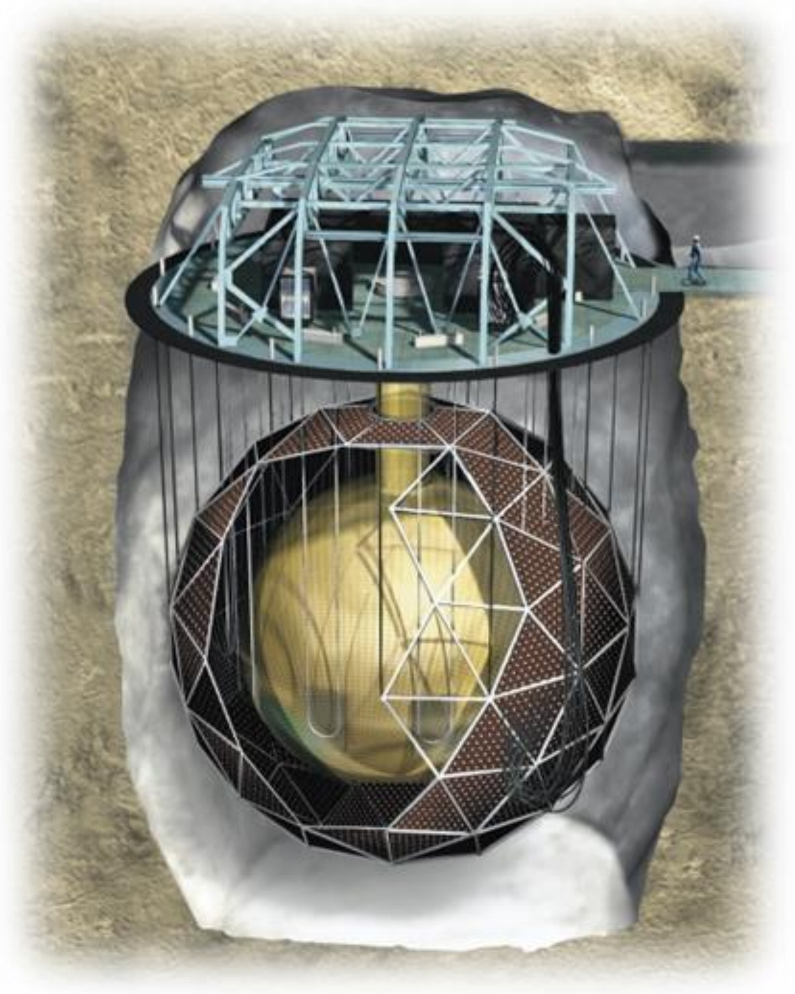


SNOLAB Land Acknowledgment

SNOLAB is located on the traditional territory of the Robinson-Huron Treaty of 1850, shared by the Indigenous people of the surrounding Atikameksheng Anishnawbek First Nation as part of the larger Anishinabek Nation.

We acknowledge those who came before us and honour those who are the caretakers of the land and the waters.

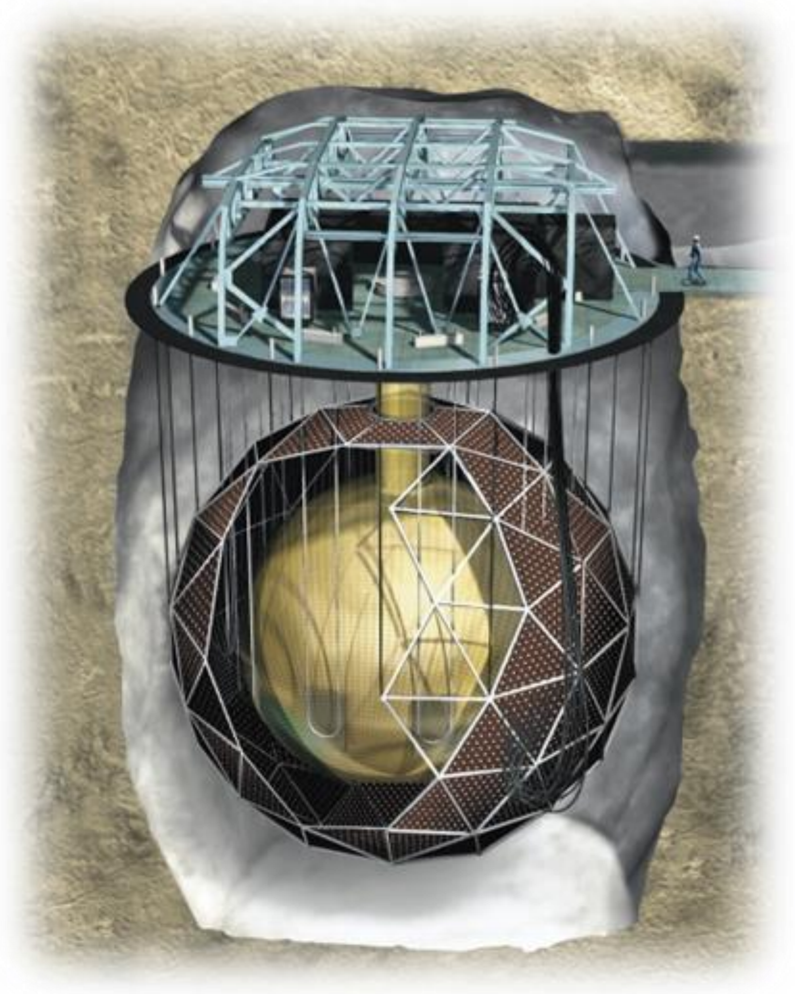
SNO+ @ SNOLAB



Broad Physics Program

- <u>Neutrinoless Double Beta Decay</u>
- Invisible Nucleon Decay modes
- High Energy Solar Neutrinos
- Low Energy Solar Neutrinos
- Reactor Antineutrinos
- Geo-Neutrinos
- Supernova-ν

SNO+ @ SNOLAB



- Water Phase (current) *PRD 99, 032008 (2019)*
  - Best limits on invisible modes of nucleon decay *PRD 105 112012 (2022)*
  - Measurement of the 8B solar neutrino flux in SNO+ with very low backgrounds *PRD 99, 012012 (2019)*
  - Highest efficiency (~50%) for neutron detection in a water Cherenkov detector *PRC 102, 014002 (2020)*
  - Detection of antineutrinos from distant reactors using only pure water *PRL 130, 091801 (2023)*

- Scintillator Phase (current)
  - Demonstrating event-by-event reconstruction of the direction of recoil electrons (from solar neutrinos) in a liquid scintillator – this result was also an achievement that hasn't been done before *PRD 109, 072002 (2024)*
  - Being only the second detector to make measurements of the neutrino oscillation parameter Δm_21^2 using antineutrinos from nuclear reactors, an important verification of the previous measurement *arxiv.org/abs/2405.19700*
  - First ever CC interaction of solar nu on ^{13}C *PRL 135, 241803 (2025)*

  - Tellurium Phase (upcoming)
  - Developing methods to load tellurium into organic liquid scintillator *NIM, 1051, 168204 (2023)*
  - Developing techniques to purify telluric acid *NIM. A. 795:132-139 (2015)*

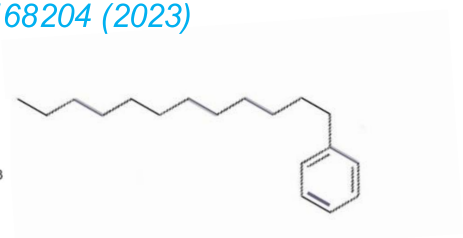
SNO+ Scintillator Cocktail

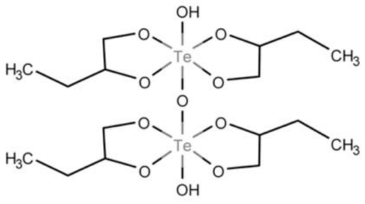
- 780 T Linear Alkylbenzene (LAB)
  + 2 g/L PPO (Primary Fluor)
  + 2 mg/L bisMSB (WS)
  + 6 mg/L BHT (Stb)

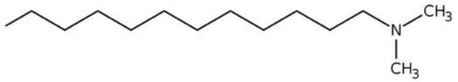
- Tellurium Butanediol (TeDiol)
  0.5% Te in LAB

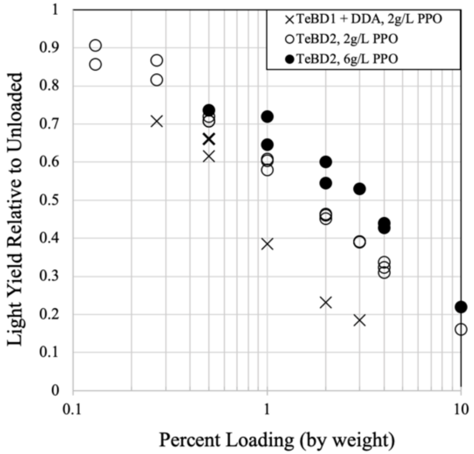
- DDA (stabilizing amine)
  0.2% in LAB

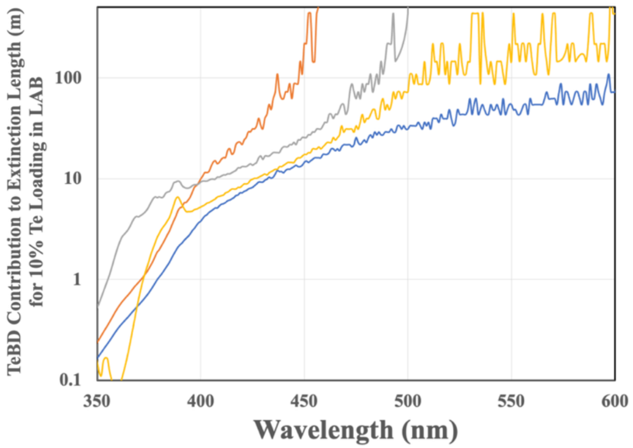
A Method to Load Tellurium in Liquid Scintillator for the Study of Neutrinoless Double Beta Decay
NIM, 1051, 168204 (2023)





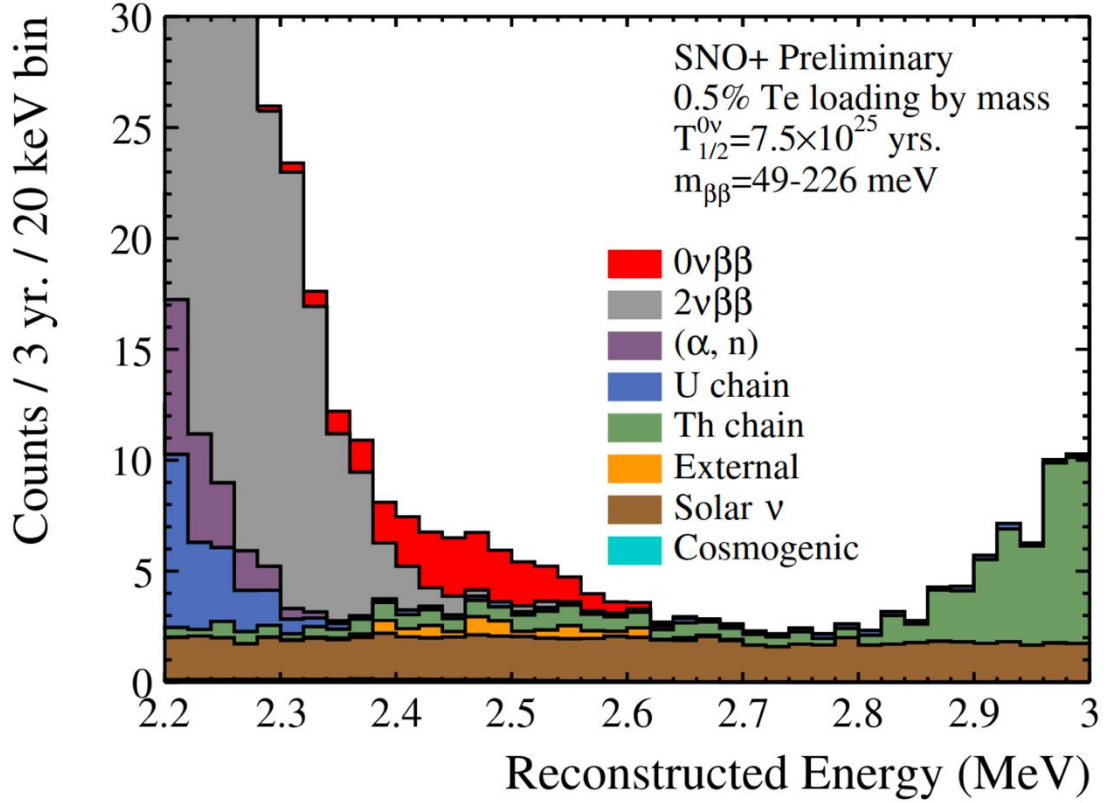


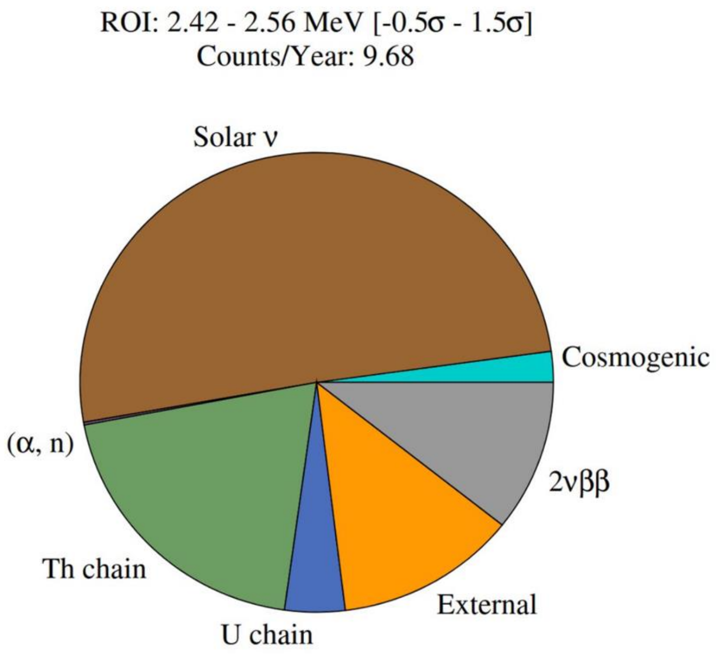




Sensitivity and Backgrounds

- At 0.5% $_{nat}$Te: $T^{0\nu}_{1/2}$ > 1.8x10^{26} yr (90% CL)
  7.4x10^{26} yr at 1.5% $_{nat}$Te





Tellurium Purification

- The purification technique relies on solubility of TeA in water based on pH
  - $Te(OH)_6$ ⬌ $Te(OH)_5O^- + H^+$

    in-soluble   soluble

- Insoluble contamination
  - Dissolve in water, and filter

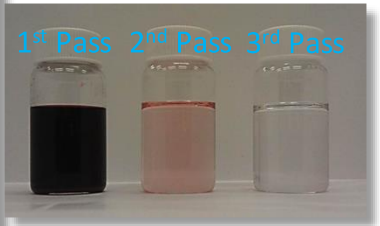
- Soluble contamination
  - Force TeA to recrystallize by adding Nitric Acid, let it precipitate out, and drain the "dirty" liquid

Nucl. Inst. Meth. A. 795:132-139 (2015)

Cosmogenic isotope	Counts in Year 1 (no purification)
^{22}Na	7.04×10^{3}
^{26}Al	9.67×10^{-2}
^{42}K	6.55×10^{2}
^{44}Sc	8.41×10^{1}
^{46}Sc	5.21×10^{-2}
^{56}Co	1.02×10^{-3}
^{58}Co	2.50×10^{-3}
^{60}Co	6.62×10^{3}
^{68}Ga	6.20×10^{2}
^{82}Rb	5.15×10^{-16}
^{84}Rb	8.88×10^{-12}
^{88}Y	2.23×10^{1}
^{90}Y	5.05×10^{2}
^{102}Rh	1.33×10^{3}
^{102m}Rh	9.54×10^{4}
^{106}Rh	8.59×10^{1}
^{110m}Ag	7.96×10^{2}
^{110}Ag	1.07×10^{1}
^{124}Sb	1.77×10^{-2}
^{126m}Sb	3.06
^{126}Sb	2.92×10^{-35}

Free purification factor due to underground cooldown

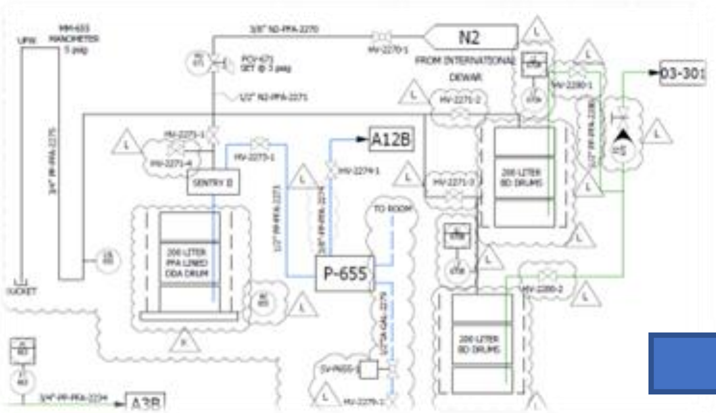
10kg pilot-scale

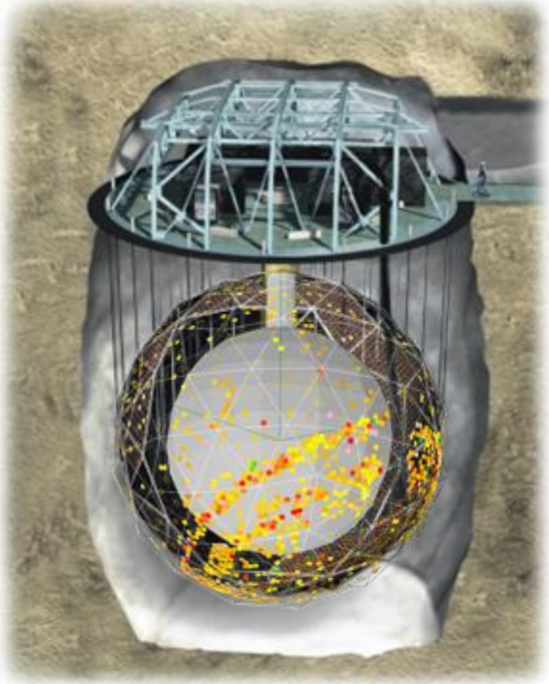


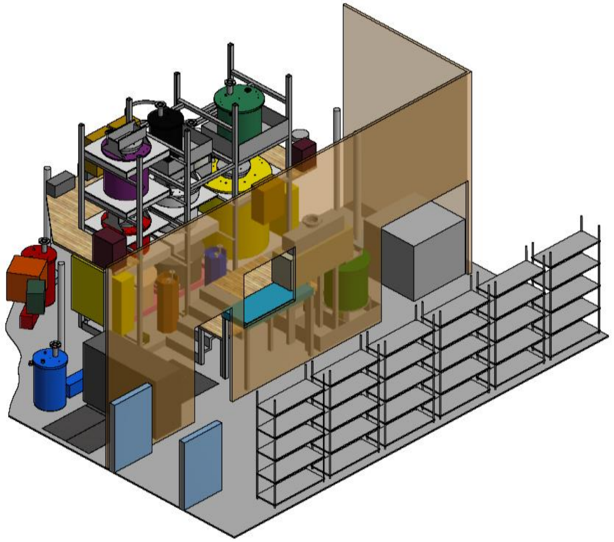
AV Target (r.f. 10^3):
^{238}U: 1.3×10^{-15} g/g
^{232}Th: 5×10^{-16} g/g

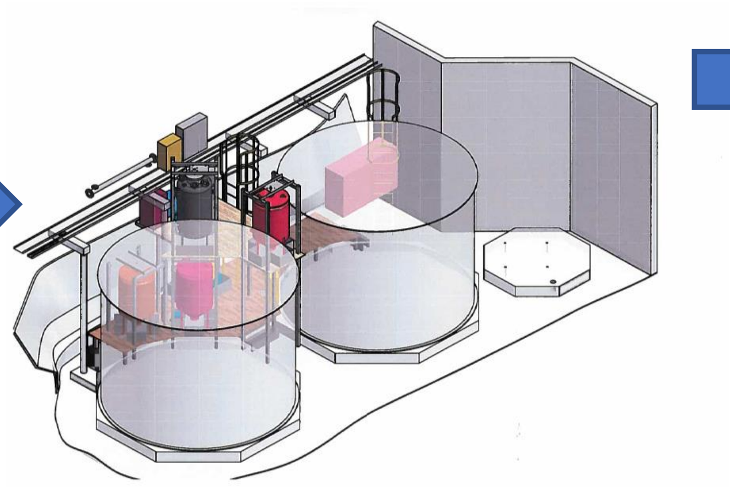
Expected r.f. for cosmogenics: 10^5-10^6

SNO+ Scintillator Plants

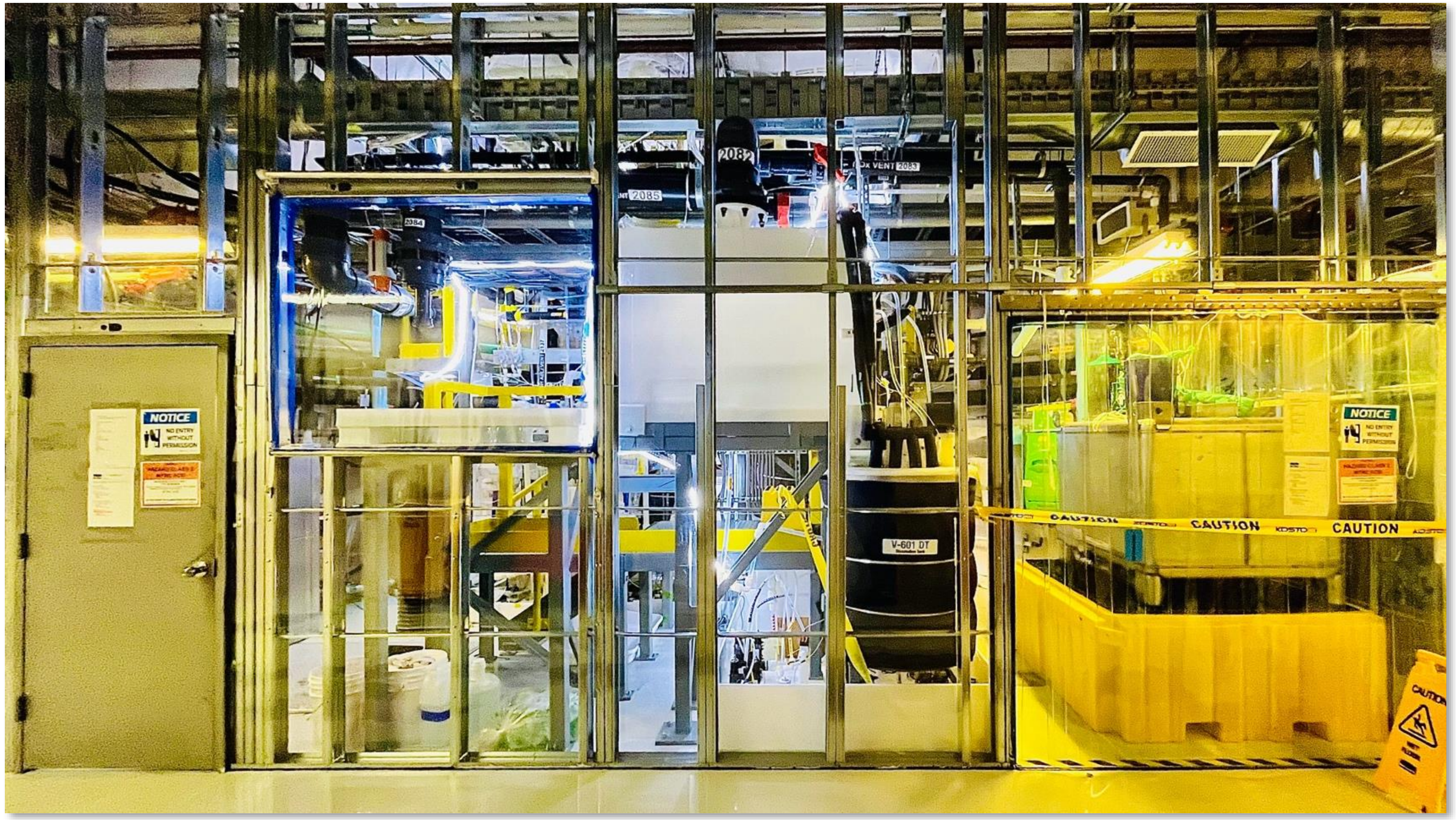








SNO+ Scintillator Plants

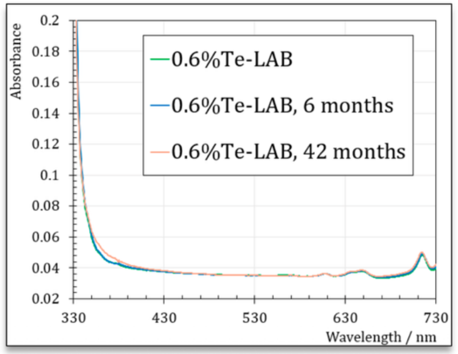


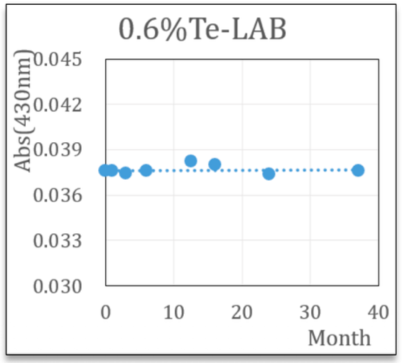
	Soak 1 (2 days)		Soak 2 (4 days)		Soak 3 (4 days)	
U	1	0.2	<0.05	<0.05	<0.05	<0.05
Th	5	1	1.1	<0.1	<0.1	<0.1
Fe	5600	5000	220	170	17	37

JUNO

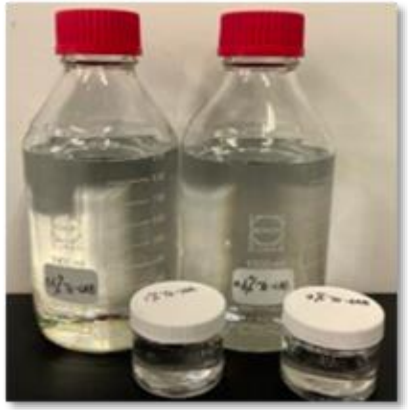
- 35-meter acrylic sphere
- 20-ktonnes of LAB
- 700 meters UG

- Tellurium synthesized directly with diols into ‘organometellics’
- 100-kg scale of Te-LS demonstrated



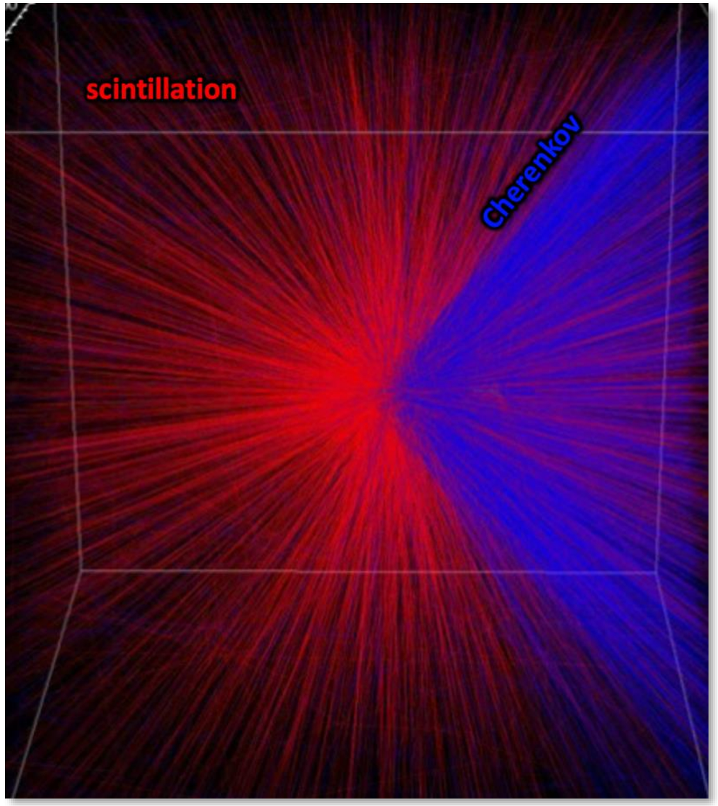


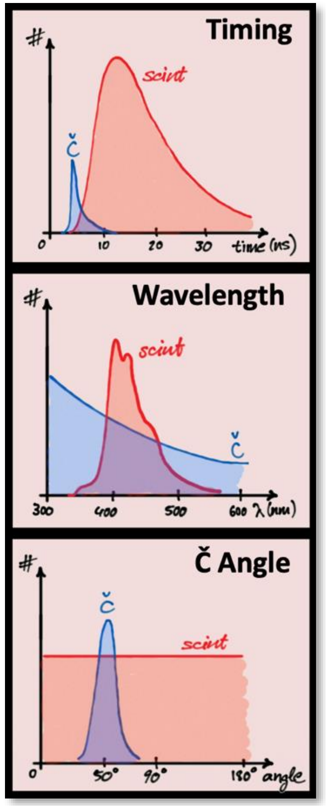
Courtesy of Y. Ding

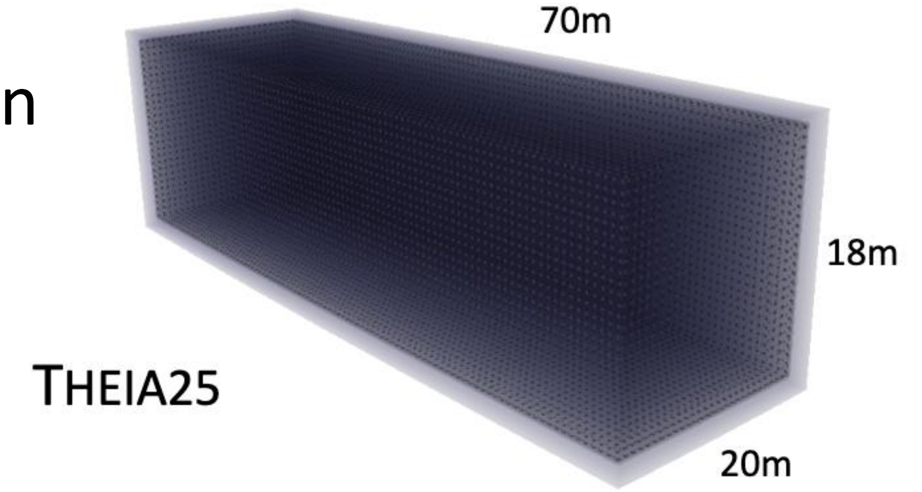


THEIA

- A hybrid detector – Cherenkov & Scintillation in Water-based Liquid Scintillator (WbLS)





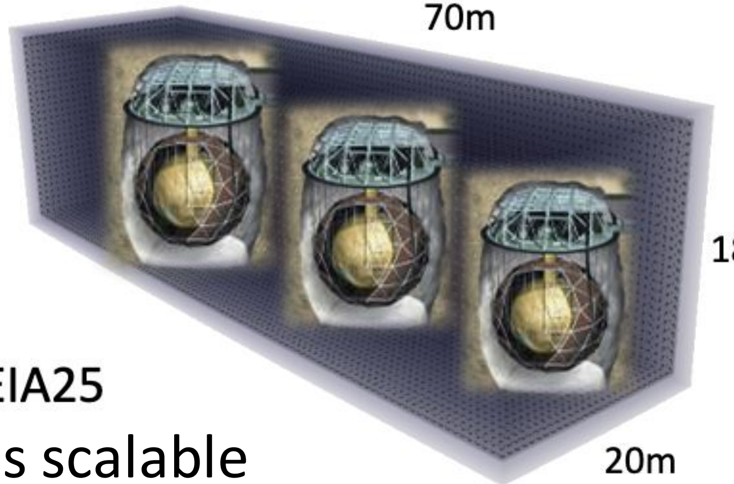


- Detector size: 25 kt → perhaps 100 kt

- Dimensions: 20m x 20m x 80m → 32,000 m^3
- Medium: WbLS with organic fraction 5-10%
- Photosensors: PMTs at 40% coverage
- ββ phase: balloon (2,000 m3) of slow scintillator

Courtesy of M. Wurm

THEIA



- Achieving normal hierarchy sensitivity requires a 100-tonne scale tellurium loading in LS
- Te in LS is a feasible method
  - Cost of isotope (high isotopic abundance)
  - Synthesis from water-soluble to scintillator-soluble is scalable
  - Purification of tellurium is now being demonstrated with SNO+
  - Scaling of the purification method has room for improvement
    - Optimization of the process and improved logistics for reagents and waste
- $0\nu\beta\beta$ sensitivity: $T^{0\nu}_{1/2} > 1.1\times10^{28}$ yr (90% CL) at 800 kt-year

NEXT & XLZD & nEXO

NEXT

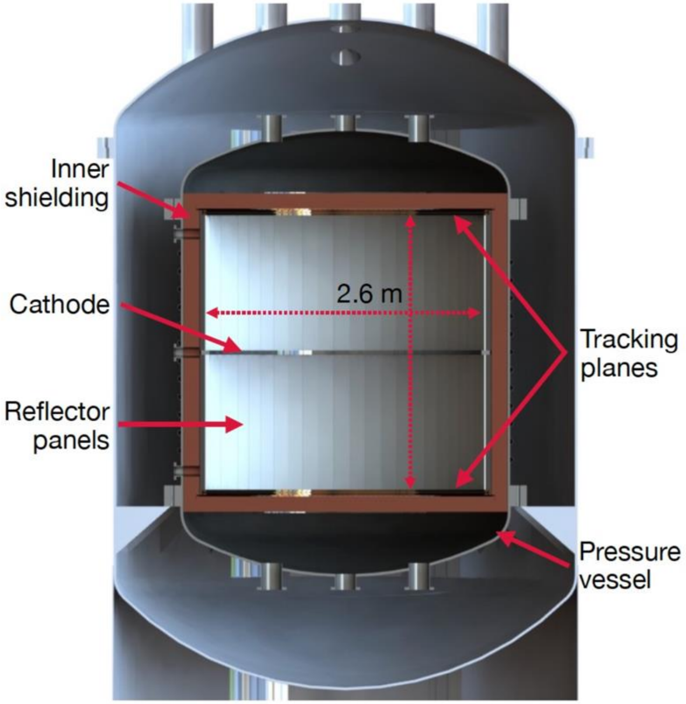
- High-Pressure Xe Gas TPC
- Excellent energy resolution (~0.5–1% FWHM at Qββ)
- Detailed event topology reconstruction

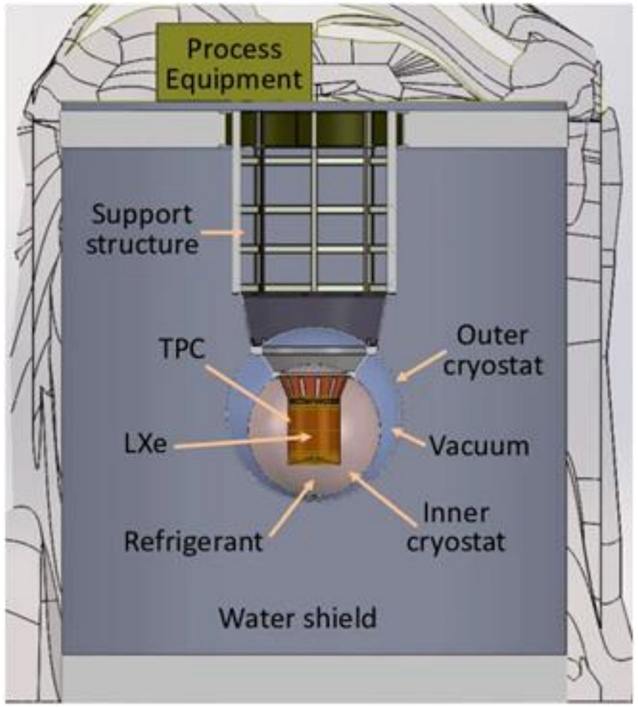
nEXO

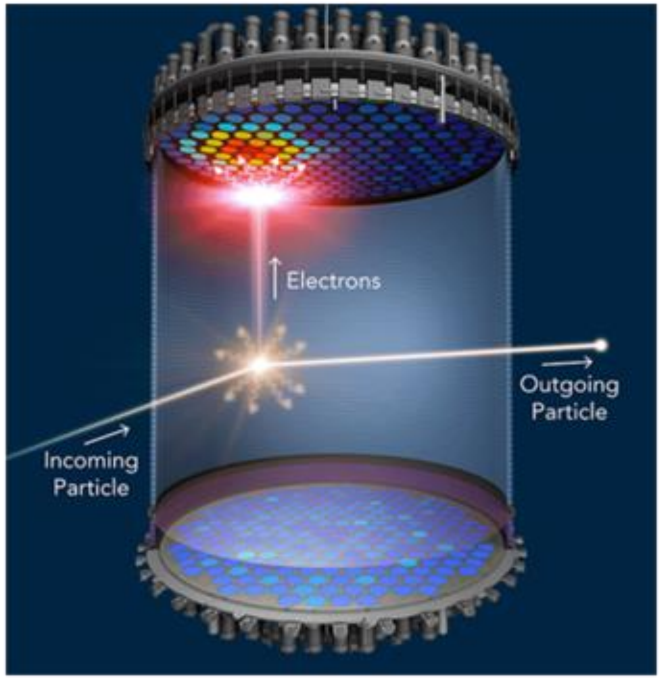
- Single-Phase Liquid Xenon TPC
- Larger target mass (5t) & good energy resolution
- Self-shielding & good event reconstruction

XLZD

- Dual-phase LXe TPC (liquid + gas for S2 amplification)
- Large mass (60-80 tonnes of L_{nat}Xe) ~5 tonnes of ^{136}Xe
- Multi-purpose detector (DM & neutrinos)







NEXT & XLZD & nEXO

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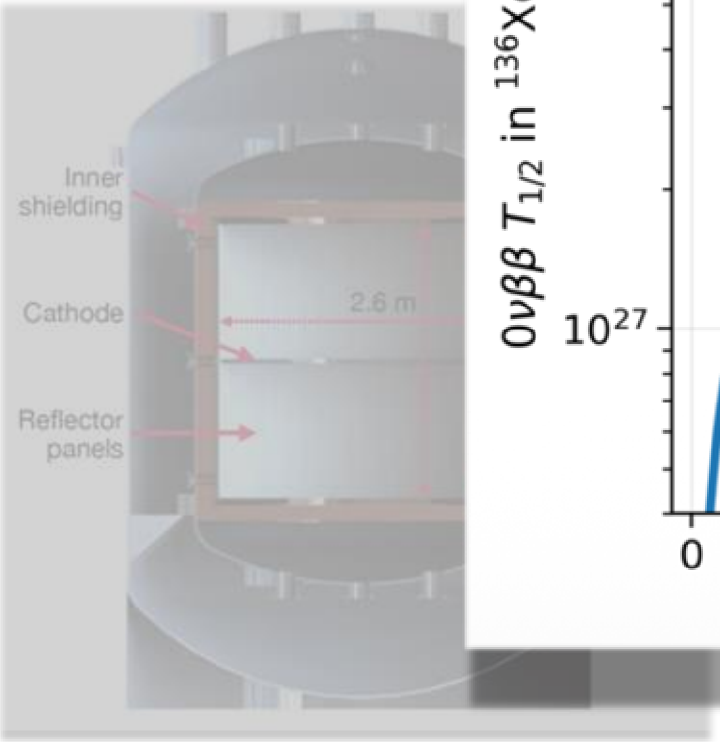
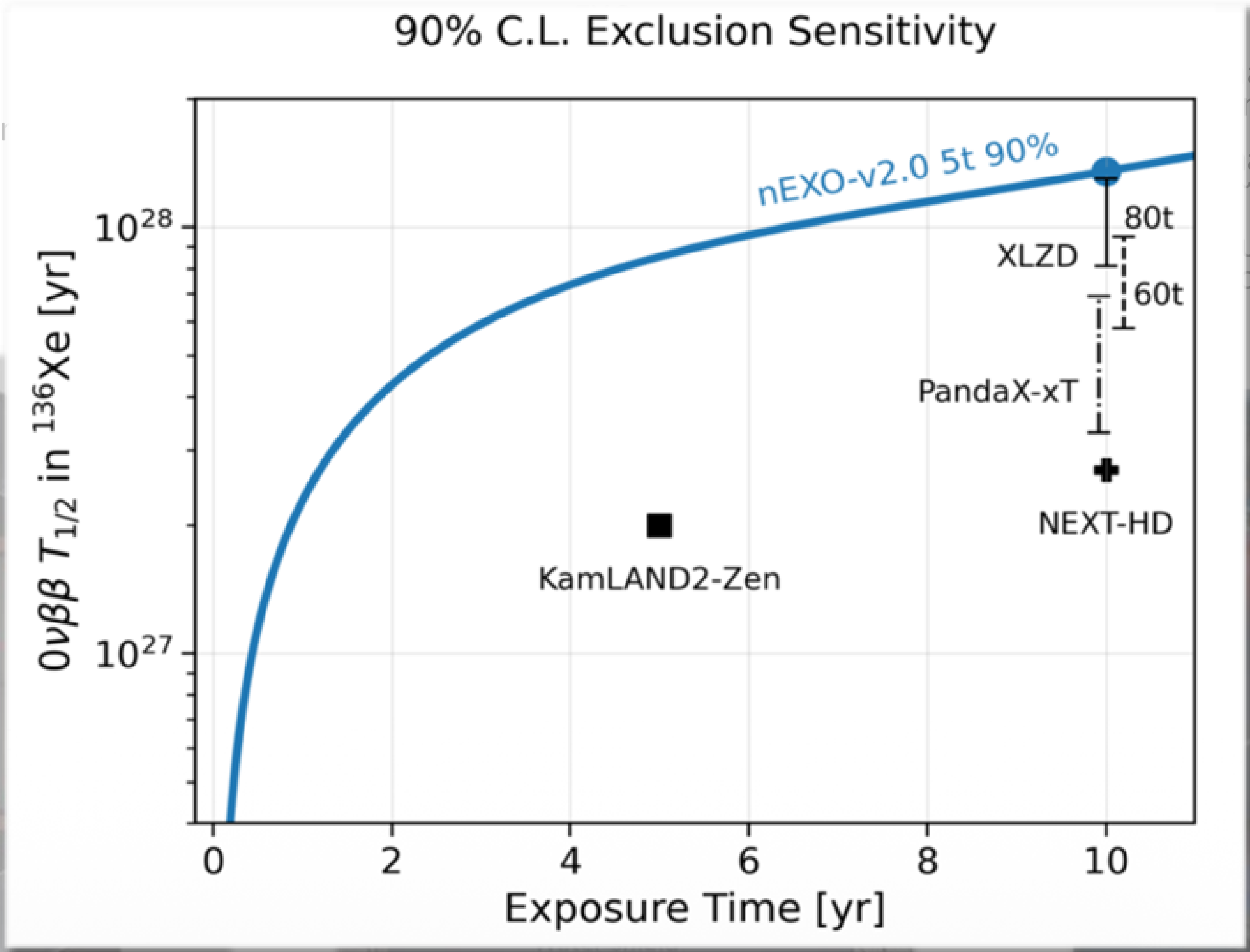


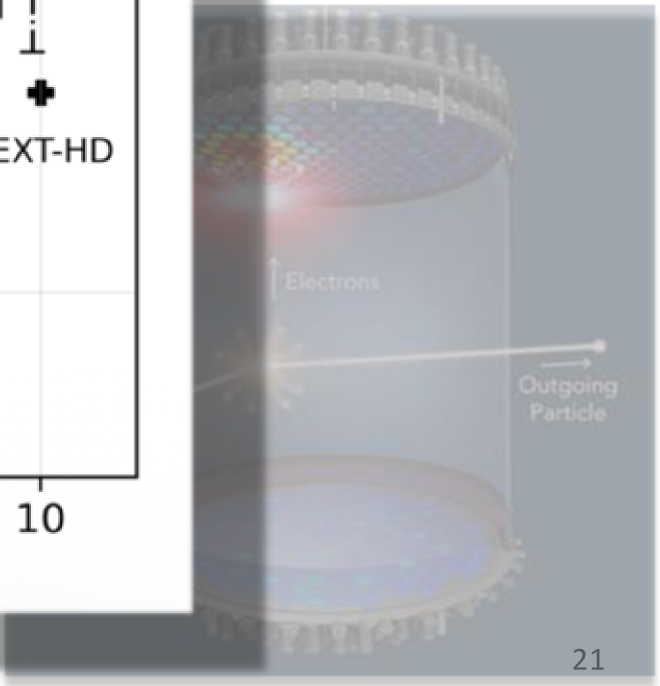


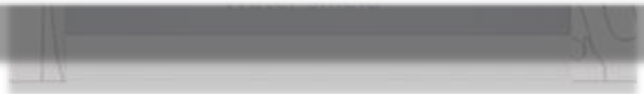
XLZD

ase LXe TPC (liquid + gas
mplification)

ass (60-80 tonnes of
5 tonnes of ^{136}Xe

urpose detector (DM &
s)



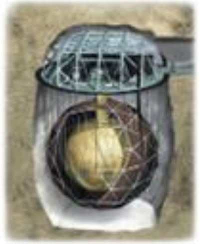


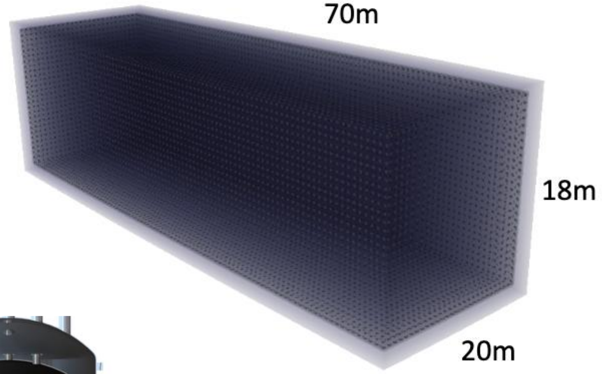
Summary

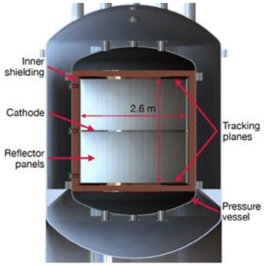
- SNOLAB is ready to host future neutrinoless double beta decay detector(s)

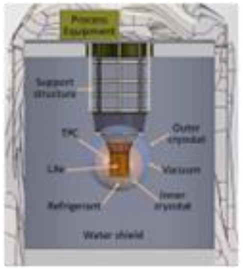
- SNO+ is in the final commissioning stages of the Tellurium System
- Tellurium loading in organic liquid scintillators is a feasible, cost-effective and scalable method
  - JUNO-II and future THEIA are carrying out advanced R&D with Te loading

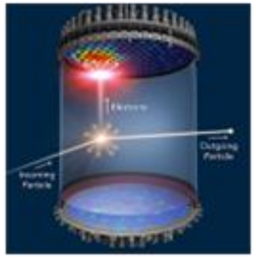
- To reach Normal Ordering, we need to build bigger or better/new detectors
  - That's a time-scale of the next 10 to 20 years





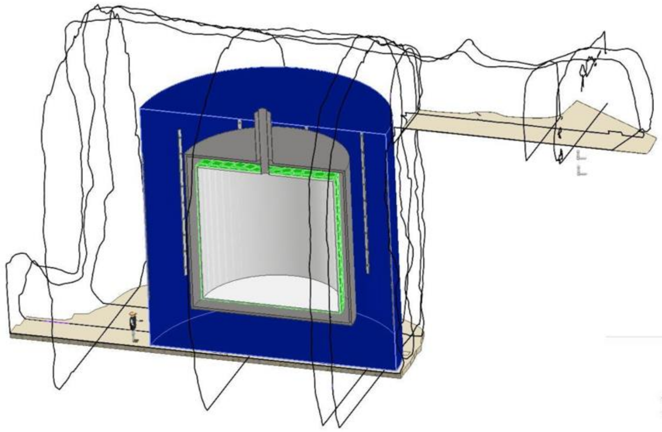


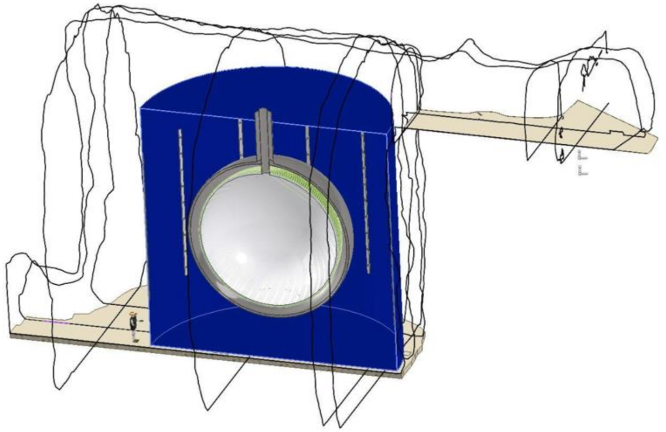


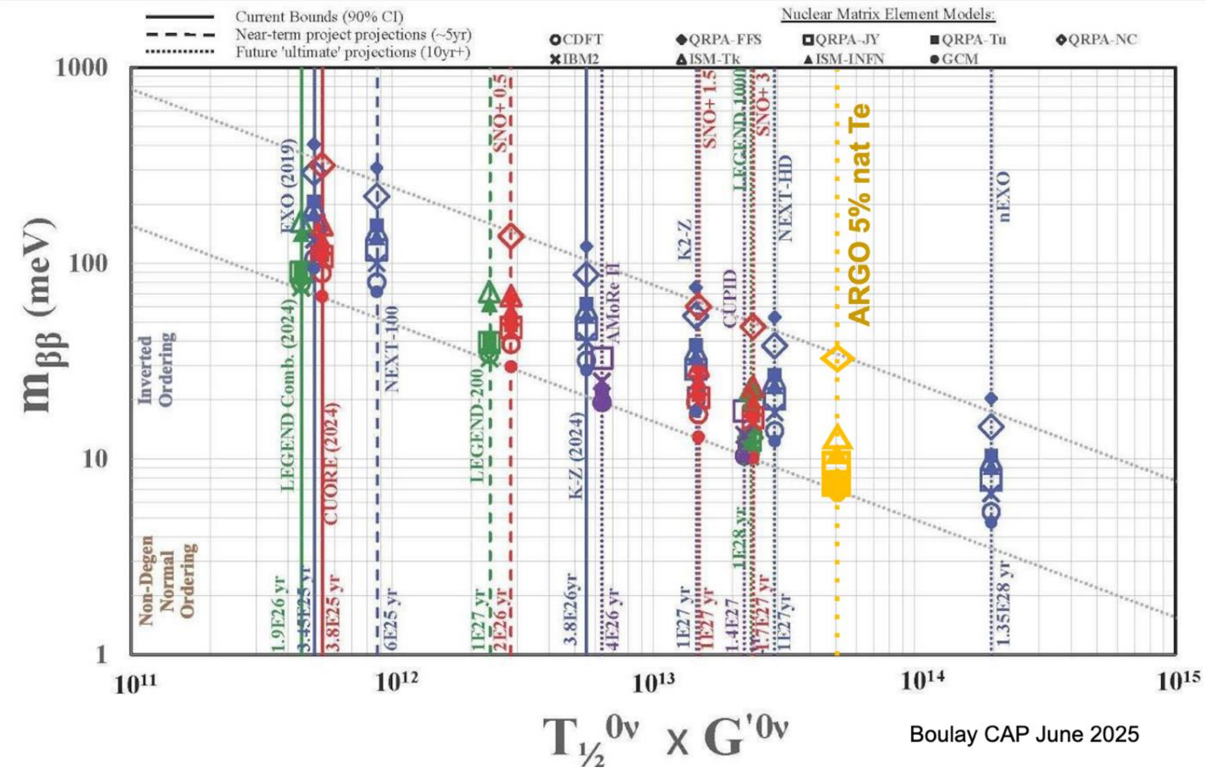


Backup

ARGO+Te

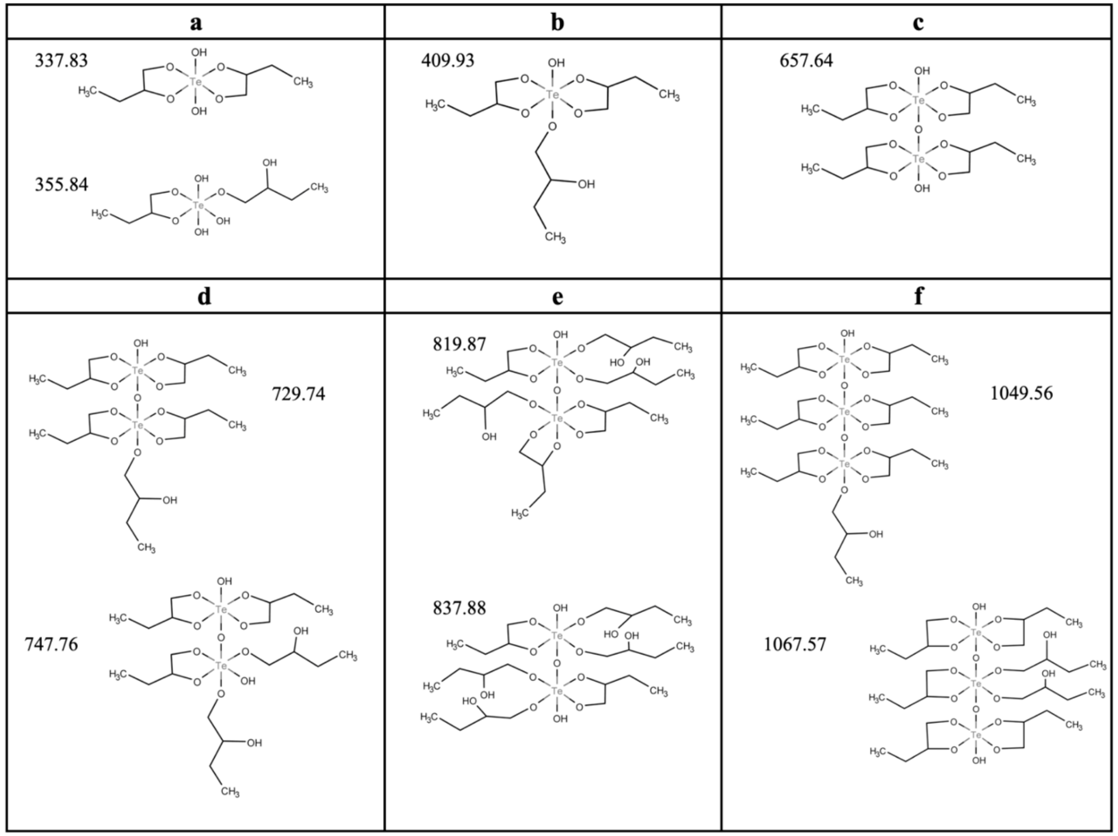





Current Bounds (90% CI)
Near-term project projections (~5yr)
Future 'ultimate' projections (10yr+)
Nuclear Matrix Element Models:
CDFT
IBM2
QRPA-FFS
ISM-Tk
QRPA-JY
ISM-INFN
QRPA-Tu
GCM
QRPA-NC
Inverted Ordering
Non-Degen Normal Ordering
ARGO 5% nat Te
nEXO
NEXT-HD
SNO+ 3
LEGEND 1000
SNO+ 1.5
K2-Z
CUPID
AMoRe II
K-Z (2024)
LEGEND-200
SNO+ 0.5
NEXT-100
CUORE (2024)
LEGEND Comb. (2024)
EXO (2019)
m$_{\beta\beta}$ (meV)
T$_{1/2}^{0\nu}$ x G'$^{0\nu}$

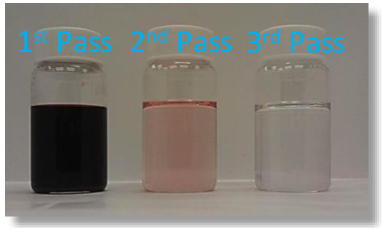
Loading method

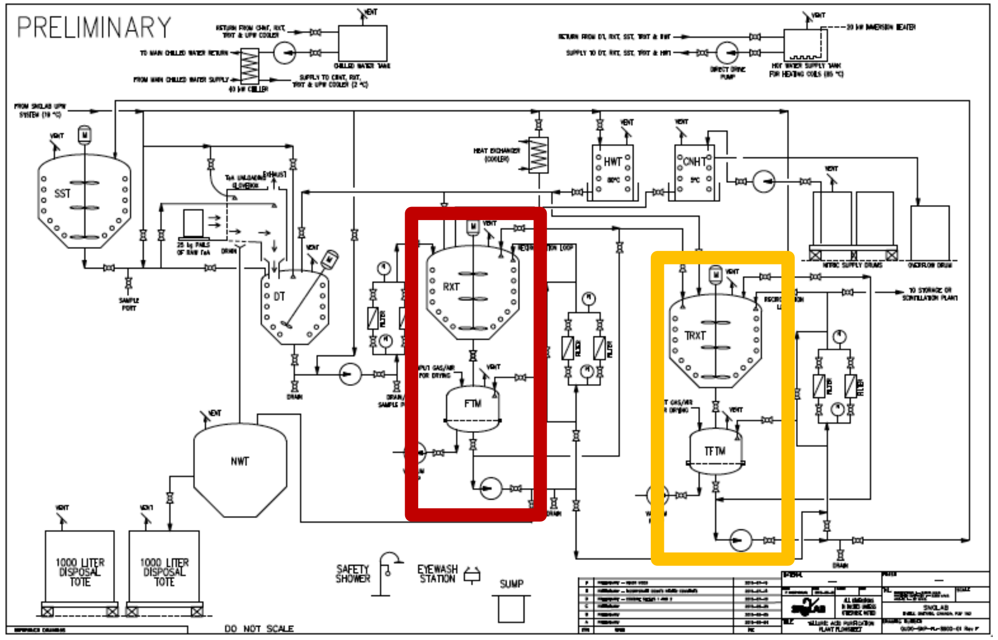
- (In the case of SNO+) LAB-soluble Tellurium-Diol complexes are formed in condensation and further oligomerization reactions

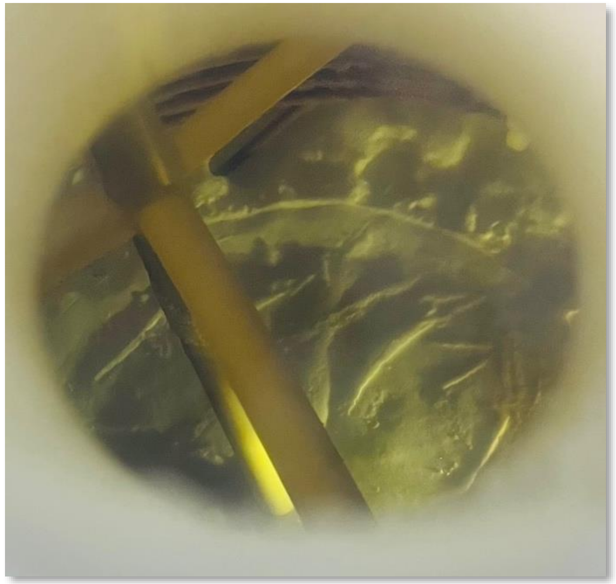


Tellurium Purification

- Relies on recrystallization and requires the use of nitric acid
  - Filter out insoluble impurities in water
  - Dissolve the rest and drain away after telluric acid is recrystallized







Loading method

- Tellurium synthesis to ‘mineral-oil-soluble’ complexes is relatively easily scalable