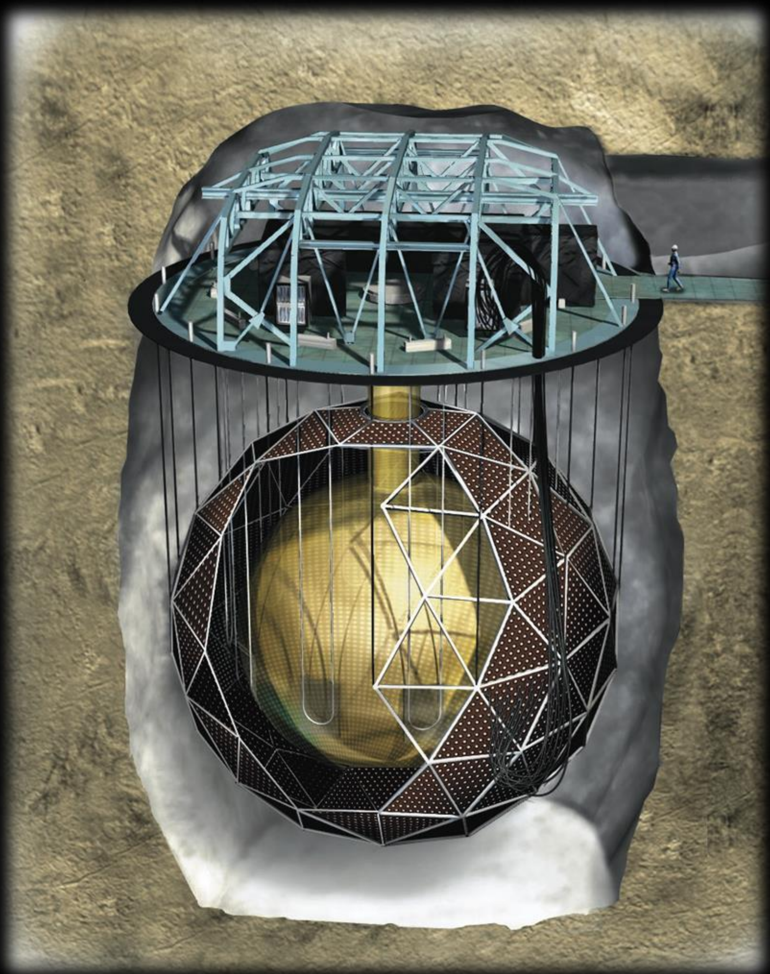
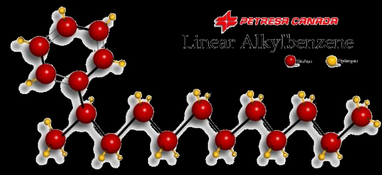
Tellurium Loading in SNO+

Szymon Manecki, Queen's University
THEIA Workshop, UC Davis, April 13th, 2018

SNOLAB Facility

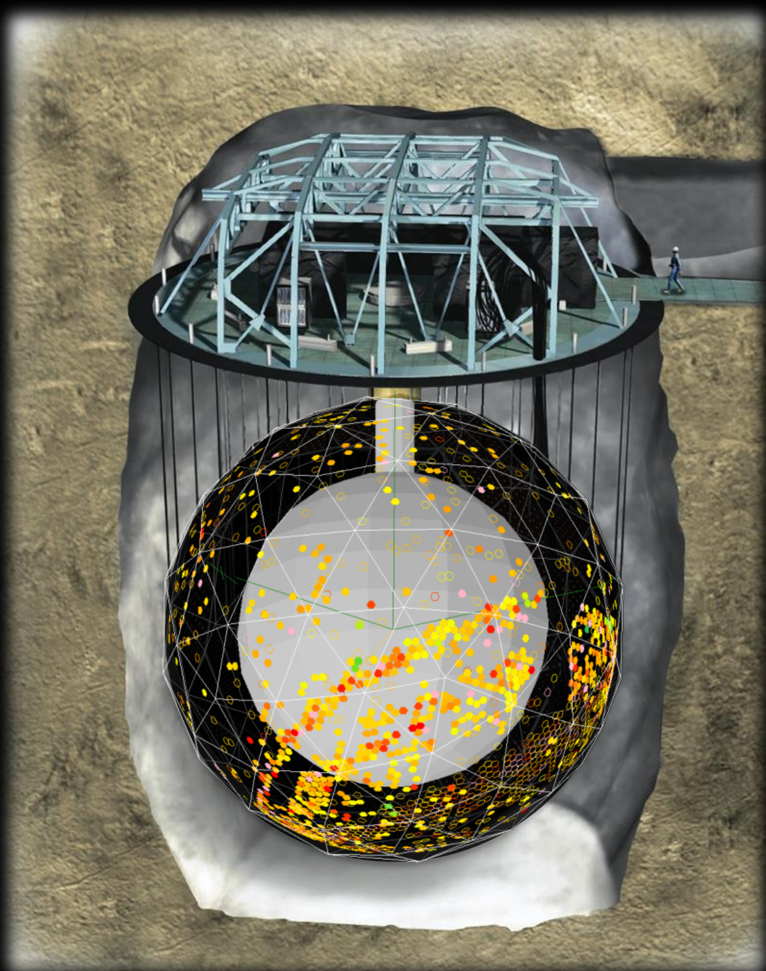
SNO+ Detector





- 780 tonnes of (LAB) scintillator
- Acrylic Vessel (AV) Φ = 12m
- 9500 PMTs, 54% coverage
- Light water (H_2O) shielding
- Urylon Liner/Radon Seal
- Norite Rock

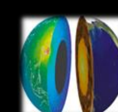
SNO+ Detector



SNO+
Physics Goals

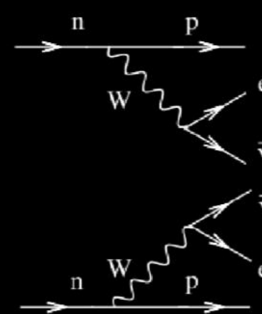
- Neutrinoless Double Beta Decay

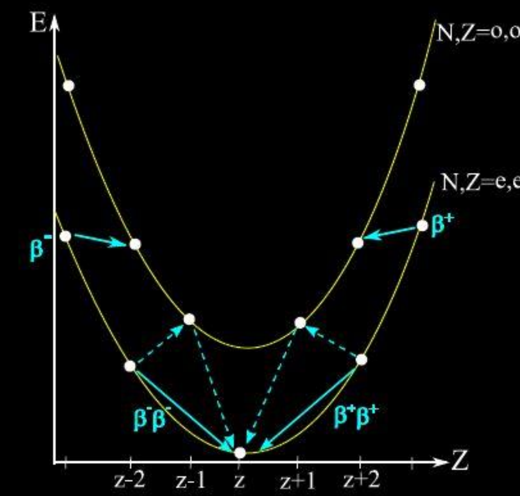
- Low Energy Solar Neutrinos

- Reactor Antineutrinos 
- Geo-Neutrinos 
- Supernova-ν

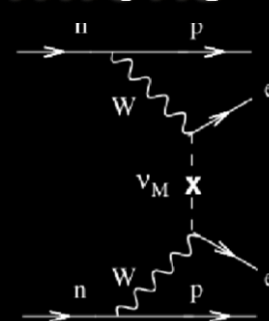
Double Beta Decay

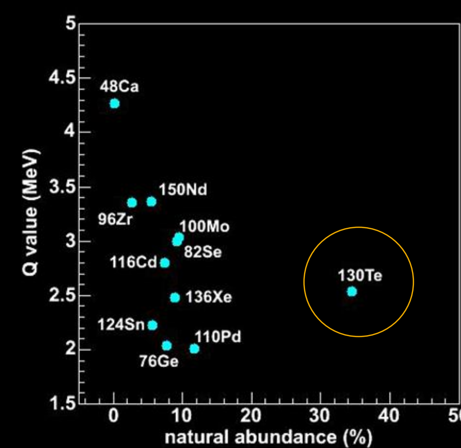
- Two neutrino double beta decay
  - Neutrinos are Dirac fermions
    $(2\upsilon\beta\beta)$ ~ 10^{18}-10^{21} years
    $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\upsilon}_e$





- Neutrinoless double beta decay
  - Neutrinos are Majorana fermions
    $(0\upsilon\beta\beta)$ > 10^{25} years
    $(A,Z) \rightarrow (A,Z+2) + 2e^-$





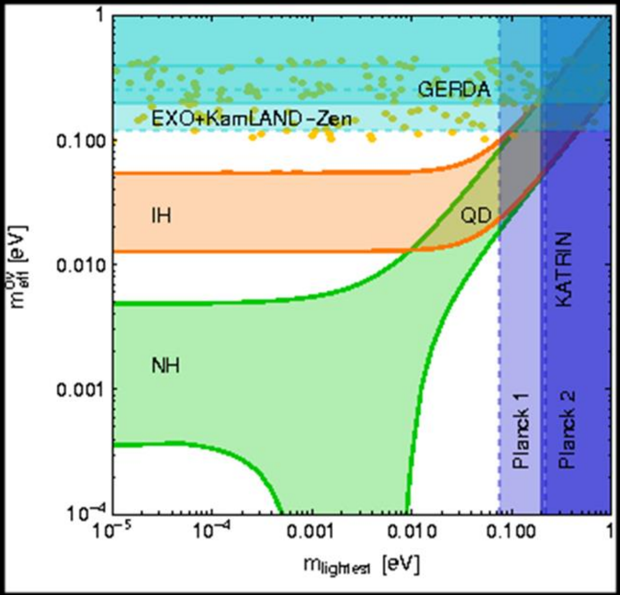
Double Beta Decay

- How to probe absolute mass scales ?
  - Assuming the "see-saw" exchange of light Majorana neutrino in 0νββ; The decay rate:

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

Where:

$$\langle m_{\beta\beta} \rangle^2 = | \sum_i U_{ei}^2 \; m_{\nu i}|^2$$

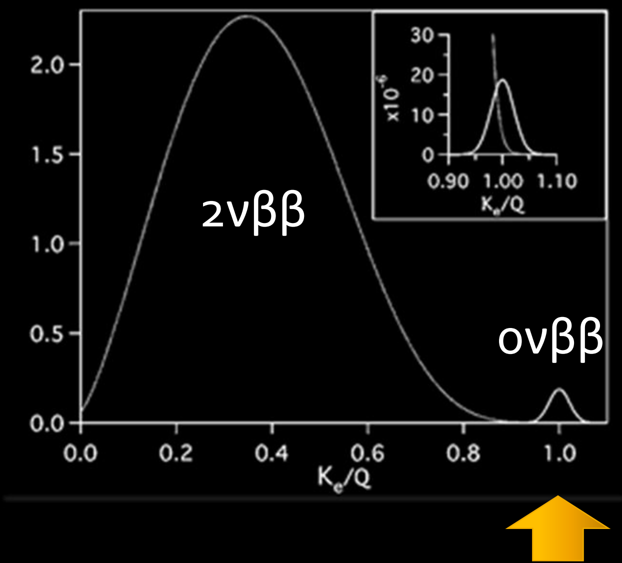


The bands allow freedom in the unknown CP phase and mixing matrix parameters

Double Beta Decay

- How to design a good 0υββ experiment ?
  - (A,Z) -> (A,Z+2) + 2e^{-}
  - A calorimetric measurement
    - Good energy resolution
      - Increase light collection
    - Large exposure time
      - Amount of source
    - Low backgrounds

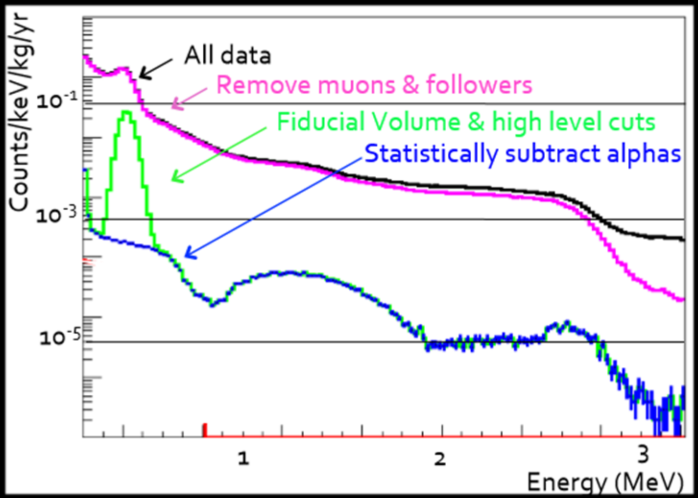
$$T_{1/2} > \frac{\ln 2 \;\; \varepsilon \cdot N_{source} \cdot T}{UL(B(T) \cdot \Delta E)}$$



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

Double Beta Decay

- Why Liquid Scintillator Technology ?
  - High efficiency for rejecting muon follower and delayed coincidence backgrounds
  - Fiducialization to suppress external backgrounds
  - Pulse shape discrimination
  - Source in/source out
  - Possibility of re-purifying *in-situ*



Borexino Data: 150 tonne-years
Background reduction methodology

LAB Scintillator

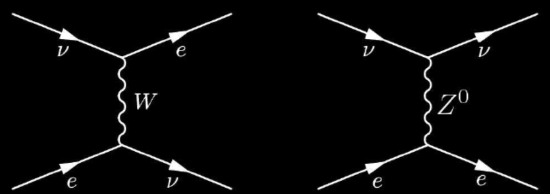
- Low cost
- High flash point 130°C
- Low toxicity

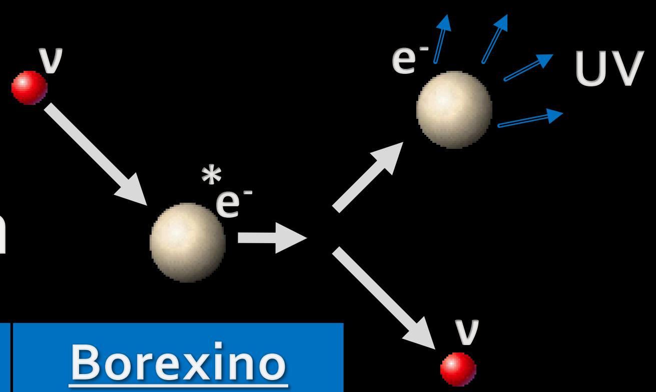
- Light attenuation length> 20 m at 420 nm
- High light yield (~10,000 photons/MeV)
- Smallest scattering of all scintillating solvents investigated

- Compatibility test with acrylic
- Metal loading possible
- Density r = 0.86 g/cm^3

LAB Scintillator

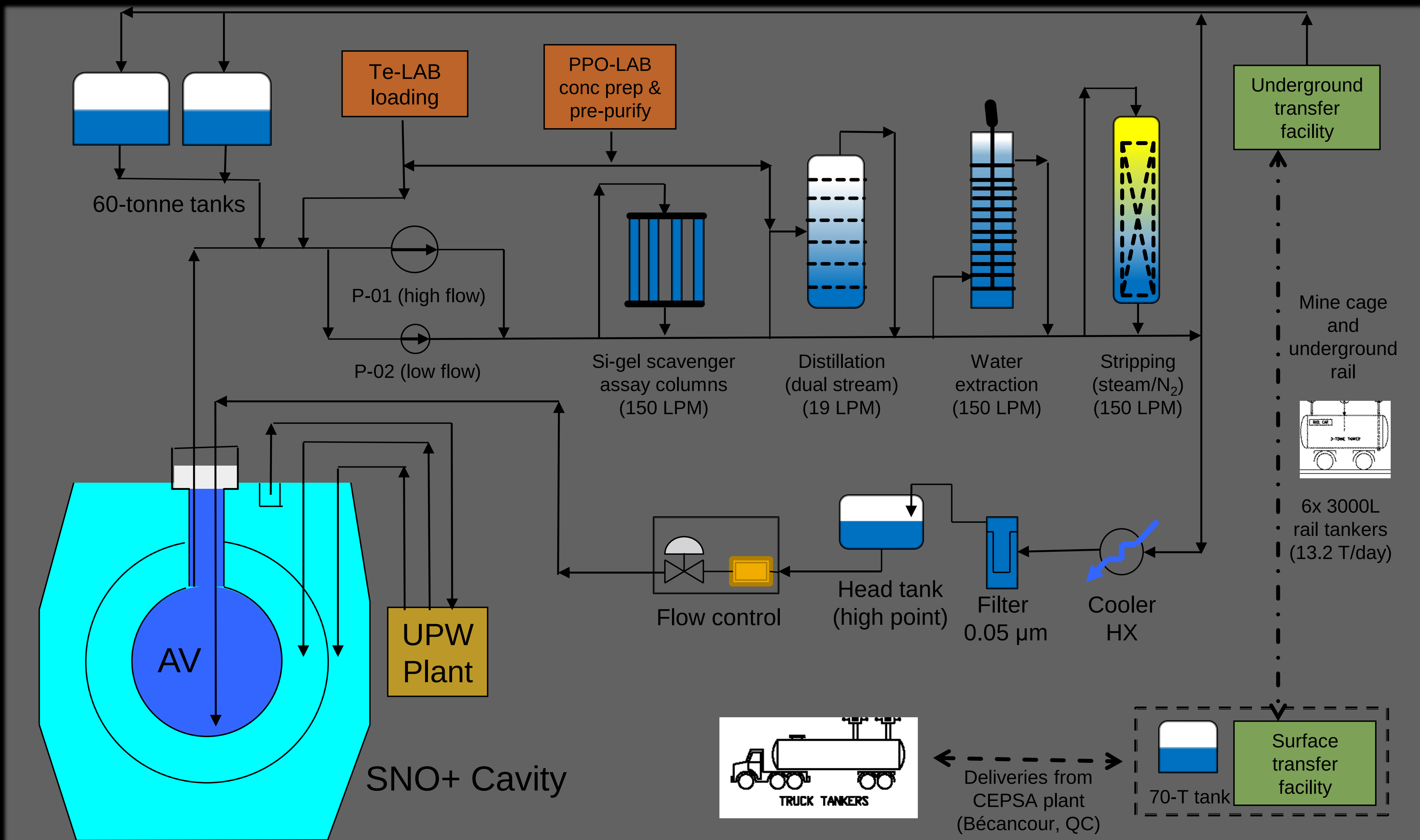
- Detection principle and backgrounds
  - Any charged particle can cause scintillation
    - Neutrino electron scattering
    - Indistinguishable from β or γ
      - α's yes: higher stopping power
    - No directional information
  - Low υ interaction cross-section





Background	Typical abundance	Goal	Borexino
^{238}U	2 x10^{-5} (dust) g/g	< 10^{-16} g/g	<9×10^{-20} g/g
^{232}Th	2 x 10^{-5} (dust) g/g	< 10^{-16} g/g	<7×10^{-19} g/g

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

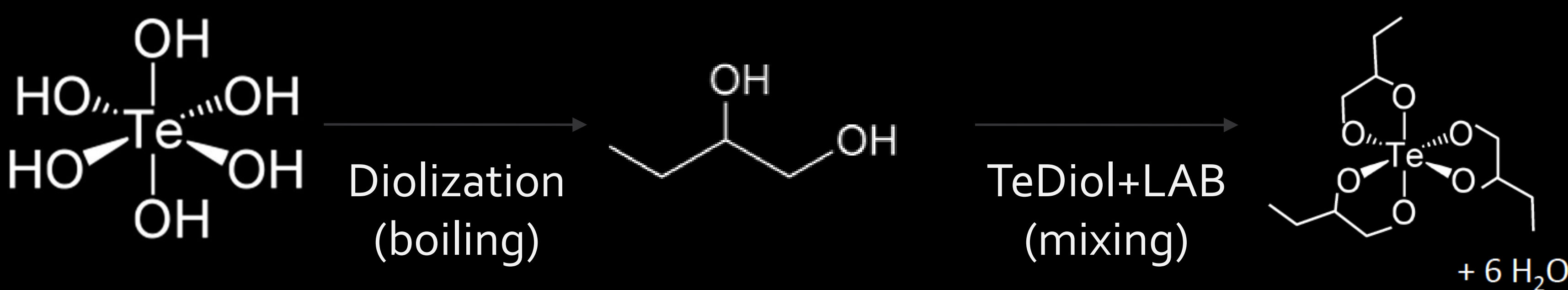
0νββ LS Requirements

- 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

- Butanediol based Te complex (“TeDiol”):

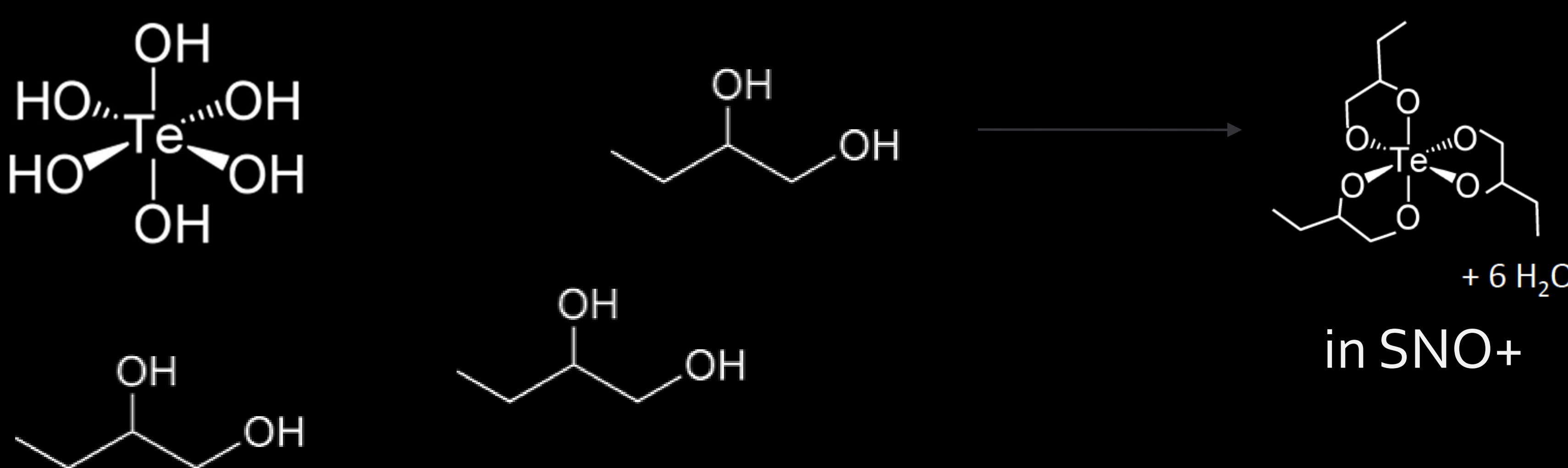


Telluric Acid Butanediol in SNO+

The TeDiol Complex

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

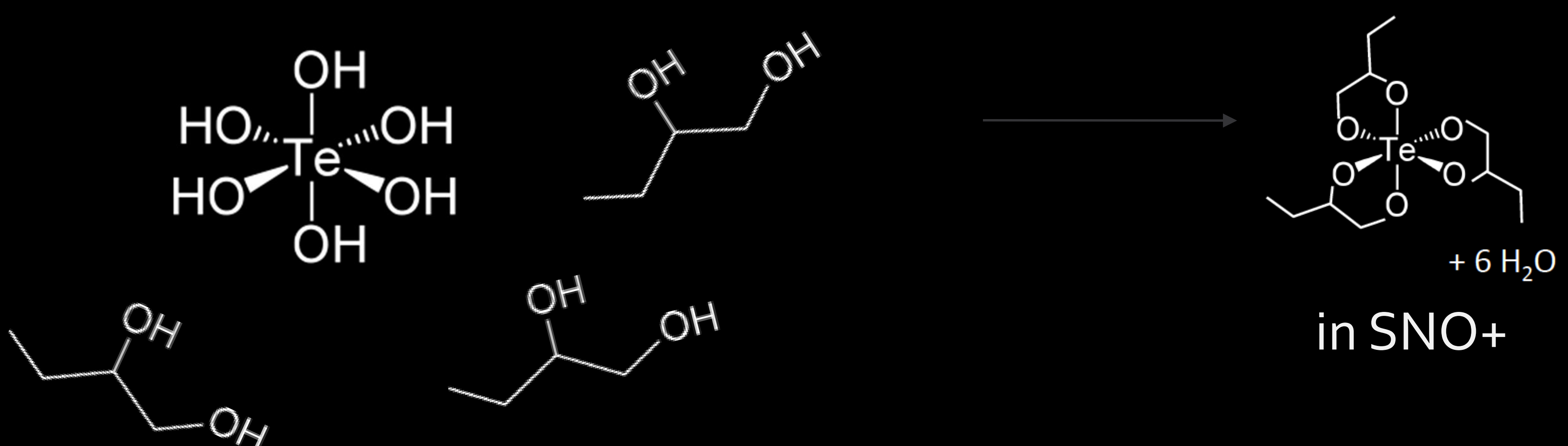
- Butanediol based Te complex ("TeDiol"):



in SNO+

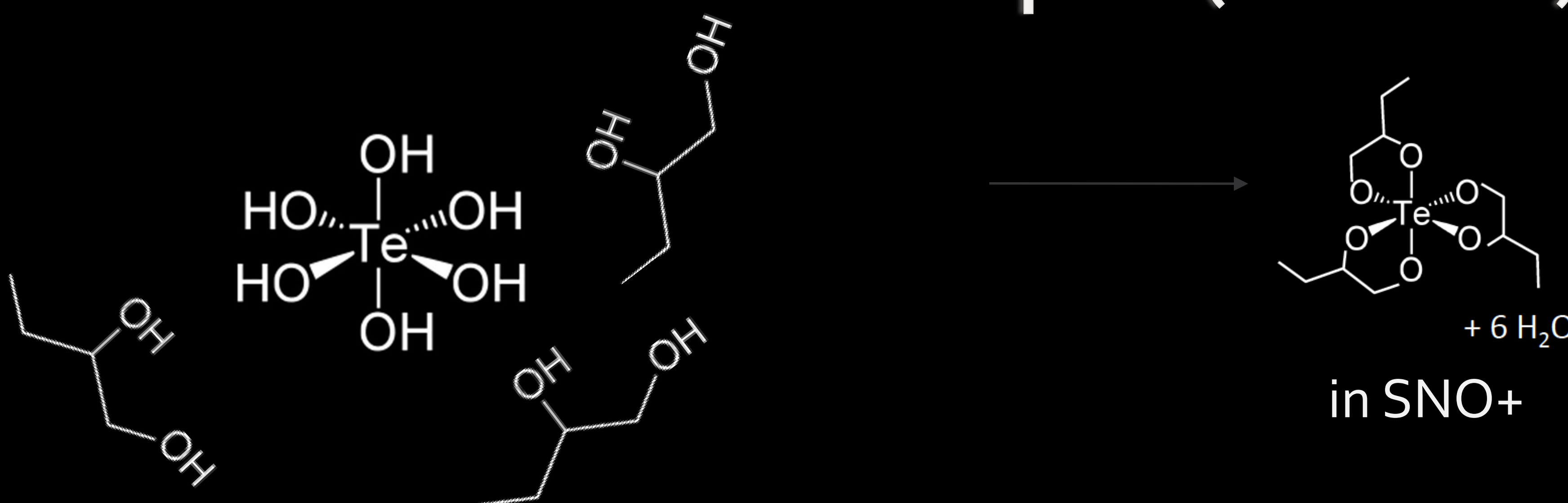
The TeDiol Complex

- Tellurium loading in Linear Alkyl Benzene
  - Through direct mixing in of an organometallic complex of Tellurium
- Butanediol based Te complex (“TeDiol”):



The TeDiol Complex

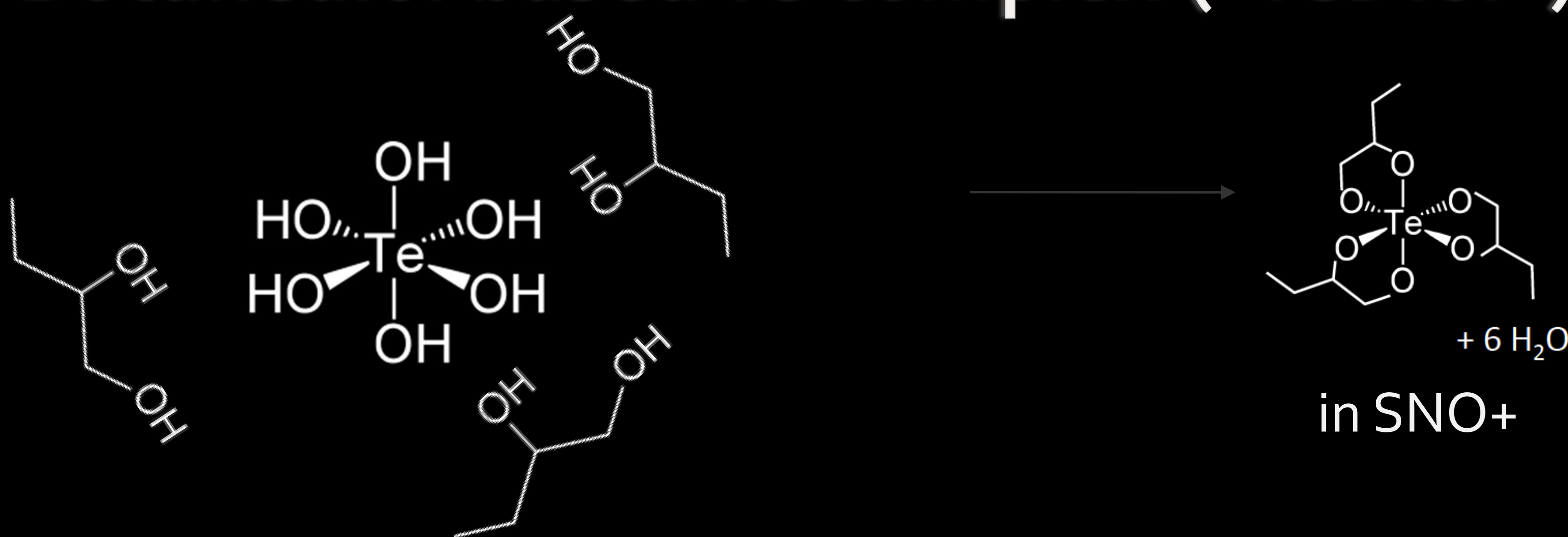
- Tellurium loading in Linear Alkyl Benzene
  - Through direct mixing in of an organometallic complex of Tellurium
- Butanediol based Te complex ("TeDiol"):



The TeDiol Complex

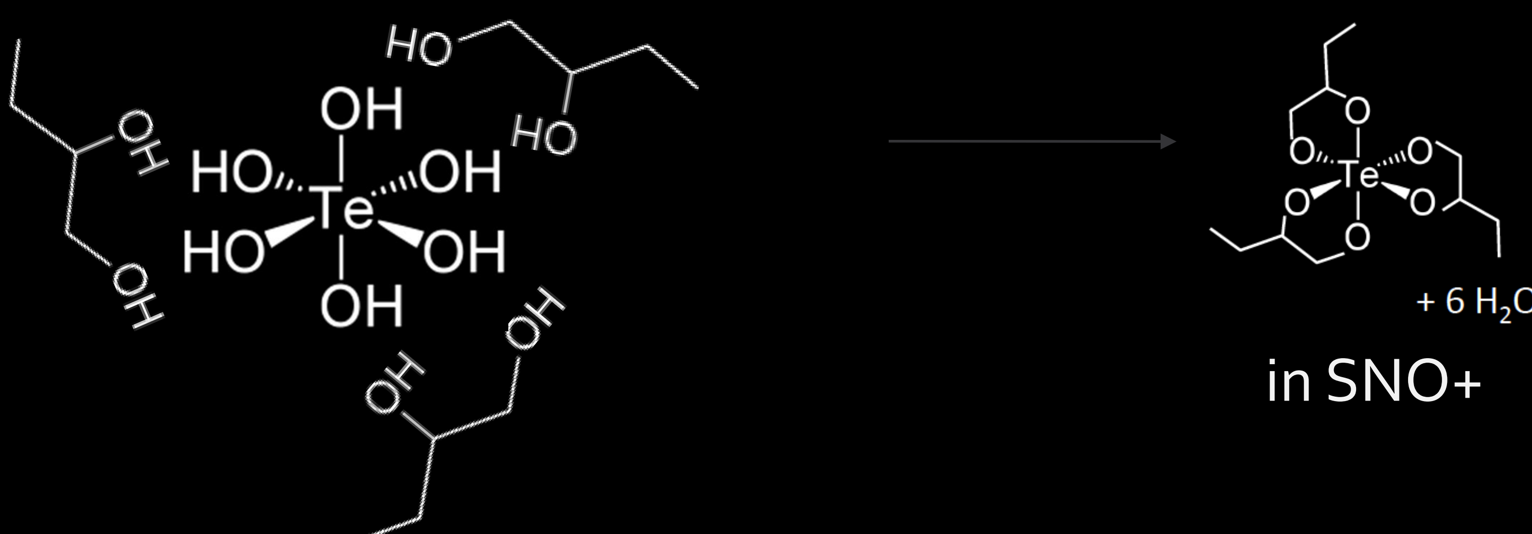
- Tellurium loading in Linear Alkyl Benzene
  - Through direct mixing in of an organometallic complex of Tellurium

- Butanediol based Te complex ("TeDiol"):



The TeDiol Complex

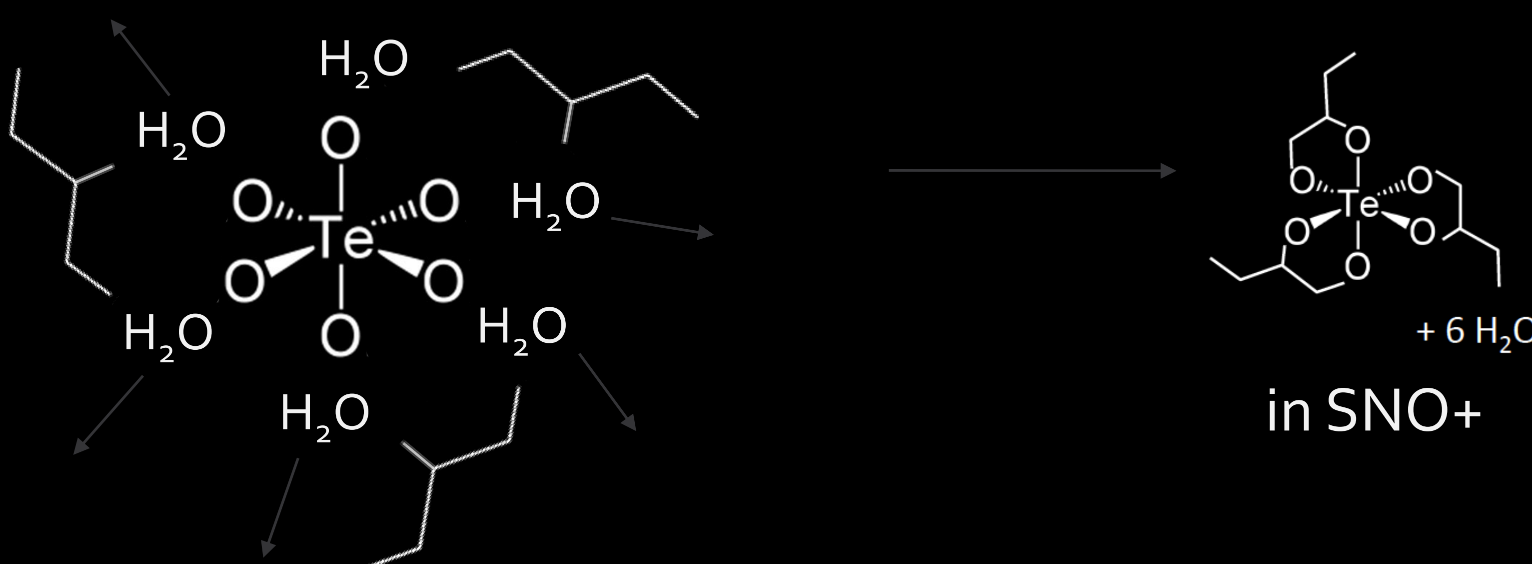
- Tellurium loading in Linear Alkyl Benzene
  - Through direct mixing in of an organometallic complex of Tellurium
- Butanediol based Te complex (“TeDiol”):



in SNO+

The TeDiol Complex

- Tellurium loading in Linear Alkyl Benzene
  - Through direct mixing in of an organometallic complex of Tellurium
- Butanediol based Te complex ("TeDiol"):

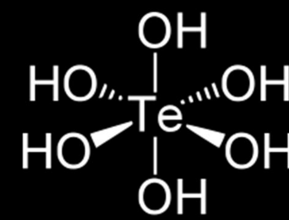


The TeDiol Complex

- Tellurium loading in Linear Alkyl Benzene
  - Through direct mixing in of an organometallic complex of Tellurium
- Butanediol based Te complex (“TeDiol”):

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

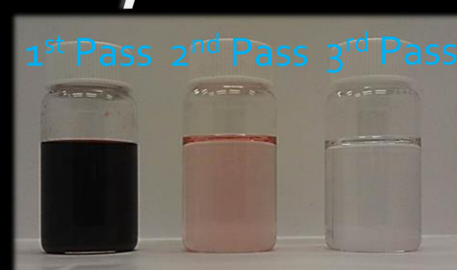
Telluric Acid Purification

- 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

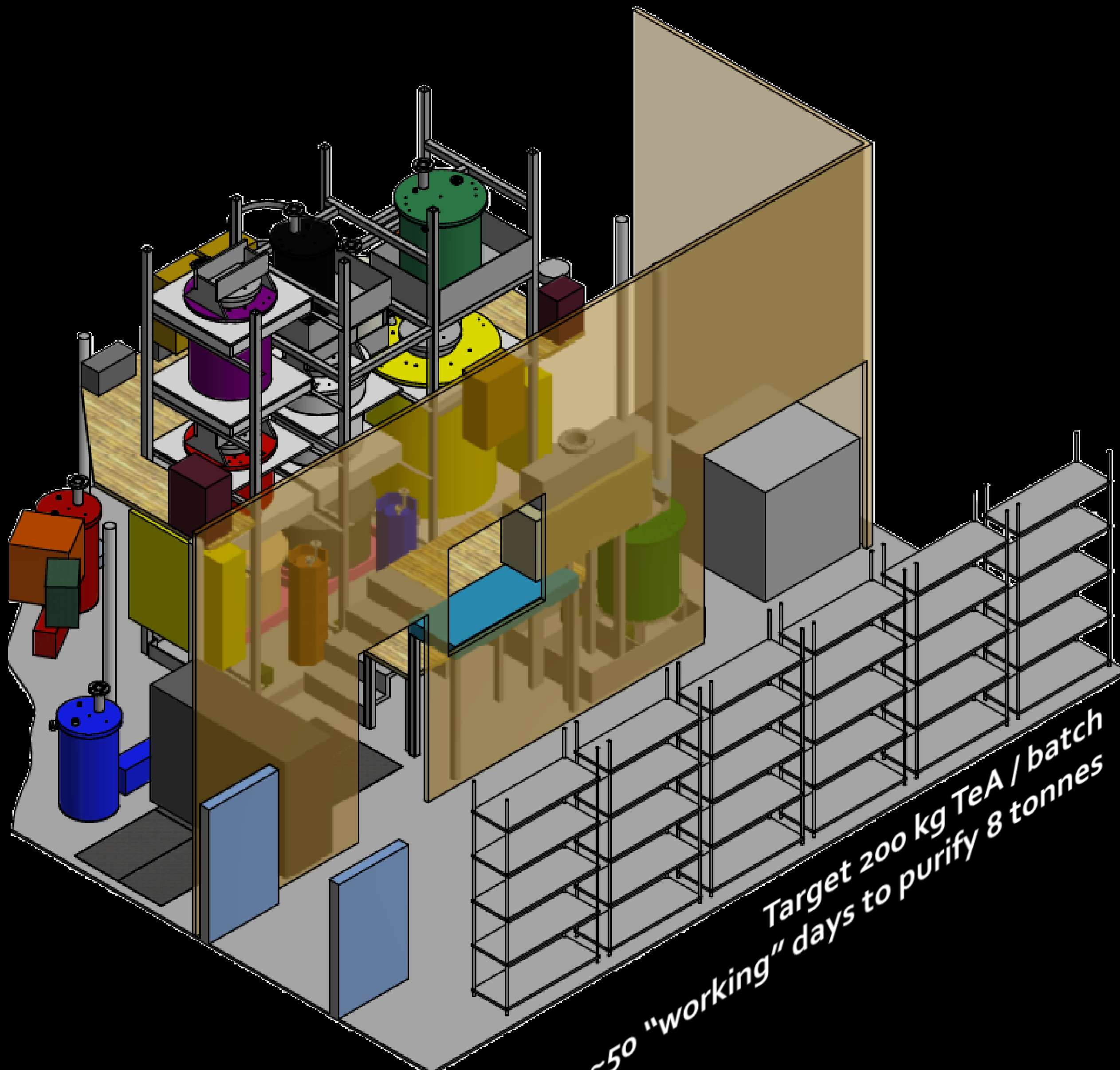
- 0.5% Tellurium Target levels:
  - 1.3×10^{-15} g/g in ^{238}U (3×10^{-8} Bq/kg)
  - 5×10^{-16} g/g in ^{232}Th (1.2×10^{-9} Bq/kg)
    - (raw Te ~10^{-11} g/g U/Th, 10^{-4} Bq/kg)
- Cosmogenic contamination from activation on Te
  - ^{60}Co, ^{110m}Ag, ^{126}Sn, ^{88}Zr, ^{88}Y, ^{124}Sb
    - Rejection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

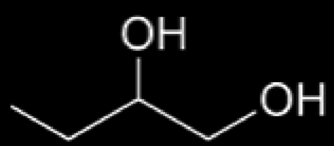


Telluric Acid Purification Plant

As of: Mar-2018

Butanediol Assay

- $^{14}C/^{12}C$ 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: $(2.5 \pm 1.2) \times 10^{-17}$



- Gamma-ray & NAA Assay
  - HPGe@SNOLAB
    - ^{238}U < 3.13 ppb
    - ^{232}Th < 0.26 ppb
    - ^{40}K < 386.56 ppb
  - NAA@UC Davis
    - ^{238}U < 0.3 ppb
    - ^{232}Th < 3.3 ppb
    - ^{nat}Na 2.2 ppb

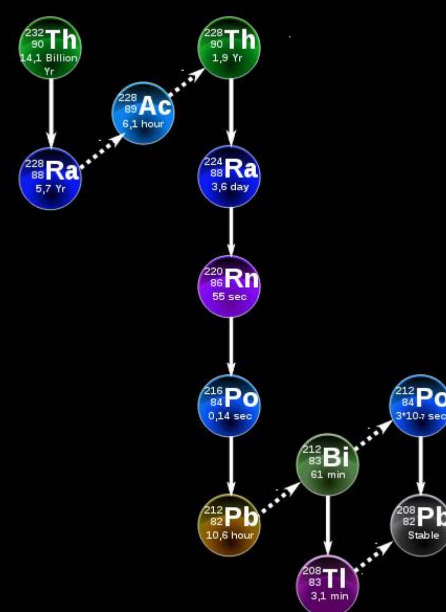
Butanediol Purification

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

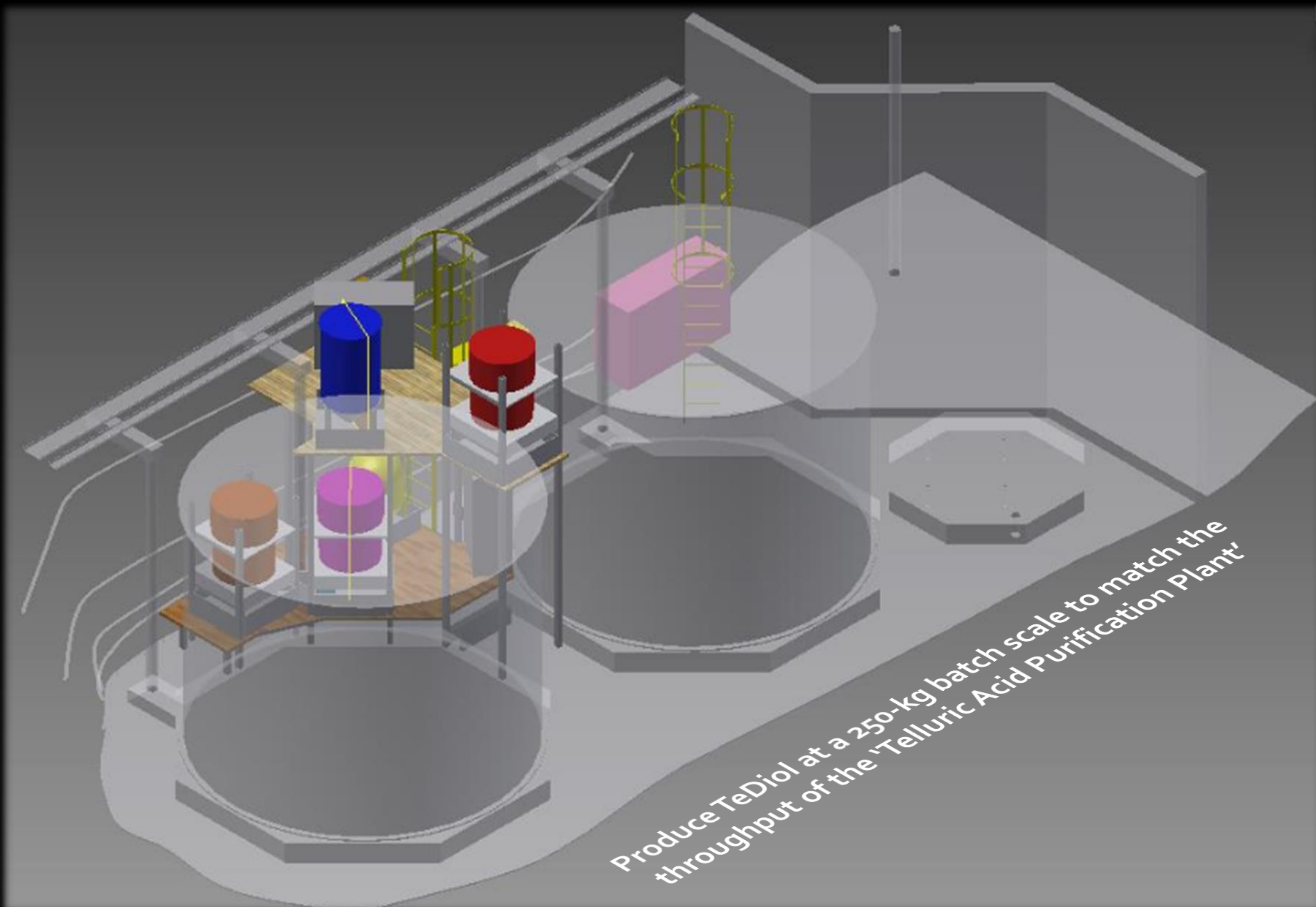
	Initial activity mBq/g	Distillate activity mBq/g	Reduction factor
^{228}Th	72	<0.014	>5100
^{224}Ra	72	<0.013	>5500

    - 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

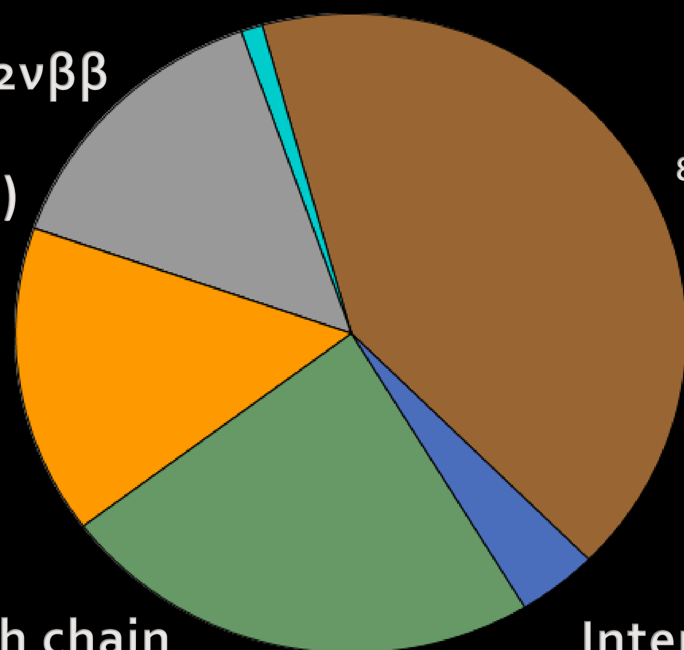
As of: Mar-2018

TeDiol & TeA Vessels

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



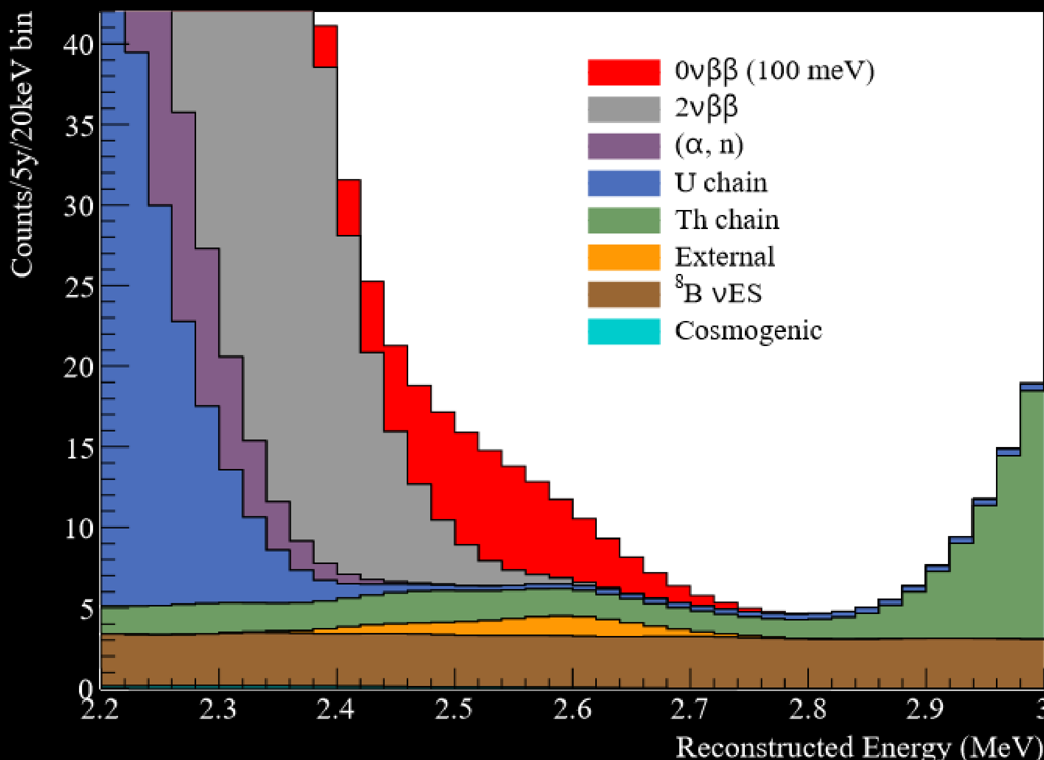
External γ
From AV, ropes, water, PMTs
Fiducial volume (20%) cut
50% extra rejection multi-site cuts

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
Β-α delayed coincidence tagging
100% rejection in RoI
In-window trigger: x50 rejection

0νββ Sensitivity

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

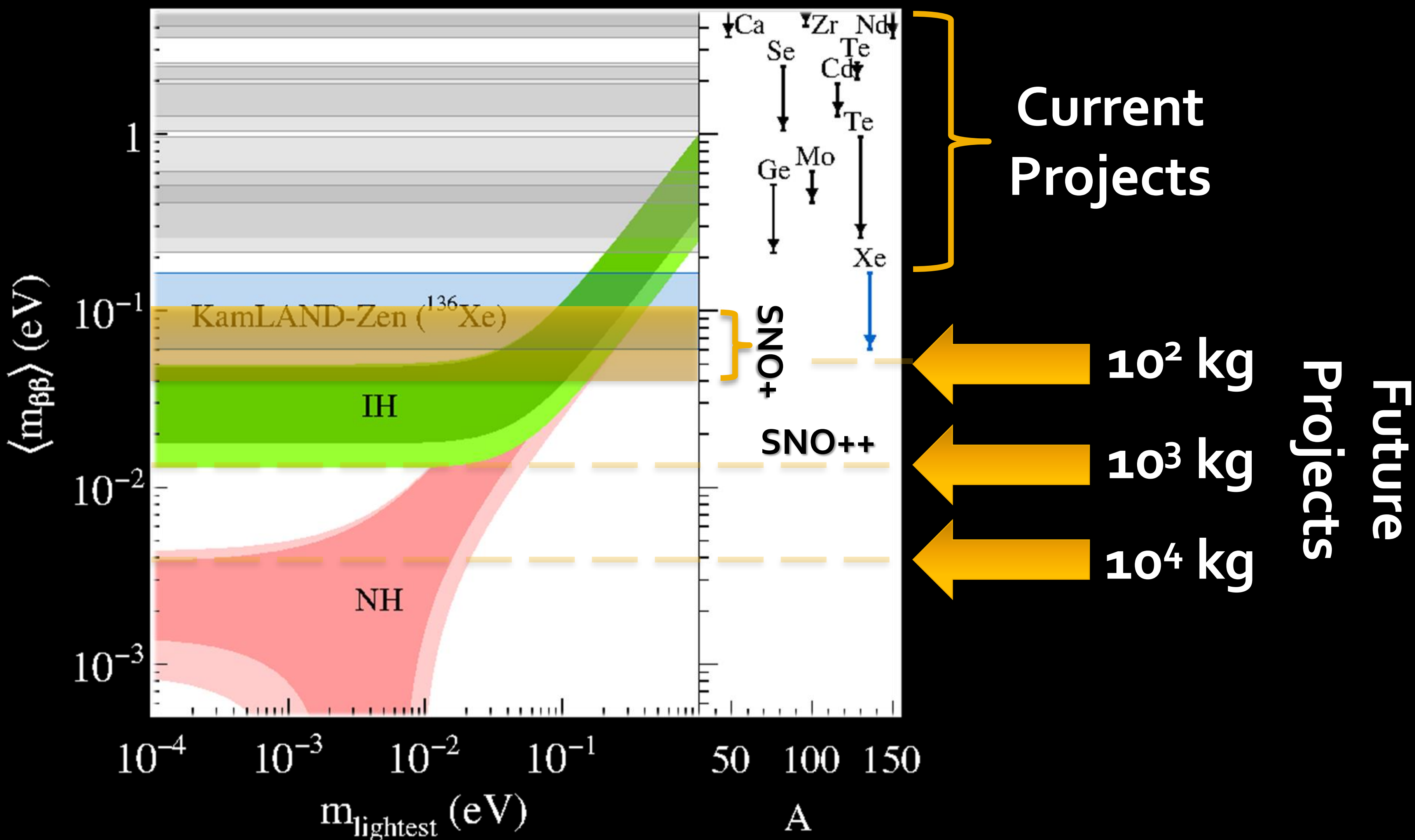


- [-0.5; +1.5] σ around $Q_{\beta\beta}$
- 390 NHits/MeV (~4% ΔE)
- Fiducial Volume: 20% total

	$T_{1/2}$ [yr]	$m_{0\nu\beta\beta}$ [meV]
1 yr	8x10^{25}	75.2
5 yrs	1.9x10^{26}	41 – 99

(@90% C.L.)

0υββ Sensitivity



SNO+ Timeline

- 2018
  - Scintillator plant commissioning
  - Scintillator fill
    - Solar neutrino phase (short)
    - Evaluation of backgrounds for $0\nu\beta\beta$
  - Commissioning of the Tellurium plant(s)
- 2018-2019
  - Tellurium loading
  - Begin $0\nu\beta\beta$ phase

The PRS Surfactant

- Tellurium loading in Linear Alkyl Benzene
  - Aqueous Telluric Acid ("TeA") loaded into the scintillator using commercially available surfactant
- LAB based surfactant ("PRS"):

LAB LAS in SNO+

The PRS Surfactant

- Tellurium loading in Linear Alkyl Benzene
  - Aqueous Telluric Acid ("TeA") loaded into the scintillator using commercially available surfactant
- LAB based surfactant ("PRS"):

LAB PRS in SNO+

PRS Purification Goals

- Improvement in optical properties
  - Successfully demonstrated on a small to medium scale (purification, synthesis)
- Removal of radio-contamination and mitigation of cosmogenic ^{22}Na (ROI)
  - U/Th reduction factor ~10^{3}x, or ~10^{-15}g/g (if custom synthesized)
  - Na reduction factor ~10^{6}x, or ~0 (UG synthesis)

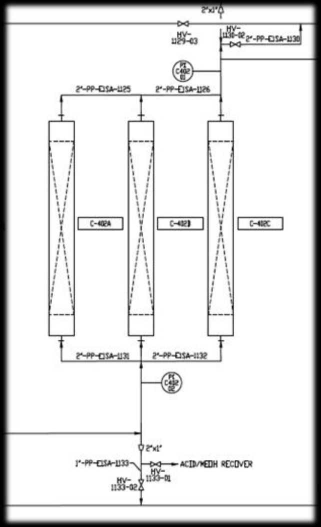
PRS Purification Techniques

- Water Extraction/Foam
- Metal Scavengers
- Nano Filtration

- Distillation
- Custom made PRS
- Combination of the above

PRS Purification Techniques

- Water Extraction/Foam
- Metal Scavengers
- Nano Filtration

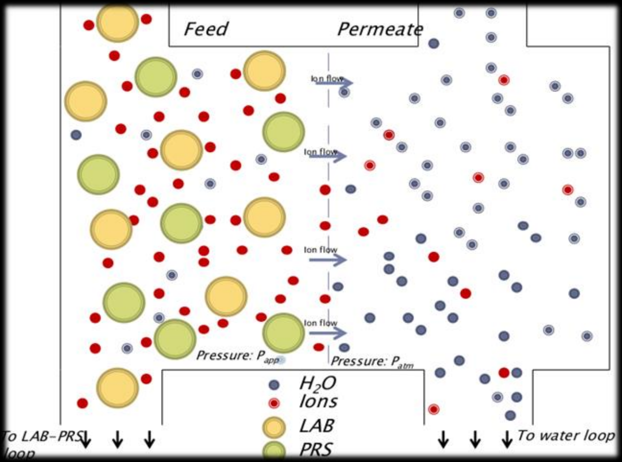


- Distillation
- Custom made PRS
- Combination of the above

PRS Purification Techniques

- Water Extraction/Foam
- Metal Scavengers
- Nano Filtration

- Distillation
- Custom made PRS
- Combination of the above

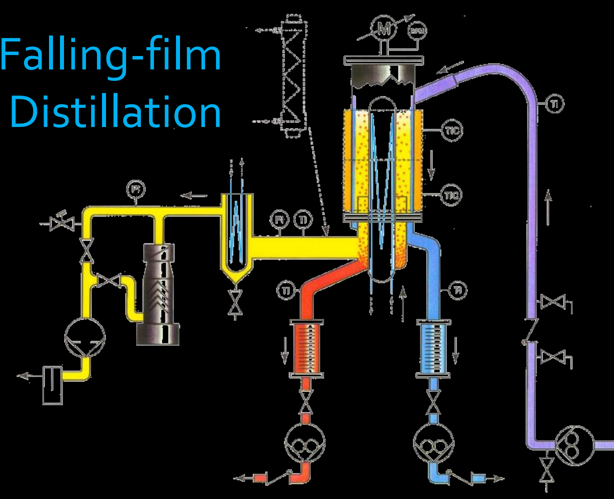


PRS Purification Techniques

- Water Extraction/Foam
- Metal Scavengers
- Nano Filtration

- Distillation
- Custom made PRS
- Combination of the above

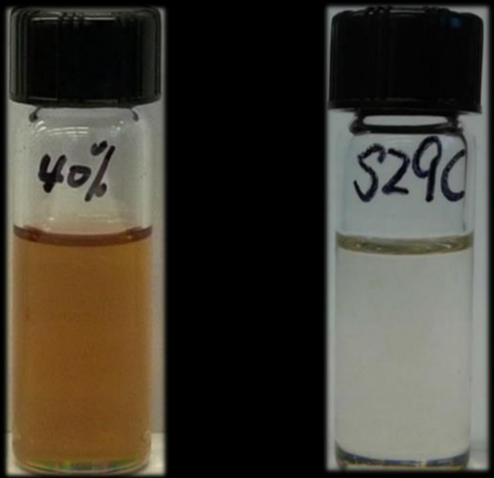
Falling-film Distillation



PRS Purification Techniques

- Water Extraction/Foam
- Metal Scavengers
- Nano Filtration

- Distillation
- Custom made PRS
- Combination of the above



Commercial Custom

40%LAS

PRS Summary

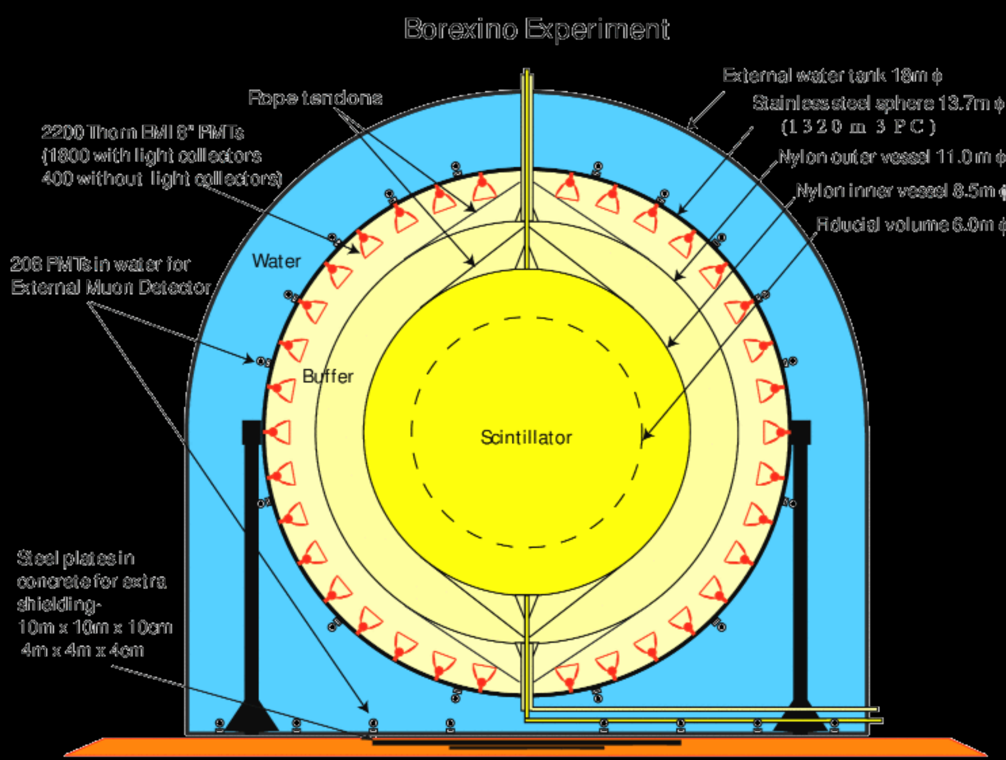
- A WbLS mix could be considered for THEIA with the following approach
  - Custom synthesized LAS (on surface)
    - Improved optical properties
  - Underground distillation
    - Reduction in cosmogenic ^{22}Na
    - Further reduction in U/Th (if needed)
- Due to the size of THEIA, the cost would be significant (potentially non-feasible)

SNO+ Collaboration

Backup

Solar Neutrino Potential

- In future phases of the solar neutrino program the AV background contribution may be mitigated with an additional bag

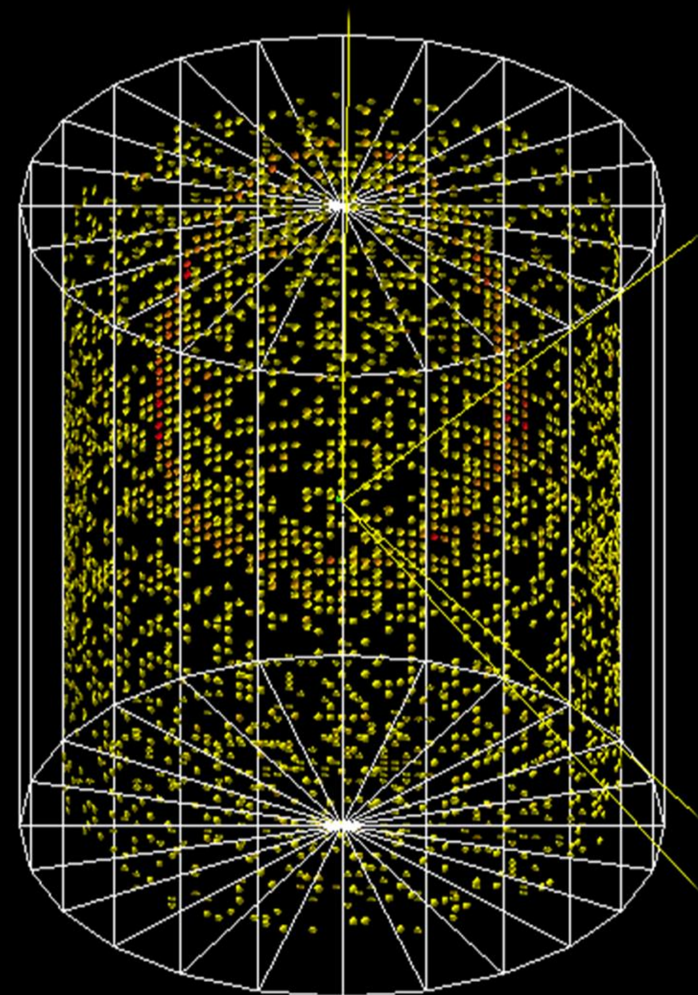


Borexino Cross-Section

THEIA

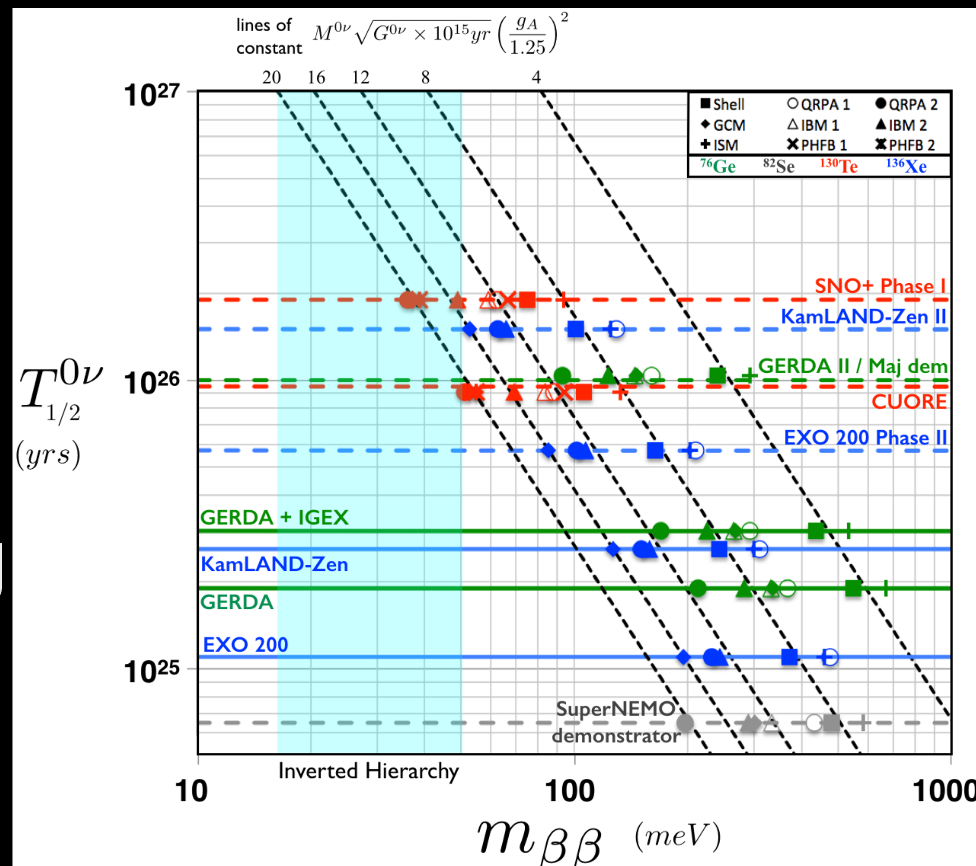
- A water-based liquid scintillator detector

- 50kT water with up to 15% scintillator
- High light yield of organic scintillator
  - Low threshold
  - Good energy resolution
- Predominantly water
  - Low light absorption
  - Directional information

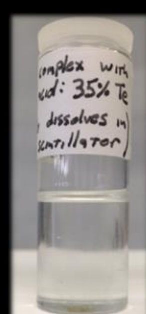


0νββ Sensitivity in Phase II

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

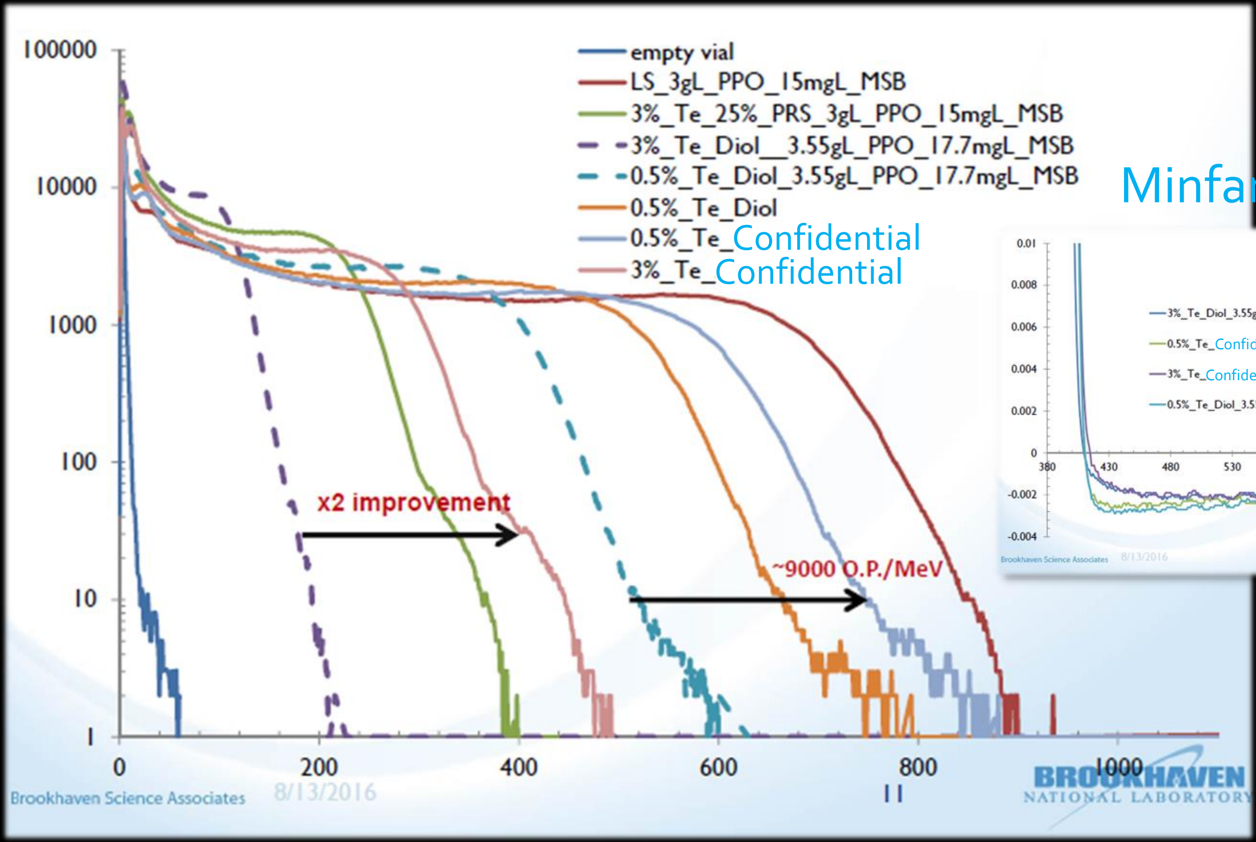


- Goal: 3% nat. Te loading
  - ~ 8 tonnes ^{130}Te
  - Higher QE PMTS
  - $T_{1/2}$ 0nbb ~ 10^{27} yr



0νββ Phase III R&D

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



Courtesy of Minfang Yeh of BNL