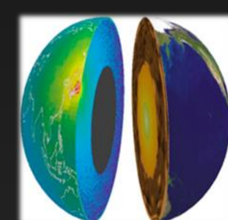
Tellurium Double Beta Decay with a Liquid Scintillator

Szymon Manecki, Queen's University,
Heavy Quarks and Leptons at Virginia Tech, May 27th, 2016

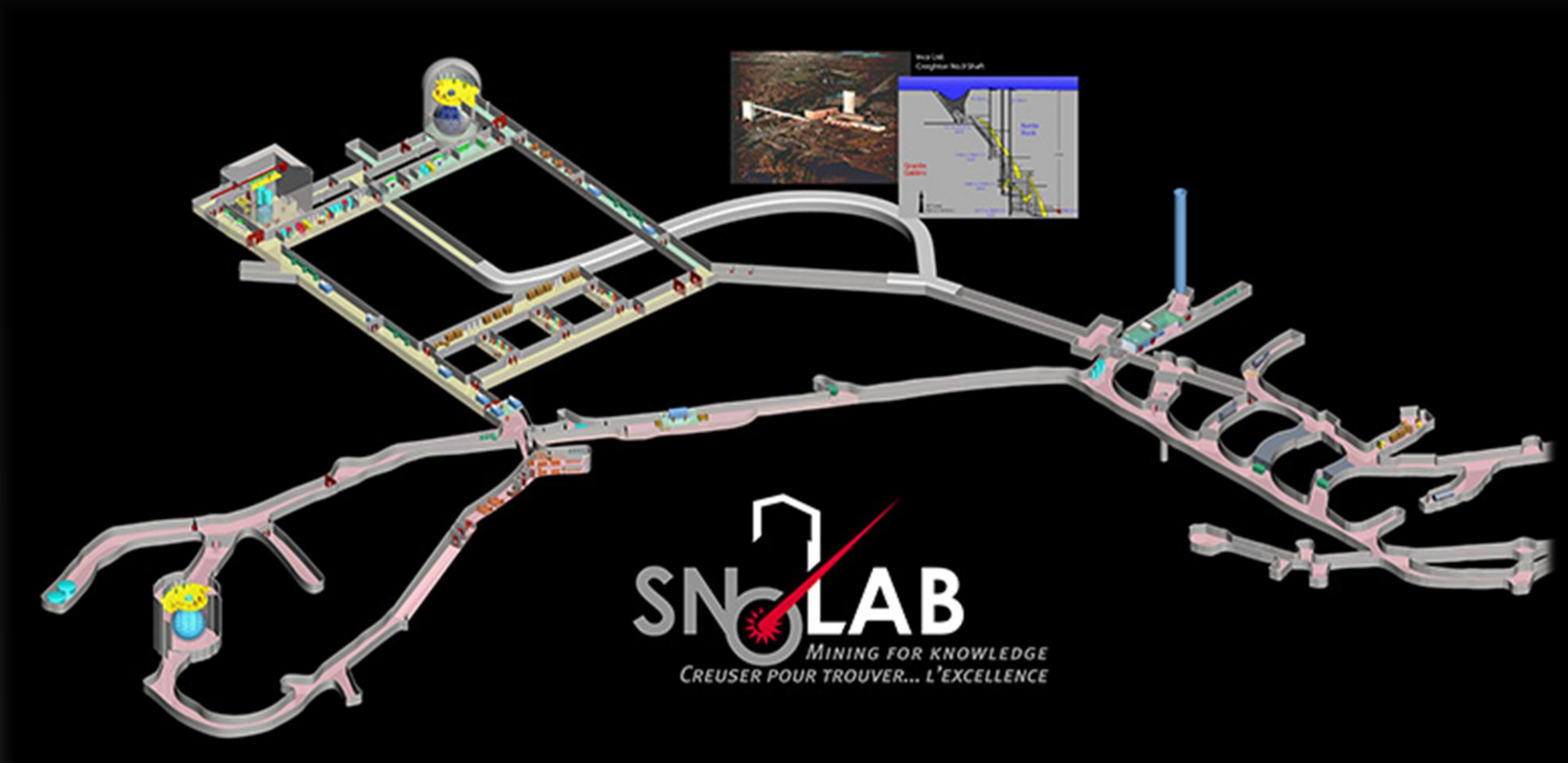
SNO+ Physics Goals

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

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

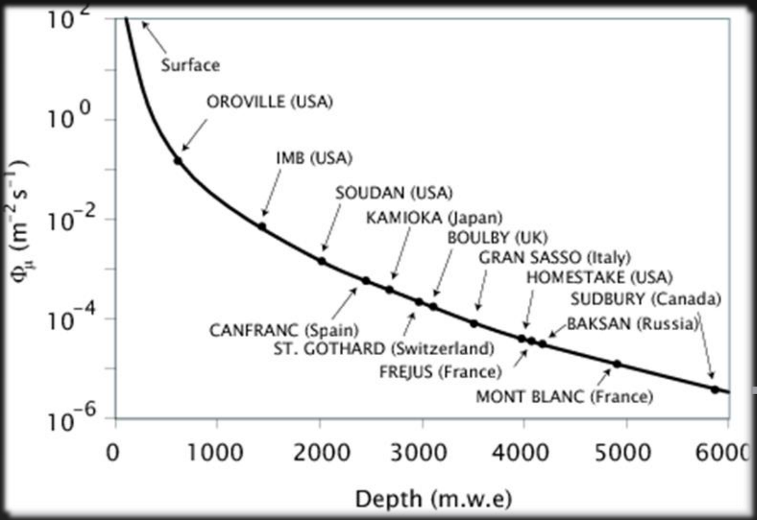


SNOLAB Facility

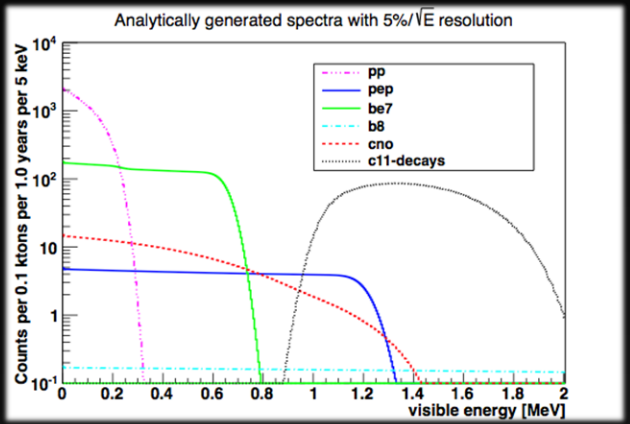


SNOLAB Facility

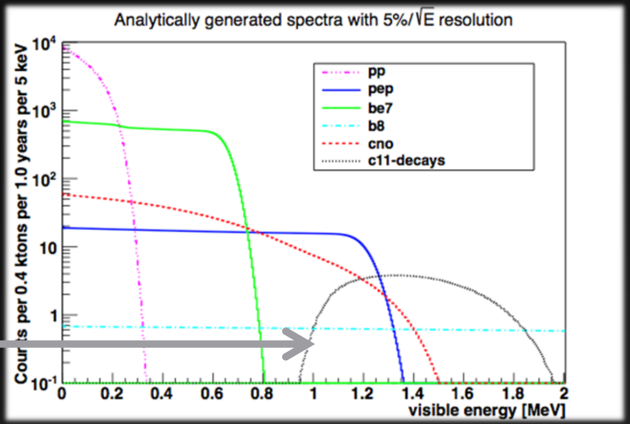
- Depth = 2070 m (6000 m.w.e.)
- 60 muons /day in SNO+
- 10,000 sq ft Class-2000 clean room



LNGS



SNOLAB



SNO+ Detector

780t of liquid scintillator
(LAB+PPO)

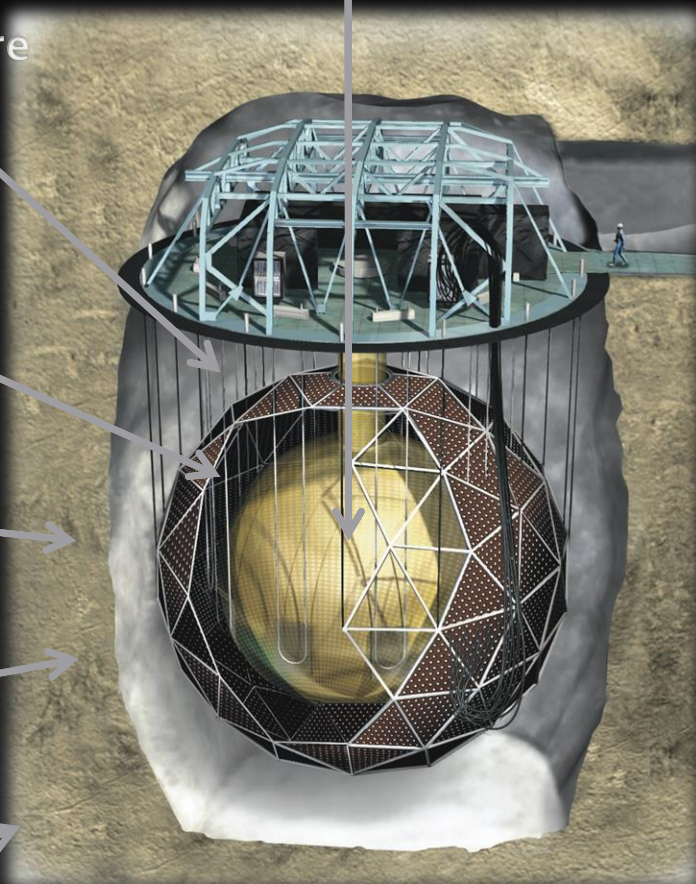
PSUP = PMT Support Structure
~9500 PMT, 54% Coverage

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

^{130}Te Double Beta Decay

- **Are neutrinos their own anti-particles?**
  - **$2\nu\beta\beta$ (Dirac)**

    $(A, Z) \longrightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$

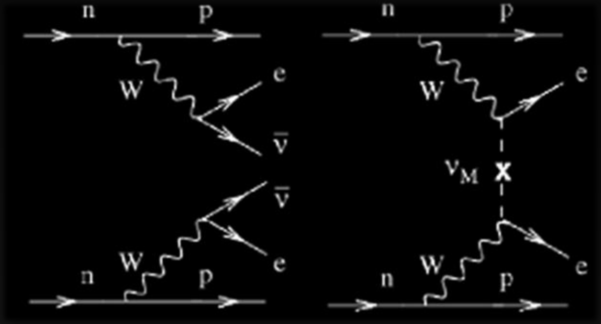
    ~ 10^{18}-10^{21} years
  - **$0\nu\beta\beta$ (Majorana)**

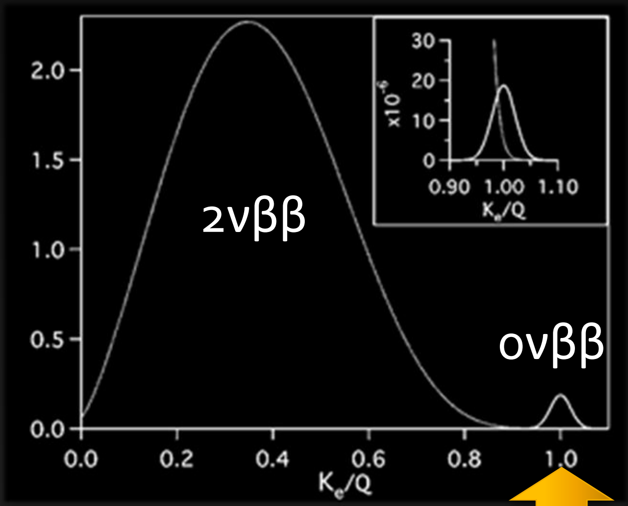
    $(A, Z) \longrightarrow (A, Z+2) + 2e^-$

    > 10^{25} years
  - **With the Mass Mechanism:**

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

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



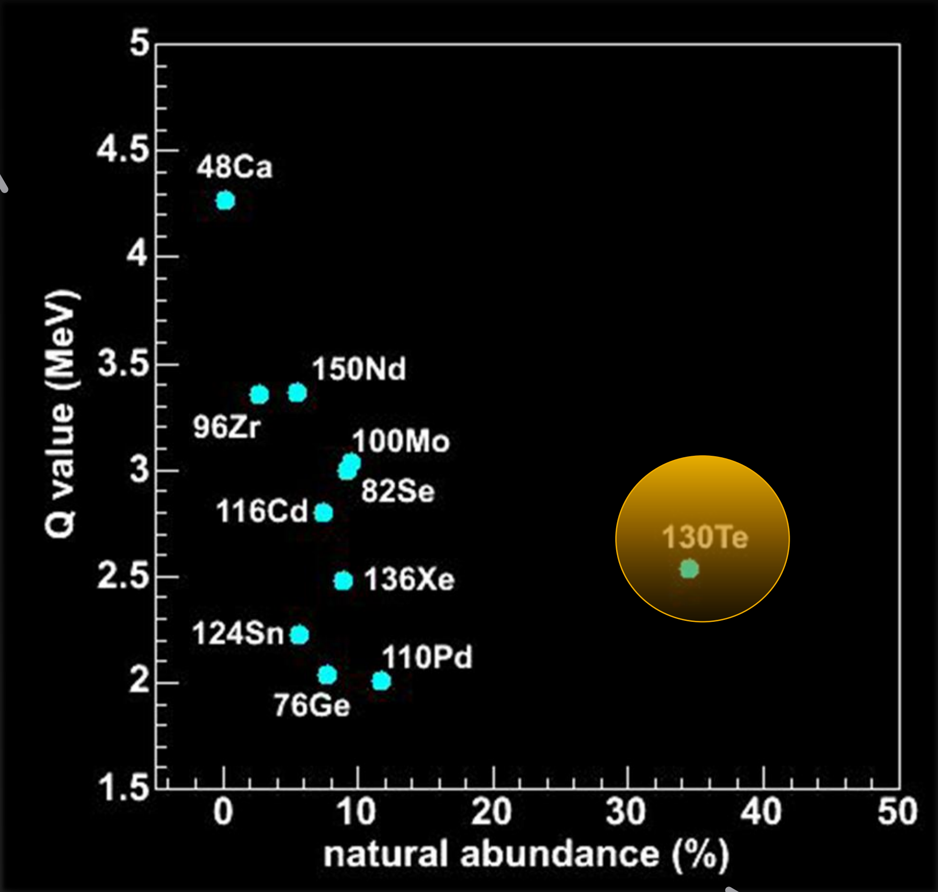


D.B.D. experiments need good energy resolution, low backgrounds, and large amounts of isotope.

^{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

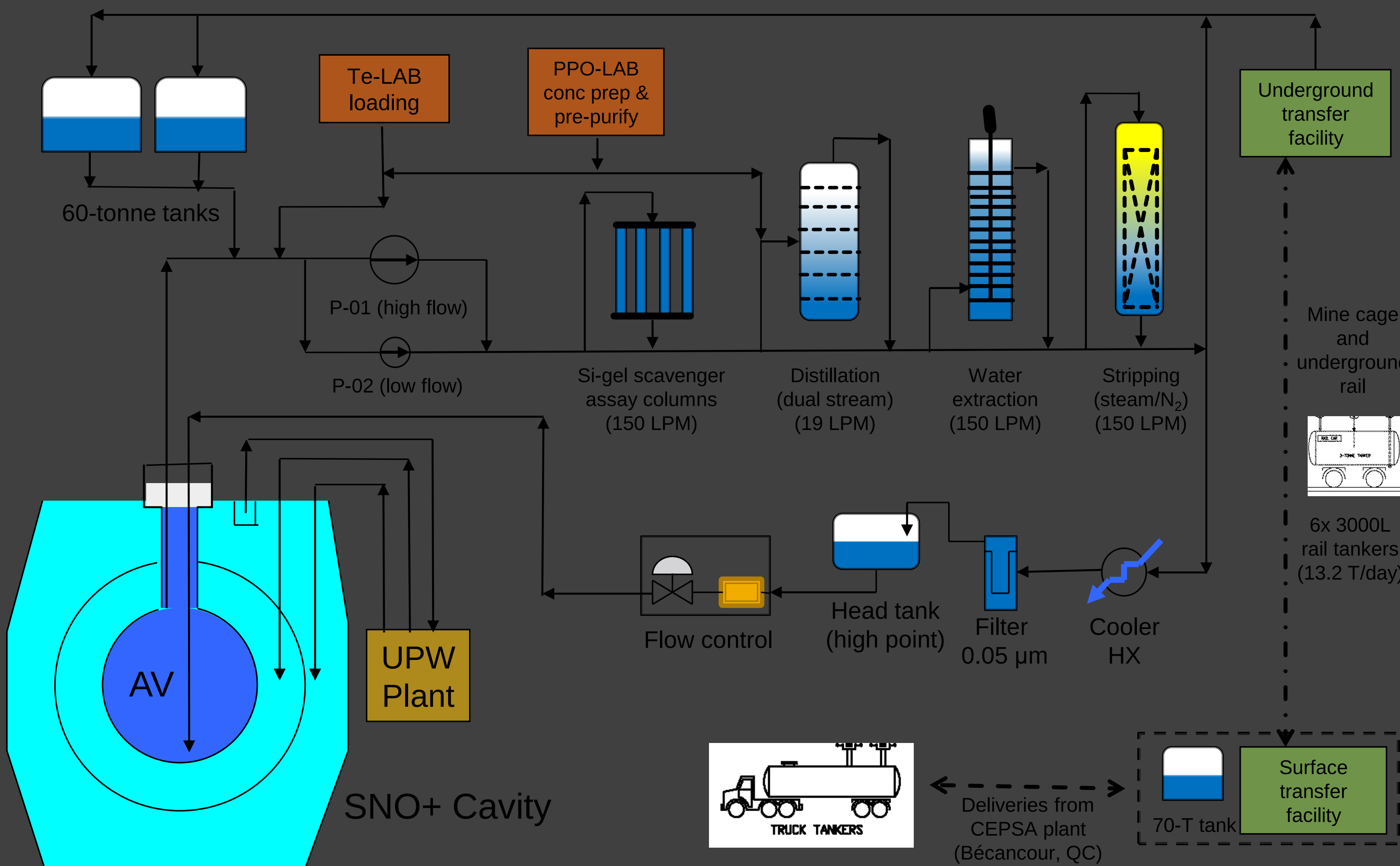
Better



Better

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

Scintillator Purification Plant

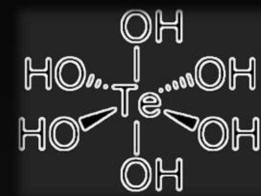


Scintillator Purification Plant

- 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 sent to SNOLAB

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

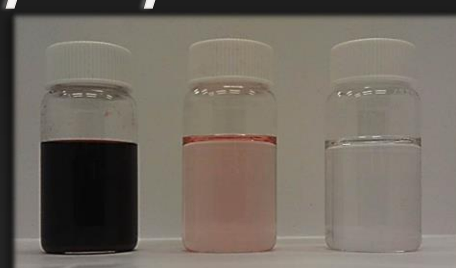
Telluric Acid Purification

- 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)

- Te contamination in U/Th cosmogenically activated
    - ^{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

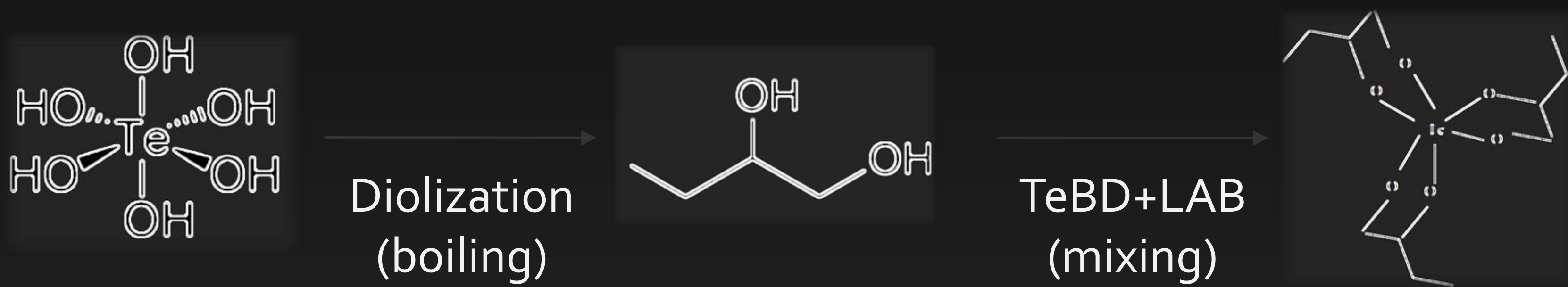


0νββ LS Requirements

- Reach high tellurium concentration
  - 0.5% ^{130}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 Te-Diol Complex

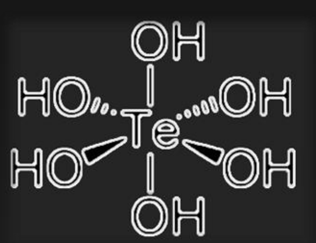
- Tellurium loading in Linear Alkyl Benzene
  - Through direct mixing in of an organometallic complex of Tellurium
- Butane-Diol based Te complex (“TeBD”):



Telluric Acid Butanediol in SNO+

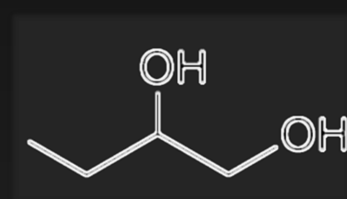
The Te-Diol Complex

- Tellurium loading in Linear Alkyl Benzene
  - Through direct mixing in of an organometallic complex of Tellurium
  - Butane-Diol purified through distillation
- Butane-Diol based Te complex (“TeBD”):



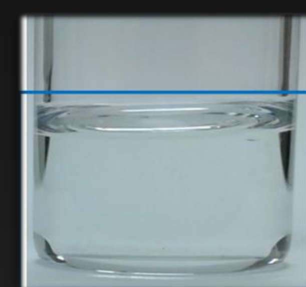
Telluric Acid

Diolization
(boiling)



Butanediol

TeBD+LAB
(mixing)



in SNO+

Irreducible Backgrounds

Internal Radioactivity

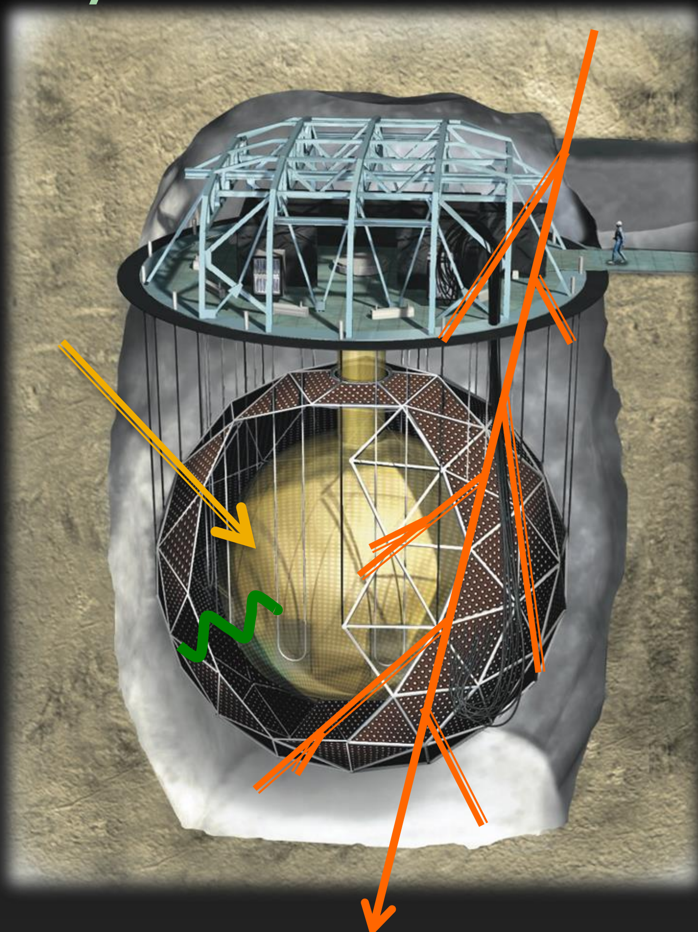
Traces of radioisotopes (U/Th chain, ^{40}K, etc) in the scintillator

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

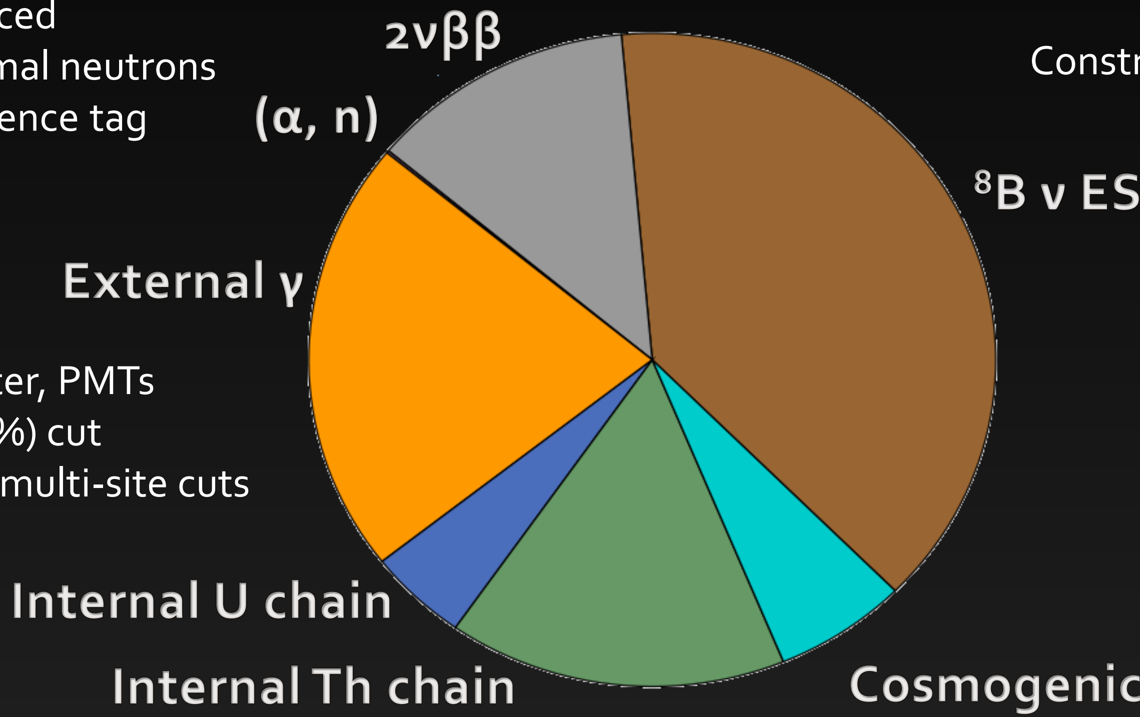
μ n γ α, β

n, p, ^{11}C...

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



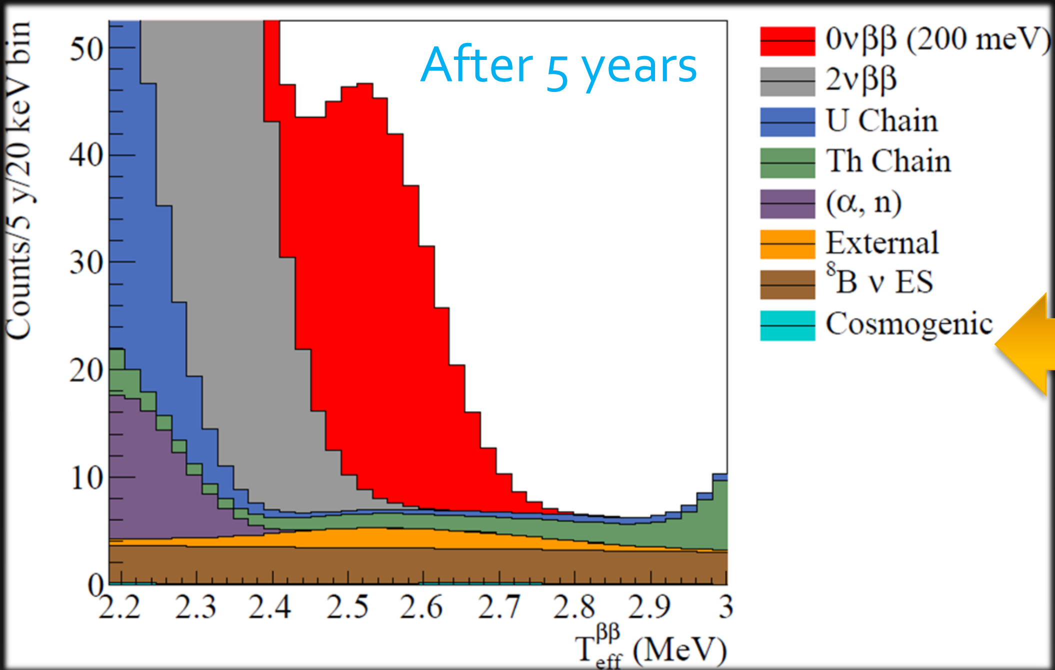
External γ
From AV, ropes, water, PMTs
Fiducial volume (20%) cut
50% extra rejection multi-site cuts

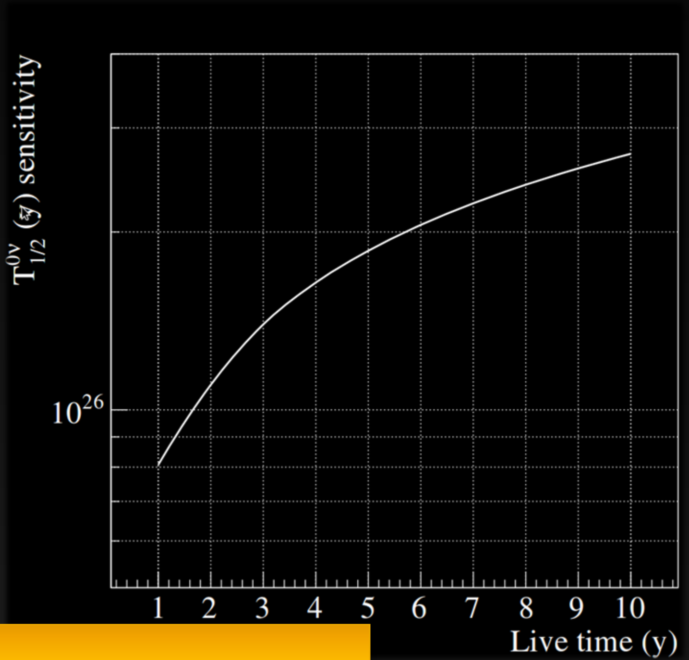
Cosmogenics
Mitigation: purification
+ "cool-down" UG
< 1ev/yr in RoI-FV
Further reduction if
needed: multi-site events

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

0νββ Sensitivity with Te-Diol

- 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

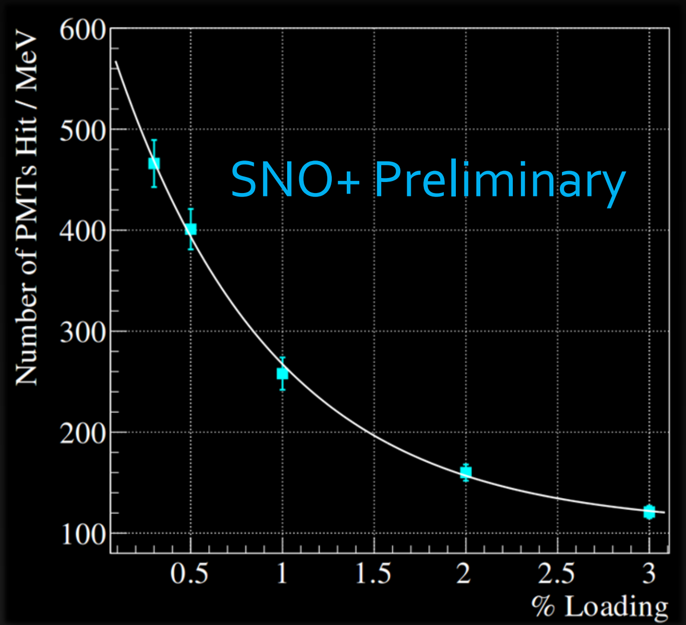




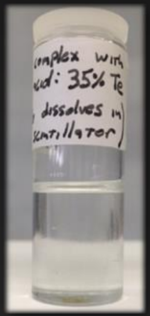
	$T_{1/2}$ [yr]	$m_{0\nu\beta\beta}$ [meV]
1 yr	8×10^{25}	75.2
5 yrs	1.96×10^{26}	38 – 92

0νββ Sensitivity in Phase II

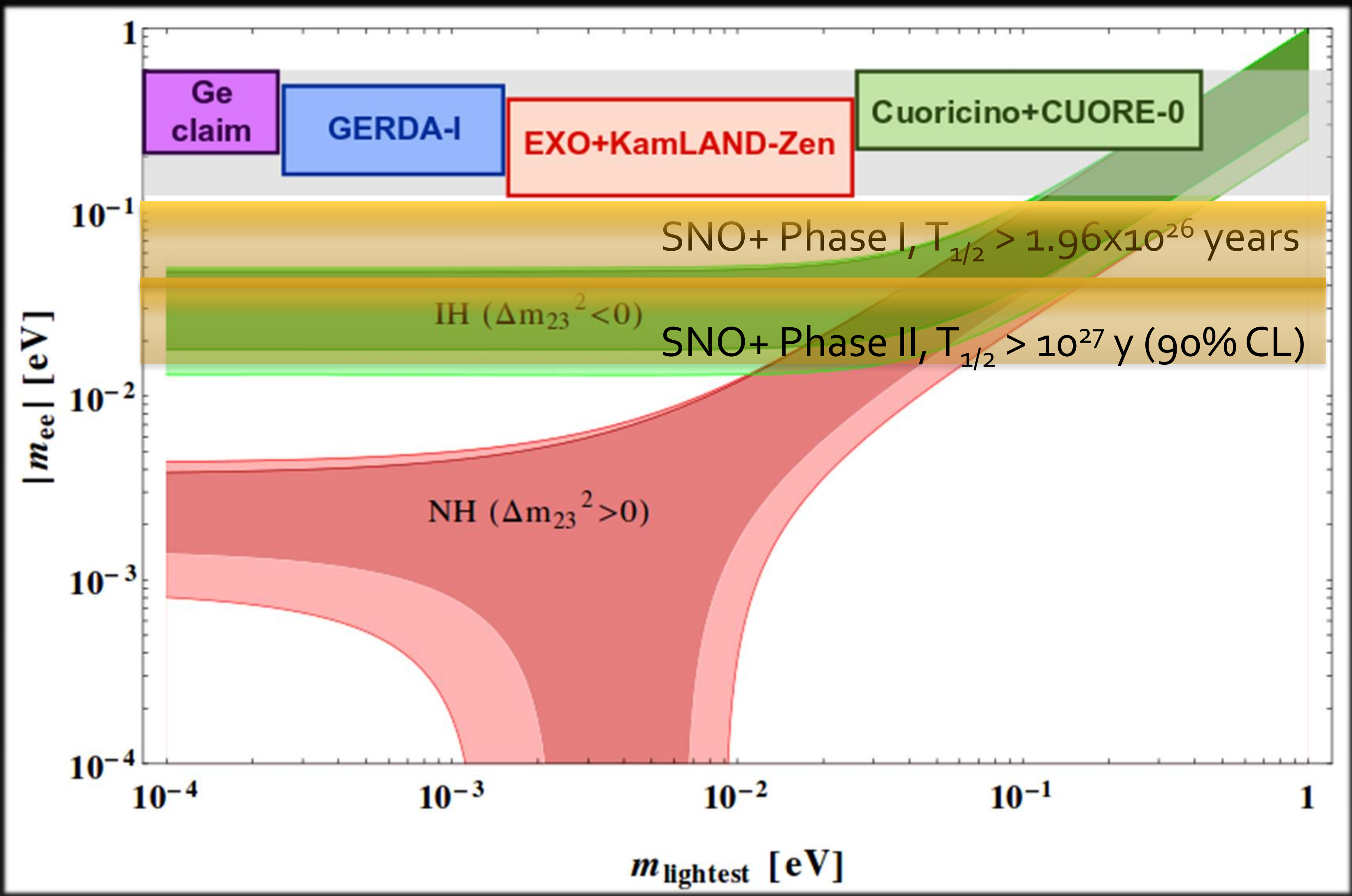
- Improve sensitivity by improving
  - Light yield and going to higher loading
    - Improve current technique
  - Higher QE PMTs
    - Improved concentrators
      - Coverage to 80%



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



0νββ Sensitivity in Phase II



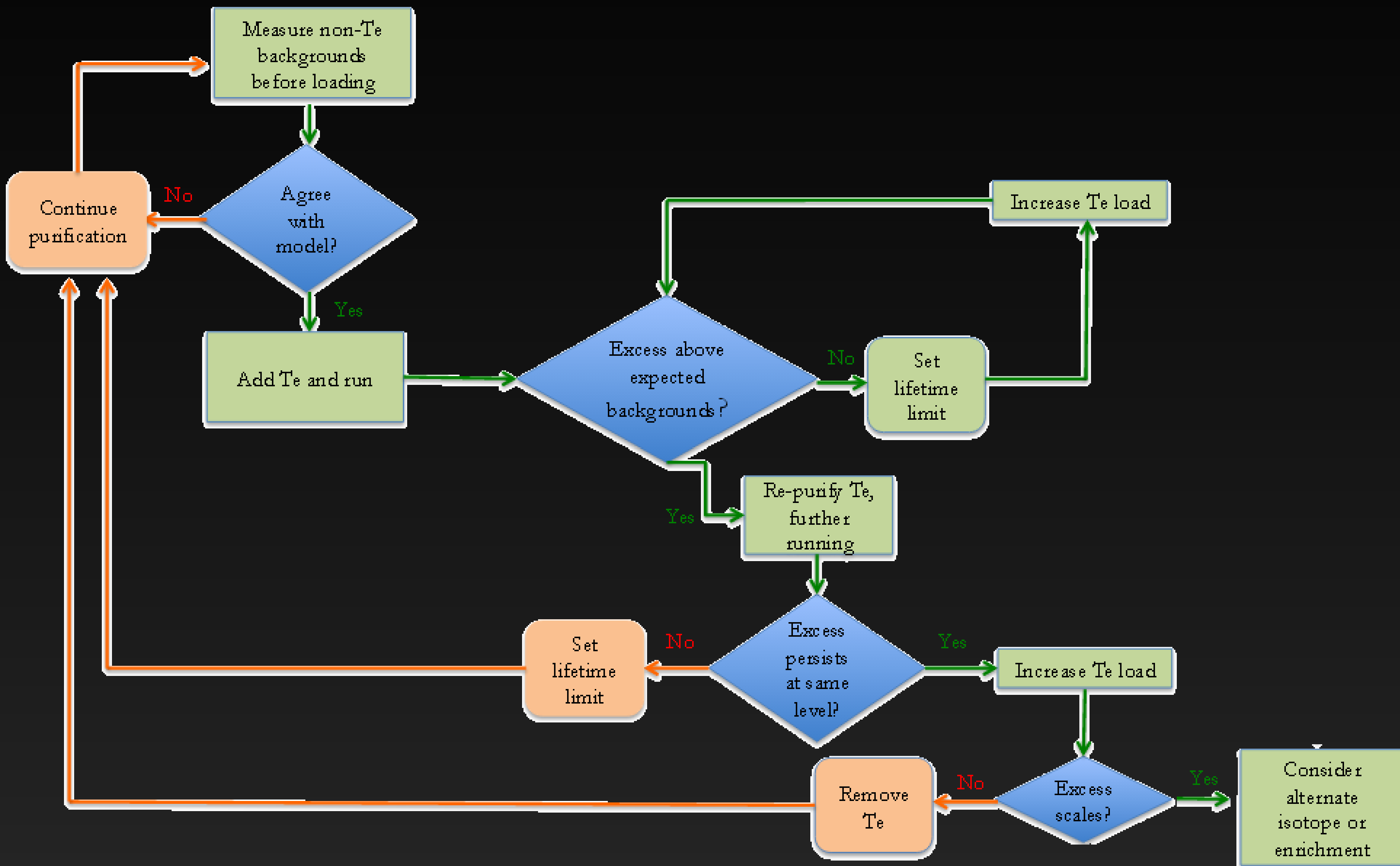
SNO+ Schedule

- 2016
  - Scintillator plant commissioning
  - Scintillator fill
    - Solar neutrino phase (short)
    - Evaluation of backgrounds for $0\nu\beta\beta$
  - Commissioning of the Tellurium plant(s)
- 2017/2018
  - Tellurium loading
  - Begin $0\nu\beta\beta$ phase

SNO+ Collaboration

Backup

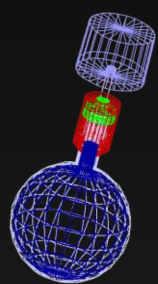
Discovery Flow



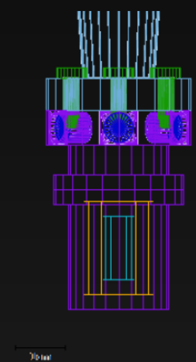
Calibration Sources

- Need Double encapsulation
  - Limitation for ^{222}Rn, ^{90}Y
- Radioactive and optical sources α, β, γ, n, with laser injection laserball and Cherenkov

LED

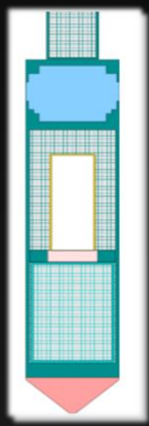


^{48}Sc

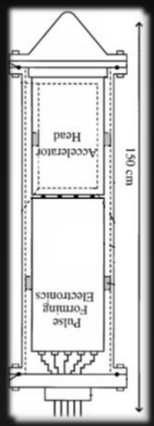


~7.12 s

$C^{16}N_2$



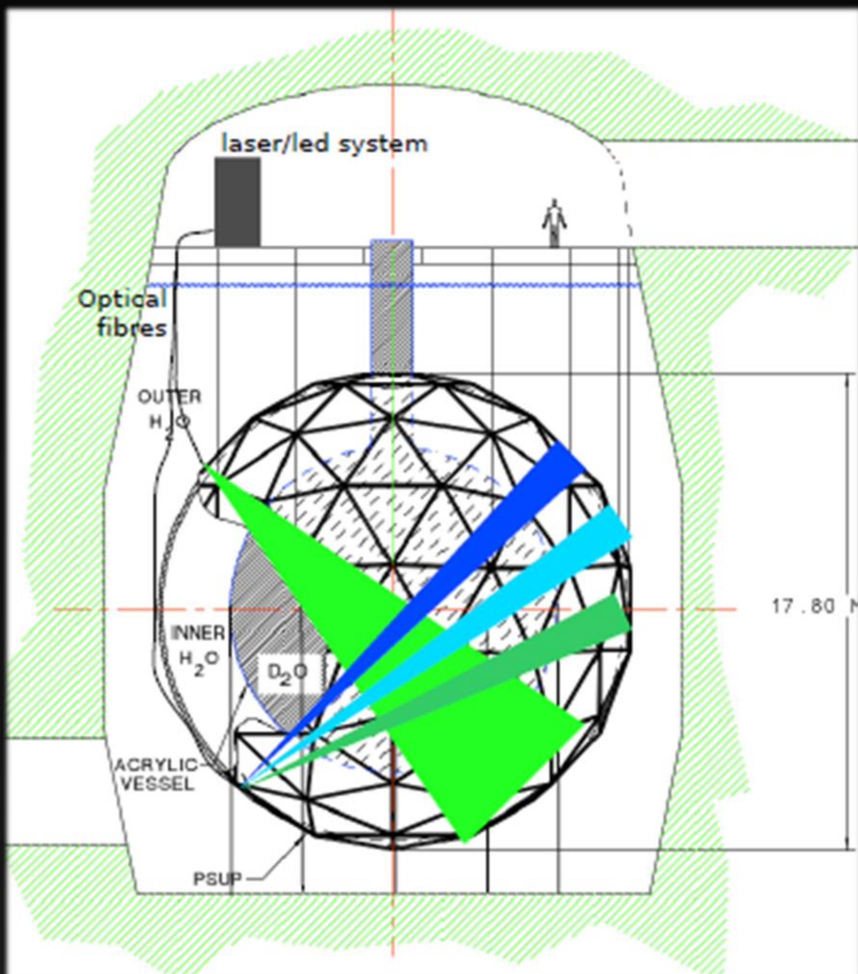
CO_2

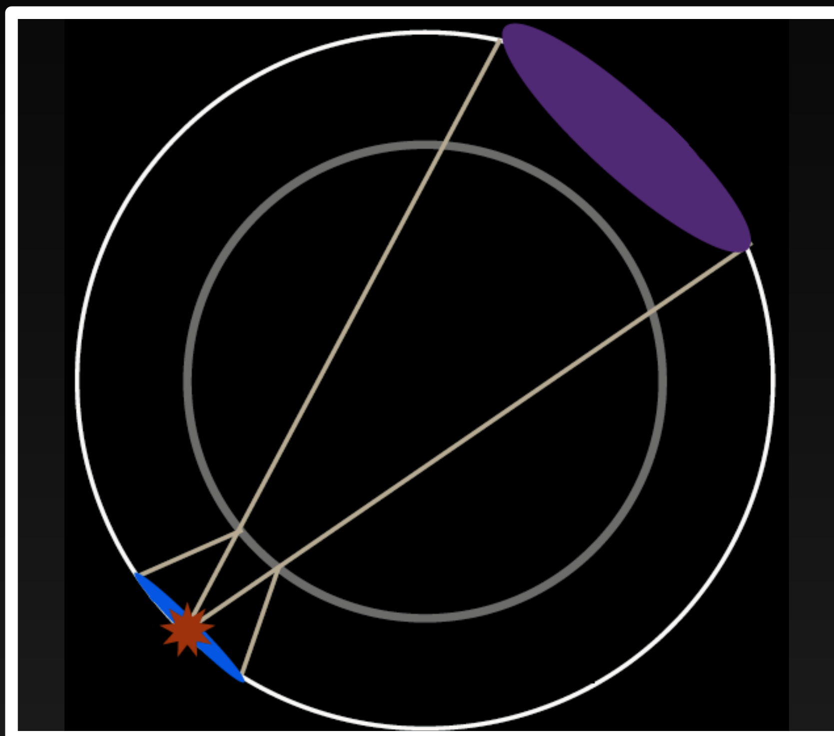


^{24}Na

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

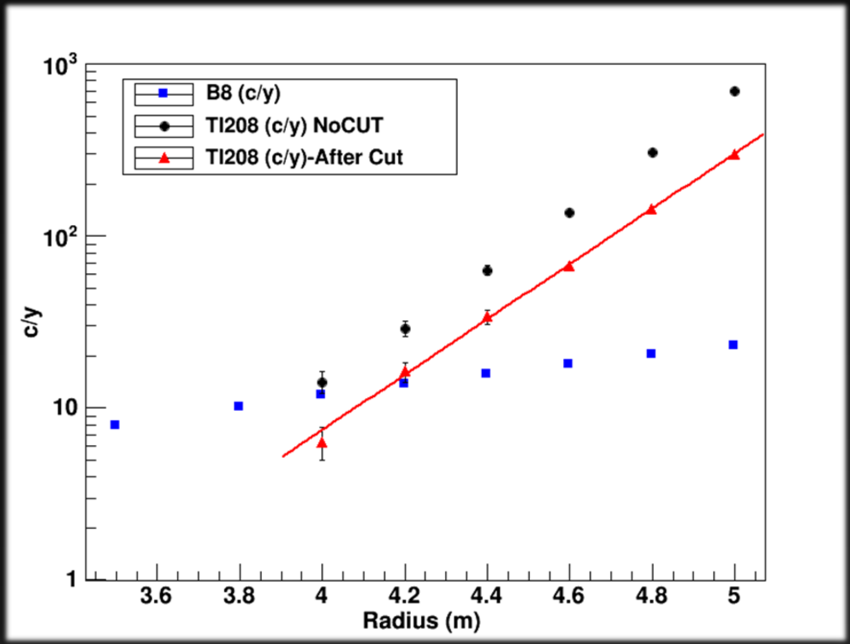




Light emitted from the support structure from 92 fibres installed between PMTs. Each gives 10E3-10E5 photons/pulse.

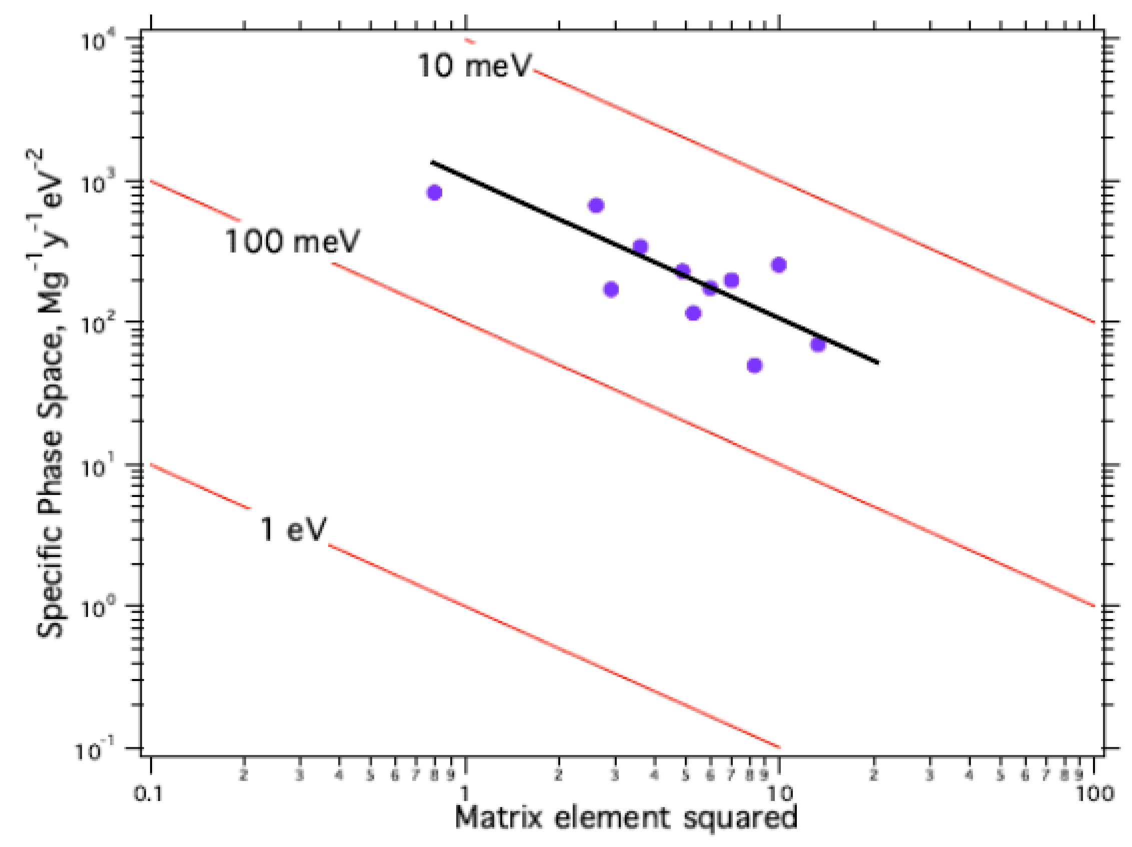
Remaining Backgrounds

- External (PMT) gammas from (^{214}Bi, ^{208}Tl)
  - 3.5 m fiducial volume (20% AV)
  - Can use residuals likelihood
- External (AV) gammas
  - Multi-site rejection (e^- - γ)
- Po (α, n) on ^{13}C
  - n + p -> d + γ (2.2 MeV)



0νββ Isotope Selection

- In principle, isotopes with the best Nuclear Factor of Merit should be favored
- A surprising inverse correlation has been observed between phase space and the square of the nuclear matrix element



A.Robertson, Mod. Phys. Lett. A, Vol. 28, No. 8 (2013) 1350021, arXiv 1301.1323

0νββ Isotope Selection