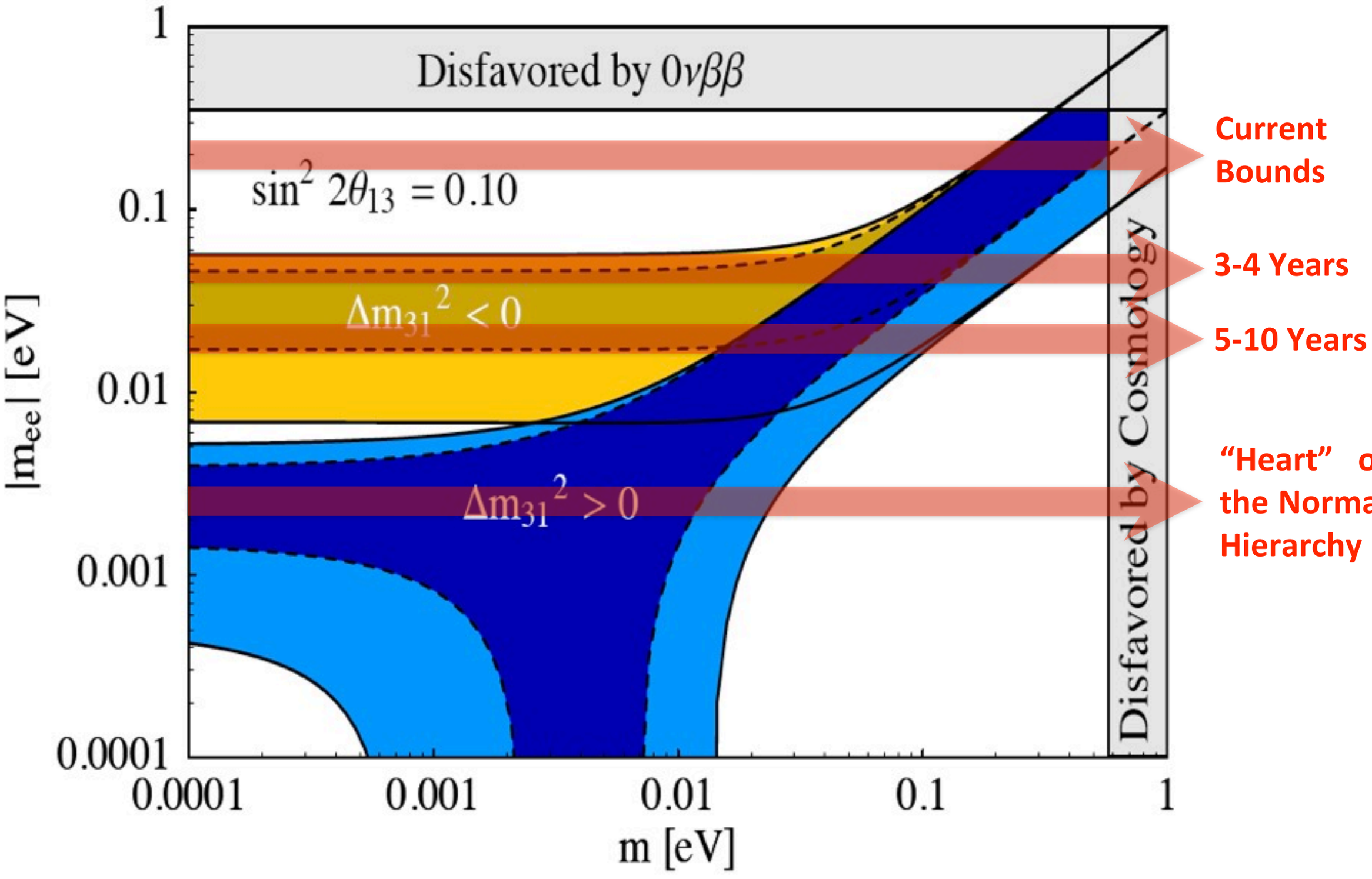
# Speculations on Accessing the Non-Degenerate Normal Neutrino Mass Hierarchy with $0\nu\beta\beta$

Steve Biller, Oxford University


Disfavored by 0νββ
$\sin^2 2\theta_{13} = 0.10$
$\Delta m_{31}^2 < 0$
$\Delta m_{31}^2 > 0$
Disfavored by Cosmology
$|m_{ee}|$ [eV]
m [eV]
1
0.1
0.01
0.001
0.0001
0.0001
0.001
0.01
0.1
1
Current Bounds
3-4 Years
5-10 Years
"Heart" of the Normal Hierarchy

# Note on Sensitivity Scaling

$$T_{1/2} \sim m^2 \qquad m_{limit} \sim \sqrt{\frac{1}{T_{1/2}^{limit}}} \sim \sqrt{\sqrt{B/S}}$$

Gaussian limit

$$S \sim M_{isotope} T_{live} \qquad B \sim T_{live}$$

In the non-Gaussian limit ($B<1$): $m_{limit} \sim T^{-1/2}$

but otherwise: $m_{limit} \sim T^{-1/4}$

If $B$ is ~independent of $M_{isotope}$: $m_{limit} \sim M^{-1/2}$

but otherwise: $m_{limit} \sim M^{-1/4}$

Killers!

## Standard Approach:

On a small scale, all isotopes have roughly the same intrinsic rate predictions. So, just try different isotopes and various approaches to see how far each technique can be pushed and worry about scaling things up later.

## Alternative Approach:

On a large scale, all isotopes are NOT the same owing to backgrounds, cost, logistics of implementation etc. So, define the practical requirements for a normal hierarchy scale first and use that to identify which isotopes and techniques to pursue.

# My Rules for the Game:

- Sensitivity should be at least that needed to achieve a 90% CL at 2.5 meV with 5 years of data using average matrix element values.

- Must observe candidate events at a reasonable rate, greater than 1 per year.

- Must be "practical": logistically feasible and having an estimated cost of less than one billion US dollars.

- Must be based on modest extrapolations from current techniques and costs (minimal dependence on miracles).

# Isotope

| Isotope | Q (MeV) | percent natural abund. | element cost [5] ($/kg) | $G^{0\nu}$ ($10^{-14}$/yr) [6] | $M^{0\nu}$ (avg) [7] | $T^{0\nu}_{1/2}$ for 2.5meV ($10^{29}$yrs) | tons of isotope for 1 ev/yr | equivalent natural tons | annual world production [5] (tons/yr) | natural elem. cost ($M) | enriched at $20/g ($M) | $0\nu/2\nu$ rate [2][8] ($10^{-8}$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $^{48}$Ca | 4.27 | 0.19 | 0.16 | 6.06 | 1.6 | 2.70 | 31.1 | 16380 | $2.4\times10^{8}$ | 2.6 | 622 | 0.016 |
| $^{76}$Ge | 2.04 | 7.8 | 1650 | 0.57 | 4.8 | 3.18 | 58.2 | 746 | 118 | 1221 | 1164 | 0.55 |
| $^{82}$Se | 3.00 | 9.2 | 174 | 2.48 | 4.0 | 1.05 | 20.8 | 225 | 2000 | 39 | 416 | 0.092 |
| $^{96}$Zr | 3.35 | 2.8 | 36 | 5.02 | 3.0 | 0.93 | 21.4 | 763 | $1.4\times10^{6}$ | 27 | 427 | 0.025 |
| $^{100}$Mo | 3.04 | 9.6 | 35 | 3.89 | 4.6 | 0.51 | 12.2 | 127 | $2.5\times10^{5}$ | 4.4 | 244 | 0.014 |
| $^{110}$Pd | 2.00 | 11.8 | 23000 | 1.18 | 6.0 | 0.98 | 26.0 | 221 | 207 | 5078 | 521 | 0.16 |
| $^{116}$Cd | 2.81 | 7.6 | 2.8 | 4.08 | 3.6 | 0.79 | 22.1 | 290 | $2.2\times10^{4}$ | 0.81 | 441 | 0.035 |
| $^{124}$Sn | 2.29 | 5.6 | 30 | 2.21 | 3.7 | 1.38 | 41.2 | 736 | $2.5\times10^{5}$ | 22 | 825 | 0.072 |
| $^{130}$Te | 2.53 | 34.5 | 360 | 3.47 | 4.0 | 0.75 | 23.6 | 68 | ~150 | 24 | 471 | 0.92 |
| $^{136}$Xe | 2.46 | 8.9 | 1000 | 3.56 | 2.9 | 1.40 | 45.7 | 513 | 50 | 513 | 914 | 1.51 |
| $^{150}$Nd | 3.37 | 5.6 | 42 | 15.4 | 2.7 | 0.37 | 13.4 | 240 | $\sim 10^{4}$ | 11 | 269 | 0.024 |

# Detector Technology

## Solid State (CUORE, GERDA, Majorana, COBRA...)

Current background target ~0.01 counts/kg/keV/yr and ~5keV resolution (CUORE), corresponding to ~$10^4$ counts/yr in ROI for 100 tonnes. The means by which to reduce this by 3-4 orders of magnitude is unclear. Cost of technology dominates and more or less scales with isotope mass. The means by which to tackle practical and logistical issues of scaling the technology by ~3 orders of magnitude is also unclear.

## Thin Film Tracking (SuperNEMO)

Scale of the technology is large and proportional to the surface area of the film, rendering it impractical for 100 tonne quantities of isotope.

## TPC (EXO, NEXT)

Cannot directly use Te as TPC medium and unclear how to do this even indirectly.

## Liquid Scintillator (KamLAND-Zen, SNO+)

Practical in terms of construction and instrumentation, even for many kilotonne detector volumes (several percent or more loading levels). Cost of technology does not necessarily scale with isotope mass. Potential for low backgrounds from self-shielding, liquid purification and coincidence-tagging techniques. No inherent Te optical absorption lines. Highly flexible configuration.

# Scaling Model:

## 0νββ

$$S = sM_I T \left( \frac{\langle m \rangle}{2.5\text{meV}} \right)^2$$

- # signal events per tonne-year for m = 2.5 meV
- Tonnes of isotope
- Exposure time

*Consider only fundamental backgrounds*

## $^8$B Solar ν

$$B_\odot = b_\odot T M_D \left( \frac{L}{1000\ \text{pe/MeV}} \right)^{-\frac{1}{2}}$$

- # 8B events in ROI per tonne-year for L = 1000 pe/MeV
- Detector Mass
- Detected scintillator light level

$$\sigma \propto 1/\sqrt{L}$$

## 2νββ

$$B_{2\nu} = b_{2\nu} M_I T \left( \frac{L}{1000\text{pe/MeV}} \right)^{-\frac{5.5}{2}}$$

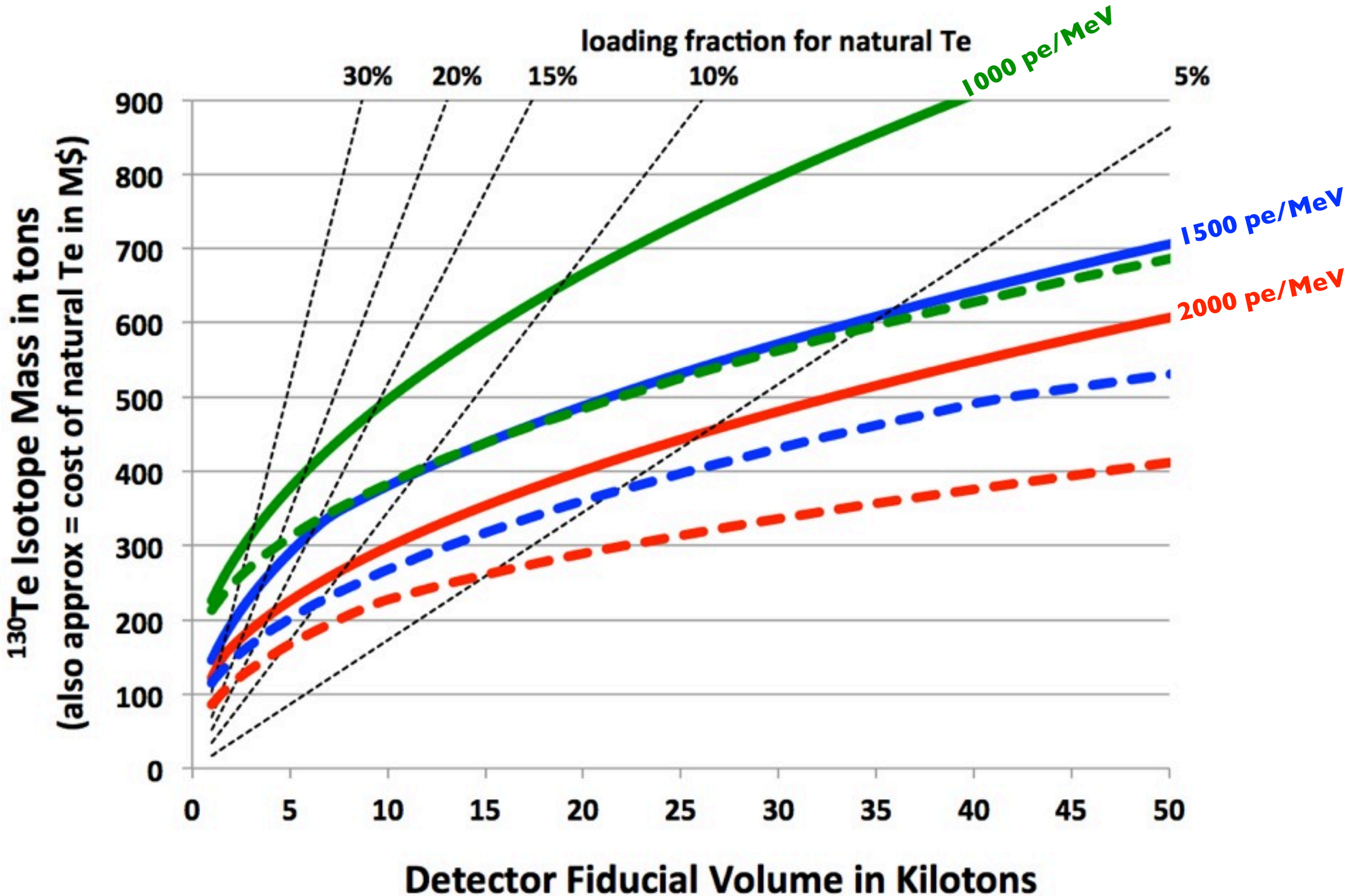
- # 2νββ events in ROI per tonne-year for L = 1000 pe/MeV

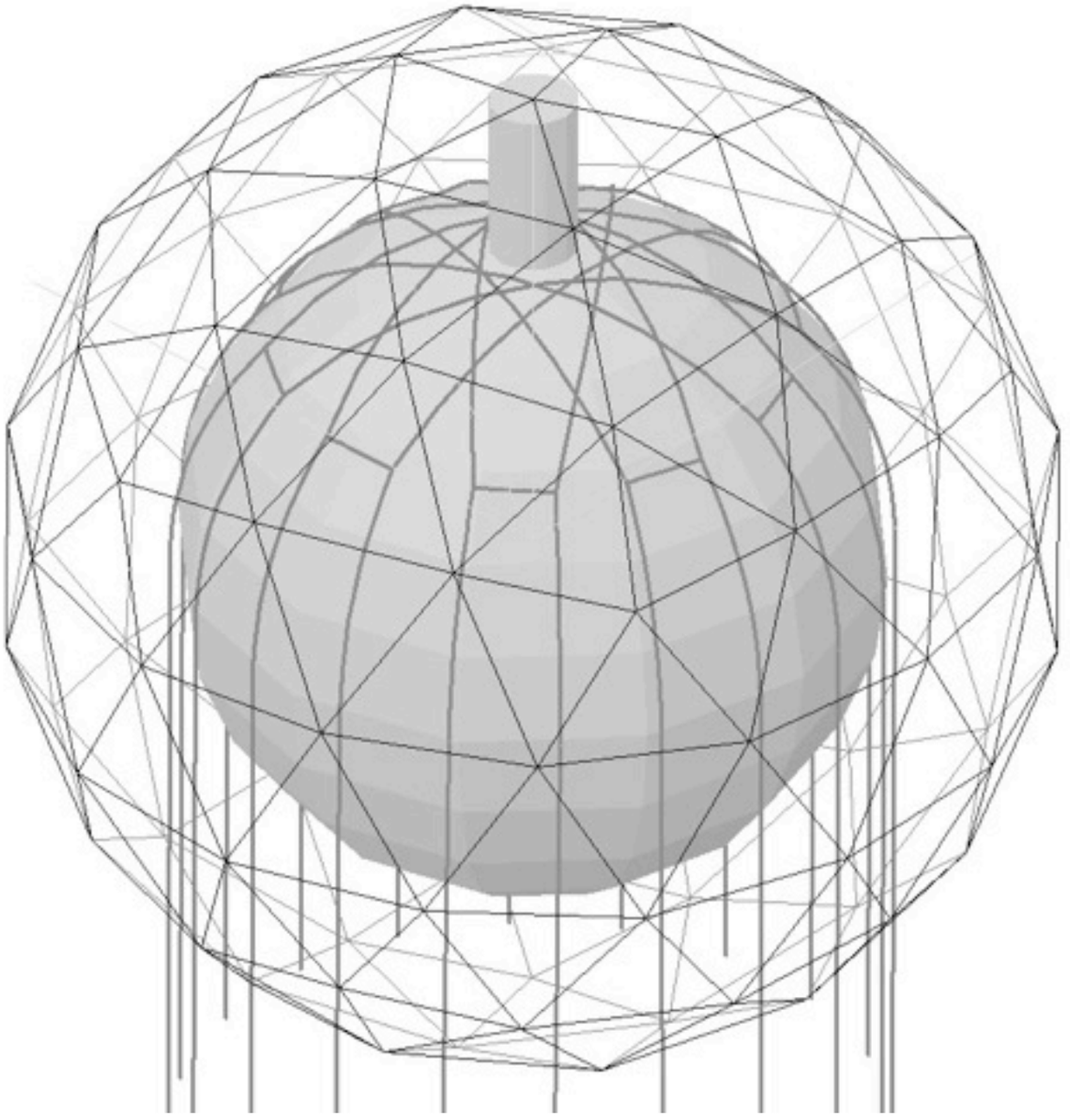
convolved 2νββ rate in ROI $\propto \sigma^{5.5}$

Significance ~ $S/\sqrt{B_\odot + B_{2\nu}}$

Requirements to achieve 90% CL sensitivity at 2.5meV after 5 live years assuming dominant backgrounds are from solar neutrinos and 2νββ

**(S. Biller, PRD 87, 071301(R), 2013)**





# SNO+ with Tellurium

# Potential for $^{130}$Te as an ideal isotope for a LS-loaded 0νββ experiment

Biller and Chen (Autumn 2011) emphasized potential advantages of Te-loading and initiated development.

- 34% natural abundance;
- Internal U/Th can be actively suppressed (Bi-Po αs);
- External gammas can be attenuated ("fiducialisation");
- 2νββ rate is low (~100 times smaller than for $^{150}$Nd);
- No inherent optical absorption lines;
- Relatively inexpensive (< a tenth the cost of $^{136}$Xe).

Initial loading/purification studies by Yeh *et al.* during 2012.

Subsequently underwent thorough, independent internal review from Aug 2012 - Feb 2013. This resulted in the decision to pursue Te as a first priority, which has since been the focus of a full collaboration development effort.


*New loading technique (BNL):*

Dissolve telluric acid in water (highly soluble), then combine a small fraction (few percent) of this mixture with LAB using a surfactant. Clear and stable (>1 yr explicitly demonstrated)

(M. Yeh et al., paper in preparation)

Spike tests show metal scavengers reduce U/Th by ~$4 \times 10^5$ with double pass (target is a reduction of ~$10^4$)

Higher U/Th than pure organic, but still low enough with SNO purification levels ($10^{-14}$-$10^{-15}$ g/g)

| Isotope (Q > 2 MeV, $T_{1/2}$ > 20 days) | $T_{1/2}$ [5] [d] | Q-value [5] [MeV] | R ($\phi$ from [6][7]) [$\mu$Bq/kg] | Events/yr in ROI after 1 yr surface exposure |
|---|---|---|---|---|
| $^{44}$Sc (daughter of $^{44}$Ti) | 0.17 (2.16E+4) | 3.65 | 1.19 (0.052) | 5.41 |
| $^{46}$Sc | 83.79 | 2.37 | 1.97 | 20.3 |
| $^{60}$Co (direct and daughter of $^{60}$Fe) | 1925.27 (5.48E+8) | 2.82 | 0.81 (0.367) | 834 |
| $^{68}$Ga (daughter of $^{68}$Ge) | 4.70E-2(271) | 2.92 | 3.14 (1.28) | 344 |
| $^{26}$Al | 2.62E+8 | 4.00 | 0.67 | 2.20E-4 |
| $^{82}$Rb (daughter of $^{82}$Sr) | 8.75E-4(25.35) | 4.40 | (2.44) | 440 |
| $^{88}$Y (direct and daughter of $^{88}$Zr) | 106.63 (83.4) | 3.62 | 3.14 (8.11) | 3.61E4 |
| $^{42}$K (daughter of $^{42}$Ar) | 0.51 (12016.73) | 3.53 | 1.33 (0.24) | 10.0 |
| $^{56}$Co | 77.2 | 4.57 | 0.13 | 0.350 |
| $^{58}$Co | 70.9 | 2.31 | 1.29 | 0.252 |
| $^{110m}$Ag [a] | 249.83 | 3.01 | 2.34 | 3.61E3 |
| $^{110}$Ag (daughter of $^{110m}$Ag) [b] | 2.85E-4 | 2.89 | (0.03) | 48.6 |
| $^{106}$Rh (daughter of $^{106}$Ru) | 3.47E-4 (371.8) | 3.54 | (0.06) | 21.8 |
| $^{126m}$Sb (direct and daughter of $^{126}$Sn) [c] | 0.01 (8.40E7) | 3.69 | 71.42 (7.87) | 8.63 |
| $^{126}$Sb (direct and daughter of $^{126m}$Sb) [d] | 12.35 (0.01) | 3.67 | 89.65 ($^{126m}$Sb) | 1.29E4 |
| $^{22}$Na | 950.6 | 2.84 | 1.01 | 1.01E3 |
| $^{84}$Rb [e] | 32.8 | 2.69 | 1.29 | 24.2 |
| $^{90}$Y (daughter of $^{90}$Sr) | 2.67 (10519.2) | 2.28 | 2.69 (0.165) | 7.90E-3 |
| $^{102}$Rh (direct and daughter of $^{102m}$Rh) [f] | 207.3 | 2.32 | 11.77 (0.03) | 35.9 |
| $^{102m}$Rh [g] | 1366.77 | 2.46 | 11.77 | 69.9 |
| $^{124}$Sb | 60.2 | 2.90 | 182.0 | 1.62E5 |

ACTIVIA code, cross sections from Silberberg et al. and TENDL-2009 database, flux parameterisations from Armstrong and Gehrels. Variations from using YIELDX code, TENDL-2012 database, and fluxes from Ziegler change estimated rates by up to a factor of two. Consistency also checked against CUORE beam activation study (Wang *et al.*) and KamLAND induced backgrounds.

(V. Lozza, paper in preparation)

**Requires a reduction factor of >$10^4$ for these isotopes, which is also comparable to the reduction required for U/Th in "raw" Te material (ICP-MS: 2-3x$10^{-11}$ g/g)**

# Outline of Te Purification Strategy

(paper in preparation)

(Stage 1)

2 Surface passes:

- Dissolve $Te(OH)_6$ in water
- Recrystalise using nitric acid
- Rinse with ethanol

**$>10^4$ reduction**

Allow up to 5 hr re-exposure to finish & transport UG

(Stage 2)

2 Underground passes:

- Dissolve in warm water (80°C)
- Cool to Recrystalise thermally

**$>10^2$ reduction**

(~50% Te "loss" recovered by recycling to surface system)

# Spike Tests (Ongoing)

| Element | Reduction Factor | Assay Technique |
|---|---|---|
| Stage 1 Te purification, single-pass spike test | | |
| Co | 1555± 326 | XRF |
| Sb | >243 | XRF |
| Sn | > 167 | XRF |
| Fe | > 100 | XRF |
| Na | > 346 | XRF |
| Sc | > 165 | XRF |
| Ge | > 333 | XRF |
| Y | > 278 | XRF |
| Zr | > 278 | XRF |
| Ag | > 278 | XRF |
| Pb-212 | 299± 22 | $\beta - \alpha$ counting |
| Bi-212 | 348± 81 | $\beta - \alpha$ counting |
| Ra-224 | 397± 20 | $\beta - \alpha$ counting |
| Th-228 | 390±19 | $\beta - \alpha$ counting |
| Stage 1 Te purification, double-pass spike test | | |
| Co | $3.7\times10^5$ | XRF |
| Pb-212 | $> 10^4$ | $\beta - \alpha$ counting |
| Bi-212 | $> 10^4$ | $\beta - \alpha$ counting |
| Ra-224 | $> 10^4$ | $\beta - \alpha$ counting |
| Th-228 | $> 10^4$ | $\beta - \alpha$ counting |
| Stage 2 (UG) Te purification, single-pass spike test | | |
| Co | 12 | XRF |
| Ag | > 20 | XRF |
| Zr | 17 | XRF |

acid-induced recrystalisation + ethanol wash

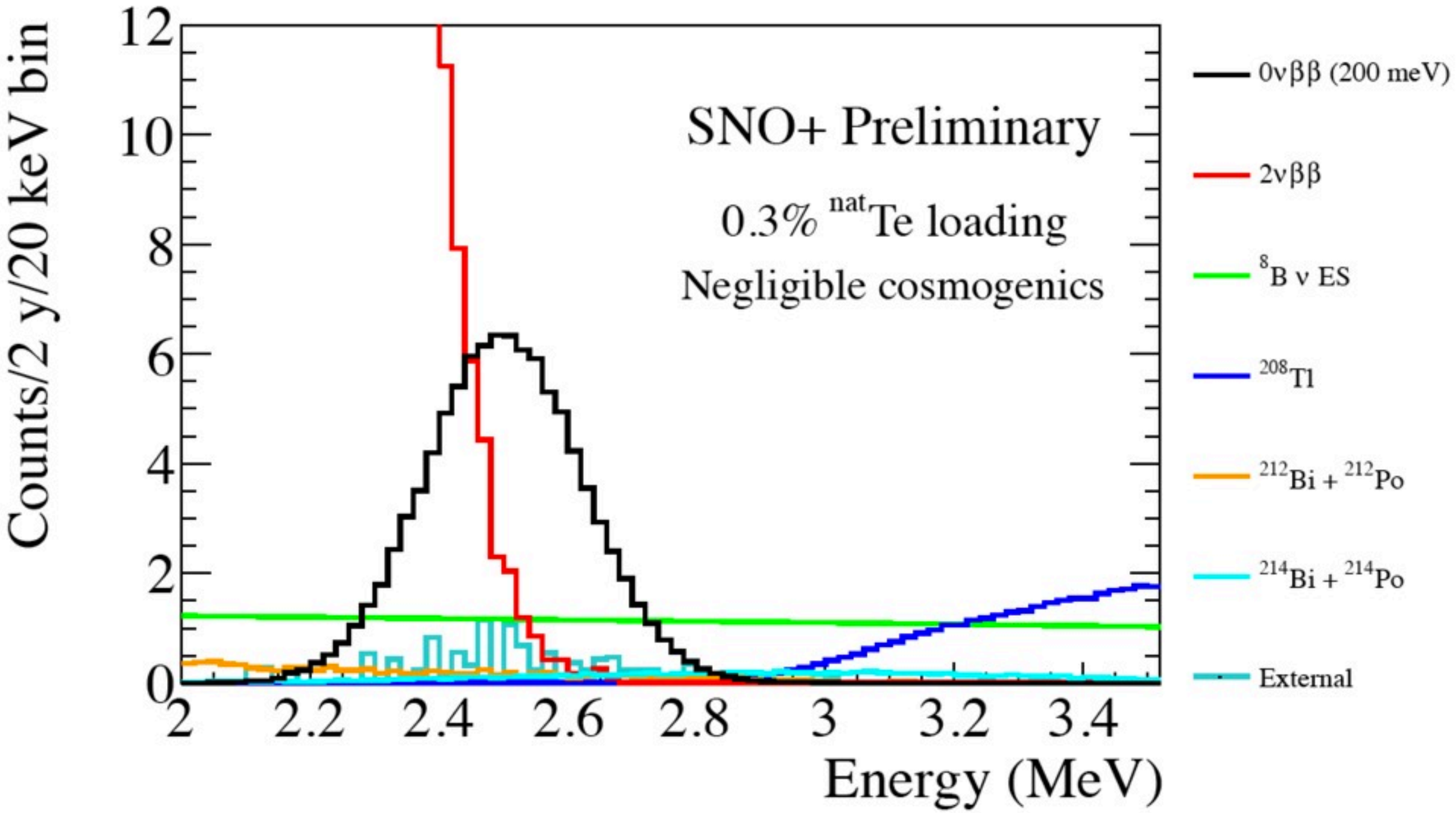
thermal recrystalisation

| Isotope (Q > 2 MeV, $T_{1/2}$ > 20 days) | Events/yr in ROI after 1 yr surface exposure | After stage 1 purification plus 5h re-exposure | After stage 2 (UG) purification plus 6 months "cool-down" |
|---|---|---|---|
| $^{44}$Sc (daughter of $^{44}$Ti) | 5.41 | 1.80 | 1.89E-5 |
| $^{46}$Sc | 20.3 | 0.04 | 9.30E-5 |
| $^{60}$Co (direct and daughter of $^{60}$Fe) | 834 | 0.511 | 4.79E-3 |
| $^{68}$Ga (daughter of $^{68}$Ge) | 344 | 0.703 | 2.03E-3 |
| $^{26}$Al | 2.20E-4 | 2.63E-7 | 2.63E-9 |
| $^{82}$Rb (daughter of $^{82}$Sr) | 440 | 2.56 | 1.74E-4 |
| $^{88}$Y (direct and daughter of $^{88}$Zr) | 3.61E4 | 37.9 | 0.213 |
| $^{42}$K (daughter of $^{42}$Ar) | 10.0 | 0.90 | 7.72E-5 |
| $^{56}$Co | 0.350 | 6.83E-4 | 1.33E-6 |
| $^{58}$Co | 0.252 | 5.29E-4 | 8.88E-7 |
| $^{110m}$Ag [a] | 3.61E3 | 3.60 | 0.022 |
| $^{110}$Ag (daughter of $^{110m}$Ag) [b] | 48.6 | 0.05 | 2.93E-4 |
| $^{106}$Rh (daughter of $^{106}$Ru) | 21.8 | 0.022 | 1.58E-4 |
| $^{126m}$Sb (direct and daughter of $^{126}$Sn) [c] | 8.63 | 8.58 | 4.34E-7 |
| $^{126}$Sb (direct and daughter of $^{126m}$Sb) [d] | 1.29E4 | 154 | 5.44E-5 |
| $^{22}$Na | 1.01E3 | 0.711 | 6.22E-3 |
| $^{84}$Rb [e] | 24.2 | 0.11 | 2.31E-5 |
| $^{90}$Y (daughter of $^{90}$Sr) | 7.90E-3 | 2.77E-4 | 1.80E-8 |
| $^{102}$Rh (direct and daughter of $^{102m}$Rh) [f] | 35.9 | 0.044 | 2.39E-4 |
| $^{102m}$Rh [g] | 69.9 | 0.060 | 5.45E-4 |
| $^{124}$Sb | 1.62E5 | 417 | 0.509 |

# Basic Detector Parameters for Phase I Demonstrator

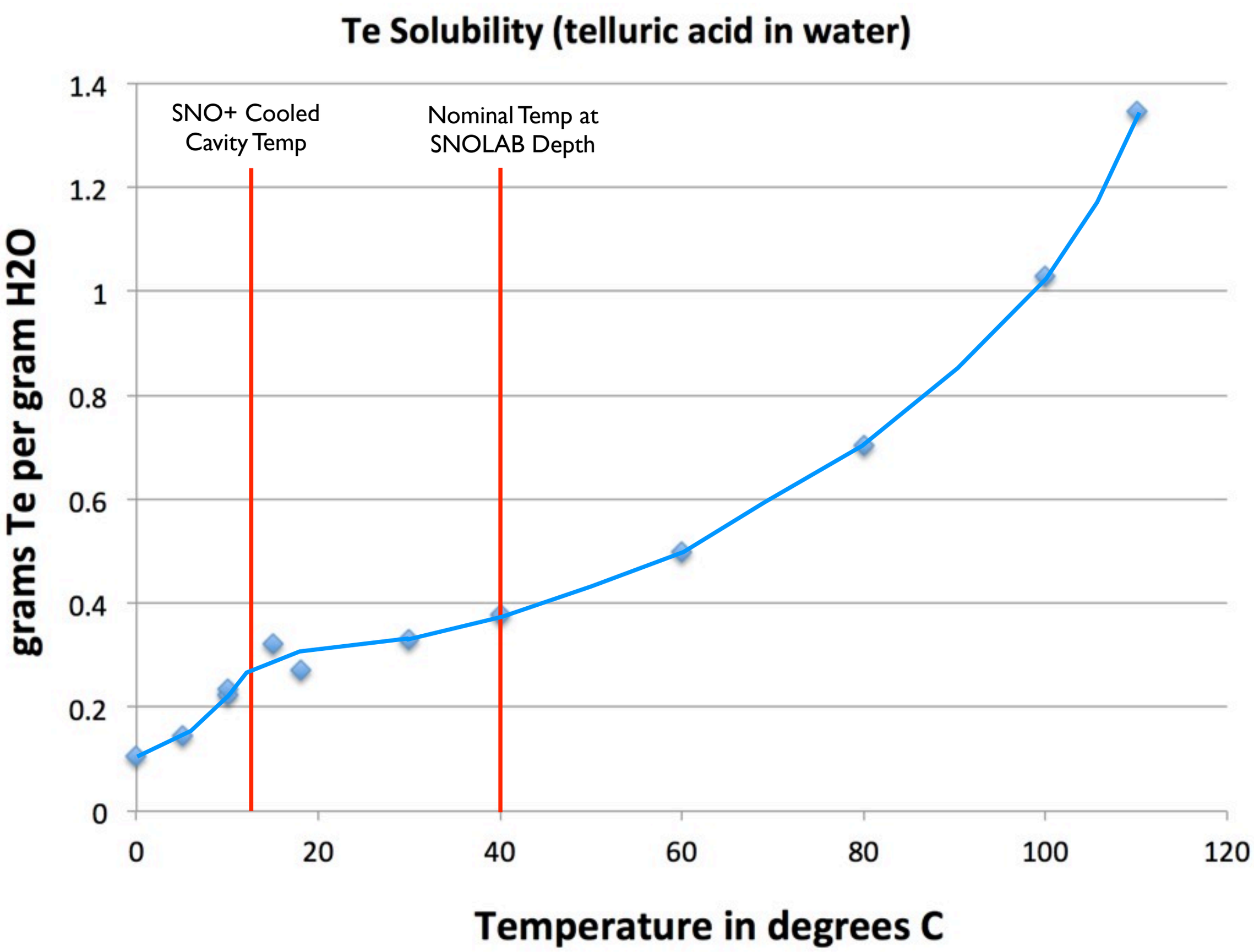
- Light Level: ~200-300 pe/MeV, depending on final optics and choice of secondary shifter. Assume 200 pe/MeV for this talk.
- Loading Level: 0.3-0.5% (0.8-1.3 tonnes $^{130}$Te), depending on final Te system resources. Assume 0.3% for this talk.
- Fiducial Volume: 20-30%, depending on light level, loading fraction and final backgrounds. Assume 20% for this talk
  (R=3.5m, ~10 times current K-Z fiducial volume)

# Expected Average Spectra of Contributing Backgrounds for Two Live Years of Data



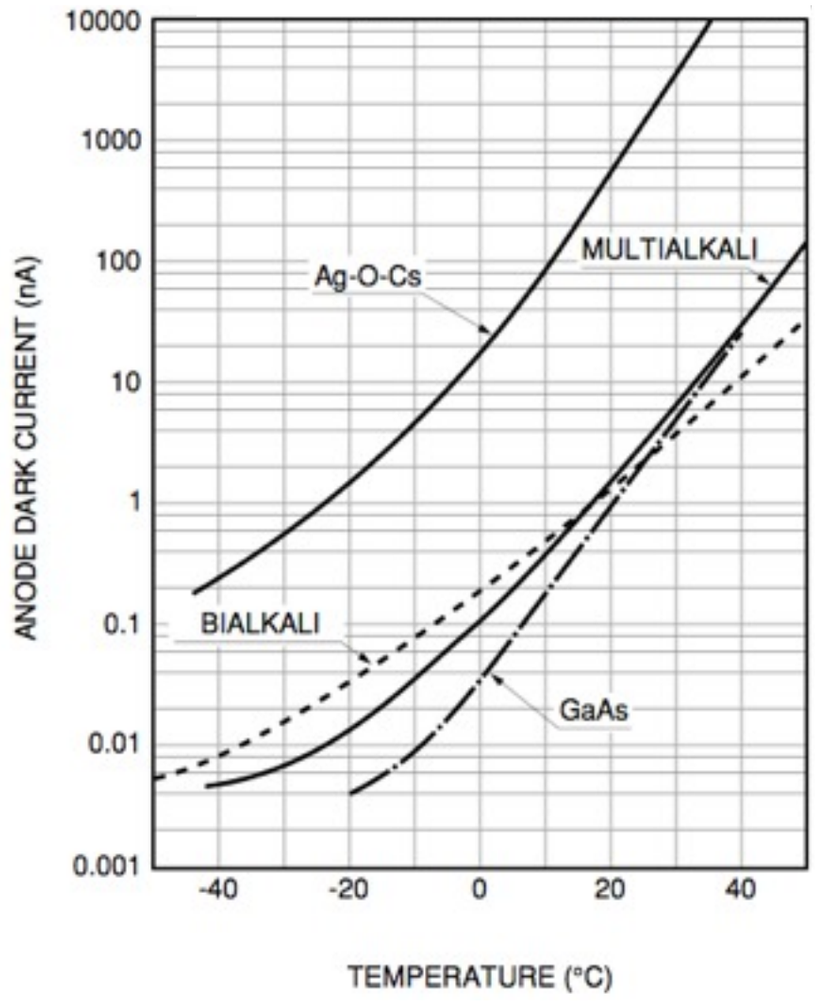
# Pushing Beyond SNO+

Mylius, Chemische Berichte **34**, 2208 (1901)

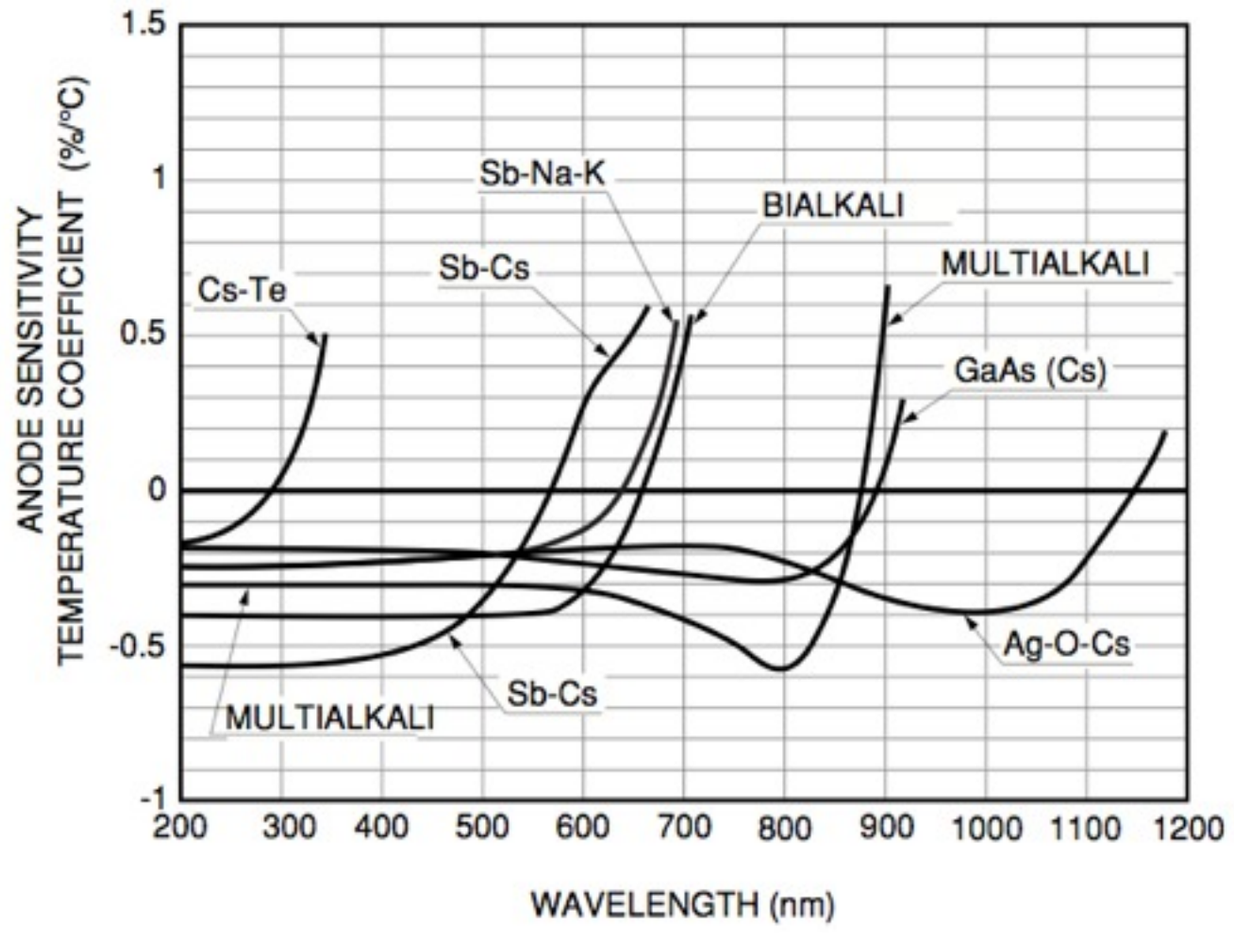


# PMT performance at higher temperatures

(Hamamatsu PMT Handbook, 2007)




Factor of ~15 increase in dark current in going from 12 to 40 °C for bialkali




Anode sensitivity changes by (28 °C)(-0.4) = -11% in going from 12 to 40 °C for bialkali

**Heating to higher temperatures would be nice, but probably requires some new technologies [high temp PMTs (SbNa2K) have lower QE]**

# Loading:

| | Temp (°C) | Solubility (g/g) | Percent Natural Te Loading 5% $H_2O$ | 25% $H_2O$ |
|---|---|---|---|---|
| Likely | 12 | 0.27 | 1.35 | 6.75 |
| Possibly | 40 | 0.38 | 1.90 | 9.5 |

Likely

Possibly

Difficult, requires R&D, but not completely mad

**Use more soluble Te compounds? Alternative loading method (maybe use organotelluric compounds)?**

# Light:

Scale light yield from SNO+ and assume a factor of ~2 light loss at higher loading

(SNO PMTs: only ~13-15% peak efficiency (25% QE, 55% collec. eff.), ~45% photocathode coverage)

**Light Yield Estimate at Higher Loading**

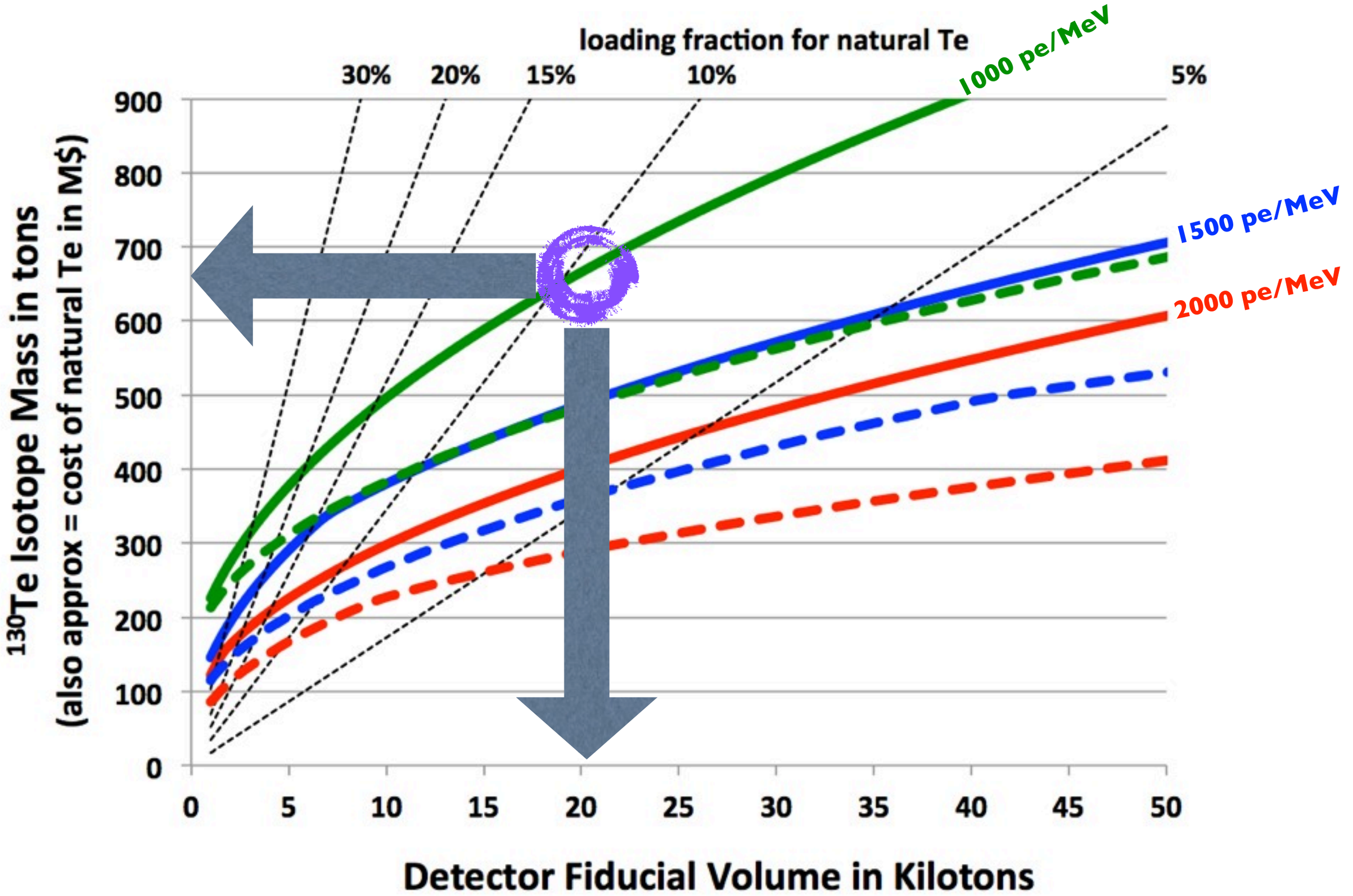
| | Potential SNO+ Light Yield (pe/MeV) at 0.3% loading | | Boost from QE x Coverage: 3 (1.7x1.7) | 4 (2x2) |
|---|---|---|---|---|
| Likely | 300 | | 450 | 600 |
| Possibly | 500 | (not currently, but pure LAB+PPO yields ~550) | 750 | 1000 |
| | | | Likely | Possibly |

# Detector Scale:

| | | |
|---|---|---|
| Absorption Length of Medium: | 20m | 30m |
| Spherical Volume (d=Λ, ρ=1): | 4 kT | 13.5 kT |
| | Likely | Possibly |

(LAB absorption above 420nm)

**However, light detection requirements favour multiple, small detectors... if finances allow.**


loading fraction for natural Te
30%
20%
15%
10%
5%
1000 pe/MeV
1500 pe/MeV
2000 pe/MeV
$^{130}$Te Isotope Mass in tons
(also approx = cost of natural Te in M$)
900
800
700
600
500
400
300
200
100
0
0
5
10
15
20
25
30
35
40
45
50
Detector Fiducial Volume in Kilotons

# Cherenkov Light?

Could this be picked out with time-separation and used to reduce $^8$B and other backgrounds (perhaps even statistically test 0νββ model)?

(S. Biller, PRD 87, 071301(R), 2013)

## Hand-Waving Argument

need loaded scint with little absorption > 400 nm

**Cherenkov:** (8 pe/MeV) x (2) x (2) x (1/2) x (2.5-0.5 MeV) = 32 pe

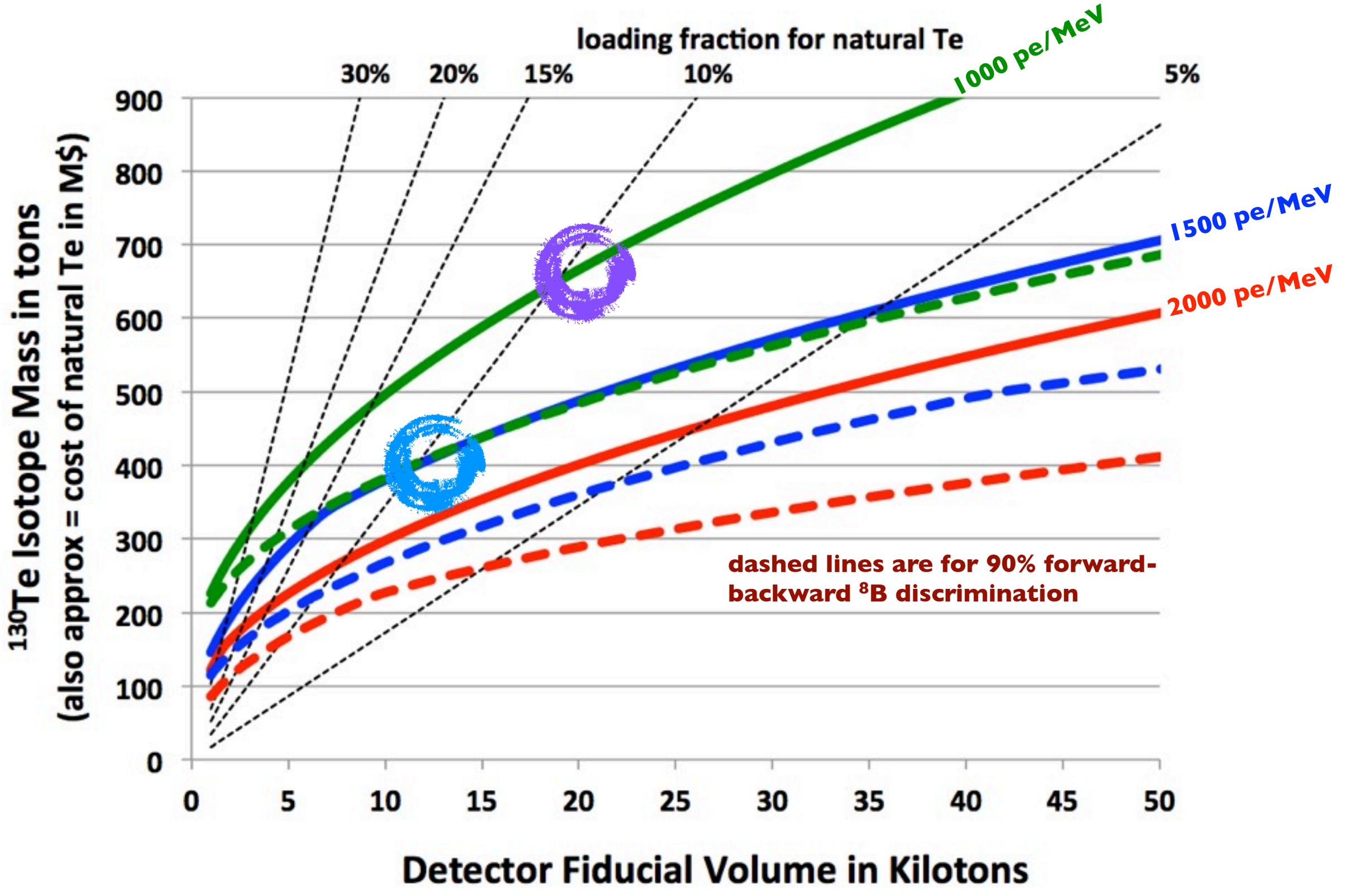
- scaling from SNO with water
- assume boost to QE & coverage
- assume half absorbed by scintillator
- electron KE in ROI minus effective Cherenkov thresh

**Scintillation:** (1000 pe/MeV) x (2.5 MeV) x (1/2) x (5ns/25ns) = 250 pe

- required light level
- electron KE in ROI
- look for Cherenkov in "forward" hemisphere
- assume 5ns prompt window and 25ns scint decay time

need Fluor with slow time const and high QY

$32/\sqrt{250} = 2\sigma$ "forward-backward" discrimination


loading fraction for natural Te
30%
20%
15%
10%
5%
1000 pe/MeV
1500 pe/MeV
2000 pe/MeV
dashed lines are for 90% forward-backward $^{8}$B discrimination
$^{130}$Te Isotope Mass in tons
(also approx = cost of natural Te in M$)
900
800
700
600
500
400
300
200
100
0
0
5
10
15
20
25
30
35
40
45
50
Detector Fiducial Volume in Kilotons

# Conclusions:

• A practical normal hierarchy 0νββ experiment is **not** out of reach ("modest extrapolation"). With targeted R&D, construction for this could potentially even start within the next decade.

• Te-loaded liquid scintillator almost certainly offers the best (probably only) chance to achieve this.

• Current efforts from SNO+ look encouraging (if preliminary) and will provide an important test-bed for gaining a better understanding of the actual issues.

• There is still a lot to explore in the general development of this technology, which constitutes a worthy investment for the future programme.