Loaded Liquid Scintillator Approach for a NH $0\nu\beta\beta$ Experiment

Steve Biller, Oxford University
Lisbon Workshop 2022

Advantages of Loaded Liquid Scintillator

- Very clean (<10^{-17} g/g U/Th)
- Self-shielding against external backgrounds
- Assayable component-by-component
- Re-configurable
- Inexpensive
- Highly scalable

Disadvantages

- Reduced energy resolution compared to other approaches

Backgrounds from ^{8}B and $2\nu\beta\beta$ "spillover" are significant for higher loadings and larger volumes

Isotope

Isotope	Q (MeV)	% nat. abund.	elem. cost $/kg	world prod. (tons/yr)	$G^{0\nu}$ (10^{-15}/yr)	Median $M^{0\nu}$ for g_A=1.25	$T_{1/2}^{0\nu}$ for m=2meV (10^{30}yr)	Ton-yrs per event	equiv. nat. elem. Ton-yrs	nat. elem. cost ($M) @1ev/yr	cost ($M) if enriched @ $20/g	0v/2v rates (10^{-10})
^{48}Ca	4.27	0.19	0.16	2.4E8	24.81	1.5	1.17	134	70766	11.3	2689	0.55
~~^{76}Ge~~	~~2.04~~	~~7.8~~	~~1650~~	~~118~~	~~2.363~~	~~5.1~~	~~1.06~~	~~193~~	~~2479~~	~~4090.2~~	~~3867~~	~~18.08~~
^{82}Se	3	9.2	174	2000	10.16	3.7	0.47	92	1002	174.3	1844	2.05
^{96}Zr	3.35	2.8	36	1.4E6	20.58	3.2	0.31	71	2544	91.6	1425	0.76
^{100}Mo	3.03	9.6	35	2.5E5	15.92	5.6	0.13	31	326	11.4	626	0.53
^{110}Pd	2.02	11.8	23000	200	4.815	6	0.38	99	841	19341.2	1985	3.98
^{116}Cd	2.82	7.6	2.8	2.2E4	16.7	4.3	0.21	59	773	2.2	1175	1.32
^{124}Sn	2.29	5.6	30	2.5E5	9.04	3.2	0.71	209	3740	112.2	4189	14.18
^{130}Te	2.53	34.5	50	400	14.22	3.8	0.32	99	287	14.3	1980	25.79
^{136}Xe	2.46	8.9	1000	50	14.58	2.6	0.66	216	2424	2424.3	4315	32.61
^{150}Nd	3.37	5.6	42	1E4	63.03	2.8	0.13	47	848	35.6	949	0.69

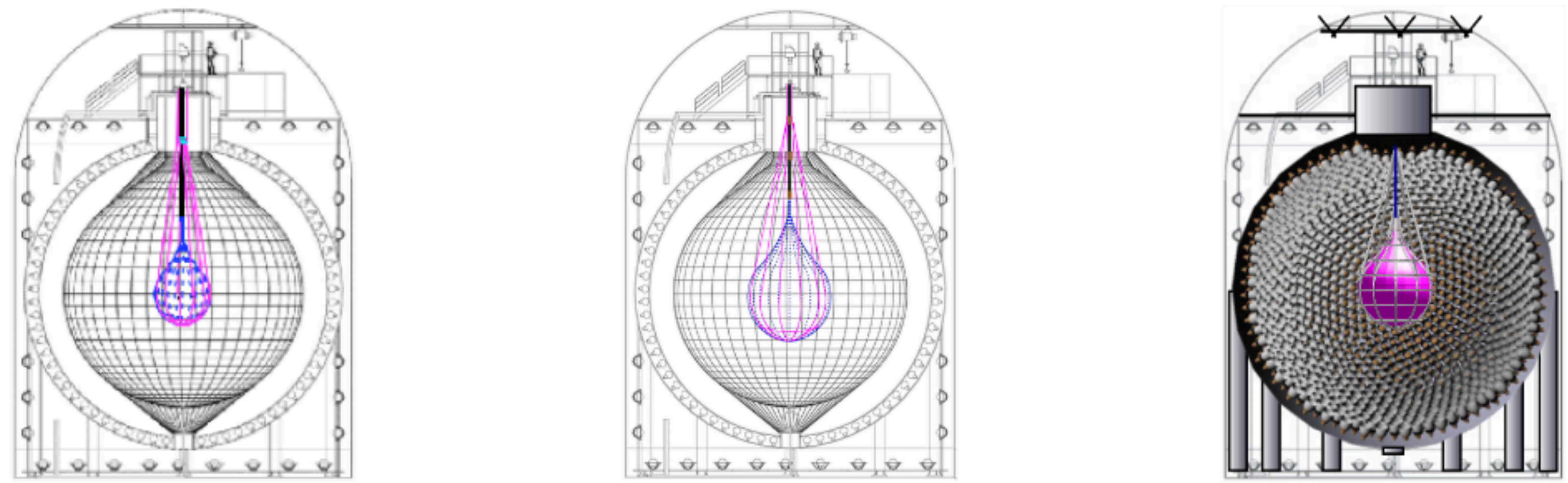
expensive, and there are better ways to use this!

^{124}Sn: not as good as Te or Xe, but should re-visit if inexpensive enrichment becomes possible

^{130}Te: to be used by SNO+

^{136}Xe: demonstrated by KamLAND-Zen

Past | Ongoing | Future



KamLAND-Zen 400	KamLAND-Zen 800	KamLAND2-Zen
R = 1.54m mini-balloon	R = 1.90m mini-balloon	
Xenon 320 ~ 380 kg →	Xenon 745 kg →	Xenon ~ 1 ton
2011 ~ 2015	Jan. 22, 2019 ~	

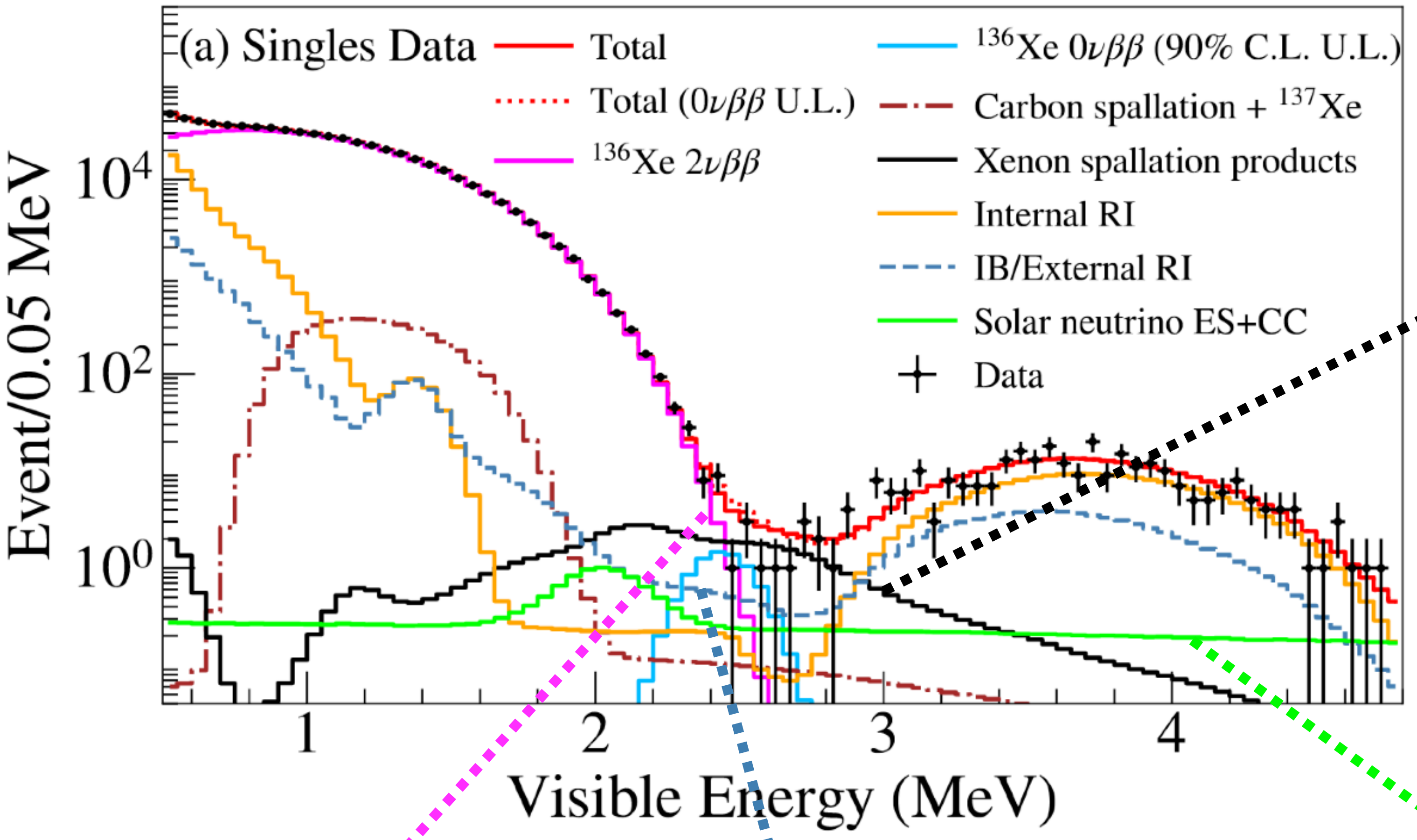
Enriched Xe gas directly dissolves in scintillator at ~3% level

Very clean - not expected to carry any significant contaminants!

Little impact on fluorescence yield

March 2022 (arXiv 2203.02139)

Best half-life bound so far: $T_{1/2} > 2.1 \times 10^{26}$ yrs



Currently dominated by spallation backgrounds (will likely limit future K-Z sensitivity)

↓

Go deep and find a discriminant!

Fighting off 2νββ spillover

↓

Improve light yield and PMT coverage (K2-Z)

Externals from bag are tricky in this scale

↓

Careful consideration of detector design to reduce impact of fiducial cuts

^{8}B low here, but will become significant for larger volumes

↓

Look for ways to suppress to sub-dominant background

Issues with ^{136}Xe

- Expensive
- Requires enrichment from 8.9%
- Relatively rare (total worldwide production ~50 tonnes = ~4.4 tonnes of isotope per yr)

↓

Hard to imagine anything more than ~5 tonnes (can't get to NH)

At the multi-tonne scale, other approaches with better energy resolution (*e.g.* nEXO or maybe NEXT) might be more suitable

The Point of Tellurium

Te relatively abundant & inexpensive (~$50/kg)
^{130}Te fraction = 34.5%

no enrichment necessary!

current loading tech is ~$1-2M/tonne

Looks like one of the very few possible contenders for a future NH experiment, and one with a potentially broad physics programme

The basic target numbers for a Te-loaded NH experiment are:
~10% ^{nat}Te loading in ~10kT fid volume with ~1000 hits/MeV
(PRD 87, 071301(R), 2013)

Backgrounds

External Backgrounds from Detector/Cavity Radioactivity

Particularly from ^{208}Tl, which can produce an un-tagged 2.6 MeV gamma. Self-shielding and fiducial volume cuts - minimise material near active volume. Solved

Internal Radioactivity (U/Th) from Scintillator

Scales with detector mass. Mainly ^{214}Bi with some from ^{212}Bi and ^{208}Tl. The vast majority can be identified by associated alpha (Bi-Po), but some inefficiency. Subdominant at higher loading levels and already handled well by scintillator purification and background rejection techniques. Solved

Internal Radioactivity (U/Th) Associated with Isotope Deployment

Scales with isotope mass. Less of an issue for Xe, which is transported as a gas. For Te, improve purification and background rejection techniques as isotope mass increases. Existing purification techniques may already be good enough, otherwise target process improvements. Solved/Solvable

Cosmogenic/Spallation Backgrounds

For ^{130}Te and ^{136}Xe, particularly isotopes such as ^{60}Co, ^{22}Na,^{110m}Ag, which have long half-lives. Purify to target these elements, go deep to prevent further activation, employ PSD techniques to identify any lingering contamination. Subdominant. Largely solved

^{8}B Solar Neutrinos

Scales with detector mass. One of the main backgrounds, becoming less dominant for higher loading levels. Modest directional discrimination (*e.g.* Cherenkov) would make this subdominant. Potentially solvable

2νββ Spill-over

Fundamental (no way to discriminate) and dominant at higher loading. Strong function of energy resolution… goes as the power of ~5.5 ! (A 22% reduction in light doubles this background!)

ABSOLUTELY MUST KEEP THE LIGHT!!

Internal Radioactivity (U/Th)
Associated with Isotope Deployment

Telluric Acid Purification via Induced Recrystallisation

S. Hans et al, Nuclear Inst. and Methods in Physics Research, A, Volume 795, p. 132-139

Dissolve TeA in UPW, filter to remove insoluble contaminants

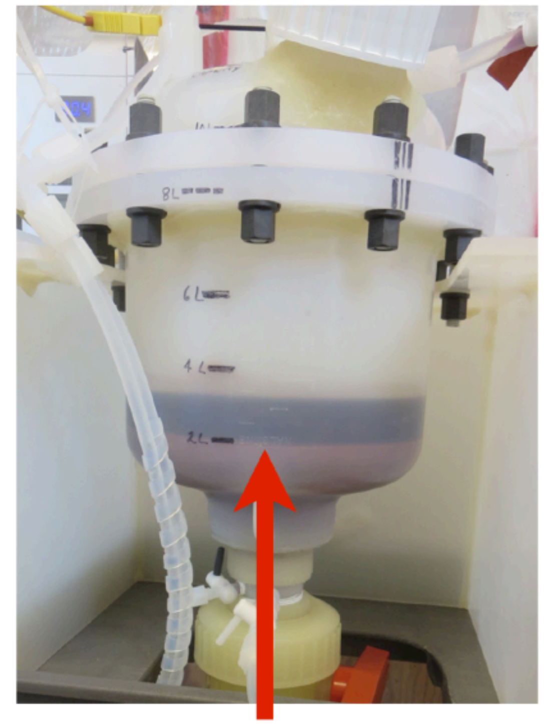
Induce recrystallisation with acid, rinse to remove soluble contaminants

Final stage thermal recrystallisation, cold water rinse to remove acid

Single Pass Reduction Factors

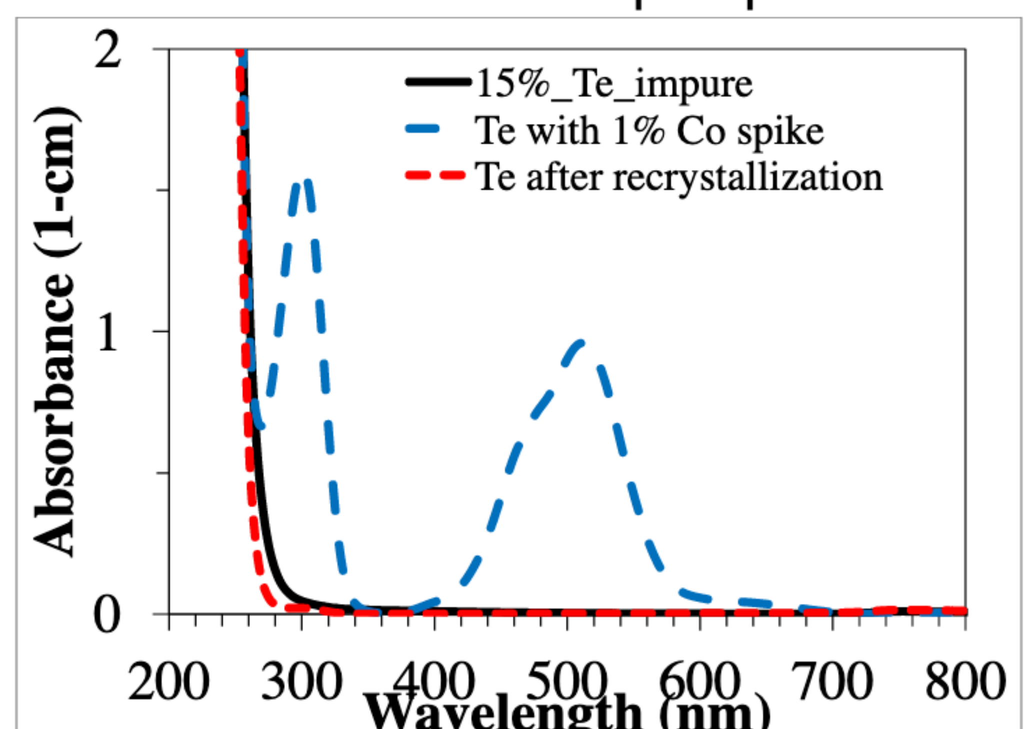
Isotope	XRF Sensitivity (ppm)[3]	Reducing Factor
Sn[1]	6.0	$>1.67\times10^2$
Zr[1]	3.6	$>2.78\times10^2$
Co[1]	1.5	$(1.15\pm0.66)\times10^3$
Ag[1]	3.6	$>2.78\times10^2$
Y[1]	3.6	$>2.78\times10^2$
Sc[1]	18	$>1.65\times10^2$
Sb[1]	12	$>2.43\times10^2$
^{228}Th[2]	-	$(3.90\pm0.19)\times10^2$
^{224}Ra[2]	-	$(3.97\pm0.20)\times10^2$
^{212}Pb[2]	-	$(2.99\pm0.22)\times10^2$
^{212}Bi[2]	-	$(3.48\pm0.81)\times10^2$

Medium-Scale (10kg) Te Purification Test

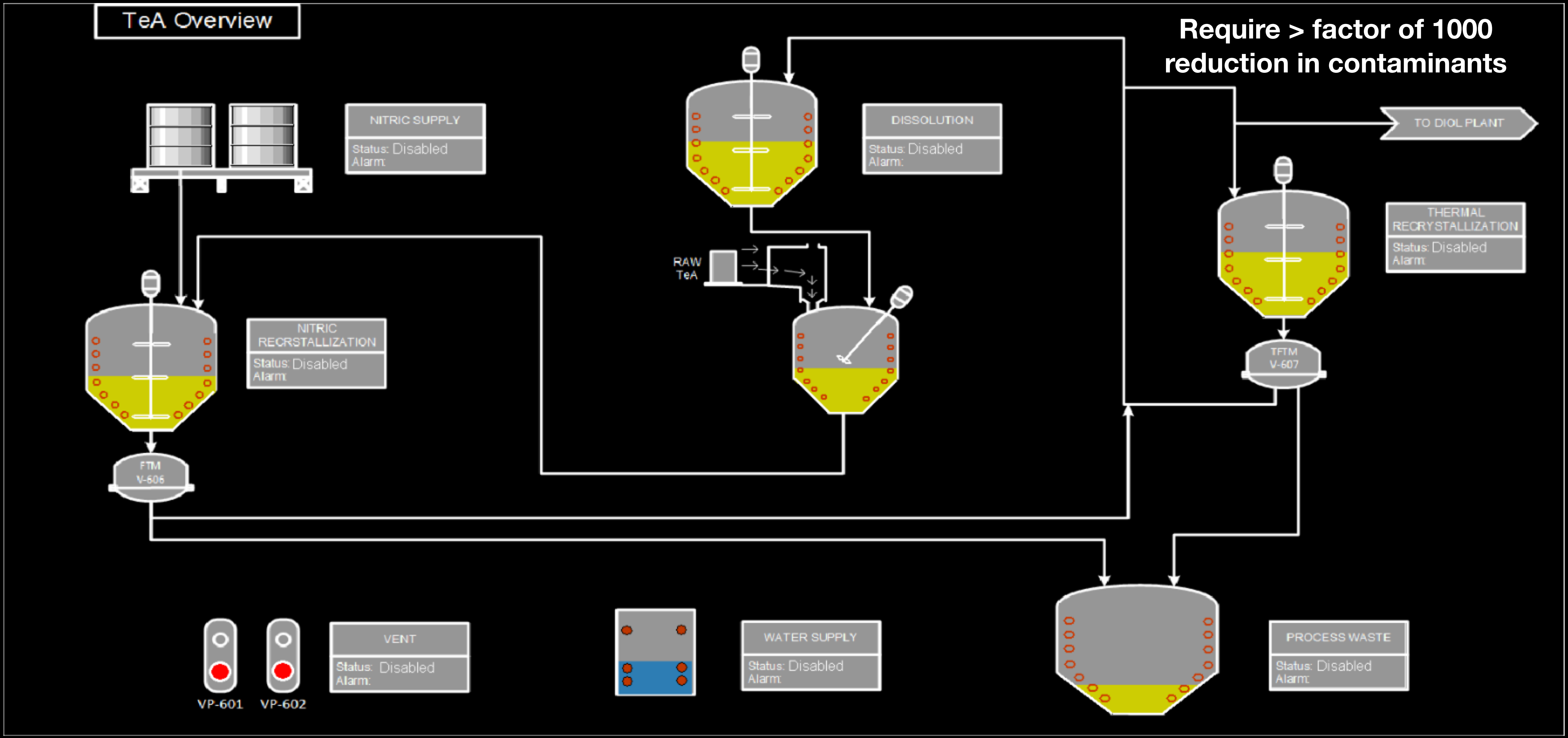


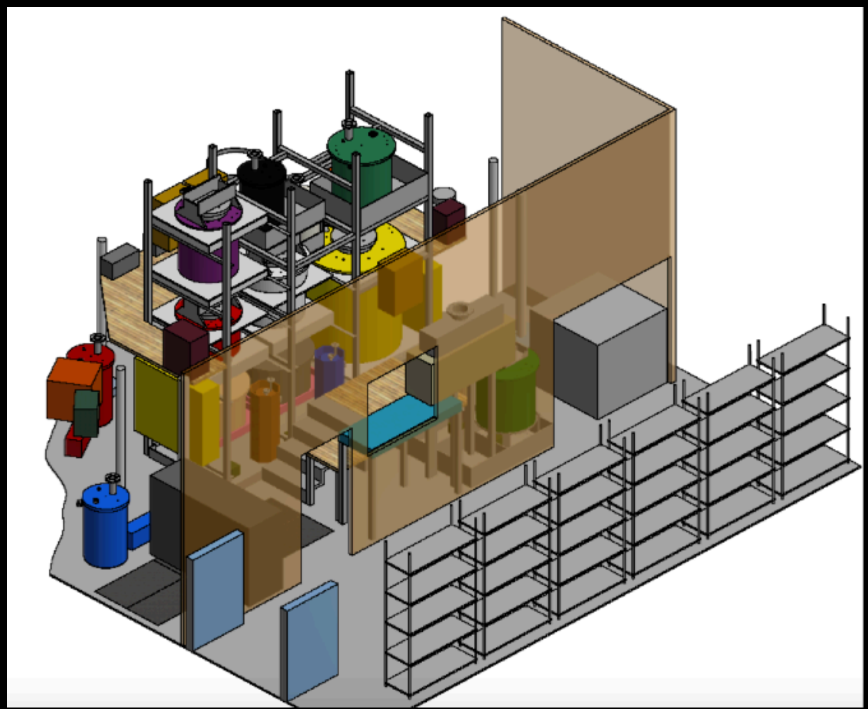
Co/Ag/Sn spike

Zoomed view post-purification



Telluric Acid Purification





- TeA dissolved in UPW
- 2 nitric acid-induced recrystallisations (pur factor >100 per pass)
- Thermal recrystallisation to remove nitric
- Redissolve in UPW

Ultimately limited by nitric and UPW wash

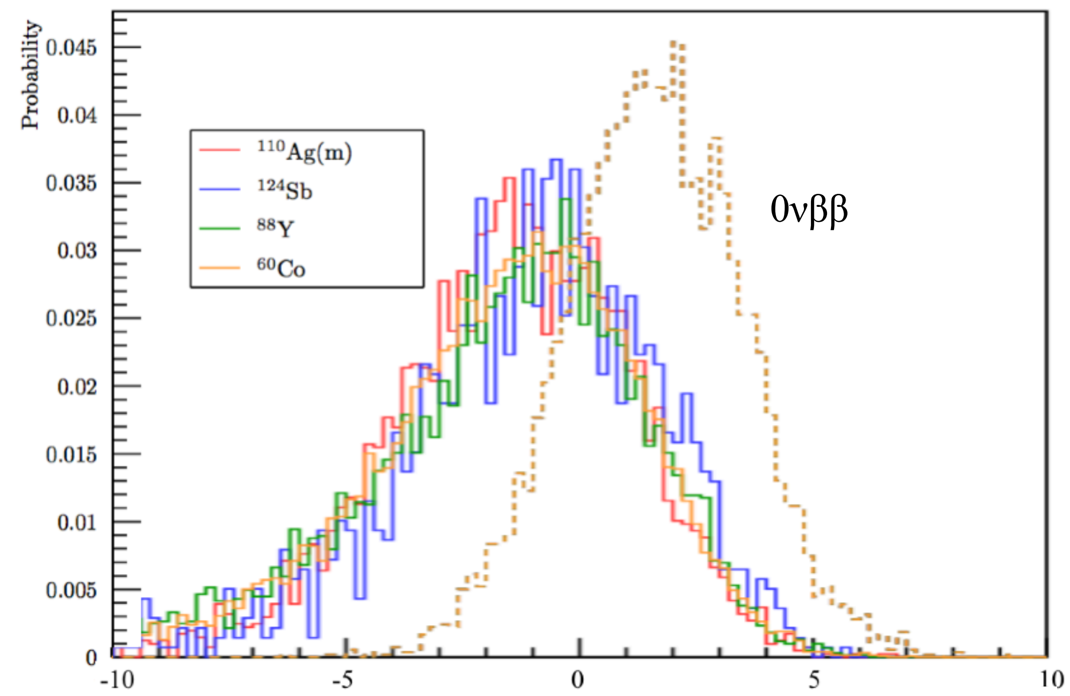
Cosmogenic/Spallation Backgrounds

Multi-site event discrimination in large liquid scintillation detectors

(Dunger and Biller, NIM, **943**, 162420, 1 November 2019, arXiv:1904.00440)

Compton length for 1 MeV γ in LAB ~20cm, vs vertex resolution of ~10cm →

use time residuals from vertex fit to form PDFs for a likelihood discriminant



Faster PMTs & LS mixtures can improve this separation further

In situ calibration of technique

multi-site events:

- α-tagged ^{214}Bi & ^{208}Tl decays
- external γ's (dominant at higher radius)

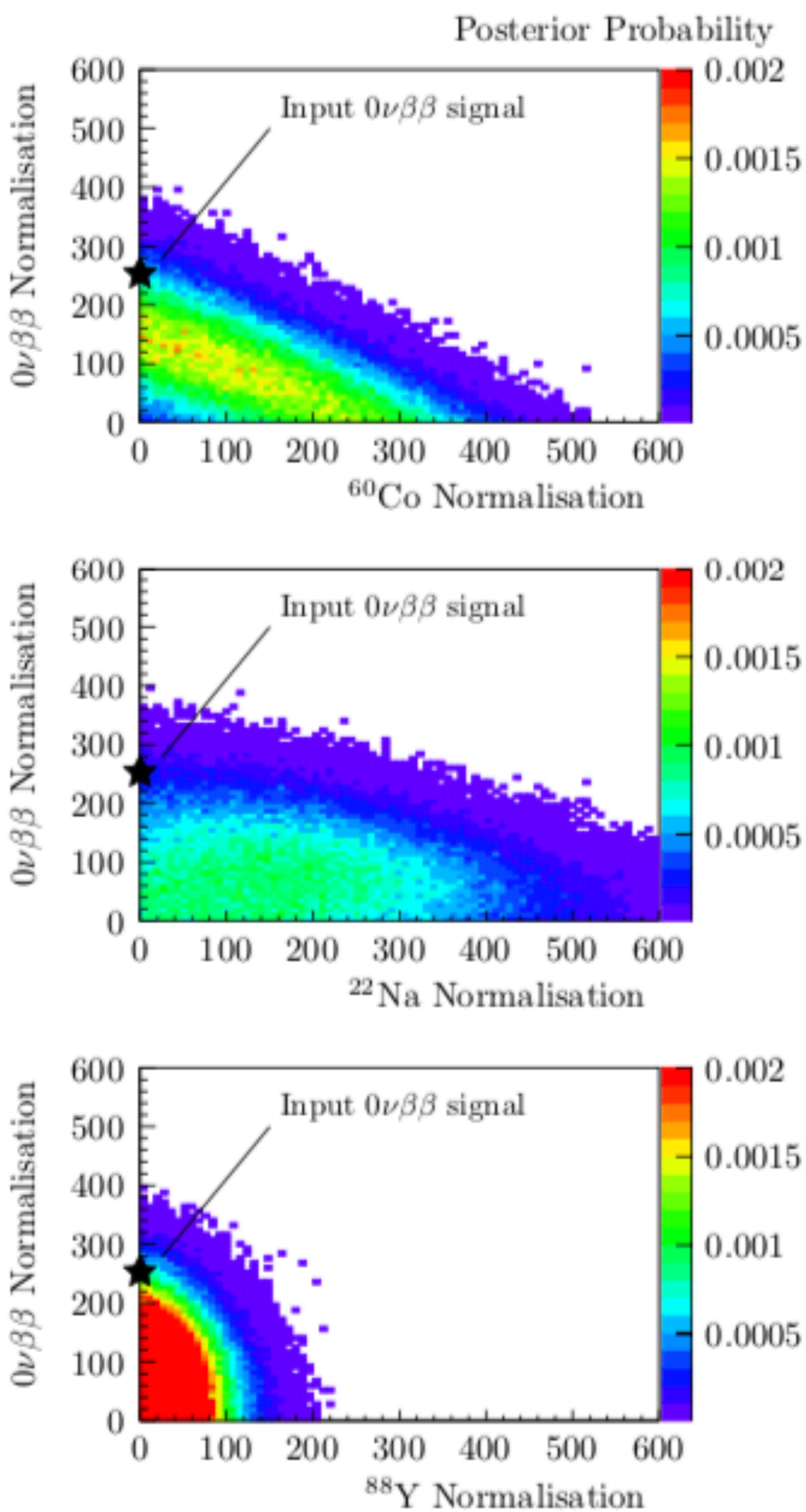
single-site events:

- 2νββ events (dominant at lower energy)
- ^{8}B solar ν (dominant at higher energies)

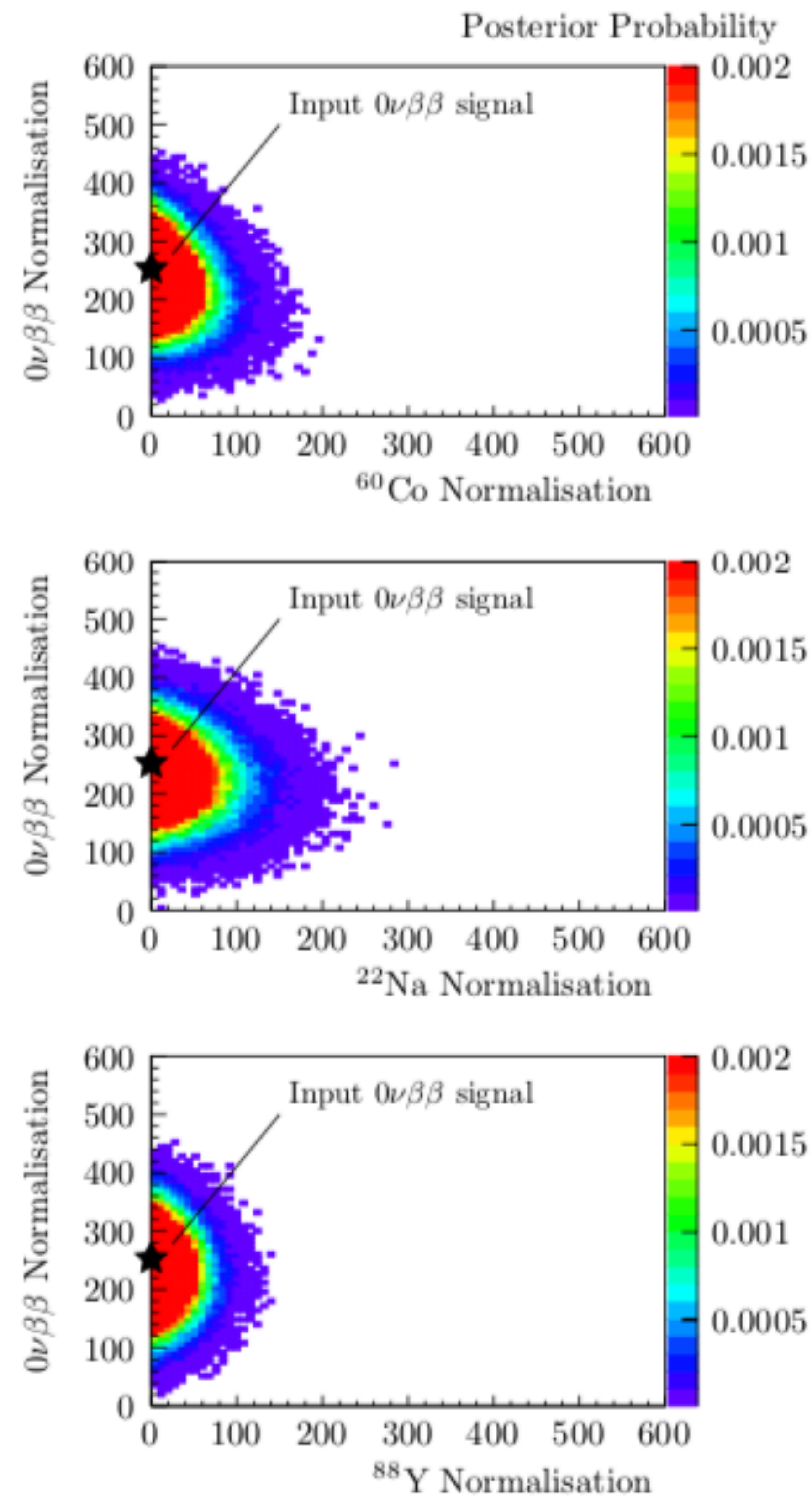
can also use deployed sources

Can identify signal as distinct from cosmogenic background -> discovery experiment!

without multi-site parameter



with multi-site parameter



^{8}B Solar Neutrino Background

Cherenkov Separation in Liquid Scintillator for Directional Rejection of ^{8}B at 2.5 MeV

C. Aberle et al., JINST 9, P06012 (2014)

1) Time separation in standard scintillator using very fast photodetectors (*e.g.* LAPPDs)

Simulations of large-scale detector performance are disappointing, largely due to covariances in vertex reconstruction and dispersion, even for ideal detectors. Plus potentially expensive.

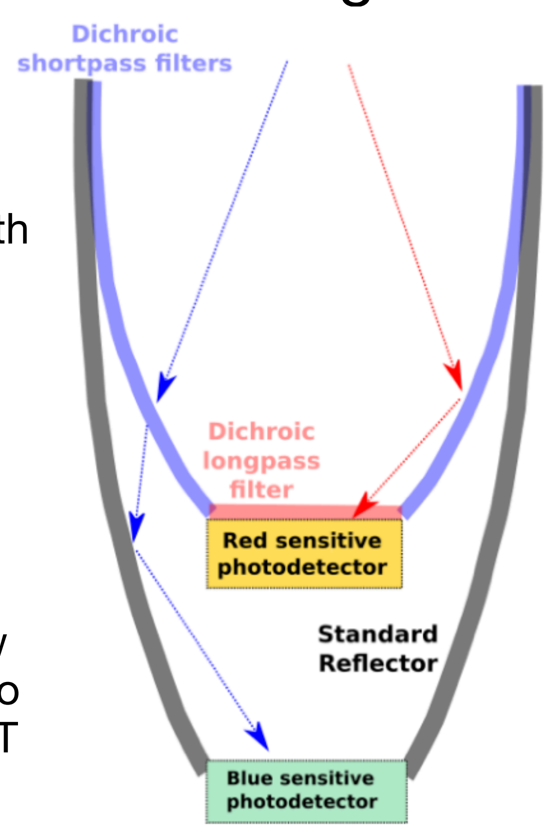
M. Li *et al.*, NIM A 830, 303 (2016),

2) Time separation aided by weak scintillators to increase the fluorescence timescale

Weak scintillators also have notably reduced light output… **must keep the light!**

3) Spectral separation using dichroic concentrators

Detect Cherenkov above ~450nm with red-sensitive PMT



Detect scint below ~450nm passing to blue-sensitive PMT

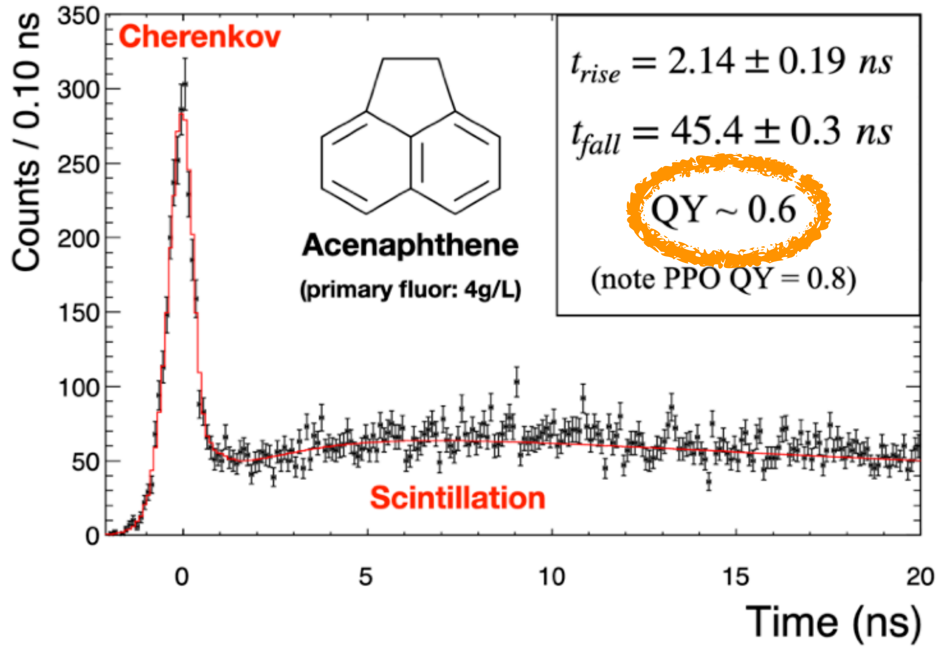
- Limited spectral range at high end for Cherenkov
- Red-sensitive PMTs expensive, noisy with modest efficiency
- Front PMT blocks light to back PMT… **must keep the light!**

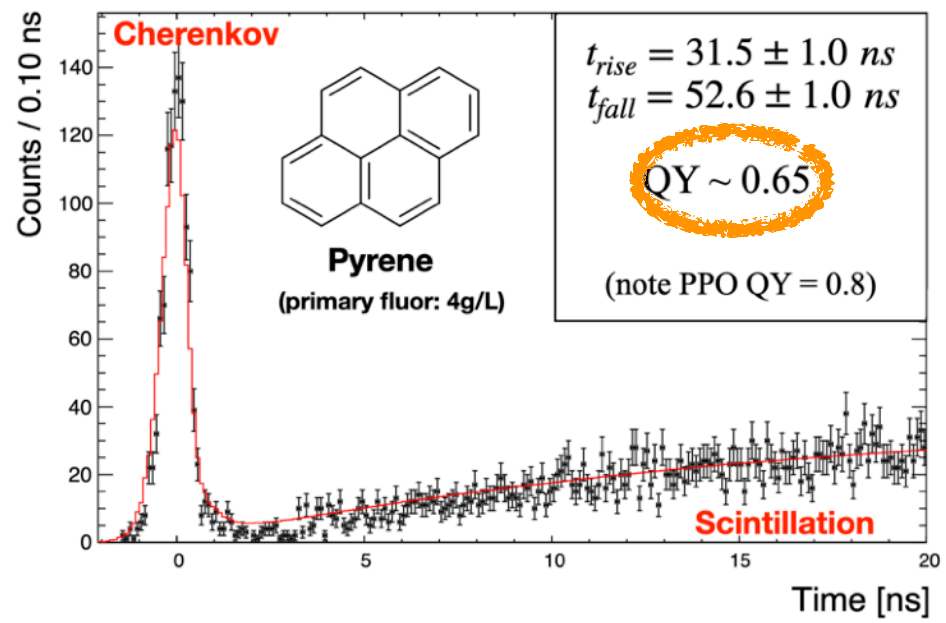
Kaptanoglu, Luo, Land, Bacon & Klein, PRD 101 (2020)

4) Slow-fluor scintillator formulations

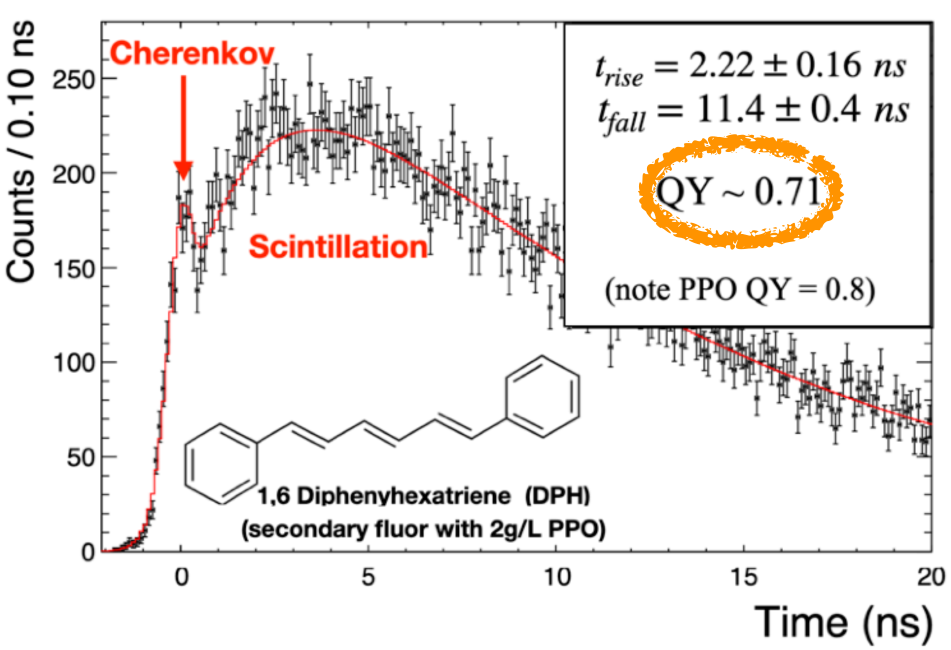
Biller, Leming & Paton, NIM A 972 (2020)

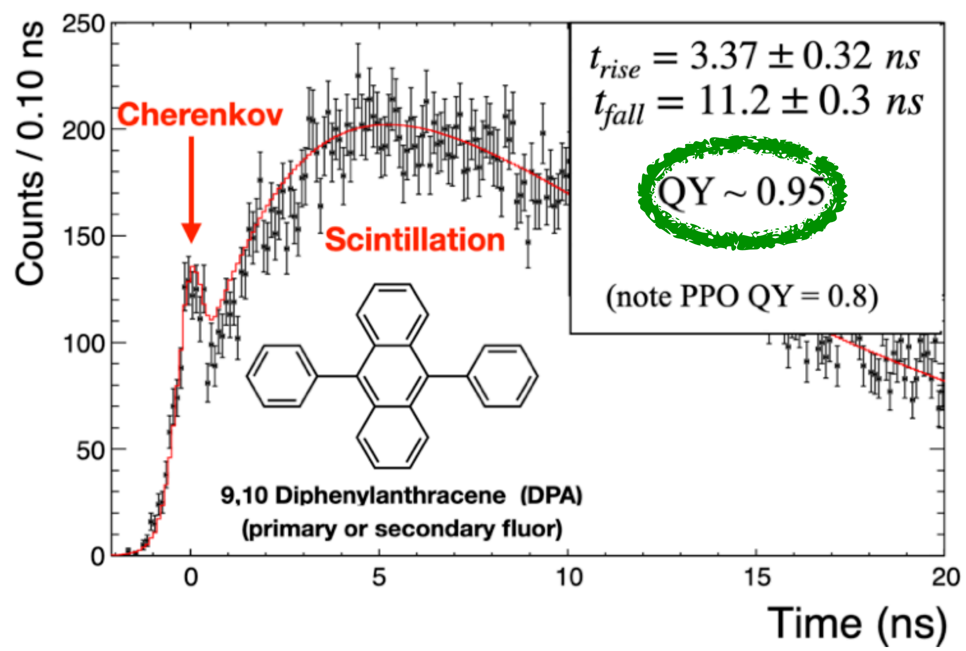
Efficient separation, wide spectral coverage for Cherenkov, full PMT coverage for all light, easy to implement. Some compromise in vertex resolution, but impact on multi-site partly compensated by discrimination based on Cherenkov light





Must keep the light!





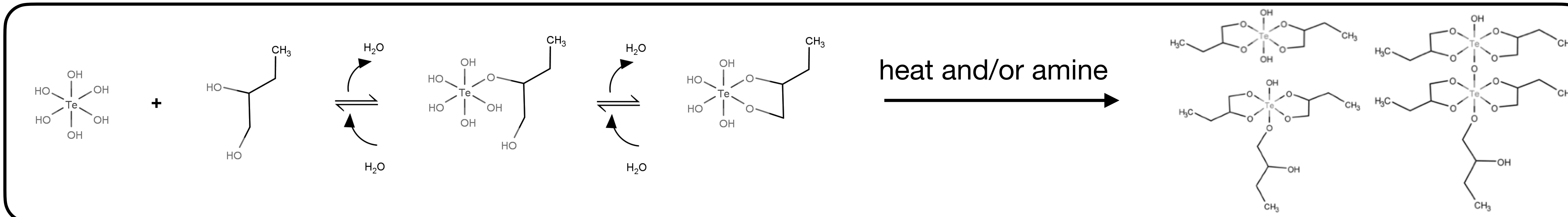
High QY and has good enough solubility to non-radiatively couple with PPO, less quenching than slower fluors.

Overall quenching from loading will enhance Cherenkov separation

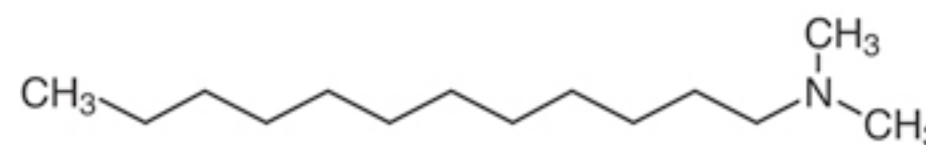
Te Loading

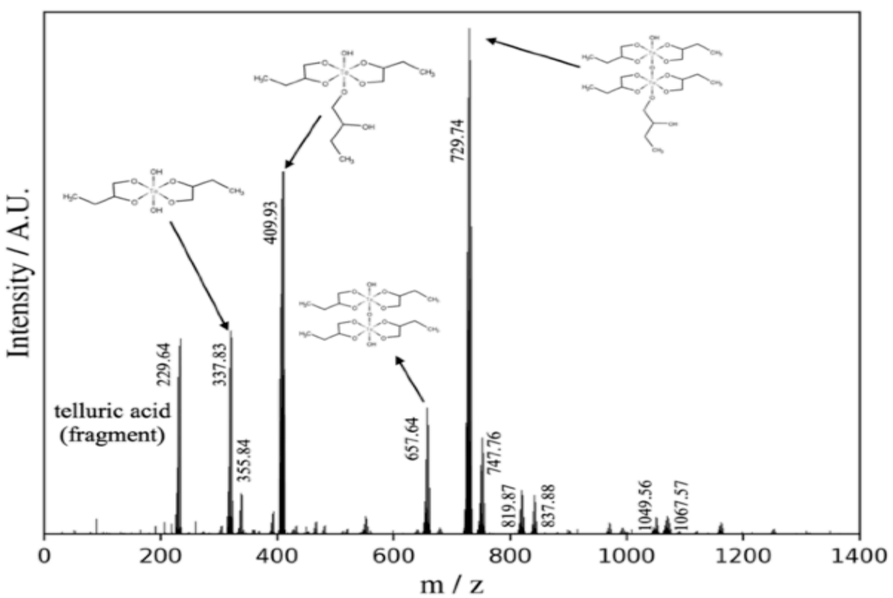
Te Loading in Liquid Scintillator for 0νββ

(paper in progress)

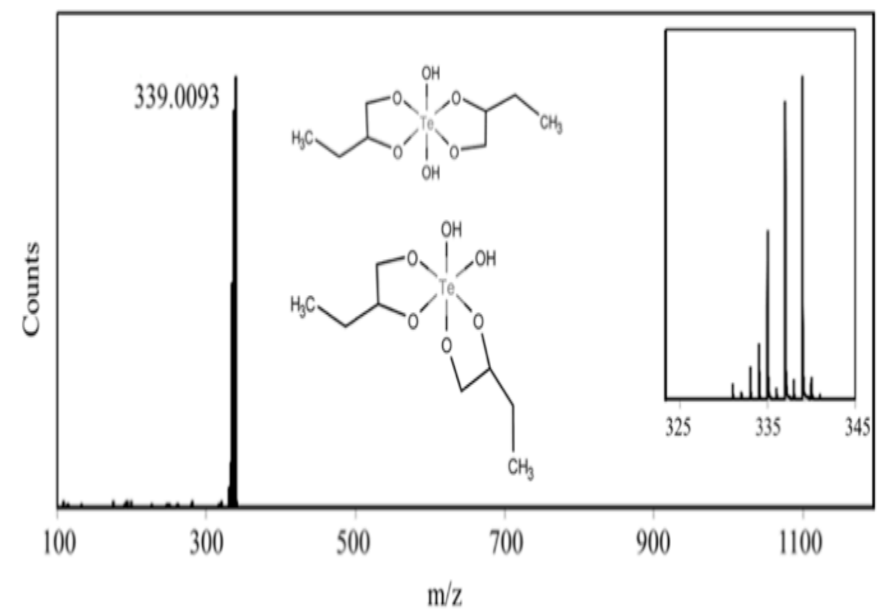


Dimethyldodecylamine (DDA) used
as a solubilising/stabilisation agent





pure heated solubilisation



pure DDA solubilisation

miscible
with LAB

Loading Stability

No "crashes" have ever been observed with the current loading technique, with loading stability in excess of 6 years demonstrated, yielding a conservative extrapolation of > 12 years in the detector (Arrhenius temperature scaling)

Optical Stability

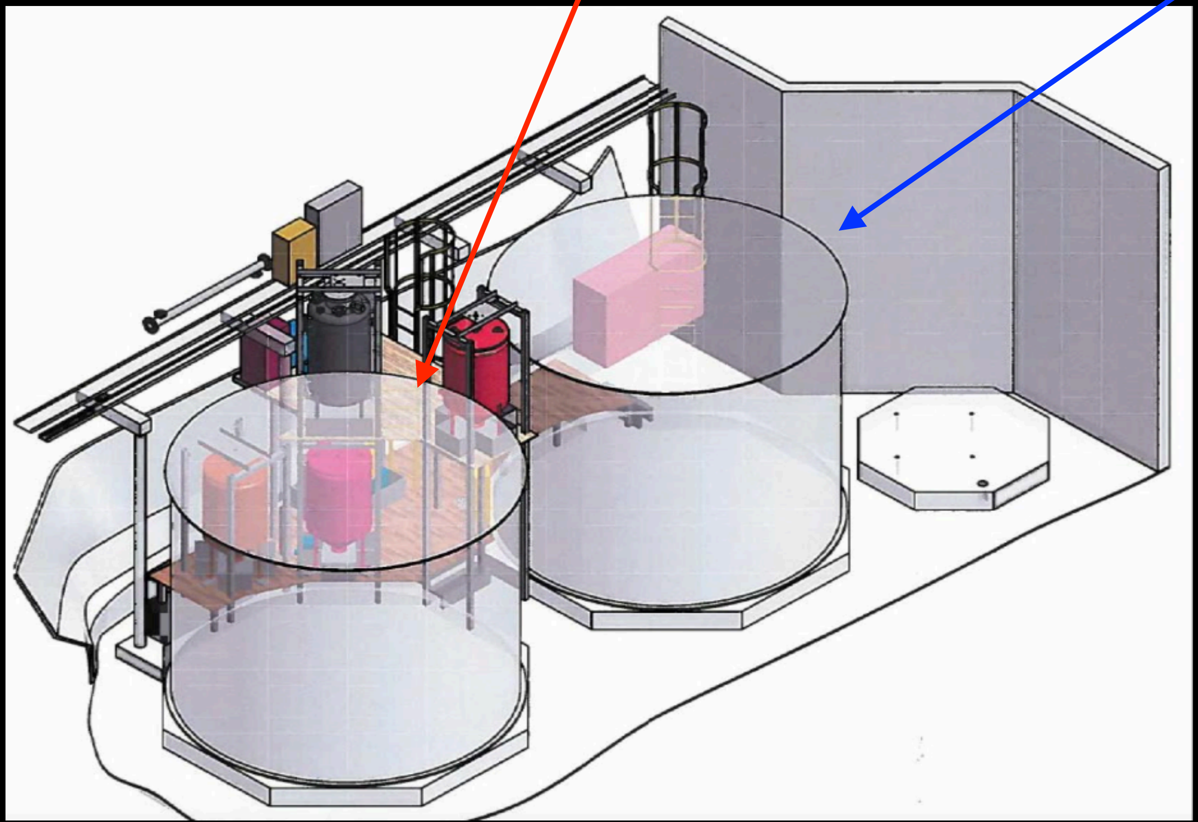
Yellowing can occur if unpurified/old LAB and DDA are used that contain high levels of free radicals (can be tracked with various tests), but samples made with appropriately purified reagents are optically stable in excess of several years at least, conservatively extrapolated to > 6 years in the detector:

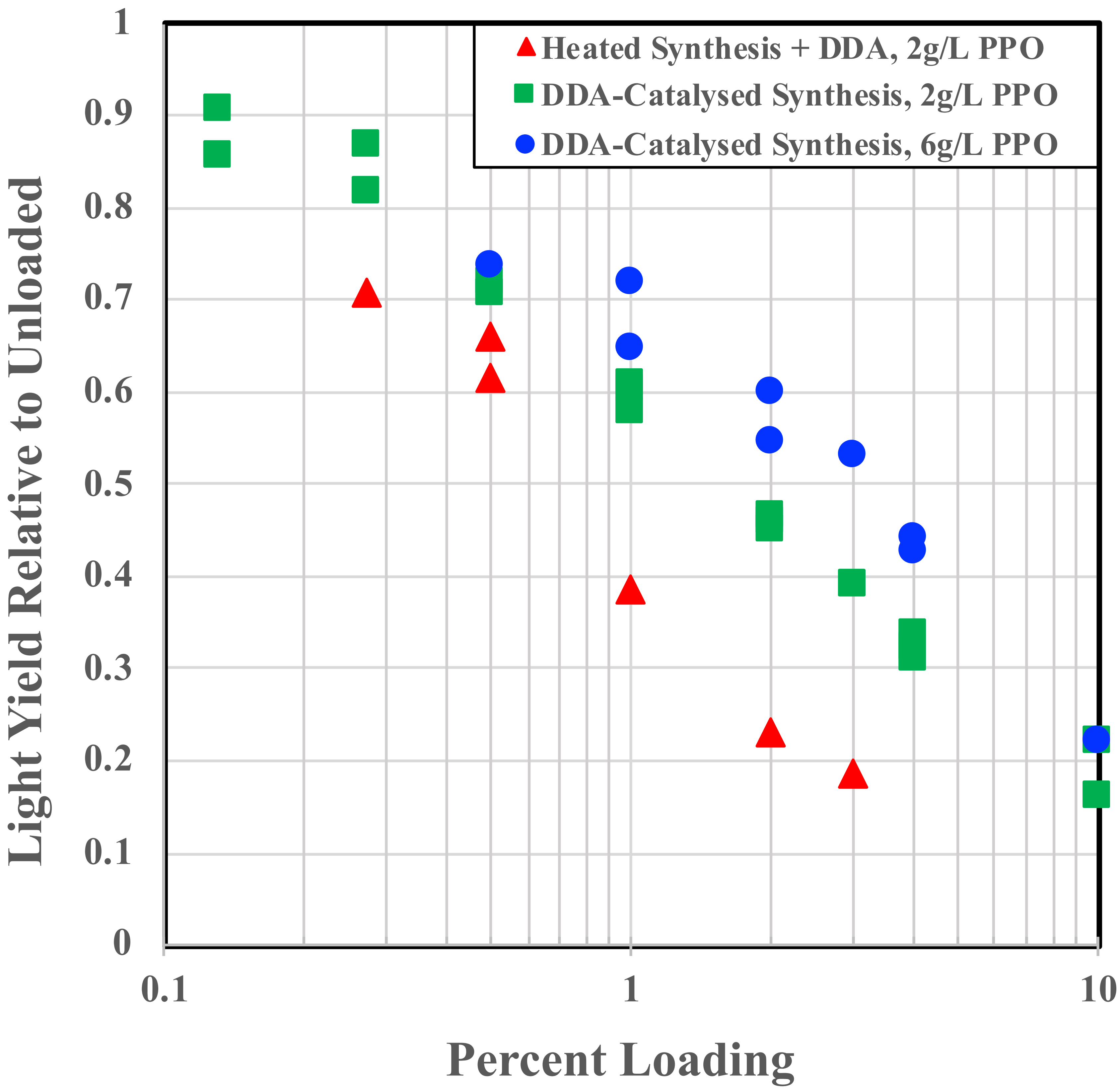
Sample	Storage Temperature (°C)	Observed Stability (years)	Conservative **projected lower limit on SNO+ TeLS lifetime (years)**
T-1000	~22	>3.3	>6.7
LT3 & subsamples	~22	>2.7	>5.2
T-1003-10	40	>0.9	>5.6

TeBD Synthesis Plant

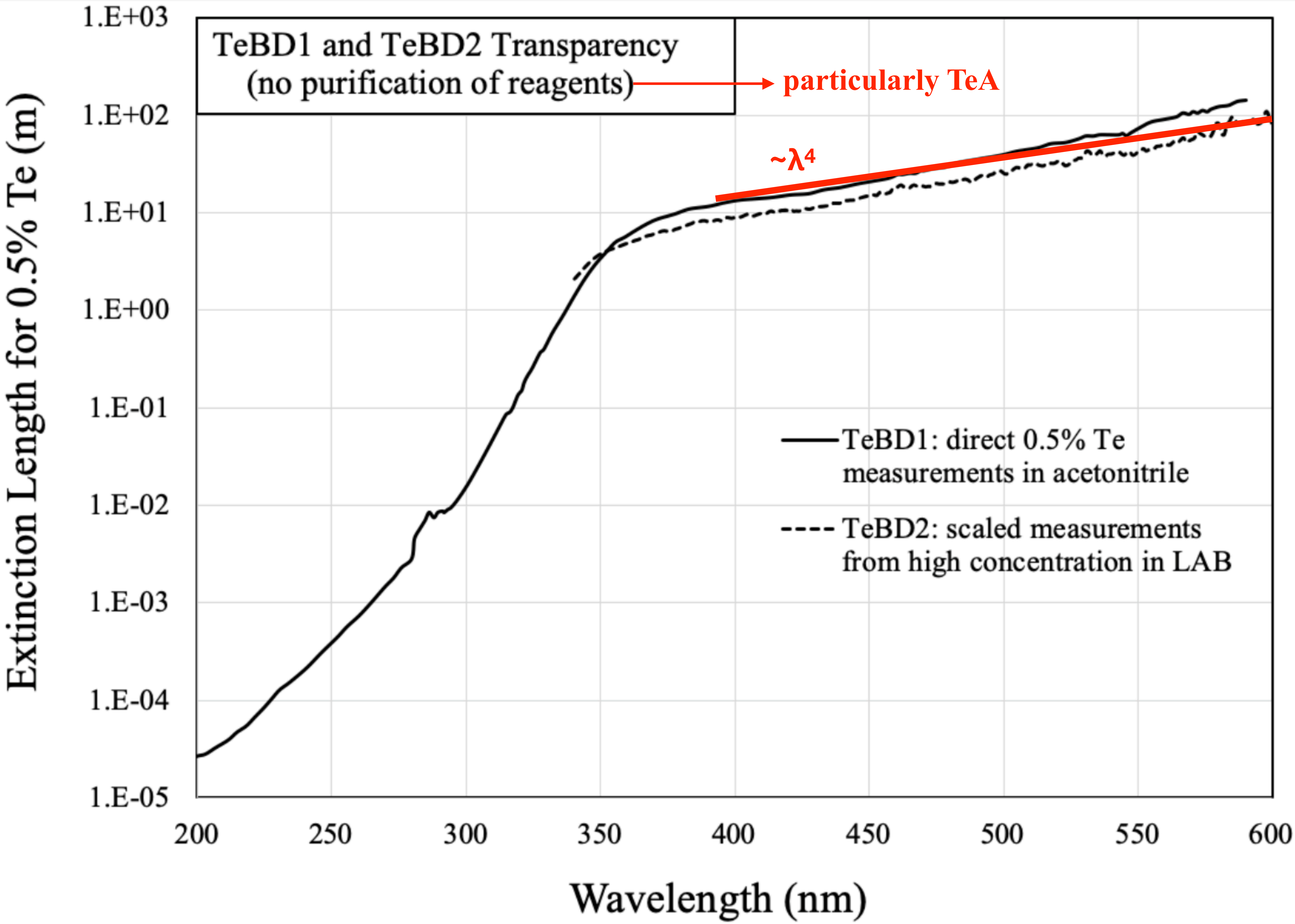
Mixture of TeA in water and distilled butanediol is heated while water is flash-evaporated in the synthesis tank

Transferred to mixing tank near solubility point to combine with LAB and 0.25mol DDA to complete solubilisation



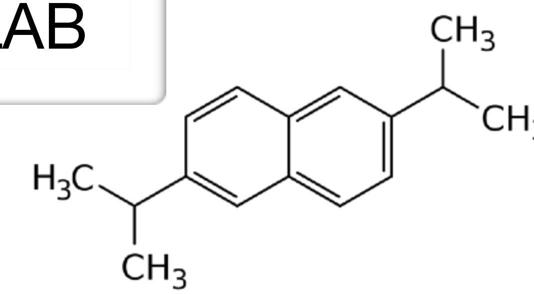


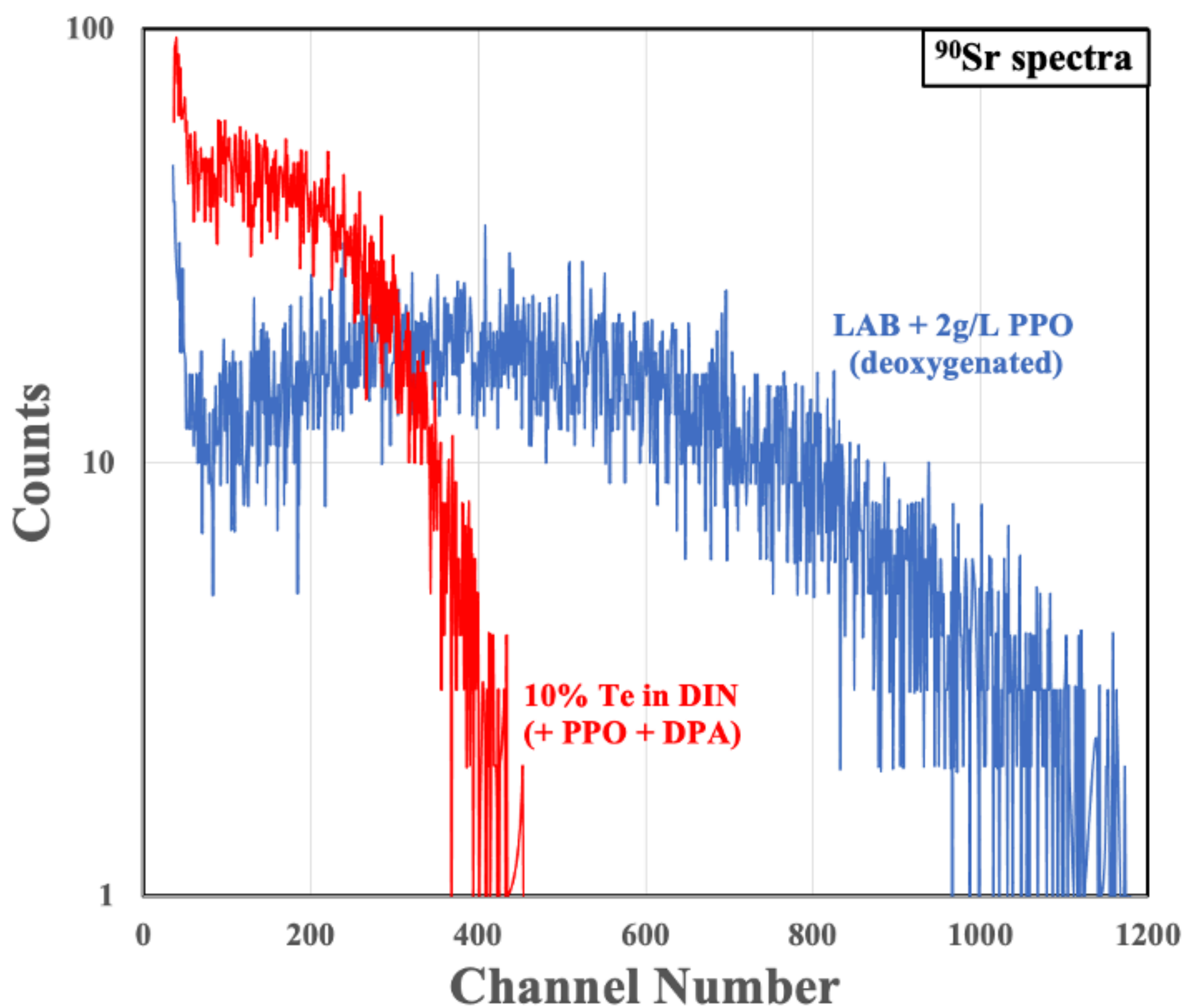
Heated Synthesis + DDA, 2g/L PPO
DDA-Catalysed Synthesis, 2g/L PPO
DDA-Catalysed Synthesis, 6g/L PPO
Light Yield Relative to Unloaded
Percent Loading
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.1
1
10



TeBD1 and TeBD2 Transparency
(no purification of reagents)
particularly TeA
~λ⁴
TeBD1: direct 0.5% Te measurements in acetonitrile
TeBD2: scaled measurements from high concentration in LAB
Extinction Length for 0.5% Te (m)
Wavelength (nm)
1.E+03
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
1.E-03
1.E-04
1.E-05
200
250
300
350
400
450
500
550
600

The solvent diisopropylnaphthalene (DIN) shows greater light yield and less fluorescence quenching when loaded than LAB





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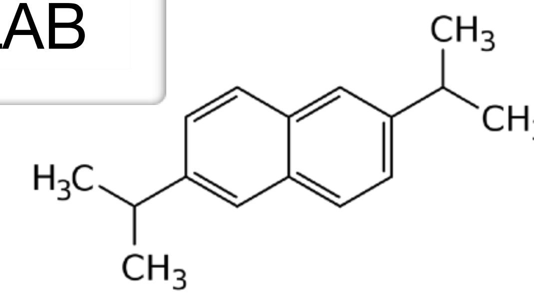
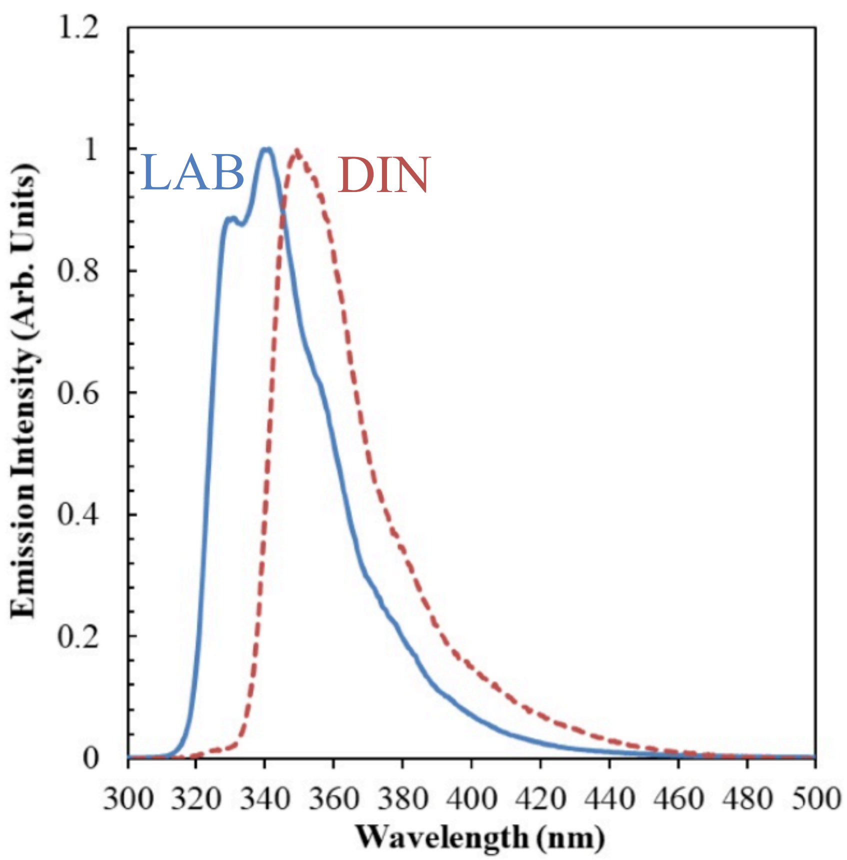




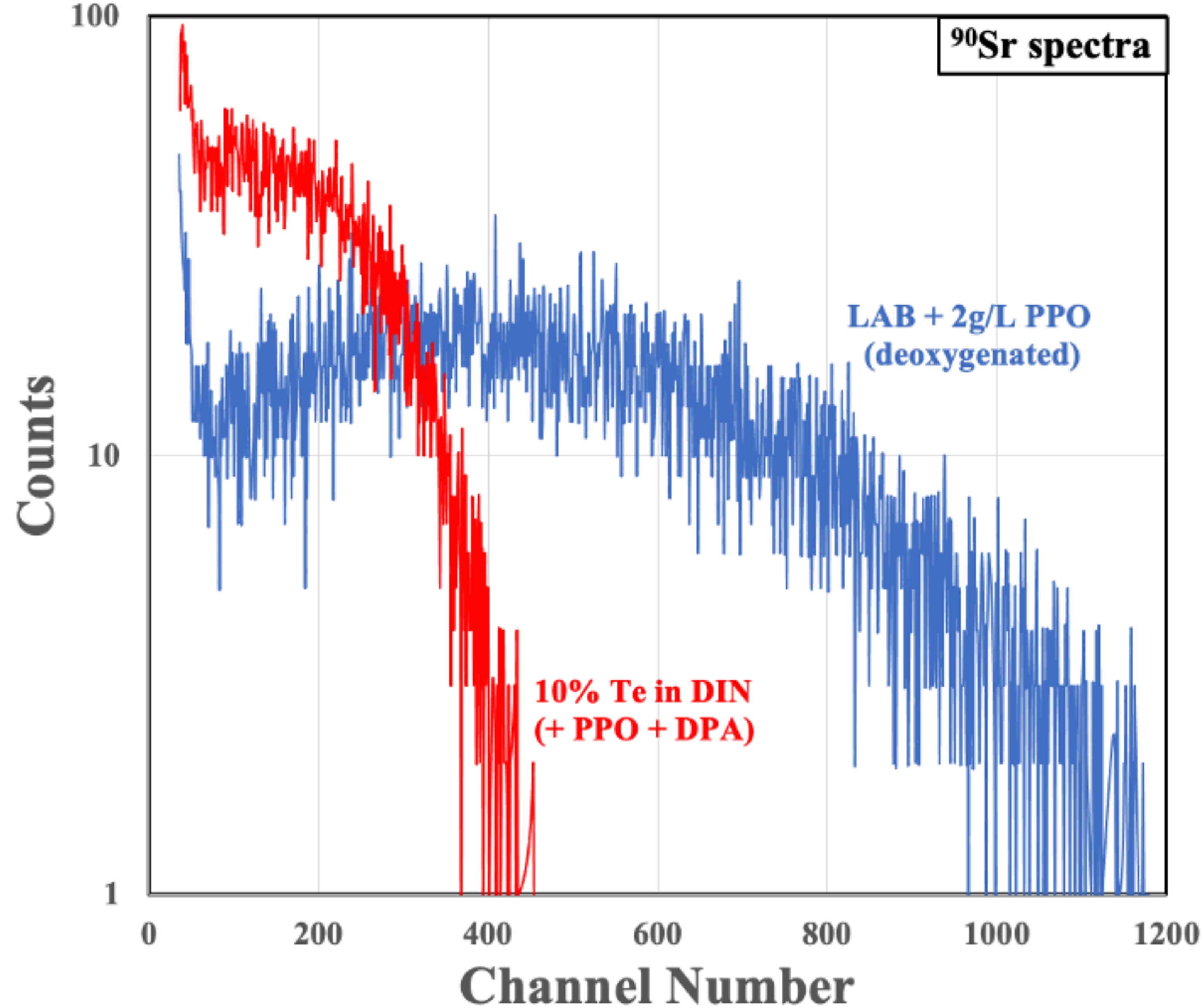
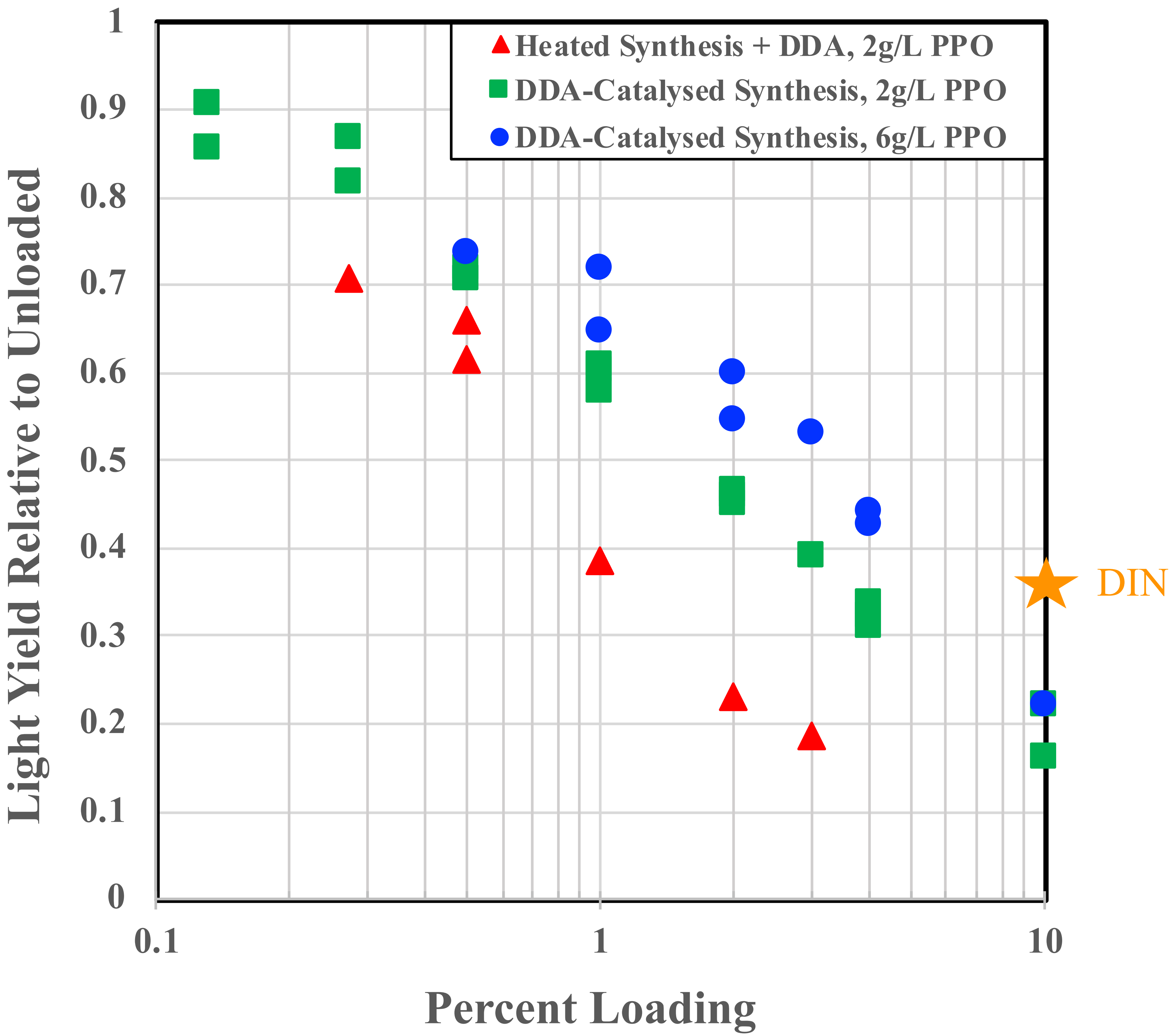


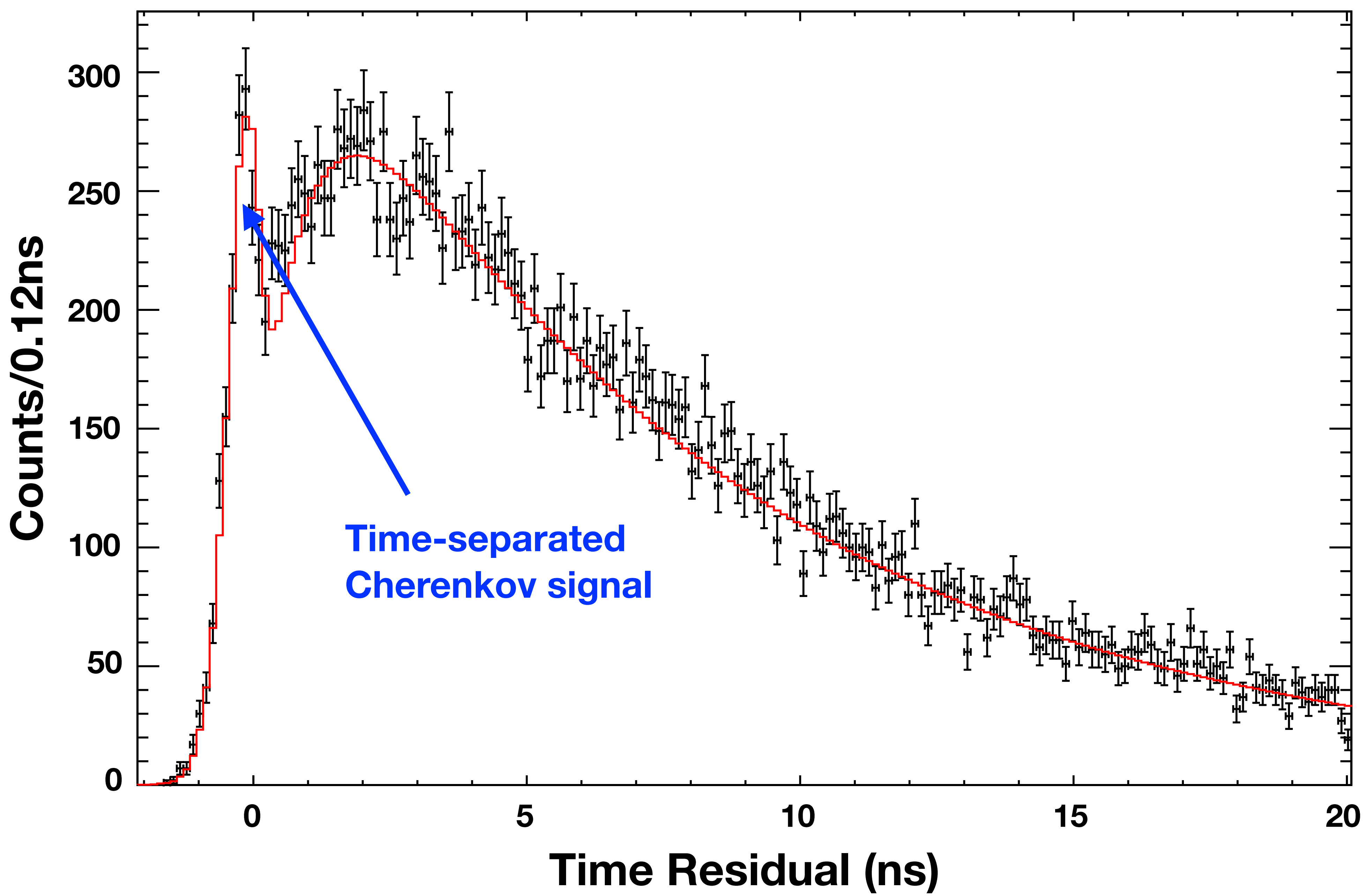
Table 1. Rayleigh scattering length as a function of wavelength for LAB and EJ309-base.

Wavelength (nm)	LAB (m)	EJ309-base (m)
410[+]	22.9 ± 2.3	5.0 ± 0.5
420[+]	25.3 ± 2.5	5.5 ± 0.5
430[+,×]	27.9 ± 2.3	6.1 ± 0.6
440[+]	30.6 ± 2.6	6.7 ± 0.5
450	33.6 ± 3.1	7.4 ± 0.7
460	36.8 ± 3.6	8.1 ± 0.8
470	40.2 ± 3.3	8.9 ± 0.7
480	43.9 ± 4.1	9.7 ± 1.0
490	47.8 ± 5.5	10.6 ± 1.2
500	51.8 ± 5.8	11.5 ± 1.2
510	56.2 ± 7.1	12.5 ± 1.3
520	60.9 ± 7.7	13.6 ± 1.6

[+]Scattering lengths extrapolated from the fitted formula using data from wavelengths of >440nm
[×]Scattering lengths for LAB available in the literatures: 26.2 ± 1.9 [27] and 28.5 ± 2.3 [28]

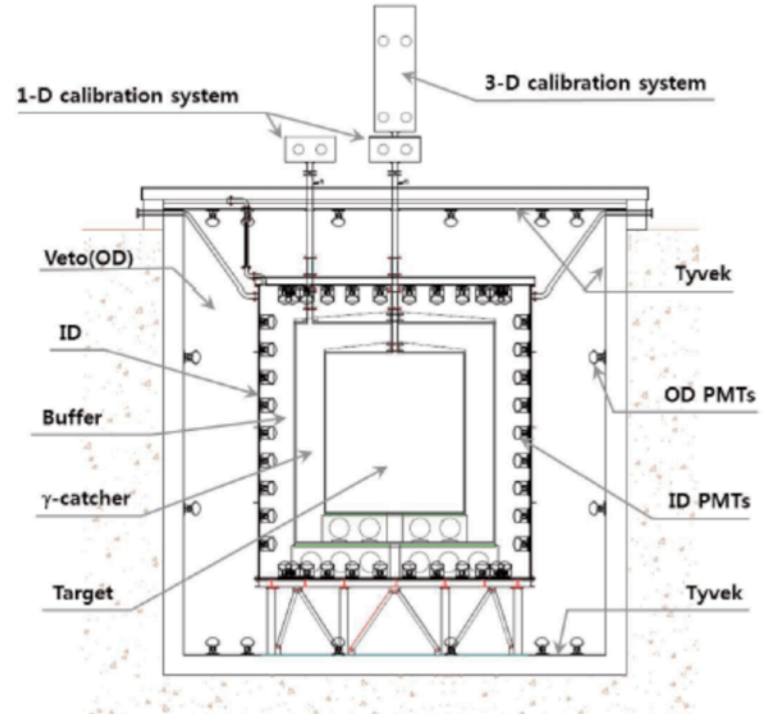


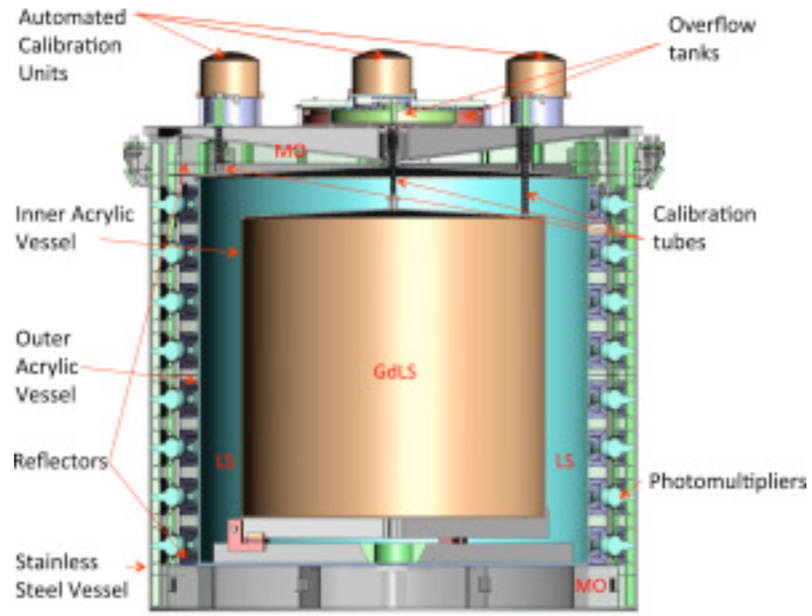
Heated Synthesis + DDA, 2g/L PPO
DDA-Catalysed Synthesis, 2g/L PPO
DDA-Catalysed Synthesis, 6g/L PPO
DIN
Light Yield Relative to Unloaded
Percent Loading
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.1
1
10

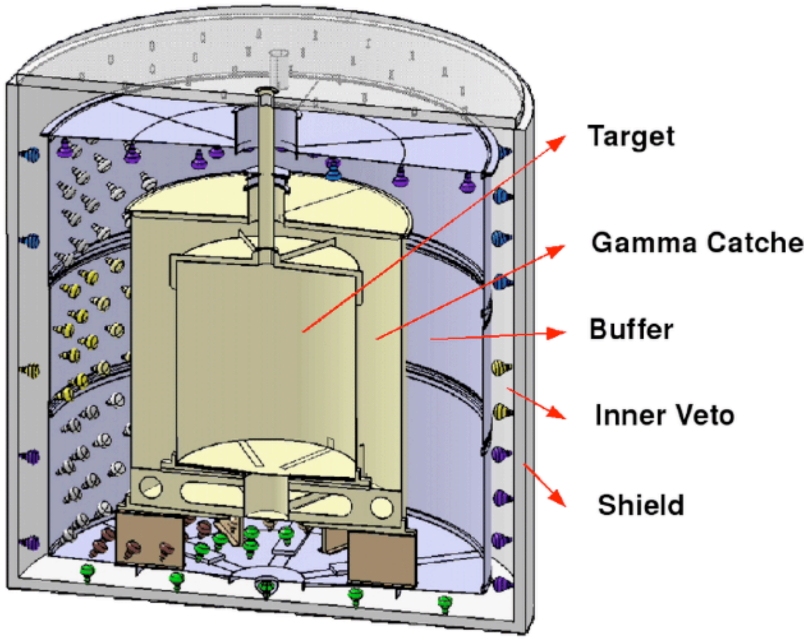


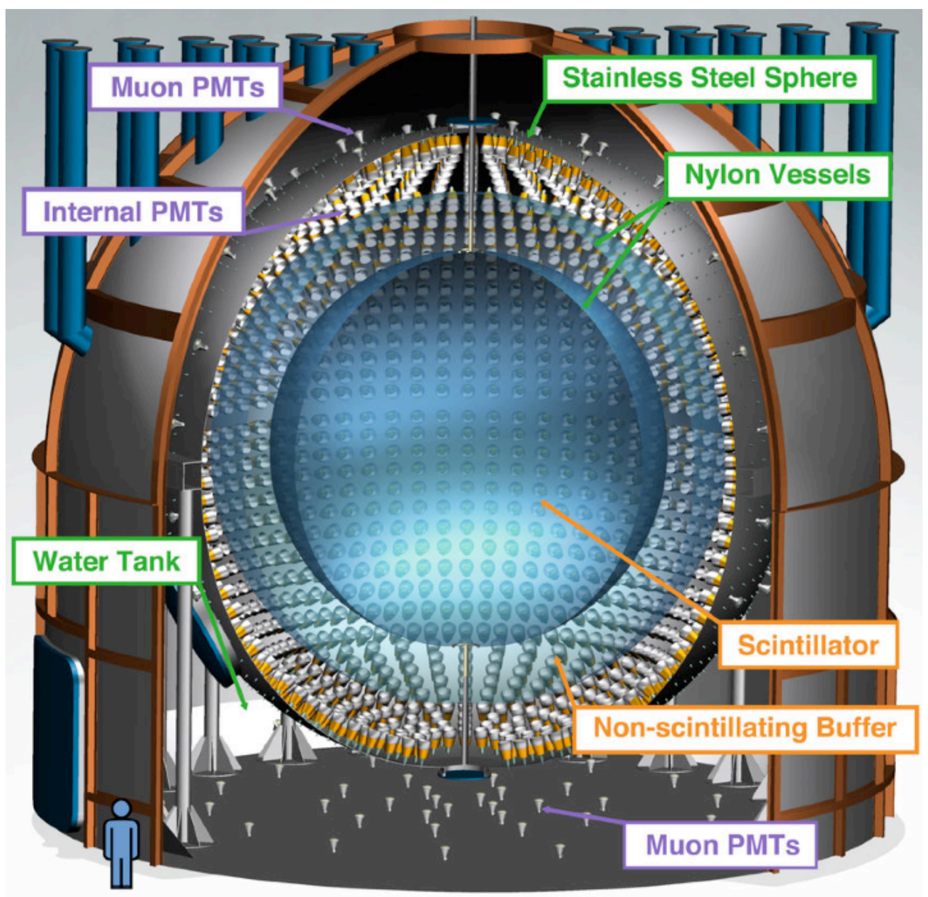
Time-separated
Cherenkov signal
Counts/0.12ns
Time Residual (ns)
0
50
100
150
200
250
300
0
5
10
15
20

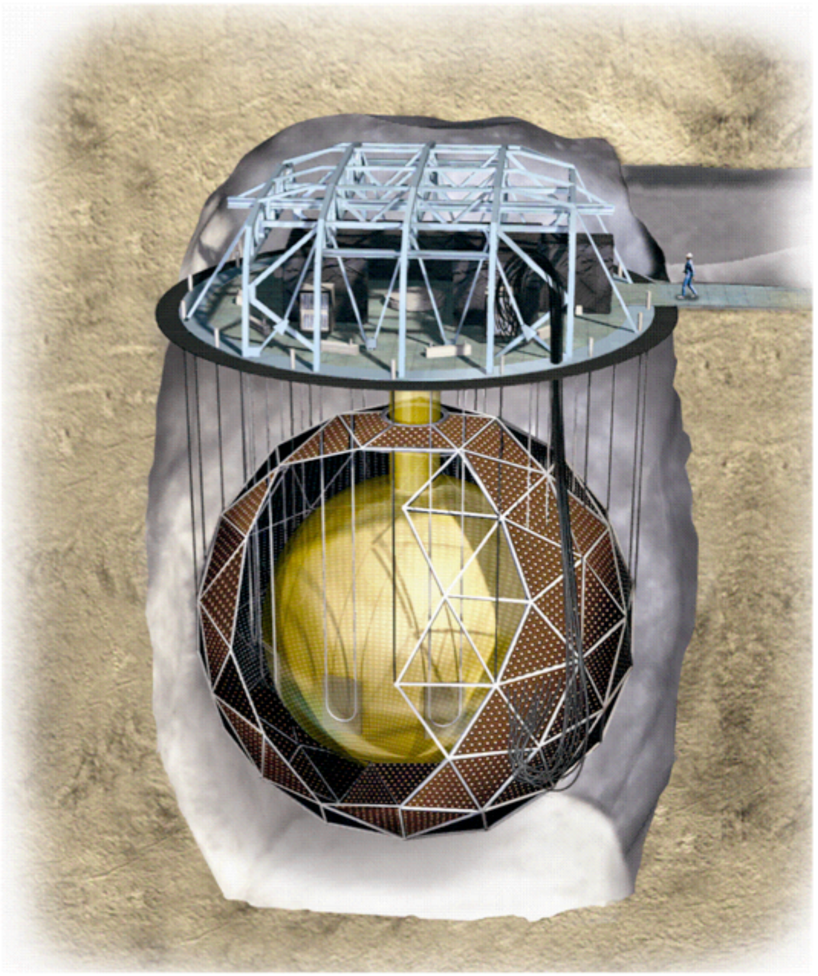
Detector Construction

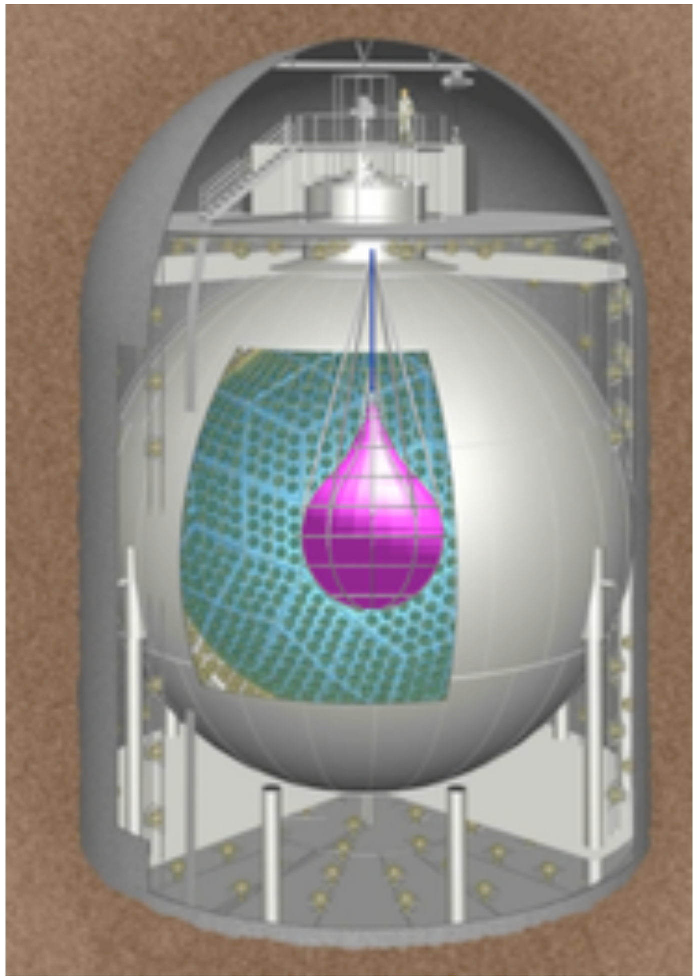

1-D calibration system
3-D calibration system
Veto(OD)
Tyvek
ID
OD PMTs
Buffer
γ-catcher
ID PMTs
Target
Tyvek

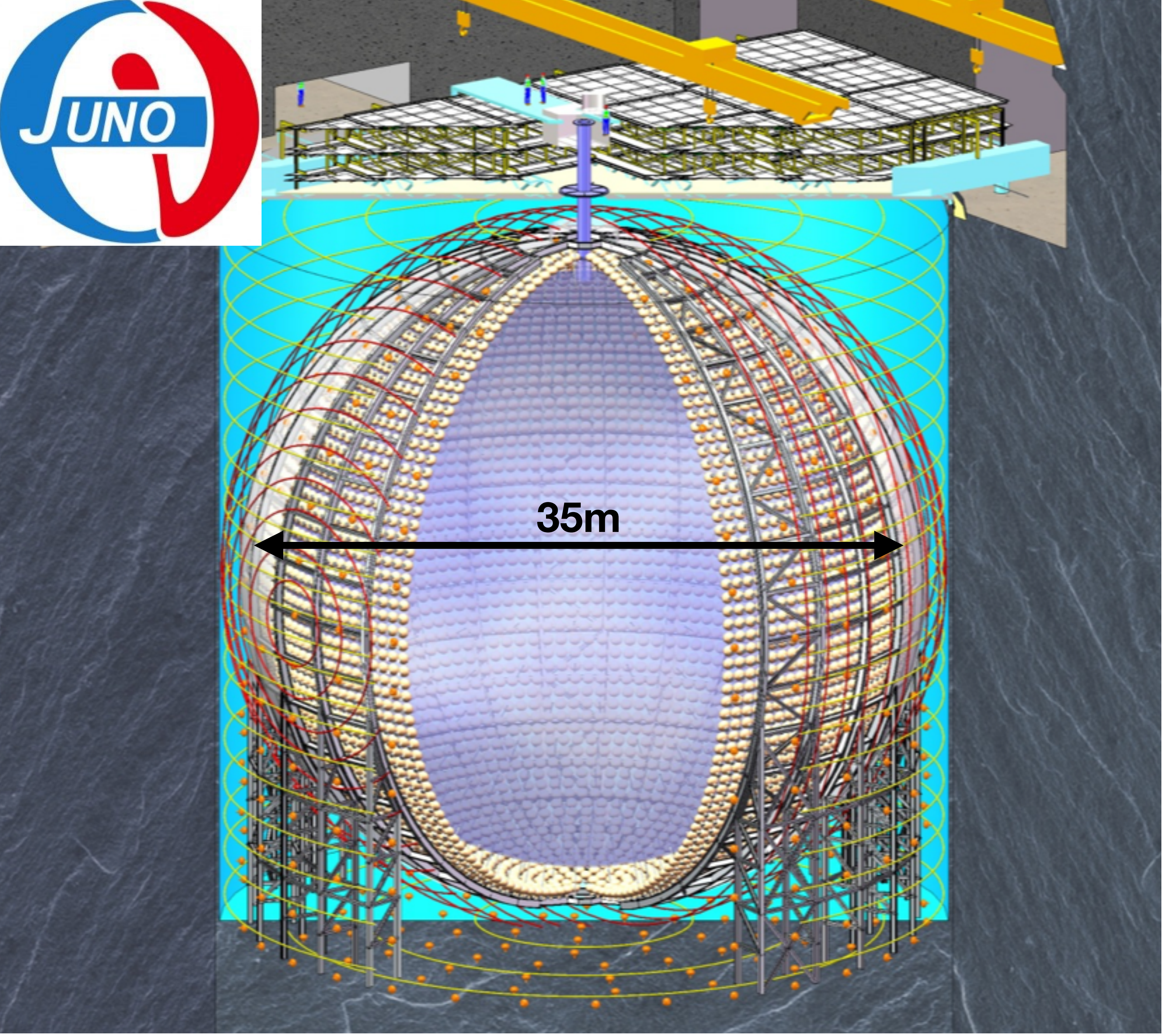

Automated Calibration Units
Overflow tanks
Inner Acrylic Vessel
Calibration tubes
Outer Acrylic Vessel
Reflectors
Photomultipliers
Stainless Steel Vessel
MO
GdLS
LS
LS
MO

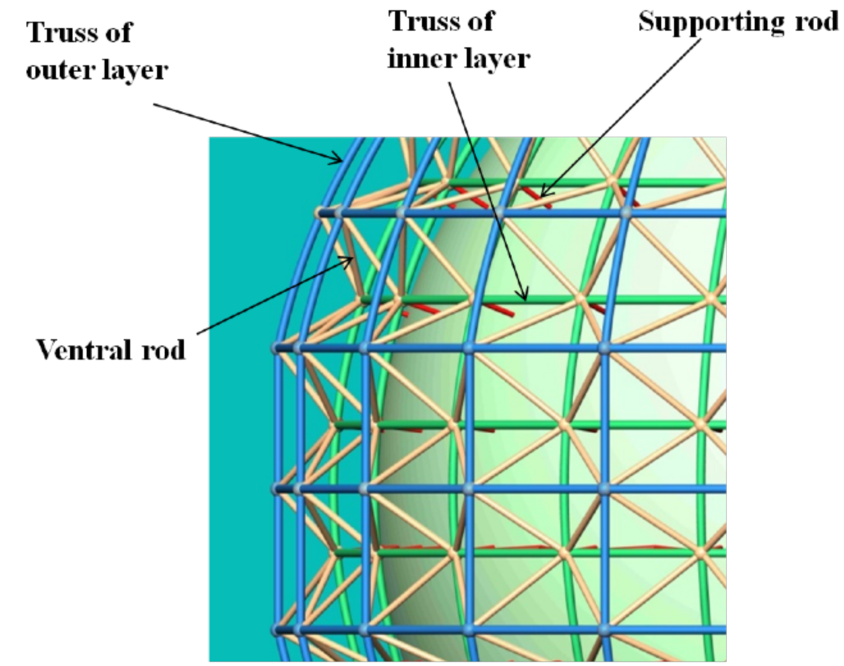

Target
Gamma Catche
Buffer
Inner Veto
Shield

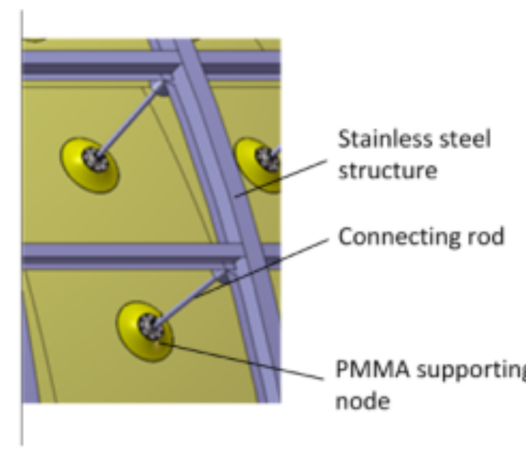

Muon PMTs
Stainless Steel Sphere
Nylon Vessels
Internal PMTs
Water Tank
Scintillator
Non-scintillating Buffer
Muon PMTs

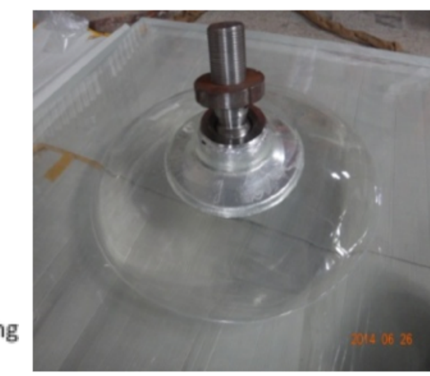




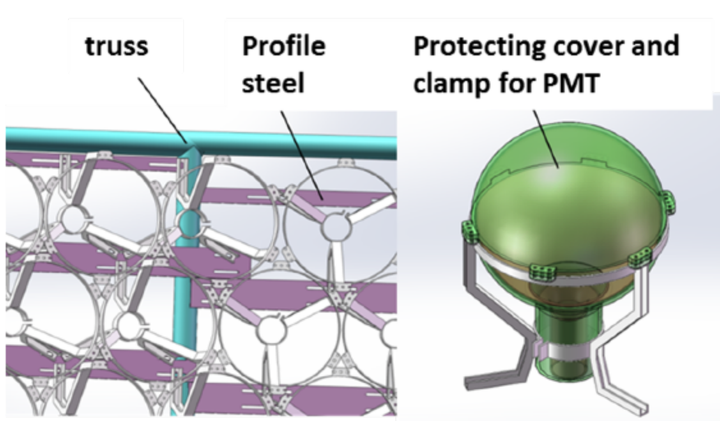


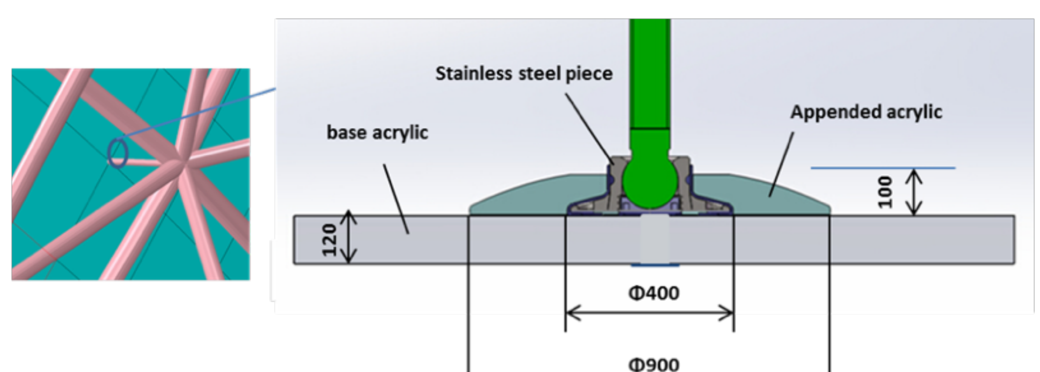






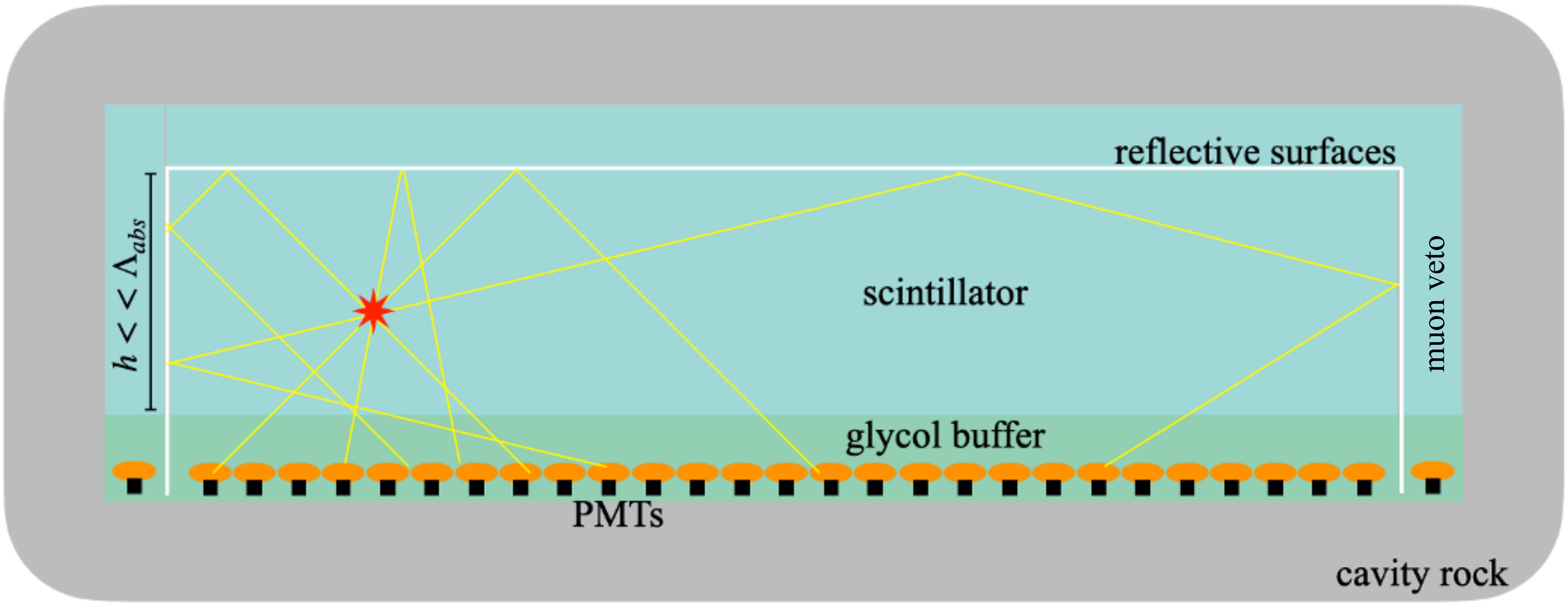
- Complex
- Expensive
- Hard to construct
- Hard to keep clean
- High bkds near edges
- Inner ballon tricky





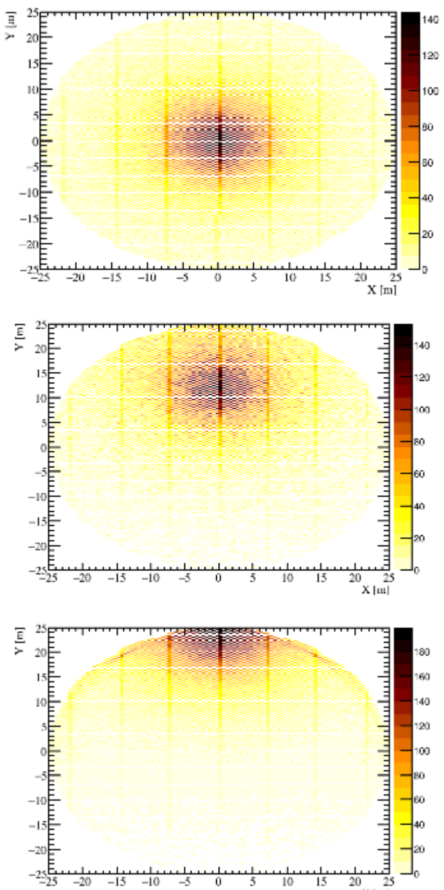
New Design Concept for Large Scale LS Detectors: Stratified Liquid Plane Scintillator (SLiPS)

Morton-Blake and Biller, Physical Review D, 105(7) (2022)

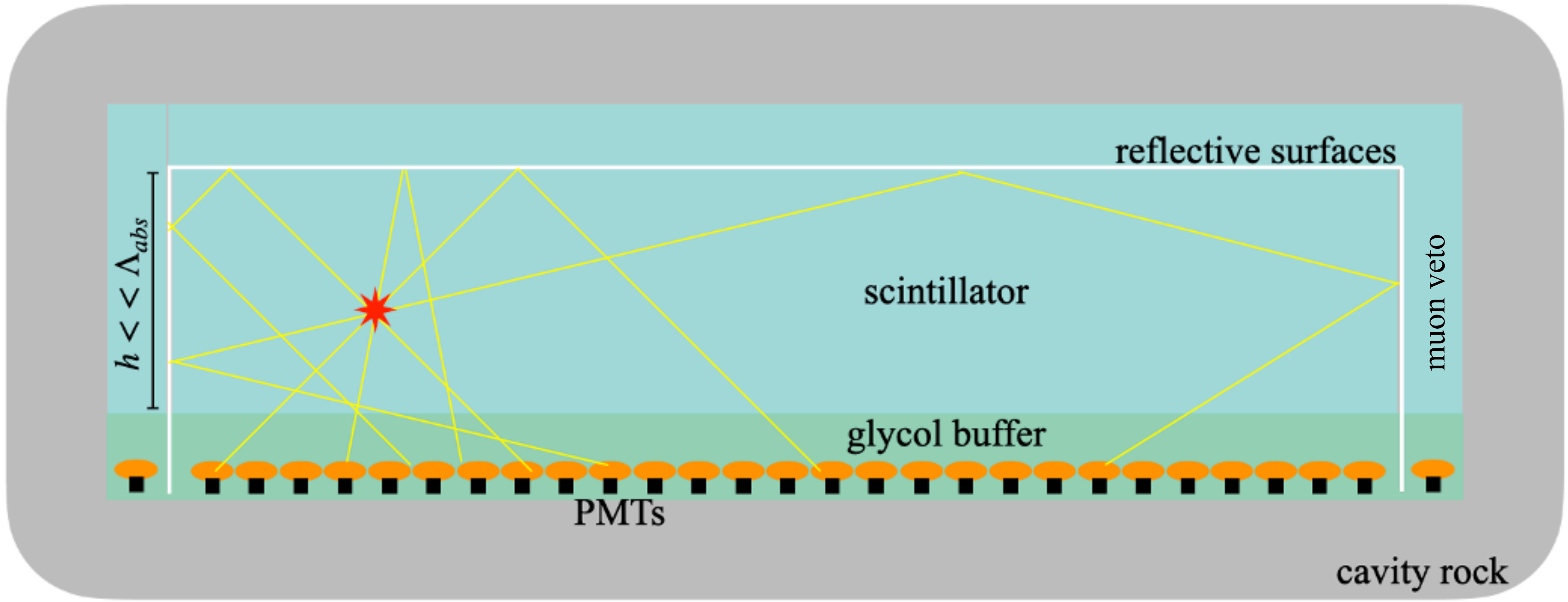


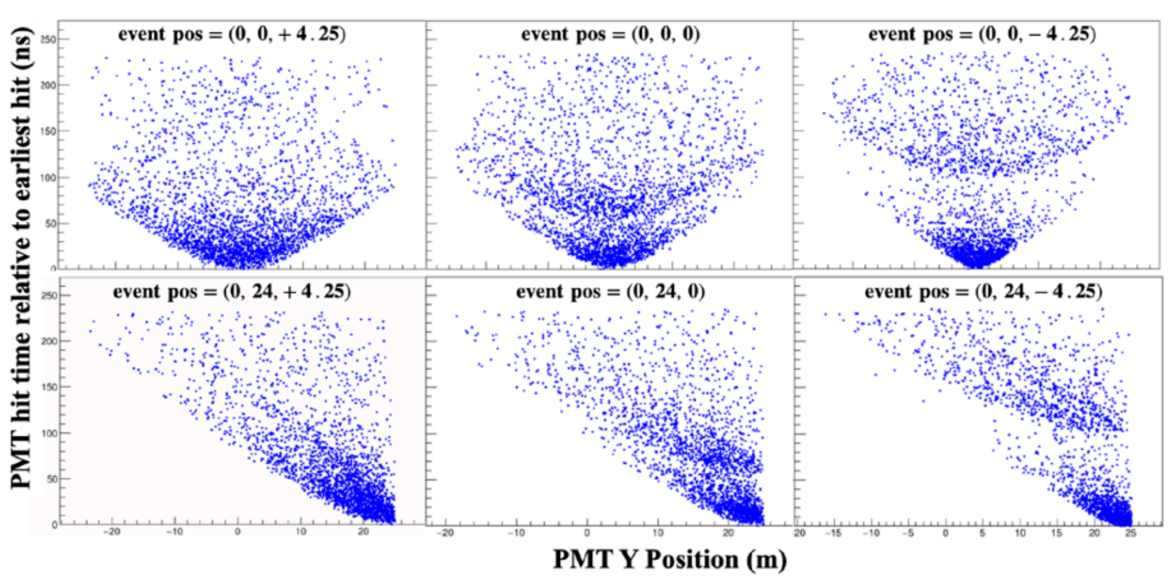
New Design Concept for Large Scale LS Detectors: Stratified Liquid Plane Scintillator (SLiPS)

Morton-Blake and Biller, Physical Review D, 105(7) (2022)

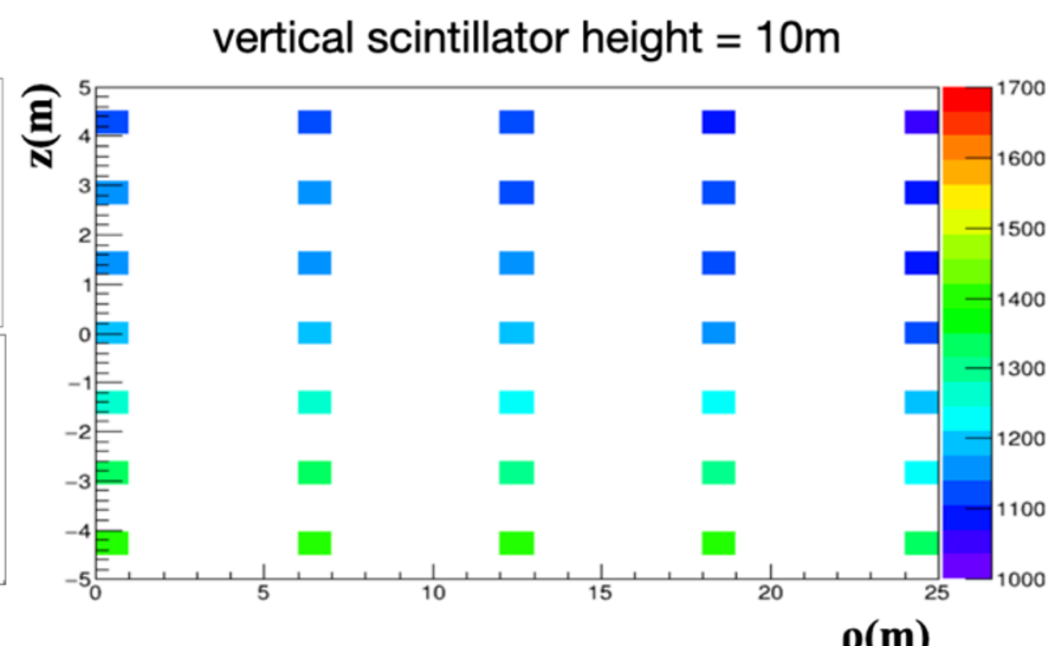


Hit density gives good resolution in X-Y plane

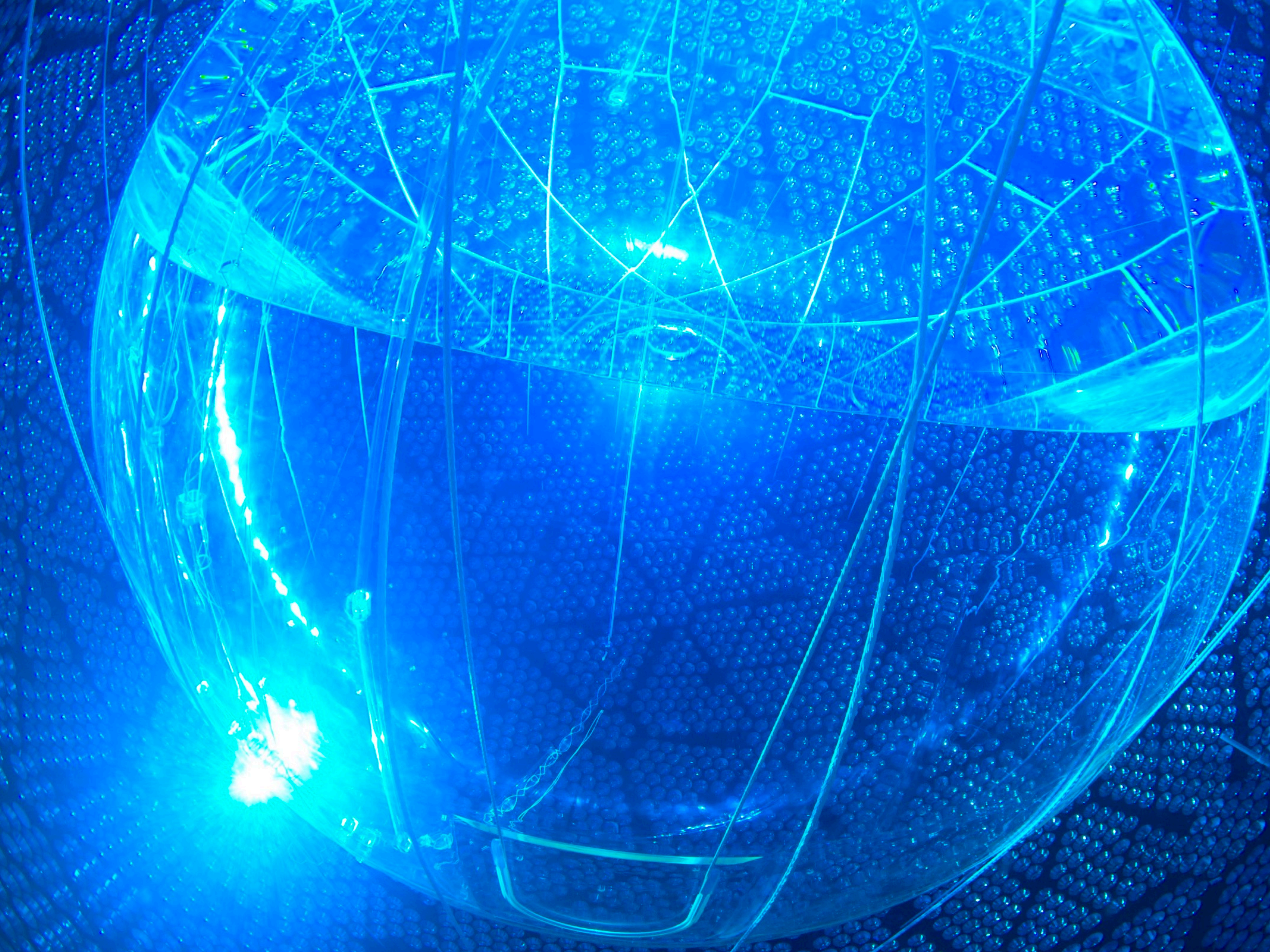




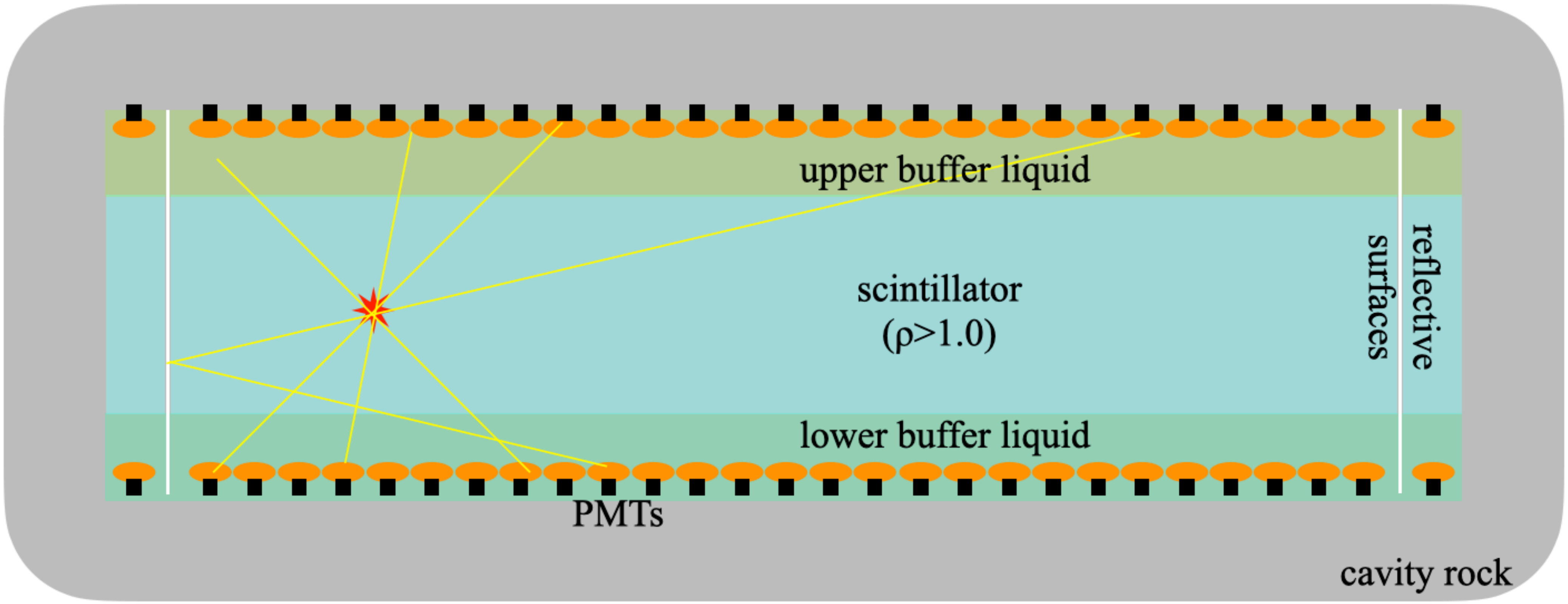
Wavefront timing give good resolution in X plane



Energy response uniform to ±4%



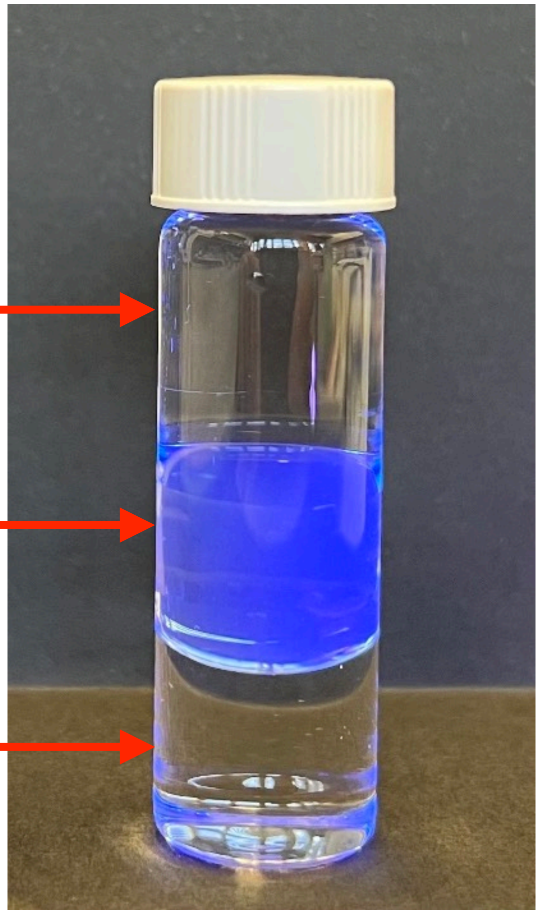
Double-Sided SLiPS



propylene glycol

DPE-based LS (ρ=1.07) under UV illumination

ethylene glycol

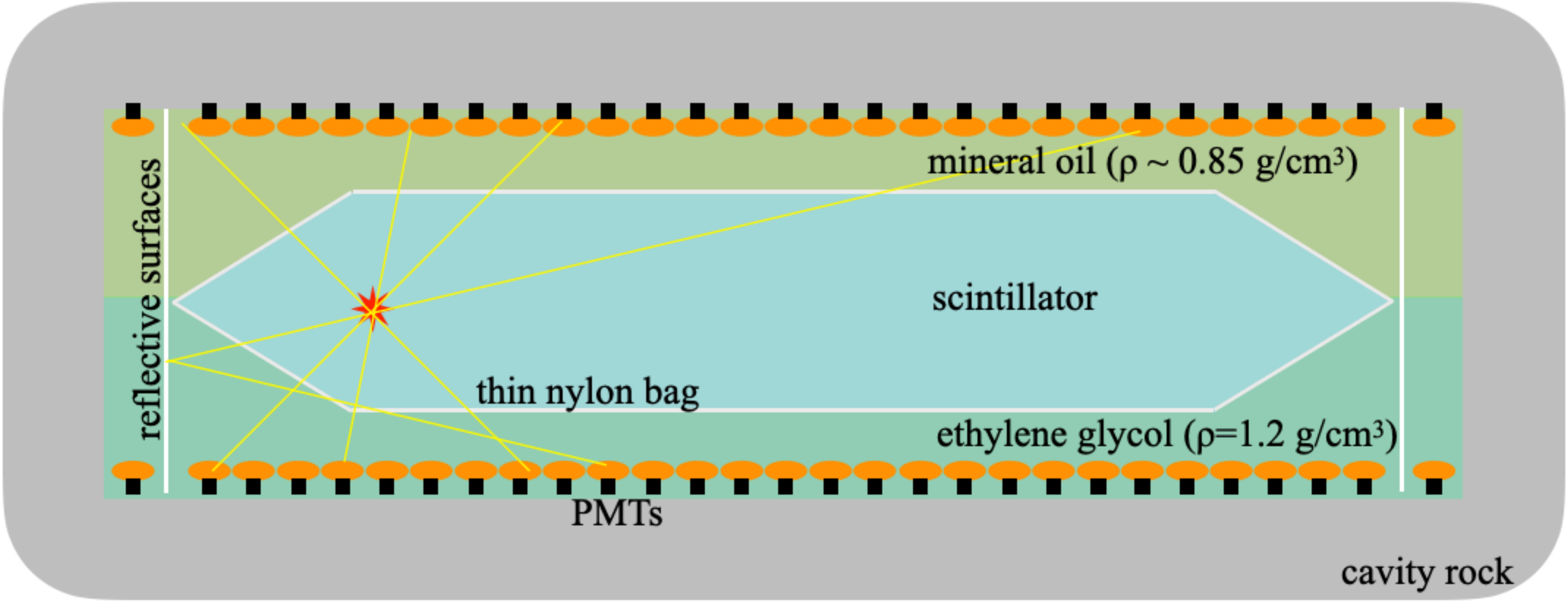


10% Te-loaded DIN: ρ~1.1

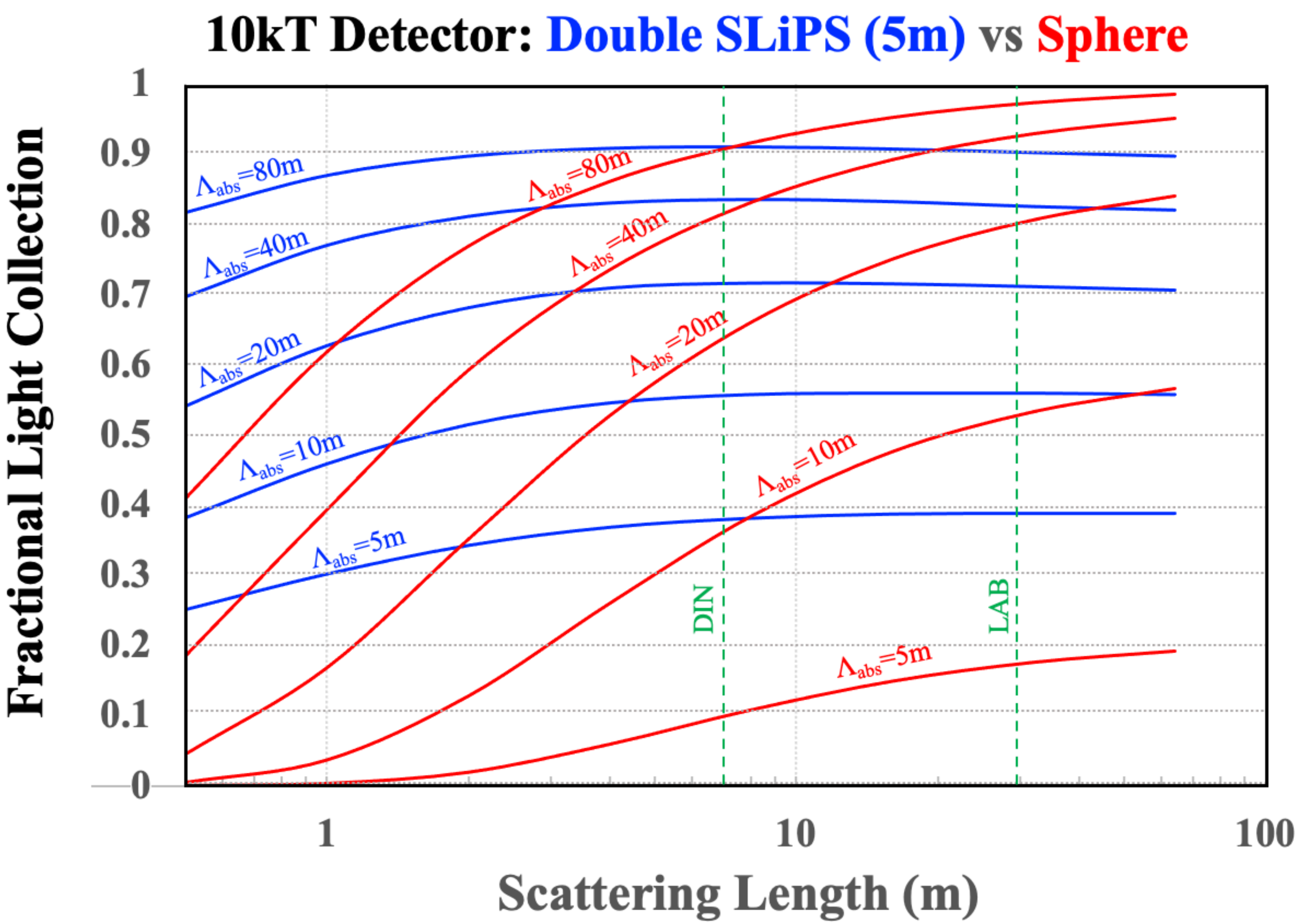
Buffer liquids need to not react and interfere with Te loading at the interfaces!

Employing silicone and fluorinated synthetic oils looks promising… but potentially expensive

Alternative “Semi-SLiPS”



A compressed SLiPS configuration can yield better notably light output than a spherical detector for scintillators with short attenuation and scatter lengths

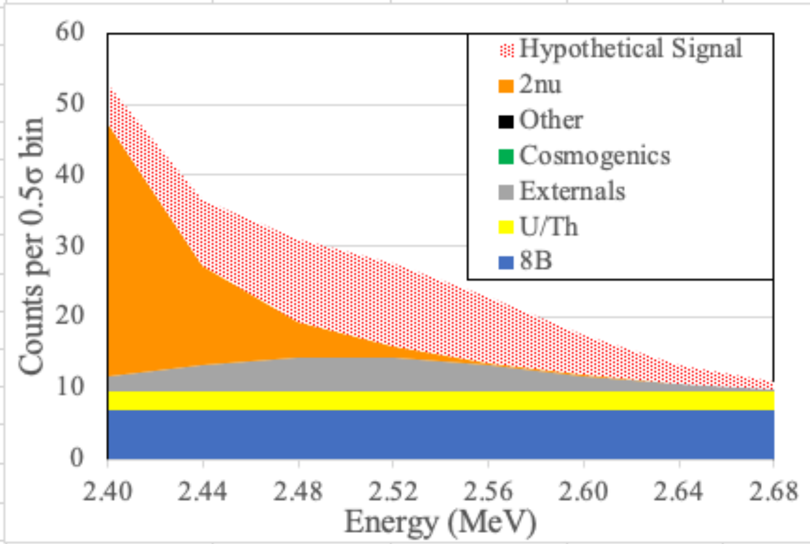


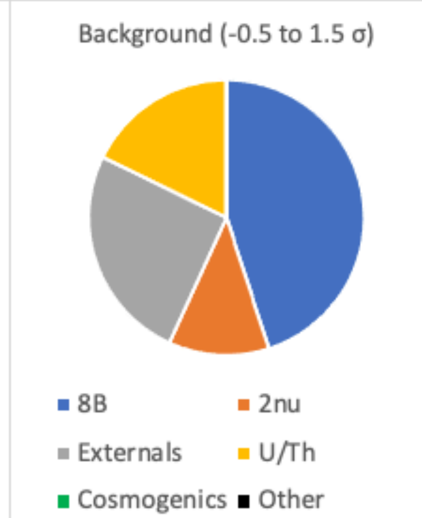
Sensitivity Projections

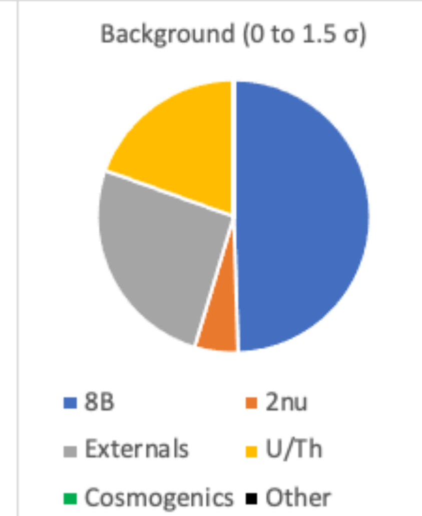
Input Assumptions	
Hits/MeV	400
Loading %	0.5
Fid Radius (m)	4.1
Livetime (yr)	3
Detector Radius (m)	6
Vessel thickness (m)	0.05
Vessel 232Th (g/g)	2.31E-13
Scint density (g/cm^3)	0.87
Scint 238U (g/g)	1.00E-16
Isotope 238U (g/g)	5.18E-12
Bi-Po min tag sep (ns)	4
Cosmo as frac of 8B	0
Other as frac of 8B	0
8B scaling:	1
Scint 238U scaling:	1
Vessel 232Th scaling:	0.5
Isotope 238U scaling:	1
Cosmo scaling:	1
Isotopic fraction:	0.34
A	130
G0v	14.22
Endpoint energy (MeV)	2.5
2nu half-life (yr)	7.70E+20
gA:	1.27

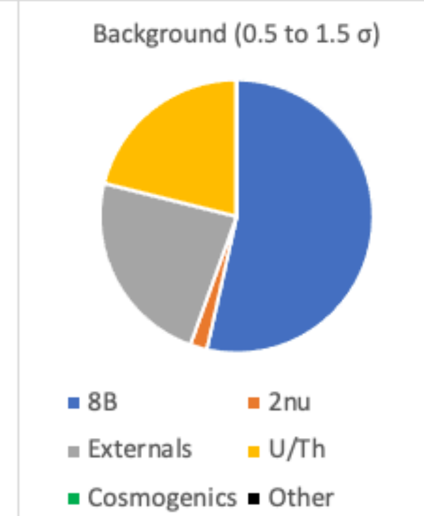
ROI (sigmas):	-2 to -1.5	-1.5 to -1	-1 to -0.5	-0.5 to 0	0 to 0.5	0.5 to 1	1 to 1.5	1.5 to 2	2 to 2.5	Sum(-.5-1.5)	Sum(0-1.5)	Sum(0.5-1.5)
Signal Fraction	0.0440	0.0919	0.1498	0.1915	0.1915	0.1498	0.0919	0.0440	0.0166			
8B	6.85	6.85	6.85	6.85	6.85	6.85	6.85	6.85	6.85	27.40	20.55	13.70
2nu	80.01	35.26	14.08	5.03	1.62	0.42	0.10	0.02	0.00	7.17	2.14	0.51
Externals	1.09	2.28	3.71	4.74	4.74	3.71	2.28	1.09	0.41	15.47	10.73	5.98
U/Th	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.70	10.80	8.10	5.40
Cosmogenics	0	0	0	0	0	0	0	0	0	0.00	0.00	0.00
Other	0	0	0	0	0	0	0	0	0	0.00	0.00	0.00
Background Sum	90.65	47.08	27.34	19.33	15.92	13.68	11.93	10.66	9.97			

Fid Vol (tonnes)	251.1649683
Isotope (tonnes)	0.426980446
Ext 208Tl (unseen e-'s)	1.16E+06
Ext fid solid angle	0.13494673
214Bi decays in fid vol	3.773E+06
Bi-Po tagging inefficiency	2.435E-05









CI:	0.9

RESULTS			CDFT	QRPA-FFS	QRPA-JY	QRPA-Tu	QRPA-NC	IBM2	ISM-Tk	ISM-INFN	GCM
Half-Life Bound:	1.99E+26	M0v:	4.89	2.9	4	3.89	1.37	4.2	2.76	3.26	6.366
TG Sensitivity:	2.83E+12	mββ (meV):	38.53	64.96	47.10	48.43	137.51	44.85	68.26	57.79	29.59

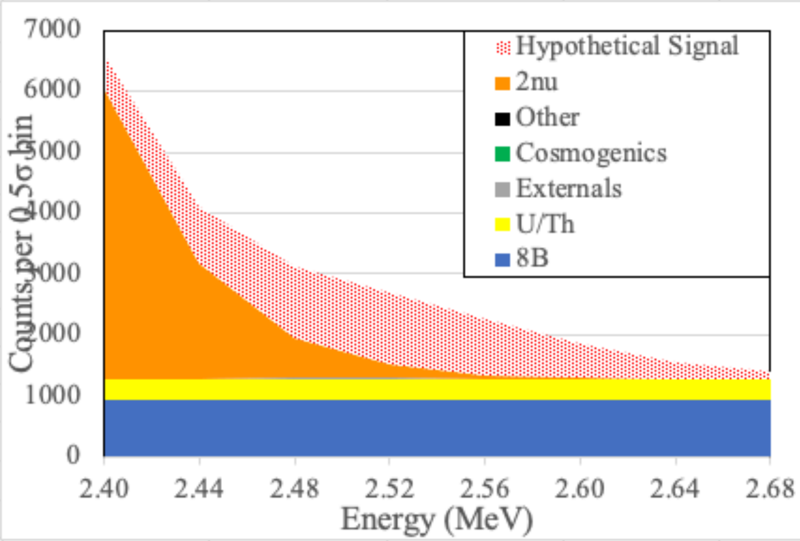
Input Assumptions	
Hits/MeV	400
Loading %	0.5
Fid Radius (m)	13
Livetime (yr)	10
Detector Radius (m)	15
Vessel thickness (m)	0.05
Vessel 232Th (g/g)	2.31E-13
Scint density (g/cm^3)	1.1
Scint 238U (g/g)	1.00E-16
Isotope 238U (g/g)	5.18E-12
Bi-Po min tag sep (ns)	4
Cosmo as frac of 8B	0
Other as frac of 8B	0
8B scaling:	1
Scint 238U scaling:	1
Vessel 232Th scaling:	0.5
Isotope 238U scaling:	1
Cosmo scaling:	1
Isotopic fraction:	0.34
A	130
G0v	14.22
Endpoint energy (MeV)	2.5
2nu half-life (yr)	7.70E+20
gA:	1.27

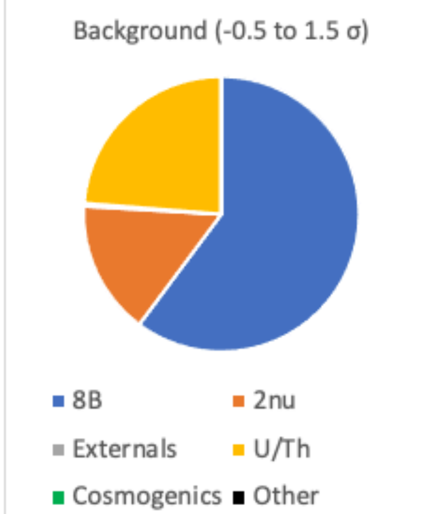
ROI (sigmas):	-2 to -1.5	-1.5 to -1	-1 to -0.5	-0.5 to 0	0 to 0.5	0.5 to 1	1 to 1.5	1.5 to 2	2 to 2.5	Sum(-.5-1.5)	Sum(0-1.5)	Sum(0.5-1.5)
Signal Fraction	0.0440	0.0919	0.1498	0.1915	0.1915	0.1498	0.0919	0.0440	0.0166			
8B	920.34	920.34	920.34	920.34	920.34	920.34	920.34	920.34	920.34	3681.36	2761.02	1840.68
2nu	10748.80	4736.76	1892.20	676.35	217.94	55.79	13.21	2.66	0.45	963.29	286.94	69.00
Externals	1.43	3.00	4.89	6.24	6.24	4.89	3.00	1.43	0.54	20.37	14.13	7.88
U/Th	362.90	362.90	362.90	362.90	362.90	362.90	362.90	362.90	362.90	1451.61	1088.70	725.80
Cosmogenics	0	0	0	0	0	0	0	0	0	0.00	0.00	0.00
Other	0	0	0	0	0	0	0	0	0	0.00	0.00	0.00
Background Sum	12033.48	6023.00	3180.33	1965.84	1507.42	1343.92	1299.45	1287.34	1284.24			

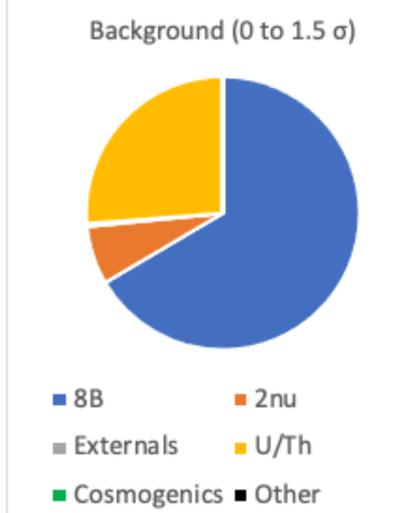
Fid Vol (tonnes)	10123.04074
Isotope (tonnes)	17.20916925

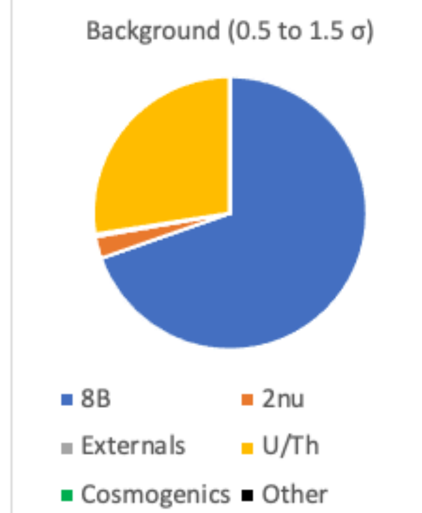
Ext 208Tl (unseen e-'s)	2.40E+07
Ext fid solid angle	0.25055617

214Bi decays in fid vol	5.069E+08
Bi-Po tagging inefficiency	2.435E-05









CI:	0.9

RESULTS	
Half-Life Bound:	2.89E+27
TG Sensitivity:	4.11E+13

	CDFT	QRPA-FFS	QRPA-JY	QRPA-Tu	QRPA-NC	IBM2	ISM-Tk	ISM-INFN	GCM
M0v:	4.89	2.9	4	3.89	1.37	4.2	2.76	3.26	6.366
mββ (meV):	10.11	17.05	12.36	12.71	36.09	11.77	17.91	15.16	7.77

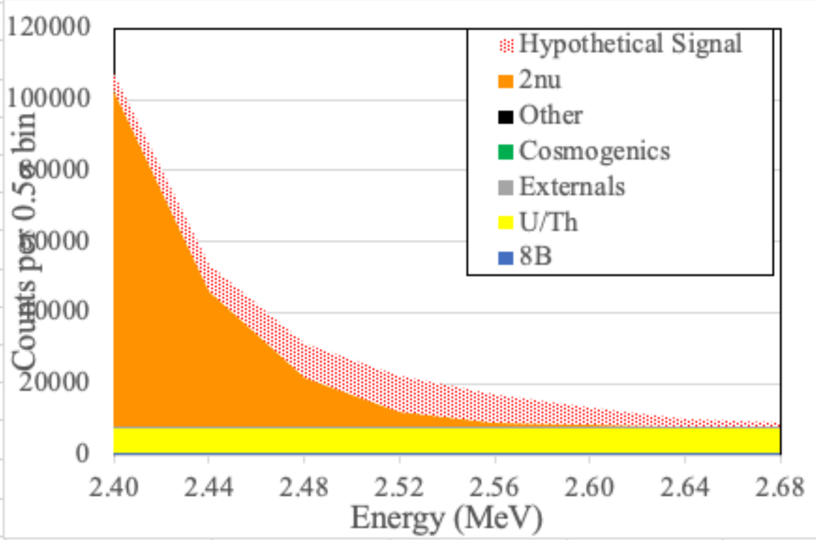
Input Assumptions	
Hits/MeV	400
Loading %	10
Fid Radius (m)	13
Livetime (yr)	10
Detector Radius (m)	15
Vessel thickness (m)	0.05
Vessel 232Th (g/g)	2.31E-13
Scint density (g/cm^3)	1.1
Scint 238U (g/g)	1.00E-16
Isotope 238U (g/g)	5.18E-12
Bi-Po min tag sep (ns)	4
Cosmo as frac of 8B	0
Other as frac of 8B	0
8B scaling:	1
Scint 238U scaling:	1
Vessel 232Th scaling:	0.5
Isotope 238U scaling:	1
Cosmo scaling:	1
Isotopic fraction:	0.34
A	130
G0v	14.22
Endpoint energy (MeV)	2.5
2nu half-life (yr)	7.70E+20
gA:	1.27
CI:	0.9

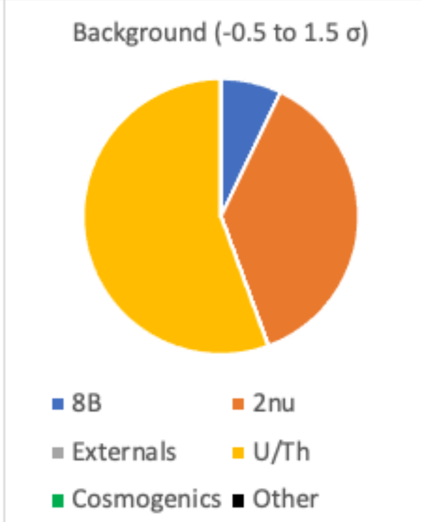
ROI (sigmas):	-2 to -1.5	-1.5 to -1	-1 to -0.5	-0.5 to 0	0 to 0.5	0.5 to 1	1 to 1.5	1.5 to 2	2 to 2.5	Sum(-.5-1.5)	Sum(0-1.5)	Sum(0.5-1.5)
Signal Fraction	0.0440	0.0919	0.1498	0.1915	0.1915	0.1498	0.0919	0.0440	0.0166			
8B	920.34	920.34	920.34	920.34	920.34	920.34	920.34	920.34	920.34	3681.36	2761.02	1840.68
2nu	214976.04	94735.20	37843.98	13527.09	4358.73	1115.87	264.17	53.29	9.06	19265.86	5738.77	1380.04
Externals	1.43	3.00	4.89	6.24	6.24	4.89	3.00	1.43	0.54	20.37	14.13	7.88
U/Th	7180.62	7180.62	7180.62	7180.62	7180.62	7180.62	7180.62	7180.62	7180.62	28722.48	21541.86	14361.24
Cosmogenics	0	0	0	0	0	0	0	0	0	0.00	0.00	0.00
Other	0	0	0	0	0	0	0	0	0	0.00	0.00	0.00
Background Sum	223078.43	102839.16	45949.83	21634.30	12465.94	9221.72	8368.12	8155.69	8110.57			

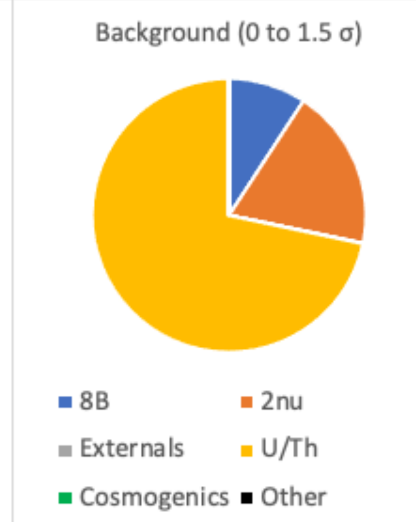
Fid Vol (tonnes)	10123.04074
Isotope (tonnes)	344.1833851

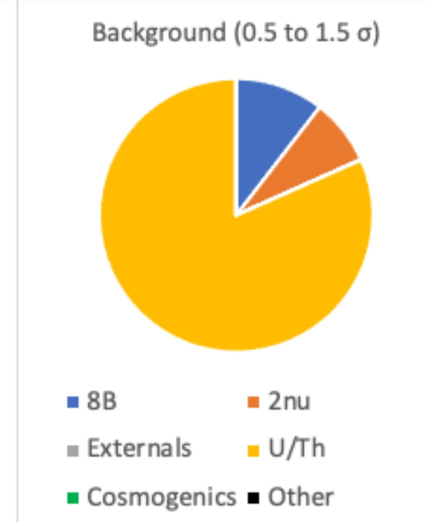
Ext 208Tl (unseen e-'s)	2.40E+07
Ext fid solid angle	0.25055617

214Bi decays in fid vol	1.003E+10
Bi-Po tagging inefficiency	2.435E-05









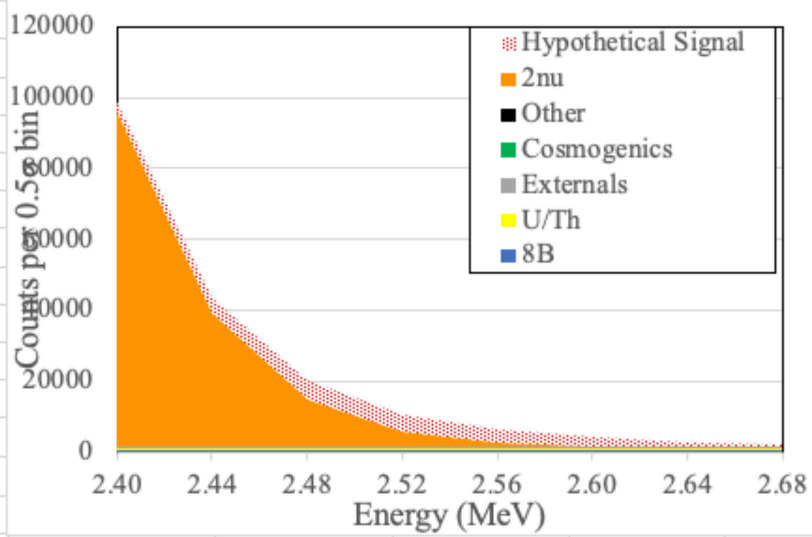
RESULTS	
Half-Life Bound:	1.98E+28
TG Sensitivity:	2.82E+14

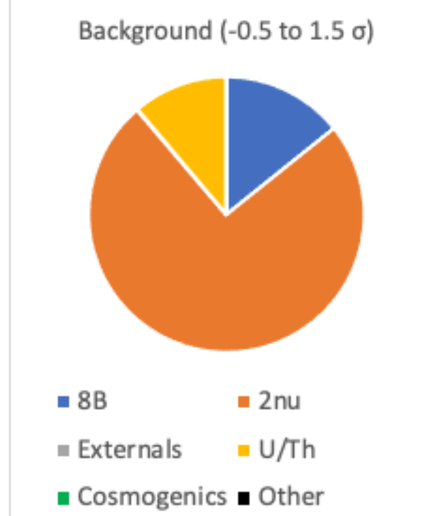
	CDFT	QRPA-FFS	QRPA-JY	QRPA-Tu	QRPA-NC	IBM2	ISM-Tk	ISM-INFN	GCM
M0v:	4.89	2.9	4	3.89	1.37	4.2	2.76	3.26	6.366
mββ (meV):	3.86	6.51	4.72	4.85	13.78	4.50	6.84	5.79	2.97

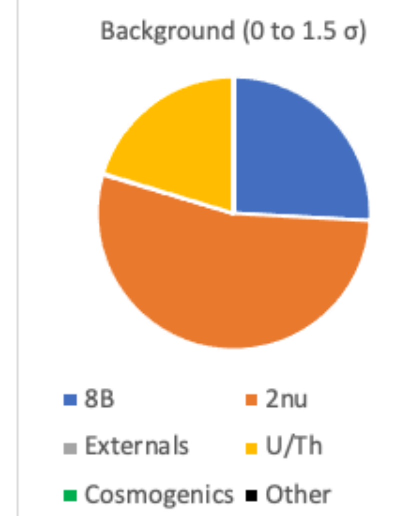
Input Assumptions	
Hits/MeV	400
Loading %	10
Fid Radius (m)	13
Livetime (yr)	10
Detector Radius (m)	15
Vessel thickness (m)	0.05
Vessel 232Th (g/g)	2.31E-13
Scint density (g/cm^3)	1.1
Scint 238U (g/g)	1.00E-16
Isotope 238U (g/g)	5.18E-12
Bi-Po min tag sep (ns)	4
Cosmo as frac of 8B	0
Other as frac of 8B	0
8B scaling:	1
Scint 238U scaling:	1
Vessel 232Th scaling:	0.5
Isotope 238U scaling:	0.1
Cosmo scaling:	1
Isotopic fraction:	0.34
A	130
G0v	14.22
Endpoint energy (MeV)	2.5
2nu half-life (yr)	7.70E+20
gA:	1.27

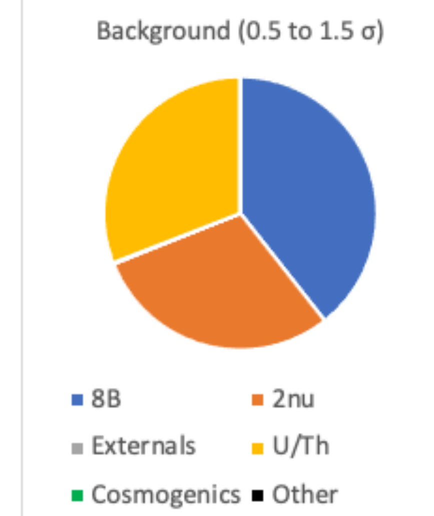
CI:	0.9

ROI (sigmas):	-2 to -1.5	-1.5 to -1	-1 to -0.5	-0.5 to 0	0 to 0.5	0.5 to 1	1 to 1.5	1.5 to 2	2 to 2.5	Sum(-.5-1.5)	Sum(0-1.5)	Sum(0.5-1.5)
Signal Fraction	0.0440	0.0919	0.1498	0.1915	0.1915	0.1498	0.0919	0.0440	0.0166			
8B	920.34	920.34	920.34	920.34	920.34	920.34	920.34	920.34	920.34	3681.36	2761.02	1840.68
2nu	214976.04	94735.20	37843.98	13527.09	4358.73	1115.87	264.17	53.29	9.06	19265.86	5738.77	1380.04
Externals	1.43	3.00	4.89	6.24	6.24	4.89	3.00	1.43	0.54	20.37	14.13	7.88
U/Th	721.73	721.73	721.73	721.73	721.73	721.73	721.73	721.73	721.73	2886.91	2165.19	1443.46
Cosmogenics	0	0	0	0	0	0	0	0	0	0.00	0.00	0.00
Other	0	0	0	0	0	0	0	0	0	0.00	0.00	0.00
Background Sum	216619.54	96380.27	39490.94	15175.41	6007.05	2762.83	1909.23	1696.79	1651.67			
Fid Vol (tonnes)	10123.04074			Ext 208Tl (unseen e-'s)		2.40E+07				214Bi decays in fid vol		1.008E+09
Isotope (tonnes)	344.1833851			Ext fid solid angle		0.25055617				Bi-Po tagging inefficiency		2.435E-05









RESULTS			CDFT	QRPA-FFS	QRPA-JY	QRPA-Tu	QRPA-NC	IBM2	ISM-Tk	ISM-INFN	GCM
Half-Life Bound:	3.15E+28	M0v:	4.89	2.9	4	3.89	1.37	4.2	2.76	3.26	6.366
TG Sensitivity:	4.48E+14	mββ (meV):	3.06	5.16	3.74	3.85	10.93	3.56	5.42	4.59	2.35

400 x (30/12) x (85/45) x (35/70) x (0.55)

SNO+	upgrade to HQE PMTs	improved coverage	scintillator light yield	Λ_{abs}=10m double-SLiPS

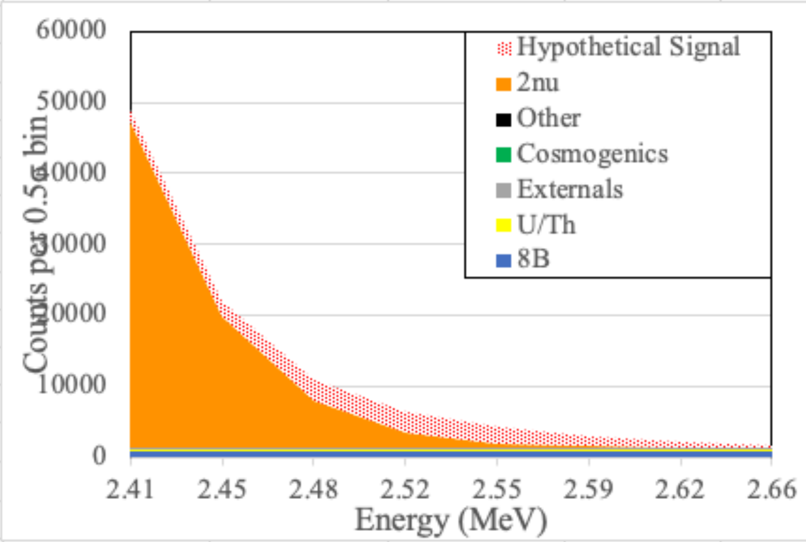
Input Assumptions	
Hits/MeV	520
Loading %	10
Fid Radius (m)	13
Livetime (yr)	10
Detector Radius (m)	15
Vessel thickness (m)	0.05
Vessel 232Th (g/g)	2.31E-13
Scint density (g/cm^3)	1.1
Scint 238U (g/g)	1.00E-16
Isotope 238U (g/g)	5.18E-12
Bi-Po min tag sep (ns)	4
Cosmo as frac of 8B	0
Other as frac of 8B	0
8B scaling:	1
Scint 238U scaling:	1
Vessel 232Th scaling:	0.5
Isotope 238U scaling:	0.1
Cosmo scaling:	1
Isotopic fraction:	0.34
A	130
G0v	14.22
Endpoint energy (MeV)	2.5
2nu half-life (yr)	7.70E+20
gA:	1.27

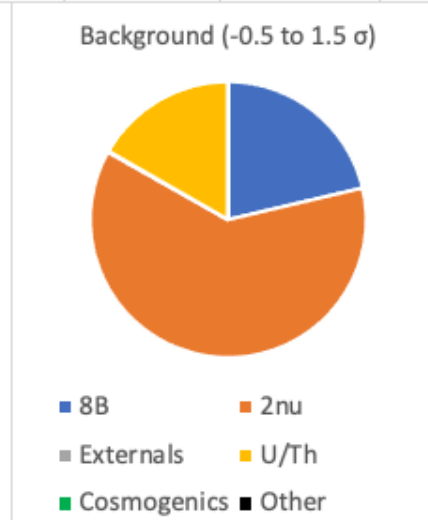
ROI (sigmas):	-2 to -1.5	-1.5 to -1	-1 to -0.5	-0.5 to 0	0 to 0.5	0.5 to 1	1 to 1.5	1.5 to 2	2 to 2.5	Sum(-.5-1.5)	Sum(0-1.5)	Sum(0.5-1.5)
Signal Fraction	0.0440	0.0919	0.1498	0.1915	0.1915	0.1498	0.0919	0.0440	0.0166			
8B	807.19	807.19	807.19	807.19	807.19	807.19	807.19	807.19	807.19	3228.77	2421.58	1614.39
2nu	104483.05	46043.38	18393.00	6574.46	2118.44	542.34	128.39	25.90	4.41	9363.63	2789.17	670.73
Externals	1.43	3.00	4.89	6.24	6.24	4.89	3.00	1.43	0.54	20.37	14.13	7.88
U/Th	633.00	633.00	633.00	633.00	633.00	633.00	633.00	633.00	633.00	2531.99	1898.99	1266.00
Cosmogenics	0	0	0	0	0	0	0	0	0	0.00	0.00	0.00
Other	0	0	0	0	0	0	0	0	0	0.00	0.00	0.00
Background Sum	105924.67	47486.56	19838.08	8020.90	3564.87	1987.41	1571.58	1467.52	1445.14			

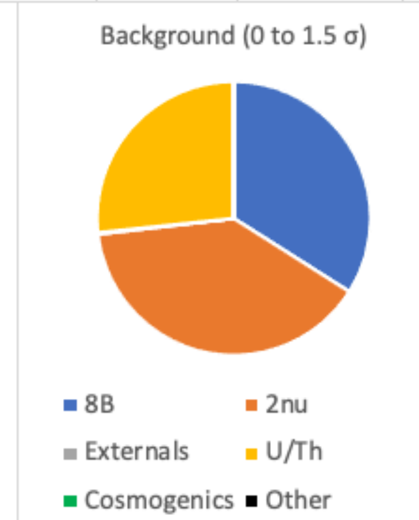
Fid Vol (tonnes)	10123.04074
Isotope (tonnes)	344.1833851

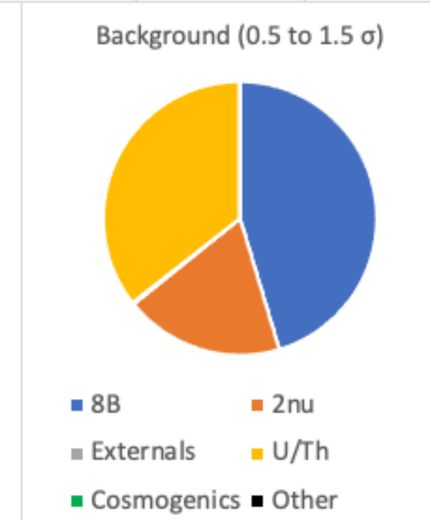
Ext 208Tl (unseen e-'s)	2.40E+07
Ext fid solid angle	0.25055617

214Bi decays in fid vol	1.008E+09
Bi-Po tagging inefficiency	2.435E-05









CI:	0.9

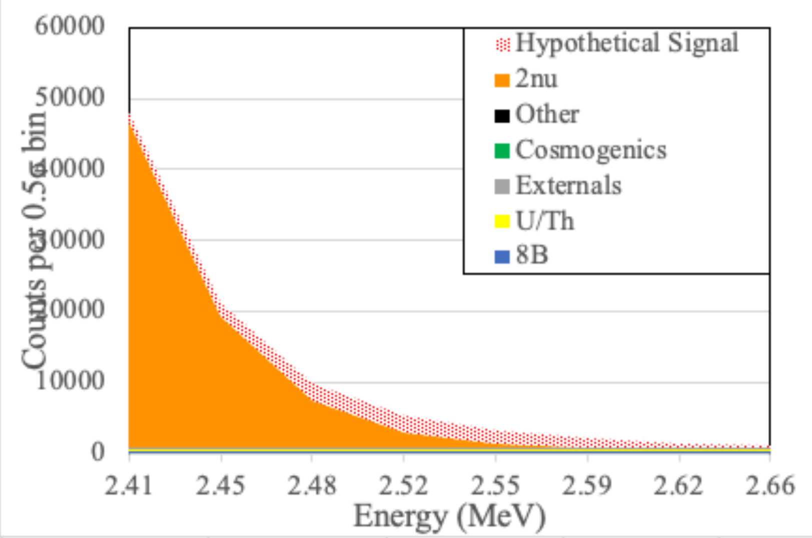
RESULTS	
Half-Life Bound:	3.89E+28
TG Sensitivity:	5.54E+14

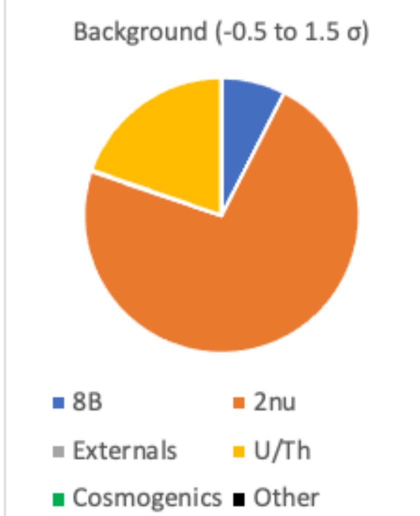
	CDFT	QRPA-FFS	QRPA-JY	QRPA-Tu	QRPA-NC	IBM2	ISM-Tk	ISM-INFN	GCM
M0v:	4.89	2.9	4	3.89	1.37	4.2	2.76	3.26	6.366
mββ (meV):	2.75	4.64	3.37	3.46	9.83	3.21	4.88	4.13	2.11

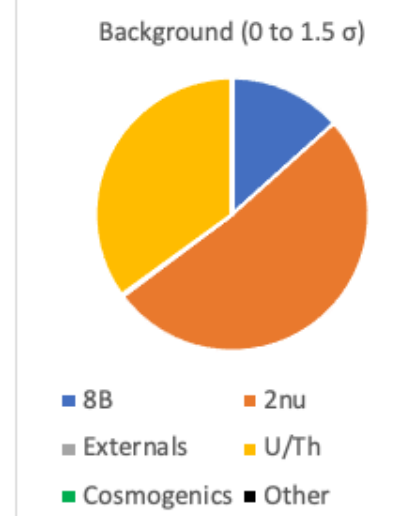
Input Assumptions	
Hits/MeV	520
Loading %	10
Fid Radius (m)	13
Livetime (yr)	10
Detector Radius (m)	15
Vessel thickness (m)	0.05
Vessel 232Th (g/g)	2.31E-13
Scint density (g/cm^3)	1.1
Scint 238U (g/g)	1.00E-16
Isotope 238U (g/g)	5.18E-12
Bi-Po min tag sep (ns)	4
Cosmo as frac of 8B	0
Other as frac of 8B	0
8B scaling:	0.3
Scint 238U scaling:	1
Vessel 232Th scaling:	0.5
Isotope 238U scaling:	0.1
Cosmo scaling:	1
Isotopic fraction:	0.34
A	130
G0v	14.22
Endpoint energy (MeV)	2.5
2nu half-life (yr)	7.70E+20
gA:	1.27
CI:	0.9

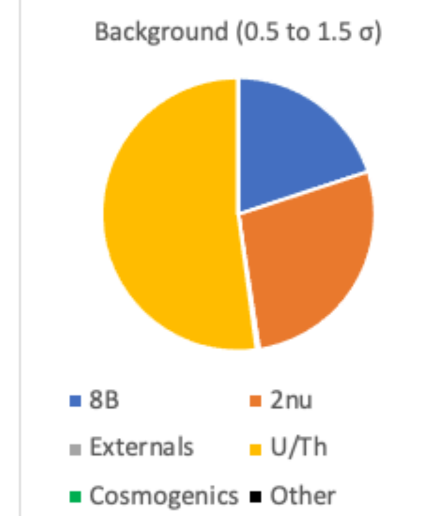
ROI (sigmas):	-2 to -1.5	-1.5 to -1	-1 to -0.5	-0.5 to 0	0 to 0.5	0.5 to 1	1 to 1.5	1.5 to 2	2 to 2.5	Sum(-.5-1.5)	Sum(0-1.5)	Sum(0.5-1.5)
Signal Fraction	0.0440	0.0919	0.1498	0.1915	0.1915	0.1498	0.0919	0.0440	0.0166			
8B	242.16	242.16	242.16	242.16	242.16	242.16	242.16	242.16	242.16	968.63	726.47	484.32
2nu	104483.05	46043.38	18393.00	6574.46	2118.44	542.34	128.39	25.90	4.41	9363.63	2789.17	670.73
Externals	1.43	3.00	4.89	6.24	6.24	4.89	3.00	1.43	0.54	20.37	14.13	7.88
U/Th	633.00	633.00	633.00	633.00	633.00	633.00	633.00	633.00	633.00	2531.99	1898.99	1266.00
Cosmogenics	0	0	0	0	0	0	0	0	0	0.00	0.00	0.00
Other	0	0	0	0	0	0	0	0	0	0.00	0.00	0.00
Background Sum	105359.64	46921.53	19273.04	7455.86	2999.84	1422.38	1006.54	902.49	880.10			

Fid Vol (tonnes)	10123.04074	Ext 208Tl (unseen e-'s)	2.40E+07
Isotope (tonnes)	344.1833851	Ext fid solid angle	0.25055617
214Bi decays in fid vol	1.008E+09	Bi-Po tagging inefficiency	2.435E-05









RESULTS			CDFT	QRPA-FFS	QRPA-JY	QRPA-Tu	QRPA-NC	IBM2	ISM-Tk	ISM-INFN	GCM
Half-Life Bound:	4.44E+28	M0v:	4.89	2.9	4	3.89	1.37	4.2	2.76	3.26	6.366
TG Sensitivity:	6.32E+14	mββ (meV):	2.58	4.35	3.15	3.24	9.20	3.00	4.57	3.87	1.98

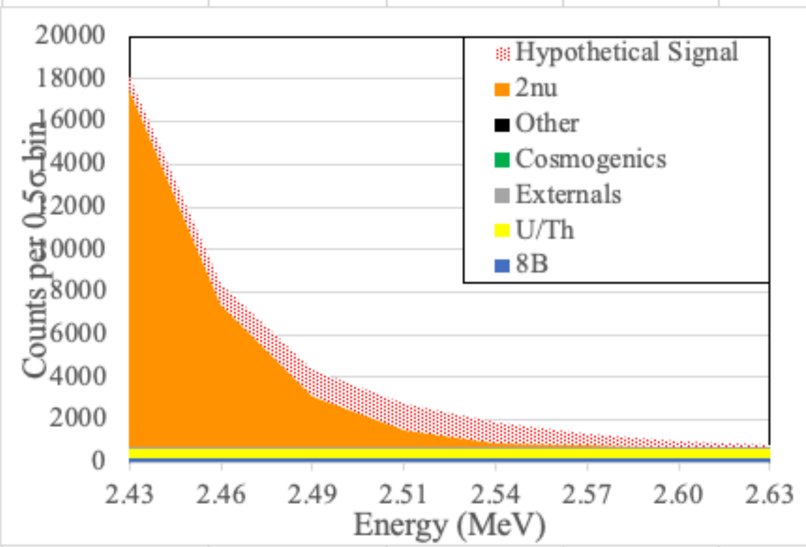
400 x (30/12) x (85/45) x (35/70) x (0.8)

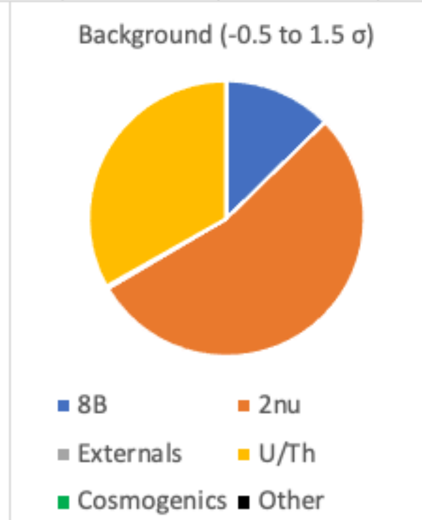
SNO+	upgrade to HQE PMTs	improved coverage	scintillator light yield	Λ_{abs}=40m (sphere or SLiPS)

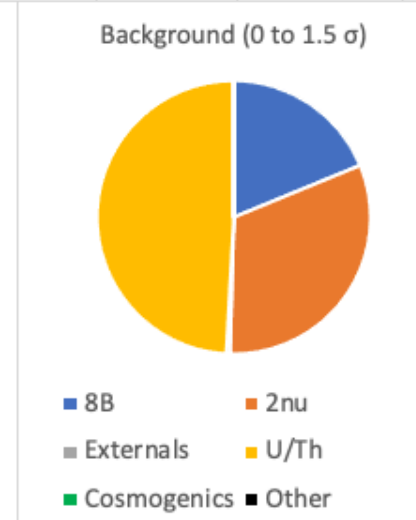
Input Assumptions	
Hits/MeV	750
Loading %	10
Fid Radius (m)	13
Livetime (yr)	10
Detector Radius (m)	15
Vessel thickness (m)	0.05
Vessel 232Th (g/g)	2.31E-13
Scint density (g/cm^3)	1.1
Scint 238U (g/g)	1.00E-16
Isotope 238U (g/g)	5.18E-12
Bi-Po min tag sep (ns)	4
Cosmo as frac of 8B	0
Other as frac of 8B	0
8B scaling:	0.3
Scint 238U scaling:	1
Vessel 232Th scaling:	0.5
Isotope 238U scaling:	0.1
Cosmo scaling:	1
Isotopic fraction:	0.34
A	130
G0v	14.22
Endpoint energy (MeV)	2.5
2nu half-life (yr)	7.70E+20
gA:	1.27
CI:	0.9

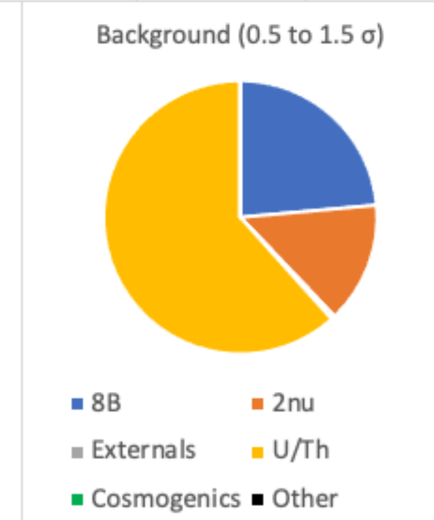
ROI (sigmas):	-2 to -1.5	-1.5 to -1	-1 to -0.5	-0.5 to 0	0 to 0.5	0.5 to 1	1 to 1.5	1.5 to 2	2 to 2.5	Sum(-.5-1.5)	Sum(0-1.5)	Sum(0.5-1.5)
Signal Fraction	0.0440	0.0919	0.1498	0.1915	0.1915	0.1498	0.0919	0.0440	0.0166			
8B	201.64	201.64	201.64	201.64	201.64	201.64	201.64	201.64	201.64	806.55	604.91	403.27
2nu	38162.48	16817.36	6718.05	2401.33	773.76	198.09	46.89	9.46	1.61	3420.07	1018.74	244.98
Externals	1.43	3.00	4.89	6.24	6.24	4.89	3.00	1.43	0.54	20.37	14.13	7.88
U/Th	527.08	527.08	527.08	527.08	527.08	527.08	527.08	527.08	527.08	2108.30	1581.23	1054.15
Cosmogenics	0	0	0	0	0	0	0	0	0	0.00	0.00	0.00
Other	0	0	0	0	0	0	0	0	0	0.00	0.00	0.00
Background Sum	38892.62	17549.07	7451.65	3136.28	1508.72	931.69	778.60	739.61	730.86			

Fid Vol (tonnes)	10123.04074
Isotope (tonnes)	344.1833851
Ext 208Tl (unseen e-'s)	2.40E+07
Ext fid solid angle	0.25055617
214Bi decays in fid vol	1.008E+09
Bi-Po tagging inefficiency	2.435E-05

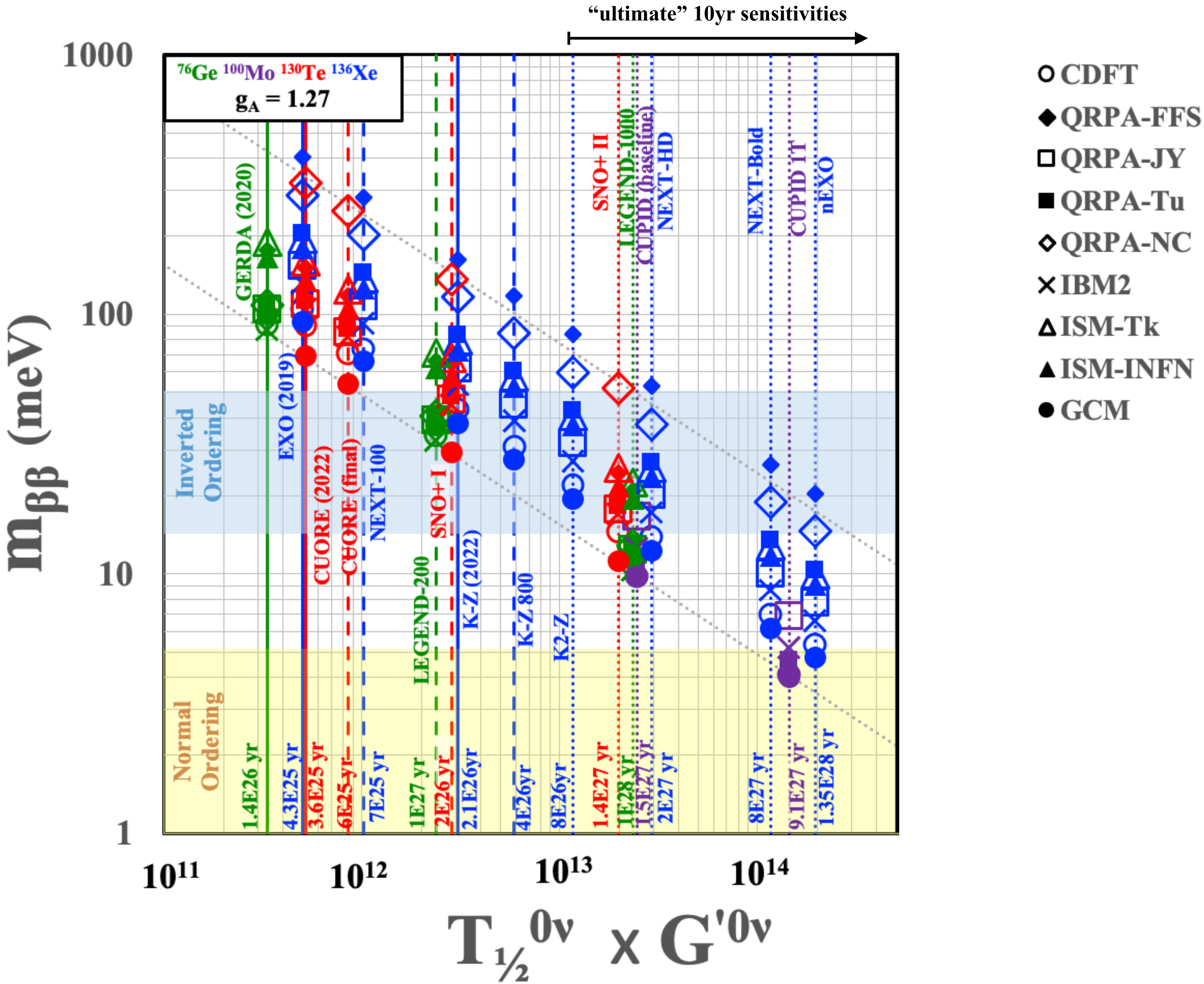




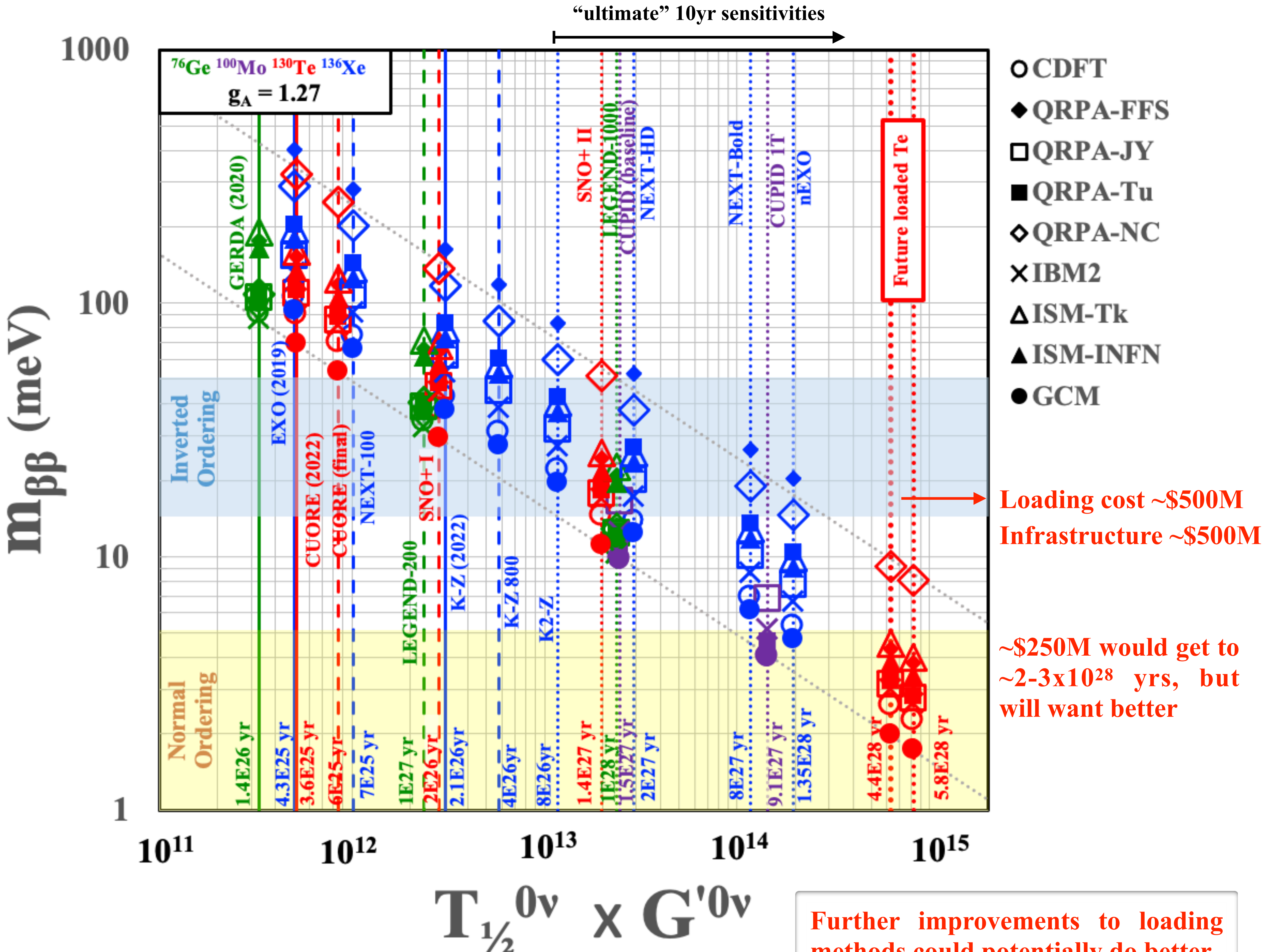




RESULTS			CDFT	QRPA-FFS	QRPA-JY	QRPA-Tu	QRPA-NC	IBM2	ISM-Tk	ISM-INFN	GCM
Half-Life Bound:	5.82E+28	M0v:	4.89	2.9	4	3.89	1.37	4.2	2.76	3.26	6.366
TG Sensitivity:	8.27E+14	mββ (meV):	2.25	3.80	2.75	2.83	8.04	2.62	3.99	3.38	1.73



"ultimate" 10yr sensitivities
76Ge 100Mo 130Te 136Xe
gA = 1.27
CDFT
QRPA-FFS
QRPA-JY
QRPA-Tu
QRPA-NC
IBM2
ISM-Tk
ISM-INFN
GCM
Inverted Ordering
Normal Ordering
GERDA (2020)
EXO (2019)
CUORE (2022)
CUORE (final)
NEXT-100
LEGEND-200
SNO+ I
K-Z (2022)
K-Z 800
K2-Z
SNO+ II
LEGEND-1000
CUPID (baseline)
NEXT-HD
NEXT-Bold
CUPID 1T
nEXO
1.4E26 yr
4.3E25 yr
3.6E25 yr
6E25 yr
7E25 yr
1E27 yr
2E26 yr
2.1E26yr
4E26yr
8E26yr
1.4E27 yr
1E28 yr
1.5E27 yr
2E27 yr
8E27 yr
9.1E27 yr
1.35E28 yr
1000
100
10
1
10^11
10^12
10^13
10^14
mββ (meV)
T½^0ν x G'^0ν



Further improvements to loading methods could potentially do better