Water Phase Results and $0\nu\beta\beta$ Prospects of the SNO+ Experiment

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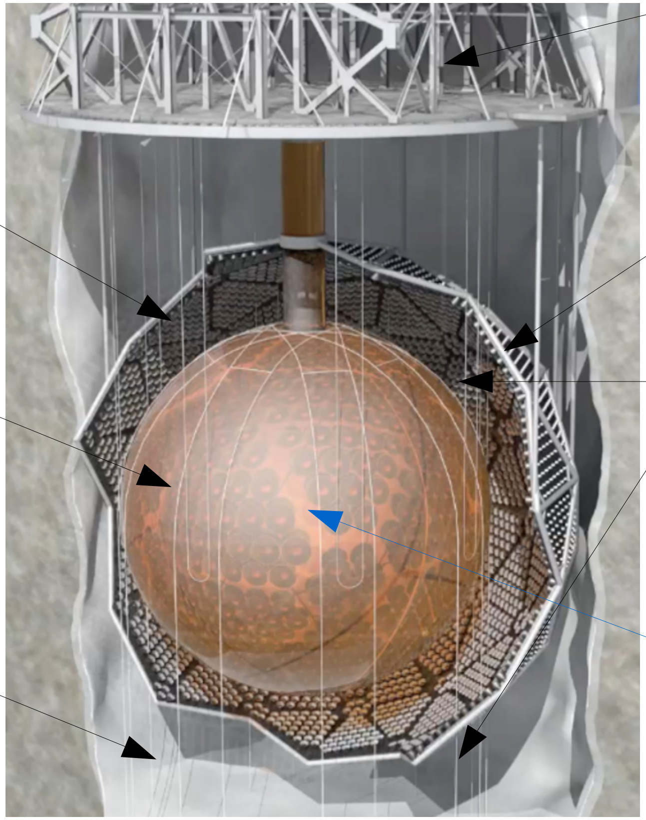
SNO+

SNO+

Multipurpose neutrino detector in Sudbury, Canada



~9300 PMTs

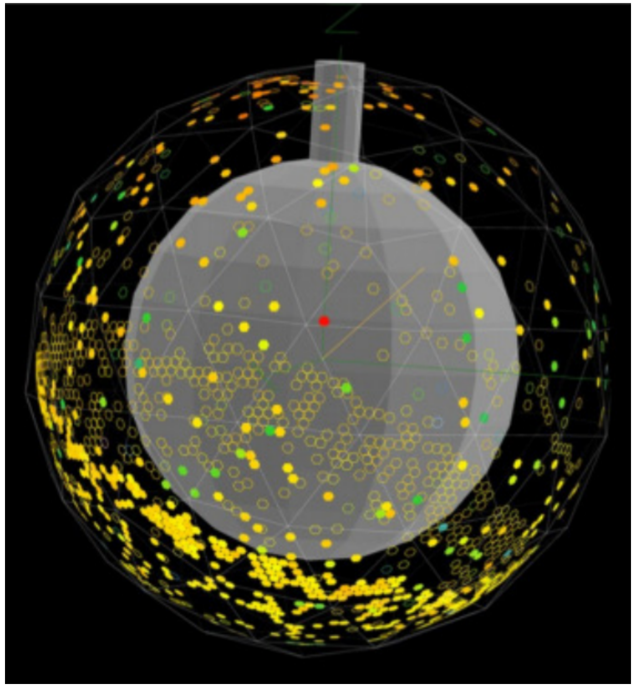
Acrylic vessel
12 m diameter

7 kt ultra pure
water shielding

2070 m of rock overburden

PMT support structure
18 m diameter

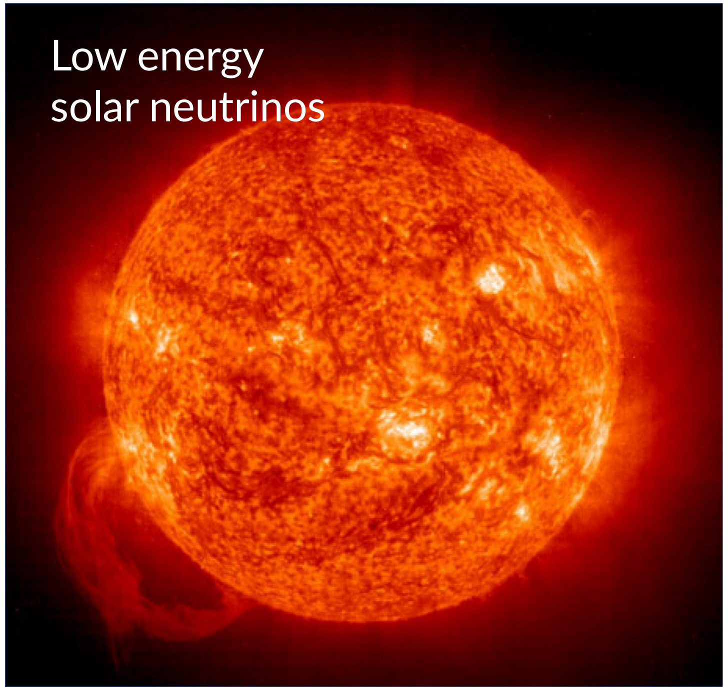
Hold up and hold down
rope systems



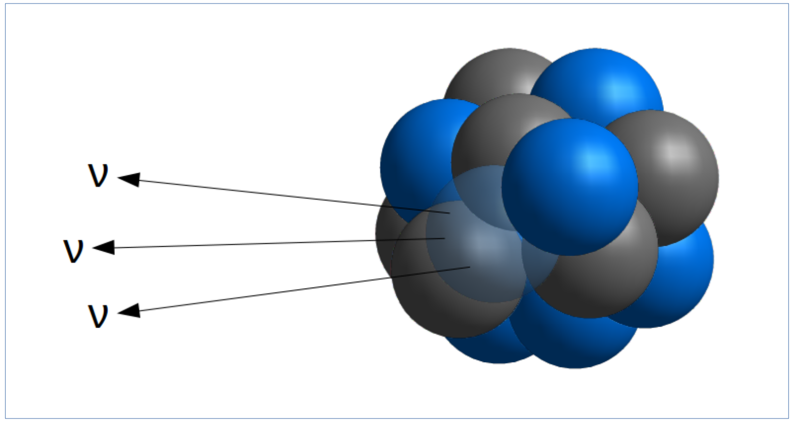
Timeline

Water phase (905 t UPW): Finished
Pure scintillator phase (780 t scintillator): Filling ongoing
Tellurium phase (4 t of Te): Loading starts 2020

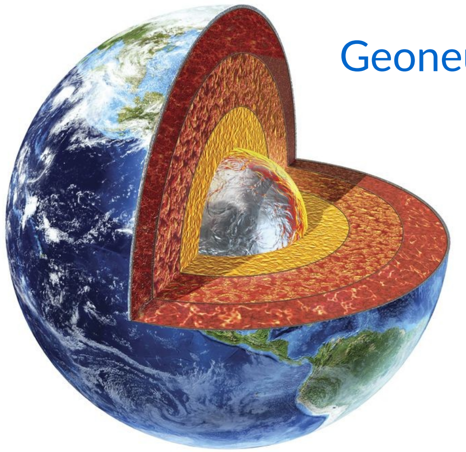
SNO+ Physics



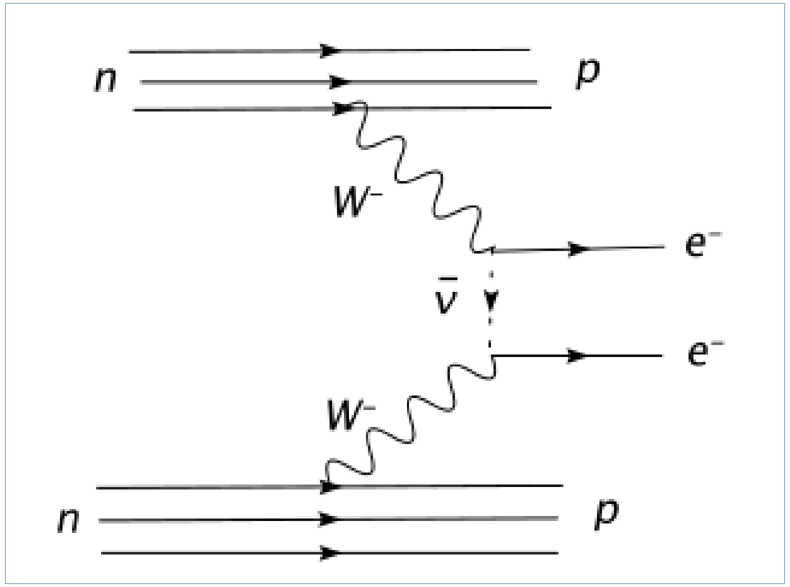
Reactor antineutrinos



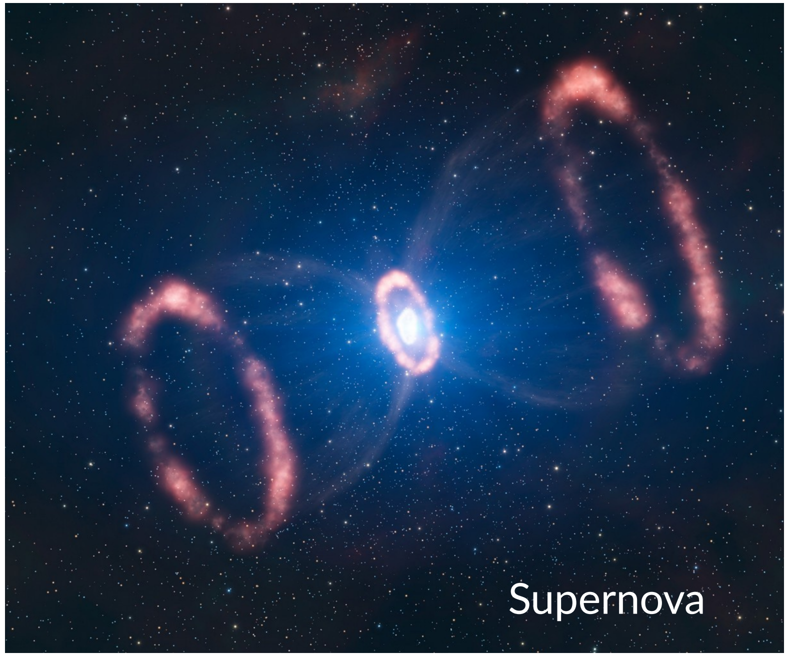
Invisible nucleon decay
+ other exotic physics



Geoneutrinos

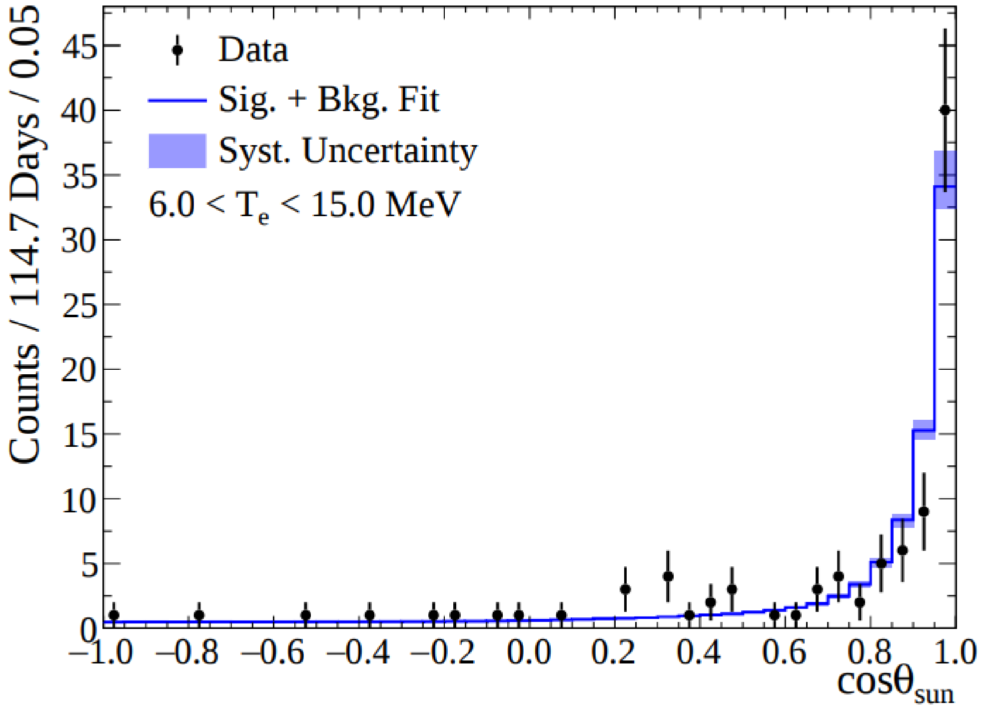


Neutrinoless double beta decay



Water results

^{8}B solar neutrino flux



Observed solar ^{8}B neutrino flux with very low backgrounds

$$2.53^{+0.31}_{-0.28}(stat.)^{+0.13}_{-0.10}(syst.)\times 10^6 cm^{-2} s^{-1}$$

consistent with previous measurements

Phys. Rev. D **99**, 012012

Invisible nucleon decay

Proton decay

$$^{16}\mathrm{O} \rightarrow {}^{15}\mathrm{N}^* + inv$$
$$^{15}\mathrm{N}^* \rightarrow {}^{15}\mathrm{N} + \gamma$$

Neutron decay

$$^{16}\mathrm{O} \rightarrow {}^{15}\mathrm{O}^* + inv$$
$$^{15}\mathrm{O}^* \rightarrow {}^{15}\mathrm{O} + \gamma$$

Measured lifetime limits

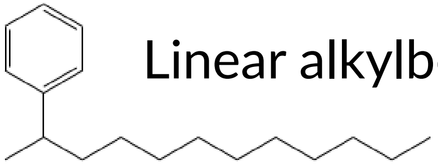
	Spectral analysis	Counting analysis
n	2.5×10^{29} y	2.6×10^{29} y
p	3.6×10^{29} y	3.4×10^{29} y
pp	4.7×10^{28} y	4.1×10^{28} y
pn	2.6×10^{28} y	2.3×10^{28} y
nn	1.3×10^{28} y	0.6×10^{28} y

Phys. Rev. D **99**, 032008

Scintillator fill ongoing…

Tellurium loaded scintillator

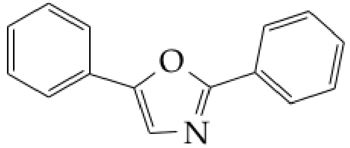
Requirements: High light yield, radiopurity, long term stability, material compatibility, safety...



Linear alkylbenzene (LAB)

+

2g/L 2,5-diphenyloxazole (PPO)

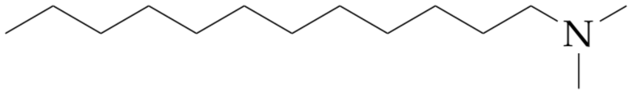


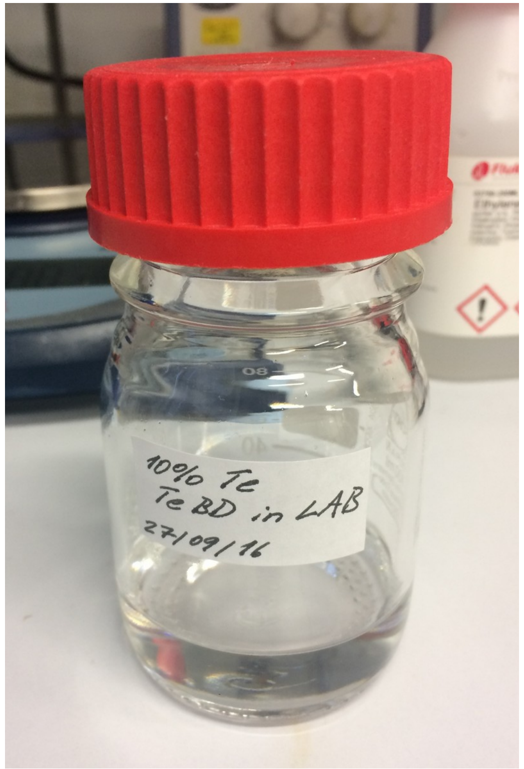
+

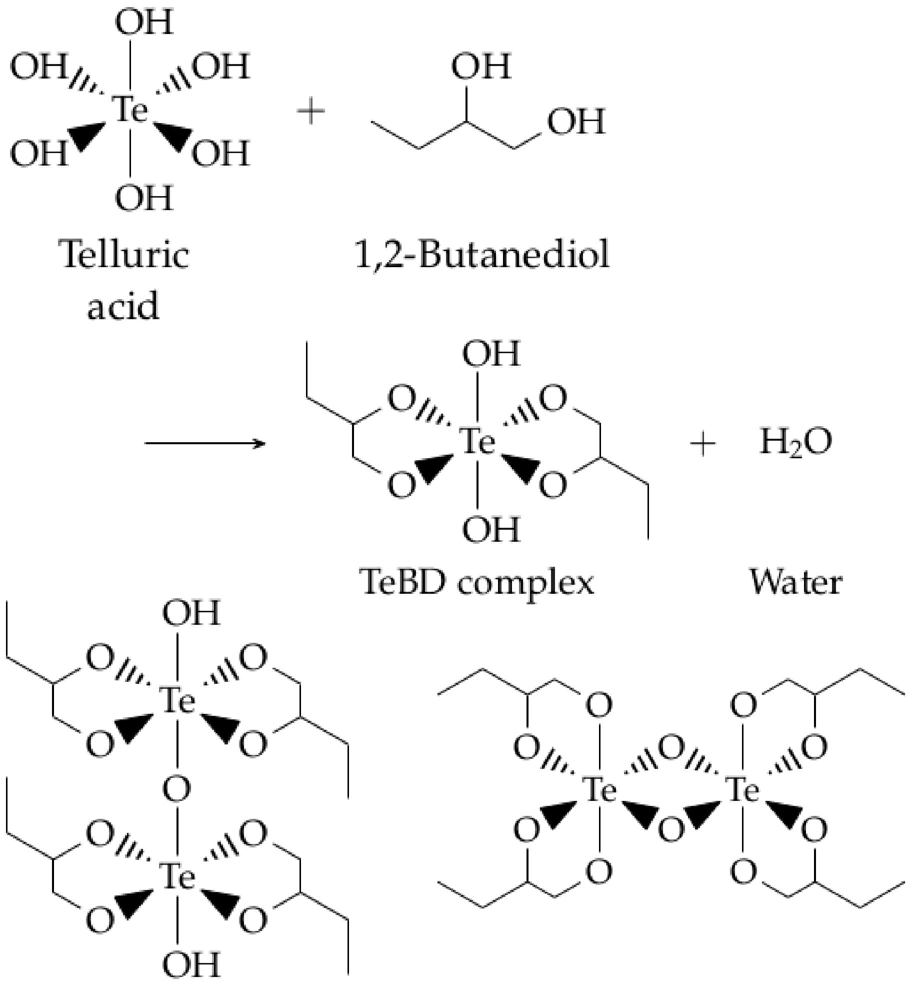
Tellurium-butanediol (TeBD)

+

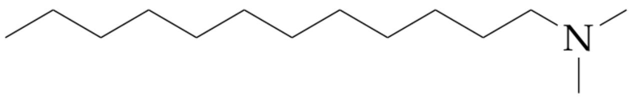
N,N-dimethyldodecylamine (DDA, 0.5 molar DDA:Te)







Amine addition

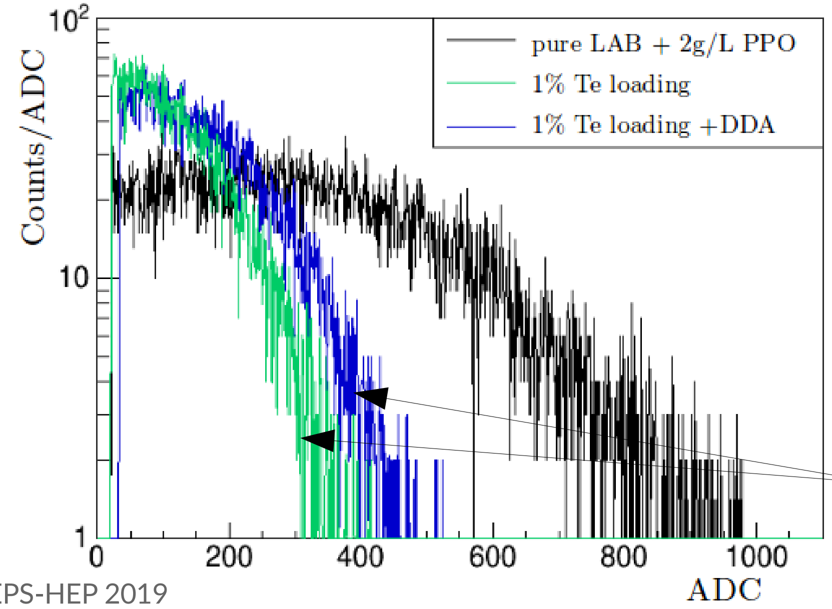


N,N-Dimethyldodecylamine

Advantages:

Helps stabilise TeBD in LAB
Safe for underground handling
Increases light yield by ~15%
Improves resistance against water

Relative light yield comparison measured with ^{90}Sr

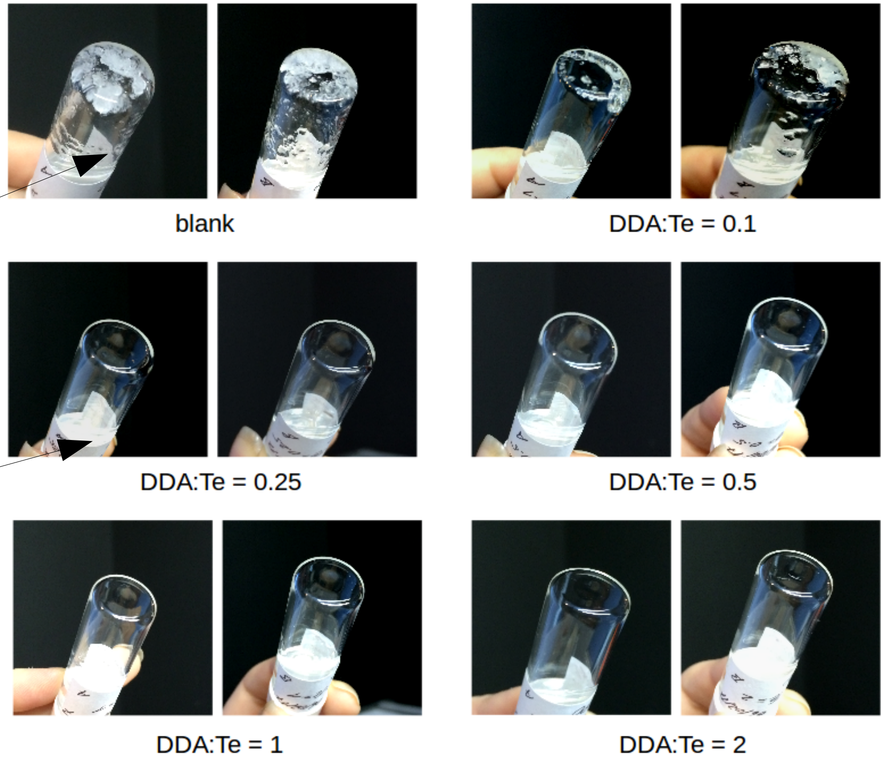


DDA offsets Te quenching to some extent
0.5 molar ratio chosen to optimise light output

DDA neutralises TeBD mixture and forms an ionic association with the complex to solubilise in LAB

Flake formation in samples without DDA upon **extreme humidity exposure**

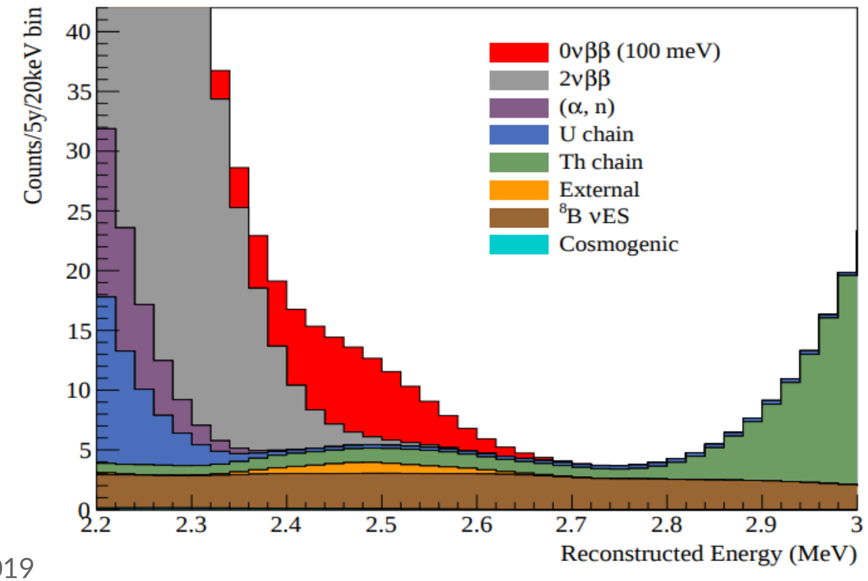
No flake formation observed in any samples with DDA:Te>0.25 molar

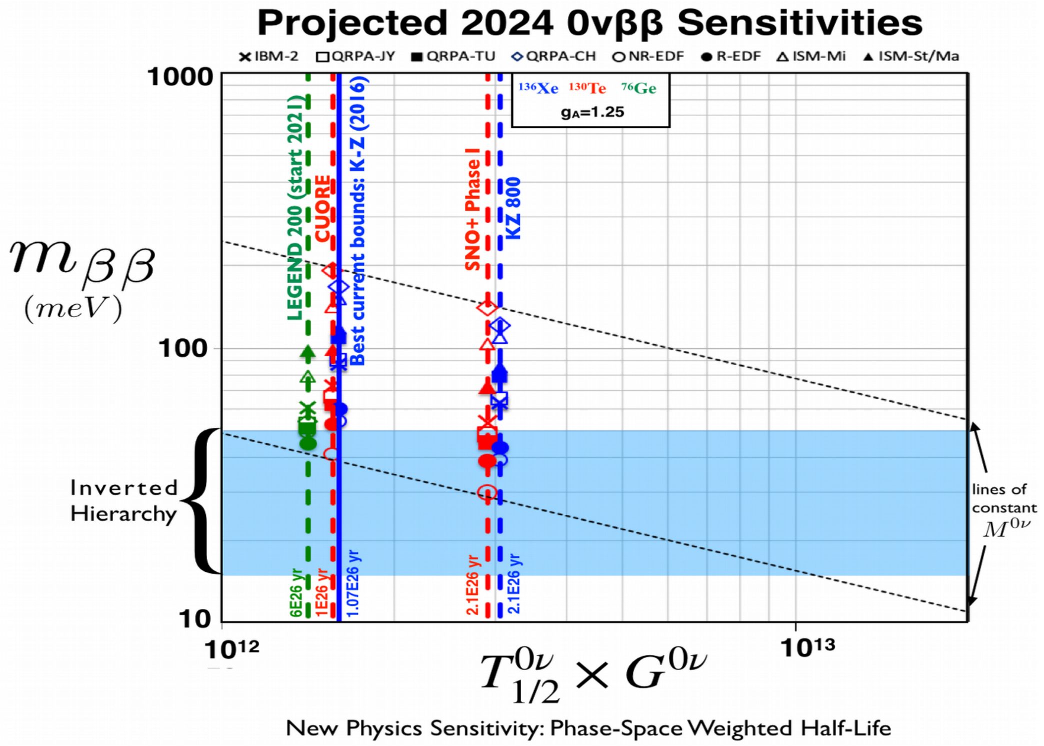


2 yrs after humidity exposure

0νββ in Phase I

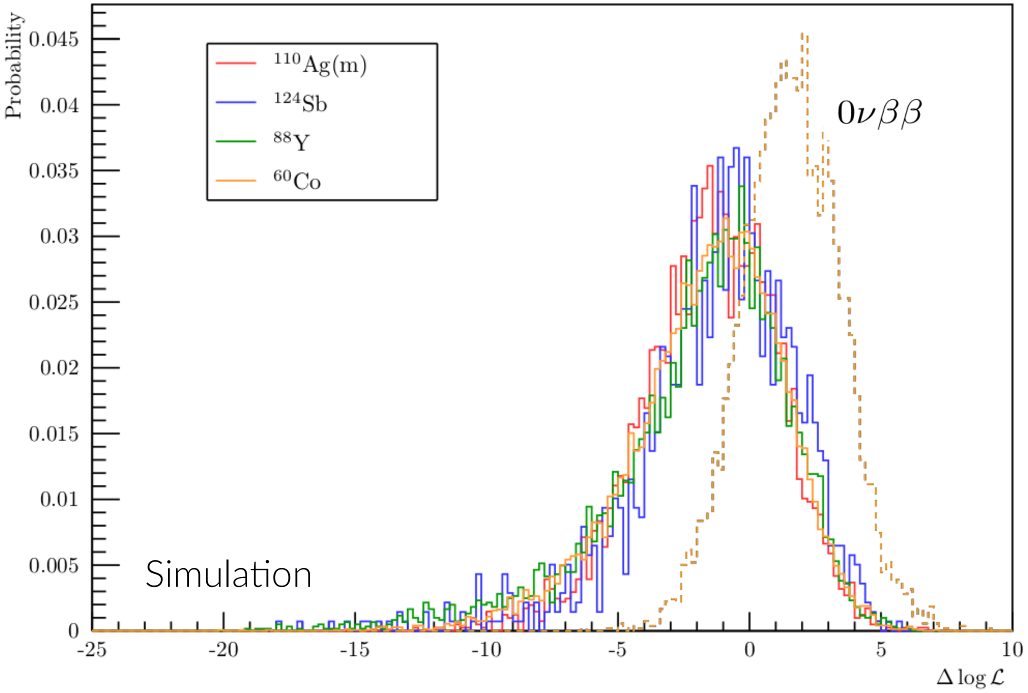
Tellurium 130
High Q value (2.5 MeV)
High natural abundance (34 %)
Long 2νββ half-life (7.9x10^{20} yrs)
Light yield of 460 PMT hits/MeV
with loading technique





Counting analysis
9.47 counts/yr → $T_{1/2}$ > 2.1x10^{26} yrs
after 5 yrs with 0.5 % Te (Phase I)

Multi-site discrimination



Dunger, Biller: "Multi-site Event Discrimination in Large Liquid Scintillation Detectors" 2019 (arXiv:1904.00440)

0νββ events have more point-like energy deposition compared to background events involving γ-rays with more spread-out deposition

Possible to break degeneracies of signal with backgrounds (cosmogenics, internal and external) using timing information

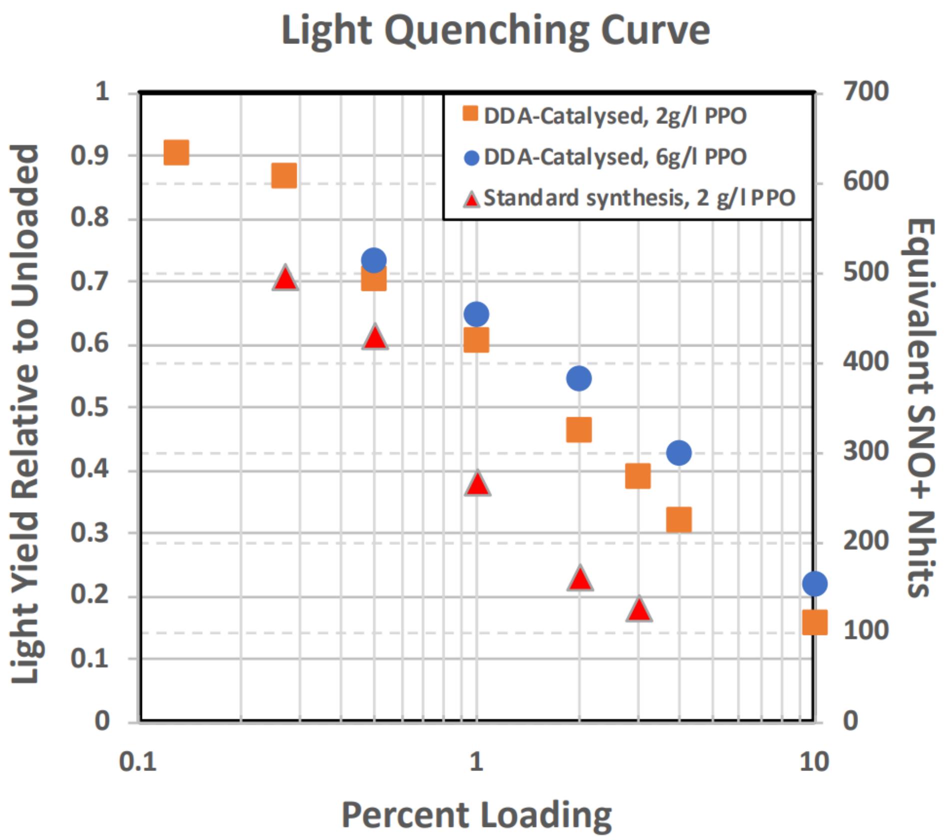
Likelihood analysis development

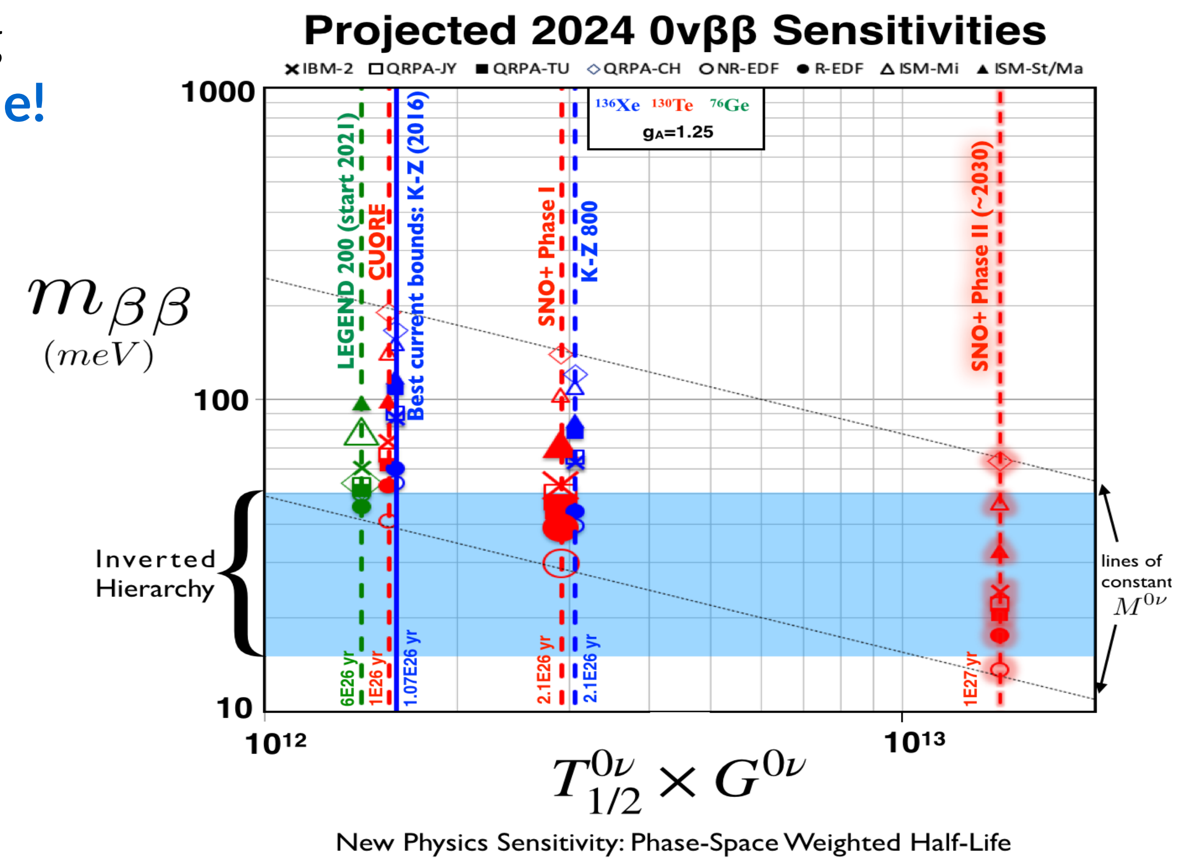
~30 background normalisations floated in the fit
Currently a 2D fit in energy and R^3
Planned extension to more dimensions using timing and topological background discrimination

Future prospects

Improve sensitivity by simply increasing loading

4% Te or higher possible with improved technique!





R&D ongoing...

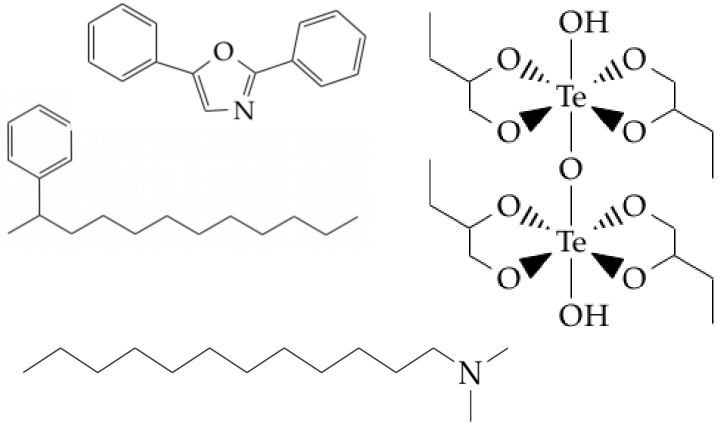
Summary

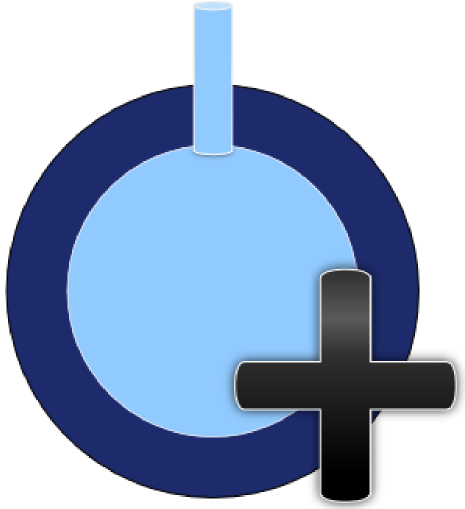
SNO+ is online and published results from water data

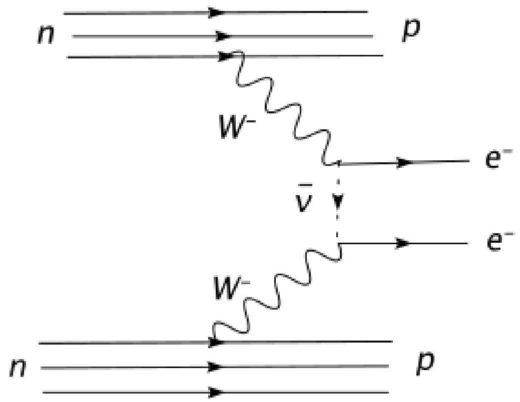
Scintillator fill ongoing, will deploy a novel technique for tellurium loading

DDA improves properties of loaded scintillator mixture (light yield and water attack resistance) and can be used in synthesis to enable higher loading in the future

SNO+ will have world leading sensitivity to $0\nu\beta\beta$ in ^{130}Te

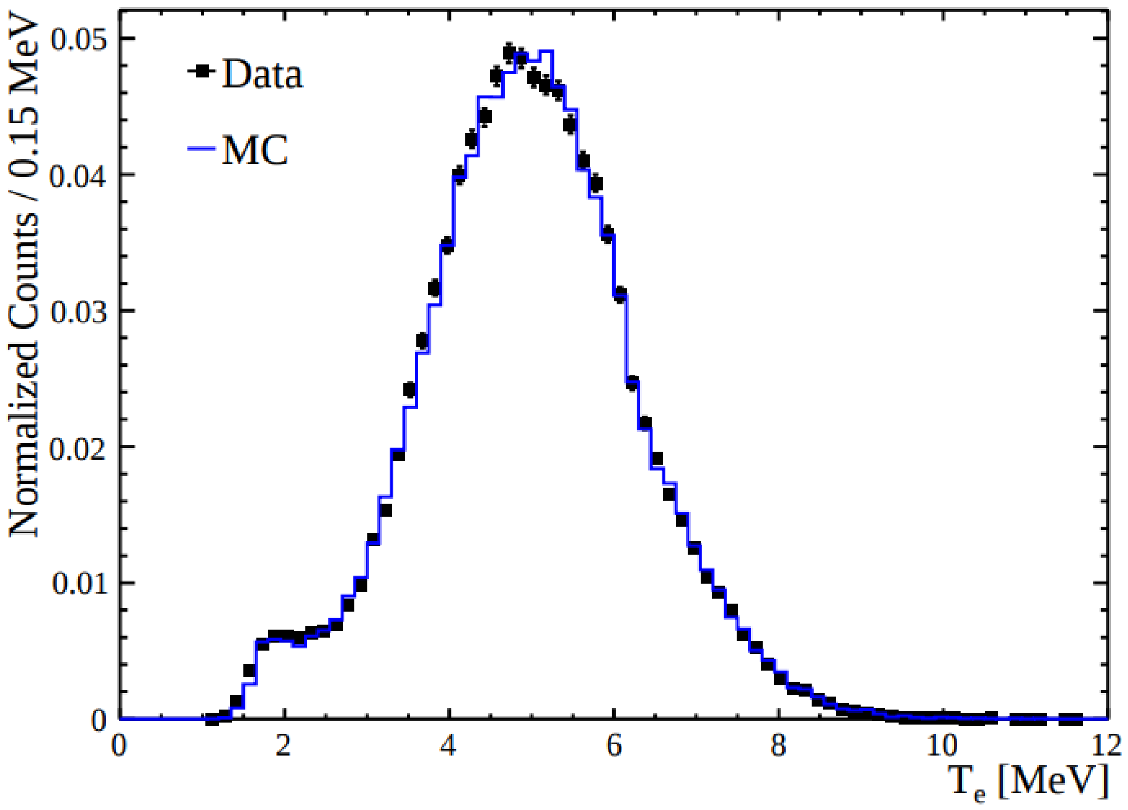


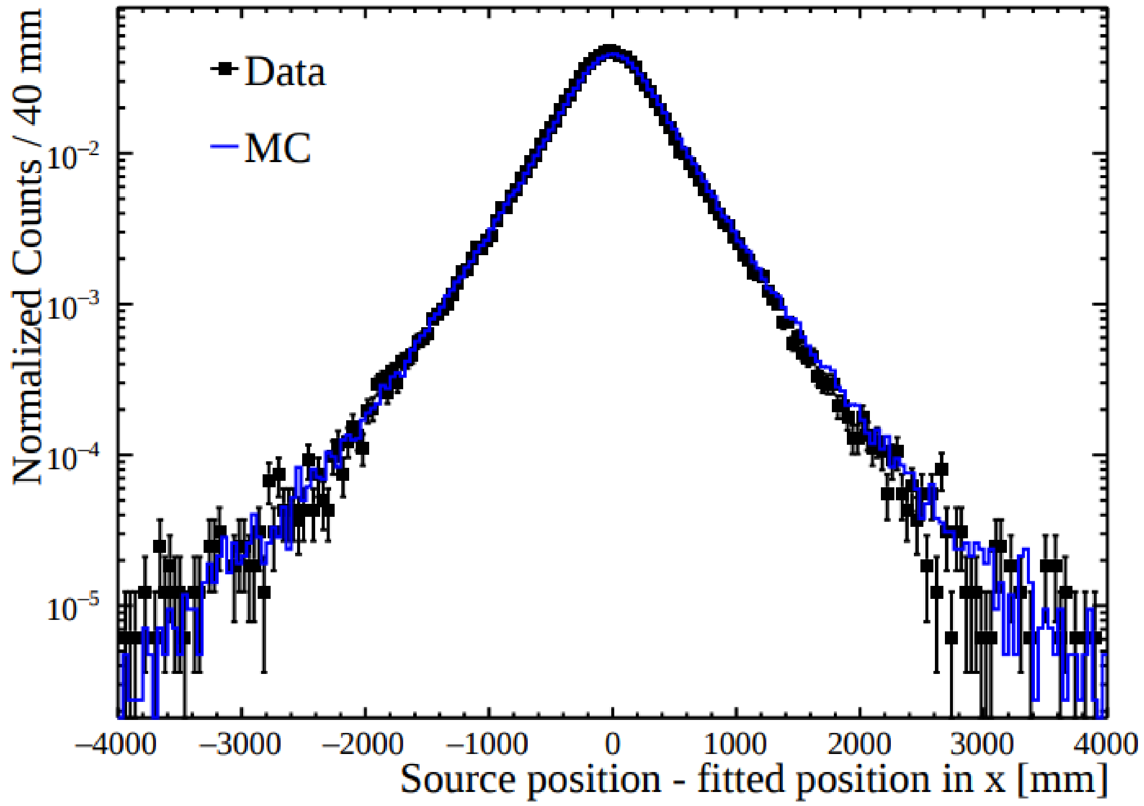




Back up

^{16}N deployed source energy and position calibration





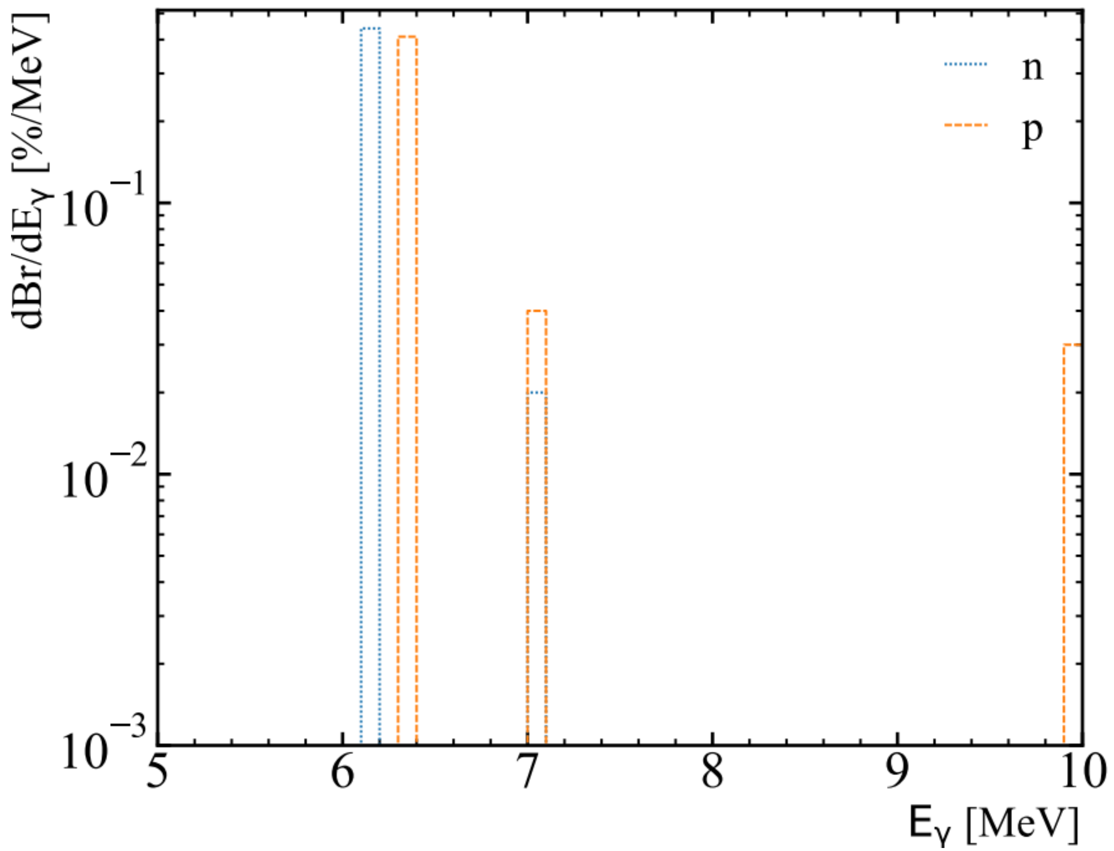
Back up

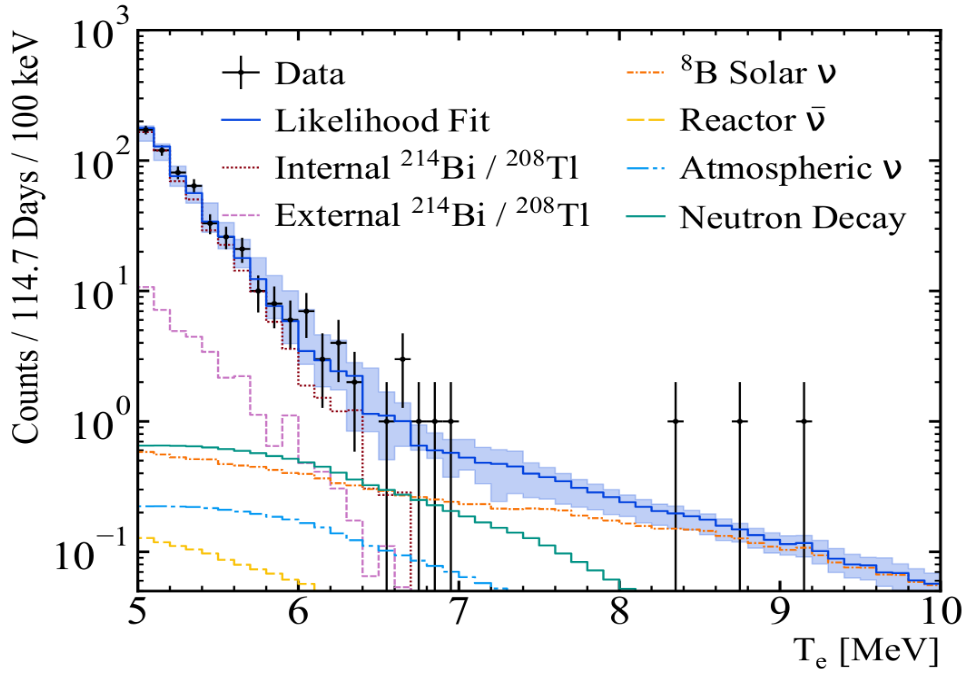
U and Th contamination during water phase data taking period presented here

Period	AV water		Water shielding		AV		Ropes
	U	Th	U	Th	U	Th	Th
	$[\times 10^{-14}\ \mathrm{gU/g}_{H_2O}]$	$[\times 10^{-15}\ \mathrm{gTh/g}_{H_2O}]$	$[\times 10^{-13}\ \mathrm{gU/g}_{H_2O}]$	$[\times 10^{-14}\ \mathrm{gTh/g}_{H_2O}]$	$[\times 10^{-12}\ \mathrm{gU/g}_{AV}]$	$[\times 10^{-12}\ \mathrm{gTh/g}_{AV}]$	$[\times 10^{-9}\ \mathrm{gTh/g}_{rope}]$
1	$19.0 \pm 1.8\ ^{+3.9}_{-3.7}$	$5.9 \pm 5.2\ ^{+4.0}_{-5.9}$	$2.2 \pm 0.3\ ^{+3.7}_{-1.3}$	$9.9 \pm 1.6\ ^{+22.9}_{-9.7}$	$5.5 \pm 1.5\ ^{+6.5}_{-5.5}$	$0.0\ ^{+0.0}_{-0.0}\ ^{+1.1}_{-0.0}$	$0.0\ ^{+0.0}_{-0.0}\ ^{+0.3}_{-0.0}$
2 (z>0)	$48.5 \pm 3.1\ ^{+11.7}_{-10.1}$	$34.5 \pm 13.7\ ^{+11.2}_{-34.5}$	$86.9 \pm 1.1\ ^{+103.2}_{-49.2}$	$207.7 \pm 6.4\ ^{+449.9}_{-173.0}$	$33.0 \pm 16.4\ ^{+60.8}_{-33.0}$	$12.5 \pm 2.4\ ^{+33.9}_{-12.5}$	$2.8 \pm 0.5\ ^{+7.7}_{-2.8}$
2 (z<0)	$3.6 \pm 0.9\ ^{+1.0}_{-0.7}$	$2.7\ ^{+4.2}_{-2.7}\ ^{+1.3}_{-2.7}$	$16.3 \pm 0.4\ ^{+24.4}_{-8.5}$	$39.8 \pm 2.8\ ^{+134.8}_{-39.8}$	$7.7 \pm 5.5\ ^{+24.4}_{-7.7}$	$3.7 \pm 1.2\ ^{+11.0}_{-3.7}$	$0.9 \pm 0.3\ ^{+2.5}_{-0.9}$
3	$8.7 \pm 0.7\ ^{+2.4}_{-1.7}$	$8.3 \pm 3.1\ ^{+3.0}_{-8.3}$	$1.7 \pm 0.1\ ^{+2.5}_{-1.1}$	$9.3 \pm 0.5\ ^{+19.1}_{-9.1}$	$1.2 \pm 0.9\ ^{+7.9}_{-1.2}$	$0.0\ ^{+0.3}_{-0.0}\ ^{+1.1}_{-0.0}$	$0.0\ ^{+0.1}_{-0.0}\ ^{+0.3}_{-0.0}$
4	$19.4 \pm 1.0\ ^{+5.8}_{-4.4}$	$9.4 \pm 4.1\ ^{+6.5}_{-9.4}$	$0.6 \pm 0.1\ ^{+1.2}_{-0.4}$	$10.6 \pm 0.6\ ^{+19.3}_{-8.8}$	$0.3\ ^{+0.8}_{-0.3}\ ^{+2.2}_{-0.3}$	$0.0\ ^{+0.1}_{-0.0}\ ^{+0.5}_{-0.0}$	$0.0\ ^{+0.0}_{-0.0}\ ^{+0.1}_{-0.0}$
5	$53.5 \pm 3.7\ ^{+19.5}_{-14.3}$	$29.0 \pm 17.1\ ^{+24.7}_{-29.0}$	$2.3 \pm 0.2\ ^{+5.3}_{-1.6}$	$8.6 \pm 1.3\ ^{+31.9}_{-8.6}$	$5.2 \pm 0.9\ ^{+6.7}_{-5.2}$	$0.1\ ^{+0.5}_{-0.1}\ ^{+0.3}_{-0.1}$	$0.0\ ^{+0.1}_{-0.0}\ ^{+0.1}_{-0.0}$
6	$67.5 \pm 2.1\ ^{+26.3}_{-20.8}$	$67.1 \pm 10.0\ ^{+38.7}_{-67.1}$	$1.2 \pm 0.1\ ^{+2.4}_{-0.8}$	$10.0 \pm 0.7\ ^{+28.8}_{-10.0}$	$1.7 \pm 0.9\ ^{+3.8}_{-1.7}$	$0.0\ ^{+0.1}_{-0.0}\ ^{+1.0}_{-0.0}$	$0.0\ ^{+0.0}_{-0.0}\ ^{+0.2}_{-0.0}$

Back up

Deexcitation spectra of ^{16}O invisible nucleon decay

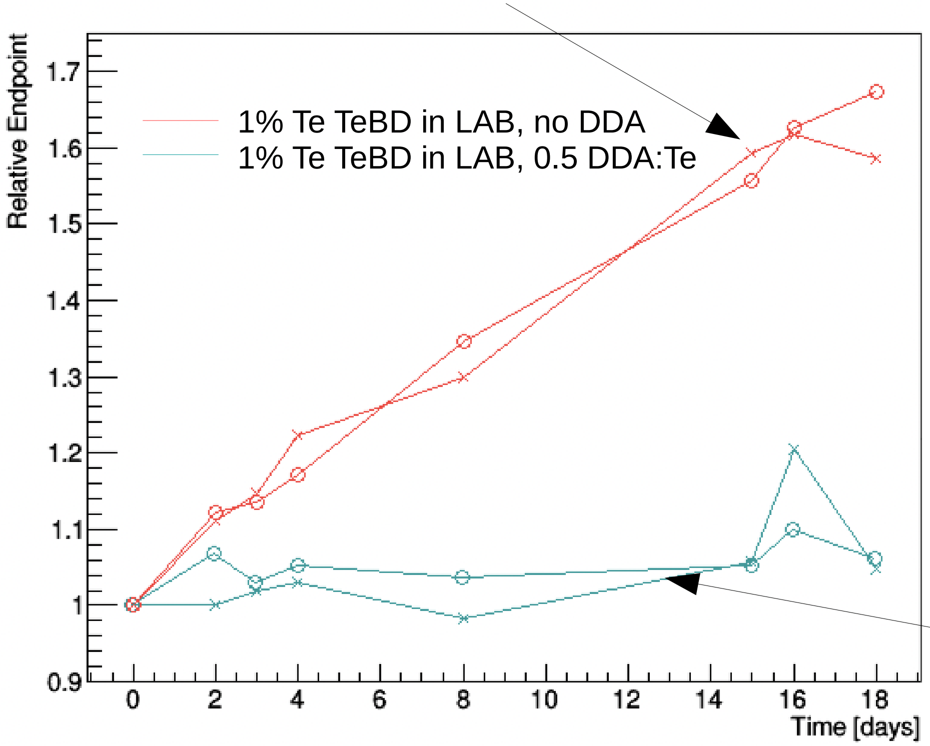




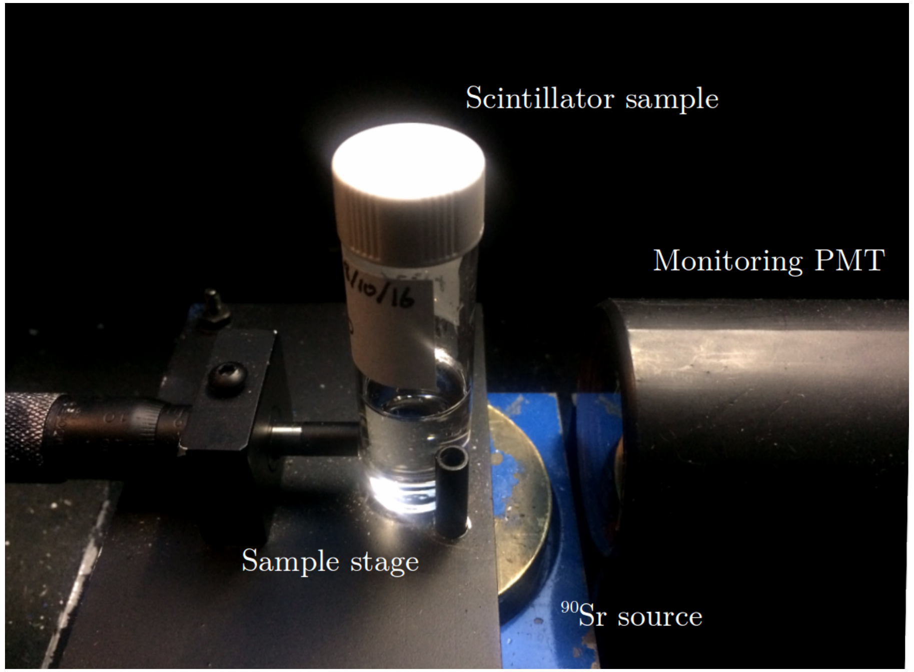
22 events in ROI
(17.3 expected)
consistent with no signal

Back up

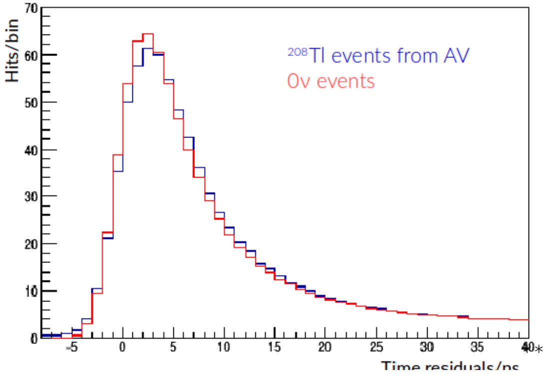
Water association can cause phase separation in samples without DDA - Te effectively falling out of solution decreases quenching and hence LY increases over time

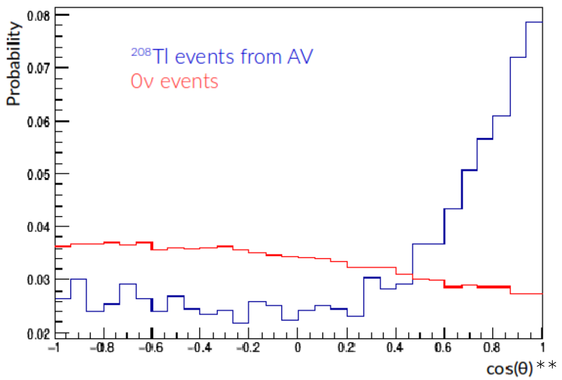


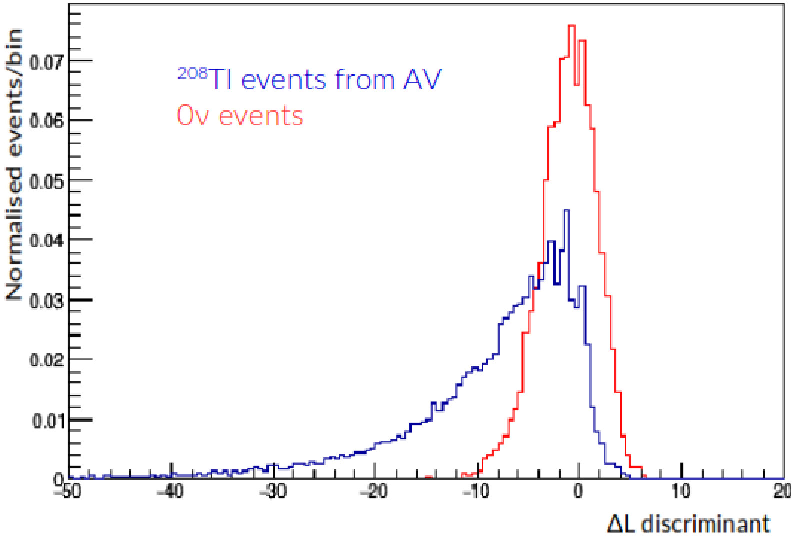
Light yield remains stable over time with DDA

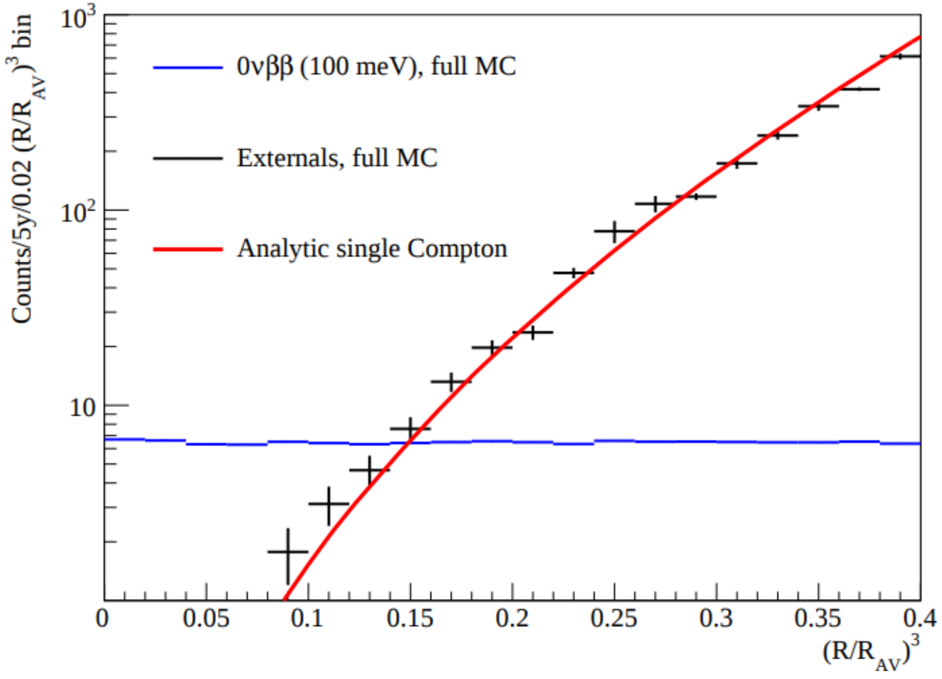


Back up









**Time residuals = $t_{hit} - t_{fit} - t_{tof}$

θ = angle between reconstructed position and hit PMT