Theia: Recent developments in water-based liquid scintillator

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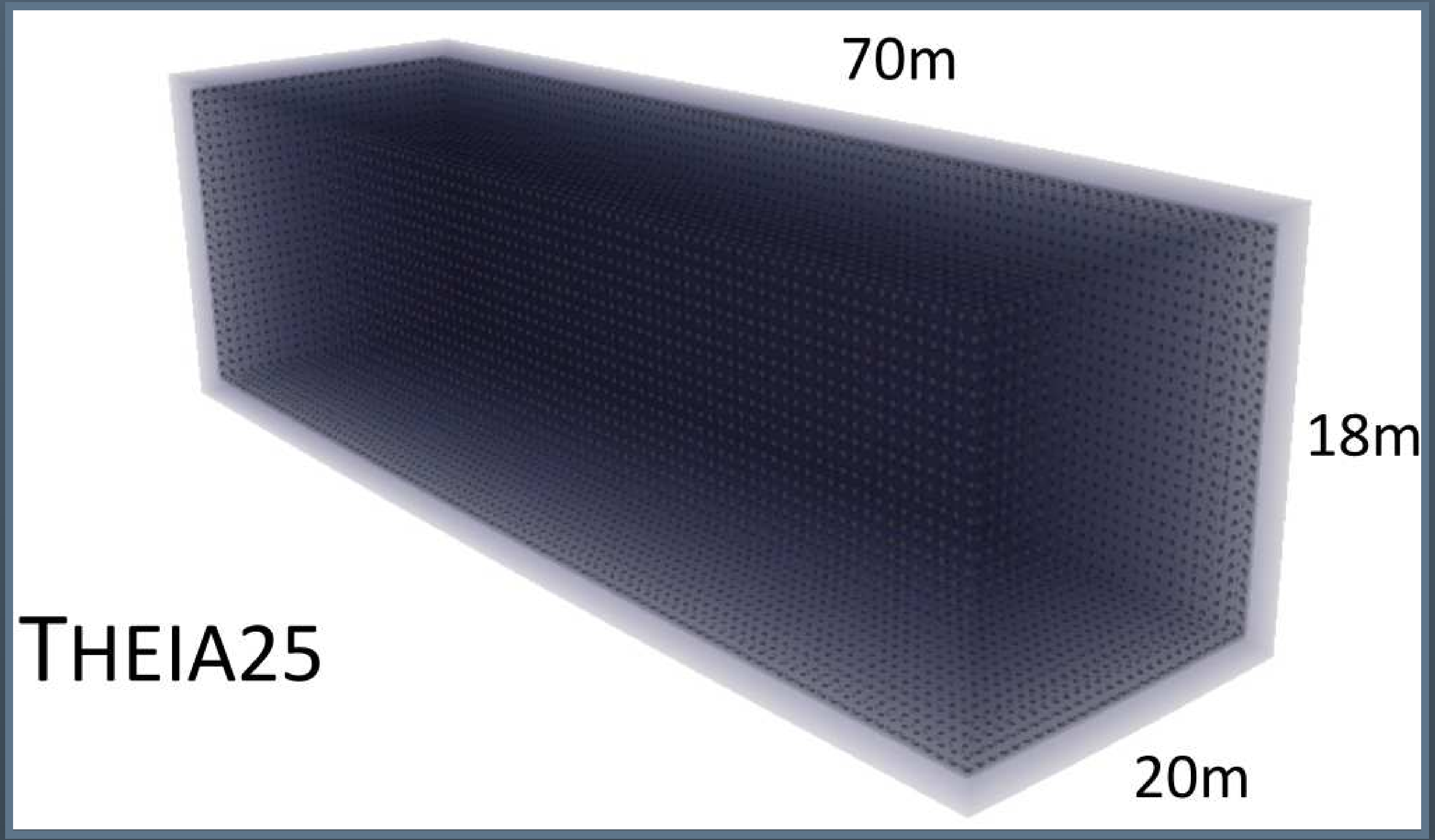
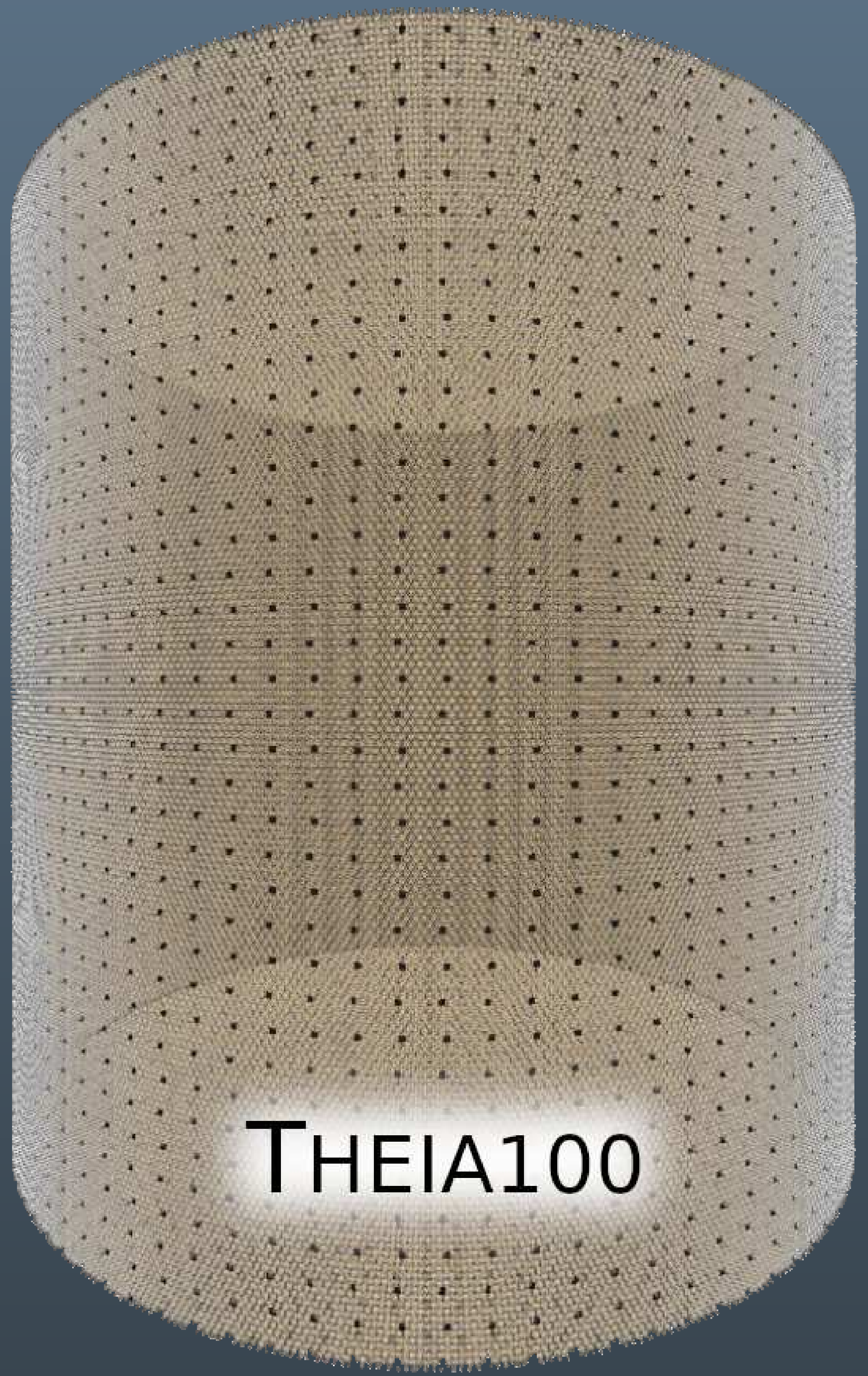
Theia Detector Concept

→ 25 to 100 kt total mass
→ Variable target material (focus on Cherenkov / Scintillation separation)
→ Up to 90% photocoverage
→ Advanced photon detection



Fits within a DUNE-like cavern



Target Physics

Broad physics program, split into multiple phases based on detector configuration and target material.

Phase	Primary Physics Goals	Detector capabilities	Configuration options
I	Long-baseline oscillations ^{8}B flux Supernova burst, DSNB	High-precision ring imaging	Low-yield WbLS Low photosensor coverage Fast timing
II	Long-baseline oscillations ^{8}B MSW transition CNO, *pep* solar Reactor and geo $\bar{\nu}$ Supernova burst ($\bar{\nu}_e$ and ν_e), DSNB (ν_e and $\bar{\nu}_e$)	Low threshold Cherenkov/scintillation separation High light yield	High-yield WbLS or slow LS Potential ^{7}Li loading High photosensor coverage Potential dichroicon deployment
III	$0\nu\beta\beta$ ^{8}B MSW transition Reactor and geo $\bar{\nu}$ Supernova burst and DSNB ($\bar{\nu}_e$)	Low threshold Cherenkov/scintillation separation High light yield	Inner vessel with LAB+PPO+isotope High photosensor coverage Potential dichroicon deployment

Combining Cherenkov and Scintillation light

Cherenkov

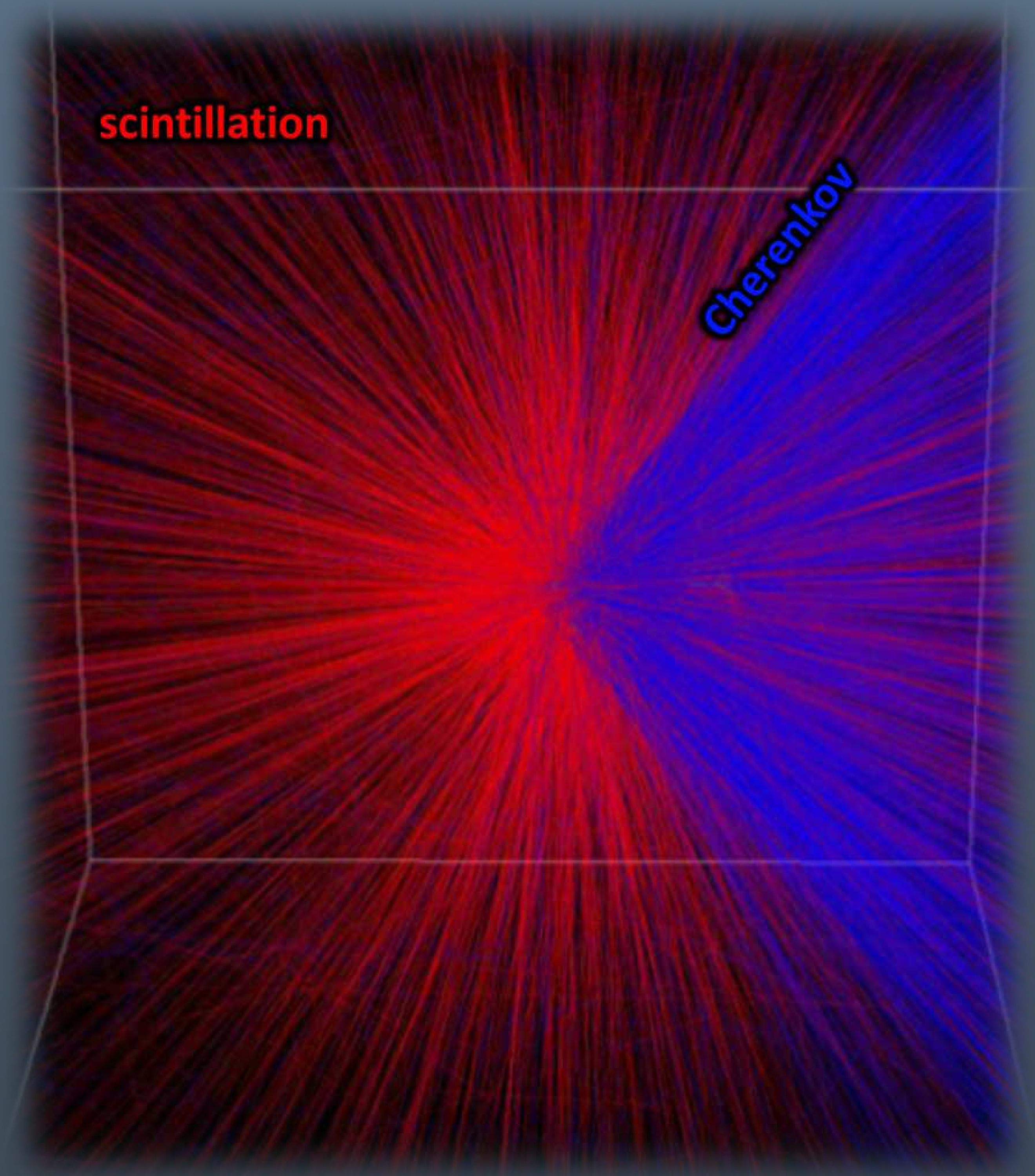
- → Preserves particle direction
- → Prompt timing with respect to interaction
- → Cut-off energy (Cherenkov Threshold)

Scintillation

- → High light-yield (energy resolution)
- → Isotropic emission

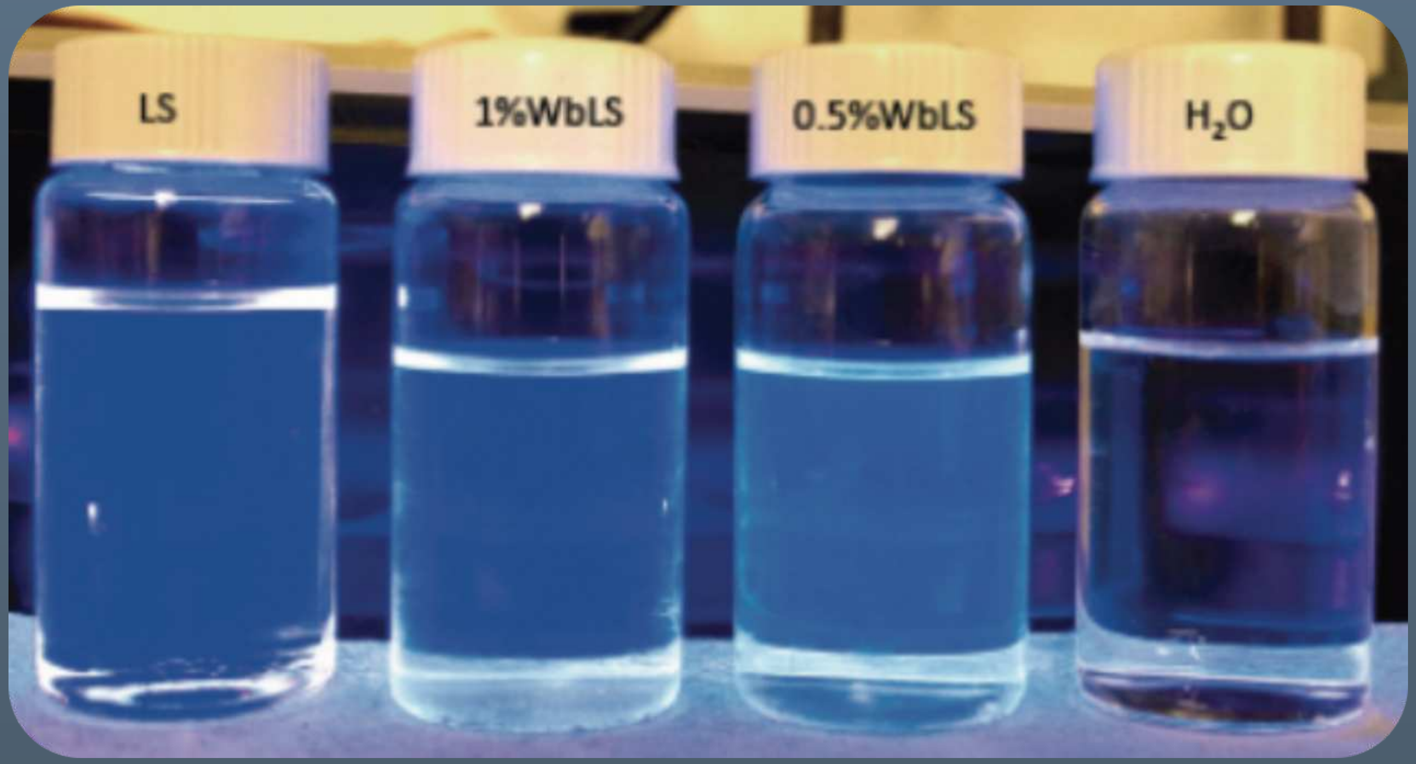
Water-based Liquid Scintillator

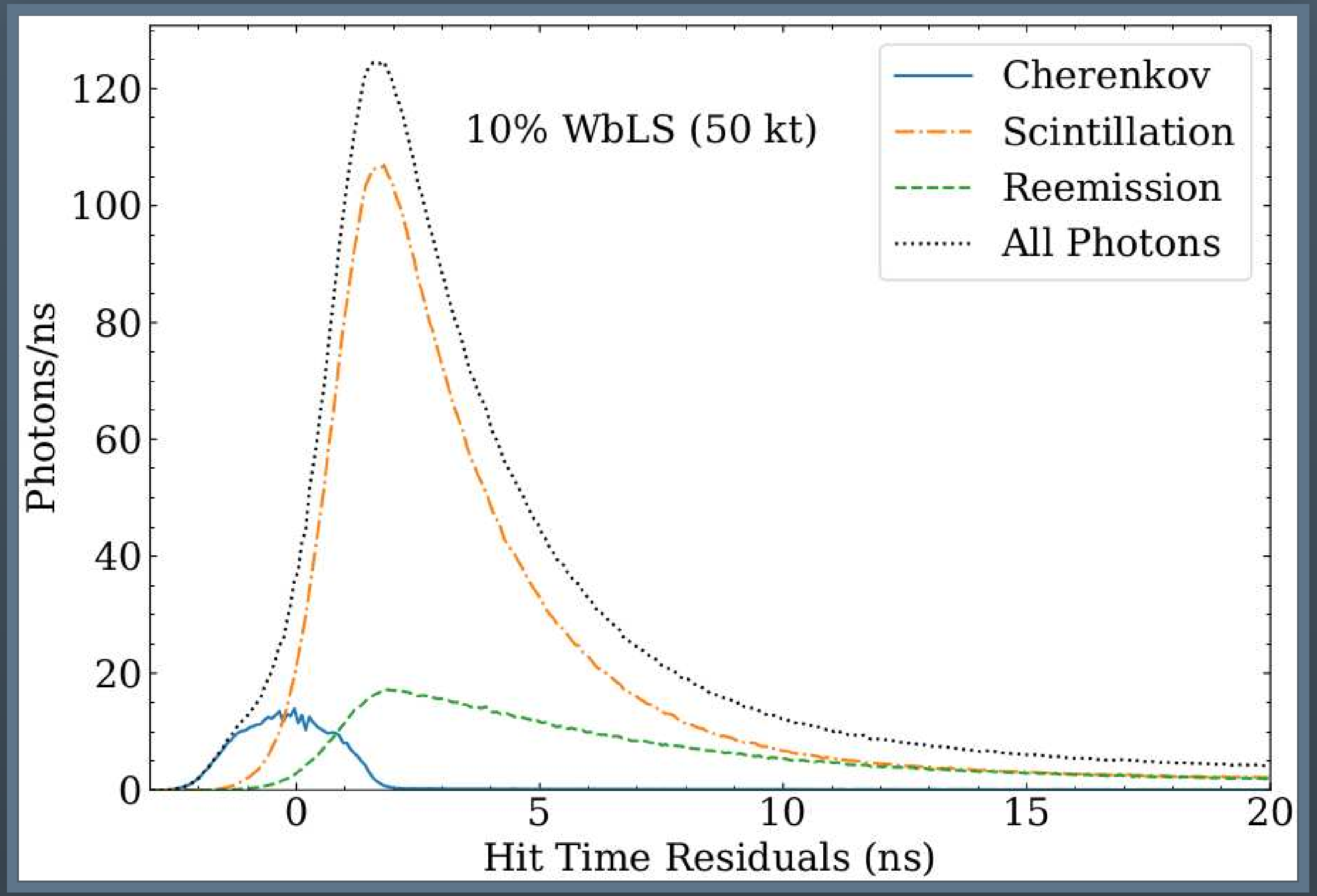
- → Aim to combine the unique aspects of these two signals to extend detector capabilities



Water-based Liquid Scintillator

- → Increased light-yield, compared with pure water, provides significant gains in position and energy resolution.
- → Separation of the Cherenkov and Scintillation signal has potential for particle identification.
- → Longer optical attenuation (compared with scintillator) scales to larger detector designs.





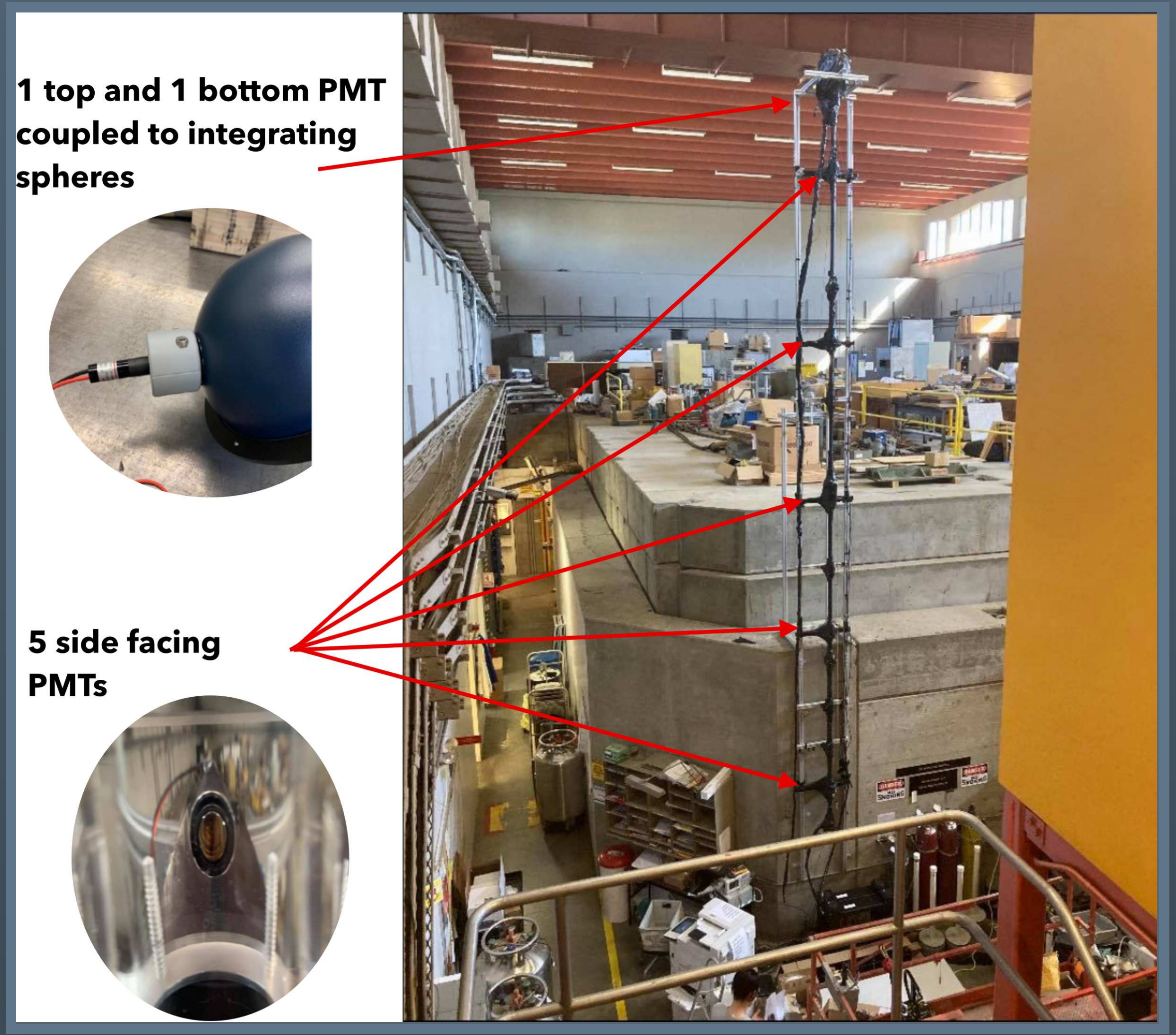
Advances in fast photodetectors and chromatic separation can be used to distinguish the two signals.

Figure showing the hit time residuals for 10% WbLS in a 50kt detector.

Nucl. Instrum. Meth. A **660**, *51*
J. Phys. G **43**, *093001*
Phys. Rev. D **103**, *052004*

Optical Attenuation and Scattering

Paramount to the performance and scaling of WbLS are the overall optical properties. Long water-like attenuation is needed to scale to large detector masses, while scattering degrades the timing and separation of the Cherenkov and Scintillation components.



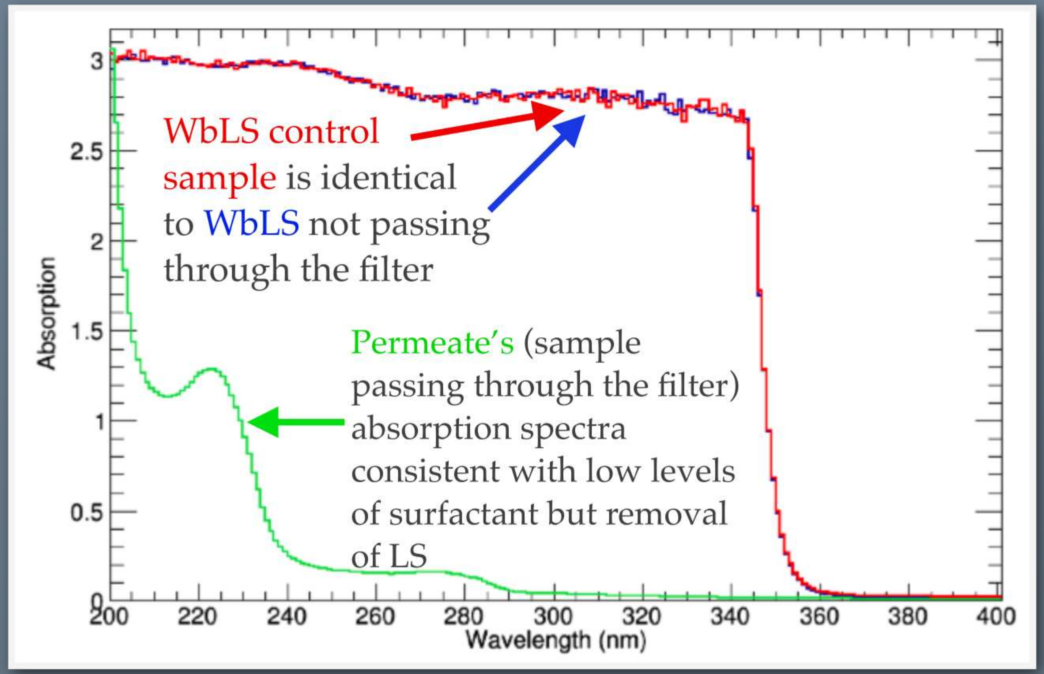
UC Davis: Robert Svoboda, Leon Pickard, Vincent Fischer, Tianqi Zhang, and Julie He

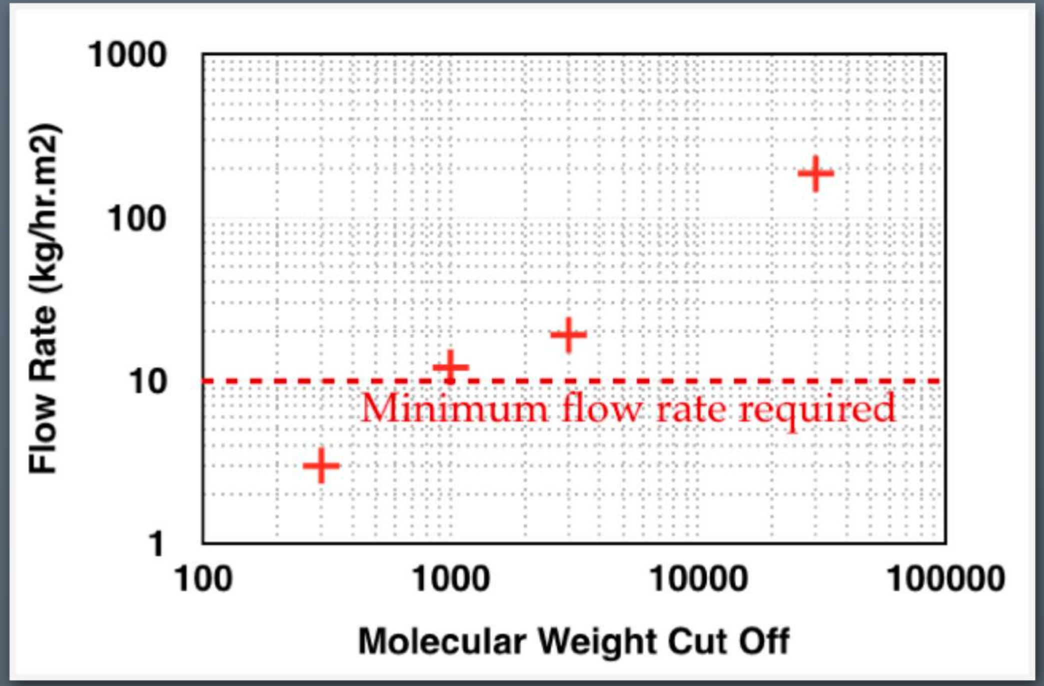
Scattering and attenuation measurement device (SAMD) at UC Davis

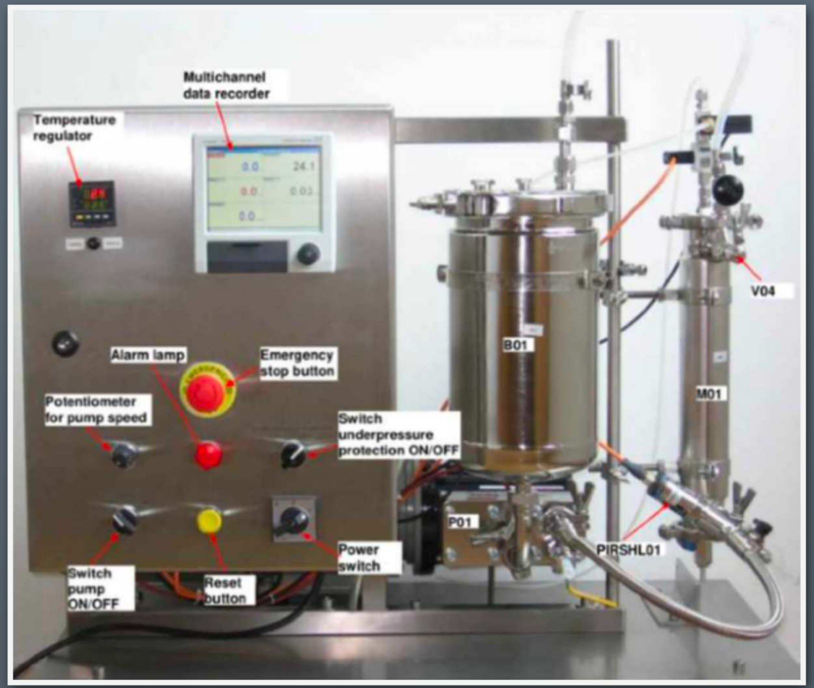
- → SAMD is a 7.5m tall, 1in diameter, attenuation arm.
- → Designed to measure wavelength-dependent attenuation and Rayleigh scattering of WbLS cocktails.
- → Consists of seven H12690 PMTs.
    - One at the top and bottom of the arm to determine the attenuation coefficent
    - 5 sideways facing PMTs to measure Rayleigh scattering
- → 4 lasers installed (420, 450, 488, and 520 nm)
- → Final stages of comissioning underway

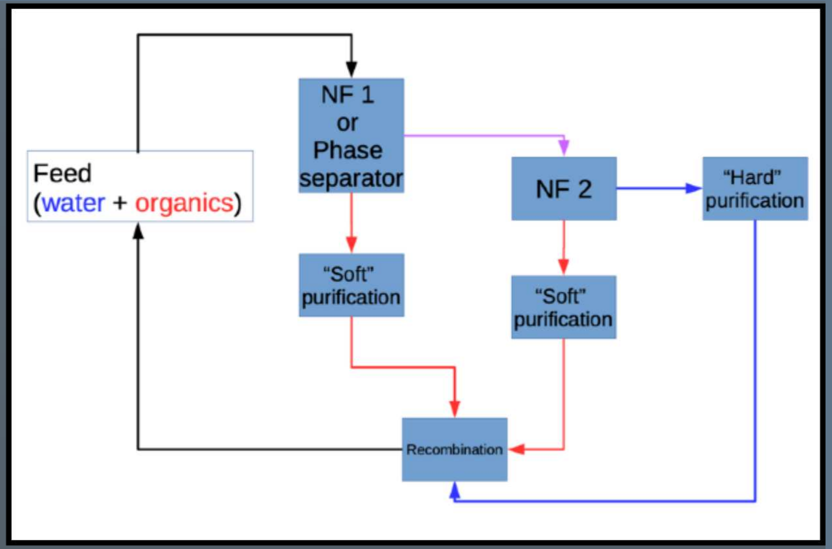
Nanofiltration of WbLS at UC Davis

- → Purification of WbLS is required to maintain optical transparency.
- → Water and ionic compounds from liquid scintillator must be separated before deionization.
- → Nanofiltration is a **membrane filtration** process that can potentially be used for this purpose.
- → System must separate water and liquid scintillator, with a flow rate suitable for Theia sized detectors, all while not damaging the liquid scintillator.







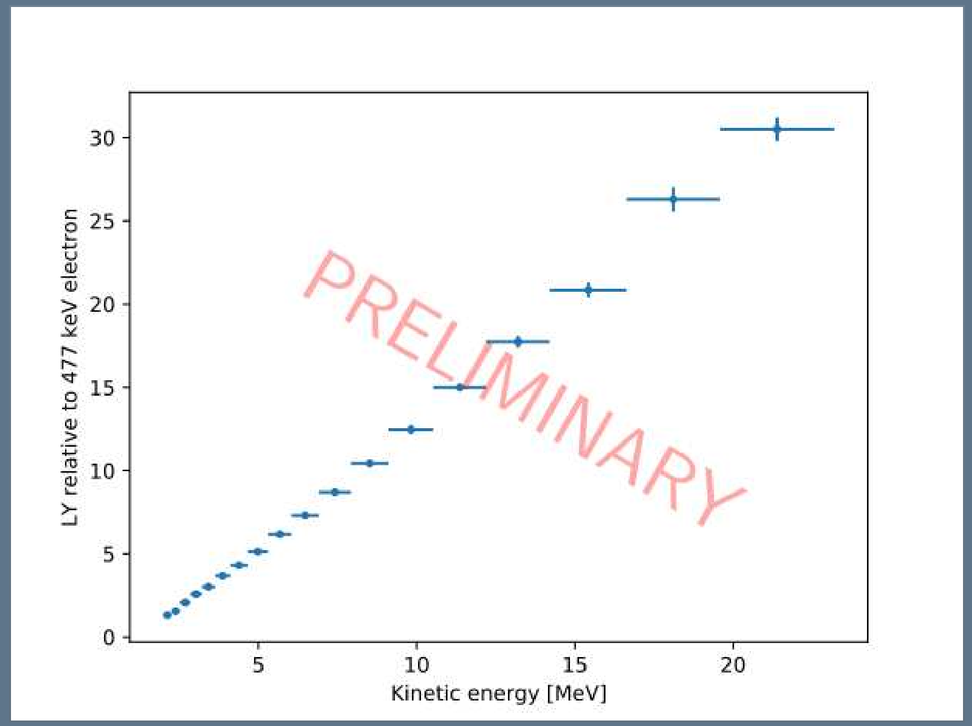


Preliminary design for a two-staged nanofiltration concept for large scale WbLS purification.

Proton Light-yield: LBL

Measurement of the proton light-yield in WbLS is critical for particle identifcation and background rejection.

→ Identification of proton ES events from Supernovae
→ Reject fast neutron backgrounds for anti-neutrino detection.



"Double time-of-flight" method

→ Pulsed deuteron beam breakup on Be target
→ PID-capable "post-scatter" detectors
→ Collaboration with **B**ay **A**rea **N**eutron **G**roup

Brown et al, Jour. Appl. Phys. **124**, 045101 (2018)

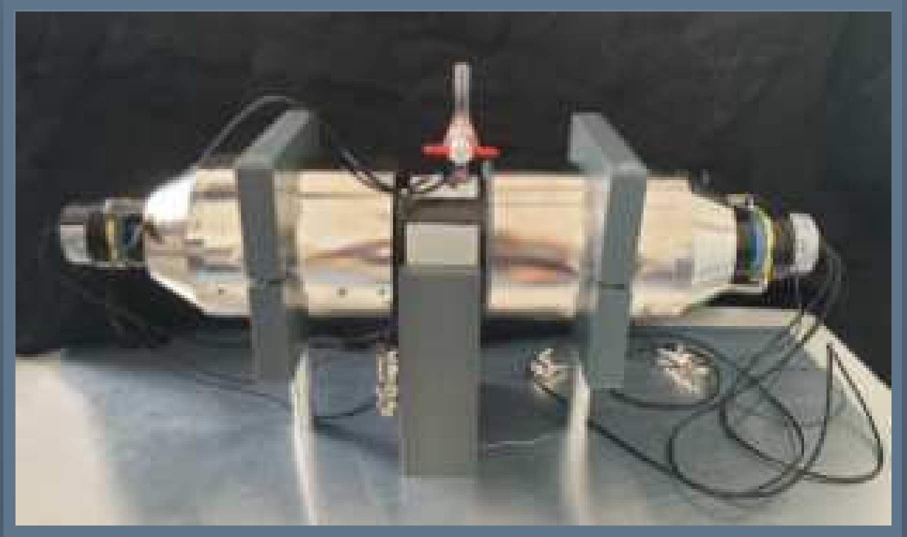
Protons excited by n-p scattering internal to measurement sample

Two measure of neutron energy

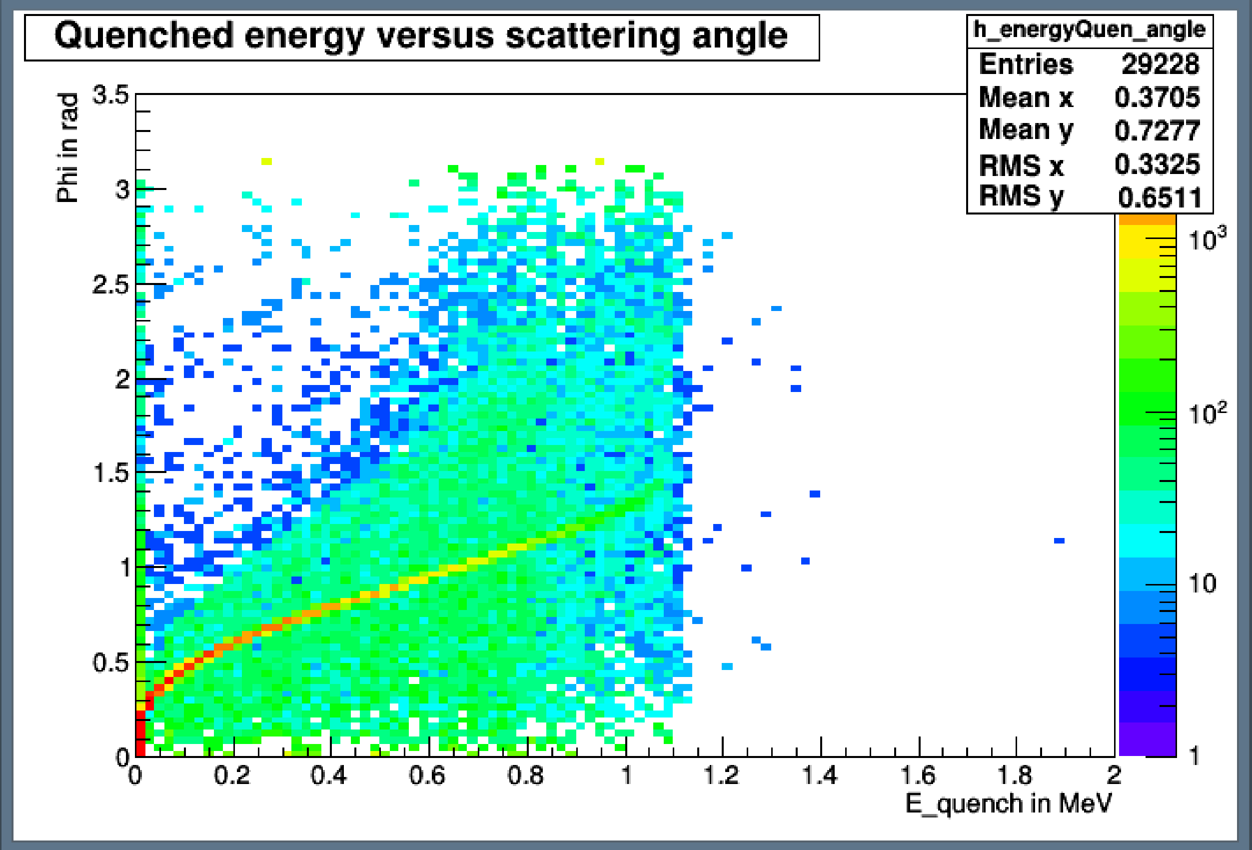
→ Before and after scattering
→ Determination of energy deposited

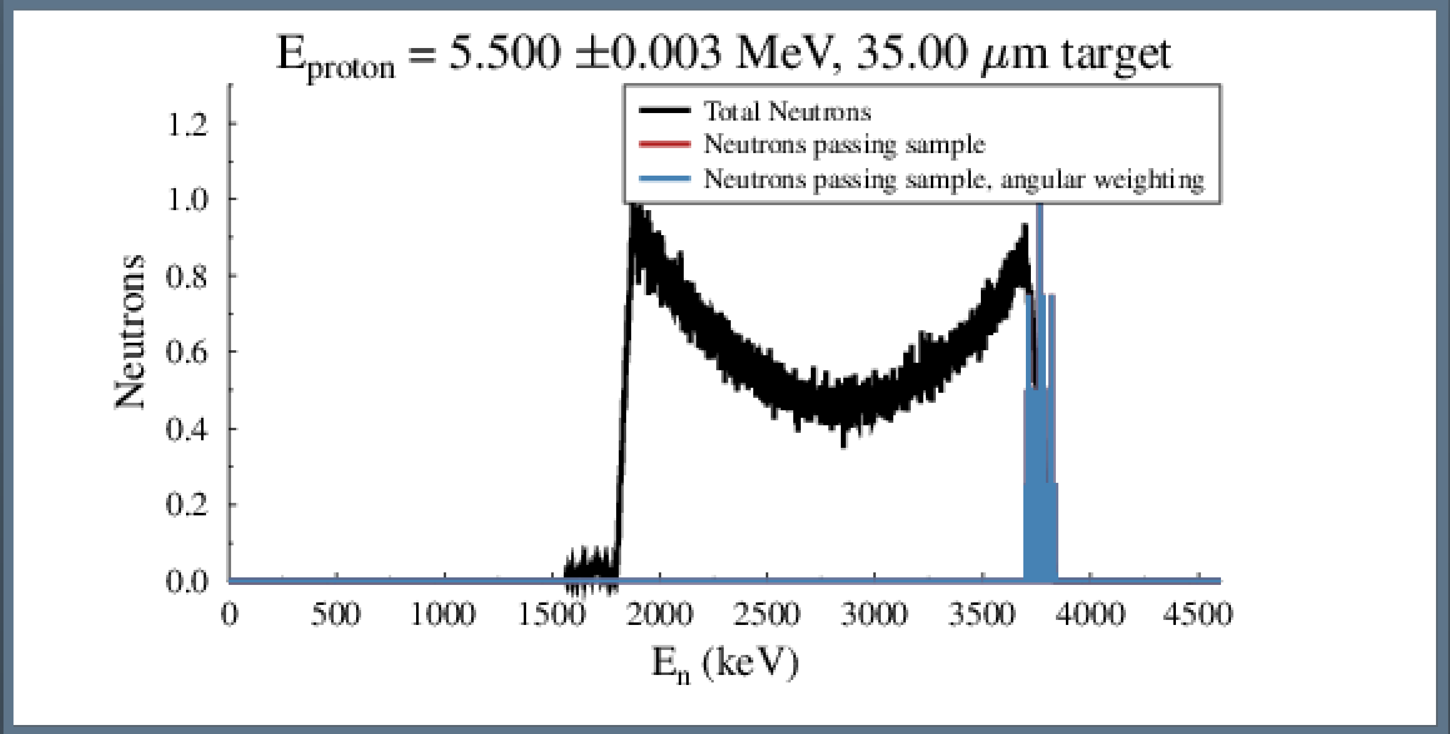
Charge collected in PMT used as proxy for light

Proton Light-yield: Munich, Mainz, Berkeley



- → BELINA: Narrow energy neutron beam at LNL Padua, Italy
- → Measurements of low energy proton quenching and time profile
- → Several setups for each purpose deployed
- → Derive particle ID from time profile and Scintillation/Cherenkov light ratio

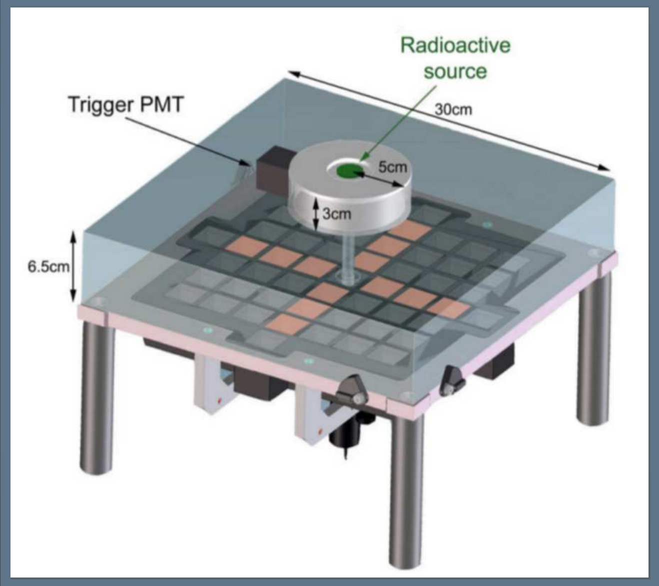




- Using RAT-PAC for simulation and analysis
- Account for multi-scatter events (~65% of events)
- Tune Microphysical parameters

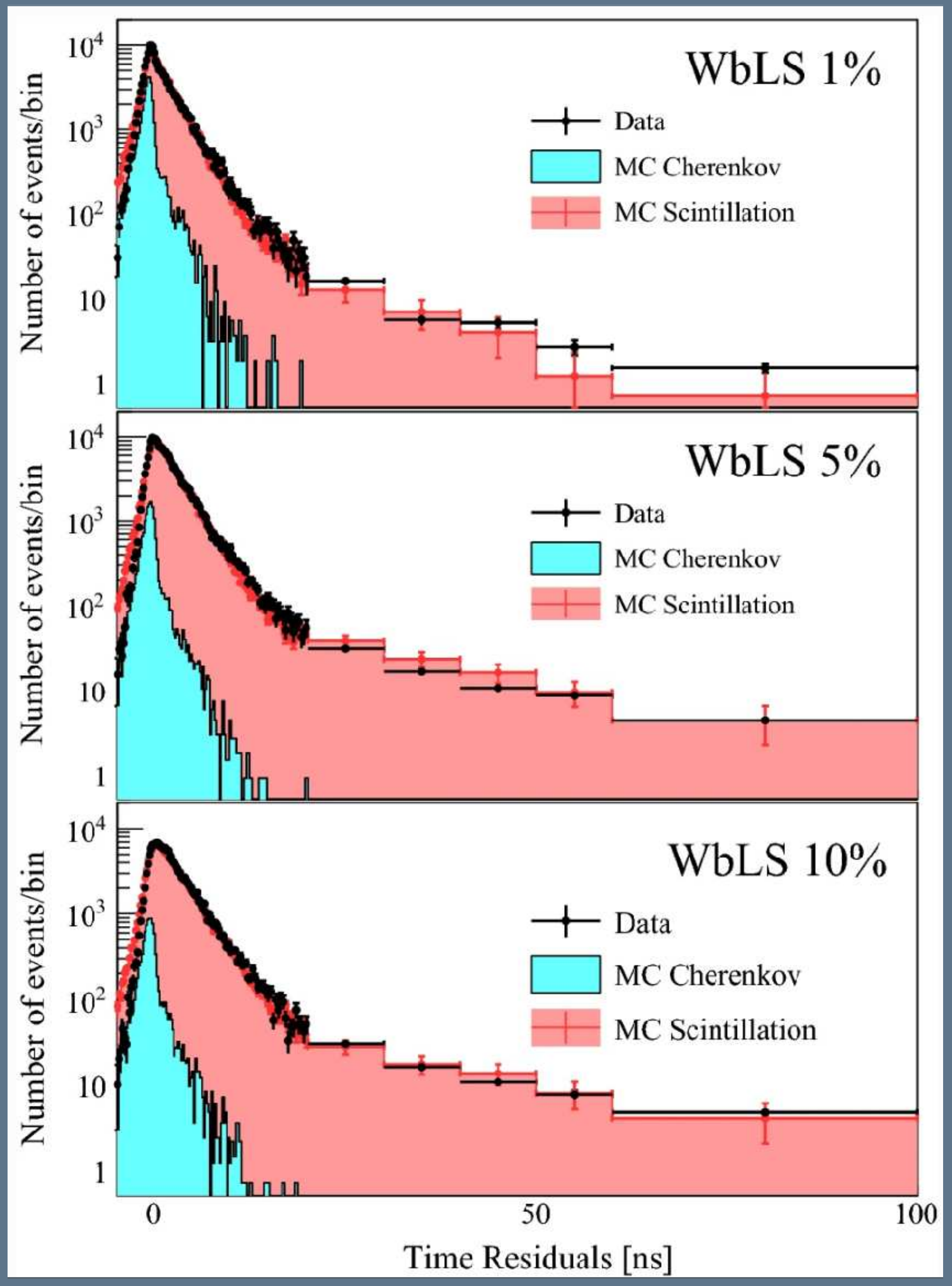
CHESS: Cherenkov / Scintillation Seperation

- Constructed from a grid of 1in fast PMTs to geometrically isolate Cherenkov light.
- Measured WbLS and pure LAB timing profiles and light-yields.
- Future upgrades include integration with other potential optical detector upgrades.



WbLS	1%	5%	10%
τ_r[ns]	0.00 ± 0.06	0.06 ± 0.11	0.13 ± 0.12
τ_1[ns]	2.25 ± 0.15	2.35 ± 0.13	2.70 ± 0.16
τ_2[ns]	15.10 ± 7.47	23.21 ± 3.28	27.05 ± 4.20
R_1	0.96 ± 0.01	0.94 ± 0.01	0.94 ± 0.01

Measurement of WbLS timing profile with a rise time plus two exponential fit.



Scintillation time profile for various WbLS loadings comparing MC to data in CHESS.

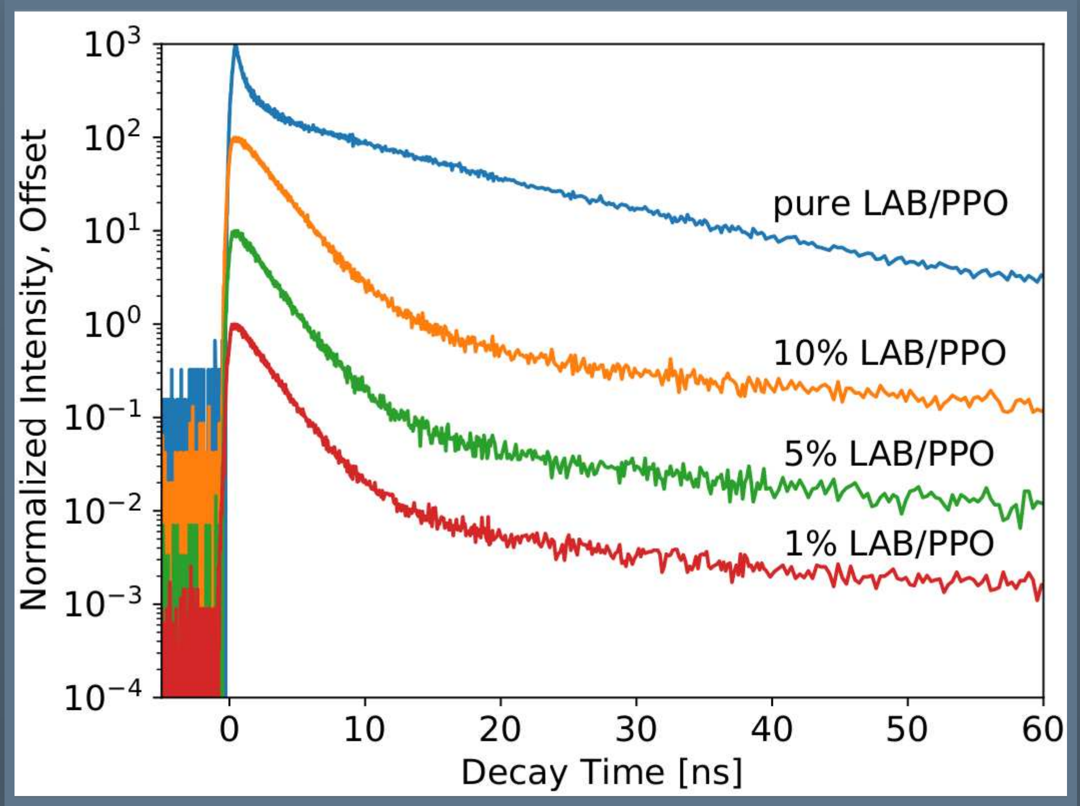
Phys. Rev. C **95**, 055801 (2017) Eur. Phys. J. C **77**, 811 (2020)
Eur. Phys. J. C **80**, 867 (2020)

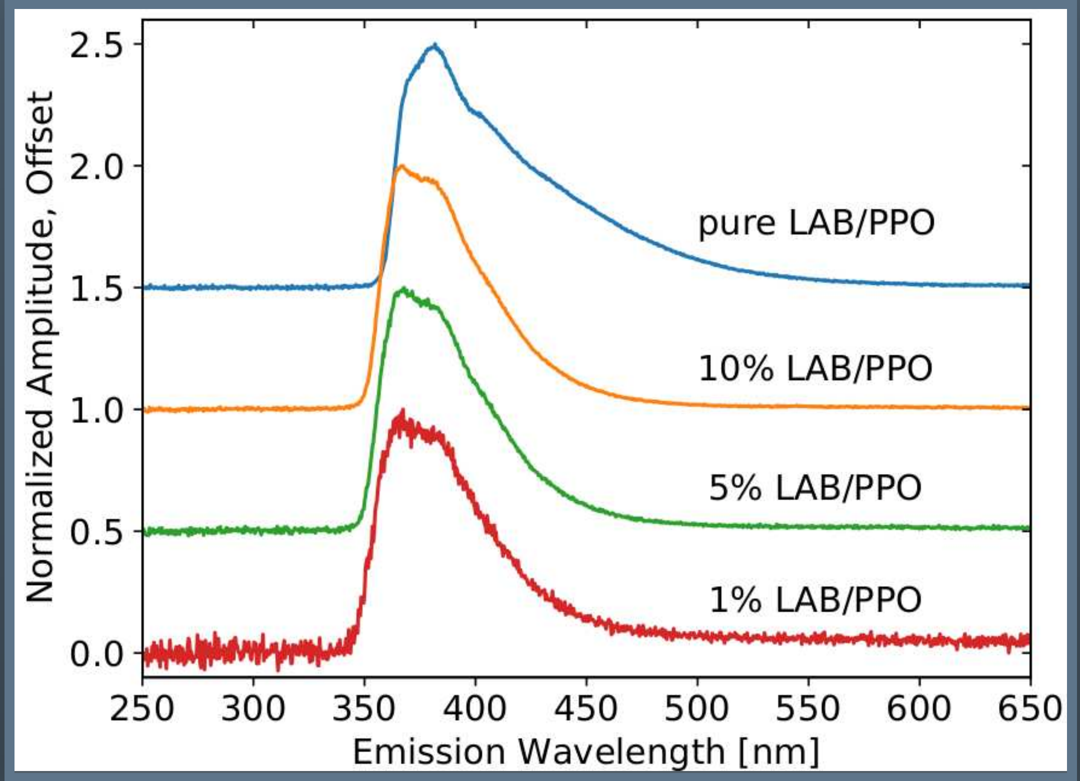
Time Response from X-ray Excitation

- Samples of 1%, 5%, and 10% WbLS prepared with 90g/L PPO in LAB.
- X-rays injected perpendicular to spectrometer.
- Measurements of emission wavelength, timing profiles, and relative light-yield are collected for each sample.

Mater. Adv. **1**, 71 (2020)

WbLS Samples	τ_{rise} [ns]	τ_1 [ns]	f_1 [%]	τ_2 [ns]	f_2 [%]	τ_3 [ns]	f_3 [%]
1% LAB/PPO	0.23 ± 0.06	2.00 ± 0.03	87	12 ± 1	6.8	110 ± 10	6.2
5% LAB/PPO	0.23 ± 0.04	2.00 ± 0.02	88	10.0 ± 0.6	6.6	106 ± 6	5.7
10% LAB/PPO	0.29 ± 0.03	2.22 ± 0.03	89	10.7 ± 0.9	6.0	102 ± 9	5.5





Summary

- → Demonstrations of the WbLS timing profiles and relative light-yields (Eur. Phys. J. C **80**, 867 — Mater. Adv. **1**, 71) show higher than expected WbLS light-yield and faster timing profiles.
- → Proton light-yield measurements will provide the basis for particle identification for background rejection in low-energy analysis such as reactor / geo anti-neutrinos as well as neutrino–proton elastic scattering.
- → Cherenkov / scintillation separation in WbLS has been shown (Phys. Rev. D **103**, 052004) to provide increased sensitivity to CNO neutrinos.
- → Optical attenuation measurements (SAMD) and purification systems are needed to scale Theia to the 100 kt scale.

See other talks for details on other supporting technologies

- → Previous talk by Benjamin Land on chromatic separation
- → Large Area Picosecond Photo-detectors (LAPPDs) by Emrah Tiras tomorrow

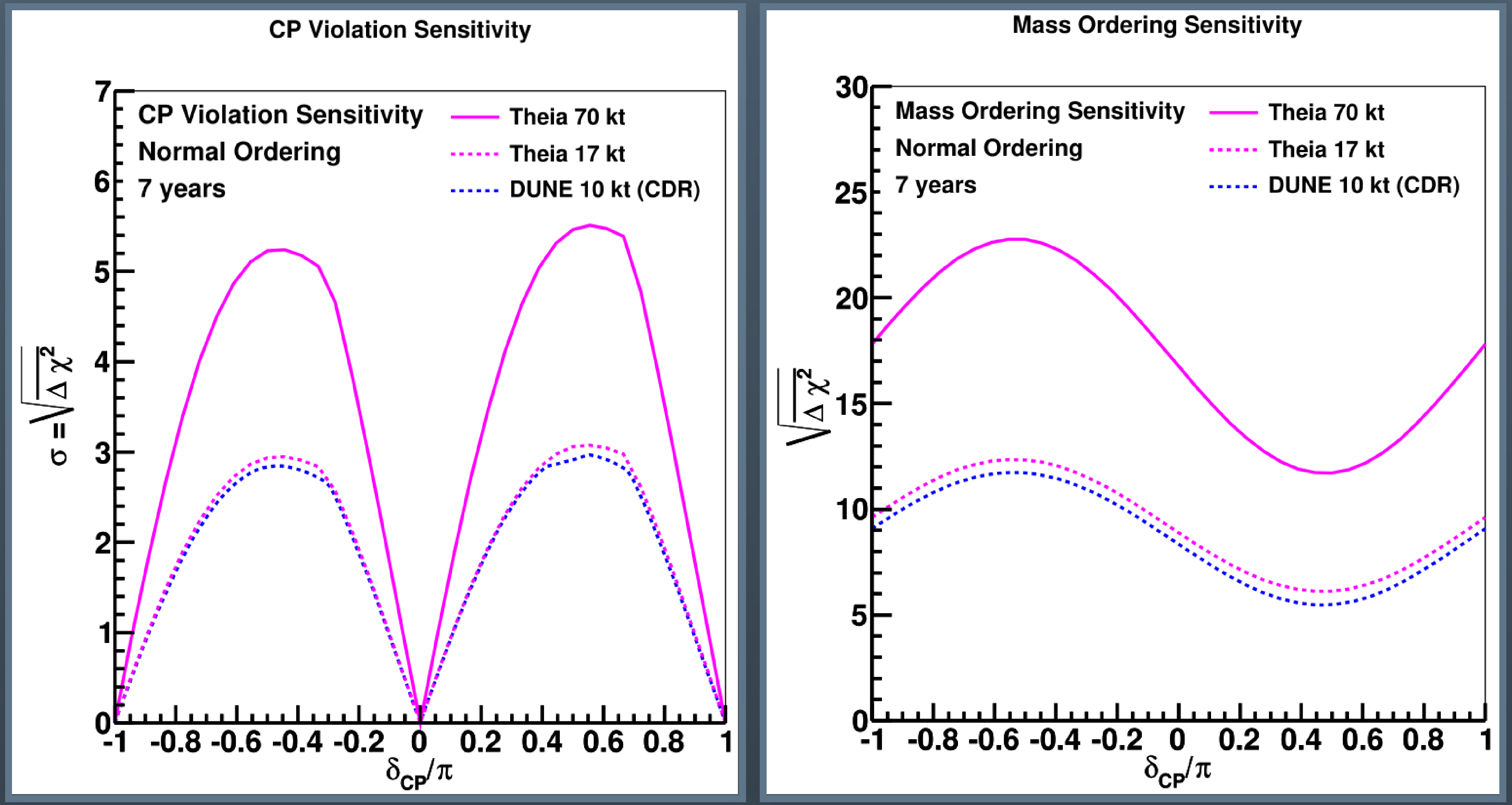
Backup

Theia Physics Reach

Primary Physics Goal	**Reach**	**Exposure / assumptions**
Long-baseline oscillations	$> 5\sigma$ for 30% of δ_{CP} values	524 kt-MW-yr
Supernova burst	$< 1(2)^\circ$ pointing accuracy	100(25)-kt detector, 10kpc
	20,000 (5,000) events	
DSNB	5σ discovery	125 kton-yr
CNO neutrino flux	< 5 (10)%	300 (62.5) kton-yr
Reactor neutrino detection	2000 events	100 kton-yr
Geo neutrino detection	2650 events	100 kton-yr
NLDBD	$T_{1/2} > 1.1 \times 10^{28}$ yr	211 ton-yr ^{130}Te
Nucleon decay $p \to \overline{\nu} K^+$	$T > 3.80 \times 10^{34}$ yr (90% CL)	800 kton-yr

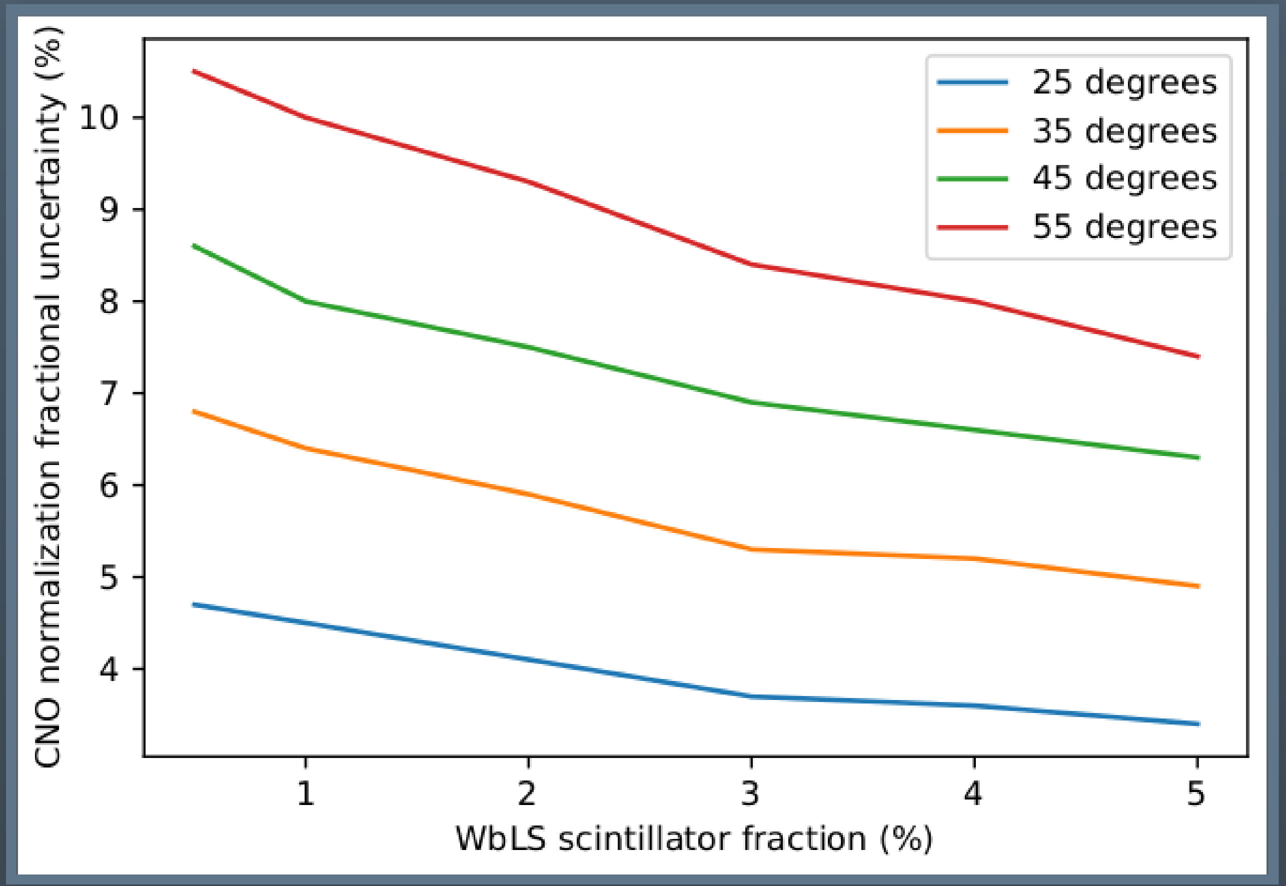
Long baseline oscillations

- Oscillation parameter sensitivity for Theia at SURF.
- 17 kt (fiducial volume) Theia compliments DUNE results, providing an independent cross-check of the extracted oscillation parameter values.
- Better than 3σ sensitivity to CP violation in 100 kt.
- Benefits from improvements in ring fitting from T2K (using fiTQun).

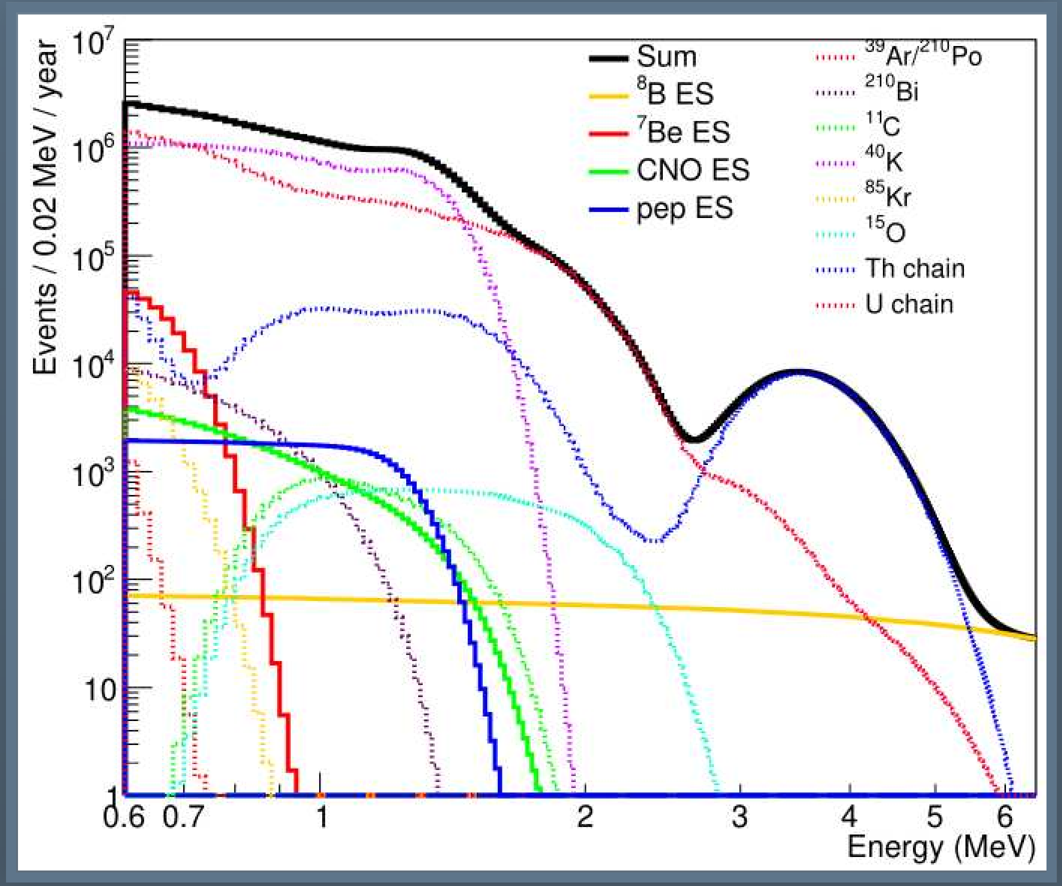


Solar neutrinos

→ Event direction provides radioactive background discrimination
→ 2D binned maximum likelihood fit in reconstructed energy and event direction.



Fractional uncertainty on the CNO normalization as a function of angular resolution and WbLS scintillator fraction for Theia-100.



Energy spectrum of expected signals for a 25 kt, 5% WbLS Theia.

Additional solar neutrino studies include

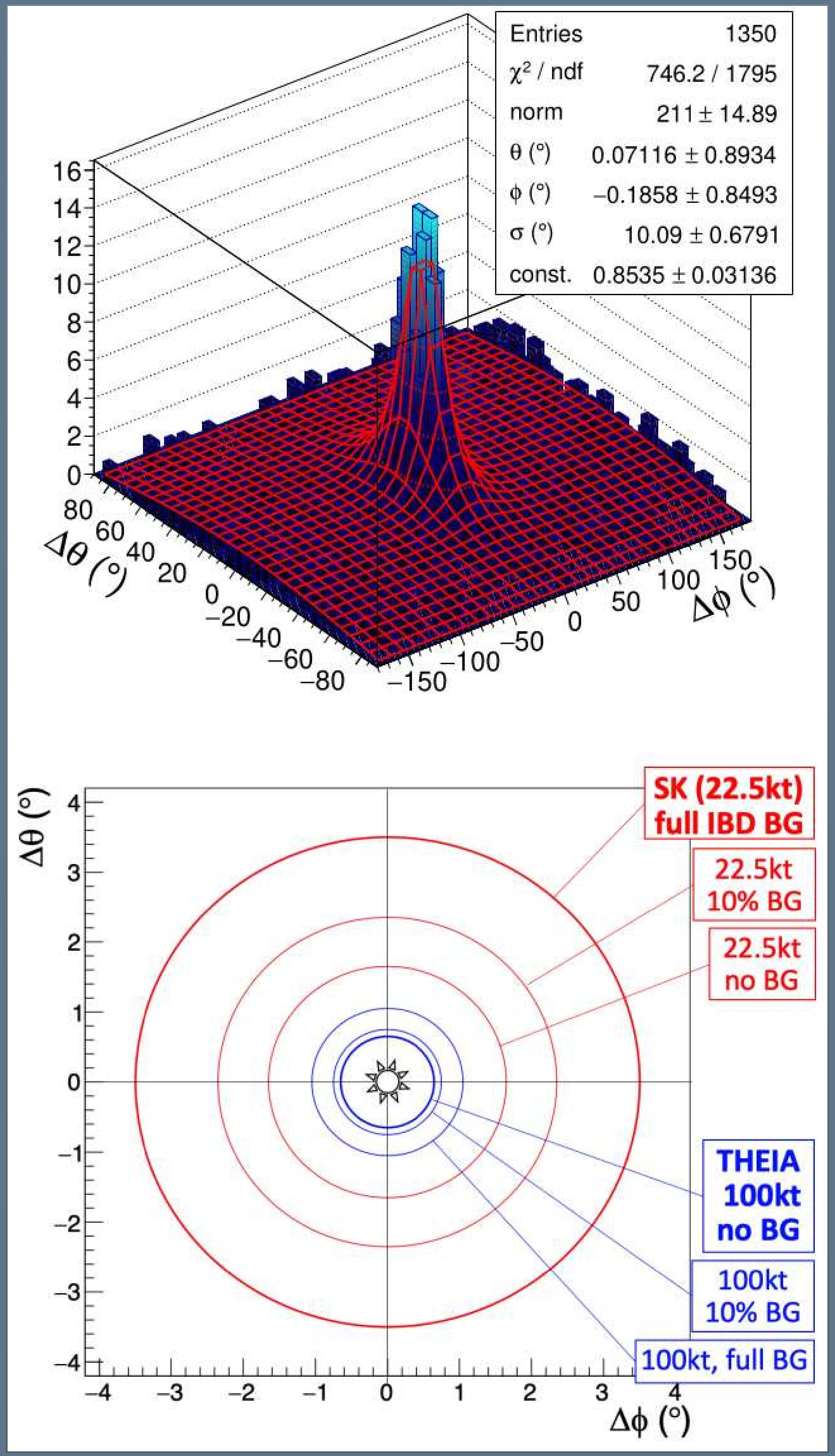
→ The ^{8}B transition between 1 and 5 MeV
→ *pp* and *pep* flux.

Supernova neutrinos

- → High-statistics (from target mass) combined with a low energy-threshold.
- → Directional signature for ES events, and tagged coincidence for IBD to distinguish ν_e and $\bar{\nu}_e$ events.
- → Supernova pointing (by rejecting IBD to get pure ES events).

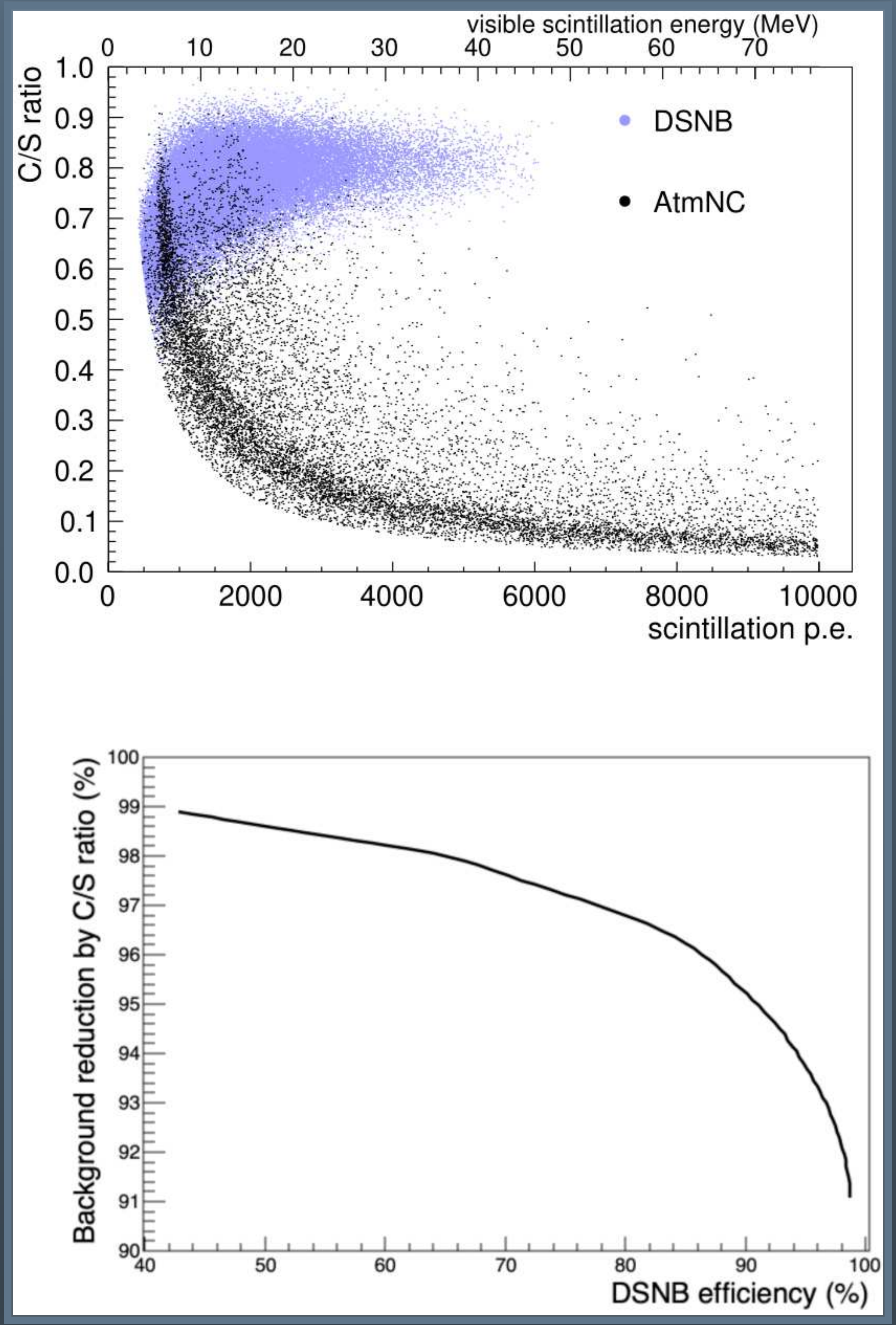
Table 5 Event rates expected in 100 kt of WbLS (10 % scintillator) for an SN at 10 kpc distance (GVKM model [109] and SNOwGLoBES). We list inverse beta decays (IBDs), elastic scattering off electrons (ES) as well as charged-current (ν_eO,$\bar{\nu}_e$O) and neutral-current (NCO) interactions on oxygen. Comparatively small event rates on carbon are not listed.

Reaction		Rate
(IBD)	$\bar{\nu}_e + p \rightarrow n + e^+$	19,800
(ES)	$\nu + e \rightarrow e + \nu$	960
(ν_eO)	$^{16}\mathrm{O}(\nu_e, e^-)^{16}\mathrm{F}$	340
($\bar{\nu}_e$O)	$^{16}\mathrm{O}(\bar{\nu}_e, e^+)^{16}\mathrm{N}$	440
(NCO)	$^{16}\mathrm{O}(\nu, \nu)^{16}\mathrm{O}^*$	1,100



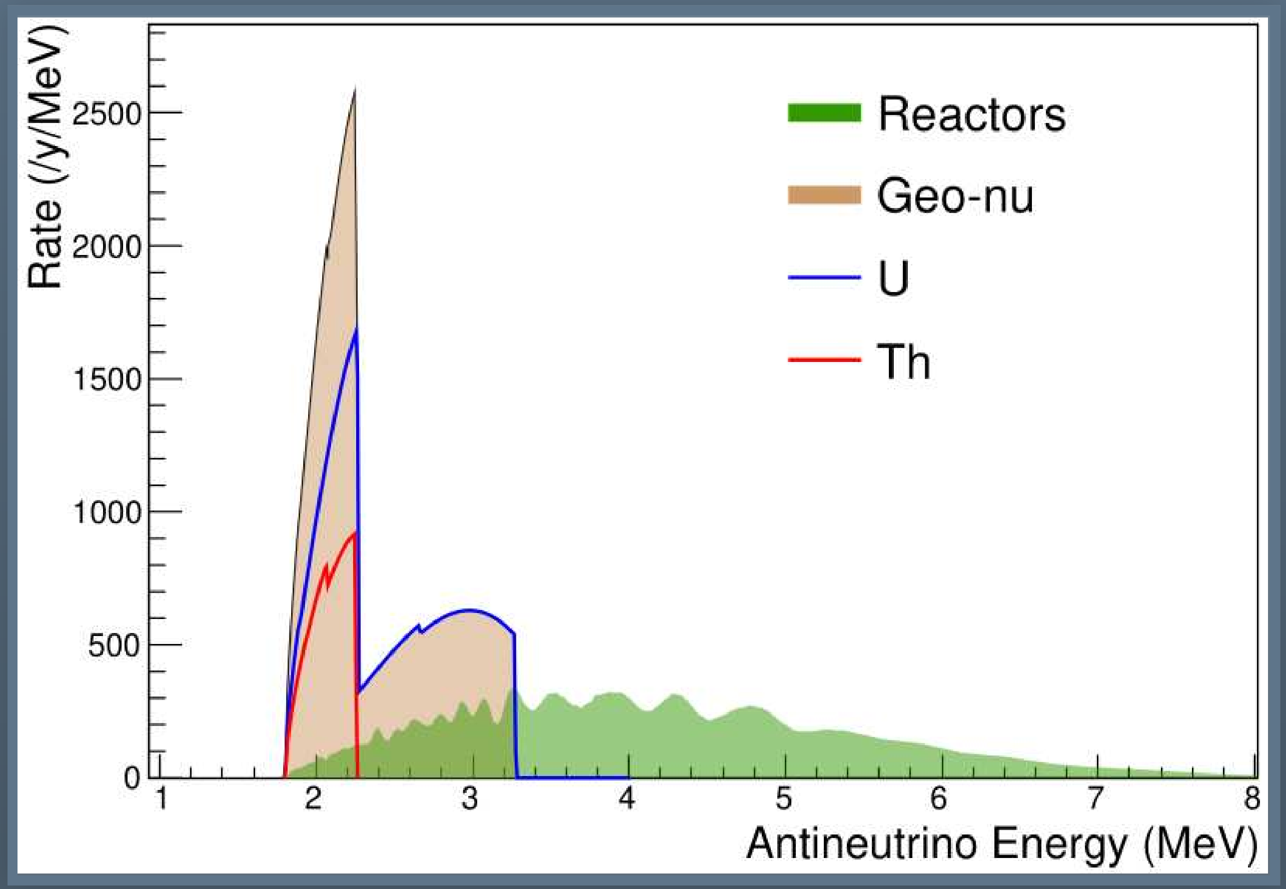
Diffuse supernova neutrino background

- → Particle identification would significantly reduce cosmogenic neutron backgrounds which IBD signals.
- → Ring counting can discriminate one-ring IBD positron events (ignoring the 511 keV γs) from multi-ring atmospheric neutral current events.
- → Rates expected at 0.1 per year per kiloton
- → 5σ discovery of SDNB in less that 1 year (for 100kt target)



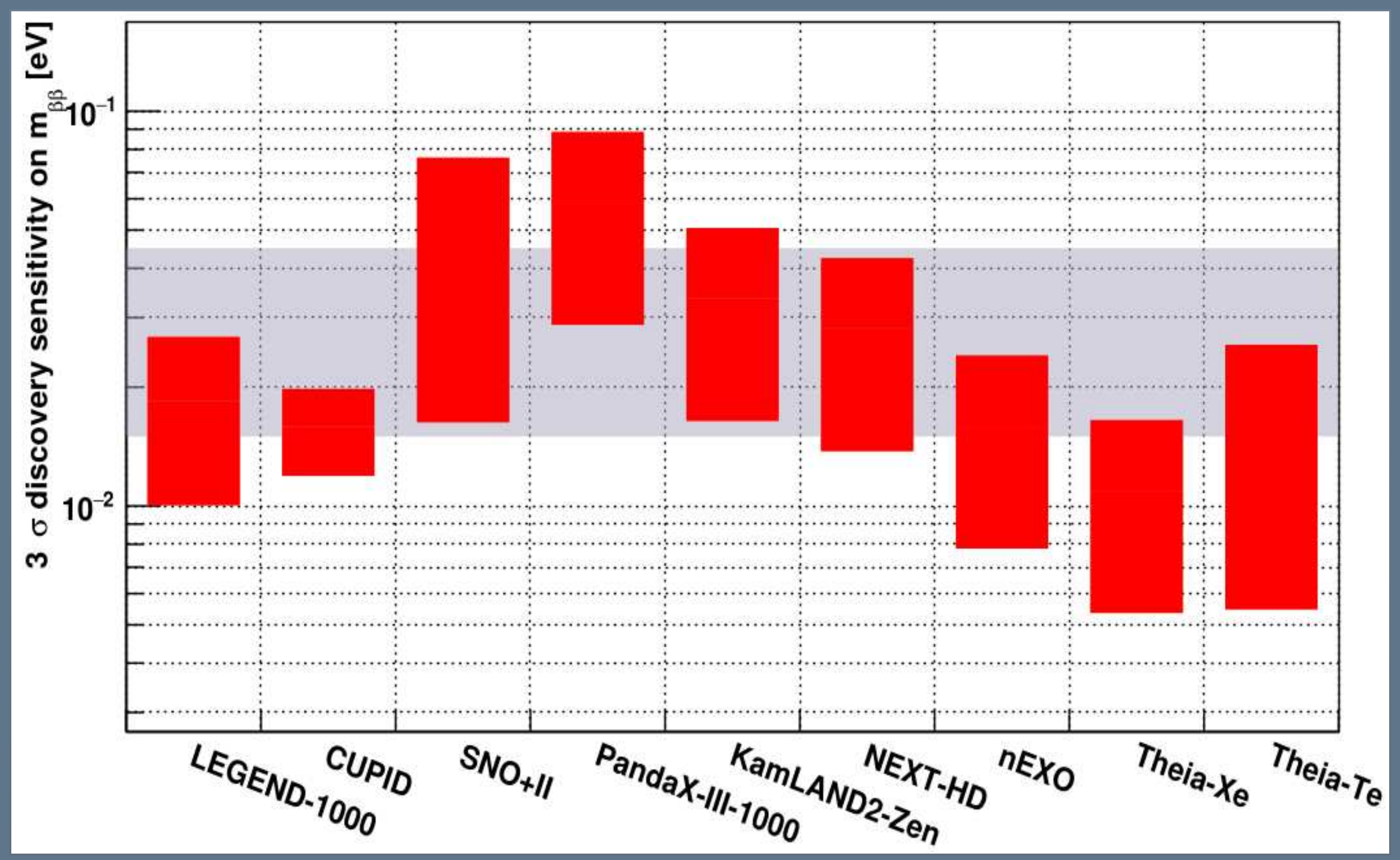
Geo/reactor antineutrinos

- Higher light-yield and energy threshold provides lower energy threshold on primary positron as well as high efficiency for the 2.2 MeV neutron capture on hydrogen.
- 26.5 geoneutrino interactions per kT-year at SURF.



Neutrinoless double beta decay

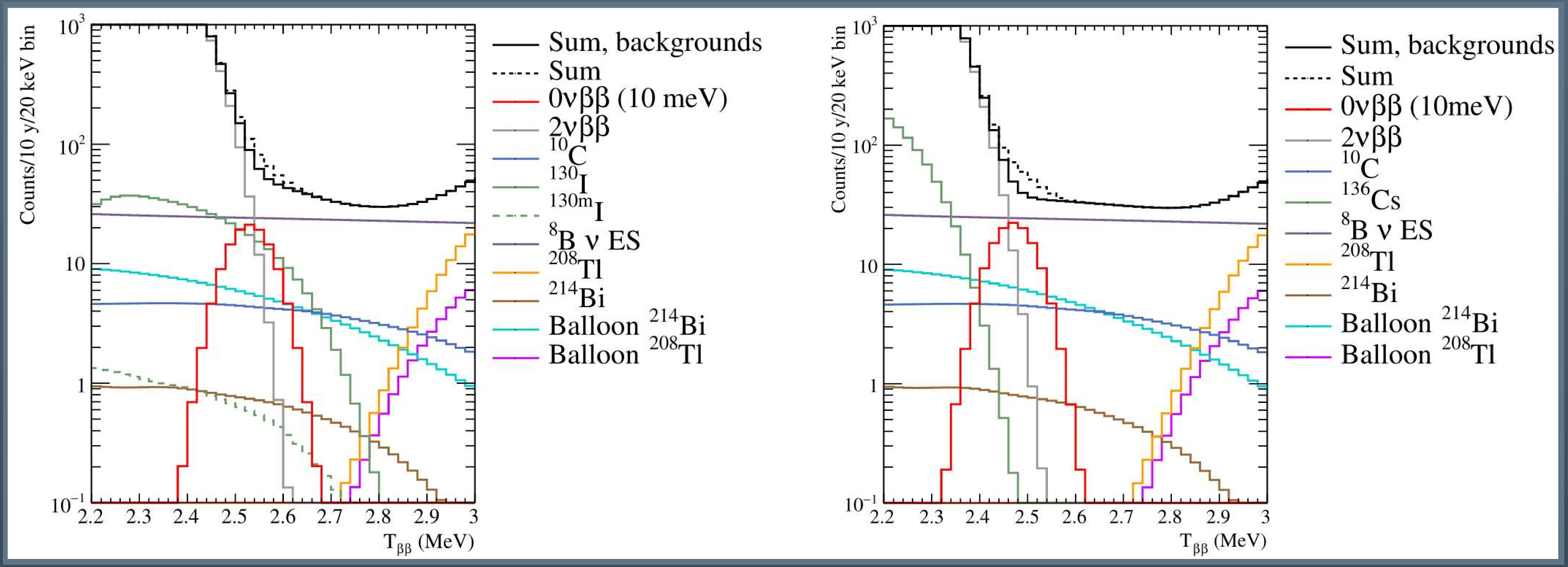
→ Achieved using a full liquid scintillator interior vessel (kamLAND-like)
→ Either 3% enriched Xe or 5% natural Te loaded (in an assumed 8m baloon)



Source	Target level	Expected events/y	Events/ROI·y 5% ^{nat}Te	Events/ROI·y 3% ^{enr}Xe
^{10}C		500	2.5	2.5
^{8}B neutrinos (flux from [124])		2950	13.8	13.8
^{130}I (Te target)		155 (30 from ^{8}B)	8.3	-
^{136}Cs (^{enr}Xe target)		478 (68 from ^{8}B)	-	0.06
$2\nu\beta\beta$ (Te, $T_{1/2}$ from [125])		1.2×10^{8}	8.0	-
$2\nu\beta\beta$ (^{enr}Xe, $T_{1/2}$ from [126,127])		7.1×10^{7}	-	3.8
Liquid scintillator	^{214}Bi: 10^{-17} g_U/g	7300	0.4	0.4
	^{208}Tl: 10^{-17} g_{Th}/g	870	-	-
Balloon	^{214}Bi: $< 10^{-12}$ g_U/g	$<2\times10^{5}$	3.0	3.4
	^{208}Tl: $< 10^{-12}$ g_{Th}/g	$<3\times10^{4}$	0.03	0.02

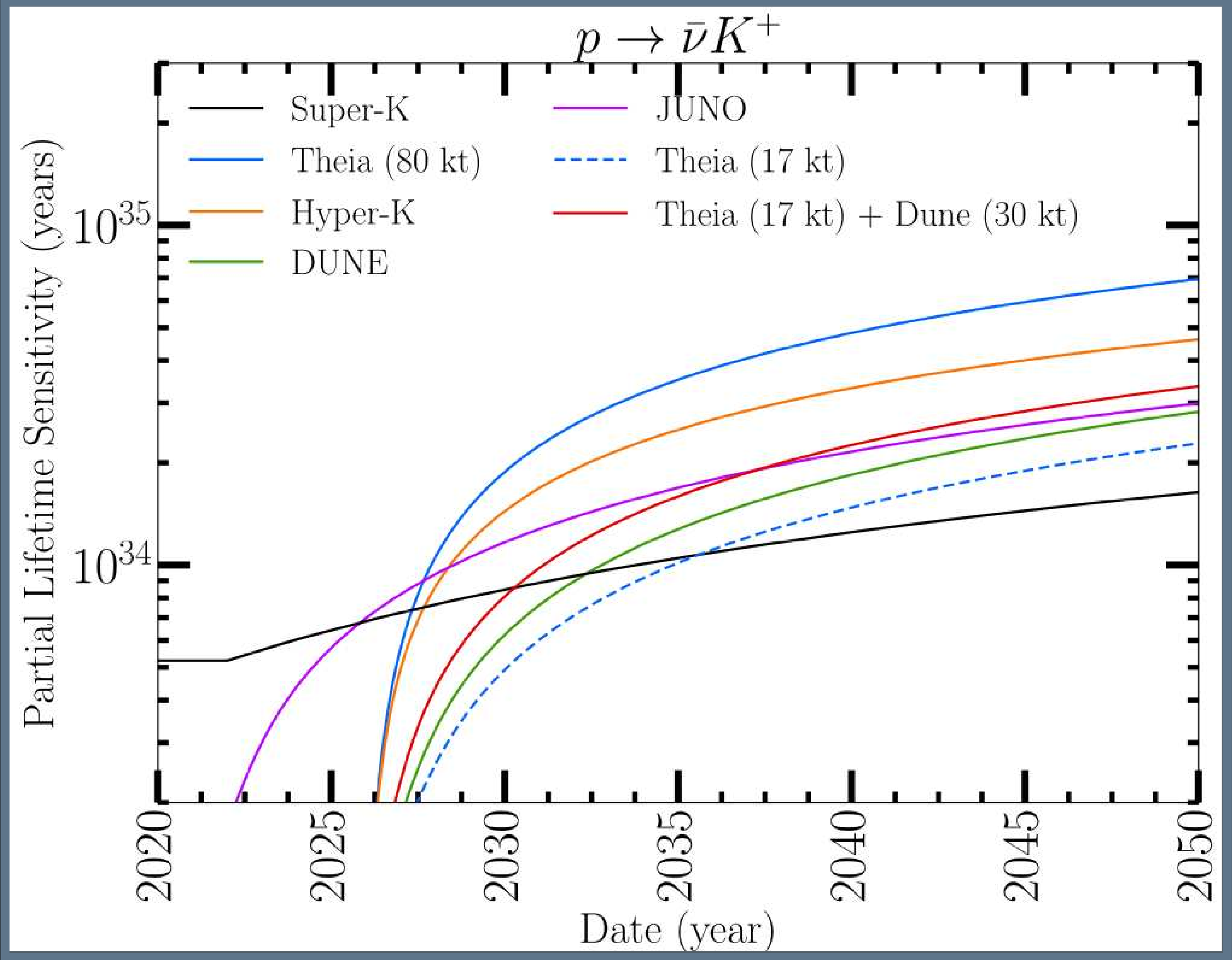
Neutrinoless double beta decay

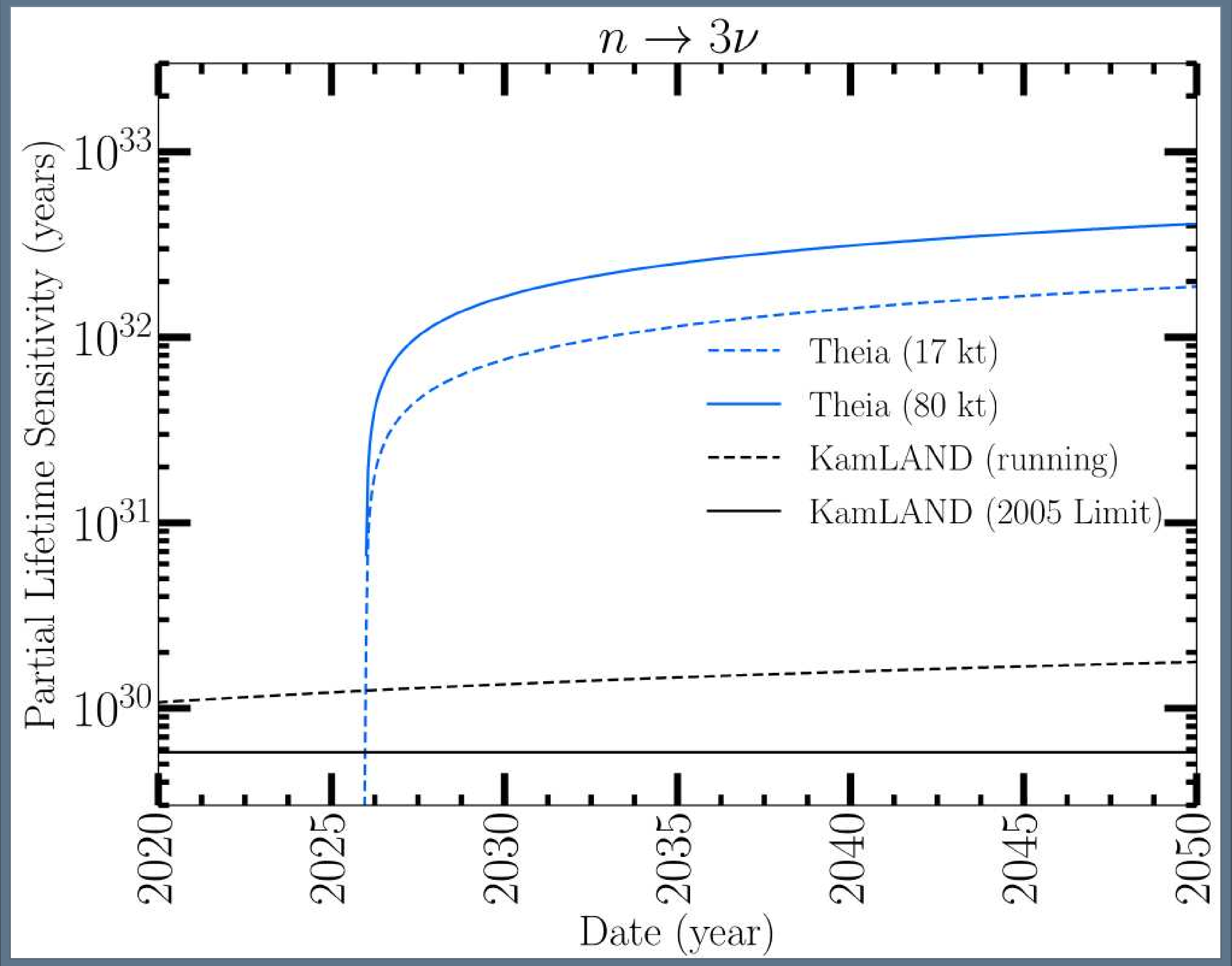
Energy spectra near the $0\nu\beta\beta$ endpoint for events within a 7m fiducial volume for 10 years data taking.



Nucleon Decay

$p \to \nu K$-like modes would benefit from chromatic sorting, as the event signature is a 3-fold coincidence with the first being a 12-ns kaon decay.





Invisible neutron decay benefits from a high branching ratio to a 6 MeV γ from oxygen.