Motivations for Hybrid Technology

Workshop on Hybrid Cherenkov / Scintillation Detection Techniques

Tanner Kaptanoglu
UC Berkeley & LBNL
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Some motivating questions

1. Why would we build a hybrid-style detector as opposed to a liquid scintillator or water Cherenkov detector?
2. What physics capabilities would a hybrid detector unlock beyond what a JUNO or Hyper-K style detector can achieve?
3. If a hybrid detector is built, for example at SURF or SNOLAB, what other physics can it achieve (“broad program”)?

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3. If a hybrid detector is built, for example at SURF or SNOLAB, what other physics can it achieve (“broad program”)?

JUNO, Hyper-K, SNO+, DUNE, SuperK-Gd, Jinping, etc., will have run and/or be running, physics motivations should go beyond what these detectors are planning.

THEIA

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In this talk, “THEIA” refers to an enormous (25 ktonne or larger) neutrino detector that has the capability to perform direction reconstruction (25° resolution or worse) by leveraging a variety of different technology summarized by A. Mastbaum and that we will hear much more about later.

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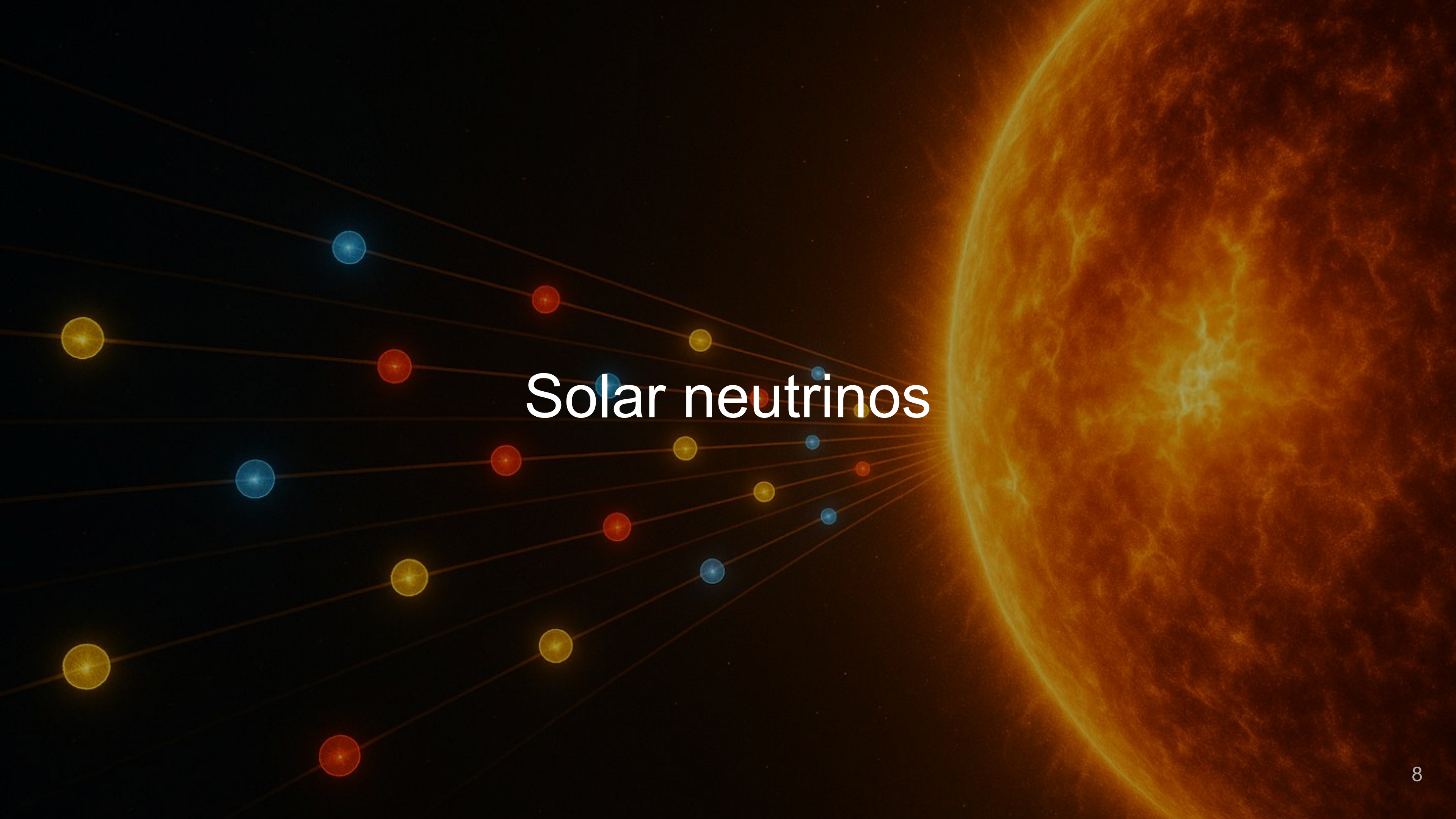
The motivations for the hybrid technology revolve around our ability to make impactful physics measurements with a future detector like THEIA.

Physics motivations for hybrid detectors

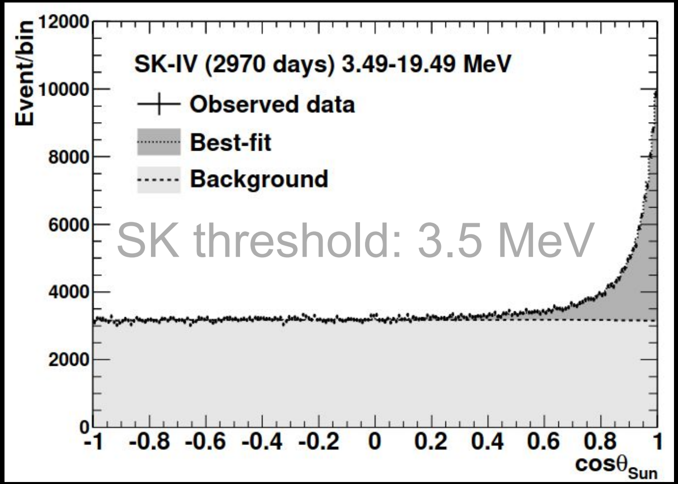
1. Solar neutrinos
2. $0\nu\beta\beta$
3. Long baseline physics
4. Diffuse supernova neutrino background (DSNB)
5. Supernova burst neutrinos



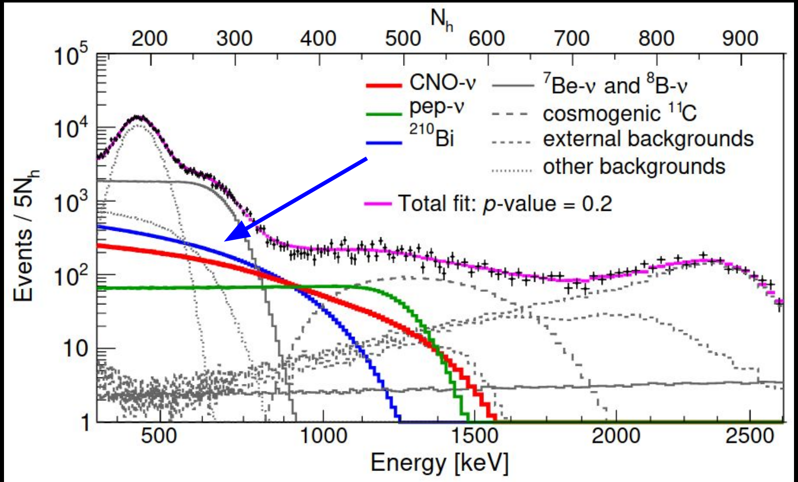
Solar neutrinos

Solar neutrinos

For low energy solar neutrinos, below ~3 MeV, water Cherenkov detectors have high thresholds & backgrounds. Scintillator detector cannot distinguish the direction of the events (thus, higher background from e.g., ^{210}Bi).



Super-Kamiokande collaboration: https://arxiv.org/pdf/2312.12907



Borexino collaboration: https://arxiv.org/pdf/2307.14636

Solar neutrinos

Both Borexino and SNO+ have explored using event directionality to improve the sensitivity of their solar neutrino measurements.

SNO+ event-by-event directionality: https://arxiv.org/pdf/2309.06341

Borexino integrated directionality: https://arxiv.org/pdf/2109.04770

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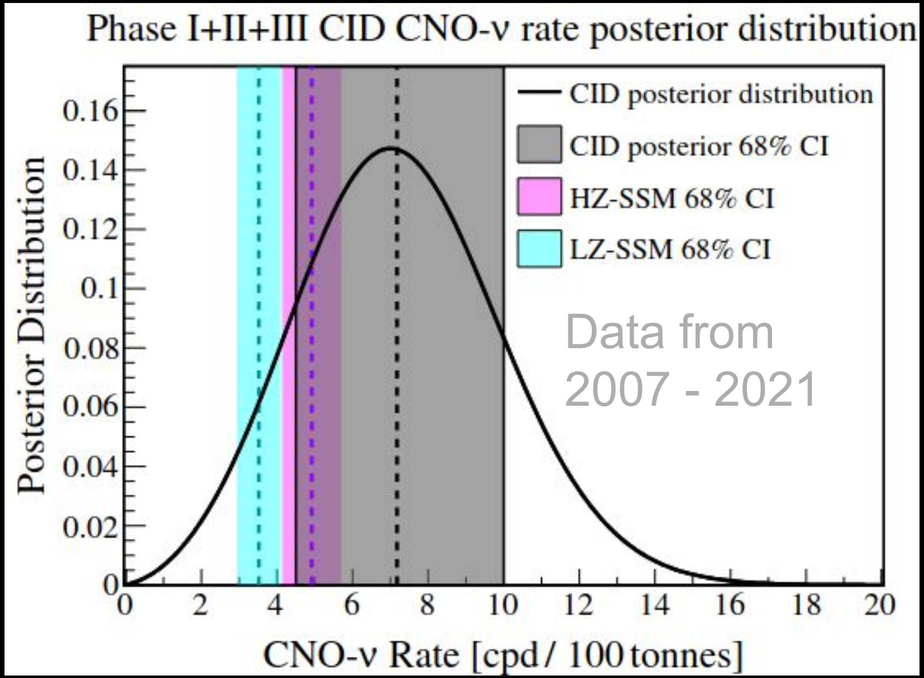
How much better can we do with a hybrid detector? Also, are there additional techniques (e.g., loading isotopes) that could expand a solar neutrino program.

CNO neutrinos

Borexino measurement of the CNO flux has ~20% uncertainties.

Prefers the HZ-SSM metallicity, but only exclude LZ-SSM a relatively low significance (< 2σ).

Used the integrated directionality of their selected events to improve sensitivity.



Borexino collaboration: https://arxiv.org/pdf/2307.14636

CNO neutrinos

Borexino collaboration “endorses” hybrid detectors:

“The results described in this work reinforce the role of the event directional information in large-scale liquid scintillator detectors and open up new avenues for the next-generation liquid scintillator or hybrid neutrino experiments. A particular relevance is expected for the latter detectors, which aim to combine the advantages from both Cherenkov-based and scintillation-based detection techniques.”

Borexino collaboration: https://arxiv.org/pdf/2307.14636

CNO neutrinos

The sensitivity to CNO for a hybrid detector was studied by R. Bonvente & G.D. Orebi Gann, and showed promise for improving on the Borexino measurement.

Table 5 CNO flux sensitivity (%) as a function of target mass, WbLS % and angular resolution for 5 years of data and 60% PMT coverage with the baseline background assumptions

Target mass	WbLS	Angular resolution 25°	35°	45°	55°
50 kT	0.5%	6.7	9.1	11.7	14.4
50 kT	1%	6.5	9.3	11.6	14.1
50 kT	2%	6.8	9.8	12.4	15.2
50 kT	3%	6.6	9.4	12.0	14.6
50 kT	4%	6.2	8.8	11.3	13.7
50 kT	5%	5.9	8.5	10.8	13.0
25 kT	0.5%	9.1	12.8	16.2	19.2
25 kT	1%	8.9	12.7	16.1	19.1
25 kT	2%	9.3	13.3	16.9	20.4
25 kT	3%	8.9	12.7	16.2	19.7
25 kT	4%	8.4	12.0	15.3	18.6
25 kT	5%	8.0	11.5	14.6	17.8

Table 7 CNO flux sensitivity (%) as a function of target mass, WbLS % and angular resolution for 5 years of data and 90% PMT coverage with the Borexino measured ^{40}K level in water

Target mass	WbLS	Angular resolution 25°	35°	45°	55°
50 kT	0.5%	14.5	20.9	26.6	31.5
50 kT	1%	13.8	20.1	25.7	31.0
50 kT	2%	13.7	20.2	25.8	31.2
50 kT	3%	12.4	17.7	22.6	27.1
50 kT	4%	11.8	16.8	21.3	25.6
50 kT	5%	11.4	16.1	20.5	24.6
25 kT	0.5%	20.0	29.2	36.9	45.5
25 kT	1%	19.3	27.3	34.6	42.4
25 kT	2%	17.9	25.9	32.6	39.0
25 kT	3%	17.1	24.2	30.8	36.5
25 kT	4%	16.3	23.2	29.3	35.3
25 kT	5%	15.6	22.2	28.2	33.9

R. Bonventre, G.D. Orebi Gann: https://arxiv.org/pdf/1803.07109

CNO neutrinos

Results depend strongly on background assumptions (^{40}K), which mostly comes from the water in the WbLS.

Perhaps even better sensitivity possible using scintillator with directionality (from fast timing, slow scintillator, and/or spectral sorting), but ^{11}C background scales with liquid scintillator concentration.

CNO neutrinos

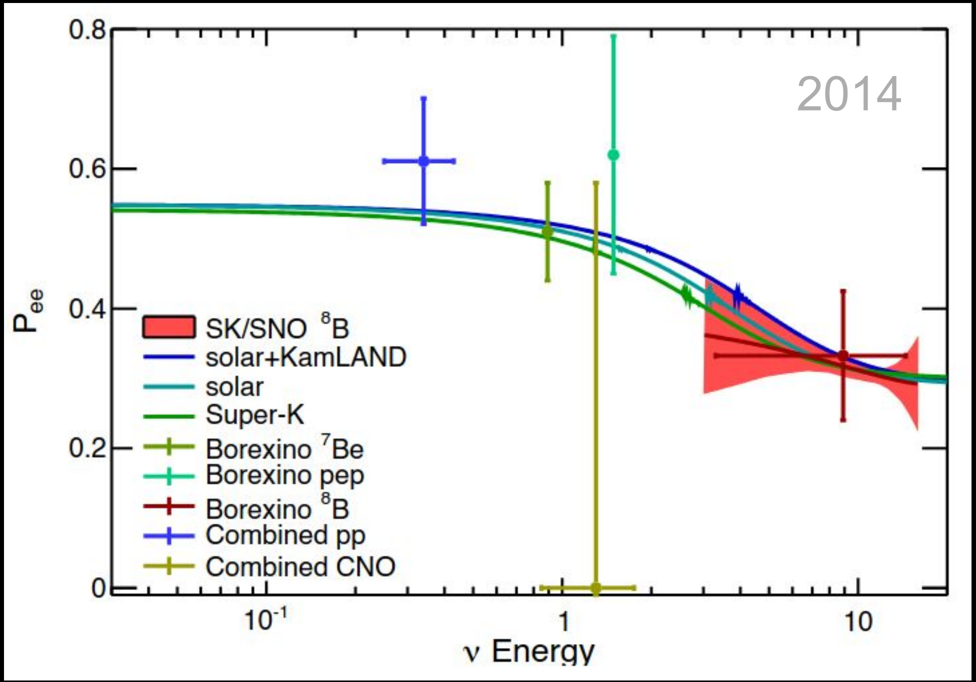
In a separate paper, B. Land et al., explored the CNO sensitivity for WbLS and pure LS and for a 50-kt detector with fast timing:

"We find that in 5 years of data taking, the CNO flux could be determined to a relative uncertainty of 18% (8%) in the 50-kt, LAPPD-instrumented 10% WbLS detector when the pep flux is unconstrained (constrained to 1.4%), and to 1% in the same detector filled with LAB+PPO."

B. Land et al.: https://arxiv.org/pdf/2007.14999

^8B transition region

Vacuum-matter transition region between roughly 1 - 5 MeV still remains largely unexplored. It is in this region where non-standard effects may be most pronounced*.



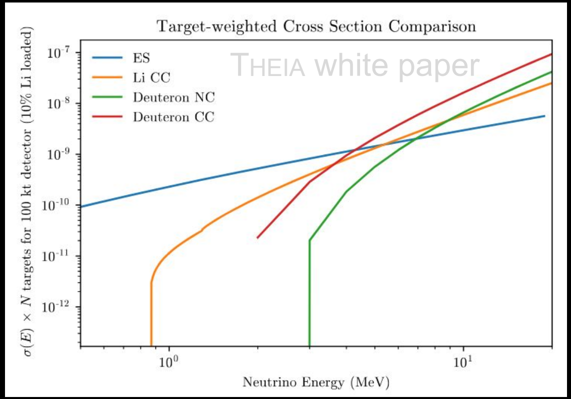
ASDC white paper https://arxiv.org/pdf/1409.5864

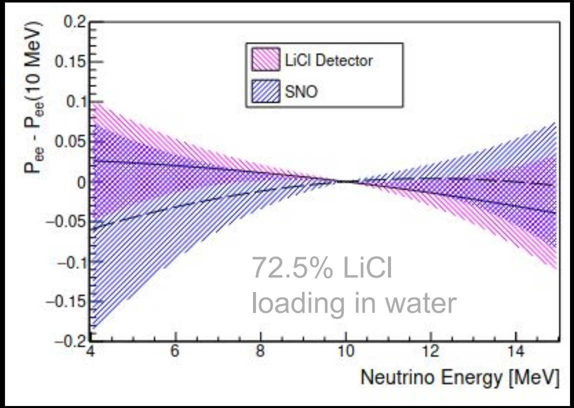
*see for example: https://arxiv.org/pdf/1305.5835, https://arxiv.org/pdf/hep-ph/0403134

^{8}B transition region

Unfortunately, the ES differential cross-section is broad, so loading of isotope (e.g., ^{7}Li) with high CC cross-section is necessary.

Motivated studies looking at sensitivities with lithium loaded WbLS (G.D. Orebi Gann, W. Haxton, M. Smiley) and LiCl (72.5%) dissolved in water. The Jinping detector is actively considering Li loading.



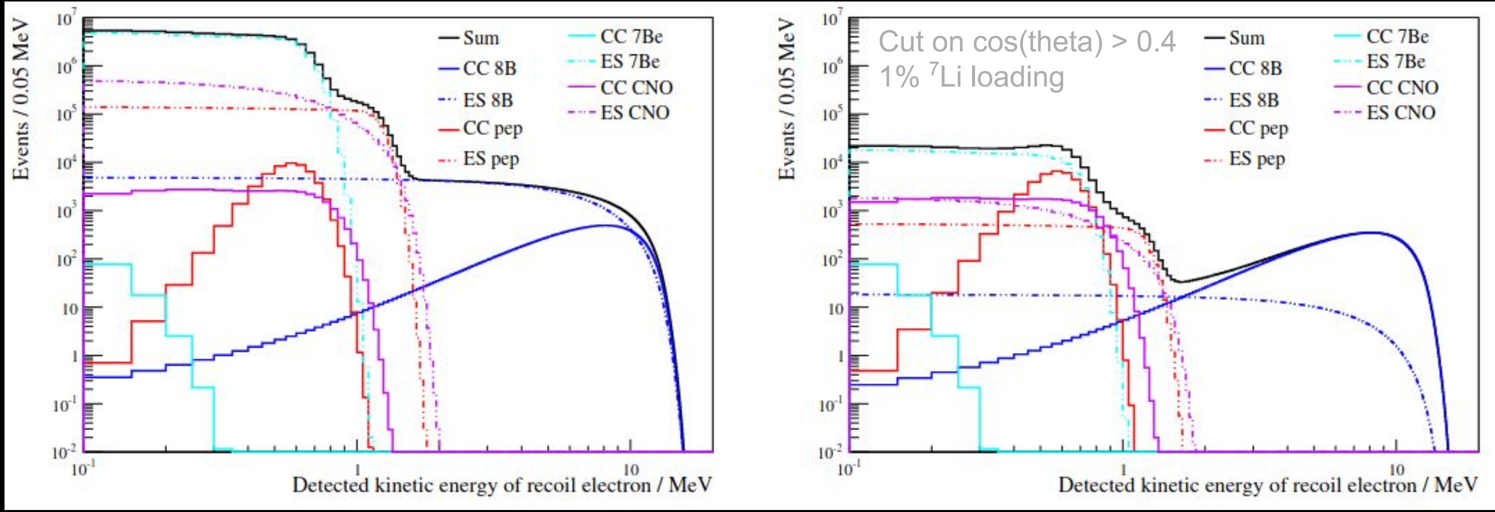


Shao et al., https://arxiv.org/pdf/2203.01860

^{8}B transition region

Directionality can be used to separate ES from ^{7}Li CC events.

ASDC paper showed ^{8}B and CNO recoil electron energy spectra; full sensitivity study in WbLS and/or slow scintillator would be very interesting.



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Future solar neutrinos

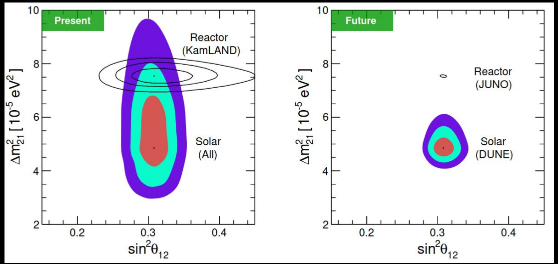
The Jinping detector in China is planning on building a roughly SNO+-size detector and fill with slow LS (potential for Li loading) (CNO and ^{8}B upturn).

JUNO claims sensitivity to CNO flux similar to BX (10-15% in 5 years).
(JUNO collaboration https://arxiv.org/pdf/2303.03910)

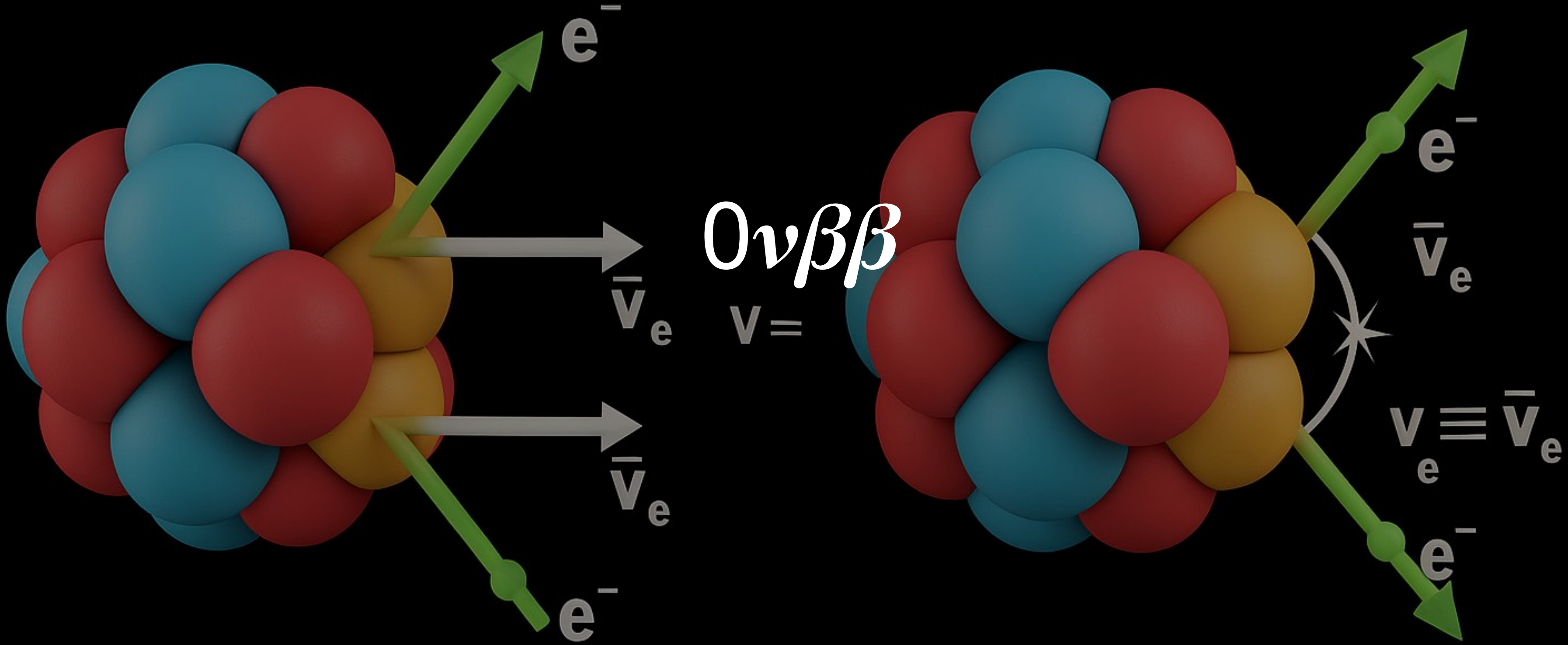
DUNE plans to measure the hep neutrinos and the day-night asymmetry.
(Beacom et al., https://arxiv.org/abs/1808.08232)

Precision measurements of the Δm^2_{21} from SNO+, JUNO, and DUNE may resolve current Solar/KamLAND tension.

THEIA should be creative and ambitious for what solar neutrino measurements can be made with a future hybrid detector.



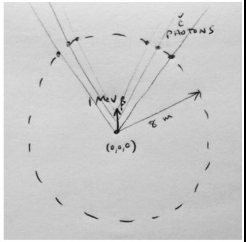
$0\nu\beta\beta$



$0\nu\beta\beta$

Large liquid scintillator detectors searching for neutrinoless double beta decay typically have large backgrounds from ^{8}B solar neutrinos.

The first paper on using directionality in large scintillation detectors was written by L. Winslow et al.*, with this use-case in mind [which then led directly to detailed SNO+ studies (A. Mastbaum, M. Mottrom, E.W. Beier)].



A. Mastbaum

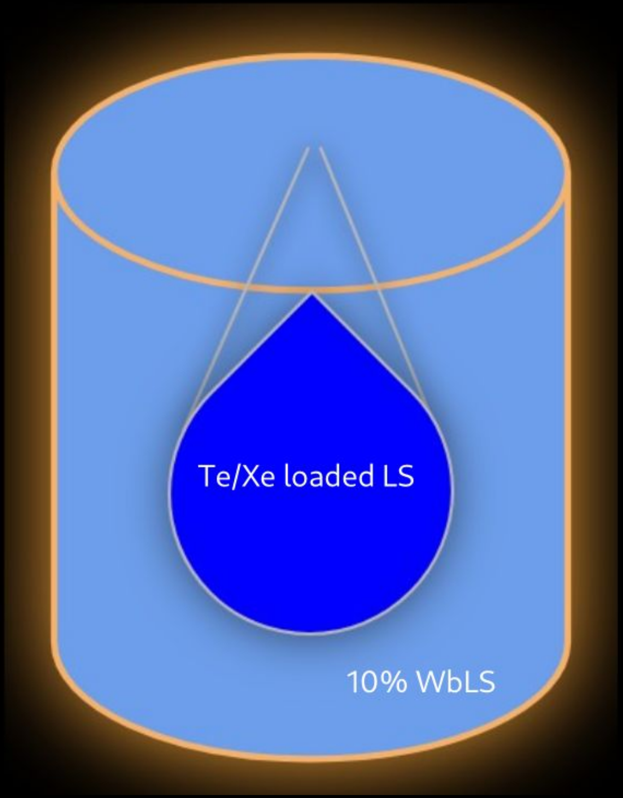
*Measuring directionality in double-beta decay and neutrino interactions with kiloton-scale scintillation detectors: https://arxiv.org/pdf/1307.5813

*Separating Double-Beta Decay Events from Solar Neutrino Interactions in a Kiloton-Scale Liquid Scintillator Detector By Fast Timing: https://arxiv.org/pdf/1609.09865

$0\nu\beta\beta$

As per the THEIA white paper, most reasonable technology choice is Te-loaded liquid scintillator.

WbLS not a reasonable option, as backgrounds are too high and the light yield is too low, but could contain LS in a bag (a la Kamland-ZEN).



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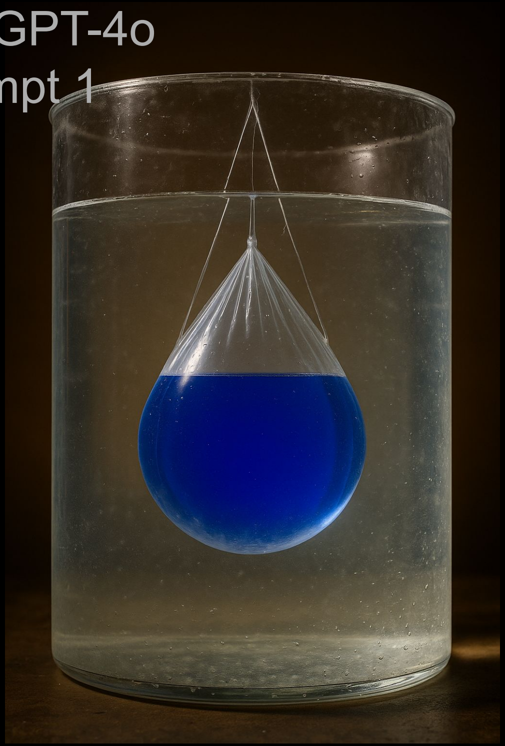
chatGPT-4o
attempt 1

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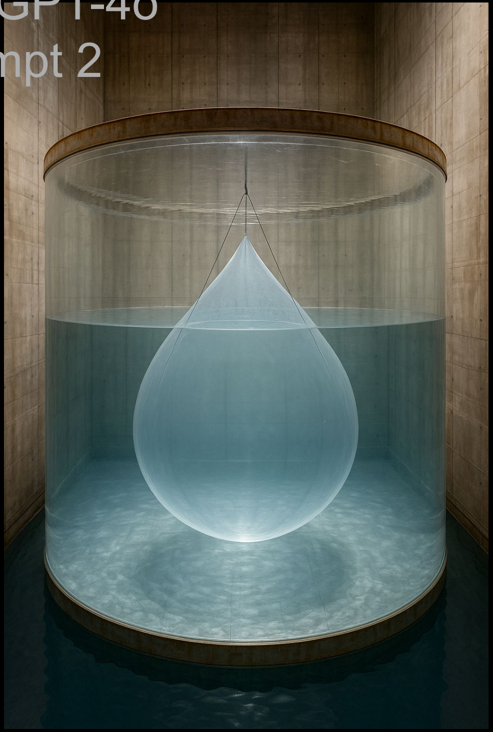

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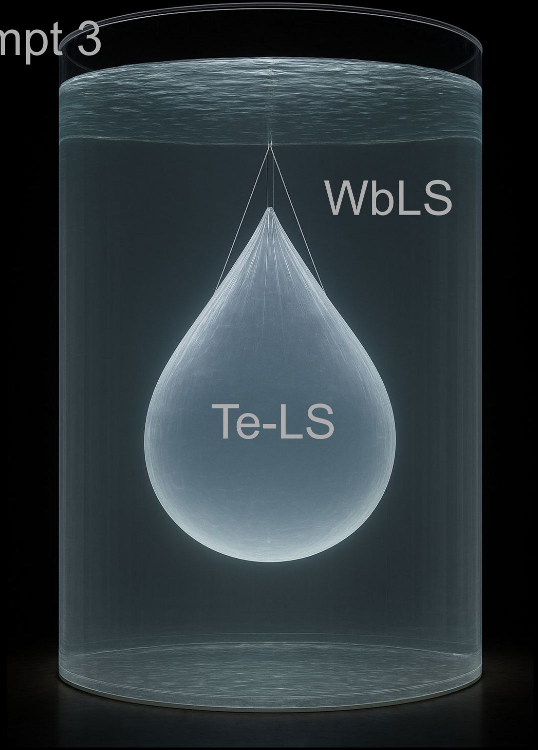

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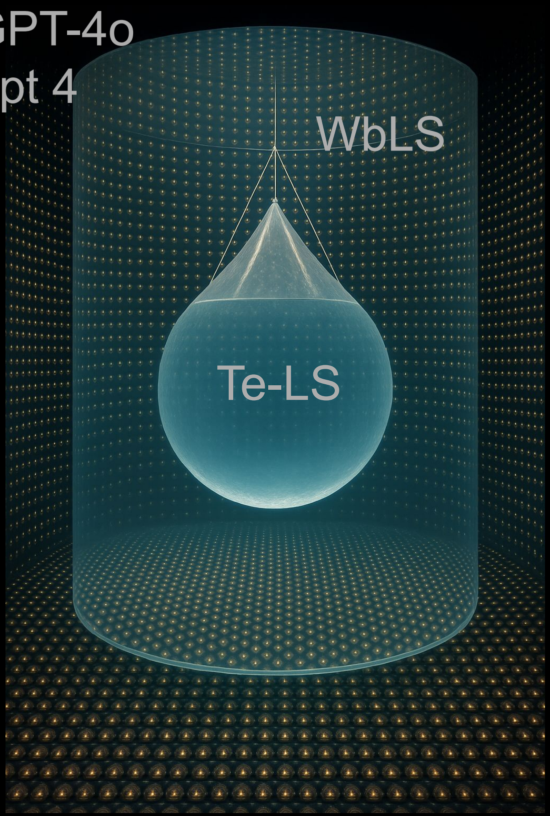


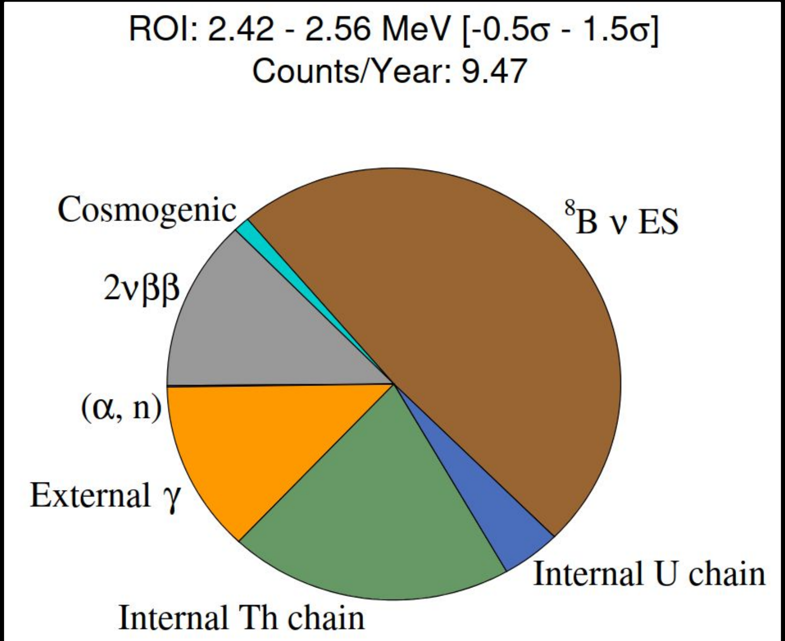
$0\nu\beta\beta$

This approach has significant advantages:

1. Demonstrated low internal backgrounds & particle ID capabilities
2. Massive detector allows fiducialization from external backgrounds
3. Many backgrounds measured prior to isotope loading
4. Isotope can be scaled, removed, enriched, or depleted from the detector to allow in-situ confirmation of signal
5. Leverages significant R&D and experience from SNO+, KamLAND-Zen, Borexino, etc.

$0\nu\beta\beta$

The dominant background for the SNO+ $0\nu\beta\beta$ search is ^{8}B solar neutrinos.



SNO+ collaboration

$0\nu\beta\beta$

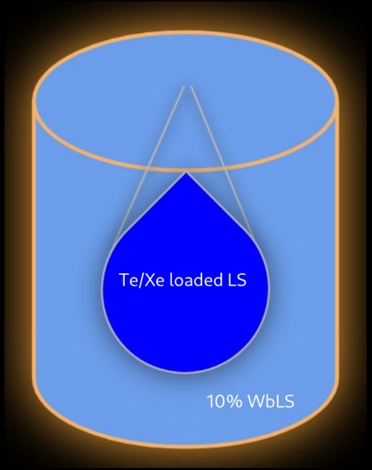
5% ^{nat}Te in LAB+PPO with a PMT coverage of 90% (light level of 1200 ph/MeV)

90% CL 10-year limit: $T_{1/2} > 10^{28}$ years ($m_{\beta\beta} < 6.3$ meV)

Table 7 Dominant background sources expected for the NLDBD search in THEIA. The assumed loading is 3% for Xe, for a ^{136}Xe mass of 49.5 t, and 5% for Te, for a ^{130}Te mass of 31.4 t. The events in the ROI/yr are given for a fiducial volume of 7 m and an asymmetric energy range around the Q-value of the reaction (*see text*). A rejection factor of 92.5% is applied to ^{10}C, of 99.9% to ^{214}Bi, of 50% to the balloon backgrounds, and of 50% to the ^{8}B solar neutrinos.

Source	Target level	Expected events/y	Events/ROI·y 5% ^{nat}Te	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

THEIA white paper



$0\nu\beta\beta$

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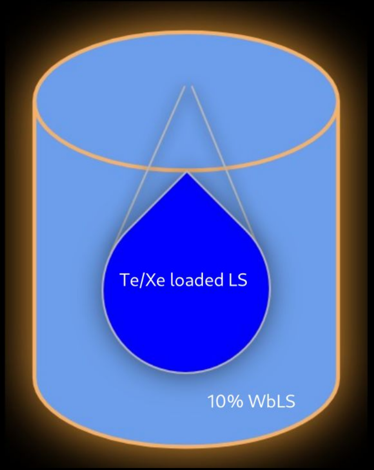
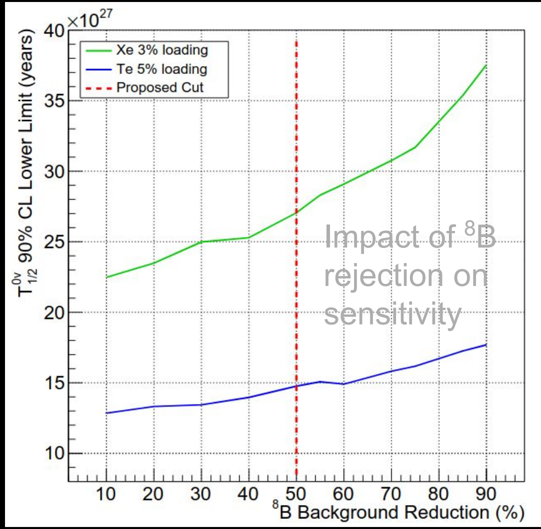


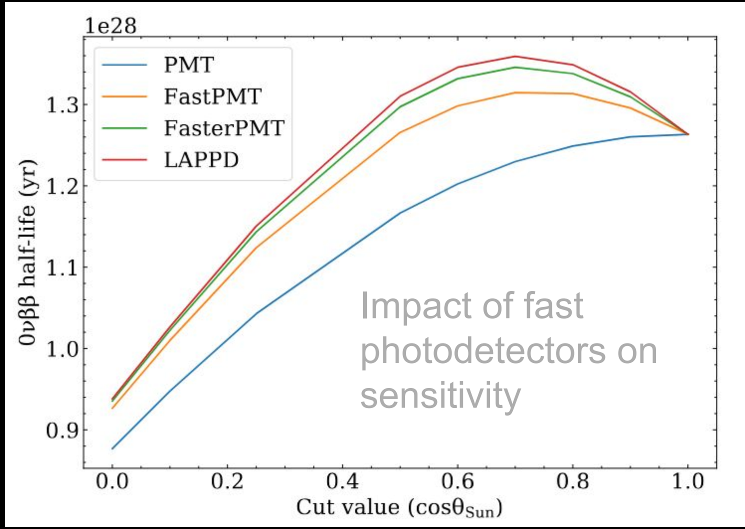
LEGEND-1000 goal: $T_{1/2} > 10^{28}$ years ($m_{\beta\beta} < 9 - 19$ meV) [https://legend-exp.org]

$0\nu\beta\beta$

Impact of directionality is important, but does not increase the sensitivity by a factor of two, even in optimistic scenario. THEIA collaboration could consider making more aggressive assumptions in future studies (e.g., about Te loading).



THEIA white paper

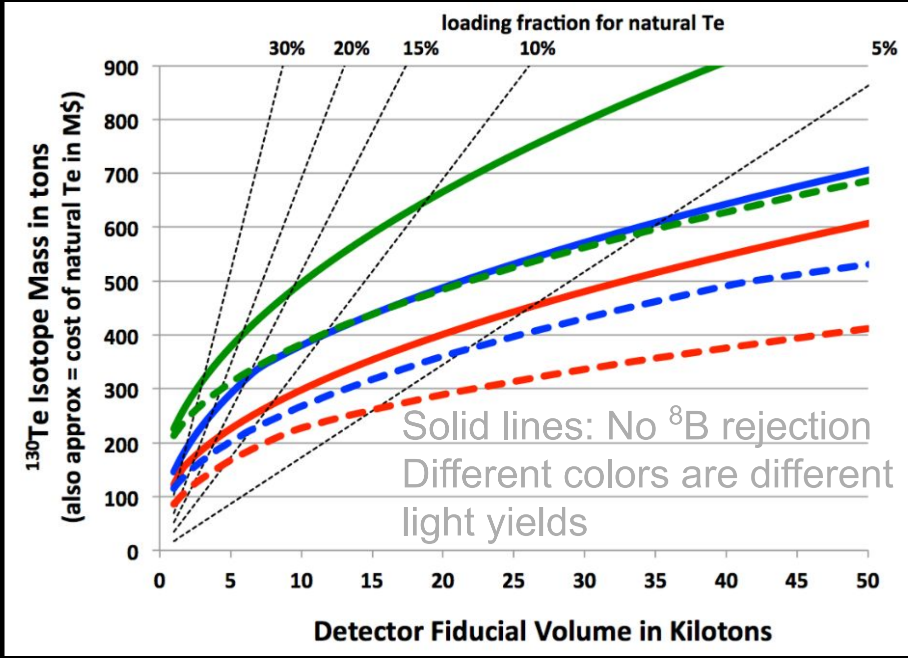


B. Land et al., https://arxiv.org/pdf/2007.14999

$0\nu\beta\beta$

S. Biller paper suggests approaches to probing the normal hierarchy ($m_{\beta\beta}$~2.5 meV) with this technology.

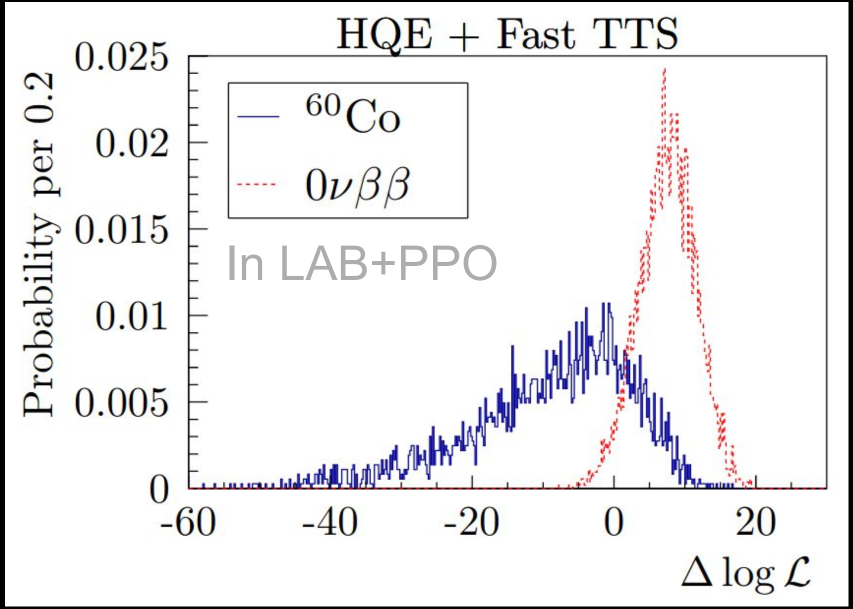
At 11 ktonne (fiducial), 1000 ph/MeV, 10% Te-loading, and 90% discrimination of the ^{8}B backgrounds – achieve normal ordering sensitivity (90% CL) in 5 years.



S. Biller, https://arxiv.org/pdf/1306.5654

$0\nu\beta\beta$

Other potential background rejection capabilities from hybrid detectors (e.g., multi-site) have yet to be explored. Could impact cosmogenics, ^{130}I, and internal radioactivity.



J. Dunger, S. Biller: https://arxiv.org/pdf/1904.00440

$0\nu\beta\beta$

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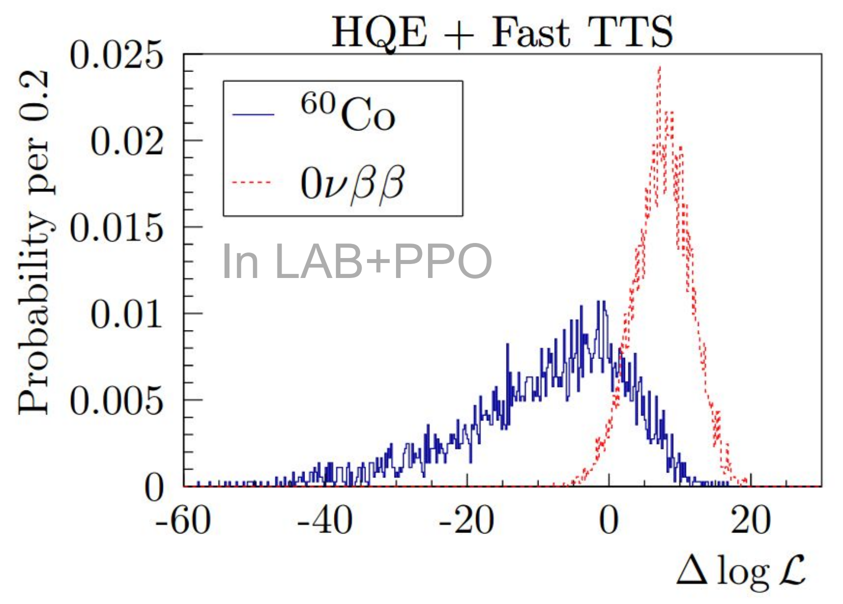
Particularly with the uncertain future for several next-generation $0\nu\beta\beta$ experiments, THEIA may be able to play a significant role pushing towards the normal hierarchy.



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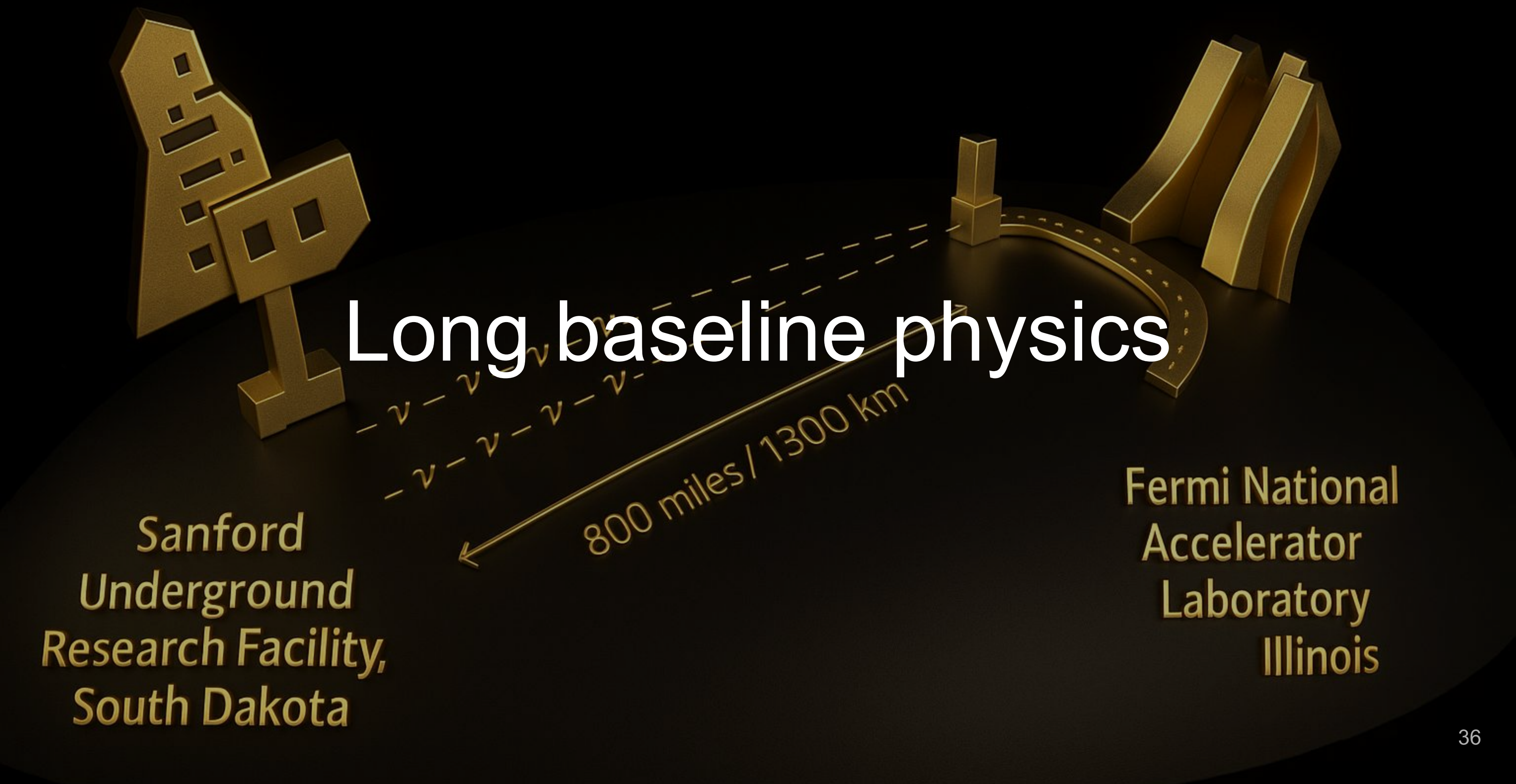
Long baseline physics

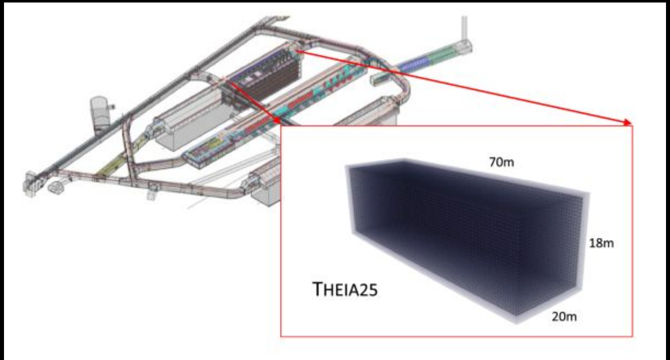


Long baseline physics

A fourth DUNE far detector using a different nuclear target would provide significant advantages including:

1. Different systematics (e.g., cross-section) in the same beam
2. Simpler nuclear system
3. Same target material as Hyper-K in a different beam

news.uchicago.edu



THEIA white paper

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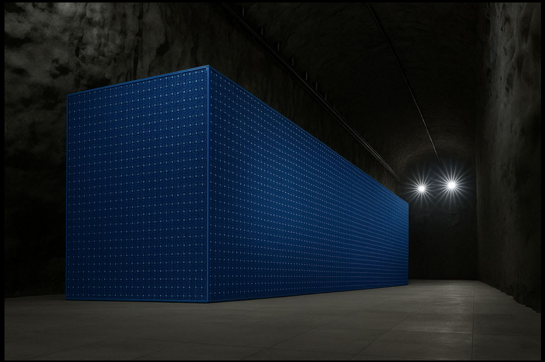
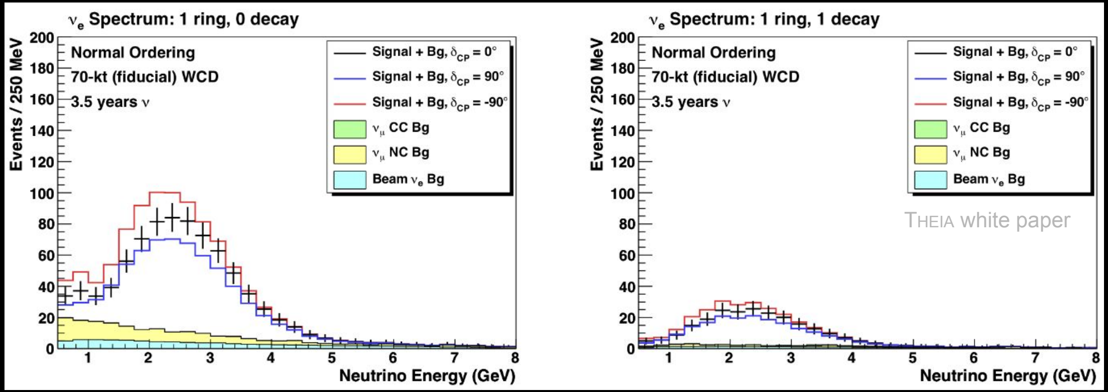


THEIA, as imagined by chatGPT

Long baseline physics

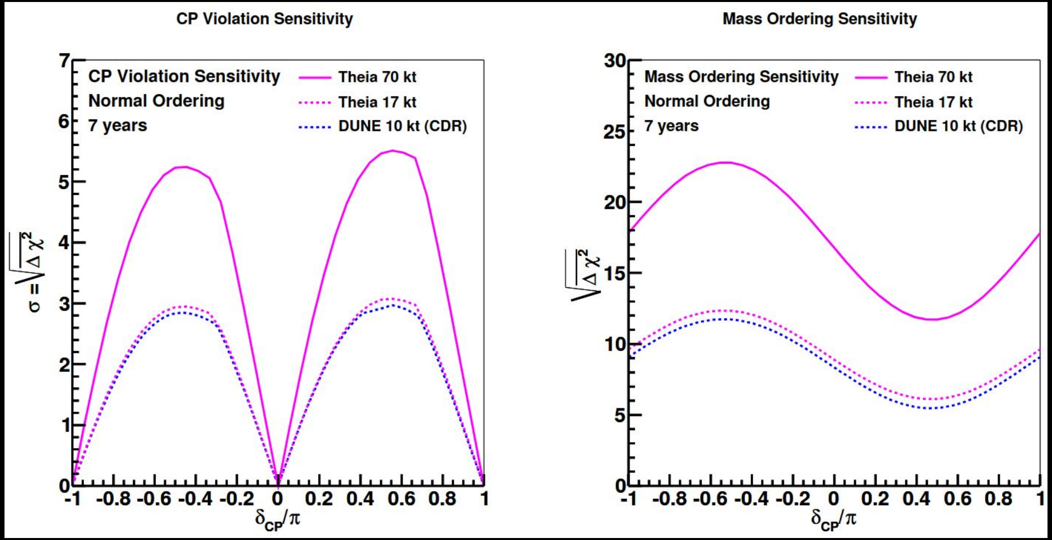
Most of the long-baseline studies for THEIA still use a water detector, but future studies (see talk later by Zhenxiong) hope to show in WbLS that THEIA can:

1. Use Cherenkov light for ring counting to remove NC backgrounds
2. Cherenkov ring for e^-/μ^- identification
3. Scintillation = calorimetry, including for particles below Cherenkov threshold



Long baseline physics

THEIA achieves similar sensitivity as DUNE module to δ_{cp} and the mass ordering



THEIA white paper

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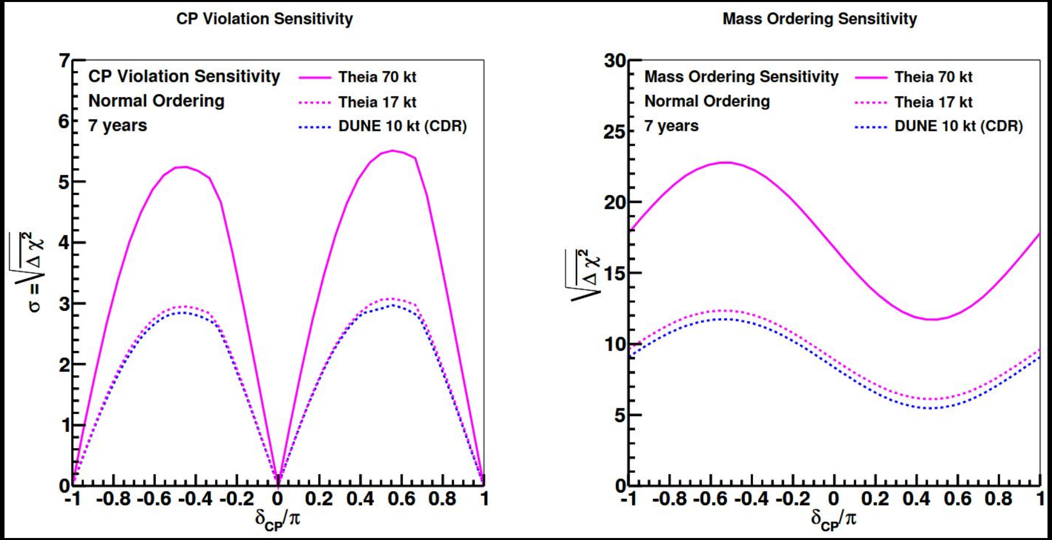


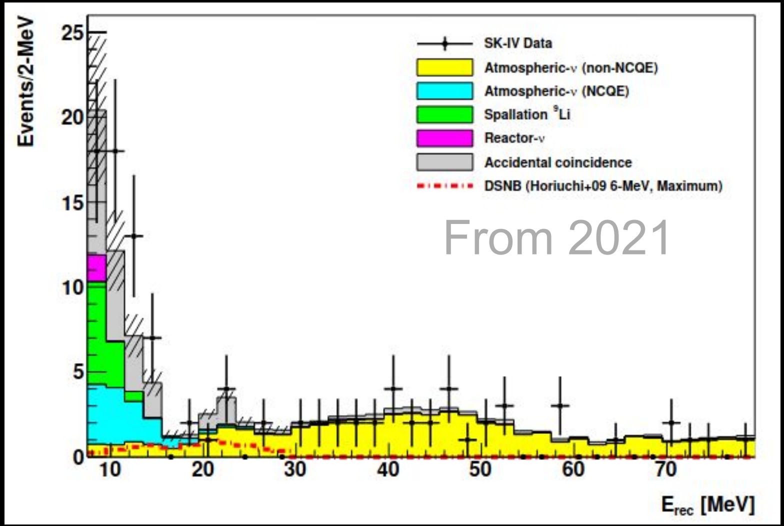
THEIA white paper

Key is that THEIA also provides breadth to the DUNE program.

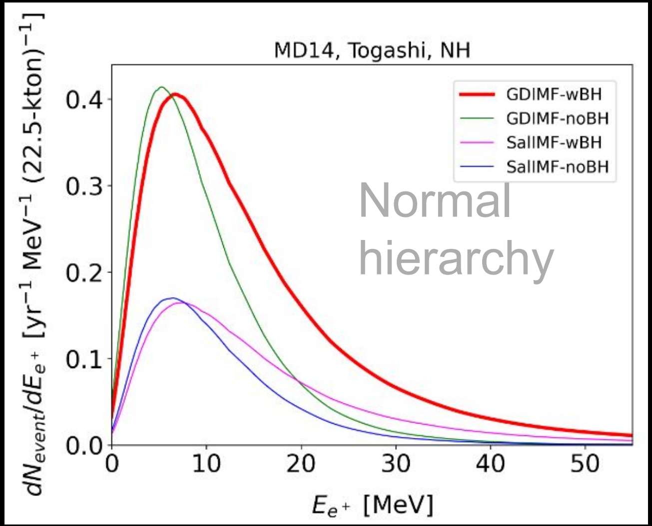
Supernova

DSNB

First observation of the DSNB by SuperK-Gd expected soon, but there may still be significant interest in improving the measurement by going to lower energy or providing better statistics in order to reject models.



Super-Kamiokande Collaboration, https://arxiv.org/pdf/2109.11174



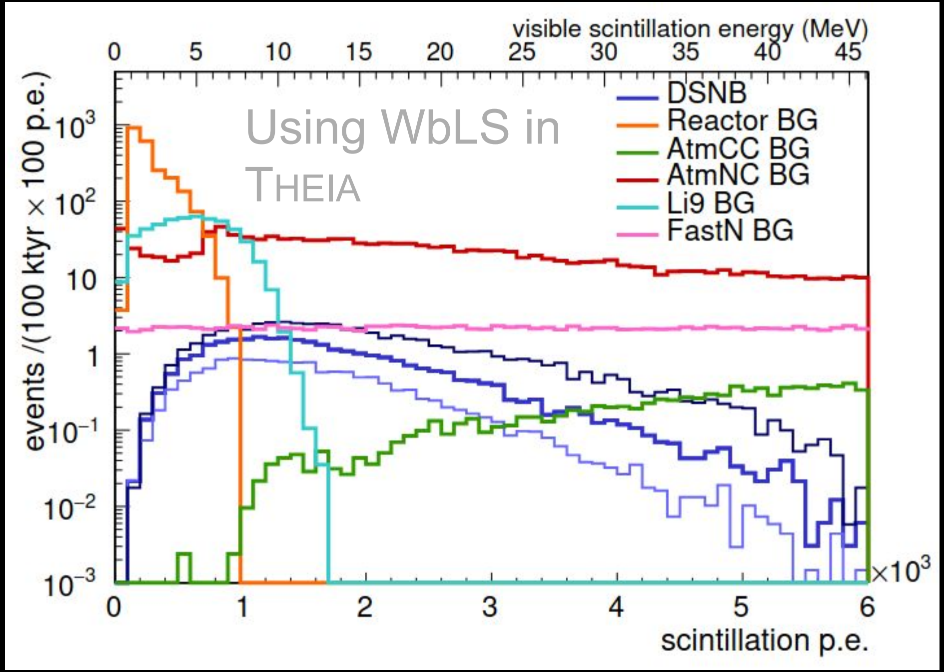
Ashida et al., https://arxiv.org/pdf/2305.13543

DSNB

Scintillation light improves the neutron detection efficiency.

Cherenkov light should provide additional discrimination, primarily against dominant atmospheric NC background.

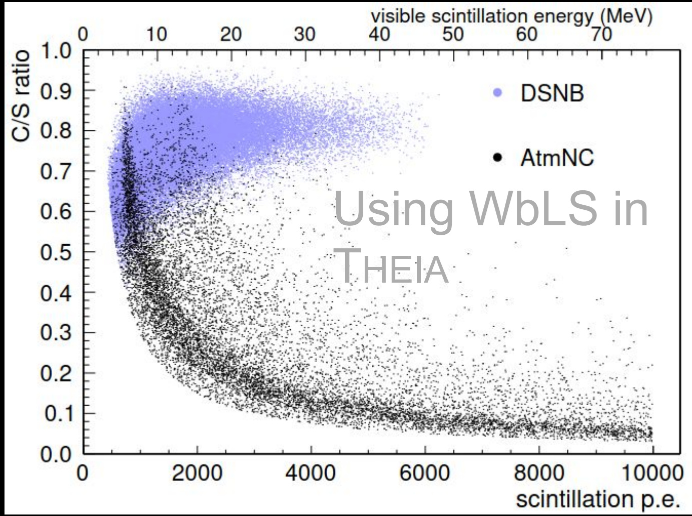
With sufficient depth (SNOLAB or SURF) cosmogenic βn emitters are negligible.

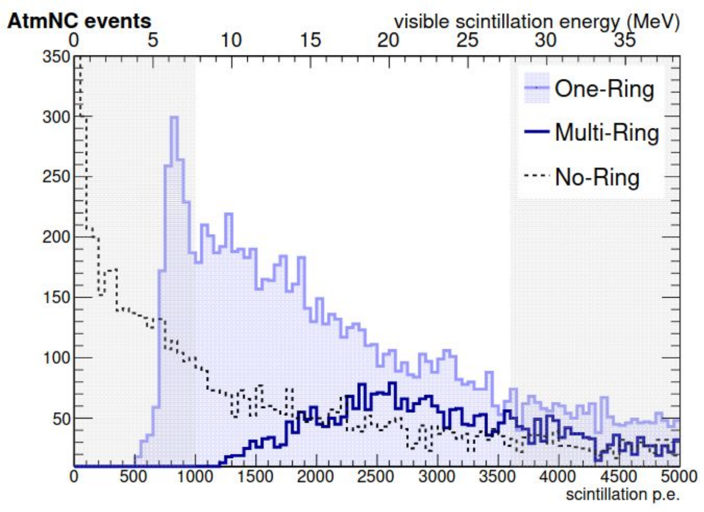


J. Sawatzki et al., https://arxiv.org/pdf/2007.14705

DSNB

A combination of ring counting & Cherenkov/scintillation ratio provide significant background rejection of the atmospheric NC (hadronic + multiple γ-rays).





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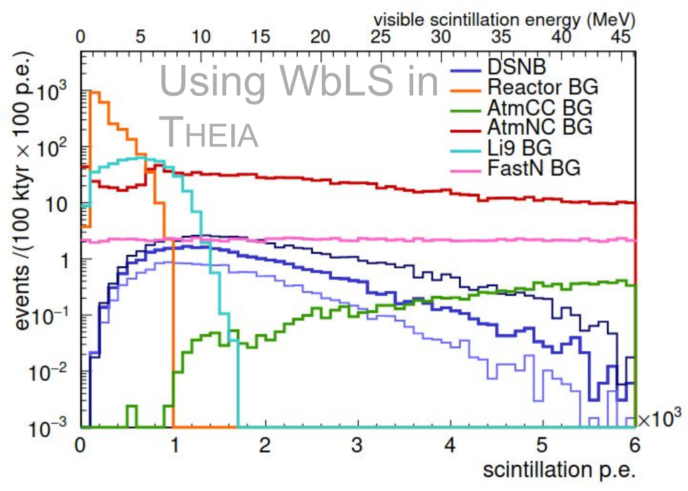

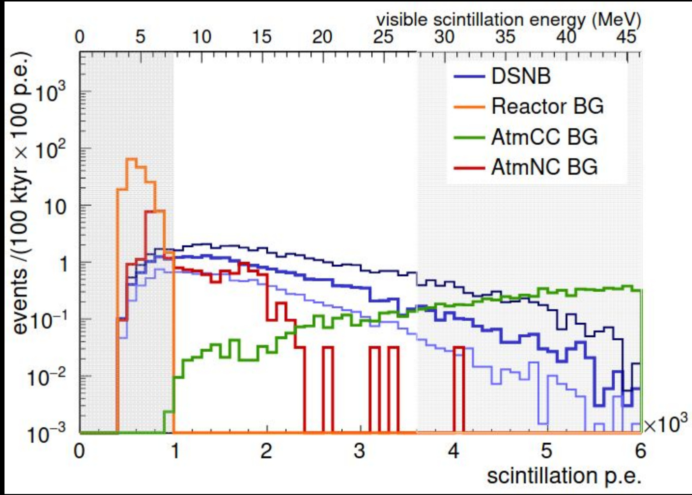

J. Sawatzki et al., https://arxiv.org/pdf/2007.14705

Similar study in slow LS for Jinping: H. Wei et al., https://arxiv.org/pdf/1607.01671

Supernova Burst

1. Directionality: Directional signature from ES provides pointing accuracy better than 1°. Separating from IBD is easy due to high efficiency neutron tag.
2. Flavor-resolved spectra: Significant flux from NCO, sensitive to all flavors
3. Co-detection with DUNE: Fast trigger, different systematics and rates, co-detection of ν_e (dominant in DUNE) and $\bar{\nu}_e$ (dominant in THEIA)
4. Co-detection with JUNO / Hyper-K: Similar target but opposite side of Earth

Reaction	10% WbLS	Rate
(IBD)	$\bar{\nu}_e + p \rightarrow n + e^+$	19,800
(ES)	$\nu + e \rightarrow e + \nu$	960
$(\nu_e \mathrm{O})$	$^{16}\mathrm{O}(\nu_e, e^-)^{16}\mathrm{F}$	340
$(\bar{\nu}_e \mathrm{O})$	$^{16}\mathrm{O}(\bar{\nu}_e, e^+)^{16}\mathrm{N}$	440
(NCO)	$^{16}\mathrm{O}(\nu, \nu)^{16}\mathrm{O}^*$	1,100

THEIA white paper

Other physics

Second geoneutrinos measurement in North America (SNO+). Capable of ~15% measurement in 1 year with sensitivity to U vs. Th contribution.
(S. Zsoldos et al., https://arxiv.org/pdf/2204.12278)

World-leading sensitivity to invisible nucleon decay, even at 17 kt (due to depth).

An 80 kt THEIA has sensitivity similar to Hyper-K for kaon decay modes.

Target material discussion

Physics	Target Option	Comment
CNO	WbLS Slow LS Fast LS	$> 5\%$ scintillator
^{8}B upturn	Li-WbLS D_20-LS Li-LS	CC interaction is critical
$0\nu\beta\beta$	Te-FastLS Te-SlowLS	Potential for bag
DSNB	WbLS Gd-WbLS SlowLS	 Increased neutron detection efficiency Fast LS may have reduced bkg rejection
Supernova burst	WbLS LS	CC interaction on oxygen sensitive to all flavors
Long-baseline	WbLS WbSS	$< 5\%$ scintillator $< 5\%$ scintillator

Table 1: Some of the technology options for the specified THEIA physics goal. Notably, the target material varies significantly depending on the physics goal. In all cases, the use of dichroicons, fast photodetectors, and potentially red-sensitive photodetectors should improve performance.

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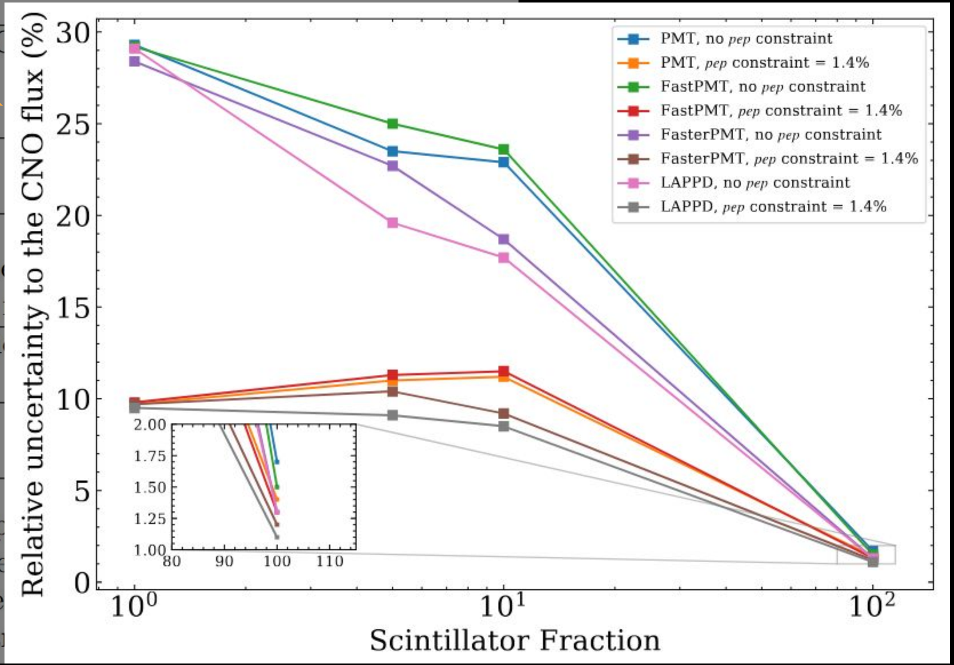

Target material discussion

For measurements where radioactive backgrounds or light yield are important (low energy solar neutrinos and $0\nu\beta\beta$) slow LS or fast LS with Ch/Sc discrimination is likely going to perform better than water-based.

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Phased target material approach will be important for any future hybrid detector.
Fast photodetectors and spectral sorting combine nicely with any target material!

Opportunities

I believe that there are significant opportunities for physics sensitivity studies that would make the case for a future large hybrid neutrino detector even stronger:

1. Solar neutrino (CNO) studies with slow LS as opposed to WbLS. Lower internal bkgs but unclear the directionality capabilities at low energy.

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4. DSNB with different target materials & potential to fit below 10 MeV (using well-known reactor flux). Can we do this in the Te-loaded scint?

Conclusions

1. Future hybrid detectors may provide unique sensitivity for low energy solar neutrinos, neutrinoless double beta decay, and the DSNB.

2. A hybrid detector located at SURF would provide significant breadth to the DUNE physics program and a bridge for comparisons with Hyper-K.

3. The extensive physics program includes additional topics such as nucleon decay and geoneutrinos.

4. There are many technology possibilities for THEIA, and broad physics program requires balancing approaches. Many interesting studies to come!