0νββ with THEIA

Tanner Kaptanoglu
on behalf of the THEIA collaboration

UC Berkeley
Oct. 26, 2023

Workshop On Xenon Detector 0νββ Searches:
Steps Towards the Kilotonne Scale

Outline

1. THEIA concept and the broad physics program

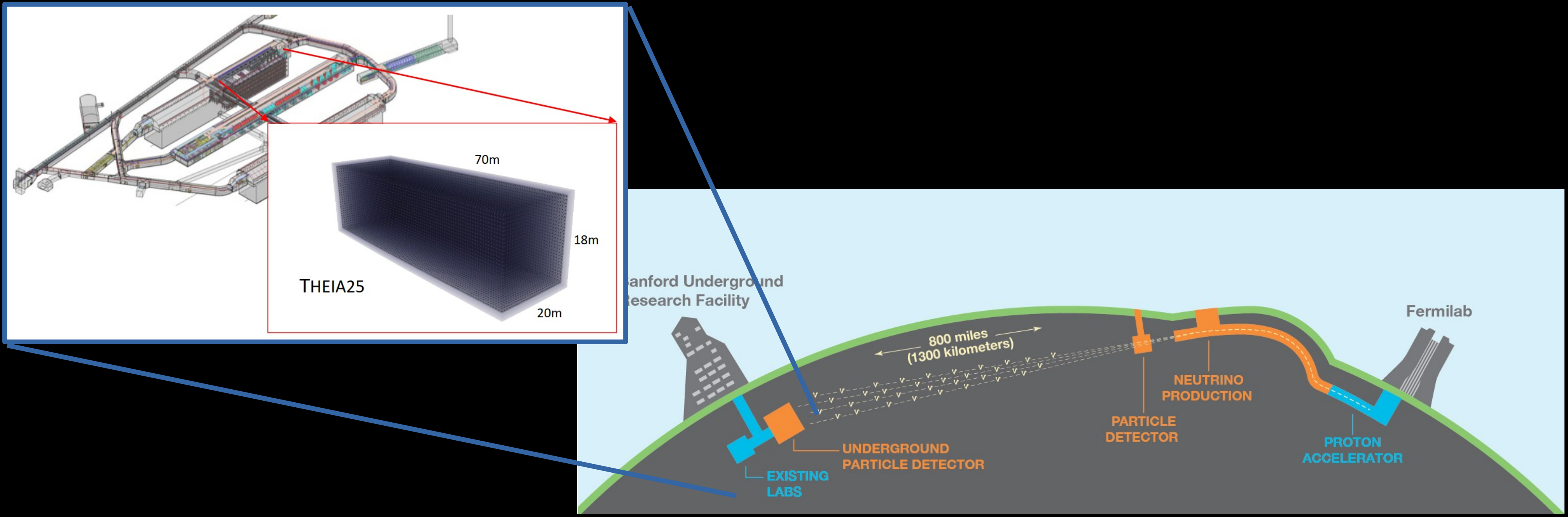
2. Motivation: 0νββ with large liquid scintillator detectors

3. The THEIA R&D program; achieving “hybrid” detectors

4. Towards the normal hierarchy: expected THEIA sensitivity for 0νββ

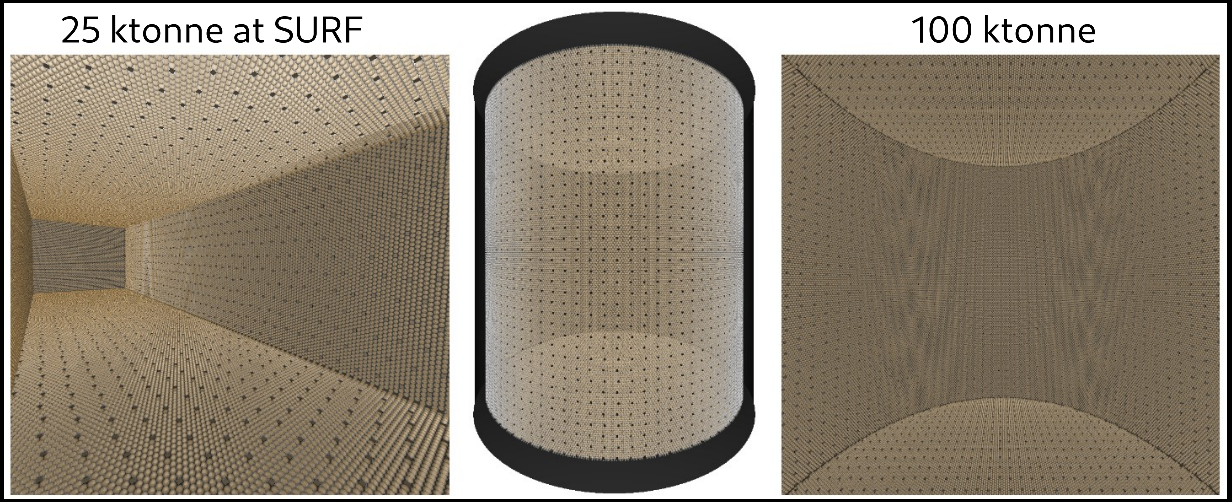
THEIA

THEIA is a proposed large liquid scintillator neutrino detector, ideally situated as the fourth DUNE far detector (ie, the module of opportunity).

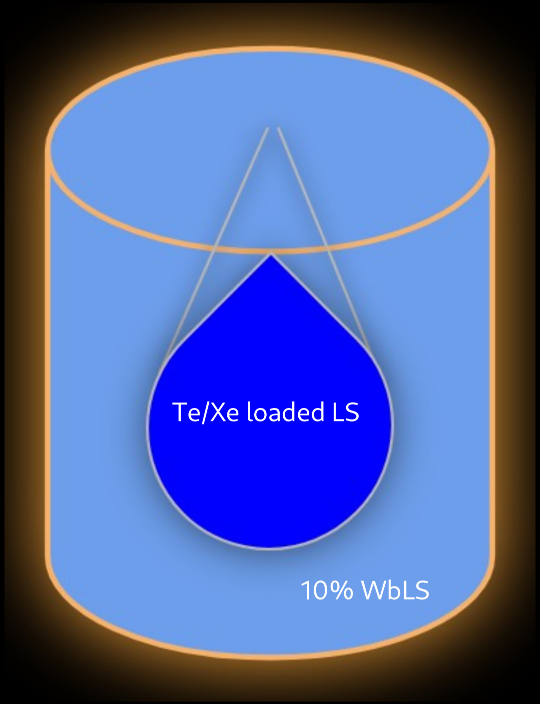


Detector design

Theia would have a 25 – 100 ktonne target volume, very high photocathode coverage (50 – 90%), and employ advanced technology (eg, water-based liquid scintillator, LAPPDs, dichroicons)



Various Theia designs, as simulated in Chroma.
M. Askins et al., EPJC 80 416, 2020



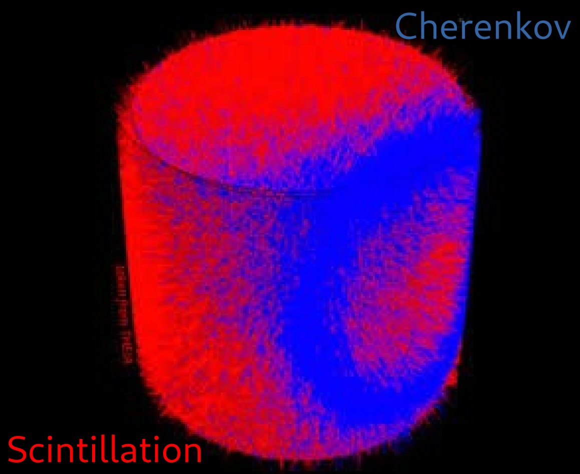
"Hybrid" concept

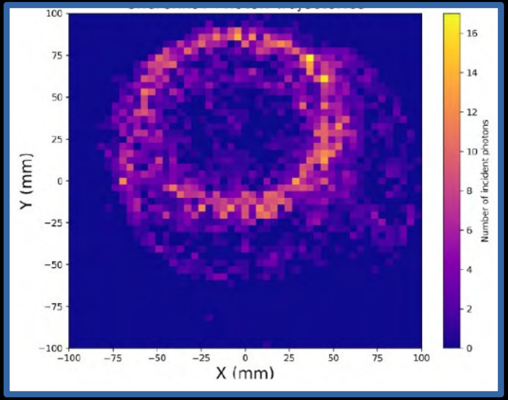
THEIA would leverage this technology to simultaneously detect Cherenkov and scintillation light in a high light yield liquid scintillator. This would:

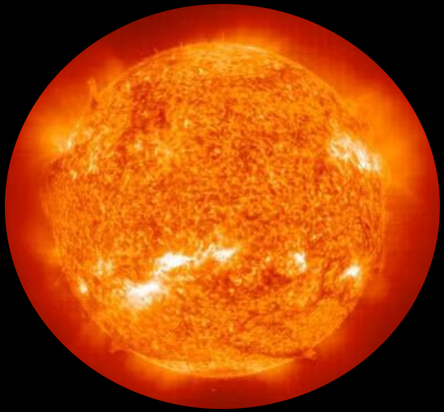
1) Allow for directional reconstruction within a liquid scintillator detector, improving background rejection and particle ID.

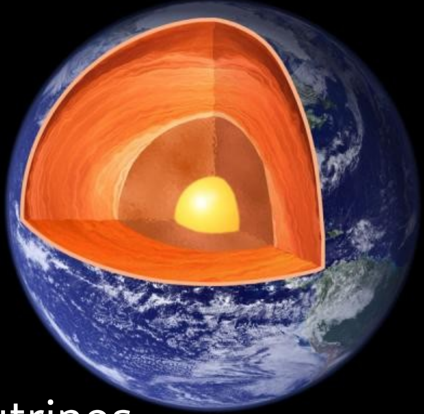
2) Maintain excellent energy and position reconstruction typical of a liquid scintillator detector.

THEIA would unlock an extremely broad physics program as the 4th detector at DUNE.

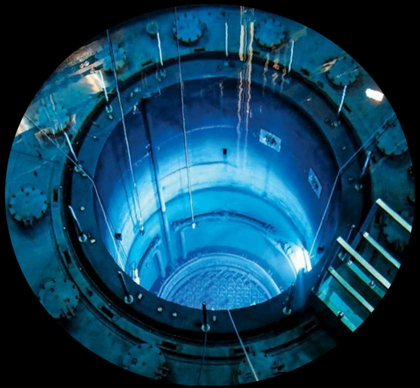








Geoneutrinos

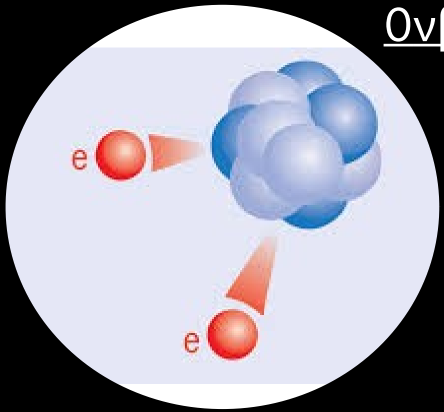


Solar neutrinos

Reactor neutrinos

Physics topics

0νββ



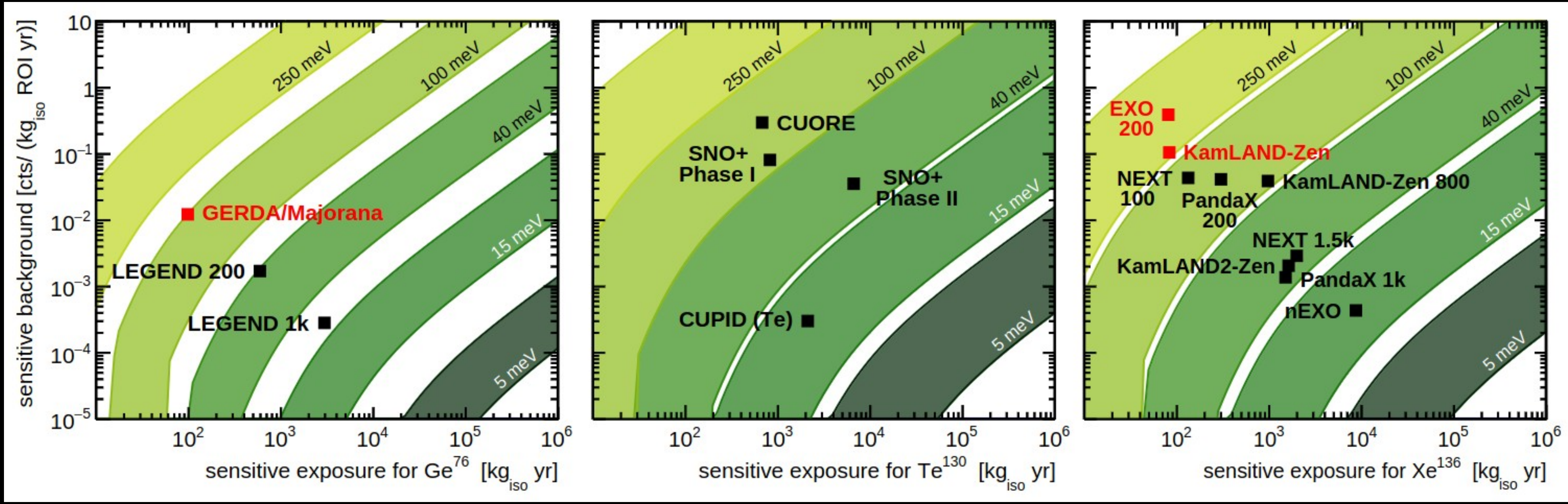
Supernova neutrinos

And more…

Long baseline neutrinos
Nucleon decay
DSNB
Exotic searches

For details see:
M. Askins et al., EPJC 80 416, 2020

0νββ status



M. Agostini et al., Phys. Rev. D 96, 053001 (2017)

0νββ

The THEIA program would build on previous and existing experience operating large liquid scintillator experiments (eg, Borexino, KamLAND-Zen, and SNO+), leveraging novel detector technologies to enable world-class sensitivity around $m_{\beta\beta}$ ~ 5 meV.

Authors: Andrew Mastbaum, Chris Grant, Valentina Lozza, Gabriel D. Orebi Gann, Lindley Winslow on behalf of the THEIA collaboration
Full author list at end of document

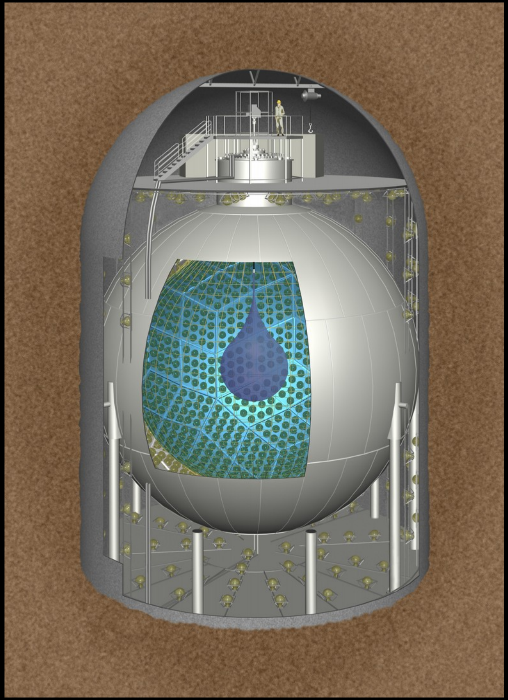
Abstract: The possibility of a Majorana neutrino, and of lepton number non-conservation, are among the most fundamental open questions in particle physics. A broad international program employing a wide variety of detector types is underway to address these these important questions via searches for neutrinoless double-beta decay (NLDBD). The THEIA program builds on the success of NLDBD searches using large liquid scintillator detectors loaded with double-beta decay isotopes, and leverages novel detector technologies to enable world-class sensitivity at the level of $m_{\beta\beta} \sim 5$ meV. This is enabled by a very large target mass coupled with excellent background rejection achieved via fast timing, advanced photon detectors, optimized scintillator properties, and next-generation reconstruction and analysis techniques.

SNOWMASS21

0νββ in large scintillation detectors

<u>KamLAND-Zen</u>

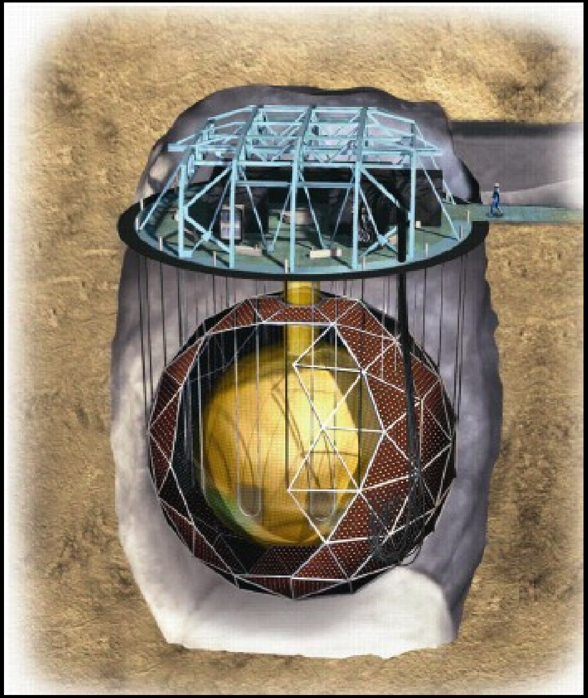
2700 m.w.e
overburden



745 kg of enriched Xe-loaded liquid scintillator in a spherical inner balloon

<u>SNO+</u>

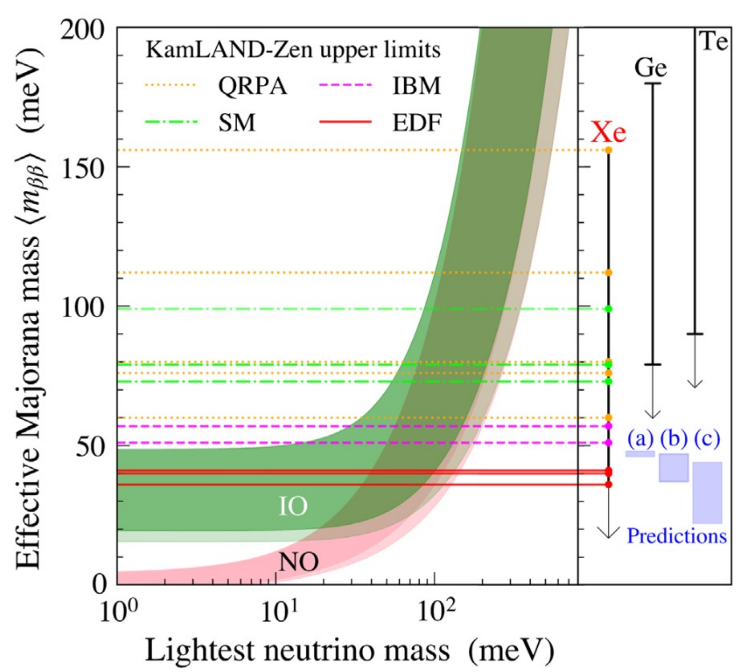
6000 m.w.e
overburden



3900 kg of natural Te-loaded liquid scintillator in a spherical acrylic vessel

0νββ in large scintillation detectors

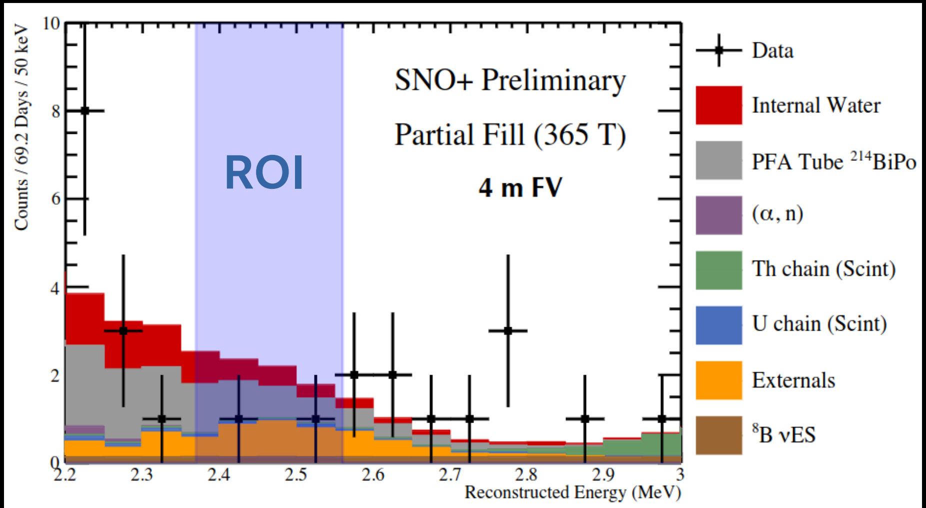
KamLAND-Zen



Most stringent limits on 0νββ thus far

S. Abe et al. (KamLAND-Zen Collaboration), PRL 130 05180, 2023

SNO+



“Target-out” analysis during scintillator phase

Advantages

1. Well-understood and relatively cheap target material

2. Demonstrated low internal backgrounds and particle ID capabilities

3. “Easy” to dissolve or chemically load enormous amounts of isotope

4. Massive detector volumes allow fiducialization from external sources

5. Many backgrounds measured prior to isotope loading

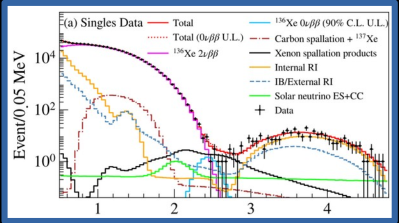
6. Isotope can be scaled, removed, enriched, or depleted from the detector to allow in situ confirmation of signal

Background budget

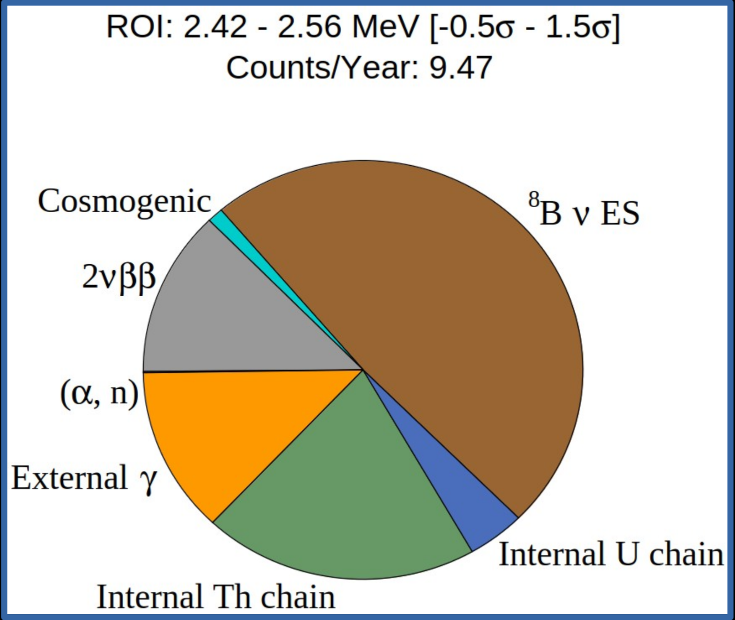
KamLAND-Zen

Background	Estimated	Best fit: Frequentist	Best fit: Bayesian
^{136}Xe $2\nu\beta\beta$	…	11.98	11.95
Residual radioactivity in Xe-LS			
^{238}U series	0.14 ± 0.04	0.14	0.09
^{232}Th series	…	0.85	0.87
External (radioactivity in IB)			
^{238}U series	…	3.05	3.46
^{232}Th series	…	0.01	0.01
Neutrino interactions			
^{8}B solar ν e^- ES	1.65 ± 0.04	1.65	1.65
Spallation products			
Long-lived	7.75 ± 0.57[a]	12.52	11.80
^{10}C	0.00 ± 0.05	0.00	0.00
^{6}He	0.20 ± 0.13	0.22	0.21
^{137}Xe	0.33 ± 0.28	0.34	0.34

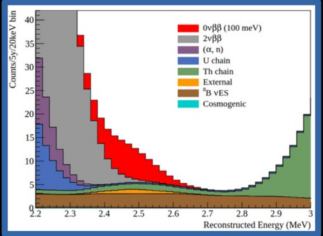
Largest backgrounds:
- Long-lived Xe spallation products
- 2νββ
- Balloon radioactivity
- Solar neutrinos



SNO+



Largest backgrounds:
- Solar neutrinos
- Internal + external radioactivity
- 2νββ



S. Abe et al. (KamLAND-Zen Collaboration), PRL 130 05180, 2023

S. Andringa et al., Adv. In High Energy Phys., vol 2016, 2015

Background budget

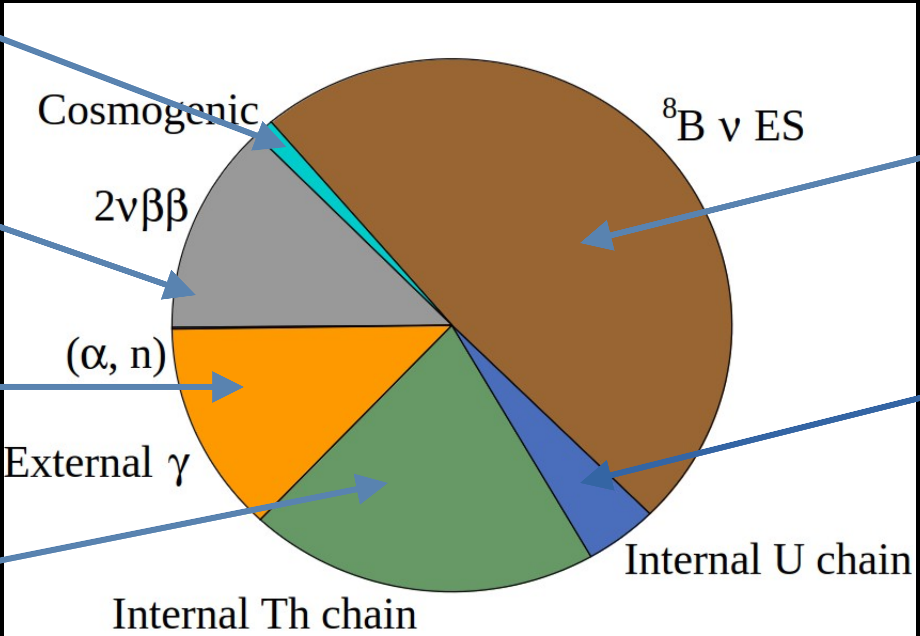
SNO+ expected backgrounds

Deep underground
(primary background for
KamLAND-Zen 800)

High light yield

Fiducialization
Large detector volume
Low radioactivity

Excellent PID
Low radioactivity



Ch/Sc separation for
directionality

Excellent PID
Low radioactivity

Background budget

THEIA would:

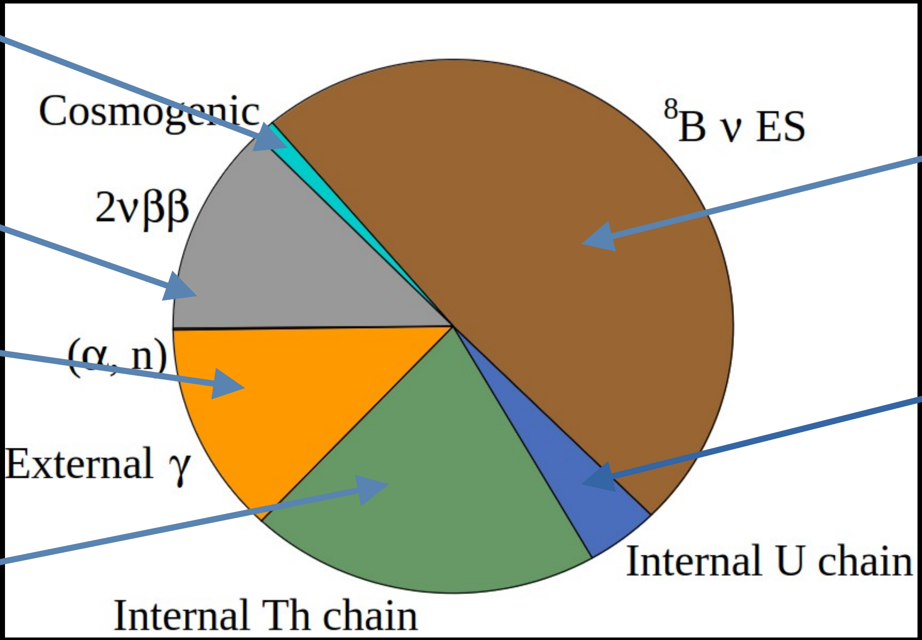
be deeper than KZ

have better energy resolution than SNO+ or KZ

fiducialize in large volume, use multi-site classifiers

expect better PID using high light yield and Ch/Sc ratio

SNO+ expected backgrounds

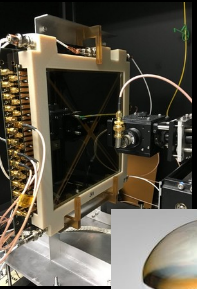


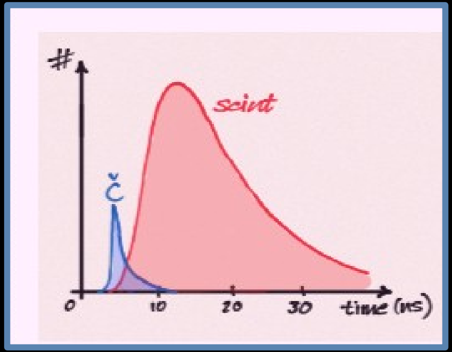
achieve Ch/Sc separation for directionality

expect better PID using high light yield and Ch/Sc ratio

Cherenkov and scintillation separation

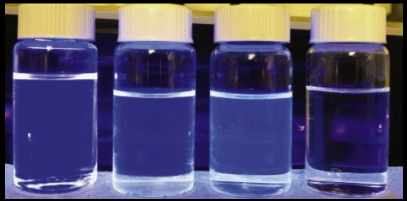
Key for hybrid detectors: separating Cherenkov and scintillation light

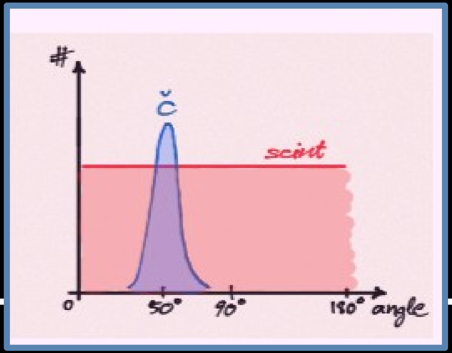


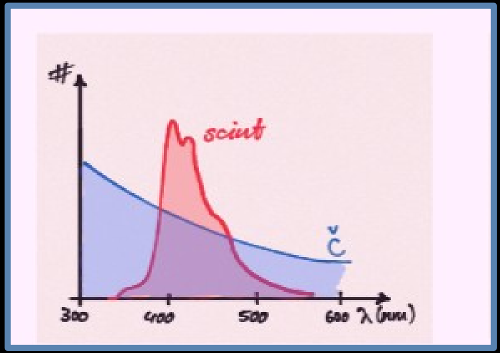


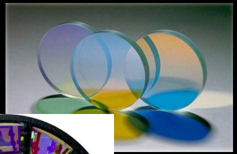
Fast PMTs and LAPPDs,
Slow scintillator

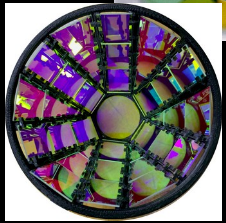
Water-based liquid scintillator,
Advanced recon. techniques



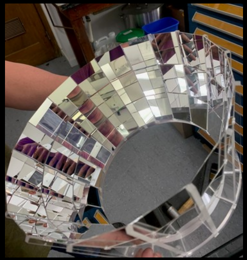






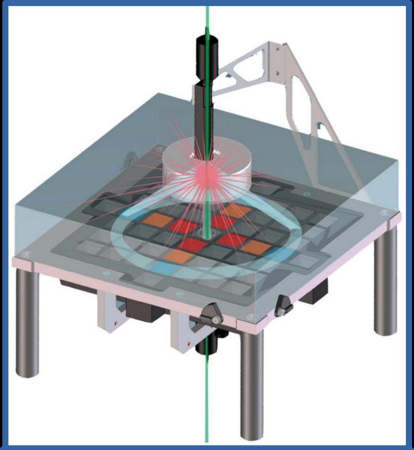


Parabolic concentrators using dichroic filters (‘dichroicons’)

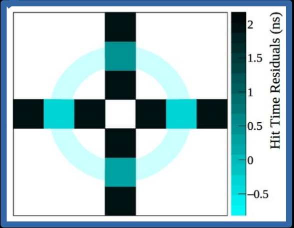


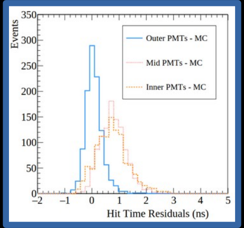
Small-scale demonstrators

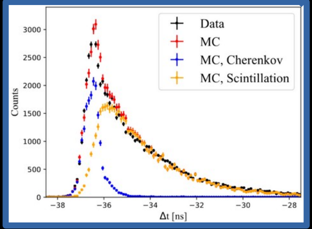
First deployment of LAPPDs and WbLS in a neutrino detector.



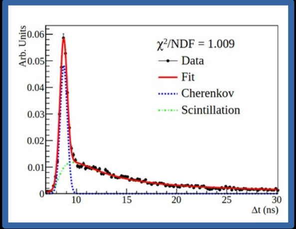
CHESS studies Cherenkov and scintillation separation using isotropy and timing







Dichroicon spectrally sorts Cherenkov and scintillation light



<u>Technology papers:</u>

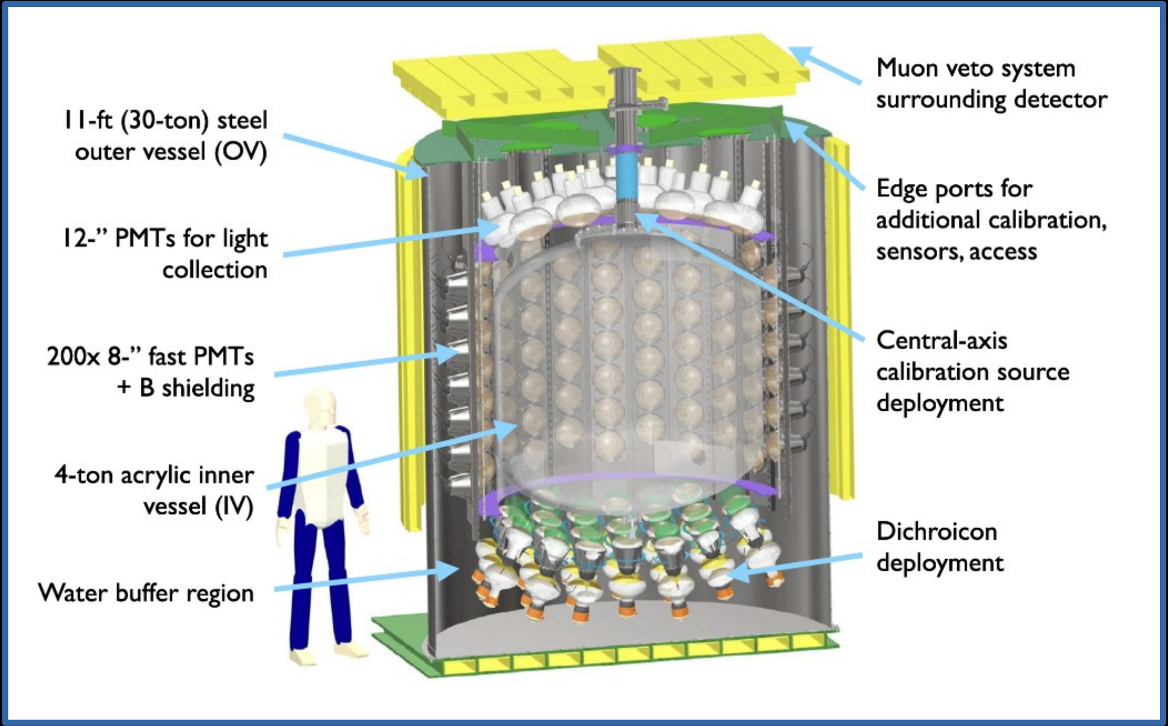
J. Caravaca et al., Eur. Phys. J. C 77, 811, 2017
J. Caravaca et al., Phys. Rev. C 95, 055801, 2017
T. Kaptanoglu et al., JINST 14, 2019
D. Onken at al., Mater. Adv. 1 71-76, 2020
J. Caravaca et al., Eur. Phys. J. C 80, 867, 2020
T. Kaptanoglu et al., Phys. Rev. D 101, 2020
T. Kaptanoglu et al., Eur. Phys. J. C 82-2, 2022
E. Callaghan et al., Eur. Phys. J. C 83, 2023

<u>Many other efforts at collaborating insitutions:</u>

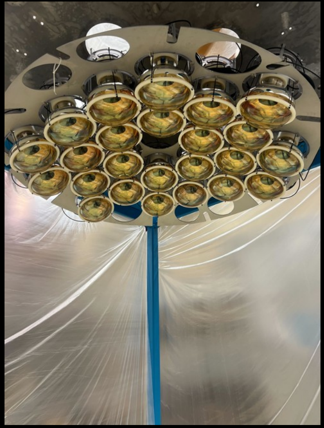
1 tonne WbLS demonstrator (BNL)
Scattering characterization (UC Davis)
Proton light yield (LBNL, Mainz)
Slow scintillator (Mainz)
Light yield characterization (Munich)
LAPPD characterization (Iowa State)

EOS

EOS is a 4 tonne demonstrator for hybrid detector technology currently under construction at UC Berkeley.



EOS



EOS

EOS is a 4 tonne demonstrator of hybrid detector technology, currently under construction at UC Berkeley.

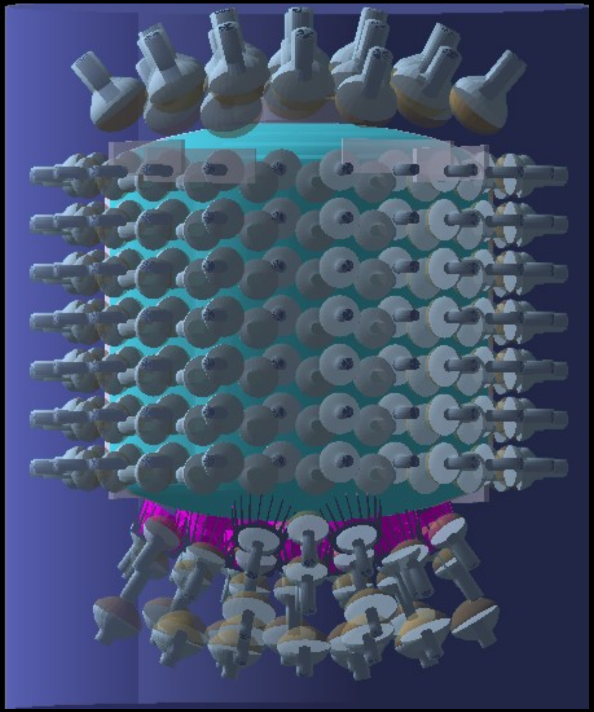
1. EOS will assess the performance of key technology such as dichroicons, fast PMTs, and WbLS

2. EOS will develop and calibrate optical models that are used to predict the performance of THEIA

3. EOS will develop shared framework (RAT-PAC and Chroma) for simulation and reconstruction for future optical neutrino detectors

4. EOS will be easily movable for deployment near a nuclear reactor or other particle source (eg, SNS)

EOS is a key stepping-stone to the broader THEIA physics program



Open source:
https://github.com/rat-pac/ratpac-two

0νββ with THEIA

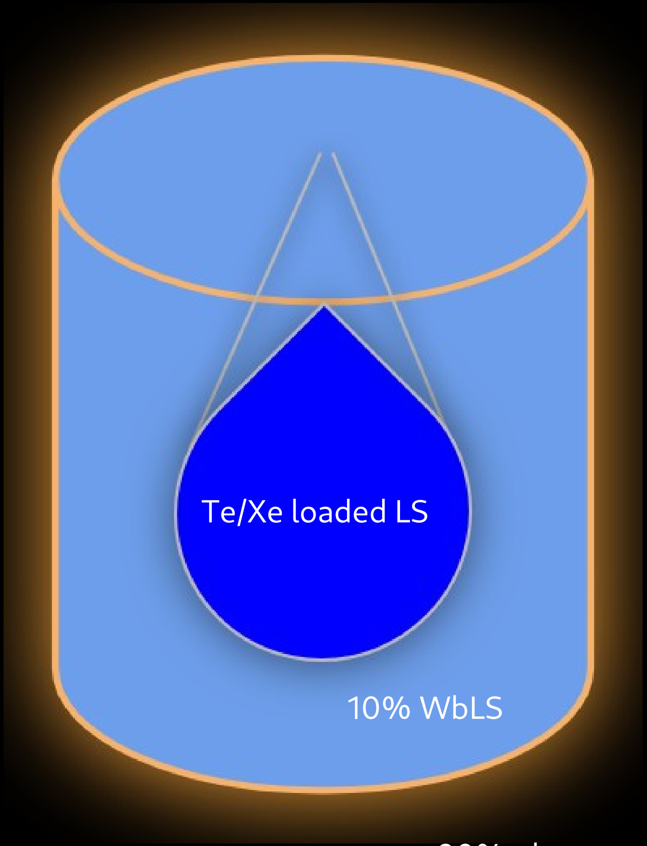
Detector configuration in sensitivity study:

1. Cylindrical detector (50 kT, 20 m x 40 m) with 90% coverage and filled with 10% WbLS

2. Central balloon (8 m radius) filled with high light yield, ultra pure, liquid scintillator

3. Two loading schemes: 3% enr-Xe and 5% natural Te

With these detector setups, we investigated the sensitivity under a variety of background rejection scenarios



90% photocoverage

Background assumptions

1. Radioactivity of balloon and scintillator from KamLAND-Zen and SNO+ measurements
2. Energy resl. of 3%/√(E) achieved with 1200 P.E./MeV (from detailed simulations)
3. Fiducial volume cut (1 m from balloon) and multi-site PID removes external γ
4. Coincidence tagging and PSD removes 99.9% of ^{214}Bi and 92.5% of cosmogenic ^{10}C
5. Directional recon. provides rejection of the ^{8}B solar neutrinos

r < 7 m

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

M. Askins et al., EPJC 80 416, 2020

Background expectation

Source	r < 7 m	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

Total backgrounds (events/ROI/y):	36.0	23.9
Background index:	1.1	0.5
(per ton isotope in full volume)		

Largest backgrounds:

Solar neutrinos, 2νββ, balloon radioactivity, solar neutrino induced ^{130}I (Te)

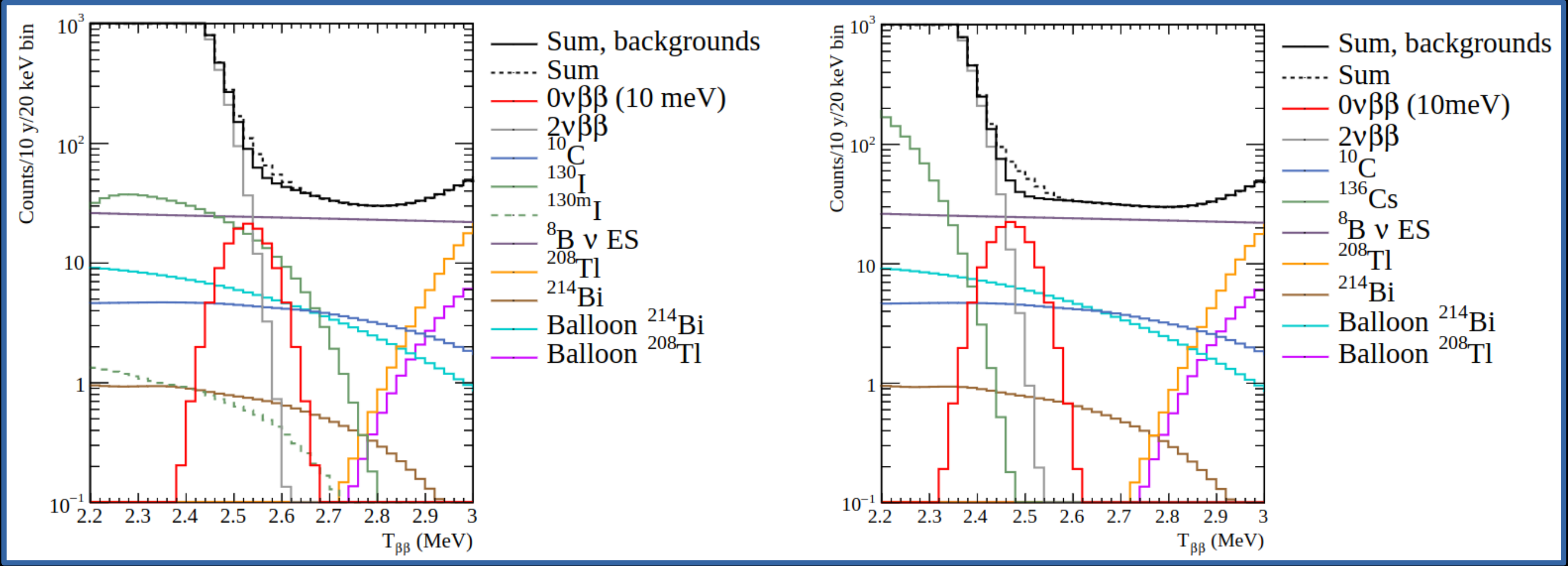
M. Askins et al., EPJC 80 416, 2020

Sensitivity

Expected sensitivity (90% CL) for 10 years of data taking with 50% solar neutrino rejection (75% signal efficiency) are:

Te: $T_{1/2}^{0\nu\beta\beta} > 1.1 \times 10^{28}$ y, $m_{\beta\beta} < 6.3$ meV

Xe: $T_{1/2}^{0\nu\beta\beta} > 2.0 \times 10^{28}$ y, $m_{\beta\beta} < 5.6$ meV

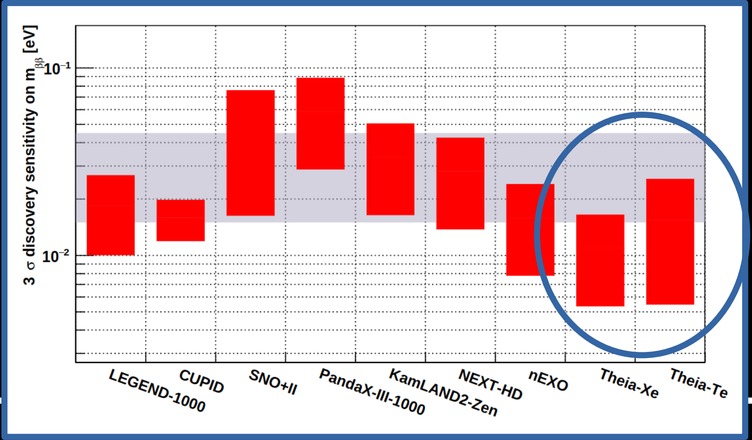


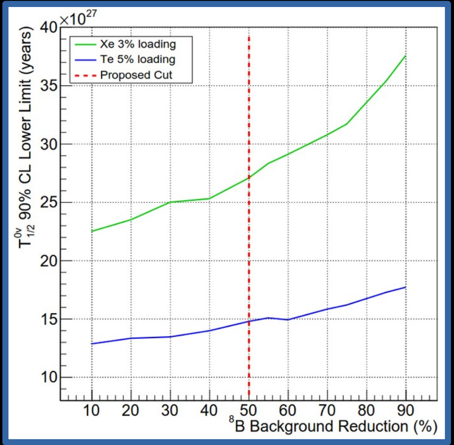
Sensitivity

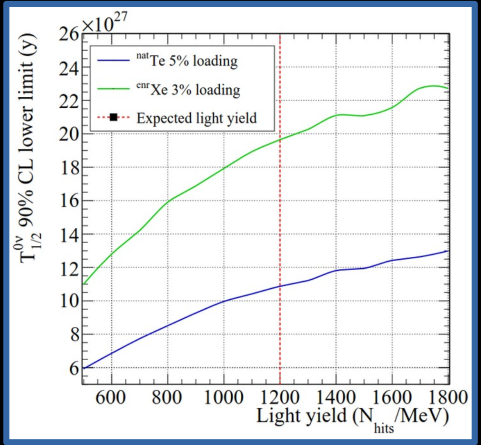
Sensitivity studied as a function of the ^{8}B background reduction and light yield. Potential to improve sensitivity by factor of 2-3.

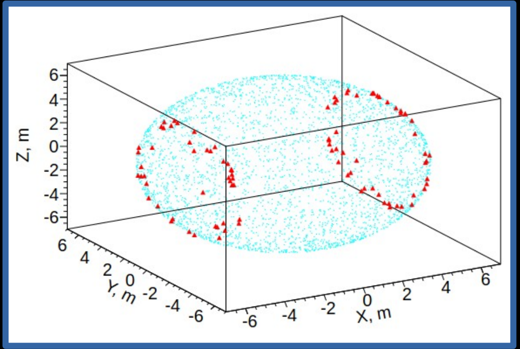
Sensitivity similar or better than next-generation $0\nu\beta\beta$ experiments

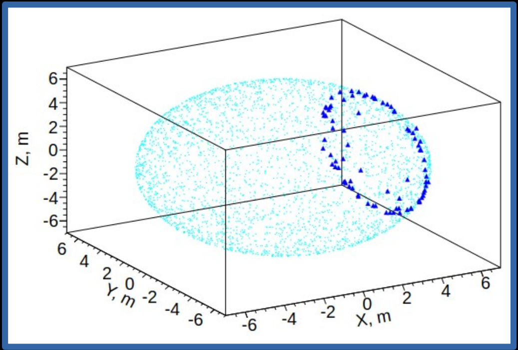
Many existing ideas for improvements (two ring identification, multi-site classifiers, etc.)











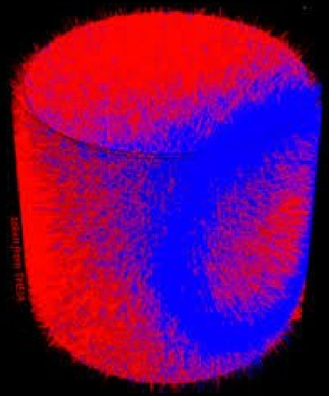
A. Elagin et al., Nucl. Instrum. Meth. A 849, 2017

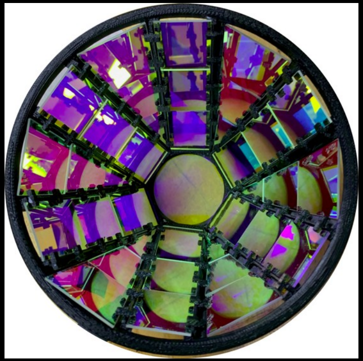
Summary

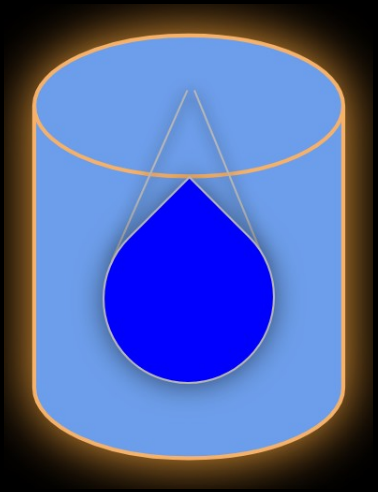
THEIA is a proposed hybrid detector, ideally situated as the 4^{th} DUNE detector, with a broad physics program facilitated by the ability to distinguish Cherenkov and scintillation light.

There is a significant R&D program building towards THEIA, including the EOS detector, under construction at UC Berkeley.

THEIA would have a $0\nu\beta\beta$ sensitivity around $m_{\beta\beta}$ ~ 5meV, competitive with other next-generation experiments, with certain advantages such as scalability.







Thank you for your attention!

THEIA collaboration, 2016