THEIA

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Introduction

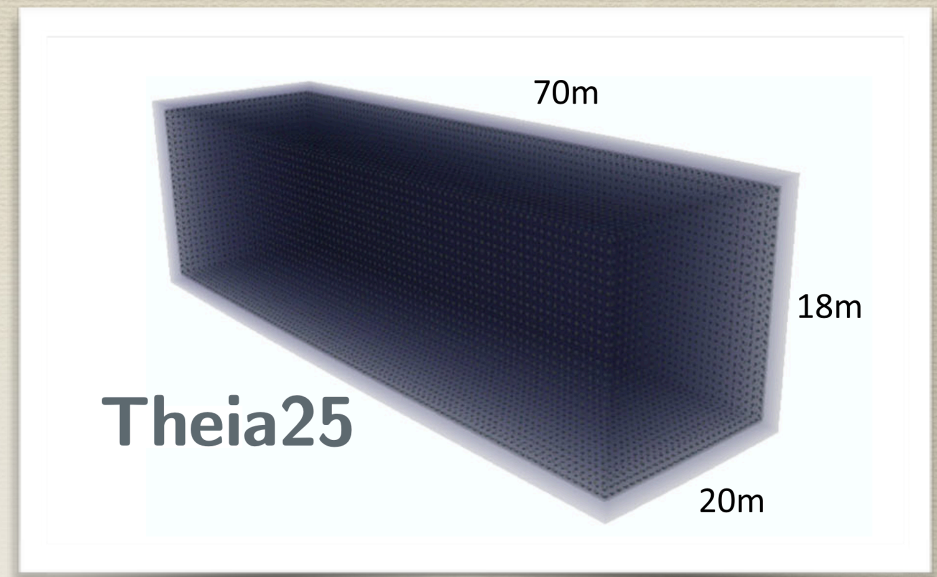
* The THEIA collaboration
* Introducing THEIA
* What is WbLS?
* Ongoing R&D
* The physics potential of THEIA

The THEIA collaboration

* A large international effort
* Over 80 collaborators
* 10 countries
* 38 institutions

* Offers an exciting expansion to the DUNE community

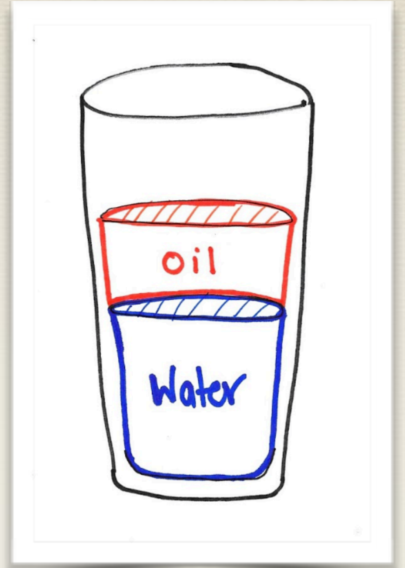
What is THEIA?



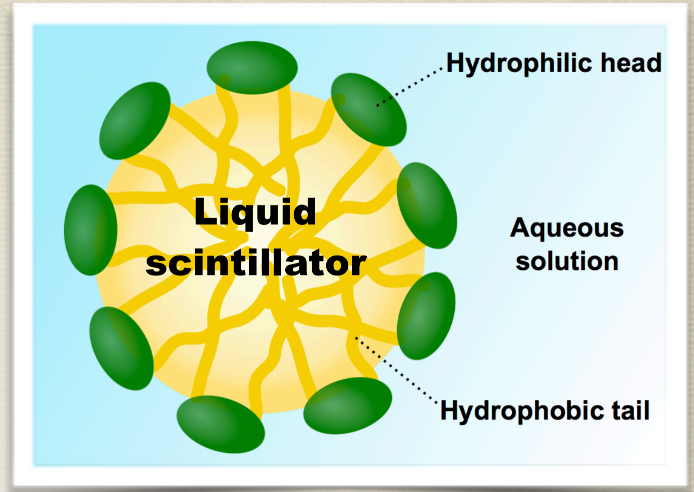
* The first stage of THEIA will consist of a 25 kTon Water-based Liquid Scintillator (WbLS) target
* Plan to implement novel fast photosensors
* Introduction of spectral sorting techniques
* By combining the benefits of Cherenkov and scintillation emission, THEIA will be able to probe physics from the MeV- to the GeV-scale
* THEIA is a next generation detector concept with the potential to be one of the most far reaching neutrino experiments ever
* Importantly, THEIA offers the exciting prospect of complementing, expanding and enhancing the physics potential of DUNE

What is WbLS?

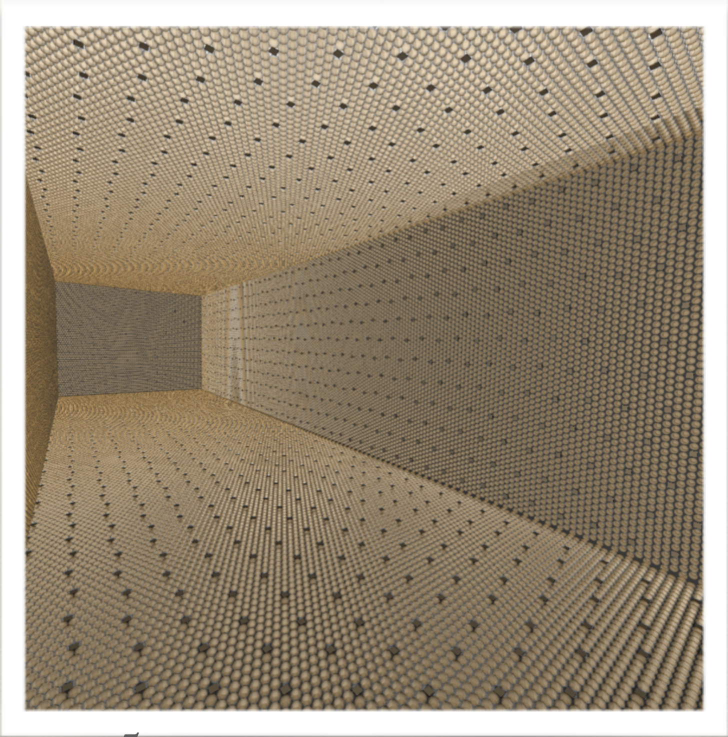
* Water-based liquid scintillator (WbLS) is an aggregation of water and oil based liquid scintillator.
* The idea is to create a novel detector medium which achieves the benefits of both water Cherenkov detection and liquid scintillator detection.
* Produce "micelles" in which the liquid scintillator, such as PPO-doped LAB, droplets are surrounded by a surfactant.
* The surfactant's hydrophilic head acts as a barrier that is "in contact" with the water, whilst its hydrophobic tail is sequestered within the scintillator medium.
* This allows the liquid scintillator micelles to homogenise throughout the water.
* This innovative detection medium has the capability to further enhance next-generation neutrino experimentation.



Combining liquid scintillators and water is non-trivial, an innovative approach is needed.

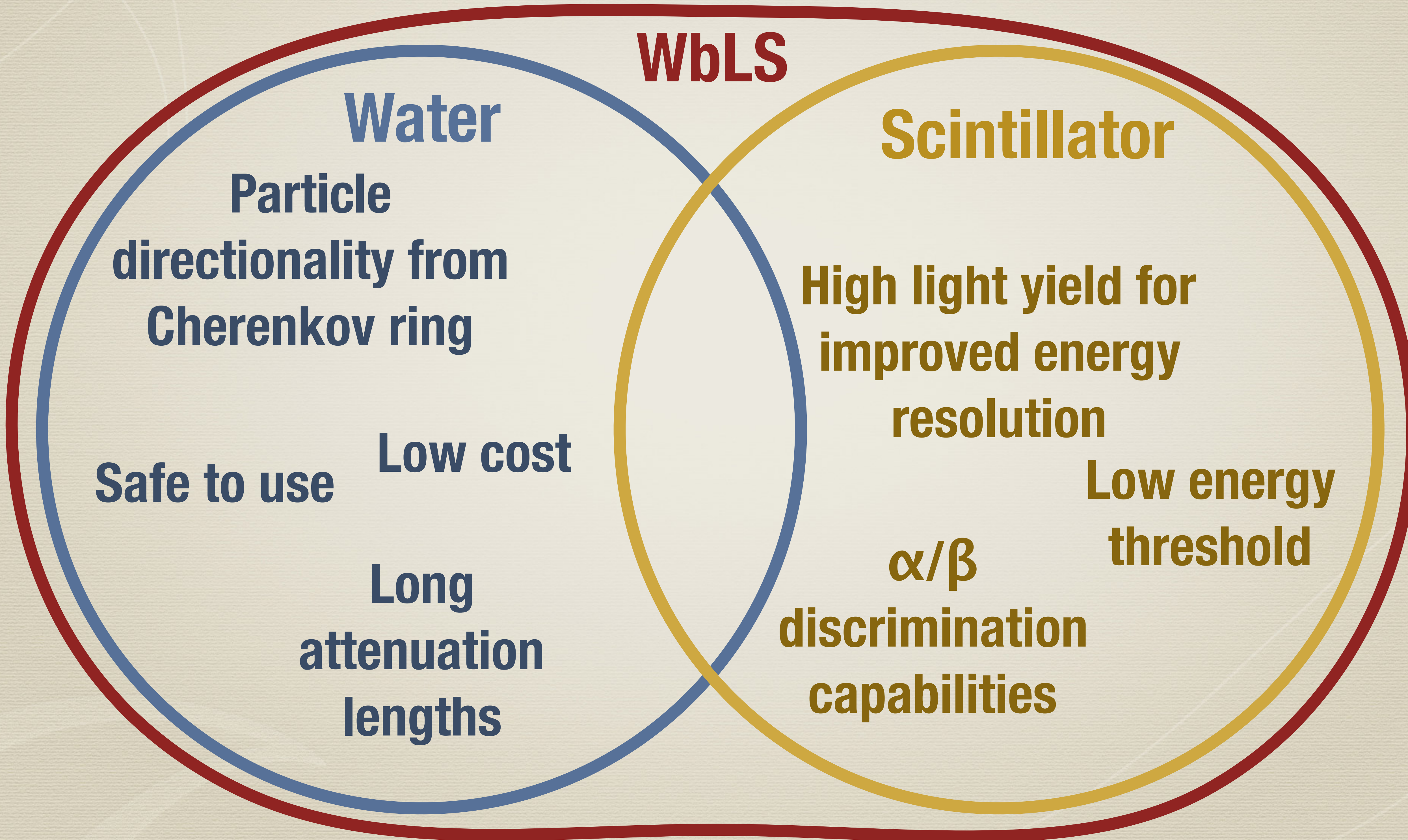


WbLS uses surfactants to form nm-scale micelles of liquid scintillator, such that a suspension can be formed.



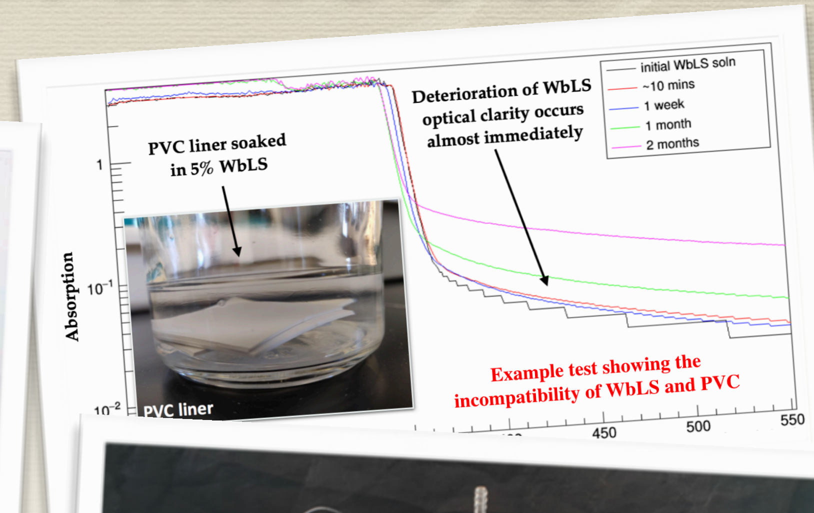
An optical simulation of the proposed THEIA far detector module. By utilising the benefits of BOTH liquid scintillator and water Cherenkov detectors, this 25 kTon WbLS detector has the potential to be one of the most far reaching next-generation neutrino detectors

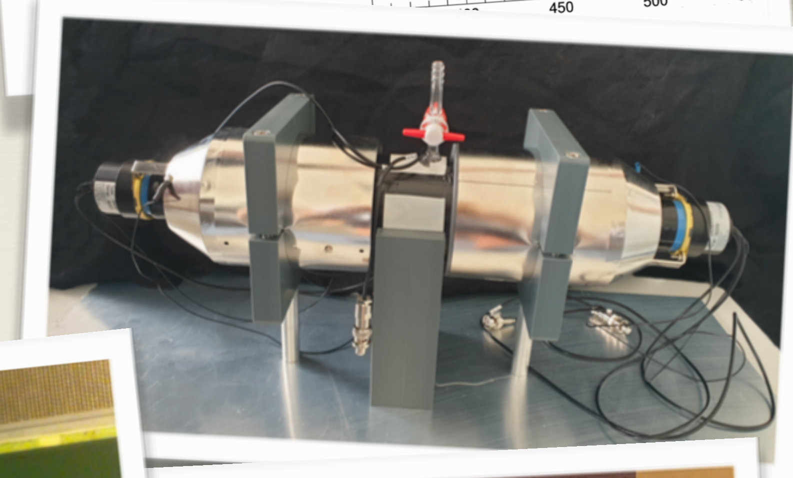
WbLS combines the benefits of water Cherenkov and liquid scintillator detectors

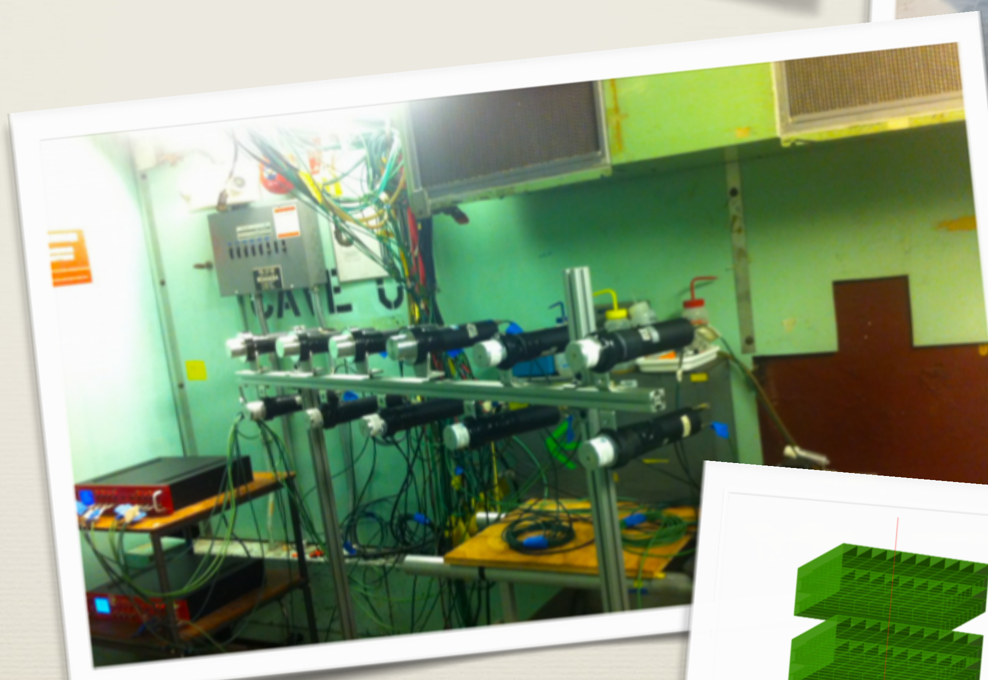


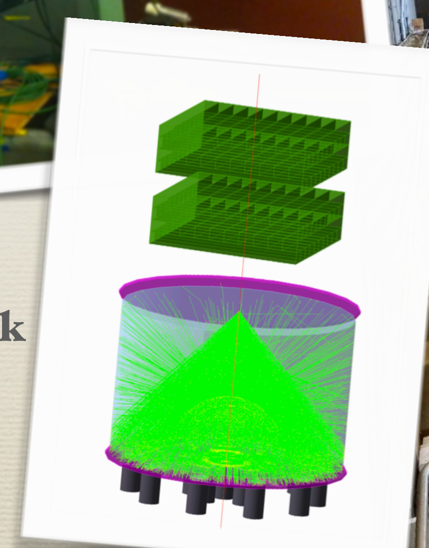
WbLS R&D is advanced

* Full characterization of WbLS has been a primary focus of the THEIA collaboration for many years.
* Groundbreaking developments in production, purification, and advanced reconstruction techniques have been realized.
* Cherenkov/scintillation separation has gone from an idea to a proven concept.
* Precision measurements of the attenuation, material compatibility, light yield and timing are currently ongoing.









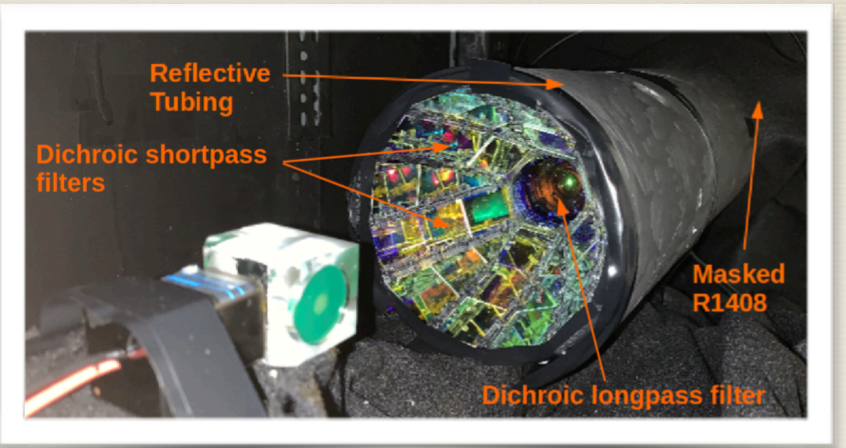
Example of ongoing work at UC Davis, Mainz, Berkeley and Munich

Dichroic filters have a proven capability to separate Cherenkov and scintillation light

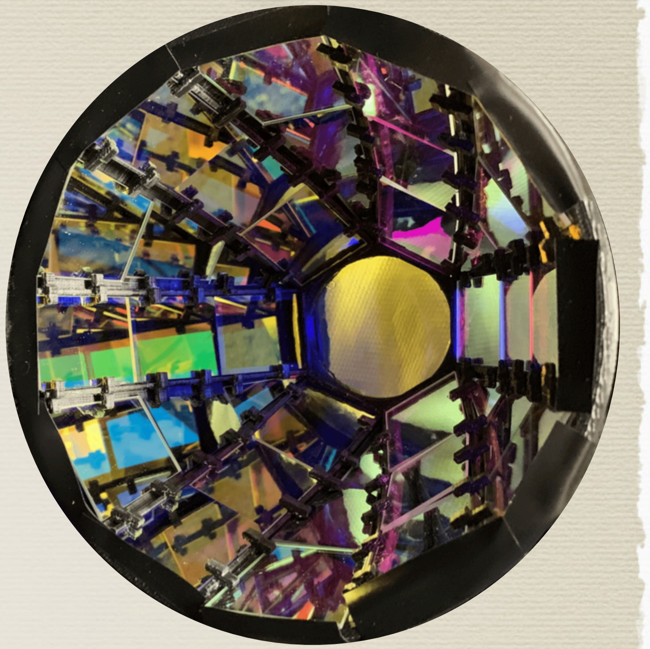
* Dichroic filters allow photons within a wavelength band to pass through while reflecting those outside that range.

* The ingenious design of the dichroicon, enables Cherenkov and scintillation light to be detected on separate photosensors within one module.

* Depending on the dichroicon design, high levels of separation have been achieved - with Cherenkov purities above 90%.



Dichroicon test stand



Example dichroicon design

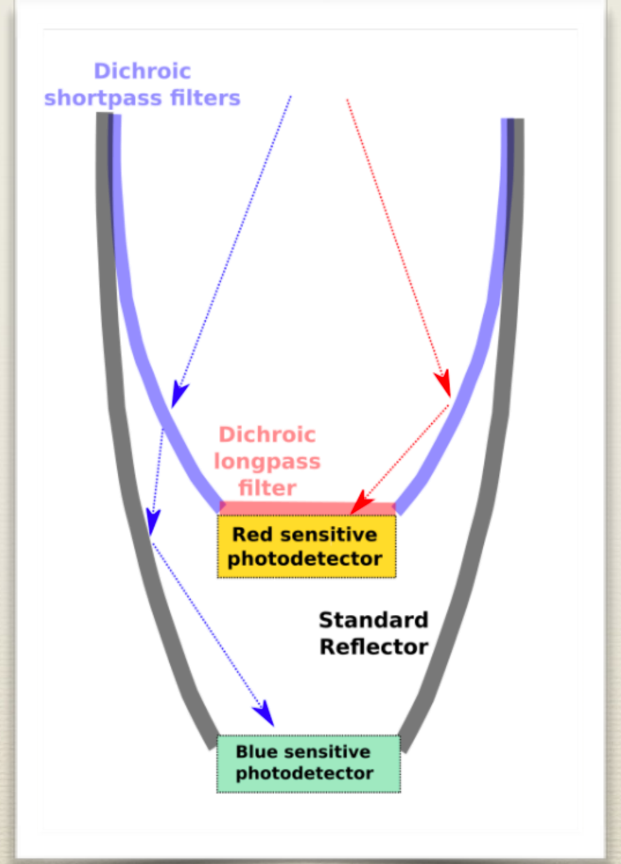
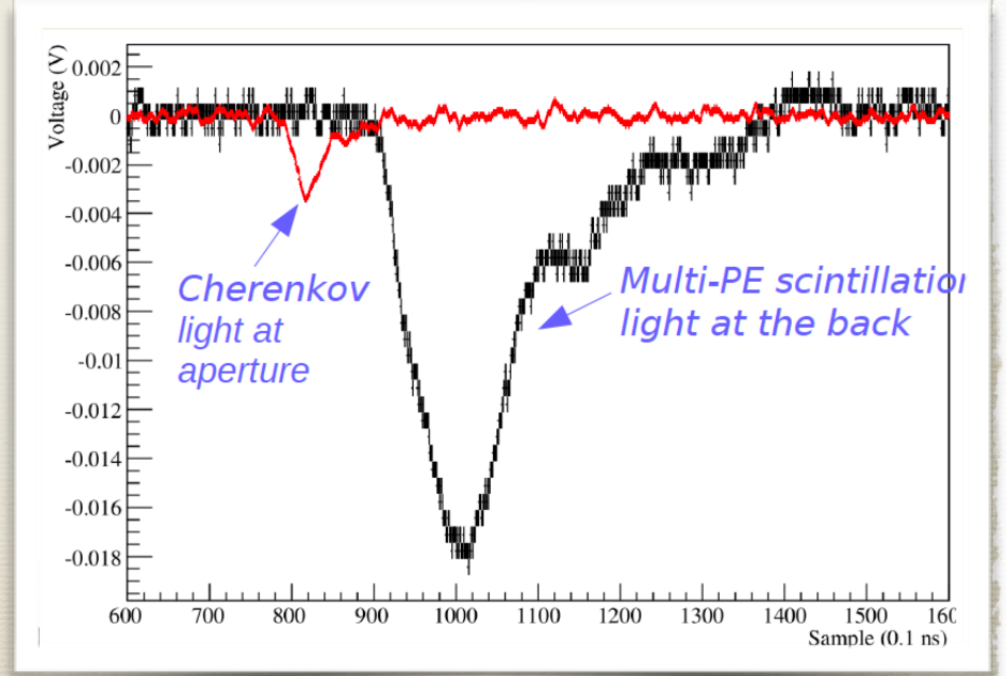


Diagram highlighting the dichroicon concept



Cherenkov and scintillation light are observed on different photosensors.

T. Kaptanoglu et al. Phys. Rev. D 101, 072002 (2020)

CHESS and the ability to separate Cherenkov and scintillation light using fast photosensors

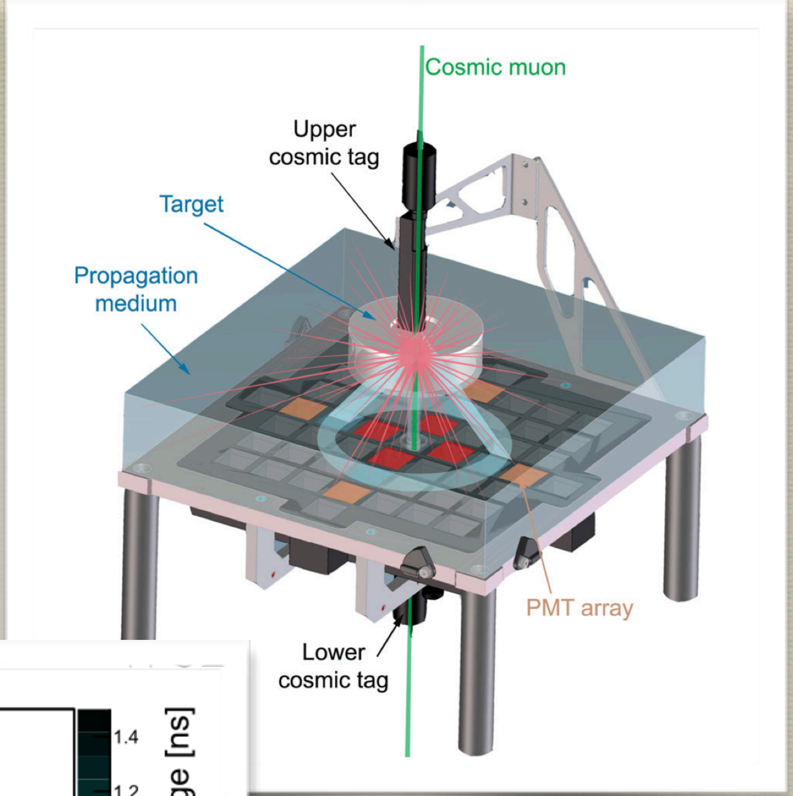
* Vertical cosmic ray muons impinging on a WbLS target volume produce a combination of Cherenkov and scintillation light.

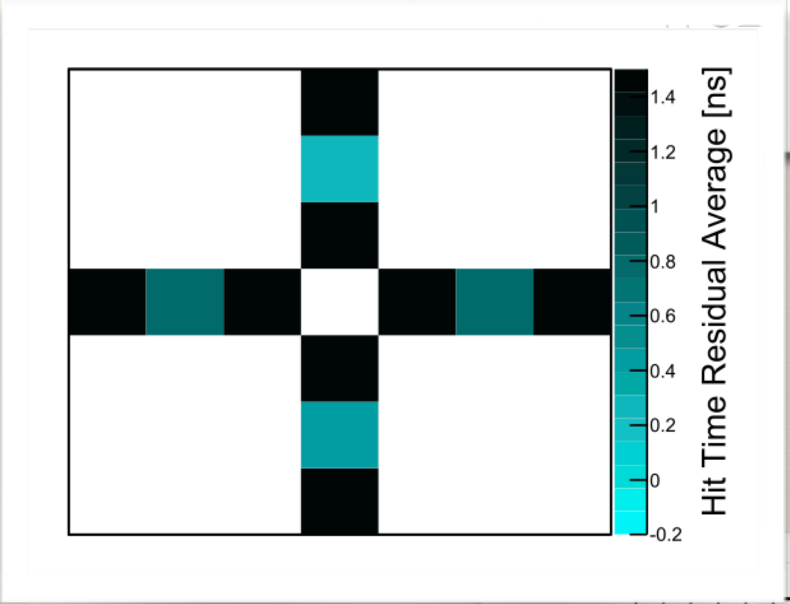
* The geometry of the experiment is such that the Cherenkov light only illuminates the central PMTs while the isotropic scintillation light illuminates the entire PMT array.

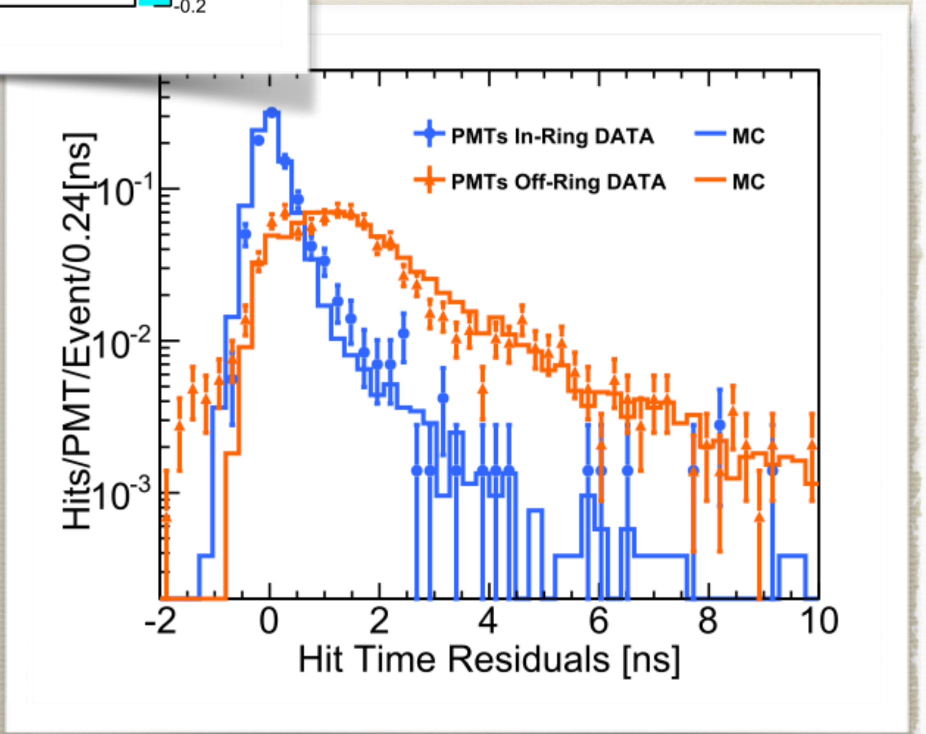
* The hit time residuals of the "in-ring" PMTs is clearly shifted compared to that of the "off-ring" PMTs.

* This is as expected due to the faster nature of the Cherenkov production mechanism.

* For all WbLS cocktails tested (1%, 5% and 10% by organic loading) Cherenkov detection efficiencies of over 80% were achieved.



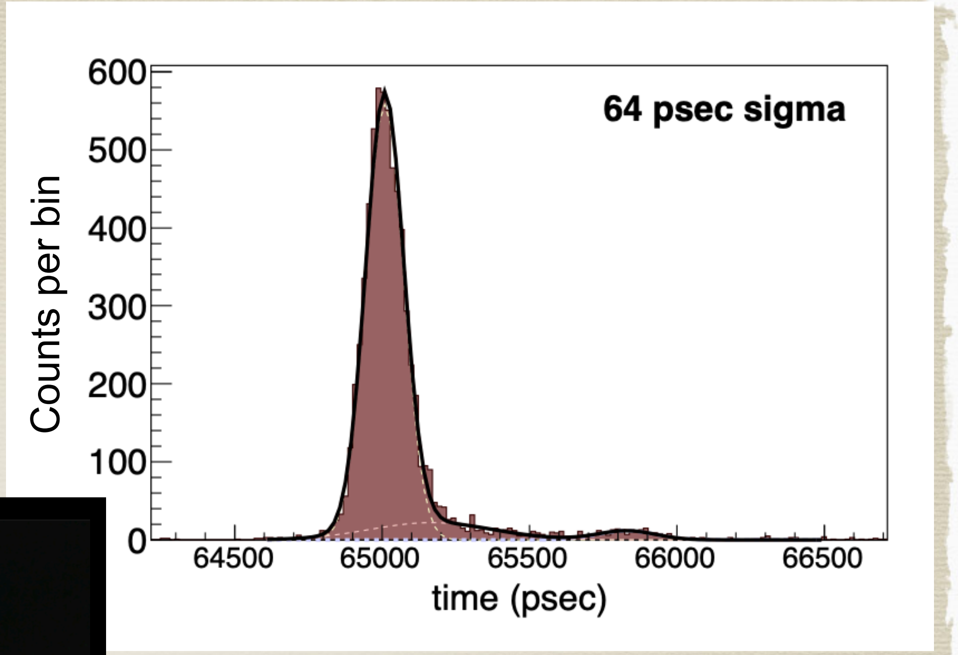


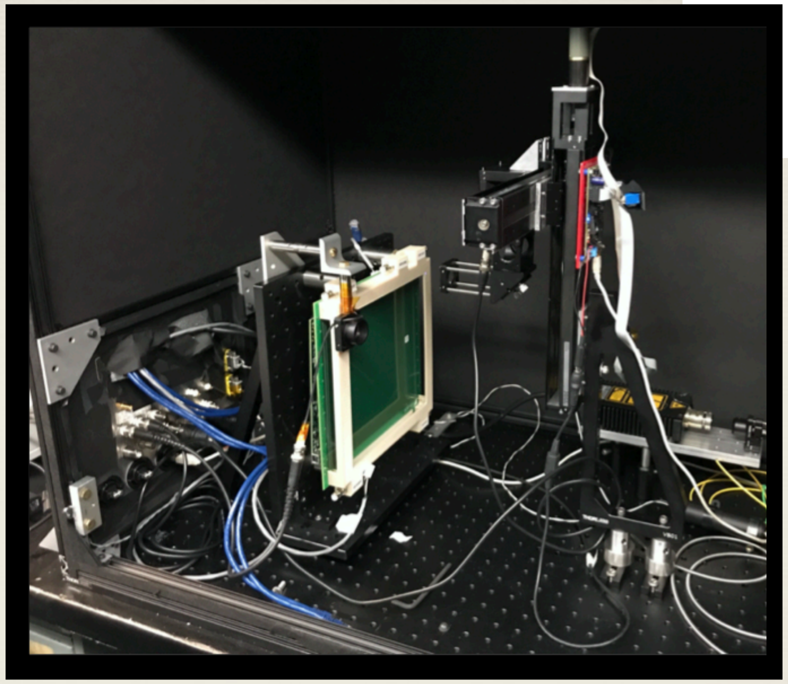


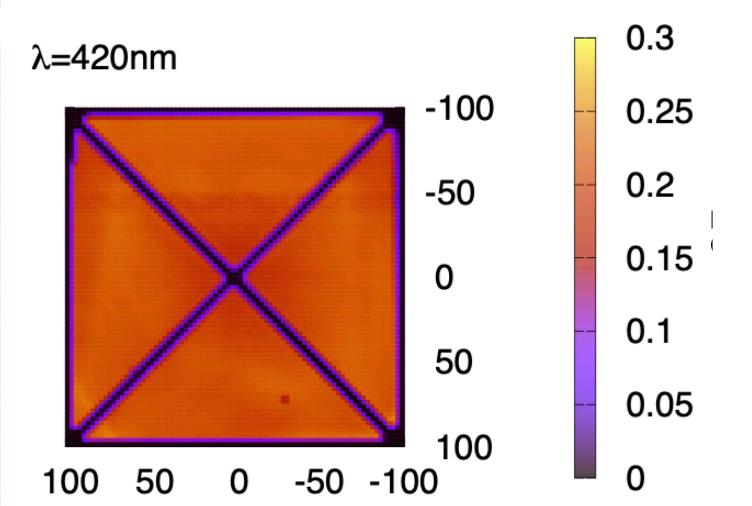
J. Caravaca et al. Eur. Phys. J. C (2020) 80:867

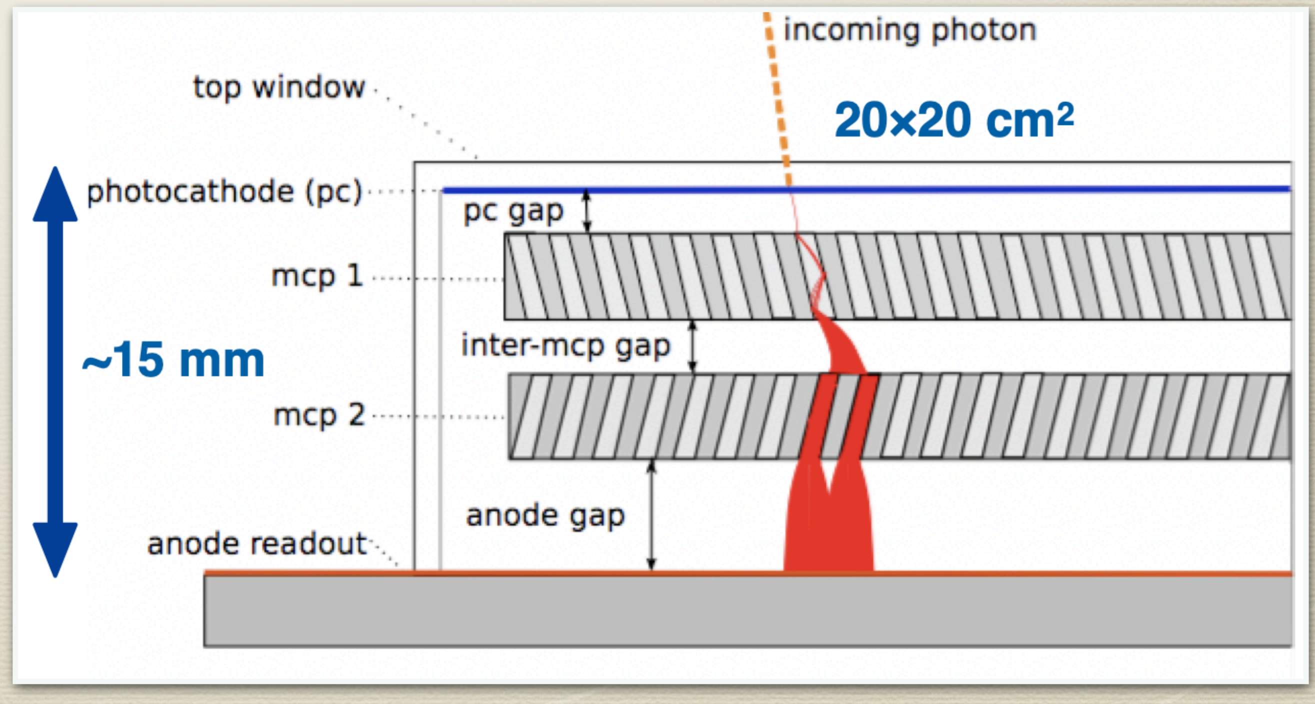
LAPPDs for ultra-fast timing

* Large-area picosecond photodetectors (LAPPDs) are cutting-edge photodetectors.
* Consist of strips of micro channel plates.
* Sub-cm spacial and ~60ps timing resolution.
* > 20% quantum efficiency.
* ANNIE has now installed its first LAPPD - a world first in a running neutrino experiment.





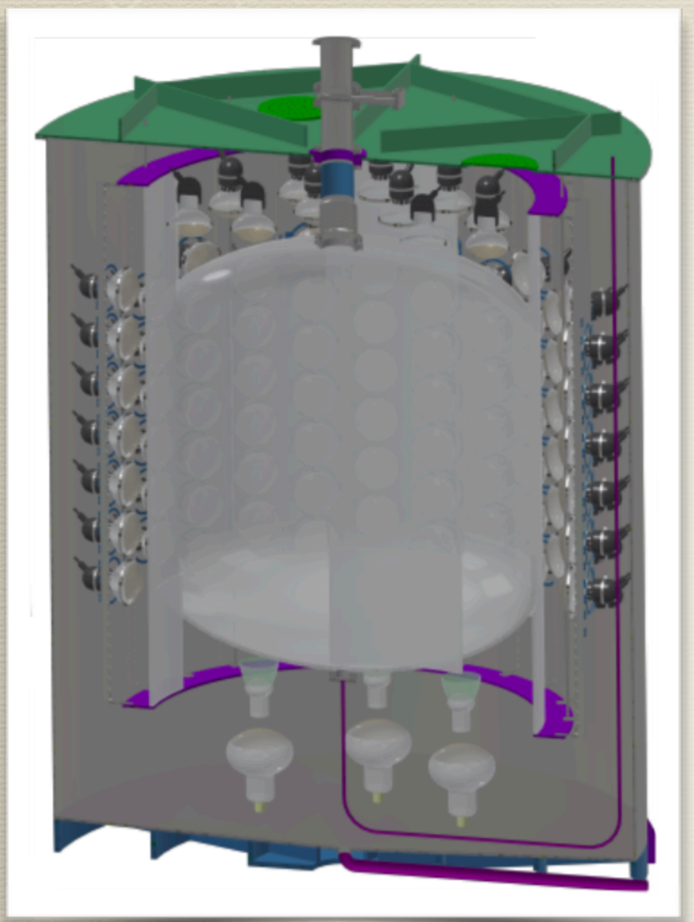




B.W. Adams et al. NIM A Volume 795, 1 (2015)
R. Back et al. arXiv:1707.08222 (2017)
T. Kaptanoglu et al. EPJC 82 2, 169 (2022)

WbLS testing facilities are already underway

EOS



* 4 tonne WbLS volume
* Instrumented with R14688-100 and R11780 ultra-fast PMTs
* Upward facing dichroicons
* Flexible testbed for state-of-the-art technology, readout design and development of analytical techniques

BNL

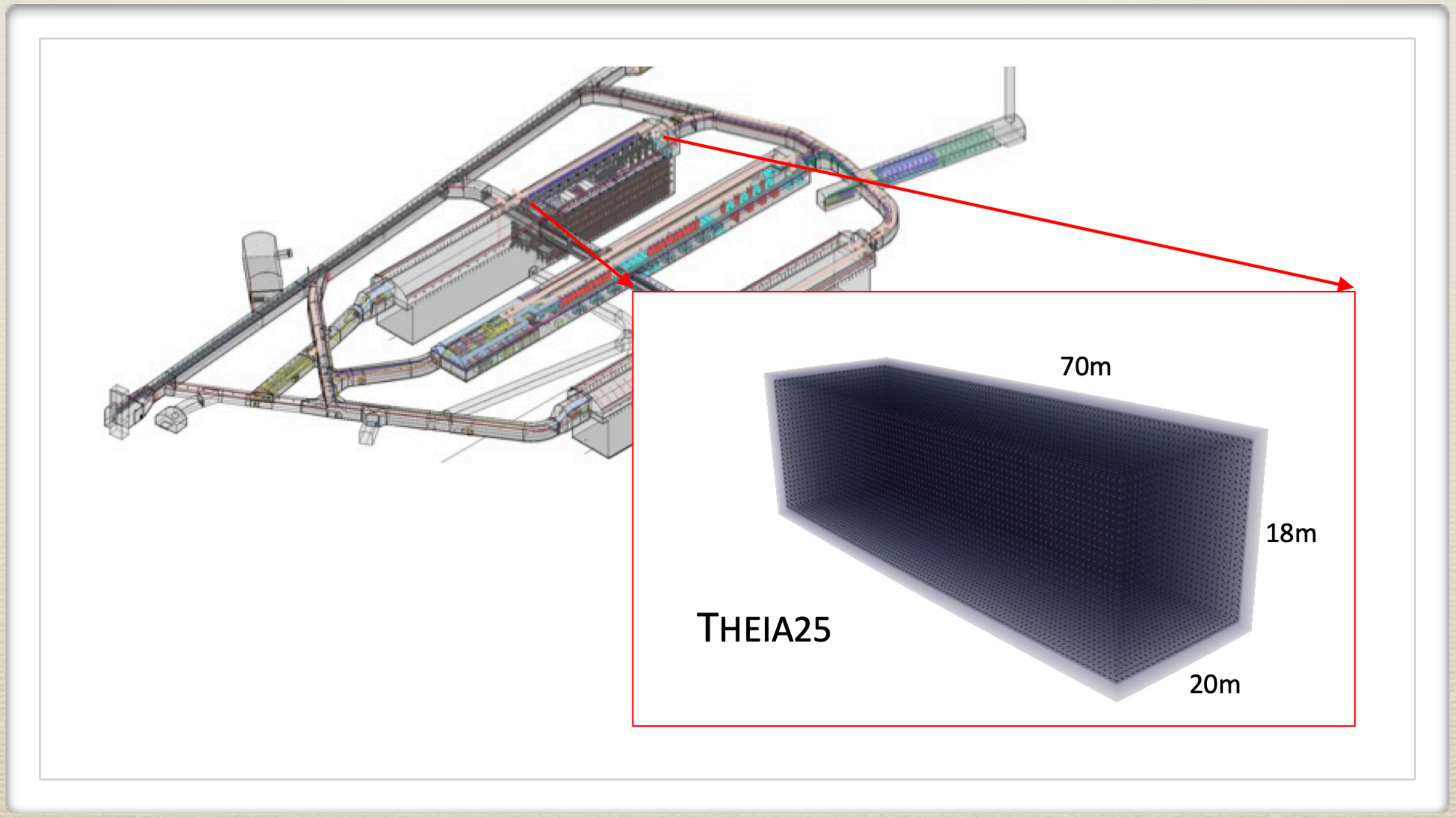
* Nominally 30 tonne WbLS volume
* Proof of concept for nanofiltration as a purification method
* Test of long term stability, transparency and deployment

ANNIE

* 400 L WbLS volume
* To be installed within the ANNIE tank
* Pioneering use of WbLS in a neutrino beam
* Complimentary to the THEIA long baseline programme
* High energy event reconstruction, neutron detection efficiency measurements, Cherenkov and scintillation separation

THEIA has an extremely broad physics program

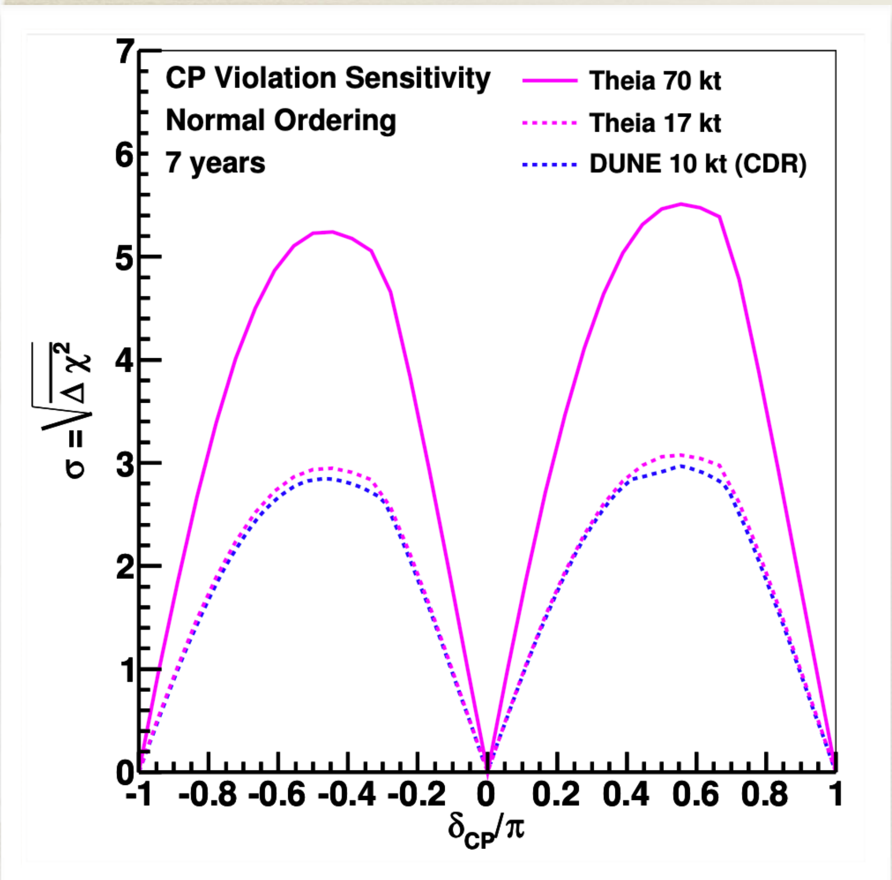
* Due to the novel benefits of WbLS, combined with fast-photosensors and advanced reconstruction techniques, THEIA offers great complementarity to DUNE.
* Low-energy, high-energy and beyond the standard model physics can all be explored in one detector.
* Furthermore THEIA will add to the physics reach of the DUNE project

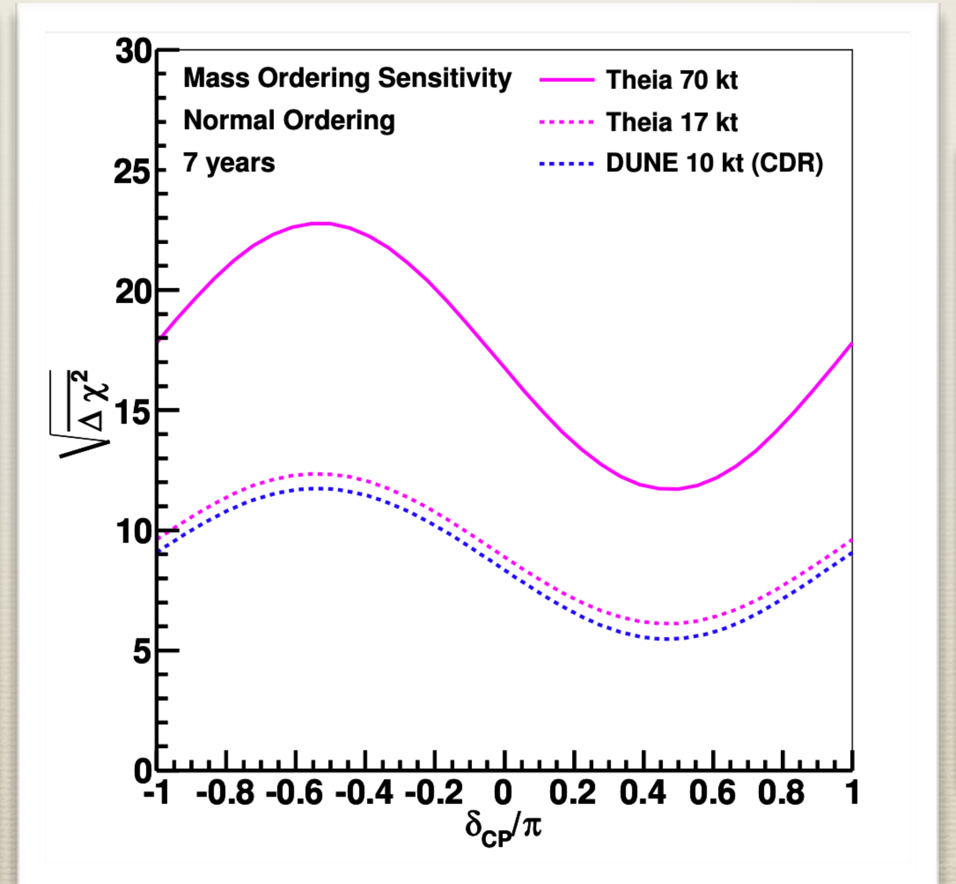


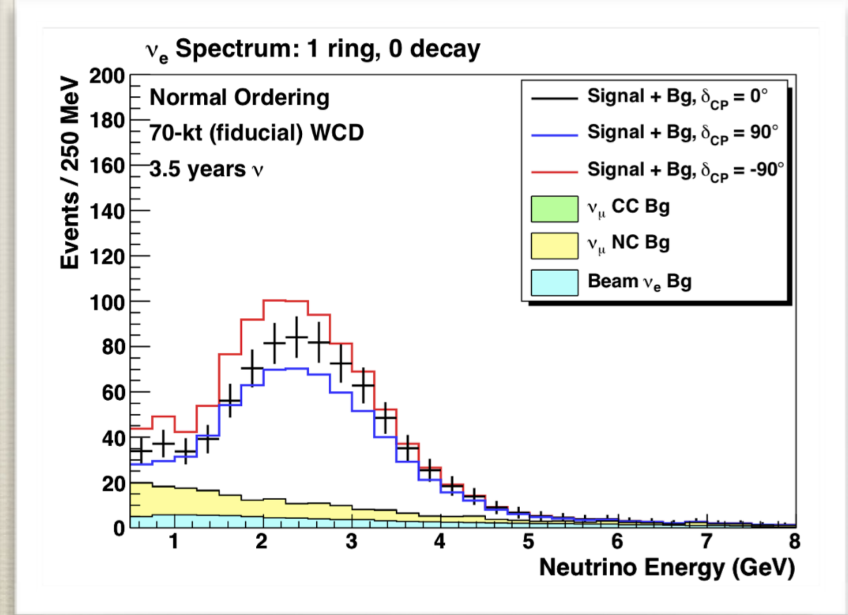
M. Askins et al. The European Physical Journal C volume 80, Article number: 416 (2020)

A combined THEIA and DUNE program will further enhance the long baseline reach of each

* THEIA offers great complementarity to the DUNE project due to its simple nuclear target volume, the well measured cross sections on similar nuclei, and the resulting different systematic uncertainties.
* If THEIA is installed at the far detector location, it will have a comparable discovery potential, for both CP violation and mass hierarchy measurements, as a DUNE module.
* In addition, they will provide an important cross check and enable a combined fit to further boost the DUNE measurement precision.



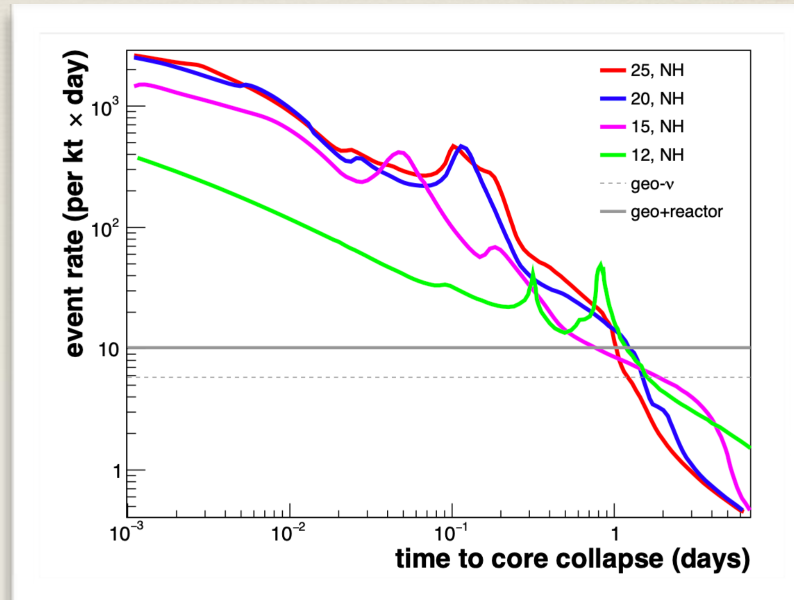




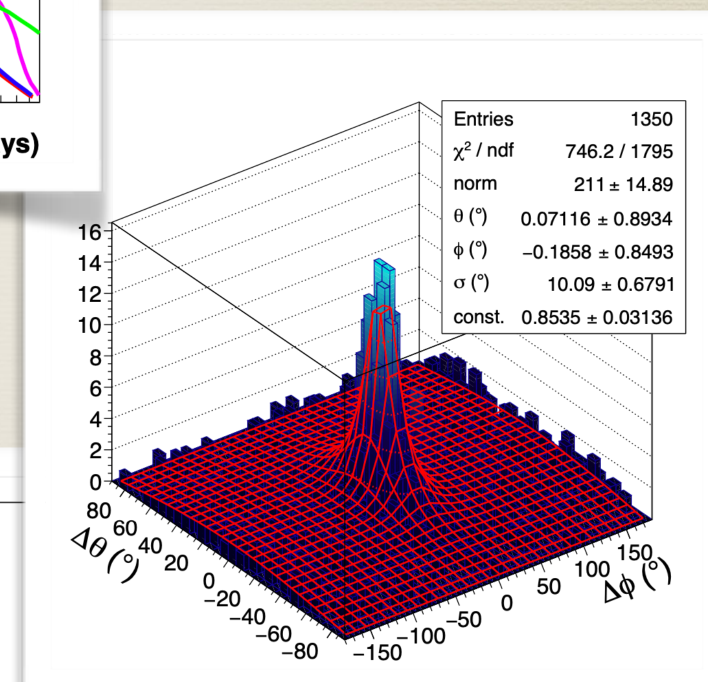
DUNE and THEIA observe different supernovae channels

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

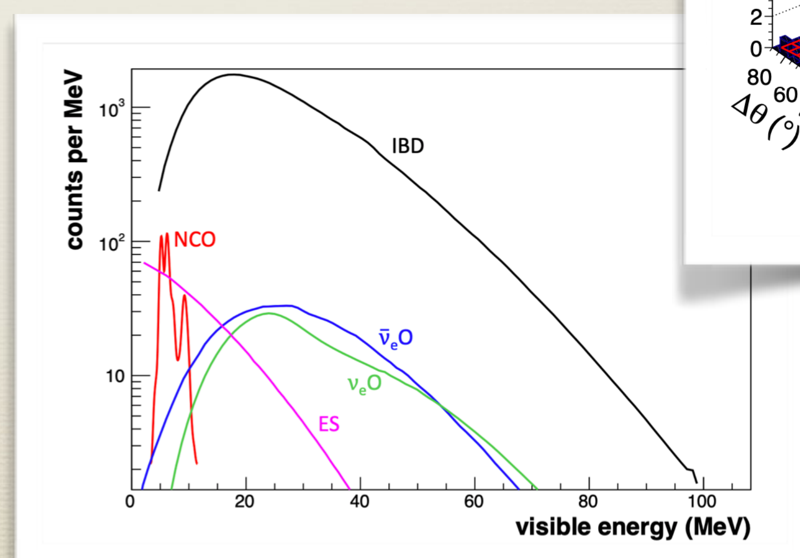
* Alongside DUNE, THEIA25 will offer a unique opportunity. The co-detection of the DUNE ν_e and THEIA ν_e-bar signal enables the only exploration of neutrino/antineutrino flavour oscillations through the Earth at one location.



* With its fast-photosensors THEIA can also perform as a trigger.



* With its high-efficiency neutron tag, THEIA will be able to effectively select ES events from the IBD background - providing directionality information.



* Flavour resolved spectroscopy of the individual components will be possible.

DUNE and THEIA join forces for nucleon decay searches

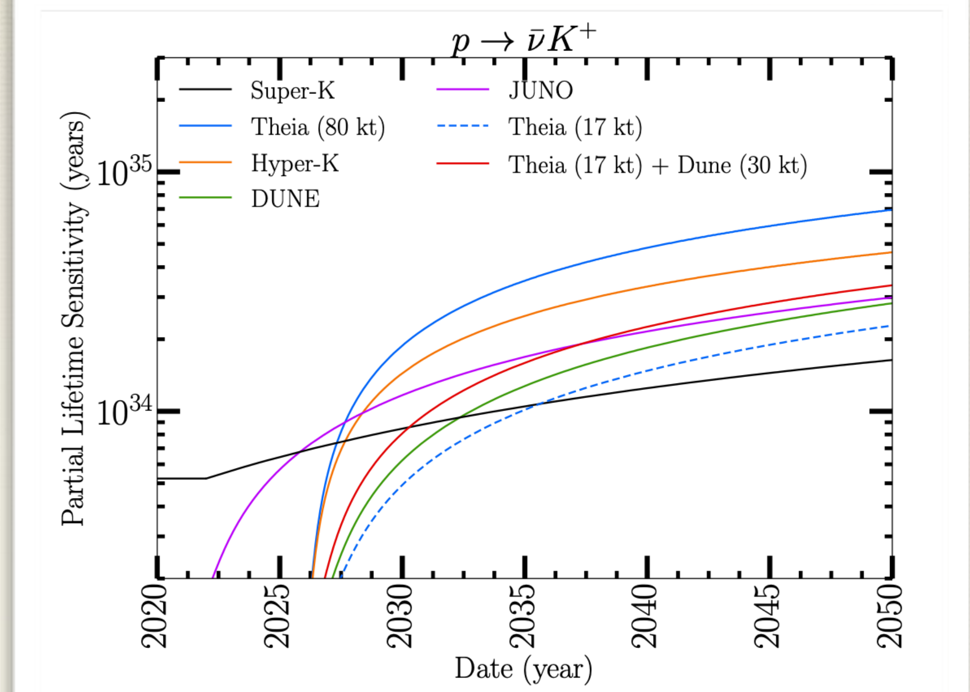
* DUNE and THEIA will both benefit from each other in the search for the nucleon decay.

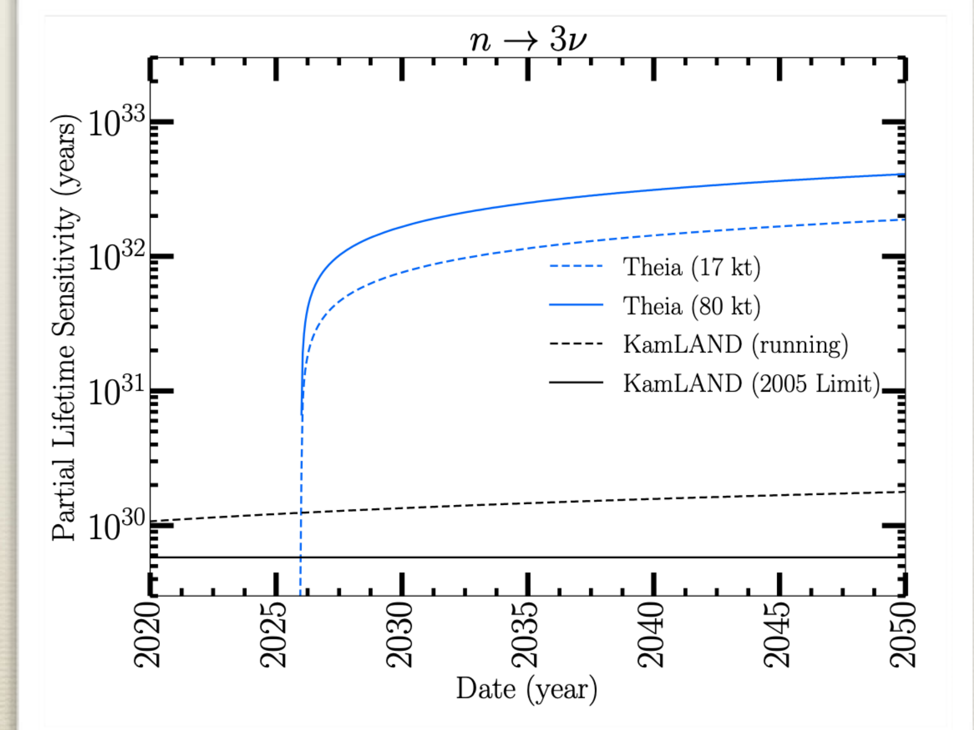
* For the p → ν̄K+ mode THEIA's detection efficiency is limited by the ability to distinguish the Cherenkov rings of the kaon decay products from the prompt kaon energy deposition.

* Conversely, DUNE will see the kaon track but is limited by intranuclear effects.

* A combined search will allow both to exceed the JUNO sensitivity.

* THEIA, with its large scintillating volume will make it the preeminent next-generation neutrino detector for invisible nucleon decay.



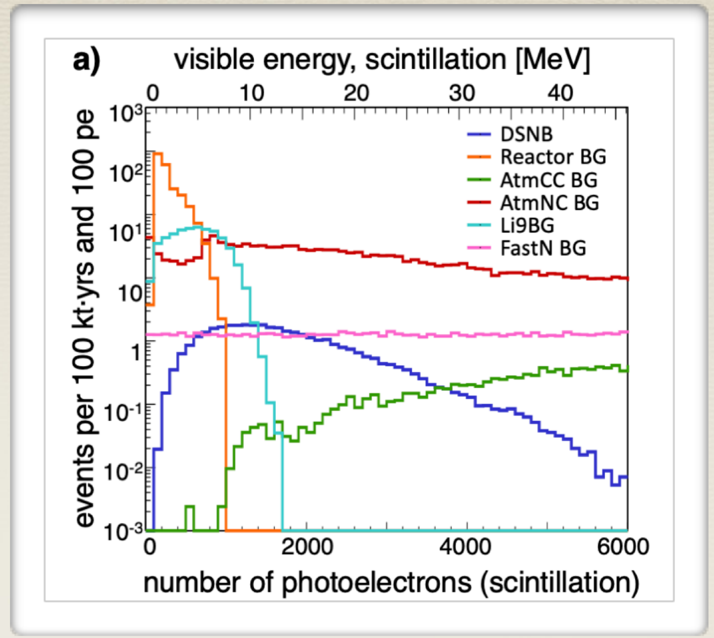


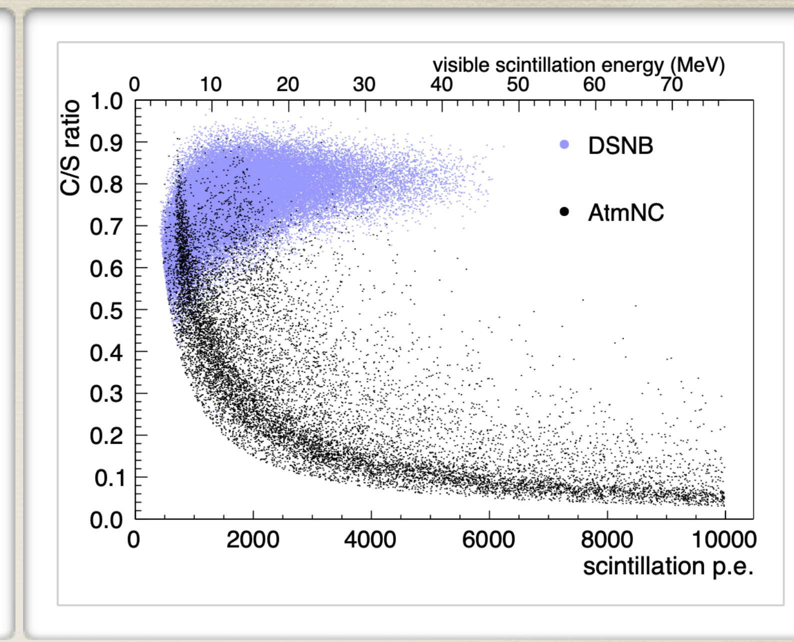
THEIA will observe the DSNB and measure its spectrum

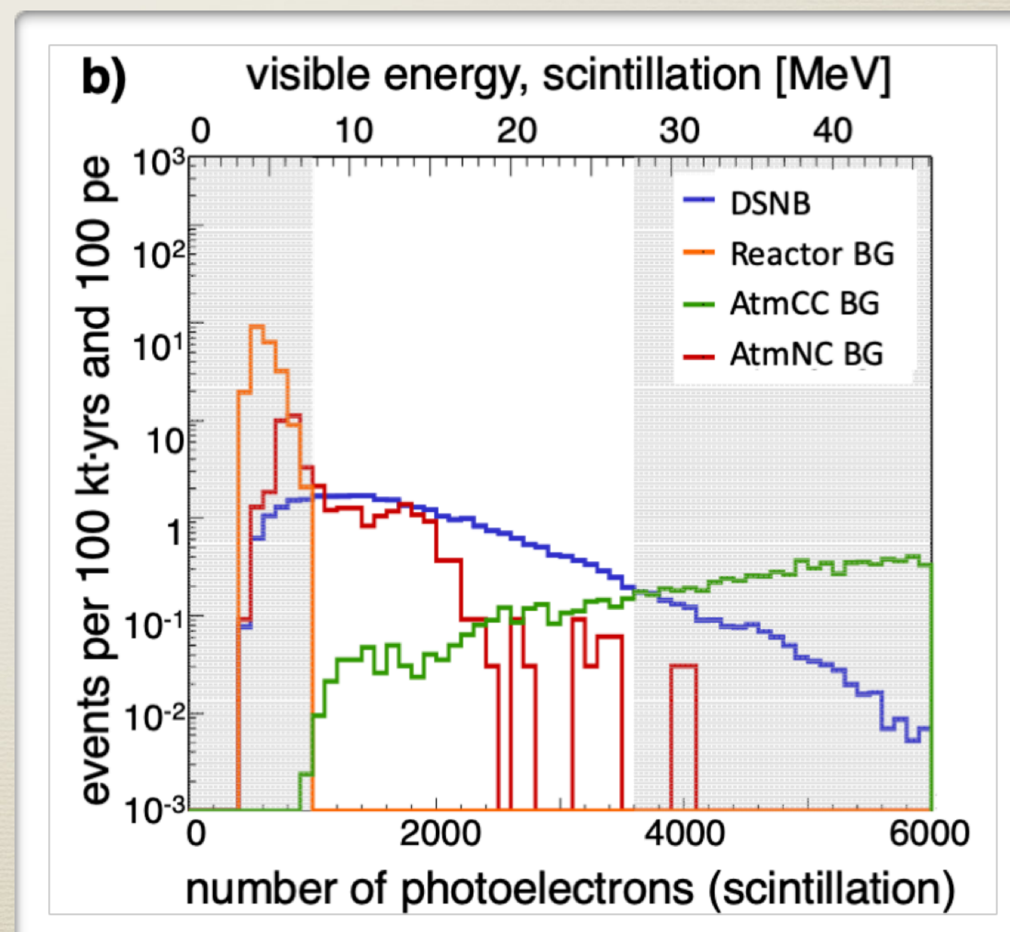
* WbLS offers excellent background reduction techniques to observe the IBD DSNB signal.

* Reduction of the atmospheric background through fiducialisation, distance cuts relative to muon tracks, ring-counting, tagging below Cherenkov threshold delayed decays, and using the Cherenkov/scintillation ratio of events.

* THEIA25 will obtain a 5σ discovery in 6 years compared to SK-Gd and JUNO with a 3σ discovery in 5-10 years.







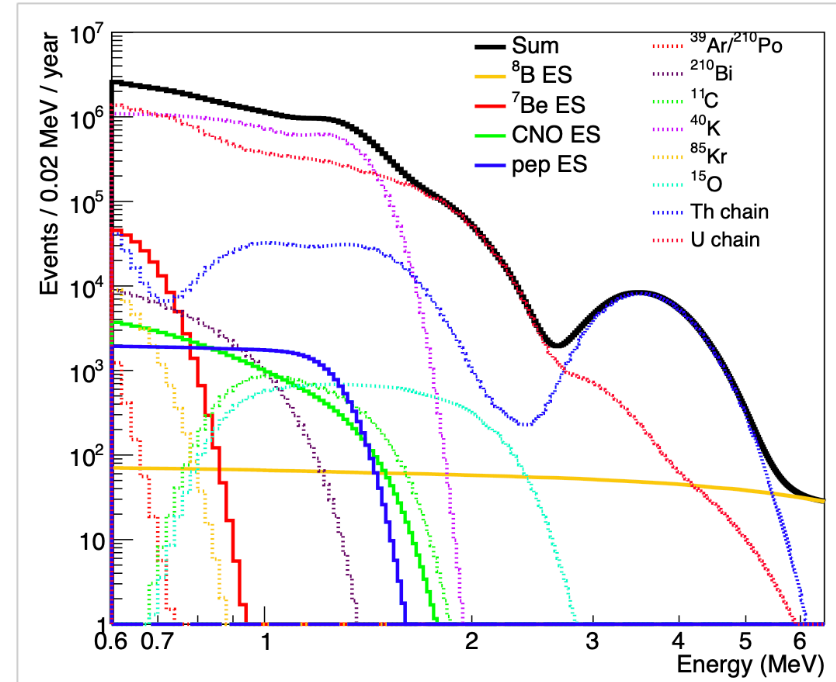
THEIA and solar neutrinos

* THEIA will be able to perform a multitude of solar observations - precise CNO measurement, measurement of the energy spectra of the 8B flux and precision measurements of pep neutrinos.

* It is unique in its ability to observe CNO neutrinos.

* As a hybrid detector, it benefits from the scintillation signal to give a low threshold while also using directionality to reject radionuclide background ES events.

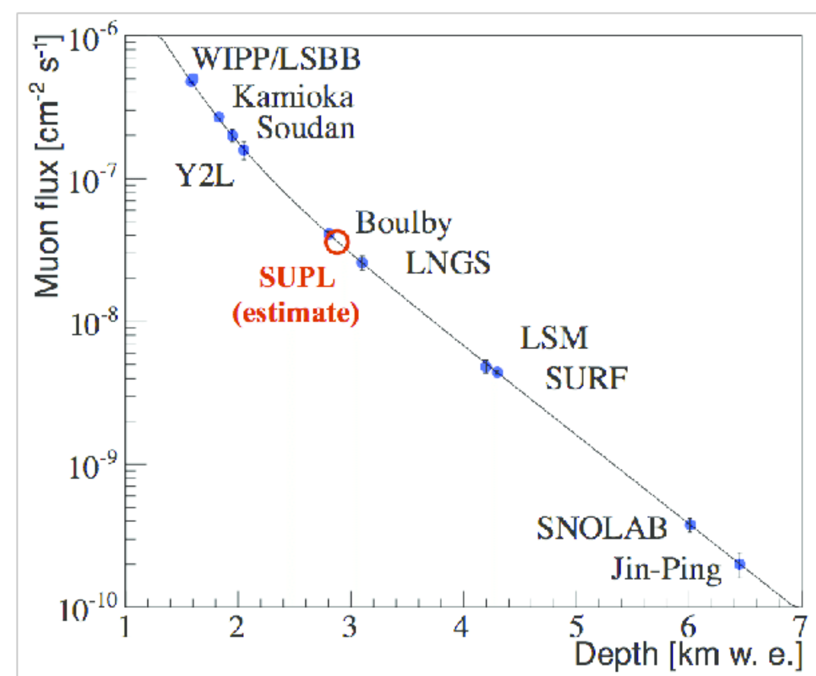
* Additionally, the depth of THEIA25 would offer a 6x reduction in the muon rate compared to Borexino.



Predicted energy spectrum for a 5% loaded THEIA

Target mass	WbLS	25°	35°	45°	55°	60°	65°
100 kt	0.5%	4.7%	6.8%	8.6%	10.5%	12.1%	13.6%
100 kt	1%	4.5%	6.4%	8.0%	10.0%	11.5%	12.9%
100 kt	2%	4.1%	5.9%	7.5%	9.3%	10.6%	12.3%
100 kt	3%	3.7%	5.3%	6.9%	8.4%	9.8%	11.3%
100 kt	4%	3.6%	5.2%	6.6%	8.0%	9.5%	10.9%
100 kt	5%	3.4%	4.9%	6.3%	7.4%	8.7%	9.9%
25 kt	0.5%	11.1%	16.2%	20.6%	24.1	28.4%	32.8%
25 kt	1%	10.0%	14.1%	18.1%	22.1%	25.8%	29.6%
25 kt	2%	8.7%	12.6%	16.1%	19.7%	23.1%	26.4%
25 kt	3%	8.0%	11.6%	14.9%	18.0%	21.5%	24.2%
25 kt	4%	7.7%	11.1%	14.3%	17.4%	20.4%	23.0%
25 kt	5%	7.2%	10.2%	12.9%	15.5%	18.0%	20.3%

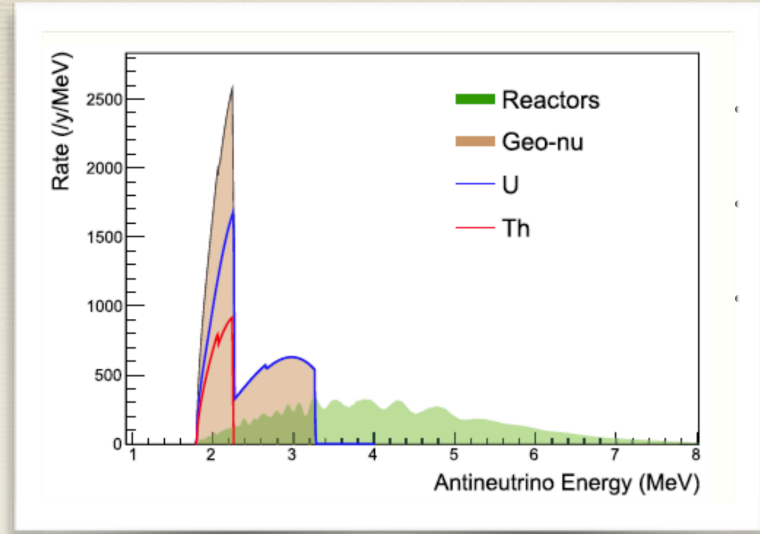
Uncertainty of the CNO normalization as a function of target mass, WbLS loading and assumed angular resolution



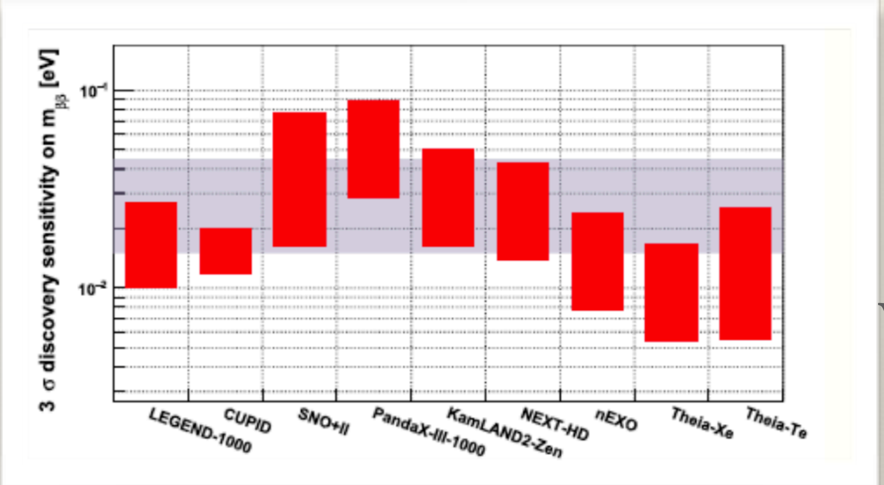
The DUNE far detector site offers a reduced muon flux compared to Borexino - improving the precision of the THEIA CNO measurement

Wait! THEIA can do more

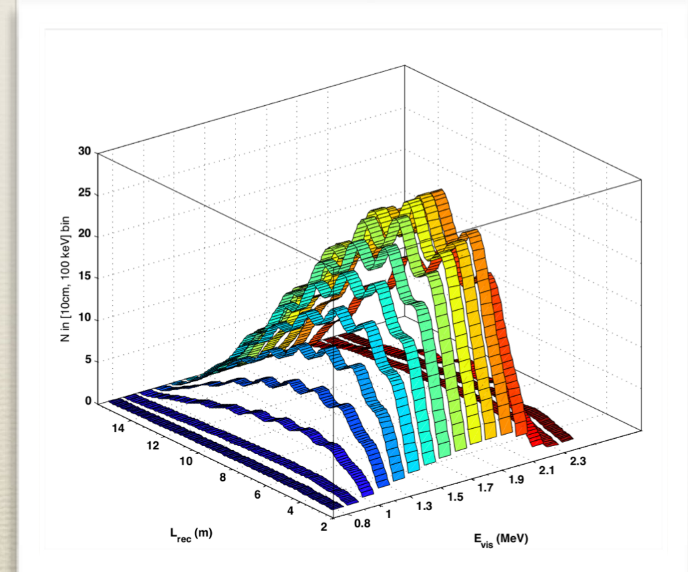
* THEIA25 has further capabilities…
* Detection of reactor and geoneutrinos
* World-leading measurement for 0νββ decay
* Potential search for sterile neutrinos…



THEIA will have the novel capability to point back to the neutrino production site, provide the largest data set of geoneutrinos and potentially make the first measurement of geographic neutrino flux variations.



Installation of a 130Te or 136Xe doped liquid scintillator balloon would add further utility to THEIA - with a goal $T_{0\nu\beta\beta\ 1/2} \sim 10^{28}$ yr.



Yet another option for THEIA would be to deploy a CeSOX style source - by measuring the position dependent flux, inference of a 4th-generation sterile neutrino may be possible.

Conclusions

* THEIA is a novel WbLS detector concept that offers a unique opportunity to complement and expand upon the DUNE project.
* Utilizing the benefits of both Cherenkov and scintillation emission in the hybrid detector will enable it to be one of the most far-reaching multi-use neutrino experiment ever built.
* R&D into the state-of-the-art detection technology is vast and well advanced.
* WbLS is a well developed medium, with a simple, extensively measured and well understood nuclear target.
* LAPPDs and fast photosensors are on the cusp of revolutionizing the next-generation of optical neutrino detectors.
* The advent of dichroic filters offers to further expand the physics reach of WbLS detectors.
* With a large, multi-national collaboration, installation of THEIA in the module of opportunity would introduce a broader range of researches into the DUNE community.