THE THEIA DETECTOR

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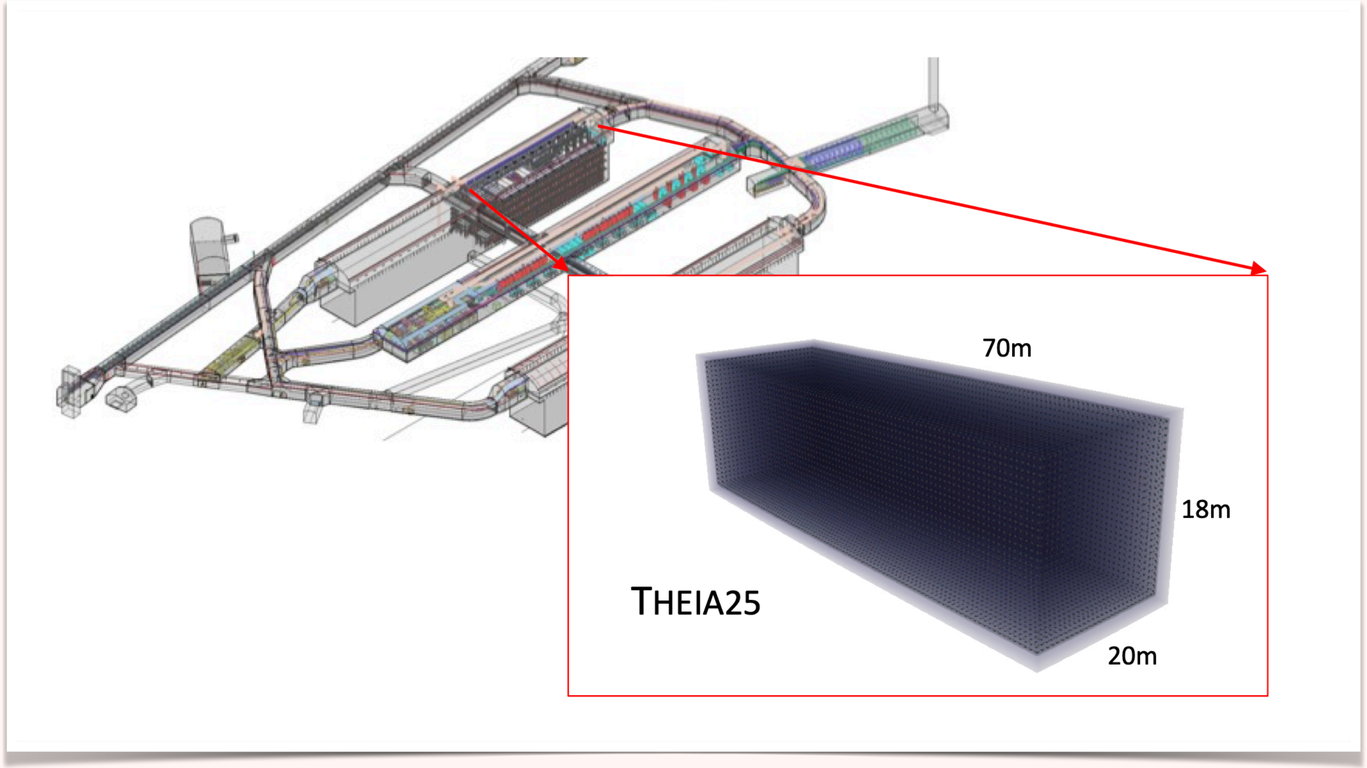
CoSSURF 14th May 2024

INTRODUCTION

- What is WbLS?
- Hybrid detector R&D
- 10 Ton-scale projects
- Introducing Theia
- Physics reach and complementarity with the DUNE program



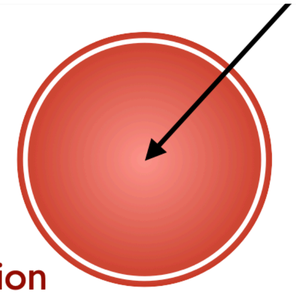
WHAT IS WBLS?

WHAT IS WATER BASED LIQUID SCINTILLATOR?

- **Water-based liquid scintillator is a combination of organic liquid scintillator (such as LAB+PPO) and water**
- **Use a surfactant with its hydrophilic head and hydrophobic tail to combine the two components**
- **This creates nm-scale "micelles" of liquid scintillator homogeneously distributed throughout the water volume**
- **It is tunable!**
- **Depending on the exact physics goal the scintillator/water ratio can be optimized during operation**
- **It is safe, cheap and the physics is well understood**

Cherenkov

- Cherenkov topology: directional sensitivity, particle ID
- Optical transparency: scaling



Scintillation

- High light yield: threshold, resolution
- Pulse shape discrimination: Particle ID
- Radiopure

The whole is greater than the sum of the parts!

The ratio of the two signals gives us additional information on the type of particle interacting

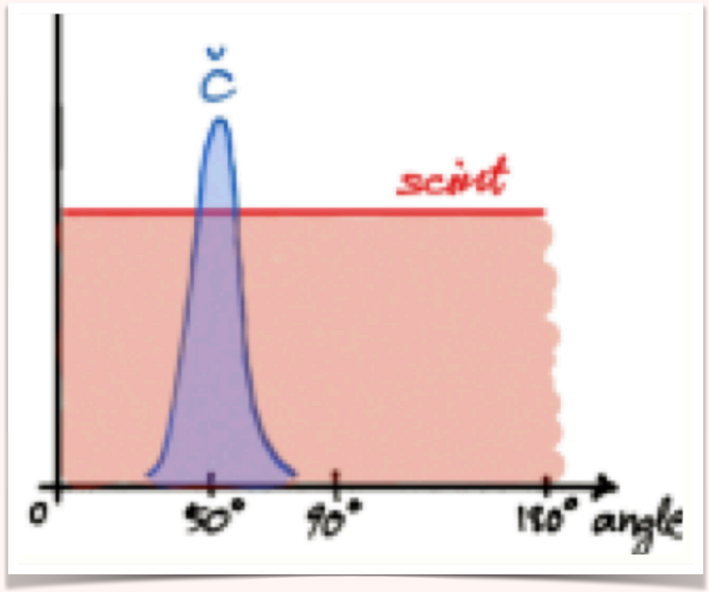
Improved background rejection for precision ν measurements

Facilitates broad program!

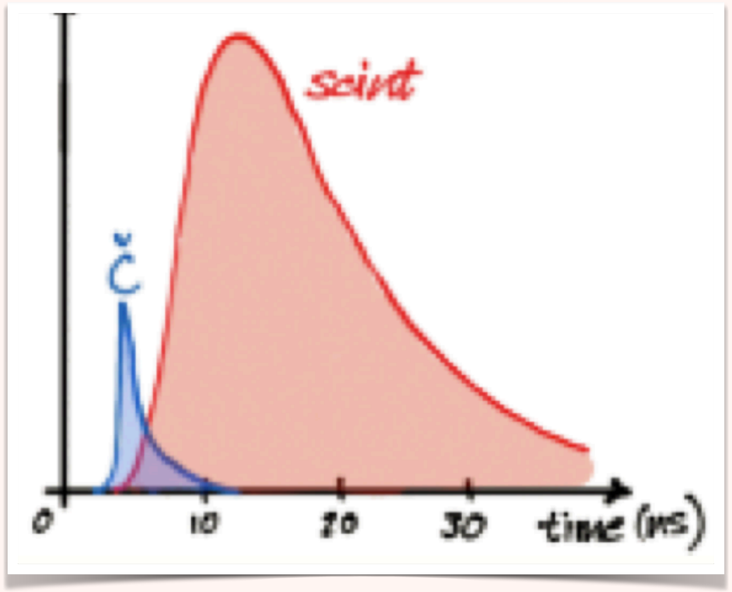
Neutrinoless double beta decay, Particle astrophysics (solar, supernova)
Long baseline physics (CPV, NMH), Nucleon decay, Geo neutrinos

HYBRID DETECTOR R&D

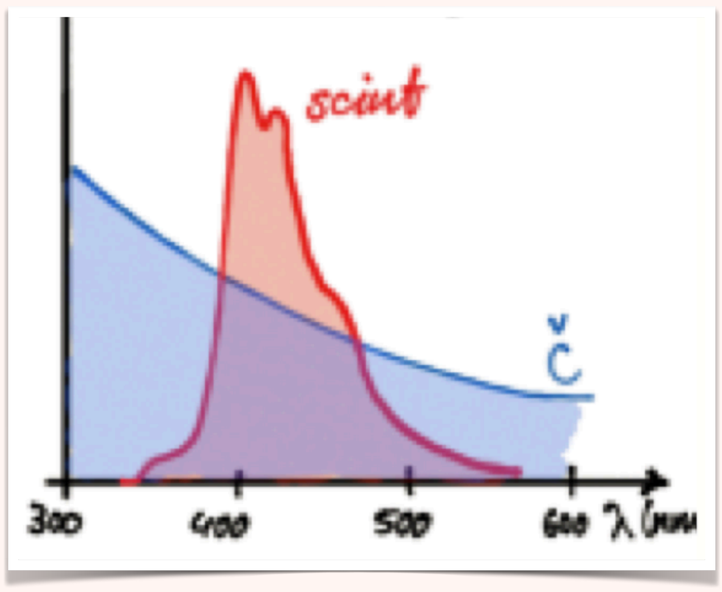
THREE METHODS TO SEPARATE THE CHERENKOV AND SCINTILLATION LIGHT



TOPOLOGICAL



TEMPORAL



SPECTRAL

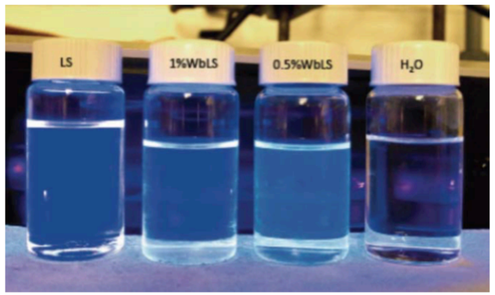
HOW CAN WE DO THIS?

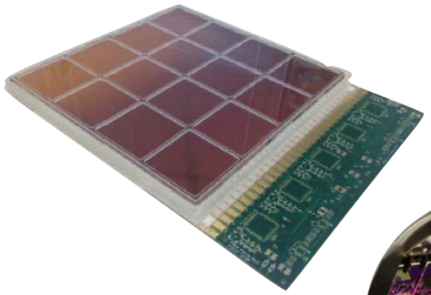
We focus our studies on three technologies that optimize hybrid Cherenkov/scintillation detection:

1. Novel targets, such as water-based liquid scintillator (WbLS). Enhances Cherenkov detection by "dialling down" or otherwise modifying the scintillation signal

2. Large-Area Picosecond Photon Detectors (LAPPDs). Fast-timing discrimination for vertex resolution and Cherenkov/scintillation separation

3. Dichroicons ("chromatic quantum sensing"). Cherenkov/scintillation separation via spectral sorting

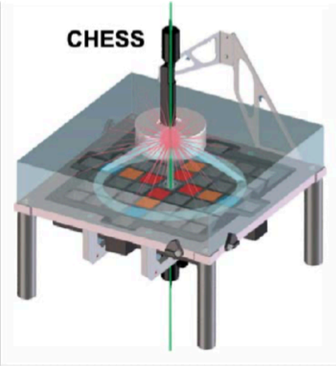


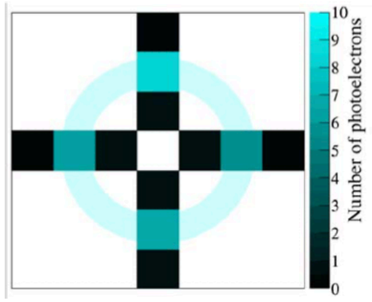


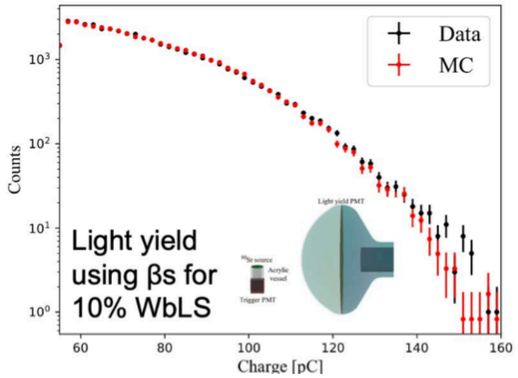
We seek to characterize behavior, understand and model performance at a microphysical level, and use results to extrapolate performance to kton scales.

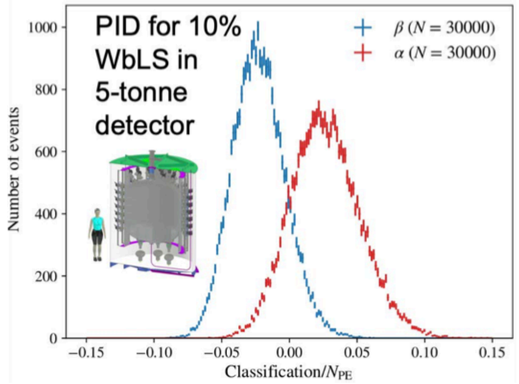
THERE IS WELL OVER A DECADE OF R&D INTO HYBRID TECHNOLOGY

WbLS characterization

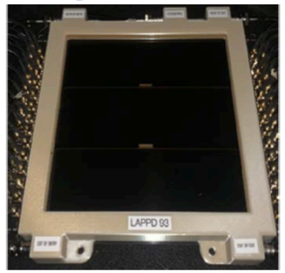


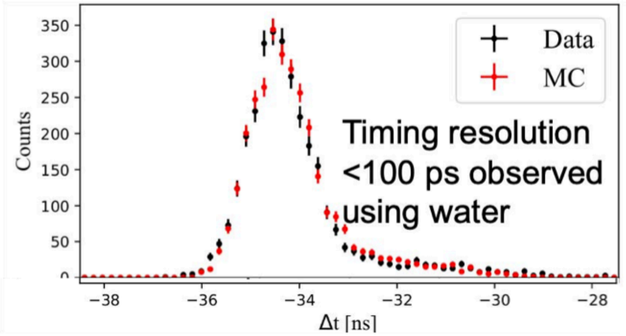


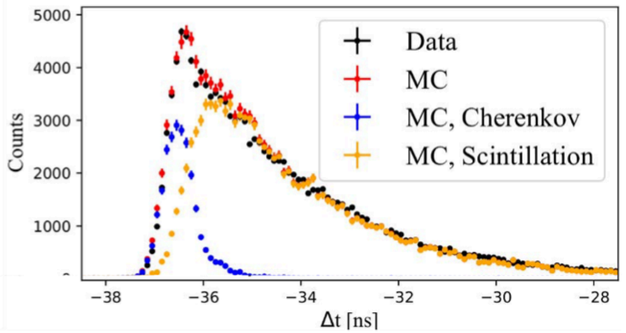




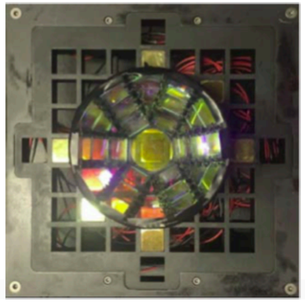
Fast timing photon detection

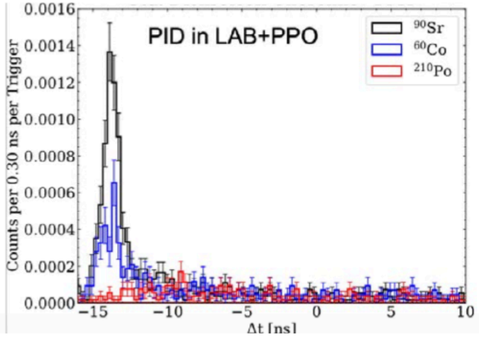






Quantum chromatic sorting





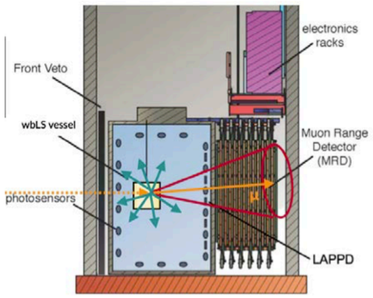
D. Onken et al., Mater.Adv. 1, 71-76 (2020); J. Caravaca et al., Eur. Phys. J. C 80, 867 (2020); E. Callaghan et al., Eur. Phys. J. C 83, 134 (2023); E. Callaghan, T. Kaptanoglu, M. Smiley et al., paper in prep.; J. Caravaca et al., Phys. Rev. C 95, 055801 (2017); J. Caravaca et al., Eur. Phys. J. C 77, 811 (2017); T. Kaptanoglu, E. Callaghan et al., Eur. Phys. J. C 82-2 (2022) 169; T. Kaptanoglu et al., Phys. Rev. D 101, 072002 (2020); S. Naugle et al., paper in prep.

10 TON-SCALE PROJECTS

THERE IS A LARGE SCALE EFFORT UNDERWAY TO DEMONSTRATE THIS NOVEL TECHNOLOGY

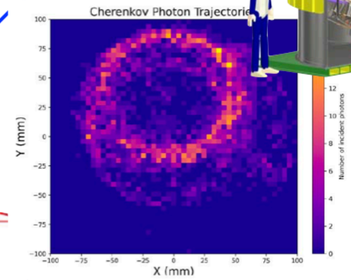
High-energy event reconstruction, neutrino detection

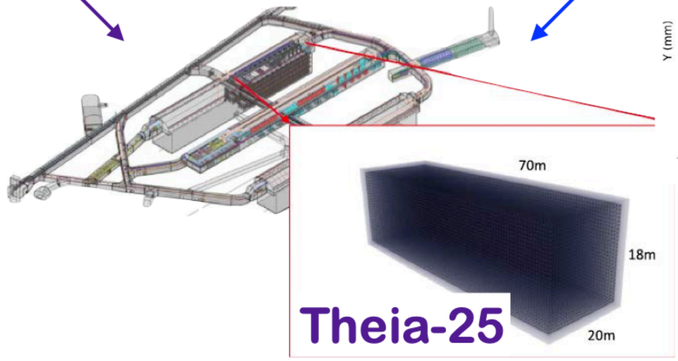
ANNIE: 365 kg



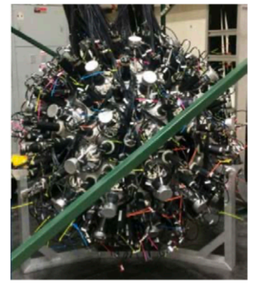
Low-energy event reconstruction, model validation

Eos: 4 ton





NuDot: 1 ton



Deployment, purification, recirculation, transparency

BNL: 1- and 30-ton

Isotope loading, NLDBD topology

INTRODUCING THEIA

THE THEIA PROTOCOLLABORATION

Canada
Alberta
Laurentian
Queens
SNOLAB
Toronto

China
Tsinghua

Finland
Jyvaskyla

Germany
Aachen
Dresden
Hamburg
Jülich
Mainz
TU Munich
Tübingen

Italy
SISSA/INFN

Korea
CUP

Portugal
LIP
Lisbon

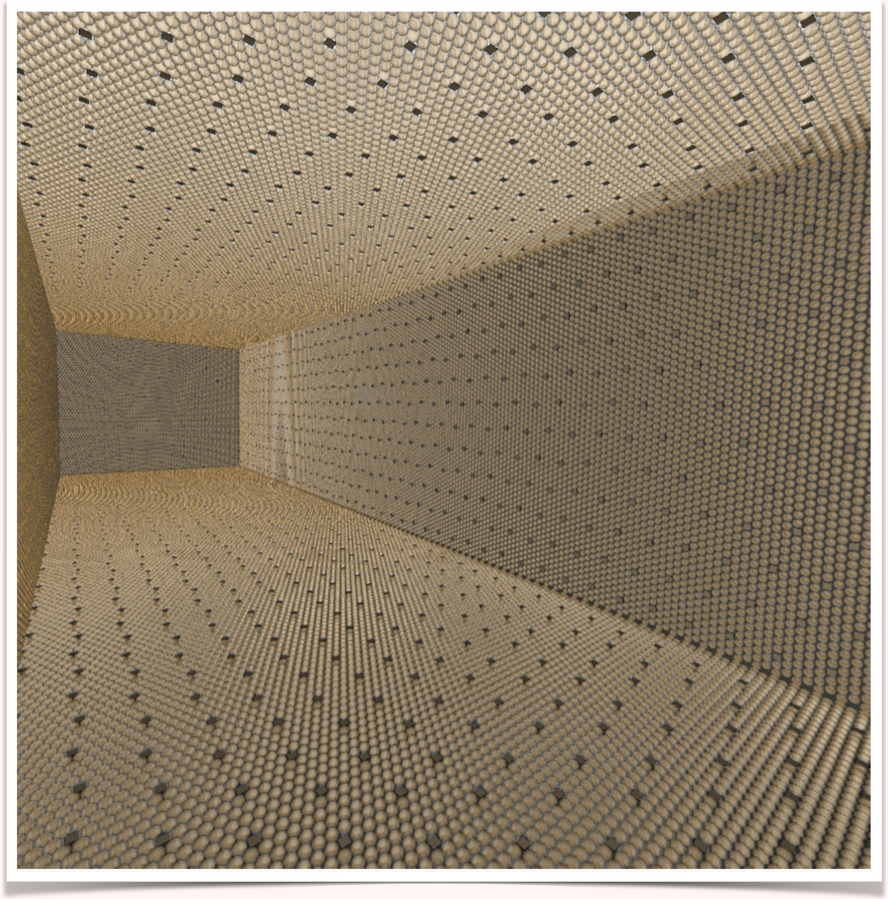
Turkey
Erciyes

UK
King's College
Sheffield

US
BNL
Boston
Chicago
Colorado
Cornell
FNAL
U. Hawaii
Iowa
Iowa State
LBNL
LLNL
LSU
MIT
U. Penn
PNNL
Rutgers
SD SMT
Stony Brook
SURF
Temple
UC Berkeley
UC Davis
UC Irvine
UCLA

THEIA 25

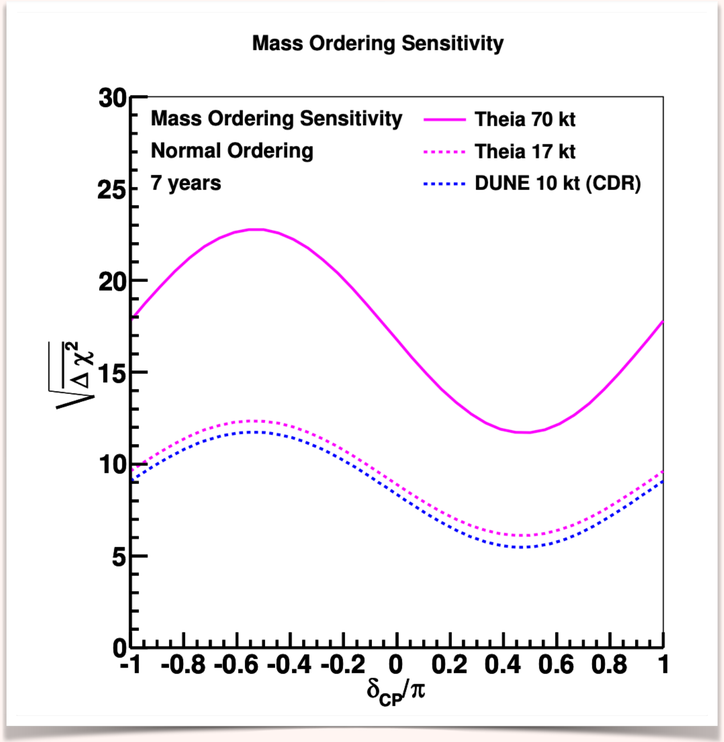
- Theia 25 is a proposed 25kT (17kT FV) WbLS detector
- The SURF location provides an exciting opportunity to create an incredibly broad, groundbreaking and rich physics program
- With a similar long-baseline sensitivity to the LAr DUNE modules it would contribute to the existing physics plan
- It would enhance the DUNE supernovae effort by opening up new detection channels
- Additionally, hybrid detection technology allows for an array of new physics opportunities

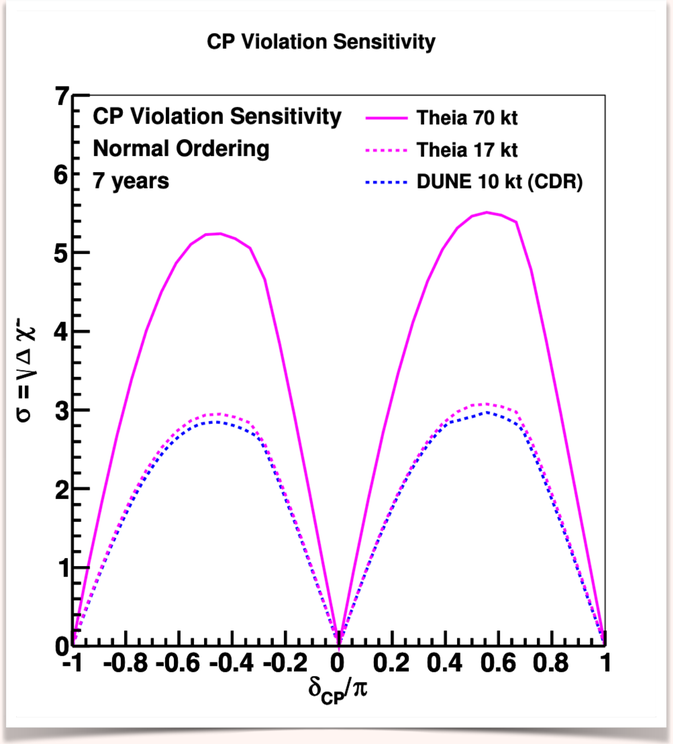


PHYSICS REACH AND COMPLEMENTARITY TO THE DUNE PROJECT

SYNERGY TO THE DUNE LONG-BASELINE PROGRAM

- **Theia 25 would add statistics to the DUNE effort with its similar performance to a 10kT LAr TPC module**
- **Furthermore, it would compliment the effort by providing independent systematics**
- **It would also offer a unique cross check of the Hyper-K/DUNE comparison**





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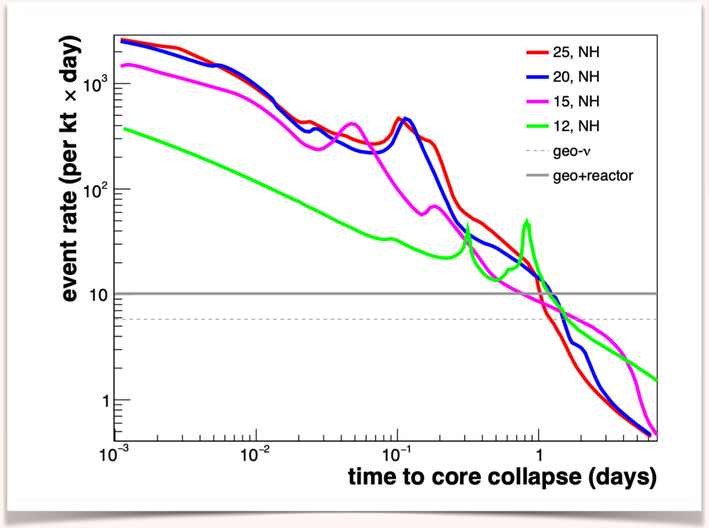
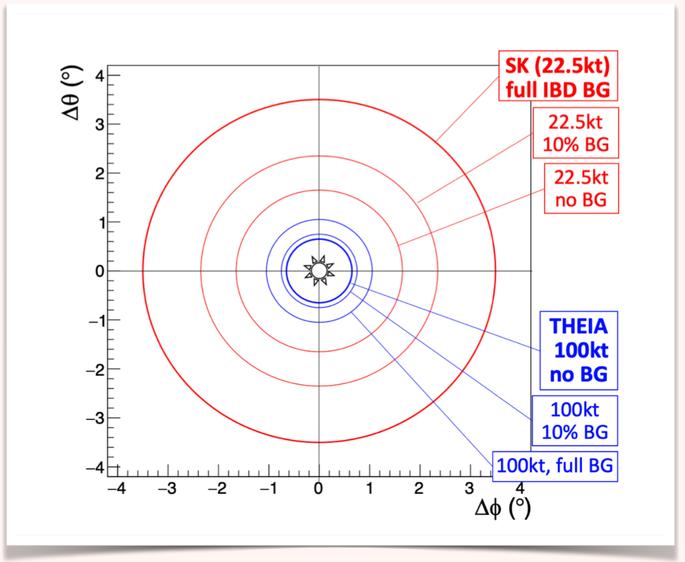
SUPERNOVAE NEUTRINOS

- ~90% of the events are IBD.
- This provides a great addition to the ν_e LAr signal
- Unique opportunity to co-detect neutrino/anti-neutrino signals at the same site and search for potential oscillation differences due to matter effects
- Would provide a reliable and fast trigger for the DUNE LArTPCs
- Neutron tagging allows the selection of a clean ES signal allowing for a <1º pointing accuracy
- Capability to resolve the entire neutrino spectrum into its individual components
- Theia 25 would be sensitive to pre-supernovae neutrinos from the Si burning phase of SN progenitors

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





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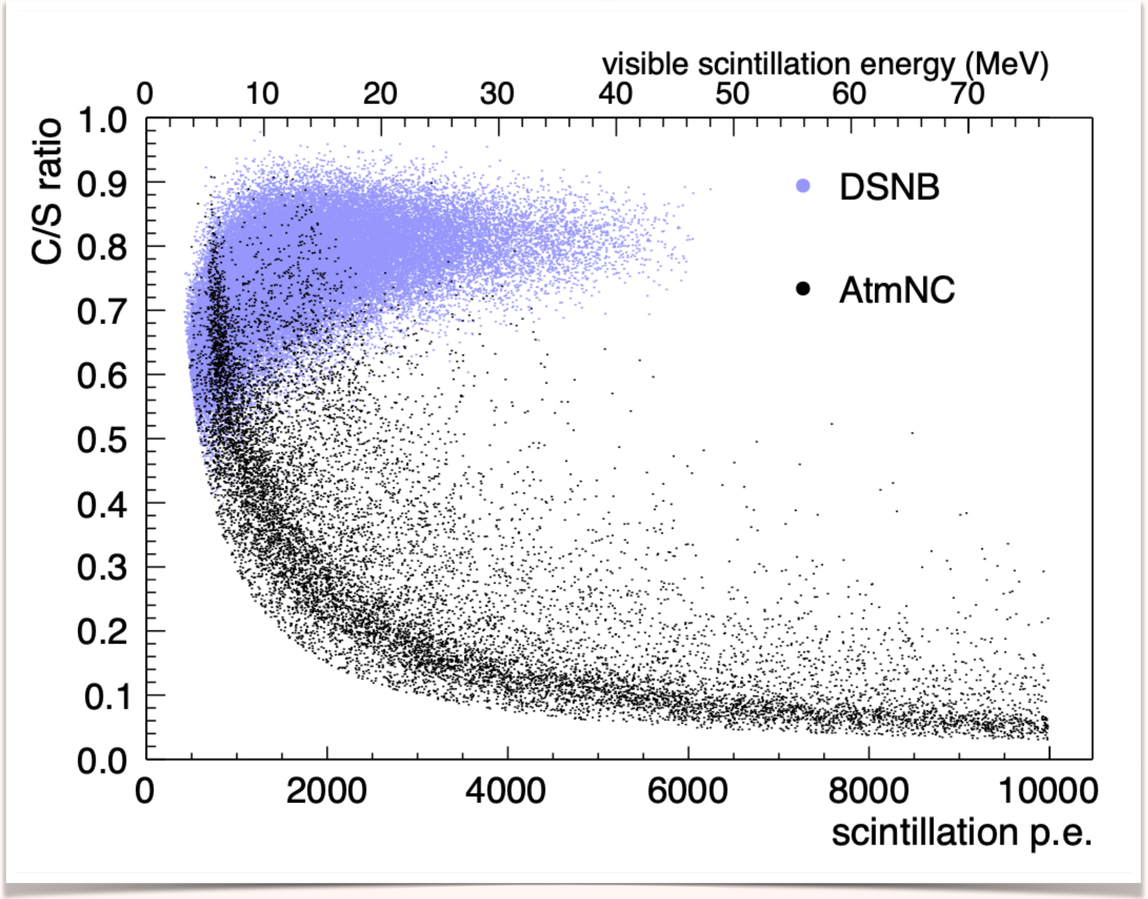
THEIA AS A DSNB DETECTOR

- Diffuse glow of neutrinos from past core collapse supernovae
- Theia would detect these through IBD interactions
- NC interactions from atmospheric neutrinos mimic this signal (nuclear recoil on C followed by neutron capture)
- Theia would have the unique capability to distinguish such events through the Cherenkov/ scintillation ratio
- 5σ discovery potential in 125 kton-yr



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THEIA AS A WORLD LEADING NUCLEON DECAY DETECTOR

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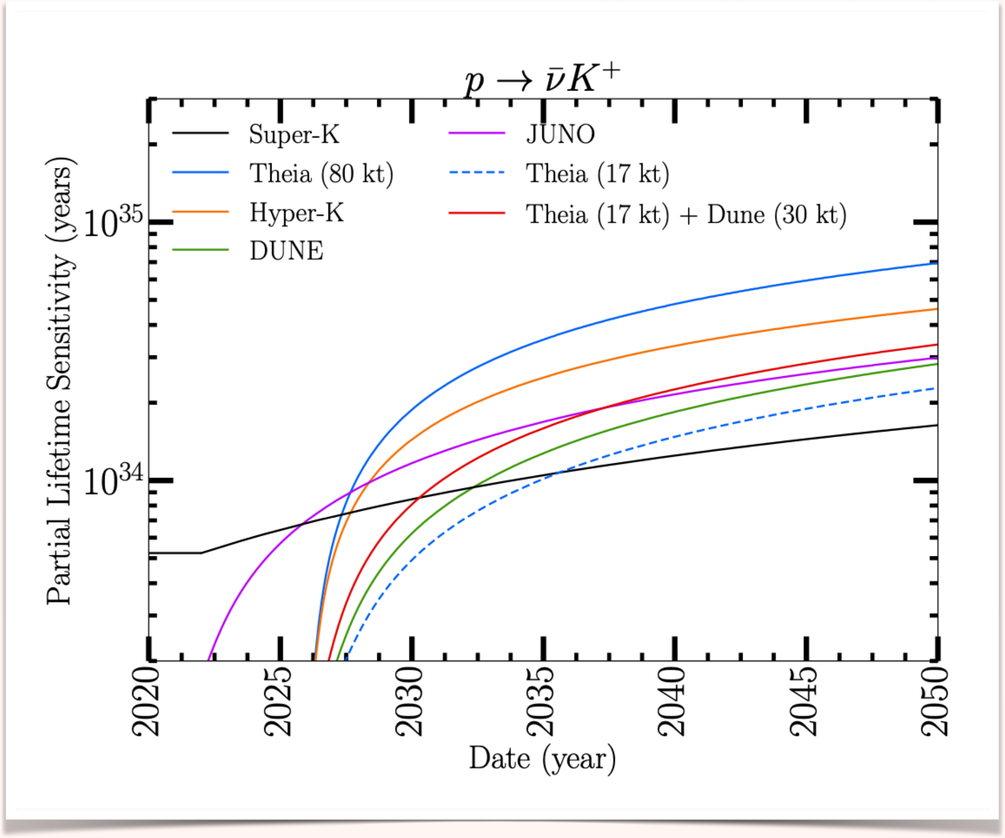
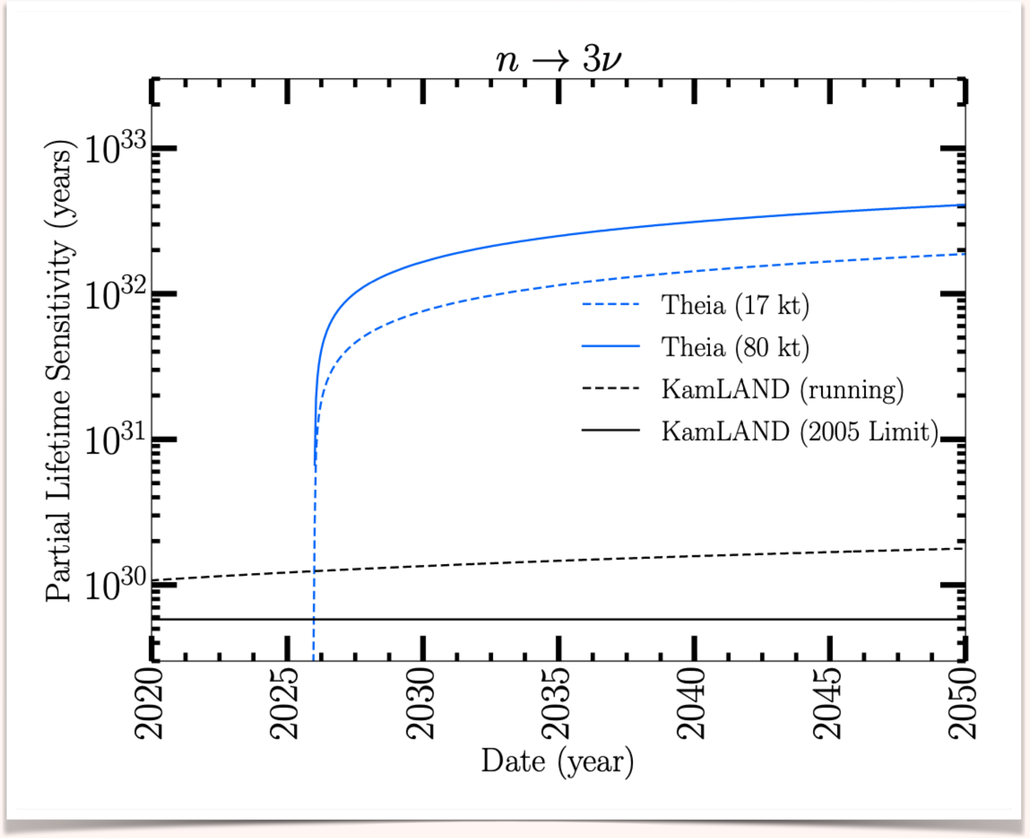


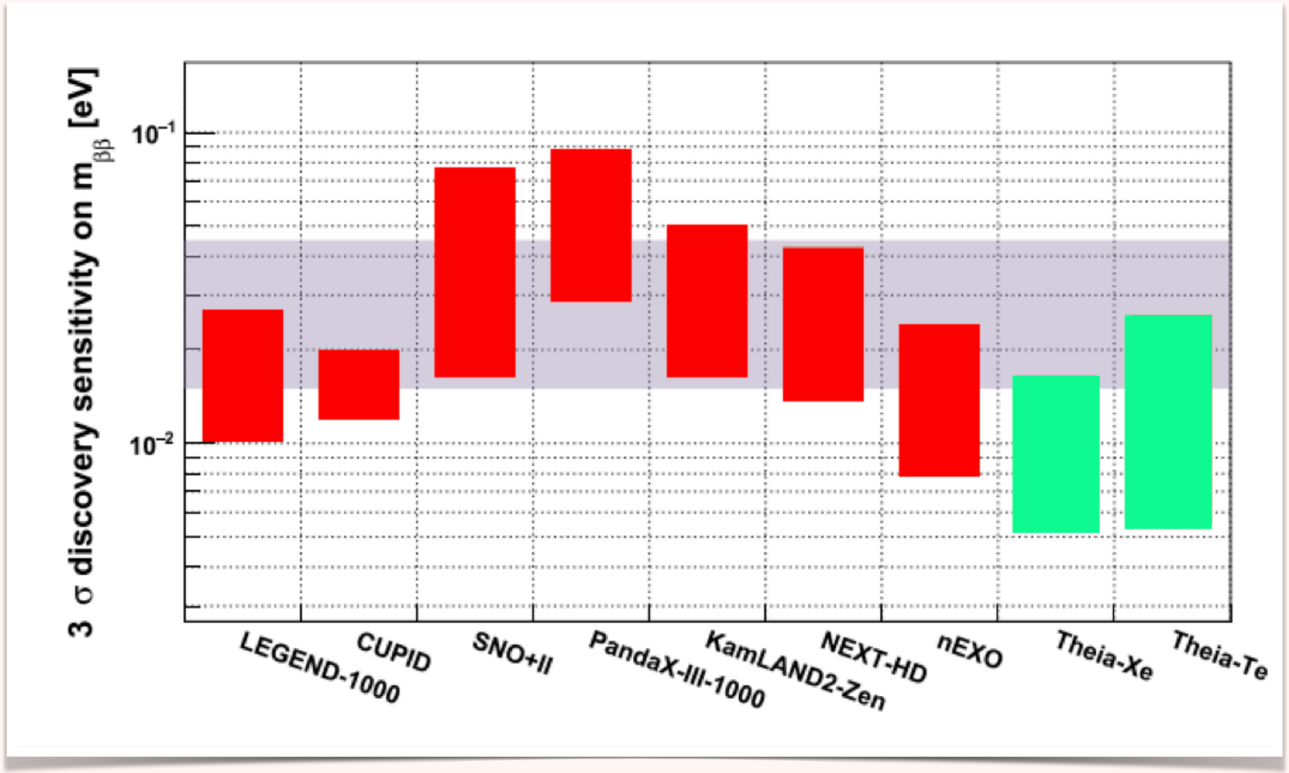


Sub-Cherenkov threshold K+ detection

World-leading in such invisible channels due to huge volume, deep underground location, directional capability and low detection threshold

NEUTRINOLESS DOUBLE BETA DECAY SEARCH

- Theia has the potential to be a world leading NLDBD detector
- Potential to install a 8m ballon filled with high-LY isotope loaded liquid scintillator
- Sensitivity when deploying Te and Xe isotopes have been explored



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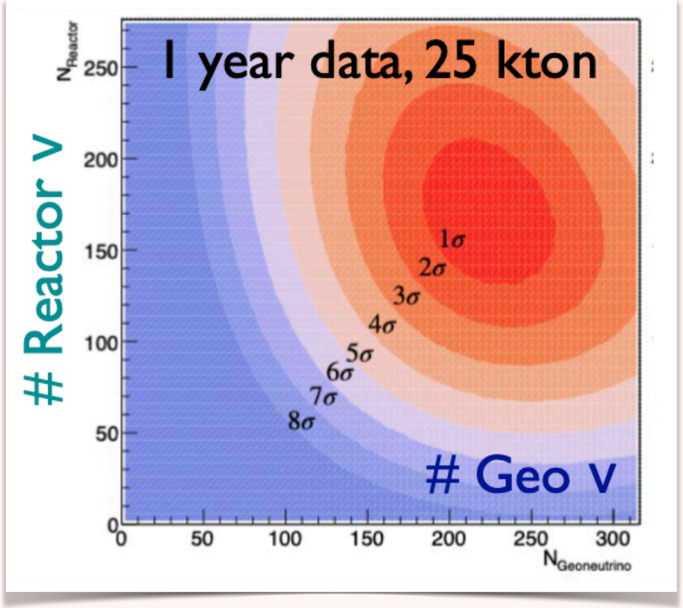
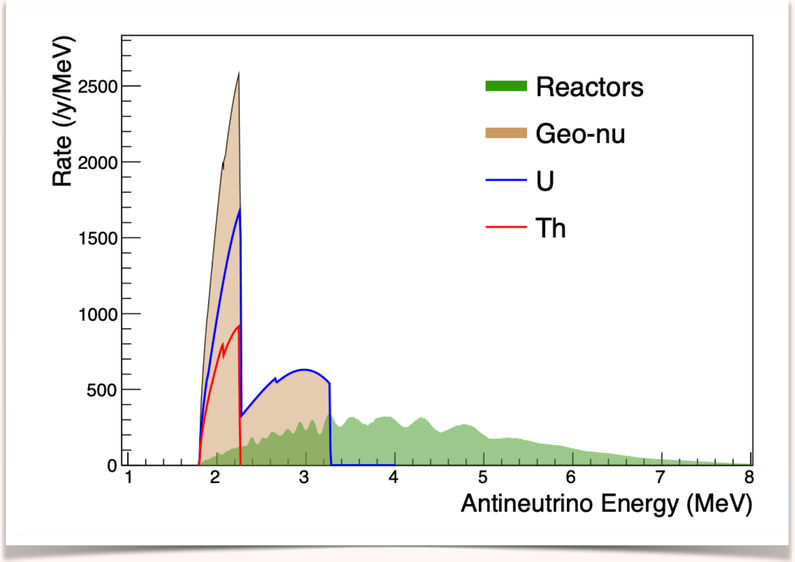
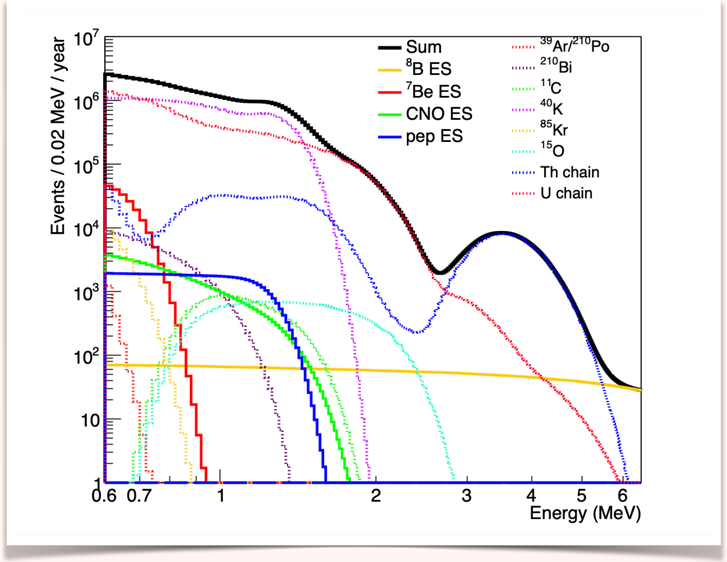
THE PHYSICS REACH DOES NOT END THERE!



- Reactor neutrinos
- ~20 reactor ev/kt-yr
- Reactor monitoring, range and direction at >1000 km



- Geoneutrinos
- 218 ev/yr compared to KL+Borexino <220 total events greatly increases statistics
- Potential first evidence in surface variation



- Solar neutrinos
- Few percent level sensitivity to CNO neutrinos
- Unique probe of matter effect/ matter vacuum transition

CONCLUSIONS

- Theia 25 is a proposed large-scale WbLS detector with an incredibly broad physics program
- Theia would provided unique complementarity with the existing DUNE effort
- It would contribute to the DUNE long-baseline measurements
- It would provide exciting new channels to the DUNE supernovae detection
- It would add to the already extensive DUNE program with the potential to study NLDBD, solar neutrinos, geoneutrinos, the DSNB, nucleon decay and reactor neutrinos
- The hybrid detection technology is well developed with over a decade of research
- Theia has a large protocollaboration from across the globe, with 45 institutions from 10 countries
- WbLS R&D is entering an exciting stage with ton-scale detectors now taking data!