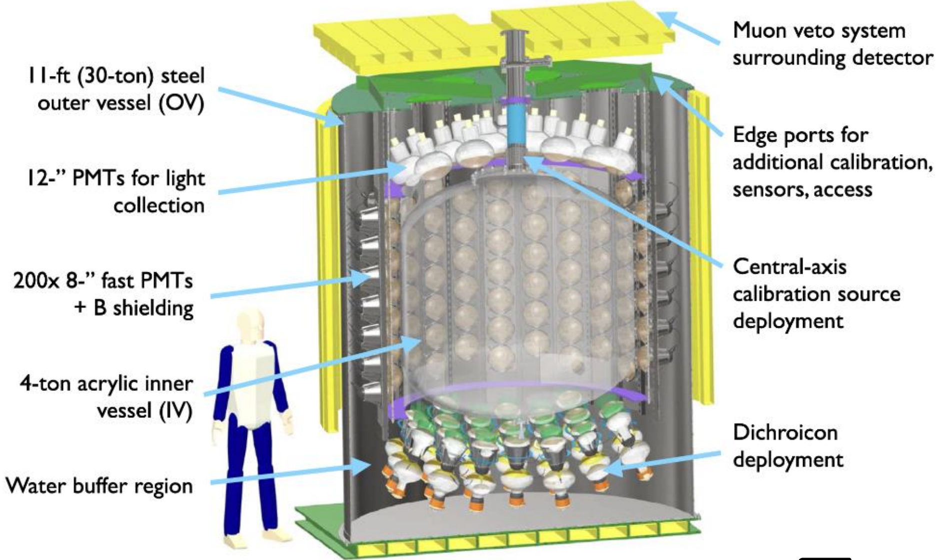
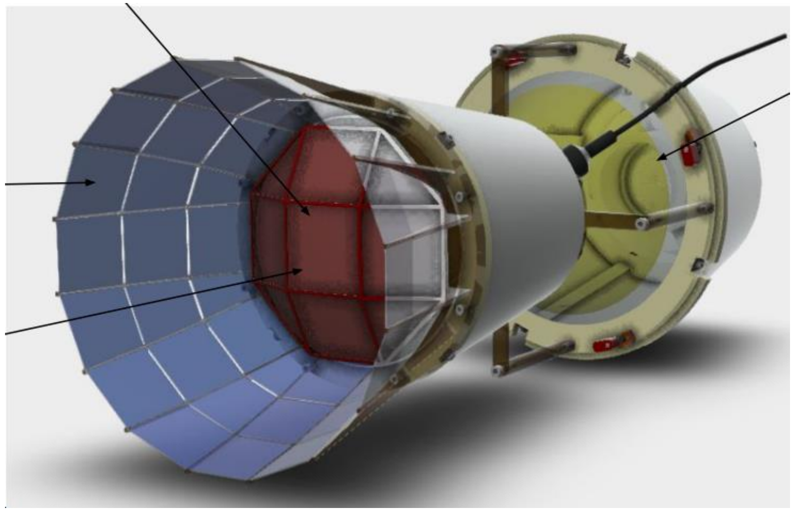




Eos Detector

Adam Baldoni
Penn State University
On behalf of the Eos project team

Nov 8 2023

Bottom line upfront

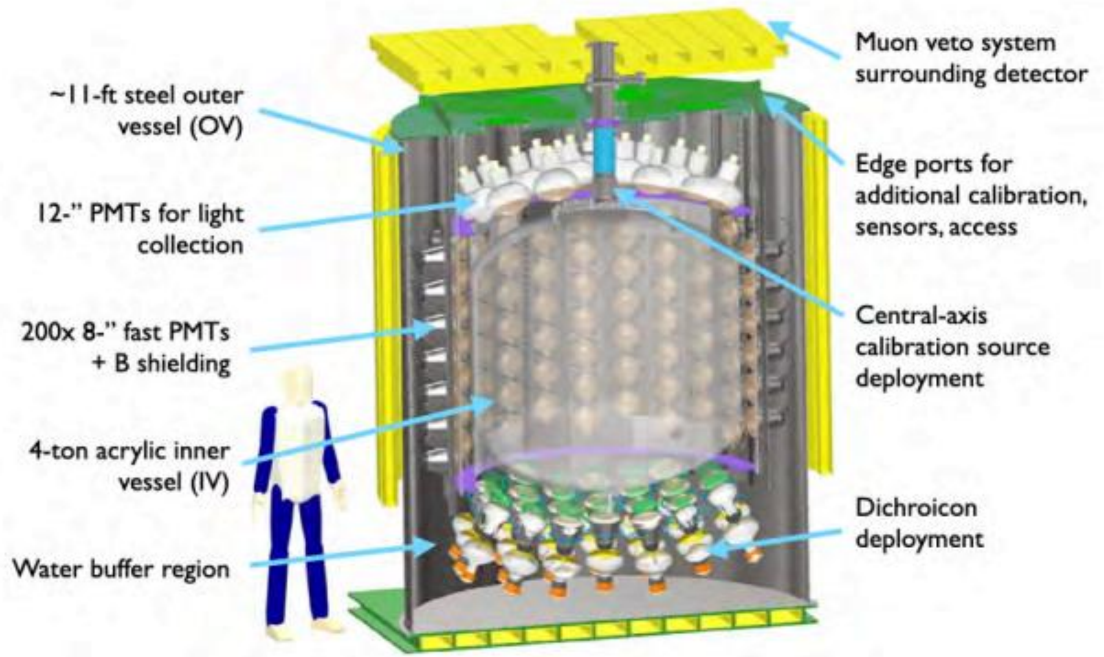
Project objective: *Enhance neutrino detection capabilities for fundamental science and nonproliferation*

Project goals:

- Demonstrate particle detection using hybrid Cherenkov + scintillation signatures
- Validate models to support performance predictions for fundamental science and nonproliferation
- Provide a flexible testbed to demonstrate impact of novel technology

Projected to complete:

- On budget
- On schedule



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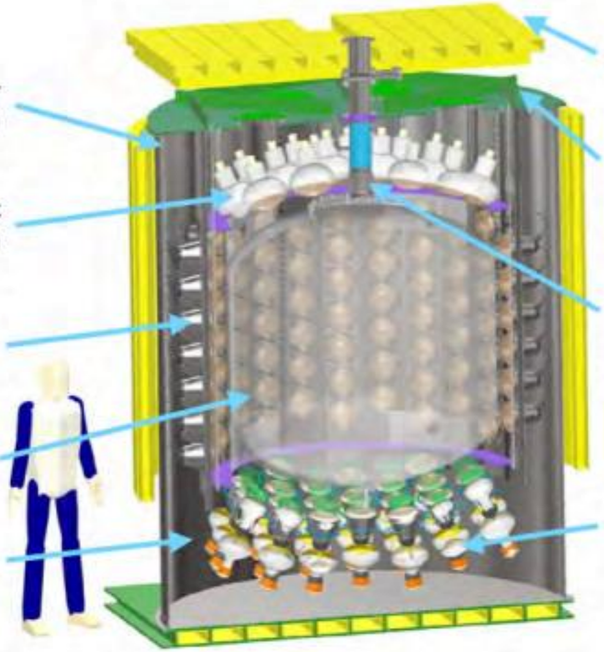

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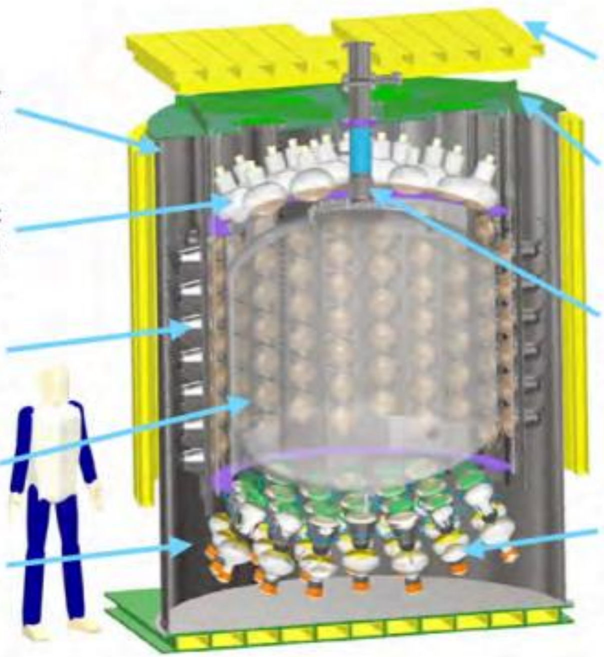

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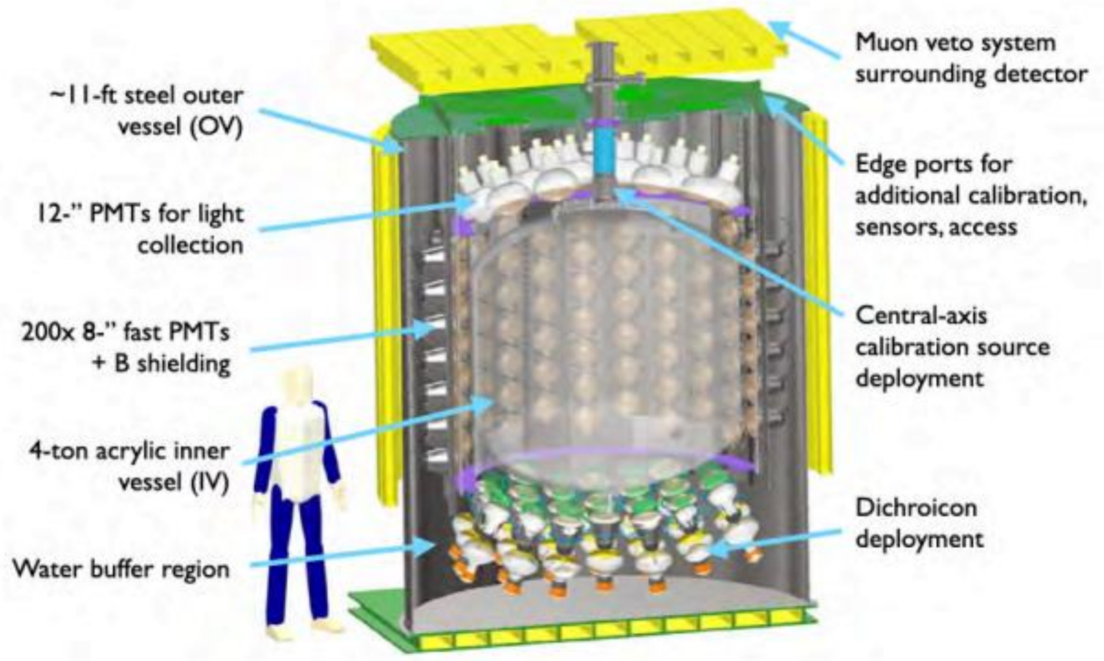

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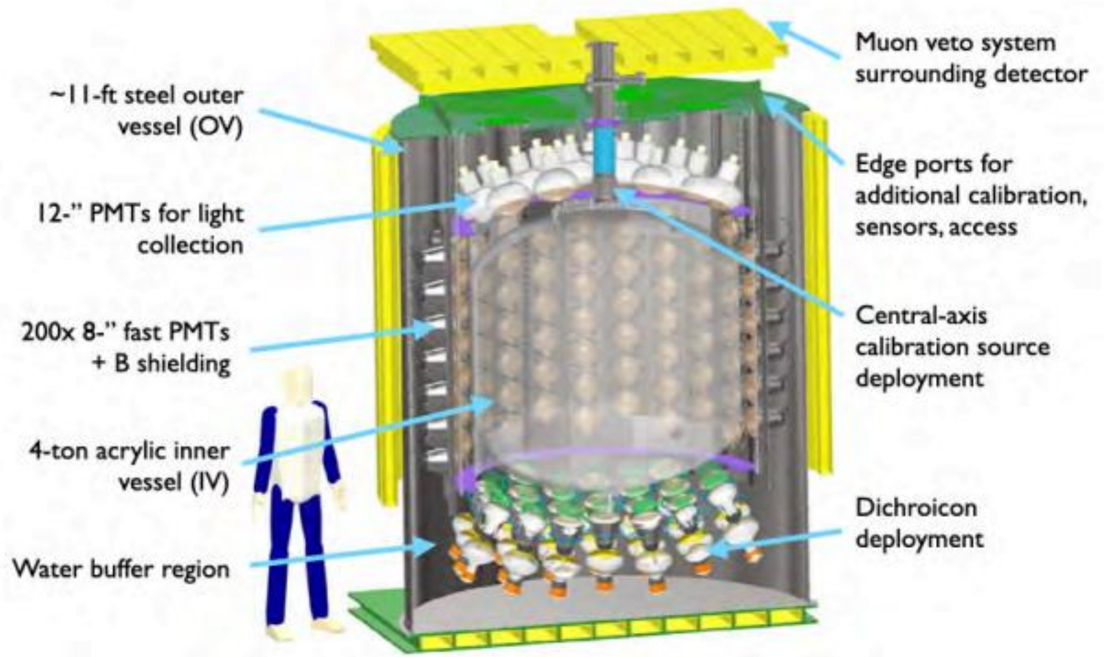

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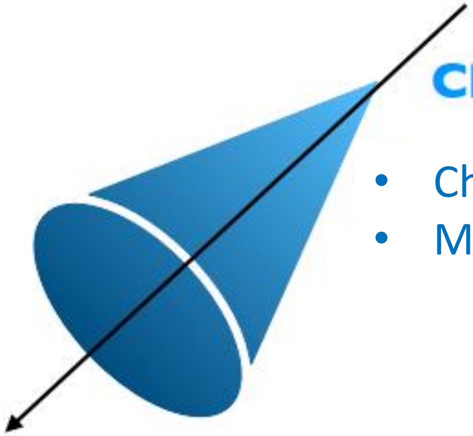
Innovative neutrino detection

Combine two well-tested methods for neutrino detection, for enhanced precision:

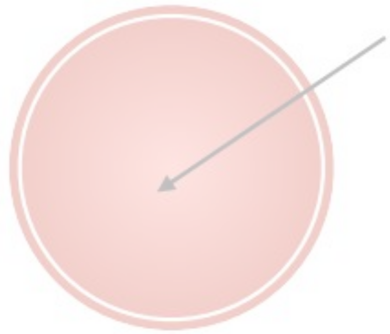


Cherenkov light

- Cherenkov cone gives directionality
- Minimum energy threshold

Scintillation light

- Extremely high light yield
- High efficiency for detection
- Particle-dependent response



Whole > Σ parts:
Can use ratio of signals ⟹ Improved background reduction

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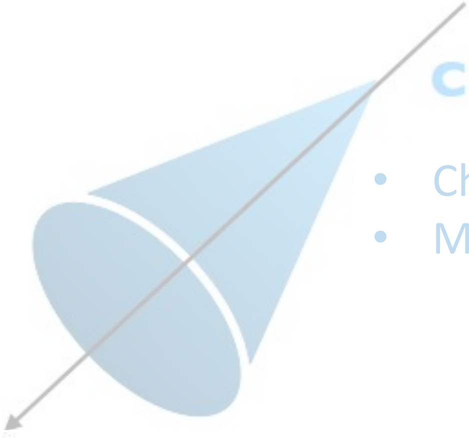

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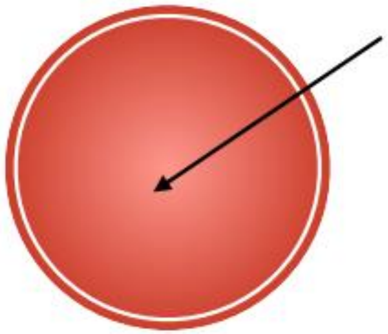

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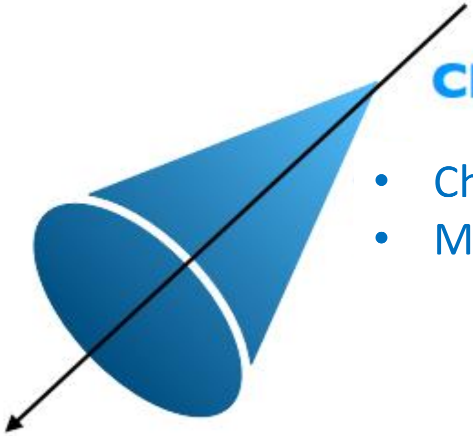

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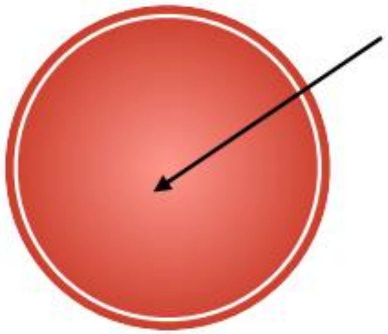

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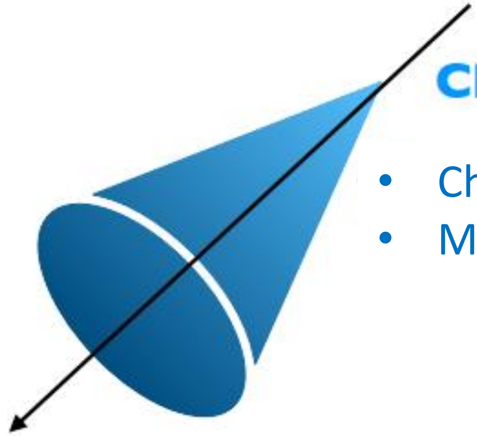

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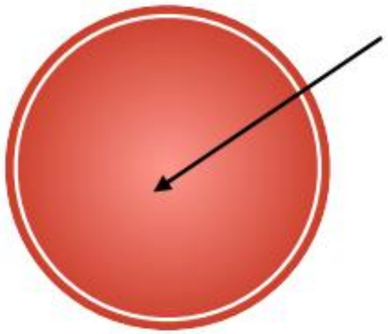

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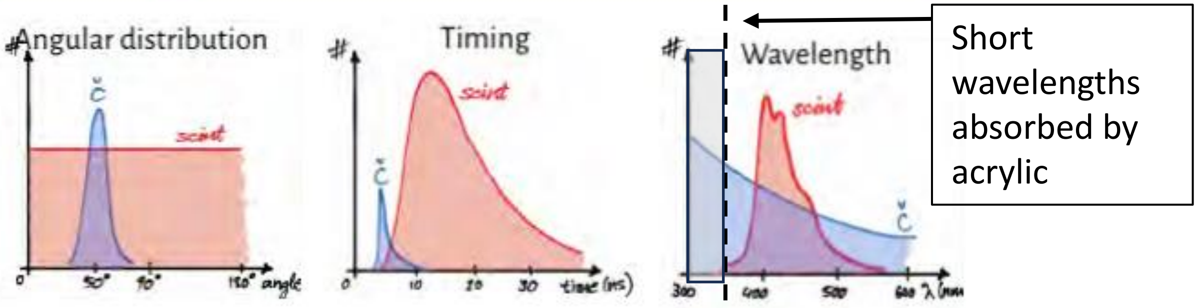
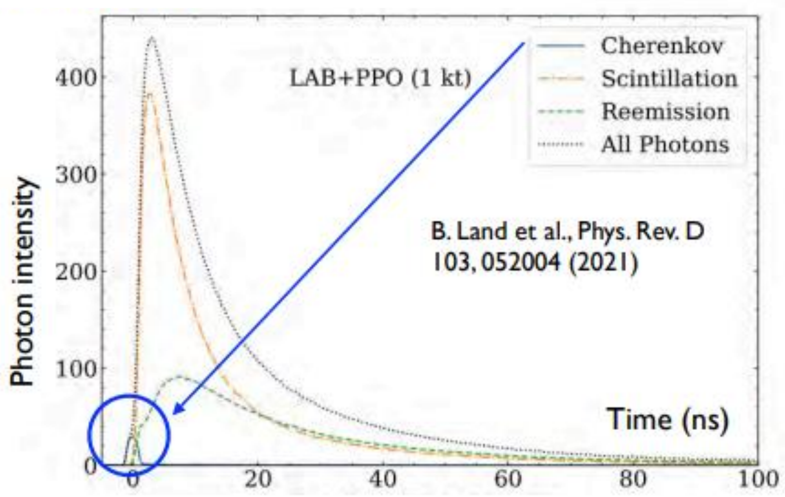
Challenging technical goal: preserve directional Cherenkov signature against more abundant scintillation yield





Fundamental Science: Theia in DUNE

Long-baseline sensitivity comparable to a LAr DUNE module
Complementary supernova sensitivity (primarily anti-ν, fast response: can act as trigger)
+ broad (new!) additional physics program

Large, multipurpose detector

- Baseline: 25 ktonne (17 kt FV)
- Ideal: 100 ktonne (70 kt FV)

THEIA: An advanced optical neutrino detector
Eur. Phys. J. C 80, 416 (2020)

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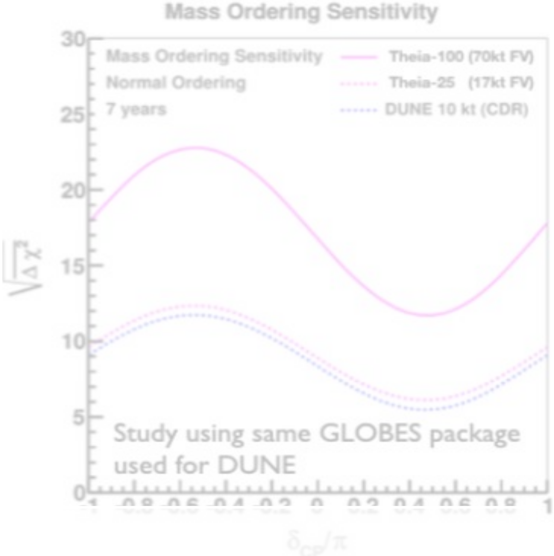

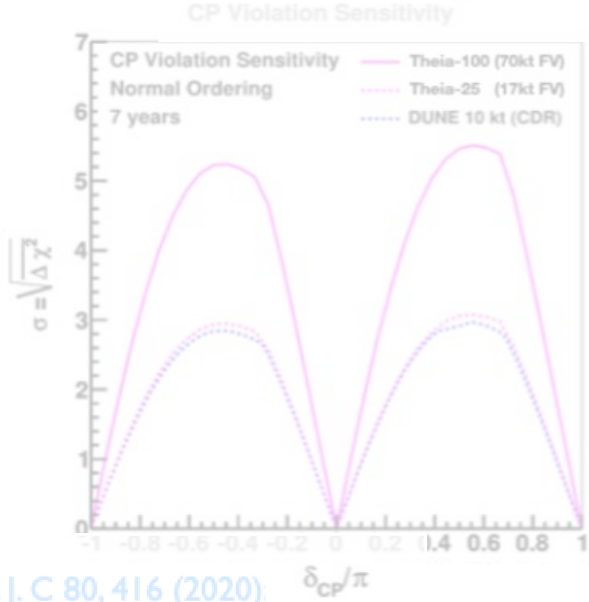

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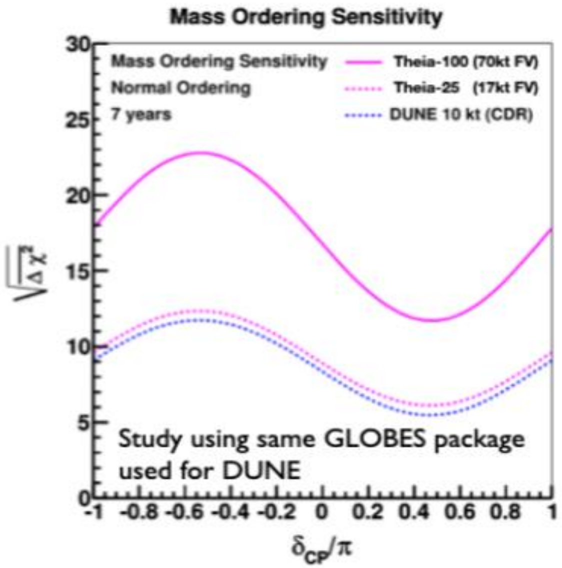

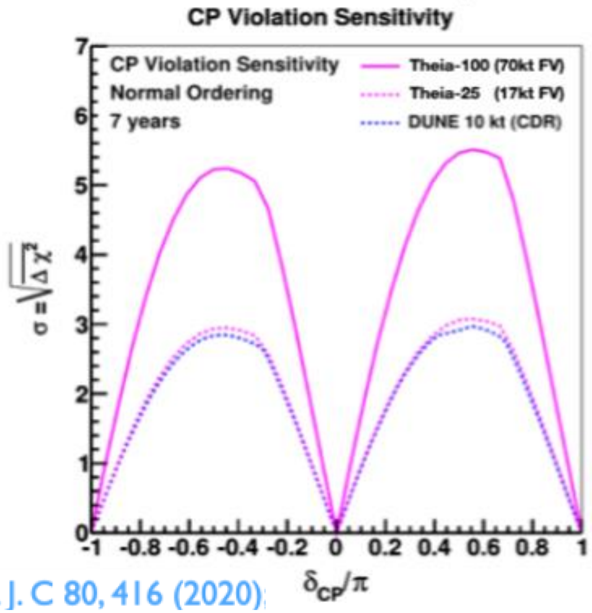

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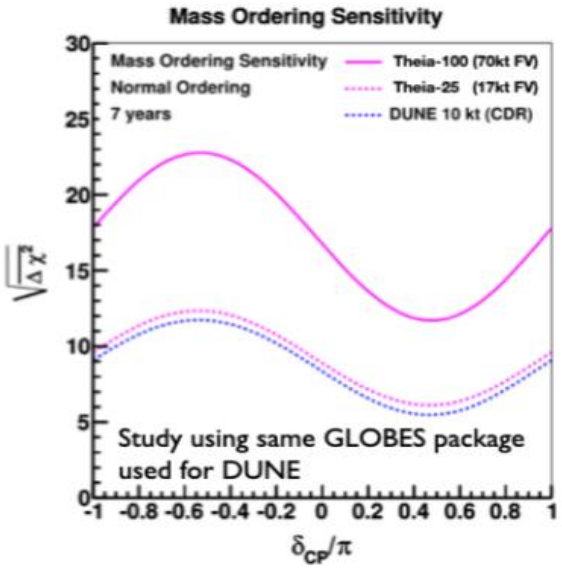

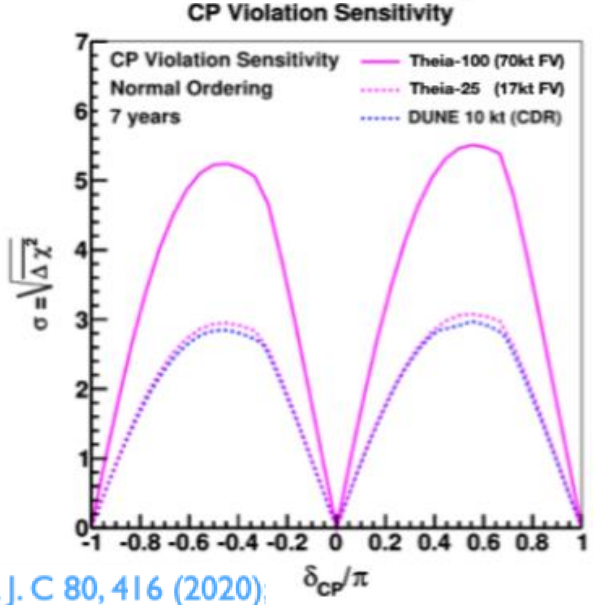

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Neutrinos for nonproliferation

Neutrino properties

Produced as a by-product of fission	⟷	*Provide a unique signature of nuclear fission*
Weakly interacting	⟷	*Signature can't be shielded*
Close to massless, travel ~c	⟷	*Near-instantaneous detection*

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- NuTools: 2021 study (Department of Nuclear Nonproliferation [DNN] R&D) "exploring practical roles for neutrinos in nuclear energy and security"
- DNN invested in demonstration of reactor monitoring with (anti)neutrinos
- LBNL' s focus is enhancing capabilities of such a detector
  - Greater standoff
  - Reduce scale

Test site transparency

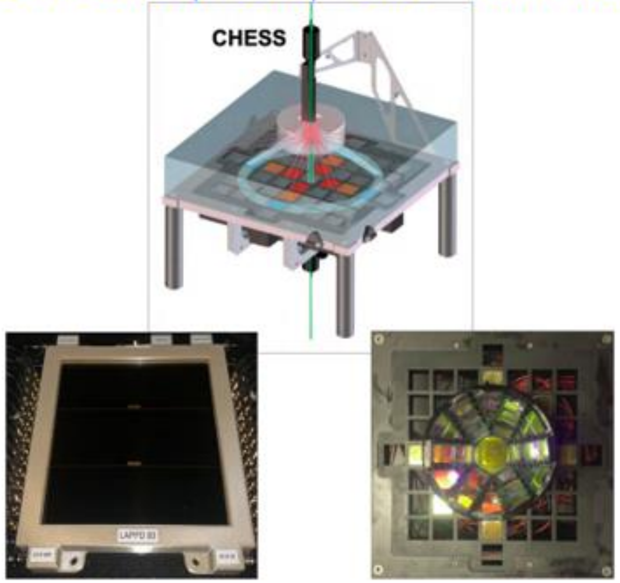
Small modular reactors

Nuclear submarines

Scaling up

Detector Size

CHESS & others, LBNL, BNL + collaborators
Broad bench-top R&D program
LBNL LDRD (FY13-14) + OHEP + DNN R&D



- *First demonstration of Cherenkov light detection from high yield liquid scintillators;*
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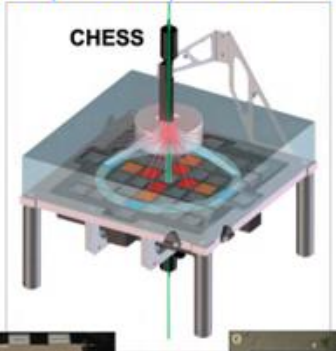

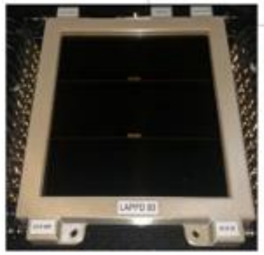

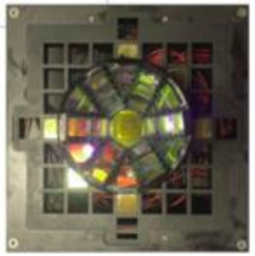

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Demonstration of next-generation detector capabilities

Develop **R&D infrastructure** — testbed for future programs

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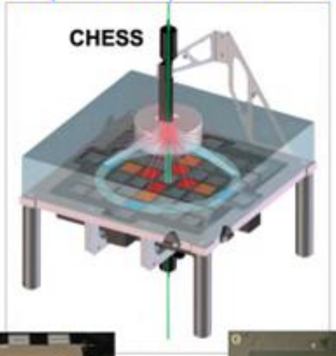

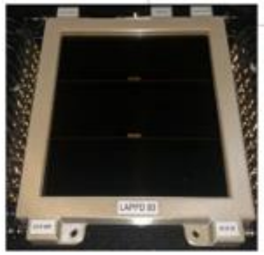

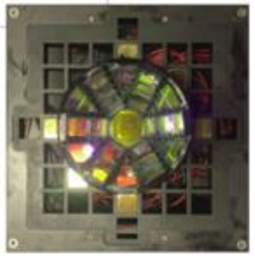

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Critical ~10s of tons scale demonstration of detector performance capabilities

Importance for programs in NNSA + ONP, OHEP, & international partners

Demonstration of next-generation detector capabilities

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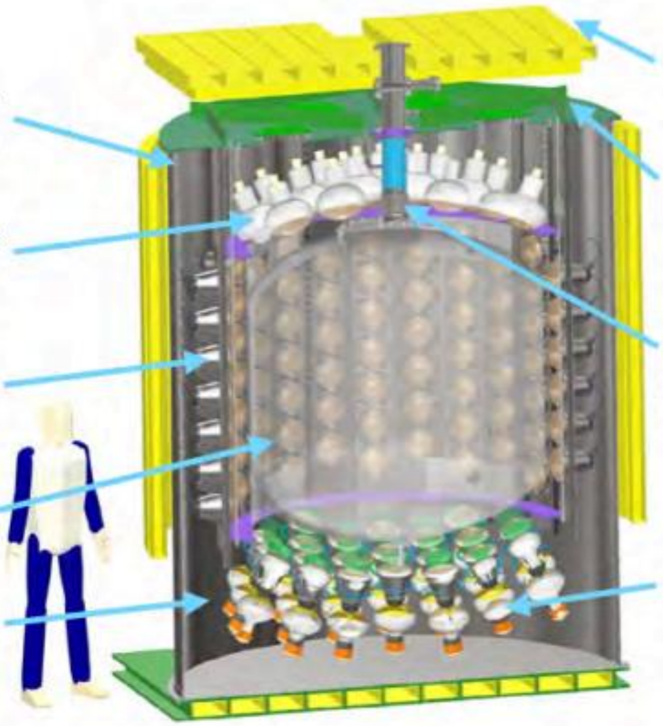
Approach: *design, construct and operate an integrated testbed to demonstrate the performance of novel technology*

Novelty / technology:

- Novel scintillating liquids — water-based scintillator, slow scintillator



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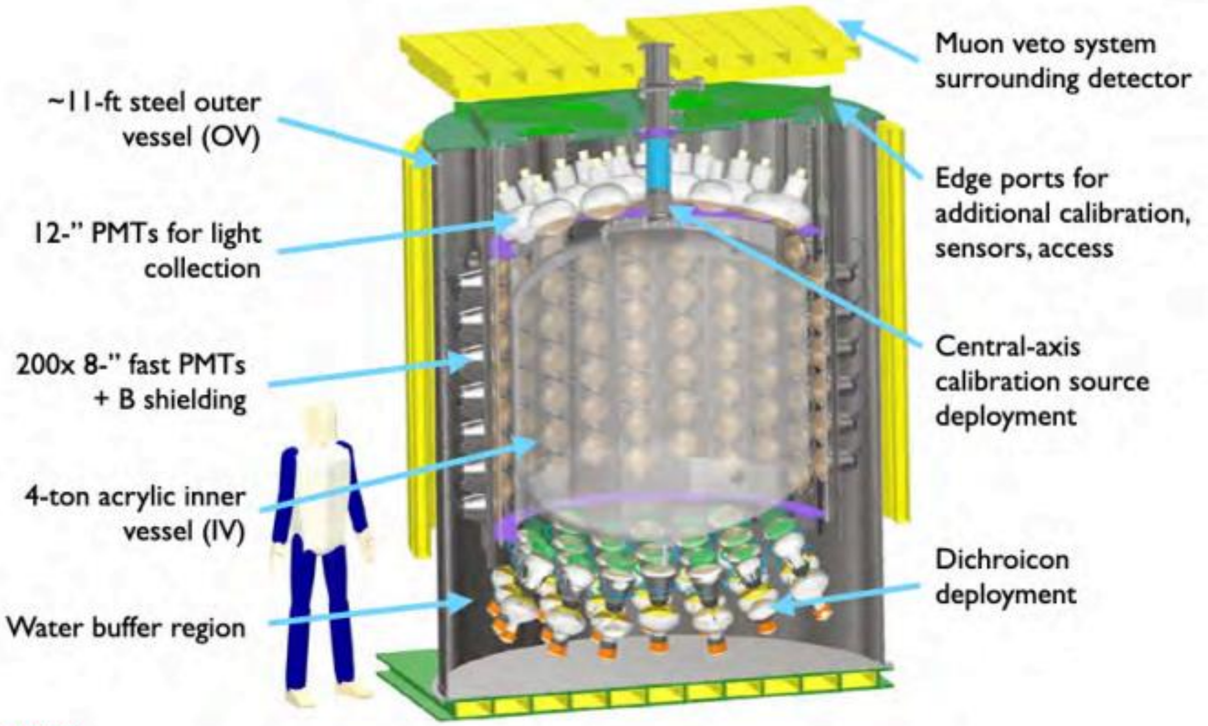

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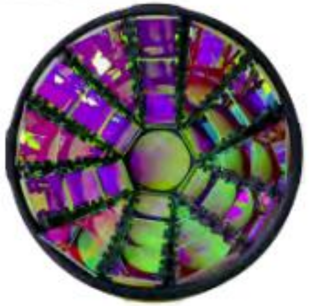
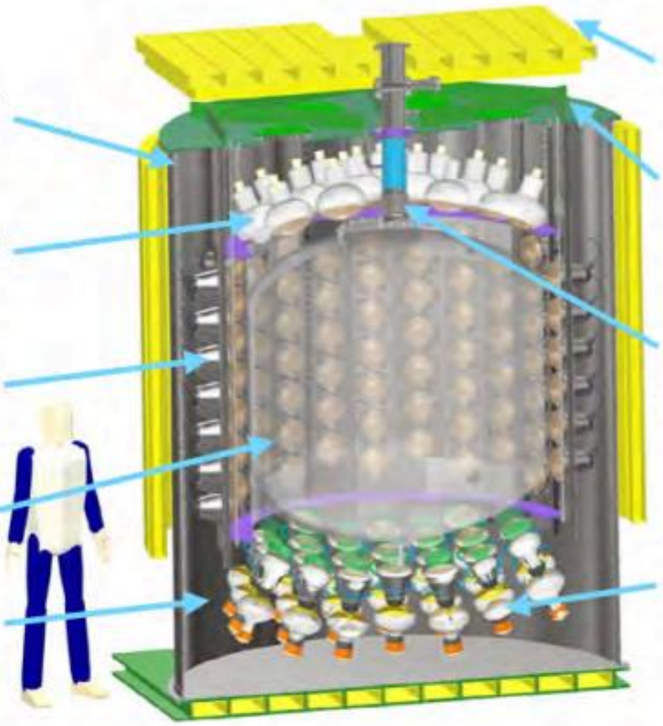


Dichroicon



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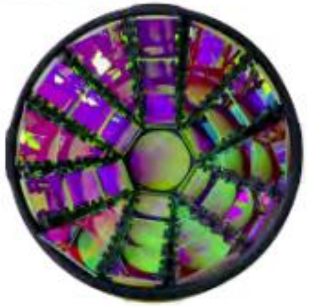

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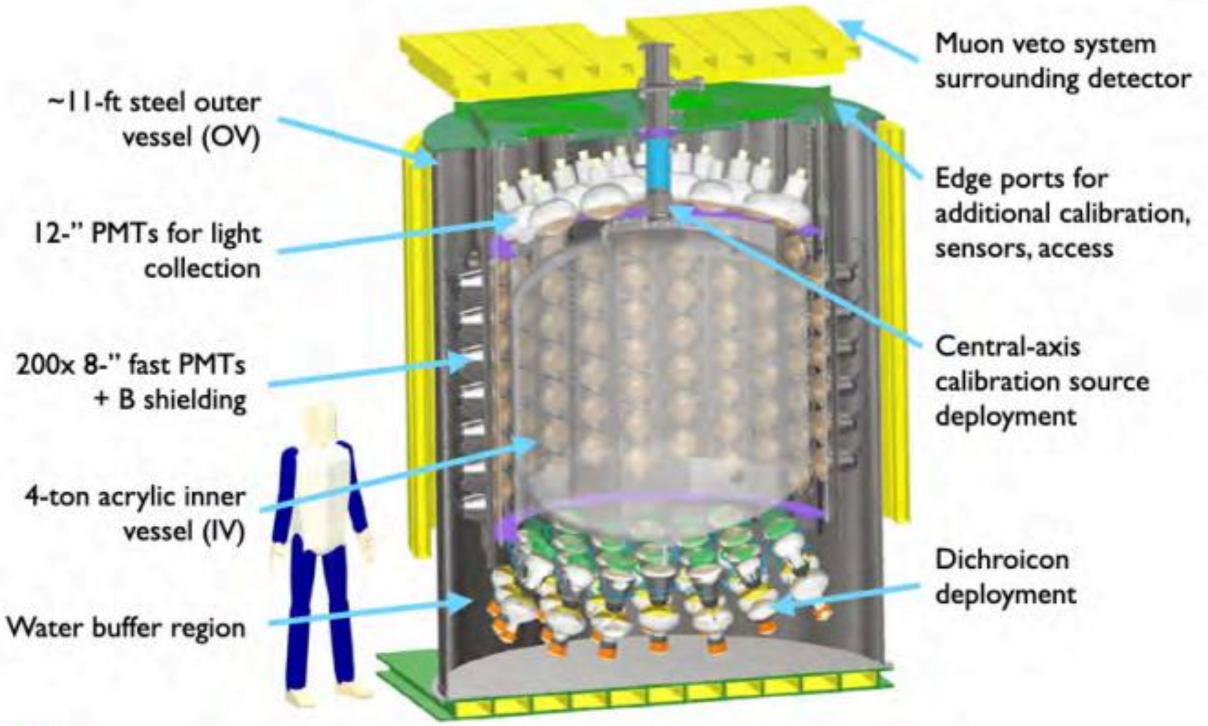

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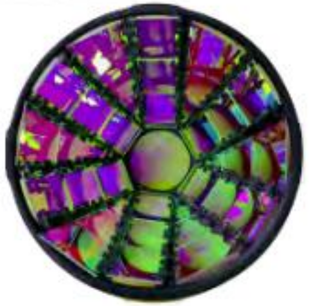

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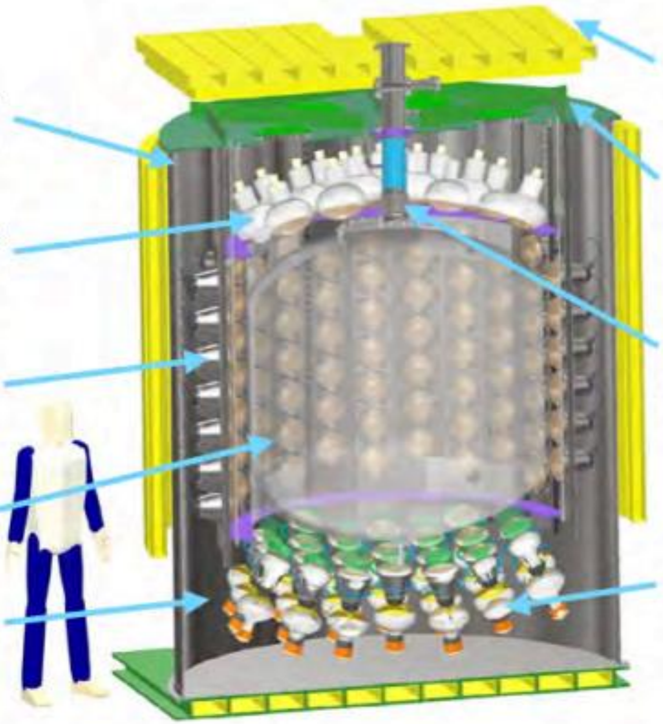

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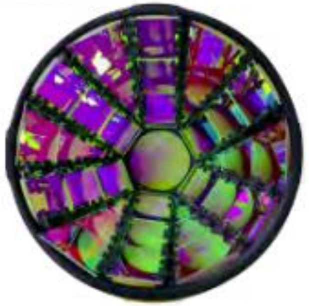

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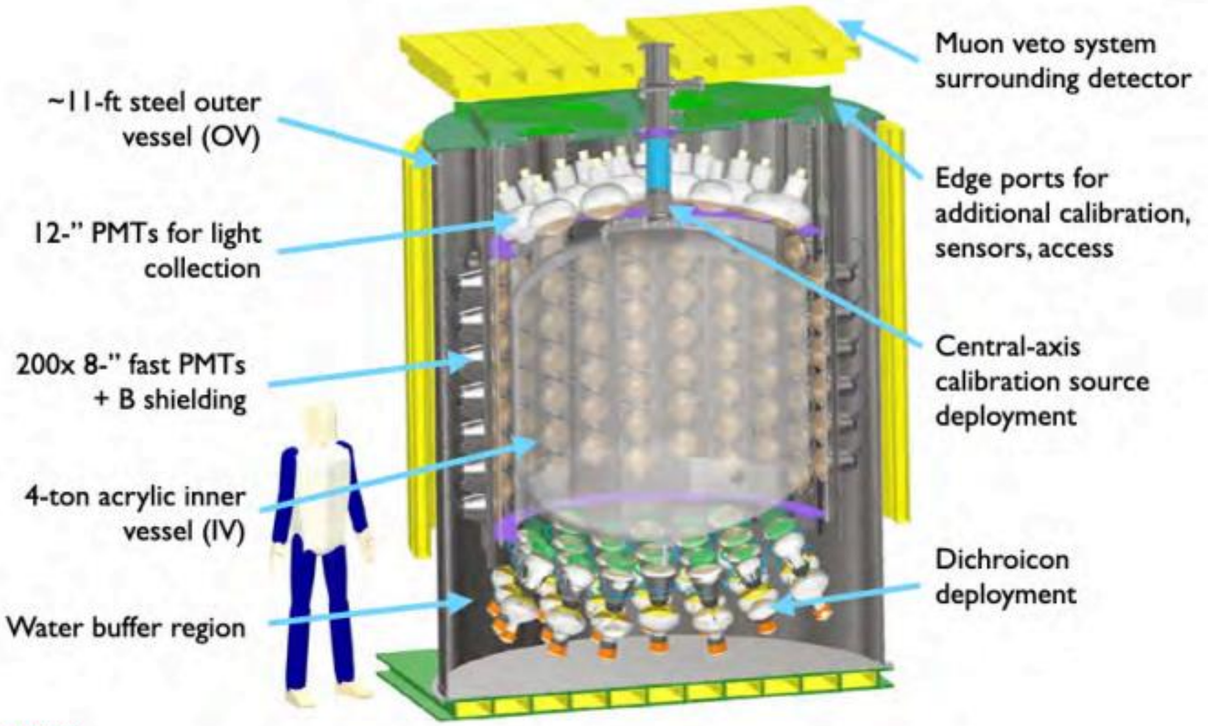
- Deployable sources for studies of vertex, energy, direction reconstruction & PID



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- IV has ~ 4T water capacity

Inner vessel (IV)

Detector Design – Tanks

- 1.8m (6’) diameter ultraviolet-transmitting acrylic inner vessel (IV) with dished end caps
- IV has ~ 4T water capacity
- 3.3m (11’) tall, 2.75m (9’) diameter stainless steel outer vessel (OV)
- Buffer between OV and IV will be filled with ultra pure water
- Detector will be placed on seismic plate base

Inner vessel (IV)

Outer vessel (OV) lowered onto seismic anchorage base plates

Detector Design – Tanks

- 1.8m (6’) diameter ultraviolet-transmitting acrylic inner vessel (IV) with dished end caps
- IV has ~ 4T water capacity
- 3.3m (11’) tall, 2.75m (9’) diameter stainless steel outer vessel (OV)
- Buffer between OV and IV will be filled with ultra pure water
- Detector will be placed on seismic plate base
- 72 muon veto panels surround OV (144 PMTs)

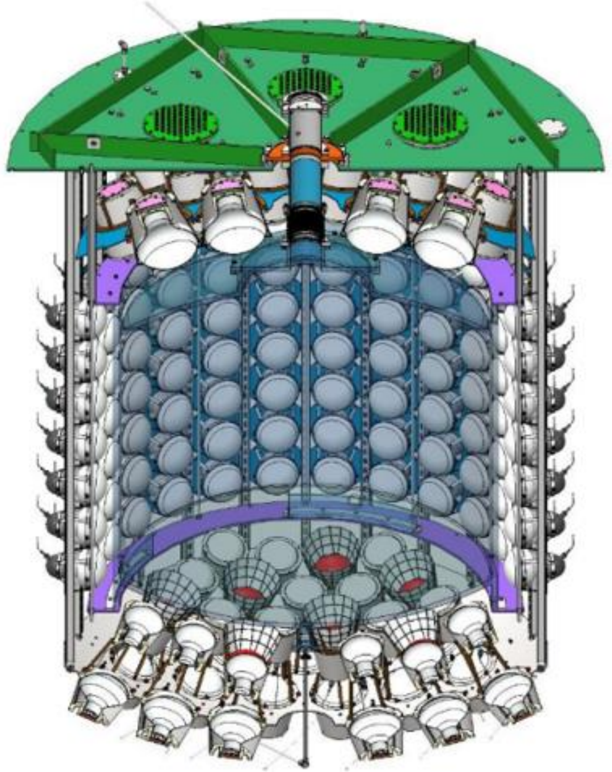
Inner vessel (IV)

Outer vessel (OV) lowered onto seismic anchorage base plates

Opened muon veto panel

PMT Overview

- Eos plans to use **242** PMTs:
  - **168** 8-inch R14688-100 (barrel)
  - **26** 12-inch R11780 (top)
  - **36** 8-inch R14688-100 (bottom)
  - **12** 10-inch R7081 (bottom – dichroicon)



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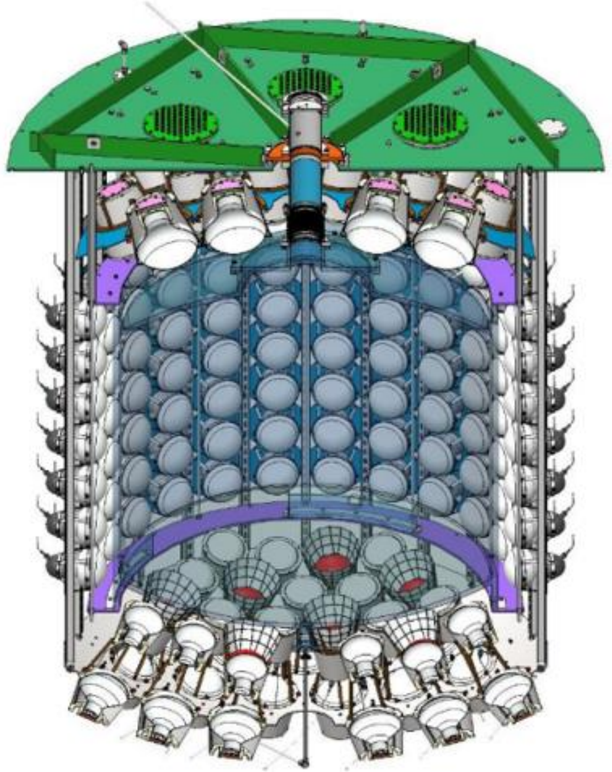

R14688-100 PMT with water proofing

R14688-100 8" PMT

- Next generation of R5912 (Daya Bay)
- ~1 ns transit time spread
  - 2-3x better than R5912
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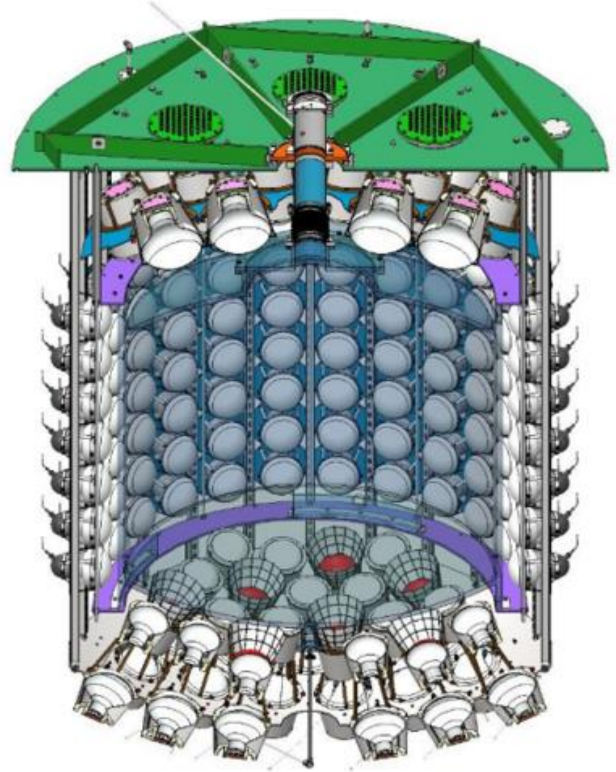

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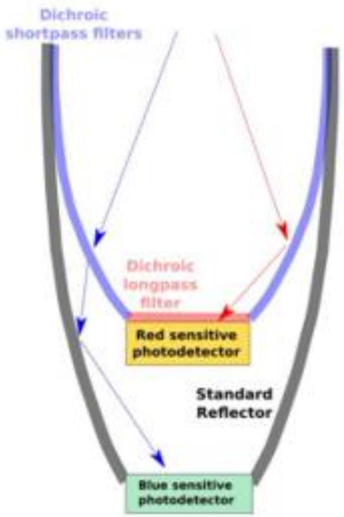
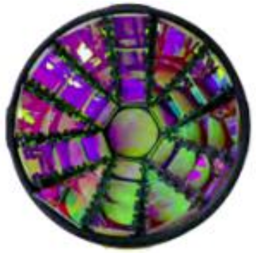
Dichroicon

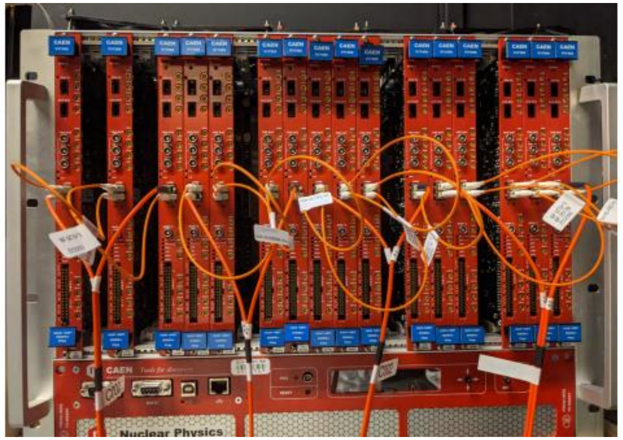
- Made from dichroic filters
- Separates Cherenkov (long wavelength) from scintillation light (short wavelength)
- Eos will have 12 dichroicons on bottom array
- 8" Cherenkov PMT
- 10" scintillation PMT





Readout System Overview

6 main blocks:



- PMT HV power: CAEN SY4527
- 17 CAEN V1730 waveform digitizers
- DAQ server reading out digitizers over optical fiber

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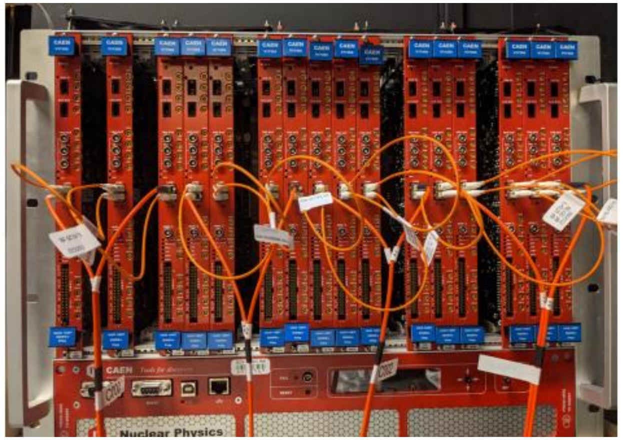

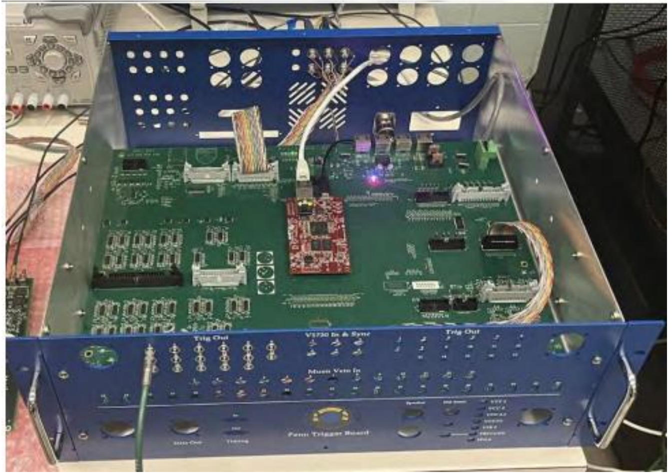

- PMT HV power: CAEN SY4527
- 17 CAEN V1730 waveform digitizers
- DAQ server reading out digitizers over optical fiber
- 16 custom-designed High Voltage Splitter and Summer
- (Up to) 3 custom-designed Central Analog Summing Boards
- 1 custom digital trigger system

Calibration Overview

1. **β** - ^{90}Sr
2. **Low-energy γ** - ^{137}Cs
3. **High-energy γ's** - AmBe/PuBe
4. **Light injection system** - mounted fibers, deployed diffuser

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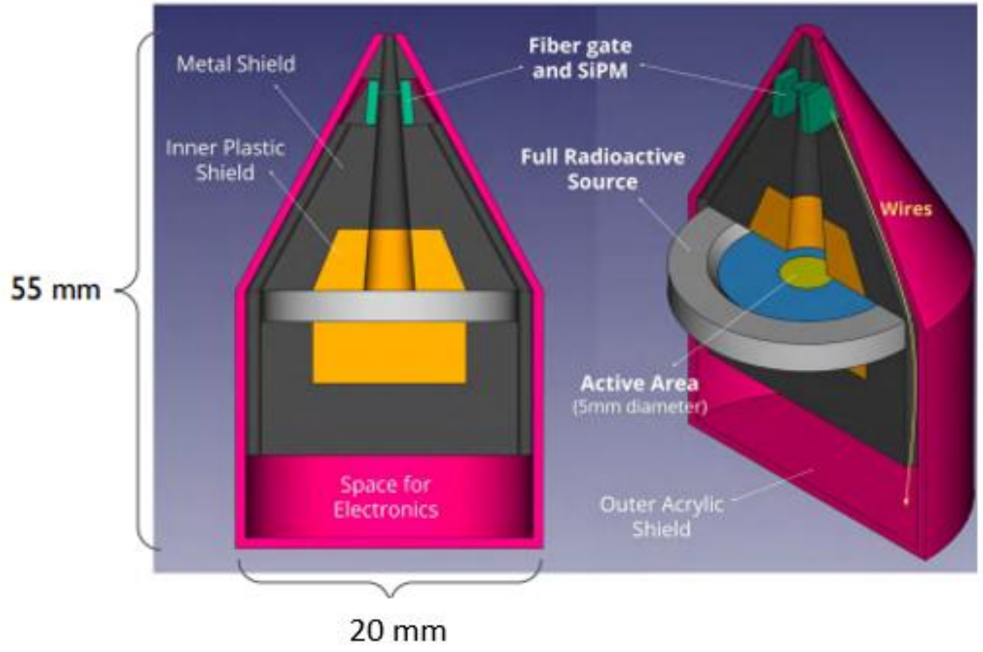

Directional β Source Design

- Modestly narrow beam of collimated electrons
- Self triggering: scintillating fibers viewed by two Silicon PhotoMultipliers (SiPMs)

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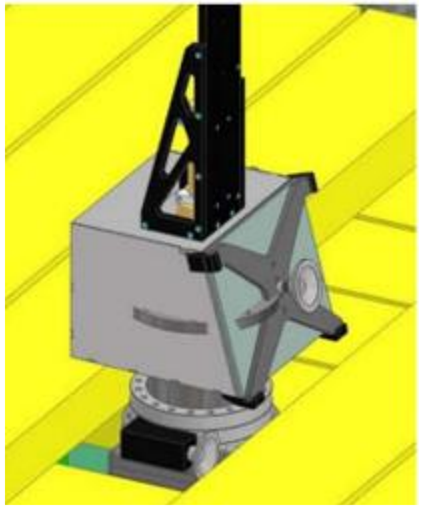

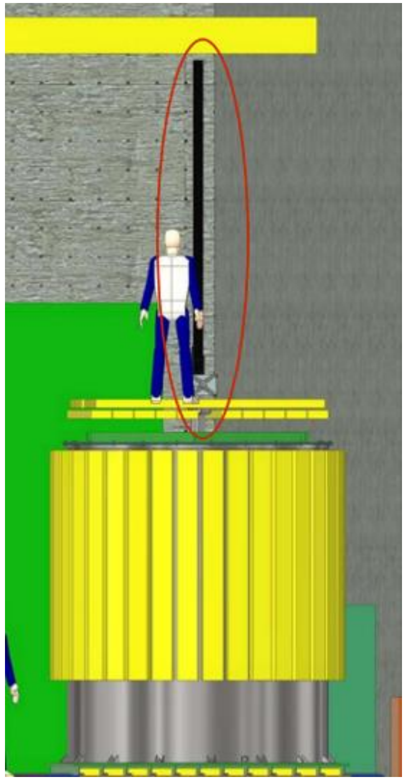

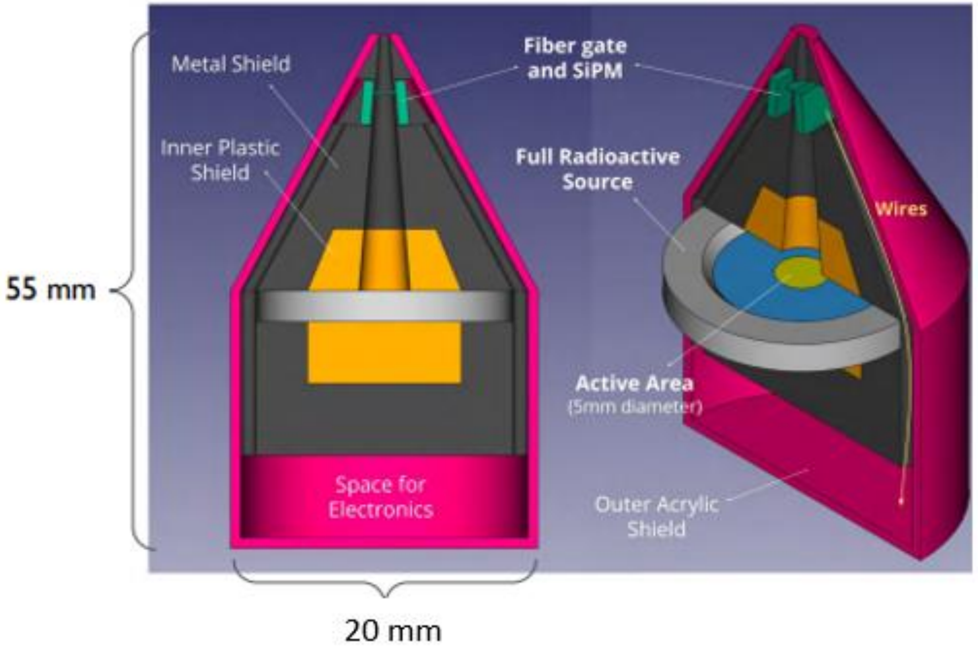

Directional β Source Design

- Modestly narrow beam of collimated electrons
- Self triggering: scintillating fibers viewed by two Silicon PhotoMultipliers (SiPMs)

Deployment

- Sources deployed in central port in tank lid
- Motorized column
- Source holder on motorized rotary joint

Software Framework and Reconstruction

Reactor **A**nalysis **T**ool – **P**lus **A**dditional **C**odes

RAT-PAC 2

- Shared software framework
- Integration of years of software advancement
    - Braidwood
    - RAT[SNO+]
    - RAT-WATCHMAN
    - RAT-THEIA
- Compatible with latest software
    - C++17
    - Geant-4 11+
    - ROOT 6+
- Waveform digitization modeling
- Cosmic ray shower simulation through CRY framework
- Machine learning compatible data format
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RATPAC 2 is now public
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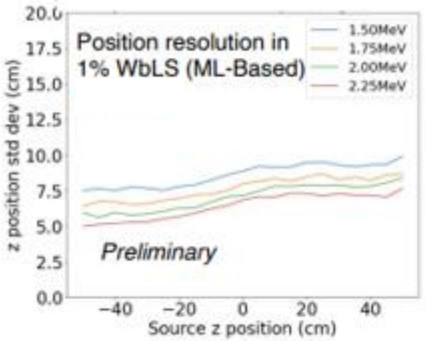
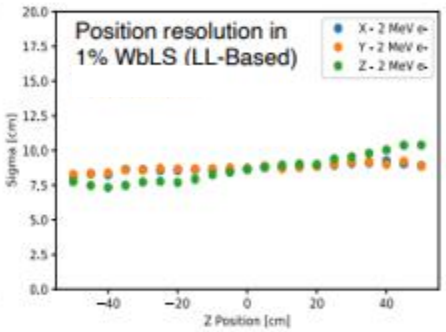
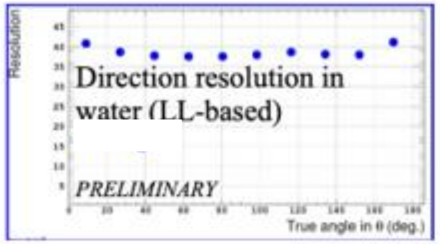
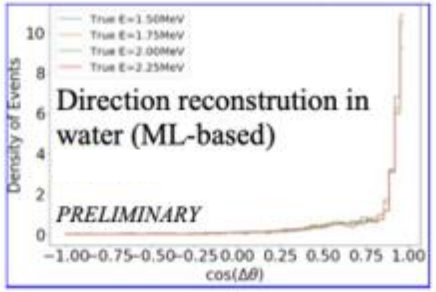
Three Independent Reconstruction Approaches

- Vertex Fitter – unbinned per PMT PDFs
- Joint Vertex/Direction Fitter – Per PMT / per Direction PDFs
- Joint Vertex/Direction/Energy Fitter – Machine Learning









Agreement observed between different methods

Milestones (per Life Cycle Plan)

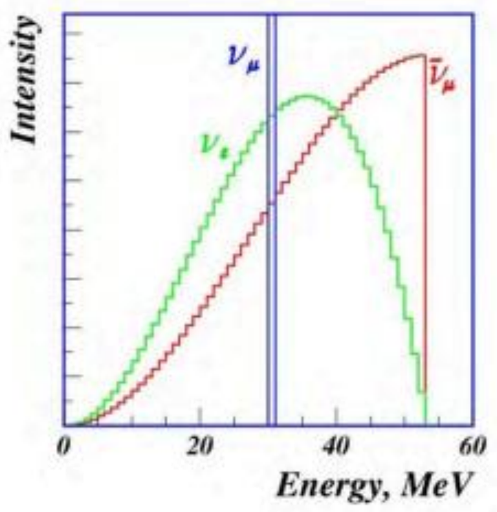
Milestone	Due date	Achieved	Anticipated
Fully defined institutional responsibilities	FY22Q1	FY22Q1	
PMT procurement initiated	FY22Q2	FY22Q2	
Vessel procurement initiated	FY22Q3	FY22Q3	
PMTs received at Berkeley	FY23Q3	FY23Q4	
PMT pre-installation testing complete	FY23Q4	FY23Q4	
Construction start	FY23Q3	FY23Q3	
Construction and installation complete	FY24Q1		FY24Q1
Detector commissioning and in-situ testing complete	FY24Q3		FY24Q3
Data taking complete	FY24Q4		FY24Q4

Detector lid with top PMT array and IV lowered onto assembly stand

Possible Future Deployment: Eos @ SNS (ORNL)

- SNS provides both neutrinos and anti neutrinos
- Detection of Inverse Beta Decay: relevant for reactors
- Detection of Elastic Scattering events: directionality "holy grail"
- Neutron studies: evaluate background rejection
- Possible space identified at ORNL
- Additional technology development opportunity:
  - Li-loaded WbLS (5% organic, 10% Li)
  - Enhanced ν_e detection : CC on ^{7}Li, spectral precision
- Supernova-relevant demonstration
- Beyond-SM searches

ν flux at SNS



Channel	Rate at 20m Standoff (ev/yr)
$\nu_e e$ ES	136.89
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ν_e-^{7}Li CC	533.30
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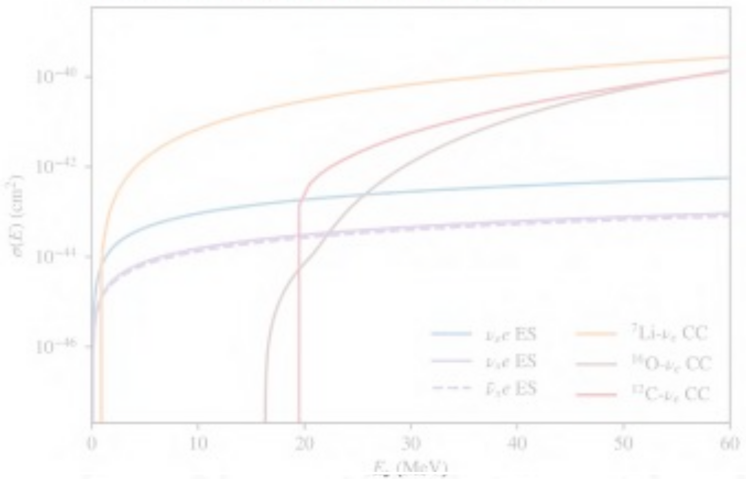
event rates expected for 4 tons of LiWbLS

neutrino cross-sections in LiWbLS



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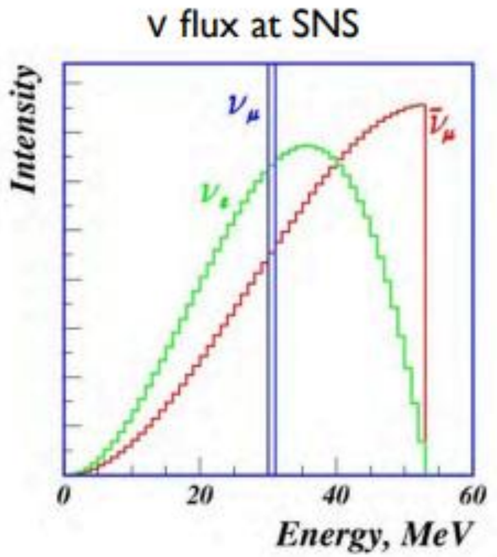

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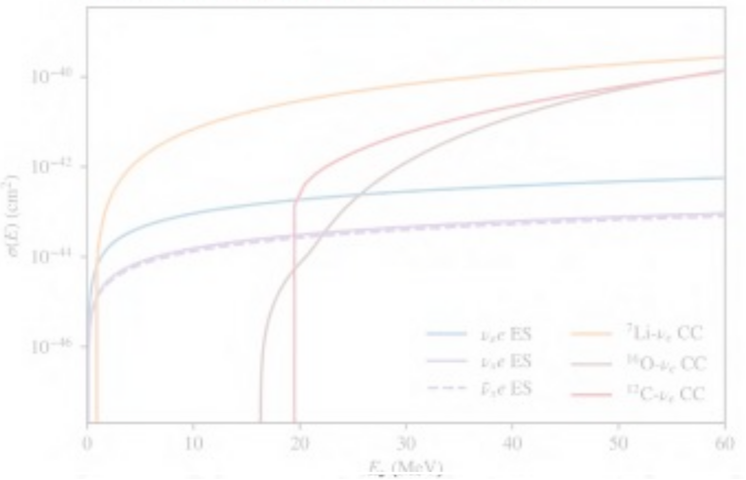

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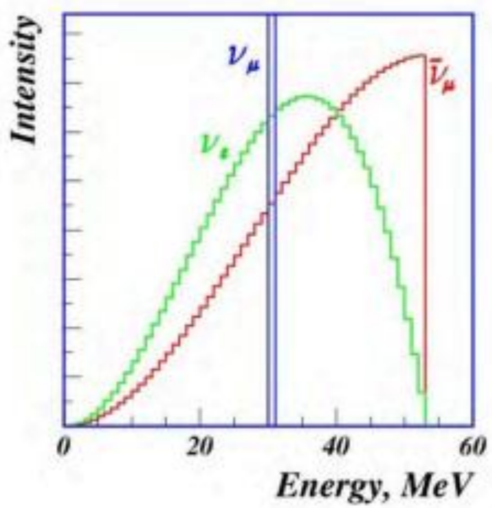

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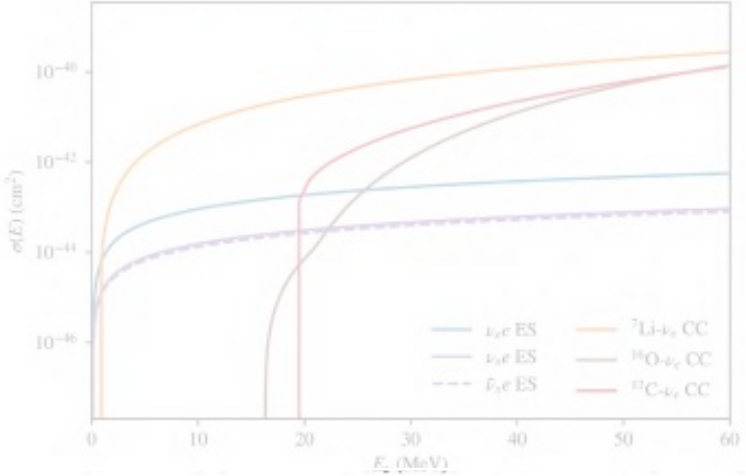

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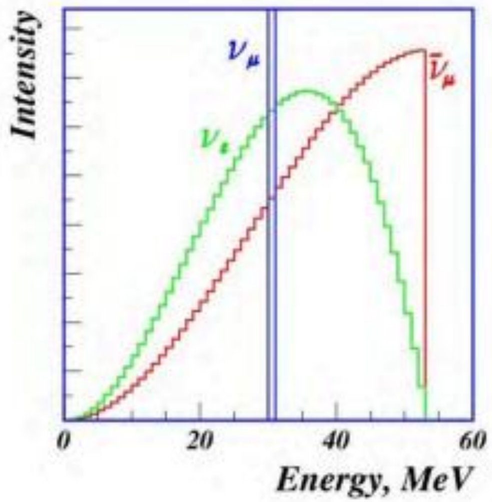

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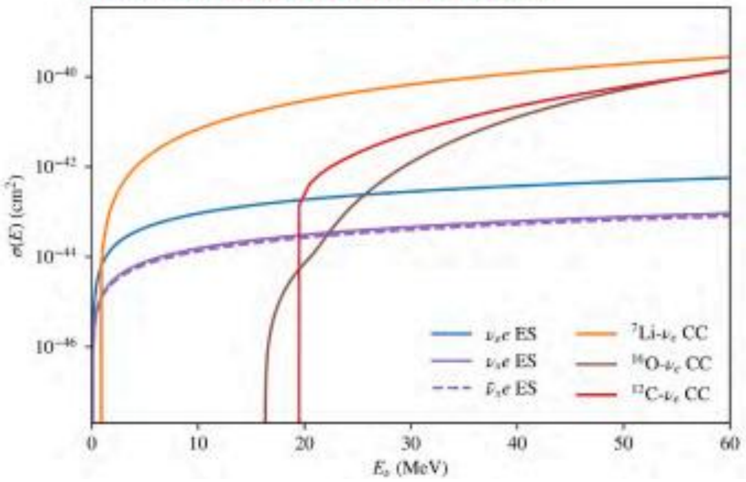

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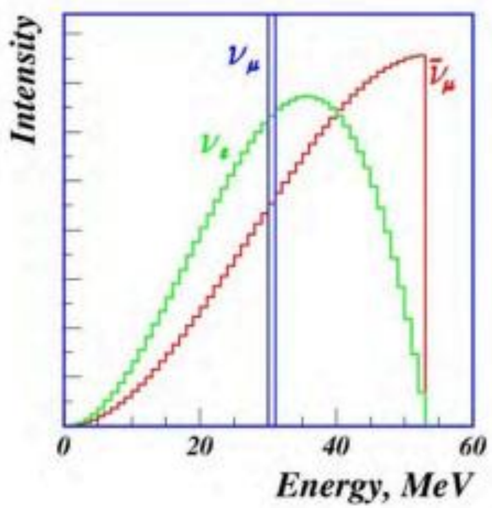

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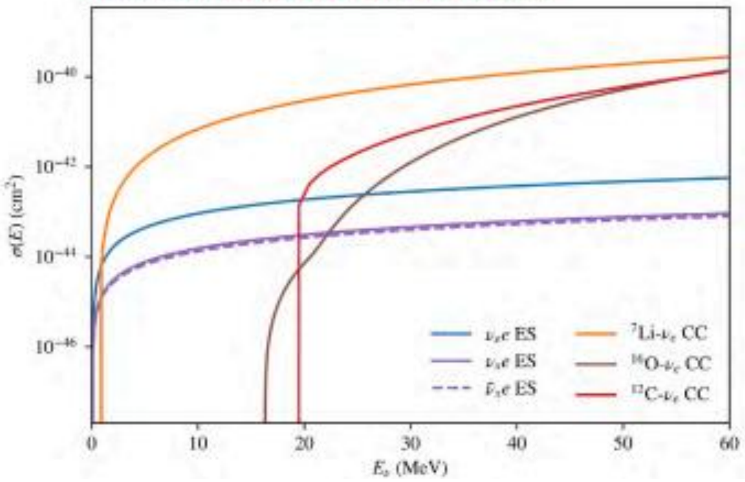
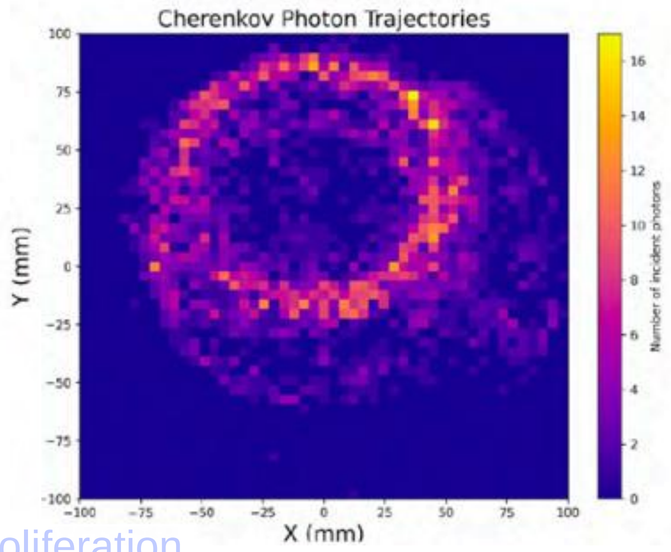


Eos: “Hybrid” technology demonstrator

Objectives:

- Enhance neutrino detection capabilities for fundamental science and nonproliferation
- First integrated, data-driven demonstration of hybrid Cherenkov+scintillation particle detection technology



Project goals:

- Demonstrate energy, position *and* direction reconstruction with hybrid technology
  - *With natural extension to particle identification and background evaluation*
- Validate models to support performance predictions for fundamental science and nonproliferation
- Provide a flexible testbed to demonstrate impact of novel technology
- *Built to be flexible for upgrade, and re-deployable at alternative sites*

Science:

- Strong collaboration with DOE-SC and many universities interested in similar development for fundamental science
- Benefiting from synergistic neutrino detector development: ANNIE, SNO+, Daya Bay, Prospect etc: demonstrations of reactor neutrino detection, burn up, technology development
- Supporting development for a multi-purpose large-scale detector (THEIA): nonproliferation demonstrations *as well as* high-energy physics, nuclear astrophysics, geophysics

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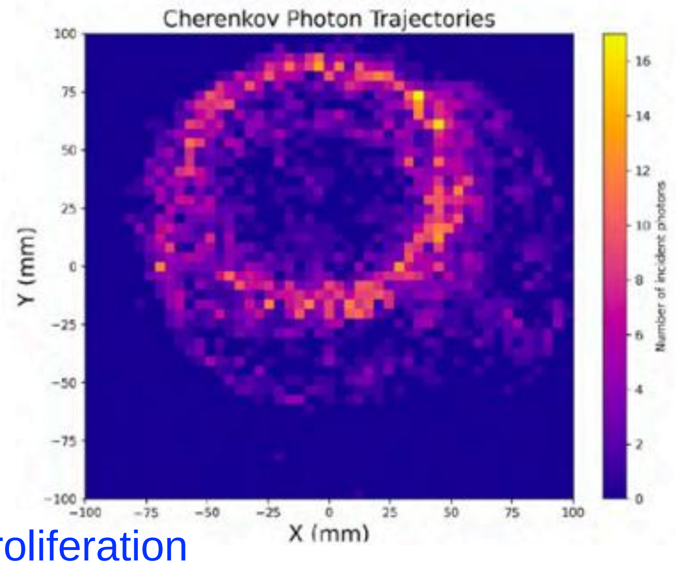

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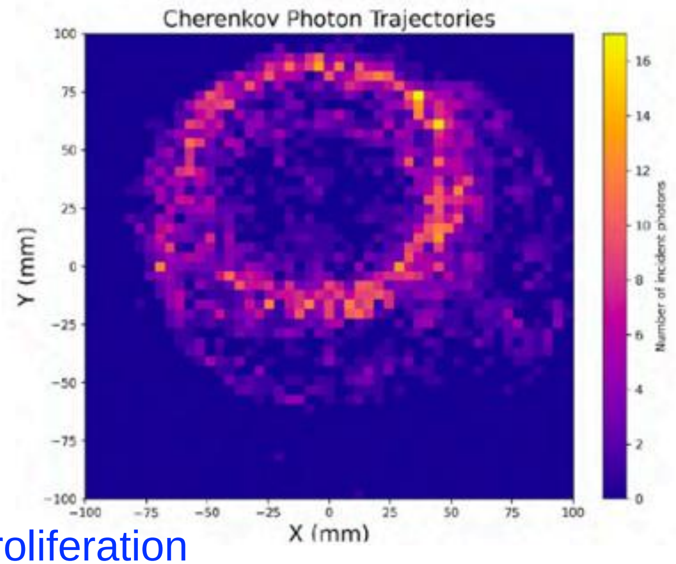

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Acknowledgements

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Thanks to Gabriel Orebi Gann, Hans Steiger, Joe Saba, Tanner Kaptanoglu, Richie Bonventre, Logan Lebanowski, and Marc Bergevin for slides, figures, and plots

USA

Germany

Portugal

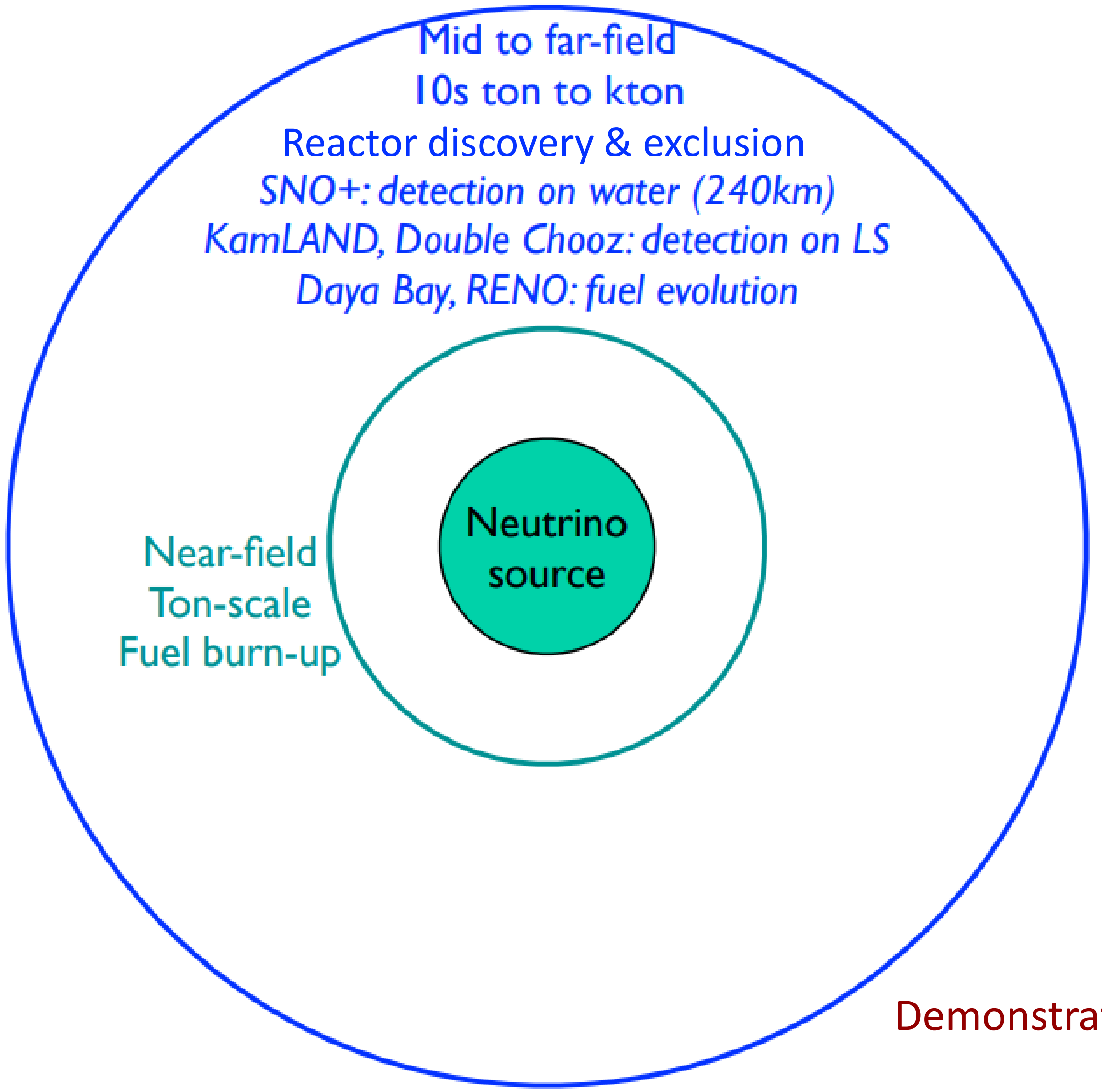
Finland

Canada

Turkey

BACKUP

Potential impact

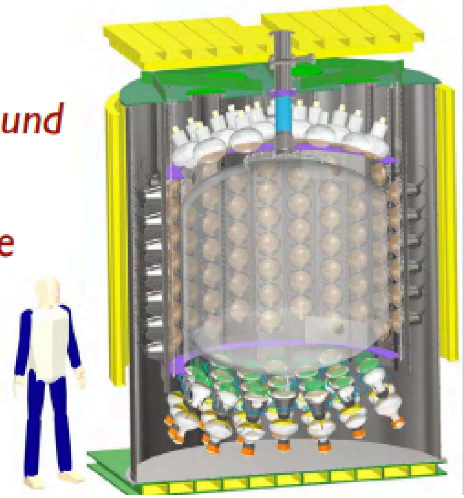


Benefits of hybrid technology

- **Scalable** to large (10s kton) scales
  - Ability to monitor ν sources at large standoff distance
  - Sensitivity to weak signals
- **High-fidelity** event reconstruction and particle identification
  - High signal efficiency
  - Powerful background rejection
  - ➡ Good signal-to-noise ratio, improved sensitivity

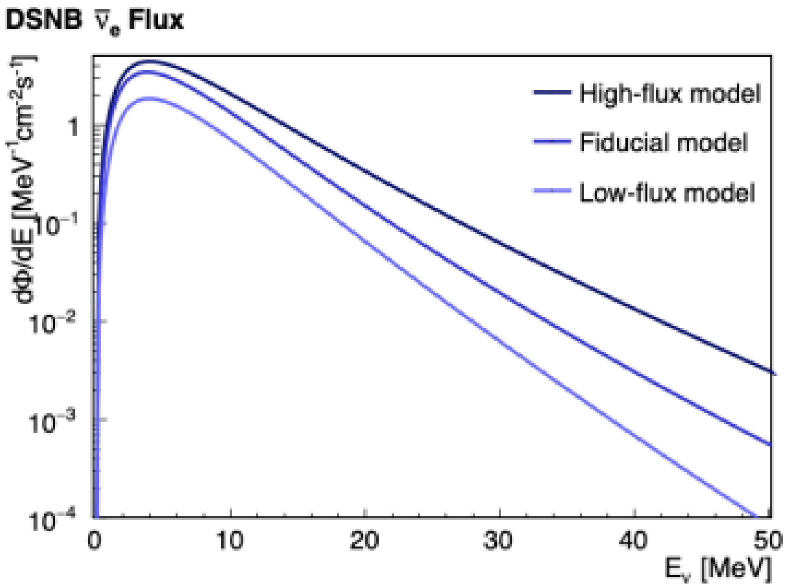
Benefits of Eos deployment

- Evaluate event reconstruction capabilities
- *Future: evaluate particle identification and background rejection capabilities*
- *Future: measure background rates at / near surface*
- *Future: direct neutrino detection from a source*

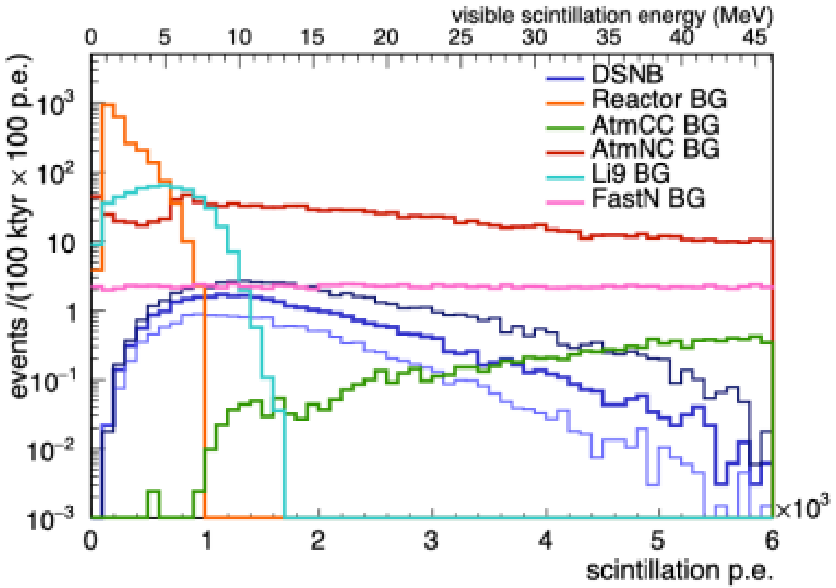


Demonstrate potential for cost-saving surface deployment

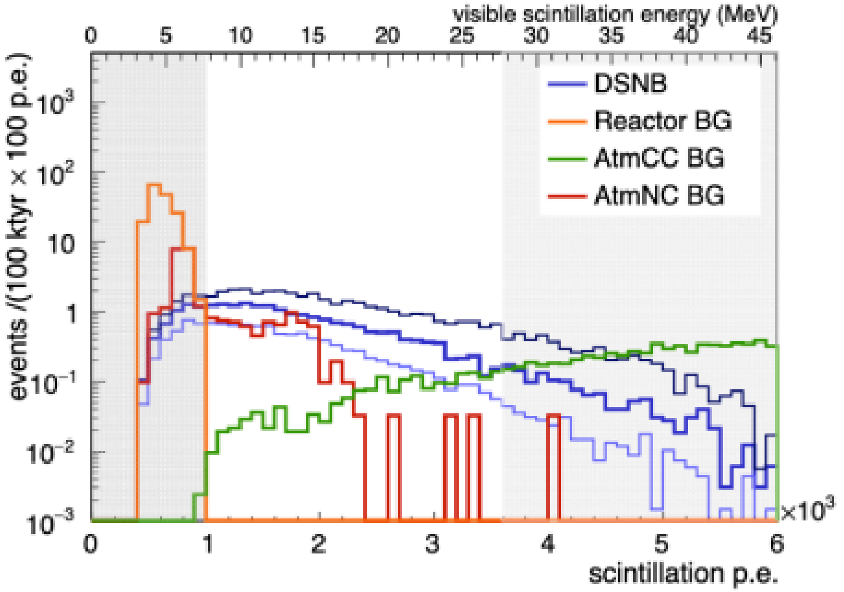
Fundamental Science: DSNB with Theia



DSNB Flux Models



Visible energy spectrum expected for the DSNB signal and its backgrounds



Visible spectrum expected for DSNB signal and backgrounds after all selection cuts

Flux Model:
G. J. Mathews, J. Hidaka, T. Kajino, and J. Suzuki, ApJ 790, 115 (2014).

Stellar collapse diversity and DSNB:
D. Kresse, T. Ertl, and H.-T. Janka, ApJ 909, 2, (2020)

Detecting the diffuse supernova neutrino background in the future water-based liquid scintillator detector Theia

Julia Sawatzki, Michael Wurm, and Daniel Kresse, Phys. Rev. D 103, 023021

Potential next steps

In order to demonstrate the viability of this technology for any chosen use case we need to understand:

- Deployment requirements and scintillator optics
- Detector performance capabilities
- Particle identification (PID) capabilities, in order to evaluate background rejection efficiency
- Background rates in the appropriate environment
  - Surface
  - Shallow depths
- Signal efficiency, and detection requirement (e.g. isotope loading)

Approach:

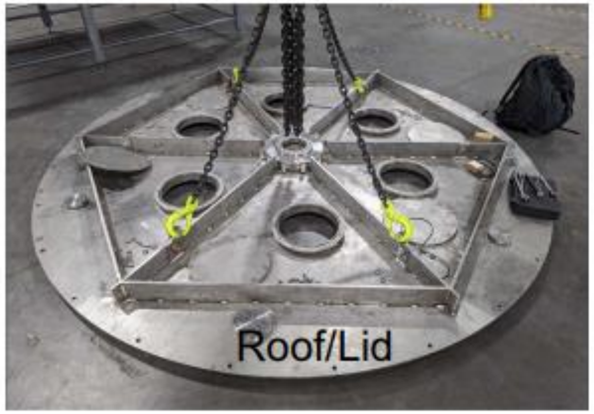
- BNL-30ton will evaluate engineering & optics
- EOS will evaluate detector performance during this LCP
- Ongoing deployment of EOS would allow for a full evaluation of particle identification capabilities (FY25)
- EOS could be used for background evaluation
  - In its current deployment location
  - Re-deployed to a shallow site
- EOS could be re-deployed to a reactor, or the Spallation Neutron Source at ORNL, for neutrino detection

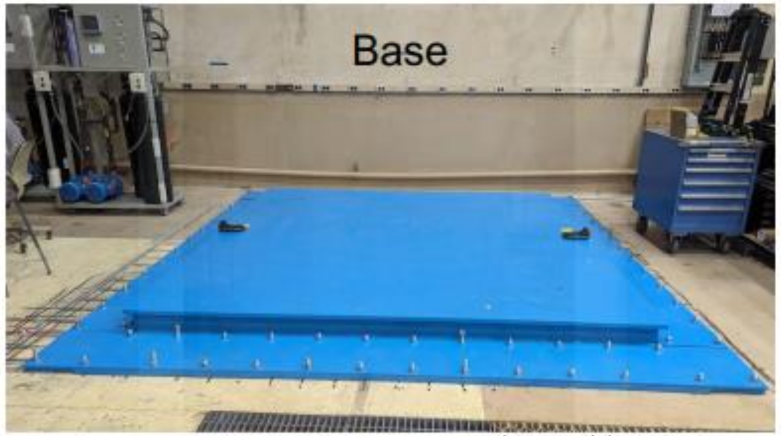
Preferred path forwards:

- *FY25: ongoing operations at Berkeley → full PID study, evaluation of backgrounds at surface*
- *FY26-27: re-deployment of EOS to SNS@ORNL for neutrino detection evaluation*

Outer Vessel (OV)

- Tank itself designed and built to API 650 standard
- Anchored against earthquake hazard per California Building Code
- ~5000 Gallon capacity, 9 feet diameter X 11 feet tall
- 304 Stainless Steel (for deionized water service)
- Manufacturer, C&C Industrial, Mount Sterling, KY
- Custom steel base designed and manufactured to distribute earthquake load and house muon veto detectors underneath tank.
- The roof (aka lid) of the tank is designed to feed all fluid, electrical, and optical connections to the detector.
- Custom steel assembly stand





Inner Vessel (IV)

- 4,000 kg water capacity (4 metric tonnes)
- Acrylic, UVT (Ultraviolet Transmitting)
- Manufacturer, Reynolds Polymer Technology, Grand Junction, CO
- 6 feet diameter cylinder and dished heads to take advantage of existing tooling at Reynolds to reduce cost and leadtime.
- Designed and tested for modest pressure handling capability, +/- 2.6 psi (0.2 bar)
- In an abundance of caution, plan is to co-fill and co-drain with surrounding DI water

Fluids, Deionized Water

- Custom deionized water (DI) systems have been procured from South Coast Water
- There are 2 DI systems, one for the OV and a separate one for the IV
- An air-cooled chiller was also purchased and installed. The DI water for the OV will go through the chiller, and operate it below ambient, ~10 C
- The OV will always be filled with DI water, but the IV will handle various fluids ranging from DI water, to some fraction of WBLS, to 100% LS

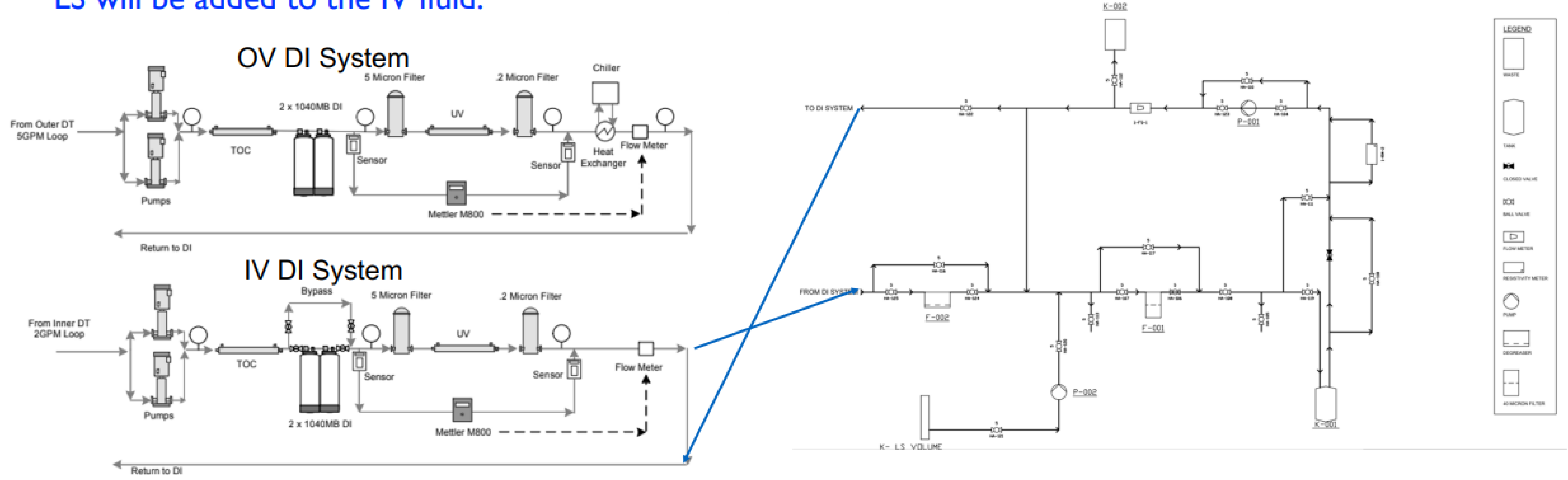
Detector Design – Liquid Handling

- Custom separate deionized (DI) water systems for IV and OV
- Air-cooled chiller for OV water ~10° C
- Custom designed liquid scintillator (LS) injection system
- Plan to fill IV with DI water, then incremental fractions of Water-based Liquid Scintillator (WbLS), and finally 100% LS

Fluids, Liquid Scintillator (LS) Handling

- A custom liquid scintillator injection system has being designed… procurements are underway.
- After the water in the IV is in equilibrium and a baseline performance has been established, small (~1%) increments of LS will be added to the IV fluid.

LS Injection System



R14688-100 PMTs

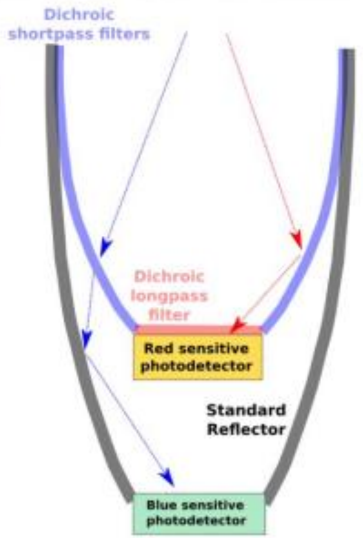
- The R14688-100 PMT is a modern 8-inch PMT, the next generation of the R5912, which was used by many experiments, such as Daya Bay.
- It has an expected transit time spread (TTS) of about 1 ns (FWHM), about 2 – 3x better than the R5912.
- It uses an ultrabialkali photocathode, which has a high quantum efficiency, peaking around ~35%.
- Hamamatsu has water proof potted and cabled the PMT.
- Eos will be the first detector to use these PMTs.

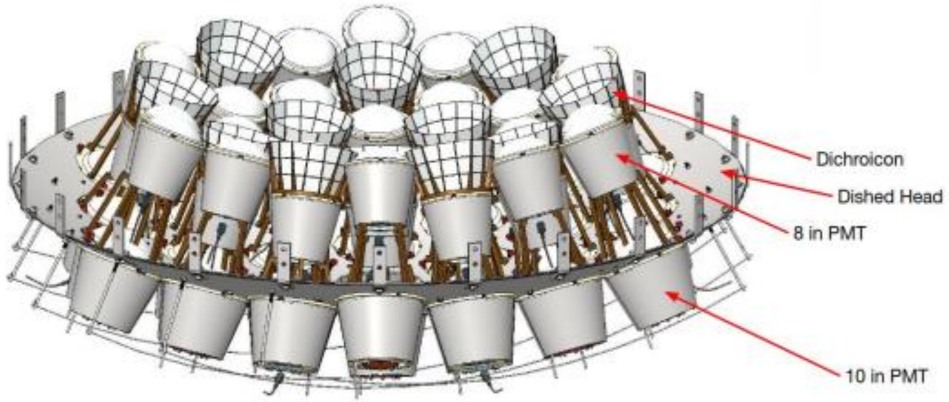
R14688-100 PMT with water proofing

Dichroicon Design

- Designed, prototyped, and tested at UPenn on the bench-top (PRD, 2020).

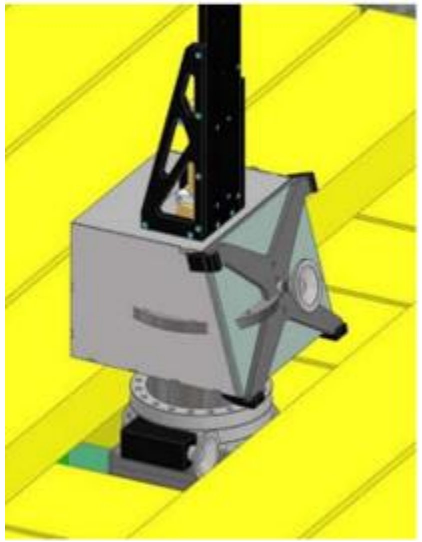
- Conceptually: sort long-wavelength (Cherenkov-rich) and short-wavelength (scintillation-rich) toward two different photodetectors using a parabolic concentrator built from dichroic filters.
- Maintain high scintillation light collection efficiency and effectively separate Ch/Sc light.
- In Eos, array of 36 8" PMTs at the bottom will be outfitted with 12 dichroicons. An array of 12 10" PMTs behind the 8" PMTs (offset so they are optimized to detect the passing scintillation light).

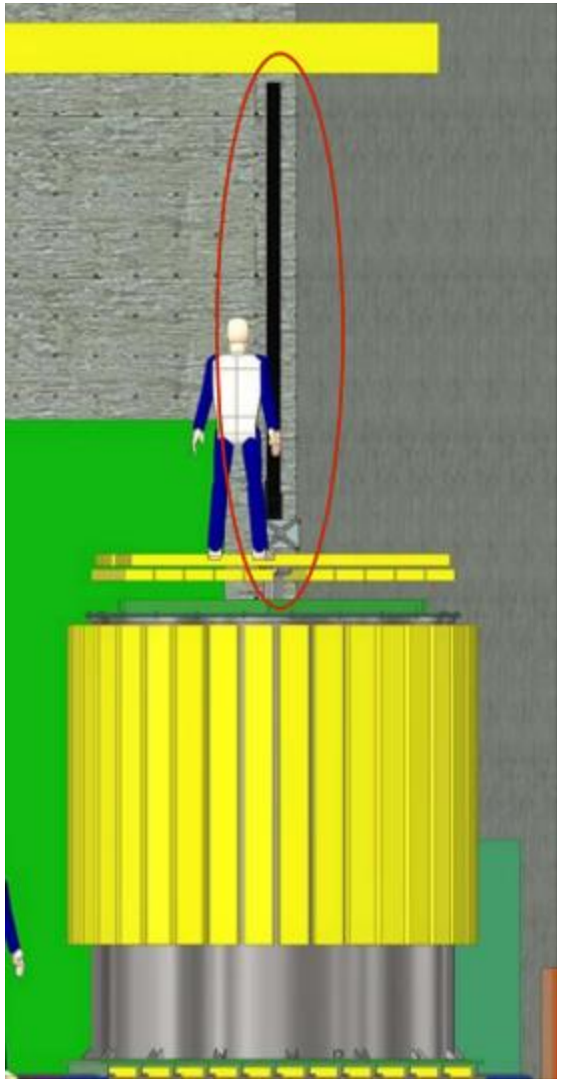




Detector Design – Calibration Deployment

- Motorized central axis column with source holder
- Calibration column will be deployed through central port in tank lid
- Source holder is on motorized rotary joint for azimuthal freedom

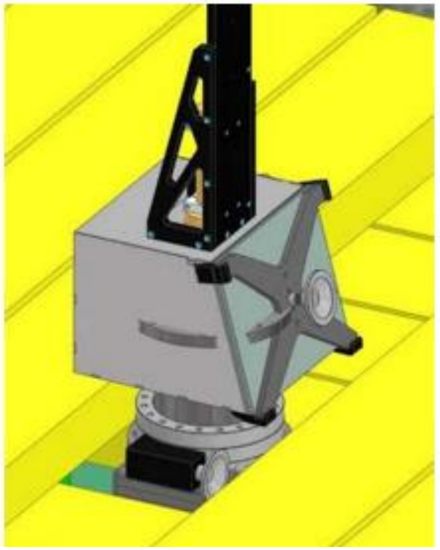
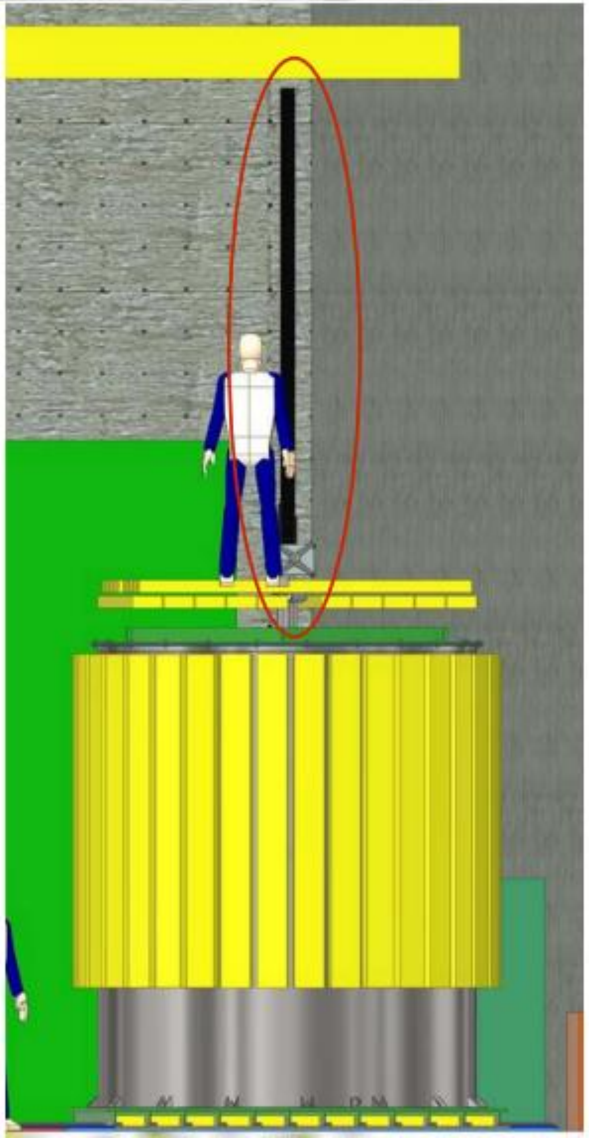




Calibration Deployment System

- The calibration deployment system is based on experience with similar devices used in previous experiments (Kamland, CUORE, Daya Bay).
- It automatically (motor driven) deploys calibration sources down the central axis of the detector volume
- In addition, there is a motorized rotary joint, which can turn the entire device in azimuth. This will be used with directional sources.
- The system has been designed and is in an intermediate stage of completion at this point. It is well off of critical path because it is one of the last things to be installed in the entire integration sequence.



Novel β source

Goals: Direction

Source(s): $^{90}Sr \rightarrow {}^{90}Y$, β-decay endpoint 2.3 MeV

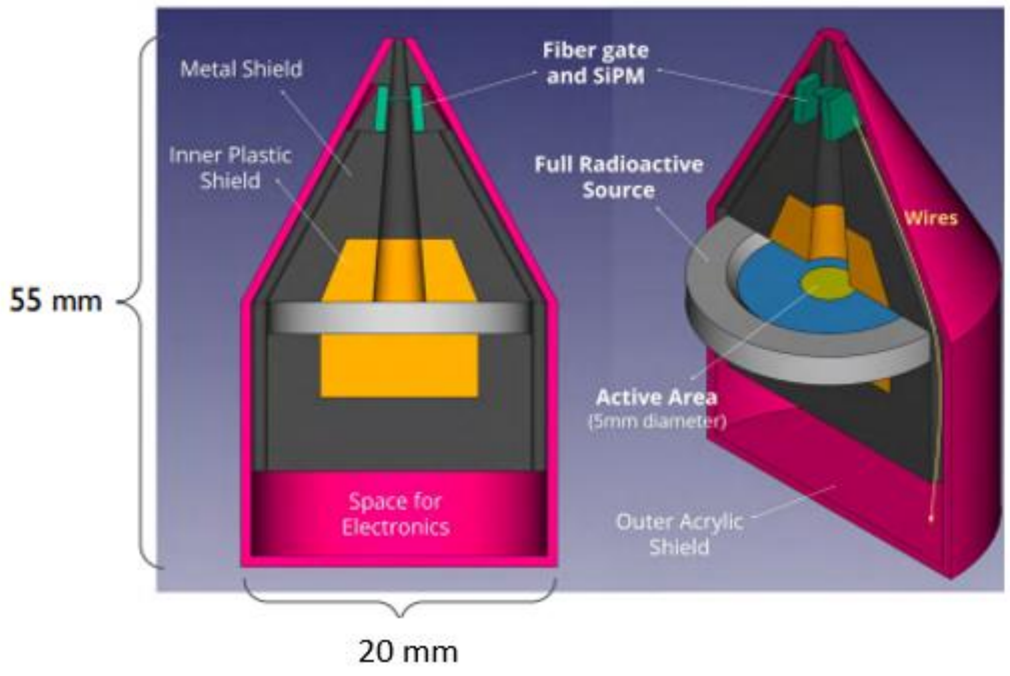
$^{106}Ru \rightarrow {}^{106}Rh$, β-decay endpoint 3.5 MeV

Design:

- Modestly narrow beam of collimated electrons
- Self triggering: scintillating fibers (0.2 mm $\Leftarrow\!\Rightarrow$ 33%) viewed by two Silicon PhotoMultipliers (SiPMs)

Expectations:

- Few 100 kBq ⇒ ~Hz of tagged events
- Deploy at different polar and azimuthal orientations



Light Injection System

Goals: WbLS attenuation; PMT timing, gain, & efficiency

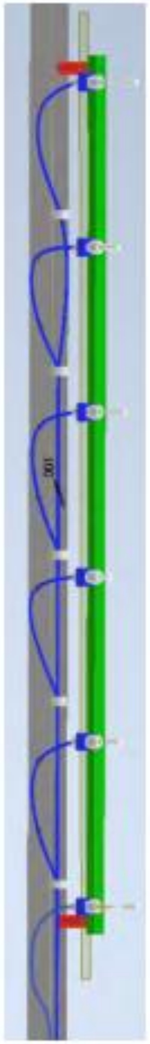
Source: Fast pulsed diode laser - 19 ps FWHM

- Wavelengths [nm]: 375, 405, 440, 510

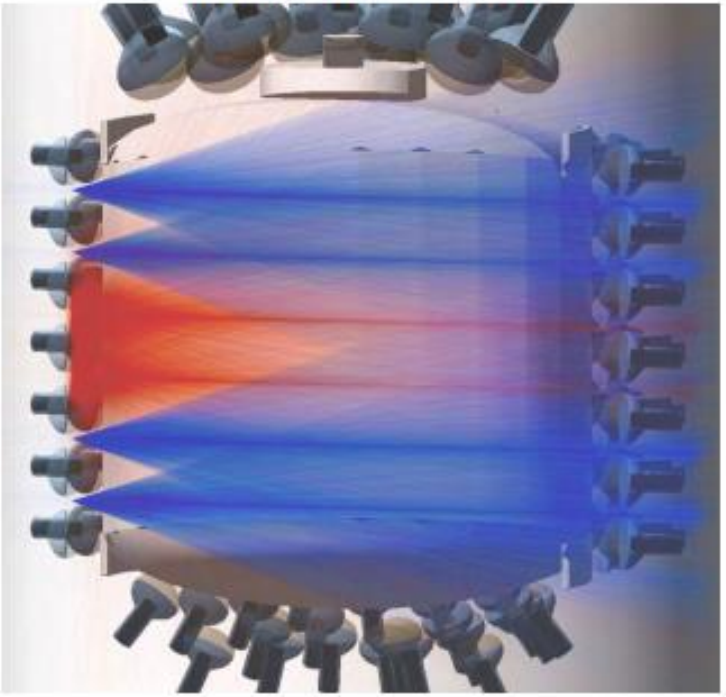
Design:

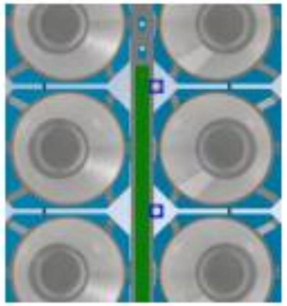
- 1 centrally deployed diffuser ball
- 36 barrel-mounted diffusers (6 columns × 6 fibers)
  - Per column:
    - **2 timing**: ~120° opening
    - **4 attenuation**: ~38° opening

- Preparing for installation of fibers in October
- Lasers received and testing beginning



Custom laser simulations





Community Software Framework

- Shared Framework
  - Integration of years of software advancement (Braidwood, RAT [SNO+], RAT-THEIA, RAT-WATCHMAN) into open-source public package
  - Compatibility with latest software: C++17, Geant-4 11+, Root 6+
  - Conversion to shared library
  - New feature: waveform digitization modeling for simulated data
  - Interface with external software: Cosmic Ray Shower simulation framework CRY now fully integrated
  - New Machine Learning compatible data format
    - Tensorflow now fully integrated

RATPAC 2 is now public
https://github.com/rat-pac/ratpac-two

Inputs from RAT-Theia

- Improved scintillation infrastructure (integration with GLG4Scint) cross-validated with the CHESS experiment.
- Updates to physics generator models (Decay0, CC)
- Optical Model Improvements

Inputs from RAT-Watchman

- Dicebox, ^{9}Li/^{8}He, IBD Generators
- Modern cross-platform build system (Cmake)
- Integration with BONSAI (Super Kamiokande reconstruction tool) [not been made public]
- Easy installation options (Docker)

Reactor **A**nalysis **T**ool – **P**lus **A**dditional **C**odes

Reconstruction

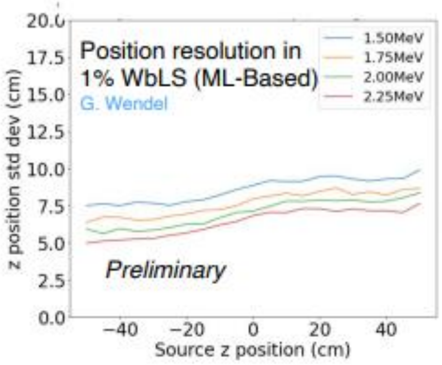
Analysis tools

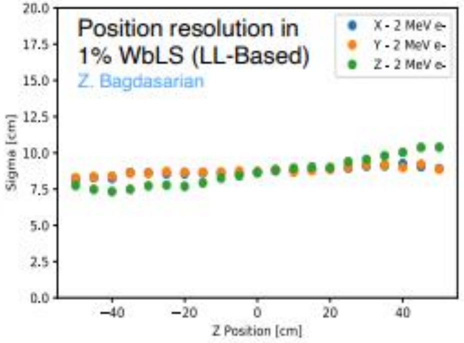
- Reconstruction

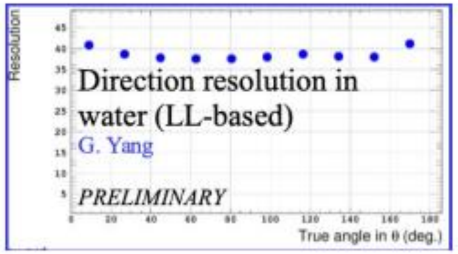
  - Developing both traditional and Machine Learning reconstruction methods. Eos will be in a position to validate Machine Learning method.
  - Requirement: Quantifiable improvements in energy and reconstruction performance between water and WbLS.
  - Three different reconstruction approach taken. Results are consistent between approaches.

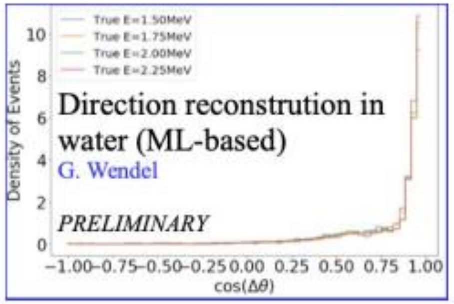
Three Independent Reconstruction Approaches

- <u>Vertex</u> Fitter – unbinned per PMT PDFs
- <u>Joint Vertex/Direction</u> Fitter – Per PMT / per Direction PDFs
- <u>Joint Vertex/Direction/Energy</u> Fitter – Machine Learning

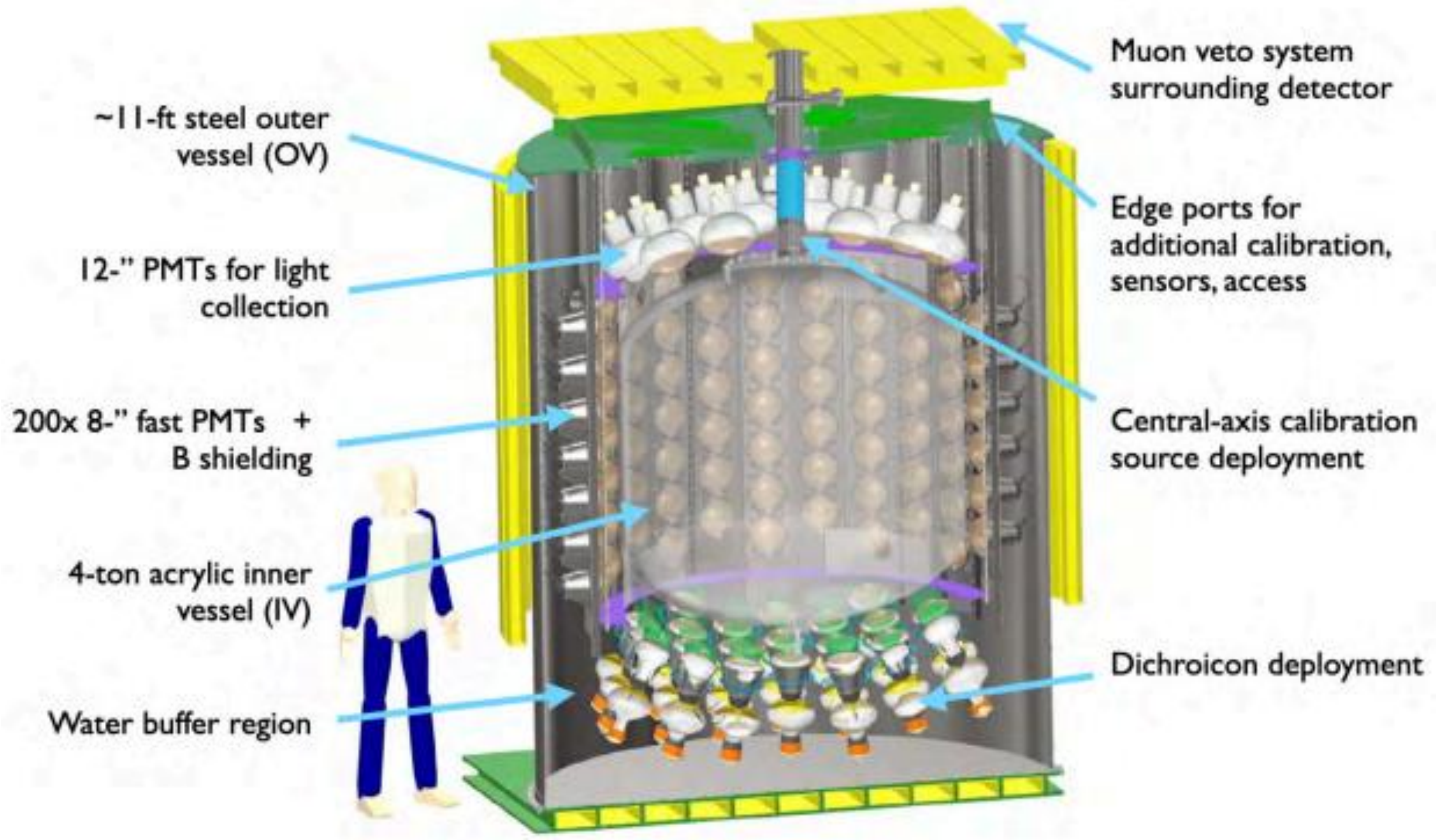








Agreement observed between different methods


~11-ft steel outer
vessel (OV)
12-" PMTs for light
collection
200x 8-" fast PMTs +
B shielding
4-ton acrylic inner
vessel (IV)
Water buffer region
Muon veto system
surrounding detector
Edge ports for
additional calibration,
sensors, access
Central-axis calibration
source deployment
Dichroicon deployment