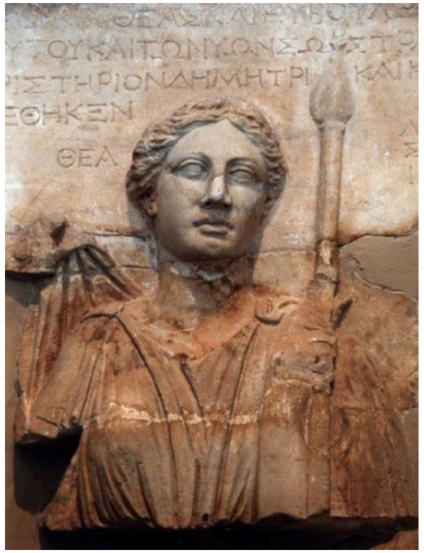
Gefördert durch DFG Deutsche Forschungsgemeinschaft
GEFÖRDERT VOM Bundesministerium für Bildung und Forschung
SFB 1258 Neutrinos Dark Matter Messengers
ORIGINS Excellence Cluster
PRISMA+ JG|U
TUM Technische Universität München

EOS – A Pathfinder Experiment for Low Energy Neutrino Physics with the Hybrid Detector THEIA

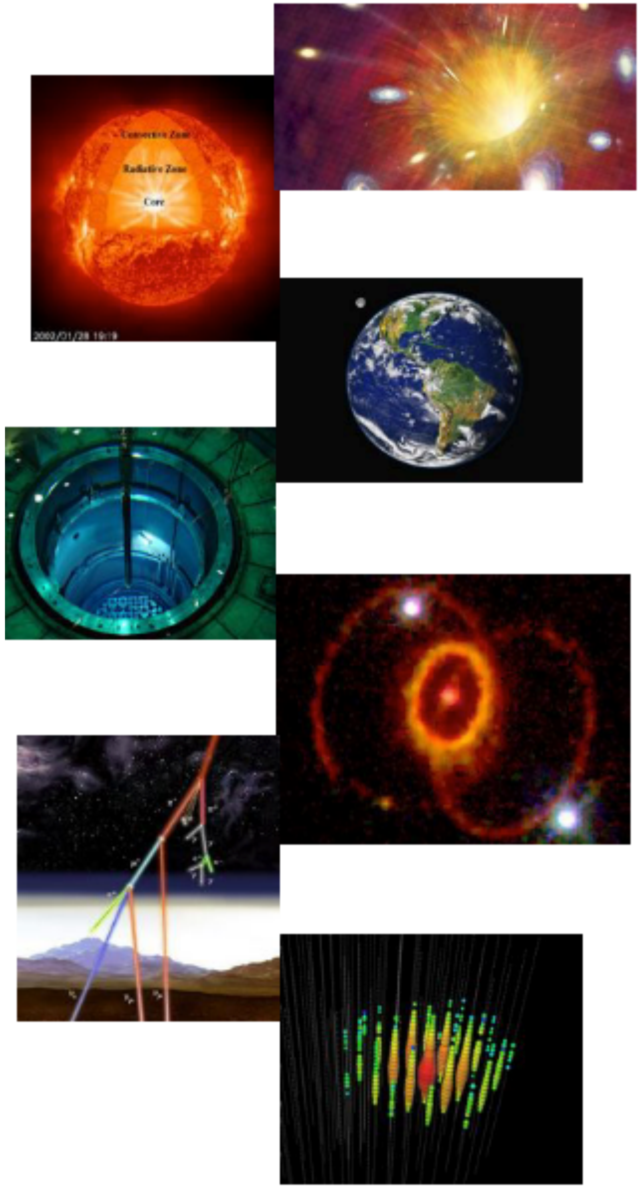


Hans Th. J. Steiger[1, 2]

on behalf of the THEIA pre-Collaboration and the EOS Collaboration

[1] Cluster of Excellence PRISMA+, Johannes Gutenberg Universität Mainz
[2] Technische Universität München, School of Natural Sciences, Physics Department

Neutrinos as probes or messenger particles in THEIA



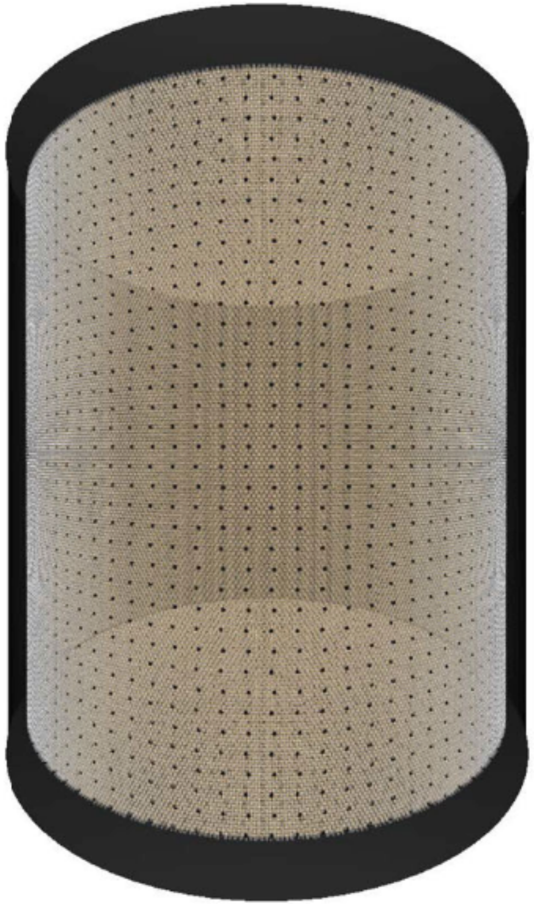
10^{-4} eV

Neutrino Energy

10^{20} eV

- **Cosmic Neutrino Background**
- **Solar Neutrinos**
- **Geo Neutrinos**
- **Reactor Neutrinos**
- **Supernova Neutrinos**
- **Diffuse Super Nova Neutrino Background (DSNB)**
- **Atmospheric Neutrinos**
- **Astrophysical Neutrinos**

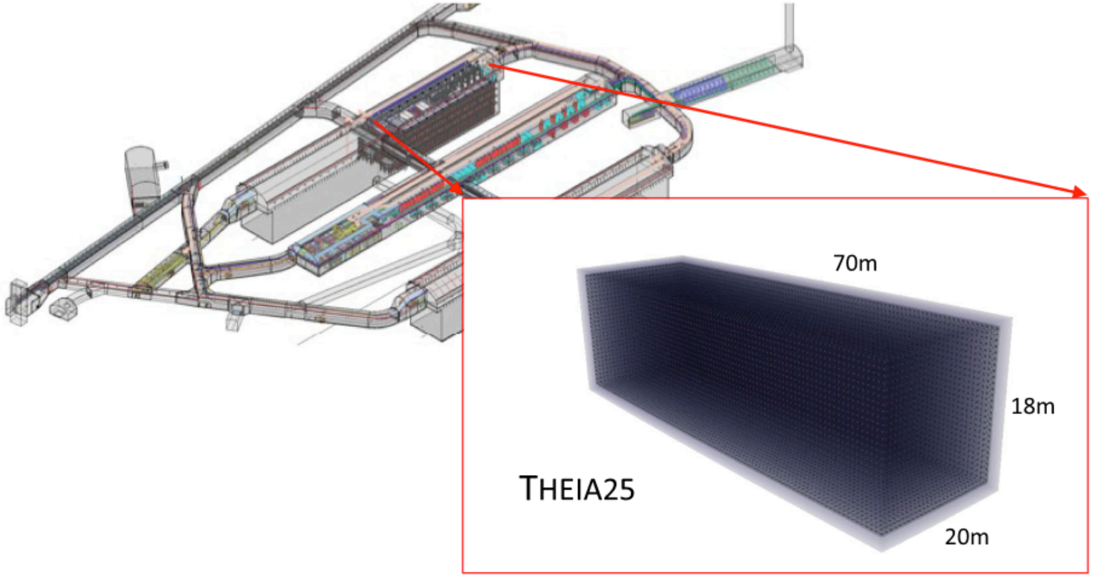
Eur. Phys. J. C (2020) 80:416

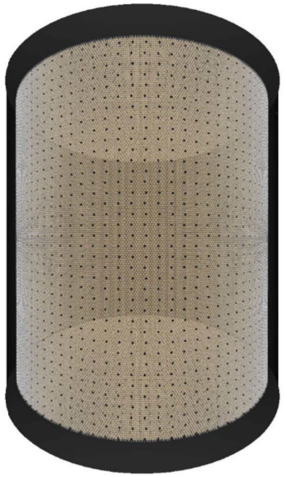


Model of THEIA – 100

(86% coverage: standard 10-inch PMTs
4% coverage: LAPPDs)

Theia: The first advanced optical multipurpose neutrino detector





Large scale, multipurpose detector:

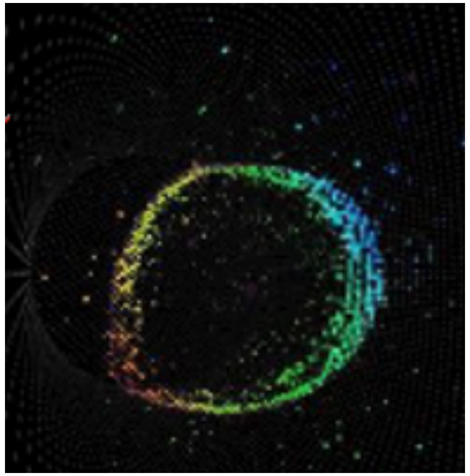
- Baseline: 25ktonne (17kt FV)
  - geometry consistent with one of the planned DUNE caverns
- Ideal: 100 ktonne (70kt FV)

M. Askins, et al., Eur. Phys. J. C 80 (2020) 5, 416, arXiv:1911.03501

The best of both worlds…

Cherenkov Detectors:

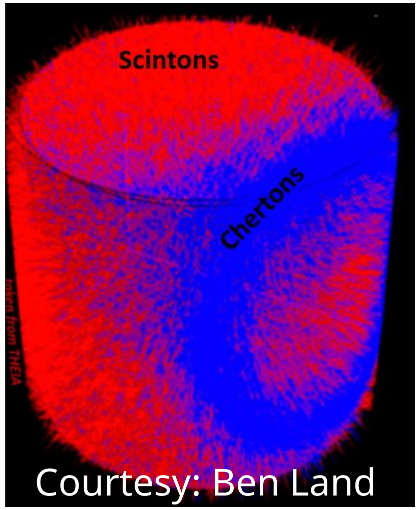
- Excellent Transparency → large size
- Cheap
- Directionality
- Particle ID
- Potential for large Isotopic Loading
- No access to physics below the Cherenkov threshold
- Low light yield



Electron Event

Conventional Scintillation Detectors:

- High light yield
- Low energy threshold
- Good energy and position resolutions
- Can be radiologically very clean
- Limited in size by absorption and cost
- Limited directionality

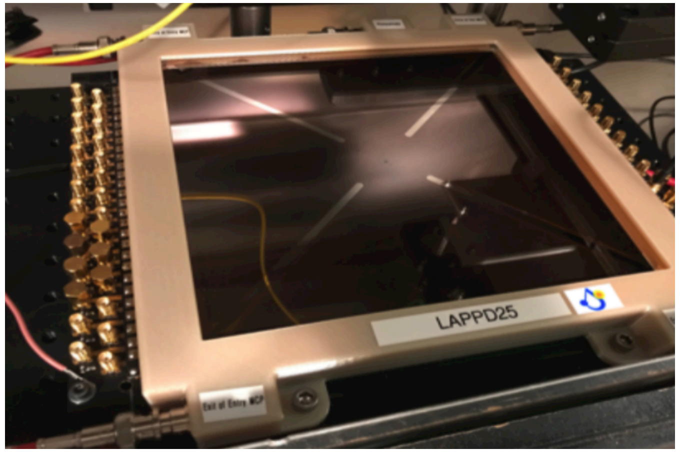


Simulation of the C/S-Light in a THEIA-like scenario

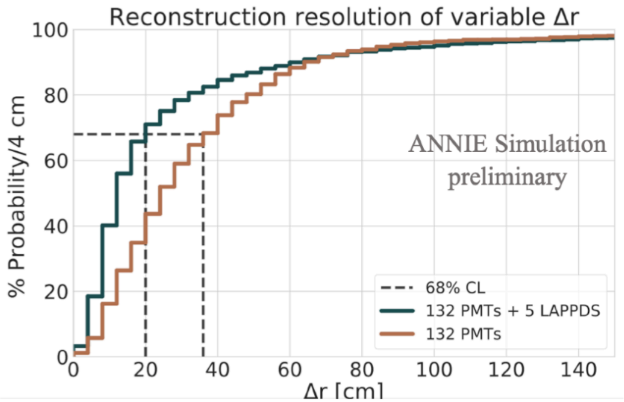
New Photosensor Development and Chromatic Separation

Large area picosecond photodetector (LAPPD):

- Micro-channel plate
- Large-area: 20 cm x 20 cm
- Intrinsic mm-cm scale position resolution
- Fast timing: ~ 70 ps time resolution
- Quantum Efficiency (QE): >20-30 %

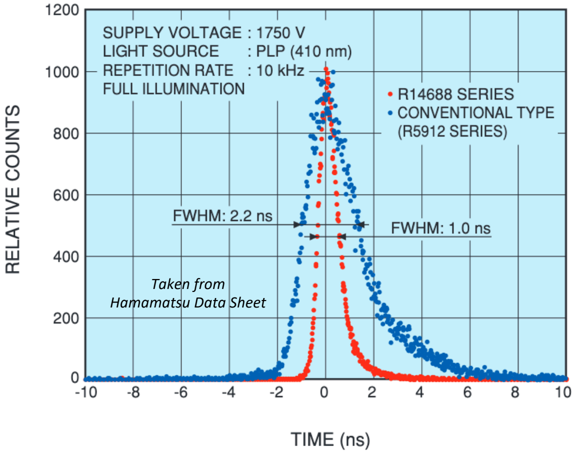


Combination of LAPPDs and PMTs



Fast and large Super-Bialkali PMTs:

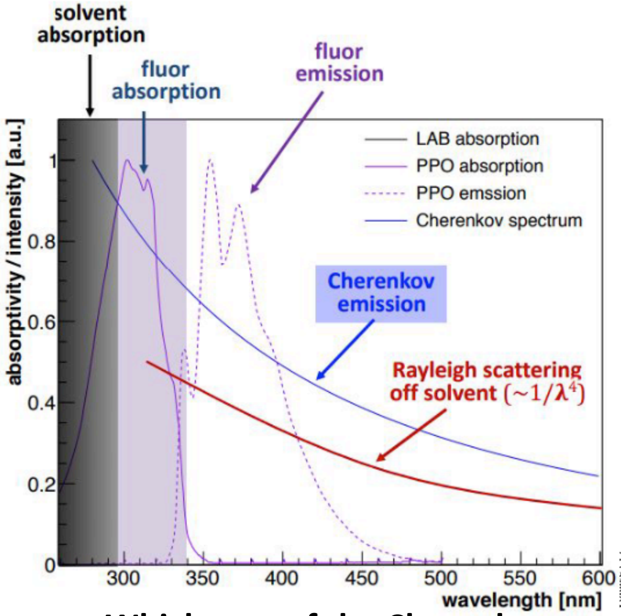
- Example: Hamamatsu R14688-100
- Size: 8-inch
- Gain: >10^7
- TTS: ~ 900ps-1000ps
- Low Dark-Rate: ~ 4 kHz
- Quantum Efficiency (QE): > 35 %



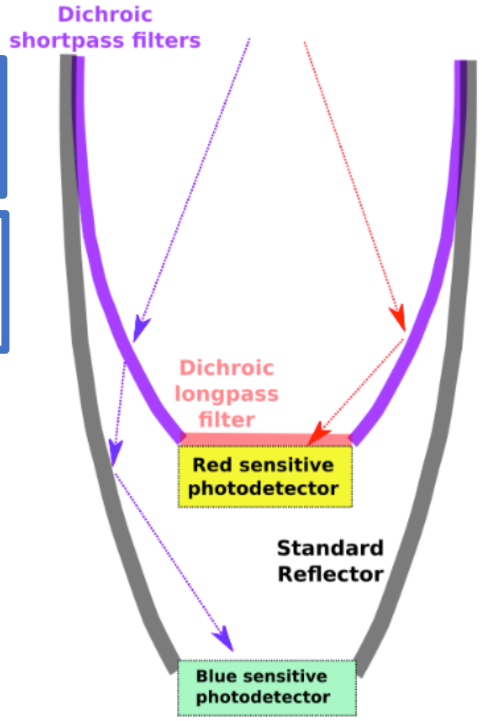
Dichroic Filters:

T. Kaptanoglu et al.,
JINST 14 T05001 (2019)

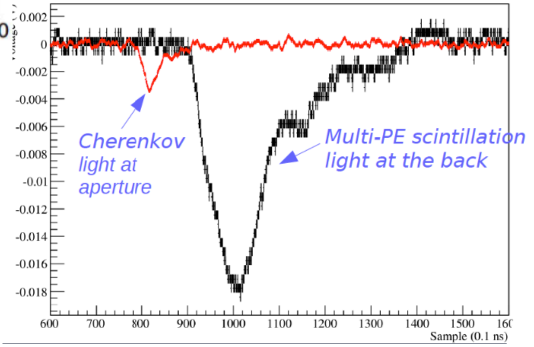
T. Kaptanoglu et al.,
Phys. Rev. D 101, 072002 (2020)



Which part of the Cherenkov spectrum is accessible?



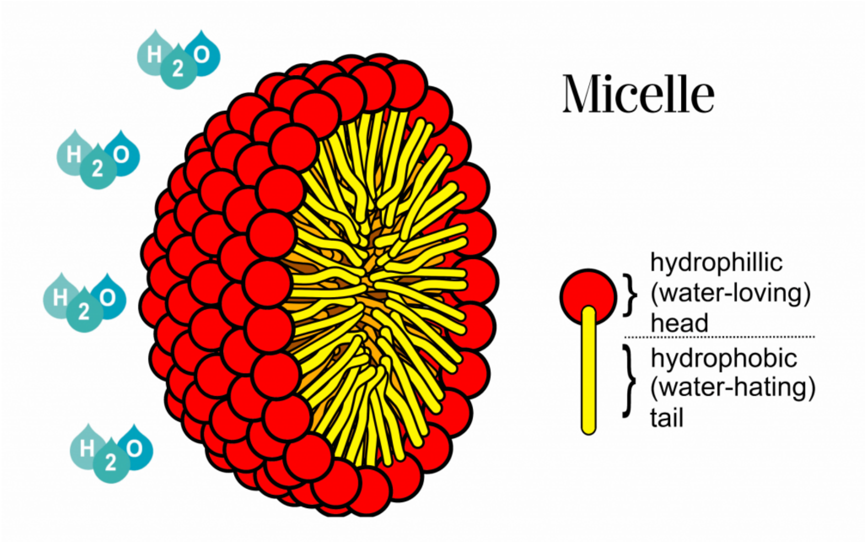
Concept of a Dichroicon

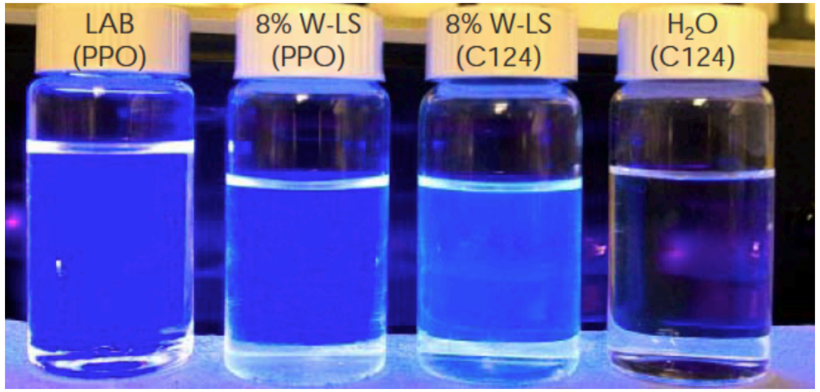


A typical event (red: Cherenkov, black: scintillation)

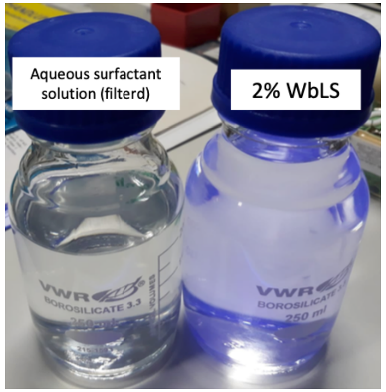
New Detection Media: Water-based liquid scintillators

- Water-based Liquid Scintillator (WbLS) is a colloidal solution of organic liquid scintillators in water
- WbLS is made using a surfactant (e.g. hydrophilic head and hydrophobic tail) to hold the scintillator molecules in a “micelle” structure in the water
- Combines the advantages of water (transparency, low cost) and liquid scintillator (high light yield)





WbLS based on LAS with different loading by BNL



WbLS using Triton X-100 (H. Steiger, PRISMA$^+$)

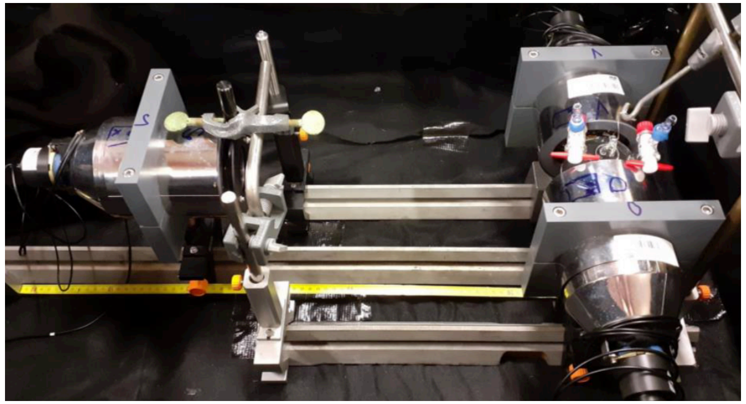
- Successful produced at BNL (M. Yeh) and JGU Mainz (H. Steiger)
- BNL already working on production of larger samples (ton-scale)
- Nanofiltration developed at UC Davis (Bob Svoboda et al.)
- Can be loaded with many elements (Li, B, Ca, Zr, In, Te, Xe, Pb, Nd, Sm, Ge, Yb)

Ton-scale production facility (BNL)

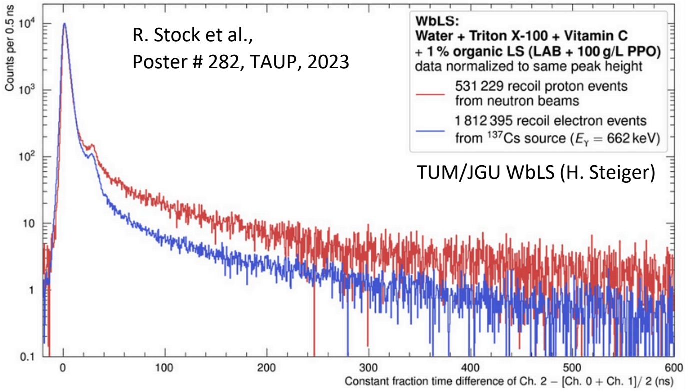
New Detection Media: Water-based liquid scintillators – R&D on the Liter-Scale

Developed Water-based Liquid Scintillator (WbLS) cocktails require extensive characterization:

- Light Yield
- Emission spectrum
- Scintillation time profile
- Scattering and attenuation length
- Nanofiltration ???
- Scintillation PSD demonstration
- Cherenkov/Scintillation separation demonstration

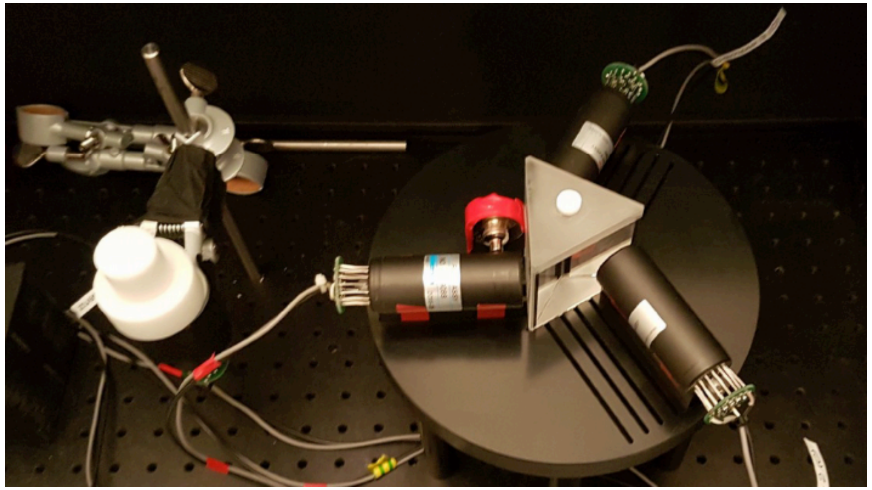


Scintillation Time Profile and PSD Experiment at the INFN-LNL using pulsed neutron beams (TUM, JGU Mainz, UC Berkeley)

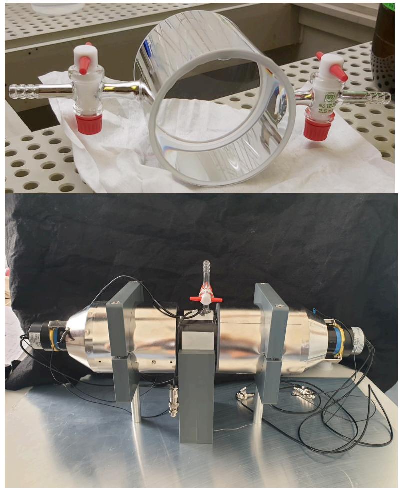


Scintillation Time Profiles of neutrons (red) and gammas (blue)

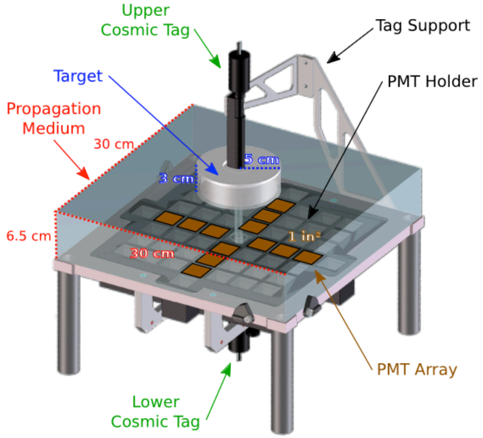
Attenuation Length Measurement Systems ~1% uncertainties up to 50 m @ 430 nm (UC Davis & PALM @ TUM)



SCHLYP: Scintillation/Cherenkov Separation by timing and enhanced with the detector geometry (JGU Mainz, M. Wurm et al.)



Light Yield and Quenching Determination with e^- and p^+ (TUM, JGU Mainz, UC Berkeley)



CHESS: (CHErenkov / Scintillation Separation)

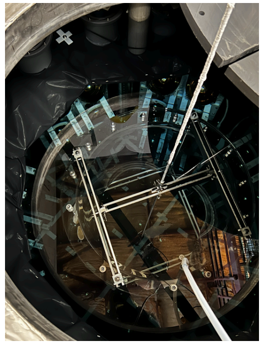
J. Caravaca et al.,
Phys. Rev. C 95, 055801

Scaling up WbLS program: EOS paves the way towards larger detectors

MASS

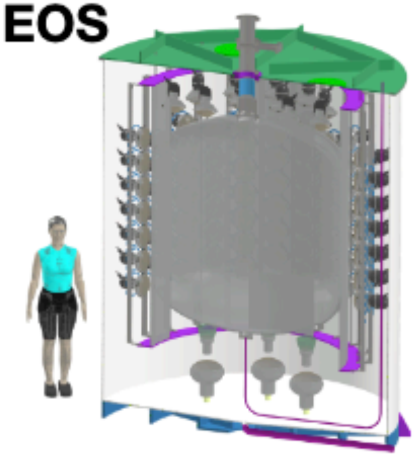
0.5-tonne WbLS volume:
neutrino beam + LAPPDs
~130 photosensors

SANDI @ANNIE



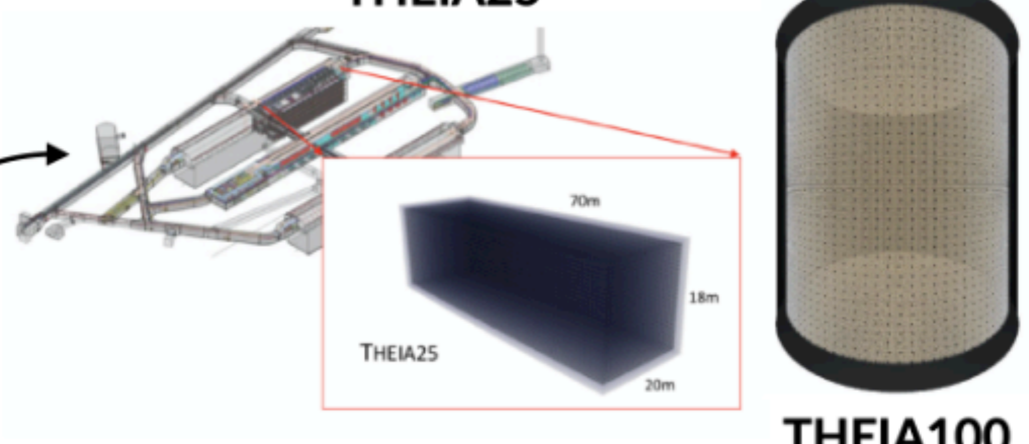
4-tonne hybrid detector:
Cherenkov/Scintillation
~230 photosensors

EOS



25- or 100-ktonne
~10000 photosensors

THEIA25



THEIA100

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

Ultimate application of WbLS to physics use case

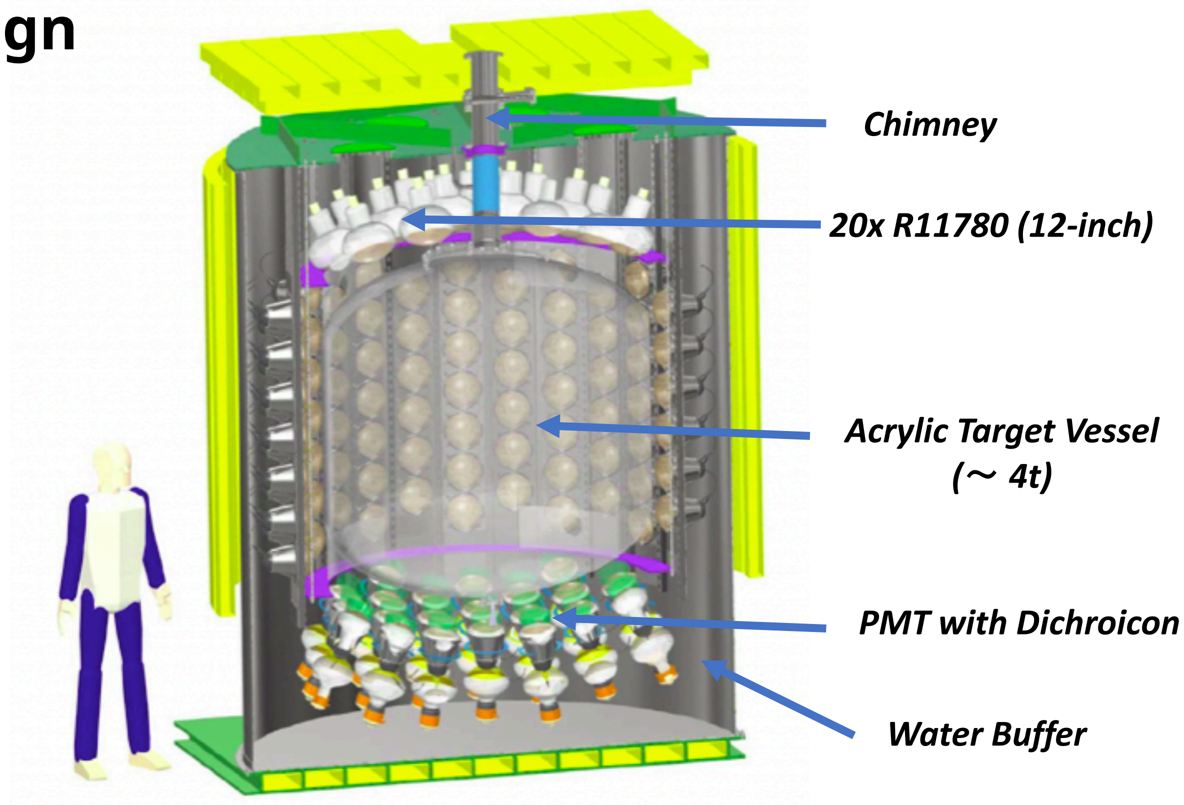
Data Taking

2022-2023 | 2024 | 20xx | TIME

EOS Design

Flexible testbed for hybrid detector technology:

- Novel target media
- Fast-timing, high QE PMTs
- Spectral sorting
- Novel readout solutions
- Advanced reconstruction algorithms



Timeline:

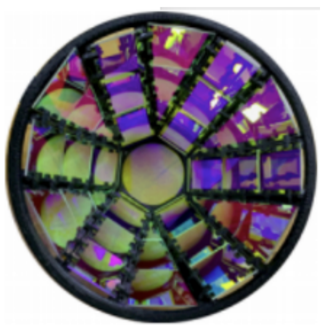
2022: Design optimization and purchasing of key equipment
2023: Construction, PMTs deployment
2024: Filling & data-taking with deployed radioactive sources

Some design features:

- 200x ultra fast 8-inch super-bialkali PMTs
- Hamamatsu R14688 (TTS: ∼ 900-1000 ps)
- 20x HQE PMT 12-inch Hamamtsu R11780
- PMTs with Dichroicons on bottom of the detector
- ps-laser light source for timing calibration
- Digitizer: CAEN V1730 14bit, 500MS/s flash ADC
- Liquid Handling System: Compatible with both WbLS and slow organic LSs

Hamamatsu R14688

PMT Assembly at LBNL



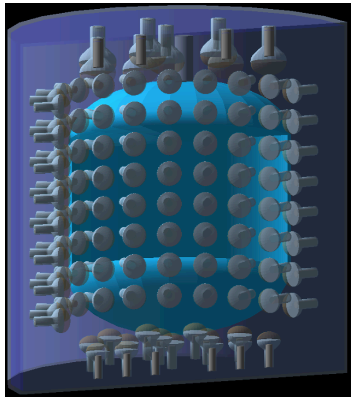
Dichroicon

EOS Status & Goals

Status:

- Dector design completed
- Experimental site (Etchevery Hall in Berkeley) ready
- Most mechanical structure already built
- All 8-inch PMTs delivered → assembly has begun
- Digitizers purchased and tested
- Good progress on the trigger and clock systems
- Muon veto panels tested successfully
- Fully detailed Monte Carlo of the detector was set up using the input from previous table-top setups

EOS Site (Etchevery Hall) Autumn 2022



EOS MC Geoemtry (Spring 2023)

Thanks to Morgan Askins!

Goals 2023-2025:

- Construct a prototype detector large enough to:
  - demonstrate & quantify the improvement afforded by a hybrid detector approach
  - demonstrate performance capabilities of hybrid neutrino detection technology
- Validate performance predictions for large detectors via:
  - data-driven demonstration of low-energy β/γ event reconstruction
  - comparison of data to model predictions as a function of the Cherenkov/ scintillation ratio
- Perform extensive studies with various calibration sources
- Varying the fraction of LS in a WbLS target cocktail
- Test of alternative target media / mixtures / loadings
- Test alternative photon detectors and readout solutions
- Prepare for EOS deployment at a neutrino beam or reactor site
- Test components for deployment at future detectors

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Thank you for your attention!

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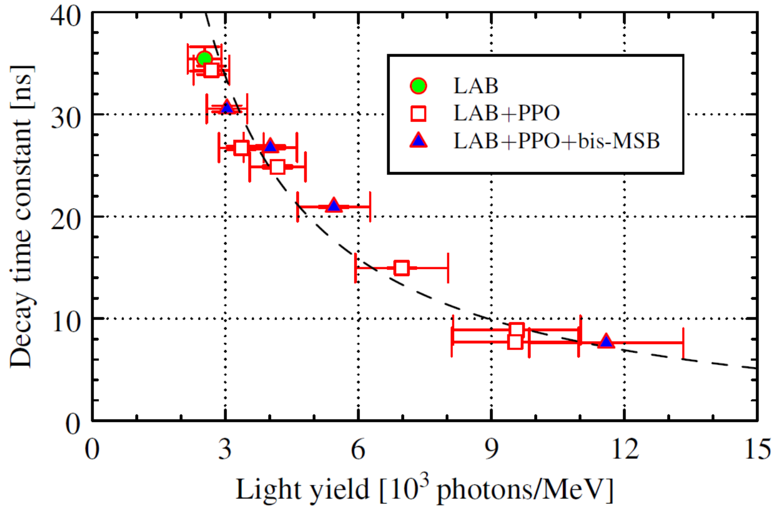
Backup Slides

Cherenkov and Scintillation Light Separation: How to get the organic LS slow?

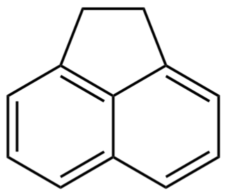
Three ways to get the scintillation emission slow:

- **Lower the fluor concentration**
  [Guo, Z. et al. – arXiv:1708.07781]
  - Low light yields
  - Limited PSD capabilities
  - Excellent transparency in case of LAB

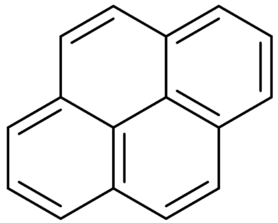


LAB/PPO-mixtures: Low PPO concentration leads to low LYs and no PSD!

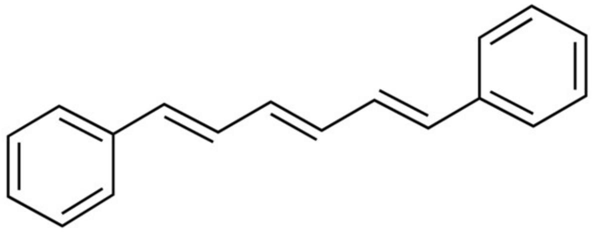
- **Slow fluors**
  [Biller, S. et al. – arXiv:2001.10825]
  - Expensive substances
  - Toxic or cancerogenic compounds?
  - Slow scintillation comes often at the cost of losses in LY
  - Often emission wavelength maximum deep in the UV-region!
  - PSD not demonstated!



Acenaphthene ($C_{12}H_{10}$)



Pyrene ($C_{16}H_{10}$)



1,6-Diphenyl-1,3,5-hexatriene (DPH, $C_{18}H_{16}$)

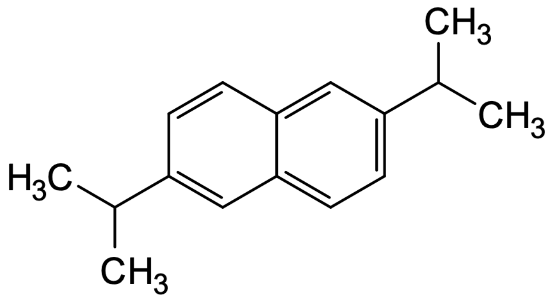
- **Blended or multi-solvent cocktails**
  [Steiger, Hans Th. J. et al. – in prep., for JINST, 2023]
  - LY typically: 10^4 Ph./MeV, $\tau_1 = 12$– 30 ns (adjustable)
  - LY and PSD can be enhanced with a carefully balanced selection of solvent and co-solvent
  - Cheap and easy to clean co-solvents

PREPARED FOR SUBMISSION TO JINST

Development of a Bi-solvent Liquid Scintillator with Slow Light Emission

Hans Th. J. Steiger,[a,b,c,1] Matthias Raphael Stock,[c] Manuel Böhles,[a,b] Sarah Braun,[c] Edward J. Callaghan,[d,e] David Dörflinger,[c] Ulrike Fahrendholz,[c] Gabriel D. Orebi Gann,[d,e] T. Kaptanoglu,[d,e] Lennard Kayser,[c] Florian Kübelbäck,[c] Meishu Lu,[c] Lothar Oberauer,[c] Korbinian Stangler,[c] Michael Wurm,[a,b] Dorina Zundel[a,b]

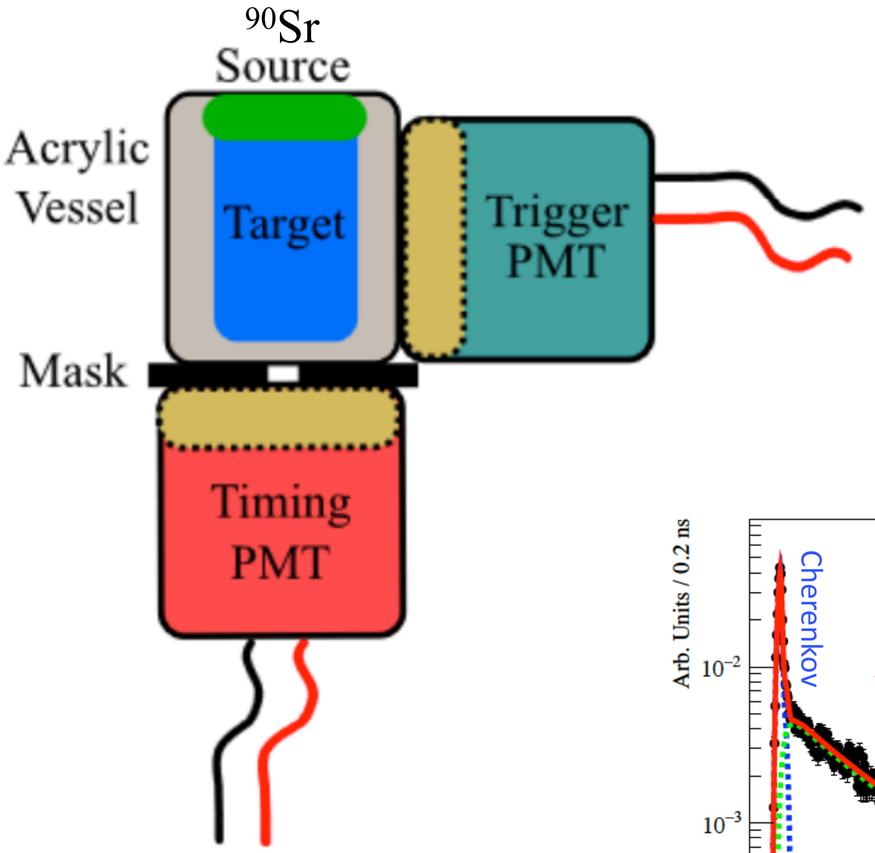
Publication underway → Stay tuned!



2,6-Diisopropylnaphthalene (DIPN, $C_{16}H_{20}$)

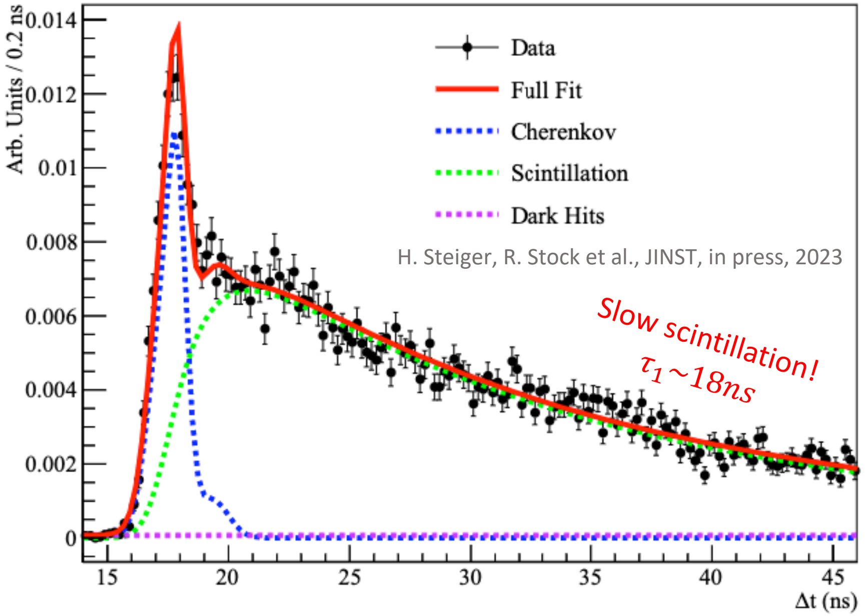
C/S-Separation in organic LS

C/S-Separation Setup at UC-Berkeley (G. Orebi-Gann)



C/S Separation Setup

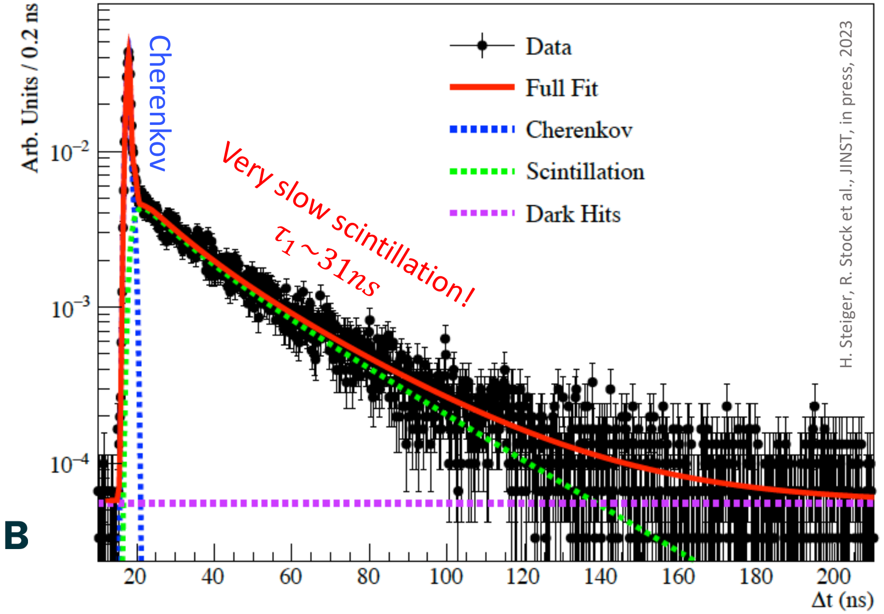
Berkeley UNIVERSITY OF CALIFORNIA   BERKELEY LAB



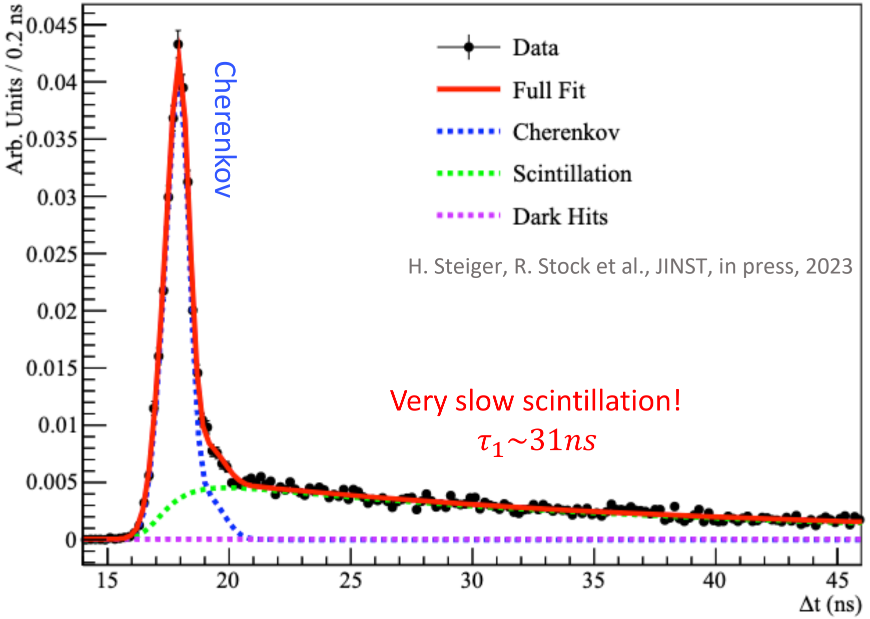
90% LAB + 10% DIN + 1.0 g/l PPO

Next Steps:

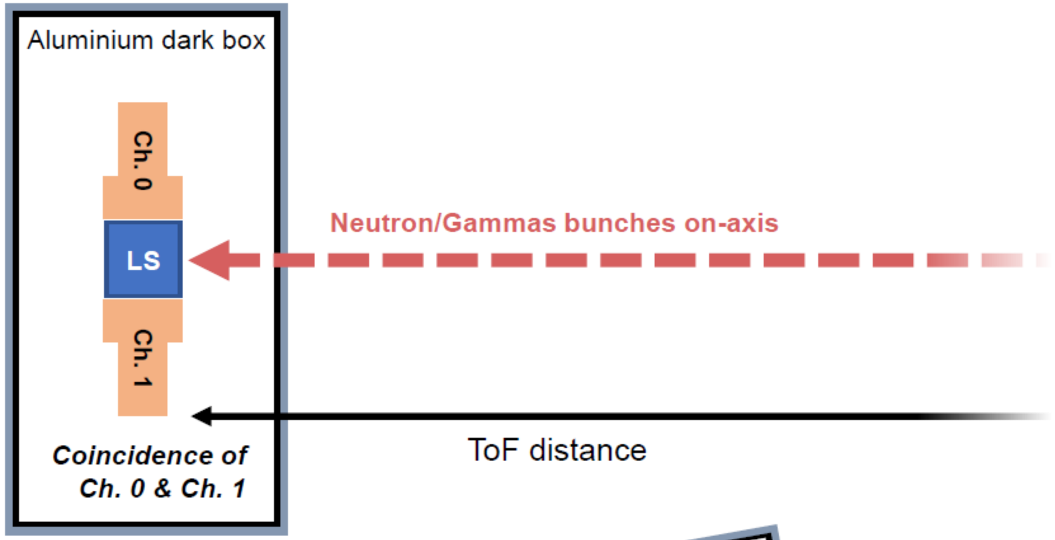
- Build an upgraded setup at TUM
- Measure C/S ratio of the JUNO and TAO mixtures!
- Demonstrator detector (target of some 10-20 liters)
- Simulation studies f

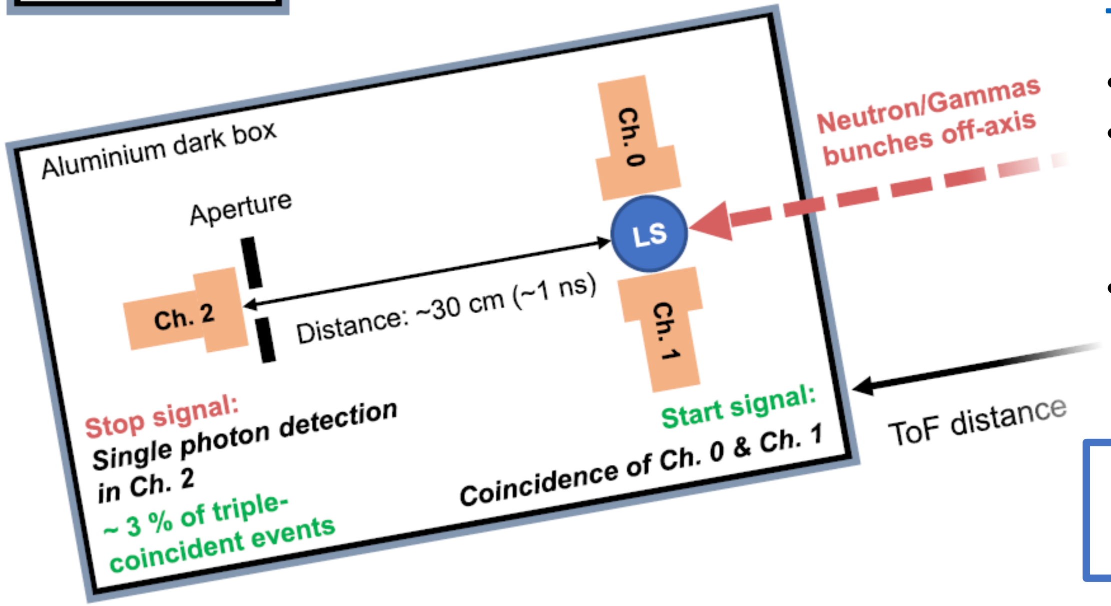


90% LAB + 10% DIN + 0.5 g/l PPO



Pulse Shape Discrimination and p-QF Study for organic, slow and water-based LS

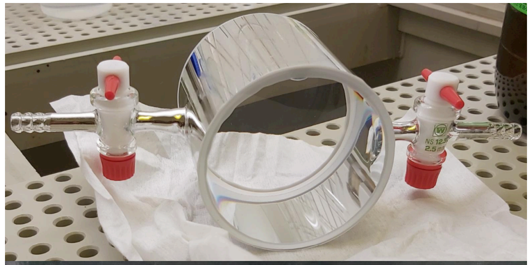


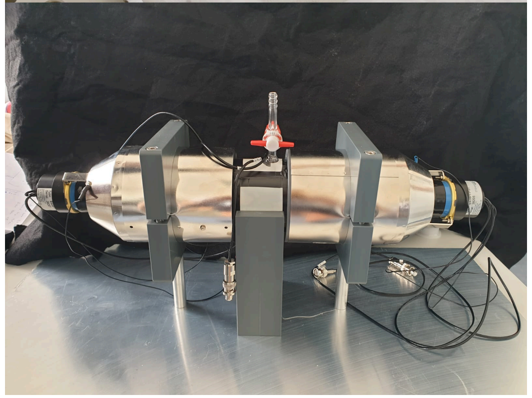


We simultaneously operate two experiments.

Quenching Factor (QF) experiment

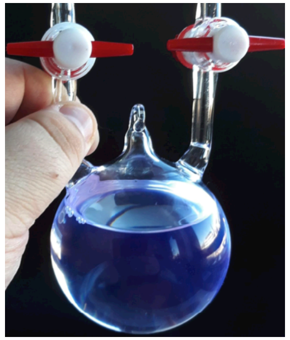
- positioned directly on the beam axis
- detector placed in its own dark box
- target vessel contains ~400 cm^3 of LS
- optimized for low energy threshold with an efficient noise suppression:
  - coincidence of 2 PMTs with the beam trigger
  - vessel walls with highly reflective aluminum mirrors (BX-CTF)





Time Profile Experiment

- Setup is placed in its own dark box.
- The vessel containing ~180 cm^3 LS is placed between two photomultiplier tubes (PMTs)
  - provide the start signal of the time measurement.
- third PMT is placed in a certain distance to ensure the detection of only a single photon from each event!
  - provides the stop signal.



In both experiments we distinguish neutron interactions from beam correlated gammas by time-of-flight (ToF) measurements!

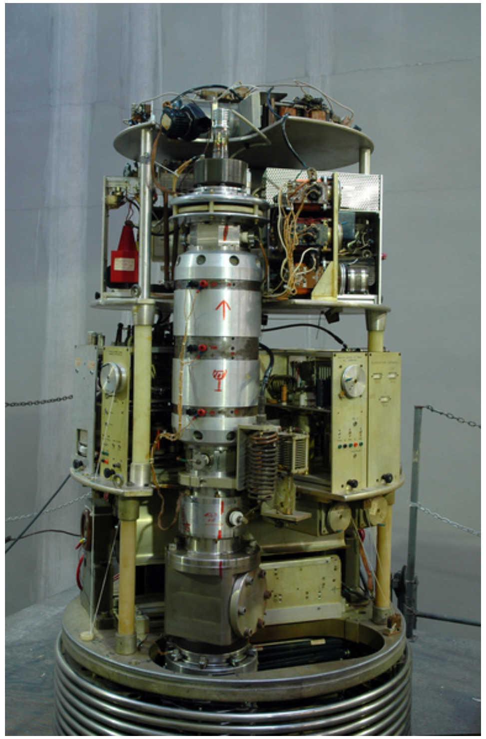
The CN Van de Graaff Particle Accelerator of the INFN-LNL as source of quasi-monoenergetic neutrons

INFN Istituto Nazionale di Fisica Nucleare — Laboratori Nazionali di Legnaro

Aerial view of the LNL with the tower of the CN accelerator

The CN HV Column

CN in operation
(closed pressure vessel)



Ion source and buncher

Proton beam with energies from 3.5 - 5.5 MeV.
(0.8-3 MV requires shorting parts of the accelerating column)

Energy stability: 2-3 keV

Currents: continous up to 3 uA, pulsed: 1 uA at 3 MHz

Pulse width: < 1ns

$$^{7}Li + p \rightarrow \ ^{7}Be + n$$

Nuclear reaction for quasi-monoenergetic neutron production
(Reaction Threshold: 1877 keV)