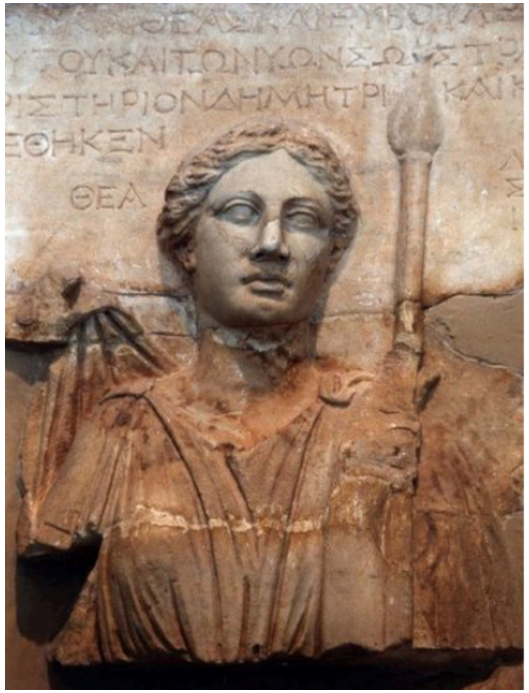
Gefördert durch DFG Deutsche Forschungsgemeinschaft
GEFÖRDERT VOM Bundesministerium für Bildung und Forschung
SFB 1258 Neutrinos Dark Matter Messengers
ORIGINS Excellence Cluster
PRISMA+ JGU
TUM Technische Universität München

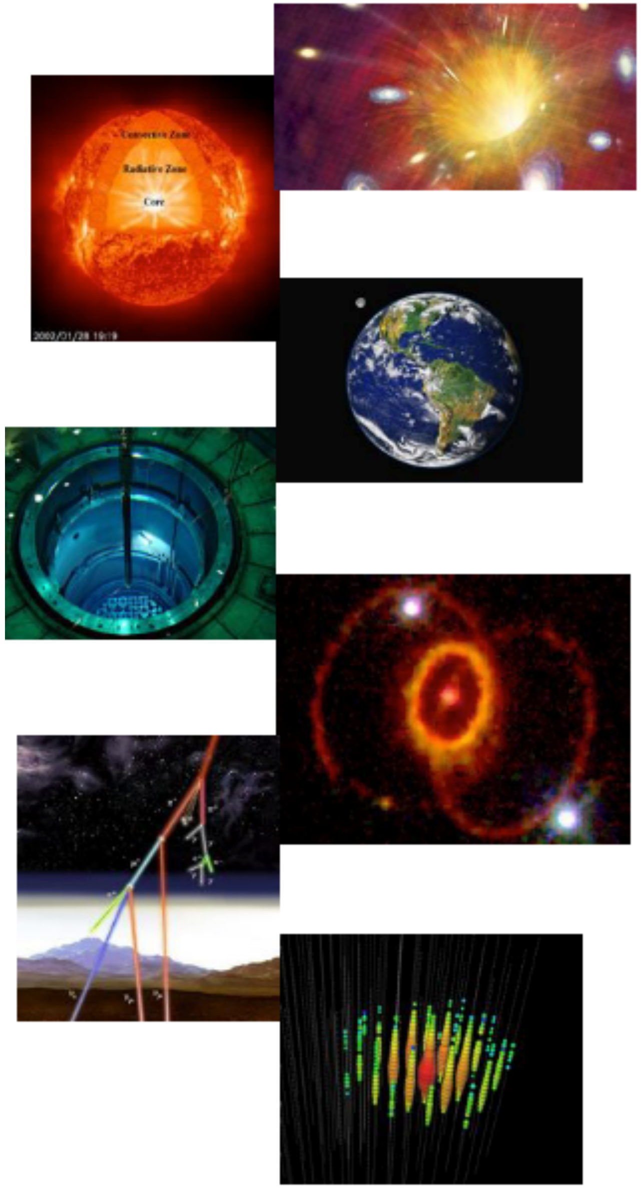
# Theia: The Technology of Advanced Hybrid Neutrino Detection



**Hans Th. J. Steiger**[1, 2]
**on behalf of the THEIA pre-Collaboration and the EOS and ANNIE Collaborations**

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

# Neutrinos as probes or messenger particles in THEIA



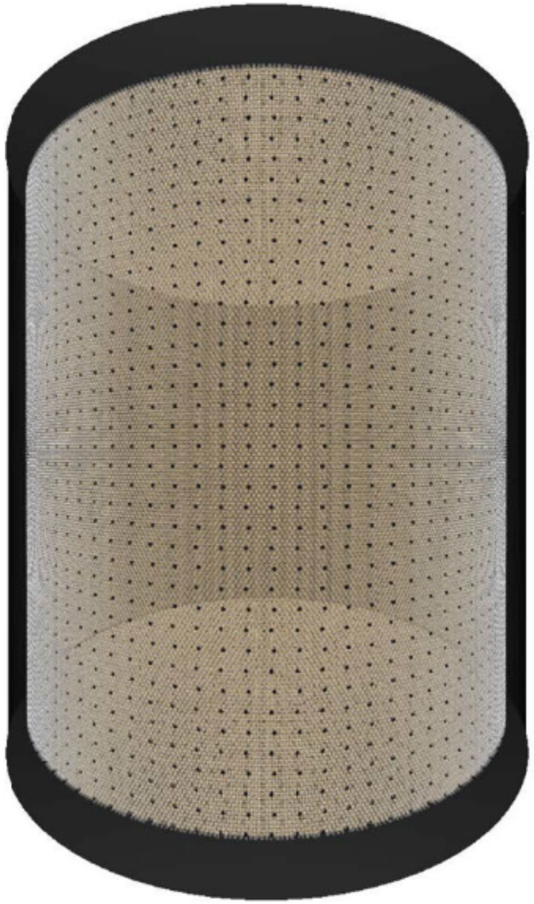

$10^{-4}$ eV

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**

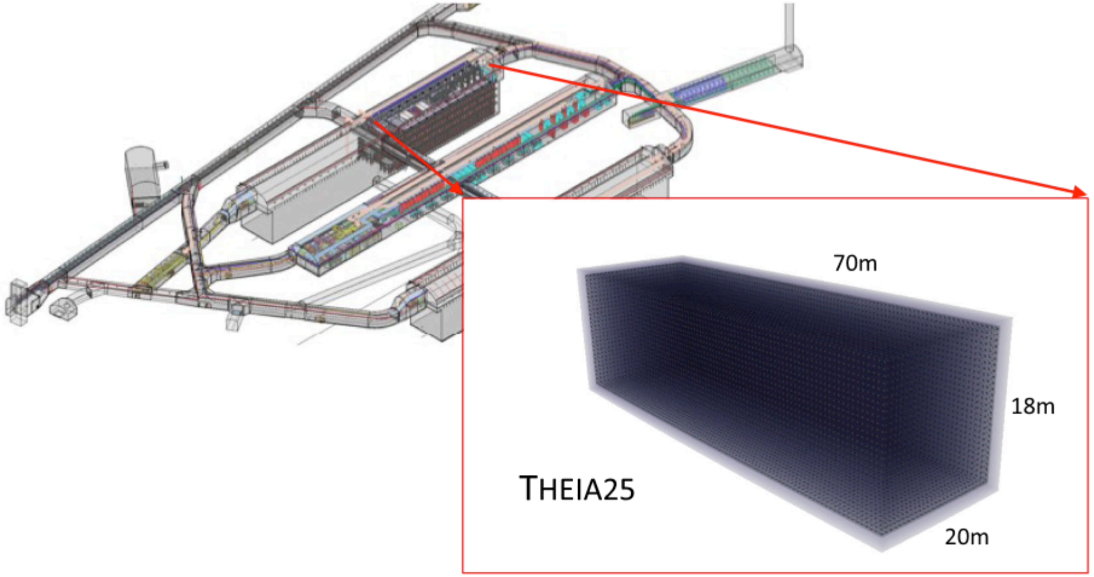
Eur. Phys. J. C (2020) 80:416



**Model of THEIA – 100**

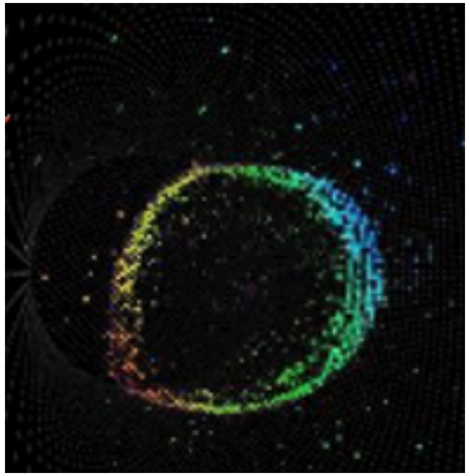
**(86% coverage: standard 10-inch PMTs**
**4% coverage: LAPPDs)**

# Theia: The first advanced optical multipurpose neutrino detector

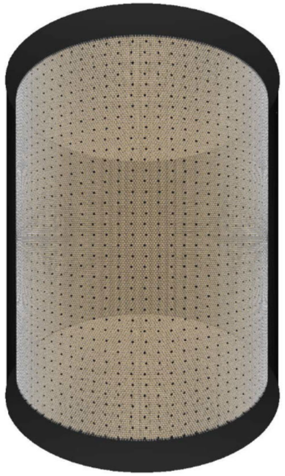



*The best of both worlds…*

**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

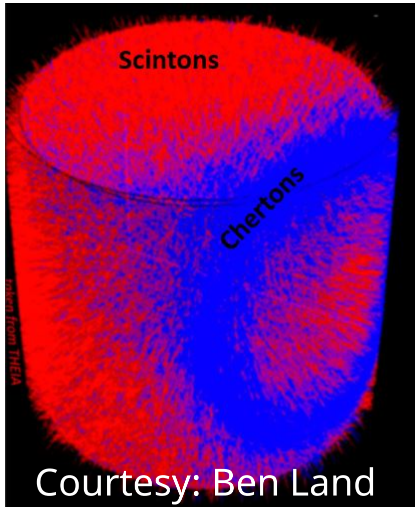


Large scale, multipurpose detector:

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

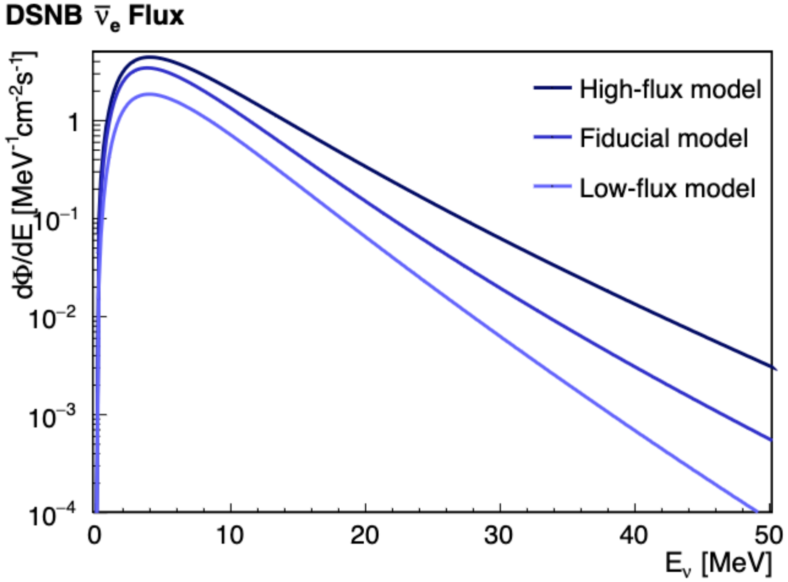
M. Askins, et al., Eur. Phys. J. C 80 (2020) 5, 416, arXiv:1911.03501

**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

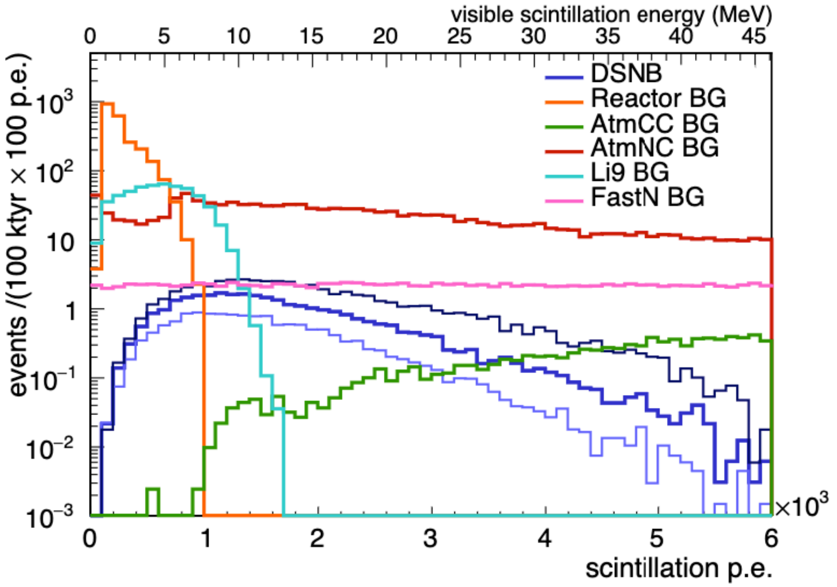



Simulation of the C/S-Light in a THEIA-like scenario

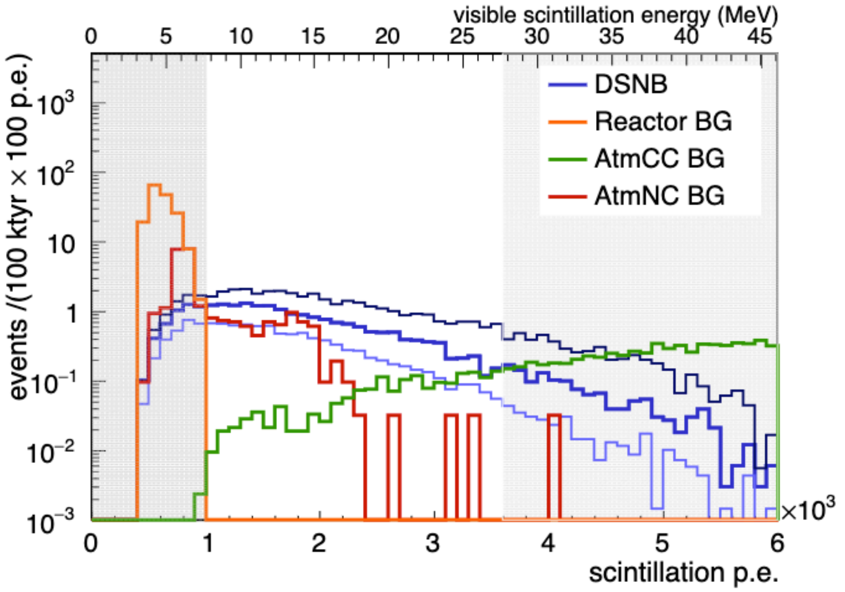
# Theia: The first advanced optical multipurpose neutrino detector
# An Example: DSNB Detection




*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

MAX PLANCK INSTITUTE FOR ASTROPHYSICS

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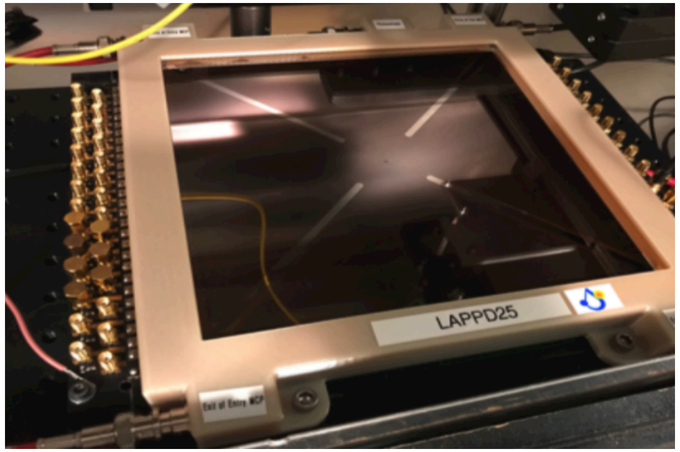
PRISMA+

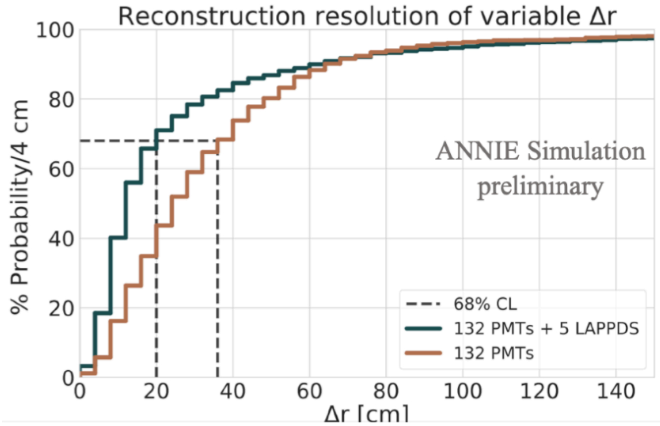
# New Photosensor Development

**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***

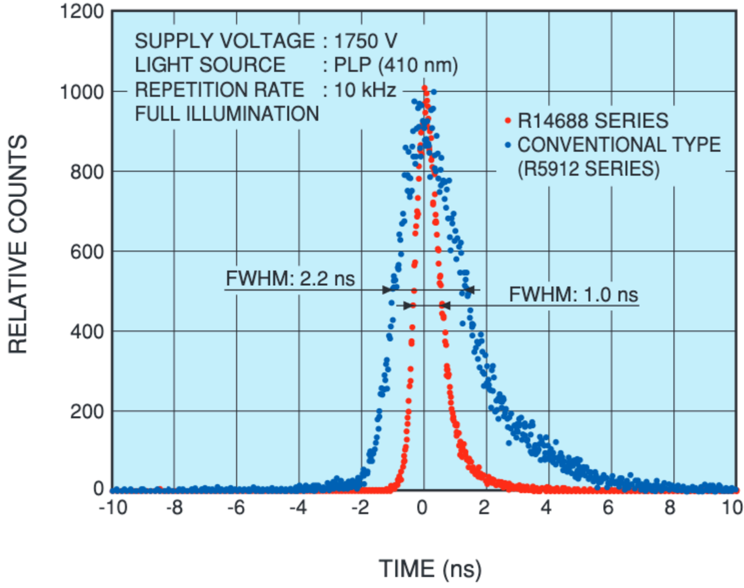



**Fast and large Super-Bialkali PMTs:**

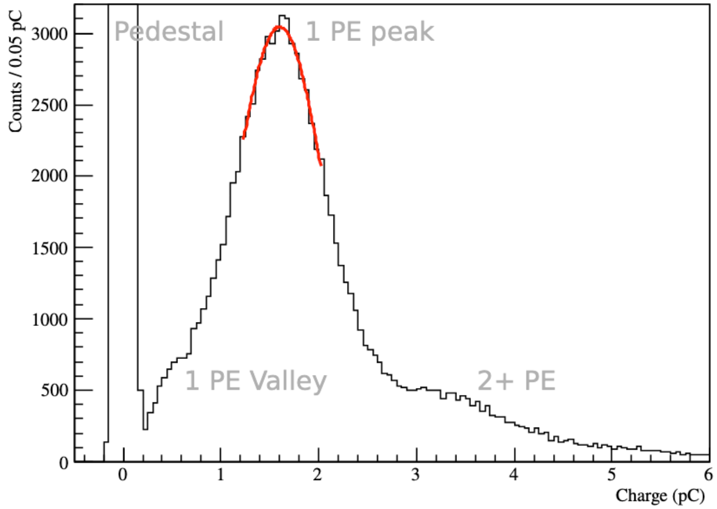
- Example: Hamamatsu R14688-100
- Size: 8-inch
- Gain: >$10^7$
- TTS: ∼ 900ps-1000ps
- Low Dark-Rate: ∼ 4 kHz
- Quantum Efficiency (QE): > 35 %

Hamamatsu R14688-100

T. Kaptanoglu et al., JINST, **19** P02032, 2024

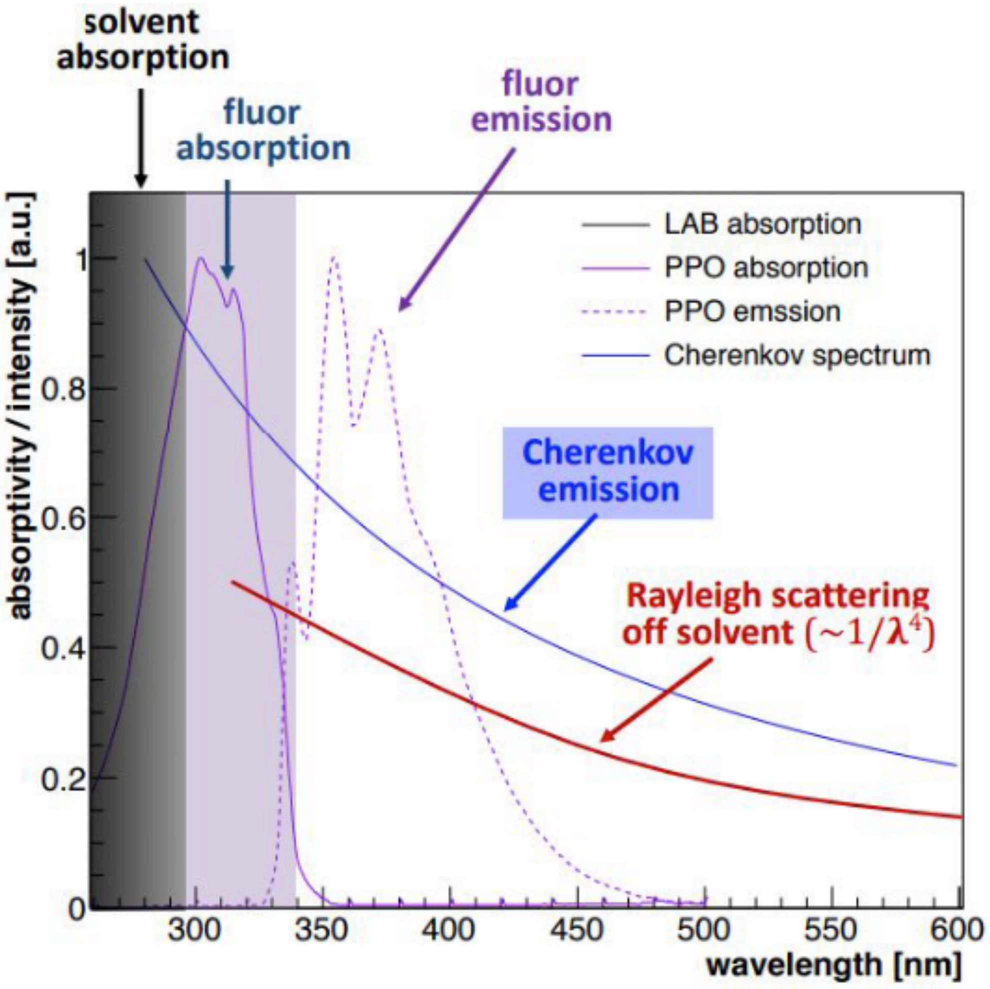



Time Resolution

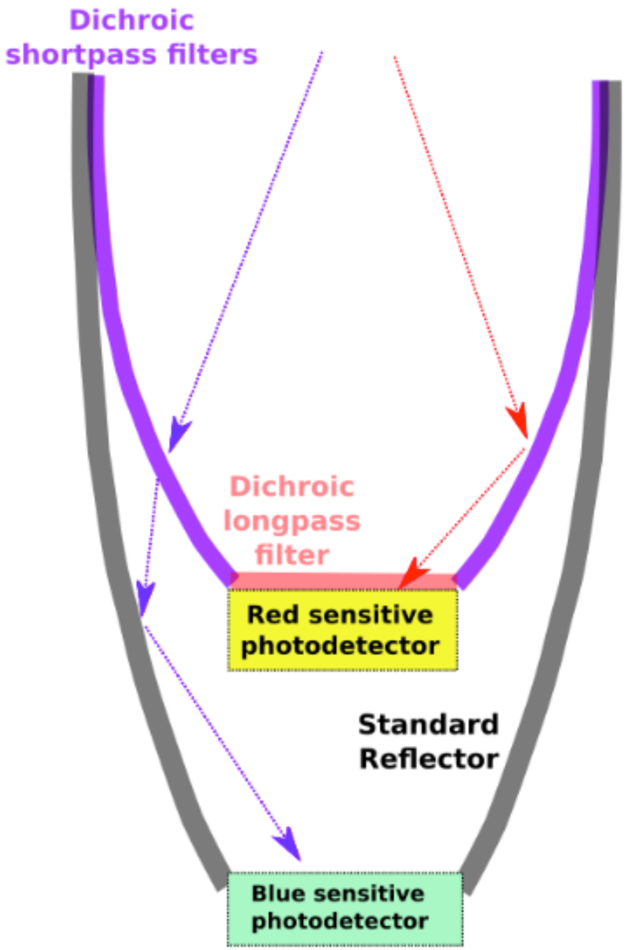



Charge Resolution

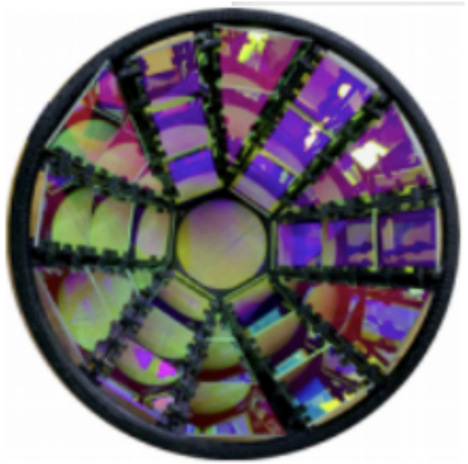
# Chromatic Separation



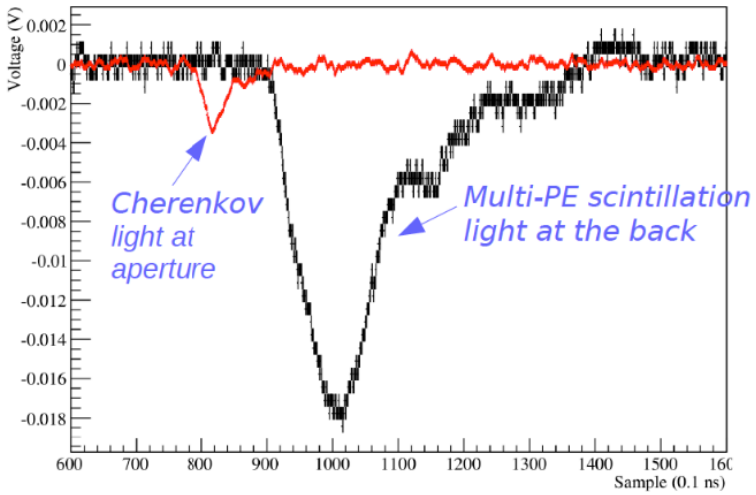

Which part of the Cherenkov spectrum is accessible?




Concept of a Dichroicon



Dichroicon



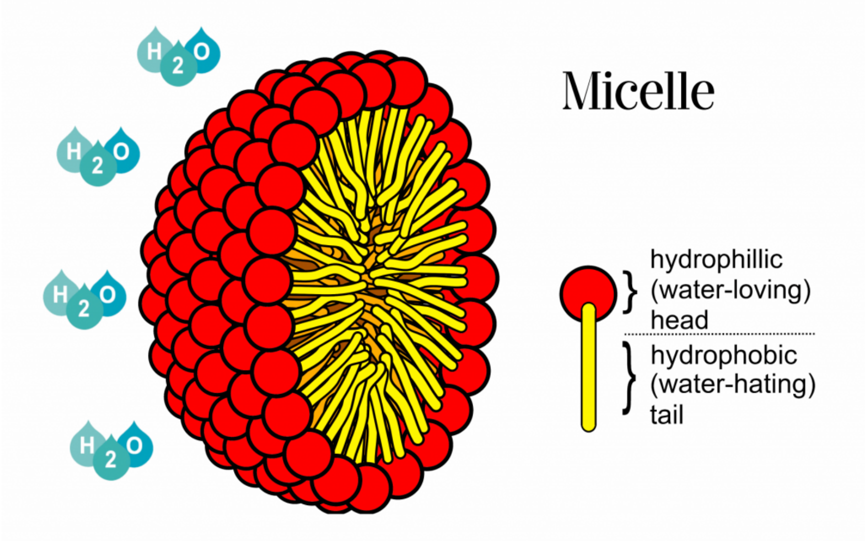

A typical event
(red: Cherenkov, black: scintillation)

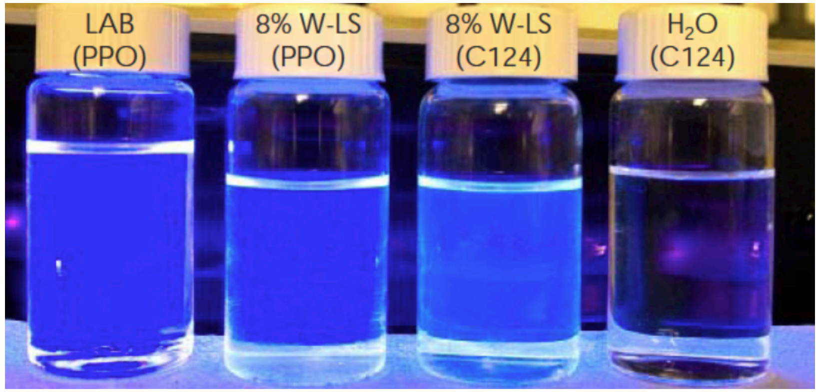
T. Kaptanoglu et al.,
JINST 14 T05001 (2019)

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

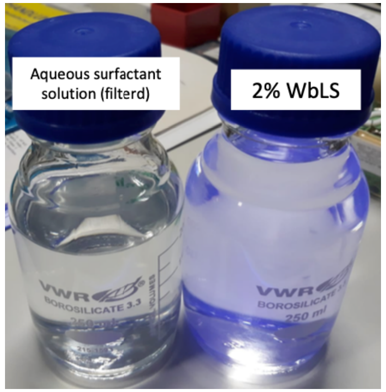
# New Detection Media: Water-based liquid scintillators

- 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+)

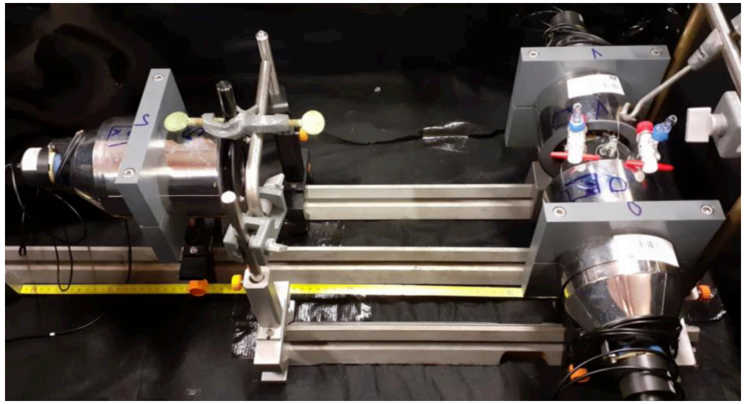
- Successful produced at BNL (M. Yeh) and TUM (H. Steiger)
- BNL already working on production of larger samples (ton-scale)
- Nanofiltration developed at UC Davis (Bob Svoboda et al.)
- Can be loaded with many elements (M. Yeh & H. Steiger)

Ton-scale production facility (BNL)

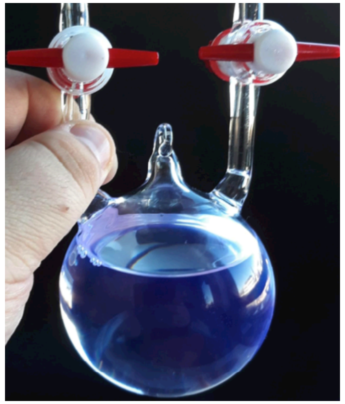
# New Detection Media: Water-based liquid scintillators – R&D on the Liter-Scale

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



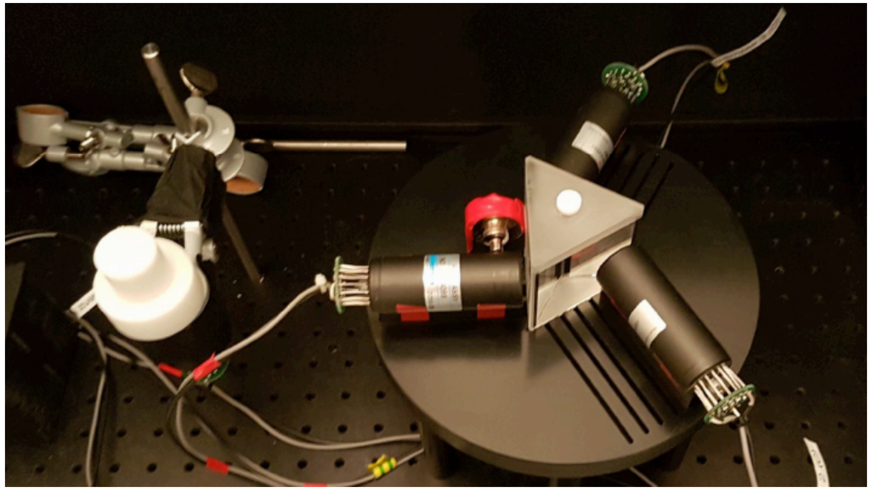
Scintillation Time Profile and PSD-Experiment at the INFN-LNL using pulsed neutron beams (TUM, JGU Mainz, UC Berkeley)



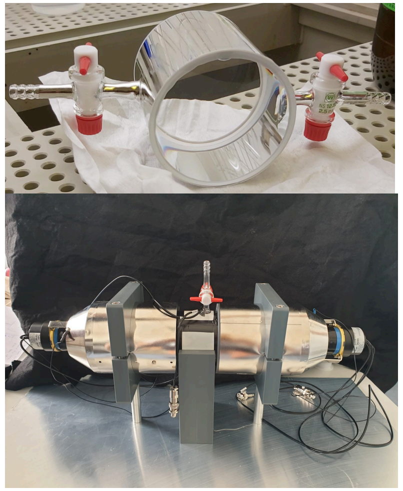
Sphere with Target Medium for the PSD-Experiment



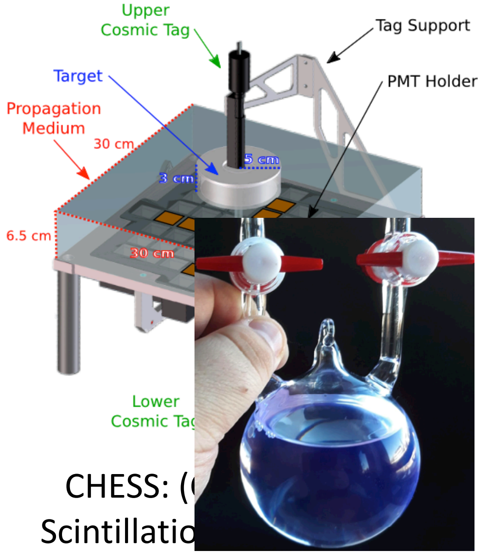
Attenuation Length Measurement Systems
∼1% uncertainties up to 50 m @ 430 nm
(UC Davis & PALM @ TUM)



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)

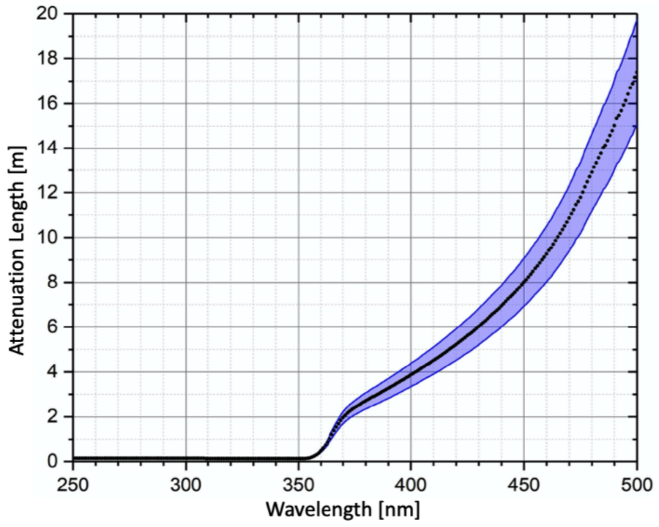



CHESS: (
Scintillatio

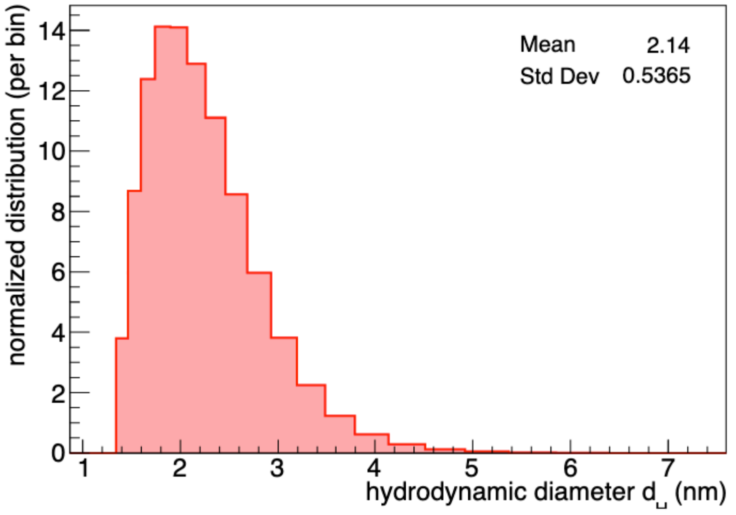
J. Caravaca et al.,
Phys. Rev. C 95, 055801

Hans Th.J. Steiger *et al.*, *JINST* **19** P09008, 2024

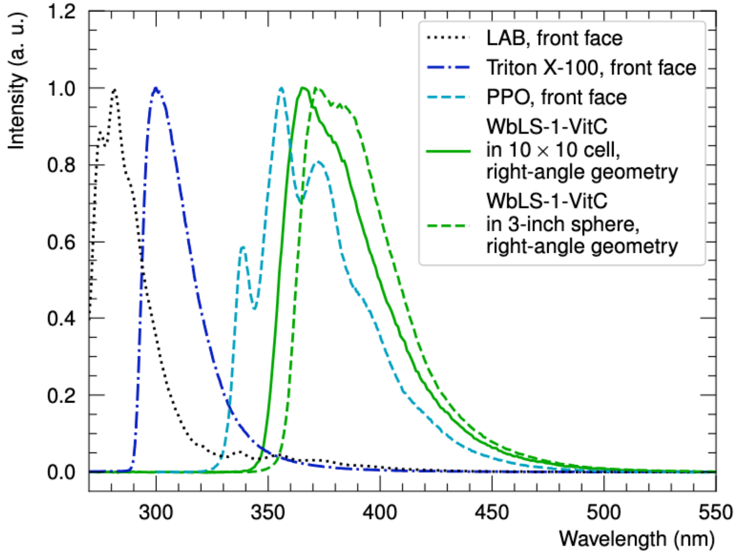
# TUM Water-based Liquid Scintillator: Full Characterization



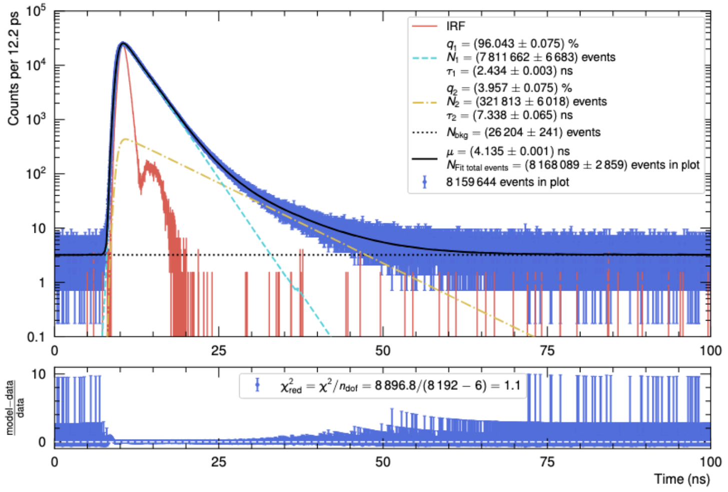

Spectral Attenuation Length of the WbLS



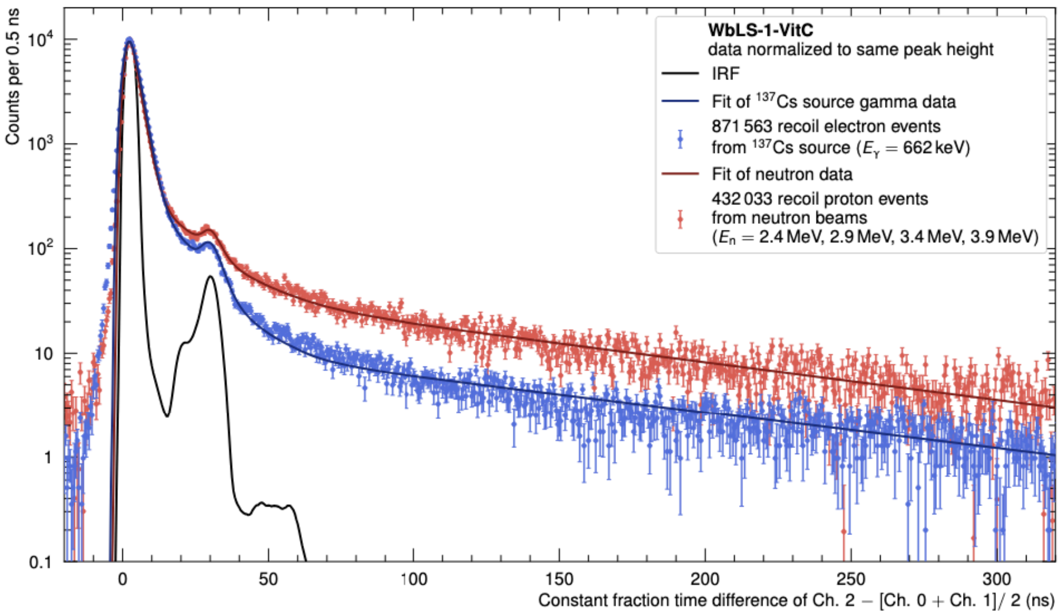

Distribution of hydrodynamic diameters of the micelles




Emission Spectra of WbLS and its Components




| Decay Profile | $\tau_i$ [ns] | $q_i$ [%] |
|---|---|---|
| fast component 1 | 2.434 ± 0.003 | 96.043 ± 0.075 |
| slow component 2 | 7.338 ± 0.065 | 3.957 ± 0.075 |




## Pulse Shape Discrimination

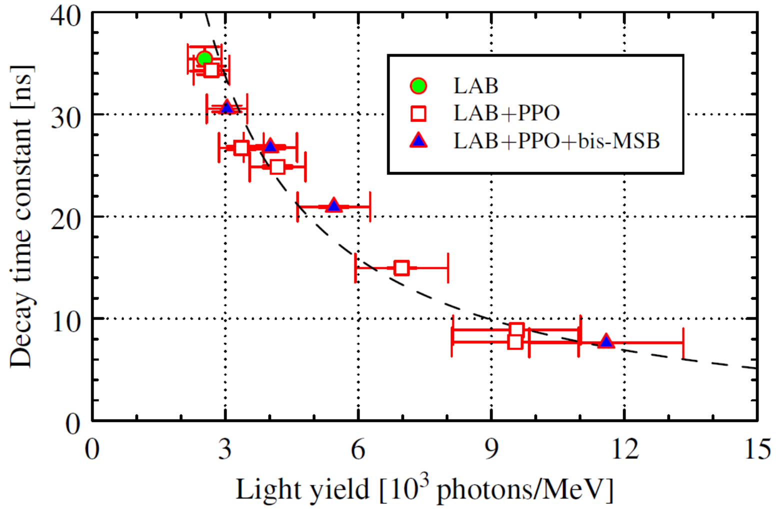
| Source | $e^-$ ($^{137}$Cs source) | p (neutron beams) |
|---|---|---|
| $q_1$ (%) | $88.288 \pm 0.134\,^{+1.071}_{-0.138}$ | $82.312 \pm 0.178\,_{-1.218}$ |
| $q_2$ (%) | $9.216 \pm 0.117\,^{+0.175}_{-1.303}$ | $9.464 \pm 0.117\,^{+0.764}$ |
| $q_3$ (%) | $2.496 \pm 0.033\,^{+0.223}$ | $8.224 \pm 0.100\,^{+0.793}$ |
| $\tau_r$ (ns) | $1.501 \pm 0.016\,^{+0.352}_{-0.277}$ | $0.745 \pm 0.008 \pm\,^{+0.420}_{-0.419}$ |
| $\tau_1$ (ns) | $2.072 \pm 0.021\,^{+0.012}_{-0.047}$ | $2.334 \pm 0.024\,_{-0.262}$ |
| $\tau_2$ (ns) | $10.305 \pm 0.104\,^{+1.140}$ | $14.727 \pm 0.148\,_{-3.008}$ |
| $\tau_3$ (ns) | $125.294 \pm 2.011\,^{+40.689}$ | $122.396 \pm 1.974\,_{-18.003}$ |
| $\tau_{life}$ (ns) | $7.408 \pm 0.072\,^{+1.116}_{-0.311}$ | $14.126 \pm 0.206\,^{+1.064}_{-1.580}$ |

| Sample | Maximal tail-to-total difference $\Delta\mu$ |
|---|---|
| WbLS-1-VitC | 0.070 ± 0.010 |
| LAB + 0.5 g/l PPO | 0.038 ± 0.001 |
| LAB + 1.5 g/l PPO | 0.067 ± 0.001 |
| LAB + 2.0 g/l PPO | 0.106 ± 0.004 |
| PC + 1.5 g/l PPO | 0.166 ± 0.002 |

# Can we have more light or how to get organic LS slow?

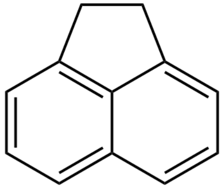
**Three ways to get the scintillation emission slow:**

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

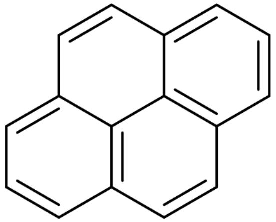



***LAB/PPO-mixtures: Low PPO concentration leads to low LYs and no PSD!***

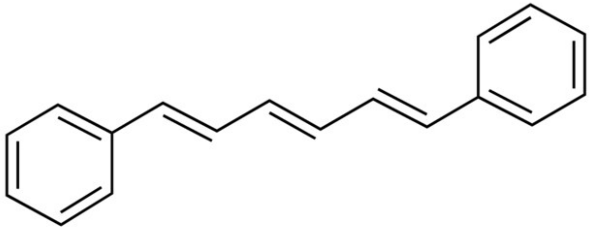
- **Slow fluors**
  [Biller, S. et al. – arXiv:2001.10825]
    - Expensive substances?
    - Toxic or cancerogenic compounds?
    - Slow scintillation comes often at the cost of losses in LY
    - Often emission wavelength maximum deep in the UV-region!
    - PSD not demonstated!



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



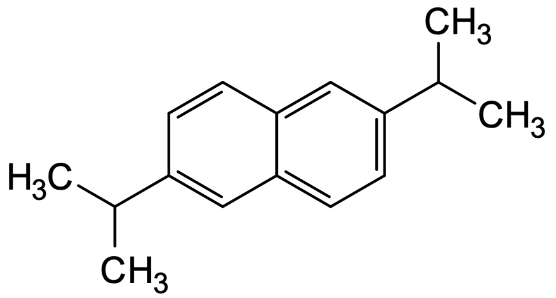
Pyrene ($C_{16}H_{10}$)



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

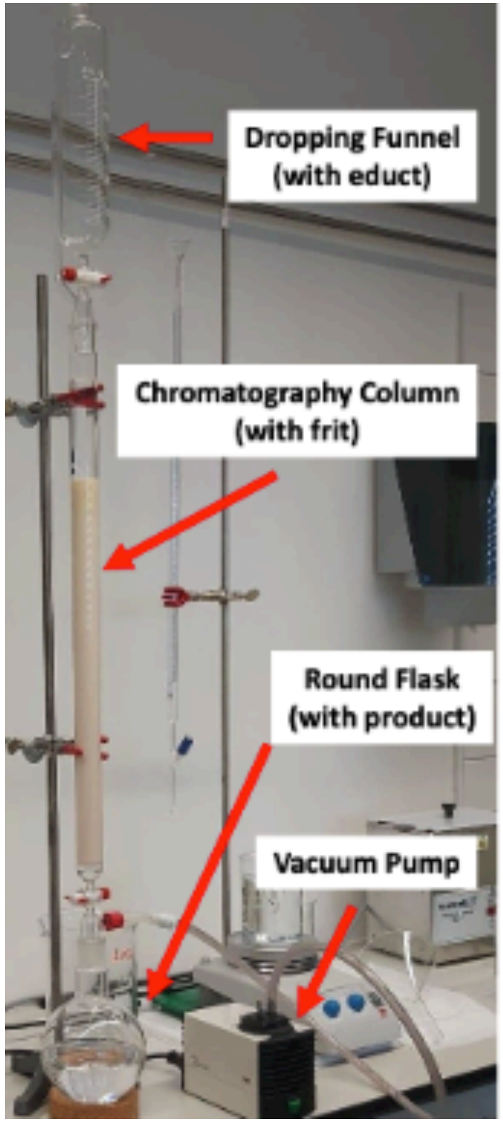
- **Blended or multi-solvent cocktails**
  [Steiger, Hans Th. J. et al. – arXiv:2405.01100, 2024]
    - LY typically: $10^4$ Ph./MeV, $\tau_1 = 12–45$ ns (adjustable)
    - LY and PSD can be enhanced with a carefully balanced selection of solvent and co-solvent
    - Cheap and easy to clean co-solvents

Hans Th.J. Steiger *et al.*, *JINST* **19** P09015, 2024

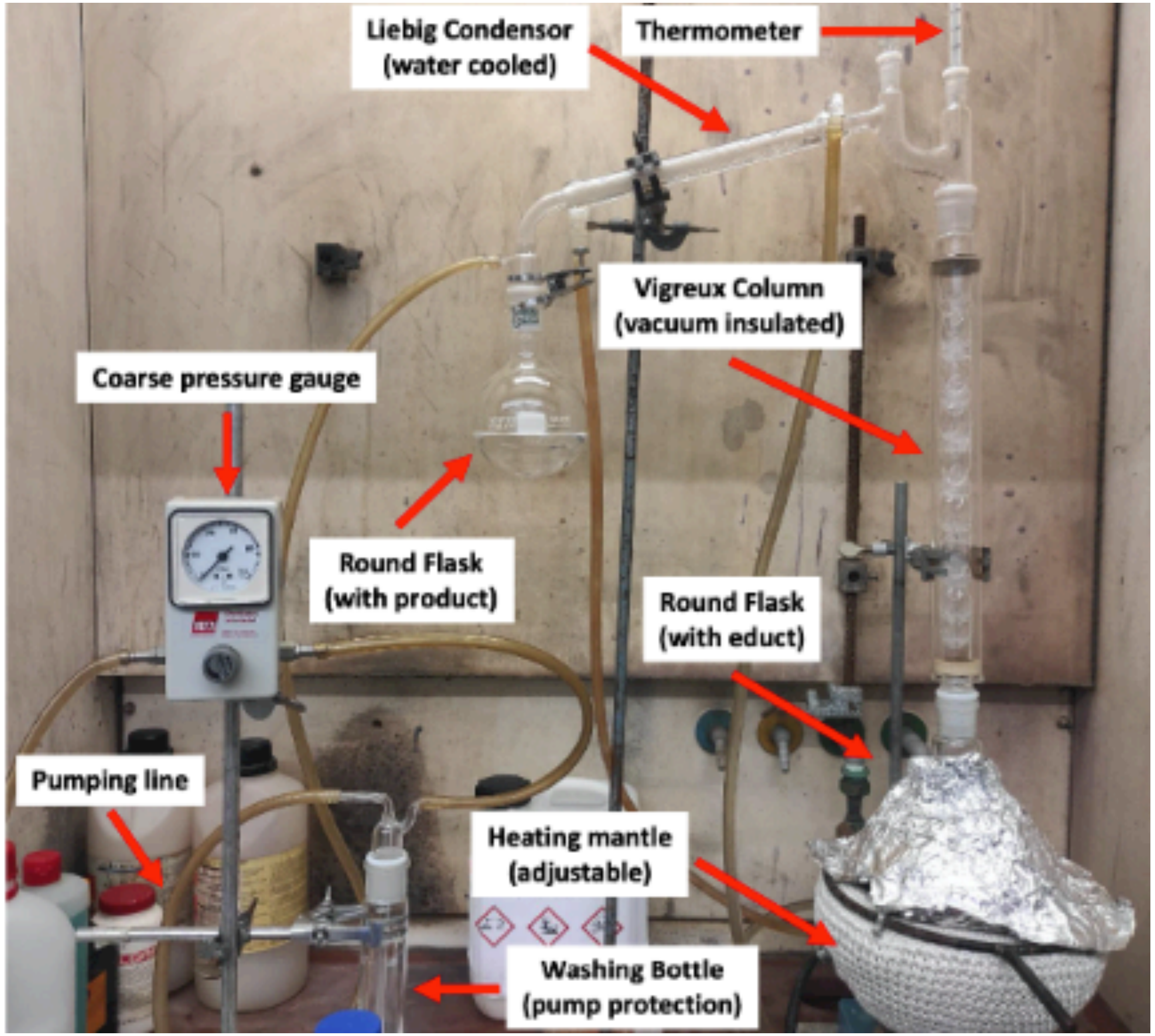



2,6-Diisopropylnaphthalene (DIPN, $C_{16}H_{20}$)

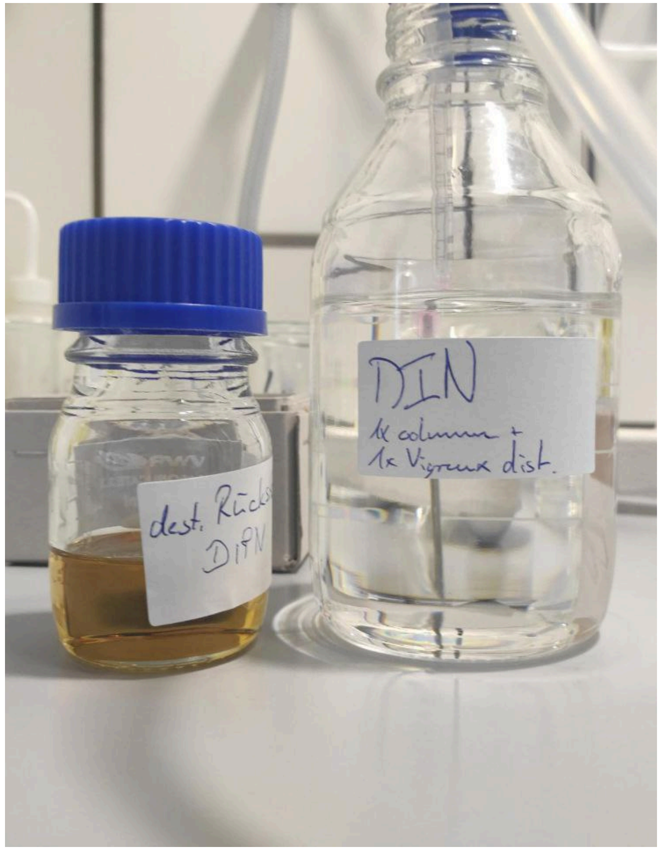
# Purification of DIN (Ruetasolv Di-S)




Long and thin $Al_2O_3$ Colum
(basic alumina of activity Super-I



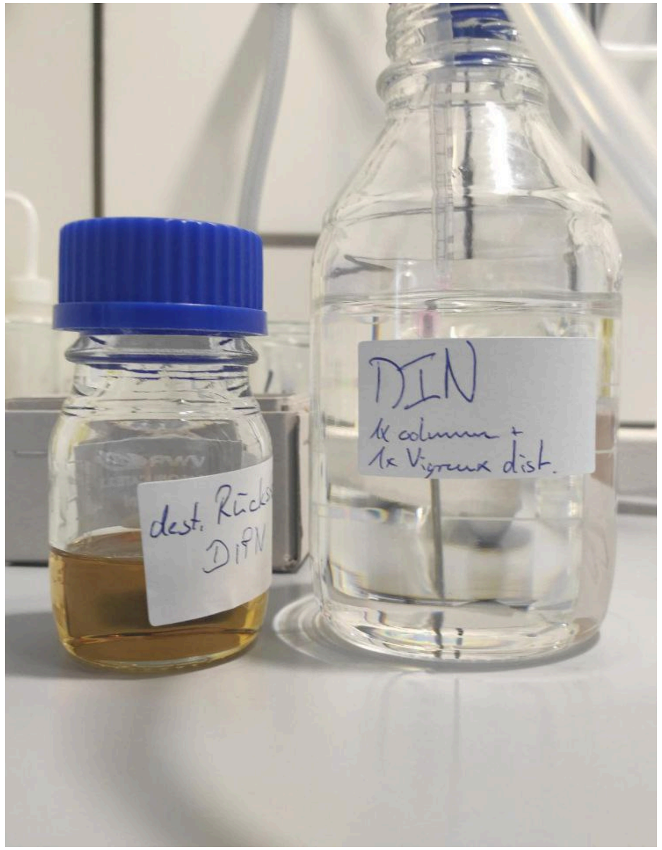

Low temperature vacuum Distillation + Vigreux Column
(product completely cooled down before exposed to air)



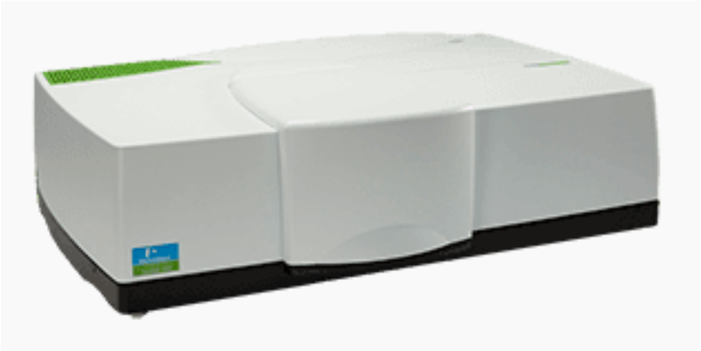

Residue and highly-pure DIN
after Distillation

Additional filtration:
200 nm + 50 nm + 20 nm
(Reduction of scattering!)

# Purification of DIN (Ruetasolv Di-S): What we reached by now

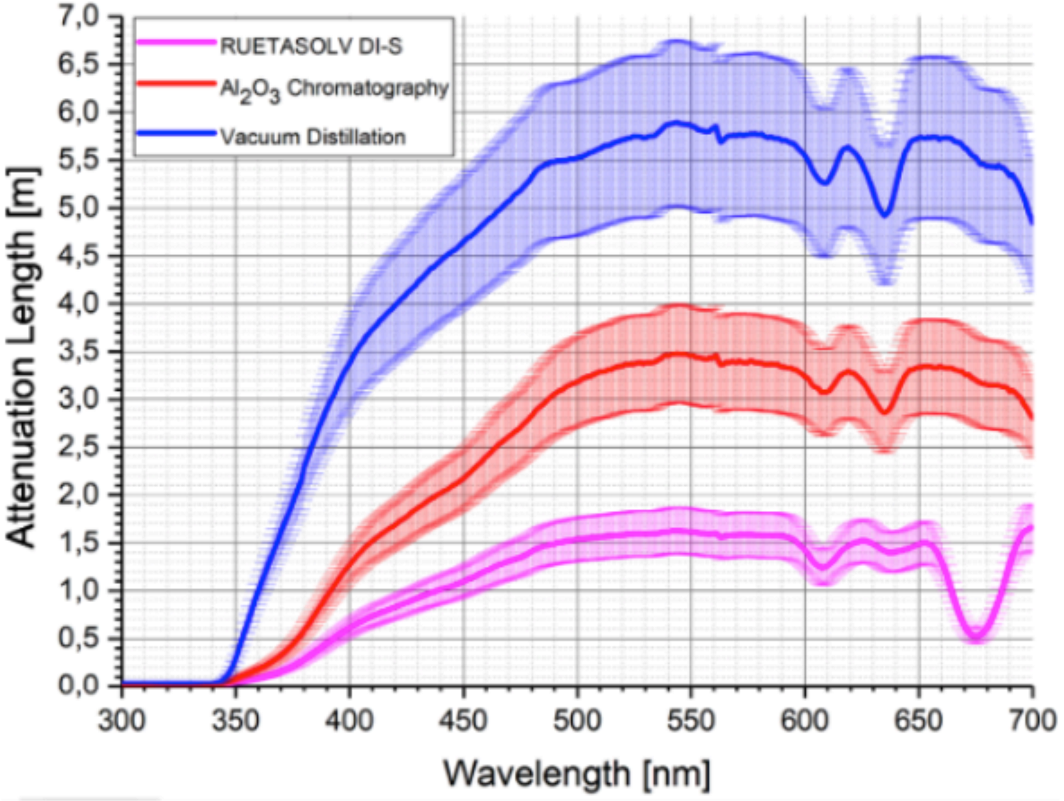



Residue and highly-pure DIN after Distillation



Attenuation Length with UV/Vis-Spectrometer:

- Perkin Elmer Lambda 850+
- 10 cm cuvette
- large uncertainties, scattering, …




Attenuation Length after purification
(Improvement by distillation larger than by alumina column)

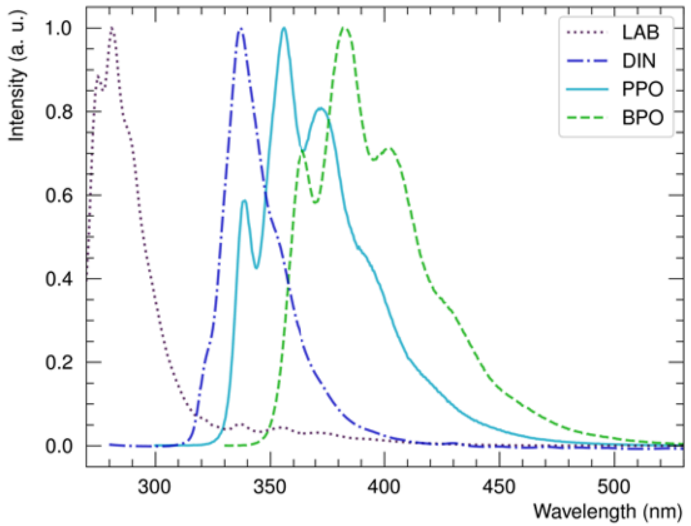
Calculation of the attenuation length of LAB/DIN mixtures with JUNO-LAB (Daya Bay) with measured att. length:
$\Lambda_{LAB}$ (430 nm) = (28.07 ± 2.94) m
(Measurement: S. Franke, PhD Thesis, PALM)

$$\frac{1}{\Lambda} = \sum_i \frac{1}{\Lambda_i}$$

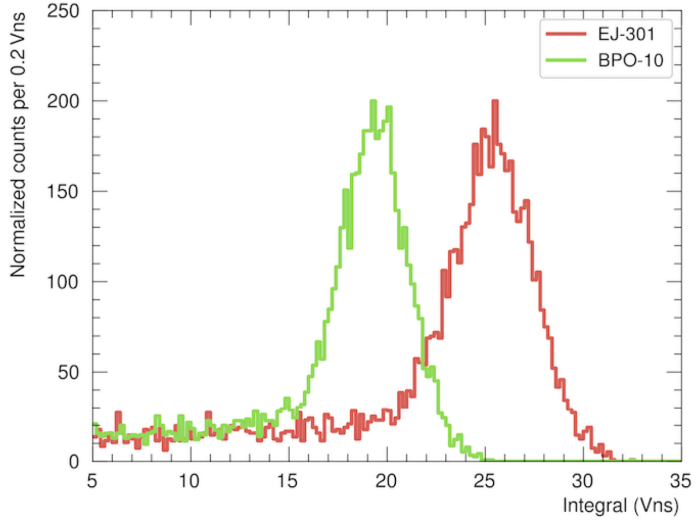
$$\Lambda_{90/10}(430\,\mathrm{nm}) = (17.5 \pm 2.3)\,\mathrm{m}$$
$$\Lambda_{80/20}(430\,\mathrm{nm}) = (13.9 \pm 1.6)\,\mathrm{m}$$

Calculation in agreement with UV/Vis direct measurements: > 13.5 m.

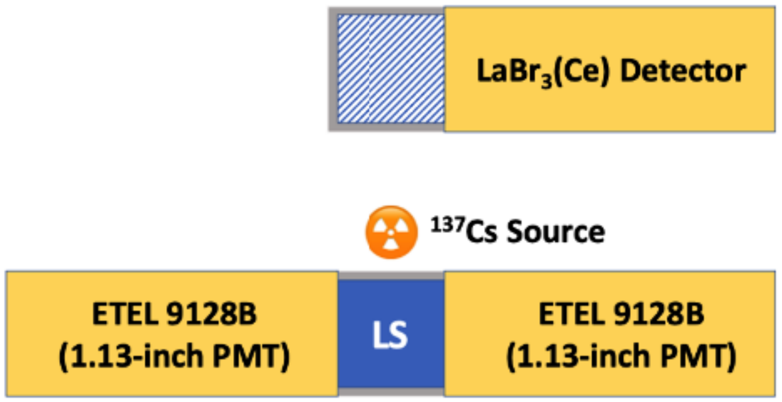
# Selection of Wavelength Shifters – Some Promising Scintillator Samples



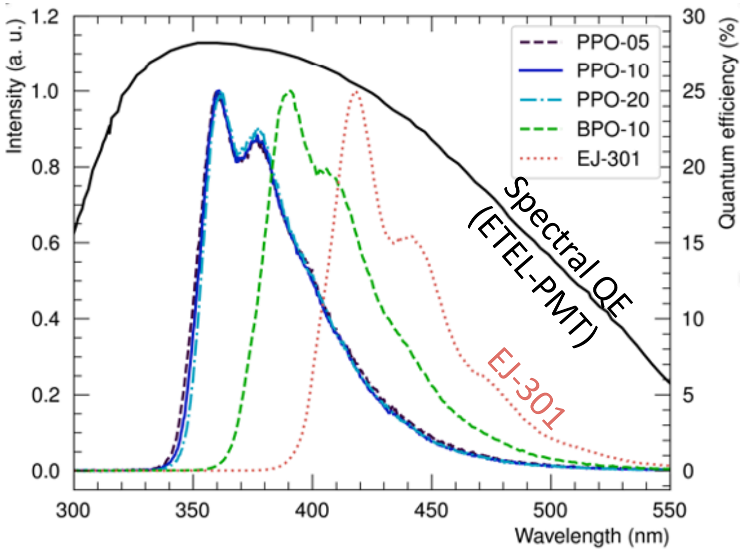

All samples diluted in CHX + Front Face Geometry!



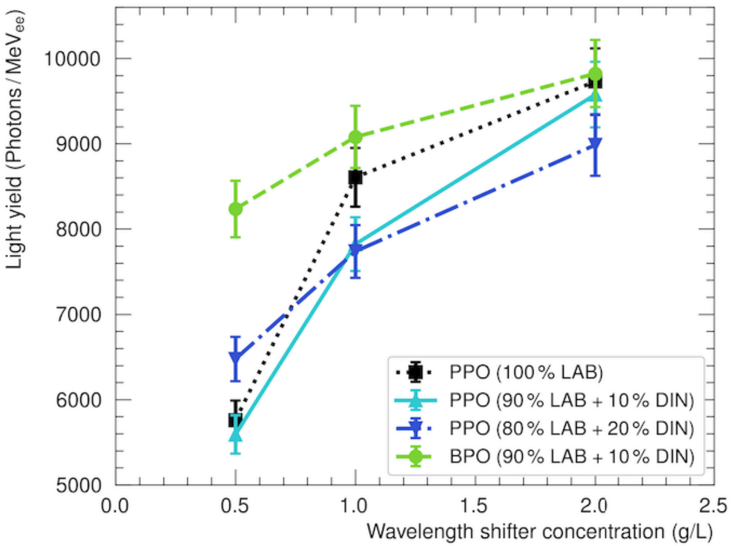

Rel. LY. Determination – Backscatter Method




LY. Setup at JGU and TUM – Backscatter Method




Effective Emission Spectra Scintillation Mixture (undiluted)

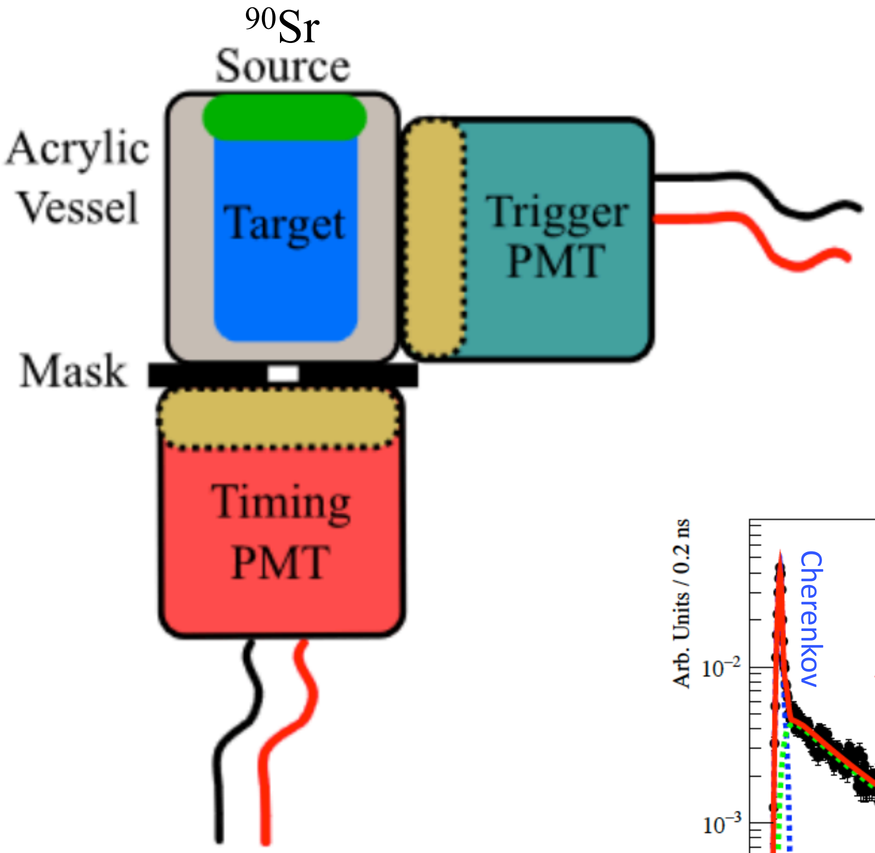



Speactral Corrected:
Usage of BPO leads to very high LY!

| Sample Name | Rel. LY in % | LY [Ph./MeV] |
|---|---|---|
| Anthracene | 100 | 17400 |
| EJ-301 | 78 | 13572 |
| LAB + 0.5 g/l PPO | 39.5 ± 1.6 | 6877 ± 275 |
| LAB + 1.0 g/l PPO | 59.1 ± 2.4 | 10281 ± 412 |
| LAB + 2.0 g/l PPO | 66.8 ± 2.7 | 11622 ± 465 |
| PPO-05 | 38.4 ± 1.6 | 6679 ± 268 |
| PPO-10 | 53.7 ± 2.2 | 9345 ± 374 |
| PPO-20 | 65.7 ± 2.7 | 11440 ± 458 |
| BPO-05 | 53.8 ± 2.2 | 9367 ± 375 |
| BPO-10 | 59.4 ± 2.4 | 10329 ± 414 |
| BPO-20 | 64.2 ± 2.6 | 11173 ± 447 |
| PPO-05-20 | 44.5 ± 1.8 | 7737 ± 310 |
| PPO-10-20 | 53.1 ± 2.2 | 9244 ± 370 |
| PPO-20-20 | 61.7 ± 2.5 | 10735 ± 430 |

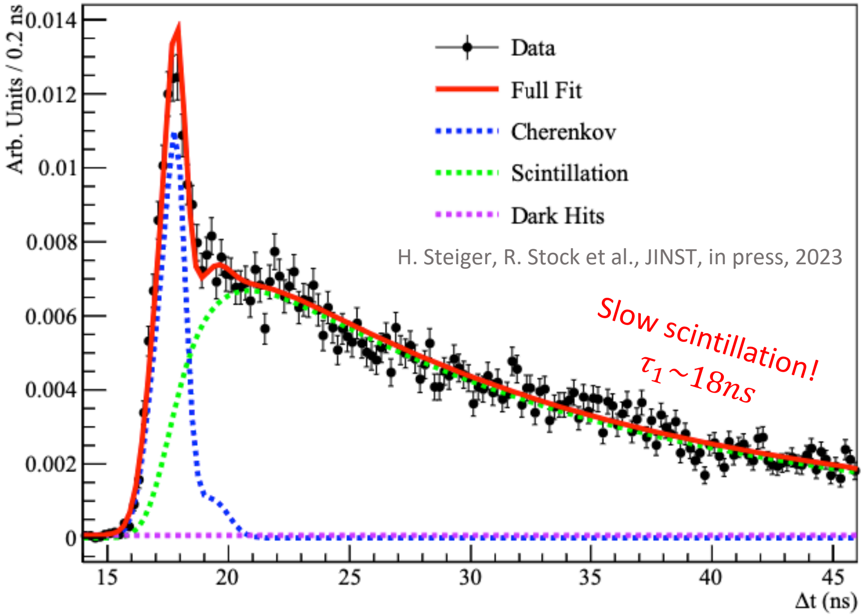
# C/S-Separation in Slow Organic LS

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



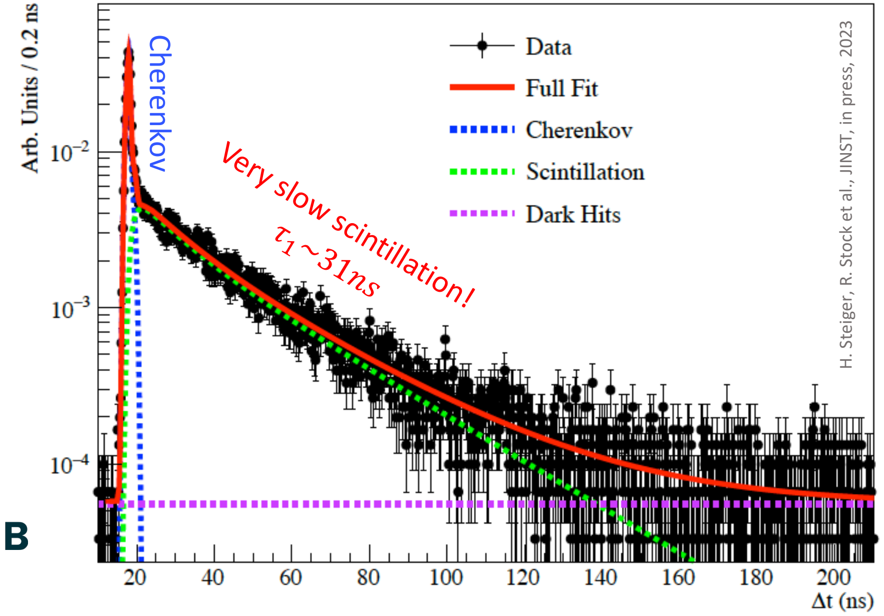

C/S Separation Setup

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

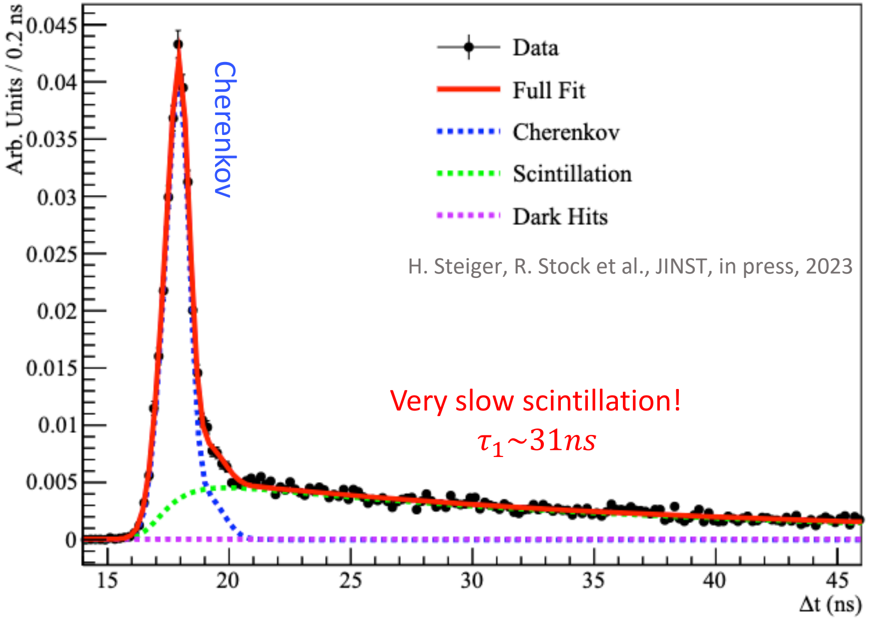



**Next Steps:**

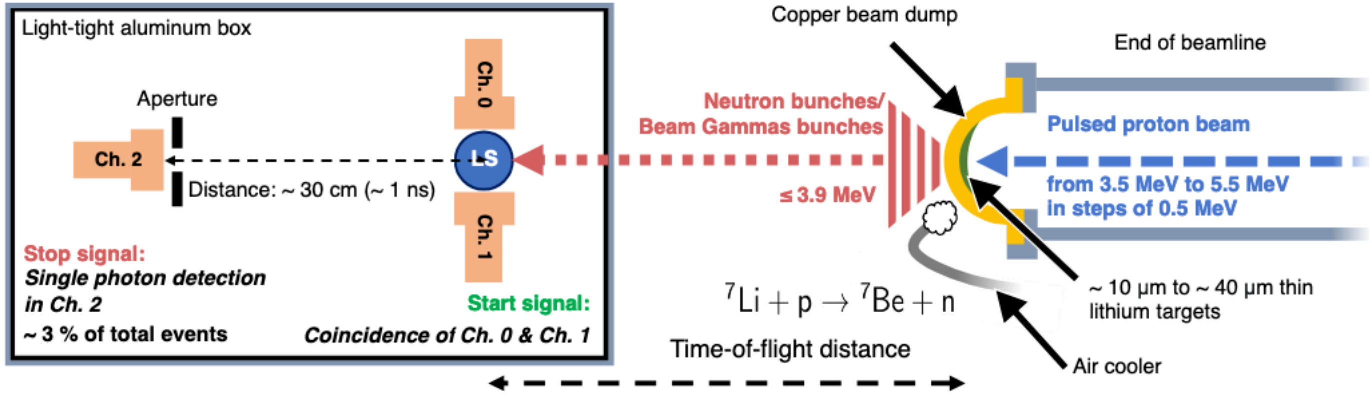
- Measure C/S ratio of the JUNO and TAO mixtures!
- **Demonstrator detector (target of some 20 liters) in cooperation with Alberto Garfagnini et al.!**
- **Joint beamtime at LNL with the demonstartor in Nov. 2024!**
- Simulation studies for an upgraded JUNO-OSIRIS detector with Slow LS!




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



# PSD in Slow Liquid Scintillators (with Pulsed Neutron Beams @ INFN-LNL)

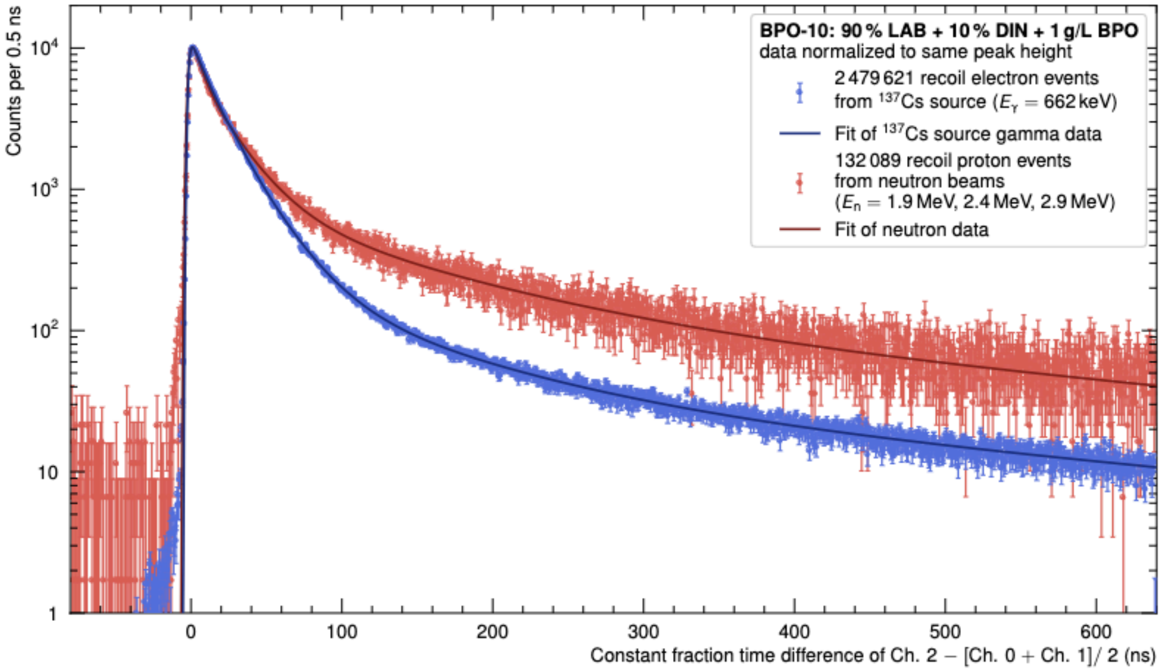



Neutron production at the CN Accelerator:

$$^7Li + p \rightarrow \; ^7Be + n$$

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

Distinguish neutron interactions from beam correlated gammas by time-of-flight (ToF) measurements!
→ very clean neutron sample




PSD exceending the JUNO-LS PSD by far! Similar to Borexino LS!
(even with lower fluor concentrations)

The second and therefore slower component is the dominant one!

The LS can be tuned to be very slow without loss in LY!

Effective Liftime: approx. 60 ns!

| Sample | PPO-05 | |
|---|---|---|
| Source | $e^-$ | p |
| $A_1$ (%) | $18.66 \pm 0.20_{-8.06}$ | $14.20 \pm 1.46^{+2.21}$ |
| $A_2$ (%) | $68.03 \pm 0.26^{+5.06}$ | $48.40 \pm 1.44$ |
| $A_3$ (%) | $7.64 \pm 0.09^{+2.94}$ | $21.46 \pm 1.61$ |
| $A_4$ (%) | $5.67 \pm 0.06_{-0.38}$ | $15.94 \pm 0.87$ |
| $\tau_r$ (ns) | $1.94 \pm 0.02^{+0.42}_{-0.42}$ | $1.37 \pm 0.02^{+0.43}_{-0.43}$ |
| $\tau_1$ (ns) | $17.79 \pm 0.18^{+0.08}_{-4.64}$ | $11.53 \pm 0.63^{+1.03}_{-0.16}$ |
| $\tau_2$ (ns) | $32.40 \pm 0.33_{-2.15}$ | $32.24 \pm 1.21$ |
| $\tau_3$ (ns) | $104.68 \pm 1.05^{+5.82}_{-17.88}$ | $135.00 \pm 19.71$ |
| $\tau_4$ (ns) | $436.13 \pm 7.52^{+55.57}_{-17.70}$ | $732.53 \pm 361.00$ |
| $\tau_{life}$ | $60.03 \pm 0.56^{+4.74}_{-3.27}$ | $164.37 \pm 58.11^{+0.52}_{-0.43}$ |

Full publication about these novel slow organic LSs:

Hans Th.J. Steiger *et al., JINST* **19** P09015, 2024

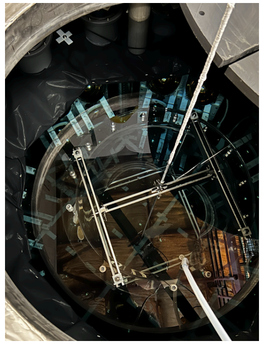
# Theia scaling up program: EOS paves the way towards larger detectors

MASS

annie

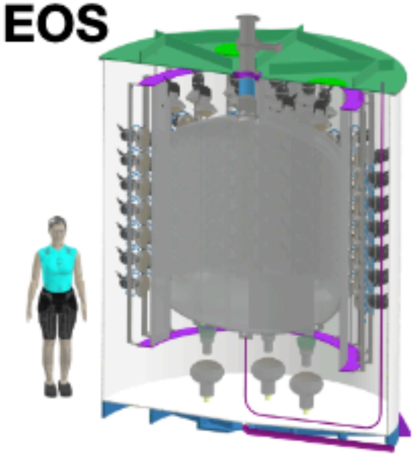
0.5-tonne WbLS volume:
neutrino beam + LAPPDs
~130 photosensors

**SANDI @ANNIE**



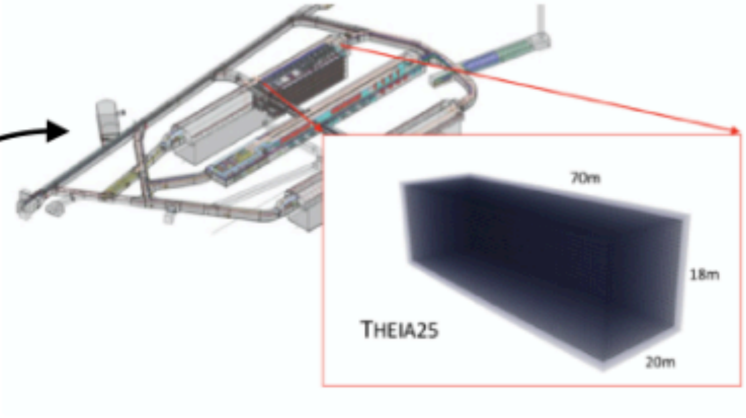
4-tonne hybrid detector:
Cherenkov/Scintillation
~230 photosensors

**EOS**



25- or 100-ktonne
~10000 photosensors

**THEIA25**




**THEIA100**

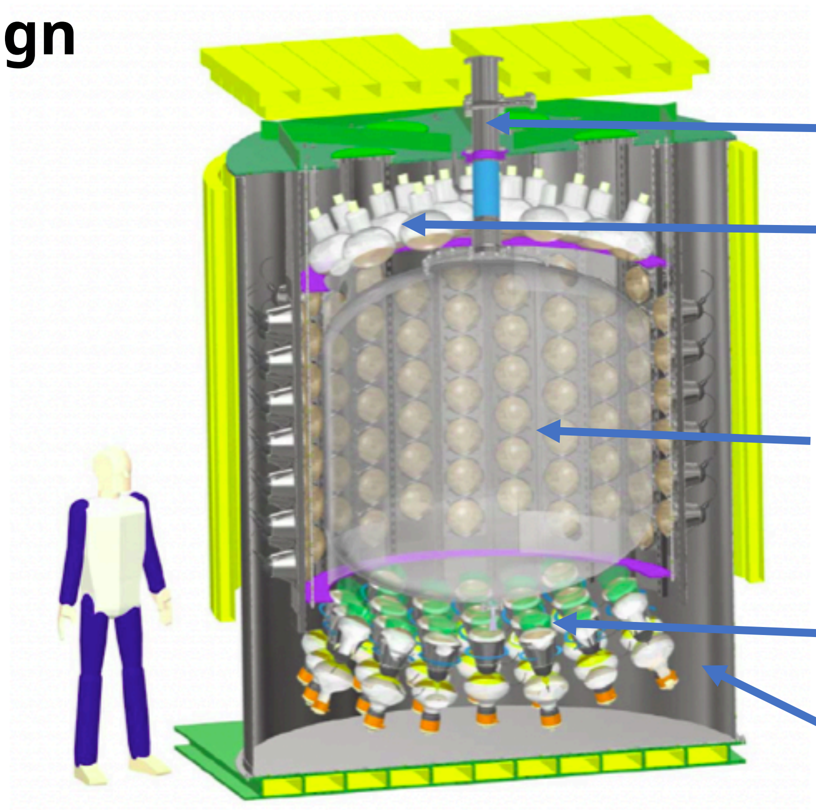
"THEIA: An advanced optical neutrino detector"
Eur. Phys. J. C (2020) 80:416

**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:**

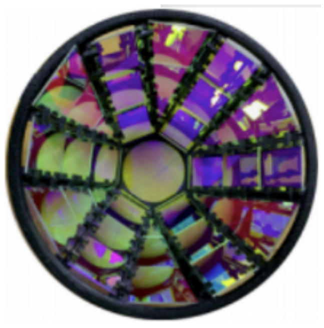
2022: Design optimization and purchasing of key equipment
2023: Construction, PMTs deployment
2024: Filling & *data-taking with deployed radioactive sources*

**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

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

# Thank you for your attention!

Gefördert durch DFG Deutsche Forschungsgemeinschaft

GEFÖRDERT VOM Bundesministerium für Bildung und Forschung

SFB 1258 Neutrinos Dark Matter Messengers

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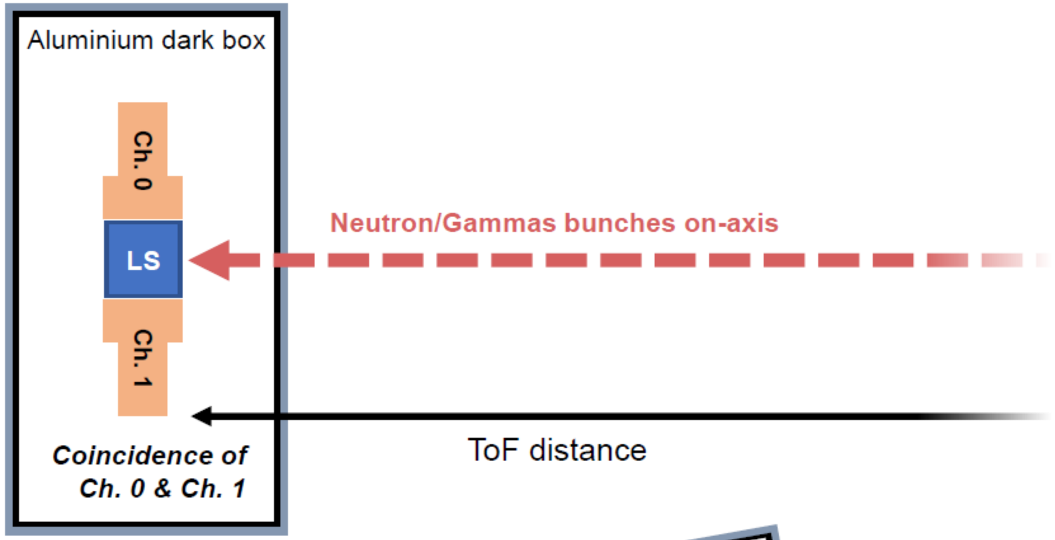
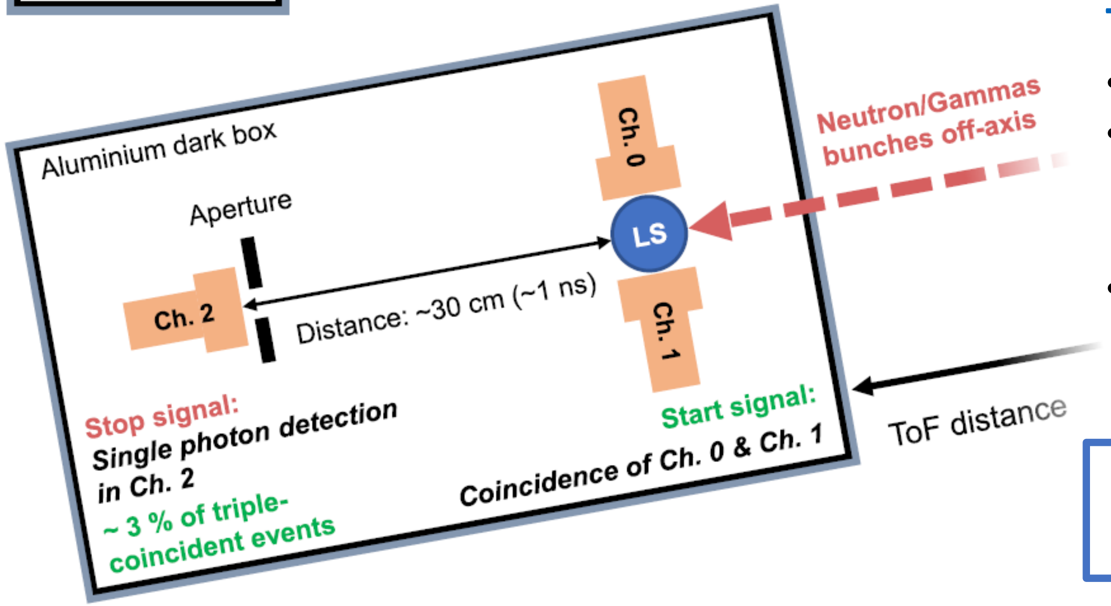
TUM Technische Universität München

# Backup Slides

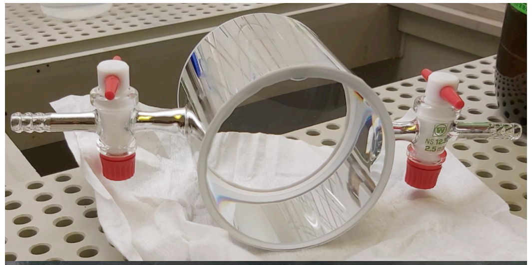
# Pulse Shape Discrimination and p-QF Study for organic, slow and water-based LS

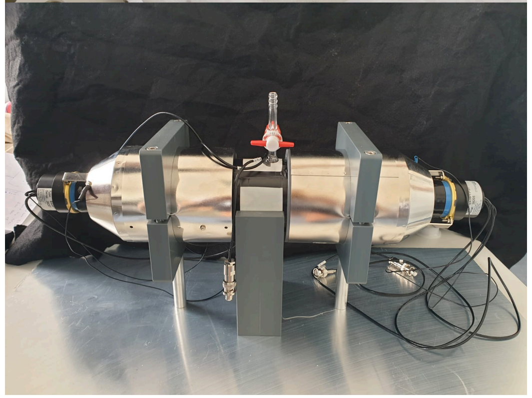



We simultaneously operate two experiments.

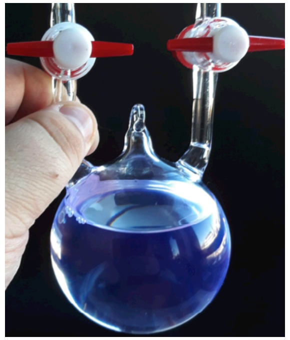
## Quenching Factor (QF) experiment





- 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!

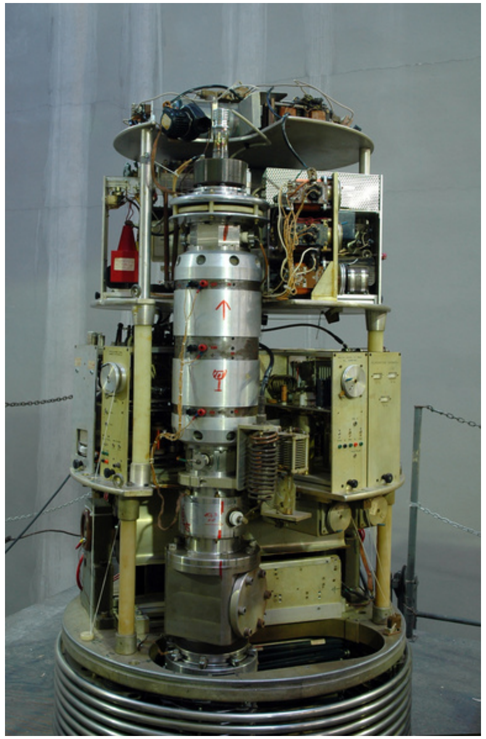
# The CN Van de Graaff Particle Accelerator of the INFN-LNL as source of quasi-monoenergetic neutrons

INFN 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

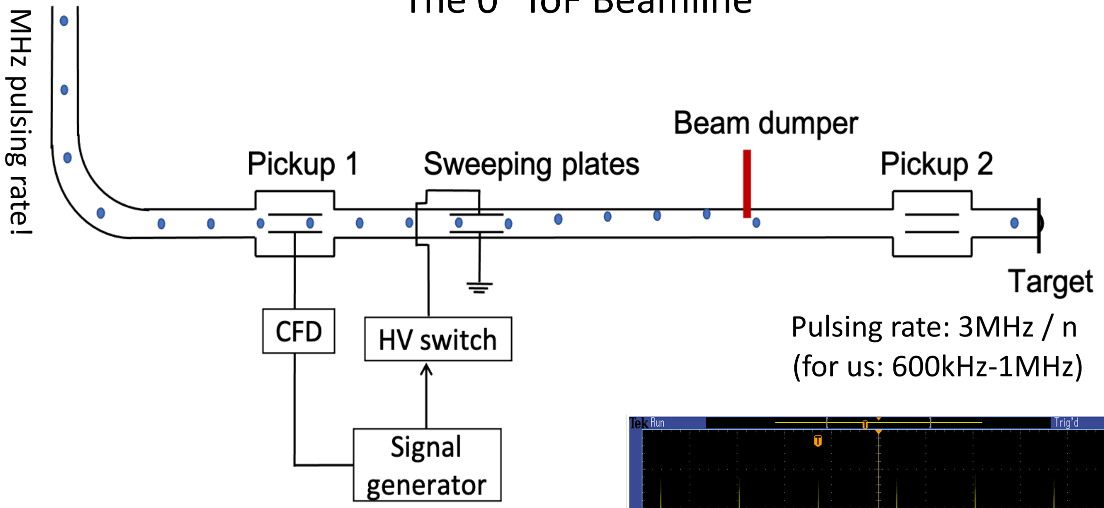
Pulse width: < 1ns

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

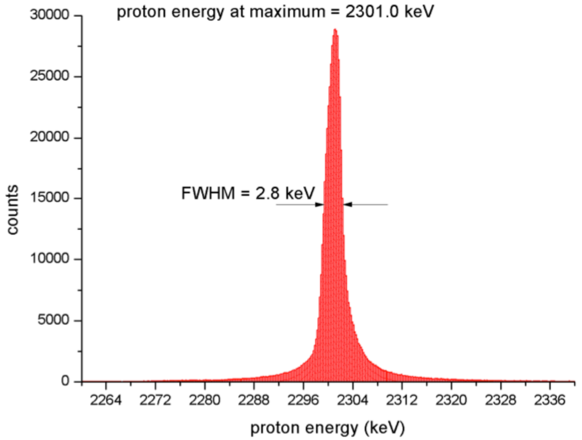
Nuclear reaction for quasi-monoenergetic neutron production
(Reaction Threshold: 1877 keV)

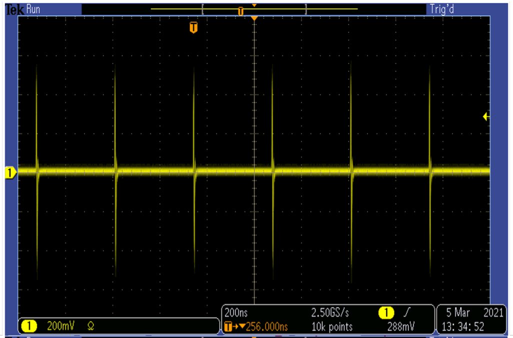
# *The CN Van de Graaff Particle Accelerator of the INFN-LNL as source of quasi-monoenergetic neutrons*

The 0° ToF Beamline

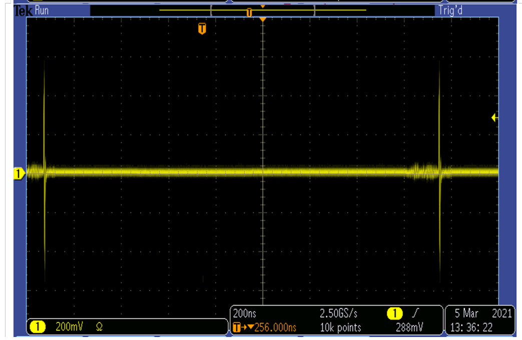



ToF of the protons between Pickup 1 and 2
→ Energy stability of the accelerator

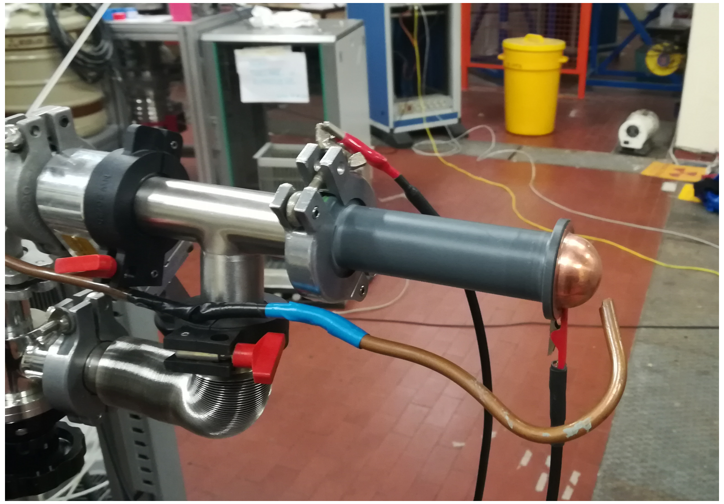


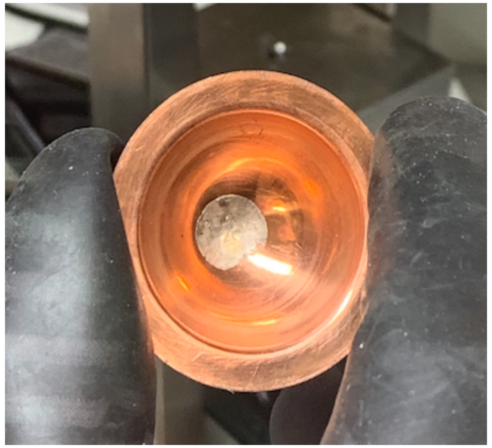
Bipolar Pickup Signal
(3 MHz)



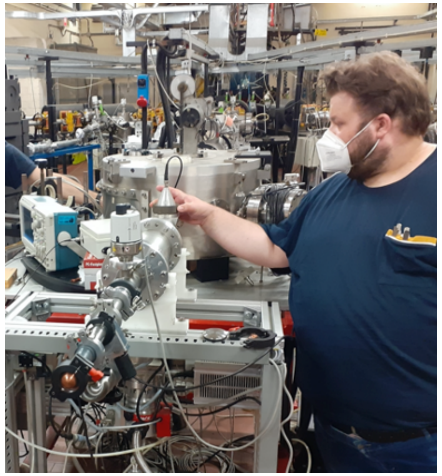
Bipolar Pickup Signal
(600 kHz)



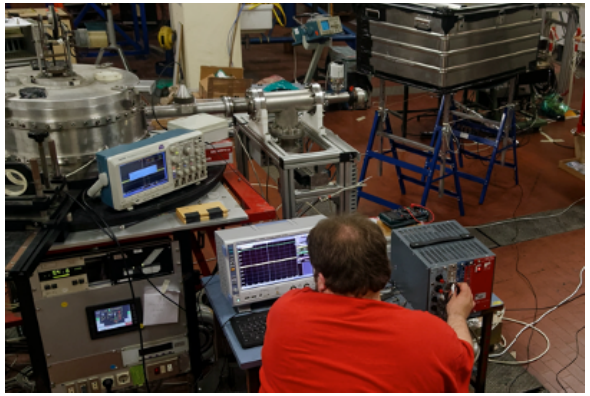
Air-cooled target
(mounted at the end of the 0° beamline)



Thin Li target
(5um – 50um)



Adjusting Pickup 2
(used for n-ToF measurement)



Adjusting the CFD discriminator
for the Pickup 2 Signal
(used for n-ToF measurement)