THEIA: An advanced optical neutrino detector

Zara Bagdasarian for the THEIA collaboration
University of California, Berkeley

NuSTEC workshop
March 18th 2021

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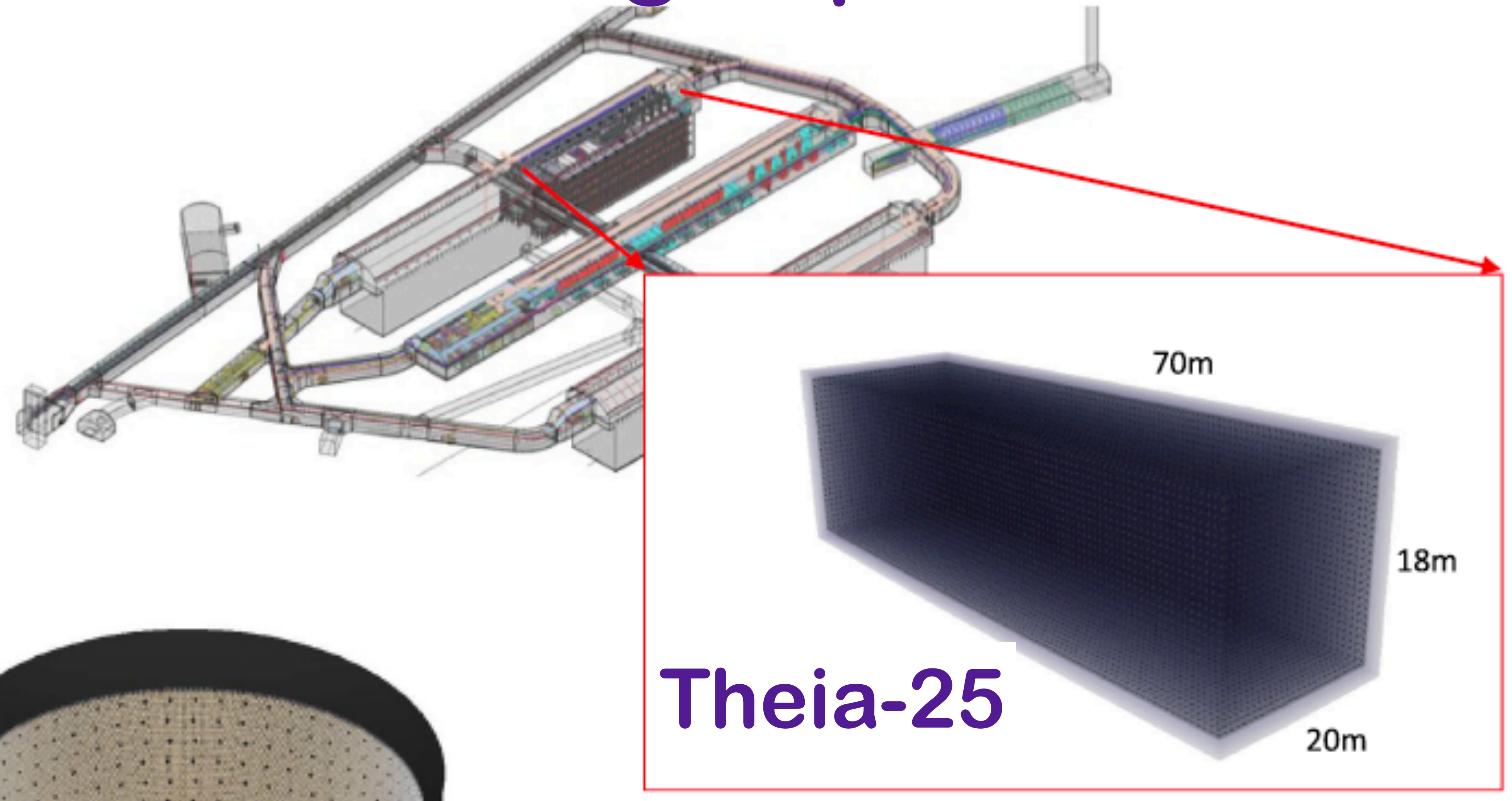
Theia: advanced optical multipurpose neutrino detector

Cutting edge developments in the target material and photodetection

Design options



Large scale, multipurpose detector

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

Broad physics program: Studying neutrino fundamental properties and astrophysical objects

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

Theia: advanced optical multipurpose neutrino detector

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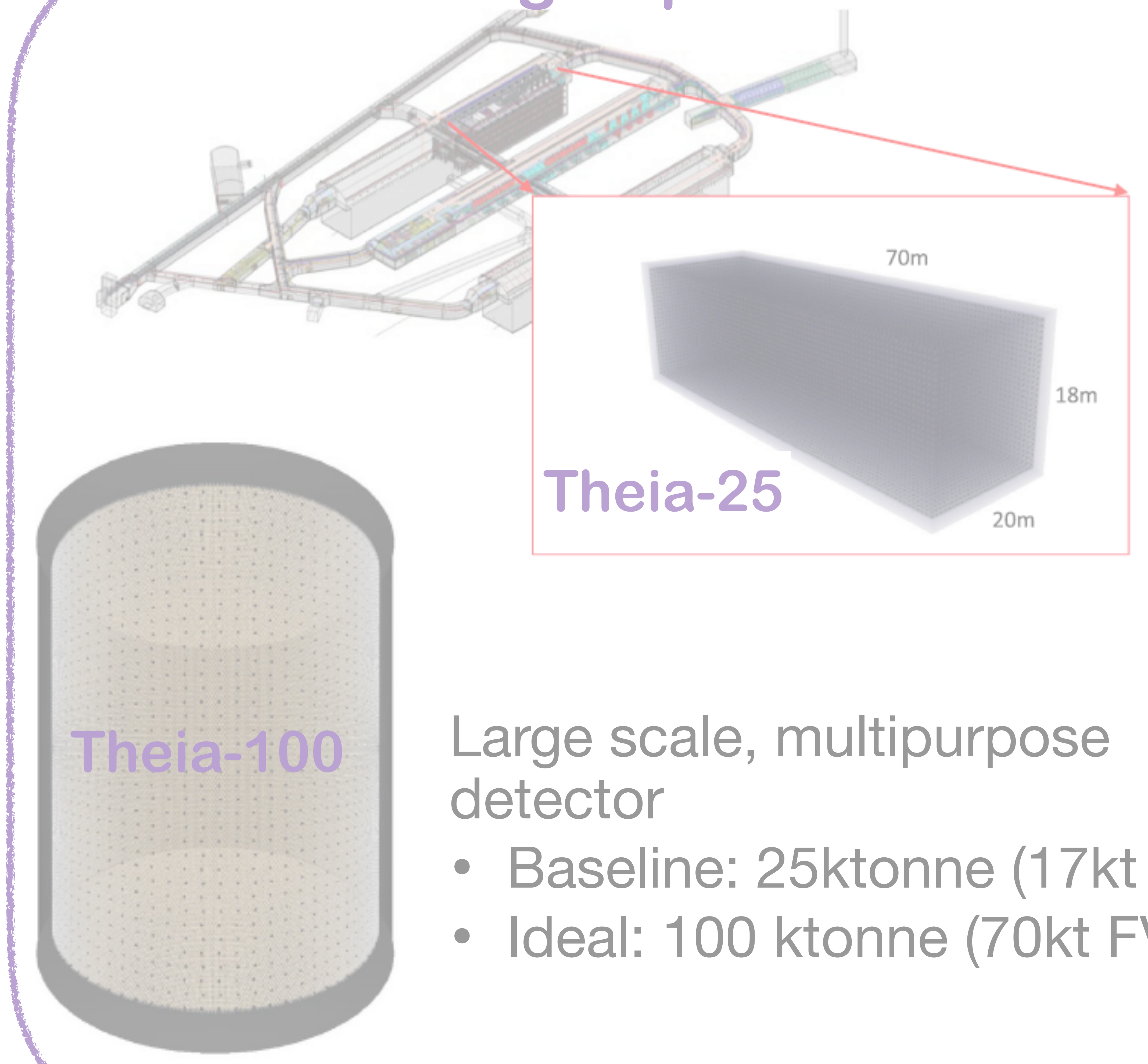

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How to broaden the current physics reach

Scintillation Detectors:

- ✅ High light yield
- ✅ Low energy threshold
- ✅ Good energy and position resolutions
- 🚫 Limited in size by absorption and cost
- 🚫 No directionality

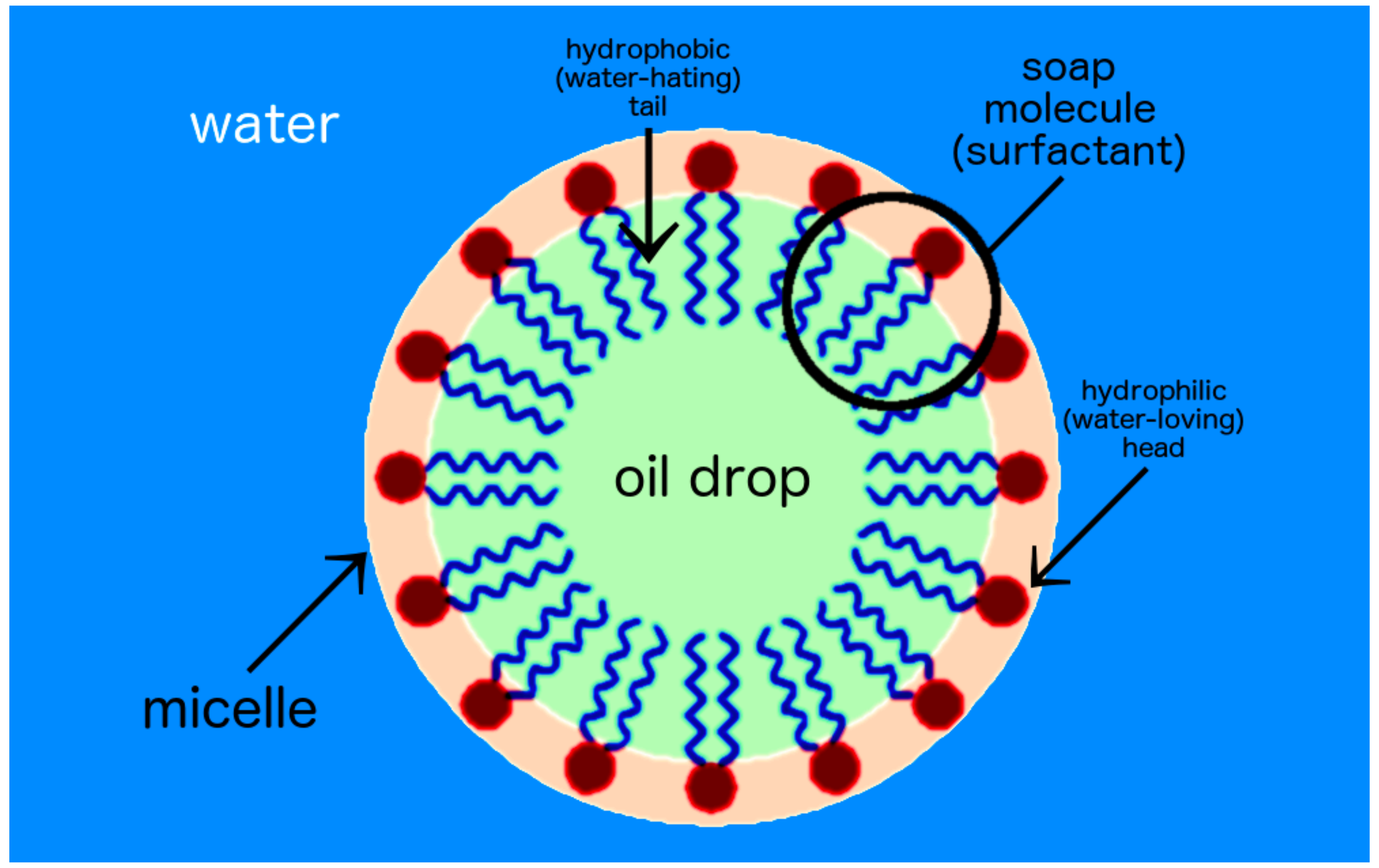
Cherenkov Detectors:

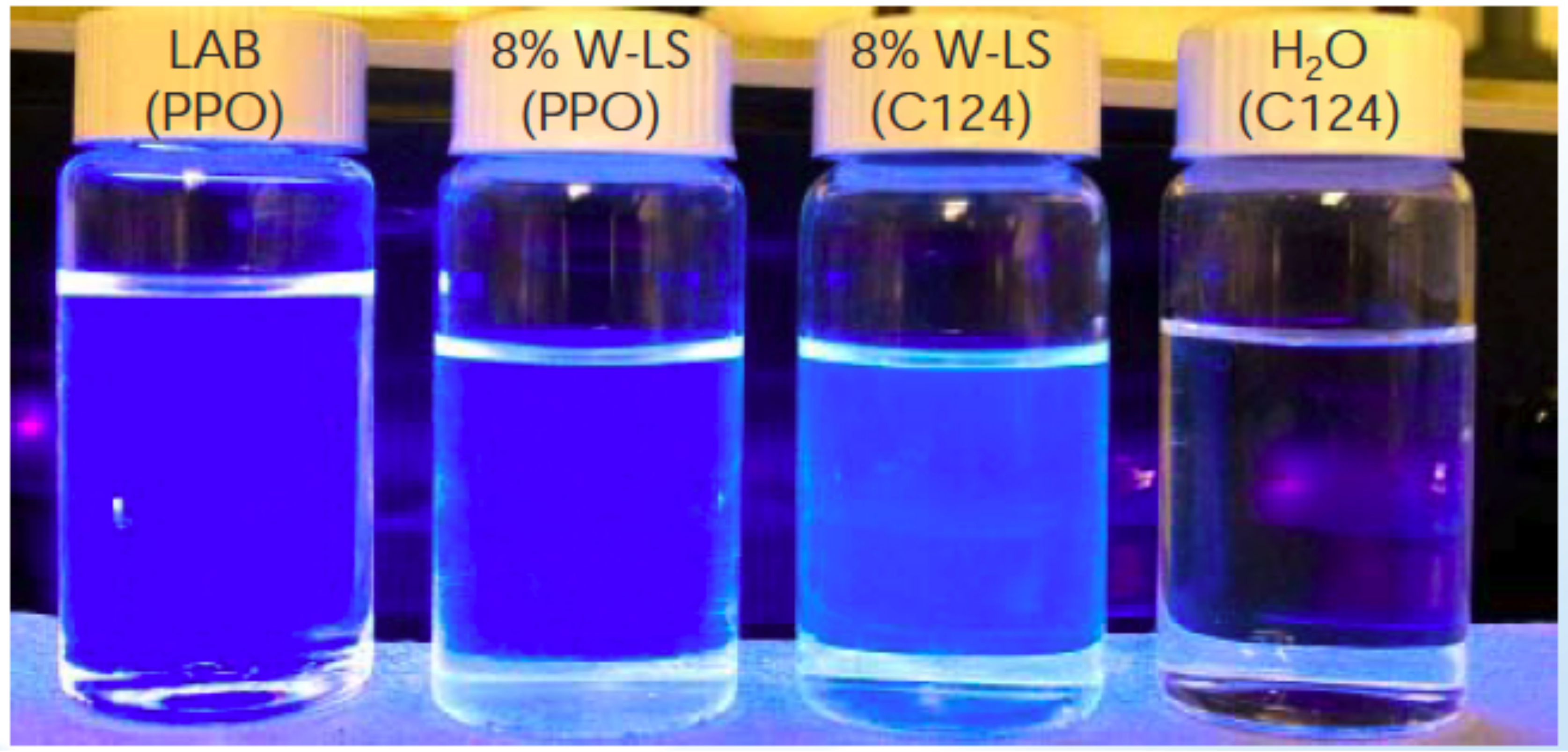
- ✅ Directional information
- ✅ Can be very large (low absorption)
- ✅ Particle ID at high energies
- 🚫 No access to physics below the Cherenkov threshold
- 🚫 Low light yield

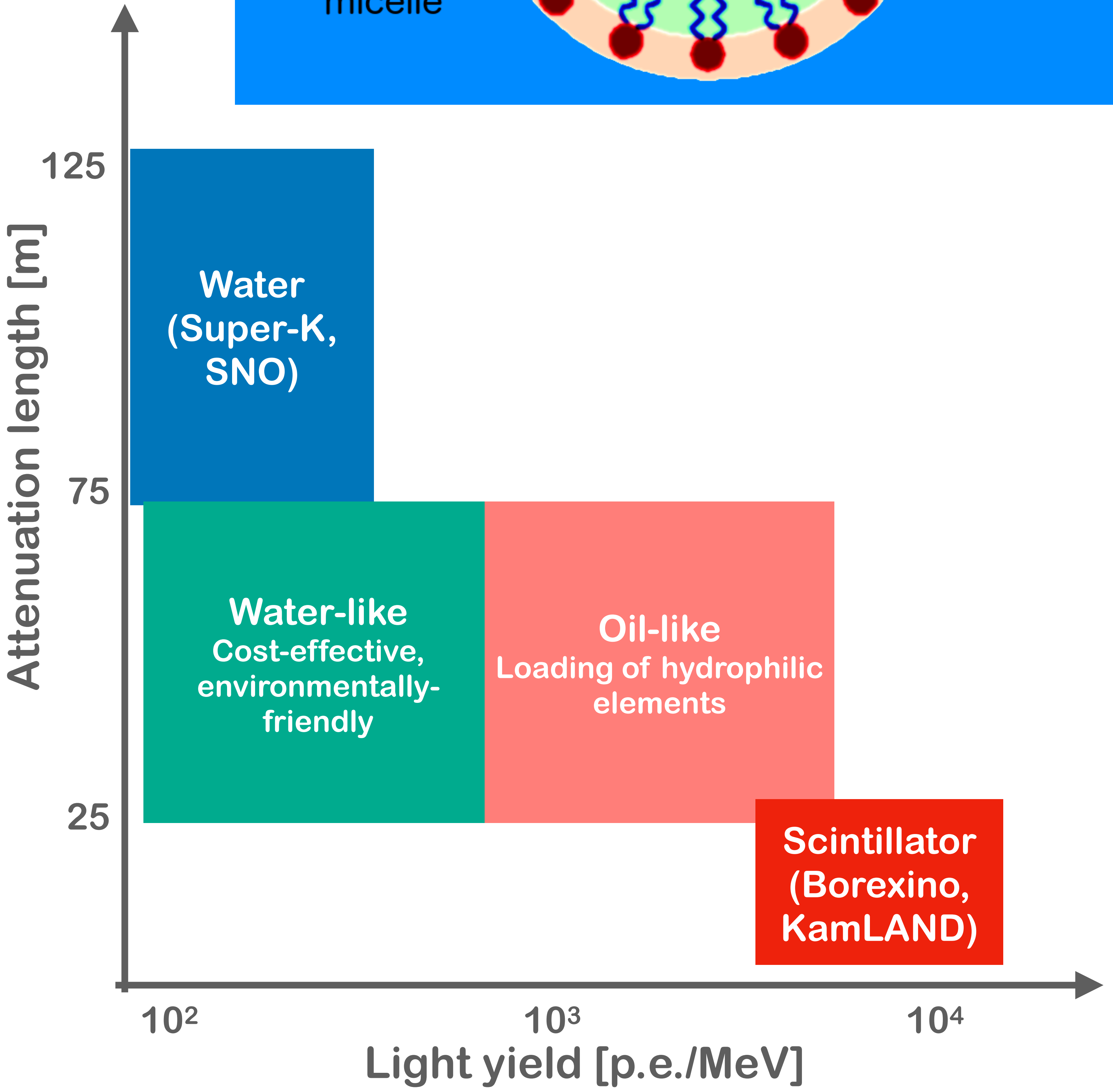
Water-based Liquid Scintillation (WbLS) Detectors: Get best of two worlds

Water-based Liquid Scintillator - Basics

- Water-based Liquid Scintillator (WbLS) is a mixture of pure water and oil-based liquid scintillator
- WbLS is made using a surfactant (soap-like) such as PRS* (hydrophilic head and hydrophobic tail) to hold the scintillator molecules in water in a "micelle" structure
- Combines the advantages of water (transparency, low cost) and liquid scintillator (high light yield)







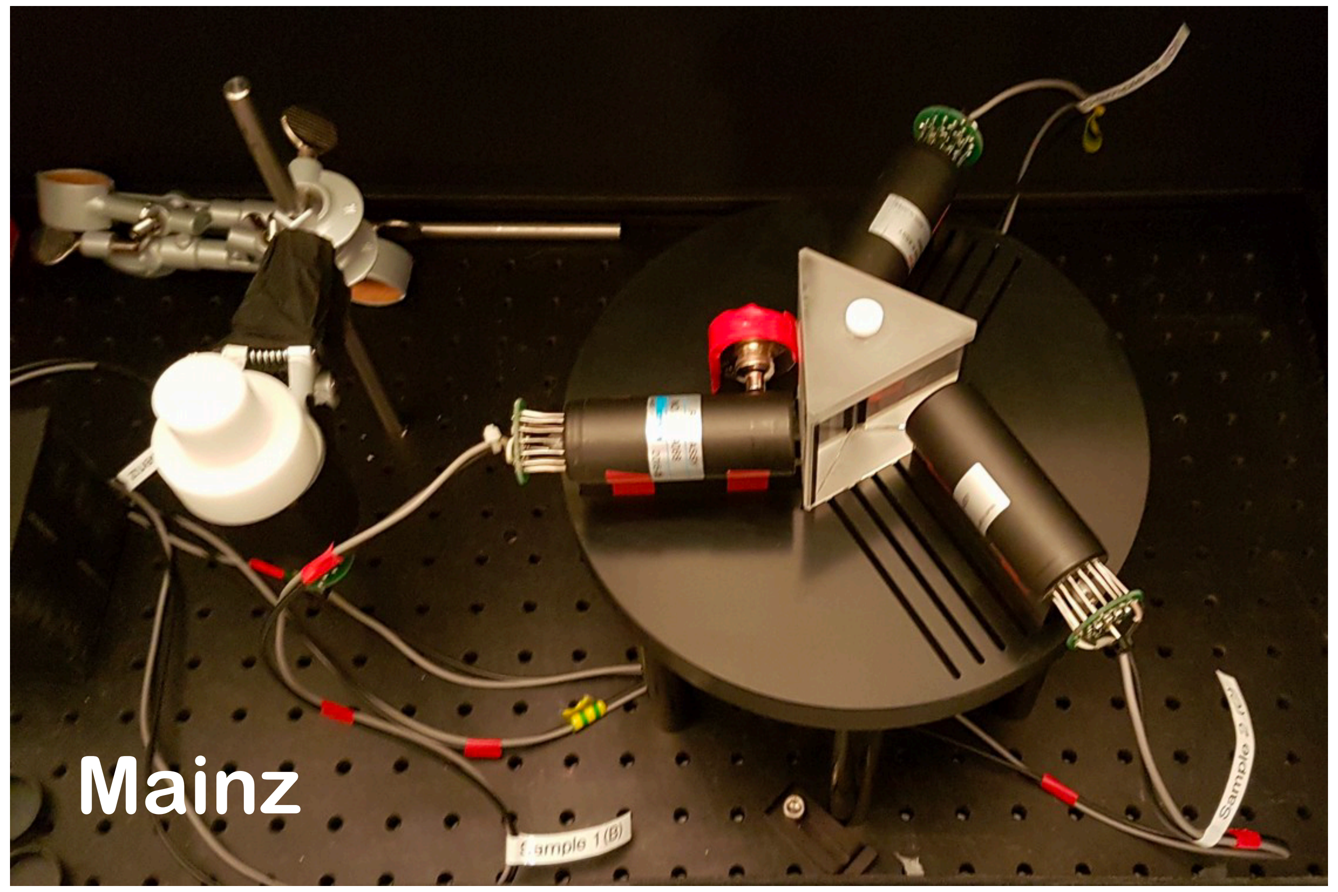
Water-based Liquid Scintillator - Advanced

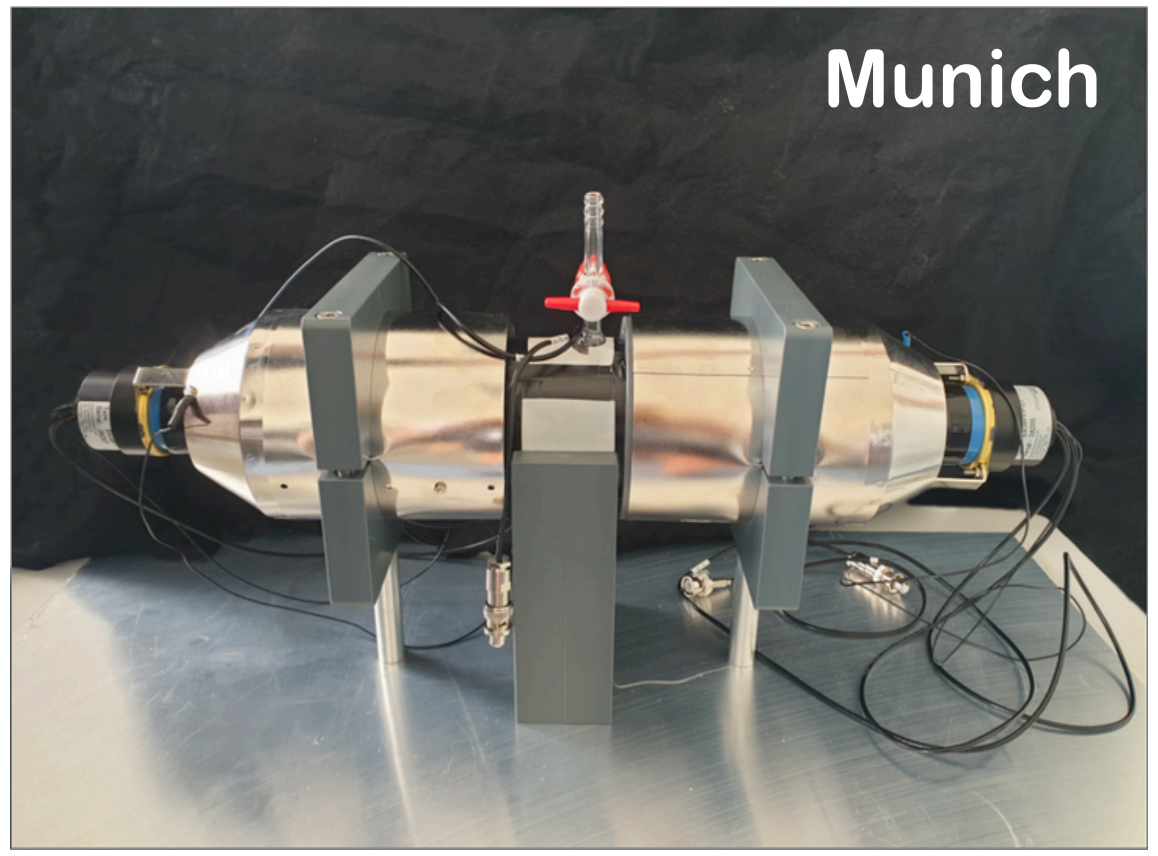
Developed Water-based Liquid Scintillator (WbLS) cocktails require extensive characterization:

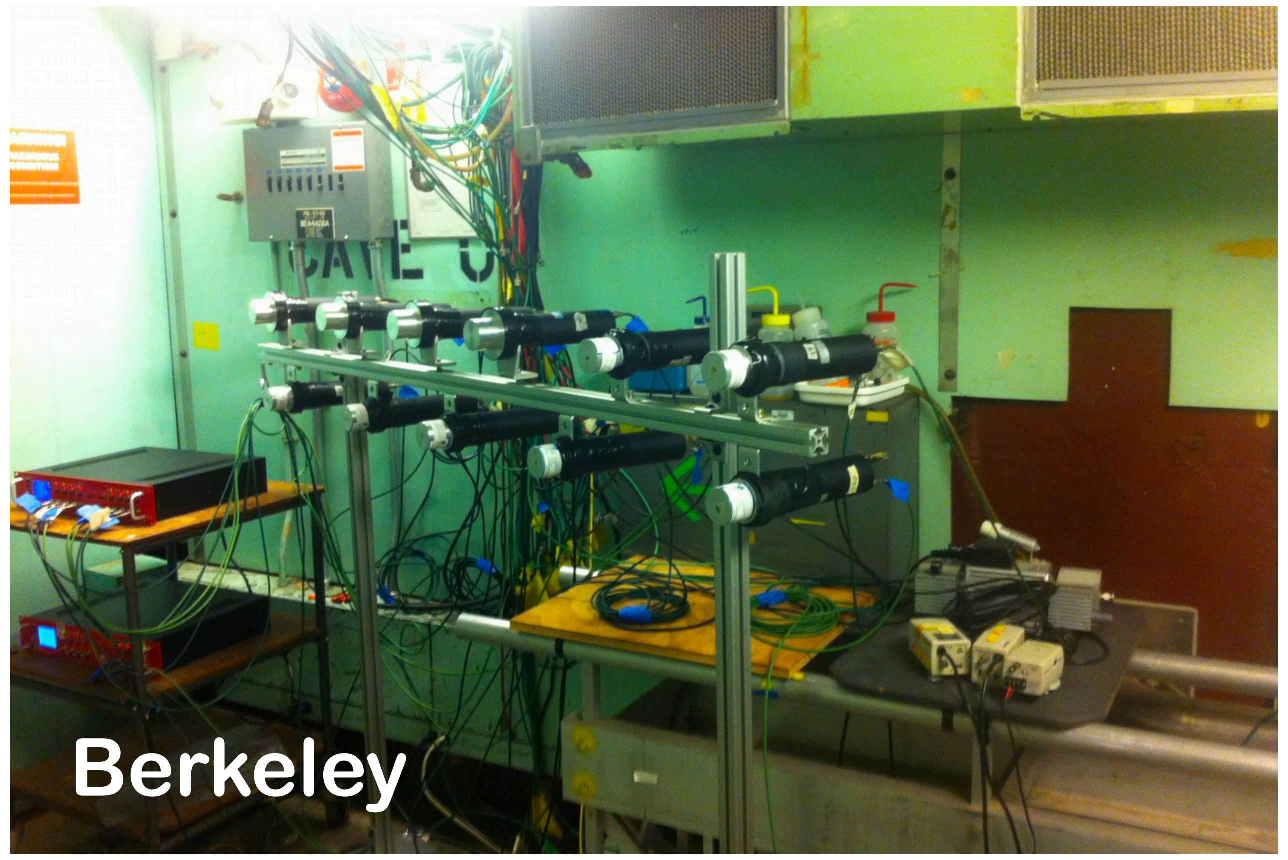
- Light Yield
- Emission spectrum
- Scintillation time profile
- Scattering and attenuation lengths

Other relevant developments:

- Nanofiltration
- Advanced reconstruction techniques, including machine learning
- Cherenkov/Scintillation separation demonstration

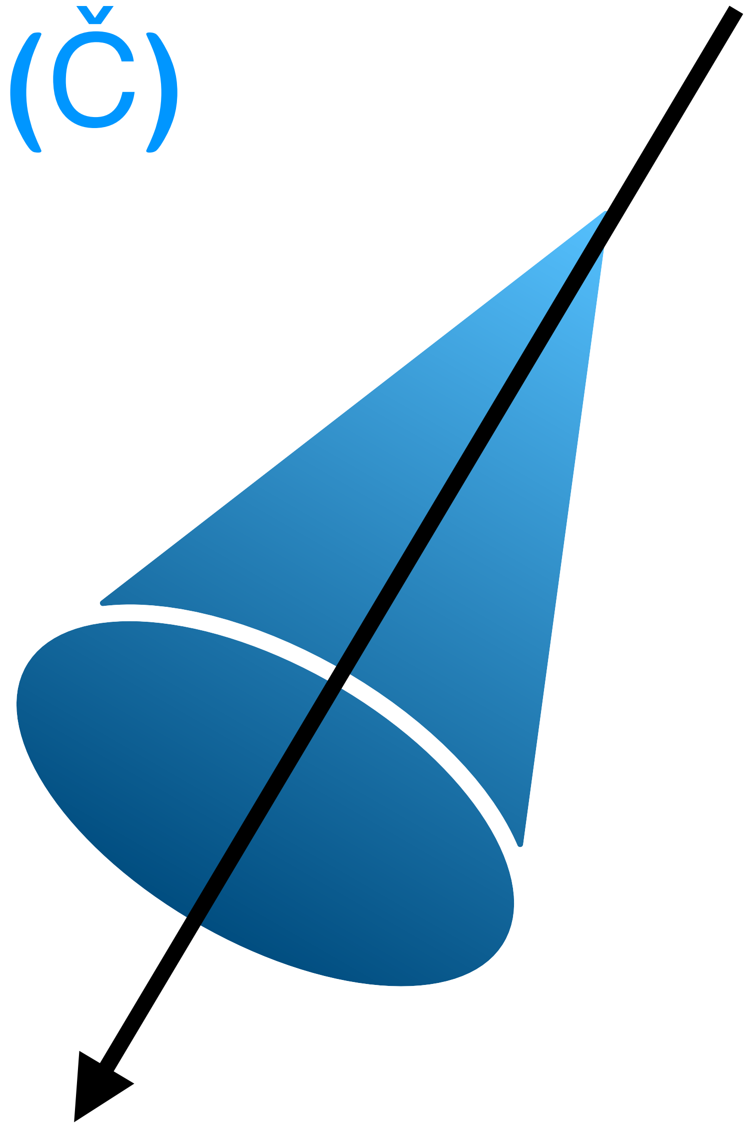




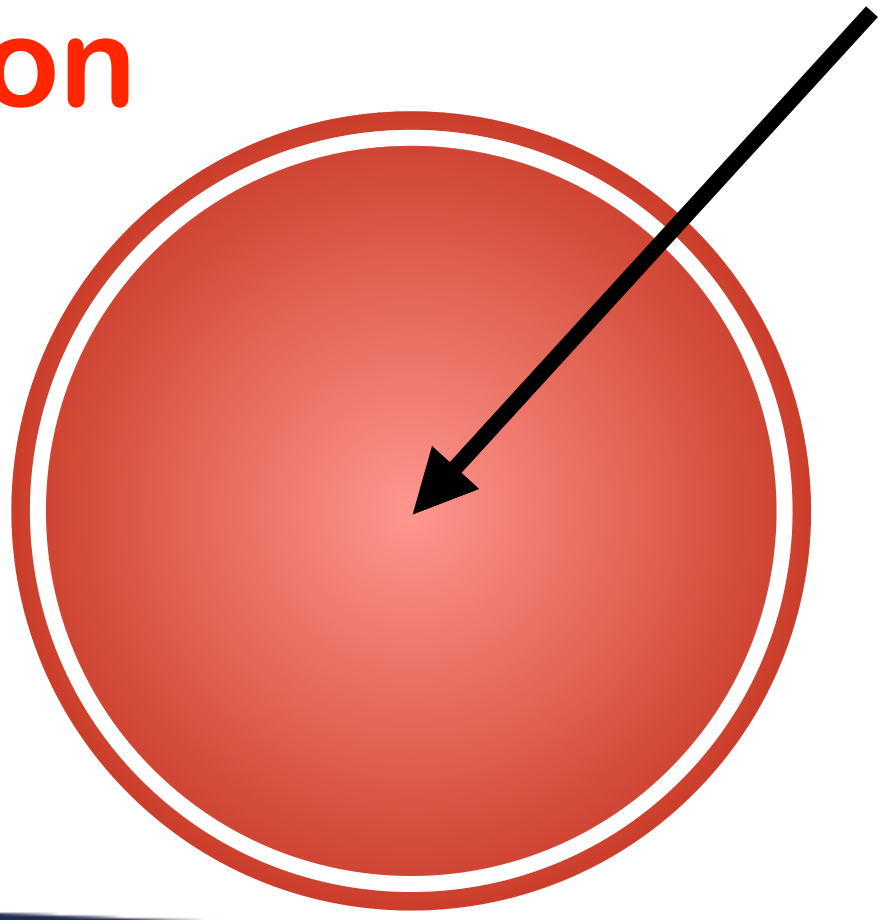


Cherenkov/scintillation photons separation

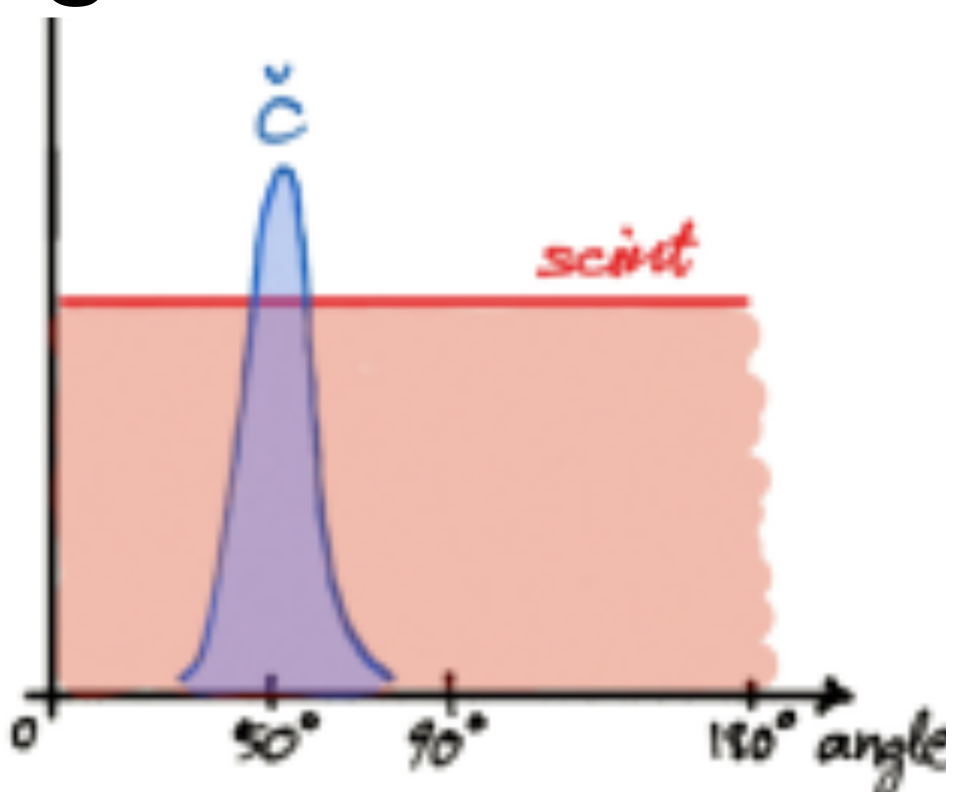
Cherenkov (Č)



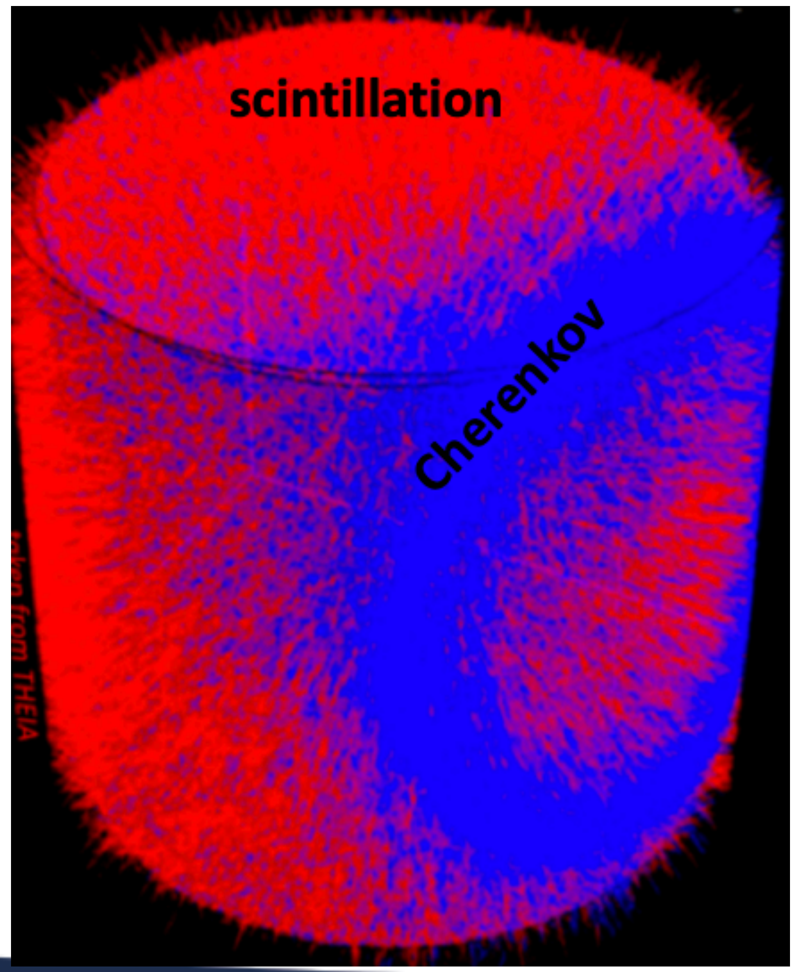
Scintillation



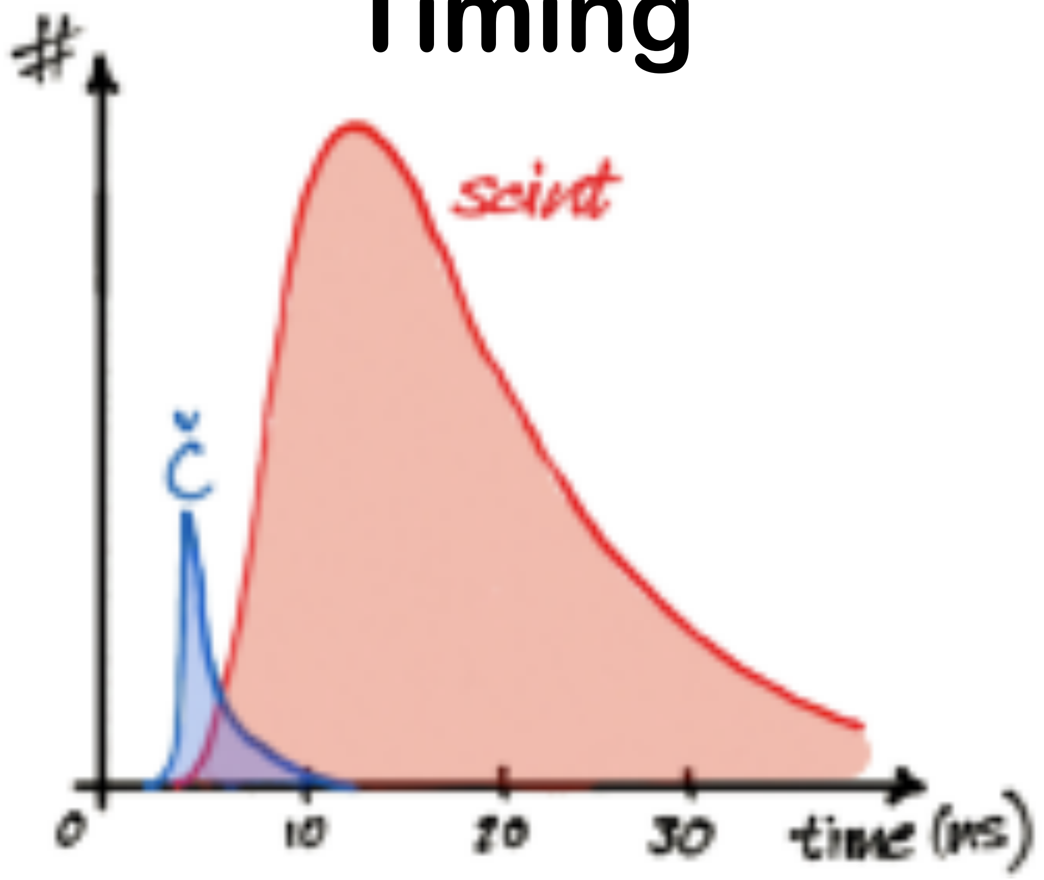
Angular distribution



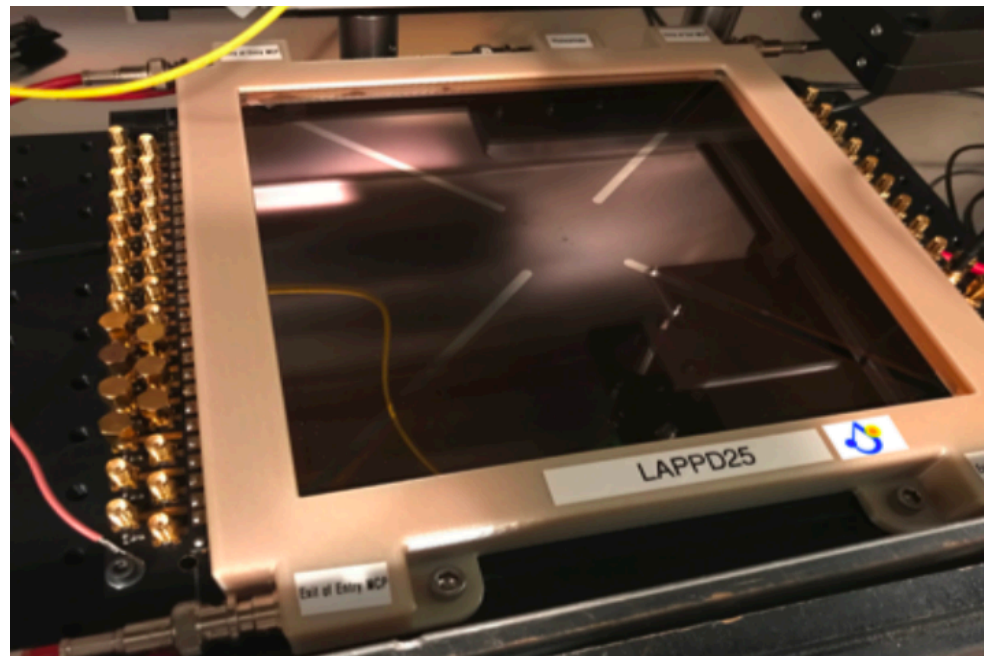
Angular resolution



Timing

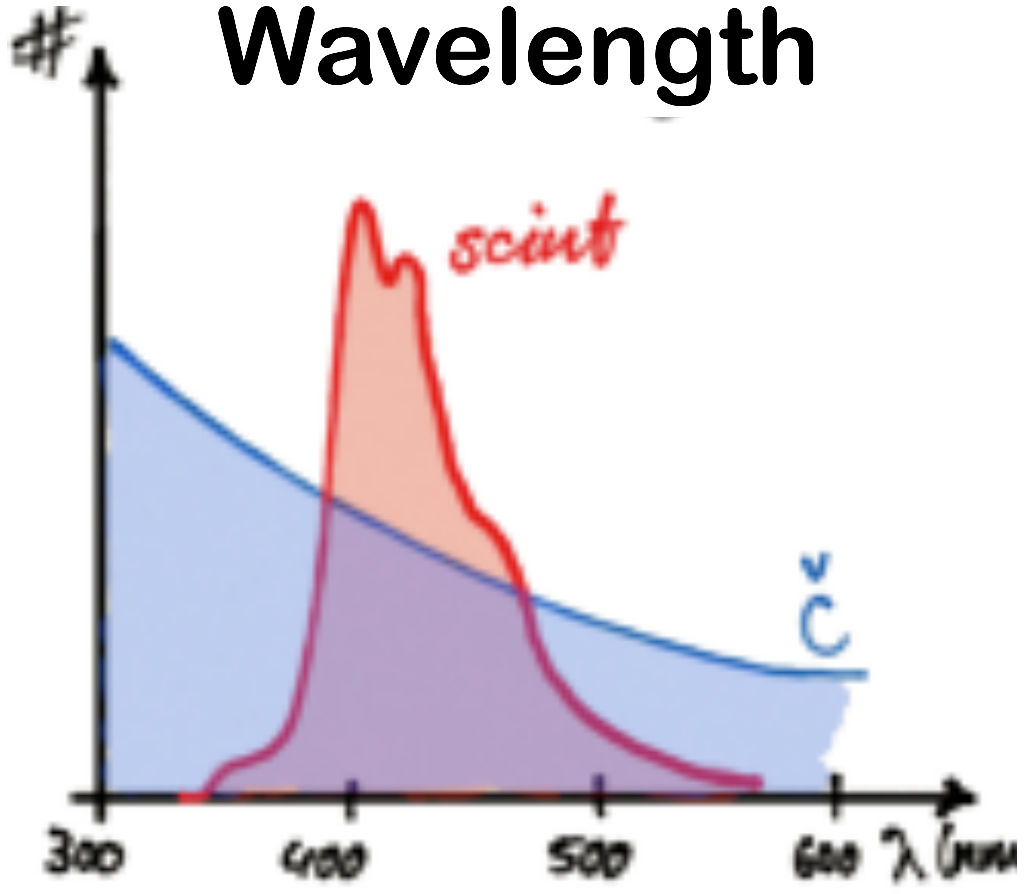


Large area picosecond photodetectors LAPPDs (~70 ps TTS) or other fast photodetectors

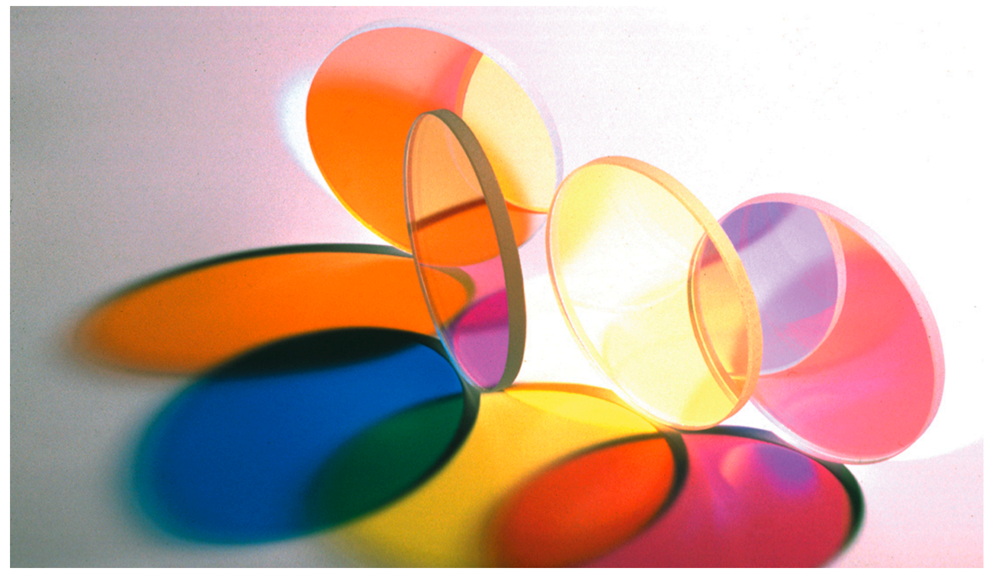


B.W.Adams et al. NIM A Volume 795, 1 (2015)

Wavelength



- Dichroic filters
- Red-sensitive PMTs
- Filtering

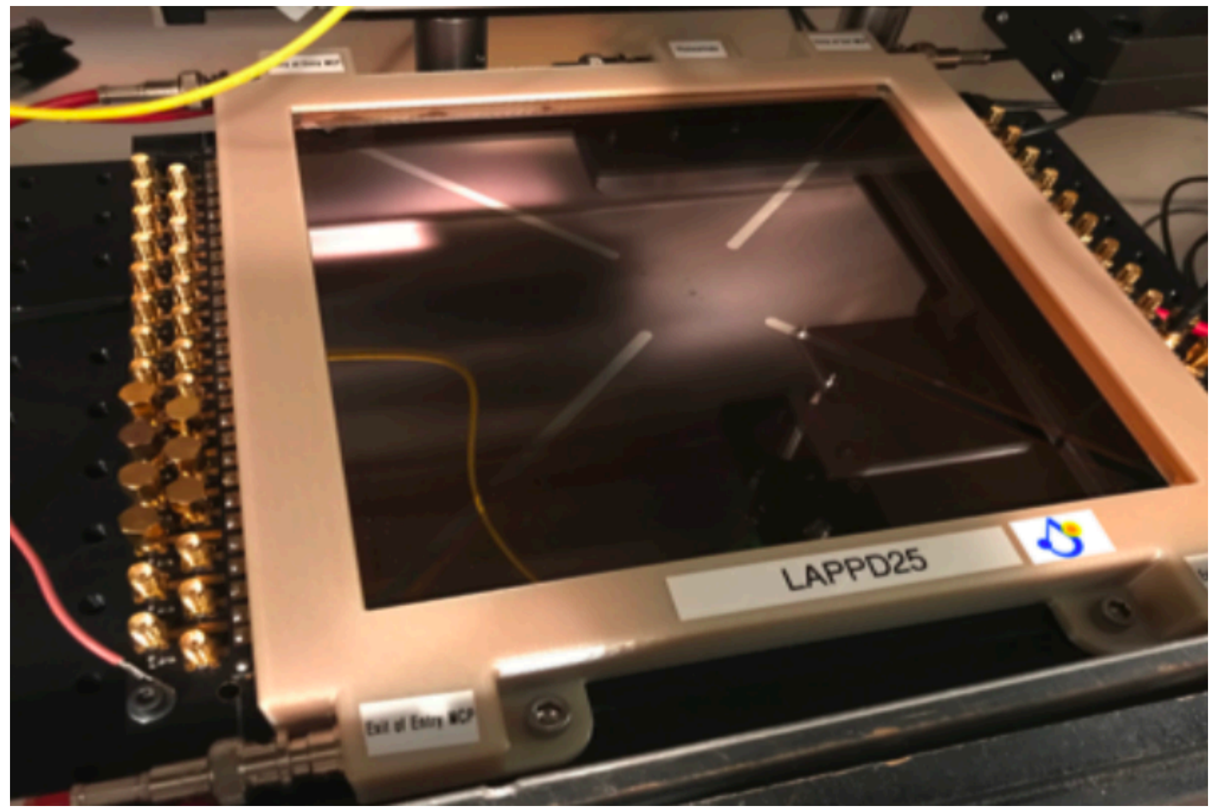


T. Kaptanoglu et al.
Phys. Rev. D 101, 072002 (2020)

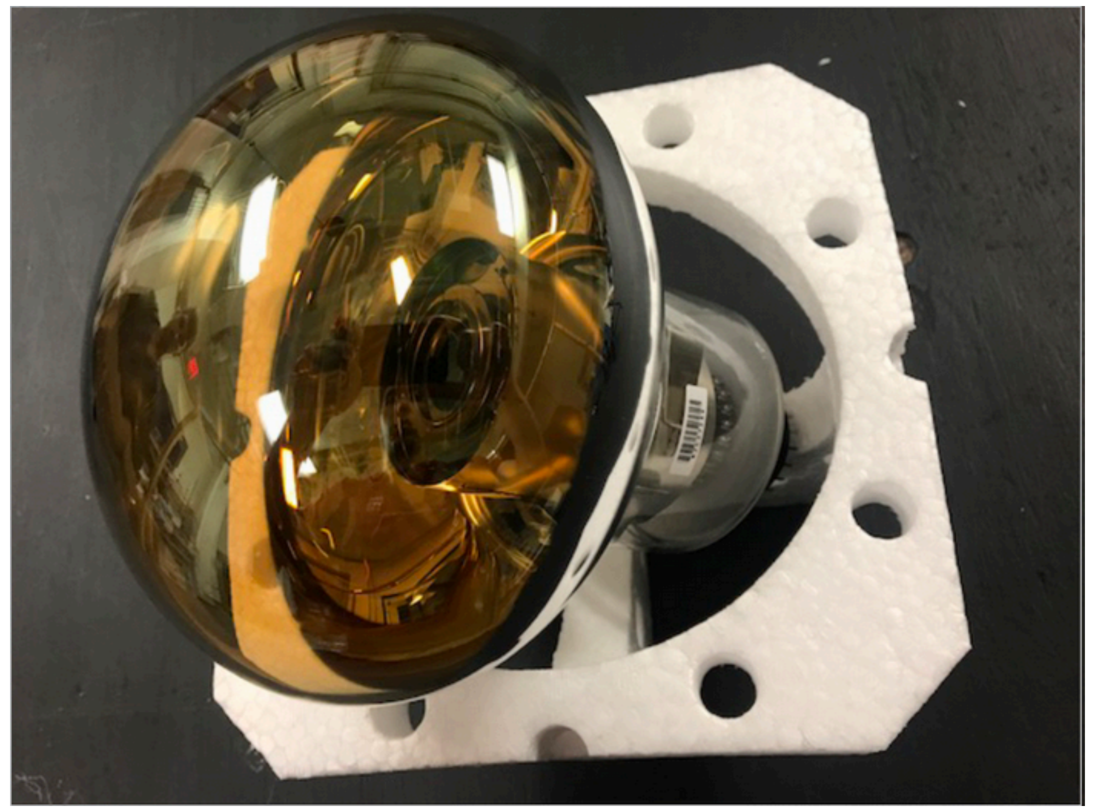
New Generation Photodetectors

Large area picosecond photodetector (LAPPD):
Micro-channel plate, fast-timing photodetectors

- Large-area: 20 $\times$ 20 cm
- Fast timing: ~70 ps time resolution
- High quantum efficiency (QE): >20-30 %
- Position resolution: mm scale



Very fast large-area & HQE PMT
TTS~500ps
Q.E. > 30%



Large-area red-sensitive PMTs
TTS~500ps
Q.E. > 30%

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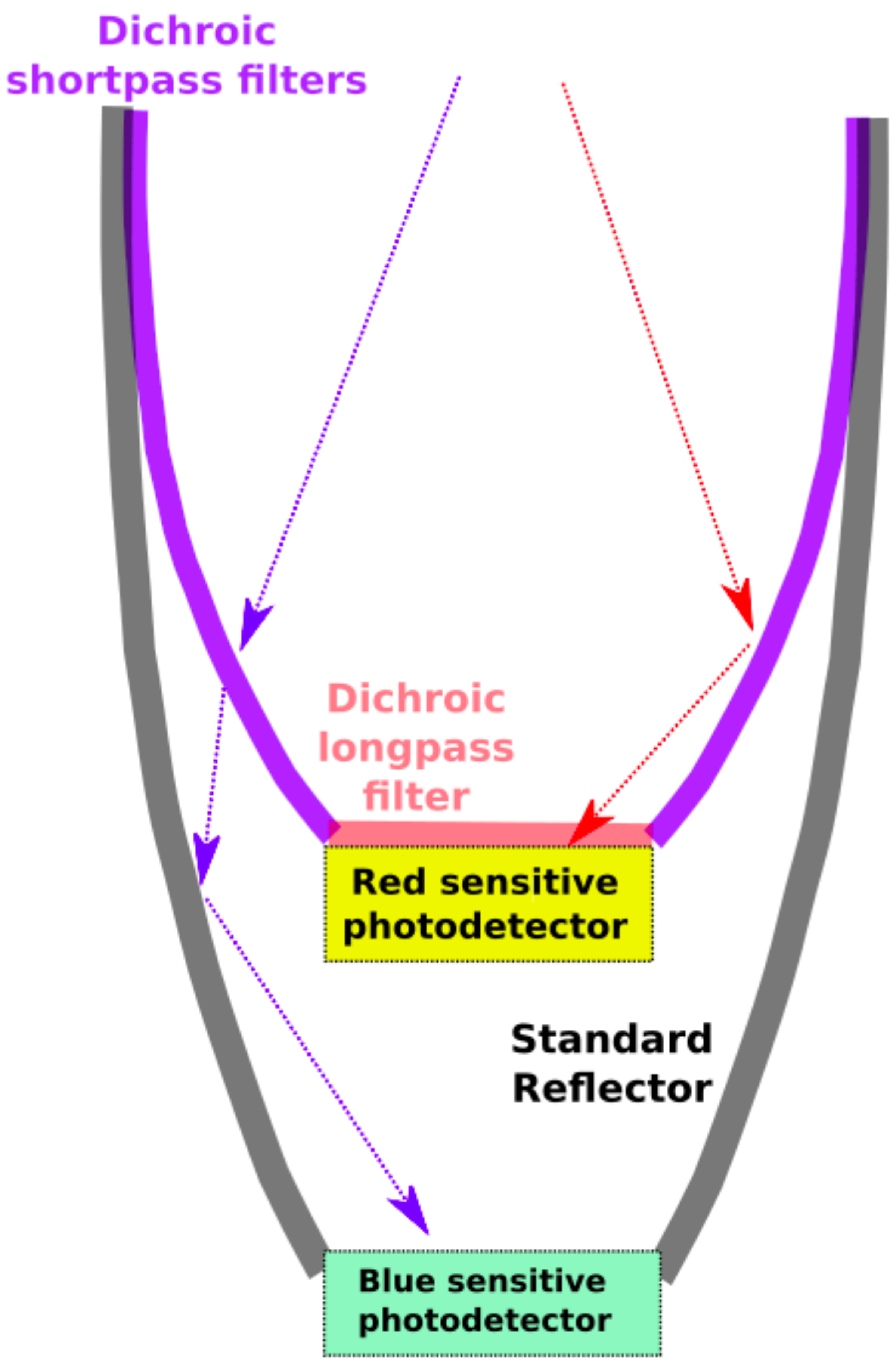
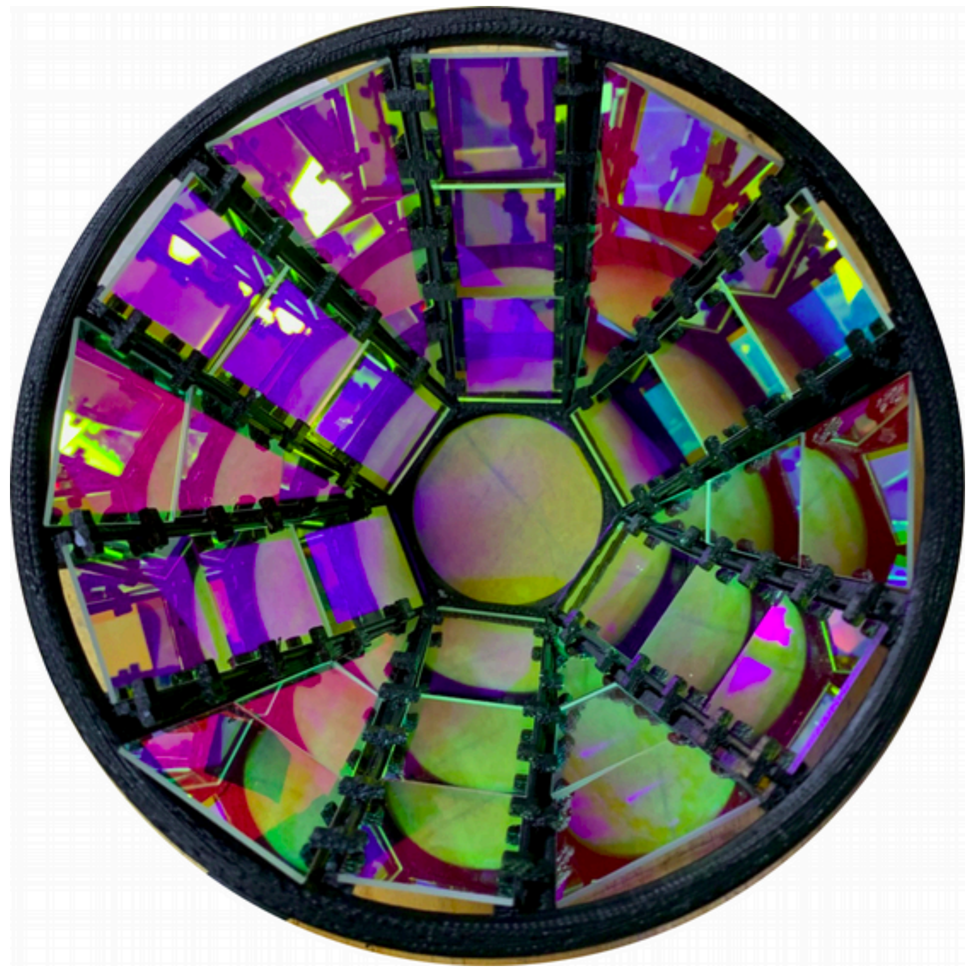
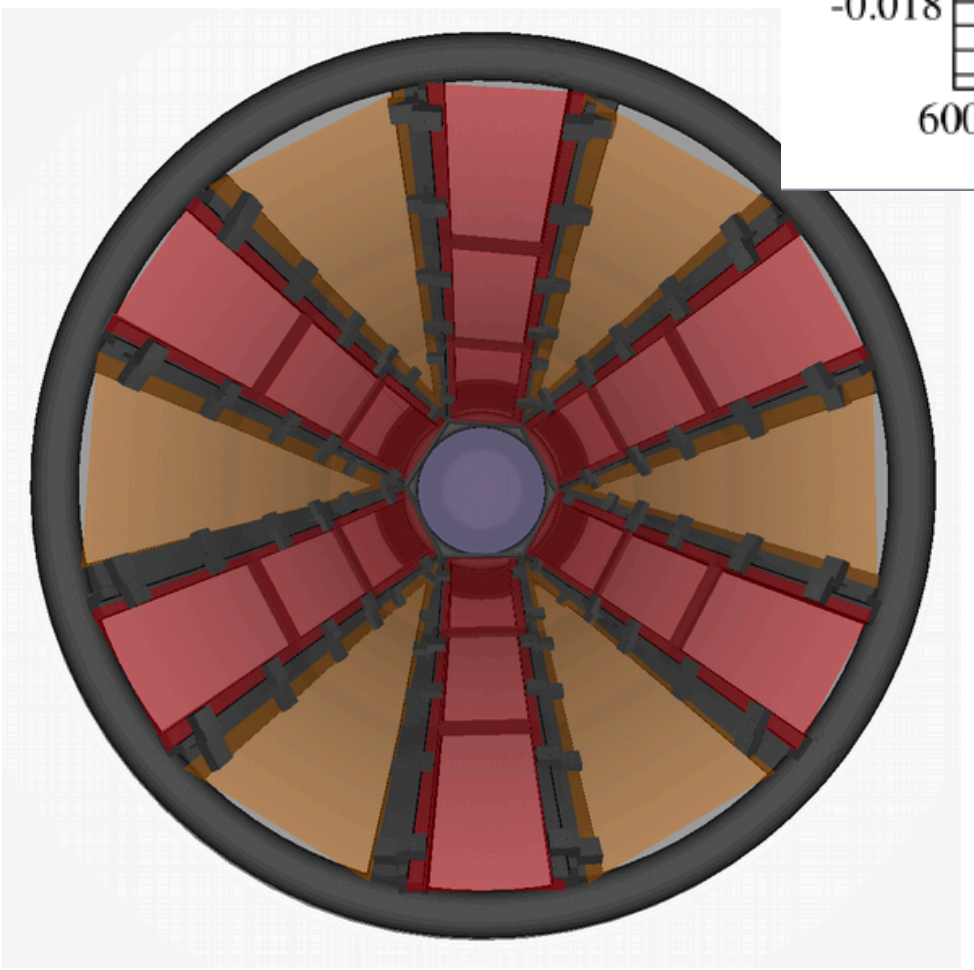
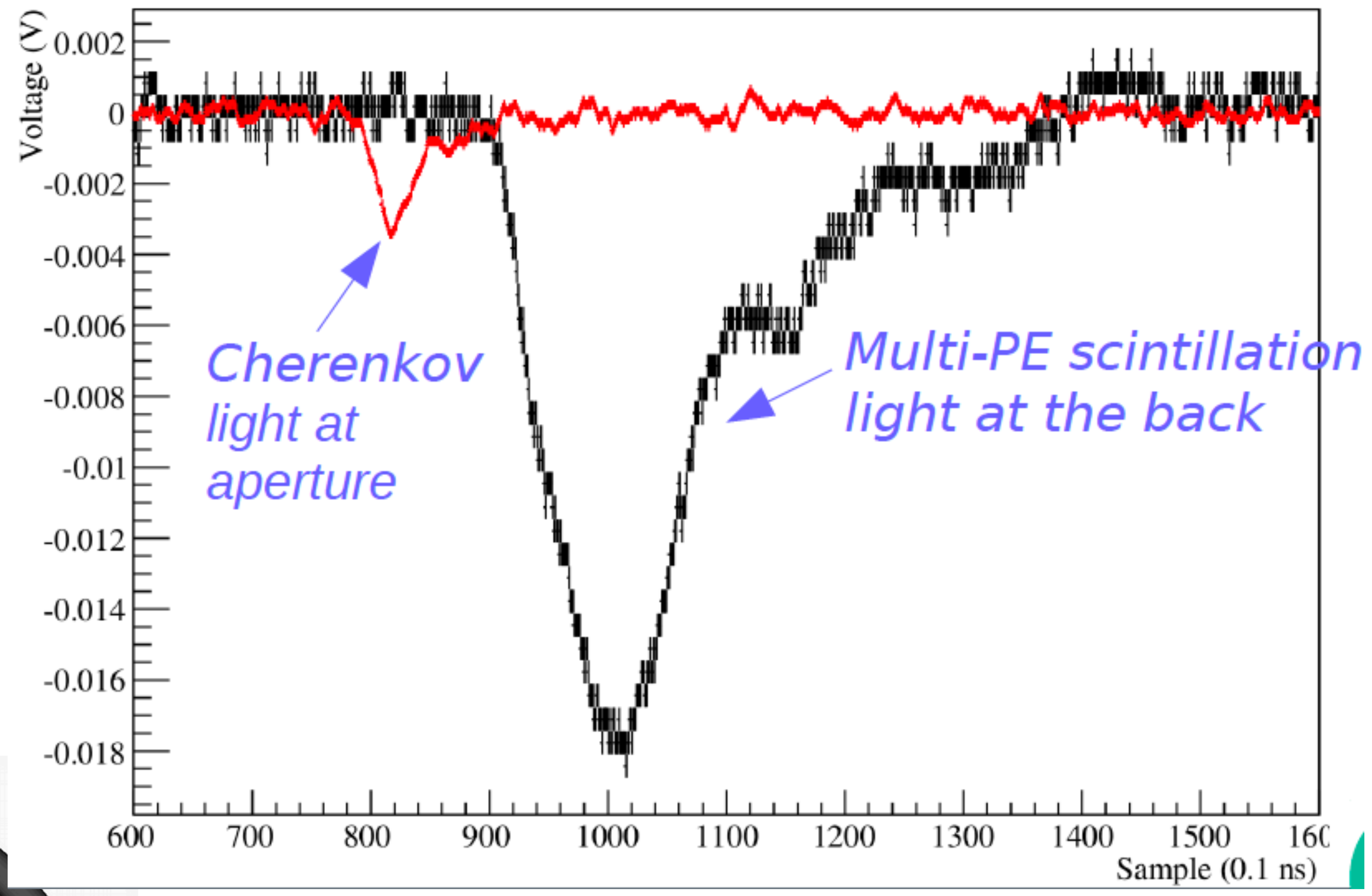
Dichroic filters (Wavelength discrimination)









T. Kaptanoglu et al JINST 14 T05001 (2019)
T. Kaptanoglu et al. Phys. Rev. D 101, 072002 (2020)

Performance measurements and MC studies

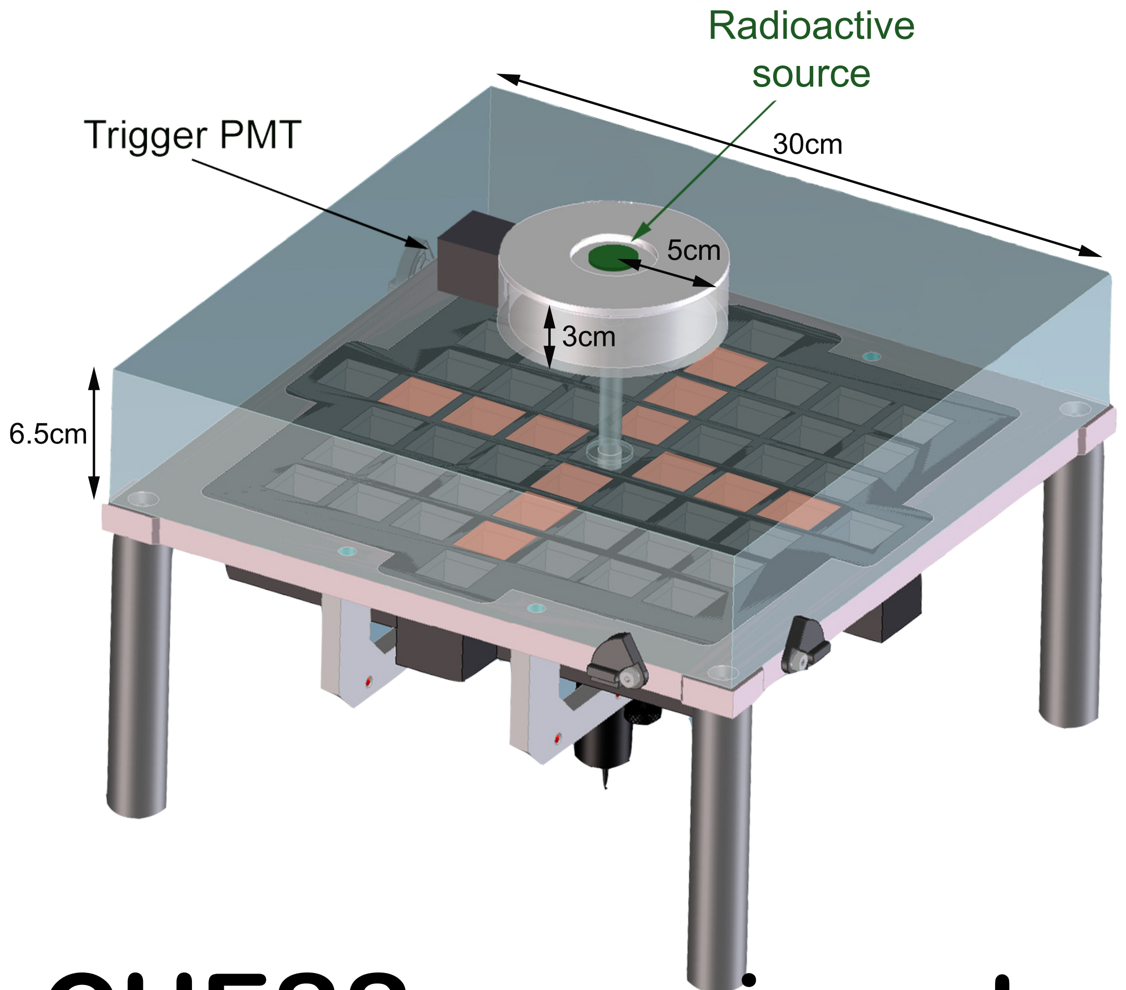
WbLS characterization:
- Scintillation light yield
- Emission time profile with betas and X-rays
- Emission spectra

→ **Monte Carlo model construction**

→ **Cherenkov/scintillation separation at small scale using muons**

→ **Monte Carlo model validation**

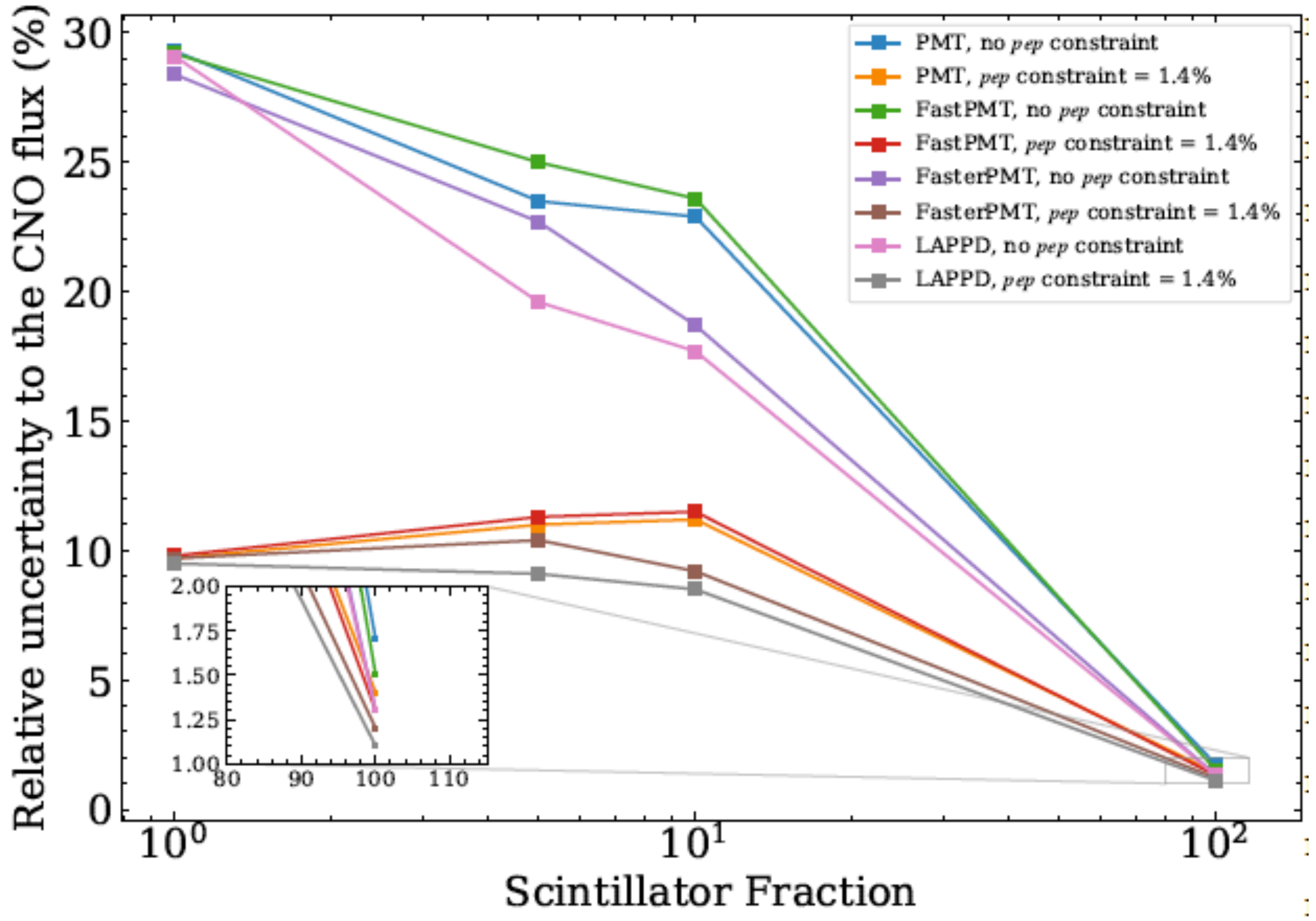
→ **Prediction of impact in large-scale detectors**



CHESS experiment at UC Berkeley

J. Caravaca et al. Eur. Phys. J. C 80, 867 (2020)
D. Onken et al., Mater. Adv., 1, 71-76 (2020)
J. Caravaca et al. Eur. Phys. J. C 77, 811 (2017)
J. Caravaca et al. Phys. Rev. C 95, 055801 (2017)

Example of impact on the CNO measurement precision:



B.Land, Z.Bagdasarian et al arXiv:2007.14999 (accepted to PRD)

Scaling up

Mass

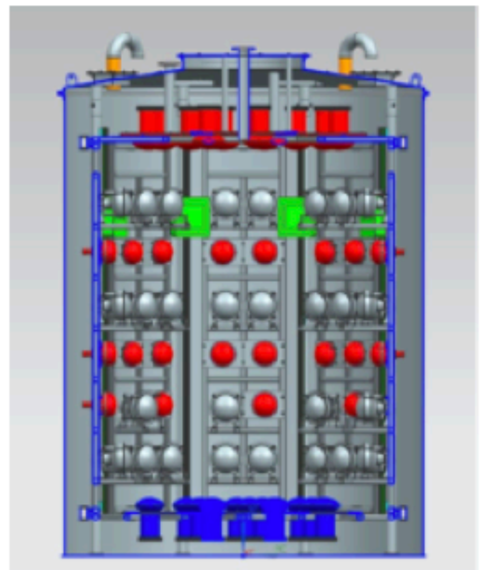
~ 25,000 tons
/100,000 tons

~ 2000 tons

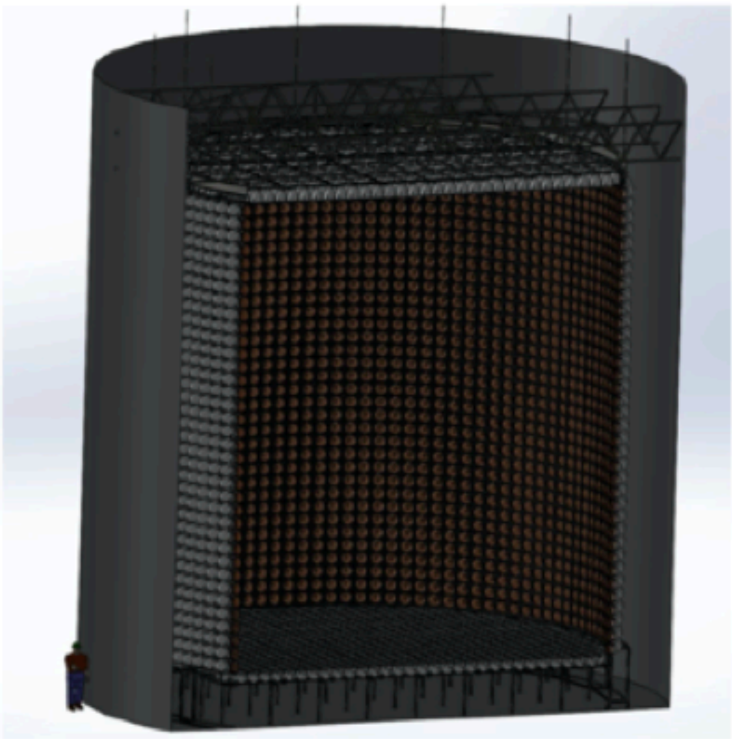
~ 30 tons

~130 photosensors
Demonstration + R&D for WbLS & fast photosensors

ANNIE

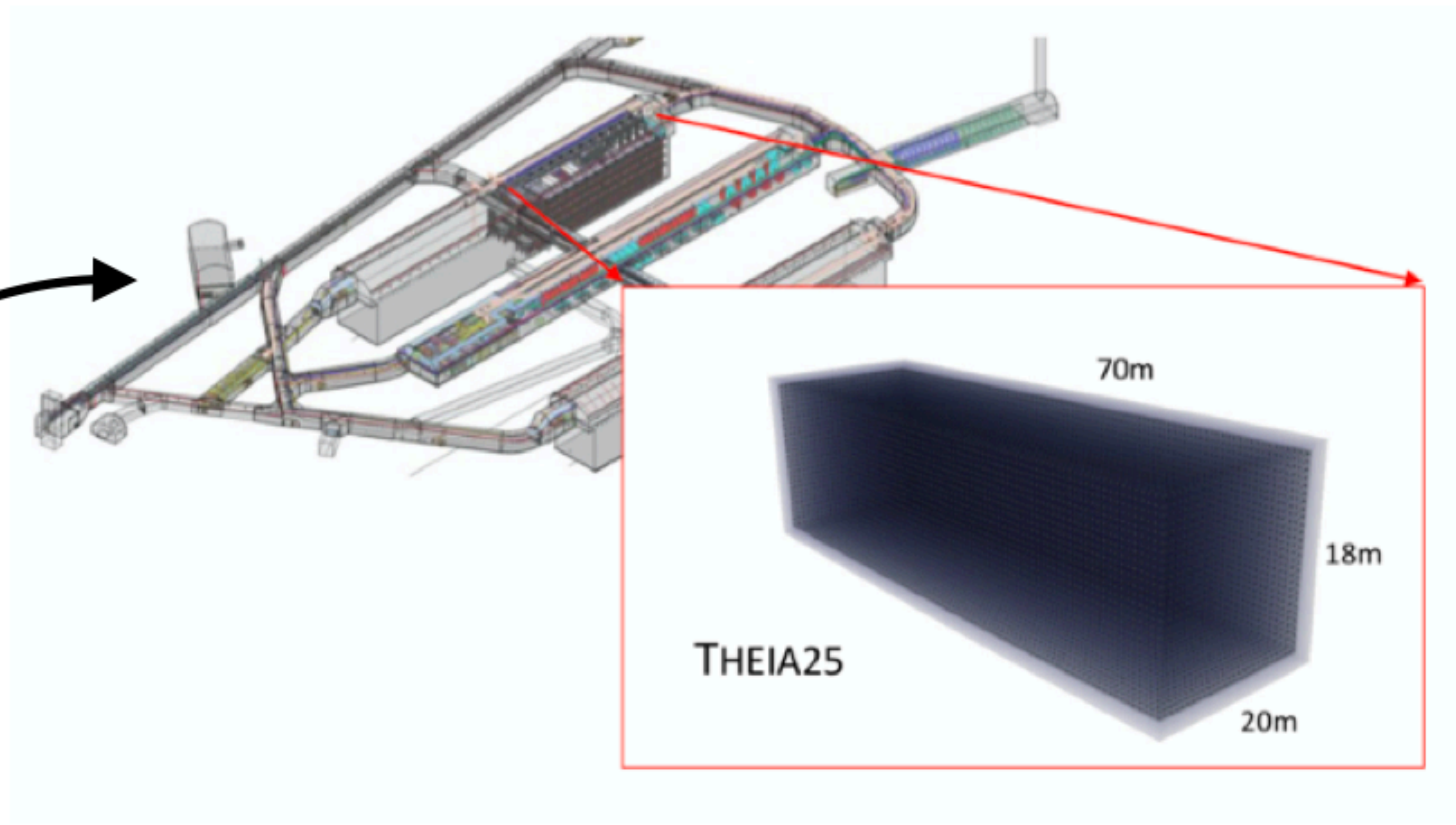


~5000 photosensors
Use of WbLS + fast photosensors in a large detector



AIT - NEO

THEIA25



THEIA100

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

~100,000 sensors
Ultimate application of WbLS to physics use case

Data taking

2021+ 2024+ 20xx

ANNIE @FermiLab

Main Goal:

understanding neutrino-nucleus interactions, focusing on production and multiplicity of final-state neutrons

Show feasibility of WbLS in a neutrino-beam environment

CV

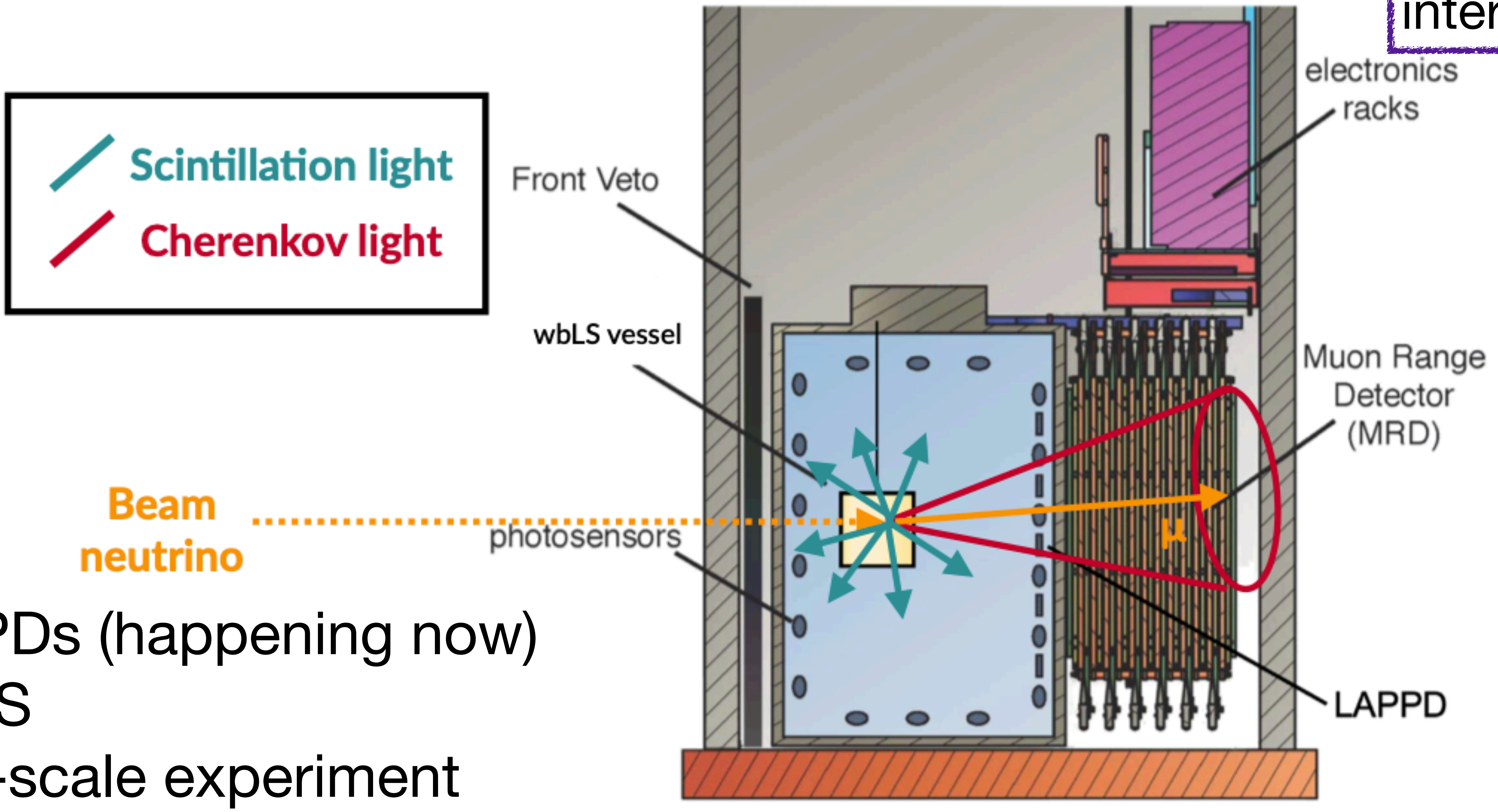
Start of data taking: ~2016 (WbLS ~2021-2022)

Location: Booster Neutrino Beam @ FermiLab (USA)

Water-volume: 26t

WbLS volume: 0.5t

Interests: neutrino-nucleus interactions



WbLS vessel

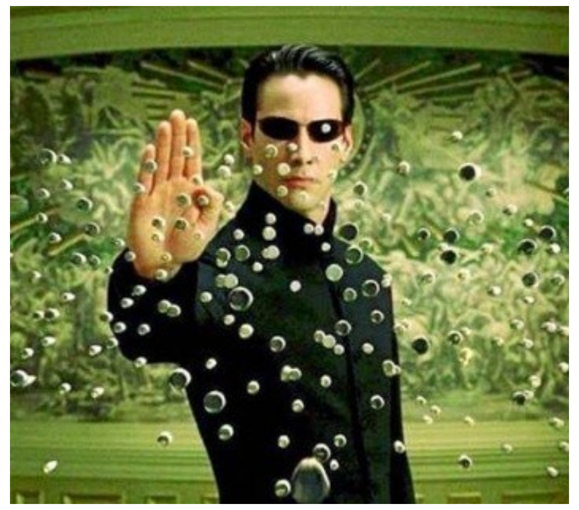
Rough visualization of vessel (NOT final design)

Interest to Theia:

- First deployment of LAPPDs (happening now)
- Deployment of 0.5 t WbLS
- C/S separation in a large-scale experiment
- High and low-energy events reconstruction
- Neutron detection

A.R. Back et al JINST 15 P03011 (2020)
M.J.Minot et al NIM A 787, 78 (2015)

Advanced Instrumentation Testbed Neutrino Experiment One (AIT/NEO)



Neutrino **E**xperiment **O**ne (NEO) the first demonstration of reactor monitoring in the far-field

Main Goal:

non-intrusively detect the ON/OFF power cycle of a single reactor

Interest to Theia:

- Deployment of kt scale WbLS
- Low energy antineutrinos detection in WbLS

CV

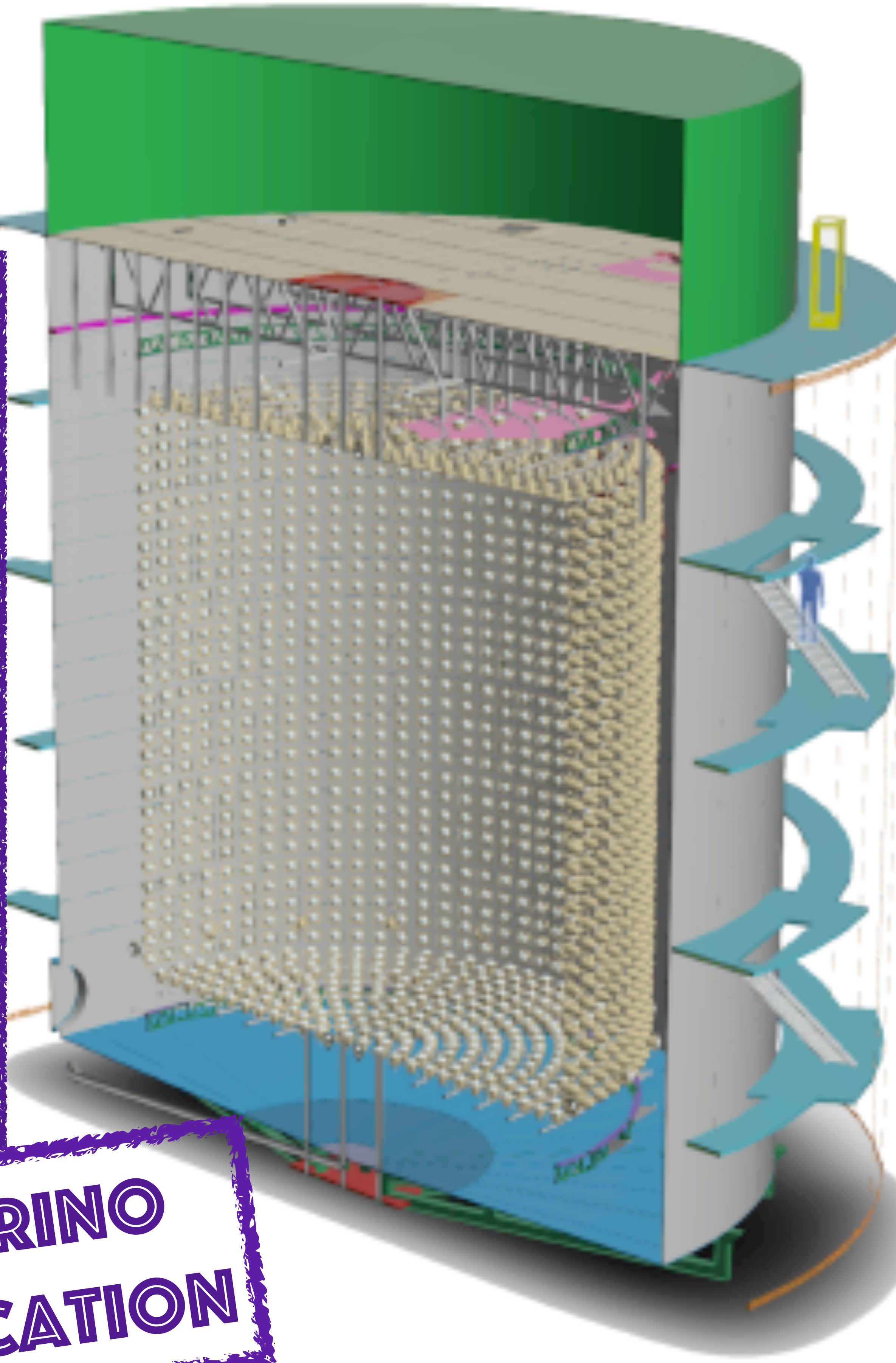
Start of data taking: ~2024

Location: Boulby Underground Lab (UK)

WbLS volume: 1kt

Interests:

Non-proliferation, Solar neutrinos, NLDBD



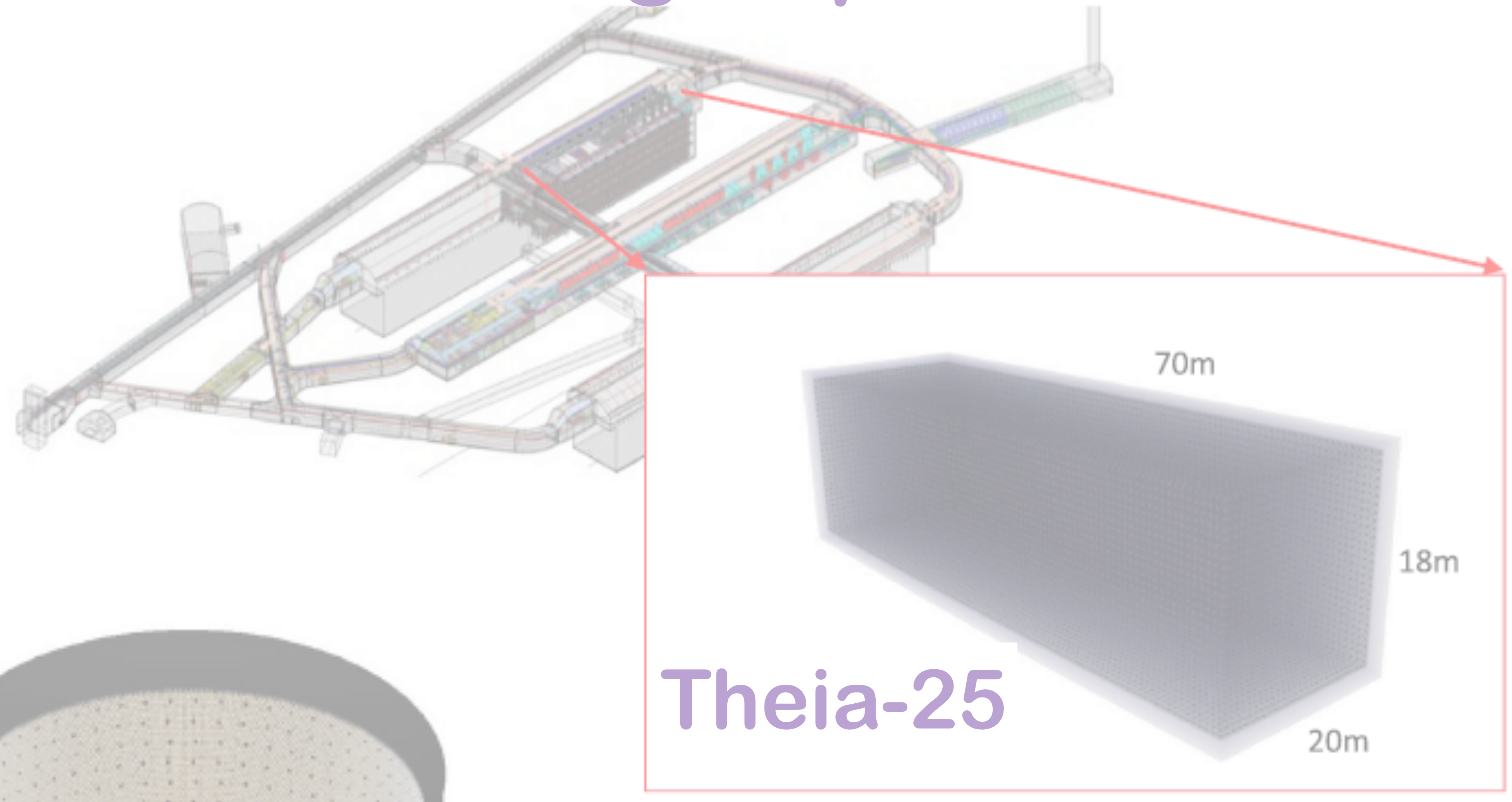
NEUTRINO APPLICATION

M. Askins et al. arXiv:1502.01132

Theia: advanced optical multipurpose neutrino detector

Cutting edge developments in the target material and photodetection

Design options



Large scale, multipurpose detector
- Baseline: 25ktonne (17kt FV)
- Ideal: 100 ktonne (70kt FV)

Broad physics program: Studying neutrino fundamental properties and astrophysical objects

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

Theia: multipurpose neutrino detector

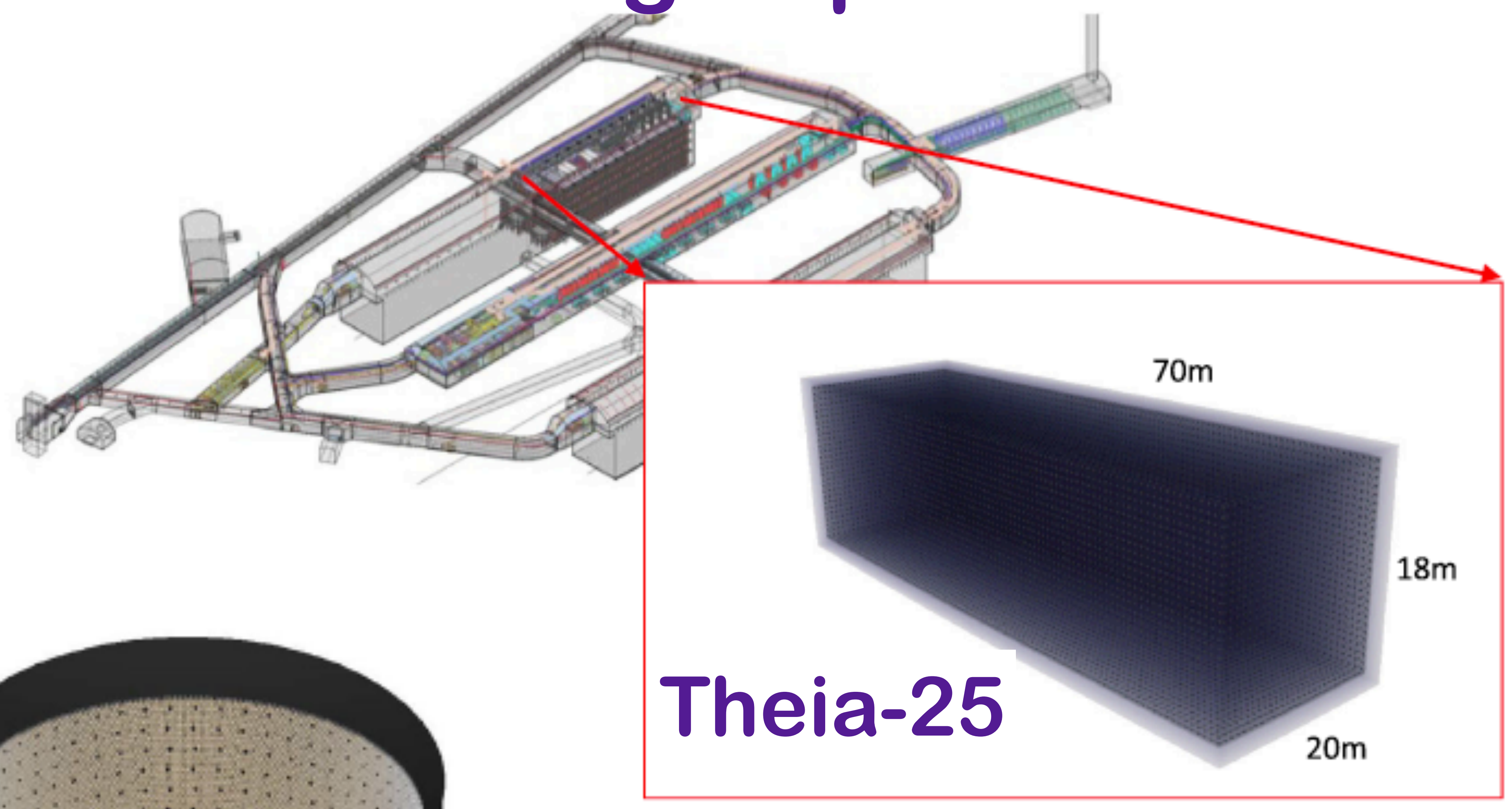
solar neutrinos (CNO, ^{8}B)

geoneutrinos

diffuse supernova neutrinos (DSNB)

supernova burst neutrinos

Design options



Large scale, multipurpose detector
- Baseline: 25ktonne (17kt FV)
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Scintillator fraction tunable depending on the physics goal ->staged approach

neutrino mass ordering

neutrino CP-violating phase δ

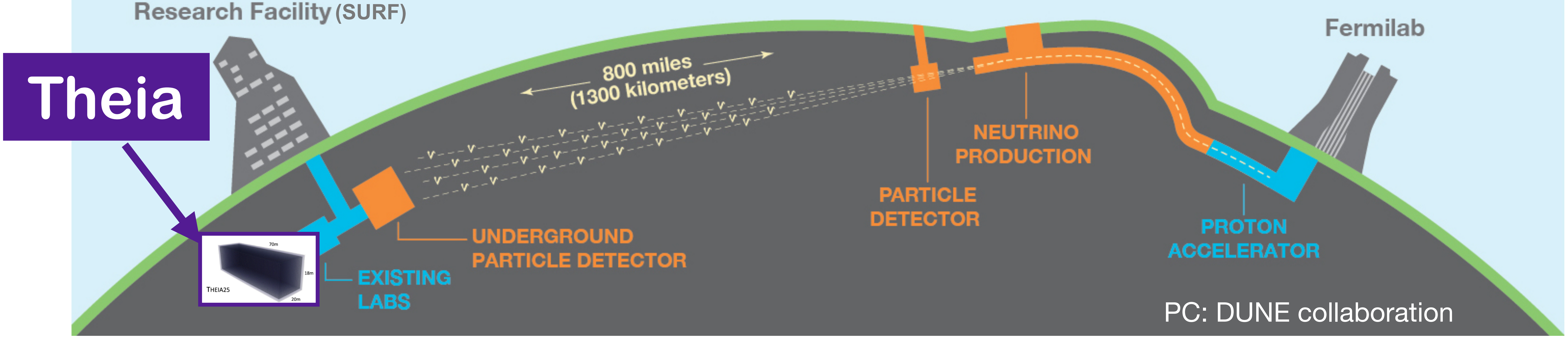
neutrinoless double beta decay

nucleon decay

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

Theia-25 at long baseline neutrino facility (LBNF)

Can be located at fourth Deep Underground Neutrino Experiment (DUNE) cavern (Depth: 4300 m.w.e.)



PC: DUNE collaboration

Phase I

- Using Fermilab's LBNF neutrino beam for **long-baseline neutrino oscillation measurements**
- Precision measurement of neutrino CP-violating phase δ

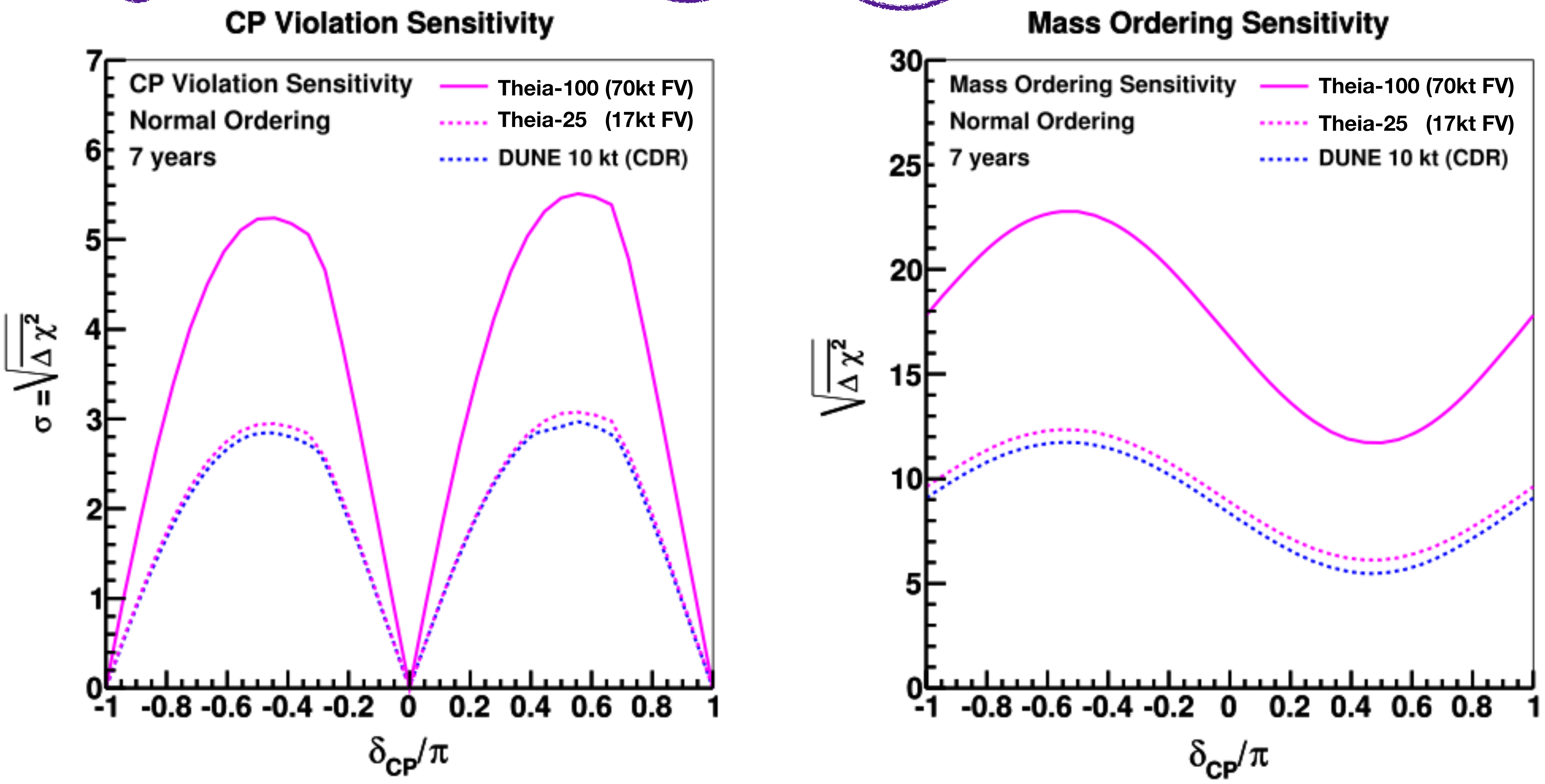
Theia: oscillation parameters

Phase I

Theia can complement DUNE measurements (same location, different target, systematics) - important cross-check

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - 2sin(2\theta_{23})sin^2\frac{1.27\Delta m^2_{32}L}{E} + f(\delta_{CP}) + \mathcal{O}(\theta^2_{13})$$

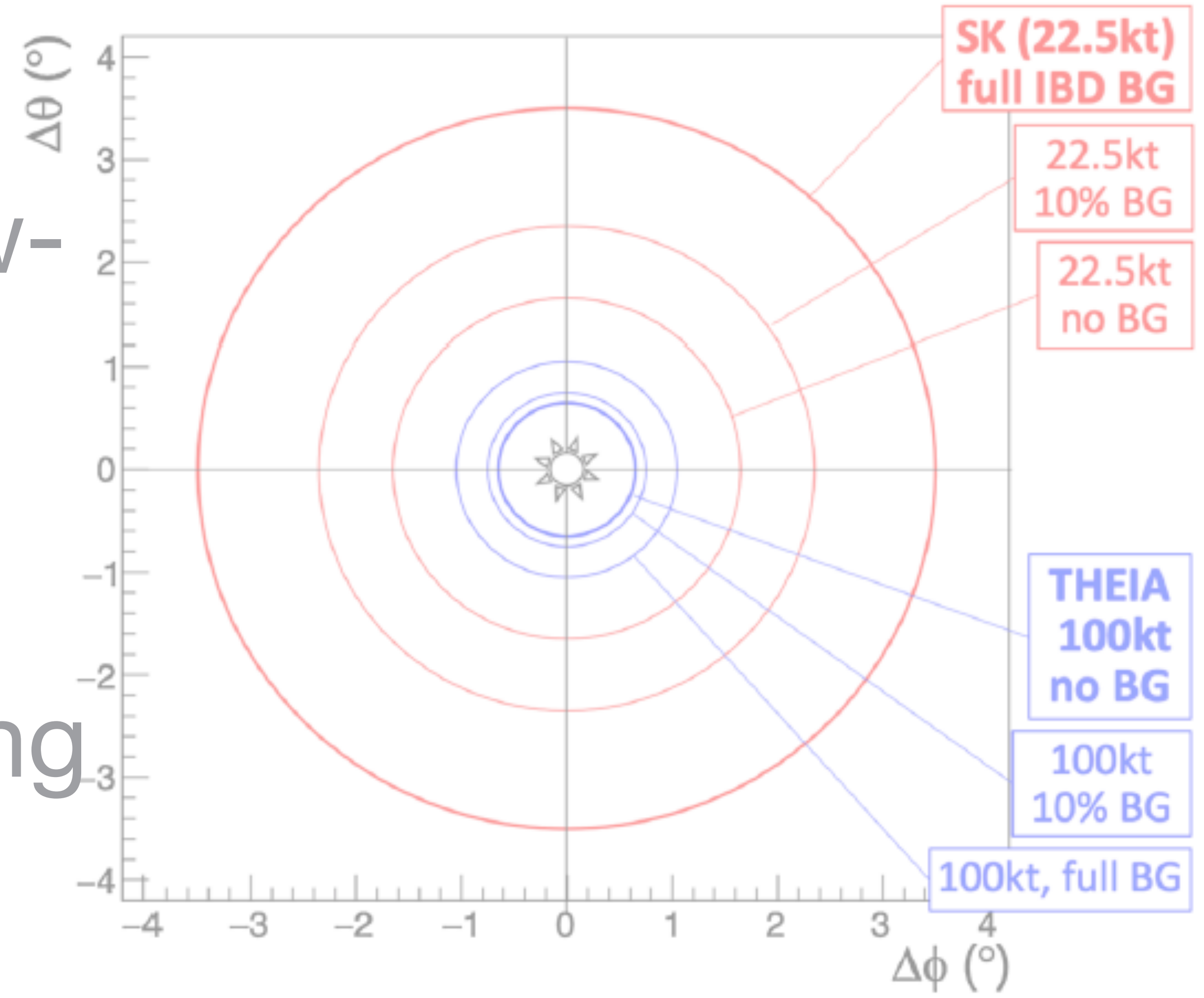
- Comparison of the unoscillated flux (measured close to the beam source) and oscillated flux at far distance.
- Combination of 3D scintillator tracker with Theia more similar to T2K
- Long baseline (1300km): more matter -> more sensitivity to mass hierarchy
- $> 5\sigma$ for 30% of δ_{CP} values (524 kt-MW-year)



M. Askins, Z.Bagdasarian et al Eur. Phys. J. C 80, 416

Theia: supernova neutrinos

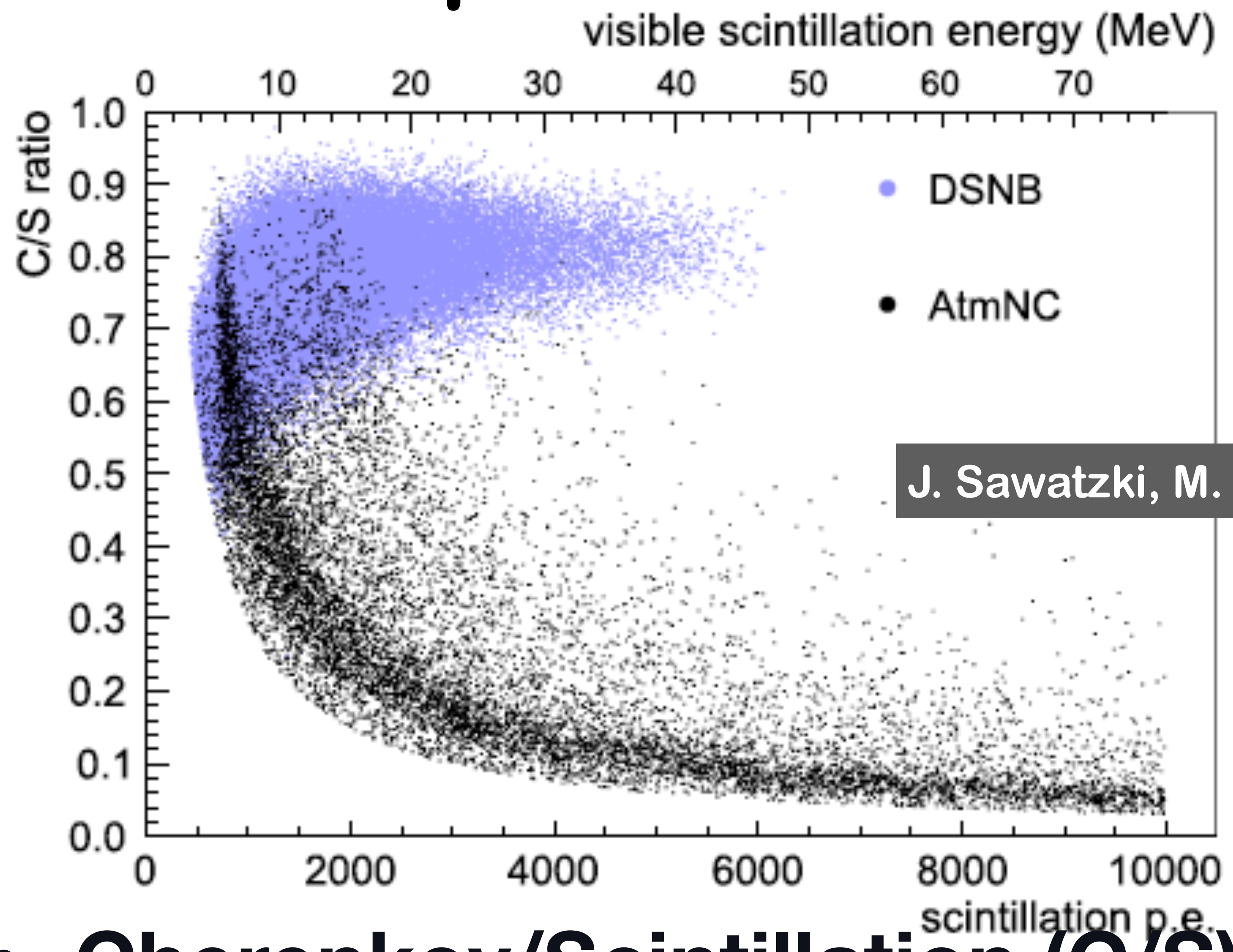
Supernova (SN) burst neutrinos



- High statistics low-threshold
- Flavor-resolved neutrino spectra
- Supernova pointing

- **At LBNF:** the combination of WbLS (THEIA) and liquid argon (DUNE) detectors at the same site -> high-statistics co-detection of neutrinos and antineutrinos.
- Complementarity to JUNO and Hyper-K: opposite side of the Earth -> Earth matter effects
- Pre-supernova neutrinos

Diffuse supernova neutrino background (DSNB) Diffuse, isotropic flux of ν from all SN explosion in the Universe.

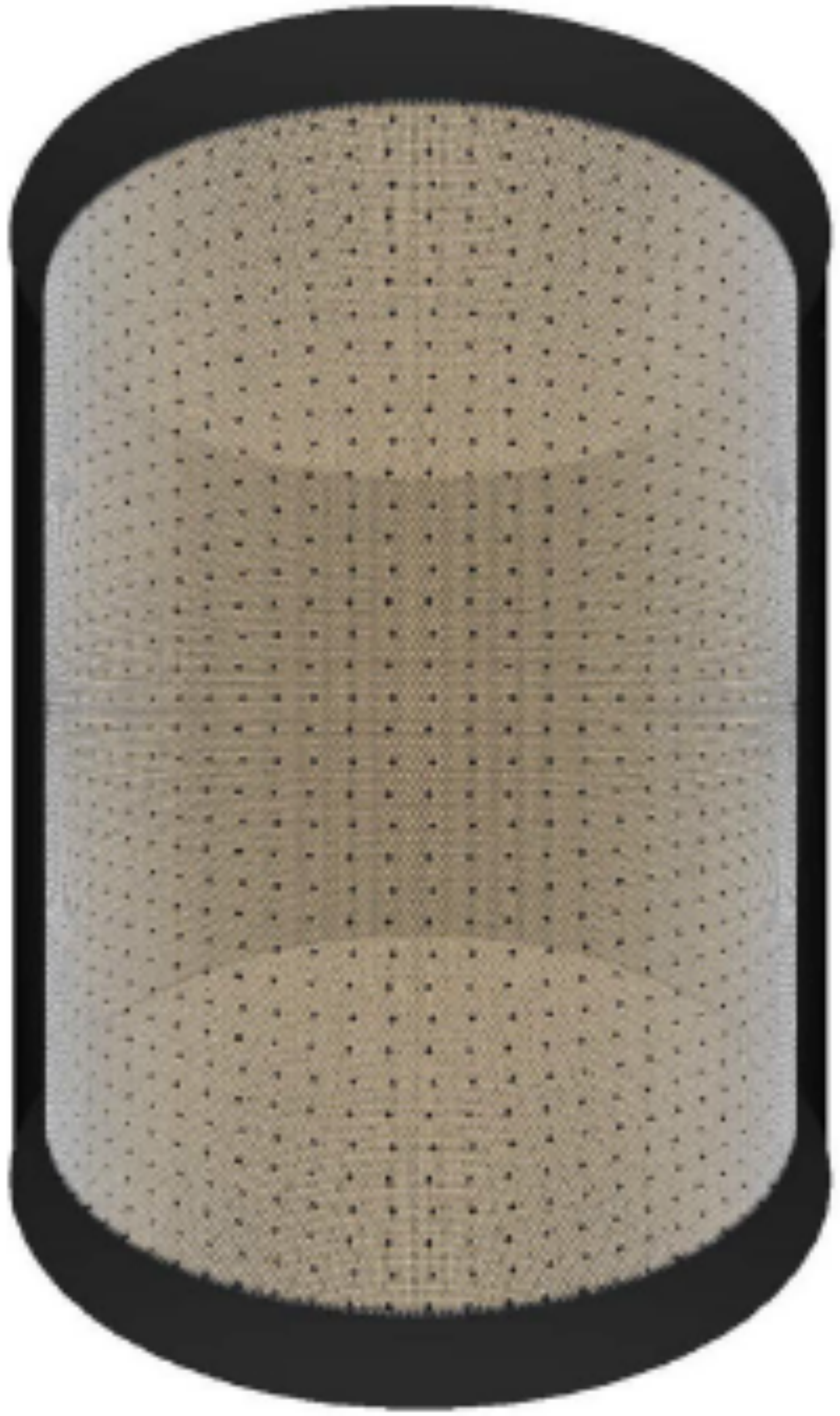


J. Sawatzki, M. Wurm et al Phys. Rev. D 103, 023021

- **Cherenkov/Scintillation (C/S) ratio** gives a powerful handle to discriminate atmospheric neutral current background signals;
- substantial increase in event statistics when added to Super-K and JUNO;
- 5σ discovery (125 kton-year): ~8 years (Theia-25) or ~2 years (Theia-100)

M. Askins, Z.Bagdasarian et al Eur. Phys. J. C 80, 416

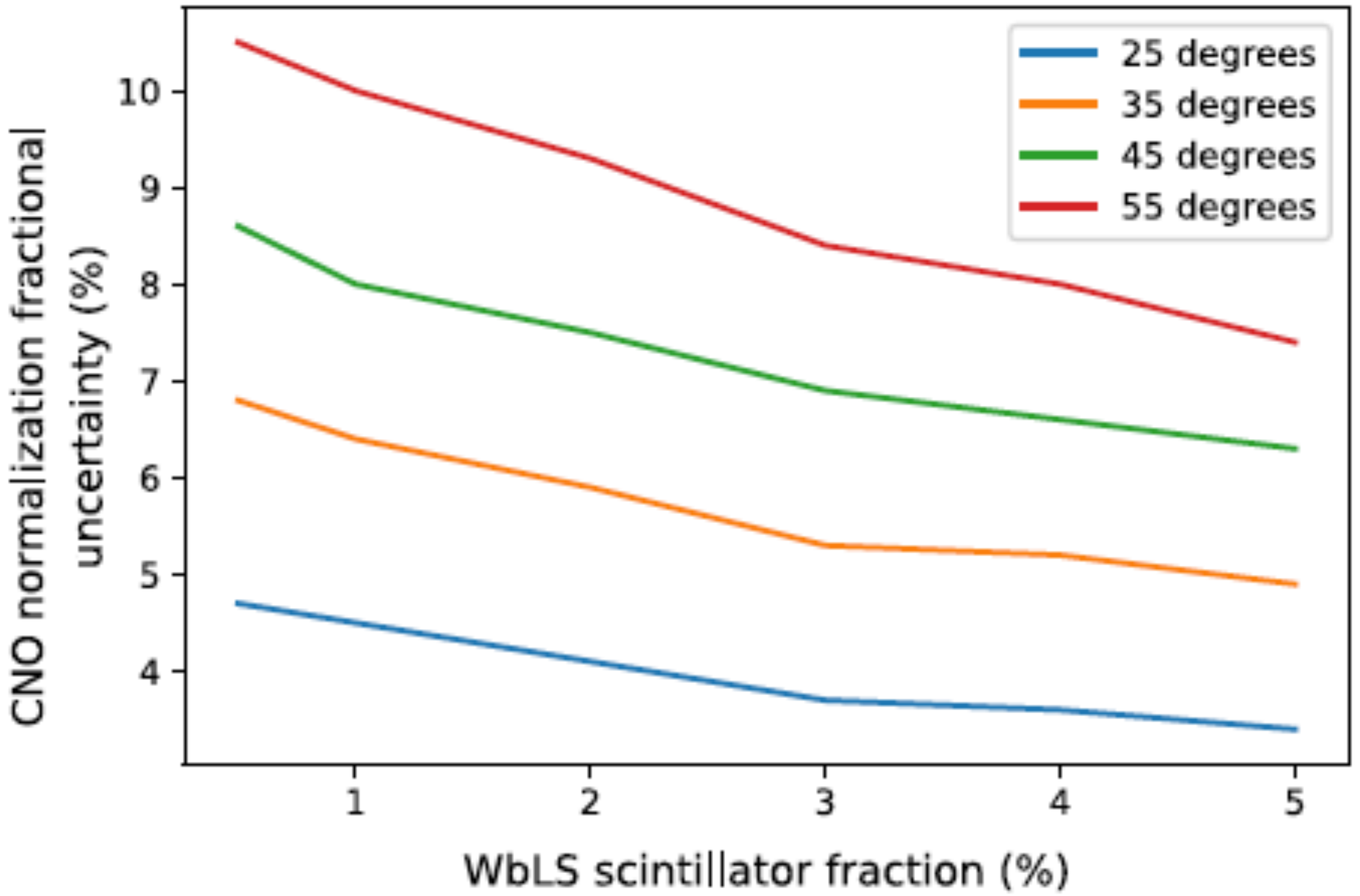
Theia: solar neutrinos



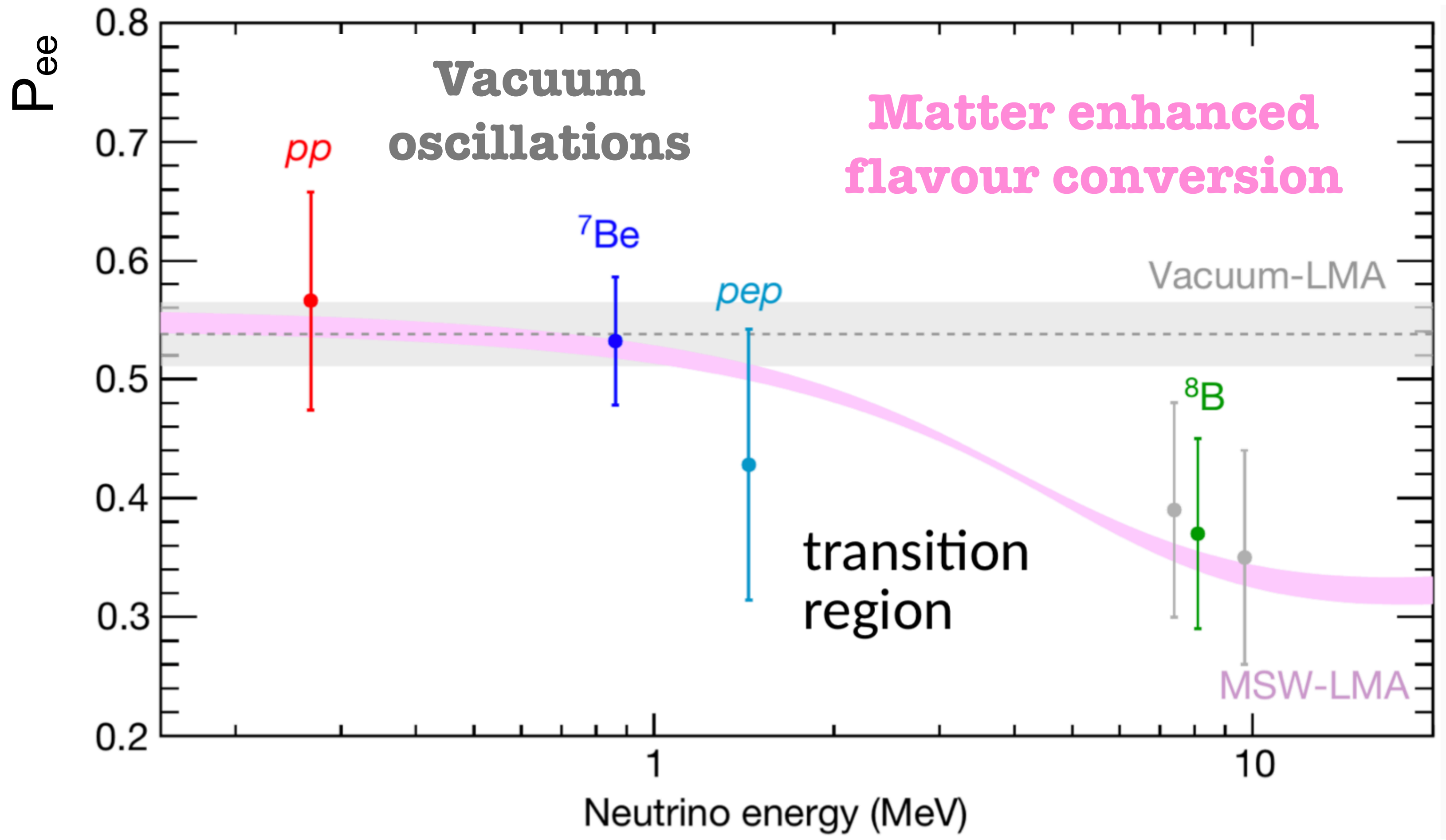
Theia can continue Borexino's solar legacy:

- CNO neutrinos (directionality based background rejection, solar metallicity puzzle)

- ^{8}B solar neutrinos high-statistics, low-threshold -> new physics in the MSW-vacuum transition region



M. Askins, Z.Bagdasarian et al Eur. Phys. J. C 80, 416



Borexino measurements Nature 562, p 505

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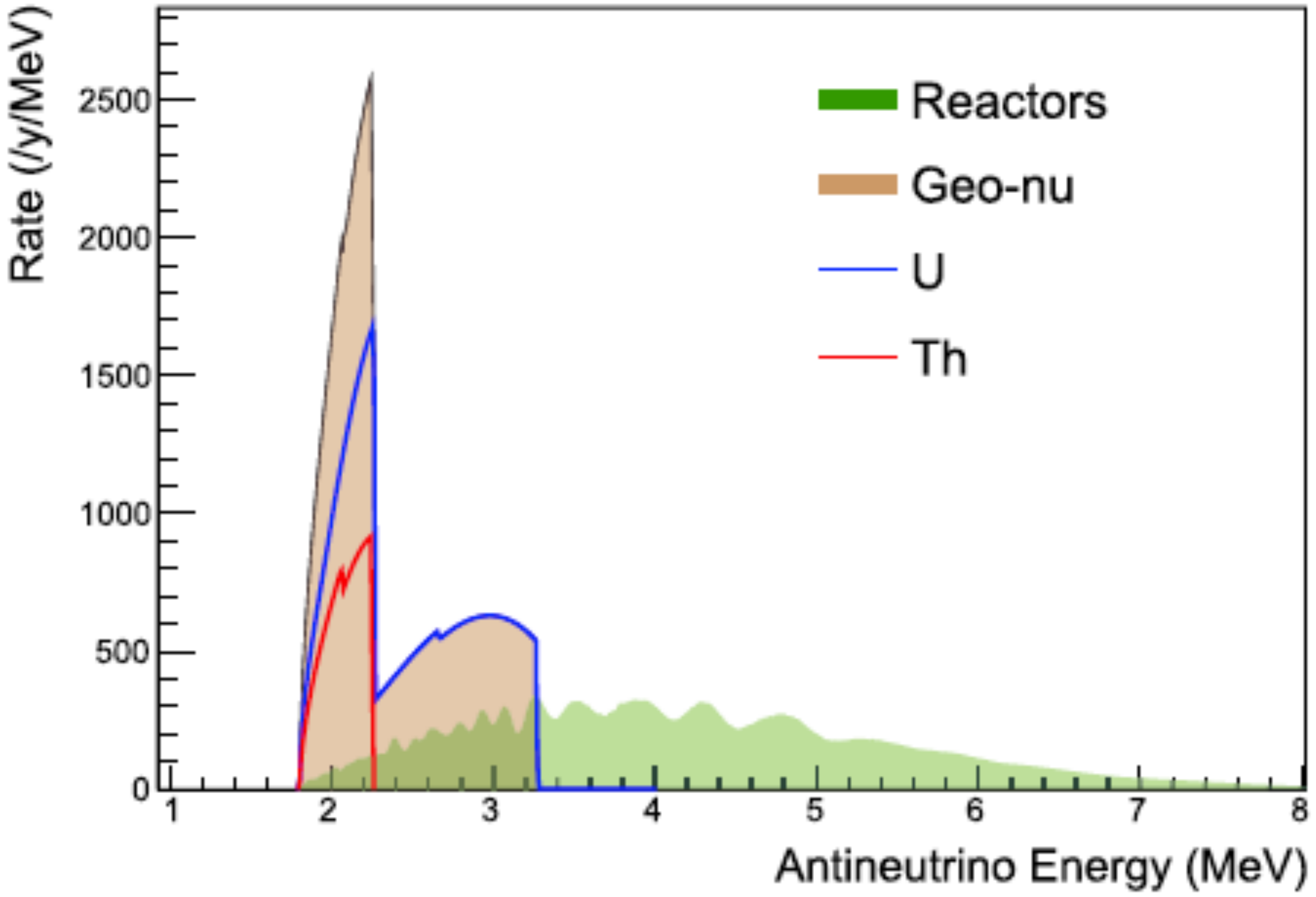
Theia: Geoneutrinos

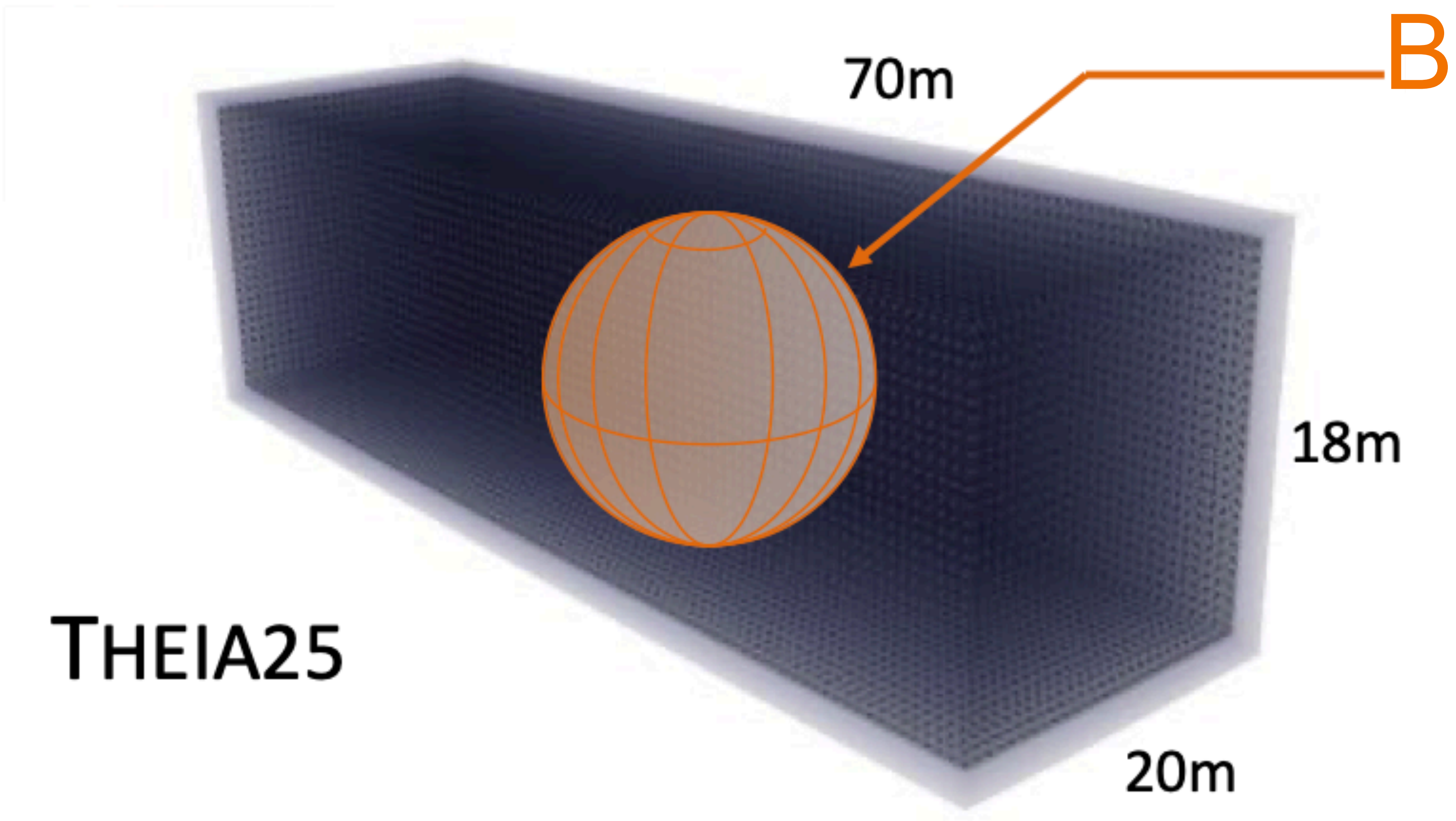
Phase II



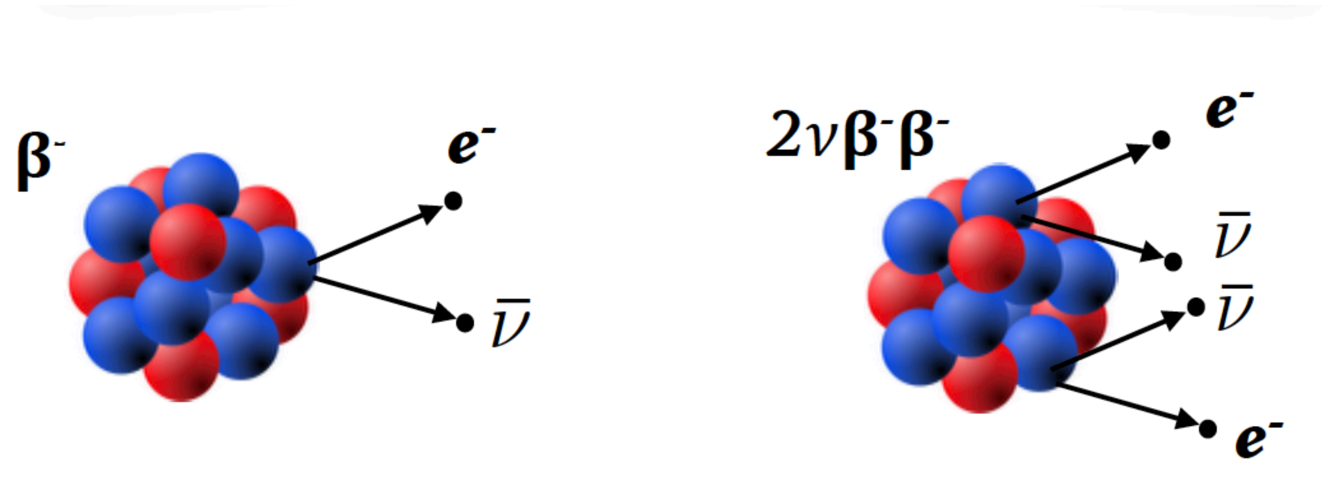
- Rate at Sanford Underground Research Facility (SURF): 26.5 interactions per kT-year
- High statistics (in comparison with existing two measurements)
- Explore geographical variations of the geoneutrino flux

Analysis of antineutrino capabilities of Theia is in preparation

Theia: Neutrinoless Double Beta Decay



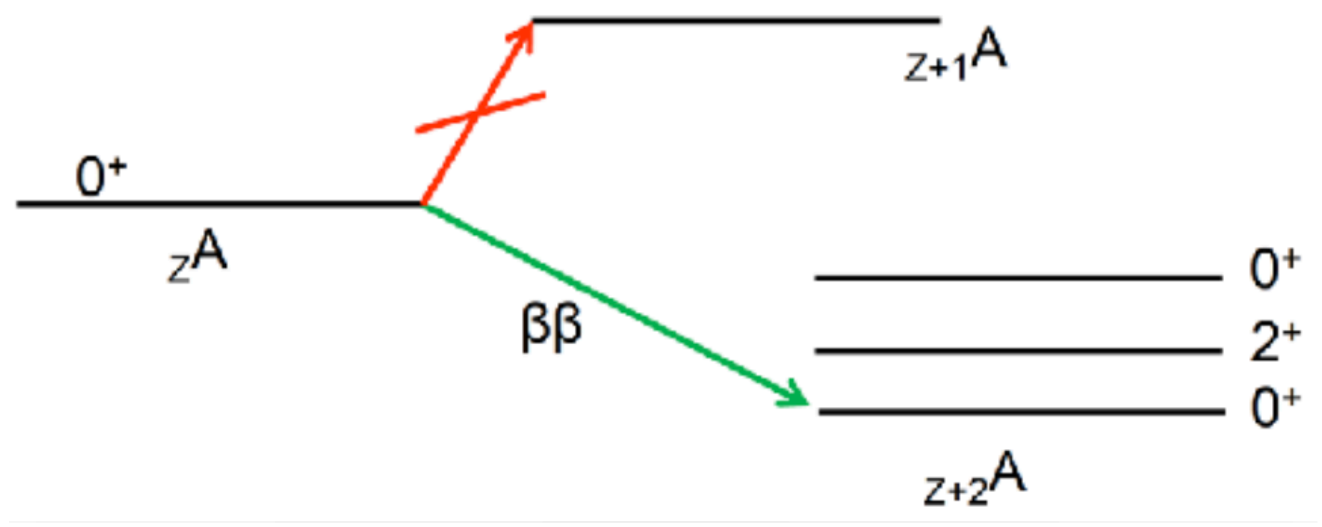
Balloon for $0\nu\nu\beta$ isotope loaded liquid scintillator



Processes within the Standard Model

Neutrinos are their own antiparticles
Lepton number is not conserved

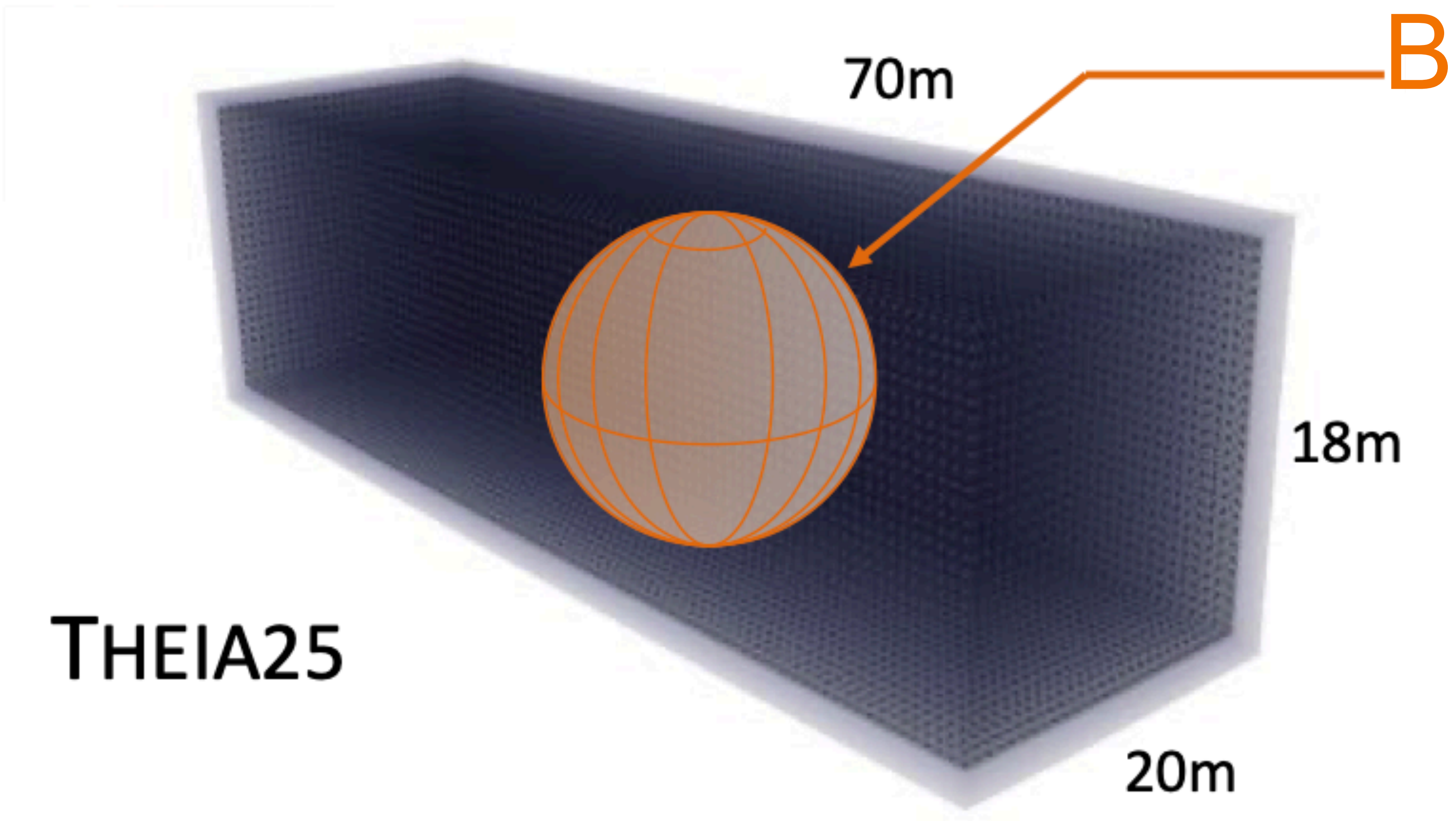
Elements for which normal beta decay is suppressed:
Germanium, Xenon, Tellurium



- violation of total lepton number conservation
- absolute neutrino masses
- mass ordering

Theia: Neutrinoless Double Beta Decay

Phase III

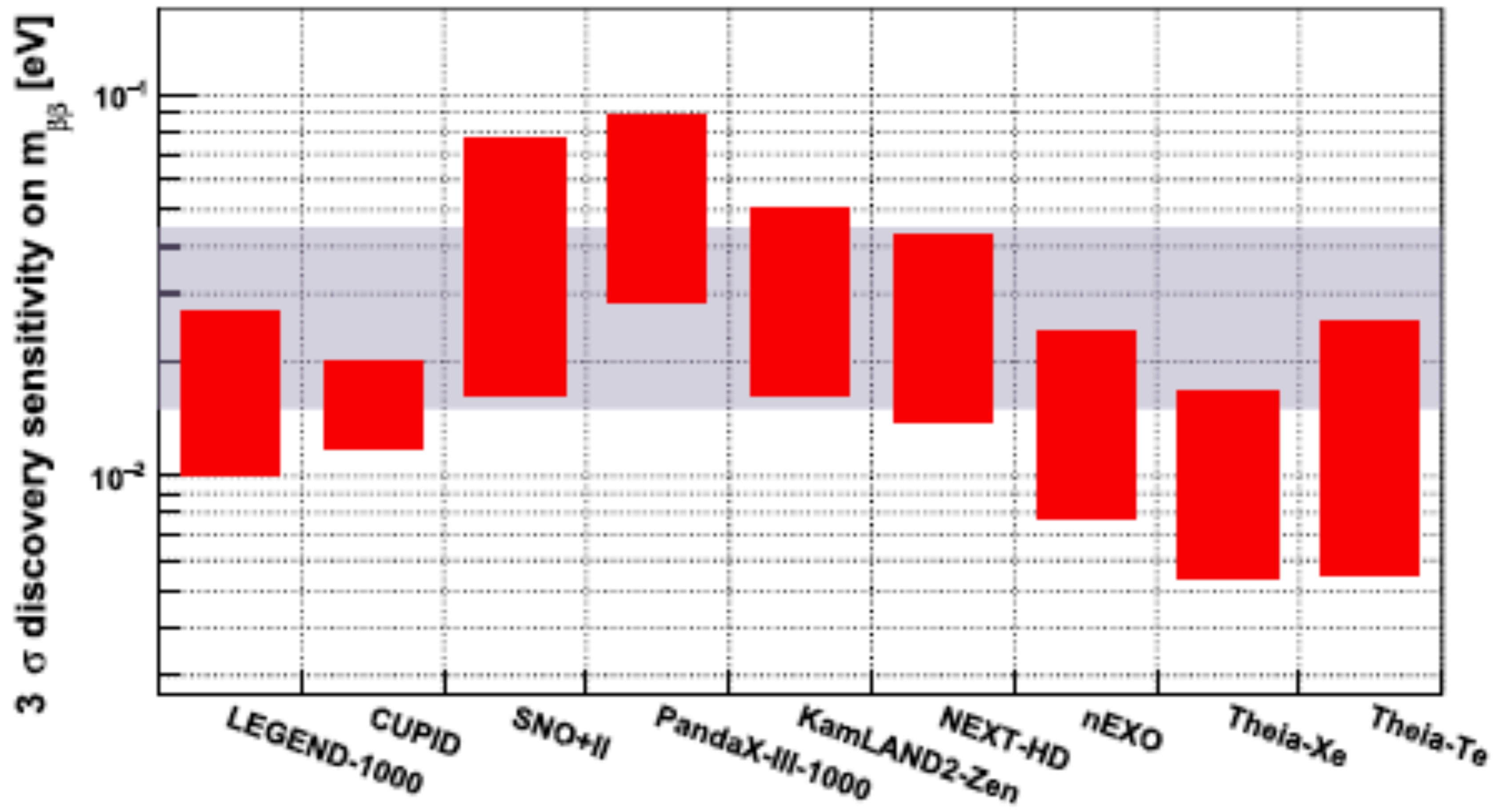


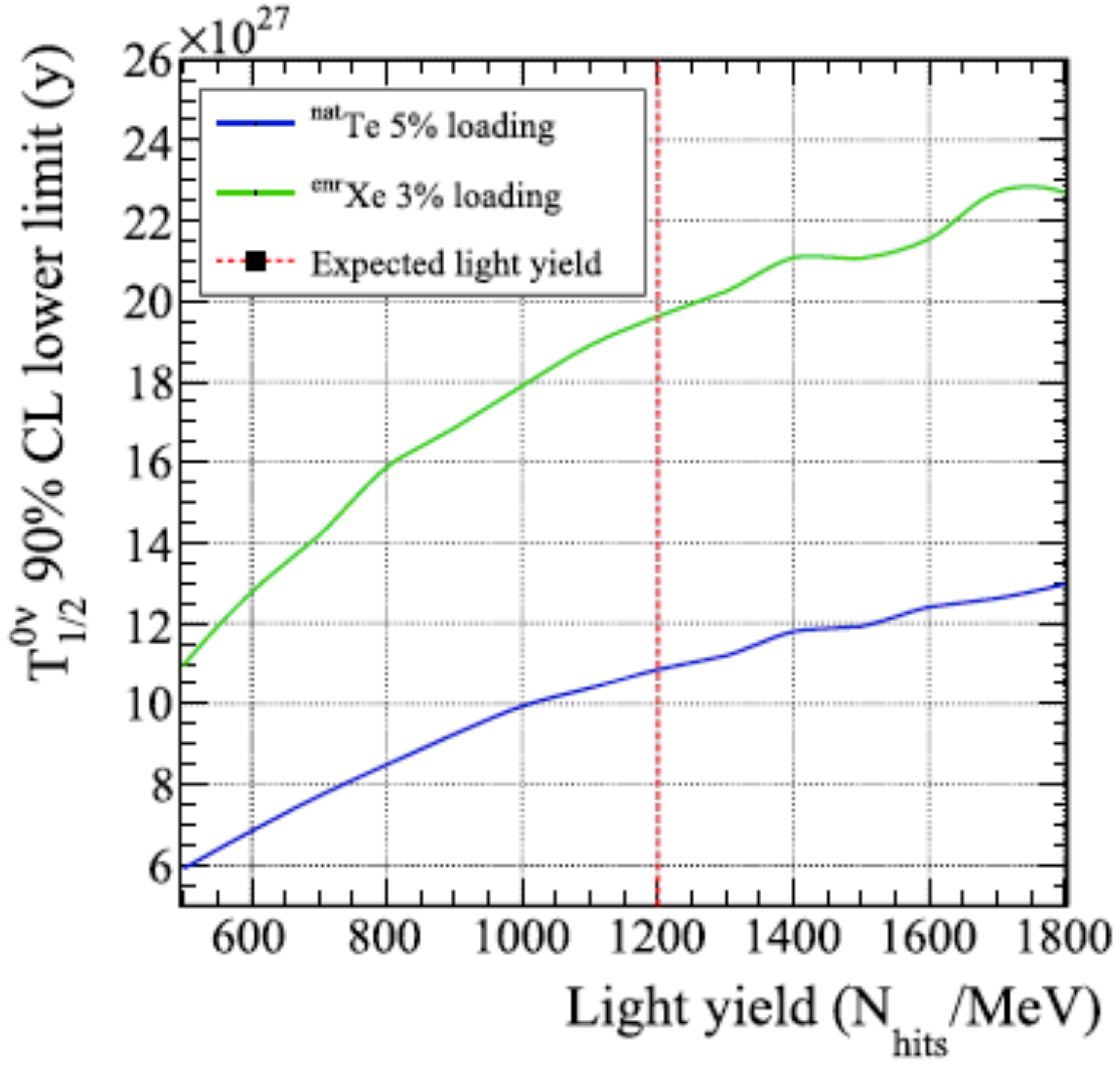
Balloon for $0\nu\nu\beta$ isotope loaded liquid scintillator

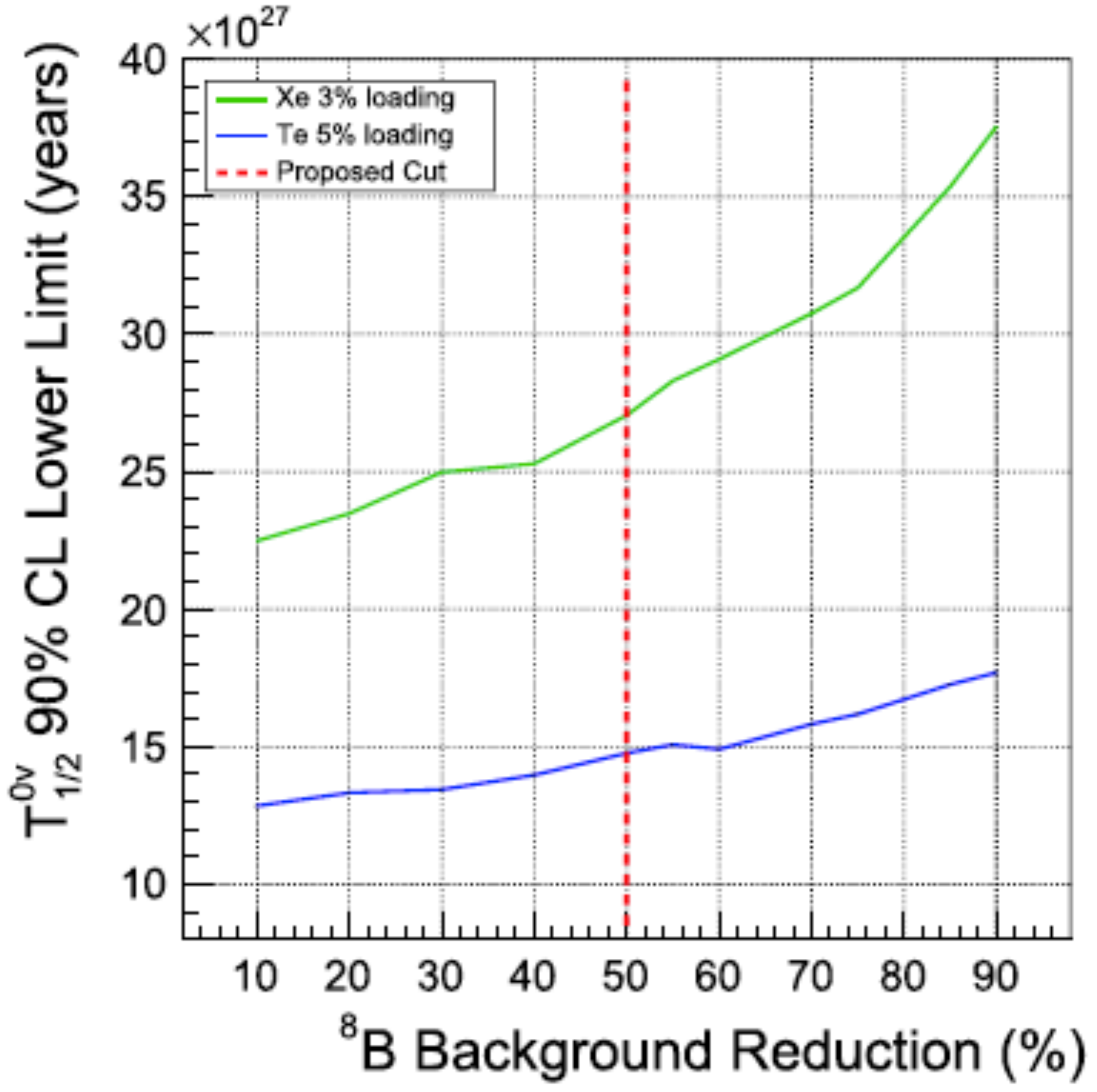
Isotopes in consideration: ^{136}Xe and ^{130}Te

Goal: Reach $T^{0\nu2\beta}_{1/2} \sim 10^{28}$ years

Fiducialization and tagging techniques (triple coincidence, directionality, etc..) greatly reduce backgrounds







Theia: staged approach to physics goals

Phase I — Using Fermilab's neutrino beam

Phase II

Phase III

Primary physics goal	Reach	Exposure/assumptions
Long-baseline oscillations	$>5\sigma$ for 30% of δ_{CP}	524kt-MW-year
Nucleon decay	T>3.8 x 10^{34} year	800 kt-year
Supernova burst	<1(2)° pointing 20K(5K) events	100(25)kt, 10kpc SN
Diffuse Supernova Neutrino Background	5σ	125kt-year
CNO neutrinos	<5(10)%	300(62.5)kt-year
Geoneutrinos	2650 events	100 kt-year
$0\nu\nu\beta$	$T_{1/2} < 1.1 \times 10^{28}$ year (90%C.L.)	800 kt-year (Multi-tonne loaded LS in suspended vessel search)

$ND : p \rightarrow \bar{\nu} K^{+}$

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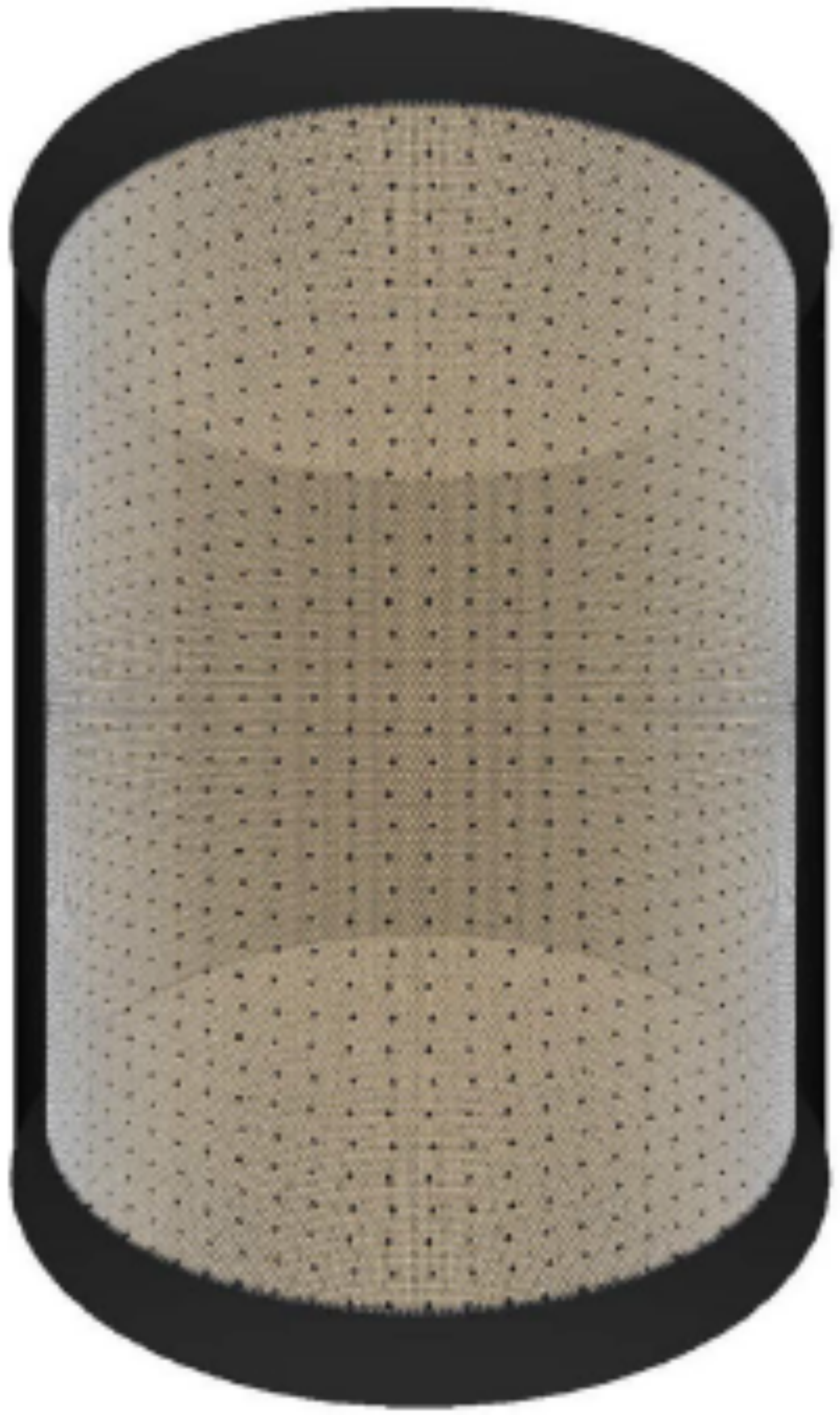
M. Askins, Z.Bagdasarian et al Eur. Phys. J. C 80, 416

Conclusions

- Progress in the **novel target materials and photodetector technologies** opened the path for the **next-generation neutrinos experiments**
- **Theia** will employ the **advantages of these developments**

  to **achieve**: *low energy threshold, good energy and position resolutions, directionality, large exposure*

  and **to tackle a broad physics agenda:** *neutrino oscillations, solar, supernova neutrinos, and neutrinoless double beta decay*



Thank you for your attention!

QUESTIONS ARE WELCOME
now

or later
@ZaraBagdasarian
zara.bagdasarian@berkeley.edu
https://www.zarabagdasarian.com

Berkeley
UNIVERSITY OF CALIFORNIA