Towards Theia: advanced optical neutrino detector

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EPAP Seminar at King's College London
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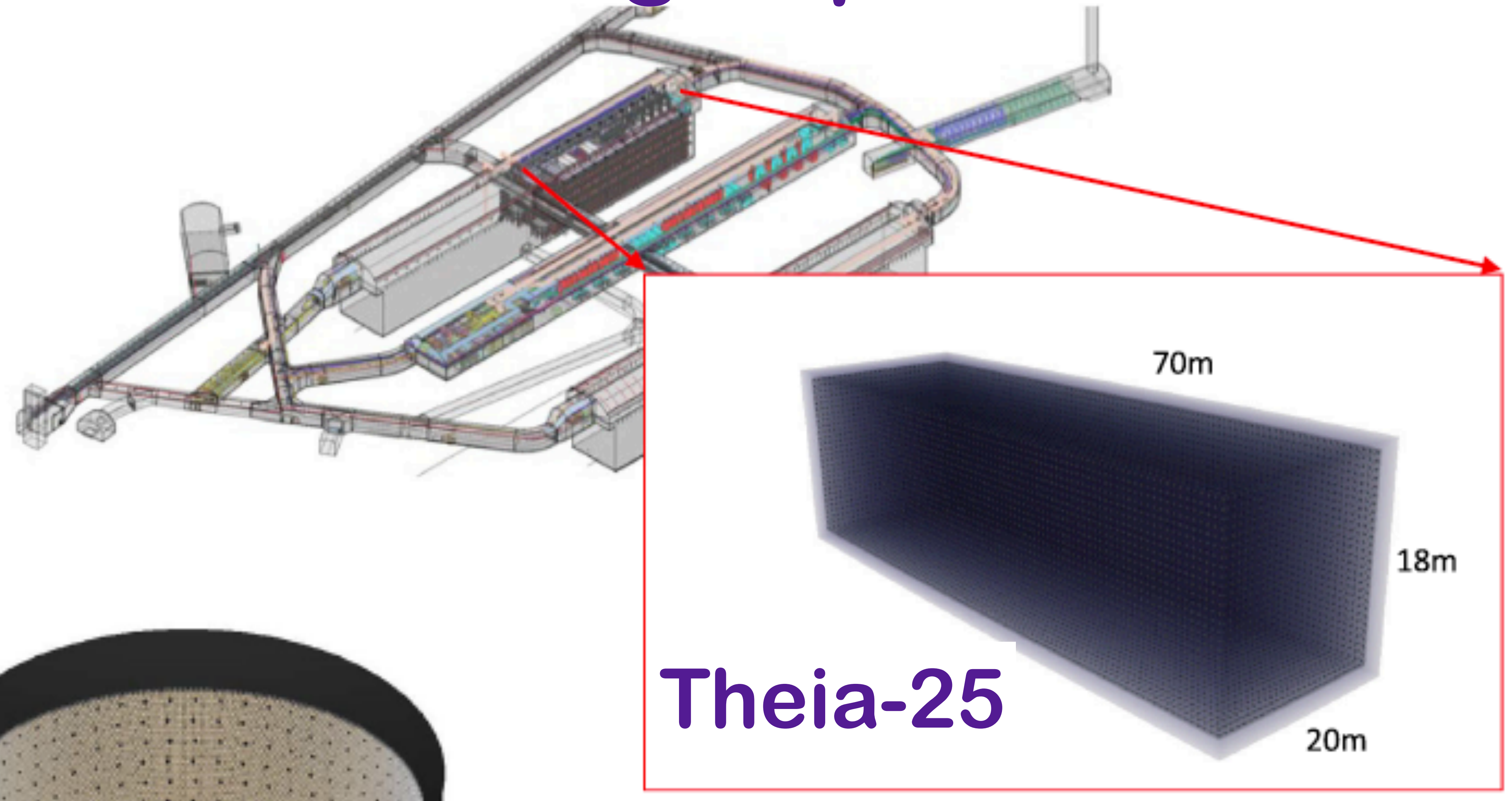
BERKELEY LAB

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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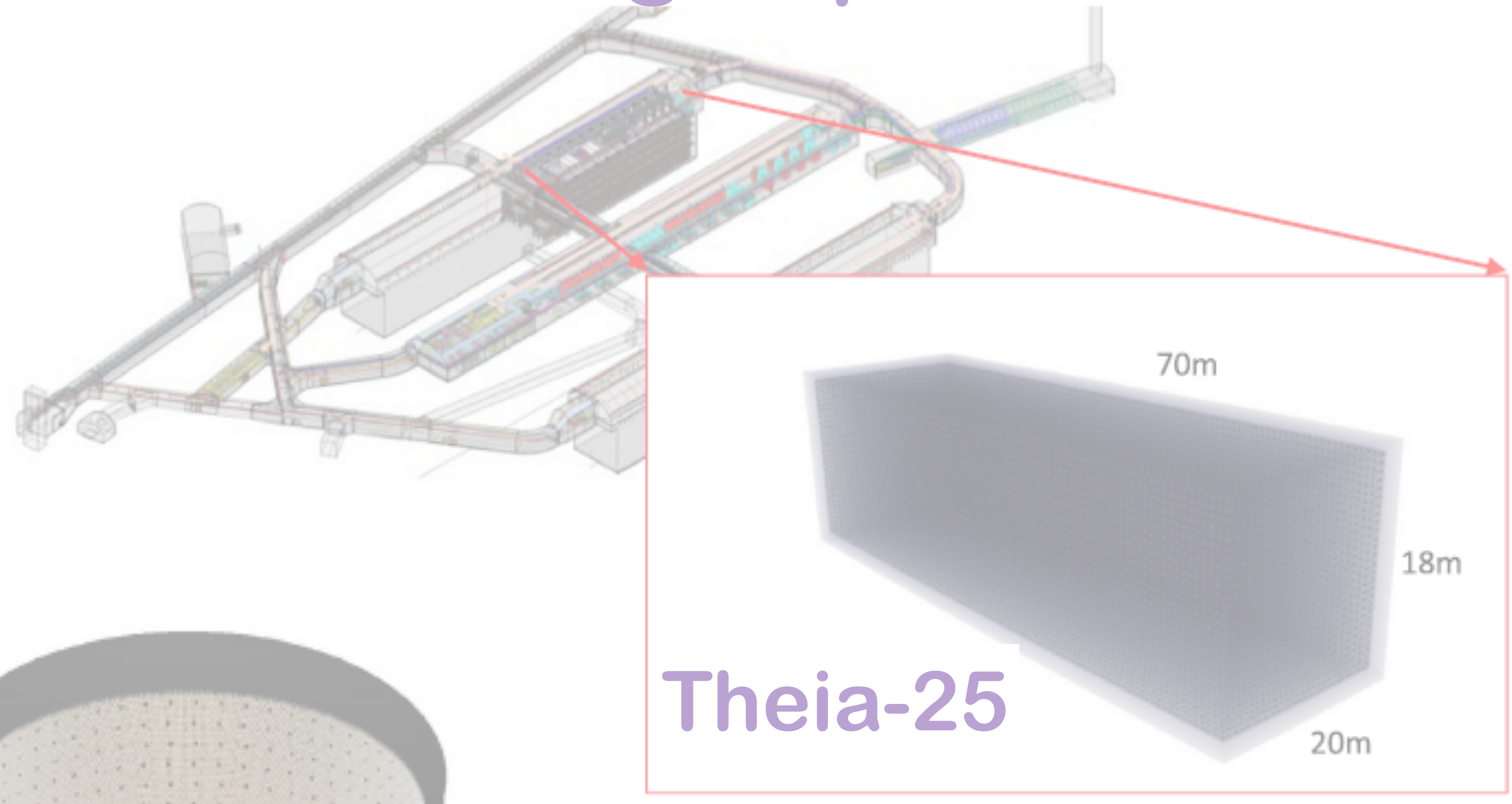

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How to broaden the current physics reach

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

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

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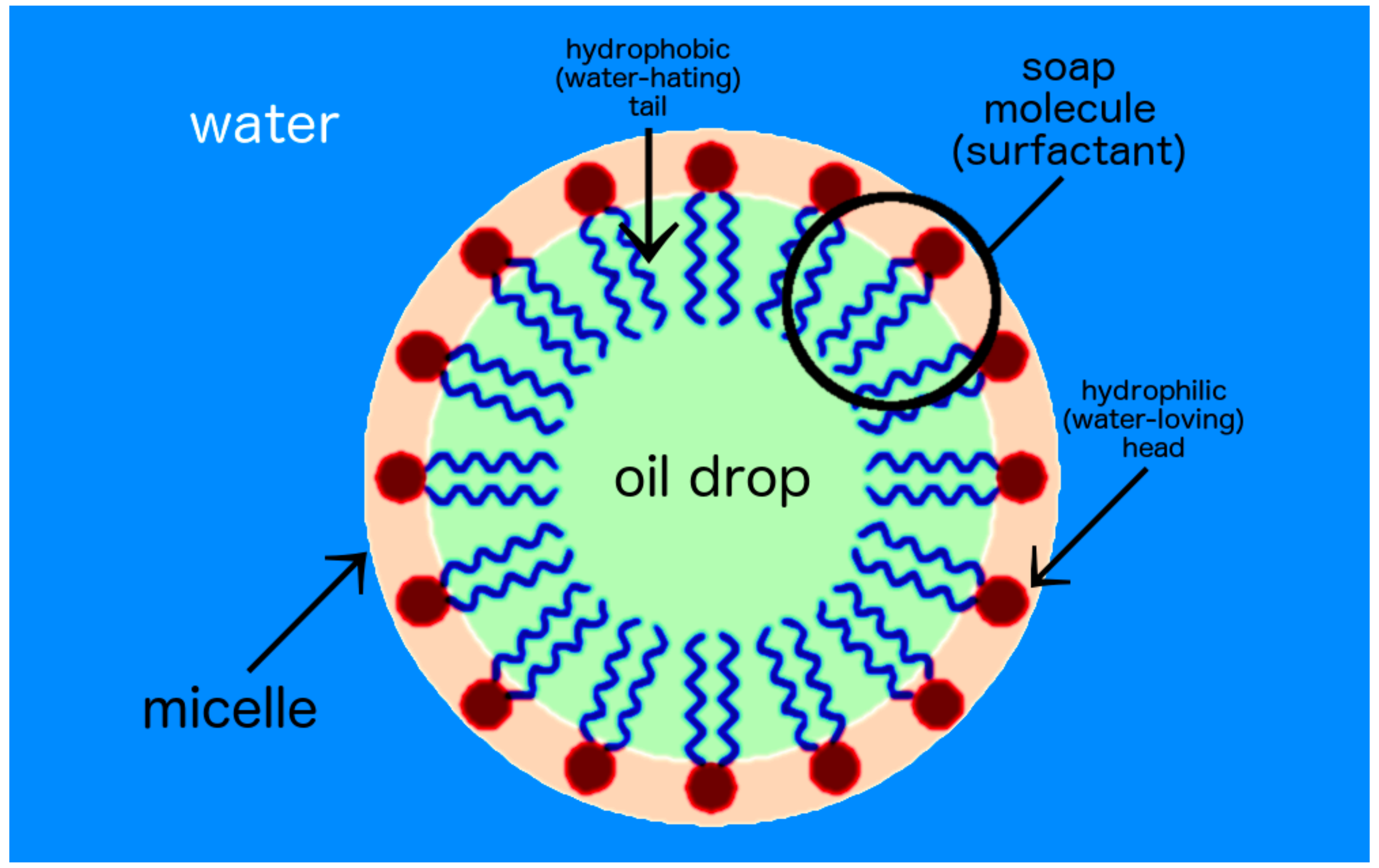
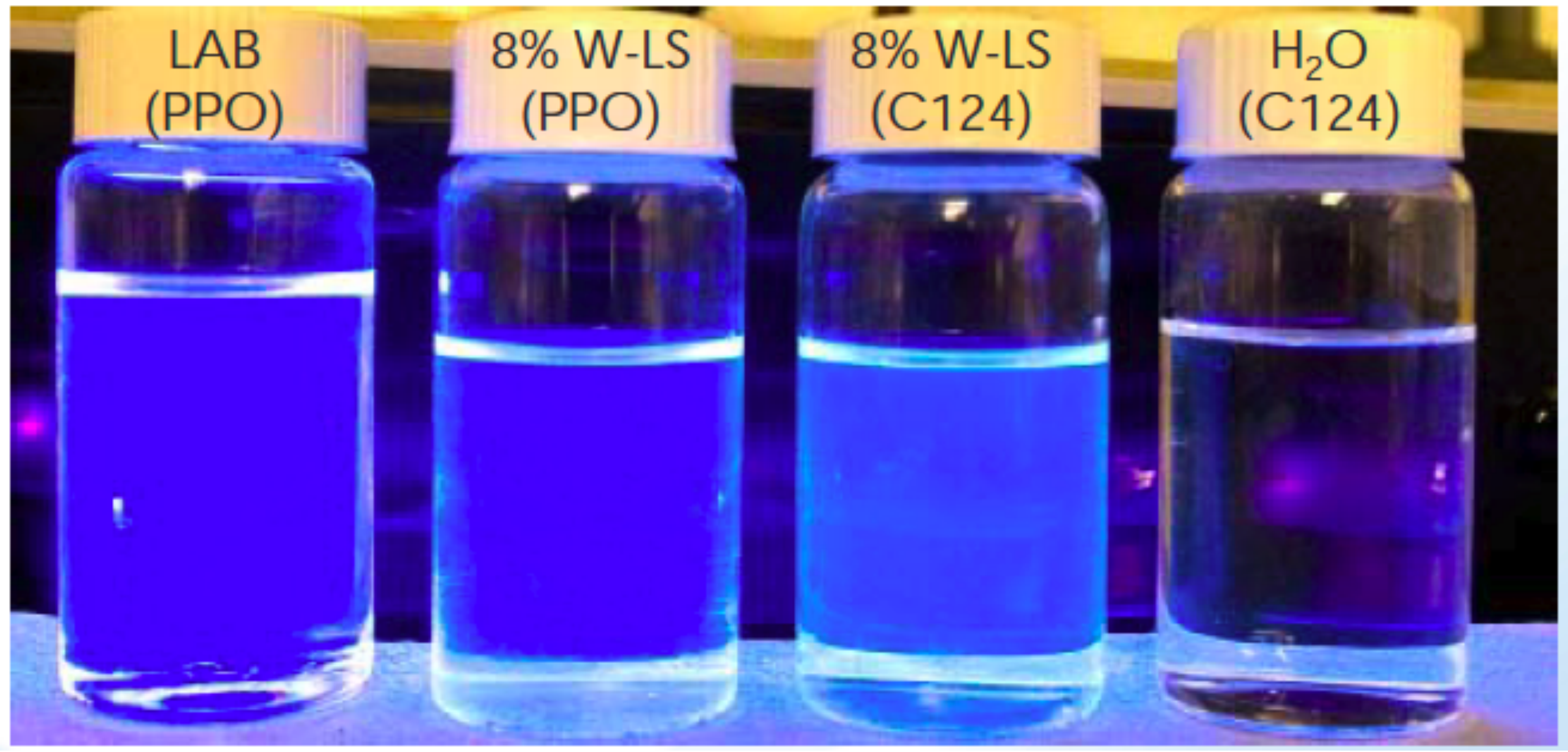
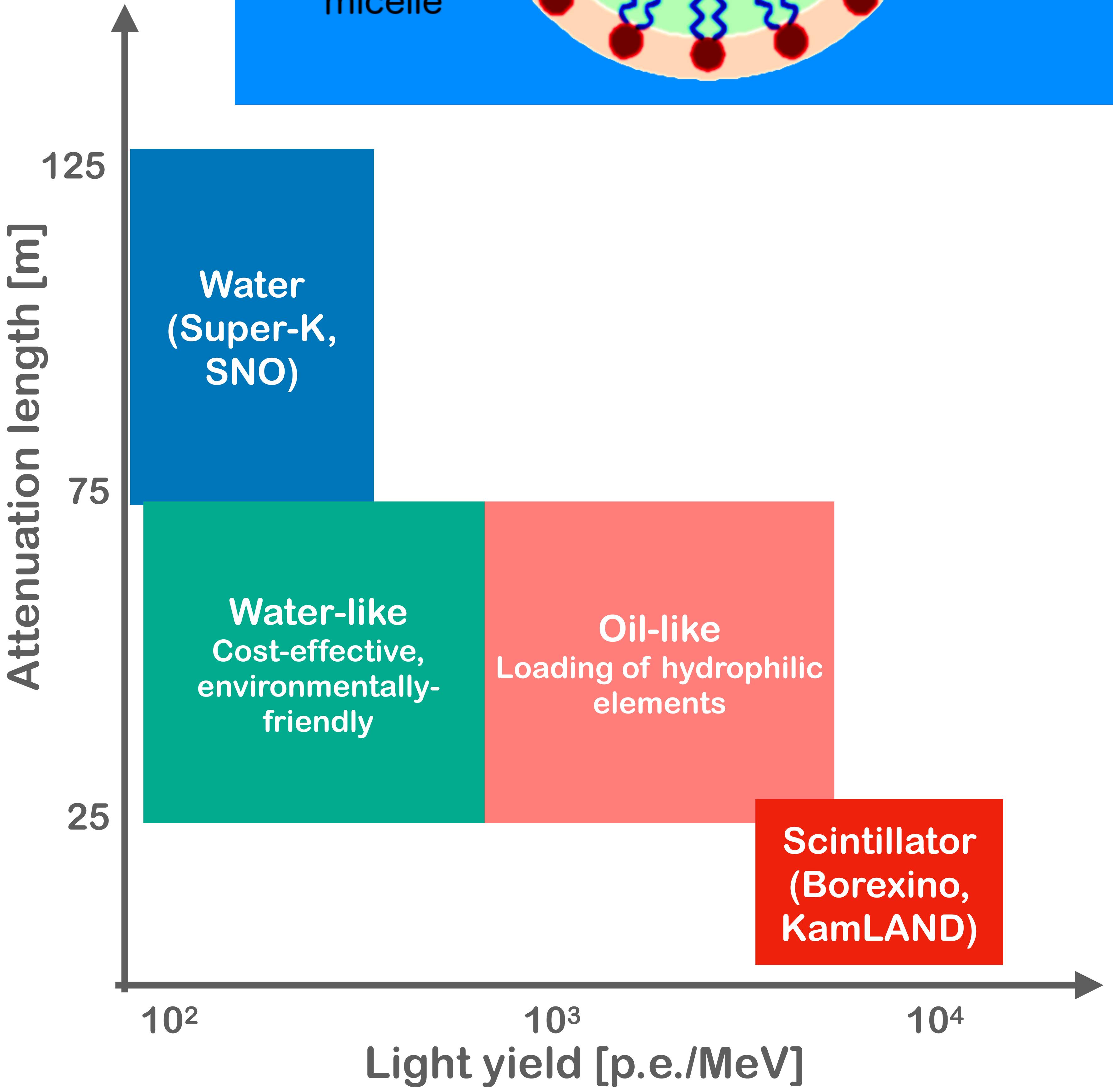
Water-based Liquid Scintillator - Basics

- 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)







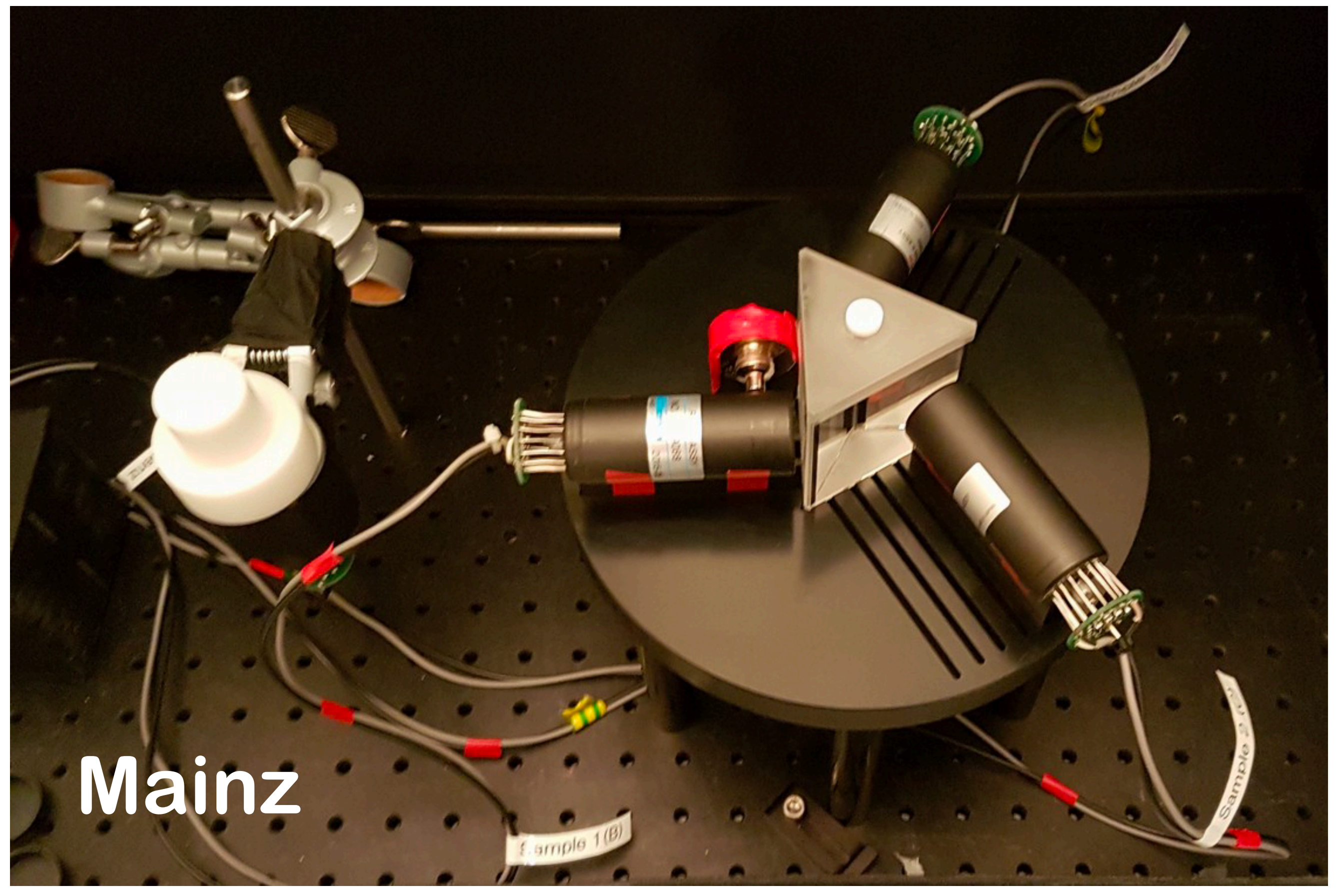
Water-based Liquid Scintillator - Advanced

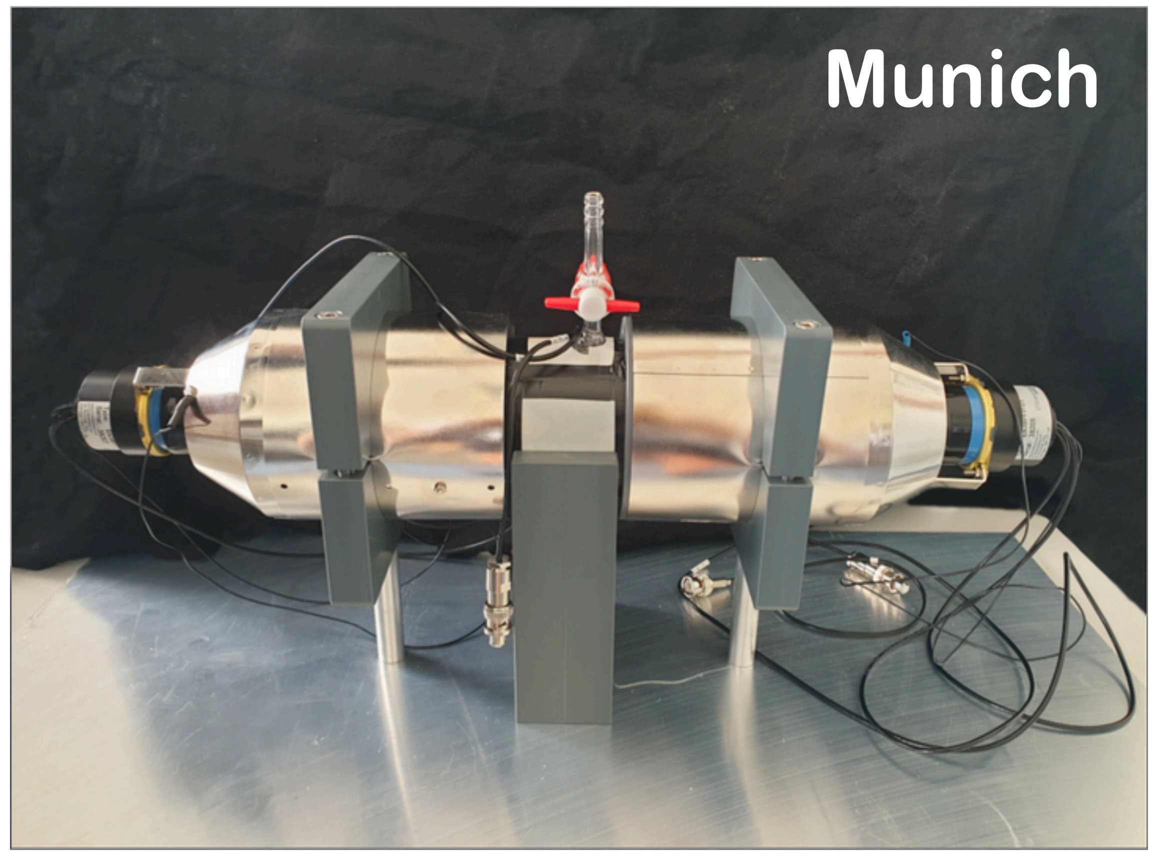
Developed Water-based Liquid Scintillator (WbLS) cocktails require extensive characterization:

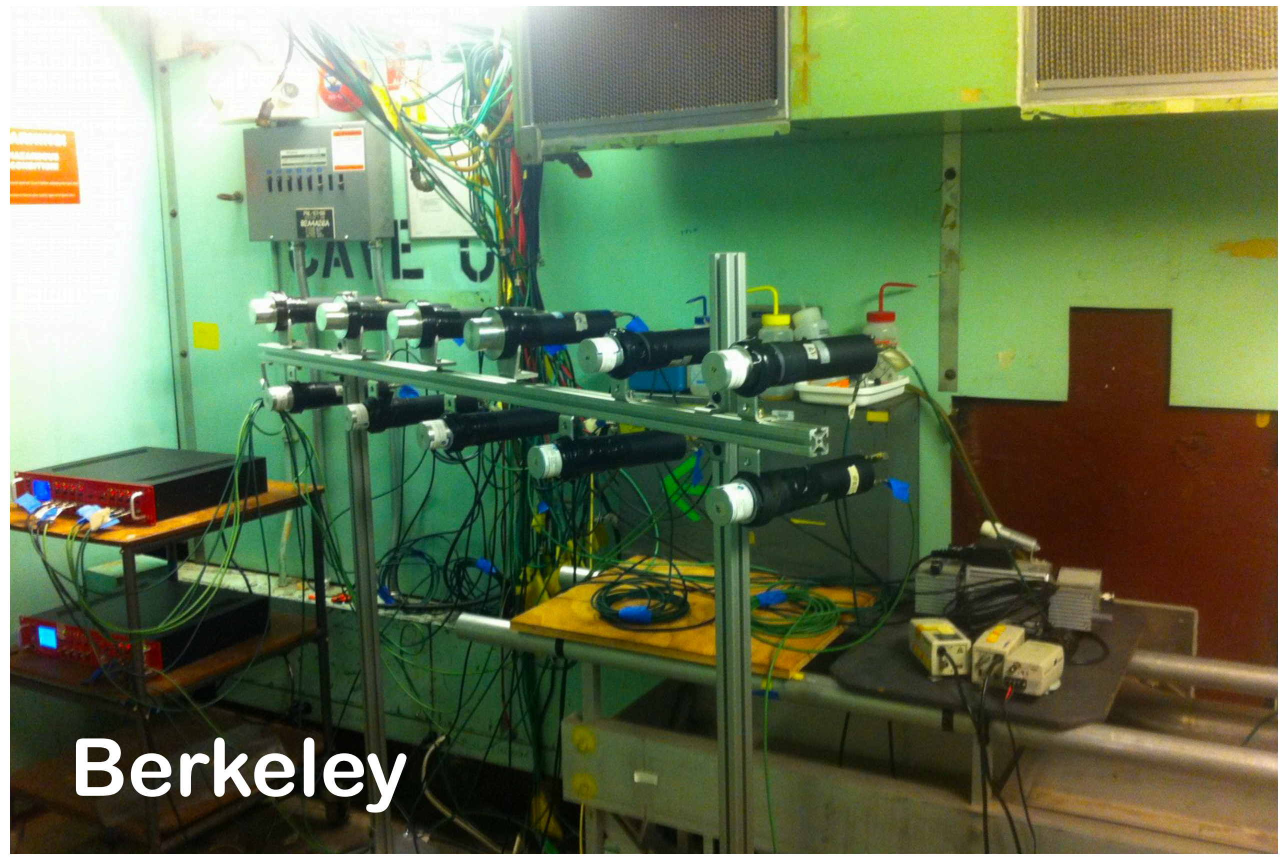
- Light Yield
- Emission spectrum
- Scintillation time profile
- Scattering and attenuation lengths

Other relevant developments:

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

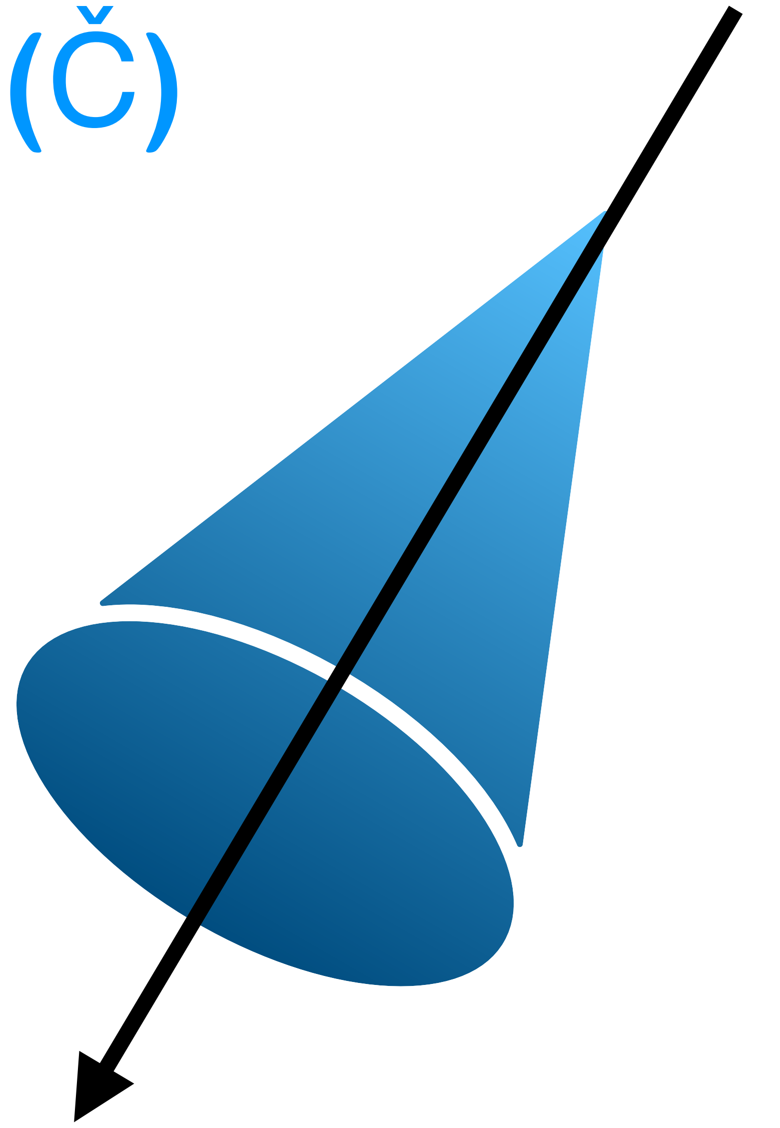




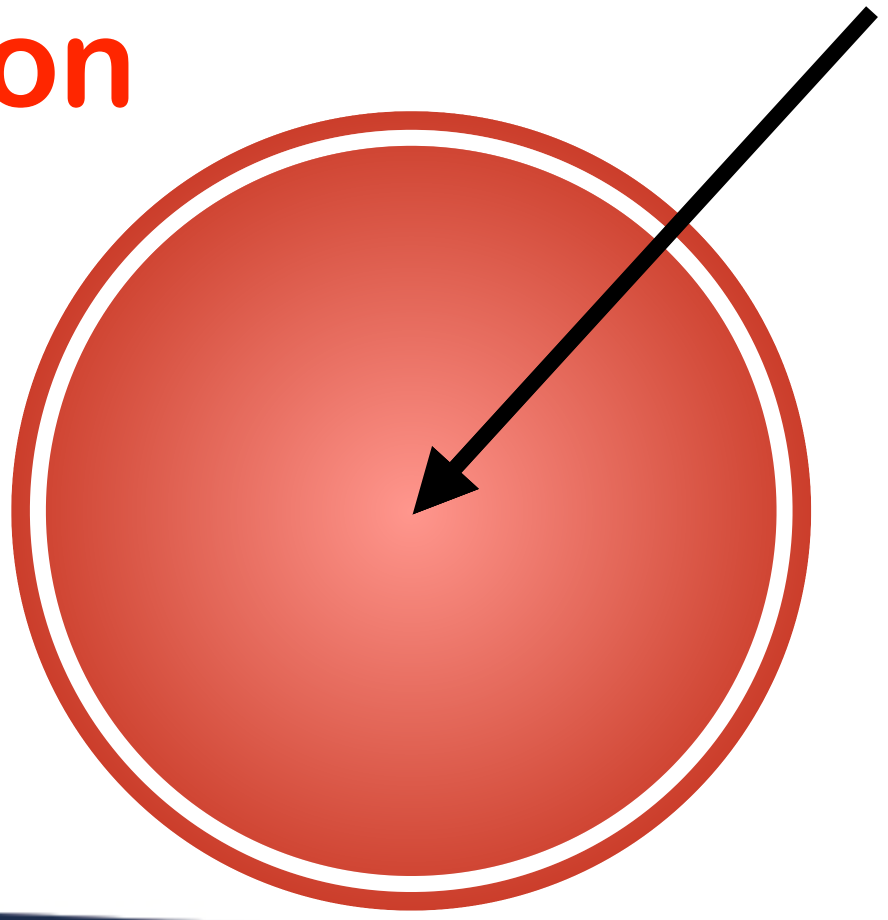


Cherenkov/scintillation photons separation

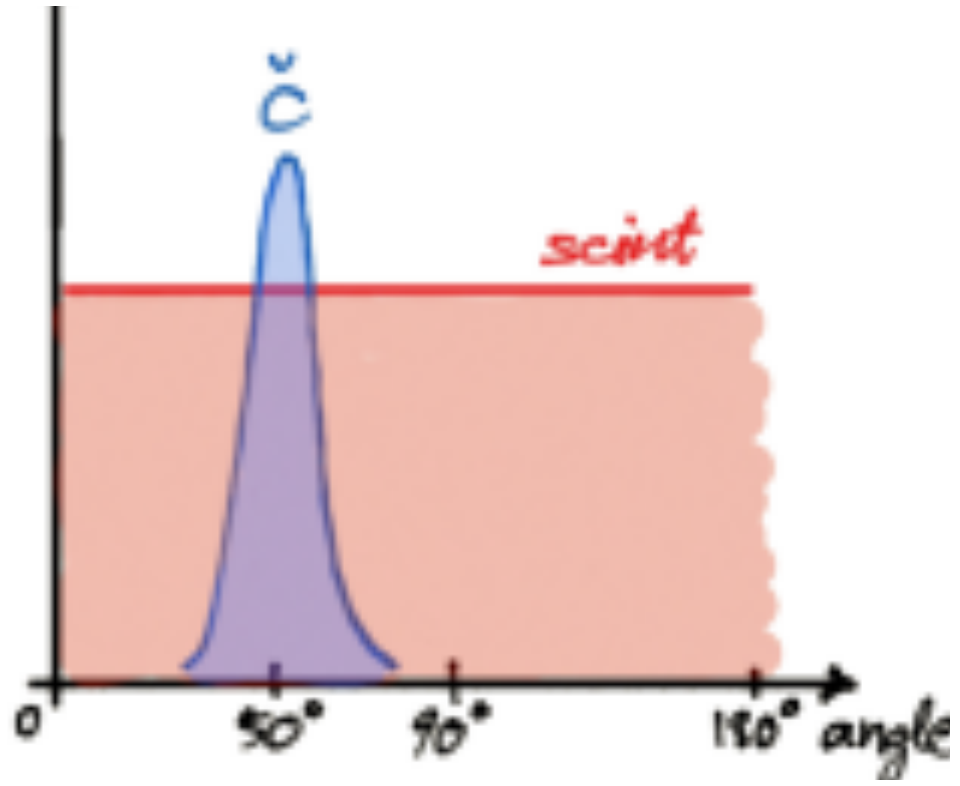
Cherenkov (Č)



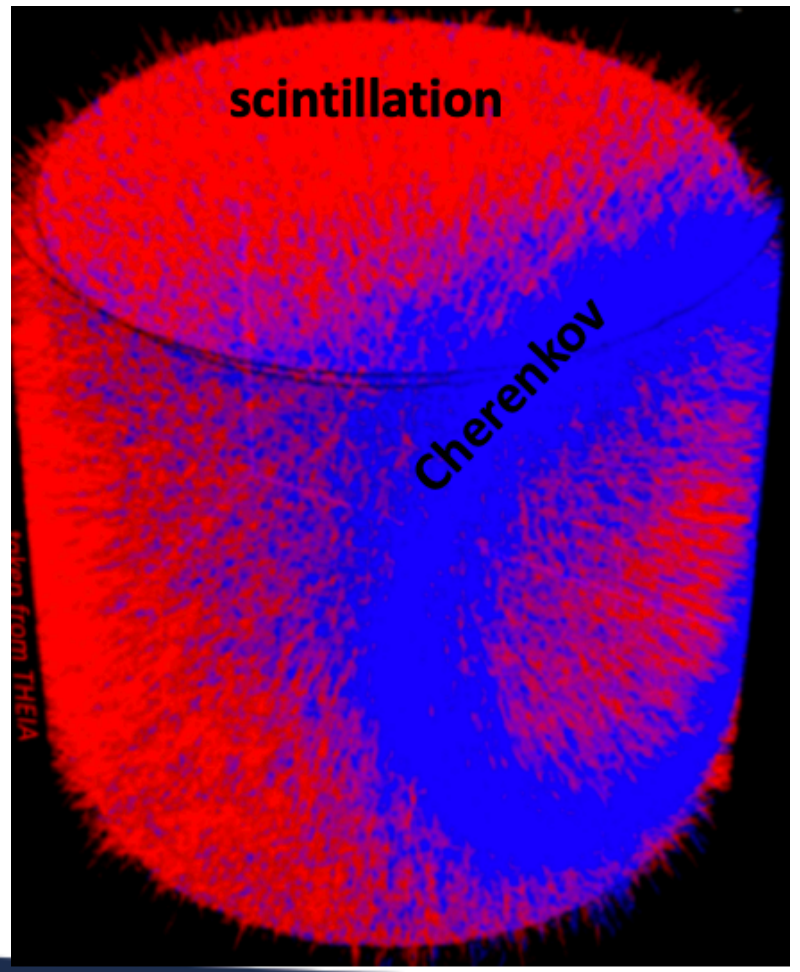
Scintillation



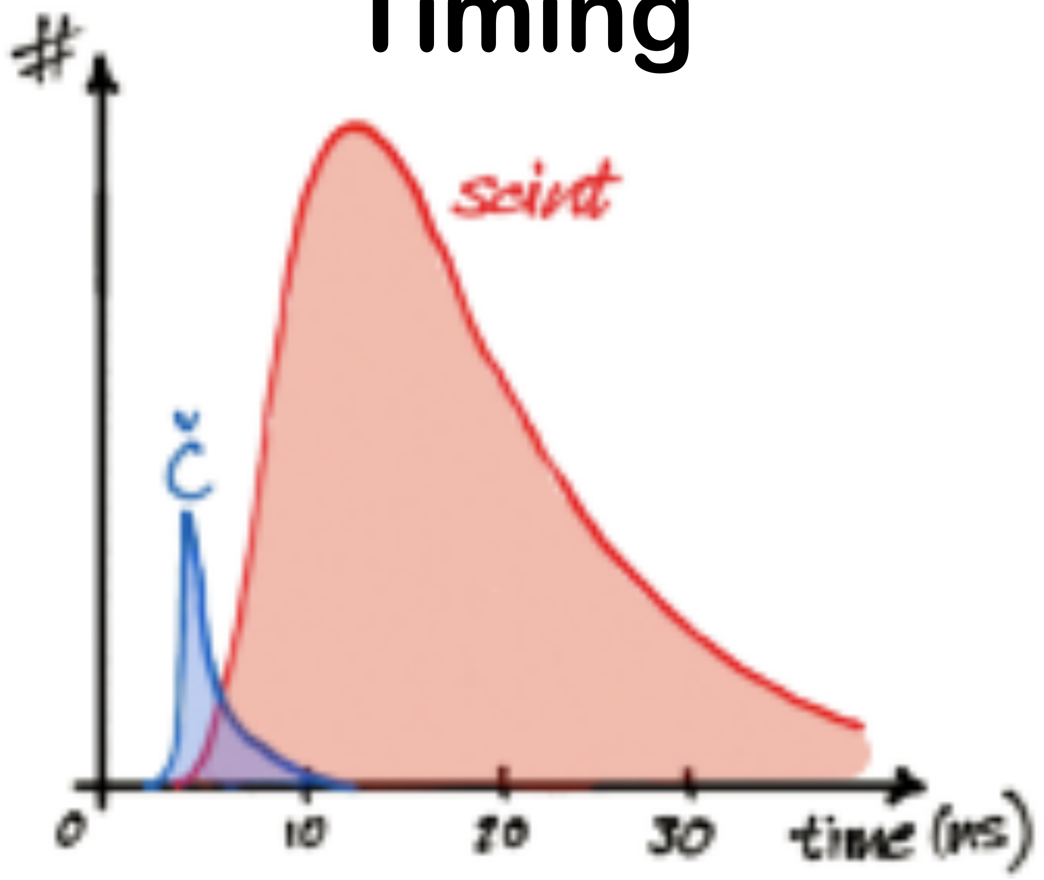
Angular distribution



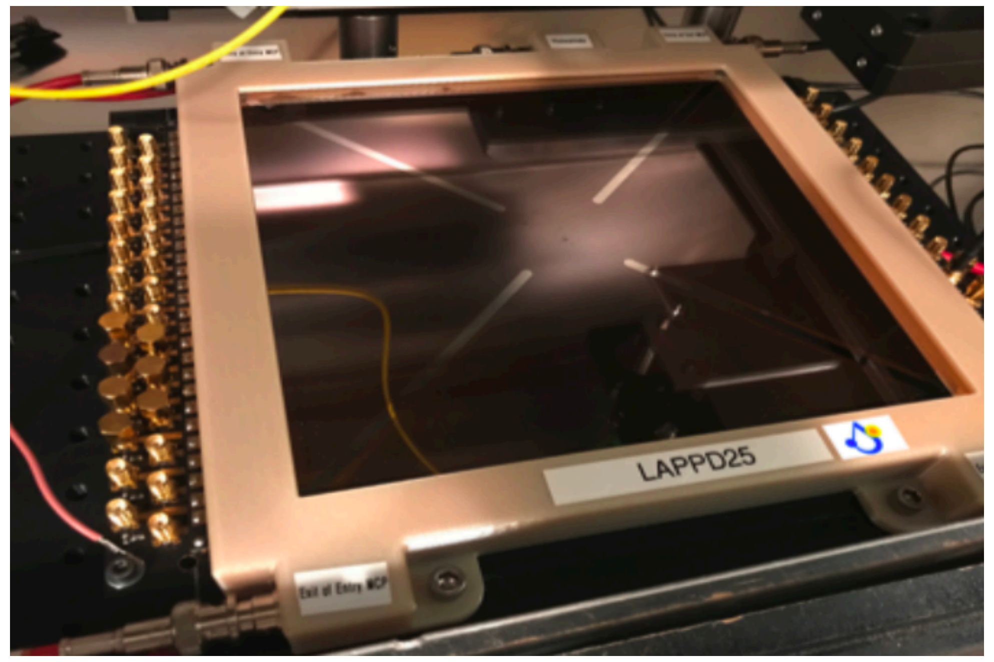
Angular resolution



Timing

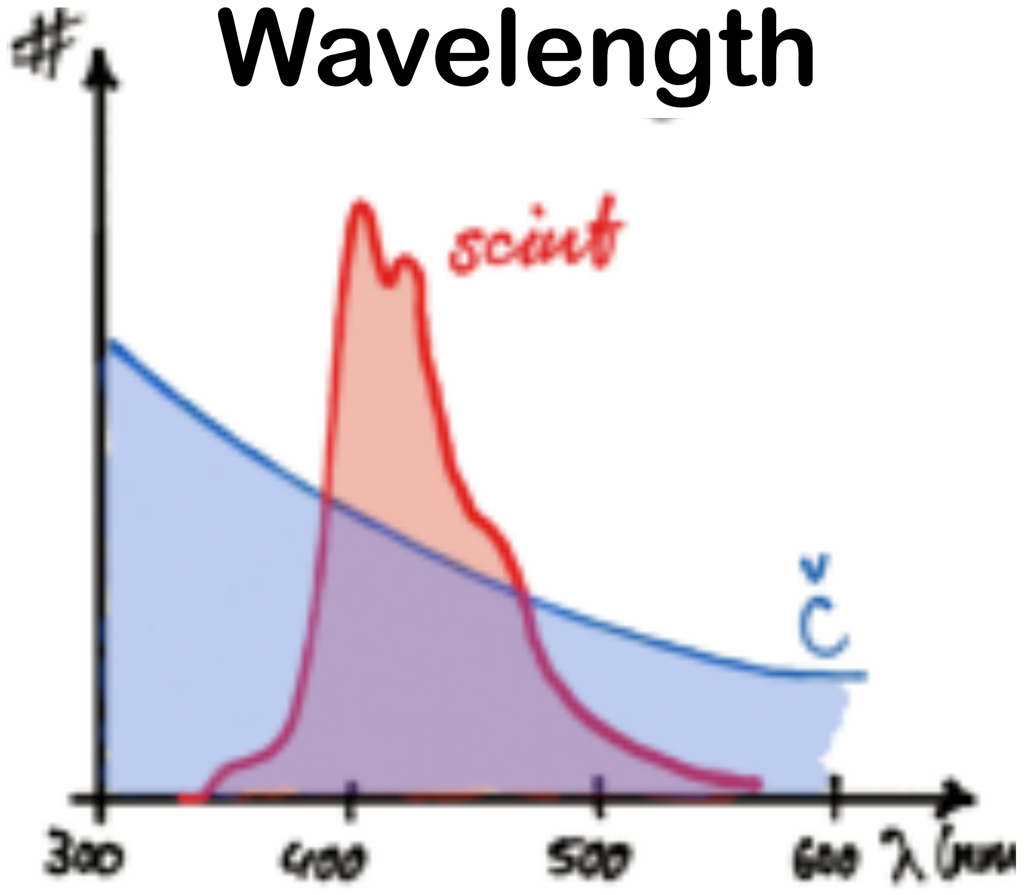


Large area picosecond photodetectors LAPPDs (~70 ps TTS) or other fast photodetectors

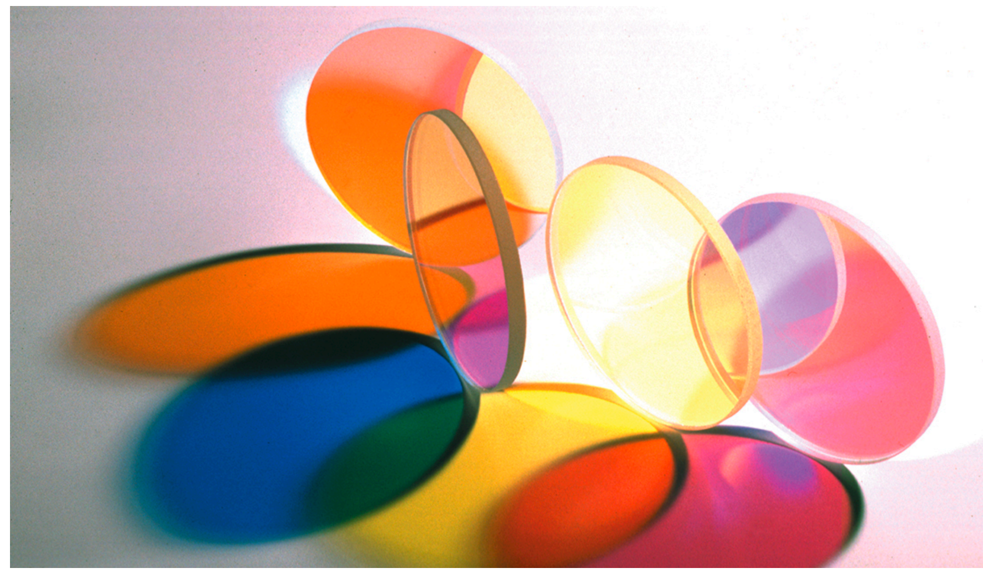


B.W.Adams et al. NIM A Volume 795, 1 (2015)

Wavelength



- Dichroic filters
- Red-sensitive PMTs
- Filtering



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

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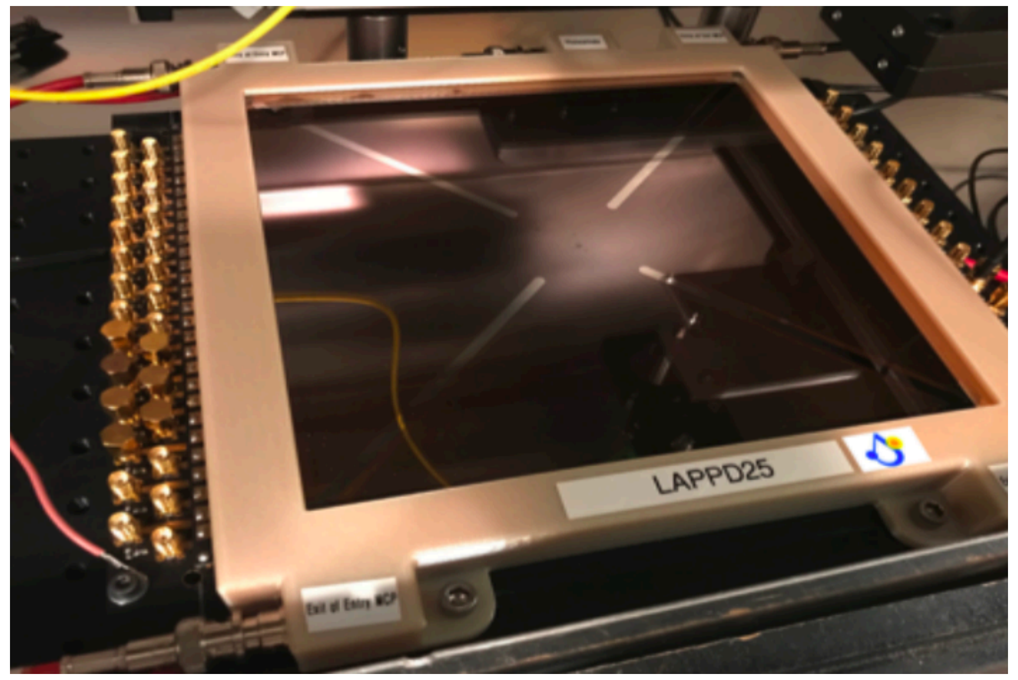
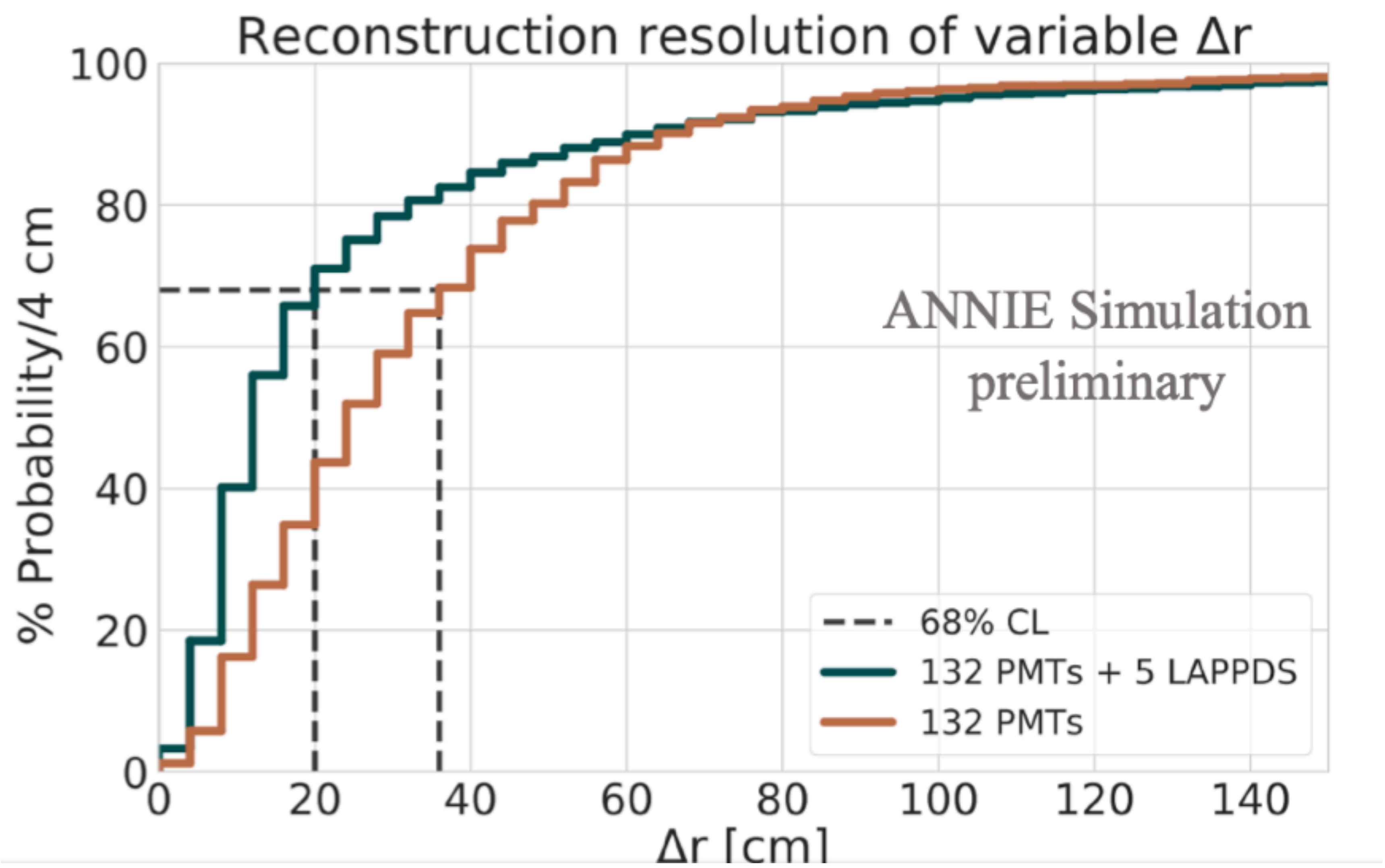
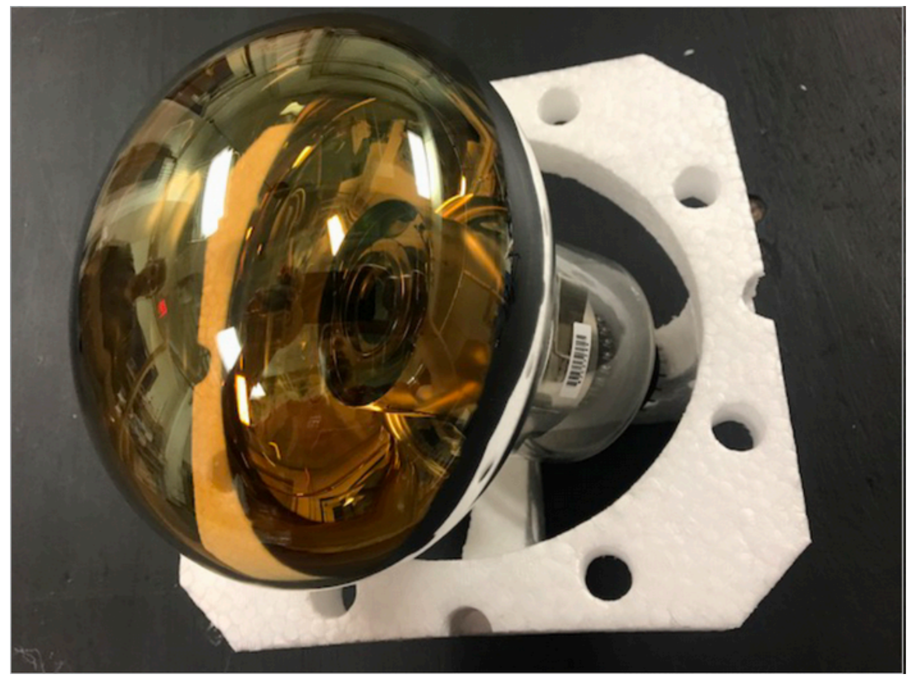
New Generation Photodetectors

Large area picosecond photodetector (LAPPD):
Micro-channel plate, fast-timing photodetectors
- Large-area: 20 cm× 20 cm with intrinsic mm-cm scale position resolution
- Fast timing: ~70 ps time resolution
- High quantum efficiency (QE): >20-30 %





Other developments:
Very fast large-area & HQE PMT
Large-area red-sensitive PMTs



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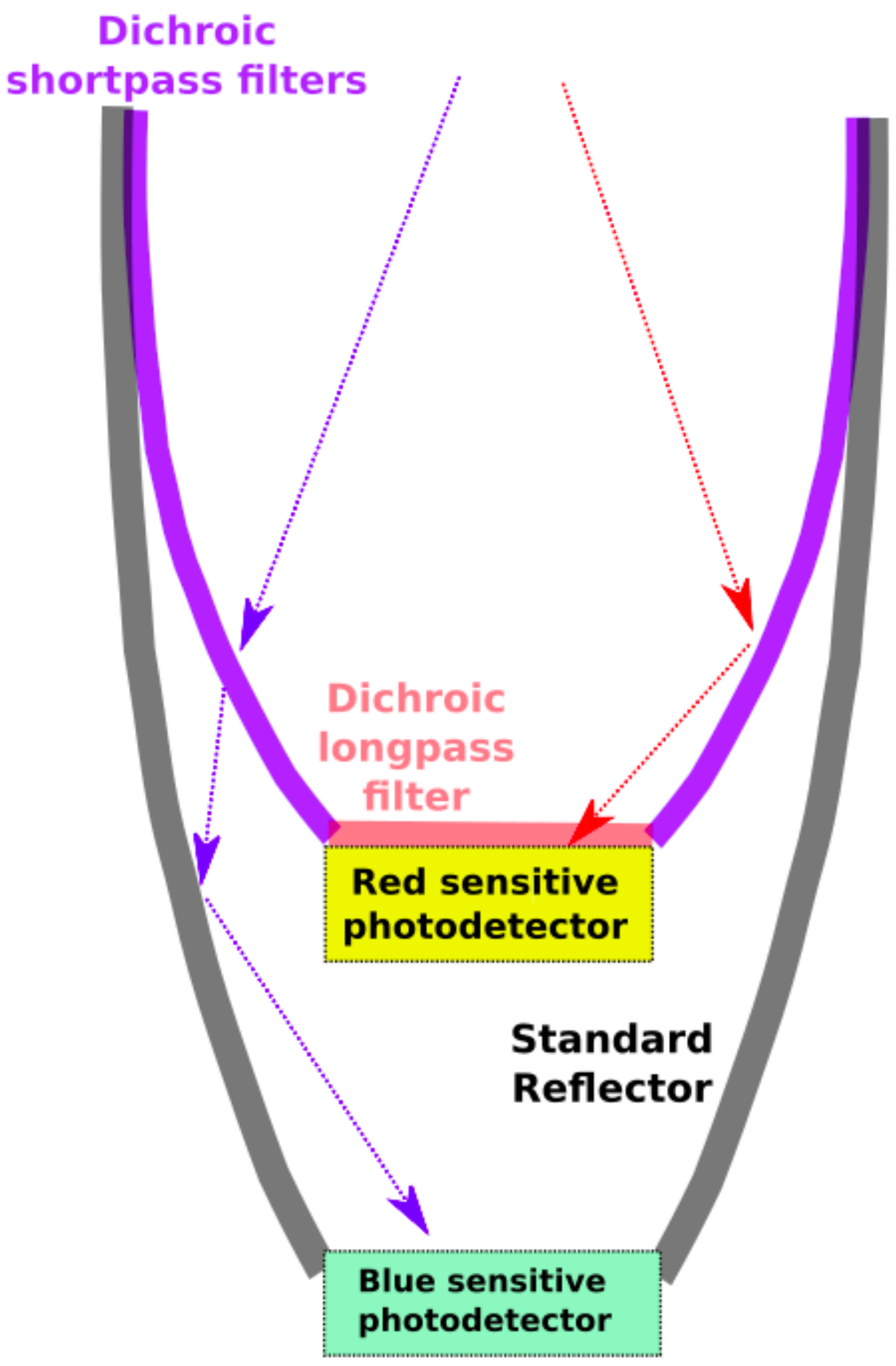
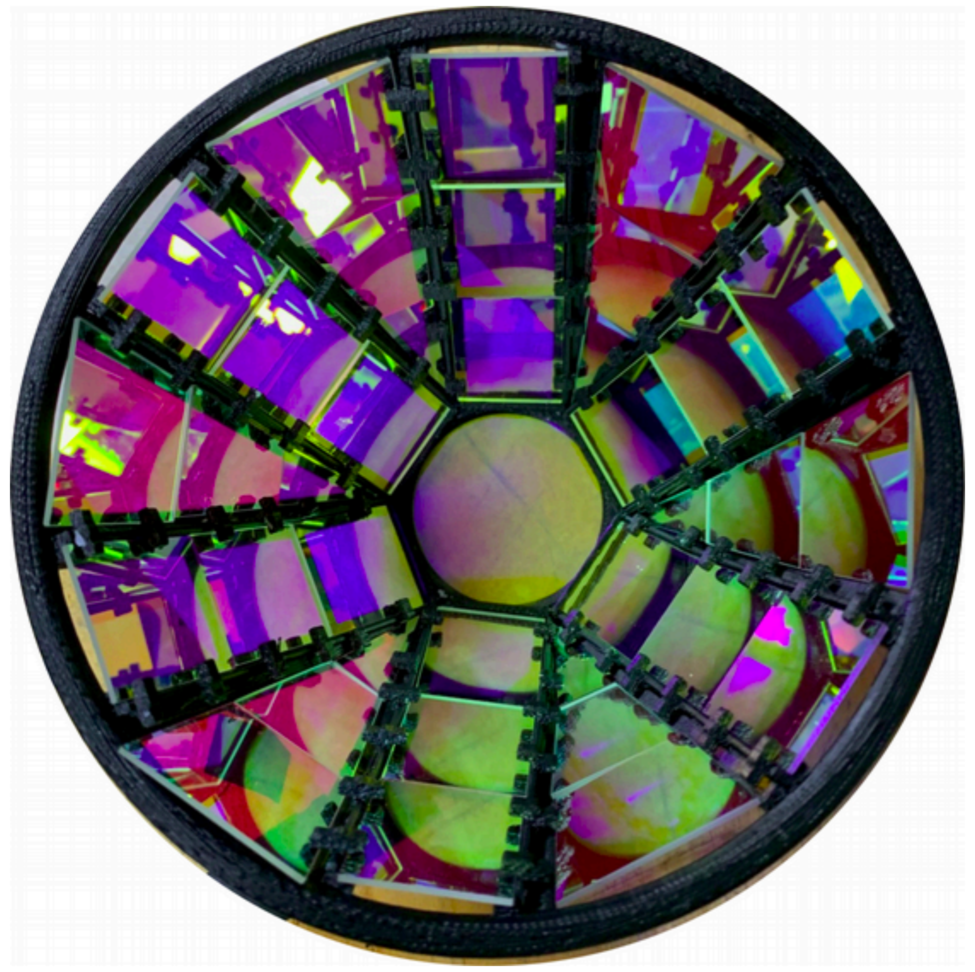
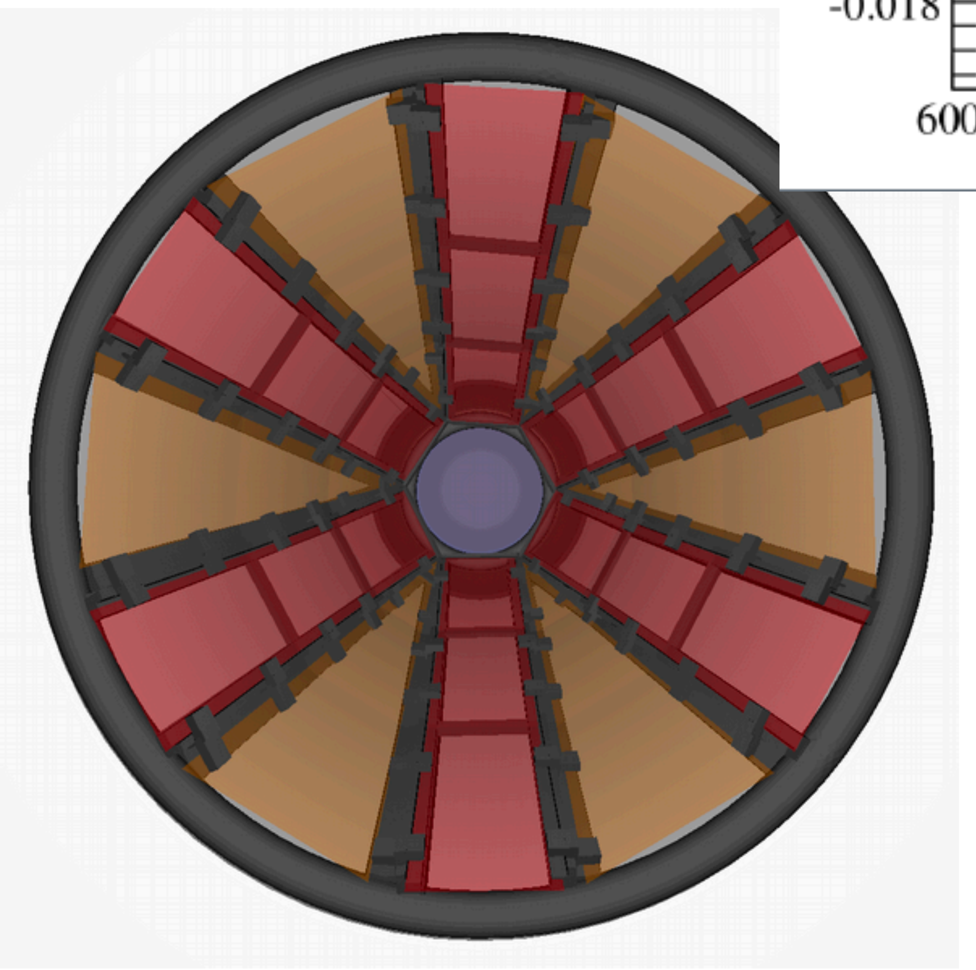
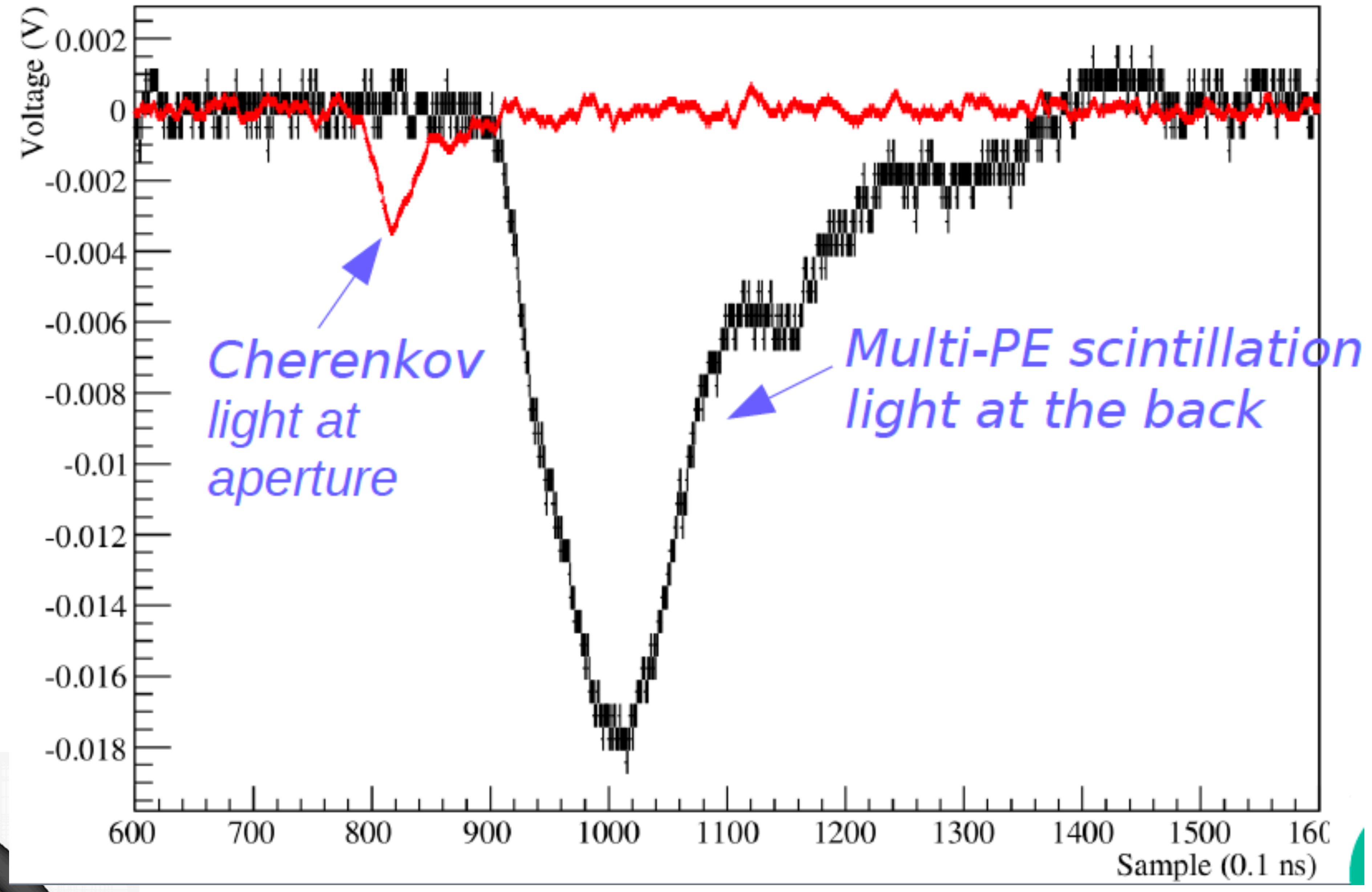
Dichroic filters (Wavelength discrimination)









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

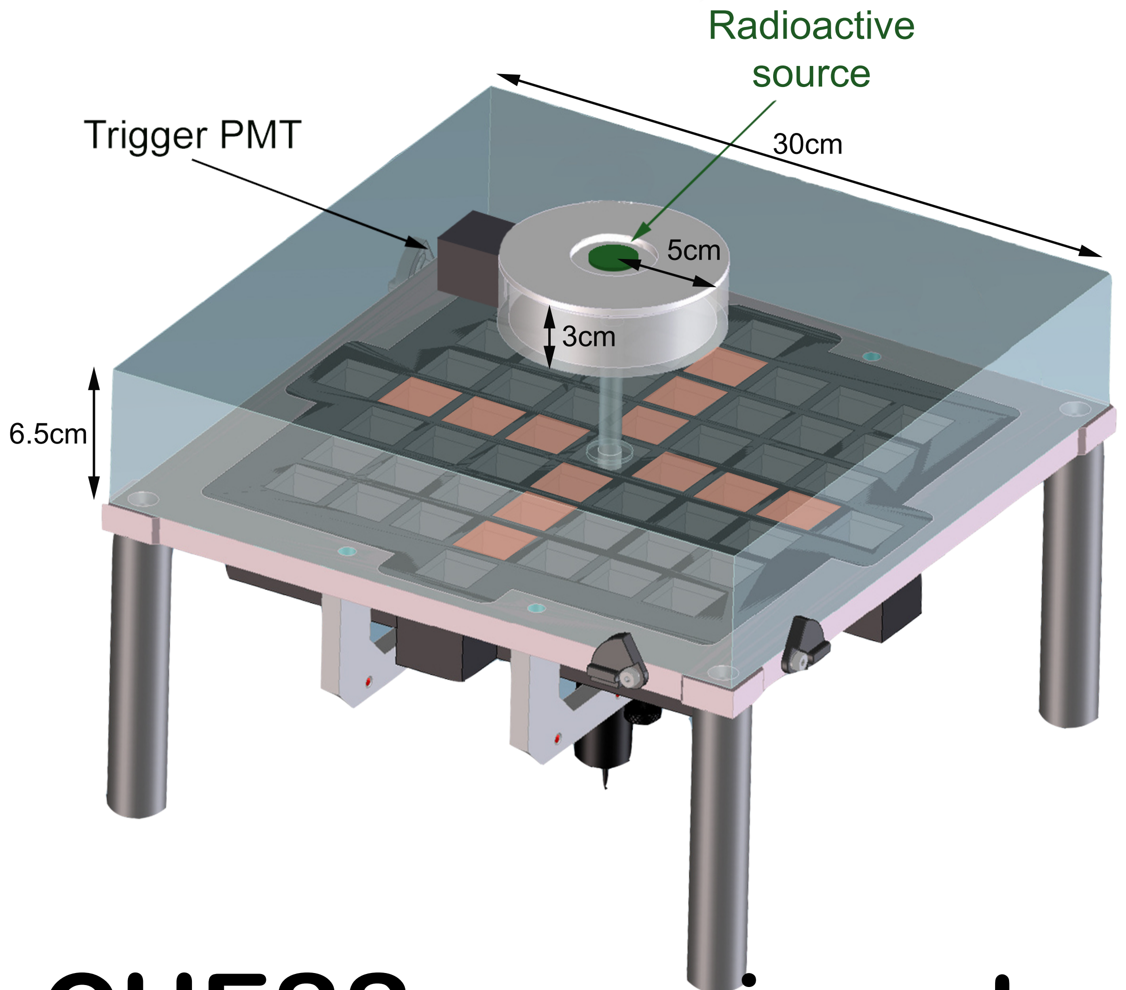
Performance measurements and MC studies

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

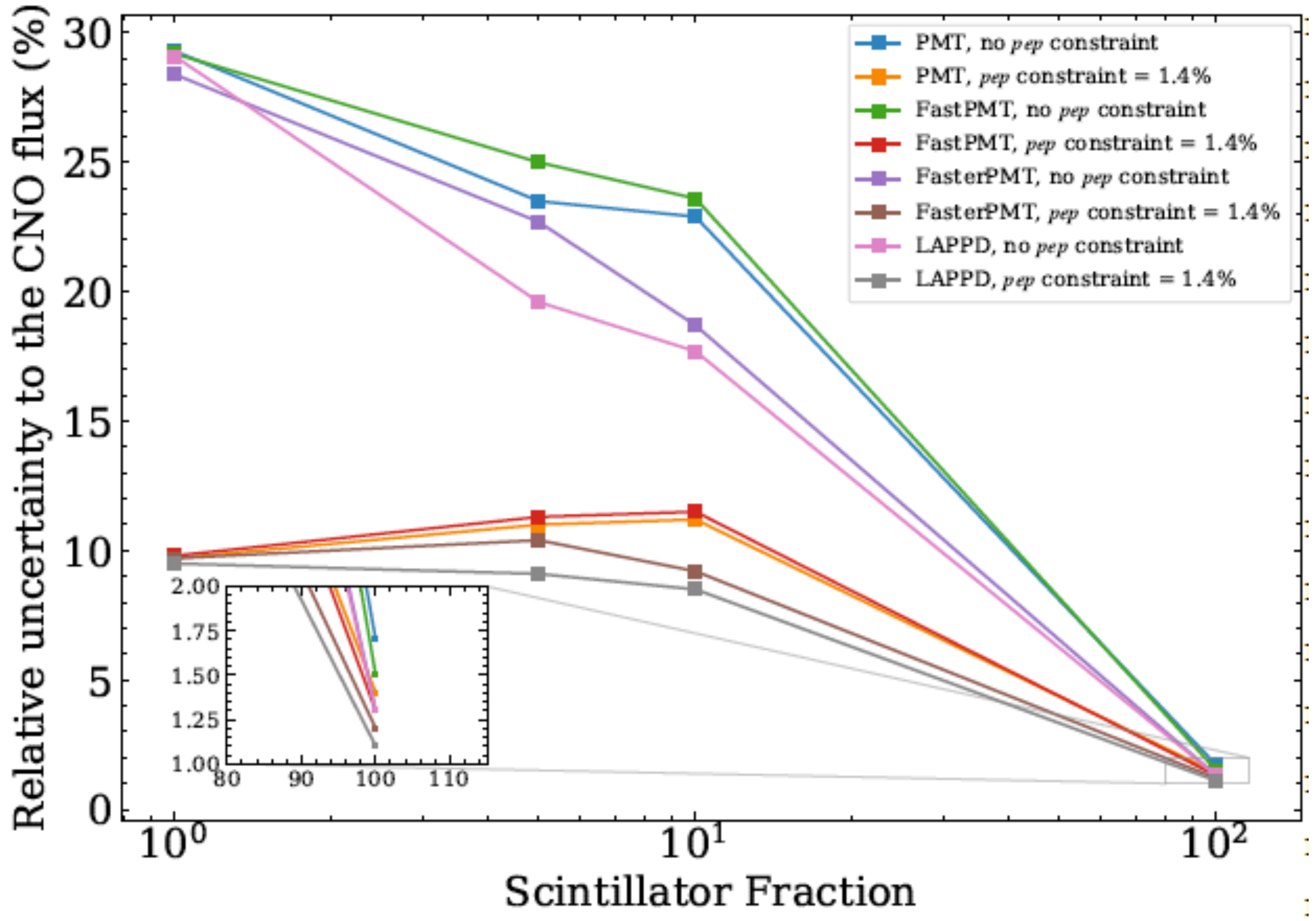
→ **Monte Carlo model validation** → **Prediction of impact in large-scale detectors**



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)

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Scaling up

Mass

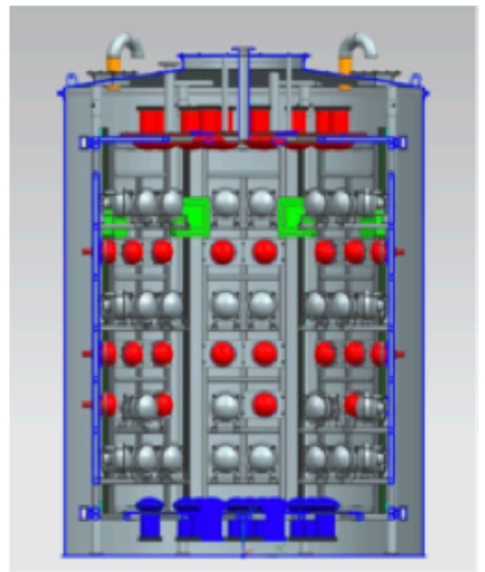
~ 25,000 tons
/100,000 tons

~ 2000 tons

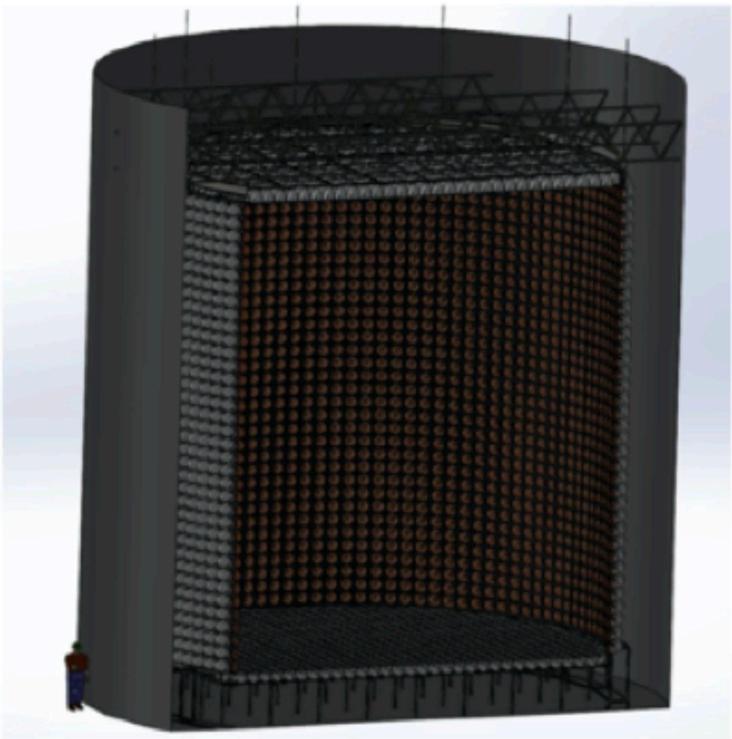
~ 30 tons

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

ANNIE

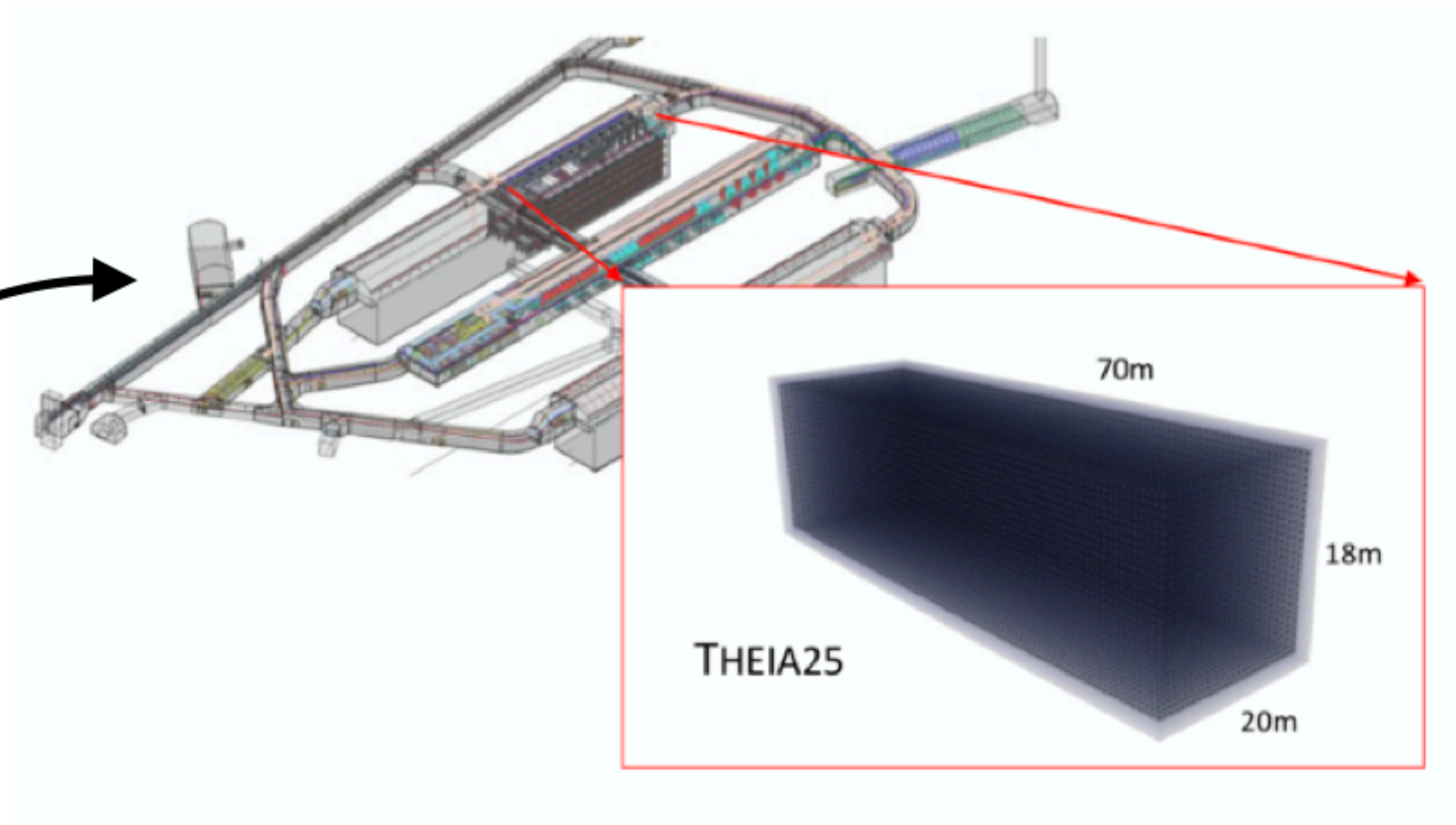


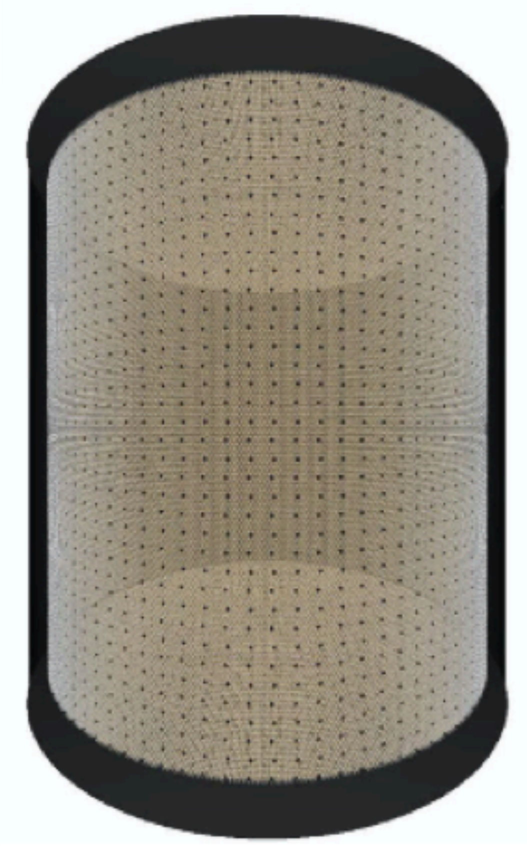
~5000 photosensors
Use of WbLS + fast photosensors in a large detector



AIT - NEO

THEIA25





THEIA100

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

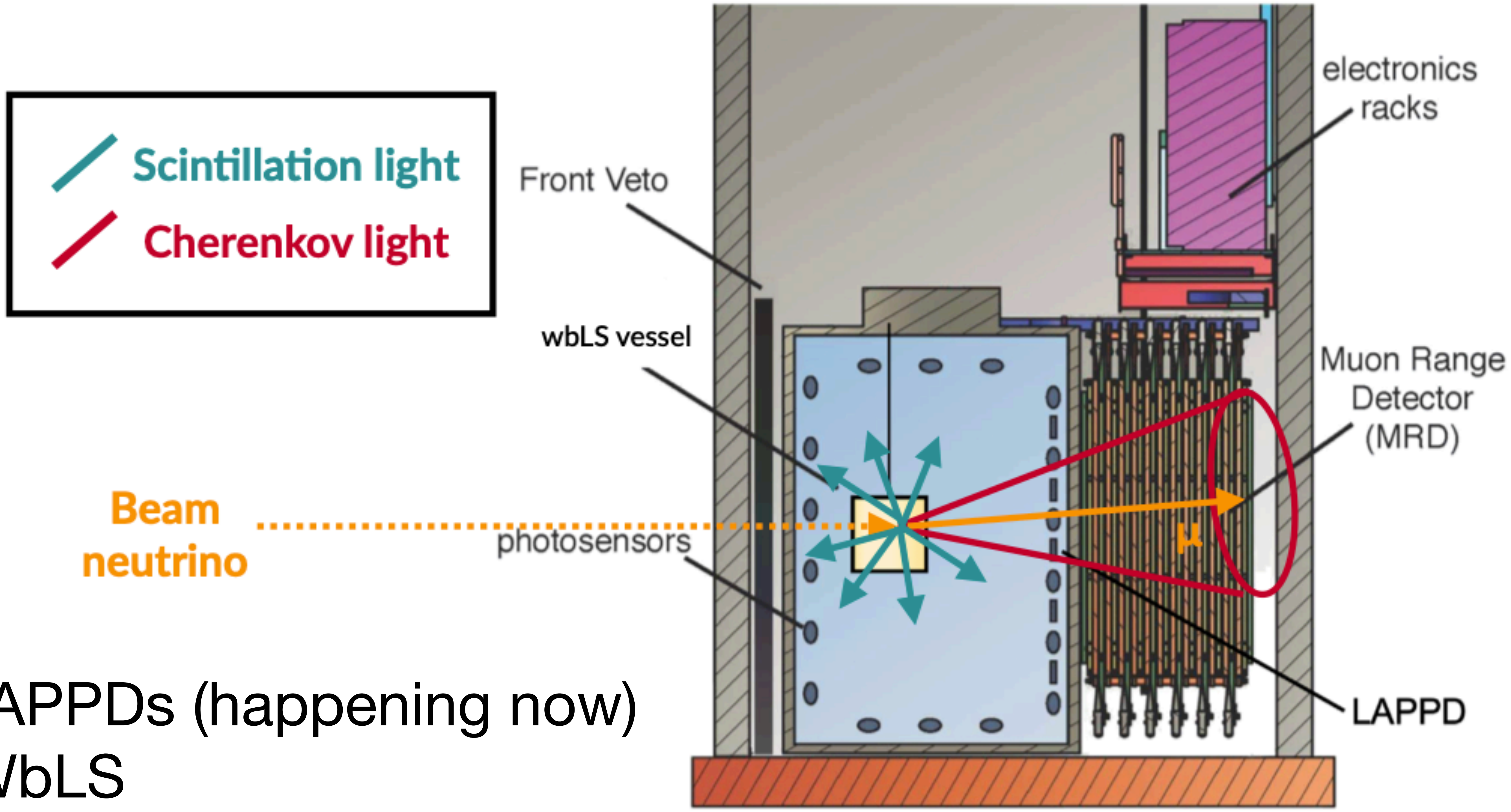
~100,000 sensors
Ultimate application of WbLS to physics use case

2021+ **2024+** **20xx** **Data taking**

ANNIE @FermiLab

Main Goal:

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



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

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

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

Show feasibility of WbLS in a neutrino-beam environment

ANNIE: Current Status

Commissioning & neutron calibration runs with 132 PMTs completed

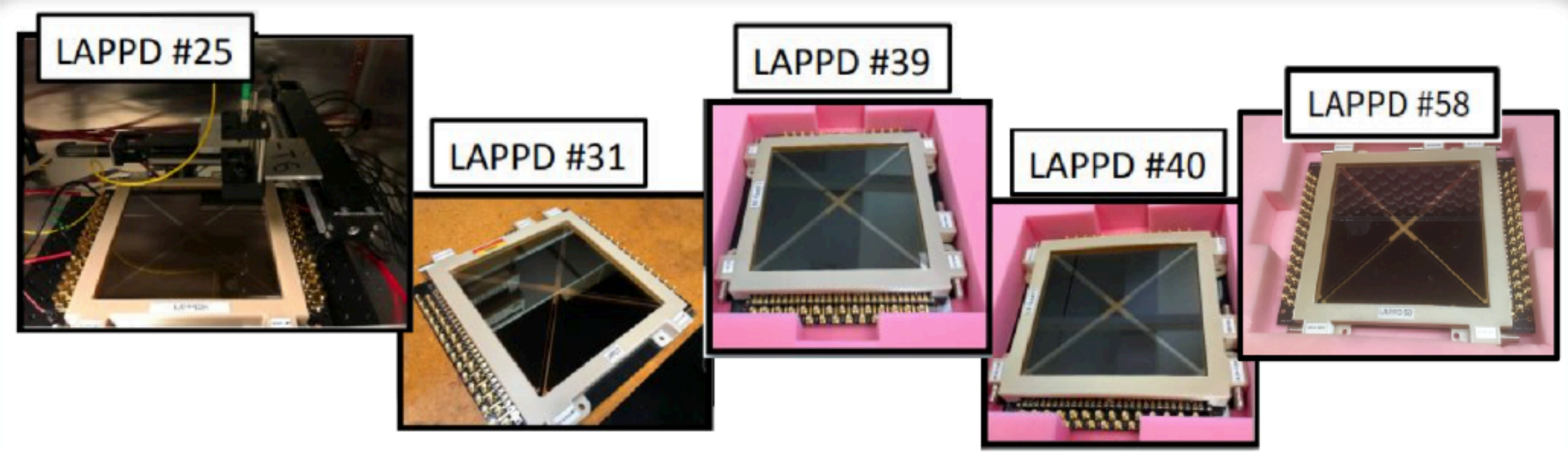
•First deployment of LAPPDs

ANNIE has 5 LAPPDs at hand, characterization ongoing at Fermilab test stand

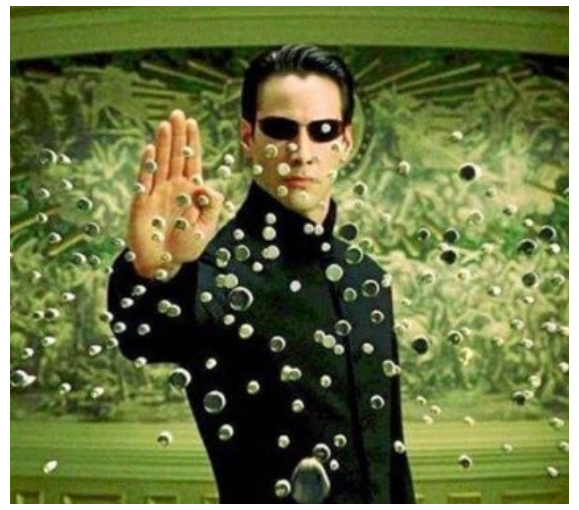
•Further calibration campaigns: Laser diffuser ball, ^{137}Cs standard candle

Production of WbLS vessel

WbLS vessel



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

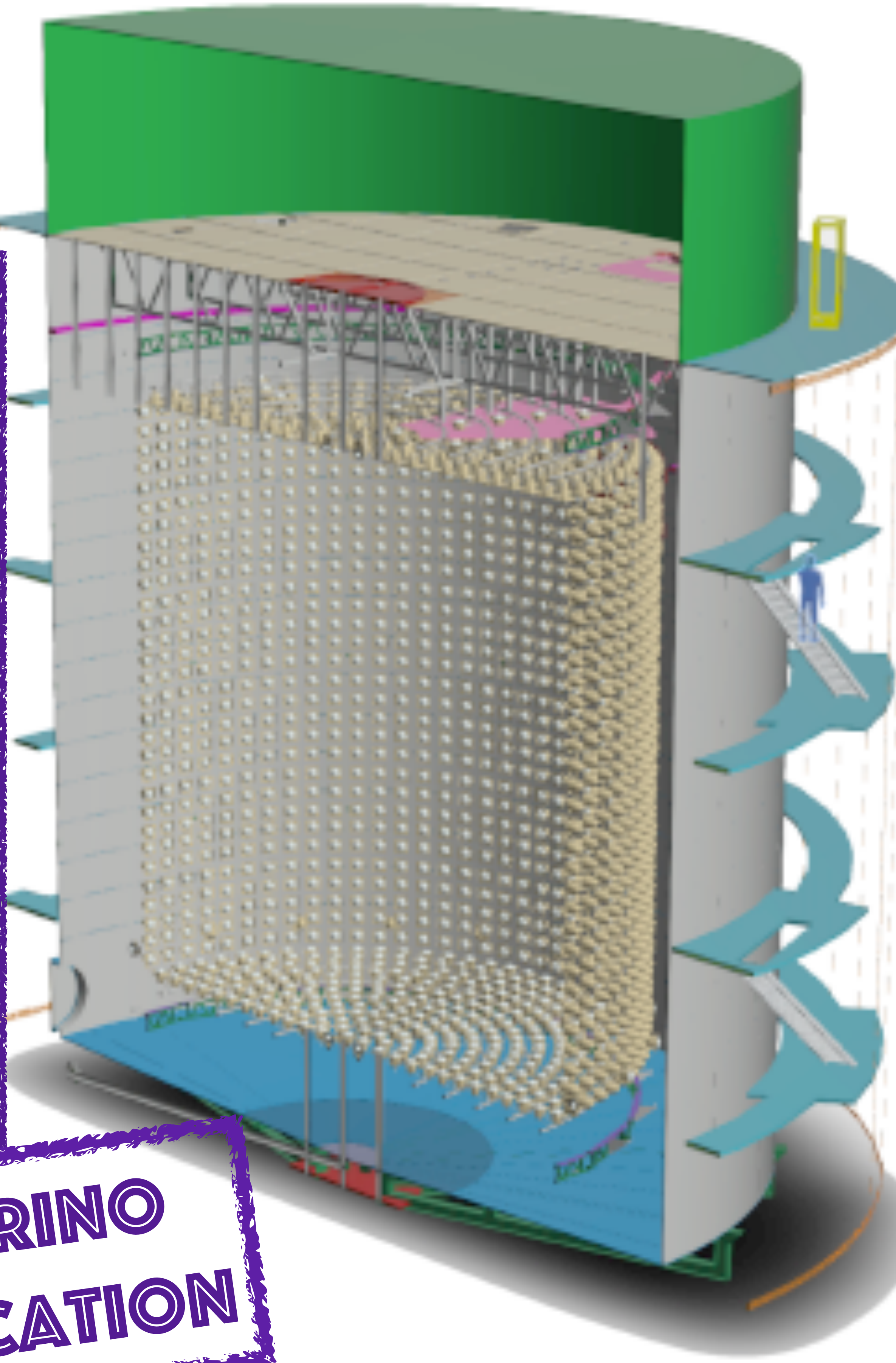
Start of data taking: ~2024

Location: Boulby Underground Lab (UK)

WbLS volume: 1kt

Interests:

Non-proliferation, Solar neutrinos, NLDBD



NEUTRINO APPLICATION

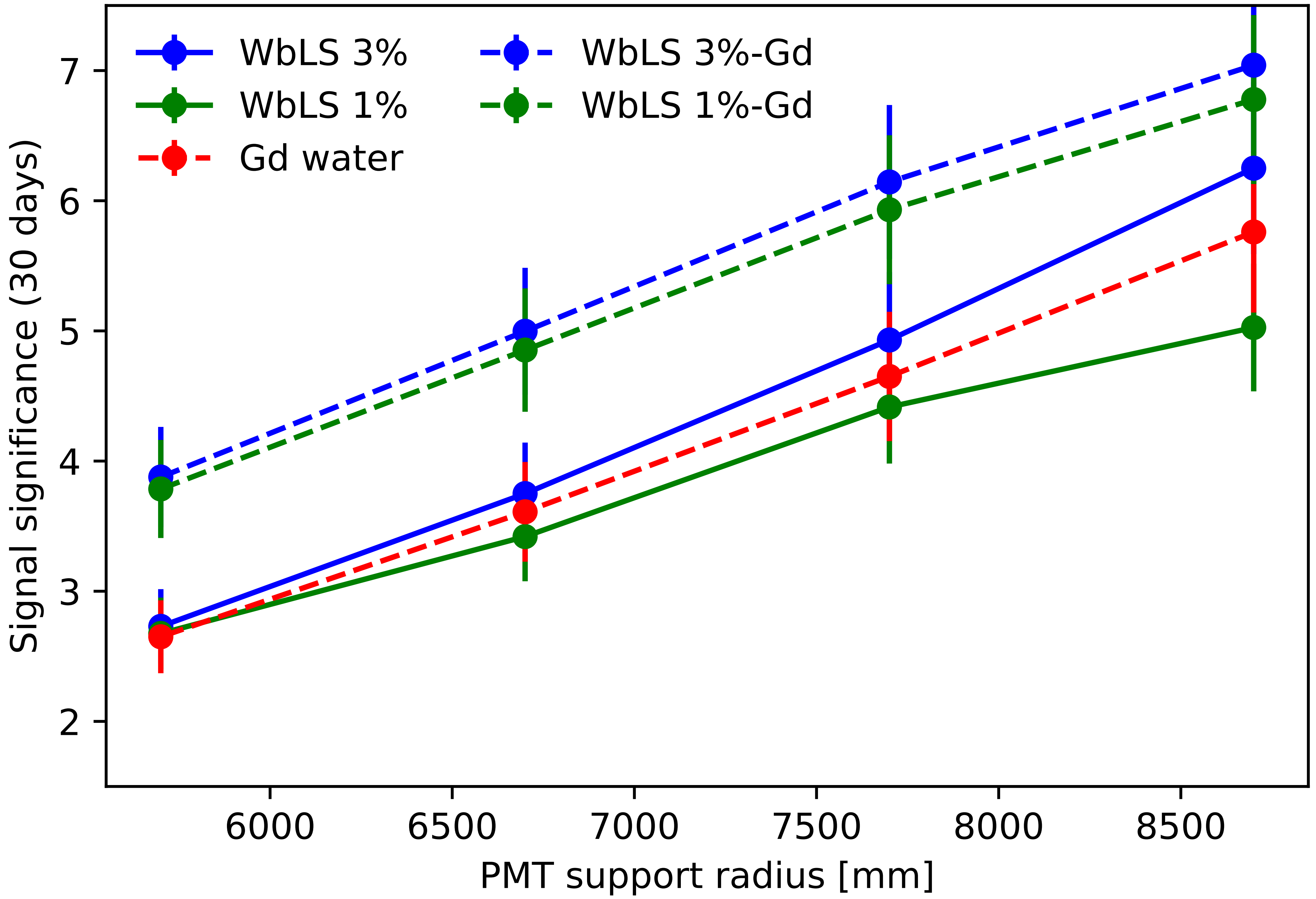
M. Askins et al. arXiv:1502.01132

AIT/NEO: Current Status

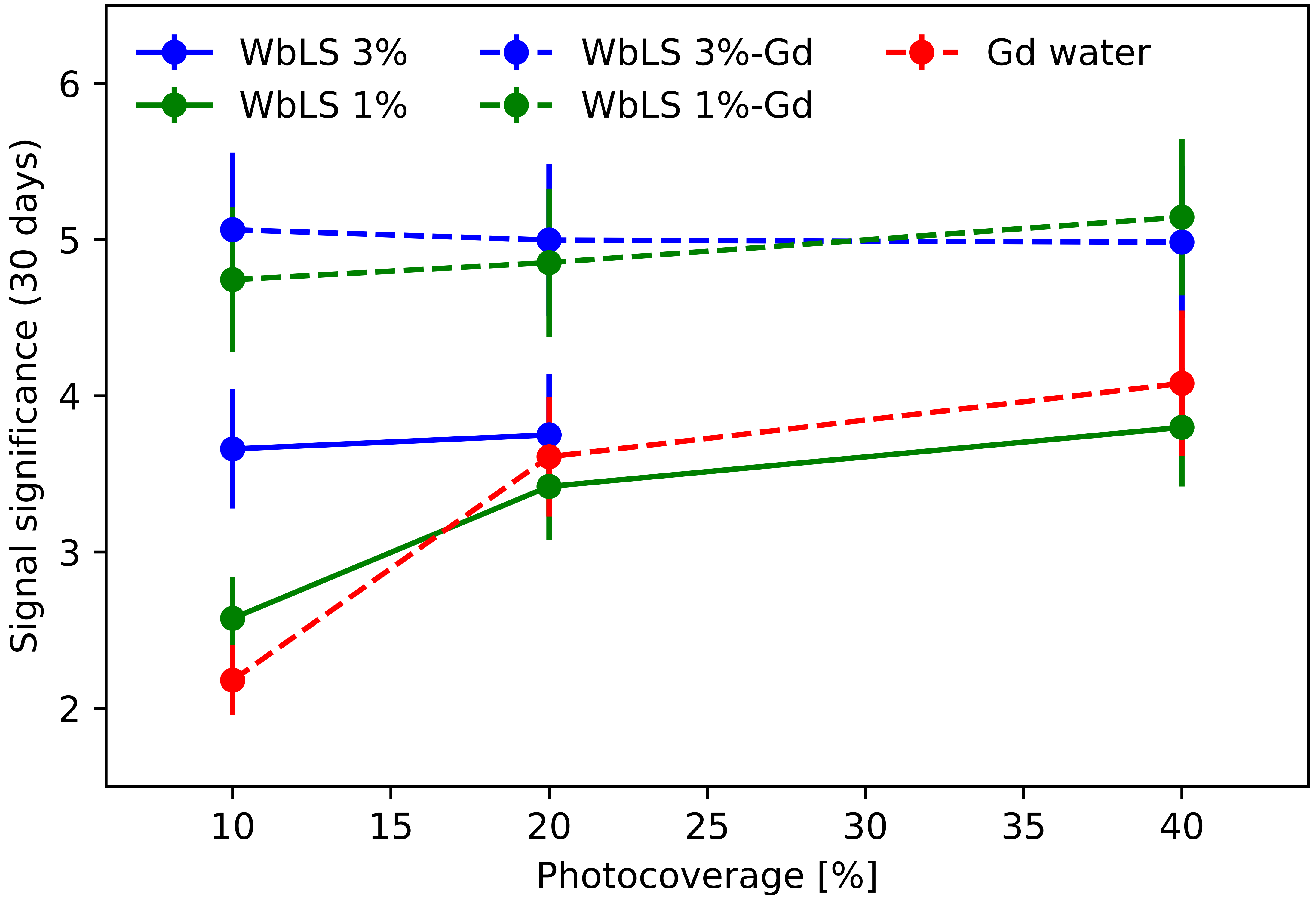
25km standoff between Hartlepool reactor and Boulby Lab

$$\frac{S}{\sqrt{S+B}}$$

- Dependence on PMT support radius:



- Dependence on photo coverage:



NEO Internal Technical Report "The AIT-NEO Project: Results from the NEO Performance Trade Study"

Theia: advanced optical multipurpose neutrino detector

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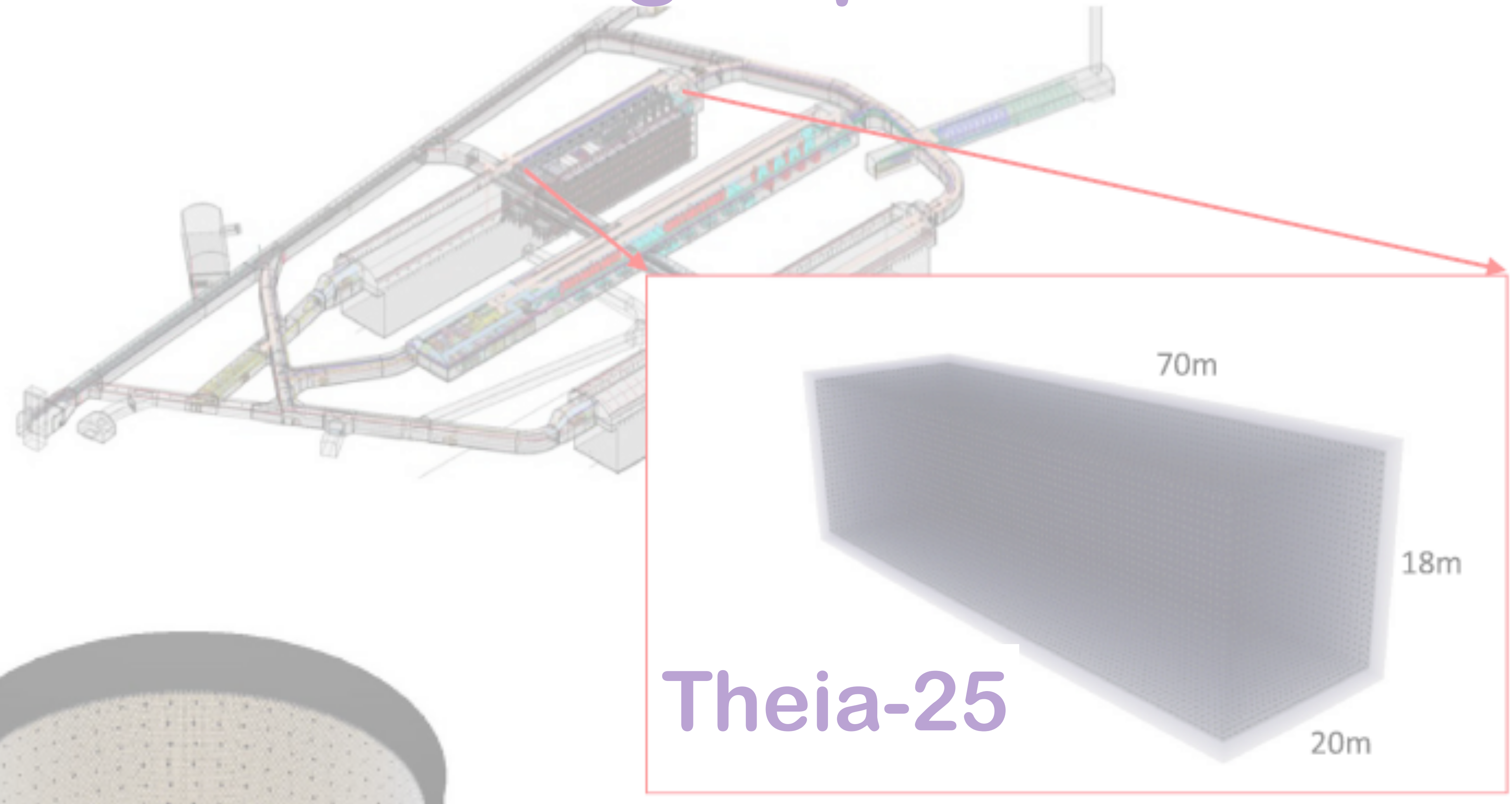

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THEIA: An advanced optical neutrino detector Eur. Phys. J. C 80, 416

Theia: multipurpose neutrino detector

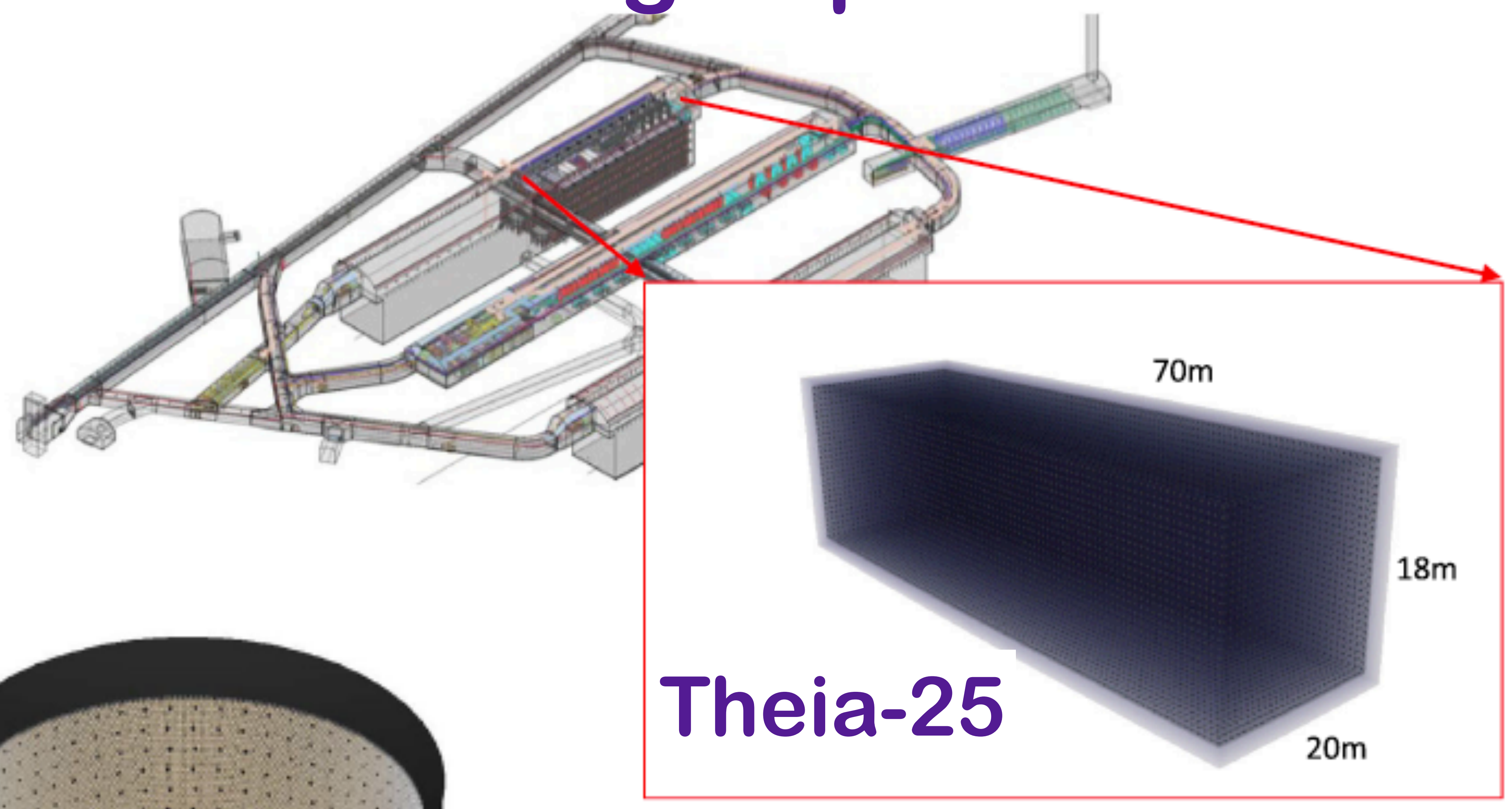
neutrino mass ordering

neutrino CP-violating phase δ

neutrinoless double beta decay

nucleon decay

Design options



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Scintillator fraction tunable depending on the physics goal ->staged approach

solar neutrinos (CNO, ^{8}B)

geoneutrinos

diffuse supernova neutrinos (DSNB)

supernova burst neutrinos

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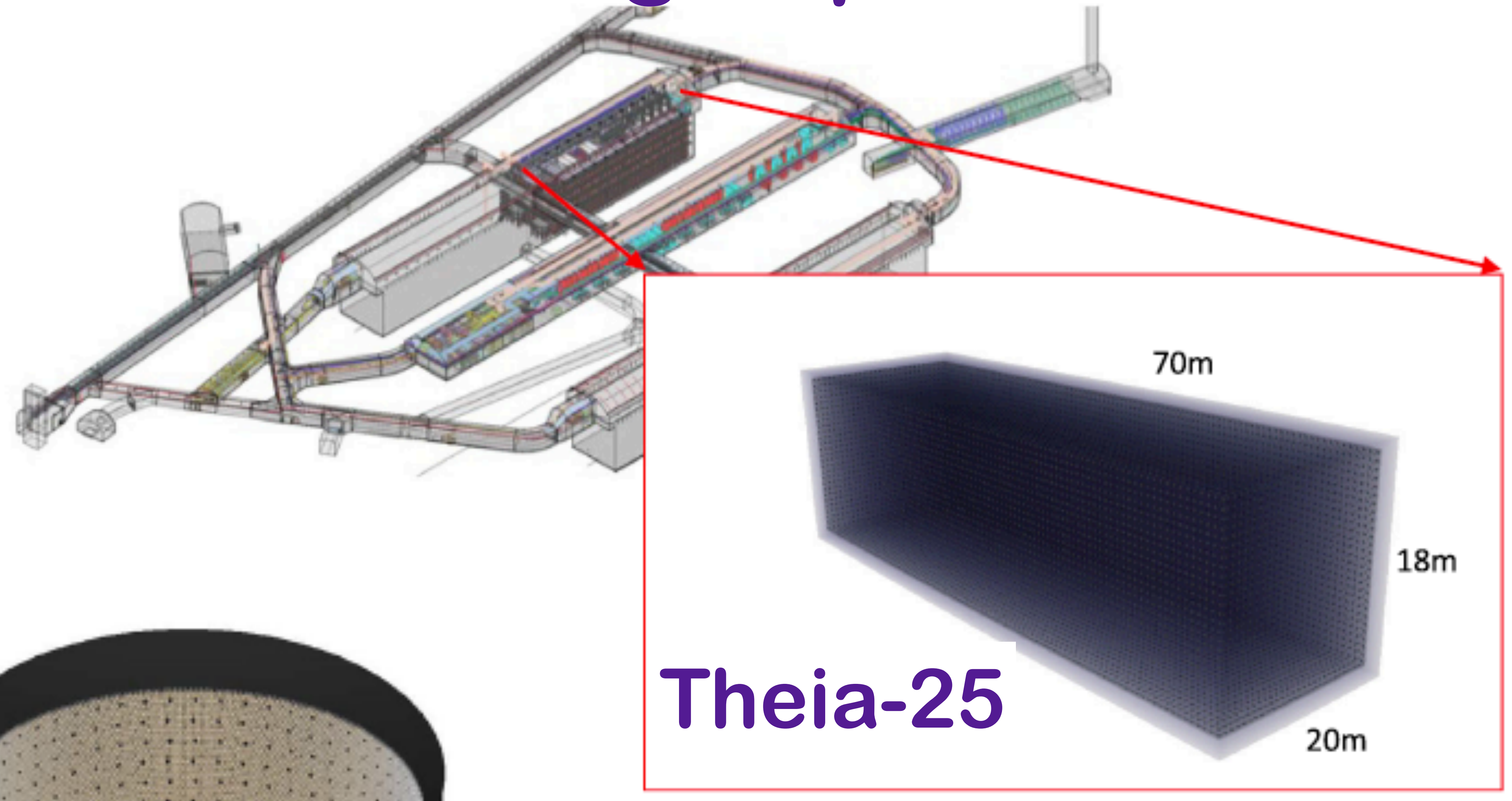

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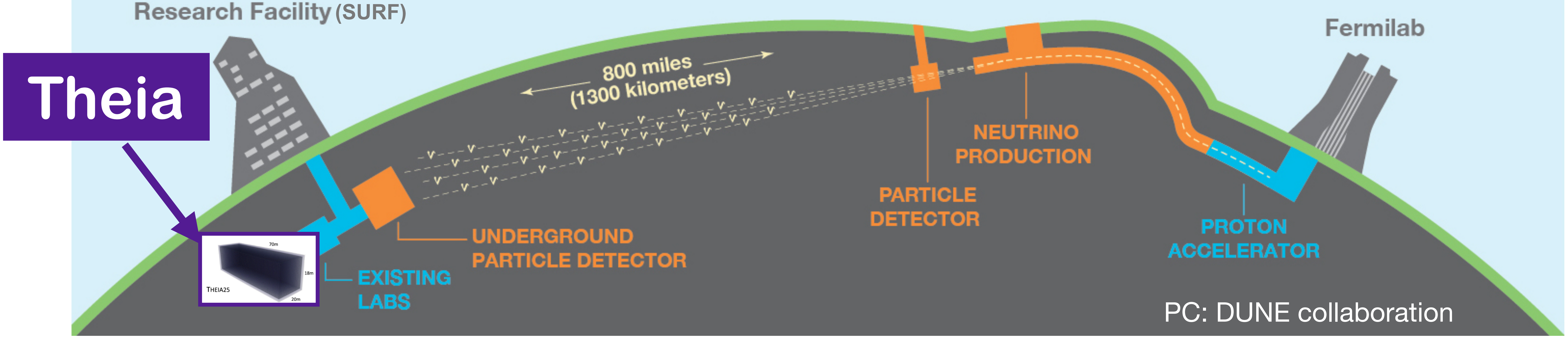
THEIA: An advanced optical neutrino detector Eur. Phys. J. C 80, 416

Theia-25 at long baseline neutrino facility (LBNF)

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



Phase I

- Using Fermilab's LBNF neutrino beam for **long-baseline neutrino oscillation measurements**

Long-baseline neutrino oscillations

Phase I

- Currently measured: $\theta_{12}, \theta_{23}, \theta_{13}$

$$\Delta m^2_{21}, |\Delta m^2_{31}| \approx |\Delta m^2_{32}|$$

- Next milestones: $\Delta m^2_{32}, \delta_{CP}$

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Long-baseline neutrino oscillations

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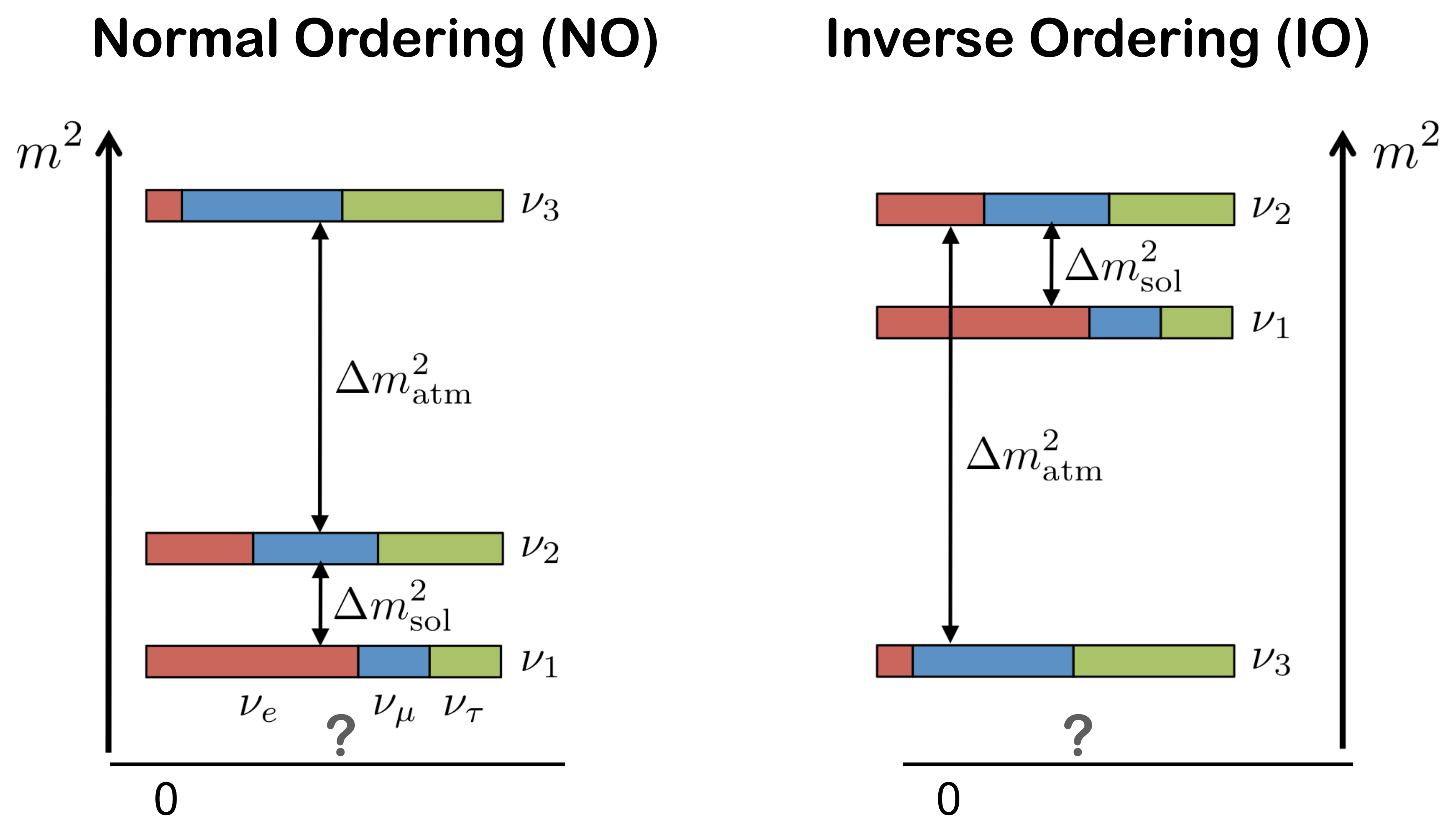

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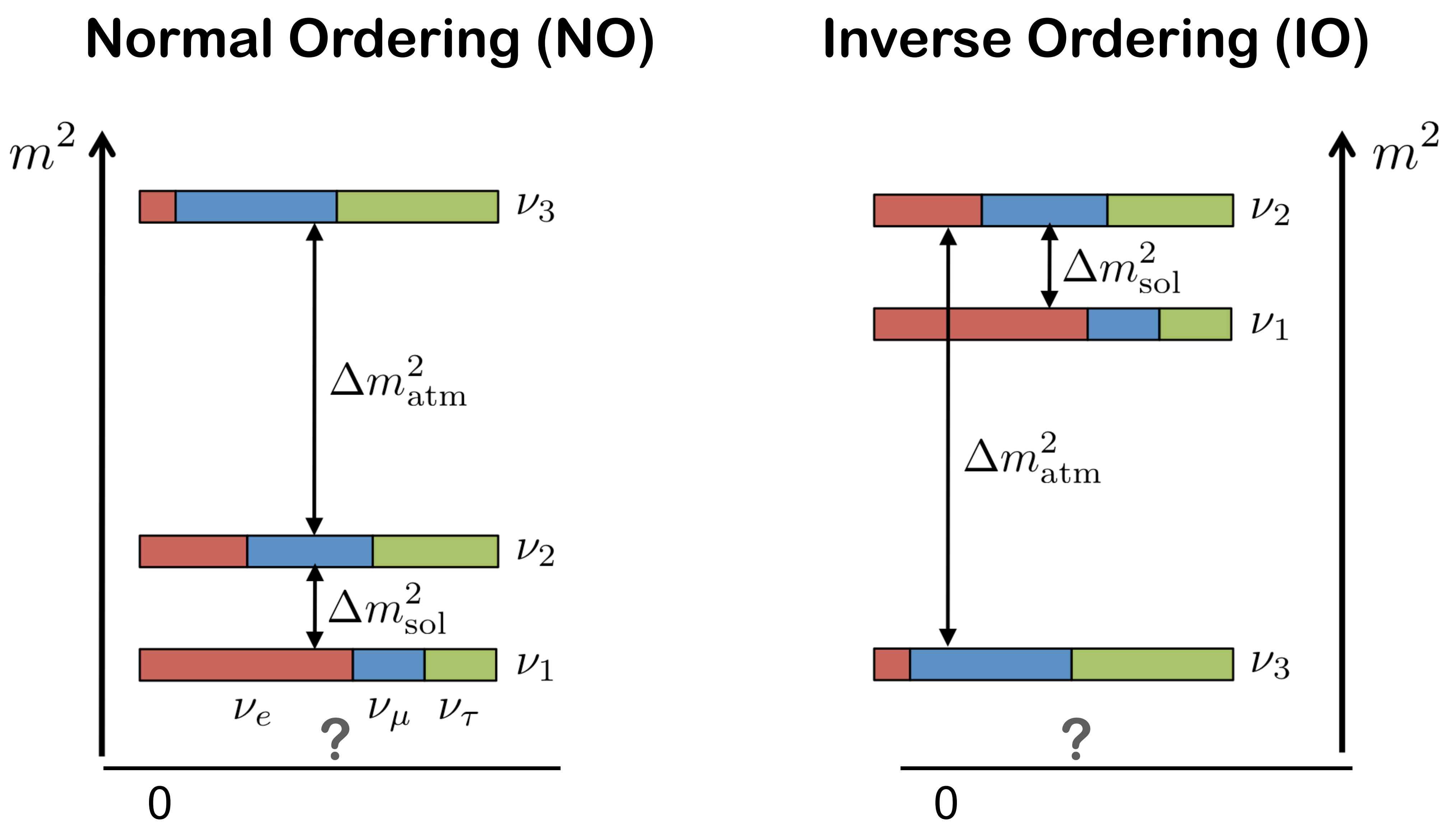
- Next milestones: $\Delta m^2_{32},\ \delta_{CP}$

- ν_e/ anti-ν_e appearance, ν_μ/anti-ν_μ disappearance:

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



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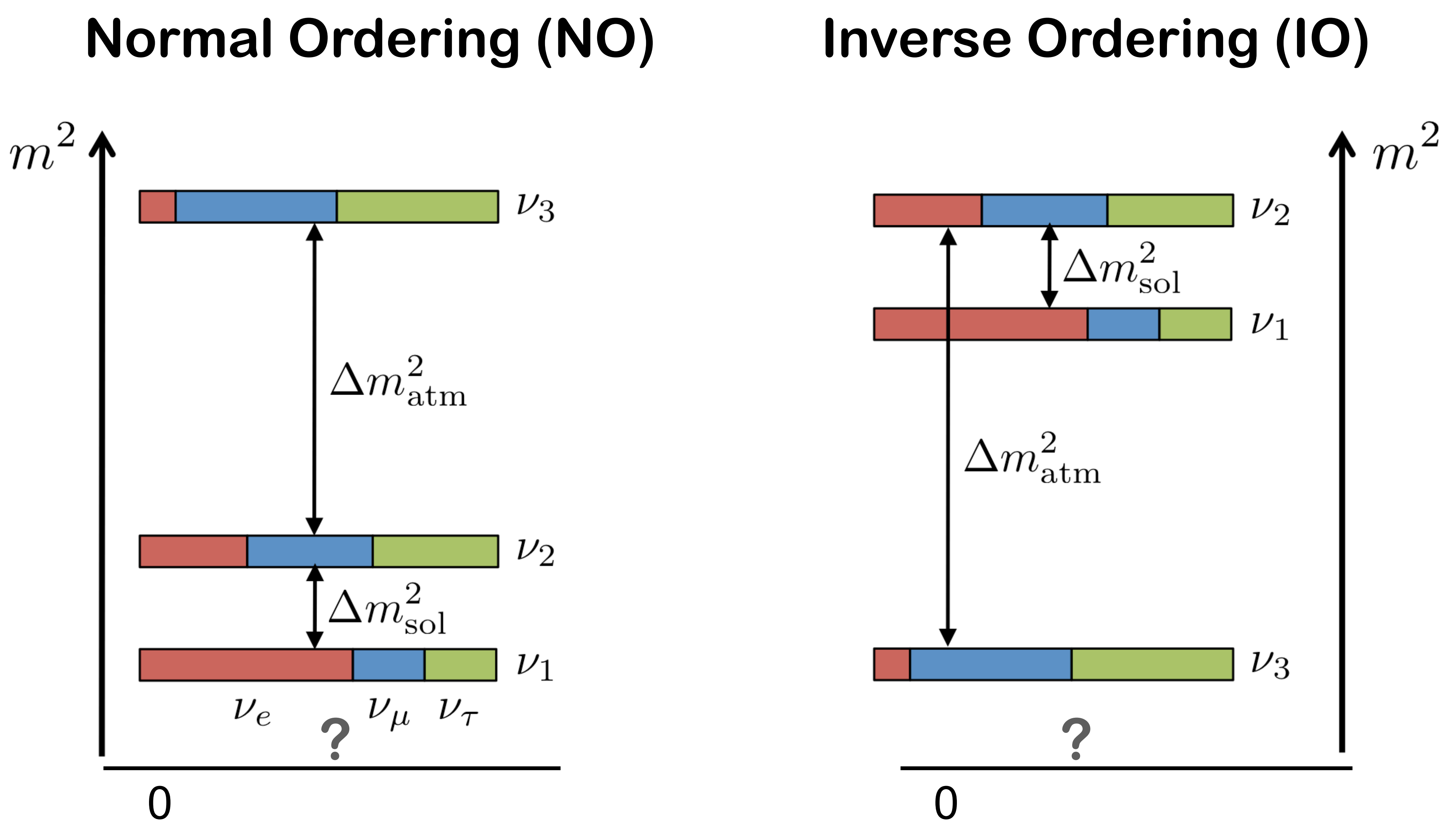

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- Long baseline (~1300km): more matter -> more sensitivity to mass hierarchy

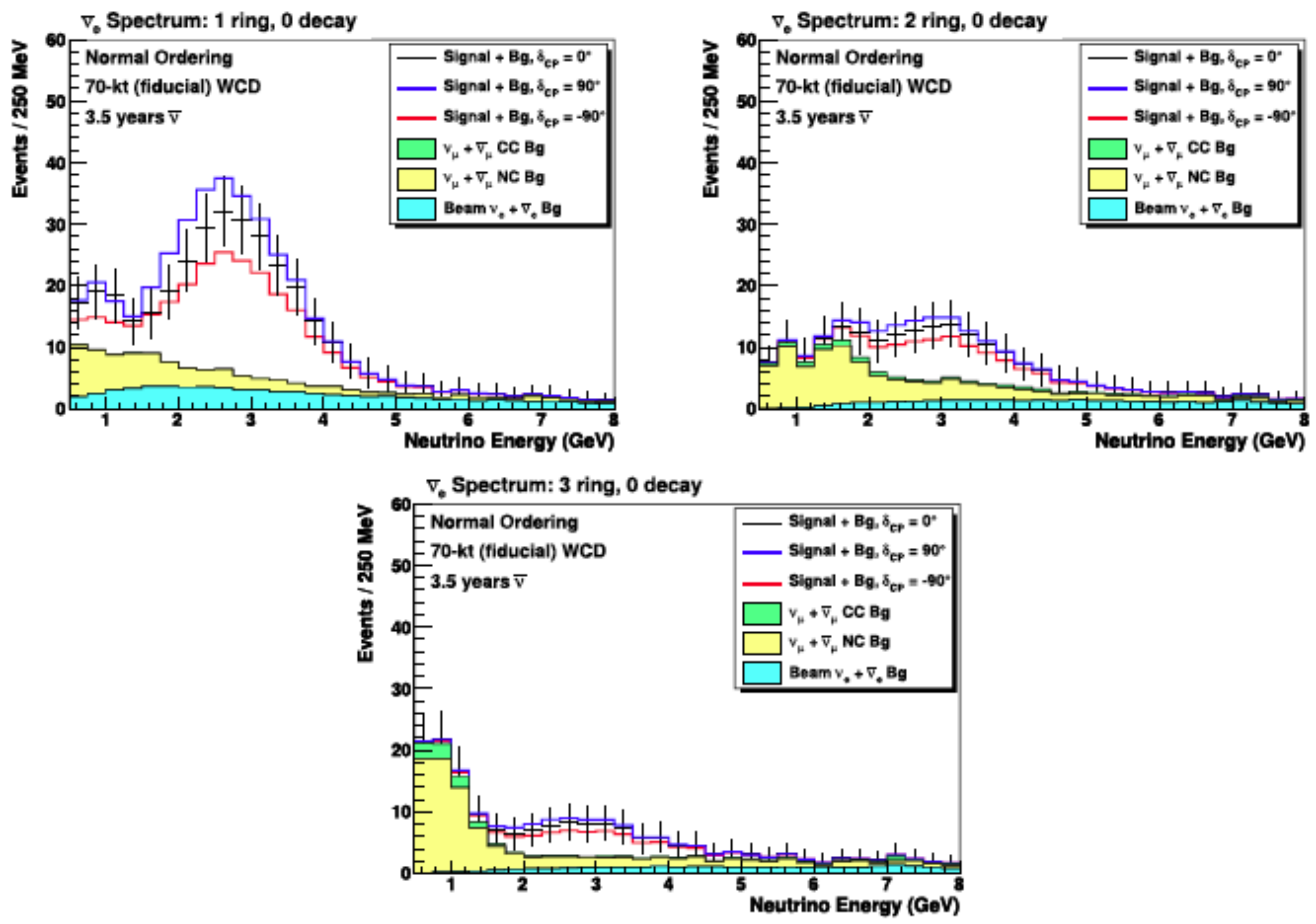
$$A = \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\overline{\nu}_\mu \to \overline{\nu}_e)}$$

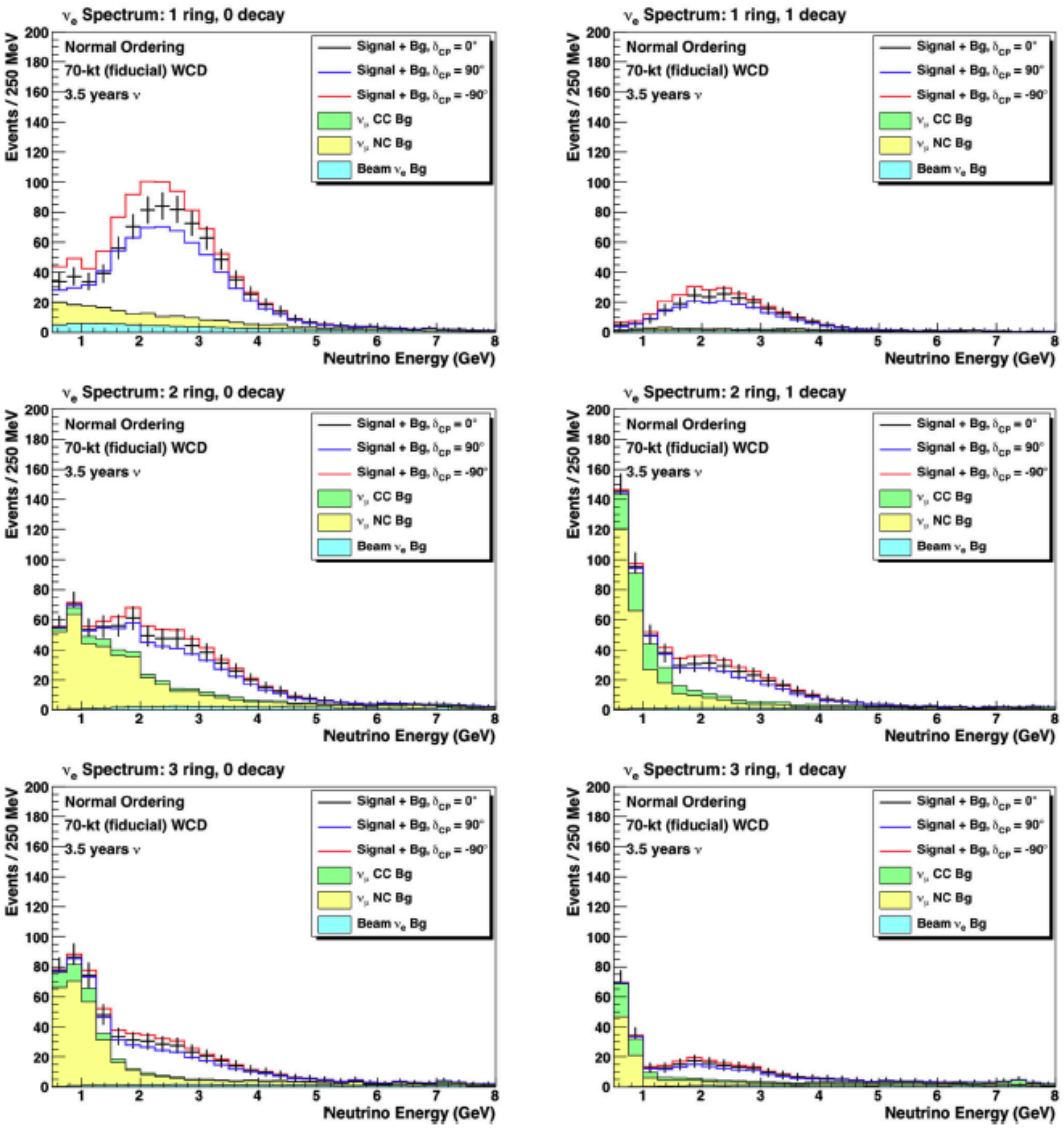
- A $\sim 40\,\%$ in the region of the peak flux in the absence of CP-violating phase

Phase I

Long-baseline neutrino oscillations

- Broad range of neutrino energies: sensitive to the shape of the oscillation spectrum for a range of neutrino energies.
- **Sensitive to both CP violating phase and mass ordering**
- Rejecting neutral current background
- Improved reconstruction methods (ring imaging)



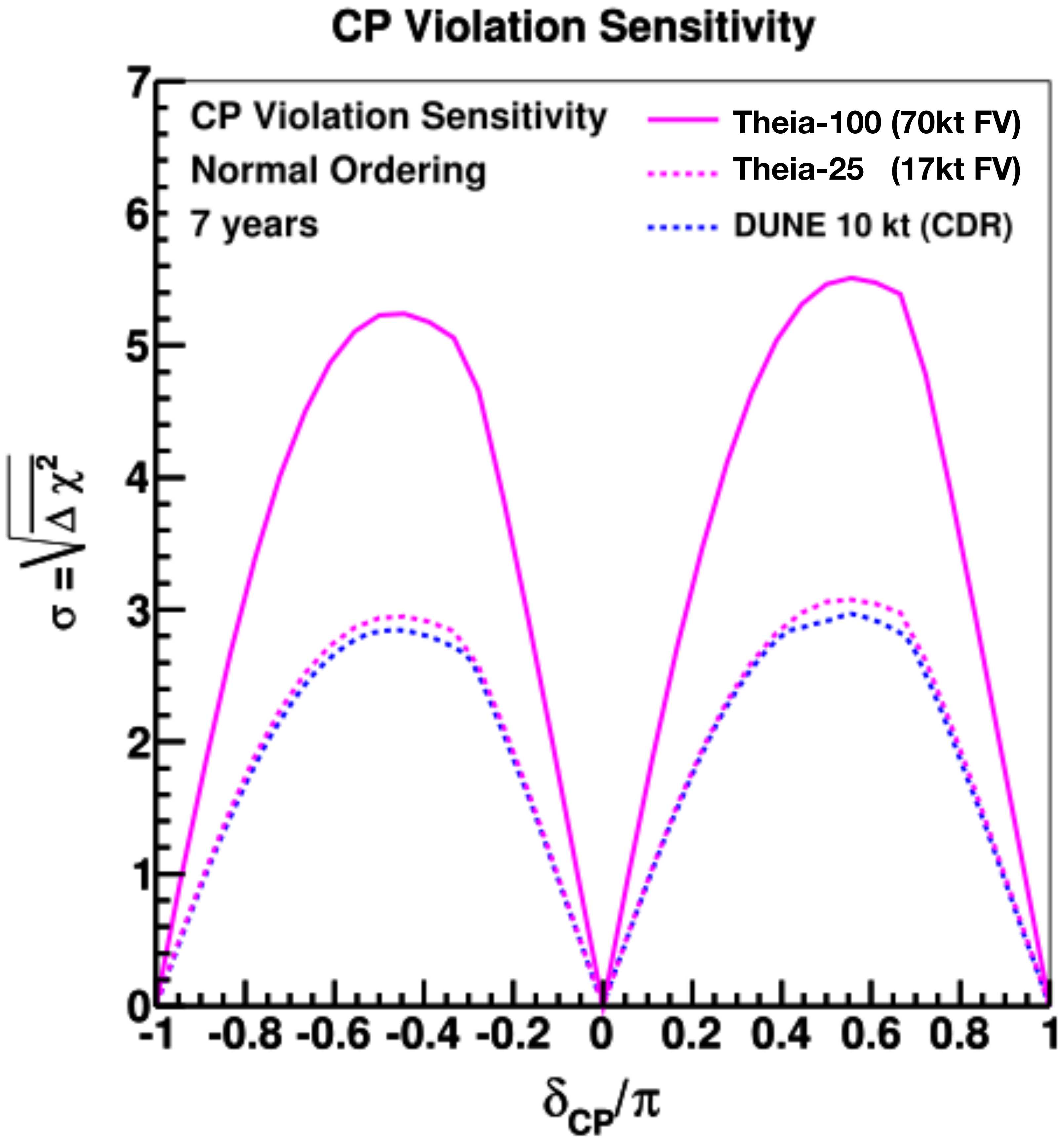


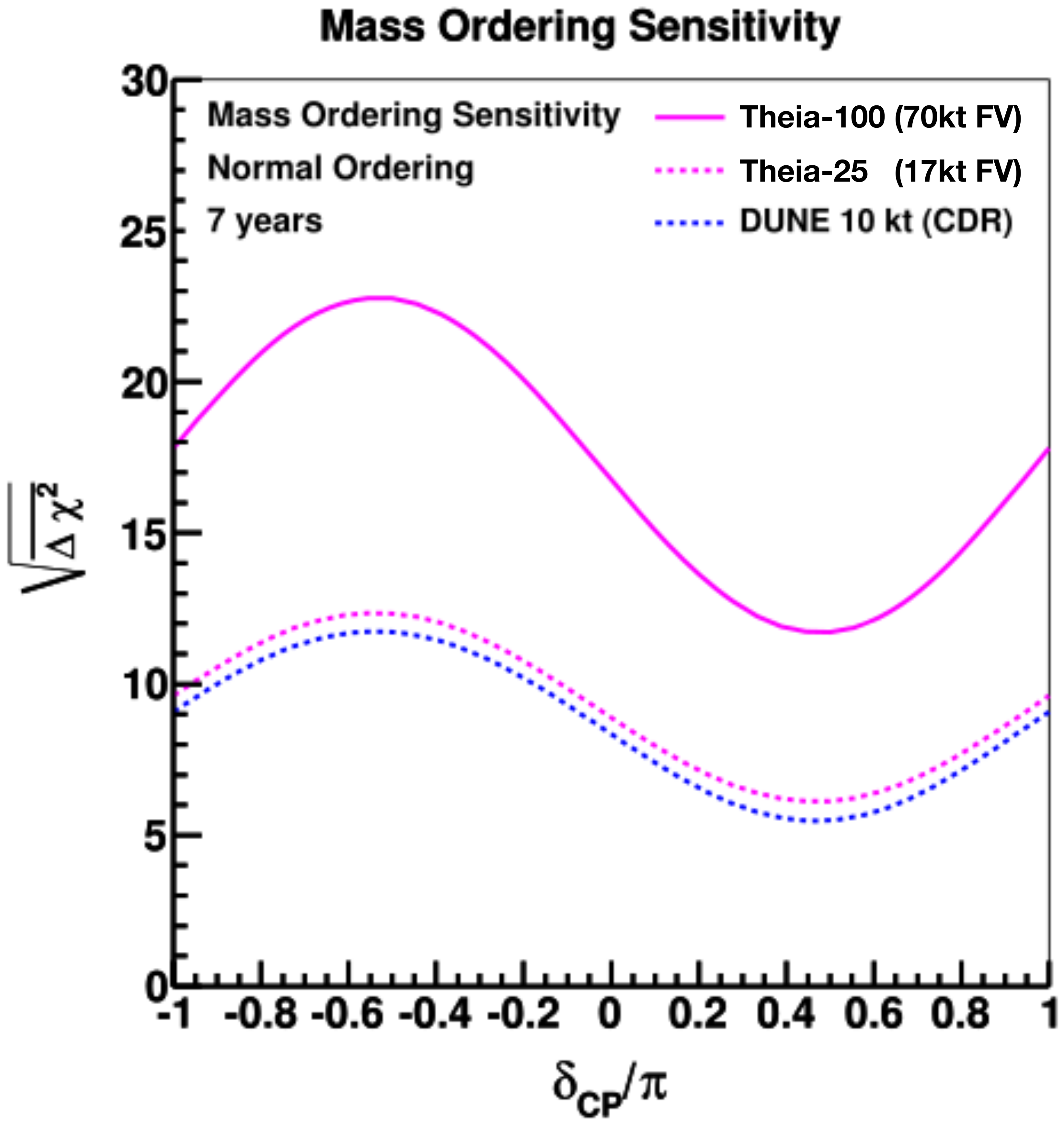
Theia: oscillation parameters

Phase I

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

- Theia can complement DUNE measurements (same location, different target, systematics) - important cross-check
- 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
- > 5σ for 30% of δ_{CP} values (524 kt-MW-year)





distinct set of detector systematic uncertainties

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

Theia: multipurpose neutrino detector

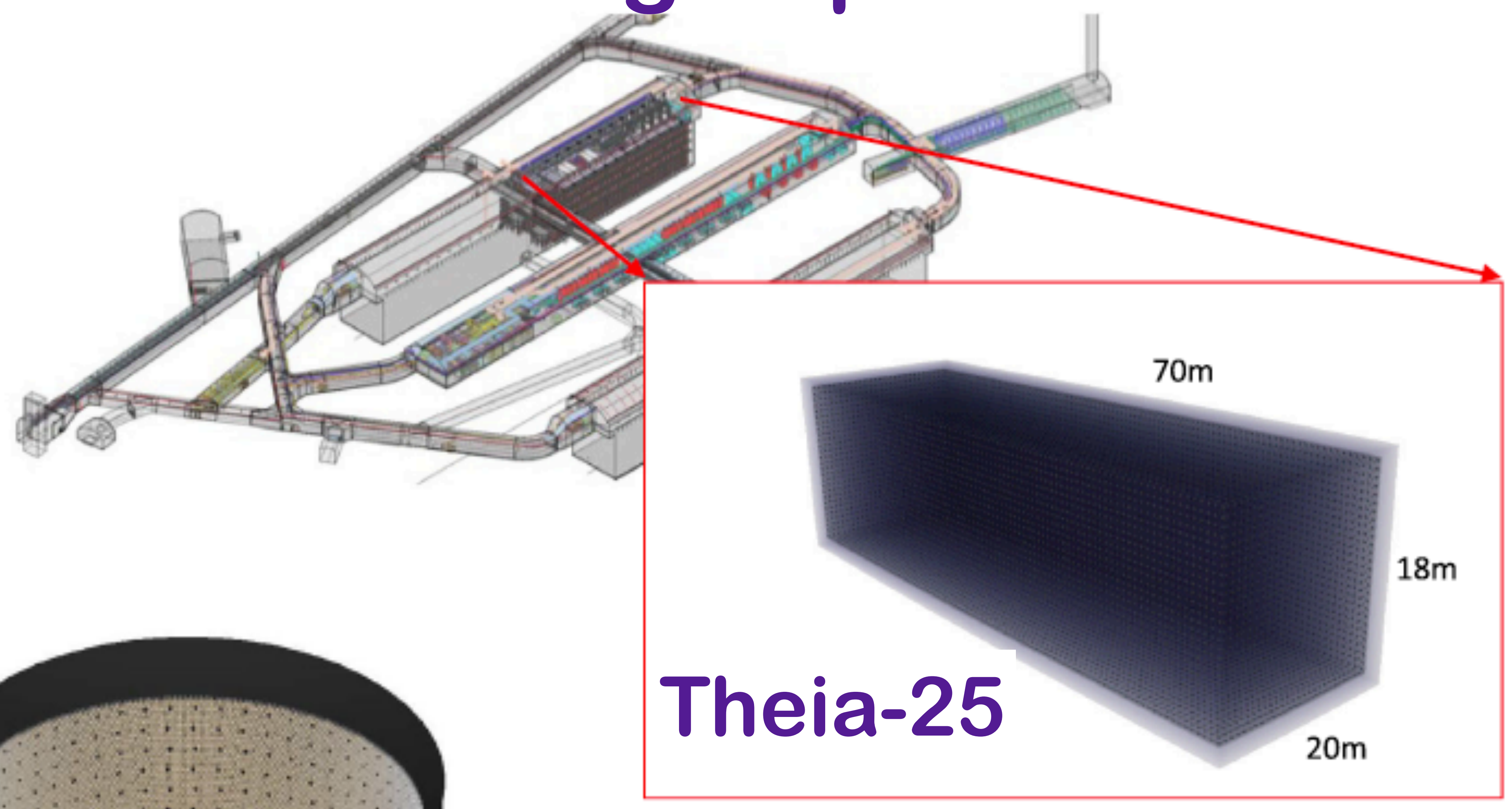
neutrino mass ordering

neutrino CP-violating phase δ

neutrinoless double beta decay

nucleon decay

Design options



Large scale, multipurpose detector

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Scintillator fraction tunable depending on the physics goal
->staged approach

diffuse supernova neutrinos (DSNB)

supernova burst neutrinos

solar neutrinos (CNO, ^{8}B)

geoneutrinos

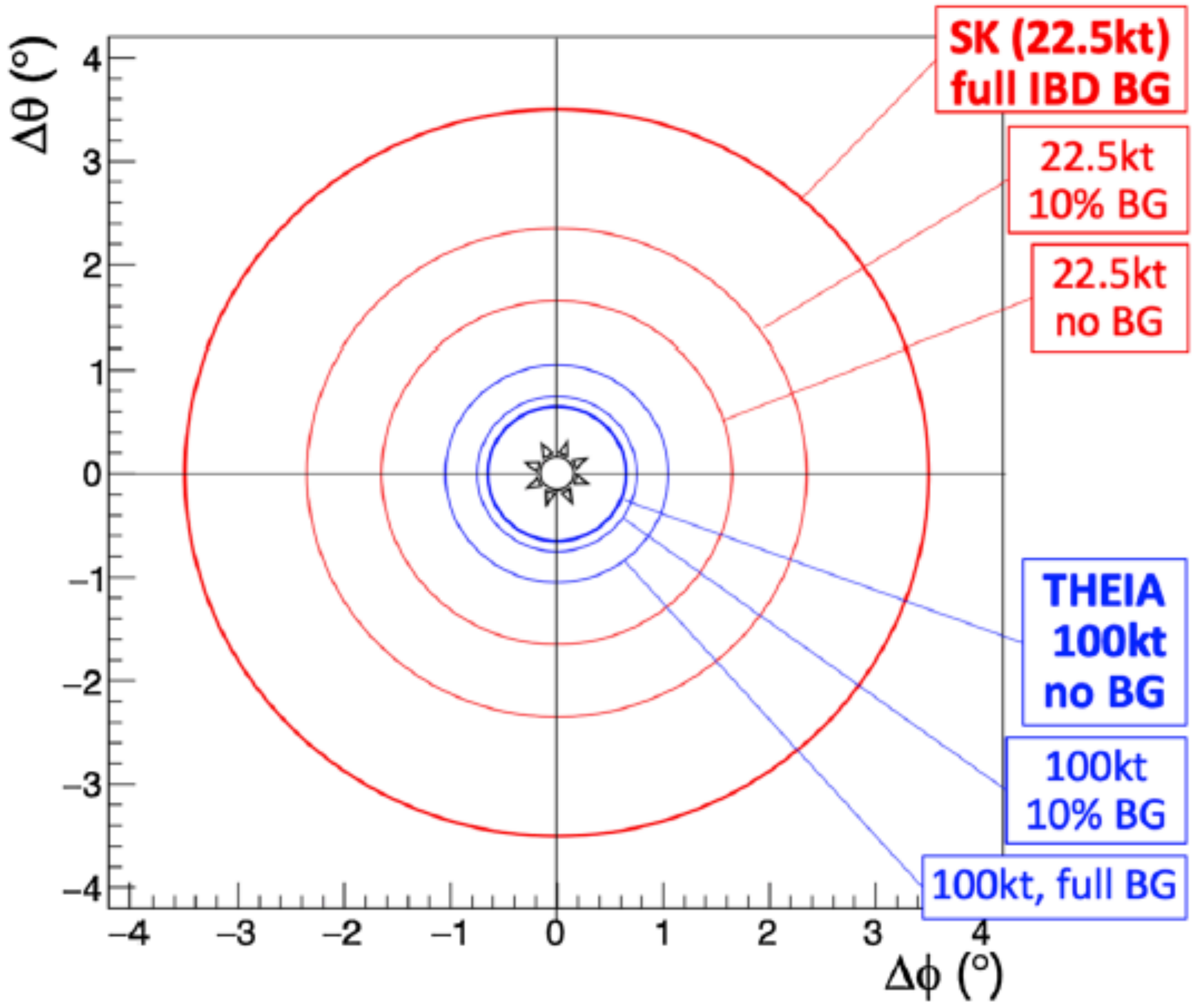
THEIA: An advanced optical neutrino detector Eur. Phys. J. C 80, 416

Theia: supernova burst neutrinos

- **dynamics of the core collapse** (neutronization, reheating, proto-neutron star cooling)
- **the properties of the neutrinos themselves** (mass hierarchy, absolute mass scale, collective oscillations)

Only one observed: SN1986A

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



Expected event rates in 100kt 10% WbLS for SN at 10kpc:

Reaction		*Rate*
(IBD)	$\bar{\nu}_e + p \rightarrow n + e^+$	19,800
(ES)	$\nu + e \rightarrow e + \nu$	960
(ν_eO)	$^{16}\mathrm{O}(\nu_e, e^-)^{16}\mathrm{F}$	340
($\bar{\nu}_e$O)	$^{16}\mathrm{O}(\bar{\nu}_e, e^+)^{16}\mathrm{N}$	440
(NCO)	$^{16}\mathrm{O}(\nu, \nu)^{16}\mathrm{O}^*$	1100

- **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

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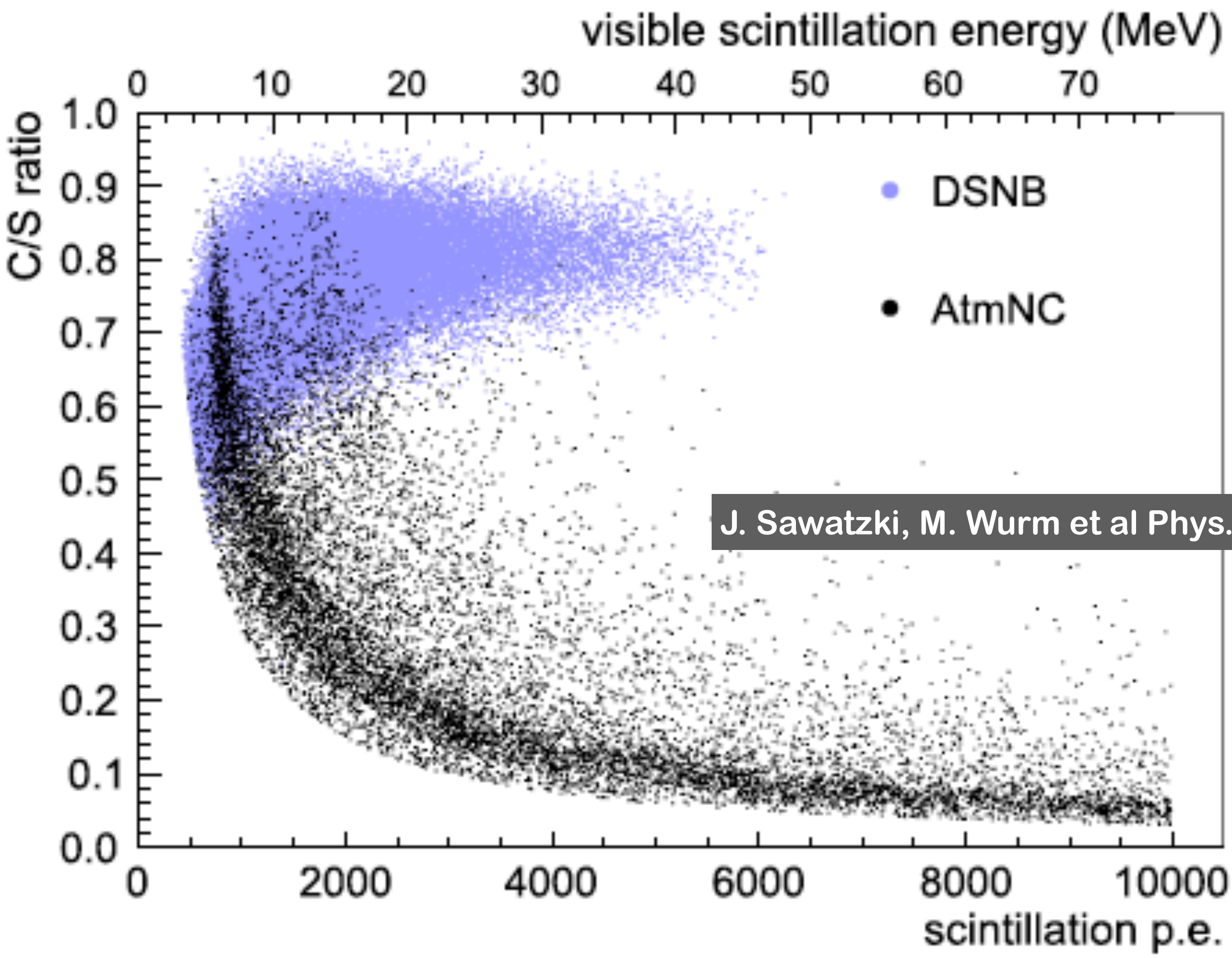
Theia: Diffuse supernova neutrino background (DSNB)

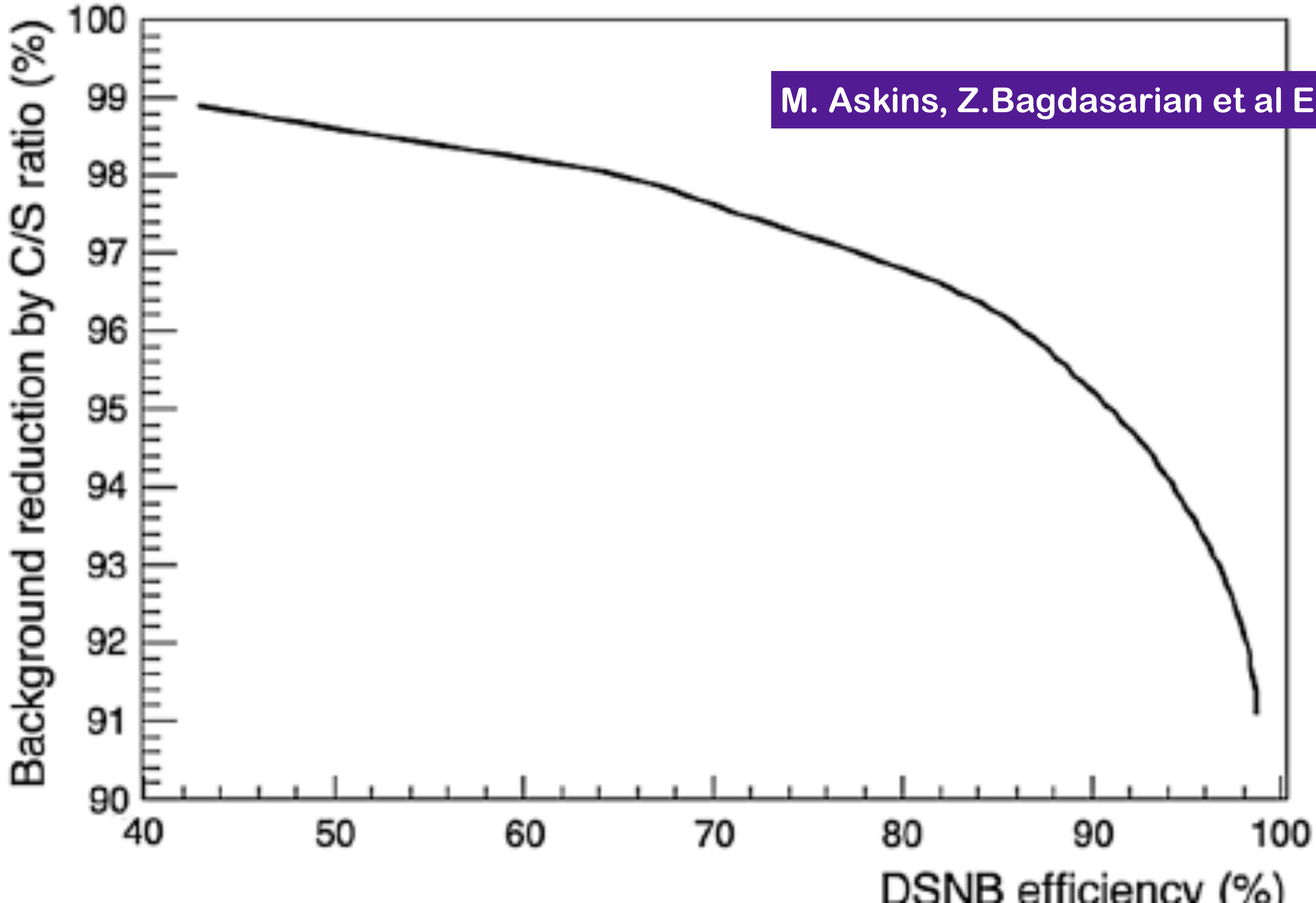
Diffuse, isotropic flux of ν from all SN explosions in the Universe.

Not yet experimentally observed

- **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)



J. Sawatzki, M. Wurm et al Phys. Rev. D 103, 02302



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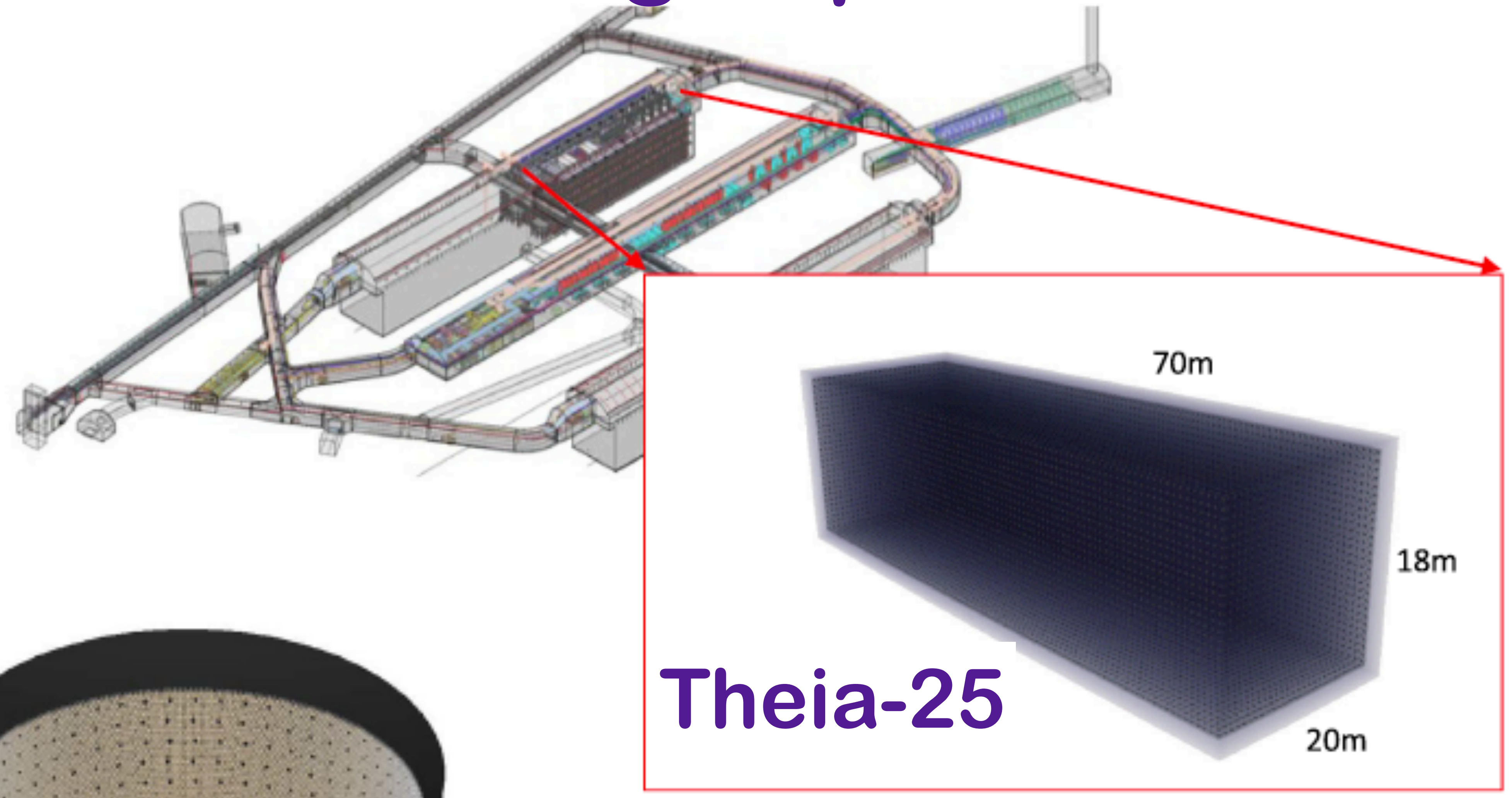

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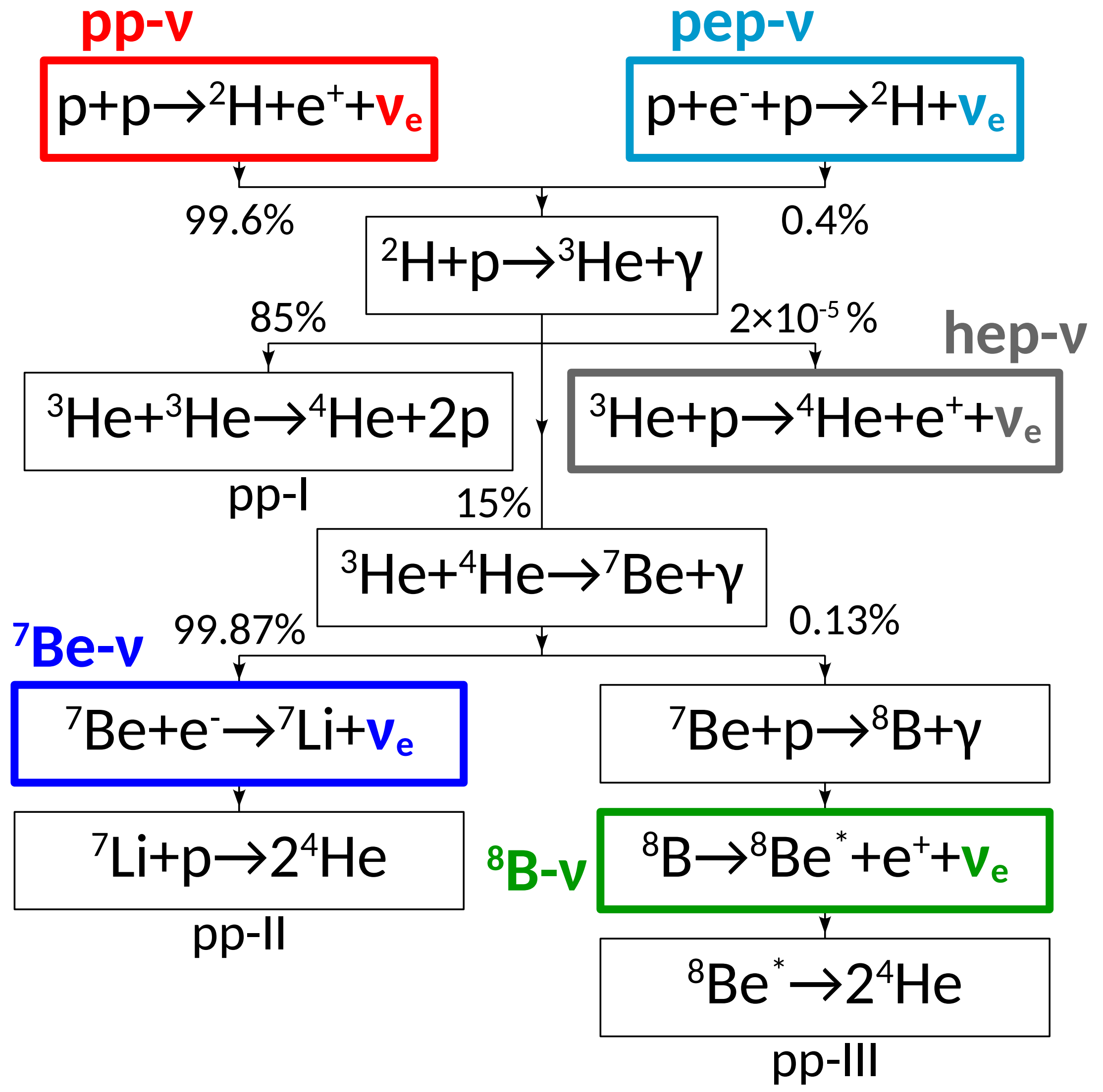
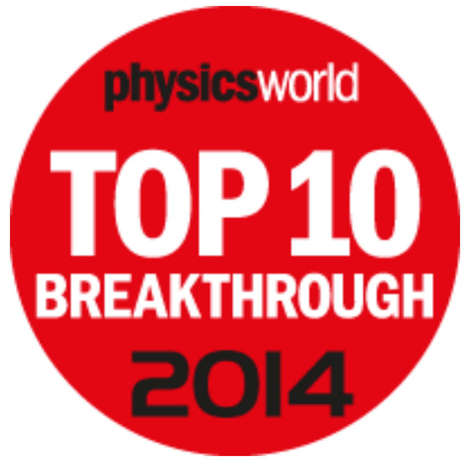
Solar neutrinos

pp chain reaction (~99%)



- The primary **fusion** mechanism **in the Sun**
- From **first-time** to **precision measurements:** ^{7}Be flux (2.8% error), pep (~20% error), and pp (~10% error)
- **Implications in solar and neutrino physics:** Composition of the Sun, neutrino flavor transition, physics beyond Standard Model



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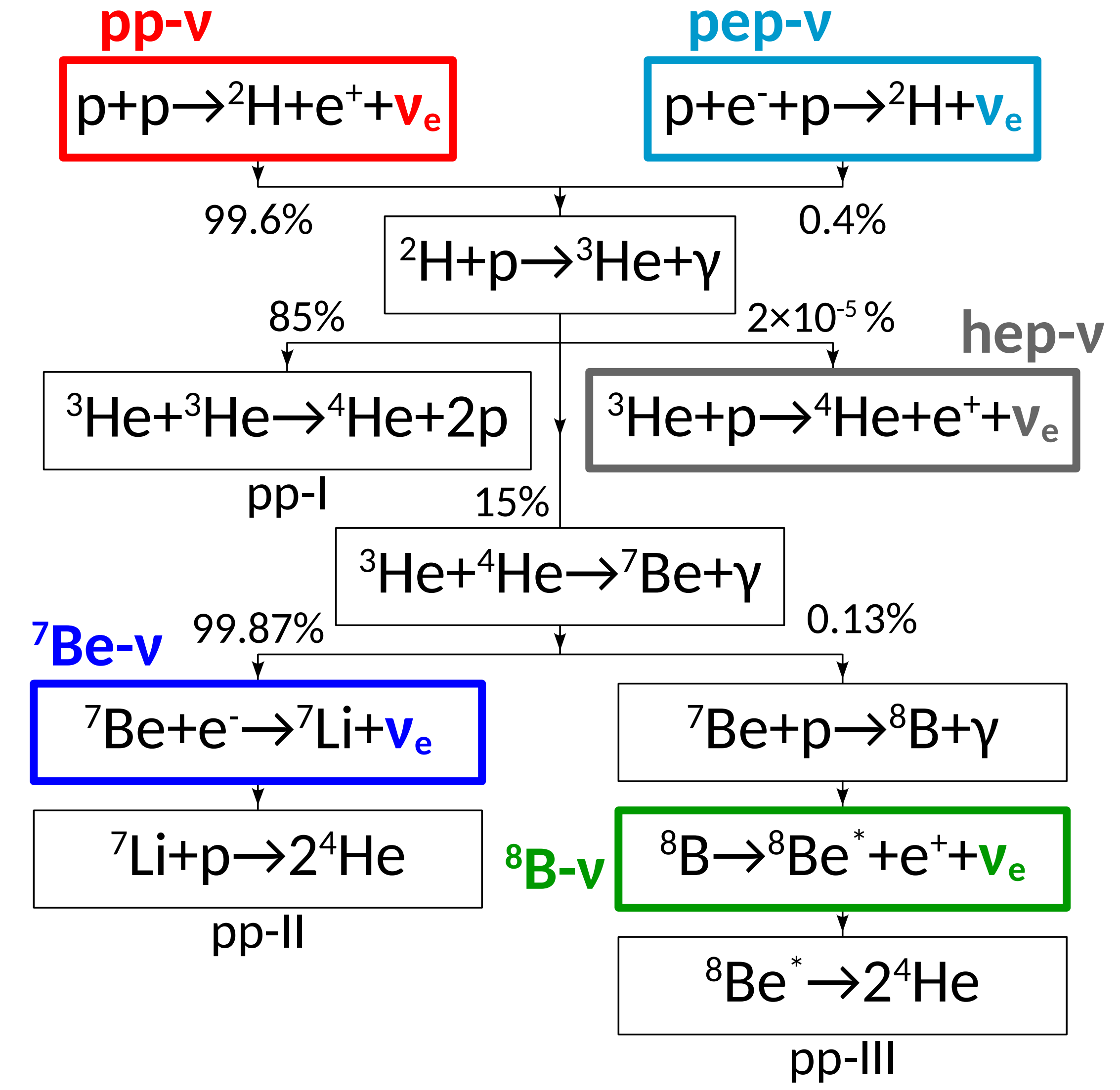

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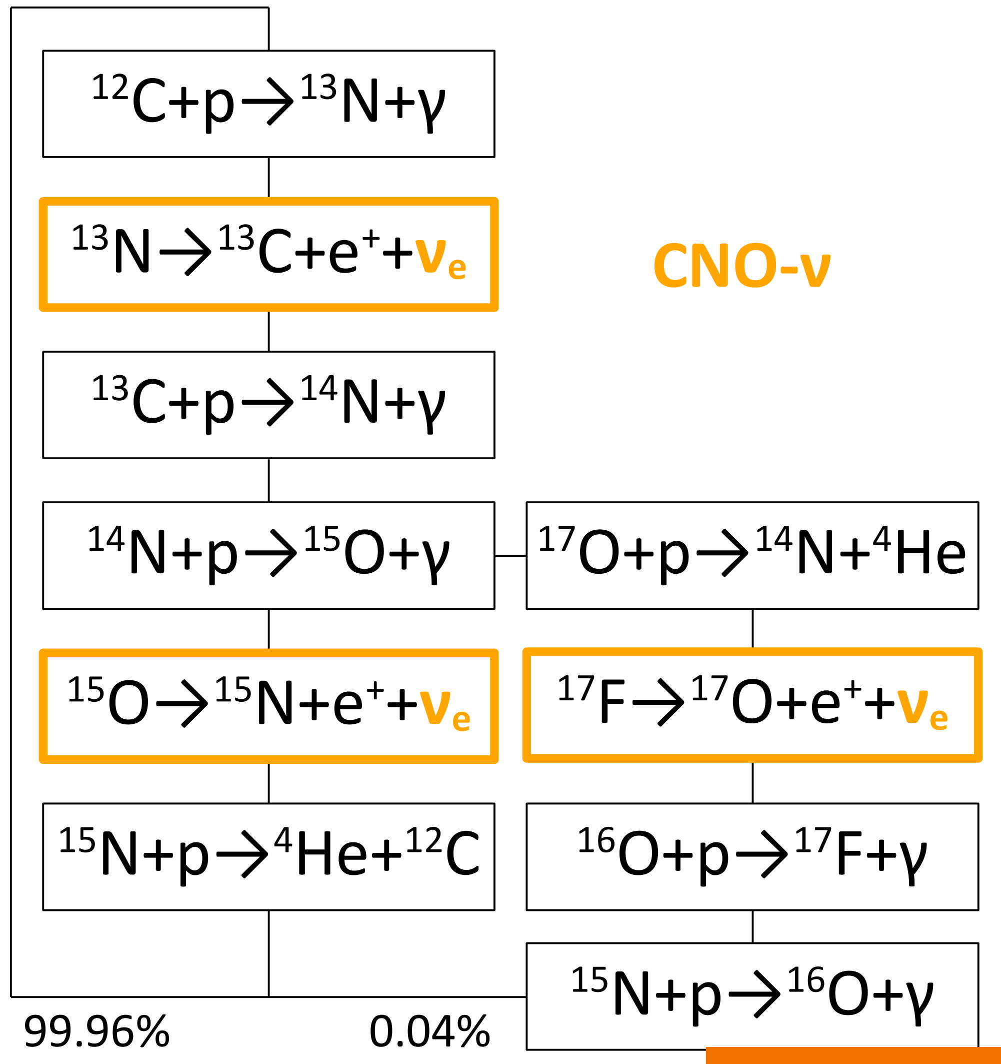
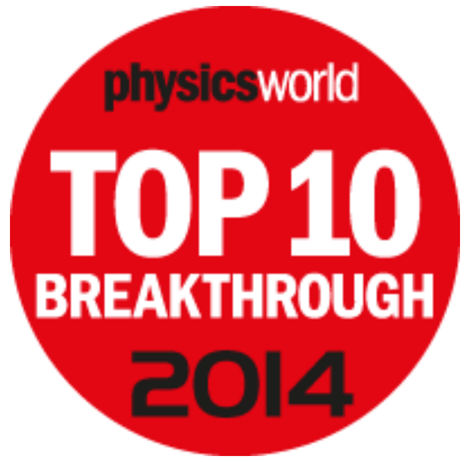
CNO cycle (< 1%)



Nature 587, p 577



- **The discovery** of neutrinos from carbon-nitrogen-oxygen fusion cycle by Borexino (2020)
- **The primary mechanism** for the stellar conversion of hydrogen into helium **in the Universe**
- Most sensitive to **Sun metallicity** (Z) puzzle

$$Z = \sum_{i>He} \frac{m_i}{M_\odot}$$

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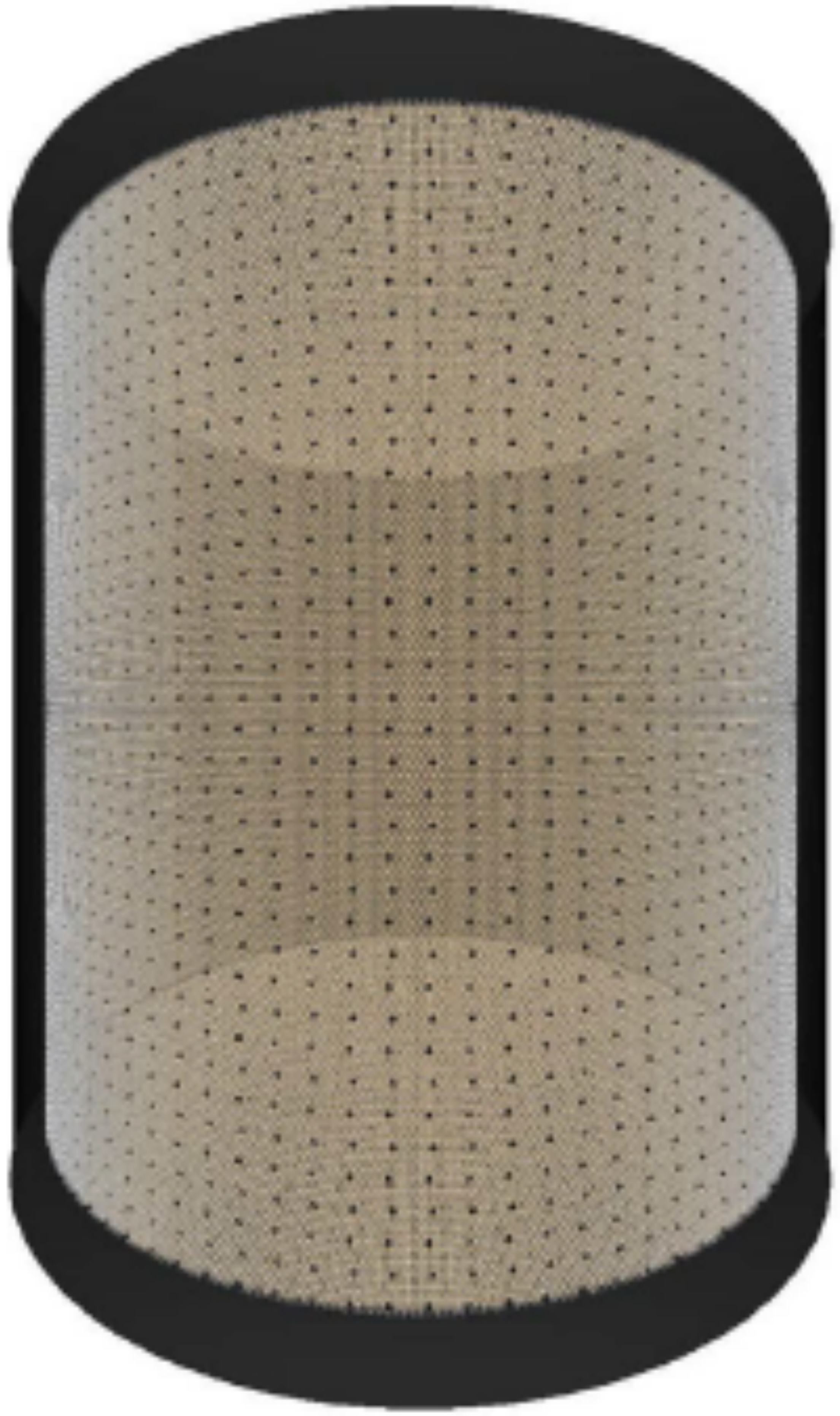
Theia: solar neutrinos

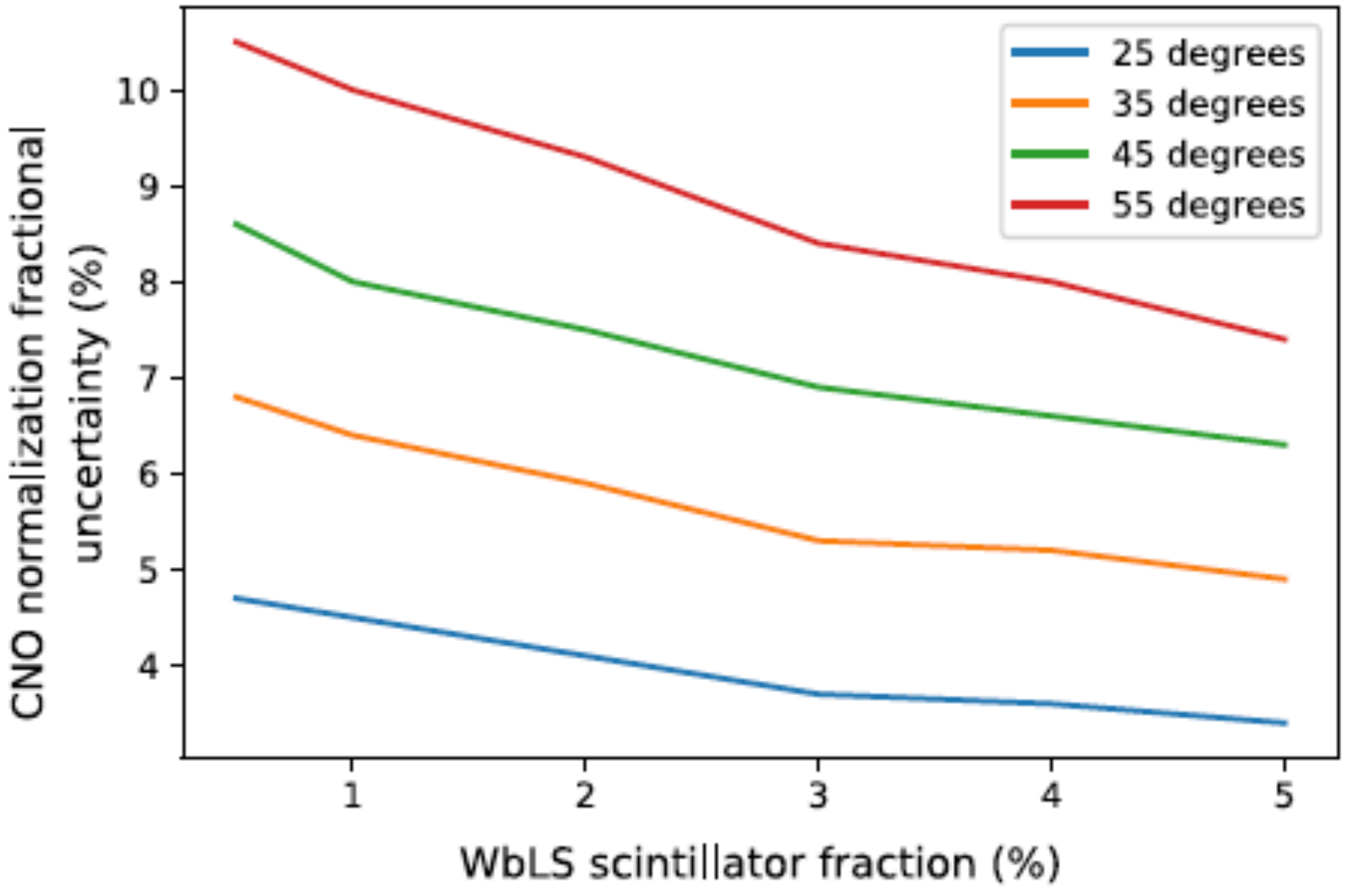
Phase II



Theia can significantly contribute to solar neutrinos studies:

- 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



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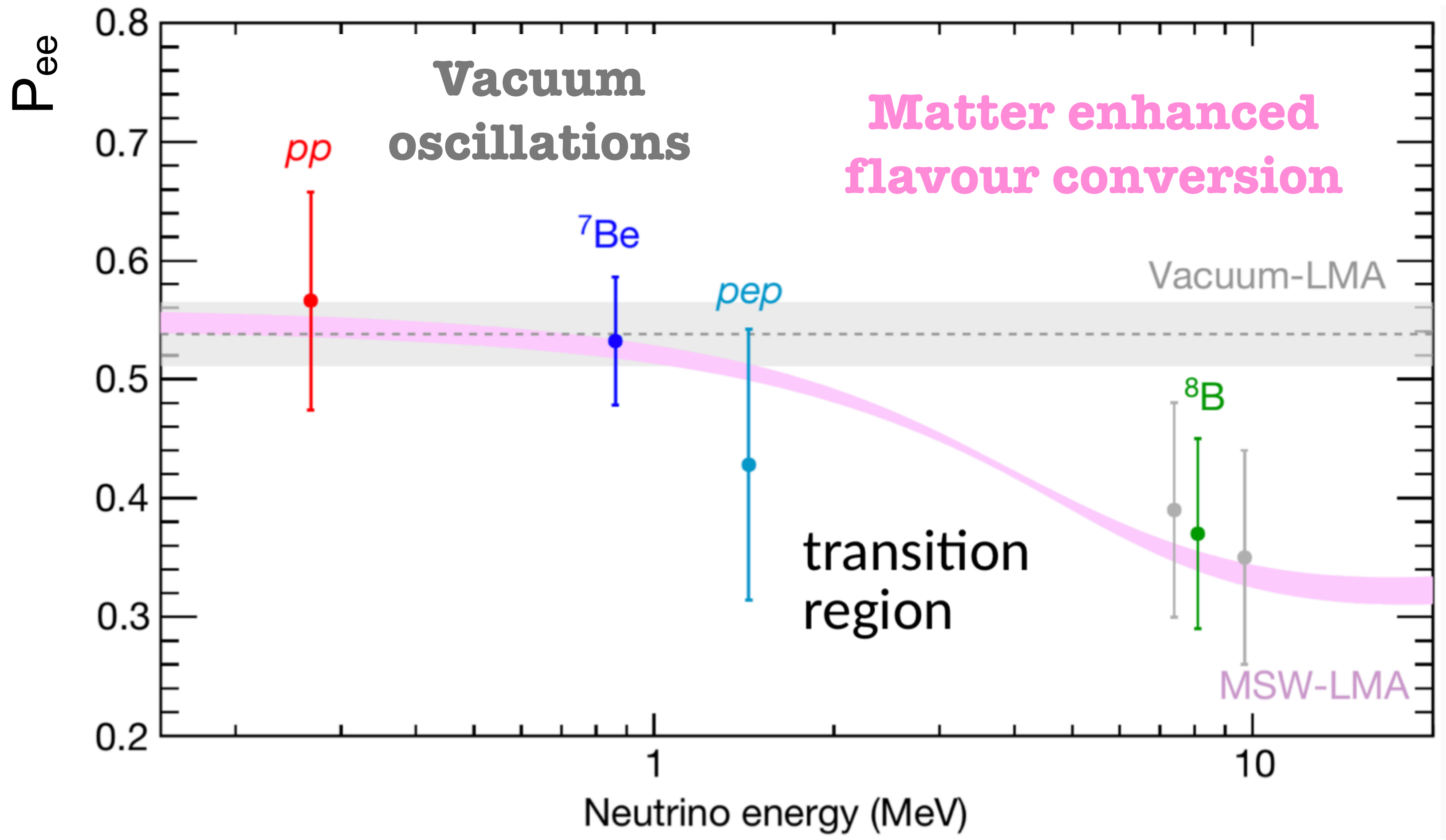

Borexino measurements Nature 562, p 505

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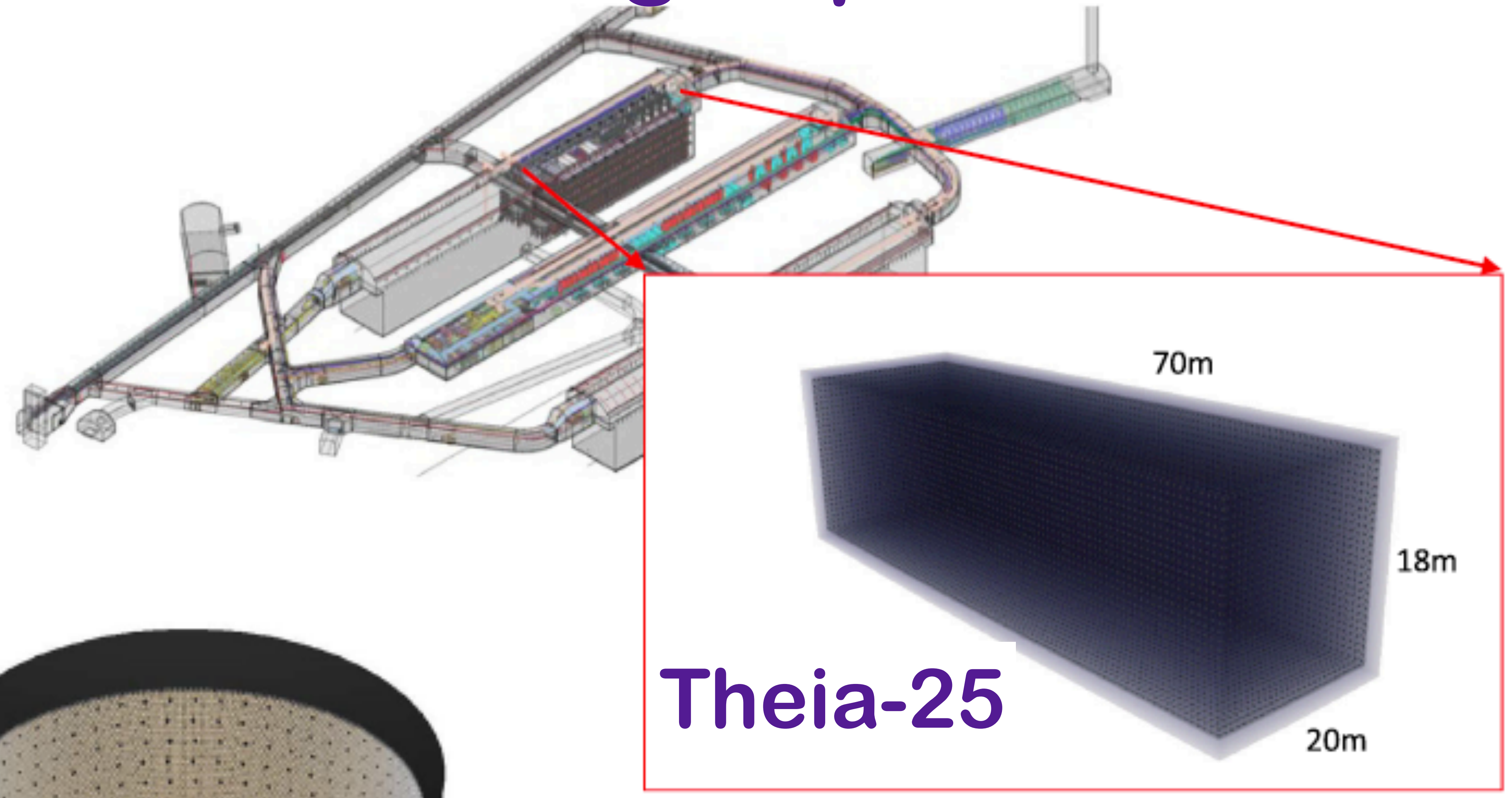

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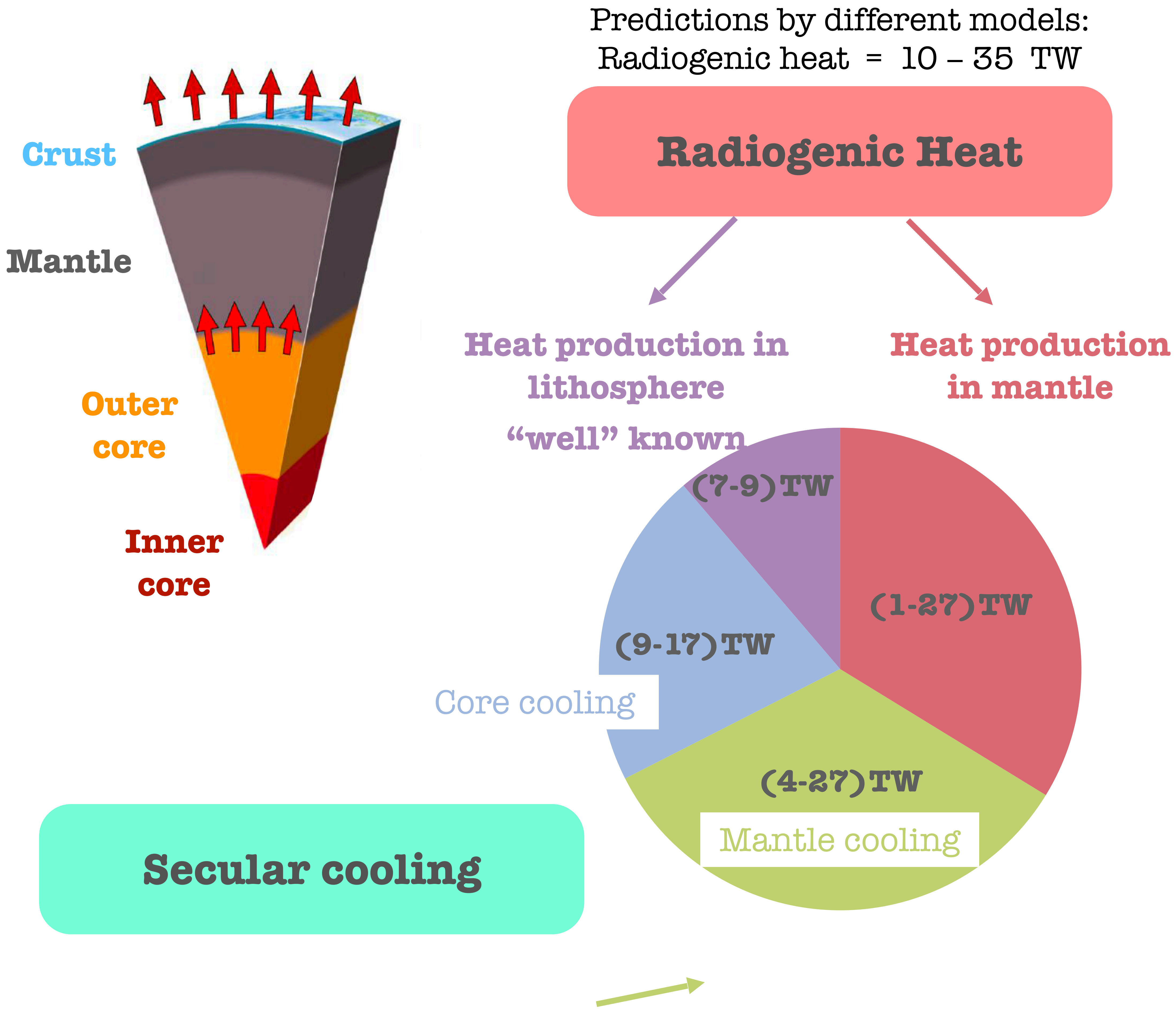
THEIA: An advanced optical neutrino detector Eur. Phys. J. C 80, 416

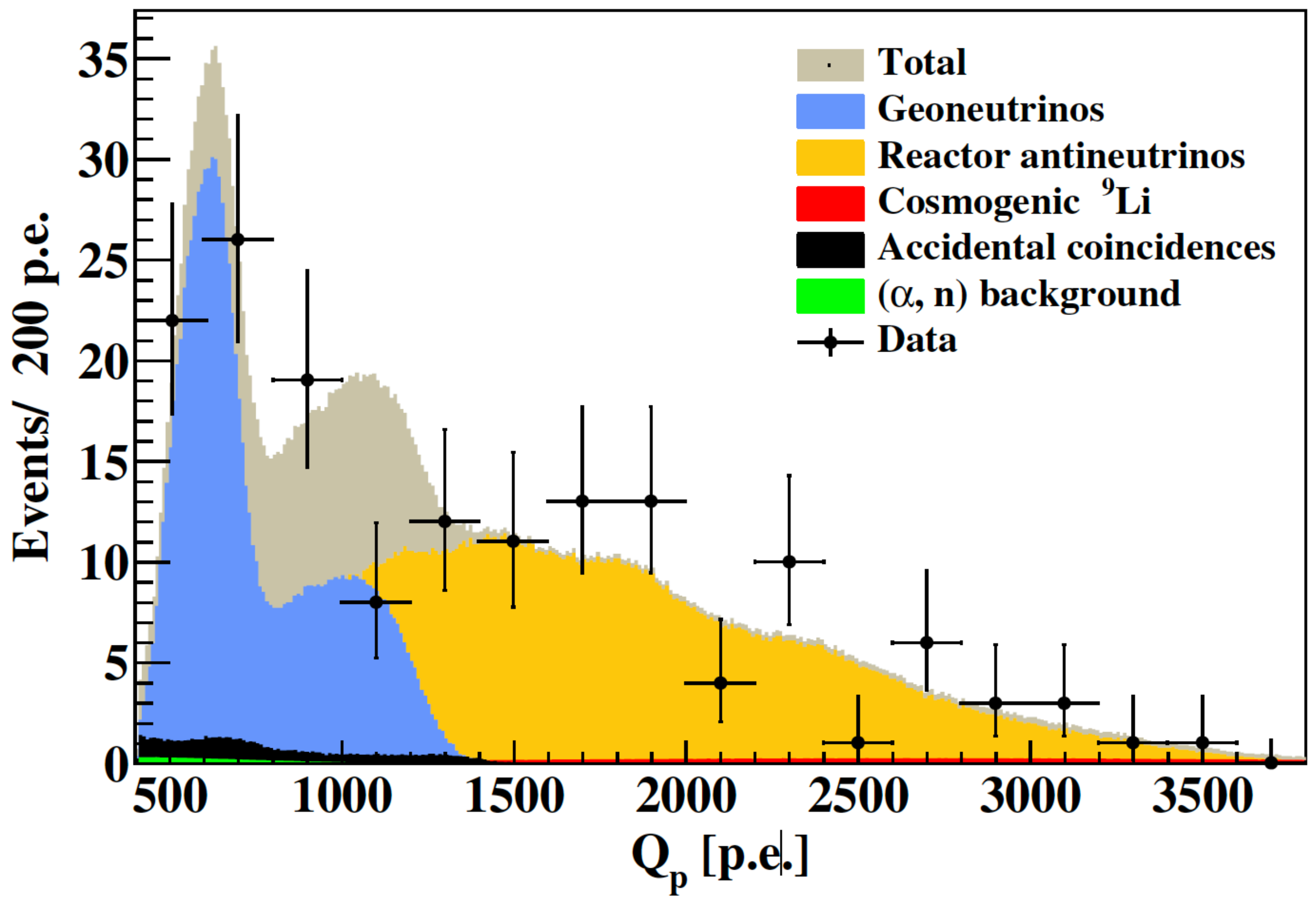
Phase II

Geoneutrinos

$$^{238}U \rightarrow ^{206}Pb + 8\,\alpha + 8\,e^{-} + 6\,\bar{\nu} + 51.7\ MeV$$
$$^{232}Th \rightarrow ^{208}Pb + 6\,\alpha + 4\,e^{-} + 6\,\bar{\nu} + 42.8\ MeV$$
$$^{40}K \rightarrow ^{40}Ca + e^{-} + \bar{\nu} + 1.32\ MeV$$



- Currently only two measurements: Borexino (Italy), KamLAND (Japan)



Borexino PRD 101 (2020) 012009 Editor's suggestion

- Next milestones:
  - Distinct rates of U and Th, U/Th ratio
  - disentangling the signals from various reservoirs
  - Test the geological models

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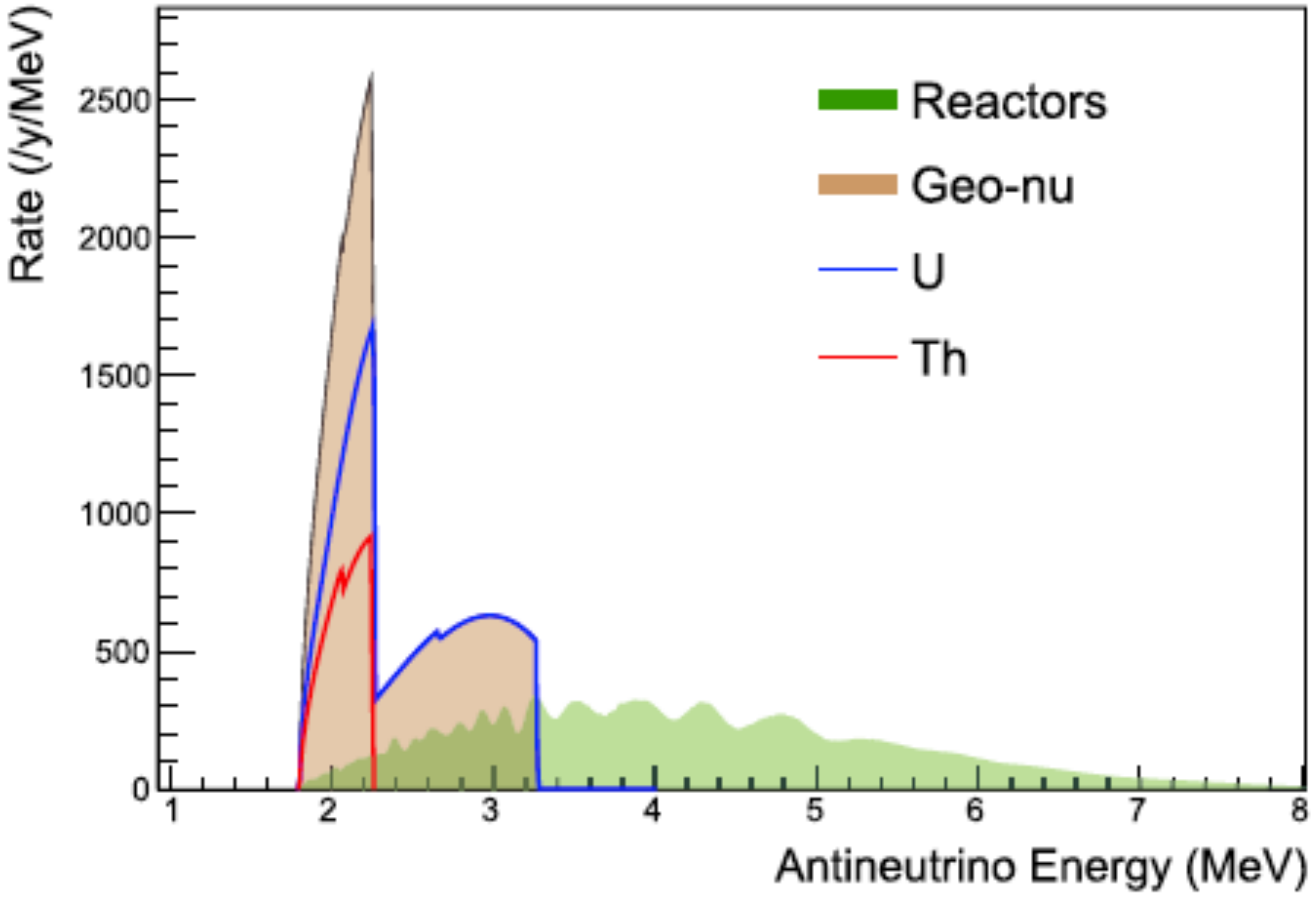
Theia: Geoneutrinos

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

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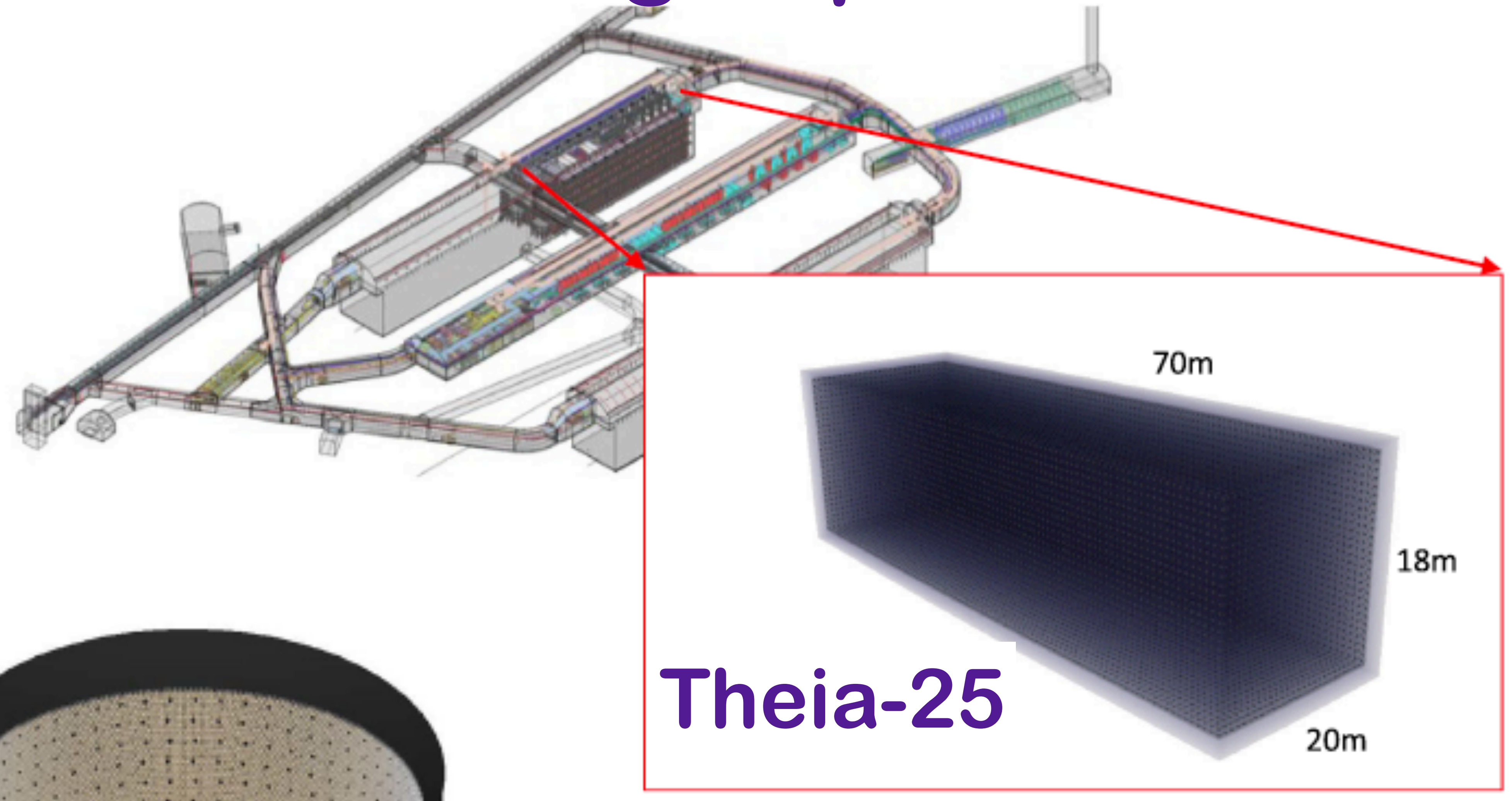

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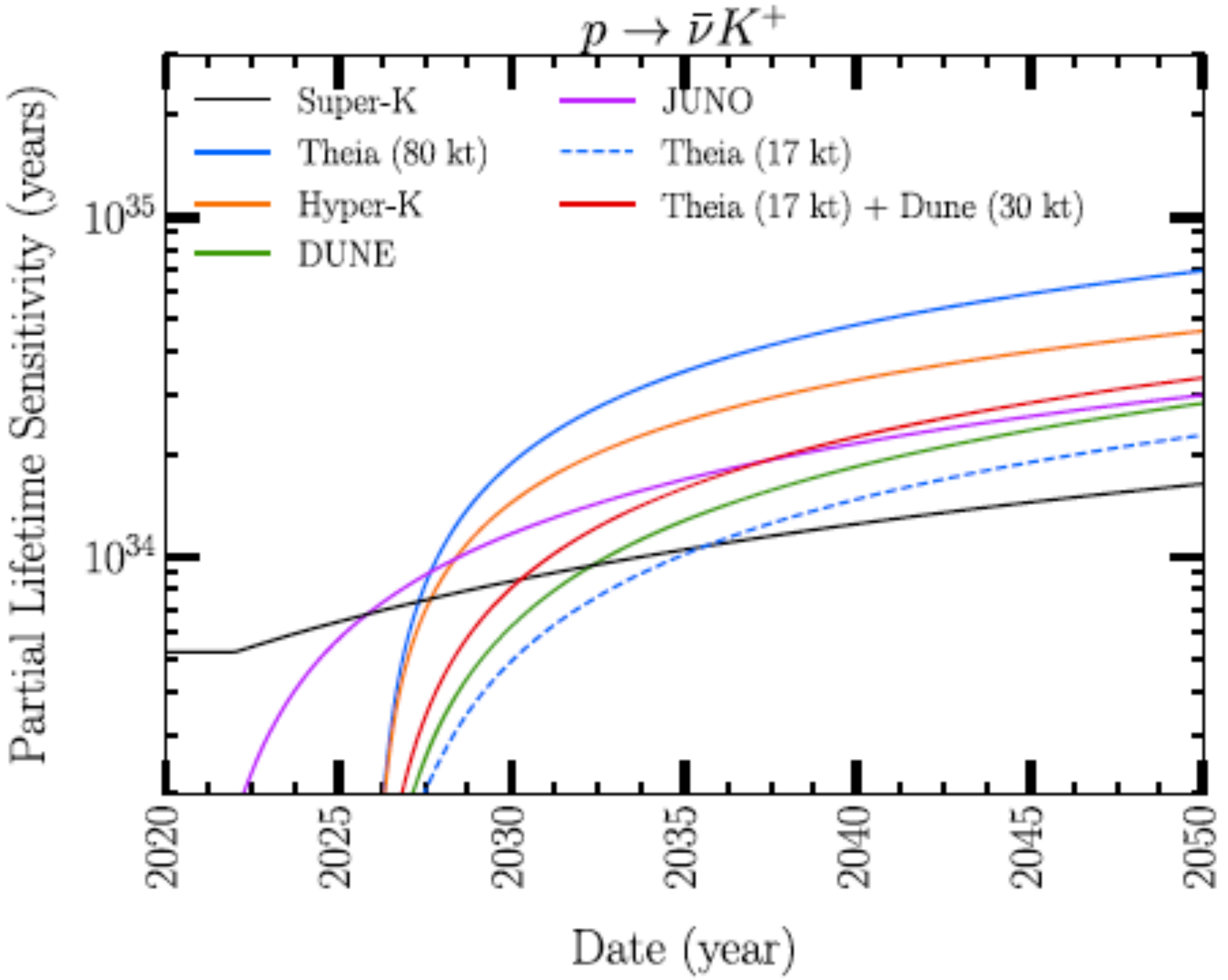
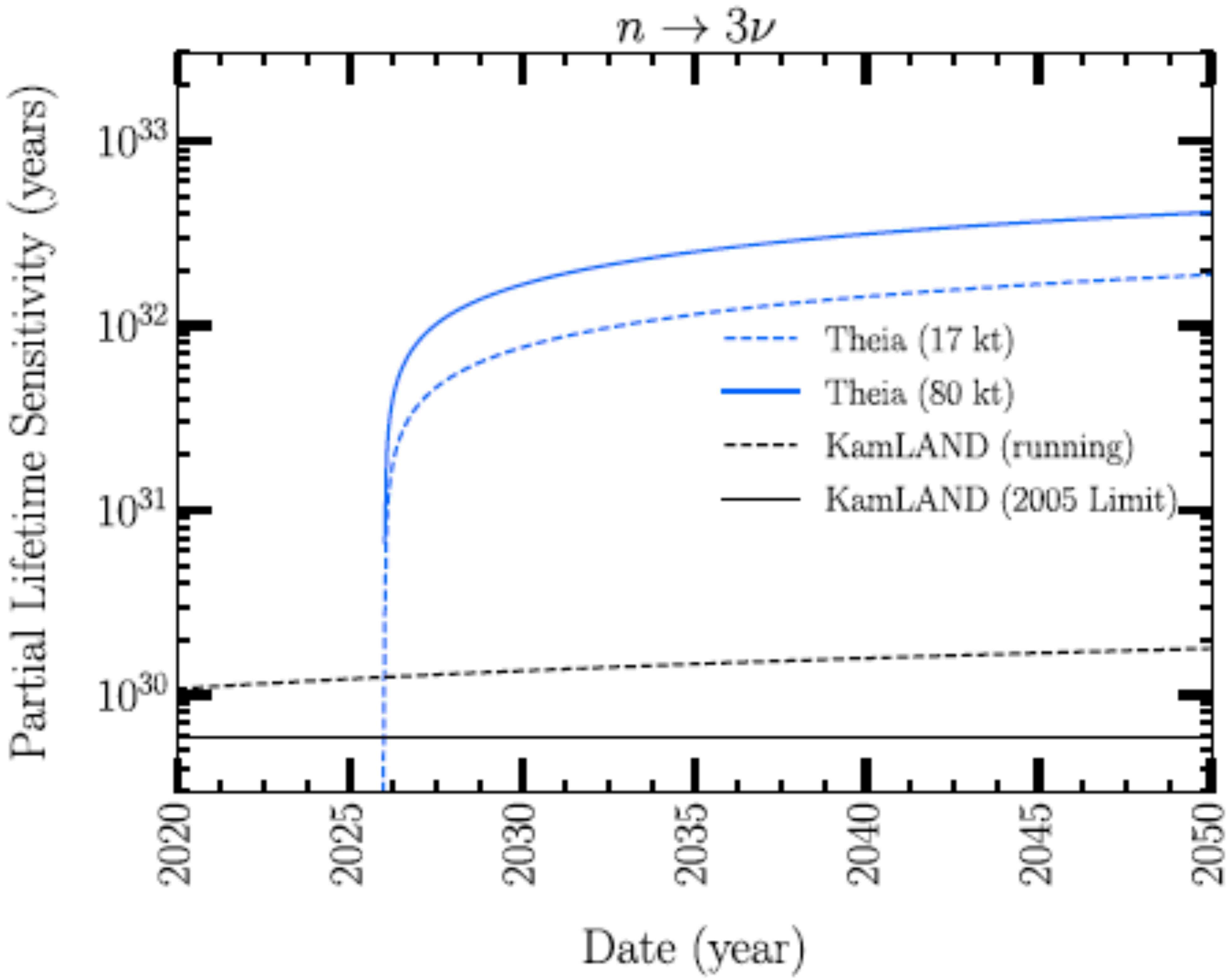
THEIA: An advanced optical neutrino detector Eur. Phys. J. C 80, 416

Theia: Nucleon decay

- Huge size, deep location and scintillation light = impressive nucleon decay detector
- Neutron tagging enhances sensitivity for proton decay and can be further improved by isotope loading
- Scintillation light allows the observation of K+ created upon a proton decay as well as the gammas emitted upon an invisible neutron or proton decay (~6 MeV)





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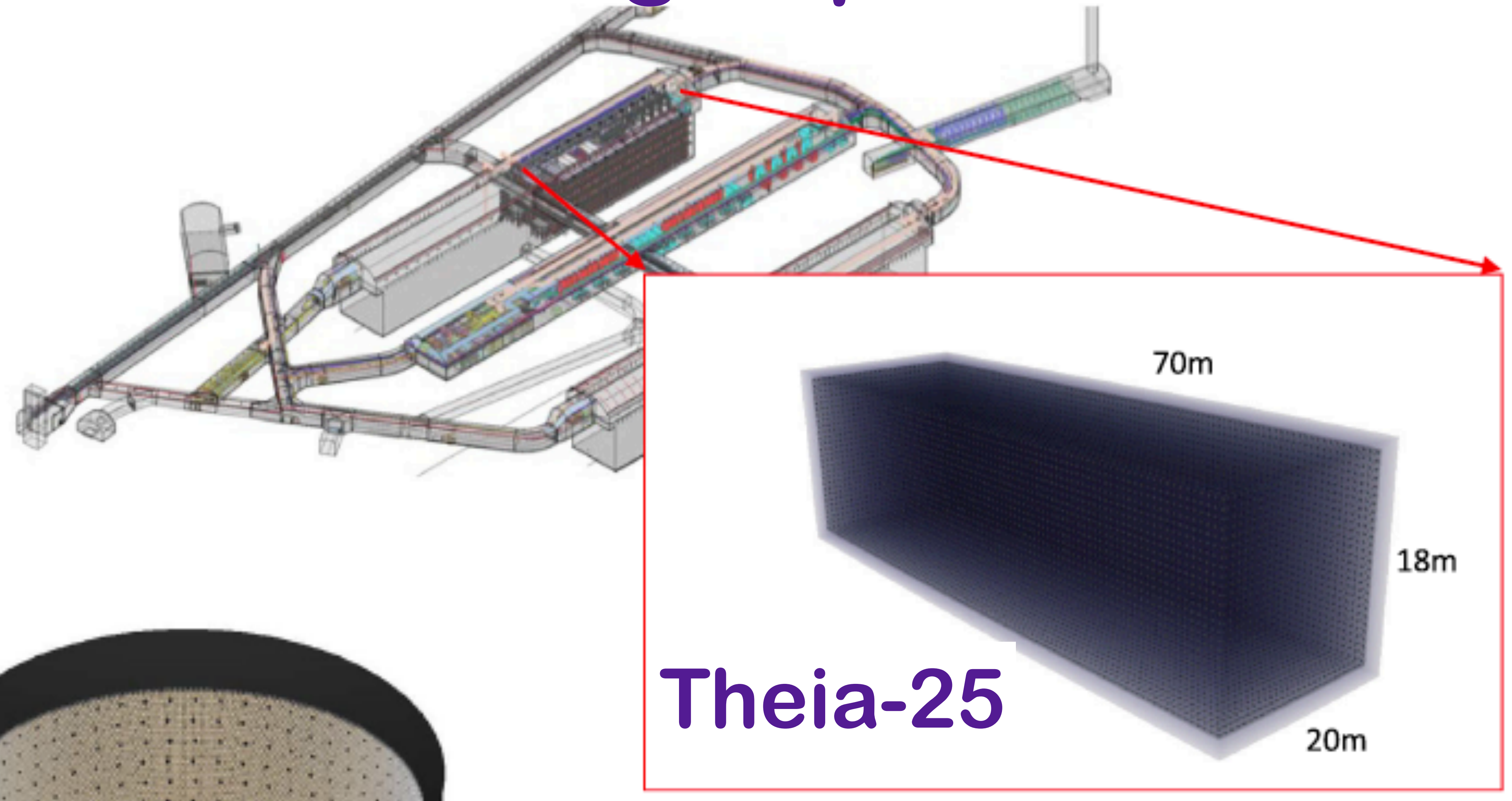

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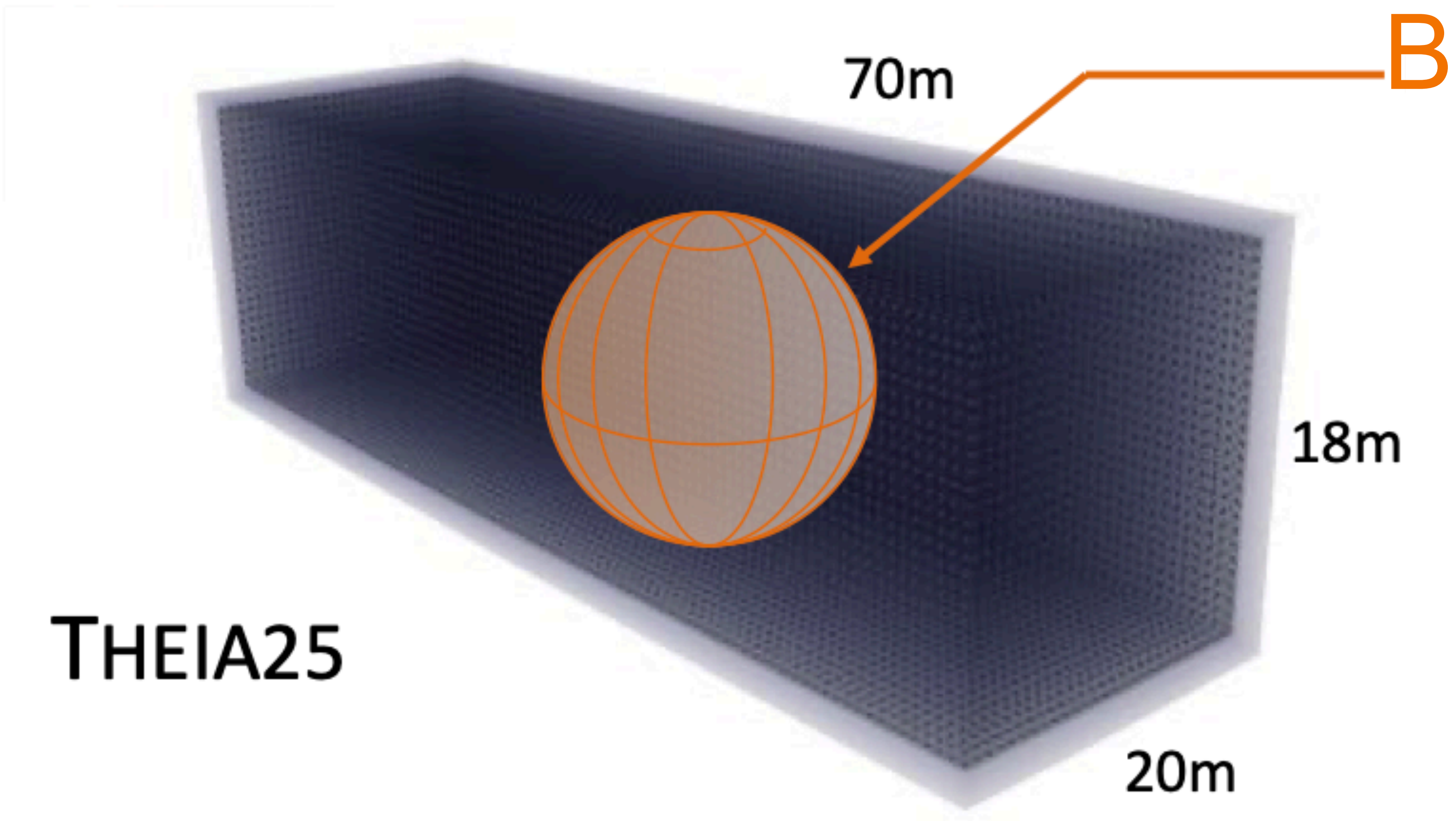
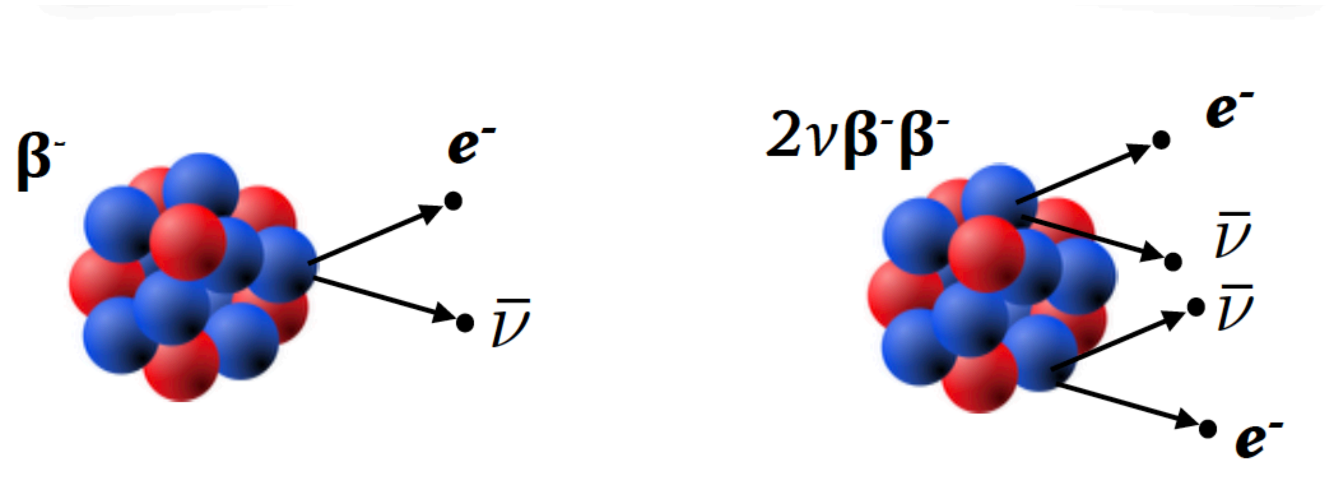
Theia: Neutrinoless Double Beta Decay

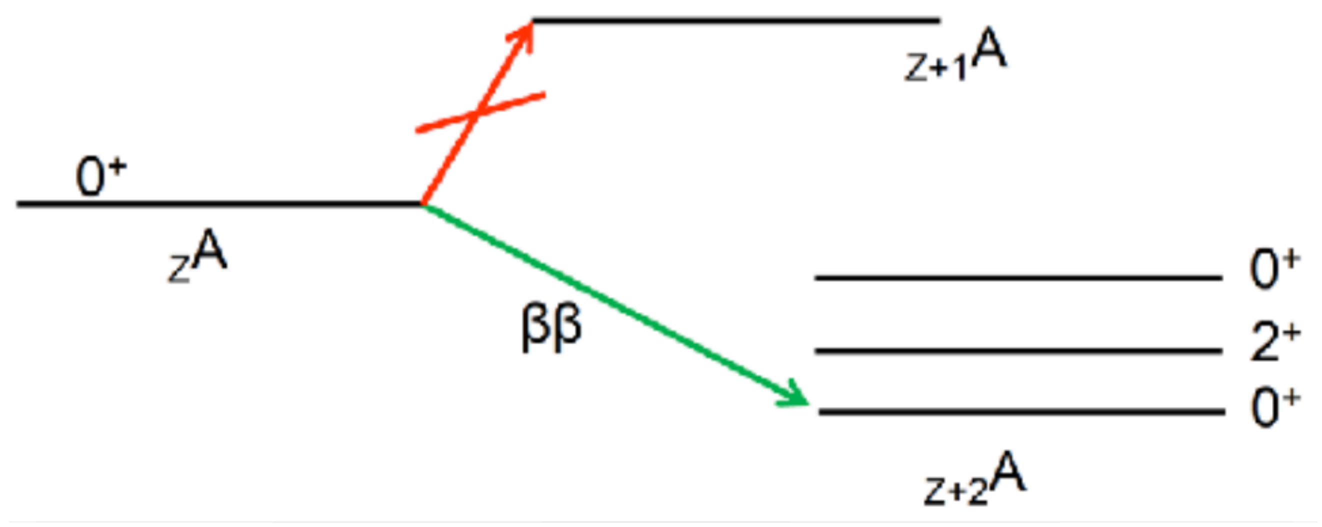




Processes within the Standard Model

Neutrinos are their own antiparticles
Lepton number is not conserved

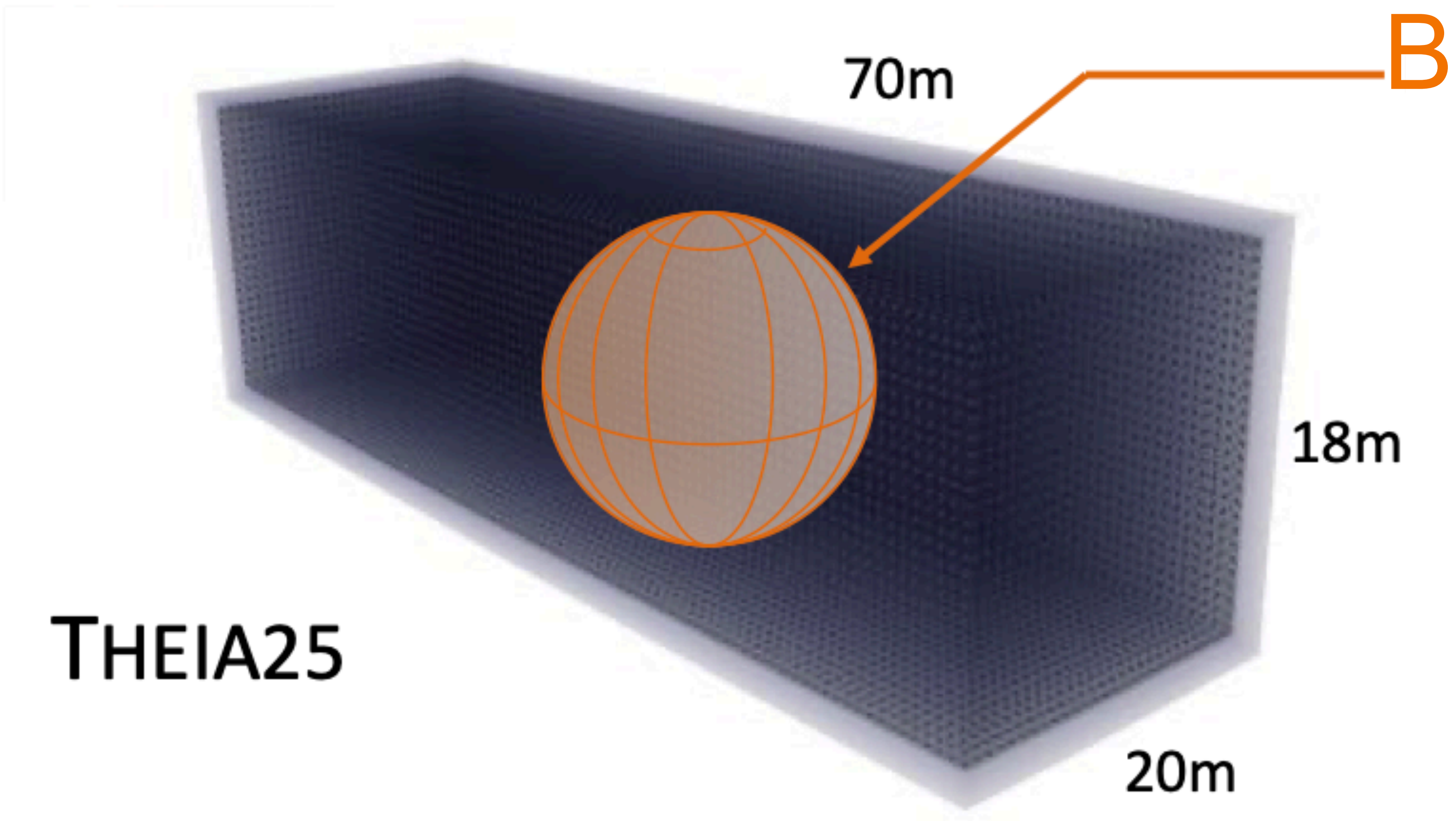
Elements for which normal beta decay is suppressed:
Germanium, Xenon, Tellurium



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

Theia: Neutrinoless Double Beta Decay

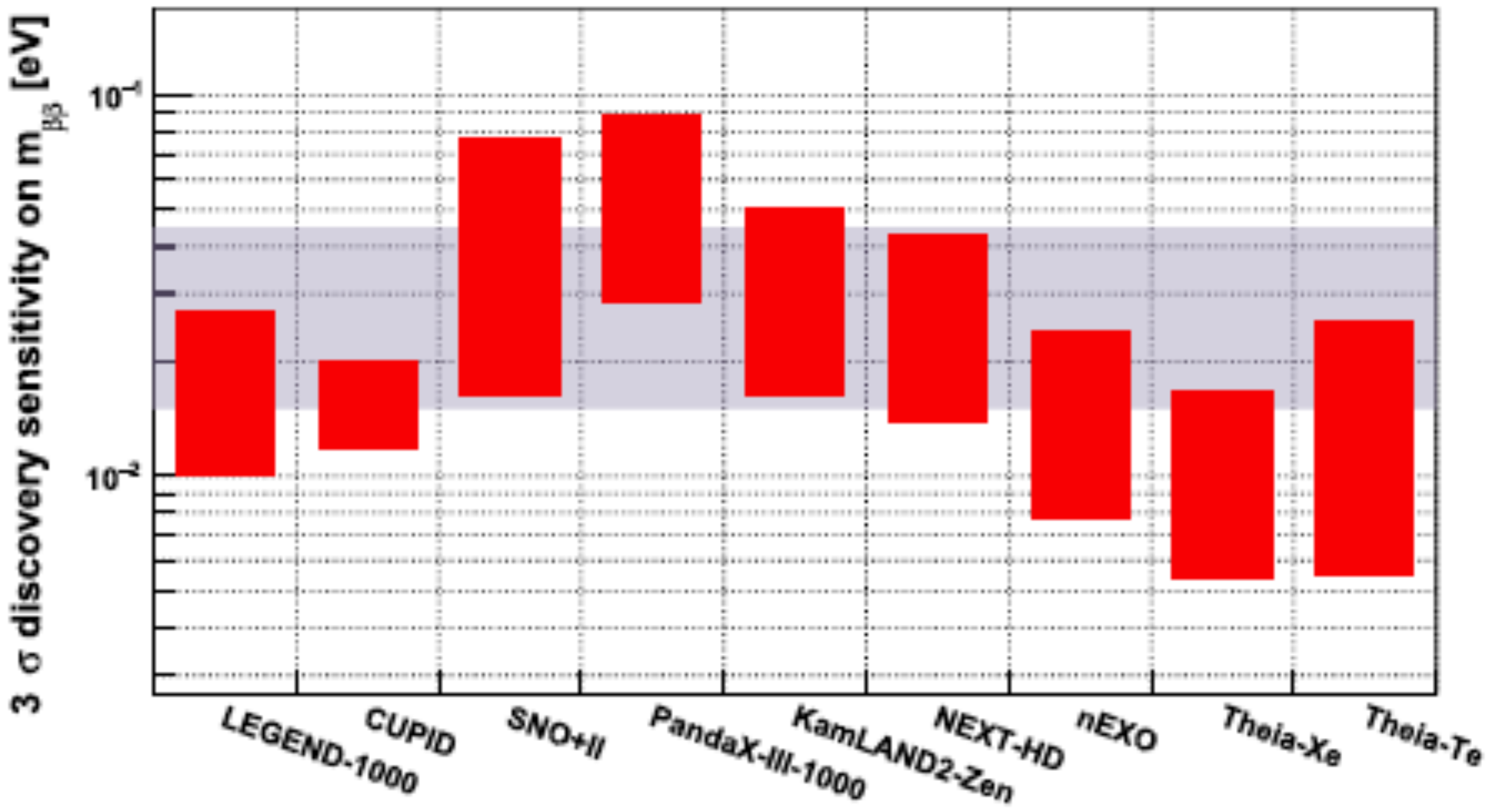
Balloon for $0\nu\nu\beta$ isotope loaded liquid scintillator

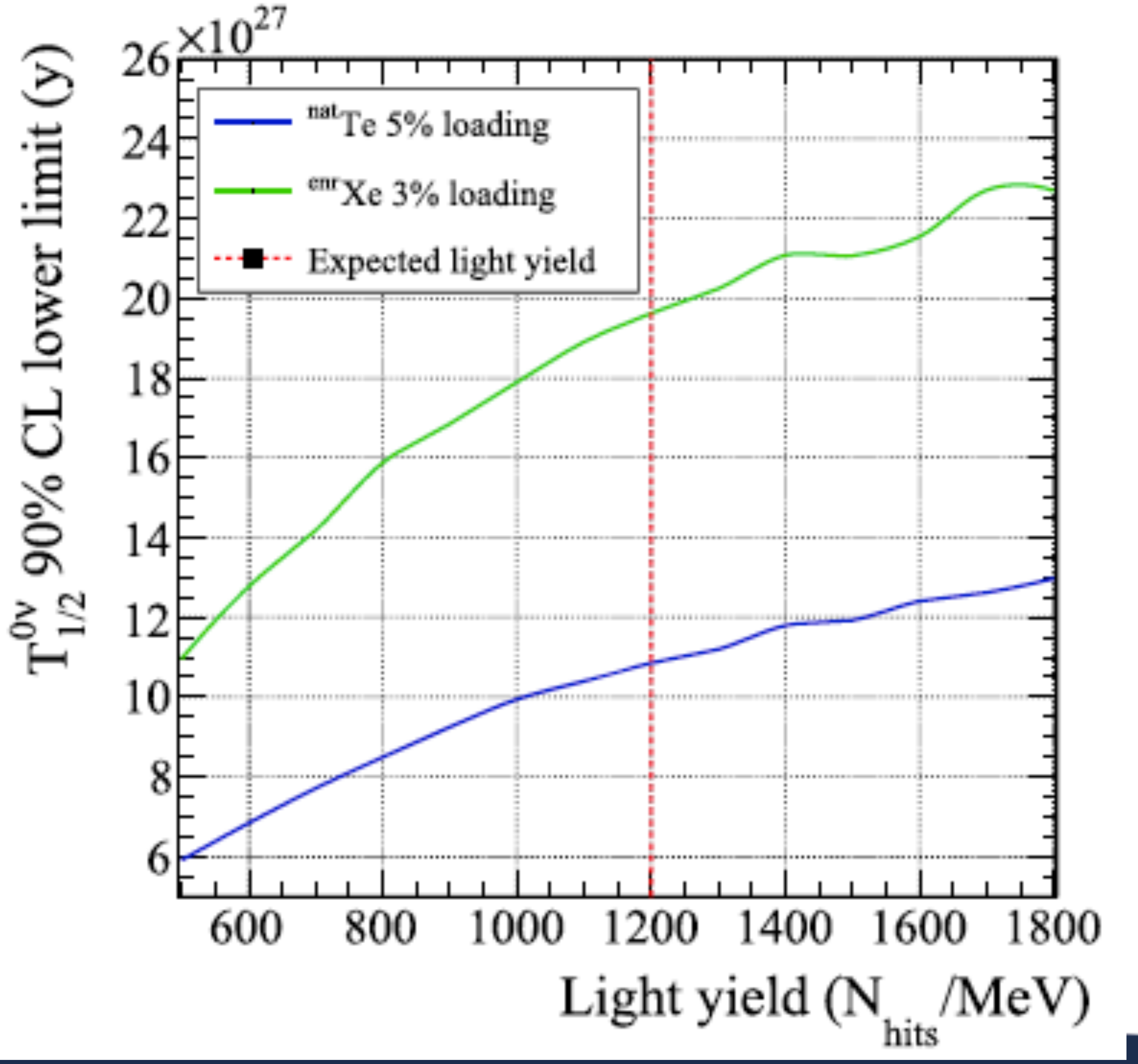


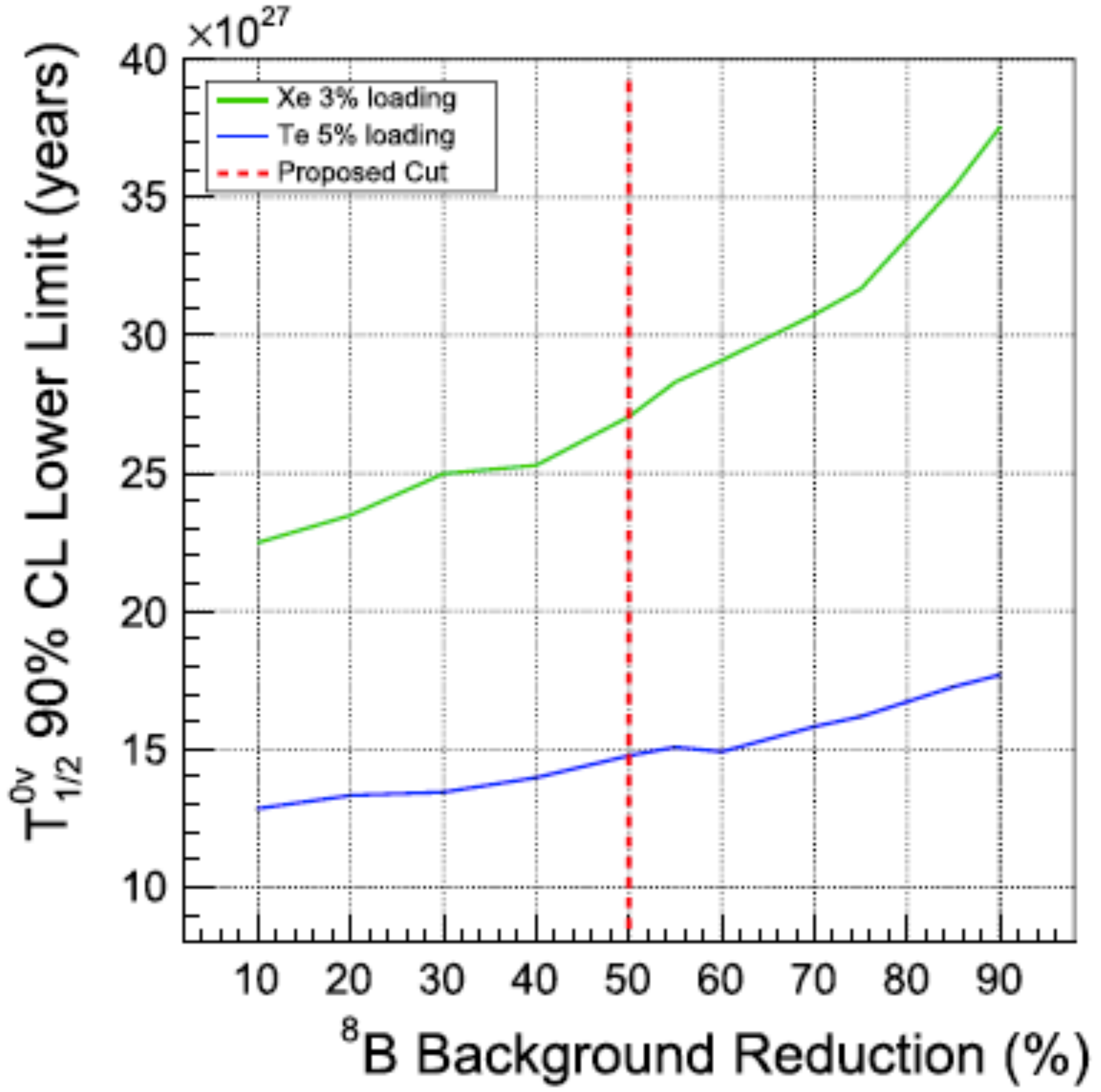
Isotopes in consideration: ^{136}Xe and ^{130}Te

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

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







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Theia: staged approach to physics goals

Using Fermilab's neutrino beam

Phase I

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 x 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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Phase I

Phase II

Primary physics goal	Reach	Exposure/assumptions
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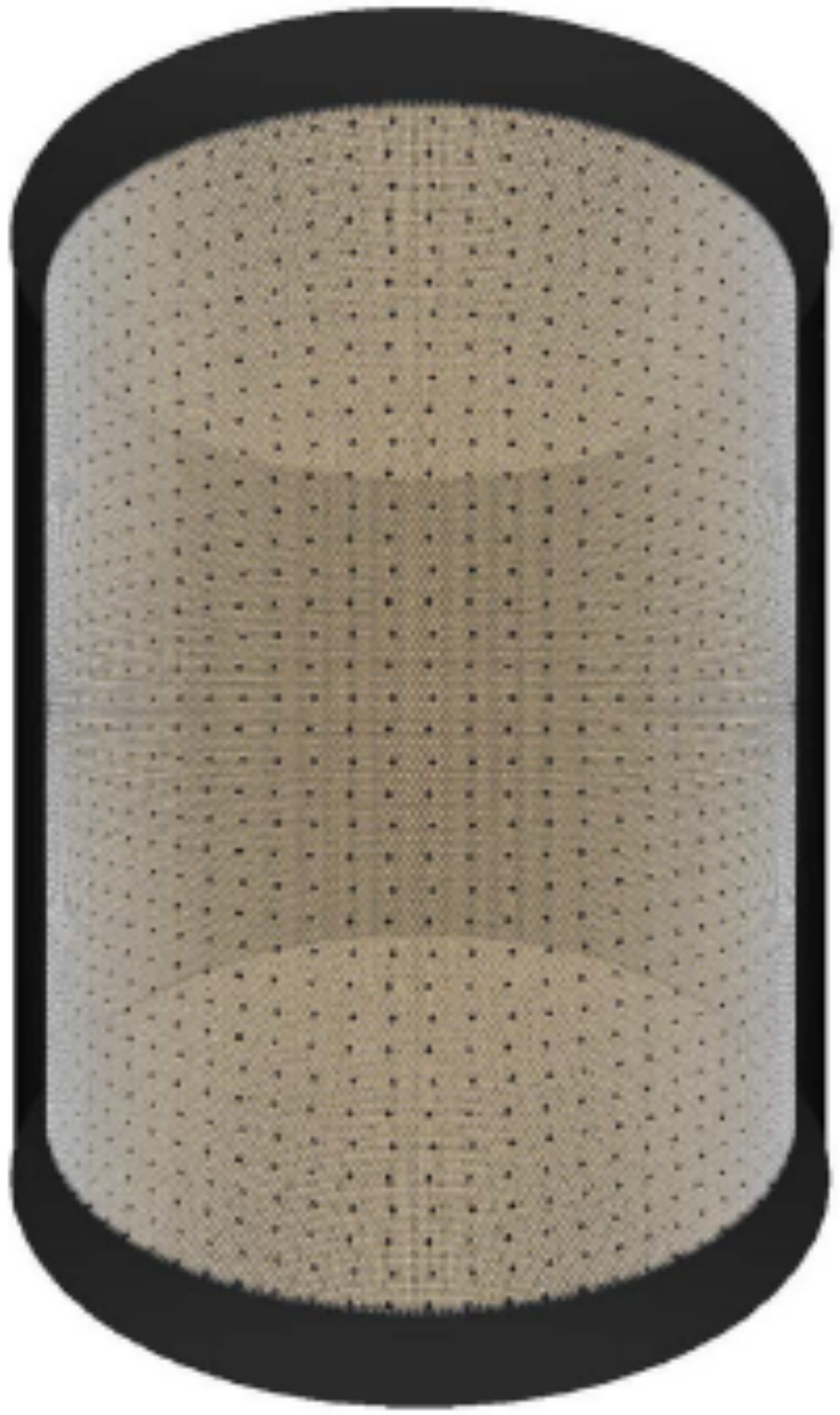
Conclusions

- 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*



- On the roadmap to Theia, opportunity to explore the technologies at large scale and tackle other physics questions and applications with **ANNIE and AIT/NEO**

Thank you for your attention!

QUESTIONS ARE WELCOME

now

or later

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https://www.zarabagdasarian.com

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