THEIA

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UC Berkeley & LBNL
Snowmass
20th July, 2022

Let there be light

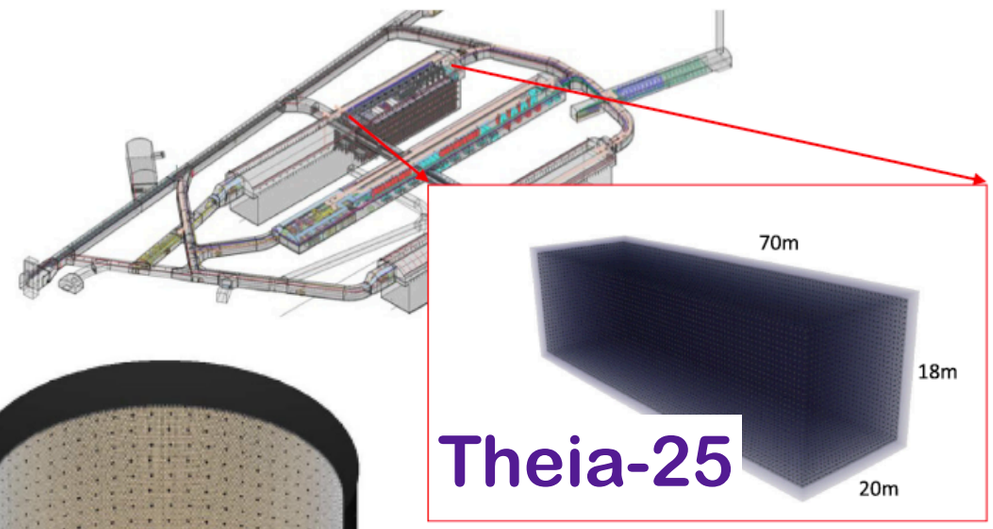
Theia as a DUNE module in Phase II

Long-baseline sensitivity comparable to a LAr DUNE module

Complementary supernova sensitivity (primarily anti-ν, fast response: can act as trigger)

+ broad additional physics program

Cutting-edge developments in target material and photon detection



Large, 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 (2020)

THEIA Collaboration

Canada
Alberta
Laurentian
Queens
SNOLAB
Toronto

China
Tsinghua

Finland
Jyvaskyla

Germany
Aachen
Dresden
Hamburg
Jülich
Mainz
TU Munich
Tübingen

Italy
SISSA/INFN

Korea
CUP

Portugal
LIP
Lisbon

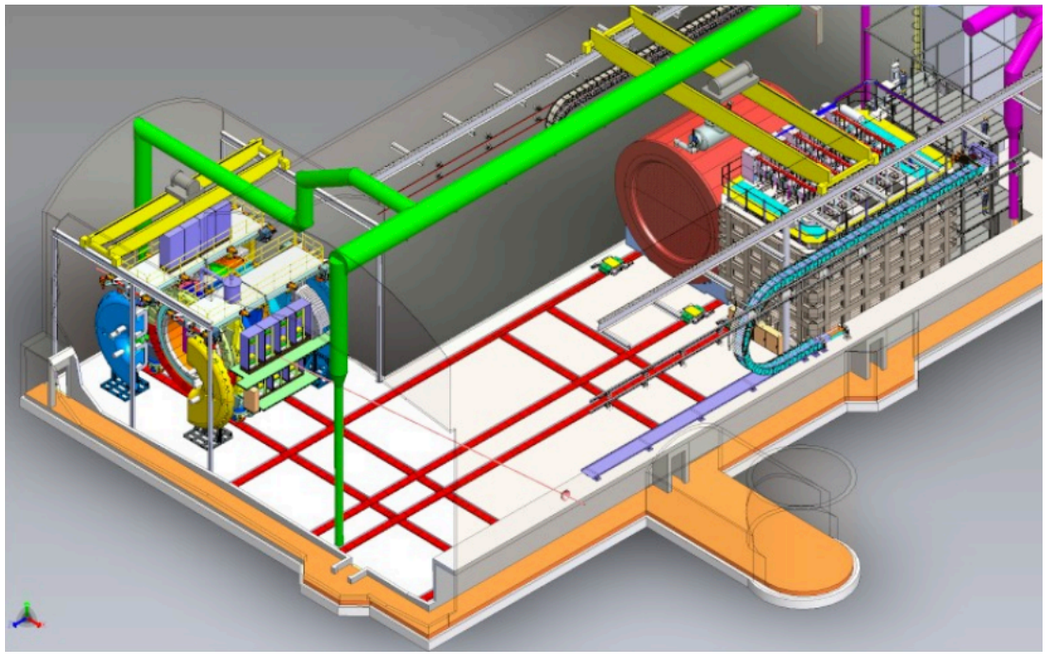
Turkey
Erciyes

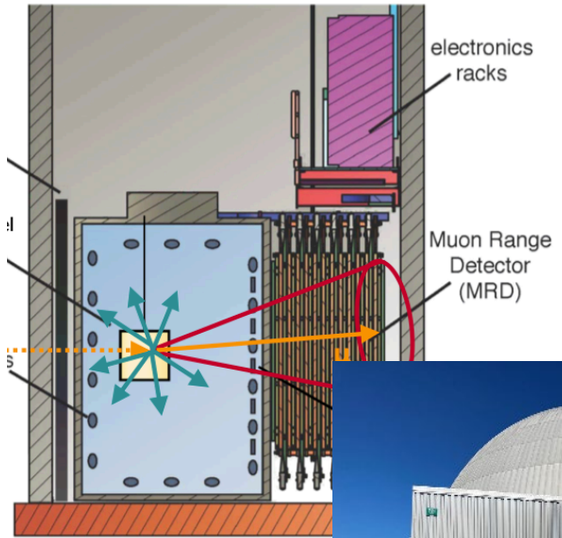
UK
King's College
Sheffield

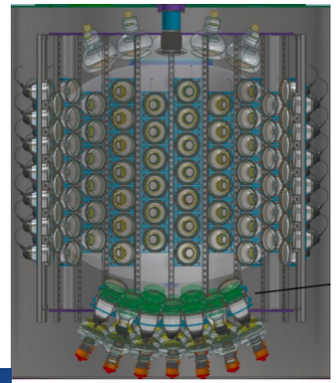
US
BNL
Boston
Chicago
Colorado
Cornell
FNAL
U. Hawaii
Iowa
Iowa State
LBNL
LLNL
LSU
MIT
U. Penn
PNNL
Rutgers
SD SMT
Stony Brook
SURF
Temple
UC Berkeley
UC Davis
UC Irvine
UCLA

Challenges

- Near detector: many options, thanks to the flexible design of this highly sophisticated facility
  - SAND: planned C & H targets
  - Potential alternative target options for ND-GAr?
  - Additional module for DUNE-PRISM?
- Cavern shape: letterbox suboptimal
- Utilities: UG deployment, sacrifice mass?
- Program of prototypes for necessary technological demonstrations



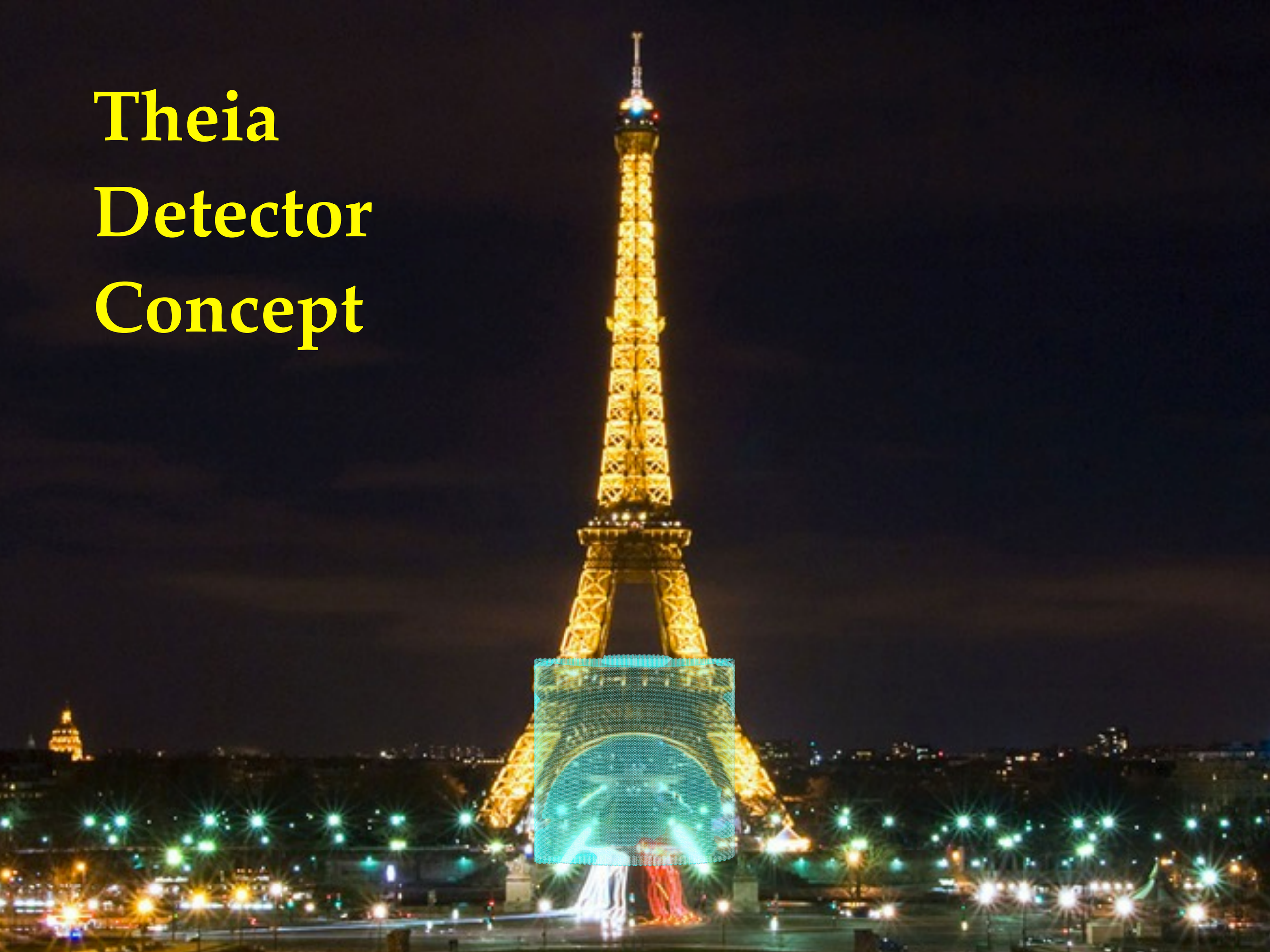




Overview

- THEIA detector
- Hybrid neutrino detection concept
- Detector development
- Prototypes *(T. Kaptanoglu, 7/24 @10.48am)*
- Physics program *(Z. Bagdasarian, L. Pickard, 7/24 @10.00, 10.20am)*

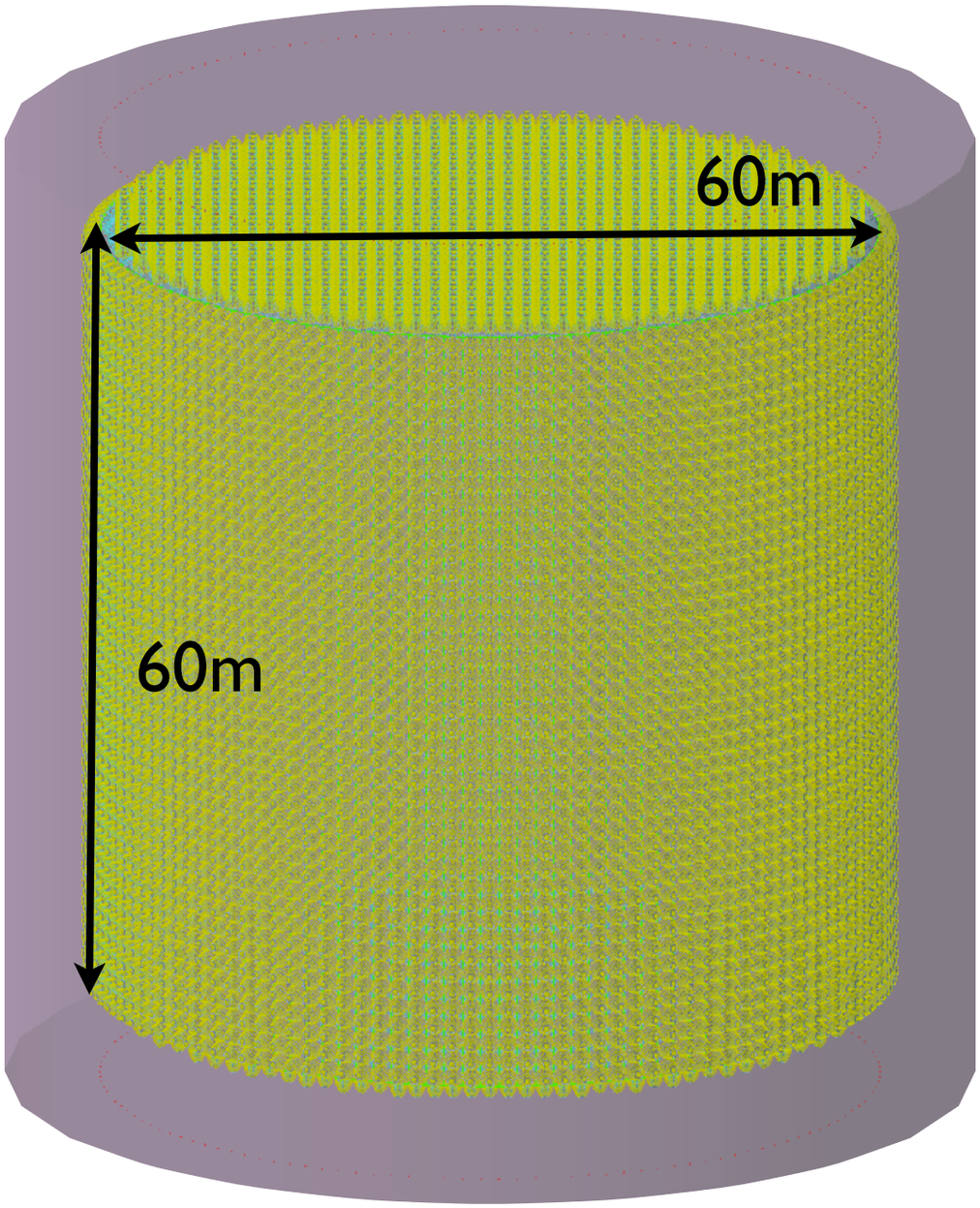
Theia Detector Concept



THEIA

- Large-scale detector (25-100 kton)
- Novel LS target e.g. WbLS
- Fast, high-efficiency (spectrally sensitive?) photon detection with high coverage
- Deep underground
- Isotope loading (Gd, Te, Li...)
- *Flexible*! Target, loading, configuration

➡ Broad physics program!



White paper - Eur. Phys. J. C 80, 416 (2020) & arXiv:2202.12839 [hep-ex]

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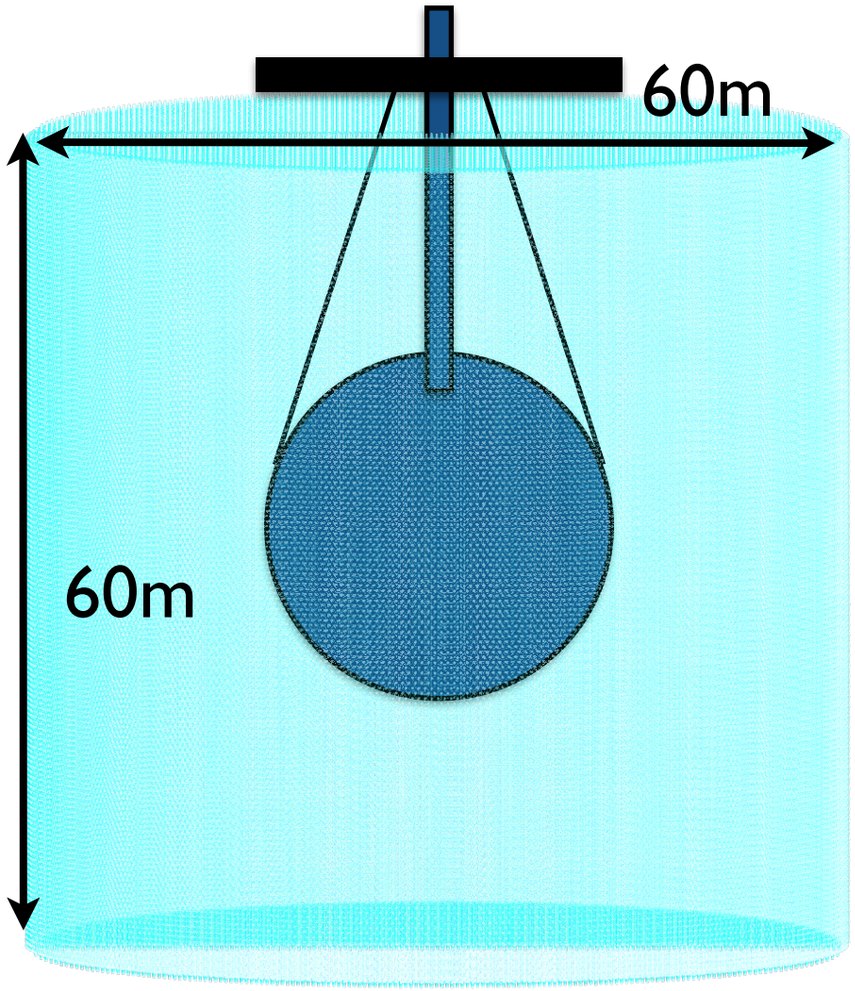

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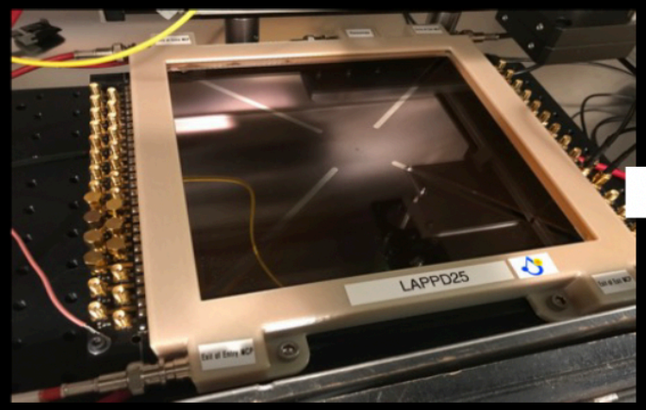
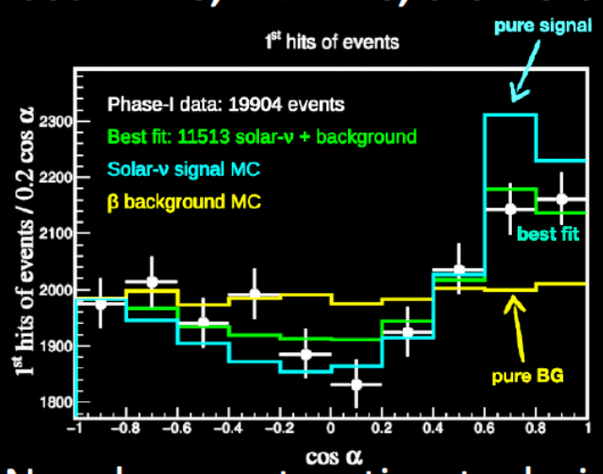
Hybrid neutrino detection

→ **Enhanced sensitivity to broad physics program**

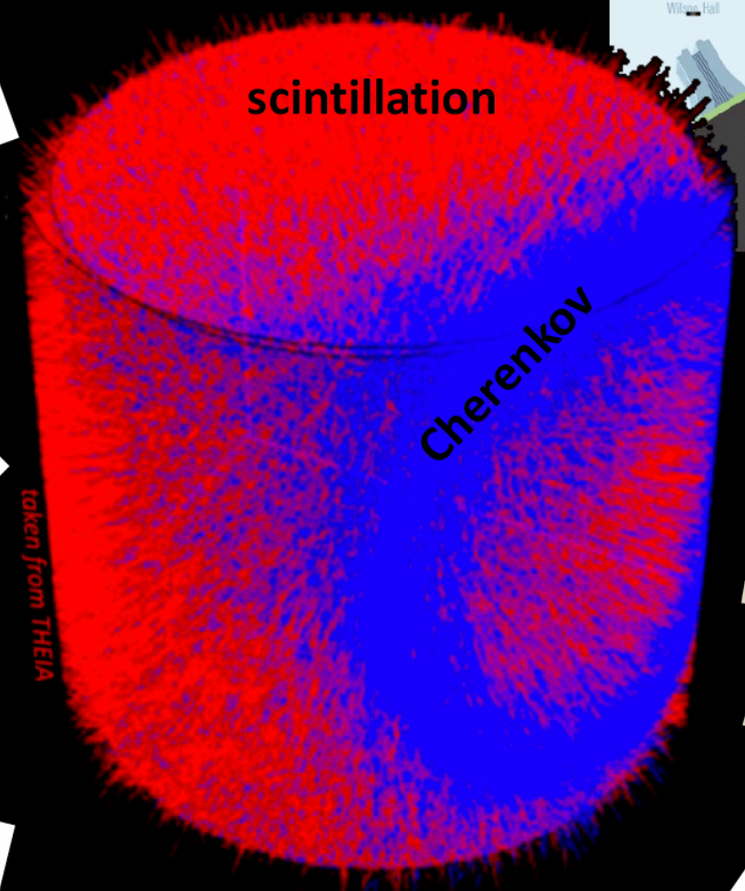
Novel target media:
Water-based/Slow Scintillator



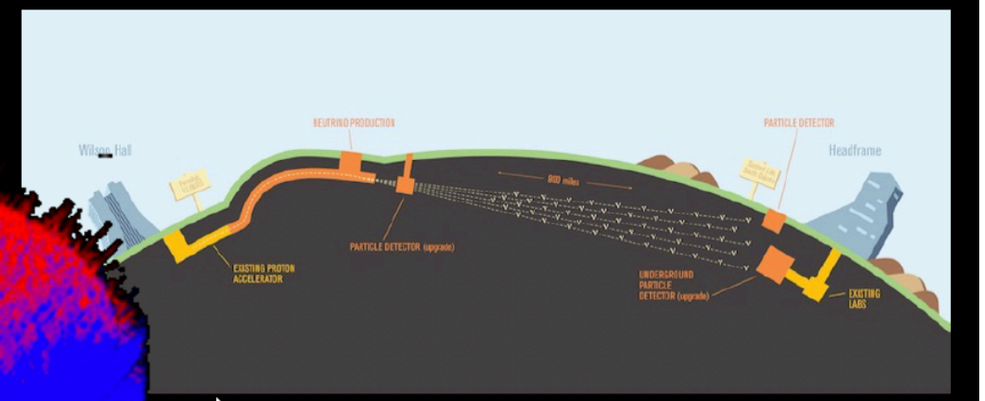
Novel light sensors:
fast PMTs, LAPPDs, dichroicons



Novel reconstruction techniques



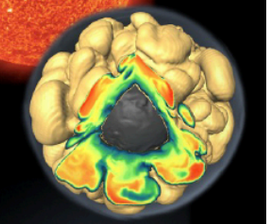
Large volume detector
able to exploit both
Cherenkov+Scintillation
signals



Long-Baseline Oscillations

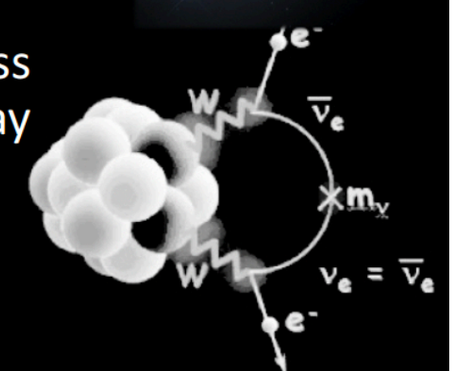
Solar neutrinos

Supernova neutrinos



Diffuse SN neutrinos

Neutrinoless
Double-Beta Decay



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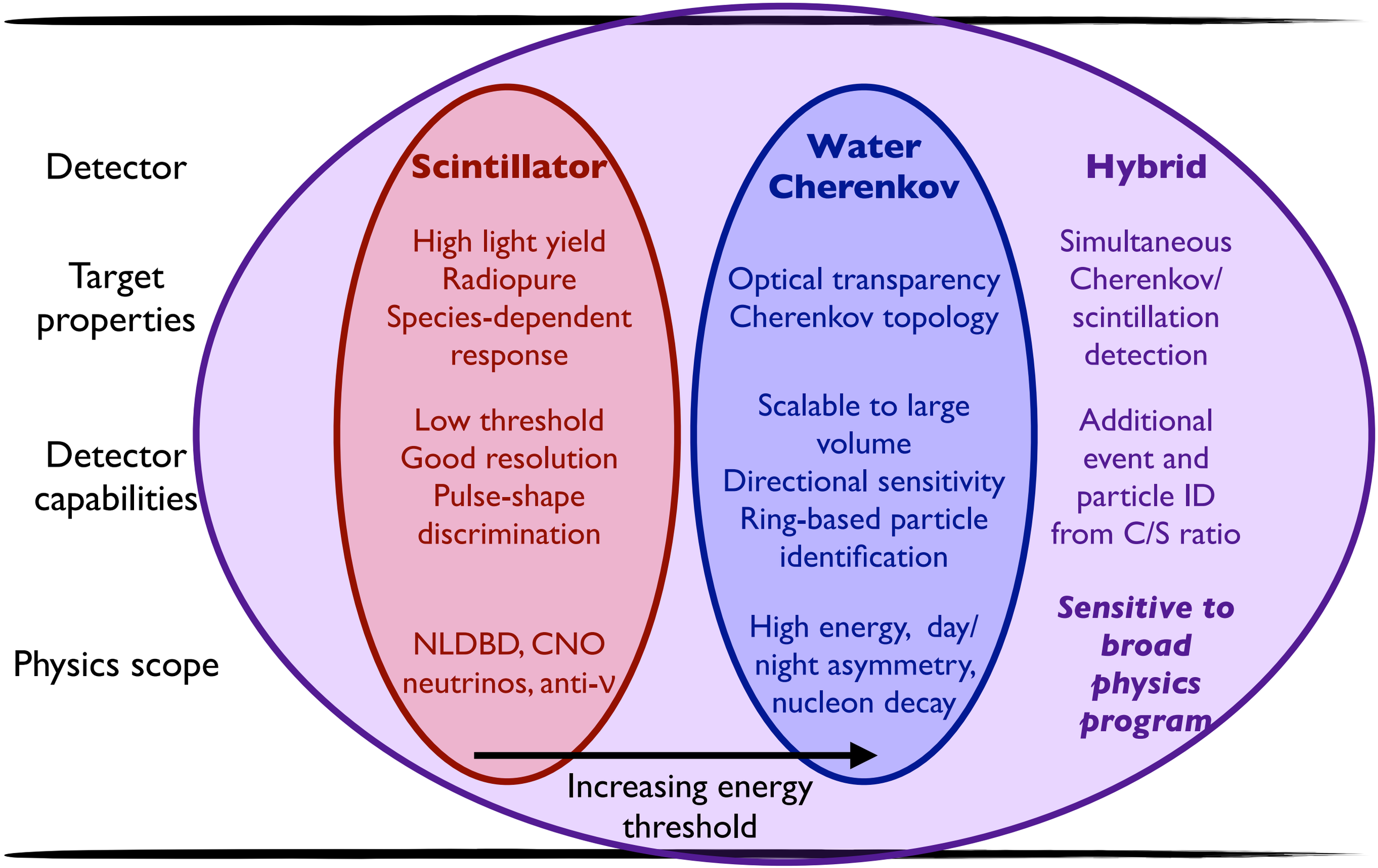
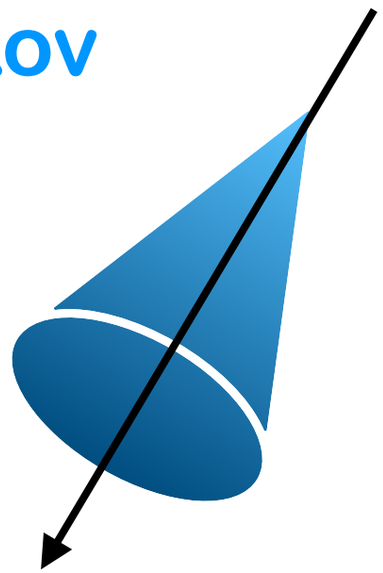
Theia @ Snowmass, G. D. Orebi Gann

Hybrid neutrino detection

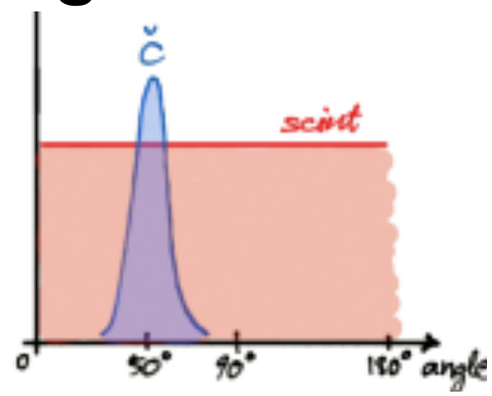


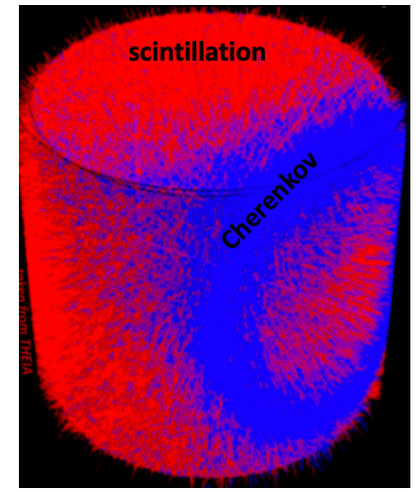
How can it be done?

Cherenkov

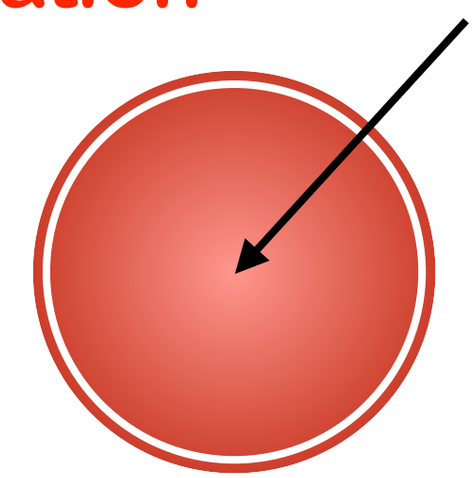


Angular distribution





Scintillation



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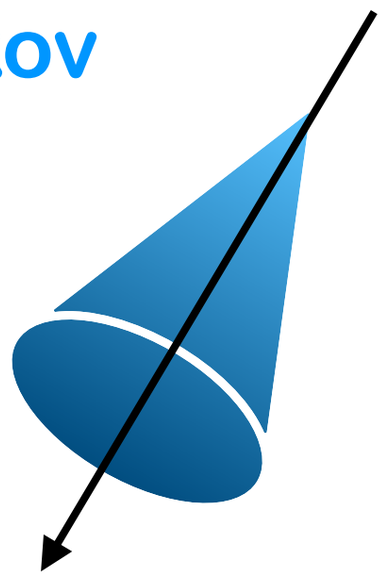

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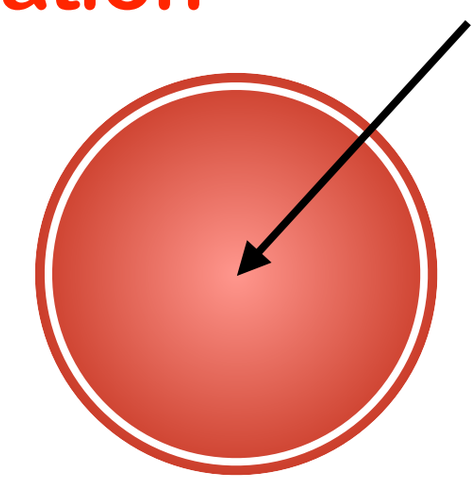
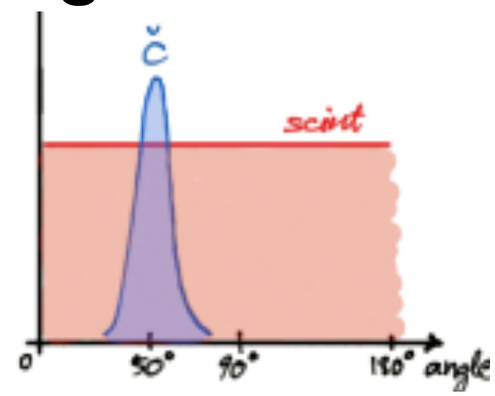
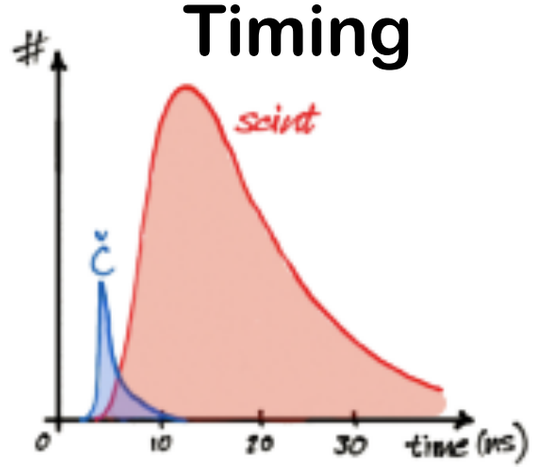
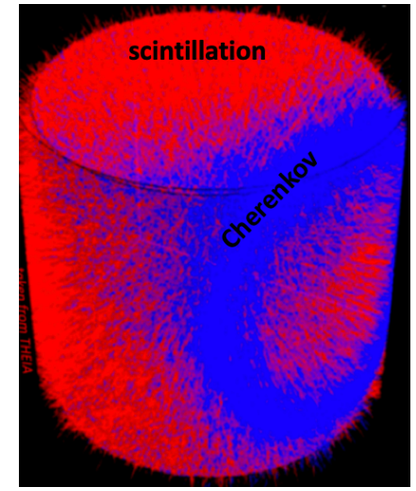


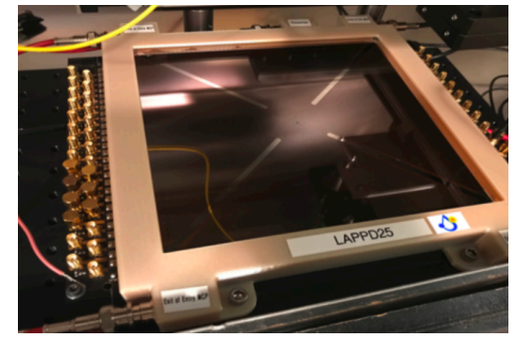
Angular distribution



Timing







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

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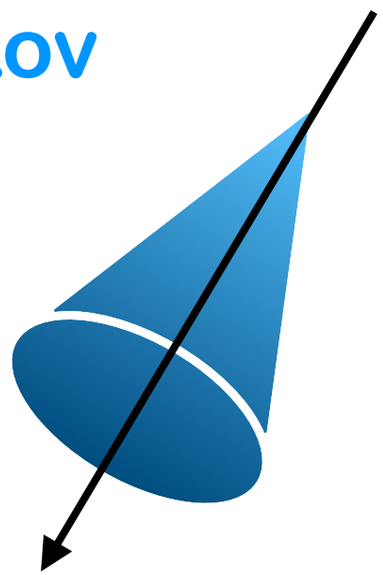

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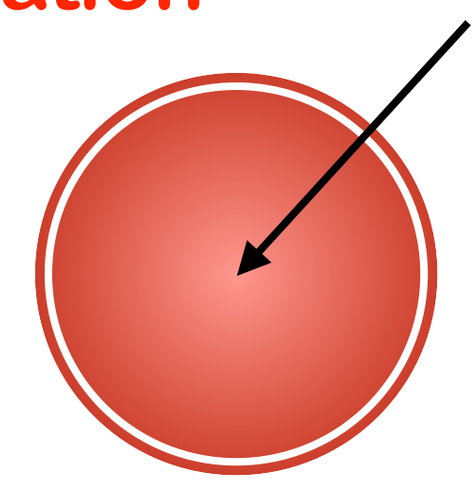

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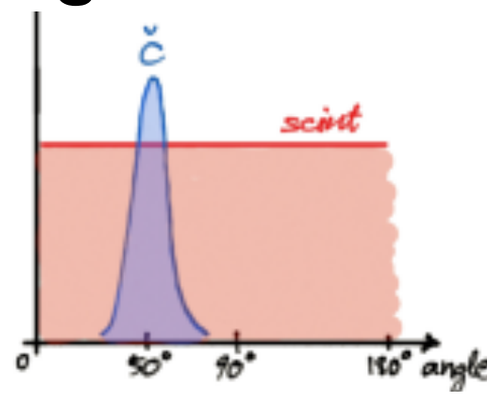

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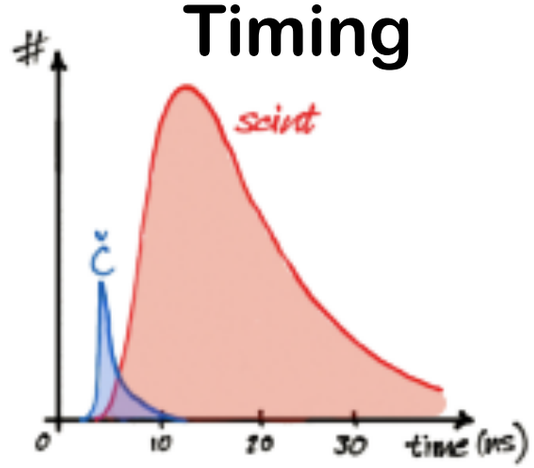
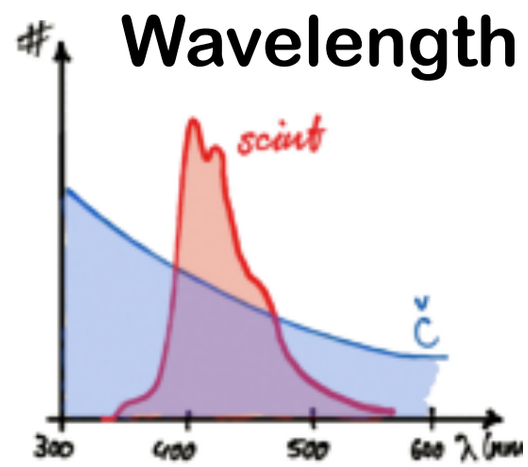
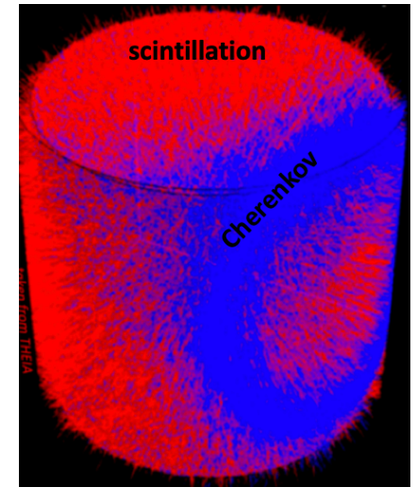
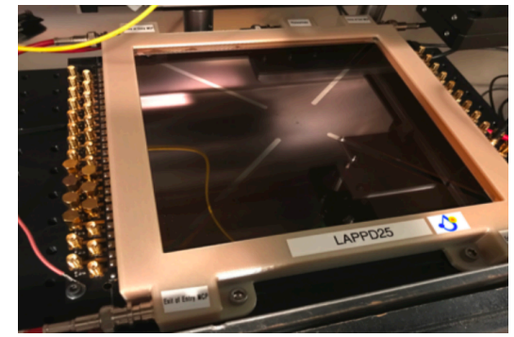


Wavelength







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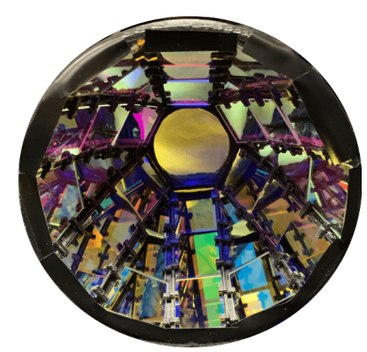
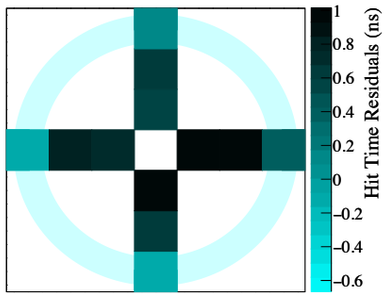


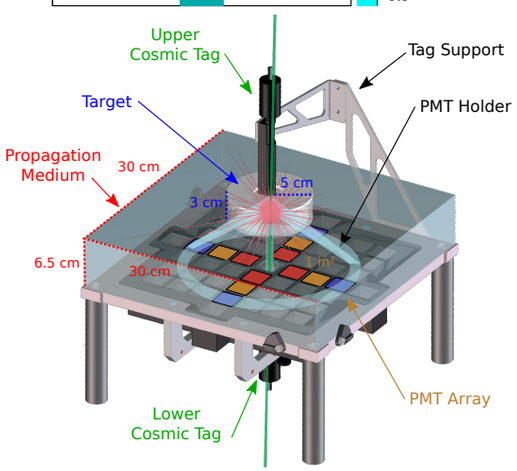
T. Kaptanoglu et al.
Phys. Rev. D 101, 072002 (2020)

Detector development

Builds on core (Wb)LS development at BNL (Yeh et al.)

CHESS detector: LBNL





Phys. Rev. C 95 055801 (2017); Eur. Phys. Jour. C 80 867 (2020); Mat. Adv. 1 71 (2020); Eur. Phys. Jour. C 82 169 (2022); NIMA 947, 162604 (2019); arXiv:1902.06912; JINST13 P07005 (2018); JINST9 P06012 (2014); NIMA 943 162420 (2019); Eur. Phys. Jour. C 77 811 (2017); arxiv:1908.03564; arXiv:1502.01132; arXiv:1707.08222; NIMA 972 164106 (2020); Astropart. Phys. 109 33 (2019); NIMA 852 15 (2017); NIMA 712 162 (2013); Phys. Rev. D 97 052006 (2018); JINST14 1 (2019); Phys. Rev. D 101 072002 (2020); arXiv:2006.00173

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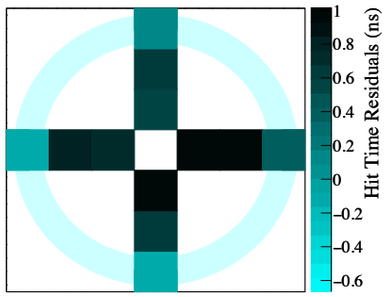
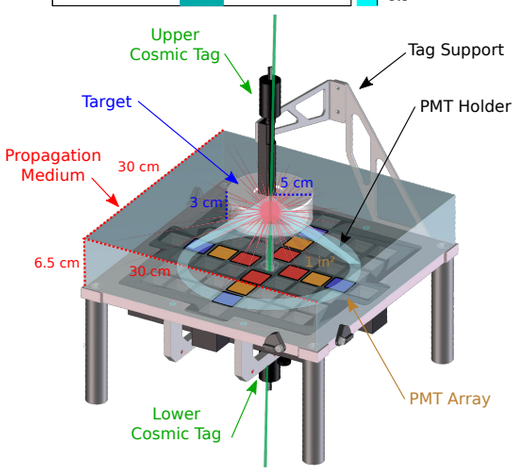
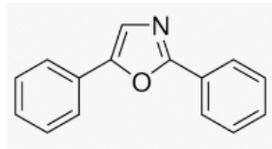
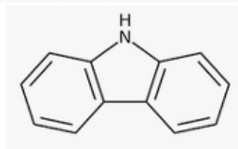




Engineering WbLS properties: Bourret (LBNL)

Example:
slowing down decay time

- Standard PPO → 
  2ns
- New carbazole → 
  15ns

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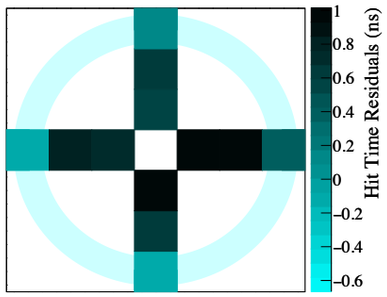

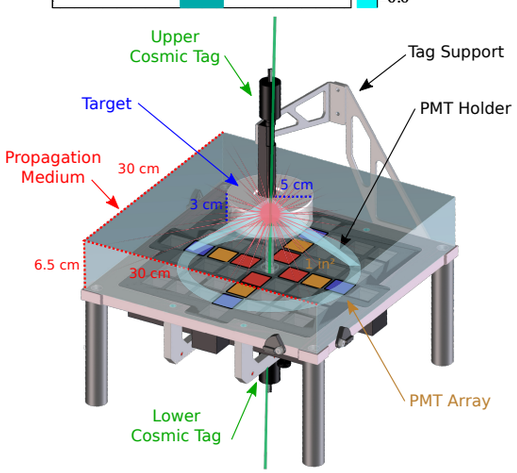

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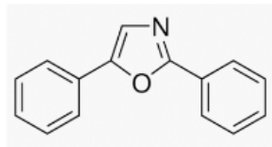
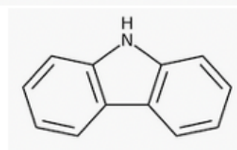
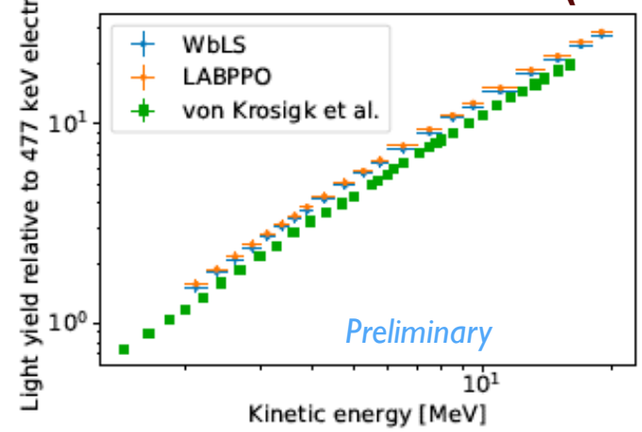
- New carbazole → 15ns





Proton LY: Goldblum (LBNL)



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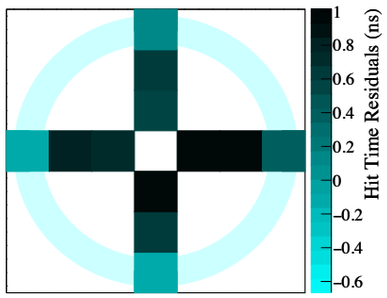

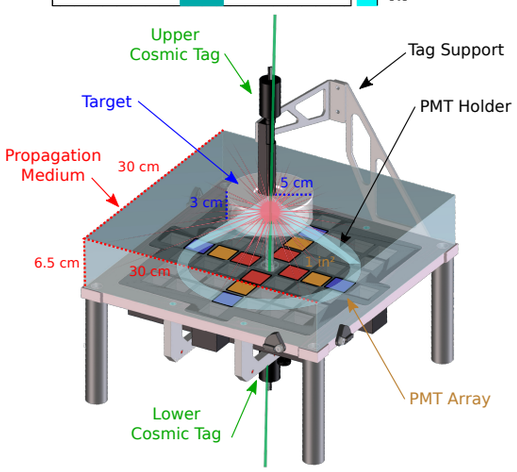

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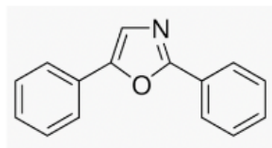

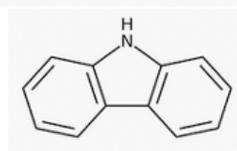

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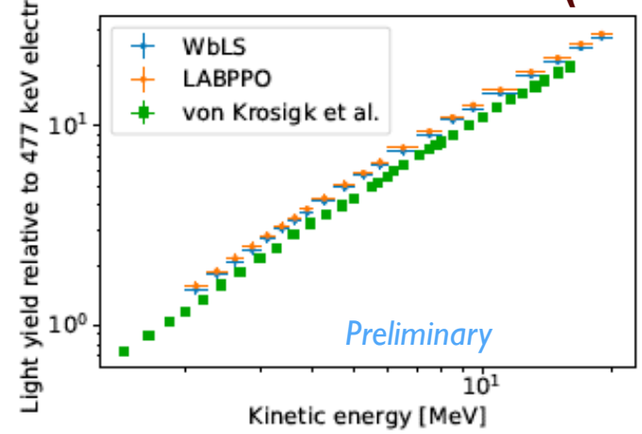

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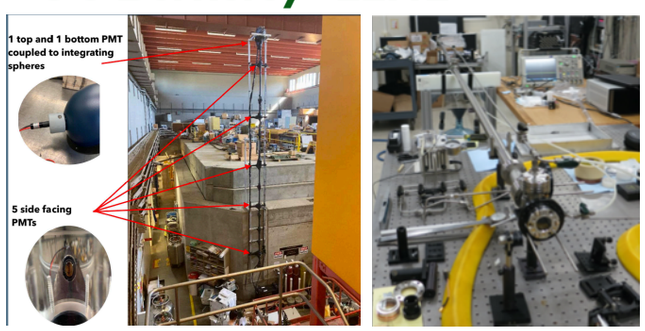

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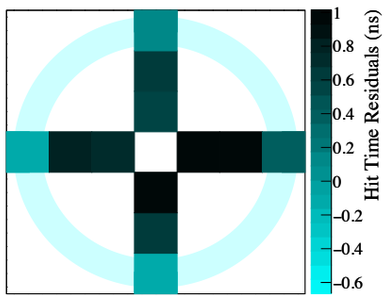

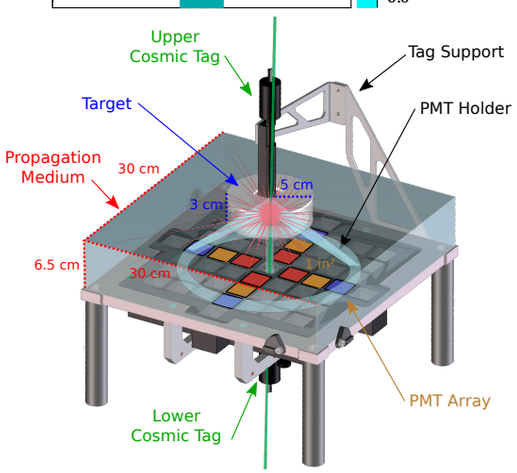

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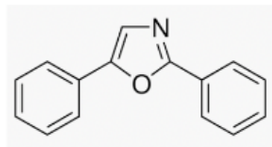

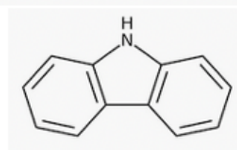

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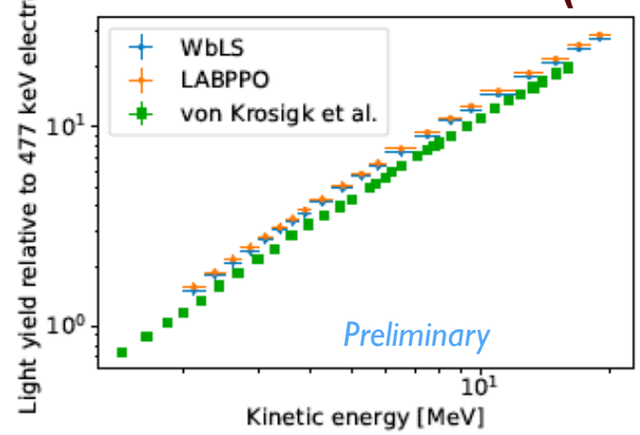

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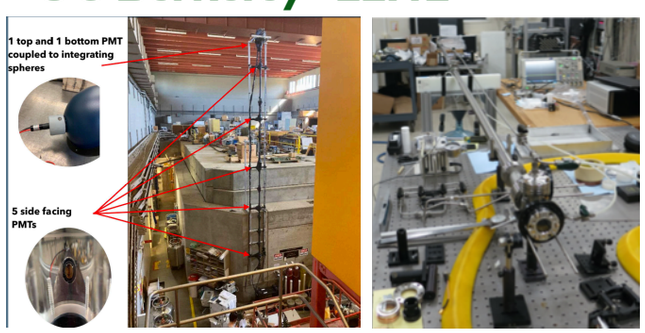

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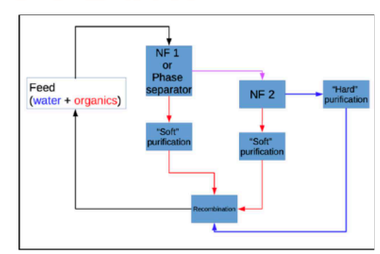

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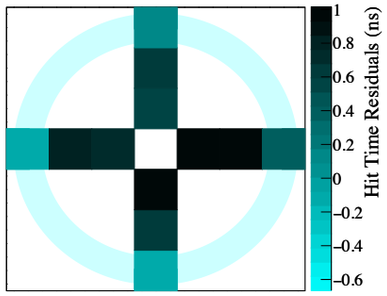

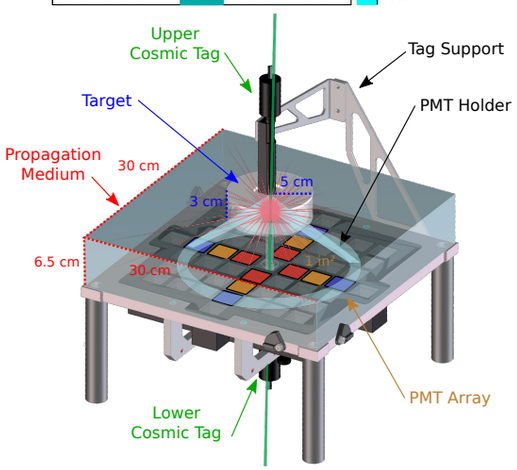

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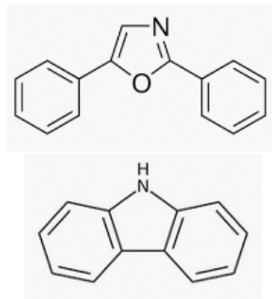

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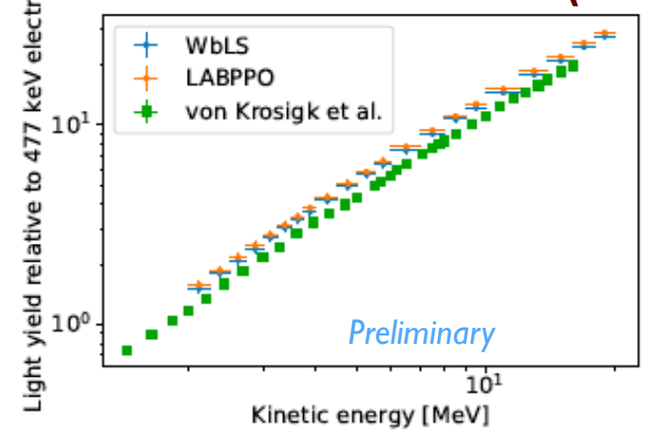

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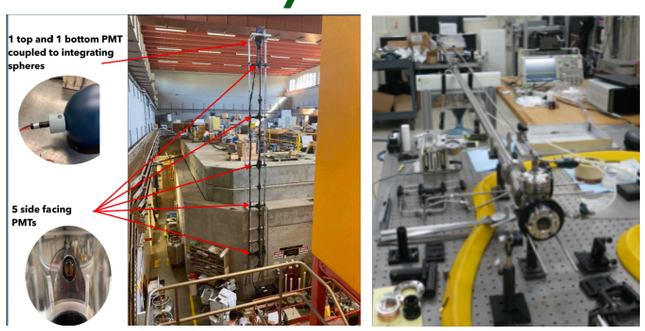

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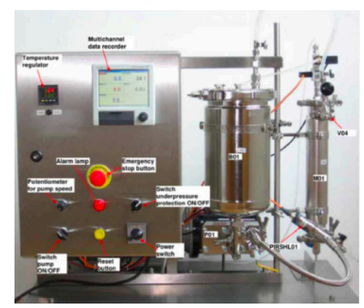

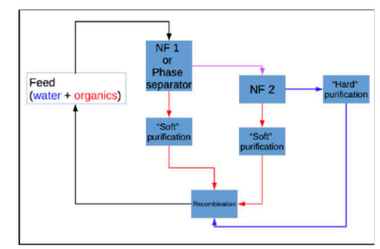

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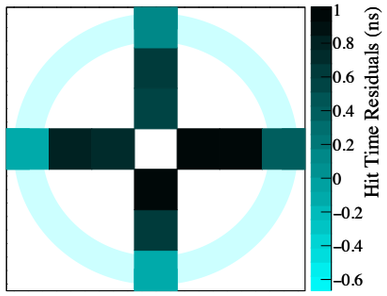

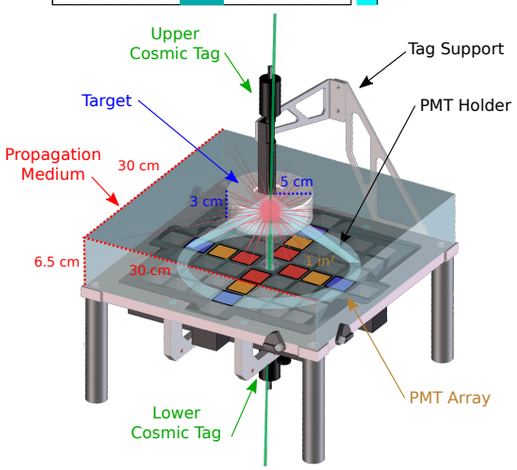

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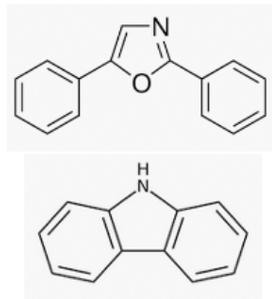

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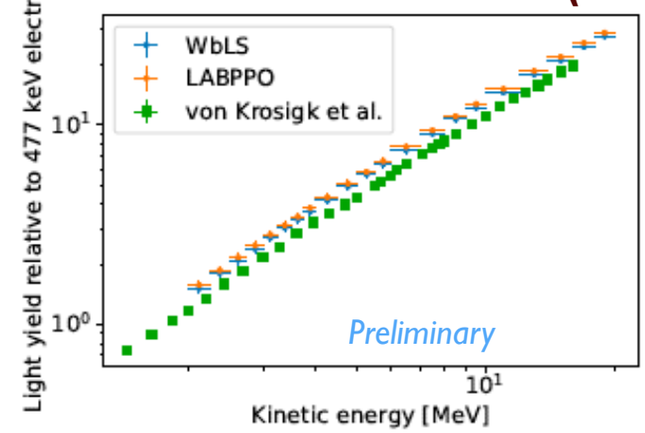

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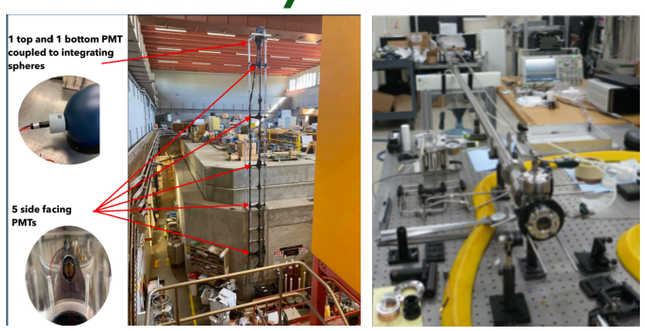

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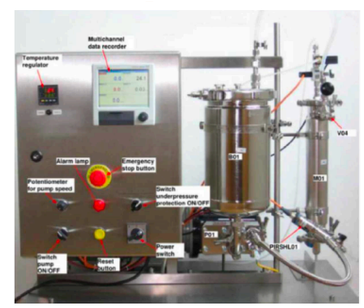

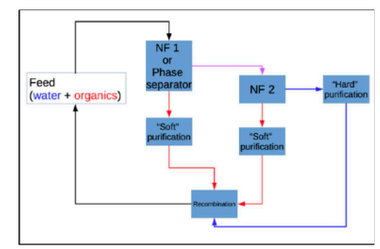

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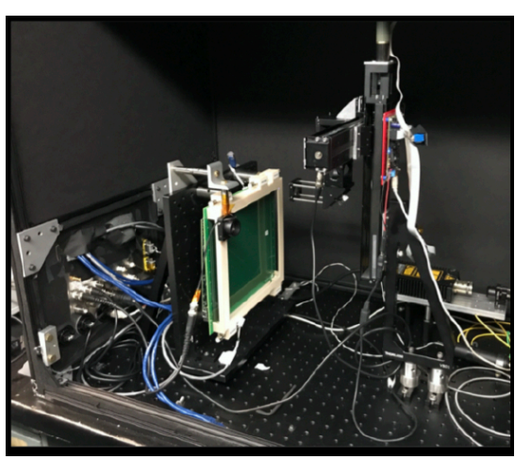

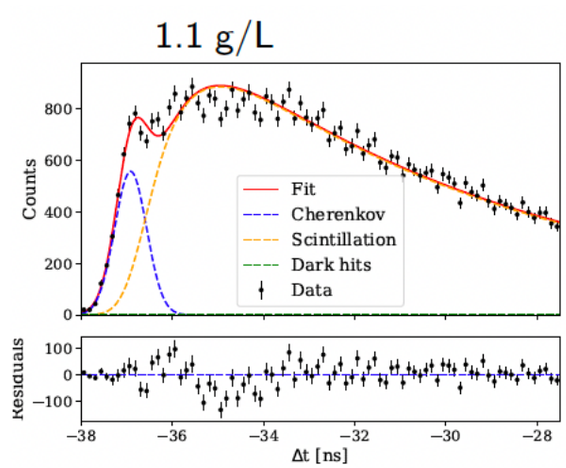

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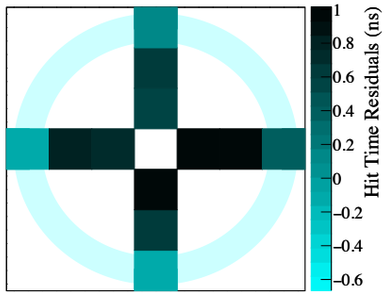

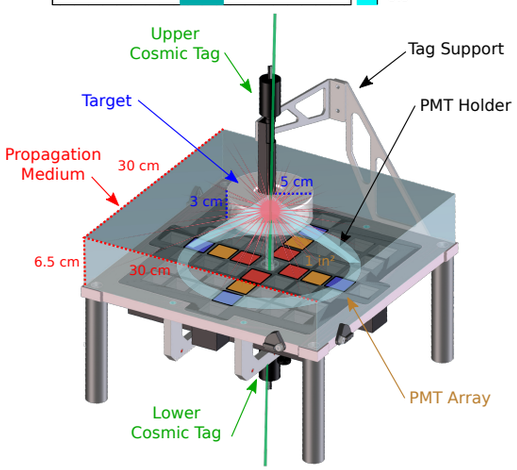

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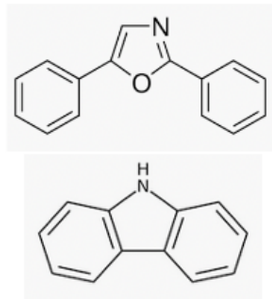

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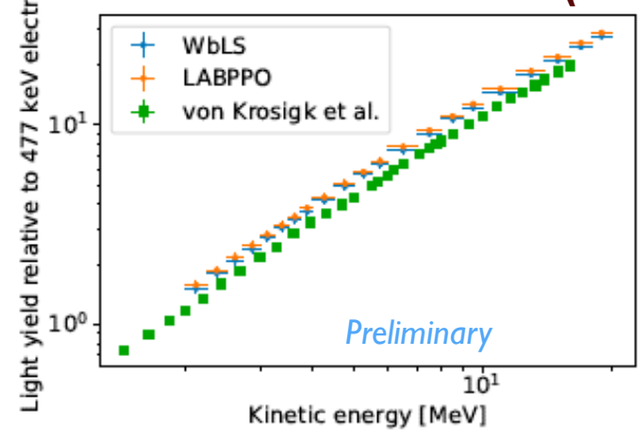

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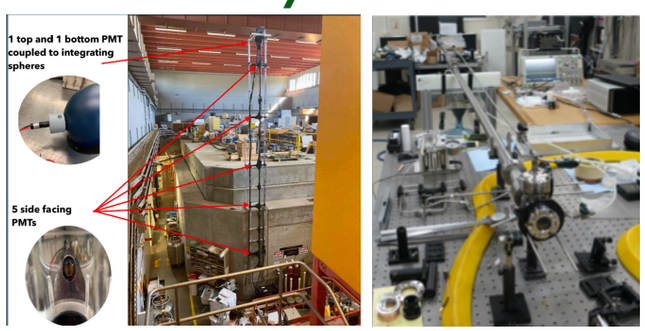

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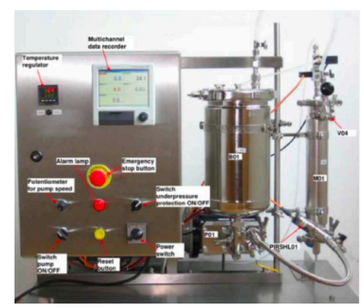

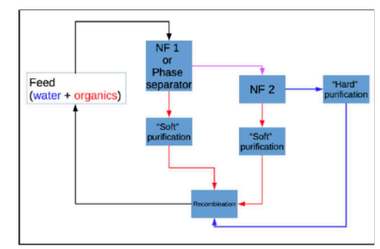

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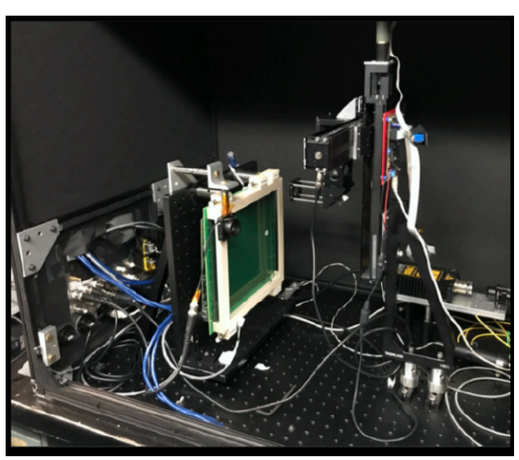

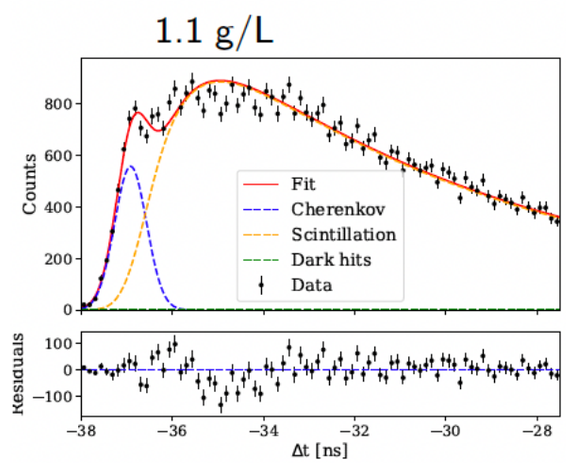

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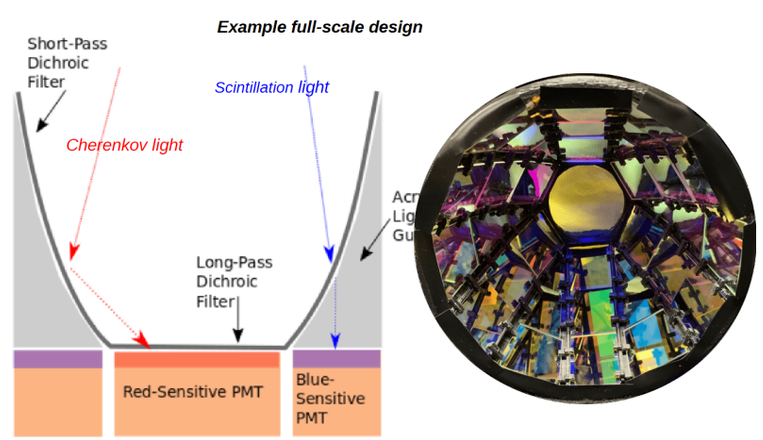

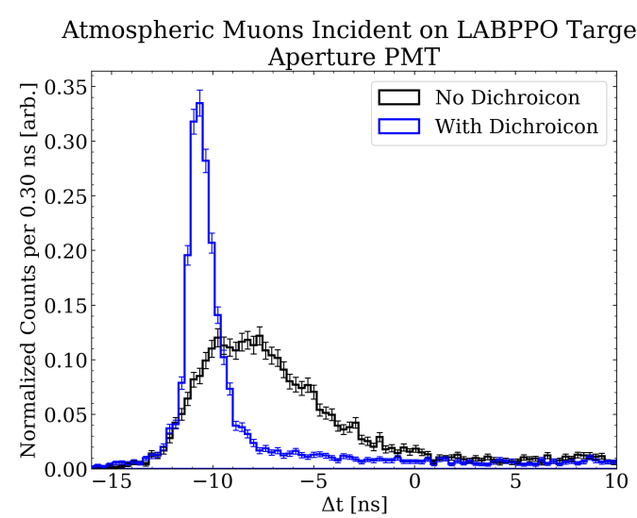

T. Kaptanoglu, Nucl. Instrum. Meth. A889 (2018) 69-77
T. Kaptanoglu, M. Luo, J. Klein, JINST 14 no. 05 T05001 (2019)

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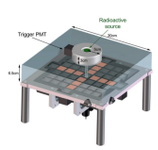
Broad R&D program



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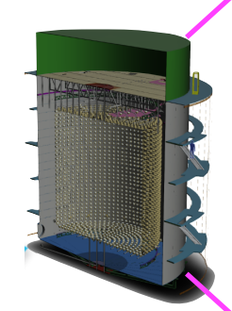

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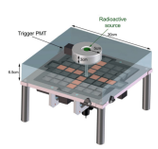

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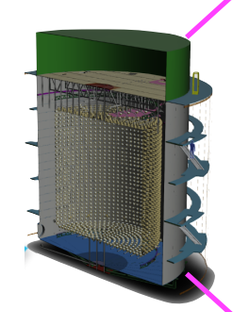
Critical ton — 10s of tons scale demonstration of detector performance capabilities

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



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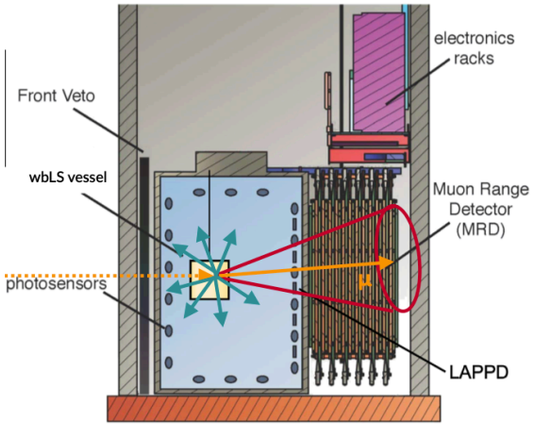

365 kg WbLS + LAPPDs
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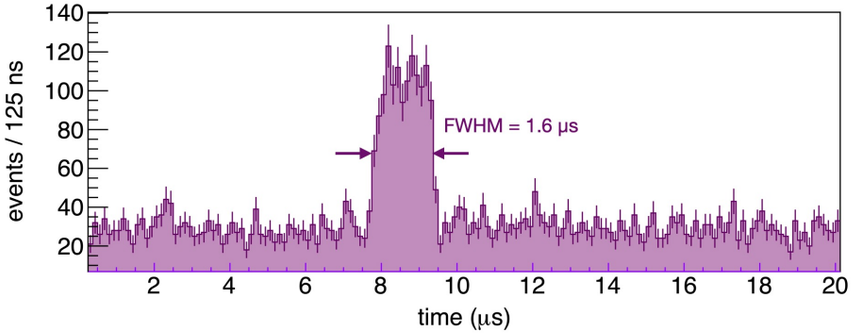
High- and low-energy events

First neutrinos detected with an LAPPD!



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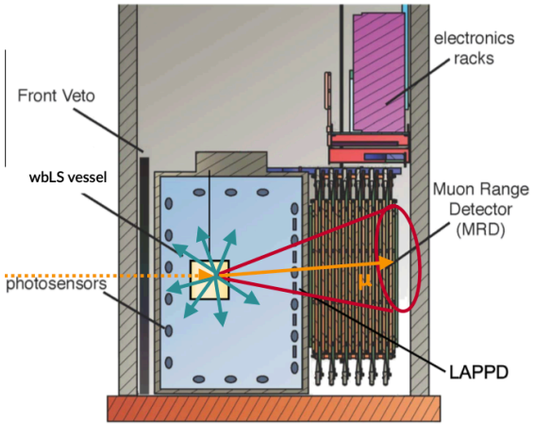

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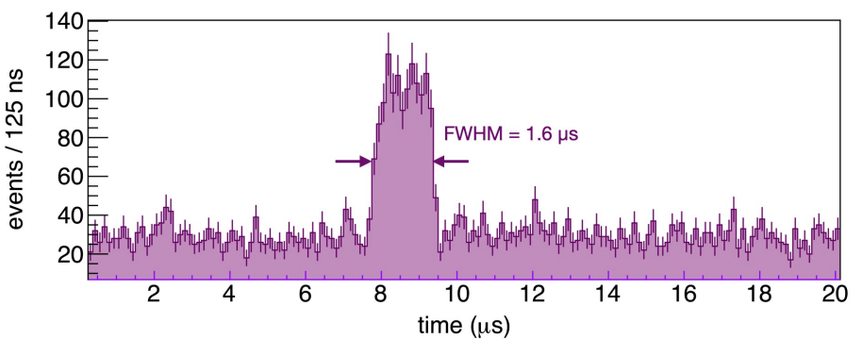
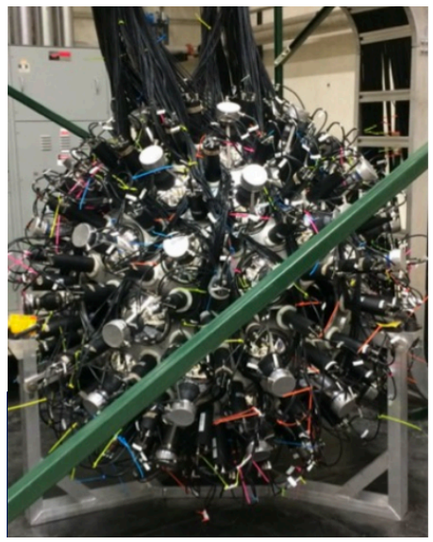
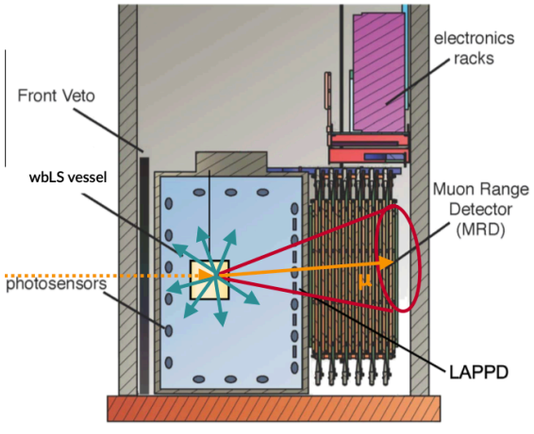


NuDot:
LS + isotope for 2νbb event reconstruction
Ton scale
Highly intstrumented



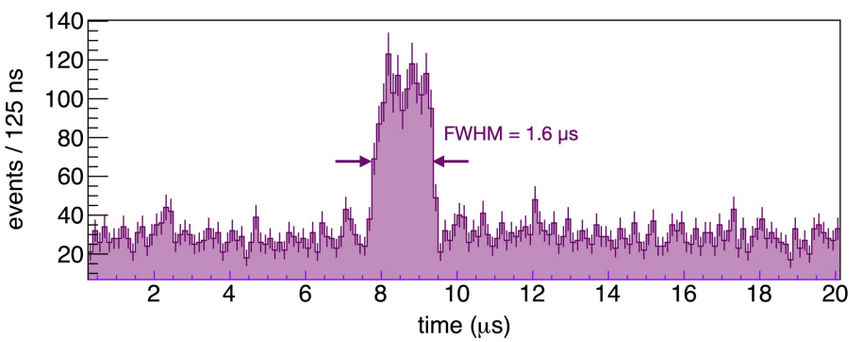
ANNIE, NuDot, EOS, BNL

ANNIE: WbLS in a ν beam



365 kg WbLS + LAPPDs
Ch/S separation
High- and low-energy events

First neutrinos detected with an LAPPD!



NuDot:
LS + isotope for 2νbb event reconstruction
Ton scale
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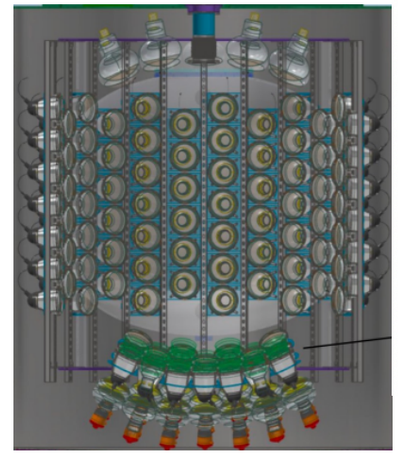

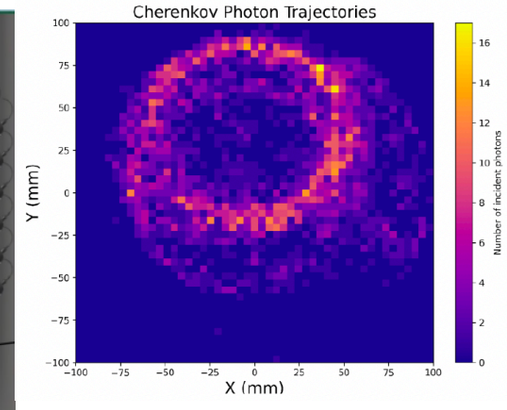

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- Vertex, energy, direction, PID

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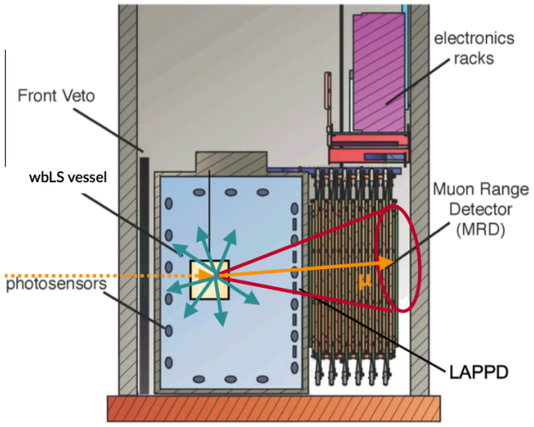

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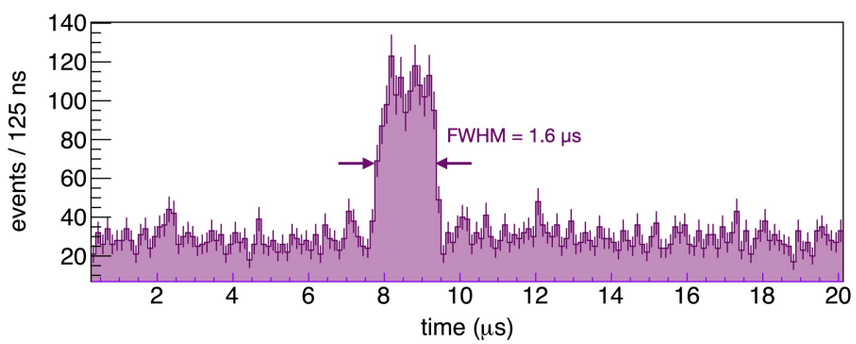

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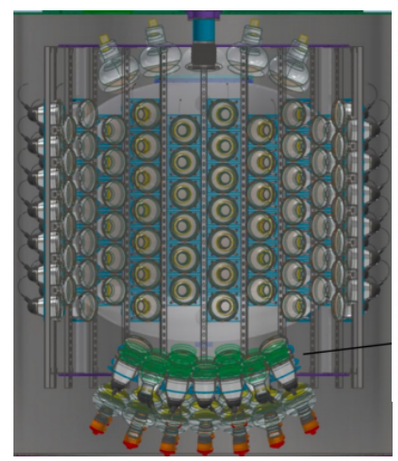

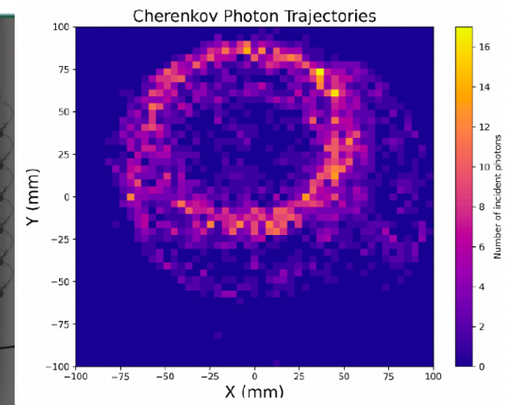

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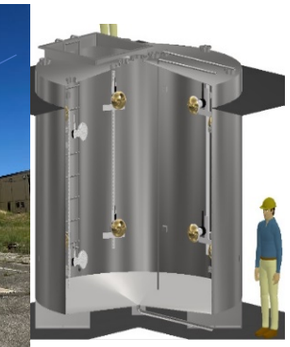
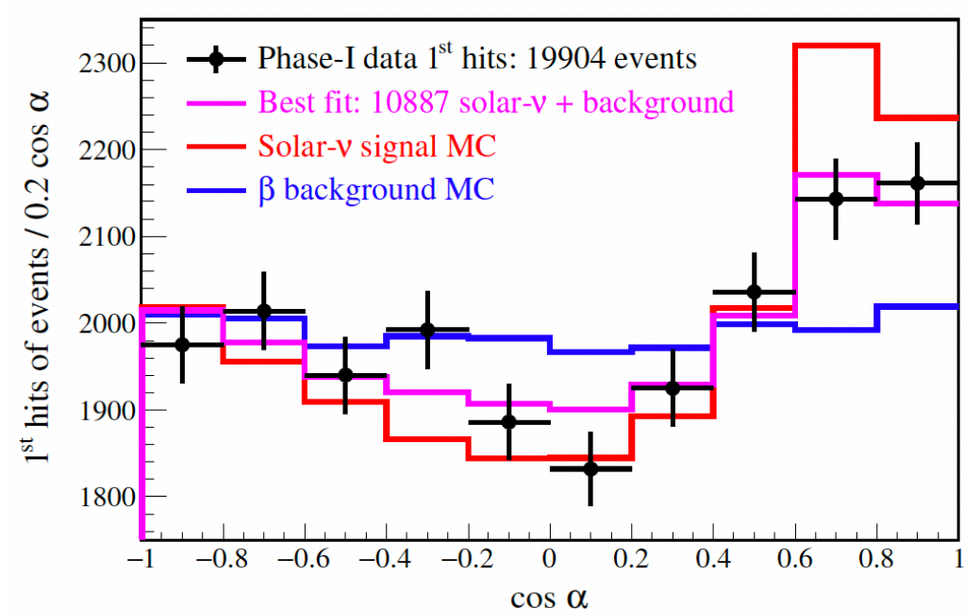
BNL: 1- and 30-ton



- First ton-scale deployment
- Optical transparency in an operating detector
- Optical stability over time
- Recirculation of WbLS (nanofiltration)

Full-scale demonstrations

- Integrated directionality at Borexino:
  - consider earliest photons in the event
  - take angle between early photons and solar direction
  - 6σ angular excess caused by Cherenkov photons
- Measurement of primarily 7Be ν demonstrates first directional detection of sub-MeV neutrinos



PRD 105.052002, PRL 128 (2022) 9, 091803

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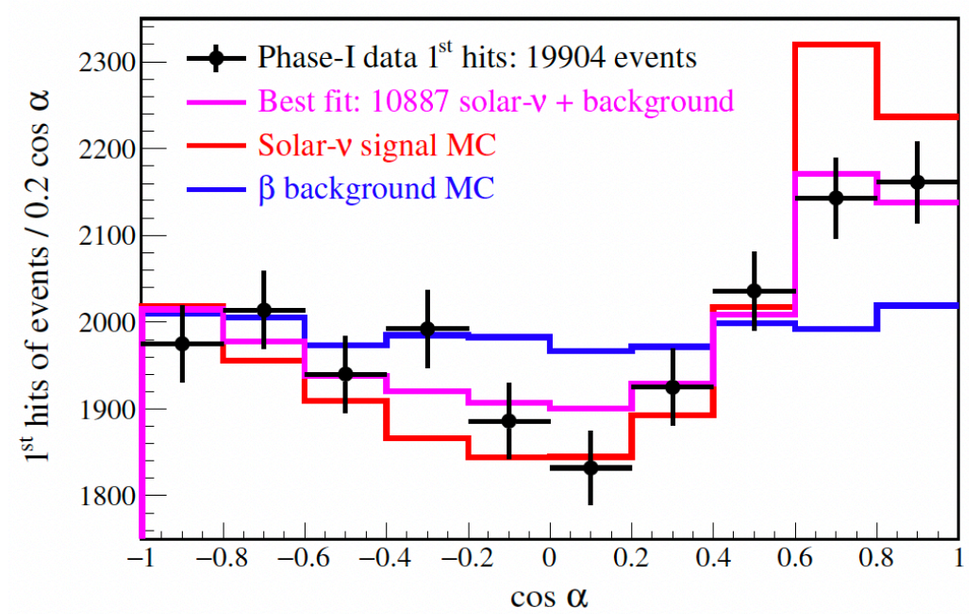
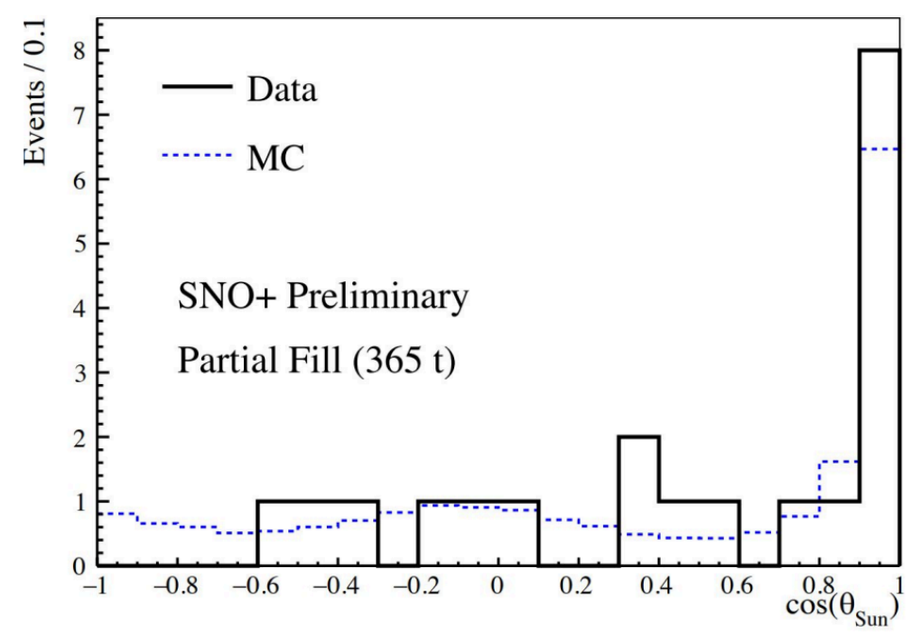


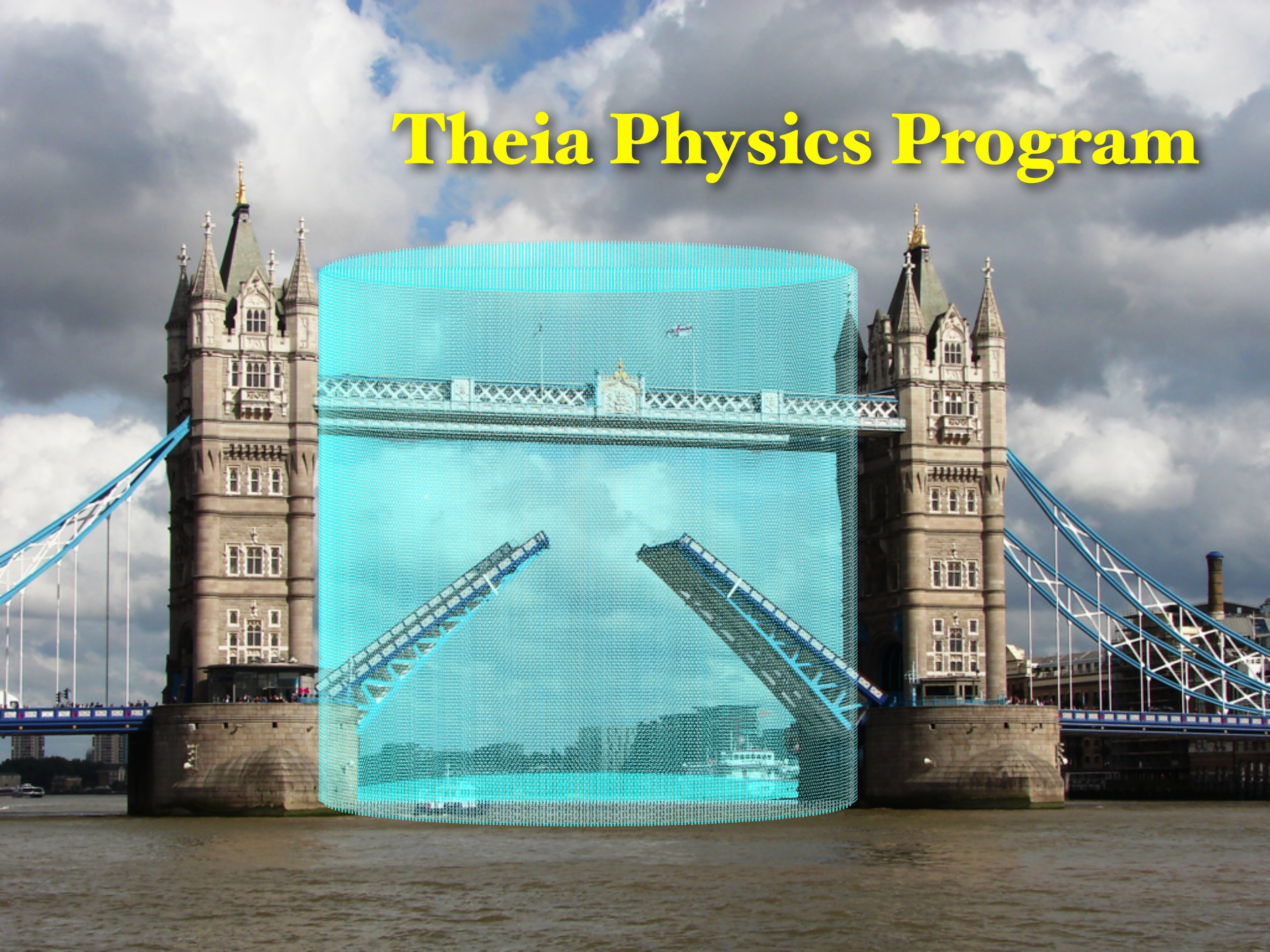
PRD 105.052002, PRL 128 (2022) 9, 091803

- Event-level directionality at SNO+:
  - Partial-filled detector (365 t LAB + 0.6 g/L PPO)
  - ToF and angular reconstruction
  - Demonstration with > 5MeV 8B ν
- First event-by-event demonstration of directional reconstruction for 8B solar ν in slow LS



SNO+, L. Lebanowski APS talk

Theia Physics Program



Physics Program

1. Neutrinoless double beta decay
2. Solar neutrinos (solar metallicity, luminosity)
3. Geo-neutrinos (& reactor neutrinos)
4. Supernova burst neutrinos & DSNB
5. Source-based sterile searches
6. Nucleon decay
7. Long-baseline physics (mass hierarchy, CP violation)

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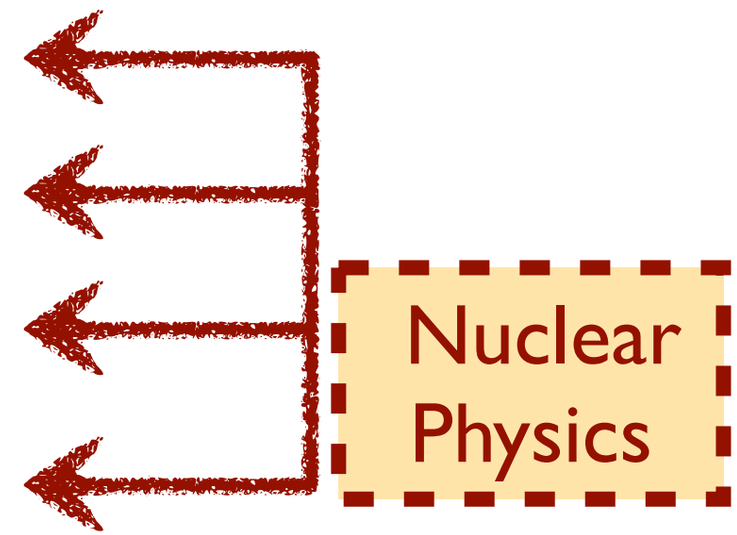

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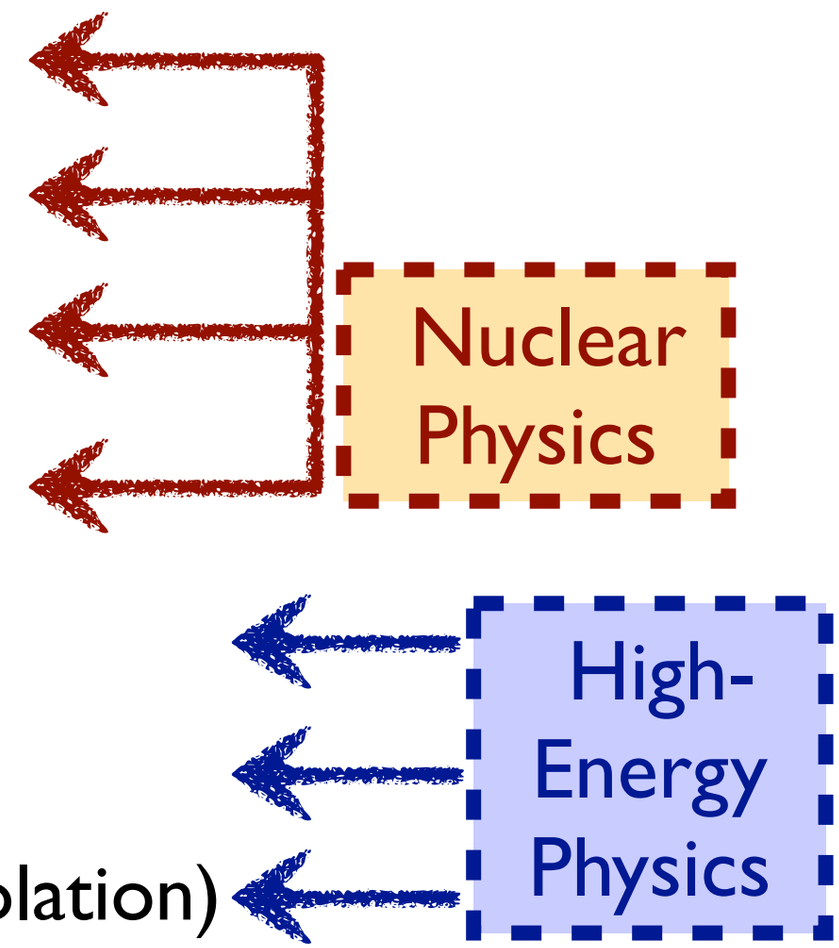

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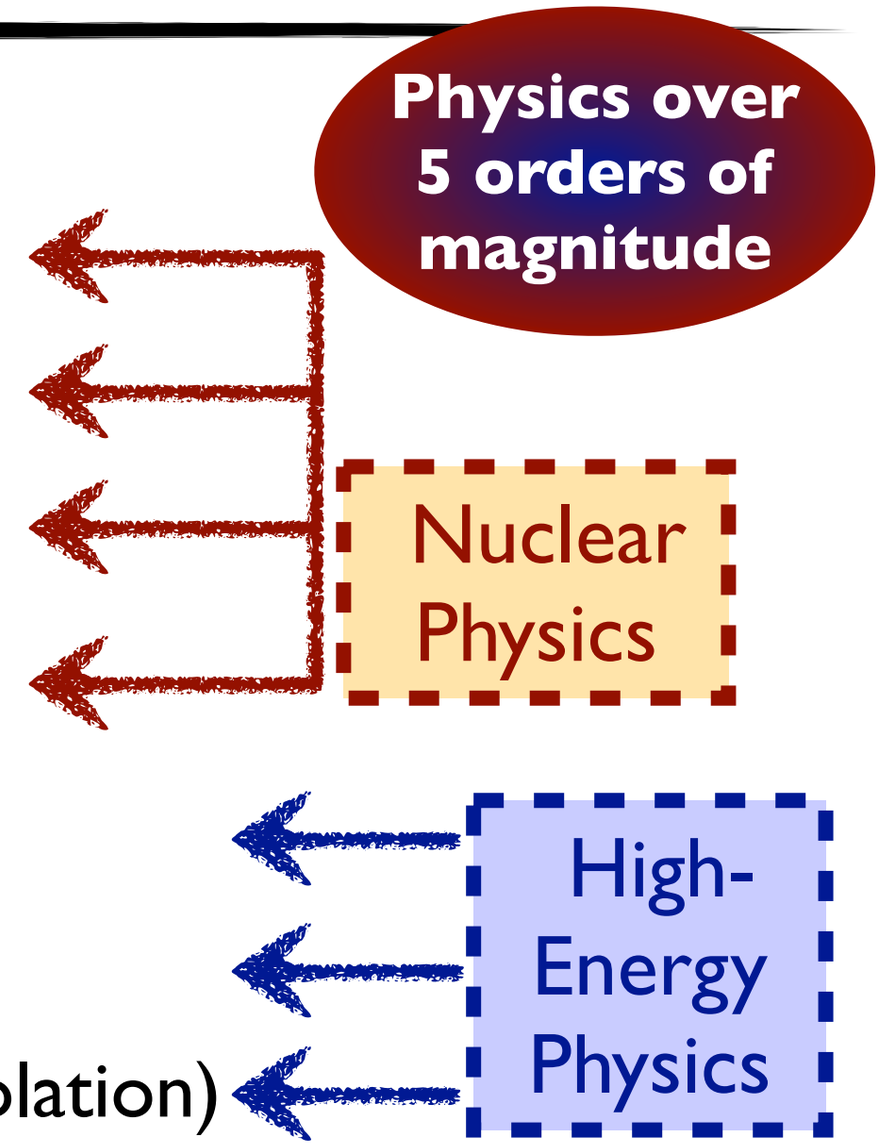

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High-Energy Physics

Remarkably, the same detector could show that neutrinos and antineutrinos are the same, ***and*** that "neutrinos" and "antineutrinos" oscillate differently

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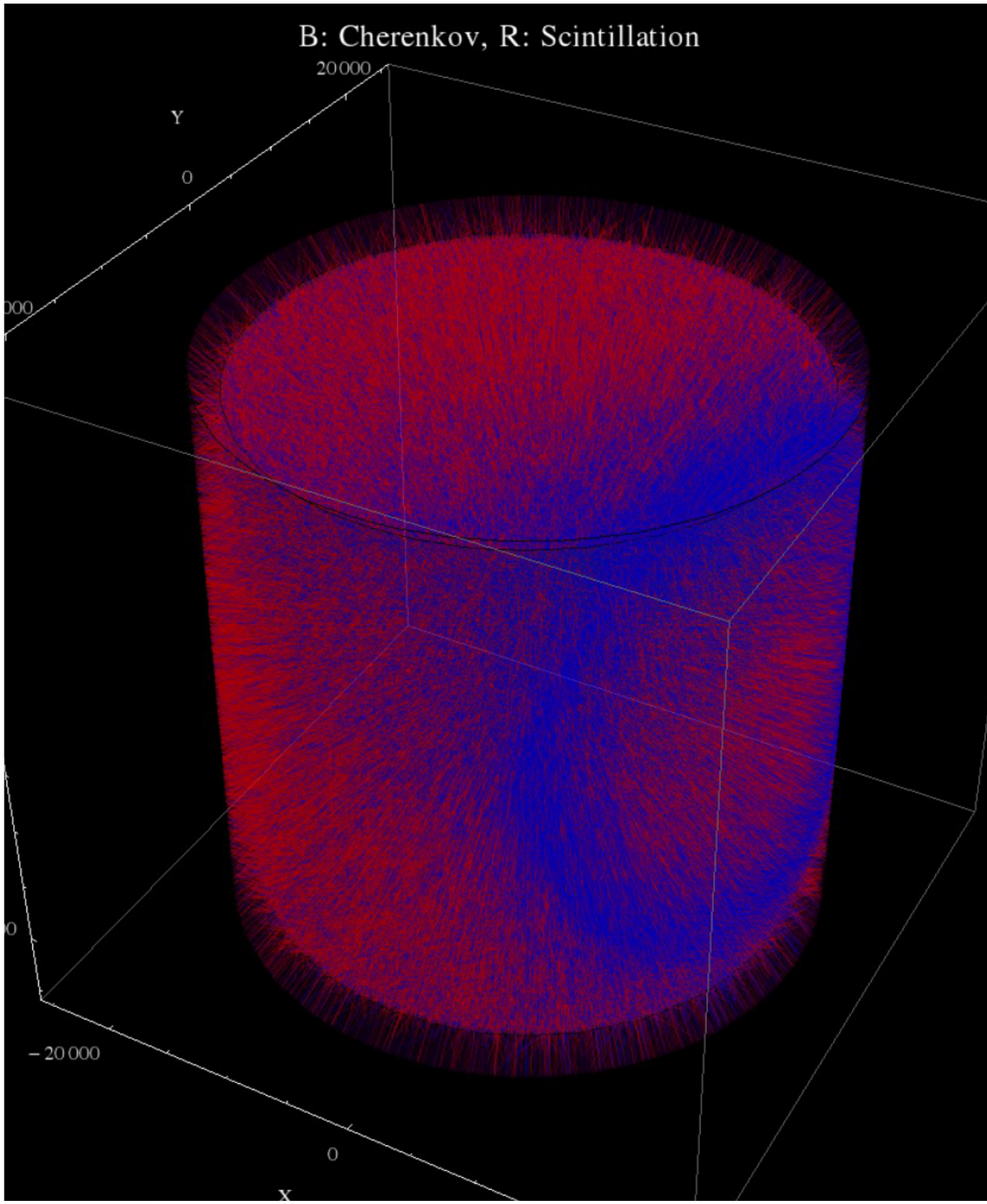
Matter-dominated universe

(Phased) Physics program

	Primary physics goal	Reach	Exposure/assumptions
I	**Long-baseline oscillations**	>5σ for 30% of δ_{CP}	524kt-MW-year
I	**Nucleon decay $p \rightarrow \bar{\nu} K^+$**	T>3.8 x 10^{34} year	800 kt-year
I	**Supernova burst**	<1(2)° pointing 20K(5K) events	100(25)kt, 10kpc SN
I	**Diffuse Supernova Neutrino**	5σ	125kt-year
II	**CNO neutrinos**	<5(10)%	300(62.5)kt-year
II	**Geoneutrinos**	< 7 %	25 kt-year
III	**$0\nu\nu\beta$**	$T_{1/2}$ > 1.1 x 10^{28} year (90%C.L.)	800 kt-year (Multi-tonne loaded LS in suspended vessel search)

Take-home message

- A hybrid detector module would add to the LBL program at DUNE and bring a broad program of additional physics
- Major technological developments have been achieved since last Snowmass
- Results from existing large detectors demonstrate the feasibility of this concept
- Prototypes underway will demonstrate the full range of capabilities
- Brings a new community of physicists to the facility and the program
- Timely to pursue serious engineering design studies to evolve the concept
- Depends on an open process for determining the future of Module 4



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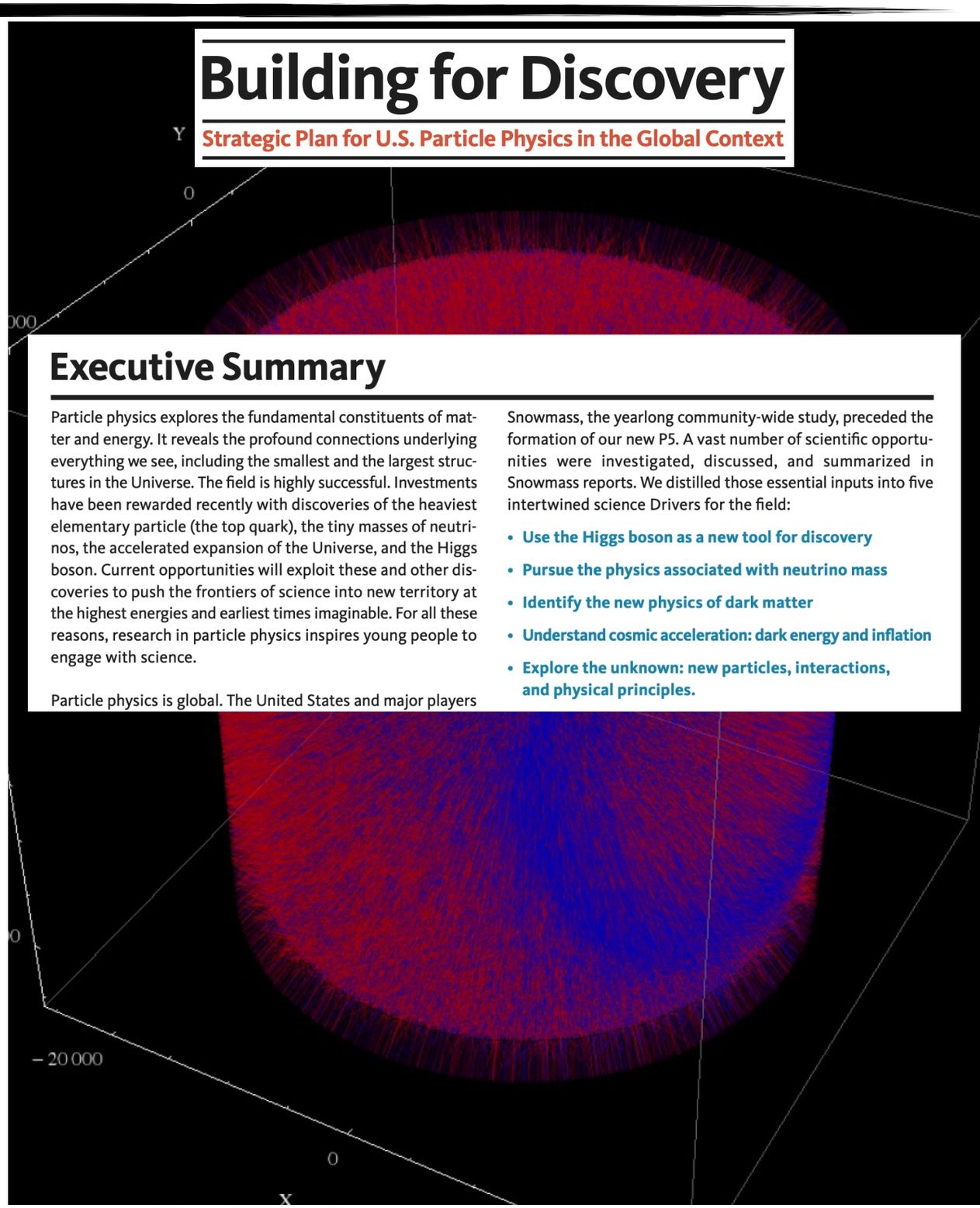

Building for Discovery

Strategic Plan for U.S. Particle Physics in the Global Context

Executive Summary

Particle physics explores the fundamental constituents of matter and energy. It reveals the profound connections underlying everything we see, including the smallest and the largest structures in the Universe. The field is highly successful. Investments have been rewarded recently with discoveries of the heaviest elementary particle (the top quark), the tiny masses of neutrinos, the accelerated expansion of the Universe, and the Higgs boson. Current opportunities will exploit these and other discoveries to push the frontiers of science into new territory at the highest energies and earliest times imaginable. For all these reasons, research in particle physics inspires young people to engage with science.

Particle physics is global. The United States and major players

Snowmass, the yearlong community-wide study, preceded the formation of our new P5. A vast number of scientific opportunities were investigated, discussed, and summarized in Snowmass reports. We distilled those essential inputs into five intertwined science Drivers for the field:

- **Use the Higgs boson as a new tool for discovery**
- **Pursue the physics associated with neutrino mass**
- **Identify the new physics of dark matter**
- **Understand cosmic acceleration: dark energy and inflation**
- **Explore the unknown: new particles, interactions, and physical principles.**

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- Host a large water Cherenkov neutrino detector to complement the LBNF large liquid argon detector, unifying the global long-baseline neutrino community to take full advantage of the world's highest intensity neutrino beam at Fermilab.

Thank you

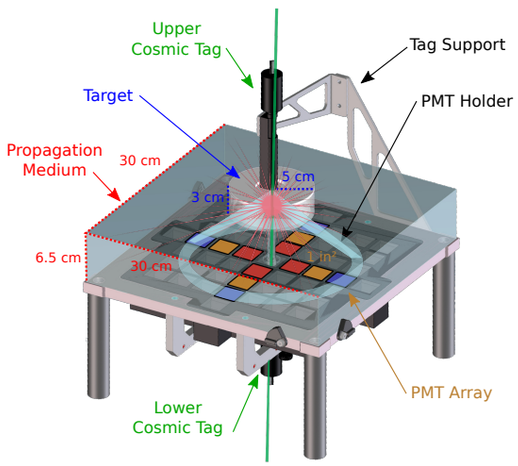
This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of High Energy Physics, under Award Number DESC0018974. Work conducted at Lawrence Berkeley National Laboratory was performed under the auspices of the U.S. Department of Energy under Contract DEAC02-05CH11231. The project was funded by the U.S. Department of Energy, National Nuclear Security Administration, Office of Defense Nuclear Nonproliferation Research and Development (DNN R&D).

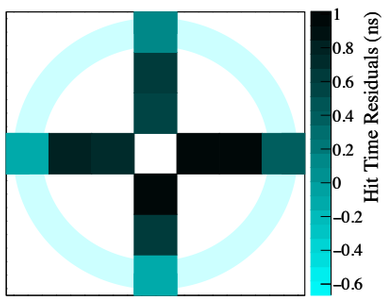
- Backup

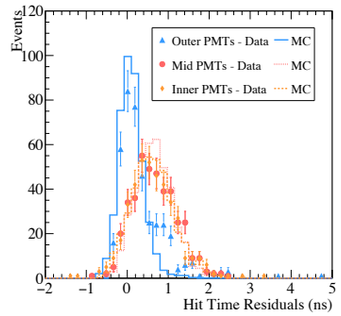
(Wb)LS development

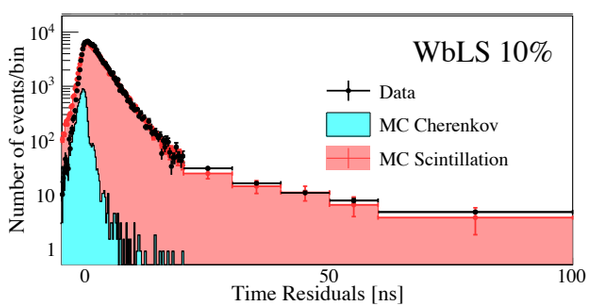
Primary development at BNL (Yeh et al)

CHESS detector, LBNL









Phys. Rev. C ***95*** *055801 (2017)*
Eur. Phys. Jour. C ***77*** *811 (2017)*
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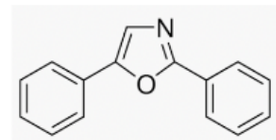
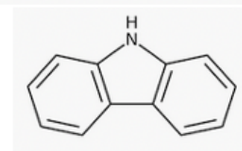
Engineering WbLS properties, LBNL

Example:
slowing down decay time

- Standard PPO → 2ns
- New carbazole → 15ns



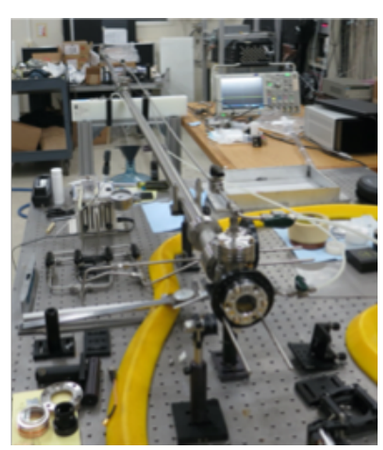


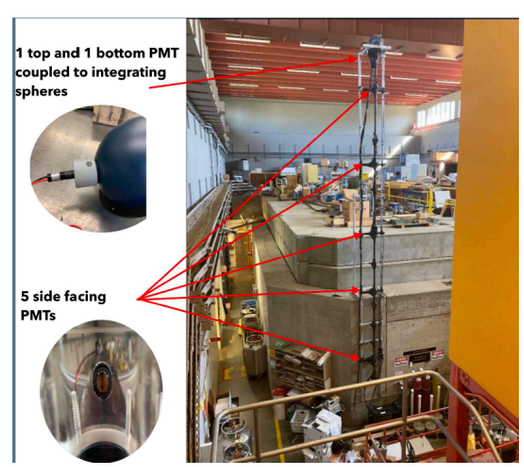
Mat. Adv. ***1*** *71 (2020)*

Extensive international effort in Germany (Mainz, Munich), UK, China

Additional work on: slow LS, alternative fluors, alternative surfactants

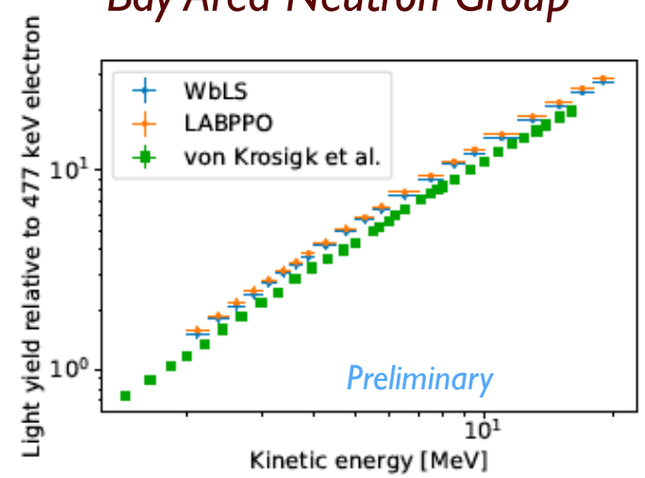
Scattering & attenuation, UC Davis, UC Berkeley+LLNL



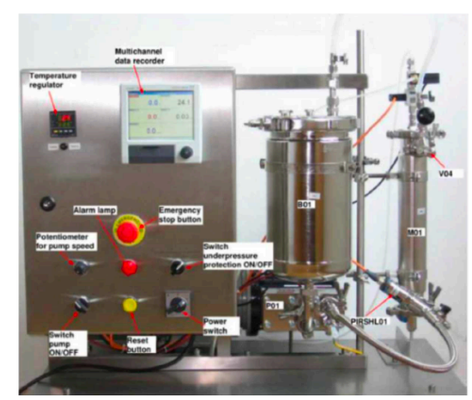


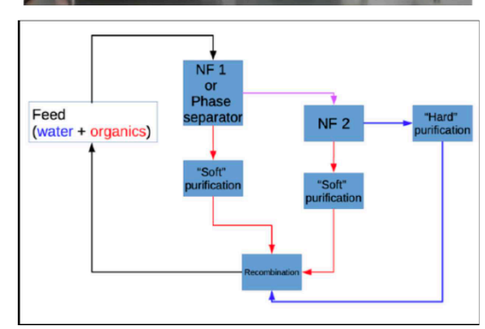
Proton LY, LBNL

Bay Area Neutron Group



Nanofiltration, UC Davis





Preliminary design for a two-staged nanofiltration concept for large scale WbLS purification.

(Wb)LS development

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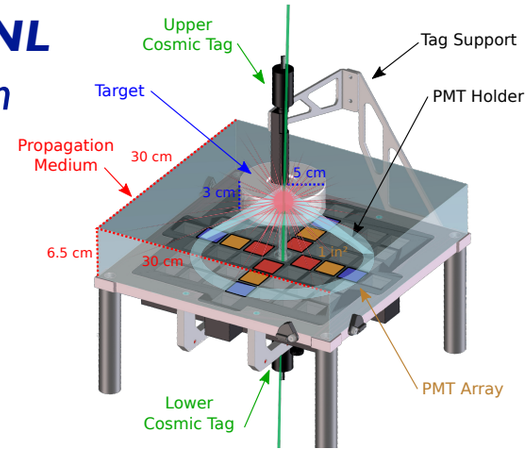

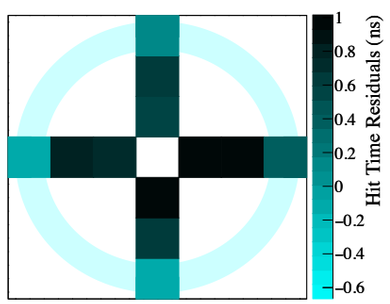

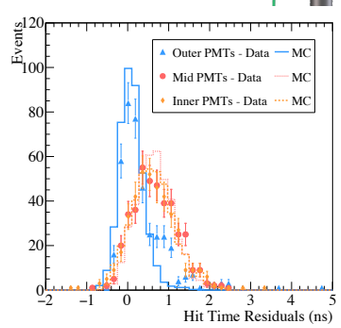

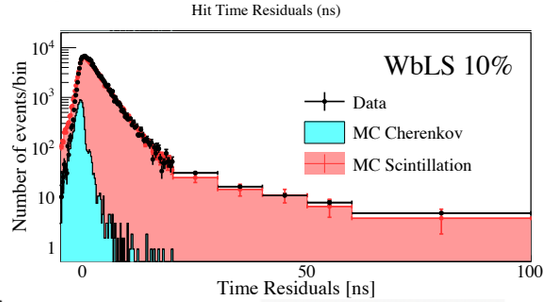

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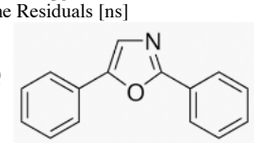
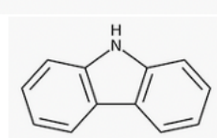


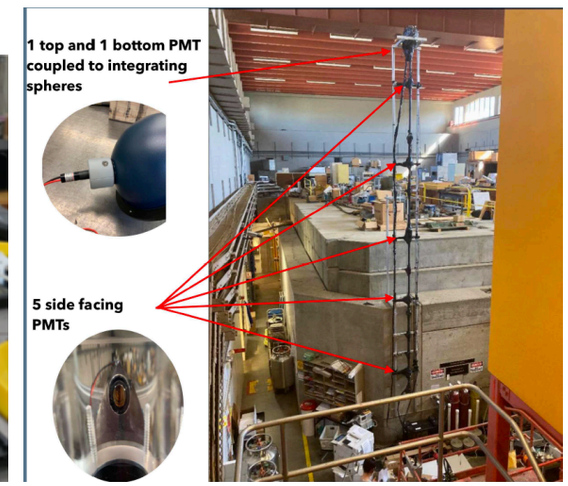


+ optical & x-ray excitation for pure scintillation characterisation; independent check of CHESS MeV-scale physics events

Mat.Adv. I 71 (2020)

Scattering & attenuation, UC Davis, UC Berkeley+LLNL

Long-arm (7.5m) scattering and attenuation measurement device; attenuation measured as a function of wavelength; side ports for scattering measurement



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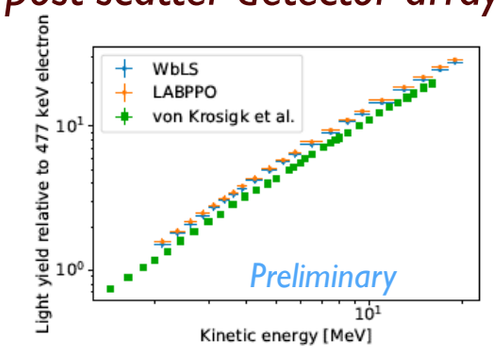
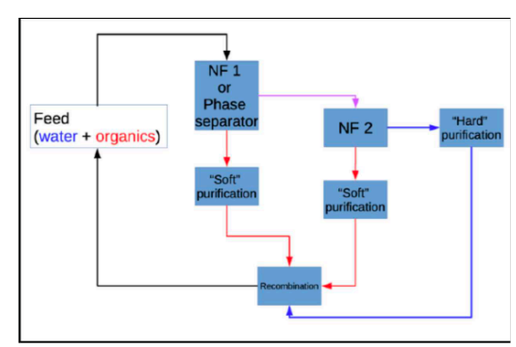
Double time-of-flight method, pulsed deuteron beam on Be breakup target; PID-capable post-scatter detector array



Nanofiltration, UC Davis

Membrane filtration process to separate water & ionic compounds from LS before deionisation. Critical to maintain optical transparency. Flow rate determined by detector size.

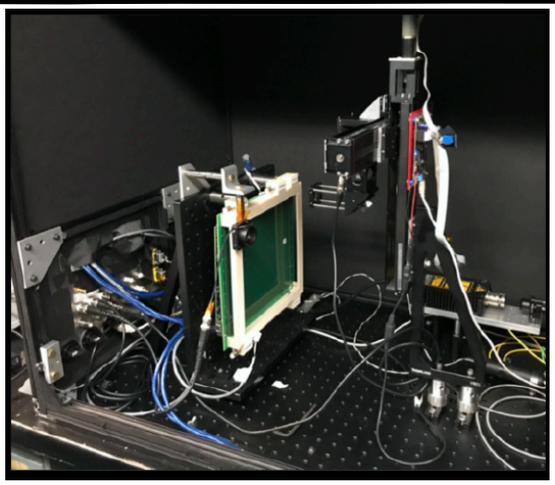


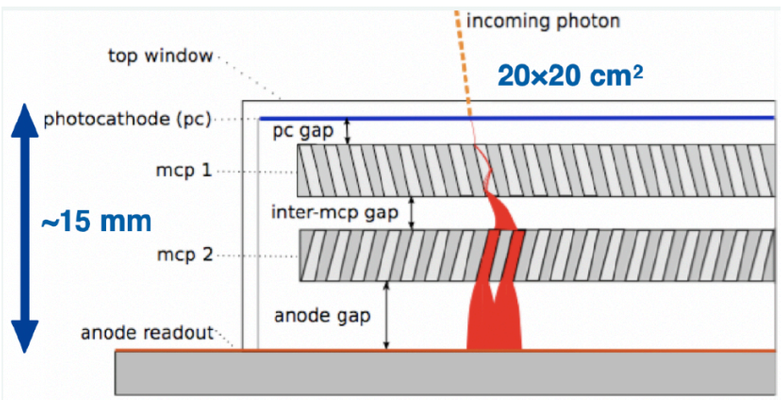
Preliminary design for a two-staged nanofiltration concept for large scale WbLS purification.

LAPPDs

Substantial work by U. Chicago, Iowa, LAPPD team, ANNIE collaboration & others

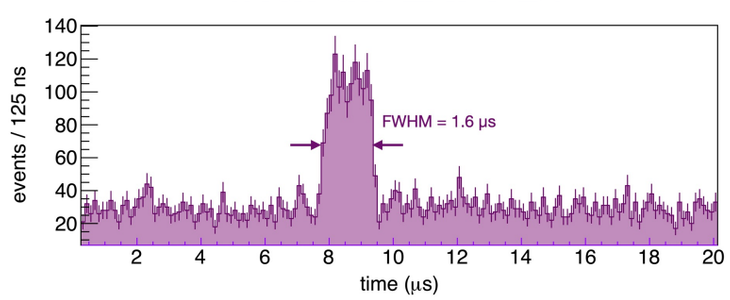
- Layered micro channel plates —> sub-cm spatial and < 70ps time resolution for SPE



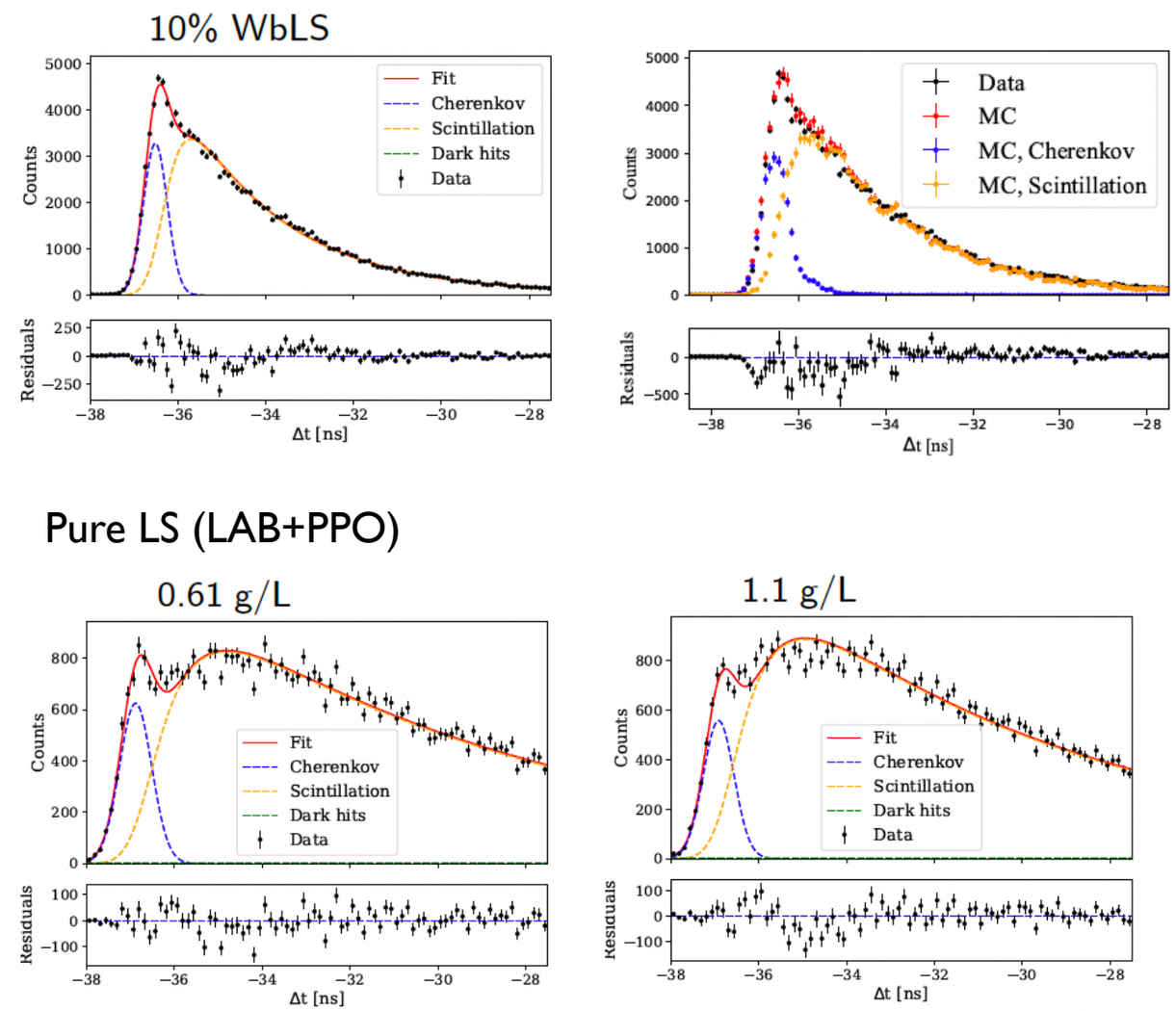


- LAPPD operating in ANNIE: world-first demonstration in running neutrino experiment (+4 planned for next beam year)

First neutrinos detected with an LAPPD!



- Deployment at CHESS with LS and WbLS demonstrate clear Cherenkov peak even in high LY scintillators



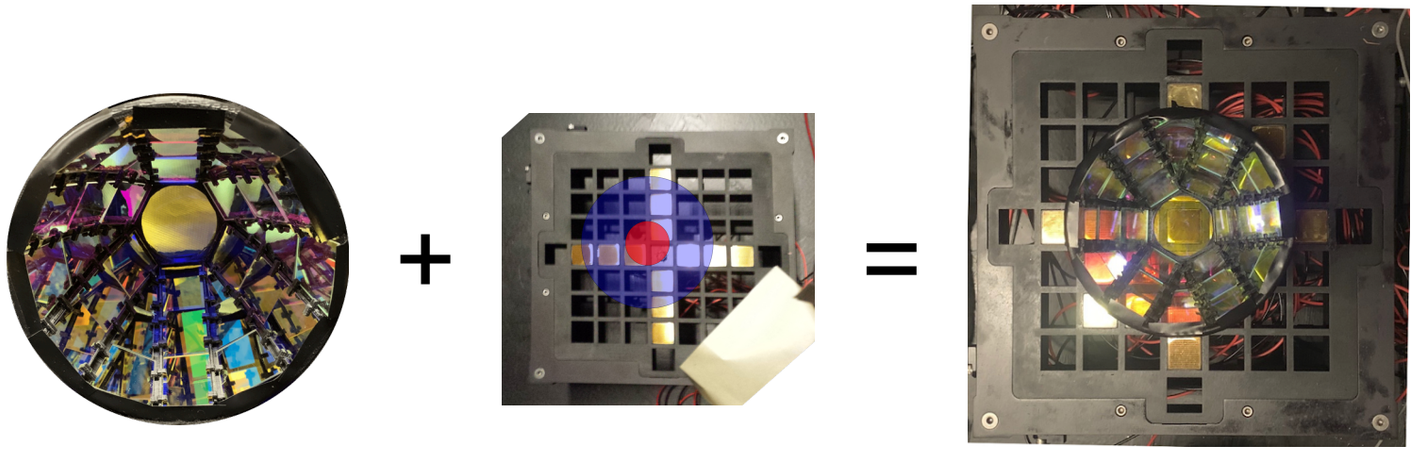
Eur. Phys. Jour. C 82 169 (2022)

Dichroicons

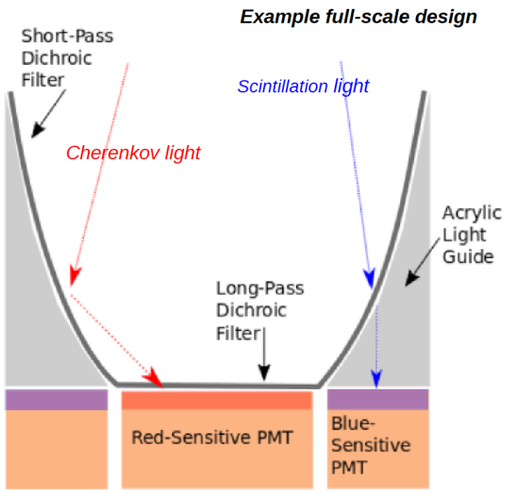
Concept developed by Penn team (Klein, Kaptanoglu et al.)

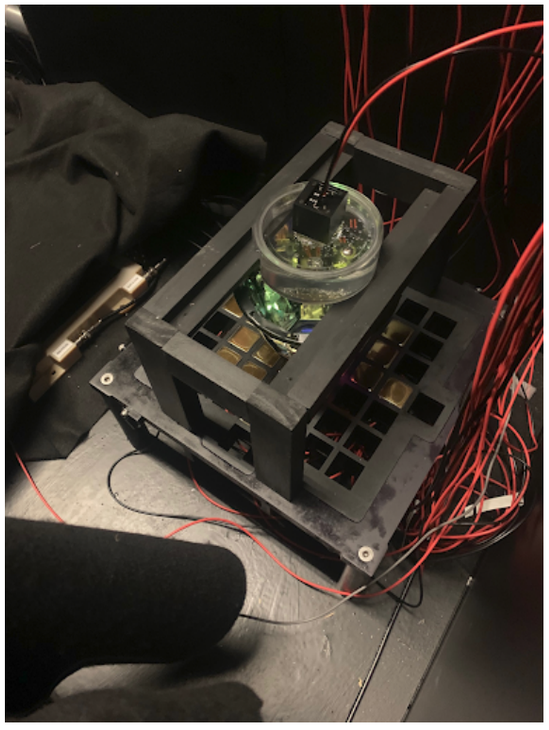
T. Kaptanoglu, Nucl. Instrum. Meth. A889 (2018) 69-77
T. Kaptanoglu, M. Luo, J. Klein, JINST 14 no. 05 T05001 (2019)

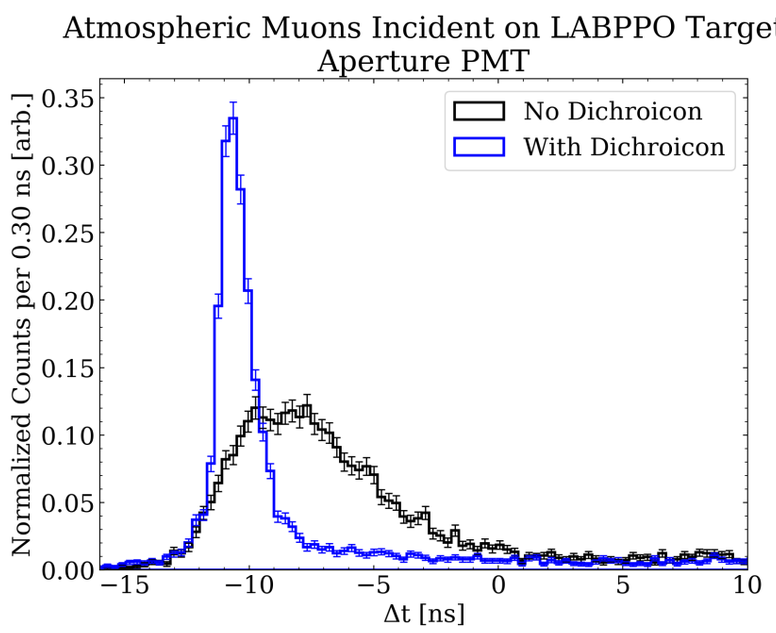
Dichroicons sort incident photons by wavelength
Achieves spectral separation of Cherenkov and scintillation.
Dichroicon deployment at CHESS demonstrates capabilities

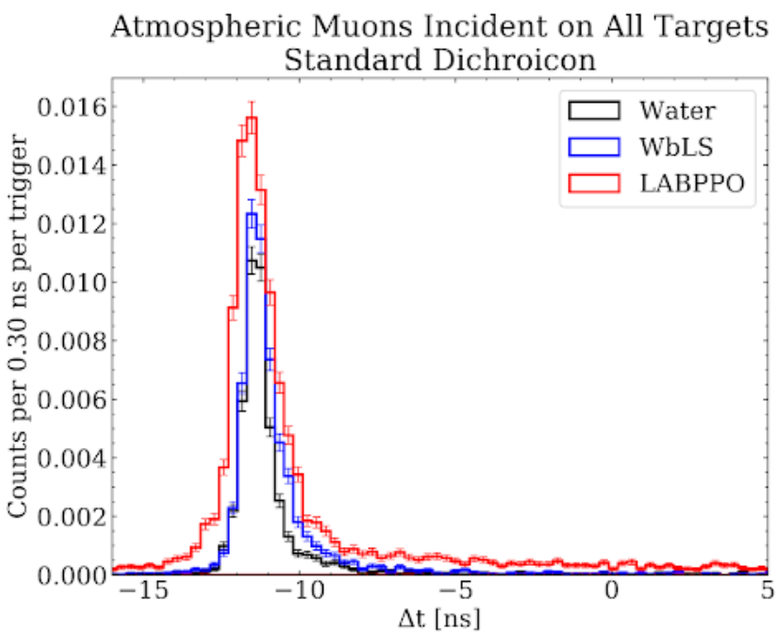


"Standard" design
Red-focusing









WbLS @ ANNIE

Show feasibility of WbLS in a neutrino-beam

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

Interest to Theia:

- First deployment of LAPPDs
- Deployment of 365 kg WbLS
- C/S separation in a large-scale experiment
- High- and low-energy event reconstruction
- Use of sub-Chr t/h scintillation for recoil p & hadron detection
- Neutron detection

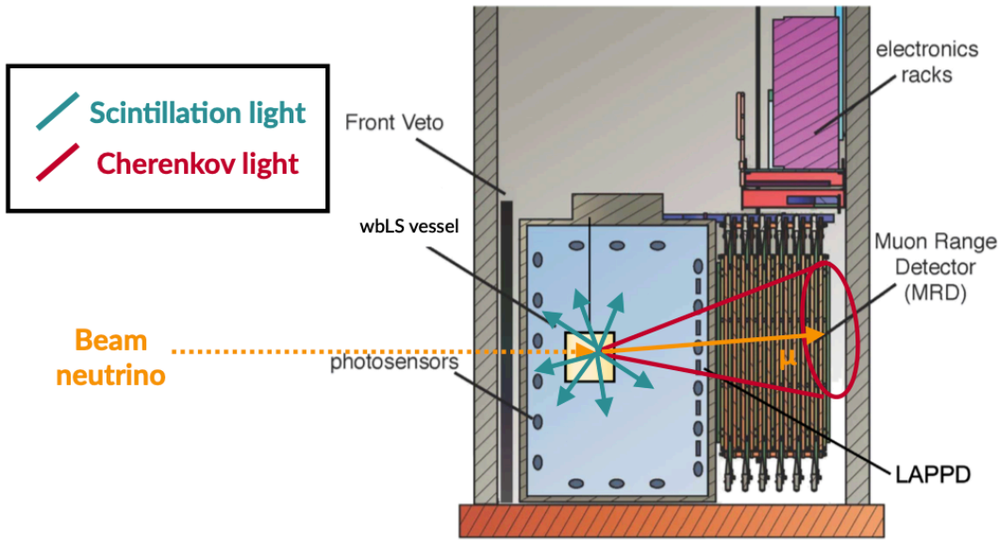
WbLS data taking: Planned for summer/fall 2022

Location: Booster Neutrino Beam @ FermiLab (USA)

Water-volume: 26t

WbLS volume: 0.5t

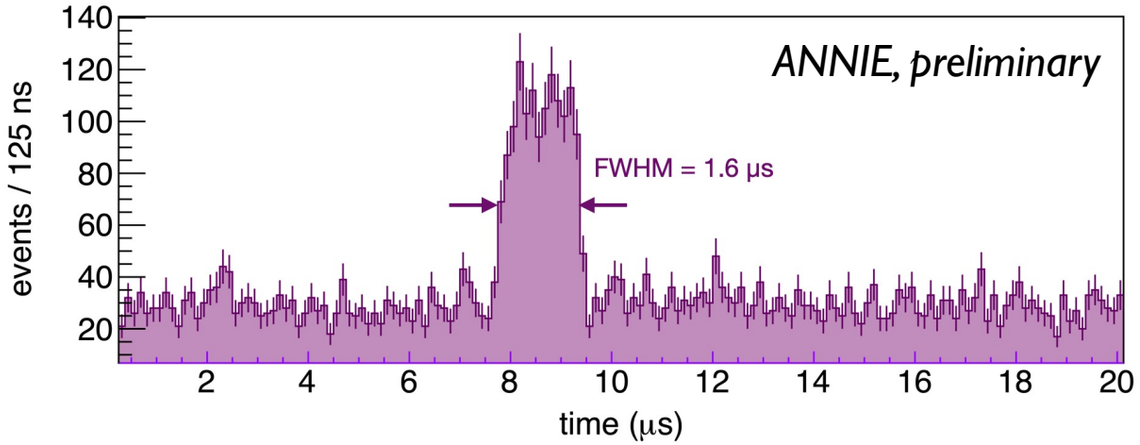
Interests: neutrino-nucleus interactions



WbLS vessel

Rough visualization of vessel (NOT final design)

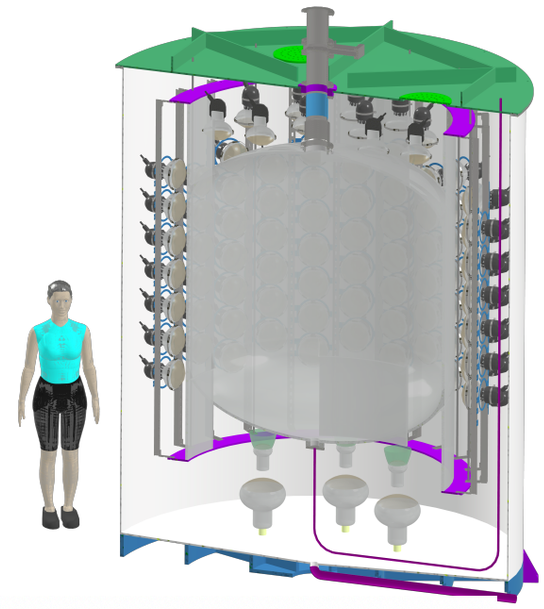
First neutrinos detected with an LAPPD!

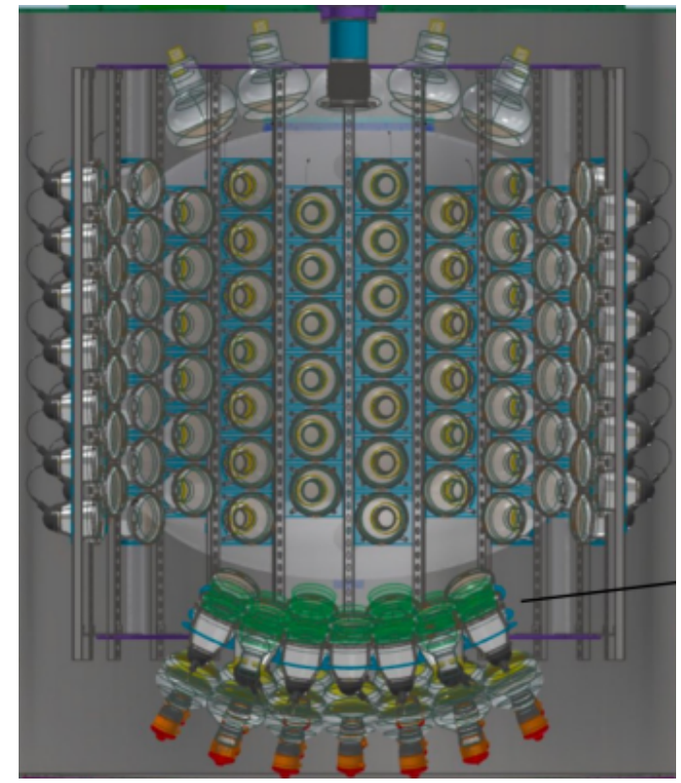


A.R. Back *et al JINST* **15** P03011 (2020)
M.J.Minot et al NIM A 787, 78 (2015)

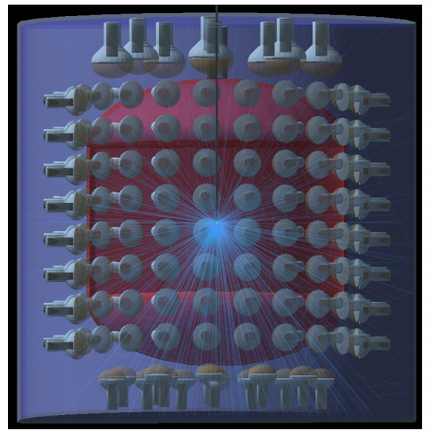
Eos: performance demonstrator for next-generation neutrino experiments

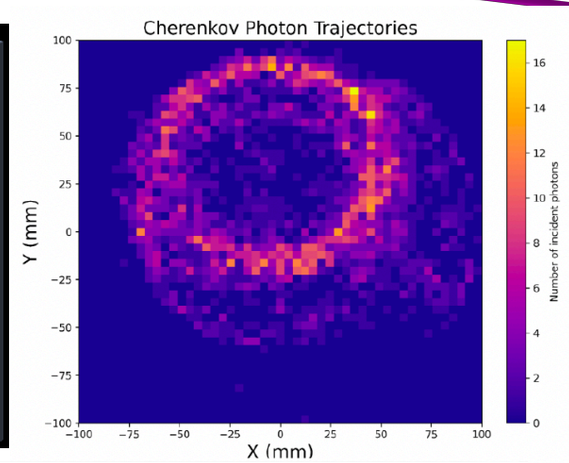
- Demonstrate event reconstruction using hybrid Cherenkov + scintillation signatures
- Validate models to support large-scale detector performance predictions
- Provide a flexible testbed to demonstrate impact of novel technology: targets, photon detectors, readout, reconstruction algorithms





- 4-ton target mass
  water, WbLS, LS
- 200 8-" PMTs
  R14688-100, 900ps FWHM
- CAEN V1730 readout
- Dichroicon deployment for spectral sorting
- Range of deployable sources for studies of vertex, energy, direction resolution and PID





USA: Berkeley Lab, UC Berkeley, UC Davis, Penn, Lawrence Livermore National Laboratory, Boston University, Penn State, State, Brookhaven National Laboratory, Fermilab, Rutgers, Iowa, Bartoszek Engineering, South Dakota School of Mines & Technology, University of Chicago, University of Colorado Boulder

Germany: JGU Johannes Gutenberg Universität Mainz, PRISMA+, TUM Technische Universität München

Portugal: LIP, 1290 Universidade de Coimbra

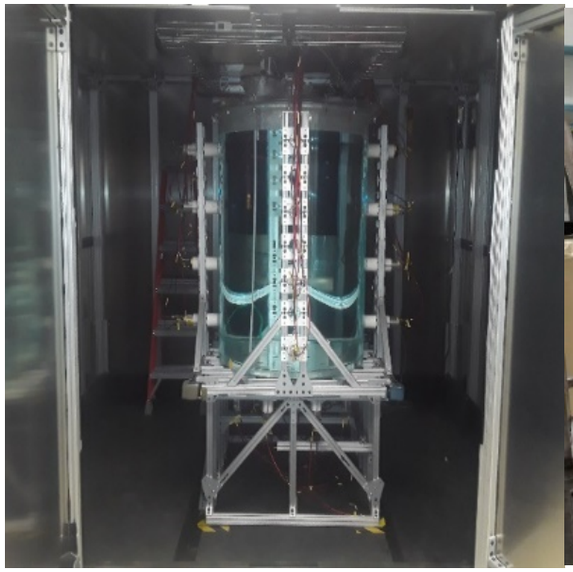
Finland: Jyväskylän yliopisto University of Jyväskylä

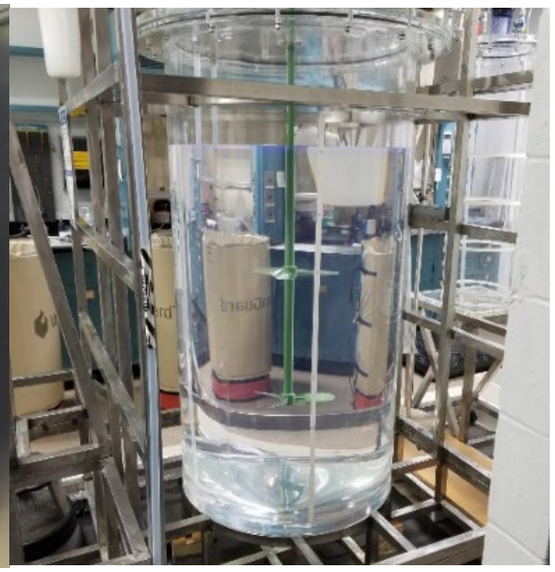
Turkey: Erciyes University

Canada: SNOLAB

BNL 1- & 30-ton demonstrators

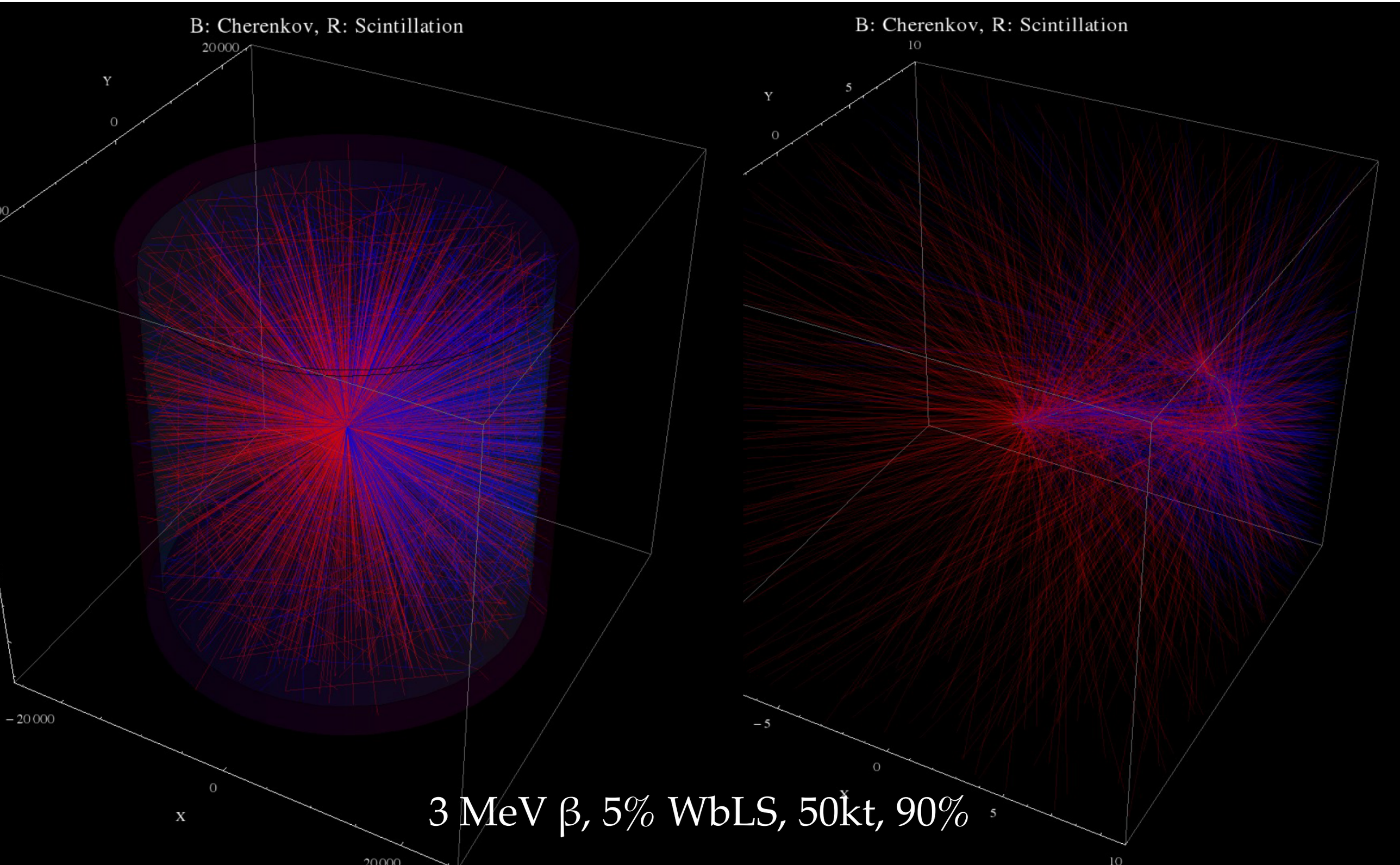
- First ton-scale deployment of WbLS
- First demonstration of:
  - Ton-scale production
  - Optical transparency in an operating detector
  - Optical stability over time
  - Recirculation of WbLS (nanofiltration)





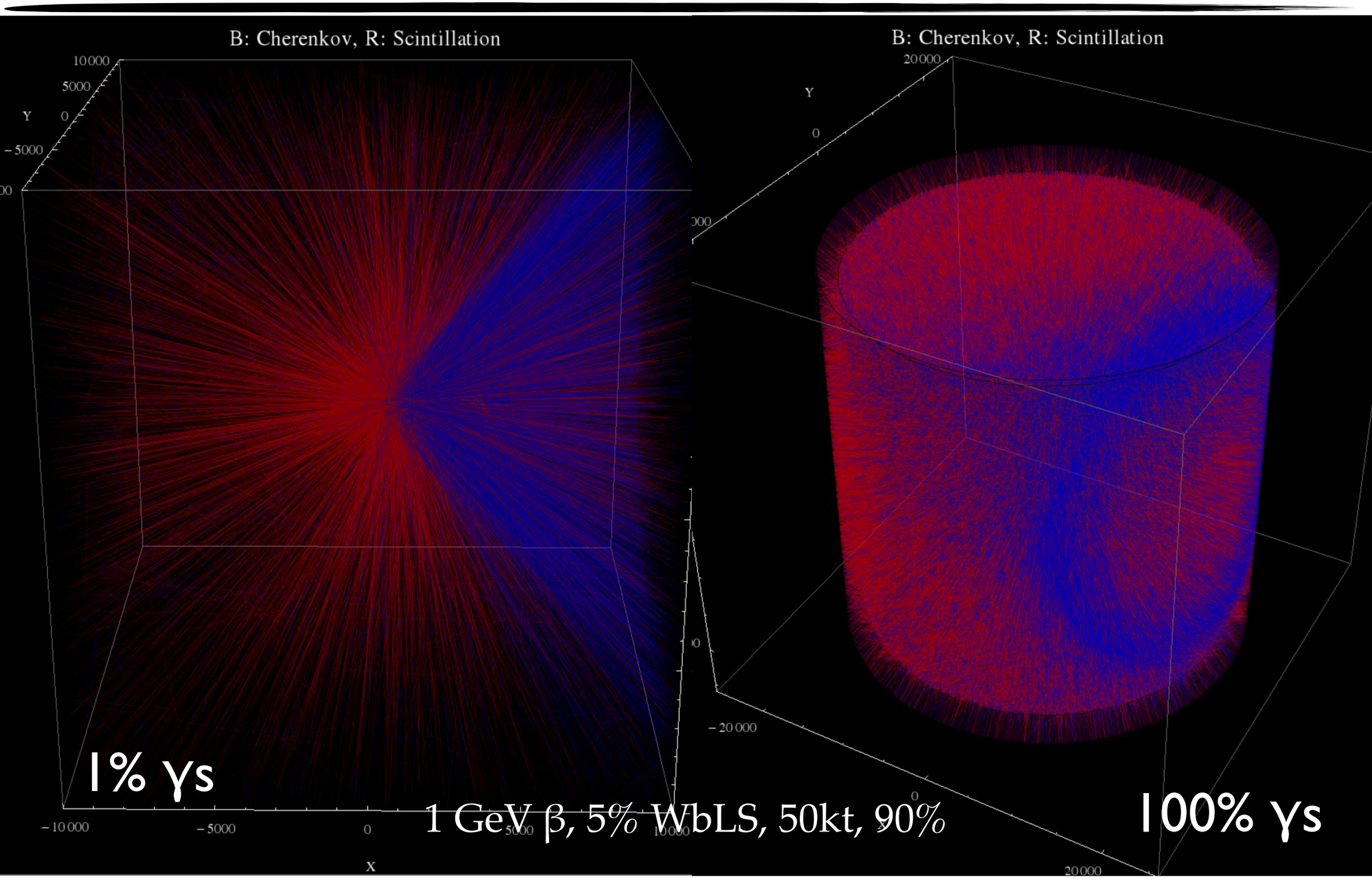
Together these prototypes will demonstrate the feasibility and capabilities of hybrid detectors for nonproliferation and fundamental physics

Signal Separation in Theia



3 MeV β, 5% WbLS, 50kt, 90%

Ring Imaging



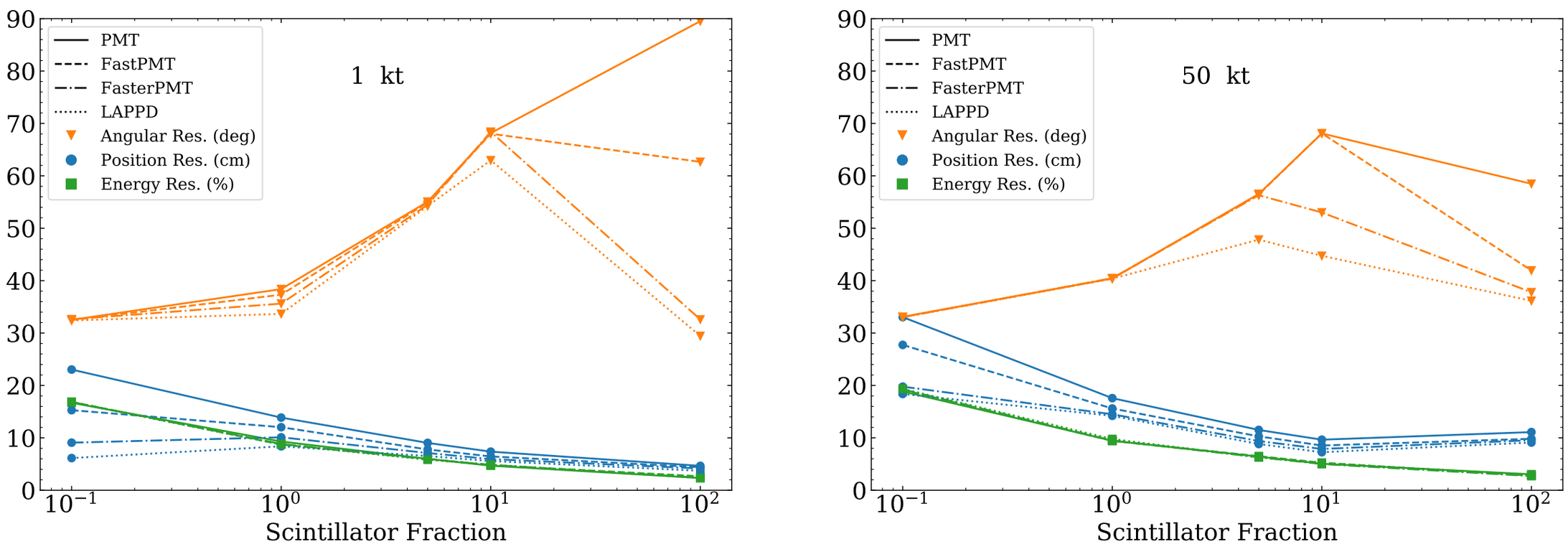
1 GeV β, 5% WbLS, 50kt, 90%

Model validation

A number of metrics are considered for detector performance:

1. Energy resolution — *Reduce flux uncertainty, increase background rejection*
2. Vertex resolution — *Reduce flux uncertainty, increase background rejection*
3. Angular resolution — *Elastic scattering event ID, physics scope*
4. Cherenkov (C) / scintillation (S) separation — *Particle & event ID*

These tools can be used to define "desired" properties for WbLS

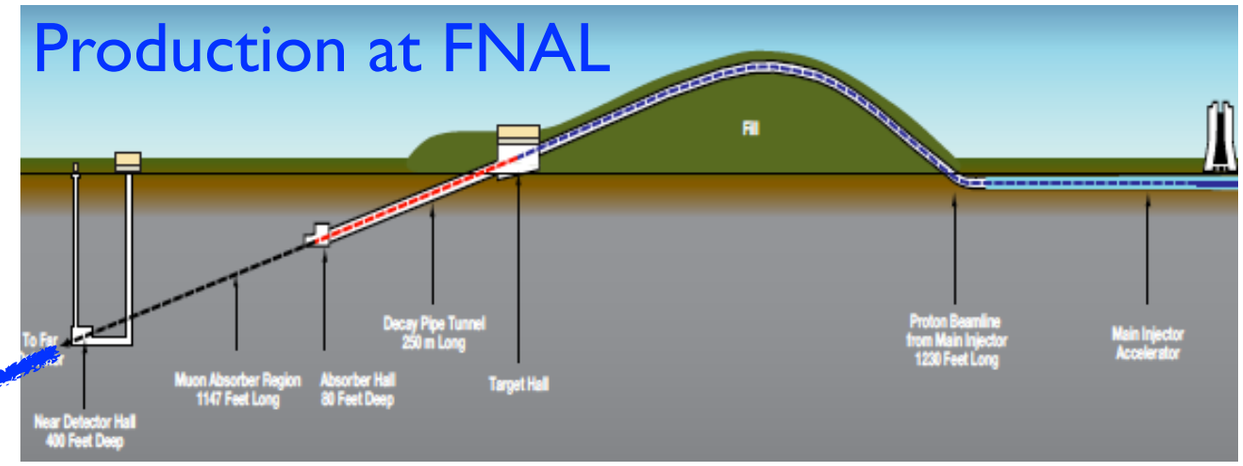


Impact of target properties and photon detector response on detector performance for (left) 1-kton and (right) 50-kton detectors

Phys. Rev. D ***103*** *052004 (2021)*

Long-Baseline Program

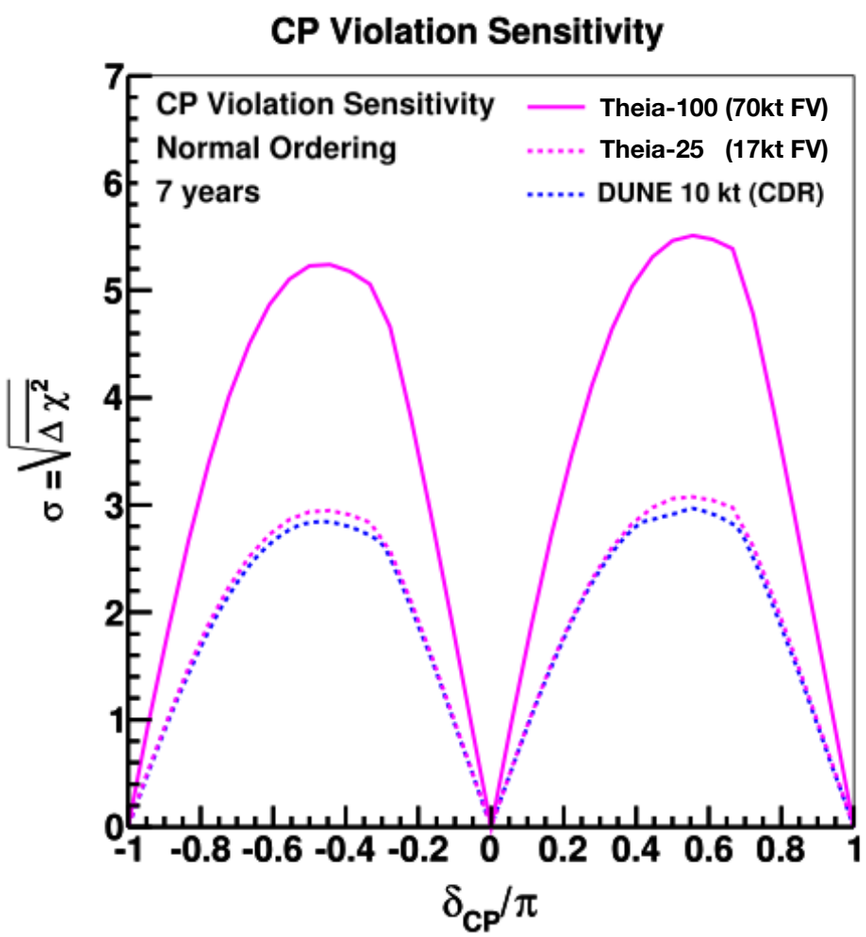
- Large-scale detector at Homestake, in the LBNF beam
- Complementary program to LArTPC (DUNE)
- Build on WCD studies (arXiv:1204.2295)

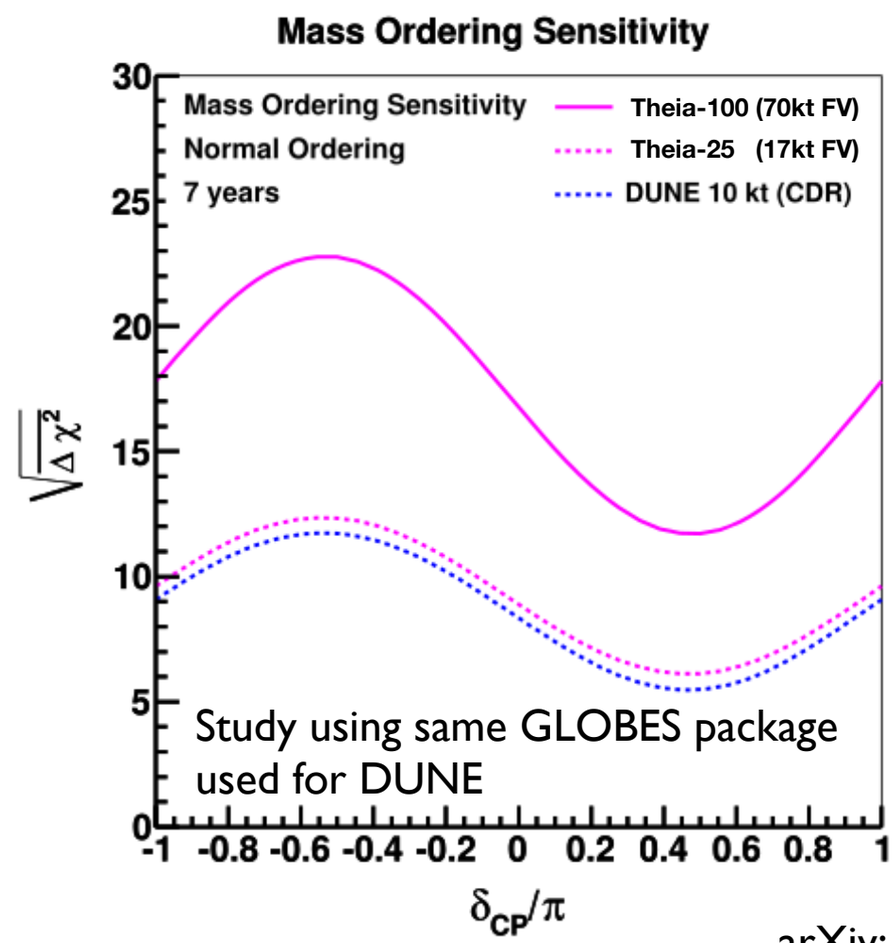


1300km

- Ring-imaging of a water Cherenkov detector
- Particle ID from Cher/scint separation
- n and low-E hadron detection (low threshold)
  - reduce wrong-sign component (ν vs anti-ν)
  - reduce NC background by detecting $\pi^0 \rightarrow \gamma\gamma$
- Large size → sensitivity to 2nd oscn max

Long-Baseline Sensitivity





Synergy with LAr TPC

Independent systematics

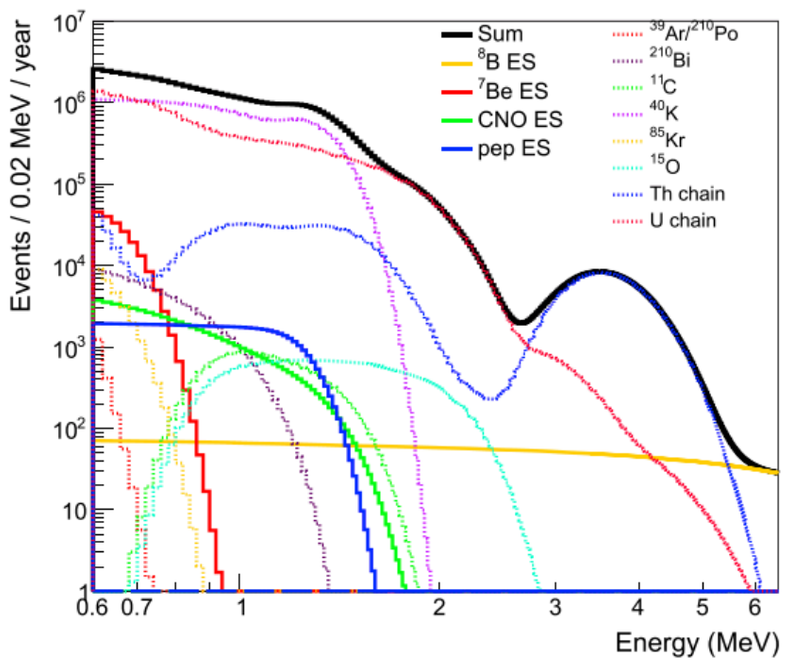
High-energy events

arXiv: 1606.09550

Performance of small (25kt) Theia module competitive with 10kt LAr TPC

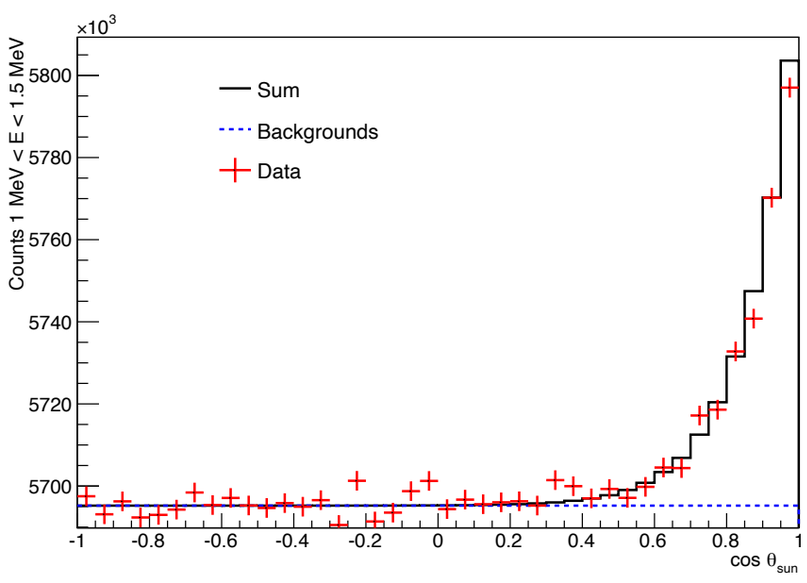
Eur. Phys. J. C 80, 416 (2020)

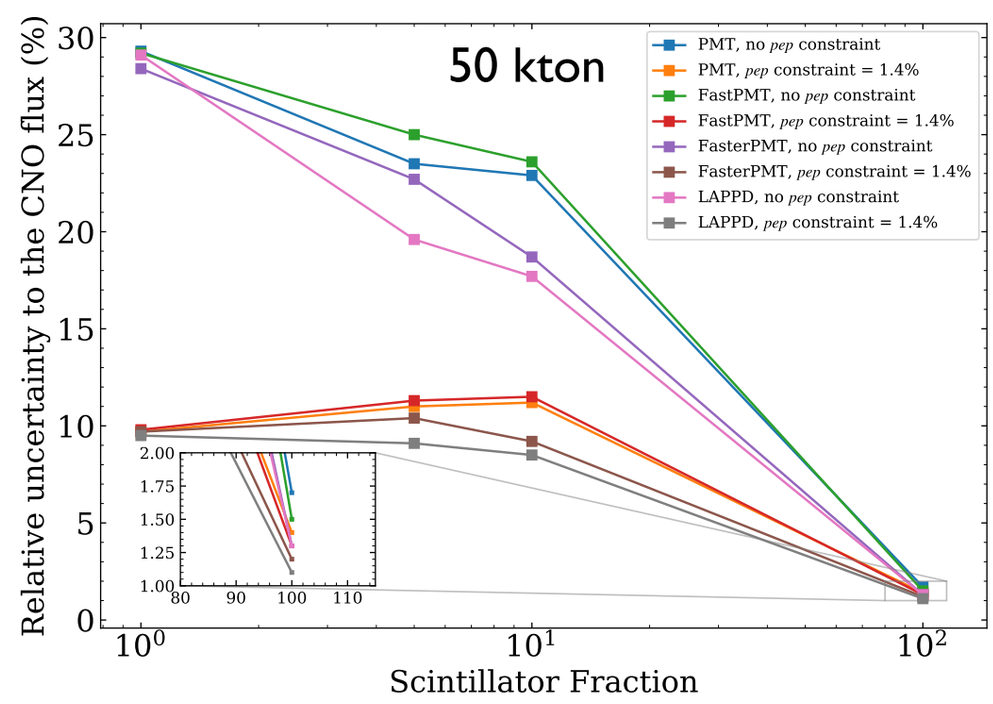
Solar Neutrinos with Theia



- Dominant background to CNO ν measurement: ^{210}Bi
- Theia offers unique low-threshold, directional detection

2D fit in energy and cos(θ_{sun})

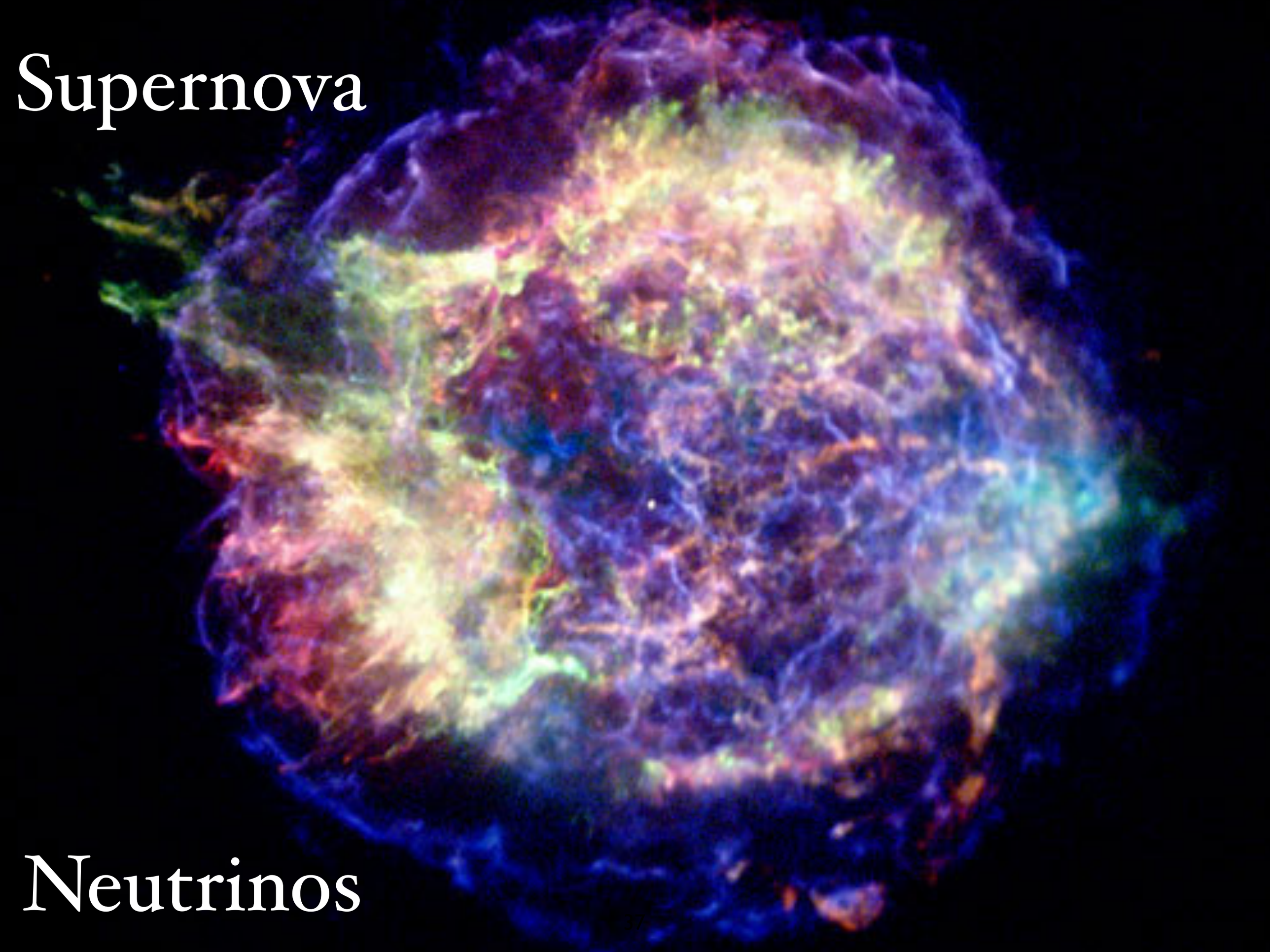




Sensitivity based on MC study of detector response, including full vertex and direction reconstruction

Phys. Rev. D 103, 052004 (2021)

Eur. Phys. J. C 80, 416 (2020); Eur. Phys. J. C (2018) 78: 435


Supernova
Neutrinos

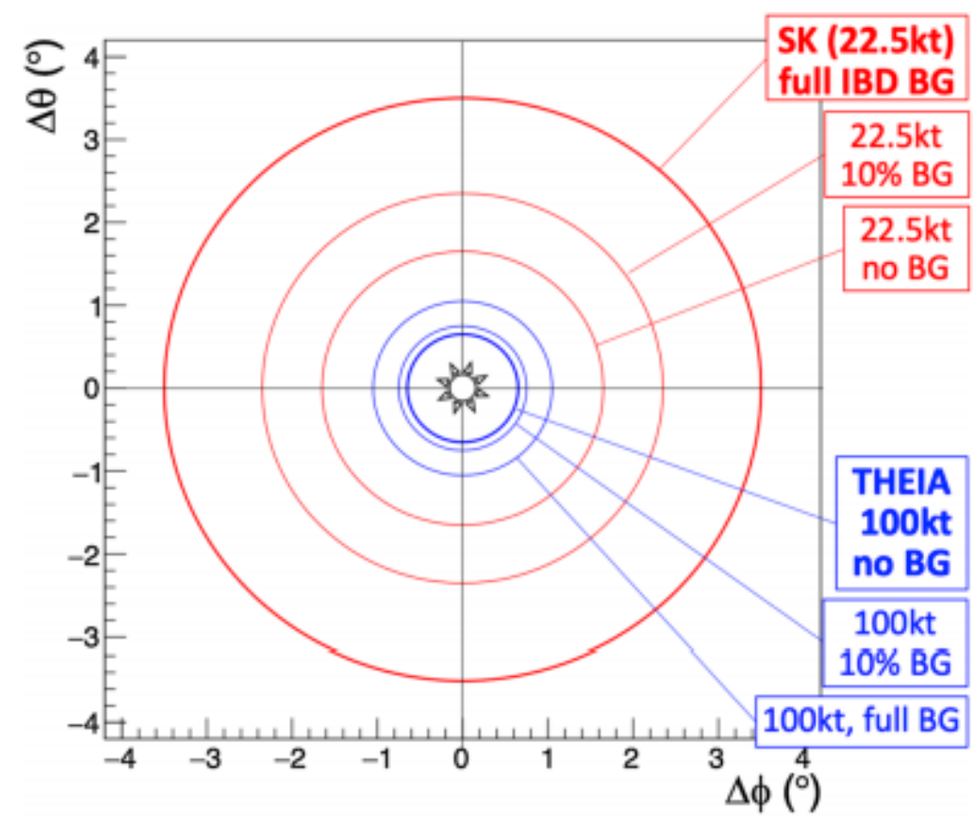
Supernova Detection

- ~90% events are IBD

  Highly complementary to ν_e LAr signal
- ES ⇒ pointing accuracy < 1°
- CC & monoE γ from NC ⇒ burst T & subsequent mixing
- Flavour-resolved neutrino spectra
- High-stats, low-threshold signal with good resolution
- Pre-supernova neutrino sensitivity

Event rate in 100-kt WbLS, SN at 10 kpc

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

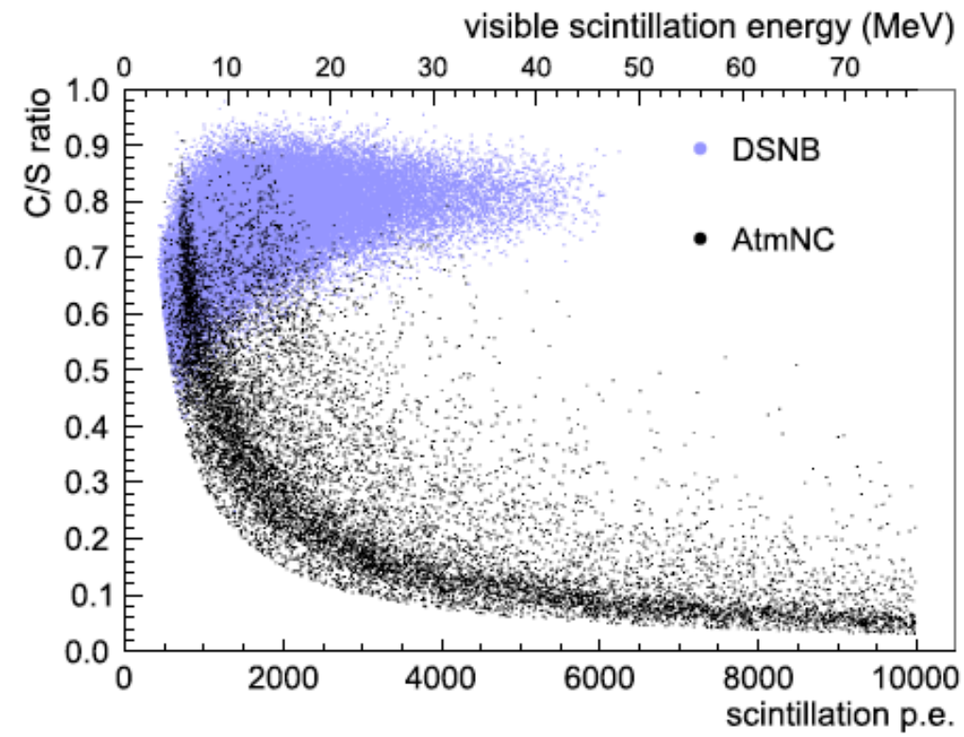


Eur. Phys. J. C 80, 416 (2020)

Anti-ν Detection

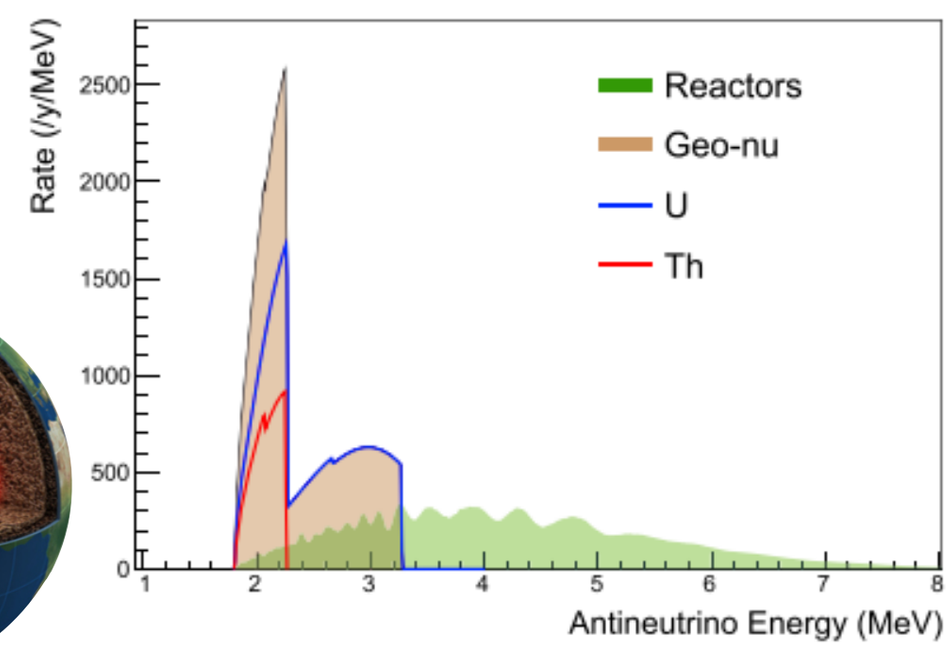
DSNB

- Diffuse ν "glow" from past core-collapse supernovae
- Cherenkov/scintillation ratio gives a powerful handle to discriminate atmospheric NC background
- 5σ in 125 kton-yrs
- Astrophysics of SNe



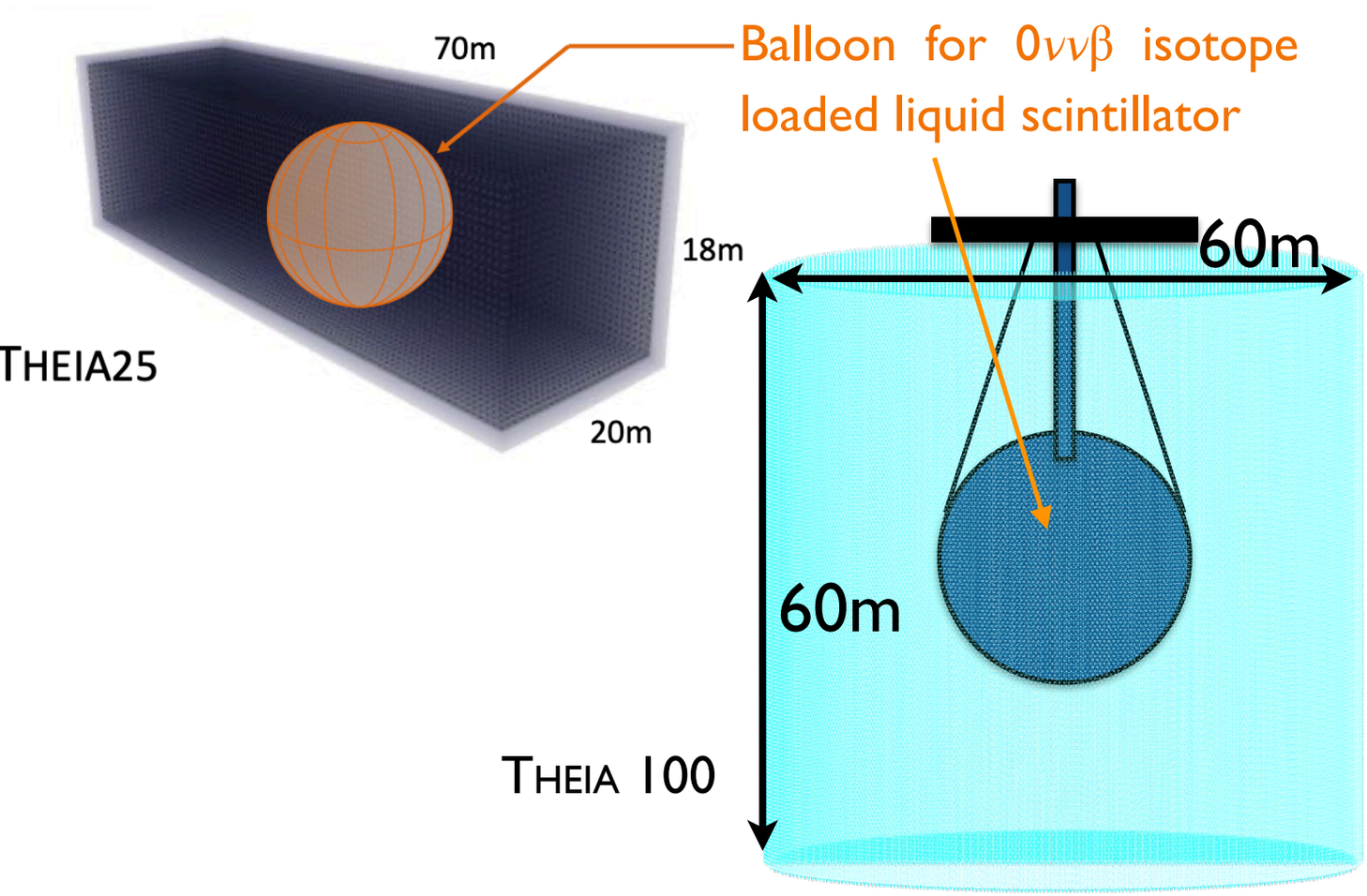
Geo- and reactor

- Current geo-ν exposure < 10kt-yr (KL + Borexino)
- **THEIA**: large statistics in a complementary geographical location: 26.5 ev/kt-yr
- Could offer first evidence for surface variation
- ~ 20 reactor ev/kt-yr
  Demonstrate techniques for remote reactor monitoring
  Range & direction at > 1000-km standoff

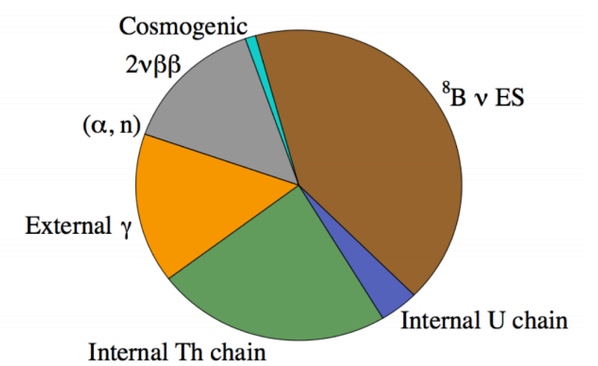


NLDBD with Theia

25-100 kton hybrid optical neutrino detector
8-m radius balloon with high-LY LS and isotope
7-m fiducial, 3% ^{nat}Te (or ^{enr}Xe), 10 years



SNO+ Collaboration



Directionality, PID and multi-site discrimination reduces backgrounds

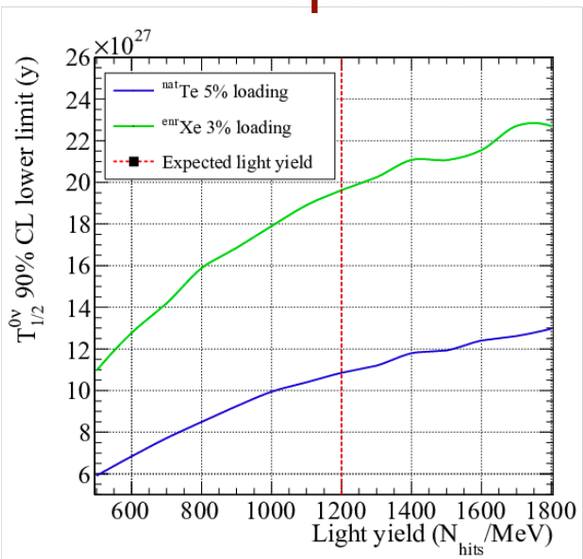
Builds on critical developments by KLZ & SNO+ collaborations

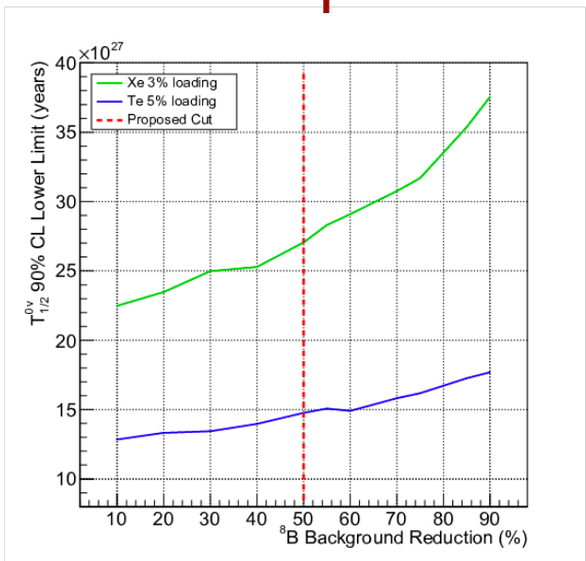
Phys.Rev.Lett.110 : 062502 (2013); Adv.High Energy Phys. 2016 (2016) 6194250; Phys. Rev. D 87 no. 7 : 071301 (2013)

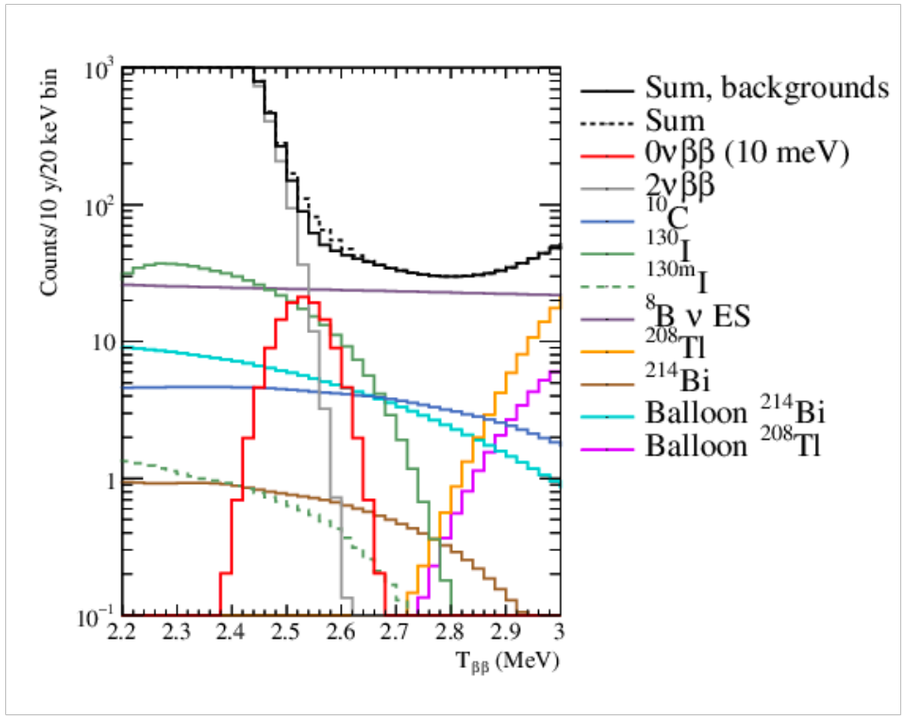
Eur. Phys. J. C 80, 416 (2020)

NLDBD with Theia

Dependence on detector response

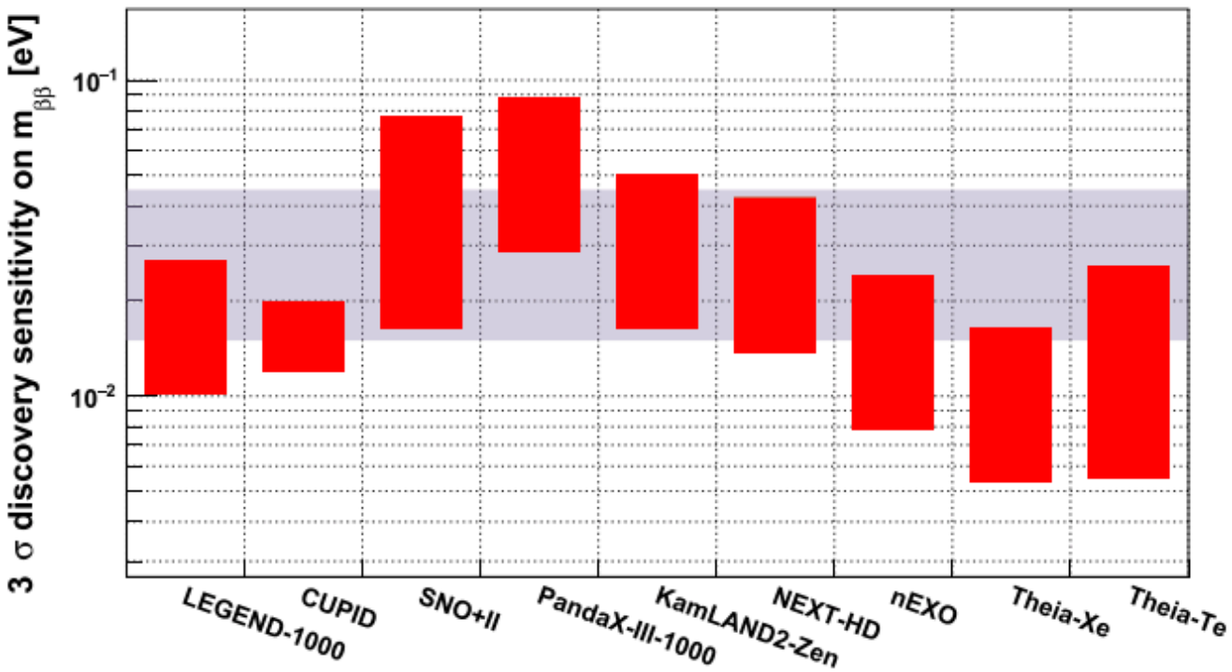






$T_{1/2}$ > 1.1 (2.0) x 10^{28} yrs
90% CL for Te (Xe)

$m_{\beta\beta}$ < 6.3 (5.6) meV



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

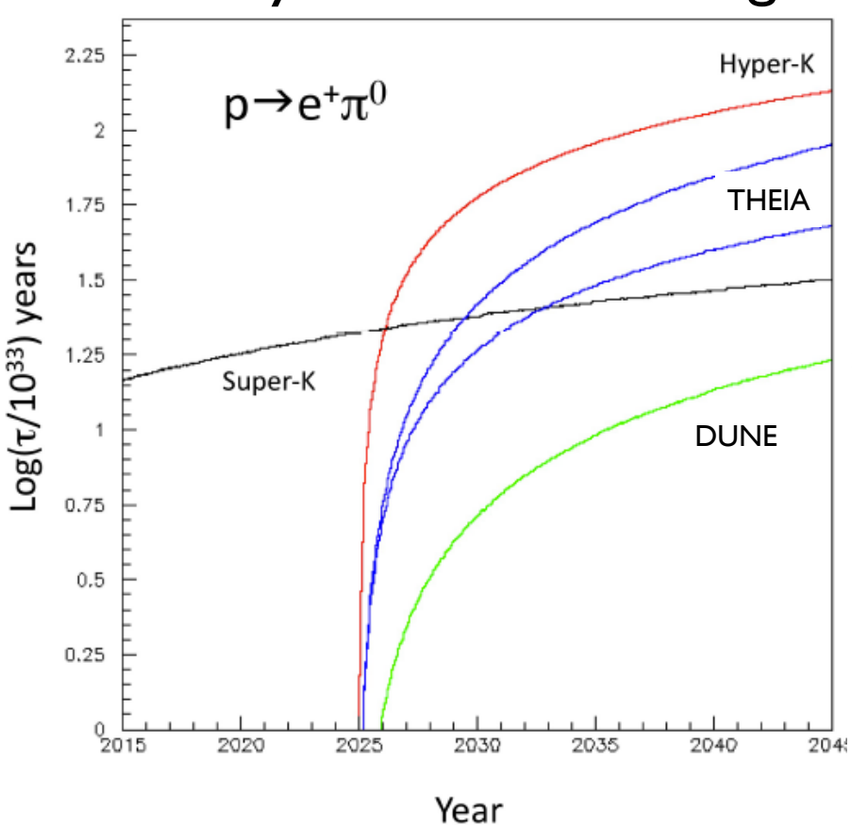
Nucleon Decay

Testing the existence of GUTs with THEIA:

- Large size (statistics), deep location, very clean
- n tagging (low threshold plus potential isotope loading)
- Sub-Cherenkov threshold detection

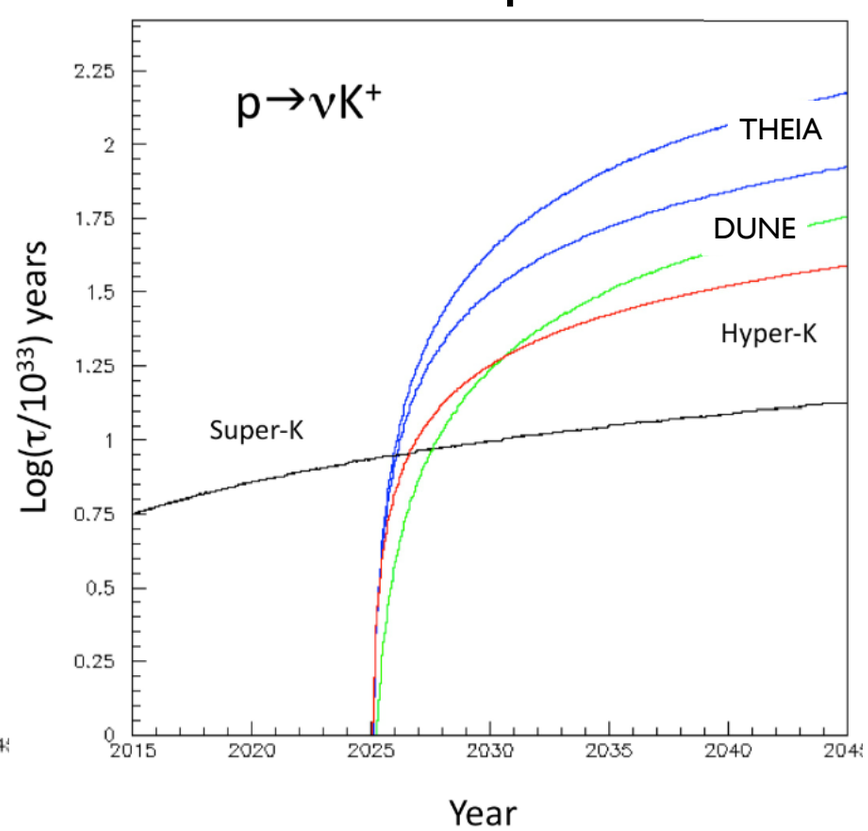
Figs from arXiv:1409.5864, assume 100t FV; studies based on Phys. Rev. D 72 , 075014 (2005); LAr from JHEP 0704:041,2007

Heavy X boson exchange



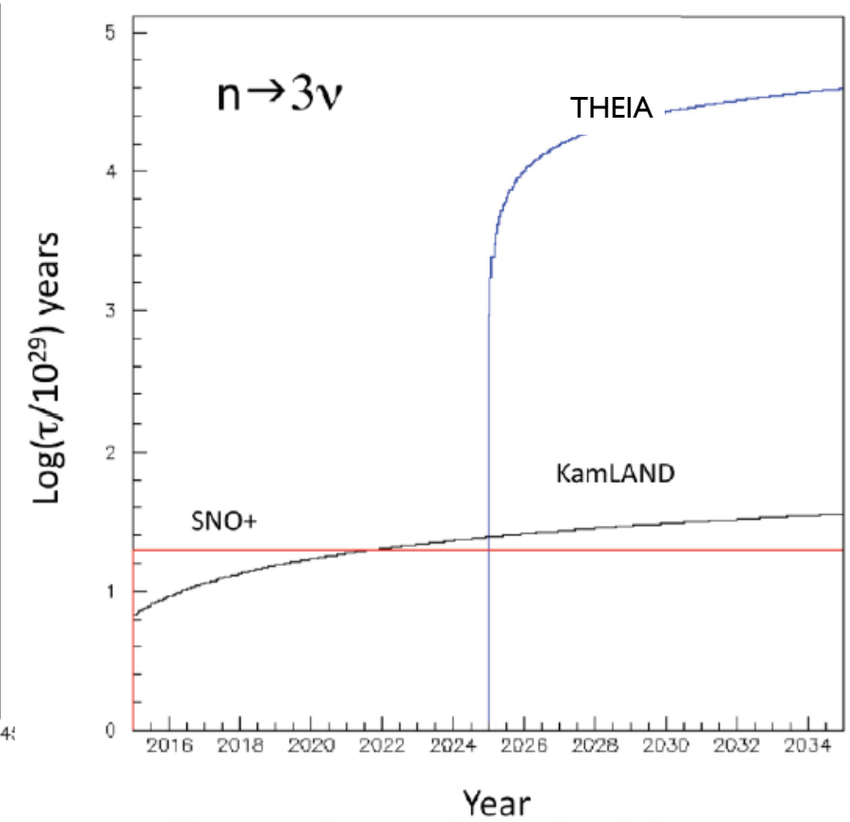
Enhanced n tag
Reduced atmos. ν bkg

2nd order processes



Sub-Chr t/h detection
⇒ Directly visible K^+

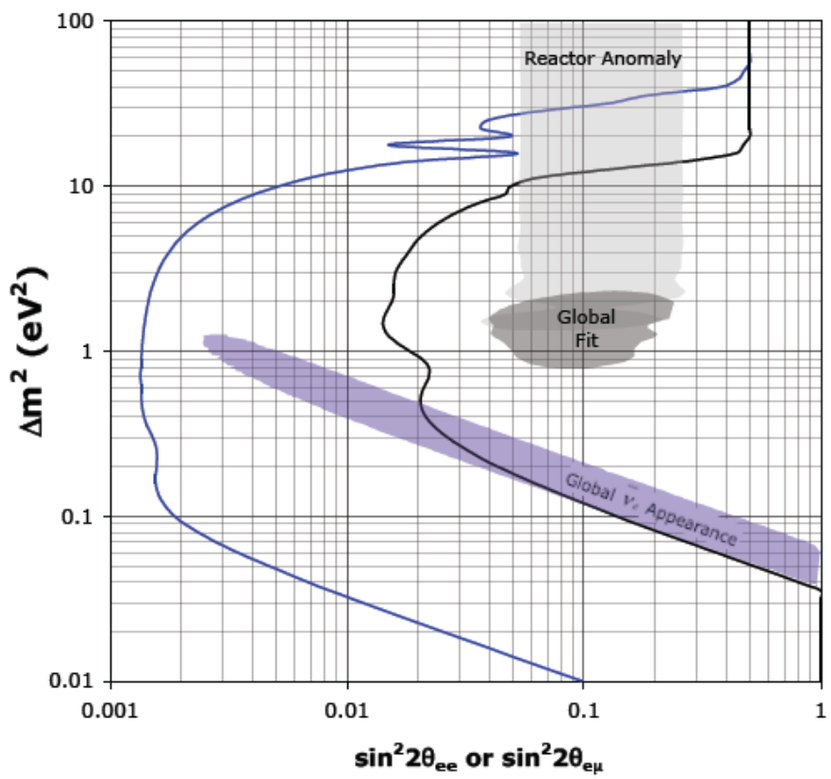
Extra dimensions



Deep, low threshold
Directionality + n tag

Sterile Neutrinos

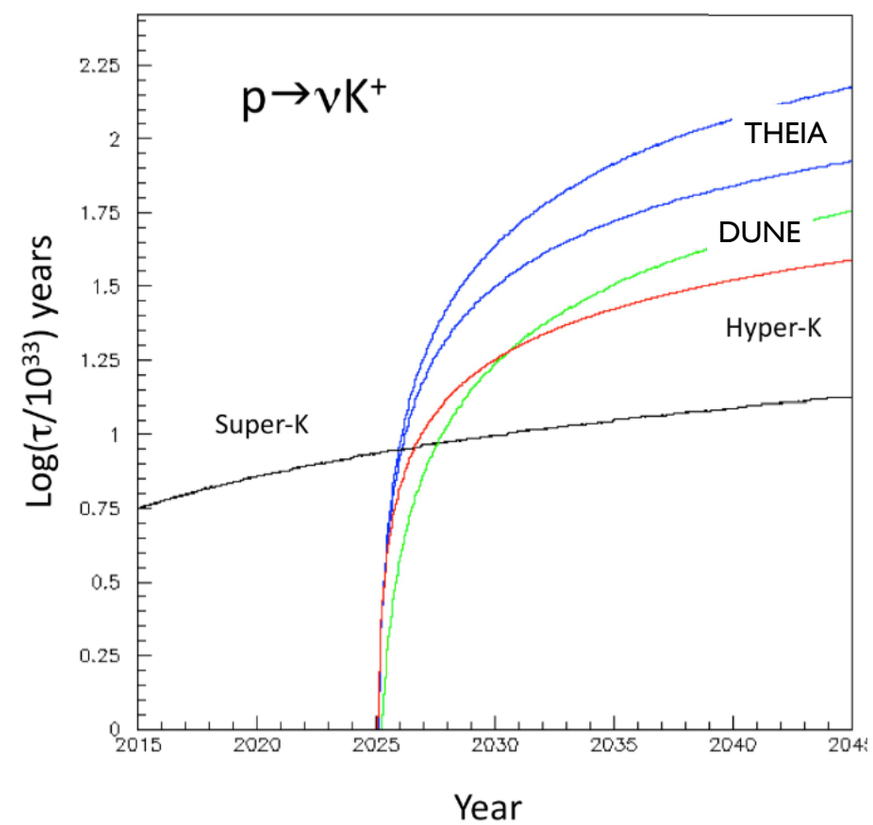
- Deploy ^{8}Li decay-at-rest (IsoDAR)
  - 13MeV endpoint (above r/a)
  - Required detector response: 15% (E) & 50cm (R)
  - 5 yrs, 1kt (black) / 20kT fid. (blue)



- Heavy-water based LS: 2n tag (reduce bkg in IBD searches)

Nucleon Decay

- Large, deep, very clean
- Enhanced n tag
- Sub-Cherenkov threshold detection
- Sensitive to several modes



Sub-Chr t/h detection
⇒ Directly visible K^+

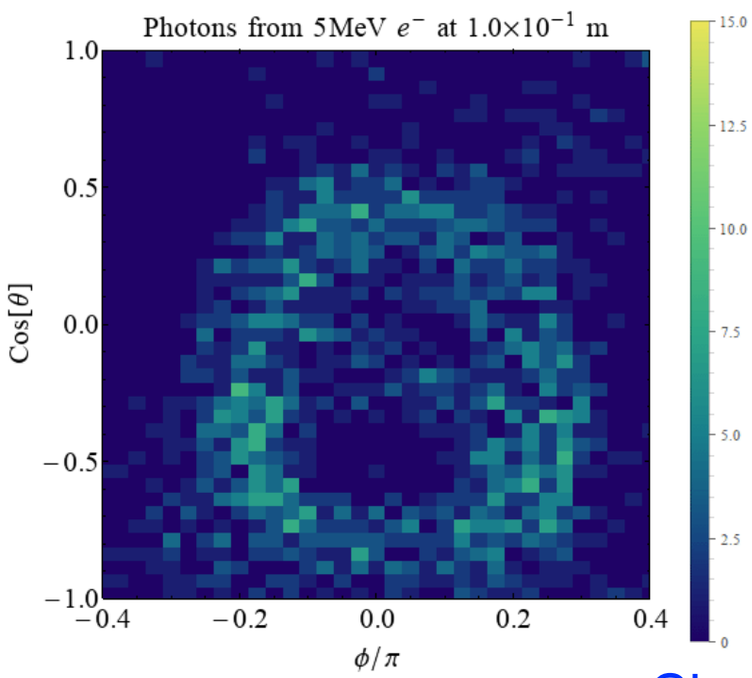
Figs from arXiv:1409.5864

Photon propagation

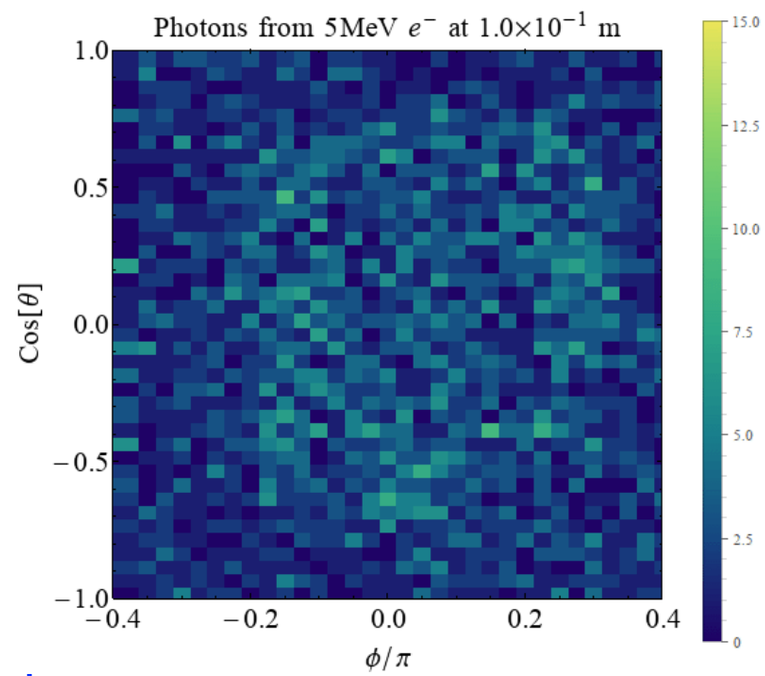
Figs from Ben Land

5-MeV electron, 7-m (radius/half-height) detector

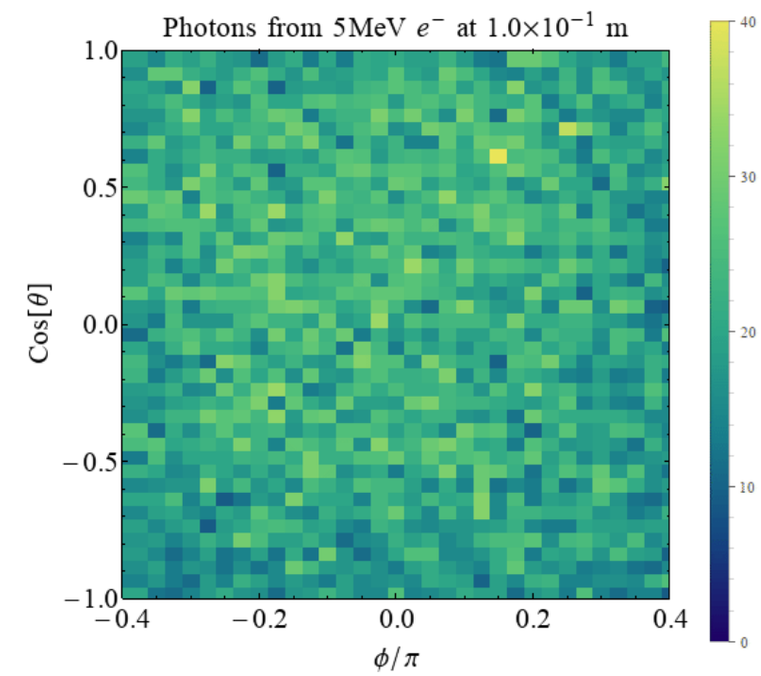
Water



WbLS



LS



Cherenkov
Scintillation
Reemission