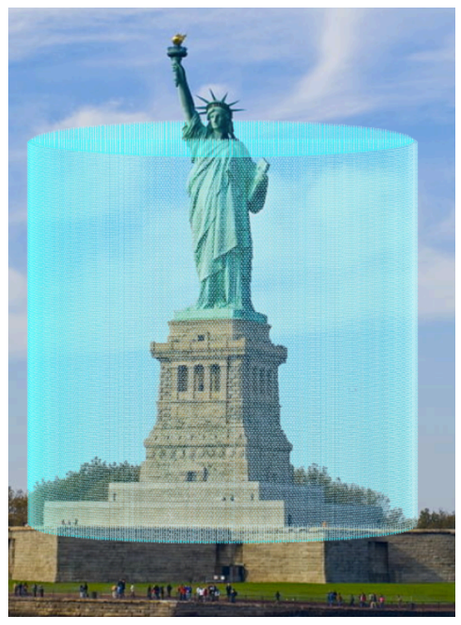
EOS: Performance demonstrator for THEIA, & next-generation reactor monitoring solutions

G. D. Orebi Gann [LBNL, UC Berkeley]

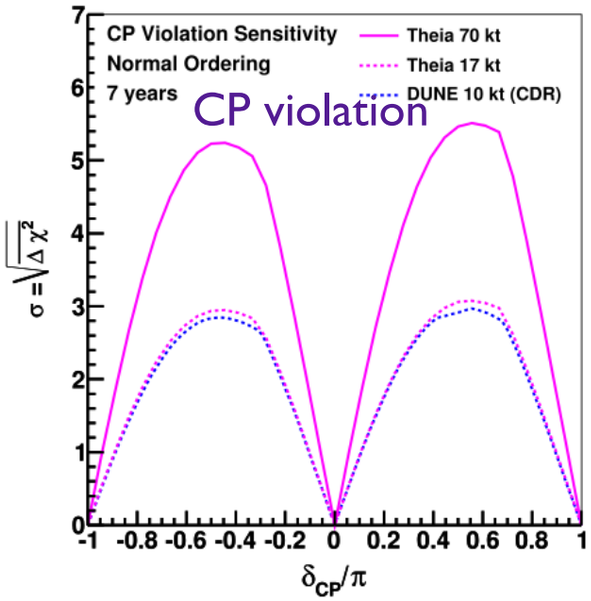
On behalf of the EOS project team

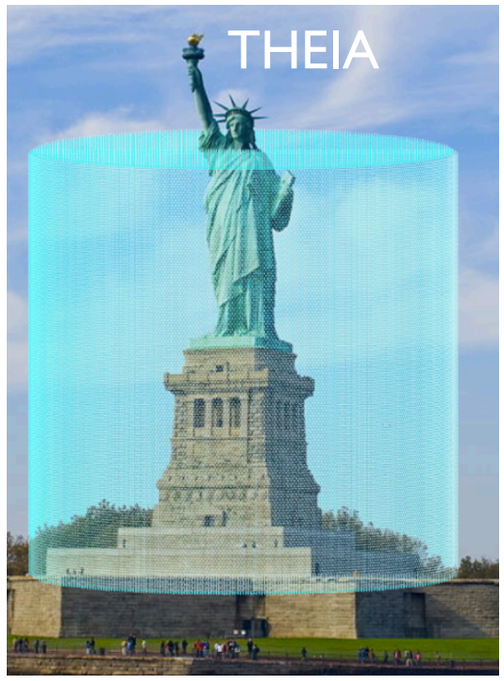


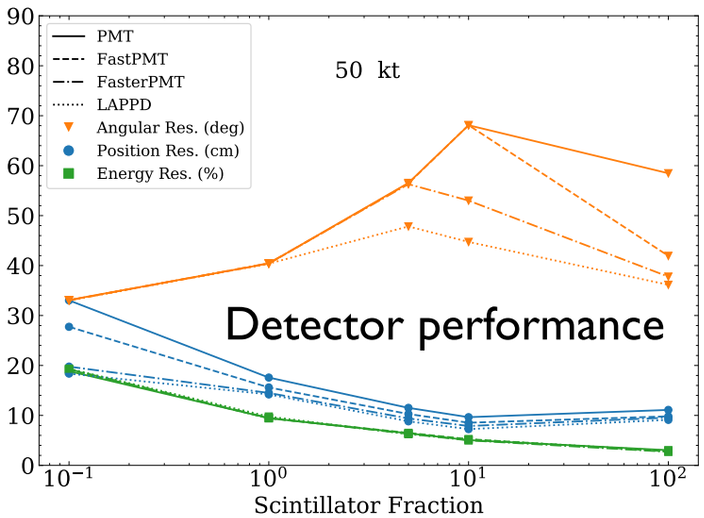
Hybrid neutrino detection

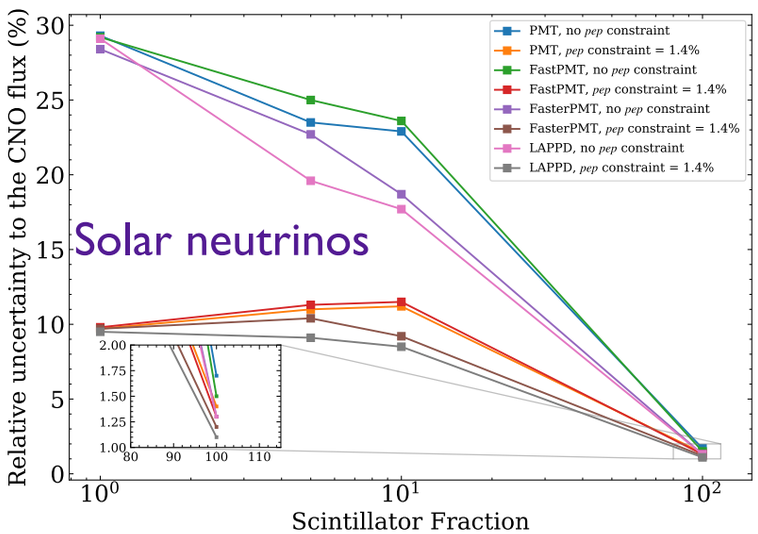
Combined Cherenkov + scintillation light event detection

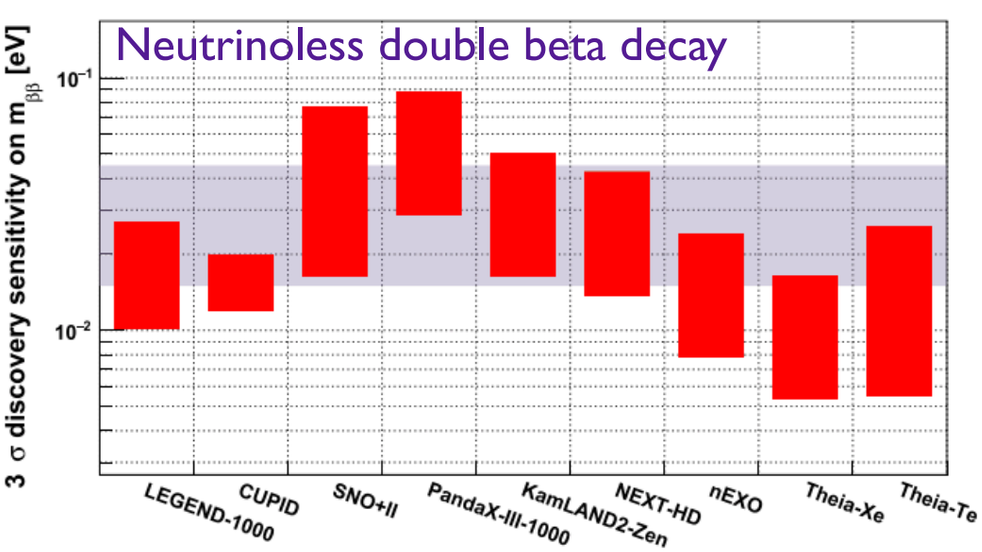
- Higher light yield —> low threshold + improved vertex, energy resolution
- Direction resolution & ring imaging from Cherenkov component
- Particle ID (full waveform analysis)
- Better signal efficiency
- Improved background discrimination
- Enhanced sensitivity for fundamental physics











Hybrid detectors at Snowmass

Neutrino Frontier report *(also BSM, terrestrial & astrophysical sections)*

- *NF: Detectors: one of 5 priorities for development*

  - **Pursuit of hybrid Cherenkov/scintillation Detectors:** Many different technologies are being developed for these, including water-based liquid scintillator, slow fluors, fast timing with LAPPDs and other devices, and spectral photon sorting with dichroicons. At very large scales like the proposed Theia detector, these could have very broad physics programs.

- *NF: Long-term outlook*

  ordering region. These next-generation LAr detector ideas go by different names, such as "SLoMo", "SoLAr", and "LArXe." Another idea is the proposed Theia detector, which is a hybrid Cherenkov/scintillation detector that could do precision measurements of very low-energy solar neutrinos, diffuse supernova neutrino detection, perform searches for sterile neutrinos, and also push well beyond DUNE in precision tests of the three-flavor mixing model (including, for example, studies of the second oscillation maximum). On the low-threshold side, much will depend on what the

Hybrid detectors at Snowmass

Neutrino Frontier report *(also BSM, terrestrial & astrophysical sections)*

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Instrumentation Frontier report *(also photon detectors & spectral sorting)*

- *IF: Going beyond DUNE*

> Of particular community interest is the development of hybrid Cherenkov-scintillation detectors, which can simultaneously exploit the advantages of Cherenkov light's reconstruction of direction and related high-energy particle identification (PID) and the advantages of scintillation light, high light-yield, low-threshold detection with low-energy PID. Hybrid Cherenkov-scintillation detectors could have an exceptionally broad dynamic range in a single experiment, allowing them to have both high-energy, accelerator-based sensitivity while also achieving a broad low-energy neutrino physics and astrophysics program. Recently the Borexino

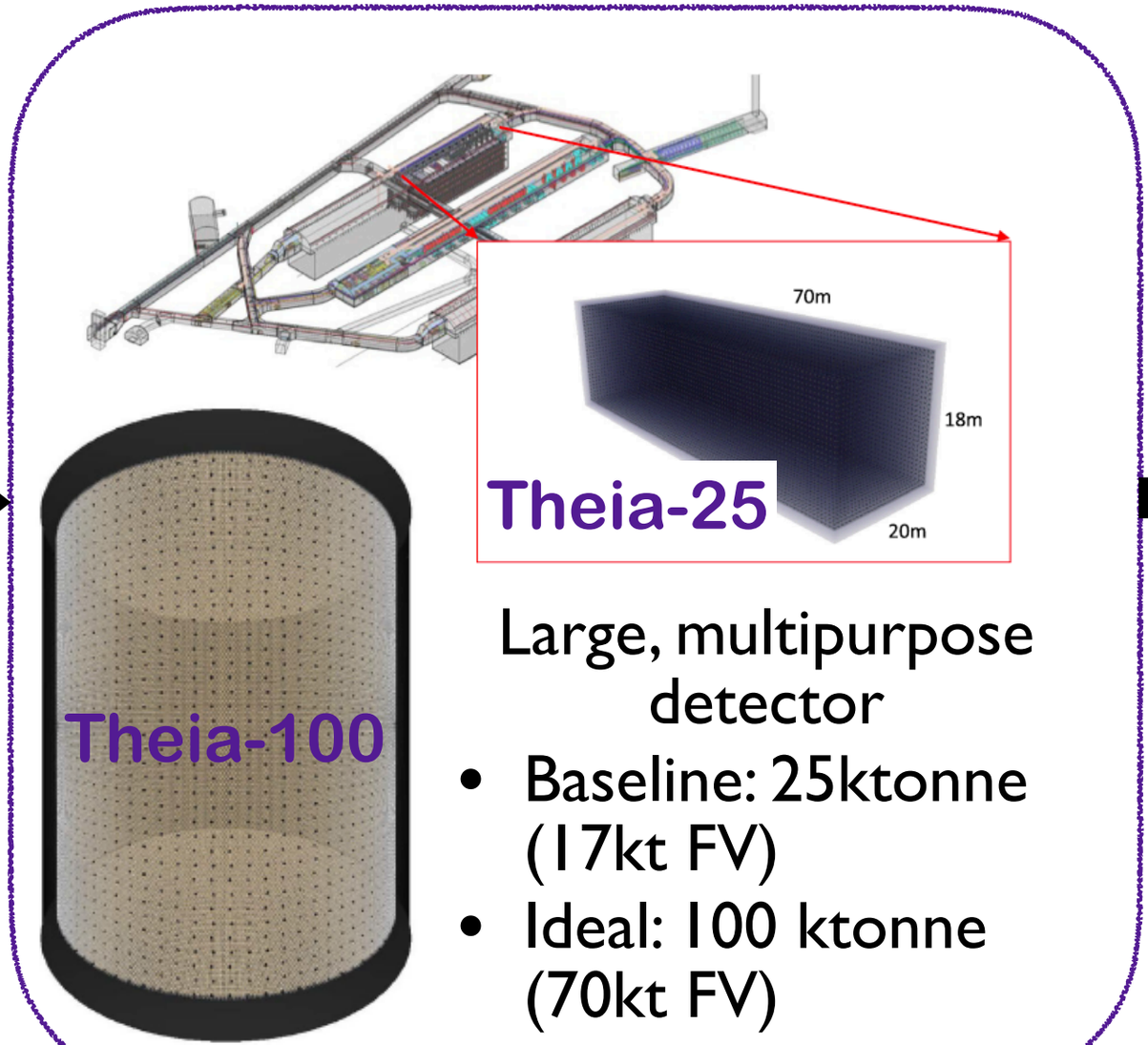
THEIA as a DUNE module in Phase II

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)

(Phased) Physics program

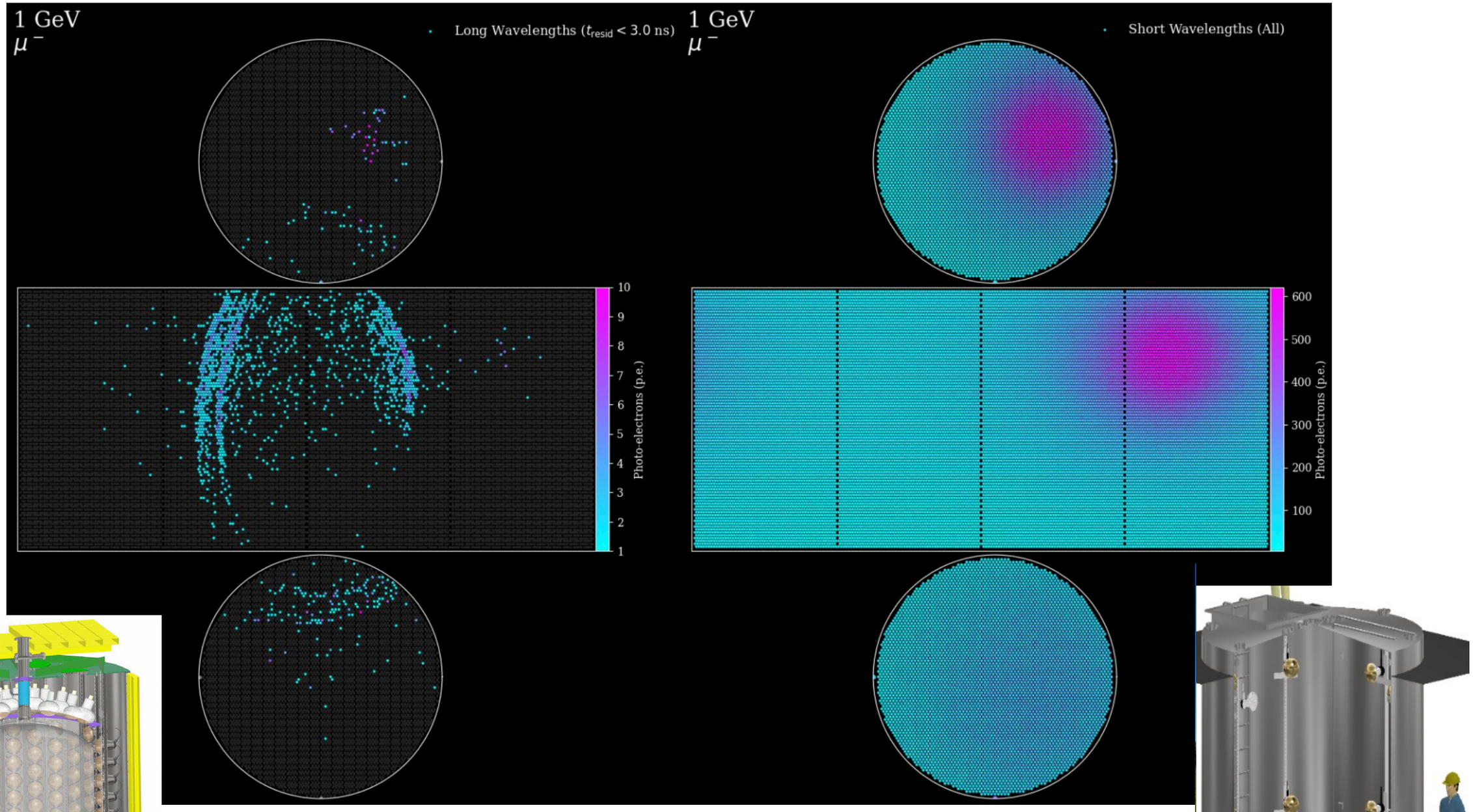
Primary physics goal	Reach	Exposure/assumptions
Long-baseline oscillations	>5σ for 30% of δ_{CP}	524kt-MW-year
Nucleon decay $p \to \bar{\nu} K^+$	T>3.8 x 10^{34} year	800 kt-year
Supernova burst	<1(2)° pointing 20K(5K) events	100(25)kt, 10kpc SN
Diffuse Supernova Neutrino	5σ	125kt-year
CNO neutrinos	<5(10)%	300(62.5)kt-year
Geoneutrinos	< 7 %	25 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)

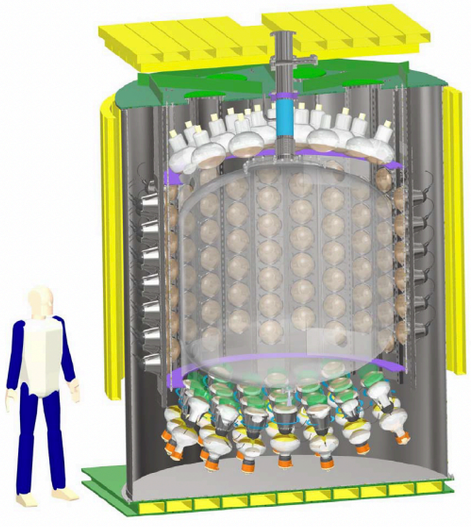
I

II

III

2-in-1





Eos: 4-ton technology demonstrator

BNL 30-ton deployment demonstrator



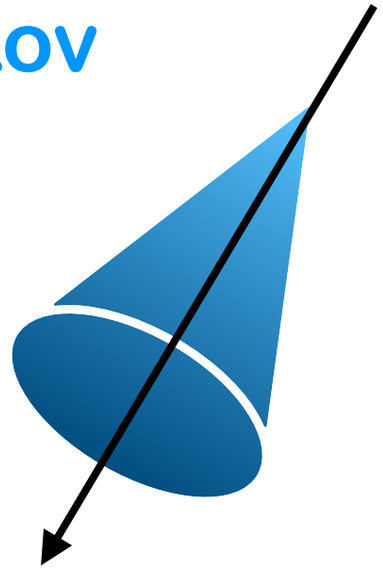
Theia

Let
There be
Light

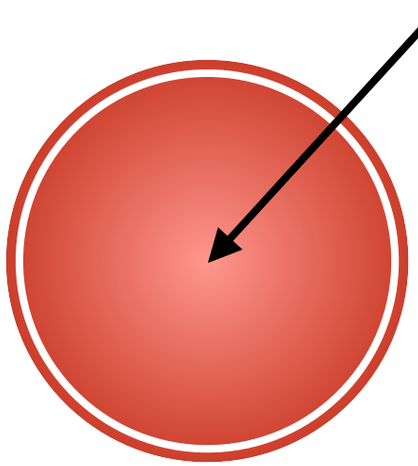
MyGodPictures.com

How can it be done?

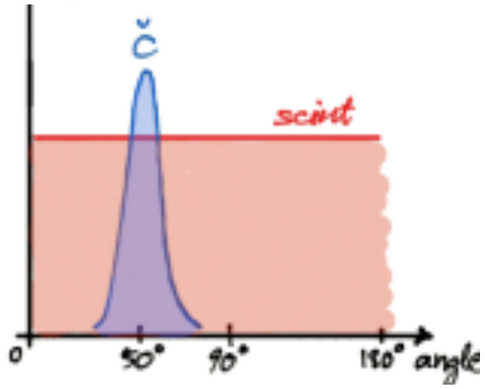
Cherenkov



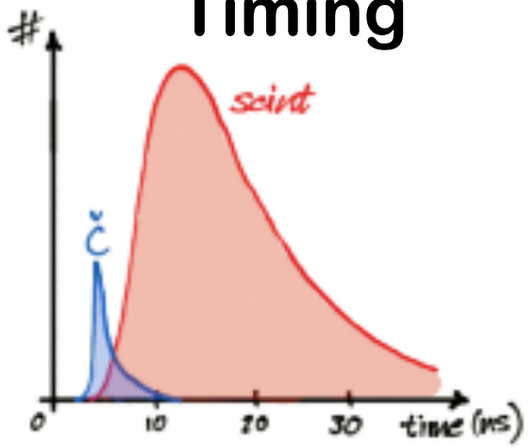
Scintillation



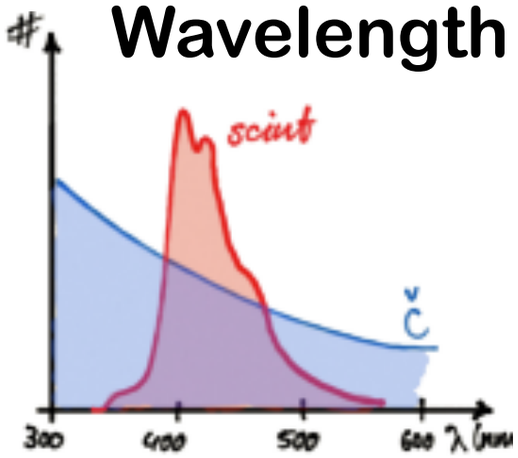
Angular distribution

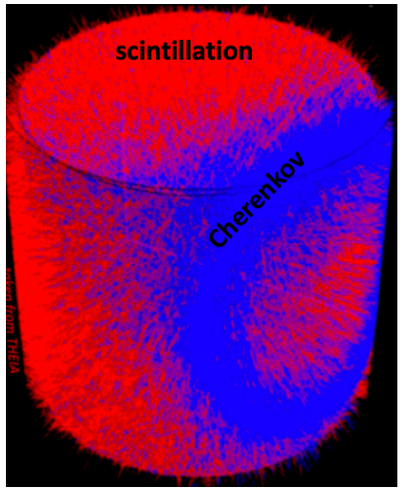


Timing

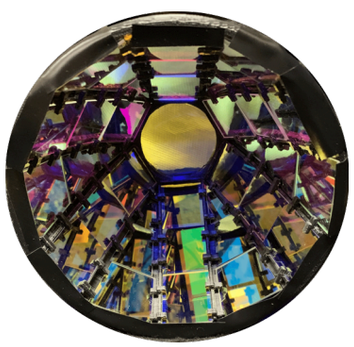


Wavelength





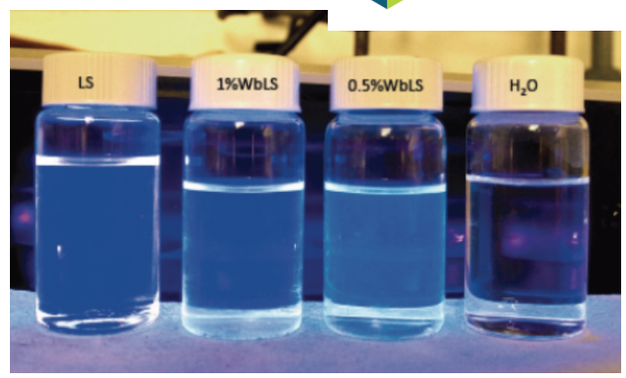
B.W.Adams et al. NIM A Volume 795, 1 (2015)



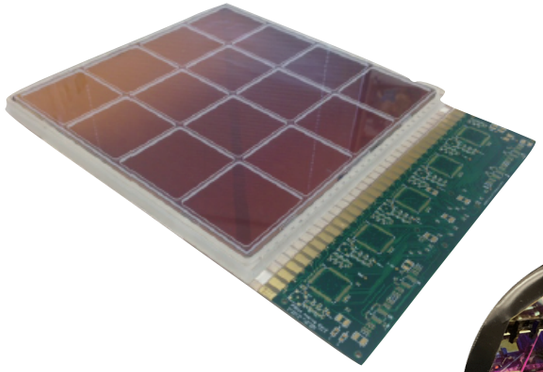
T. Kaptanoglu et al.
Phys. Rev. D 101, 072002 (2020)

Enabling technology

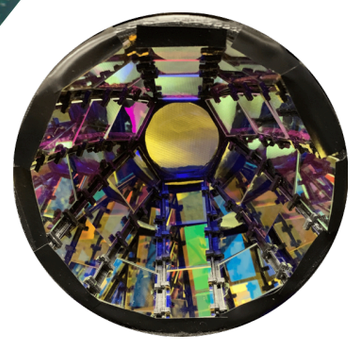
We focus our studies on three technologies that optimize hybrid Cherenkov/scintillation detection:



1. Novel targets, such as water-based liquid scintillator (WbLS) or slow scintillator. Enhances Cherenkov detection by modifying the scintillation signal



2. Fast photon detectors such as Large-Area Picosecond Photon Detectors (LAPPDs). Fast-timing discrimination for vertex resolution and Cherenkov/scintillation separation



3. Dichroicons ("chromatic quantum sensing"). Cherenkov/scintillation separation via spectral sorting

We seek to characterize behavior, understand and model performance at a microphysical level, and use results to extrapolate performance to kton scales.

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

Technical accomplishments

NIMA 889 69 (2018); JINST 14 T05001 (2019); Phys. Rev. D 105 (7) 2022; 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

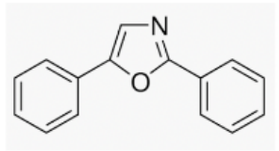
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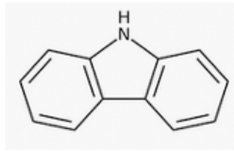
Technical accomplishments

Engineering WbLS properties: Bourret (LBNL)

Example:
slowing down decay time

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





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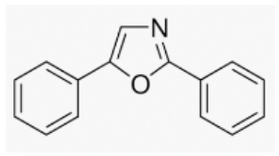
Builds on core (Wb)LS development at BNL (Yeh et al.)

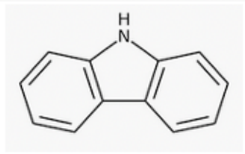
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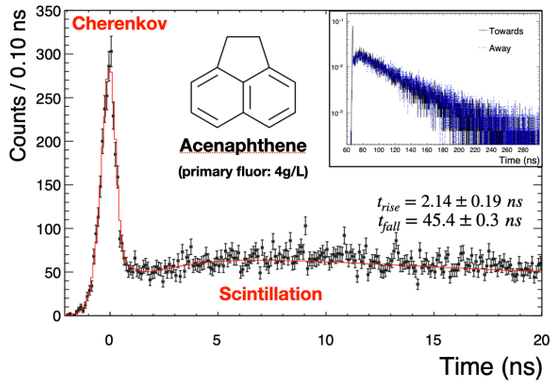
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Slow LS: Oxford, Mainz



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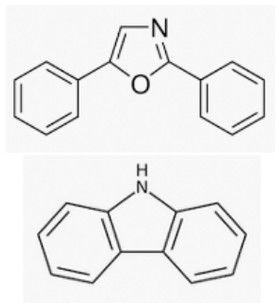
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Technical accomplishments

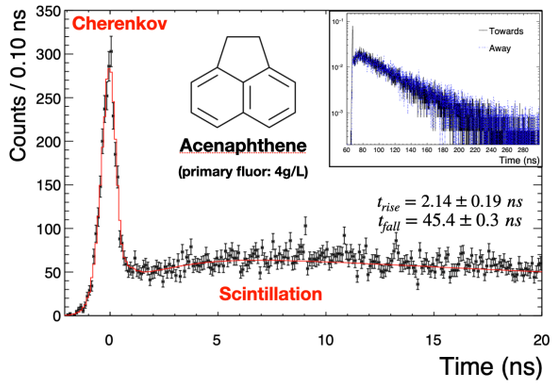
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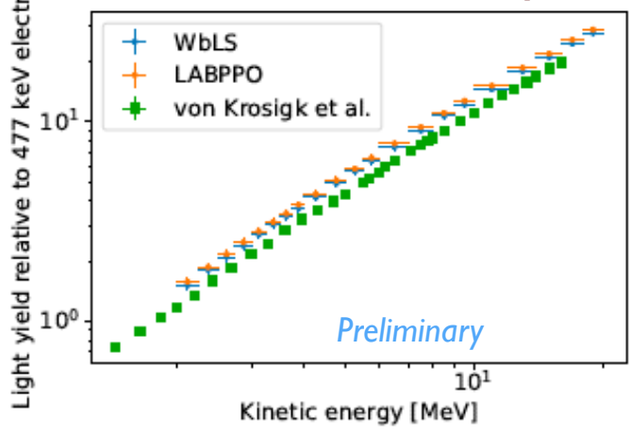
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Slow LS: Oxford, Mainz



Proton LY: Goldblum (LBNL)



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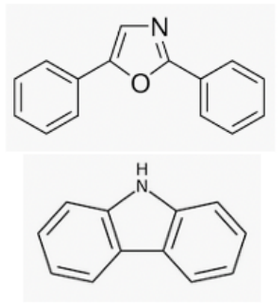
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Technical accomplishments

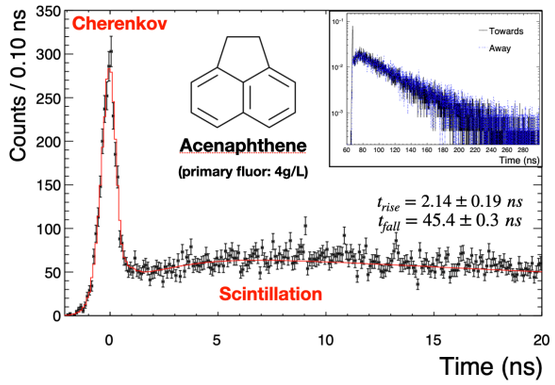
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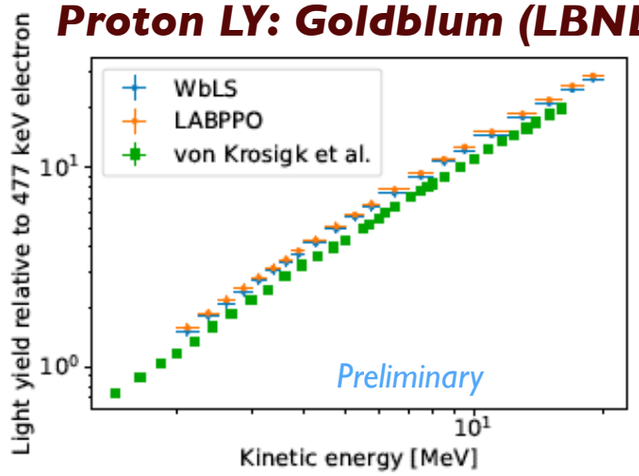
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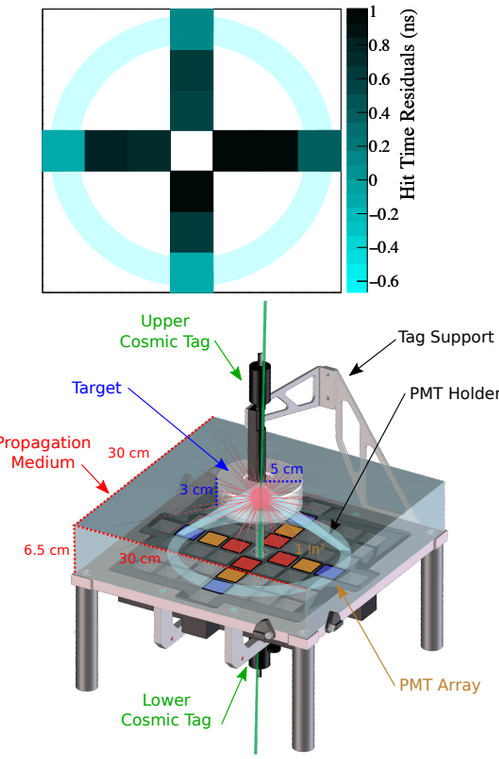
Slow LS: Oxford, Mainz



Proton LY: Goldblum (LBNL)



CHESS detector: LBNL



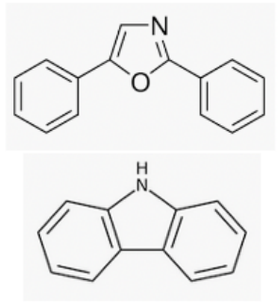
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Builds on core (Wb)LS development at BNL (Yeh et al.)

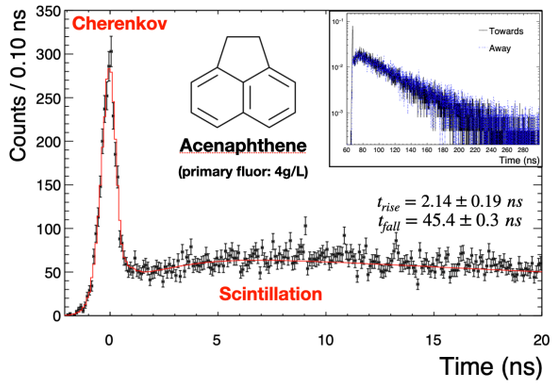
Technical accomplishments

Engineering WbLS properties: Bourret (LBNL)

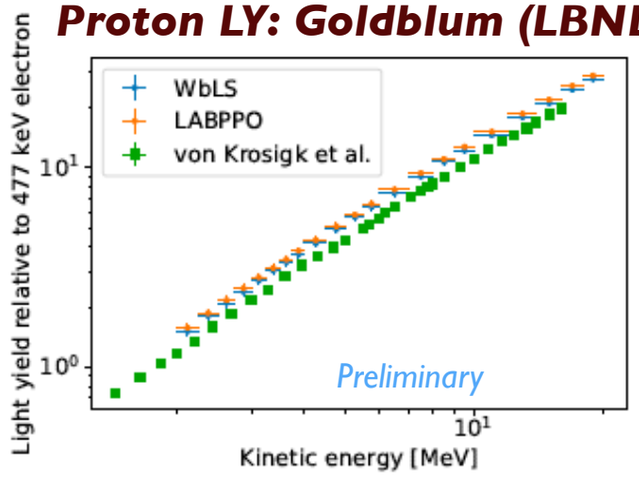
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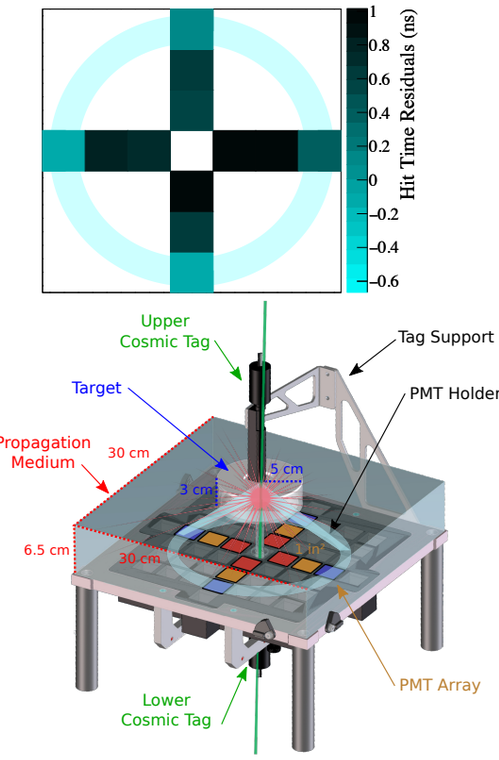
Slow LS: Oxford, Mainz



Proton LY: Goldblum (LBNL)



CHESS detector: LBNL



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

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

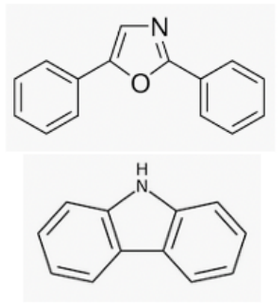
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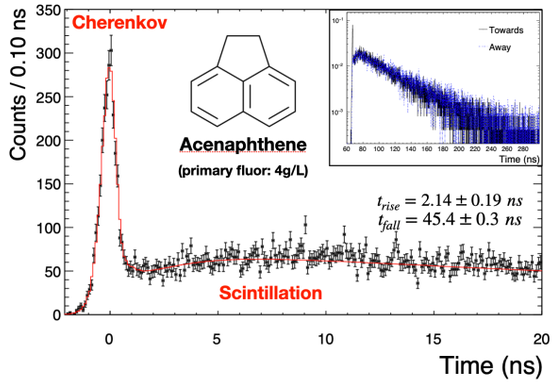
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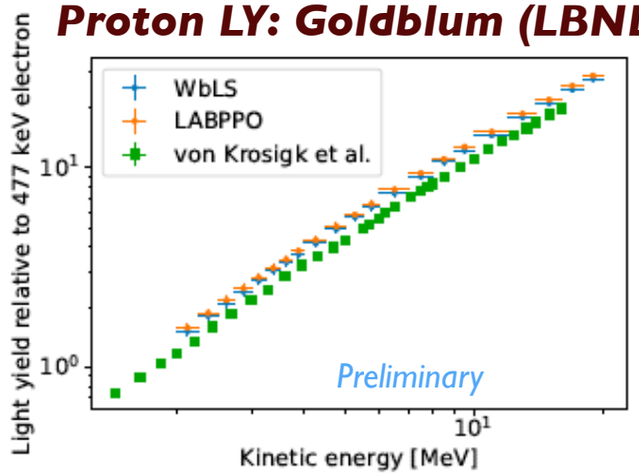
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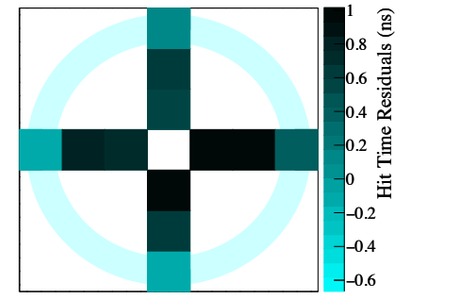
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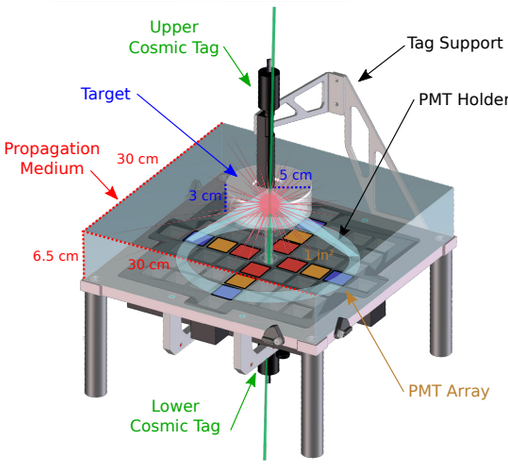


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CHESS detector: LBNL

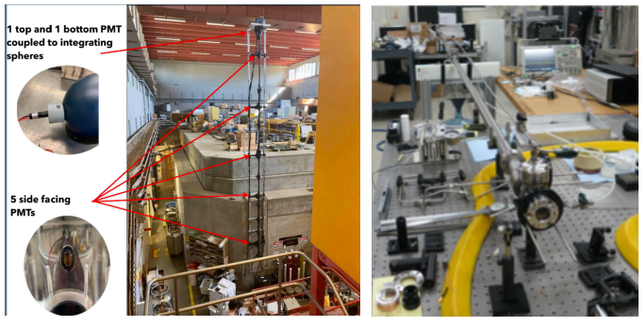




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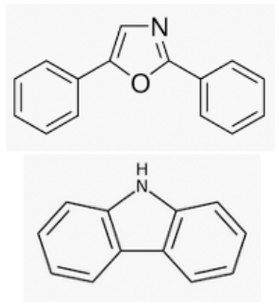
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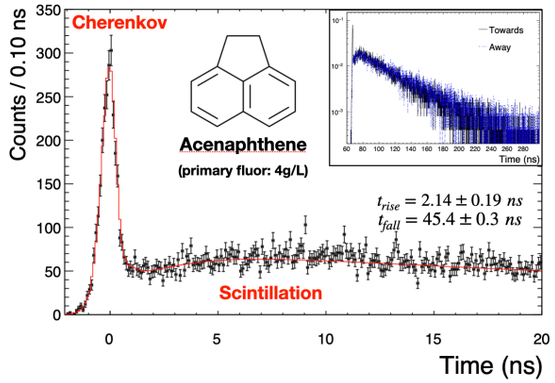
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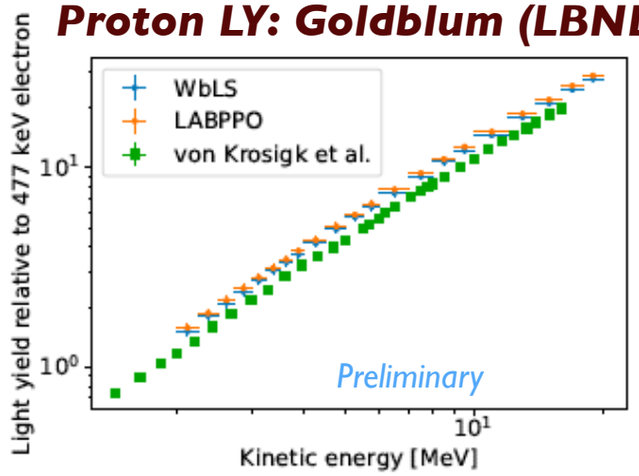
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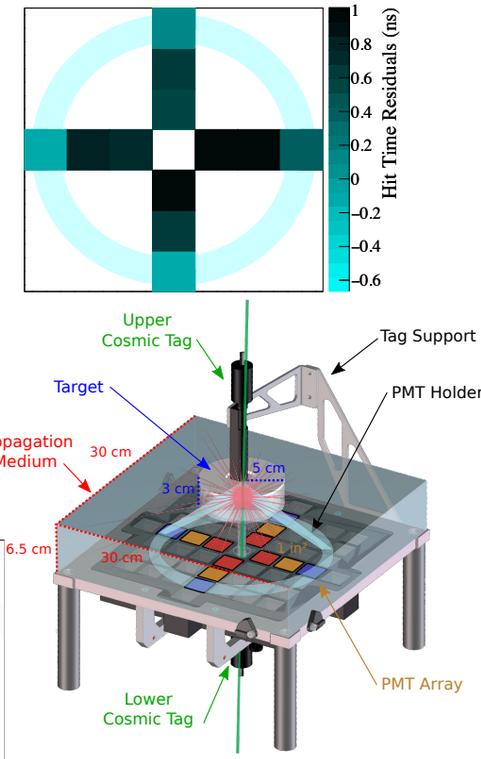
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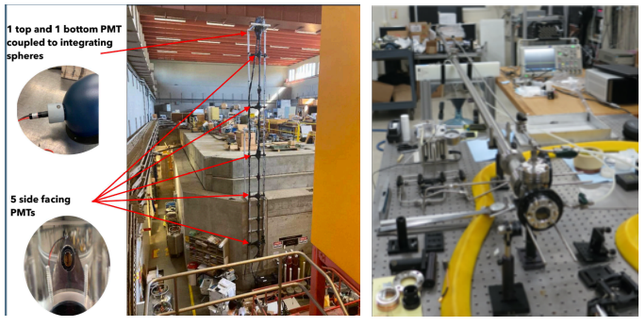
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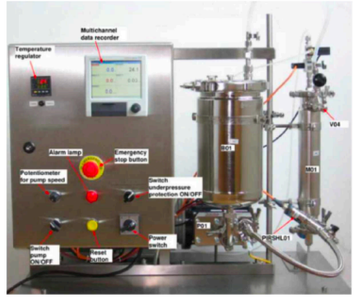
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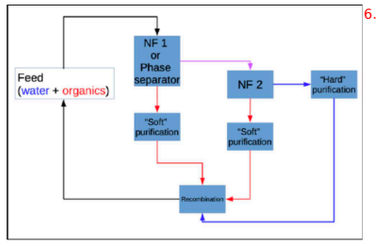
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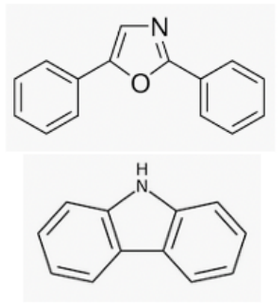
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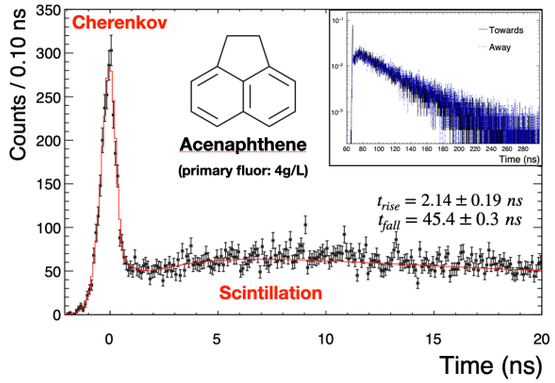
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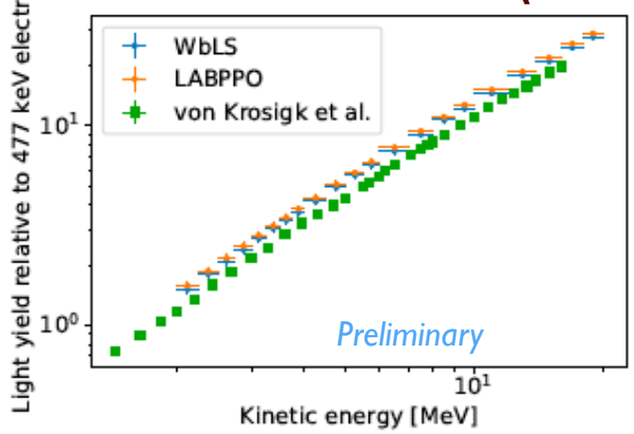
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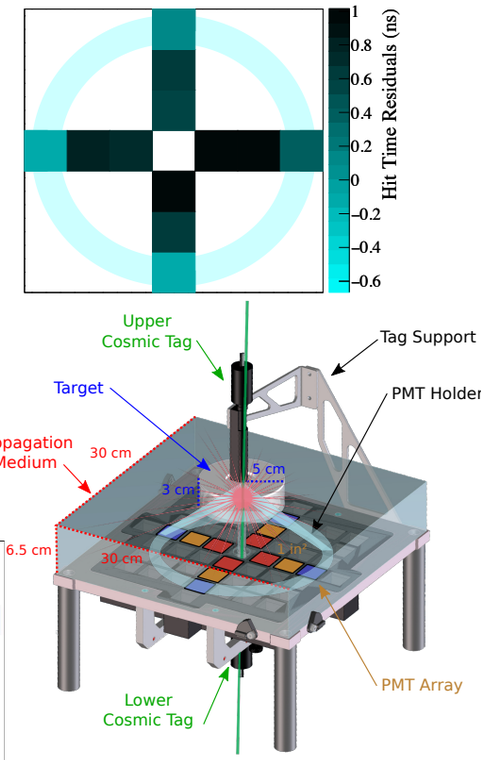
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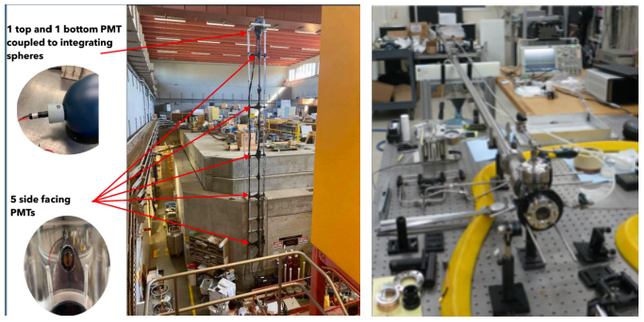
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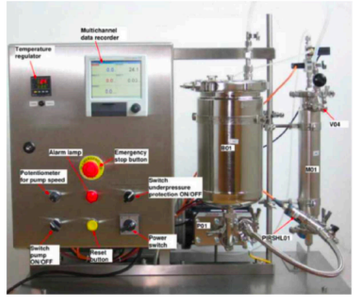
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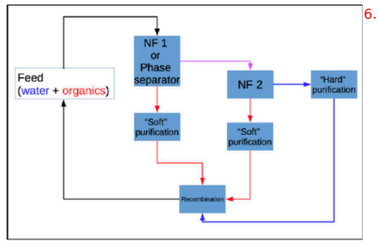
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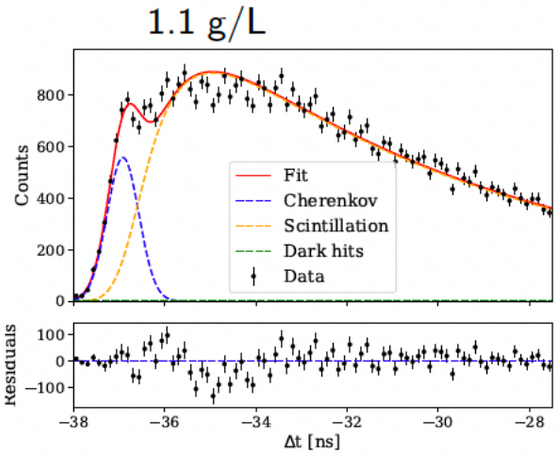
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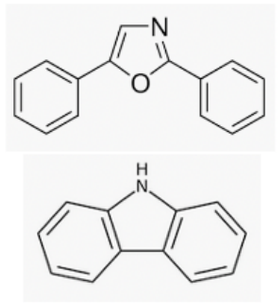
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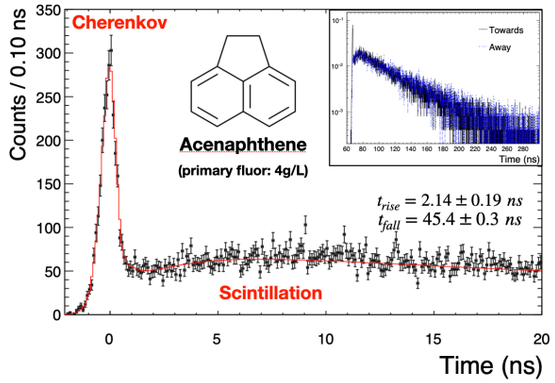
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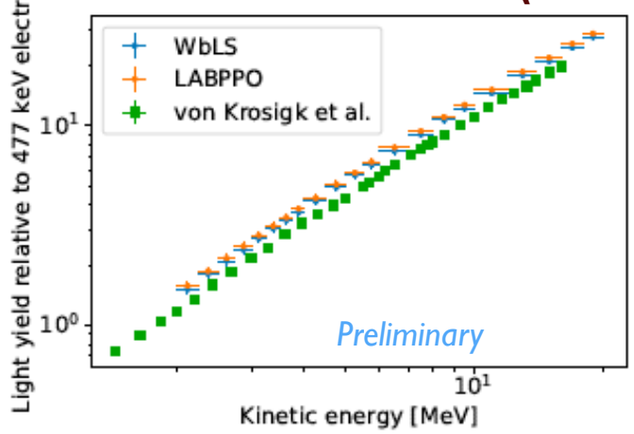
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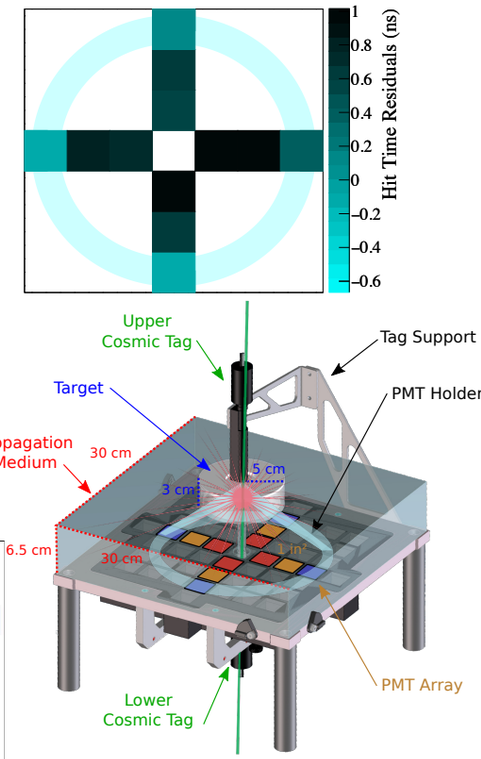
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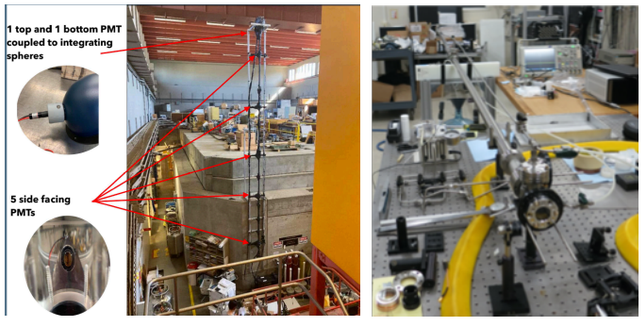
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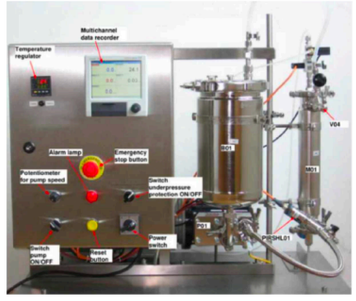
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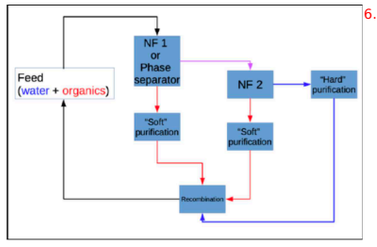
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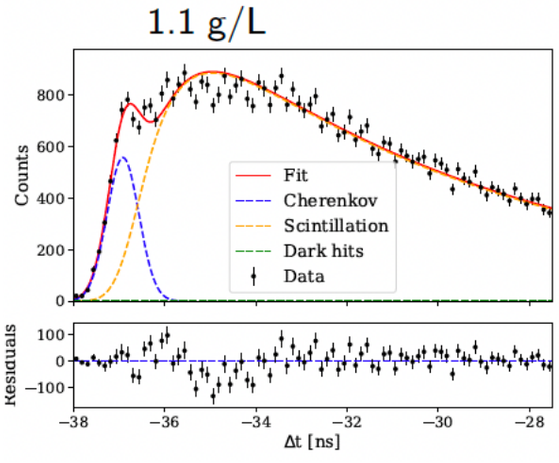
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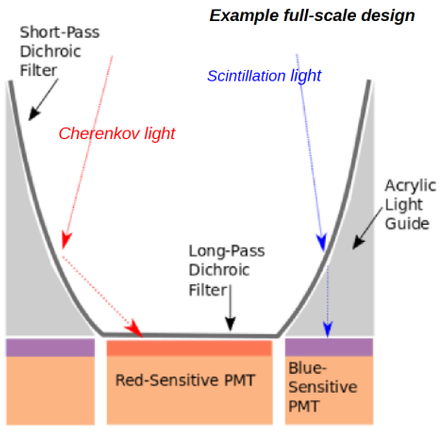


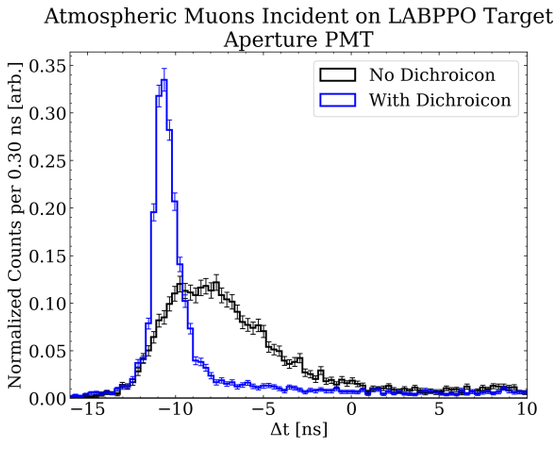
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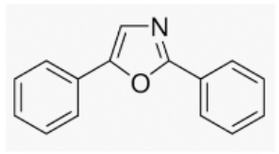
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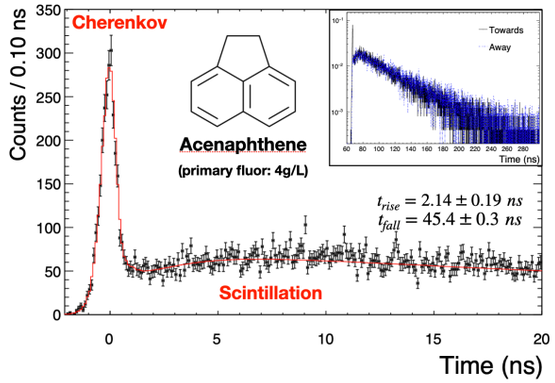
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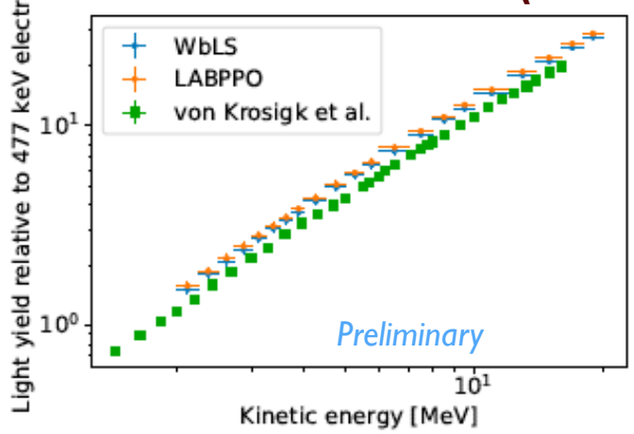
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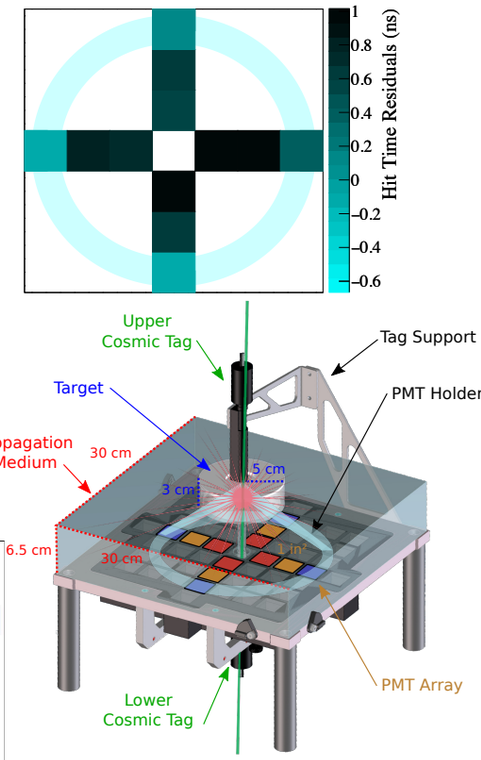
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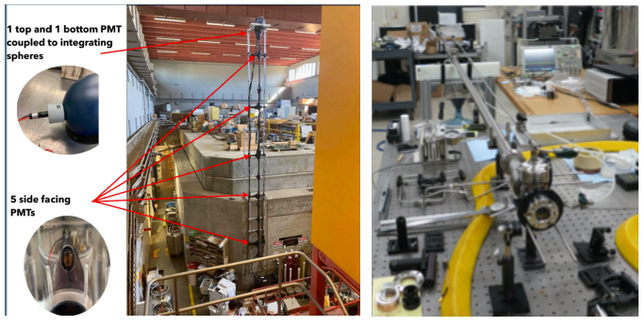
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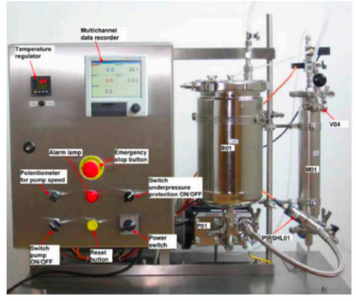
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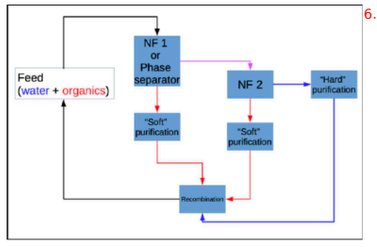
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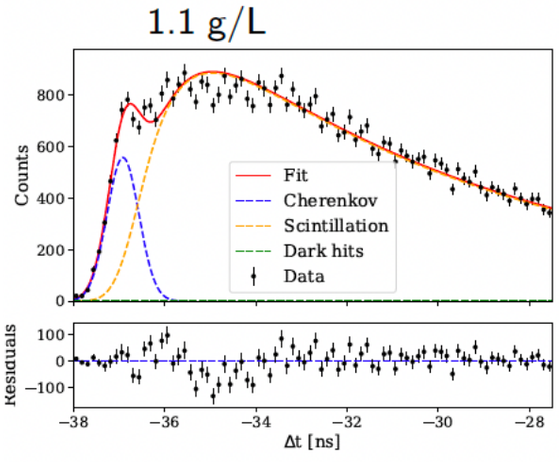
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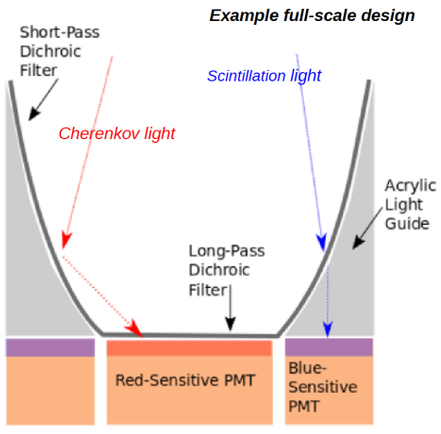


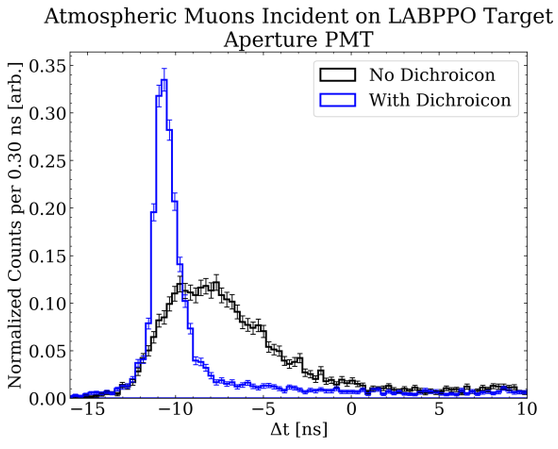
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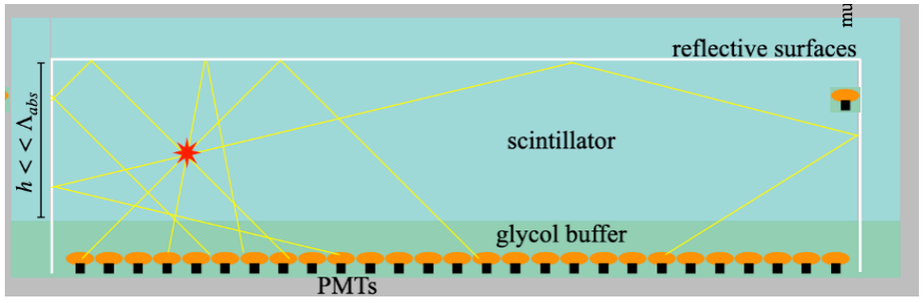
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SLIPS concept: Oxford, UK



Demonstrators

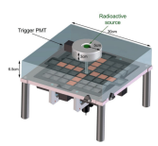
Data-driven demonstration

- ✓ *Demonstrate Cher+scint reconstruction*
- ✓ *Demonstrate Cher+scint particle ID*
- ✓ Enable broad, world-leading physics & nonproliferation program

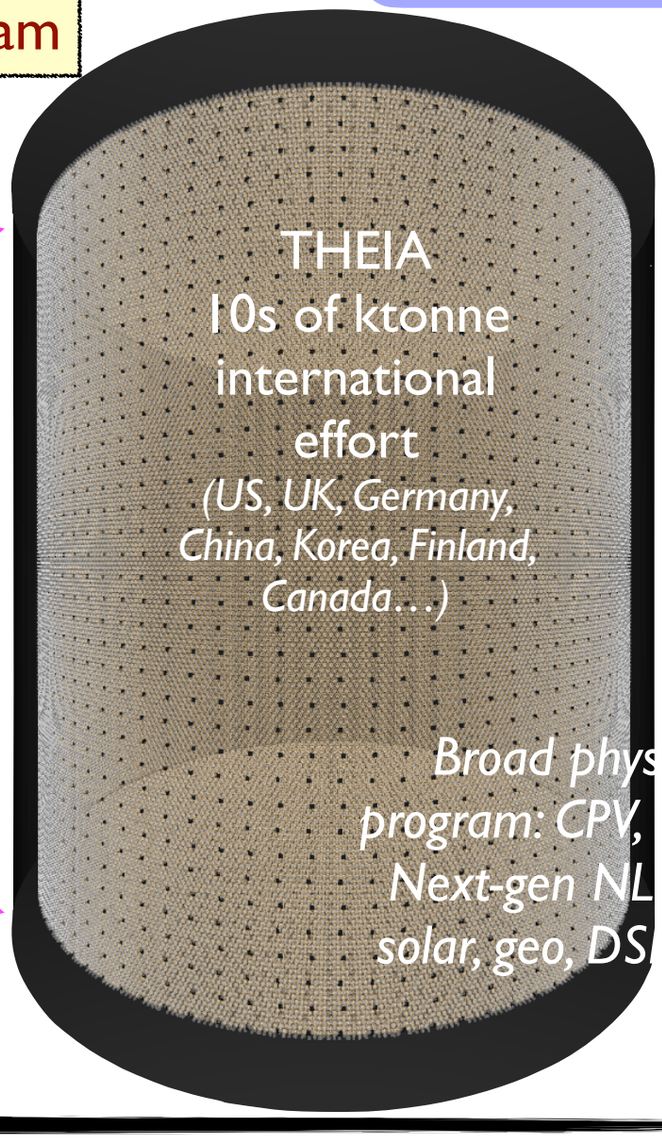
Demonstration of next-generation detector capabilities

Develop **R&D infrastructure** — testbed for future programs

Broad R&D program



Ch/S separation, microphysical parameter measurements



Phys. Rev. D 103 052004 (2021), Mat. Adv. 1 (2020) 71-76, Eur. Phys. J. C (2020) 80: 867, Eur. Phys. J. C (2020) 80: 416, Eur. Phys. J. C (2018) 78: 435, Phys. Rev. C95 055801 (2017), Eur. Phys. J. C (2017) 77: 811

Demonstrators

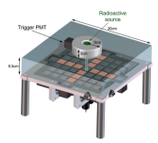
Data-driven demonstration

- ✓ *Demonstrate Cher+scint reconstruction*
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Demonstration of next-generation detector capabilities

Develop **R&D infrastructure** — testbed for future programs

Broad R&D program



Ch/S separation, microphysical parameter measurements

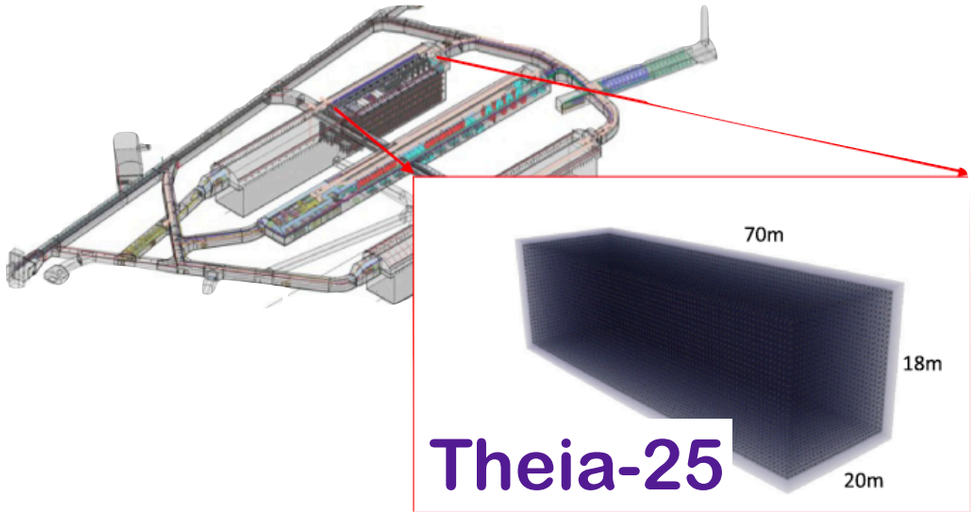
Critical ton — 10s of tons scale demonstration of detector performance capabilities

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



Phys. Rev. D 103 052004 (2021), Mat. Adv. 1 (2020) 71-76, Eur. Phys. J. C (2020) 80: 867, Eur. Phys. J. C (2020) 80: 416, Eur. Phys. J. C (2018) 78: 435, Phys. Rev. C95 055801 (2017), Eur. Phys. J. C (2017) 77: 811

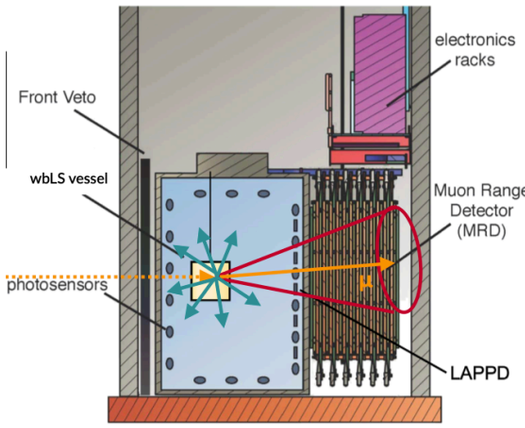
The path to THEIA

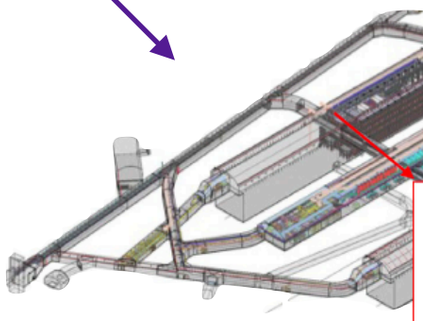


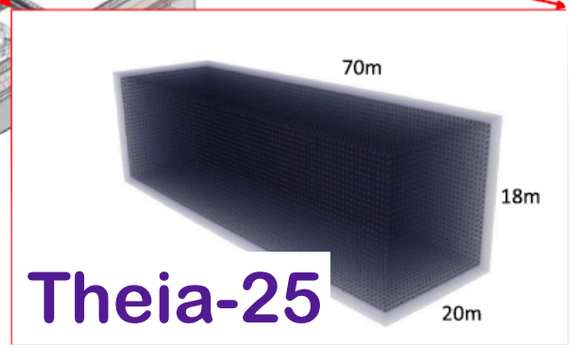
The path to THEIA

High-energy event reconstruction, neutrino detection

ANNIE: 365 kg





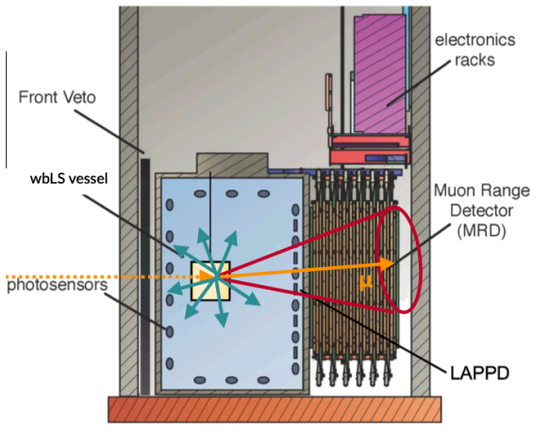


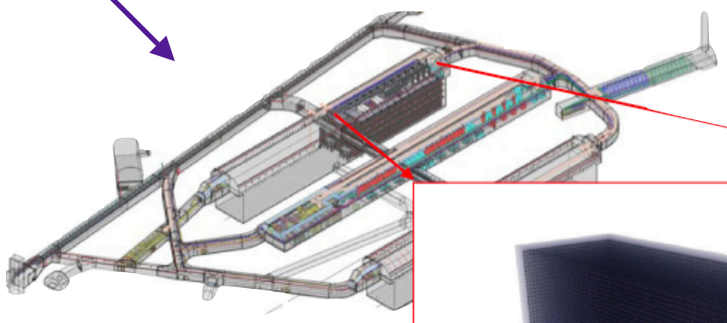
The path to THEIA

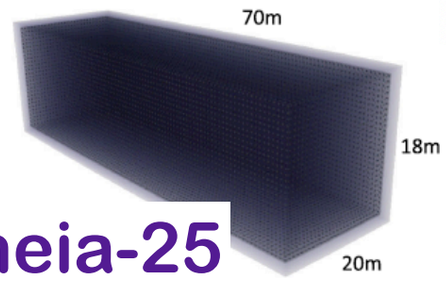
High-energy event reconstruction, neutrino detection

Low-energy event reconstruction, model validation

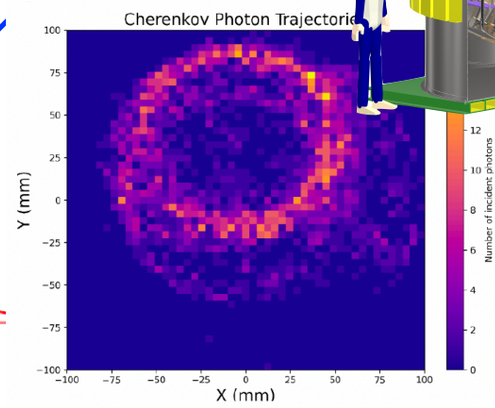
ANNIE: 365 kg

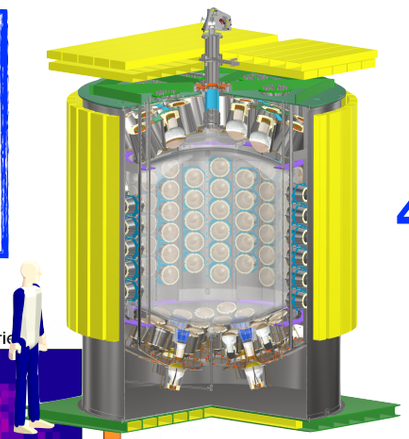






Theia-25



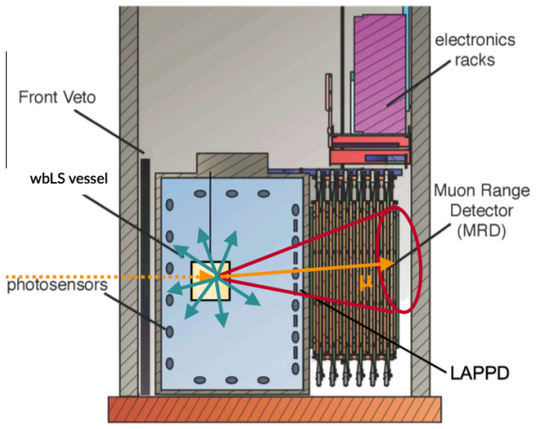


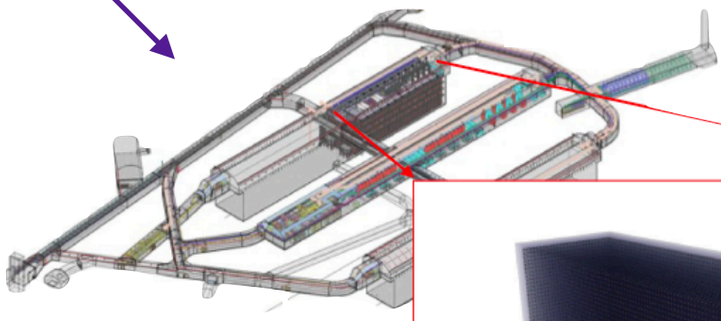
Eos: 4 ton

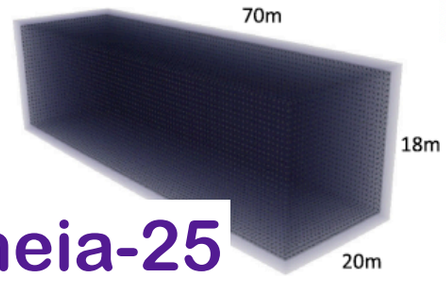
The path to THEIA

High-energy event reconstruction, neutrino detection

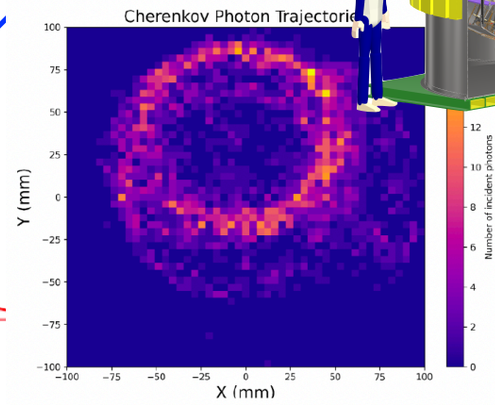
ANNIE: 365 kg

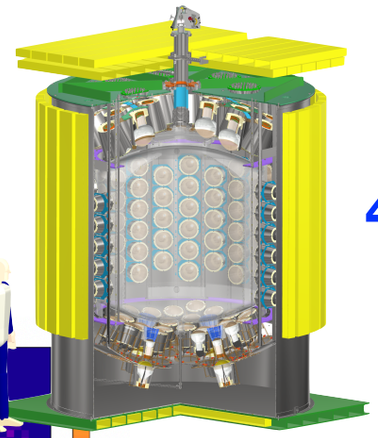






Low-energy event reconstruction, model validation





Eos: 4 ton

Deployment, purification, recirculation, transparency

BNL: 1- and 30-ton

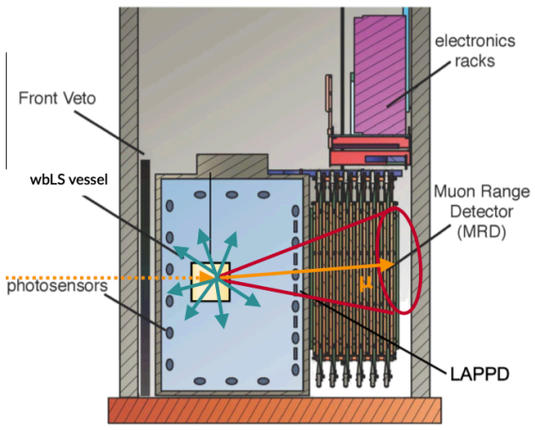


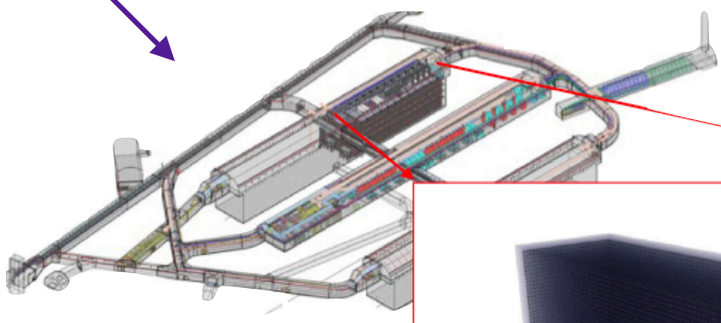


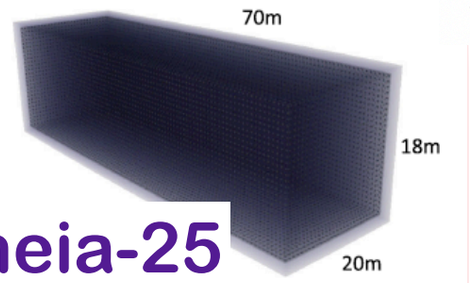
The path to THEIA

High-energy event reconstruction, neutrino detection

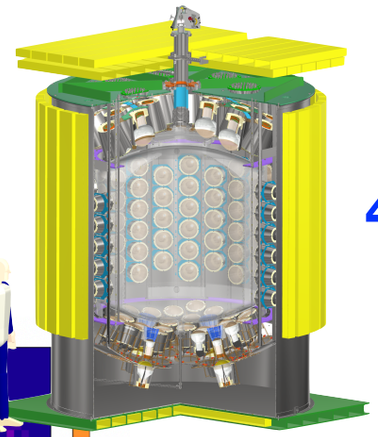
ANNIE: 365 kg



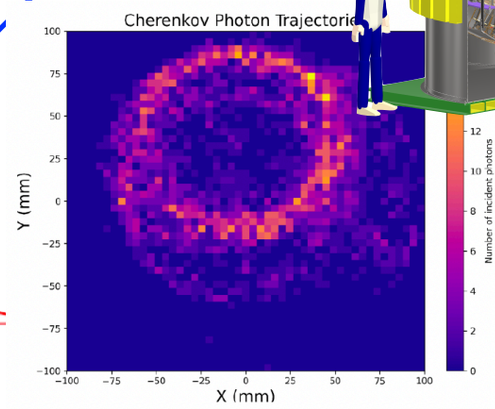




Low-energy event reconstruction, model validation



Eos: 4 ton



NuDot: 1 ton



Isotope loading, NLDBD topology

BNL: 1- and 30-ton





Deployment, purification, recirculation, transparency

Eos (Dawn)

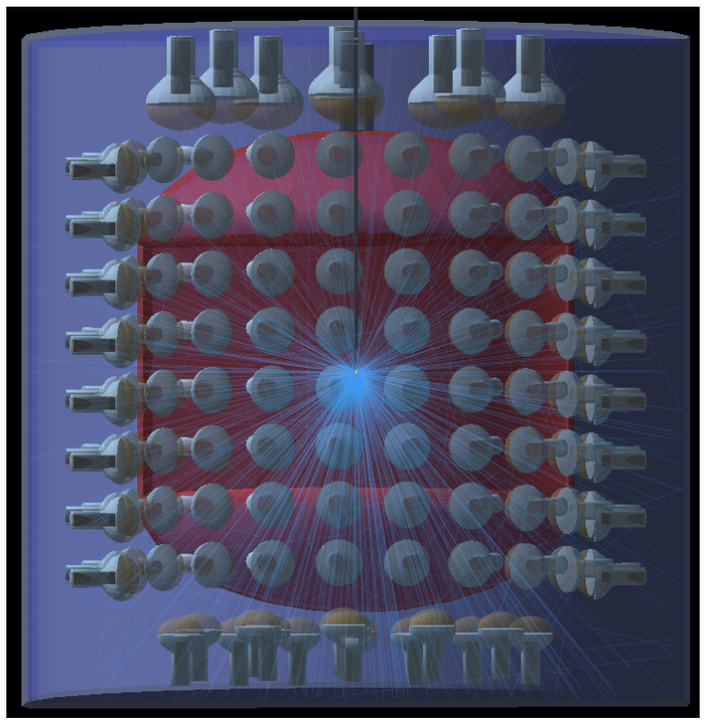
Funded by NNSA,
DNN R&D
FY22-24



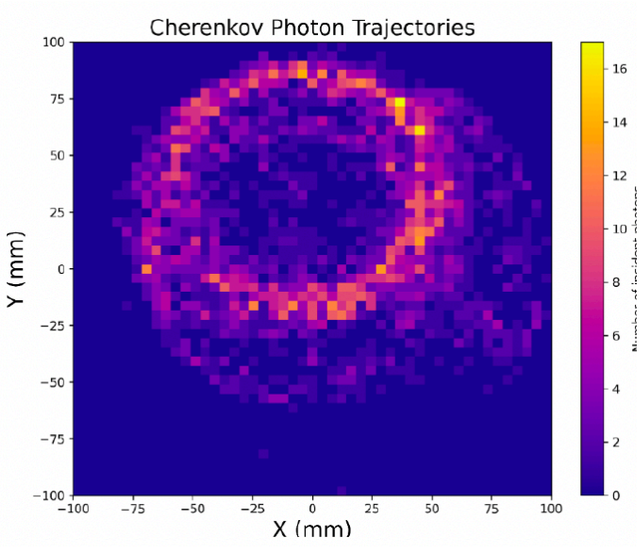
Let There be Light

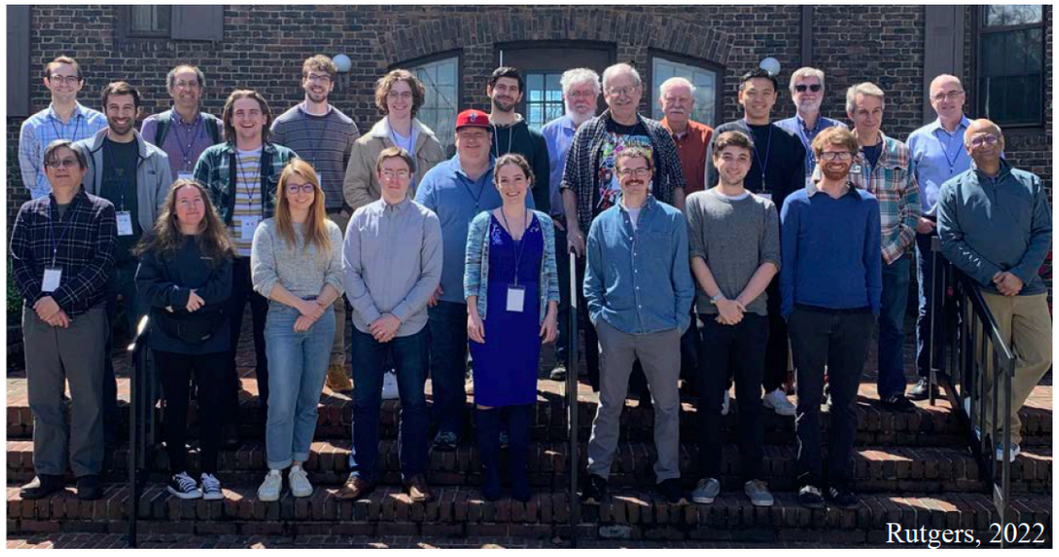
EOS: performance demonstrator

- 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



- 4-ton target mass
  water, WbLS, organic LS
- 200 8-" PMTs.
  R14688-100, 900ps FWHM
- CAEN V1730 readout
- Dichroicon deployment for spectral sorting
- Deployable sources for studies of vertex, energy, direction reconstruction & PID





USA

Germany

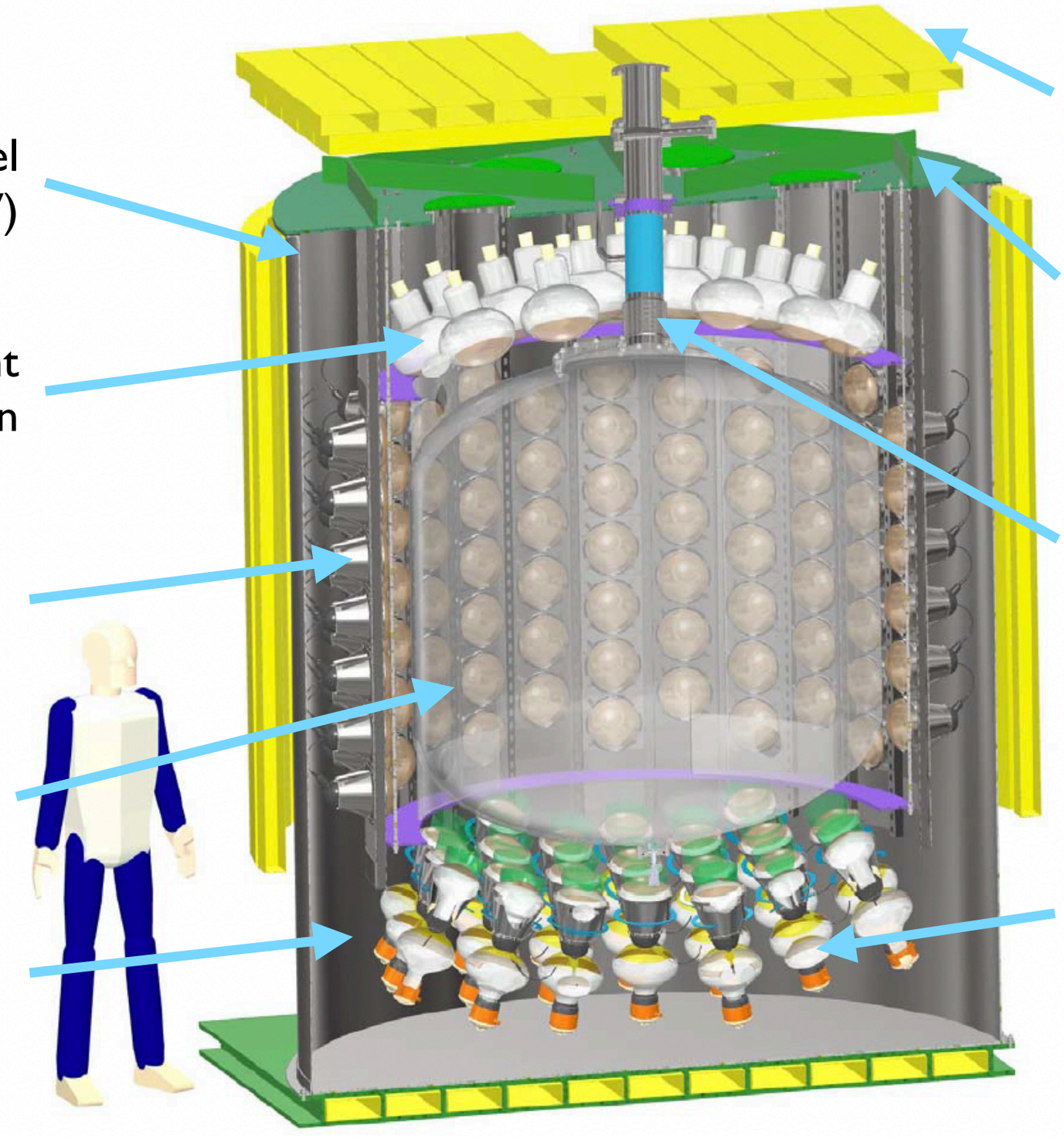
Portugal

Finland

Turkey

Canada

EOS Detector design



11-ft (30-ton) steel outer vessel (OV)

12-” PMTs for light collection

200x 8-” fast PMTs + B shielding

4-ton acrylic inner vessel (IV)

Water buffer region

Muon veto system surrounding detector

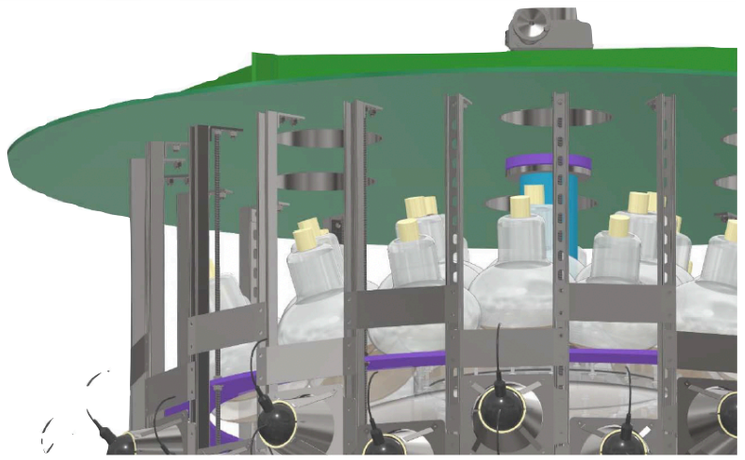
Edge ports for additional calibration, sensors, access

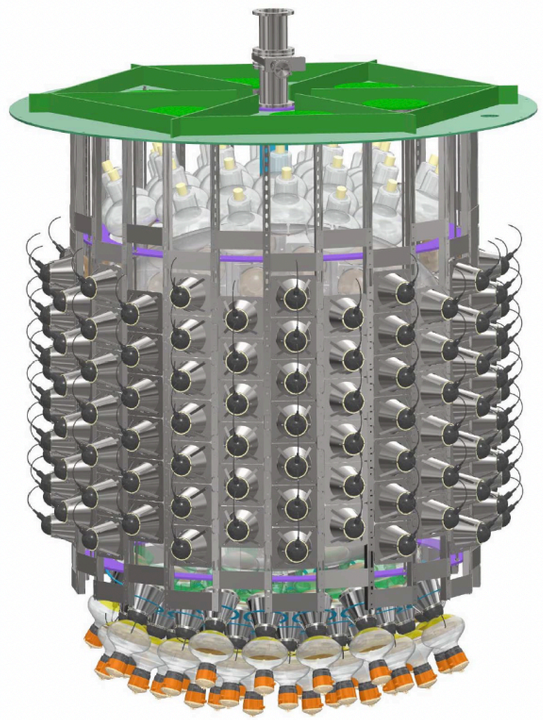
Central-axis calibration source deployment

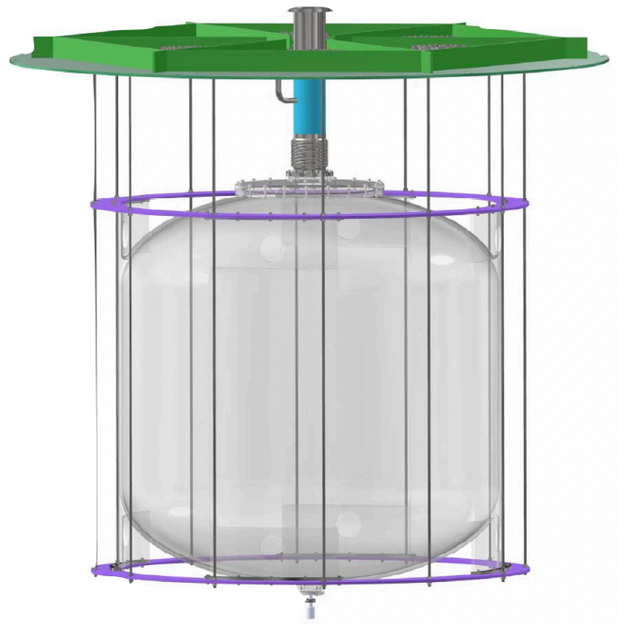
Dichroicon deployment

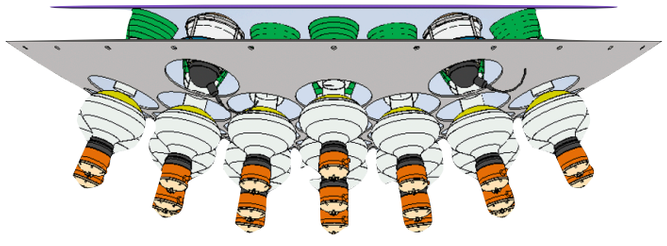
Assembly & status

- Suspend detector assembly from the lid of the OV
- IV under contract, delivery due May ’23 (Reynolds Polymer)
- OV: contract with seismic engineer to determine anchorage req; build-to-print RFP on completion
- PSUP design complete, moving to prototype and purchase
- Hamamatsu PMTs (200x fast 8”), batch delivery Nov ’22 — Jul ’23 (16 received)
- Digitisers & HV boards (CAEN), first batch received











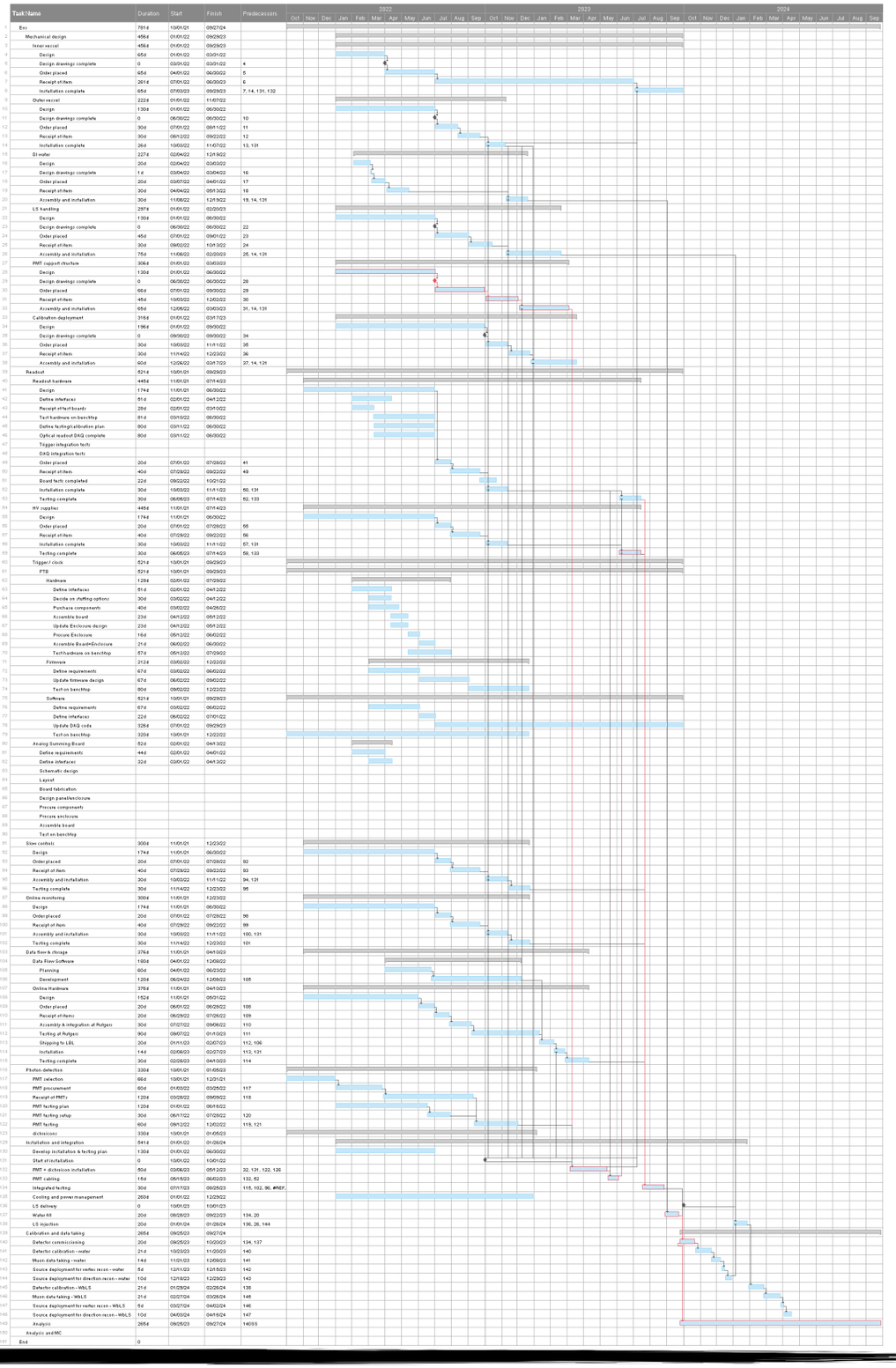
Schedule: 3-year life cycle

Project phases (high-level milestones)

- FY22 Detector design and procurement;
- FY23 Detector construction and installation;
- FY24Q1-2 Detector commissioning and calibration;
- FY24Q3-4 Data taking and data analysis for primary objective. (*Aggressive project scope).*

Proposed filling scheme

- Initial pure water fill to baseline performance
- Inject small (~1%) fraction LS for testing
- Increase %LS to study dependence of performance on Chr/scint ratio



Task Name	Duration	Start	Finish	Predecessors
Exc	791 d	10/01/21	09/27/24	
Mechanical design	456 d	01/01/22	09/29/23	
Inner vessel	456 d	01/01/22	09/29/23	
Design	65 d	01/01/22	03/31/22	
Design drawings complete	0	03/31/22	03/31/22	4
Order placed	65 d	04/01/22	06/30/22	5
Receipt of item	261 d	07/01/22	06/30/23	6
Installation complete	65 d	07/03/23	09/29/23	7, 14, 131, 132
Outer vessel	222 d	01/01/22	11/07/22	
Design	130 d	01/01/22	06/30/22	
Design drawings complete	0	06/30/22	06/30/22	10
Order placed	30 d	07/01/22	08/11/22	11
Receipt of item	30 d	08/12/22	09/22/22	12
Installation complete	26 d	10/03/22	11/07/22	13, 131
Gd water	227 d	02/04/22	12/19/22	
Design	20 d	02/04/22	03/03/22	
Design drawings complete	1 d	02/04/22	02/04/22	16
Order placed	20 d	03/07/22	04/01/22	17
Receipt of item	30 d	04/04/22	05/13/22	18
Assembly and installation	30 d	11/08/22	12/19/22	19, 14, 131
LS handling	297 d	01/01/22	02/20/23	
Design	130 d	01/01/22	06/30/22	
Design drawings complete	0	06/30/22	06/30/22	22
Order placed	45 d	07/01/22	09/01/22	23
Receipt of item	30 d	09/02/22	10/13/22	24
Assembly and installation	75 d	11/08/22	02/20/23	25, 14, 131
PMT support structure	306 d	01/01/22	03/03/23	
Design	130 d	01/01/22	06/30/22	
Design drawings complete	0	06/30/22	06/30/22	28
Order placed	65 d	07/01/22	09/30/22	29
Receipt of item	45 d	10/03/22	12/02/22	30
Assembly and installation	65 d	12/05/22	03/03/23	31, 14, 131
Calibration deployment	316 d	01/01/22	03/17/23	
Design	196 d	01/01/22	09/30/22	
Design drawings complete	0	09/30/22	09/30/22	34
Order placed	30 d	10/03/22	11/11/22	35
Receipt of item	30 d	11/14/22	12/23/22	36
Assembly and installation	60 d	12/26/22	03/17/23	37, 14, 131
Readout	521 d	10/01/21	09/29/23	
Readout hardware	445 d	11/01/21	07/14/23	
Design	174 d	11/01/21	06/30/22	
Define interfaces	61 d	02/01/22	04/12/22	
Receipt of front boards	20 d	02/01/22	03/01/22	
Test hardware on benchtop	61 d	03/10/22	06/30/22	
Define testing/calibration plan	60 d	03/11/22	06/30/22	
Optical readout DAQ complete	60 d	03/11/22	06/30/22	
Trigger integration tests				
DAQ integration tests				
Order placed	20 d	07/01/22	07/28/22	41
Receipt of item	40 d	07/29/22	09/22/22	49
Board tests completed	22 d	09/23/22	10/21/22	
Installation complete	30 d	10/03/22	11/11/22	50, 131
Testing complete	30 d	06/05/23	07/14/23	52, 133
HV supplies	445 d	11/01/21	07/14/23	
Design	174 d	11/01/21	06/30/22	
Order placed	20 d	07/01/22	07/28/22	55
Receipt of item	40 d	07/29/22	09/22/22	56
Installation complete	30 d	10/03/22	11/11/22	57, 131
Testing complete	30 d	06/05/23	07/14/23	58, 133
Trigger/ clock	521 d	10/01/21	09/29/23	
PTB	521 d	10/01/21	09/29/23	
Hardware	129 d	02/01/22	07/29/22	
Define interfaces	61 d	02/01/22	04/12/22	
Decide on stuffing options	30 d	03/02/22	04/12/22	
Purchase components	40 d	03/02/22	04/26/22	
Assemble board	23 d	04/12/22	05/12/22	
Update Enclosure design	23 d	04/12/22	05/12/22	
Procure Enclosure	16 d	05/13/22	06/02/22	
Assemble Board+Enclosure	21 d	06/02/22	06/30/22	
Test hardware on benchtop	67 d	05/12/22	07/29/22	
Firmware	212 d	03/02/22	12/2/22	
Define requirements	67 d	03/02/22	06/02/22	
Update firmware design	67 d	06/02/22	09/02/22	
Test on benchtop	80 d	09/02/22	12/22/22	
Software	521 d	10/01/21	09/29/23	
Define requirements	67 d	03/02/22	06/02/22	
Define interfaces	22 d	06/02/22	07/01/22	
Update DAQ code	326 d	07/01/22	09/29/23	
Test on benchtop	320 d	10/01/21	12/2/22	
Analog Summing Board	52 d	02/01/22	04/13/22	
Define requirements	44 d	02/01/22	04/01/22	
Define interfaces	32 d	03/01/22	04/13/22	
Schematic design				
Layout				
Board fabrication				
Design panel/enclosure				
Procure components				
Procure enclosure				
Assemble board				
Test on benchtop				
Slow controls	300 d	11/01/21	12/23/22	
Design	174 d	11/01/21	06/30/22	
Order placed	20 d	07/01/22	07/28/22	92
Receipt of item	40 d	07/29/22	09/22/22	93
Assembly and installation	30 d	10/03/22	11/11/22	94, 131
Testing complete	30 d	11/14/22	12/23/22	95
Online monitoring	300 d	11/01/21	12/23/22	
Design	174 d	11/01/21	06/30/22	
Order placed	20 d	07/01/22	07/28/22	98
Receipt of item	40 d	07/29/22	09/22/22	99
Assembly and installation	30 d	10/03/22	11/11/22	100, 131
Testing complete	30 d	11/14/22	12/23/22	101
Data flow & storage	376 d	11/01/21	04/10/23	
Data Flow Software	190 d	04/01/22	12/28/22	
Planning	60 d	04/01/22	06/23/22	
Development	120 d	06/24/22	12/28/22	105
Online Hardware	376 d	11/01/21	04/10/23	
Design	152 d	11/01/21	06/01/22	
Order placed	20 d	06/01/22	06/28/22	108
Receipt of items	20 d	06/29/22	07/26/22	109
Assembly & integration at Pultgen	30 d	07/27/22	09/06/22	110
Testing at Pultgen	90 d	09/07/22	01/10/23	111
Shipping to LBL	20 d	01/11/23	02/07/23	112, 106
Installation	14 d	02/08/23	02/27/23	113, 131
Testing complete	30 d	02/28/23	04/10/23	114
Photon detection	339 d	10/01/21	01/05/23	
PMT selection	66 d	10/01/21	12/31/21	
PMT procurement	60 d	01/03/22	03/25/22	117
Receipt of PMTs	120 d	03/28/22	09/09/22	118
PMT testing plan	129 d	01/01/22	06/15/22	
PMT testing setup	30 d	06/17/22	07/28/22	120
PMT testing	60 d	09/12/22	12/02/22	119, 121
dichroicons	339 d	10/01/21	01/05/23	
Installation and integration	541 d	01/01/22	01/28/24	
Develop installation & testing plan	130 d	01/01/22	06/30/22	
Start of installation	0	10/01/22	10/01/22	
PMT + dichroicon installation	150 d	03/06/23	09/12/23	32, 131, 122, 126
PMT cabling	15 d	05/15/23	06/02/23	132, 82
Integrated testing	30 d	07/17/23	08/25/23	115, 102, 96, #NEP,
Cooling and power management	280 d	01/01/22	12/29/22	
LS delivery	0	10/01/23	10/01/23	
Water fill	20 d	08/28/23	09/22/23	134, 20
LS injection	20 d	01/01/24	01/28/24	136, 26, 144
Calibration and data taking	265 d	09/05/23	09/27/24	
Detector commissioning	20 d	09/05/23	10/03/23	134, 137
Detector calibration - water	21 d	10/03/23	11/02/23	140
Muon data taking - water	14 d	11/01/23	12/08/23	141
Source deployment for vertex recon - water	5 d	12/11/23	12/15/23	142
Source deployment for direction recon - water	10 d	12/18/23	12/29/23	143
Detector calibration - WbLS	21 d	01/29/24	02/26/24	139
Muon data taking - WbLS	21 d	02/27/24	03/26/24	145
Source deployment for vertex recon - WbLS	5 d	03/27/24	04/02/24	146
Source deployment for direction recon - WbLS	10 d	04/03/24	04/16/24	147
Analysis	265 d	09/05/23	09/27/24	140SS
Analysis and MC				
Exc	0			

Thanks to the EOS team!

USA

































University of Colorado
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Germany



JOHANNES GUTENBERG
UNIVERSITÄT MAINZ





TECHNISCHE
UNIVERSITÄT
MÜNCHEN

Portugal





UNIVERSIDADE D
COIMBRA

Finland



JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

Turkey

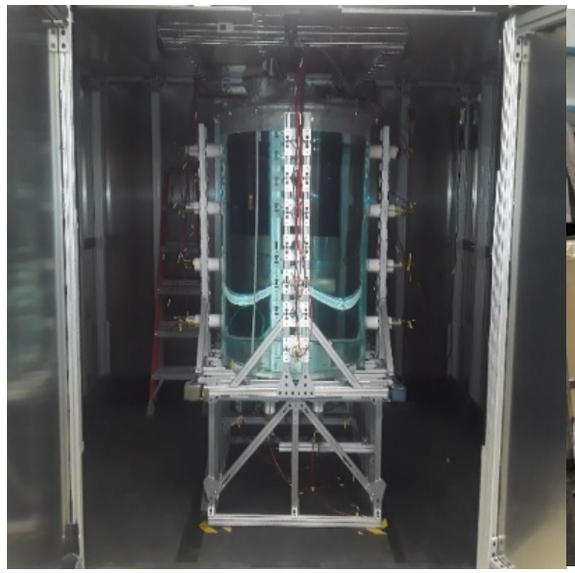


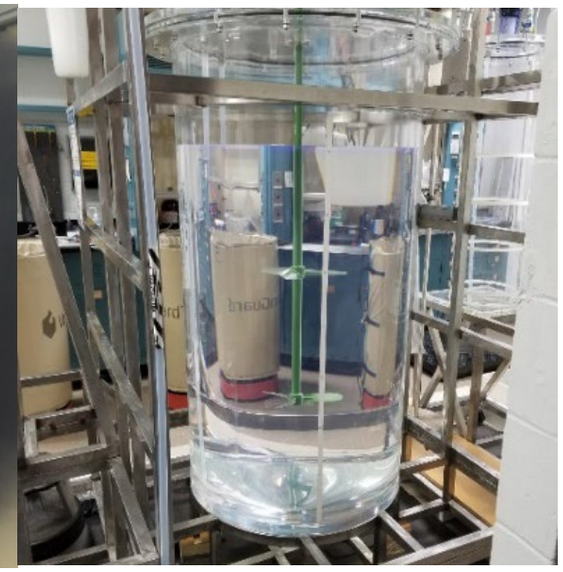
Canada



BNL 1- & 30-ton demonstrators FY 22-24

- 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)







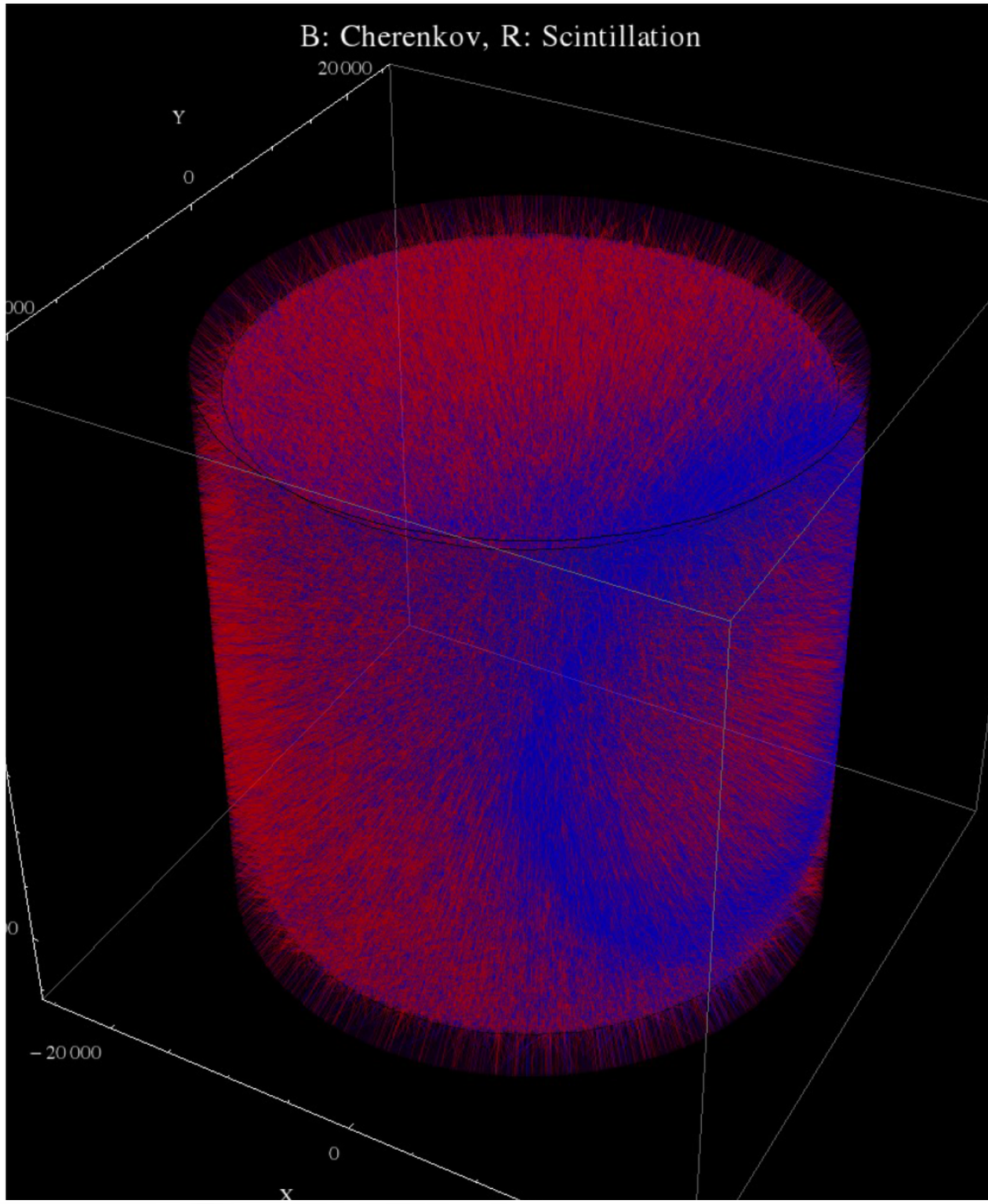




Together these prototypes will demonstrate the feasibility and capabilities of hybrid detectors for fundamental physics

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



Thank you

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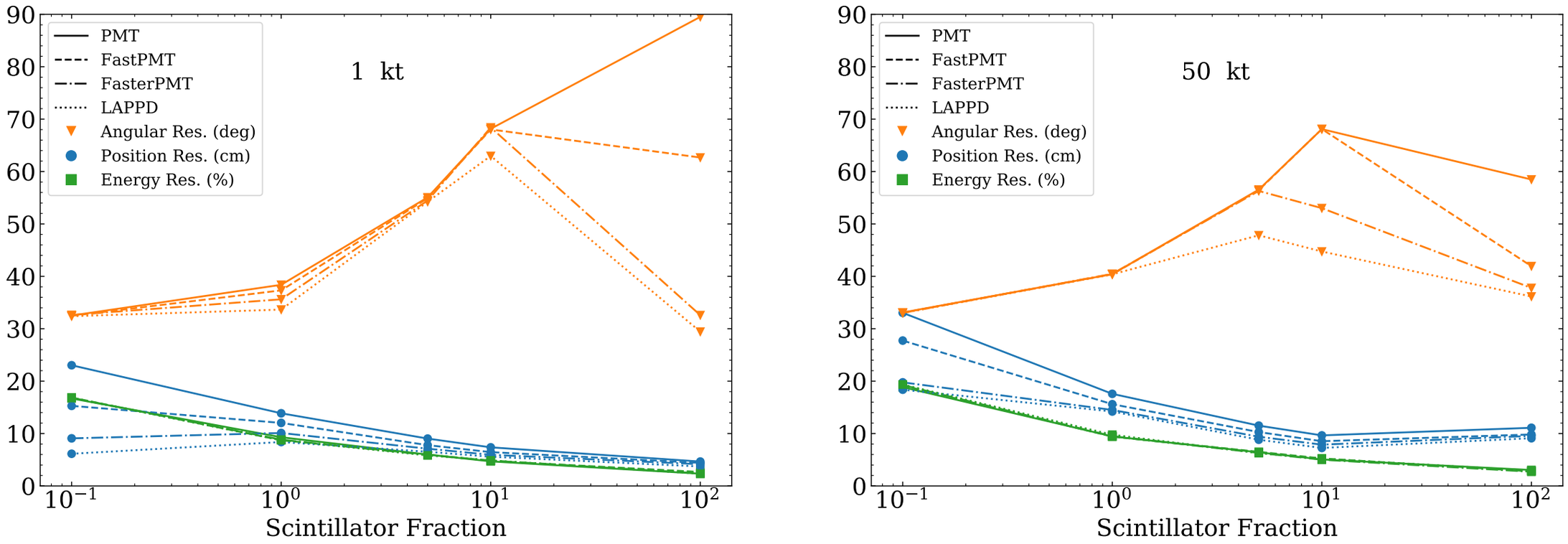


Model validation

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

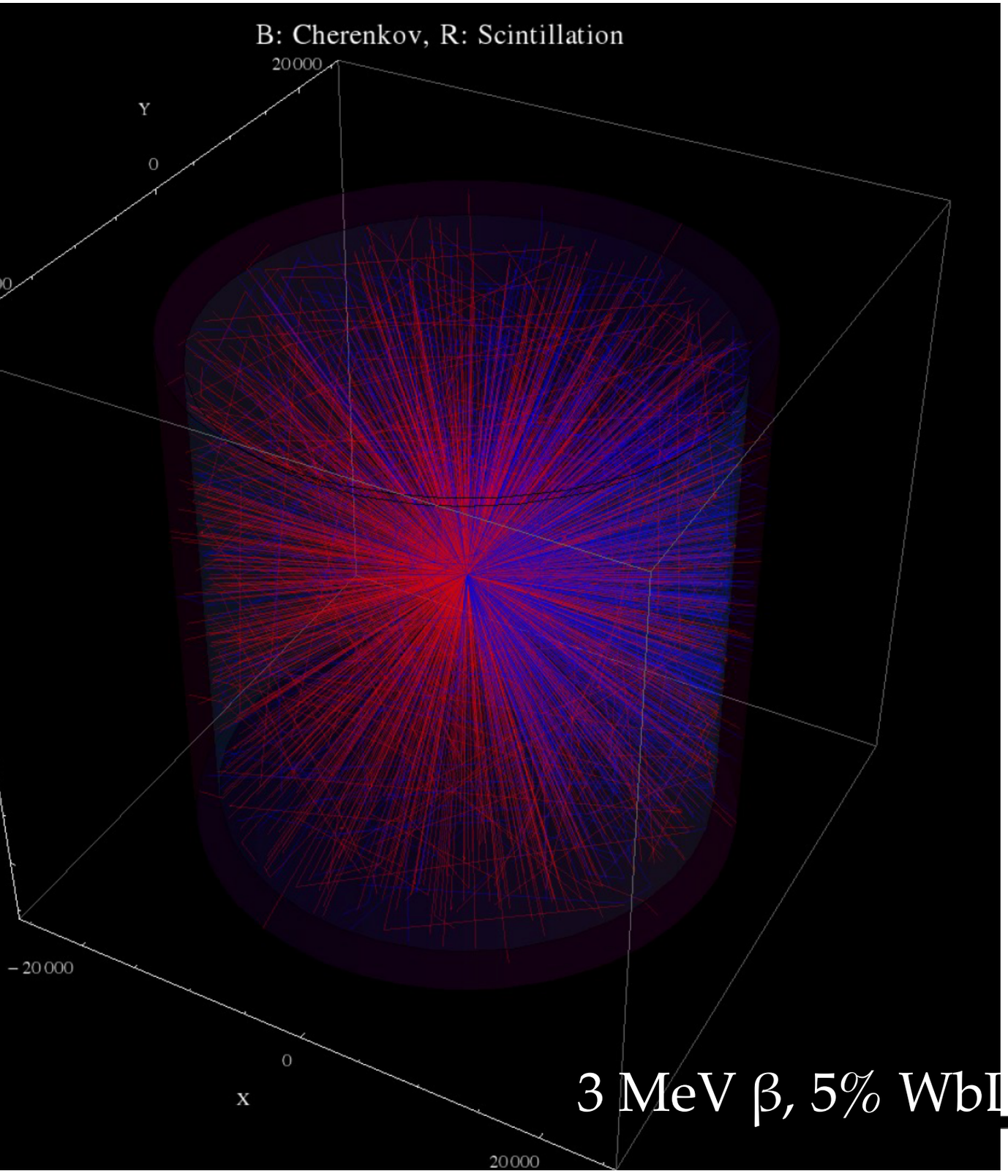


Impact of target properties and photon detector response on detector performance for (left) 1-kton and (right) 50-kton detectors

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

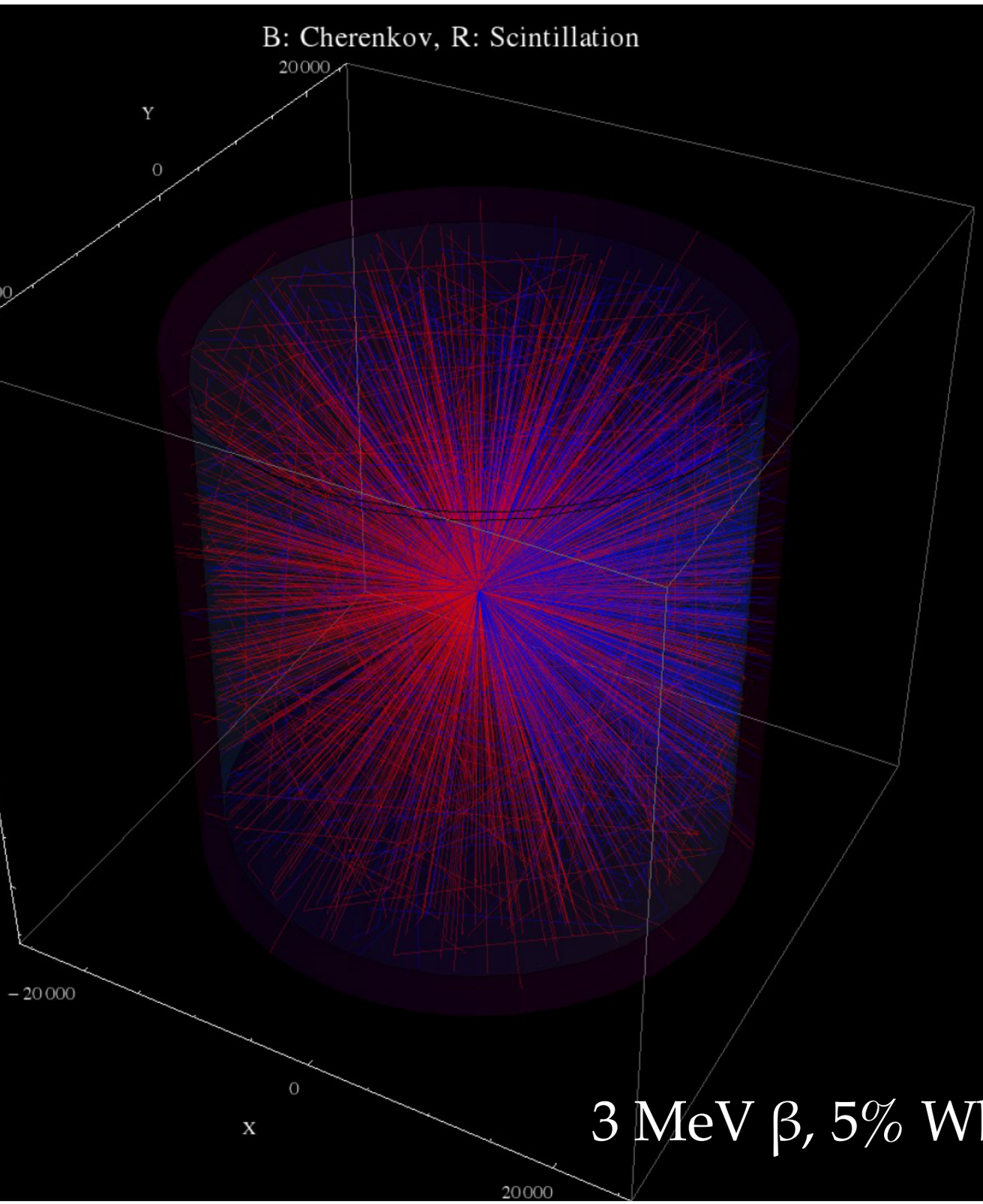
Signal Separation

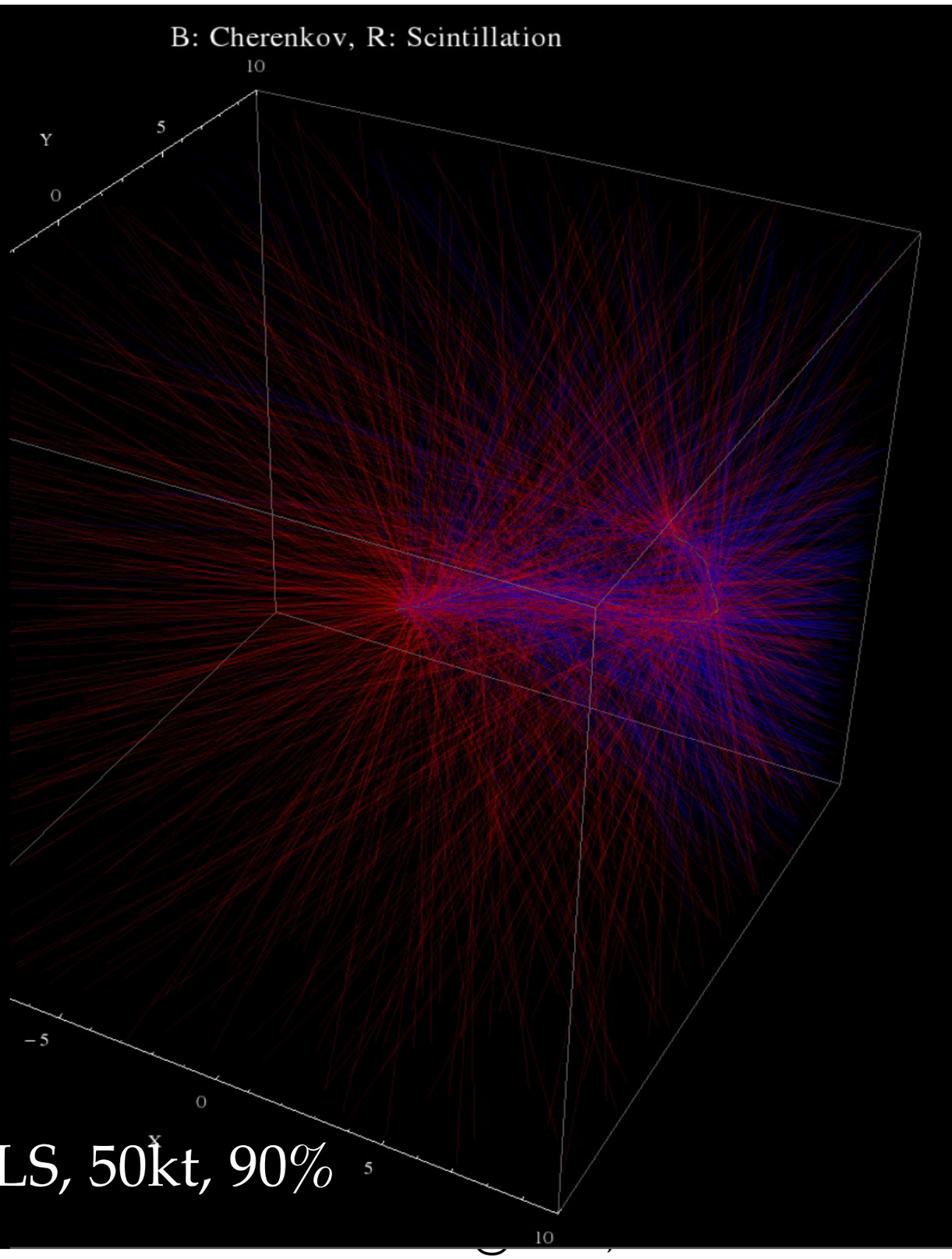
Signal Separation



3 MeV β, 5% WbL

Signal Separation

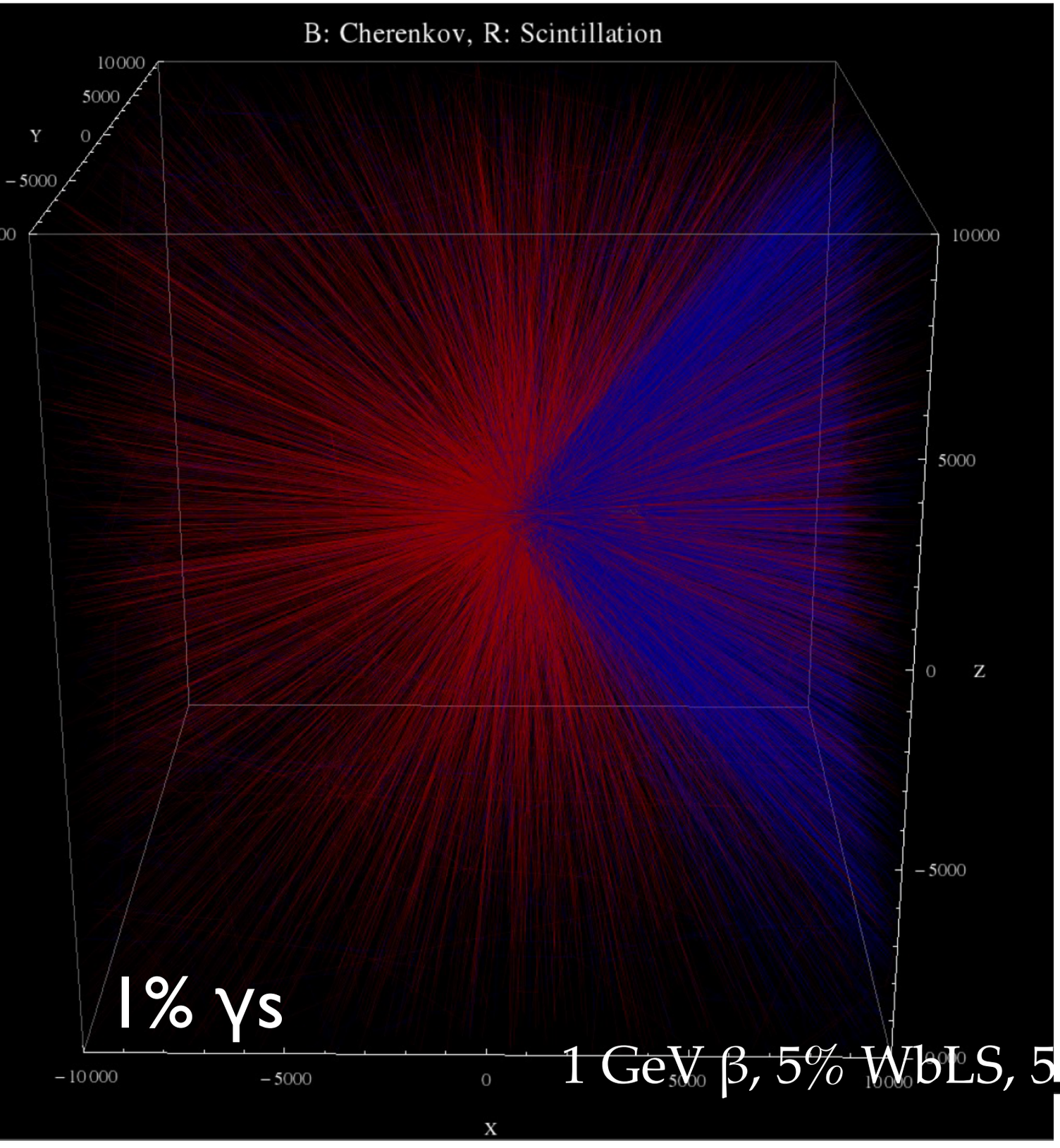




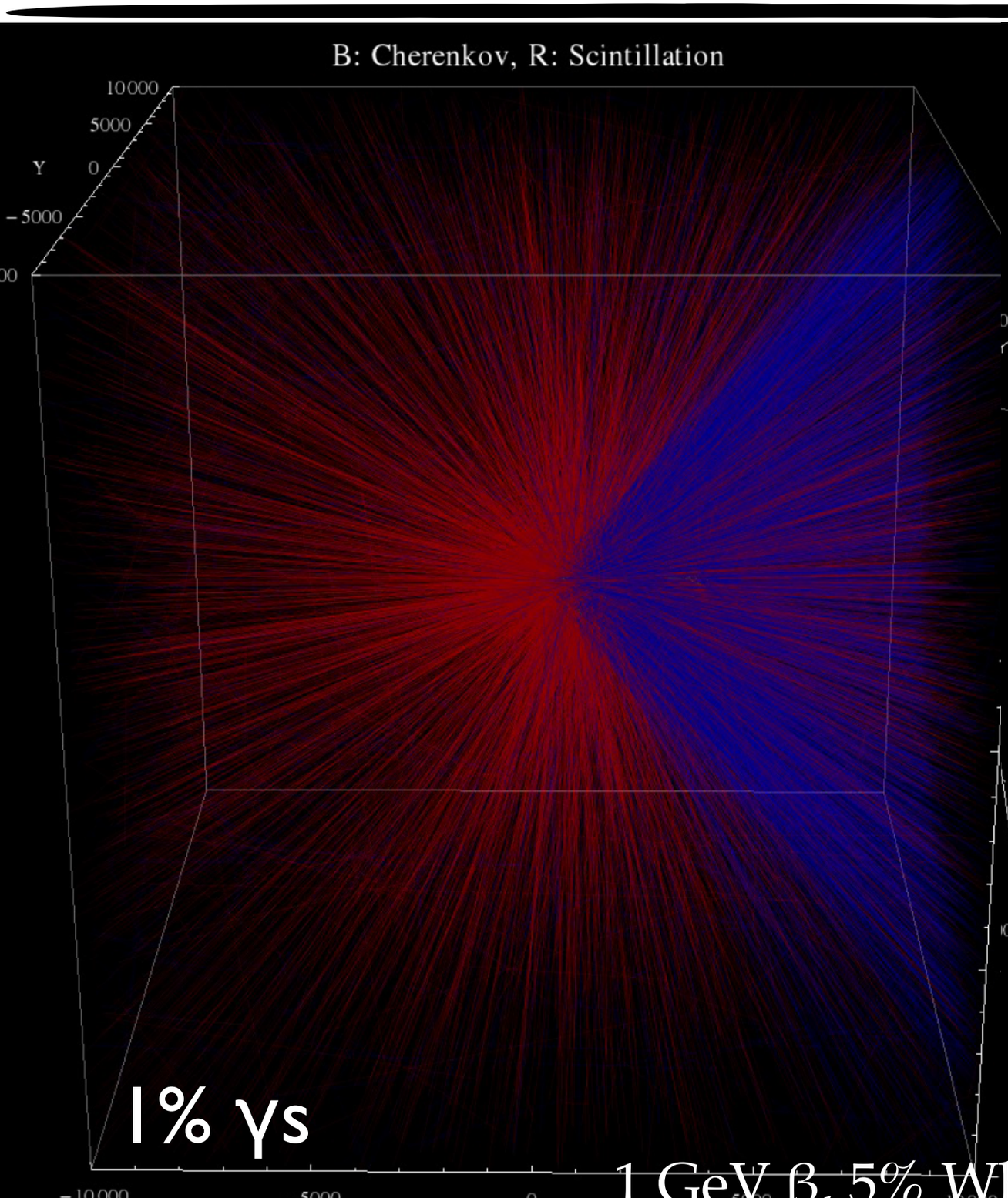
3 MeV β, 5% WbLS, 50kt, 90%

Ring Imaging

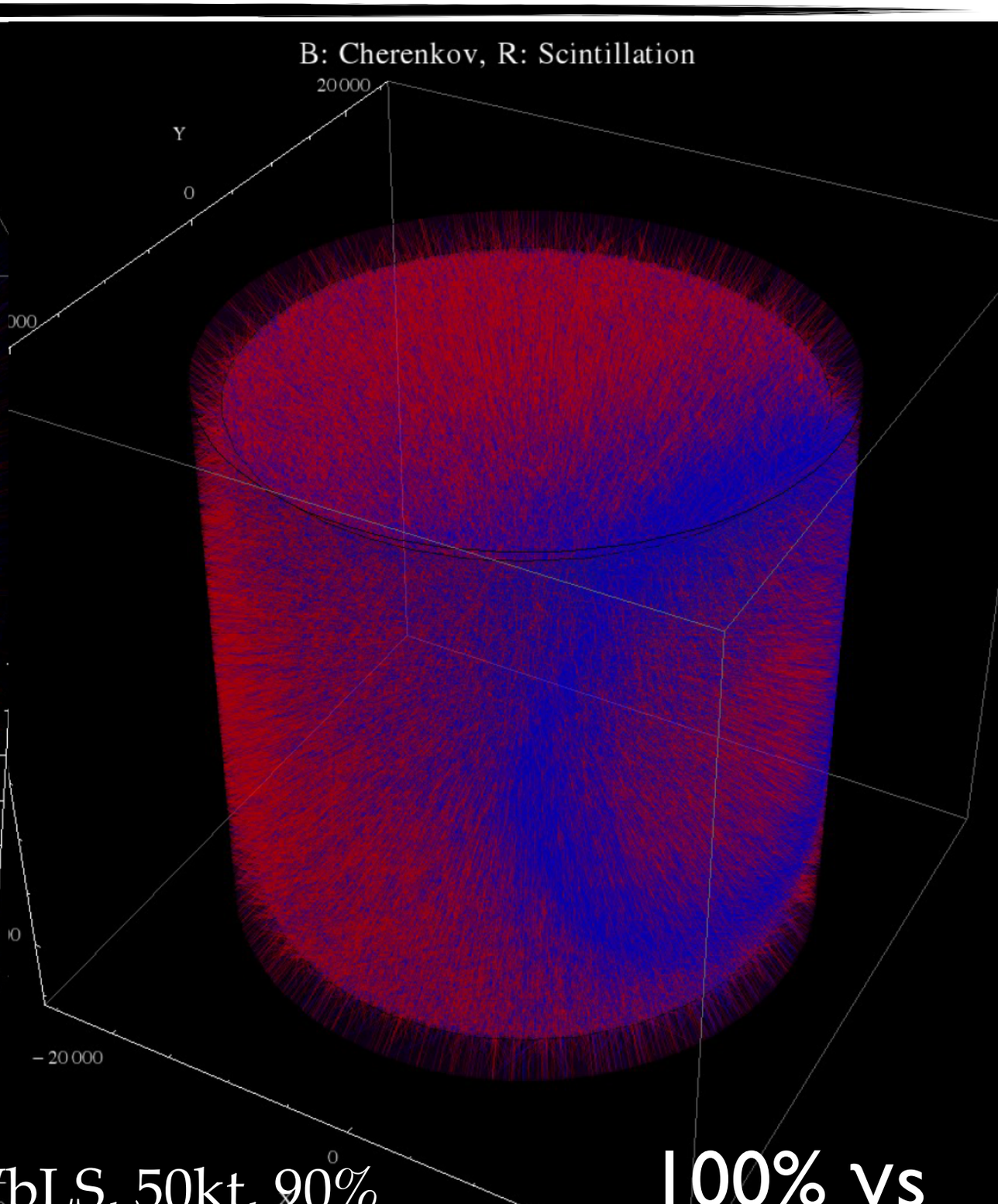
Ring Imaging



Ring Imaging



1% γs

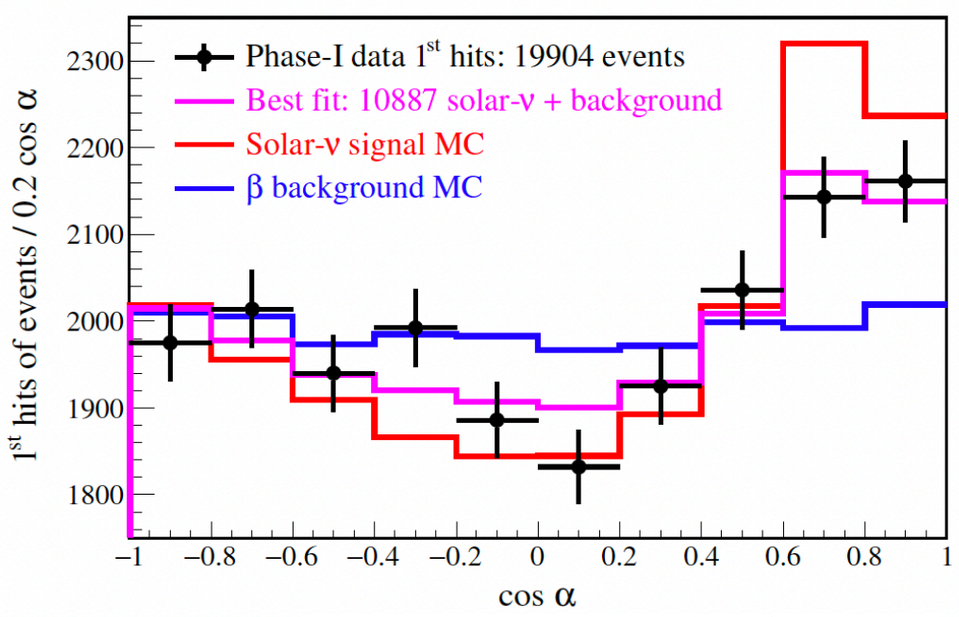


100% γs

1 GeV β, 5% WbLS, 50kt, 90%

Full-scale demonstrations

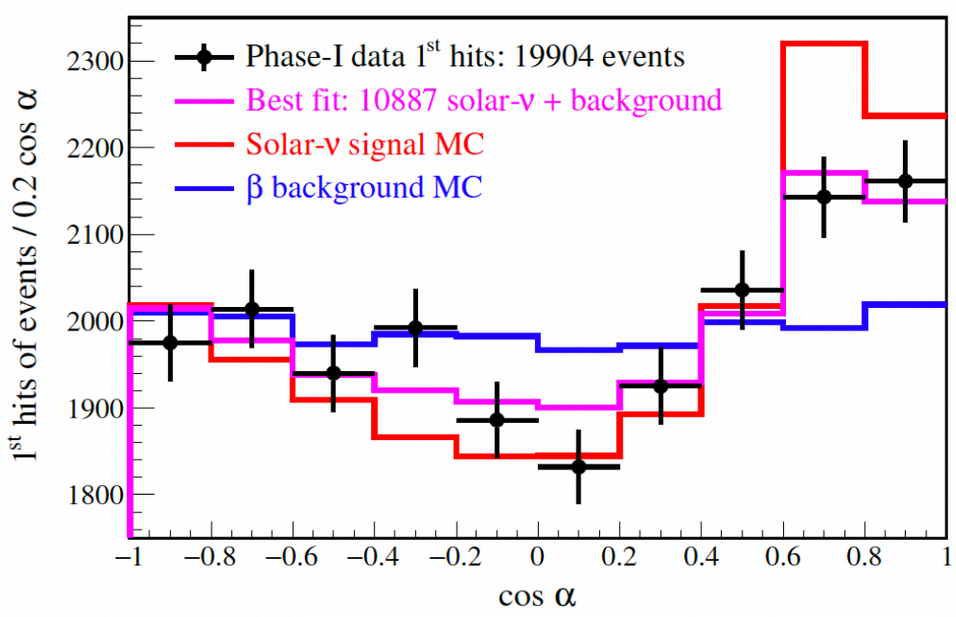
- Integrated directionality at Borexino:
  - consider earliest photons in the event
  - take angle between early photons and solar direction
  - 6σ angular excess caused by Cherenkov photons
- Measurement of primarily 7Be ν demonstrates first directional detection of sub-MeV neutrinos



PRD 105.052002, PRL 128 (2022) 9, 091803

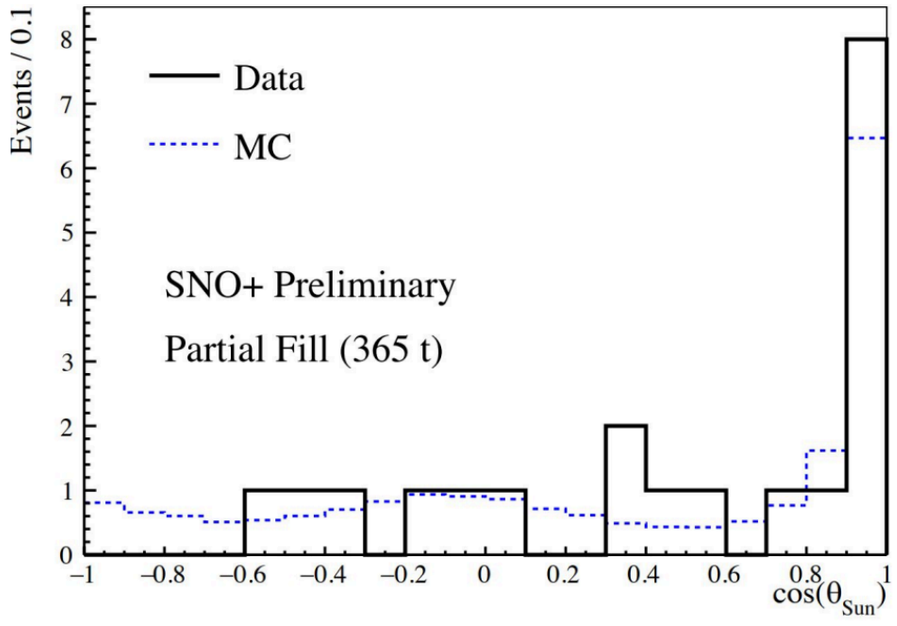
Full-scale demonstrations

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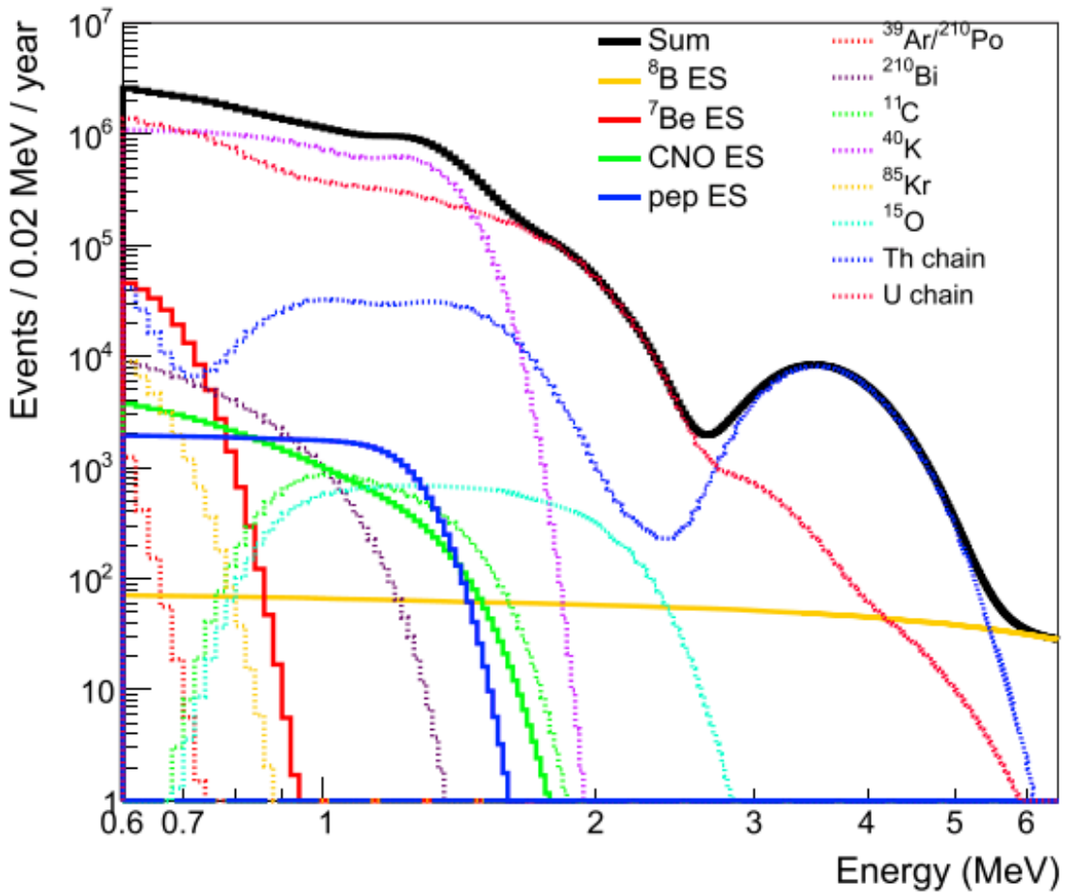
PRD 105.052002, PRL 128 (2022) 9, 091803

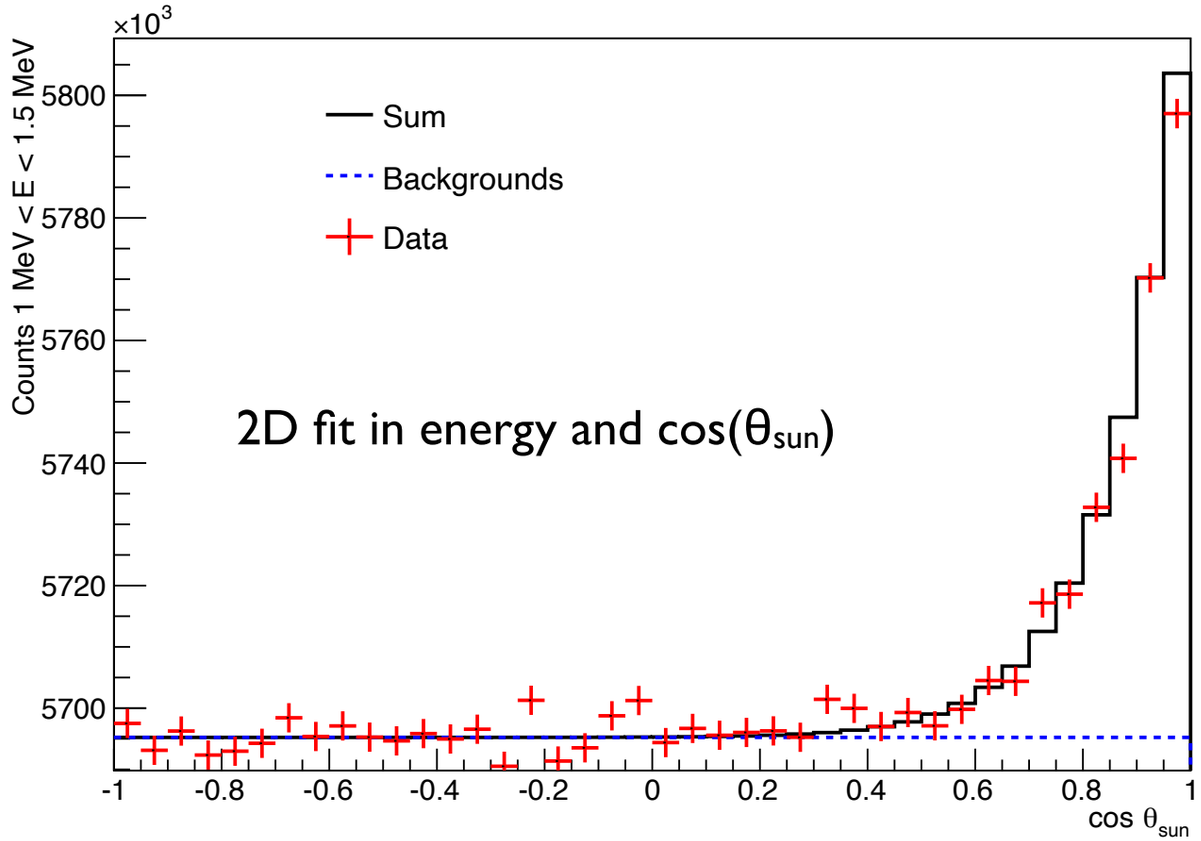
- Event-level directionality at SNO+:
  - Partial-filled detector (365 t LAB + 0.6 g/L PPO)
  - ToF and angular reconstruction
  - Demonstration with > 5MeV 8B ν
- First event-by-event demonstration of directional reconstruction for 8B solar ν in slow LS



SNO+, L. Lebanowski APS talk

The challenge of backgrounds



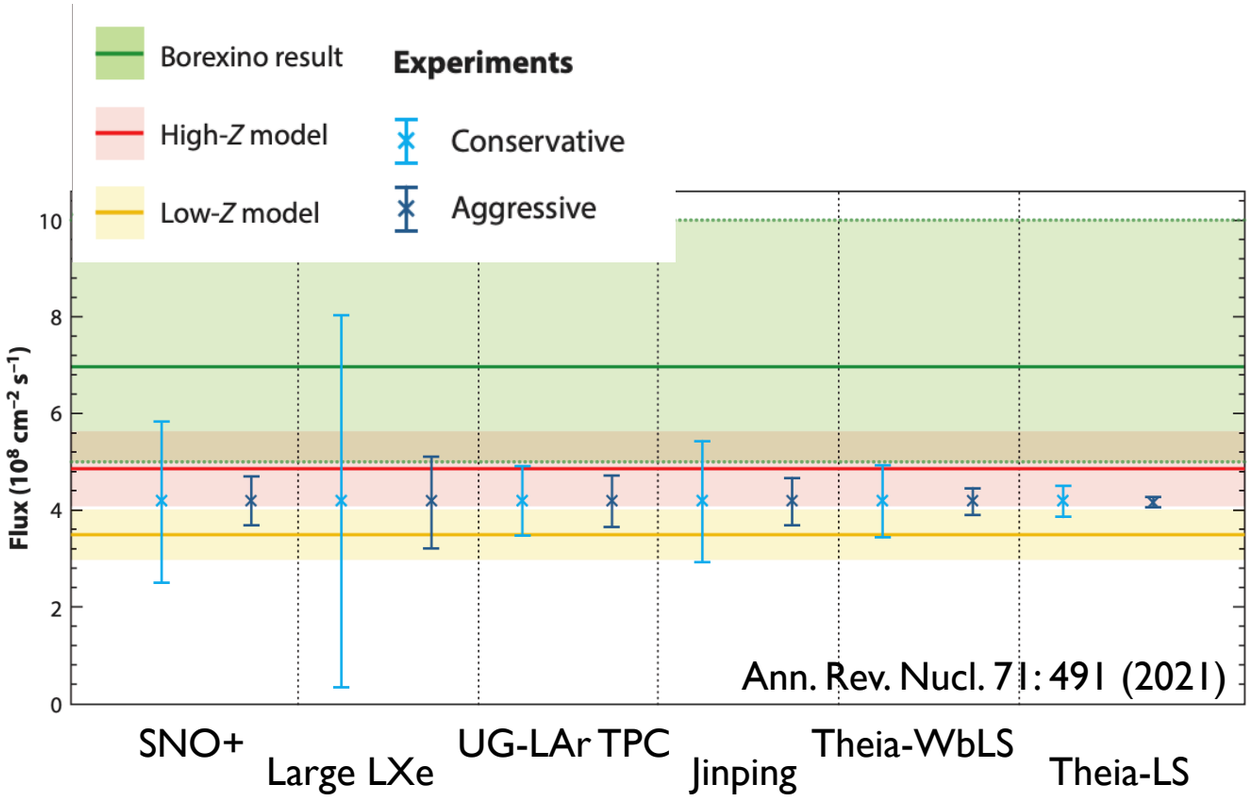


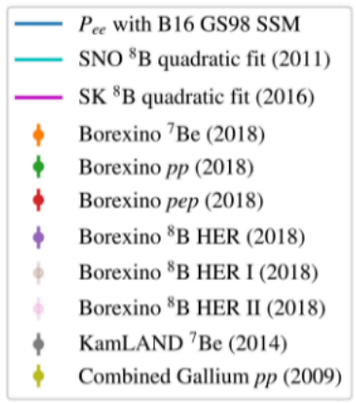
Eur. Phys. J. C 80, 416 (2020); Eur. Phys. J. C (2018) 78: 435

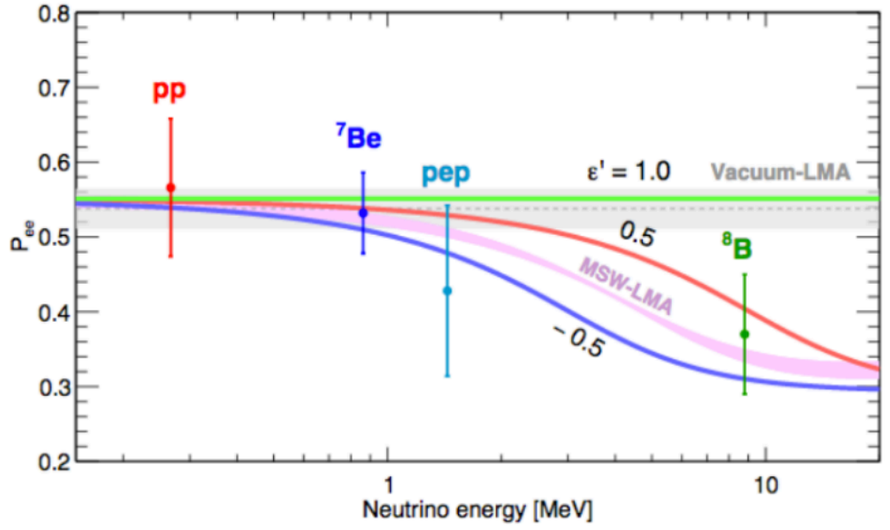
Solar Neutrinos

- Dominant background: natural radioactivity e.g. ^{210}Bi
- Theia offers unique low-threshold, directional detection
- Particle and event ID from LS time profile, quenching, Ch/S ratio

- Unique few-% level sensitivity to CNO ν
- Precision pp: luminosity, understand solar energy production
- Unique probe of matter effect / matter-vacuum transition
- Potential Li loading for CC (Haxton)





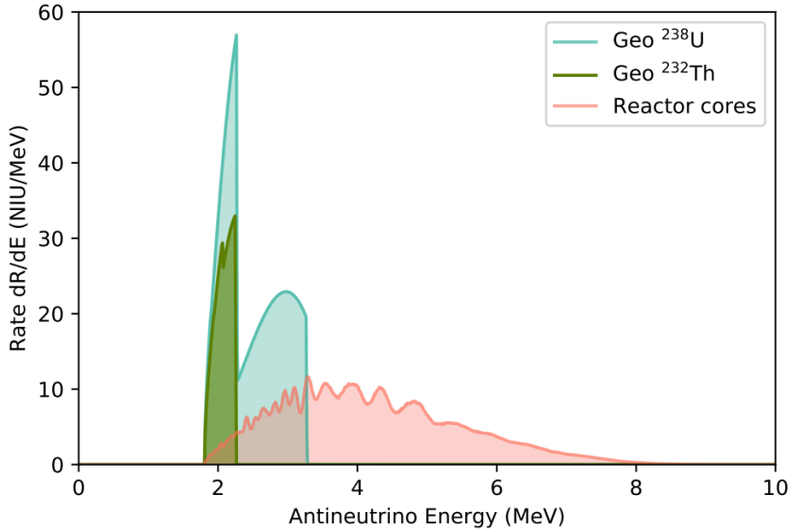


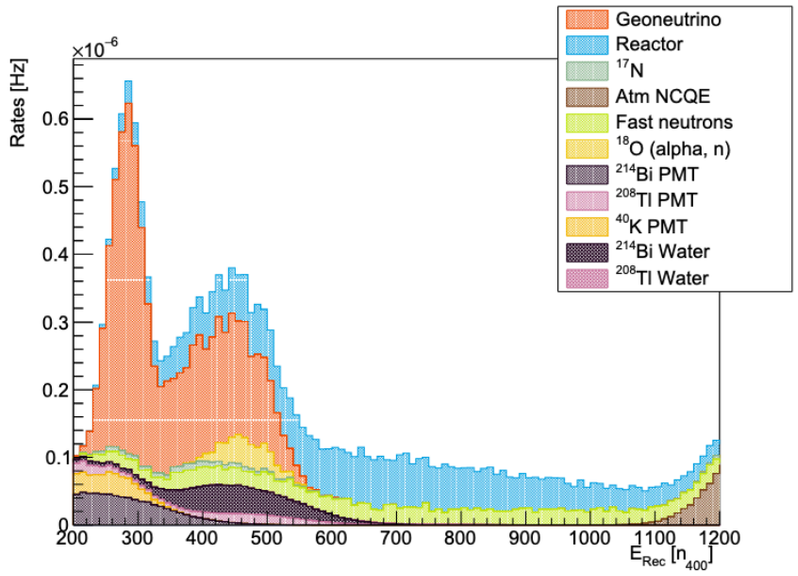
Eur. Phys. J. C 80, 416 (2020); Eur. Phys. J. C (2018) 78: 435; Phys. Rev. D 103, 052004 (2021)

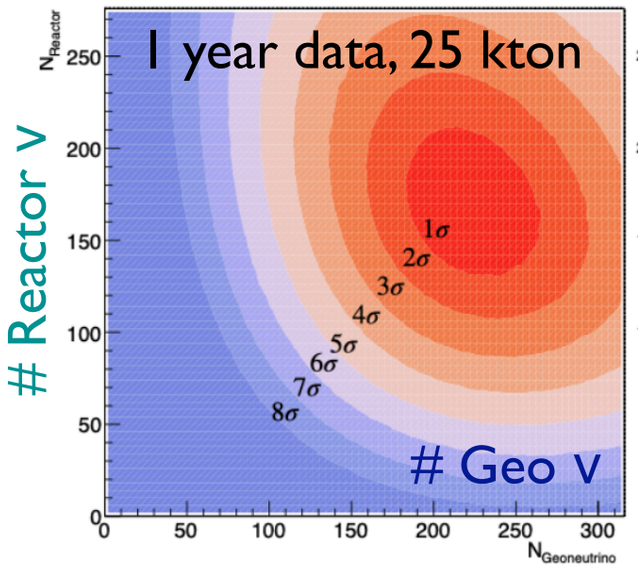
Anti-ν Detection

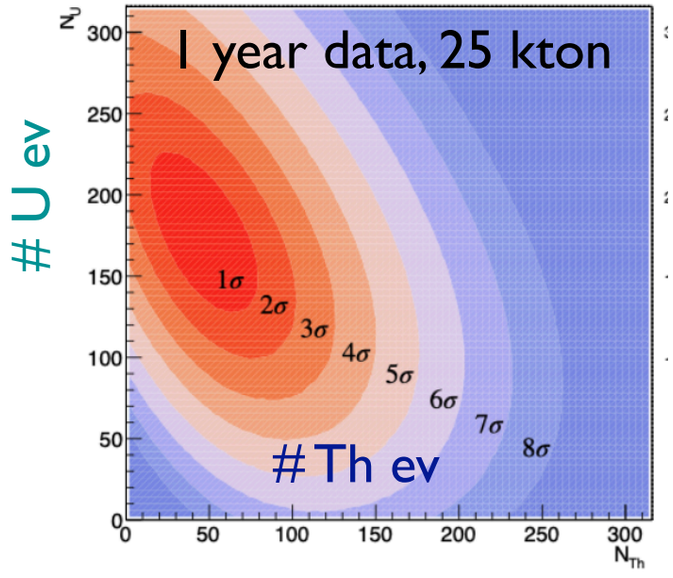


- **Geo-ν** observation by KL, Borexino (< 220 ev)
- **THEIA**: large statistics, complementary site: 218 ev/yr (25 kt)
- Full spectral analysis with BDT for bkg rejection
- Future improvements: PID (p/e+, e-/e+)
- Could offer first evidence for surface variation
- U/Th ratio to 15% precision in 10 years
- **Reactor ν** prospects: ~ 20 reactor ev/kt-yr
- Demonstrate techniques for remote reactor monitoring
- Range & direction at >1000km standoff



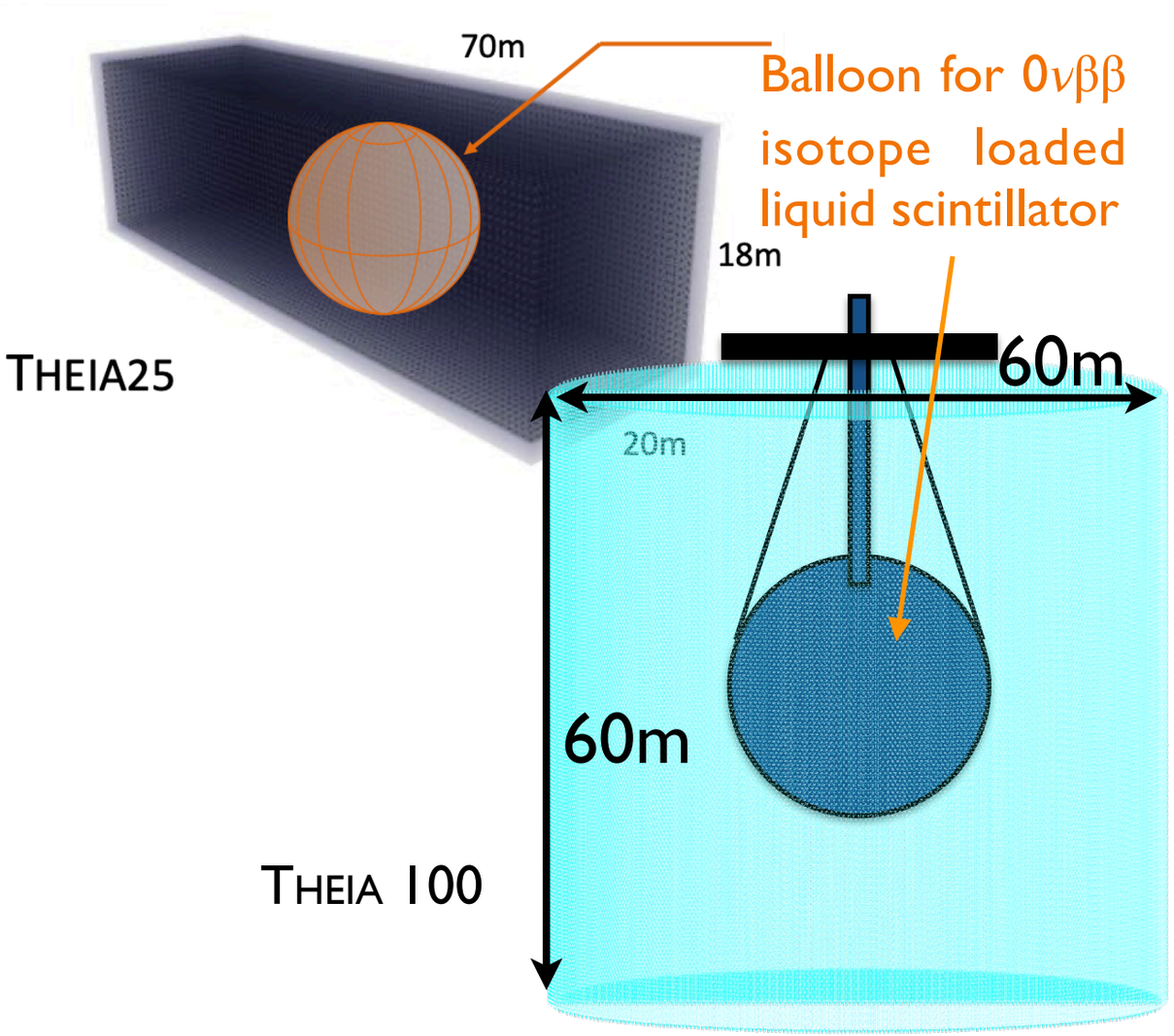




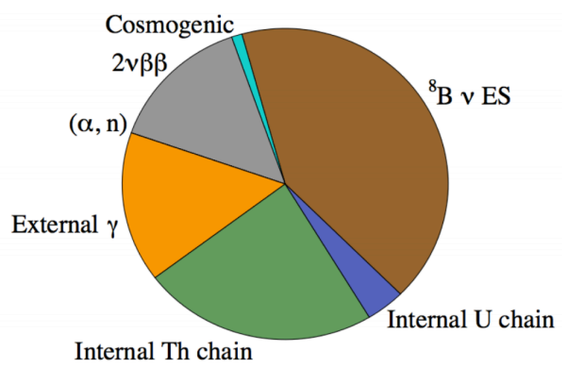


ονββ with hybrid detectors

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



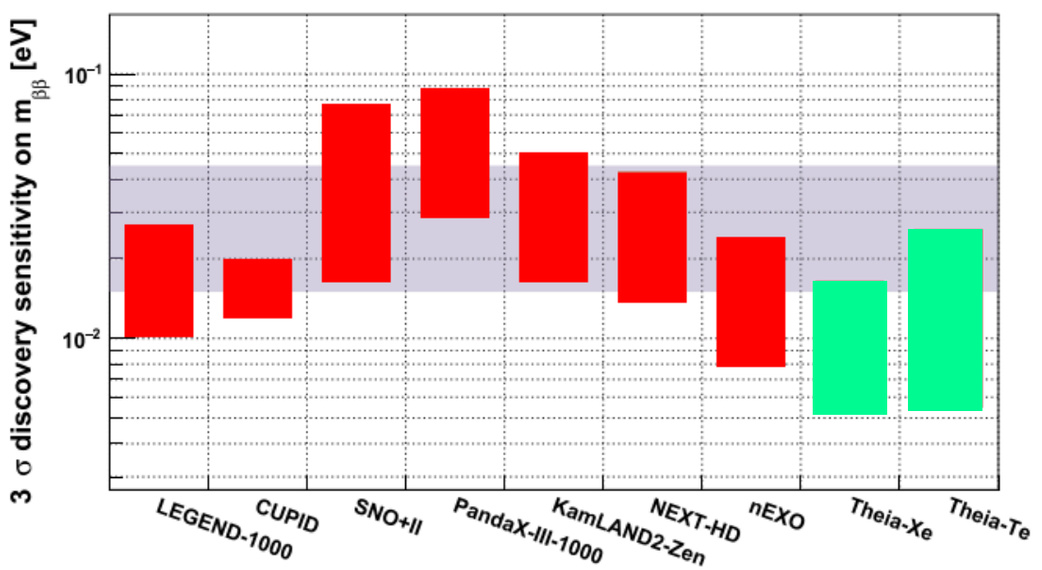
SNO+ Collaboration



Background reduction via event imaging: PID, multi-site, directionality

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

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



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)

Hybrid detector development



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

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Queens
SNOLAB
Toronto

China
Tsinghua

Finland
Jyvaskyla

Germany
Aachen
Dresden
Hamburg
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