Let There be Light

The development of "Hybrid" Cherenkov / scintillation neutrino detectors

Next-generation neutrino detection with EOS & THEIA

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UC Berkeley & LBNL

Pisa Meeting 2024

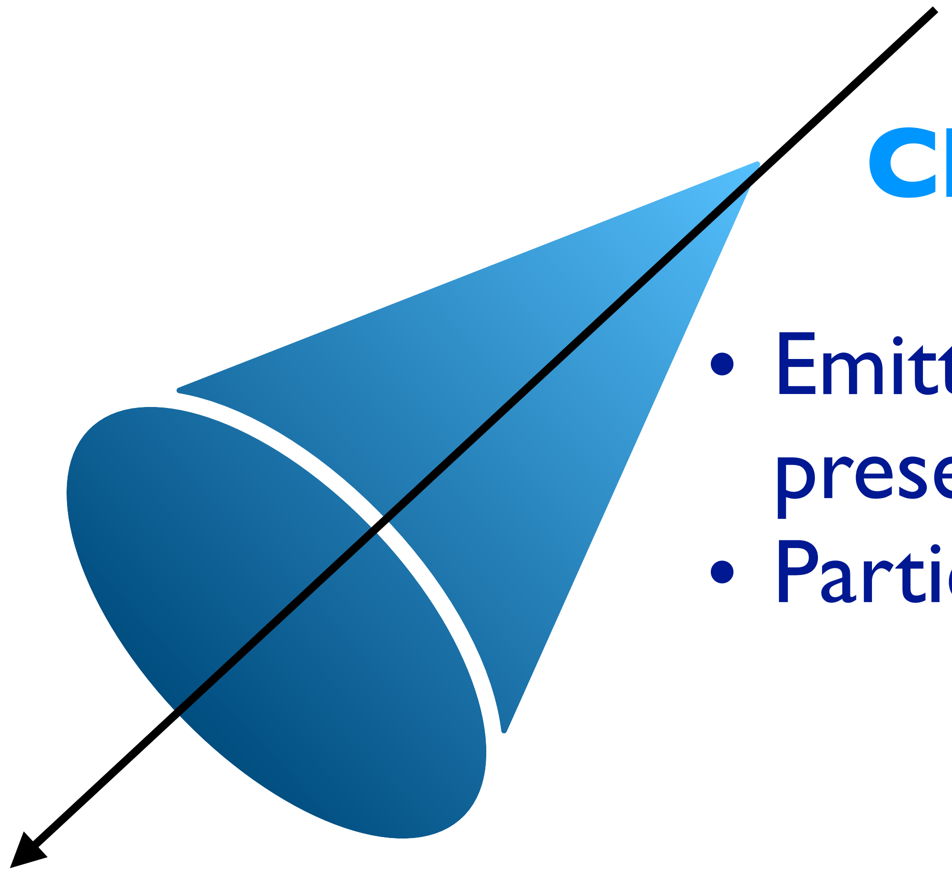
THEIA

- **Hybrid Cherenkov/ scintillation detector**
- **Multi-messenger astrophysics**
- **Probe the fundamental nature of matter: CPV and Majorana ν**
- **Unique opportunity to engage a broad community in world-leading "big science"**

Disclaimer: calls out a subset of the critical team involved in this effort; all citations at the end

Innovative neutrino detection

Combine two well-tested methods for neutrino detection, for enhanced precision:

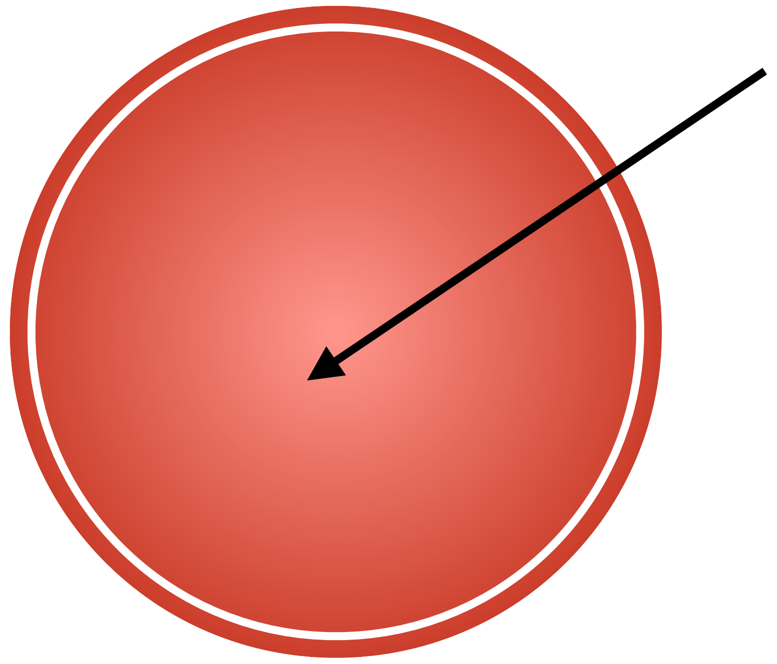


Cherenkov light

- Emitted with a unique topology that preserves directional information
- Particle-dependent threshold

Scintillation light

- Extremely high light yield: high efficiency for detection
- Particle-dependent response offers particle identification



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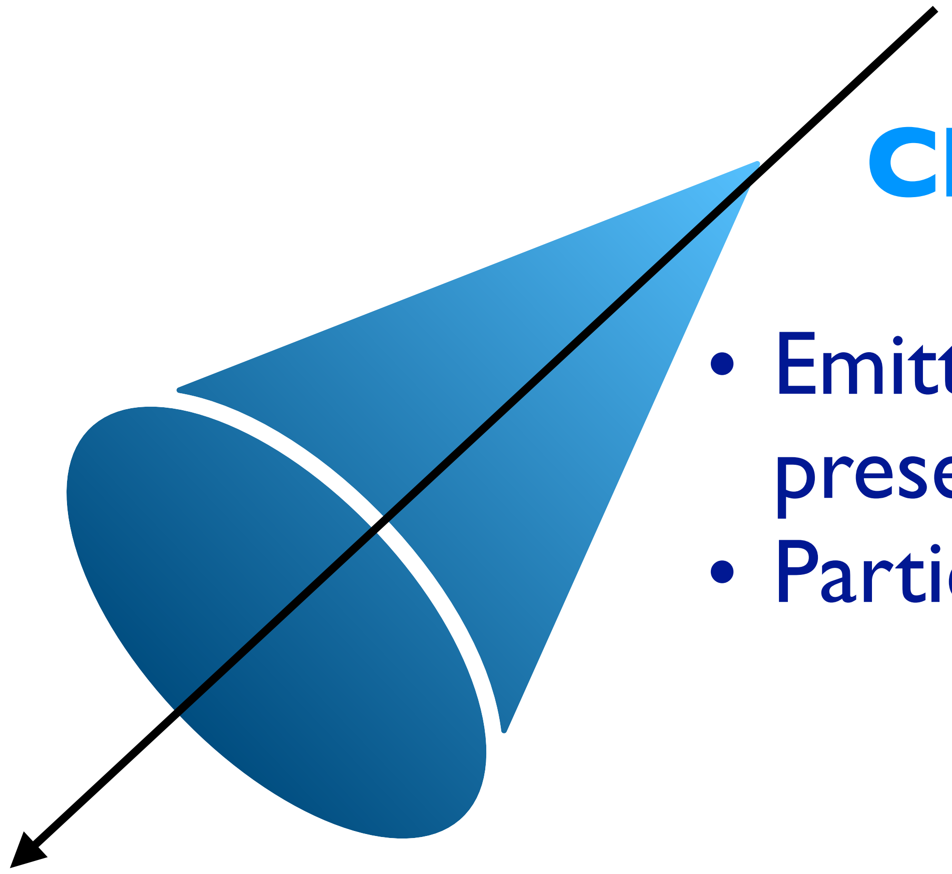

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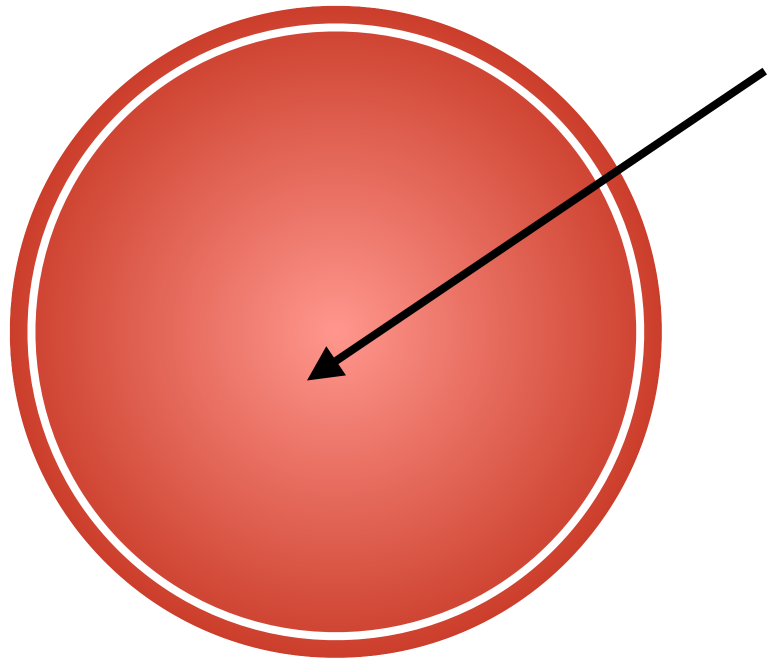

The whole is greater than the sum of the parts

The ratio of the two signals provides additional information on the type of particle interacting: Improved background rejection for precision measurements

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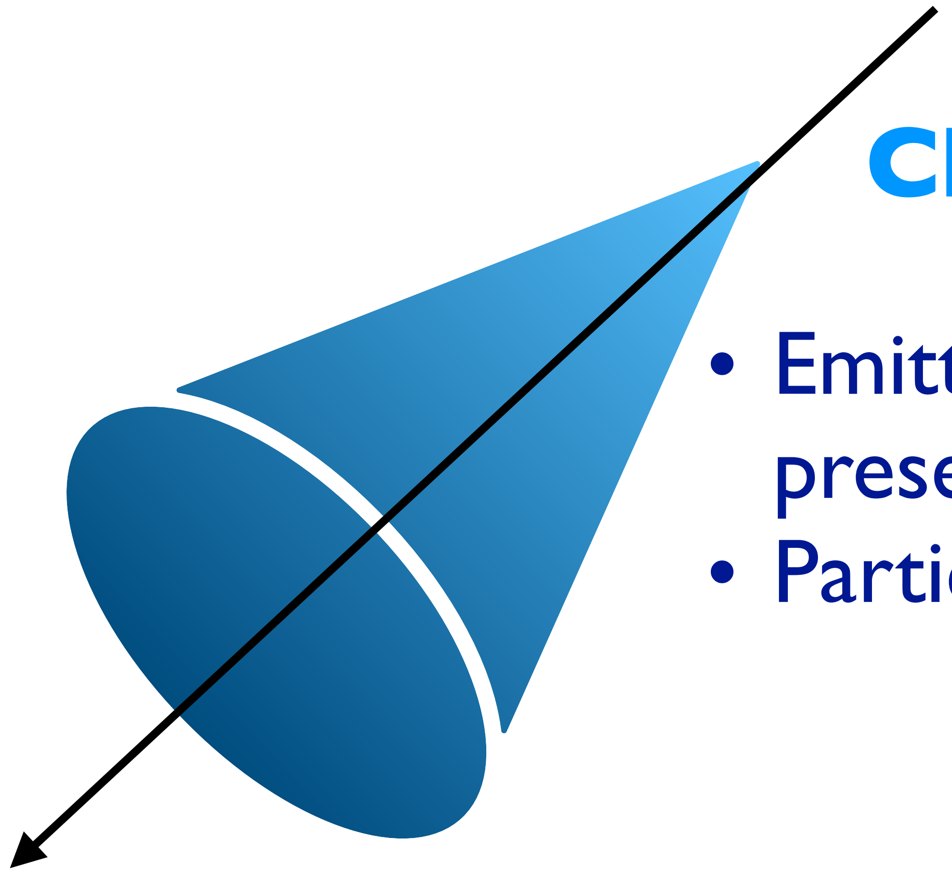

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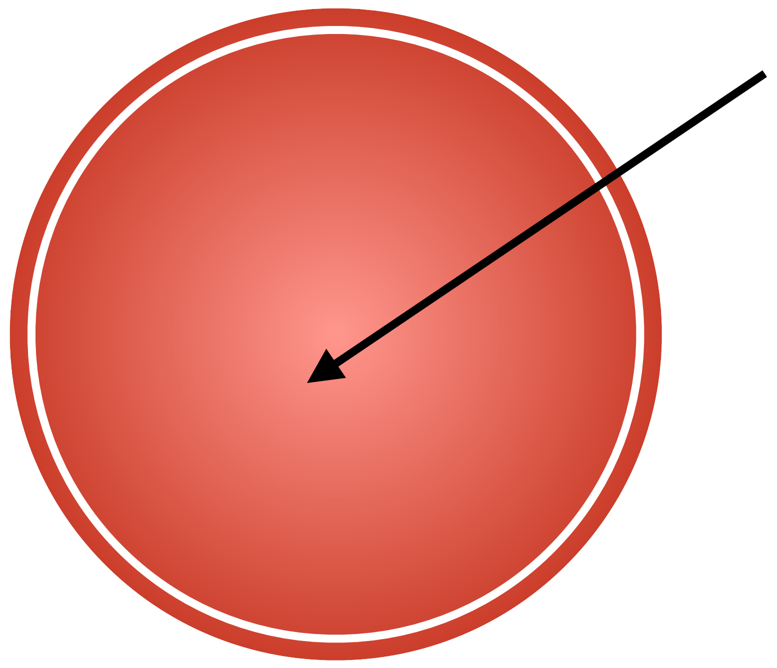

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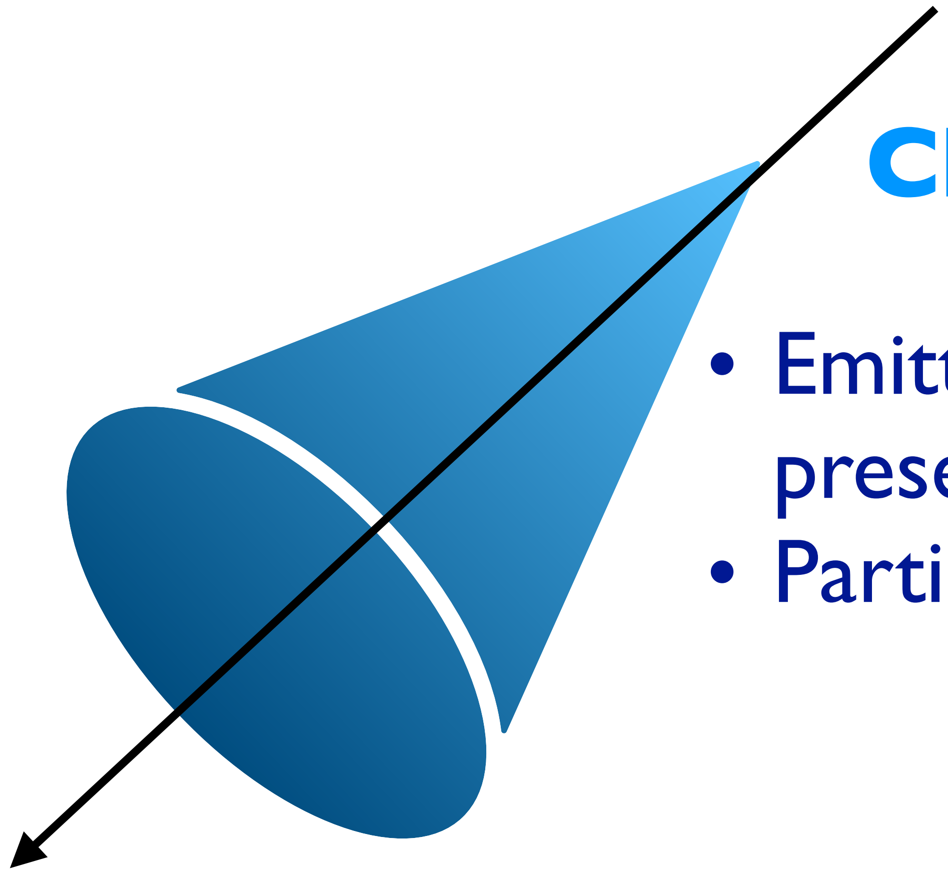

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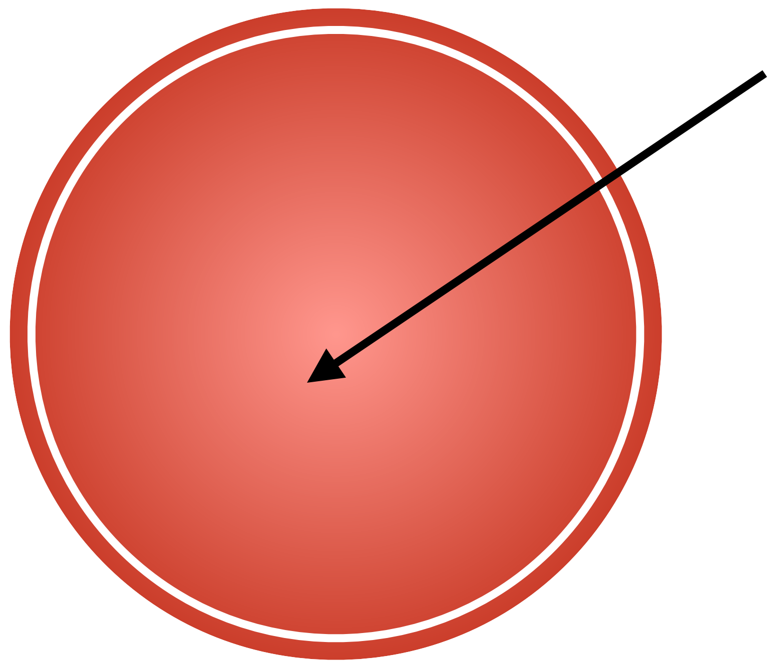

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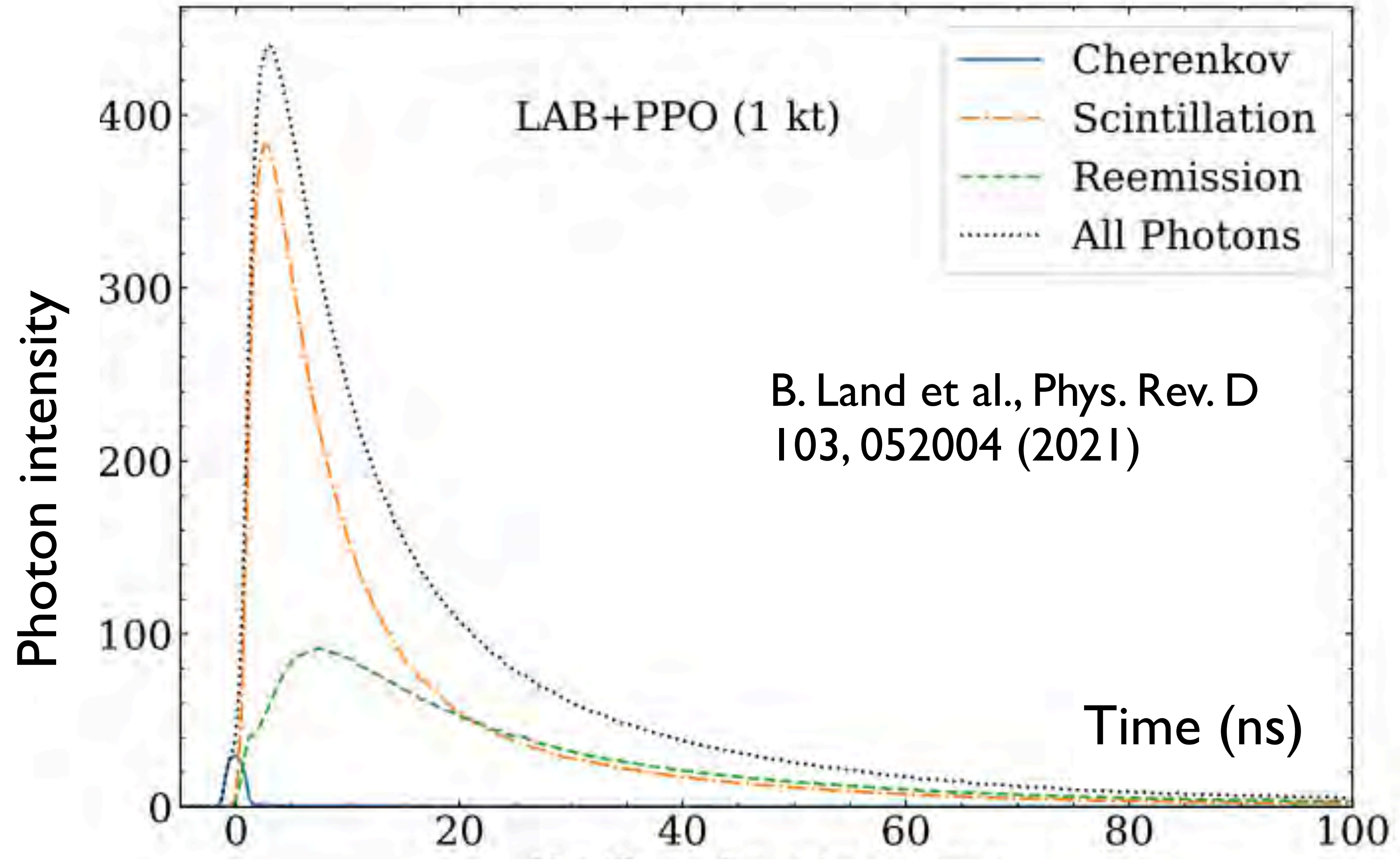

B. Land et al., Phys. Rev. D 103, 052004 (2021)

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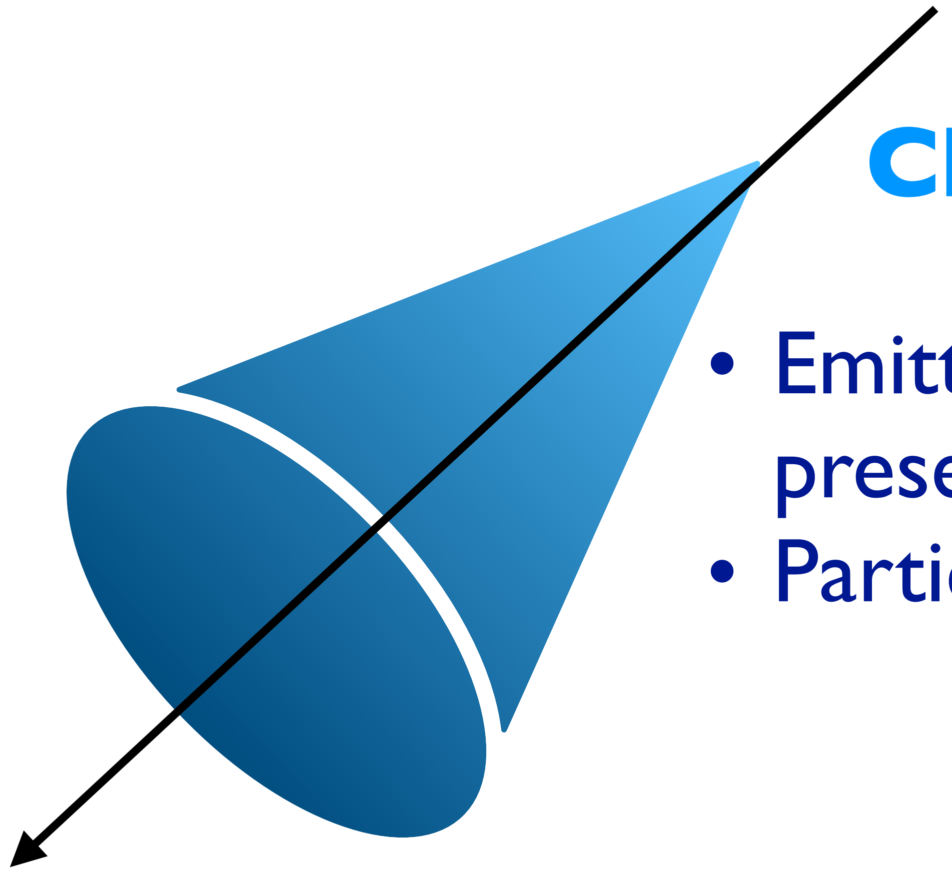

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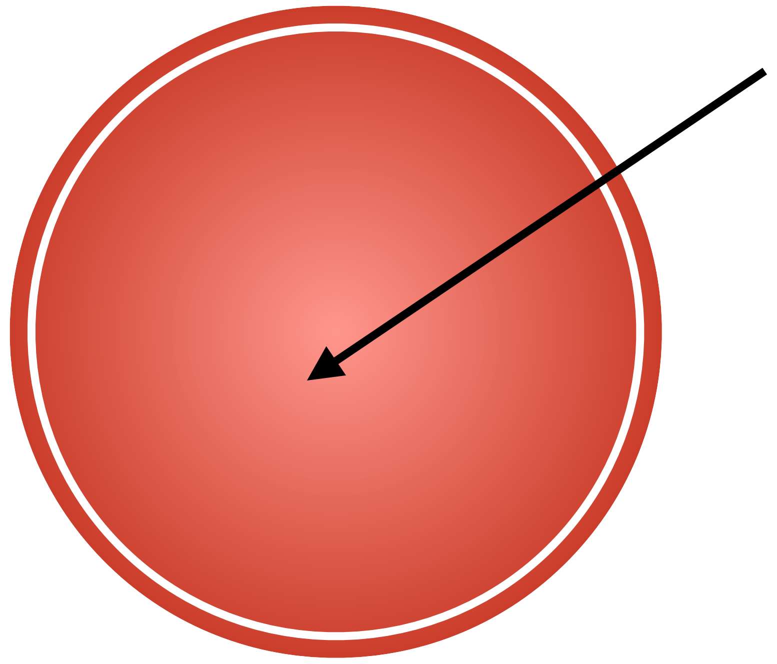

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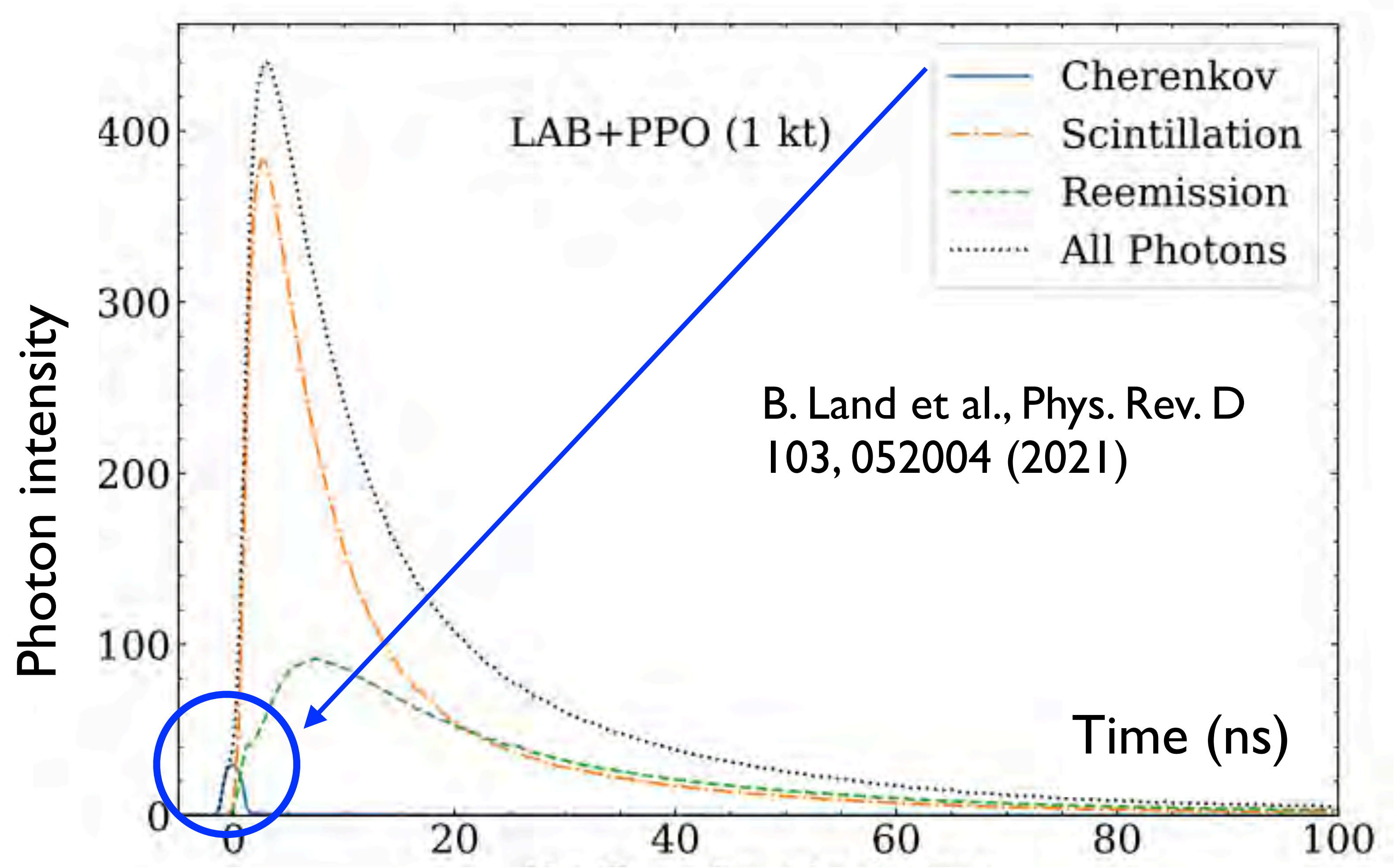

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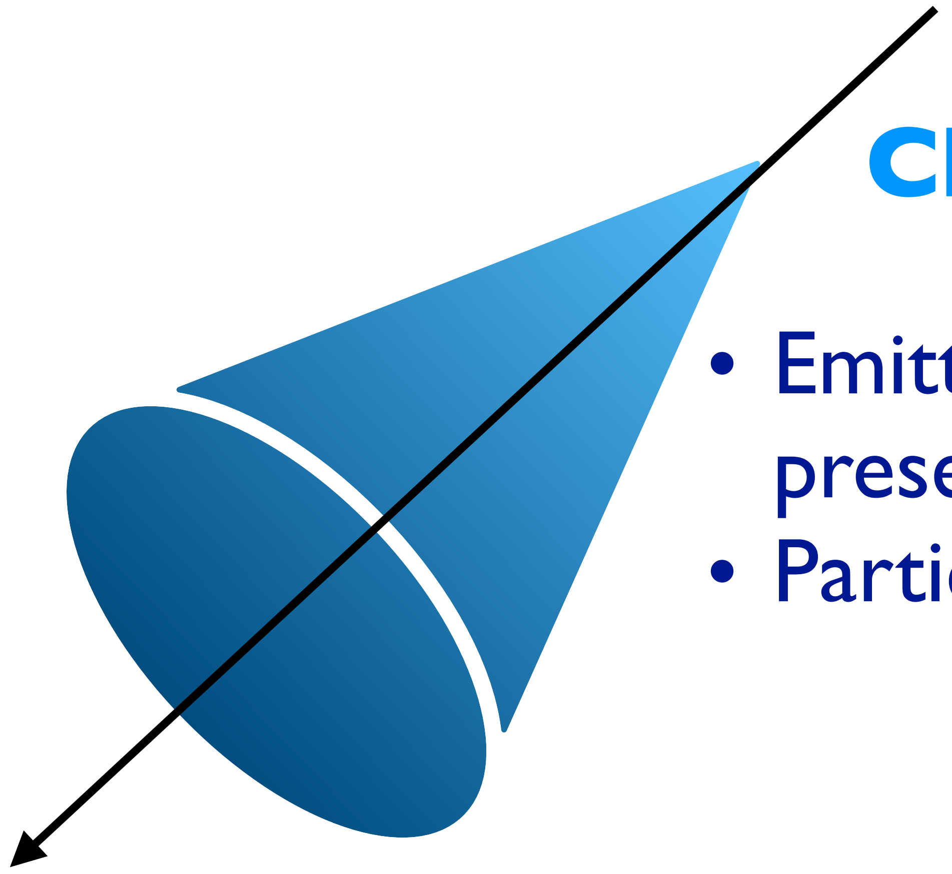

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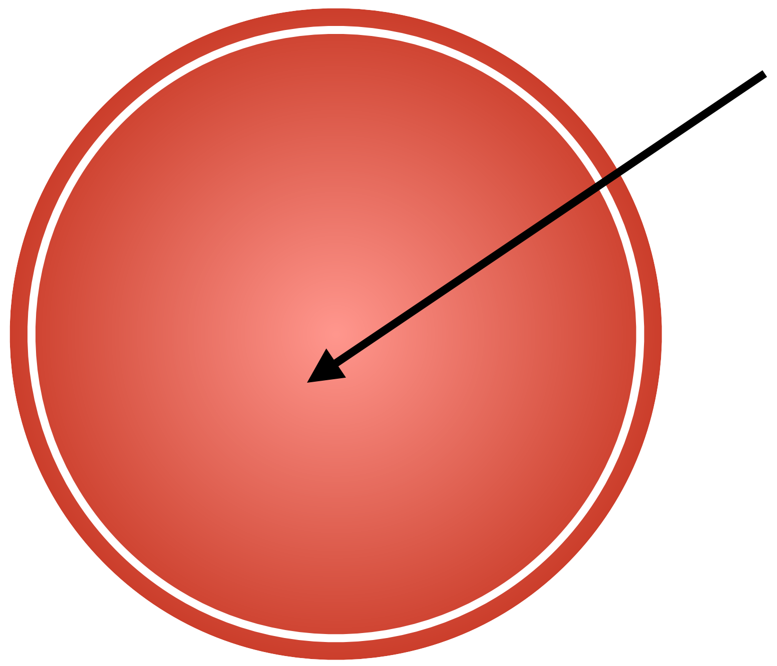

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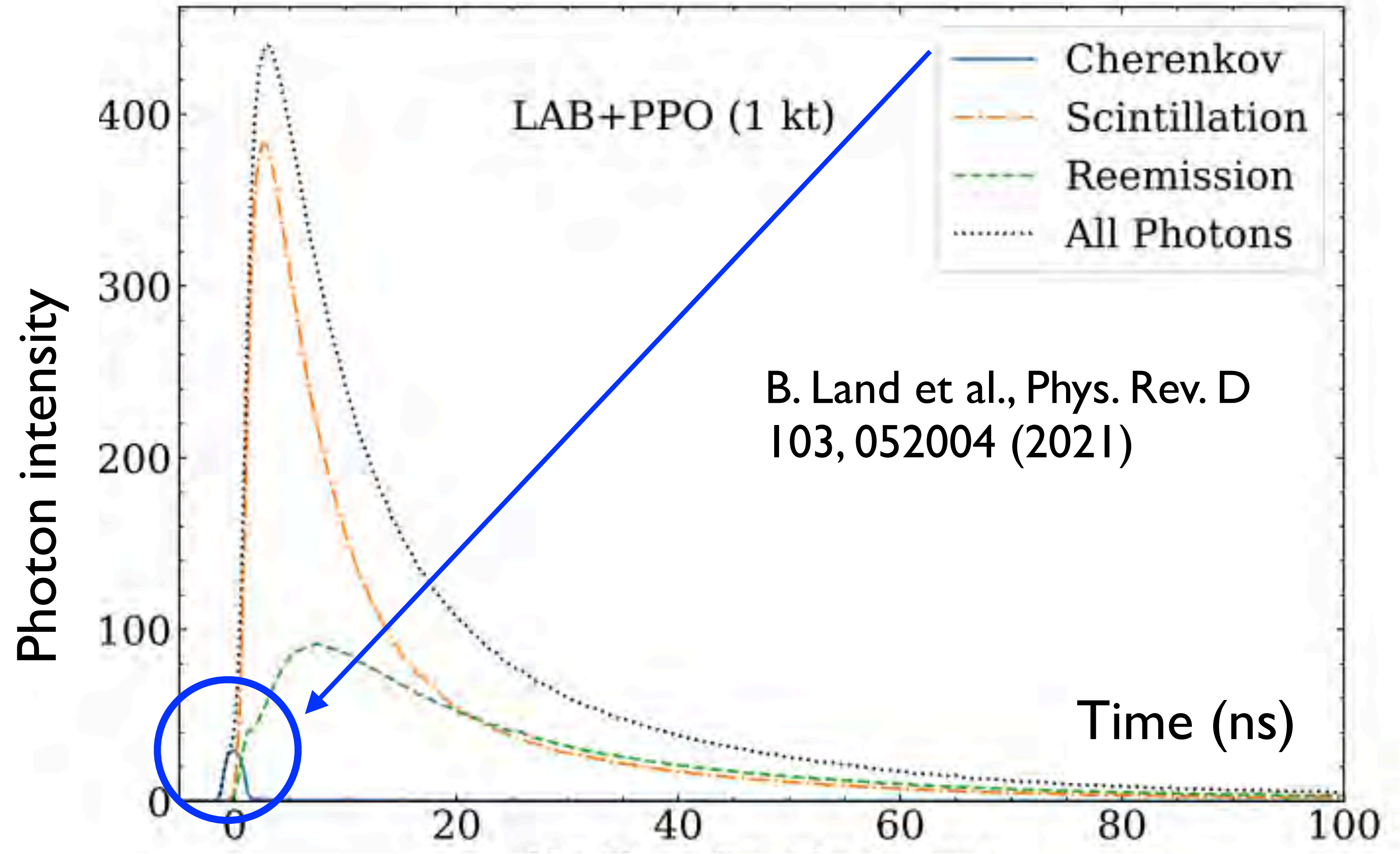
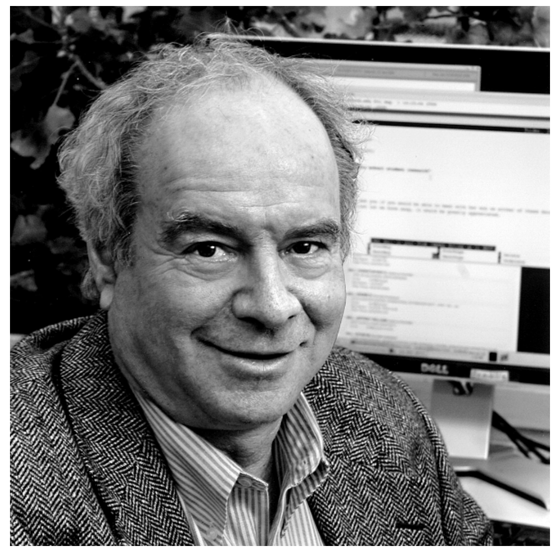
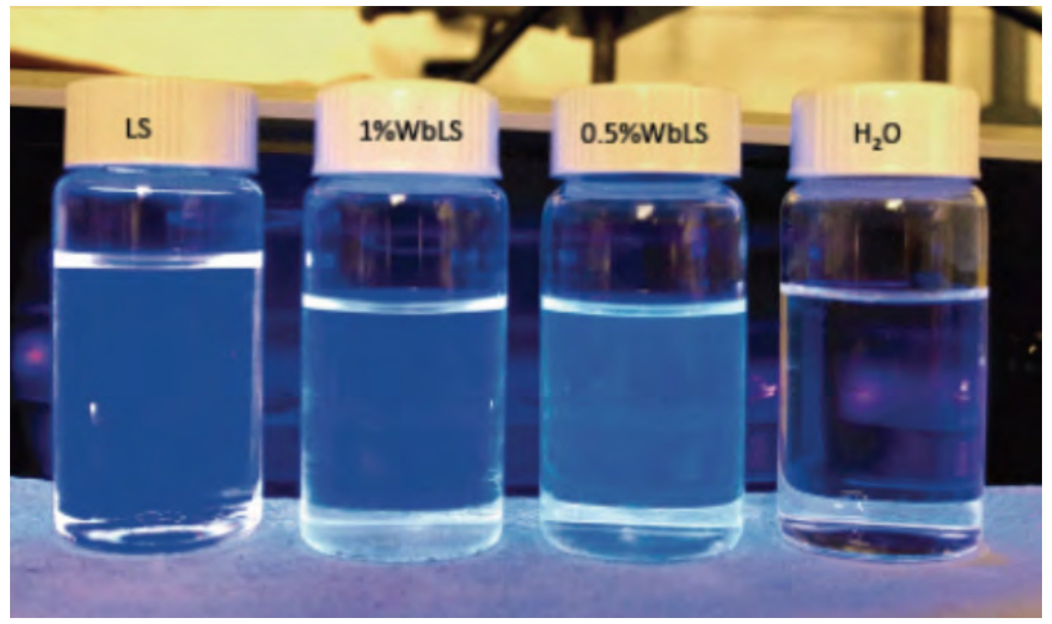


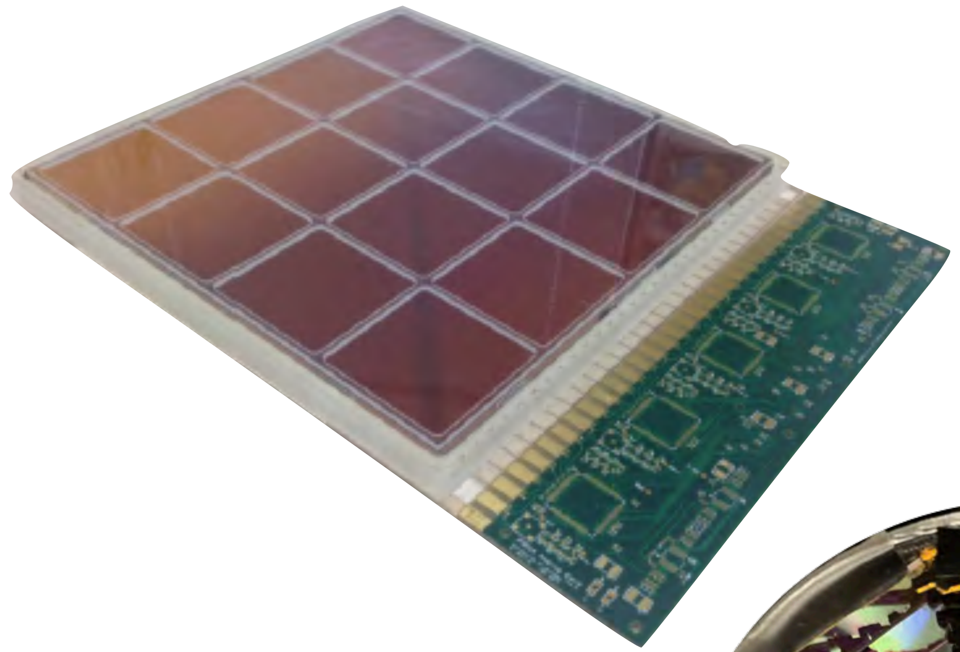
Enabling technology

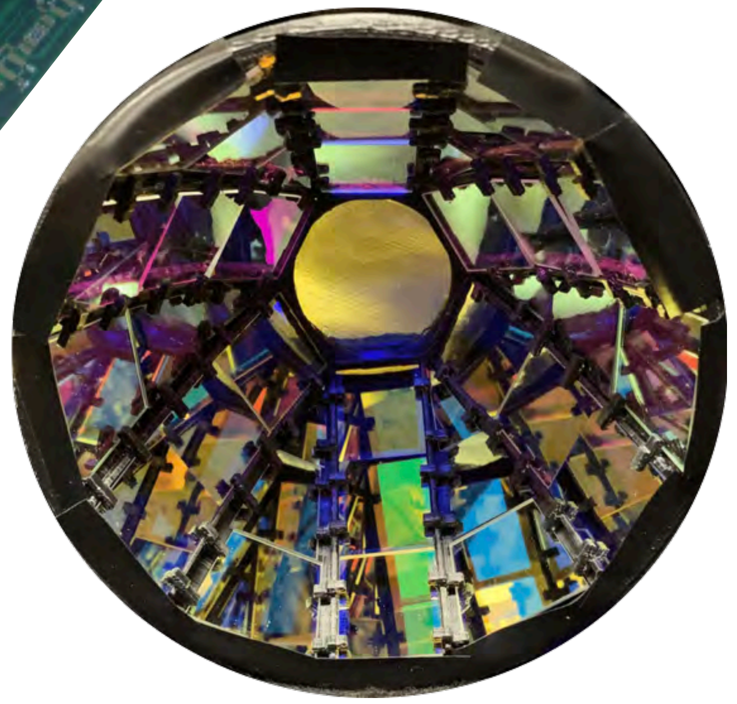



We focus our studies on three technologies that optimize hybrid Cherenkov/scintillation detection:







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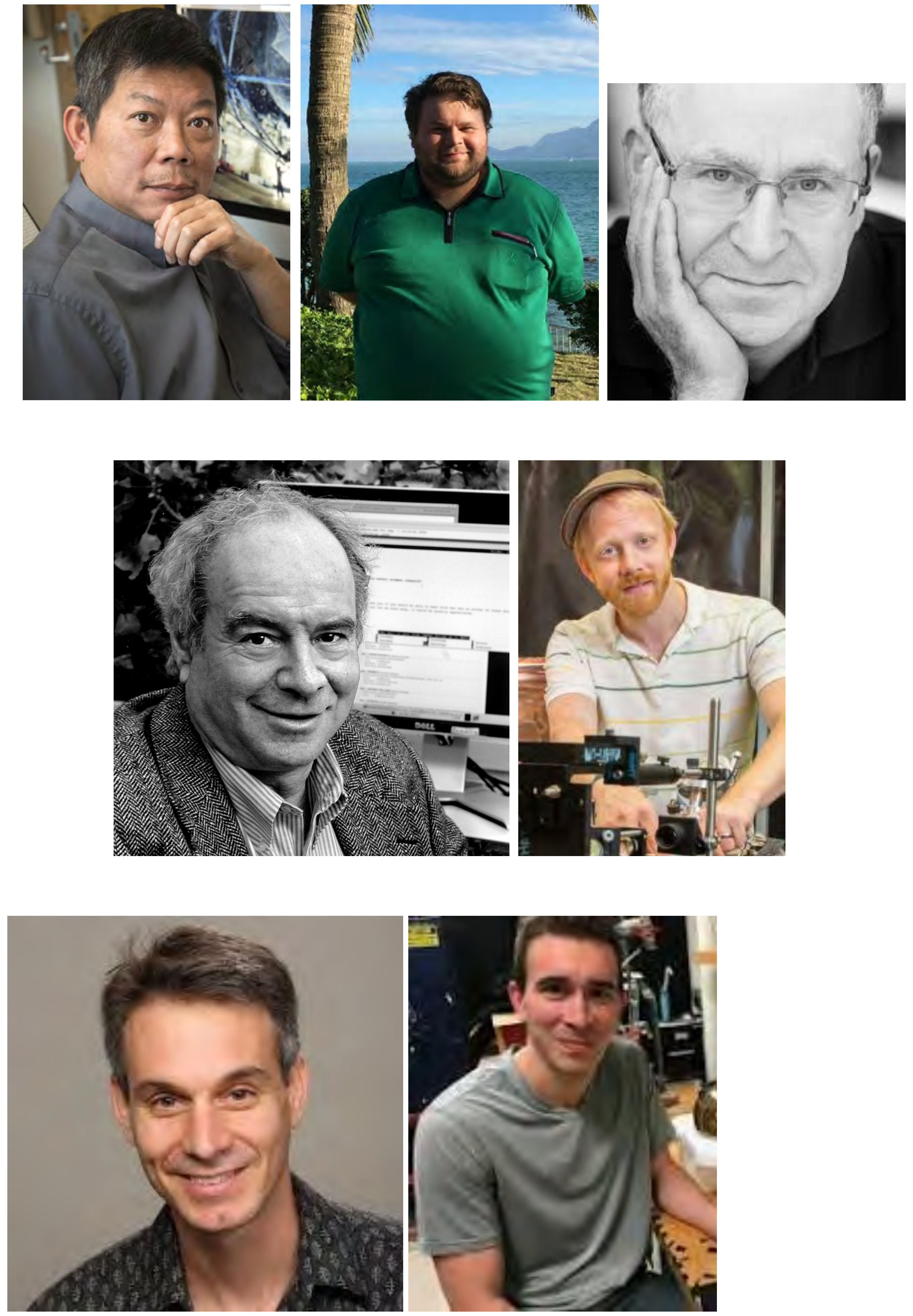

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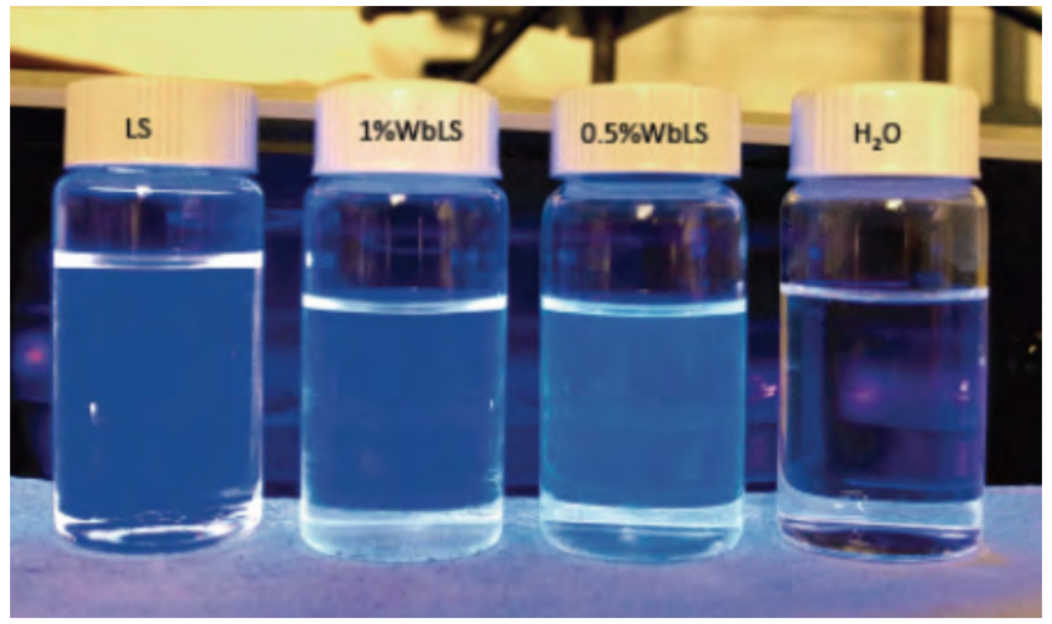

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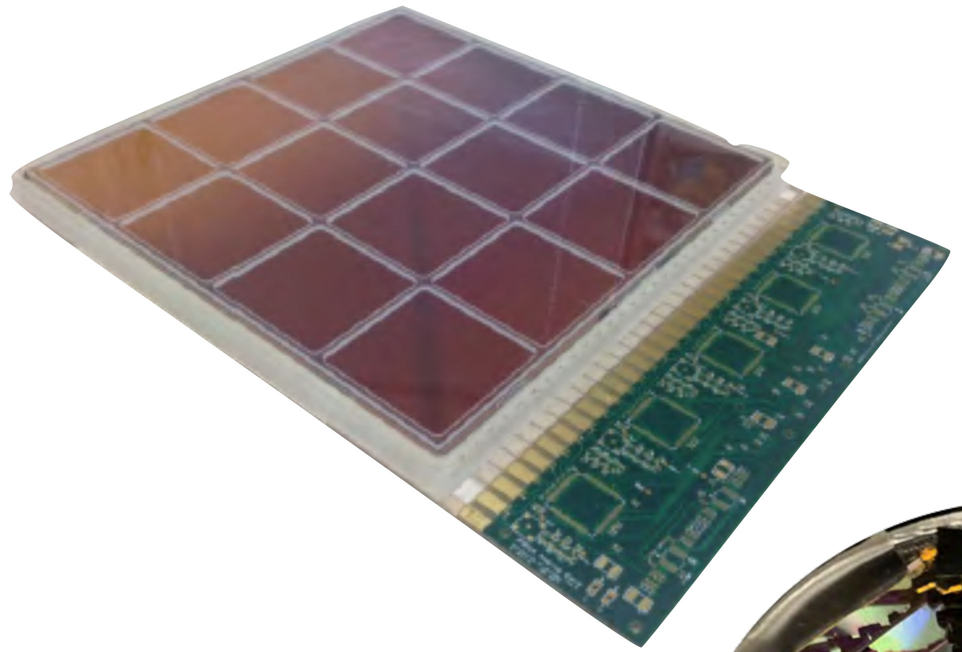

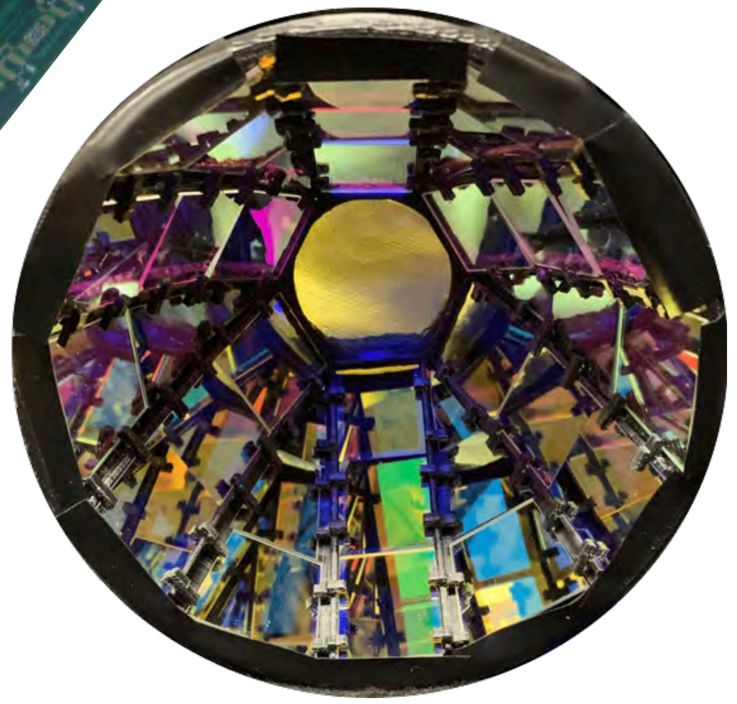

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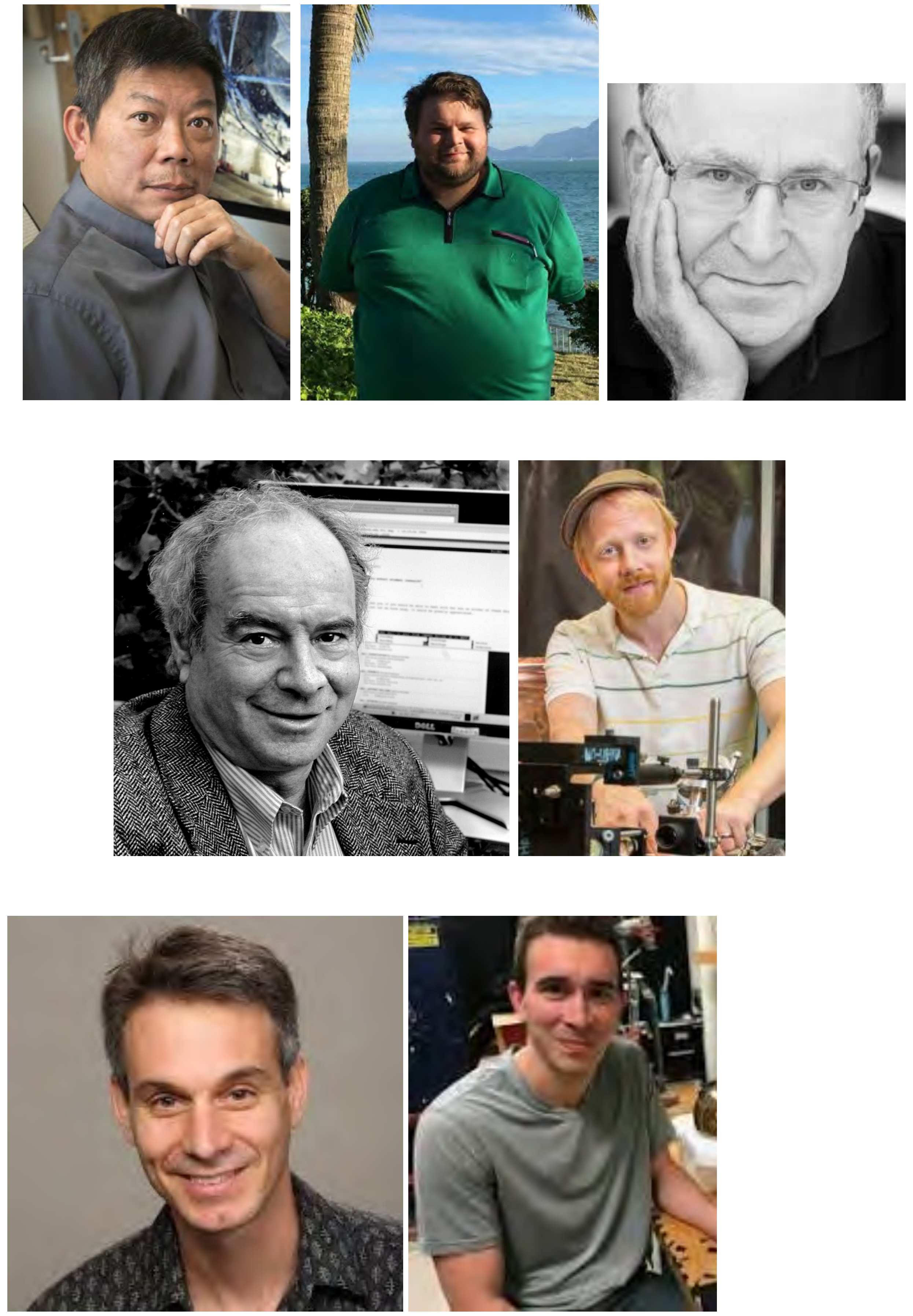

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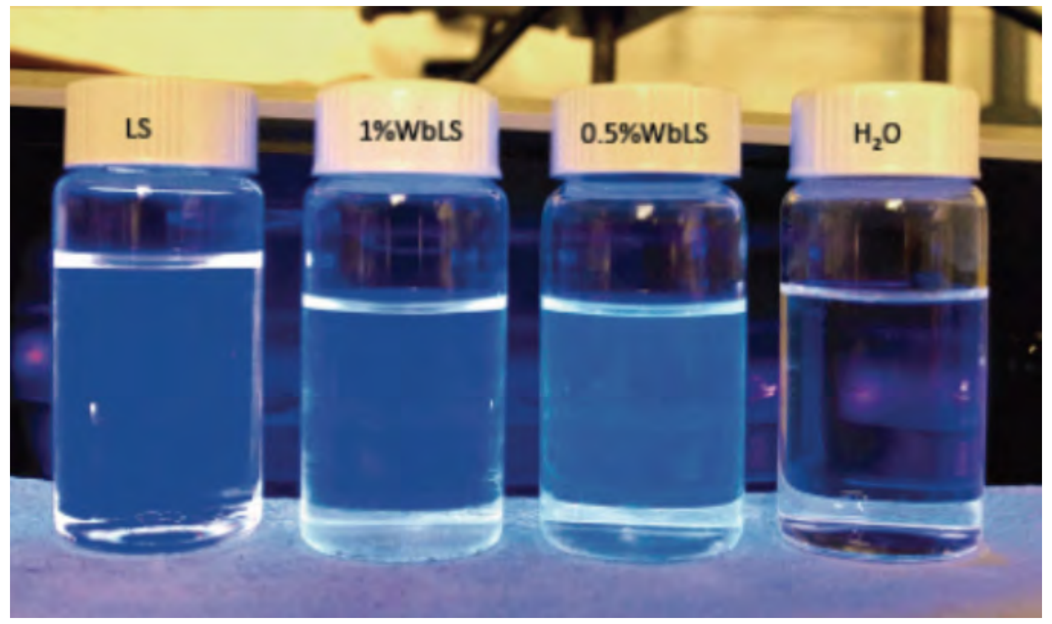

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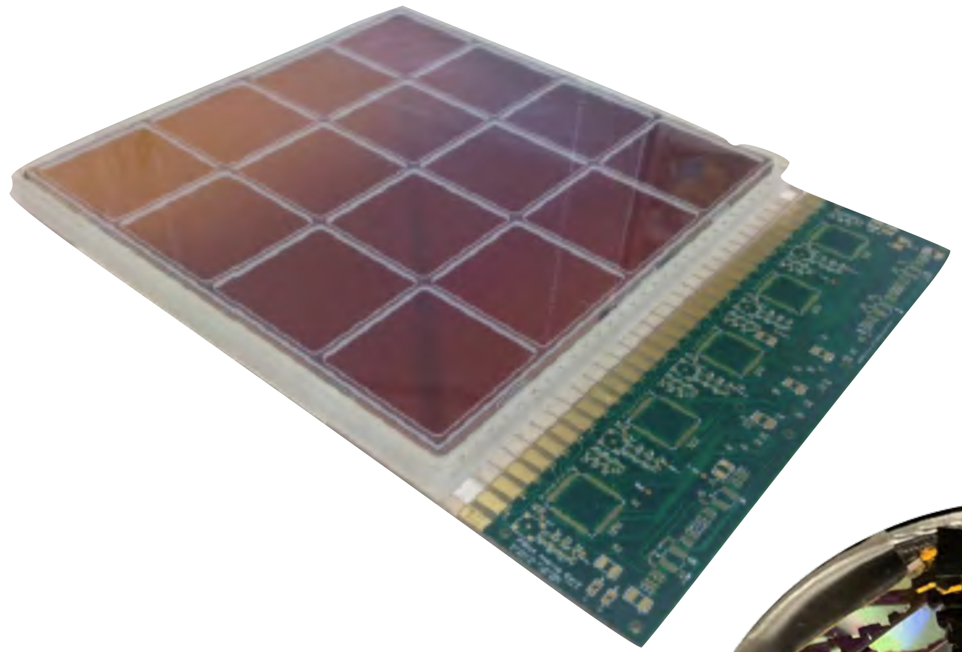

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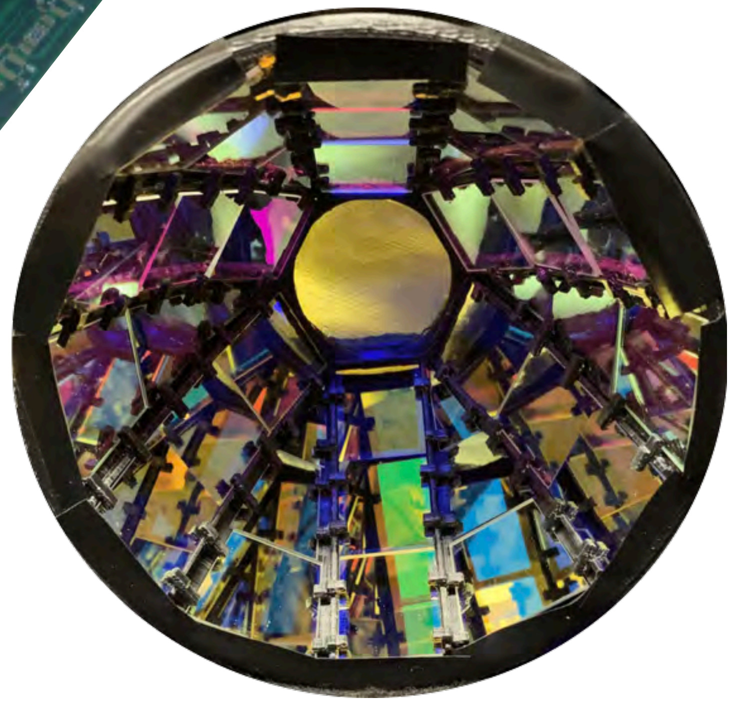

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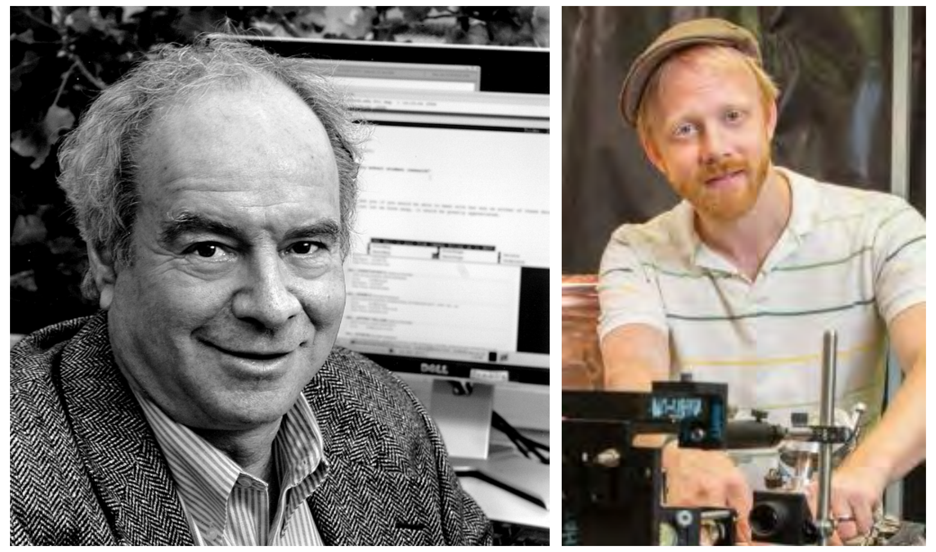

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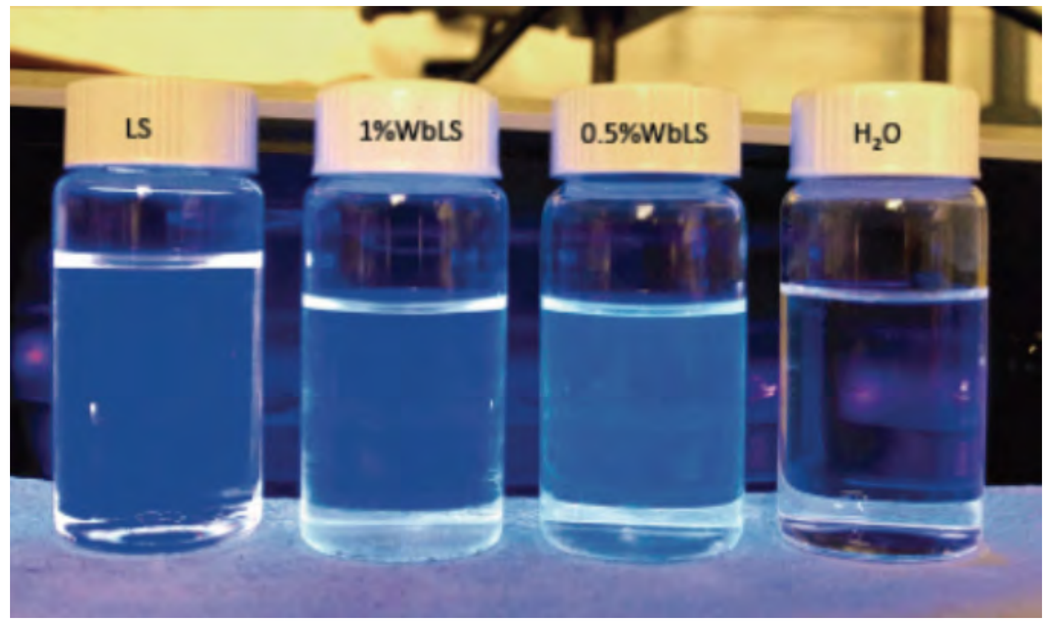

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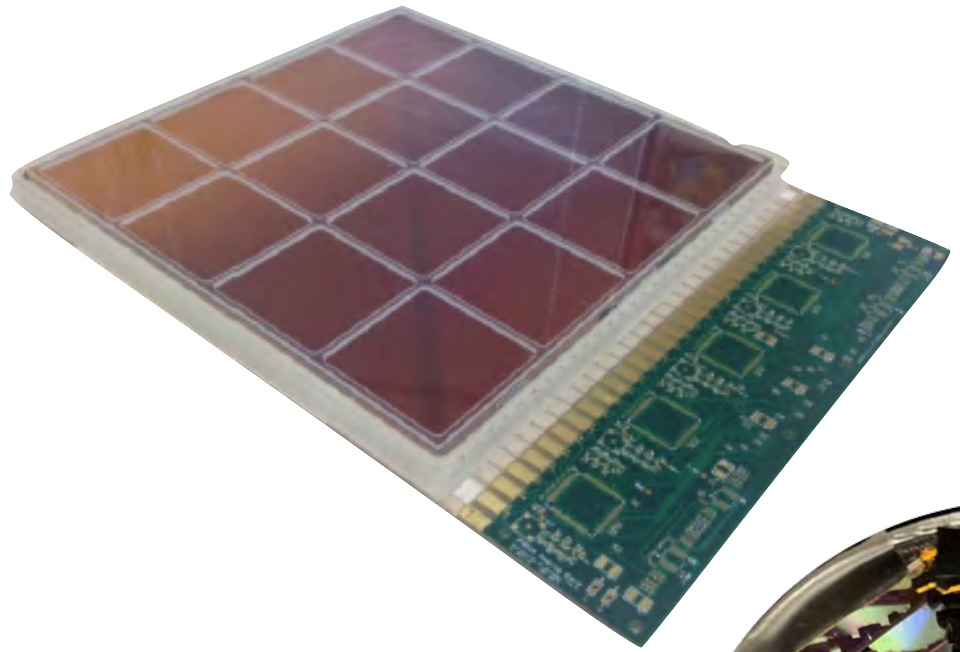

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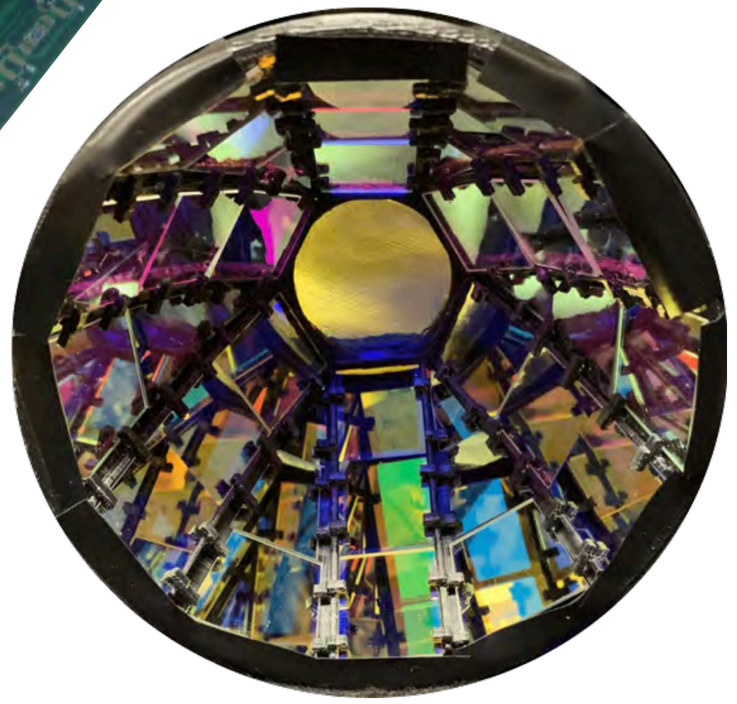

3. Dichroicons ("chromatic quantum sensing"). Cherenkov/scintillation separation via spectral sorting

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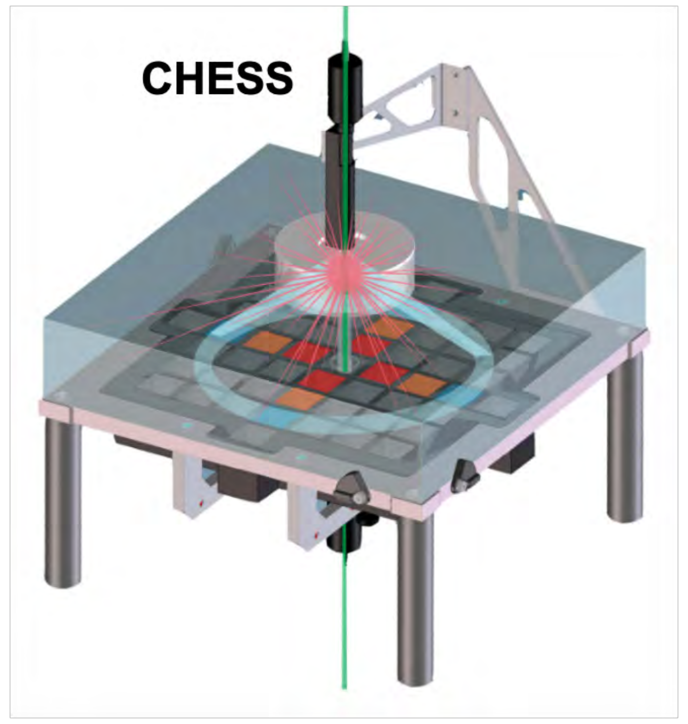
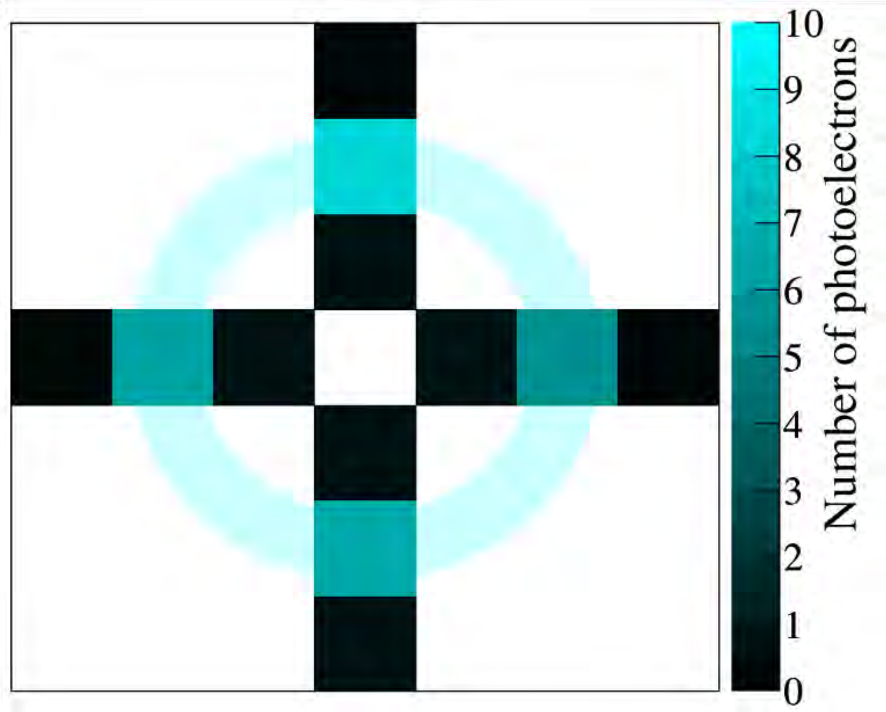
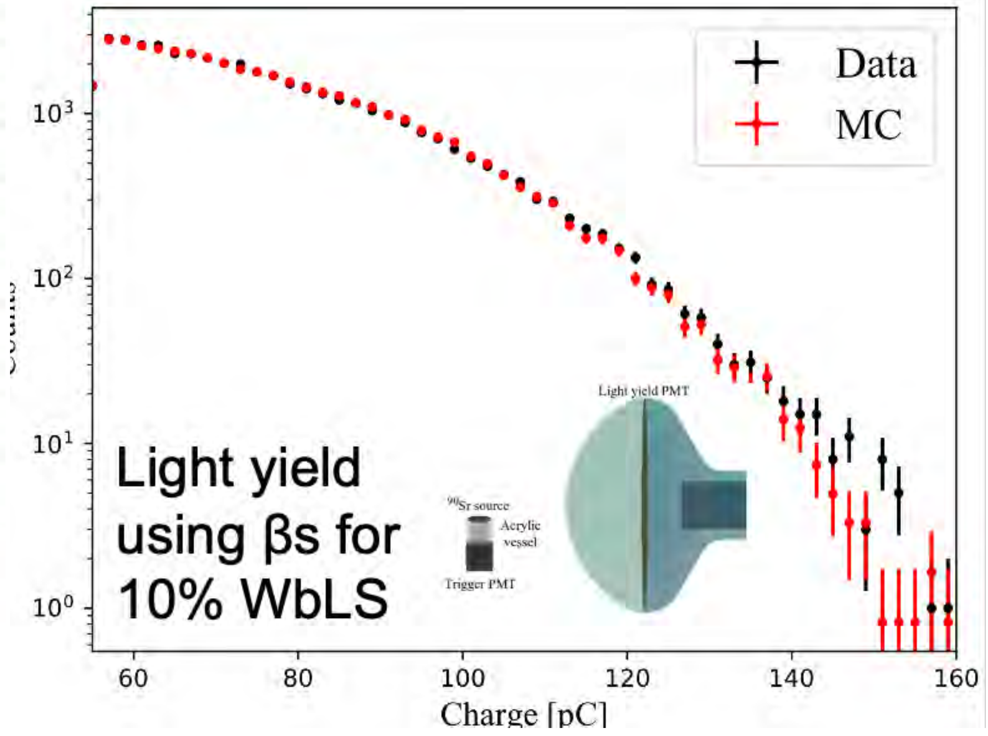
Builds on core (Wb)LS development at BNL (Yeh et al.)

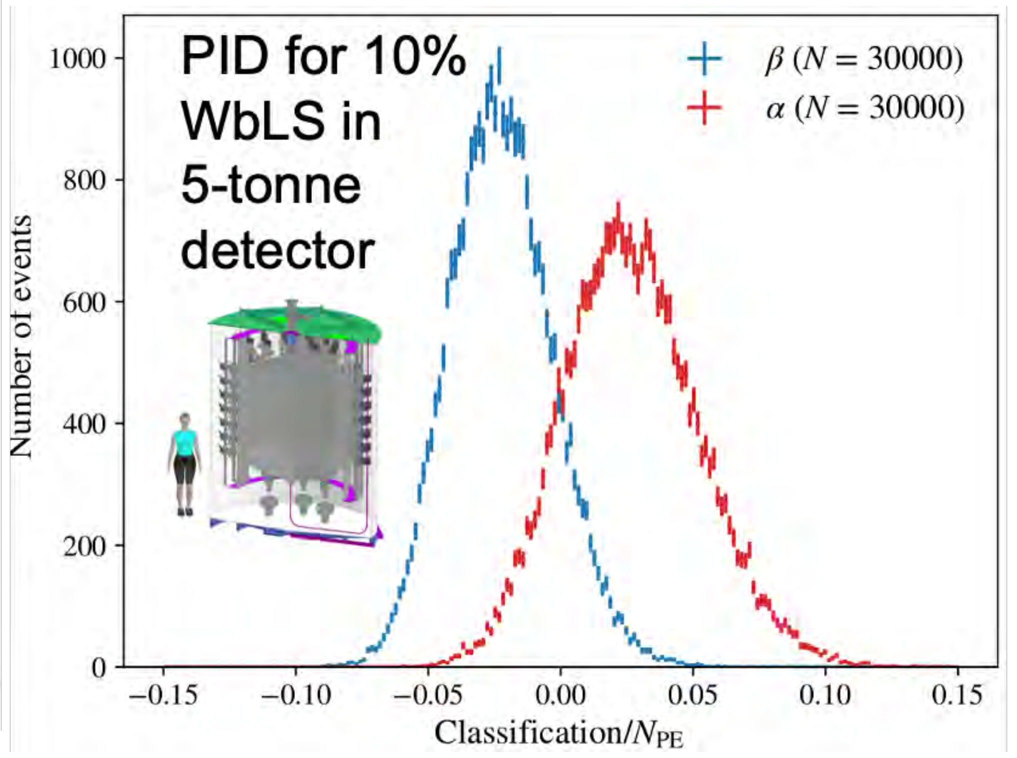
Technical accomplishments

WbLS characterization













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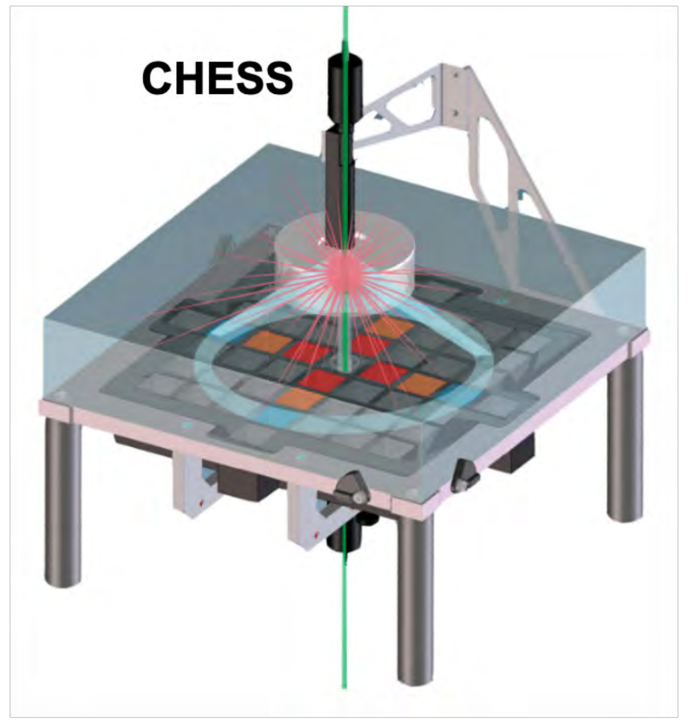
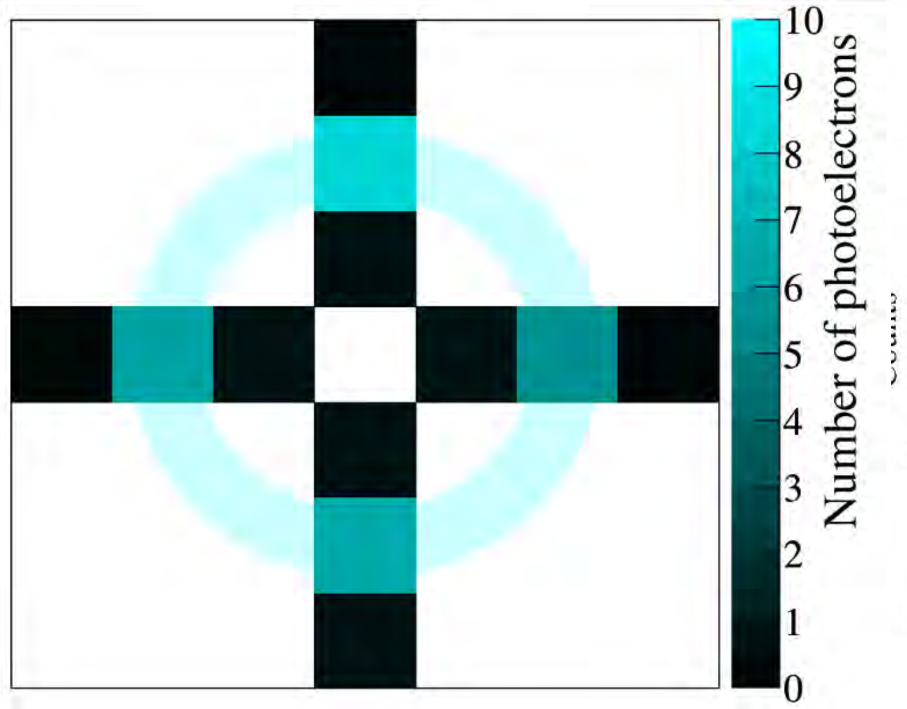
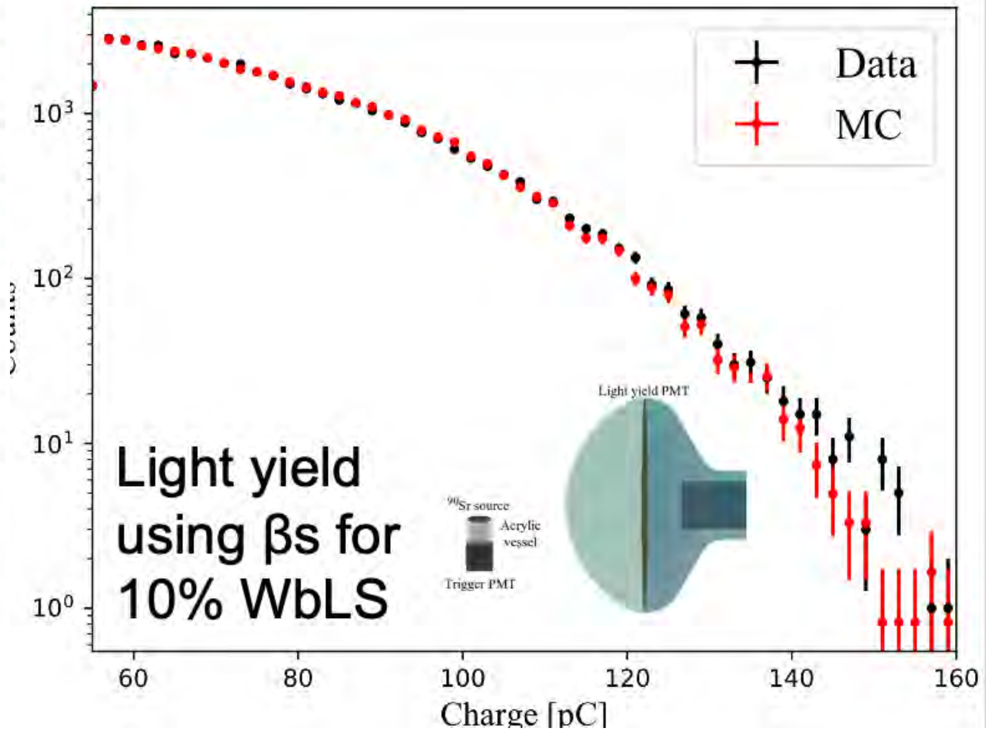
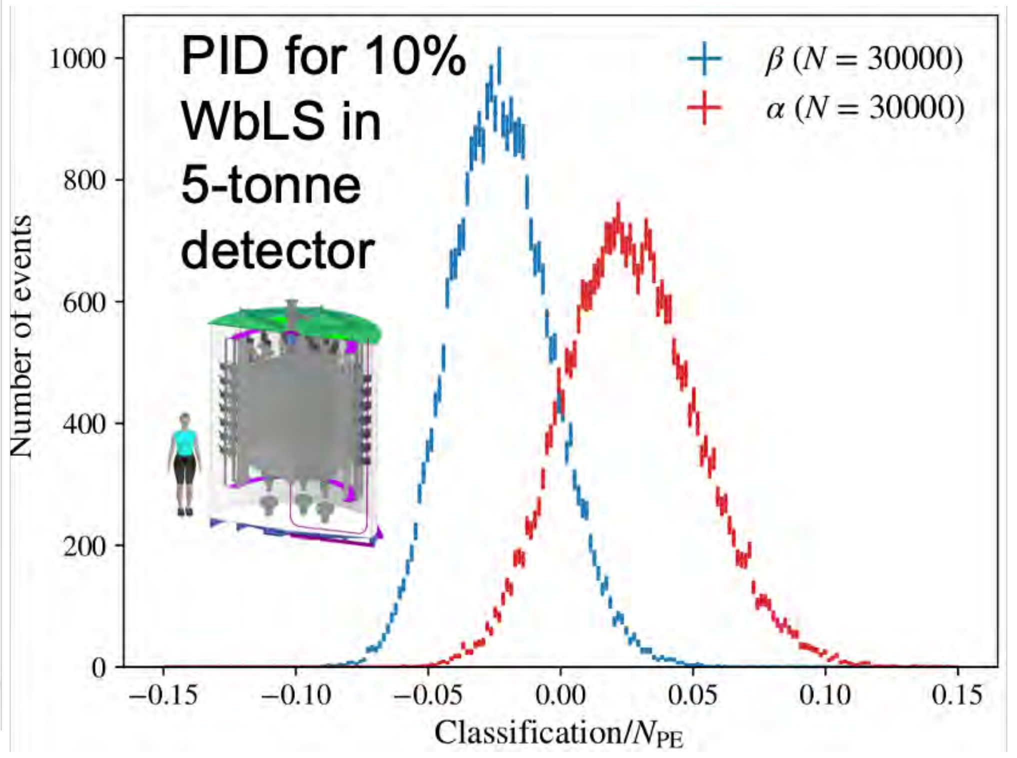
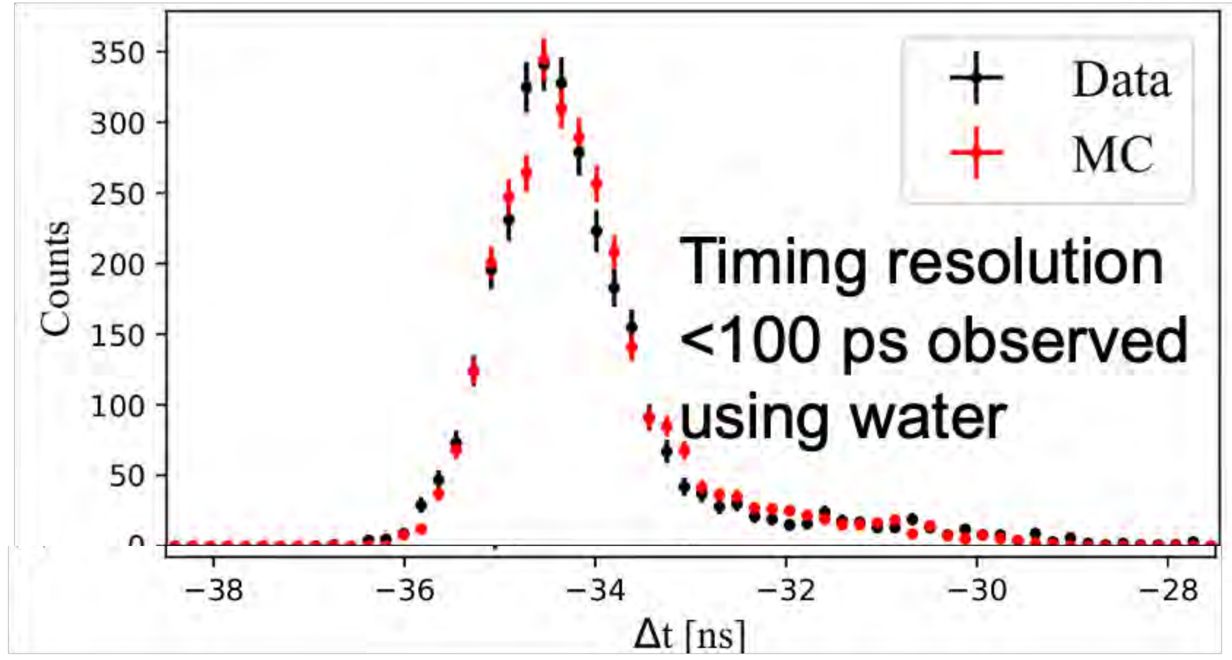


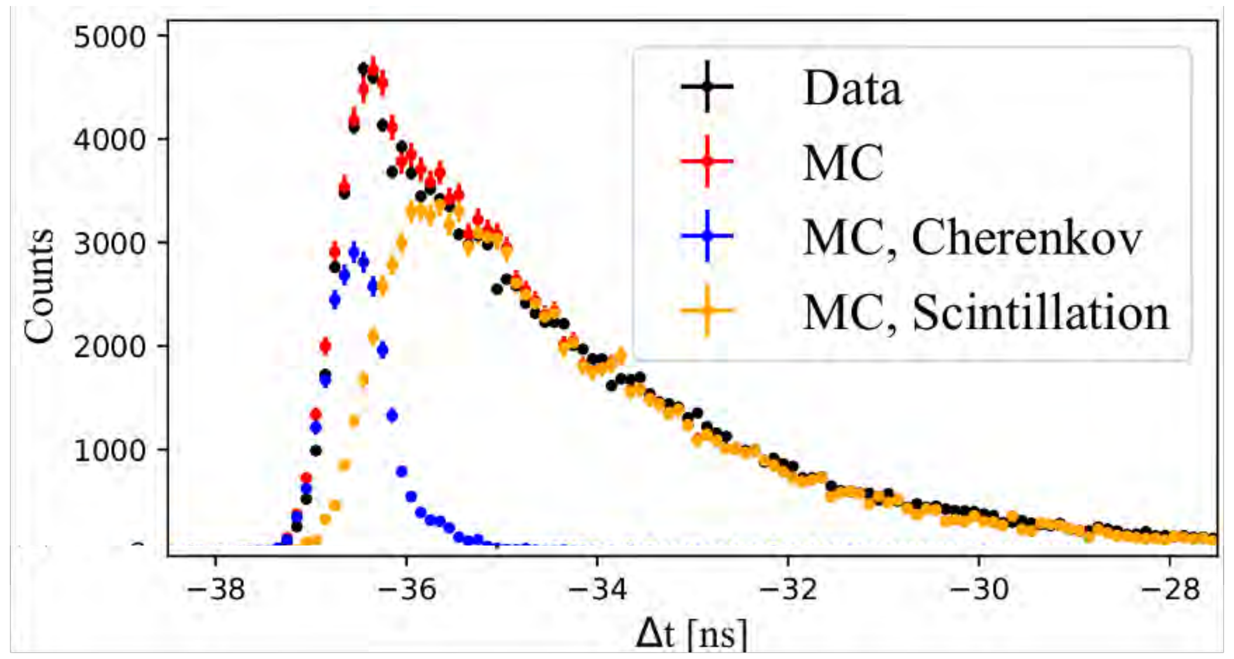






Fast timing photon detection





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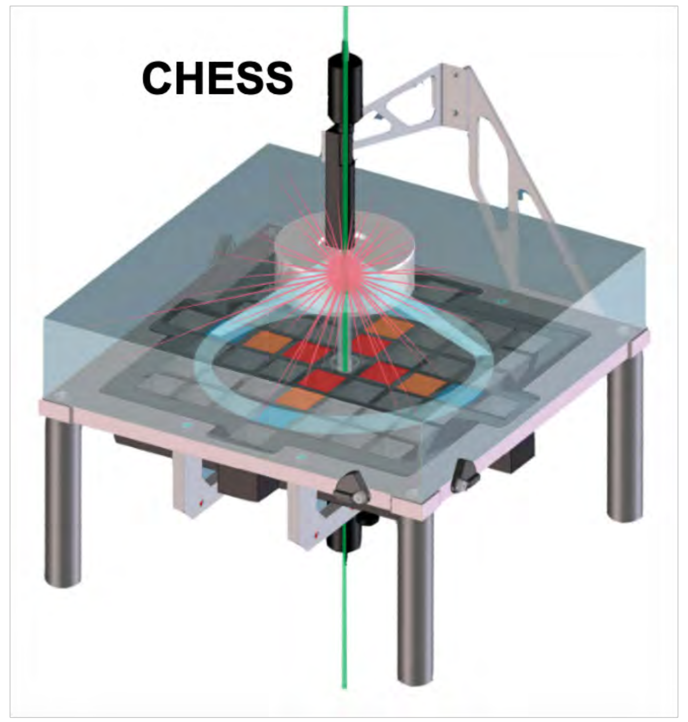

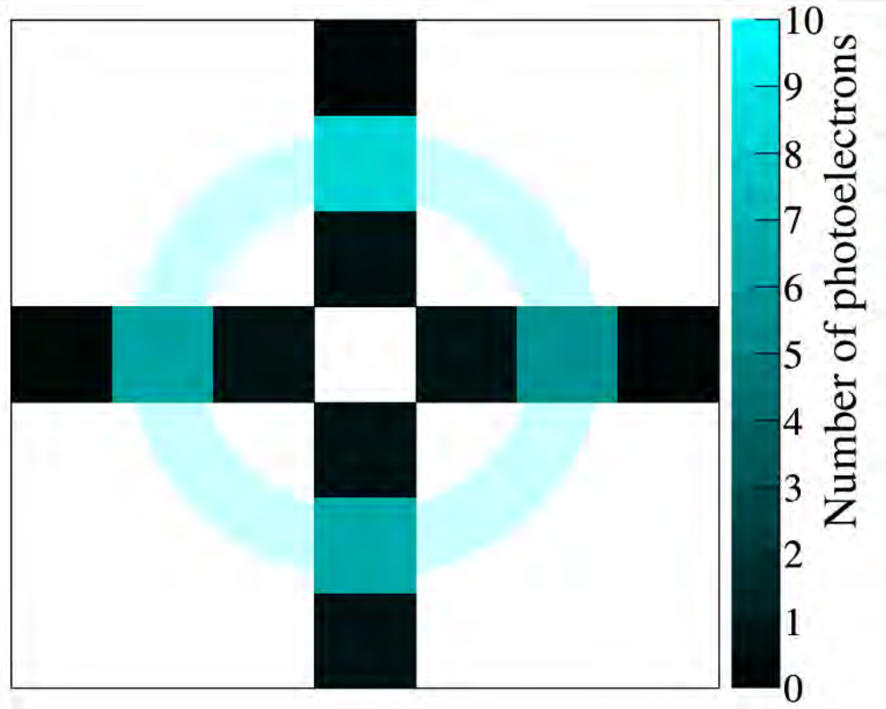

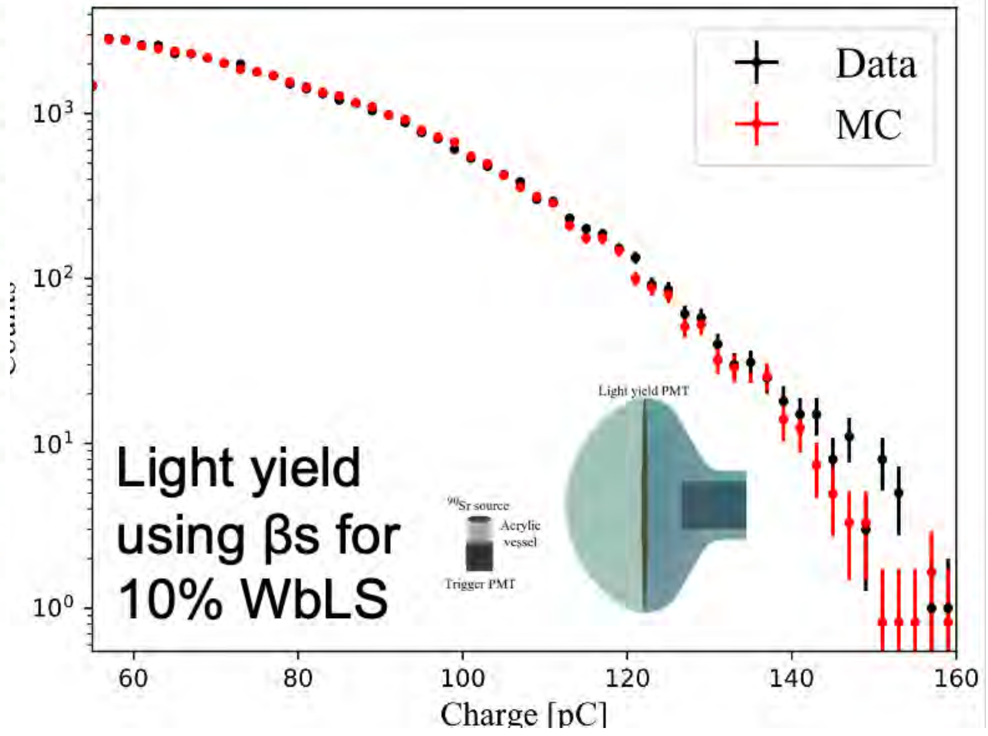

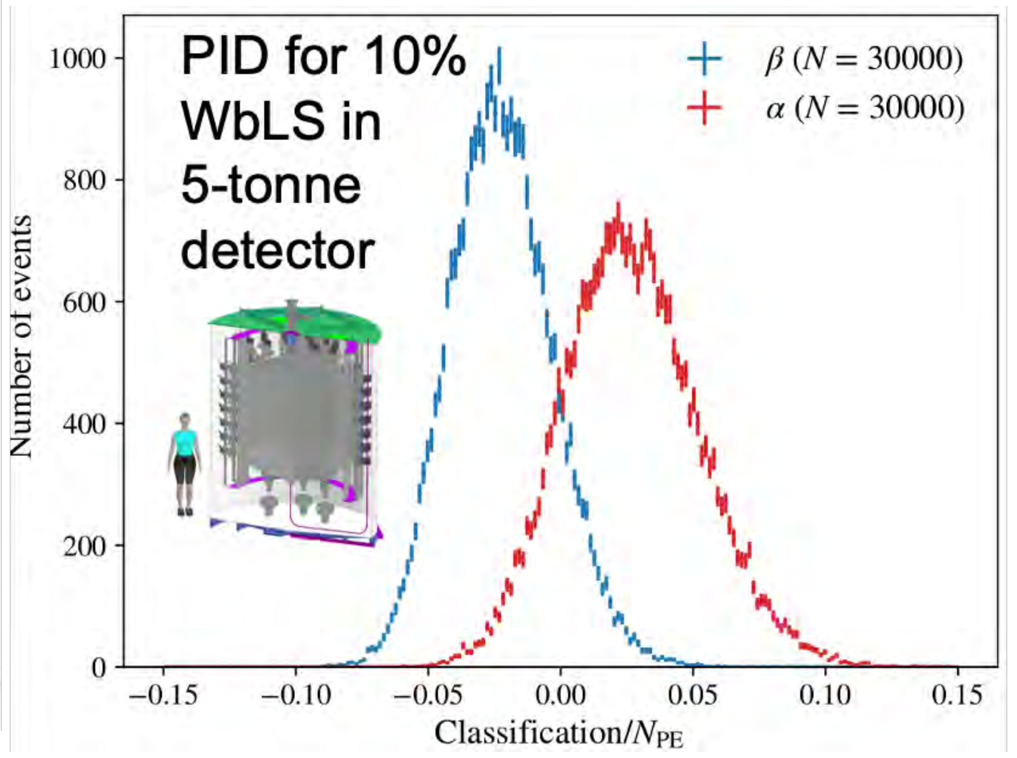

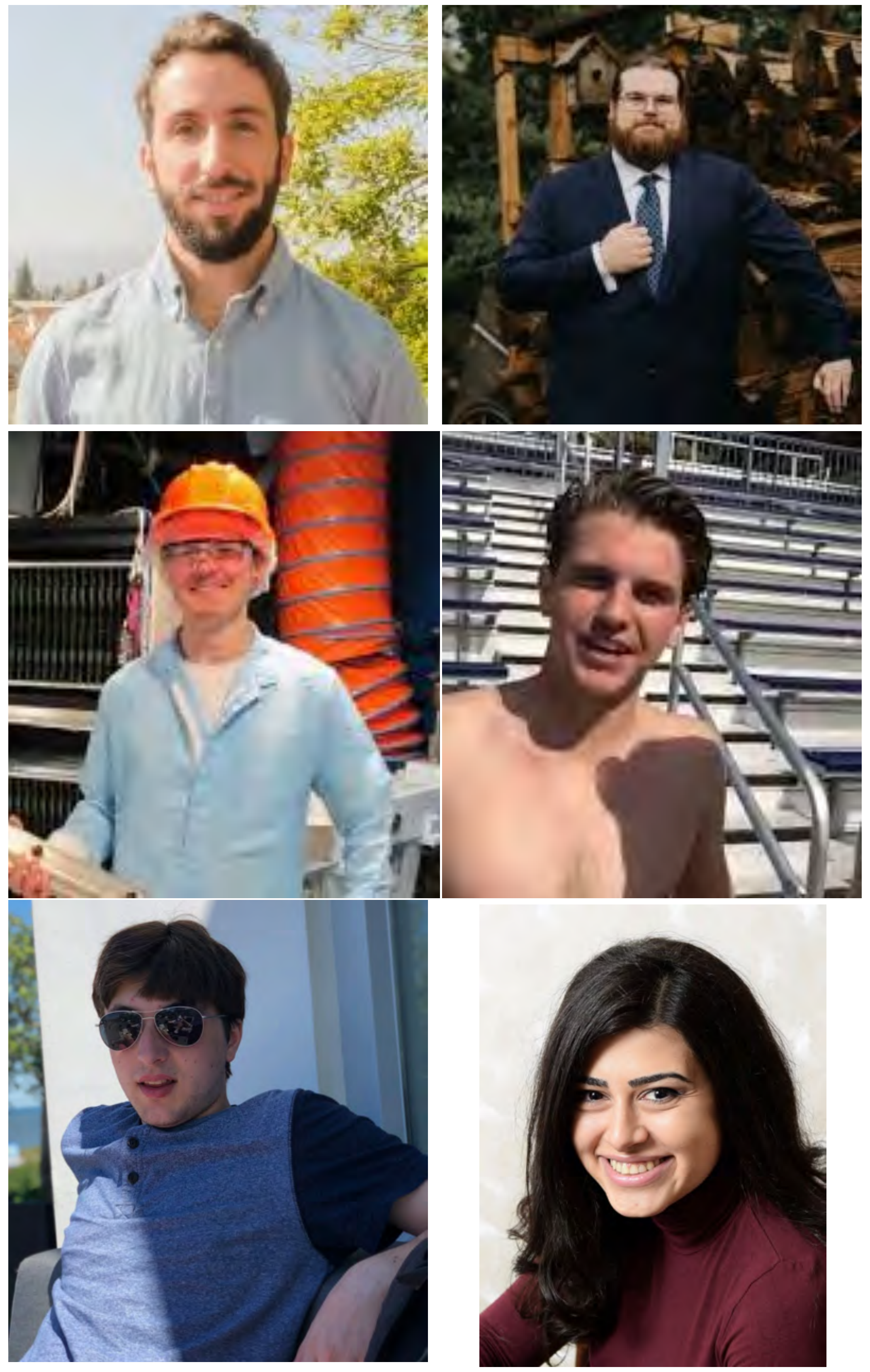

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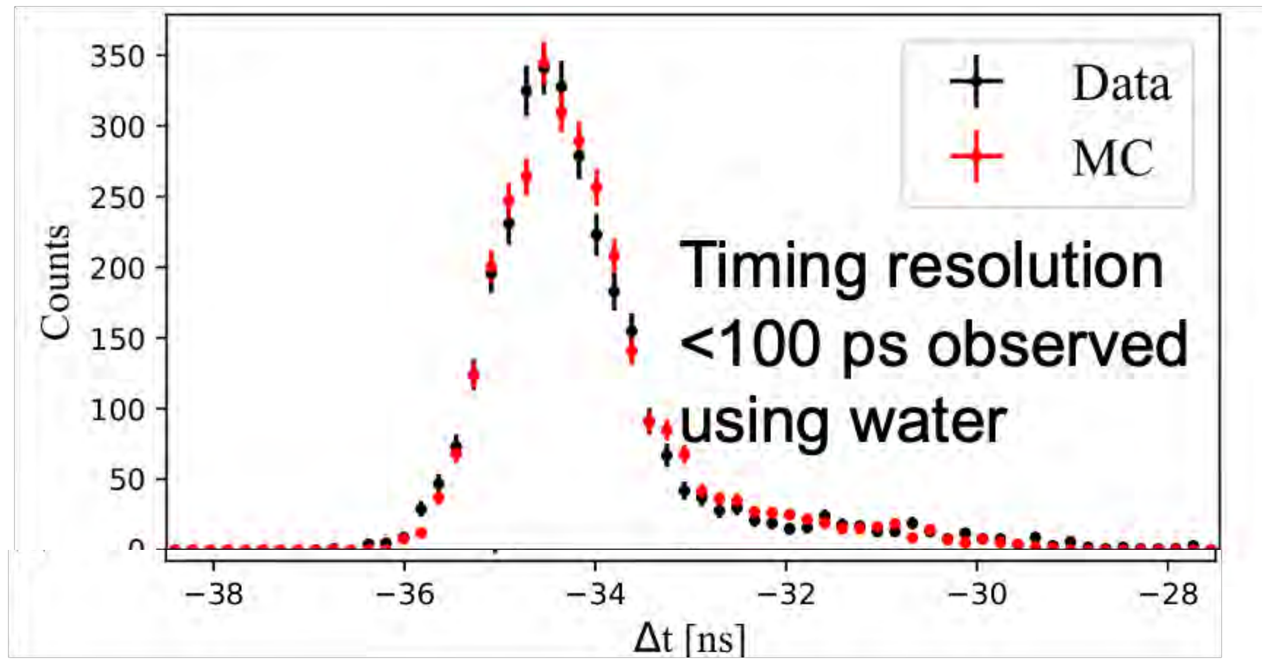
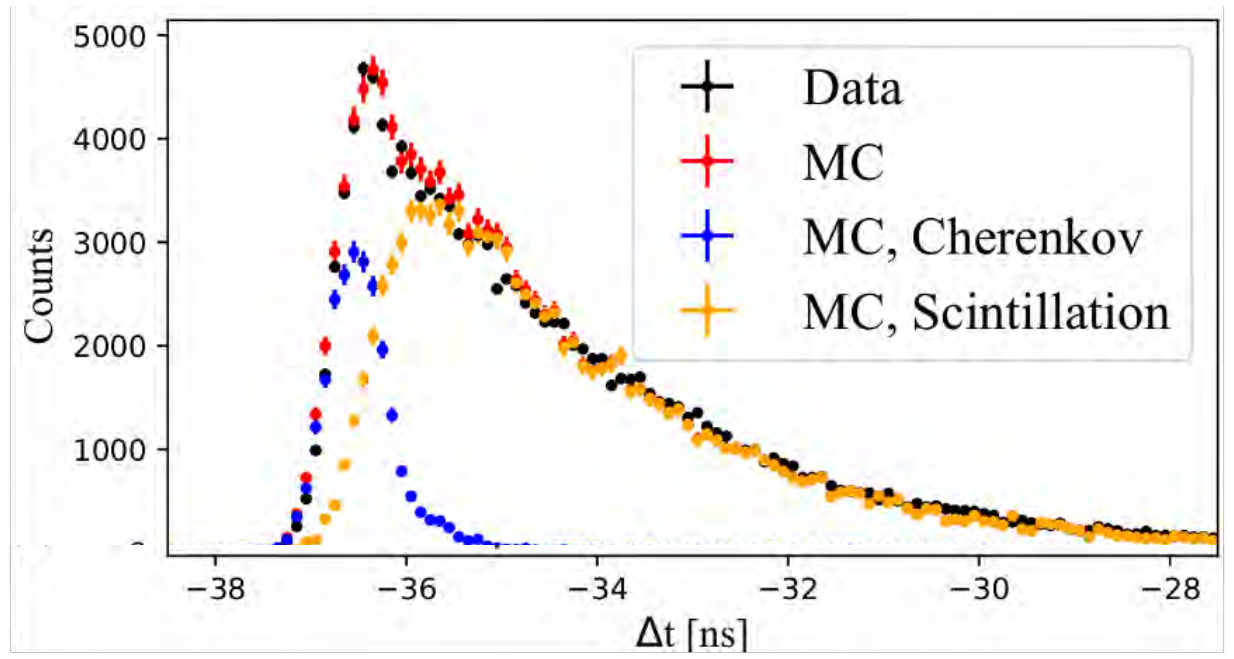
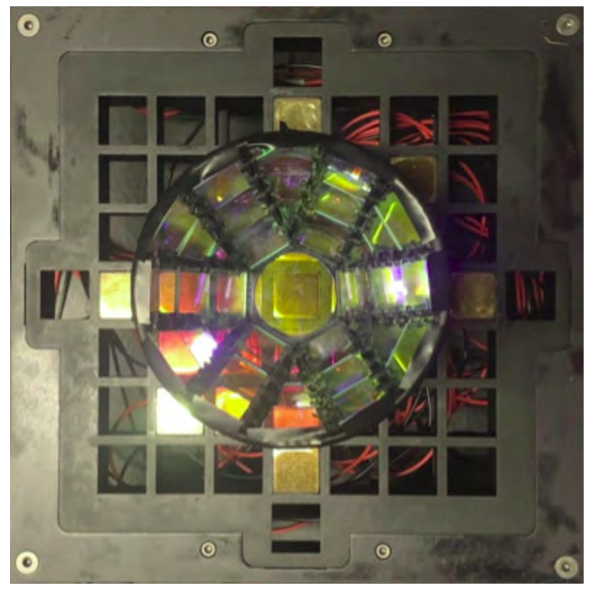
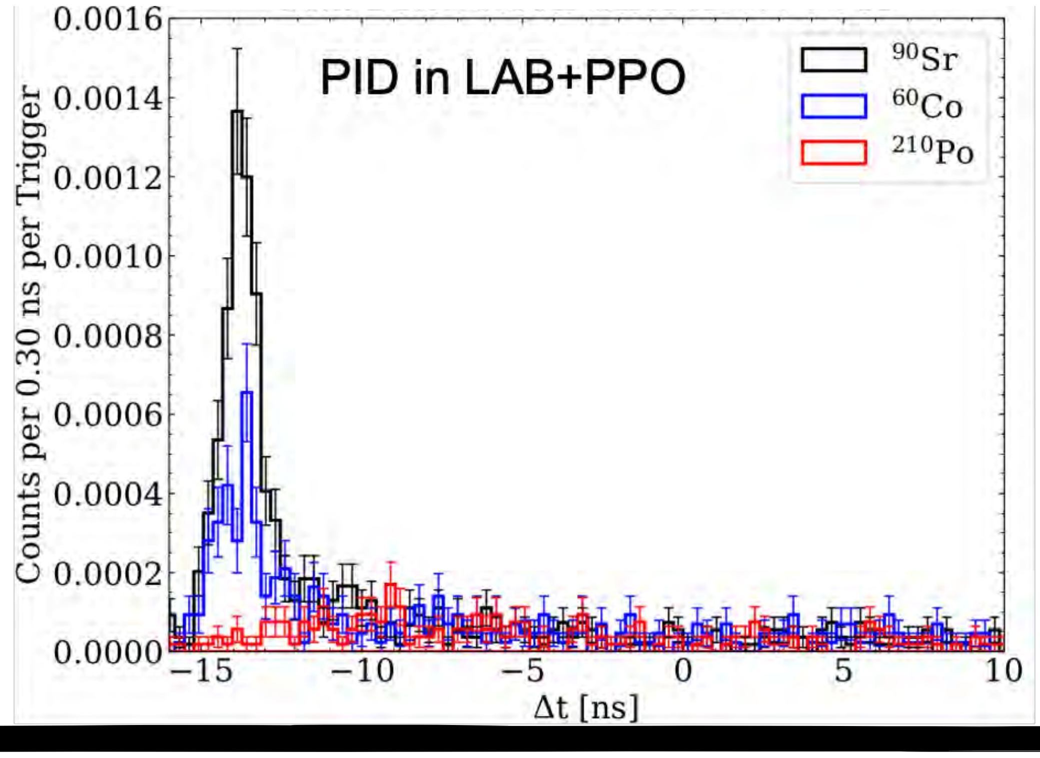




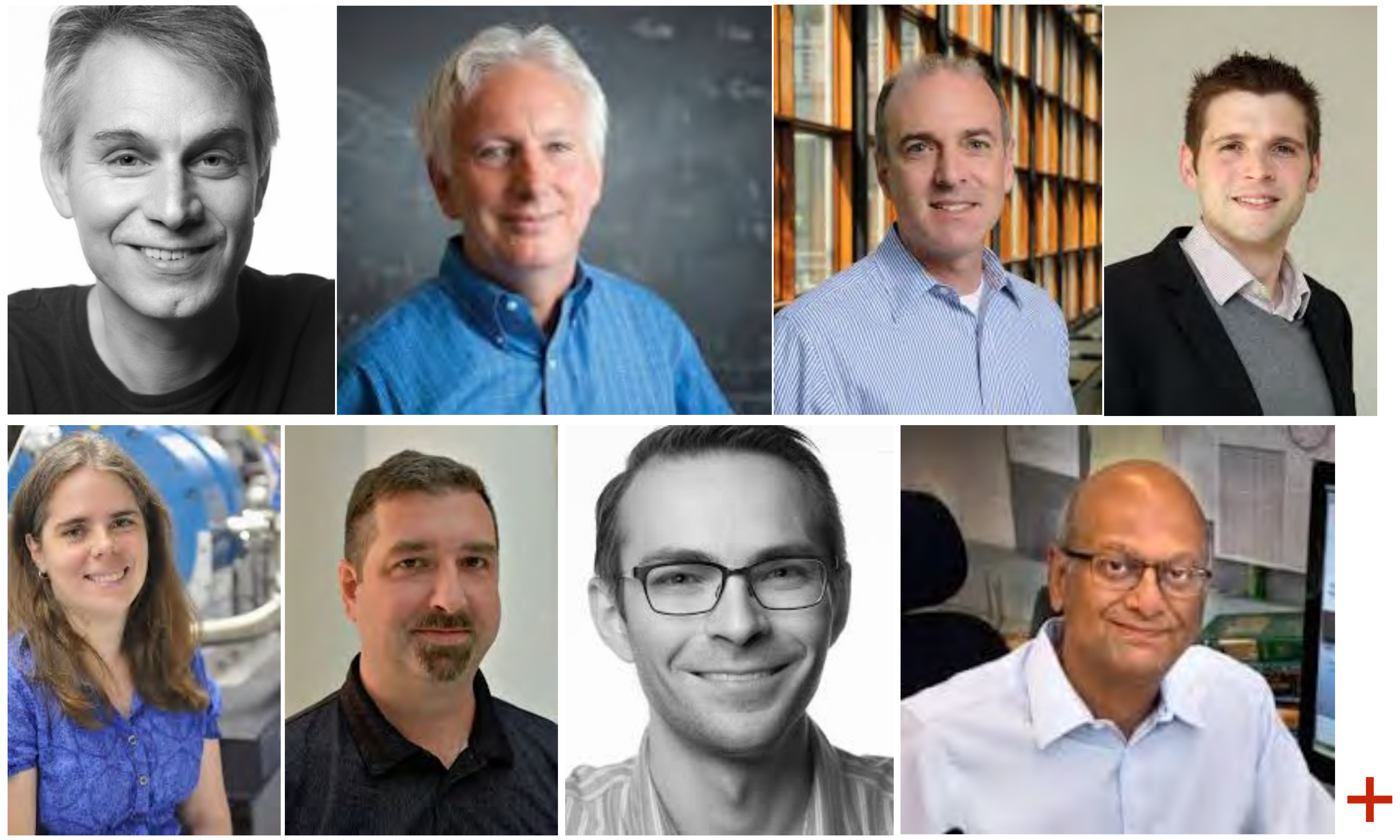
Quantum chromatic sorting

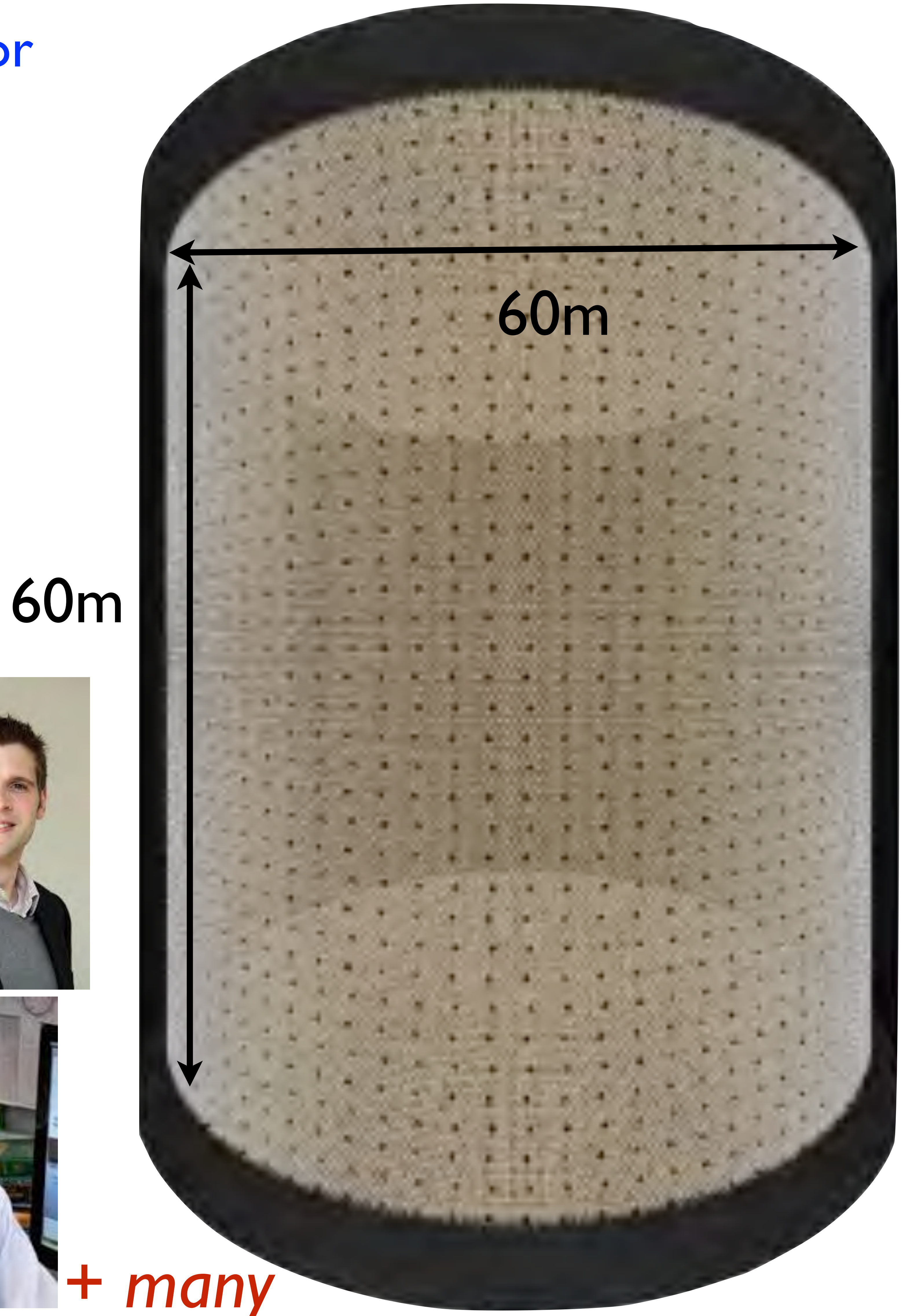




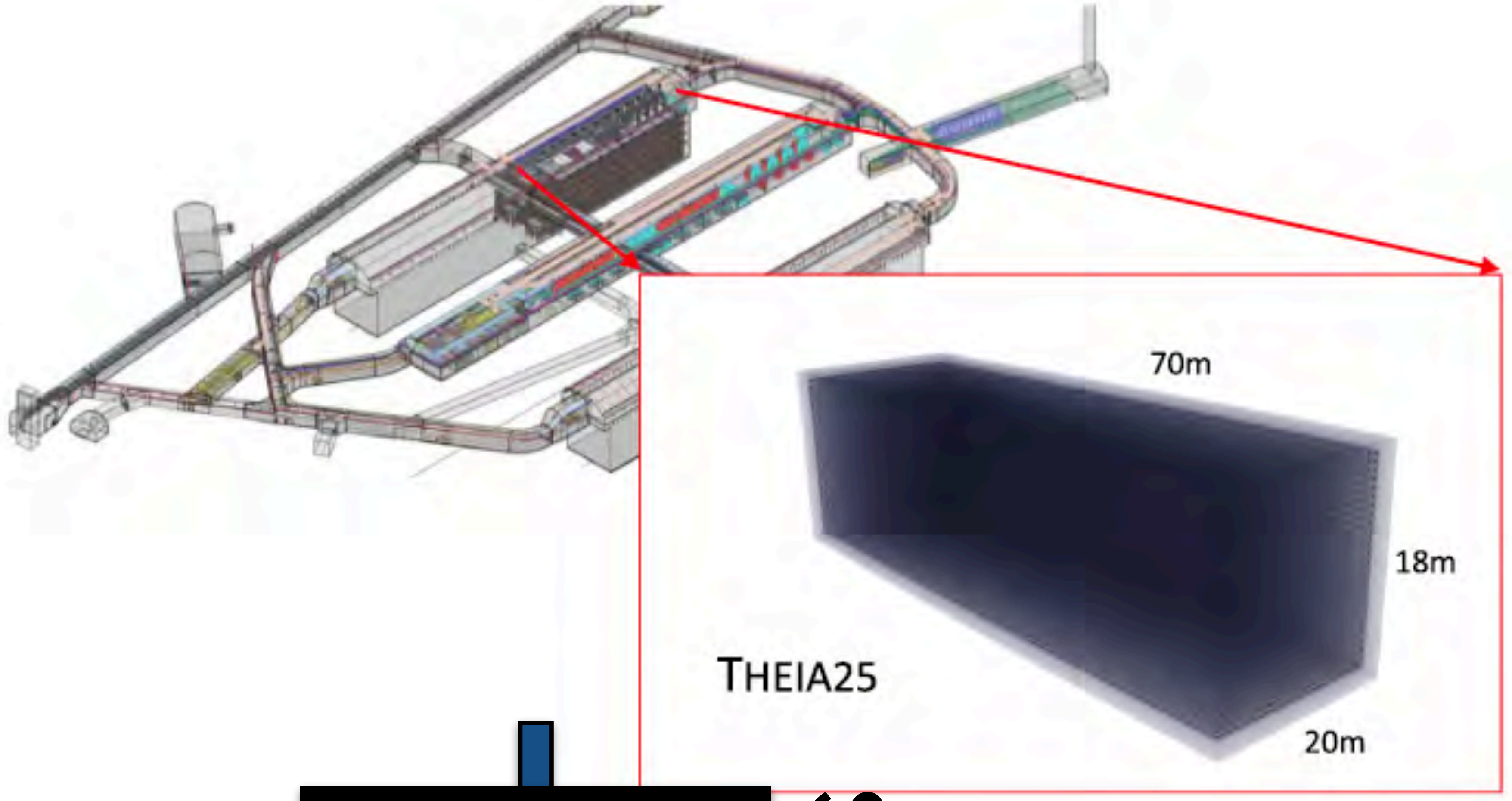
THEIA

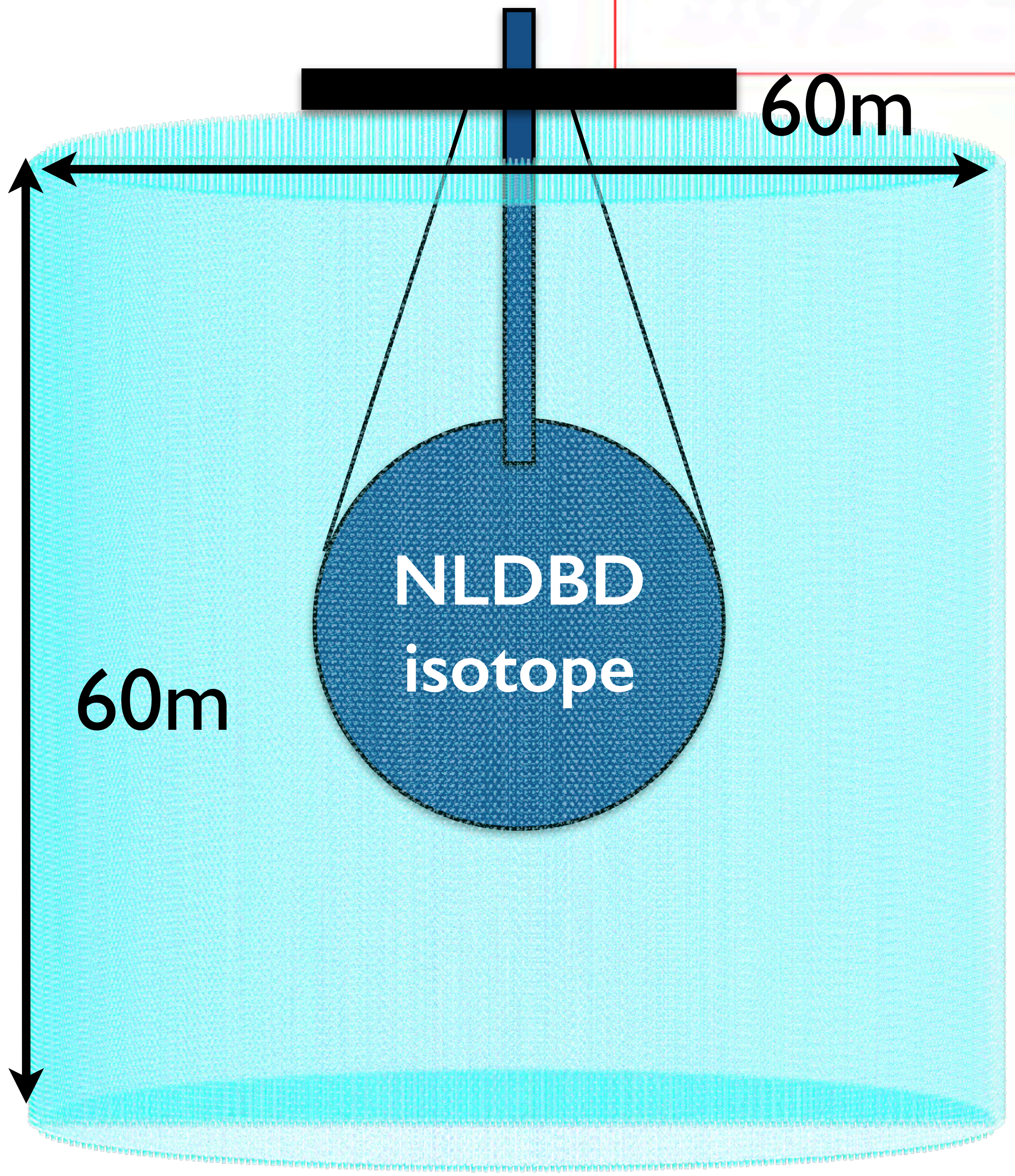
- Hybrid Cherenkov/scintillation detector (25-100 kton)
- Novel LS target e.g. WbLS, slow LS
- Fast, high-efficiency spectrally sensitive photon detection with high coverage
- Isotope loading (Gd, Te, Li...)
- Flexible! Target, loading, configuration
- Broad physics program

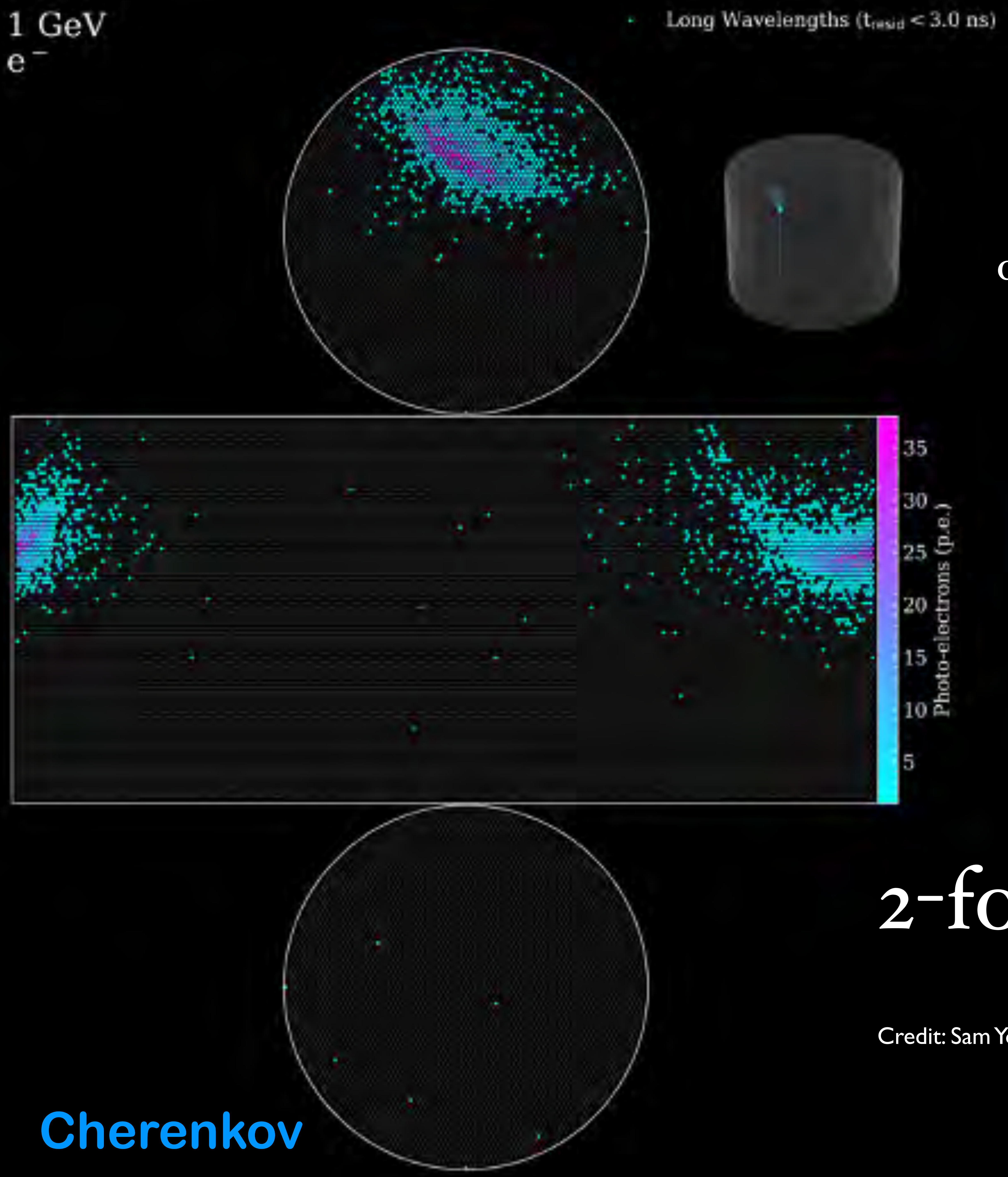




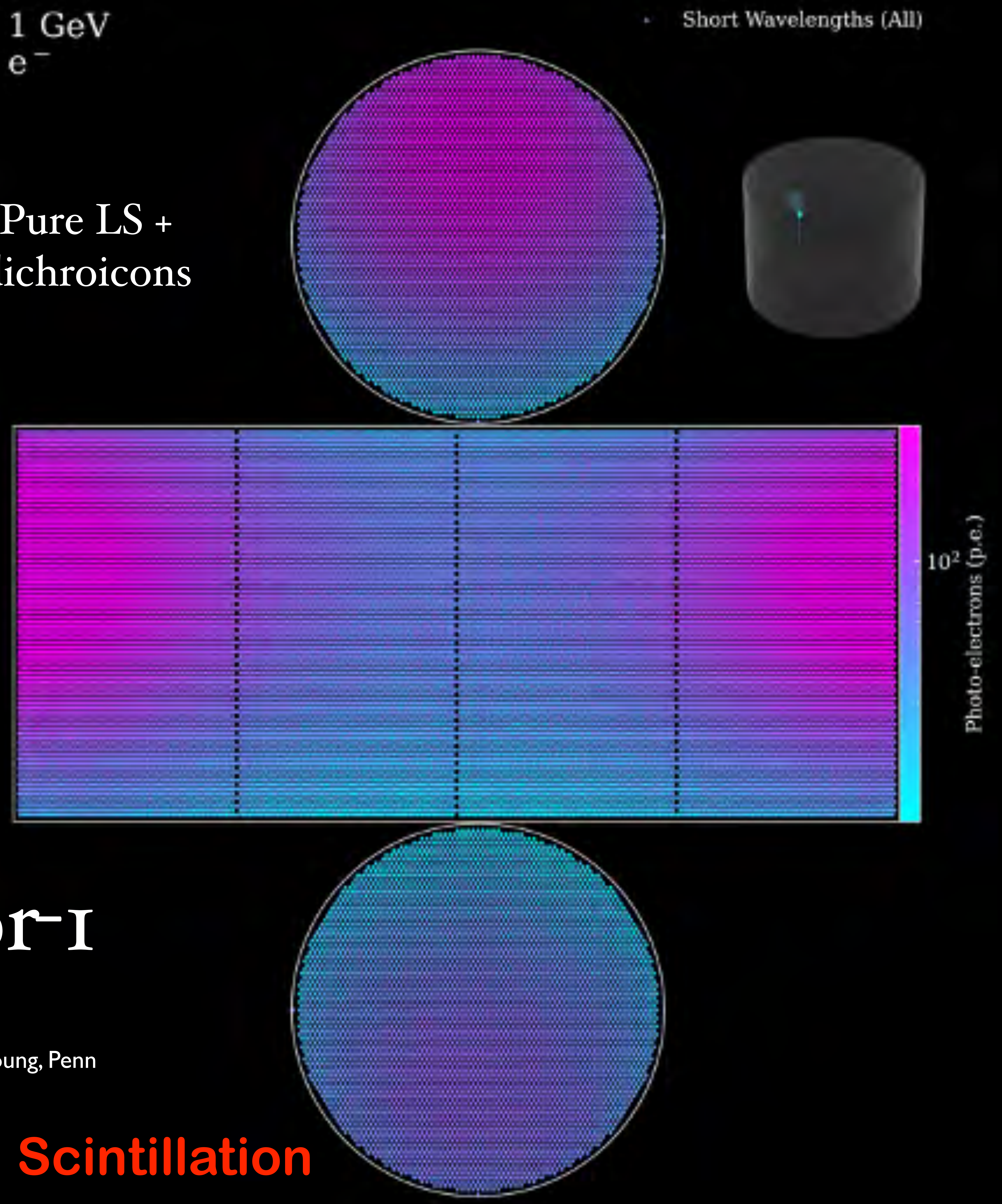
+ many







Pure LS +
dichroicons



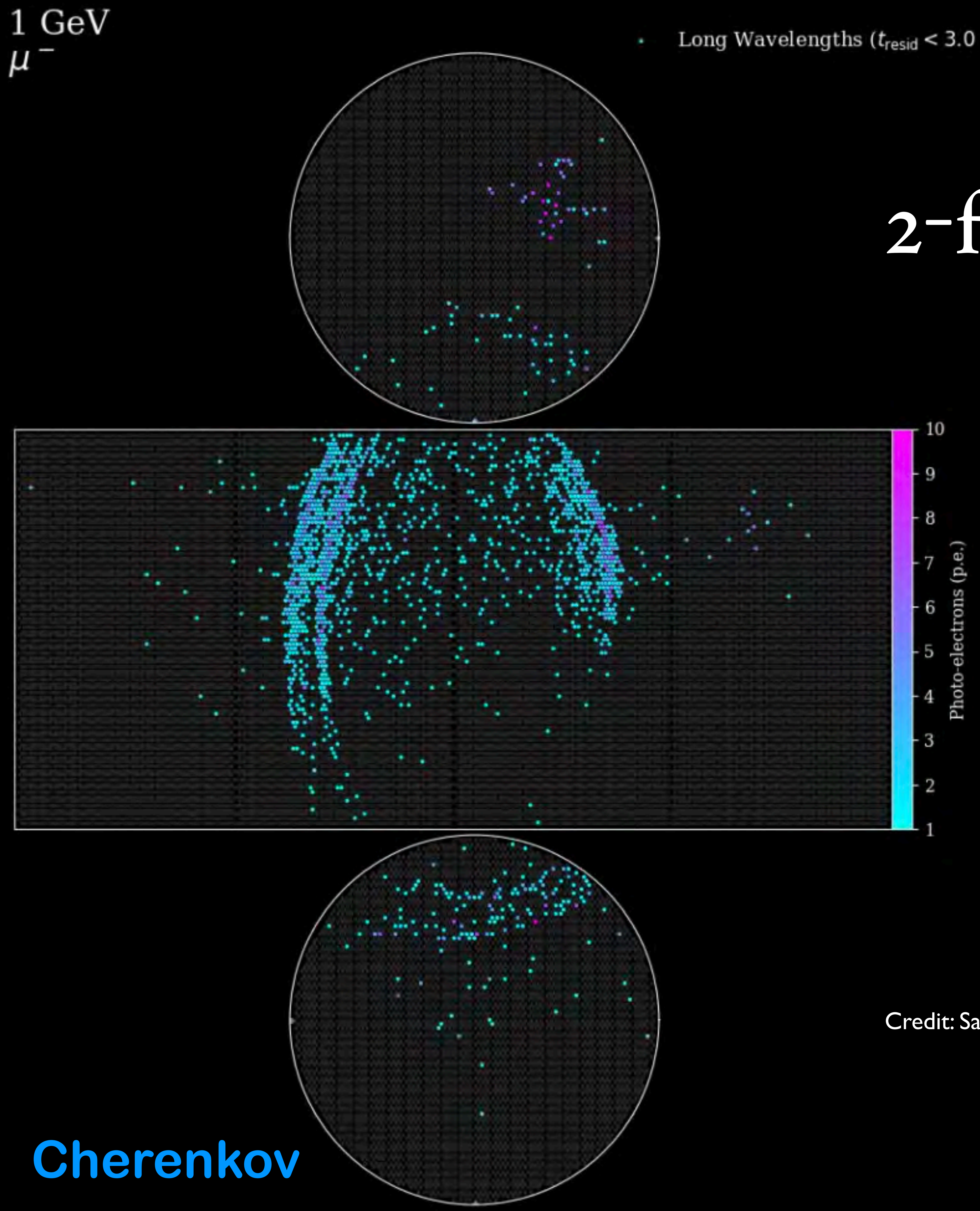
2-for-1

Credit: Sam Young, Penn

Cherenkov

Scintillation

2-for-1



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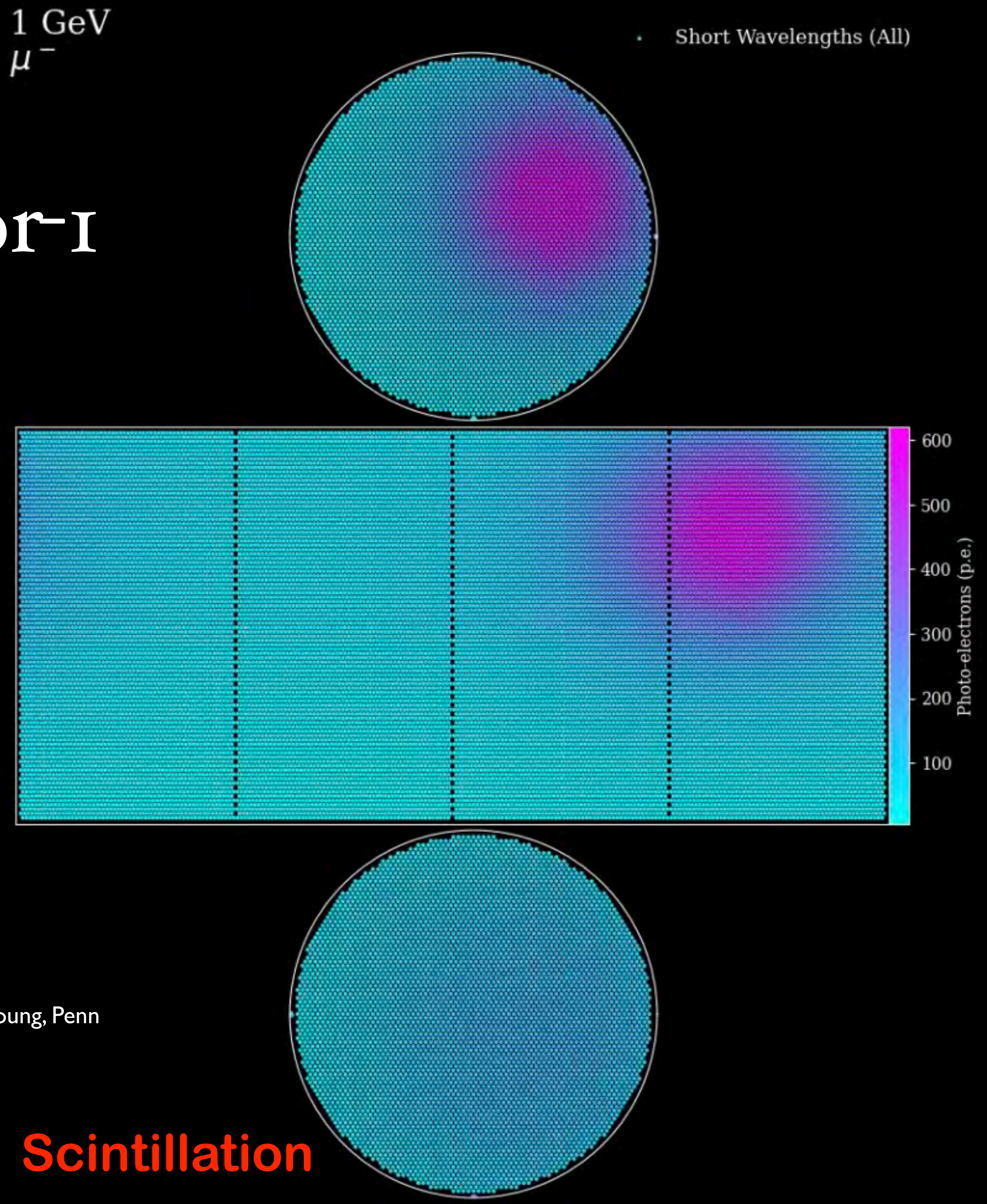
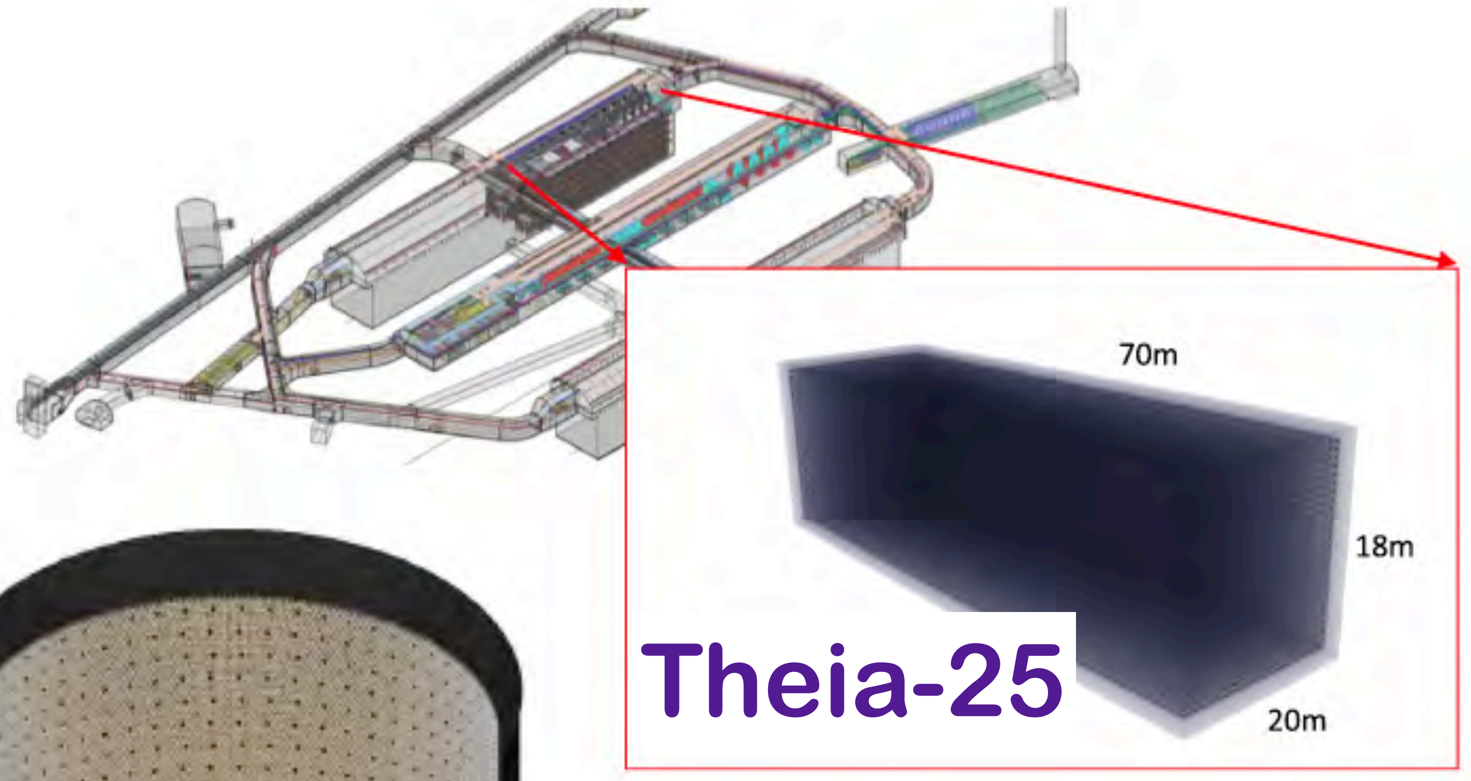


Scintillation

Credit: Sam Young, Penn

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 (new!) additional physics program



Large, multipurpose detector

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

- DUNE Phase II formal process includes Theia as 1 of 3 options
- Theia is technically mature, and brings a broad physics program beyond any alternative (LAr) tech.
- Strong international team actively engaged
- Current R&D support from HEP, NNSA; LDRD at BNL to study ND requirements
- Technical demonstrators underway (BNL 30t, Eos @ LBL, ANNIE, BUTTON)

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

THEIA physics program

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Neutrinos as a probe of nature

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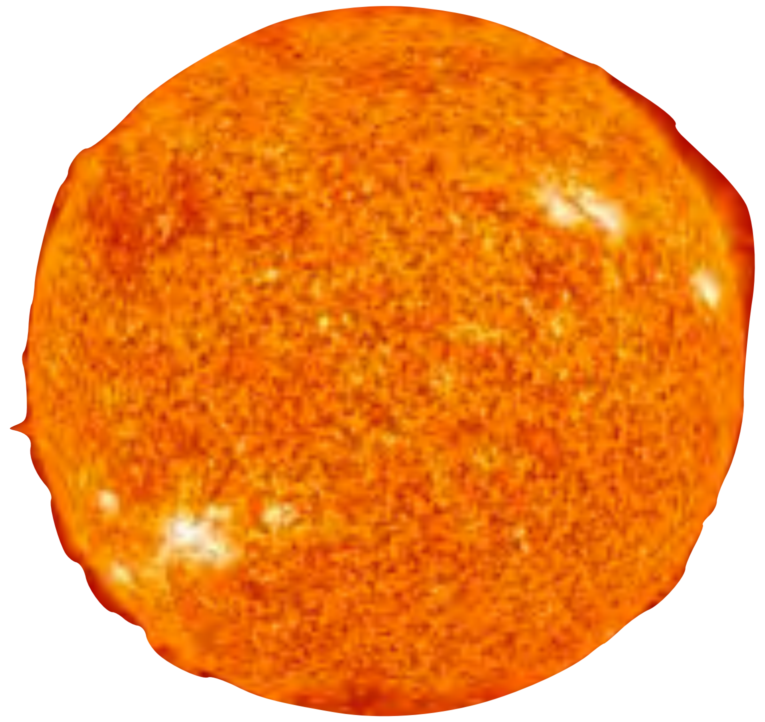
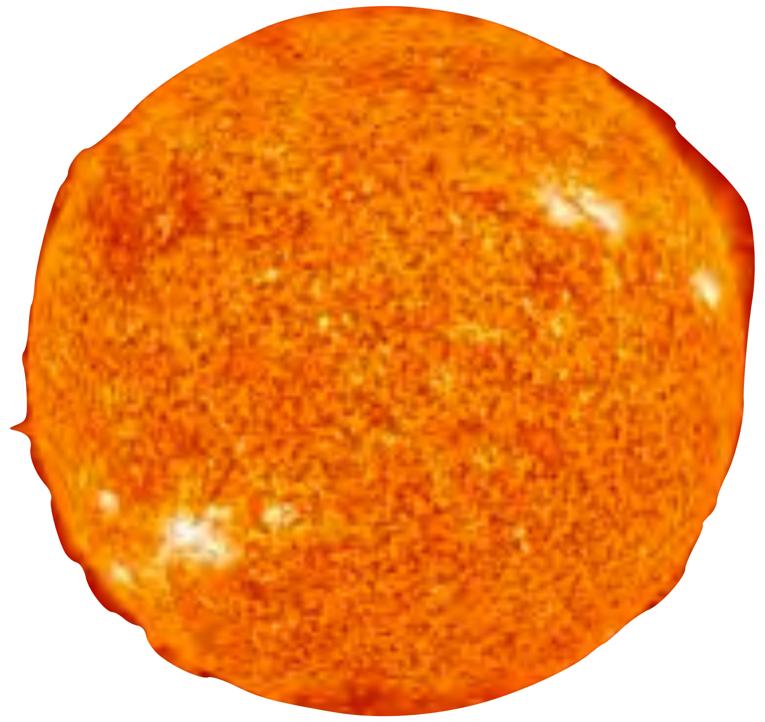
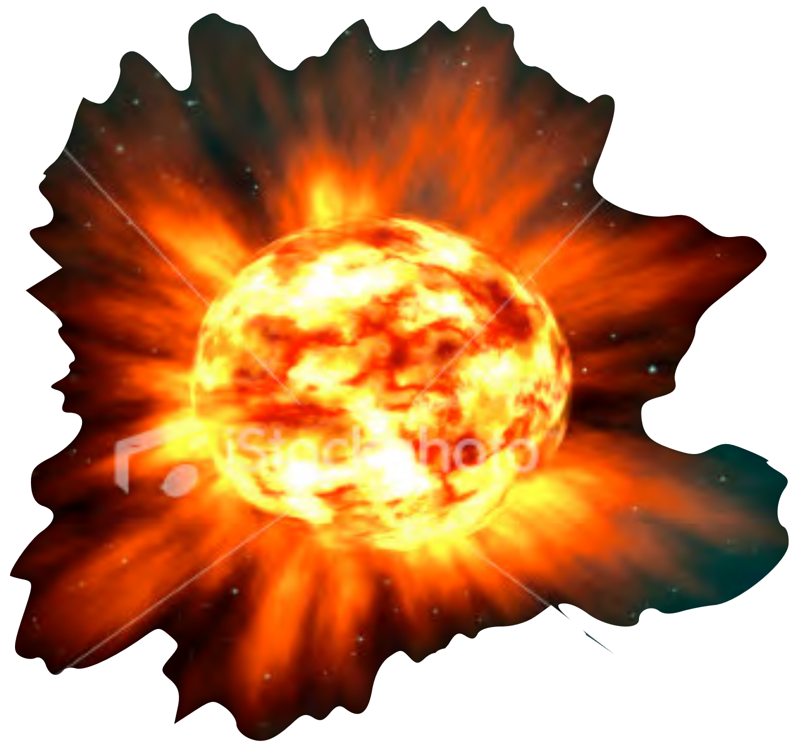


THEIA physics program

Neutrinos as a probe of nature





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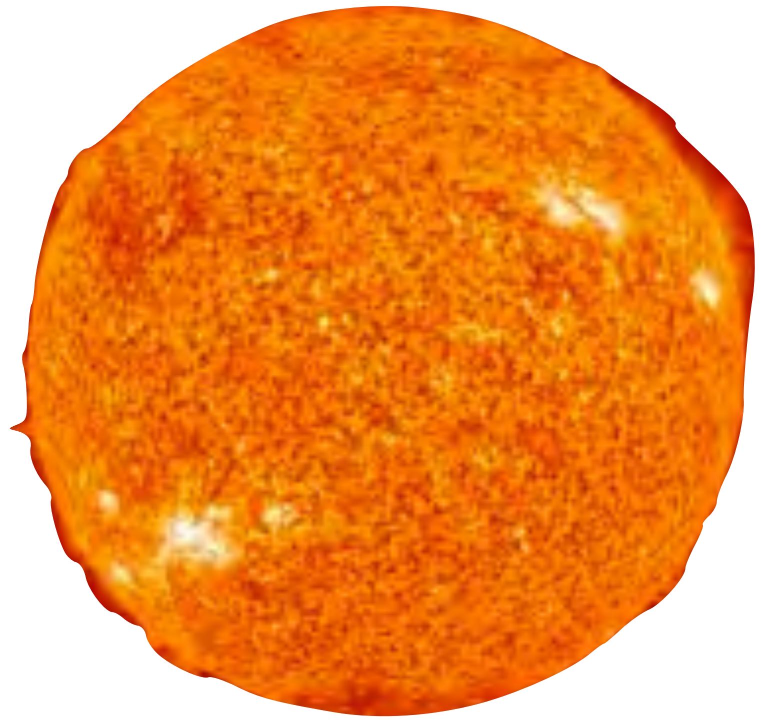

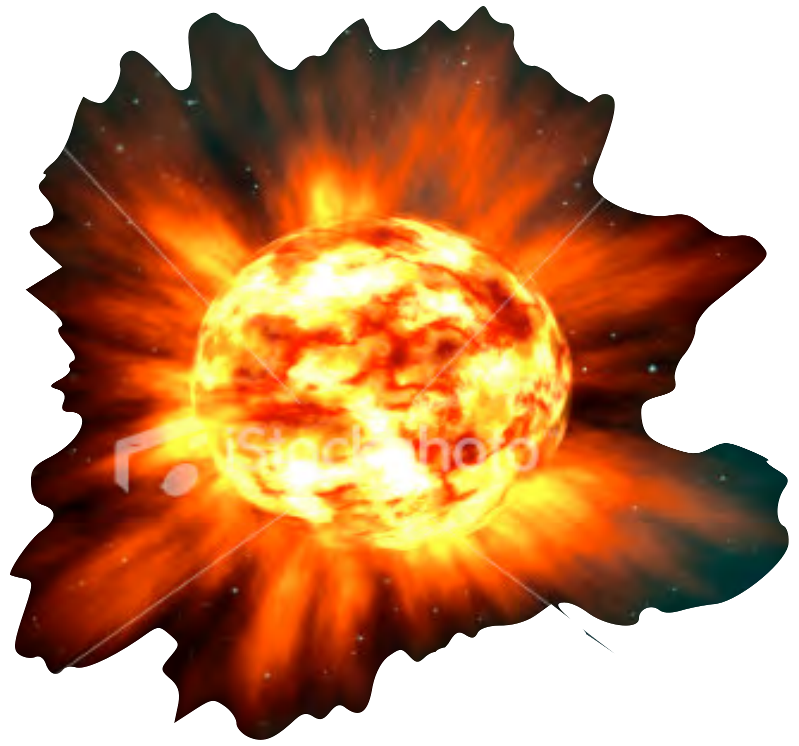

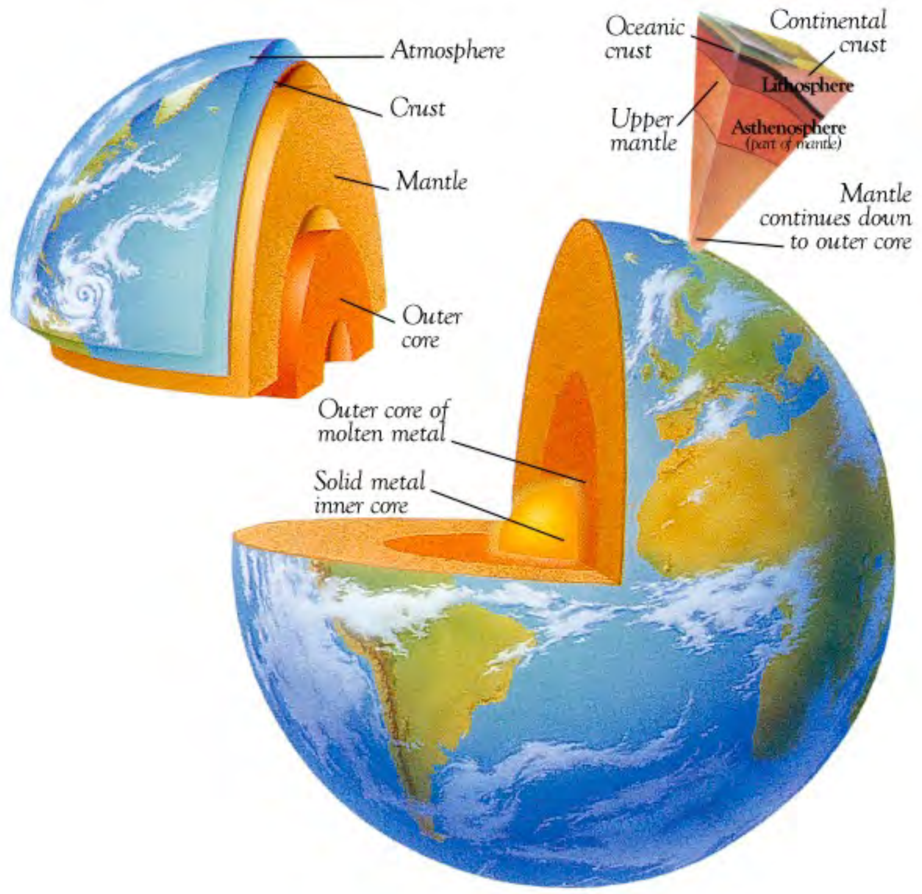

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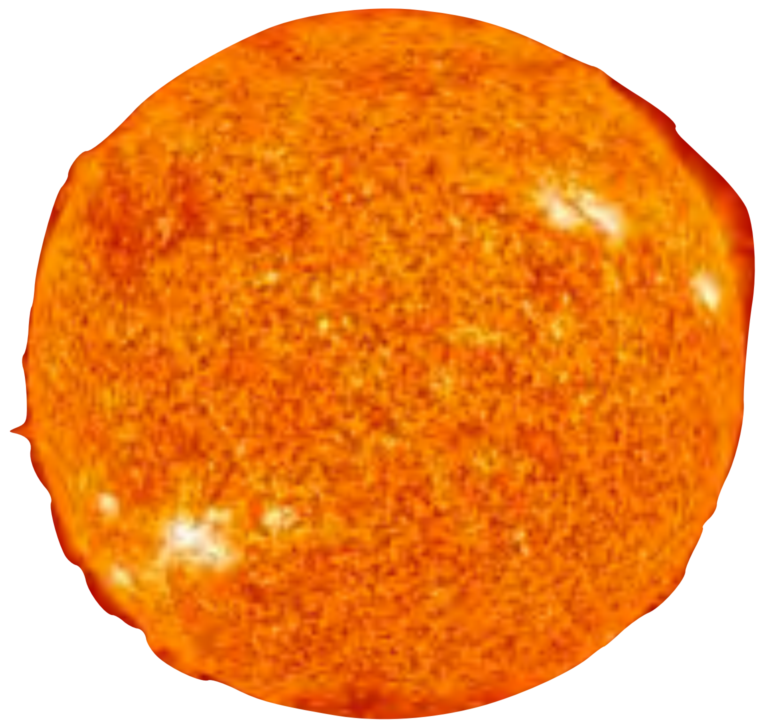
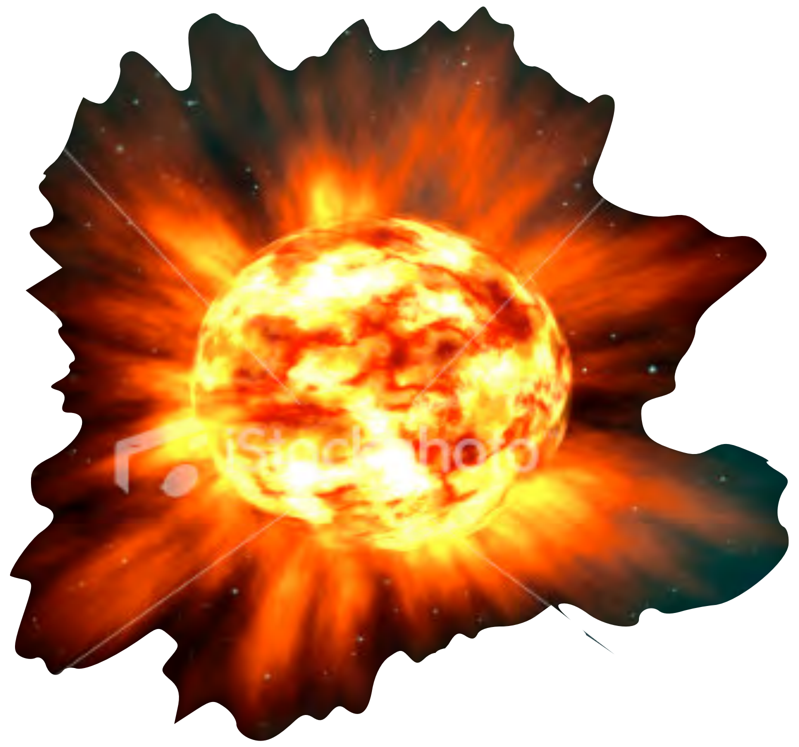
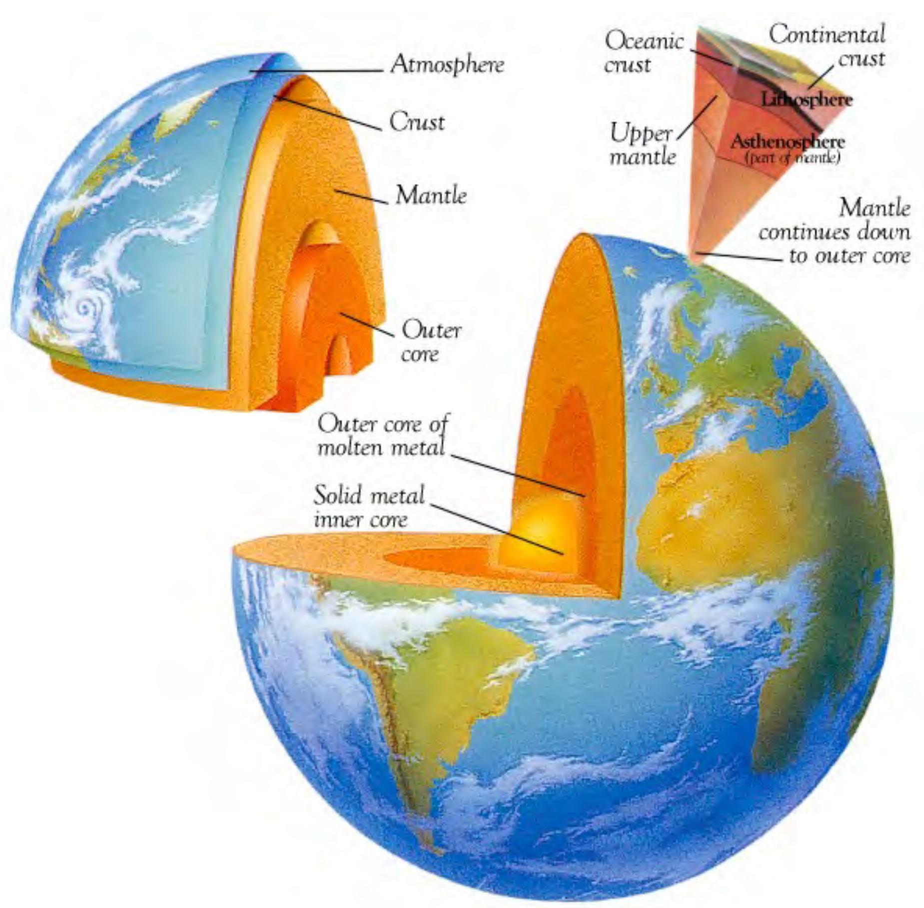


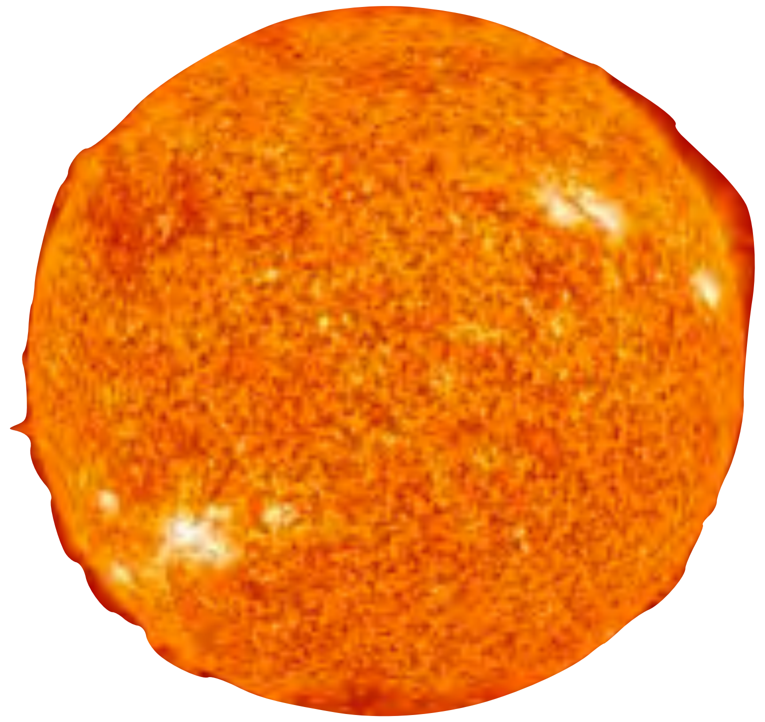


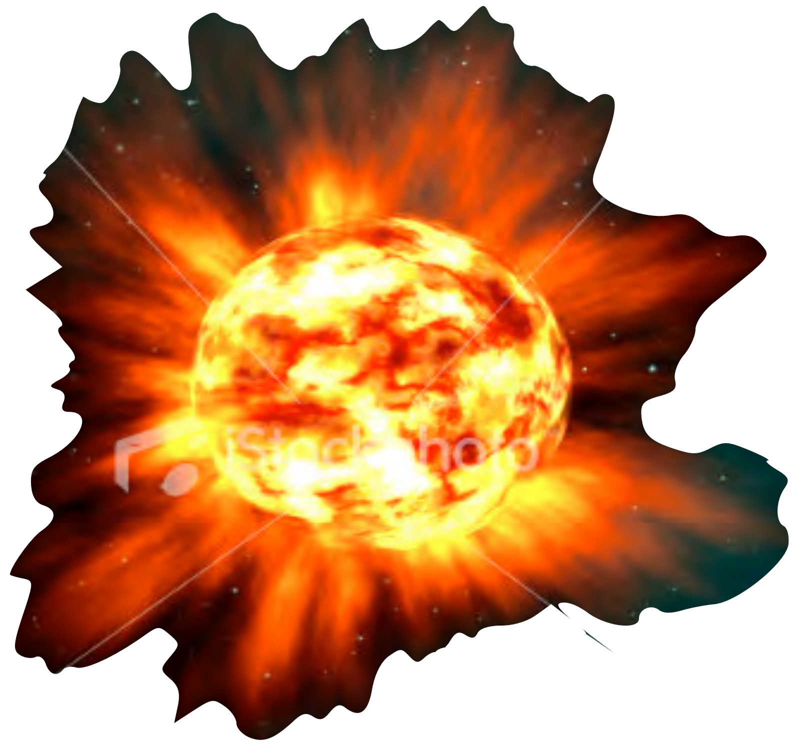


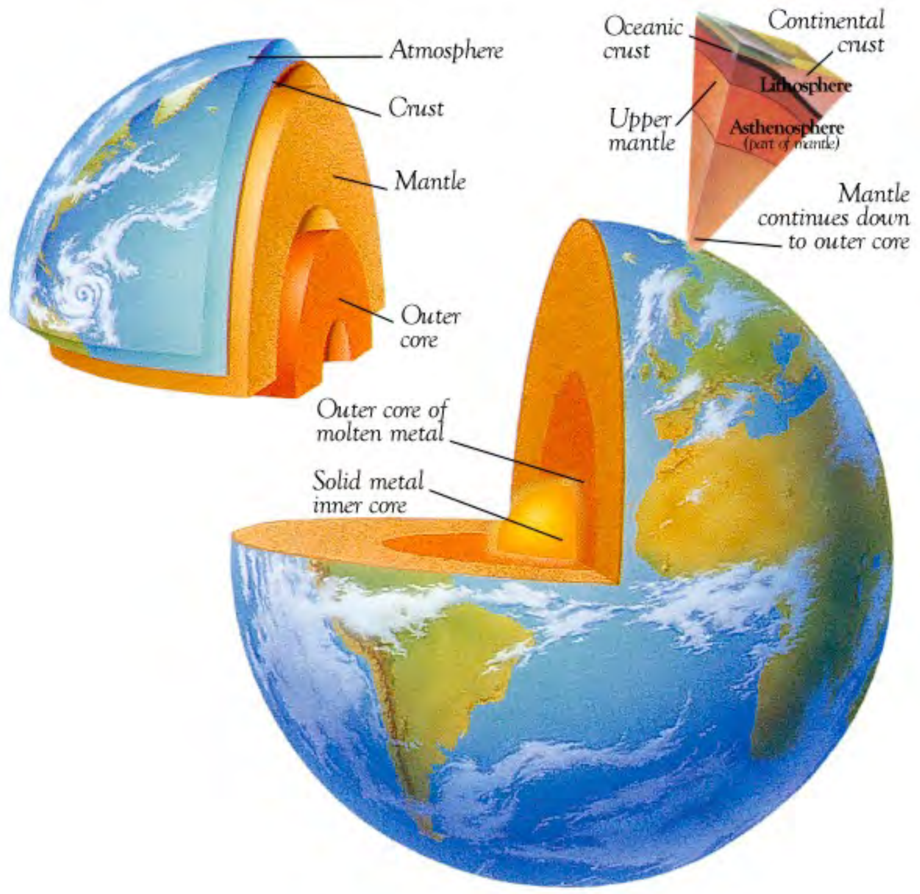
Studying the fundamental nature of matter

THEIA physics program

Neutrinos as a probe of nature







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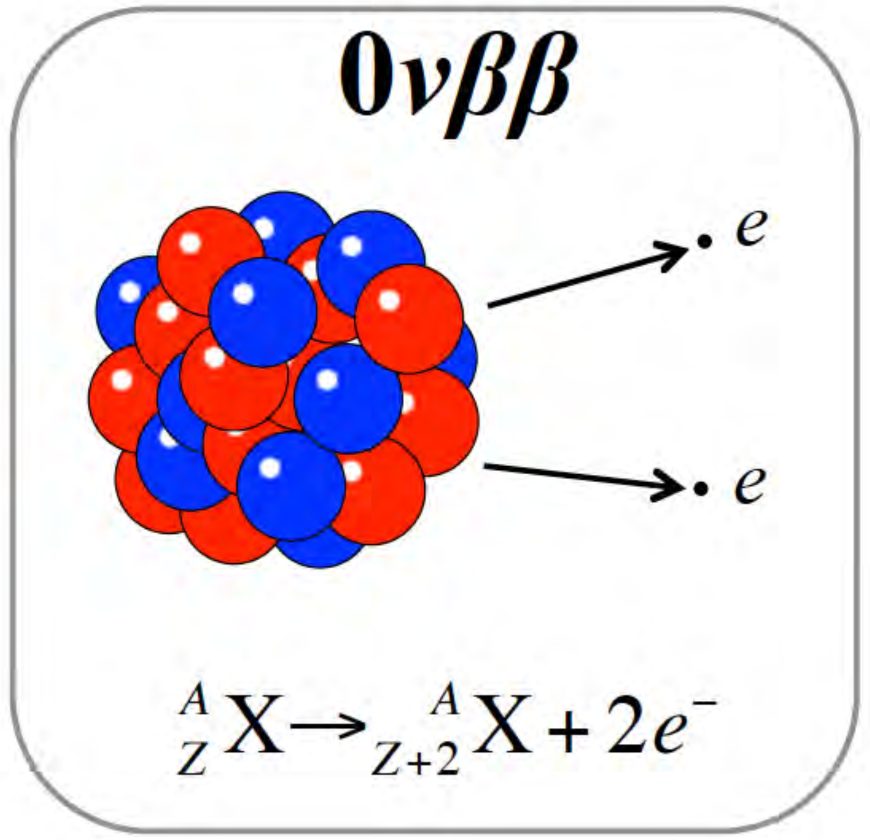

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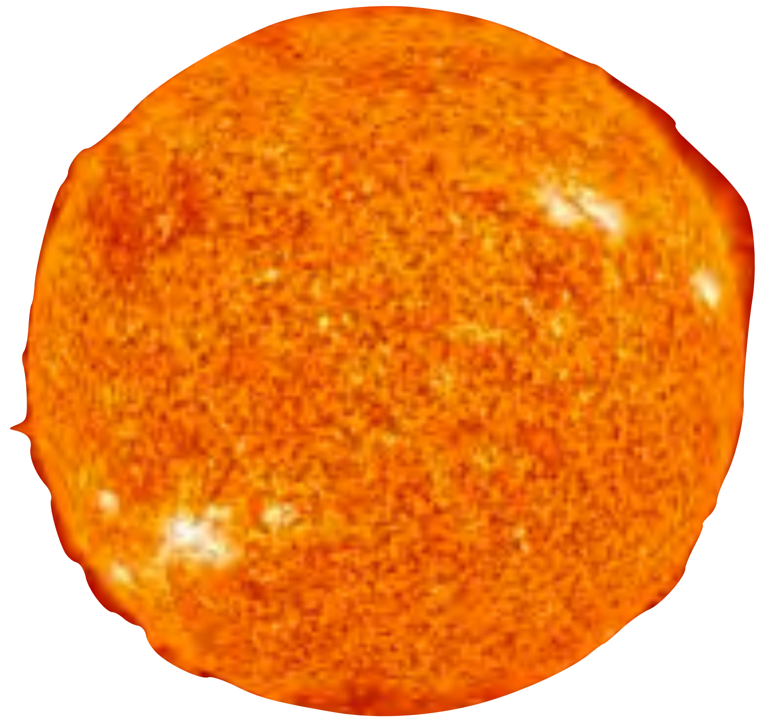

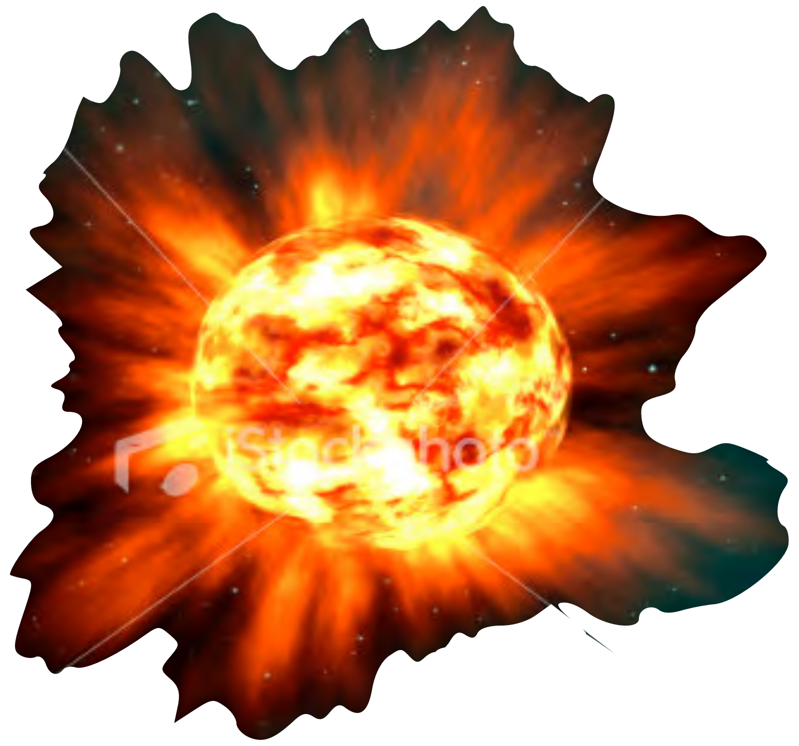

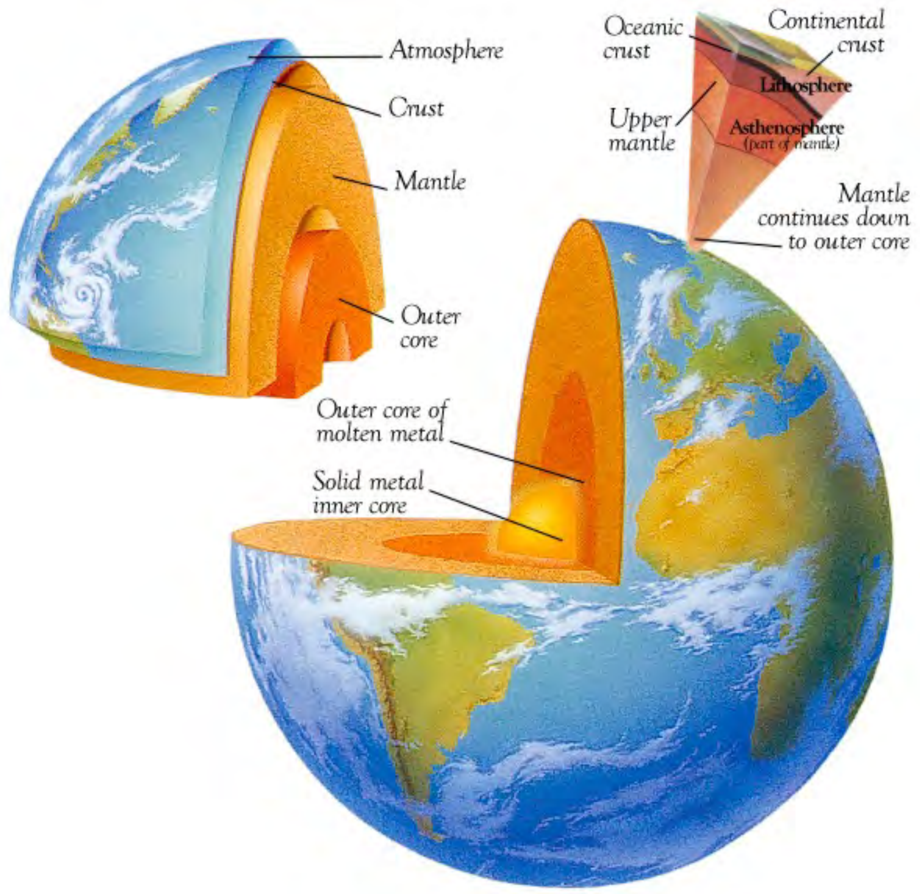

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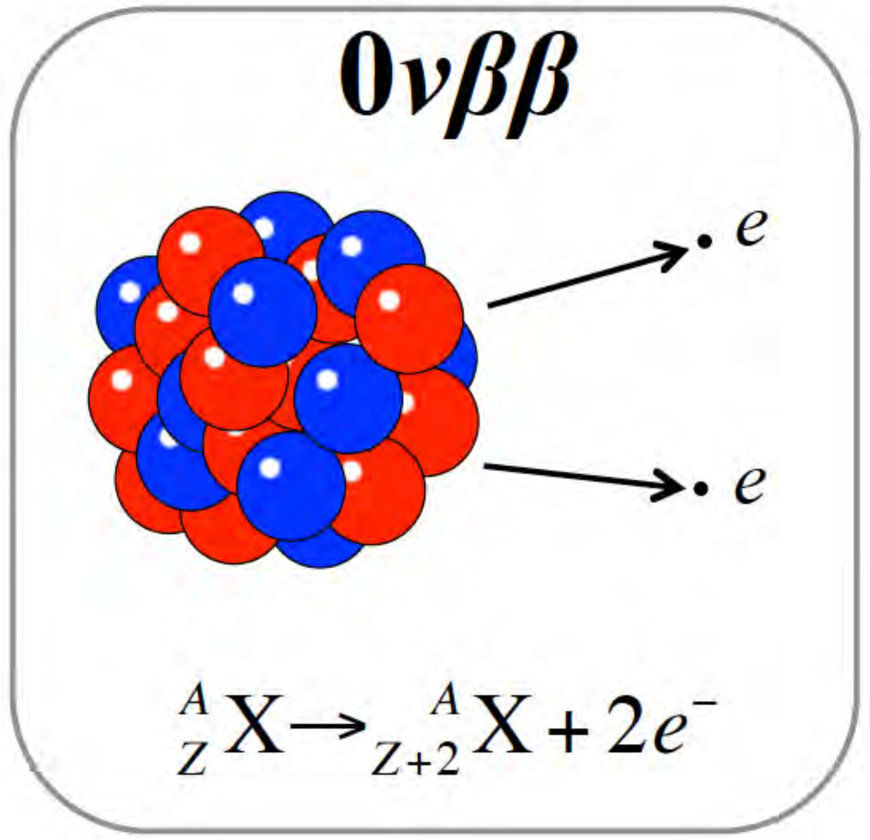

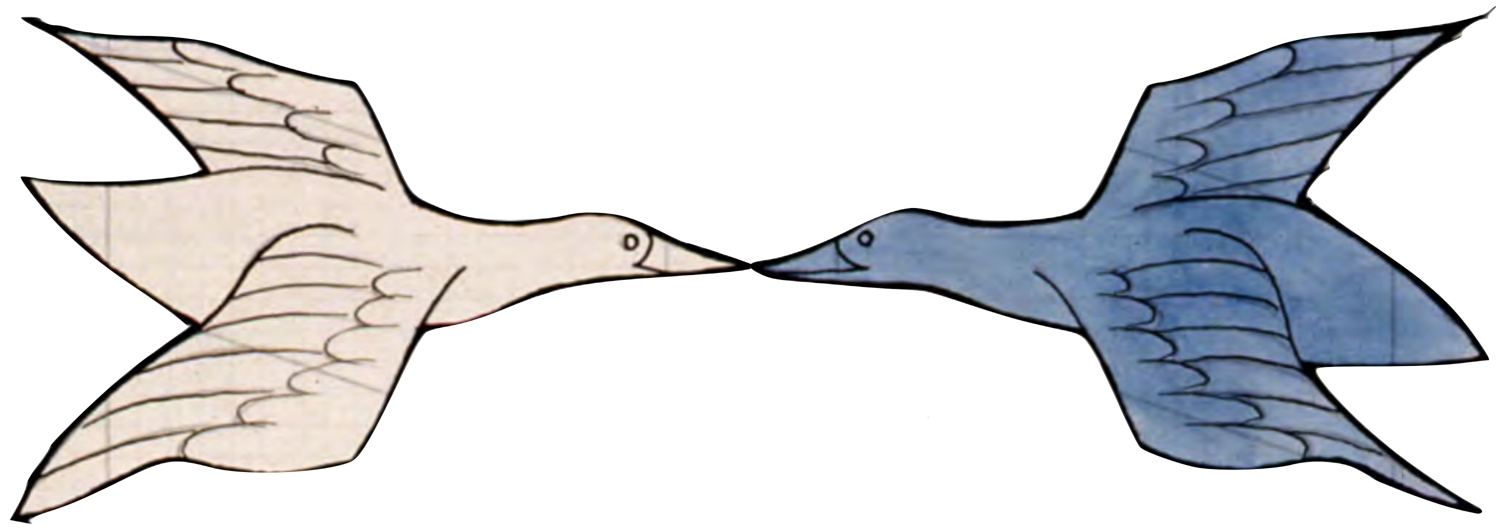

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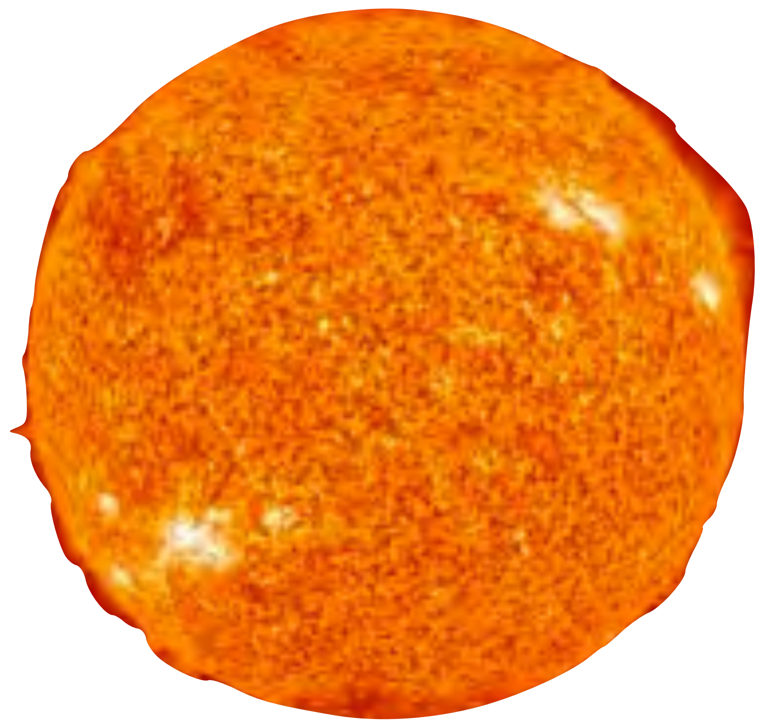
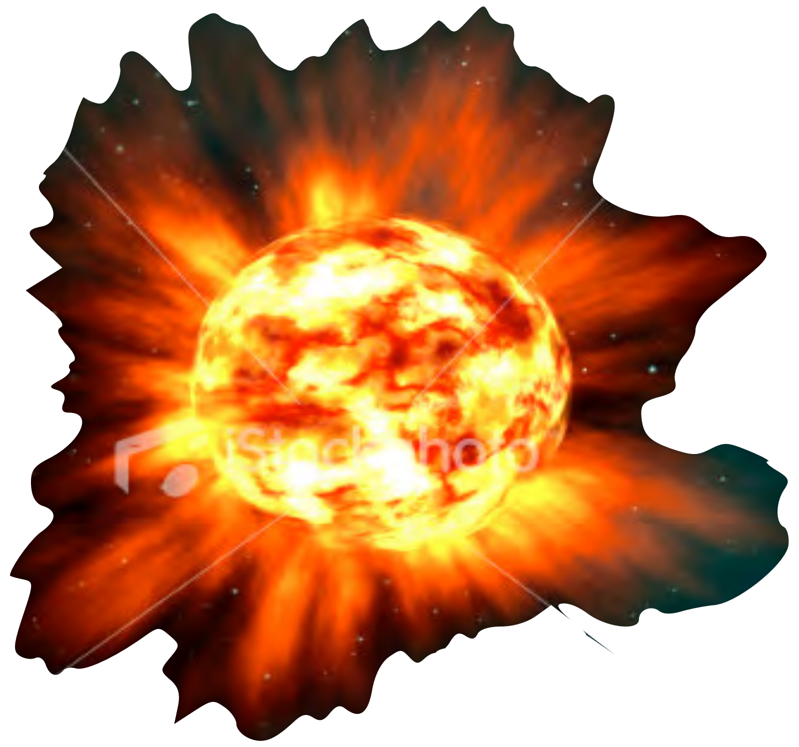
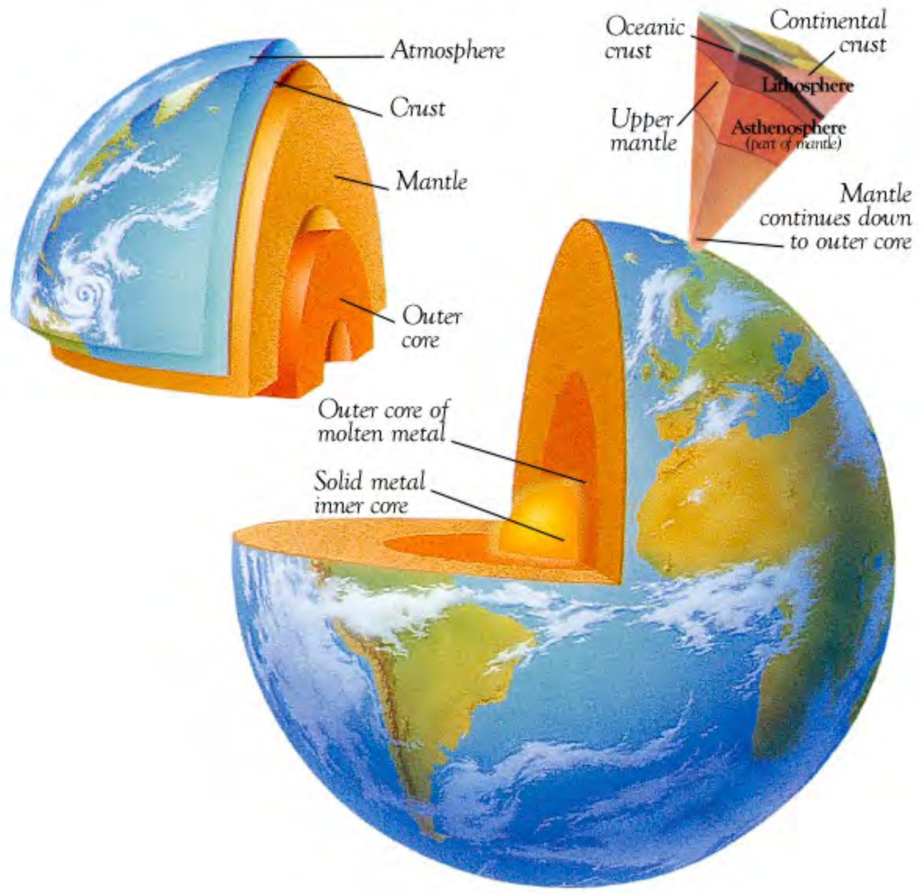
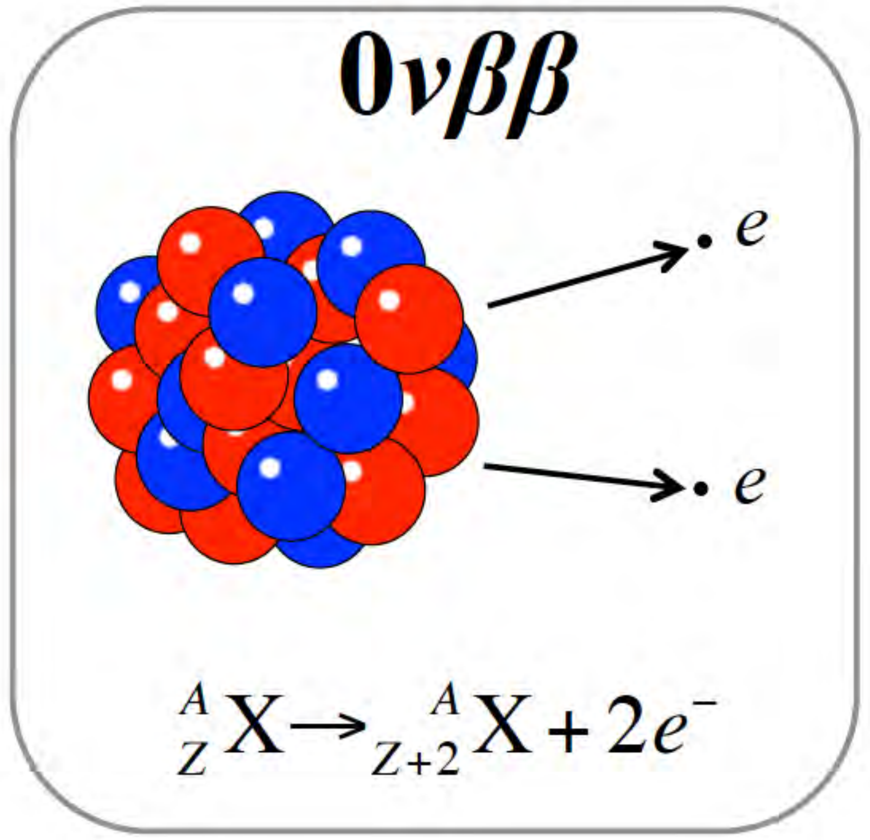


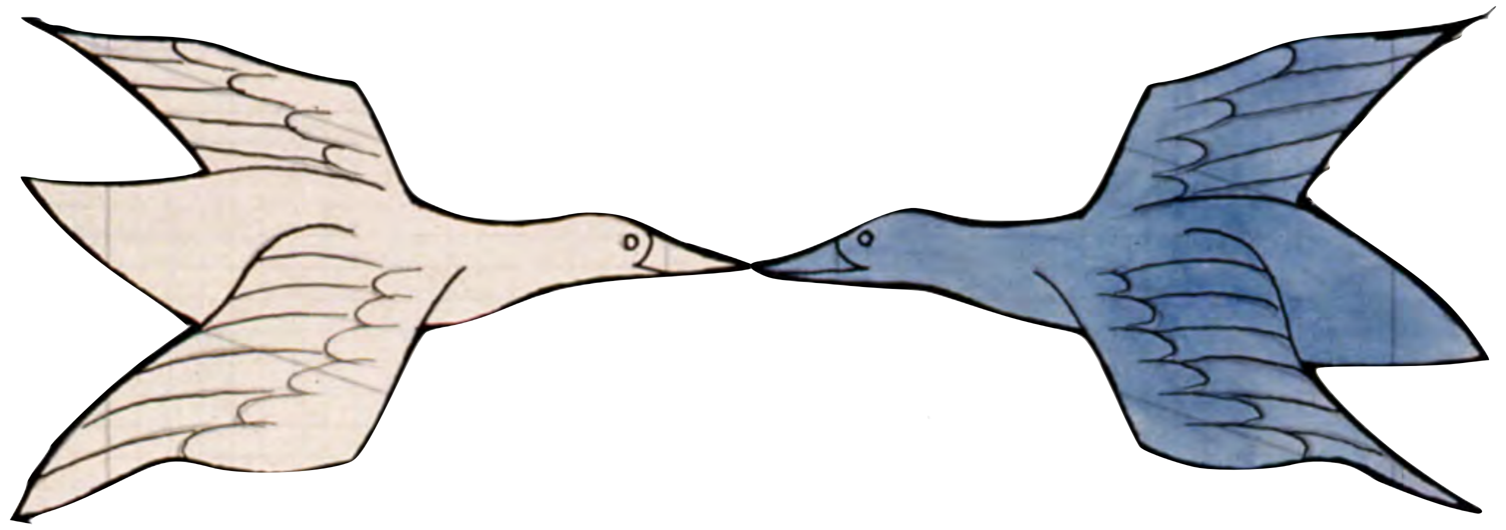




Particle astrophysics

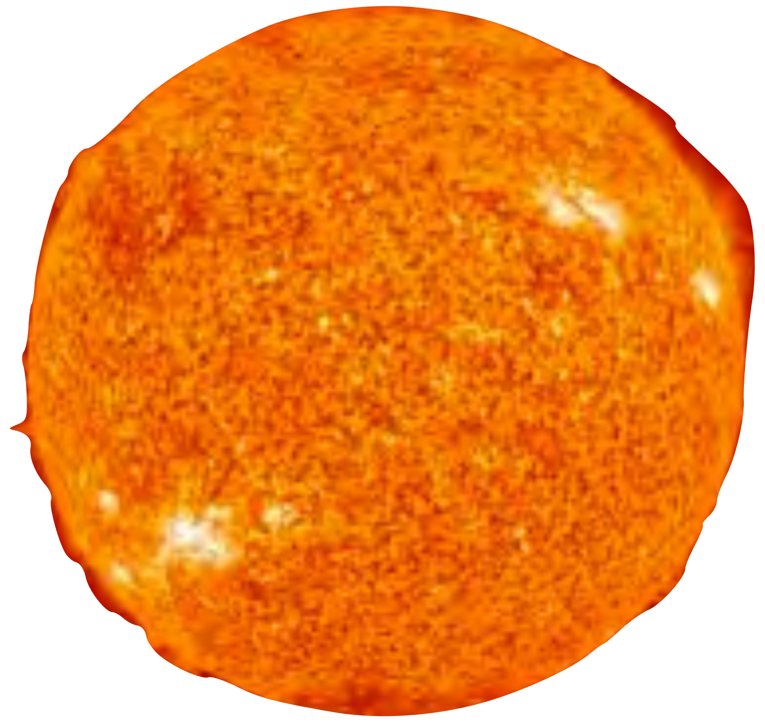
Studying the fundamental nature of matter

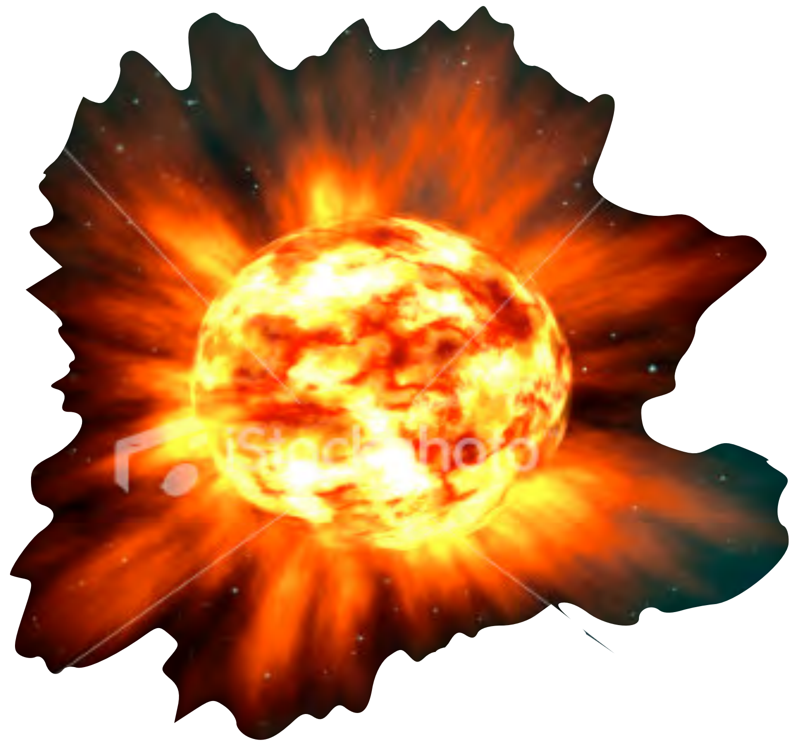


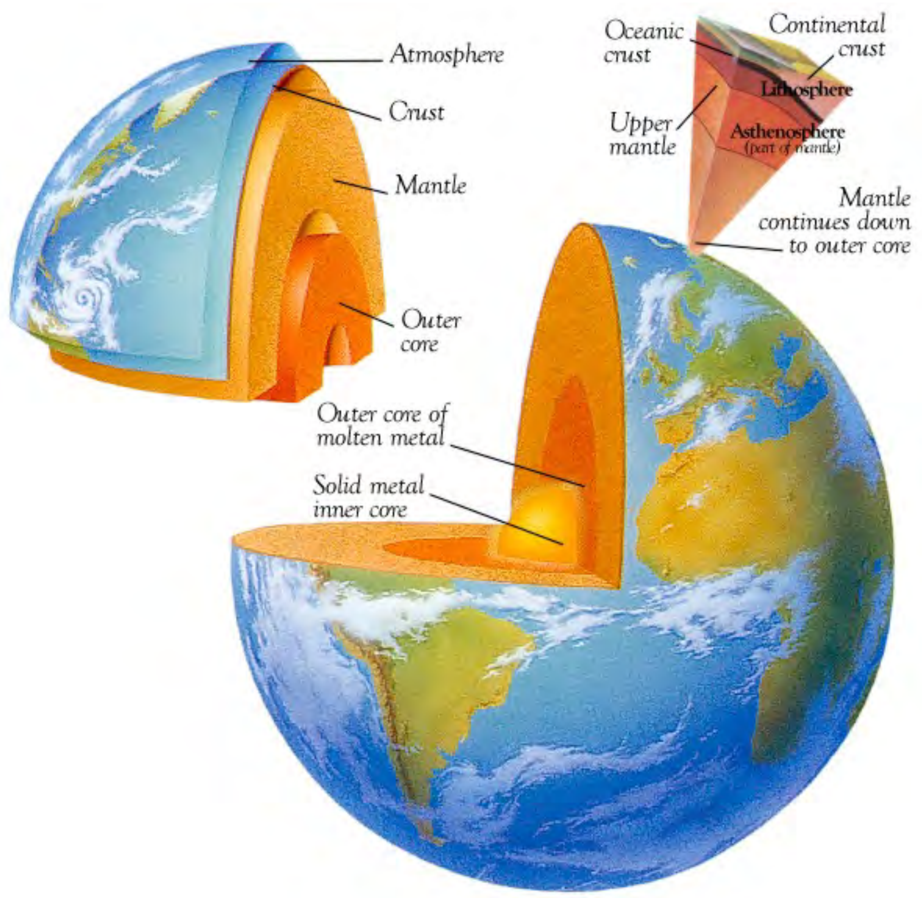


Theia physics program

Neutrinos as a probe of nature



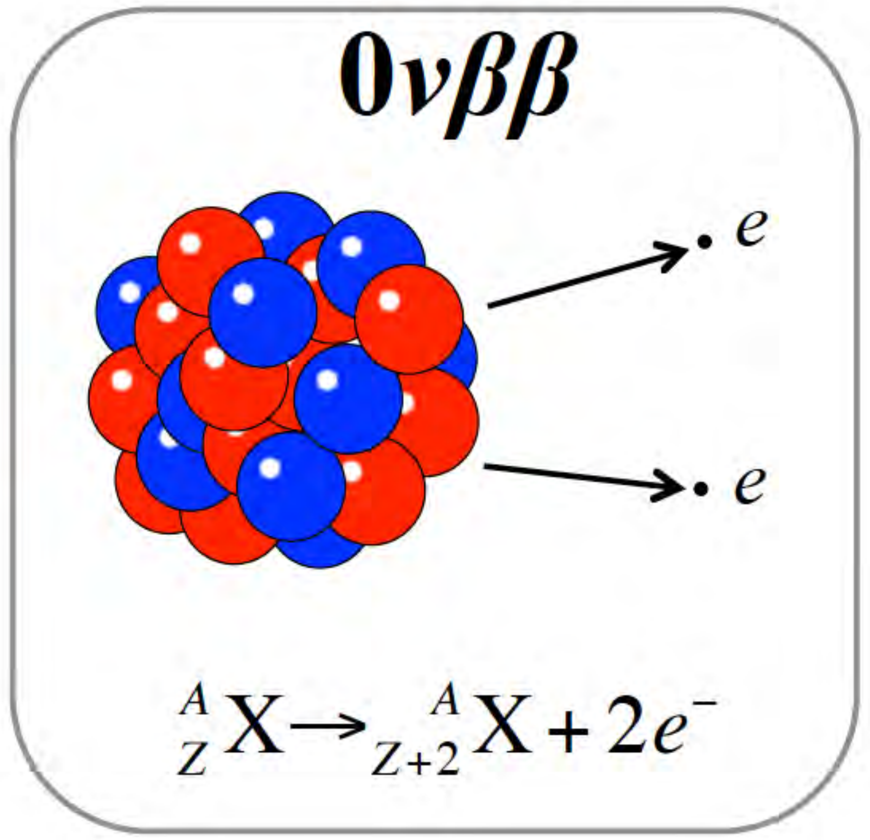


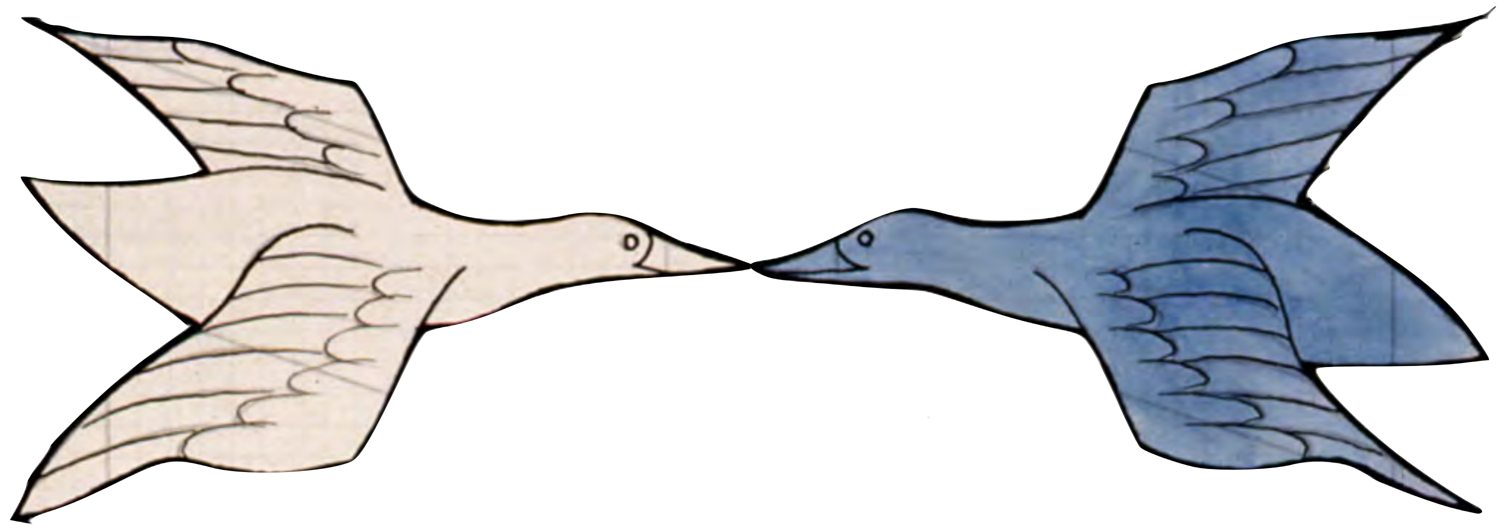


Particle astrophysics

Studying the fundamental nature of matter

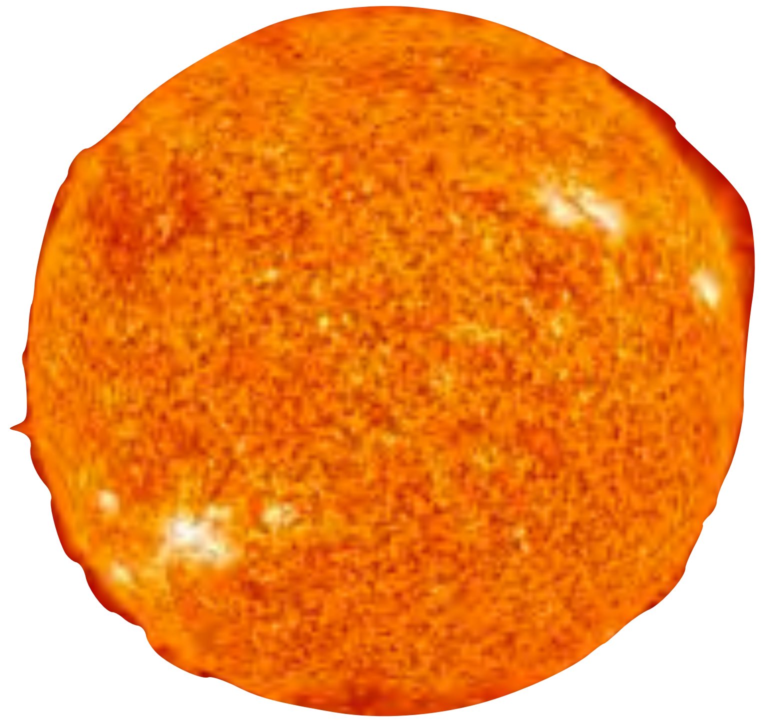
Nuclear physics

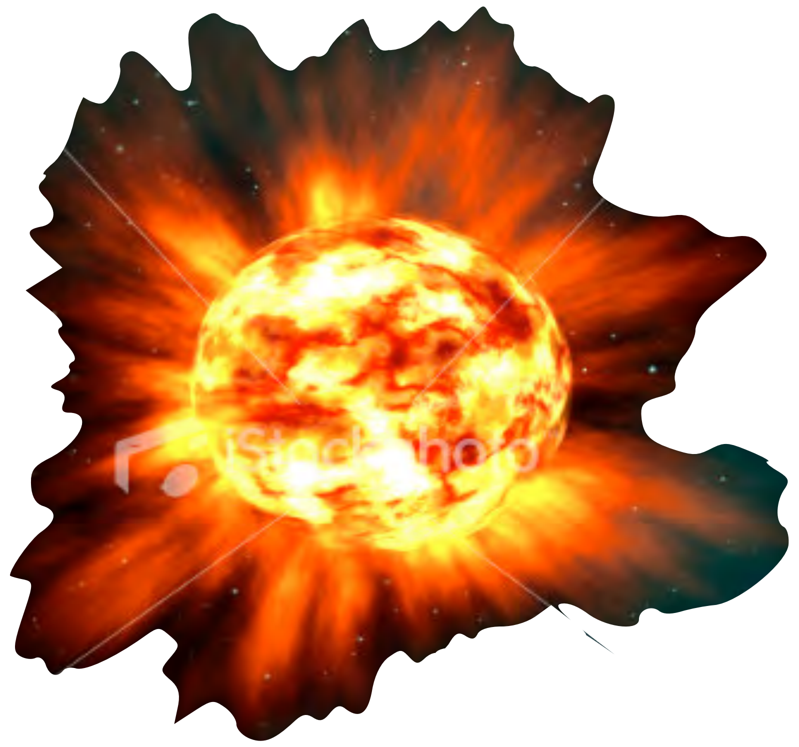


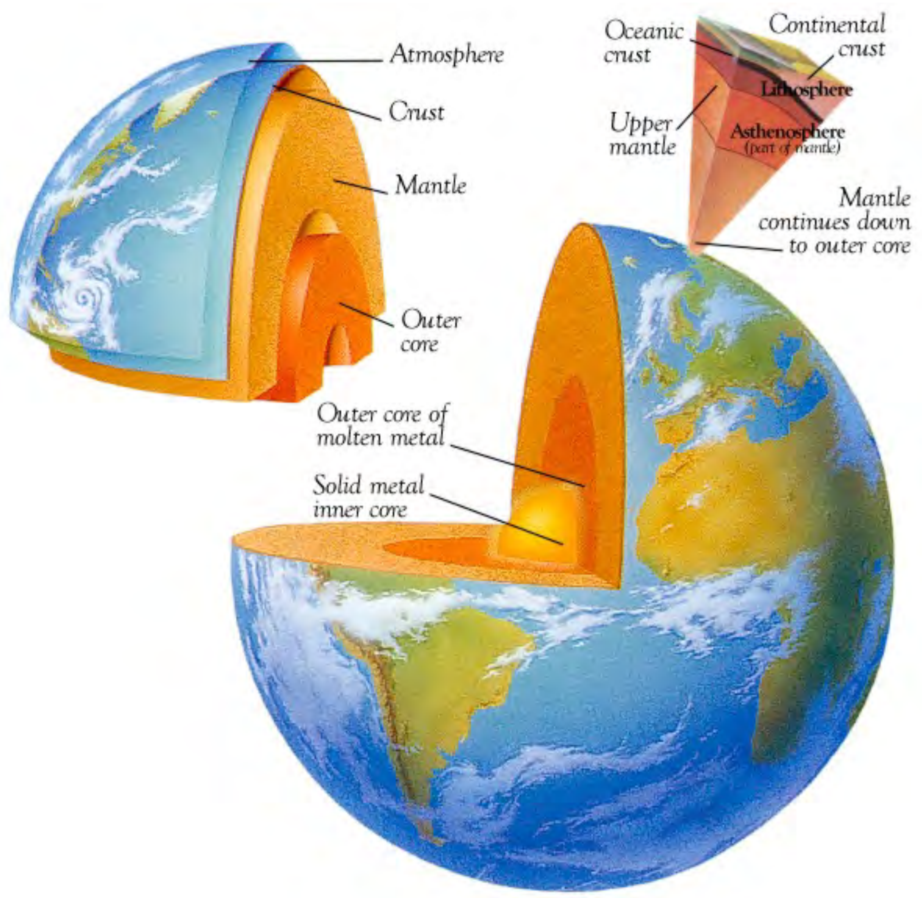


THEIA physics program

Neutrinos as a probe of nature







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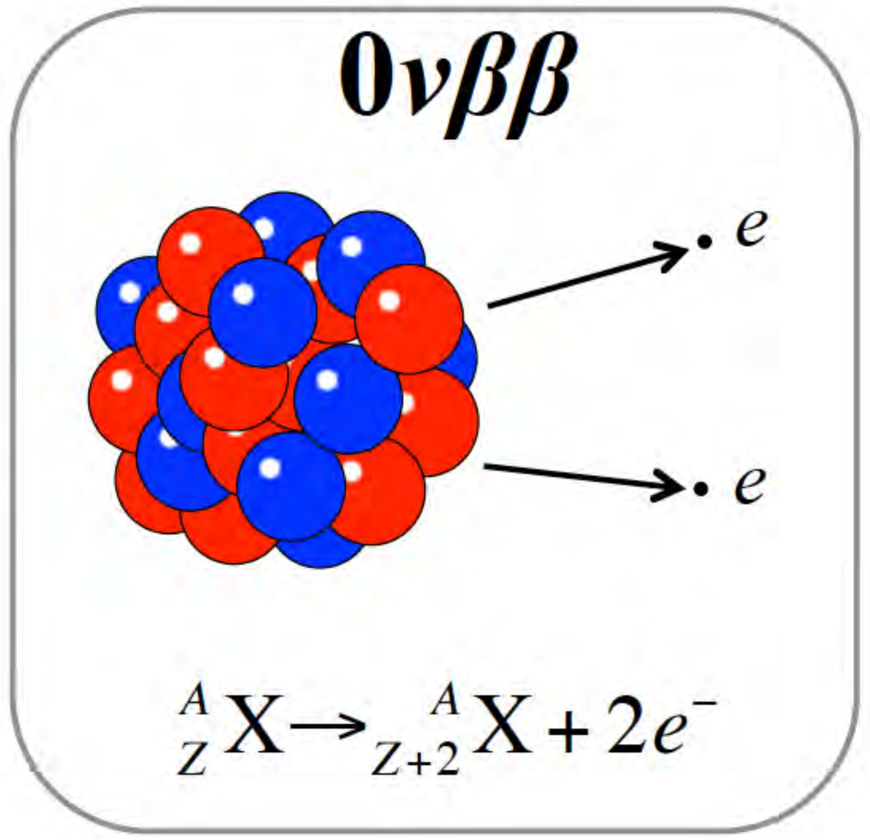

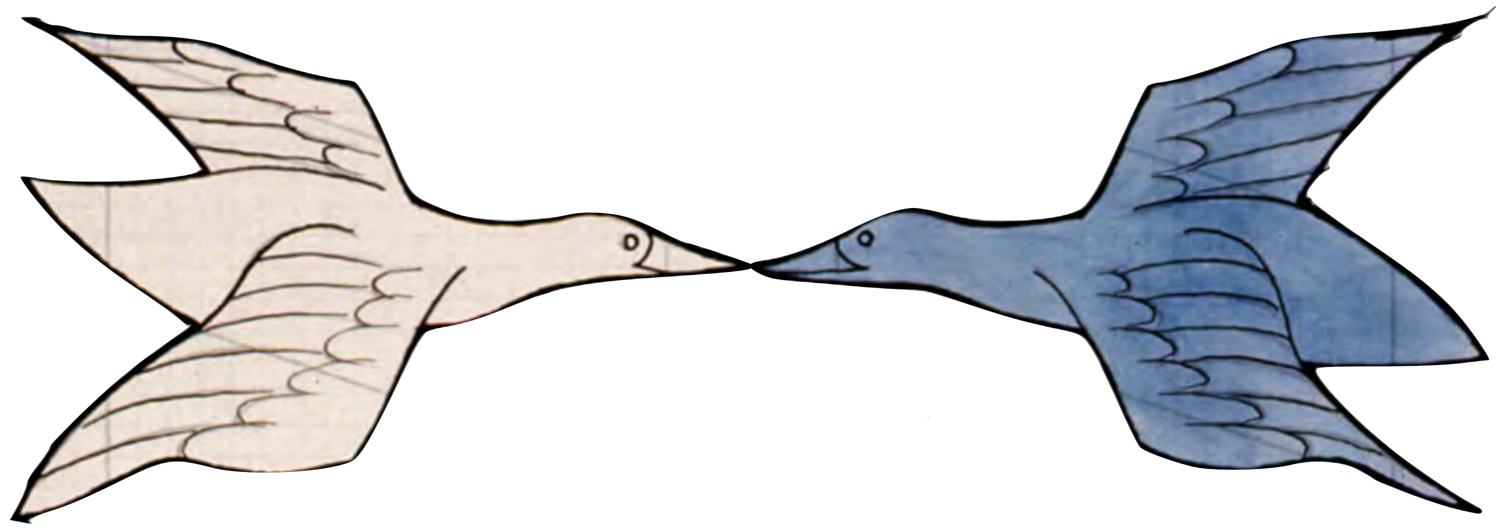

Particle astrophysics

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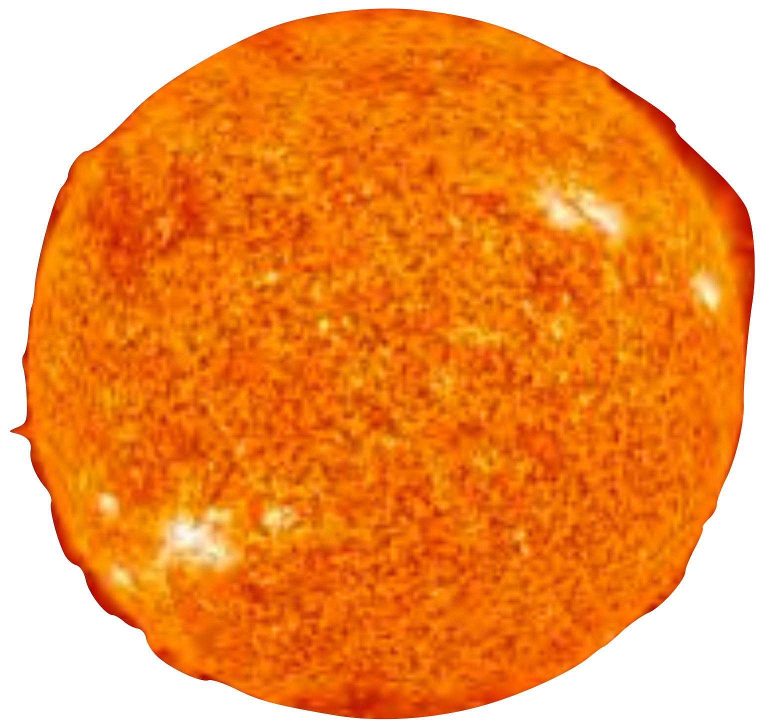
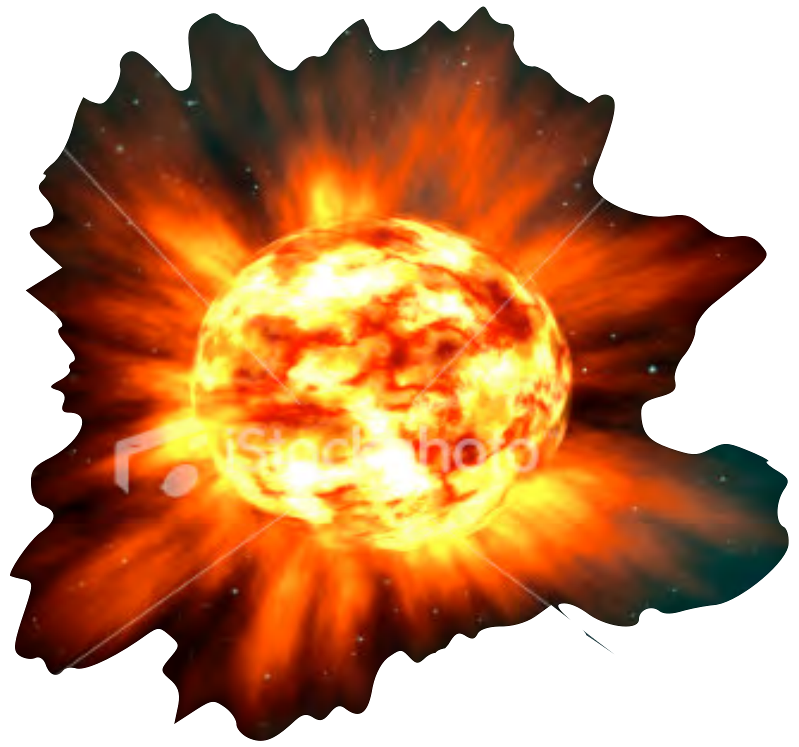
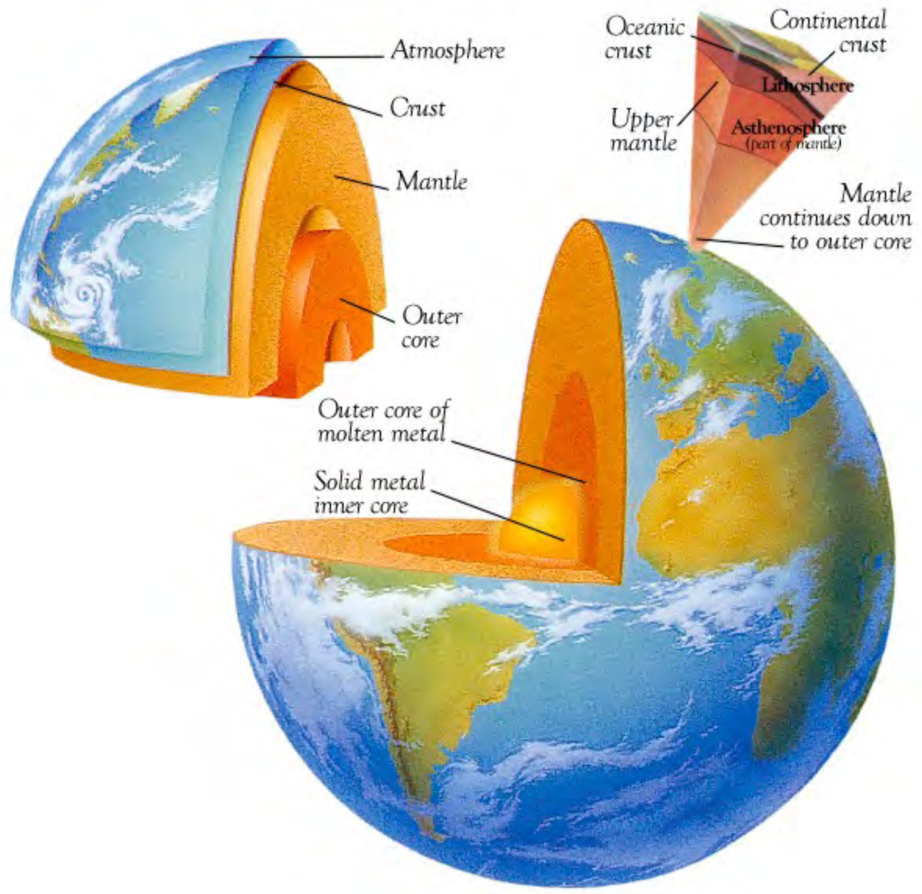
High energy physics

THEIA physics program

Neutrinos as a probe of nature







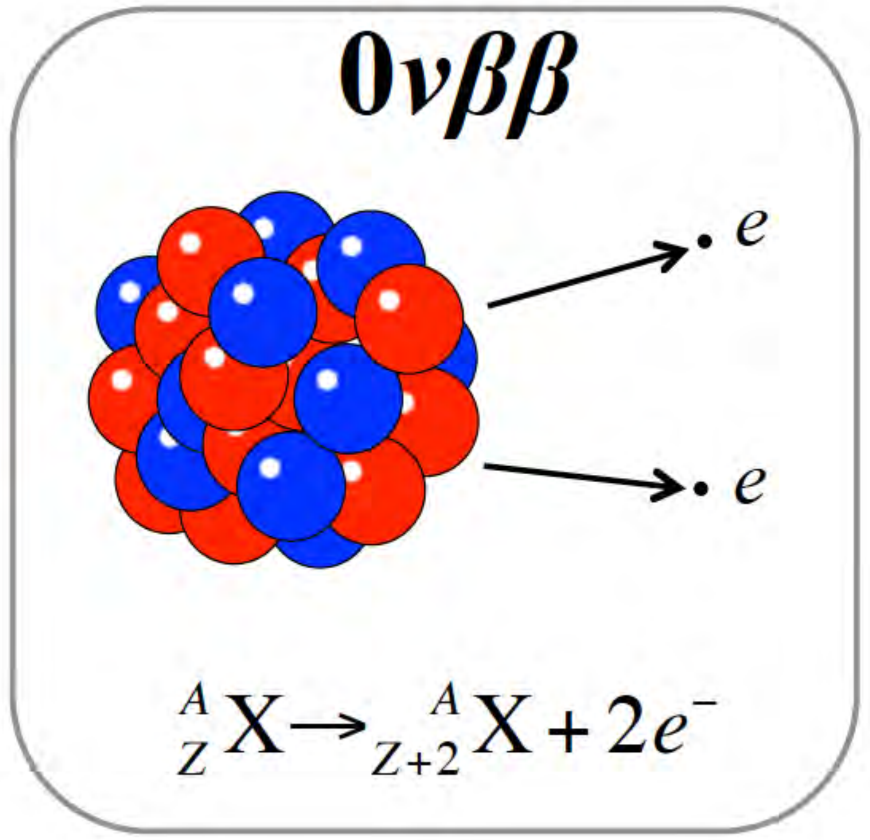
Physics over 5 orders of magnitude

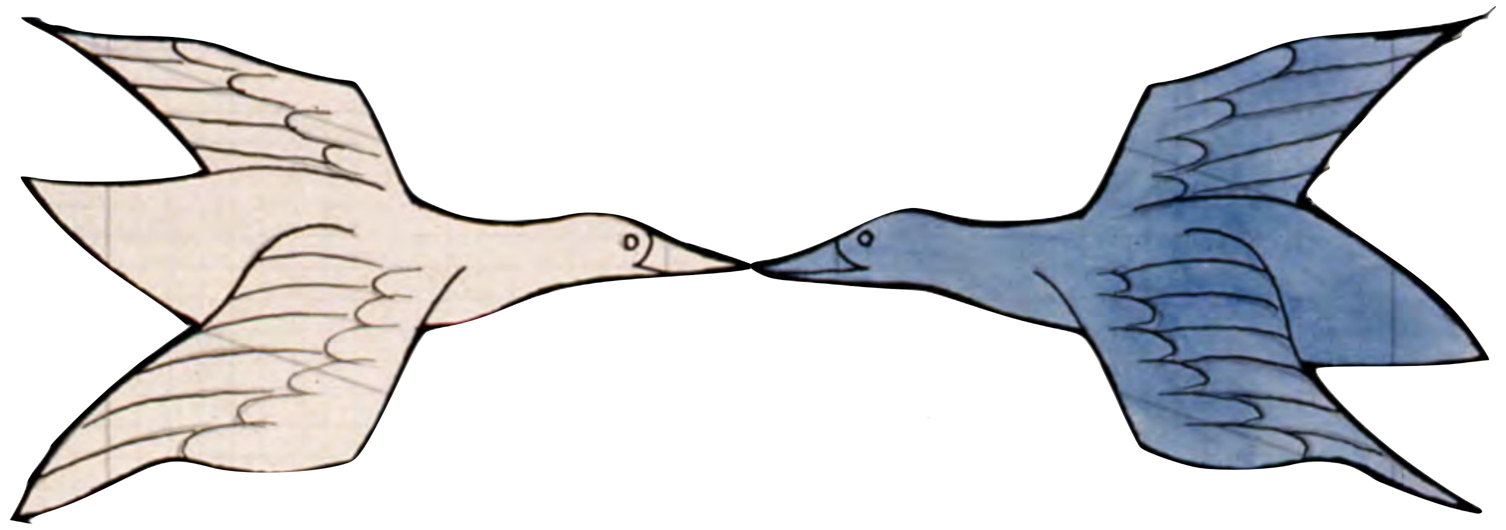
Particle astrophysics

Nuclear physics

High energy physics

Studying the fundamental nature of matter





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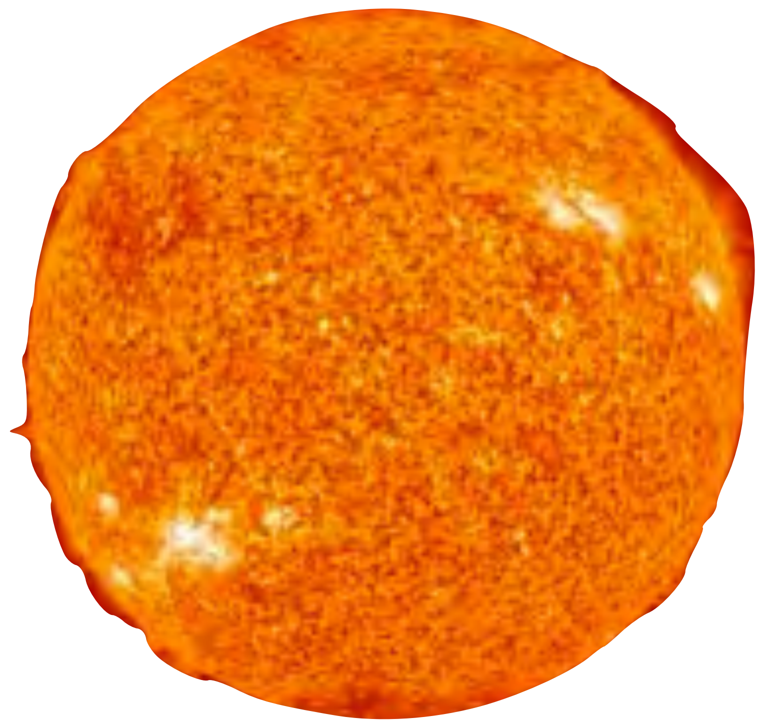
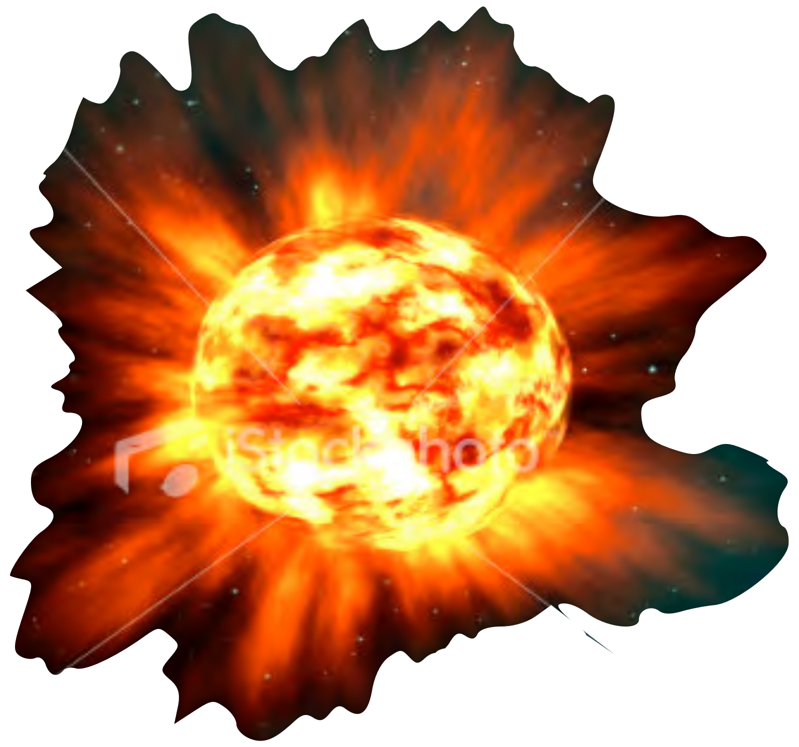
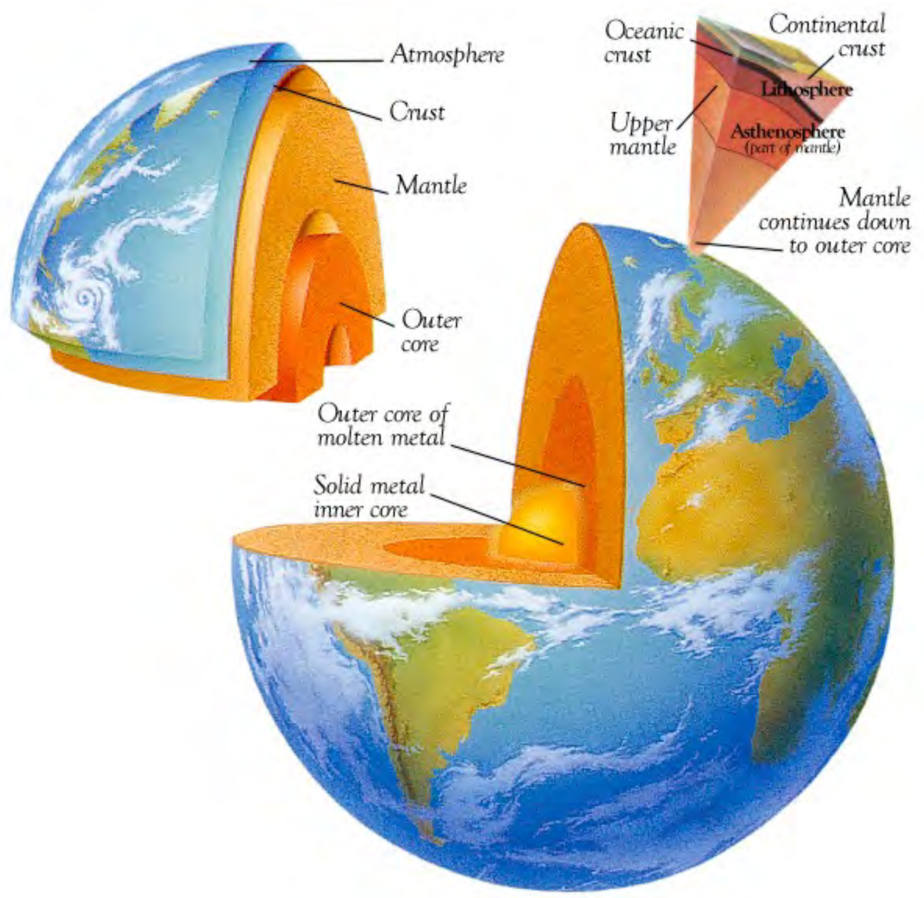
Neutrinos as a probe of nature







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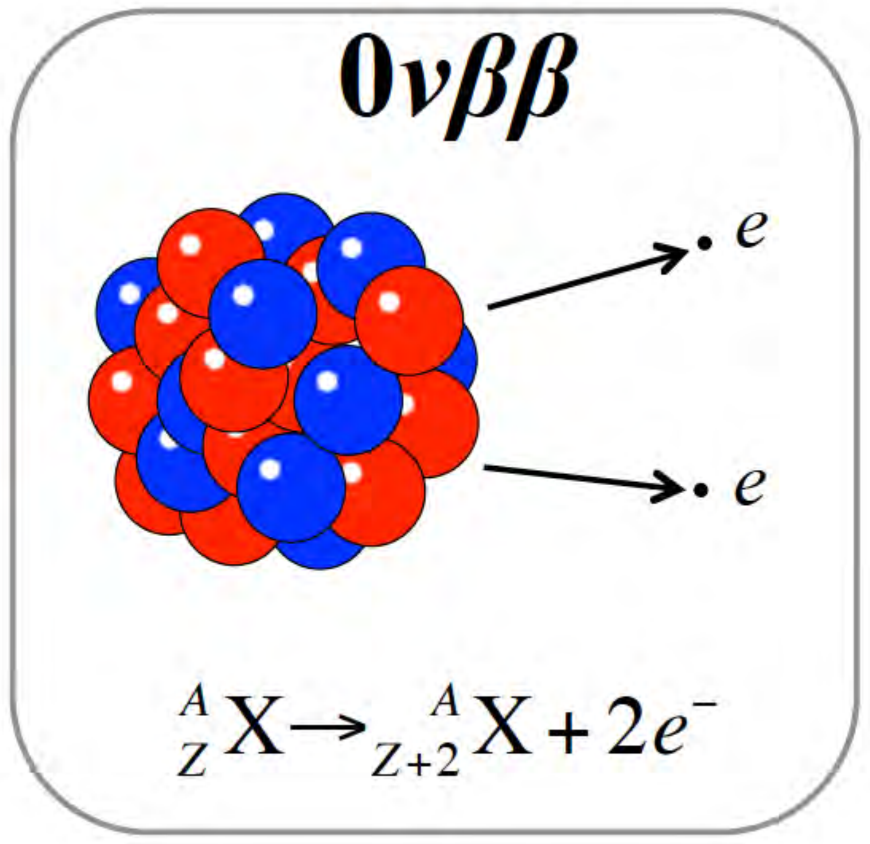

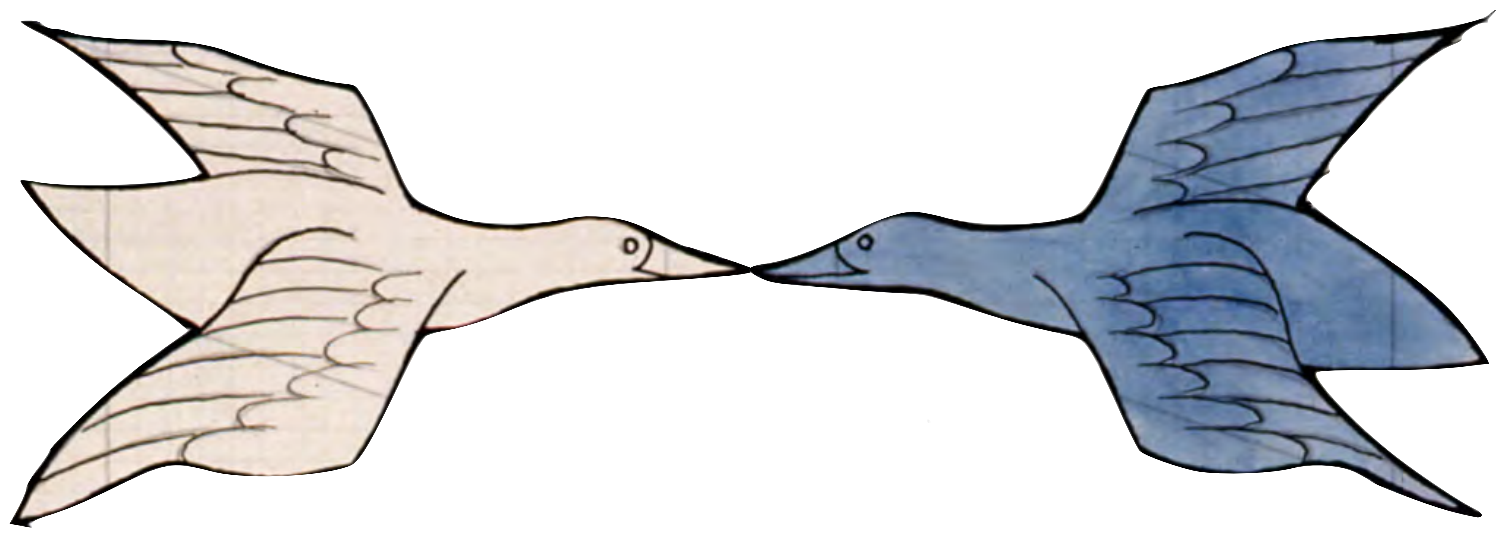

Remarkably, the same detector could show that neutrinos and antineutrinos are the same, ***and*** that "neutrinos" and "antineutrinos" oscillate differently

THEIA physics program

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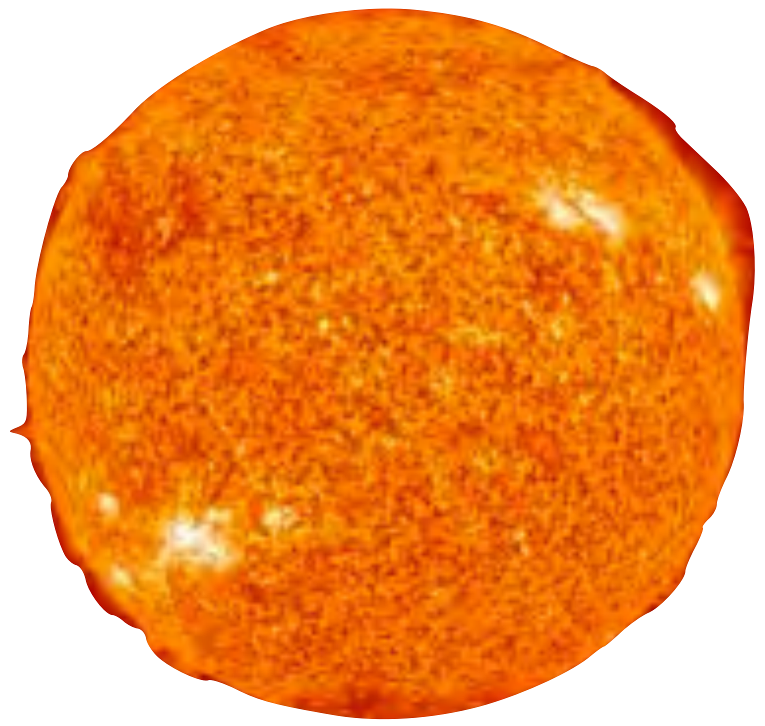

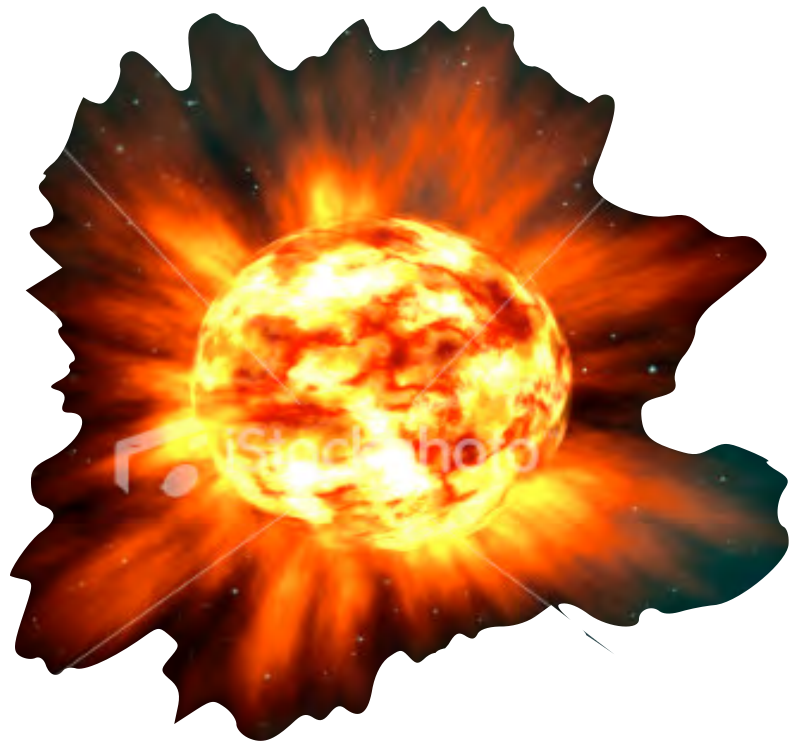

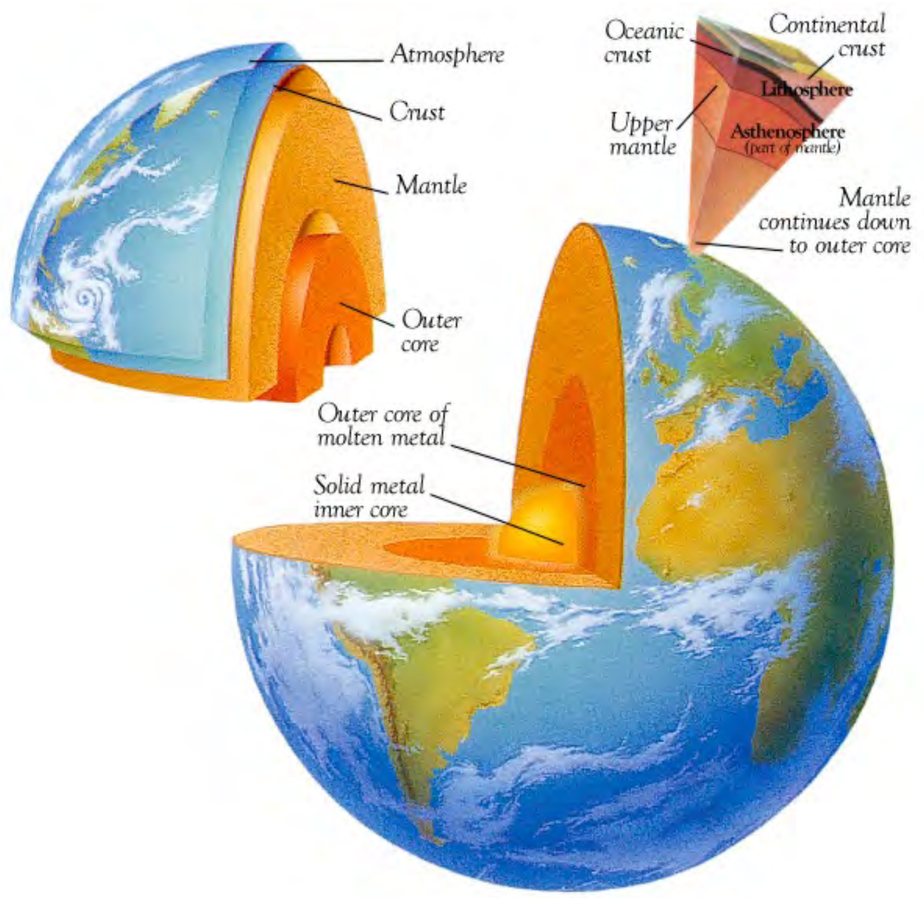

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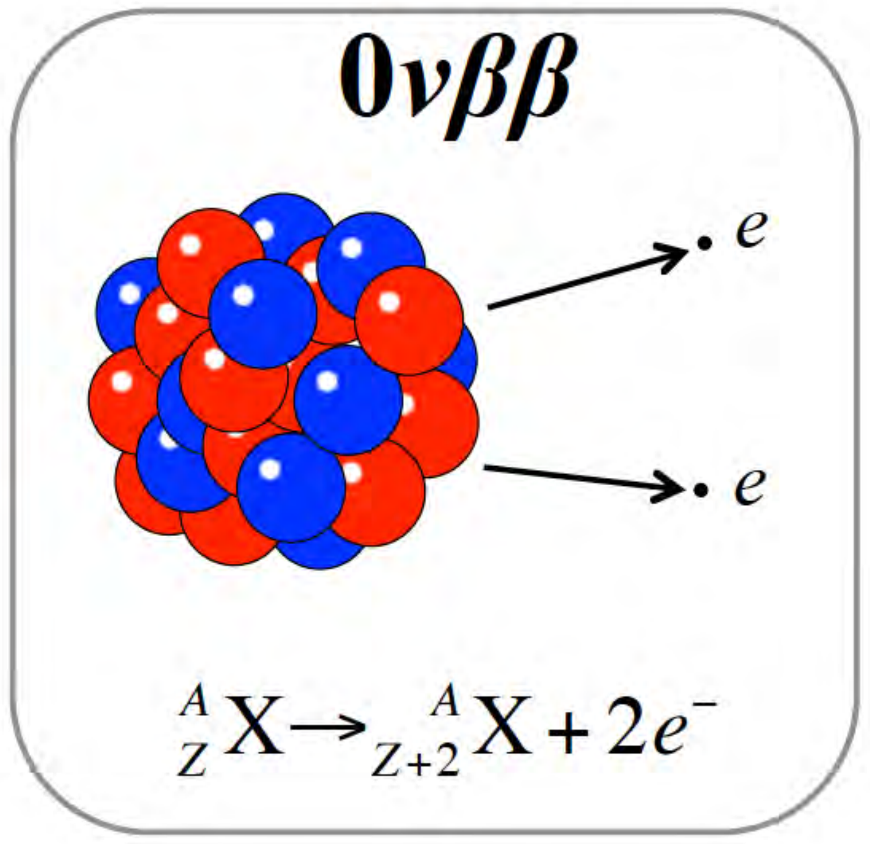

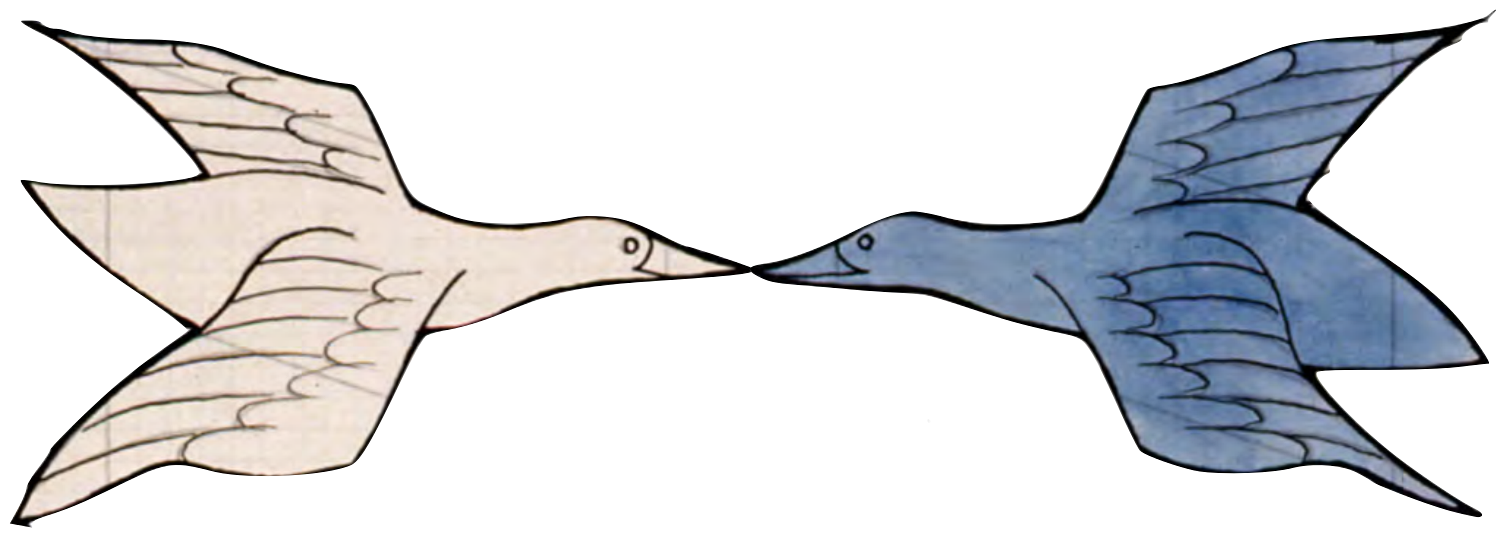

Remarkably, the same detector could show that neutrinos and antineutrinos are the same, ***and*** that "neutrinos" and "antineutrinos" oscillate differently

Physics over 5 orders of magnitude

Particle astrophysics

Nuclear physics

High energy physics

Matter-dominated universe

Neutrinos for nonproliferation

Neutrino properties

Produced as a by-product of fission and fusion	⟷	*Provide a unique signature of nuclear fission / fusion*
Weakly interacting	⟷	*Signature can't be shielded*
Close to massless, travel ~c	⟷	*Near-instantaneous detection*
Interaction products preserve incident direction	⟷	*Can be used to "point" back to the source*

Test site transparency

Small modular reactors

Maritime sensing

Neutrinos for nonproliferation

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Interaction products preserve incident direction	⟷	*Can be used to "point" back to the source*

- NuTools: 2021 study (DNN R&D) "exploring practical roles for neutrinos in nuclear energy and security"
- LBNL's focus is to advance the technology to enhance the capabilities of such a detector
  - Reduce the required scale, increase standoff, and provide additional synergies with Office of Science interests
- Close partnership with related efforts at BNL & LLNL

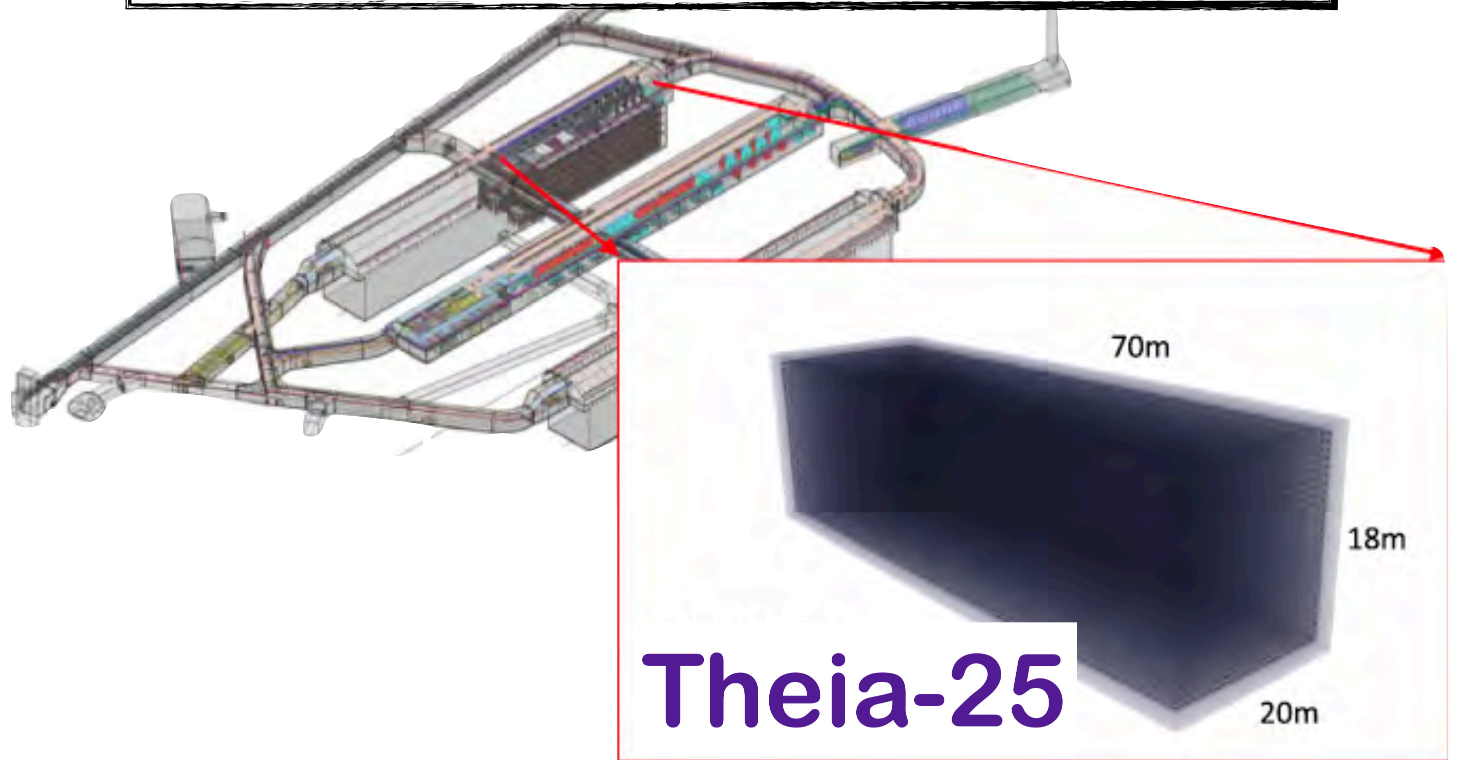
Test site transparency

Small modular reactors

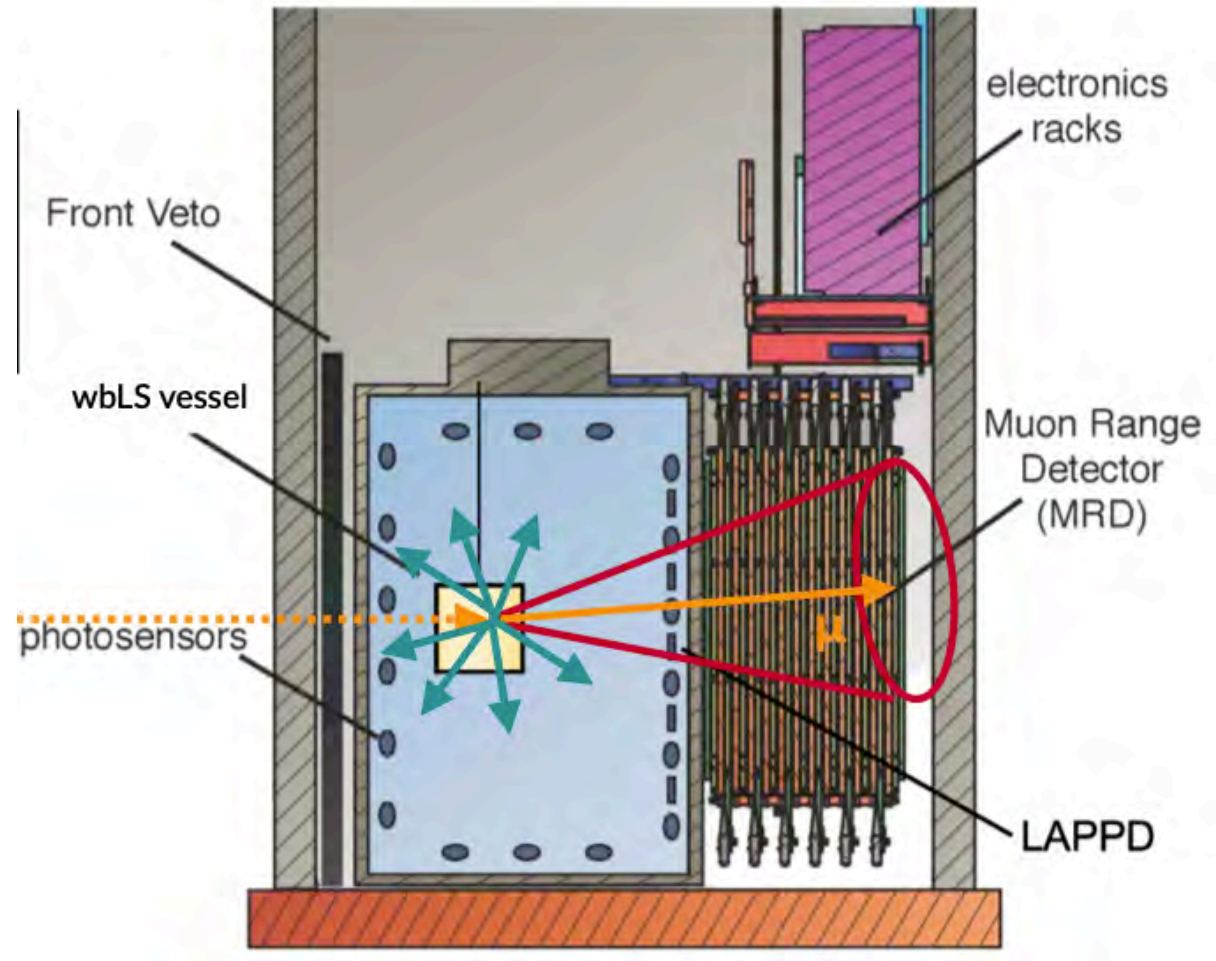
Maritime sensing

The path to THEIA

Building on a broad program of bench-top scale development



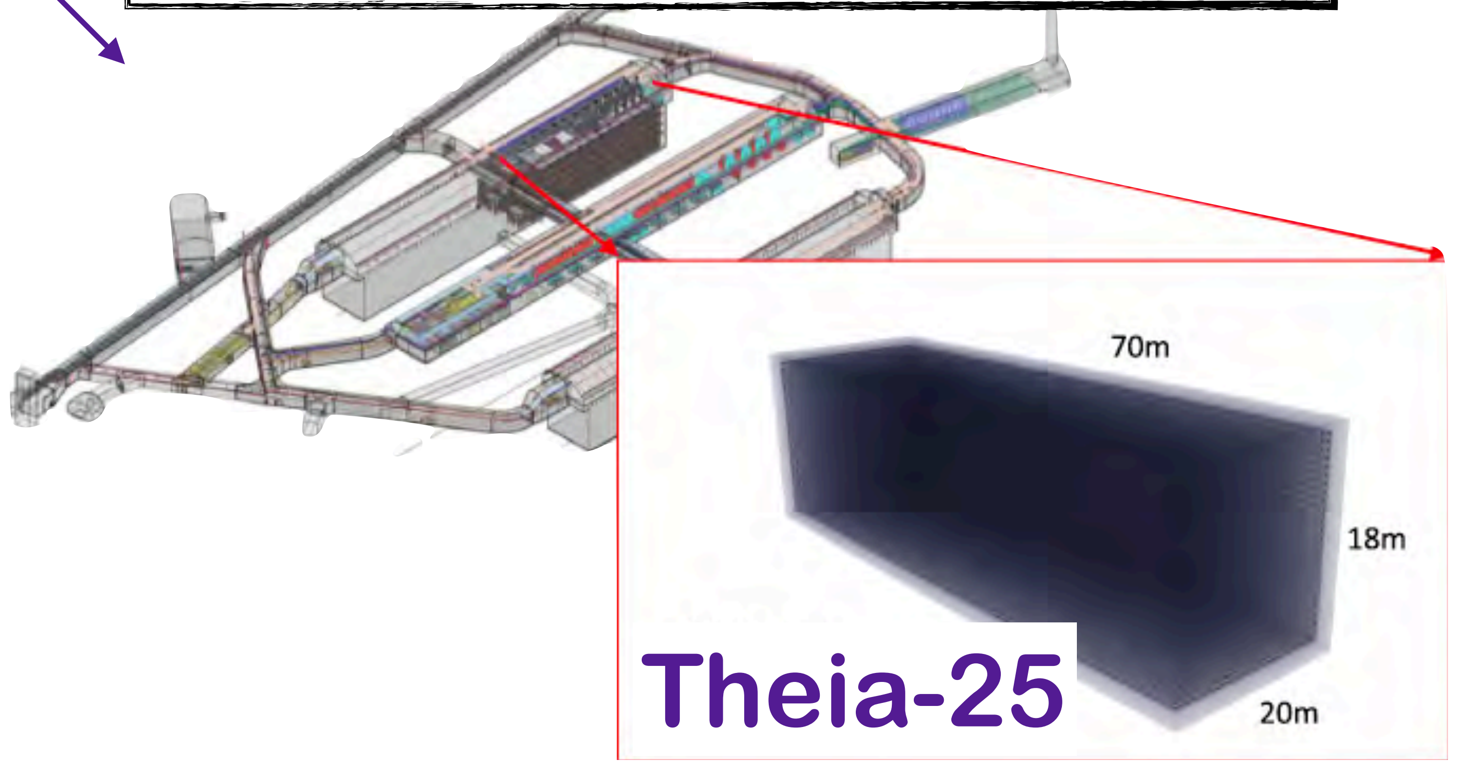
The path to THEIA



ANNIE: 365 kg

High-energy event reconstruction, neutrino detection

Building on a broad program of bench-top scale development



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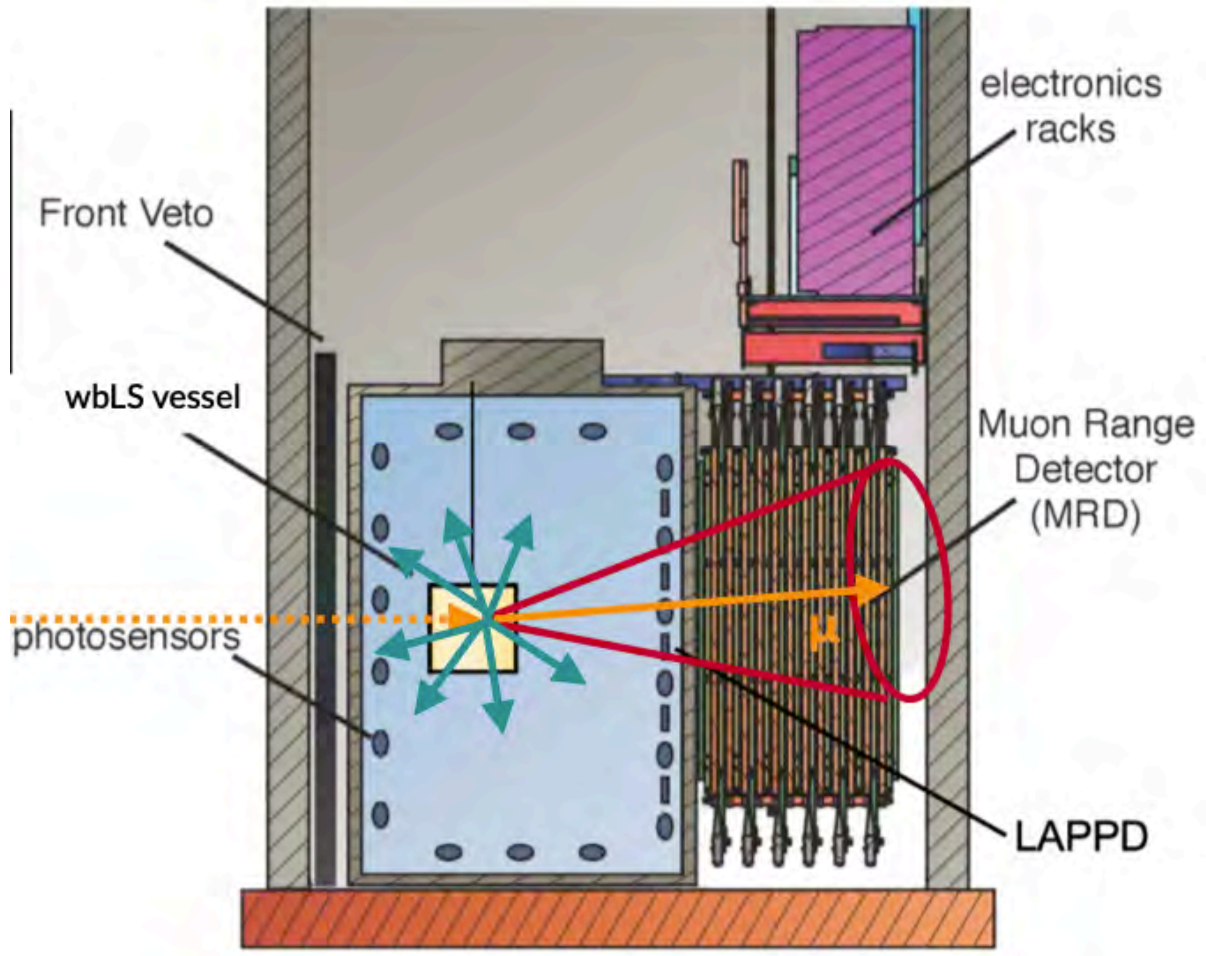

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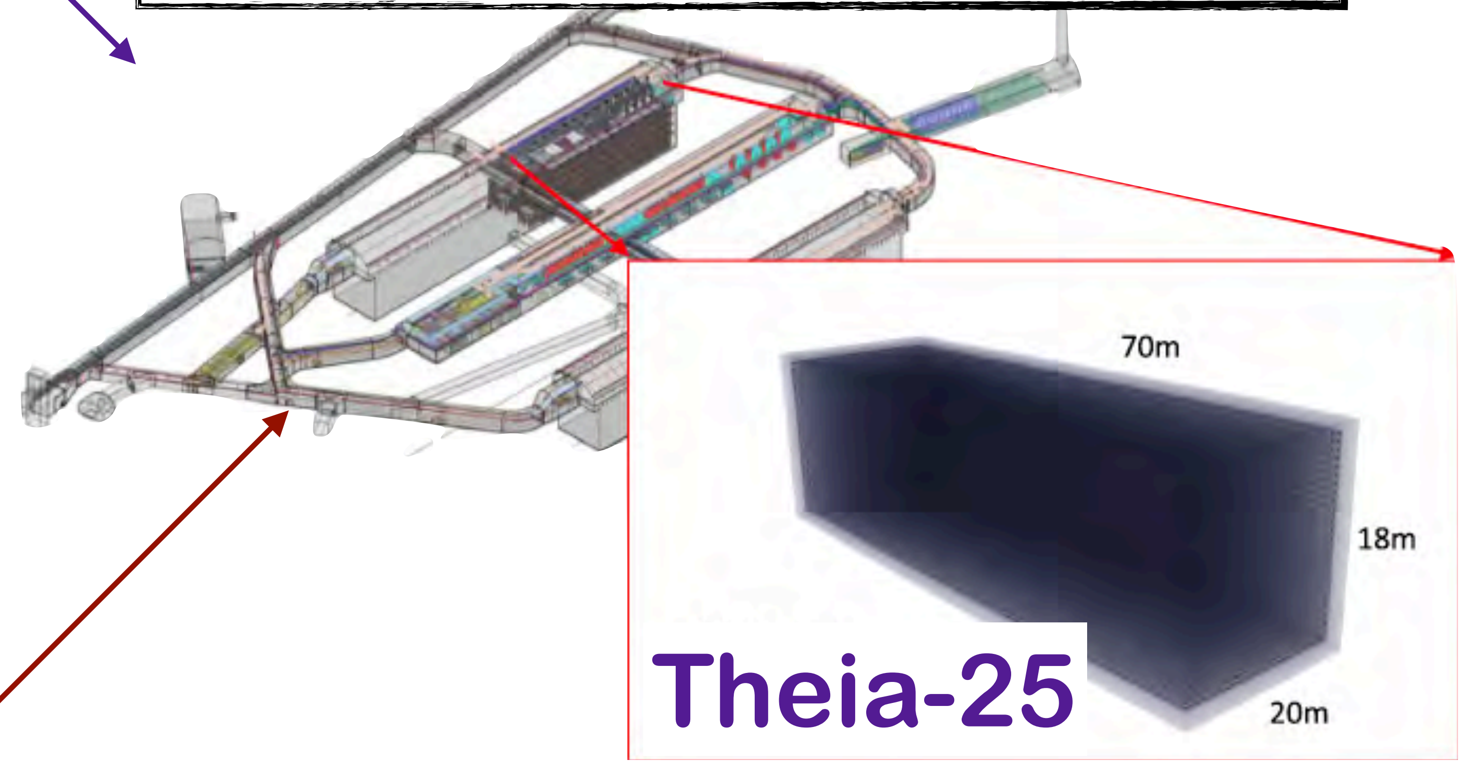
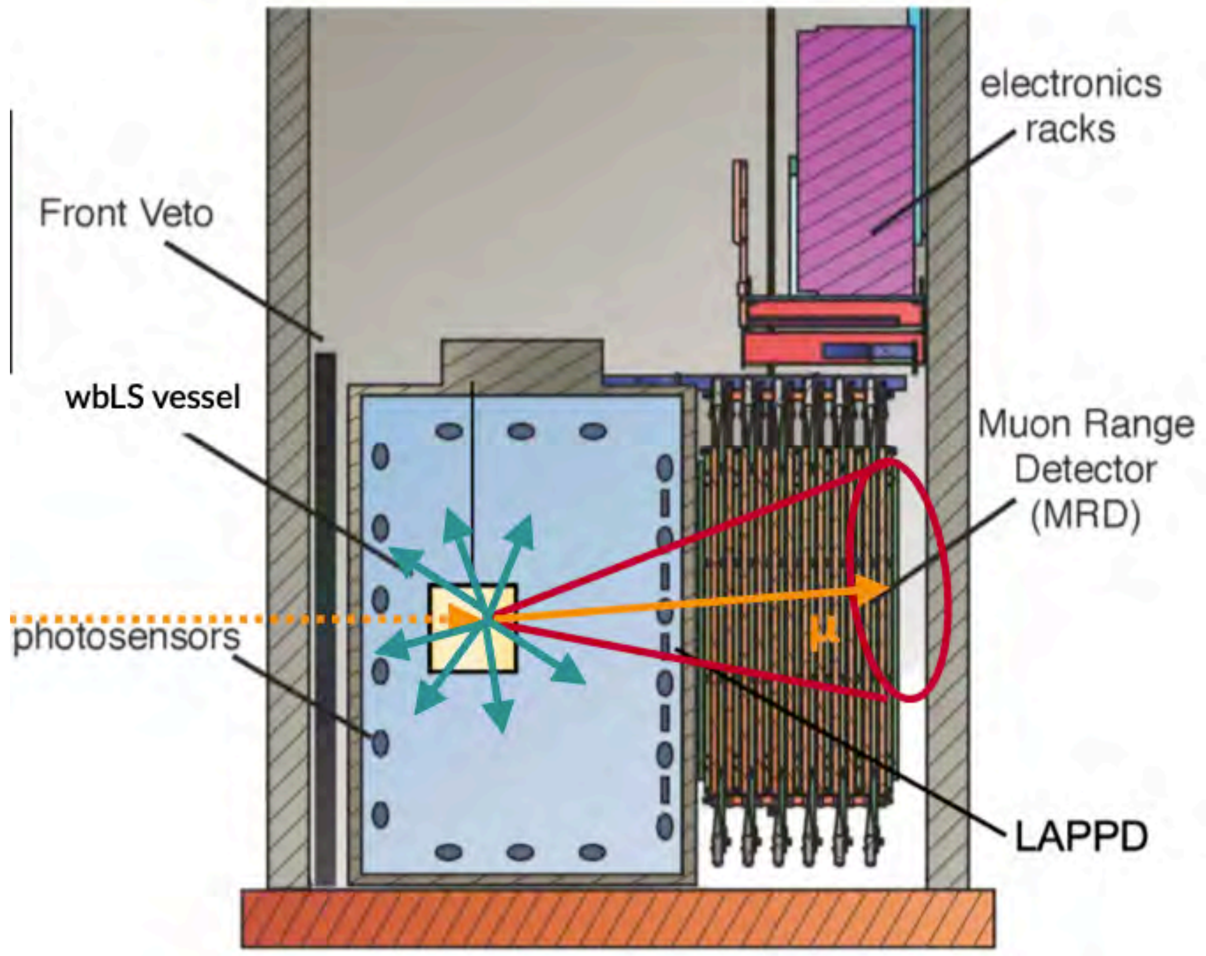


BNL: 1- and 30-ton

Deployment, purification, recirculation, transparency

The path to THEIA



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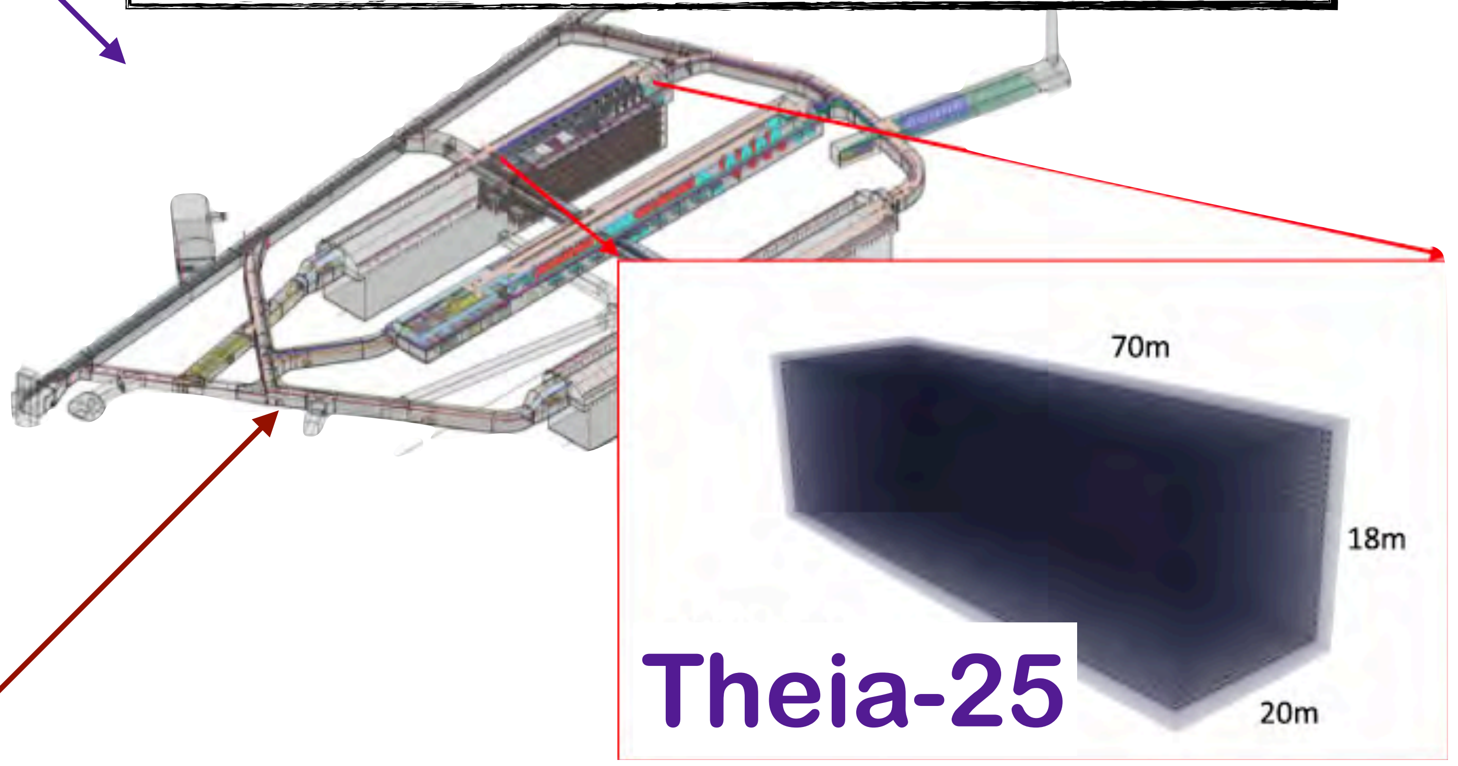


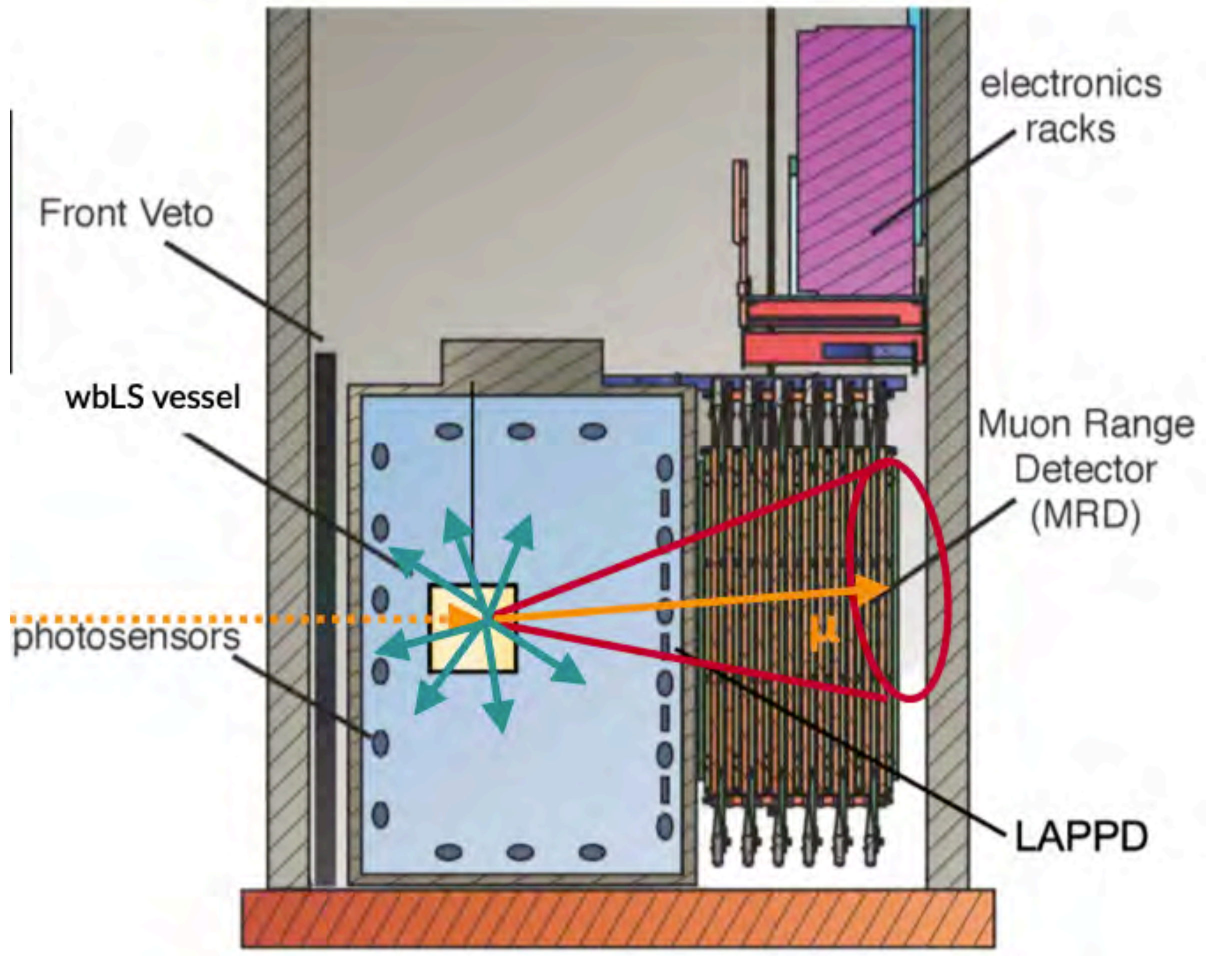
BNL: 1- and 30-ton

Deployment, purification, recirculation, transparency

NuDot: 1 ton

Isotope loading, NLDBD topology

The path to THEIA



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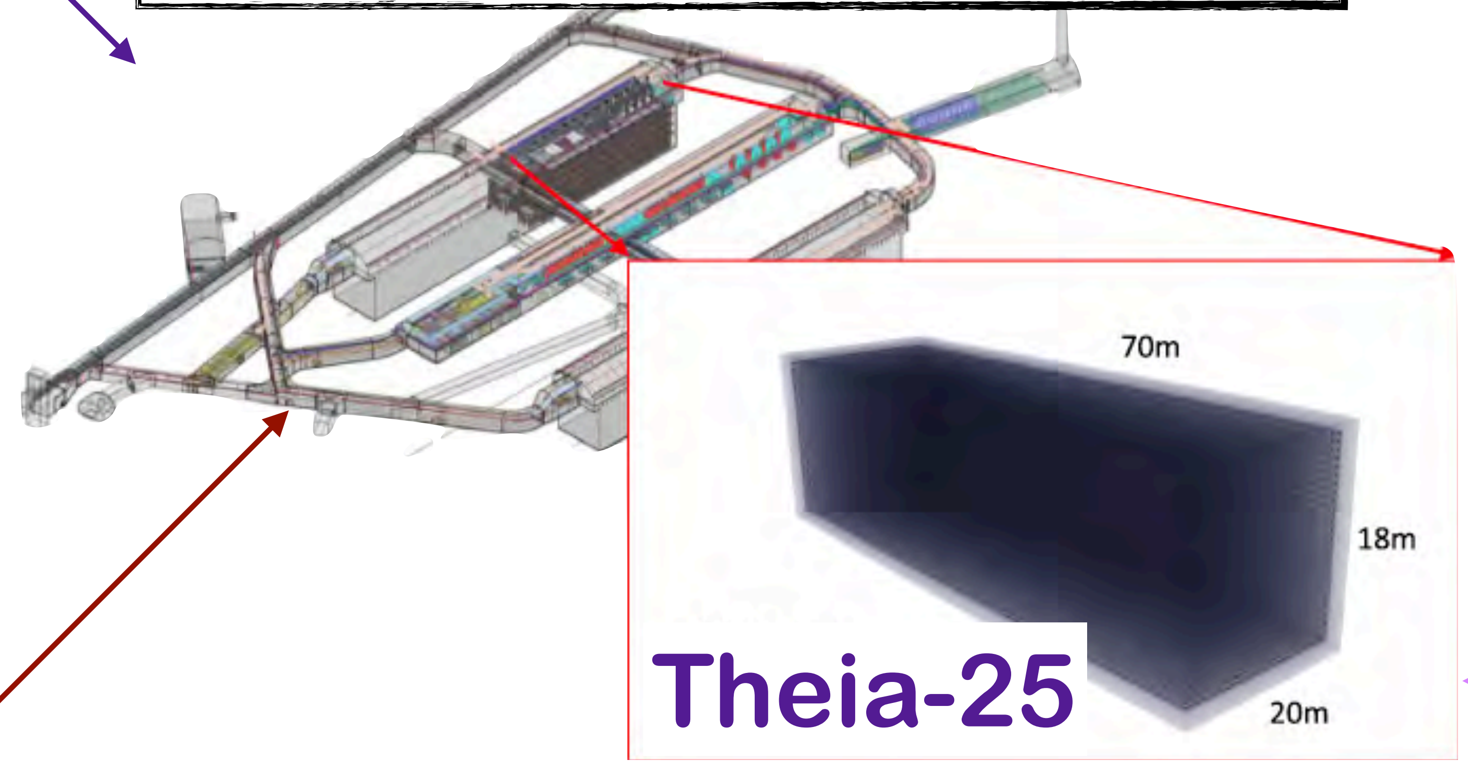


BNL: 1- and 30-ton

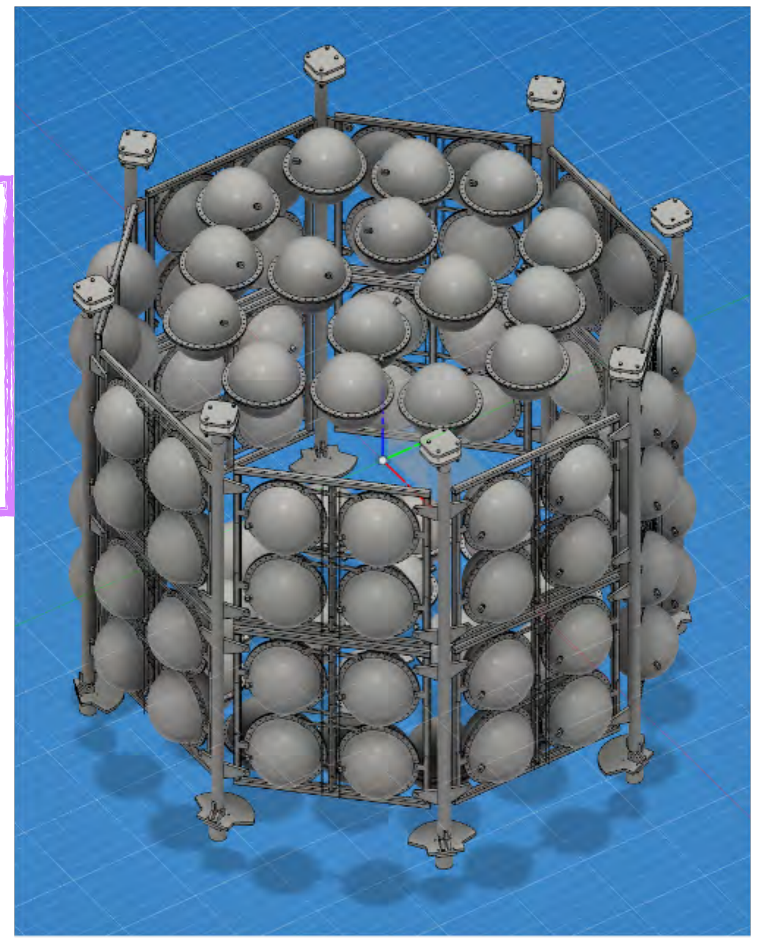
Deployment, purification, recirculation, transparency

NuDot: 1 ton

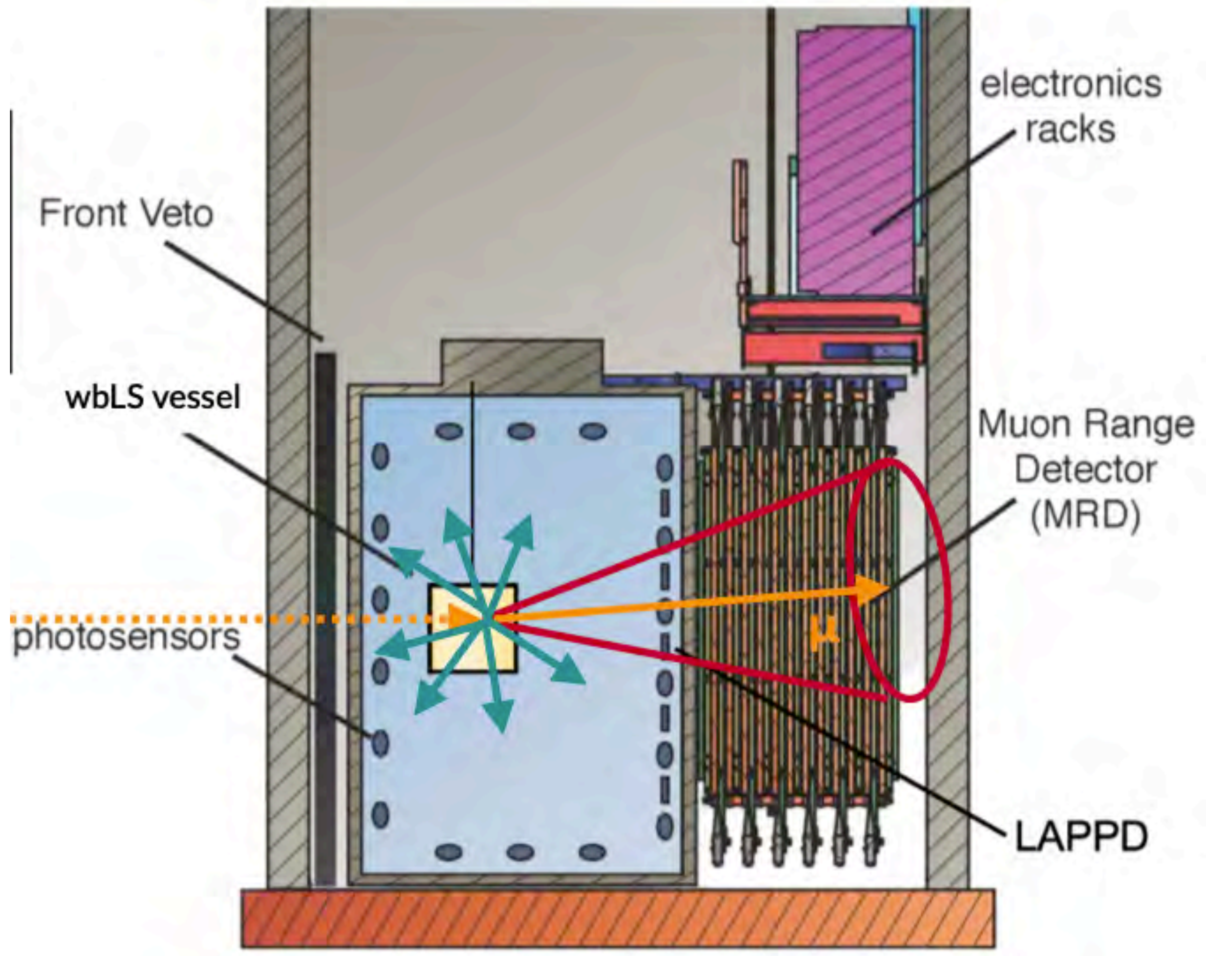
Isotope loading, NLDBD topology

BUTTON: 30 ton

Underground deployment, low bkg verification

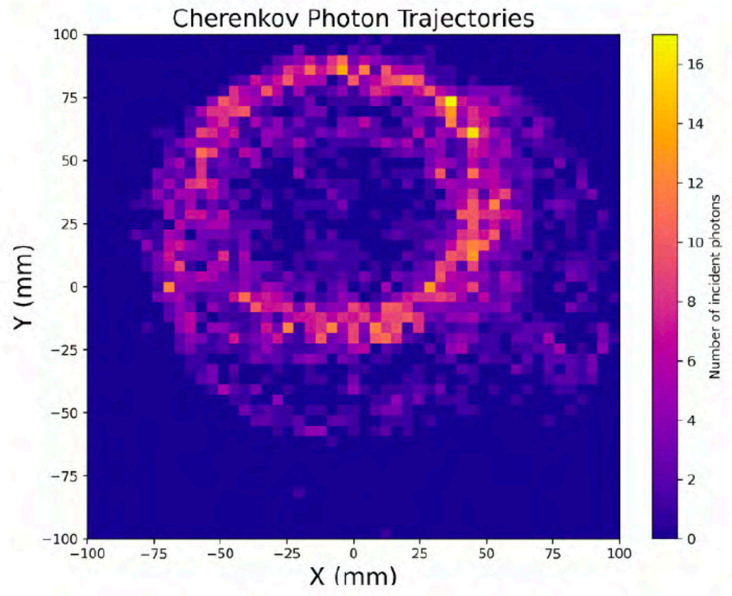


The path to THEIA



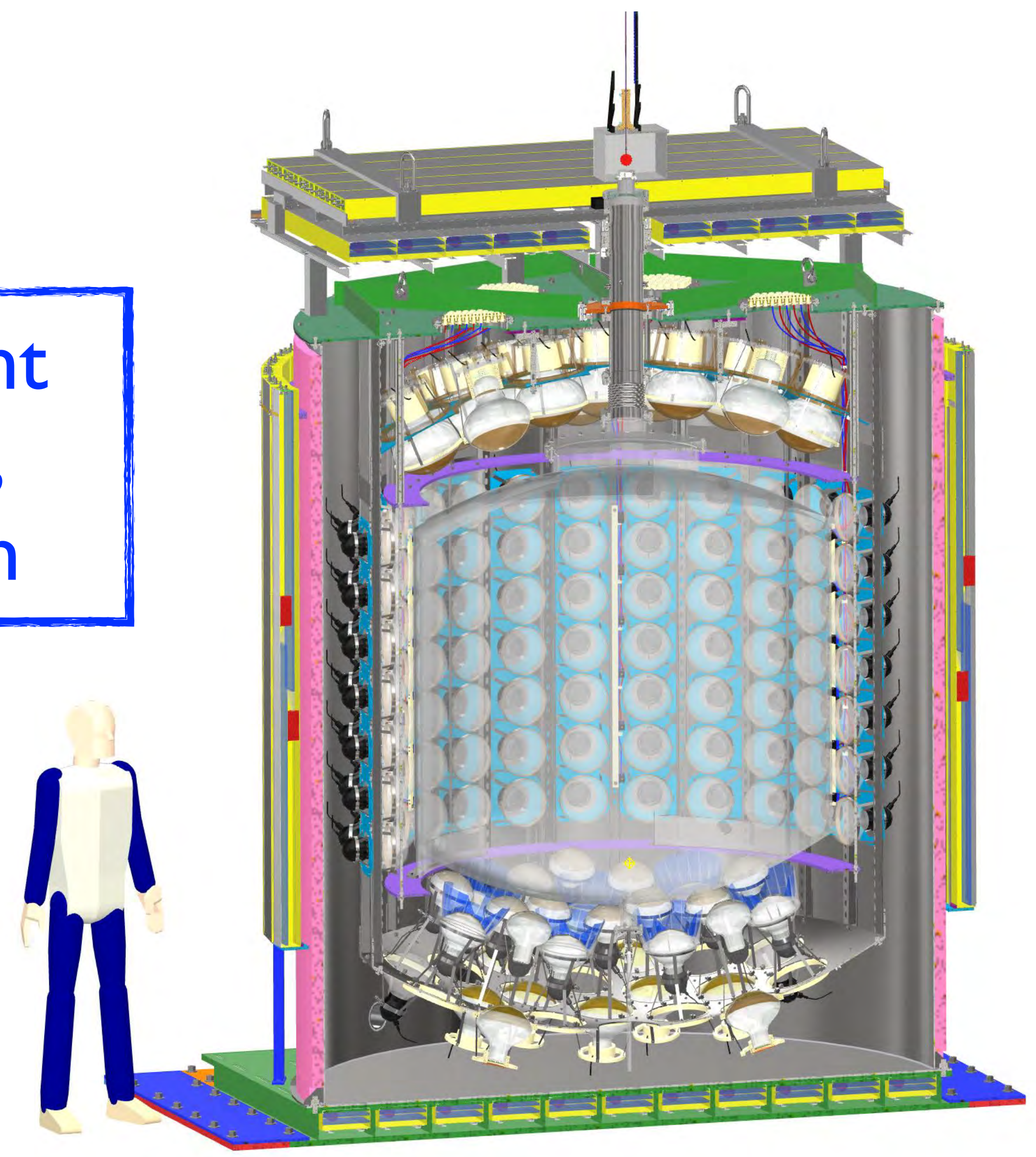
ANNIE: 365 kg

High-energy event reconstruction, neutrino detection

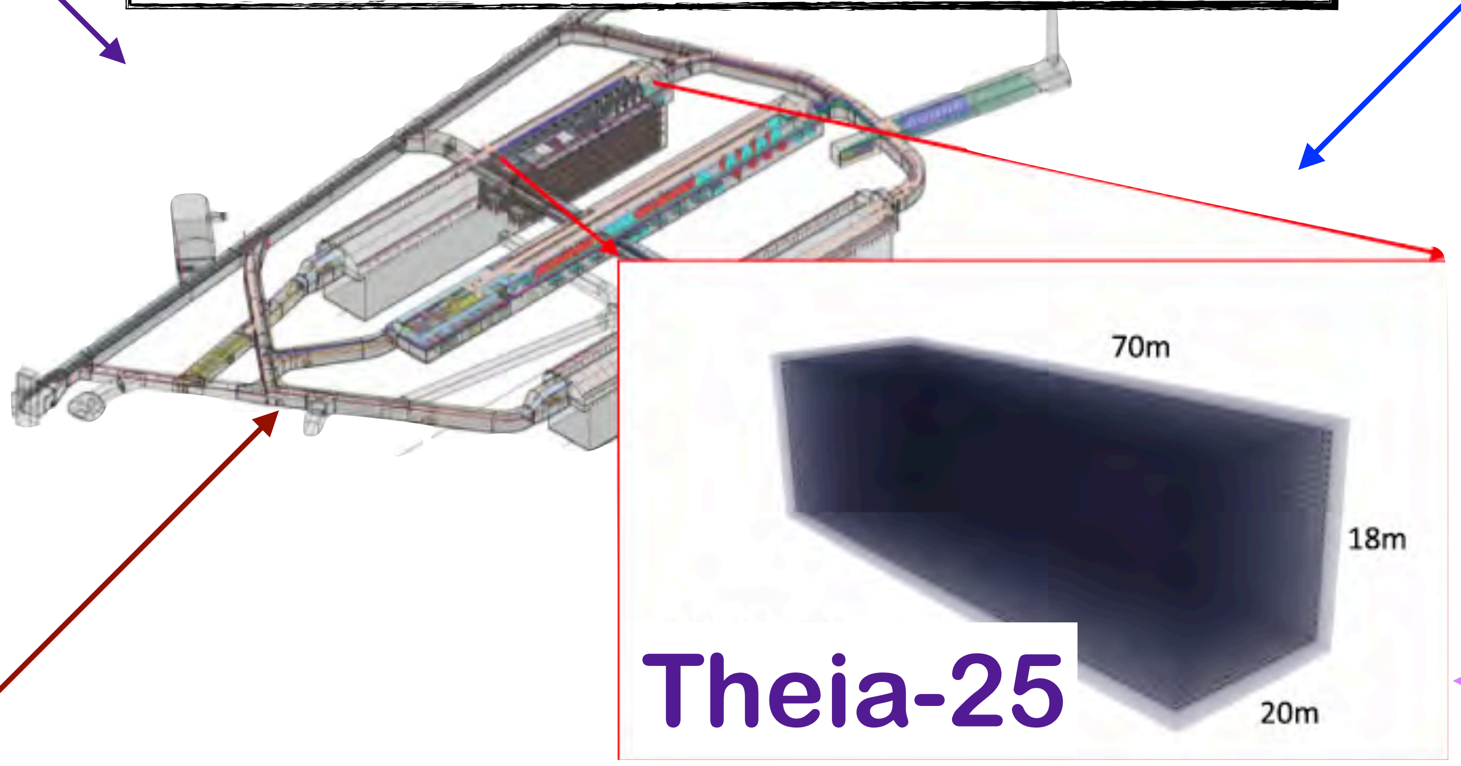


Eos: 20 ton

Low-energy event reconstruction, model validation



Building on a broad program of bench-top scale development



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Deployment, purification, recirculation, transparency

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BUTTON: 30 ton

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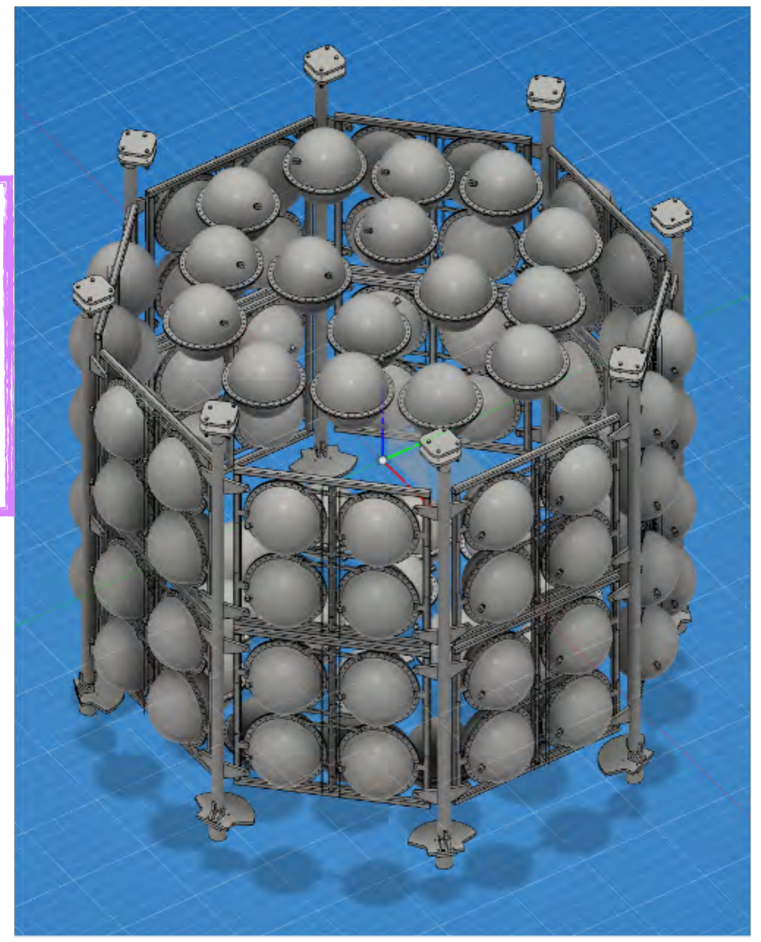


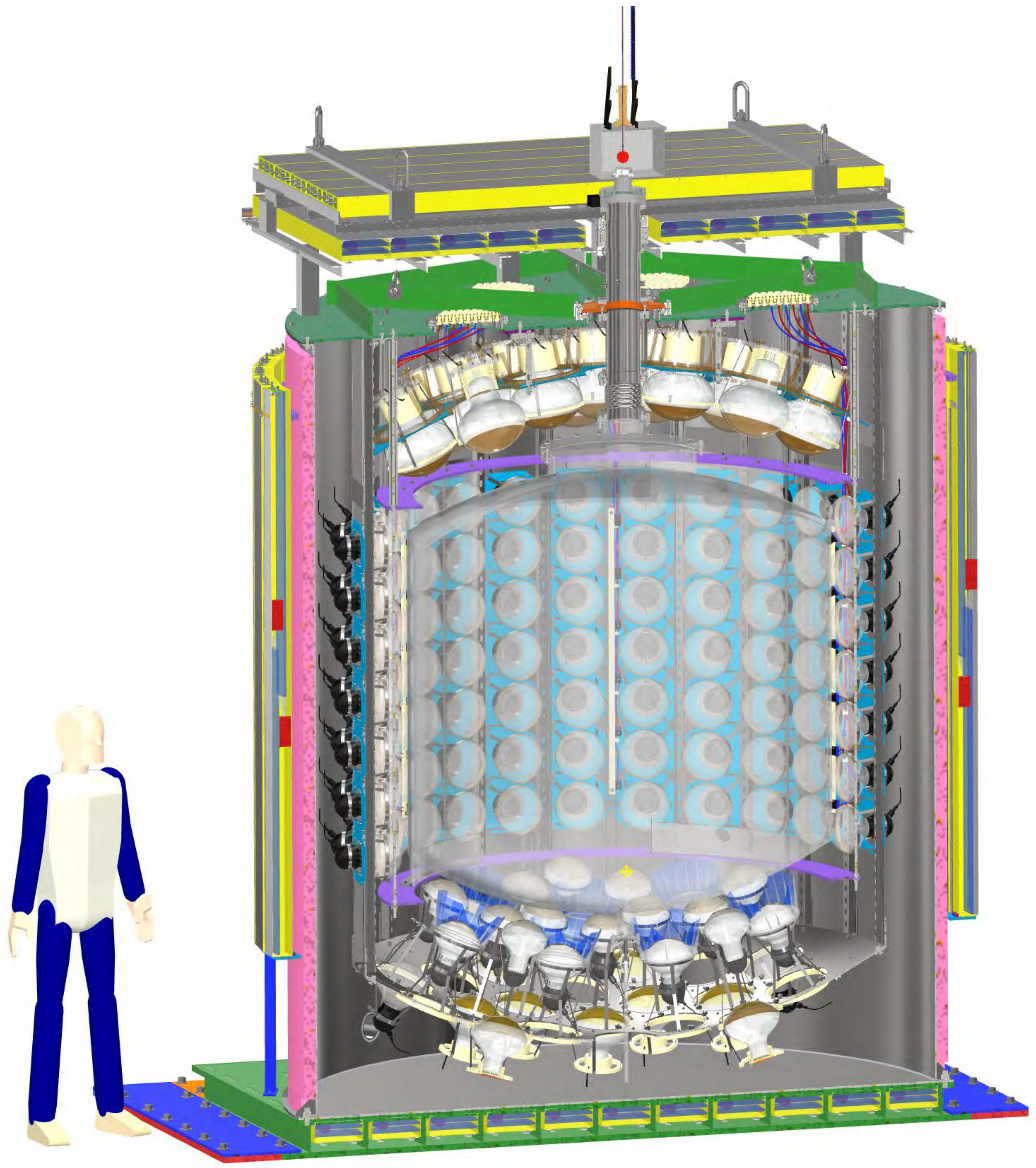

Eos (Dawn)
Funded by NNSA,
DNN R&D
FY22-24
Let There be Light

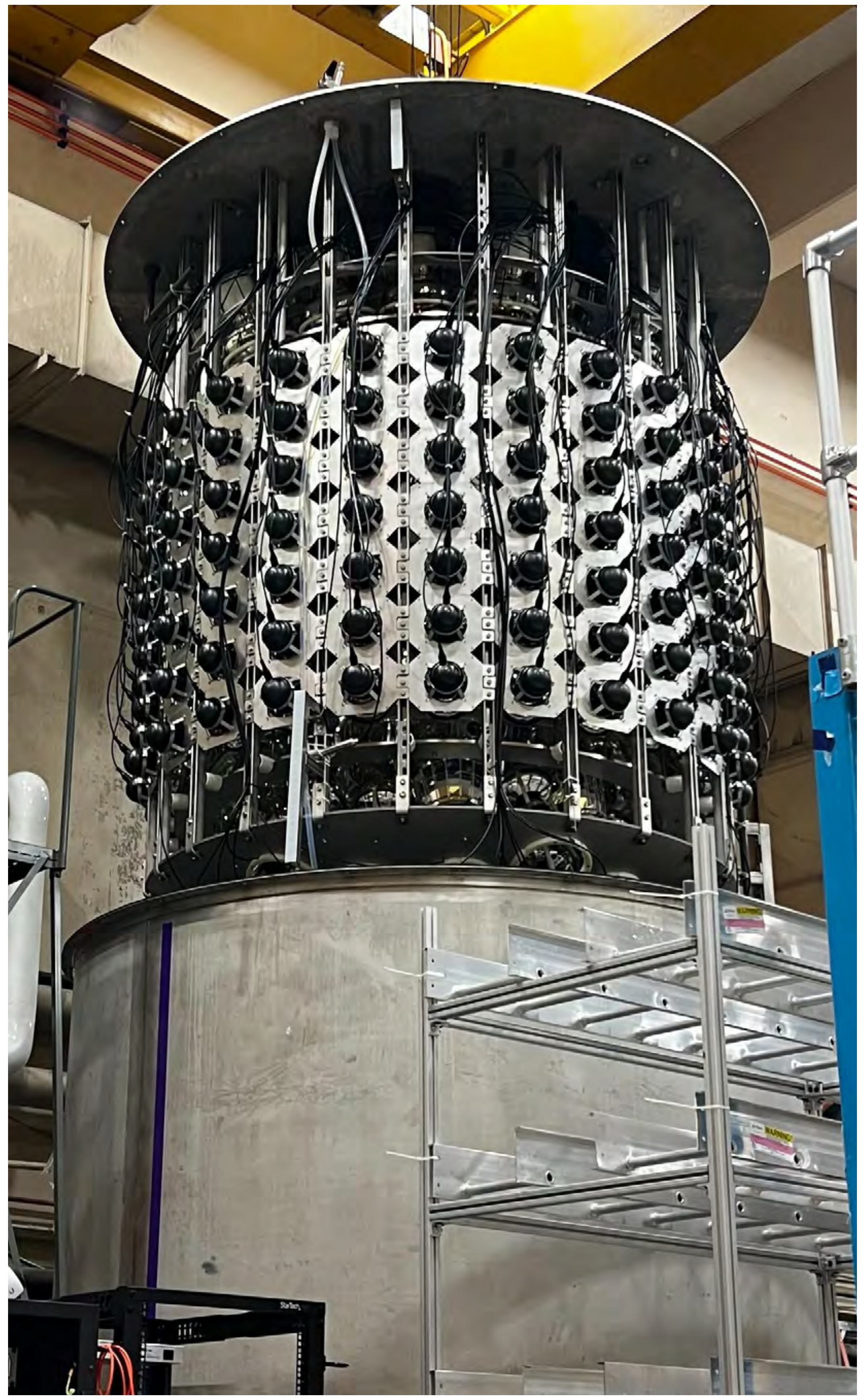
EOS: performance demonstrator

Approach: *design, construct and operate an integrated testbed to demonstrate the performance of novel technology*

Novelty / technology:

- Novel scintillating liquids — water-based scintillator, slow scintillator
- Ultra-fast photon detectors — novel 8" PMTs (200 8" PMTs: R14688-100, 900ps FWHM)
- "Quantum chromatic sorting": dichroicons for spectrally sensitive photon detection
- AI/ML-based analysis techniques
- Deployable sources for studies of vertex, energy, direction reconstruction & PID
- 36-fiber light injection system for optical calibration





- Sited on UC Berkeley campus, in Nuclear Engineering (NE) department

Designed for flexible upgrade paths & to be redeployed at a neutrino source → demonstrate viability of future applications

EOS concept paper published: *JINST 18 P02009 (2023), https://doi.org/10.1088/1748-0221/18/02/P02009*

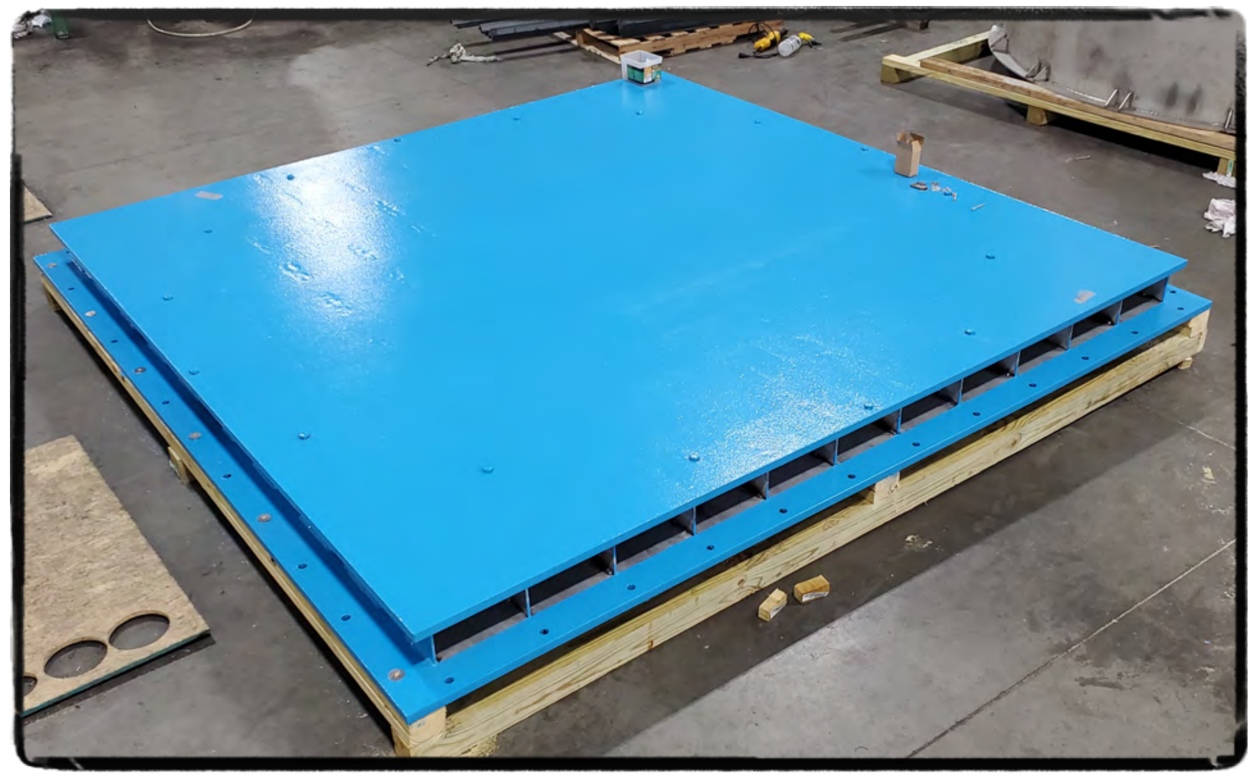
Eos Demonstrator timeline

- $10M supported by DOE-NNSA-DNN R&D
- Led by LBNL
- FY22-24

Challenges faced

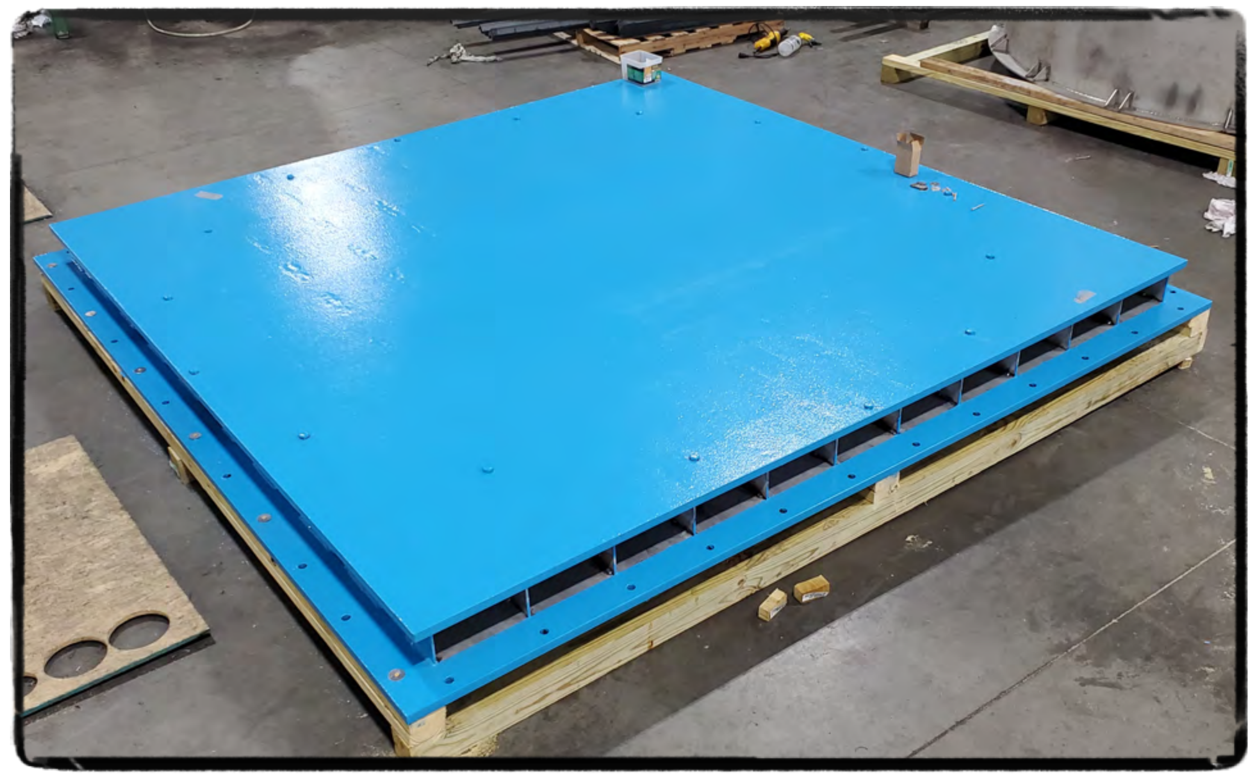
Challenges faced

Outer vessel and assembly stand, May '23



Challenges faced

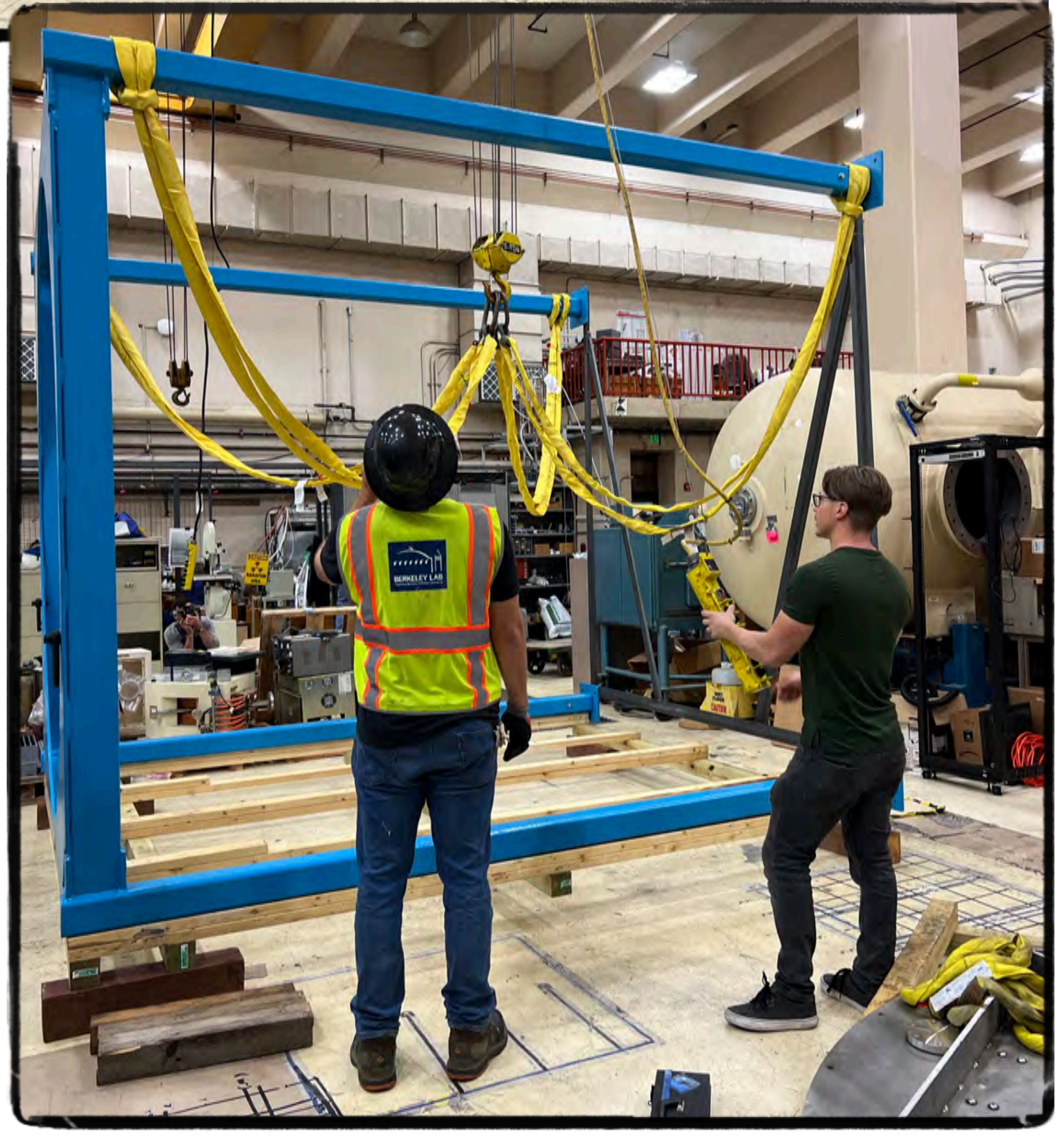
Outer vessel and assembly stand, May '23



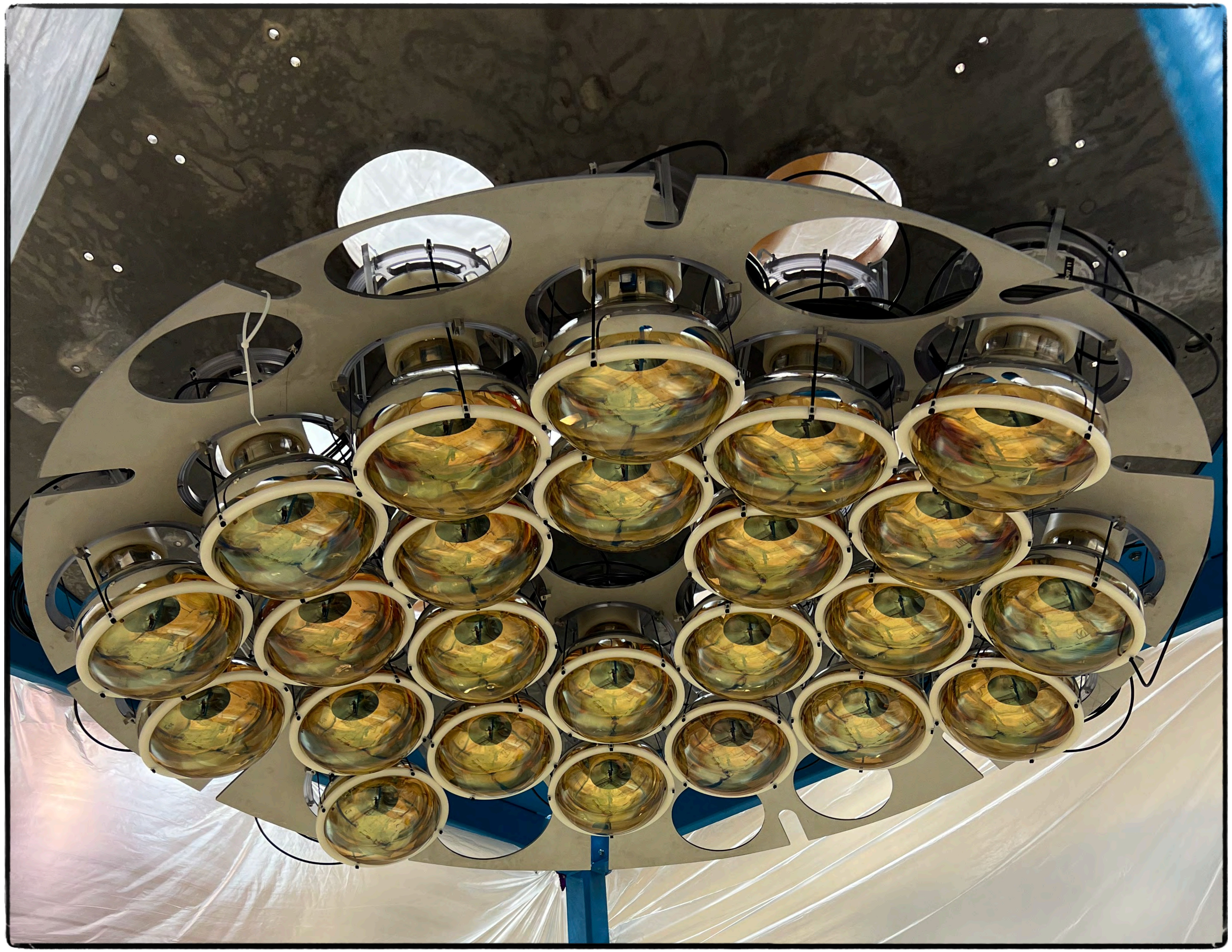
Shipping, June 1 '23

June 2, 2023

Tank install (Sept 14th)

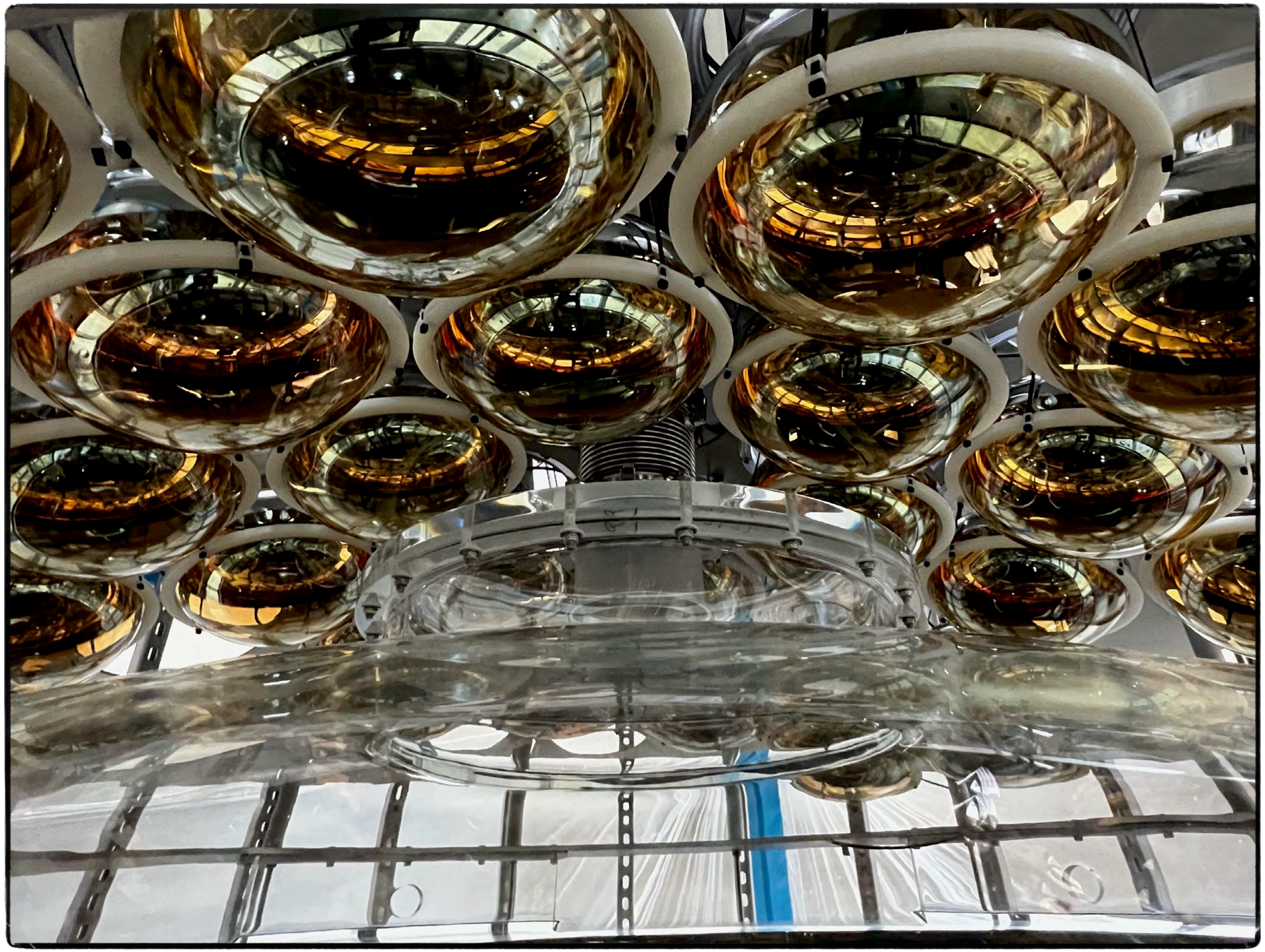


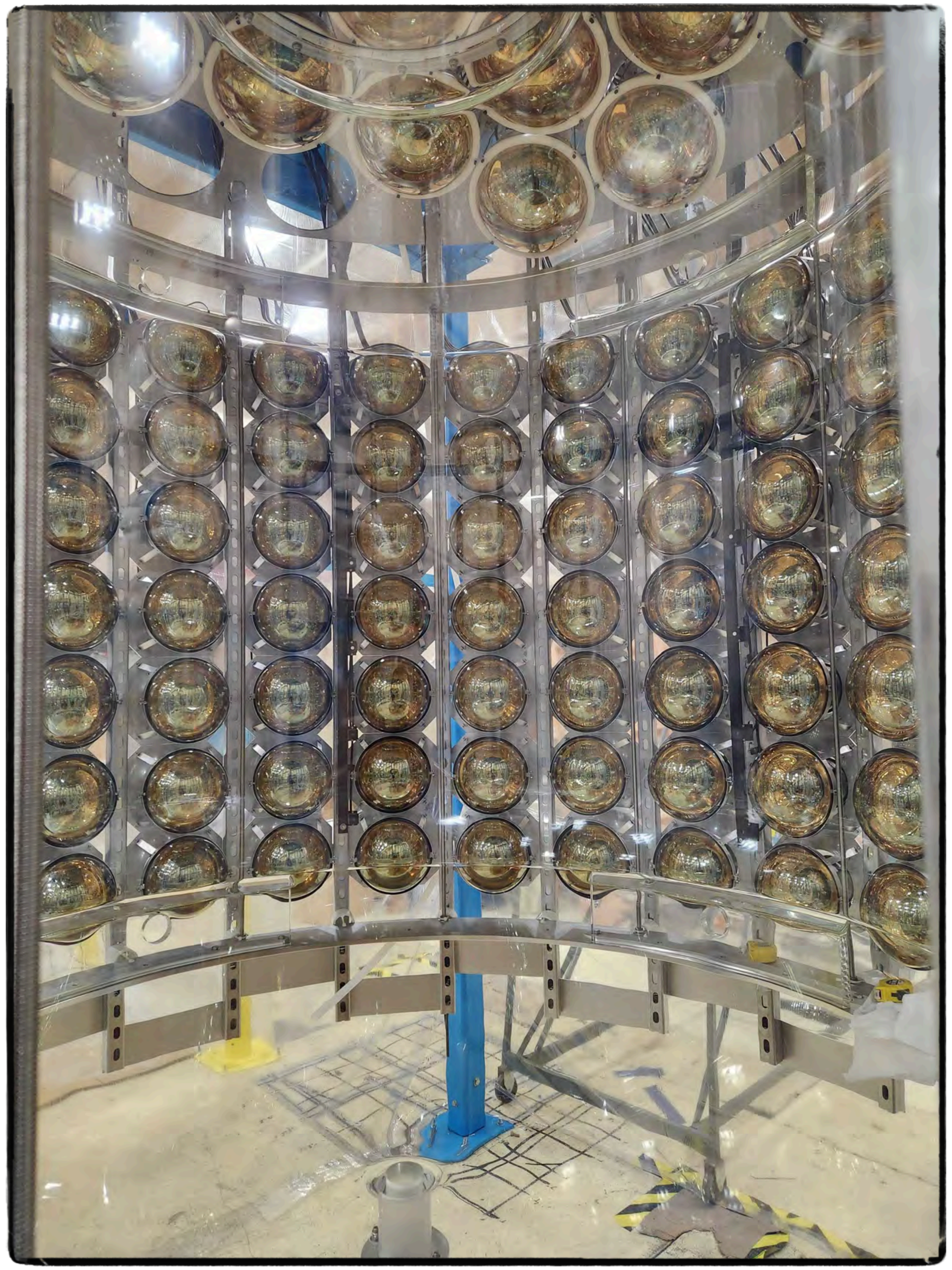
Upper PMT array (Oct 18)



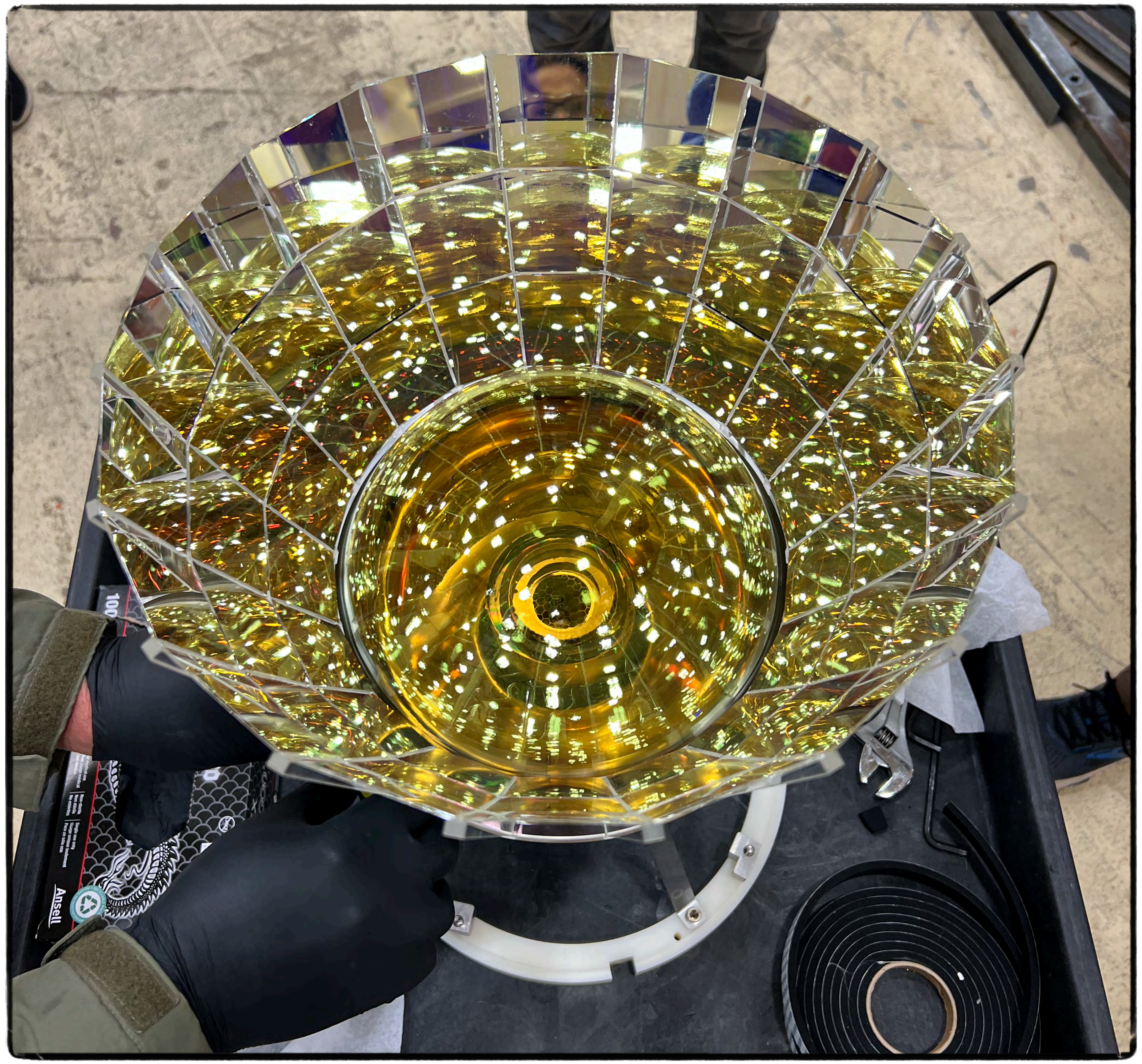
Inner vessel (Oct 25)

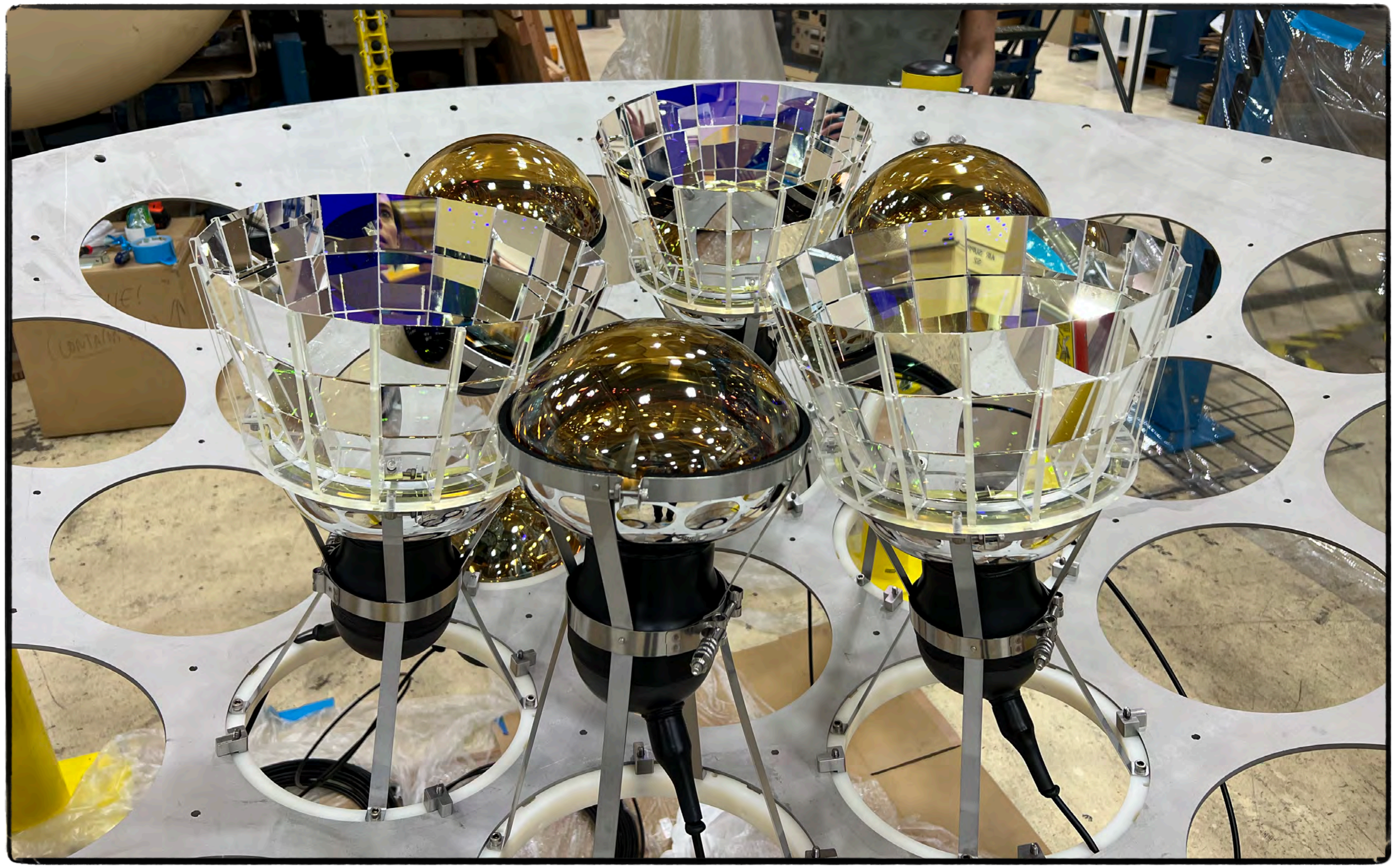
IV unveiling, Barrel PMTs (early Nov)



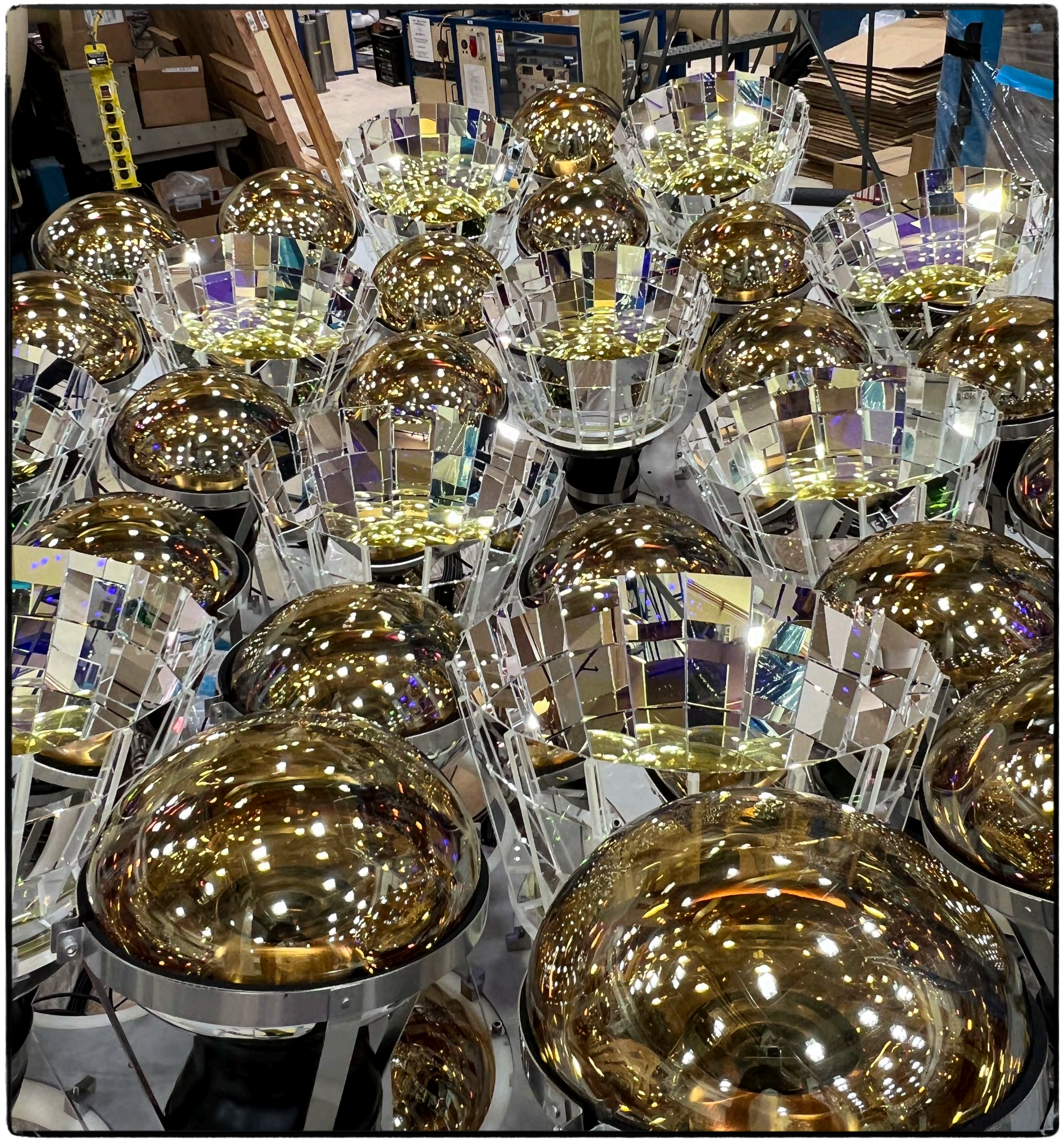


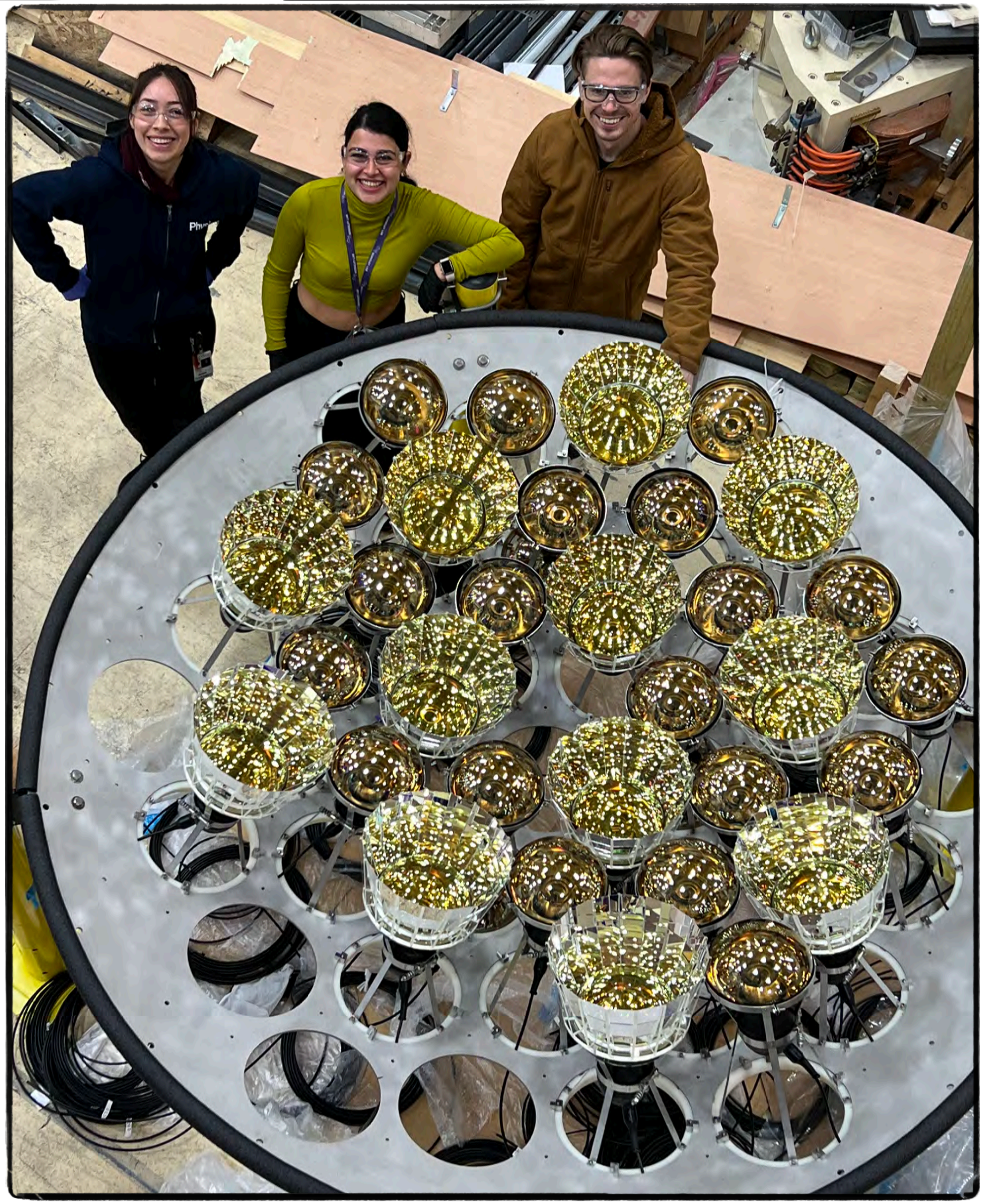
First dichroicon install (Nov 13)



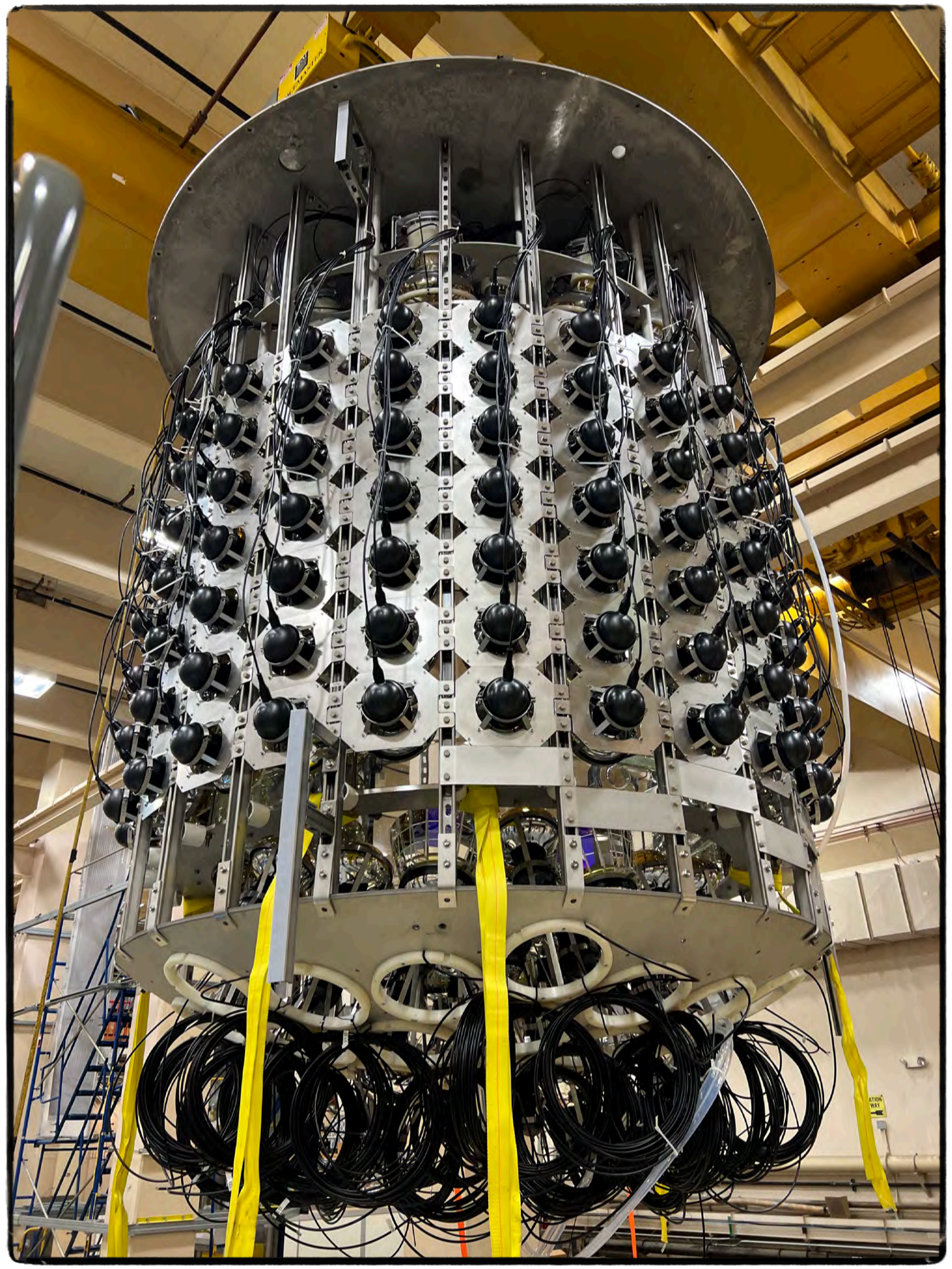


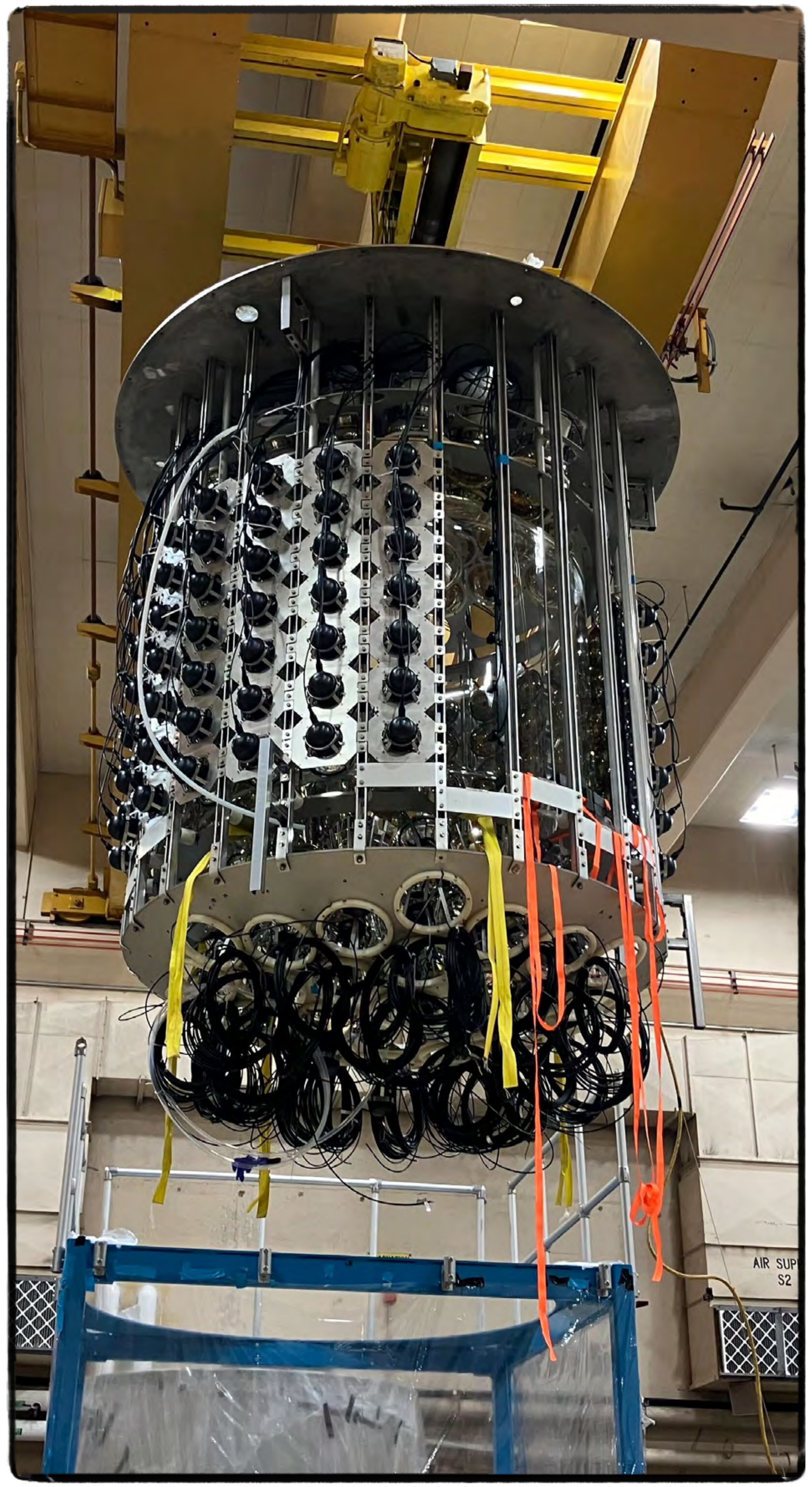
Complete dichroicon install (Nov 17)



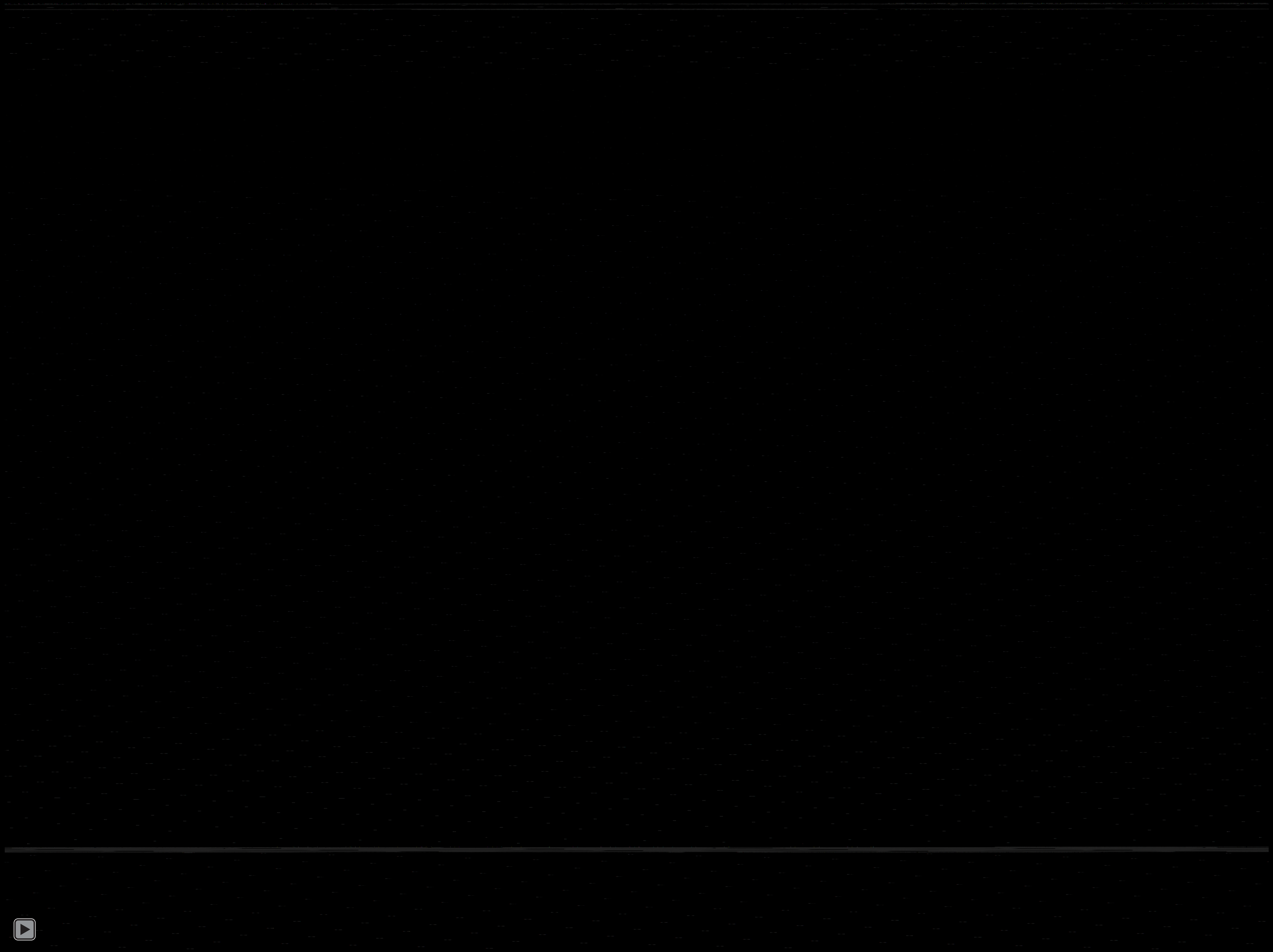


Lower array connection (Nov 24)

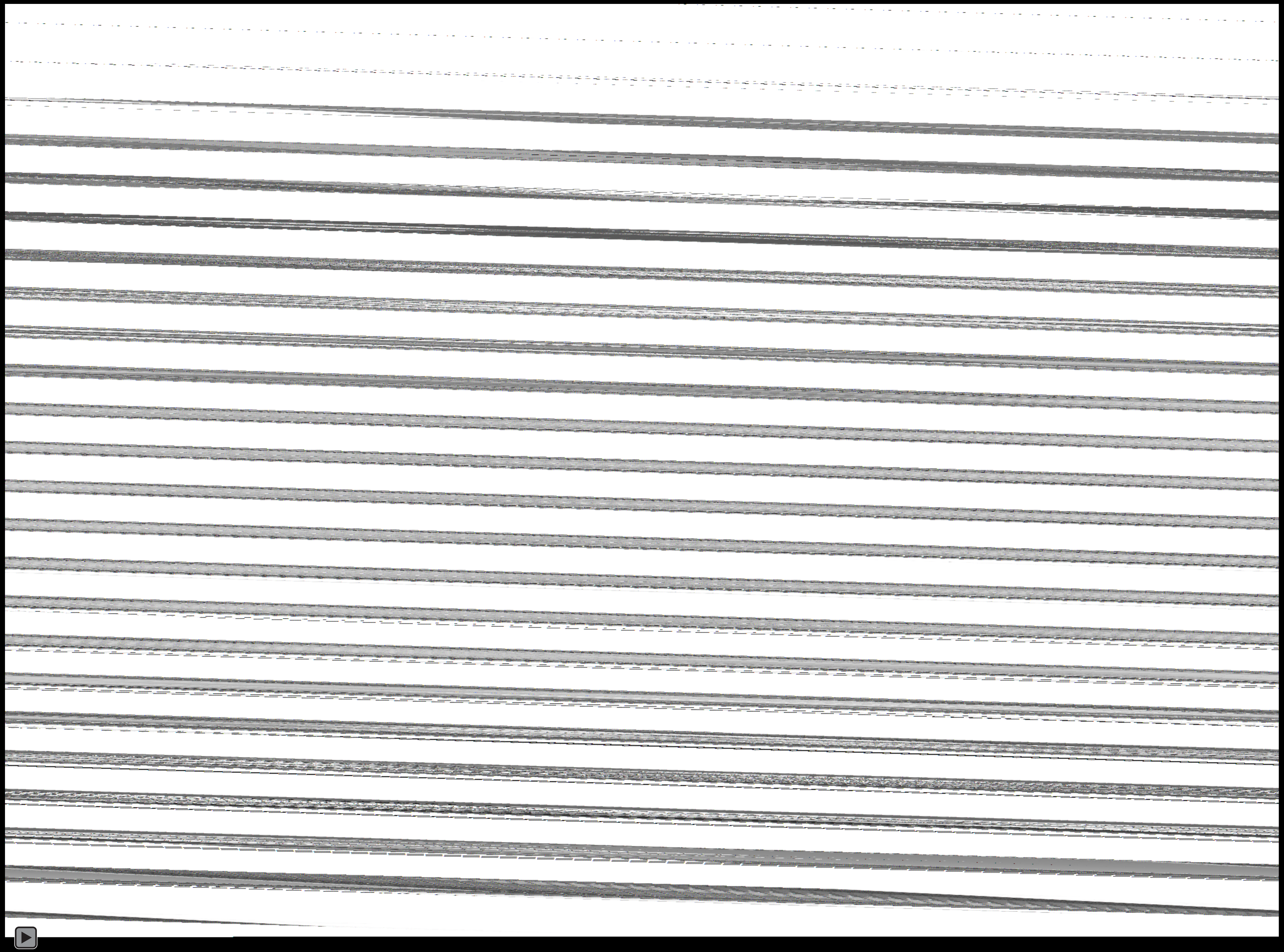




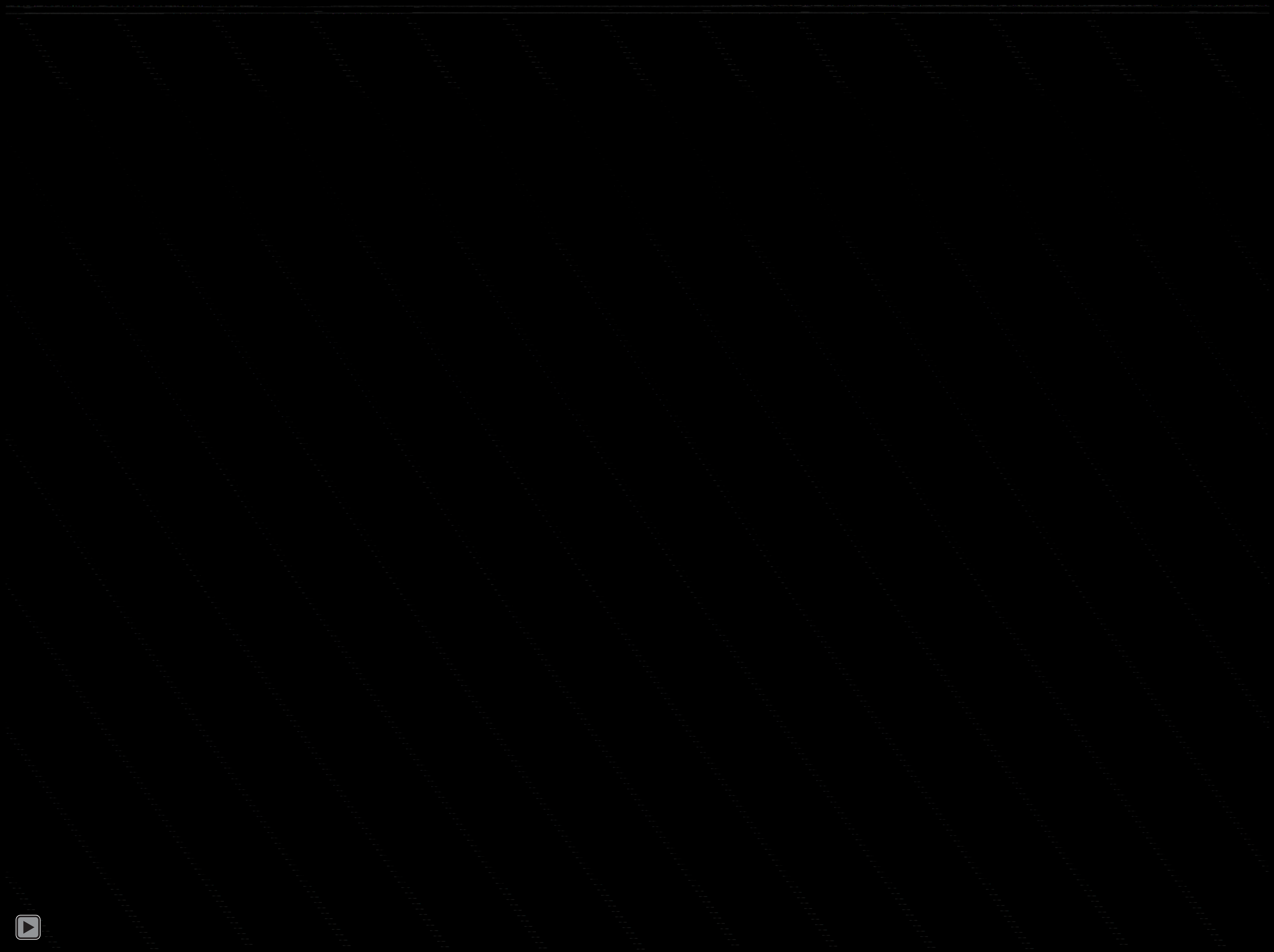
Detector lift (Jan 26)



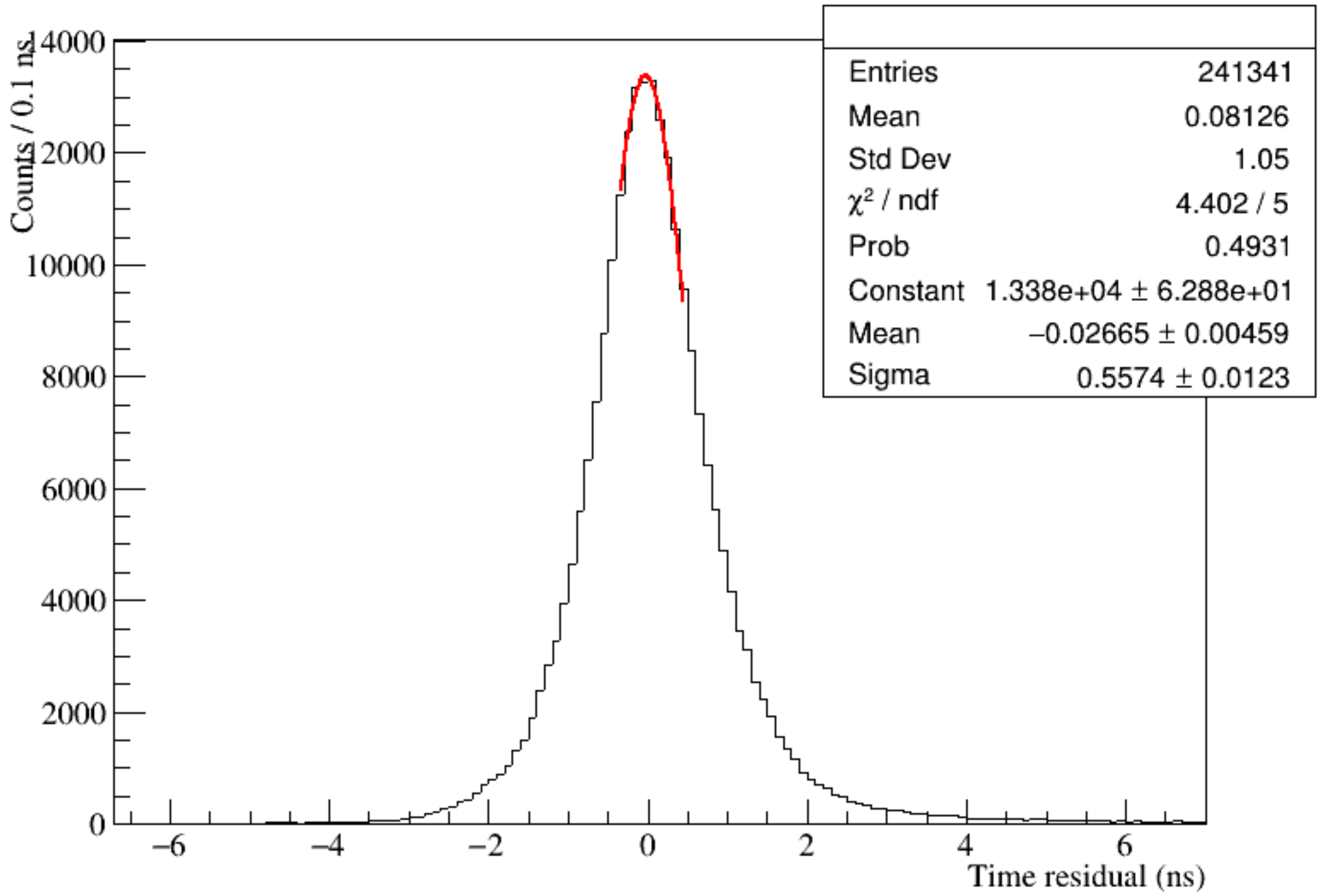
Detector lift (Jan 26)

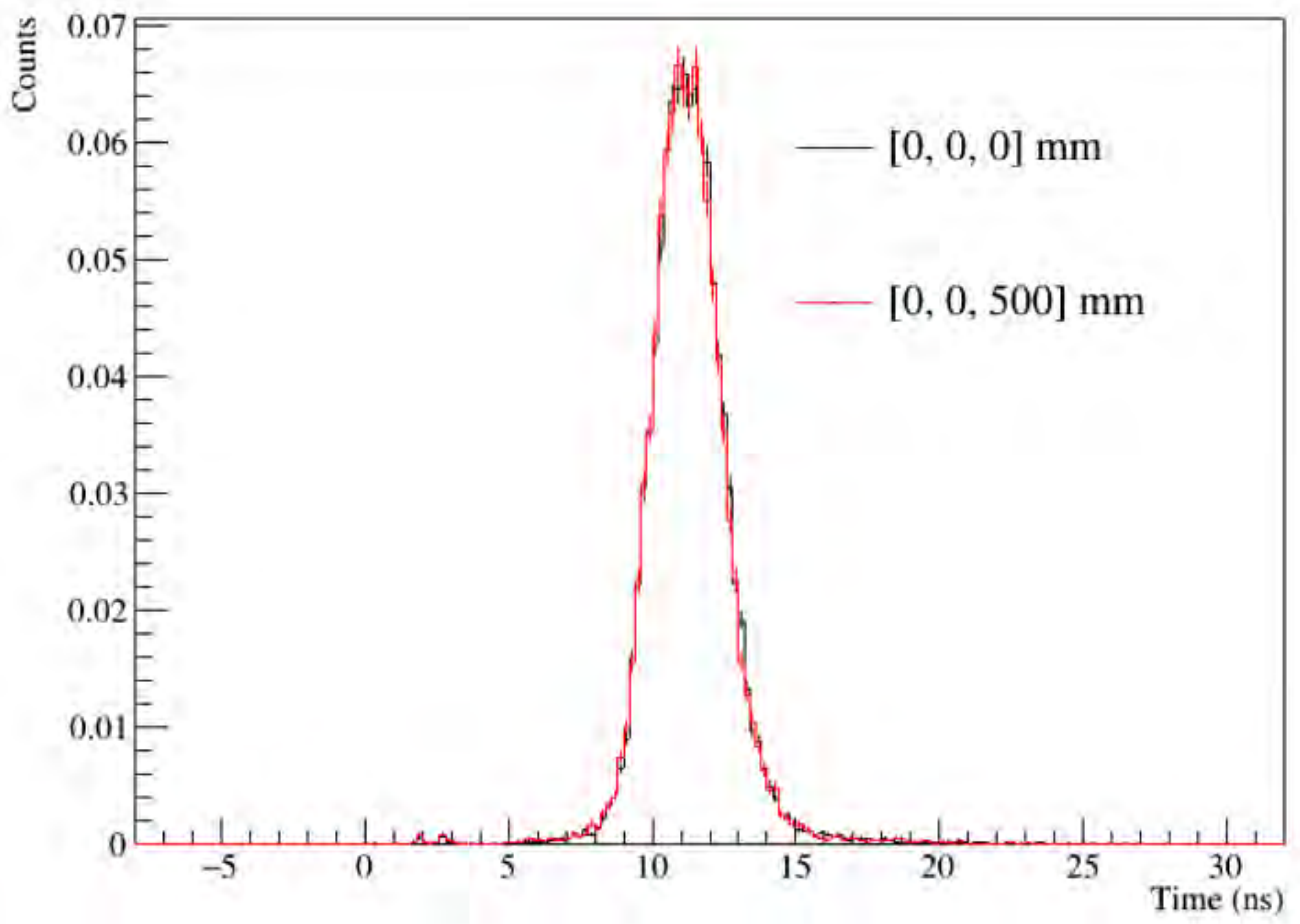


Detector lift (Jan 26)



Preliminary data





- Time precision evaluated using a pico-second laser injected into a single-mode optical fiber, terminating in a teflon diffuser ball
- < 600ps time resolution across all PMTs (8”, 10”, 12”)
- Stable and reproducible across runs
- Next step: evaluate energy / vertex / direction reconstruction

The EOS team

USA

Team breakdown:

3 national laboratories
18 top-tier US institutions
8 international collaborating institutions

10 postdoctoral scholars
9 graduate students
18 undergraduate students

Germany

Portugal

Finland

Turkey

Canada

Theia (proto-)Collaboration

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

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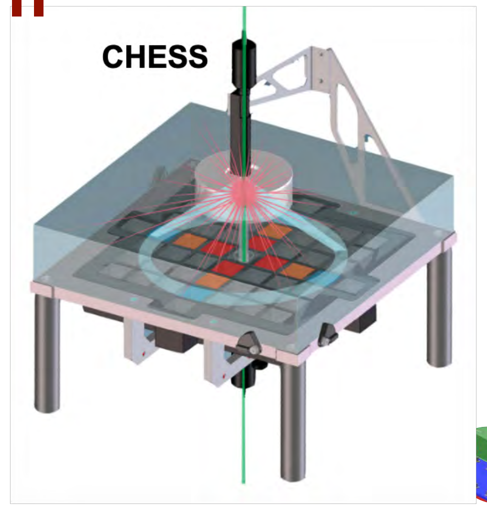
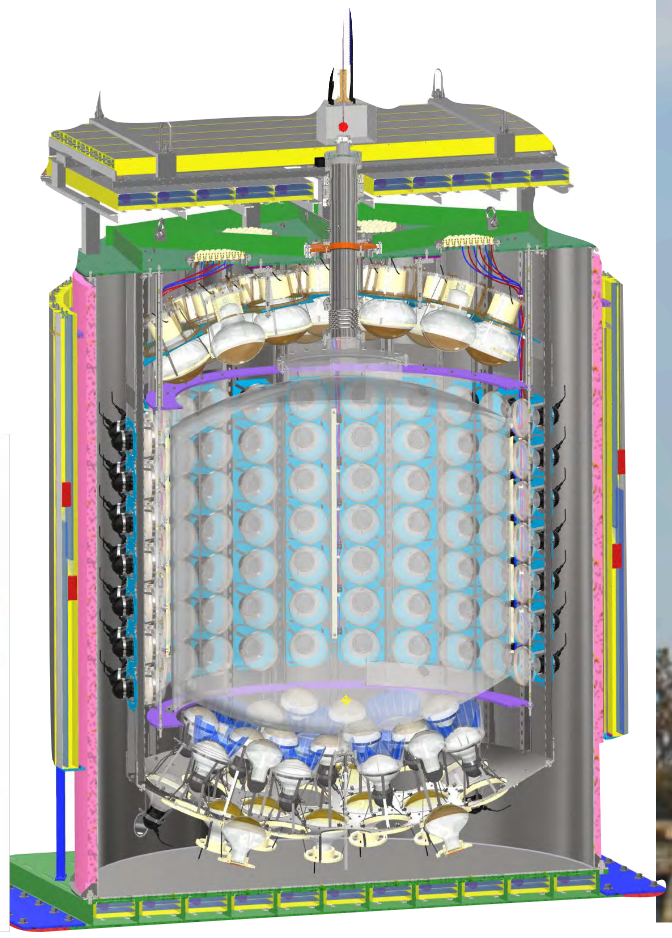
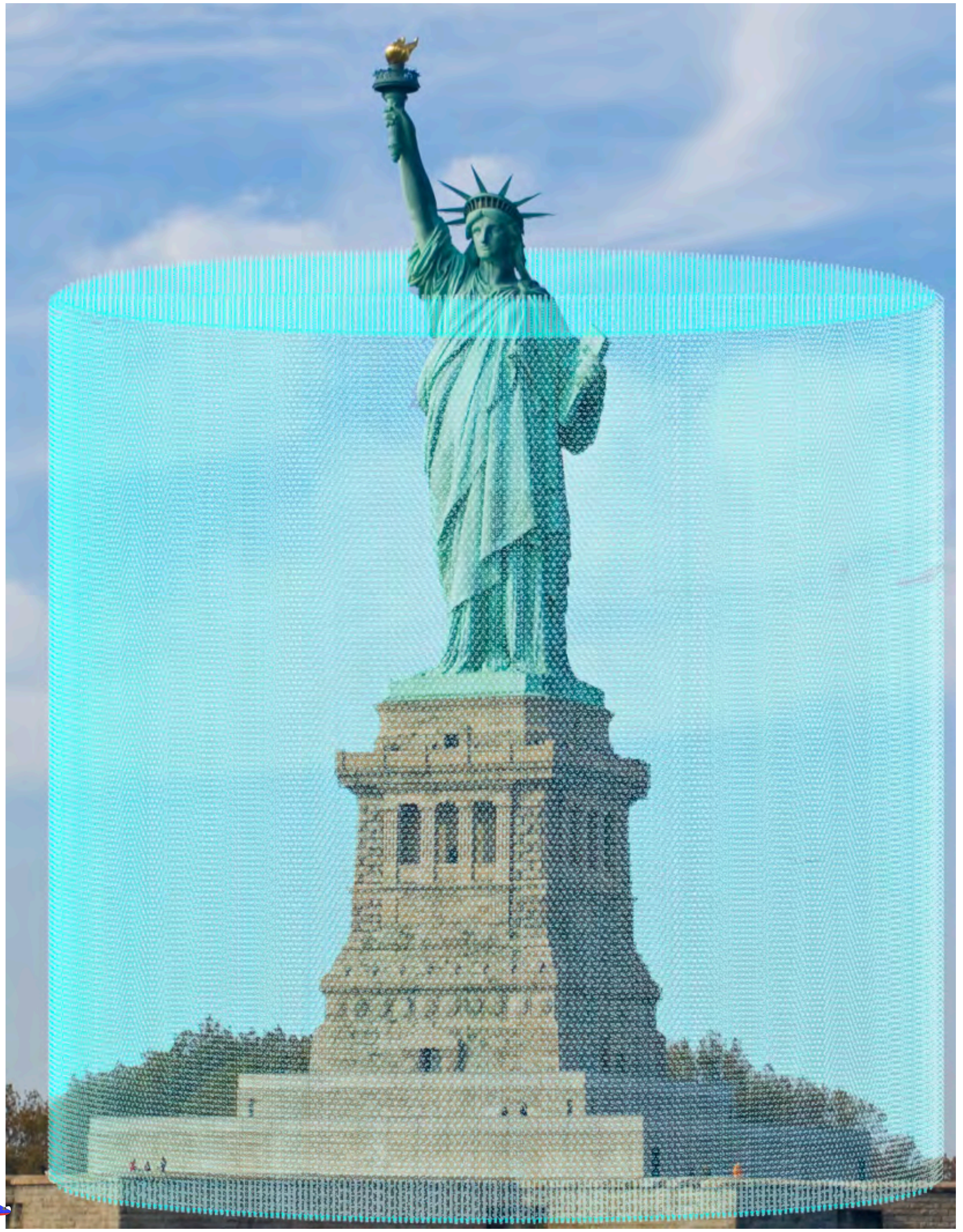
Summary

- Hybrid Cherenkov/scintillation technology can interrogate a broad program of compelling science
- Conventional neutrino physics & rare-event searches in a single, large detector
- A hybrid detector module would add to the LBL program at DUNE and bring a broad program of additional physics
- THEIA offers inspirational physics to motivate a new, broad community of scientists
- Technological developments have evolved from bench-top to fully integrated demonstrators
- Prototypes underway will demonstrate the full range of capabilities
- ***Exciting physics to come!***







Non-comprehensive list of citations

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- Phys. Rev. D 105 (2022) 7 https://doi.org/10.1103/PhysRevD.105.072003
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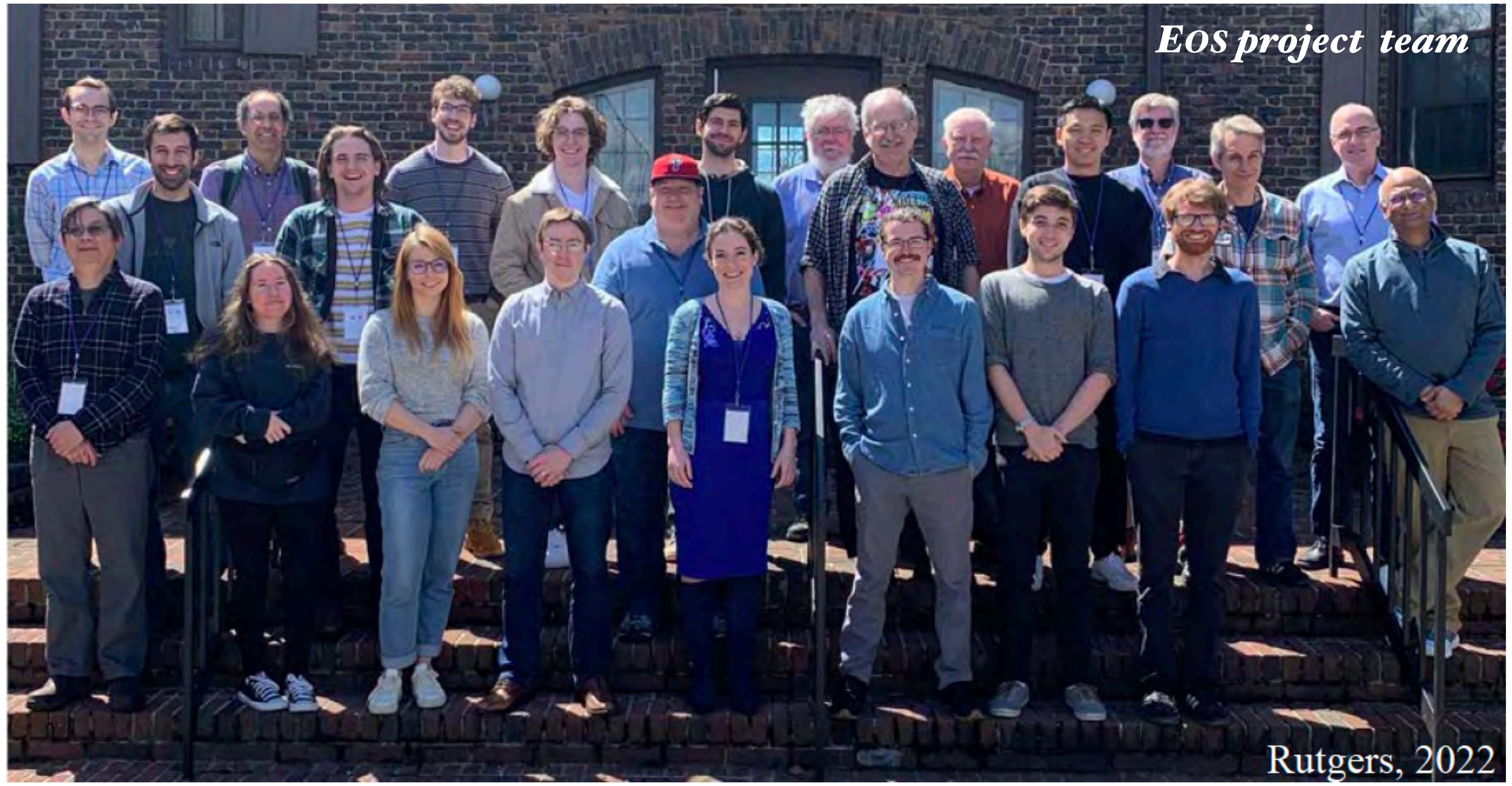


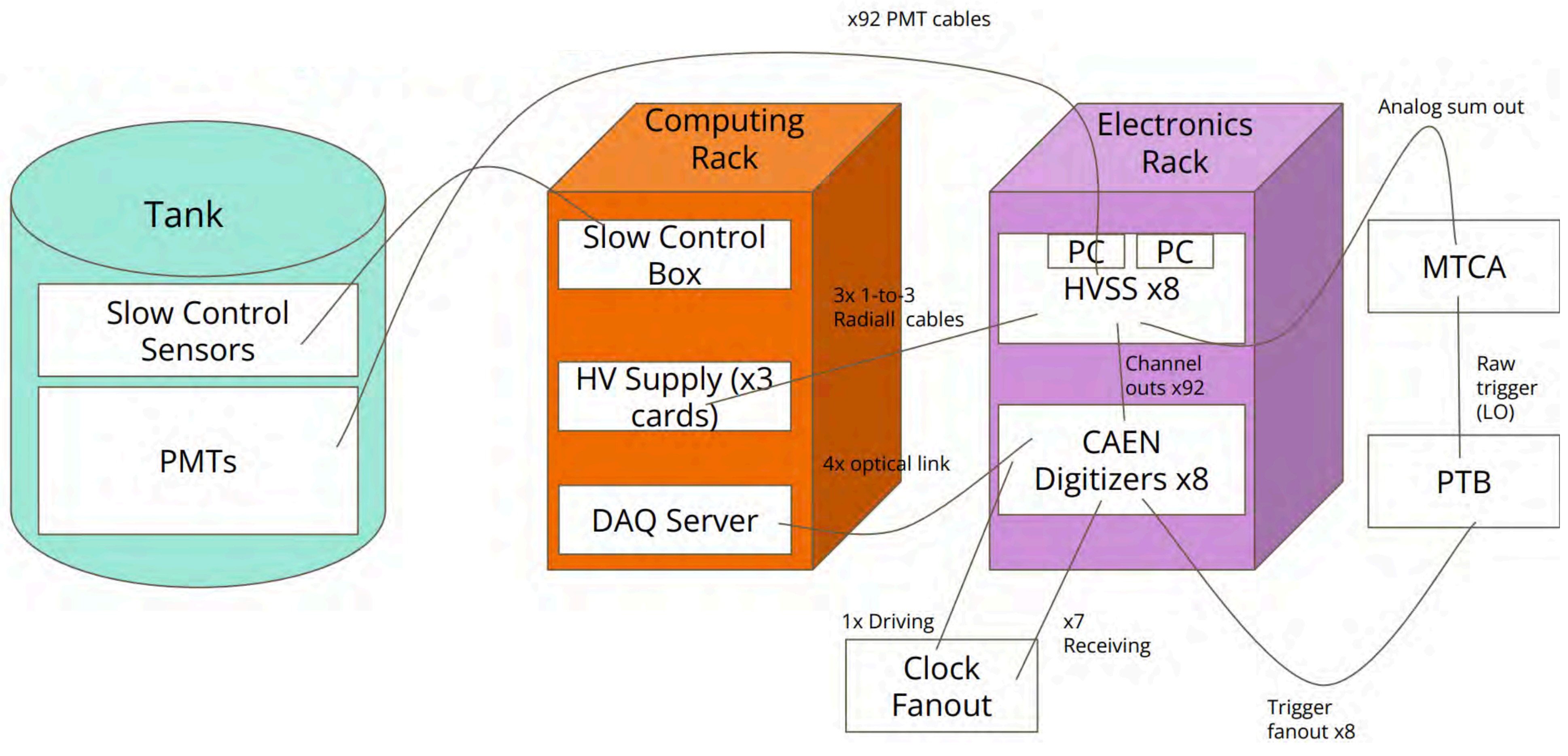
Thank you!

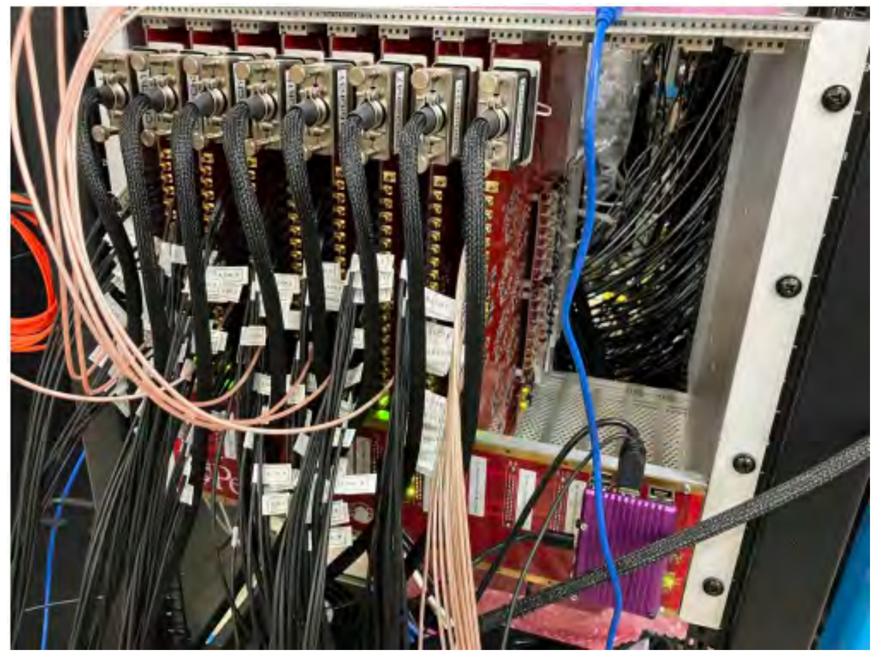
- *Thank you to DNN R&D: Chris Ramos, Brian Yoxall, Craig Sloan for their support*
- *Thank you to DOE-SC HEP: Helmut Marsiske, Brian Beckford, Alan Stone, Glen Crawford*
- *Thank you to DOE-SC NP: Paul Sorensen, Tim Hallman*
- *Thank you to this audience for your attention!*

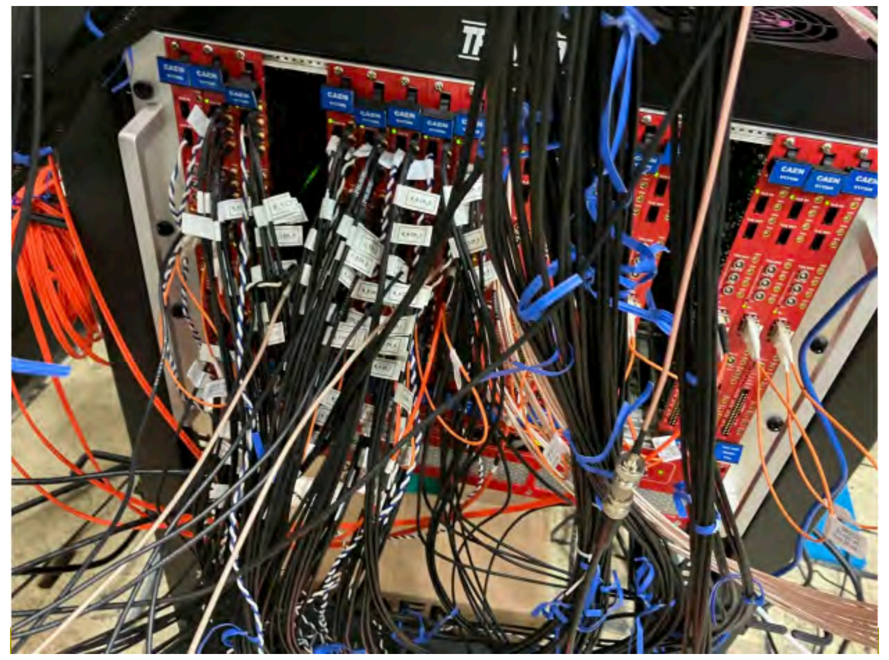
BACKUP

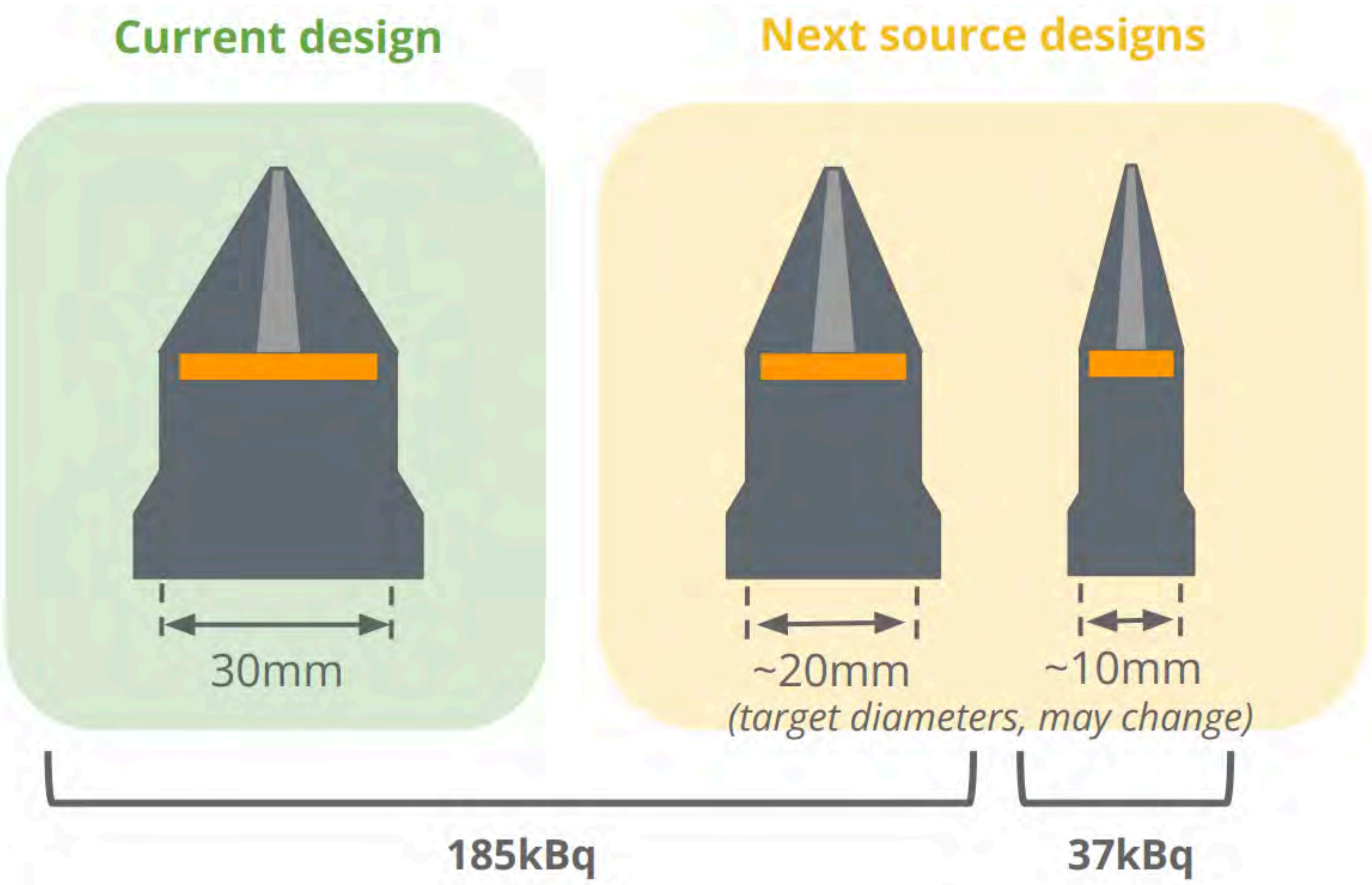
Subsystem status

Electronics / readout

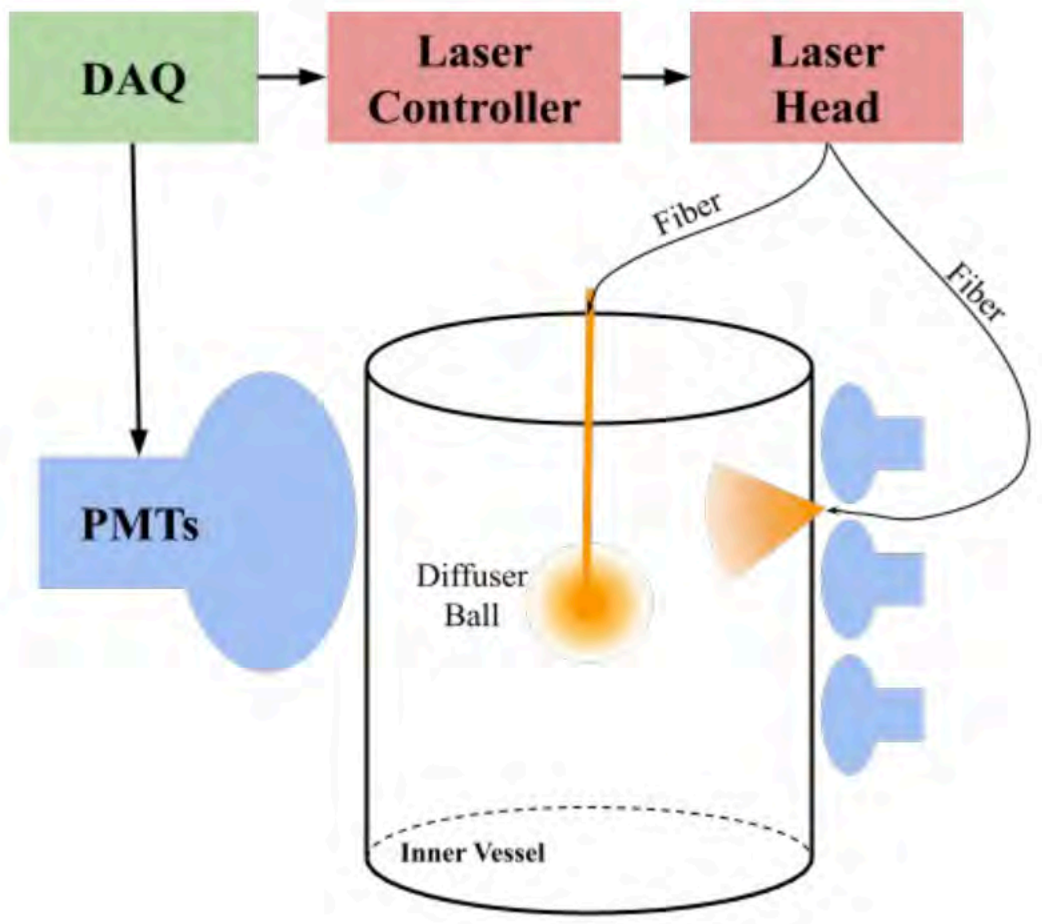


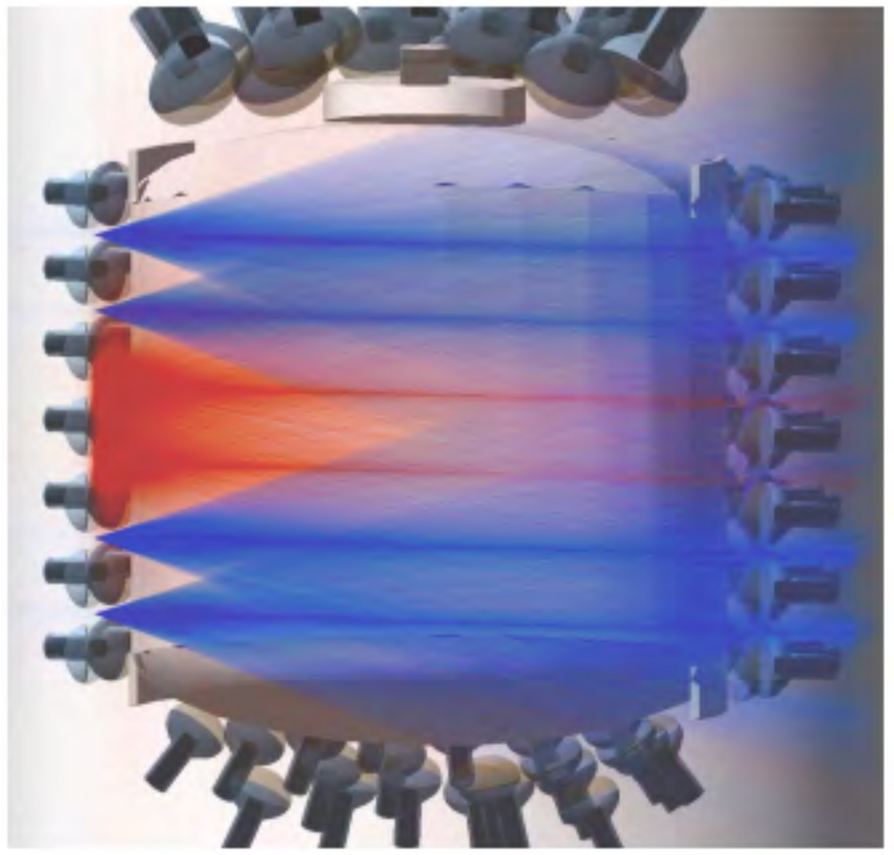


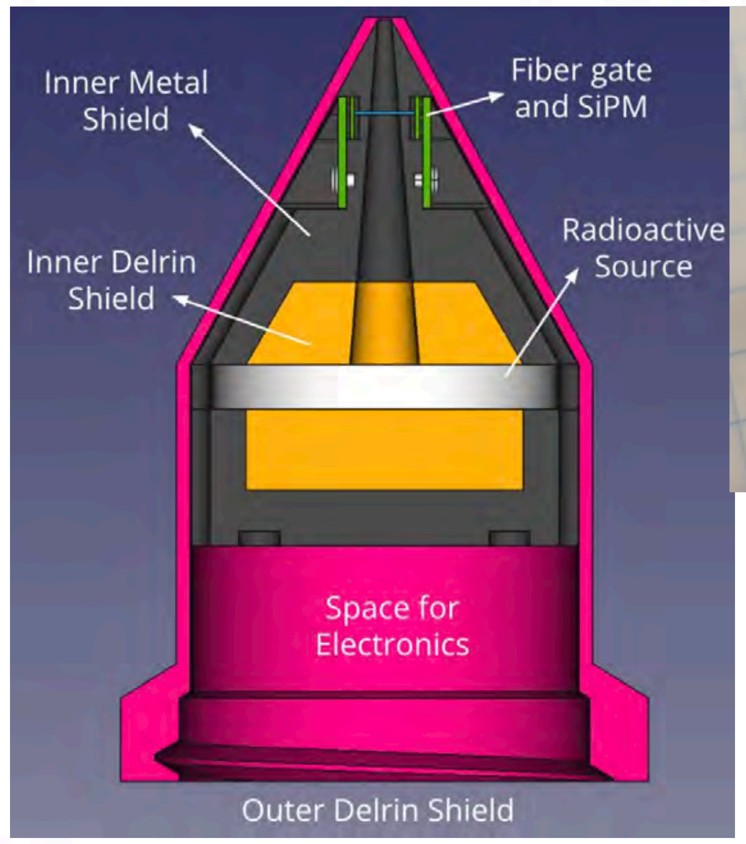


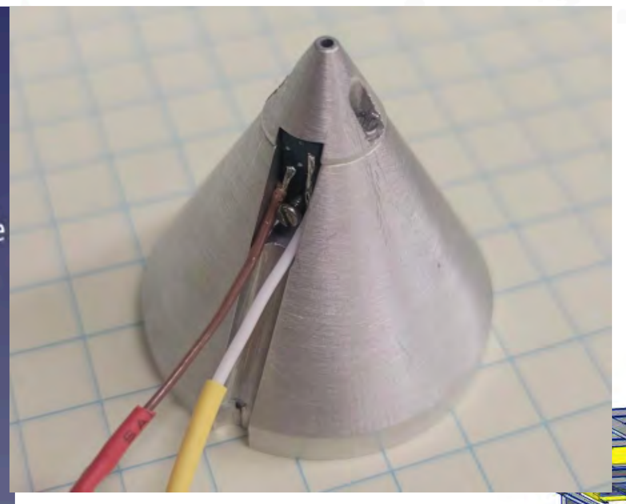


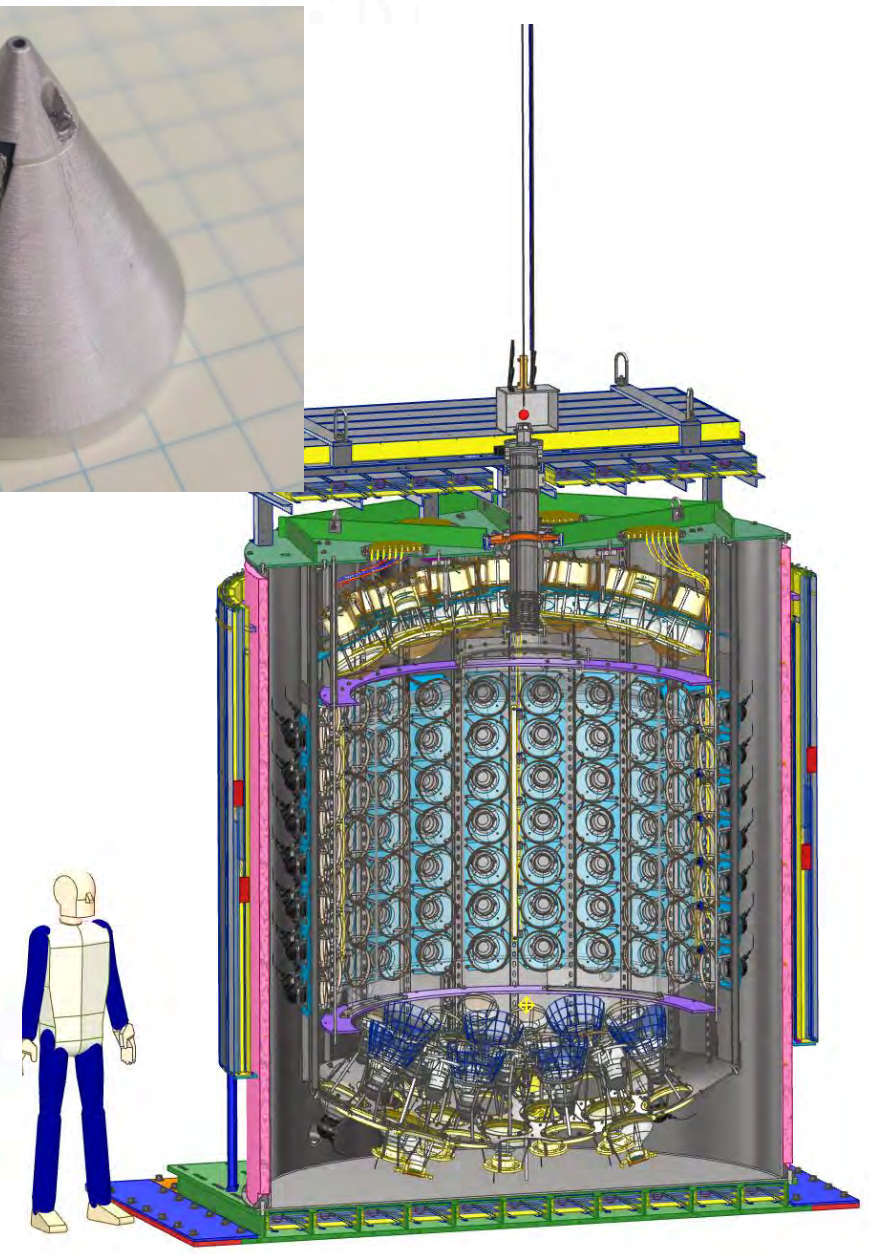
Laser light injection







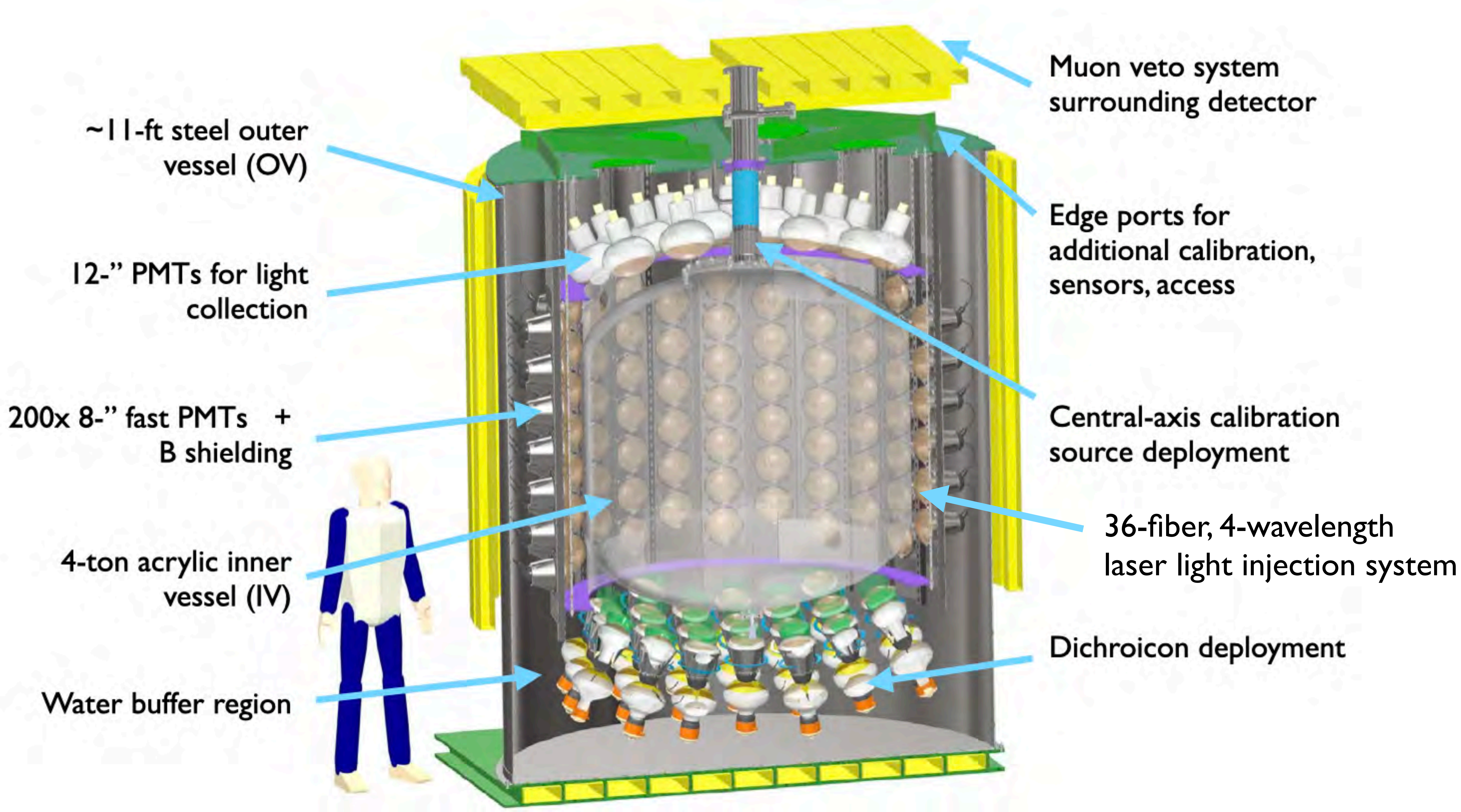


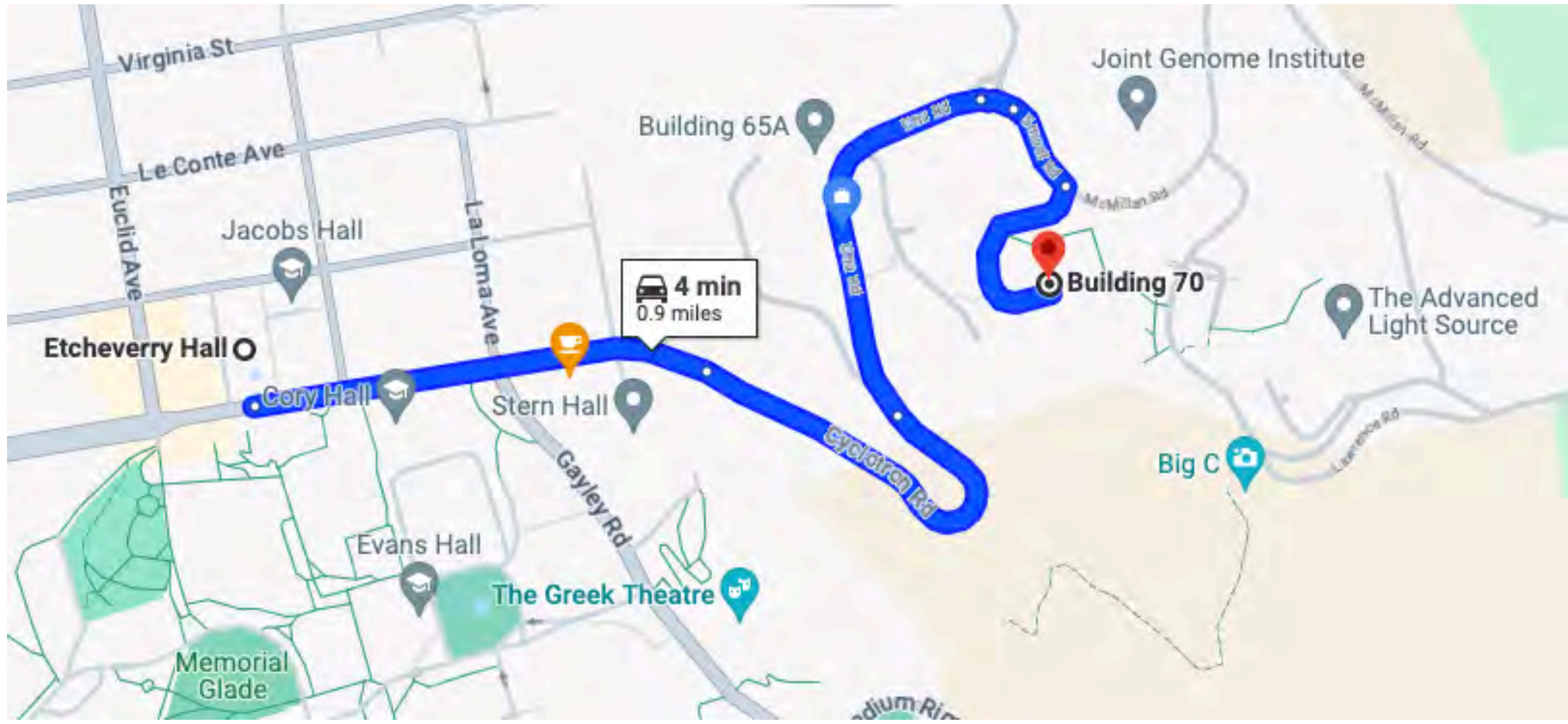


Calibration

- **β** - $^{90}Sr/^{106}Ru$
- **Low-energy γ** - ^{137}Cs
- **High-energy γ's** - AmBe/PuBe
- **Light injection system** - mounted fibers, deployed diffuser
- **Natural sources** - cosmogenics, radioactivity

EOS detector design & site selection





- Sited on UC Berkeley campus, in Nuclear Engineering (NE) department
- Supported by NSSC & NE colleagues
- High-bay area with 5-ton capacity bridge crane

Community planning

Snowmass Neutrino Frontier

- *NF: Detectors: one of 5 priorities for development*
- *NF: Long-term outlook*
  also BSM, terrestrial & astrophysical nu

- **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.

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

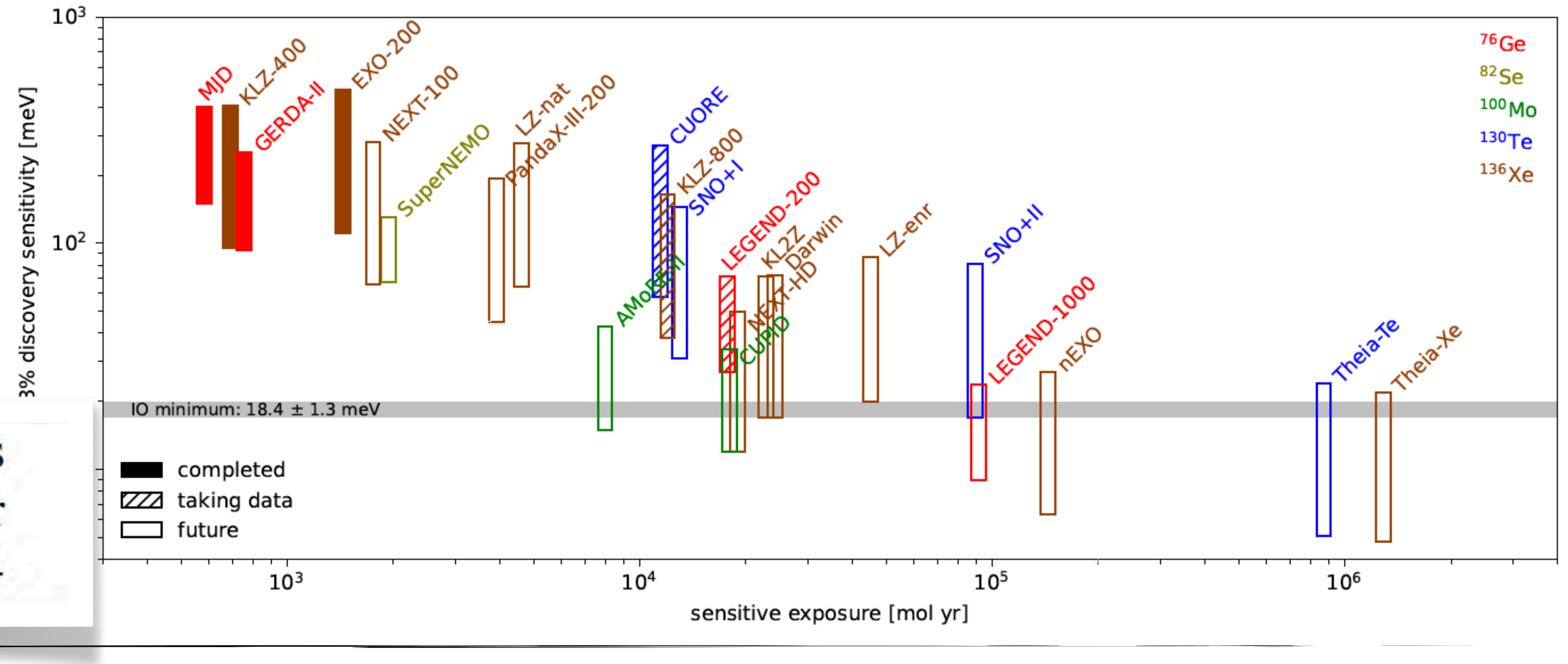
Snowmass Instrumentation Frontier

- *IF: Going beyond DUNE*
  also photon detectors & spectral sorting

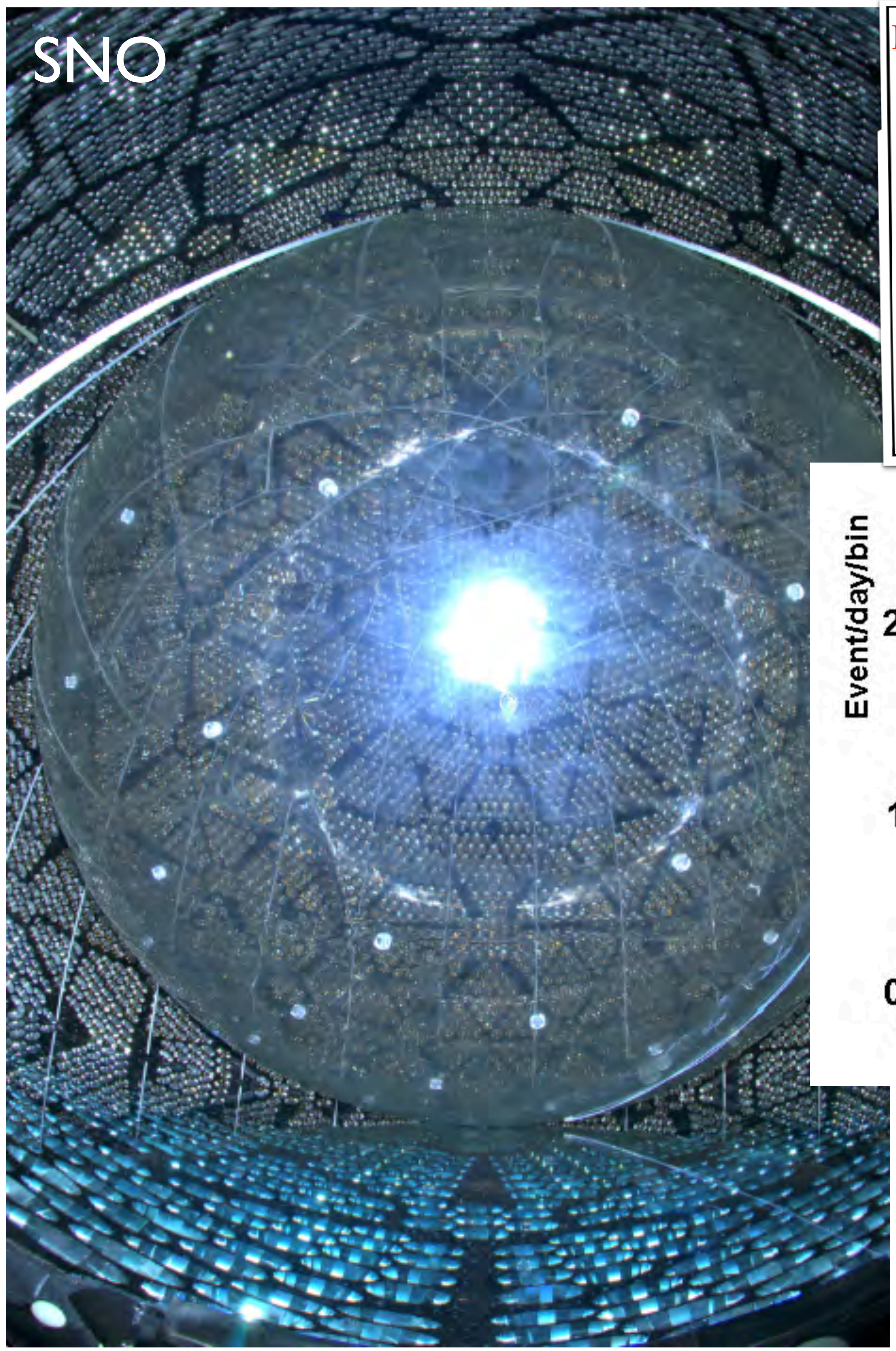
Of particular community interest is the development of hybrid Cherenkov-scintillation detectors, which can simultaneously exploit the advantages of Cherenkov light's reconstruction of direction and related high-energy particle identification (PID) and the advantages of scintillation light, high light-yield, 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

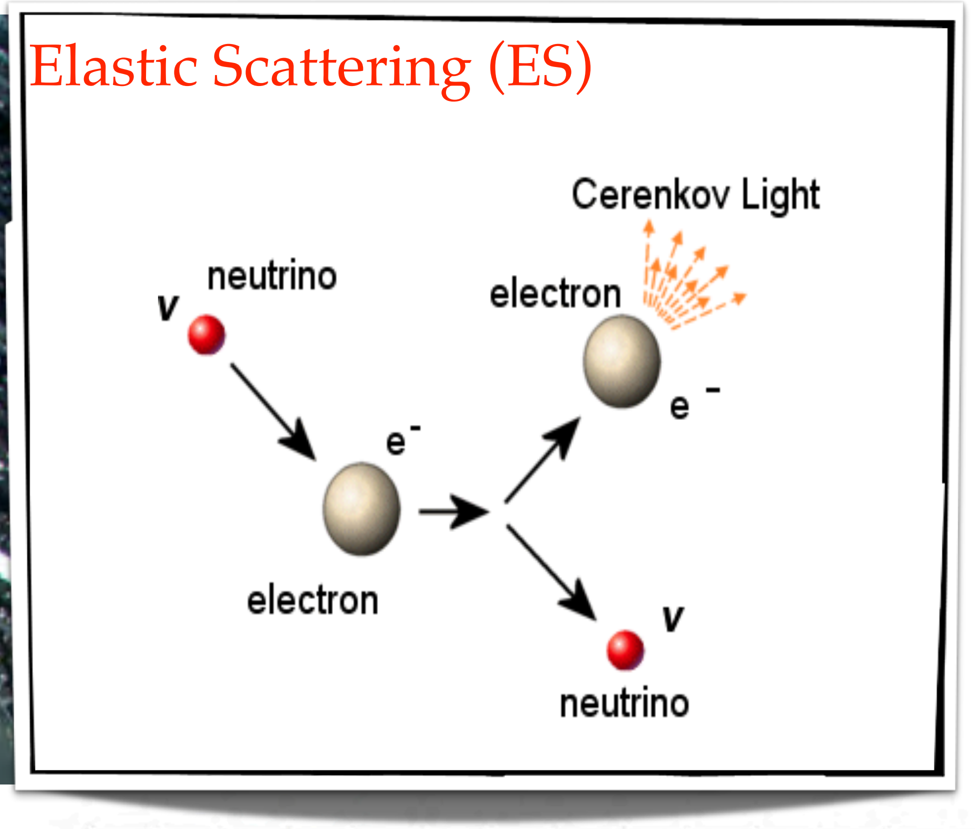
NP LRP - Fundamental Symmetries, Neutrons, and Neutrinos Whitepaper

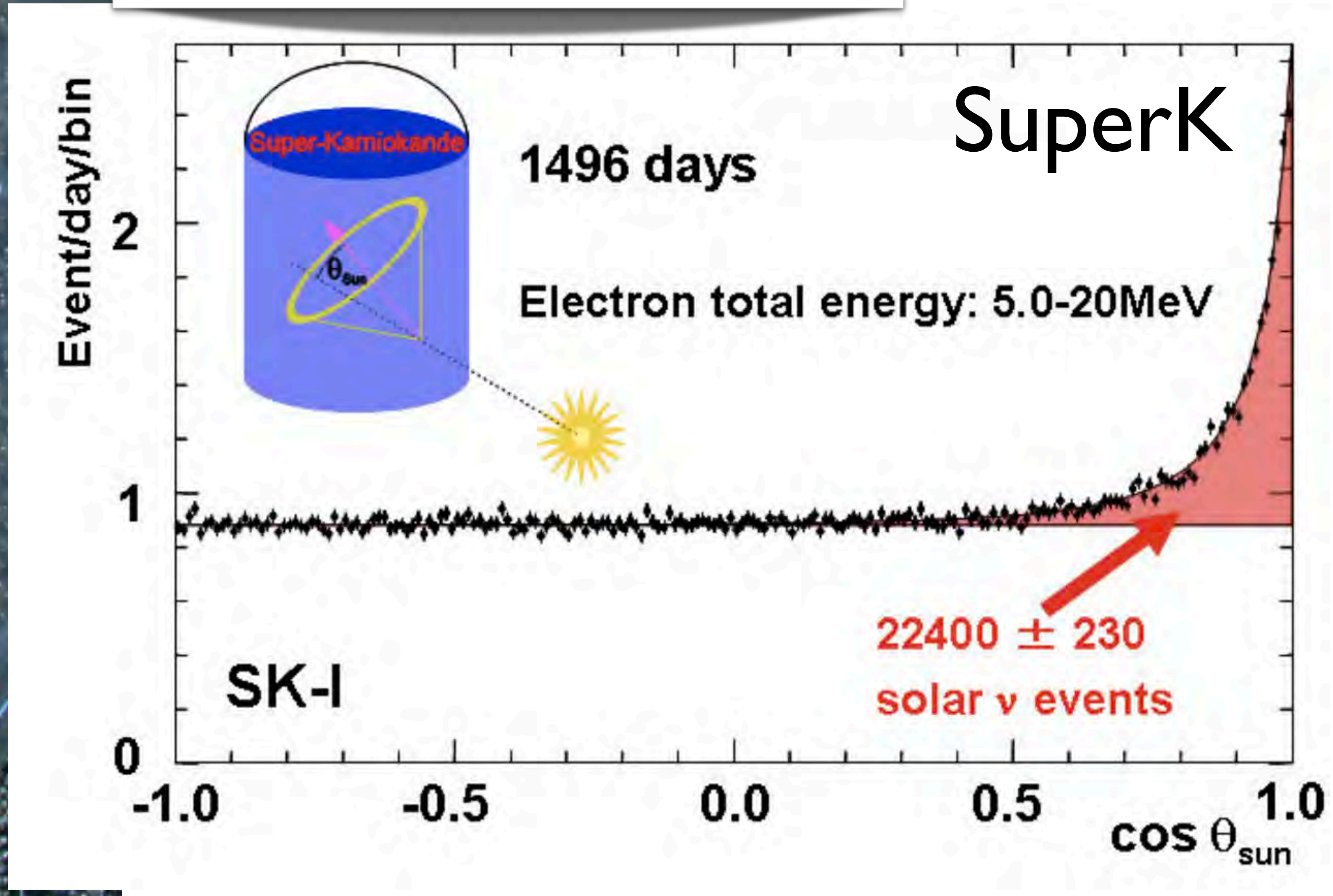
Among possible beyond-ton-scale experiments are: NEXT, which will employ high pressure xenon gas time projection chambers with barium tagging; THEIA, a large-scale hybrid Cherenkov/scintillation detector that will be an outgrowth of the SNO+ and KamLAND-Zen experiments; Selena, which will employ high-

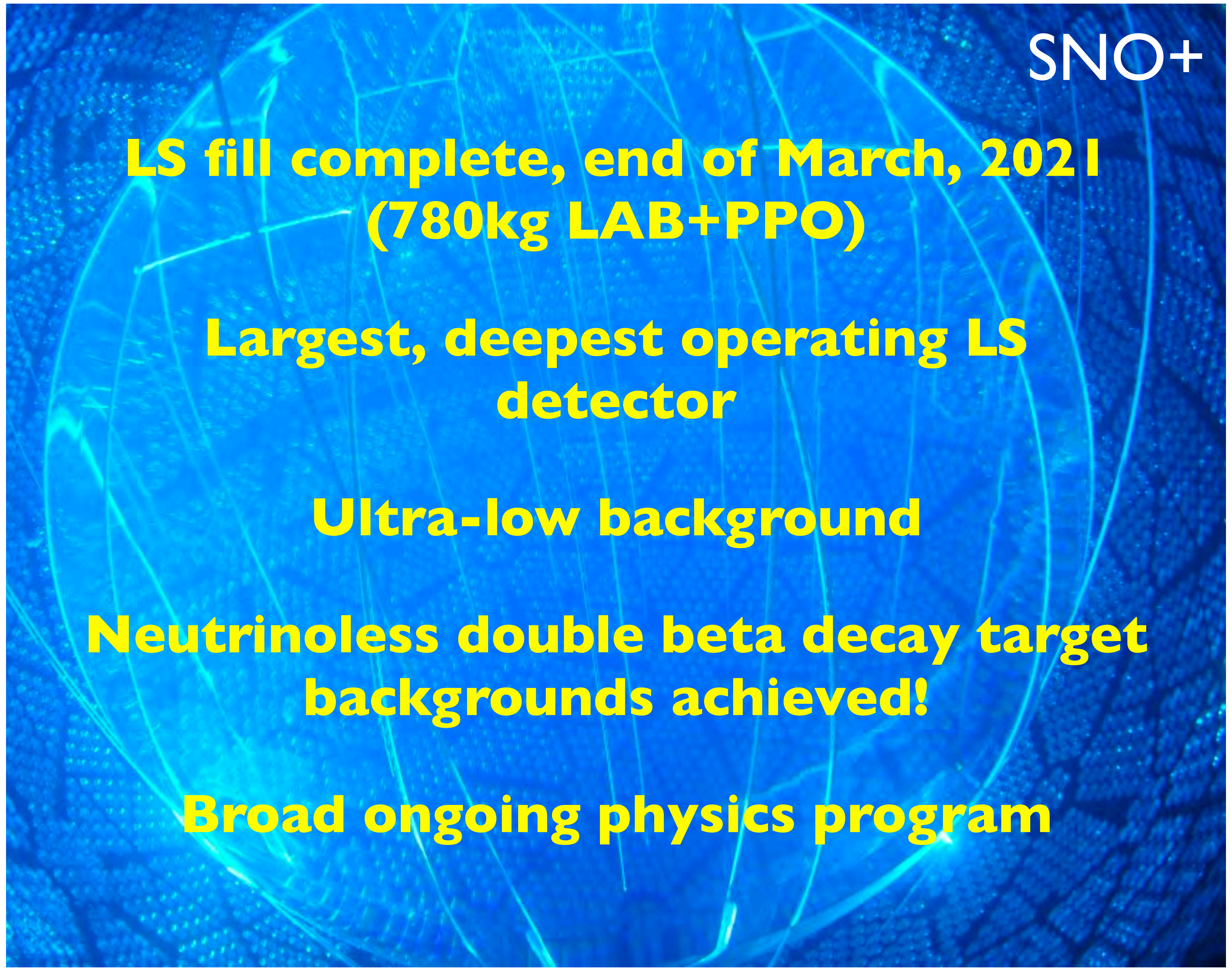


Cherenkov vs Scintillation





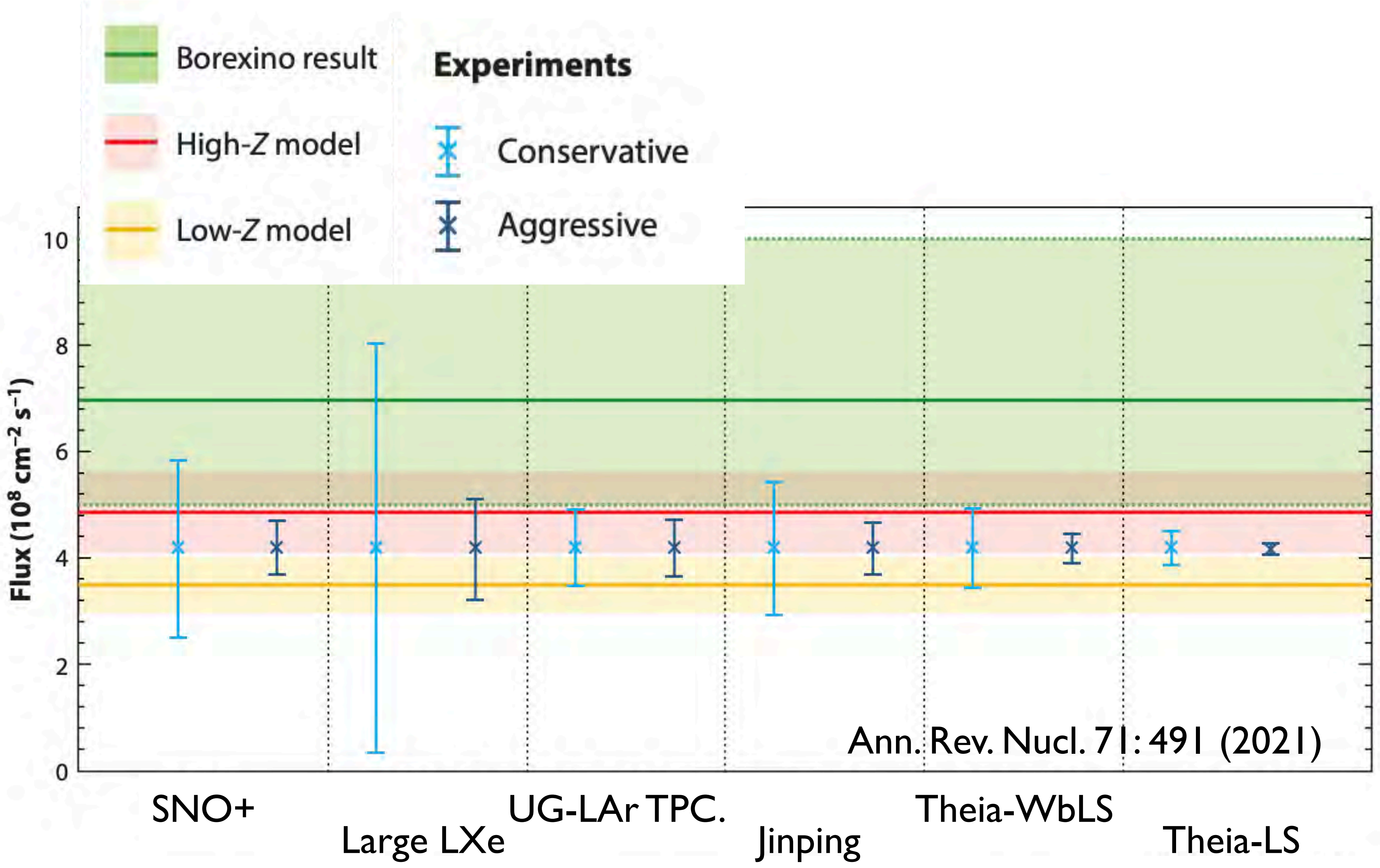




- Directional Cherenkov
- Intense scintillation

Physics Highlights

- Solar neutrinos
- Unique low-threshold, directional detection
- Particle and event ID from LS time profile, quenching, Ch/S ratio
- Few-% level sensitivity to CNO ν
- Plus precision pp, 8B shape



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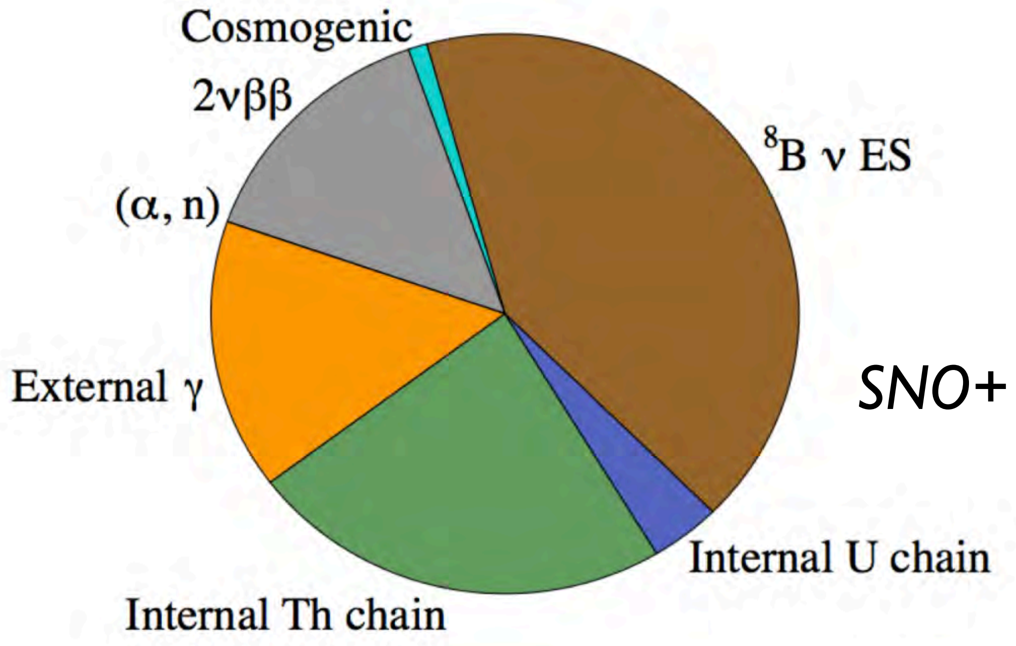
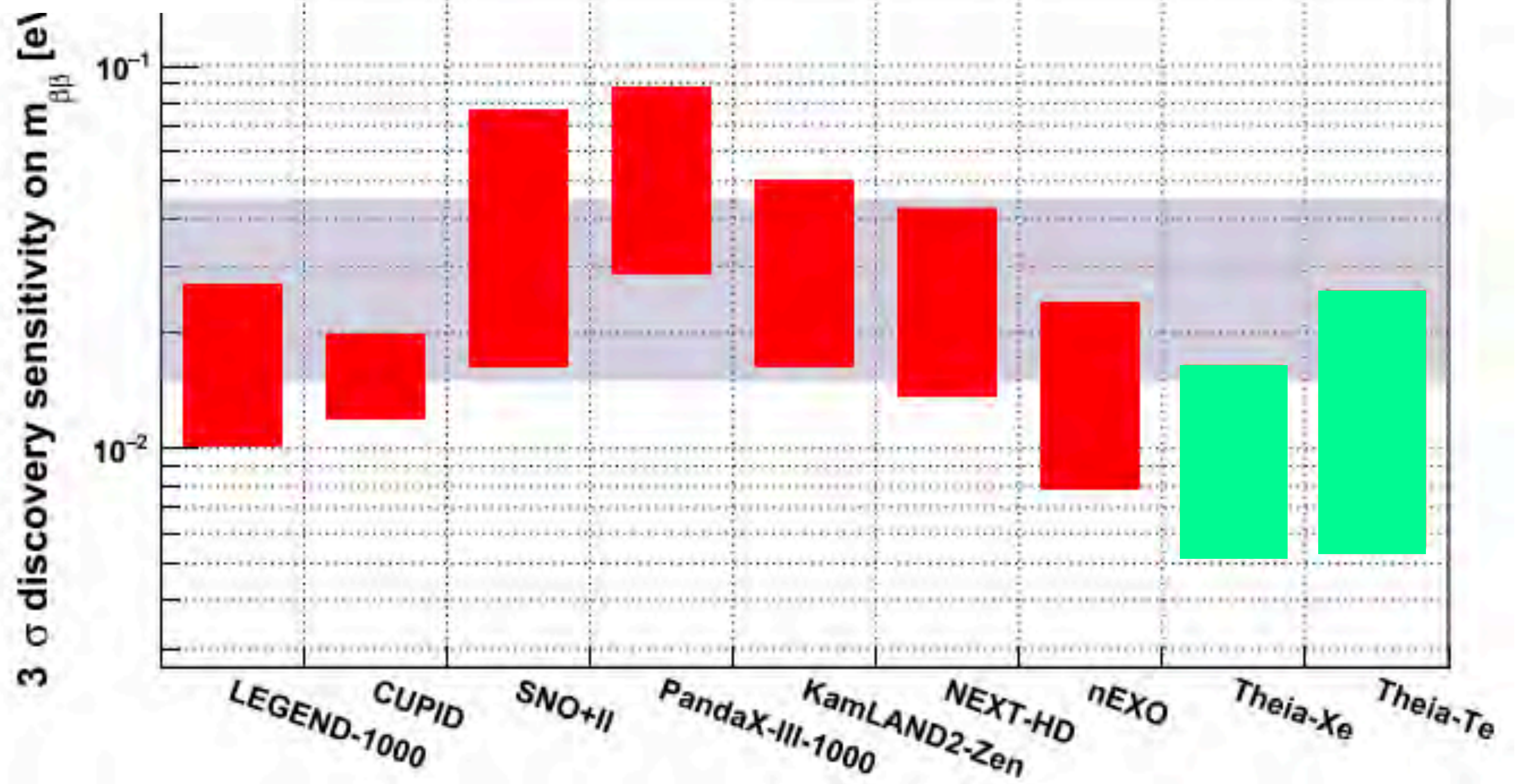
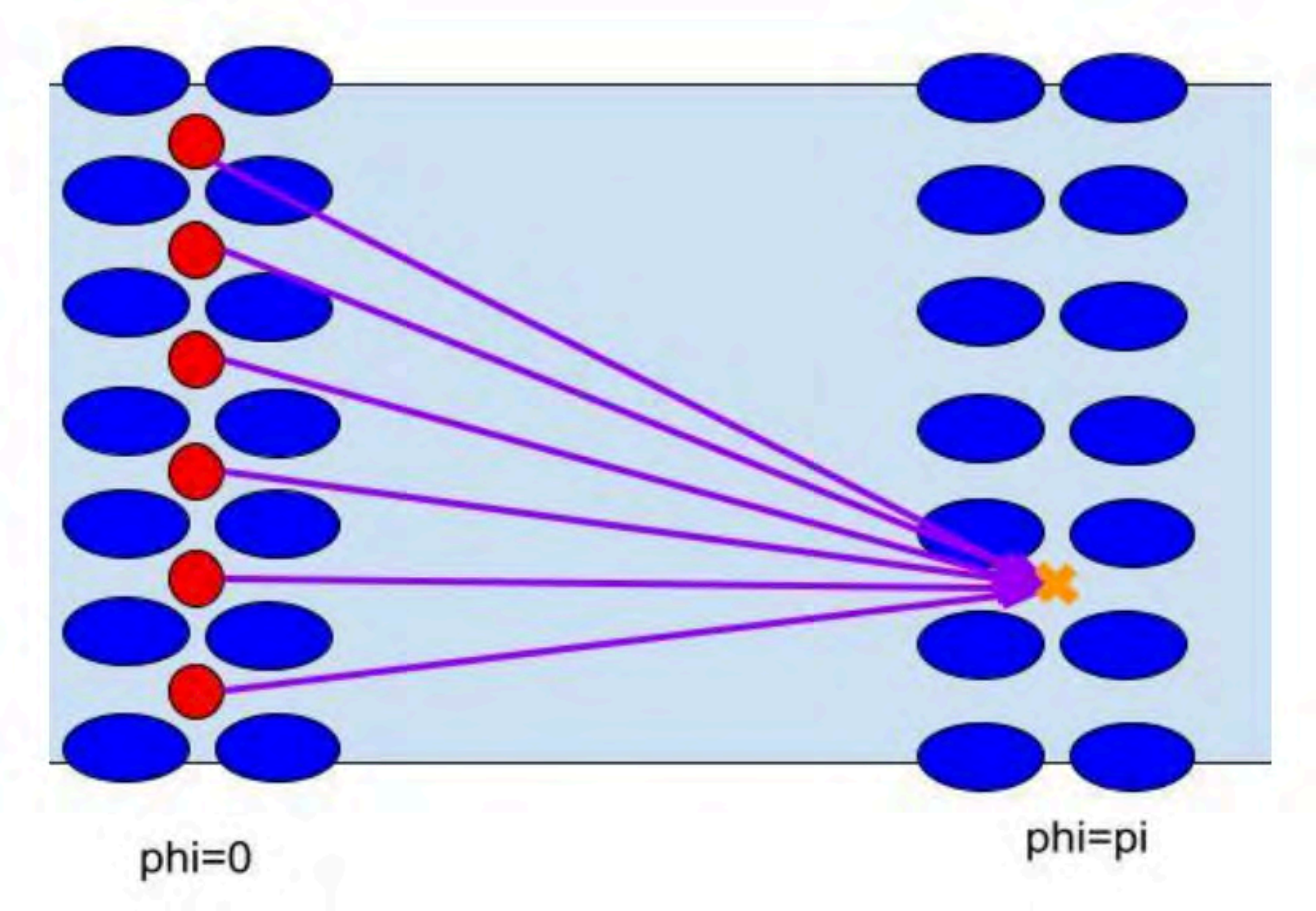
- Neutrinoless double beta decay
- Inner containment vessel with high-LY LS and isotope
- Background reduction via event imaging: PID, multi-site, directionality

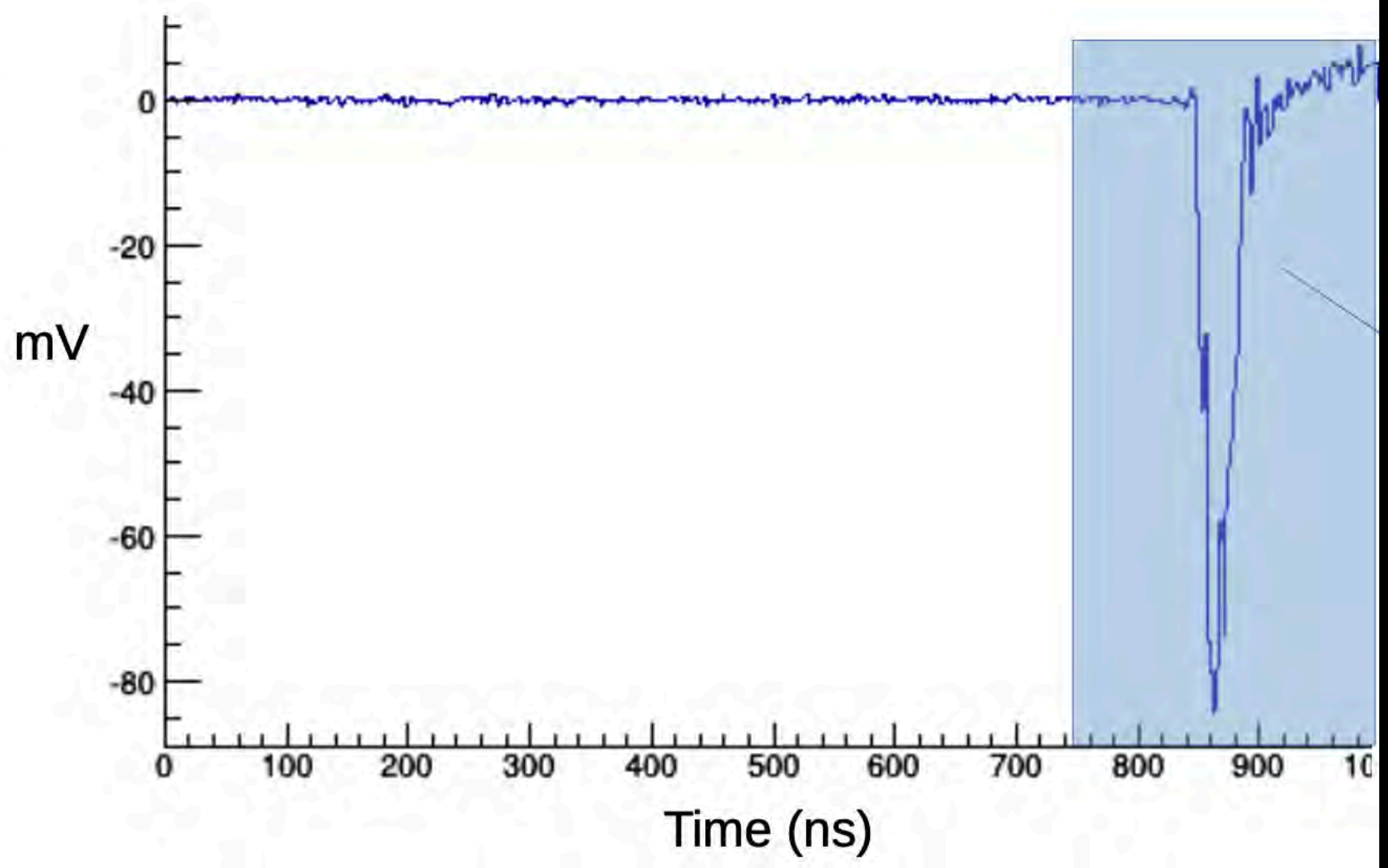


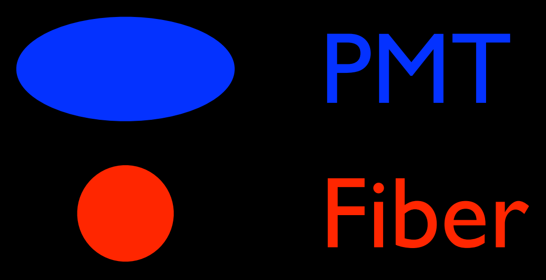
SNO+ Collaboration

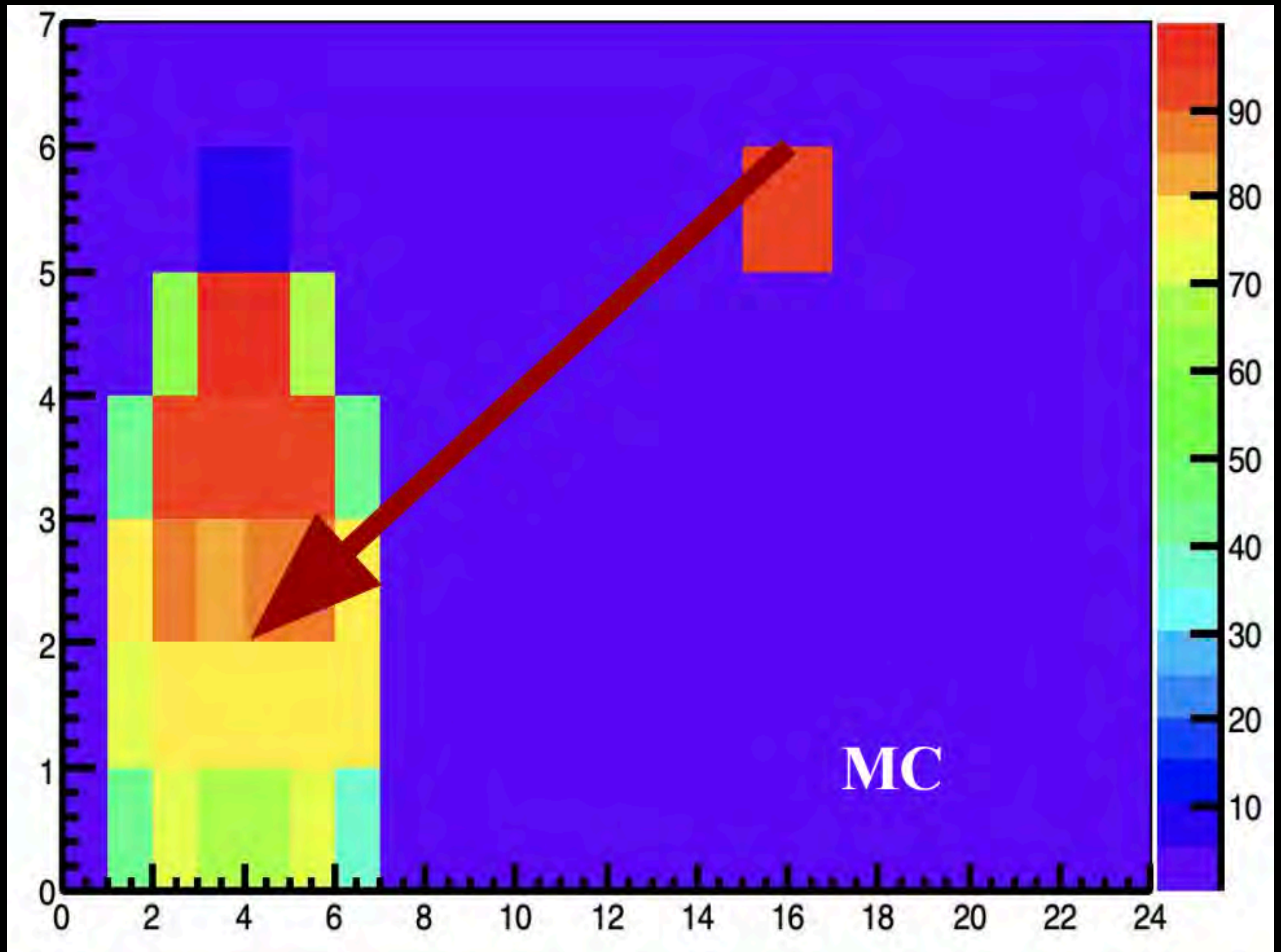


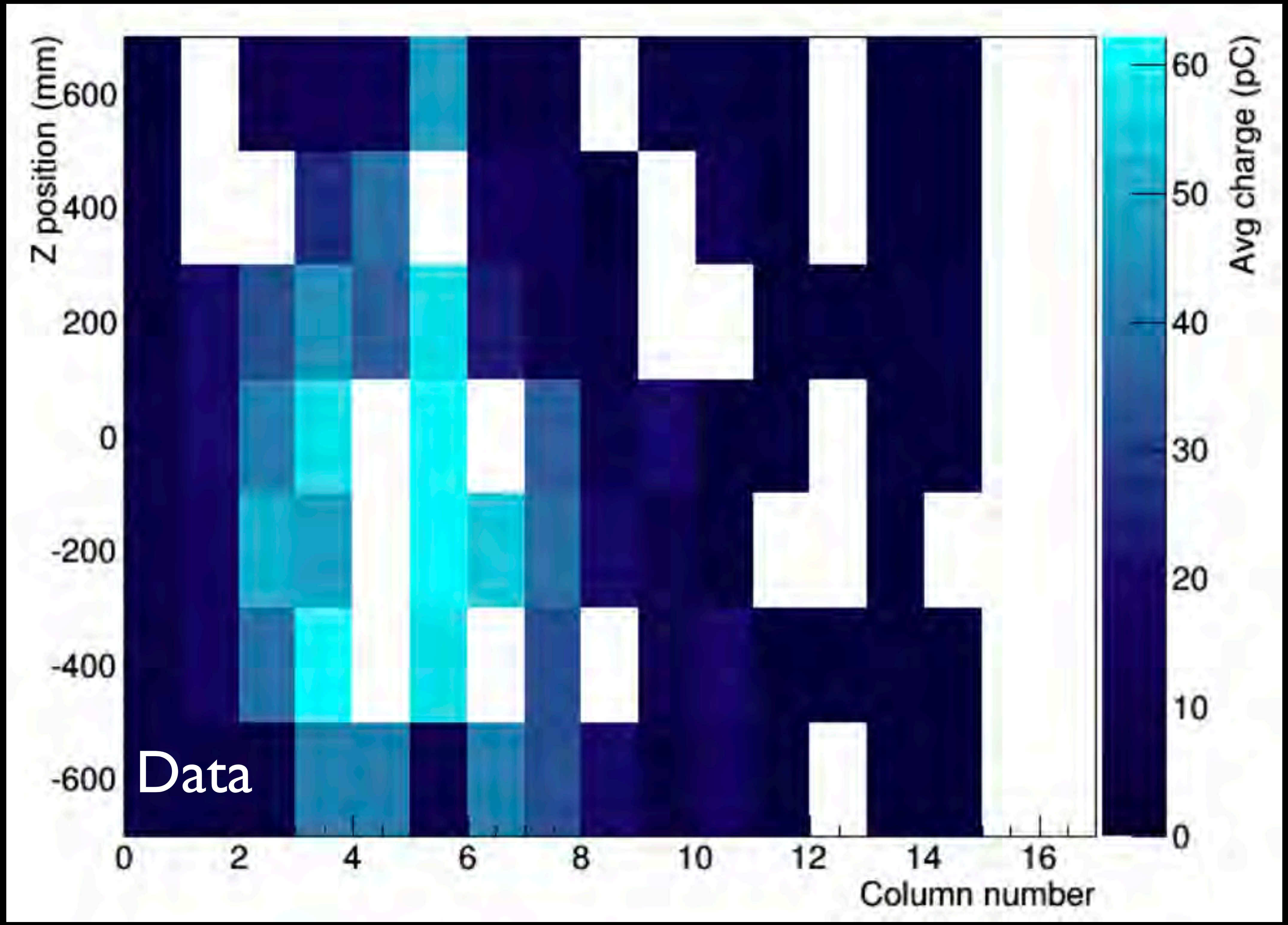
First light (Mar 8)







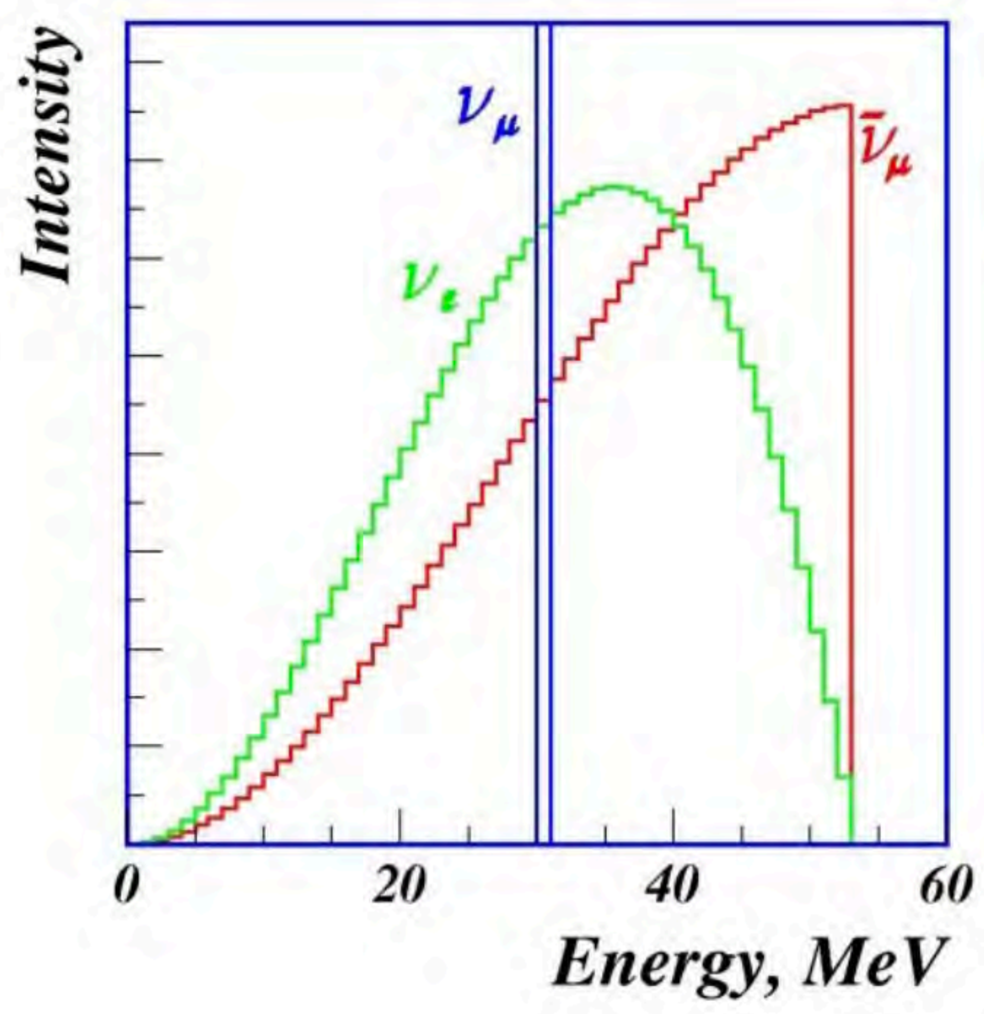


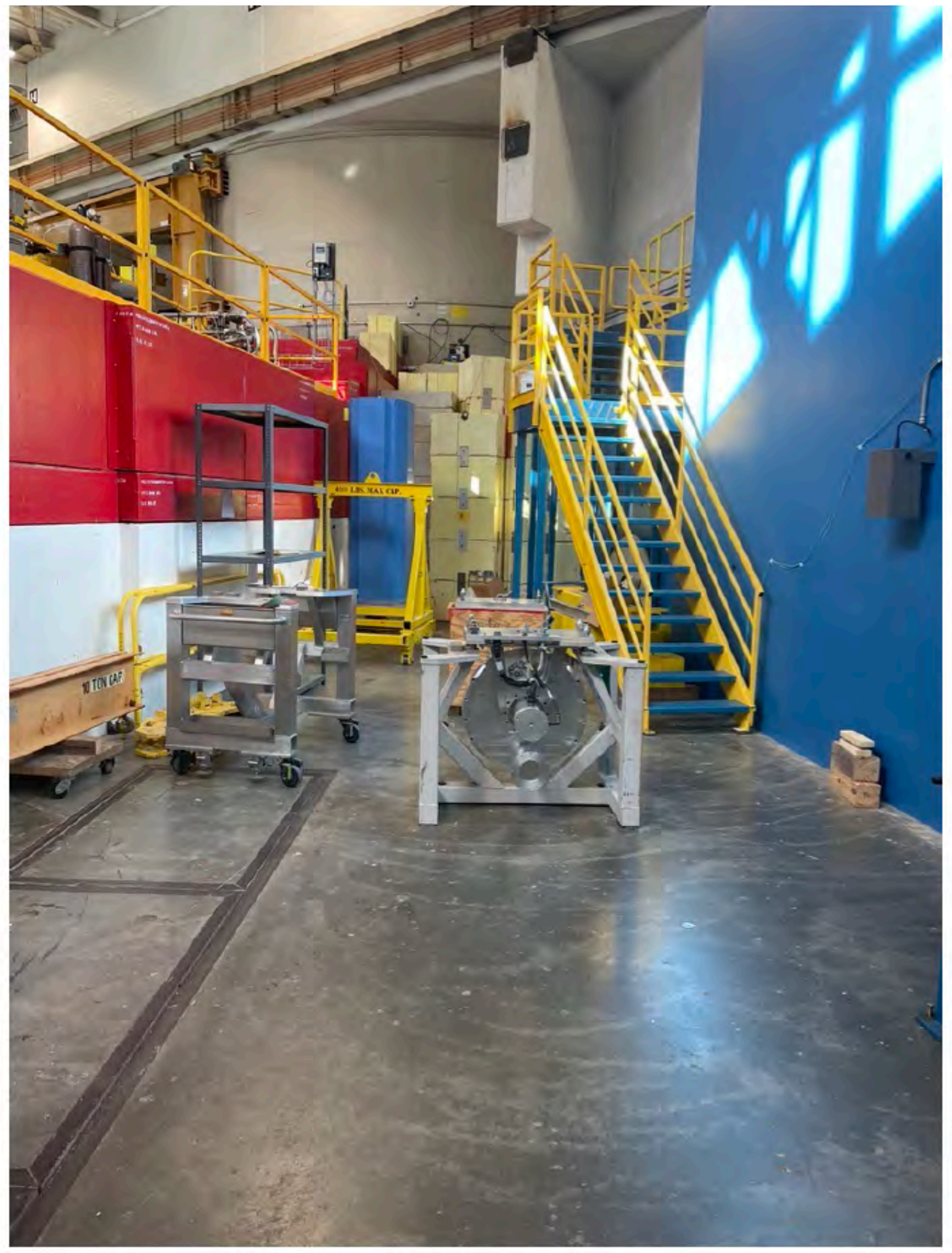


EOS @ SNS (ORNL)

- SNS provides both neutrinos and anti neutrinos
- Detection of Inverse Beta Decay: relevant for reactors
- Detection of Elastic Scattering events: directionality "holy grail"
- Neutron studies: evaluate background rejection
- Possible space identified at ORNL
- Additional technology development opportunity:
  - Li-loaded WbLS (5% organic, 10% Li)
  - Enhanced ν_e detection : CC on ^{7}Li, spectral precision
- Supernova-relevant demonstration
- Beyond-SM searches

ν flux at SNS



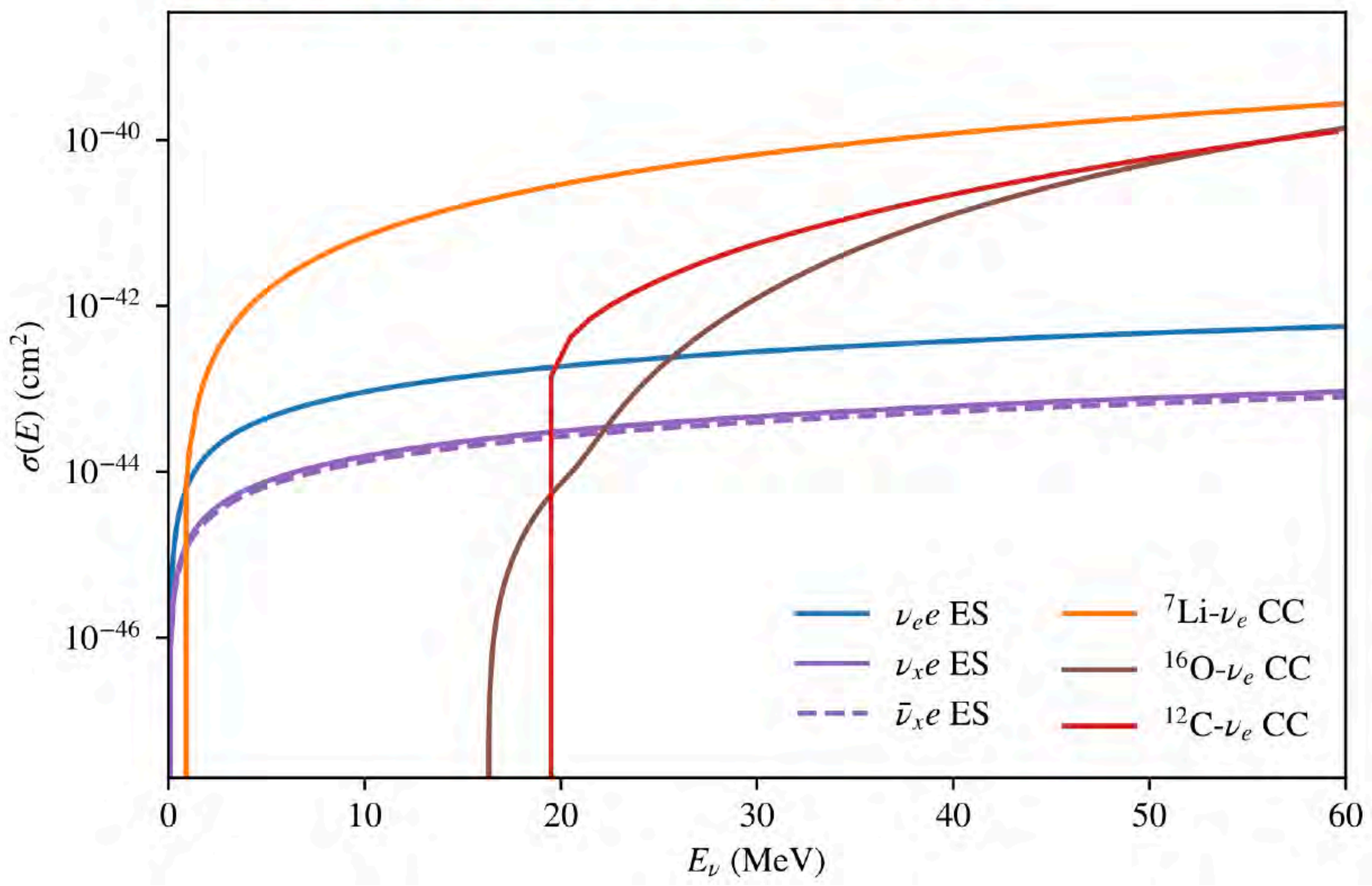


possible site for EOS deployment

Channel	Rate at 20m Standoff (ev/yr)
$\nu_e e$ ES	136.89
$\nu_\mu e$ ES	20.89
$\bar{\nu}_\mu e$ ES	22.48
ν_e-^{7}Li CC	533.30
ν_e-^{16}O CC	459.34
ν_e-^{12}C CC	37.08

event rates expected for 4 tons of LiWbLS

neutrino cross-sections in LiWbLS



Physics program

Primary physics goal	Reach	Context
Long-baseline oscillations	>5σ for 30% of δ_{CP}	Comparable / complementary to DUNE
Nucleon decay $p \rightarrow \bar{\nu} K^{+}$	T>3.8 x 10^{34} year	Complementary to DUNE (sensitivity to different modes)
Supernova burst	<1(2)° pointing 20K(5K) events	Complementary to DUNE (nu vs anti-nu)
Diffuse Supernova Neutrino	5σ	Unique background rejection (deep, Cher+scint ratio)
CNO neutrinos	<5(10)%	Unique capability, order of magnitude improvement
MSW transition	5σ	Unique capability: depth, low-bkg, low-threshold, PID
Geoneutrinos	< 7 %	Only plausible high stats measurement in North America
$0\nu\nu\beta$	$T_{1/2}$ > 1.1 x 10^{28} year (90%C.L.)	Beyond ton-scale sensitivity

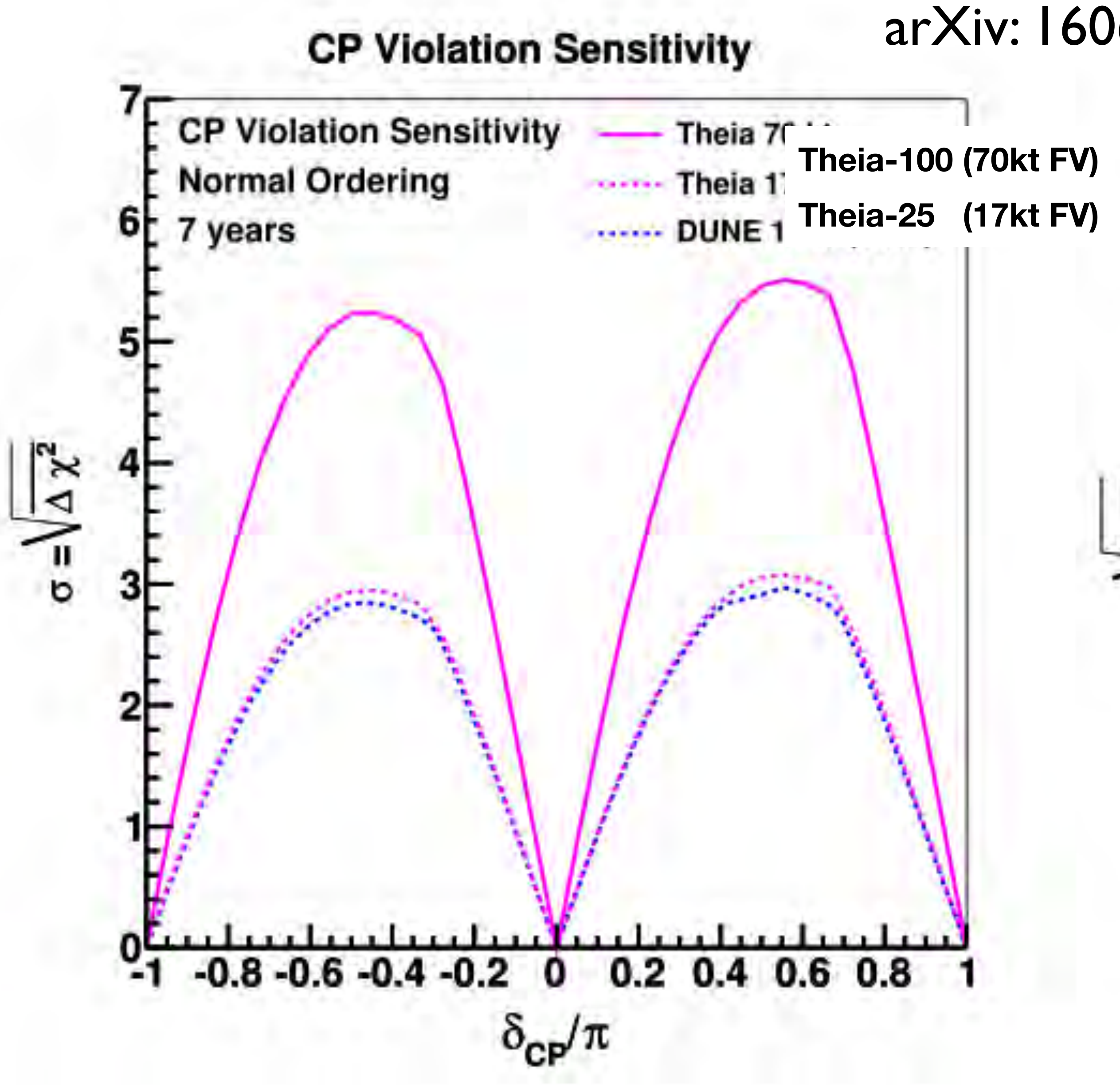
- Low-energy (< 5 MeV) Solar νs
  - No long-lived cosmogenics
  - Naturally neutron-shielding
  - High light-yield for good resolution/low threshold
- SN Burst and Diffuse SN anti-ν Background
  - Literally complementary to LAr: anti-ν vs. ν
  - Atmospheric NC rejected via Cher+scint
- 0νββ with *natural* isotopic (e.g. ^{nat}Te) loading
  - Beyond tonne-scale at low cost
- Long-baseline oscillations
  - Similar CP sensitivity to 10 kt LAr
  - Lighter target, different systematics
  - Very narrow energy resolution

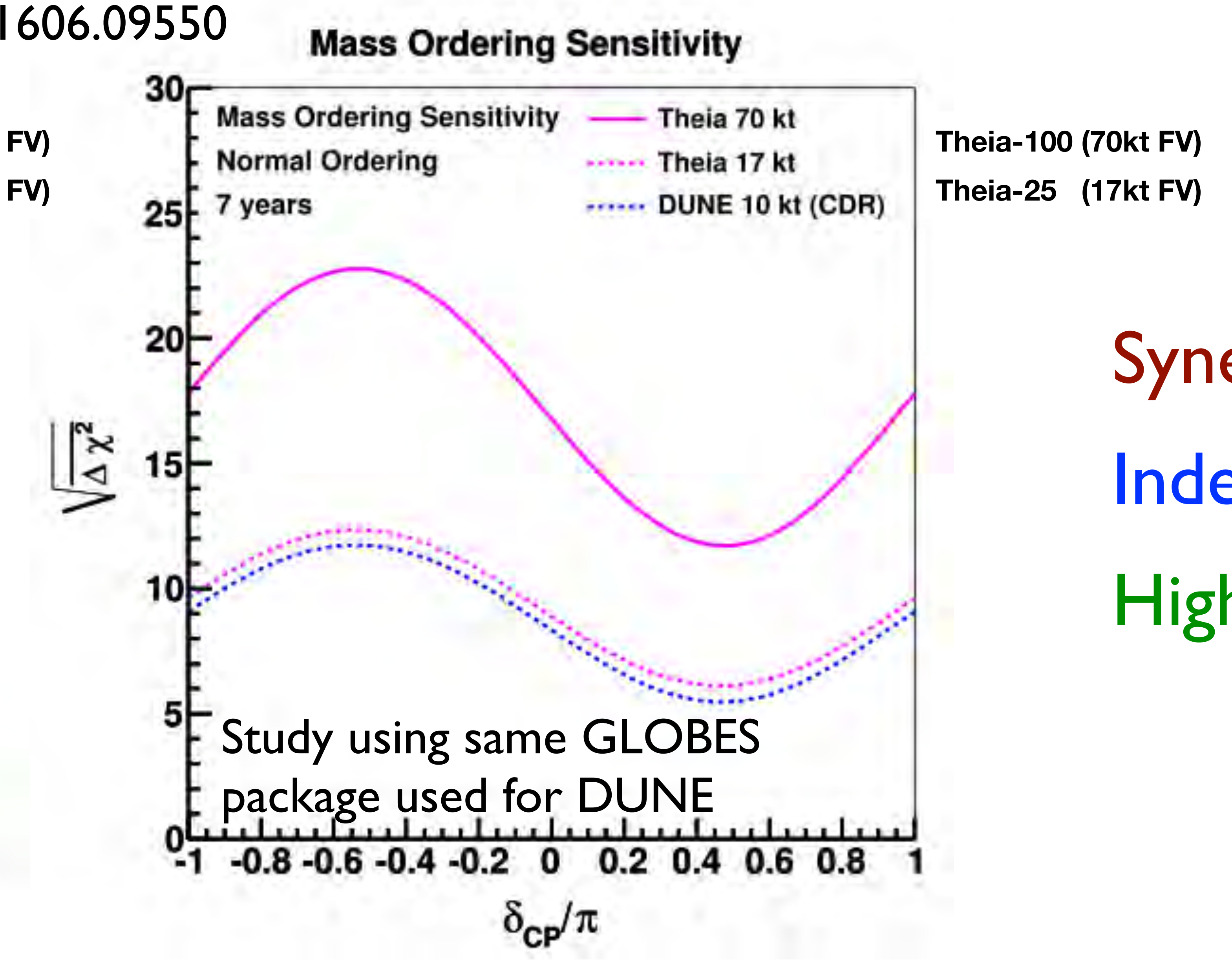
Antinu signal >> nu signal

Require UAr + n shield to achieve this physics in LArTPC DUNE due to intrinsic 39Ar and 42Ar & neutron background

Long-Baseline Sensitivity

arXiv: 1606.09550





Synergy with LAr TPC

Independent systematics

High-energy events

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

- 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 $\pi^0 \rightarrow \gamma\gamma$
- THEIA100: large size → sensitivity to 2nd oscn max

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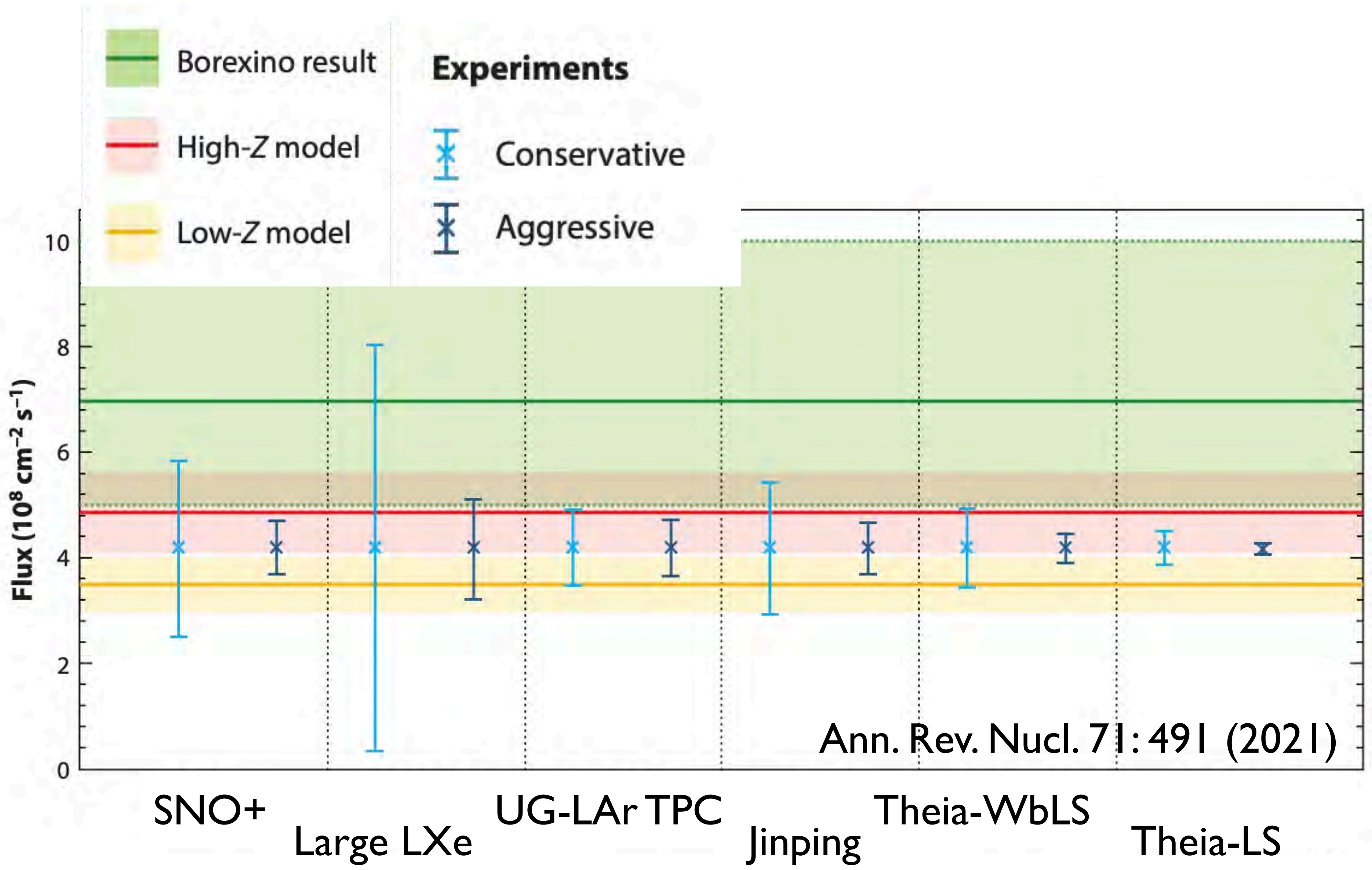
Solar Neutrinos with THEIA

- 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



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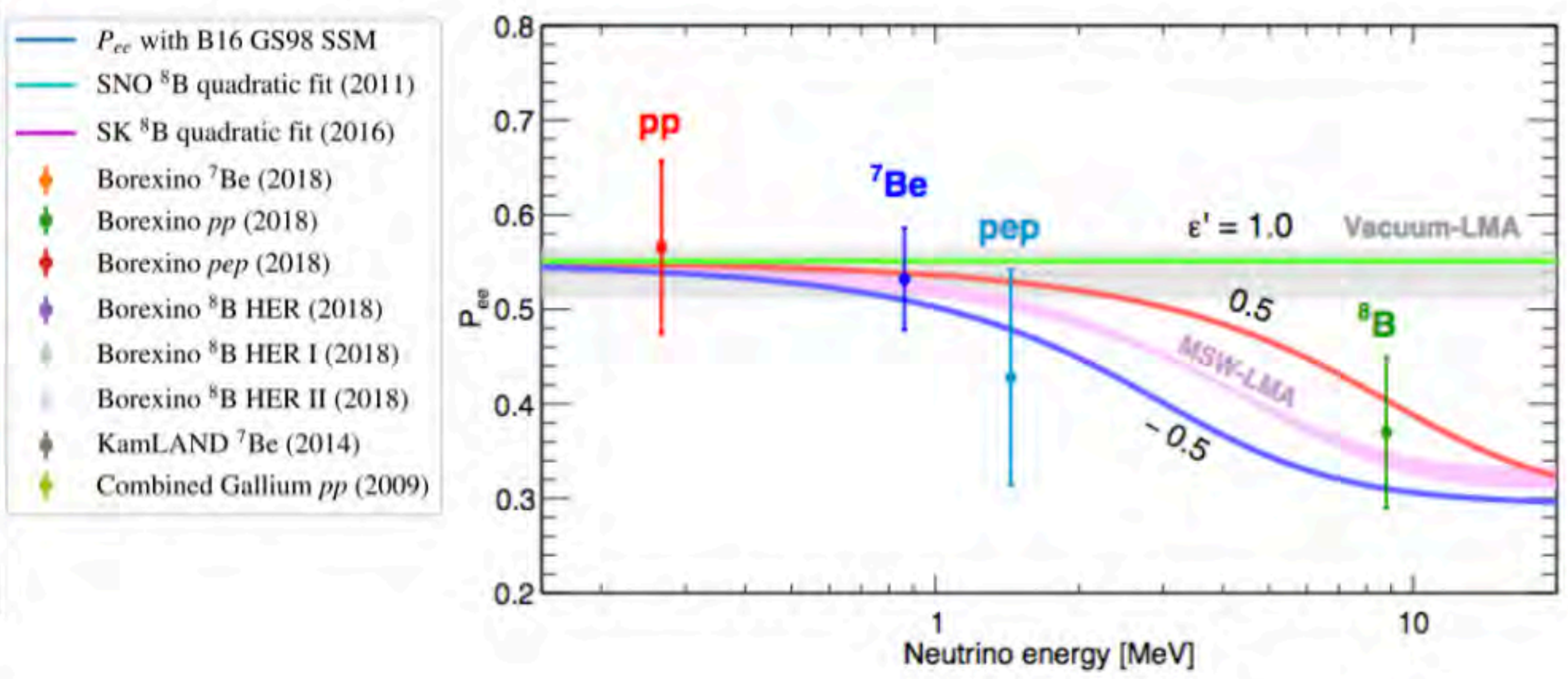
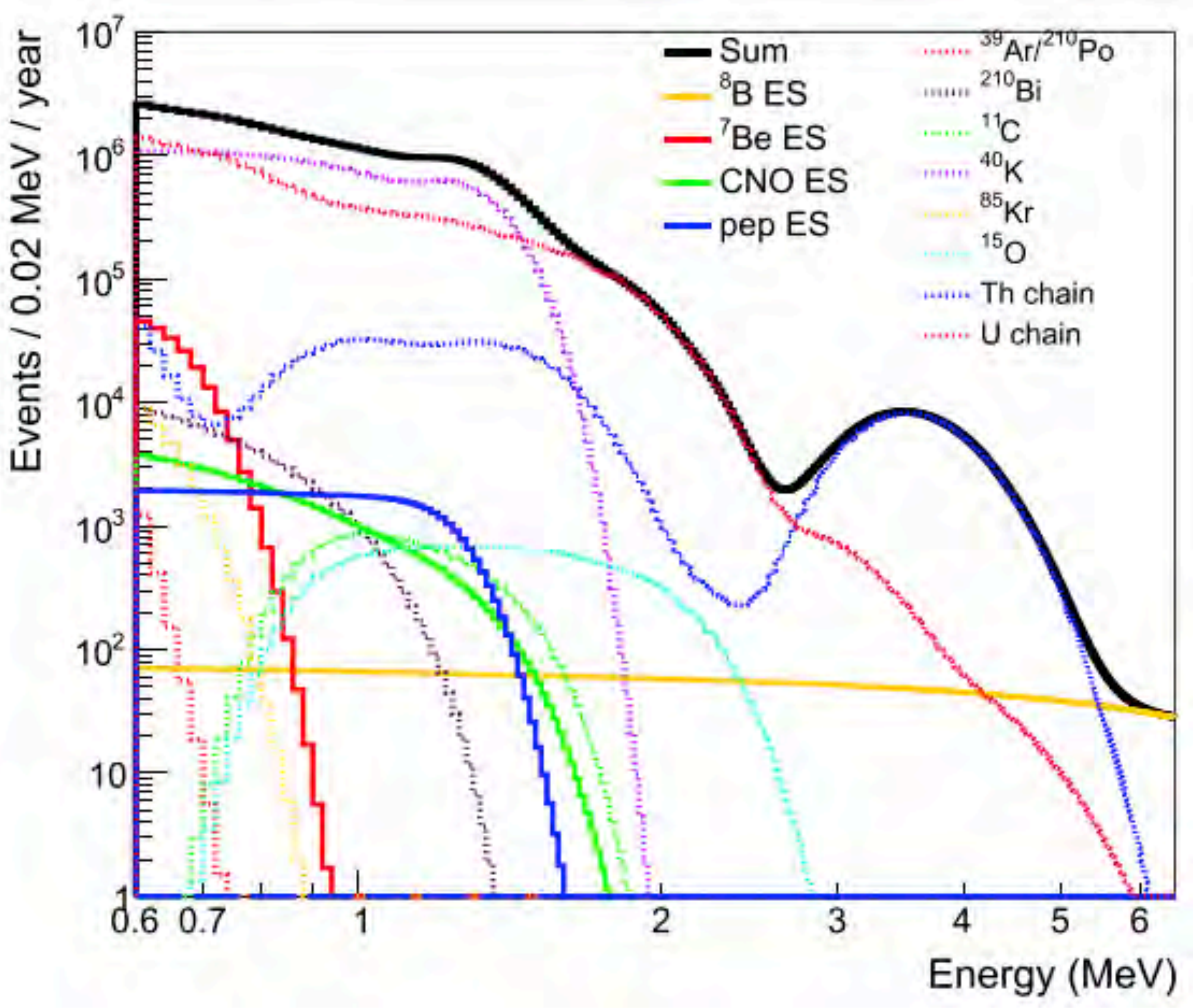
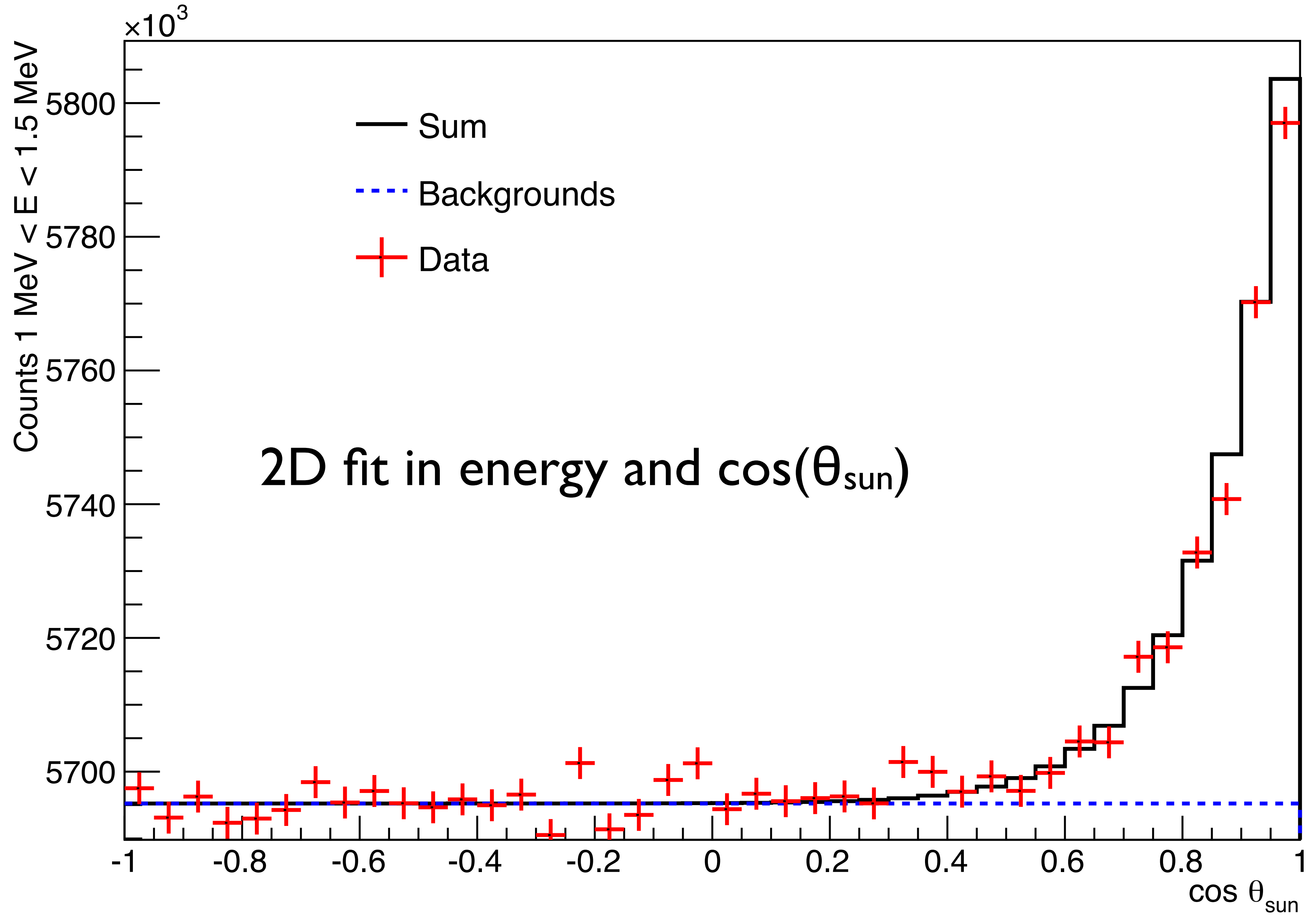
- Unique few-% level sensitivity to CNO ν
- Precision pp: luminosity, understand solar energy production
- Unique probe of matter effect / matter-vacuum transition
- Potential Li loading for CC (Haxton)



The challenge of backgrounds





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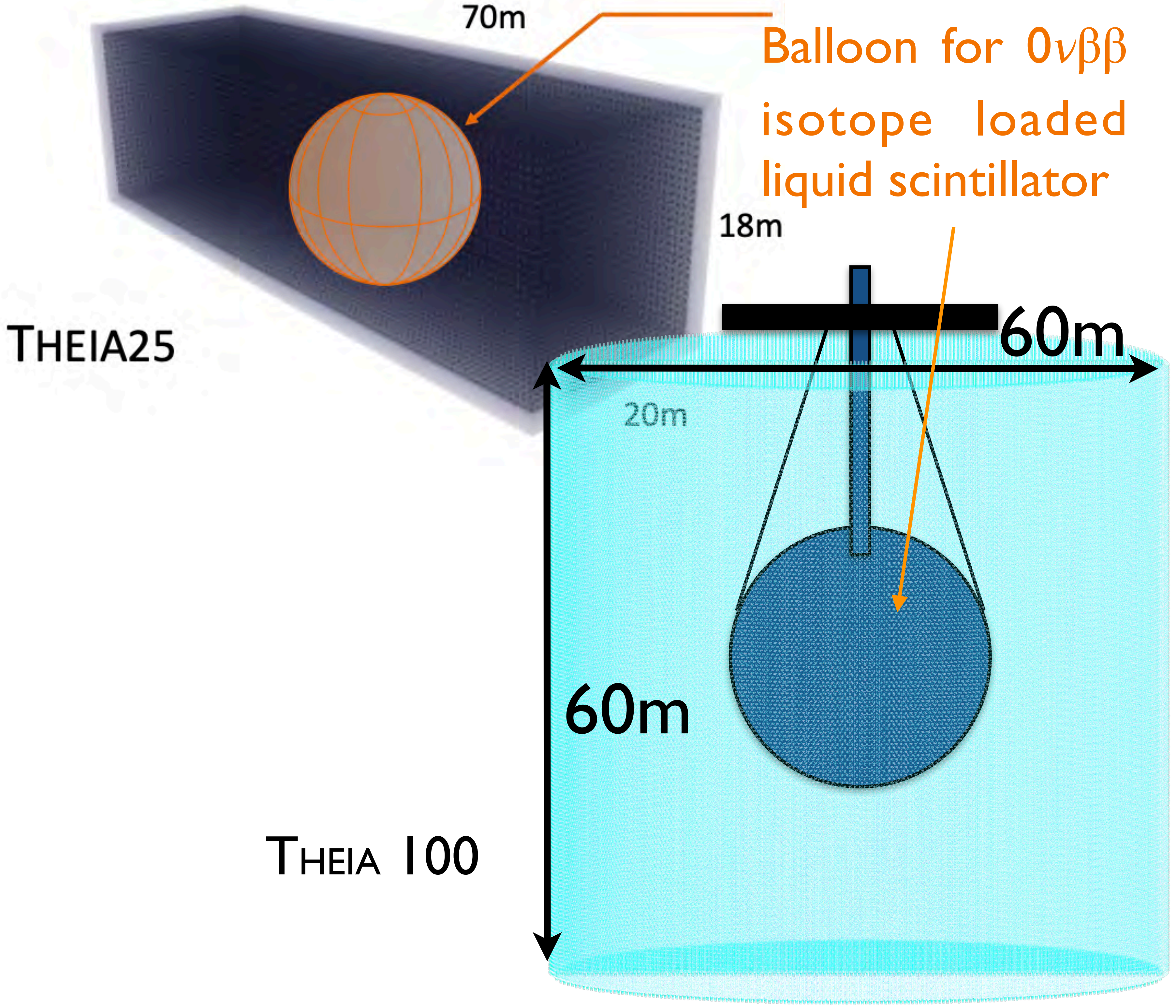
$0\nu\beta\beta$ with THEIA

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



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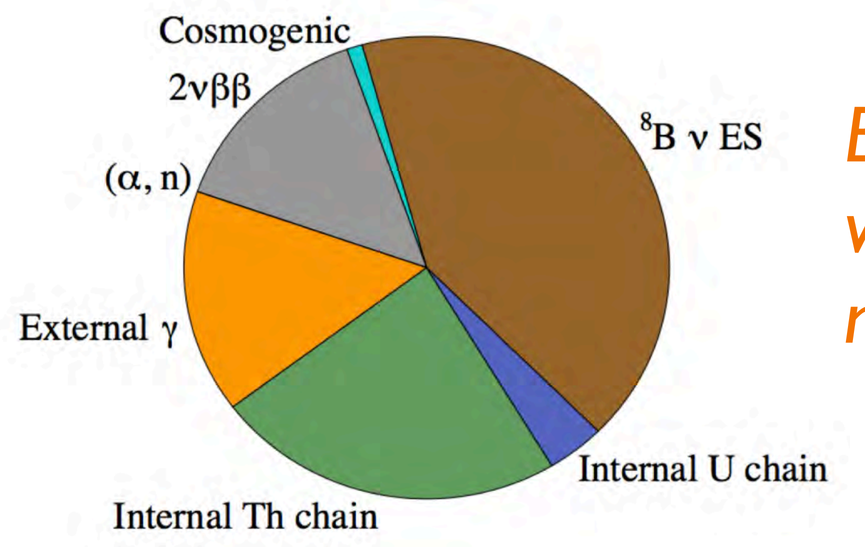
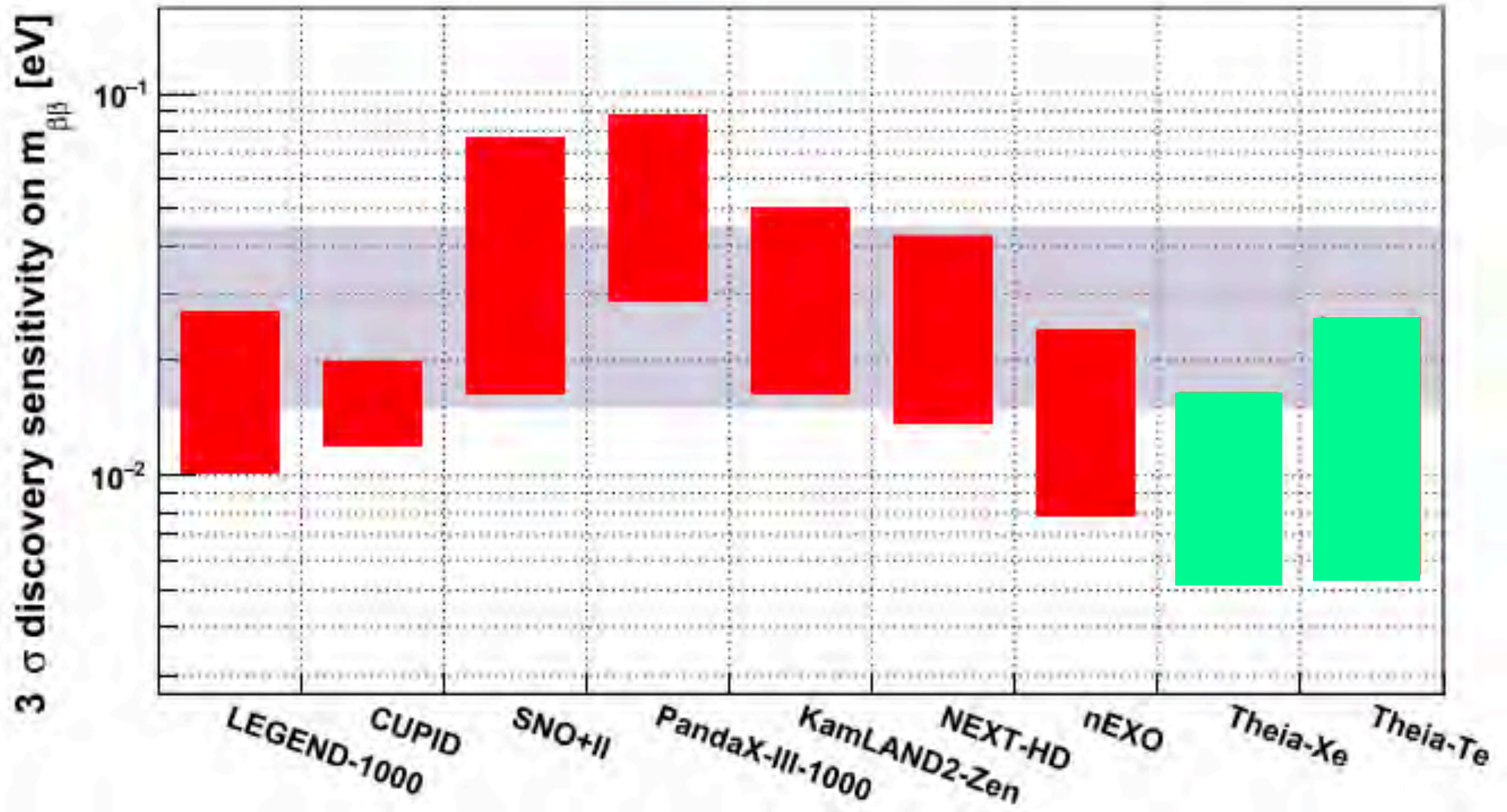
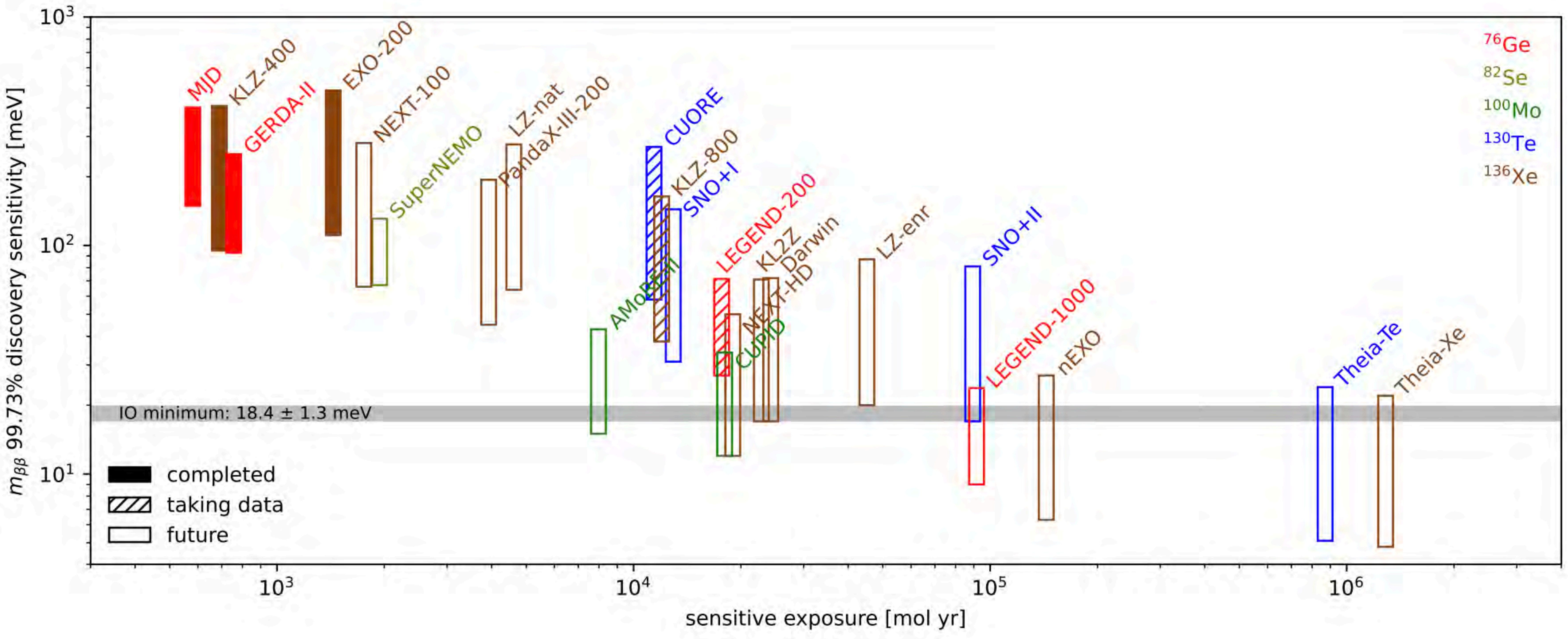


Background reduction via event imaging: PID, multi-site, directionality



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)

Sensitivity



NP-LRP White Paper on neutrino less double beta decay, by the NP community: https://arxiv.org/pdf/2212.11099.pdf

Supernova Detection

- ~90% events are IBD

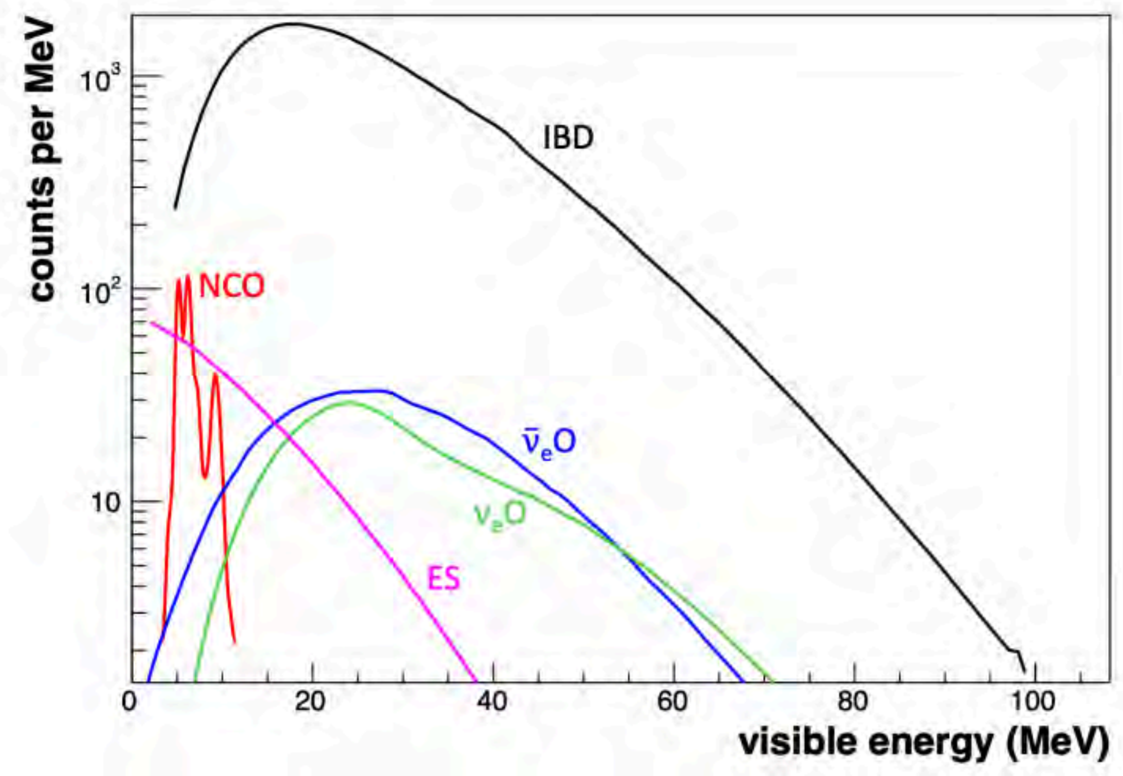
  Highly complementary to ν_e LAr signal

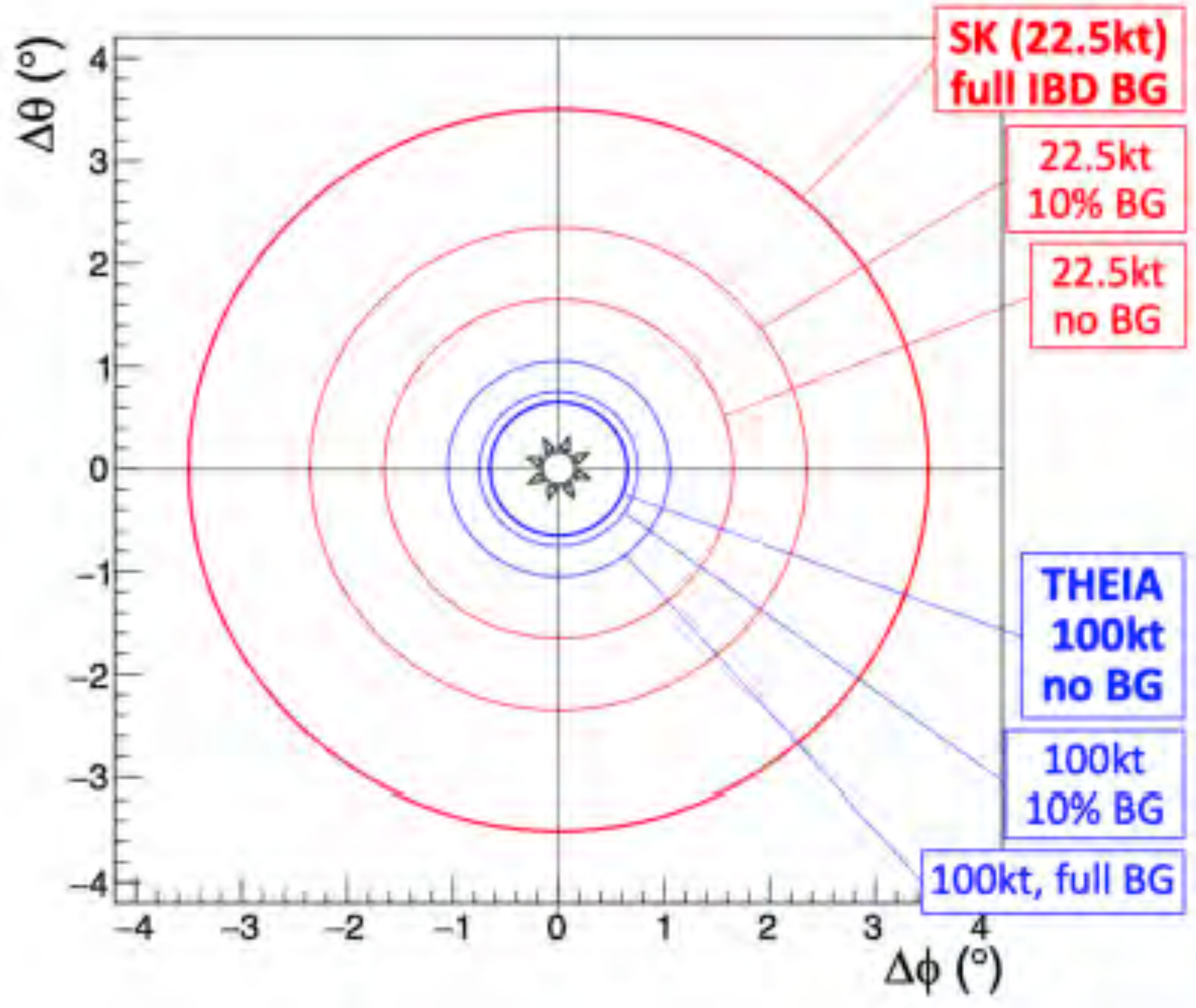
  Fast, can act as trigger for DUNE
- ES ⇒ pointing accuracy < 1°
- CC & monoE γ from NC ⇒

  burst T & subsequent mixing
- Flavour-resolved neutrino spectra
- High-stats, low-threshold signal with good resolution
- Pre-supernova ν sensitivity
- Enhanced CC with

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





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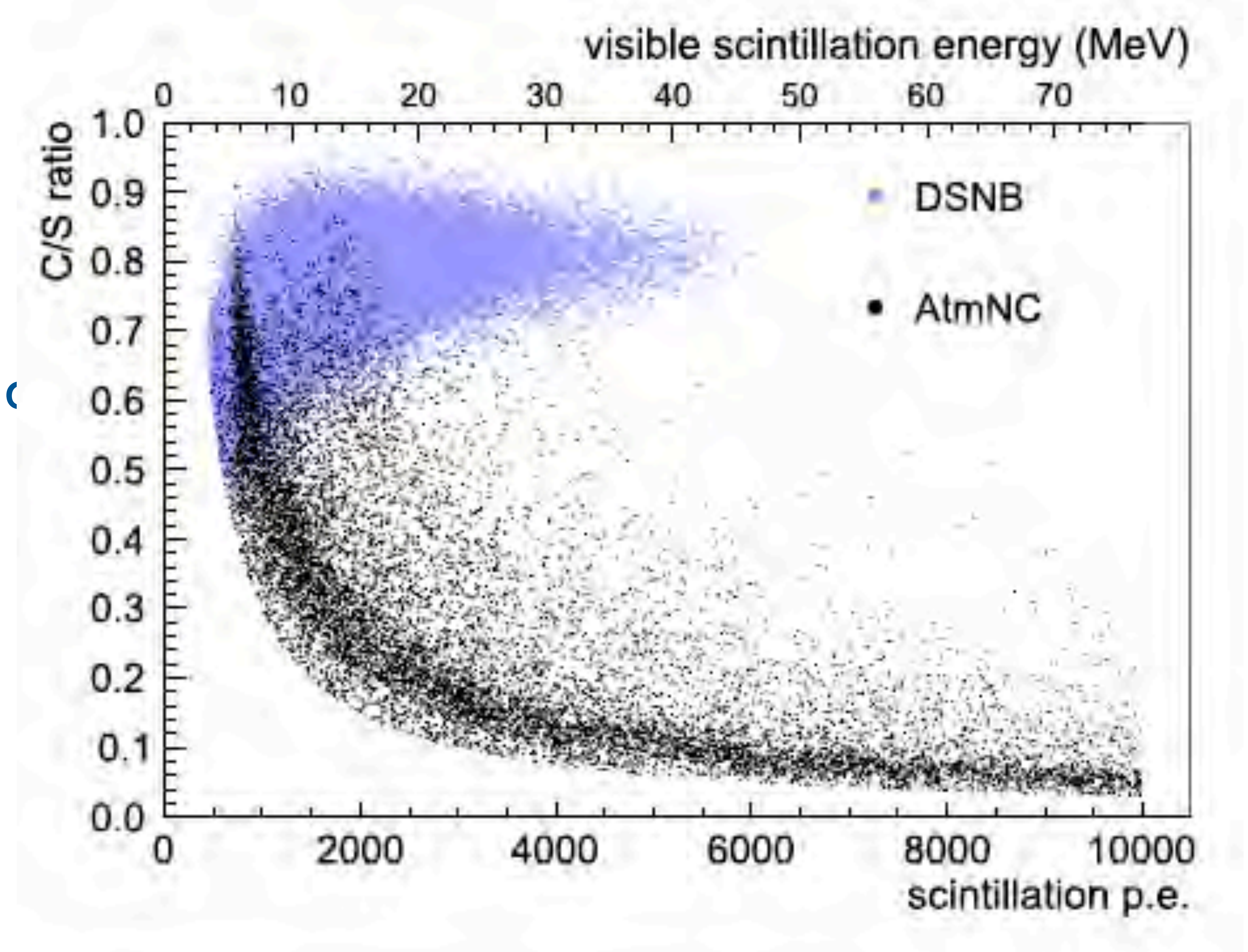
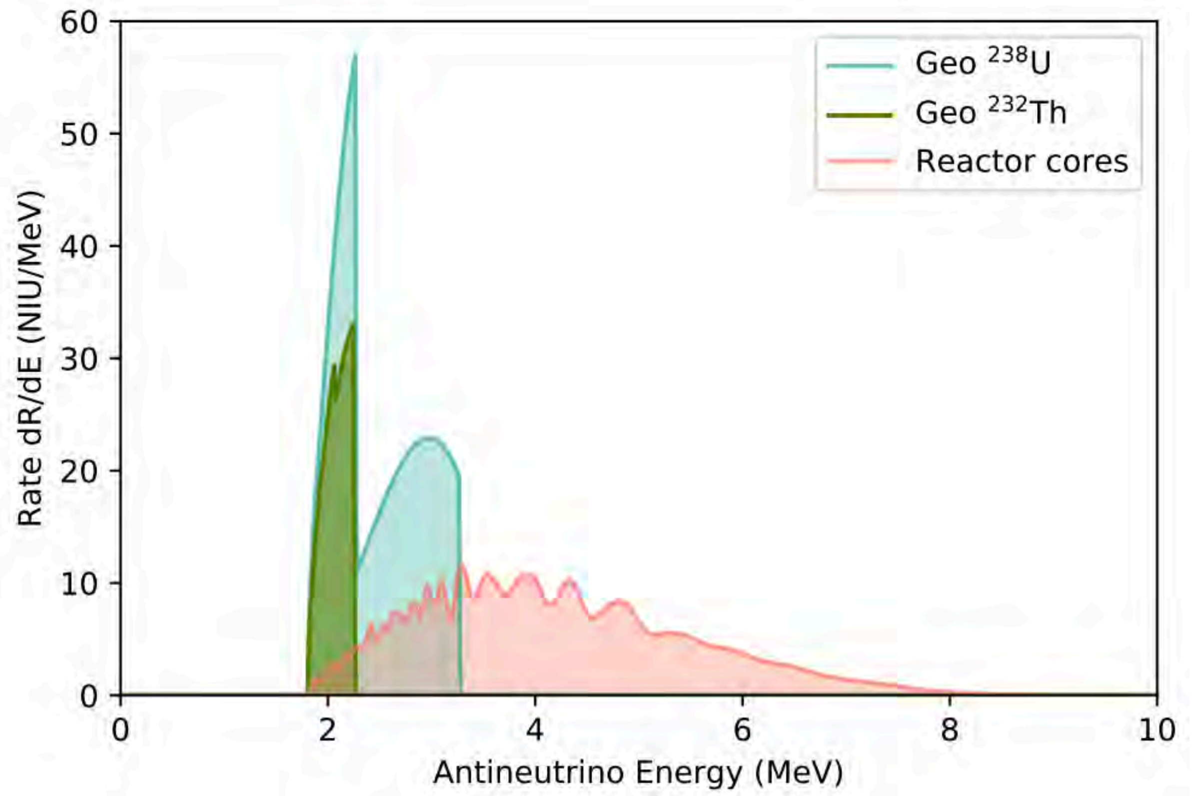
Diffuse Supernova ν Background

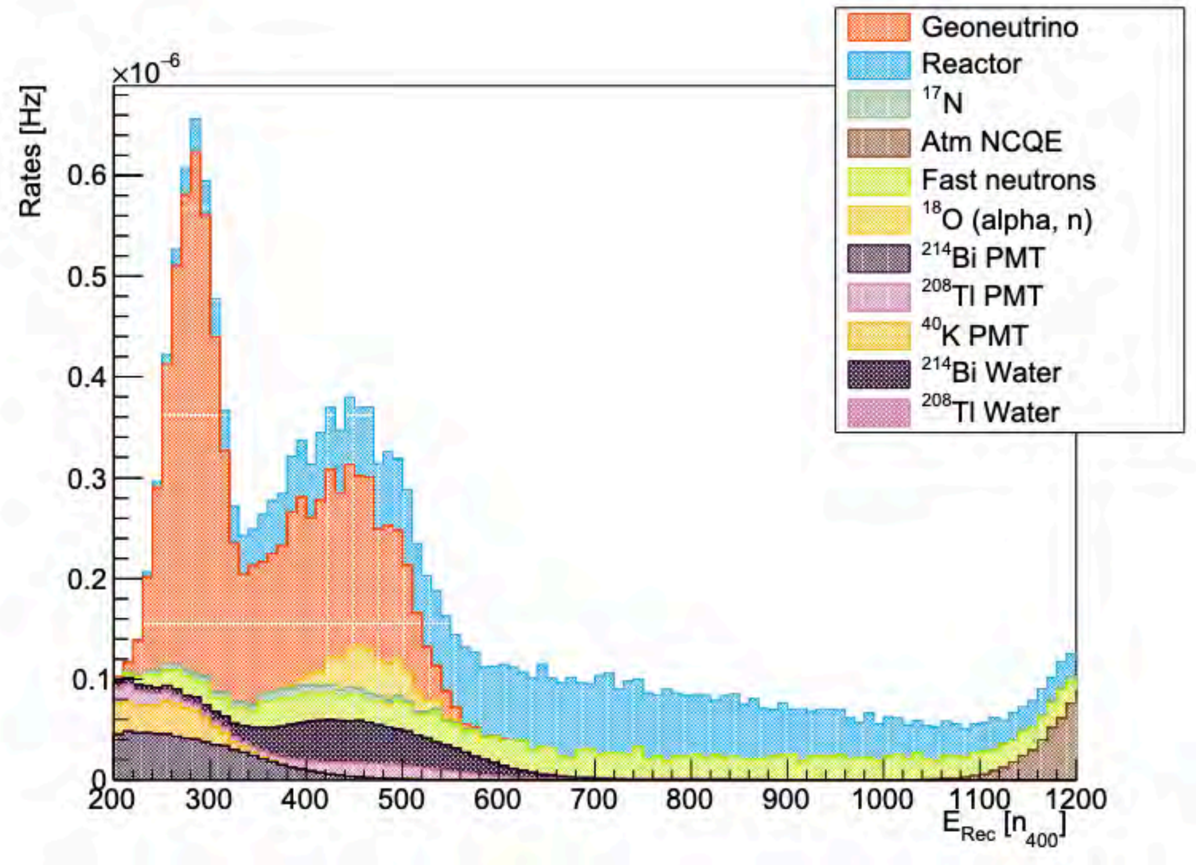
- Diffuse ν "glow" from past core-collapse supernovae
- Astrophysics of SNe
- Signature: IBD detection of antineutrino signal
  - Prompt e+ and delayed n-capture signal
- Main background: NC interaction of atmospheric ν
  - ν hits C nucleus, causing recoil
  - n captures
  - Can mimic signal
- Cherenkov/scintillation ratio provides a powerful handle for background
- 5σ in 125 kton-yrs

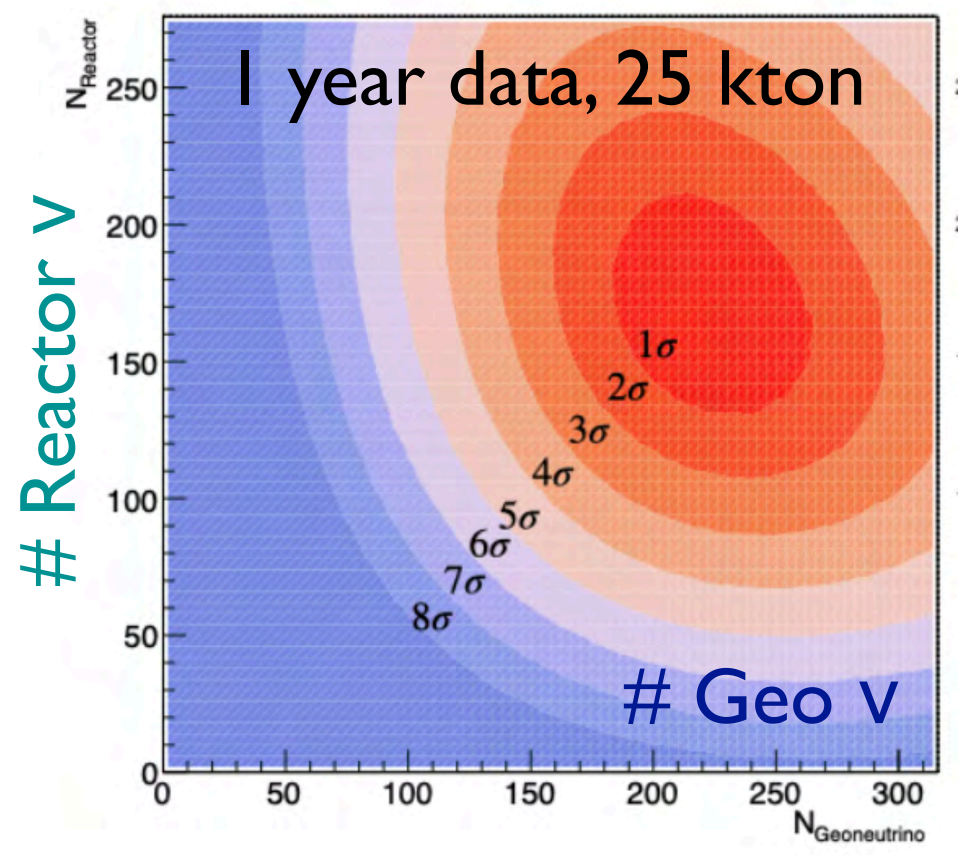


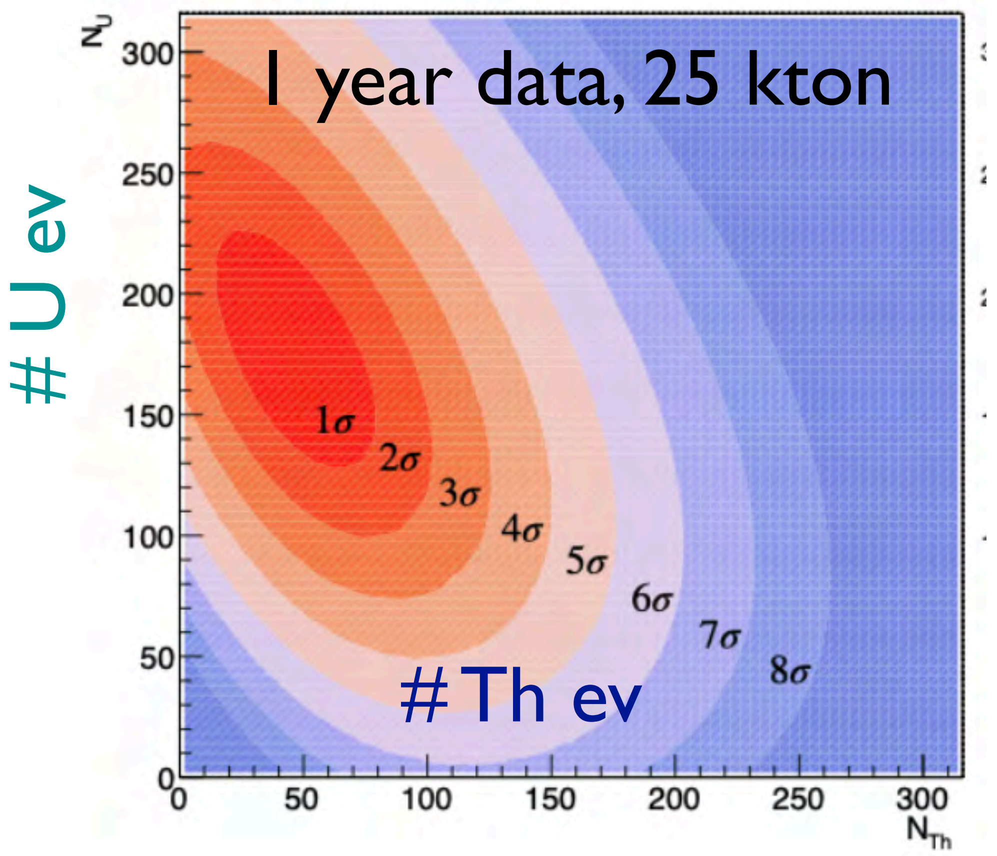
Anti-ν Detection

- **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





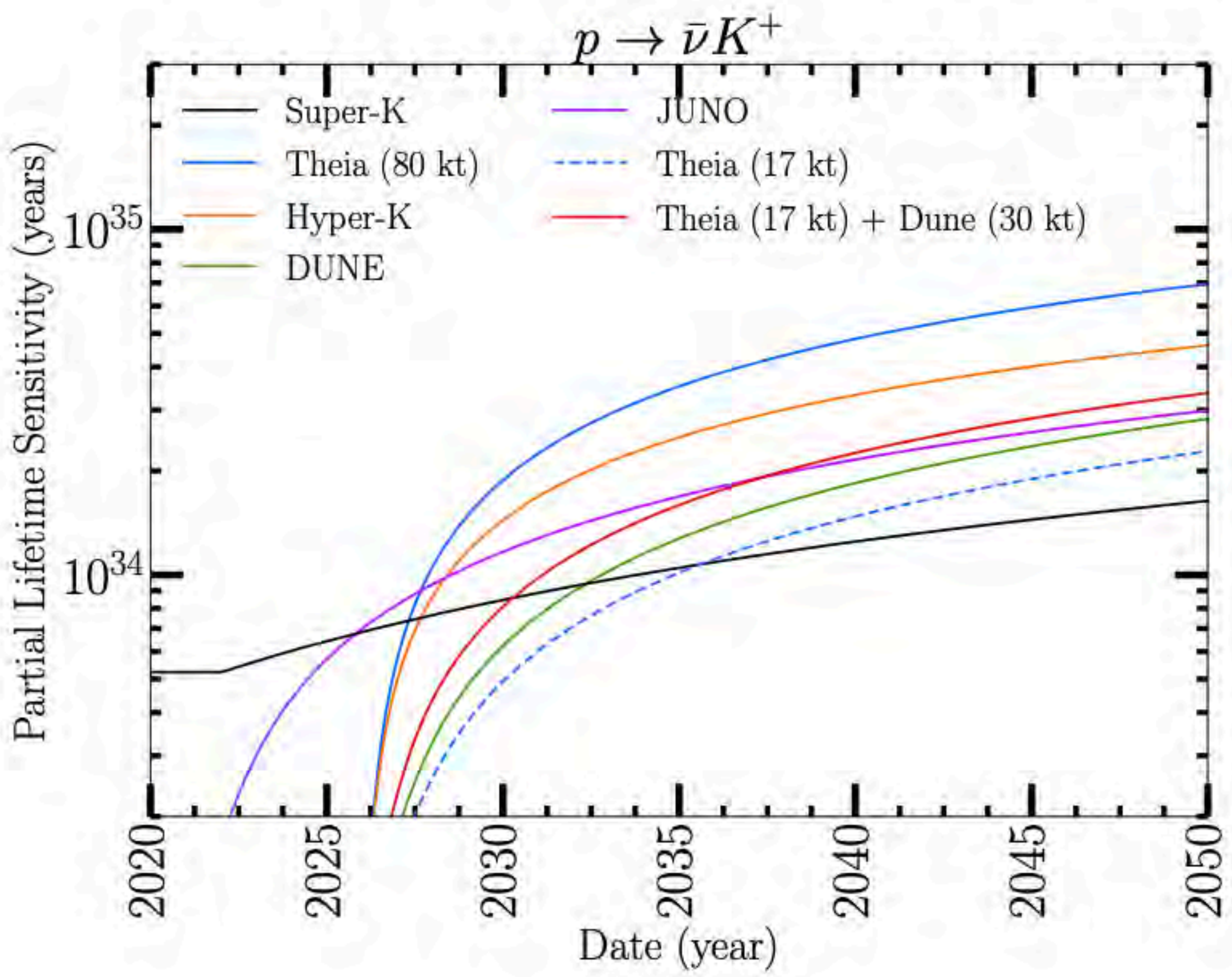




Nucleon Decay

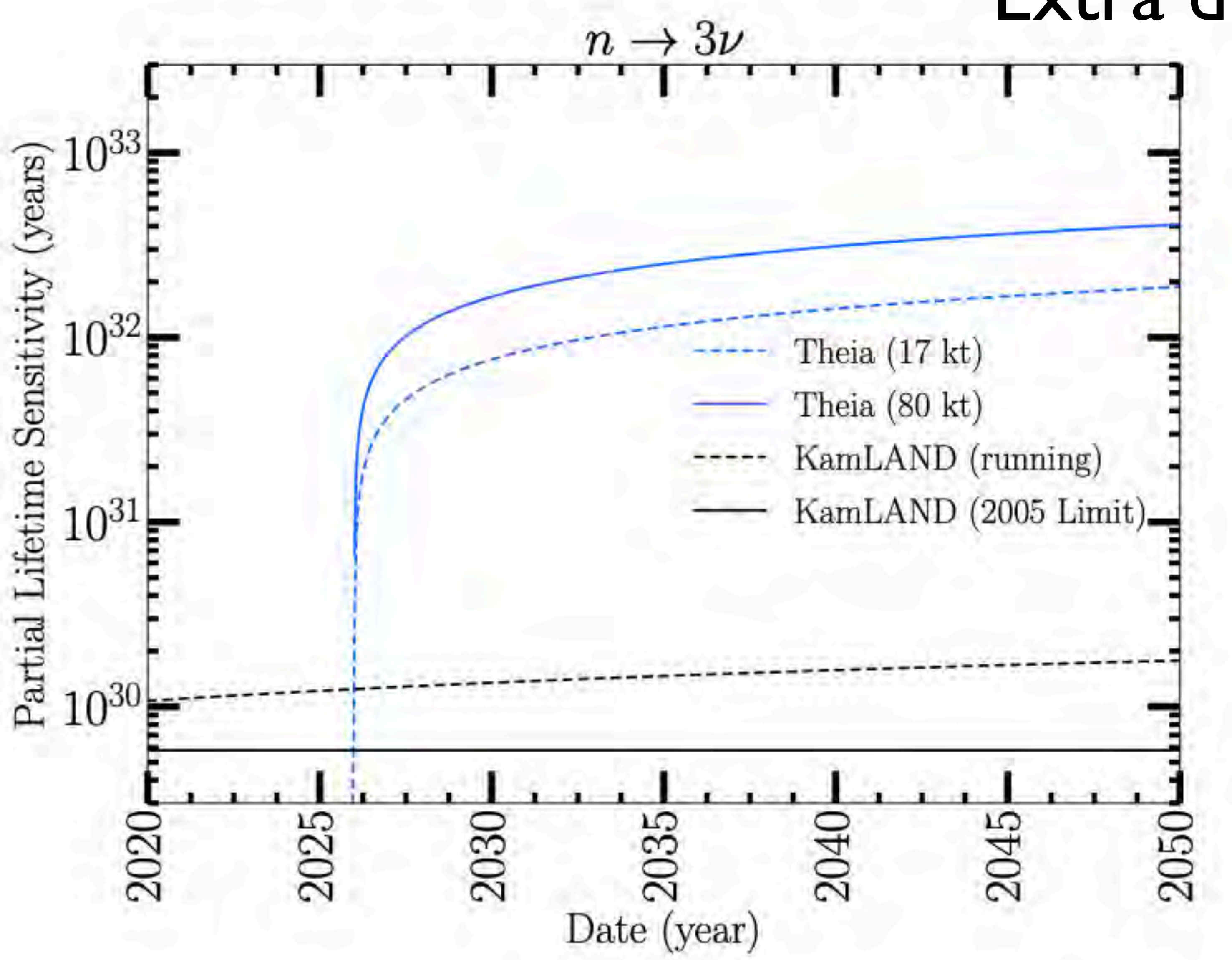
Testing the existence of GUTs with THEIA:

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



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

Extra dimensions



Deep, low threshold
Directionality + n tag