Let There be Light

Next-generation neutrino detection at THEIA

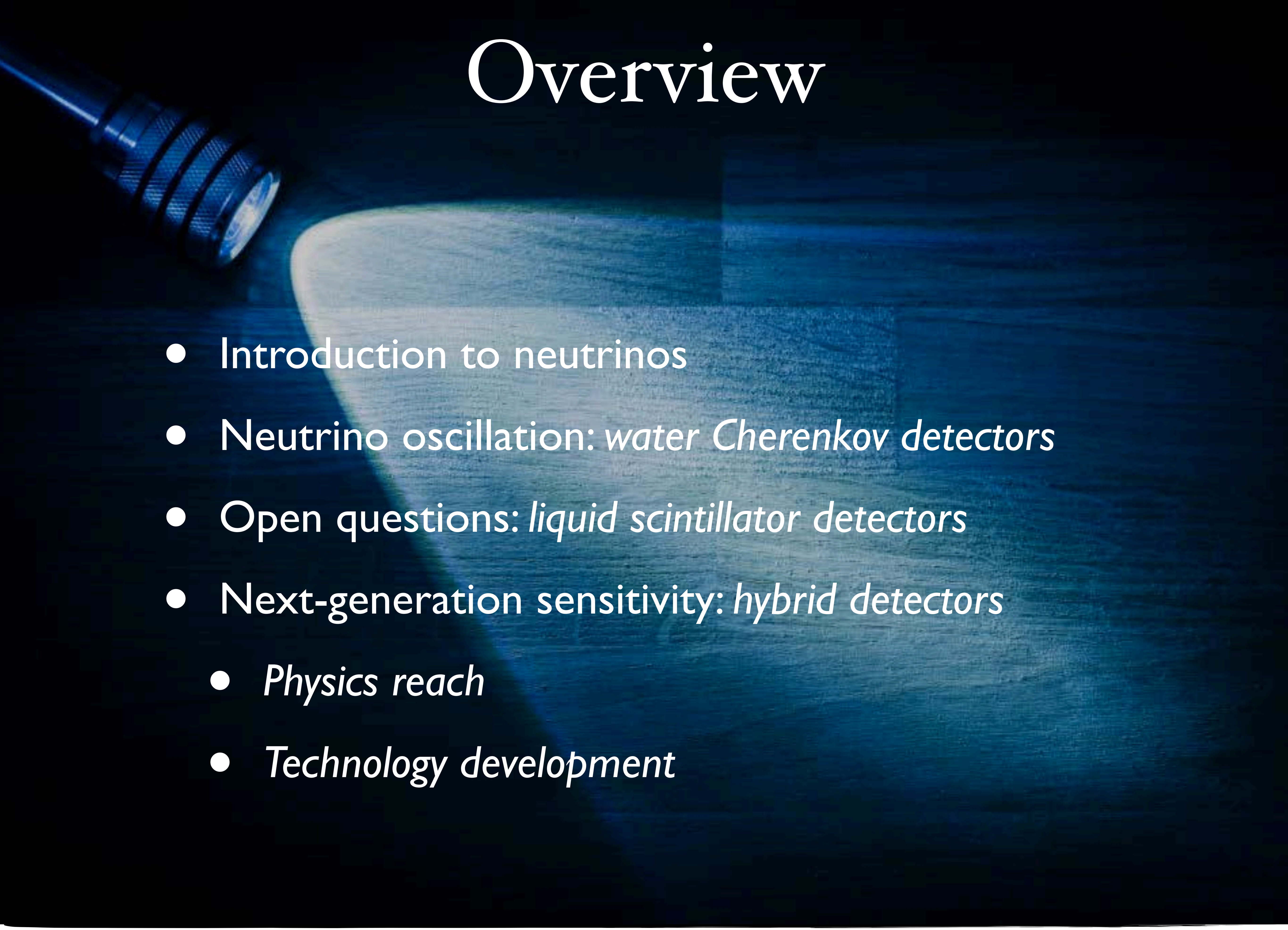
BERKELEY LAB

Gabriel D. Orebi Gann
UC Berkeley & LBNL

SLAC FPD seminar
30th May, 2023

THEIA

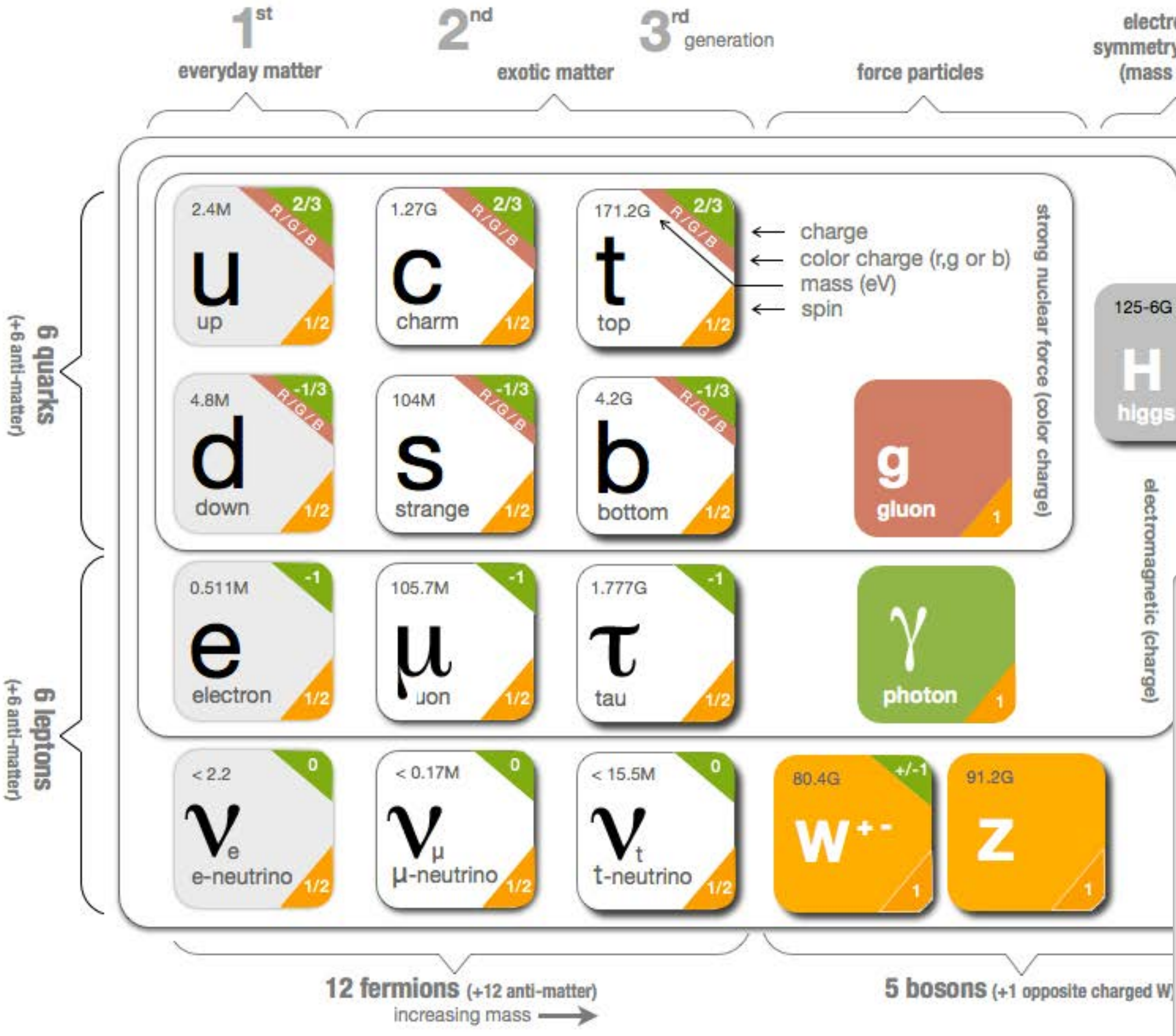
- Hybrid Cherenkov/ scintillation detector
- Multi-messenger astrophysics
- Probe the fundamental nature of matter: CPV and Majorana ν
- Unique opportunity to engage a broad community in world-leading “big science”



Overview

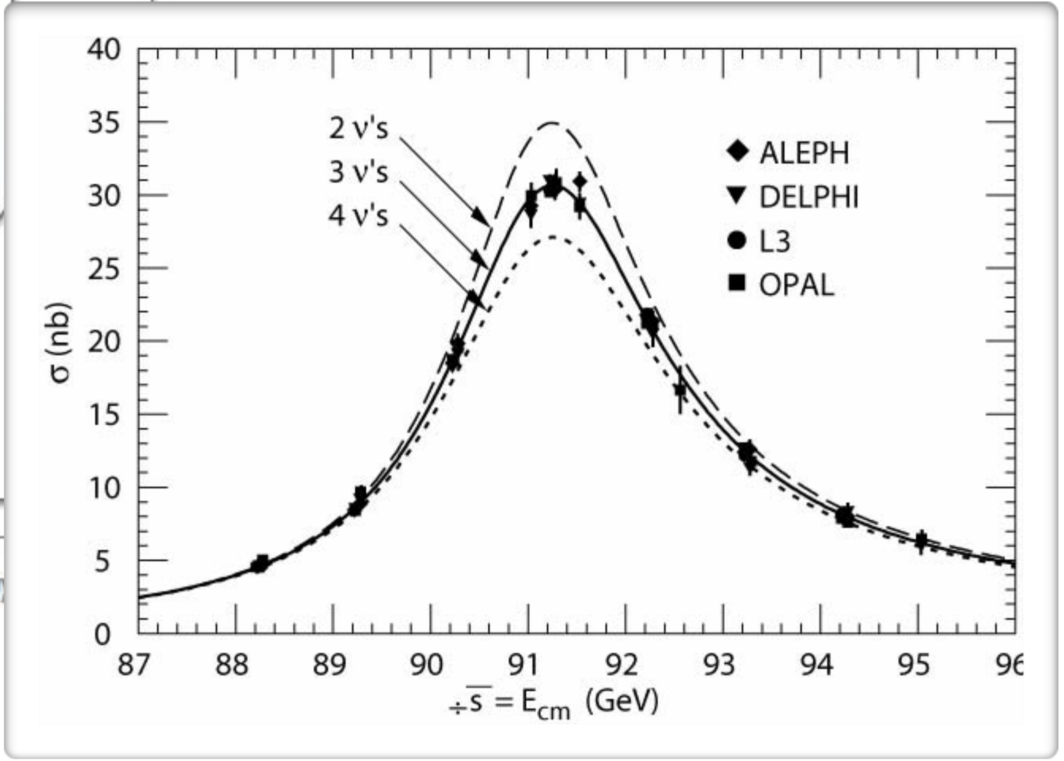
- Introduction to neutrinos
- Neutrino oscillation: *water Cherenkov detectors*
- Open questions: *liquid scintillator detectors*
- Next-generation sensitivity: *hybrid detectors*
  - *Physics reach*
  - *Technology development*

Standard Model Neutrinos

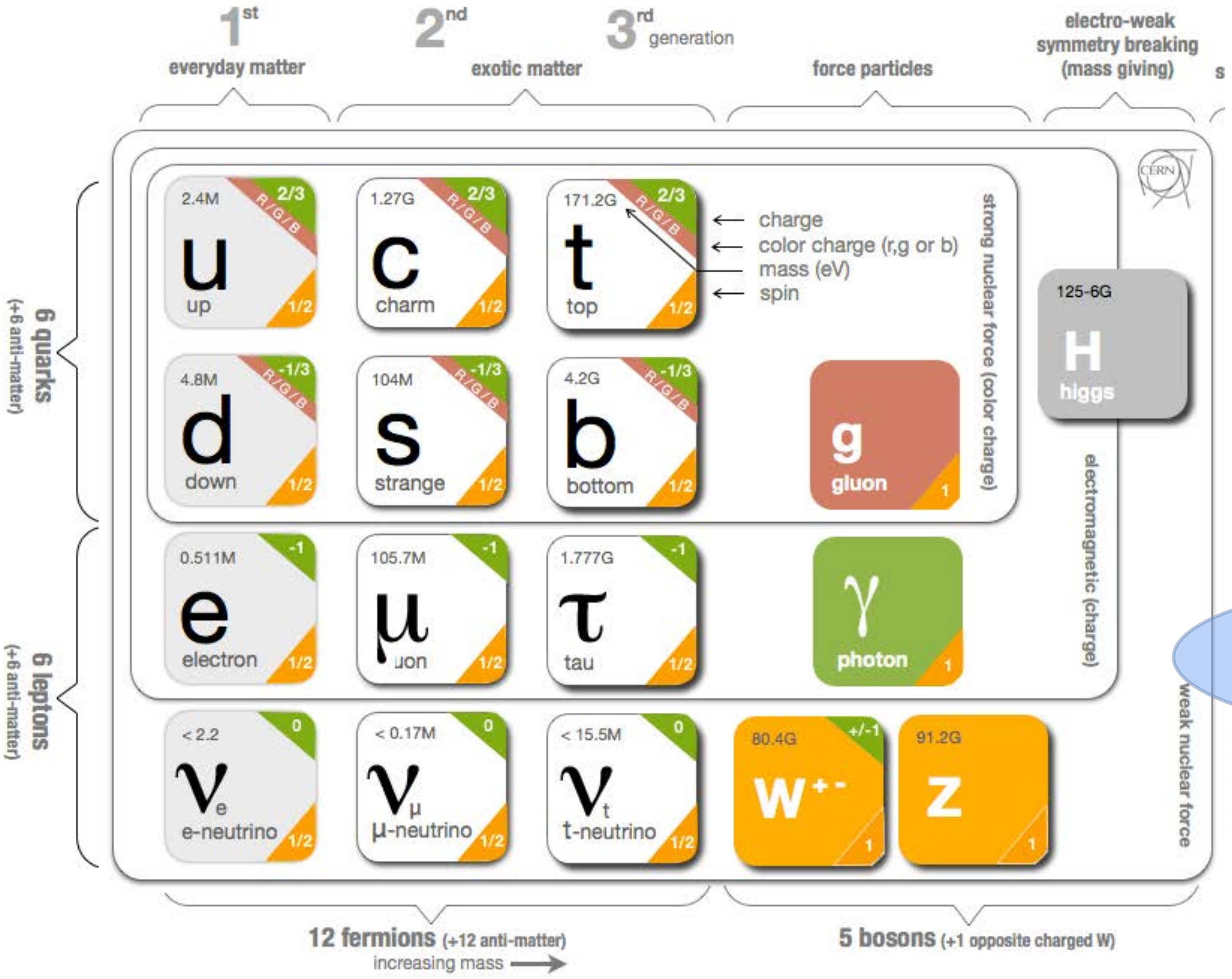


Neutrino properties:

1. Interact weakly
2. Very tiny masses
3. Three flavours



Standard Model Neutrinos



Neutrino properties:

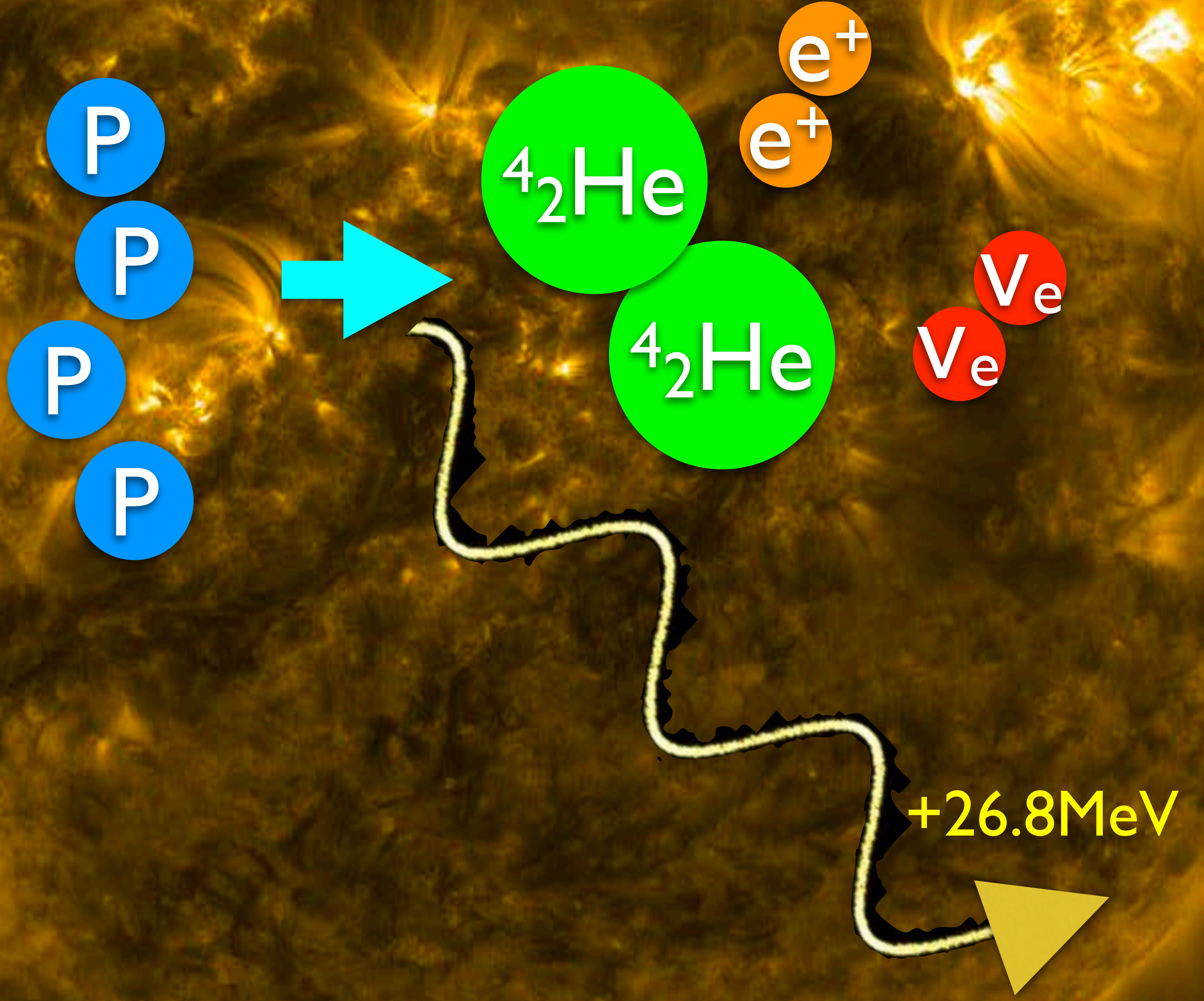
1. Interact weakly
2. Very tiny masses
3. Three flavours

ν_e - The Sun, nuclear reactors

ν_μ - Cosmic rays, man-made

ν_τ - Man-made beams
First observation in 2000

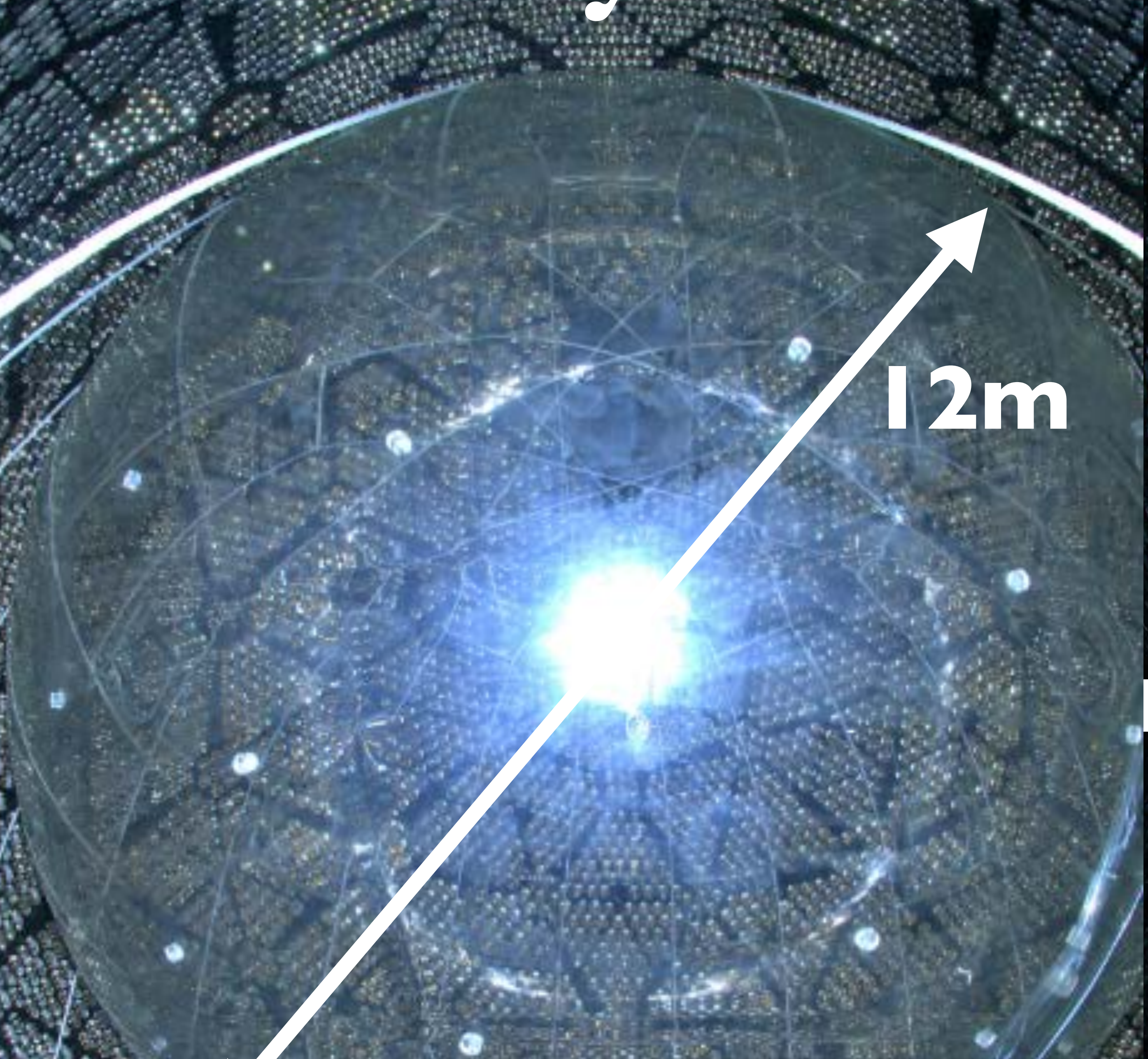
How Does the Sun Shine?



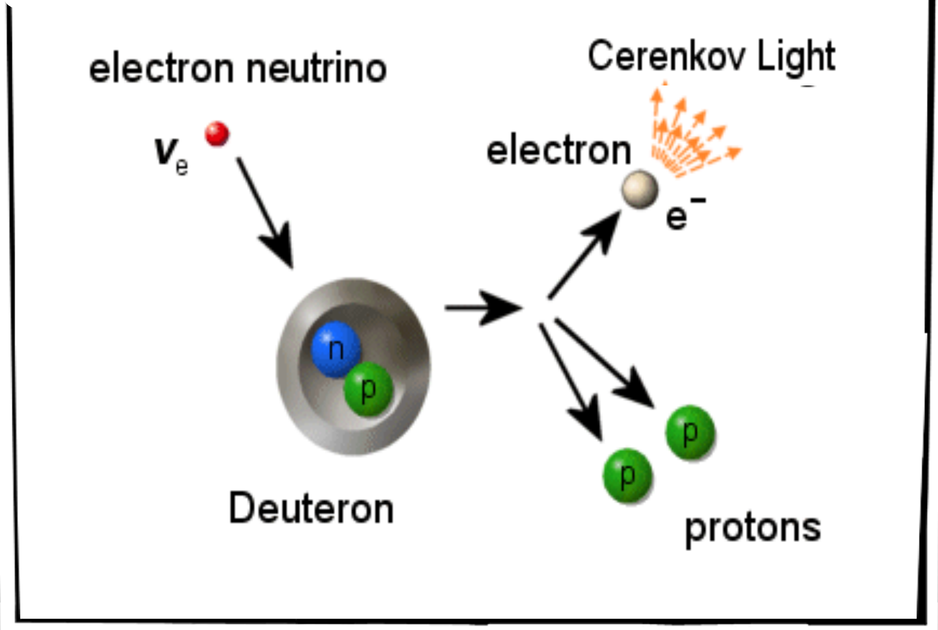
Nuclear fusion reactions in the core produce:

- Helium
- Energy (heat, light)
- Neutrinos

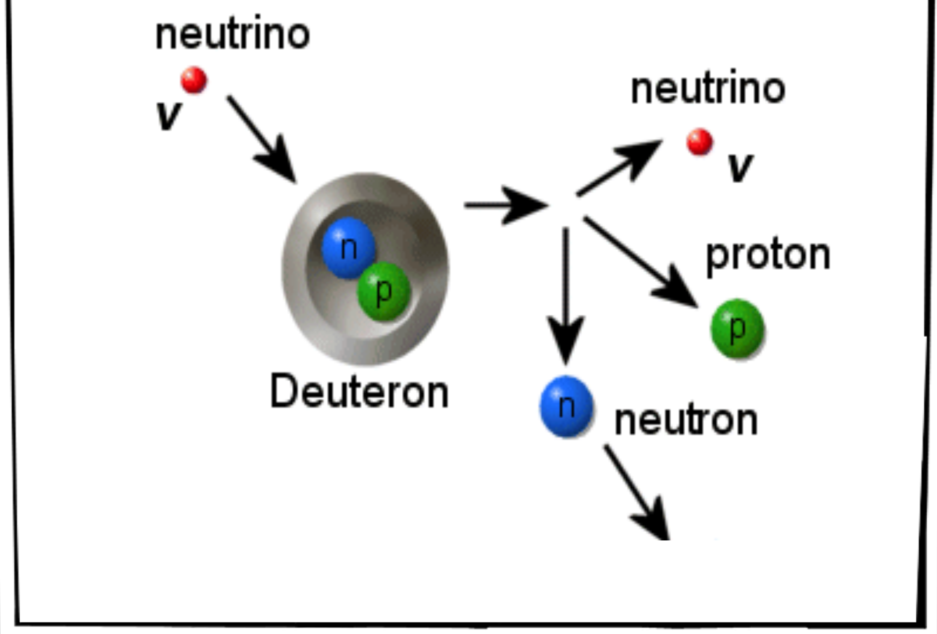
Sudbury Neutrino Observatory



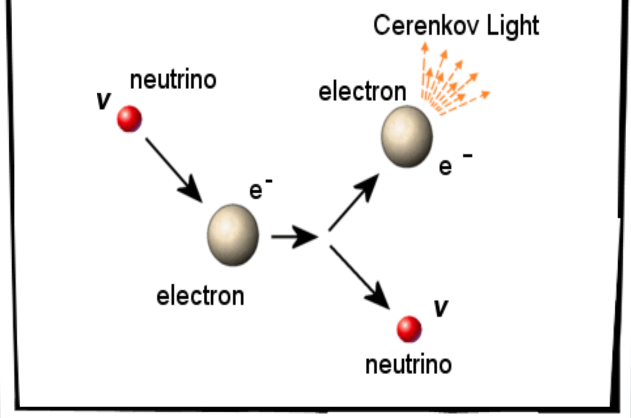
Charged Current (CC)



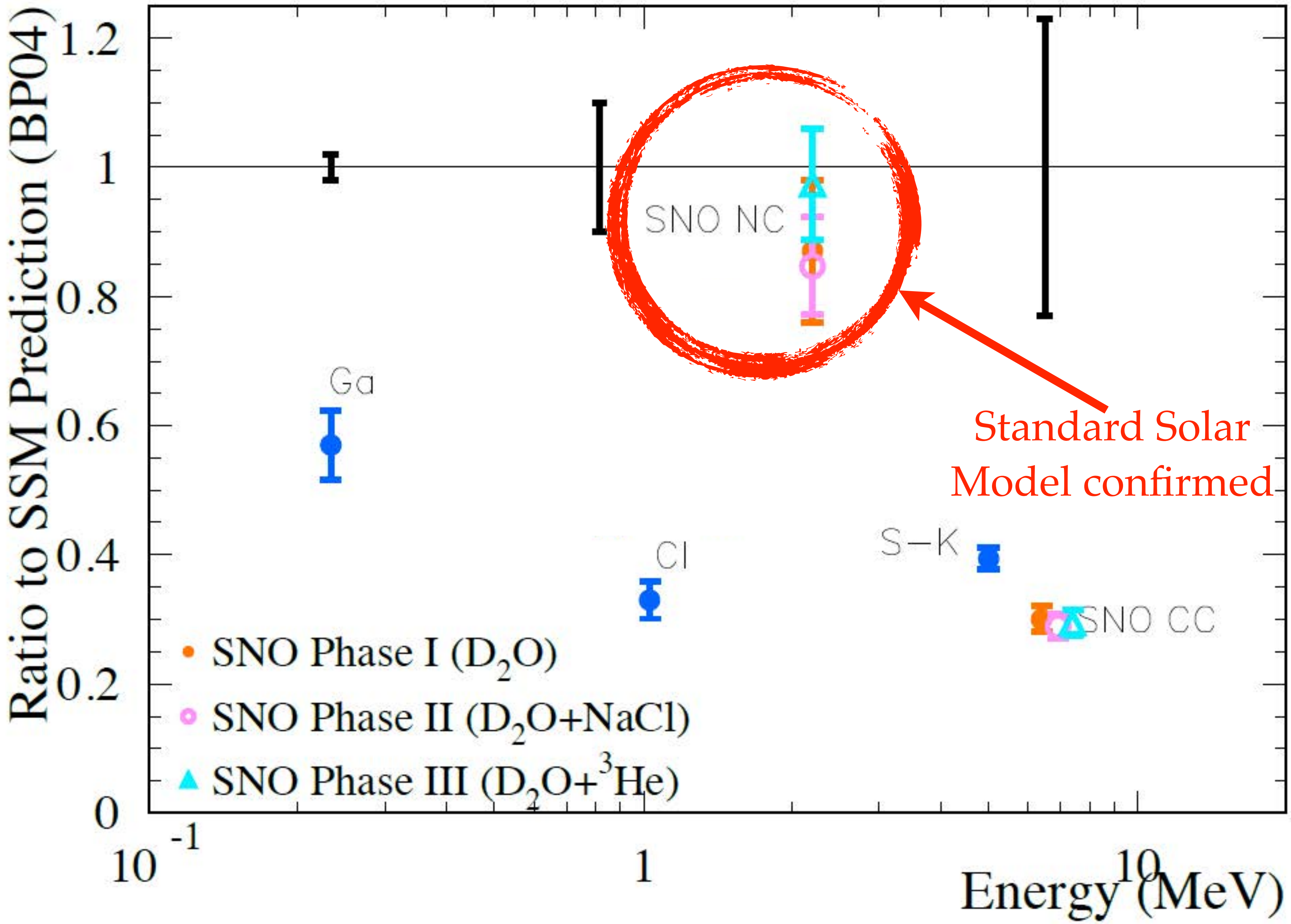
Neutral Current (NC)



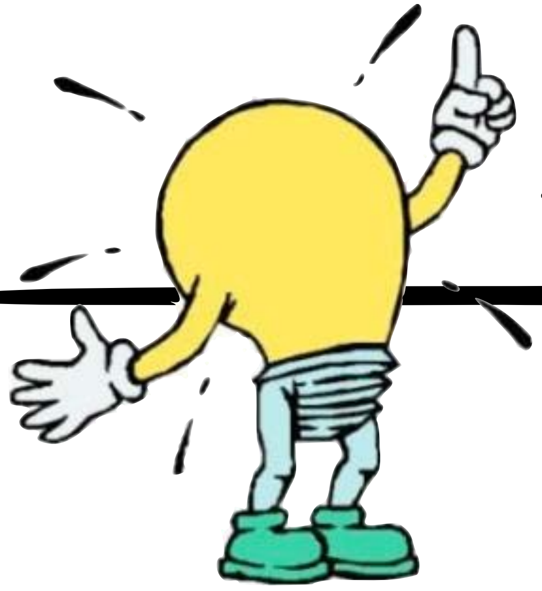
Elastic Scattering (ES)



Solar Neutrino Problem Resolved



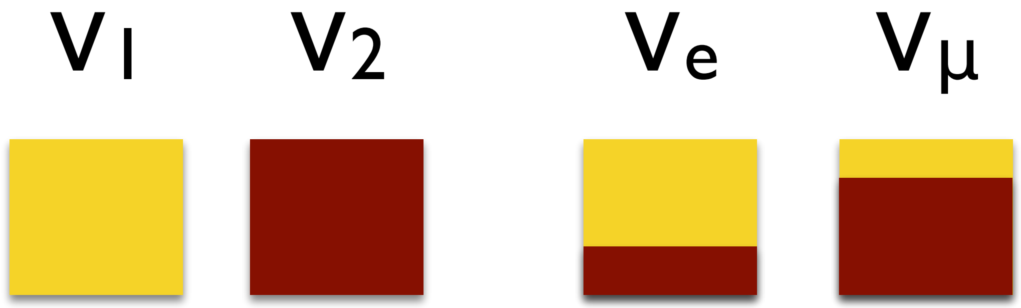
Standard Solar Model confirmed

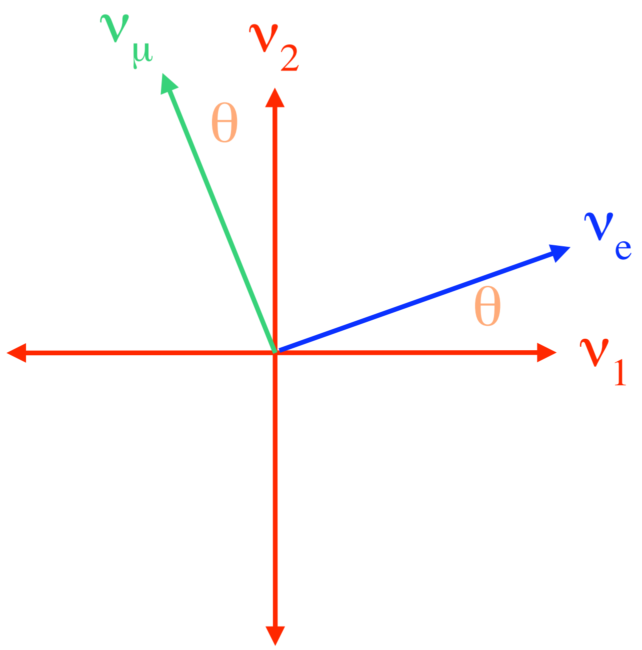


Neutrino Oscillation

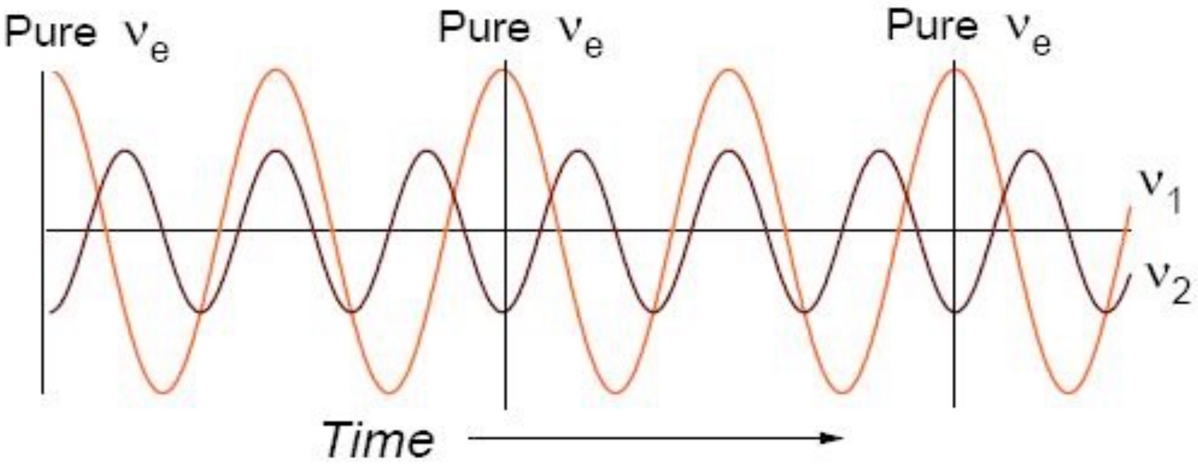
Produced as weak (flavour) eigenstates (ν_e, ν_μ, ν_τ)
Propagate as physical (mass) eigenstates (ν_1, ν_2, ν_3)

Simplified 2-neutrino scenario:





$$P_{\nu_e \to \nu_x} = \sin^2 2\theta \sin^2 \left(\frac{1.27 \Delta m^2 L}{E_\nu} \right)$$



$$\begin{bmatrix} \nu_e \\ \nu_\mu \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \end{bmatrix}$$

$\Delta m^2 = m_2^2 - m_1^2$: requires non-zero neutrino mass!

2015 Nobel Prize in Physics

SuperK

SNO

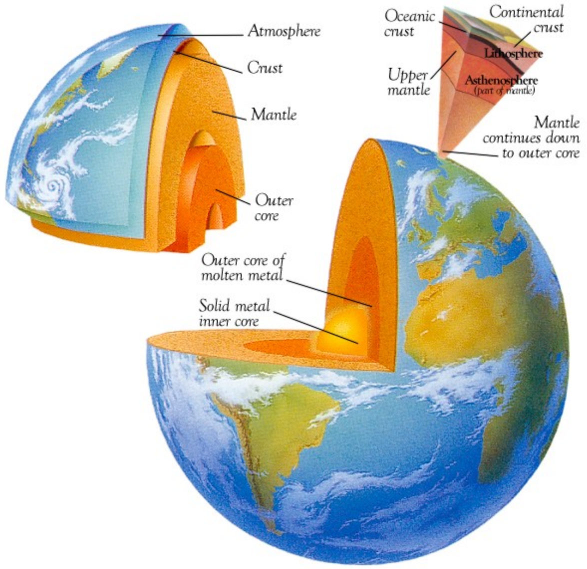
Takaaki Kajita

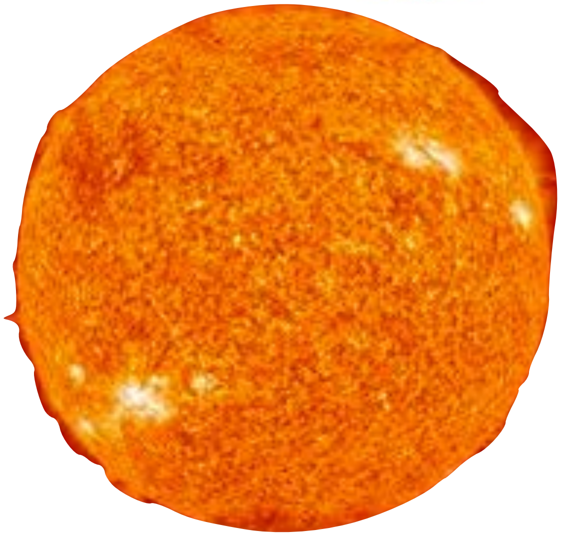
Arthur B. McDonald

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass"

Neutrinos 101: Why do we (still) study them?

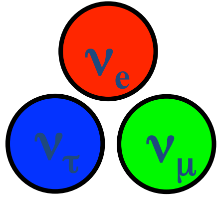
Unique probe of otherwise unreachable regions

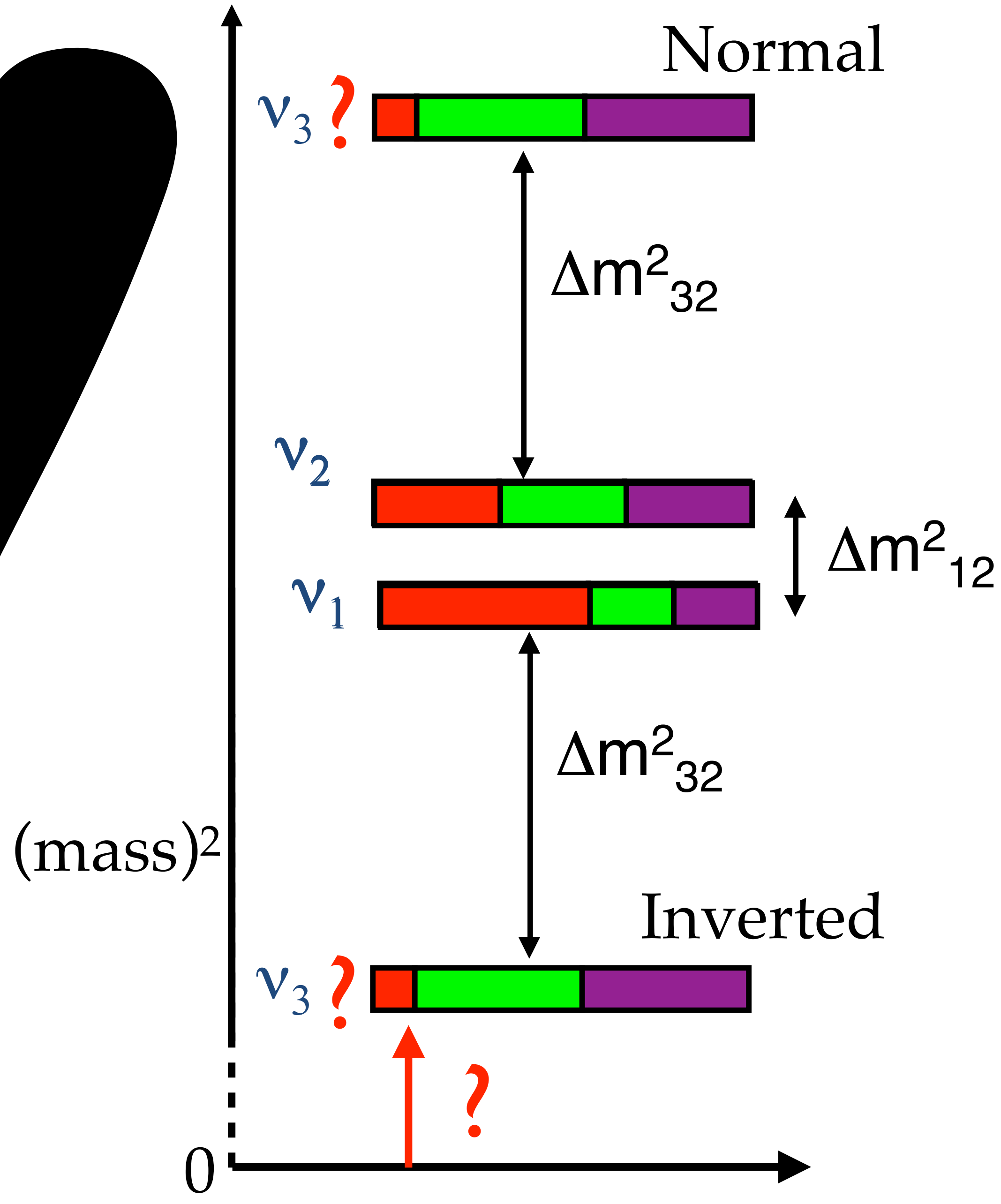


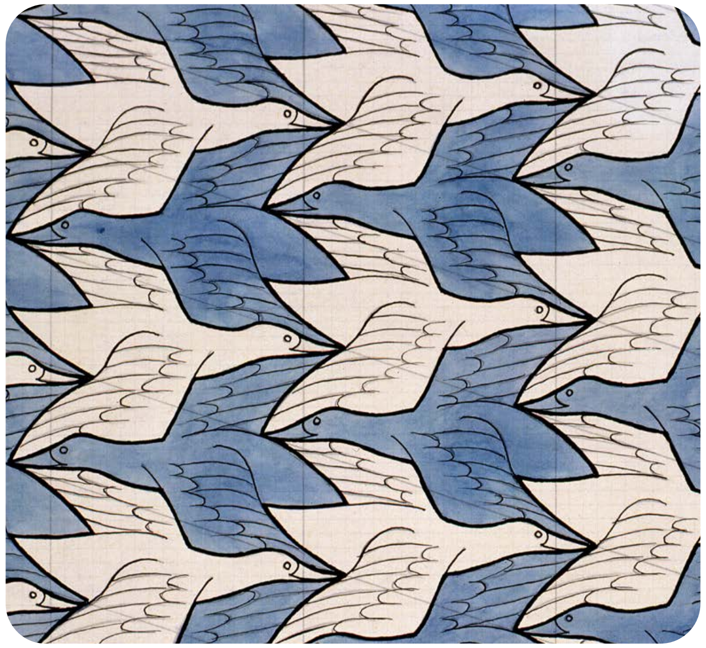


ν

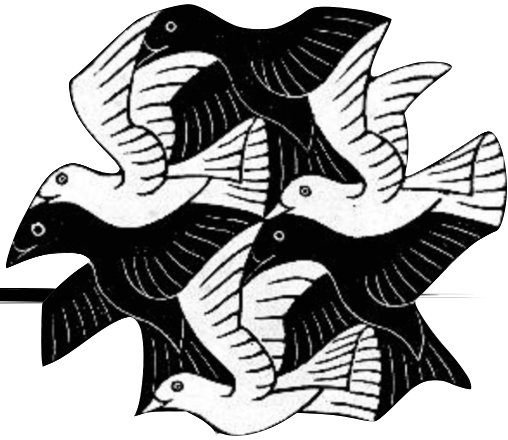
Fascinating particle in its own right







Majorana Neutrinos

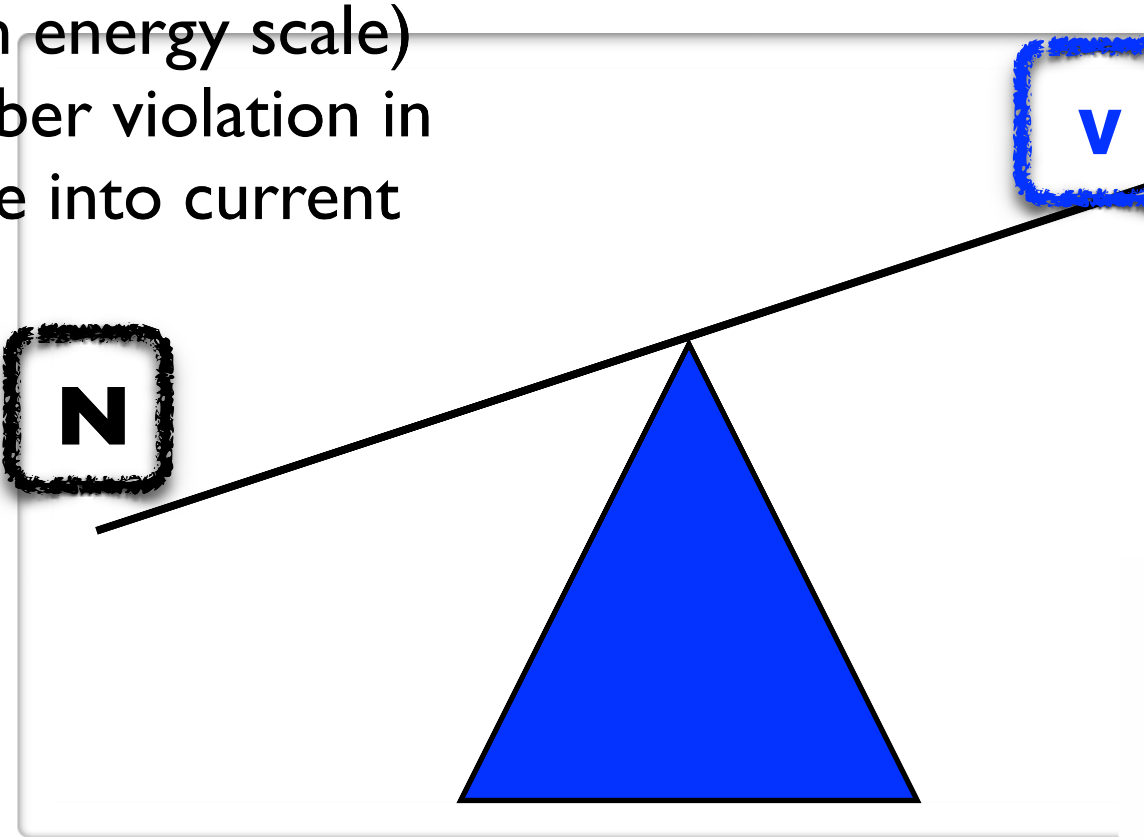


M.C. Escher

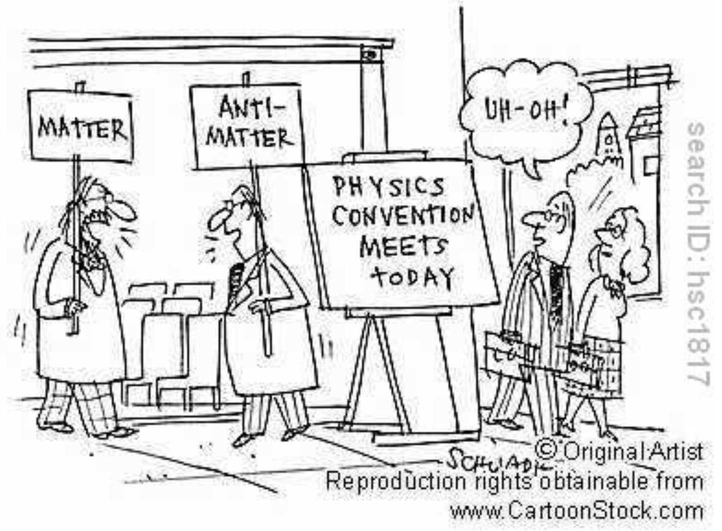
Can undergo the “See-Saw” mechanism

A big Majorana mass splits the Dirac neutrino into two neutrinos: the light neutrino **ν** and a heavy neutrino **N**

Made in the Big Bang (high energy scale) CP violation + lepton number violation in their decay could translate into current asymmetry

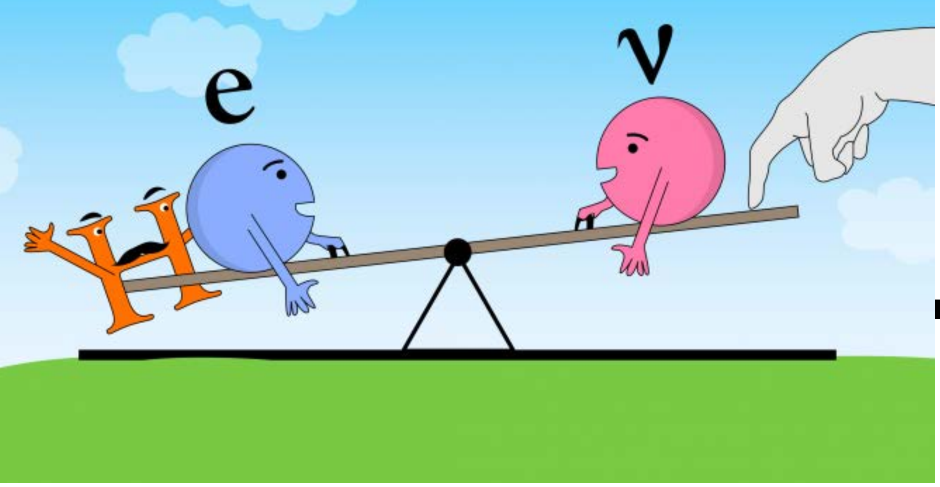


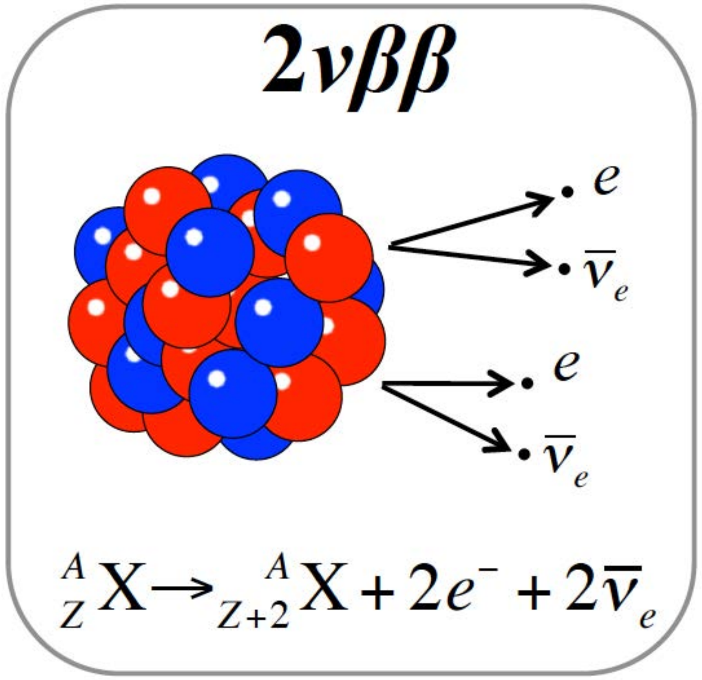
Our familiar light ν, made and detected in terrestrial experiments



http://www.research.vt.edu/resmag/sciencecol/2002asymmetry.html

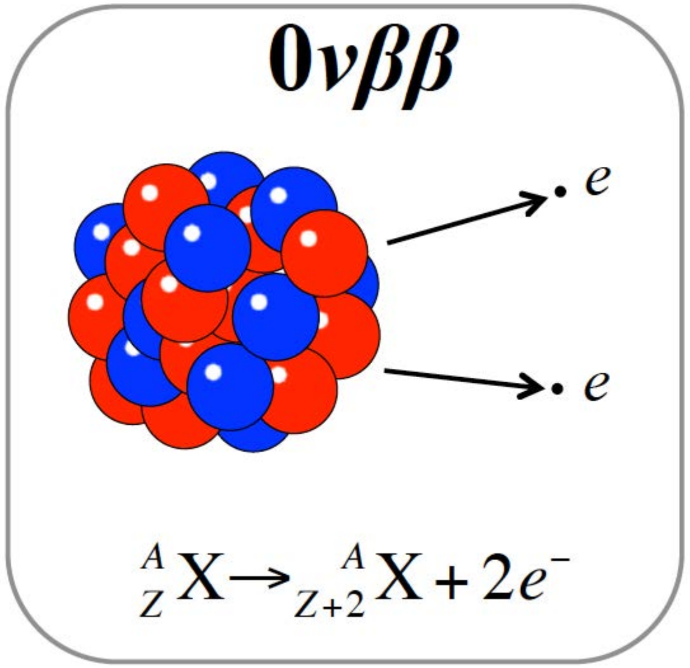
0ν double beta decay





$${}^{A}_{Z}X \rightarrow {}^{A}_{Z+2}X + 2e^{-} + 2\bar{\nu}_e$$

$\tau \geq 10^{19}$ y

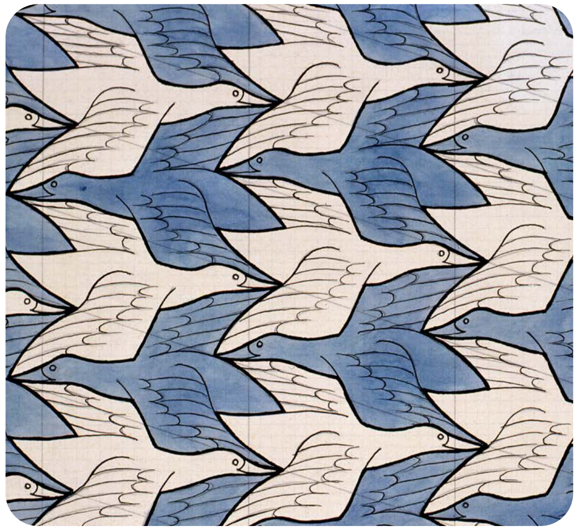


$${}^{A}_{Z}X \rightarrow {}^{A}_{Z+2}X + 2e^{-}$$

$\tau \geq 10^{26}$ y

Fortunately,
N_A is very large!

M.C. Escher

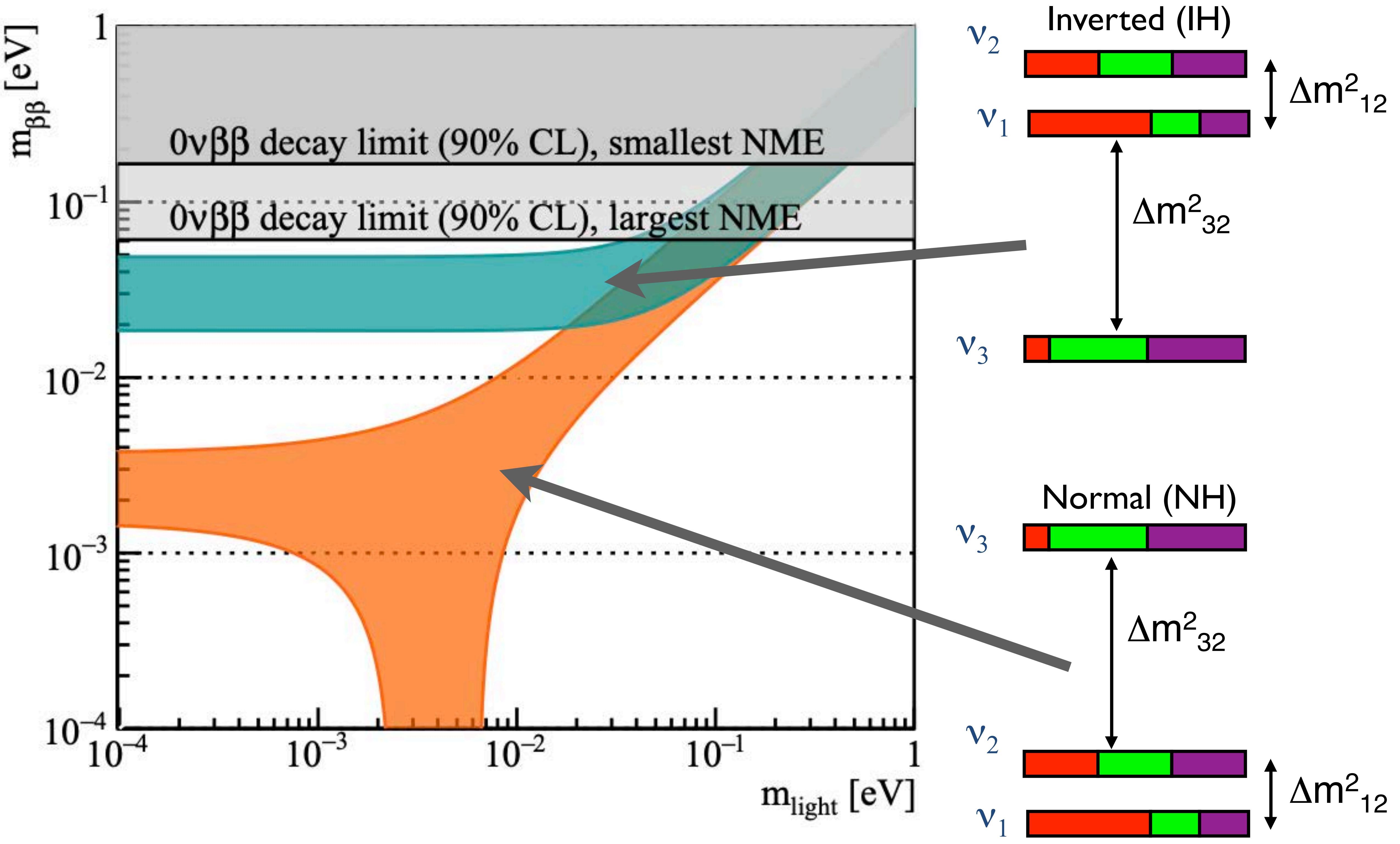


1. *Lepton number violation*
2. *Majorana nature of neutrinos*
3. *Rate measures (effective) $m_{\nu e}$*

The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE

We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.

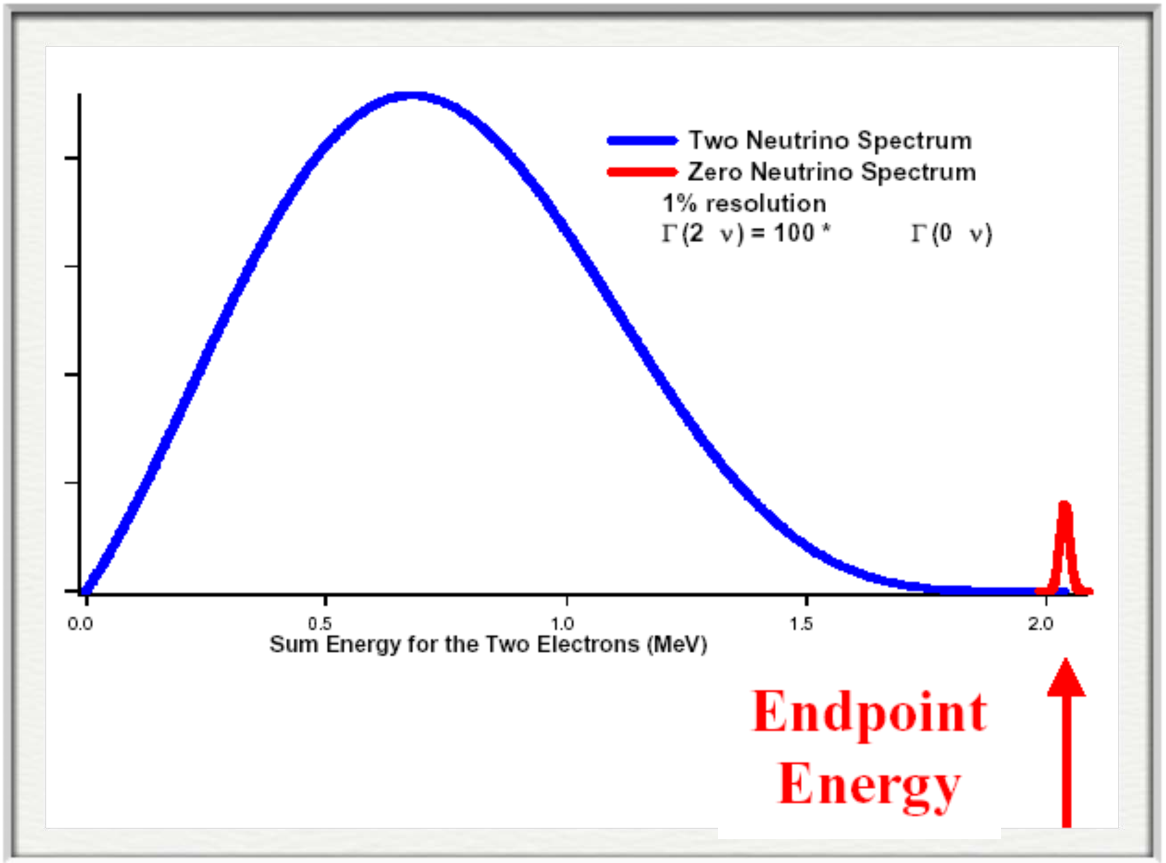
Phase space



M. Agostini et al, https://arxiv.org/abs/2202.01787

Experimental Challenges

Ultra small signal ⇒



Endpoint Energy

- Large mass (signal stats)
- Low bkg
  - Deep underground
  - Purification
  - Bkg ID methods
- Good E resolution
- Interchangeable isotopes
- Tracking

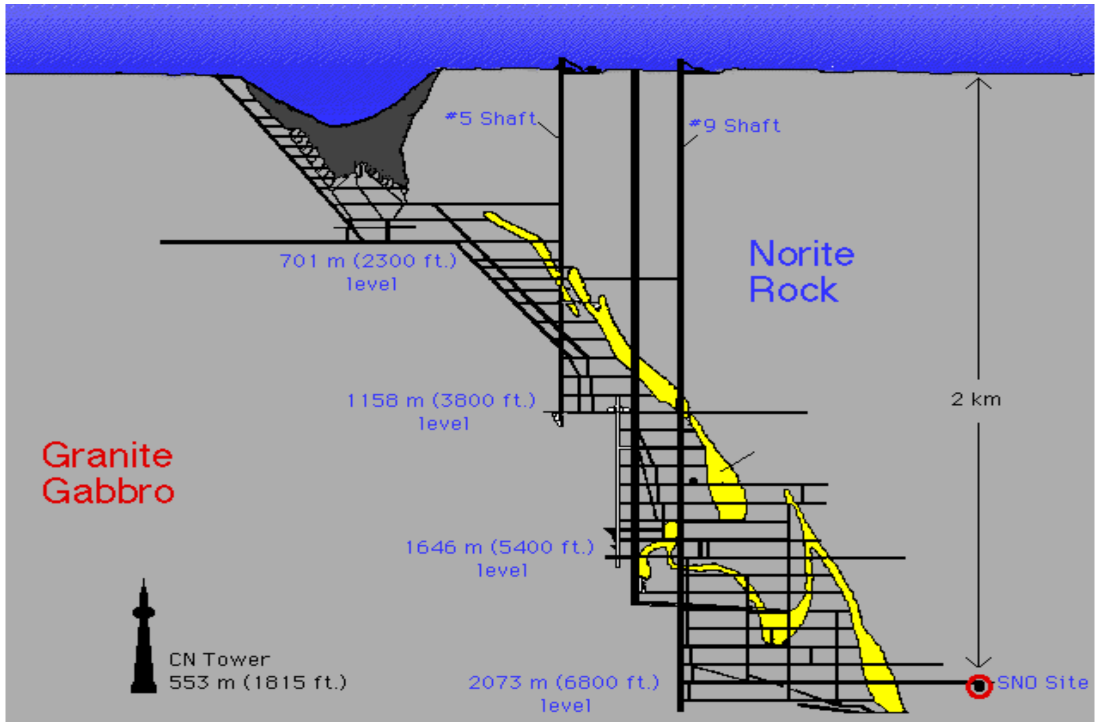
New physics: a light in dark places

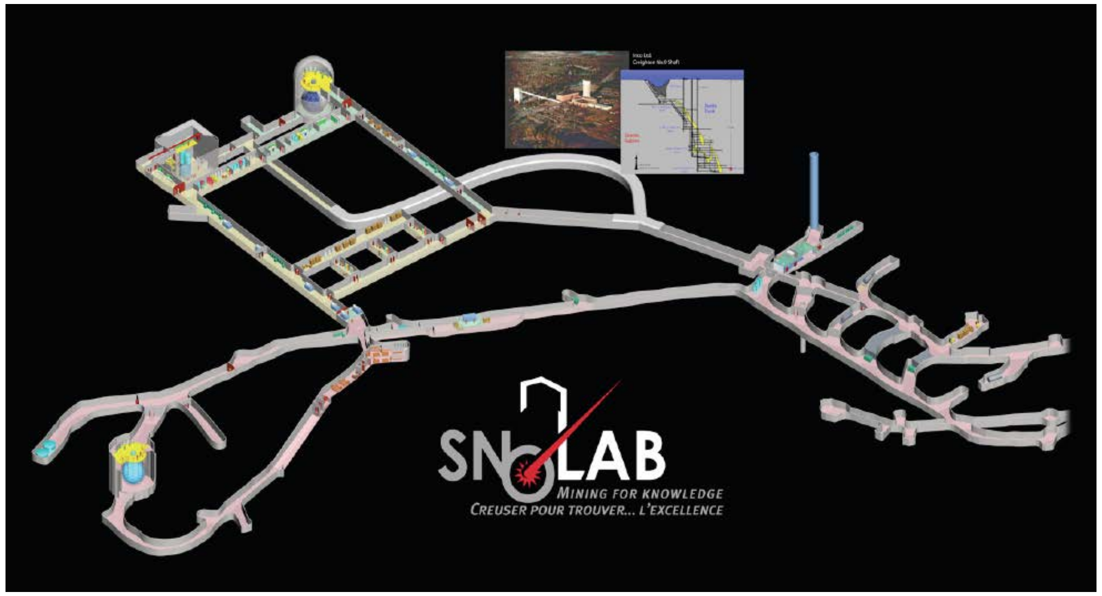
High intensity signal

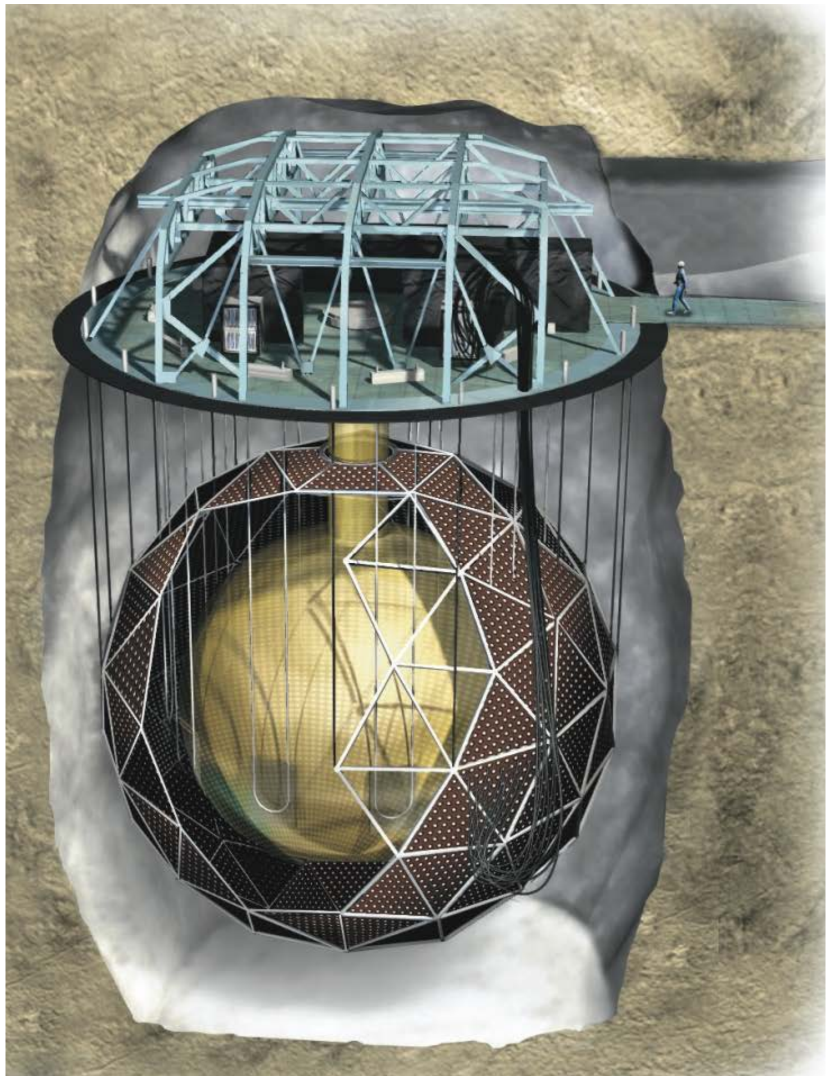
SNO ⇛ SNO+

DEEP
UNDERGROUND

Liquid scintillator
+ ^{130}Te







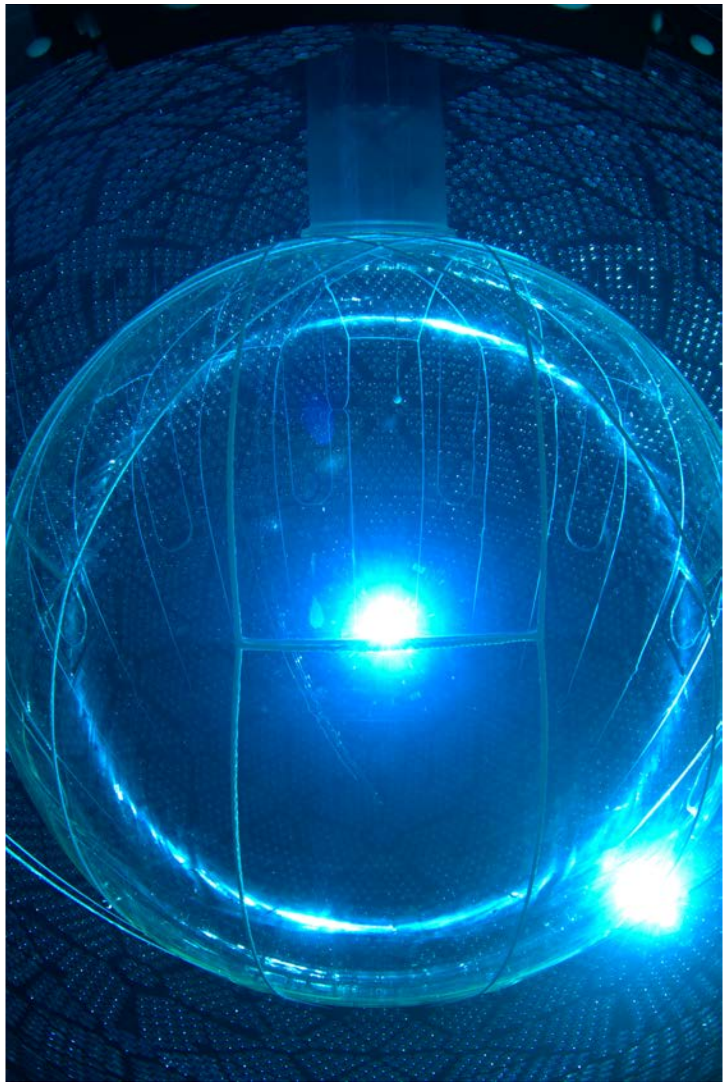
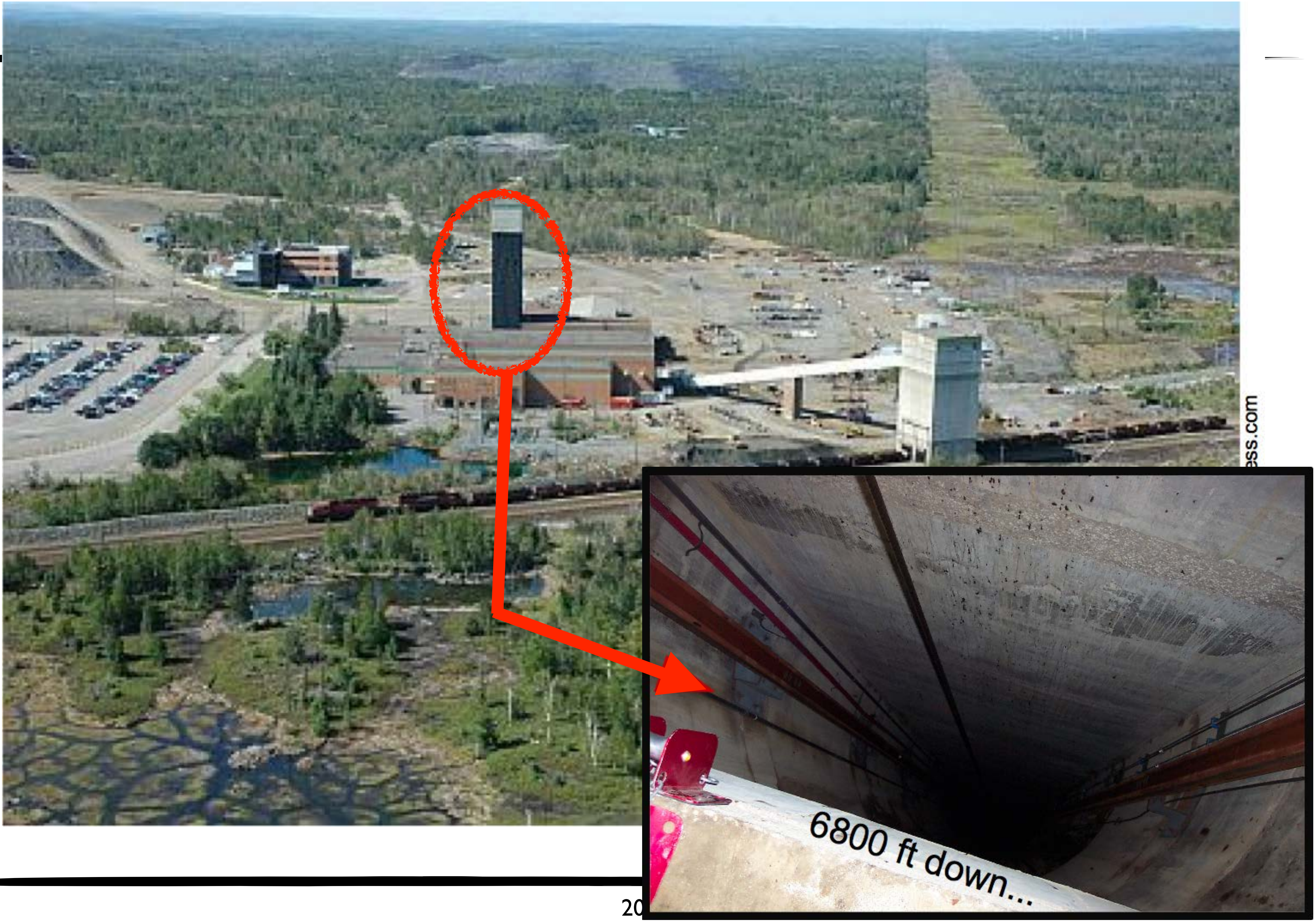


Image from www.northernontariobusiness.com

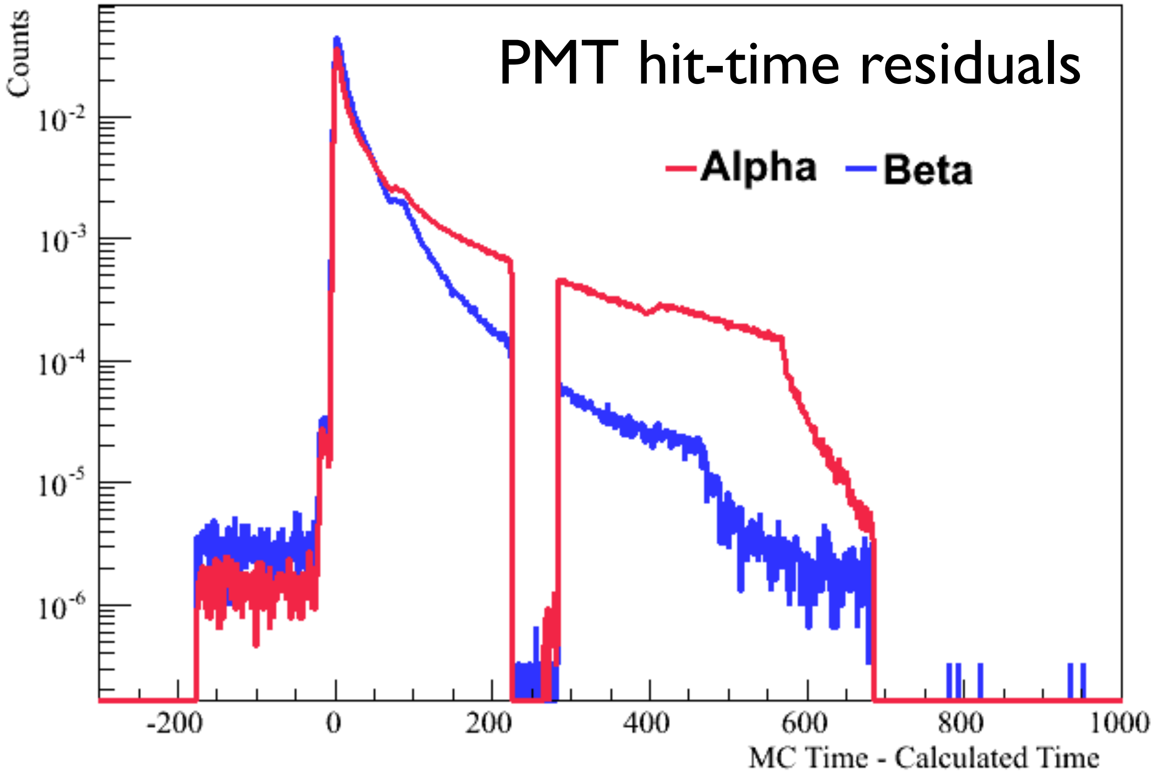


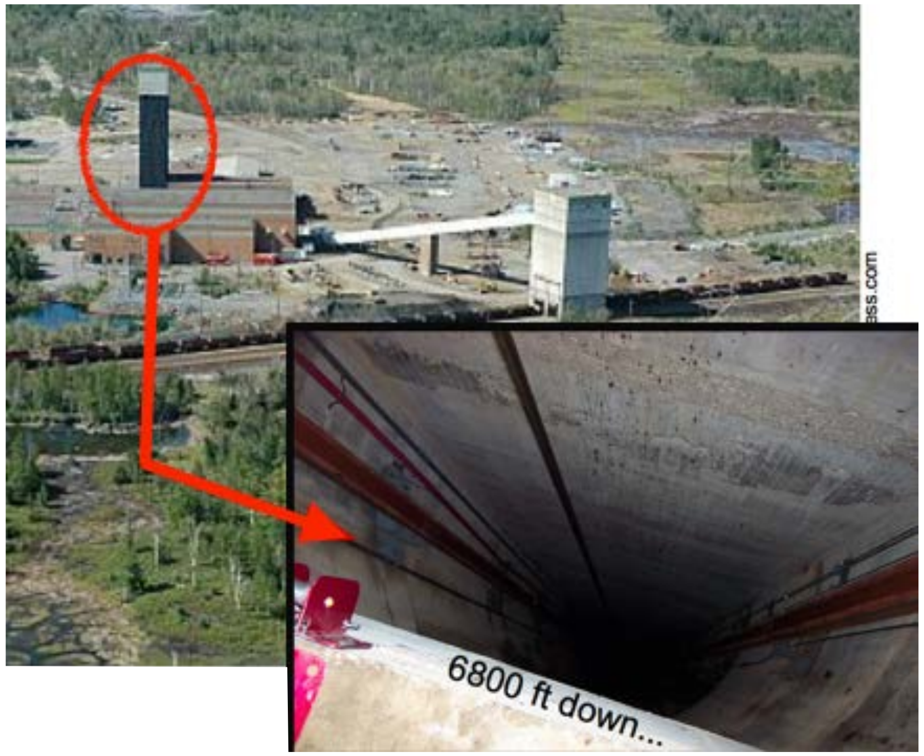
6800 ft down...

ess.com

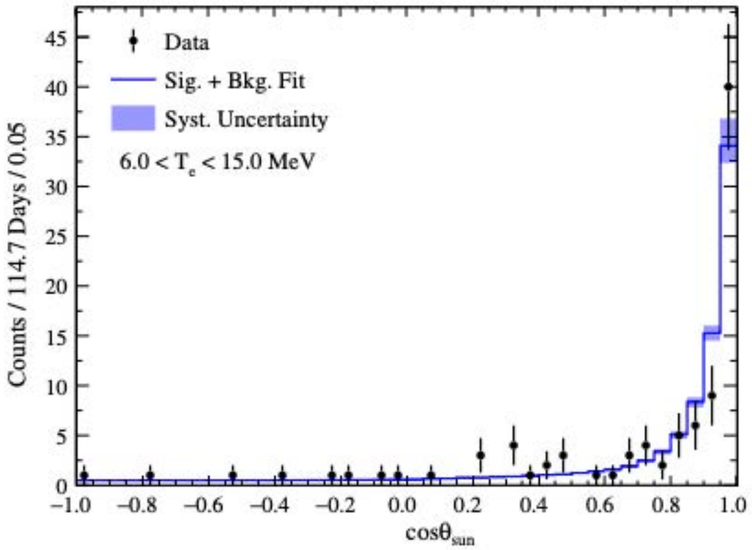
Advantages of LS approach

- Low backgrounds (dominated by ^{8}B solar neutrinos)
  - Fiducialisation ⇒ self-shielding
  - Background rejection via particle ID and coincident timing
  - Deep location (6000 m.w.e.)
- High detection efficiency
- Source in / out calibration
- Large target mass, easy scaling
- *Bonus: broad program includes solar, geo, reactor, supernova* ν *& nucleon decay*





SNO+ physics results

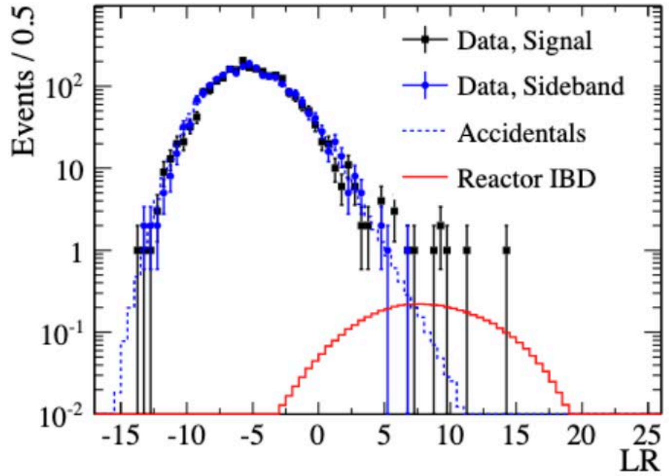


Measurement of 8B solar ν flux with very low backgrounds: 0.25 +0.09/-0.07 ev/kt-day

$$\Phi_{^8\mathrm{B}} = 5.95^{+0.75}_{-0.71}(\mathrm{stat})^{+0.28}_{-0.30}(\mathrm{syst}) \times 10^6\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

Phys. Rev. D ***99*** *012012 (2019)*

Evidence of antineutrinos from distant reactors using pure water at SNO+

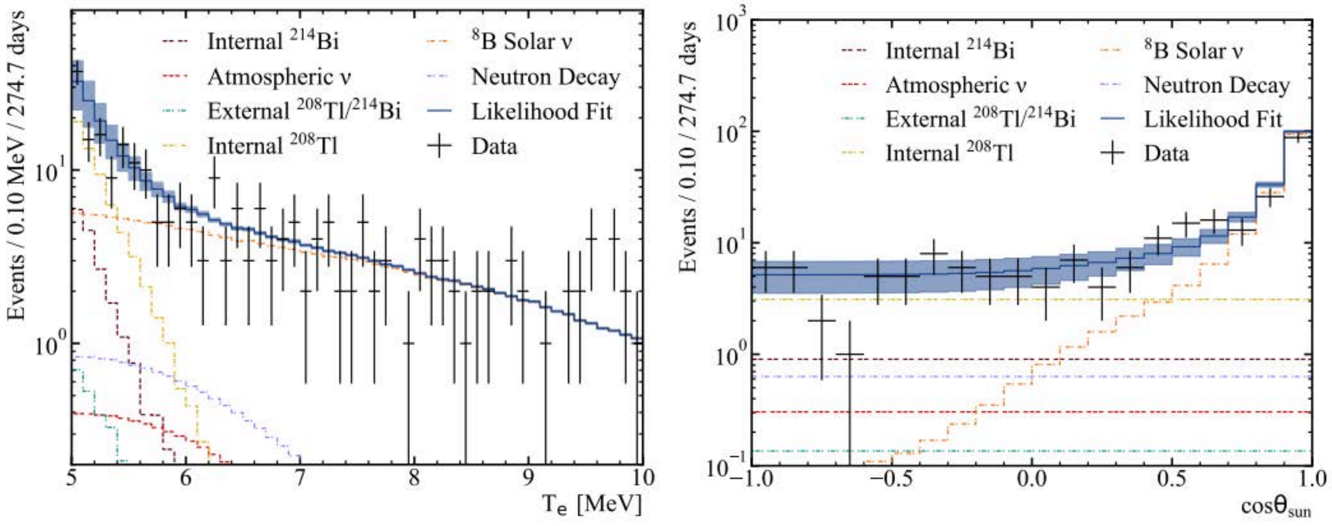


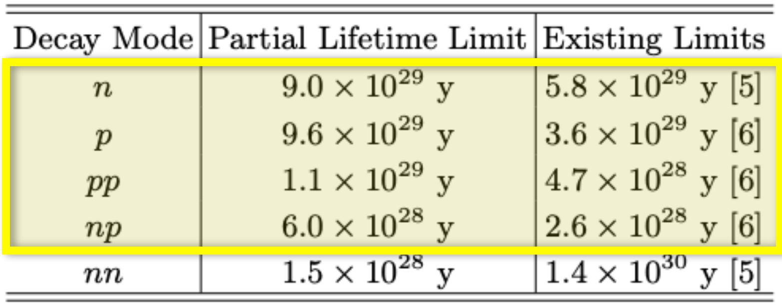
Collaboration, SNO+, et al. "Observation of Antineutrinos from Distant Reactors using Pure Water at SNO+." *arXiv preprint arXiv:2210.14154* (2022).

PRL ***130*** *091801 (2023)*

Searches for invisible modes of nucleon decay via observable de-excitation γs

Phys. Rev. D ***105*** *112012 (2022)*





Decay Mode	Partial Lifetime Limit	Existing Limits
n	9.0×10^{29} y	5.8×10^{29} y [5]
p	9.6×10^{29} y	3.6×10^{29} y [6]
pp	1.1×10^{29} y	4.7×10^{28} y [6]
np	6.0×10^{28} y	2.6×10^{28} y [6]
nn	1.5×10^{28} y	1.4×10^{30} y [5]

SNO+ sensitivity

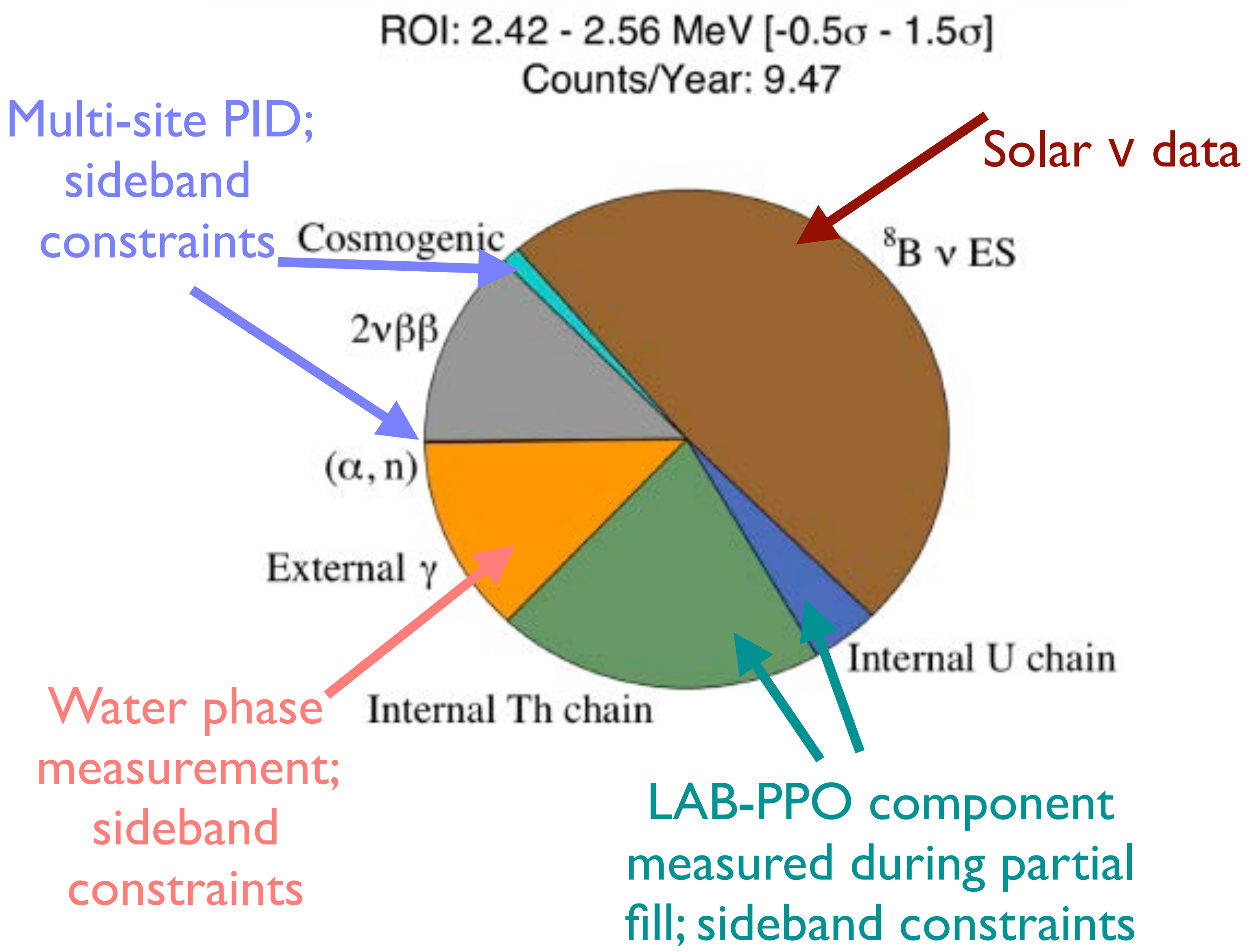
Detector configuration:

0.5% natural Te

5 years live time

Ex-situ optics (Penn/BNL)

3.3m fiducial volume (20%)

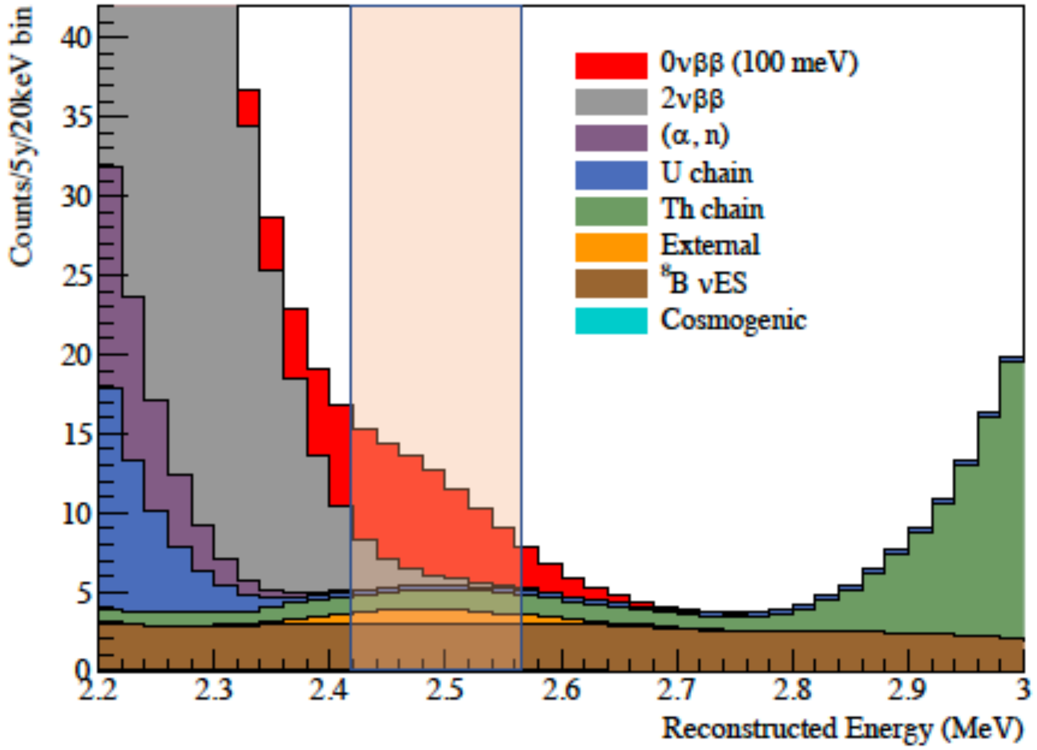


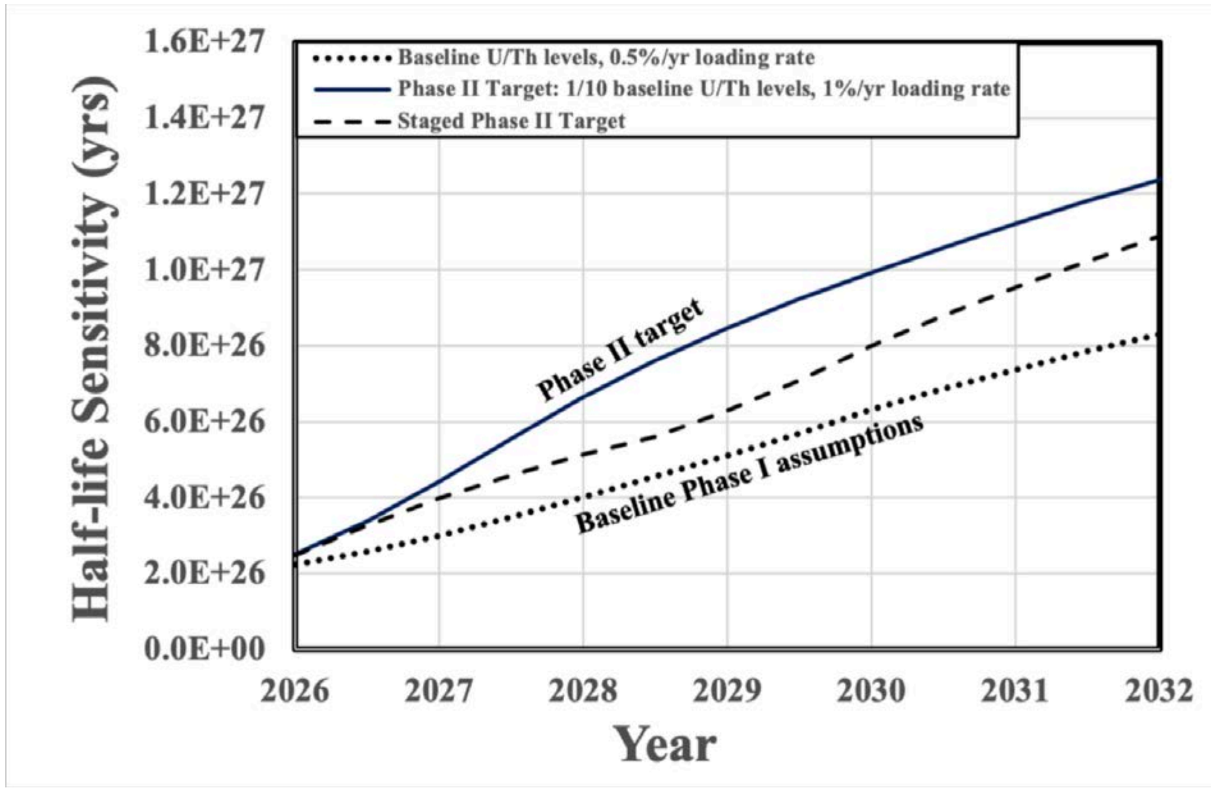
Multi-site PID; sideband constraints

Solar ν data

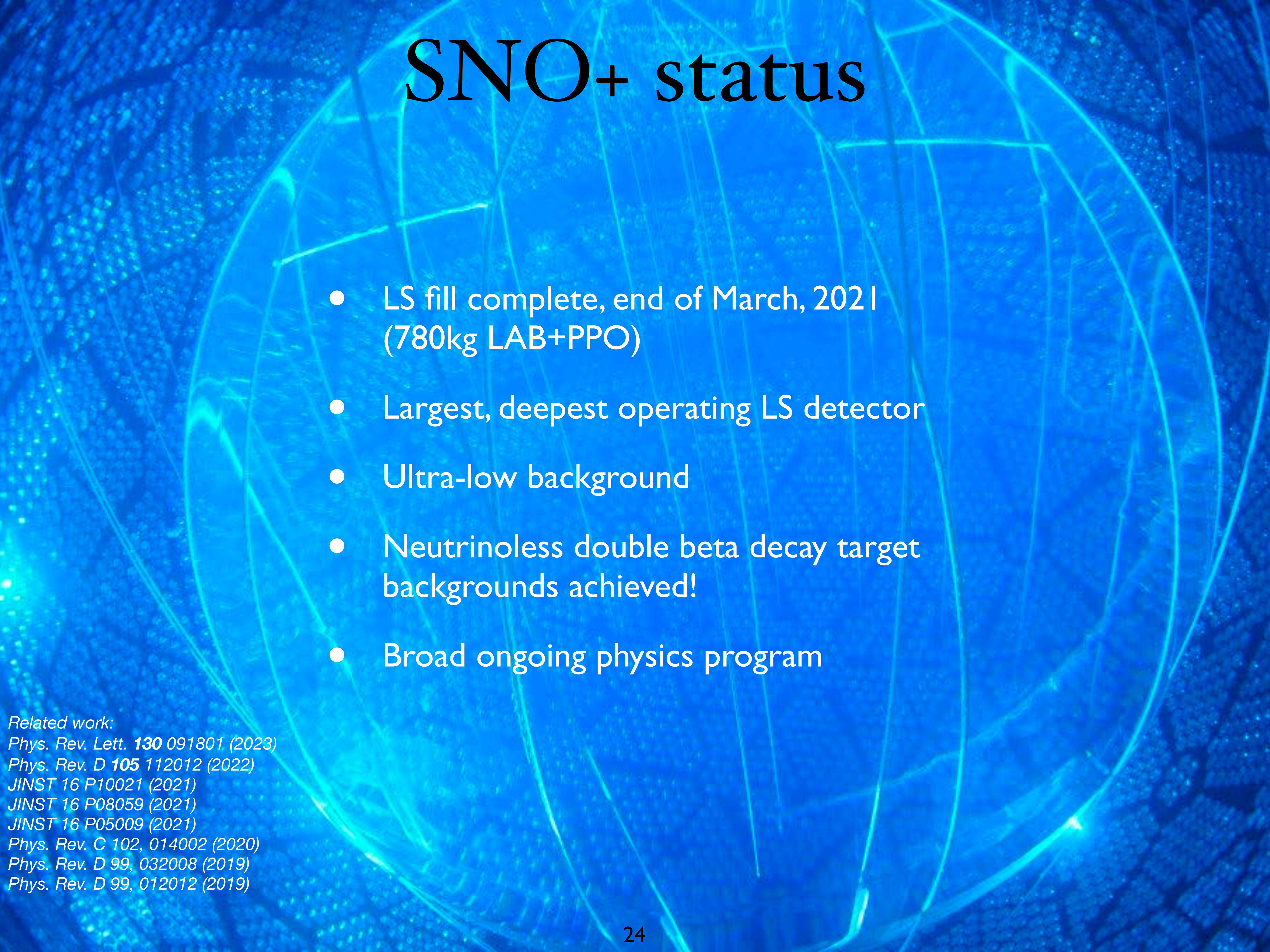
Water phase measurement; sideband constraints

LAB-PPO component measured during partial fill; sideband constraints



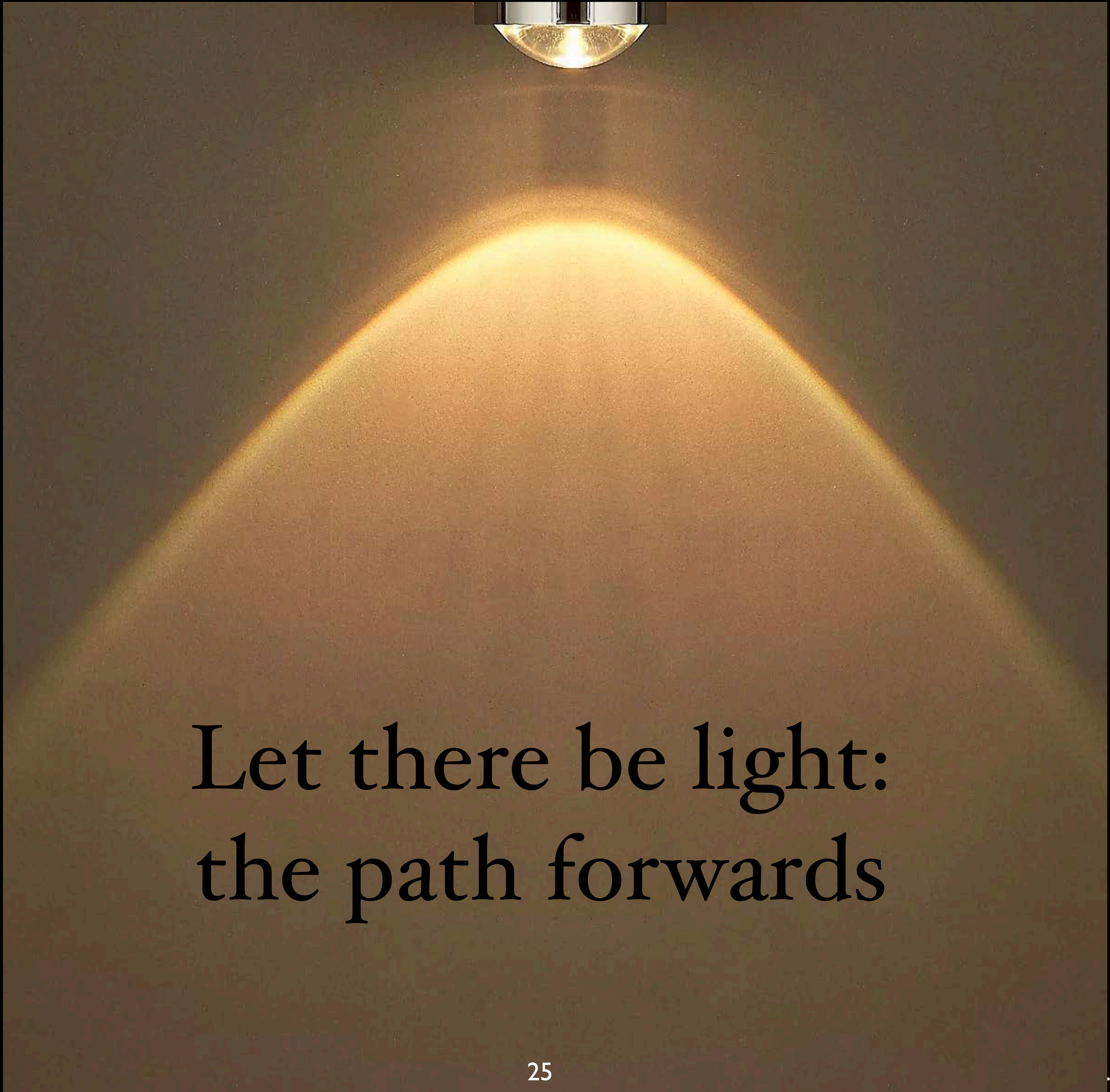


SNO+ status



- LS fill complete, end of March, 2021 (780kg LAB+PPO)
- Largest, deepest operating LS detector
- Ultra-low background
- Neutrinoless double beta decay target backgrounds achieved!
- Broad ongoing physics program

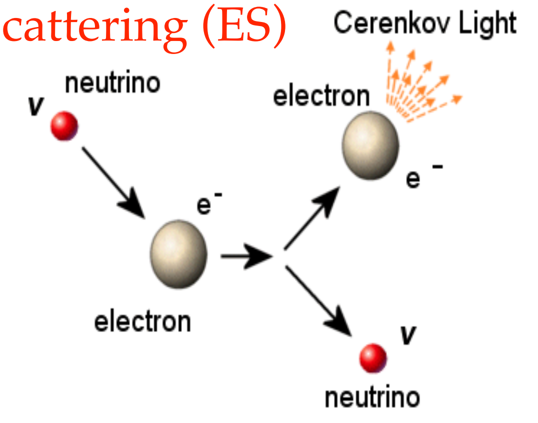
Related work:
Phys. Rev. Lett. ***130*** *091801 (2023)*
Phys. Rev. D ***105*** *112012 (2022)*
JINST 16 P10021 (2021)
JINST 16 P08059 (2021)
JINST 16 P05009 (2021)
Phys. Rev. C 102, 014002 (2020)
Phys. Rev. D 99, 032008 (2019)
Phys. Rev. D 99, 012012 (2019)



Let there be light: the path forwards

Water Cherenkov detectors

Neutrino-Electron Scattering (ES)



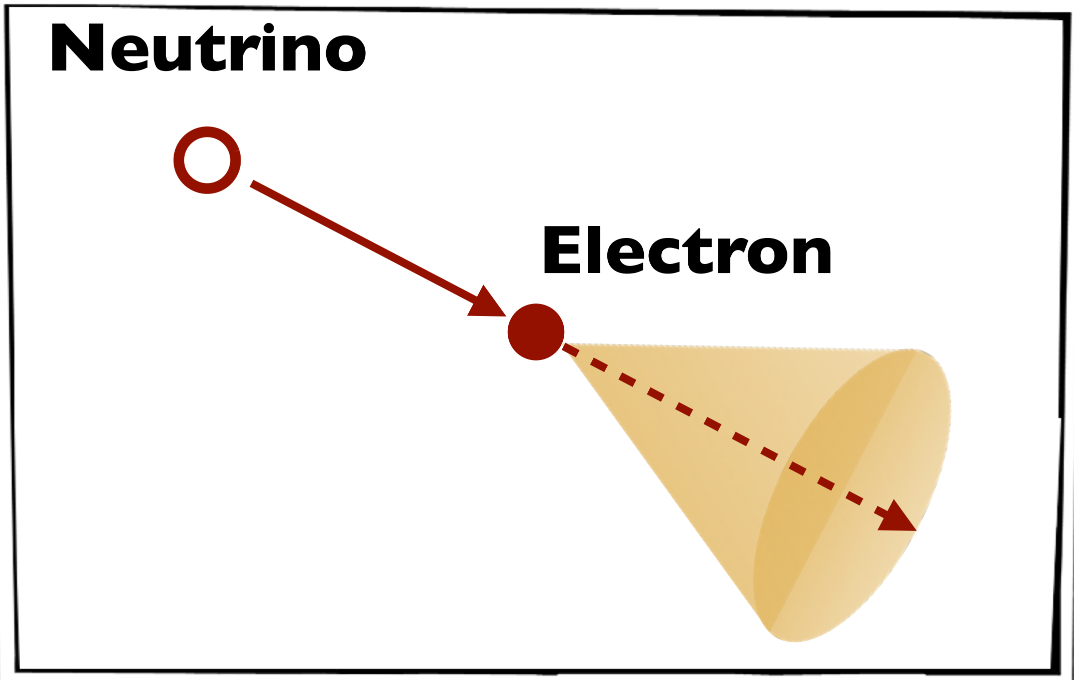
Cherenkov light

Steeply falling spectrum

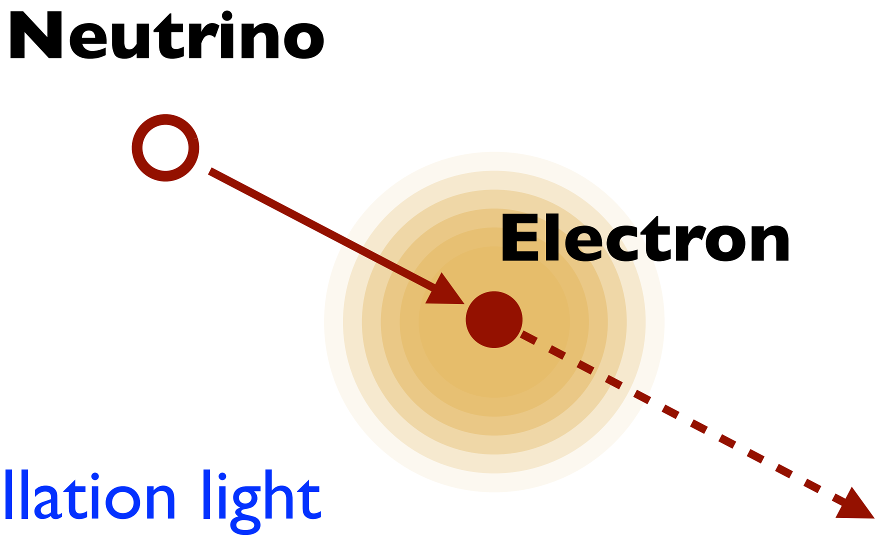
Emitted with cone-like topology

Directional information

⇒ identify event source



Scintillation detectors



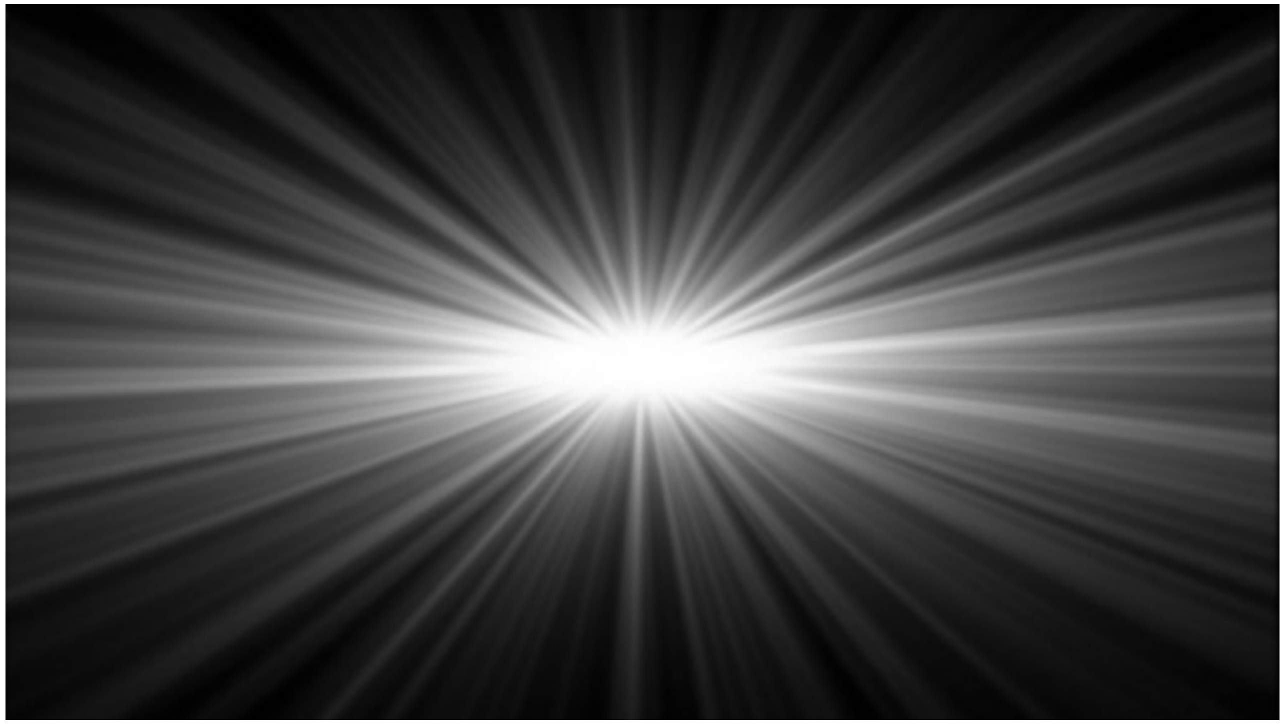
Scintillation light

Narrow-band spectrum

Emitted isotropically

Significantly higher light yield

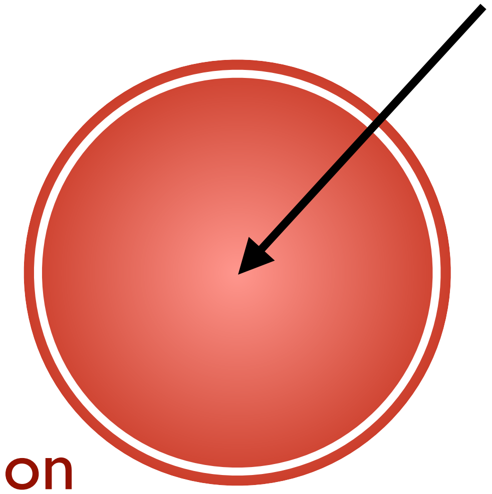
⇒ improved detector resolution



New technology: Hybrid Detectors

Cherenkov

- Cherenkov topology: directional sensitivity, particle ID
- Optical transparency: scaling



Scintillation

- High light yield: threshold, resolution
- Pulse shape discrimination: Particle ID
- Radiopure

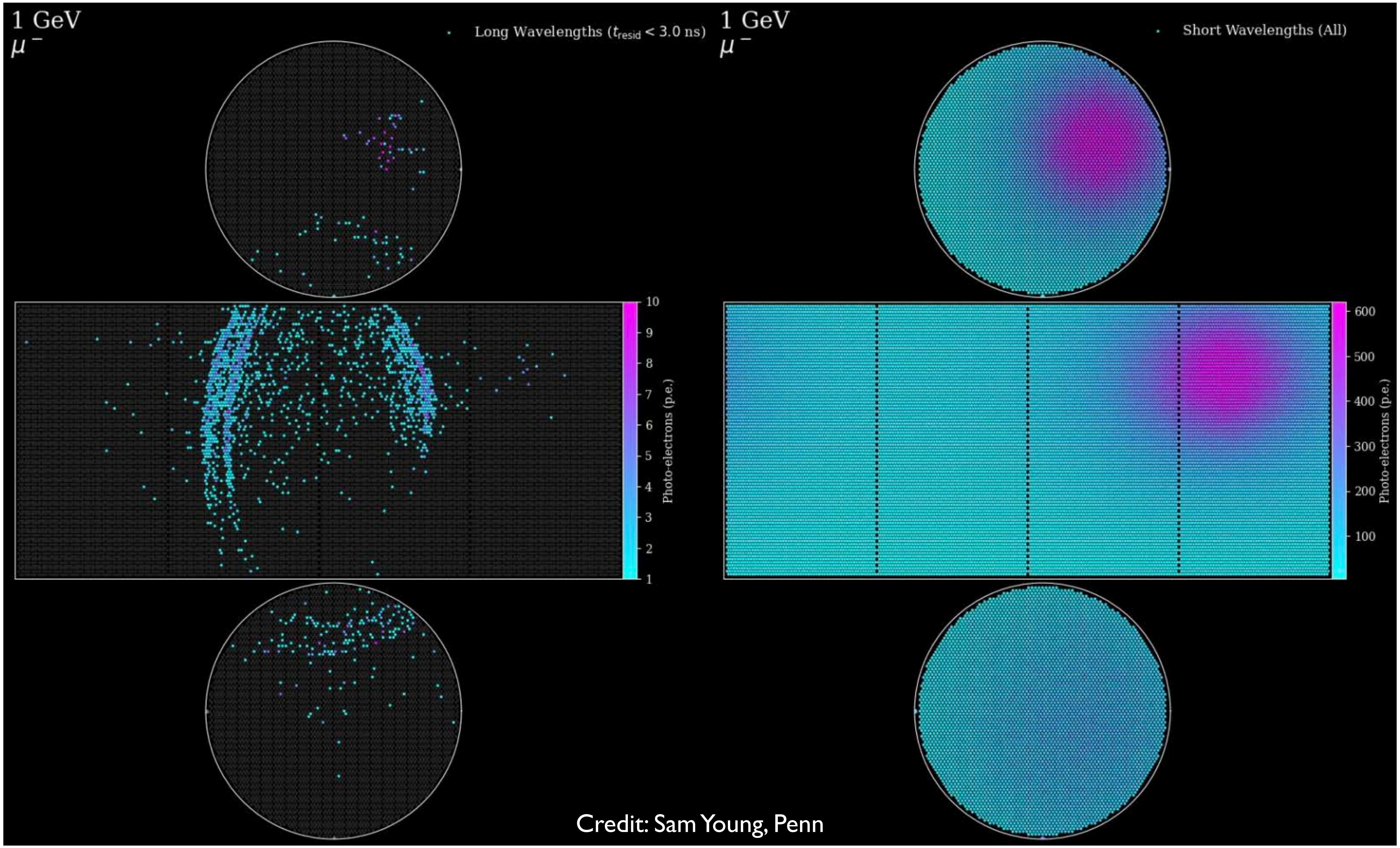
The whole is greater than the sum of the parts!

The ratio of the two signals gives us additional information on the type of particle interacting

Improved background rejection for precision ν measurements

Facilitates broad program!
Neutrinoless double beta decay, Particle astrophysics (solar, supernova)
Long baseline physics (CPV, NMH), Nucleon decay, Geo neutrinos

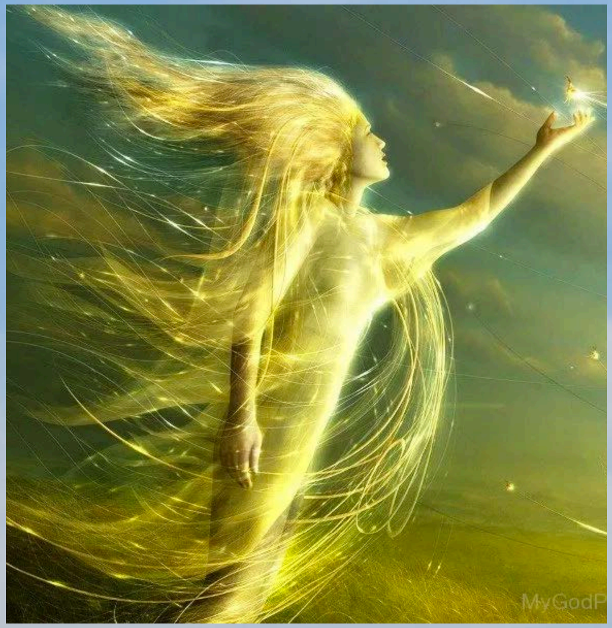
Goal: 2-in-1



Credit: Sam Young, Penn

Cherenkov **Scintillation**

THEIA



THEIA

The Goddess THEIA

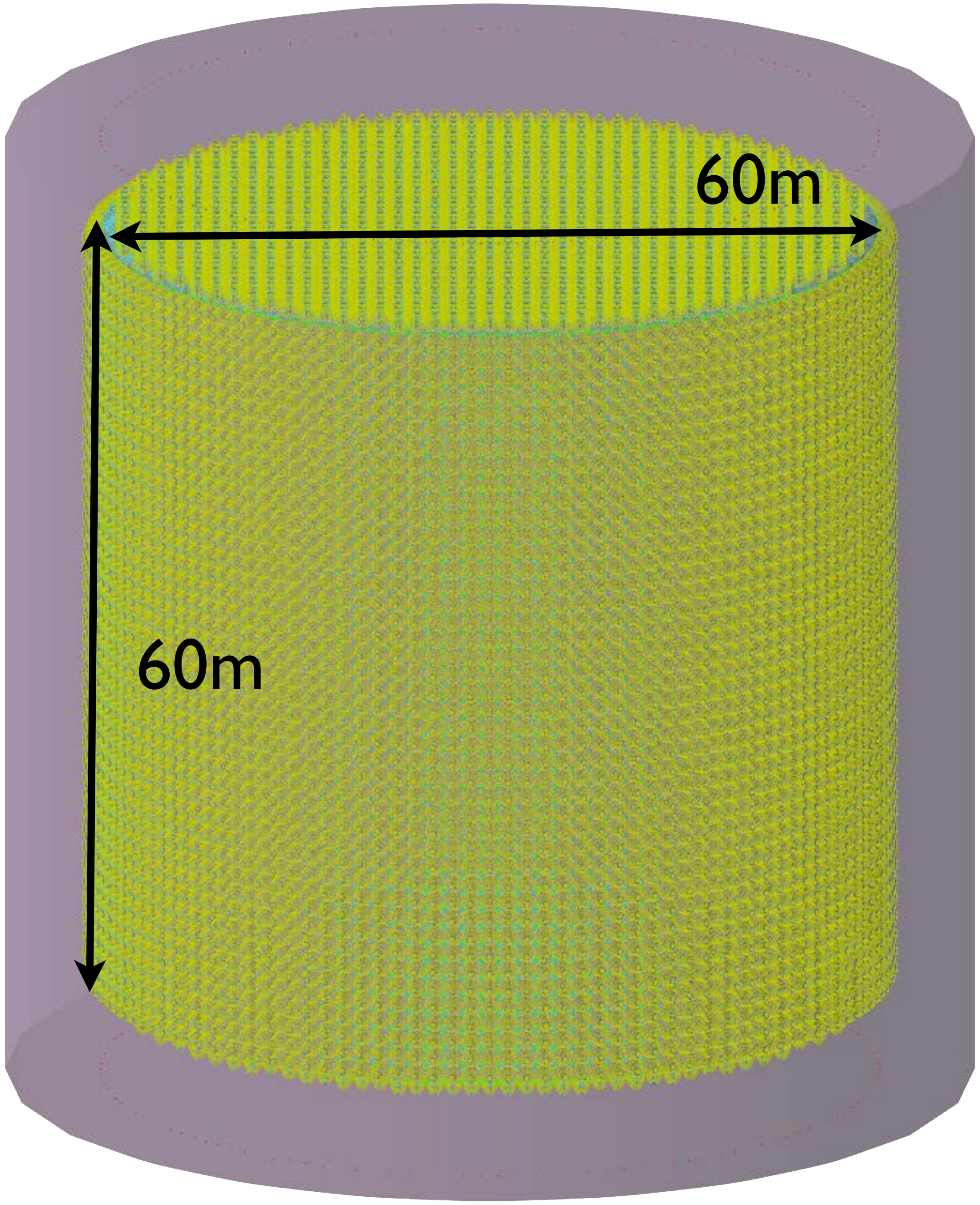
The THEIA collection was created to bring out a women's inner goddess

THEIA Detector Concept

THEIA

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

➡ Broad physics program!



White paper - [Eur. Phys. J. C 80, 416 (2020)]

THEIA

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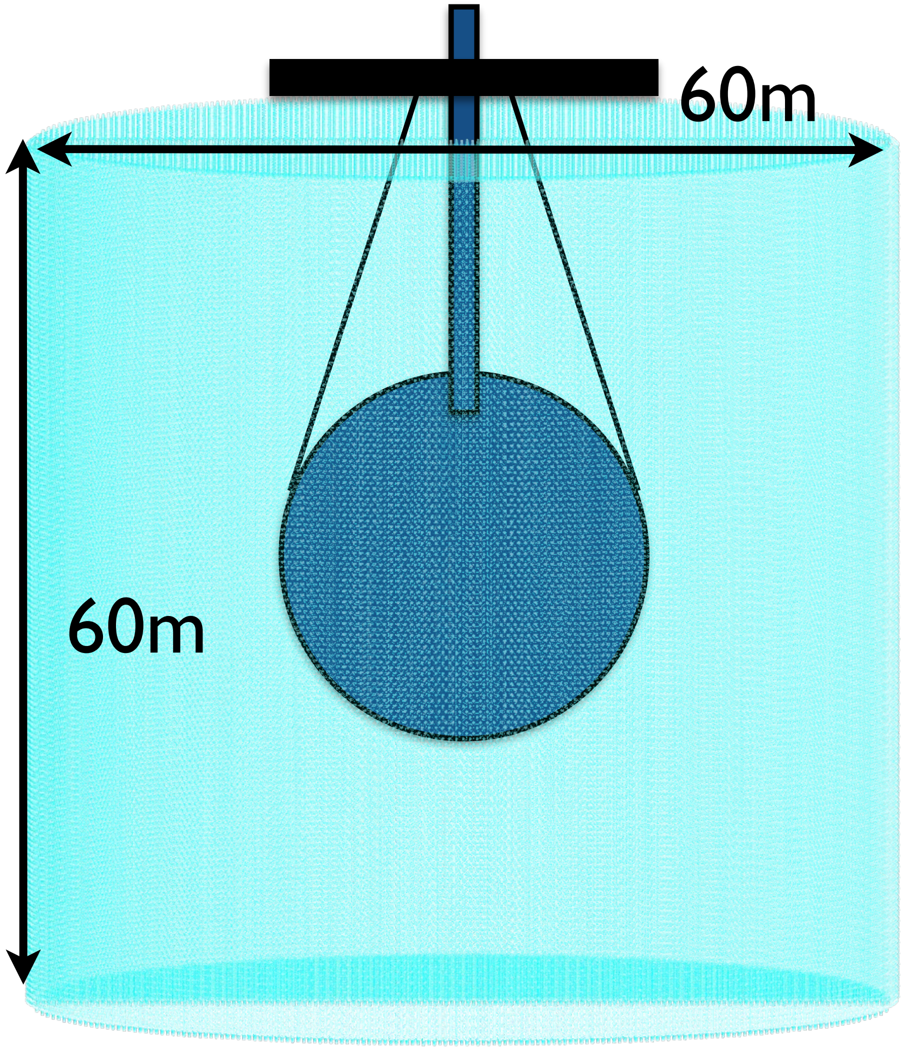
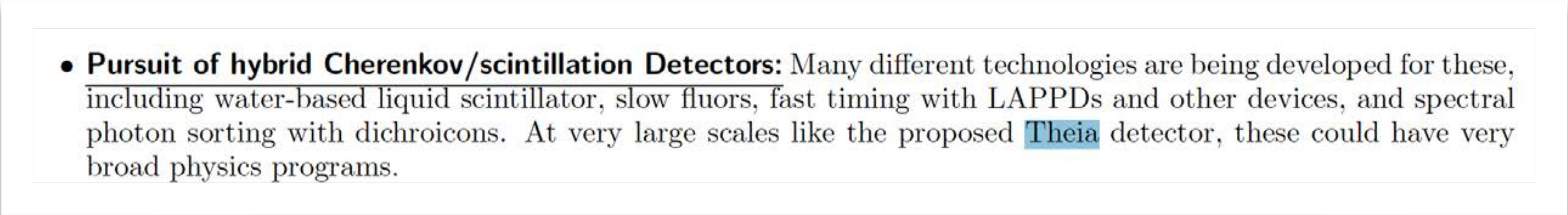


White paper - Eur. Phys. J. C 80, 416 (2020)

Community planning

Snowmass Neutrino Frontier

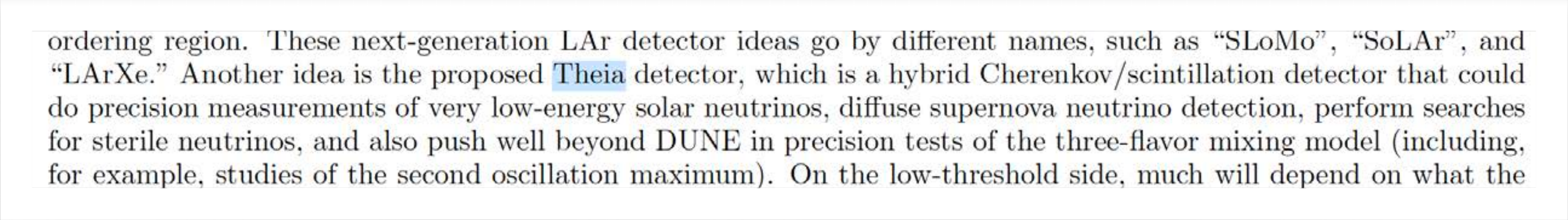
- *NF: Detectors: one of 5 priorities for development*



- **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*

also BSM, terrestrial & astrophysical nu

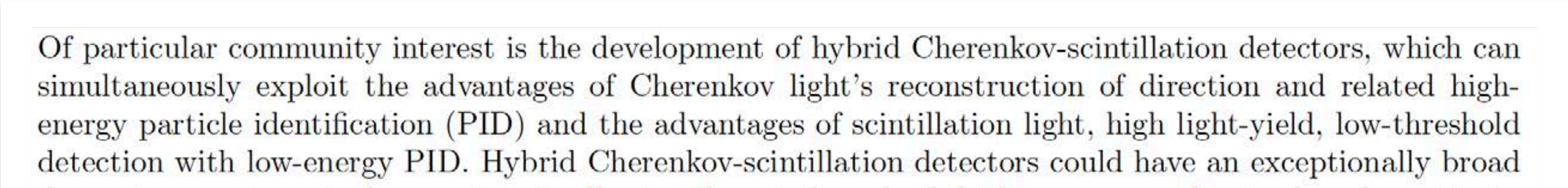


ordering region. These next-generation LAr detector ideas go by different names, such as "SLoMo", "SoLAr", and "LArXe." Another idea is the proposed Theia detector, which is a hybrid Cherenkov/scintillation detector that could do precision measurements of very low-energy solar neutrinos, diffuse supernova 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

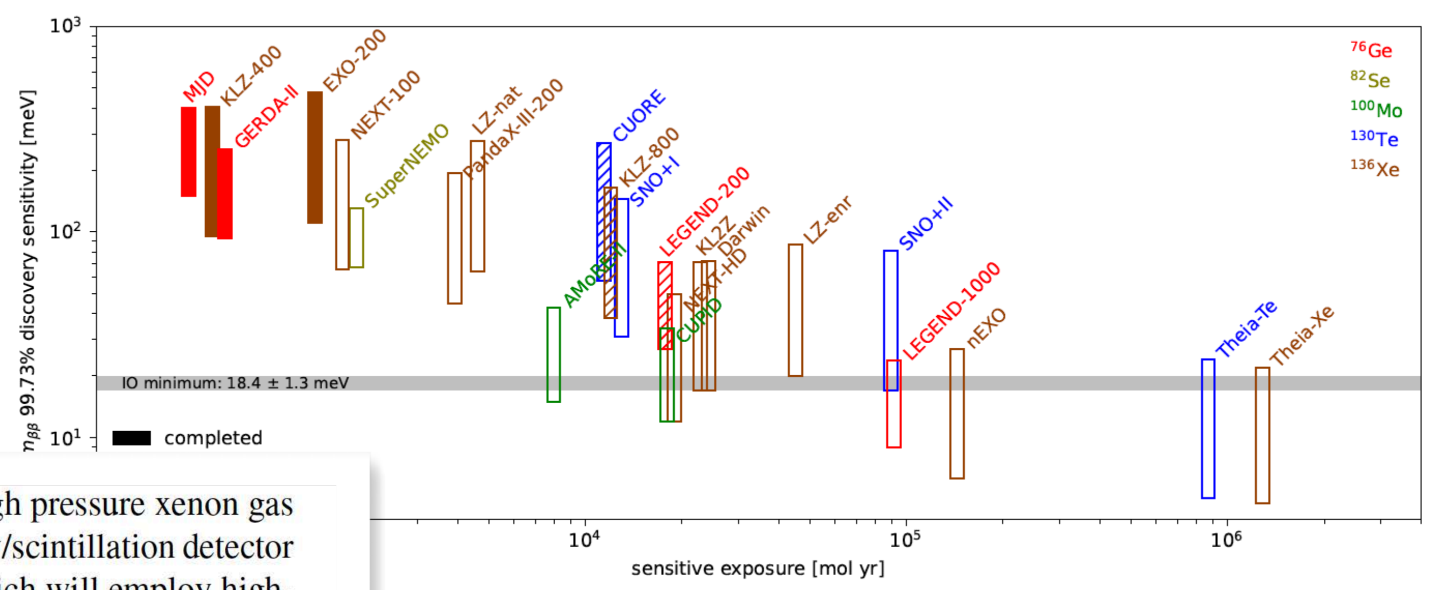
- *IF: Going beyond DUNE*

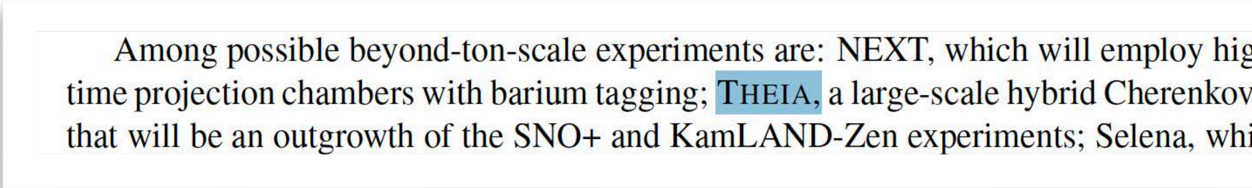
also photon detectors & spectral sorting



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

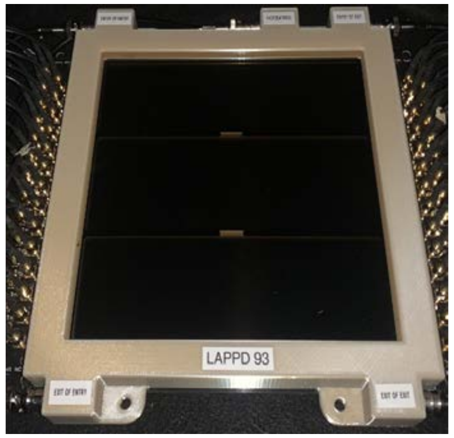


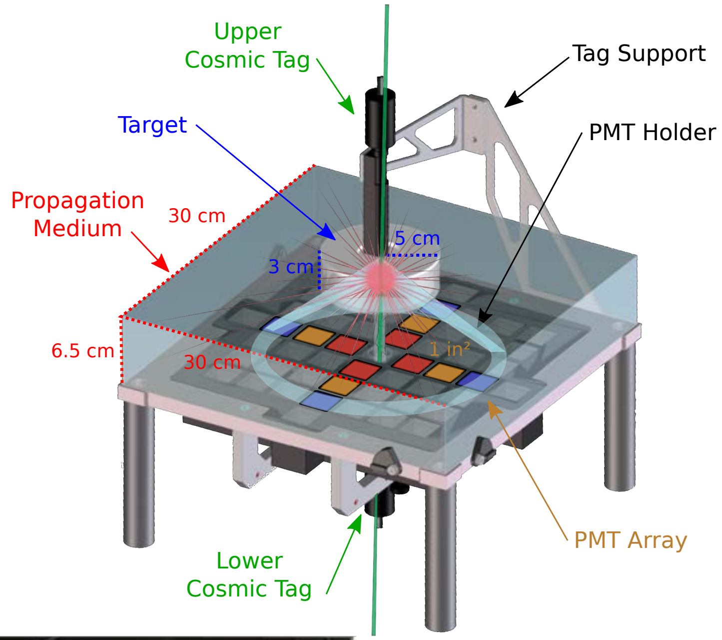


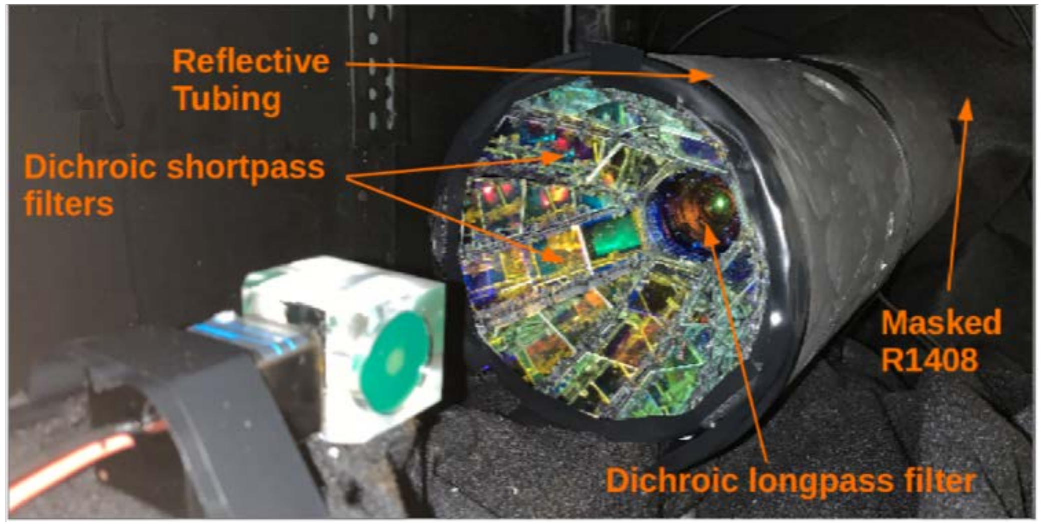
Among possible beyond-ton-scale experiments are: NEXT, which will employ high pressure xenon gas time projection chambers with barium tagging; THEIA, a large-scale hybrid Cherenkov/scintillation detector that will be an outgrowth of the SNO+ and KamLAND-Zen experiments; Selena, which will employ high-

THEIA as a tool for increasing diversity in STEM

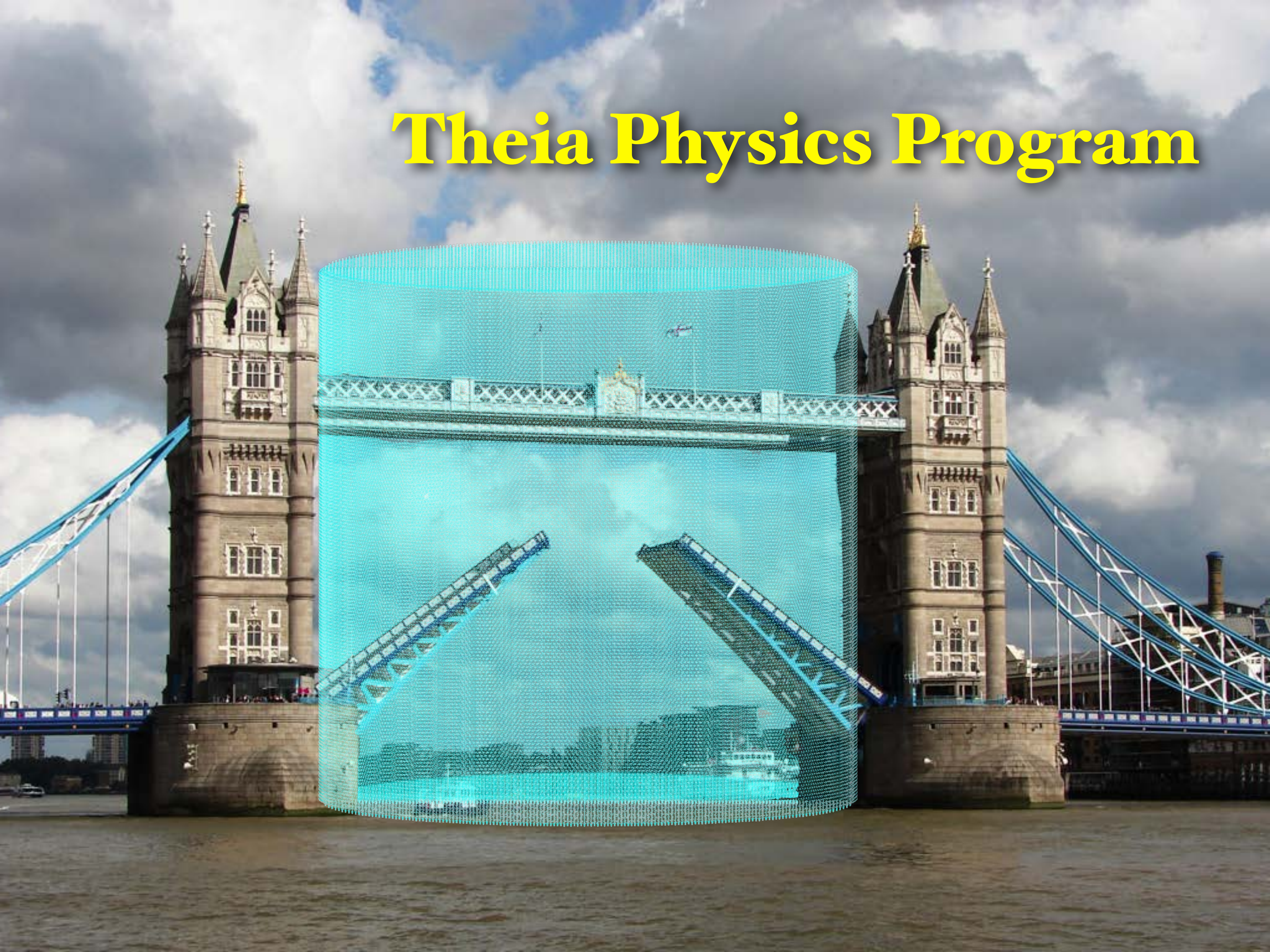
- Central tenet of this project from day zero, active ongoing effort
  - 3-point coordination for participation of MSIs — Cal State Stan, UT San Antonio, Black Hills
  - K-12 science education program based at SURF
- The science of THEIA is inspirational & motivational
- Opportunity for under-represented groups to make meaningful contributions to “big science”, in an EPSCOR state
- Readily accessible to smaller institutions with more limited resources
  - Benchtop measurements are critical component in design efforts
  - No need for cryogenics, purification etc







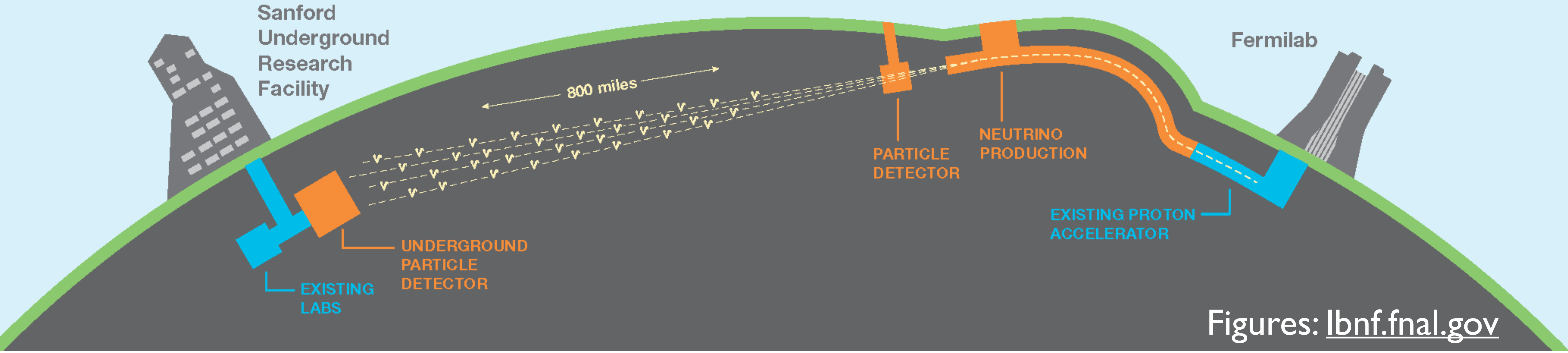
Theia Physics Program



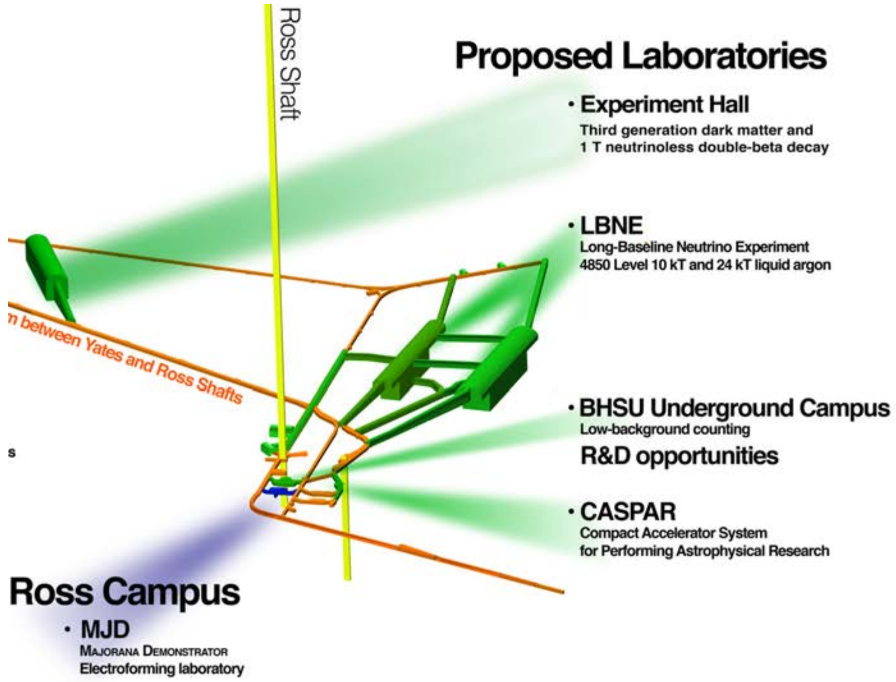
The Missing Ingredient: CP Violation

Deep Underground Neutrino Experiment (DUNE)

“Sending neutrinos on an 800-mile journey”



Figures: lbnf.fnal.gov



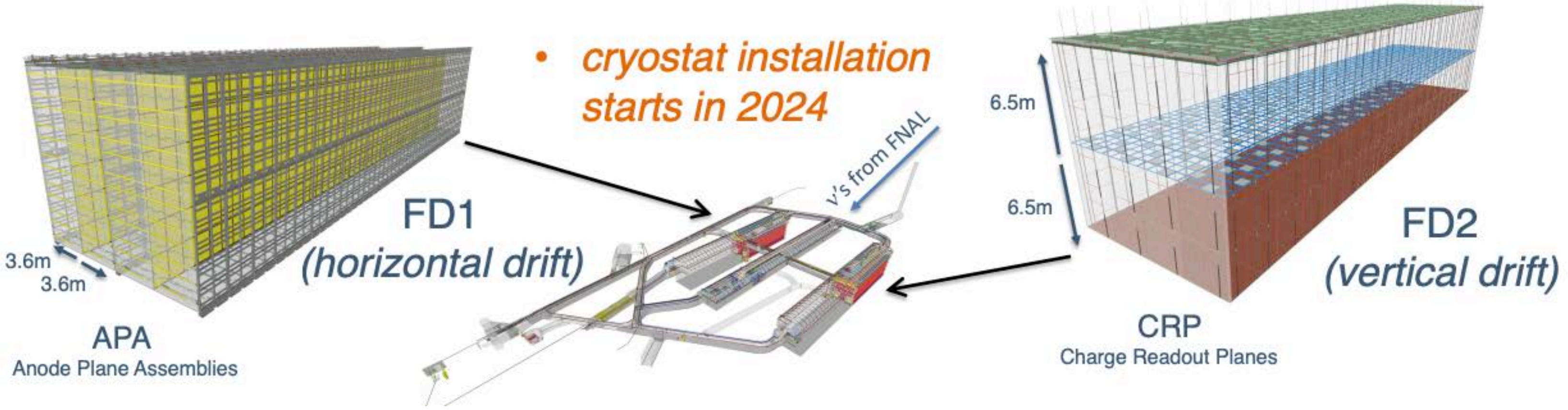
Full DUNE scope:

1. 1.2 MW beam, upgradeable to 2.4MW
2. Four Far Detector (FD) modules, 40kt+ fiducial
3. Near Detector suite (ND)

DUNE phasing

DUNE Phase I:

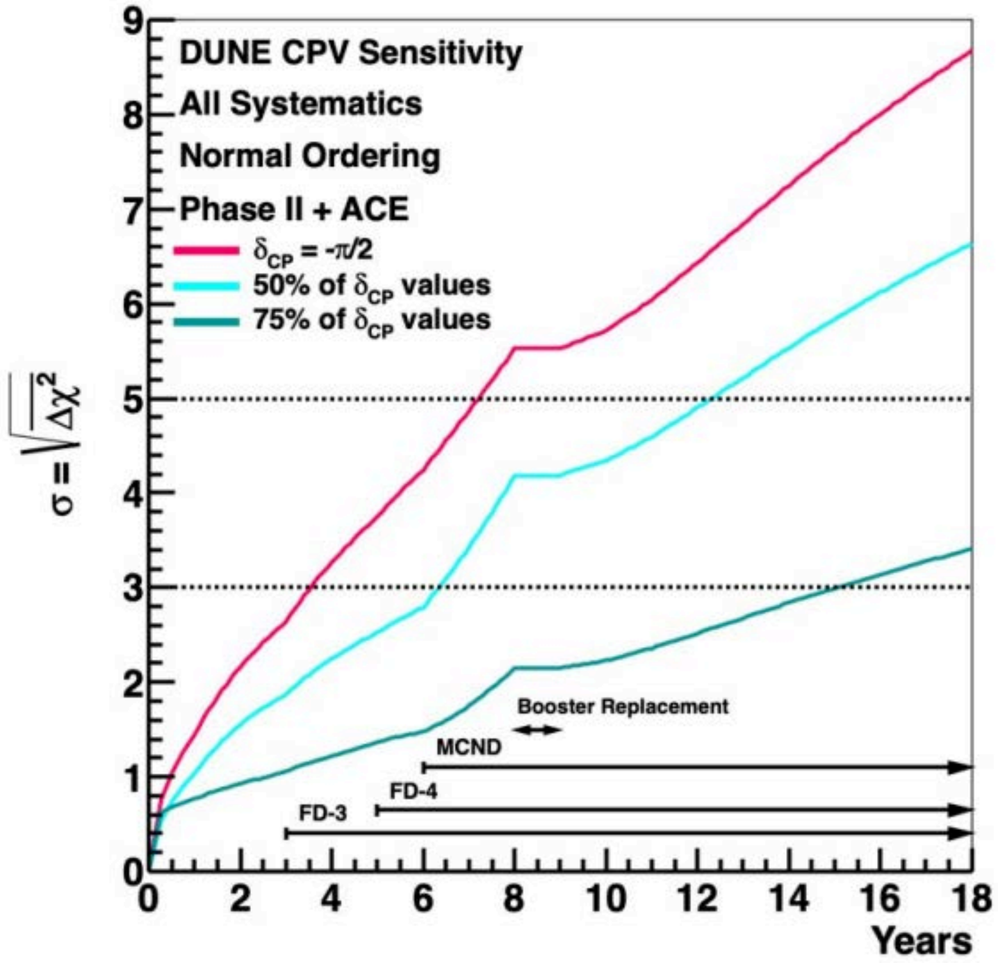
1. 1.2 MW beam
2. Two Far Detector (FD) modules, 2x10 kt liquid argon TPC
3. Reduced Near Detector suite (ND)



- *cryostat installation starts in 2024*

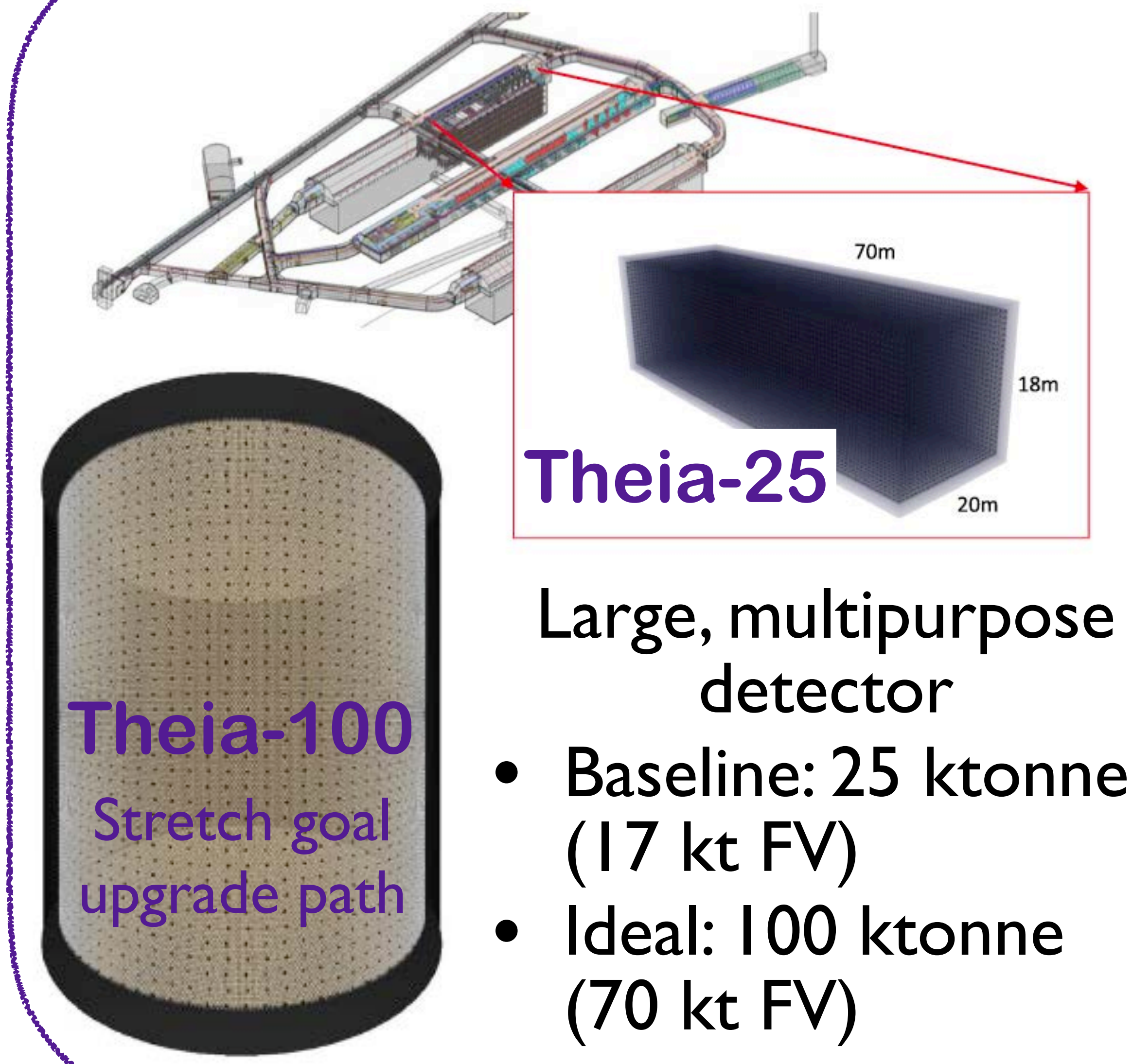
DUNE Phase II:

1. Upgraded beam
2. Two additional Far Detector (FD) modules, technology TBD
3. More Capable Near Detector (MCND)



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



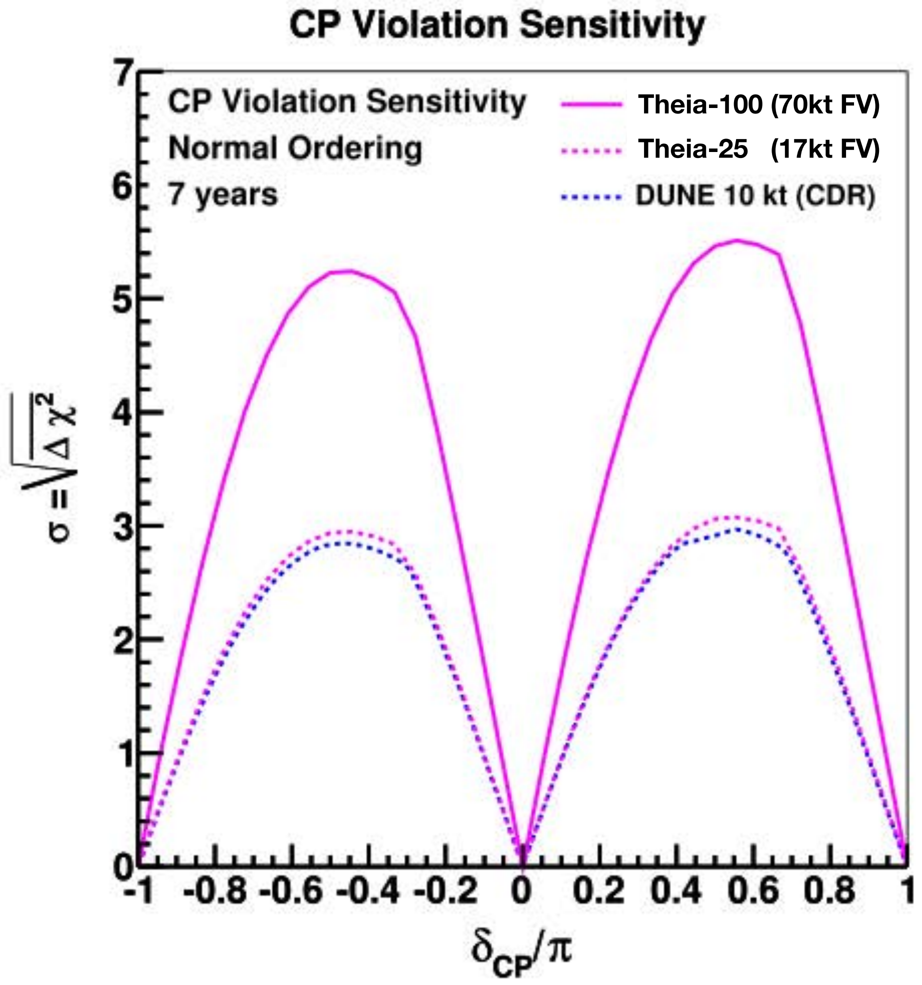
Large, multipurpose detector

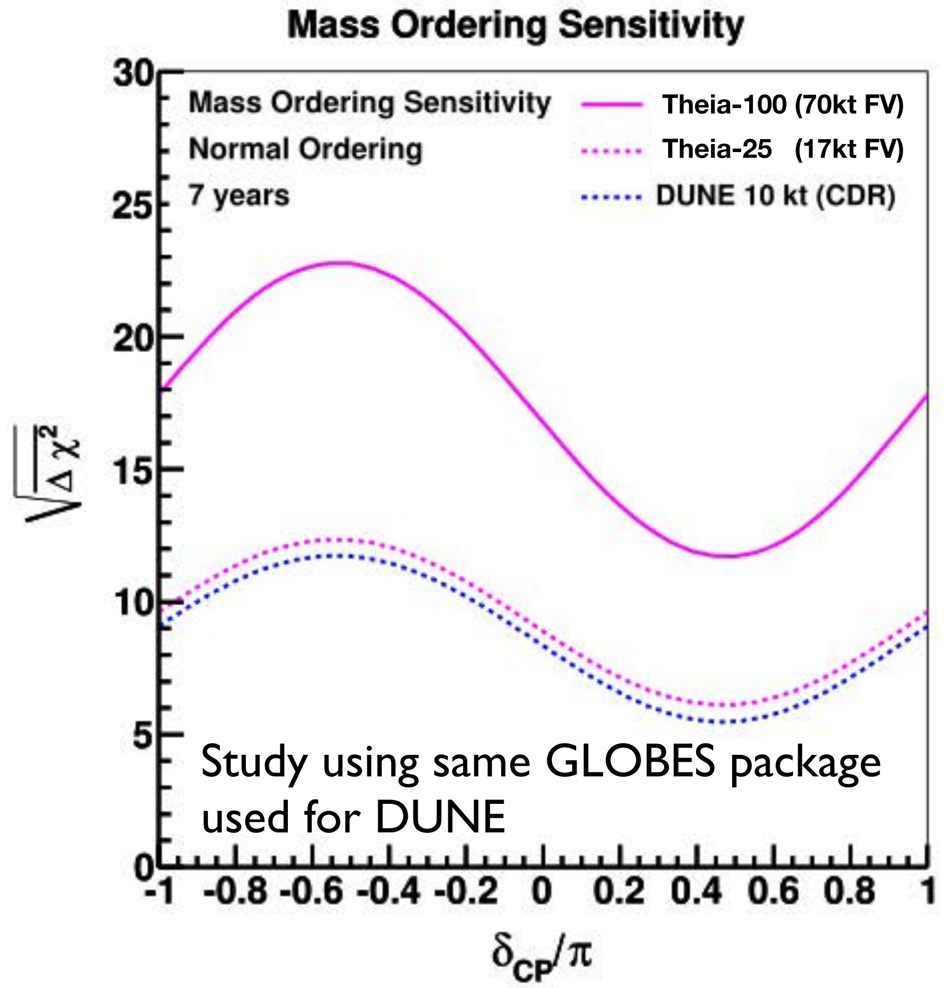
- Baseline: 25 ktonne (17 kt FV)
- Ideal: 100 ktonne (70 kt FV)

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

- 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)

Long-Baseline Sensitivity





Study using same GLOBES package used for DUNE

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

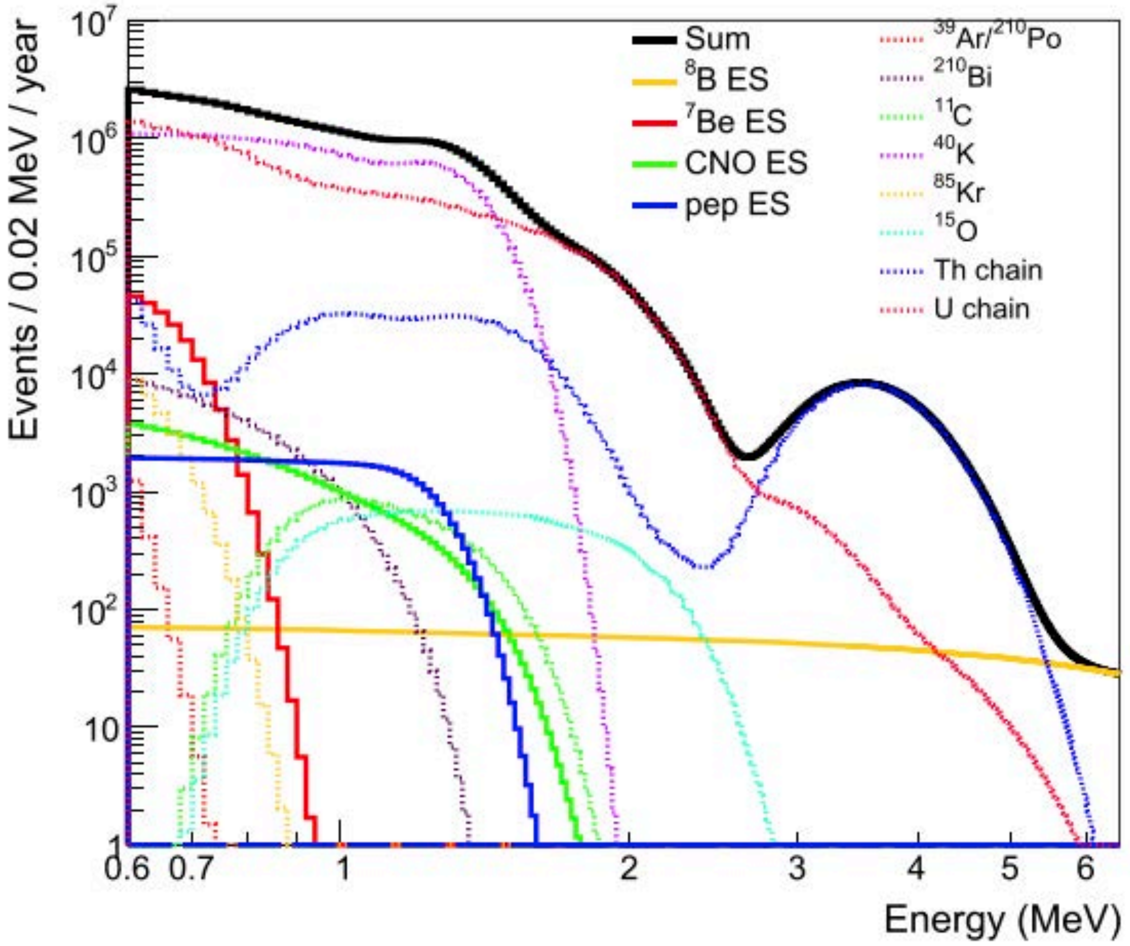
Synergy with LAr TPC

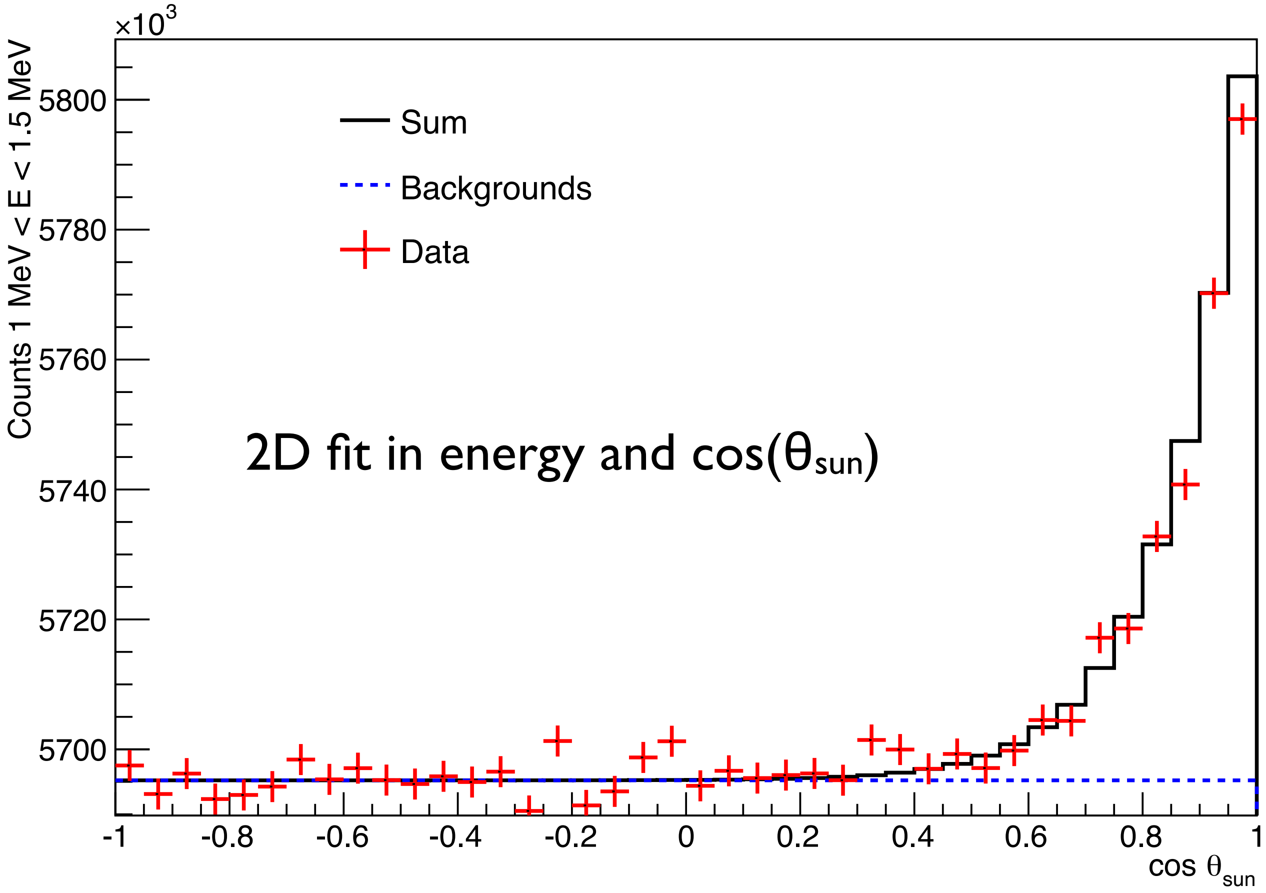
Independent systematics

Unique cross check of HK/DUNE comparison!

Eur. Phys. J. C 80, 416 (2020); arXiv: 1606.09550

The challenge of backgrounds





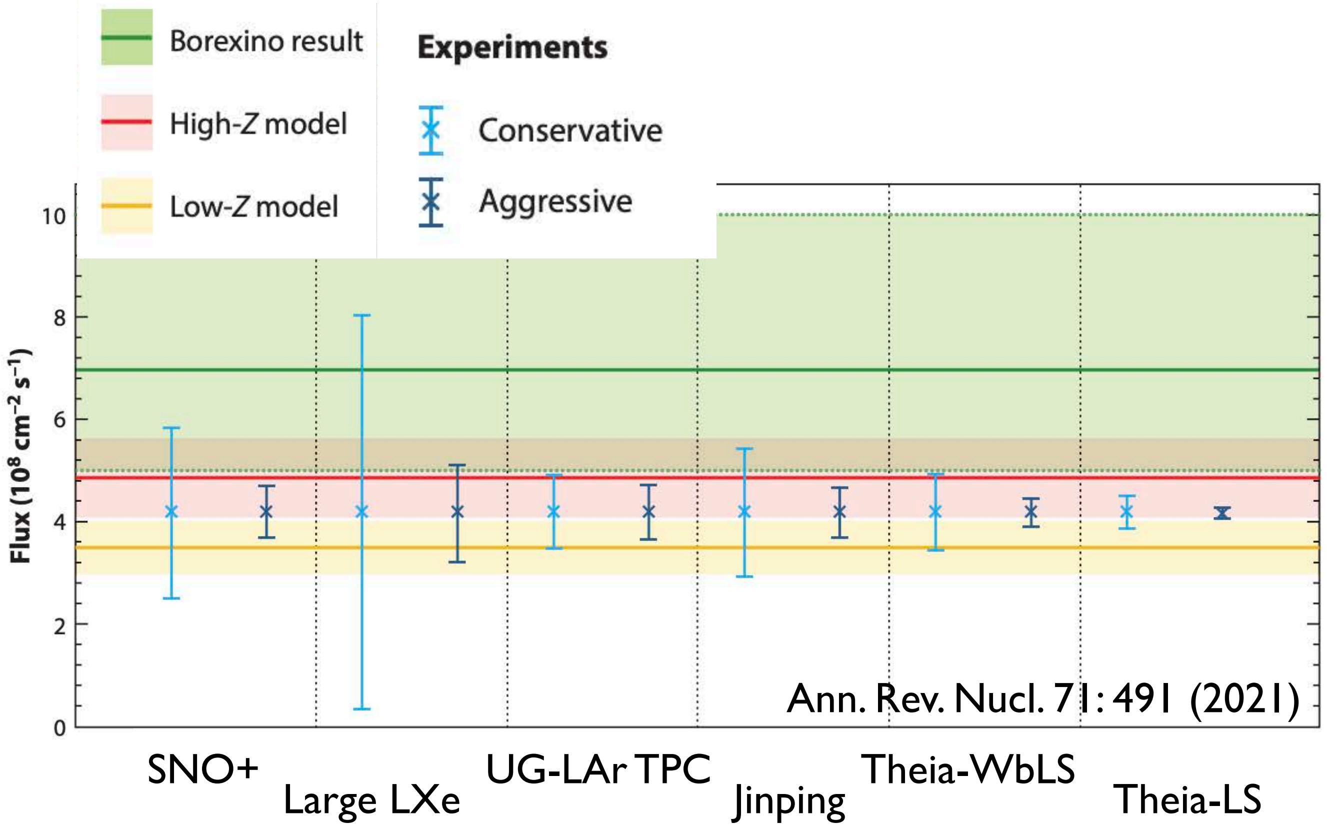
2D fit in energy and cos(θ_{sun})

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

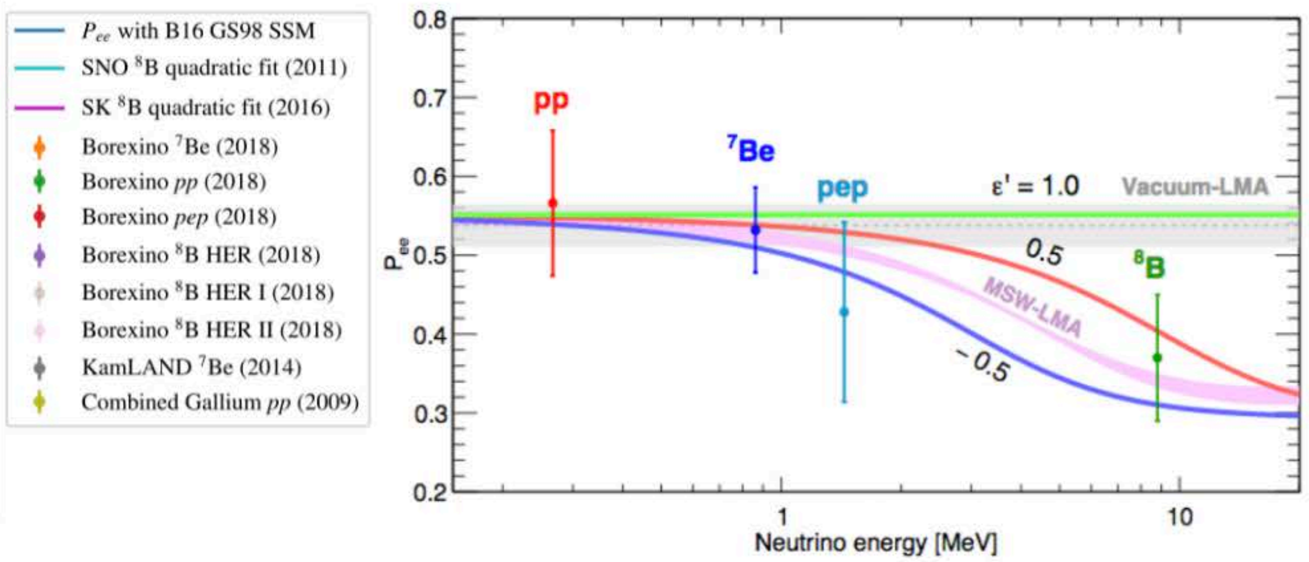
Solar Neutrinos with THEIA

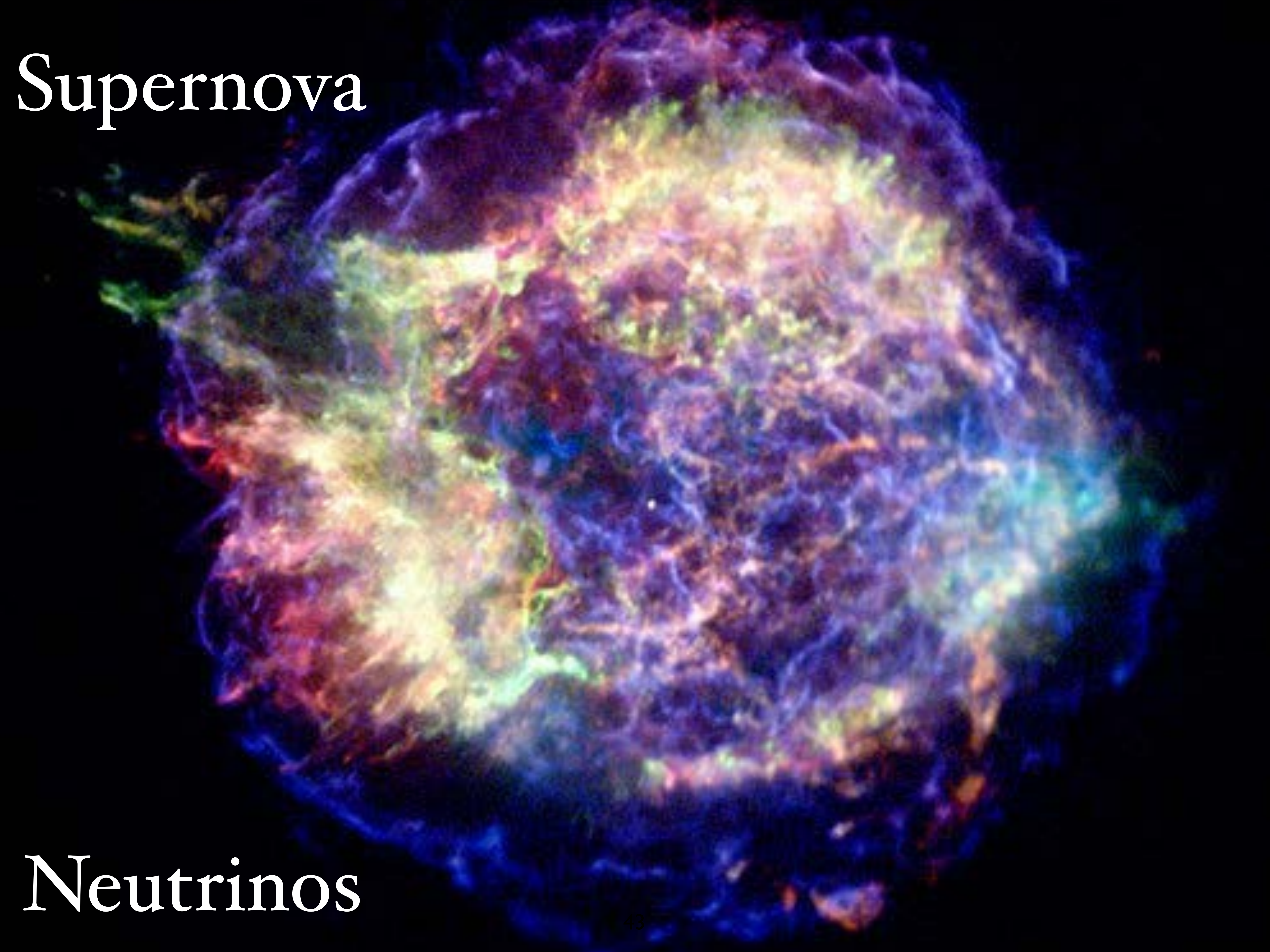
- Dominant background: natural radioactivity e.g. ^{210}Bi
- Theia offers unique low-threshold, directional detection
- Particle and event ID from LS time profile, quenching, Ch/S ratio

- 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)



Ann. Rev. Nucl. 71: 491 (2021)





Supernova

Neutrinos

Supernova Detection

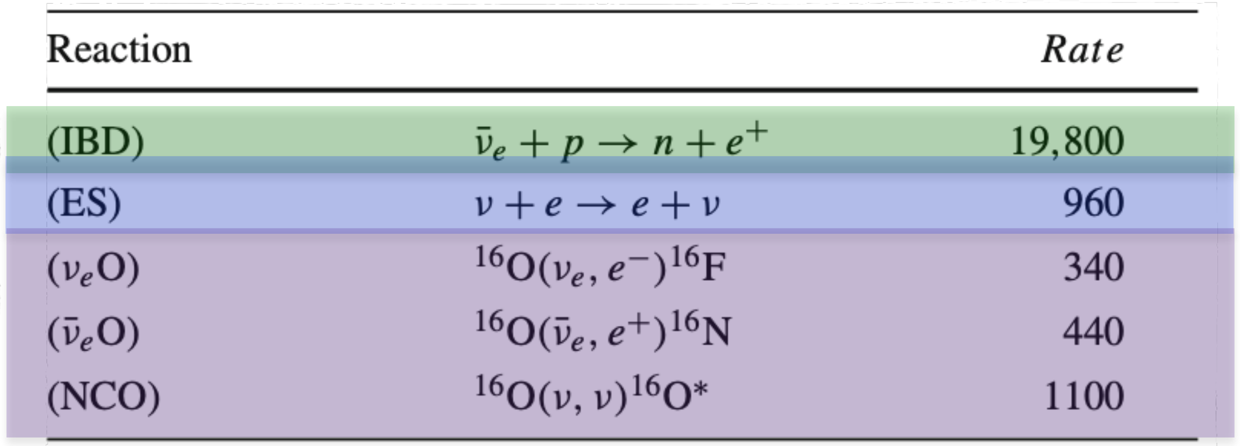
- ~90% events are IBD

  Highly complementary to ν_e LAr signal

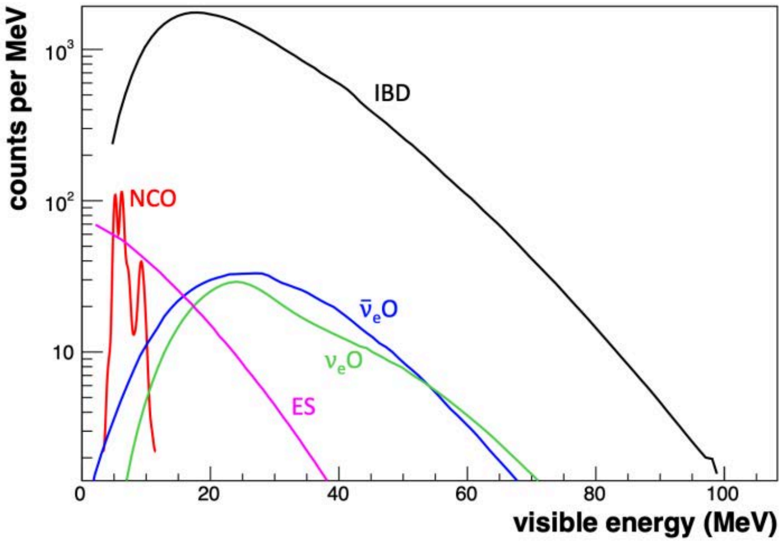
  Fast, can act as trigger for DUNE
- ES ⇒ pointing accuracy < 1°
- CC & monoE γ from NC ⇒

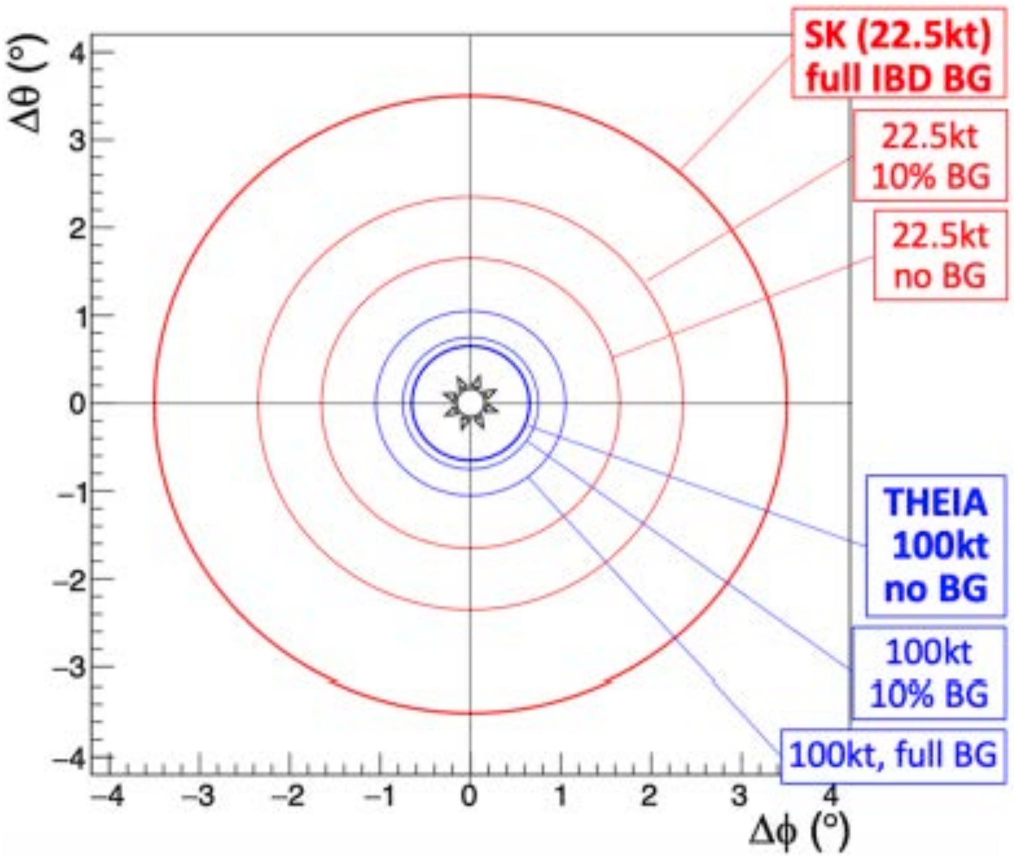
  burst T & subsequent mixing
- Flavour-resolved neutrino spectra
- High-stats, low-threshold signal with good resolution
- Pre-supernova ν sensitivity
- Enhanced CC sensitivity with Li doping

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)	$^{16}\mathrm{O}(\nu_e, e^-)^{16}\mathrm{F}$	340
($\bar{\nu}_e$O)	$^{16}\mathrm{O}(\bar{\nu}_e, e^+)^{16}\mathrm{N}$	440
(NCO)	$^{16}\mathrm{O}(\nu, \nu)^{16}\mathrm{O}^*$	1100

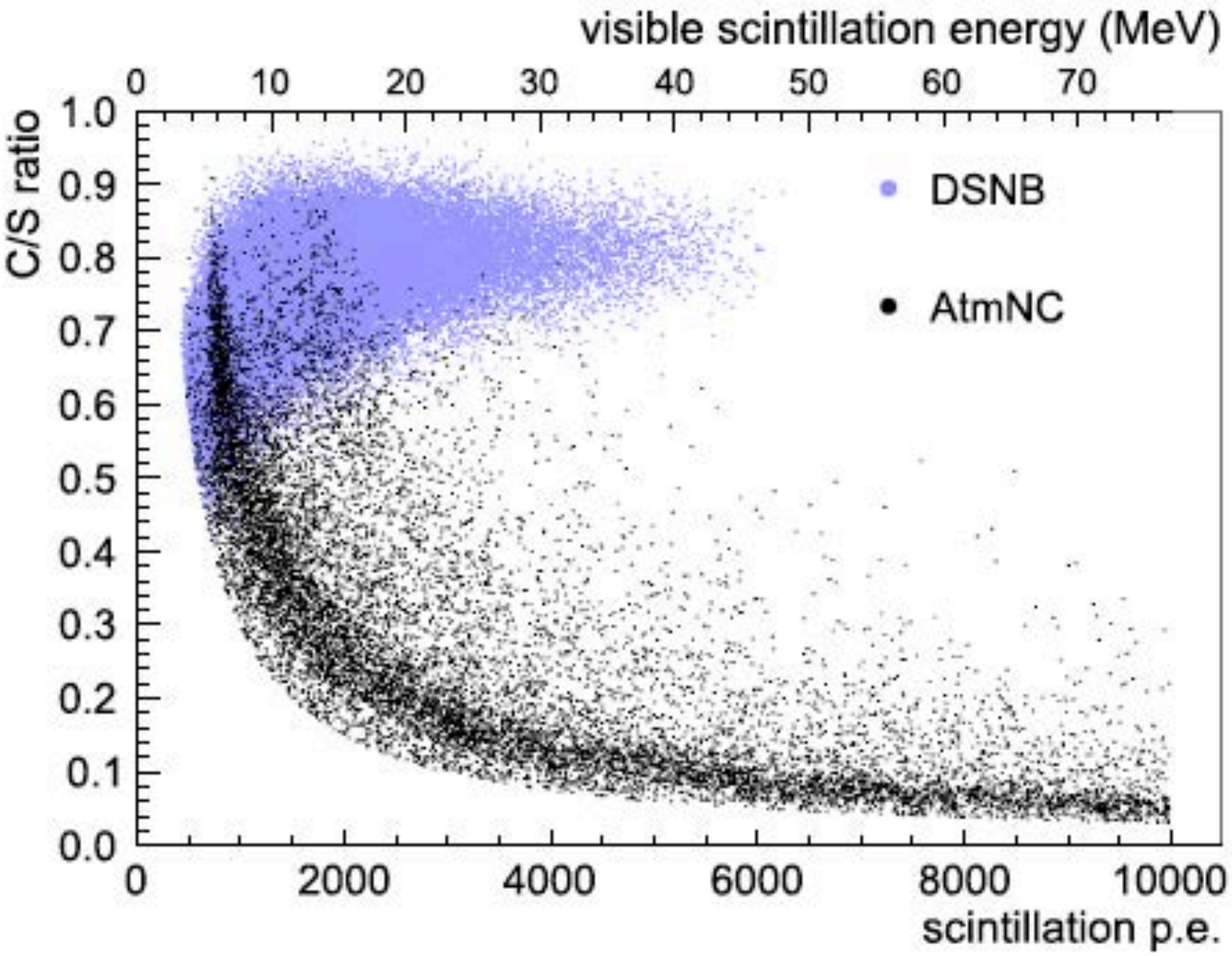




Eur. Phys. J. C 80, 416 (2020)

Diffuse Supernova ν Background

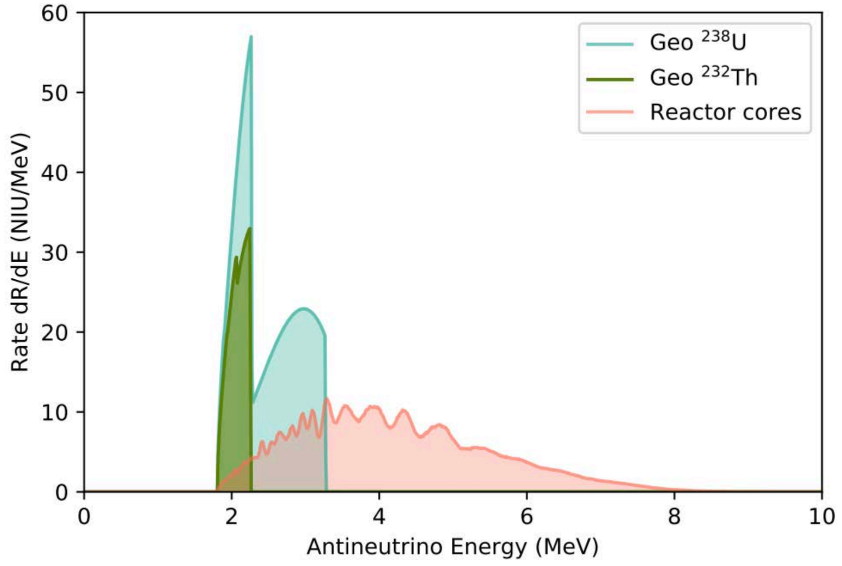
- Diffuse ν "glow" from past core-collapse supernovae
- Astrophysics of SNe
- Signature: IBD detection of antineutrino signal
  - Prompt e+ and delayed n-capture signal
- Main background: NC interaction of atmospheric ν
  - ν hits C nucleus, causing recoil
  - n captures
  - Can mimic signal
- Cherenkov/scintillation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

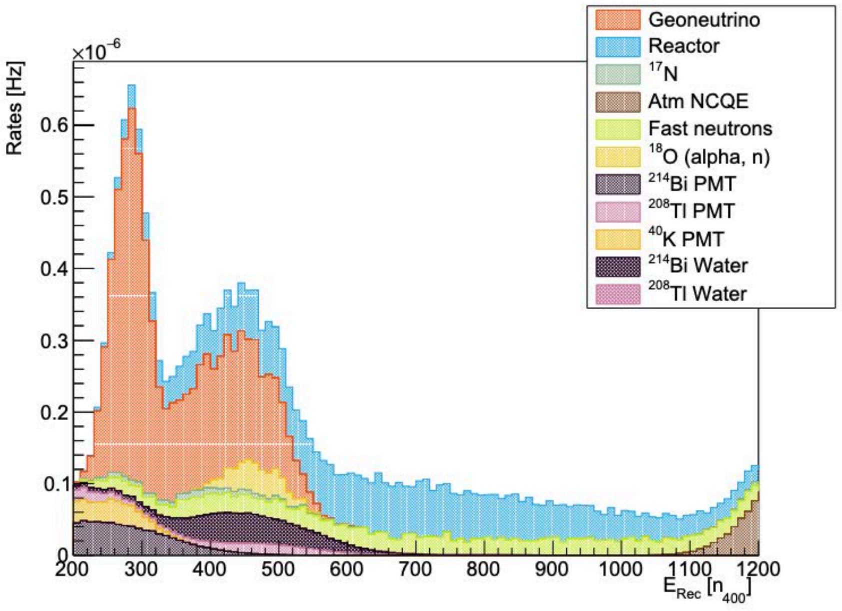


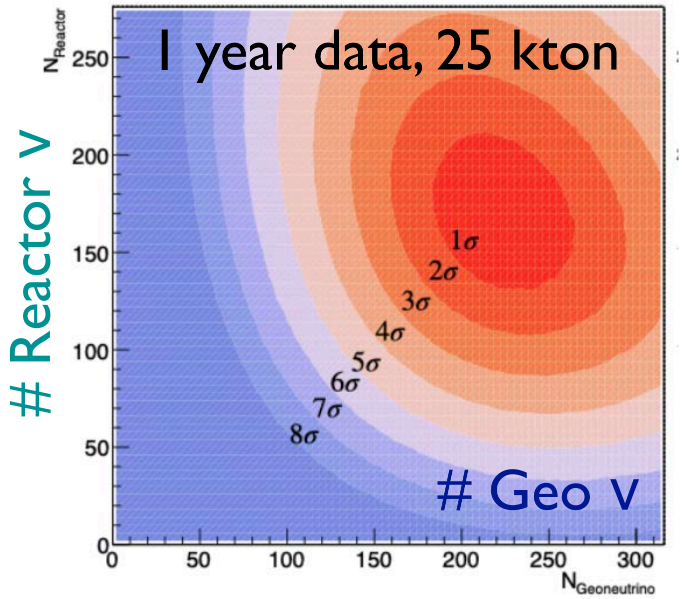
Eur. Phys. J. C 80, 416 (2020); Phys. Rev. D 103, 023021

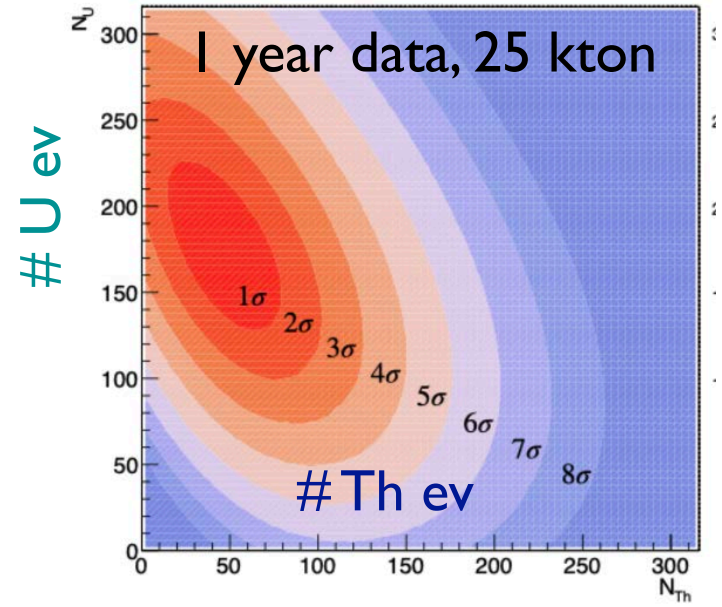
Anti-ν Detection

- **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







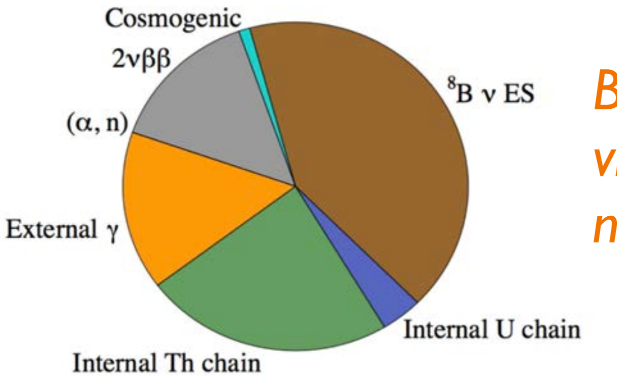


Eur. Phys. J. C 80, 416 (2020); arXiv:2204.12278

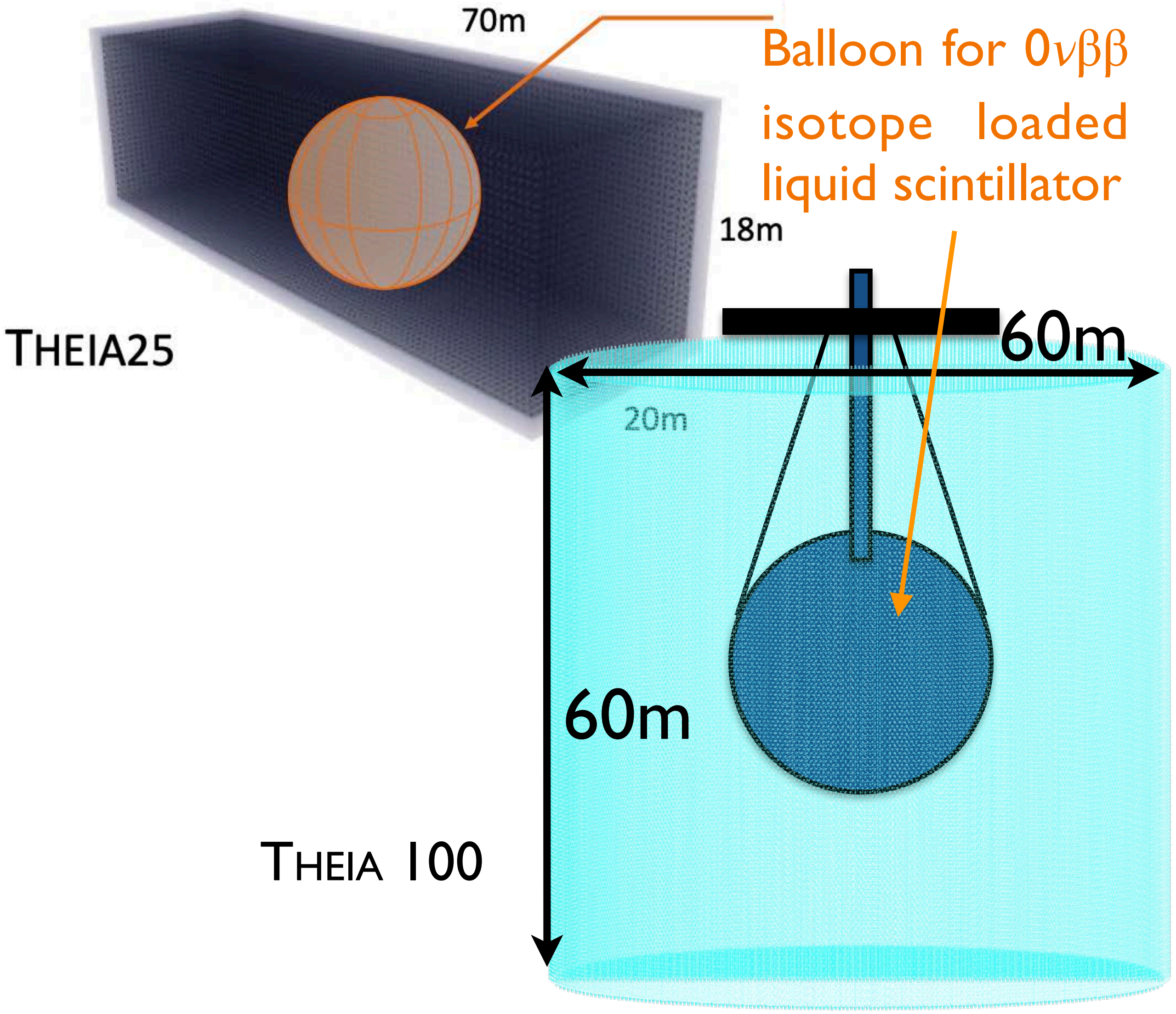
$0\nu\beta\beta$ with THEIA

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

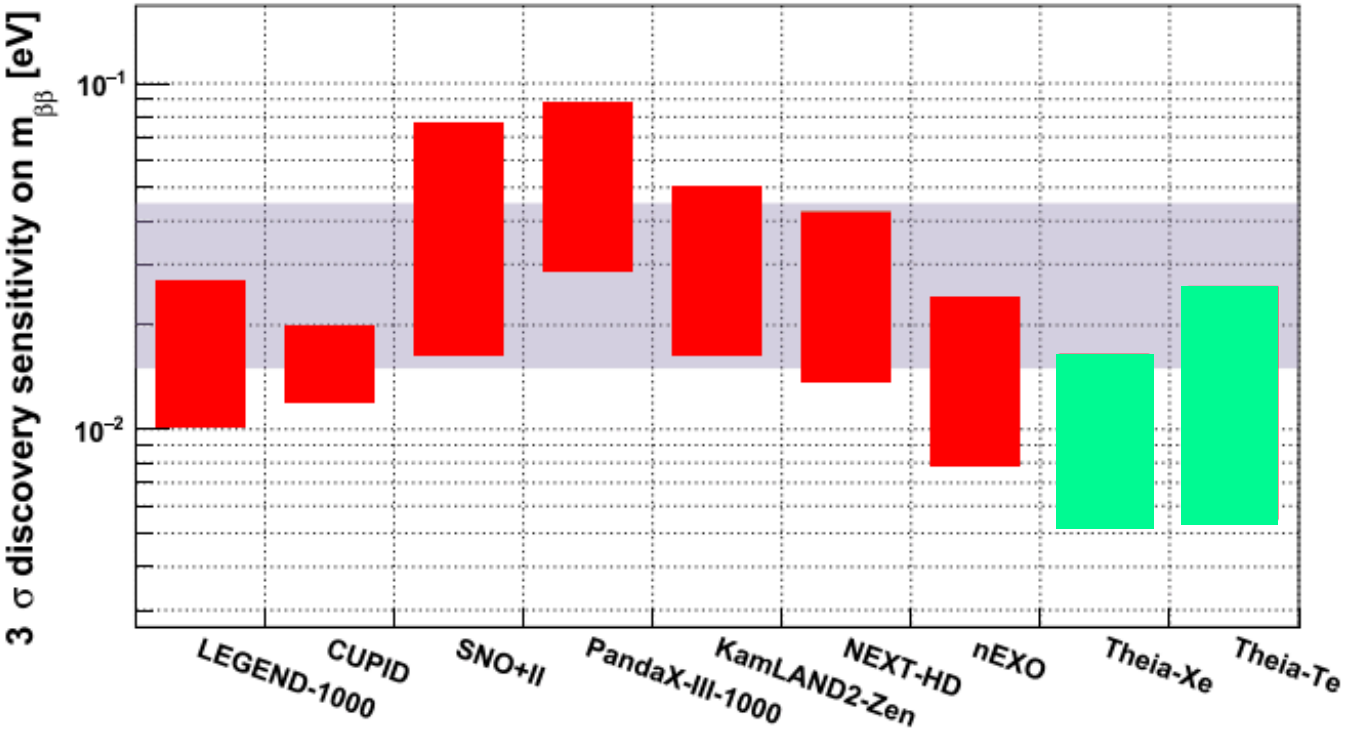
SNO+ Collaboration



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



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



Builds on critical developments by KLZ & SNO+ collaborations

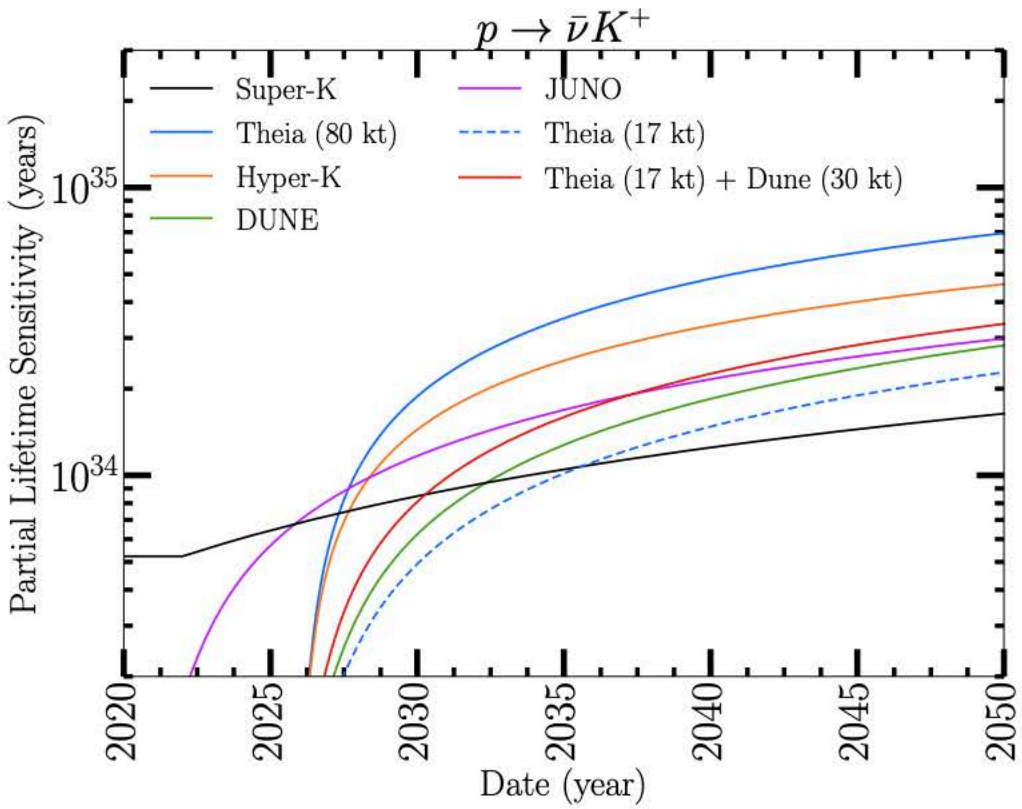
Phys.Rev.Lett.110 : 062502 (2013);Adv.High Energy Phys. 2016 (2016) 6194250; Phys. Rev. D 87 no. 7 : 071301 (2013)

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

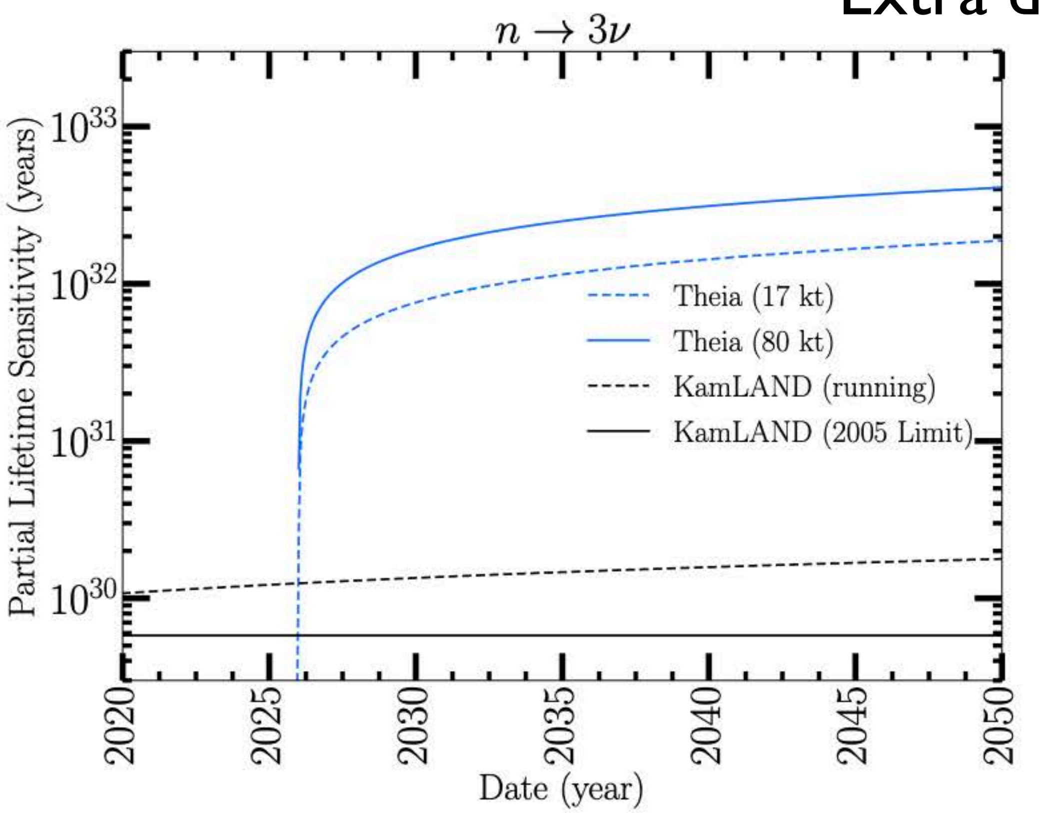
Nucleon Decay

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



Extra dimensions



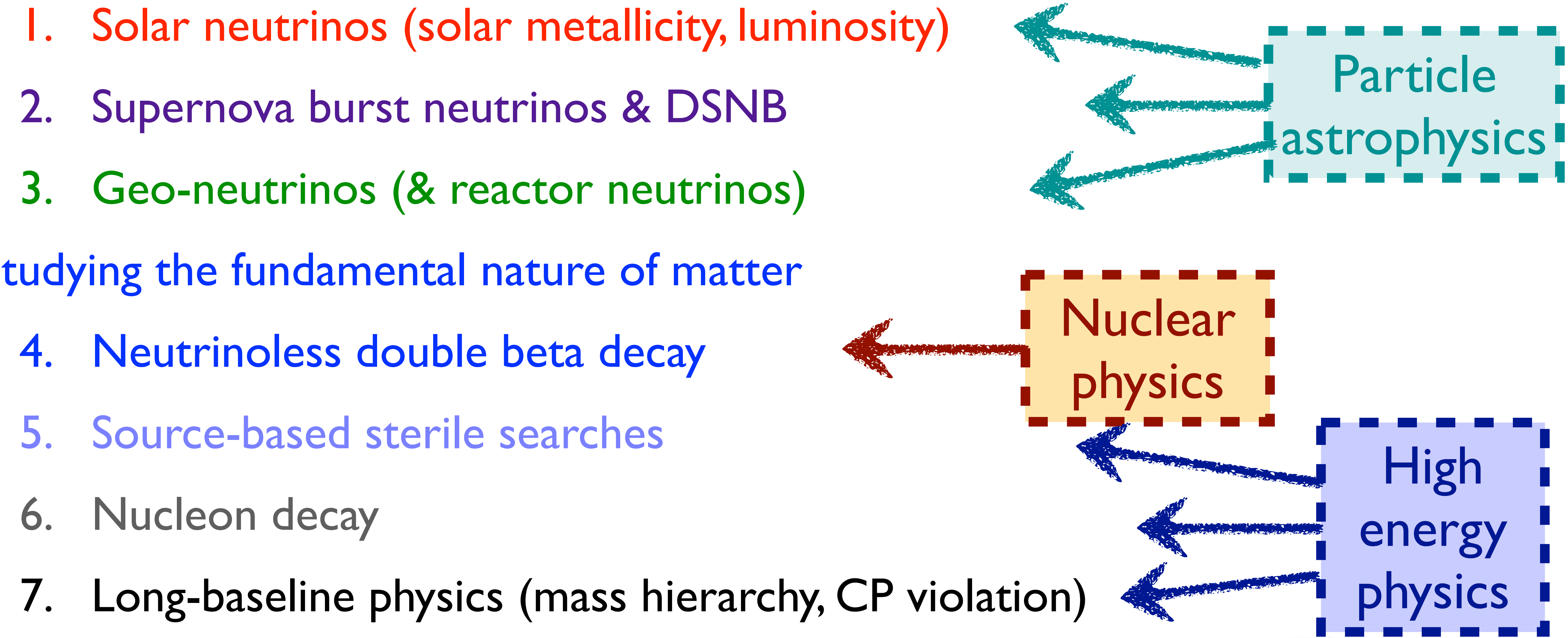
Sub-Chr t/h detection
⇒ Directly visible K$^+$

Deep, low threshold
Directionality + n tag

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

Physics Program

Physics over 5 orders of magnitude



Neutrinos as a probe of nature

1. Solar neutrinos (solar metallicity, luminosity)
2. Supernova burst neutrinos & DSNB
3. Geo-neutrinos (& reactor neutrinos)

Particle astrophysics

Studying the fundamental nature of matter

4. Neutrinoless double beta decay
5. Source-based sterile searches
6. Nucleon decay
7. Long-baseline physics (mass hierarchy, CP violation)

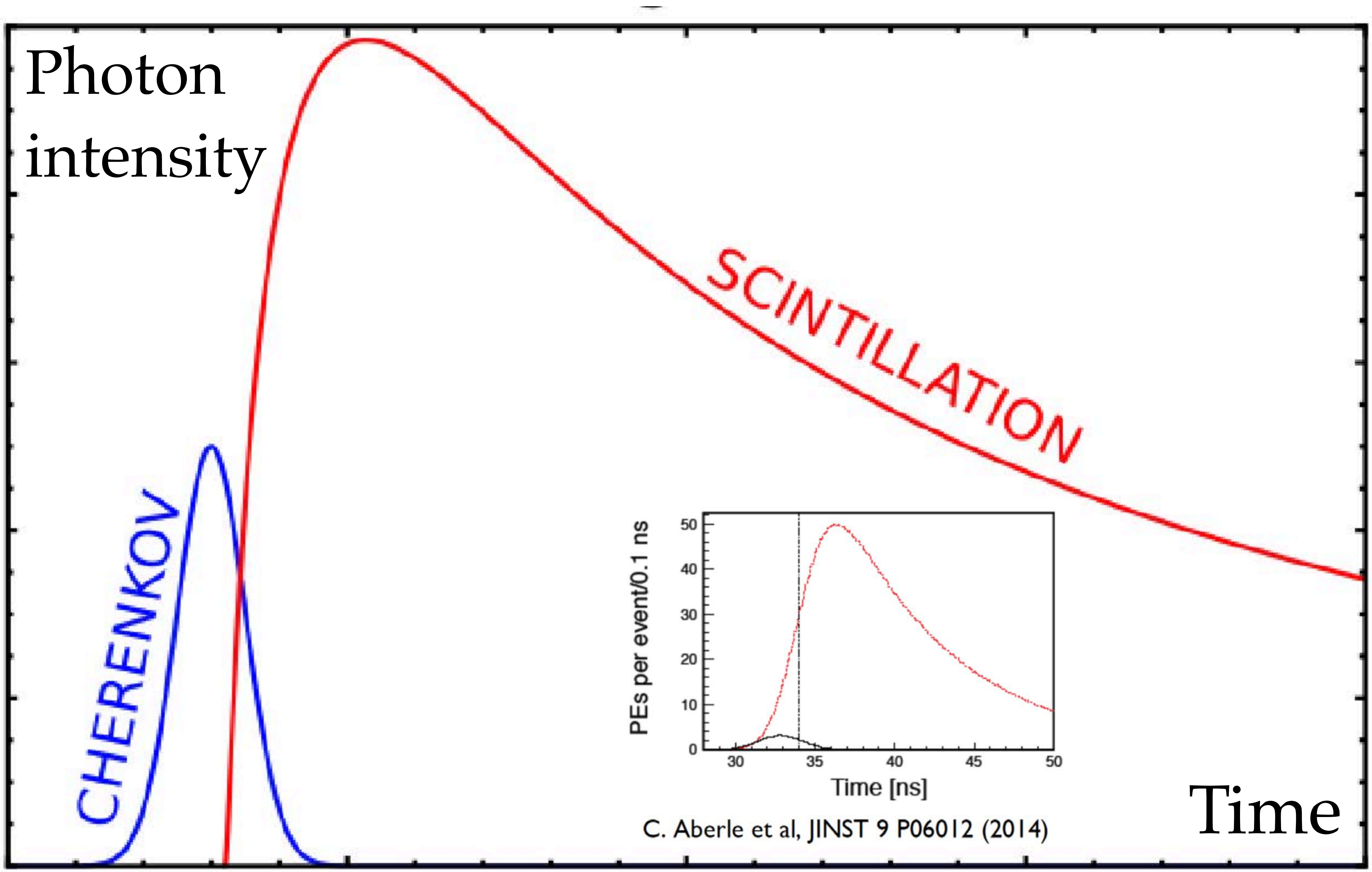
Nuclear physics

High energy physics

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

Matter-dominated universe

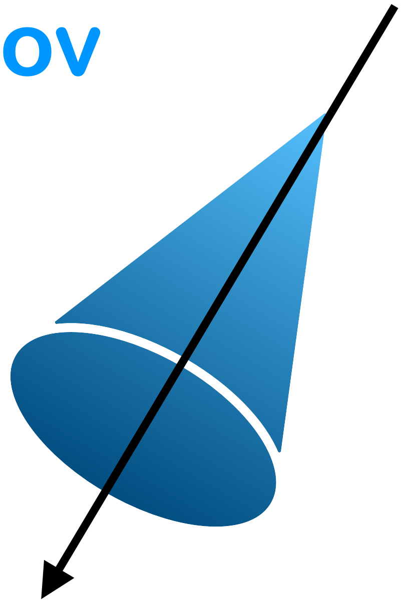
Why is it Hard?



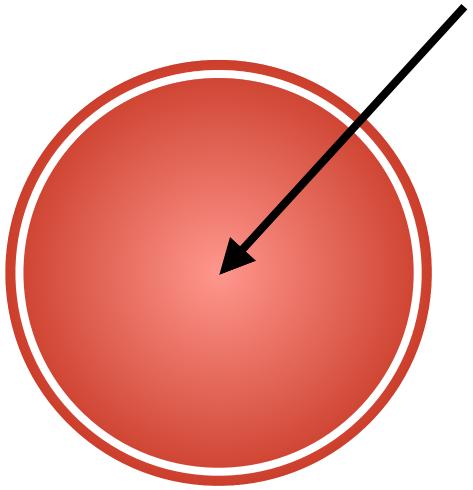
C. Aberle et al, JINST 9 P06012 (2014)

How can it be done?

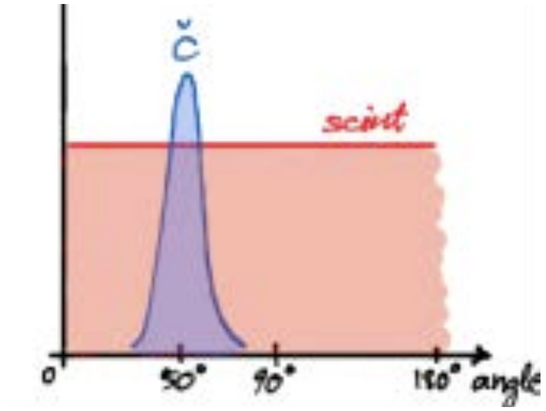
Cherenkov



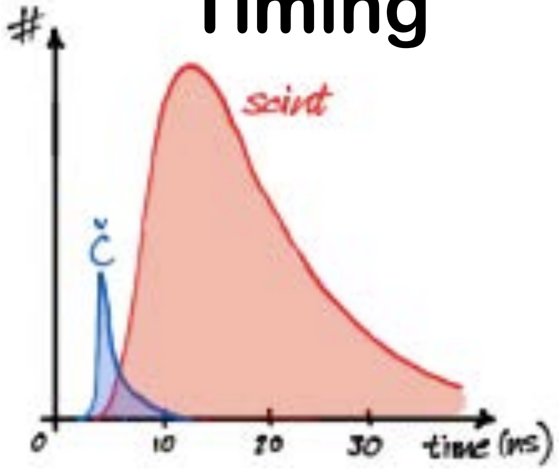
Scintillation



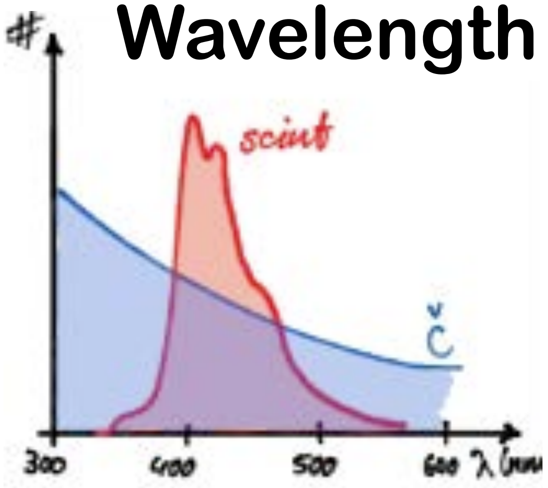
Angular distribution

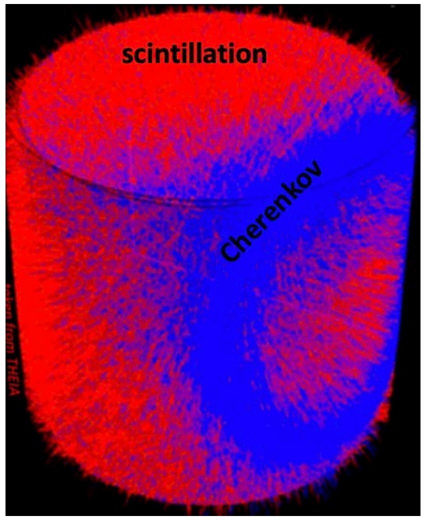


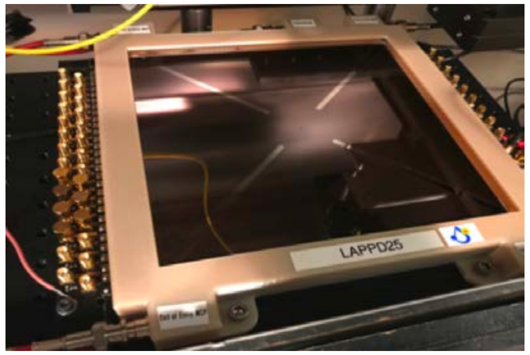
Timing



Wavelength





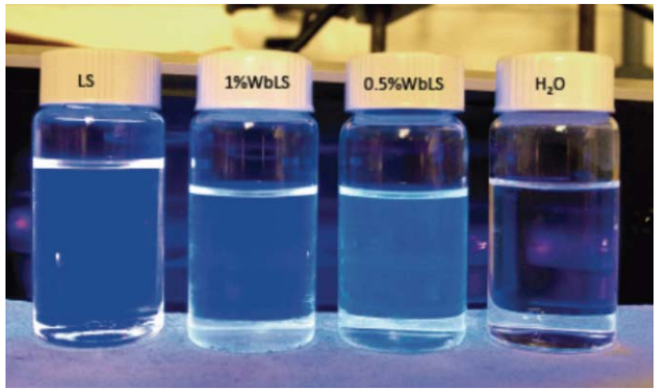


B.W.Adams et al. NIM A Volume 795, 1 (2015)

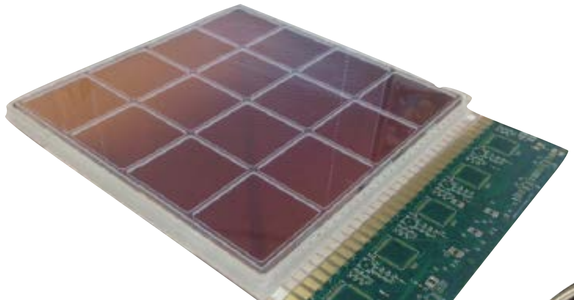
T. Kaptanoglu et al.
Phys. Rev. D 101, 072002 (2020)

Enabling technology

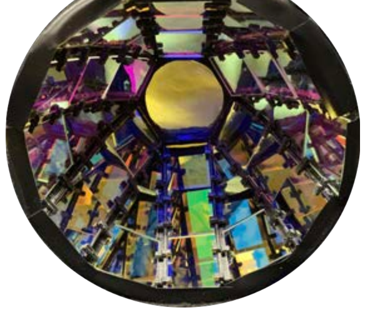
We focus our studies on three technologies that optimize hybrid Cherenkov/scintillation detection:



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



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



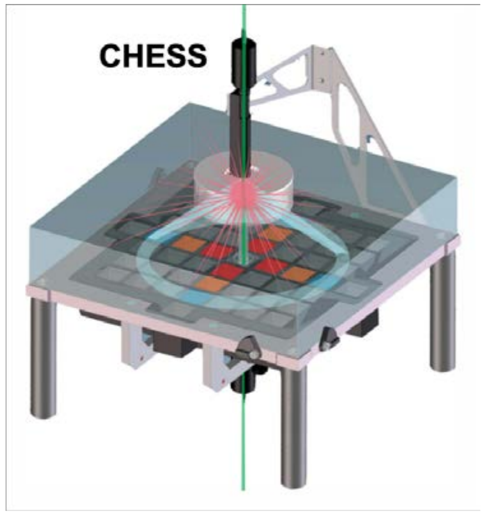
3. Dichroicons ("chromatic quantum sensing"). Cherenkov/scintillation separation via spectral sorting

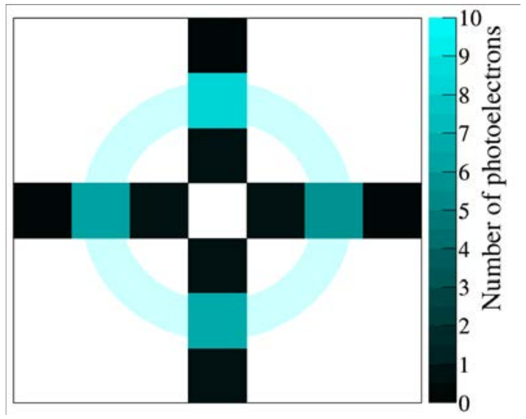
We seek to characterize behavior, understand and model performance at a microphysical level, and use results to extrapolate performance to kton scales.

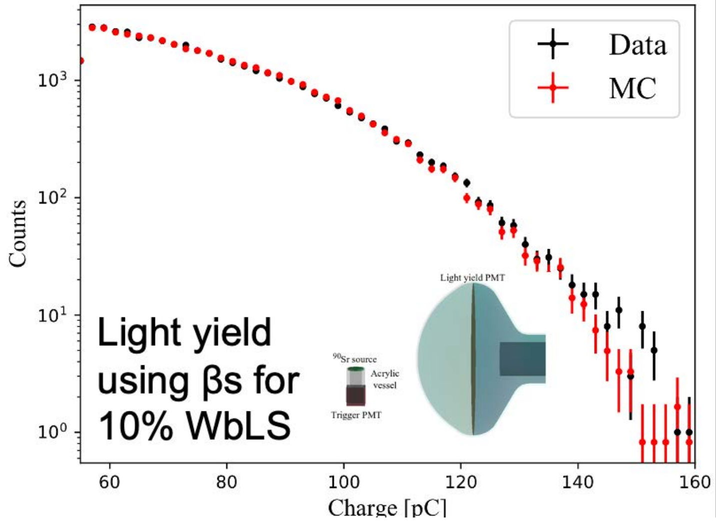
Builds on core (Wb)LS development at BNL (Yeh et al.)

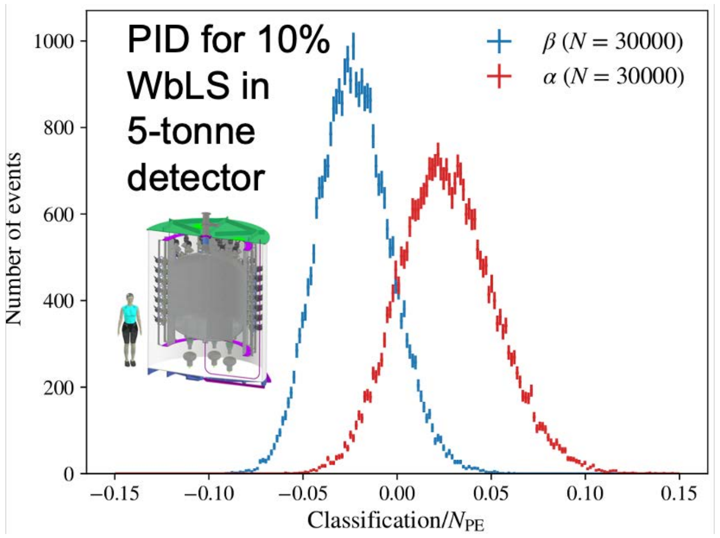
Technical accomplishments

WbLS characterization

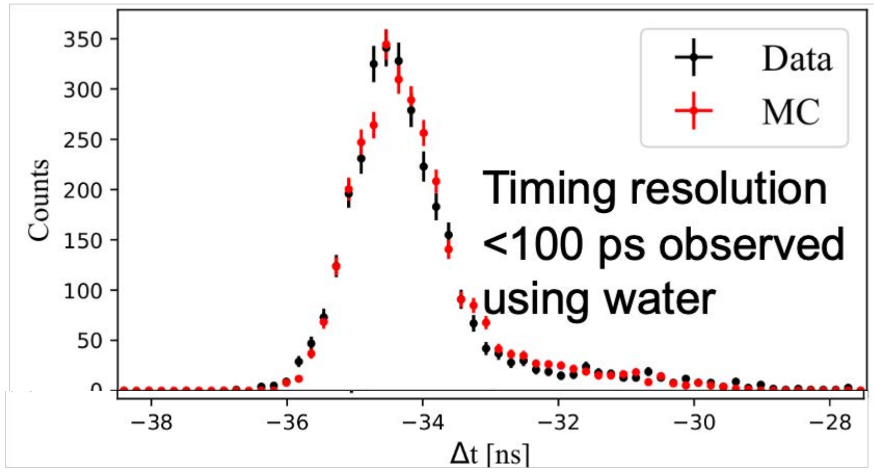


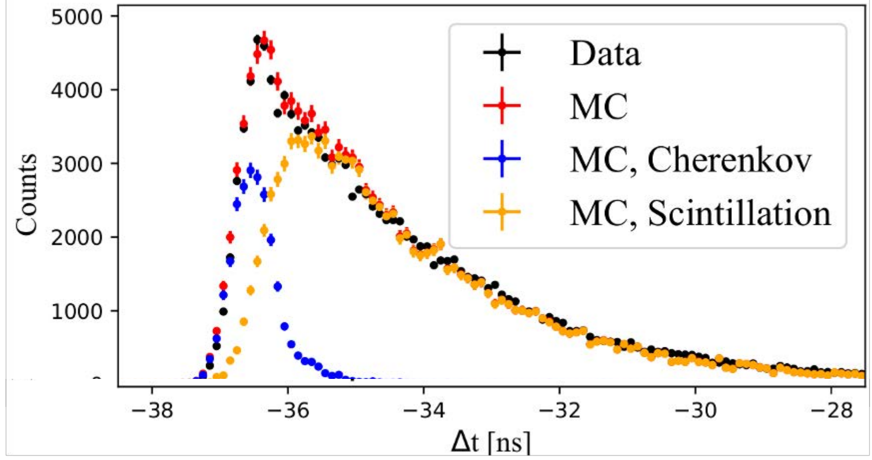



Light yield using βs for 10% WbLS

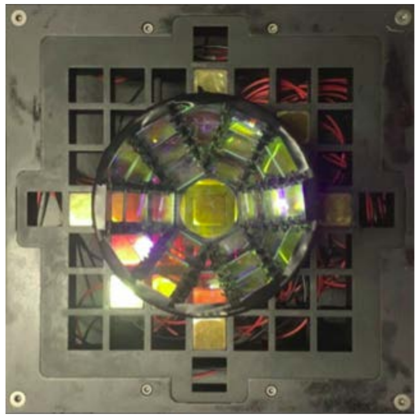

PID for 10% WbLS in 5-tonne detector

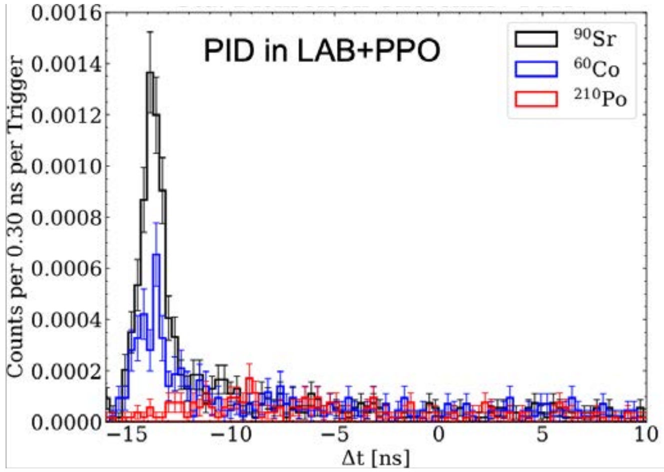
Fast timing photon detection


Timing resolution <100 ps observed using water



Quantum chromatic sorting




PID in LAB+PPO

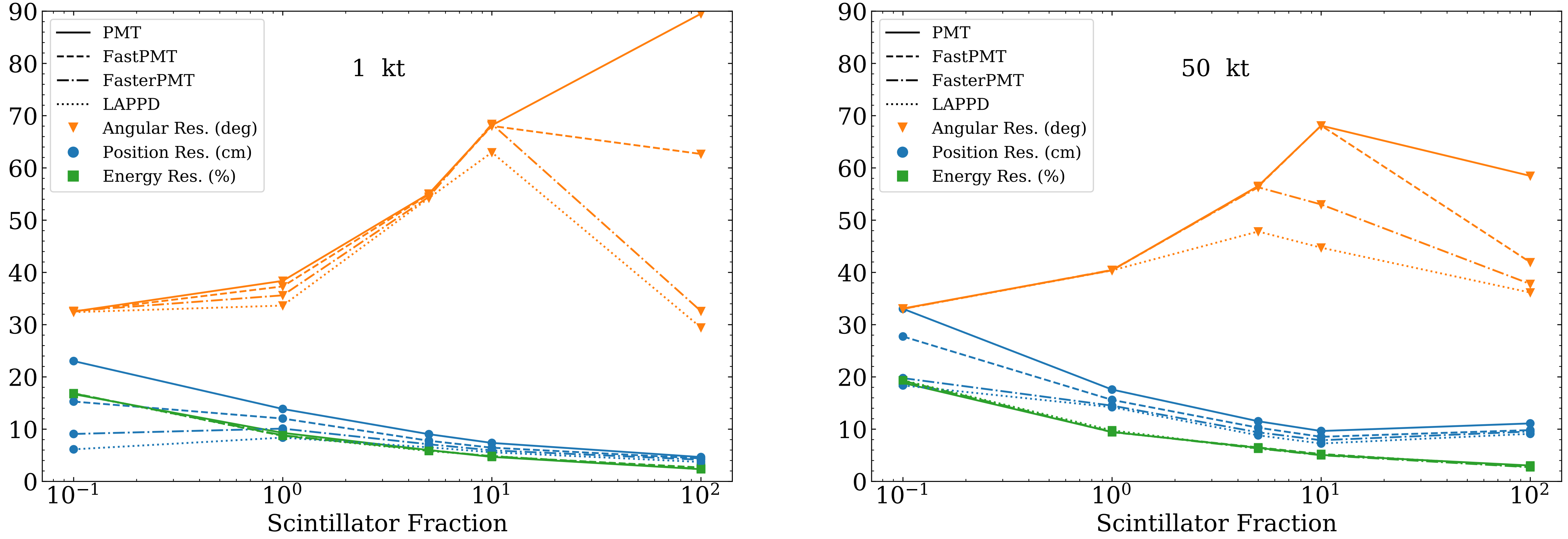
D. Onken et al., Mater. Adv. 1, 71-76 (2020); J. Caravaca et al., Eur. Phys. J. C 80, 867 (2020); E. Callaghan et al., Eur. Phys. J. C 83, 134 (2023); E. Callaghan, T. Kaptanoglu, M. Smiley et al., paper in prep.; J. Caravaca et al., Phys. Rev. C 95, 055801 (2017); J. Caravaca et al., Eur. Phys. J. C 77, 811 (2017); T. Kaptanoglu, E. Callaghan et al., Eur. Phys. J. C 82-2 (2022) 169; T. Kaptanoglu et al., Phys. Rev. D 101, 072002 (2020); S. Naugle et al., paper in prep.

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*

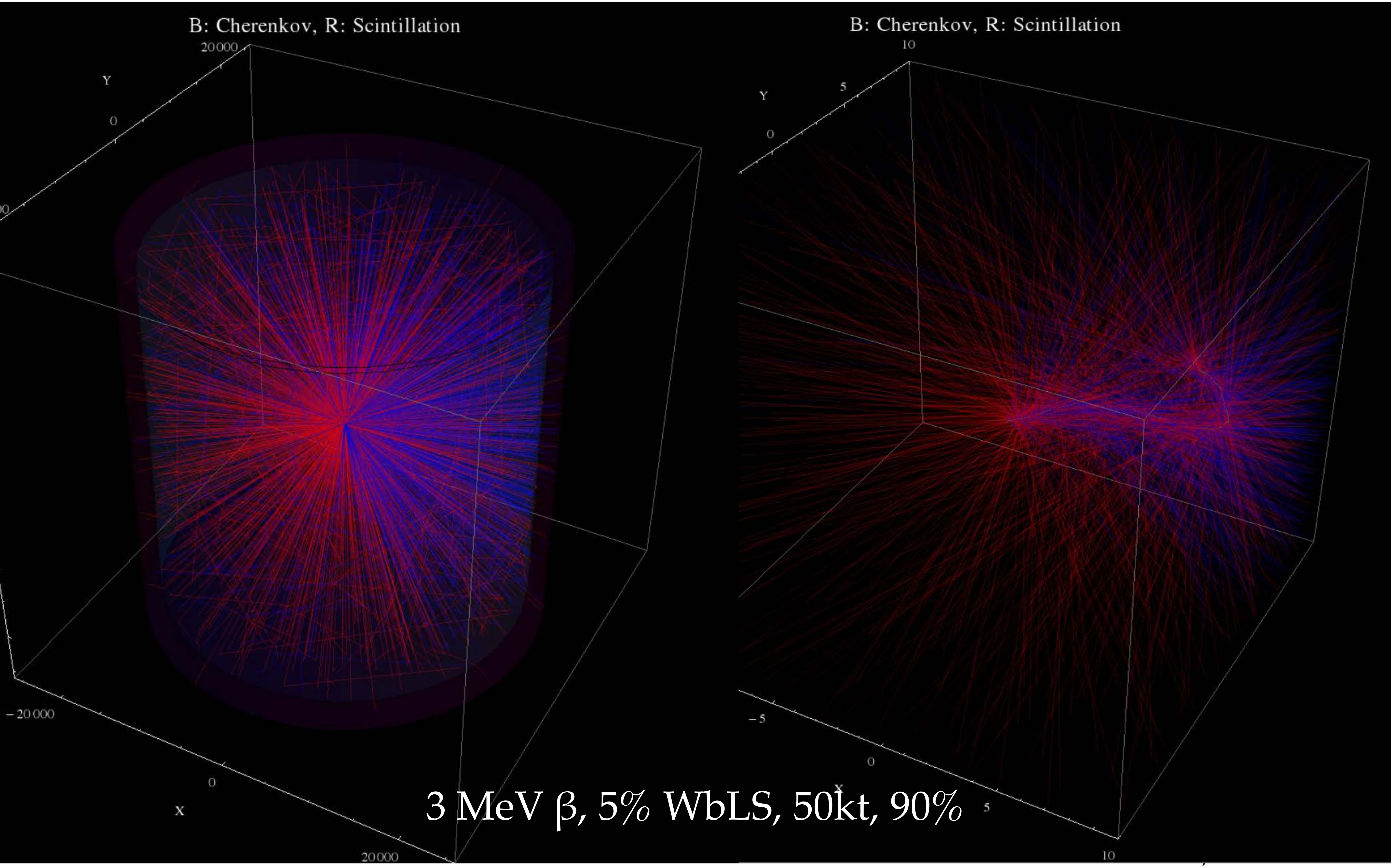
These tools can be used to define "desired" properties for WbLS



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

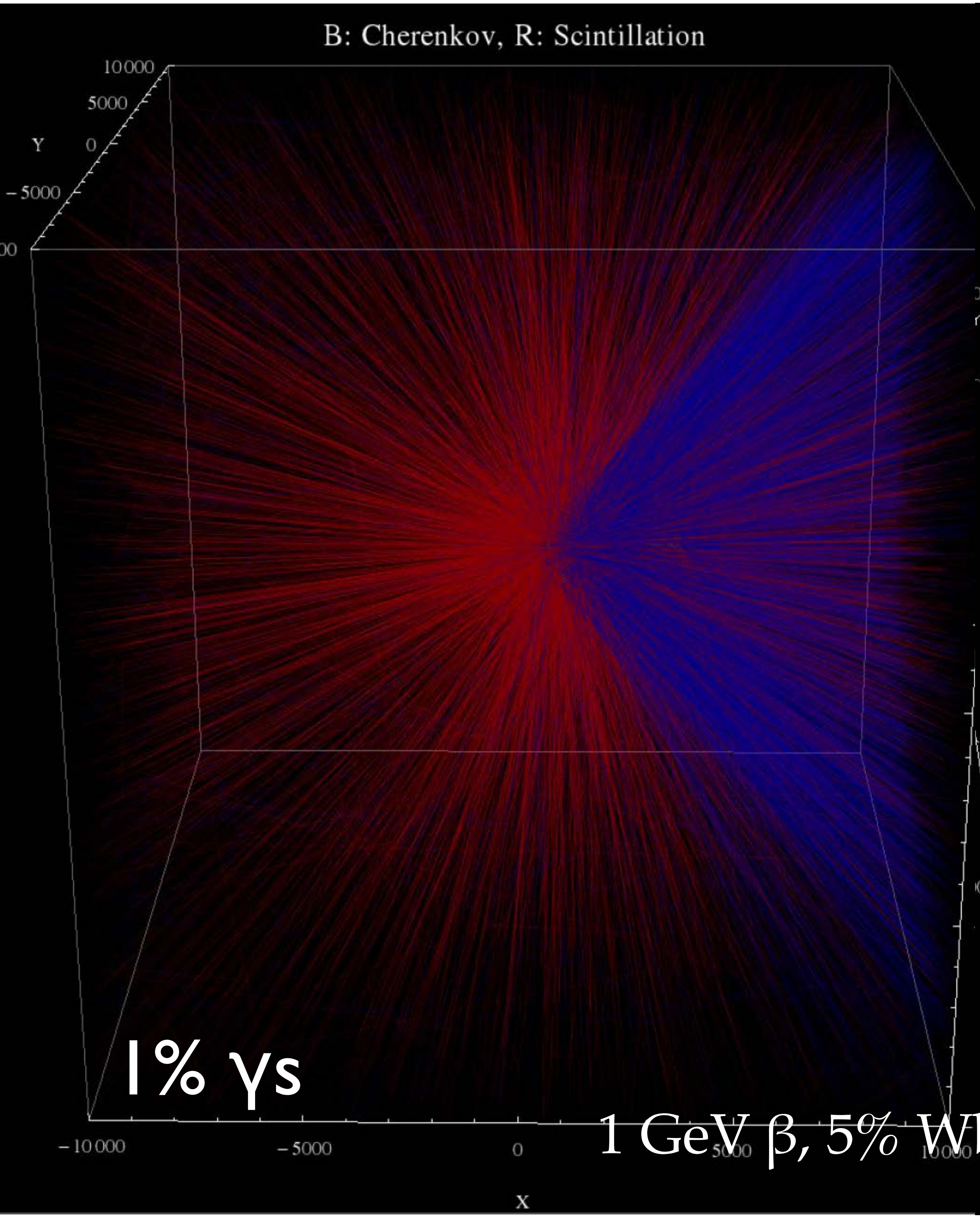
Phys. Rev. D ***103*** *052004 (2021)*

Signal Separation in Theia

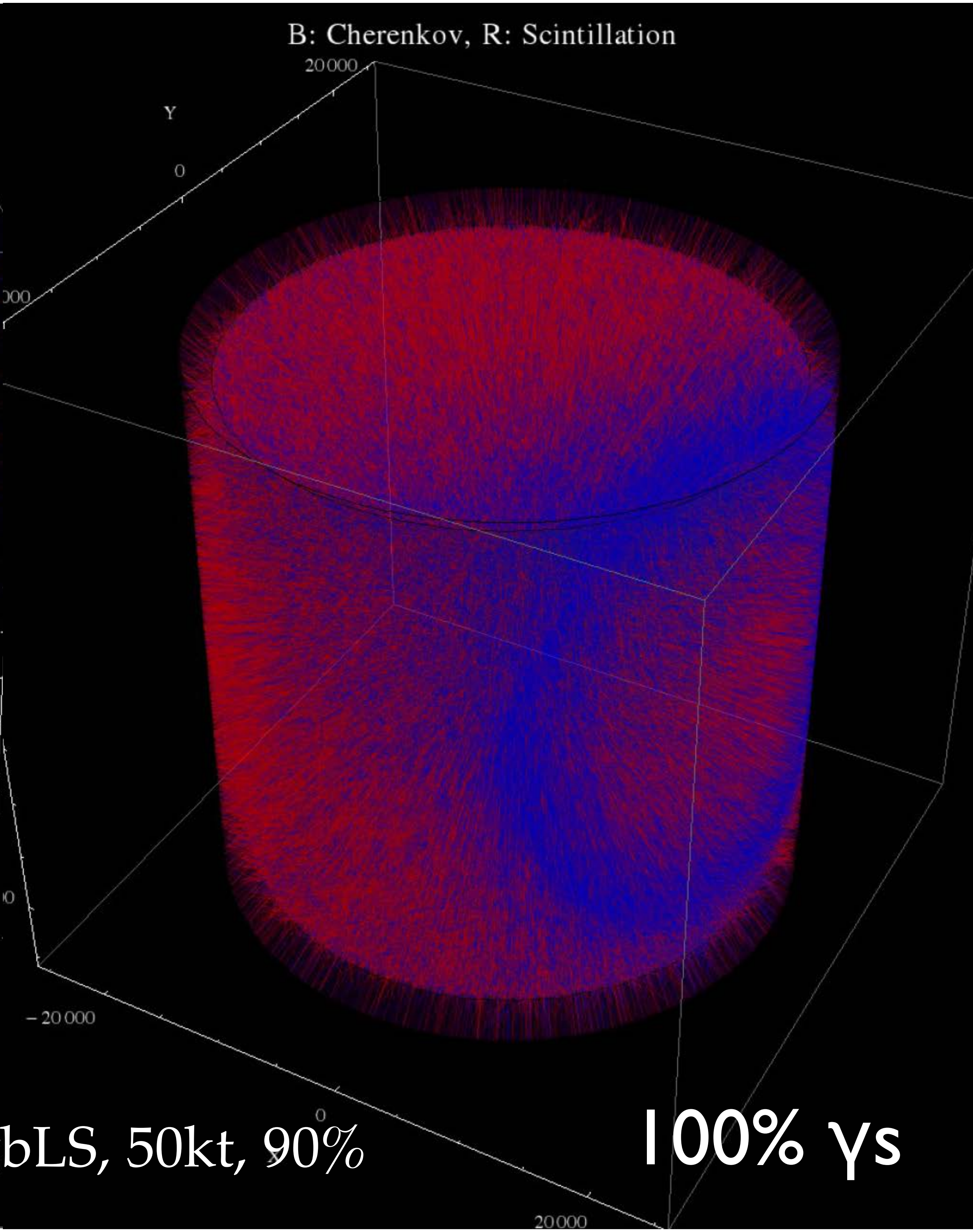


3 MeV β, 5% WbLS, 50kt, 90%

Ring Imaging



1% γs



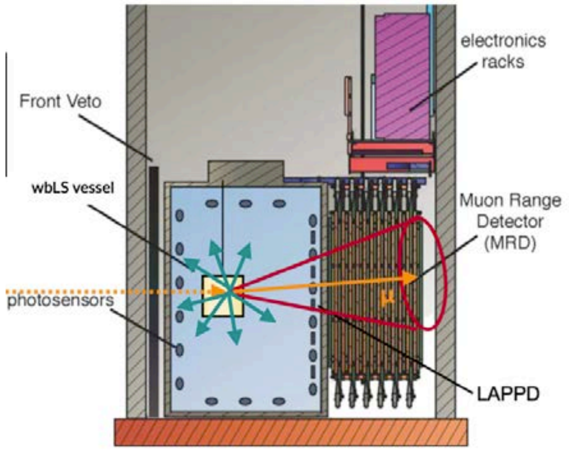
1 GeV β, 5% WbLS, 50kt, 90%

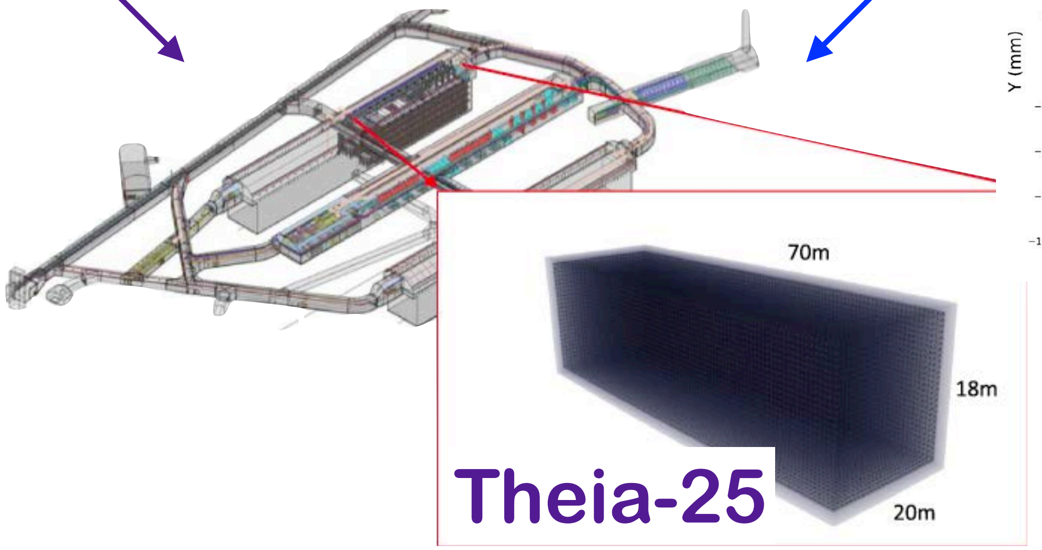
100% γs

The path to THEIA

High-energy event reconstruction, neutrino detection

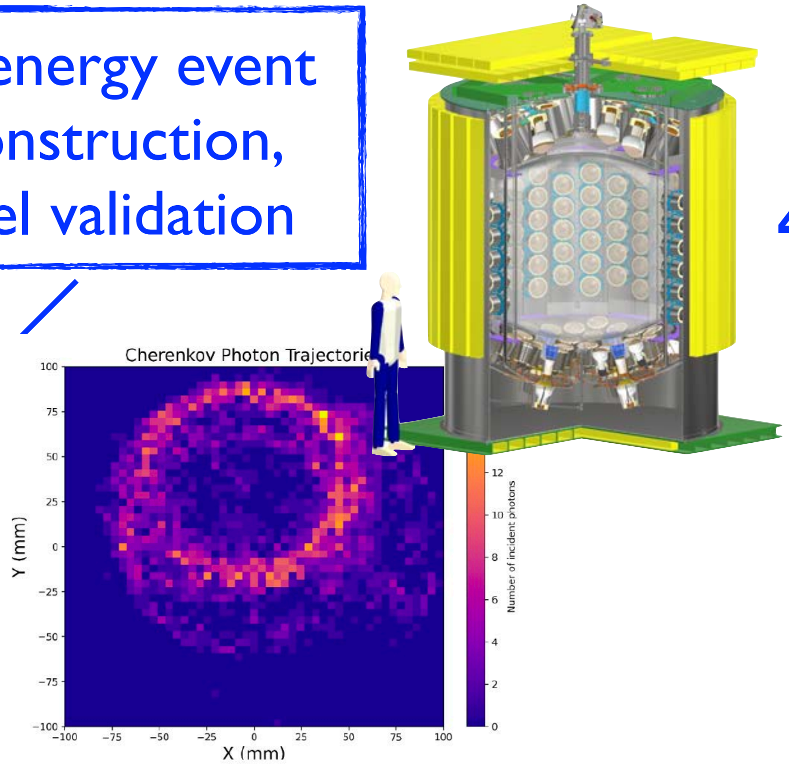
ANNIE: 365 kg





Low-energy event reconstruction, model validation

Eos: 4 ton



NuDot: 1 ton

BNL: 1- and 30-ton

Deployment, purification, recirculation, transparency

Isotope loading, NLDBD topology

Broad support

Topic	DNN	HEP	NP	NSF
WbLS dev.	X	X		
LAPPDs		X		
Dichroicons	X	X		
APP		X		
Metal loading			X	X
ANNIE		X		
Eos	X			
BNL-30ton	X			
SNO+			X	
NuDot				X
Borexino				X

Eos (Dawn)

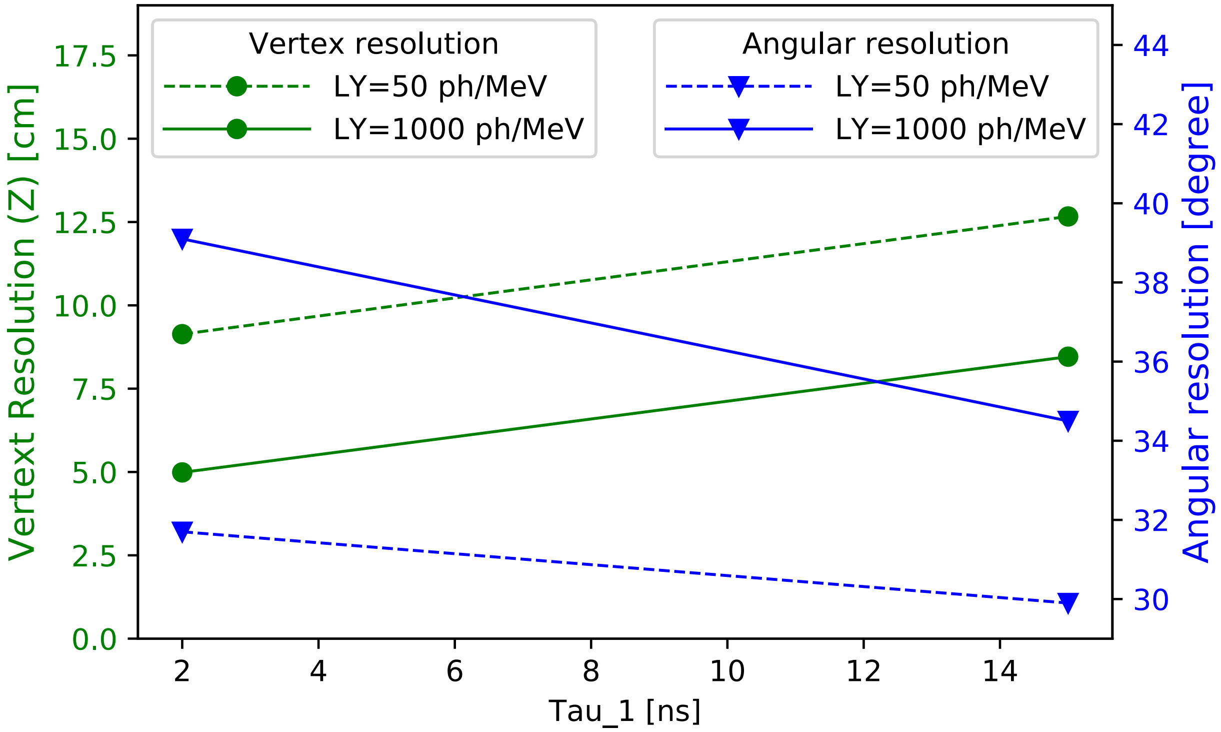
Funded by NNSA,
DNN R&D
FY22-24

Let There be Light

EOS: performance demonstrator

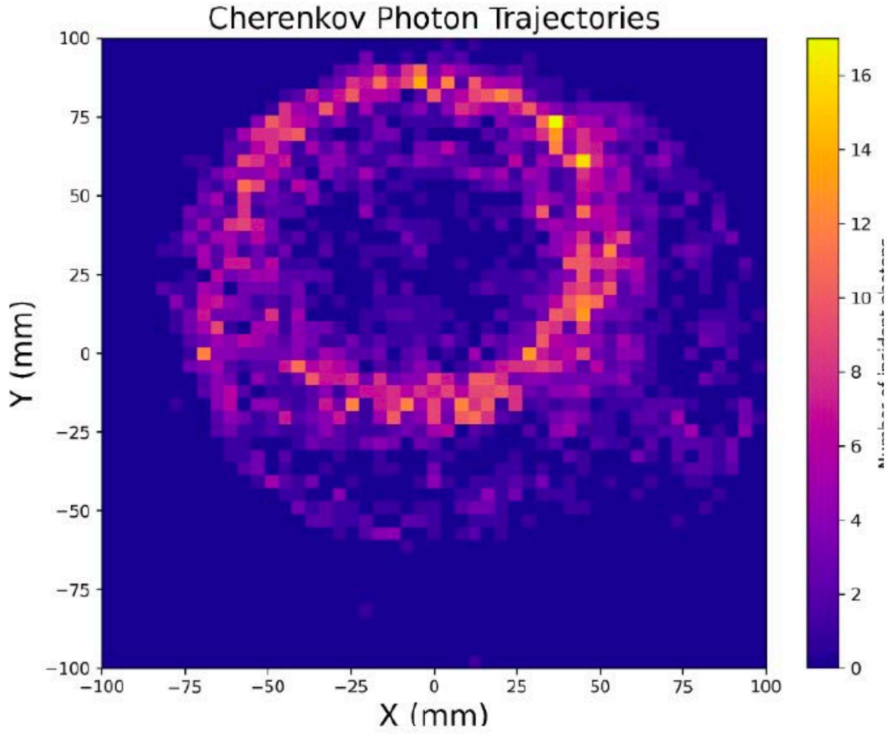
Project goals:

- 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

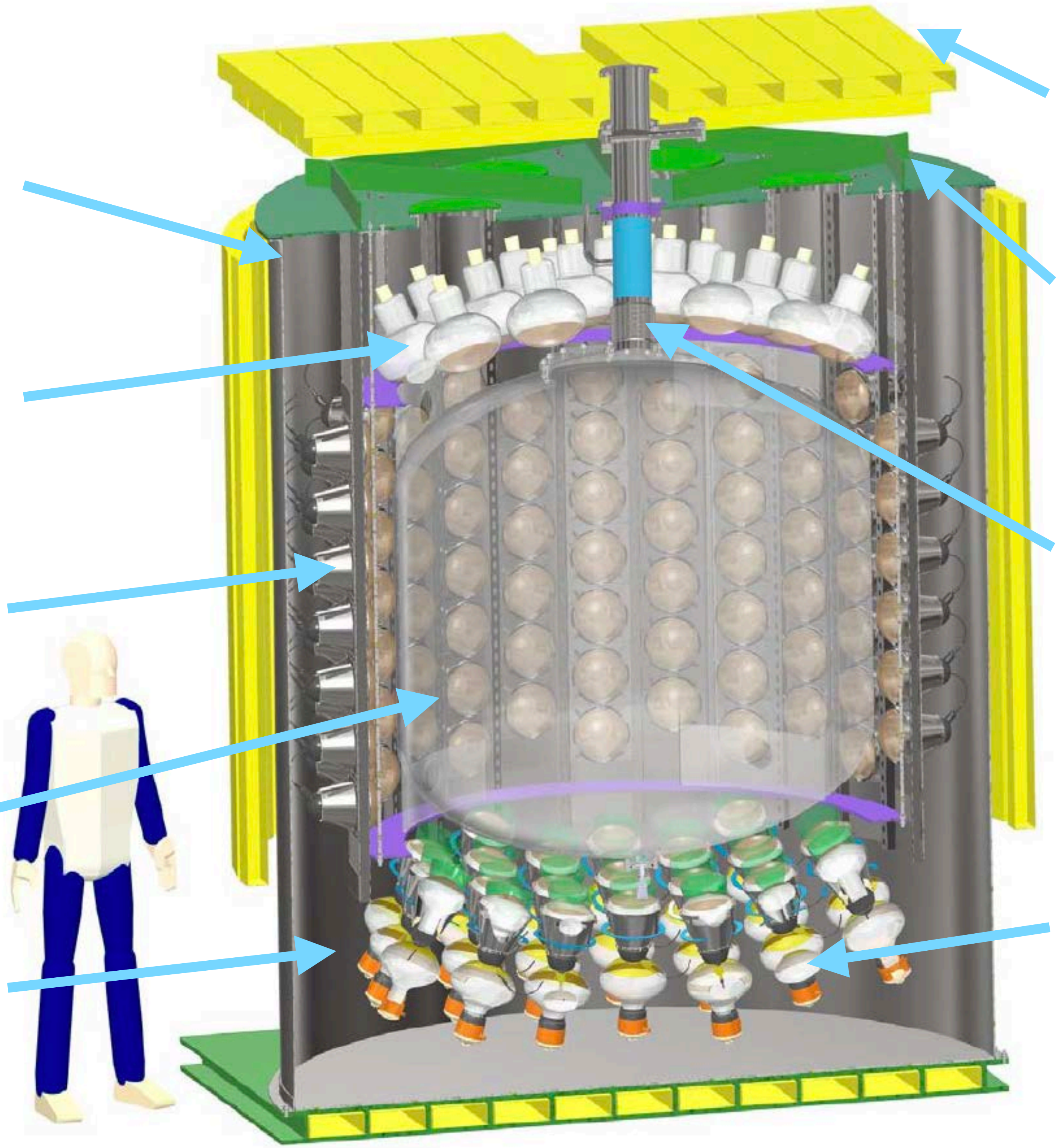


Approach: *design, construct and operate an integrated testbed to demonstrate the performance of novel technology*

- 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



EOS Detector design



~11-ft 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

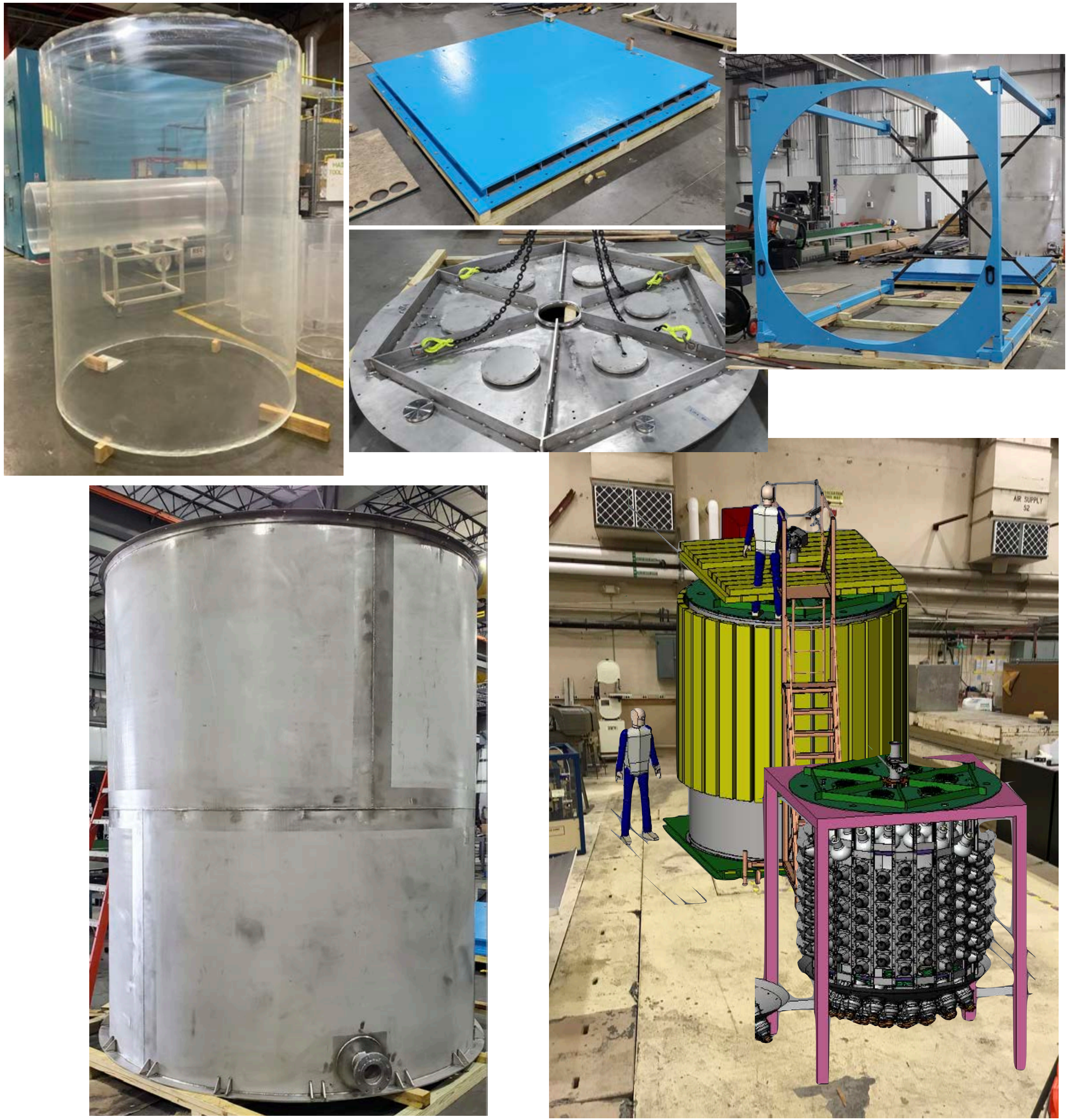
Central-axis calibration source deployment

Dichroicon deployment

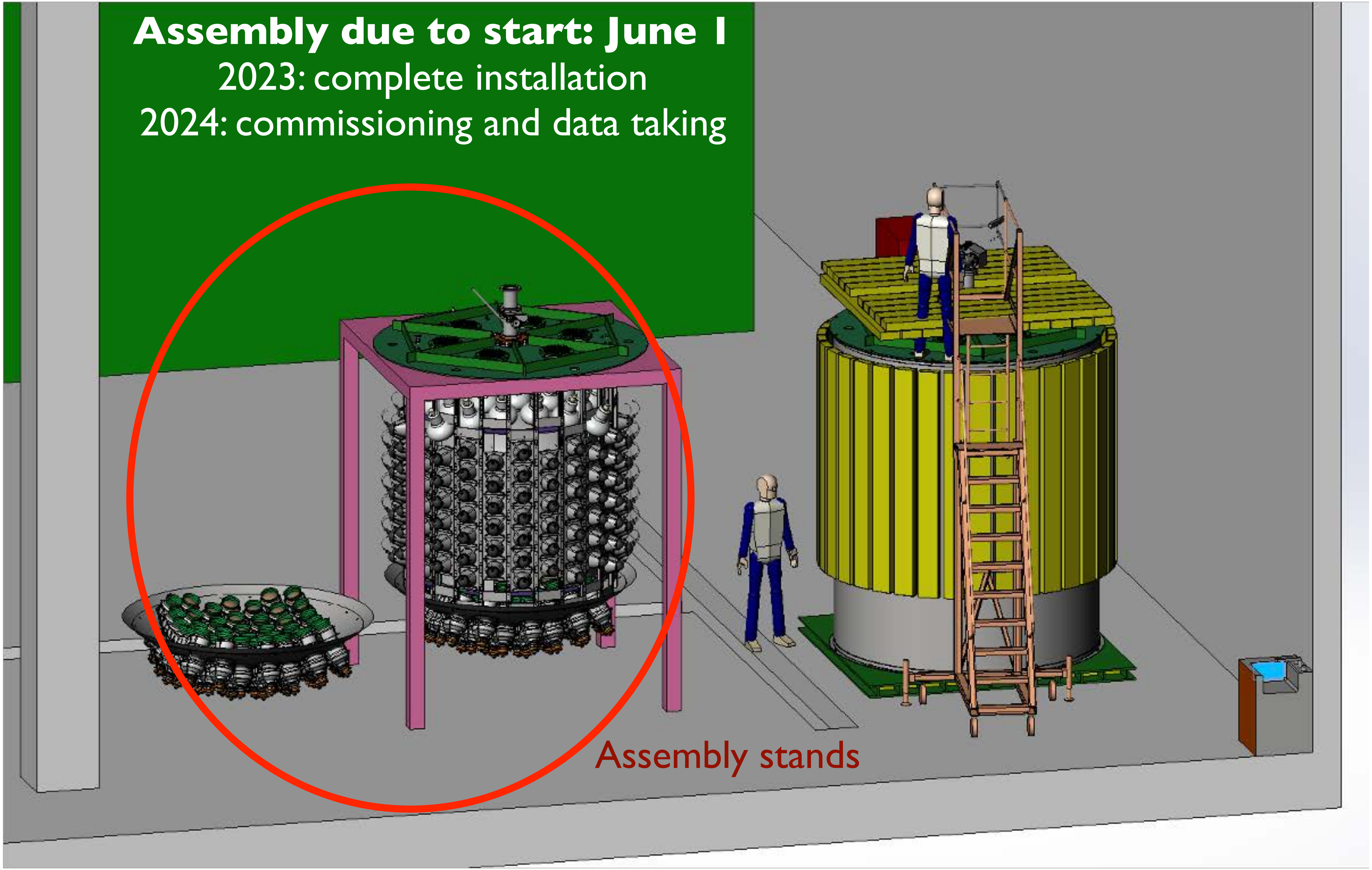
EOS paper published:
JINST 18 P02009 (2023), https://doi.org/10.1088/1748-0221/18/02/P02009

Status

- IV under contract, delivery due June ’23 (Reynolds Polymer)
- OV: seismic engineering complete, under contract, delivery due June ’23 (C&C Industrial)
- PMT support design complete, prototyping and purchase
- Hamamatsu PMTs (206x fast 8”), batch delivery Nov ’22 — Jul ’23 (128 received), testing ongoing
- Digitisers & HV boards (CAEN), all received
- Calibration deployment & laser light injection systems designed
- Space available as of April 1



Deployment



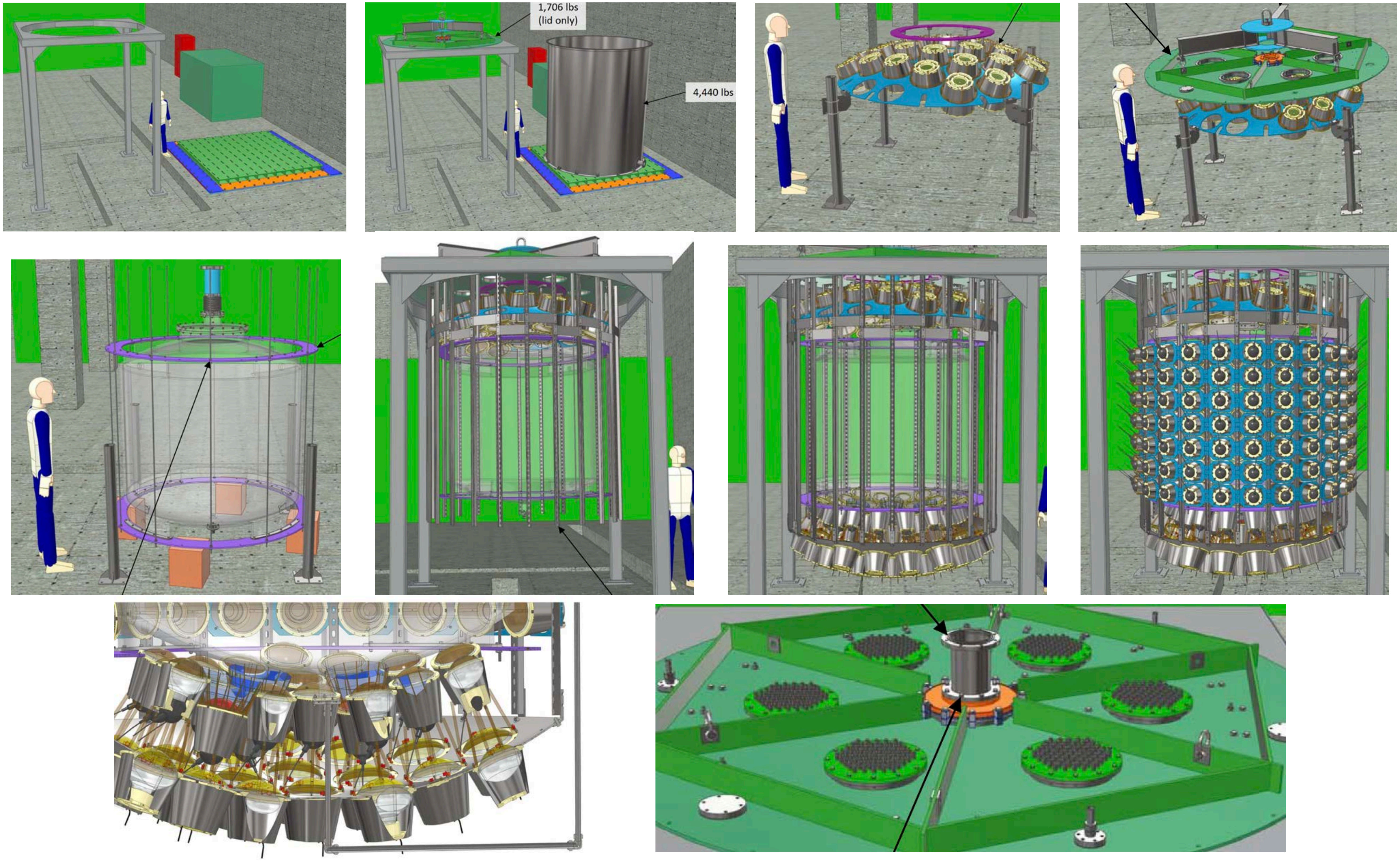
Assembly due to start: June 1

2023: complete installation

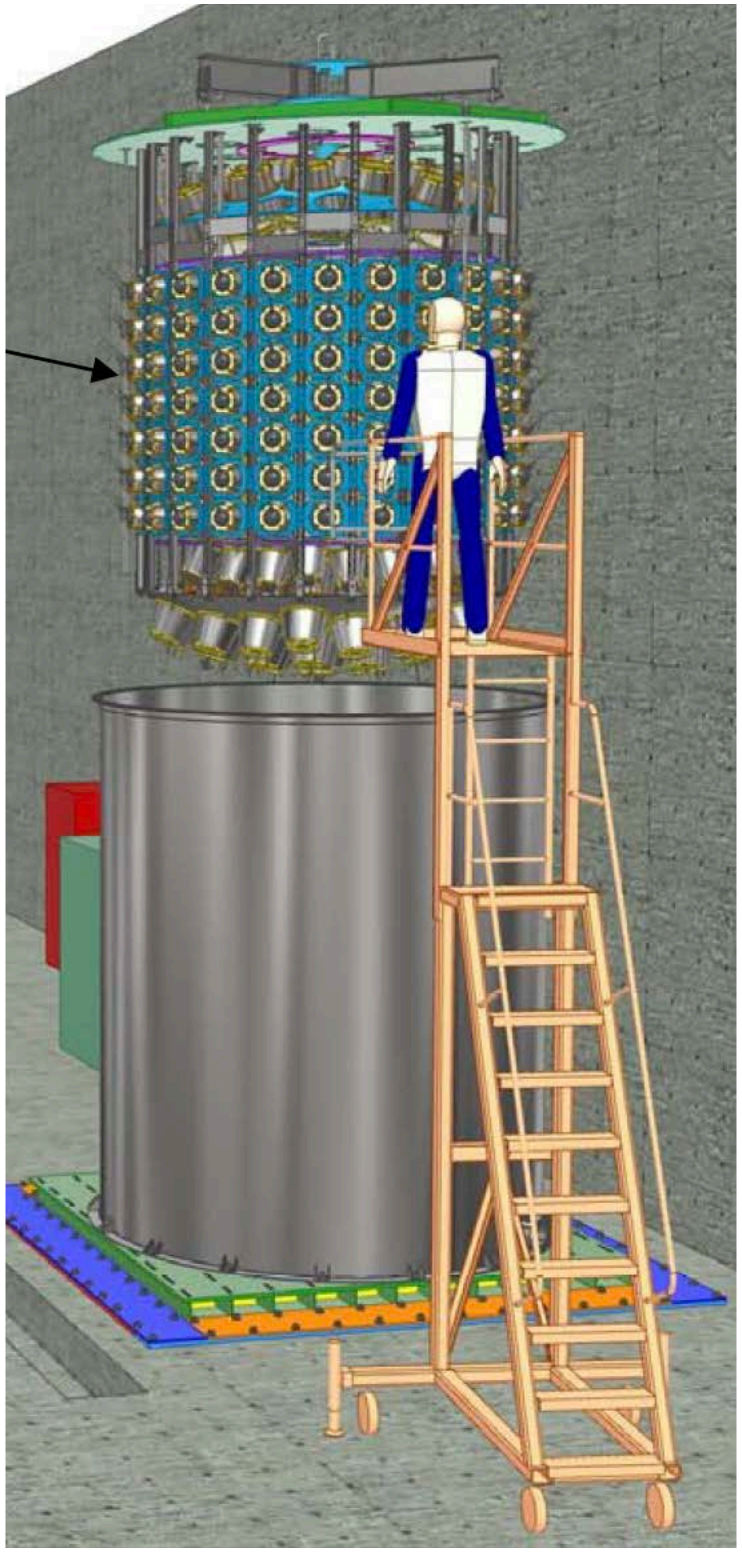
2024: commissioning and data taking

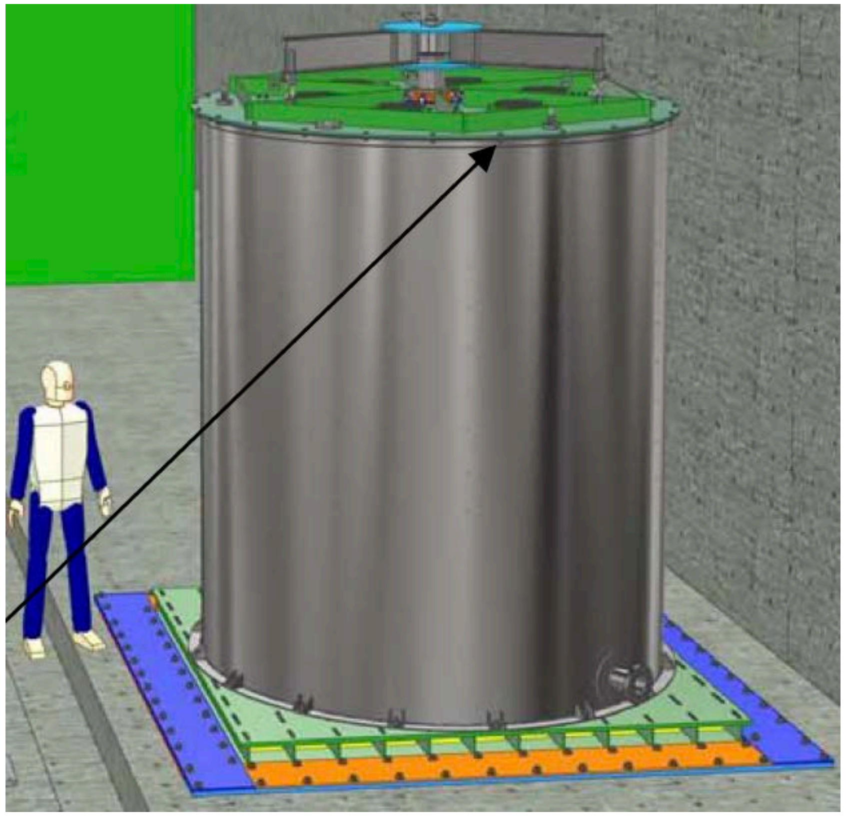
Assembly stands

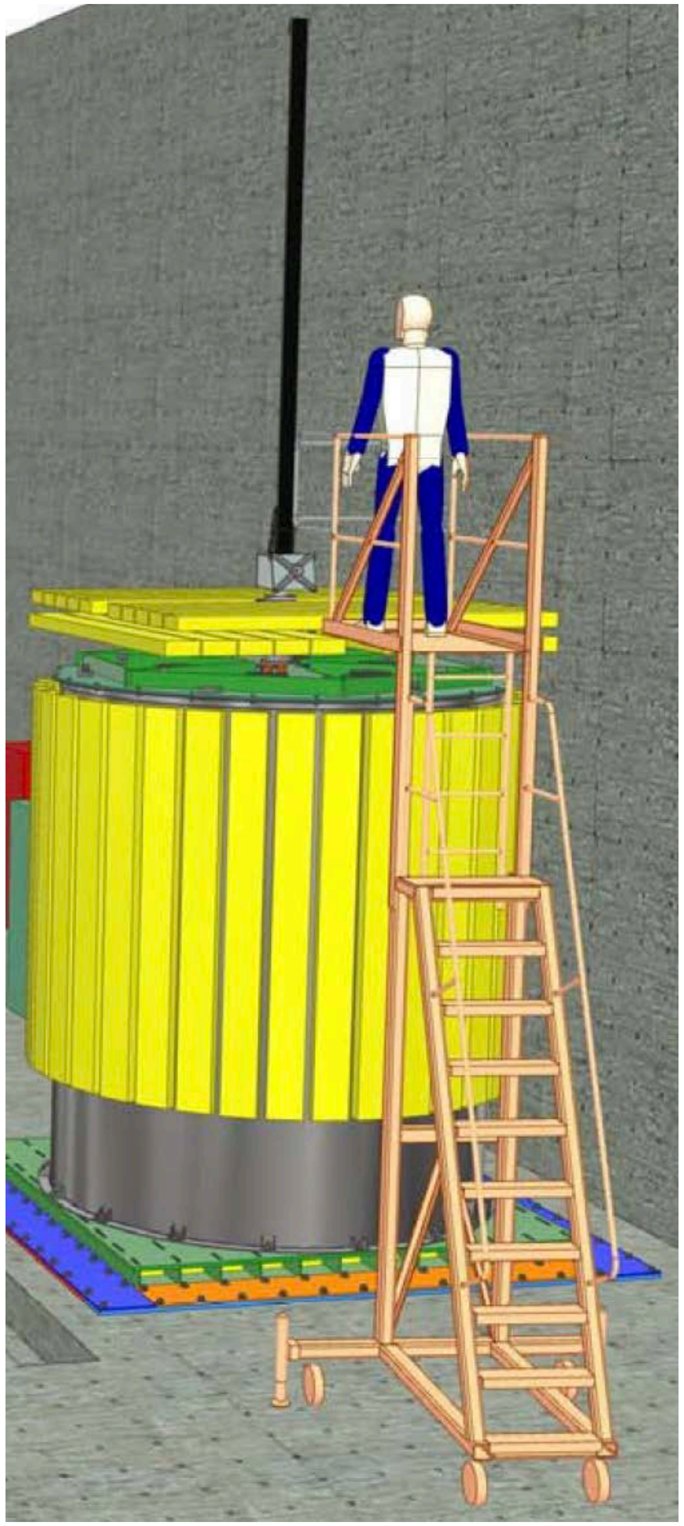
Assembly process



Assembly process





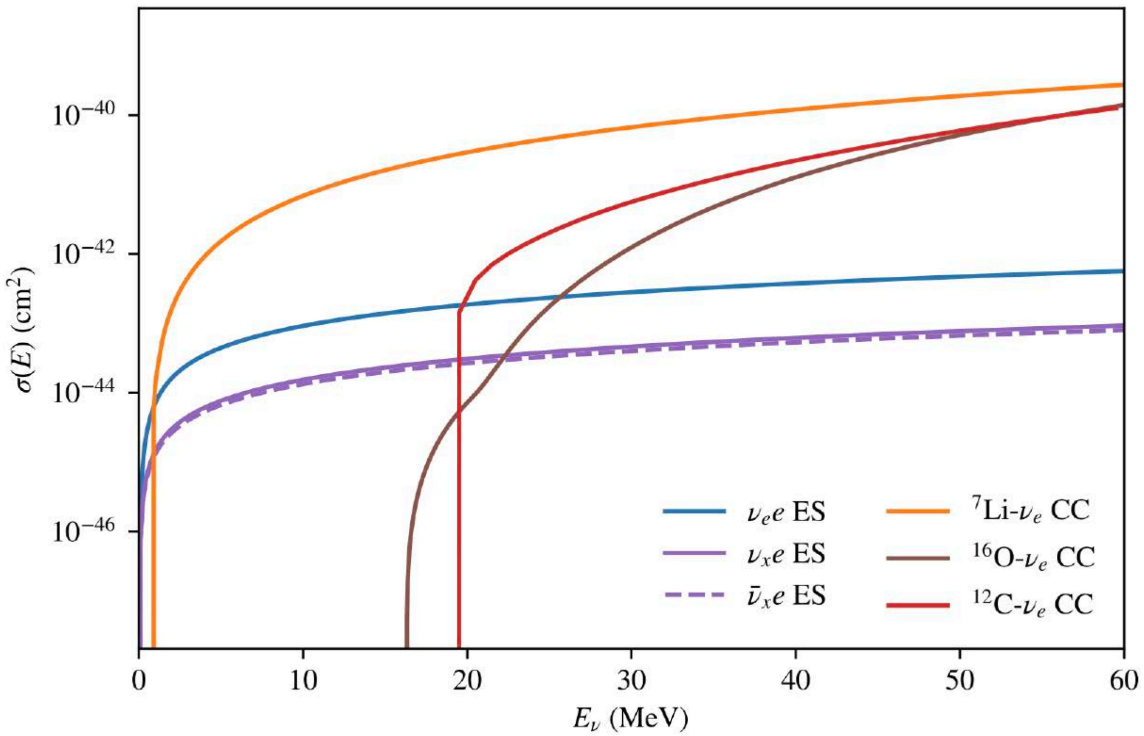


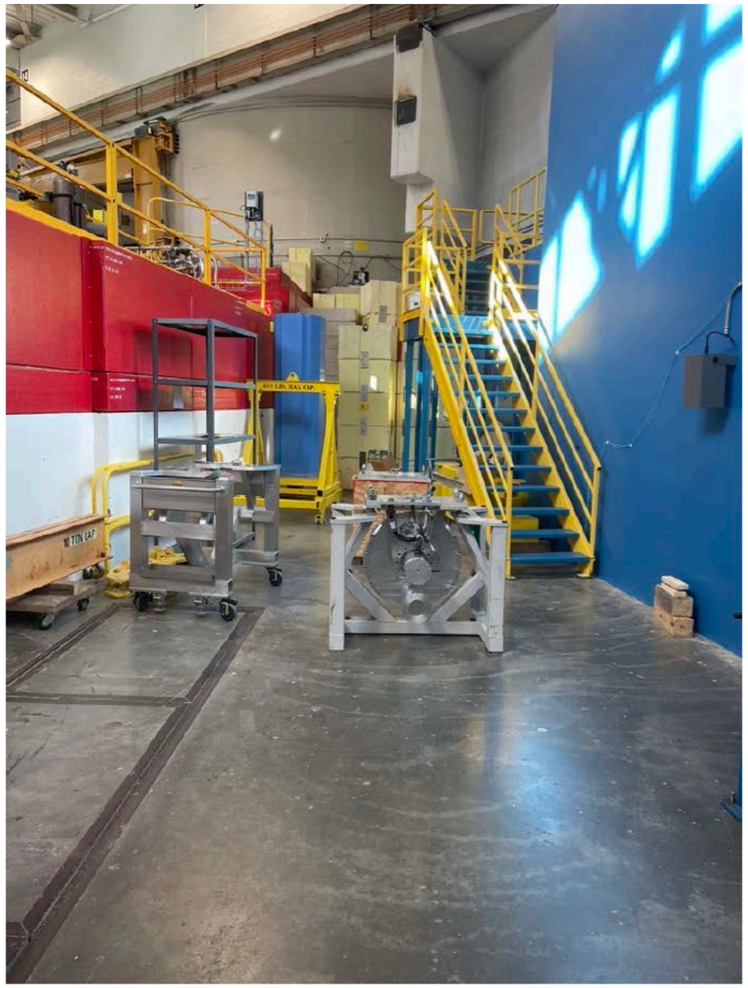
Assembly due to start:
June 1
2023: complete installation
2024: commissioning and data taking

Eos @ SNS (ORNL)

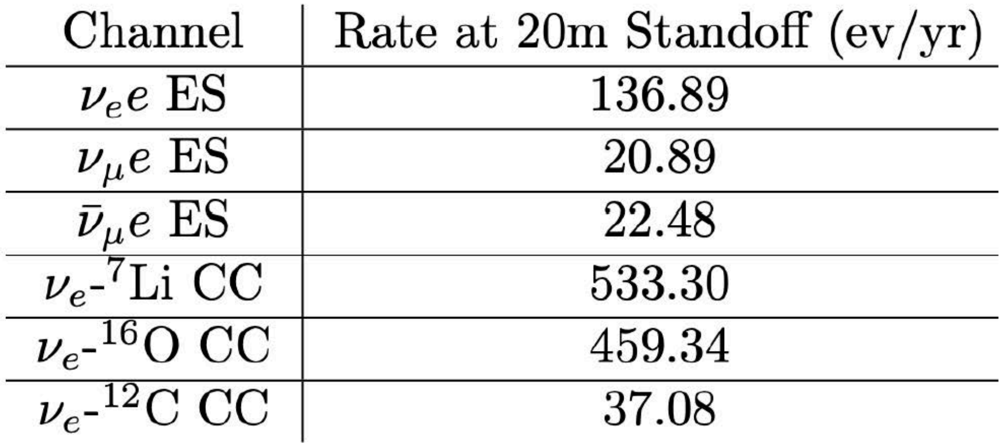
- Detection of IBD and ES events: directionality
- Neutron studies: background rejection
- Too large for neutrino alley: alternative location
- Later stage: Li-loaded WbLS (5% organic, 10% Li)
  - Enhanced ν_e detection : CC on ^{7}Li

neutrino cross-sections in LiWbLS





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

Thanks to the EOS team!

Grad students
Undergrad students

USA

BERKELEY LAB
The University of California Berkeley 1868
The University of California Davis
Penn University of Pennsylvania
Lawrence Livermore National Laboratory
Boston University
PennState
Iowa State
Brookhaven National Laboratory
Fermilab
Rutgers
Iowa
Bartoszek Engineering
South Dakota School of Mines & Technology
The University of Chicago 1890
University of Colorado Boulder
California State University Stanislaus

Local heroes:

ME team: J. Saba, J. Wallig
Installation lead: L. Pickard
DAQ team: R. Bonventre, E. Callaghan, G. Yang
PMT team: T. Kaptanoglu, A. Rincon, H. Ryoo
Calibration team: L. Lebanowski. N. Rowe
Analysis team: M. Askins, Z. Bagdasarian,
T. Kaptanoglu, M. Smiley


BNL, 2023


Rutgers, 2022

Germany

Johannes Gutenberg Universität Mainz
PRISMA+
Technische Universität München

Turkey

Erciyes University 1978 Research University

Portugal

LIP
Universidade de Coimbra 1290

Finland

Jyväskylän Yliopisto University of Jyväskylä

Canada

SNOLAB

THEIA (proto-)Collaboration

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

Canada
Alberta
Laurentian
Queens
SNOLAB
Toronto

China
Tsinghua

Finland
Jyvaskyla

Germany
Aachen
Dresden
Hamburg
Jülich
Mainz
TU Munich
Tübingen

Italy
SISSA/INFN

Korea
CUP

Portugal
LIP
Lisbon

Turkey
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King's College
Sheffield

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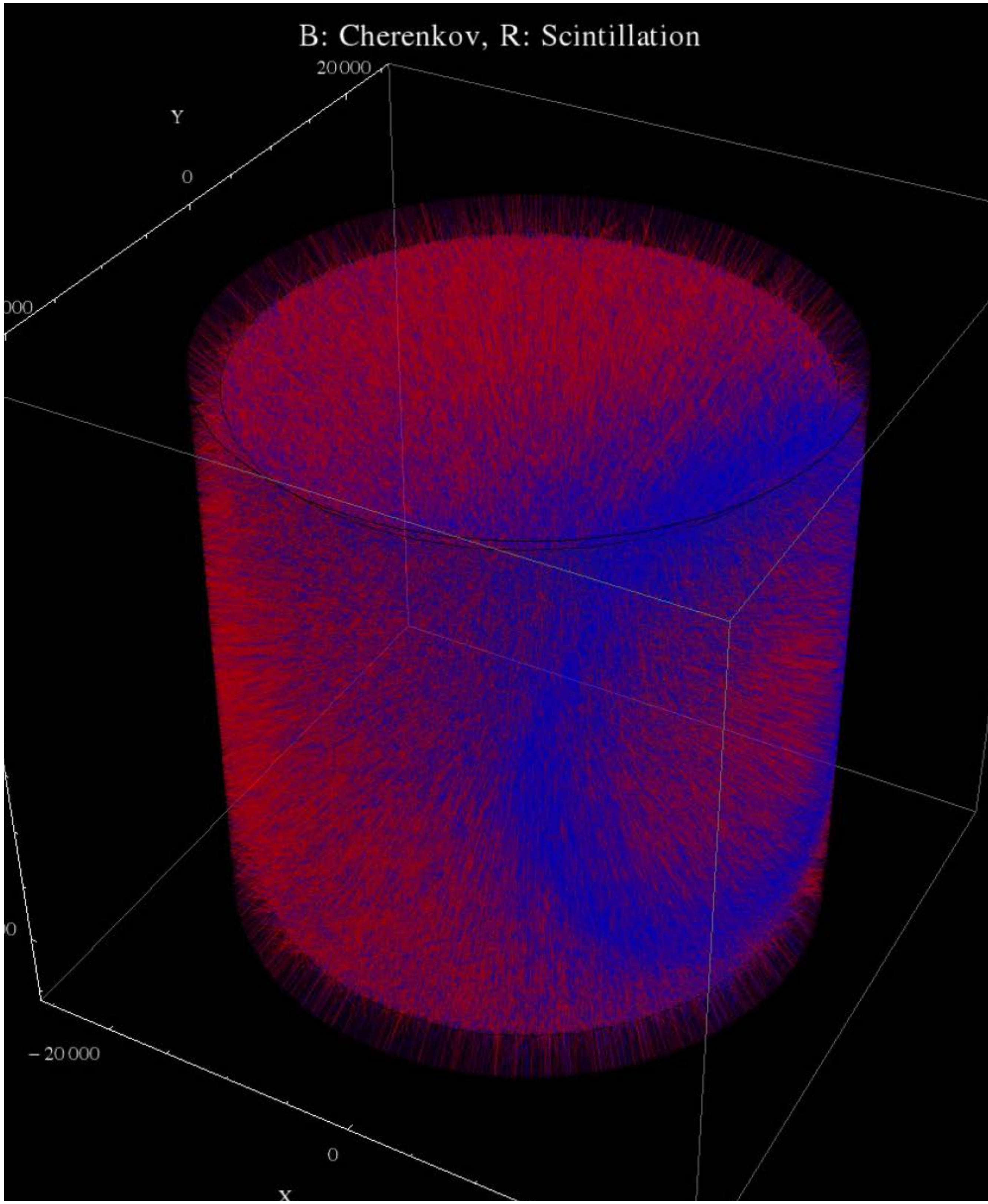
Colorado
Cornell
FNAL
U. Hawaii
Iowa
Iowa State
LBNL
LLNL
LSU
MIT
U. Penn
PNNL
Rutgers
SD SMT
Stony Brook
SURF
Temple
UC Berkeley
UC Davis
UC Irvine
UCLA

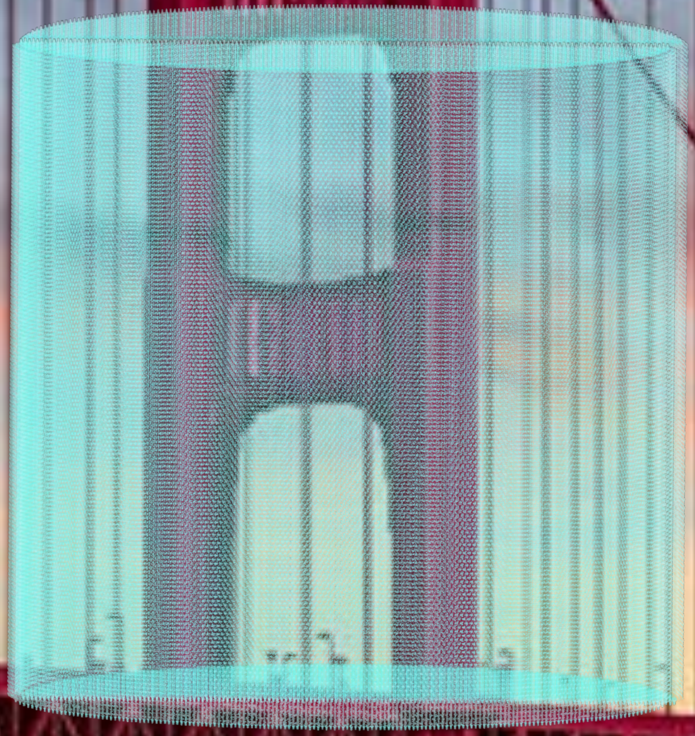
Summary

- THEIA 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
- Major technological developments have been achieved
- Results from existing large detectors demonstrate the conceptual feasibility
- Prototypes underway will demonstrate the full range of capabilities



Thank you

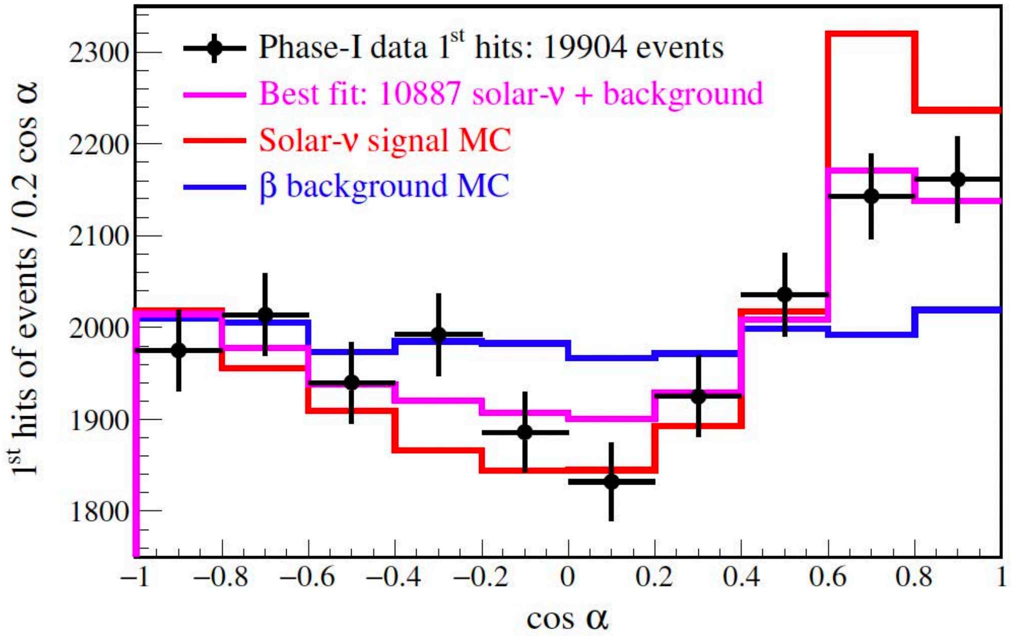
This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of High Energy Physics, under Award Number DESC0018974. Work conducted at Lawrence Berkeley National Laboratory was performed under the auspices of the U.S. Department of Energy under Contract DEAC02-05CH11231.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



Back up

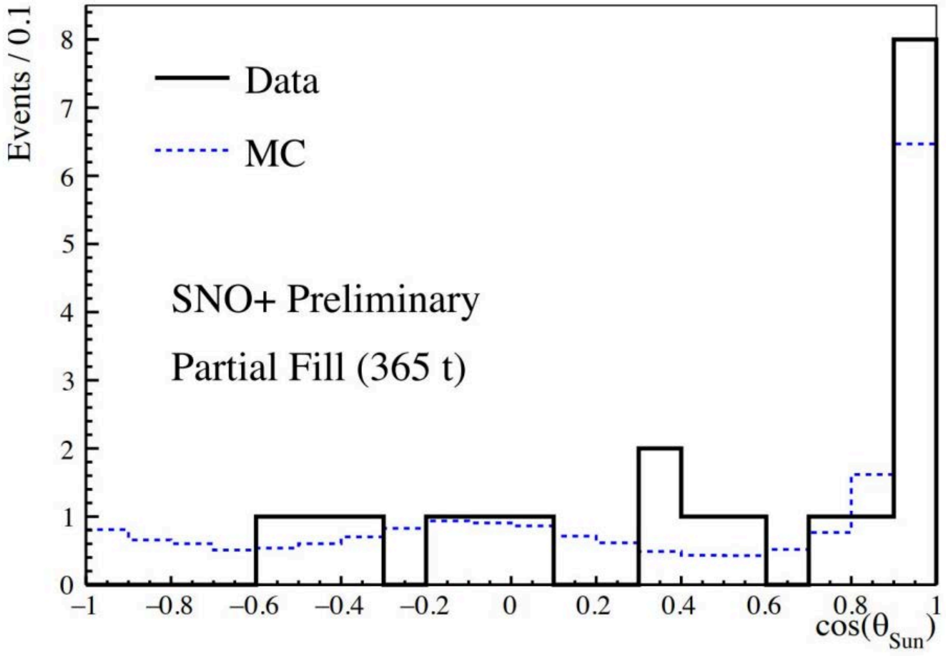
Full-scale demonstrations

- 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

- 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

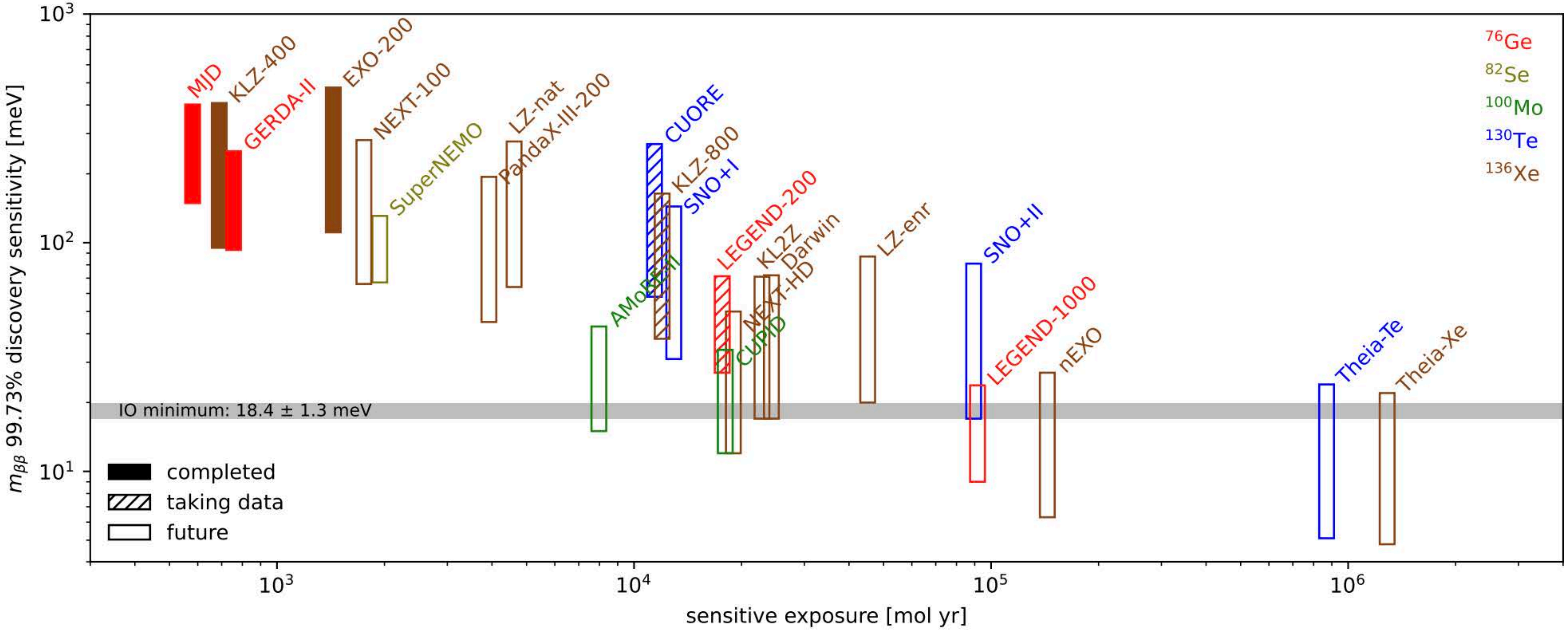


SNO+, L. Lebanowski APS talk

Physics program

Primary physics goal	**Reach**	**Context**
Long-baseline oscillations	$>5\sigma$ for 30% of δ_{CP}	Comparable / complementary to DUNE
Nucleon decay $p \rightarrow \bar{\nu} K^+$	$T > 3.8 \times 10^{34}$ year	Complementary to DUNE (sensitive to different modes)
Supernova burst	<1(2)° pointing 20K(5K) events	Complementary to DUNE (nu vs anti-nu)
Diffuse Supernova Neutrino	5σ	Beyond DUNE reach
CNO neutrinos	<5(10)%	Beyond DUNE reach
Geoneutrinos	< 7 %	Beyond DUNE reach
$0\nu\nu\beta$	$T_{1/2} > 1.1 \times 10^{28}$ year (90%C.L.)	Beyond DUNE reach

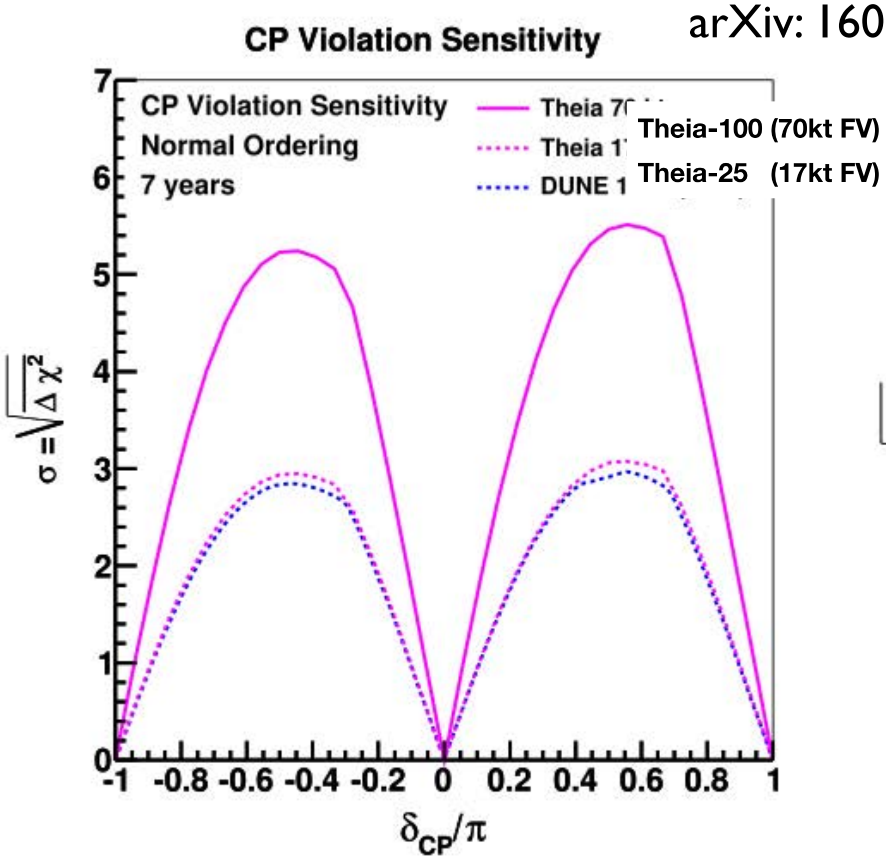
Sensitivity

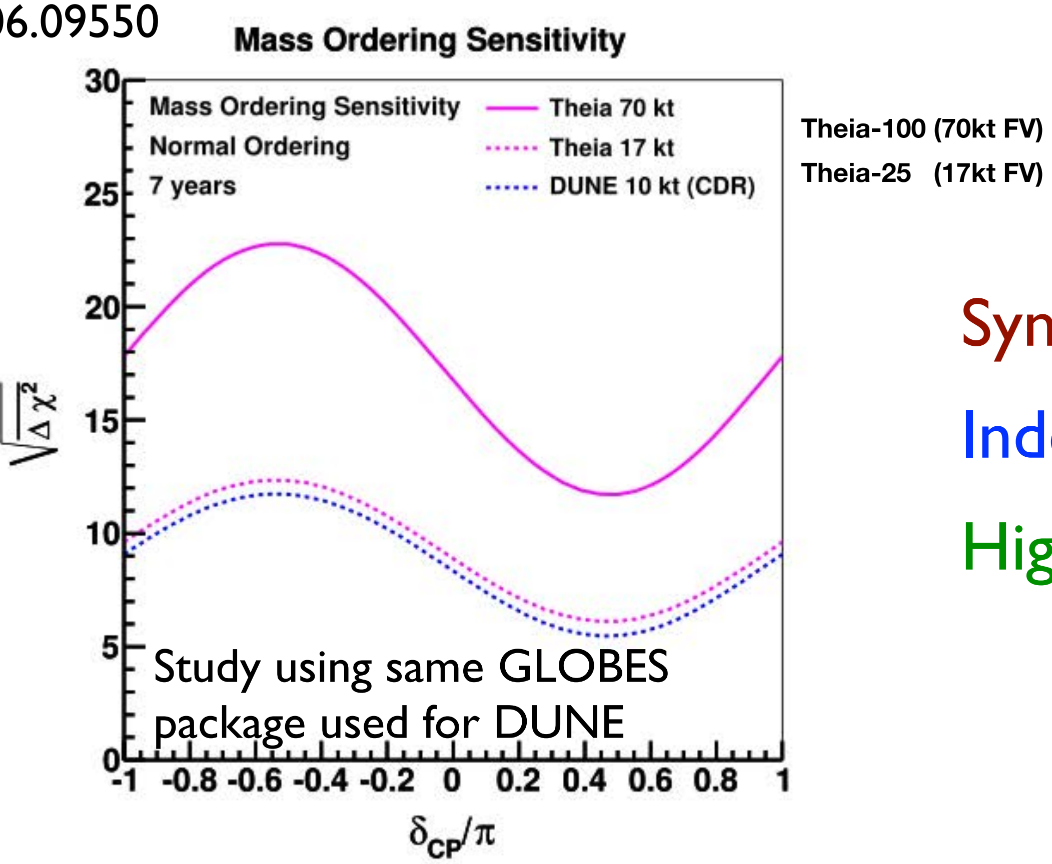


NP-LRP White Paper on neutrino less double beta decay, by the NP community: https://arxiv.org/pdf/2212.11099.pdf

Long-Baseline Sensitivity

arXiv: 1606.09550





Study using same GLOBES package used for DUNE

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

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

Near Detector ideas: SAND

System for on-Axis Neutrino Detection (SAND)

a) Straw-tube tracker designed to monitor beam flux and spectrum

b) Different detector, target, and interaction systematics from LArTPC — important point of comparison and systematic crosscheck for ND-LAr

   i. Integrated pure C (graphite) target

   ii. "Solid" hydrogen target from a subtraction of CH2 & C

   iii. Interactions on oxygen from subtraction between polyoxymethylene (delrin) and default CH2 targets

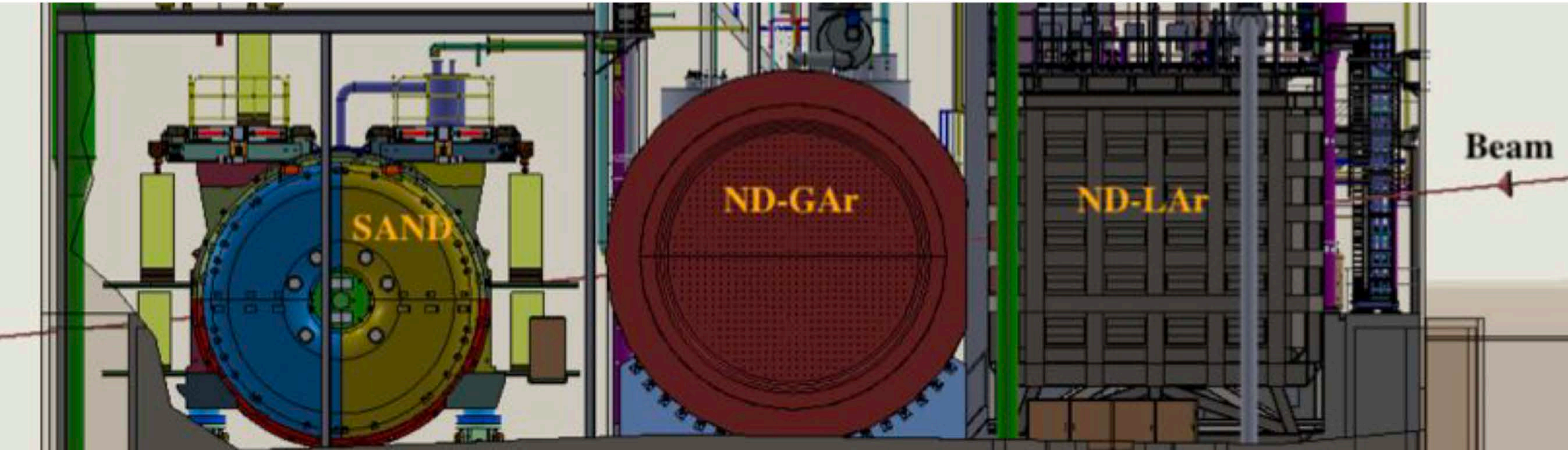
   iv. Interactions on water from subtraction between polyoxymethylene (CH2O) and graphite (C) targets

   v. Thin passive water targets can also be integrated in STT

Calibrate Eν energy scale

ND ii: modify ND-GAr

- The most minimally invasive option for off-axis ND WbLS is to incorporate targets into ND-GAr
  - Unlike a LAr detector, which relies on hadronic calorimetry, Theia only requires measurements of particles above Cherenkov threshold (e.g. T2K ND strategy – see next slide)
- The upstream ECAL for ND-GAr is already envisioned to be "thin" to enhance muon catching
  - In this case, it would be possible to incorporate WbLS targets/cells/bars/cubes in the upstream ECAL
- This could also provide useful synergy -> multiple groups working toward a multipurpose ND-GAr

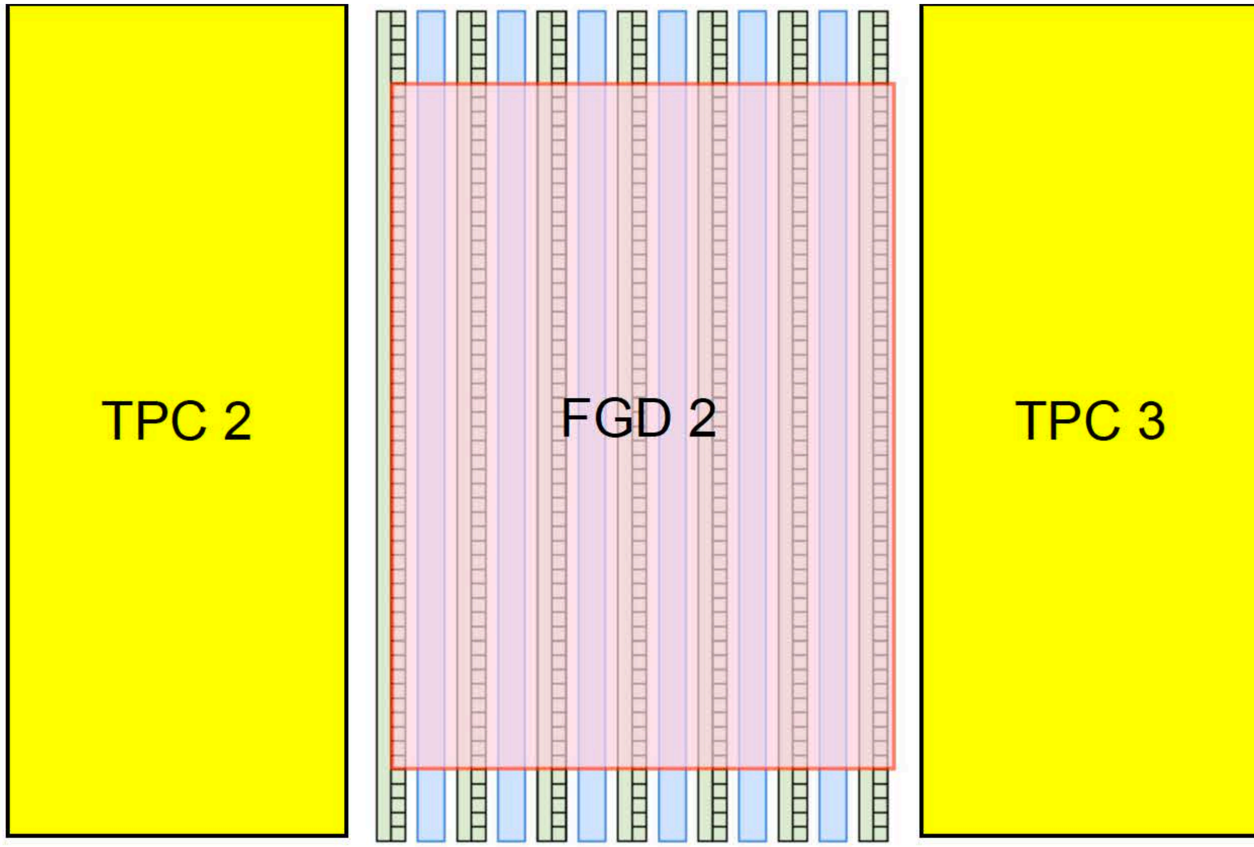


Courtesy: M. Wilking

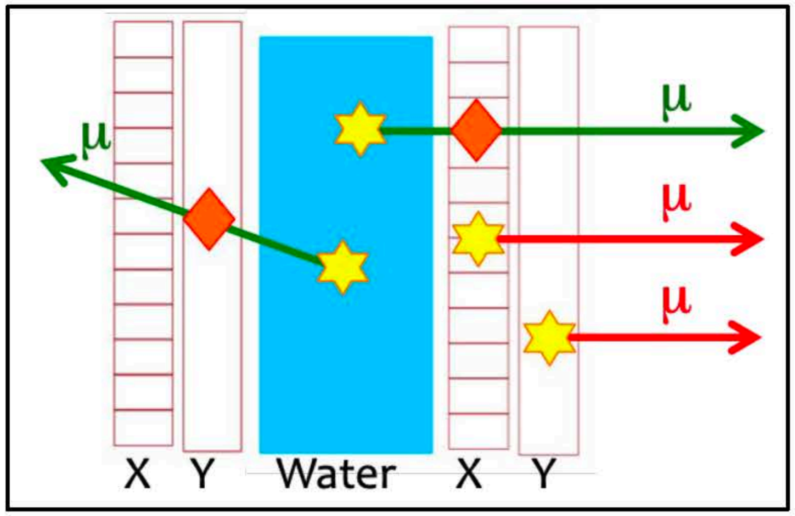
T2K approach

T2K Fine-Grained Detector (FGD2)

- T2K already employs water targets embedded within X & Y layers of scintillator bars
  - This reduced T2K's neutrino interaction uncertainties on water by ~30%
- One of the most important detector uncertainties is disentangling events occurring within water to events occurring in adjacent scintillator layers
- With WbLS, it may be possible to instrument the water layers to reduce these uncertainties
  - A sufficient scintillator fraction / light yield to record MIPs would be needed



7 xy + 6 water modules
192x2 bars/layer

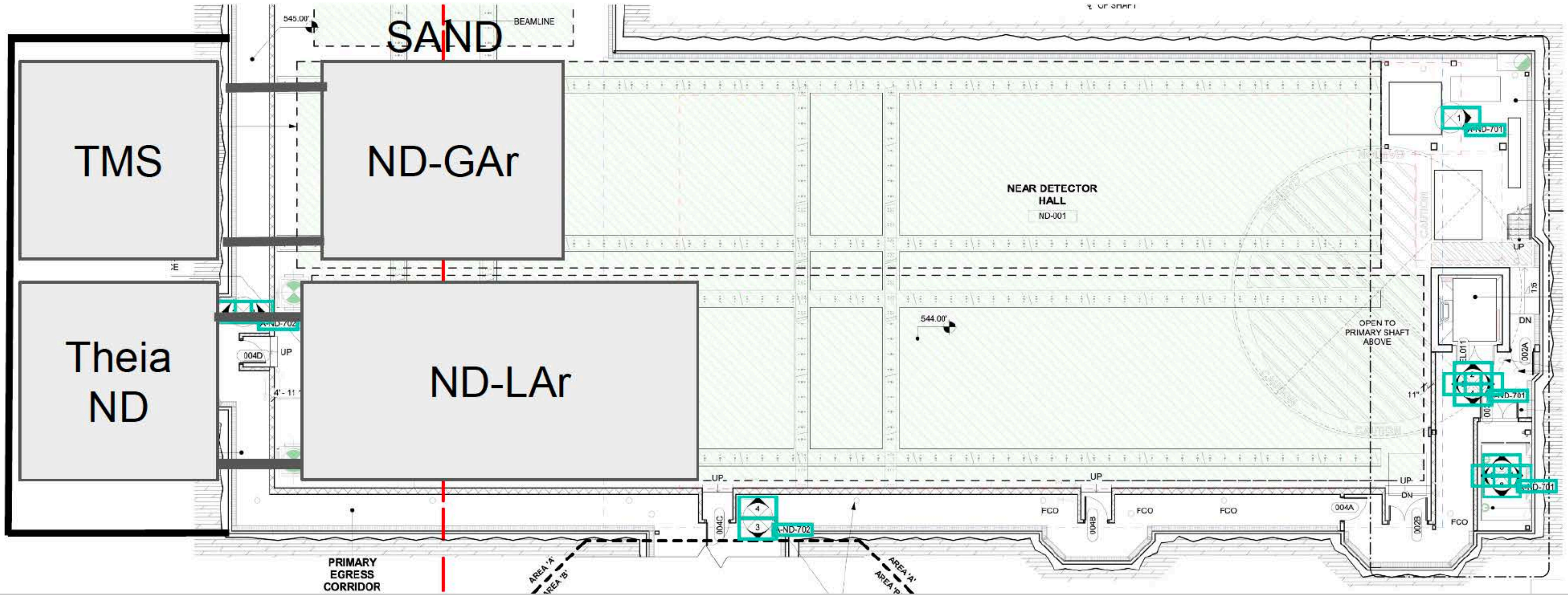


Phys. Rev. D 101, 11 (2020) pp.112004

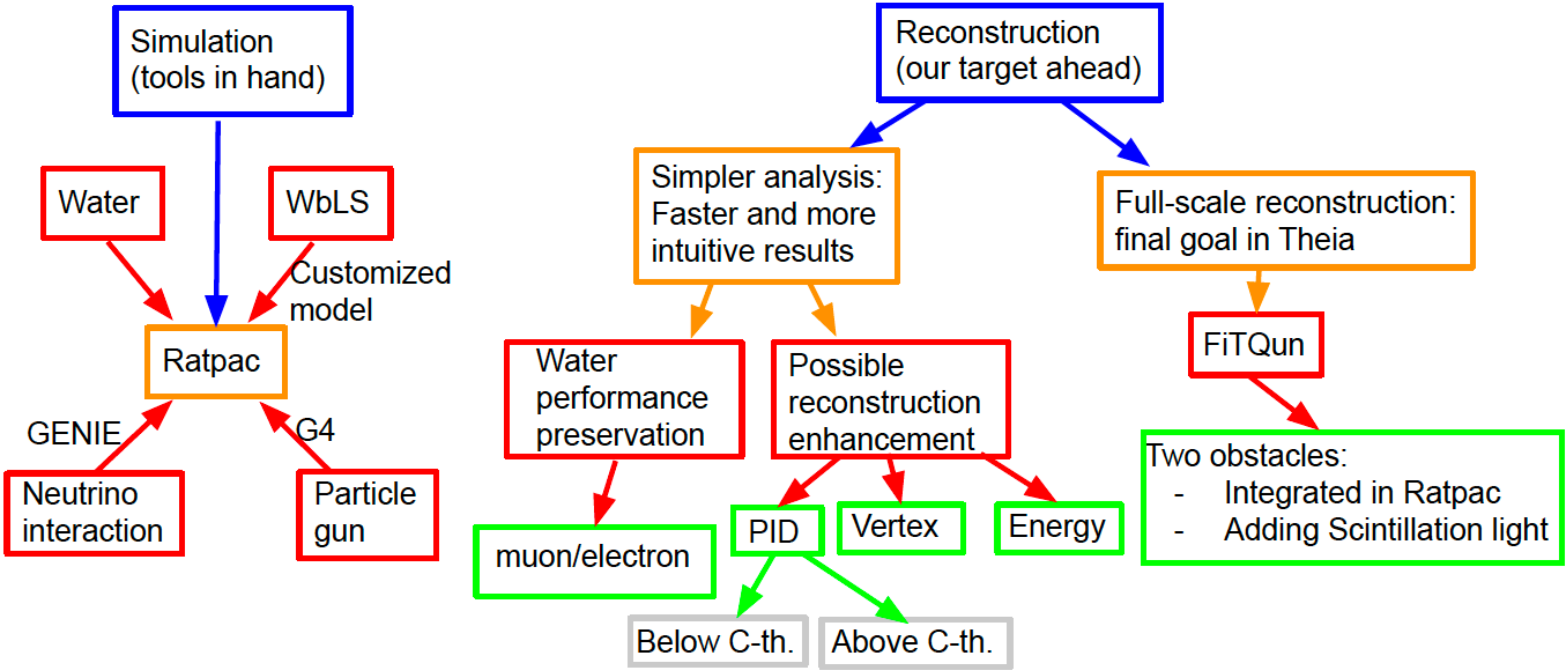
Courtesy: M. Wilking

ND iii: dedicated WbLS-ND

- The PRISM rail system allows detectors to be moved off-axis during beam running
- If the long dimension of the ND Hall can be further extended, can create a “garage” for a Theia ND
  - The garage need not extend to the full cavern height; just tall enough to fit the detectors
- If ND-GAr is also built, TMS would no longer be needed for ND-LAr, and could become the muon catcher for Theia ND



High energy simulation



Simulation (tools in hand)

Water

WbLS

Customized model

Ratpac

GENIE

G4

Neutrino interaction

Particle gun

Reconstruction (our target ahead)

Simpler analysis: Faster and more intuitive results

Full-scale reconstruction: final goal in Theia

Water performance preservation

Possible reconstruction enhancement

FiTQun

muon/electron

PID

Vertex

Energy

Below C-th.

Above C-th.

Two obstacles:
- Integrated in Ratpac
- Adding Scintillation light

Sterile neutrinos

- Particularly promising venue for a decisive test using ν and anti-ν generators
- Probe for distance-dependent ν flux
- Baseline within THEIA comparable to possible oscillation length (few m ~ > 1 eV^2)
- 144Ce-144Pr anti-ν source: millions of events
  - *Robust measurement even at order of magnitude fewer*
- 51Cr ν source: direct cross-check of Ga and BEST
  - *Real-time spectral measurement of Compton shoulder*

Photon propagation

Figs from Ben Land

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

Water WbLS LS