Beyond ton-scale neutrinoless double beta decay experiments

Non-Xe options

And

How Theia formed

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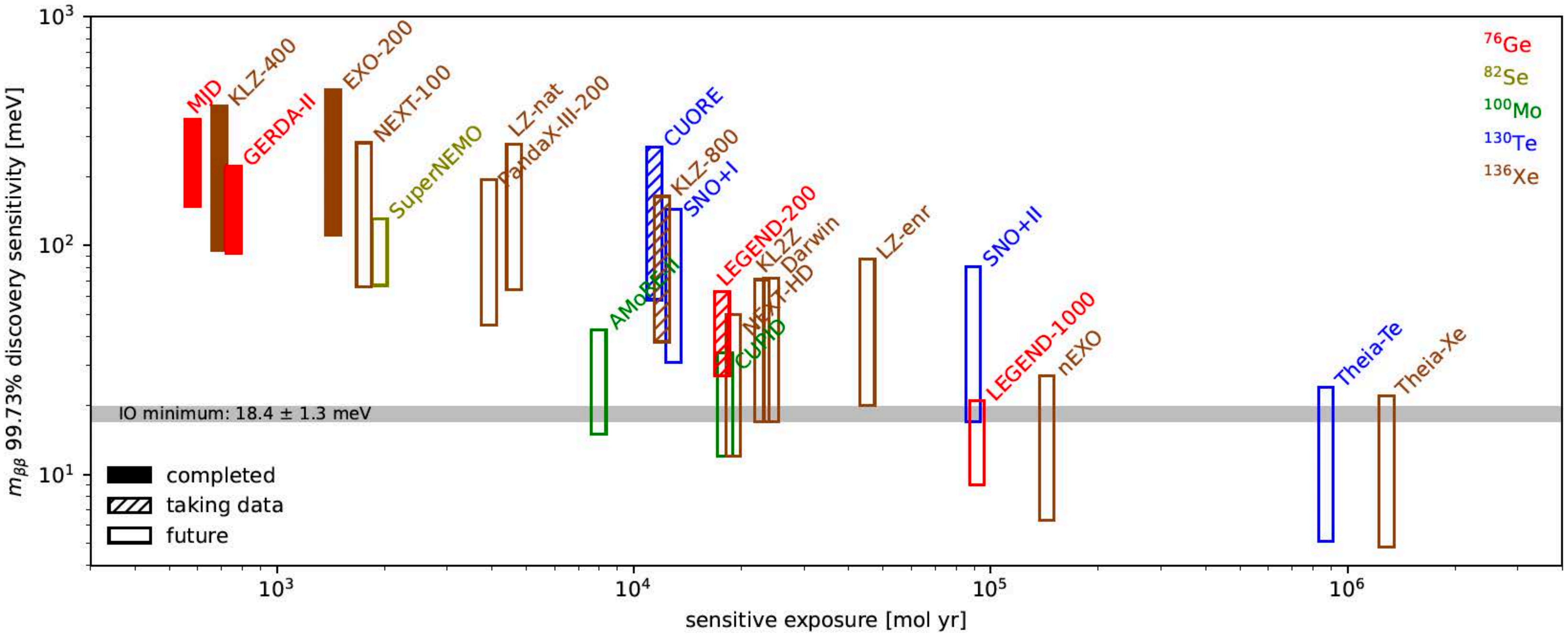
With many thanks to those who provided material:

Alvaro Chavarria, Jason Detwiler, Steve Elliott, Karsten Heeger, Yury Kolomensky, Stefan Schoenert, John Wilkerson, Lindley Winslow, Michi Wurm

Context

- An observation of 0νββ (demonstrating the Majorana nature of neutrinos) would reshape our understanding of the origins of mass and matter
- A definitive demonstration that neutrinos are *not* Majorana implies the existence of a new fundamental global symmetry associated with lepton number
- Discovery at the ton-scale would motivate advanced techniques to probe the mechanism
- Else, new detectors with greater sensitivity are needed to reach sensitivity beyond inverted mass ordering



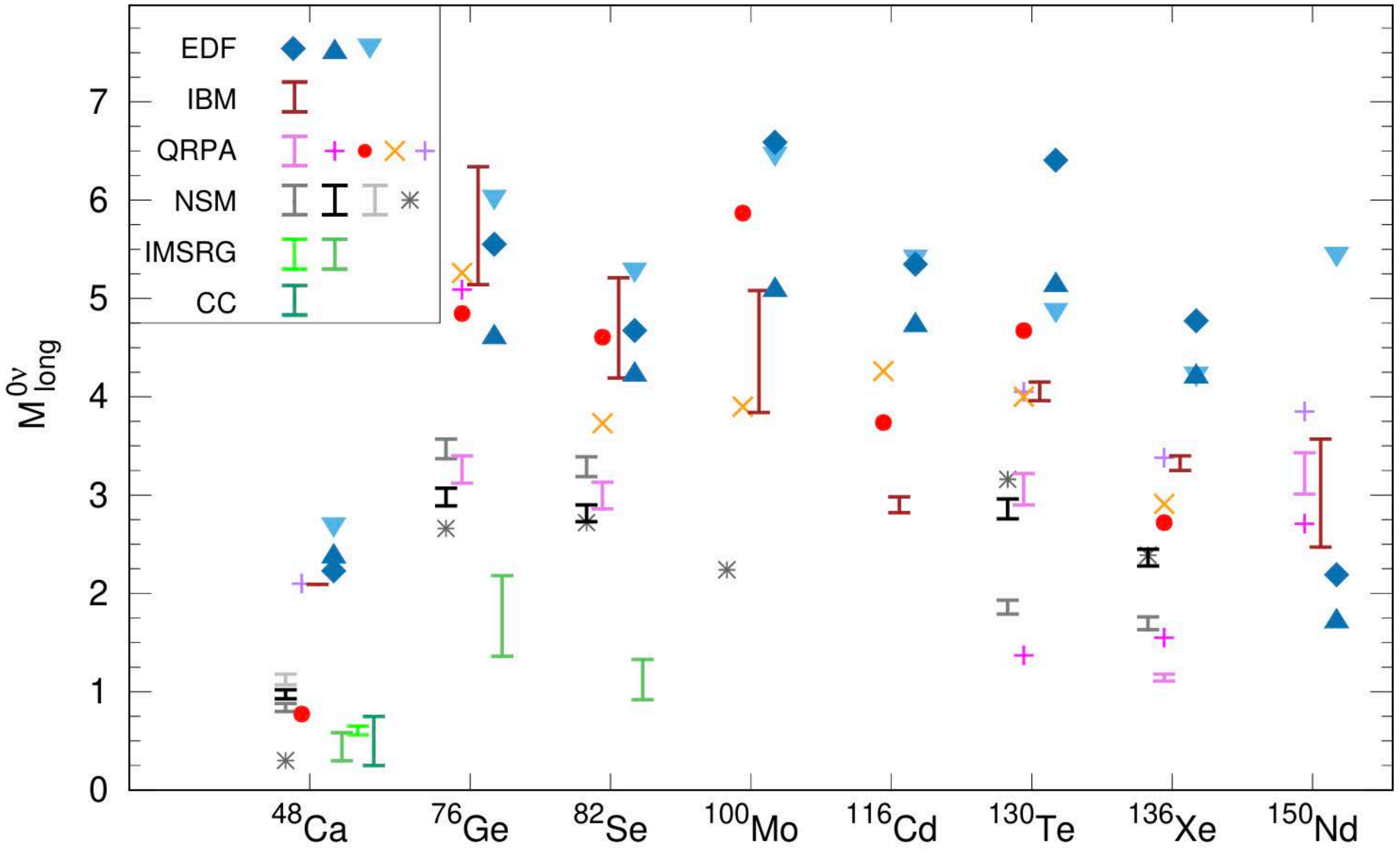
Overview

1. The need for multiple isotopes
2. Proposed beyond-ton-scale experiments
3. Community building

Multiple isotopes

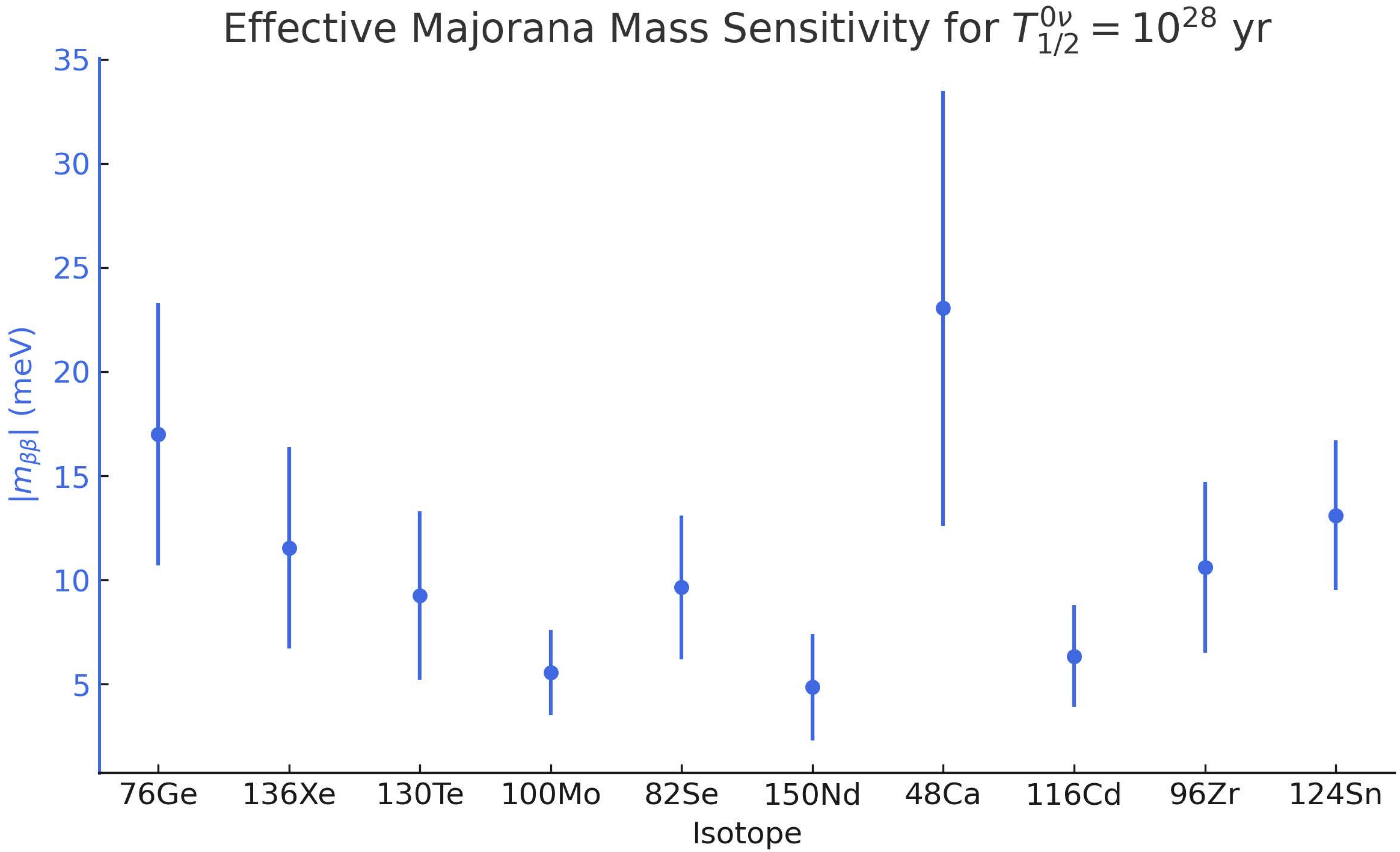
NMEs

- Large uncertainty in NMEs
- Large spread between different model predictions
- Supports the case for more than one isotope
- (And more work on nuclear theory!)



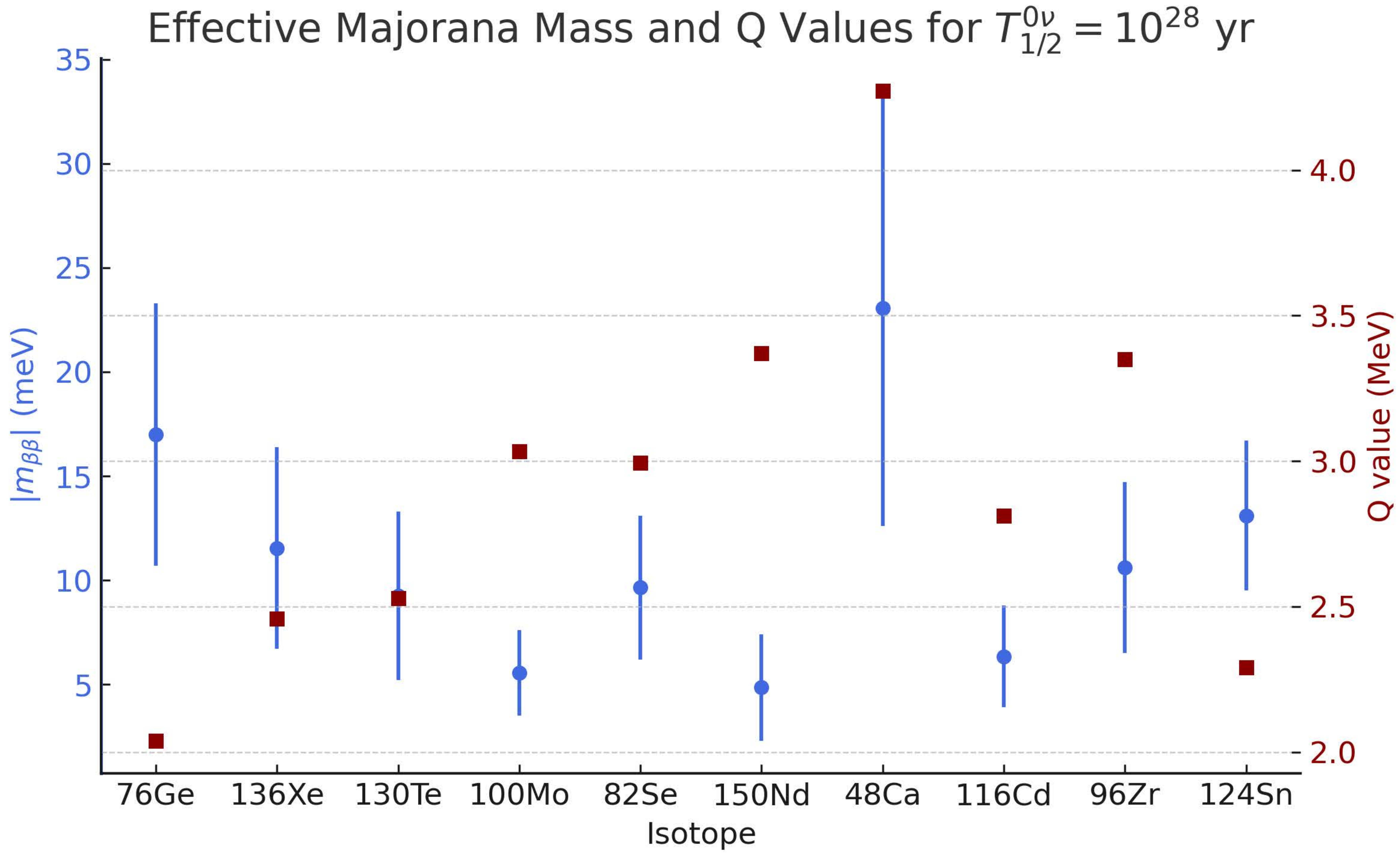
Nuclear matrix elements M0 for light-neutrino exchange from different many-body methods
M. Agostini et al, Rev. Mod. Phys. 95, 025002 (2023)

$T_{1/2}$ vs $m_{\beta\beta}$



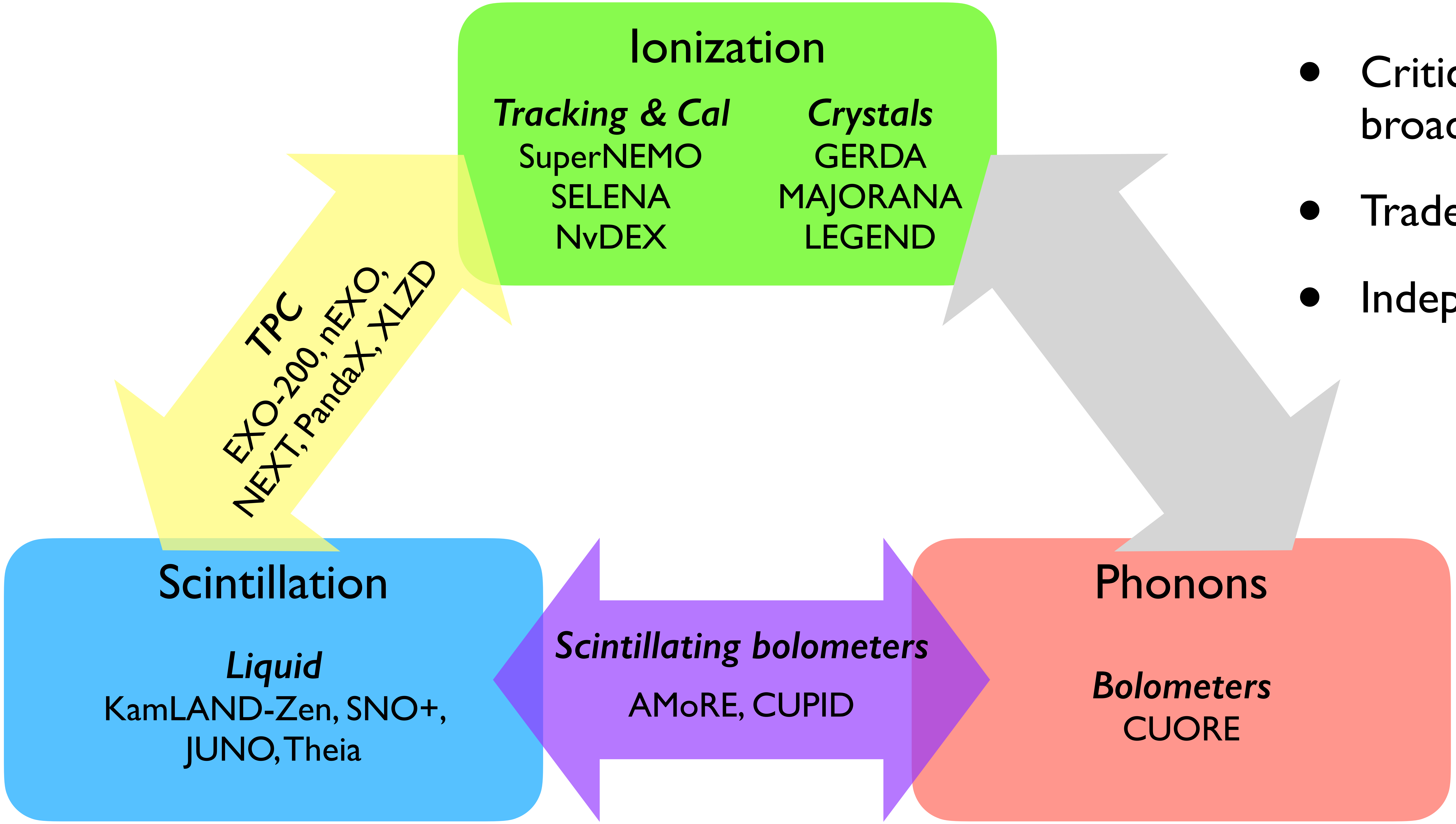
- Different isotopes offer different mass reach for the same half life sensitivity

Q value



- Different isotopes have different backgrounds due to different Q values

Diverse technology



- Critical to the field to have a broad range of technologies
- Trade offs in performance
- Independent systematics

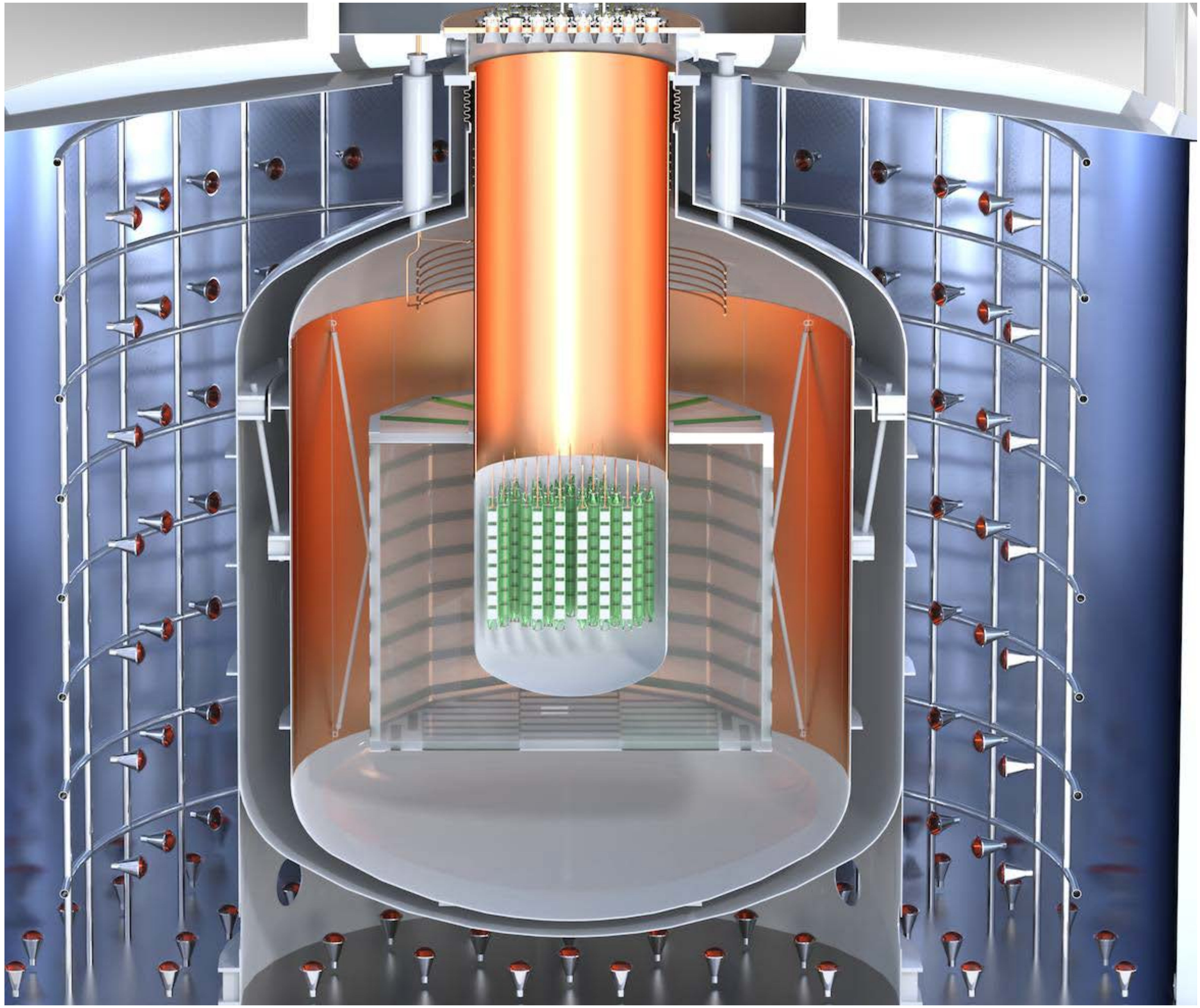
The need for multiple isotopes

- Verification of observation given spread / uncertainty in NMEs
- Different reach in $m_{\beta\beta}$
- Subject to different backgrounds
- Independent systematics
- Probe mechanism

Proposed experiments

LEGEND-6000: Ge

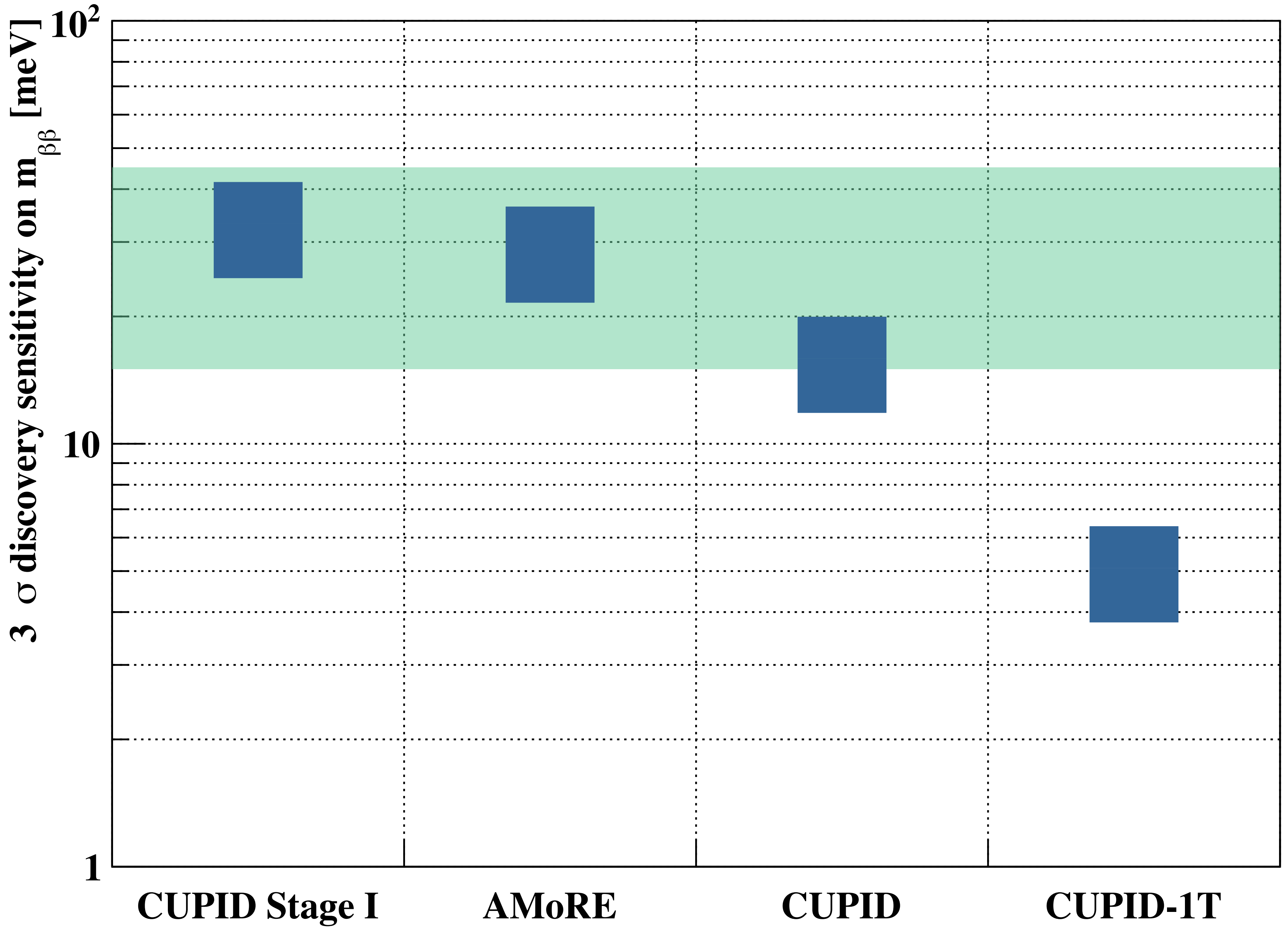
- Remove reentrant tube, use only UAr
- Larger detectors, 133 strings (from 42)
- ~ 6-ton total mass, 15 yrs livetime (100 t-yr)
- Needs ~ x2 detector production rate,
- & ~x2.5 isotope production rate
  - Well below global Ge production limits
- Background reduction ~x3-5
  - In situ cosmogenics, material purity
- x10 improvement in $T_{1/2}$ ~ 10^{29} yr ($m_{\beta\beta}$ ~ 3-6 meV)



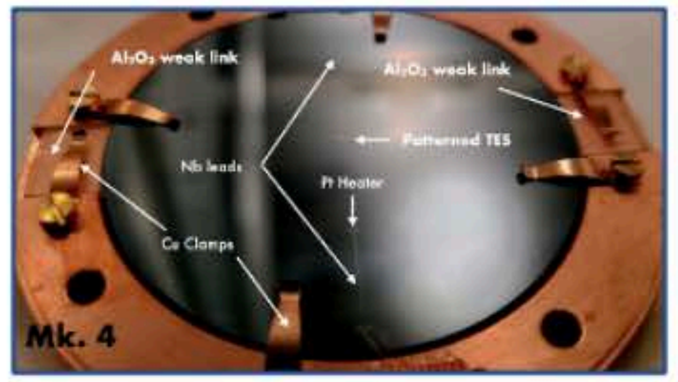
CUPID-1 ton

Staged Approach: CUPID Stage I → CUPID → Beyond CUPID

- **Mass:** increase to ~1 ton (CUPID x4), reduce background ~x20
- **Isotopes:** ^{100}Mo current CUPID baseline, with multi-isotope options (e.g. ^{130}Te, ^{82}Se, ^{116}Cd, …)
- **Multi-site:** Distributed multi-cryostat deployment
- **Half-life:** $T_{1/2}$ ~ 10^{28} yr (^{100}Mo)
- **Worldwide consortium:** Envision future collaboration of multiple bolometric experiments



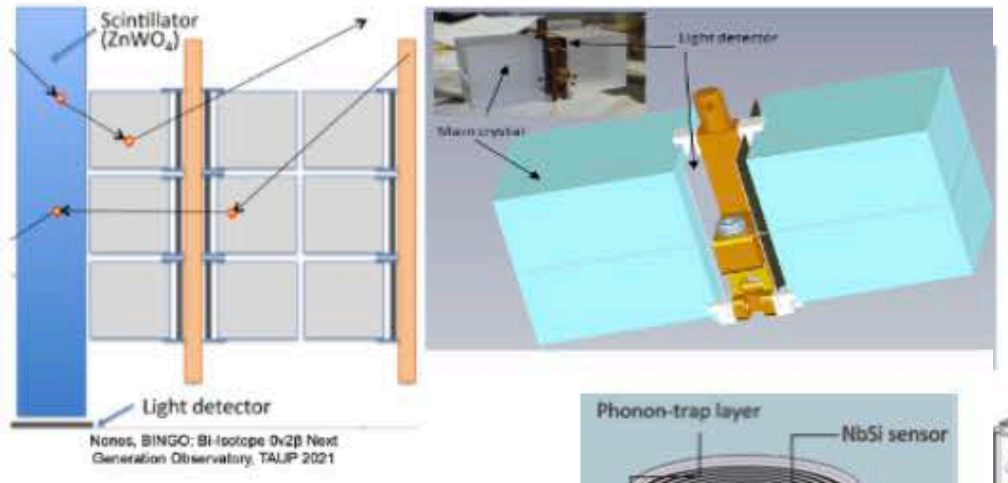
Quantum Sensors



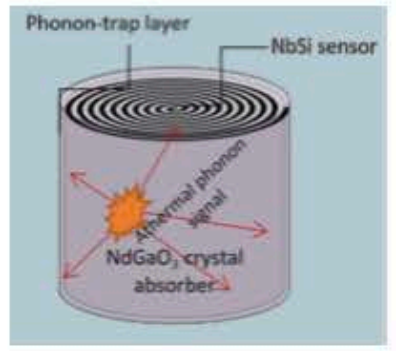
TES Light detectors

Hennings-Yeomans et.al. Journal of Applied Physics 128, 154501 (2020)
Singh et al. arXiv:2210.15619

BINGO: Geometry optimization + active γ veto

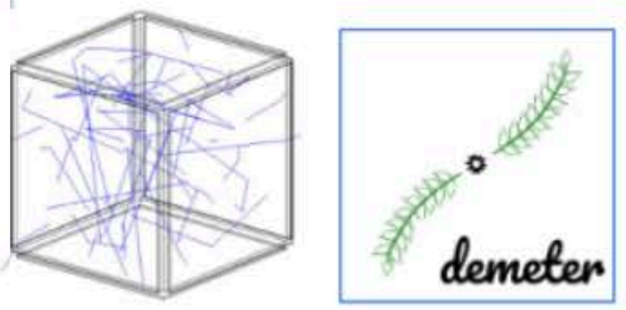


TINY: Novel crystals



Event Topology

DEMETER, CERES, OPOSSUM

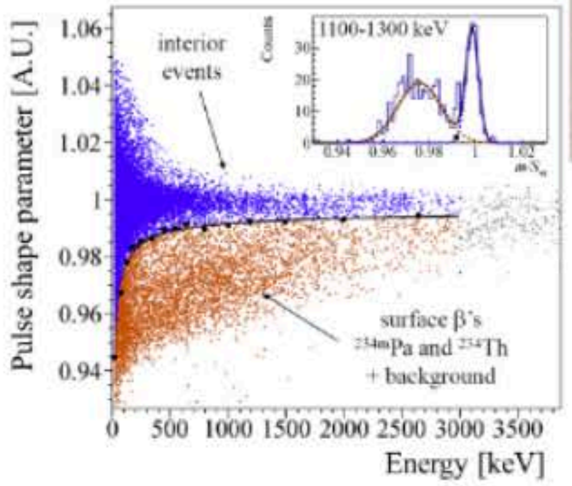


Erin Hansen, Snowmass 2022

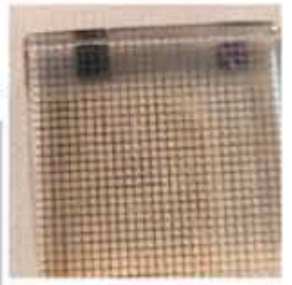
Active Background Mitigation

CROSS : Al-Pd coating on LMO for surface-event identification

Armatol, A. et al. J. Inst. 16, P02037 (2021).



CROSS

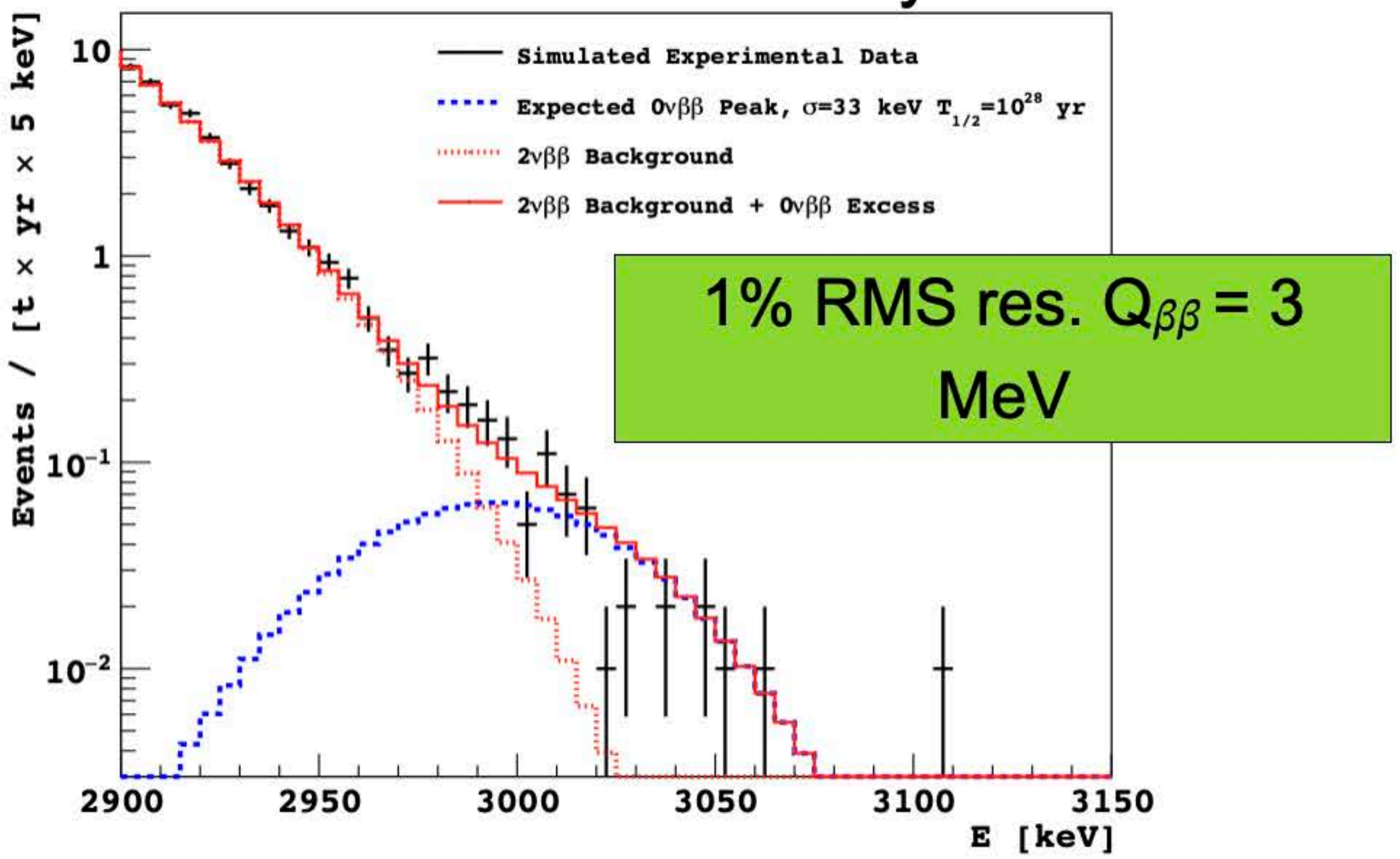


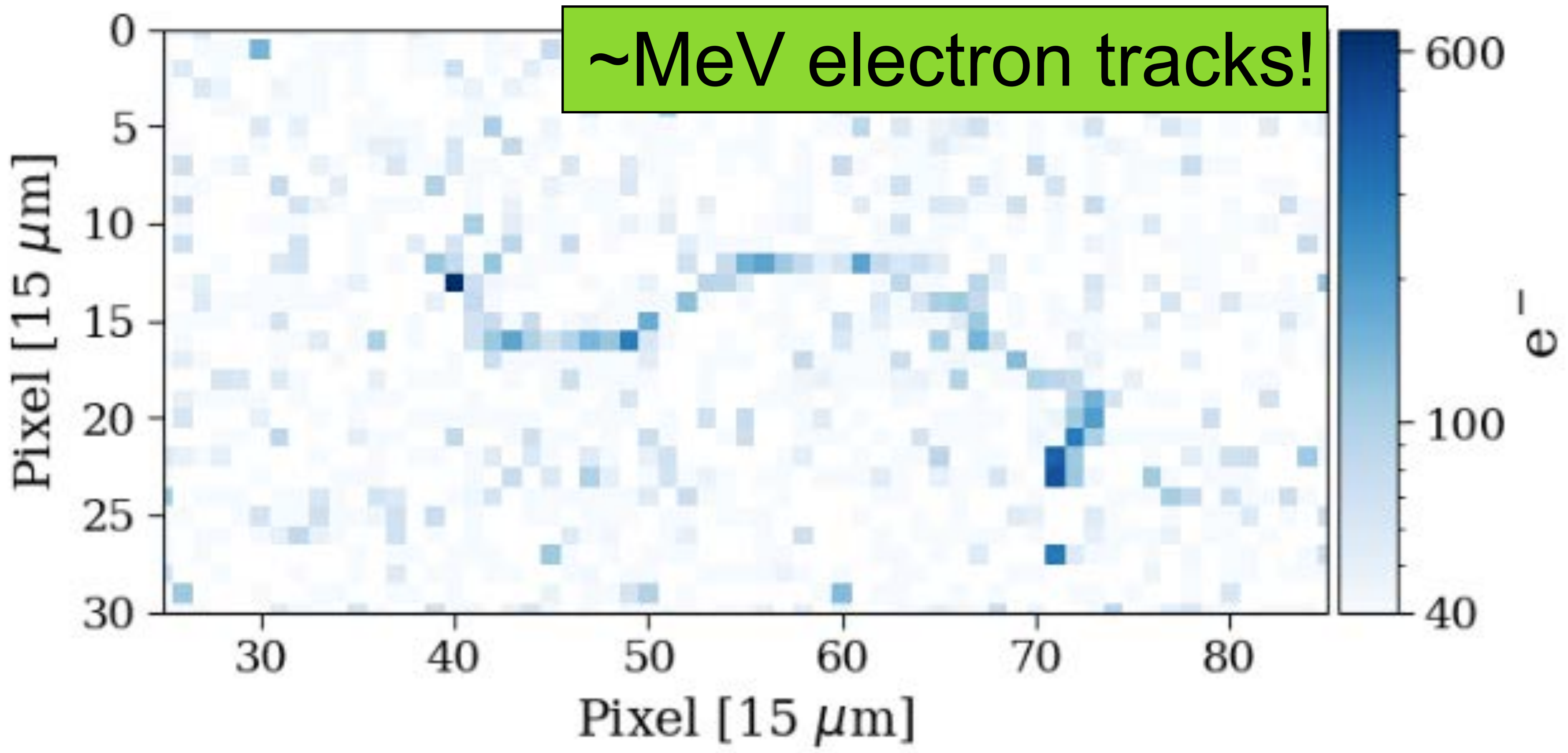
- **Active R&D:** Particle ID, topological event reconstruction, quantum sensors, active background suppression

Selena

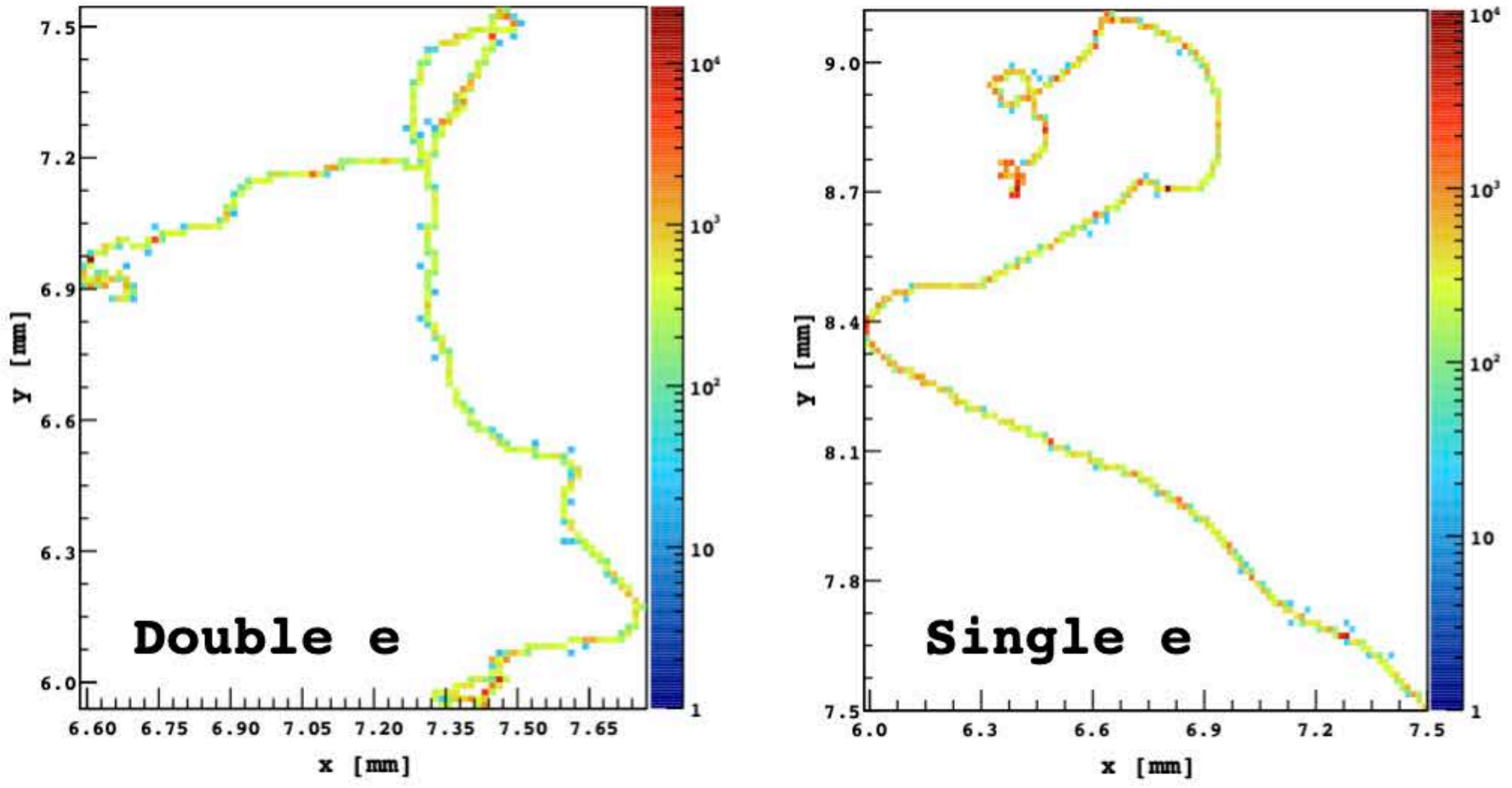
- 10-ton ^{82}Se active target with exquisite spatial resolution
- Large-area hybrid CMOS imagers, ~5-mm thick layers of amorphous ^{82}Se
- Identification of Bragg peaks → 10^{-3} suppression single e^- background, 50% signal acceptance.
- Bulk backgrounds suppressed by α/β particle ID, spatial correlations
- Background rate < 6 x 10-5 /keV/ton/year
- Sensitivity: $m\beta\beta$ = 4 to 8 meV (3σ) in 100-ton year
  - 3σ discovery for $T_{1/2} = 2 \times 10^{28}$ y in ^{82}Se
- Or study $0\nu\beta\beta$ mechanism after ton-scale discovery

100 ton-year simulation



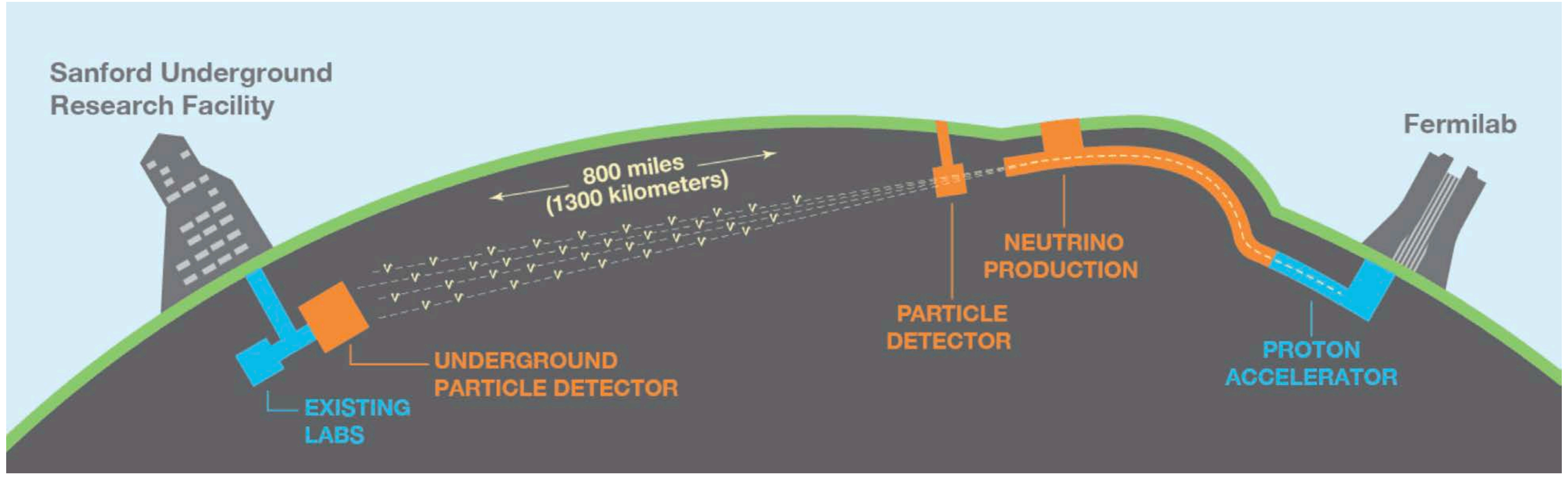


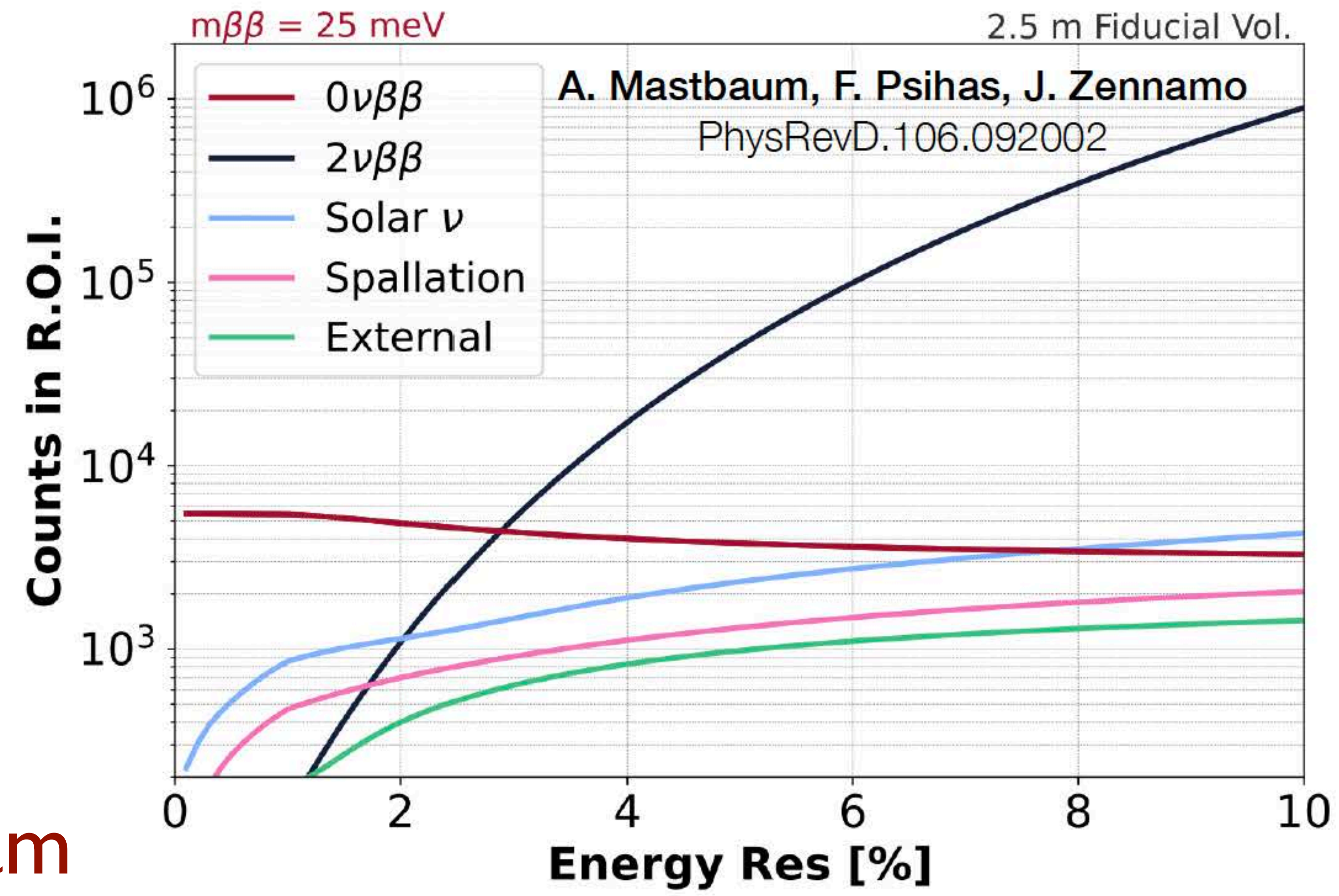
Simulation:

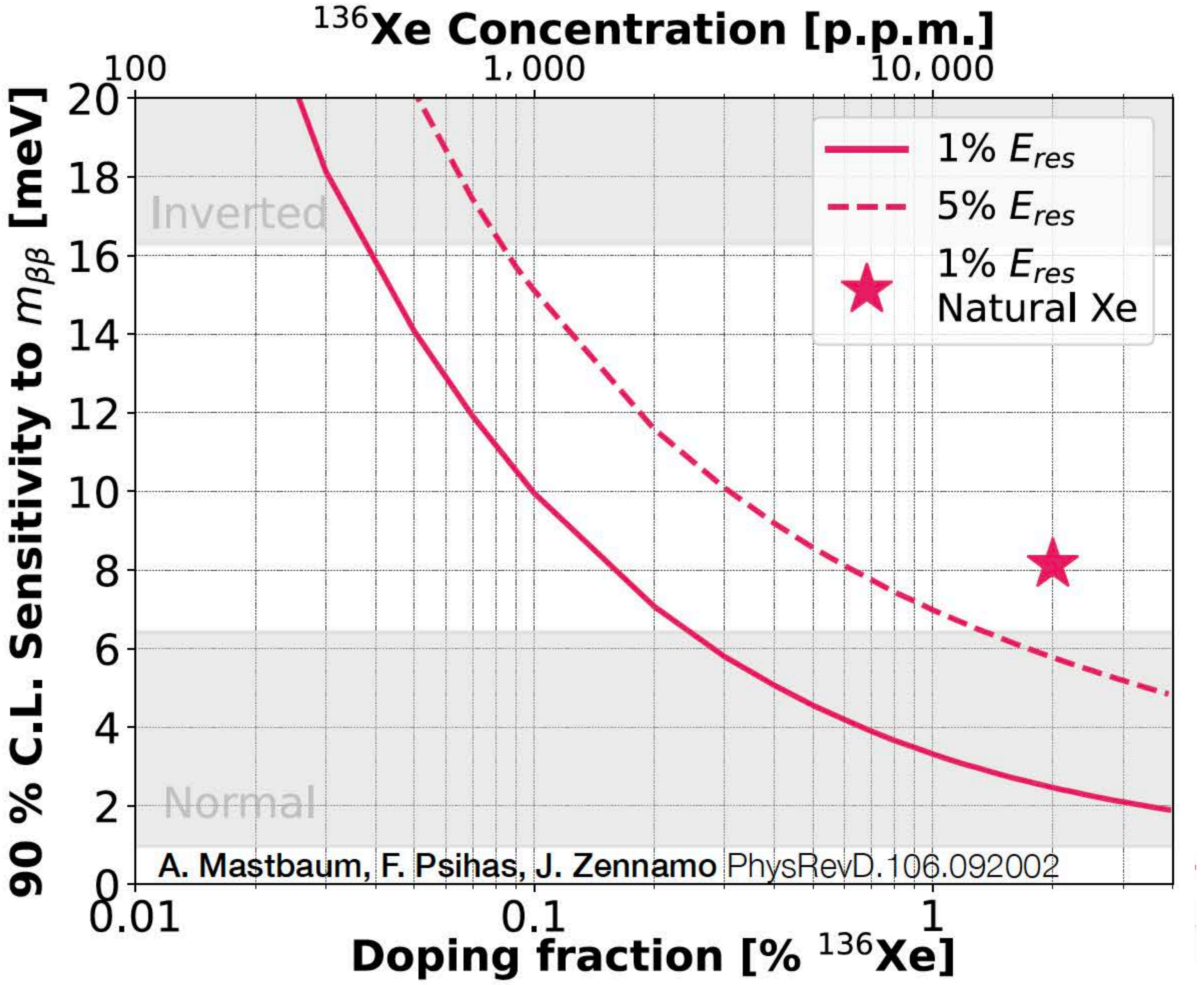


Xe-doped Argon

- Doped ton-scale LAr detector with LXe
- Compatible with other concepts for low energy physics in DUNE — FD4
  - 2% Xe doping
  - Solar neutrino dominates background
  - $T_{1/2} \sim 10^{29}$ yr
- Requirements:
  - Depleted argon
  - 3% energy resolution
- DUNE phase I moving ahead (FD 1&2)
- Novel technology being studied for FD3, 4
- P5 urged FD4 to broaden the physics program

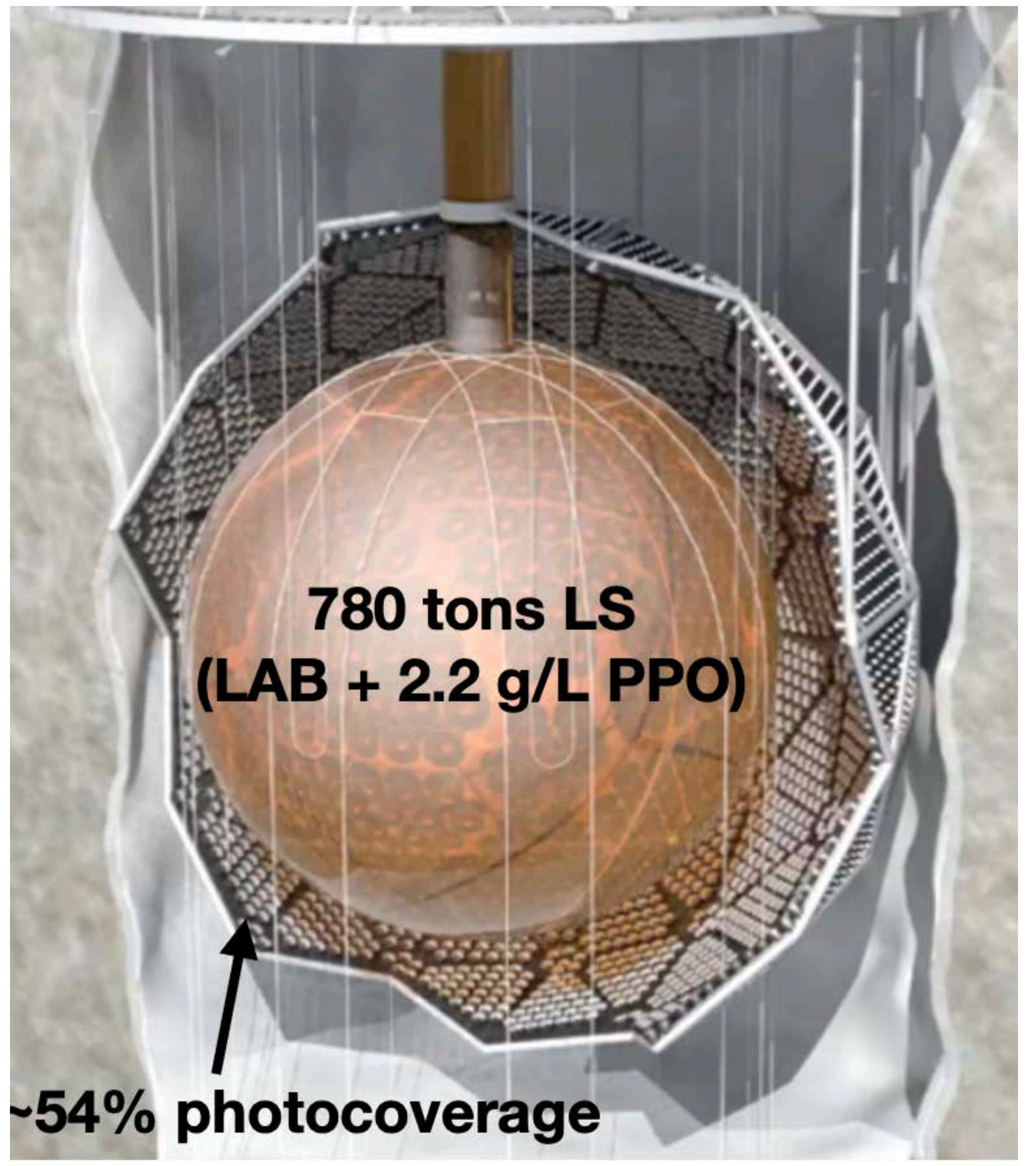






Loaded scintillator

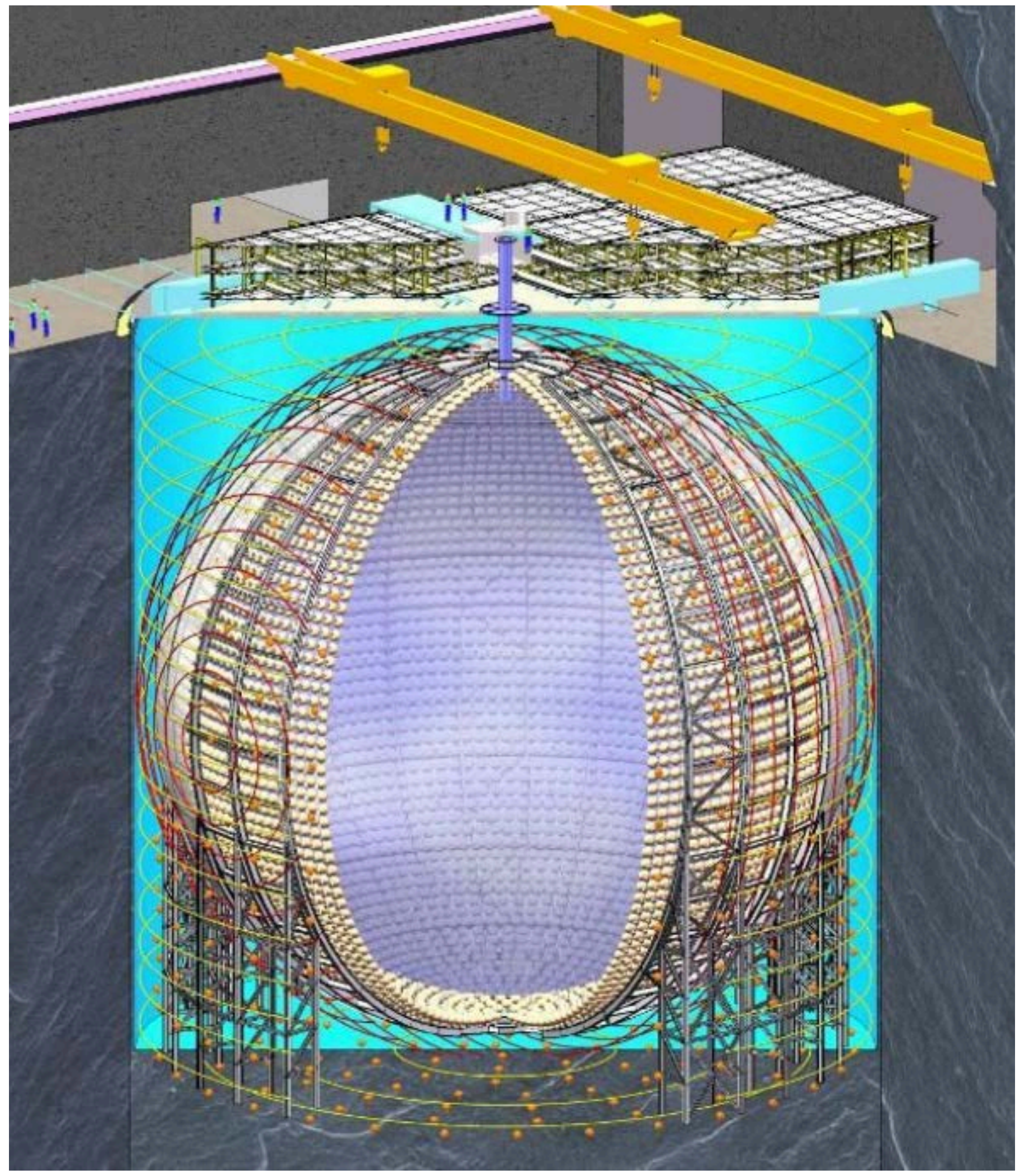
SNO+: Te-LS



$T_{1/2} > 2\times10^{26}$ yr (0.5%)
$T_{1/2} > 8\times10^{26}$ yr (1.5%)

Currently operational
Loading in 2026

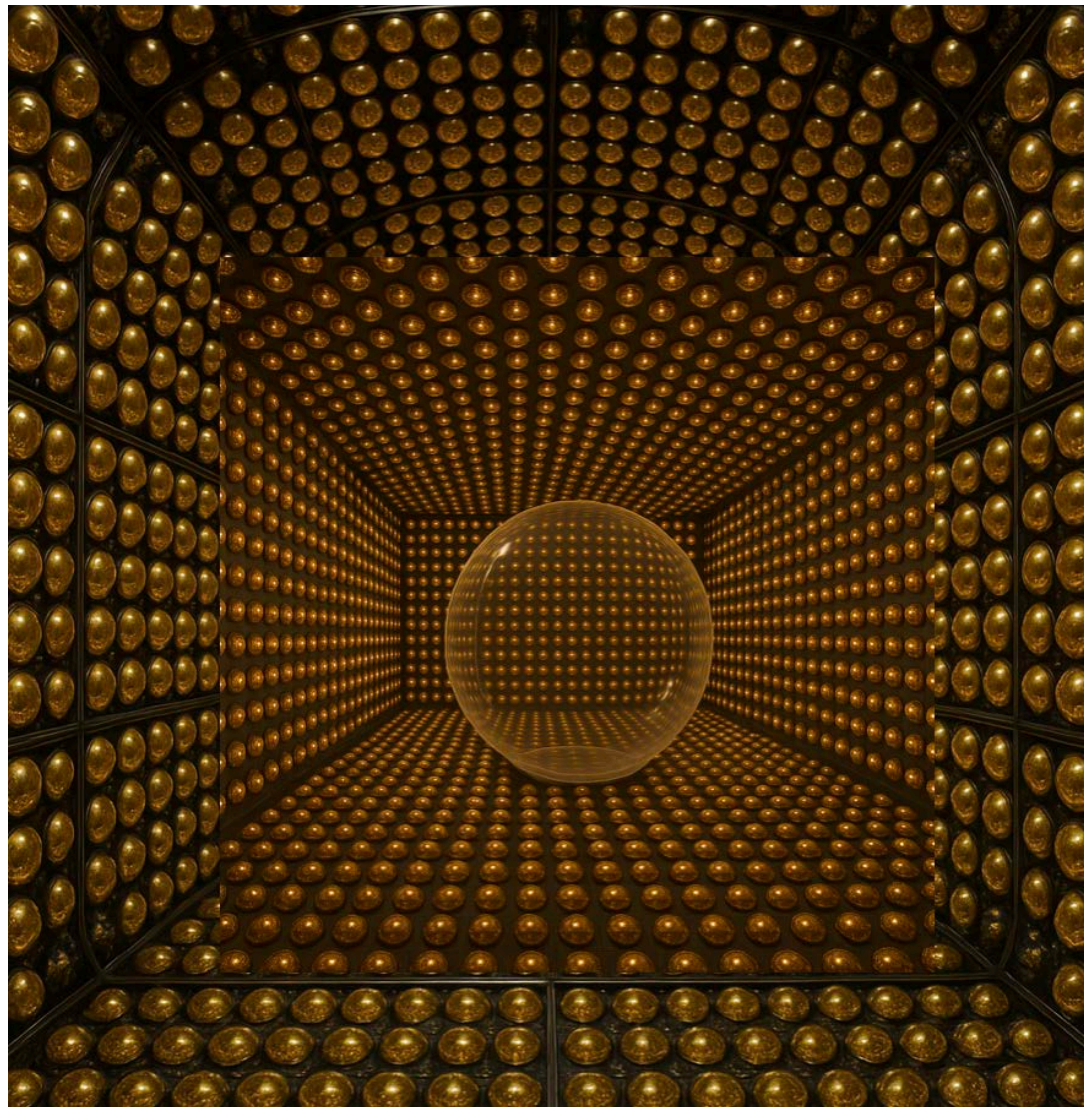
JUNO: LS



Potential to load isotope into 20-kt LS detector, 3% ERes

Operational summer 2025!
Reactor antinu primary goal

Theia

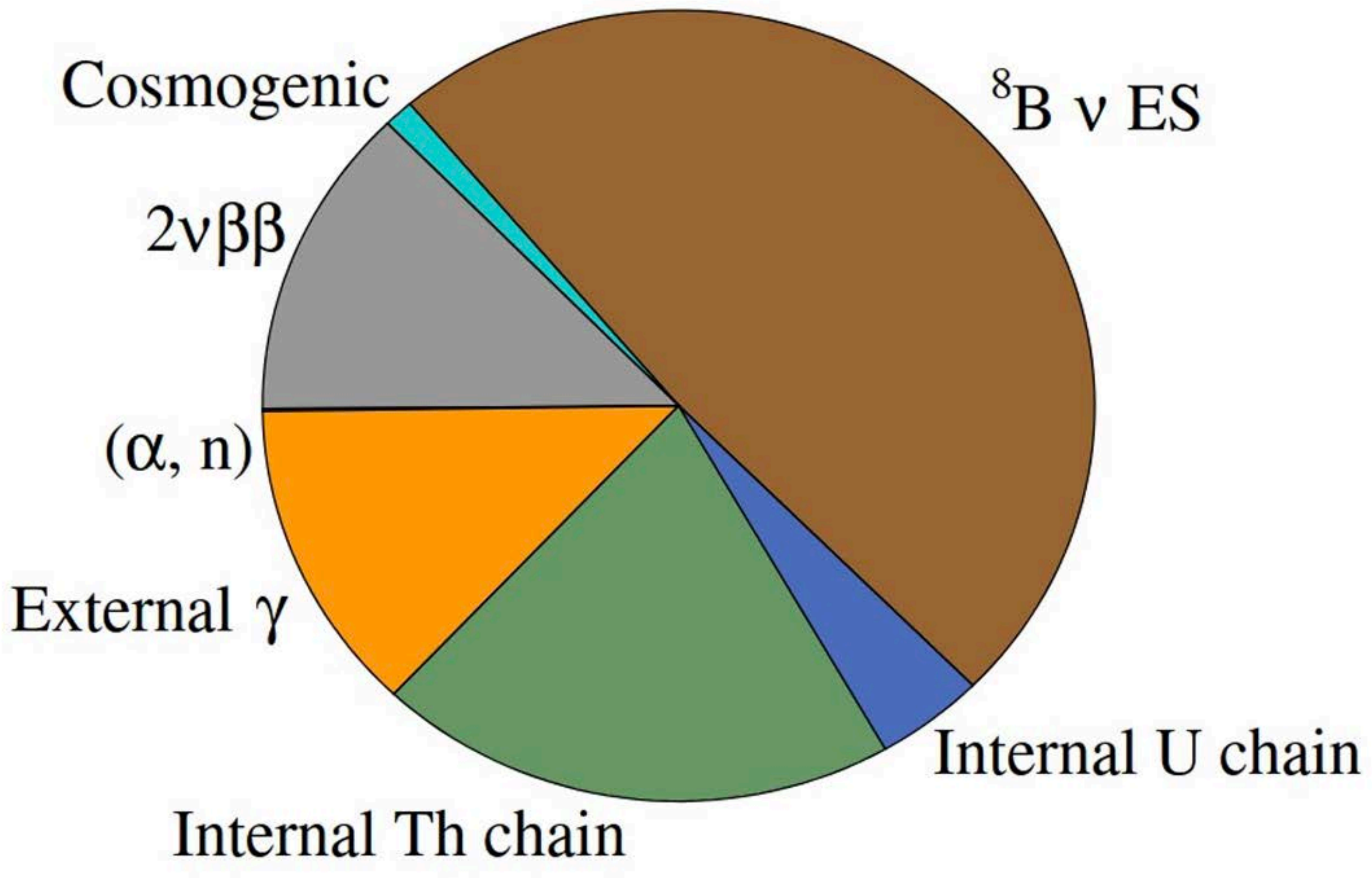


Targeting normal ordering

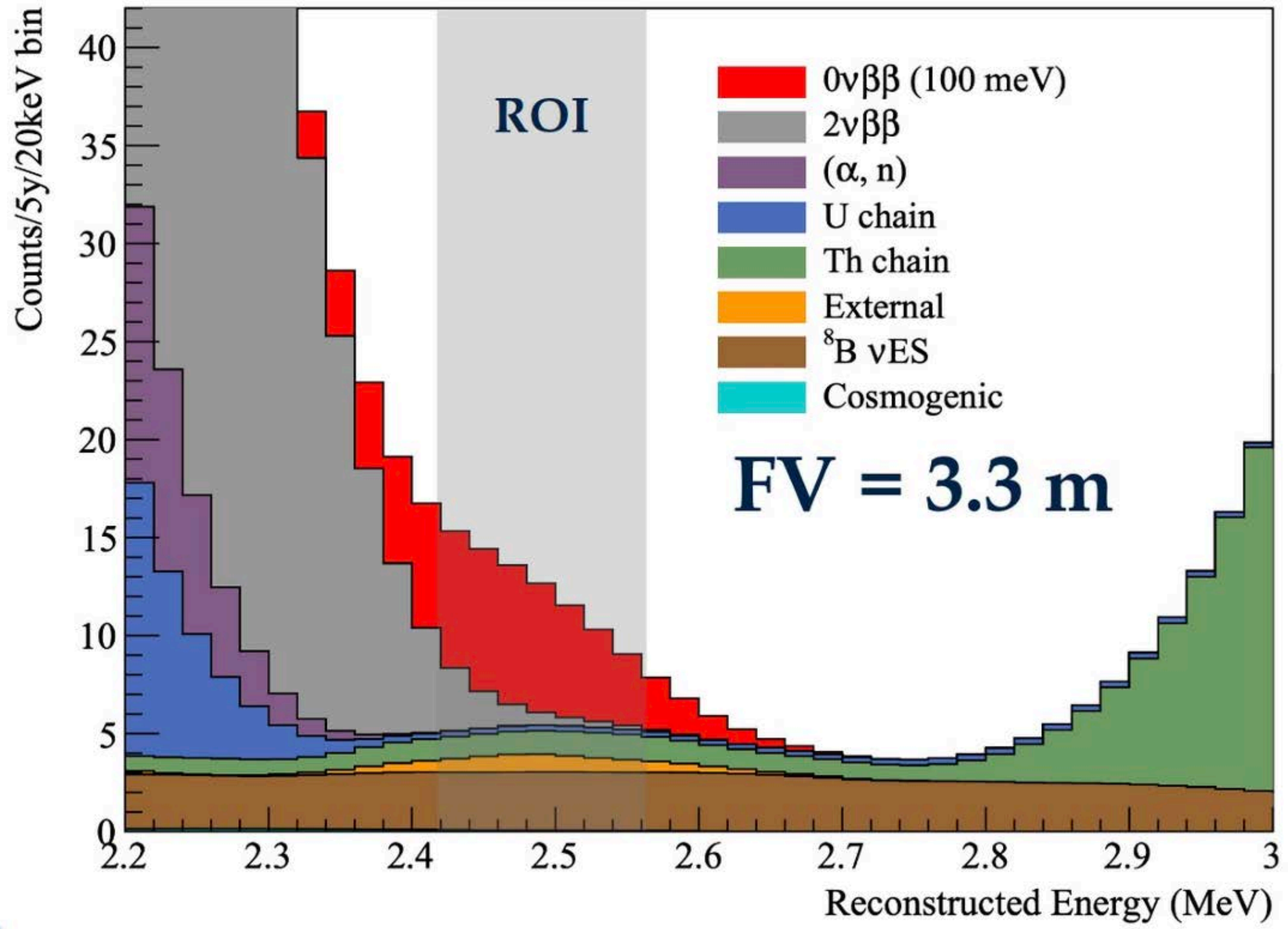
Proposed next-gen project
SURF or SNOLAB

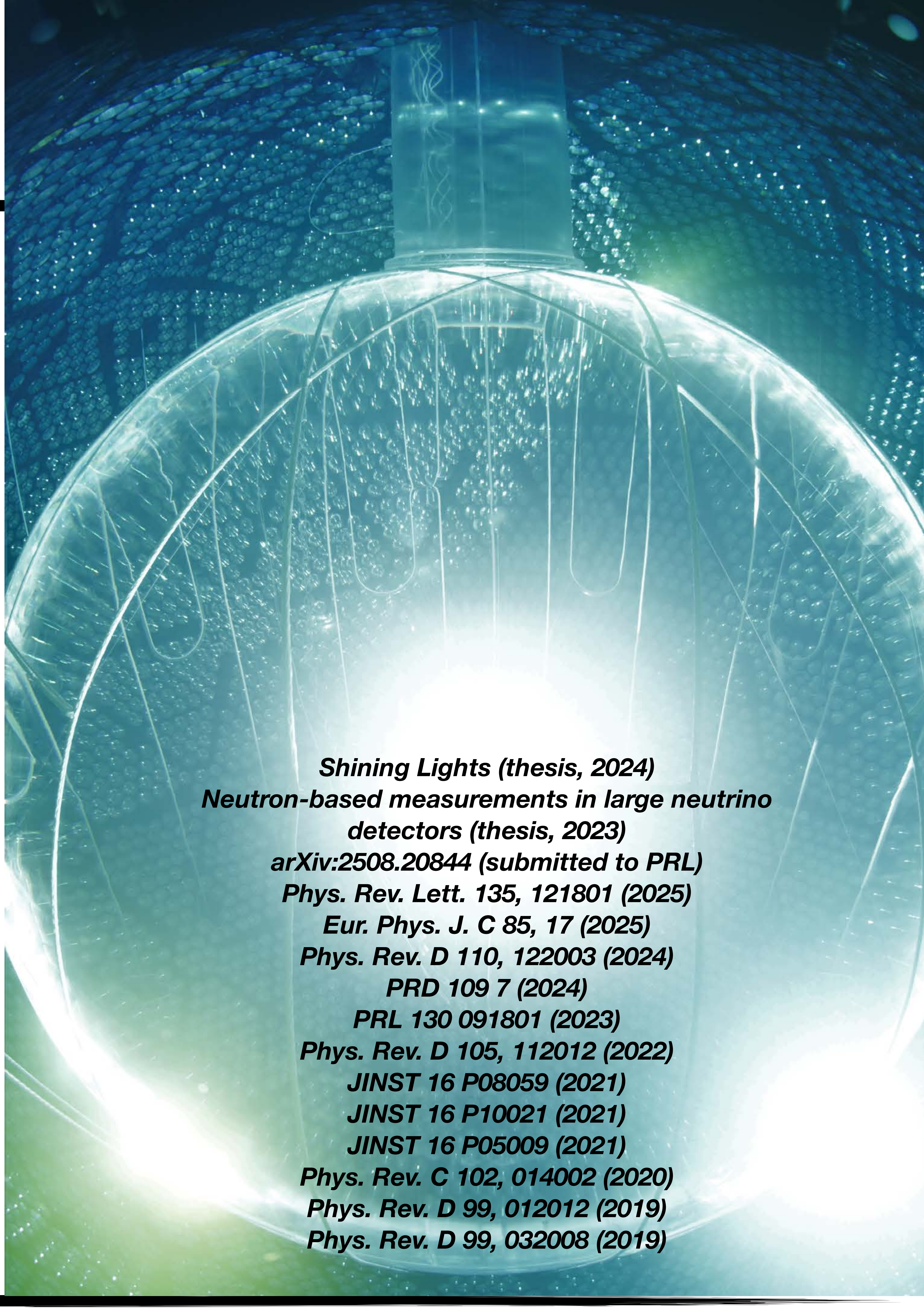
SNO+

- Phase I complete: water-fill
- Phase II data taking:
  780kg LAB + 2.2 g/LPPO
- 0.5% Te loading: 2026
- NLDBD target backgrounds achieved
- Broad ongoing physics program
- natural Te, 5 years
  - 0.5%: 2.3x10^{26} yr limit (90% CL)
  - 1.5%: 7.5x10^{26} yr limit (90% CL)
- One of few operating NLDBD experiments before 2030



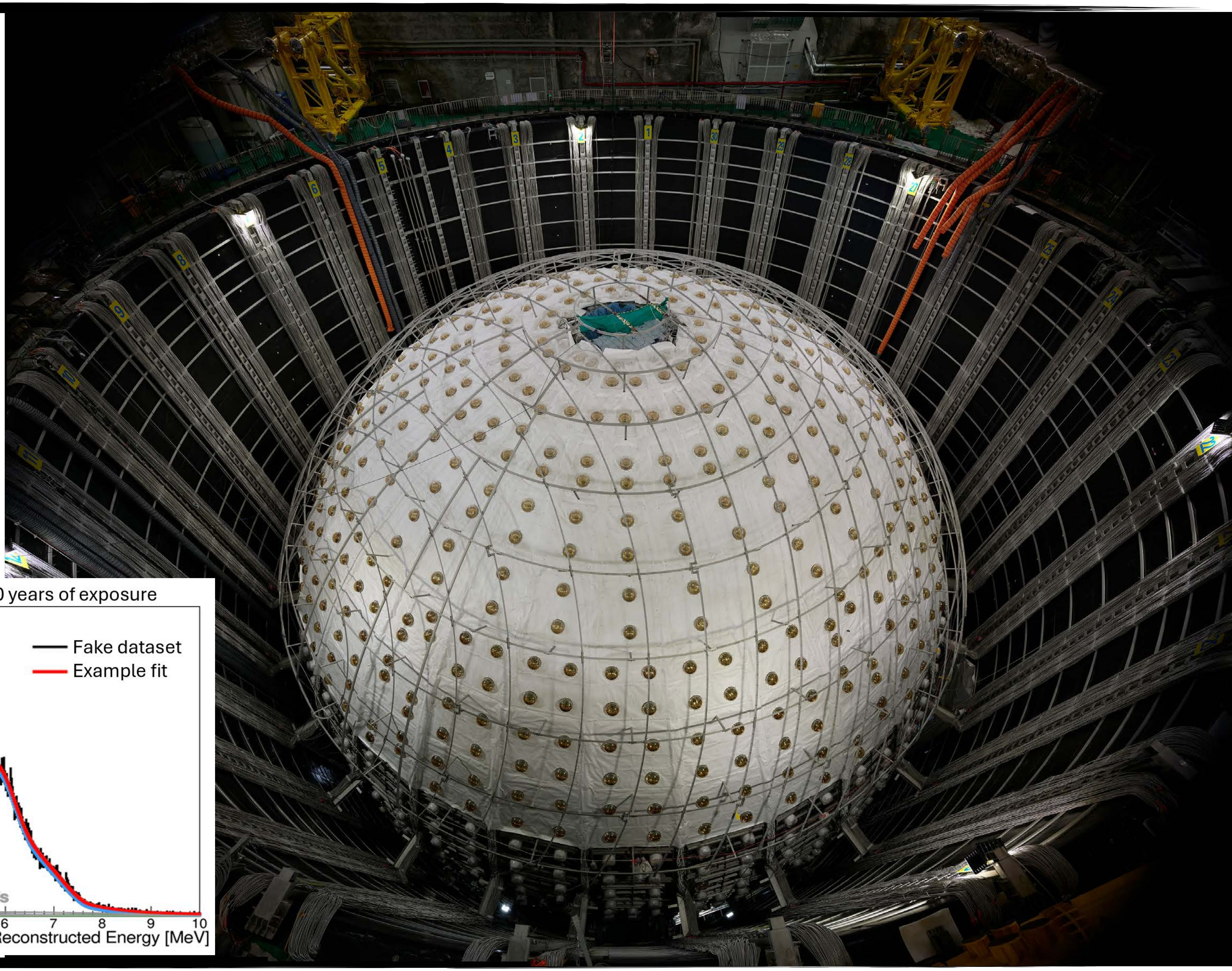
ROI: 2.42 - 2.56 MeV [-0.5σ - 1.5σ]
Counts/Year: 9.47

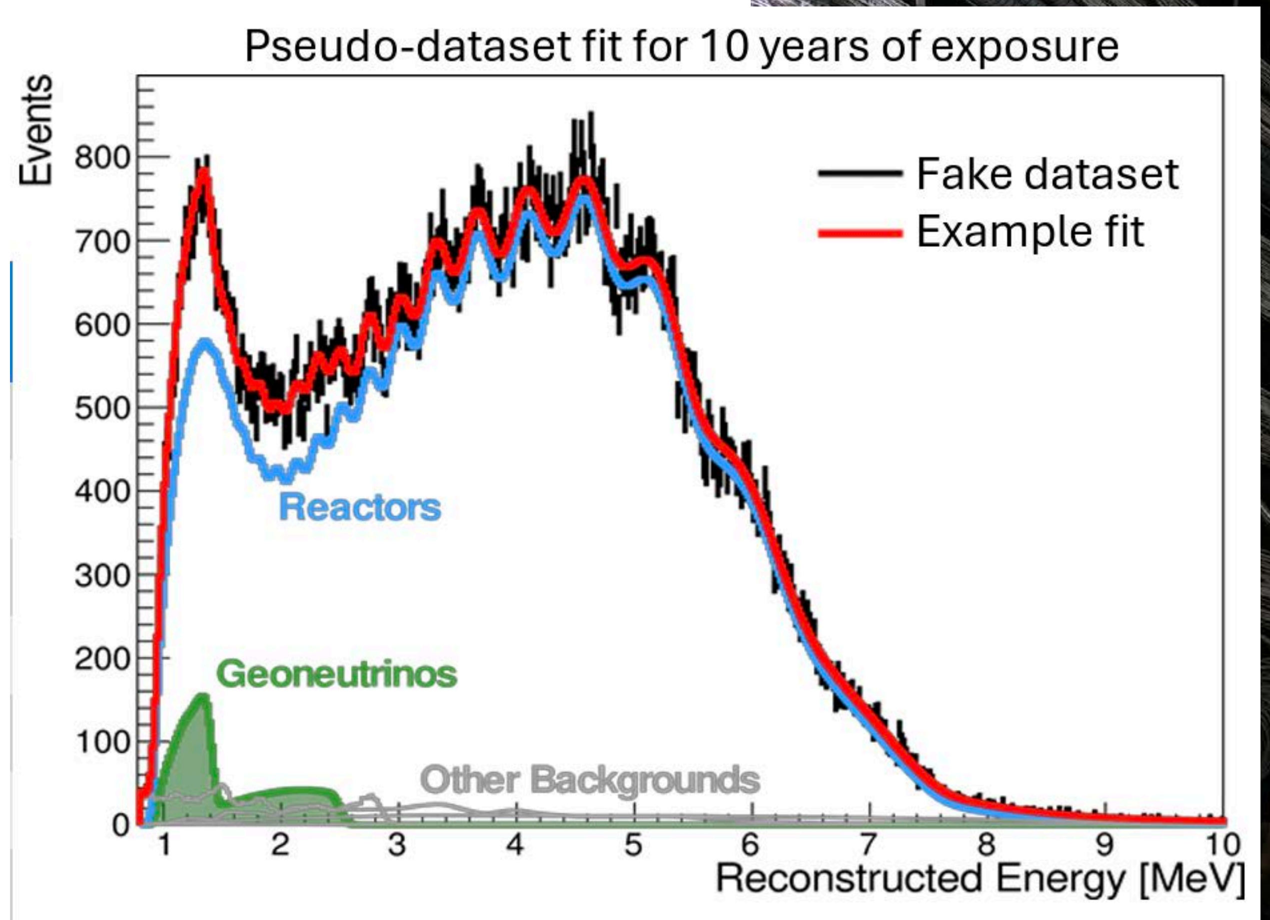




JUNO

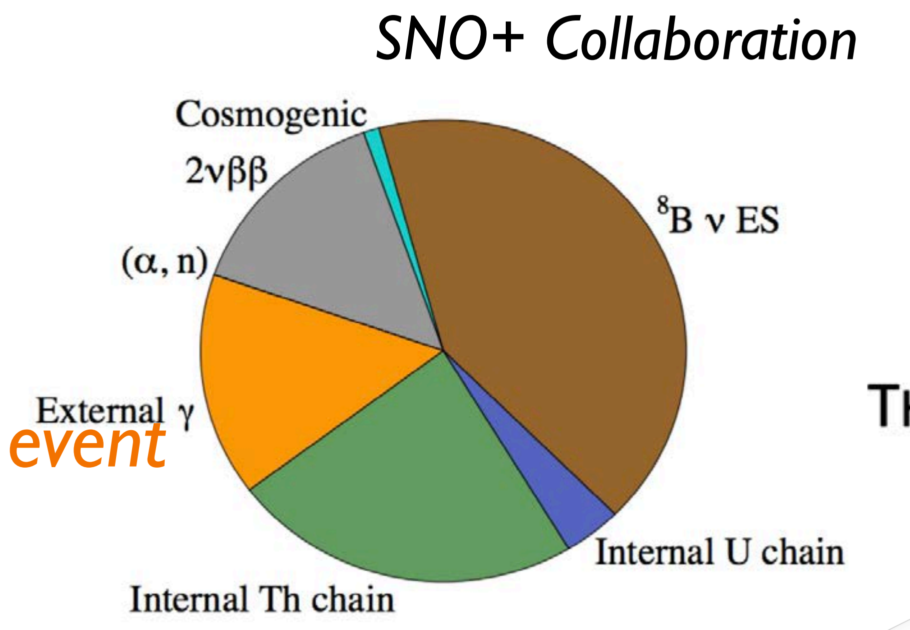
- End of construction and installation: Dec 2024
- Water filling from Dec - Feb 2025
- LS fill completed 22nd of August
- Now taking data!
- Goal of 3% energy resolution (preliminary data consistent with target)
- Primary goal: neutrino mass ordering (reactor)
- Plan to convert to DBD after 10 years
- Considering Te, Xe
- Need to consider cosmic backgrounds at this relatively shallow depth (700m / 1800 mwe)



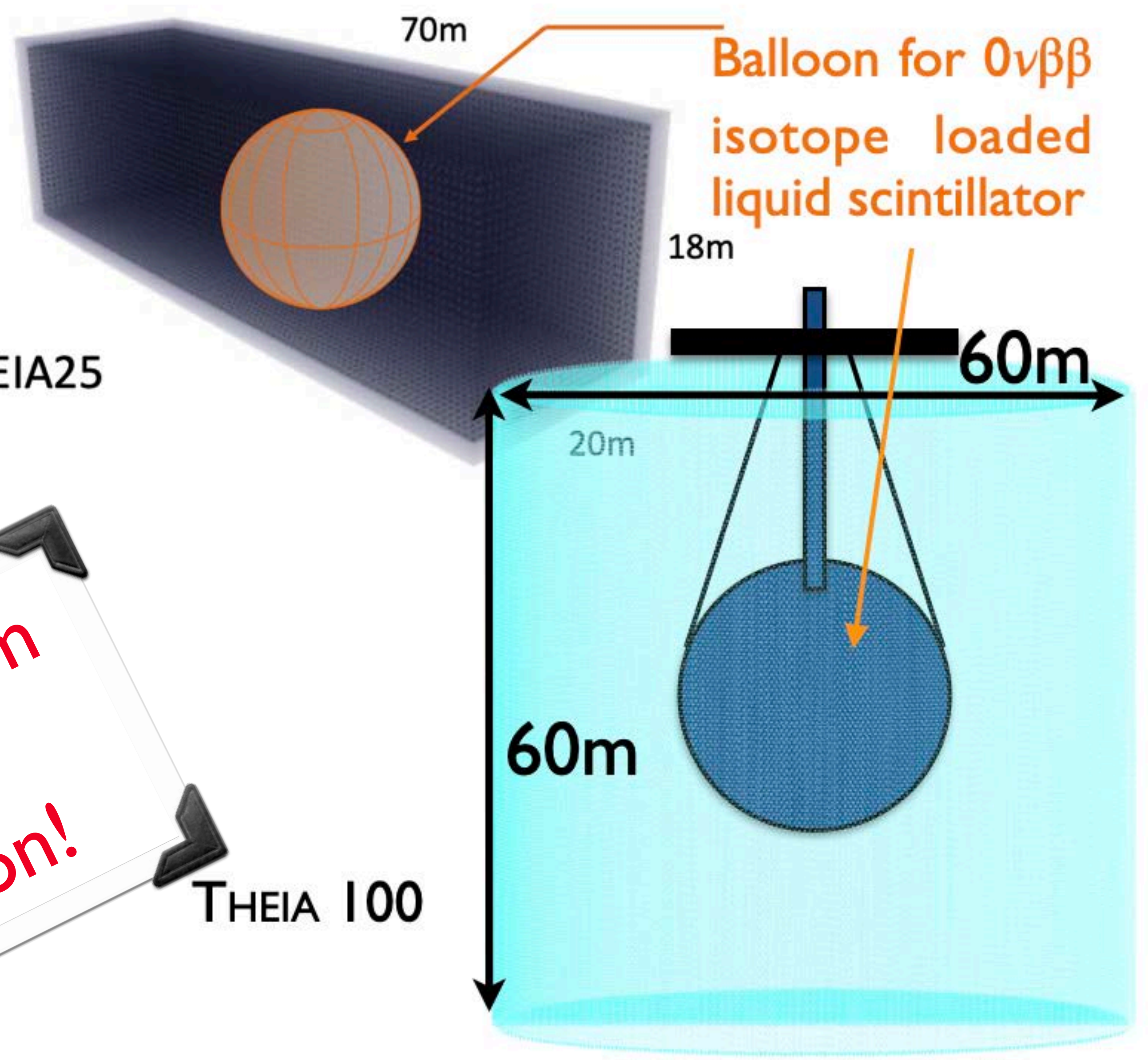


Theia

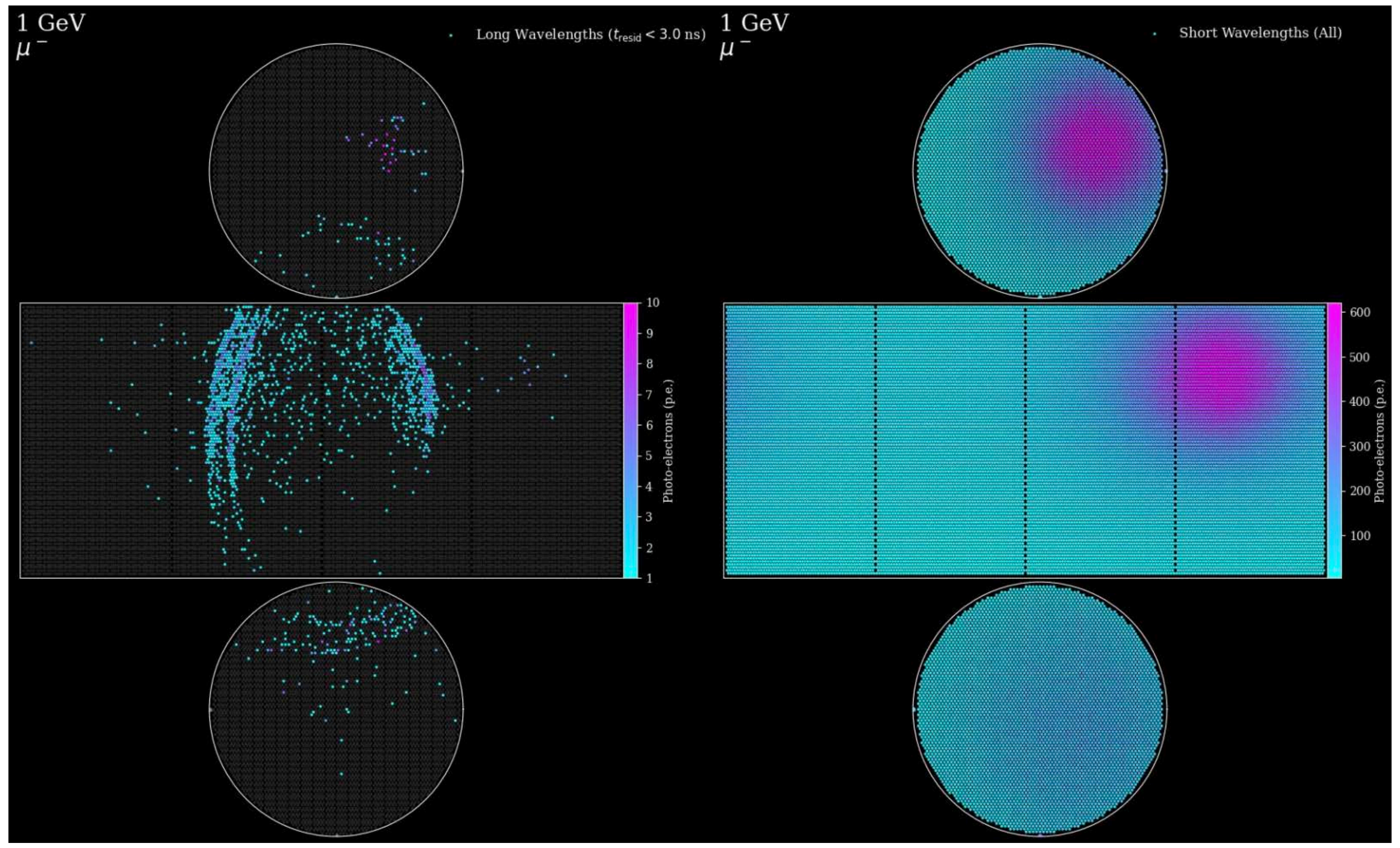
- Hybrid Cherenkov / scintillation detector improves background rejection via PID and event topology
- Scalable, ultra-clean liquid detector
- Potential to deploy a 25-kton Theia module at LBNF, in FD4
- GATEWAY-0 approval at SNOLAB (Aug'25)
- Scheduled a visit to SURF Dec'25
- 2020 White Paper sensitivity $T_{1/2} > 10^{28}$ yrs
  - ~4—22 meV
  - Room for improvement
  - Targeting 1-2 meV
- Broad program of other physics

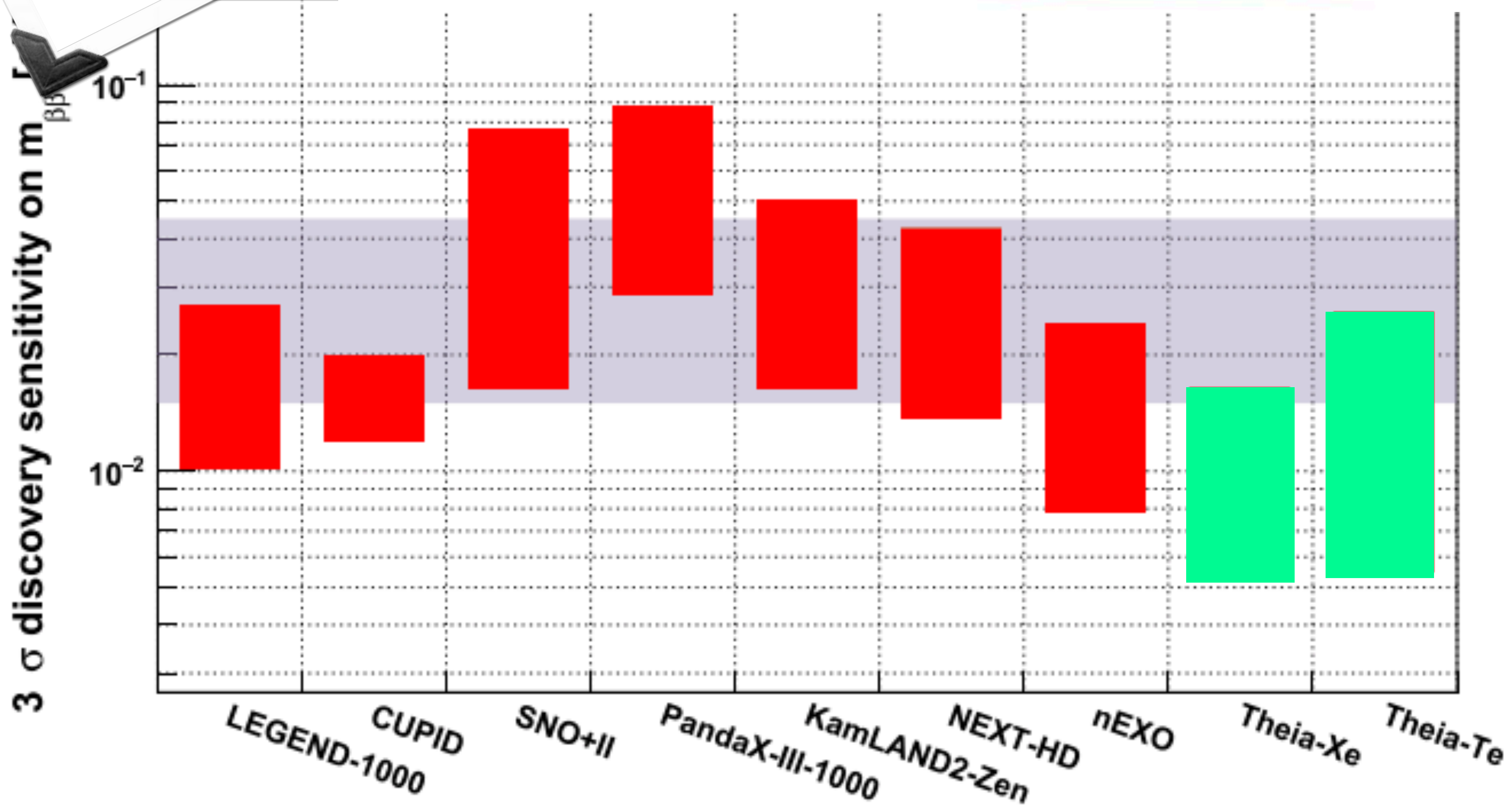


Background reduction via event imaging: PID, multi-site, directionality

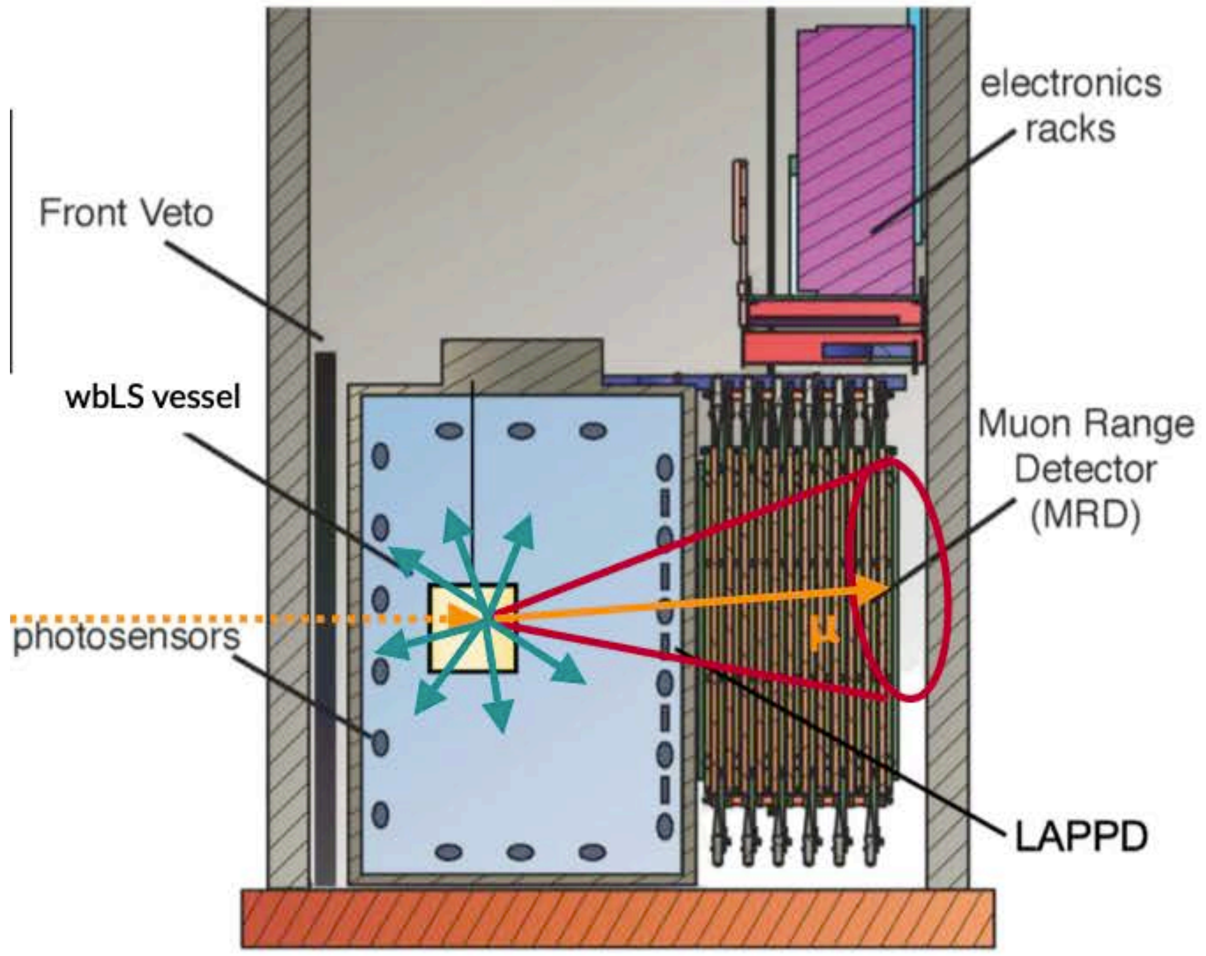


Significant room for further optimization!



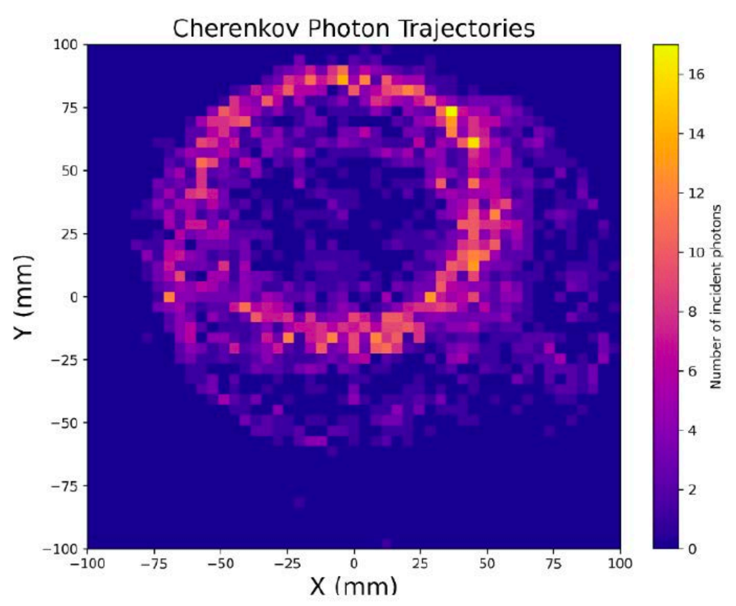


The path to THEIA



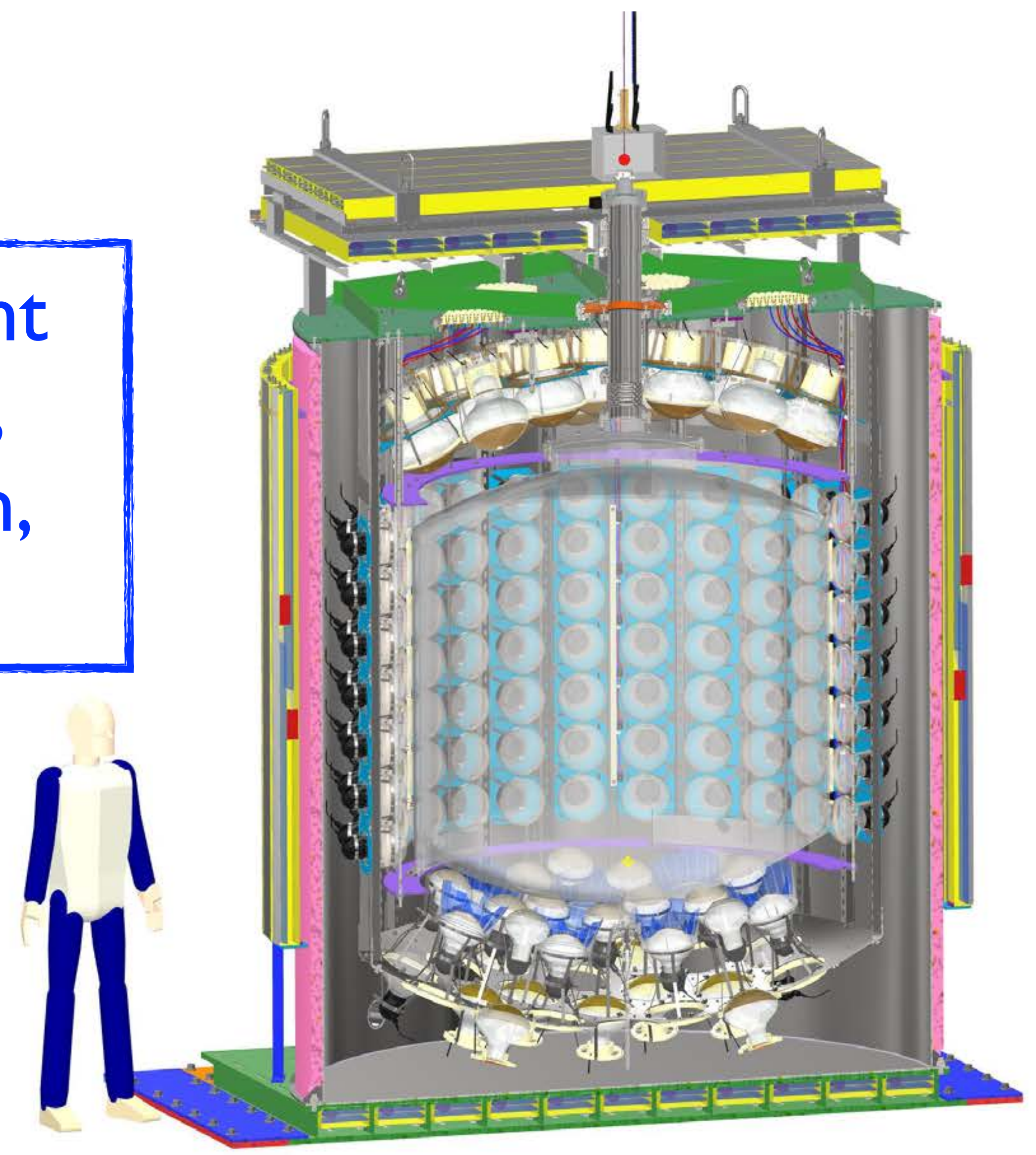
ANNIE: 365 kg

High-energy event reconstruction, neutrino detection, LAPPDs

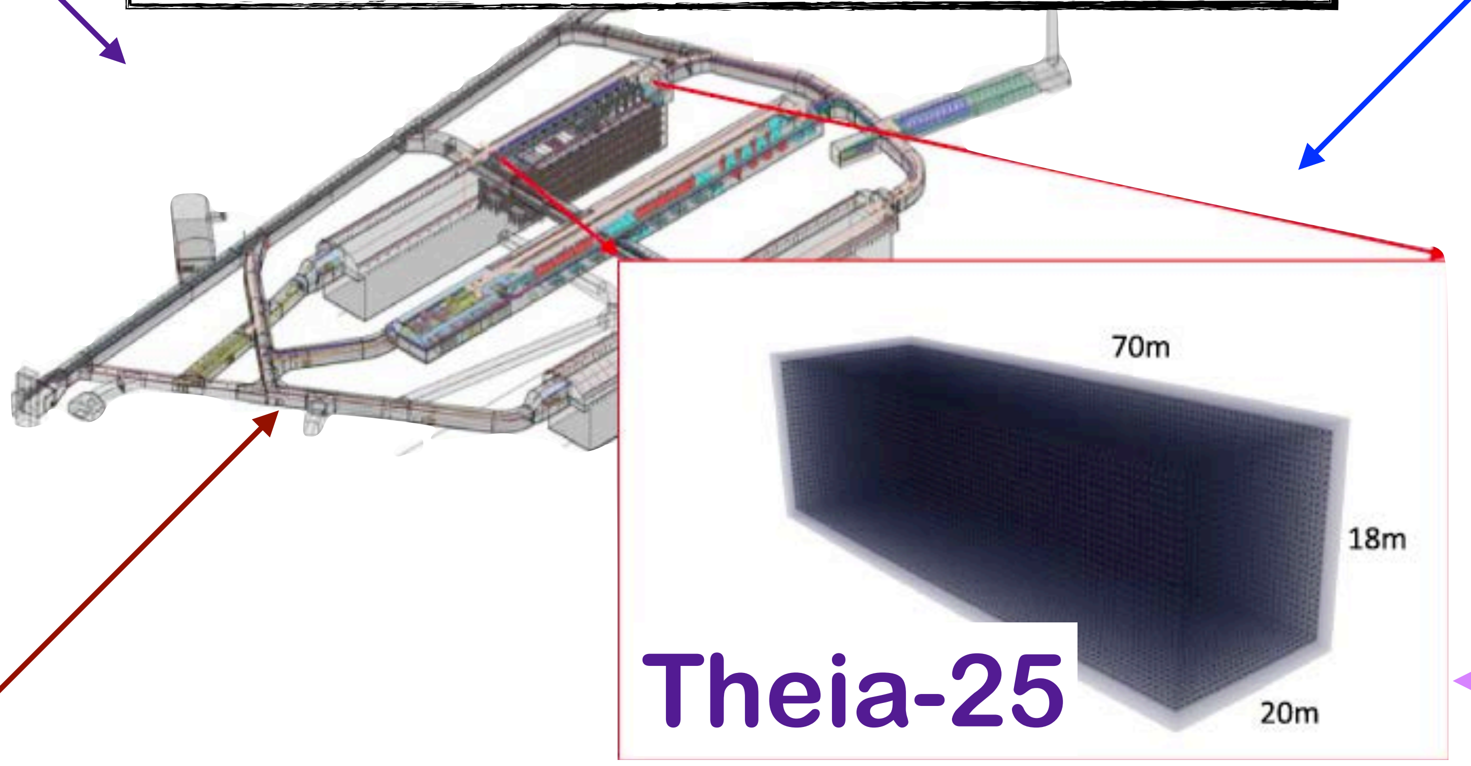


Eos: 20 ton

Low-energy event reconstruction, model validation, dichroicons



Building on a broad program of bench-top scale development



BNL: 1- and 30-ton

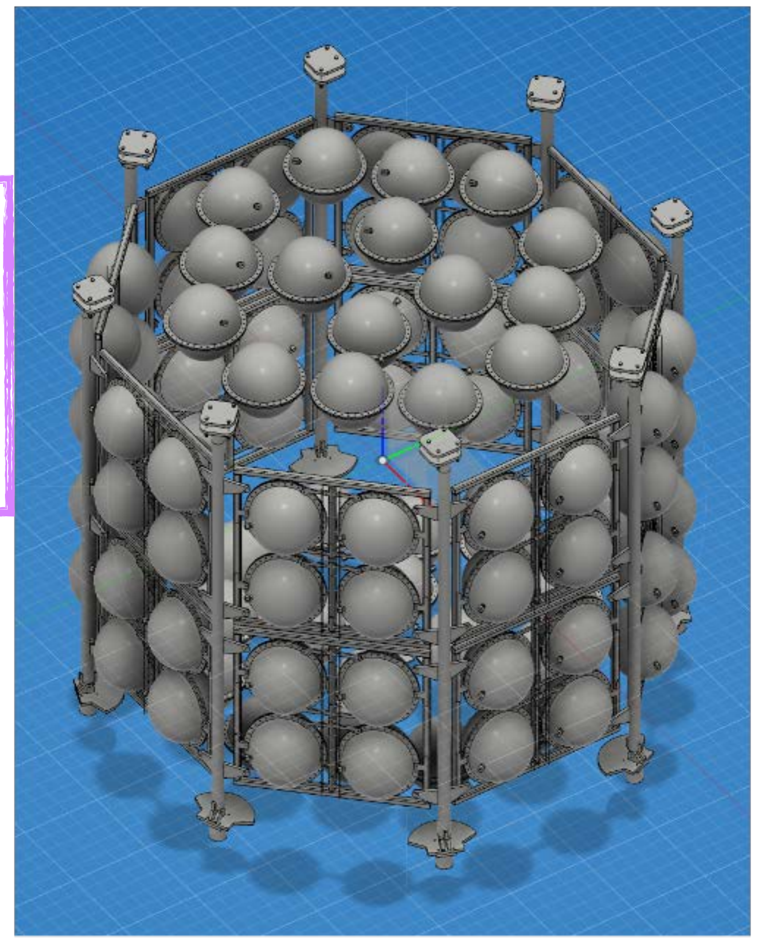
Deployment, purification, recirculation, transparency

NuDot: 1 ton

Isotope loading, NLDBD topology

BUTTON: 30 ton

Underground deployment, low bkg verification



Community building

Key differences

- **THEIA needs a large cavern (10s kTon)**
- Under consideration for DUNE FD4
- Targeting next-next-Gen DBD (beyond ton-scale)
- Large set of potential "predecessor" projects
  / not the natural evolution of any specific one-or-few
  - SNO, SuperK, T2K, LBNE, HyperK…
  - SNO+, Borexino, KamLAND(-Zen), JUNO…

Timeline

2013:	Snowmass engagement	
May 2014:	First workshop on "advanced scintillation detection" hosted at LBNL	*Centred around single technology*
Sept 2014:	First paper on arXiv: "Advanced Scintillator Detector Concept (ASDC): A Concept Paper on the Physics Potential of Water-Based Liquid Scintillator"	
2014 —	Many talks presented to introduce the concept to the community	
2014:	Cher / scint concept mentioned as blue-sky R&D in P5 report	
2015:	ASDC concept renamed to "THEIA"	
2015-16:	Workshop series, hosted at UC Davis, FNAL, Mainz "Frontiers Of liquid Scintillator Technology"	*Low threshold for engagement*
2016:	External papers start to reference THEIA	
2019:	Nat. Sec. funding begins // Mid-scale proposal to NSF (not successful)	*Agencies want a process for FD4*
2020:	White paper: "THEIA: An advanced optical neutrino detector"	*Much broader range of technology*
2021:	$22M funding to construct EOS and BNL-30T technical demonstrators	*Huge boost to momentum*
2021-2:	Snowmass engagement; THEIA technology referenced in P5 for FD4	*Path to broad physics program*
2022 —	Engage in US RDC and European DRD processes	*Connections to related efforts*
2023:	Second proposal to NSF mid-scale (not successful)	***Be resilient***
2025:	GATEWAY-0 at SNOLAB; THEIA Exec visit to SURF; physics WGs revived	*Gaining momentum*
2025 —	Annual workshop series revised, hosted at Penn, Mainz, (Triumf? SNOLAB?)	*Considering formalising collab.*

THEIA community

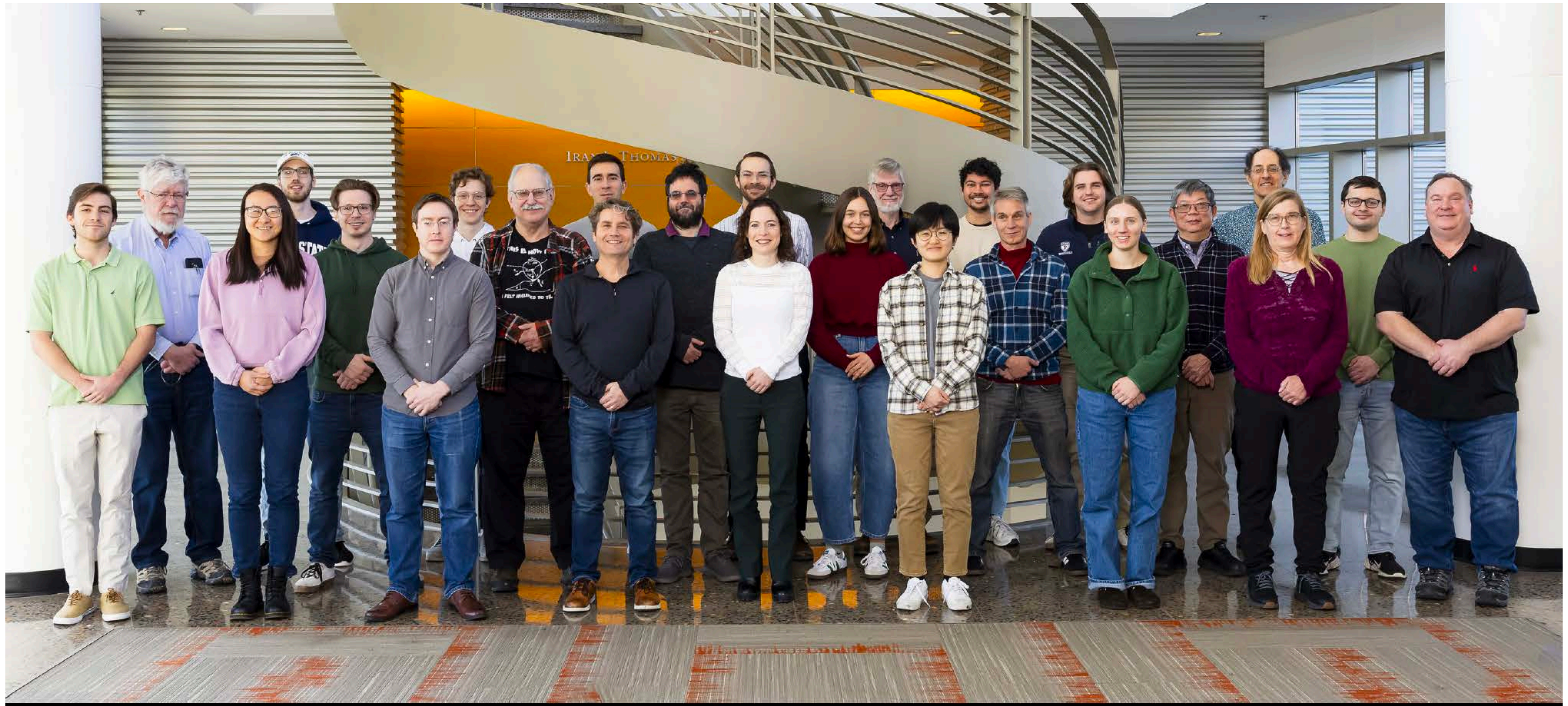
White paper - Eur. Phys. J. C 80, 416 & arXiv:2202.12839 [hep-ex]

- THEIA consortium: 117 authors, 48 institutions,
- Authors of THEIA White Paper:
    - 35+ institutions
    - 9 countries (CA, CN, DE, FI, IT, KR, PT, UK, US)
- Effort embedded in international R&D programs like DRD2, RDC9

- Main experimental effort & demonstrator development:
    - ANNIE WbLS+LAPPDs, GeV reco
    - BNL-1T/30T WbLS circulation/purification
    - BUTTON low-background WbLS
    - EOS MeV reco with WbLS/slow LS

\+ Large international community working on bench-top

The EOS team



Oak Ridge National Lab (2025)

Team breakdown:

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

10 postdoctoral scholars
9 graduate students
18 undergraduate students

USA

Germany

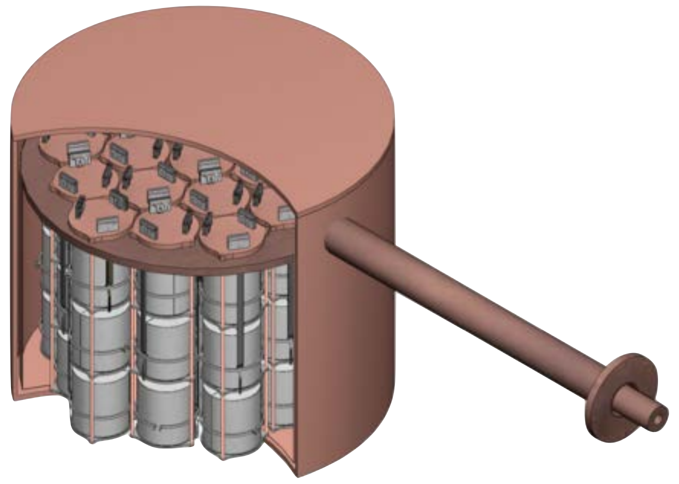
Portugal

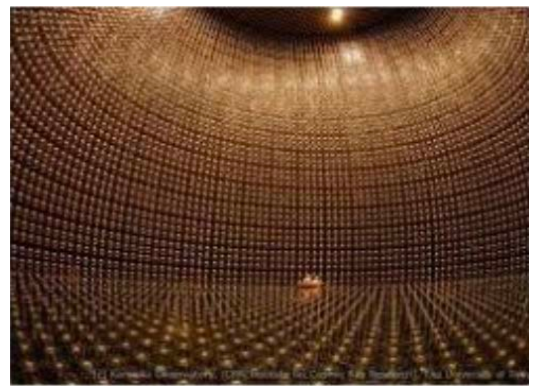
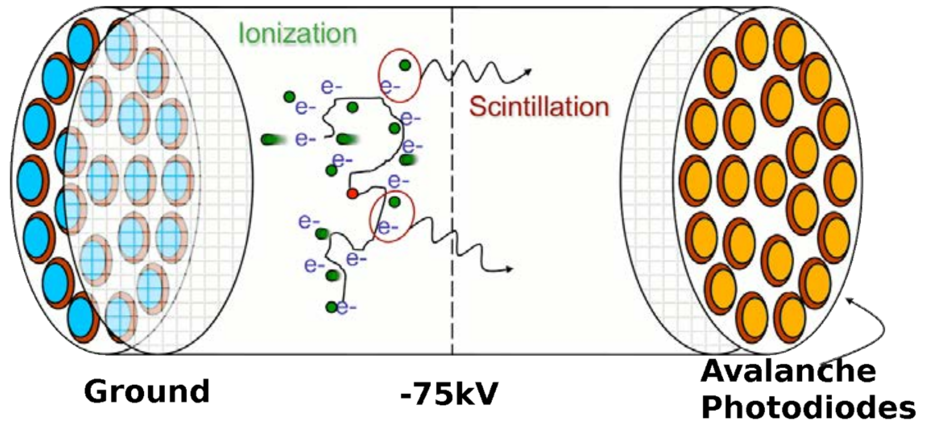
Finland

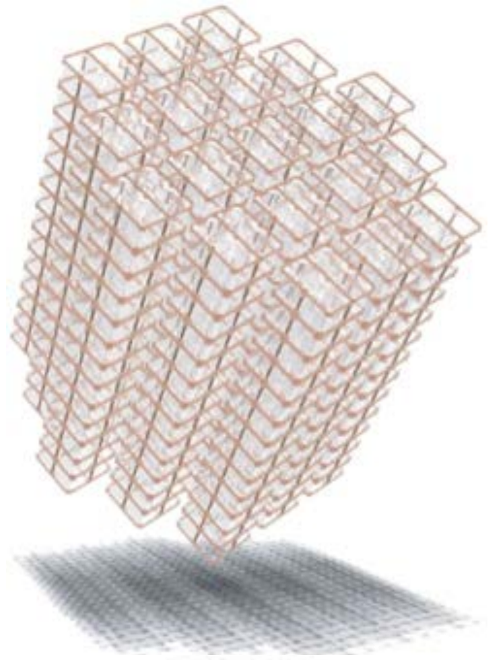
Turkey

Canada

Take-home thoughts



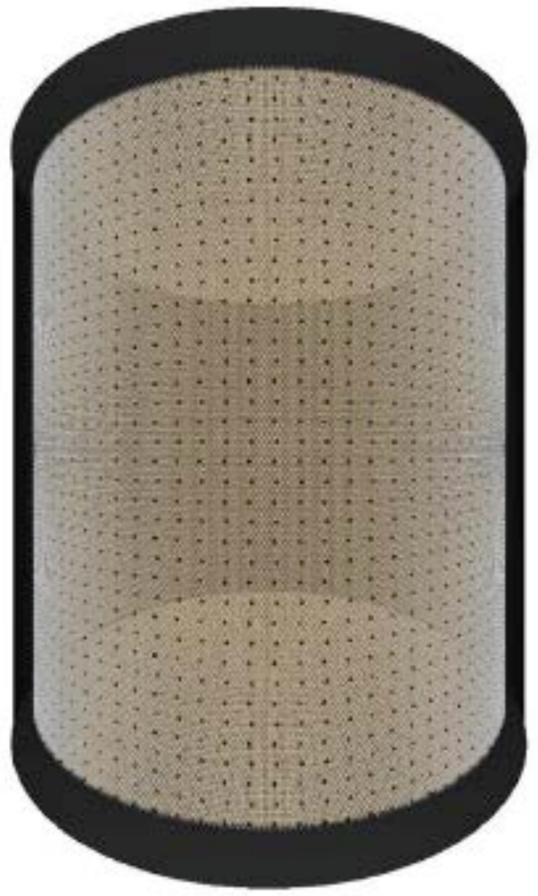
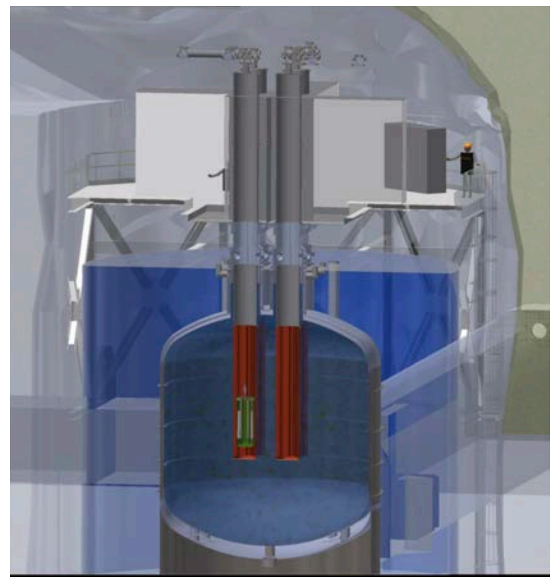
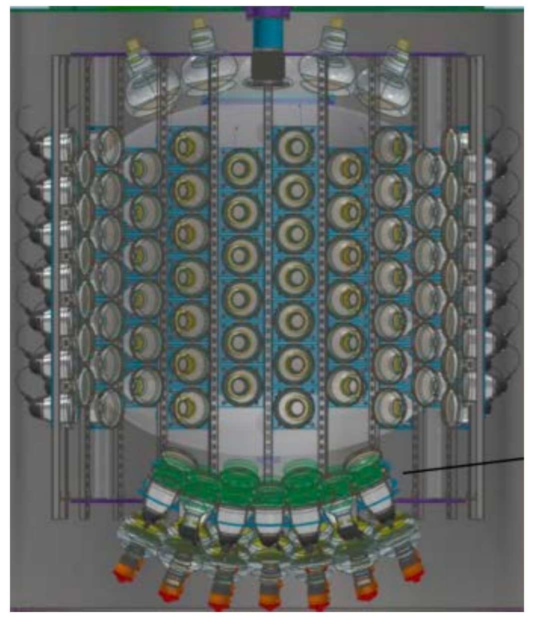

$0\nu\beta\beta$ offers exciting discovery potential beyond ton-scale

Critical to continue support for technology development
Informs & benefits from development in other fields

Isotope acquisition will be a common challenge

Leverage and strengthen synergies with other physics
Supports impactful physics discoveries in dark matter, and neutrinos: solar ν, geo-ν, supernova, DSNB, other…

The team is the most important part of the experiment

Thank you

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