Neutrino physics II: Neutrino properties

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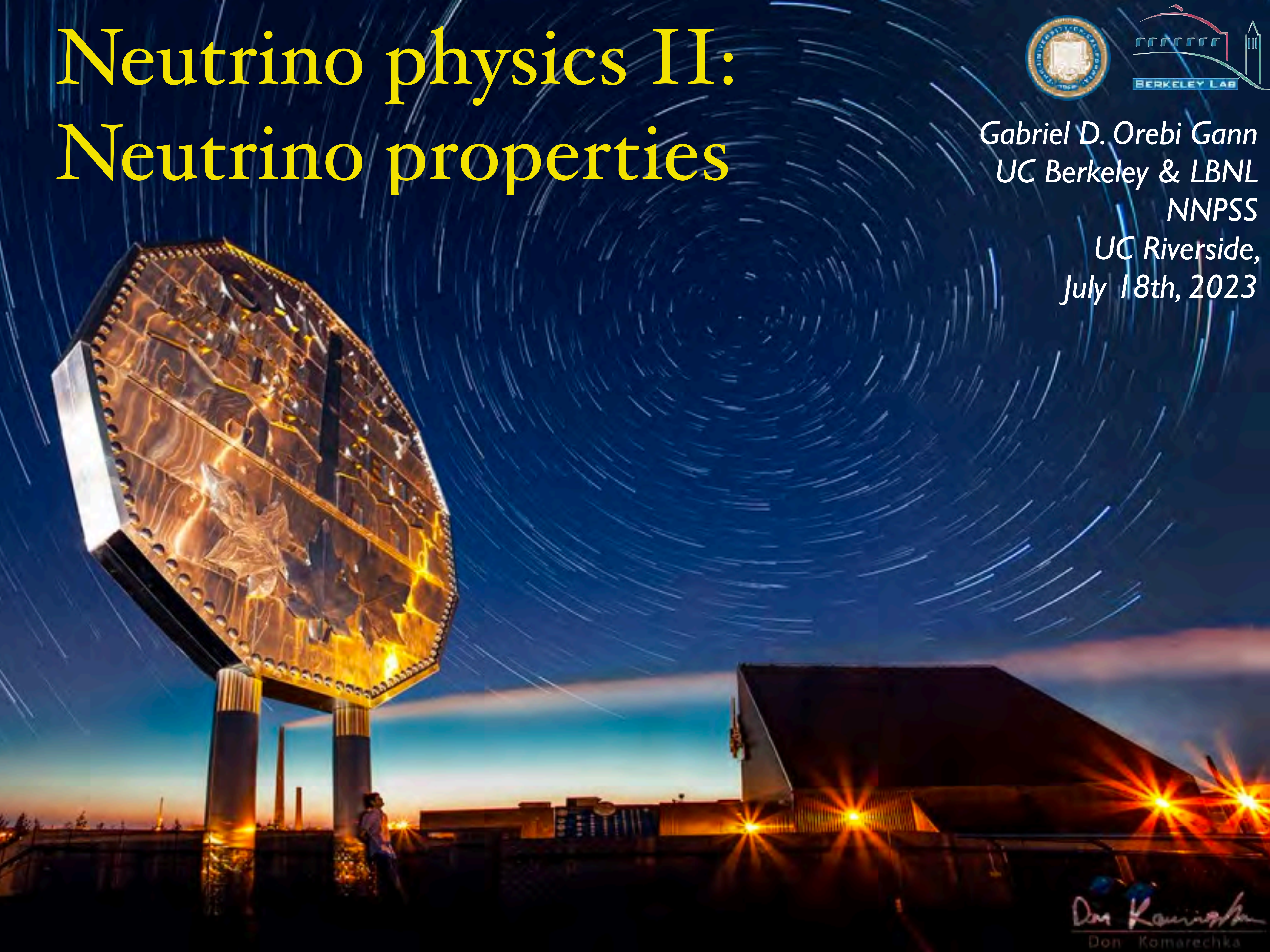
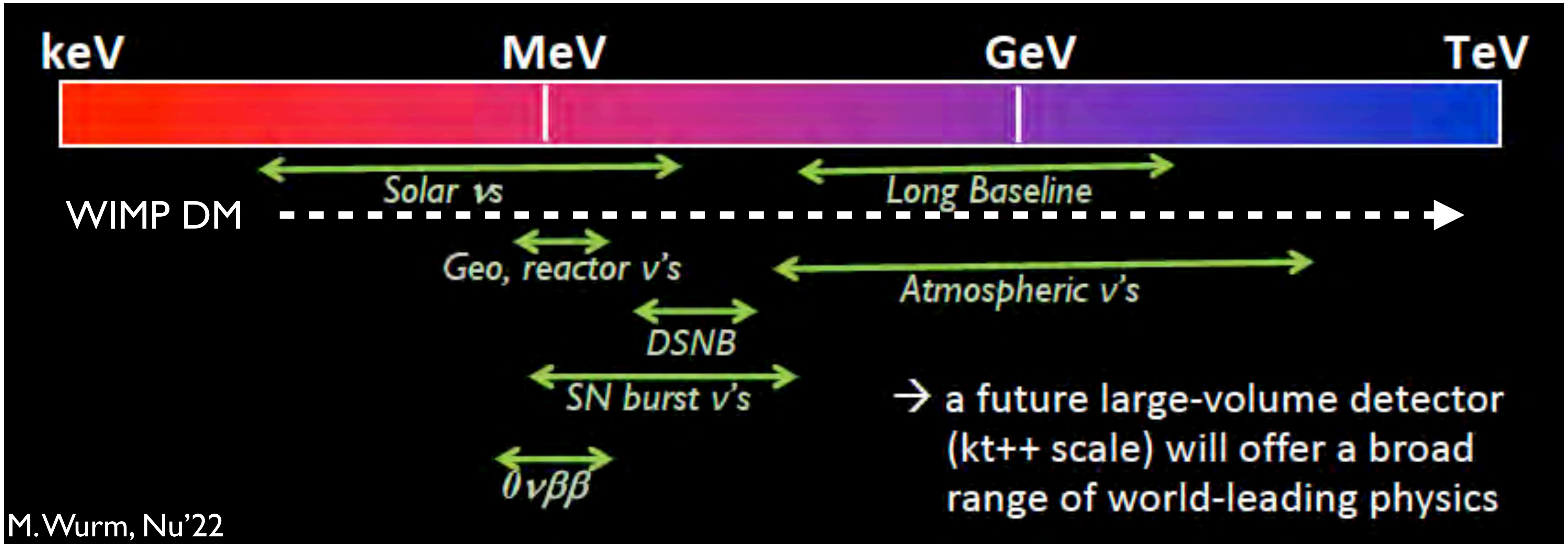
July 18th, 2023



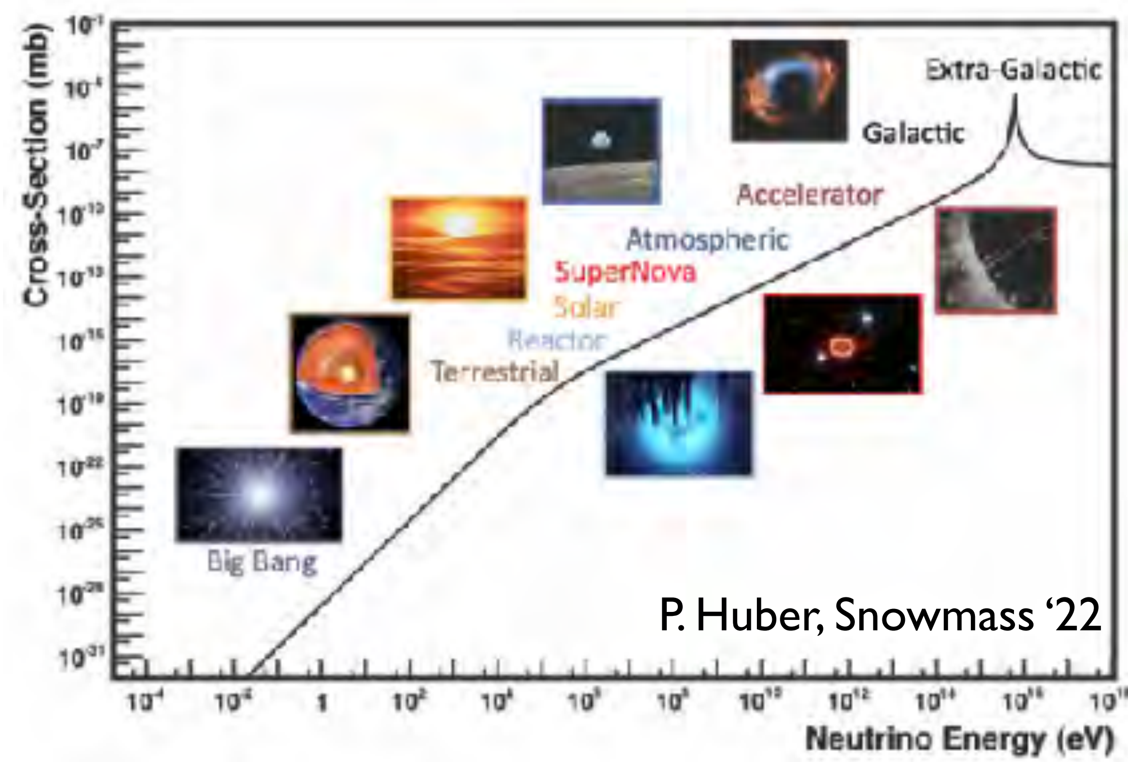
Overview

- Open questions in neutrino physics
- Neutrino mass
- Majorana neutrinos
  - Neutrinoless double beta decay
  - Detector technology
- CP violation
- Outlook

Broad physics program

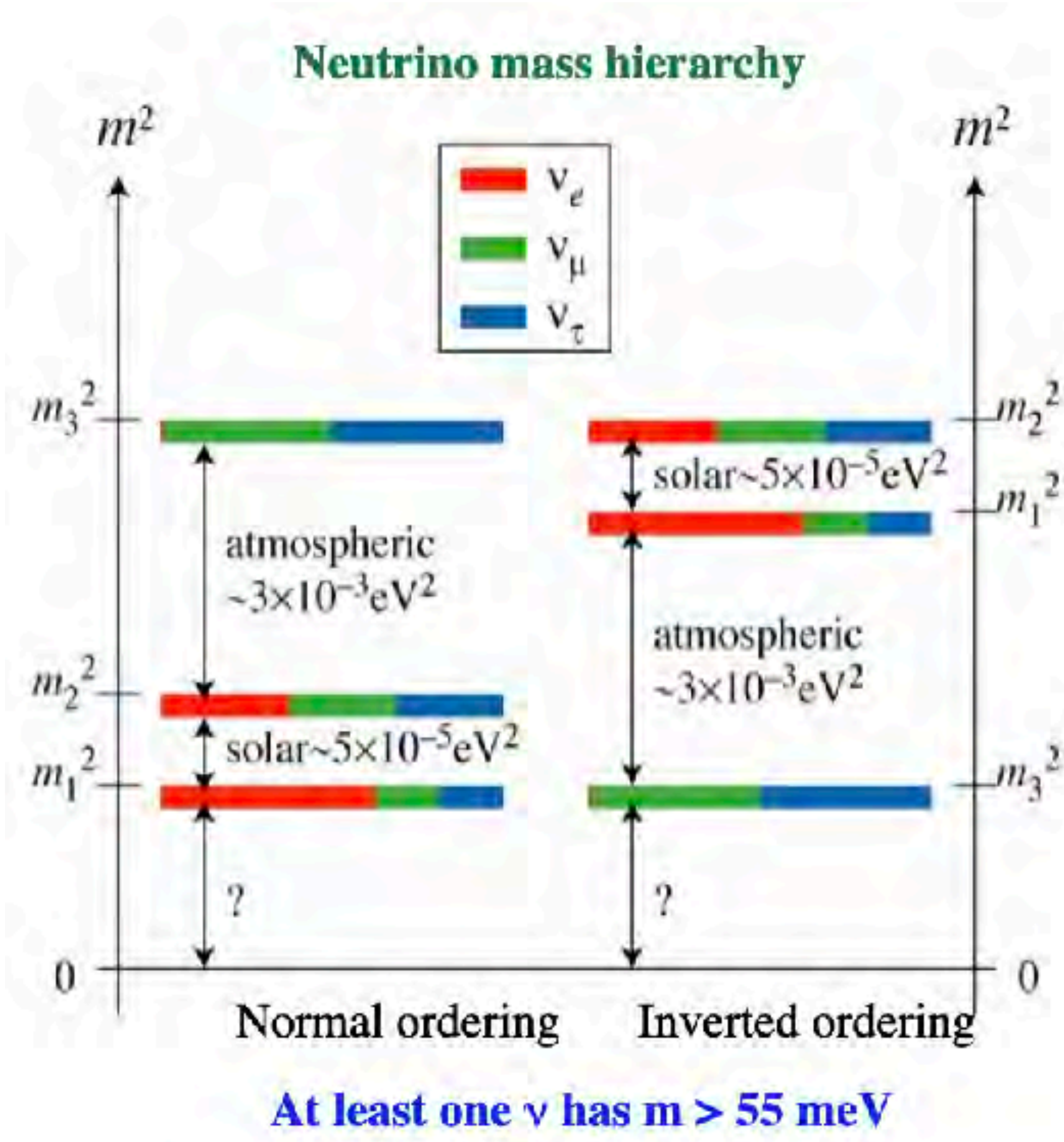


- Low energy threshold (but not as low as for nuclear recoils!)
- High detection efficiency
- Large exposure
- Directionality
- Broad detection range



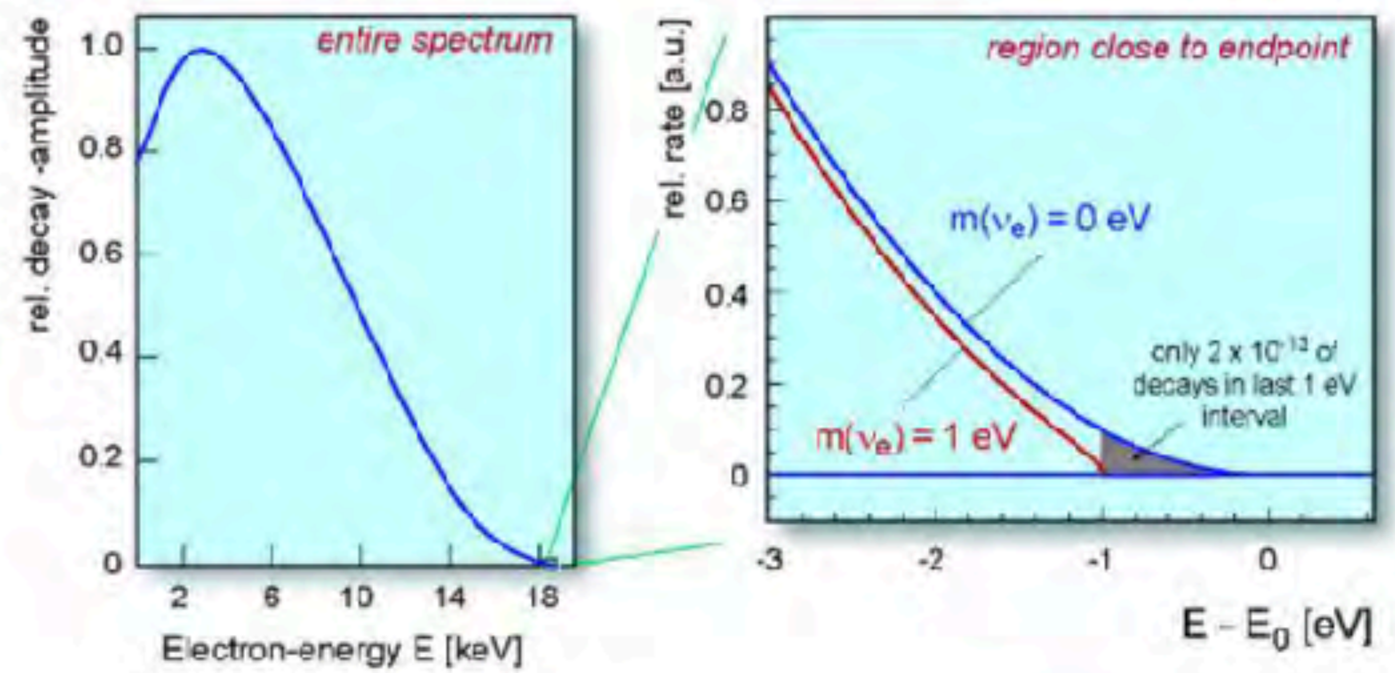
Neutrino landscape

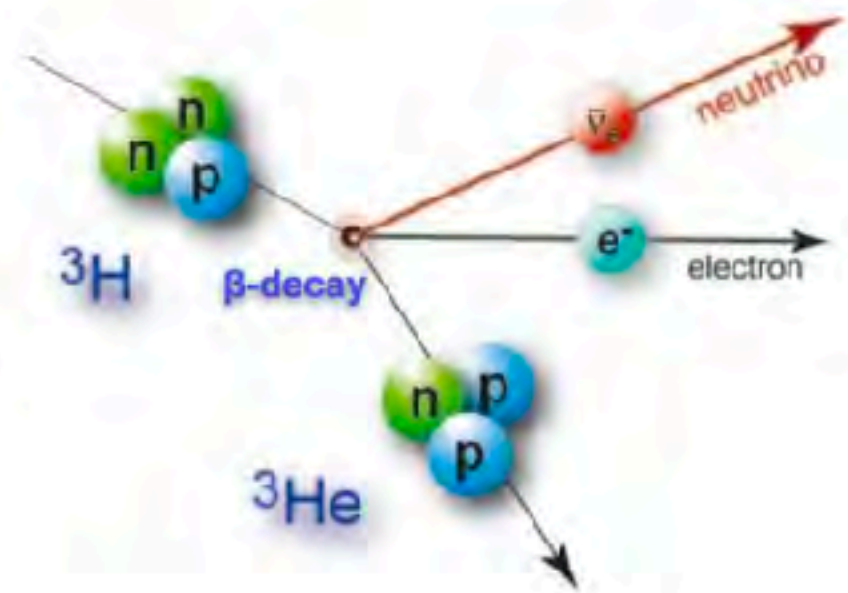
- ***Compelling evidence for***
  - Neutrino flavor-changing oscillations
  - (therefore) finite neutrino masses
  - Mixing angles well measured
- ***Open questions in ν Physics:***
  - How many neutrinos?
    - Sterile neutrinos?
  - Absolute scale of ν mass
  - How are the masses arranged?
  - Are neutrinos responsible for matter-antimatter asymmetry?
  - Are neutrinos Majorana or Dirac?
  - Is Lepton Number conserved?



Neutrino mass

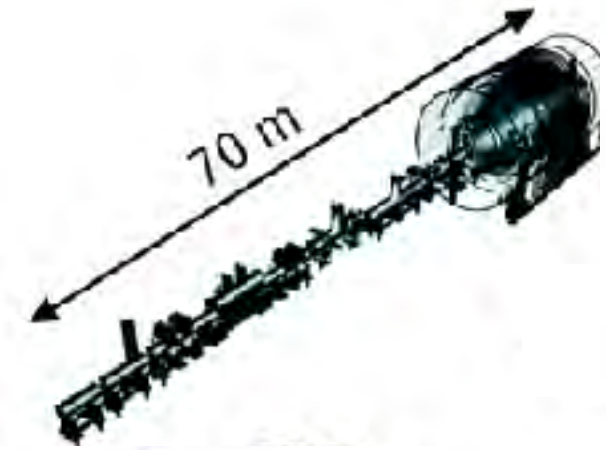
- Model-independent approach: study kinematics of weak decays
- Looking for anomalies in the beta-decay spectrum
- Need to be able to measure the electron energy with high precision
    - KATRIN: high resolution spectrometer using magnetic adiabatic collimation and electrostatic (MAC-E) filter → integral mode
    - Project-8: radio-frequency based detection using cyclotron radiation emission spectroscopy (CRES) → continuous mode

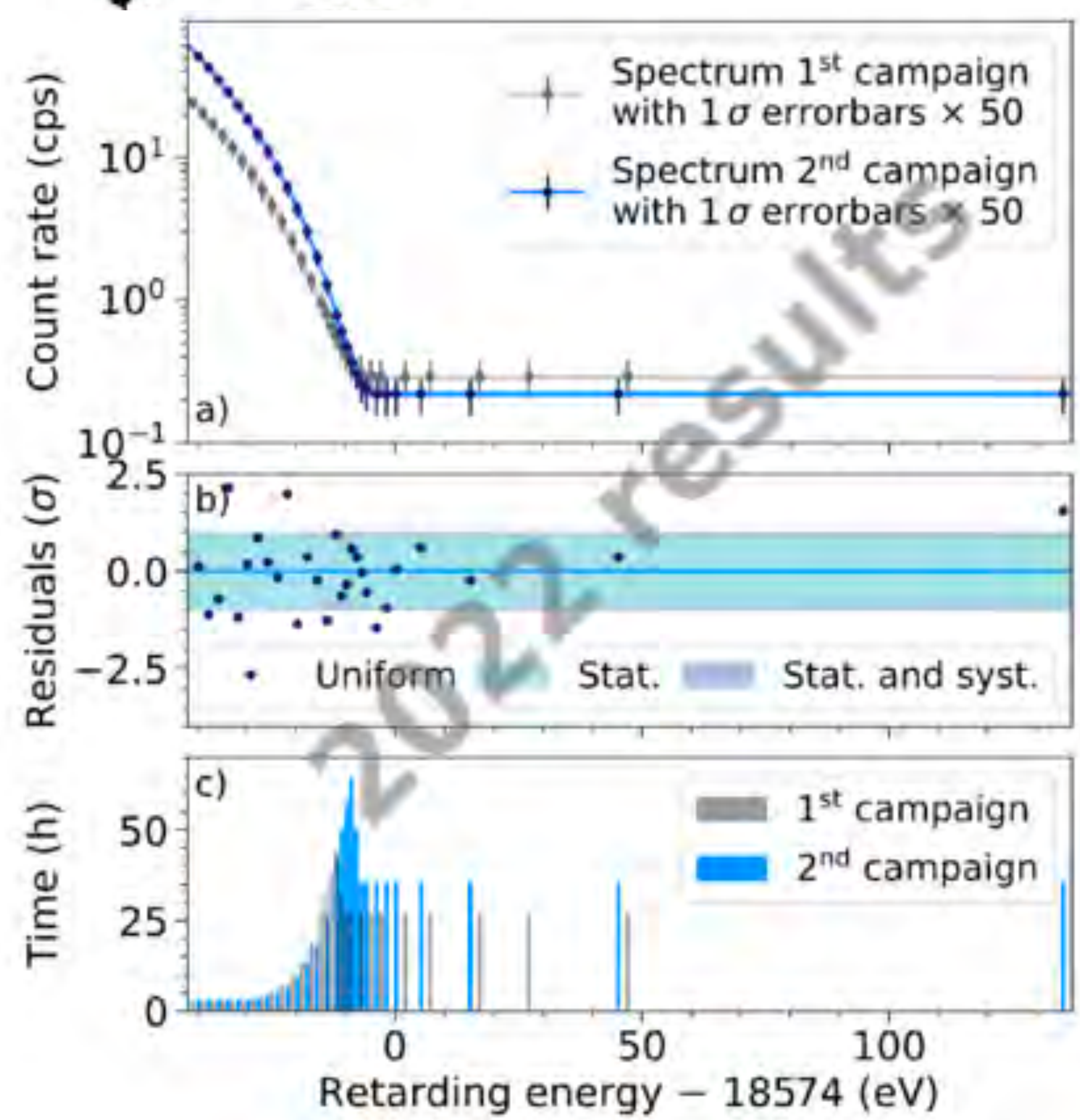




KATRIN

- Tritium: low end point (18.6keV), fast, super-allowed beta decay (12.3yr), solid and gaseous sources
- MAC-E filter with windowless gaseous T2 source → spectrometer experiment
- Running since 2019, completing data taking in 2025
- Sensitivity goal: 0.3 eV 90% CL
- Energy resolution <3 eV @18 keV.
- 2022: mν < 0.8 eV 90% CL Nat. Phys. 18, 160–166 (2022)
- New data in 2024
  → 0.5 eV sensitivity expected
- Next-gen: R&D into source & detection





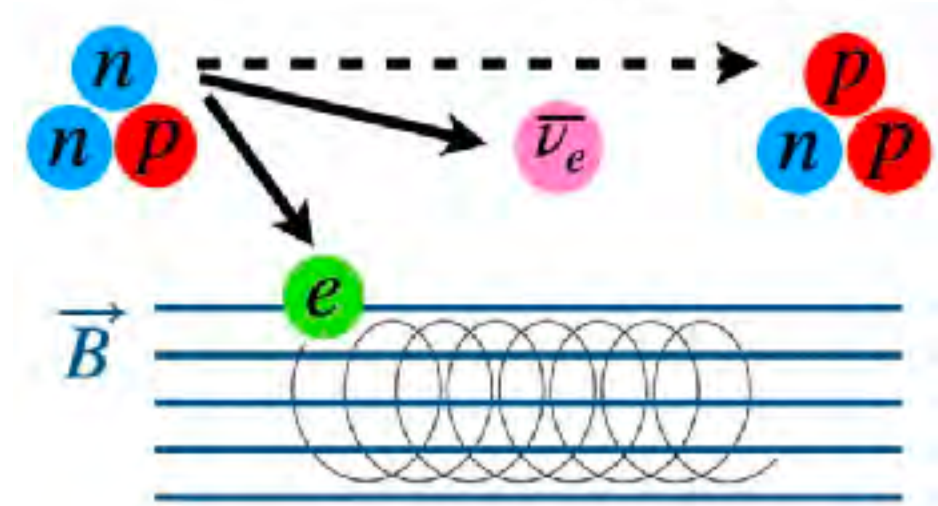
Project-8

- Cyclotron Radiation Emission Spectroscopy (CRES)
  - gas source decays in B-field → emitted electrons follow cyclotron trajectories along B-field lines, measure frequency (to infer E)
  - axial magnetic field applied to keep particles in the sensitive region of the volume
- Advantages:
  - Precision measurement in frequency domain
  - Simple low-pass filters can remove a lot of low-energy background → better scaling
  - Better statistical sensitivity and fewer systematic uncertainties than integrating spectrometers
- Technique successfully demonstrated
- Energy resolution ΔE_{FWHM}= 1.7eV at 18keV

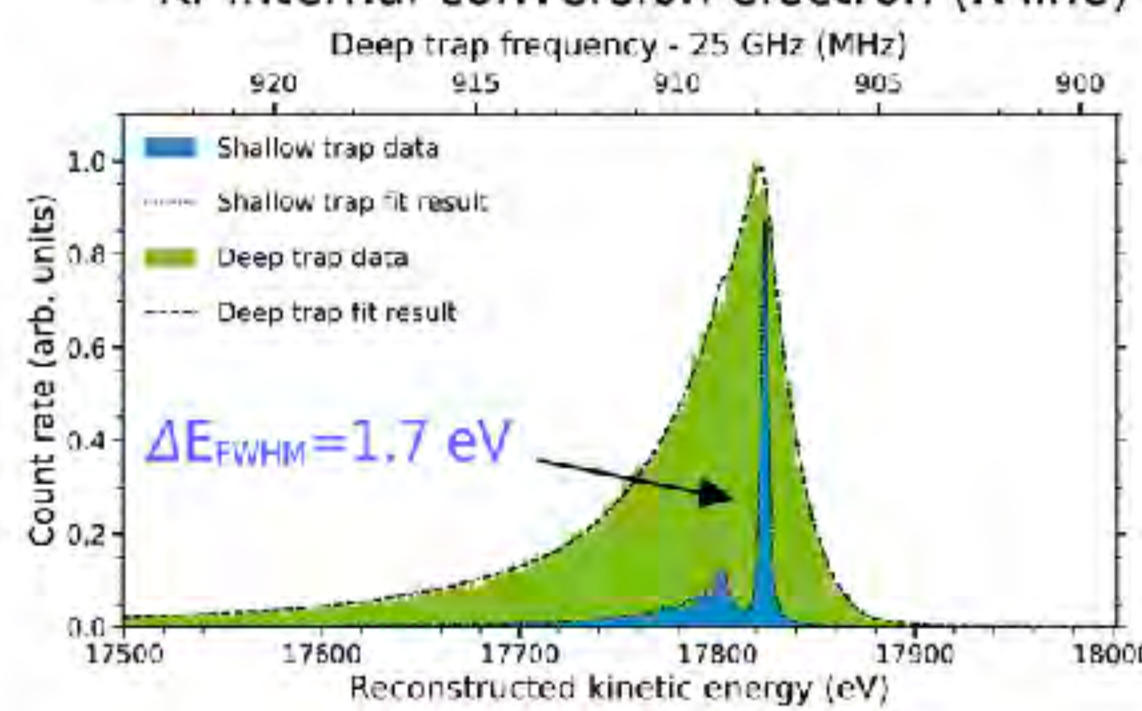
cyclotron emission frequency

$$2\pi f(E_\beta) = \frac{eB}{E_\beta + m_e} = \frac{eB}{\gamma m_e}$$

energy resolution $\frac{\Delta E}{m_e} = \frac{\Delta f}{f}$

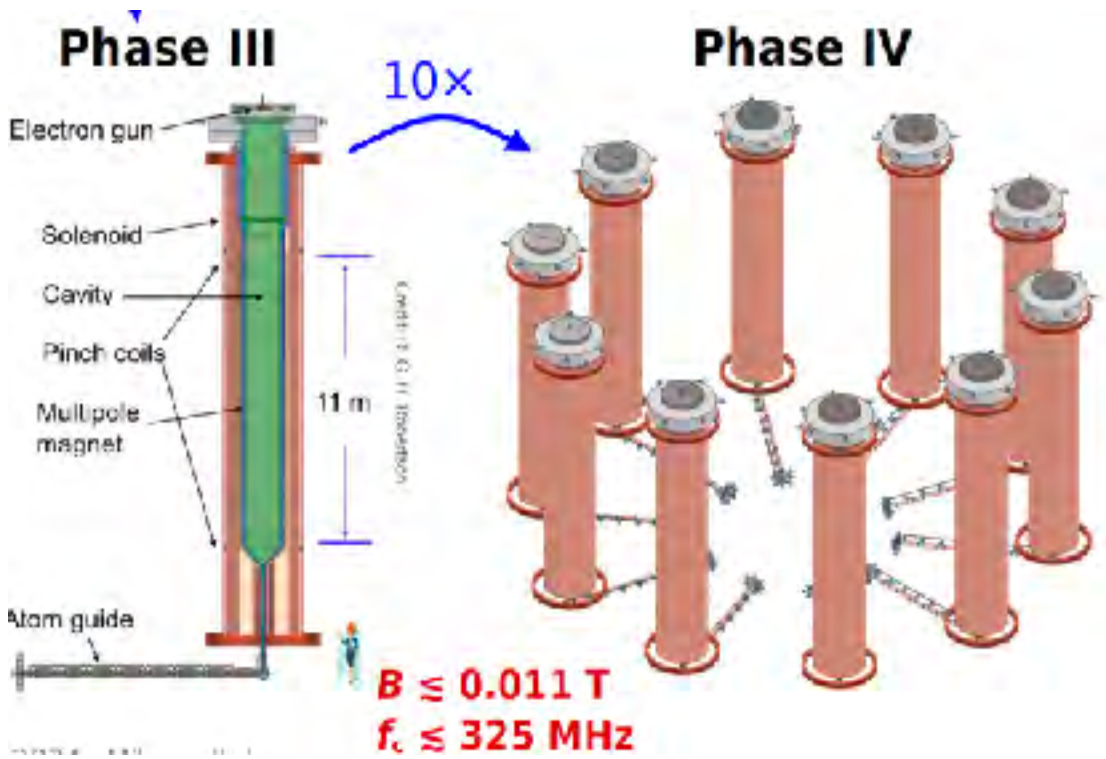


^{83m}Kr internal conversion electron (K line)

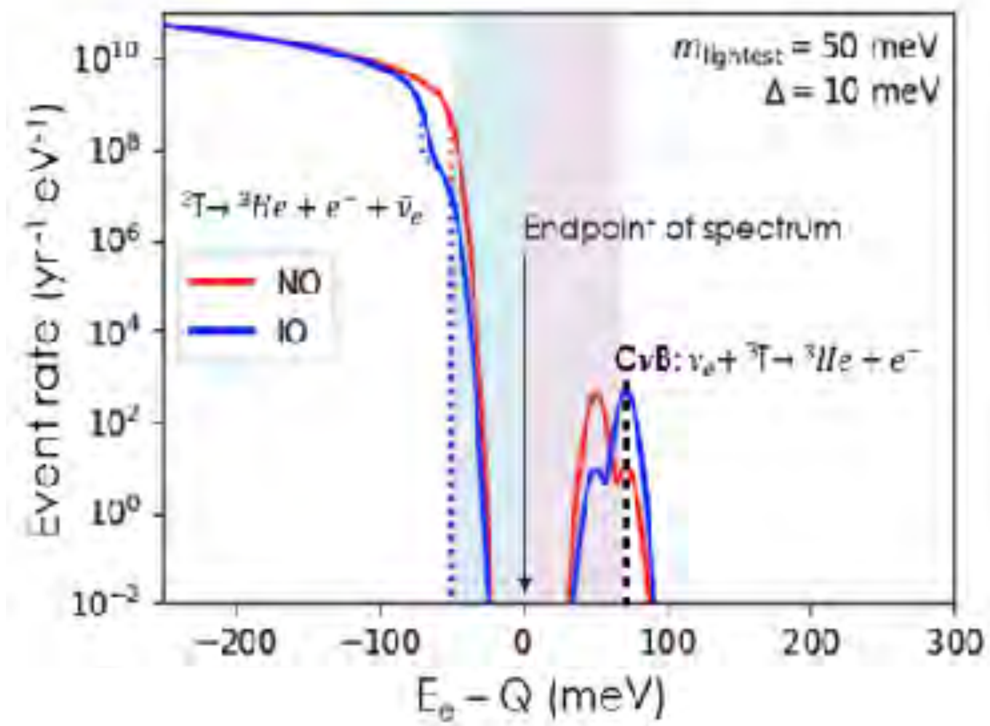


Future prospects

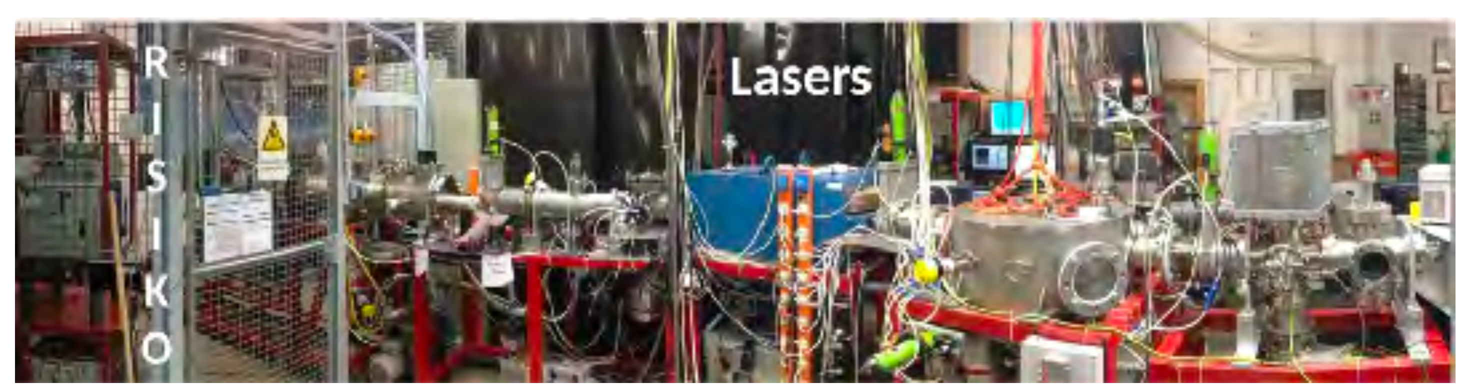
Project-8 Phase III (IV)
CRES with T2
Goal mν < 0.2eV (0.04eV)



PTOLEMY
Detect CνB via neutrino capture on tritium



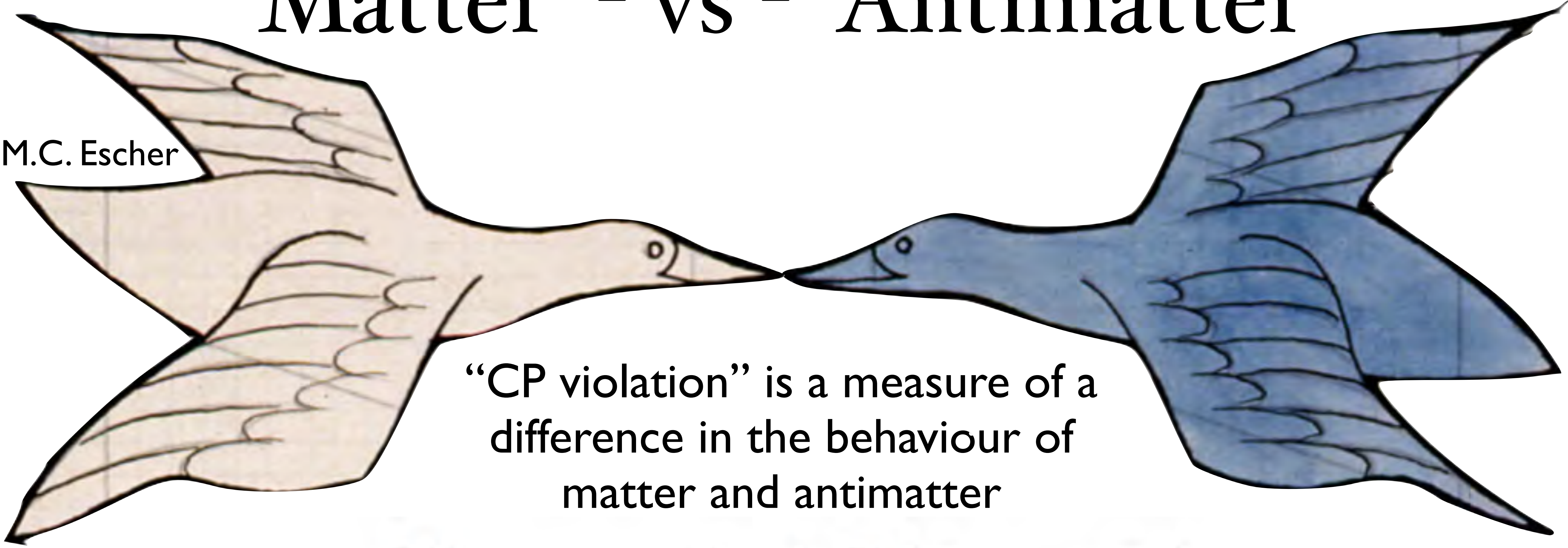
Electon-capture calorimetric experiments
ECHo, HOLMES
low temperature microcalorimeter arrays
with ion-implanted 163Ho
scalable proof-of-principles for an
experiment with ≲0.1 eV mν sensitivity



The nature of neutrinos

$$\nu$$

Matter - vs - Antimatter

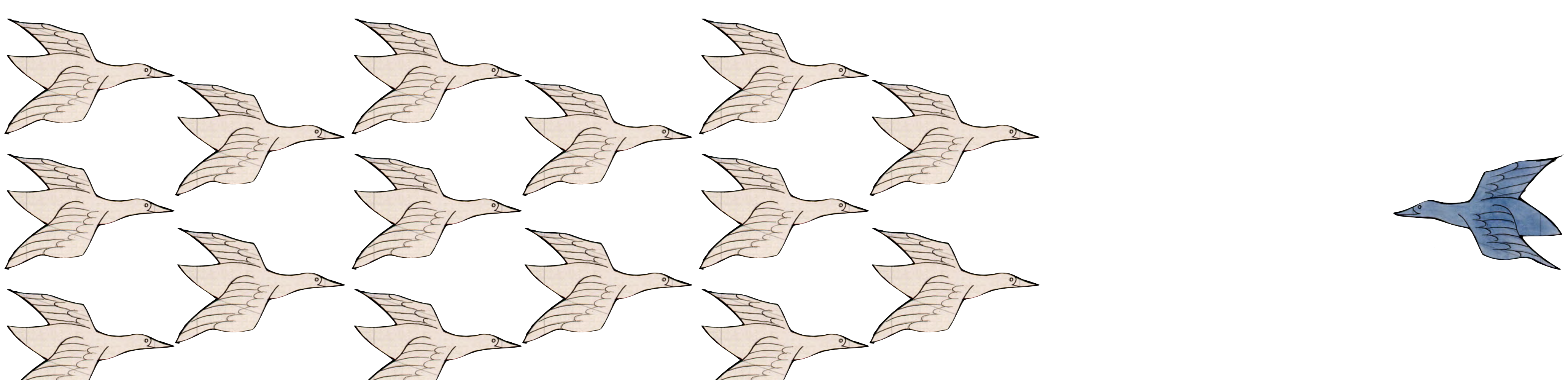


M.C. Escher

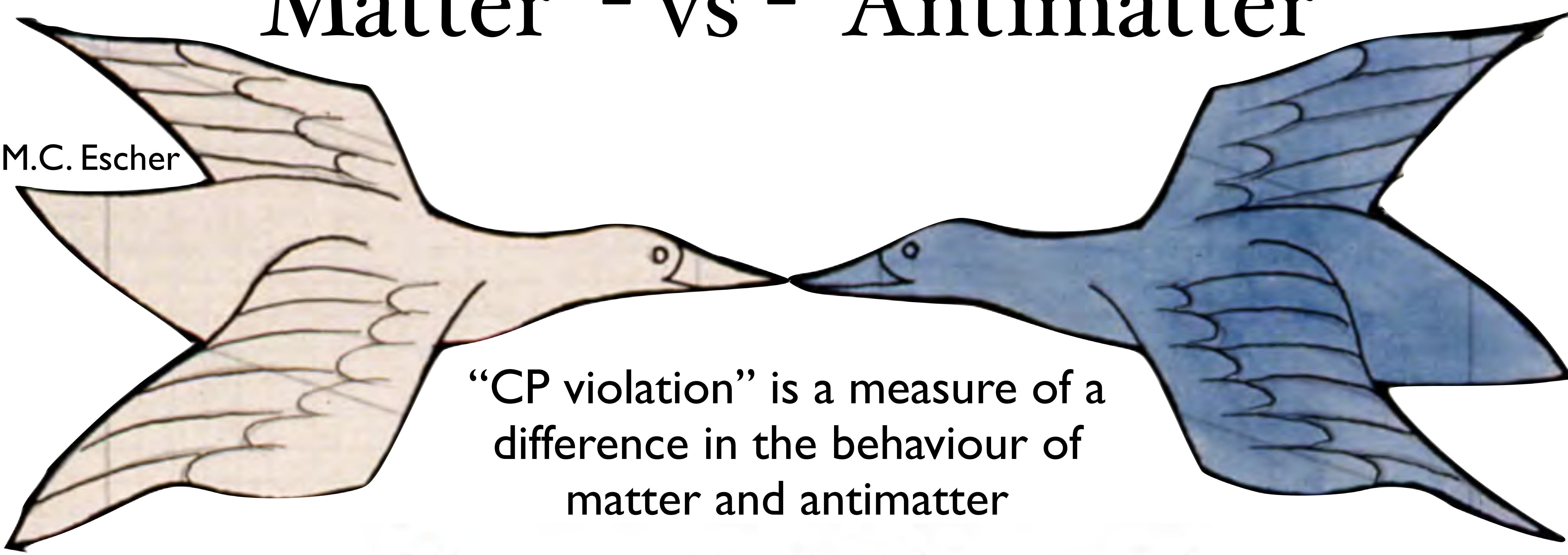
“CP violation” is a measure of a difference in the behaviour of matter and antimatter

$$P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

The Universe is out of balance: matter far outweighs antimatter



Matter - vs - Antimatter



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The Universe is out of balance: matter far outweighs antimatter

fortunately for us!

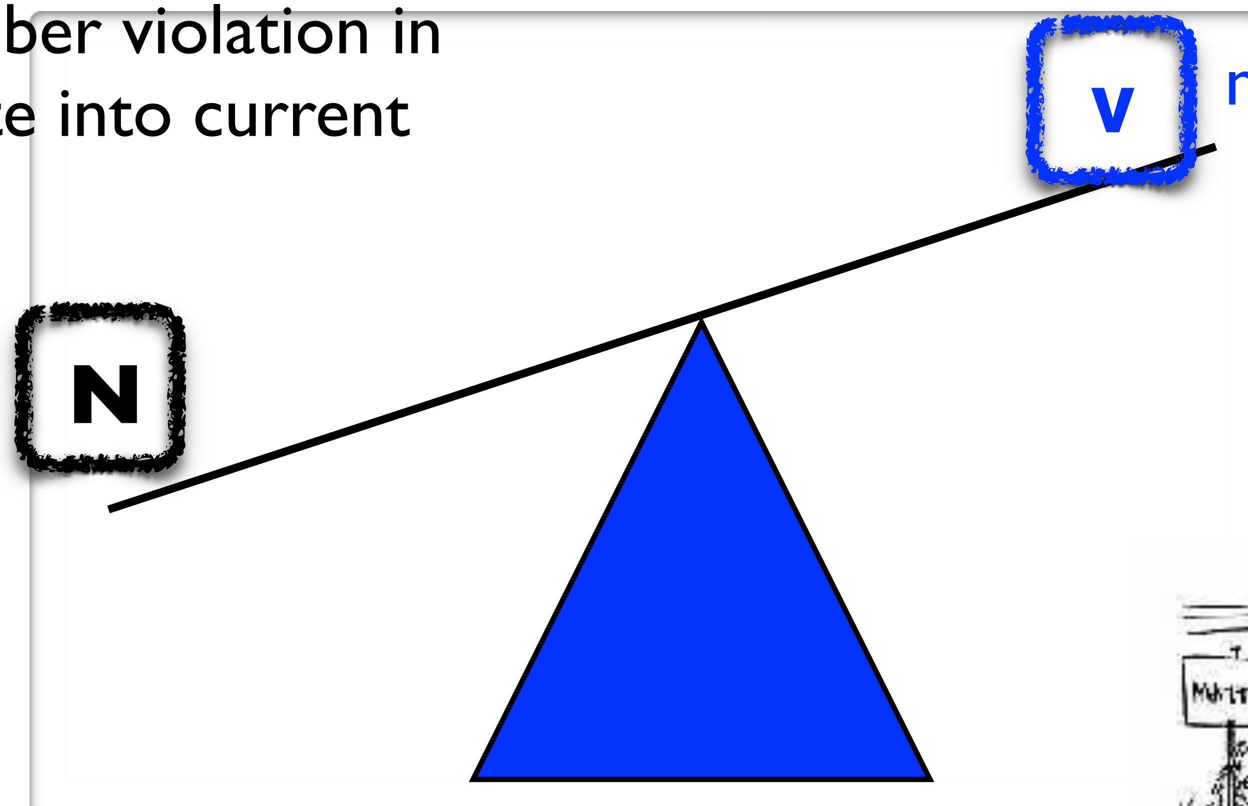
Majorana Neutrinos

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

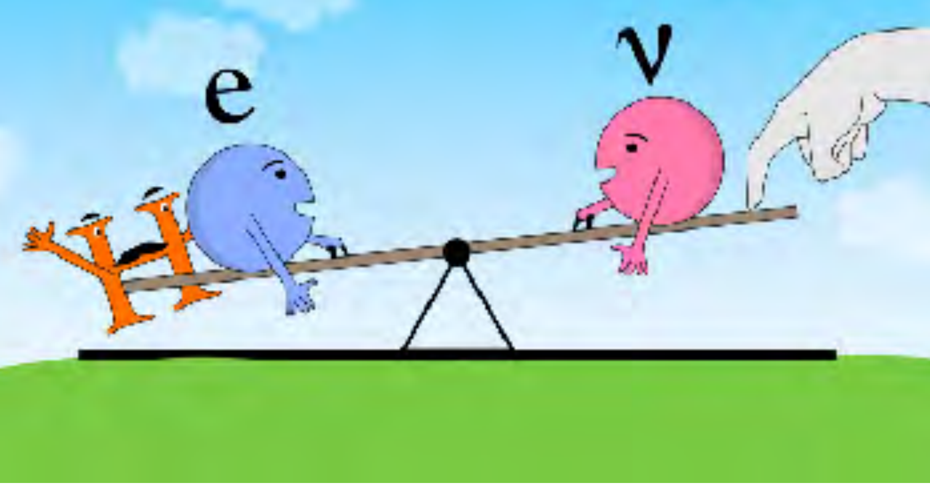
Dirac vs Majorana

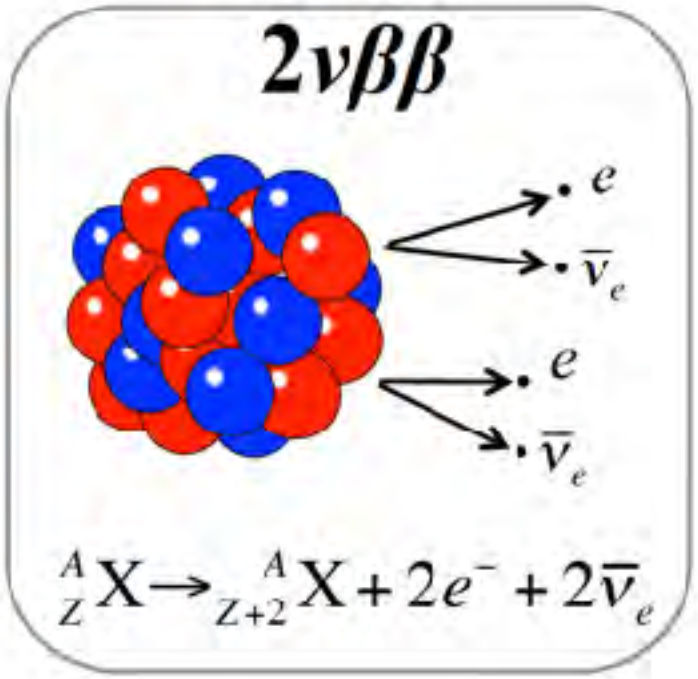
- ***Dirac***
- Requires new fundamental global symmetry U(1)lepton number
- New physics ?
- Matter and antimatter are fundamentally different

- ***Majorana***
- Cannot be explained by "standard" Higgs Yukawa coupling
- Lepton number violated: New Physics !
- Potentially sensitive to very high mass scales (see-saw mechanism)
- Can generate matter⇔antimatter transitions

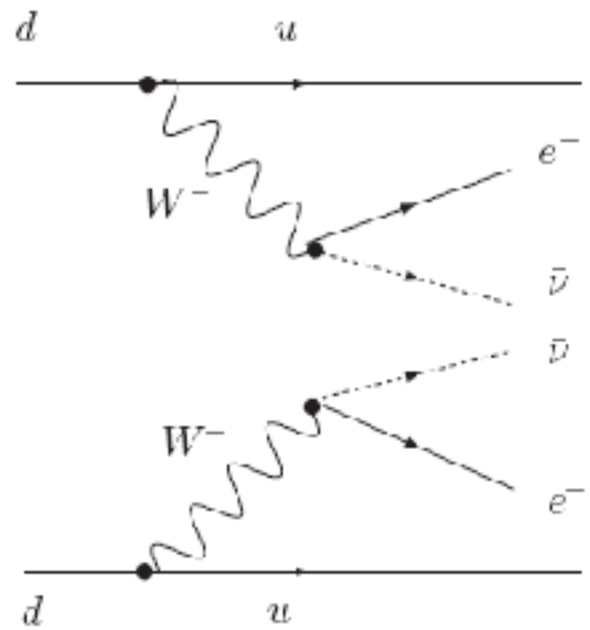
?

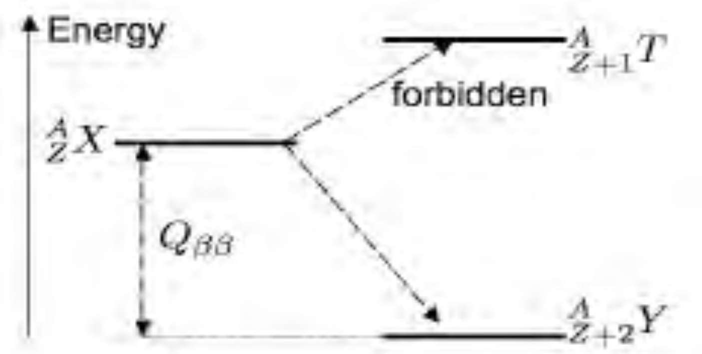
0ν double beta decay

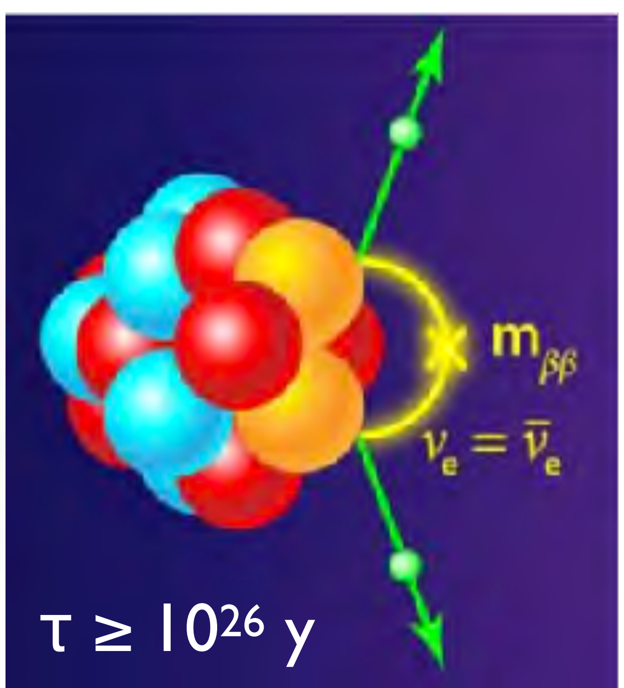


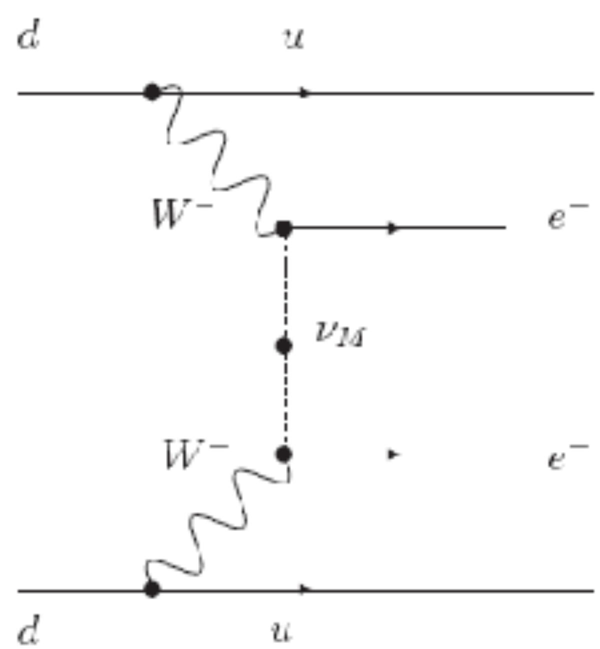


$\tau \geq 10^{19}$ y





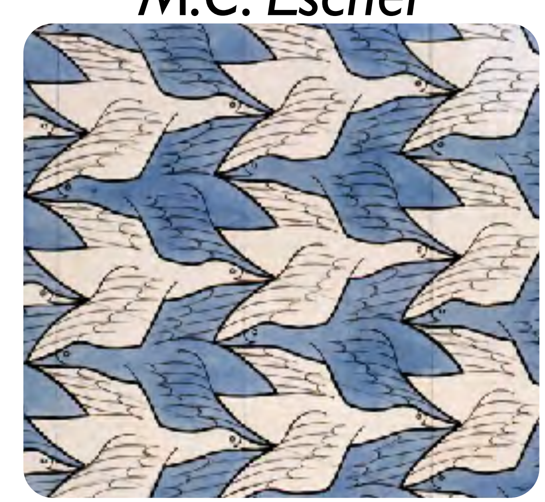




Fortunately,
N_A is very large!

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

M.C. Escher



0νββ Decay Rate

$$\Gamma = \left(T_{1/2}\right)^{-1} = G^{0\nu}\left|M'^{0\nu}\right|^2\left|\frac{m_{\beta\beta}}{m_e}\right|^2$$

Phase space factor
Well defined

Nuclear Matrix Element
Nuclear theory

Effective
Neutrino Mass

$$M'^{0\nu} = \left(\frac{g_A^{eff}}{g_A}\right)^2 M^{0\nu}$$

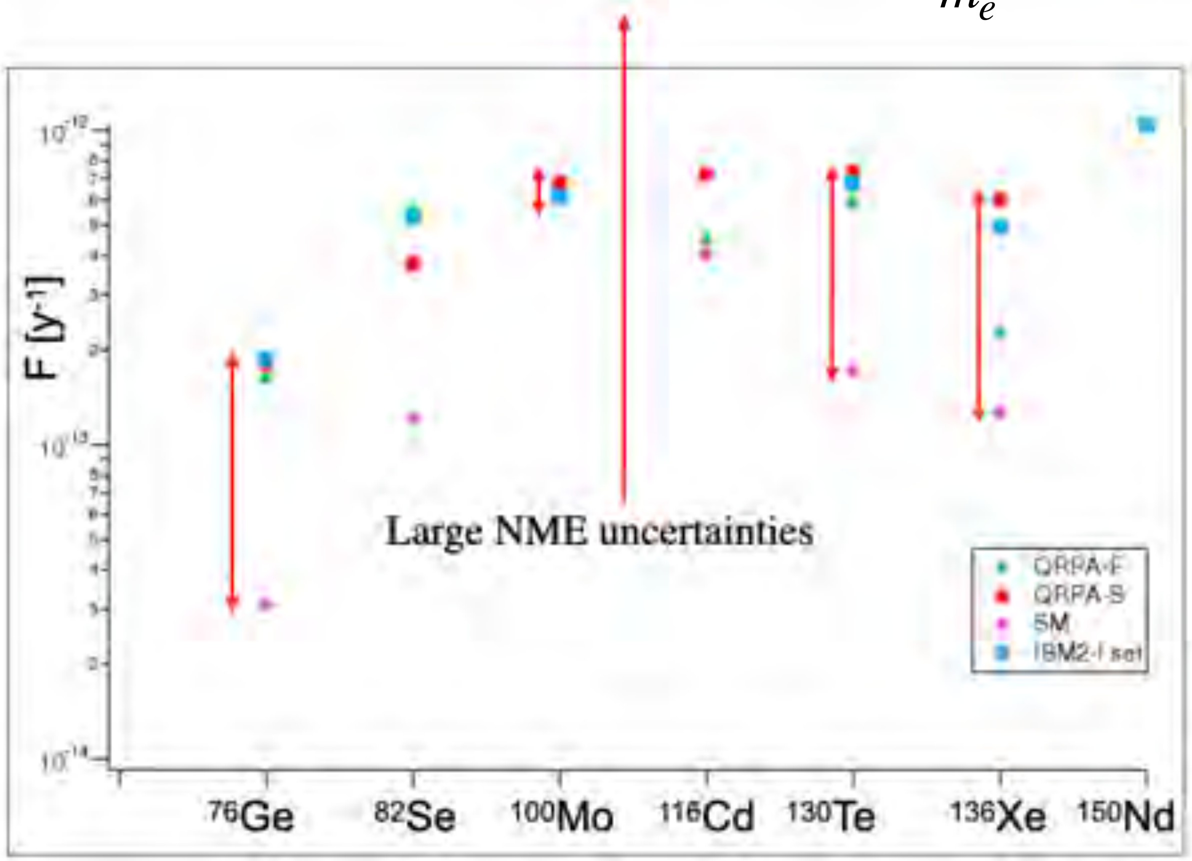
Phenomenological correction
Accounts for use of nuclear models
to estimate NME
Taken from single-β decay
Some controversy over value

Probes absolute neutrino mass scale
Also sensitive to mass hierarchy

$$m_{\beta\beta} = \left|\sum_i m_i U_{ei}^2\right|$$
$$= \cos^2\theta_{12}\cos^2\theta_{13}e^{i\alpha}m_1$$
$$+ \sin^2\theta_{12}\cos^2\theta_{13}e^{i\beta}m_2 + \sin^2\theta_{13}e^{-2i\delta}m_3$$

Isotope selection

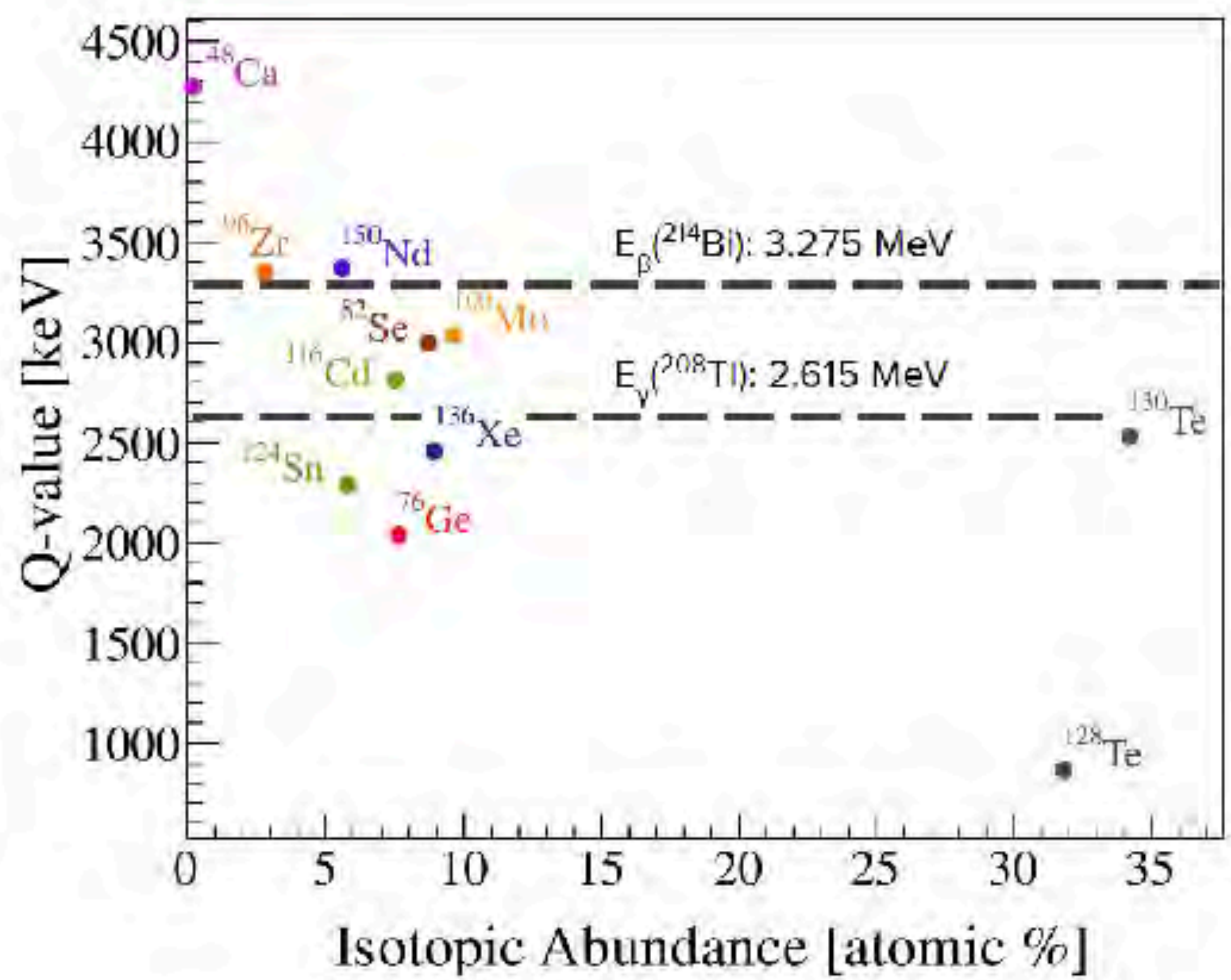
$$T_{1/2}^{-1} = G_F^2 \Phi(Q,Z)\,|M_{0\nu}|^2 m_{\beta\beta}^2 \equiv F\frac{m_{\beta\beta}^2}{m_e^2}$$



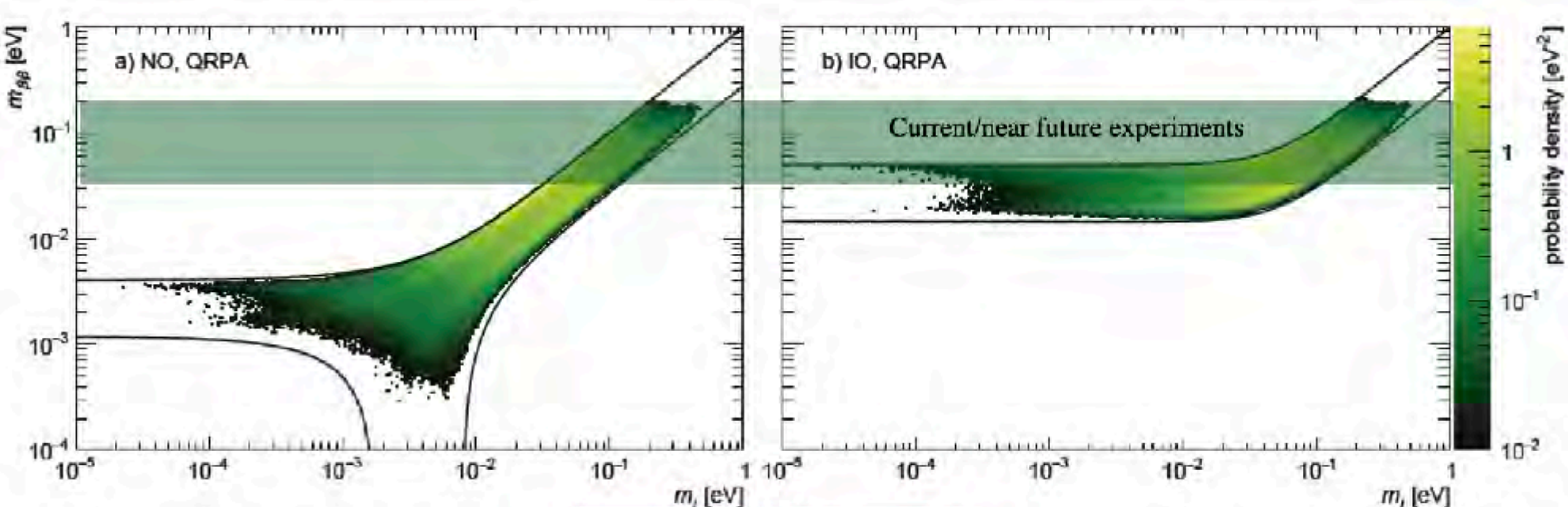
$F = G_F^2 \Phi(Q,Z) |M_{0\nu}|^2 m_e^2$ [y^{-1}]

Experimental constraints:

- Detector technology
- Backgrounds
- Isotopic abundance



Parameter space

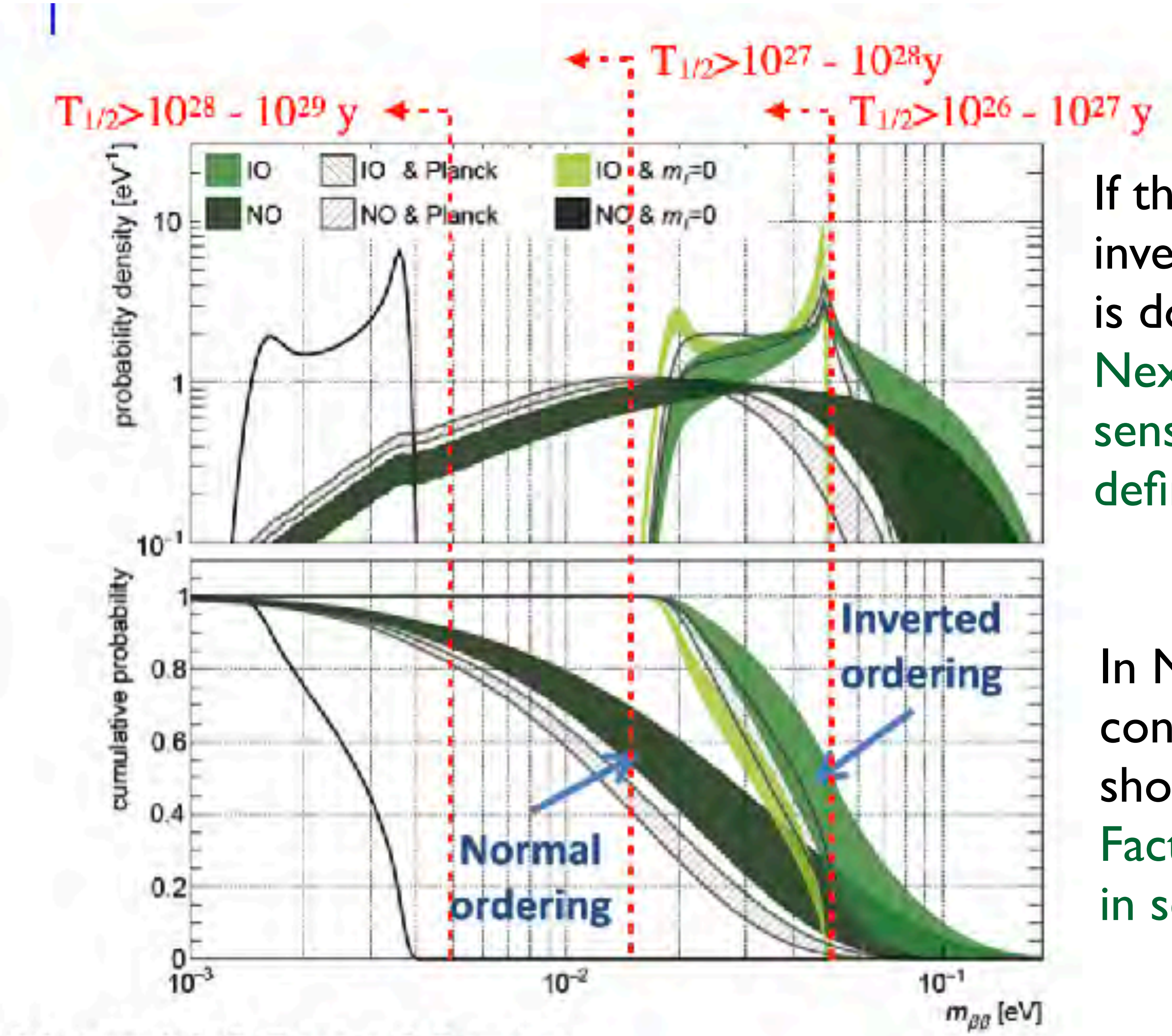


$$m_{\beta\beta} = |\sum_i m_i \cdot U_{ie}^2|$$

M. Agostini, G. Benato, J. Detwiler, Phys. Rev. **D96**, 053001 (2017)

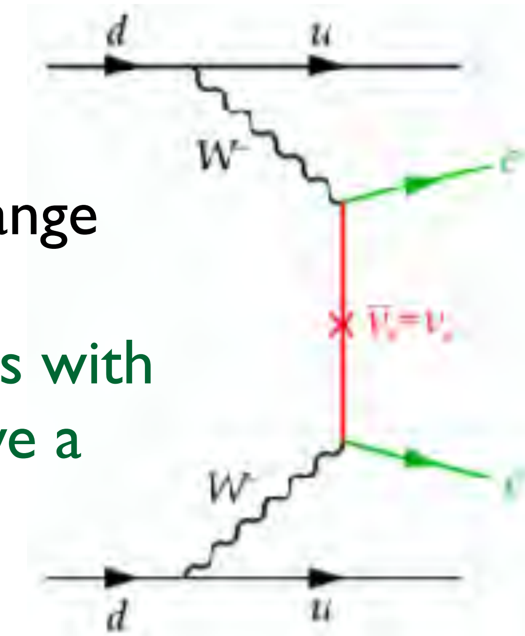
Note: this is under the simplest interpretation (of 3 light neutrinos). Sterile neutrinos, or heavy new physics, could change the interpretation dramatically!

Opportunity for discovery

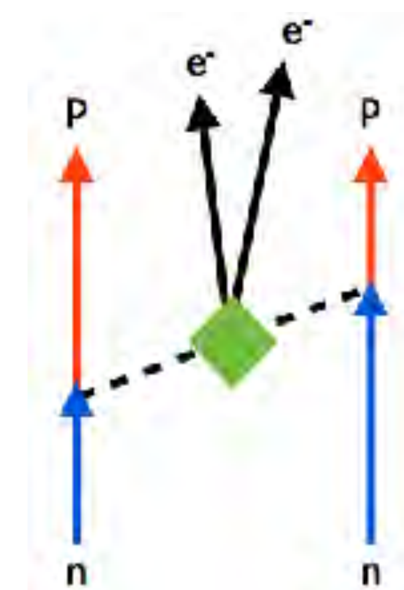


M. Agostini, G. Benato, J. Detwiler, Phys. Rev. **D96**, 053001 (2017)

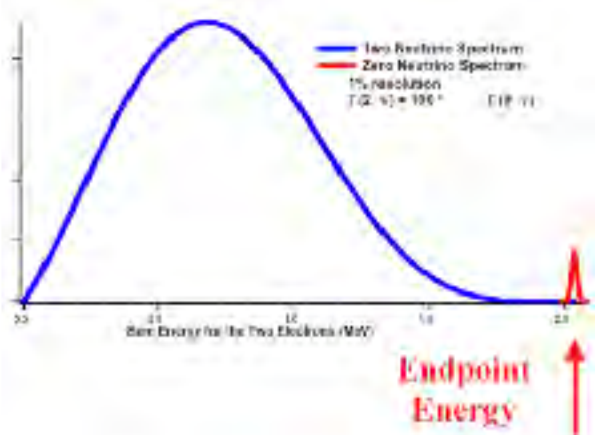
If the neutrino hierarchy is inverted, light neutrino exchange is dominant.
Next-generation experiments with sensitivity $T_{1/2}>10^{27}$ years have a definite target



In NO case the leading contribution could come from short-range new physics effects.
Factor of 10-100 improvement in sensitivity next decade.



Challenge: rare event search



Practical challenge: very rare process !

Half-life	Expected Signal (counts/tonne-year)
10^{26} years	~50
10^{27} years	~5
10^{28} years	~0.5

current gen

next gen

next-next gen

Experimental challenge -- sensitivity scaling:

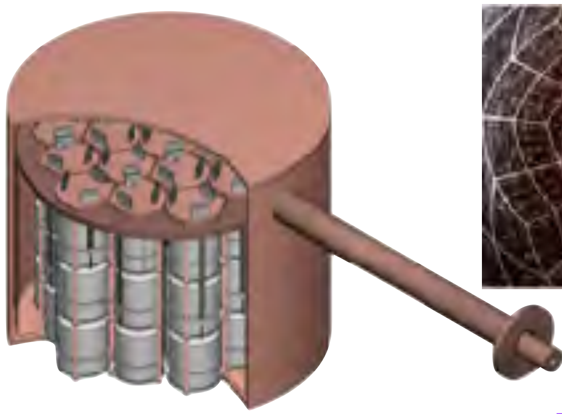
Non-zero backgrounds (most current experiments):

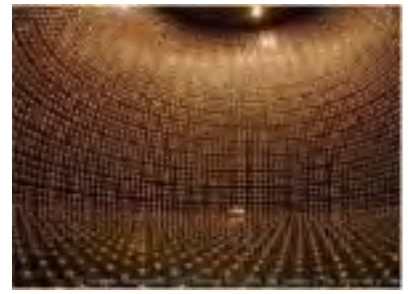
$$\left[T_{1/2}^{0\nu}\right] \propto \varepsilon \cdot I_{\mathrm{abundance}} \cdot \sqrt{\frac{\mathrm{Mass} \cdot \mathrm{Time}}{\mathrm{Bkg} \cdot \Delta E}}$$

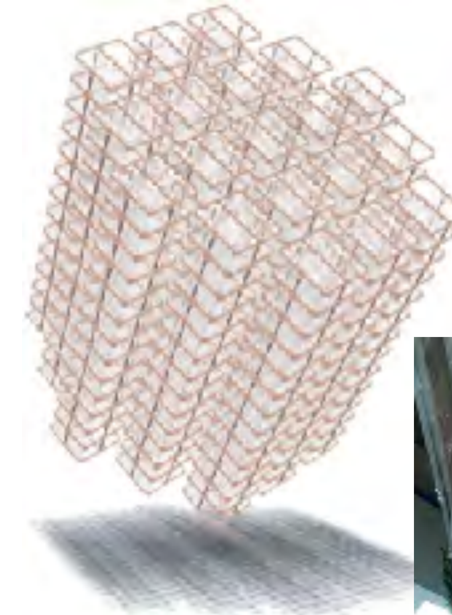
$$\left[T_{1/2}^{0\nu}\right] \propto \varepsilon \cdot I_{\mathrm{abundance}} \cdot \mathrm{Mass} \cdot \mathrm{Time}$$

(background-free, next generation)

Neutrino detection technology

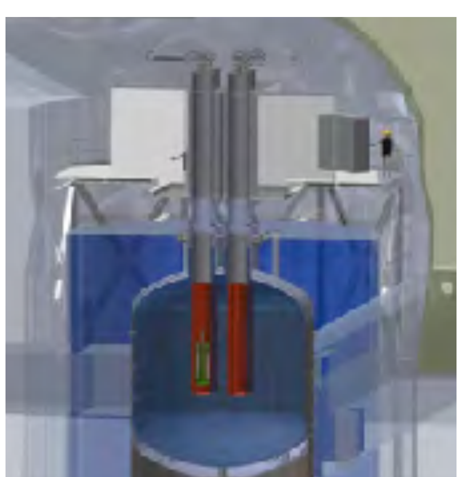
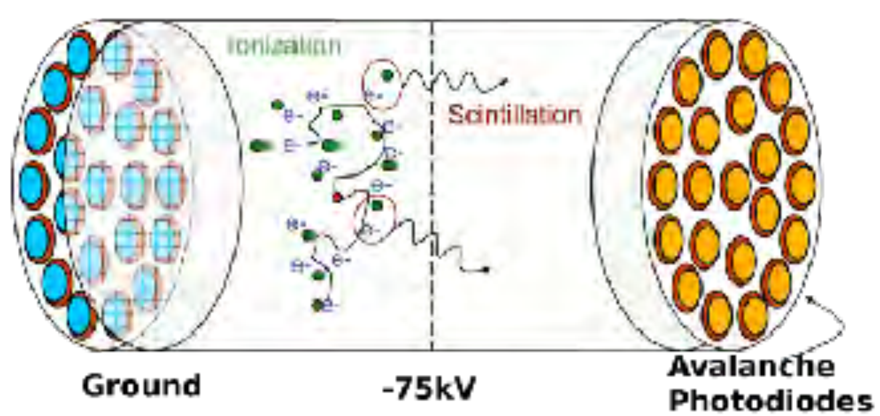


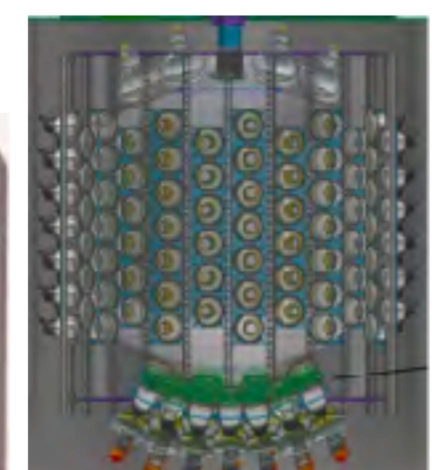




- Ultra-pure Ge
- High resolution bolometry
- Noble liquid / gas TPCs: LAr, LXr, GXe (S+I)
- Water Cherenkov
- Organic liquid scintillator / "Hybrid" detection (S+Ch)

✳ *Sample of approaches relevant for this topic*

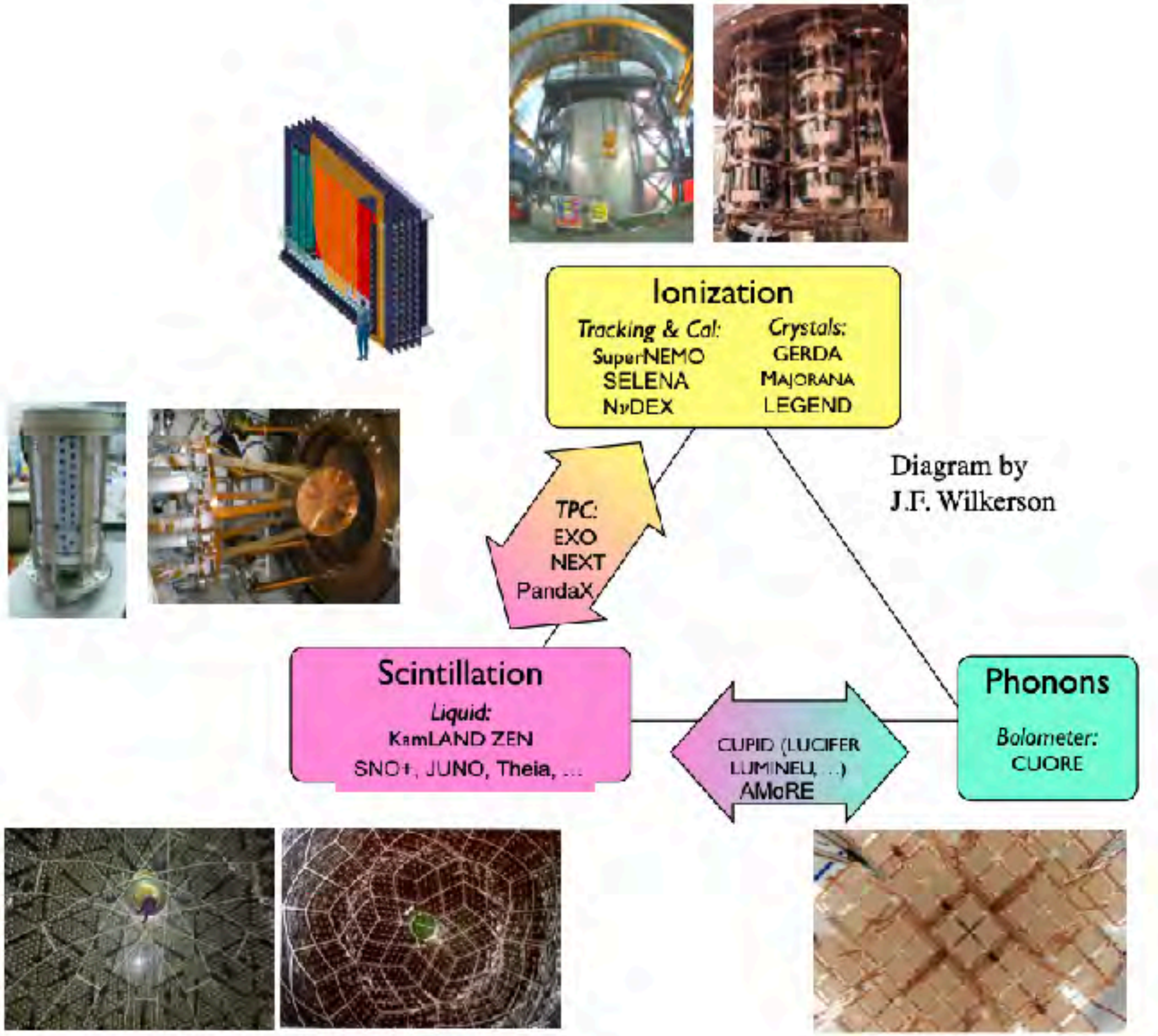




Experimental Techniques

Approach	Pros	Cons
Large self-shielding calorimetry	• Self-shielding: low ext bkg • Easily scalable to large M • Source in / source out caln • High detection efficiency	• Relatively poor E resn
Xe TPC	• Relatively easy to enrich • No long-lived r/a isotopes • Scint + ionisation signals	• $Q_{\beta\beta}$ (2.46MeV) close to ^{208}Tl • %-level E resn
High-resolution calorimetry	• Excellent E resn • Simple, compact	• No tracking • Ltd bkg suppression (exc E) • Reduced self-shielding
Tracko-calo expt	• Good bkg rejection	• Low detection efficiency • Low E resn • Very hard to scale

Diverse program

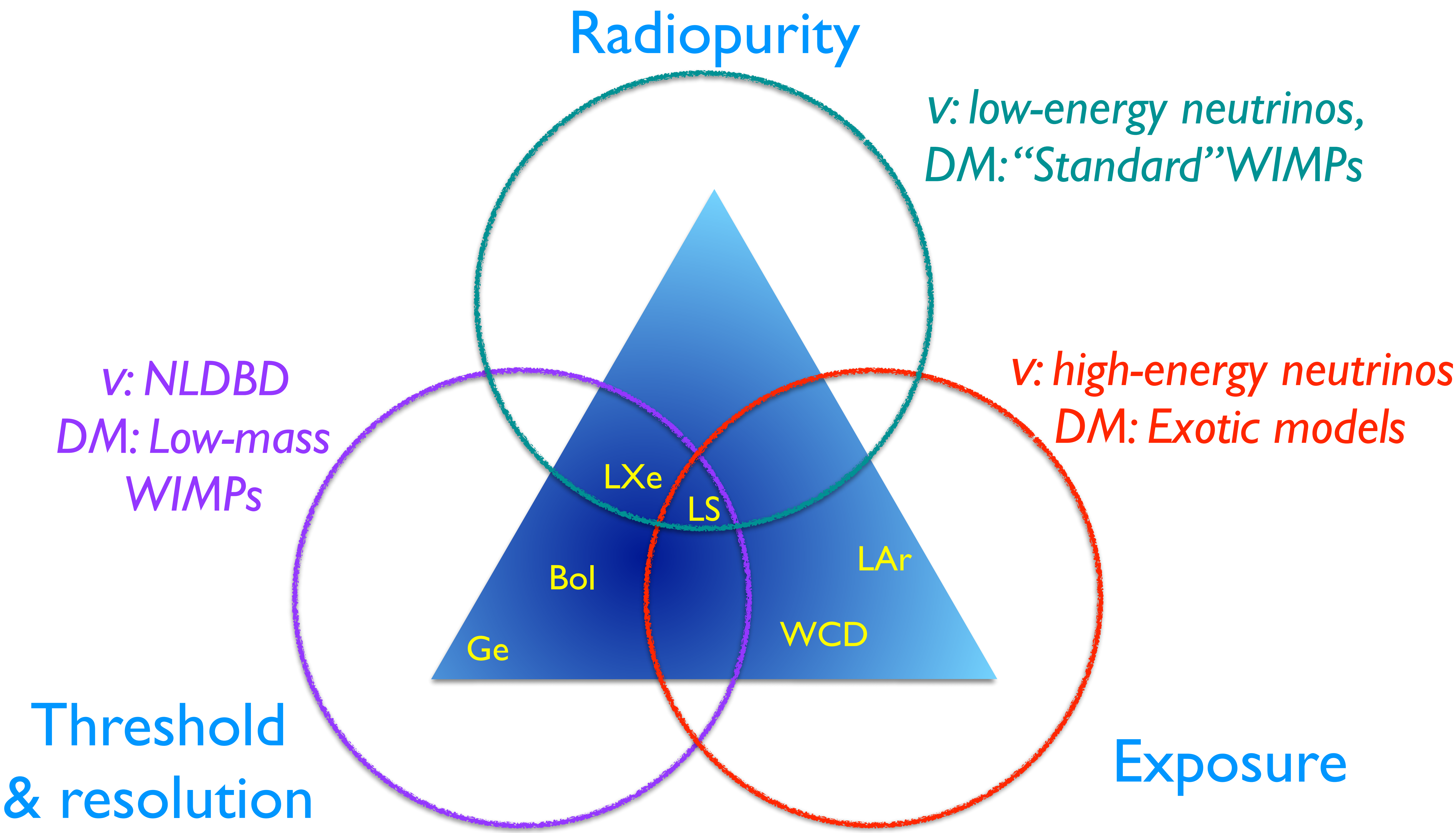


Convincing discovery requires

Multiple isotopes
Technological tradeoffs
Different systematics

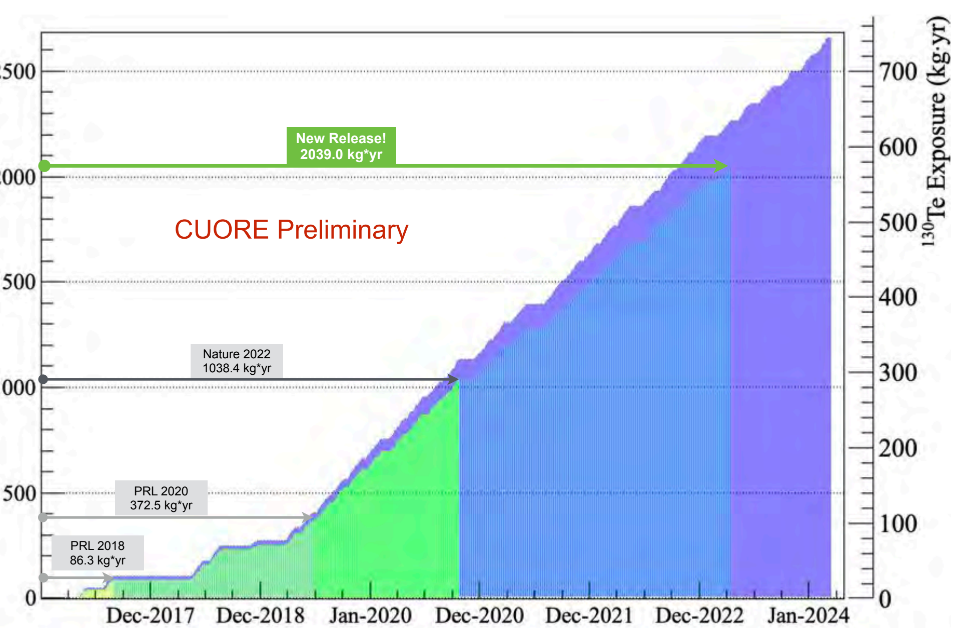
Next generation (ton-scale):
3-4 experiments worldwide

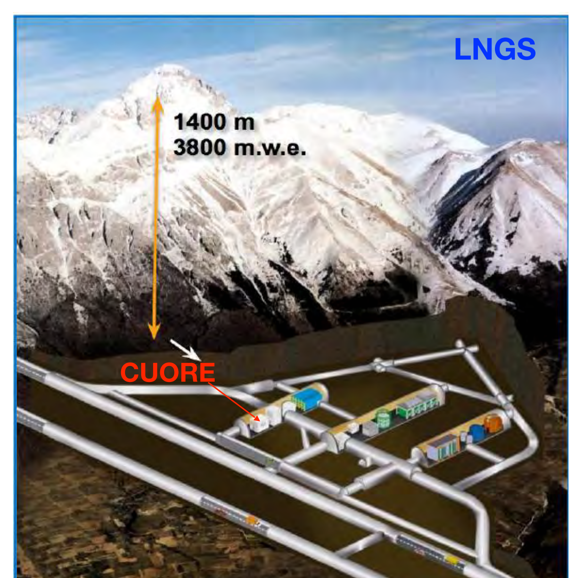
Detector technology

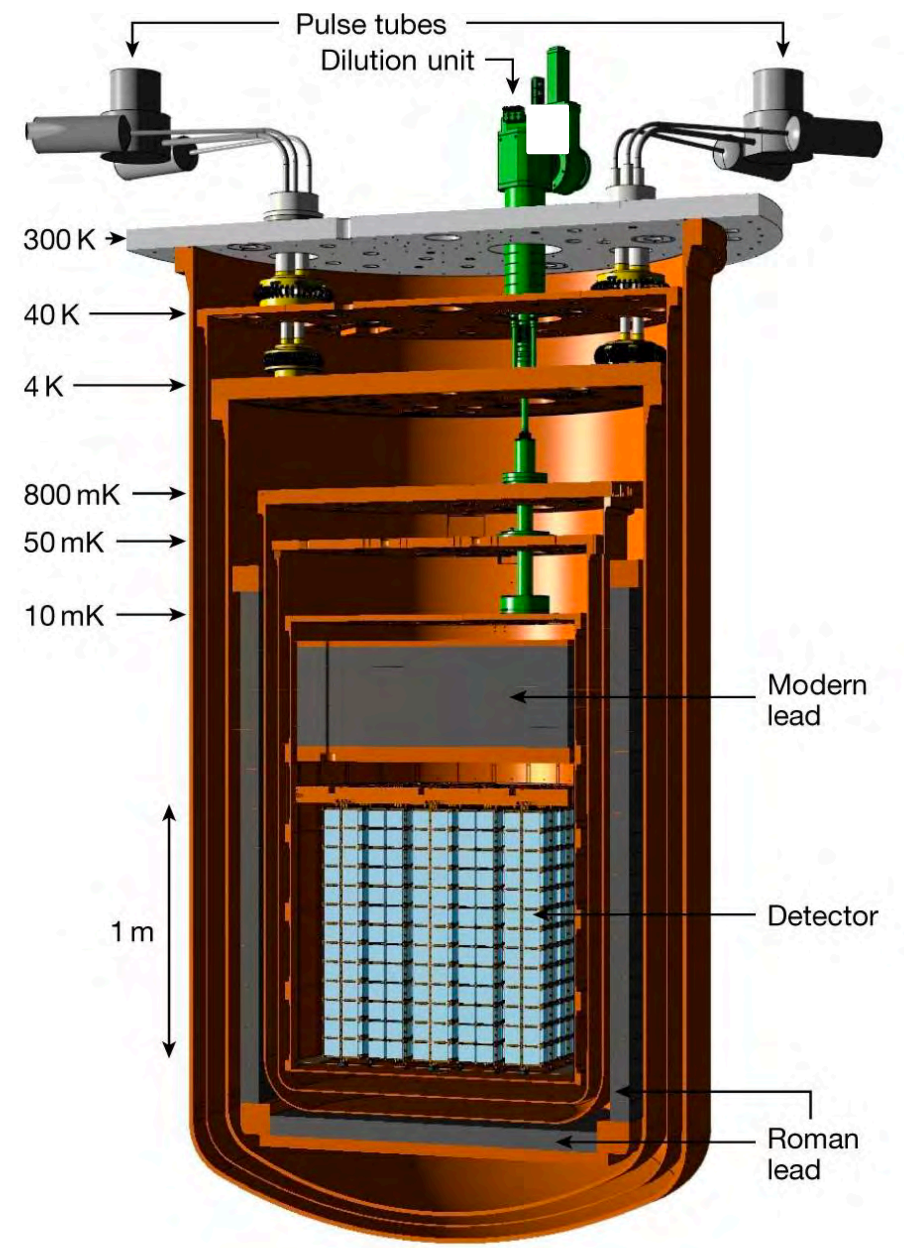


CUORE

- Array of 988 TeO_2 crystals
- 19 towers x 13 levels x 4 crystals suspended in a cylindrical structure
- 5x5x5 cm^3 (750g each); ^{130}Te: 34.1% natural isotope abundance —> 750 kg TeO_2 => 206 kg ^{130}Te
- Pulse tube refrigerator and cryostat
- Radio-purity + high resolution: low backgrounds
- Italy (INFN) and US (DOE, NSF) at LNGS in Italy
- Data taking since 2017, >2.5 ton-years of TeO_2 exposure

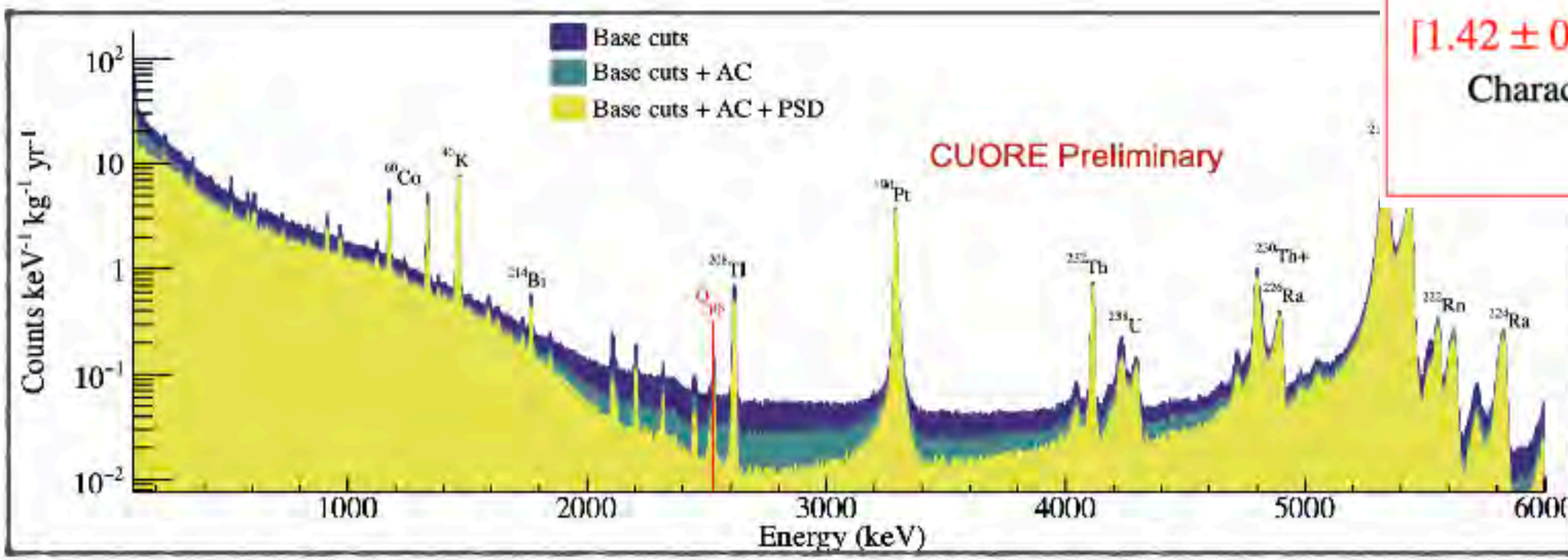






Dell'Oro S. et al., Cryogenics 102, 9, (2019)
https://doi.org/10.1016/j.cryogenics.2019.06.011
Adams D. et al. (CUORE collaboration), Prog.Part.Nucl.Phys. 122 (2022) 103902,
https://doi.org/10.1016/j.ppnp.2021.103902

CUORE results



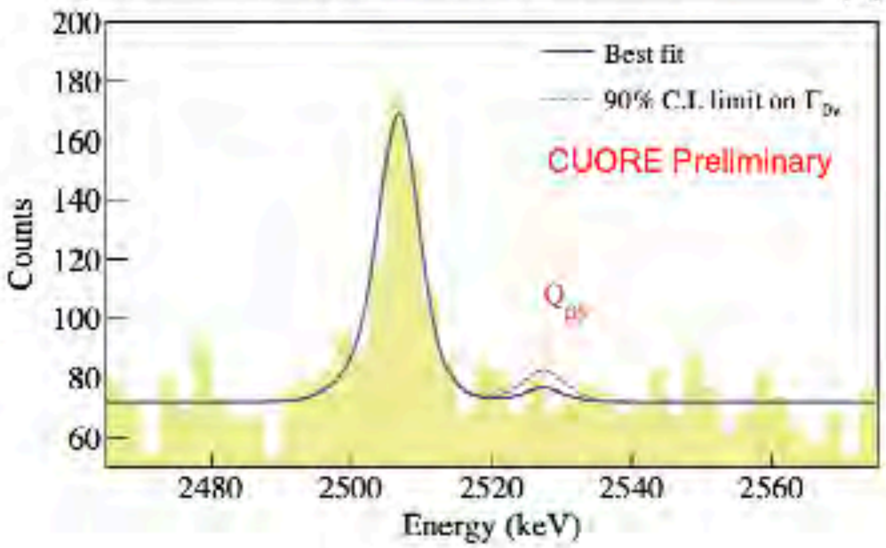
Background Index

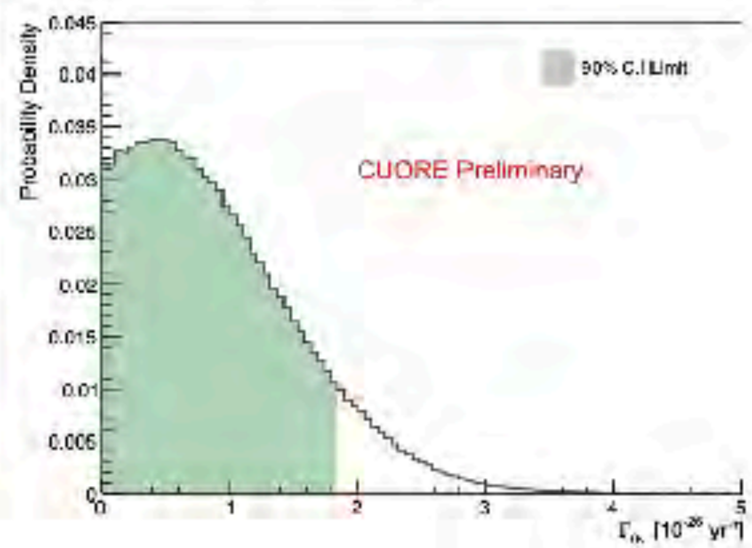
$[1.42 \pm 0.02] \times 10^{-2}$ cts/kg/keV/yr

Characteristic FWHM ΔE at $Q_{\beta\beta}$

$7.53^{+1.45}_{-1.15}$ keV

β/γ and $2\nu\beta\beta$ backgrounds — α backgrounds





No evidence for 0νββ decay

$T^{0\nu}_{1/2} > 3.8 \times 10^{25}$ years (90 % CI)

Interpretation in context of light Majorana neutrino exchange

$m_{\beta\beta} < 70 - 240$ meV

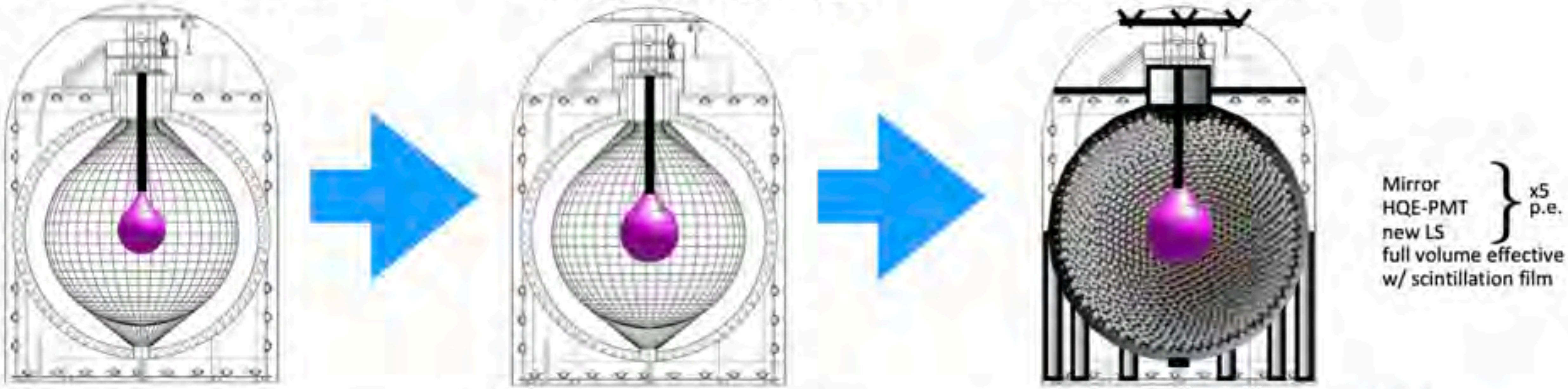
arXiv:2404.04453

KamLAND-Zen

KamLAND-Zen 400

KamLAND-Zen 800

KamLAND2-Zen



380kg deployed

$T^{0\nu}_{1/2} > 1.07 \times 10^{26}\,\mathrm{yr}$

PRL117, 082503 (2016)

Now, 745kg deployed

$> 2.3 \times 10^{26}\,\mathrm{yr}$

PRL130, 051801 (2023)

Further improvements going on;
better neutron tagging
machine learning (ML) for long-lived tagging
ML for beta/gamma discrimination
muon-bundle tracking, and so on

1 ton planned (scalable)

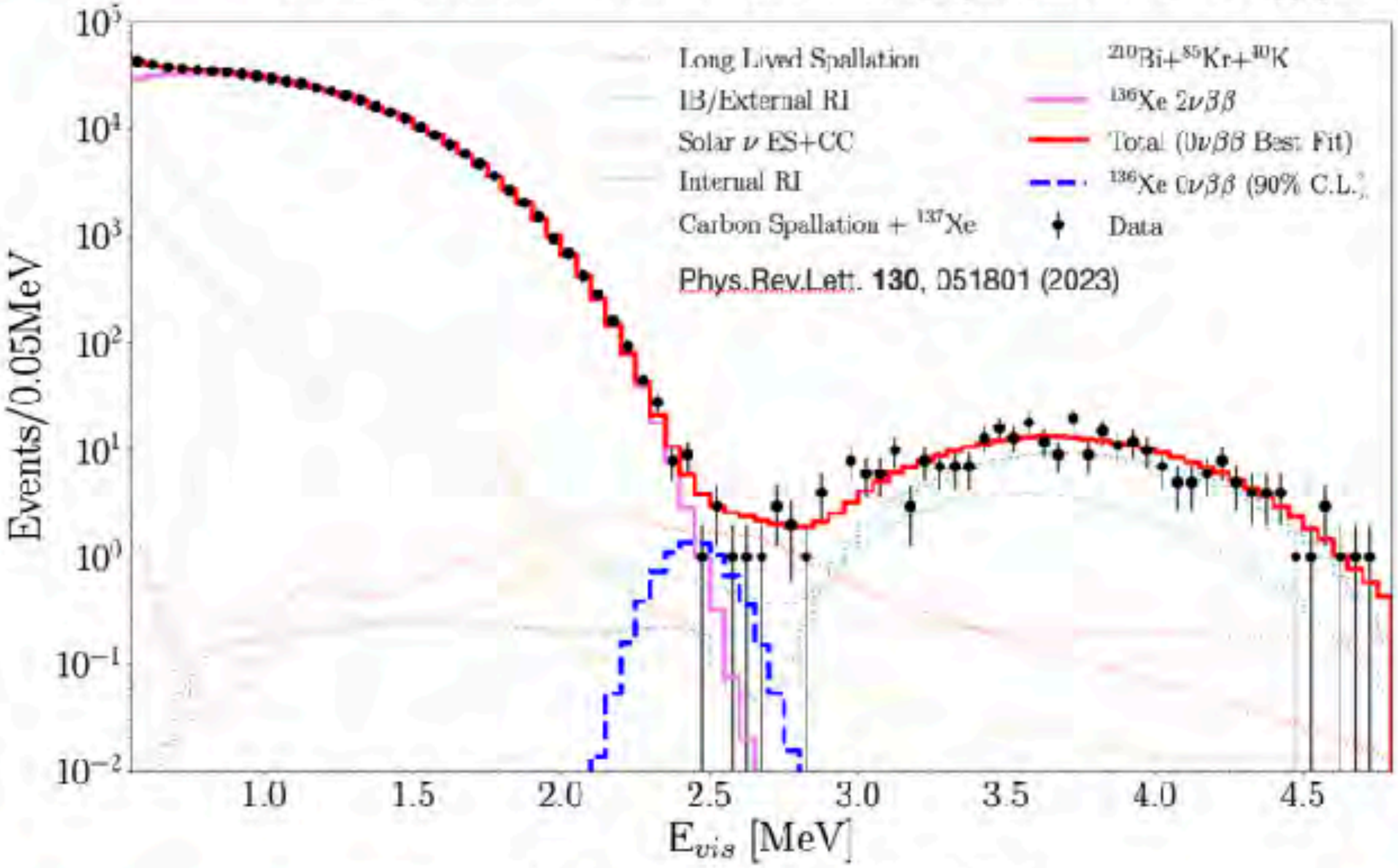
$> 2 \times 10^{27}\,\mathrm{yr}$ (target sensitivity)

$< 12 \sim 53\,\mathrm{meV}$ (corresponding mass limit)

Further technologies being developed
imaging sensor (1/10 reduction of long-lived BG)
high-p xenon deployment (2 times more xenon)

KLZ results

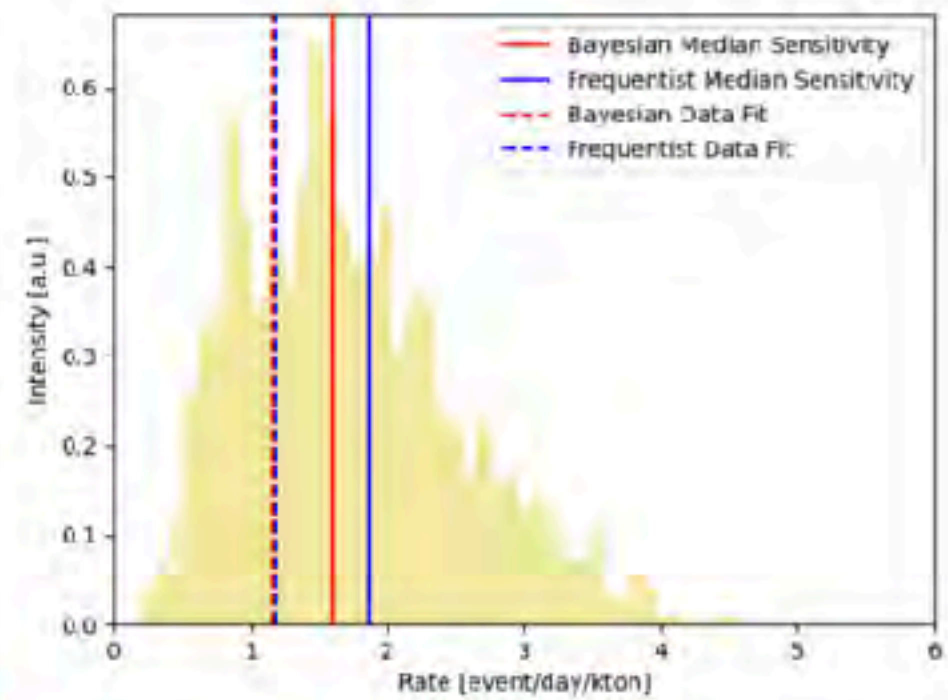
Total Livetime = 523 days   Exposure = 970 kg·yr



$T_{1/2}^{0\nu\beta\beta} > 2.0 \times 10^{26}$yr 90 % C.L.

N. Kawada: Neutrino 2022

C. Grant



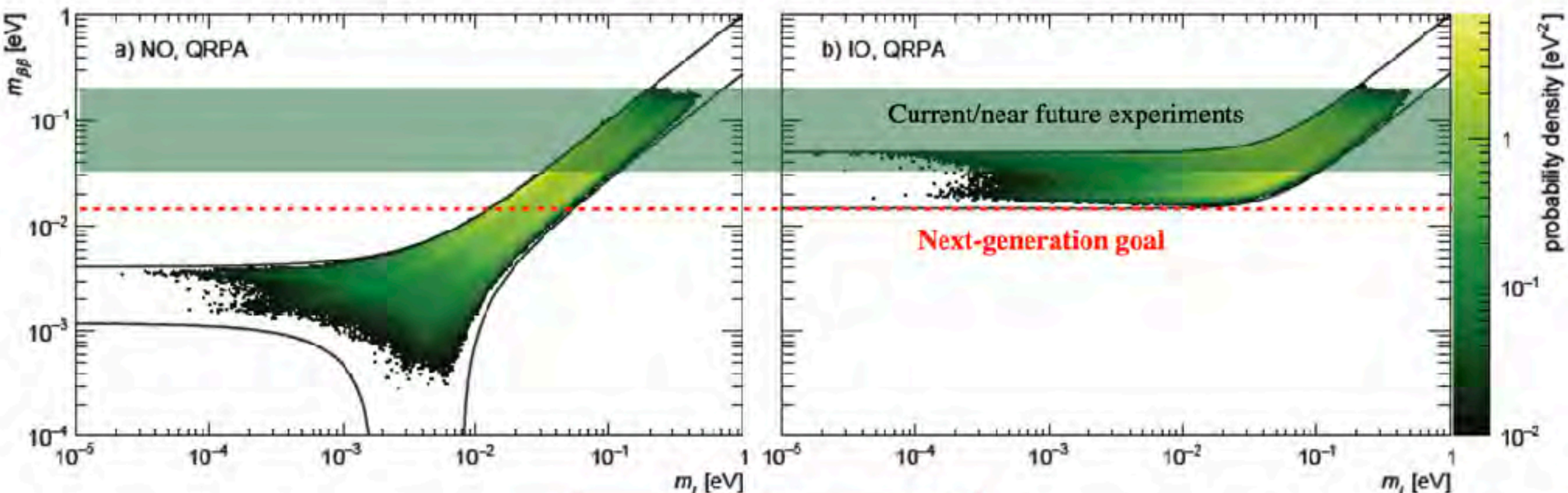
Median Sensitivity:
$T_{1/2}^{0\nu\beta\beta} > 1.5 \times 10^{26}$yr (90 % C.L.)

Combination of KLZ-400 and KLZ-800

$T_{1/2}^{0\nu\beta\beta} > 2.3 \times 10^{26}$yr

$\langle m_{\beta\beta} \rangle < 36 - 156$ meV

Status

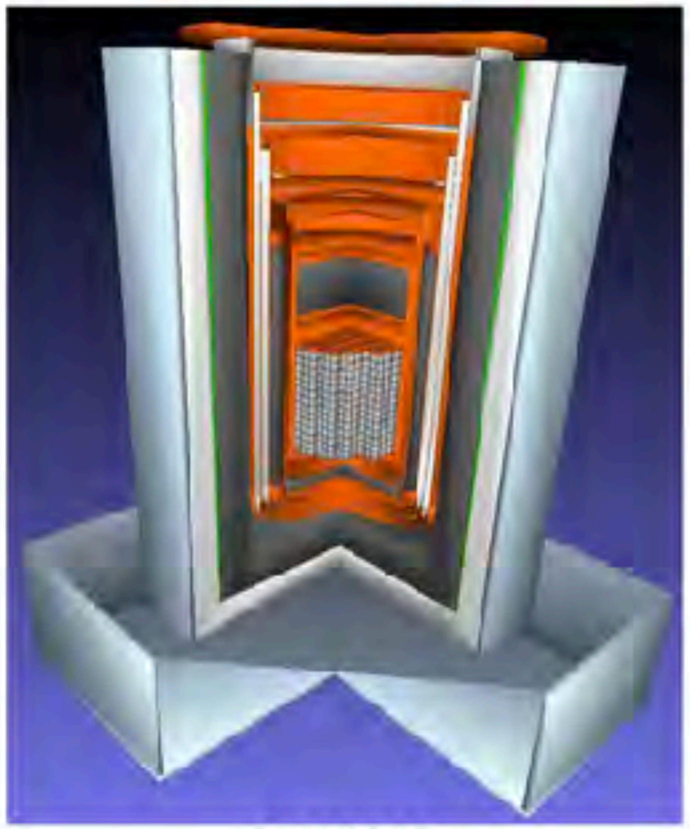


$$m_{\beta\beta} = |\sum_i m_i \cdot U_{ie}^2|$$

M. Agostini, G. Benato, J. Detwiler, Phys. Rev. **D96**, 053001 (2017)

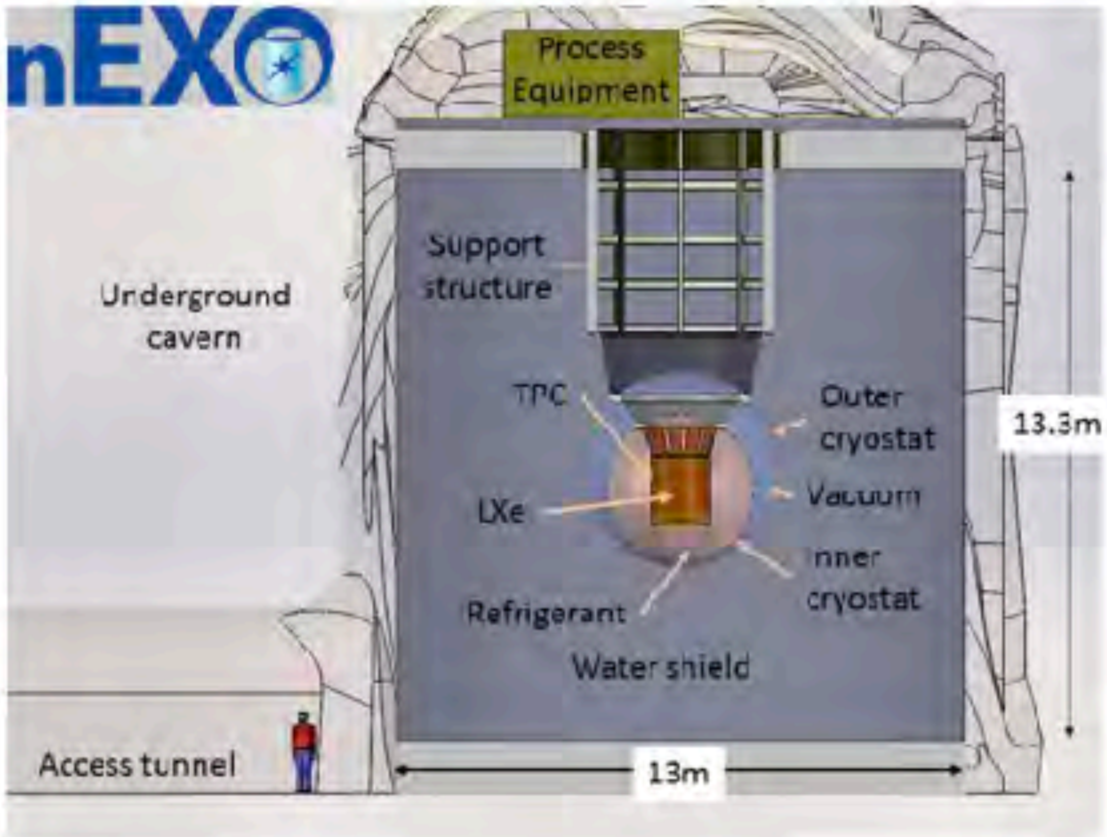
Next-gen: ton-scale

Goal: $0\nu\beta\beta$ discovery if $m_{\beta\beta}$ is above ~10-20 meV in the next decade



CUPID

LEGEND-1000



Complemented by a world-wide suite of efforts developing technologies for ton-scale and beyond, with comparable scientific sensitivities

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

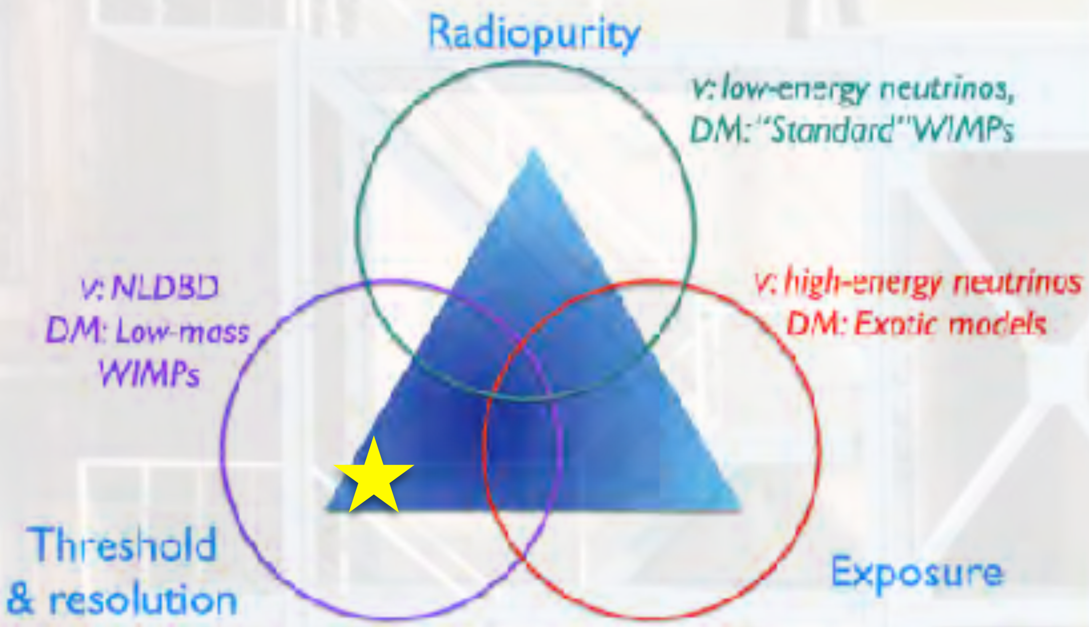
Phased 76Ge-based 0νββ program with discovery potential at a half-life beyond 10^28 years

Enriched 76Ge diodes (HPGe detectors): best energy resolution

LEGEND combines the best aspects of GERDA and MJD:

- Ultra-low background materials, FEE (MJ)
- Low-Z active veto (GERDA)

LEGEND-200 to -1000



- Enriched HPGe (76Ge)
- Drifted charge, point contact
- GERDA + Majorana merger
- Excellent energy resolution
- LAr veto to reduce bkg
- LEGEND-200 underway
- Zero bkg goal for 10^{28} yr $\tau_{1/2}$

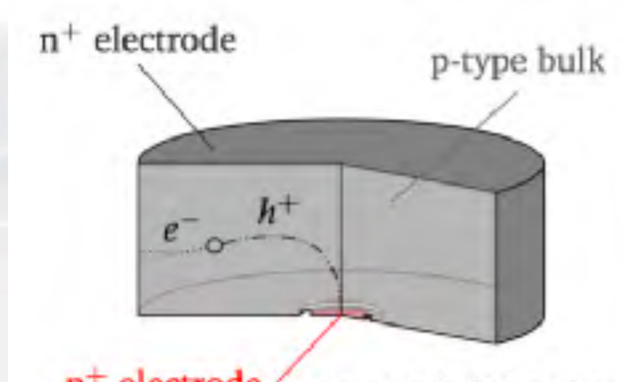


Image: C. Wiesinger

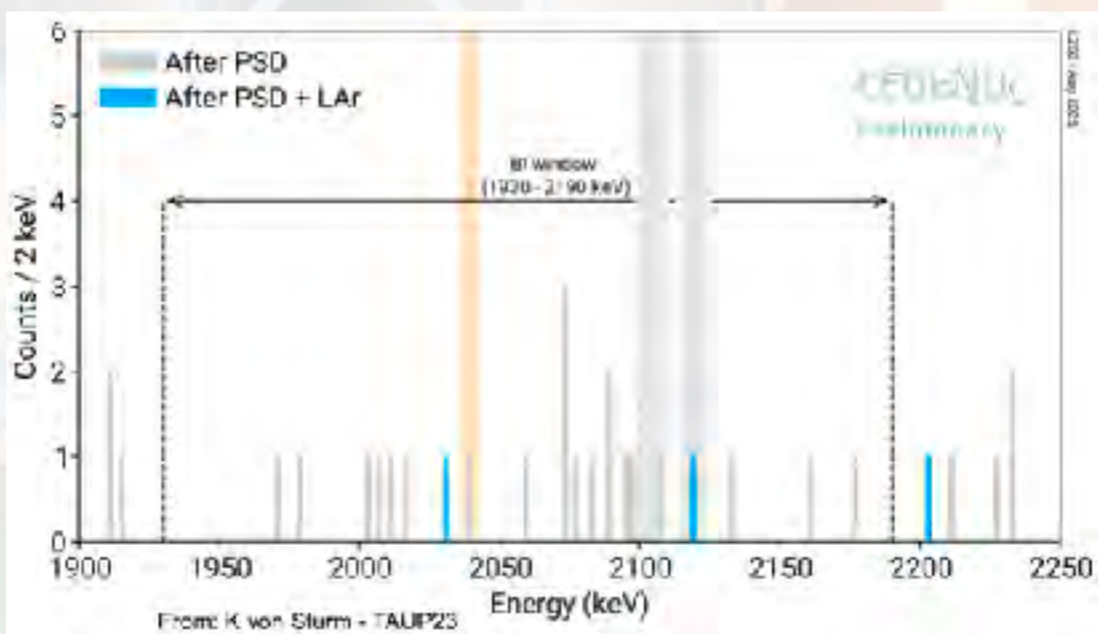
M. Willers TAUP2023

- L200: 142kg enriched HPGe (LAr)
- Data taking since 2023

Projected limits (5 years):

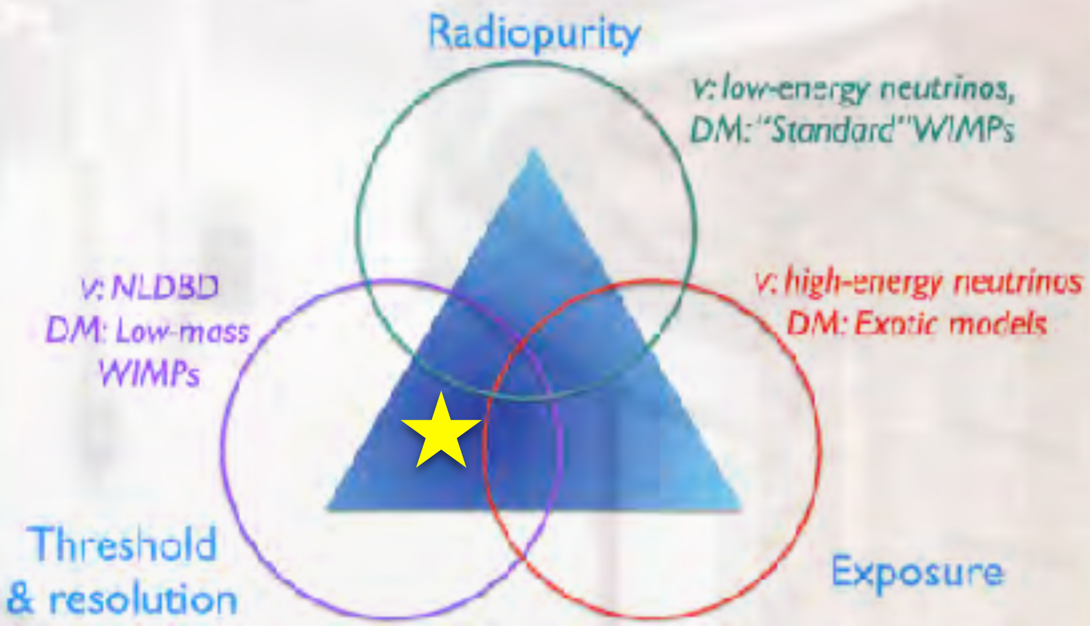
$T^{0\nu}_{1/2} > 1.5 \times 10^{27}$ years

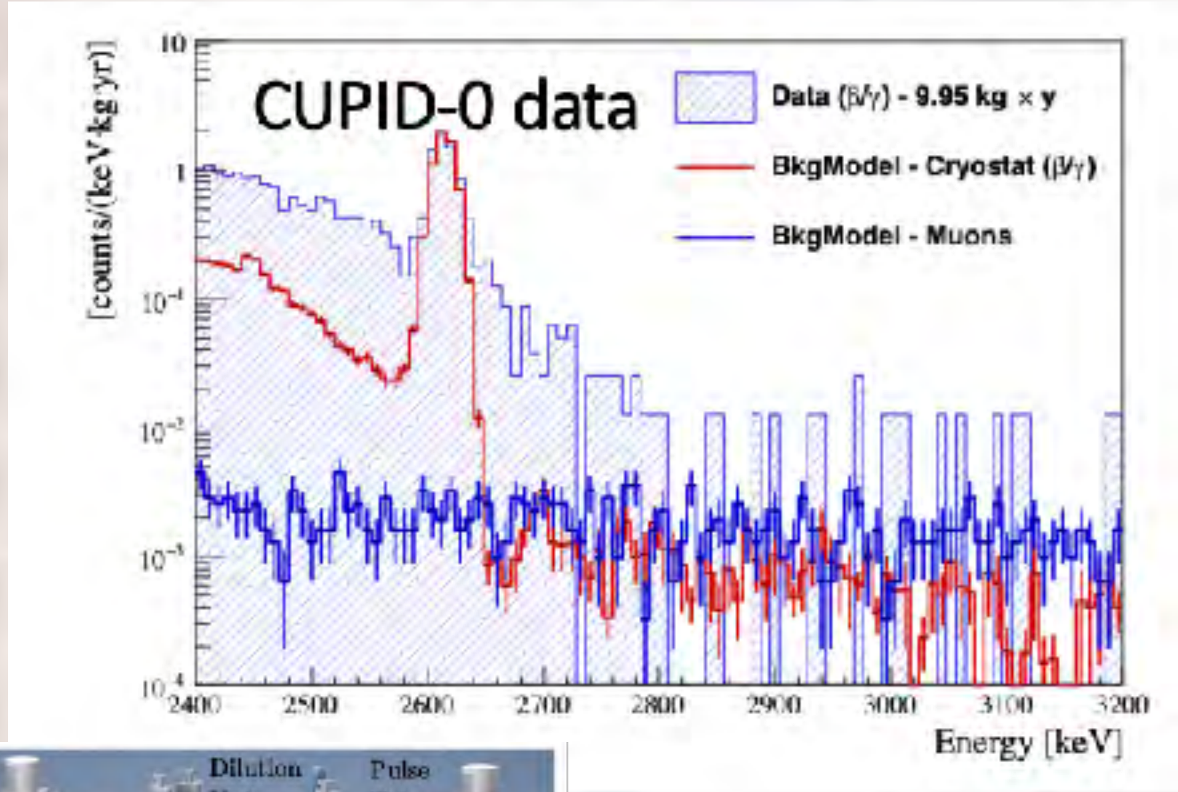
$m_{\beta\beta} < 34 - 78$ meV

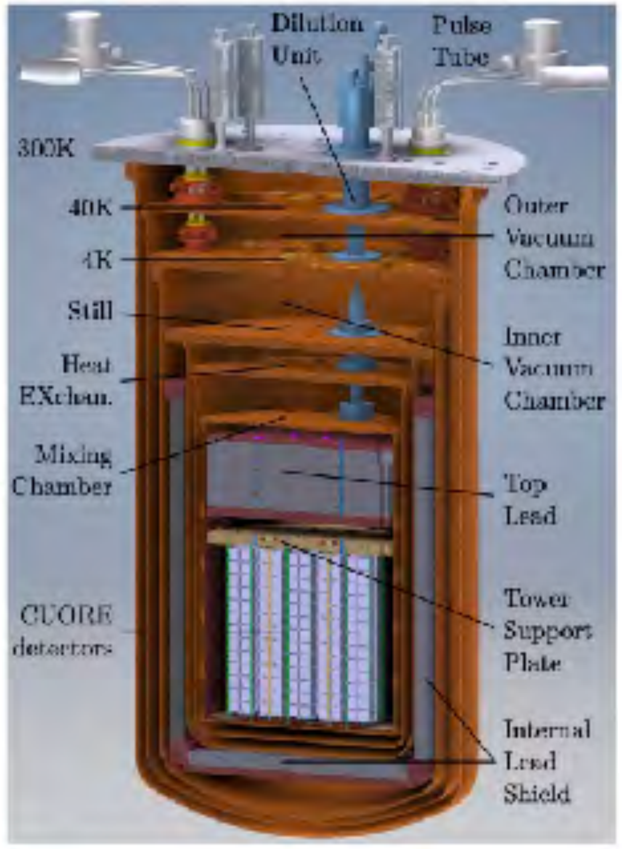


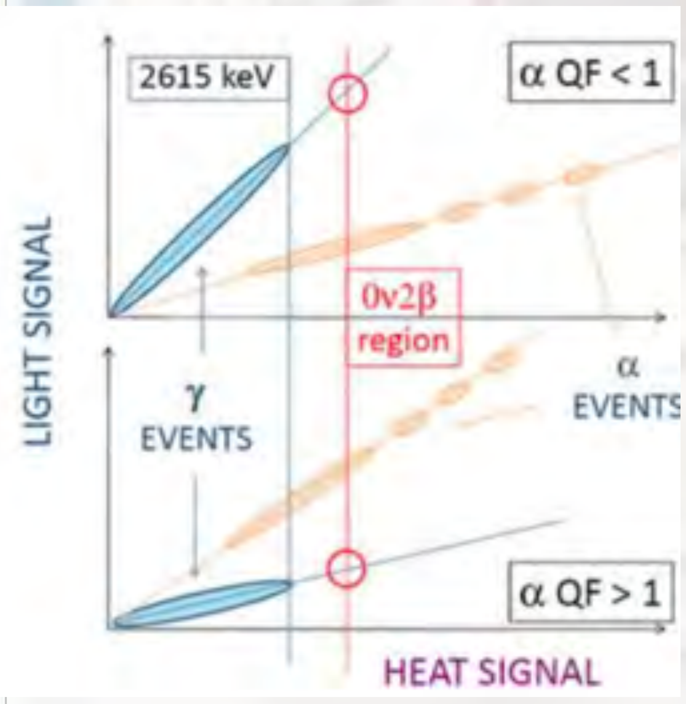
CUPID

LNGS, Italy





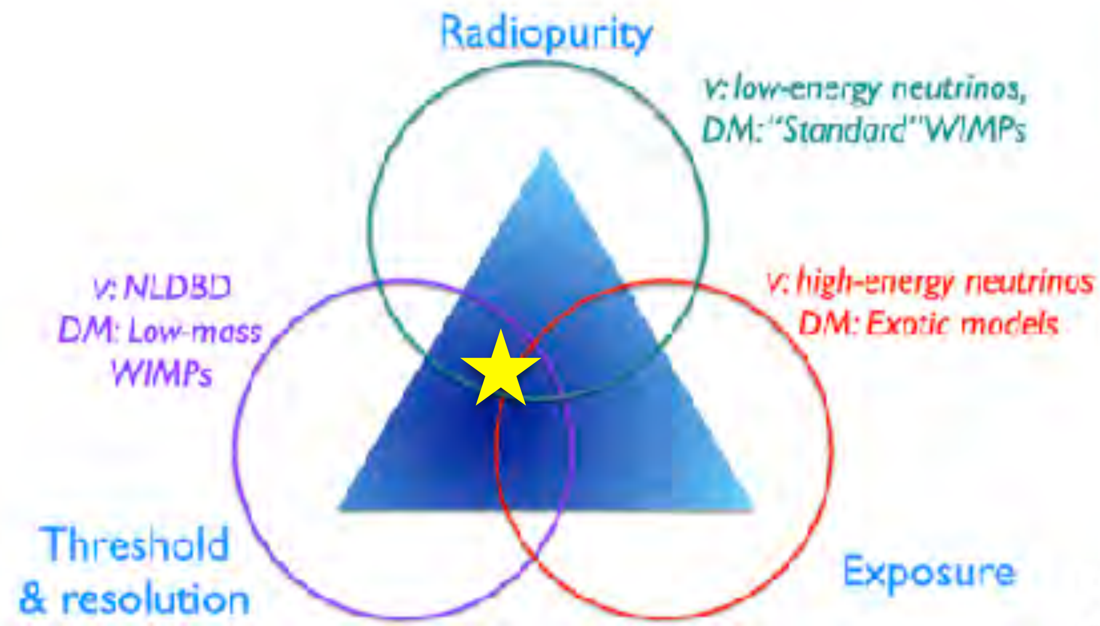




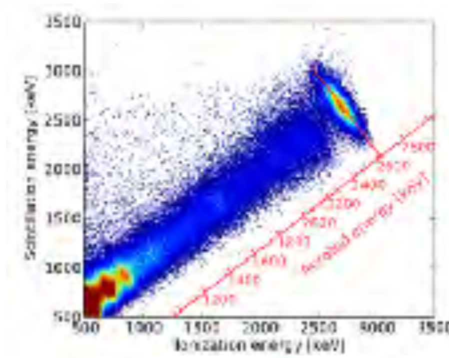
- CUORE: 742 kg TeO2
- ~5keV energy resolution (2.5MeV)
- CUORE + Particle ID: scintillating bolometers (heat/light ratio)
- 450 kg 100Mo, plan for 1 ton
- LNGS (INFN), Italy

nEXO

SNOLAB



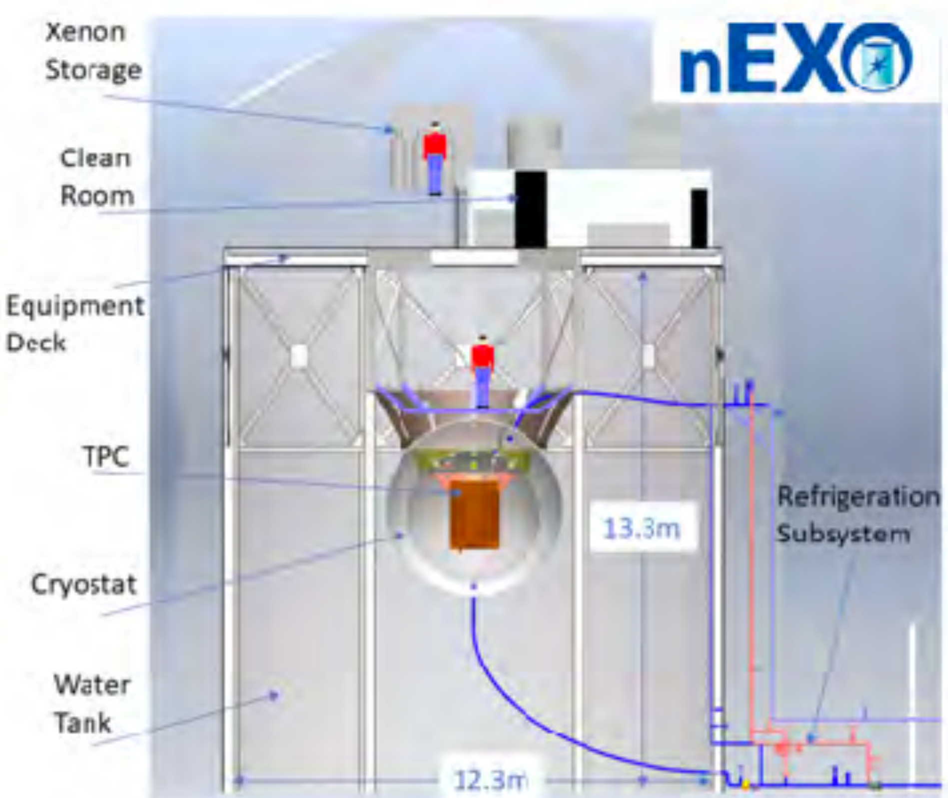
- Large, monolithic LXe TPC (5t, 90% 136Xe)
- EXO-200[kg] successful operations
- 0.8% energy resolution
- Fiducialisation, event-topology, multi-site rejection
- Full multi-D likelihood fit

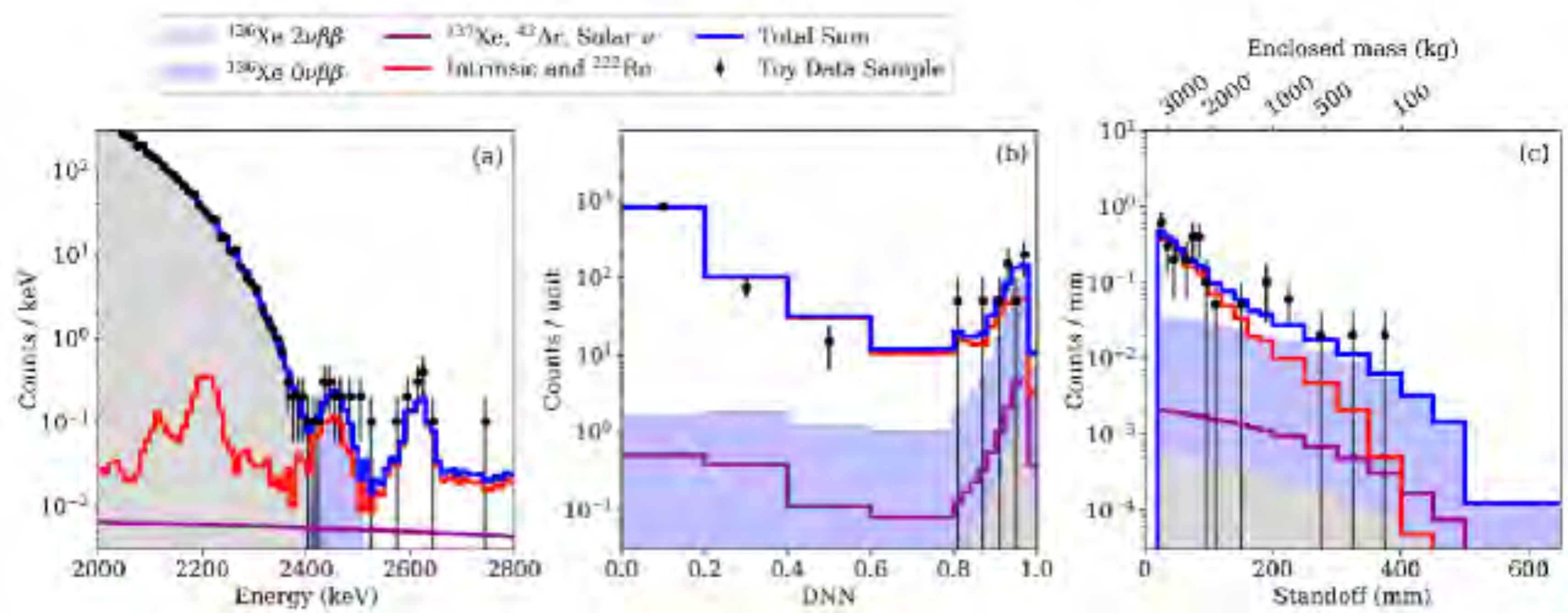


Discovery (3σ): $T_{1/2}$ = 7.4×10^{27} yr

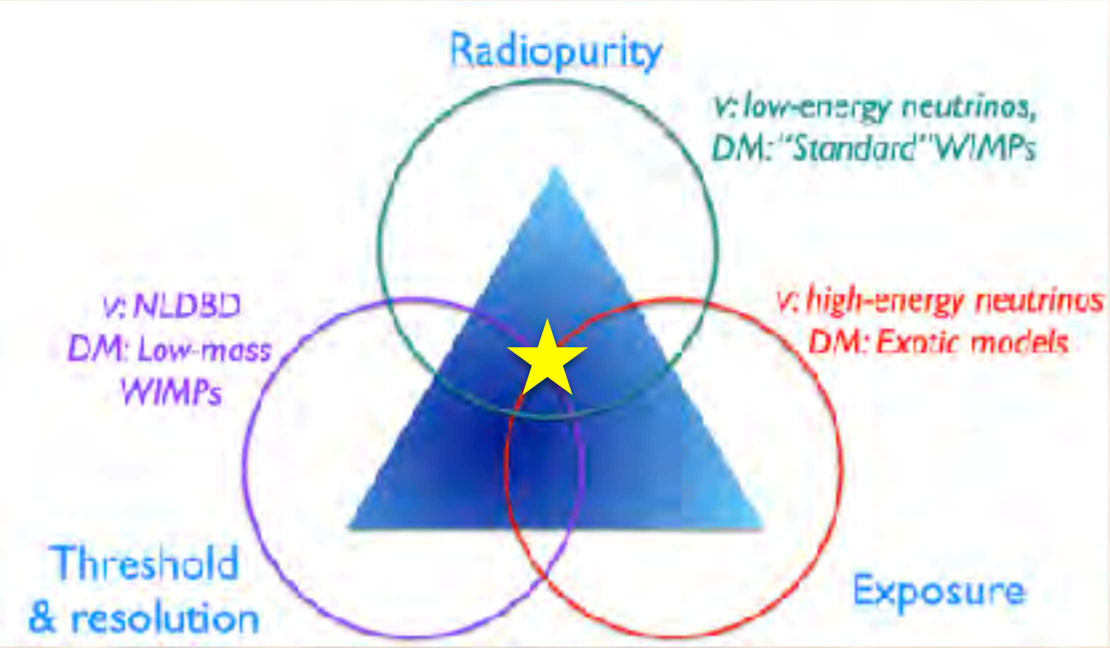
$m_{\beta\beta}$ discovery: 5-27meV

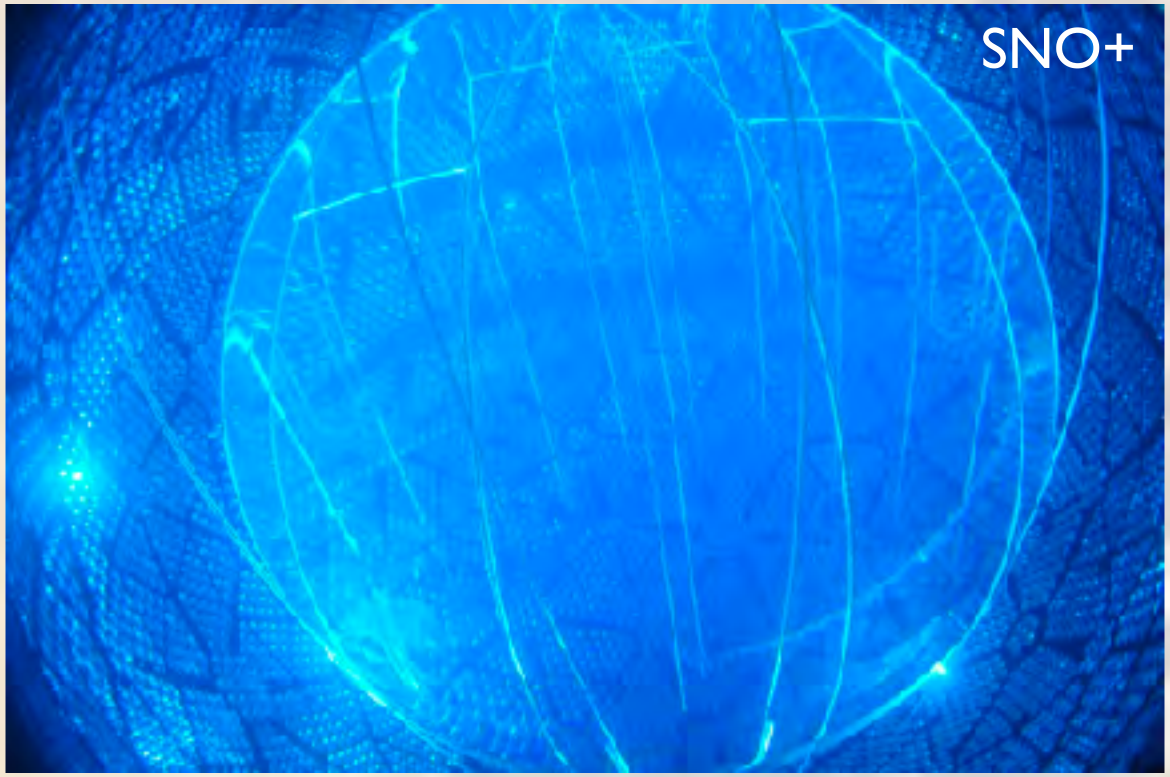
arXiv:2106.16243; J.Phys.G **49**, 015104 (2022)





LS detectors



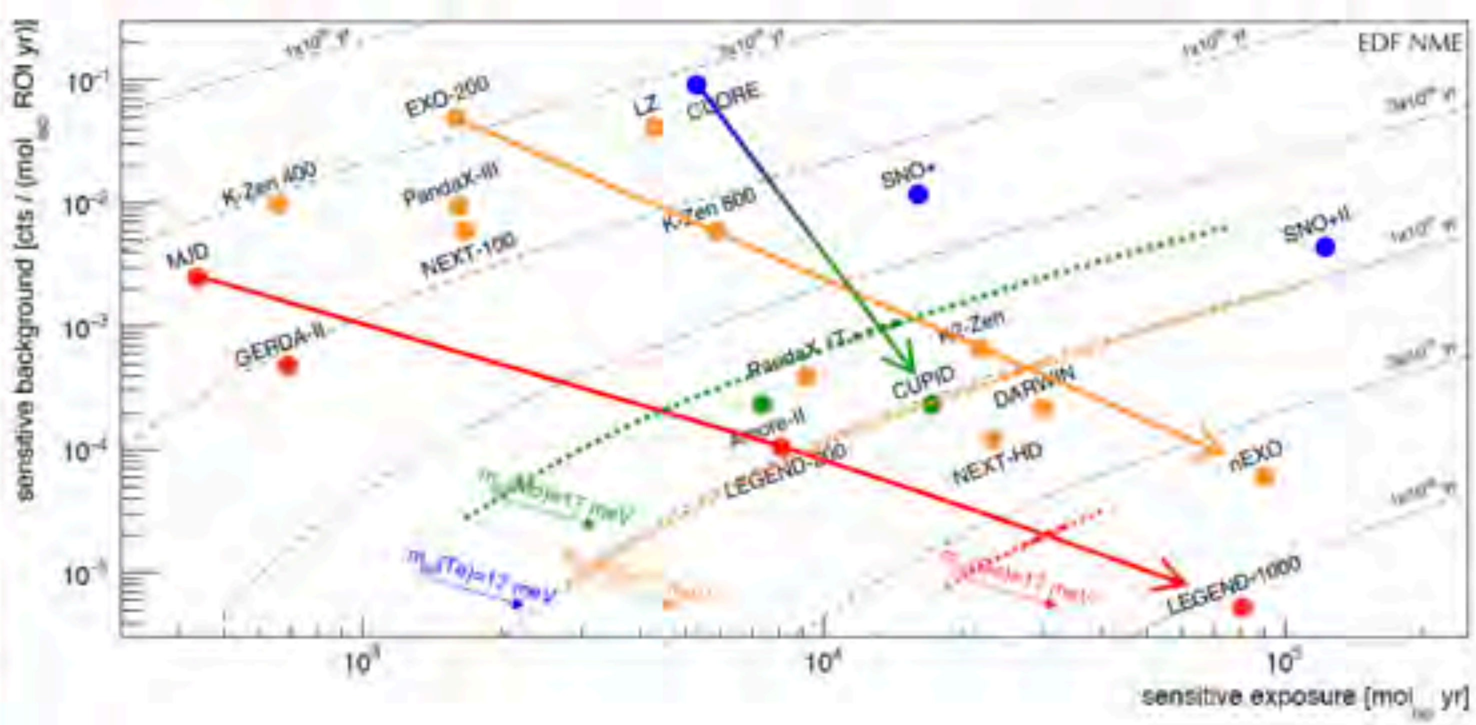


- Large exposure
- Particle ID, fiducialisation, ML
- Fast timing: reject coincident bkg
- Break the detector = isotope scaling
- KamLAND-Zen: 745kg ^{136}Xe in LS
- SNO+: 0.5% (3%) ^{nat}Te by mass

The path forwards

The Ton-Scale Strategy and Beyond

	$T_{1/2}$ (10^{28} years)		$m_{\beta\beta}$ (meV) 3σ Discovery	
	Excl. Sens.	3σ Disc	Median	Range
CUPID Mo	0.14	0.10	15	12 to 20
LEGEND Ge	1.60	1.30	12	9 to 21
nEXO Xe	1.35	0.74	11	7 to 32



Each experiment is world leading in its isotope. Each provides unique benefits. Portfolio review (July 2021) put highest priority on LEGEND-1000.

International stakeholders endorsed the goal of creating a consortium to support a multi-experiment campaign with a large experiment in Europe and in North America

DOE envisions construction funding in FY 2024 (Oct 2023) and continued support toward CD-1 with program funds in FY23.

This is a world-wide, multi-stage campaign requiring at least one more leap in sensitivity beyond ton-scale. Investments in R&D remain an important component of the Fundamental Symmetries portfolio

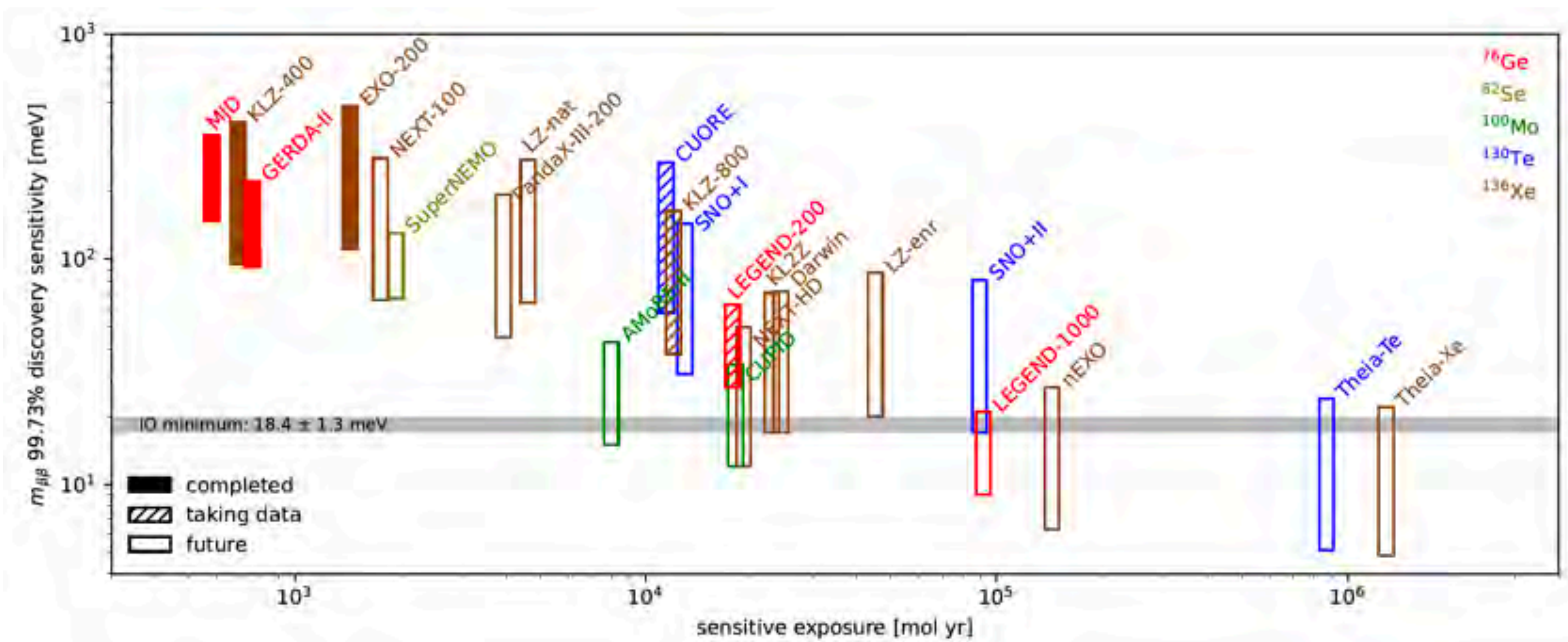
U.S. DEPARTMENT OF ENERGY | Office of Science

Shown by DOE-NP Fundamental Symmetries program manager Paul Sorensen, Snowmass

Funding promised to 3 projects from IRA (FY22-23)

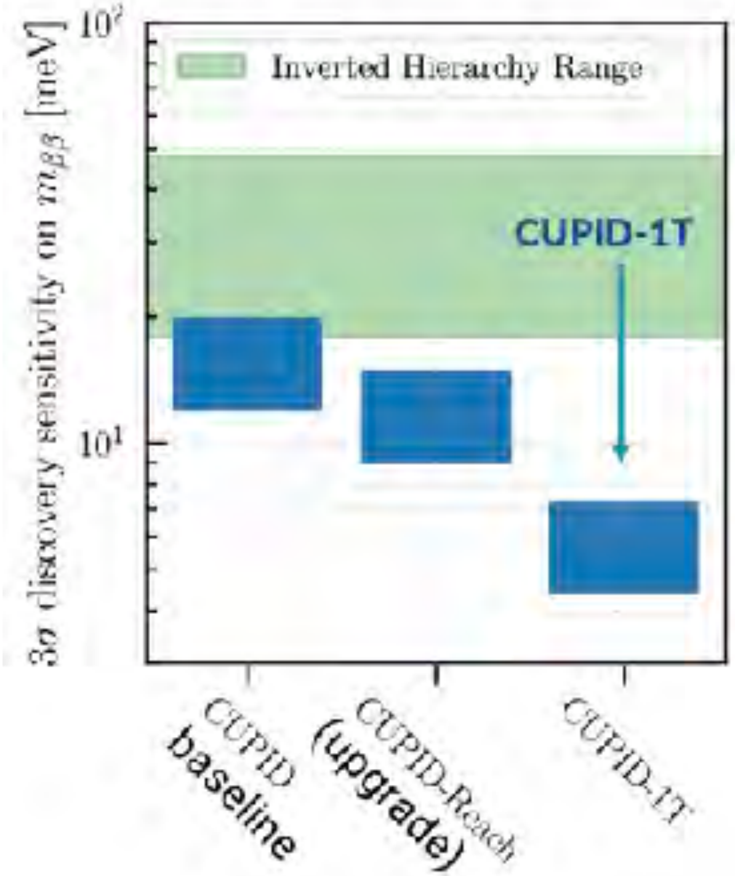
Going beyond ton-scale

- 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

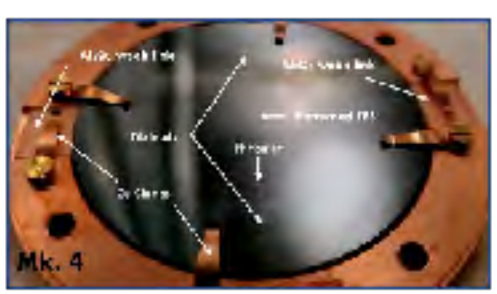


CUPID-1T

- 1000 kg 100Mo (4x baseline CUPID mass)
- Candidate isotopes: $Zn^{82}Se$, $Li_2{}^{100}MoO_4$, $^{116}CdWO_4$, $^{130}TeO_2$
- Large cryostat (self shielding) or distributed multi-cryostat setup
- Background goal: $5x10^{-3}$ counts/(keV.ton.yr)
- $T_{1/2}$ ~ $8x10^{27}$ yr
- Active R&D includes PID and topological reconstruction, quantum sensor development, and active background suppression



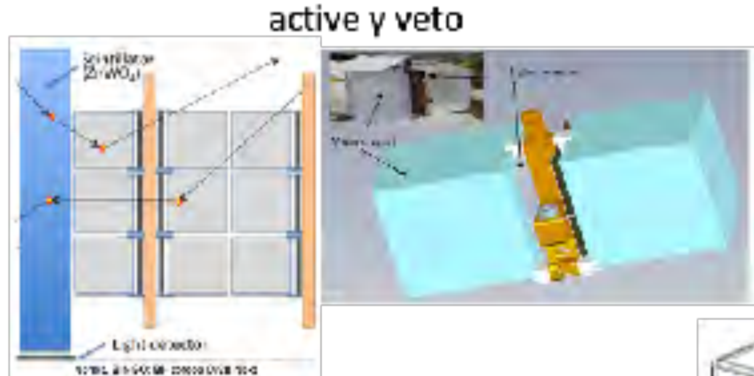
Quantum Sensors



TES Light detectors

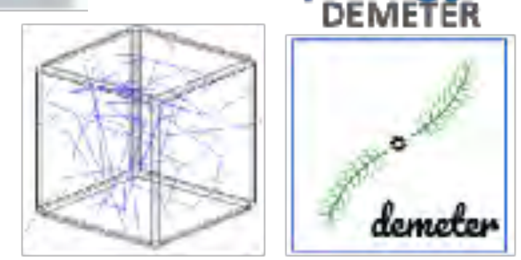
Henning-Yoomans et al. Journal of Applied Physics 128, 154501 (2020)
Singh et al. arXiv:2210.15519

BINGO: Geometry optimization + active γ veto



Event Topology

DEMETER

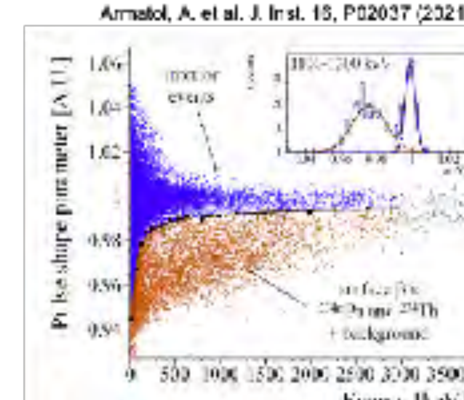


Erin Hansen, Snowmass 2022

Active Background Mitigation

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

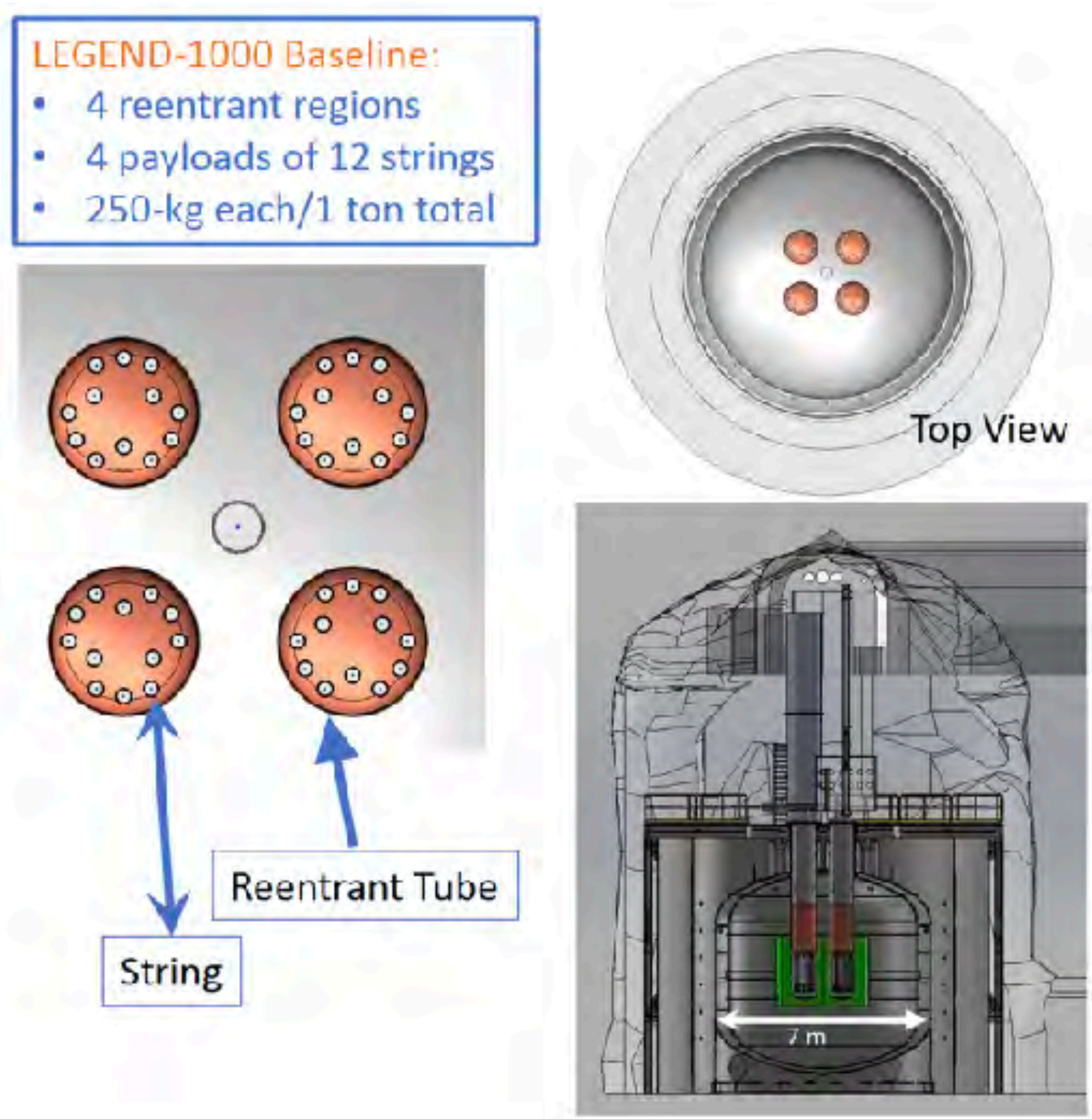
Armatol, A. et al. J. Inst. 16, P02037 (2021)



CROSS

LEGEND-6000

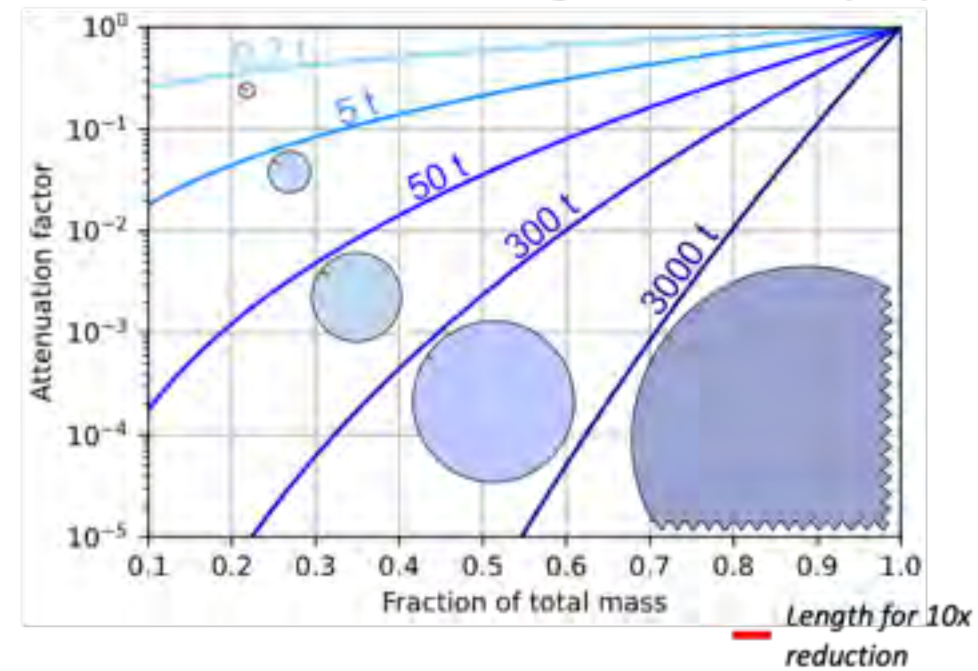
- Remove reentrant tubes, use only UAr
- Increase to 133 strings (from 48)
- Larger detectors
- ~ 6-ton total mass
- Needs ~ x2 detector production rate, and ~x2.5 isotope production rate (well below global Ge production limits). Discussions with vendors ongoing.
- Assume 15 yrs livetime → ~ 100 t-yr
- x3-5 background reduction
  - In-situ cosmogenics, material purity
- x10 improvement in $T_{1/2}$ ~ 10^{29} yr ($m_{\beta\beta}$ ~ 3-6 meV)



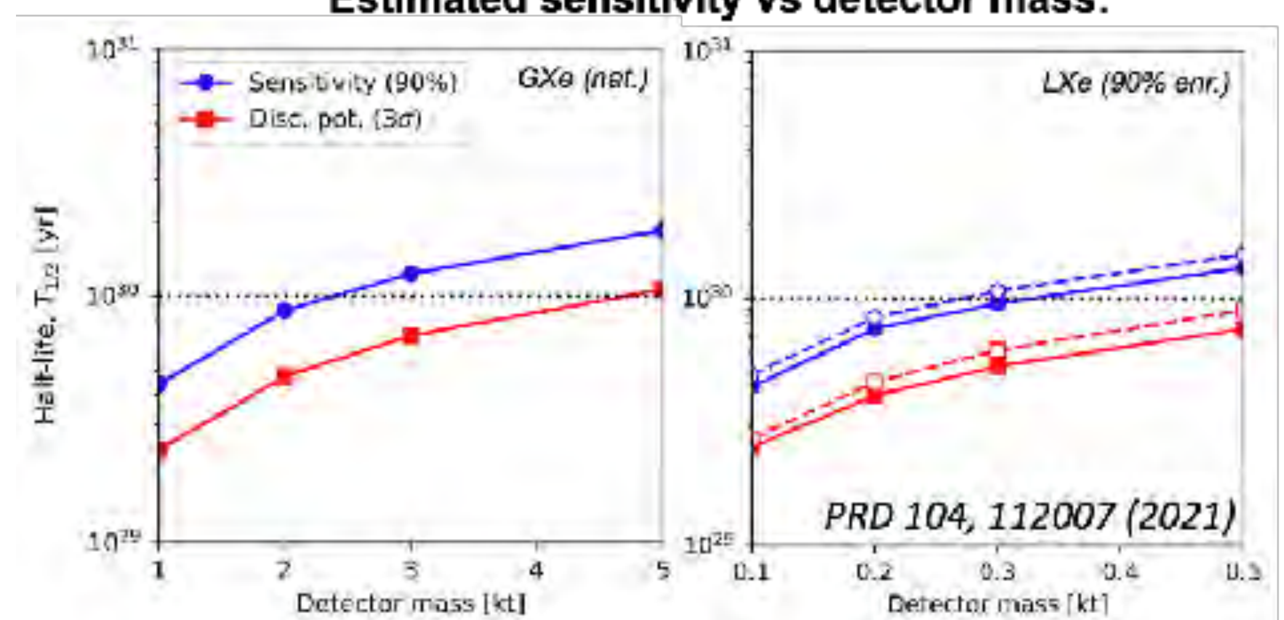
Large Xe TPCs

- A Xe TPC scaled to 0.1-1kt could reach $T_{1/2} \sim 10^{30}$ yr
- Primary challenge is acquiring sufficient Xe
- Benefits from self-shielding
- Primary backgrounds are $2\nu\beta\beta$ and solar ν
  - ➡ ≲ 0.5% energy resolution
  - ➡ Efficiency of target volume use (eliminate materials other than isotope of interest)
- Synergy with G3 DM detectors

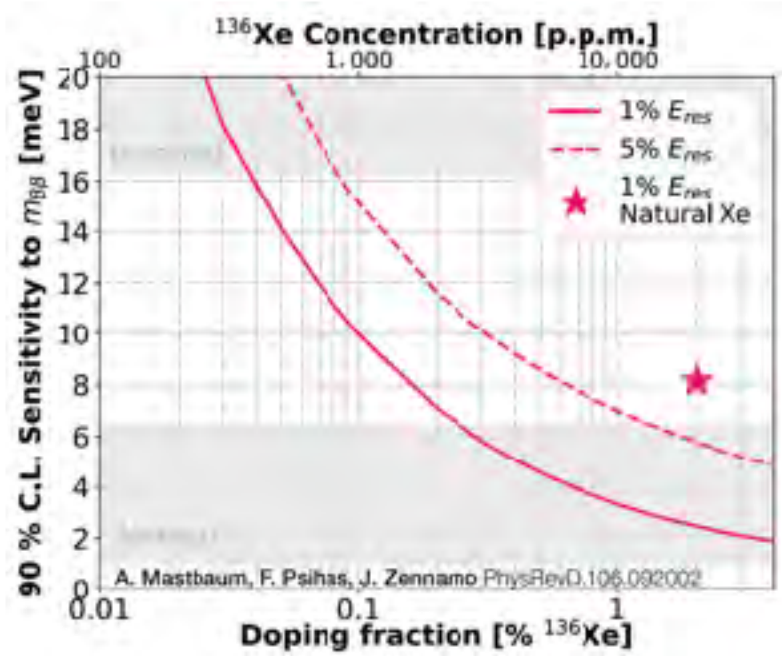
Attenuation of external backgrounds vs size (LXe):



Estimated sensitivity vs detector mass:



Xe-doped large LAr TPC

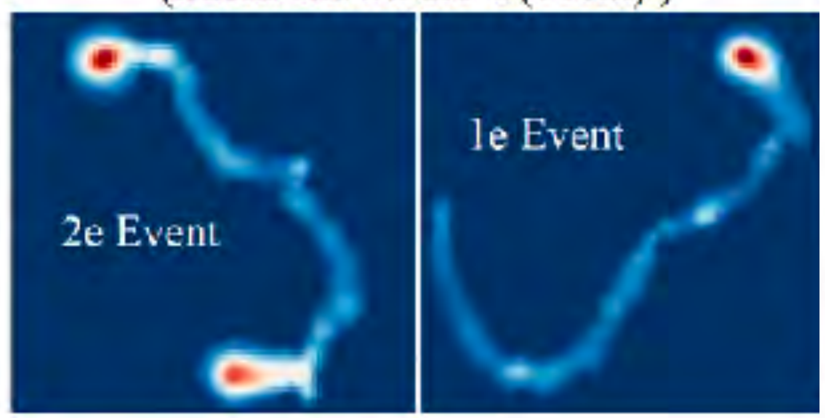


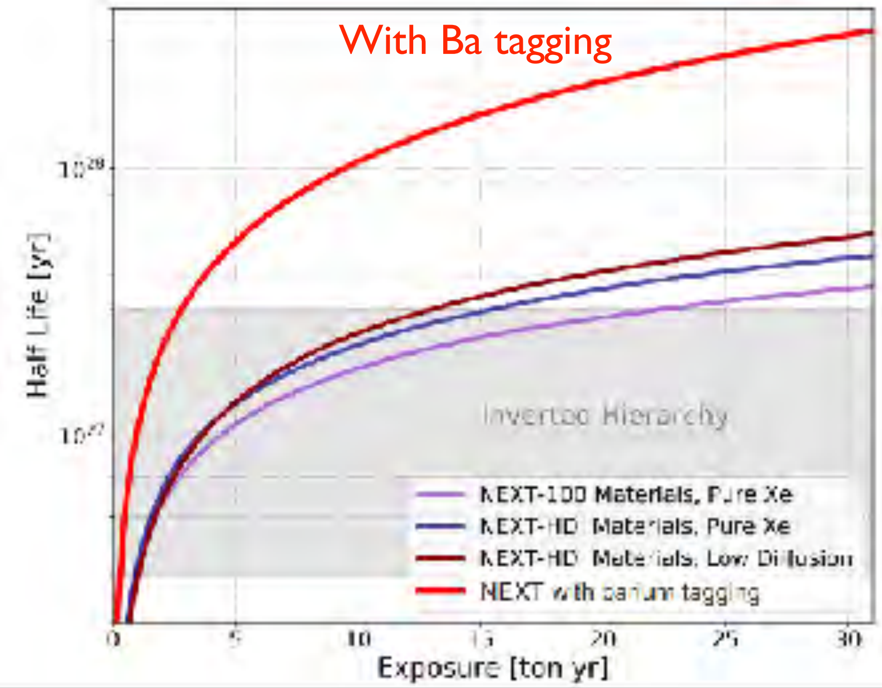
Tracking detectors

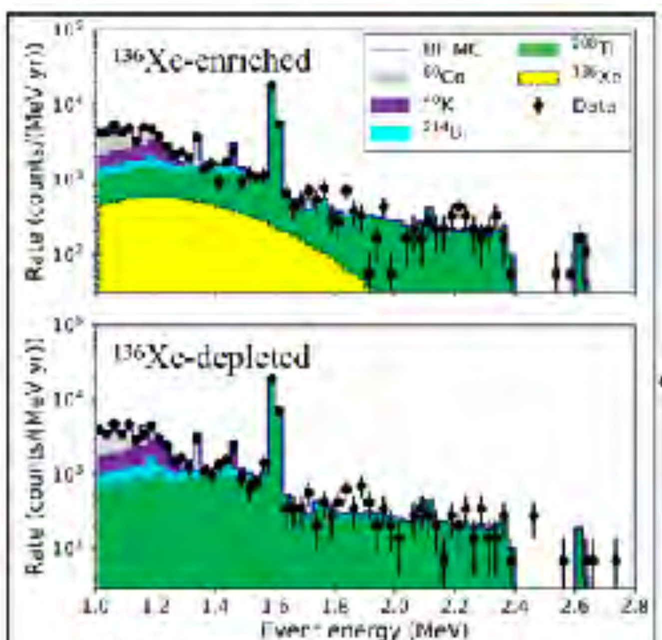
NEXT

- High-pressure gas TPC
- Sensitive & scalable
- Topological resolution offers insight into β kinematics
- Energy res <1% FWHM demonstrated at Q_{bb}
- Suite of demonstrators: NEXT-White (5 kg), NEXT-100

Proven Topological Separation
(tracks shown are O(10cm))



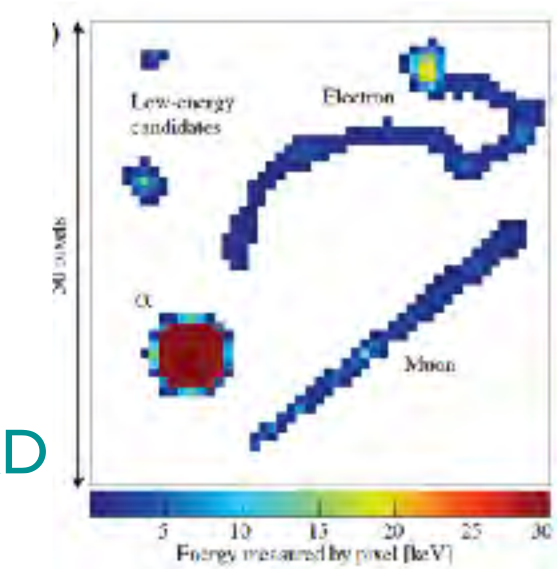


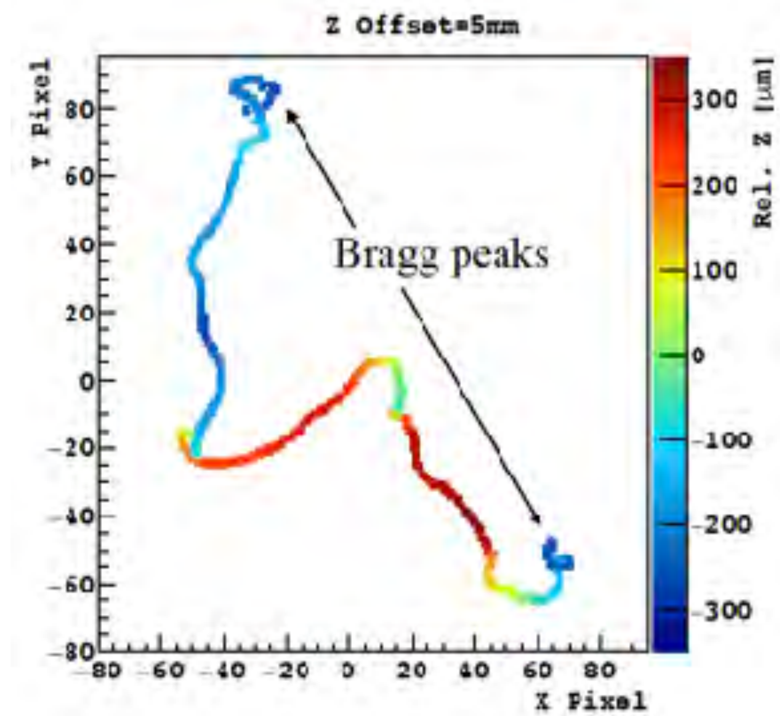


Understood Background model (and 2nuBB observation) from NEXT-White.

Selena

- Highly pixelated solid state detector
- Topological info / PID
- Large-area hybrid CMOS imagers with ~5-mm ^{82}Se layers
- Small-scale R&D



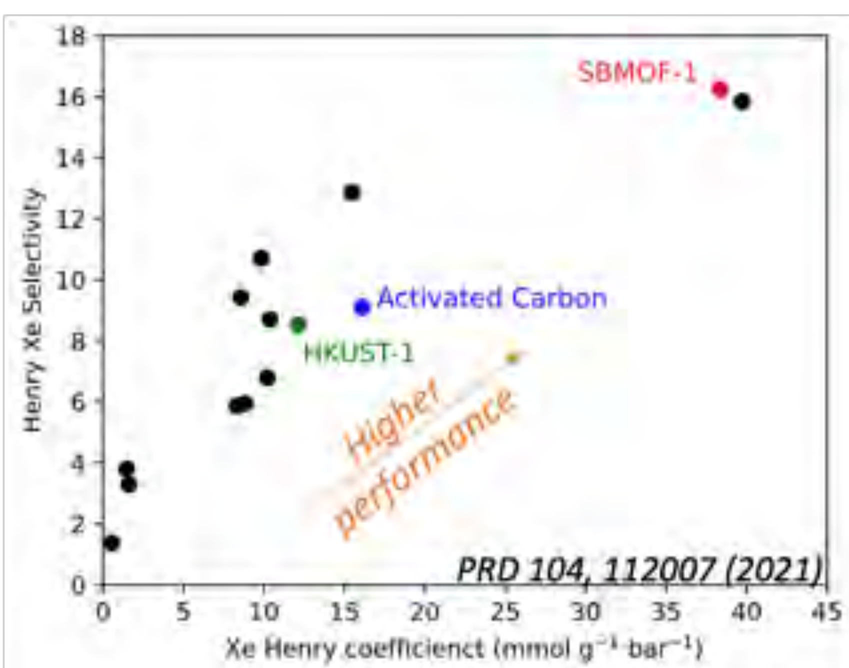


R&D for next-gen Xe

Xe sourcing

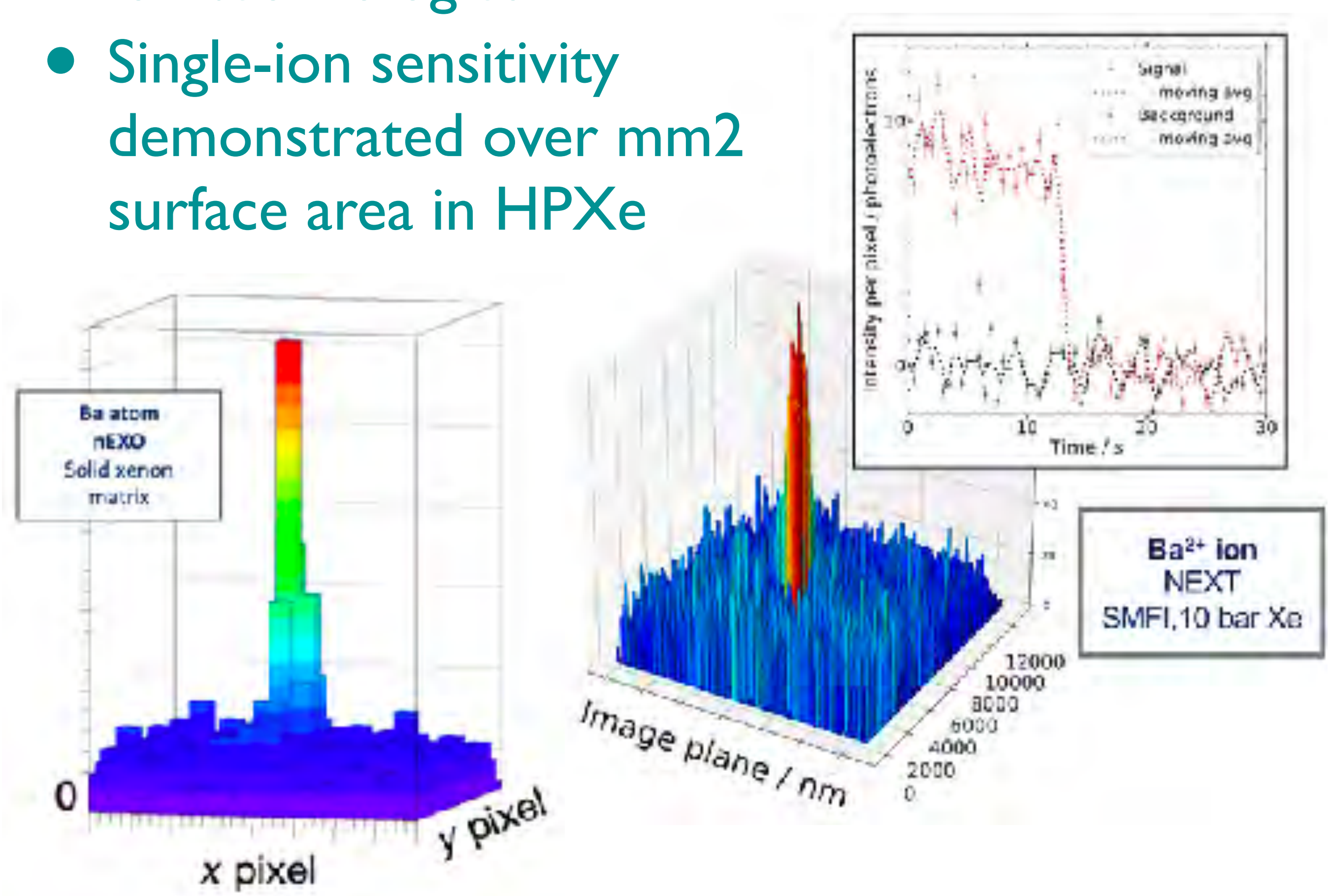
- Current global Xe production: 50-100 t / yr, based on O2 production for steel industry
- Source from nuclear fuel processing (~40% ^{136}Xe)
- Direct air capture (DAC): efficient, scalable
- R&D underway for DAC pilot plant based on advanced adsorbents tuned for Xe

Selectivity vs adsorption coeff for various materials:



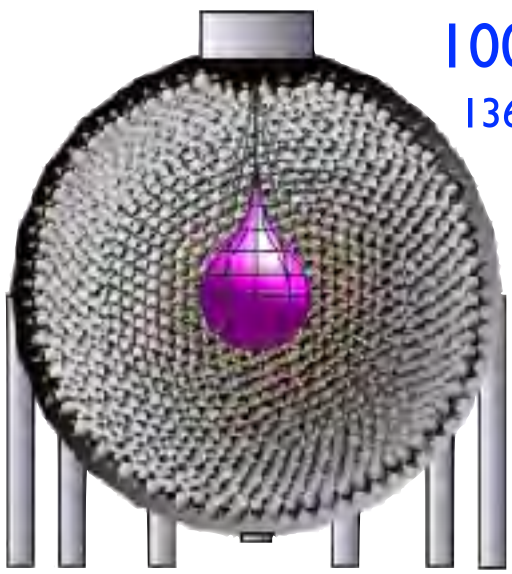
Barium tagging

- Potential for additional enhancement from Ba tagging
- Multiple approaches under development
- Exploring ion-to-sensor and sensor-to-ion technologies
- Single-ion sensitivity demonstrated over mm2 surface area in HPXe



Large LS Detectors

KamLAND-Zen: LXe

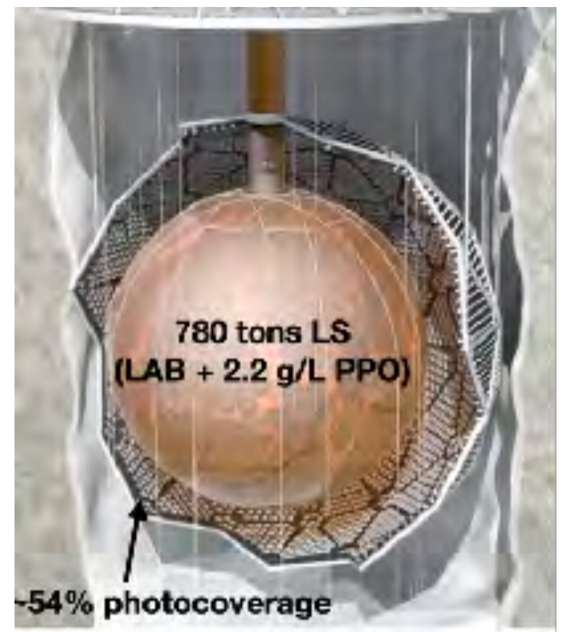


1000kg ^{136}Xe

$m_{\beta\beta}$ < 20—80meV

$T_{1/2} > 1 \times 10^{27}$ yr

SNO+: Te-LS

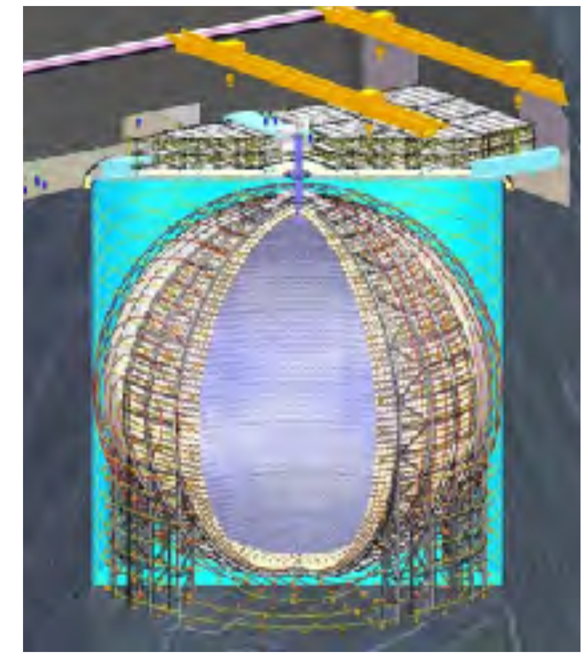


0.5% nat Te

$T_{1/2} > 2 \times 10^{26}$ yr (0.5%)

$T_{1/2} > 1 \times 10^{27}$ yr (3.0%)

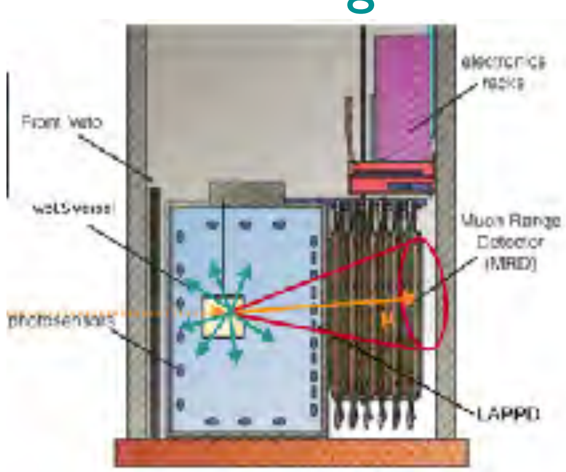
JUNO: LS



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

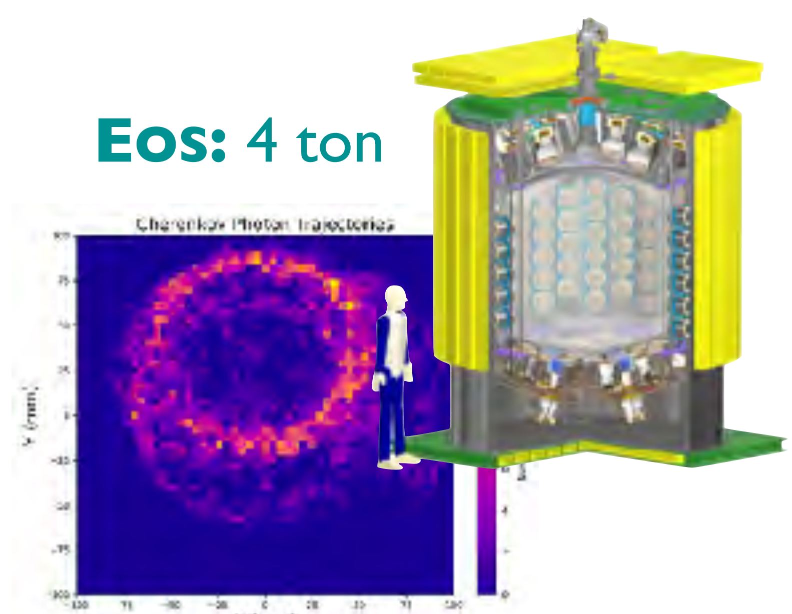
R&D into next-gen LS detectors

ANNIE: 365 kg



NuDot: 1 ton

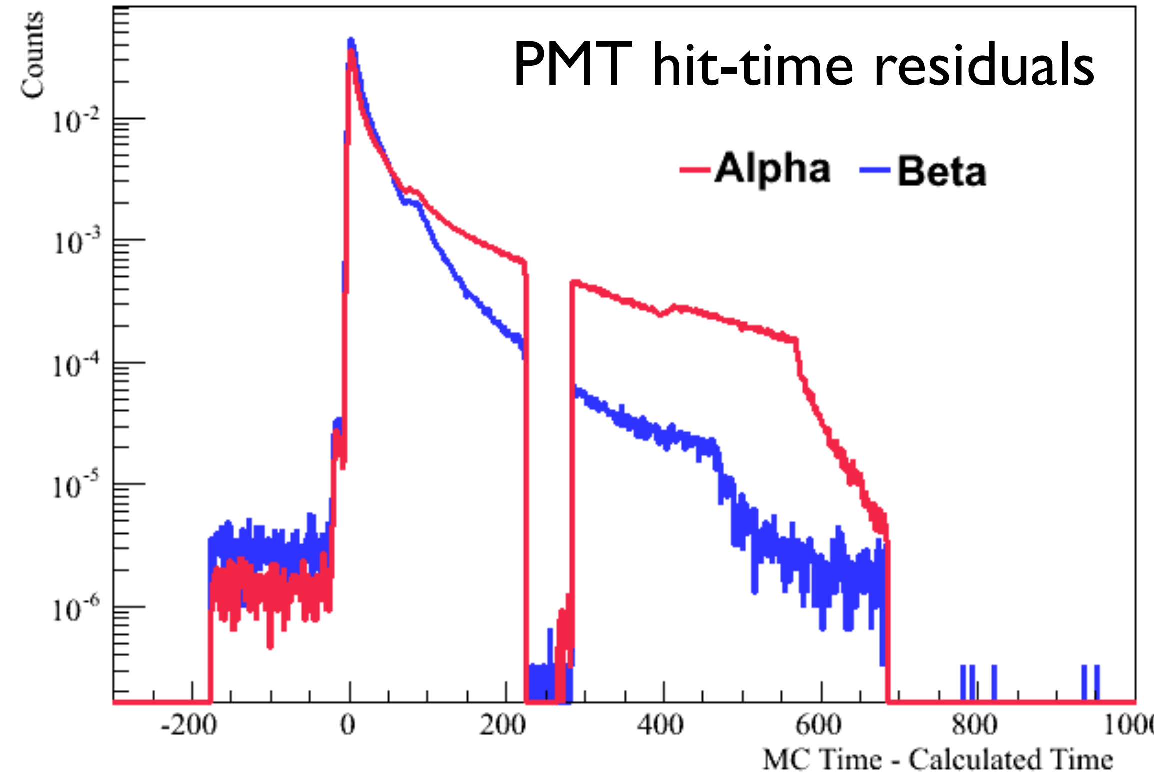
Eos: 4 ton



BNL: 1- and 30-ton

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+ sensitivity

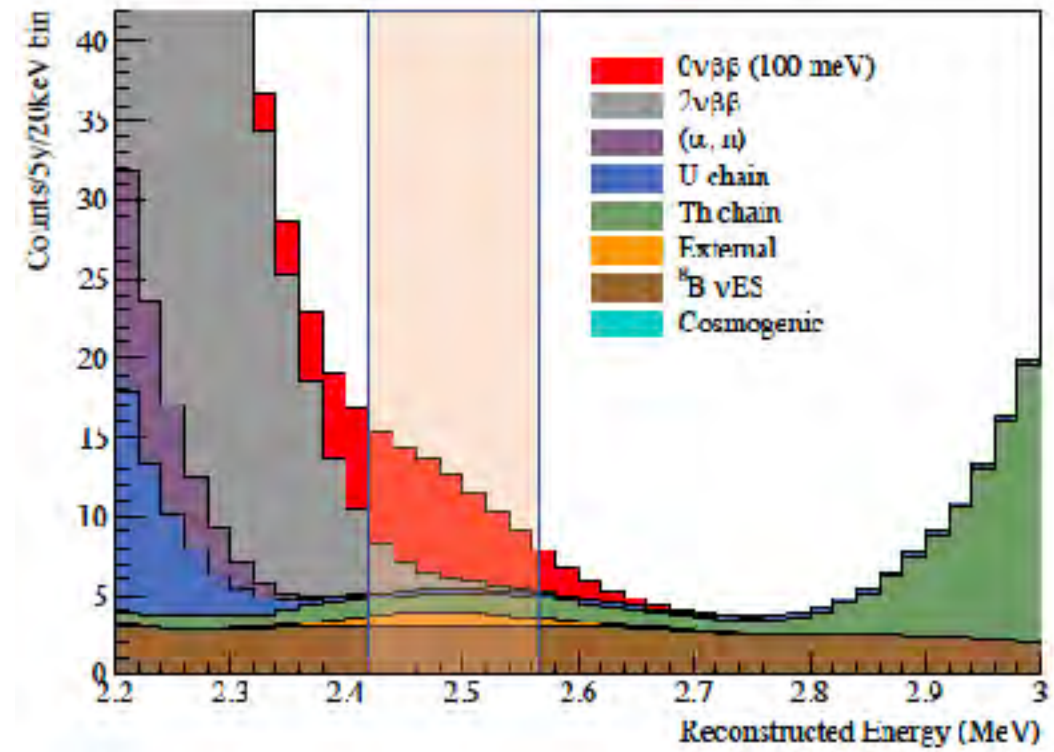
Detector configuration:

0.5% natural Te

5 years live time

Ex-situ optics (Penn/BNL)

3.3m fiducial volume (20%)



Te "cooling" UG for several years

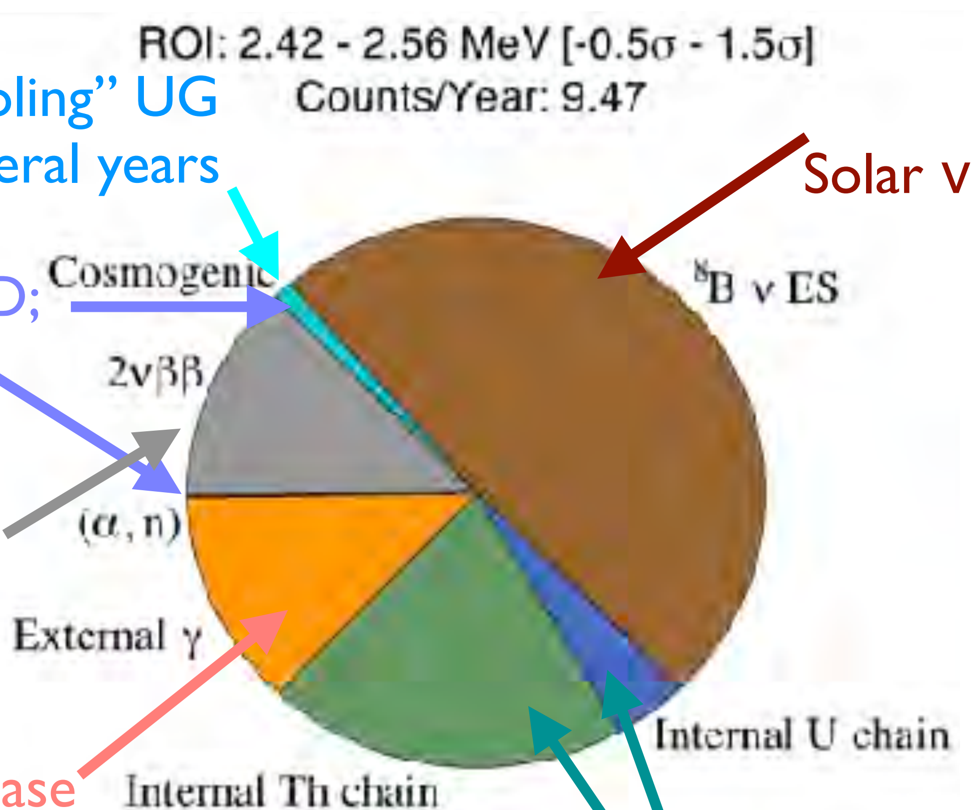
Multi-site PID; sideband constraints

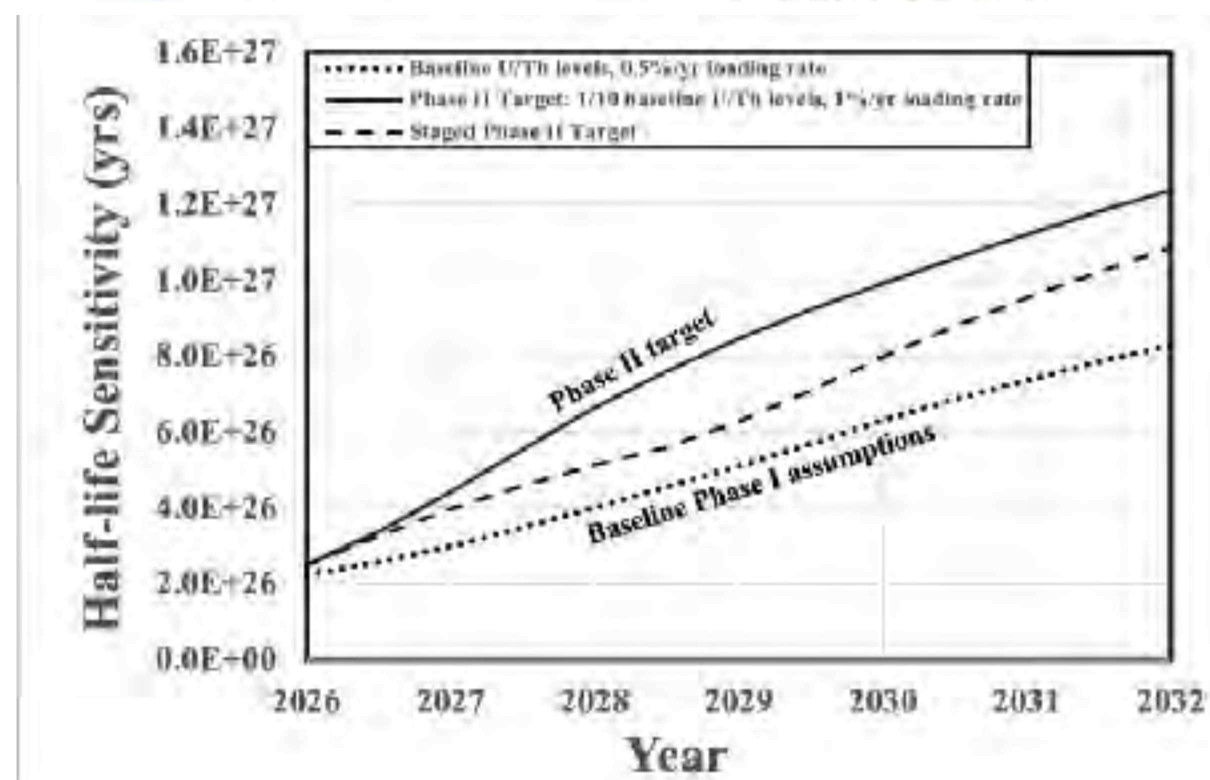
Asymmetric ROI

Water phase measurement; sideband constraints

Solar ν data

LAB-PPO component measured during partial fill; sideband constraints



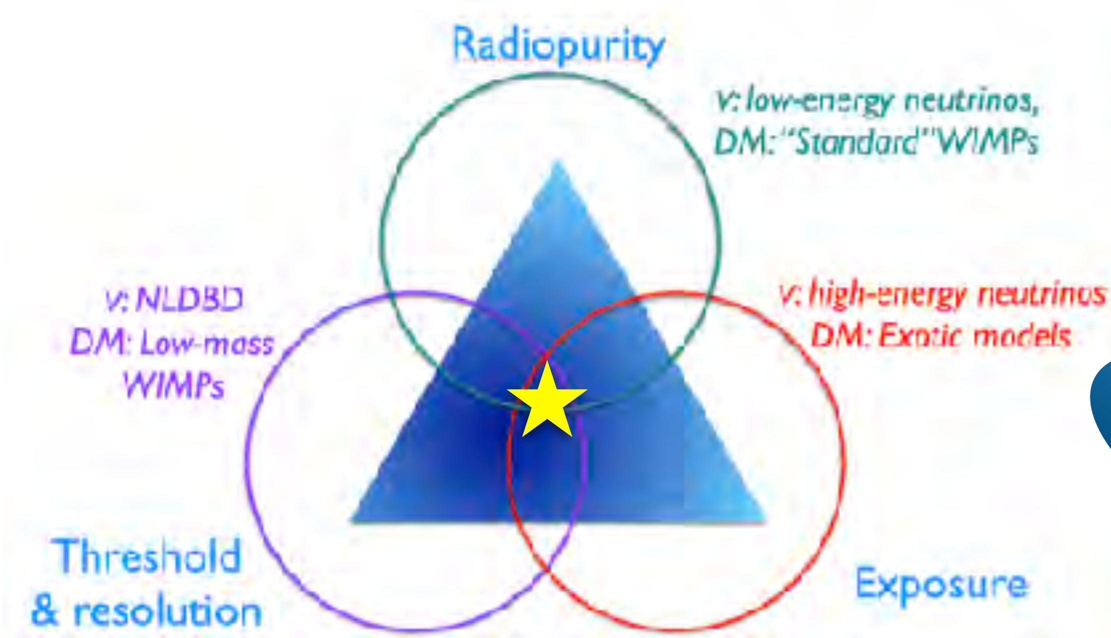


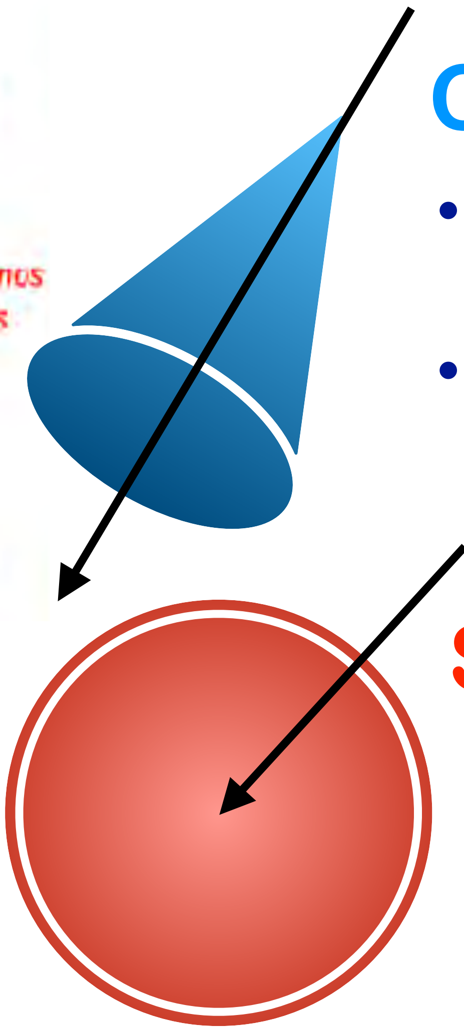
SNO+ status

- 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)

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

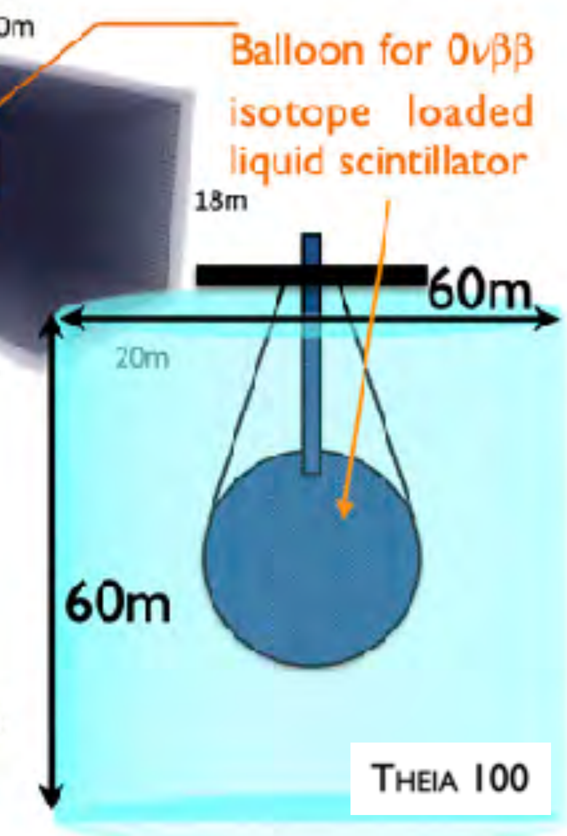
Improved background rejection for precision ν measurements

Facilitates broad program!

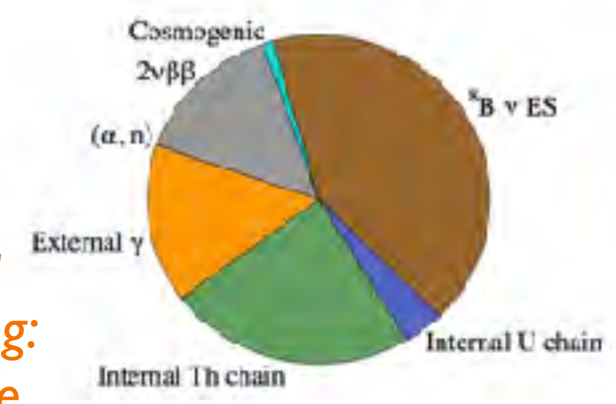
Neutrinoless double beta decay
Particle astrophysics (solar, supernova)
Long baseline physics (CPV, NMH)
Nucleon decay
Geo neutrinos

THEIA

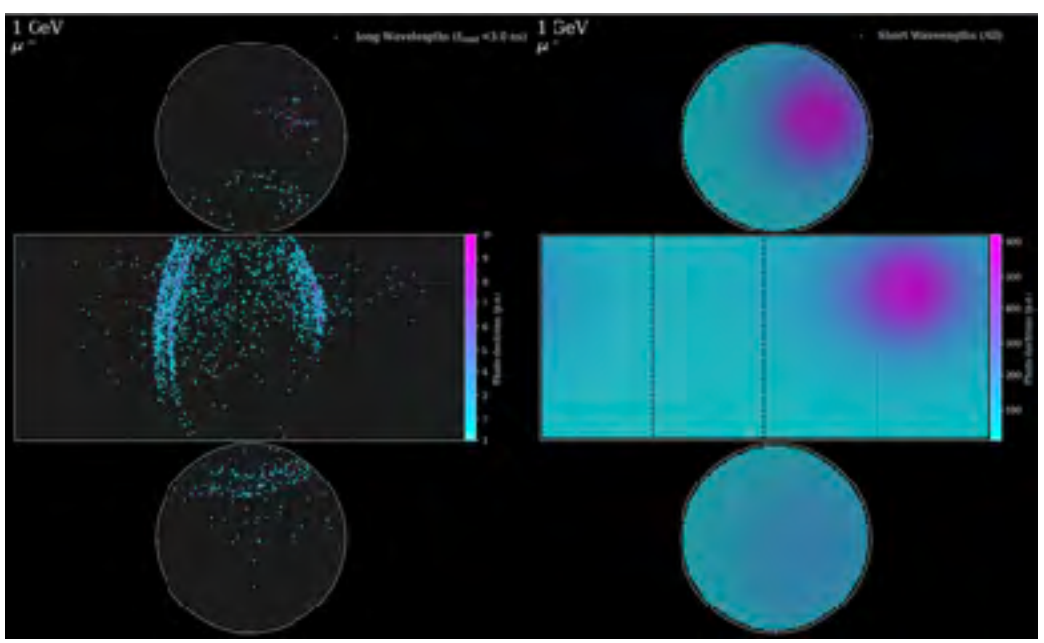
- Hybrid Cherenkov / scintillation detector improves background rejection via PID and event topology
- Scalable, ultra-clean liquid detector
- Potential to deploy a 25-kton THEIA module at LBNF, in a Module of Opportunity
- Mass sensitivity of ~4—22 meV
- Broad program of other physics

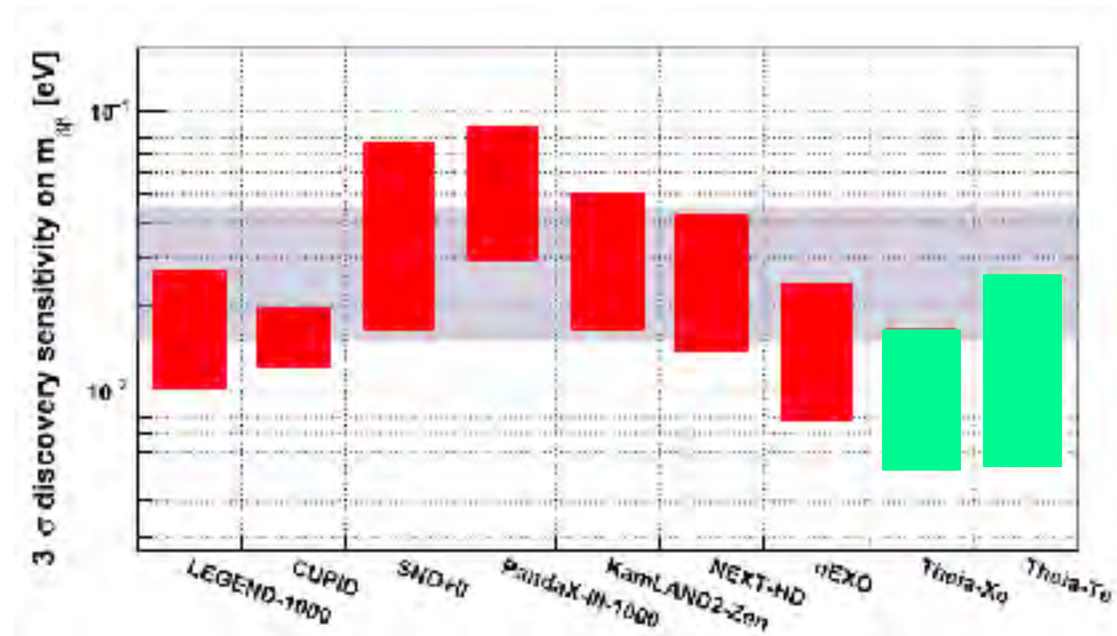


SNO+ Collaboration



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



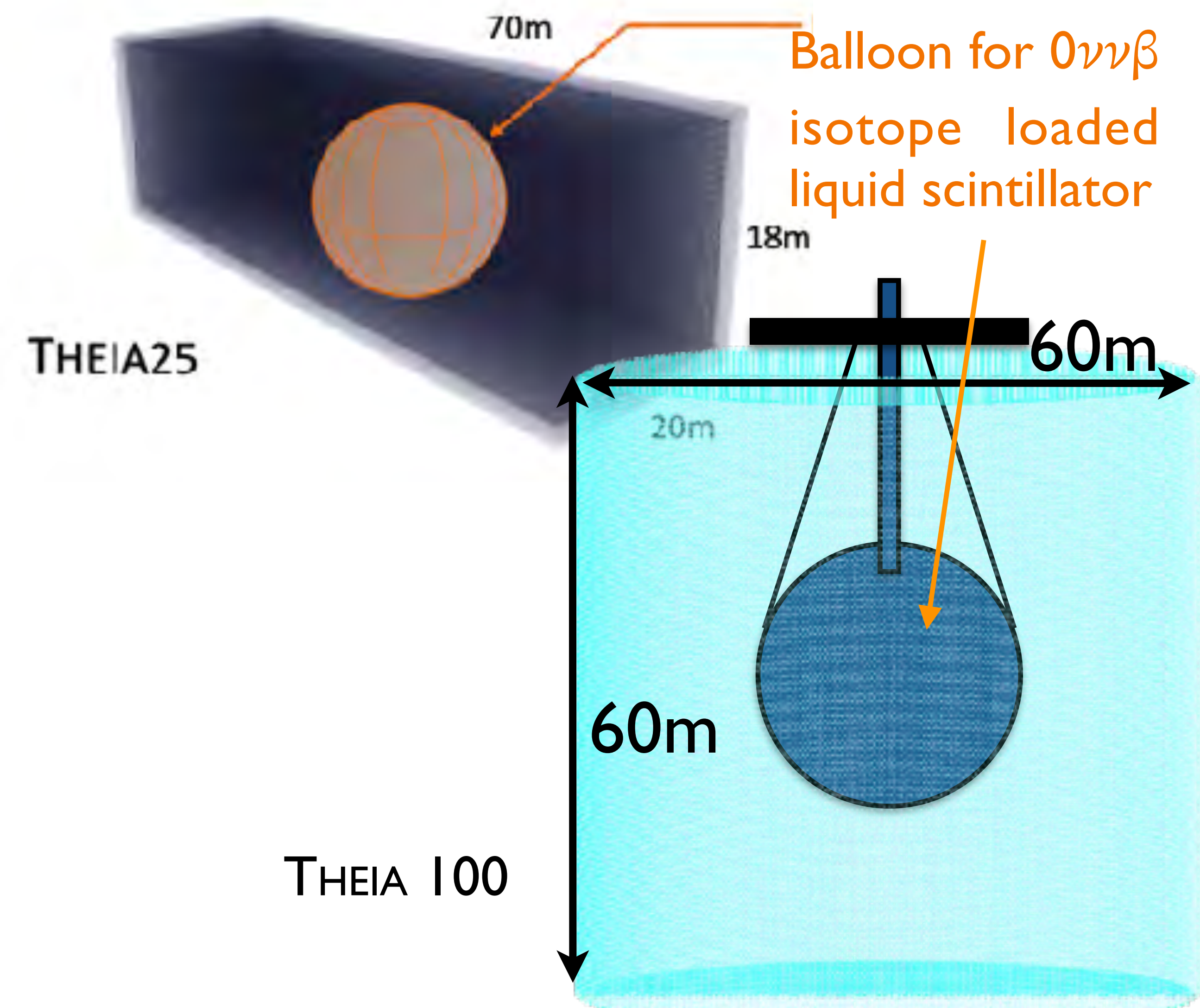


Builds on critical developments by KLZ & SNO+ collaborations

NLDBD with Theia

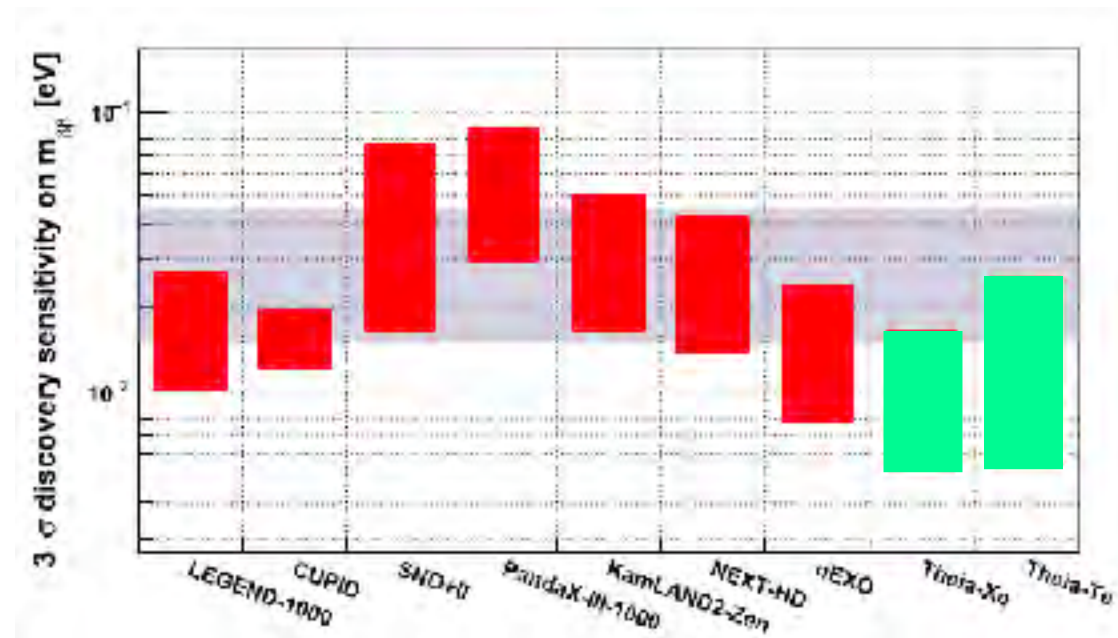
25-100 kton hybrid optical neutrino detector
8-m radius balloon with high-LY LS and isotope
7-m fiducial, 3% ^{nat}Te (or ^{enr}Xe), 10 years

Directionality, PID and multi-site discrimination reduces backgrounds



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

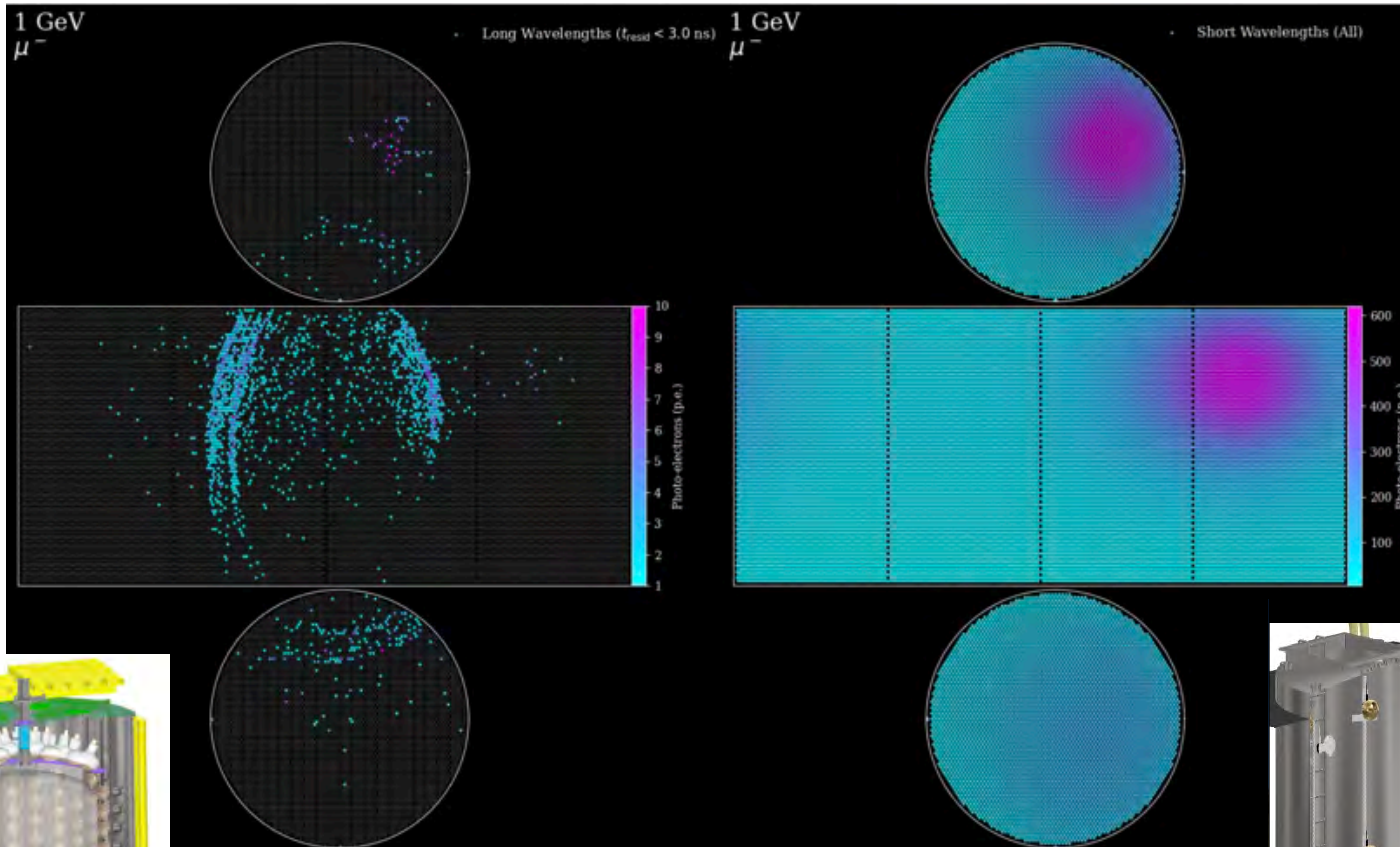
$m_{\beta\beta}$ < 6.3 (5.6) meV



Builds on critical developments by KLZ & SNO+ collaborations

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

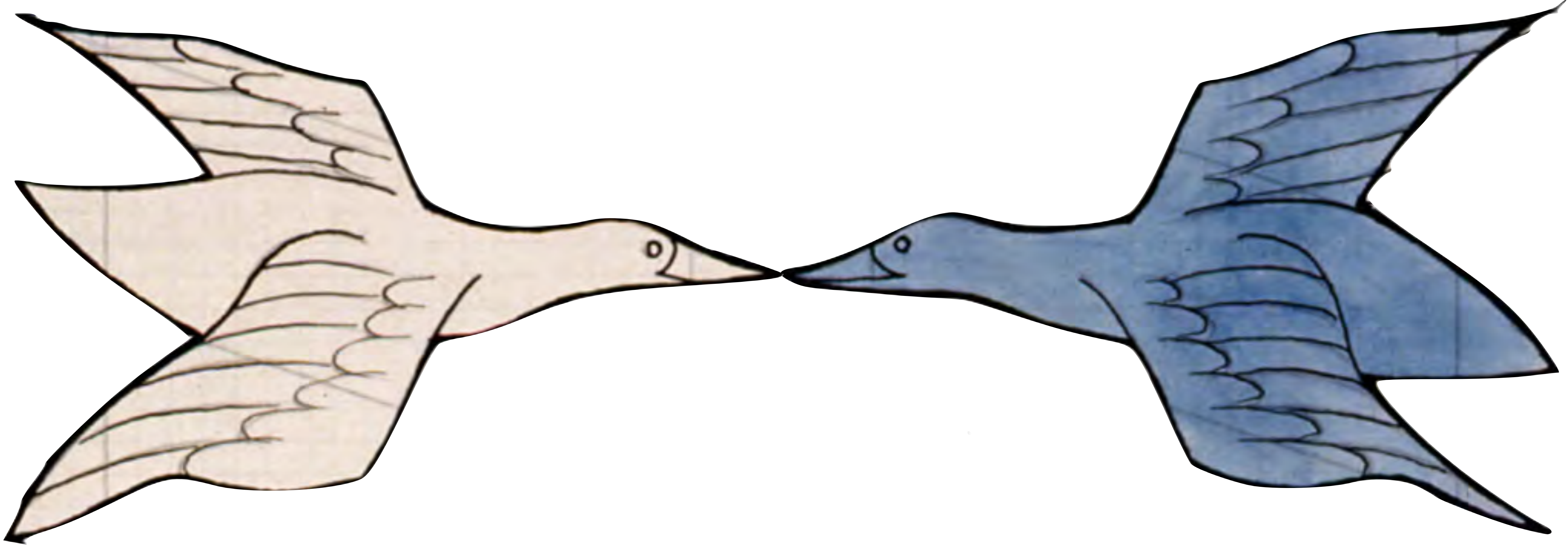
The future



BNL 30-ton deployment demonstrator

Eos: 4-ton technology demonstrator

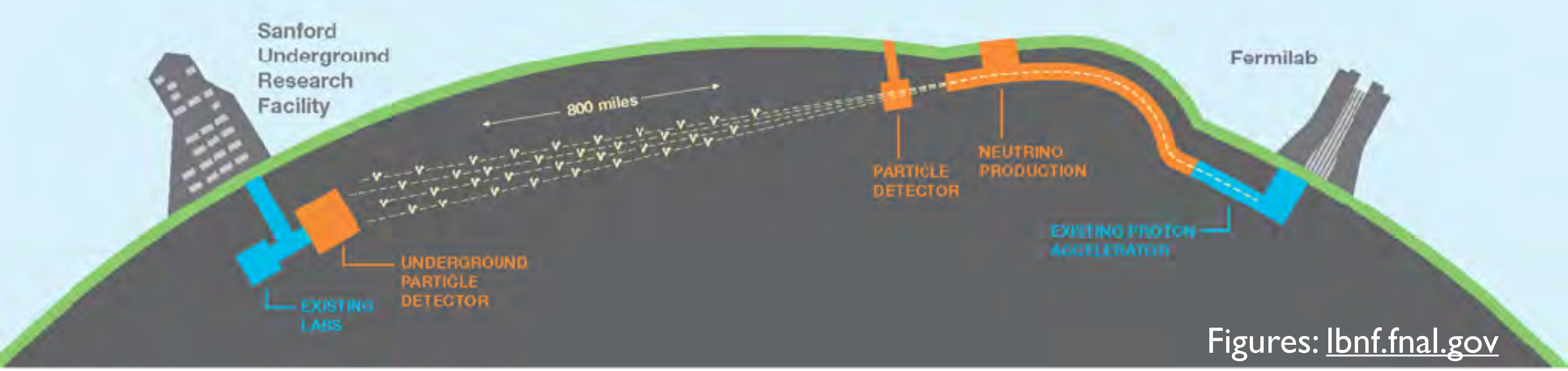
CP Violation



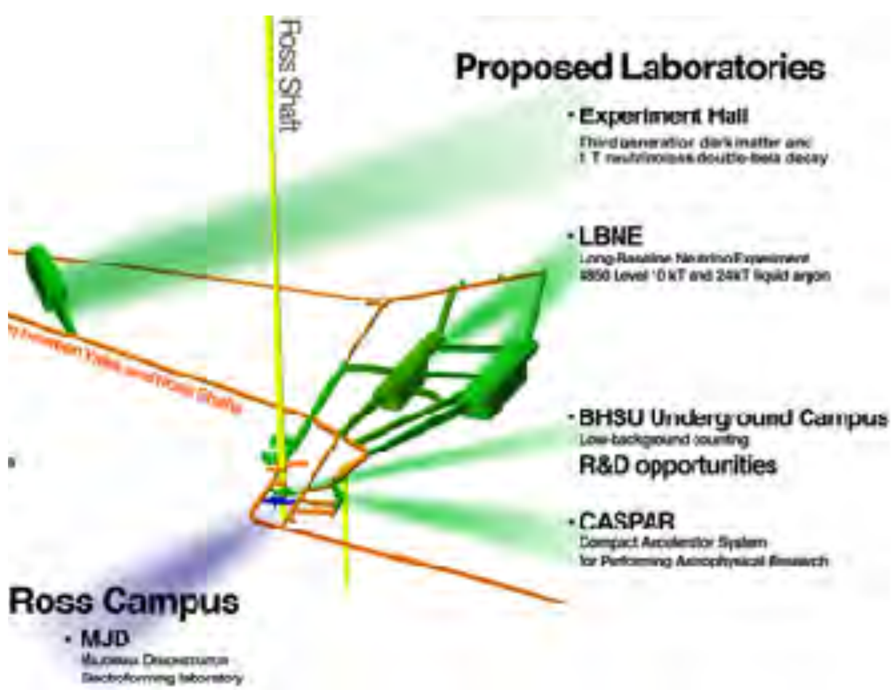
The Missing Ingredient: CP Violation

Deep Underground Neutrino Experiment (DUNE)

“Sending neutrinos on an 800-mile journey”



Figures: lbnf.fnal.gov

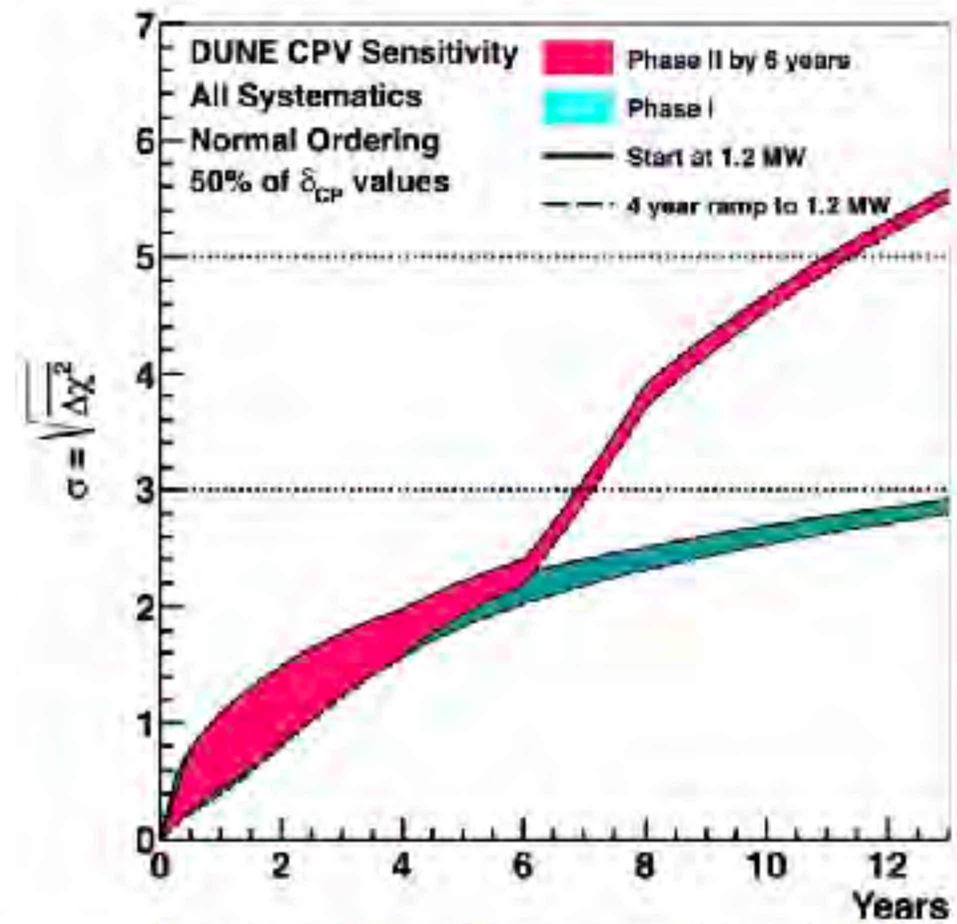


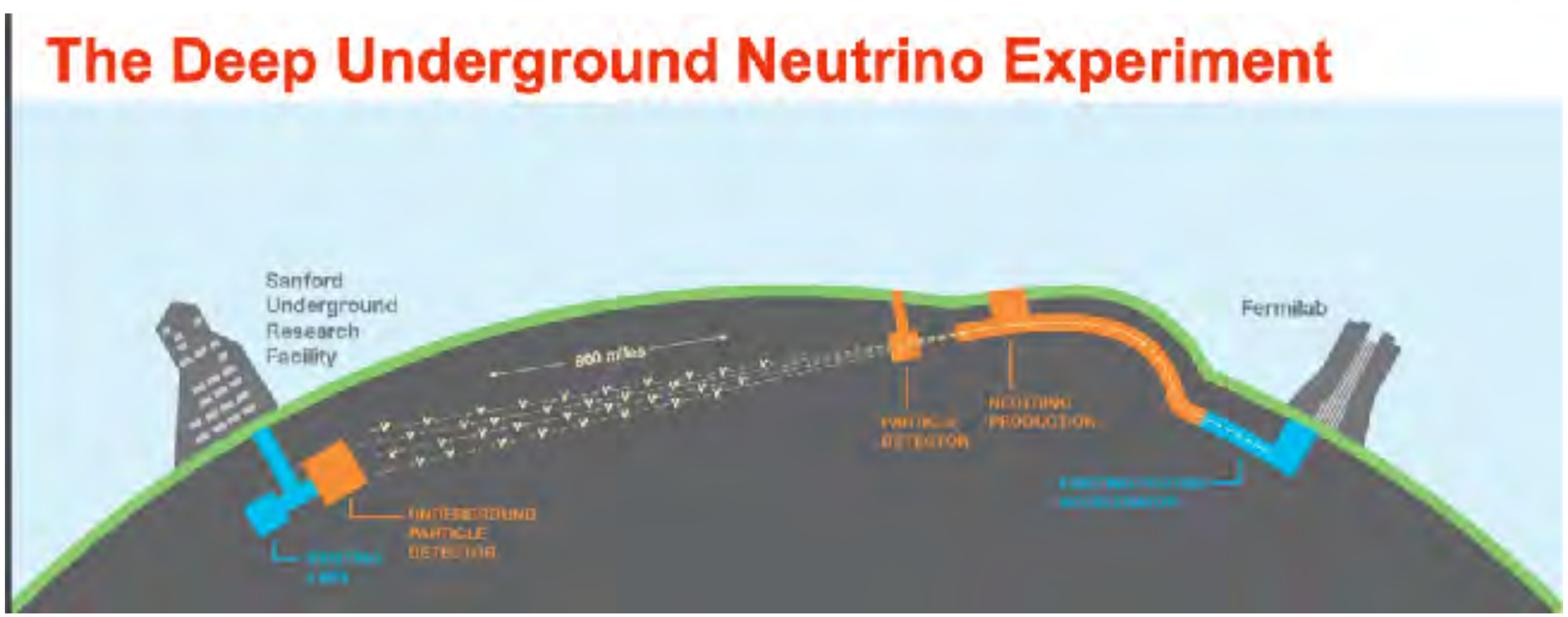
Full DUNE scope:

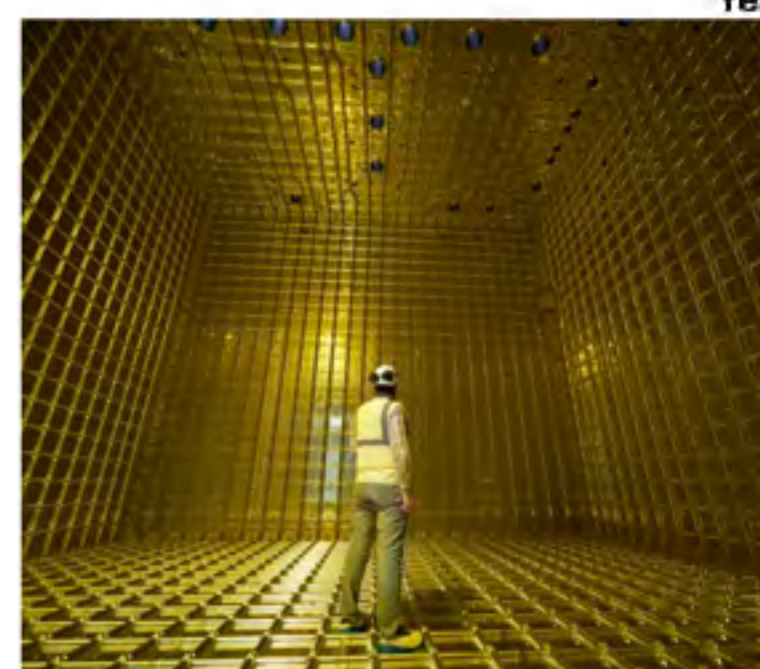
1. 1.2 MW beam, upgradeable to 2.4MW
2. Four Far Detector (FD) modules, 40kt+ fiducial
3. Near Detector suite (ND)

CP violation: DUNE

- CP violation and ν mass ordering
- Oscillation parameters
- Multi-messenger astronomy
- Beyond-SM physics
- Two-phase program
  1. Mass ordering; 3σ CPV at maximal δ_{CP}
  2. 5σ CPV for 50% of δ_{CP}







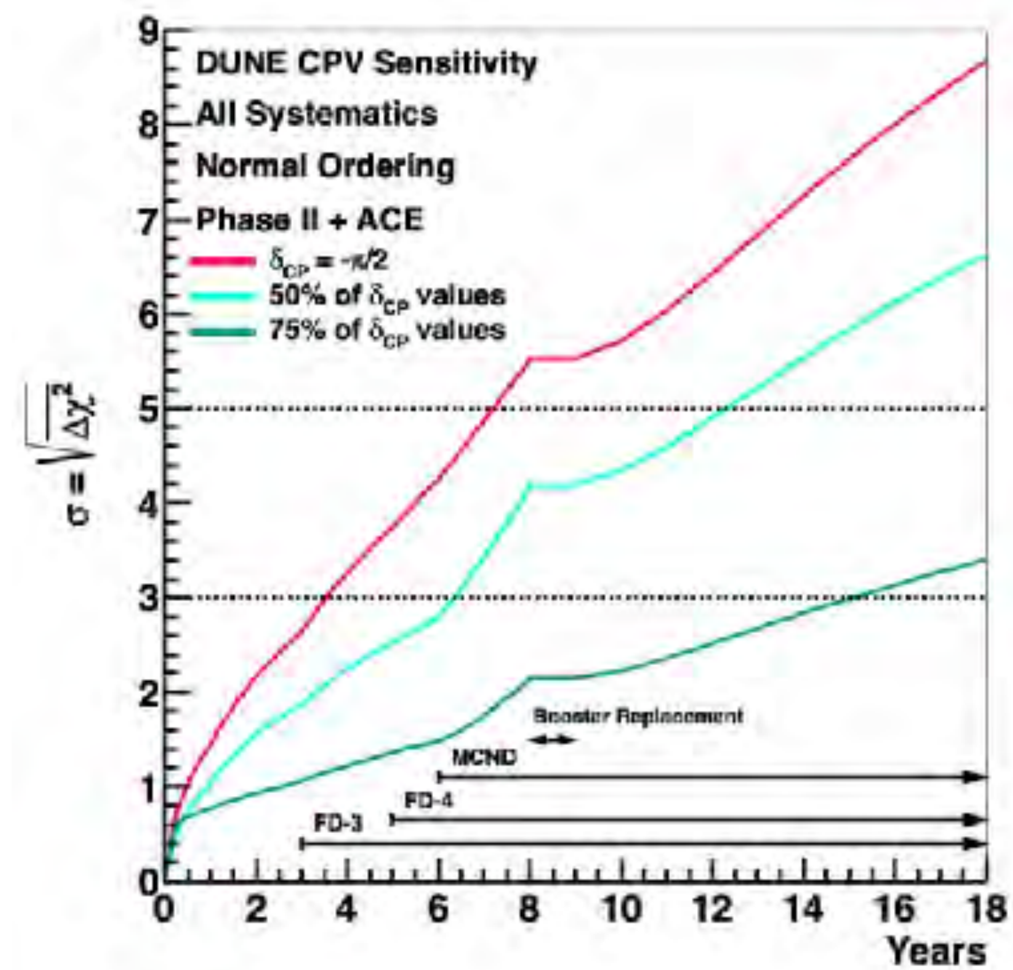
DUNE phasing

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)

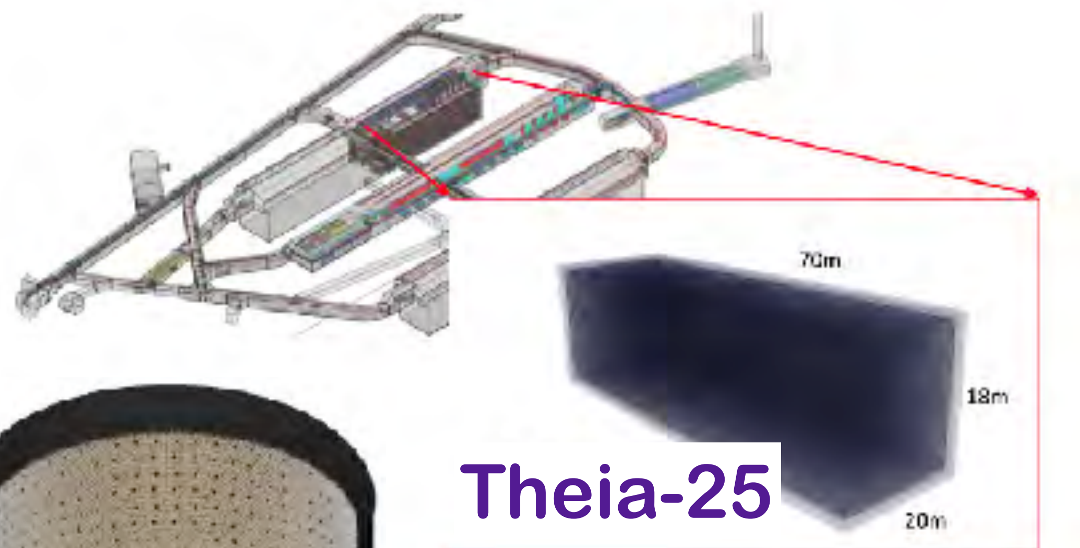
DUNE Phase II:

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

Broad low-energy & precision physics program
Long-baseline sensitivity comparable to a LAr DUNE module
Complementary supernova sensitivity: primarily anti-ν, fast response: act as trigger



Large, multipurpose detector

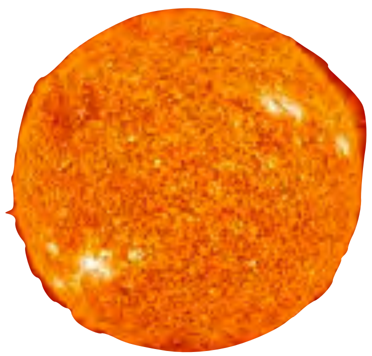
- Baseline: 25 ktonne (17 kt FV)
- Ideal: 100 ktonne (70 kt FV)

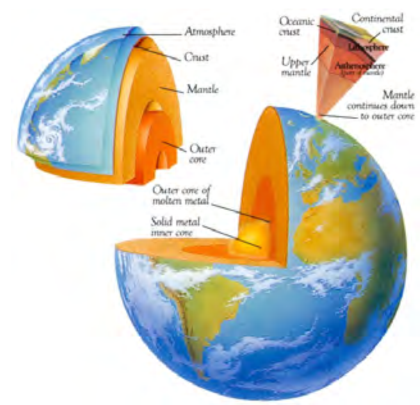
- DUNE Phase II formal process includes Theia as 1 of 3 options
- Theia is technically mature, and brings a broad physics program beyond any alternative (LAr) tech.
- Strong international team actively engaged
- Current R&D support from HEP, NNSA; LDRD at BNL to study ND requirements
- Technical demonstrators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

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

Physics Program

Neutrinos as a probe of nature

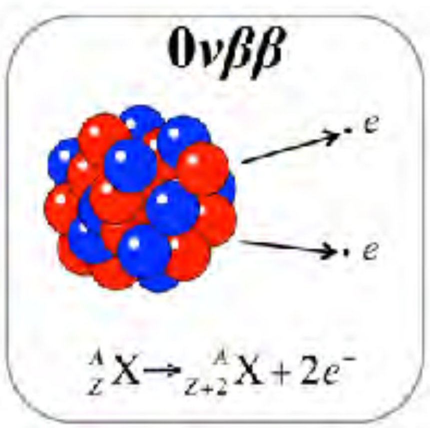


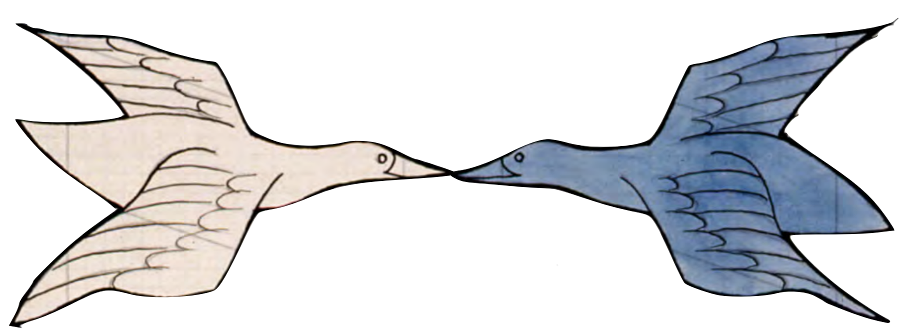


Particle astrophysics

Physics over 5 orders of magnitude

Studying the fundamental nature of matter





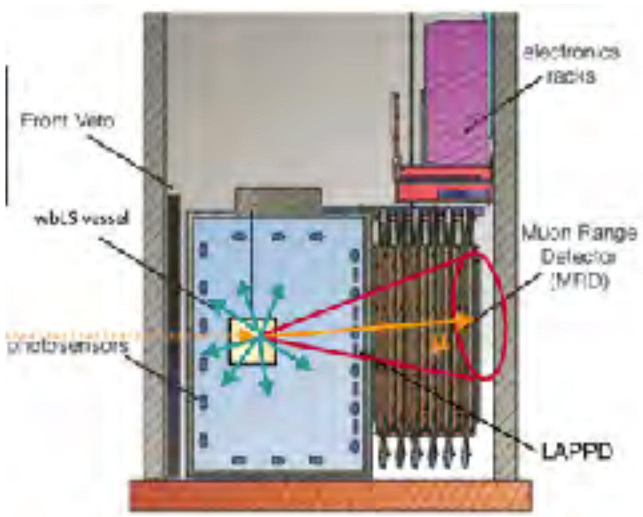
Nuclear physics

High energy physics

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

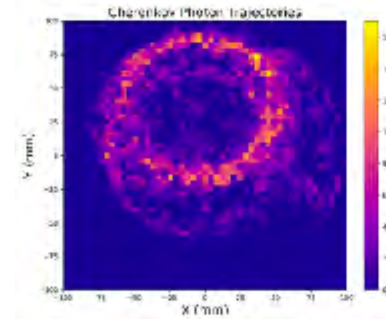
Matter-dominated universe

The path to THEIA



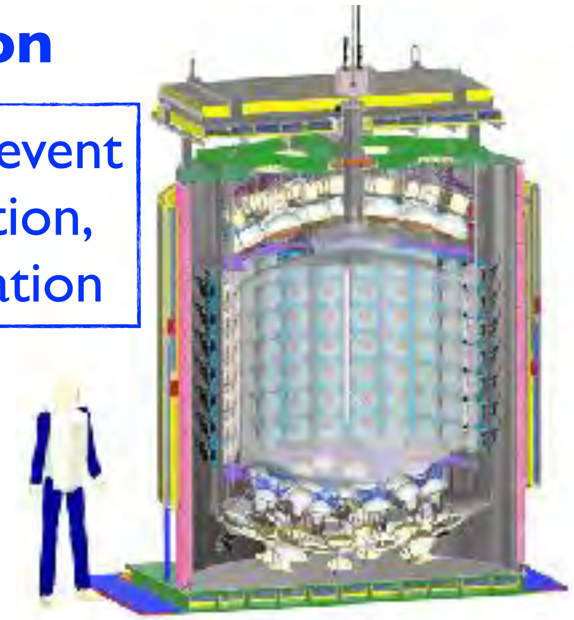
ANNIE: 365 kg

High-energy event reconstruction, neutrino detection

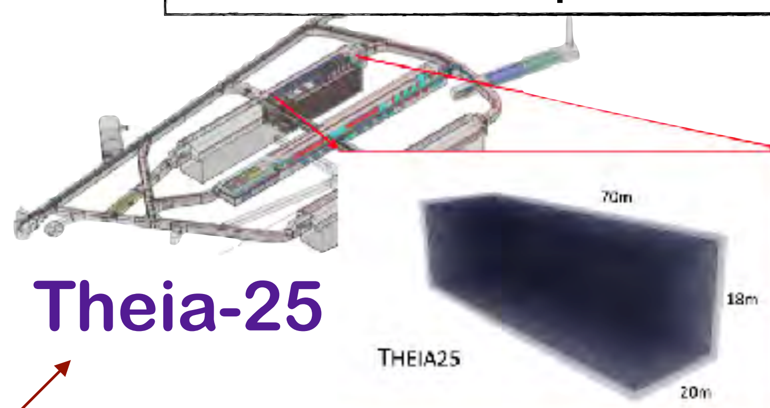


Eos: 20 ton

Low-energy event reconstruction, model validation



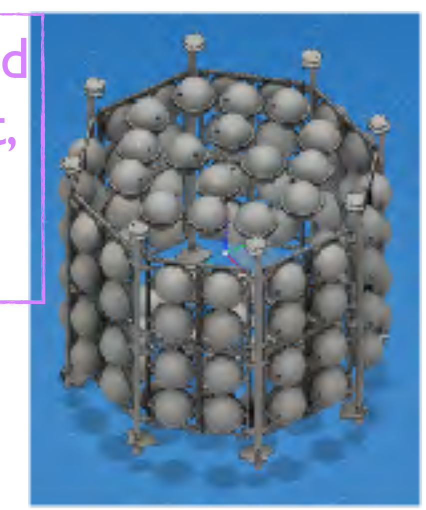
Building on a broad program of bench-top scale development



Theia-25

BUTTON: 30 ton

Underground deployment, low bkg verification



BNL: 1- and 30-ton

Deployment, purification, recirculation, transparency

NuDot: 1 ton

Isotope loading, NLDBD topology

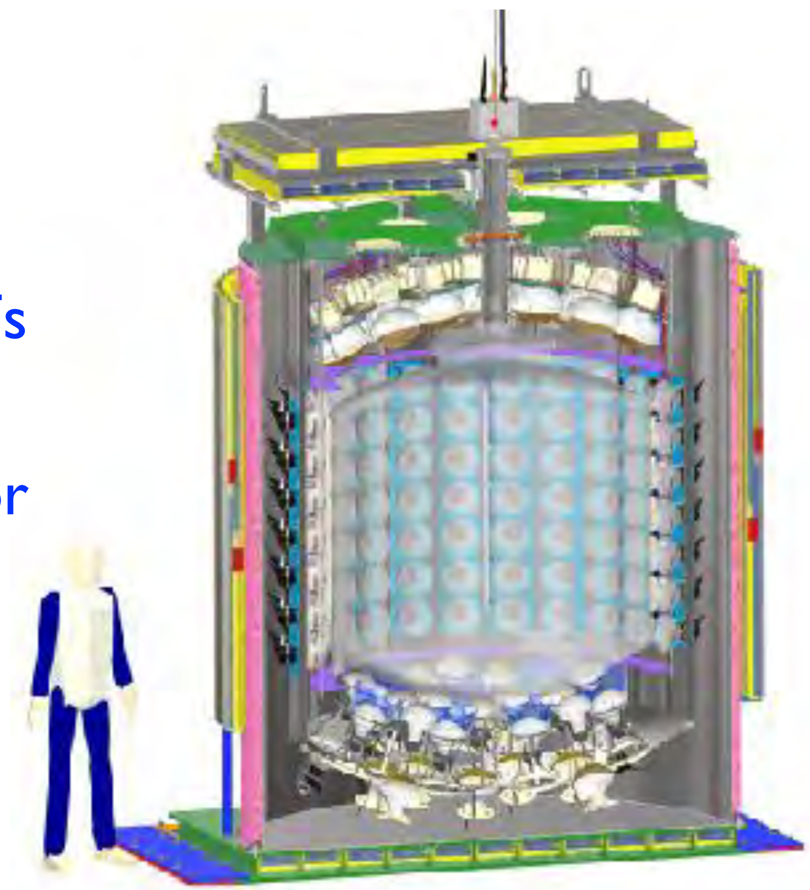
EOS: performance demonstrator

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 4-wavelength picosecond laser light injection system for optical and timing calibration

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



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

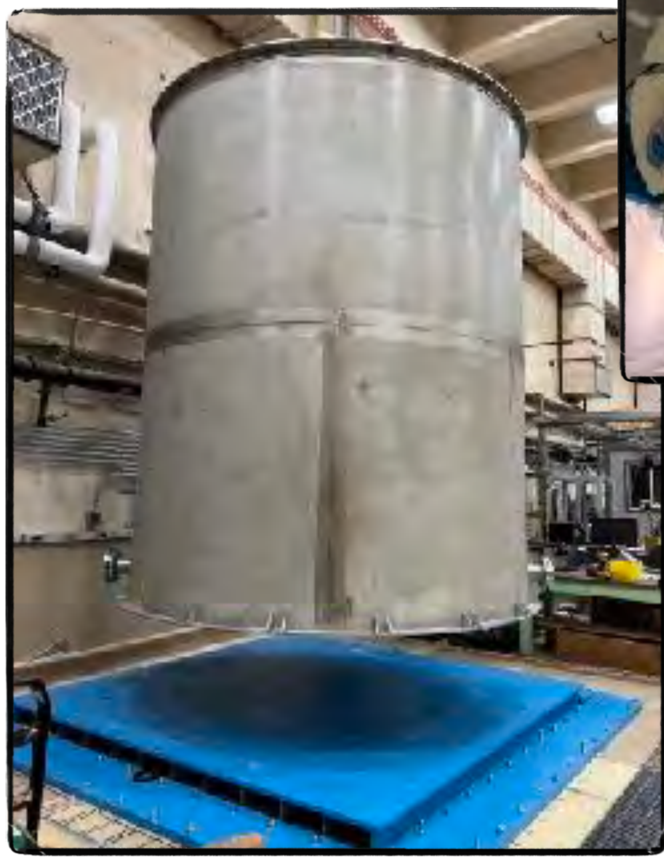
EOS concept paper published: *JINST 18 P02009 (2023), https://doi.org/10.1088/1748-0221/18/02/P02009*

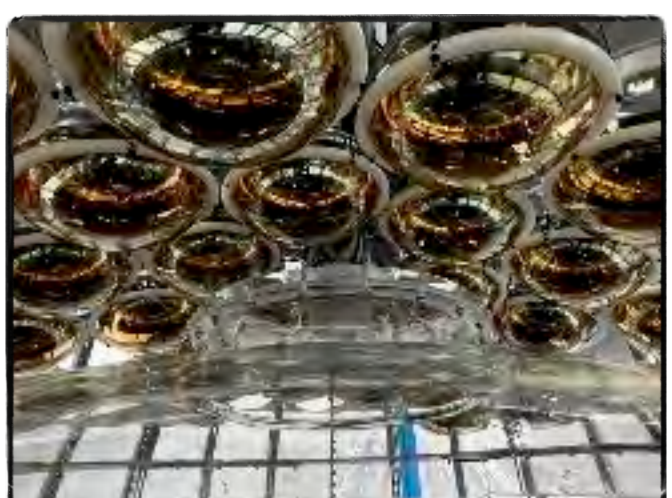
Challenges faced

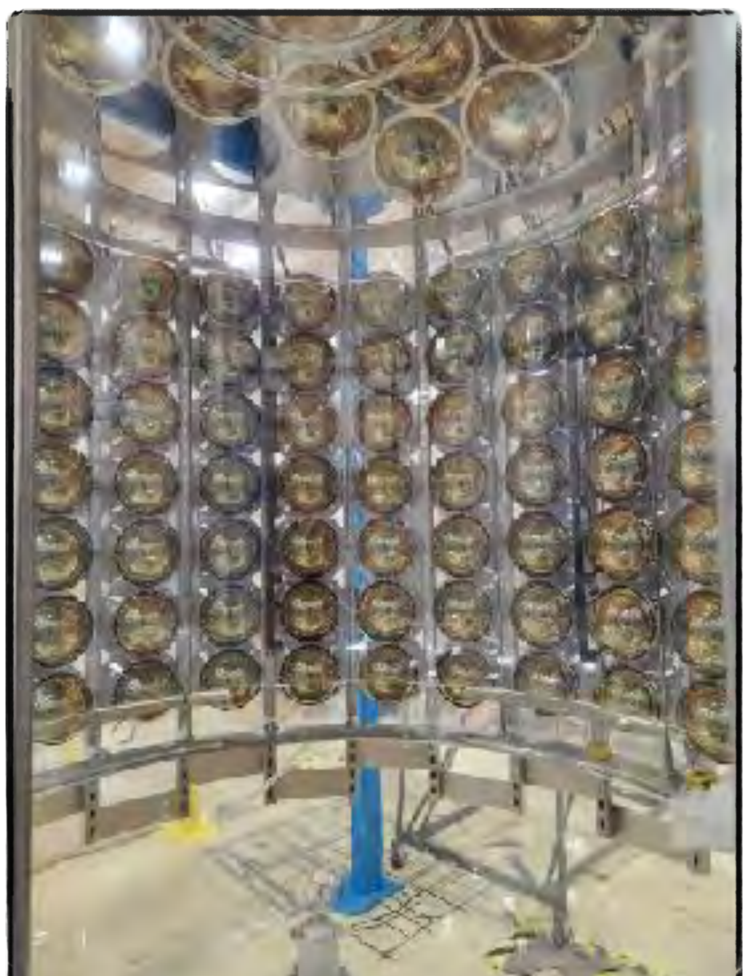
Outer vessel and assembly stand, May ‘23

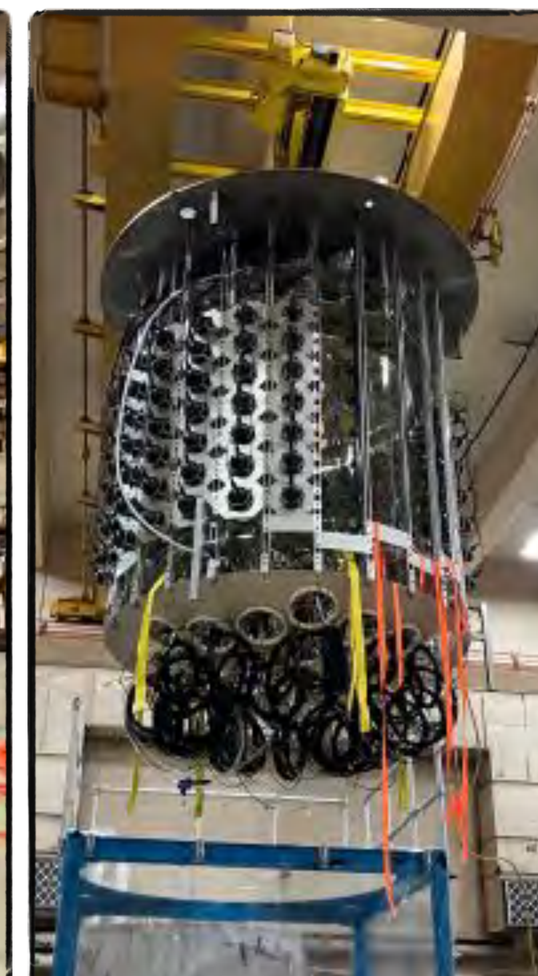
Shipping, June 1 ‘23

Construction



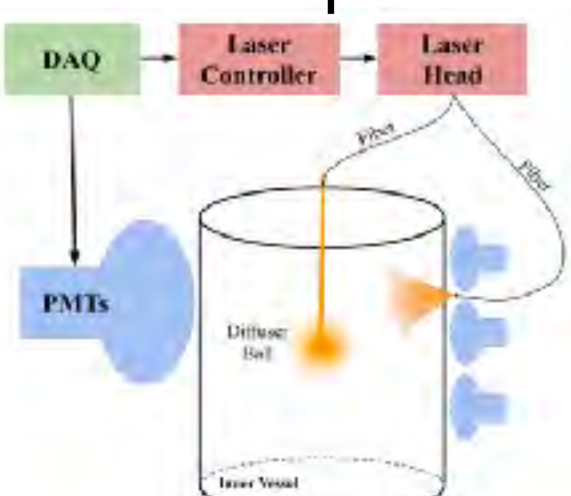


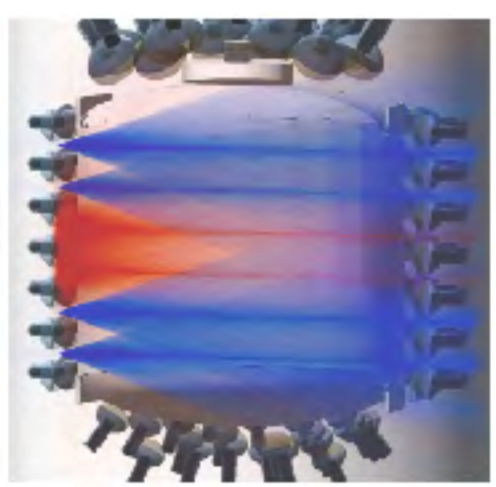


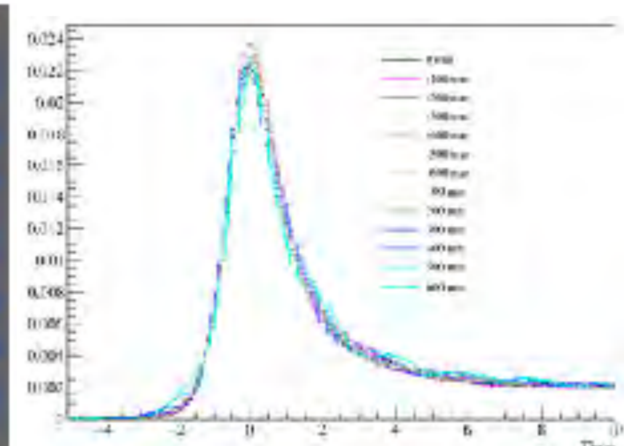


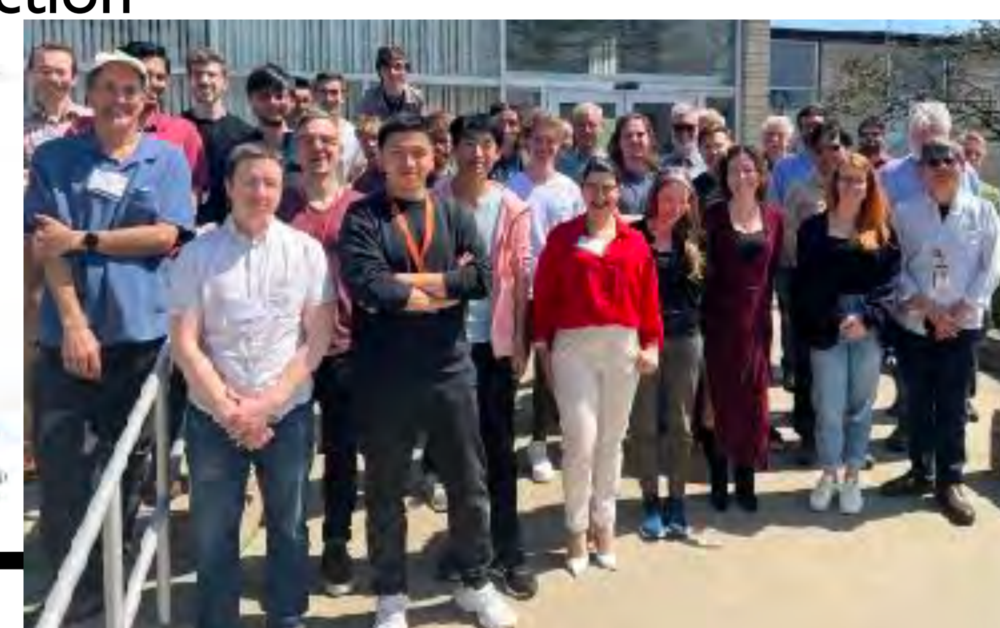
EOS status

- Detector performance currently being evaluated with water target
- Plan to inject first WbLS this summer
- Hope to fully explore WbLS phase space, and pure LS, in following years
- 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

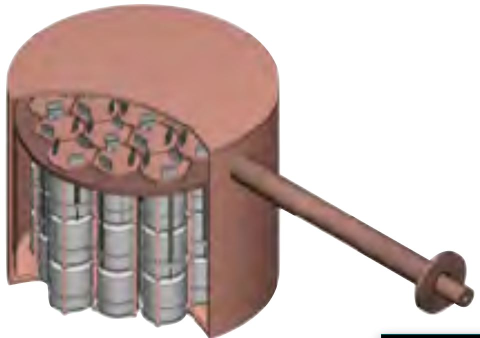


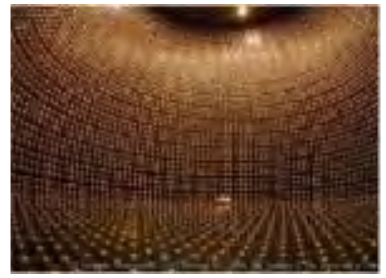
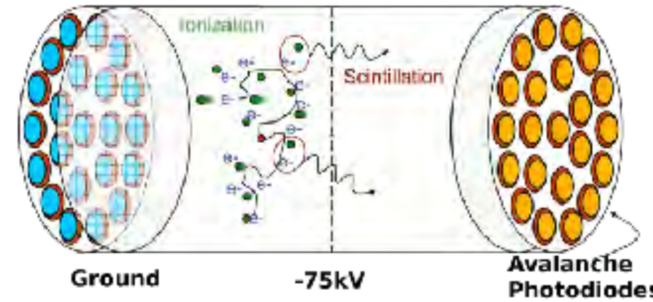


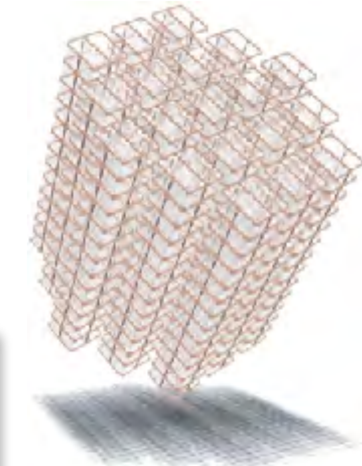


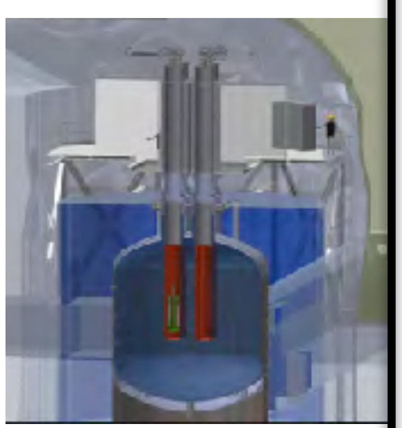


Summary



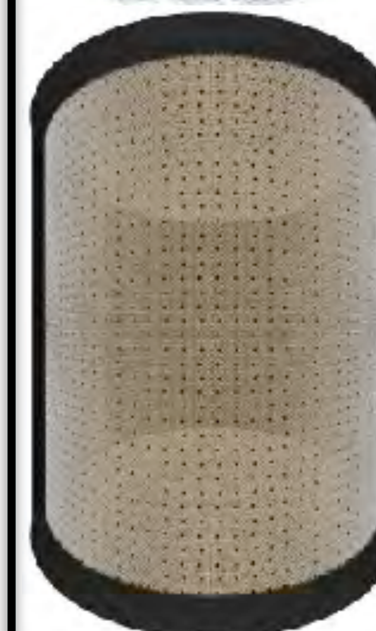
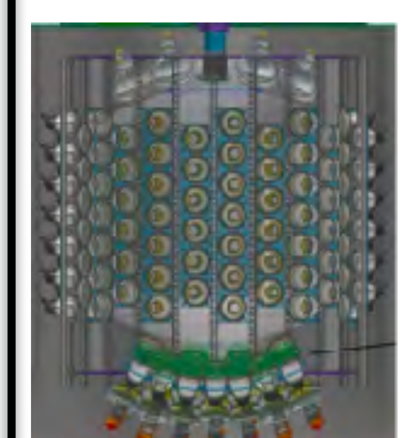


Exciting discovery potential in the next decade!

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

Leverage and strengthen synergies with other physics.
Supports impactful physics discoveries in solar ν, geo-ν and other areas in next-gen detectors

A future, robust neutrino program will be a broad program, bringing together expertise from different technologies and different energy regimes

Thank you for your attention

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