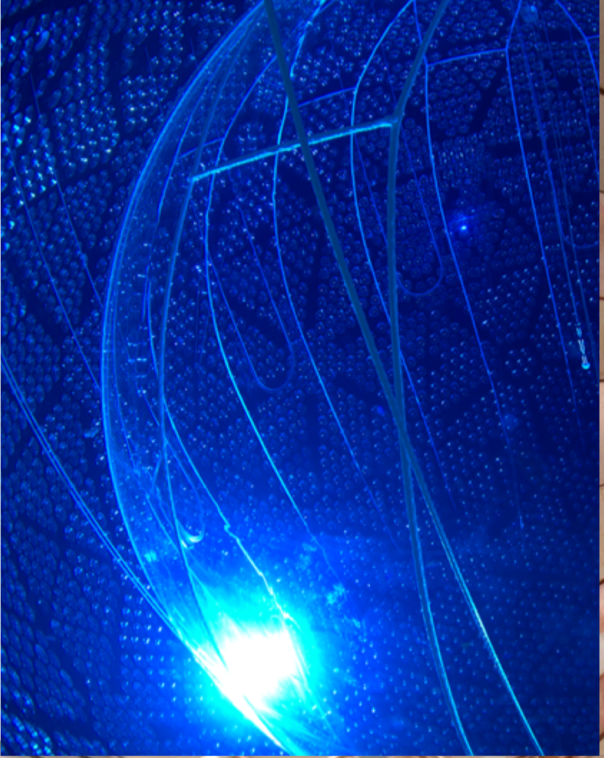
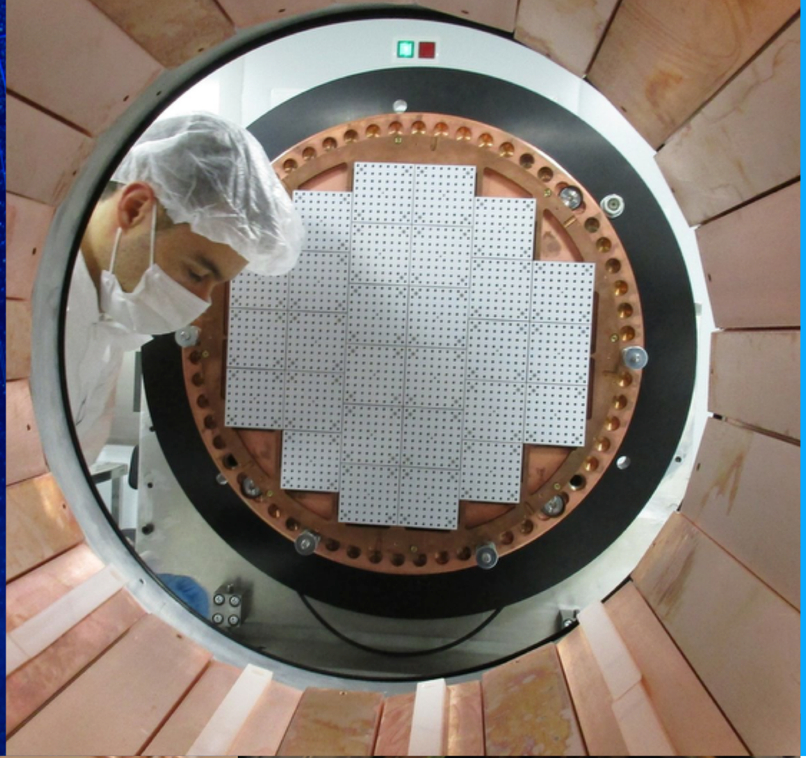
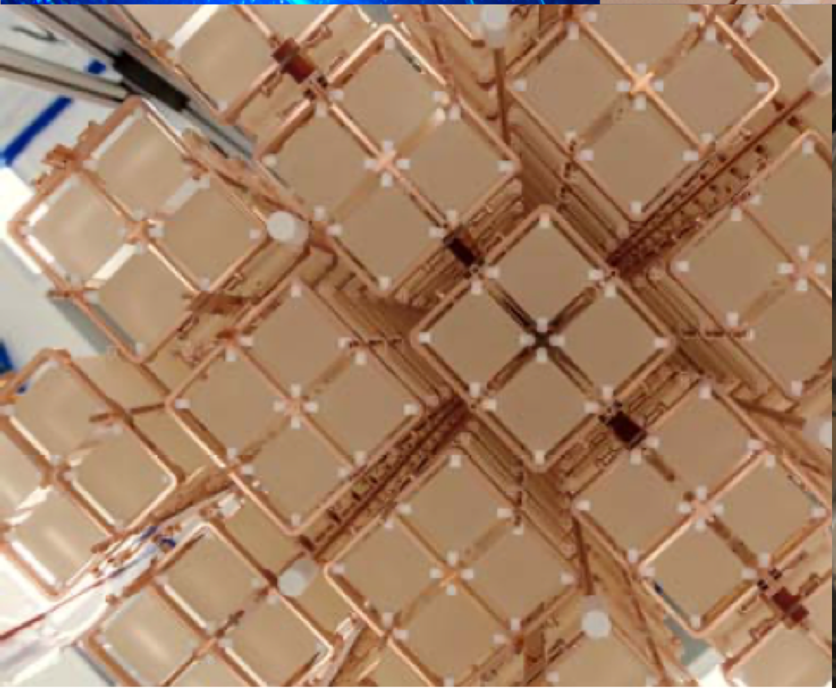
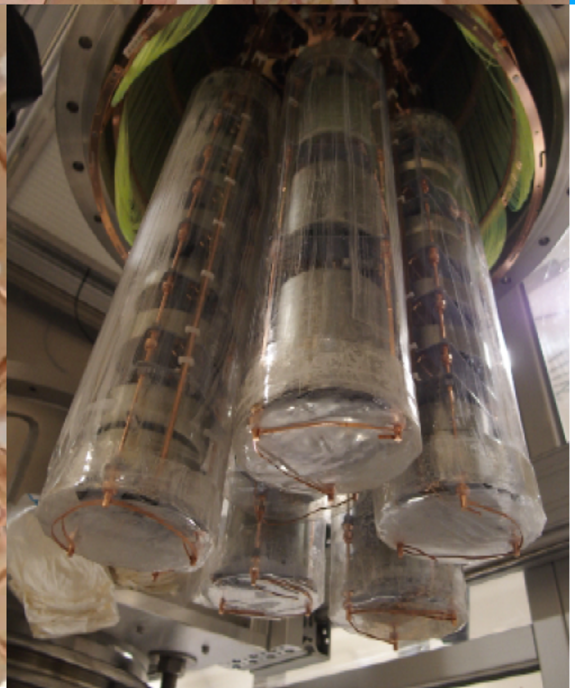



Neutrinoless Double-Beta Decay: To the Ton Scale and Beyond

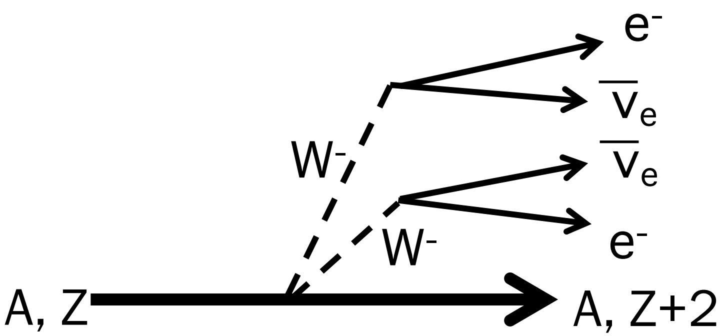
Julieta Gruszko
University of North Carolina at Chapel Hill
SNOWMASS NF Colloquium
April 27, 2022

Outline

- The nature of neutrinos
- Connections between $0\nu\beta\beta$ and other physics
- Current and next-generation experiments
- Going beyond the ton scale

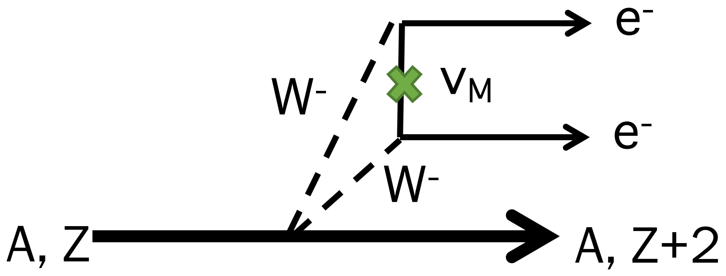
2νββ and 0νββ

2νββ



Majorana neutrinos

0νββ

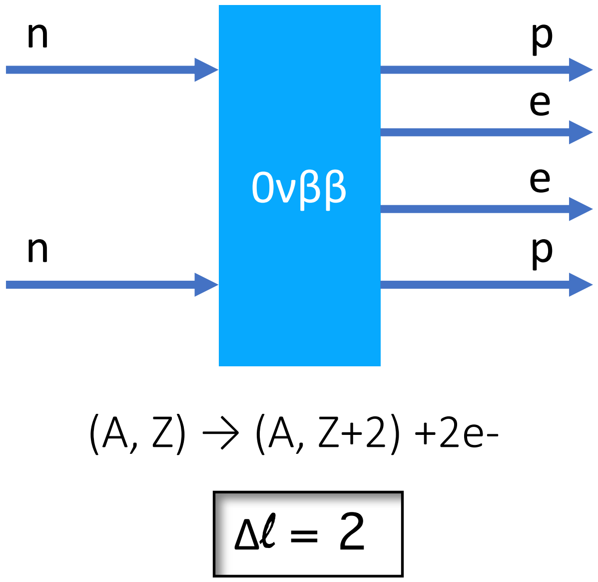


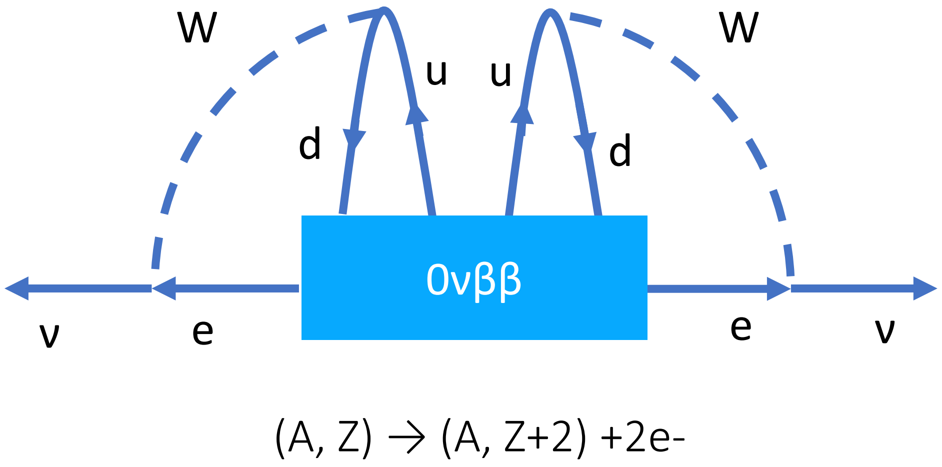
- Standard model process that occurs in some β-decay-blocked isotopes
- Second-order weak process

  $T_{1/2} \sim 10^{19}$ -10^{21} years
- Electron capture variant is longest-lifetime process we've ever observed

- If neutrinos are Majorana, 0νββ could occur
- In this case, I've drawn the exchange of a light neutrino, but other mechanisms are possible
- Would motivate non-zero neutrino mass

0νββ: A Portal to BSM Physics

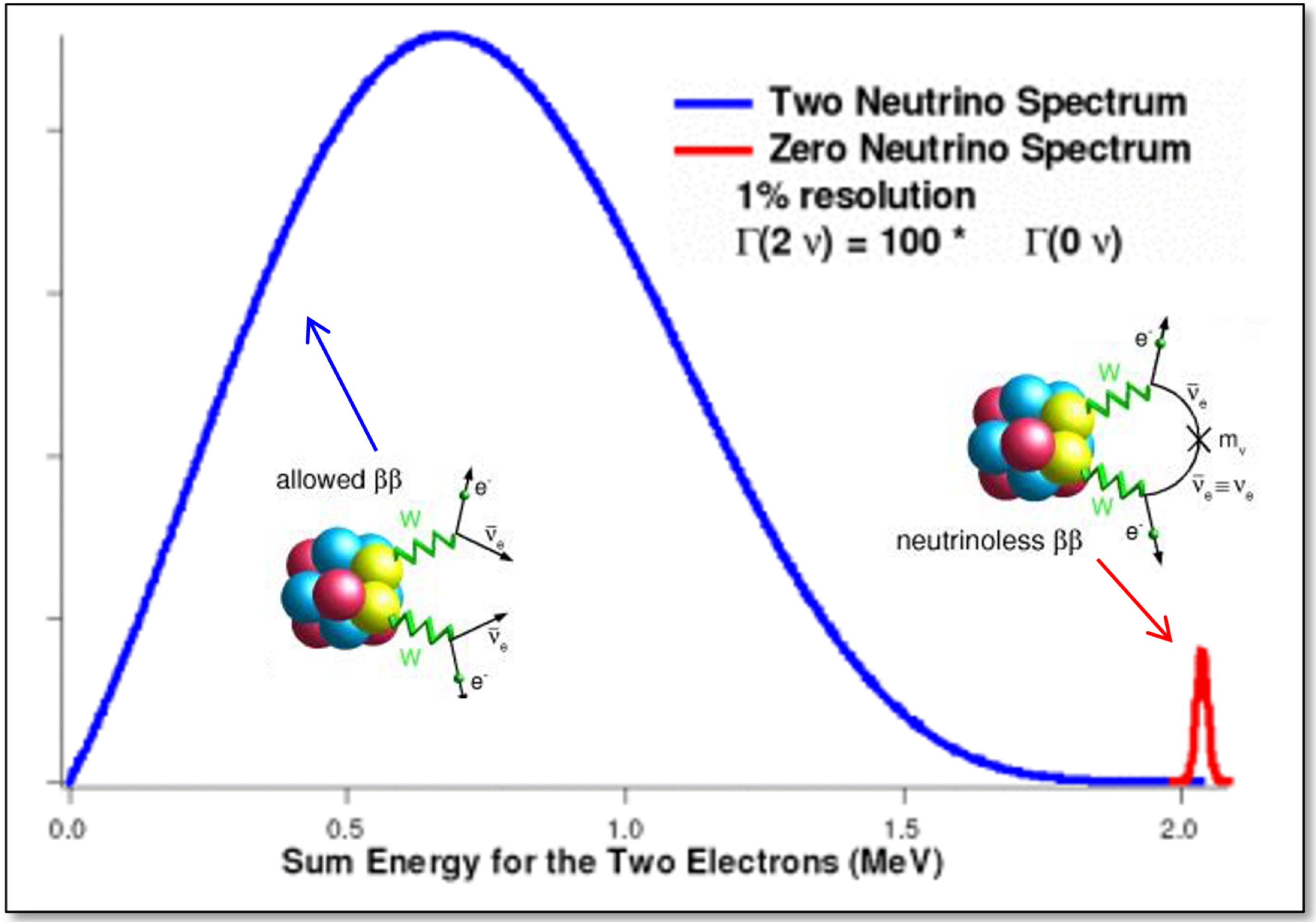




Model-independent implications of 0νββ:

- Lepton number violation, CP violation in the weak sector
- Neutrino-antineutrino oscillation, implying a non-zero Majorana mass term
- Leptogenesis could serve as a portal to early-universe baryogensis

Searching for 0νββ



Standard Model, 2νββ:

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

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

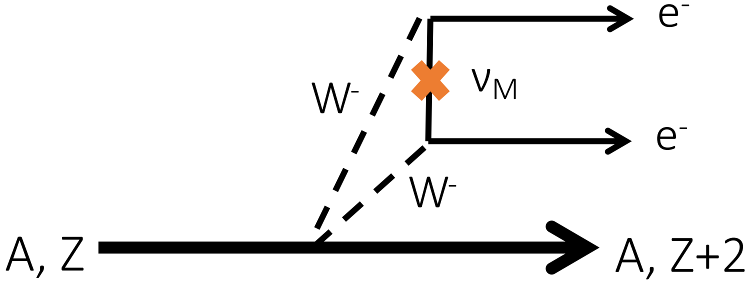
New Physics, 0νββ:

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

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

Due to phase space, $0\nu\beta^{-}\beta^{-}$ is far more studied and sets the tightest limits on lepton number violation

The 0νββ Rate for Light Majorana Neutrino Exchange



$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}|M_{0\nu}|^2 \left(\frac{\langle m_{\beta\beta}\rangle}{m_e}\right)^2$$

Effective Majorana mass for light neutrino exchange:

$$\langle m_{\beta\beta}\rangle = |\sum_{i=1}^{3} U_{ei}^2 m_i|$$

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix}$$

$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} e^{i\alpha 1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$, δ = Dirac CP violation, α_i = Majorana CP violation

Even under simple assumptions, the 0νββ rate depends on:

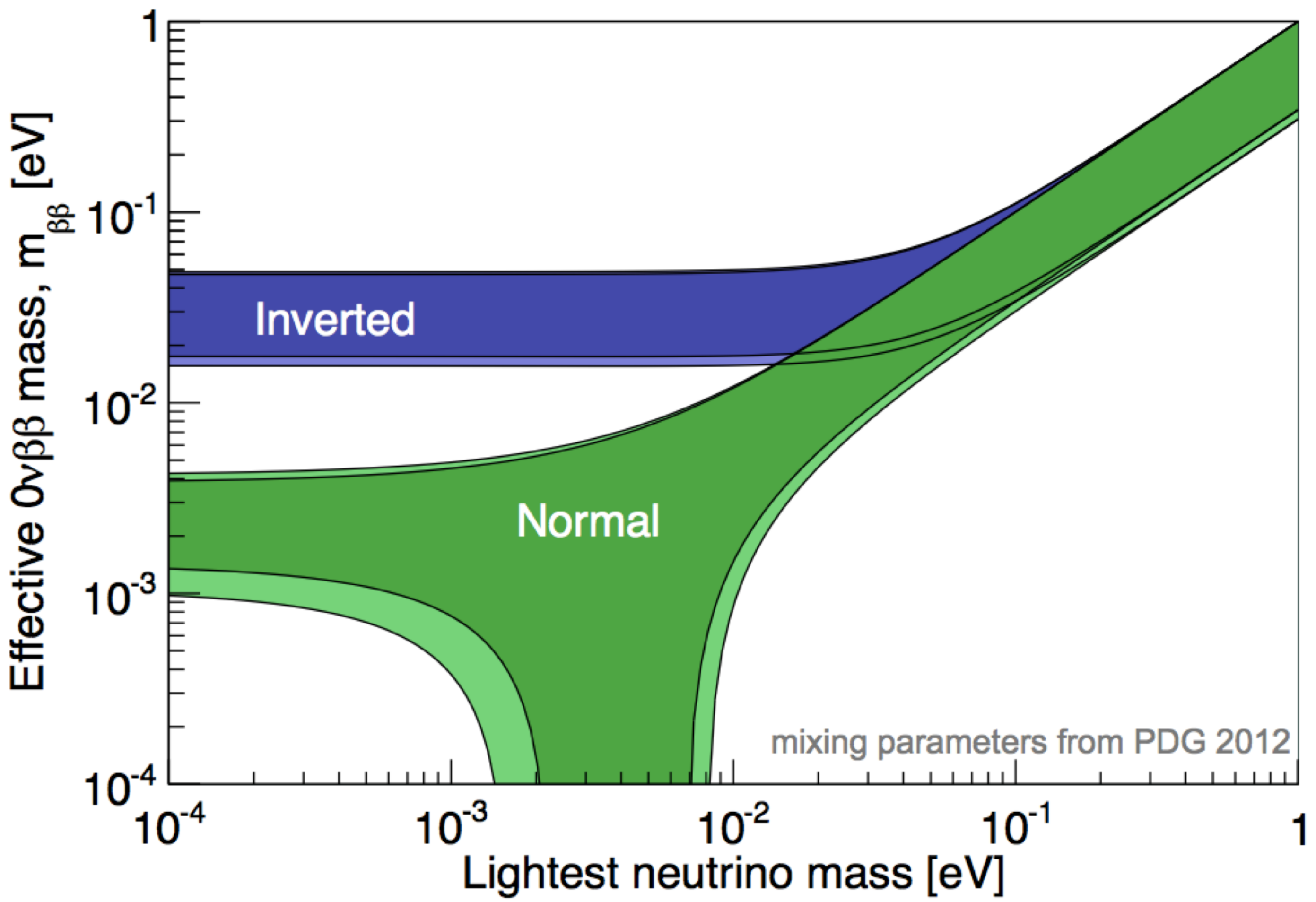
- ν mixing angles
- δ_{CP}
- ν masses
- mass hierarchy
- 2 totally unknown phases

Interpretation of Half-Life Sensitivity

$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu}|M_{0\nu}|^2 \left(\frac{\langle m_{\beta\beta}\rangle}{m_e}\right)^2$$

$$\langle m_{\beta\beta}\rangle = |\sum_{i=1}^{3} U_{ei}^2 m_i|$$

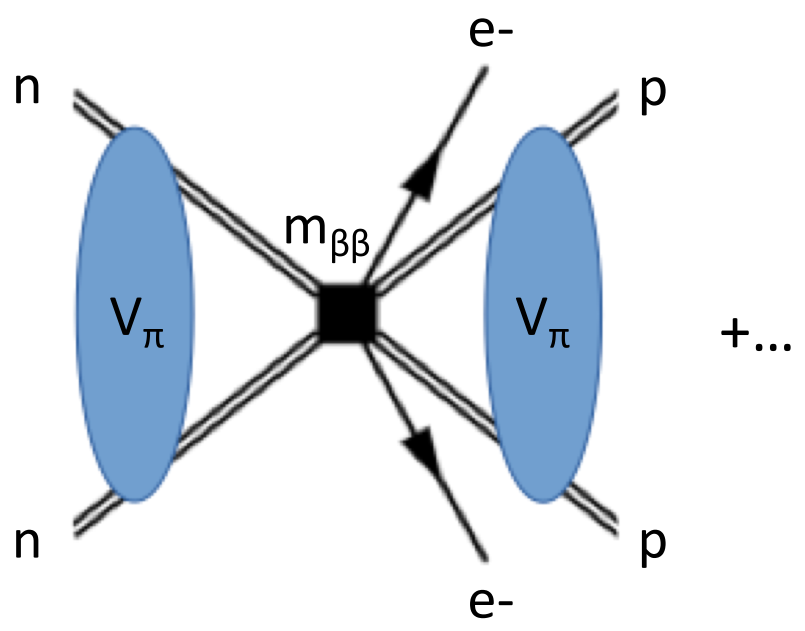
- Light Majorana neutrino exchange: assumes new physics is at GUT scale, 0νββ mediated by dim. 5 operator
- Used to compare and set goals for future experiments



0νββ Theory: Contact Term

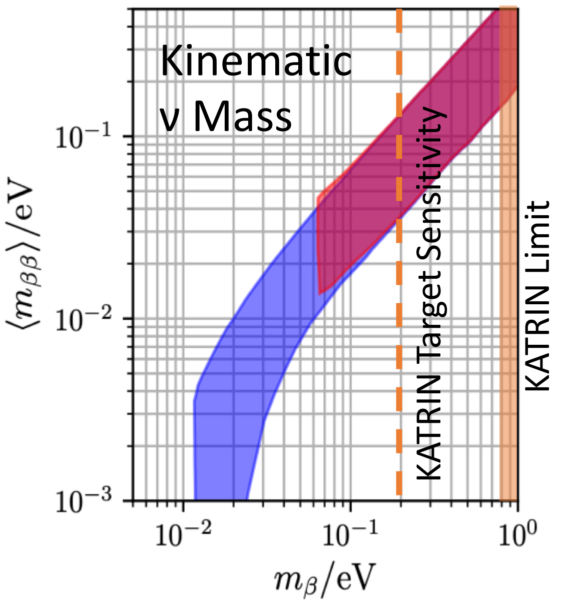
- Even in the simple "desert model" of light Majorana neutrino exchange, there are remaining theoretical uncertainties
- In the last few years, a missing leading order contact term was identified using EFT methods
- Initial calculations indicate an enhancement of the 0νββ rate
- Implementation for heavy isotopes is still underway

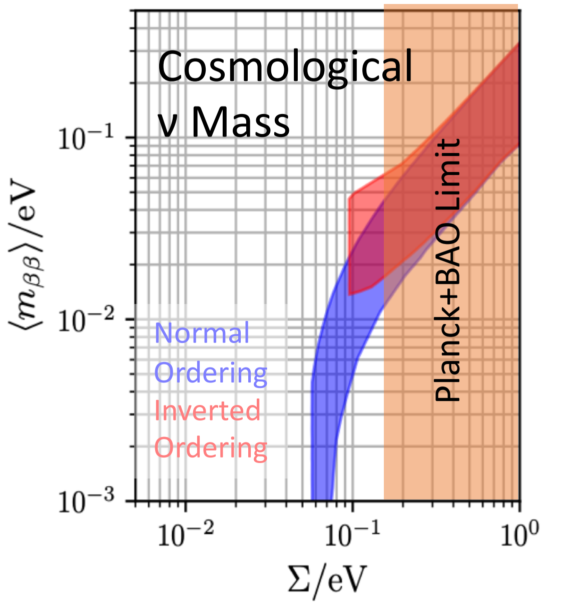
$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}\, g_A^4 \left(M_{0\nu} + \frac{g_\nu^{NN} m_\pi^2}{g_A^2} M_{0\nu}^{cont} \right)^2 m_{\beta\beta}^2$$



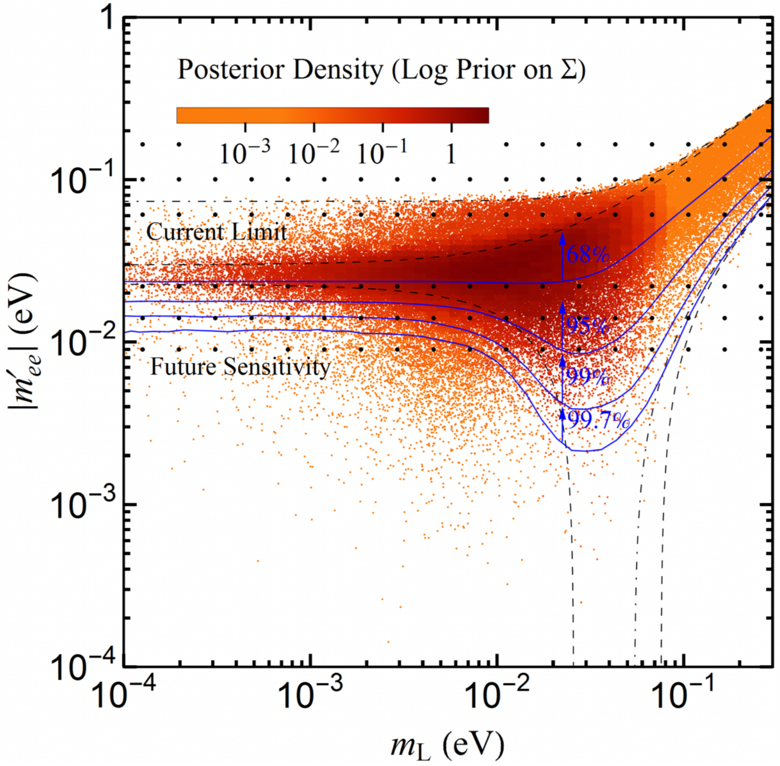
0νββ Rate and ν Physics

3 Neutrino Paradigm



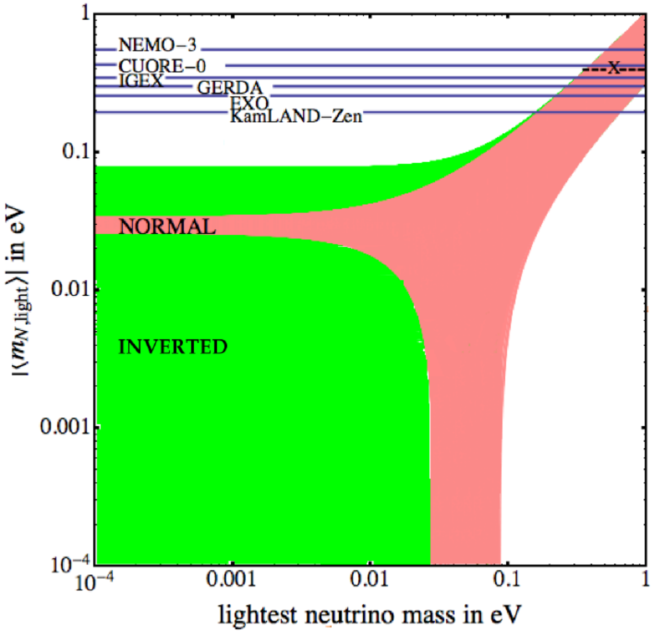


Light Sterile Neutrino Contribution



(3+1)ν mixing, flat prior on Σm
$\Delta m^2_{41} \equiv 1.7$ eV^2 and $\sin^2\theta = 0.019$
Nuc. Phys. B 945, 114691 (2019)

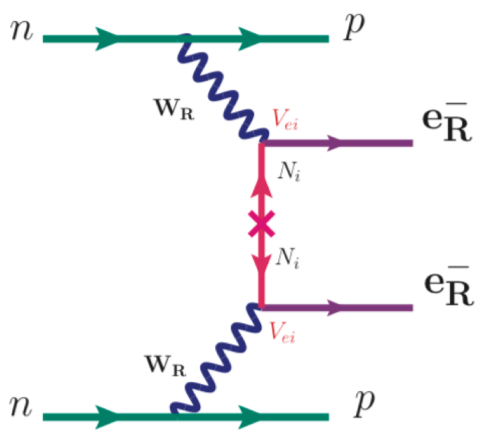
The addition of sterile neutrinos would modify the rate of 0νββ and can switch IO/NO allowed regions



(3+1)ν mixing
m_4 = 1 eV and $|U_{e4}|^2 = 0.03$
PRD 92, 093001 (2015)

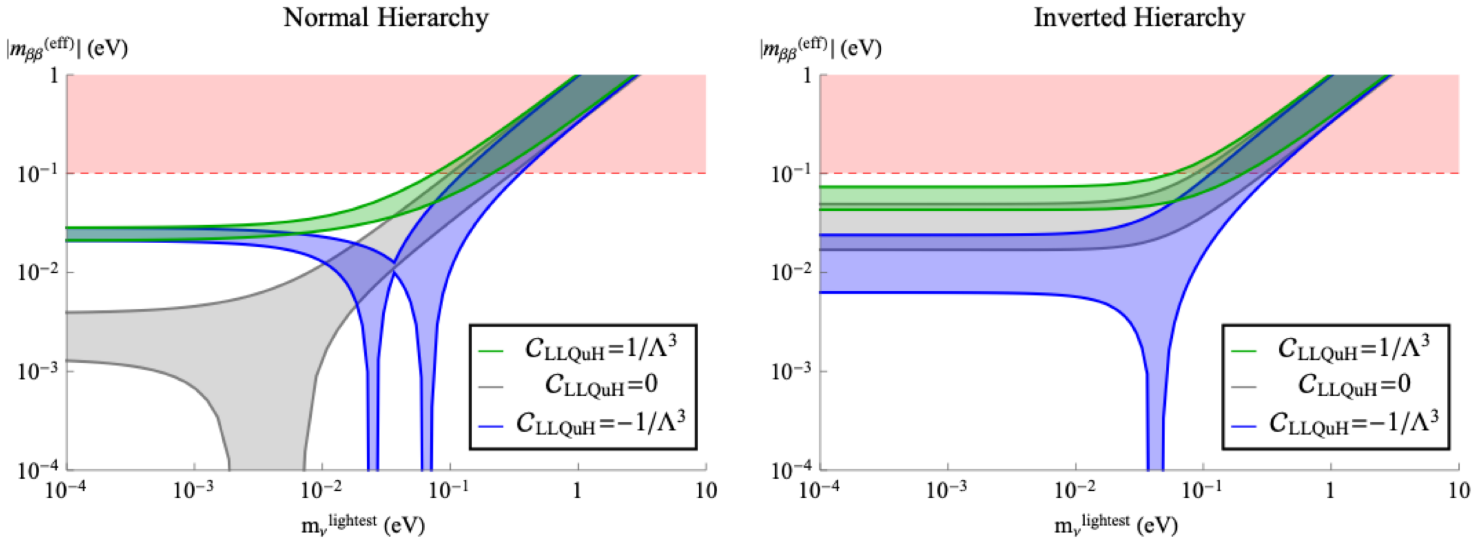
0νββ Rate and New Physics

- The situation changes significantly if new physics is at lower scales
- EFT methods are being used to describe the effects of generic operators, which can then be matched to specific particle physics scenarios

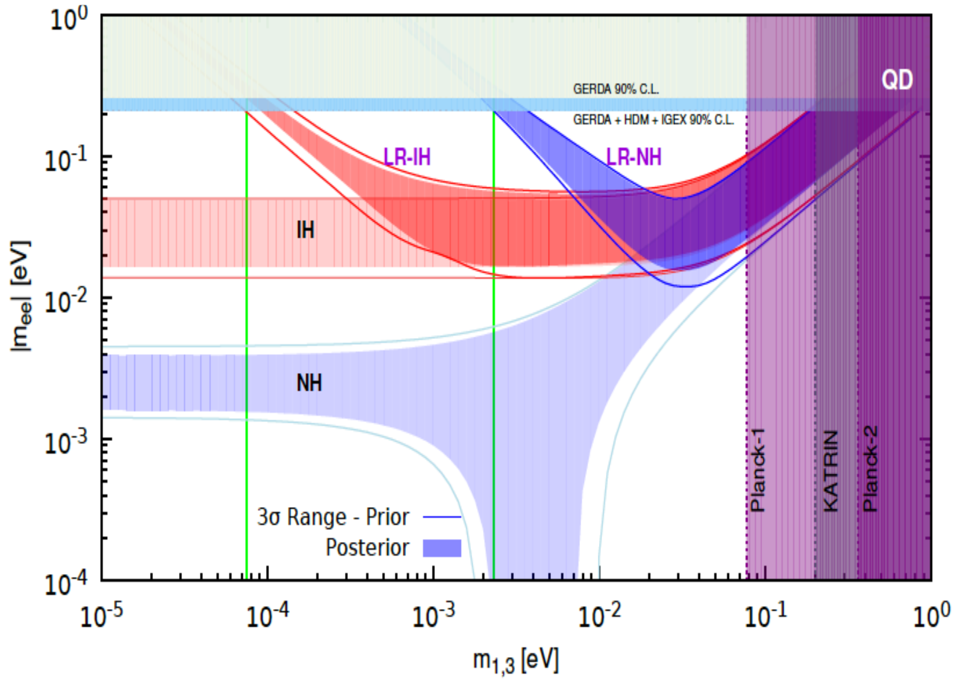


Left-Right Symmetric Model, $M_{W_R} \sim 2$ TeV, $M_N = 1$ TeV, $g_R \sim 2/3\ g_L$

JHEP 10 (2015) 077



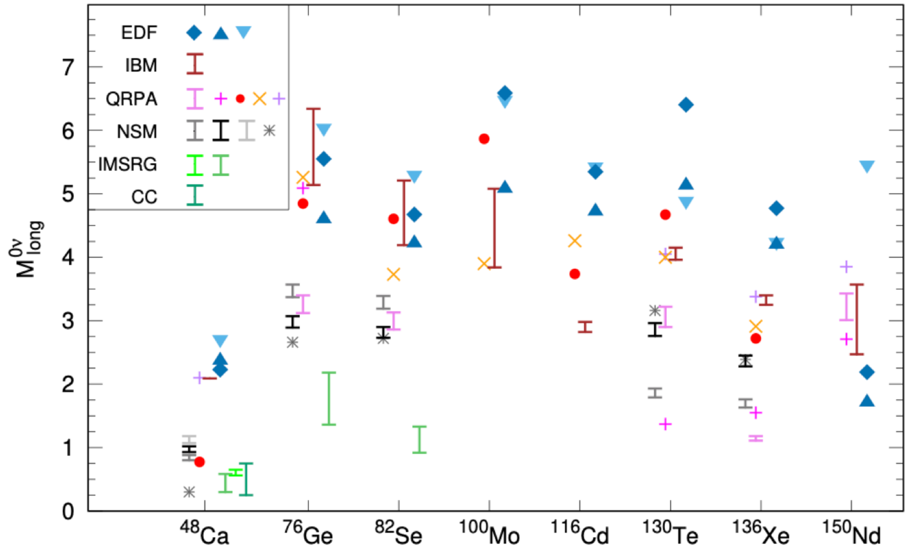
Role of additional dimension-7 operators, Λ = 600 TeV
JHEP 2017, 82 (2017)



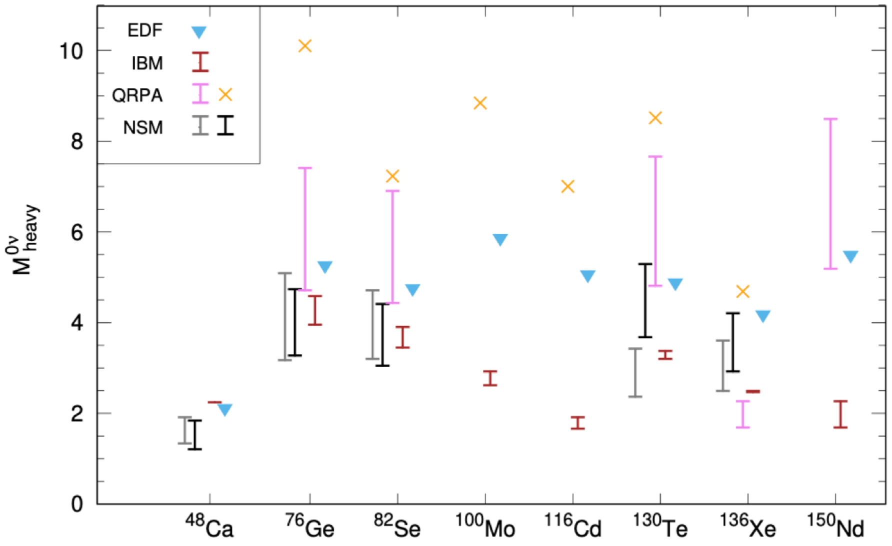
Nuclear Matrix Elements

- $0\nu\beta\beta$ mediated by higher-dimensional operators would have different dominant NMEs
- NME calculations differ by a factor of ~3, and full model uncertainties cannot be quantified
- Progress is underway on *ab initio* methods, which allow improved uncertainty determination
- In the case of $0\nu\beta\beta$ discovery, comparison between isotopes could provide insight into mechanism

Long-range light neutrino exchange

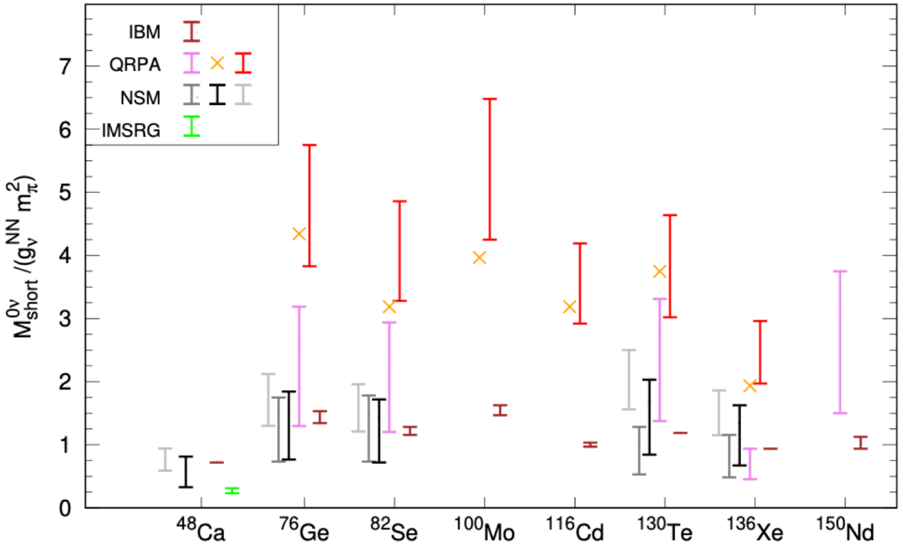


Heavy neutrino exchange



arXiv:2202.01787

Short-range light neutrino exchange



Interpreting $0\nu\beta\beta$

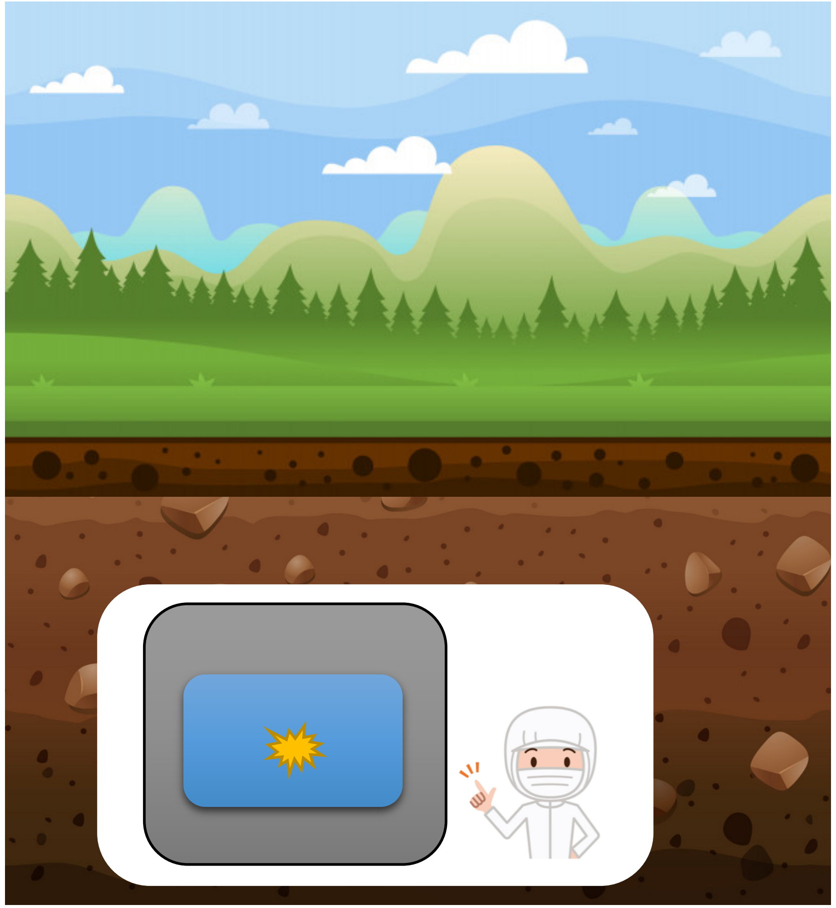
To make a convincing discovery of $0\nu\beta\beta$, we need to observe it in multiple experiments.

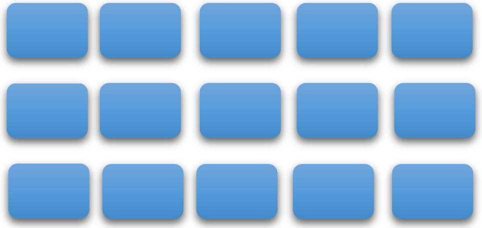
If $0\nu\beta\beta$ is seen, the qualitative conclusions are profound, but observations in several nuclei will be required to fully understand the underlying physics.

0νββ Experiments

Experimental Techniques

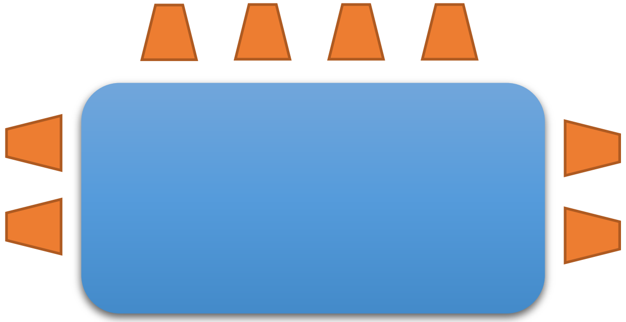
Most Experiments





Granular Detectors

- Bolometers and semiconductors
- E.g. CUPID, LEGEND

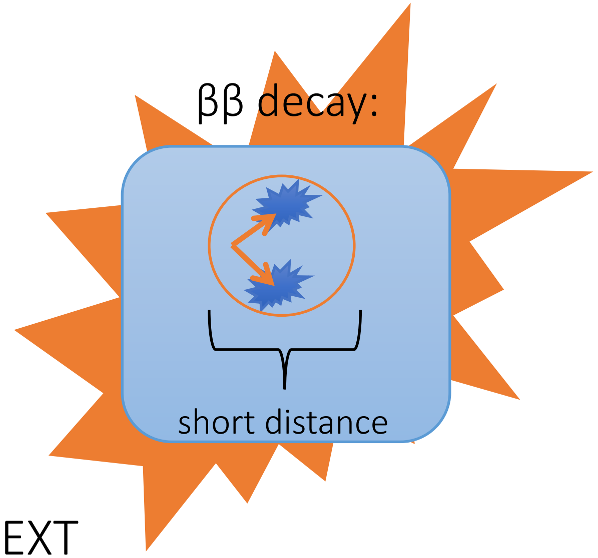


Monolithic Detectors

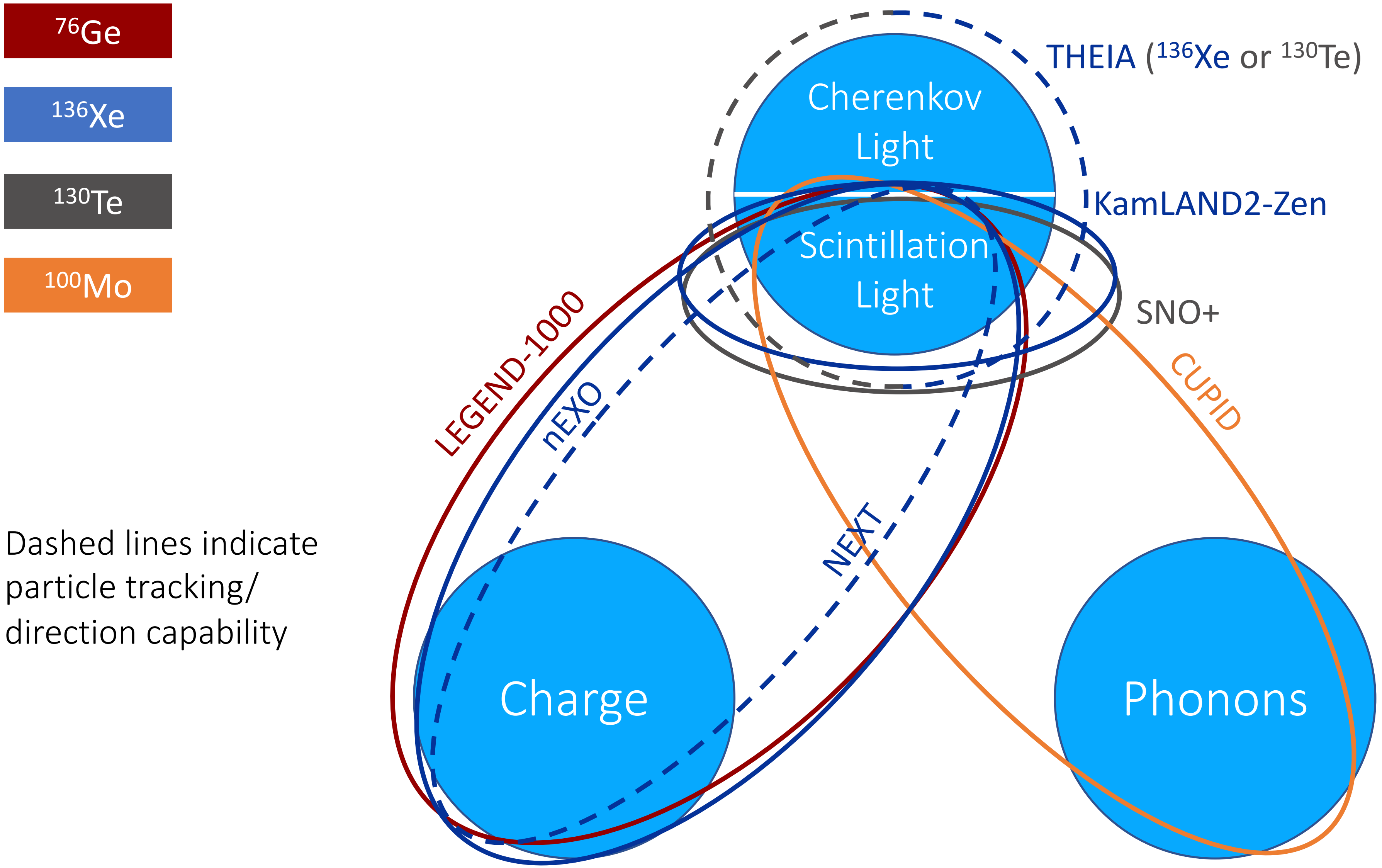
- Scintillators and TPCs
- E.g. KamLAND-Zen, SNO+, THEIA, nEXO, NEXT

Experiments also rely on additional background-rejection techniques:

- Event topology
- Particle discrimination
- Fiducialization/vertex reconstruction



Experimental Techniques: Ton Scale and Beyond

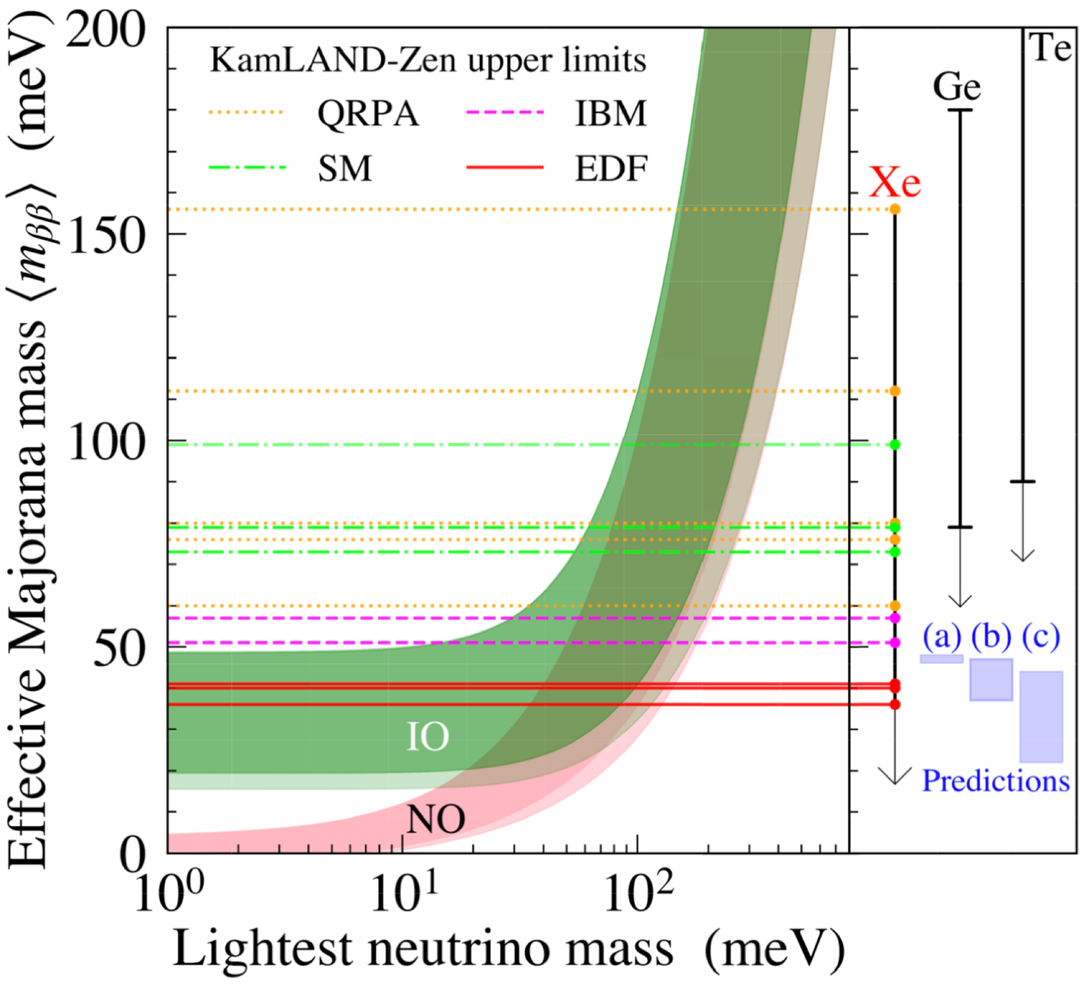


Dashed lines indicate particle tracking/ direction capability

+ plans for daughter isotope tagging

Interpretation of Half-Life Sensitivity

Current Best Limits on 0νββ

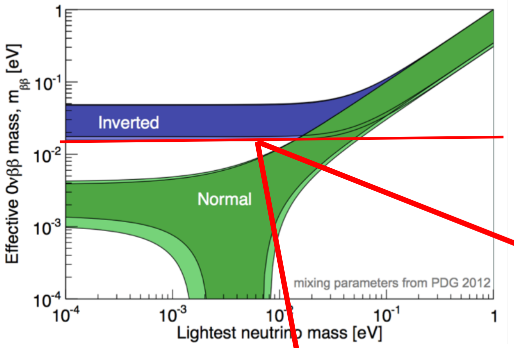


arXiv: 2203.02139

Experiment	Isotope	Exposure [kg yr]	$T^{0\nu}_{1/2}$ [10^{25} yr]	$m_{\beta\beta}$ [meV]
Gerda	^{76}Ge	127.2	18	79-180
Majorana	^{76}Ge	26	2.7	200-433
KamLAND-Zen	^{136}Xe	970	23	36-156
EXO-200	^{136}Xe	234.1	3.5	93-286
CUORE	^{130}Te	1038.4	2.2	90-305

NSAC recommendation: quote a range of $m_{\beta\beta}$ using the largest and smallest available NME from the 4 main calculation methods; g_A=1.27; no contribution from the contact term

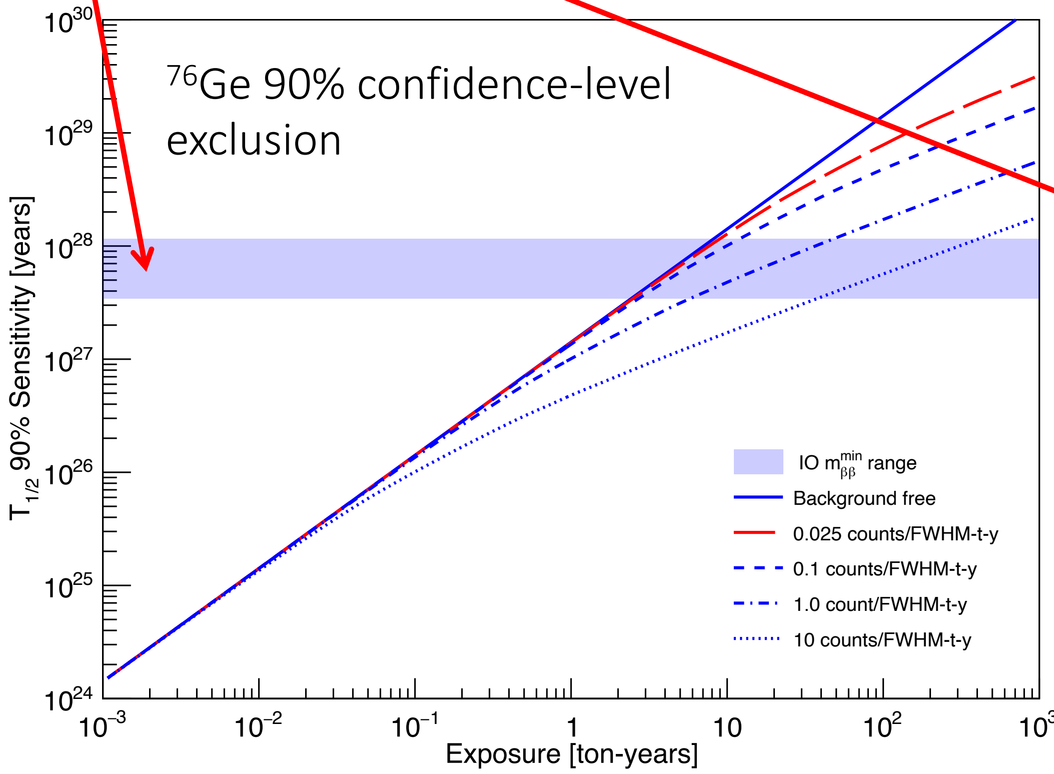
Discovery, Background, and Exposure

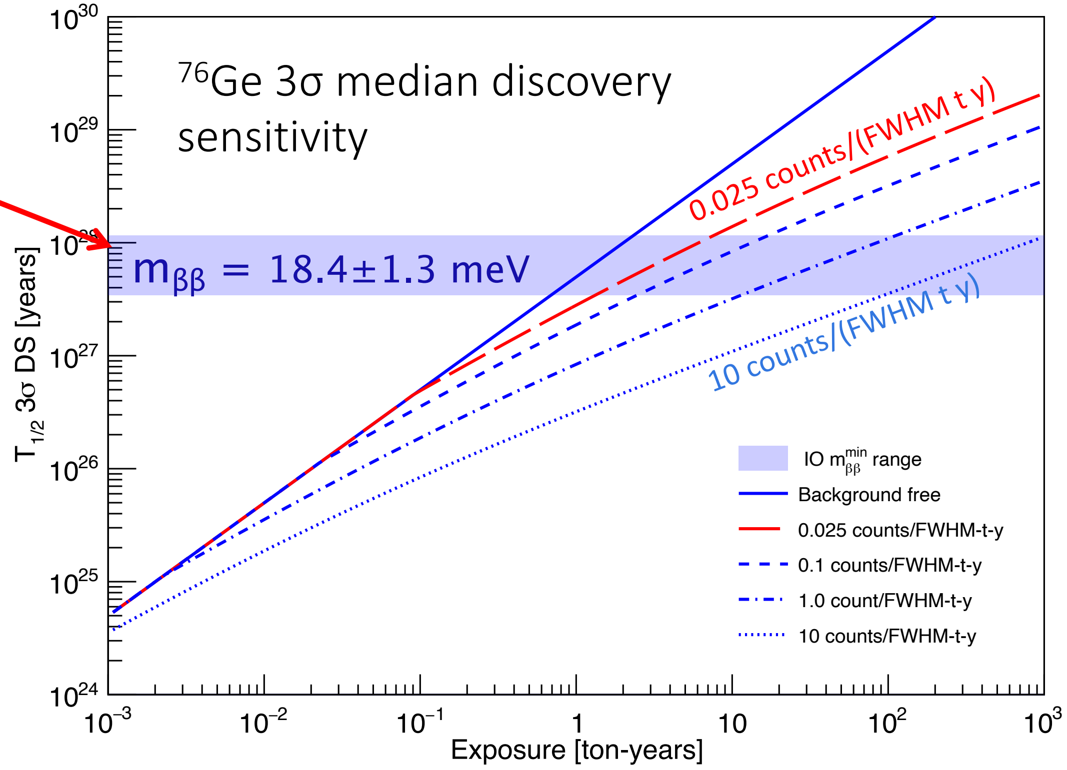


Setting a Limit

Discovery at 3σ

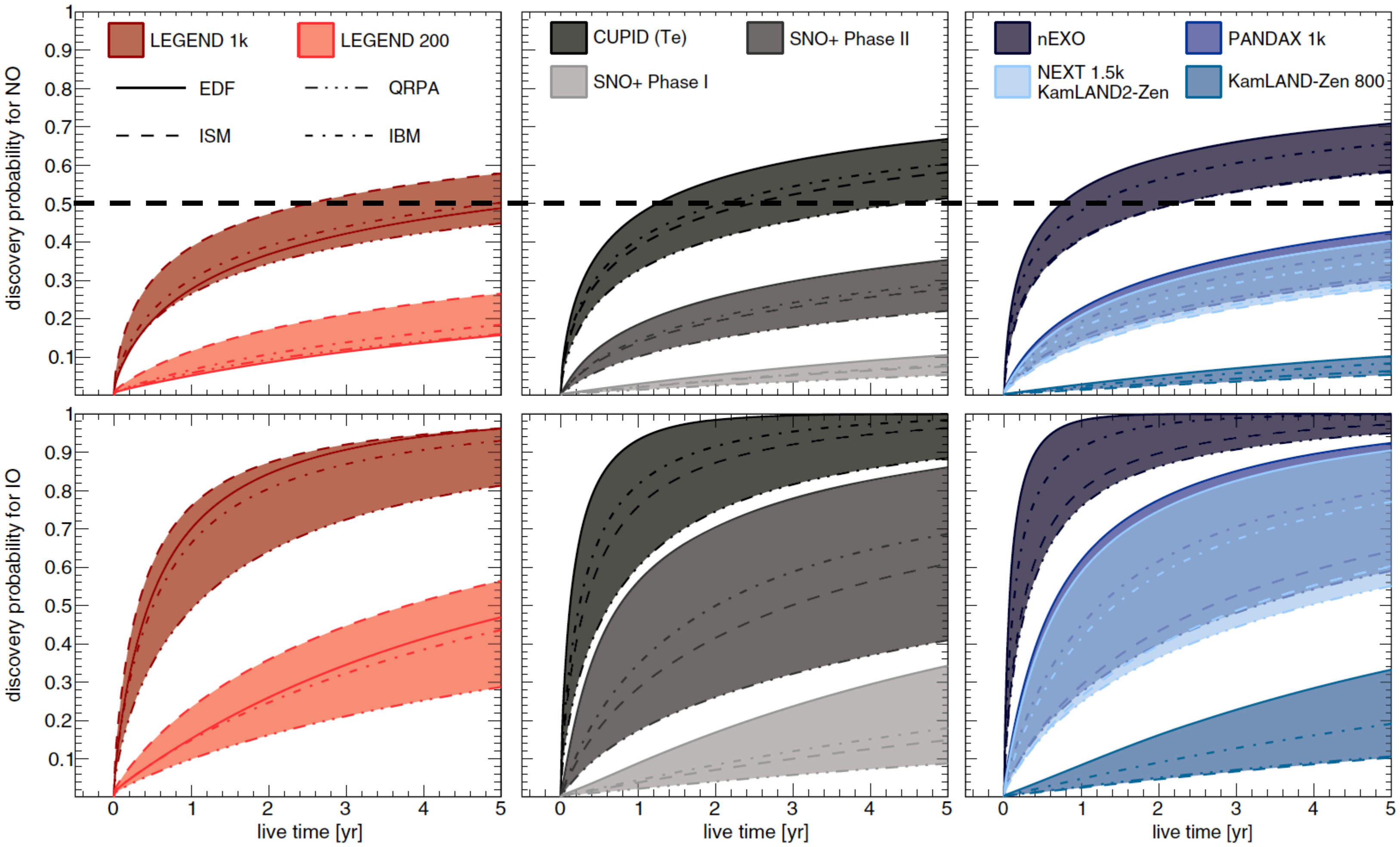
Discovery goal places additional demands on background levels





Discovering 0νββ at the Ton Scale

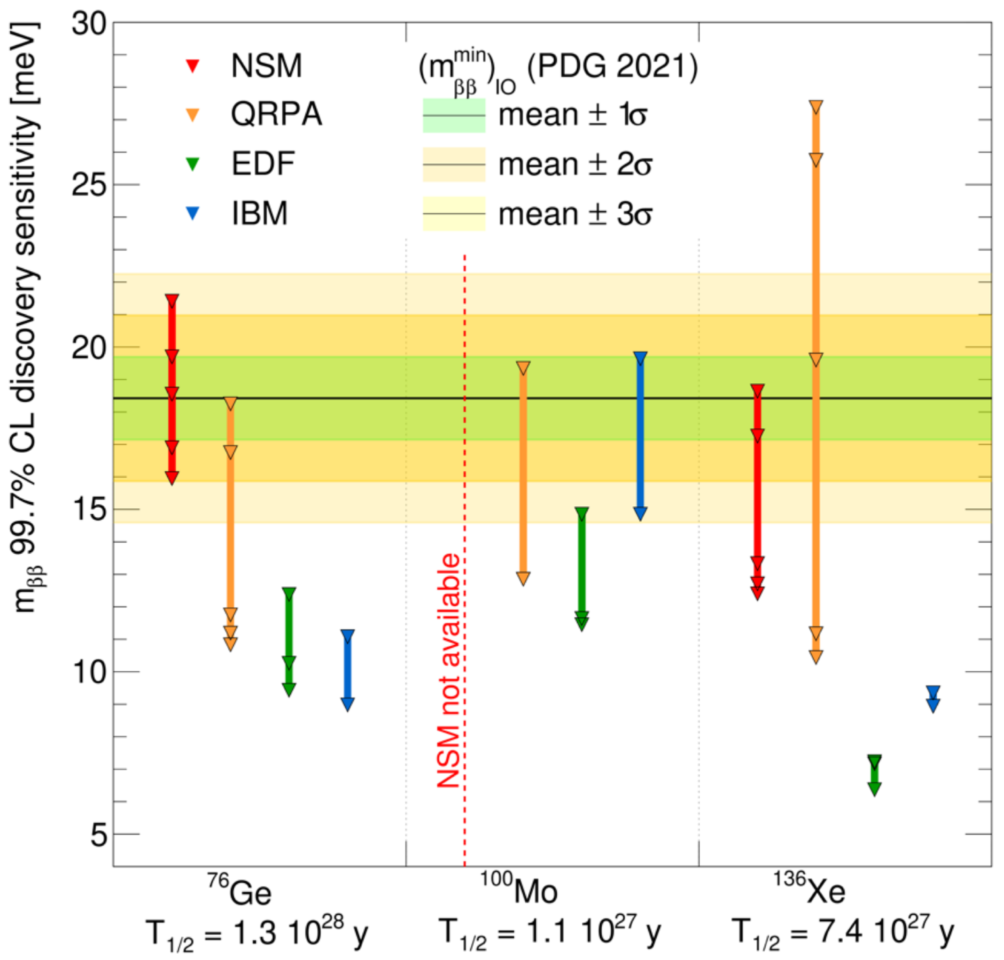
- The goal of ton-scale experiments is discovery
- The good news: next-generation experiments have a significant chance of discovering 0νββ regardless of the neutrino mass ordering!



Example analysis from *PRD 96, 053001 (2017)*
Projected experimental sensitivities have been updated since publication

Ton-Scale Status

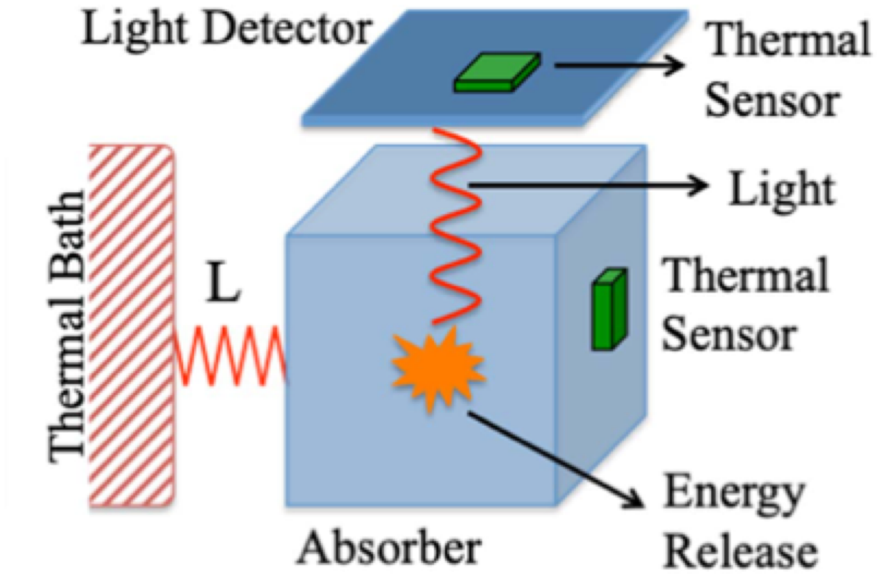
- Ton-scale goal: 3σ discovery for $m_{\beta\beta} \geq 18$ meV under all available matrix element calculations
- This is the value needed to cover the inverted ordering region
- Summer 2021: DOE Portfolio Review of 3 ton-scale projects (LEGEND-1000, nEXO, and CUPID)
- DOE-NP is seeking international support to move forward with all projects
- pre-Conceptual Designs available for LEGEND-1000, nEXO, CUPID, and NEXT



PRC 104 L042501 (2021)

CUPID

- Tonne-scale bolometer approach demonstrated in CUORE
- Scintillating bolometer technique demonstrated in CUPID-Mo and other experiments, allows for α rejection
- Switch from CUORE crystals to scintillating bolometers with light readout in existing infrastructure



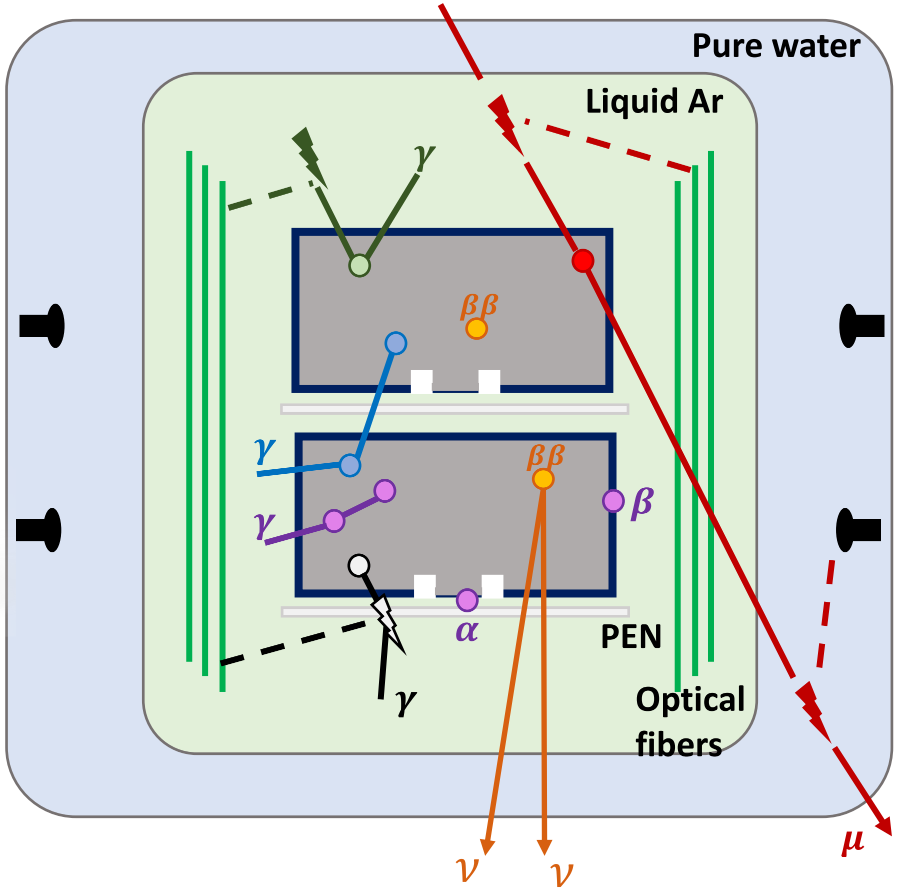
- Crystal: $Li_2{}^{100}MoO_4$
- Enrichment > 95% → 253 kg of ^{100}Mo
- Energy res. (FWHM): 5 keV
- BI < 10^{-4} cnts/(keV kg yr)
- Discovery sensitivity: $T_{1/2} \sim 1.1{\times}10^{27}$yrs
- $m_{\beta\beta}$ discovery sensitivity: 12-20 meV

Material provided by CUORE, CUPID, CUPID-Mo, and CUPID-0 Collaborations

LEGEND

- Builds on techniques from MJD, GERDA, and LEGEND-200
- New cryostat at SNOLAB or LNGS
- HPGe point-contact detectors in LAr active shield:
  - Multi-site and surface event rejection
  - Excellent energy resolution (~0.1% FWHM)

- 1000 kg of ^{76}Ge
- Energy res. (FWHM): 2.5 keV
- BI < 10^{-5} cnts/(keV kg yr)
- Discovery sensitivity: $T_{1/2} \sim 1.3{\times}10^{28}$yrs
- $m_{\beta\beta}$ discovery sensitivity: 9-21 meV



Pulse shape discrimination (PSD) for multi-site and surface α events

Ge detector anti-coincidence

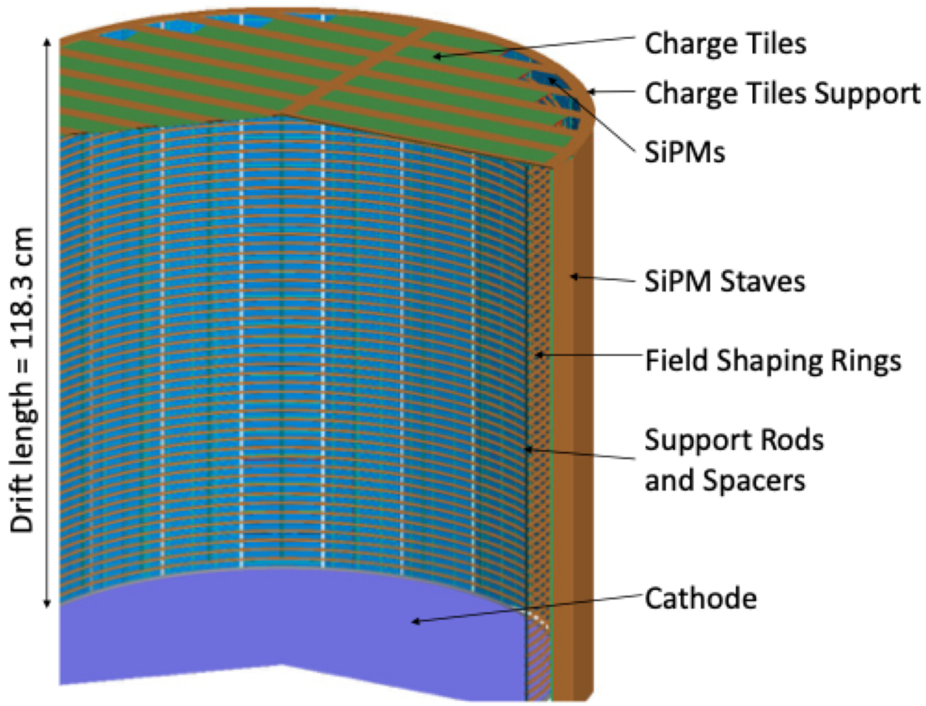
Scintillating PEN structural materials

LAr veto based on Ar scintillation light read by fibers and PMT

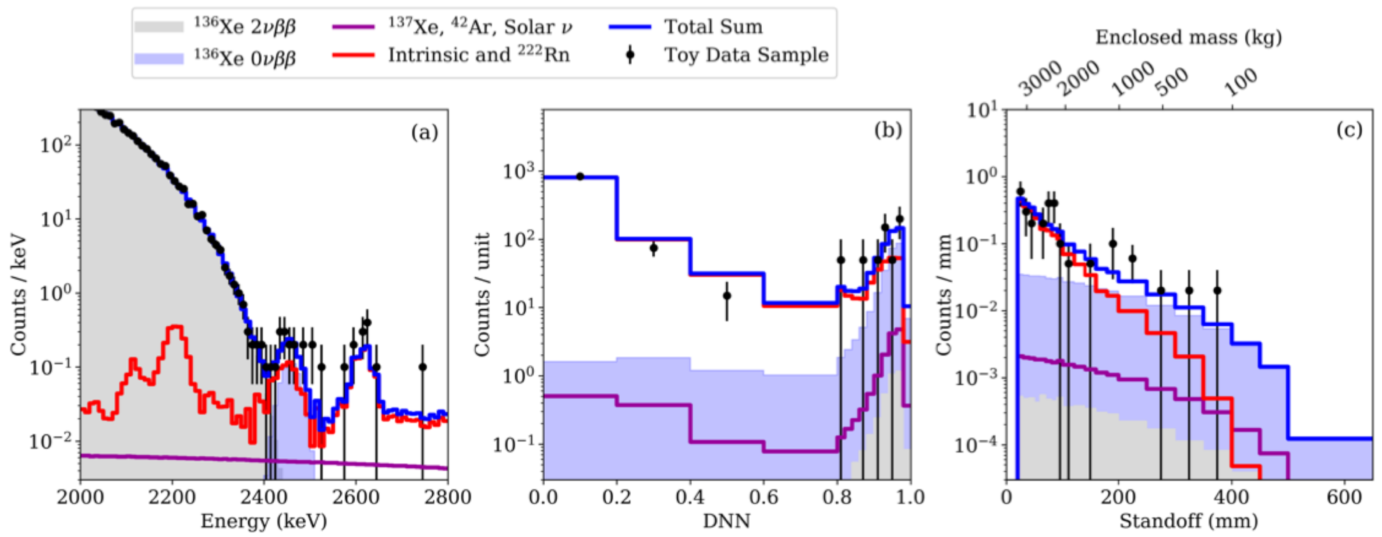
Muon veto based on Cherenkov light and/or plastic scintillator

$\beta\beta$ decay signal: single energy deposition in a 1 mm^3 volume

nEXO



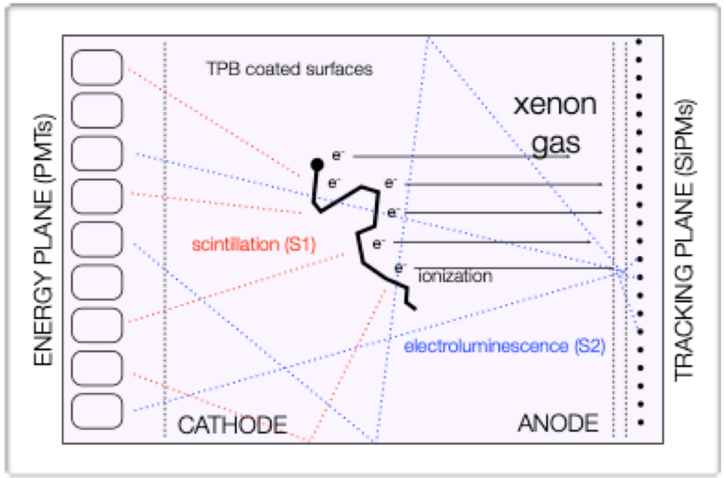
- Large single-phase LXe TPC, building on EXO-200 experience
- Take advantage of self-shielding, vertex reconstruction, and event topology information to reduce backgrounds

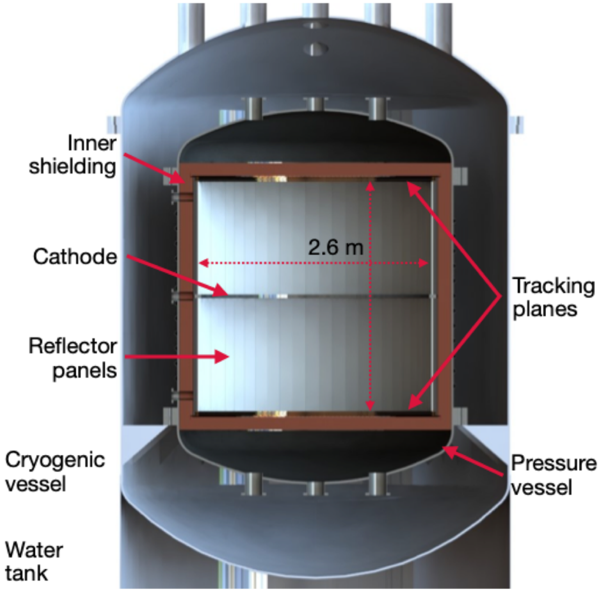


J. Phys. G: Nucl. Part. Phys. 49, 015104 (2022)

- 5000 kg of ^{enr}Xe
- Enriched to 90% ^{136}Xe
- Energy res. (σ_E/E): 0.8%
- Discovery sensitivity: $T_{1/2} \sim 7.4\times10^{27}$yrs
- $m_{\beta\beta}$ discovery sensitivity: 5-27 meV

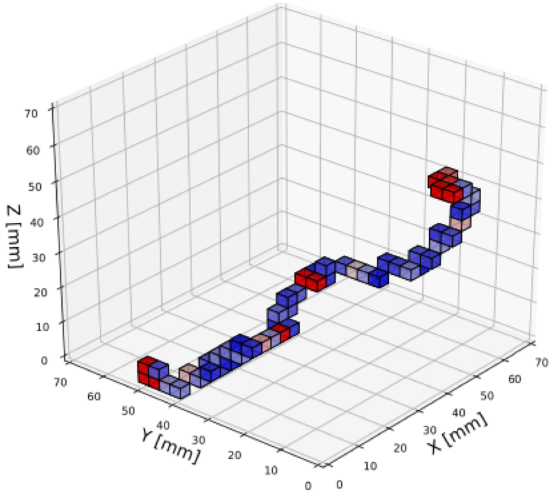
NEXT



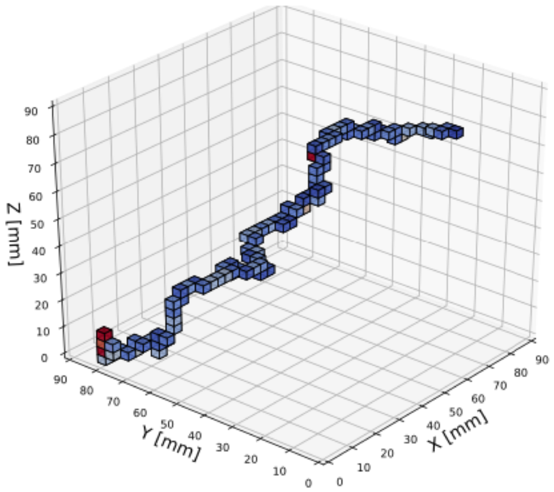


High-pressure gas Xenon time projection chamber:

- Energy resolution is intrinsically better in gas
- Event topology tracking information, fiducialization, and particle ID



ββ Signal



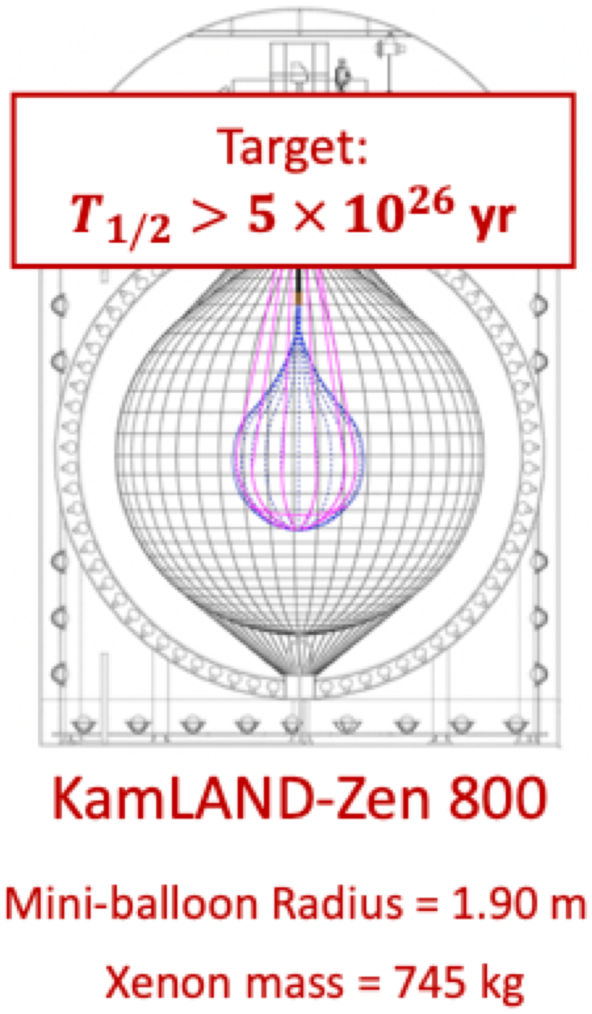
e- Track Background

- 1230 kg of ^{enr}Xe
- 1109 kg of ^{136}Xe
- Energy res. (FWHM/E): 0.5%
- BI < 4×10^{-6} cnts/(keV kg yr)
- Discovery sensitivity: $T_{1/2} \sim 2.7{\times}10^{27}$yrs
- $m_{\beta\beta}$ discovery sensitivity: 8-45 meV

arXiv:2005.06467

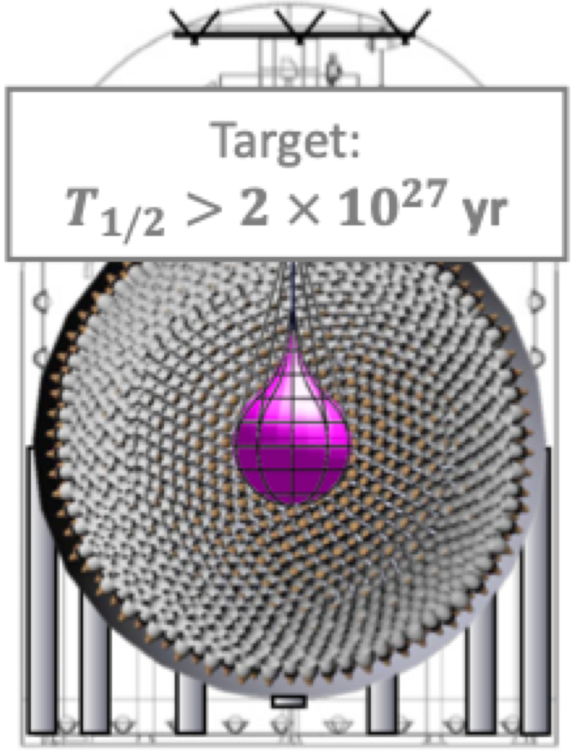
KamLAND-Zen

KamLAND-Zen 800



90% exclusion sensitivity

KamLAND2-Zen



- 1 ton of ^{enr}Xe
- New LAB-based scintillator
- Winston cones and HQE PMTs
- Scintillating balloon film
- Improved front-end electronics

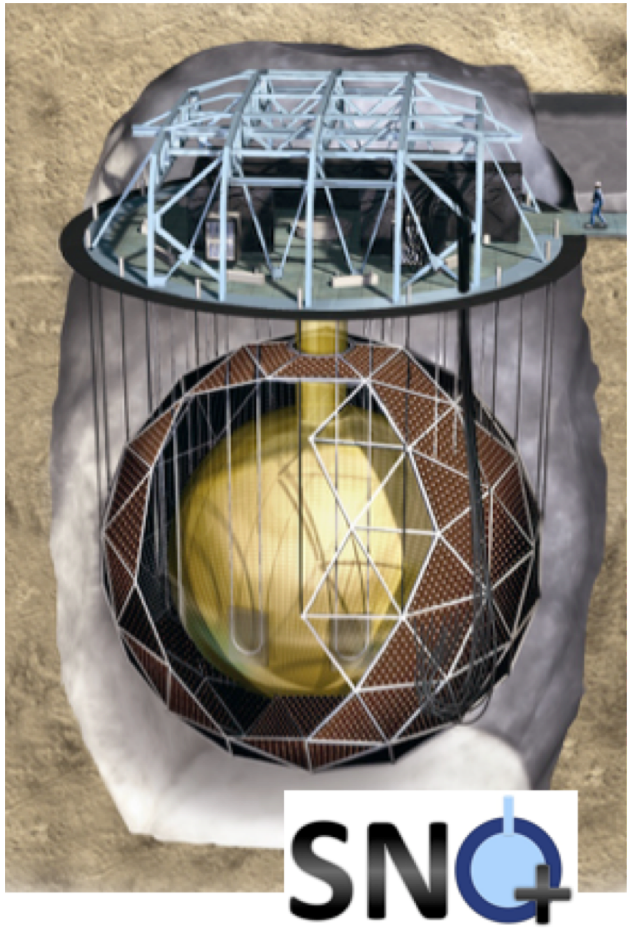
Liquid Scintillators:

- Self-shielding, fiducialization
- Interior materials can be made extremely pure
- Event topology and particle ID, with additional future improvements expected
- Measurement with and without isotope is possible

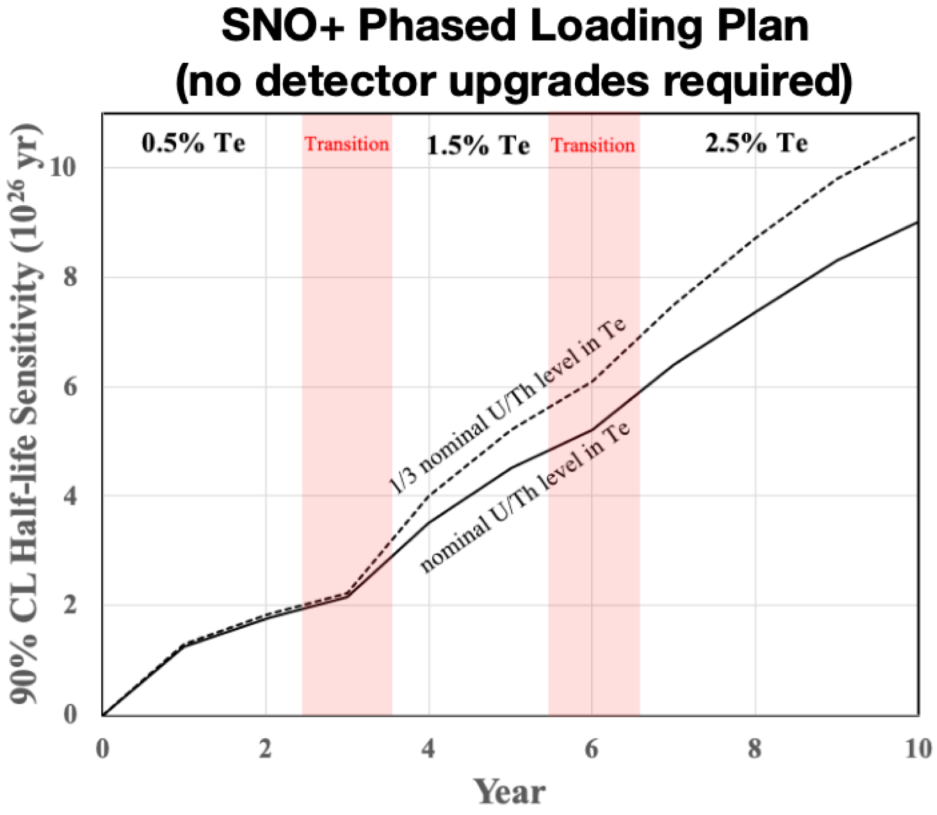
KamLAND-Zen:

- ^{136}Xe concentrated in inner balloon
- 3.13% enriched Xenon by weight
- Relatively shallow site, spallation backgrounds dominate

SNO+



Initial loading: 0.5% natural Te by weight



Planning to move to 3% ^{nat}Te loading for future data-taking

Extends exclusion sensitivity to > ~10^{27} yrs

Liquid Scintillators:

- Self-shielding, fiducialization
- Interior materials can be made extremely pure
- Event topology and particle ID, with additional future improvements expected
- Measurement with and without isotope is possible

SNO+:

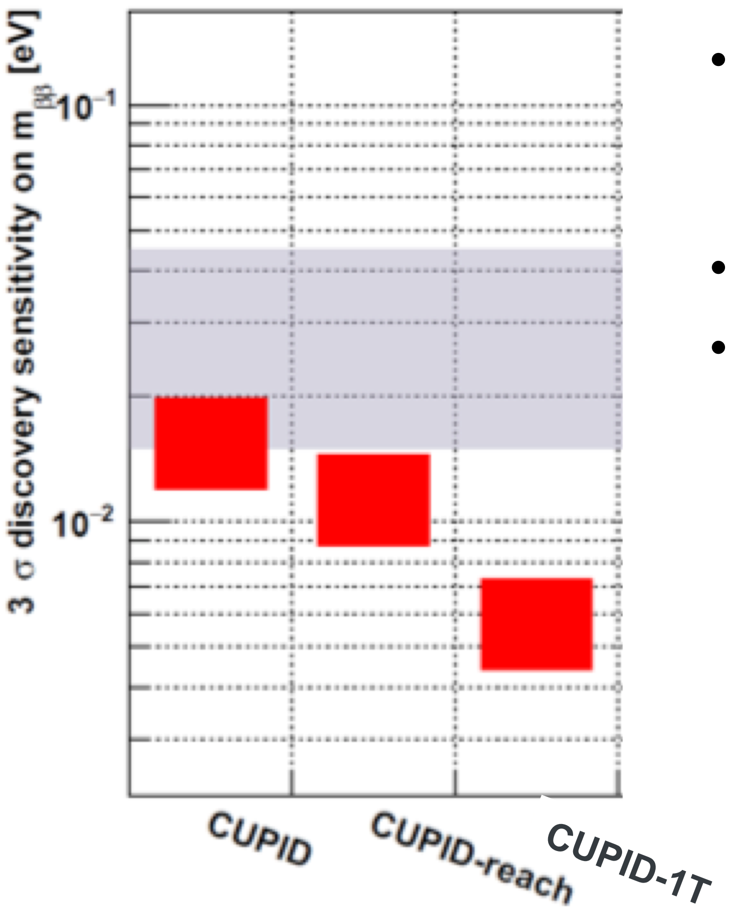
- ^{nat}Te loaded throughout
- Deeper site, solar ν backgrounds expected to dominate

Going Beyond the Ton Scale

Where to go next?

- Next-next-generation experiments are targeting $m_{\beta\beta}$ ~ 10 meV or smaller
- At the moment, there is no "magic bullet" to reach the 1 meV level
- There are, however, many ideas and there is a rich R&D program pursuing the needed techniques
- Many of these R&D efforts have synergies across $0\nu\beta\beta$ techniques, to other neutrino physics experiments, and with other rare-event searches
- I'll cover some highlights, far more information can be found in white papers and the NF05 report

Solid-State Detectors: CUPID-1T

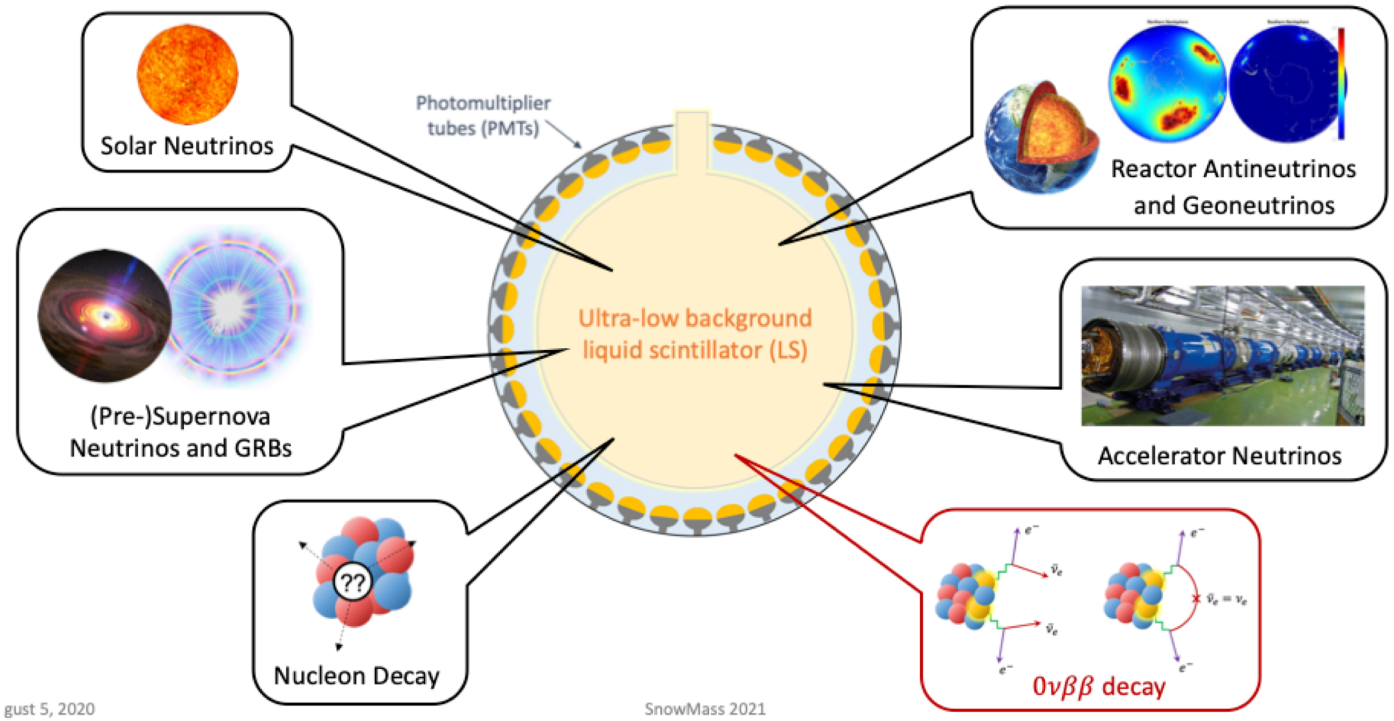


- R&D Areas: high-speed superconducting sensors, multiplexed readout technologies, active γ veto, CMOS and ASIC instrumentation for quantum sensors, superconducting crystal coatings for improved PSD
- Synergies: CMB, QIS, Dark Matter Searches
- Could adopt a diffuse staging technique, with sites around the world

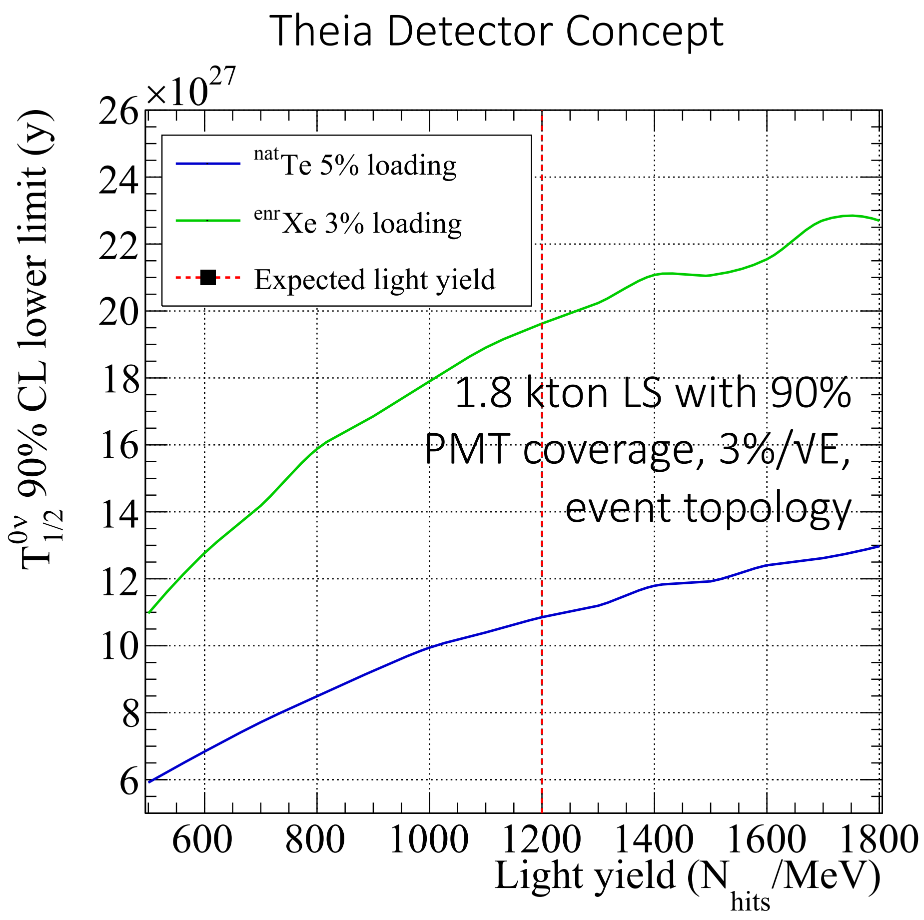
Parameter	CUPID Baseline	CUPID-reach	CUPID-1T
Crystal	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$
Detector mass (kg)	472	472	1871
^{100}Mo mass (kg)	253	253	1000
Energy resolution FWHM (keV)	5	5	5
Background index (counts/(keV·kg·yr))	10^{-4}	2×10^{-5}	5×10^{-6}
Containment efficiency	79%	79%	79%
Selection efficiency	90%	90%	90%
Livetime (years)	10	10	10
Half-life exclusion sensitivity (90% C.L.)	1.5×10^{27} y	2.3×10^{27} y	9.2×10^{27} y
Half-life discovery sensitivity (3σ)	1.1×10^{27} y	2×10^{27} y	8×10^{27} y
$m_{\beta\beta}$ exclusion sensitivity (90% C.L.)	10–17 meV	8.2–14 meV	4.1–6.8 MeV
$m_{\beta\beta}$ discovery sensitivity (3σ)	12–20 meV	8.8–15 meV	4.4–7.3 meV
	Ready today	Improvements before construction	New larger cryostat

"Toward Sensitivity to the Neutrino Normal Hierarchy with Quantum Calorimetry," D. Speller, Y. Kolomensky, L. Winslow, Snowmass LOI

Large Multi-Purpose Scintillator Detectors



Courtesy of R. Svoboda



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

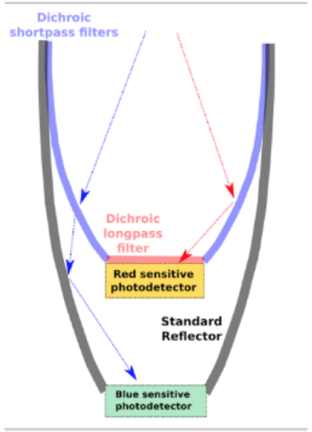
JUNO 0νββ Search Proposal:

- 50 tons of ^{136}Xe, expected energy resolution better than 2% (σ/E)
- Exclusion sensitivity: 1.8×10^{28} yr, 5-12 meV
- 0νββ upgrade starting in 2030s

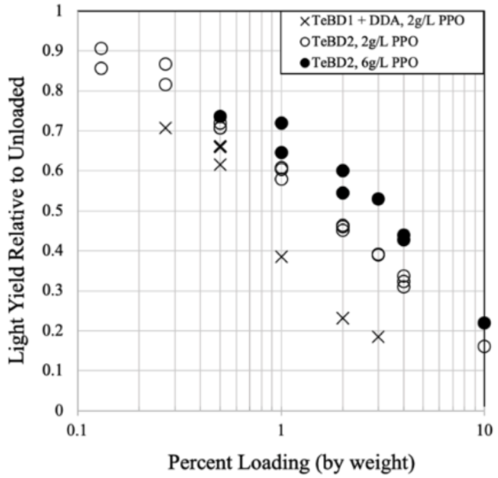
R&D for Scintillator Detectors

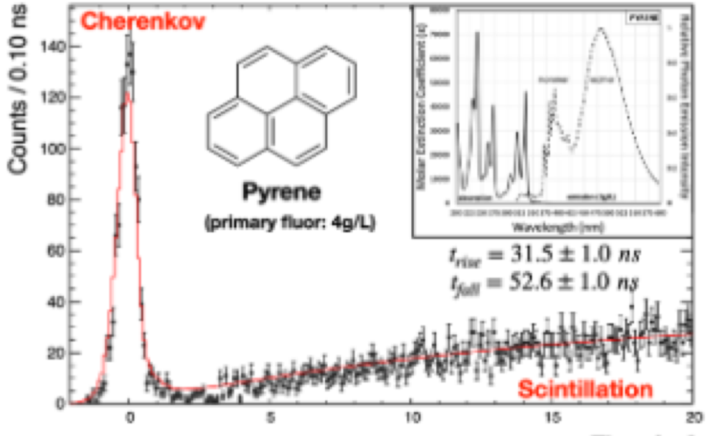
- Hybrid Cherenkov/scintillation detectors:
  - Reduce backgrounds by measuring 2 e- signature
  - Timing-based separation: slower fluors, faster photodetectors
  - Wavelength-based separation: dichroic filers
- New scintillator cocktails and isotopic loading techniques:
  - Water-based Liquid Scintillator: purification and stability, gadolinium loading, pulse shape discrimination
  - Tellurium loading: several % loading demonstrated, increased loading and purification R&D underway
  - Quantum dot-based isotope loading: production scaling, stability, and optical performance studies underway
- Advanced photon sensors and collectors:
  - LAPPDs: ongoing R&D on high-channel-count readout techniques, self-triggering and synchronization, streamlined fabrication
- Advanced simulation and analysis techniques

Dichroicon



Te Loading





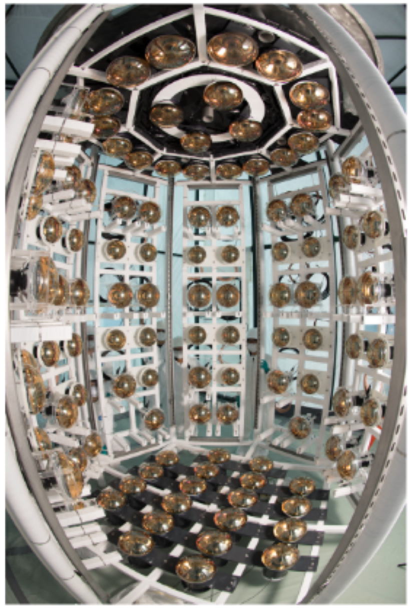
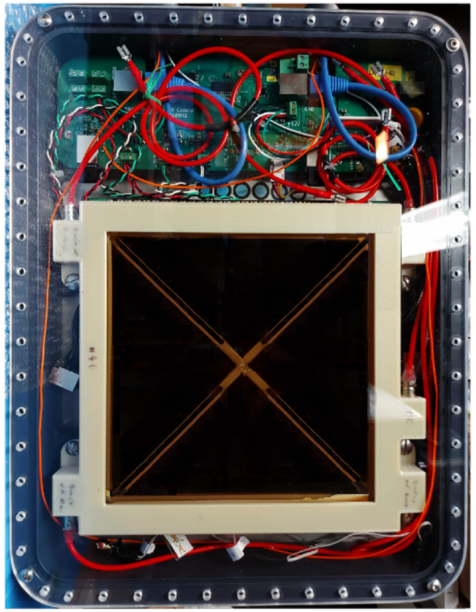
Slow Fluor

…and much more!
see “Future Advances in Photon-Based Neutrino Detectors: A SNOWMASS White Paper”

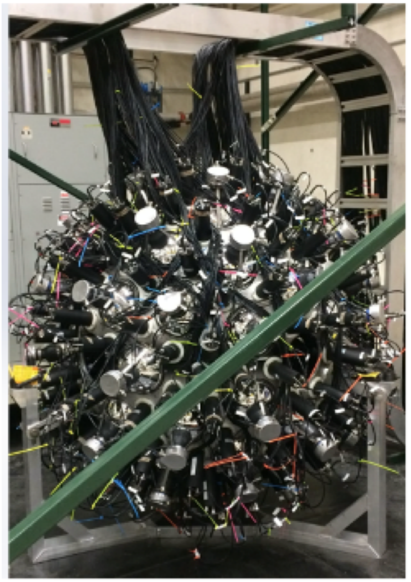
Mid-Scale Test Stands for Scintillator R&D

R&D is beginning to move beyond the benchtop scale

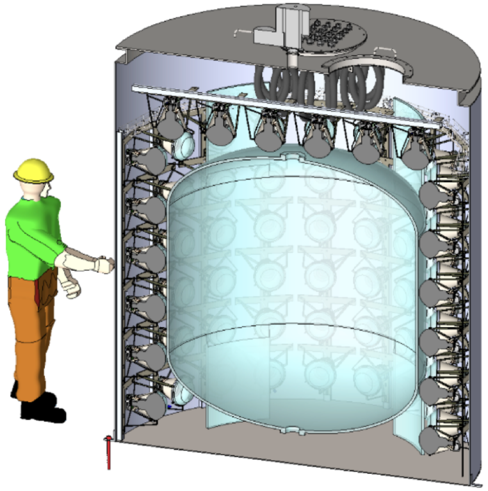
- ANNIE: first large-scale test of LAPPDs, planning for Gd-loaded WbLS

ANNIE detector and LAPPD module



NuDot: ½ ton test stand



Eos: few-ton WbLS

- NuDot: timing-based Cherenkov/scintillation separation and quantum dot loading
- Eos: Cherenkov/scintillation separation and WbLS, validation of microphysics simulations at low energy

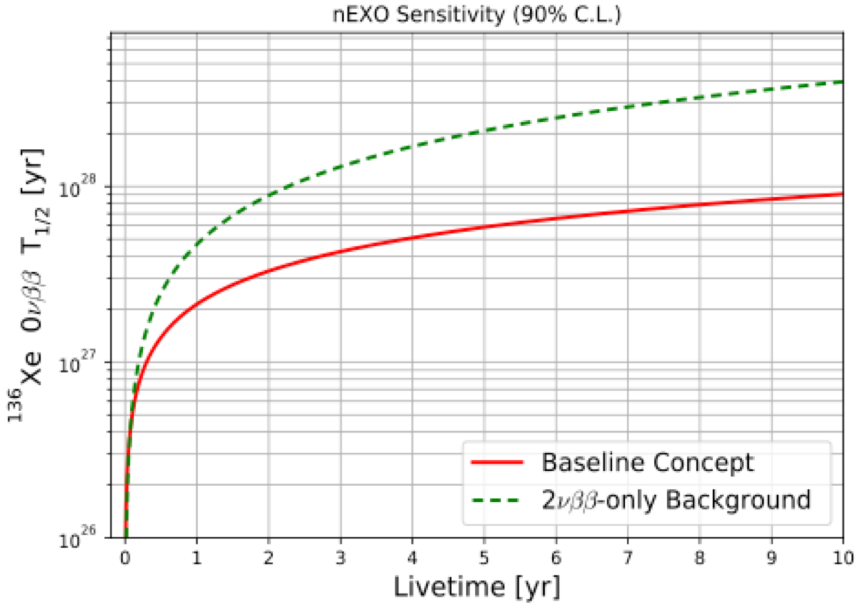
Barium Tagging in ^{136}Xe Detectors

$$^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^{-}$$

"Tagging" Ba daughter has potential to eliminate all but 2νββ backgrounds

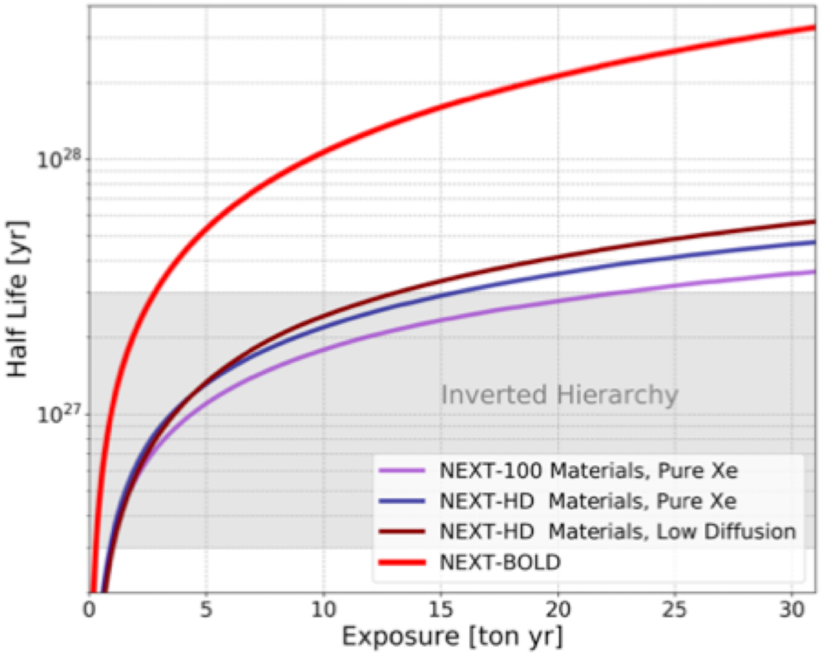
M. Moe, Phys. Rev. C 44, R931 (1991)

In nEXO, eliminating other backgrounds could give up to 4x higher sensitivity



nEXO Collaboration, *Phys. Rev. C* **97**, 065503 (2018)

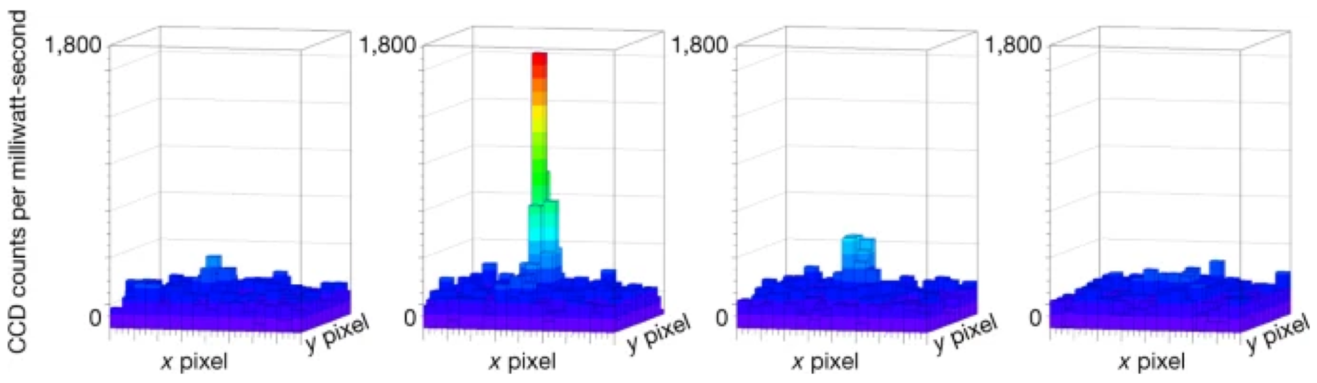
In NEXT, higher efficiency with Ba tagging and eliminating other backgrounds could provide up to a factor of 6 higher sensitivity



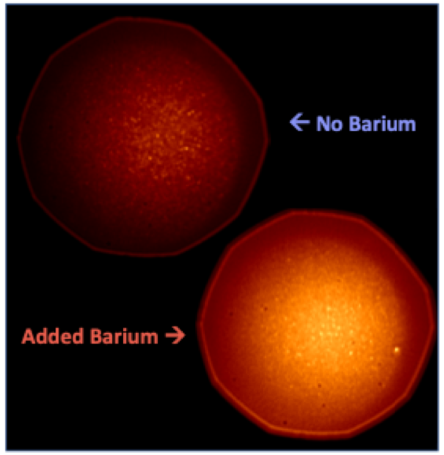
Materials courtesy of the NEXT and nEXO Collaborations, from B. Fairbank

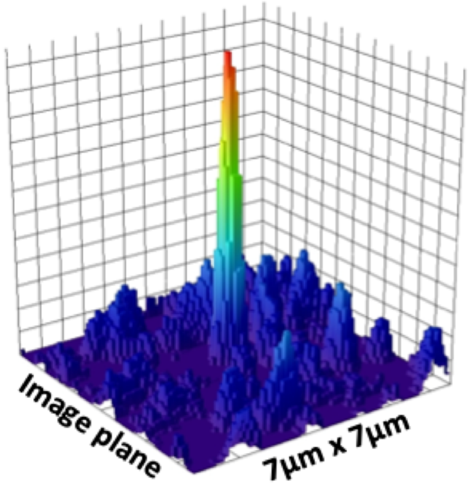
- Considered a possible upgrade path for the tonne-scale TPC experiments
- Could extend sensitivity (further) into the normal ordering region!

R&D for Barium Tagging



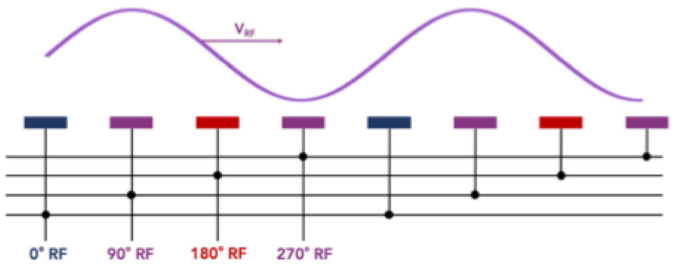
Laser-based ID in solid Xe for nEXO, *Nature 569, 203-207 (2019)*





Fluorescent molecule-based ID for NEXT,
ACS Sens. 2021, 6, 1, 192–202 (2021)

Cryoprobe-based extraction for nEXO



RF carpet-based transport for NEXT,
arXiv:2111.11091 (2021)

- Feasible single-ion sensing techniques have been demonstrated in GXe and LXe
- Next steps: Barium capture, transport, and sensing in more-realistic detector environments

R&D for Large TPC Detectors

For Xe, isotope acquisition is a challenge:

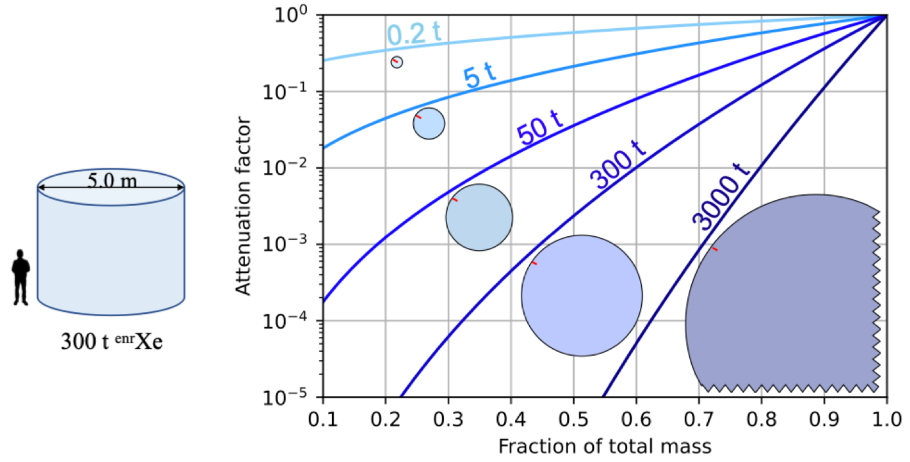
- Currently depends on liquid oxygen production for steel industry, limiting supply
- R&D on alternative extraction methods: Xe-adsorbing materials, could be implemented at CO2 capture plants

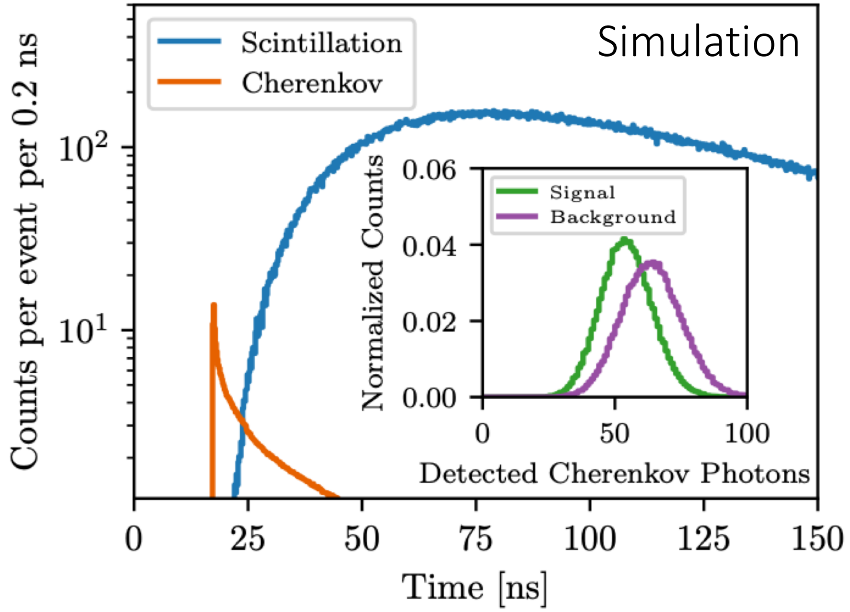
If acquisition can be resolved, kiloton-scale GXe and LXe TPCs should be feasible:

- R&D: increasing light detection efficiency, Cherenkov light-based background reduction
- Projected sensitivity ~10^{30} yrs

Other ideas:

- DUNE and DarkNoon: Xe-doped LAr; R&D on energy resolution, gas mixture handling, and Cherenkov/scintillation response
- SeF_6 TPCs: R&D on ion readout techniques

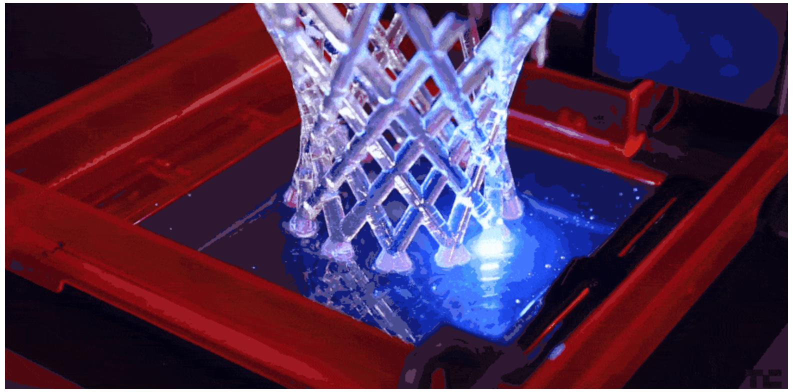




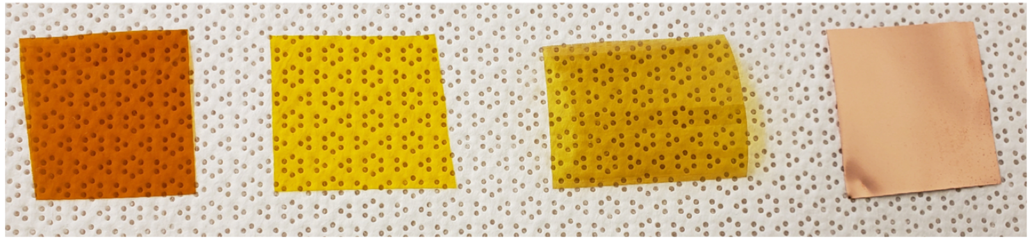
Physical Review D 104 (11): 112007 (2021)

R&D Synergies

- Electronics: ASICs, multiplexing, low-background cables
- Ultra-low background materials: electroforming, scintillating structural materials, additive manufacturing
- Detectors: photodetectors, superconducting sensors, SiPMs, and more
- Underground and assay facilities
- Neutron moderation and tagging
- Cherenkov/scintillation separation and directional reconstruction
- Simulations and analysis: machine learning, GPUs, and more



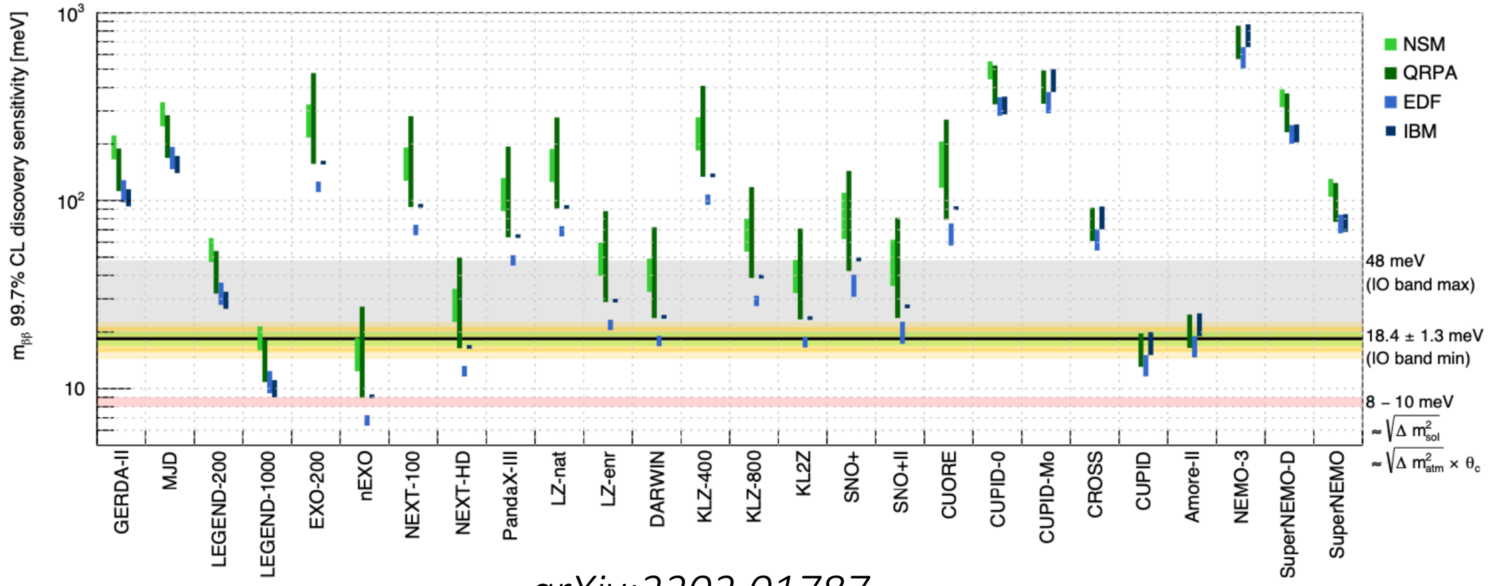
“Contact-free” machining with stereolithography



Ultra-clean Kapton, *NIM A, 959 (2020) 163573*

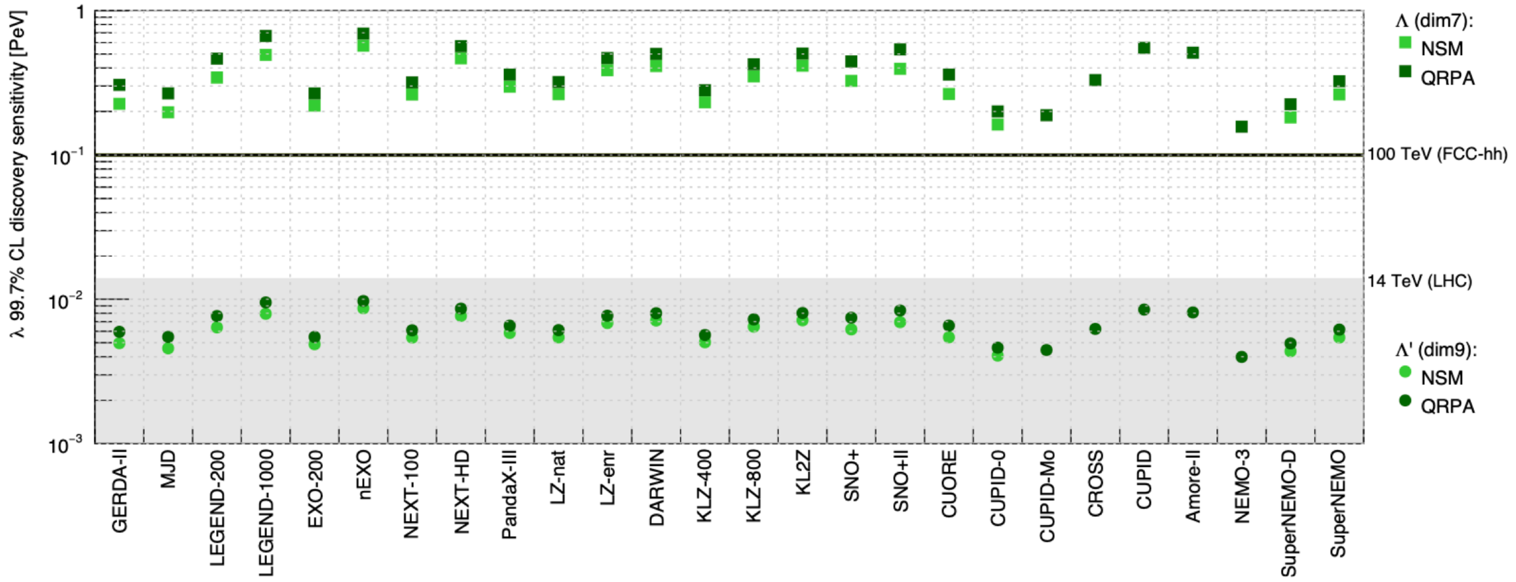
The Future of 0νββ Searches

Light Majorana neutrino exchange (dim 5):



arXiv:2202.01787

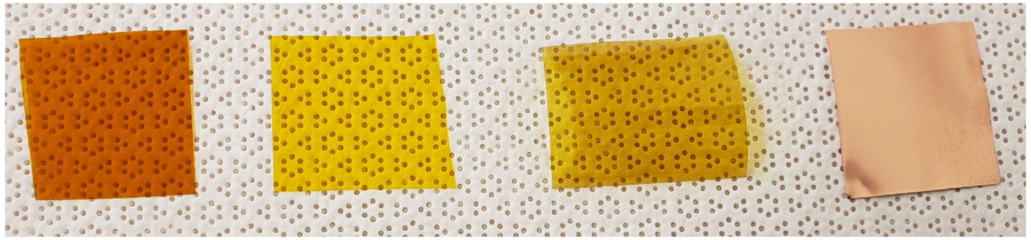
0νββ via dimension 7 and 9 operators:



- The coming generation of 0νββ experiments will fully explore the inverted hierarchy region
- Corresponds to searching for new physics at the 10's - 100's of TeV scale
- R&D is underway to reach $m_{\beta\beta} \sim 1\ meV$
- Discovery could come at any time!

Extra Slides

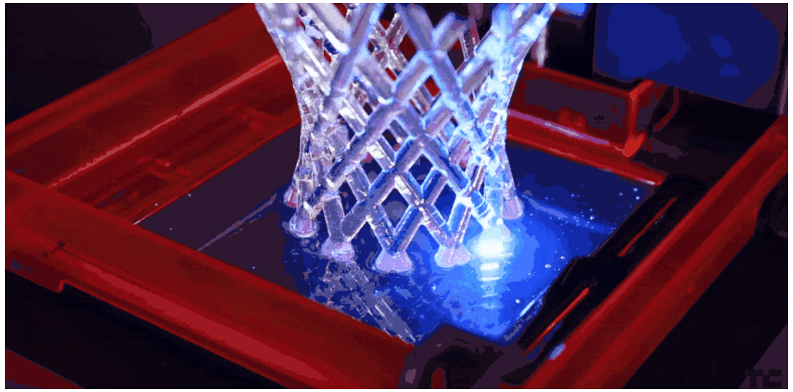
Synergies: Low-Background Techniques



Ultra-clean Kapton, *NIM A, 959 (2020) 163573*

Cables and electronics:

- Increasing channel counts and background demands make ASIC development a priority
- Cabling backgrounds must be addressed by using ultra-clean materials; multiplexing would help in some cases



"Contact-free" machining with stereolithography

Ultra-low background materials:

- R&D on underground electroformed copper alloys
- Increasing use of scintillating structural materials, R&D on additive manufacturing

Cosmogenic and solar ν backgrounds

- Need for underground spaces for cool-down, neutron moderation and tagging
- Cherenkov/scintillation separation and directional reconstruction being pursued in many media

Synergies: Underground Laboratories and Assay

- As background demands increase, so do depth and assay requirements
- Future experiments will need increased underground staging and storage space, in addition to experimental halls
- $0\nu\beta\beta$ experiments work at the limit of assay capabilities: new and improved methods needed

Laboratory	Country	Experiment(s)	Access	Depth (m.w.e)
Laboratoire Souterrain de Modane (LSM)	France	CUPID-Mo, SuperNEMO	Horizontal	4,800
Laboratorio Subterraneo de Canfranc (LSC)	Spain	NEXT-WHITE, NEXT-100, NEXT-HD module 1	Horizontal	2450
Yangyang Underground Laboratory	South Korea	AMoRE	Horizontal	2000
Kamioka Observatory	Japan	KamLAND-Zen, KamLAND2-Zen, CANDLES	Horizontal	2700
China Jinping Underground Laboratory (CJPL)	China	PandaX-III	Horizontal	6700
Sudbury Neutrino Observatory (SNOLAB)	Canada	SNO+, nEXO, LEGEND-1000	Vertical	6010
Sanford Underground Research Facility (SURF)	USA	Majorana Demonstrator, Theia	Vertical	4300
Gran Sasso National Laboratory (LNGS)	Italy	CUORE, CUPID, GERDA, LEGEND-200, LEGEND-1000	Horizontal	3400
Waste Isolation Pilot Plant (WIPP)*	USA	EXO-200	Vertical	2000