Review of Neutrinoless Double-Beta Decay Experiments

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THE UNIVERSITY
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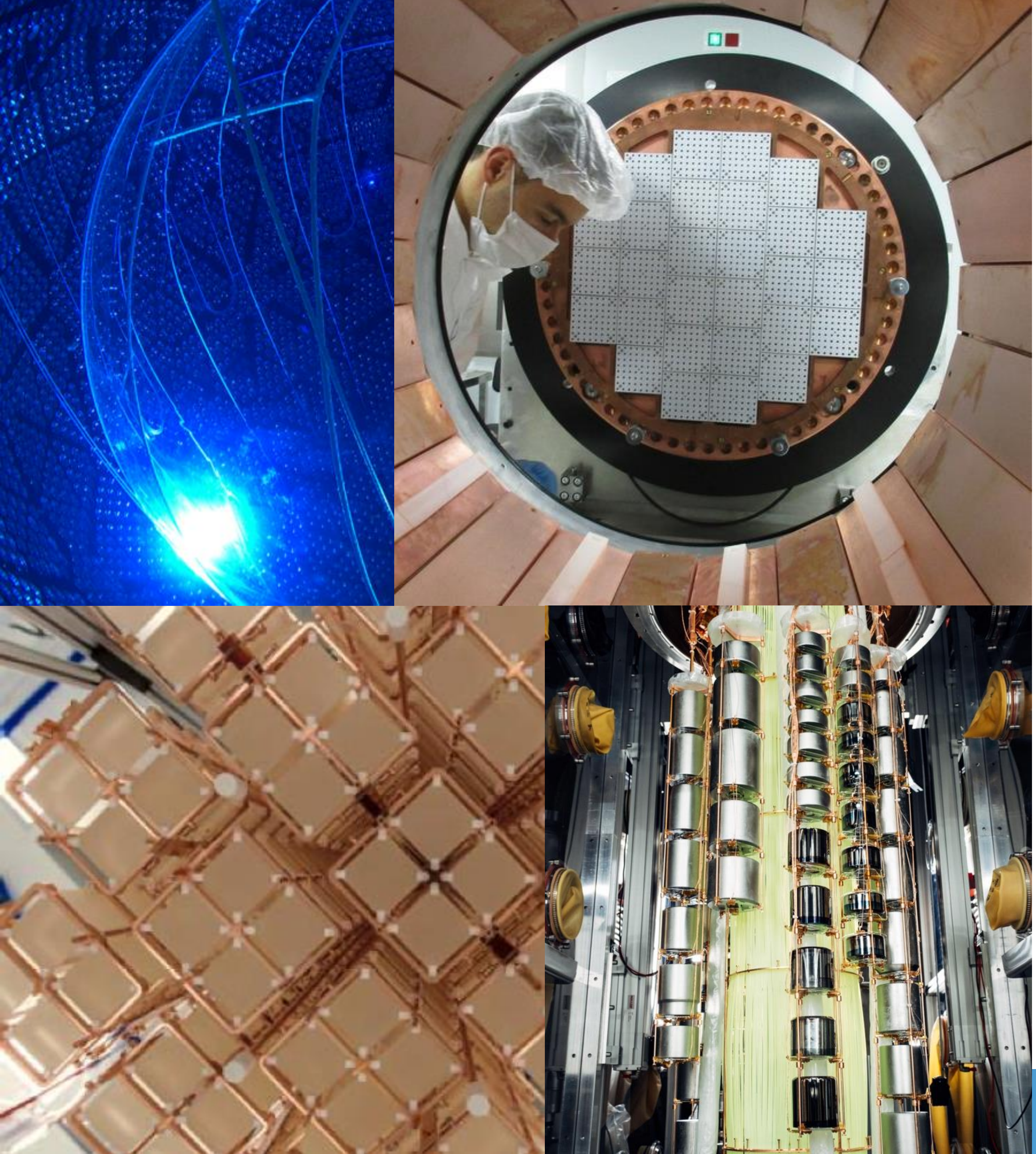
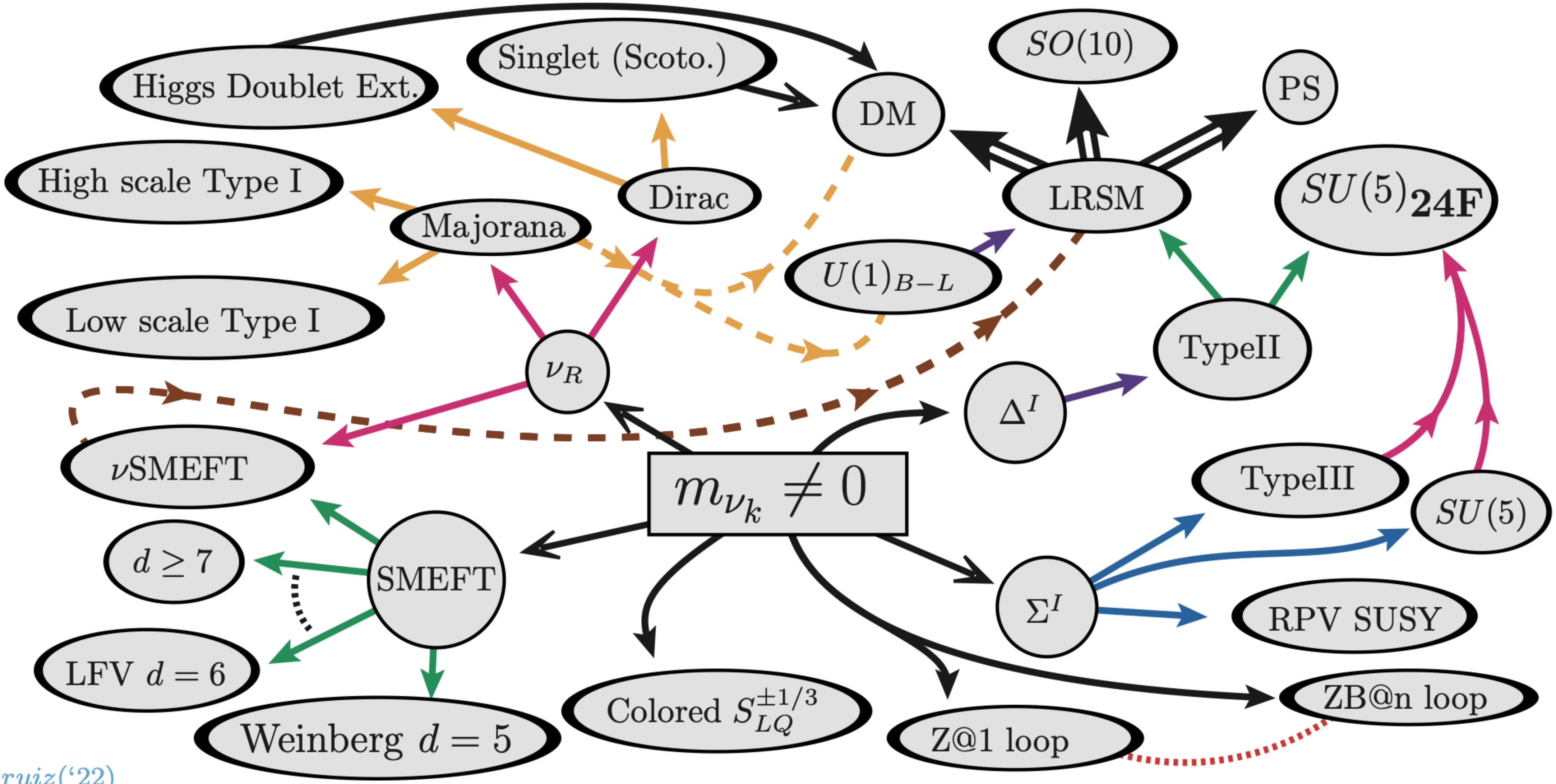


Outline

- A quick review of 0νββ
- Searching for 0νββ
- 0νββ experiments

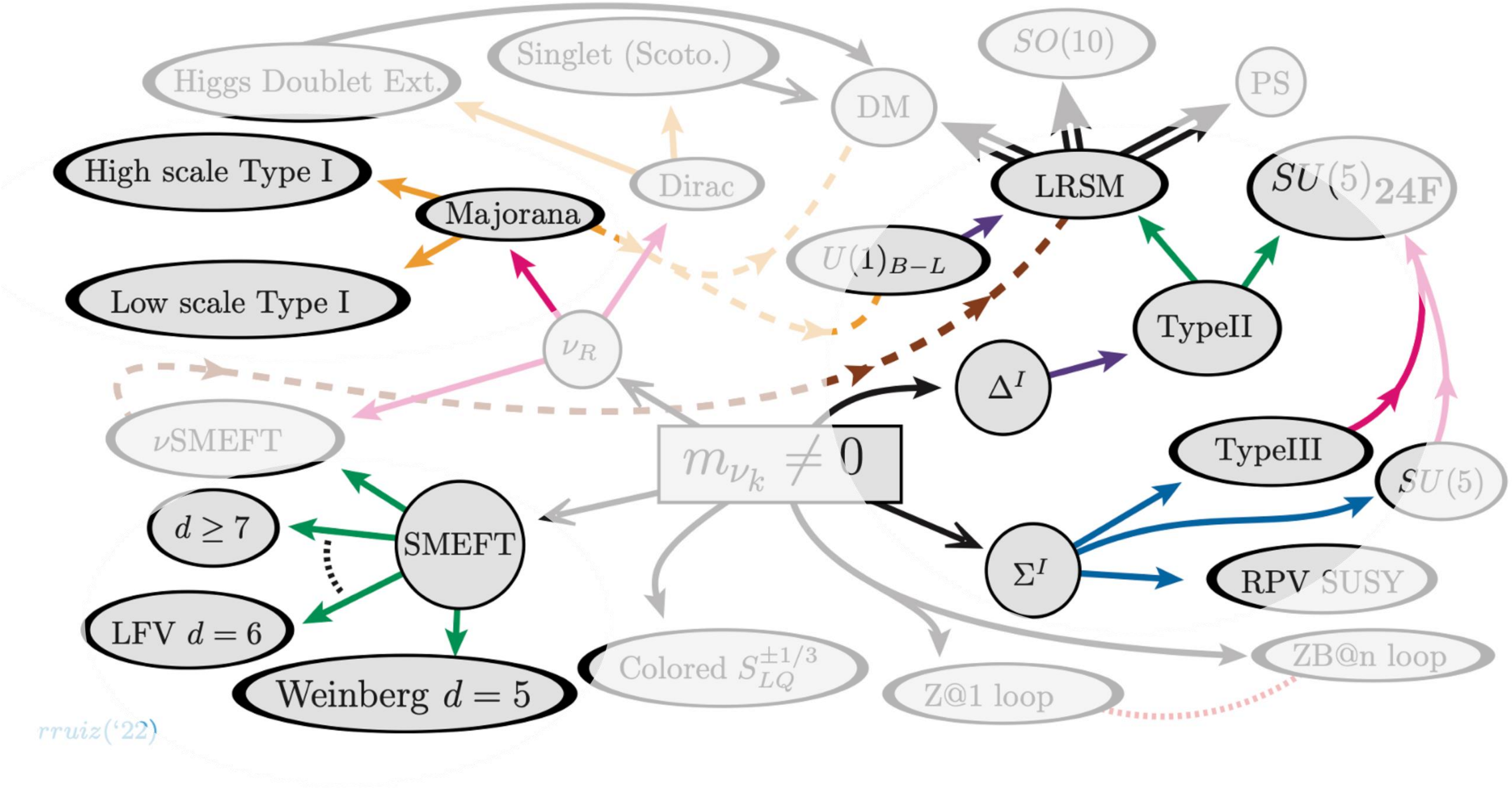
A Quick Review of 0vββ

Shamelessly stealing from Richard Ruiz…



rruiz('22)

Shamelessly stealing from Richard Ruiz…



* speaking as an experimentalist

Pros and cons of different benchmarks*

Simplified models

Ease of comparison between analyses and experiments

Tractable parameter space to understand extent of coverage

Can lead to over-simplified view of what is “excluded” or uncovered

Complete/ complex models

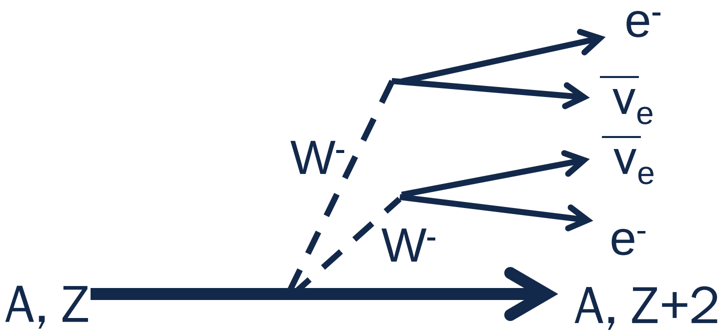
Theoretically robust

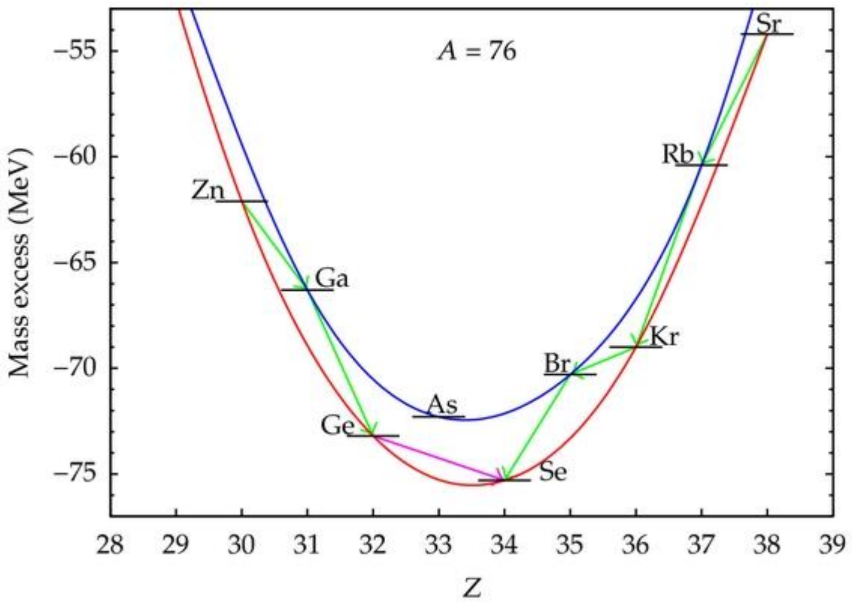
Illuminate wide range of final states that are needed for thorough coverage of cases

Hard to form complete picture; hard to compare across contexts

Slide by Katherine Pachal

Standard Model: Two Neutrino Double-Beta Decay

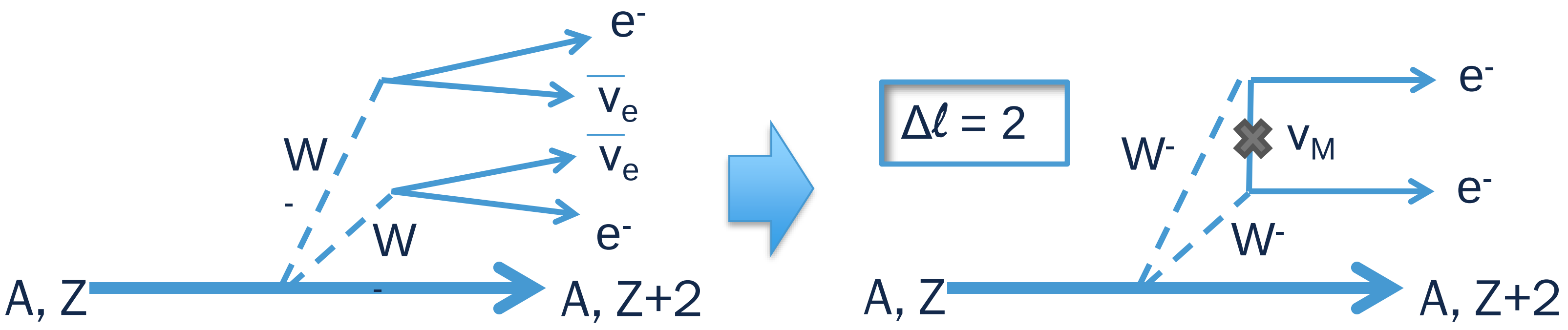




- For certain even-even nuclei, single beta decay is disallowed b/c of energy or momentum
- Instead, they double-beta decay dominates
- Second-order weak process

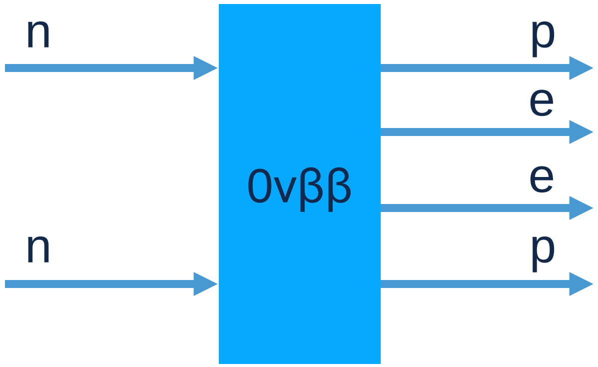
  $T_{1/2} \sim 10^{19}$ -10^{21} years
- Electron capture variant is longest-lifetime process ever observed

Neutrinoless Double-Beta Decay

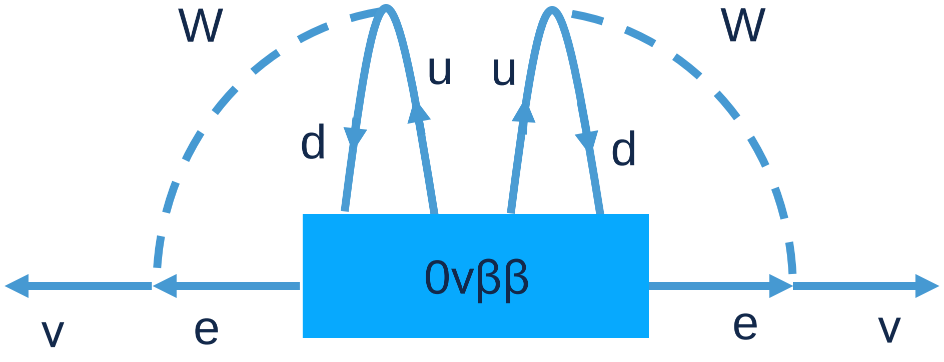


- If neutrinos have a non-zero Majorana mass term, 0νββ could occur
- Lepton number conservation is violated by 2 units
- In this case, I’ve drawn the exchange of a light neutrino, but you can think of that “x” as a contracted diagram of any sort (with new physics in it)

Majorana Neutrinos and 0νββ



(A, Z) → (A, Z+2) +2e-



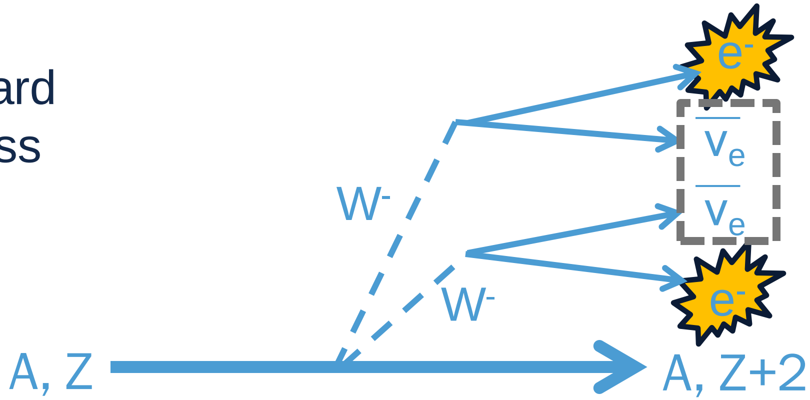
(A, Z) → (A, Z+2) +2e-

Model-independent implications of 0νββ:

- Lepton number violation
- Neutrino-antineutrino oscillation, implying a non-zero Majorana mass term

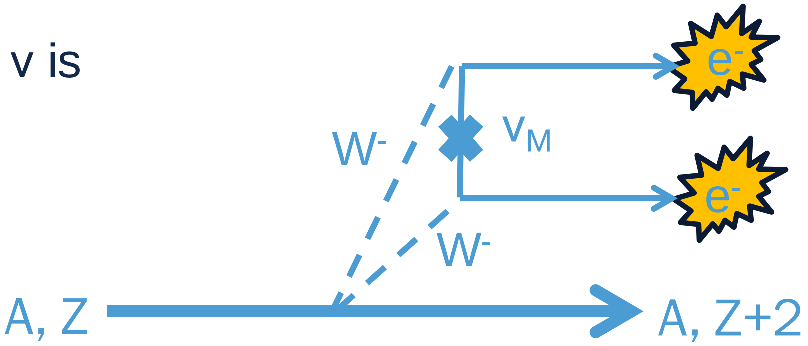
The Decay Signature

2νββ: Standard Model process

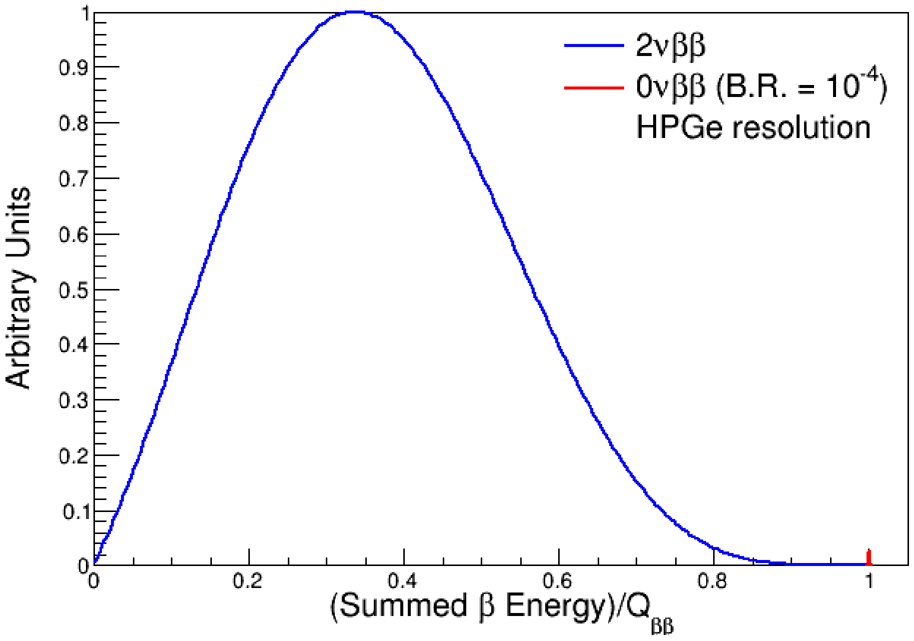


Missing energy

0νββ: Only if ν is Majorana



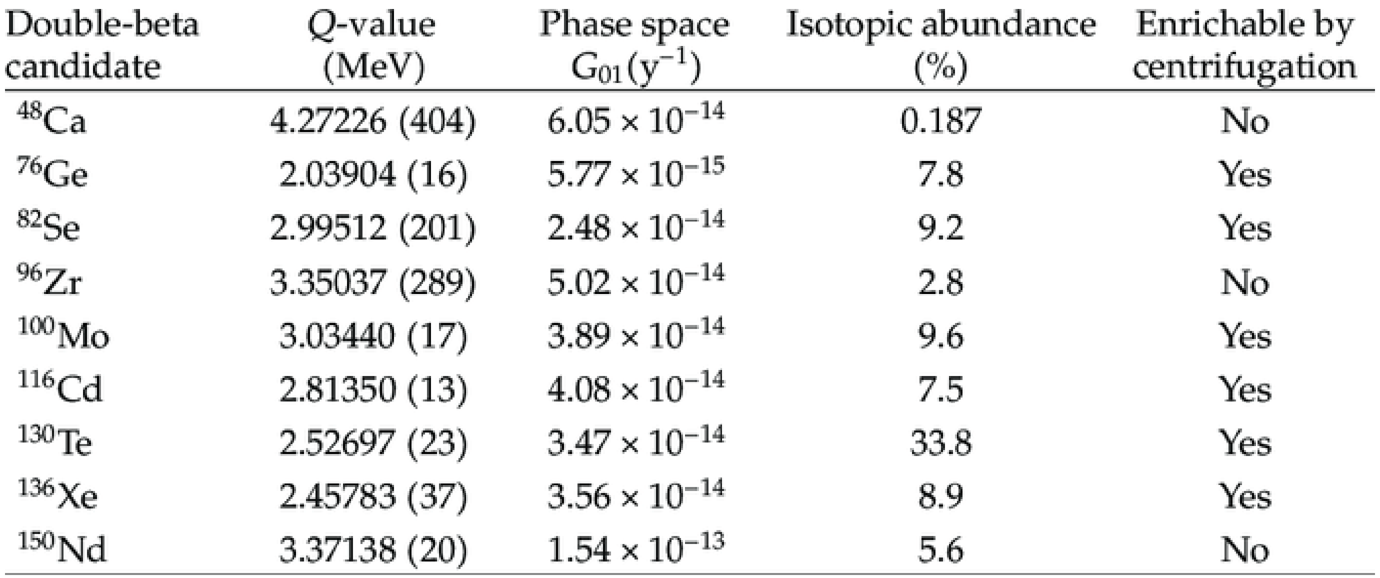
No missing energy



+ event topology information

Double-Beta Decay Isotopes

- 35 naturally-occurring isotopes are capable of double-beta decay; we've observed it in 14 of these
- These 14 "golden nuclei" are particularly well-suited to experiments:
  - High Q-values
  - High abundance or ability to enrich (with some exceptions)
  - Other abundant isotopes of the element not highly radioactive

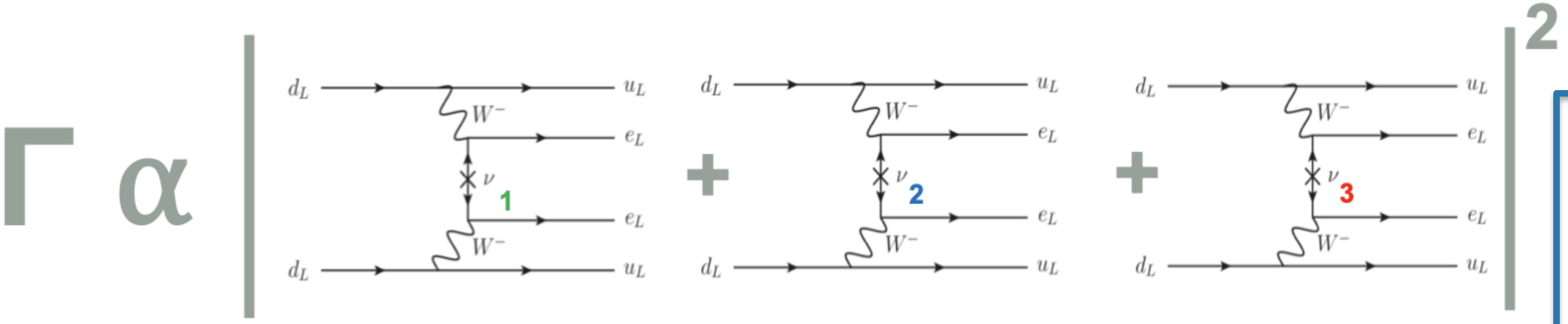


Double-beta candidate	Q-value (MeV)	Phase space $G_{01}(y^{-1})$	Isotopic abundance (%)	Enrichable by centrifugation
^{48}Ca	4.27226 (404)	6.05×10^{-14}	0.187	No
^{76}Ge	2.03904 (16)	5.77×10^{-15}	7.8	Yes
^{82}Se	2.99512 (201)	2.48×10^{-14}	9.2	Yes
^{96}Zr	3.35037 (289)	5.02×10^{-14}	2.8	No
^{100}Mo	3.03440 (17)	3.89×10^{-14}	9.6	Yes
^{116}Cd	2.81350 (13)	4.08×10^{-14}	7.5	Yes
^{130}Te	2.52697 (23)	3.47×10^{-14}	33.8	Yes
^{136}Xe	2.45783 (37)	3.56×10^{-14}	8.9	Yes
^{150}Nd	3.37138 (20)	1.54×10^{-13}	5.6	No

Searching for 0νββ

Neutrino Physics and 0νββ

Light Majorana neutrino exchange: assumes new physics is at high scale, 0νββ mediated by dim. 5 operator



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

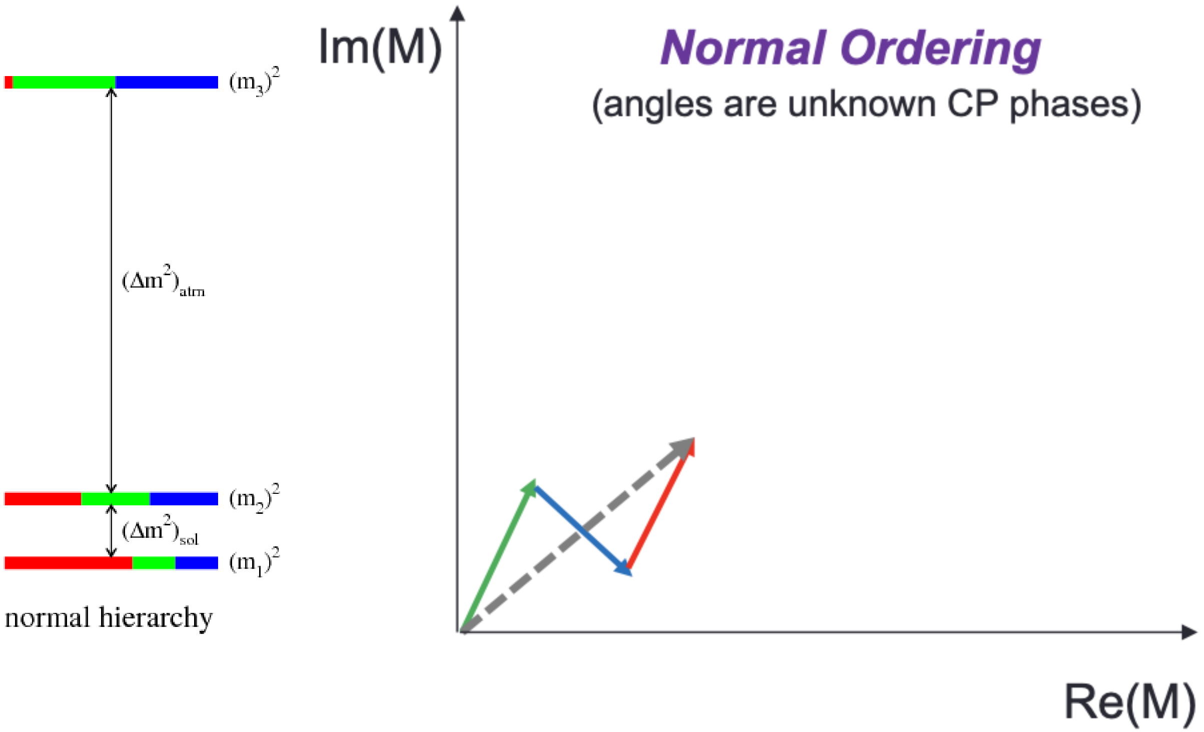
- ν mixing angles
- ν masses
- mass hierarchy
- 2 totally unknown phases

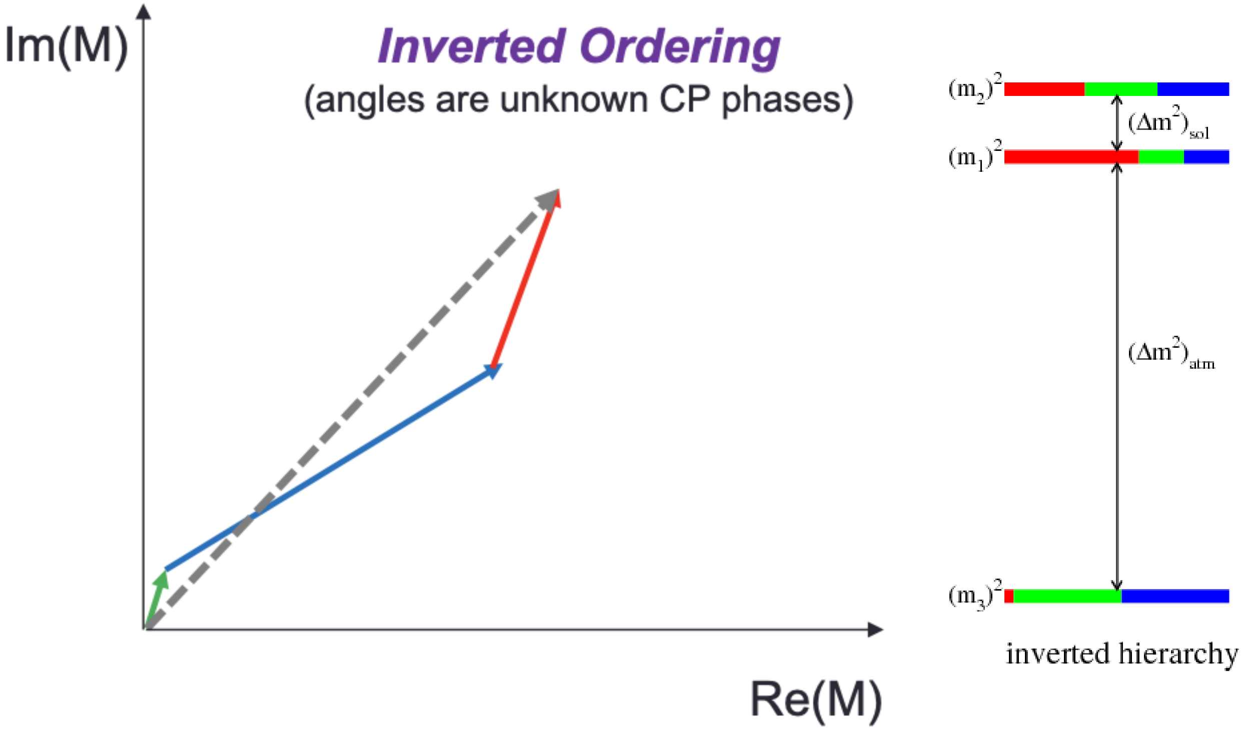
$$\langle m_{\beta\beta}\rangle = |\sum_{i=1}^{3} U_{ei}^2 m_i|$$

$$\langle m_{\beta\beta}\rangle = \cos\theta_{12}^2 \cos\theta_{13}^2 e^{2i\alpha} m_1 + \cos\theta_{12}^2 \sin\theta_{12}^2 e^{2i\beta} m_2 + \sin\theta_{13}^2 m_3$$

Neutrino Physics and 0νββ

$$\langle m_{\beta\beta}\rangle = \cos\theta_{12}^2\cos\theta_{13}^2 e^{2i\alpha} m_1 + \cos\theta_{12}^2\sin\theta_{12}^2 e^{2i\beta} m_2 + \sin\theta_{13}^2 m_3$$





Adding a light sterile neutrino can change the parameter space dramatically

Figures by B. Jones

Light Majorana Neutrino "Theory Islands"

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

- With unknown neutrino mass, mass hierarchy, and phases, we get these theory islands for light Majorana neutrino exchange
- Used to compare and set goals for future experiments

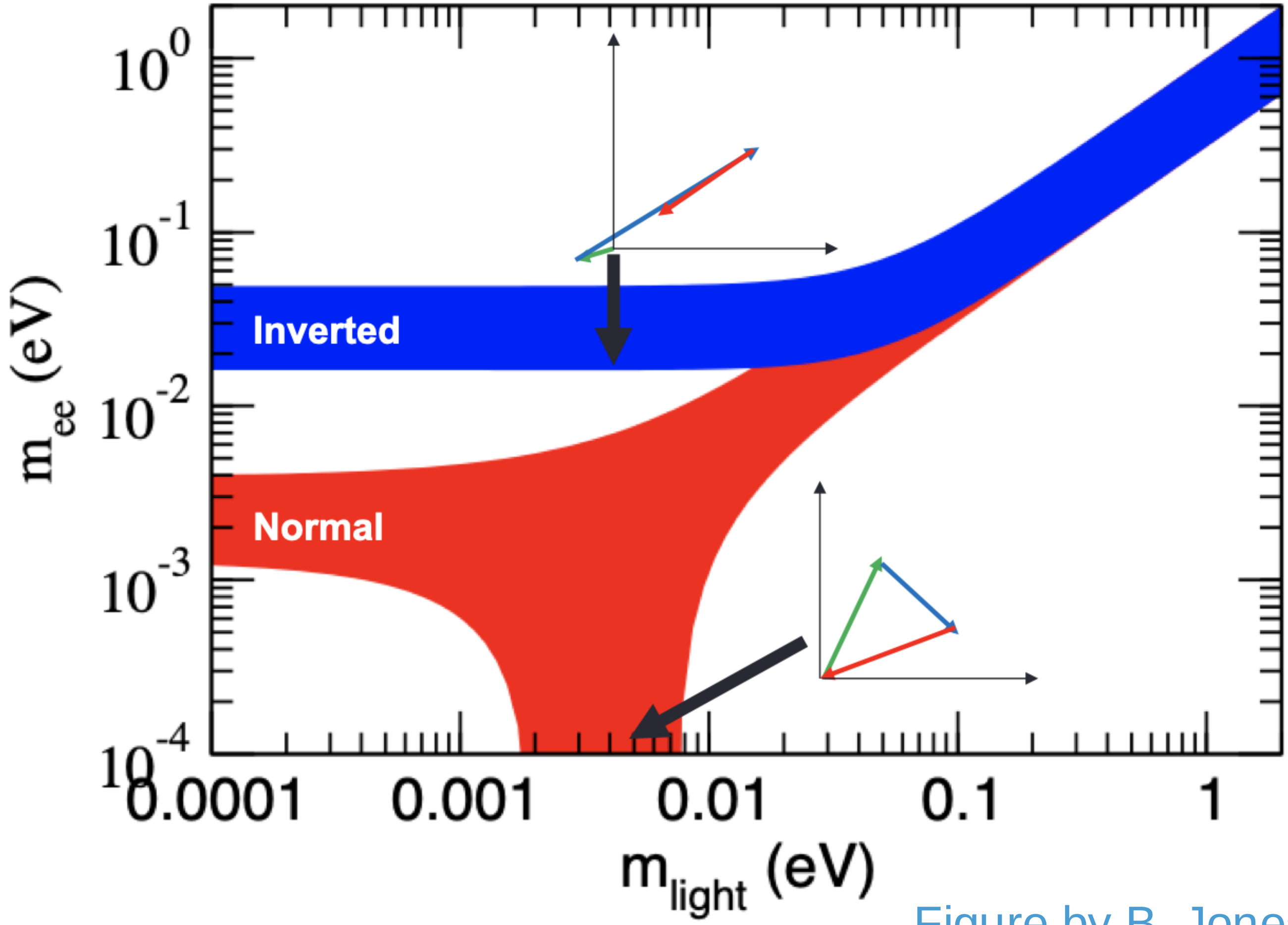


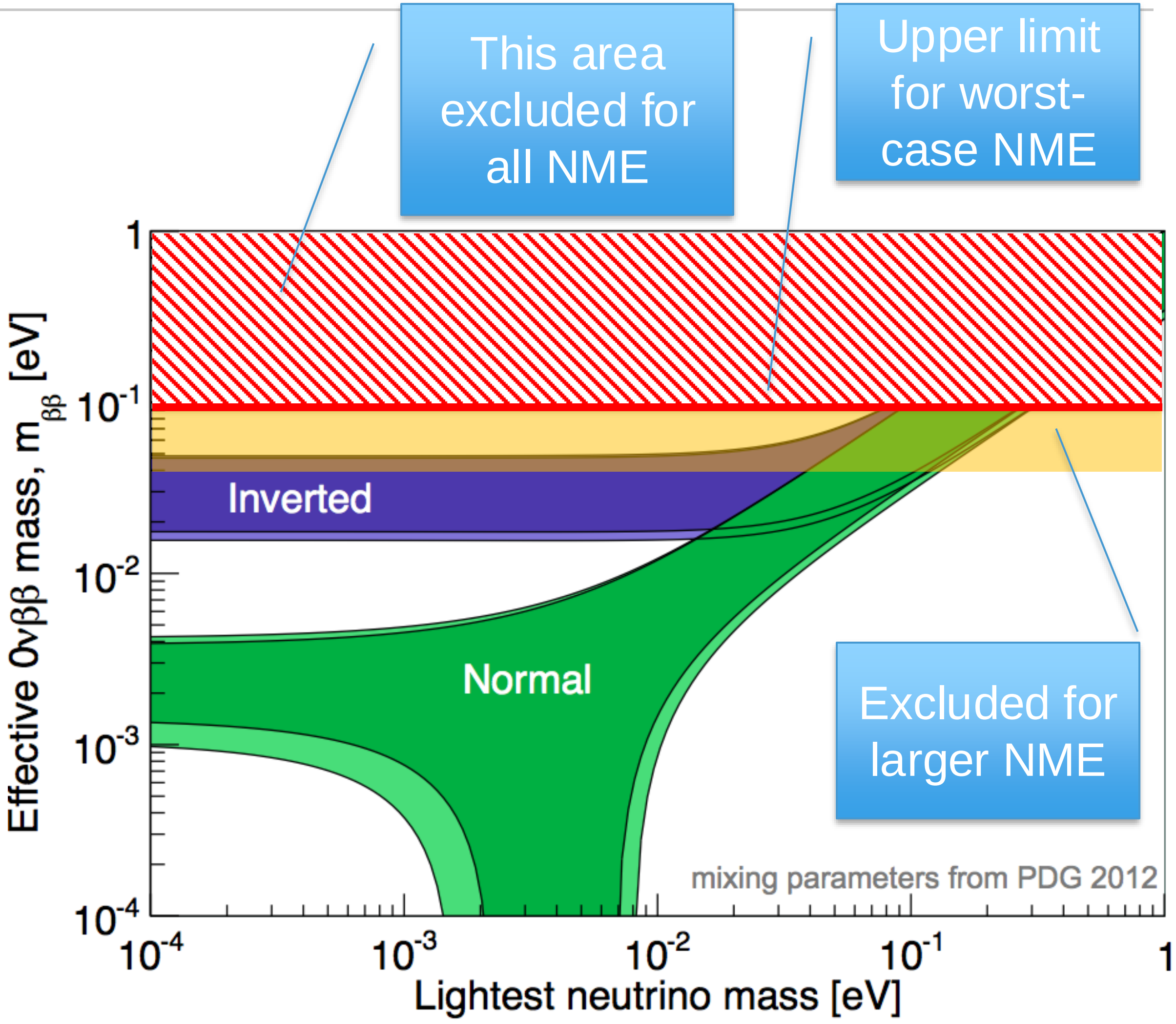
Figure by B. Jones

Nuclear Physics and 0νββ

Experiments don’t measure $m_{\beta\beta}$ directly, they measure half-life:

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

- Need to use a particular model, the phase space factor and a nuclear matrix element to turn half-life into $m_{\beta\beta}$
- Results are generally reported for the full set of NMEs; upper limit in $m_{\beta\beta}$ has a range



This area excluded for all NME

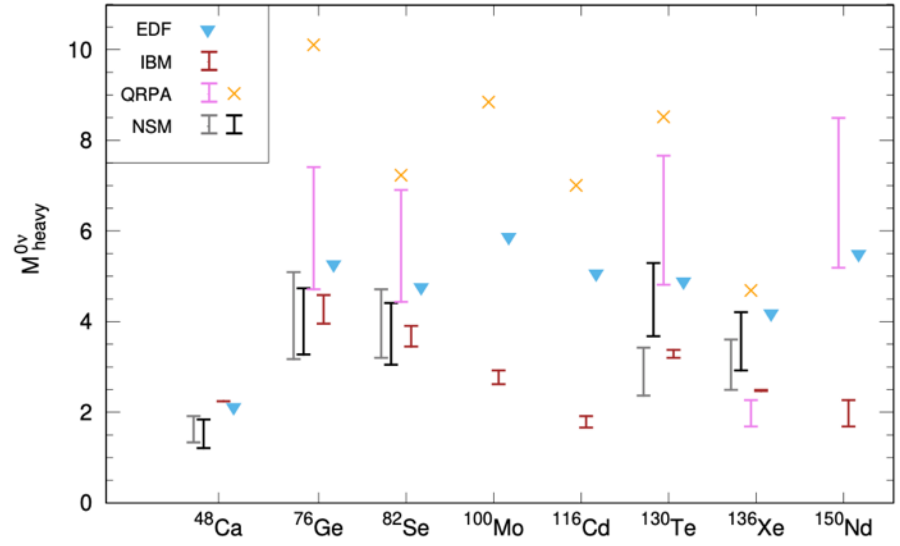
Upper limit for worst-case NME

Excluded for larger NME

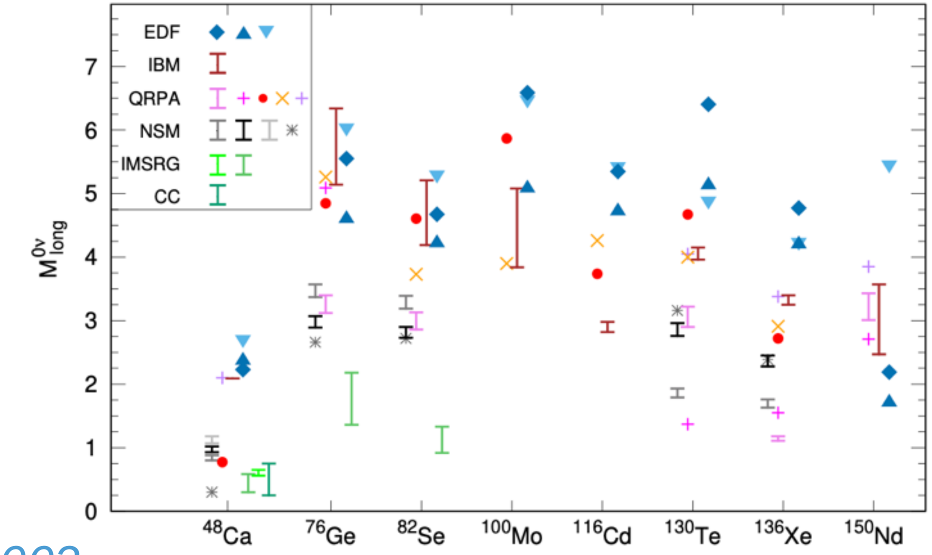
Nuclear Matrix Elements

- NME calculations differ by a factor of ~3-5, and full model uncertainties cannot be quantified
- 0νββ mediated by higher-dimensional operators would have different dominant NMEs
- In the case of 0νββ discovery, comparison between isotopes could provide insight into mechanism

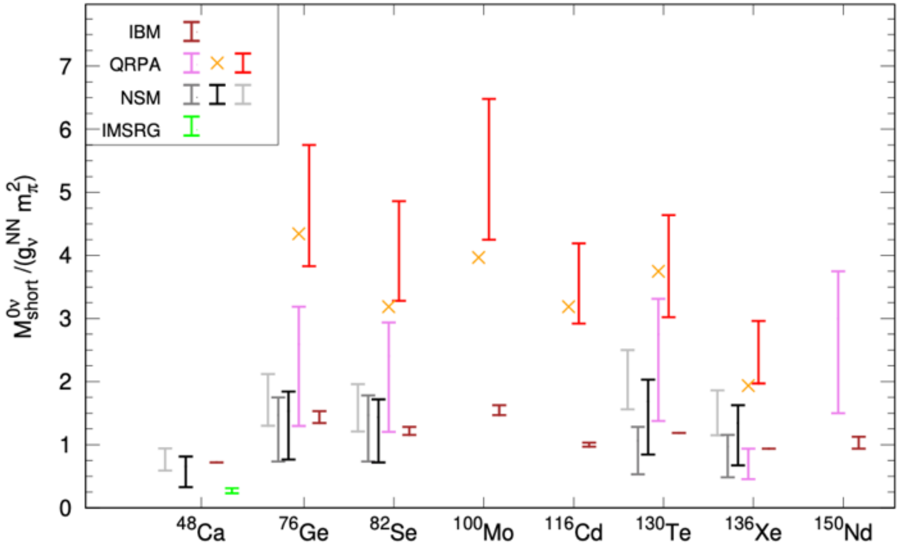
Heavy neutrino exchange



Long-range light neutrino exchange



Short-range light neutrino exchange

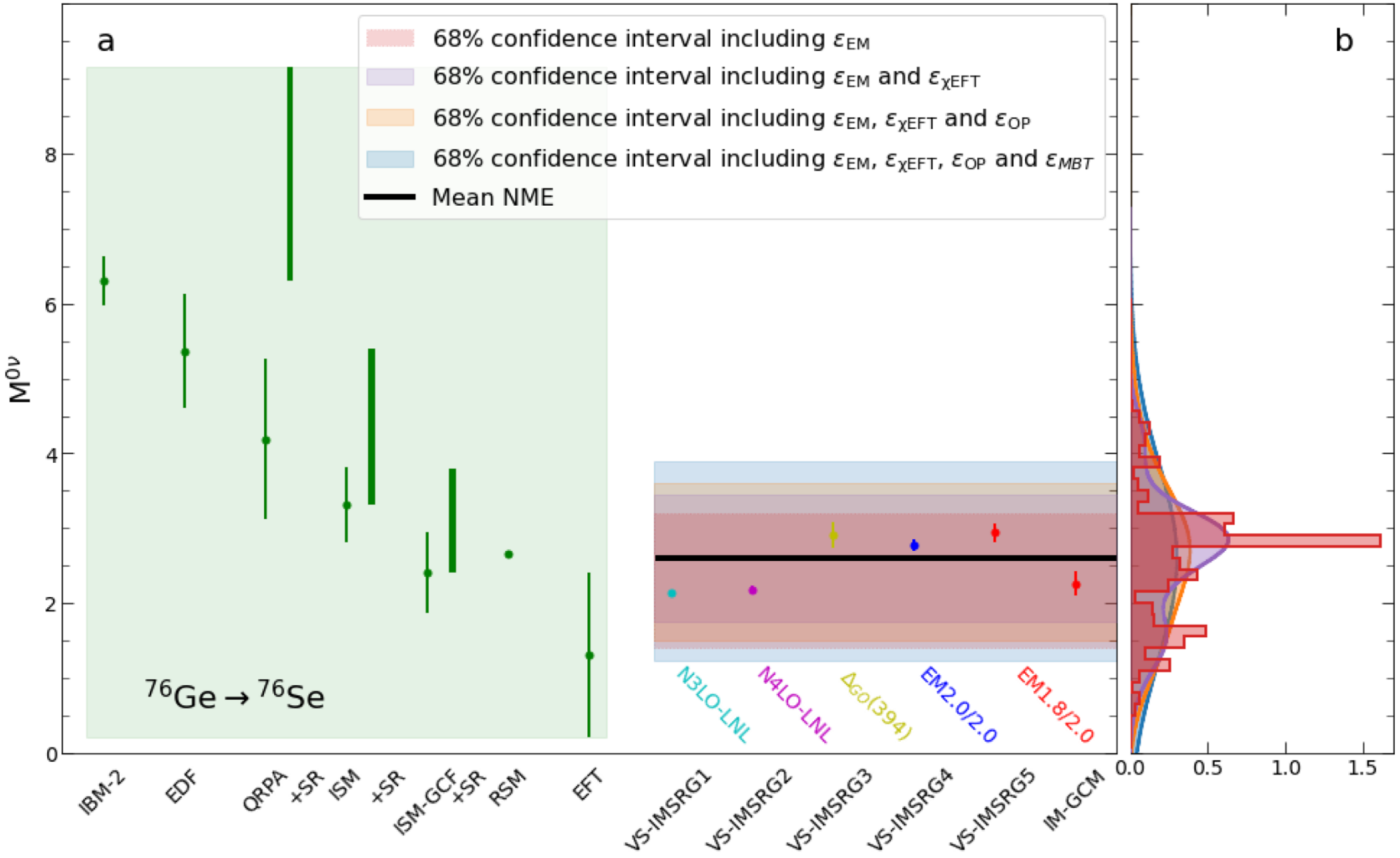


10.1103/RevModPhys.95.025002

Ab Initio Calculations

- The bad news: ab-initio matrix elements seem to be small, making 0νββ searches more challenging
- The good news: more reliable uncertainties
- As ab-initio calculations start to become a reality, we need to rethink how we treat uncertainties when quoting results
- How long should old calculations stick around?

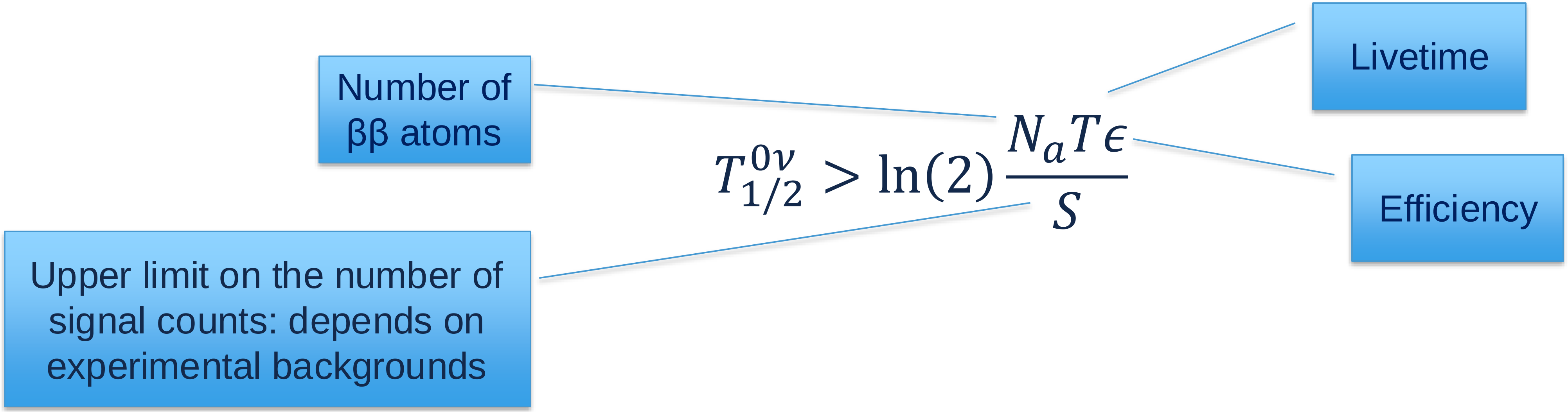
From 10.1103/PhysRevLett.132.182502



Discovery and Sensitivity

After you run a 0vββ search…

- You either see an excess at the Q value and fit a peak with some rate to it.
- Or you don’t see an excess. In that case, you set a lower limit on half-life:



$$T_{1/2}^{0\nu} > \ln(2)\,\frac{N_a T \epsilon}{S}$$

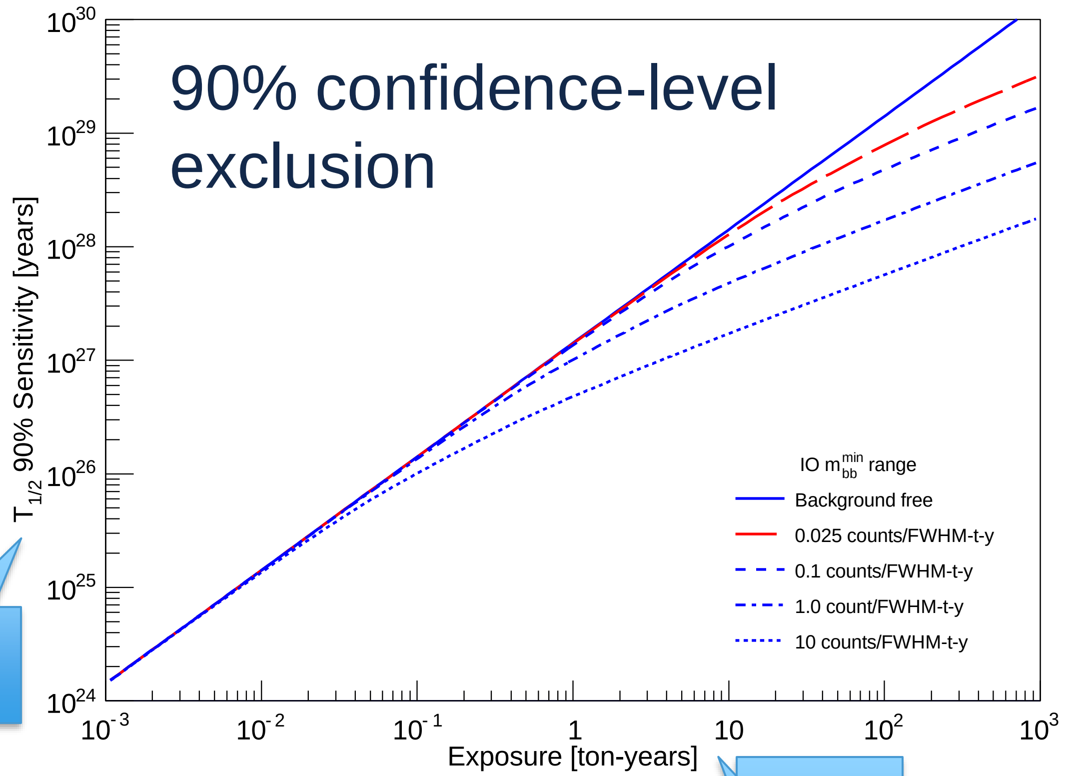
Number of ββ atoms

Livetime

Efficiency

Upper limit on the number of signal counts: depends on experimental backgrounds

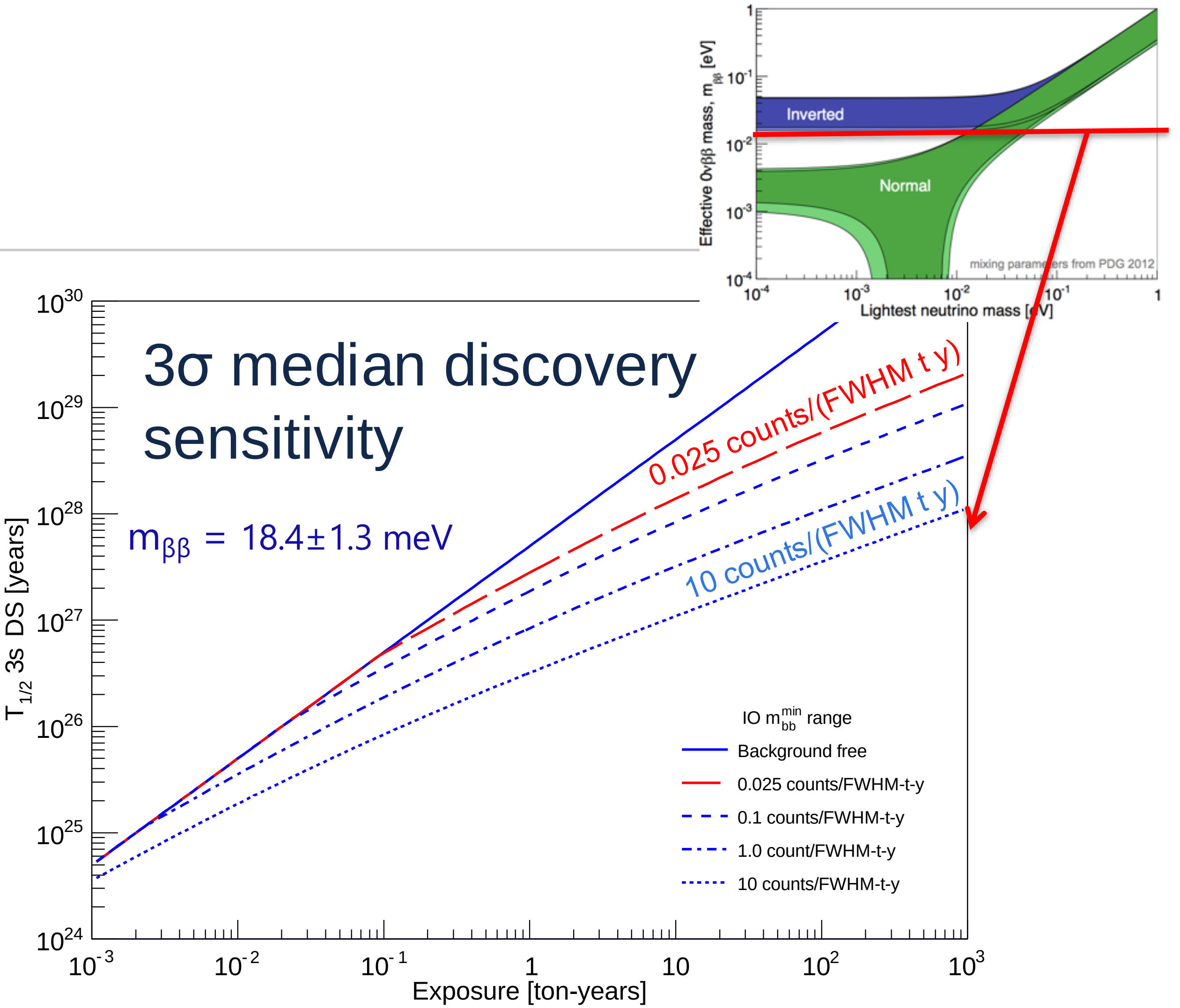
Sensitivity vs. Discovery



90% confidence-level exclusion

$T_{1/2}^{0\nu}$

$N_a T \epsilon$



3σ median discovery sensitivity

$m_{\beta\beta}$ = 18.4±1.3 meV

Example in ^{76}Ge -- $m_{\beta\beta}$ = 18.4 meV corresponds to different $T_{1/2}$ in other isotopes

Reaching Ultra-Long Half-Life

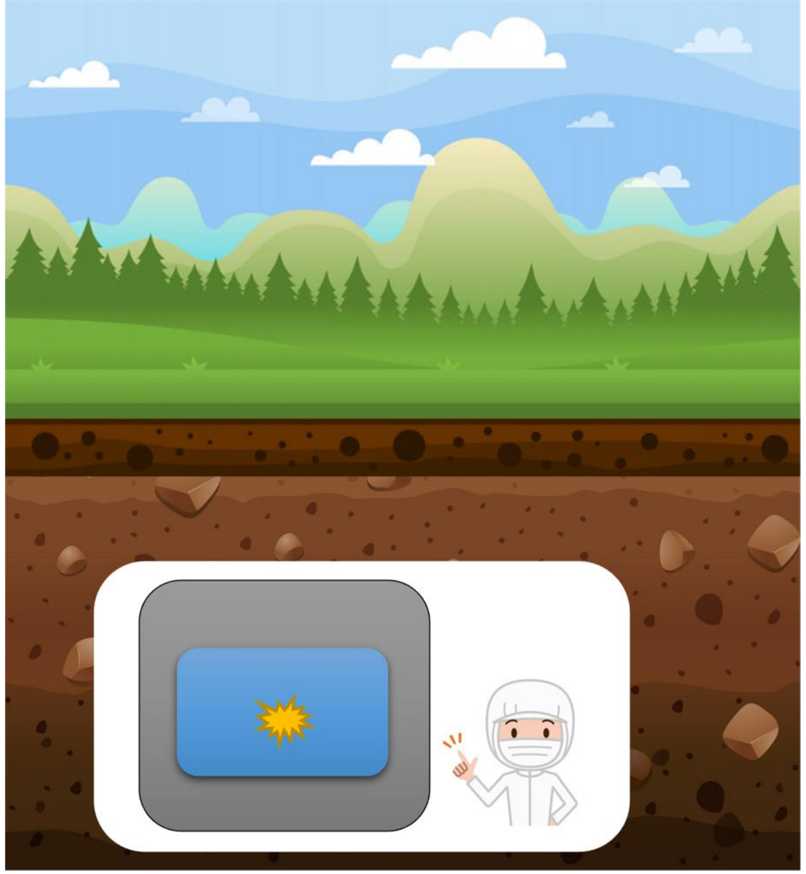
- Best-case scenario: quasi-background-free experiment, 3σ = 3 counts
- Long half-lives mean you need large exposures. For 3-4 counts of 0νββ at…
  - 10^{26} years: 100 kg-years
  - 10^{27} years: 1 ton-year
  - 10^{28} years: 10 ton-years

For higher backgrounds, required exposure increases accordingly

- Goal of the next generation of experiments: cover the bottom of the IO region in discovery mode for most nuclear matrix elements
  - Implies required discovery sensitivities of 10^{27} to 10^{28} years
  - Implies required experimental masses at the ton-scale
- Once you've built a very large, low-background detector, you can search for other things: axions, WIMPs, other exotic BSM

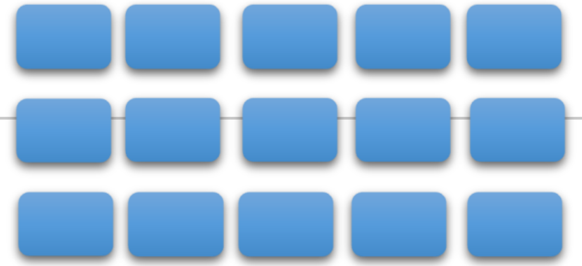
Experimental Techniques

Most Experiments



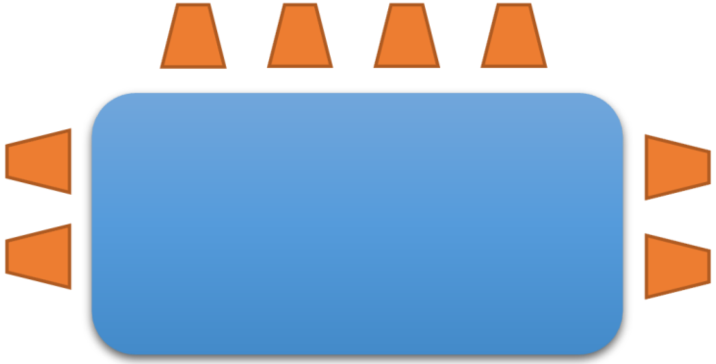
Advantages:
- Energy resolution
- Staging

Granular Detectors



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

Monolithic Detectors



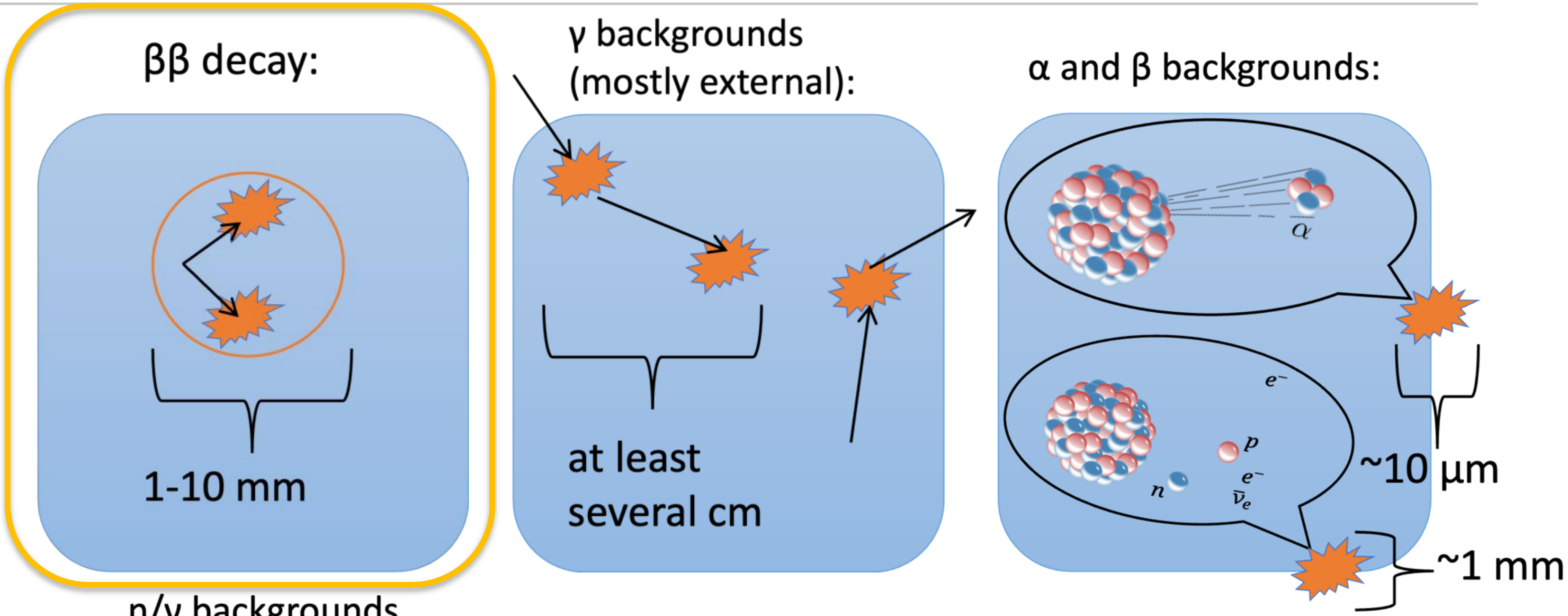
- Scintillators and TPCs
- E.g. KamLAND-Zen, SNO+, nEXO, NEXT

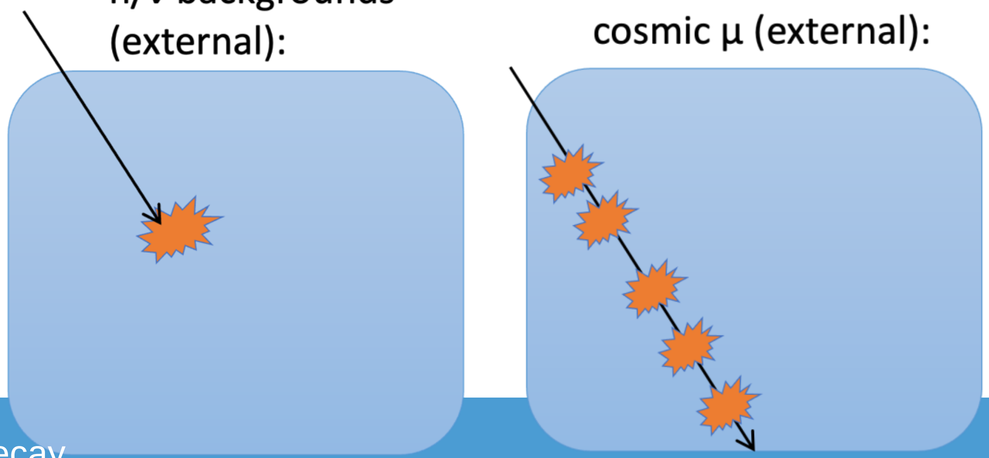
Advantages:
- Self-shielding
- Scalability

0νββ Signal and Backgrounds

Techniques for background suppression:

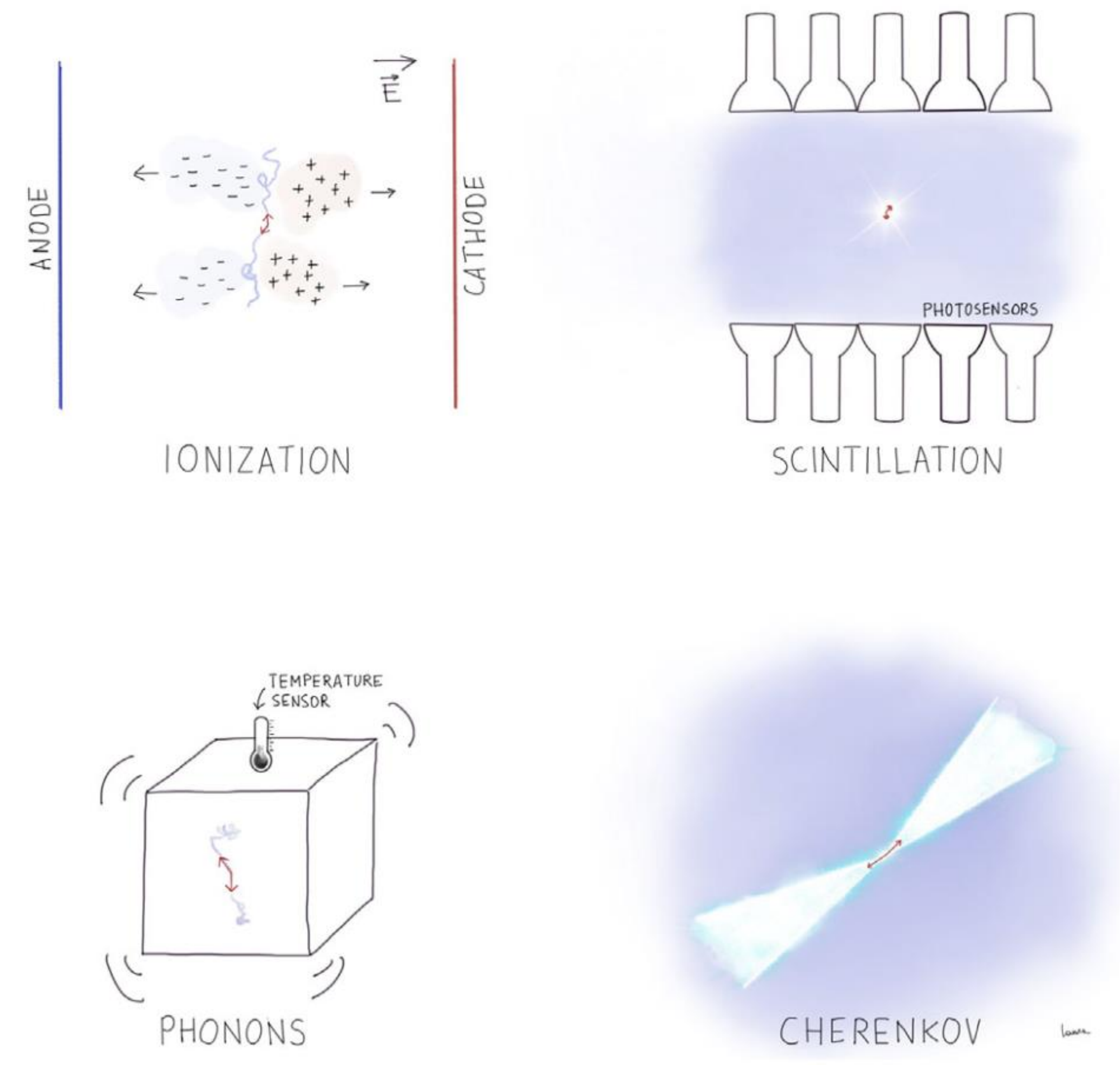
- Event topology
- Time coincidence
- Surface/bulk discrimination
- Veto systems
- Particle identification: distinguish nuclear and electron scatters, dE/dx, etc.
- Tag the daughter atom (R&D)





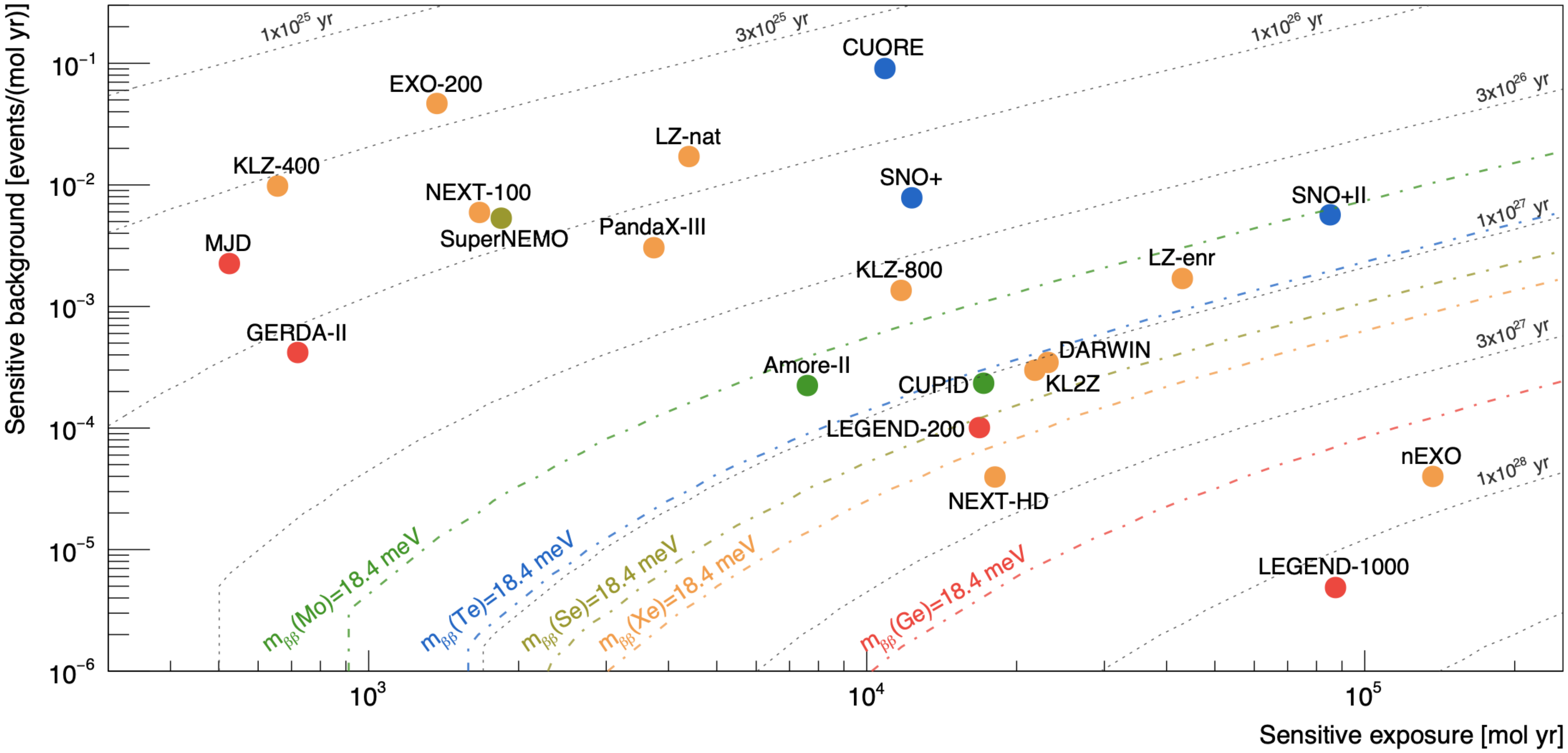
- Differences in range and type of interaction
- γ, β, and μ interact with electrons
- α, ν, and n scatter off of nuclei

0νββ Experiments

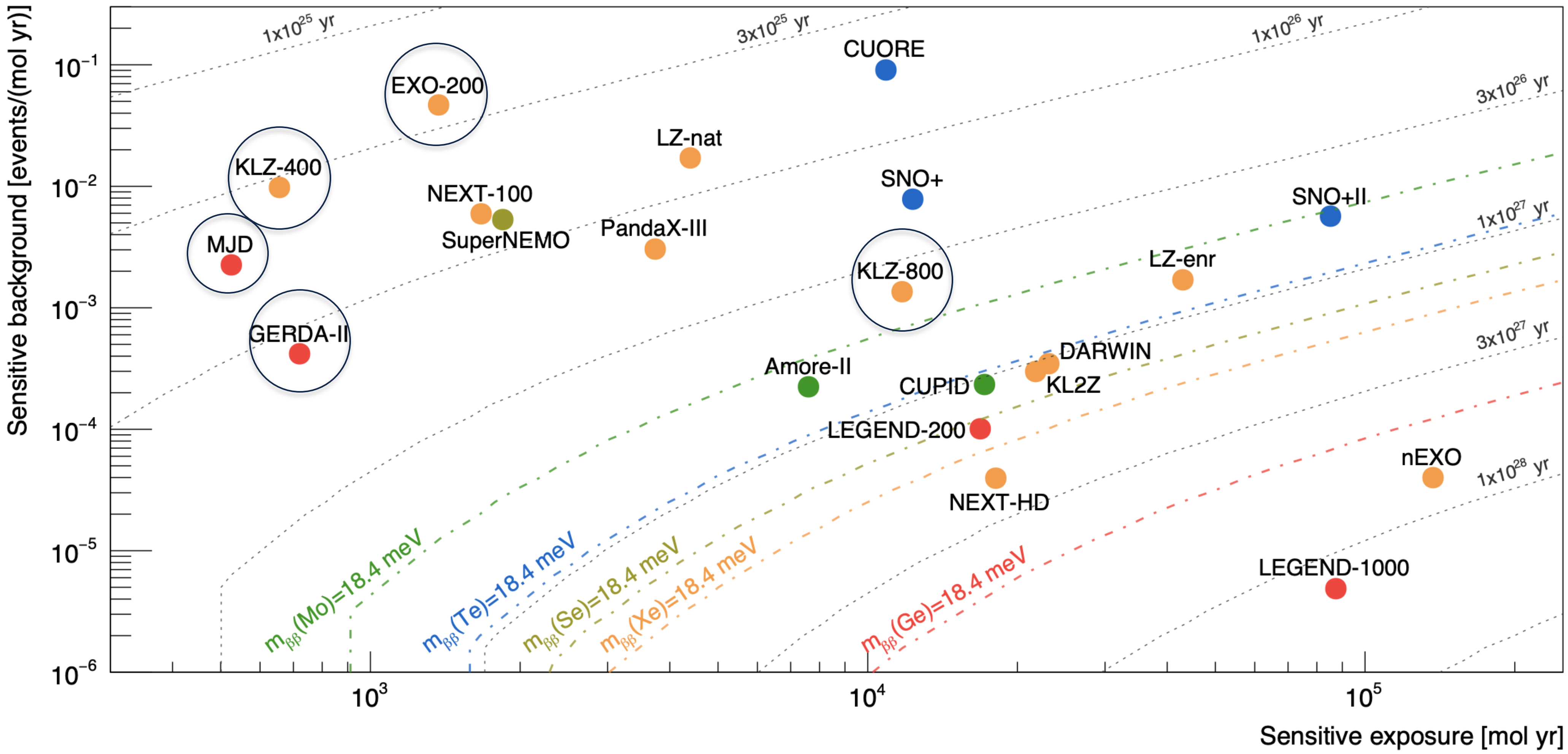


Courtesy L. Maneti, from Agostini et al., Rev. Mod. Phys. 95 (2023)

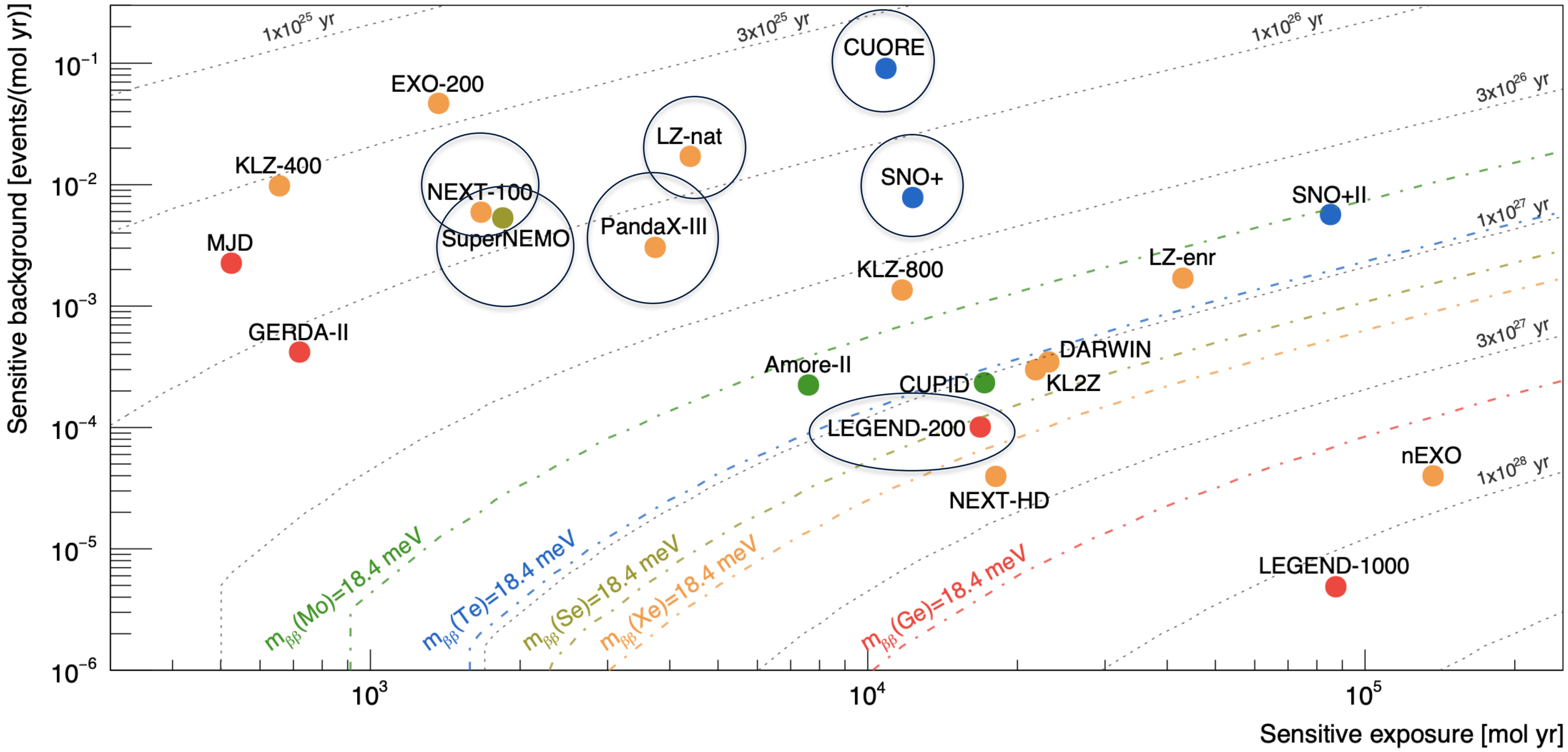
The Experimental Landscape



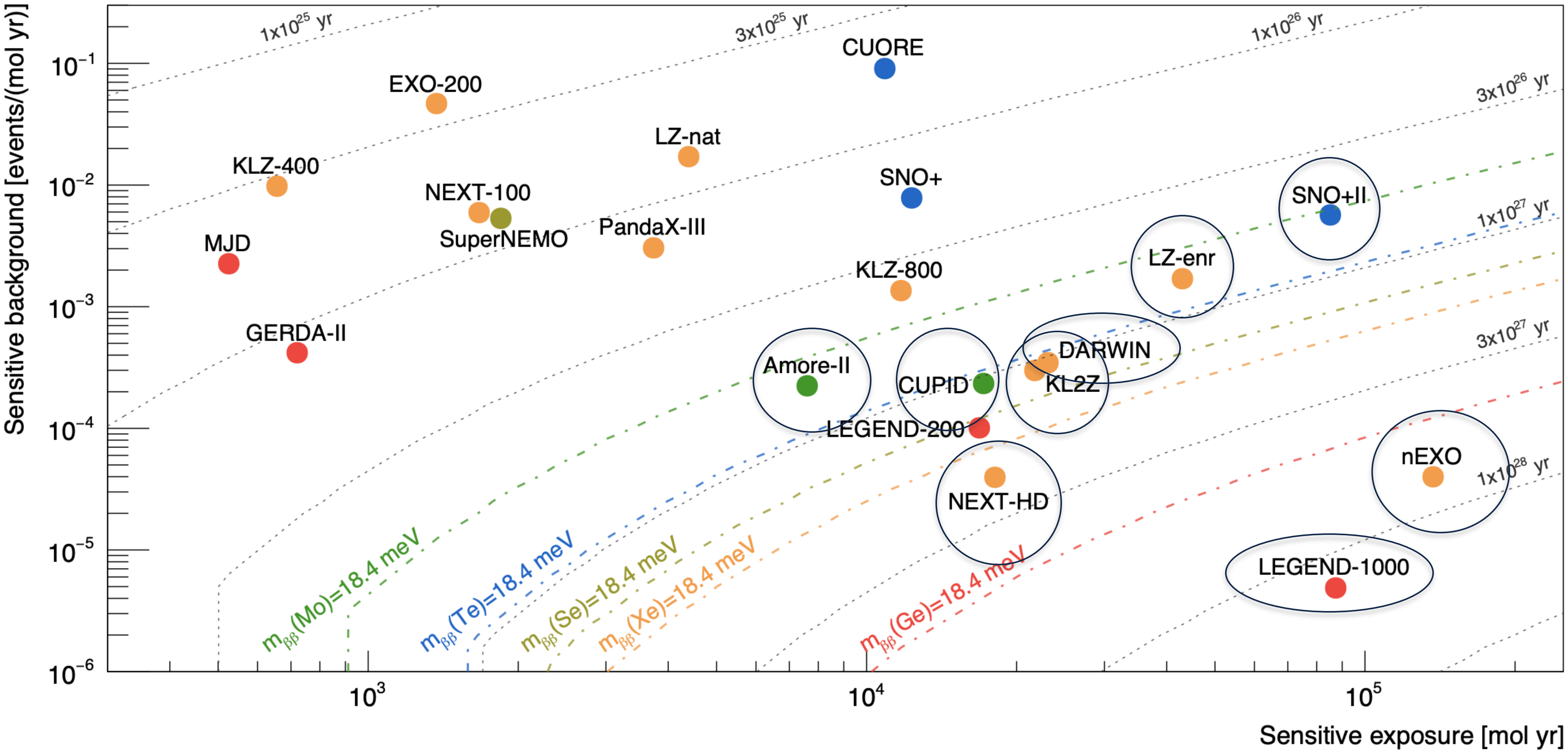
Completed Experiments



Running and Under Construction

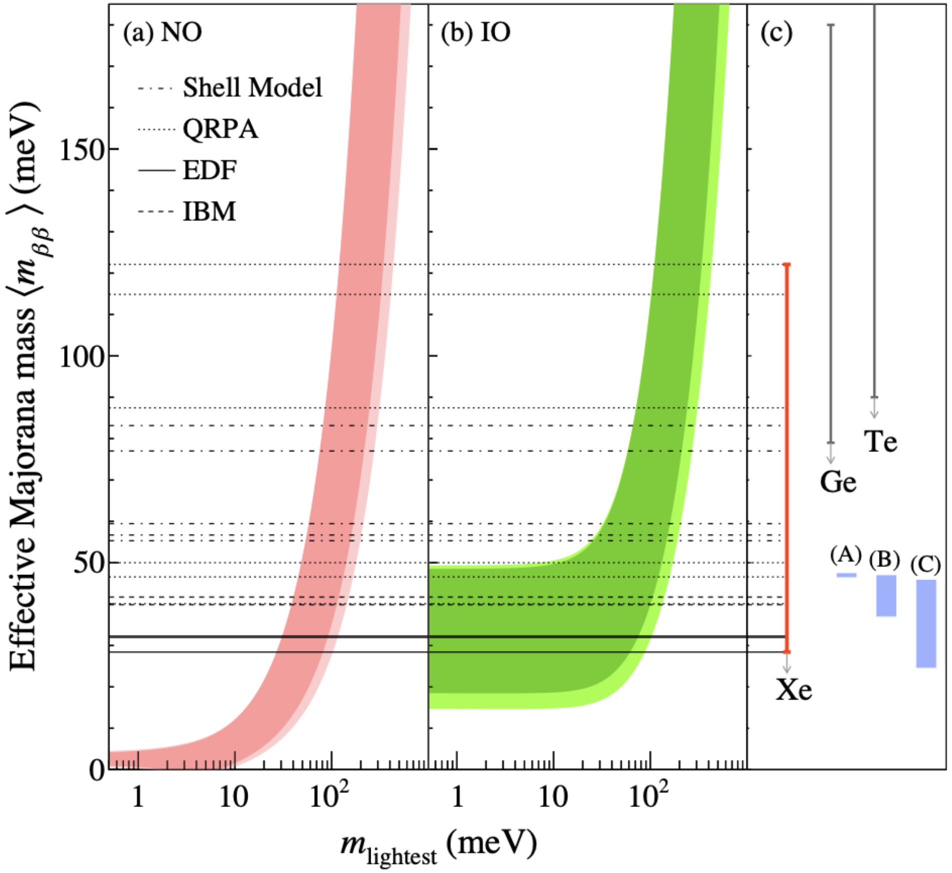


Proposed



Sensitive background [events/(mol yr)]
Sensitive exposure [mol yr]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^3
10^4
10^5
1x10^{25} yr
3x10^{25} yr
1x10^{26} yr
3x10^{26} yr
1x10^{27} yr
3x10^{27} yr
1x10^{28} yr
CUORE
EXO-200
LZ-nat
KLZ-400
NEXT-100
SuperNEMO
PandaX-III
SNO+
MJD
KLZ-800
GERDA-II
SNO+II
LZ-enr
DARWIN
KL2Z
Amore-II
CUPID
LEGEND-200
NEXT-HD
nEXO
LEGEND-1000
$m_{\beta\beta}$(Mo)=18.4 meV
$m_{\beta\beta}$(Te)=18.4 meV
$m_{\beta\beta}$(Se)=18.4 meV
$m_{\beta\beta}$(Xe)=18.4 meV
$m_{\beta\beta}$(Ge)=18.4 meV

Current Best Limits on 0νββ



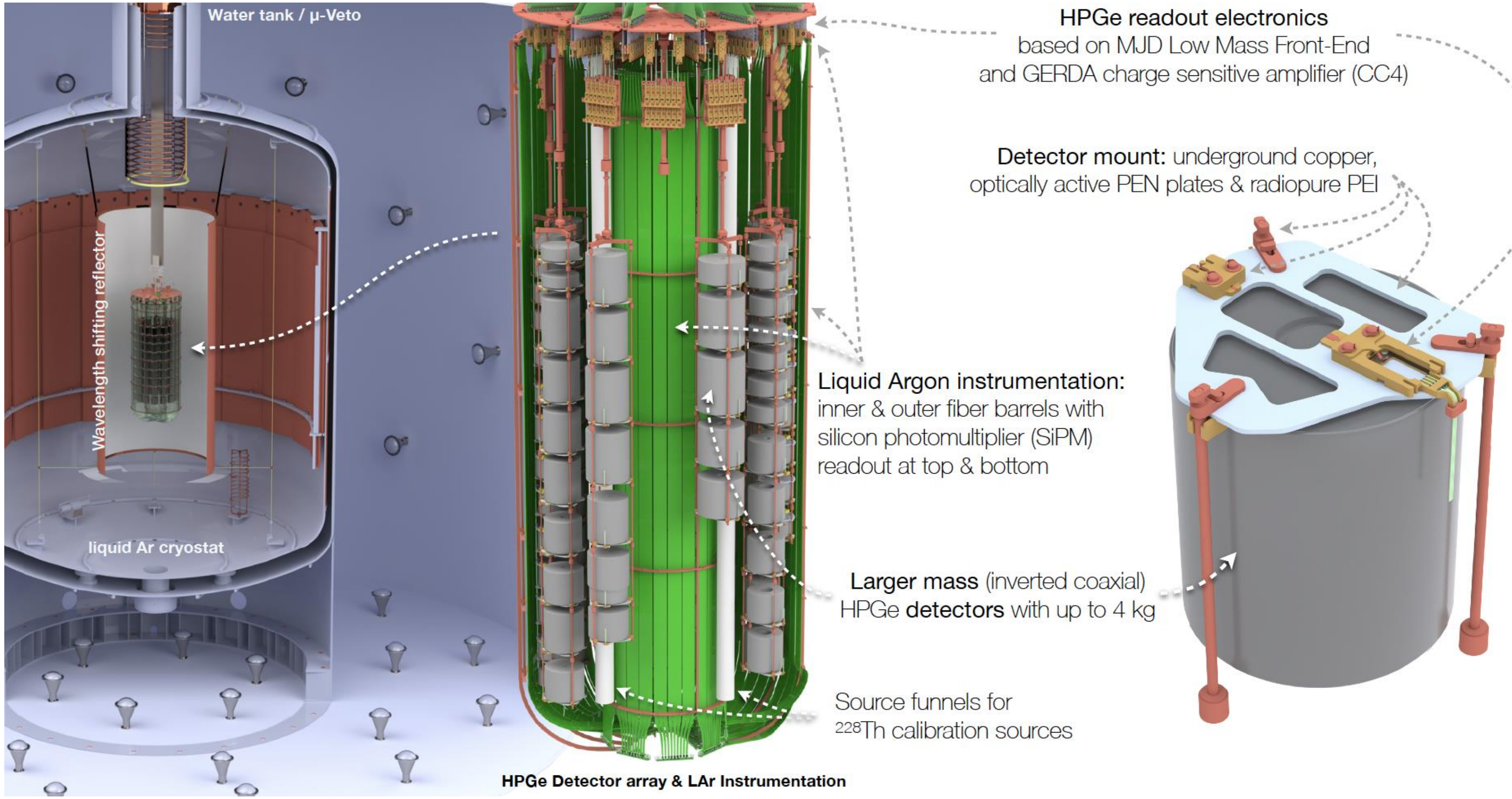
arXiv: 2406.11438

Experiment	Isotope	Exposure [kg yr]	$T^{0\nu}_{1/2}$ [10^{25} yr]	$m_{\beta\beta}$ [meV]
GERDA+MJD +L200	^{76}Ge	246.8	19	77-175
KamLAND-Zen 800	^{136}Xe	2097	38	28-122
CUORE	^{130}Te	2039	3.8	70-240

New results from LEGEND-200 and CUORE announced at Neutrino ‘24, not yet published

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

LEGEND-200



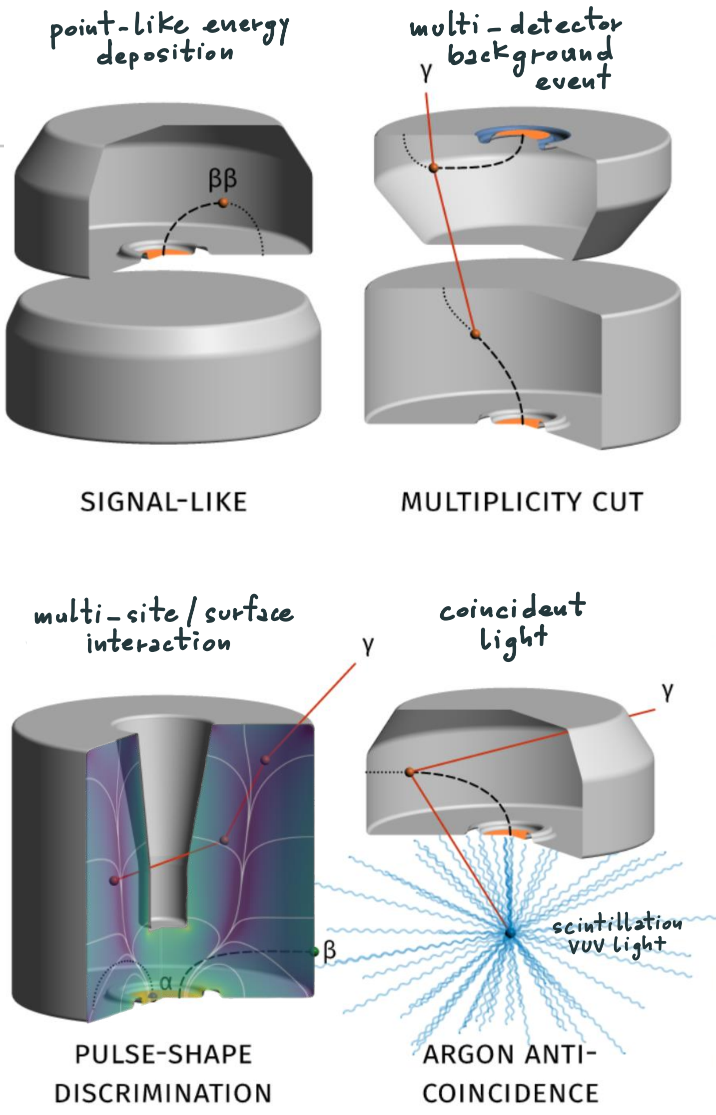
HPGe readout electronics
based on MJD Low Mass Front-End
and GERDA charge sensitive amplifier (CC4)

Detector mount: underground copper,
optically active PEN plates & radiopure PEI

Liquid Argon instrumentation:
inner & outer fiber barrels with
silicon photomultiplier (SiPM)
readout at top & bottom

Larger mass (inverted coaxial)
HPGe **detectors** with up to 4 kg

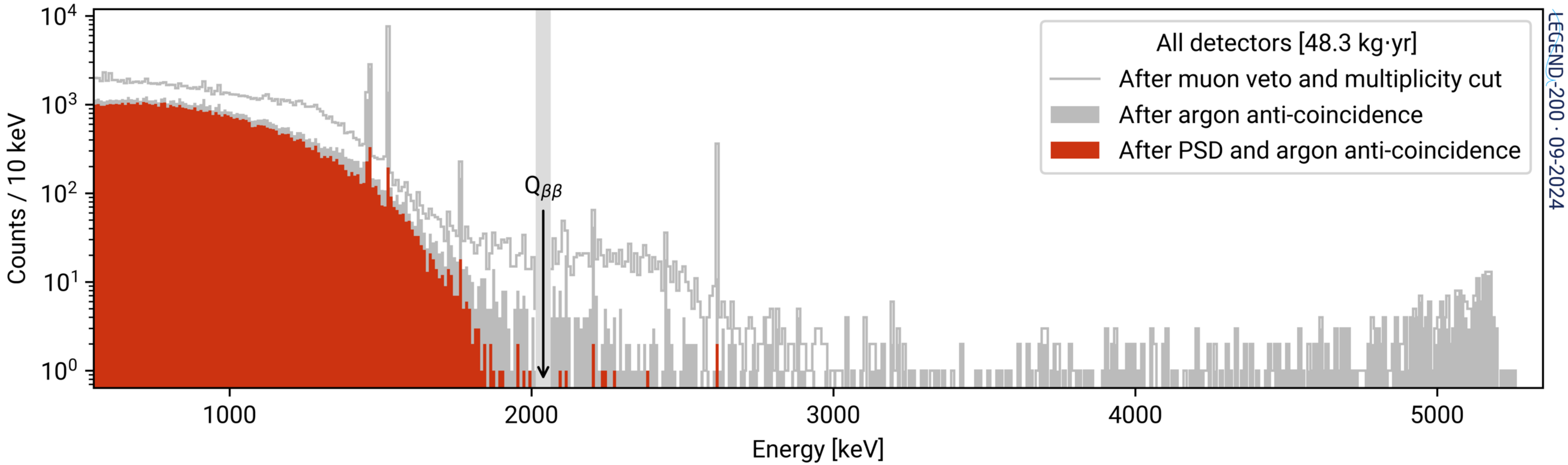
Source funnels for
^{228}Th calibration sources



New LEGEND-200 Results

March 2023 - February 2024: Initial physics data taking with 142 kg of detectors

Golden Dataset: 48.3 kg yr initially unblinded



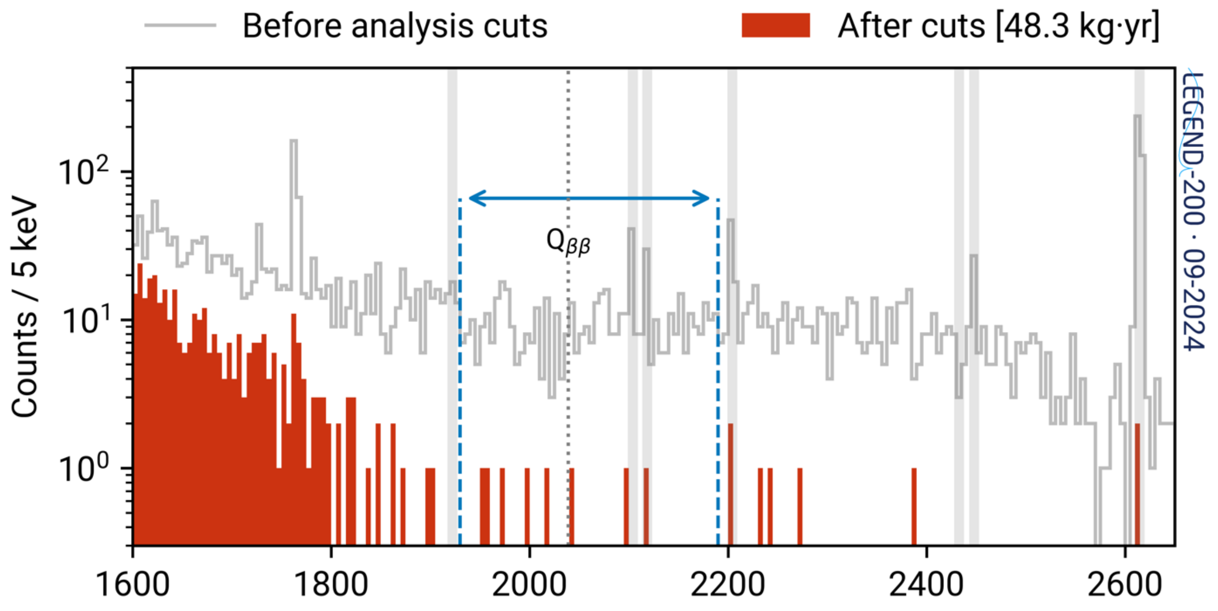
New LEGEND-200 Results

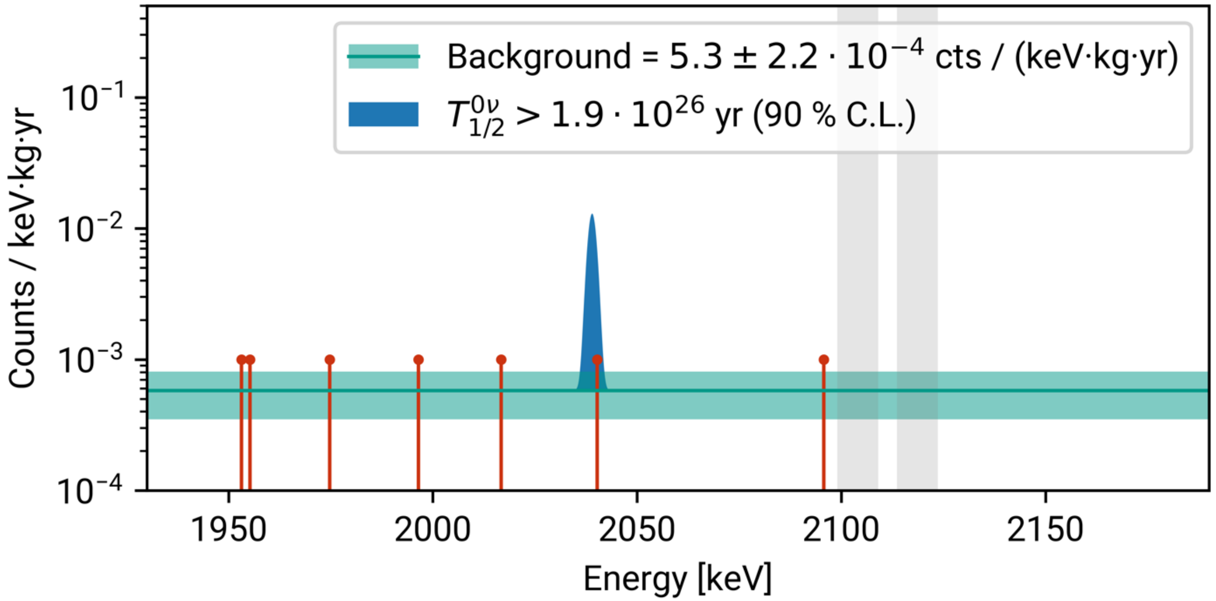
March 2023 - February 2024: Initial physics data taking with 142 kg of detectors

Golden Dataset: 48.3 kg yr initially unblinded

Background Index = $(5.2 \pm 2.2) \times 10^{-4}$ cts/(keV kg yr)

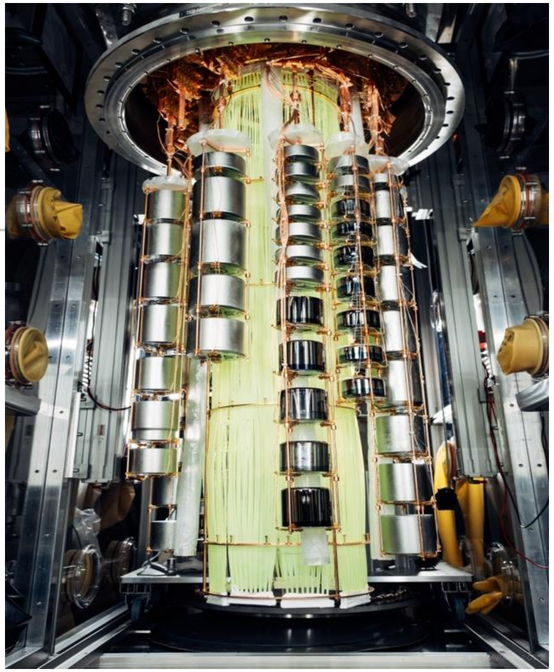
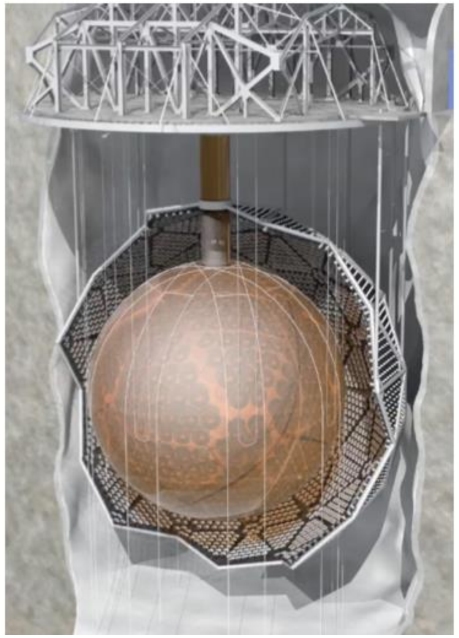
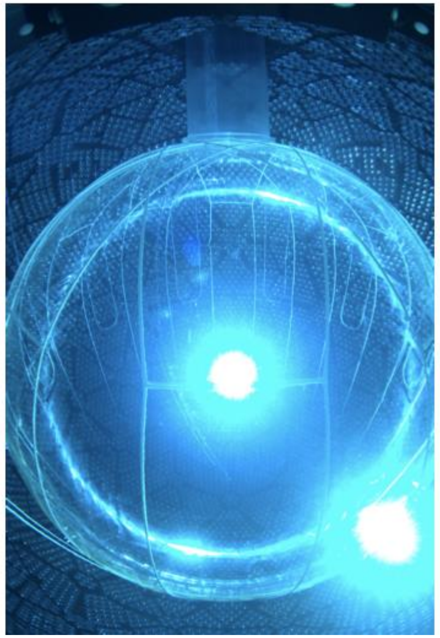
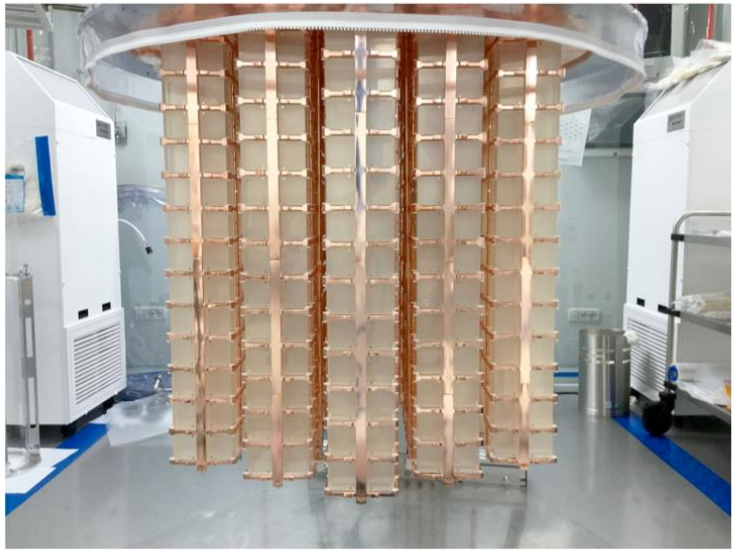
Combined fit: $T^{0\nu\beta\beta}_{1/2} > 1.9 \times 10^{26}$ yr





More Results Coming Soon…

- CUORE: continuing to run (background-limited)
- LEGEND-200: continuing to run, expect ultimate half-life sensitivity of 1×10^{27} yrs
- SNO+ Te-loading due to begin in 2025, with initial planned sensitivity of 2×10^{26} yrs
- KamLAND2-Zen: upgrade beginning, with planned sensitivity of 2×10^{27} yrs

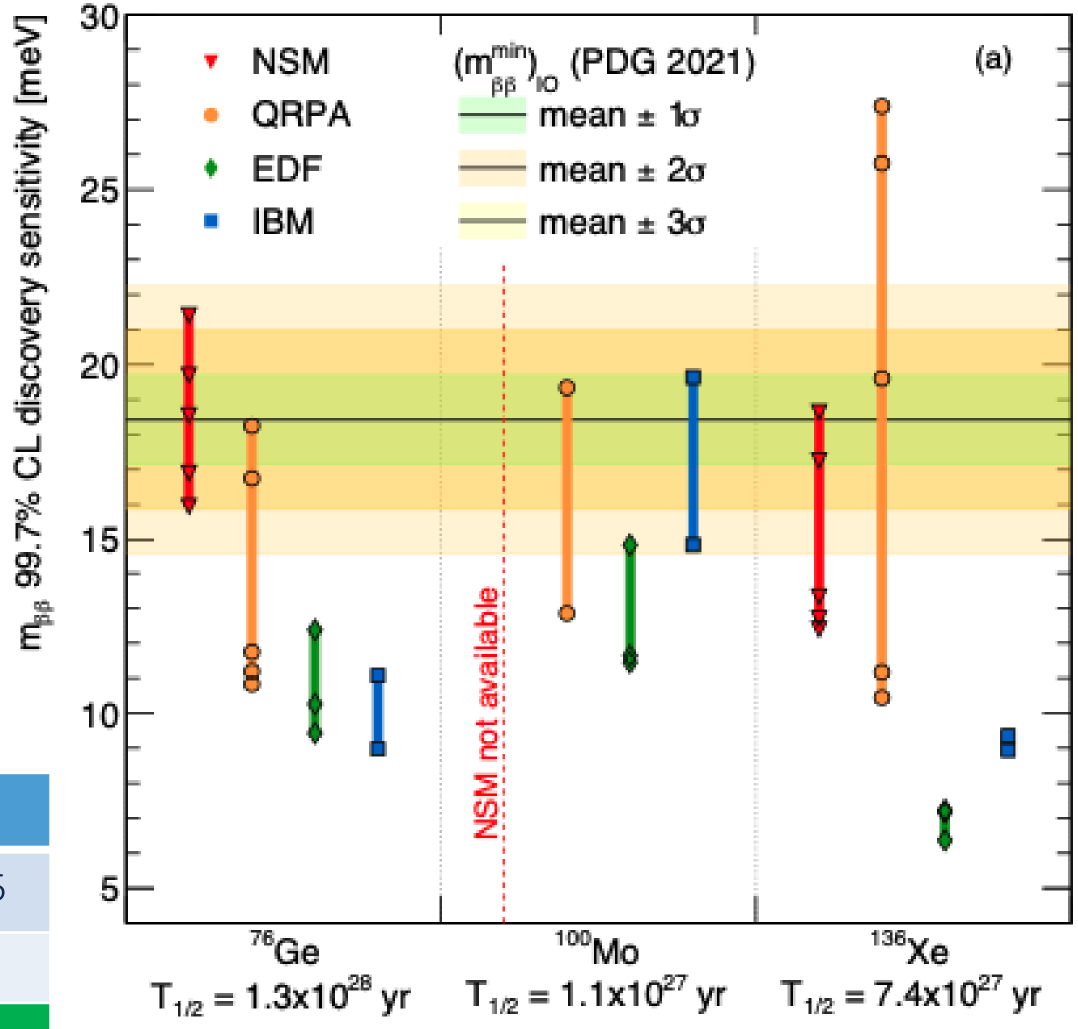






The Ton-Scale Generation

- Covering the IO in discovery mode requires O(1 ton) of isotope
- 3 candidate experiments currently in design and proposal phase: LEGEND, nEXO, and CUPID
- All 3 experiments cover the IO for some matrix elements, and miss for others

LEGEND-1000 Timeline				
2024 -2025	2026-2029	2030	2031-2035	2036-2045
Design	Construction			
		Early Physics Data		Operations

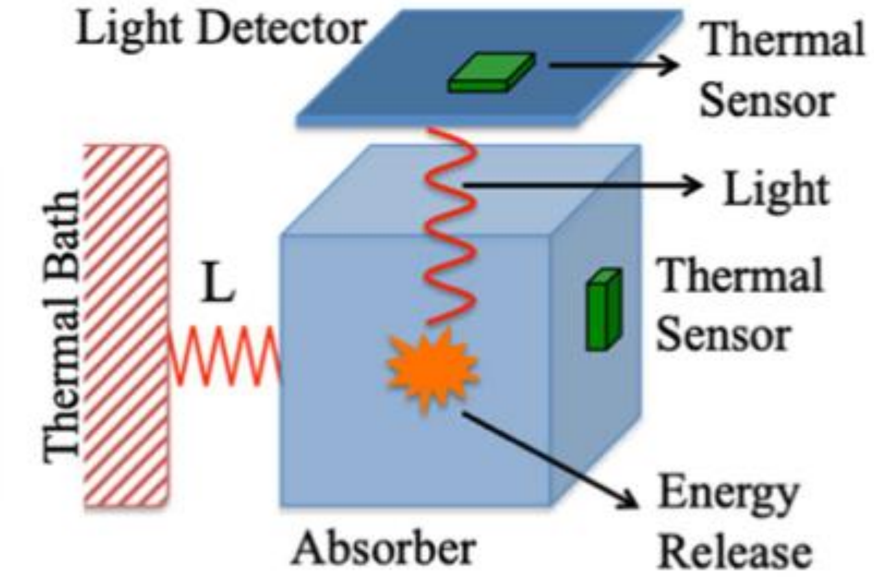
Discovery Sensitivity for the "Big 3"



10.1103/PhysRevC.104.L042501

CUPID

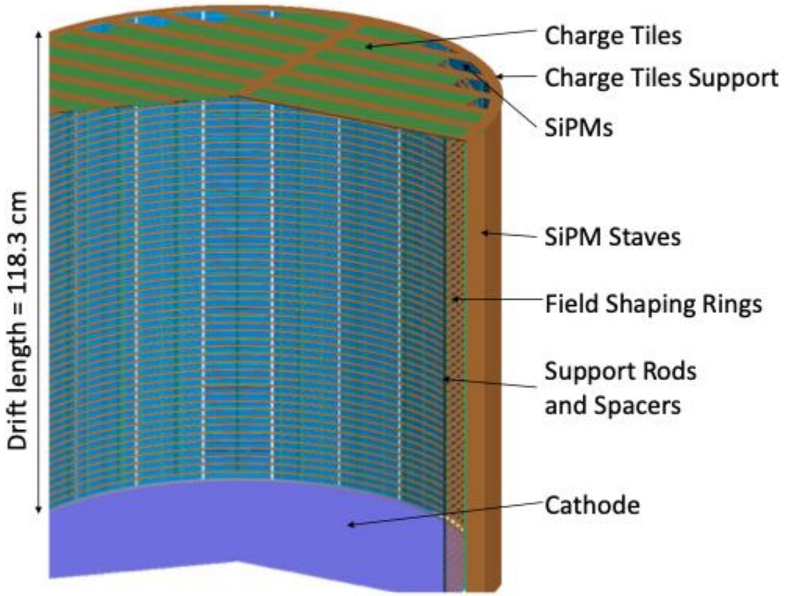
- Tonne-scale bolometer approach demonstrated in CUORE
- Scintillating bolometer technique demonstrated in CUPID-Mo and other experiments, allows for α rejection
- Switch from CUORE crystals to scintillating bolometers with light readout in existing infrastructure



- 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

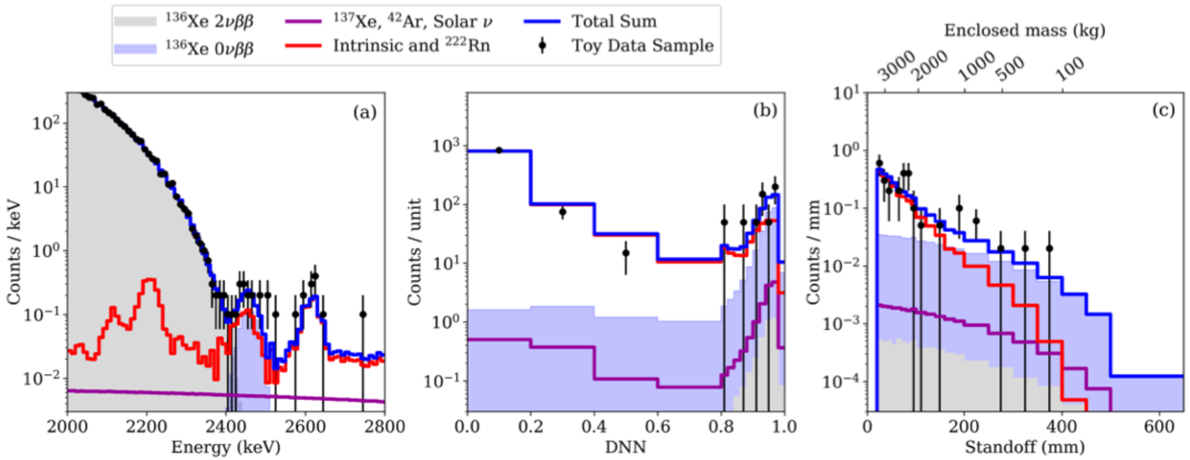
Material provided by CUORE, CUPID, CUPID-Mo, and CUPID-0 Collaborations

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

- 5000 kg of ^{enr}Xe
- Enriched to 90% ^{136}Xe
- Energy res. (σ_E/E): 0.8%
- Discovery sensitivity: $T_{1/2} \sim 7.4 \times 10^{27}$yrs
- m discovery sensitivity: 5.27 meV

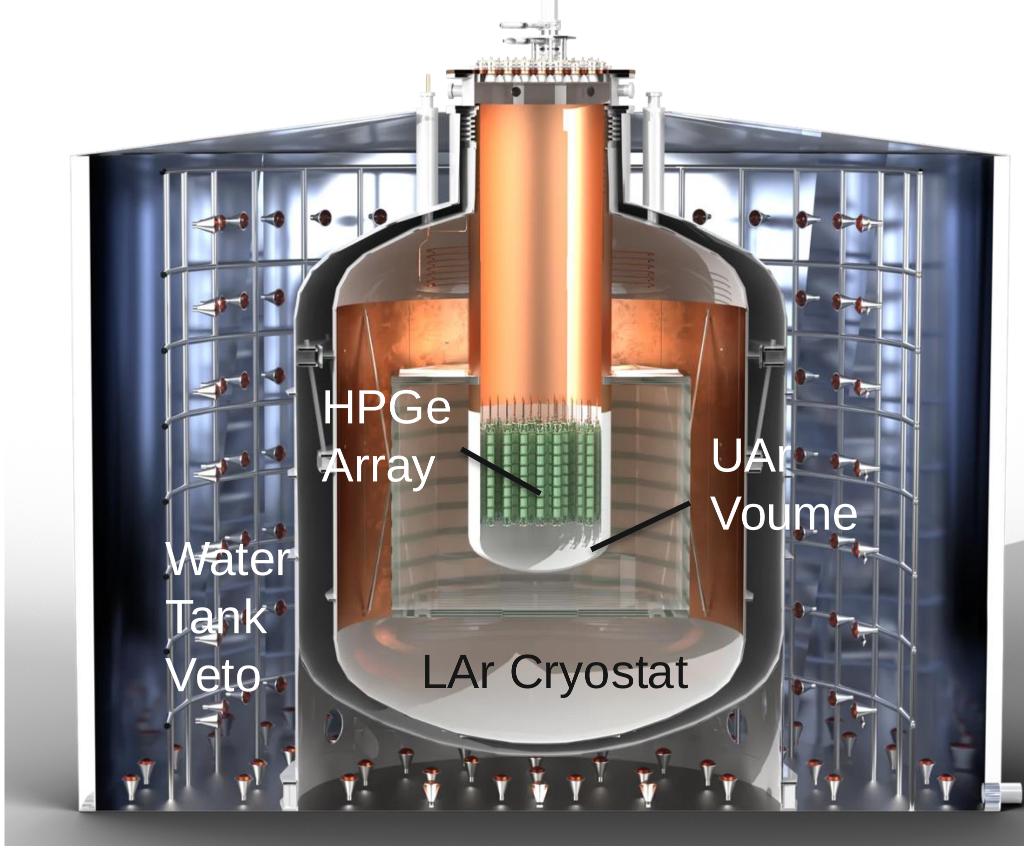


J. Phys. G: Nucl. Part. Phys. 49, 015104 (2022)

LEGEND-1000

- Builds on techniques from MJD, GERDA, and LEGEND-200
- HPGe inverted-coaxial point-contact detectors in LAr active shield:
  - Multi-site and surface event rejection
  - Excellent energy resolution (~0.1% FWHM)
- New cryostat LNGS using underground Argon, cleaner electronics, and larger-mass detectors

- 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



What Comes Next?

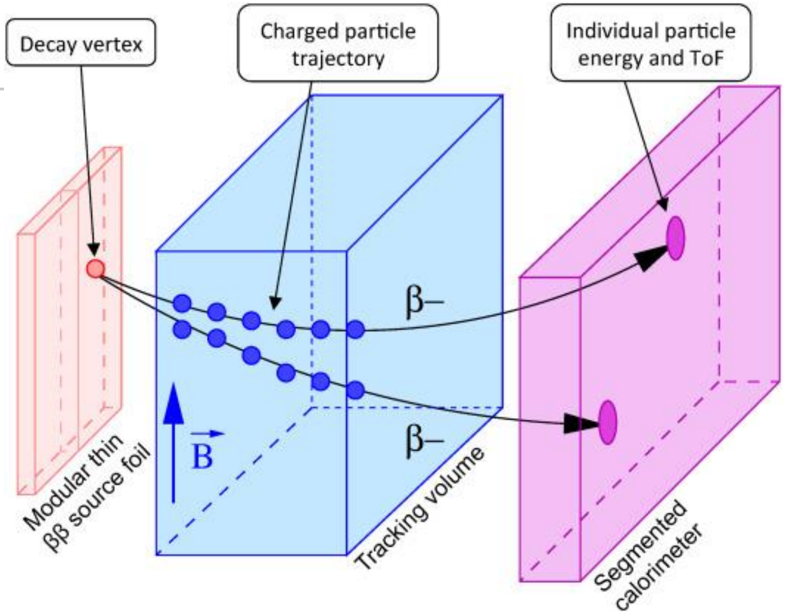
If we make a discovery at the ton scale (or before):

- Measure in more isotopes
- “HyperNEMO” or other options to measure ββ kinematics

If not:

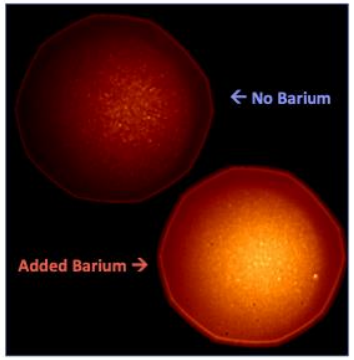
- Next-next-generation experiments are targeting $m_{\beta\beta} \sim 10$ meV or smaller
- At the moment, there is no “magic bullet” to reach the 1 meV level
- There are, however, many ideas and there is a rich R&D program pursuing the needed techniques

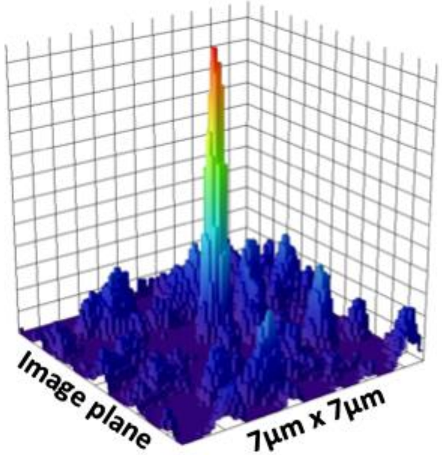
SuperNEMO



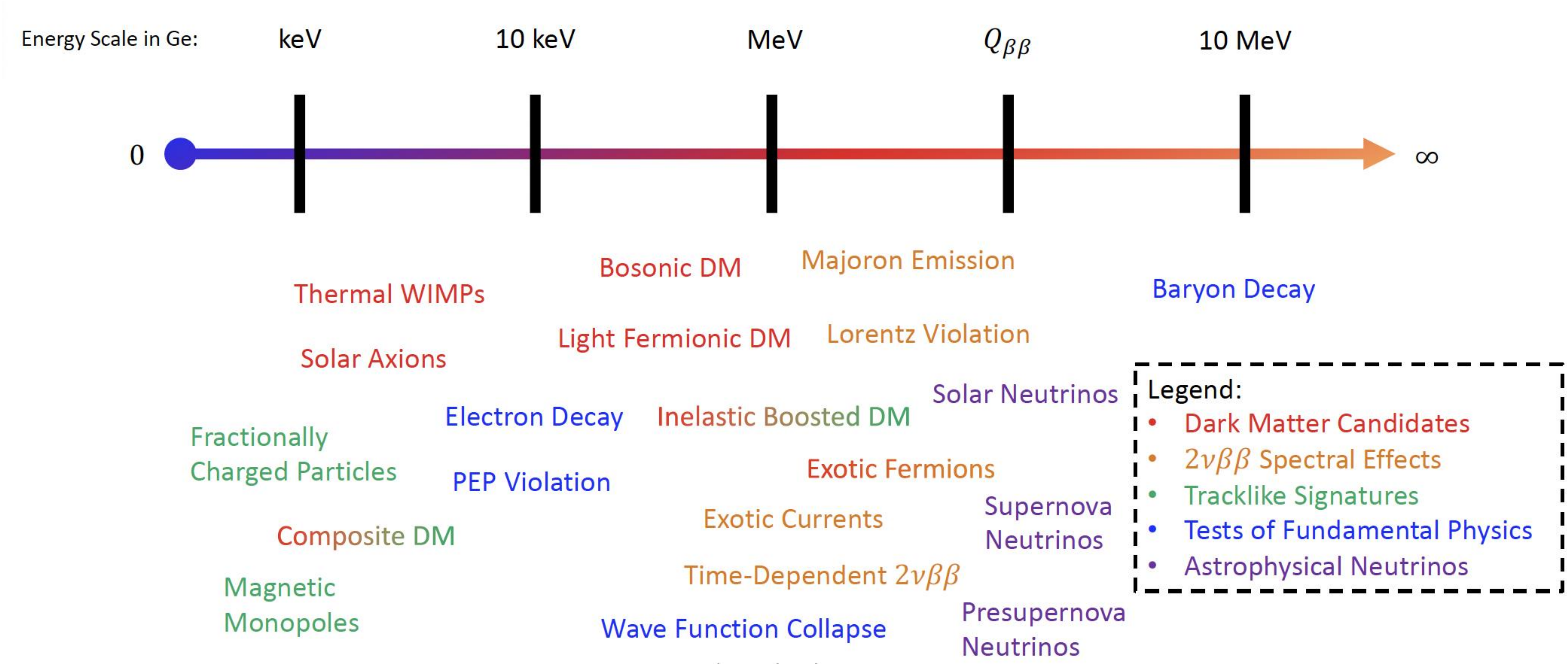
R&D for ultra-large Xe TPCs: new acquisition strategies and Ba tagging

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





BSM and Other Physics in 0νββ Detectors



Thermal WIMPs

Solar Axions

Fractionally Charged Particles

Composite DM

Magnetic Monopoles

Bosonic DM

Light Fermionic DM

Electron Decay

PEP Violation

Inelastic Boosted DM

Exotic Currents

Time-Dependent $2\nu\beta\beta$

Wave Function Collapse

Majoron Emission

Lorentz Violation

Exotic Fermions

Solar Neutrinos

Supernova Neutrinos

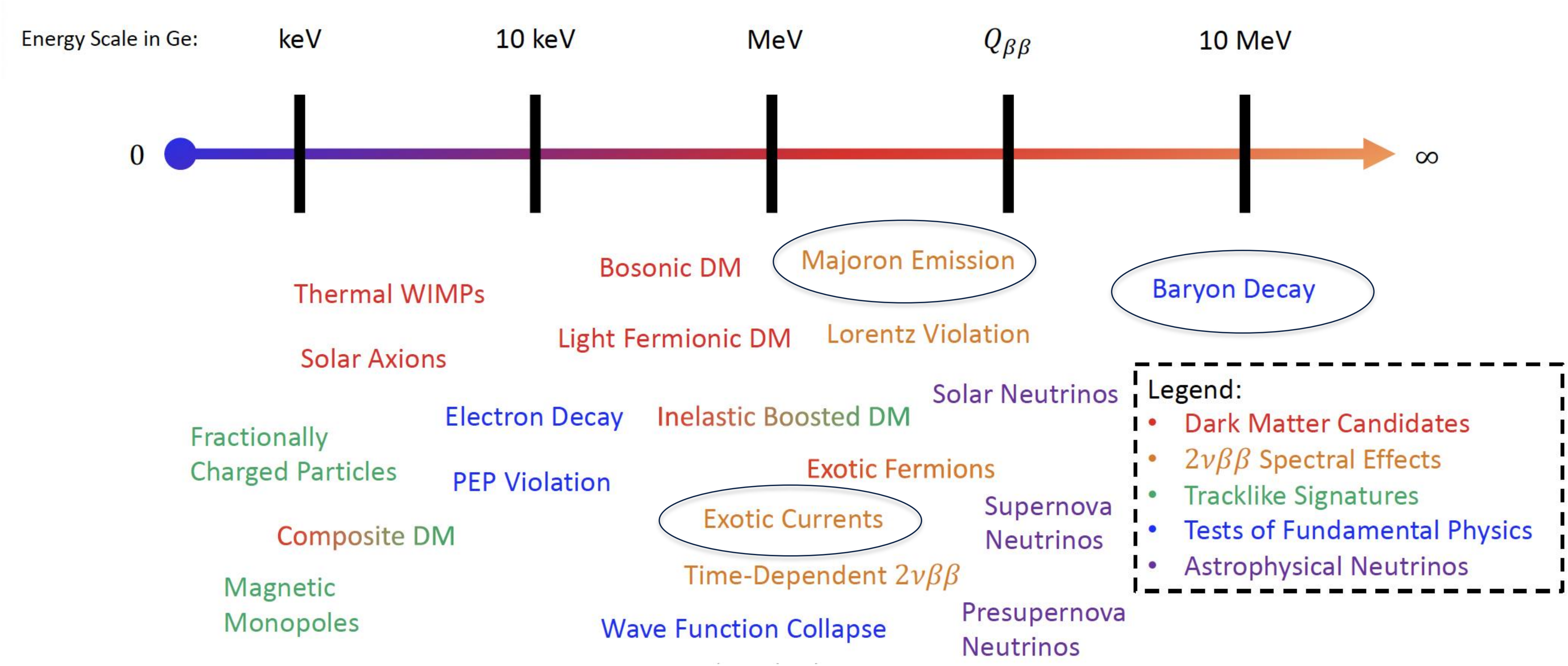
Presupernova Neutrinos

Baryon Decay

Legend:

- Dark Matter Candidates
- $2\nu\beta\beta$ Spectral Effects
- Tracklike Signatures
- Tests of Fundamental Physics
- Astrophysical Neutrinos

Baryon and Lepton Number Violation Searches



Energy Scale in Ge: keV 10 keV MeV $Q_{\beta\beta}$ 10 MeV

0 ∞

Thermal WIMPs

Solar Axions

Fractionally Charged Particles

Composite DM

Magnetic Monopoles

Electron Decay

PEP Violation

Bosonic DM

Light Fermionic DM

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Legend:
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- Astrophysical Neutrinos

BSM and Other Physics in 0νββ Detectors

Mechanism	Signature	Energy range	Status	*Recent* Germanium References
Bosonic Dark Matter	Peak at m_b	5 — 100keV	Done in MJD, GERDA	PRL 118 (2017) 161801, PRL 125 (2020) 011801, PRL 132 (2024) 041001, EPJ C84 (2024) 940
Baryon Decay	Time Correlation, High Energy	0-10 MeV	Done in MJD	PRD 99 (2019) 072004 EPJ C83 (2023) 778
Fractionally Charged Cosmic rays	High Multiplicity-coincidence events	Few keV	Done in MJD	PRL 120 (2018) 211804
WIMP searches	Exponential Excess + Annual Modulation. Migdal Effect	< 10 keV	CDEX/MALBEK/CoGeNT	PRL 120 (2018) 241301, Phys. Procedia 61 (2015) 77
Solar axions	Peaked Spectra + daily modulation	< 10 keV	Partially Done in MJD	PRL 118 (2017) 161801; Astropart.Phys. 89 (2017) 39, Wiseman PhD Thesis
Majoron Emission	2νββ spectral distortion	$Q_{\beta\beta}$	Done in GERDA	EPJ. C75 (2015) 416
Lorentz Violation	2νββ spectral distortion	$Q_{\beta\beta}$		PRD 88 (2013) 071902
Electron Decay	Peak at 11.8 keV	~10 keV	Done in MJD	PRL 118 (2017) 161801, Nat. Phys. 20 (2024) 1078, EPJ C84 (2024) 940
Pauli Exclusion Principle Violation	Peak at 10.6 keV	~ 10 keV	Done in MJD	PRL 118 (2017) 161801, Nat. Phys. 20 (2024) 1078
BSM physics in Ar	Features in Ar Veto spectrum		ECEC in Ar36 (GERDA)	EPJ C75 (2015) 416

+ Prompt Supernova Neutrinos, SuperWIMPS, Solar Neutrinos, QM Wavefunction Collapse…

Conclusion

- Neutrino mass is BSM physics, and we still haven't explained it
- 0νββ gives access to Lepton Number Violation up to the highest energy scales
- Regardless of the mechanism, 0νββ would be a direct observation of lepton number violation and prove that neutrinos have Majorana mass
- Expect searches reaching further into the IO band in the next 5 years
- The coming generation of experiments is exploring very rich parameter space and (hopefully) beginning very soon, with rich R&D to go further