DUNE Expanded Scope Session: 0νββ

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Snowmass Community Summer Study

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THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

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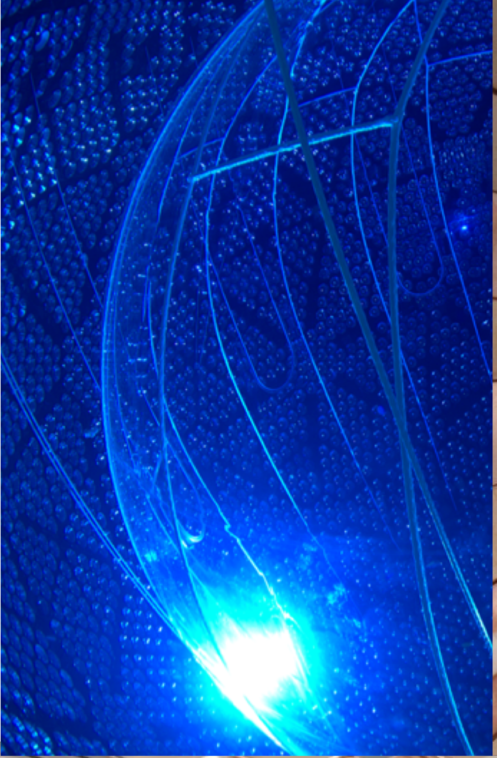
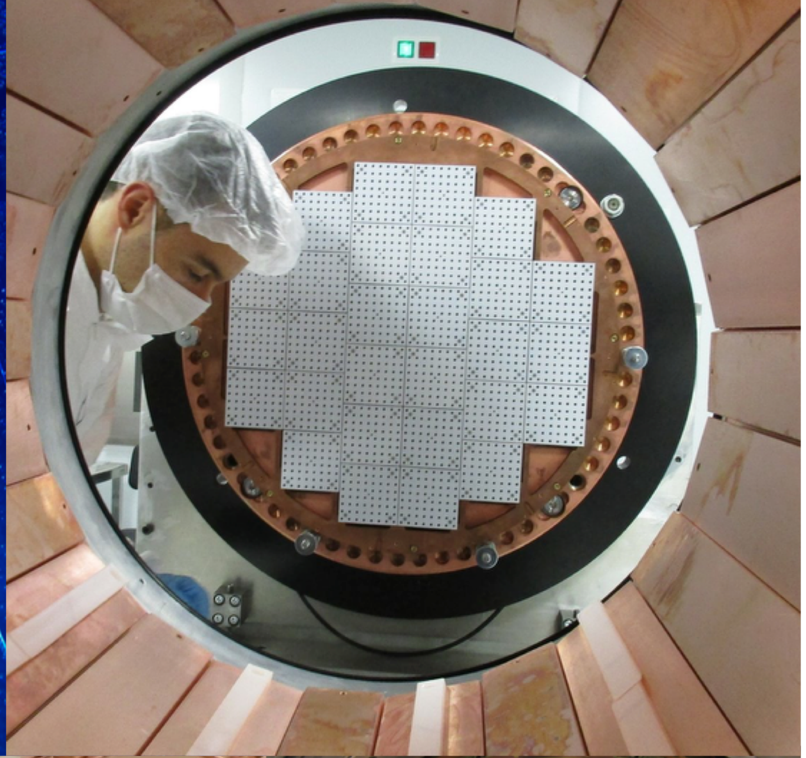
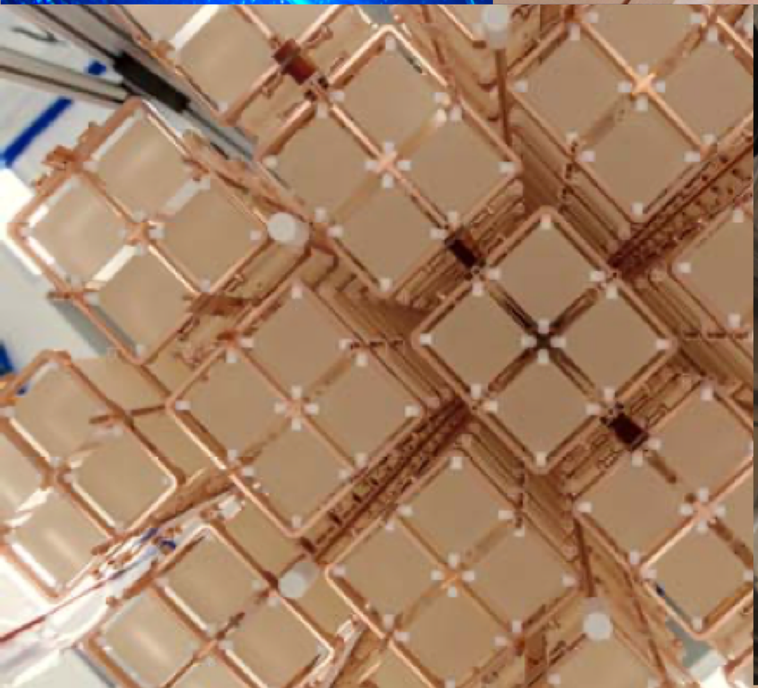
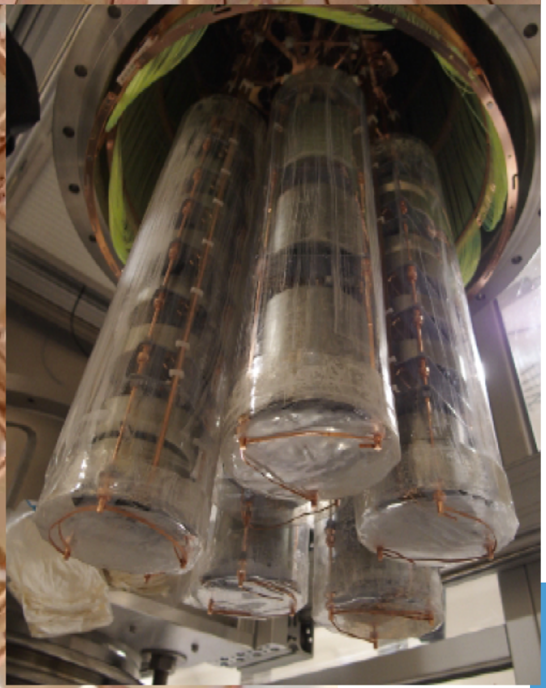





Outline

- Why look for 0νββ?
- 0νββ sensitivity and discovery
- Current status and near-term future

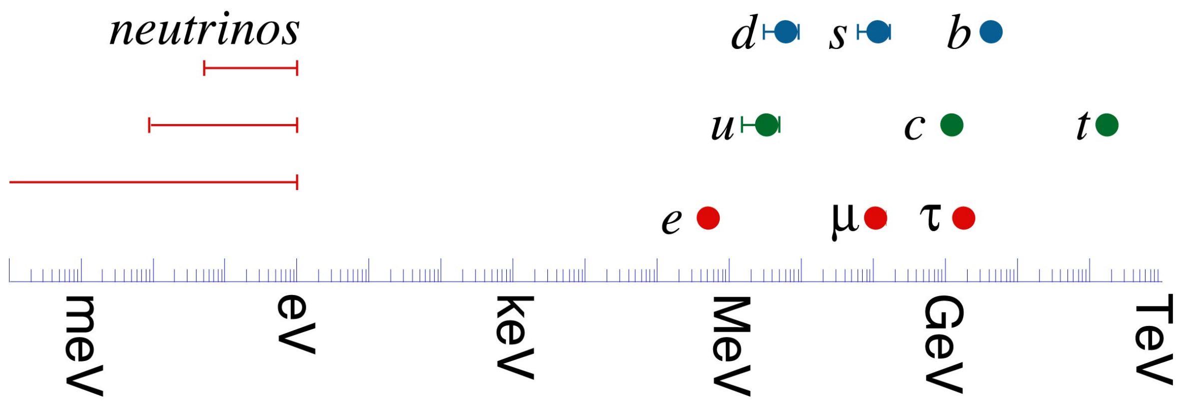
Why look for 0νββ?

Motivating BSM Physics

- Need answers to:
  - What is dark matter?
  - What is dark energy/the mechanism behind the cosmological constant?
  - What generates neutrino mass?
  - What created the matter/antimatter asymmetry?
- Would like answers to:
  - Naturalness problems
  - CP conservation in QCD
  - Unification, flavor, etc…

The Surprising Neutrino Mass

- A reminder: neutrino mass is not in the Standard Model!
- This is one of the few observations we have of Beyond-the-Standard Model physics
- Another surprise: neutrino mass is very small



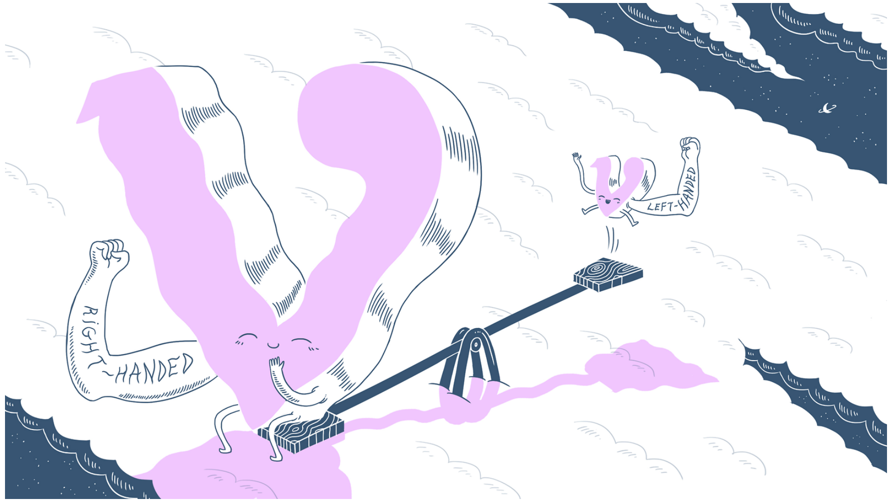
The Surprising Neutrino Mass

Two options for neutrino mass terms:

- Dirac mass:
  - Requires two **non-interacting** new fields, ν_R and $\overline{\nu_L}$
  - Leads to hierarchy problem
- Majorana mass:
  - No new fields required; $\overline{\nu_R} = \nu_R$ and $\nu_L = \overline{\nu_L}$
  - Can be generated by new physics at TeV - GUT scale
- Both may be present; any non-zero Majorana mass makes the neutrino a Majorana fermion
- Majorana neutrino masses can be generated by a range of models

The Type I See-Saw Mechanism

- Including both Majorana and Dirac mass terms can generate two light neutrinos, ν and $\bar{\nu}$, and two heavy neutrinos, N and $\bar{N}$
- If the Majorana mass term is of the GUT scale (~10^{14} GeV) and Dirac mass term is of EW scale (~100 GeV):
  - $m_{\nu} \sim 0.1$ eV
  - $m_N \sim 10^{14}$GeV
- This gives a “natural” neutrino of the correct mass by introducing a new GUT-scale particle



The Matter Asymmetry Problem

- Today, all the structure we see in the universe is made up of matter, with no significant quantity of antimatter
- Baryon asymmetry measurements give $\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 6\times10^{-10}$
- We believe this asymmetry has to have been **generated dynamically**, not as an initial condition

Making an Asymmetry: The Sakharov Conditions

In 1967, Sakharov proposed 3 conditions required for baryon-generating interactions that would generate an asymmetry:

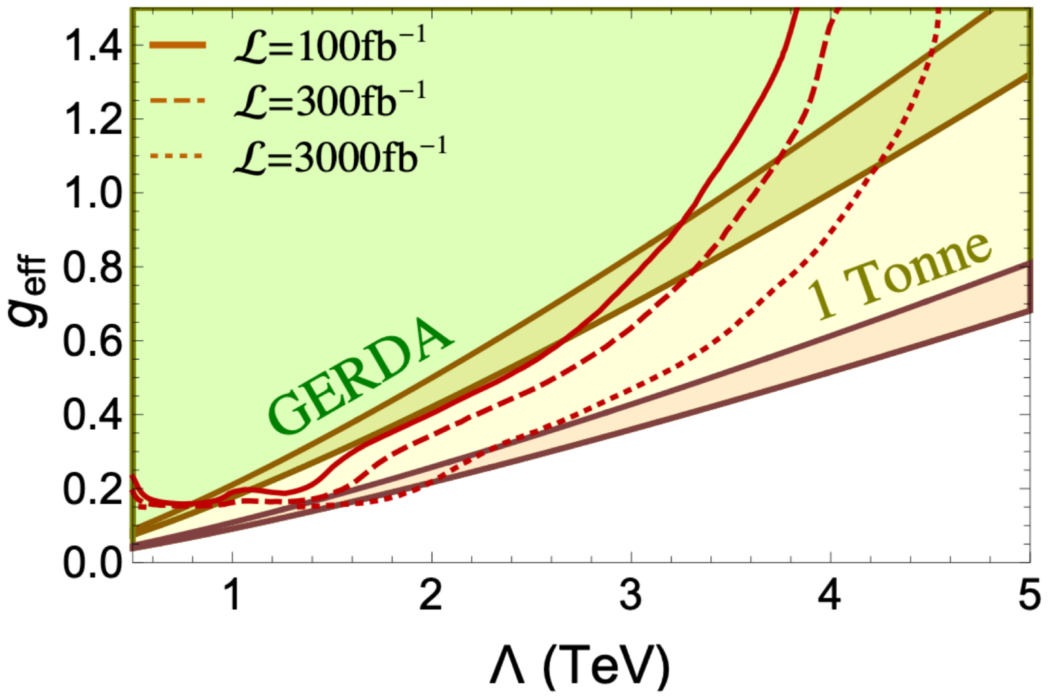
1. Baryon number violation — From SM at high temperature
2. Interactions out of thermal equilibrium — ( ) Majorana neutrinos can do this in many models
3. C and CP violation: need more than the CP violation observed in the SM (even if δ_{CP} is maximal) — ( ) Majorana neutrinos can do this in many models

Majorana neutrinos could be a low-energy signature of the high-energy physics that generated baryon asymmetry

Other Majorana Mass Mechanisms and Model-Building

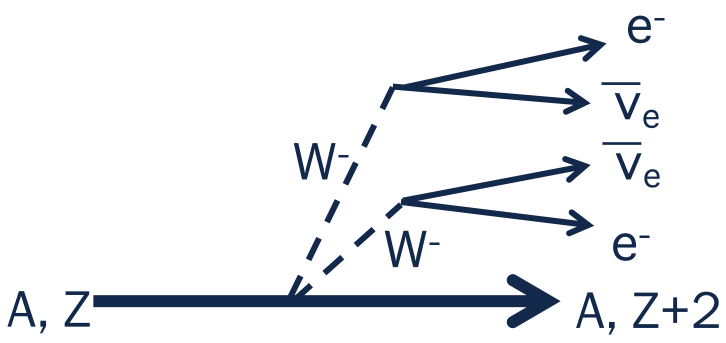
- There are many mechanisms beyond Type I see-saw that would generate neutrino mass
- Some generate the baryon asymmetry or dark matter candidate particles
- Many of these also predict new particles that could be observed at accelerators (O(1-10's of TeV))
- Many models of flavor predict Majorana neutrinos with specific Majorana phases

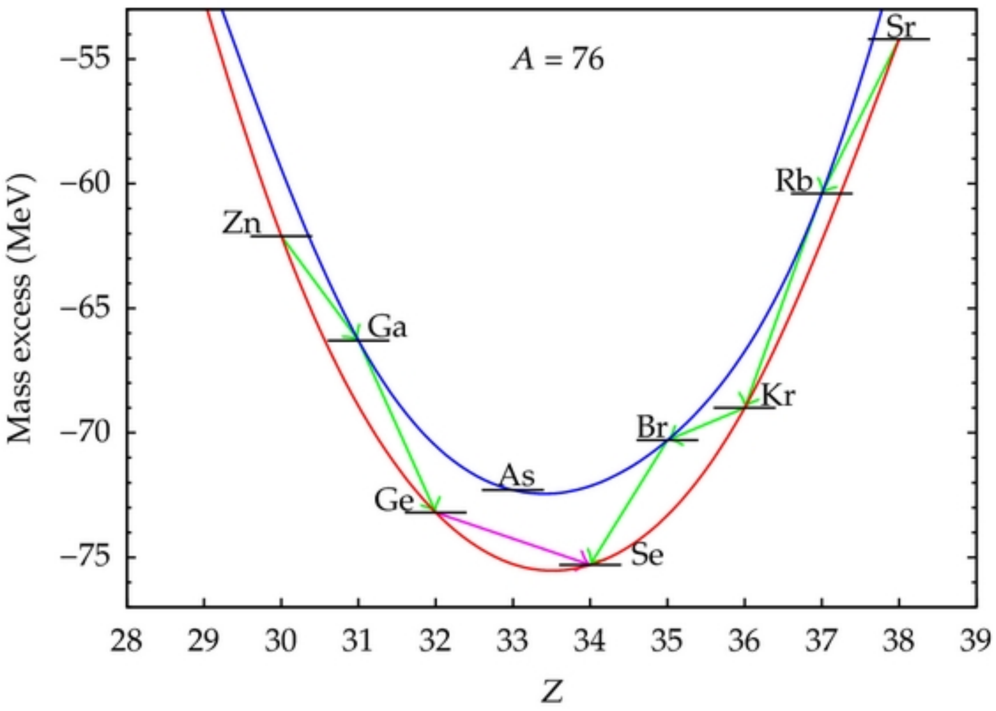
Comparing LHC and 0νββ limits on TeV-scale Lepton number violation



Peng, Ramsey-Musolf, and Winslow
Phys. Rev. D **93**, 093002 (2016)

Standard Model: 2νββ





Double-Beta Decay

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

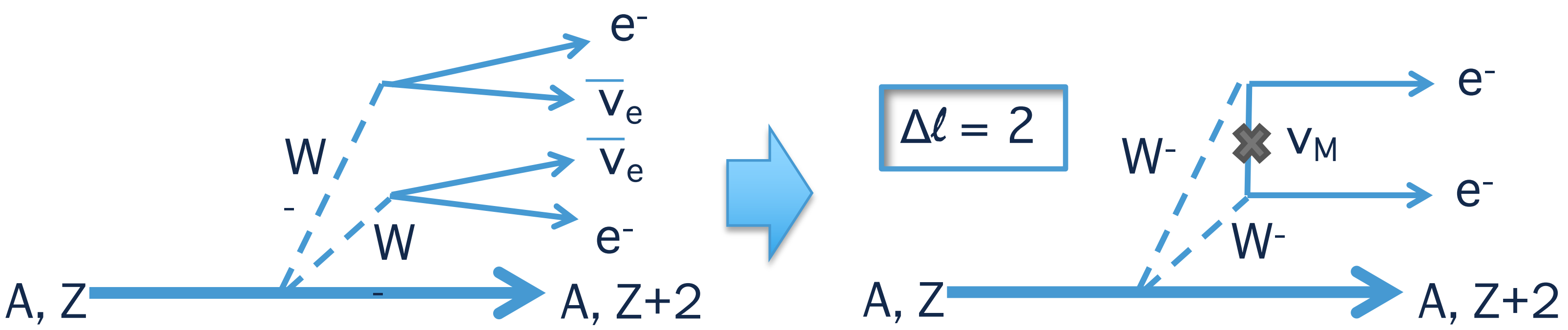
  $T_{1/2} \sim 10^{19}$ -10^{21} years
- Electron capture variant is longest-lifetime process ever observed

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

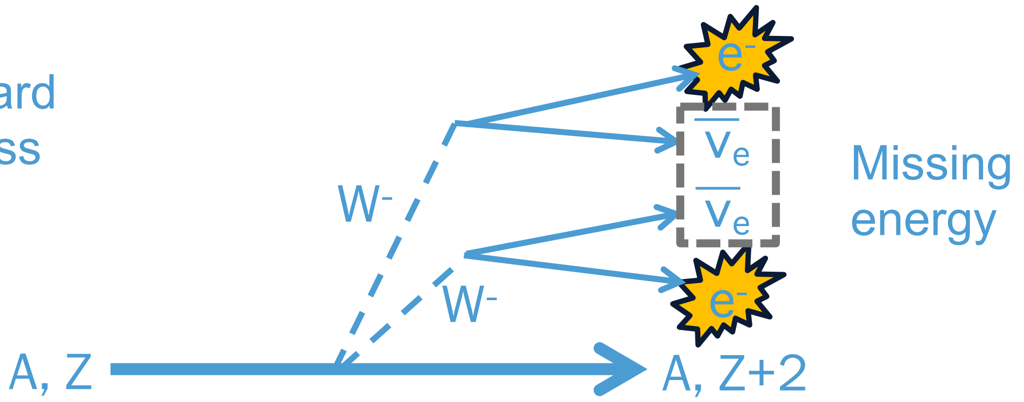
Neutrinoless Double-Beta Decay



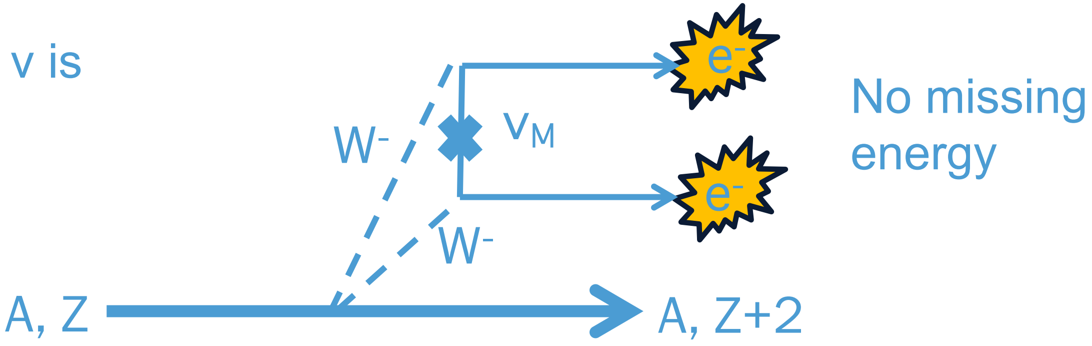
- If neutrinos are Majorana, 0νββ could occur
- Lepton number conservation is violated by 2 units
- In this case, I've drawn the exchange of a light neutrino, but you can think of that "x" as a contracted diagram of any sort (with new physics in it)

The Decay Signature

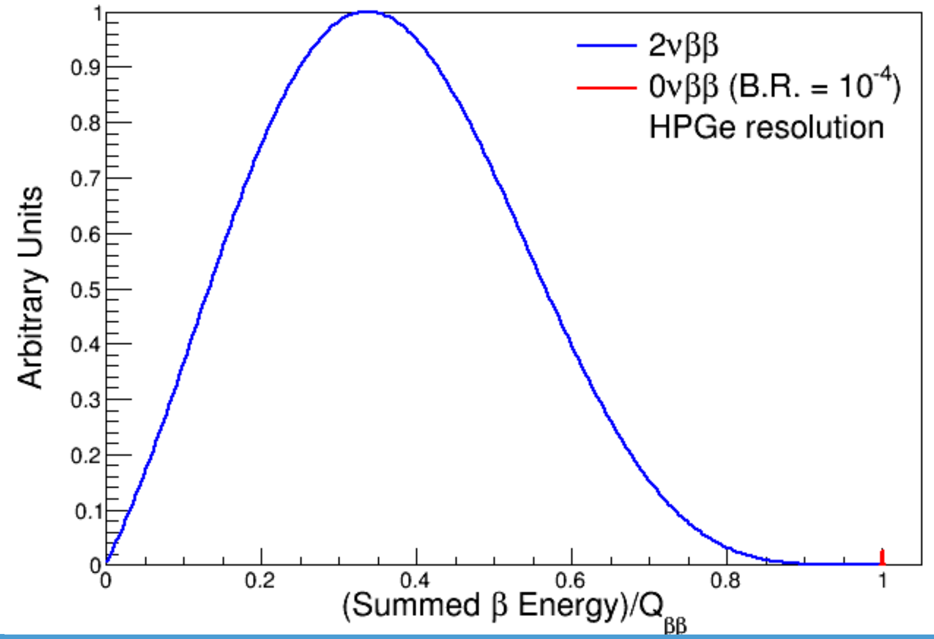
2νββ: Standard Model process



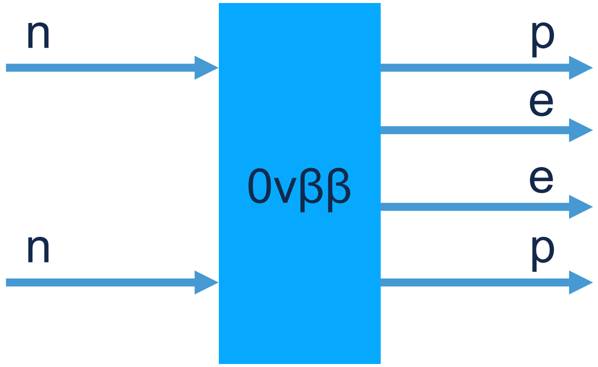
0νββ: Only if ν is Majorana



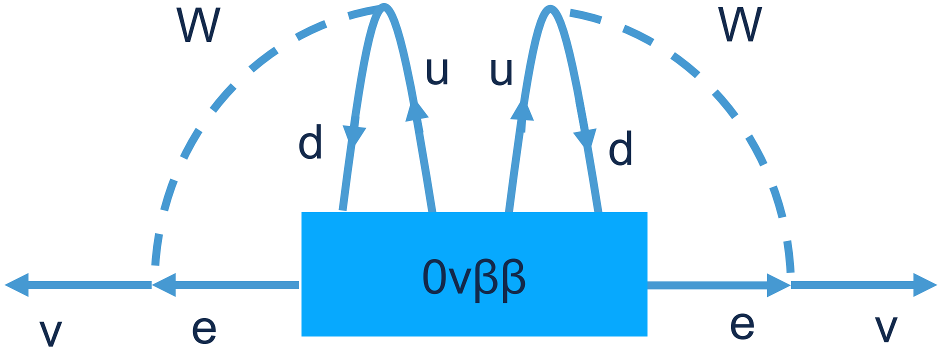
- In non-gaseous detectors, looks like a single-site event (modulo Cherenkov light)



Majorana Neutrinos and 0νββ



(A, Z) → (A, Z+2) +2e-



(A, Z) → (A, Z+2) +2e-

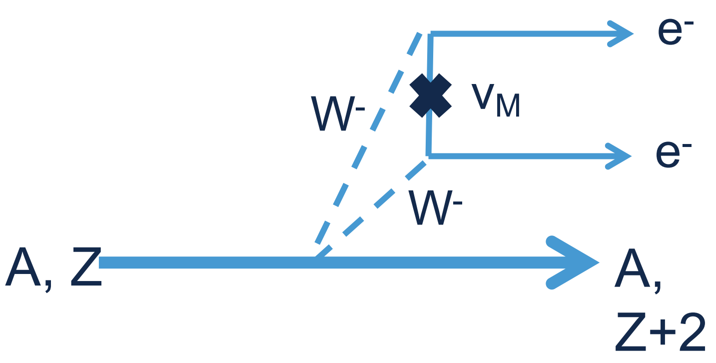
Model-independent implications of 0νββ:

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

The mechanism of 0νββ determines the rate along with the parameters of the model

0νββ Sensitivity and Discovery

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:

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

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

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

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

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

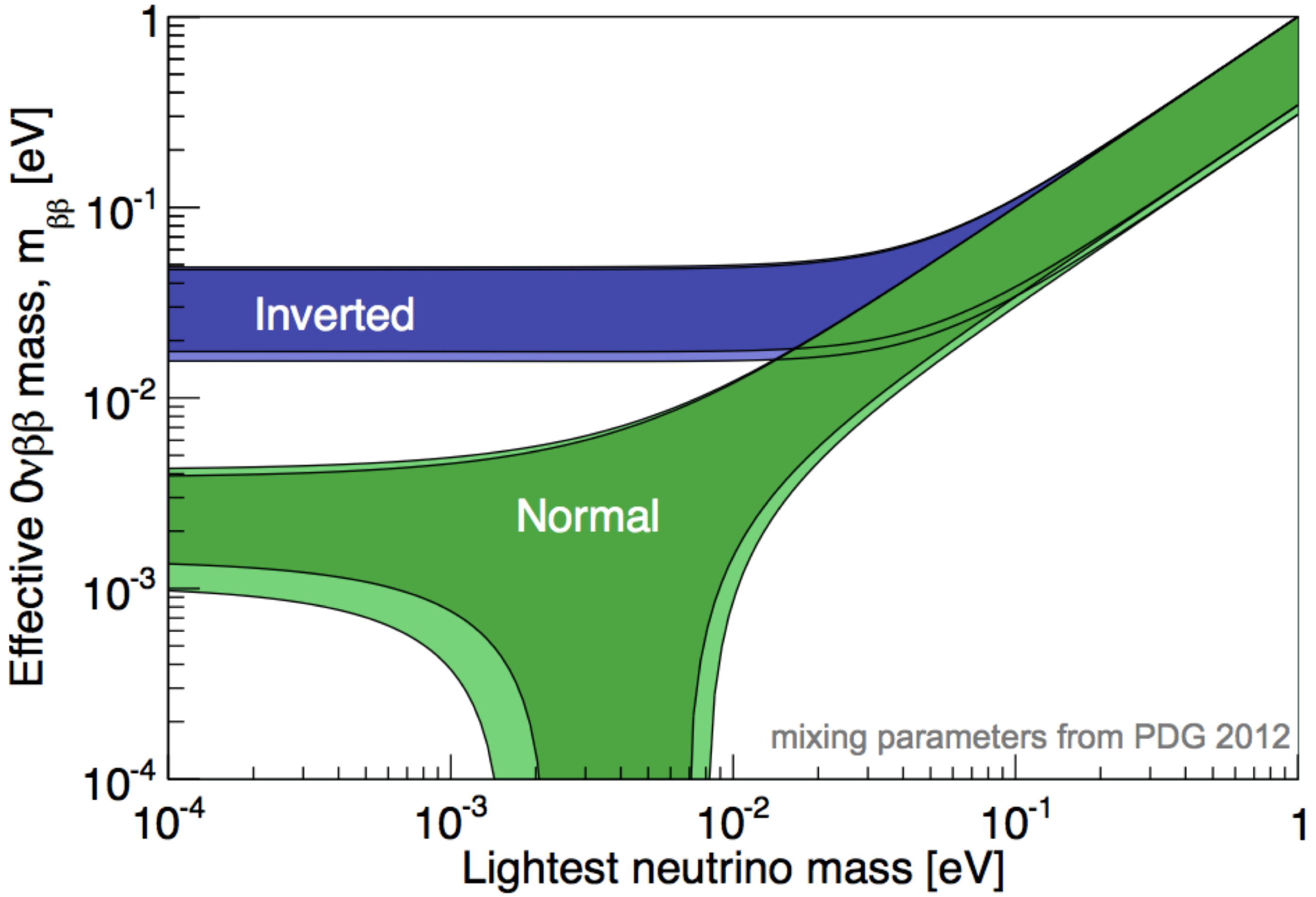
- ν mixing angles
- ν masses
- mass hierarchy
- 2 totally unknown phases

Interpretation of Half-Life Sensitivity

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

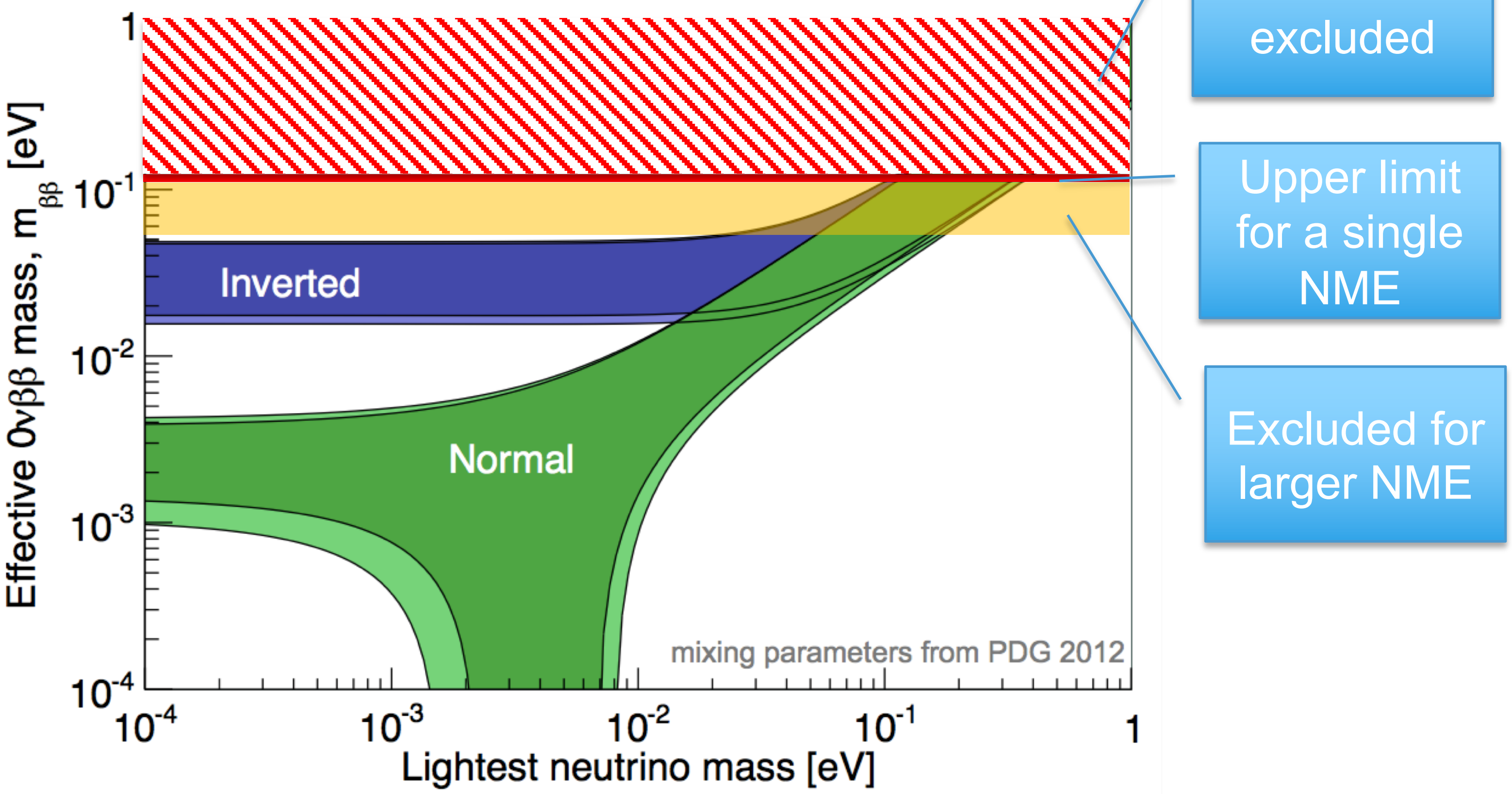
$$\langle m_{\beta\beta}\rangle = |\sum_{i=1}^{3} U^2_{ei} m_i|$$

- 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



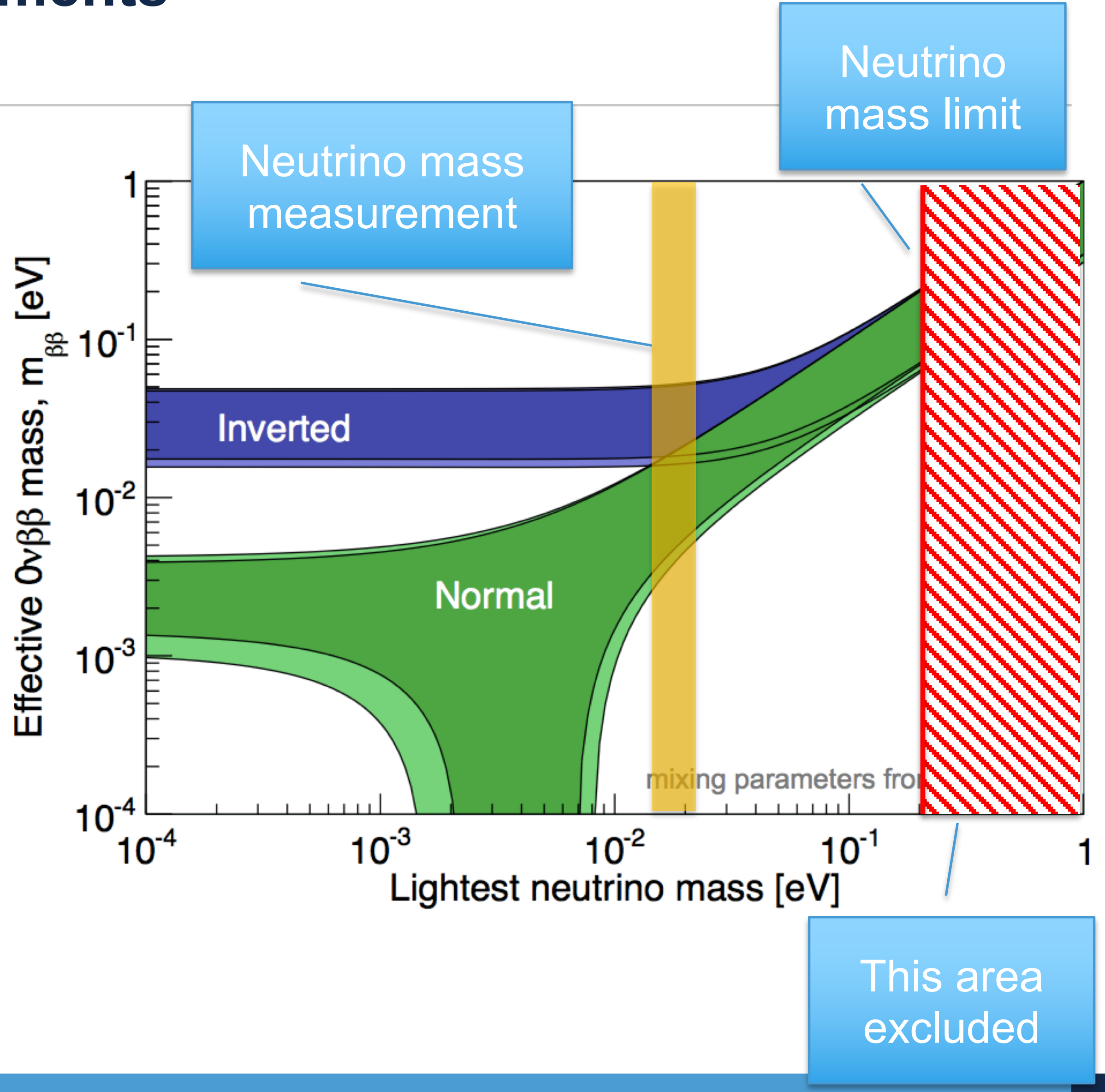
Translating Half-Life to $m_{\beta\beta}$

- 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, so the upper limit in $m_{\beta\beta}$ has a range



Information from Other Neutrino Experiments

- Light-colored edges are 3σ uncertainty on neutrino mixing and mass splittings
- Measuring hierarchy would tell us which branch we need to look in
- Mass measurement would tell us which vertical band to look in



Discovery and Sensitivity

After you run a 0νββ 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:

Number of ββ atoms

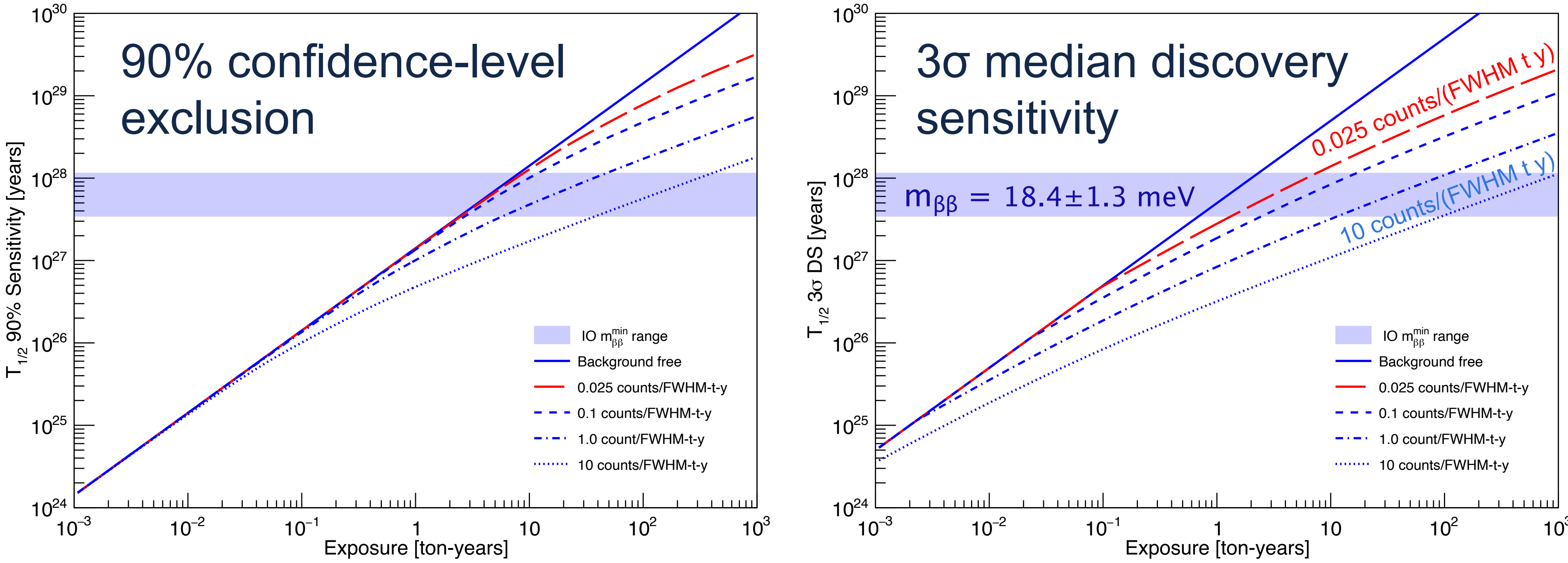
Livetime

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

Efficiency

Upper limit on the number of signal counts

Sensitivity vs. Discovery



Background demands are more stringent if you want to make a discovery

Reaching Ultra-Long Half-Life

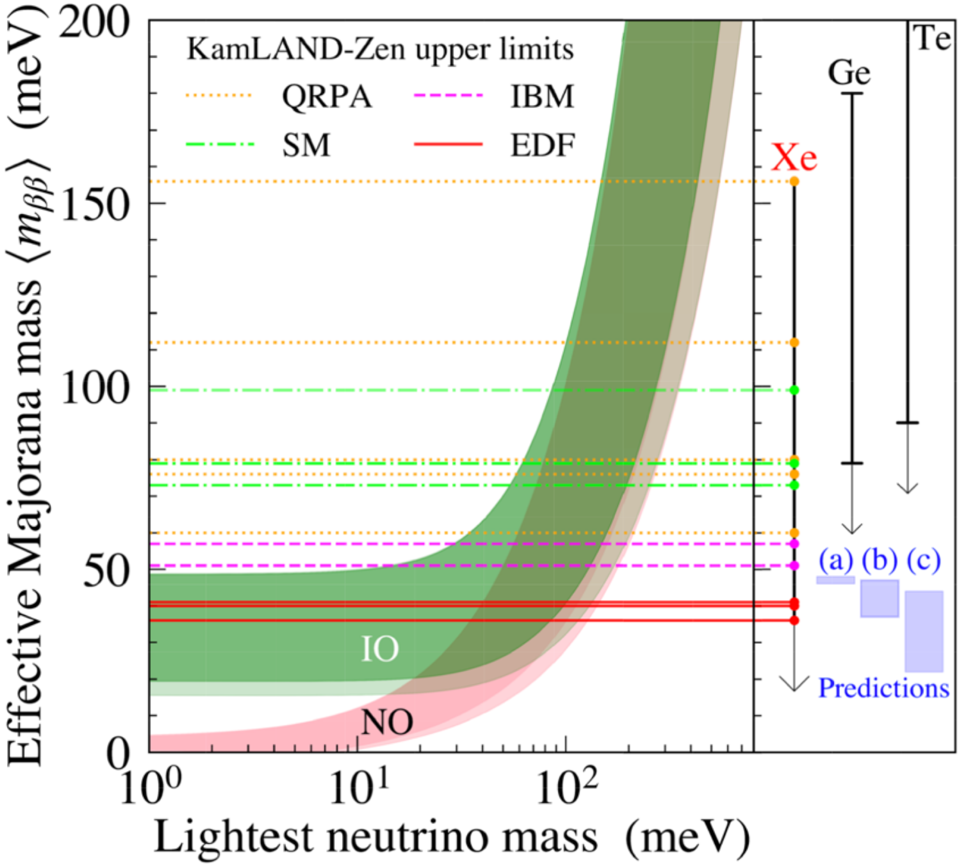
- Best-case scenario: quasi-background-free experiment, 3σ = 3 counts
- Long half-lives mean you need large exposures. For 3-4 counts of $0\nu\beta\beta$ at…
  - 10^{26} years: 100 kg-years
  - 10^{27} years: 1 ton-year
  - 10^{28} years: 10 ton-years

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

Current status and near-term future

Current Best Limits on 0νββ



arXiv: 2203.02139

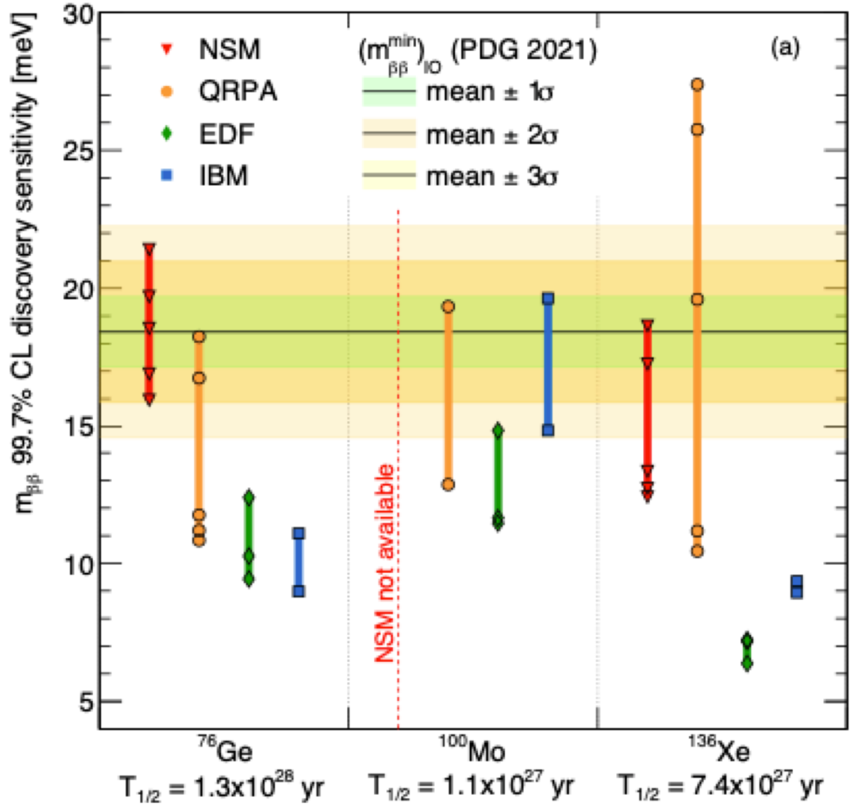
Experiment	Isotope	Exposure [kg yr]	$T^{0\nu}_{1/2}$ [10^{25} yr]	$m_{\beta\beta}$ [meV]
Gerda	^{76}Ge	127.2	18	79-180
Majorana	^{76}Ge	26	8.3	113-269
KamLAND-Zen	^{136}Xe	970	23	36-156
EXO-200	^{136}Xe	234.1	3.5	93-286
CUORE	^{130}Te	1038.4	2.2	90-305

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

The Ton-Scale Generation

- Covering the IO in discovery mode requires O(1 ton) of isotope
- 3 candidate experiments with US participation, in addition to other ongoing efforts: LEGEND, nEXO, and CUPID
- All 3 experiments cover the IO for some matrix elements, and miss for others
- All 3 were evaluated by the DOE in Summer 2021. DOE-NP is seeking international support to pursue all 3 experiments.

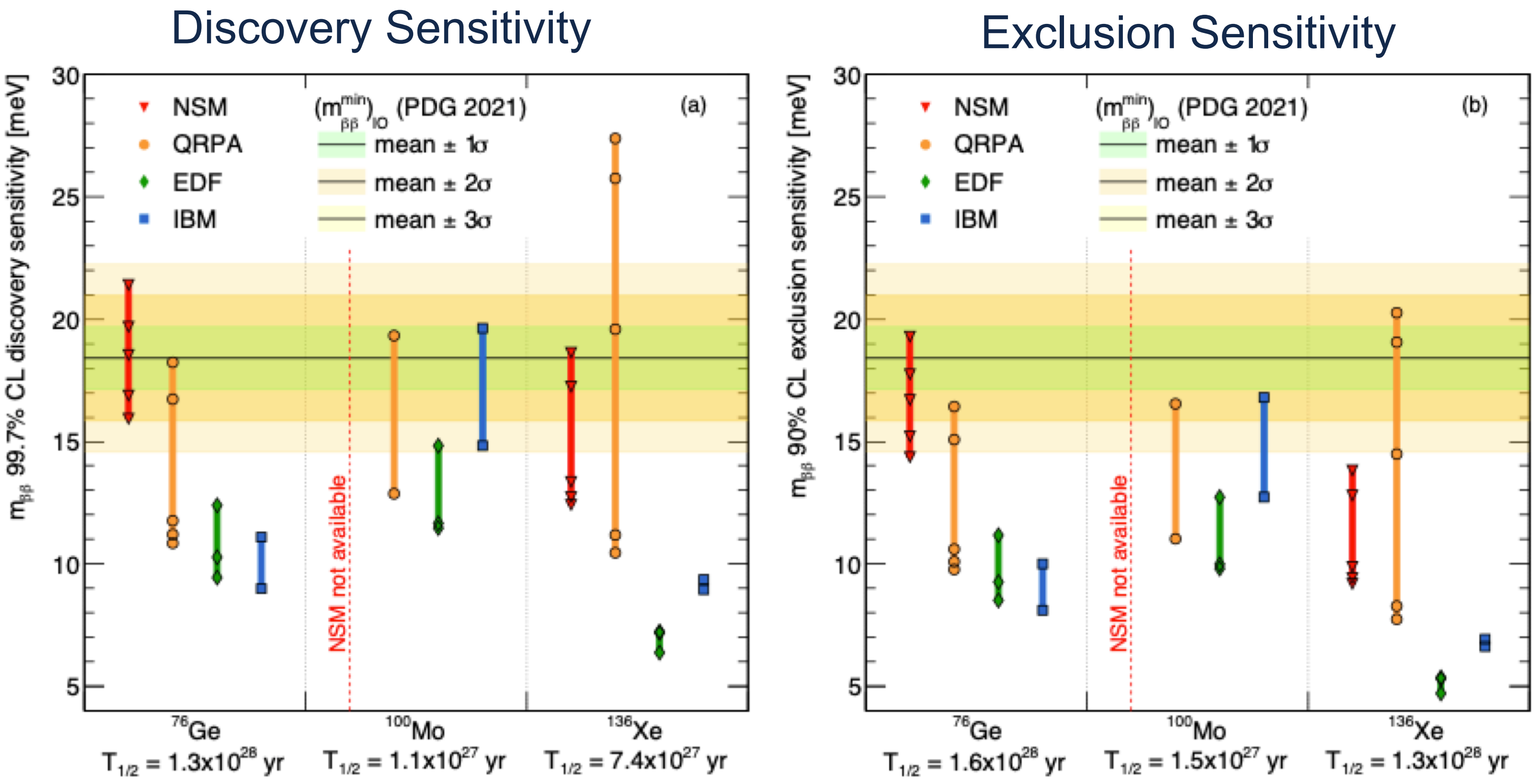
Discovery Sensitivity for the "Big 3"



10.1103/PhysRevC.104.L042501

Discovery and Sensitivity

- Larger background = more difference between discovery and exclusion
- Liquid scintillator experiments will have competitive sensitivity, but generally don't publish discovery projections:
  - KL2Z: $T_{1/2} > 2{\times}10^{27}$
  - SNO+ with increased Te loading: $T_{1/2} > 1{\times}10^{27}$



From Agostini et al., PRC **104**, L042501 (2021)

Timeline for Ton-Scale Experiments

- Depends on funding availability
- The 3 ton-scale experiments are moving towards CD-1, hoping for projected construction start in ~2024-2025
- Construction estimate: ~5 to 10 years*
- All plan for 10 years of running, full-exposure results in ~2040

* Just my guess, $0\nu\beta\beta$ collaborations may disagree

Conclusion

- $0\nu\beta\beta$ is some of the most exciting physics we can look for! It could provide insight into…
  - The origin of neutrino mass
  - The mechanism that drove baryogenesis
  - The origin of flavor/particle generations, dark matter, etc…
- Regardless of the mechanism, $0\nu\beta\beta$ would be a direct observation of lepton number violation and prove that neutrinos have Majorana mass
- The coming generation of experiments is exploring very rich parameter space and (hopefully) beginning very soon
- For a competitive $0\nu\beta\beta$ search, an experiment would need to have high $\beta\beta$ isotope mass and ultra-low backgrounds at $Q_{\beta\beta}$