Double Beta Decay

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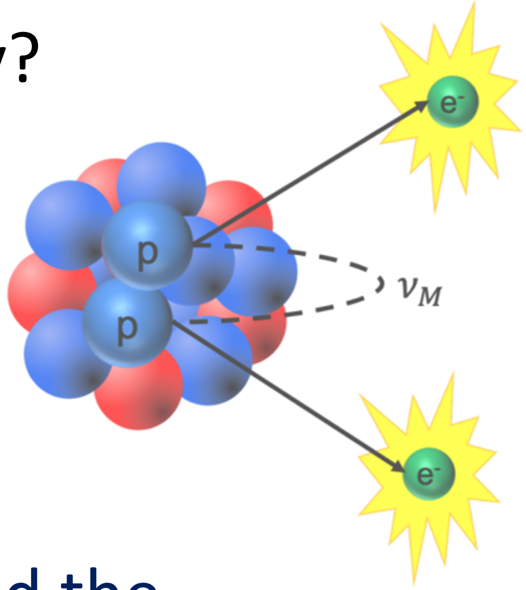
My Experience

- Double Beta Decay
  - LEGEND co-spokesperson (2017-present)
  - MAJORANA spokesperson (2009-2017)
  - UCI-TPC
- Solar Neutrinos
  - SNO NCD construction manager
  - SAGE analyst
- Atomic Physics
  - QED studies in trapped, highly charged ions

Big Science Questions

- What is the origin of the Matter, Anti-Matter Asymmetry?
- Is Lepton number conserved?
- Is the Neutrino is own anti-particle?
- What is the neutrino mass?



- A strong double-beta-decay program will help understand the answers.

$$\Gamma_{0\nu} = G_{0\nu}|M_{0\nu}|^2 m_\nu^2$$

Upcoming Experiments

- Present experiments are reaching below an effective mass of 100 meV
- Next generation experiments are being reviewed. nEXO, LEGEND-1000, CUPID

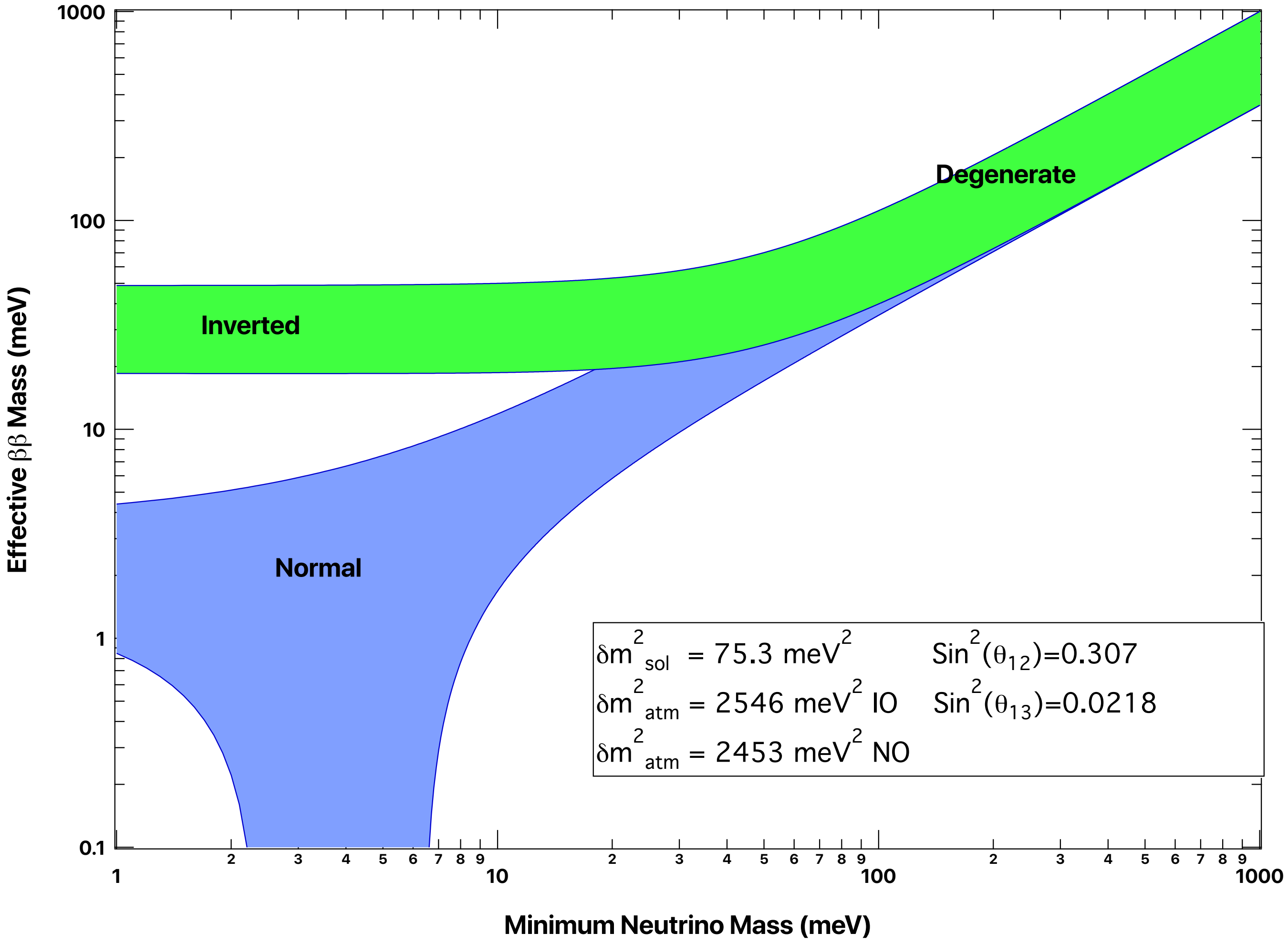
- This generation of experiments will ‘cover’ the inverted ordering region between about 15 and 50 meV. Should begin to see results near end of decade (assuming a sufficient funding profile).
- Half-life sensitivity of 10^{28} years or longer

Future Steps: if no signal seen.

(If seen, will want to observe in several isotopes.)

$$\Gamma_{0\nu} = G_{0\nu}\left|M_{0\nu}\right|^2 m_\nu^2$$

- Natural next goal: Normal Ordering
  - Effective mass goal of 1-5 meV
- This goal is a factor of 10 improvement in effective mass
- Requires factor of 100 improvement in half life sensitivity, 10^{30} years or longer



Fully understanding the underlying physics requires results in several isotopes
In a wonderful world where we see double beta decay

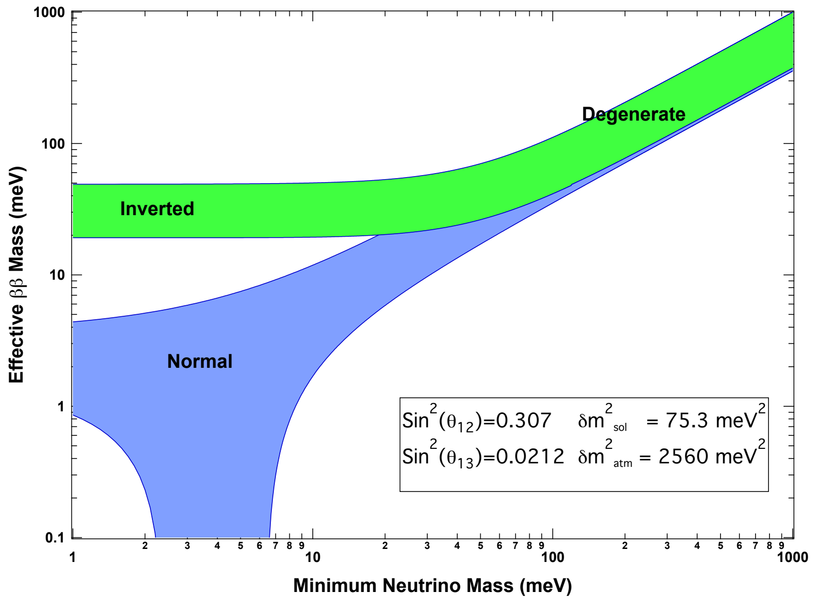
If $\Gamma^{0\nu}$ is non-zero, ν's are massive Majorana particles, but…

$$\Gamma_{0\nu} = G_{0\nu} \left| M_{0\nu} \eta \right|^2 \quad \text{or} \quad G_{0\nu} \left| M_{0\nu} \right|^2 m_{\beta\beta}^2$$

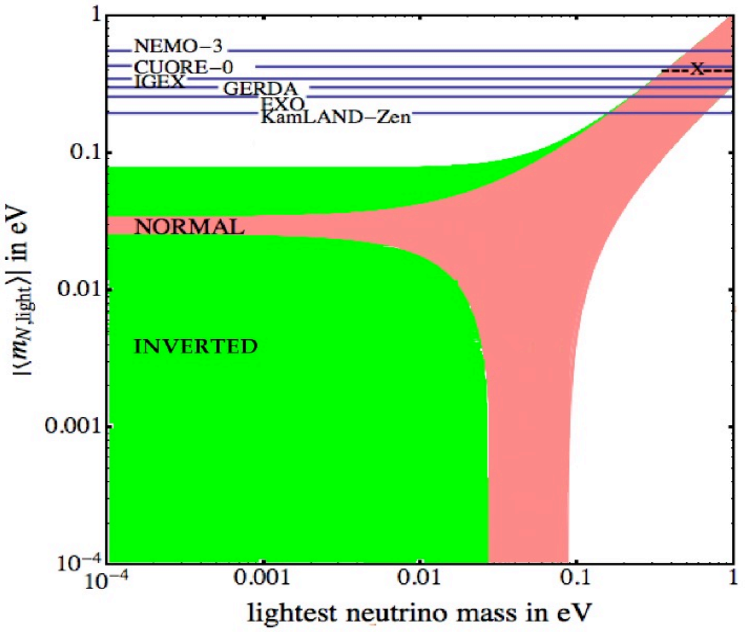
- There are many physics models that lead to Lepton Number Violation (η), |M| can change with the model
  - Light neutrino exchange
  - Heavy neutrino exchange
  - R-parity violating supersymmetry
  - RHC
  - etc.

Deppish/Pas Phys. Rev. Lett. 98, 232501 (2007)
Gehman/Elliott J. Phys. G 34, 667 (2007) [Erratum G35, 029701 (2008)
Fogli/Lisi/Rotunno Phys. Rev. D 80, 015024 (2009)

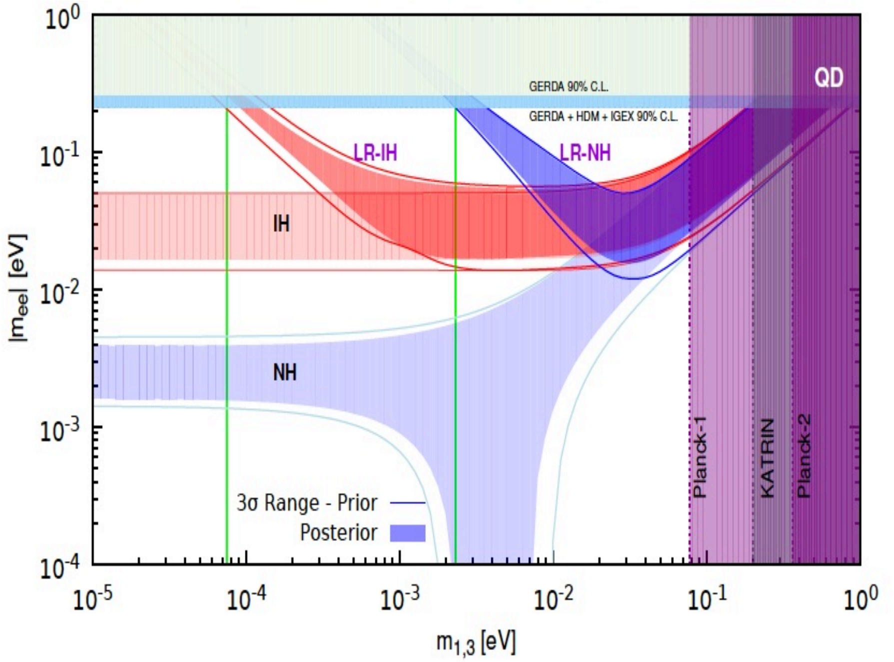
ββ Addresses Key Physics Regardless of Mass Ordering



3 neutrino paradigm



Light sterile neutrino contribution
An example: PRD92, 093001 (2015)
Many papers on this topic.



Left-Right symm., Type II contributions
From J. HEP 10, 077 (2015)
Also many papers on this topic.

If ββ is seen, the qualitative conclusions are profound, but observations in several nuclei will be required to fully understand the underlying physics.

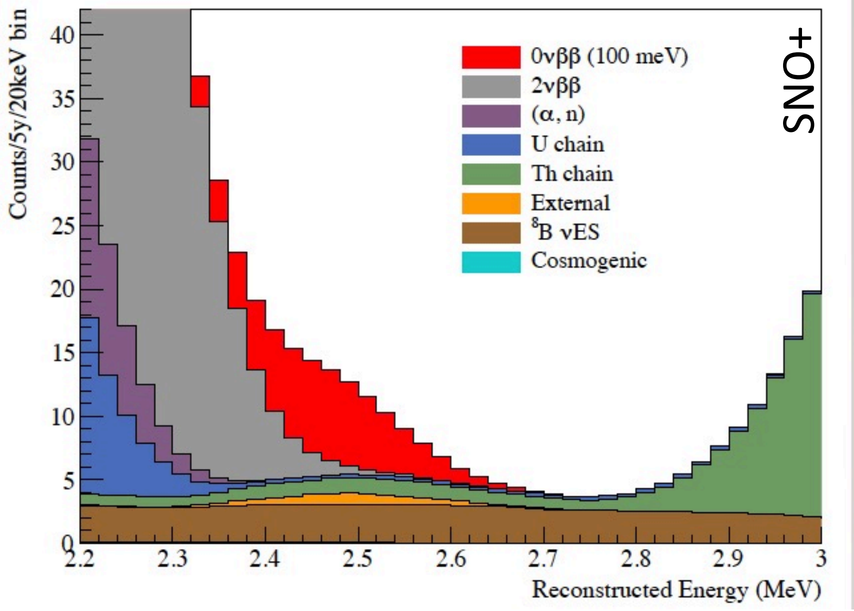
Two-key experimental features, often in tension: Large Mass and Good Energy Resolution

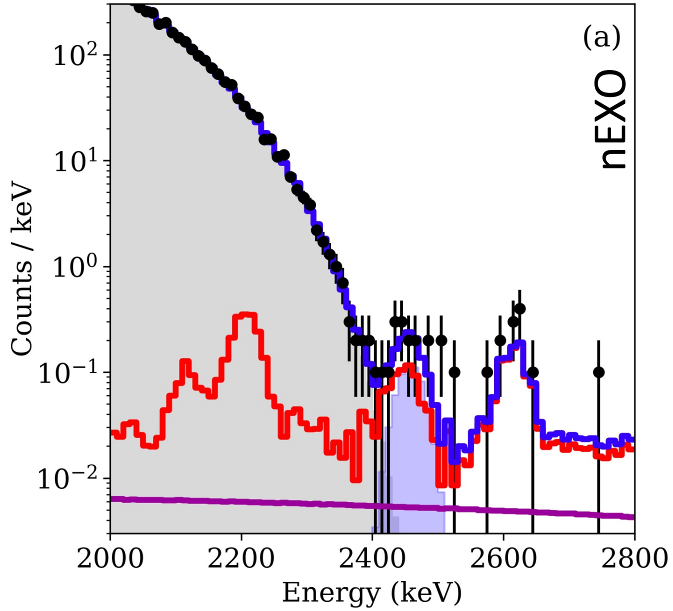
These examples are not an apples-to-apples sensitivity comparison.

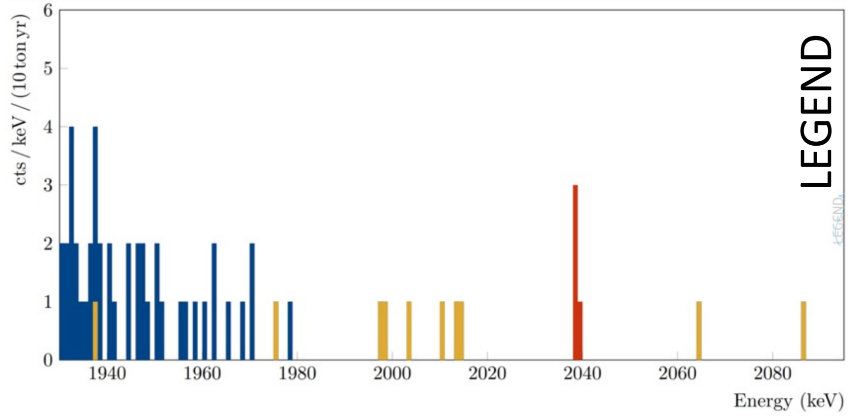
Doped Scintillator
Example: SNO+, Kamland-Zen

Monolithic Detector
Example: nEXO, NEXT

Crystal Array
Example: LEGEND, CUPID







Large Mass or Good Energy Resolution

Doped Scintillator

Strength:
- potential for large mass

Concern:
- poor resolution
- inactive material mass

Monolithic Detector

Strength:
- significant mass

Concern:
- volume edge effects
- modest resolution

Crystal Array

Strength:
- very low background
- very good resolution

Concern:
- modest mass
- lots of individual crystals
- surface effects

Very Restrictive Background Requirements

- At 10^{28} year half life. Count rates are about 1 count/ton yr
  - Need ~10 t-yr exposure
- Requires a background expectation <1 count/(10 t yr) to be a ‘nearly background free’ measurement – half-life limit scales linearly with exposure

- Sensitivity at 10^{30} years will require a commensurate x100 decrease in background
- New or emerging backgrounds will be significant
  - Solar neutrinos (charge current and elastic scattering)
  - Muon induced neutron effects (in situ isotope production)
  - Something not yet recognized?
  - And controlling U/Th at these levels will be challenging

Possible Configurations for 100 tons

- 3 kt of scintillator (~3% loading of isotope)
- 100 t monolithic detector
- 20,000 crystal detectors (5 kg each)

All seem plausible, but perhaps expensive due to isotope quantity

Other emerging technologies might play a role in reducing background or elucidating the underlying physics.

quantum dots, daughter identification, electron tracking

Requirements

- ~100 tons or more of isotope, with extensive shielding
  - Sizable underground room, but modest compared to some existing cavities
  - Maybe scale goal by half life instead of effective mass (x10 -> ~10 tons isotope)
- Isotope cost will be an issue. Need R&D on enrichment technologies to address cost and production rate.
  - High natural abundance of ^{130}Te might be a driver
  - The quantities of natural isotope required is a concern in some cases
- Background ~10^{-7} counts/keV kg yr
  - Deep, clean laboratory space
  - High throughput assay capacity
- Potential synergies with other low-background programs (dark matter, e.g.)