Neutrinoless Double-Beta Decay

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The Future of High Energy Physics: A New Generation, A New Vision

March 27, 2024

THE UNIVERSITY *of* NORTH CAROLINA *at* CHAPEL HILL

TUNL
TRIANGLE UNIVERSITIES NUCLEAR LABORATORY

The Funding Agency Perspective

Double-beta decay

Solar neutrinos

Neutrino mass

Sterile neutrino searches without beams

Some aspects of CEvNS

Neutrino-nuclear cross sections (sometimes)

Nuclear Physics

Astrophysical neutrinos

Atmospheric neutrinos

CEvNS

Neutrino oscillations (as long as they're not solar neutrinos)

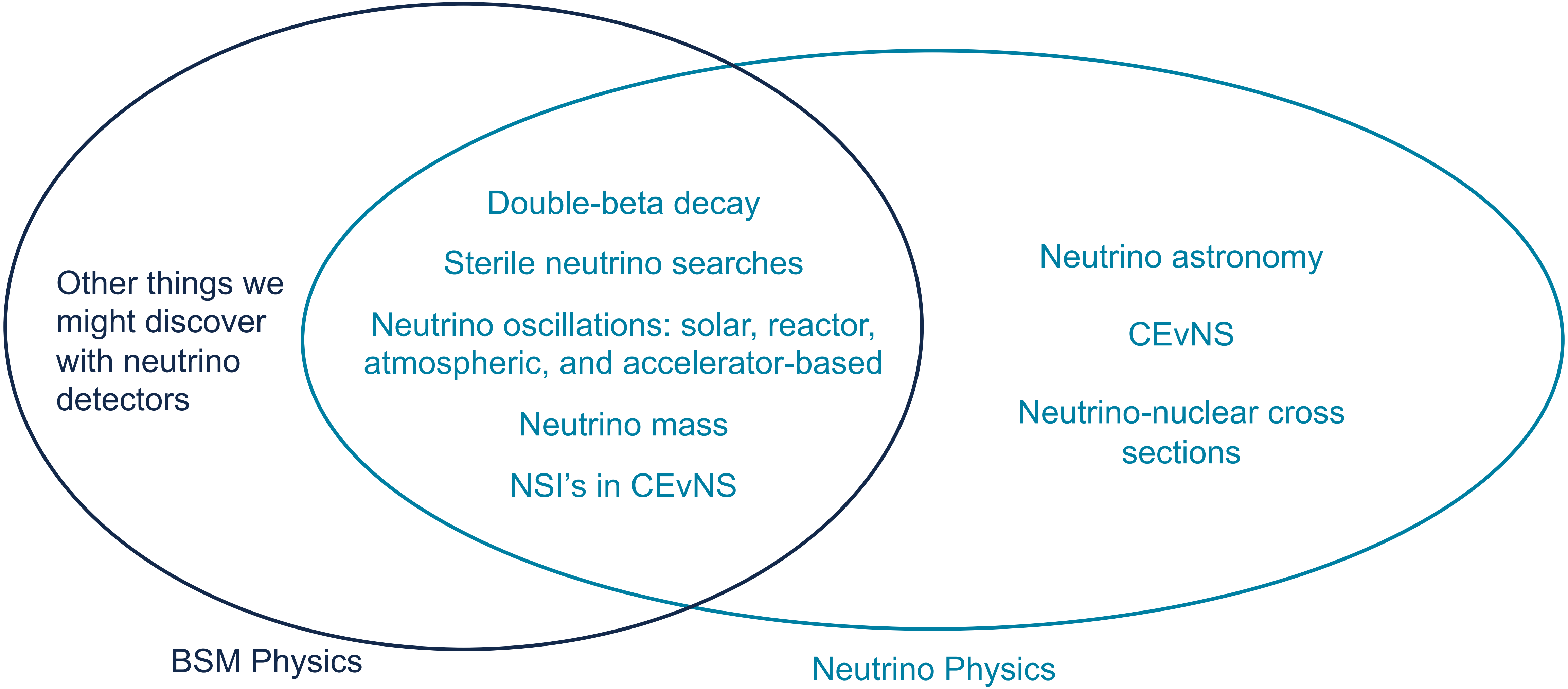
Sterile neutrino searches with beams

Reactor neutrinos (these days)

Neutrino-nuclear cross sections (sometimes)

HEP

The Physicist's Perspective



Exploring the Quantum Universe

Pathways to Innovation and Discovery in Particle Physics

DRAFT Report of the 2023 Particle Physics Project Prioritization Panel

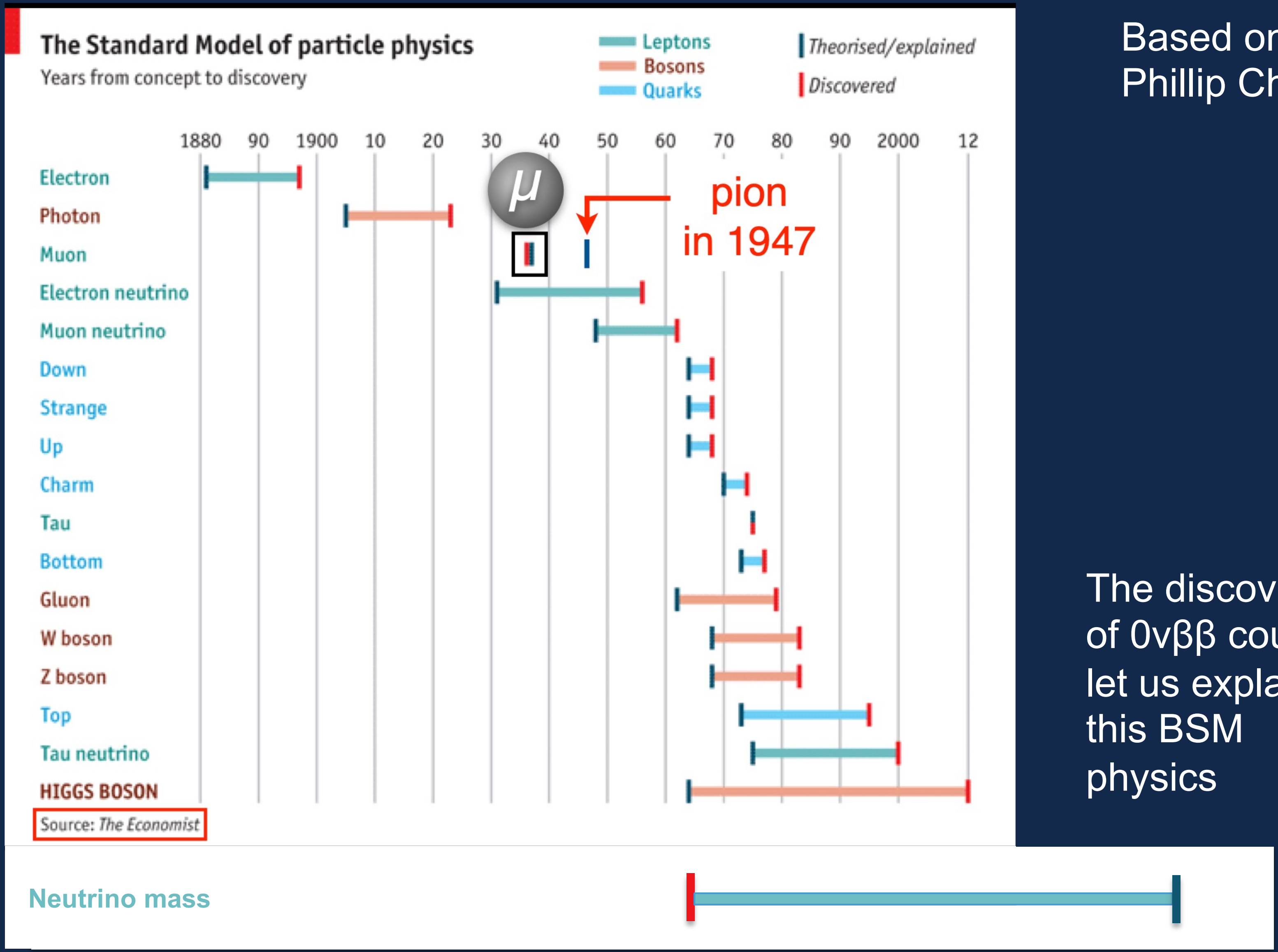
3.1.5 – Interplay with Other Measurements of Neutrino Properties

Understanding the origins of neutrino mass is one of the big questions in physics. However, neutrino masses have not yet been directly measured. There are three approaches to measuring the neutrino mass: direct kinematic mass searches in nuclear beta decay, neutrinoless double beta decay, and cosmology. The first two approaches are under the stewardship of the DOE nuclear science program. Similarly, the question of whether neutrinos are their own antiparticles—Majorana particles—is one of the top science topics highlighted in the recent Nuclear Science Advisory Committee (NSAC) long-range plan via the pursuit of ton-scale neutrinoless double beta decay experiments. Measurements of the mass ordering by the particle physics program set the expected scale for these experiments. The outcome of these experiments is one of the most eagerly anticipated pieces to the puzzle of neutrino mass.

A strategic plan for the High Energy Physics Advisory Panel

RECOMMENDATION 2

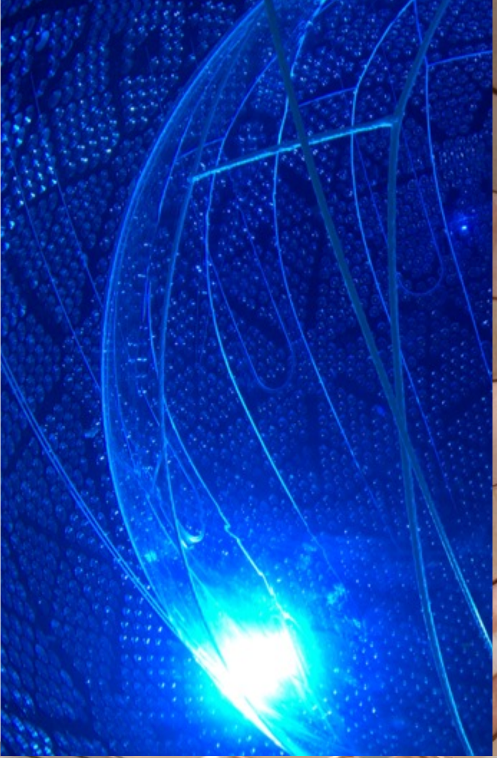
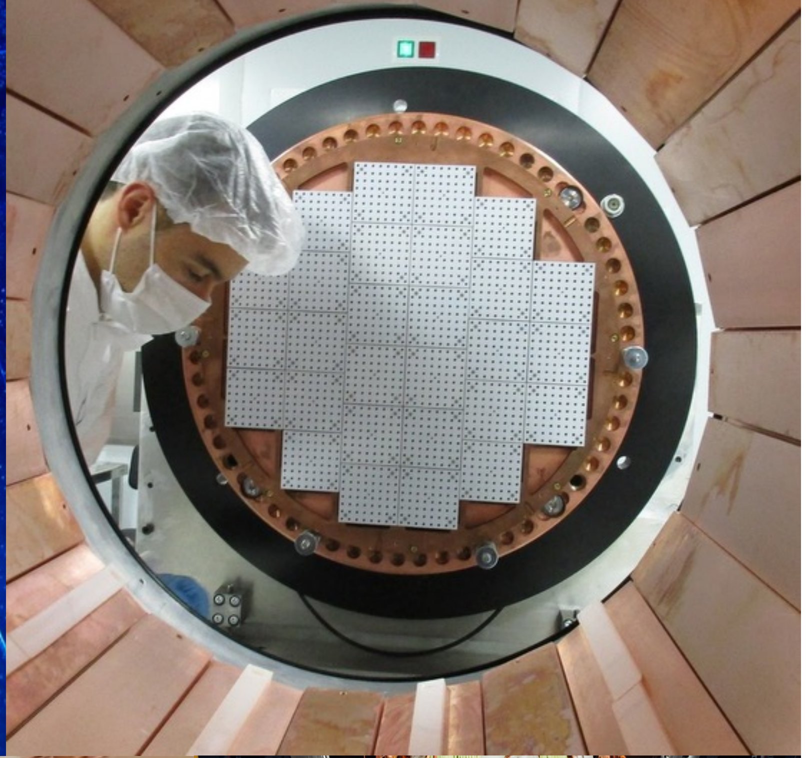
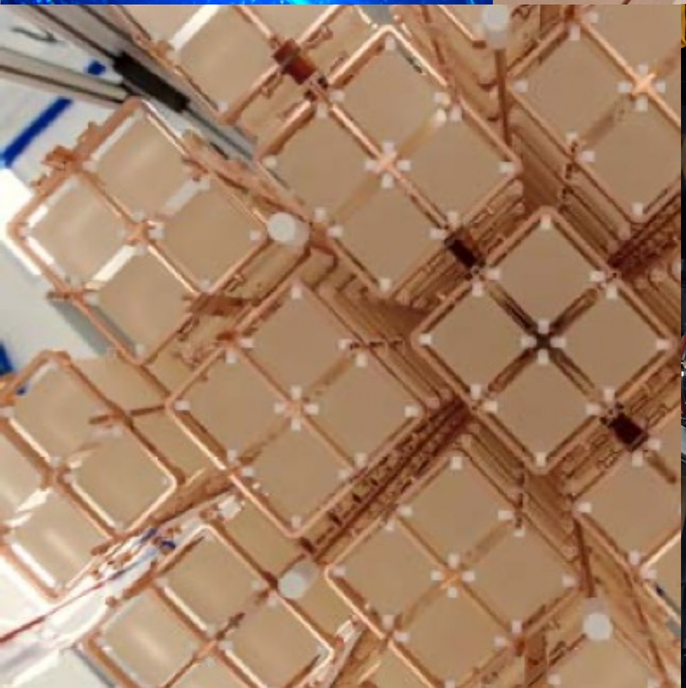
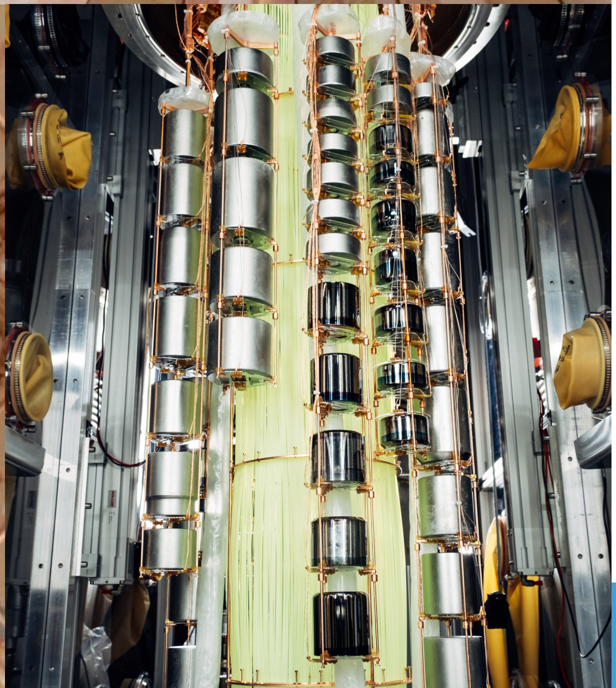
As the highest priority for new experiment construction, we recommend that the United States lead an international consortium that will undertake a neutrinoless double beta decay campaign, featuring the expeditious construction of ton-scale experiments, using different isotopes and complementary techniques.



Based on a slide by Phillip Chang

The discovery of 0νββ could let us explain this BSM physics

Making a discovery is exciting, but we also need to be in a position to convert discoveries to new models

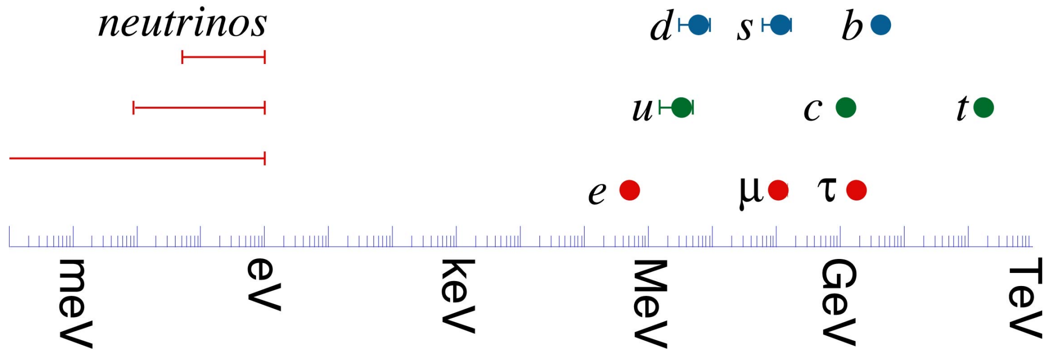
Outline

- Why look for $0\nu\beta\beta$?
- Searching for $0\nu\beta\beta$
- $0\nu\beta\beta$ experiments

Why look for $0\nu\beta\beta$?

Neutrino Mass is Proven BSM Physics, Observed in the Laboratory

- A reminder: neutrino mass is not in the Standard Model!
  - The SM contains only left-handed neutrinos and right-handed anti-neutrinos
- This is a $\gg 5\sigma$ laboratory observation of BSM physics
- The remaining question: is it "boring BSM" or "interesting BSM"?



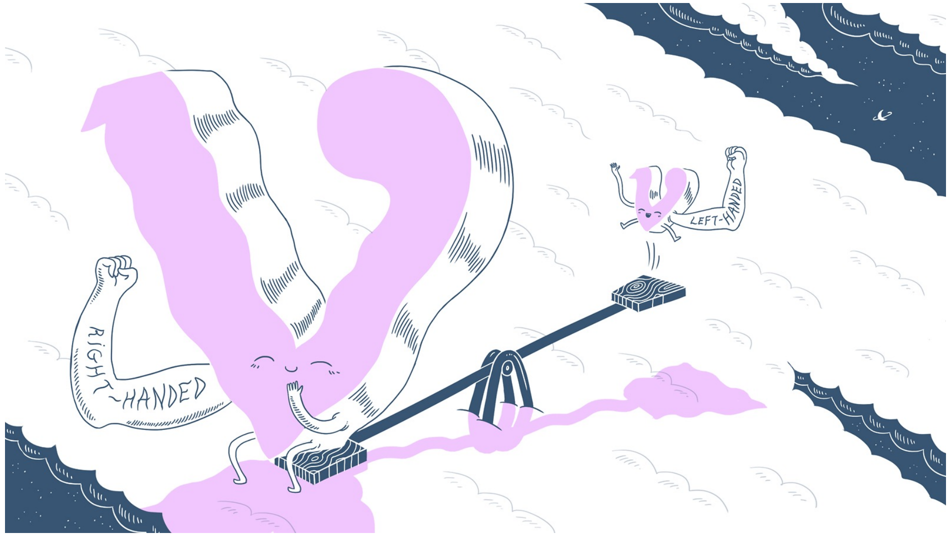
The Surprising Neutrino Mass

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

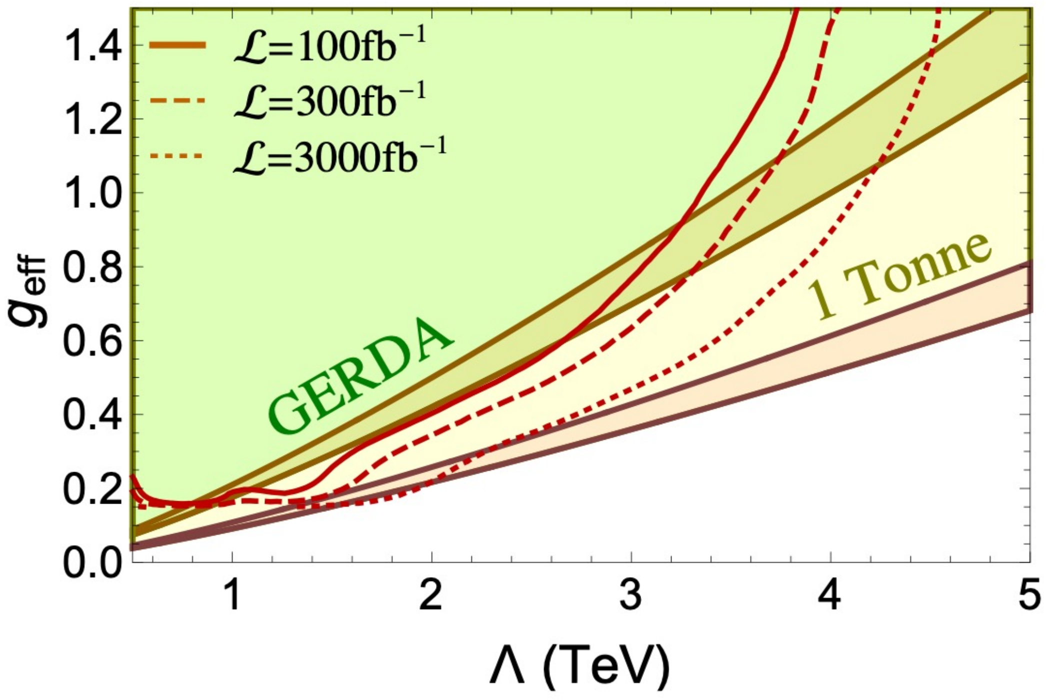
- Including both Majorana and Dirac mass terms can generate two light neutrinos, ν and $\bar{\nu}$, and two heavy neutrinos, N and $\bar{N}$
- If the Majorana mass term is of the GUT scale and Dirac mass term is of EW scale:
  - $m_\nu \sim 0.1$ eV
  - $m_N \sim 10^{14}$GeV
- This gives a “natural” neutrino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



Other Majorana Mass Mechanisms and Model-Building

- There are many mechanisms beyond Type I see-saw that would generate light neutrino masses
- Some generate the baryon asymmetry or dark matter candidate particles
- Many of these also predict new particles that could be observed at the LHC (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)

* 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

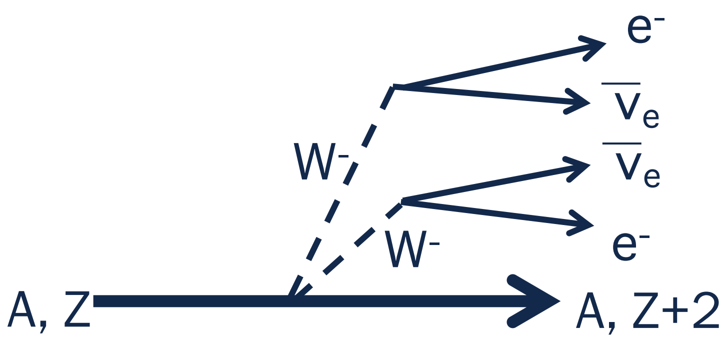
Making Baryon Asymmetry: The Sakharov Conditions

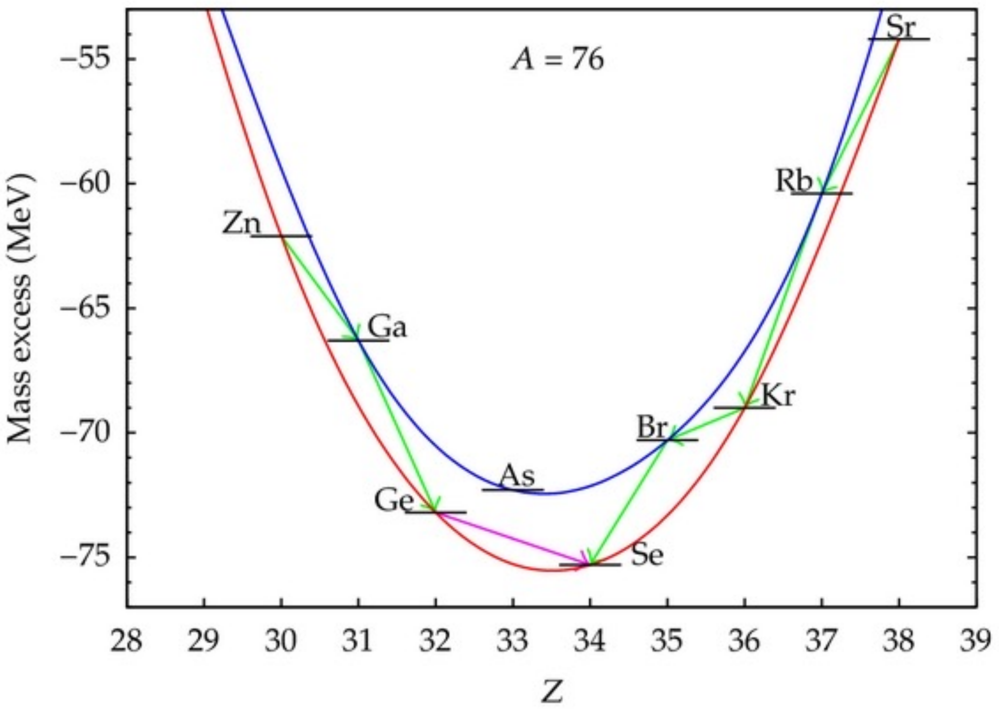
Sakharov proposed 3 conditions required for baryon-generating interactions that would generate an asymmetry:

1. Baryon number violation ✅ From SM at high temperature, with B-L conserved
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

Standard Model: 2νββ



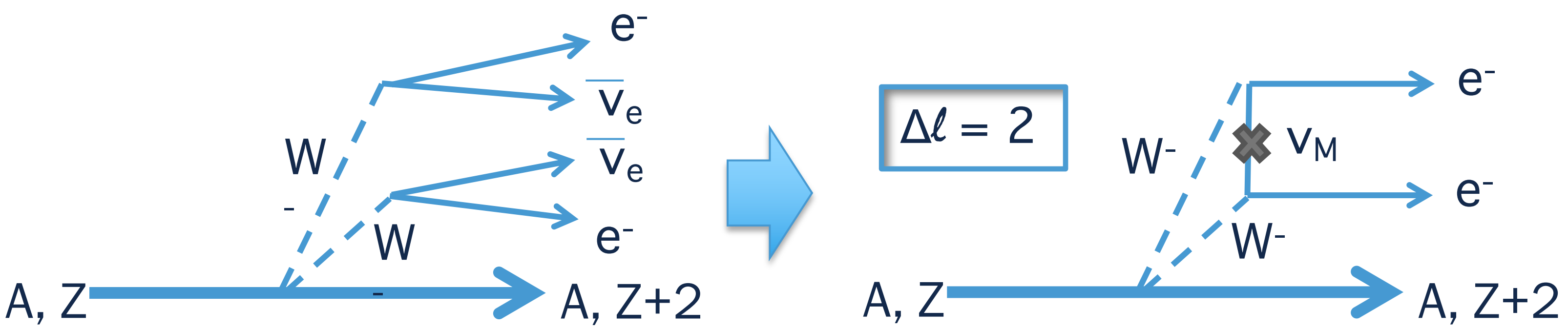


Double-Beta Decay

- 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

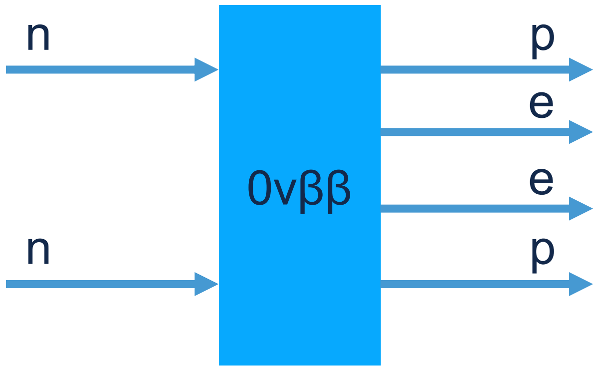
  $T_{1/2} \sim 10^{19}$ -10^{21} years
- Electron capture variant is longest-lifetime process ever observed

Neutrinoless Double-Beta Decay

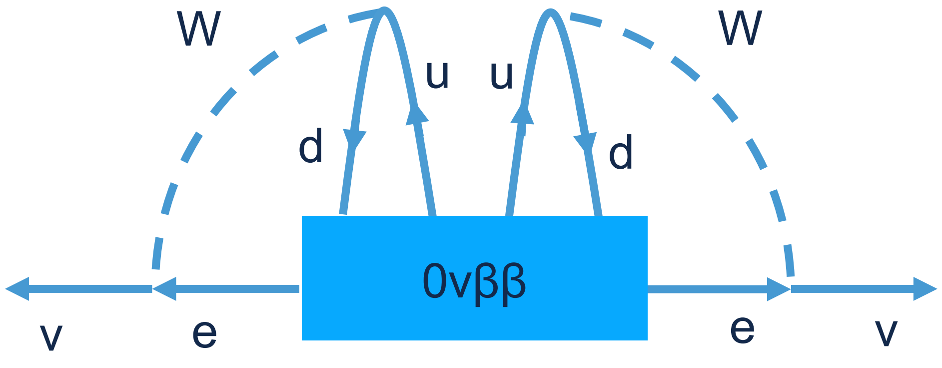


- If neutrinos are Majorana, 0νββ could occur
- Lepton number conservation is violated by 2 units
- In this case, I've drawn the exchange of a light neutrino, but you can think of that "x" as a contracted diagram of any sort (with new physics in it)

Majorana Neutrinos and 0νββ



(A, Z) → (A, Z+2) +2e-



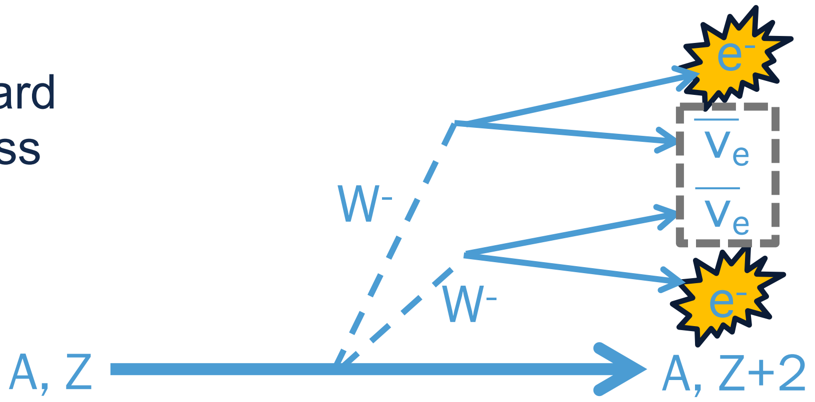
(A, Z) → (A, Z+2) +2e-

Model-independent implications of 0νββ:

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

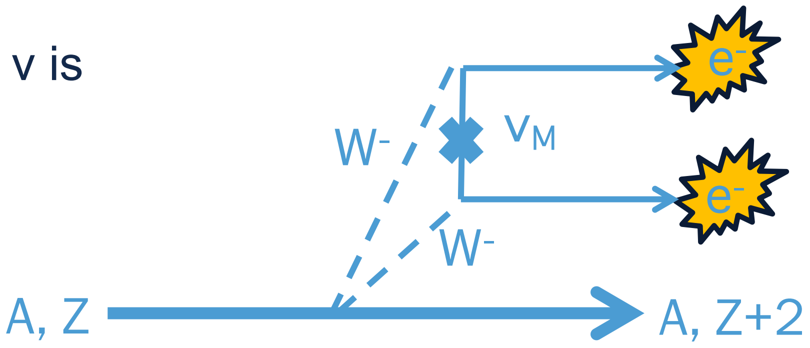
The Decay Signature

2νββ: Standard Model process

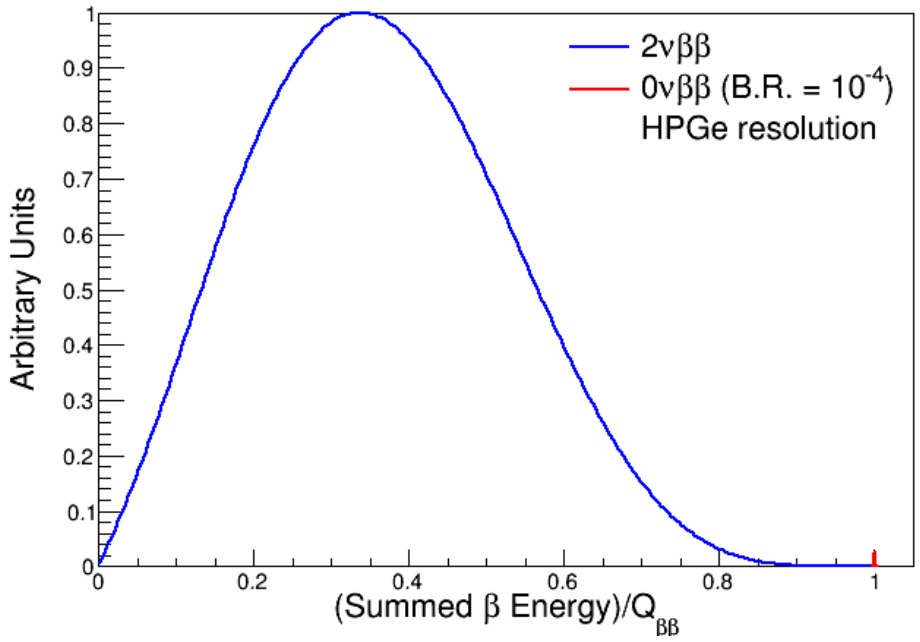


Missing energy

0νββ: Only if ν is Majorana



No missing energy



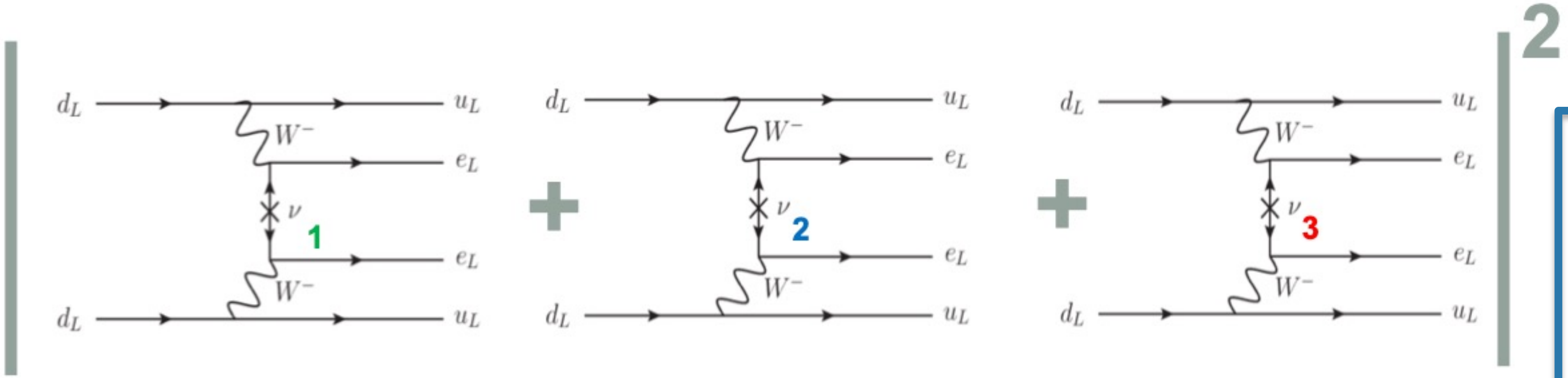
+ event topology information

Searching for 0νββ

Neutrino Physics and 0νββ

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

$\Gamma \propto$



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

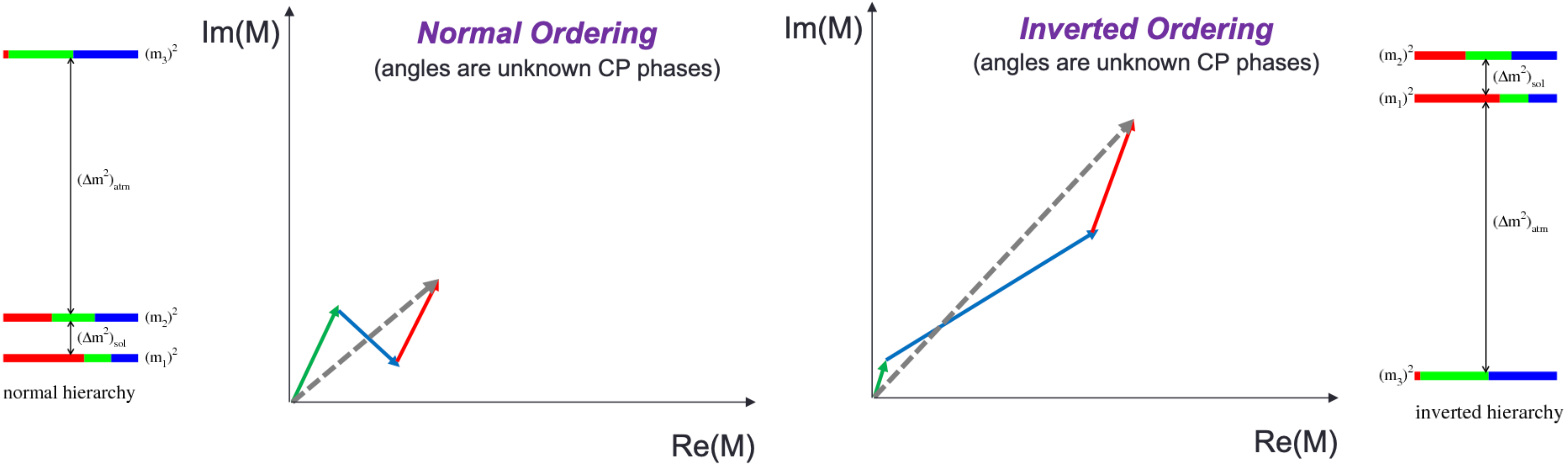
$$\langle m_{\beta\beta}\rangle = \cos\theta_{12}^2 \cos\theta_{13}^2 e^{2i\alpha} m_1 + \cos\theta_{12}^2 \sin\theta_{12}^2 e^{2i\beta} m_2 + \sin\theta_{13}^2 m_3$$

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

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

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 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

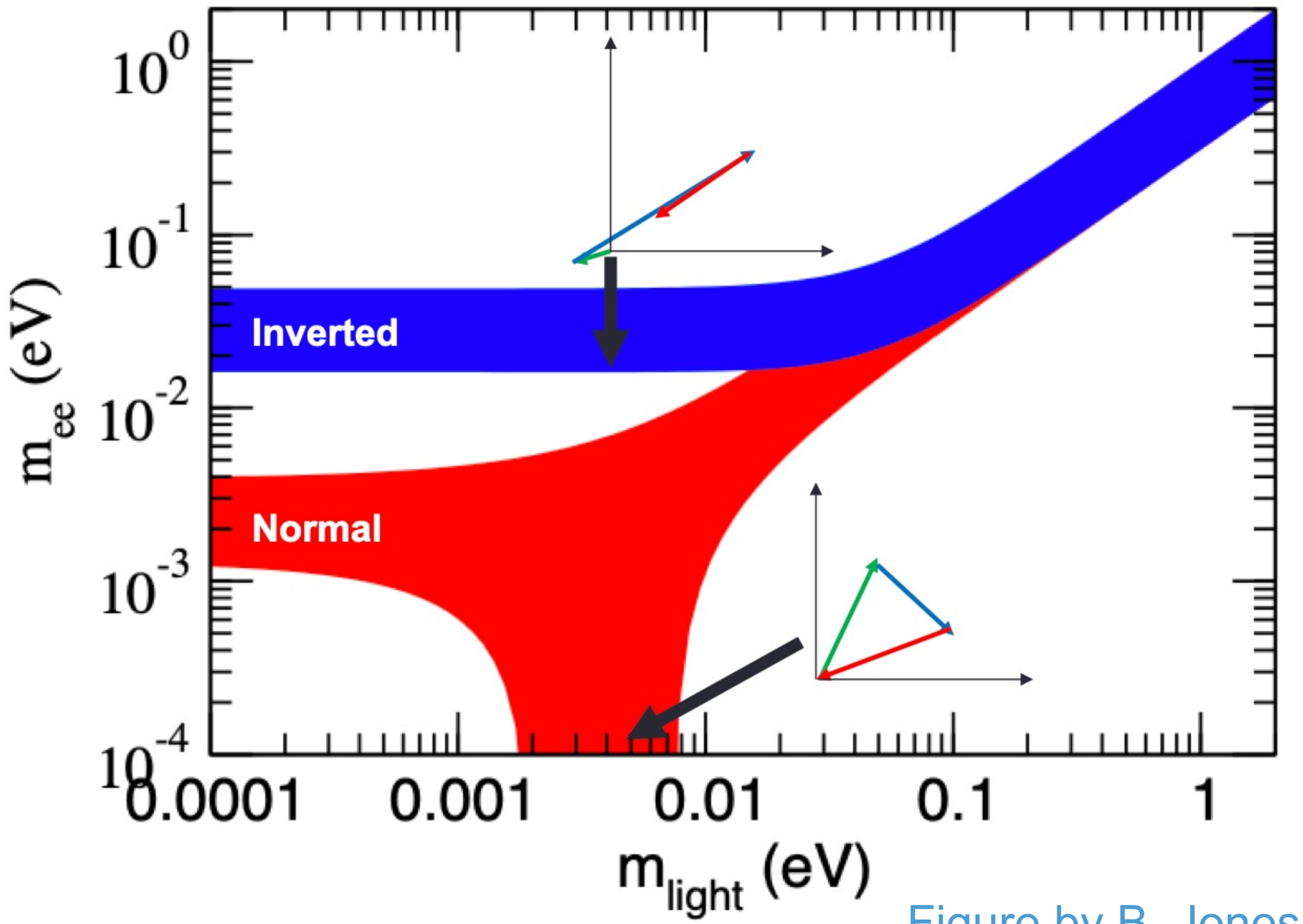
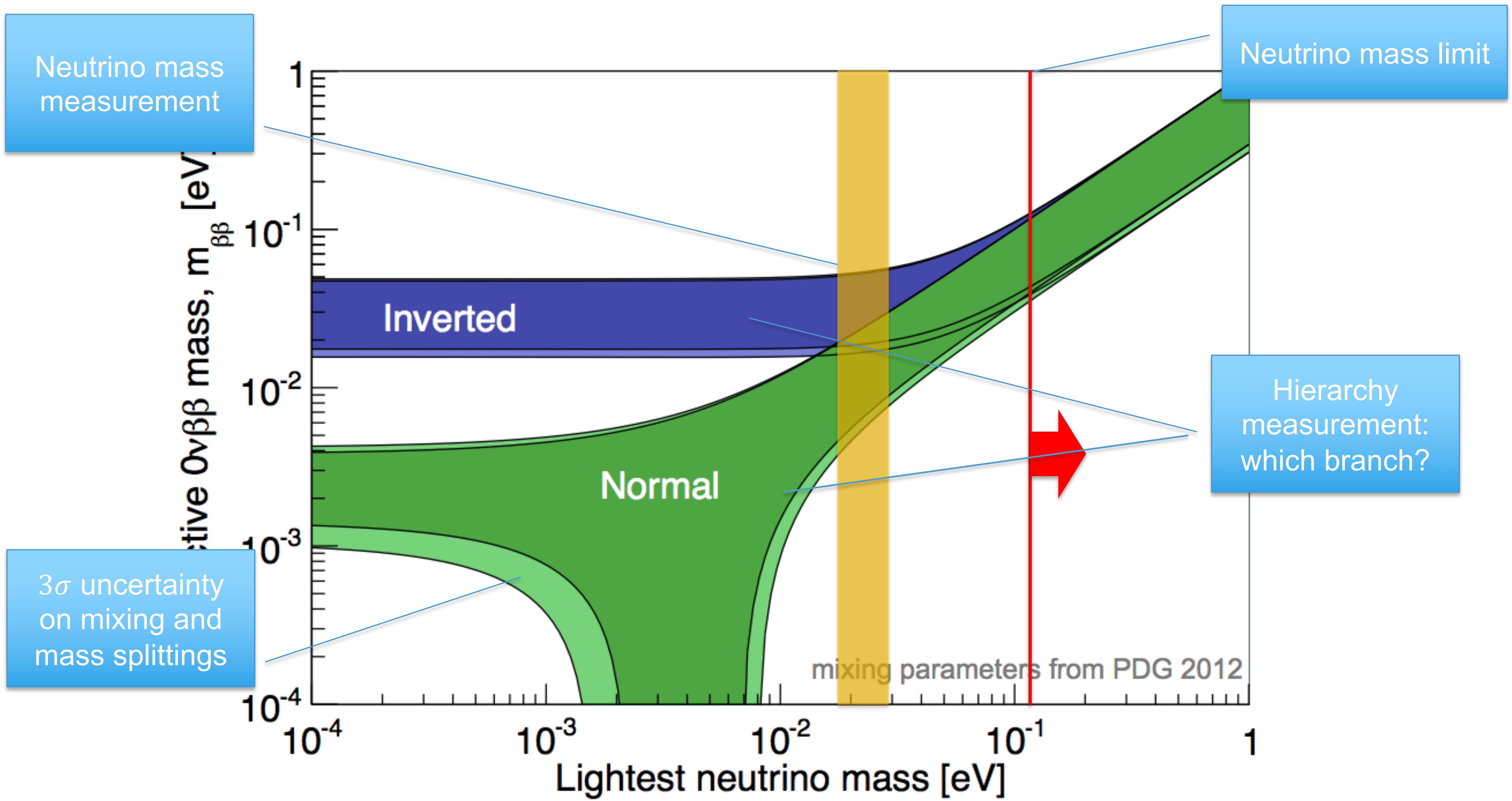
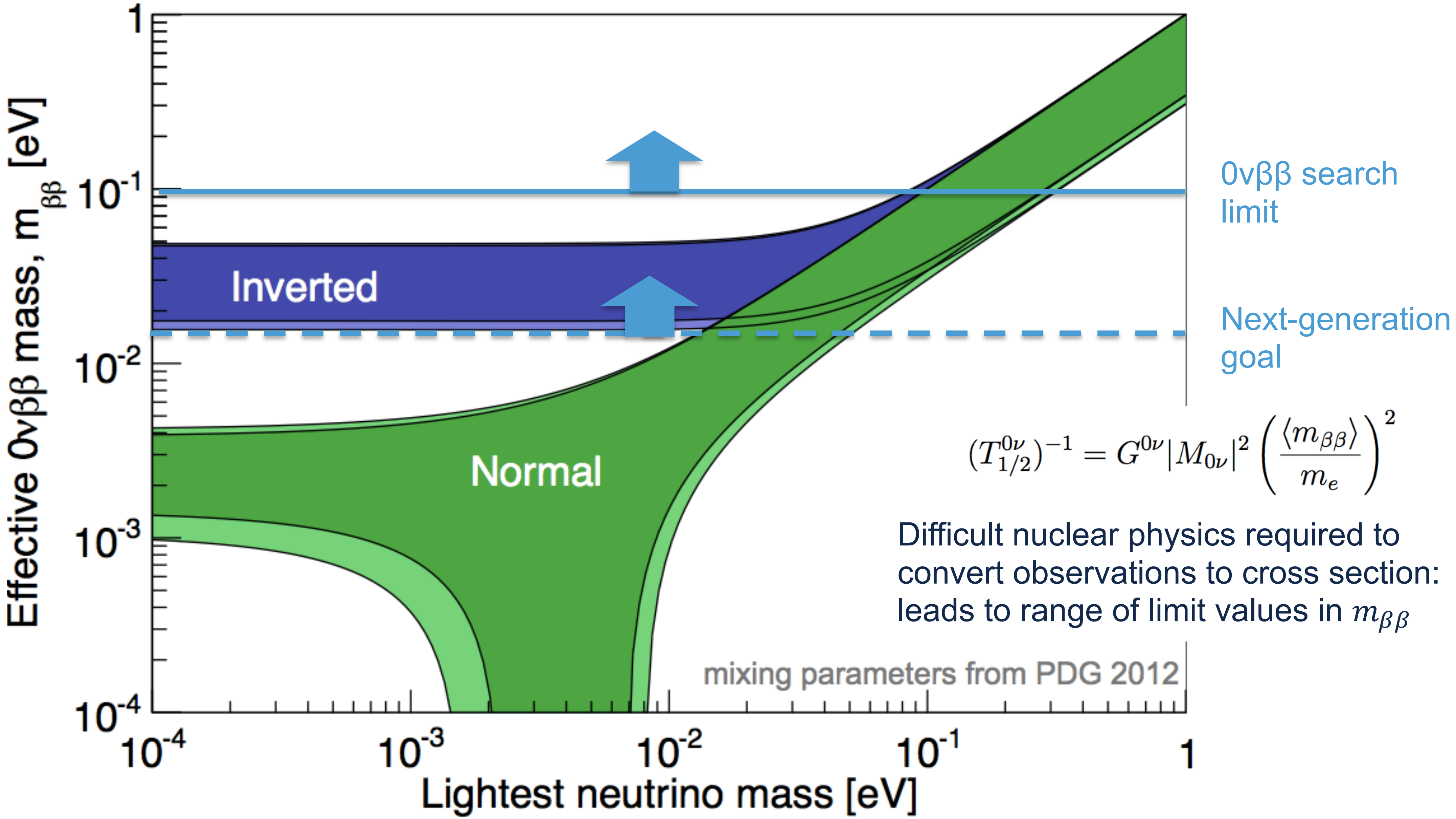


Figure by B. Jones


Neutrino mass measurement
Neutrino mass limit
Hierarchy measurement: which branch?
3σ uncertainty on mixing and mass splittings
Inverted
Normal
mixing parameters from PDG 2012
ctive 0νββ mass, m_ββ [eV]
Lightest neutrino mass [eV]
1
10^-1
10^-2
10^-3
10^-4
10^-4
10^-3
10^-2
10^-1
1



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

Difficult nuclear physics required to convert observations to cross section: leads to range of limit values in $m_{\beta\beta}$

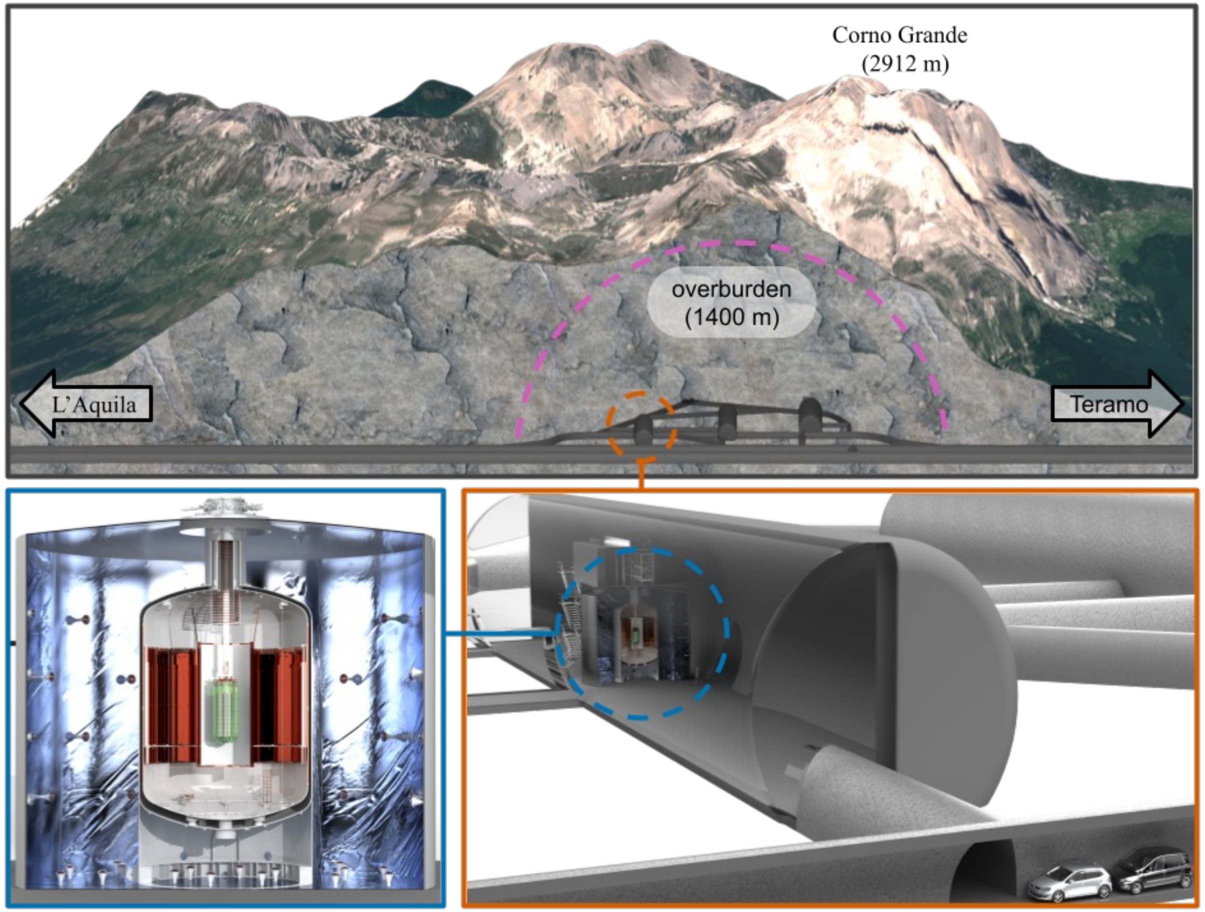
Reaching Ultra-Long Half-Life

- 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

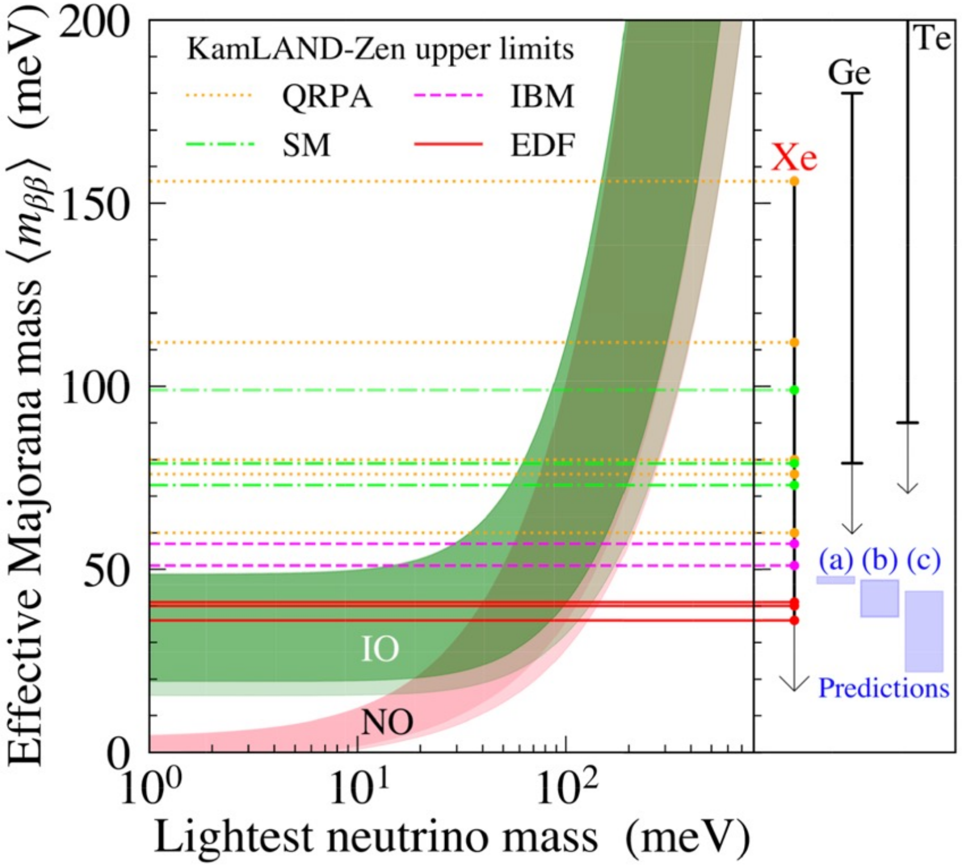
For higher backgrounds, required exposure increases accordingly

- 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

0νββ Experiments



Current Best Limits on 0νββ



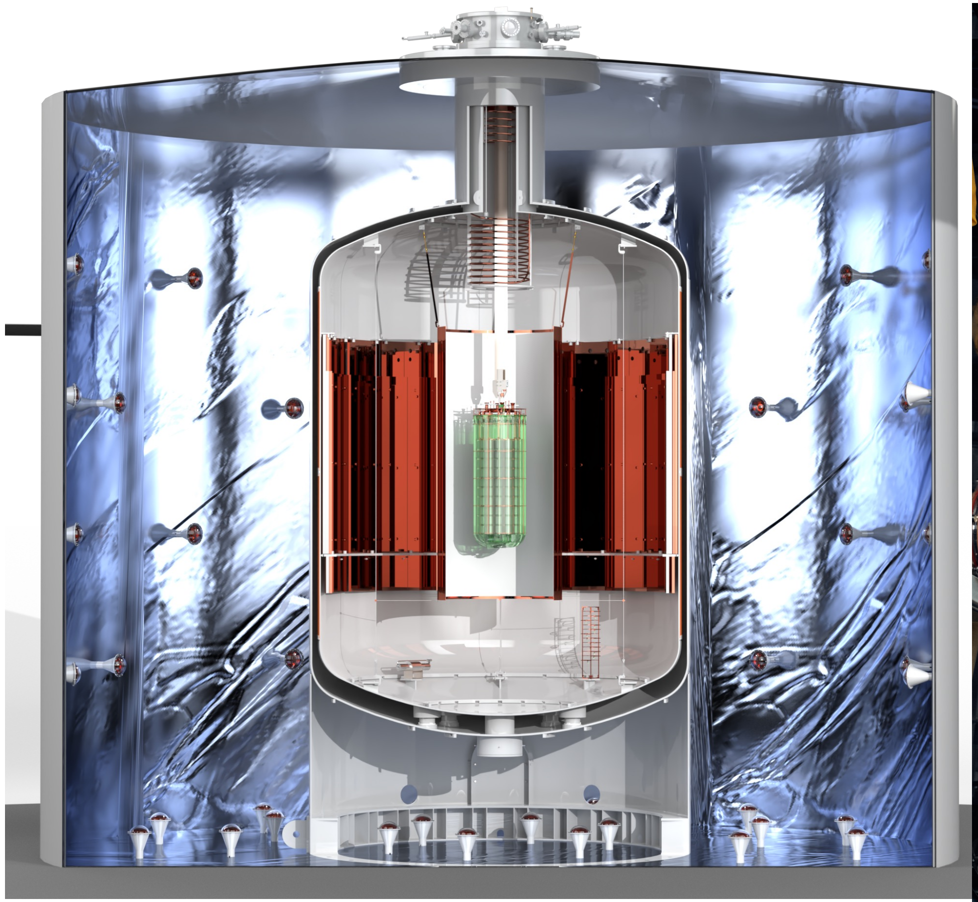
arXiv: 2203.02139

Experiment	Isotope	Exposure [kg yr]	$T_{1/2}^{0\nu}$ [10^{25} yr]	$m_{\beta\beta}$ [meV]
Gerda	^{76}Ge	127.2	18	79-180
Majorana	^{76}Ge	64.5	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

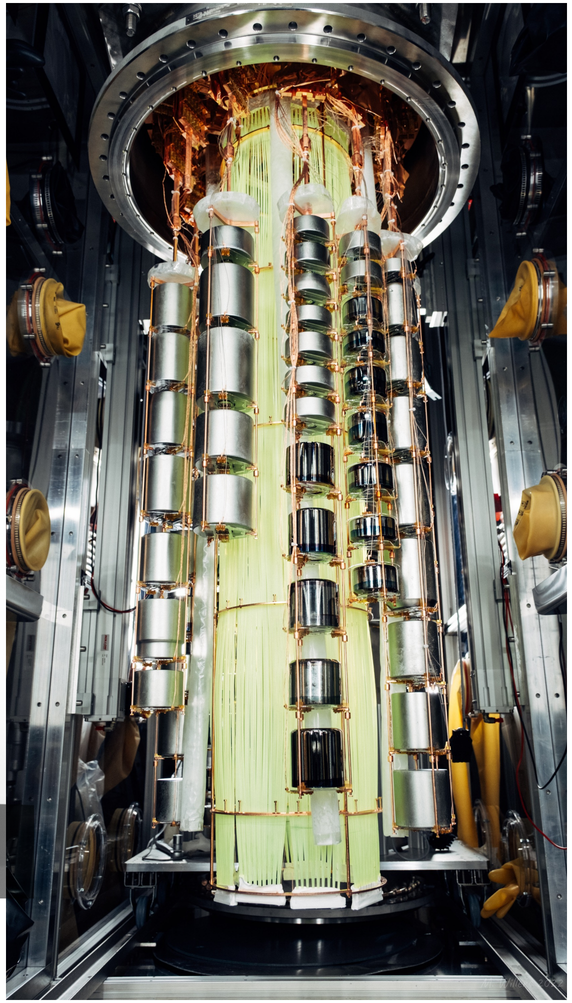
NSAC recommendation: quote a range of $m_{\beta\beta}$ using the largest and smallest available NME from the 4 main calculation methods; g_A=1.27; no contribution from the contact term

Intermediate-scale Experiments: Running Now

- LEGEND-200: 200 kg ^{76}Ge-based experiment using HPGe detectors in LAr
- KamLAND-Zen-800: 745 kg ^{136}Xe-based experiment using liquid scintillator
- + smaller-mass experiments

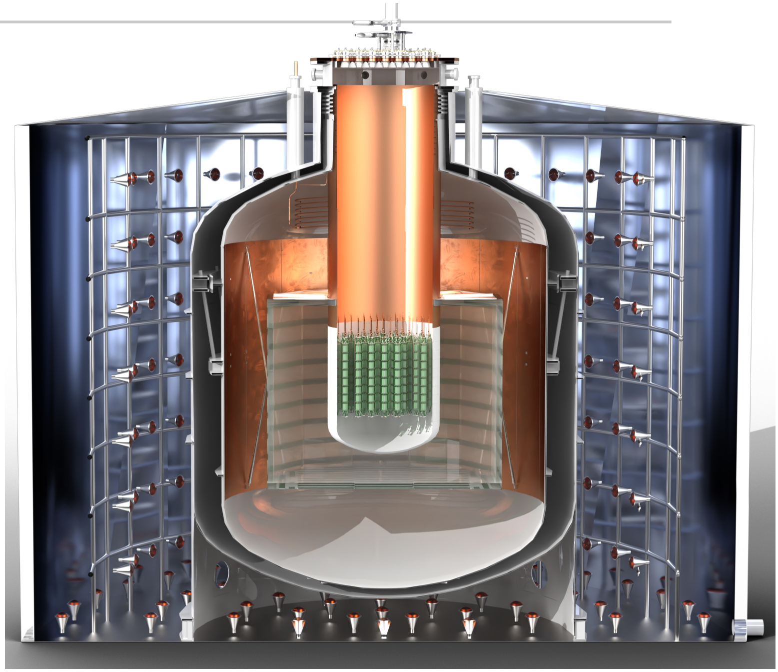


LEGEND-200



The Ton-Scale Generation

- Covering the IO in discovery mode requires O(1 ton) of isotope
- 3 candidate experiments with large US involvement: LEGEND-1000, nEXO, and CUPID
- All 3 experiments cover the IO in “discovery mode” for most matrix elements
- These experiments are ready to begin construction!



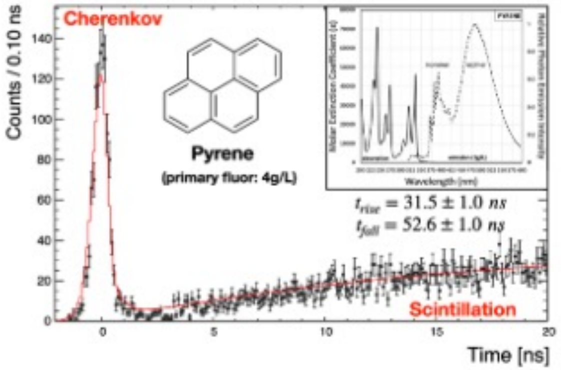
LEGEND Timeline

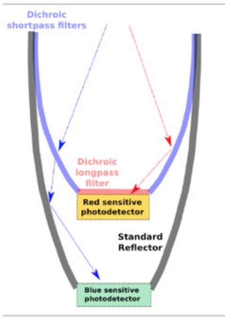
2022-2023	2024	2025	2026	2027	2028	2029	2030	2031-2035	2036-2045
Design			Construction						
							Early Physics Data		Operations

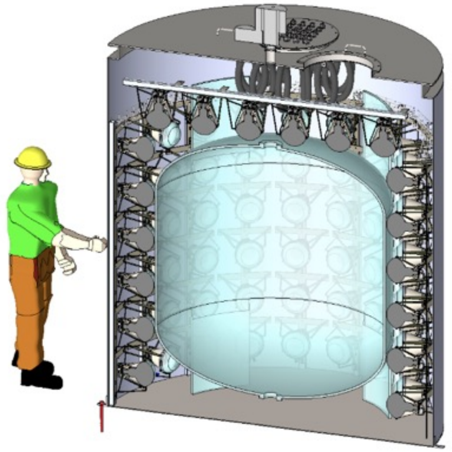
What Comes Next?

- 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
- Are "neutrino observatories" the path forward?

R&D for hybrid scintillator detectors: slow scintillators, spectral sorting and Eos

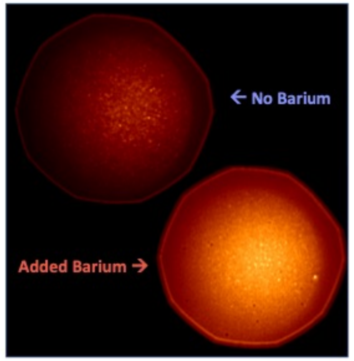


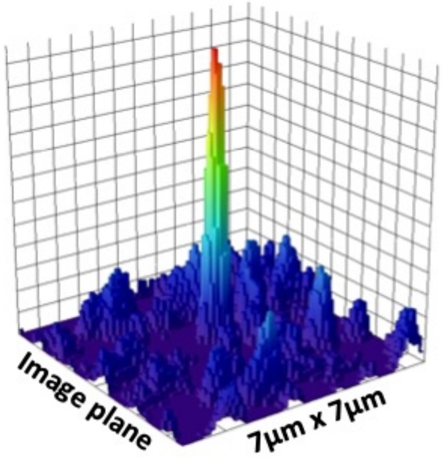




R&D for ultra-large Xe TPCs: new acquisition strategies and Ba tagging

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





Conclusion

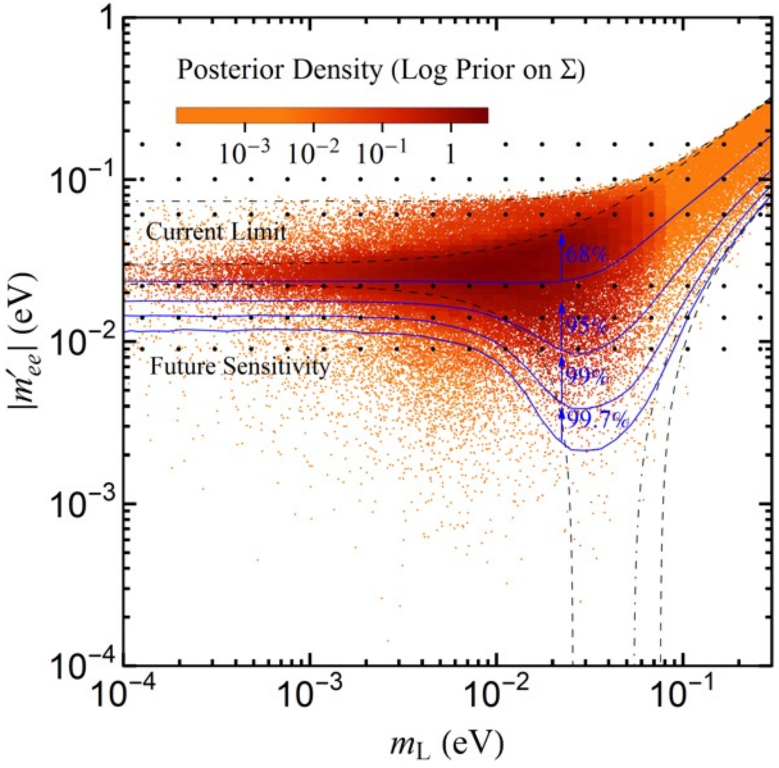
- Neutrino mass is BSM physics, and we still haven't explained it
- 0νββ is some of the most exciting physics we can look for! It could provide insight into the origin of neutrino mass and the mechanism that drove baryogenesis
- Regardless of the mechanism, 0νββ would be a direct observation of lepton 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, with rich R&D to go further

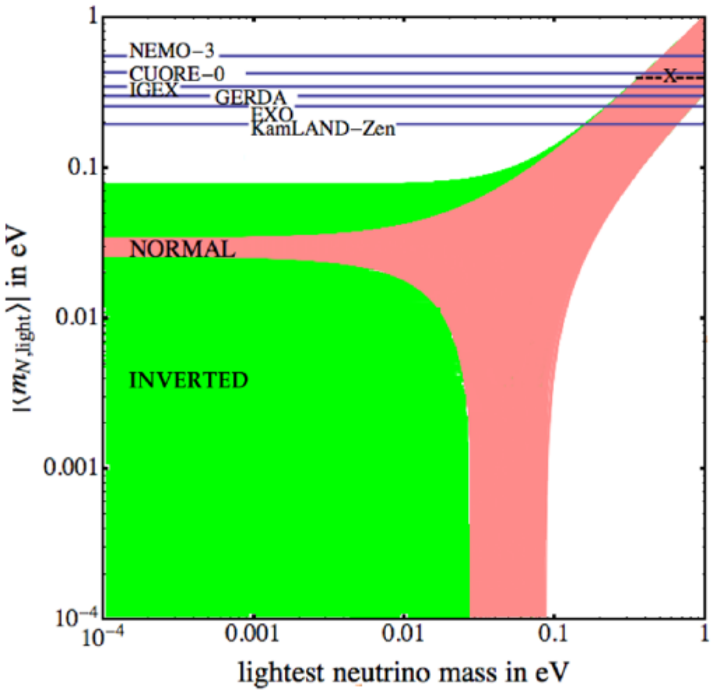
Extra Slides

Sterile Neutrinos and the 0νββ Rate

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

(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)

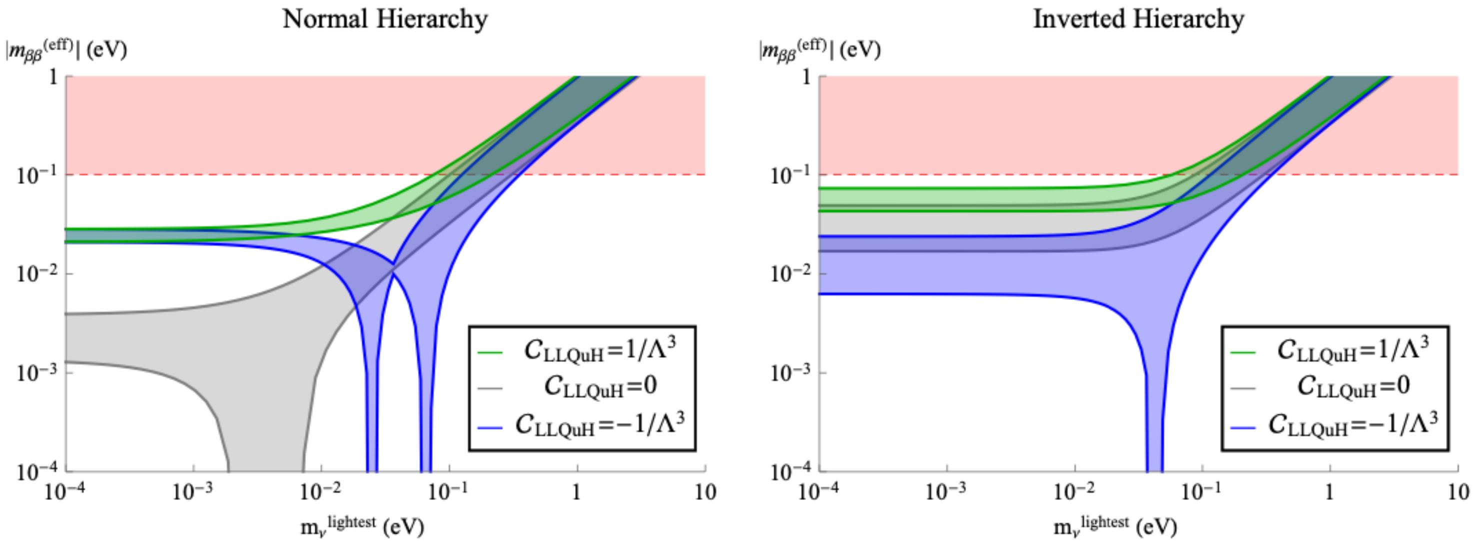




(3+1)ν mixing
m_4 = 1 eV and
$|U_{e4}|^2 = 0.03$
PRD 92, 093001 (2015)

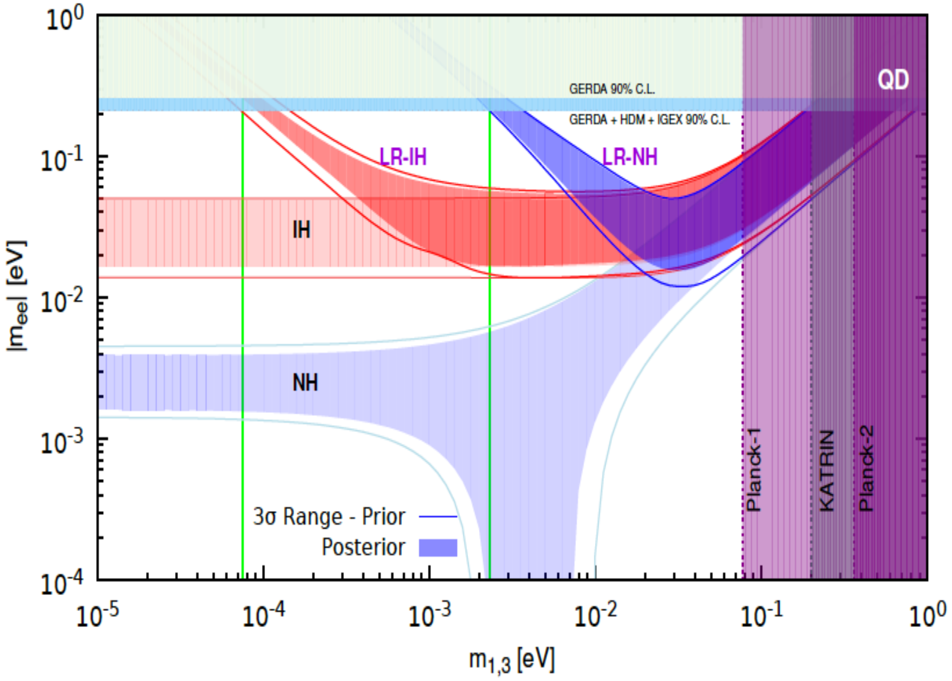
The Rate In Alternative Mechanisms

- 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



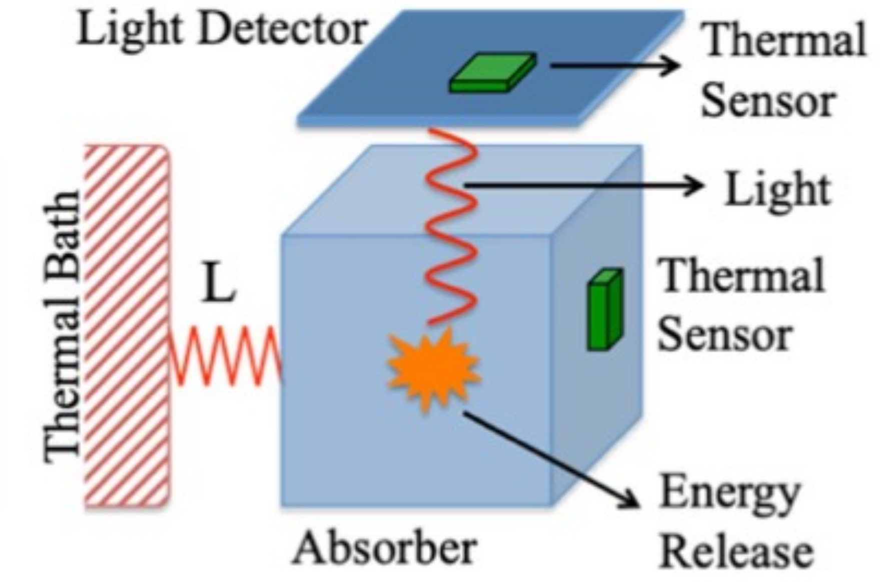
Role of additional dimension-7 operators, Λ = 600 TeV
JHEP 2017, 82 (2017)

Left-Right Symmetric Model
JHEP 10 (2015) 077



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

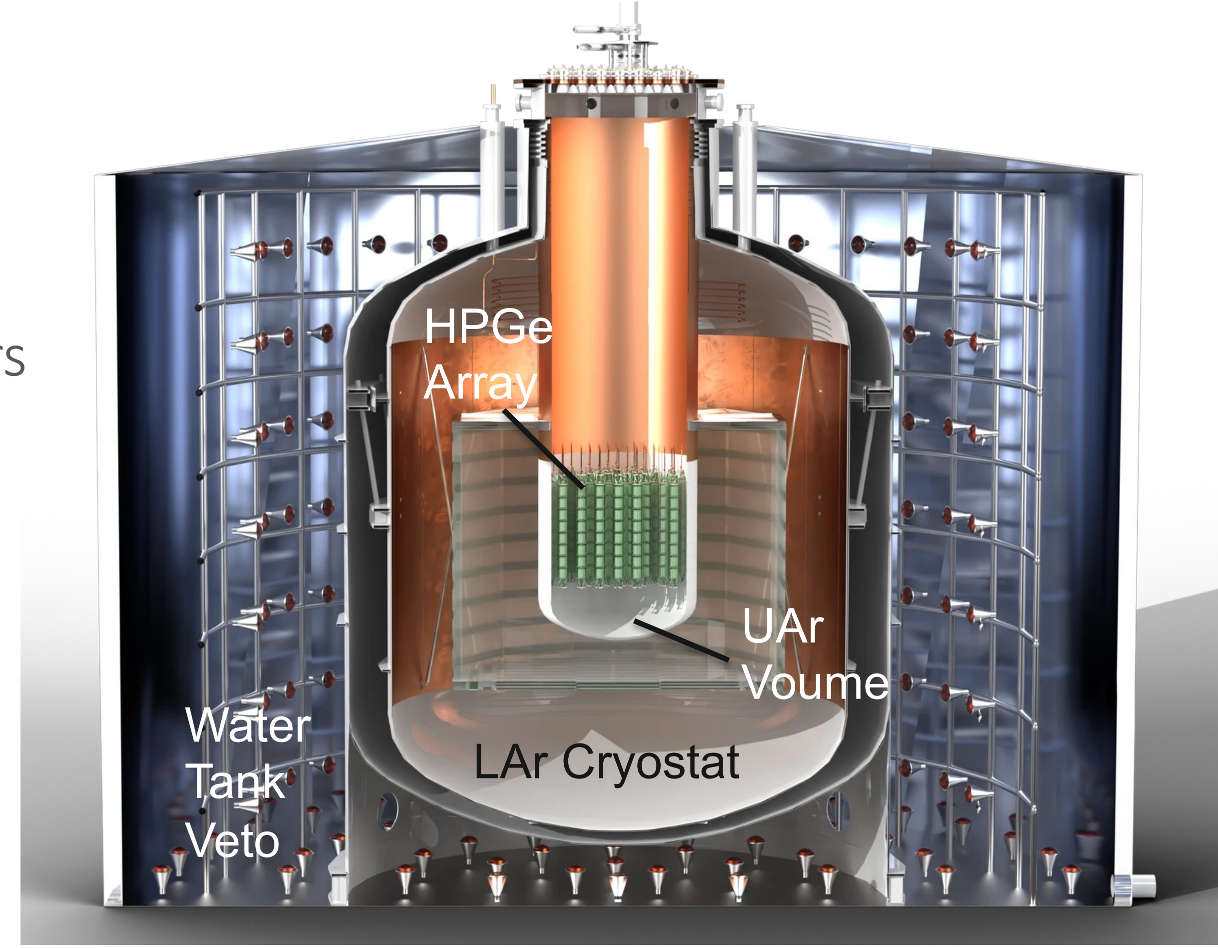


- Crystal: $Li_2{}^{100}MoO_4$
- Enrichment > 95% → 253 kg of ^{100}Mo
- Energy res. (FWHM): 5 keV
- BI < 10^{-4} cnts/(keV kg yr)
- Discovery sensitivity: $T_{1/2} \sim 1.1\times10^{27}$yrs
- $m_{\beta\beta}$ discovery sensitivity: 12-20 meV

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

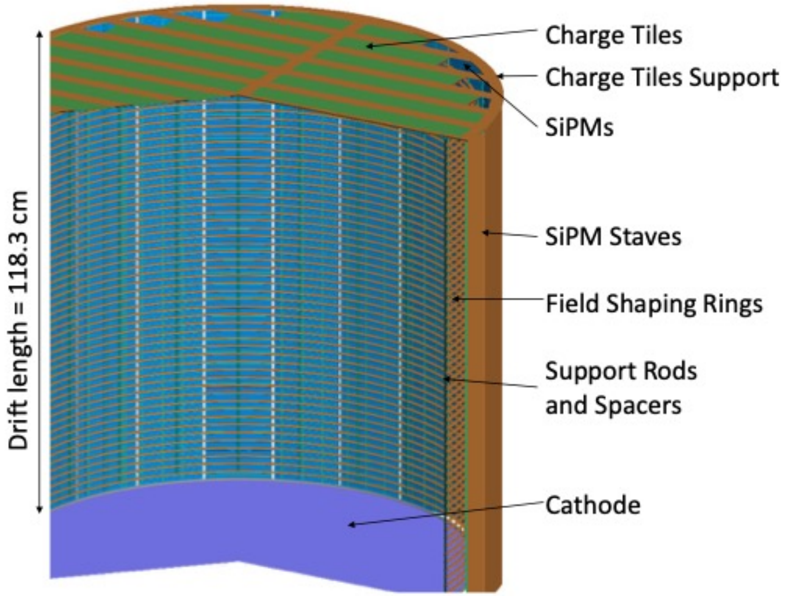
LEGEND-1000

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

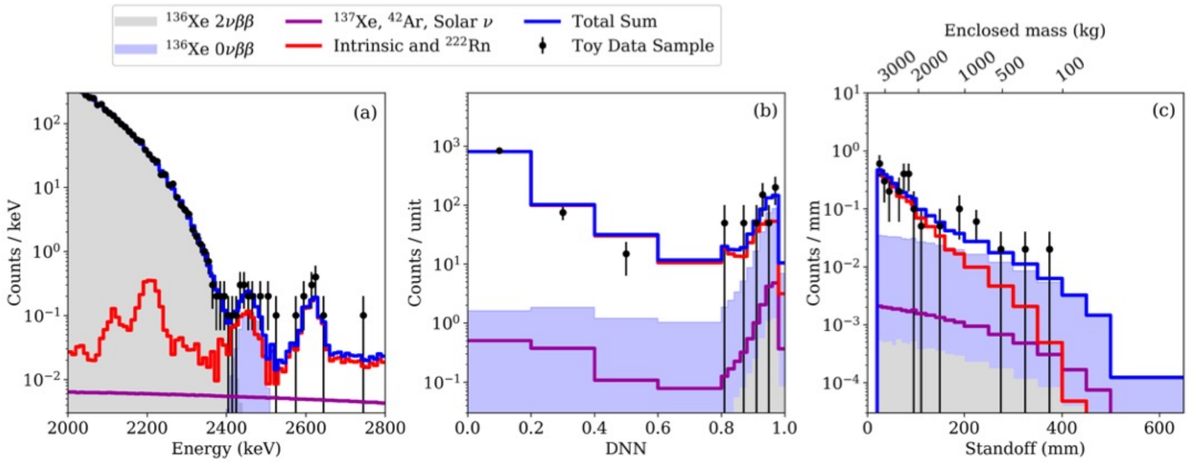


- 1000 kg of ^{76}Ge
- Energy res. (FWHM): 2.5 keV
- BI < 10^{-5} cnts/(keV kg yr)
- Discovery sensitivity: $T_{1/2} \sim 1.3\times10^{28}$yrs
- $m_{\beta\beta}$ discovery sensitivity: 9-21 meV

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



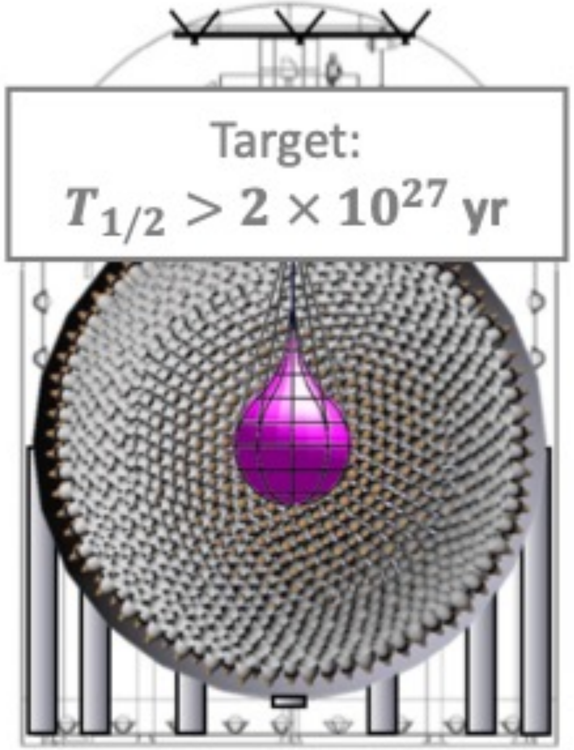
J. Phys. G: Nucl. Part. Phys. 49, 015104 (2022)

- 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

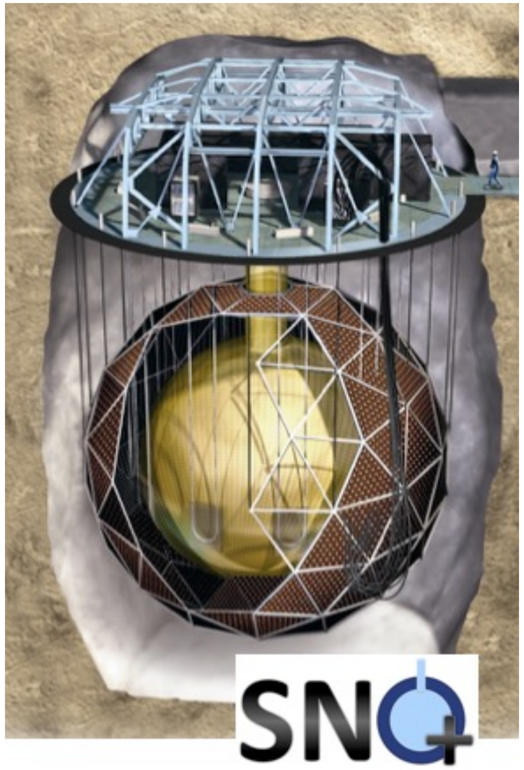
Liquid Scintillators: KamLAND-Zen and SNO+

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

KamLAND2-Zen



- 1 ton of ^{enr}Xe in inner balloon



- Initial loading: 0.5% natural Te by weight
- Scaling to 3% for $T_{1/2} > \sim 10^{27}$ yrs

What about other low-energy neutrino physics?

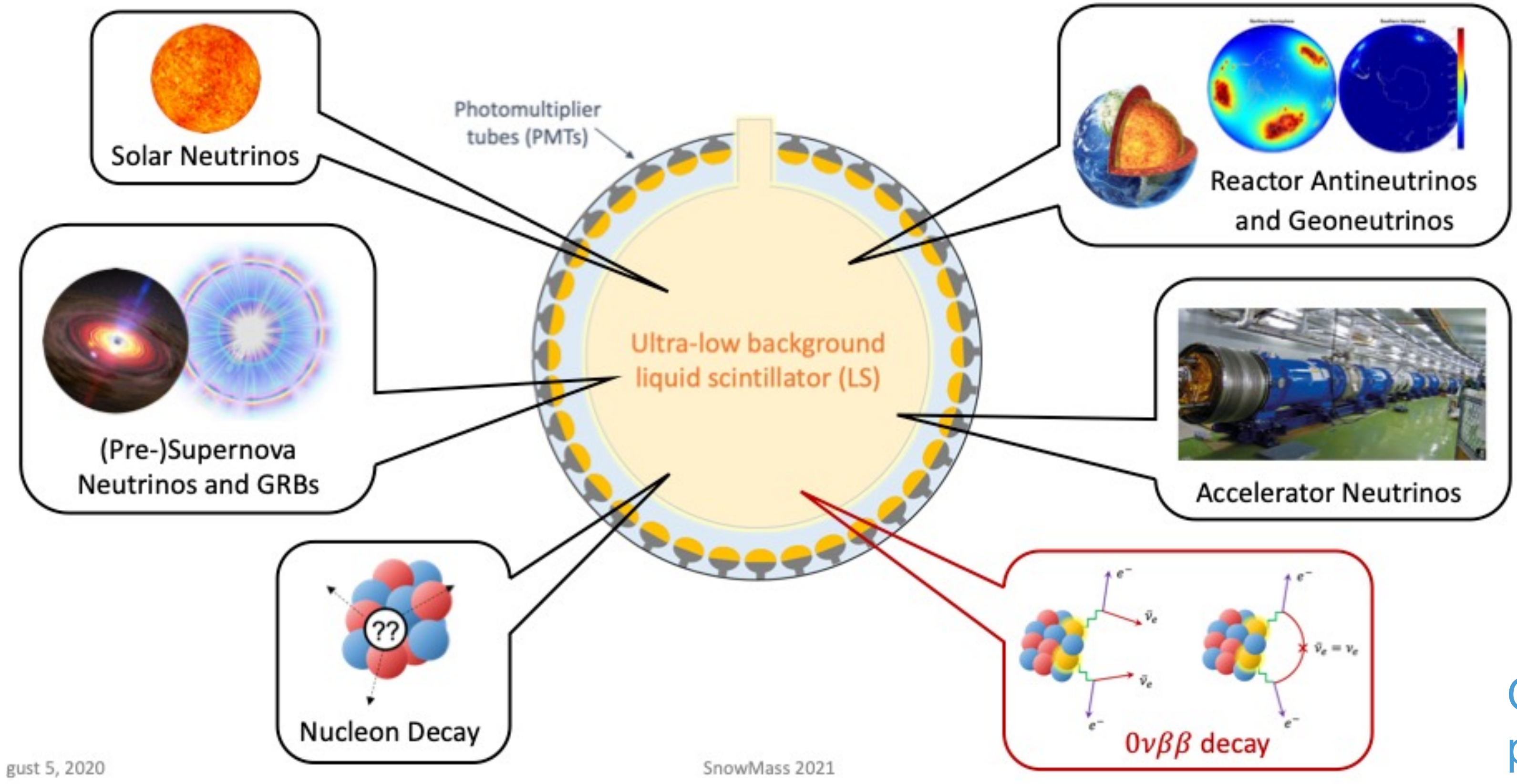


Image courtesy of the Theia Collaboration, from R. Svoboda

Large liquid scintillator detectors are also well-suited to pursuing other neutrino physics measurements

This is the concept behind Theia and other WbLS concepts

KLZ and SNO+ demonstrate this capability!

Other experiments also have broader physics programs: supernova neutrinos, dark matter searches, etc…