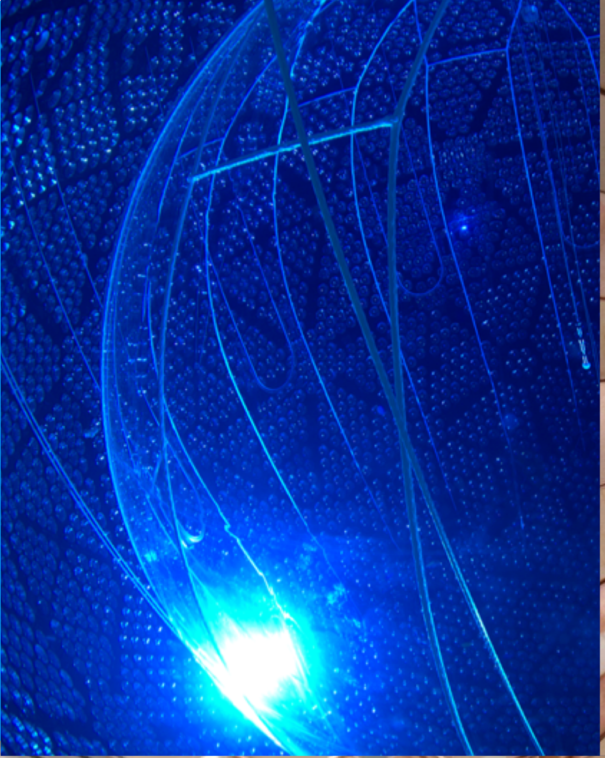

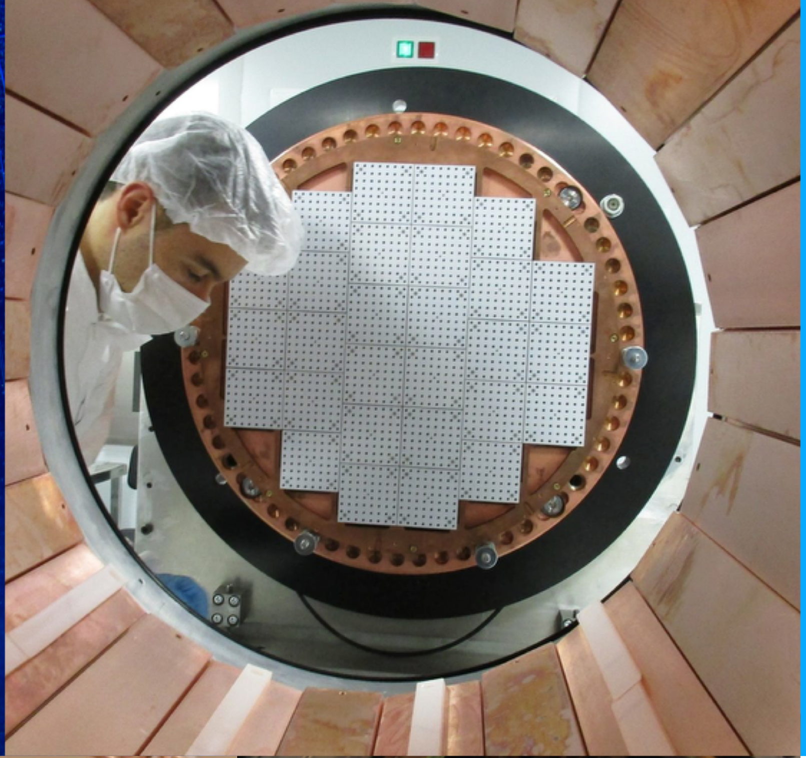

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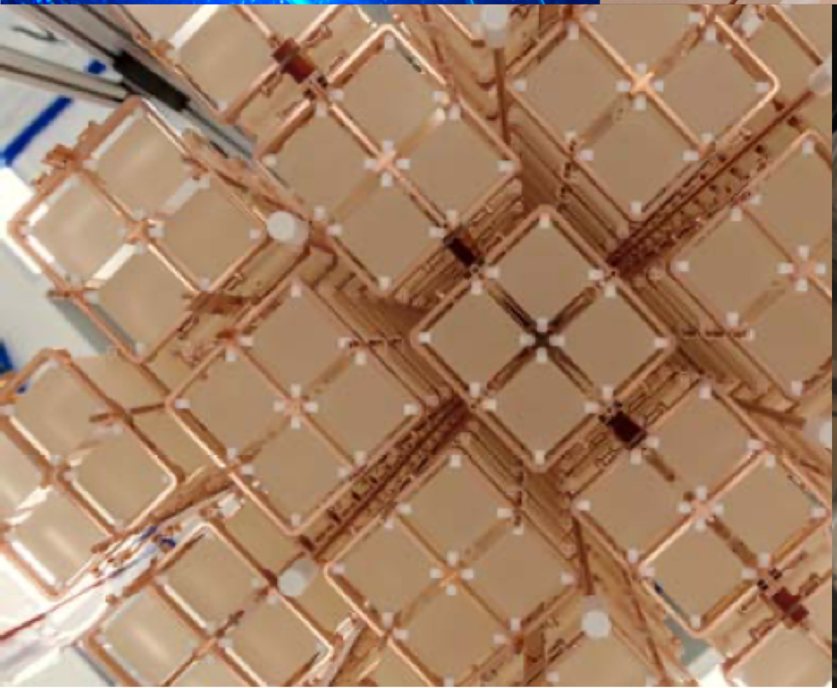
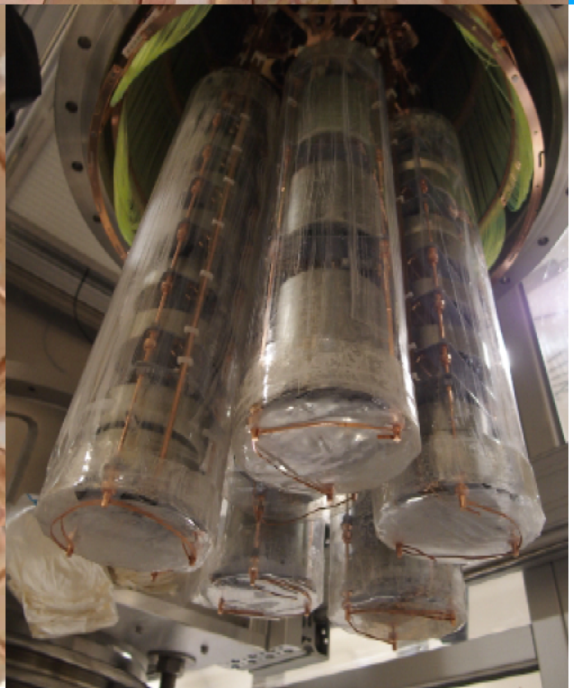
Neutrinoless Double-Beta Decay: To the Ton Scale and Beyond





Julieta Gruszko

University of North Carolina at Chapel Hill

Fermilab Neutrino Summer School

July 8, 2021

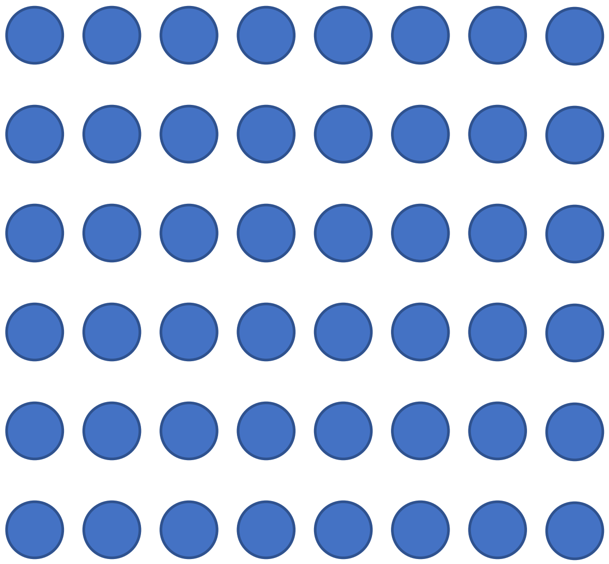
Outline

- Why look for Majorana neutrinos?
  - The matter/anti-matter asymmetry
  - The problem of neutrino mass
- The Majorana mass mechanism
  - Dirac and Majorana mass terms
  - Type I see-saw, leptogenesis, and other options
- Nature's laboratory: neutrinoless double-beta decay
  - Nuclear physics and double-beta decay
  - The rate of $0\nu\beta\beta$, sensitivity, and discovery
  - Building low-background experiments
- Current experiments and future prospects

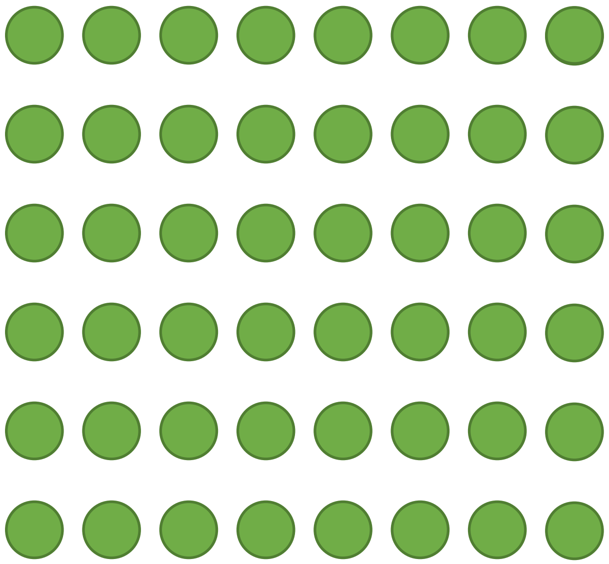
Why Look for Majorana Neutrinos?

Early Universe

Matter



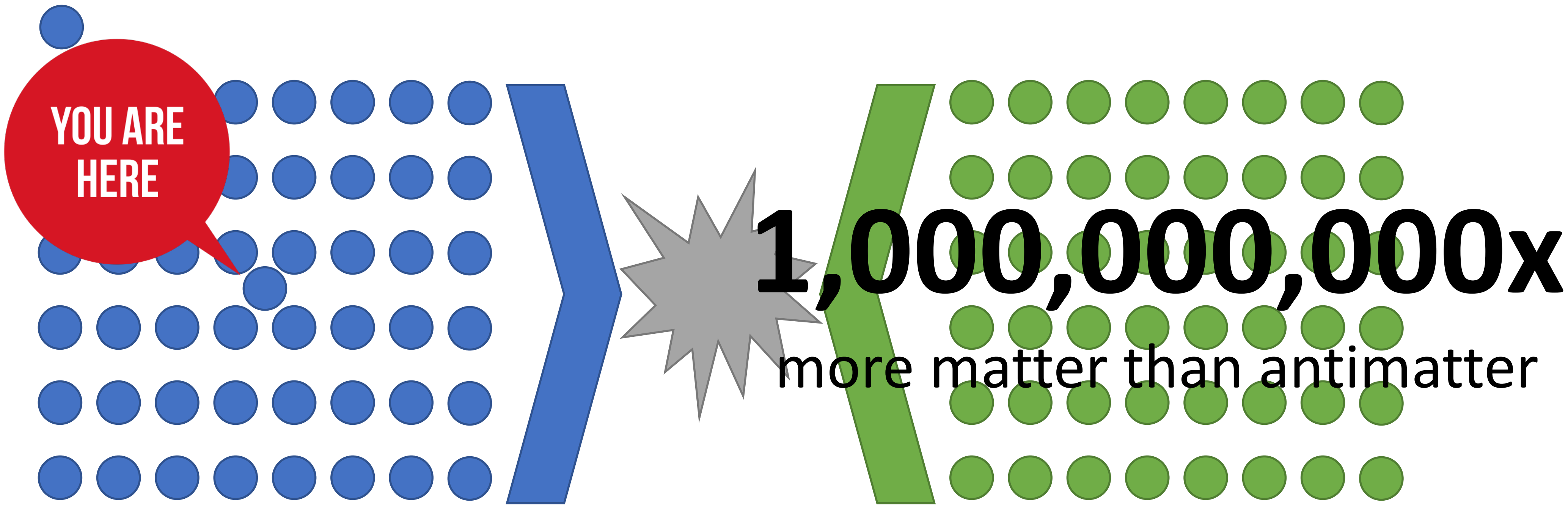
Antimatter



Early Universe
Today

Matter

Antimatter



10,000,000,001
1

10,000,000,000
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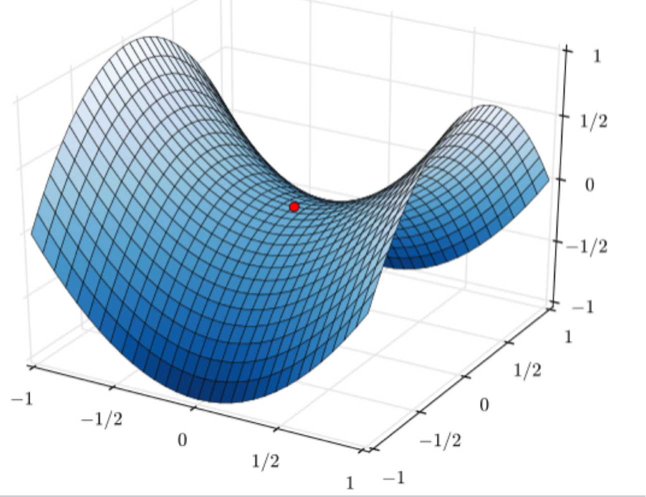
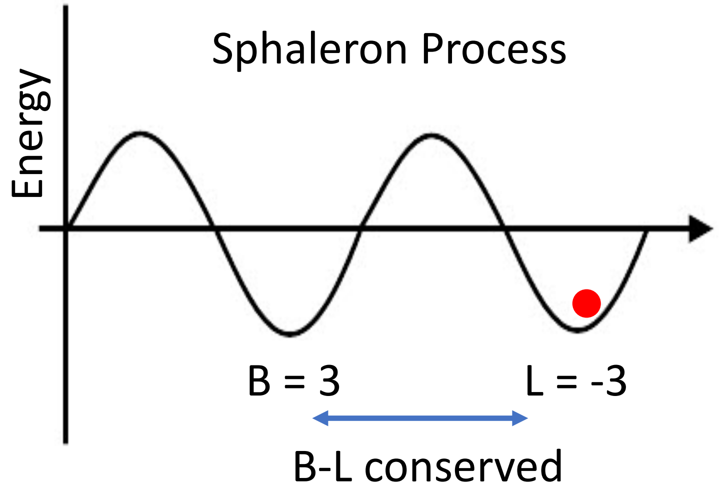
Creating Matter: The Sakharov Conditions

- In 1967, Sakharov proposed 3 conditions required for baryon-generating interactions that would generate an asymmetry:
  1) Baryon number violation
  2) C and CP violation
  3) Interactions out of thermal equilibrium
  - The paper is only 3 pages, available here: http://jetpletters.ru/cgi-bin/articles/download.cgi/1643/article_25089.pdf
- B and L aren't separately conserved in the SM: B-L is
  - If your theory can generate lepton number violation, that can be converted into baryon number violation
  - See the 1986 paper, by M. Fukugita & T. Yanagida, here: https://doi.org/10.1016/0370-2693(86)91126-3

Saddle point in the EW potential:





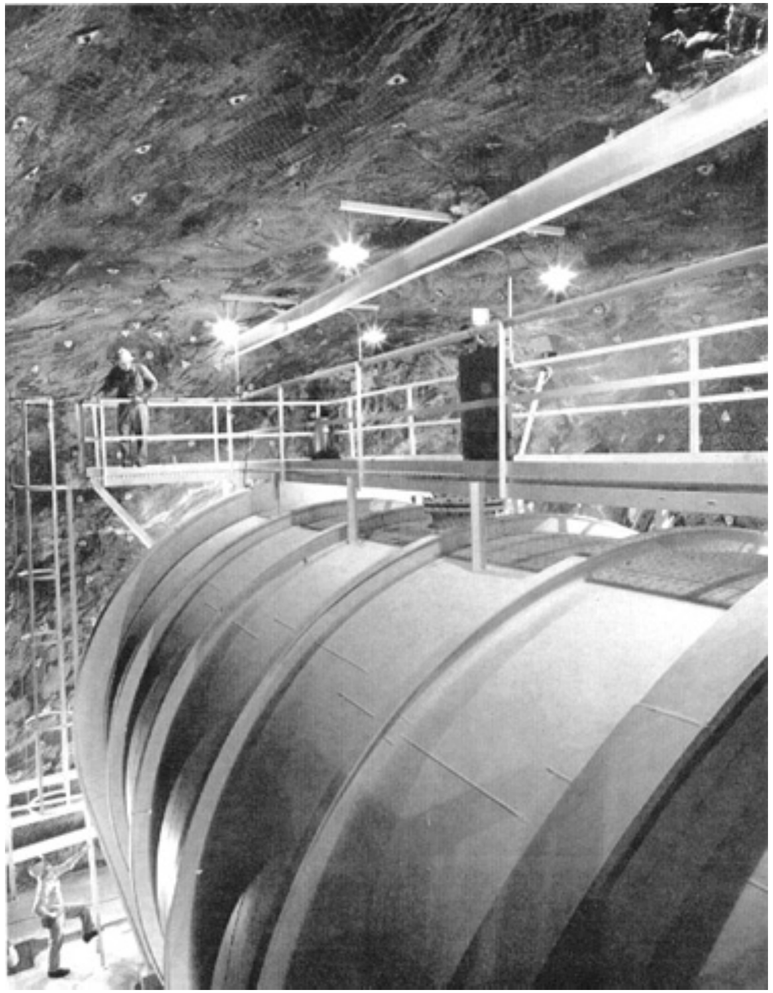
The Solar Neutrino Problem and Neutrino Mass

Fusion in the sun produces a lot ($7x10^{10}$ $\nu/cm^2/s$) of ν_e

Let's measure them!

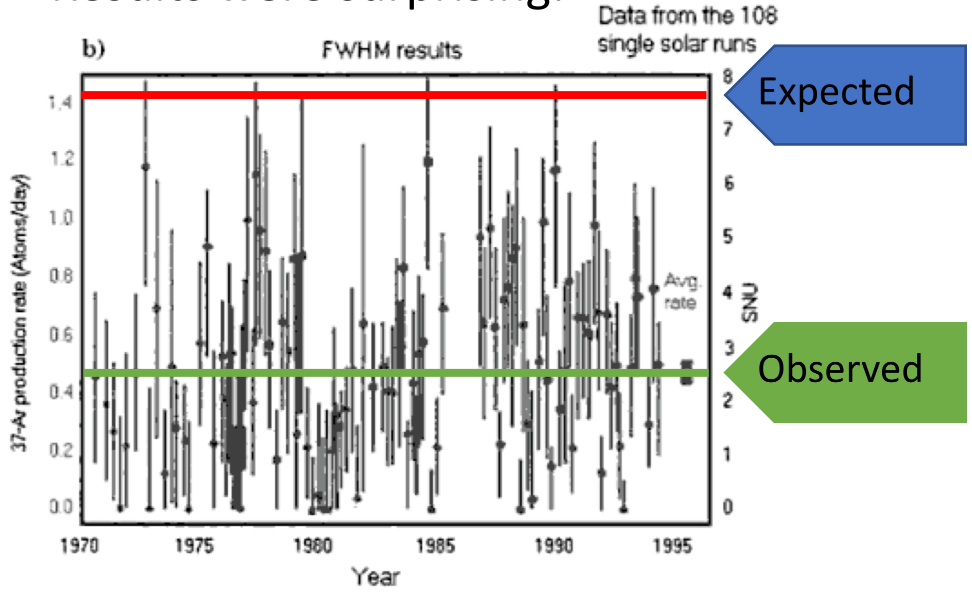
$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$

Every few weeks, filter to find the atoms created by ~1.5 captures per day



The Davis experiment, at Homestake Mine (now SURF)

Results were surprising:

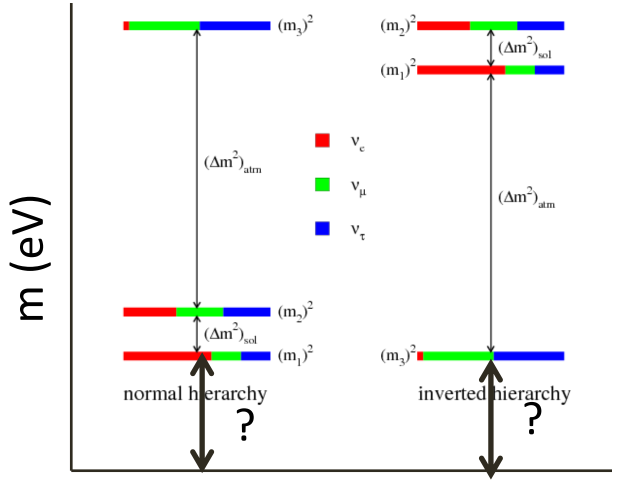


Decades of follow-up experiments showed that neutrinos were changing from one type to another

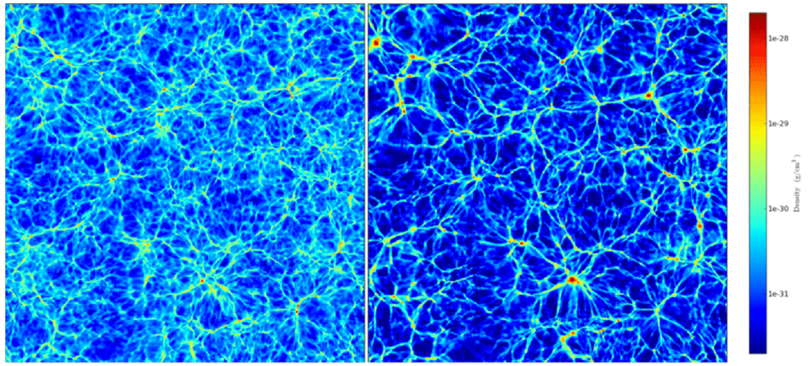
Neutrinos must have mass

What do you mean by mass?

$m_{lightest}$:



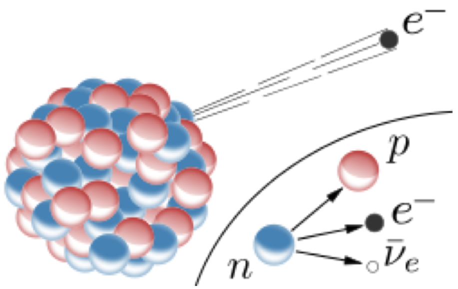
Structure Formation Simulations



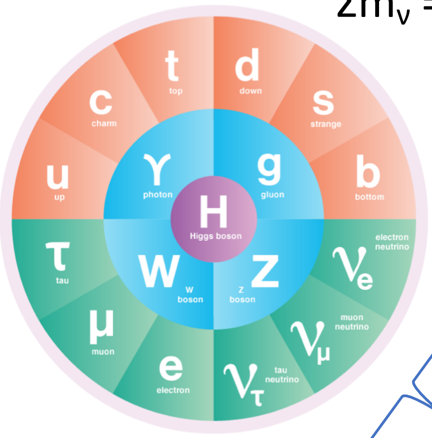
$\Sigma m_\nu = 1.9$ eV

$\Sigma m_\nu = 0$

m_β:

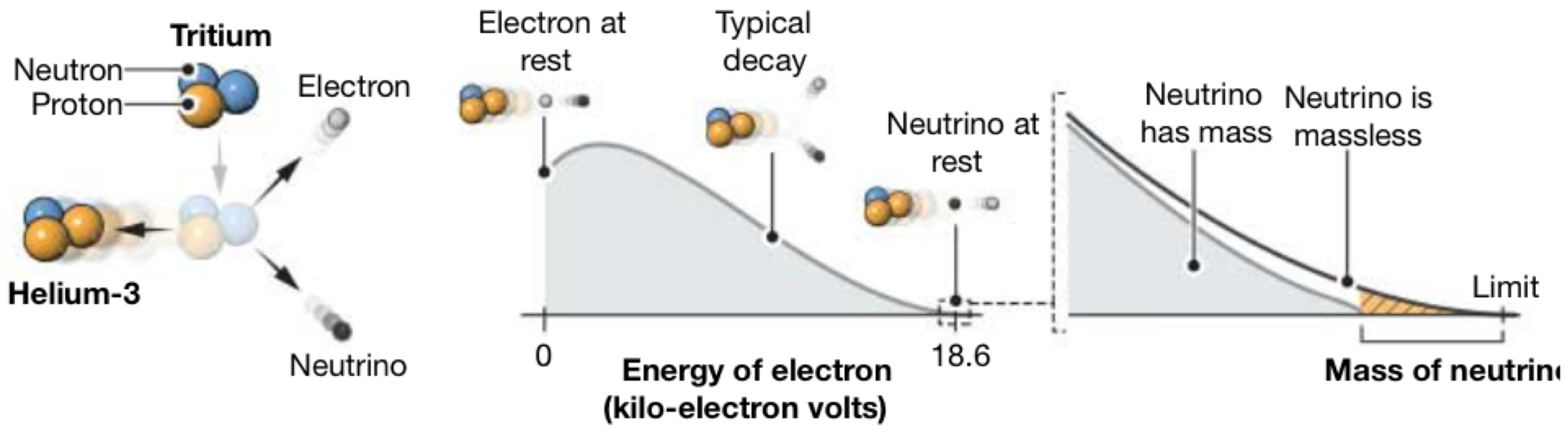


Σm:



KATRIN, DOI:
10.1103/PhysRevLett.123.221802

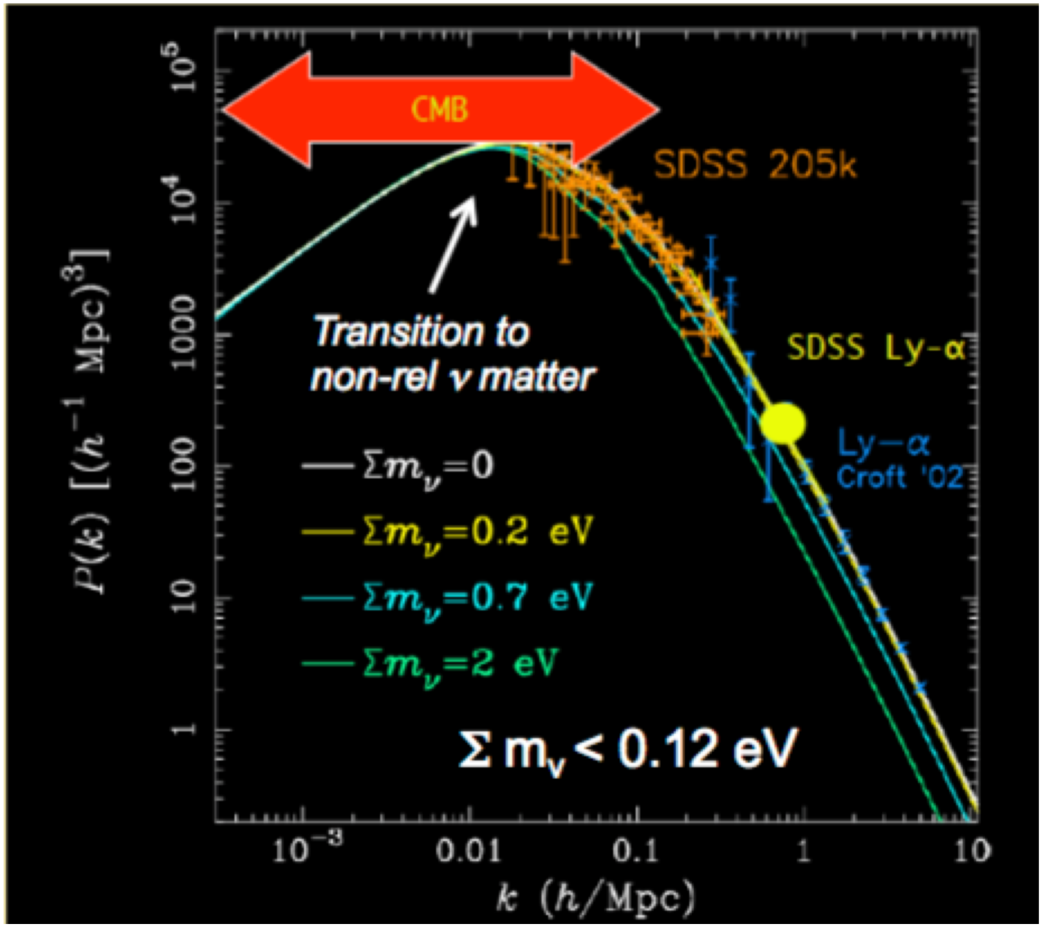
Beta Decay Kinematics



- Watch many (10^{11} per second) beta decays
- Detect only the highest-energy decays (1 of every 5×10^{12}) decays)
- Measure the shape of the spectrum endpoint
- Measures m_β directly, no model-dependence
- Current best limit: $m_\beta < 1.1$ eV (KATRIN experiment, 2019)

Cosmological Limits

- In the early universe, neutrinos have a characteristic "free streaming scale" (how far they go before scattering)
- $L_{fs} \propto \sqrt{m_\upsilon}$
- Neutrinos inhibit structure formation below L_{fs}
- Lowest limits combine data from many sources– Planck CMB, BAO, Type Ia supernovae, galaxy surveys, weak lensing measurements, etc.
- Σm < 120-230 meV, Planck best fit is to Σm = -50 meV
- New result using SDSS: Σm = 110 meV



Neutrino Mass

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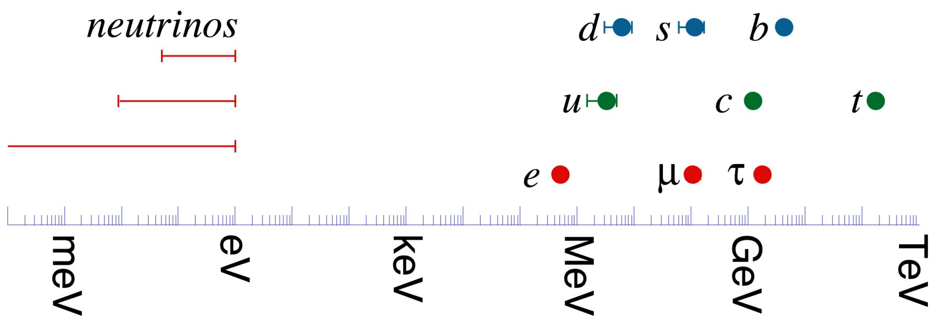
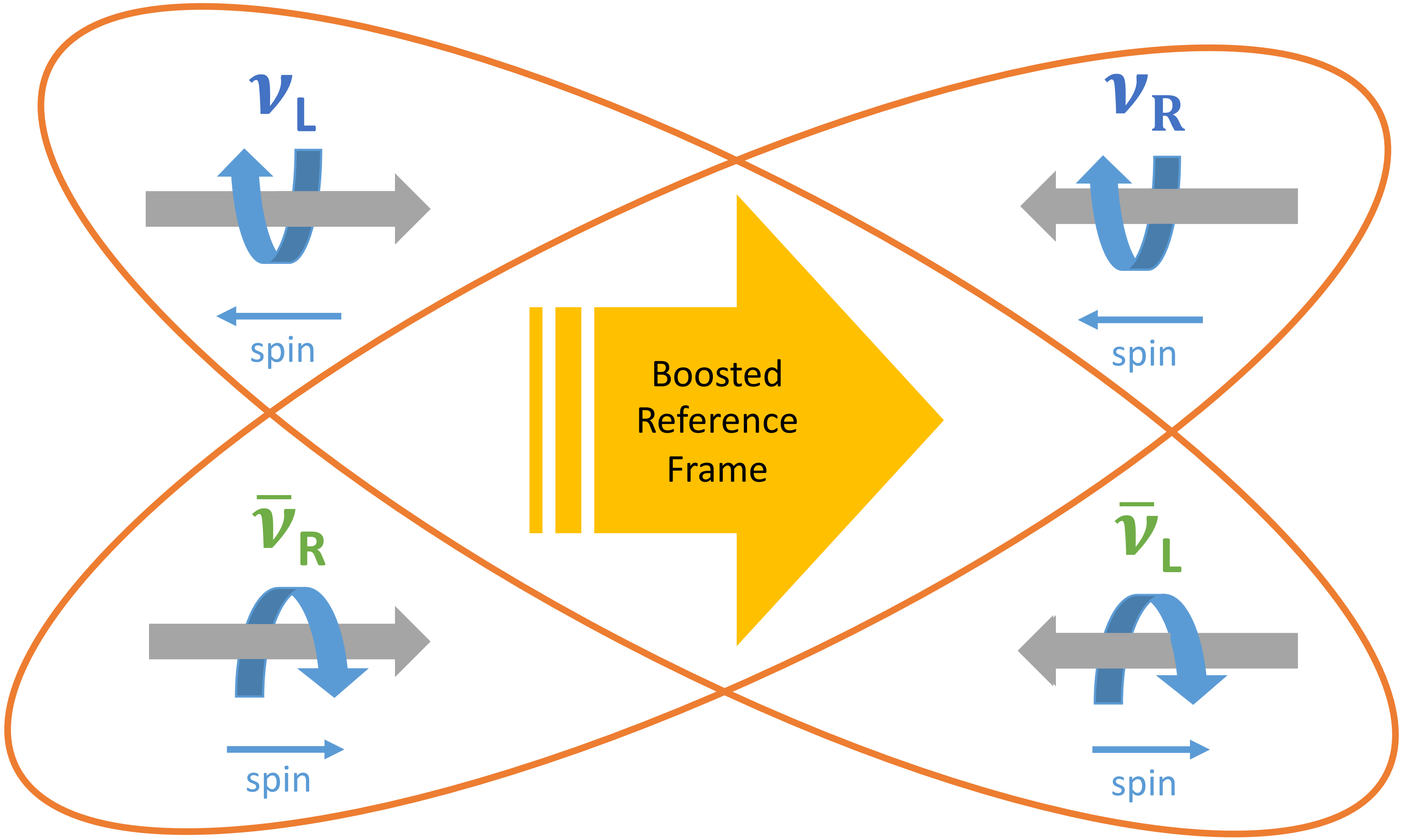
Technique	Sensitivity	Current limit
Neutrino Oscillations	$\Delta m_{ij}^2 = m_i^2 - m_j^2$	IO: Σm > 98 meV NO: Σm > 59 meV
Cosmological modeling of Astrophysical Observations	$\sum m_i + \ light\ dof$	Σm < 120 – 230 meV, depending on data sets used Planck best fit: Σm = -50 meV
Beta Decay Kinematics	$\sum \lvert U_{ei} \rvert^2 m_i^2$	Σm < 3000 meV

No matter which mass you mean, the mass of neutrinos is small!



The Majorana Mass Mechanism



$\nu_R = \bar{\nu}_R$

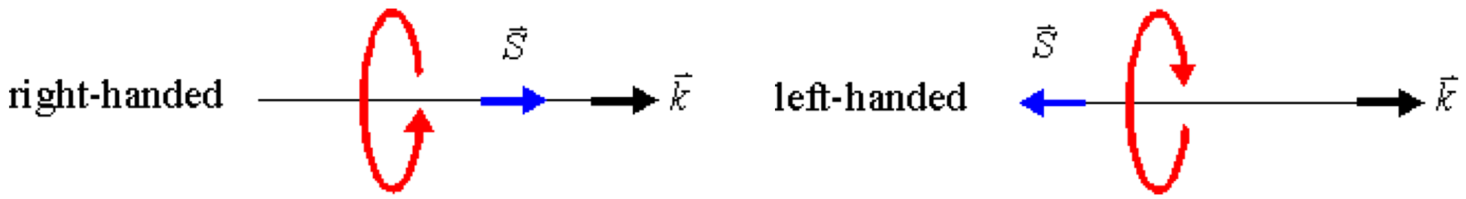
$\bar{\nu}_L = \nu_L$

This is what it means to say “Neutrinos are Majorana particles”

Helicity and Chirality

- Helicity describes the alignment of spin and momentum:

$$\hat{h} = \frac{\vec{S}\cdot\vec{P}}{s\left|\vec{P}\right|}$$



  - ➢ For massless particles, eigenvalues are ±1
  - ➢ For massive particles, reference-frame dependent
- Chirality is fundamental, it describes the field's transformation under γ^5:
  - ➢ Define chiral spinors (ψ_R , ψ_L) as the eigenfunctions of γ^5 with eigenvalues (1, -1):

    $\psi_{L,R} = \frac{1}{2}(1 \mp \gamma^5)\psi$ for particles, opposite sign for antiparticles

  Writing the Dirac free fermion Lagrangian in terms of the chiral fields, we get the field equations:

$$i\partial\!\!\!/\,\psi_R = m\psi_L \qquad i\partial\!\!\!/\,\psi_L = m\psi_R$$

$$\partial\!\!\!/ \equiv \gamma^\mu \partial$$

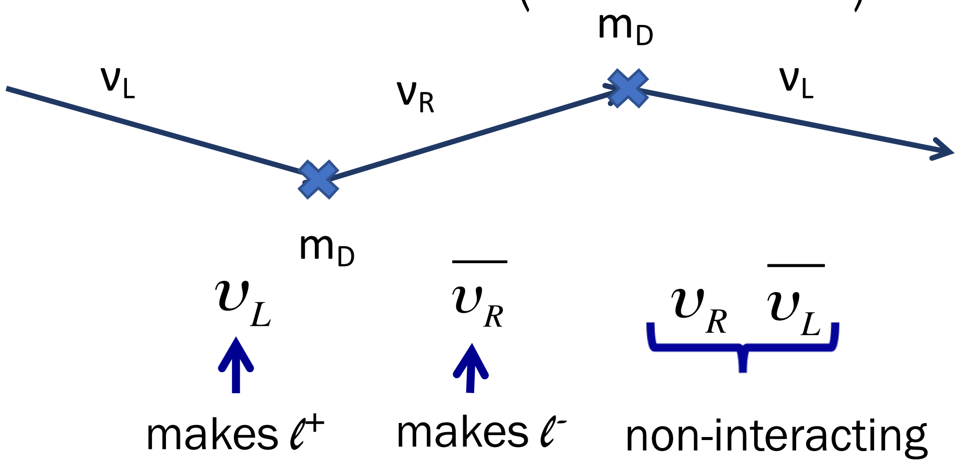
➢ Mass couples the left- and right-chiral fields together

  ➢ If E>>mc^2, helicity~chirality

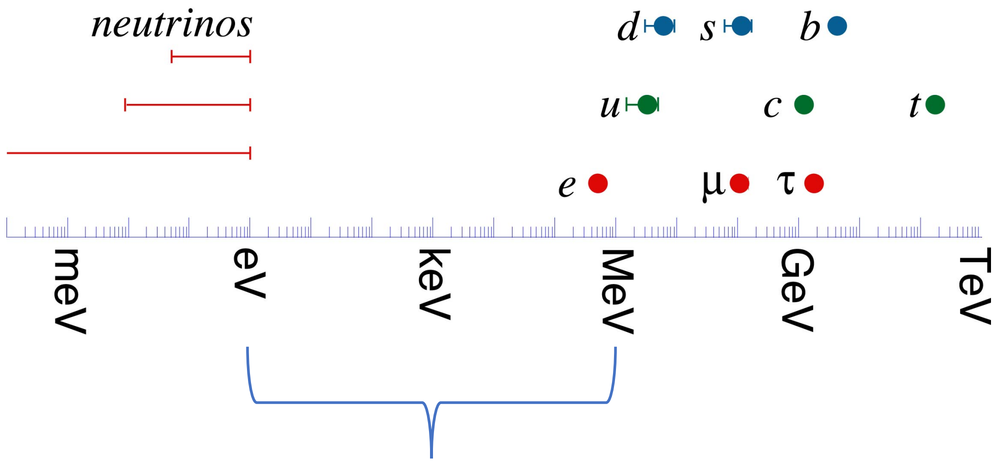
Dirac Mass Term

- The neutrino could get its mass the same way other leptons do
- Add a non-interacting right-chiral neutrino field to the SM

$$L^{D}_{mass} = -m_D\left(\overline{\nu_L}\nu_R + \overline{\nu_R}\nu_L\right)$$



Leads to the "hierarchy problem":



Over 6 orders of magnitude difference in Yukawa couplings: Why?

Majorana Mass Term

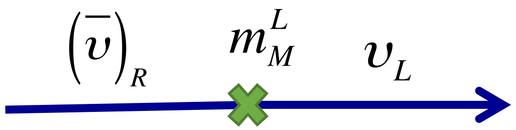
- Because the neutrino is neutral, we have another option:

$\psi=\psi^C$ (AKA the Majorana condition)

- Then ν_L^C is right-handed, and we can write a non-zero left-handed Majorana mass term:

$$L^L_{mass} = -\frac{1}{2} m^L_M \left(\overline{\upsilon_L} \upsilon_L^C + \overline{\upsilon_L^C} \upsilon_L \right)$$

- We can identify ν_L^C with the particle we observe as the anti-neutrino:



Lepton number not conserved!

2 mass-degenerate states:

υ_L ↑ makes ℓ^+

υ_R ↑ makes ℓ^-

More on Majorana Mass Terms

- One problem: left-handed term isn't renormalizable in the SM. It's not invariant under SU(2)xU(1):

$$L^{L}_{mass} = -\frac{1}{2} m^{L}_{M} \left(\overline{\upsilon_{L}} \upsilon^{C}_{L} + \overline{\upsilon^{C}_{L}} \upsilon_{L} \right)$$

- This term is allowed if you introduce new physics at high energy to cut off the infinities
- The right-handed Majorana mass term is allowed:

$$L^{R}_{mass} = -\frac{1}{2} m^{R}_{M} \left(\overline{\upsilon_{R}} \upsilon^{C}_{R} + \overline{\upsilon^{C}_{R}} \upsilon_{R} \right)$$

Dirac + Majorana Mass Terms = The See-Saw Mechanism

- If we include all the terms (Dirac, left-handed Majorana, right-handed Majorana):

$$L_{mass} = \frac{1}{2}\begin{pmatrix} \overline{\upsilon_L} & \overline{\upsilon_R^C} \end{pmatrix}\begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix}\begin{pmatrix} \upsilon_L^C \\ \upsilon_R \end{pmatrix} + h.c.$$

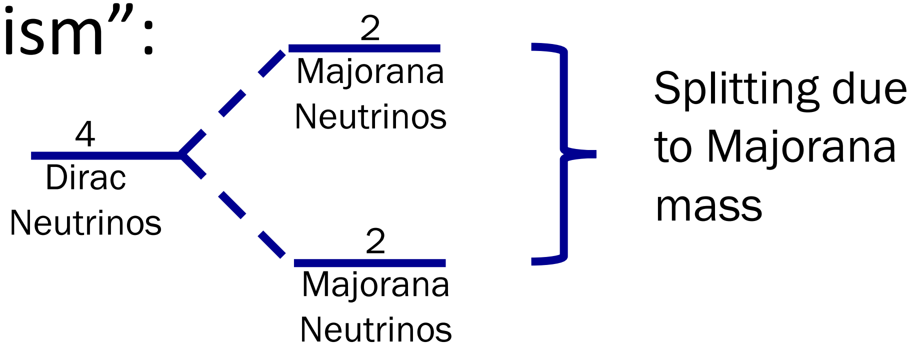
- Setting m_L to 0, mass eigenvalues are

$$\lambda = \frac{m_R}{2} \pm \frac{m_R}{2}\sqrt{1 + \frac{4m_D^2}{m_R^2}}$$

- If $m_R >> m_D$,

$$\lambda_1 = m_R \qquad \lambda_2 = \frac{2m_D^2}{m_R}$$

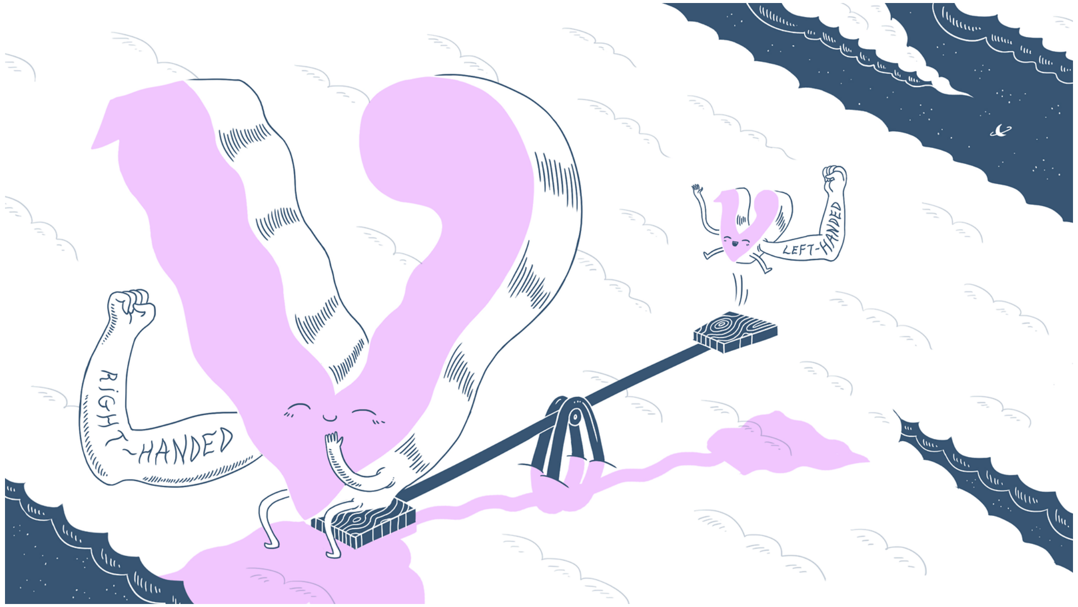
- Called the "see-saw mechanism":



The Type 1 See-Saw

- If m_R is of GUT scale (about 10^{15} GeV) and m_D is EW scale (about 100 GeV), mass eigenvalues are:

$$M_\upsilon \sim \frac{m_D^2}{m_R} \sim .01\,eV \qquad M_N \sim m_R \sim 10^{15}\,GeV$$



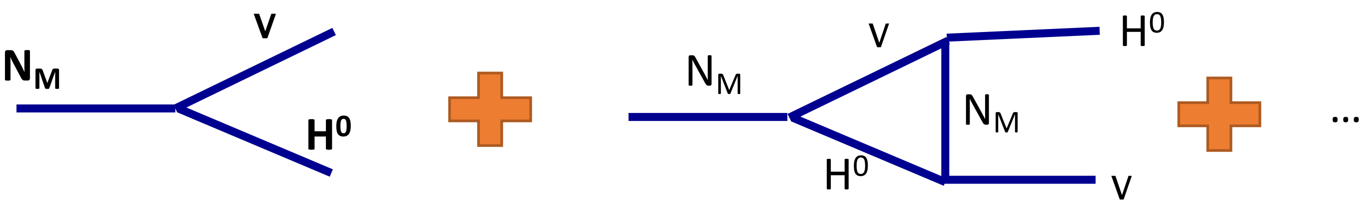
- So you get a “natural” neutrino of the correct mass by introducing a new GUT-scale particle, a heavy neutrino N
- Many consider this the simplest model for Majorana neutrinos, it’s used to compare experiments and measure their progress
- Could solve two problems: neutrino mass and baryogenesis!

Leptogenesis →Baryogensis and the Type-1 See-Saw

Could satisfy 2 (or 2.5) of the 3 Sakharov Conditions:

- Interactions out of thermal equilibrium – heavy neutrinos would decay out of equilibrium in the early universe, and "freeze-in" asymmetry at the right time
- C and CP symmetry violation – loop diagrams have extra CP violation
- The 3rd condition (baryon number violation) can be achieved via SM processes if lepton number violation is present

$$\Gamma\left(N_M \rightarrow \upsilon + H^0\right) \neq \Gamma\left(N_M \rightarrow \overline{\upsilon} + \overline{H^0}\right)$$



Other Models for Majorana Neutrinos

- Type 1 See-Saw is not the only option!
- Type 2 and 3 see-saws introduce other new particles (Higgs fields, additional heavy leptons, etc) which generate a Majorana neutrino mass
- These other models often predict new particles and lepton number violating processes at lower energy scales accessible to colliders
- See https://doi.org/10.3389/fphy.2018.00040 for a nice review

Some More Details

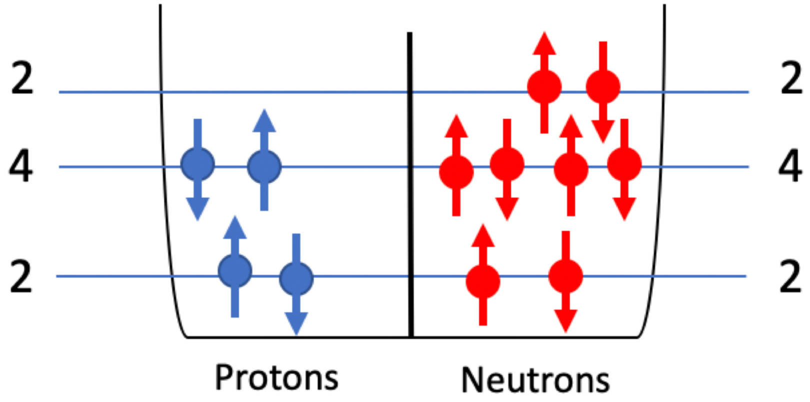
- The neutrino is a Majorana particle as long as it has a non-zero Majorana mass term, no matter the relative sizes of the terms (if it has both MJ and Dirac mass)
- Majorana neutrinos have two more allowed CP-violating phases

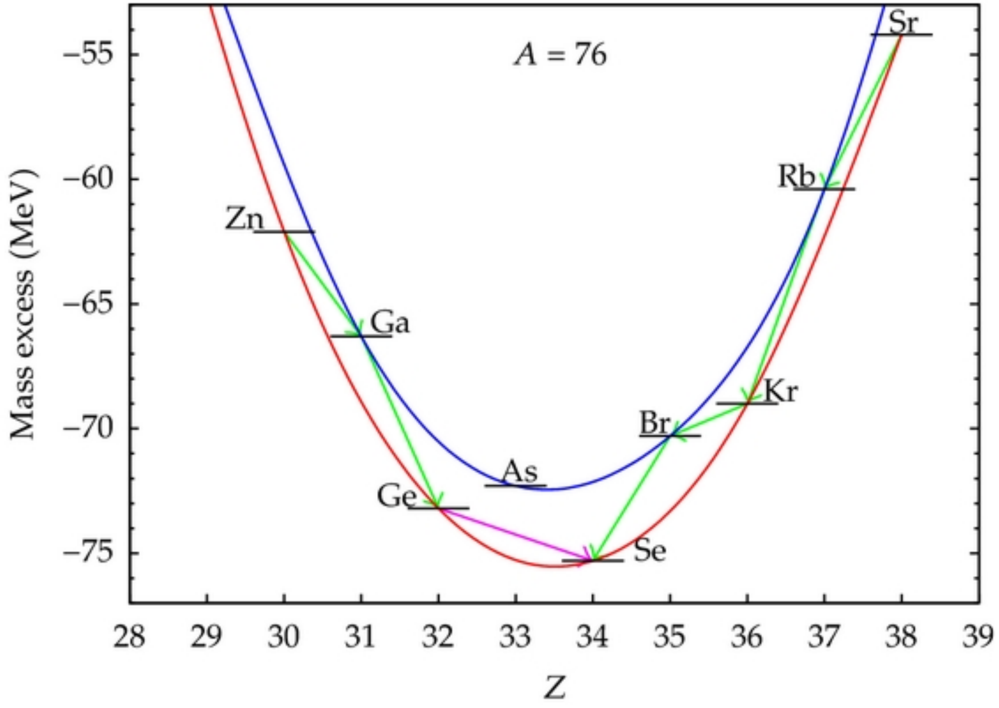
$$U = \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\text{PMNS Matrix}} \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_1}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_2}{2}} \end{bmatrix}}_{\text{New!}}$$

Nature’s Laboratory: Neutrinoless Double-Beta Decay

Double-Beta Decay

- Because of Pauli exclusion, nuclei are lower in energy if they have even numbers of protons and neutrons– they prefer to have paired spins
- For certain even-even nuclei, single beta decay is disallowed b/c of energy or momentum
- Instead, they double-beta decay, as predicted in 1935





From doi:10.1155/2012/857016

Double-Beta Decay

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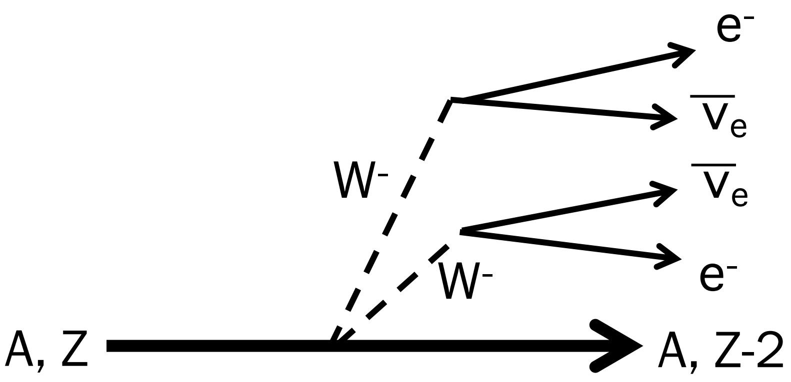
- Second-order weak process, $t_{1/2} \sim 10^{19}$ to 10^{21} years
- One of the longest-lifetime process we've ever observed. Not seen until 1987!
- In the SM, two electron antineutrinos are emitted



Neutrinoless Double Beta Decay

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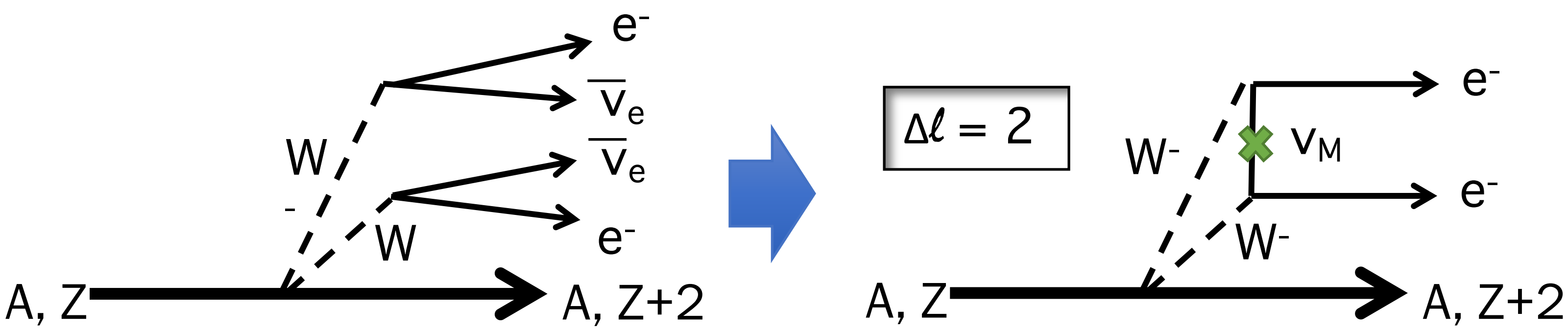
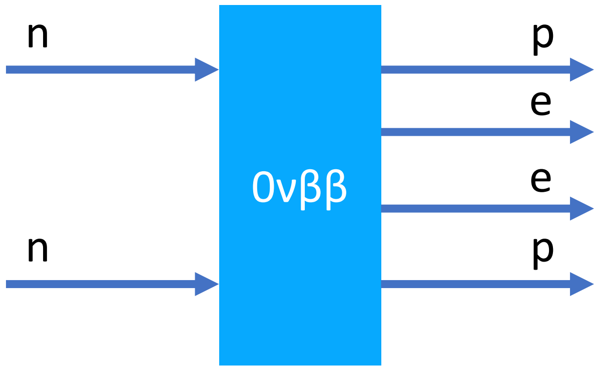
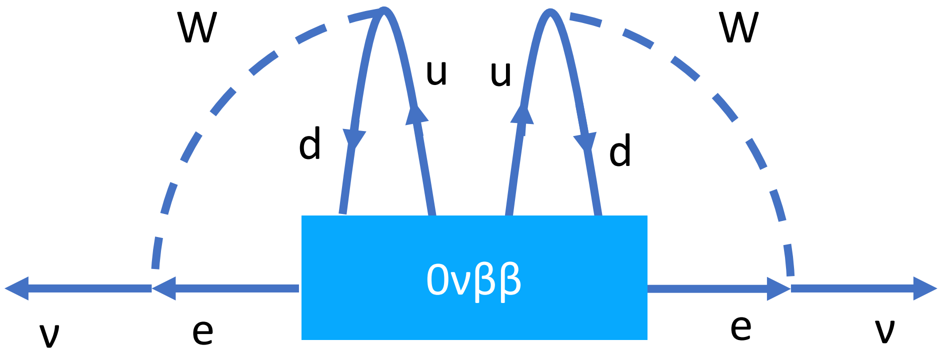


- If neutrinos are Majorana, 0νββ could occur
- Lepton number conservation is violated
- In this case, I've drawn the exchange of a light neutrino, but you can think of that "x" as a contracted diagram of any sort (with new physics in it)

0νββ: A Portal to BSM Physics



(A, Z) → (A, Z+2) +2e-

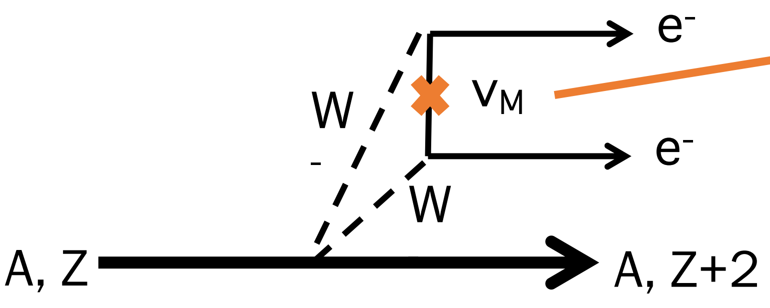


(A, Z) → (A, Z+2) +2e-

Model-independent implications of 0νββ:

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

The 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:

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

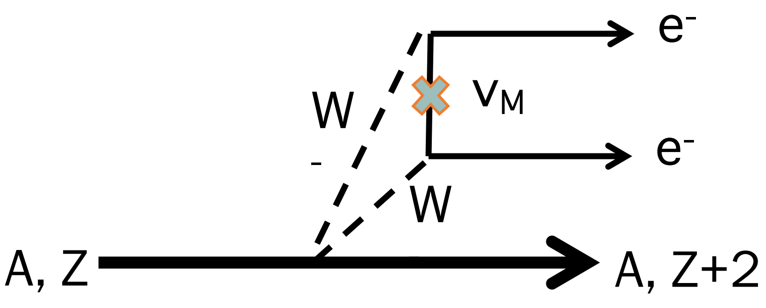
$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

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

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

Even under the simplest assumptions, the 0νββ rate depends on mixing angles, δ_{CP}, neutrino masses, mass hierarchy, and 2 totally unknown phases

The 0νββ Rate for Light Majorana Neutrino Exchange



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

Effective Majorana mass for light neutrino exchange:

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

Phase space: difference between initial and final energy and momentum

- Higher Q value, higher rate

The 0νββ Rate for Light Majorana Neutrino Exchange

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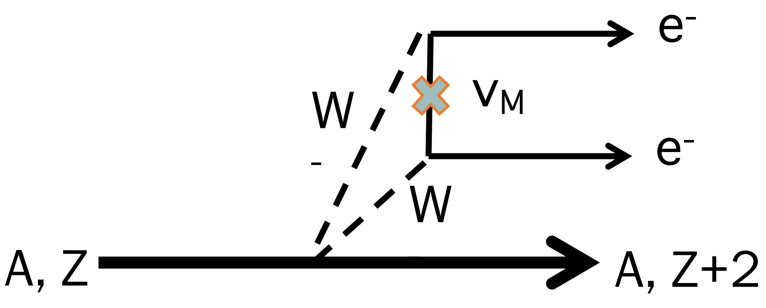


$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}|M_{0\nu}|^2 \left(\frac{\langle m_{\beta\beta}\rangle}{m_e}\right)^2$$

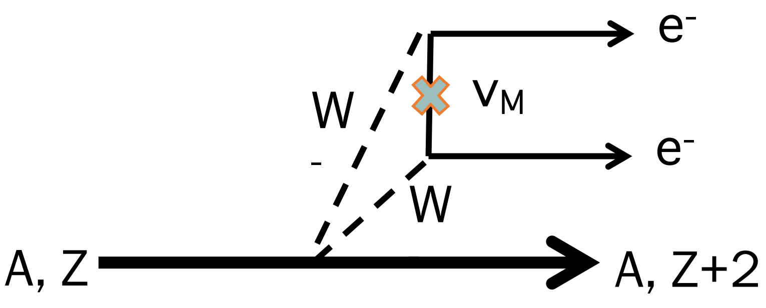
Effective Majorana mass for light neutrino exchange:

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

$T_{1/2}$ = what experiments measure

$m_{\beta\beta}$ = the physics we're trying to extract

The 0νββ Rate for Light Majorana Neutrino Exchange



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

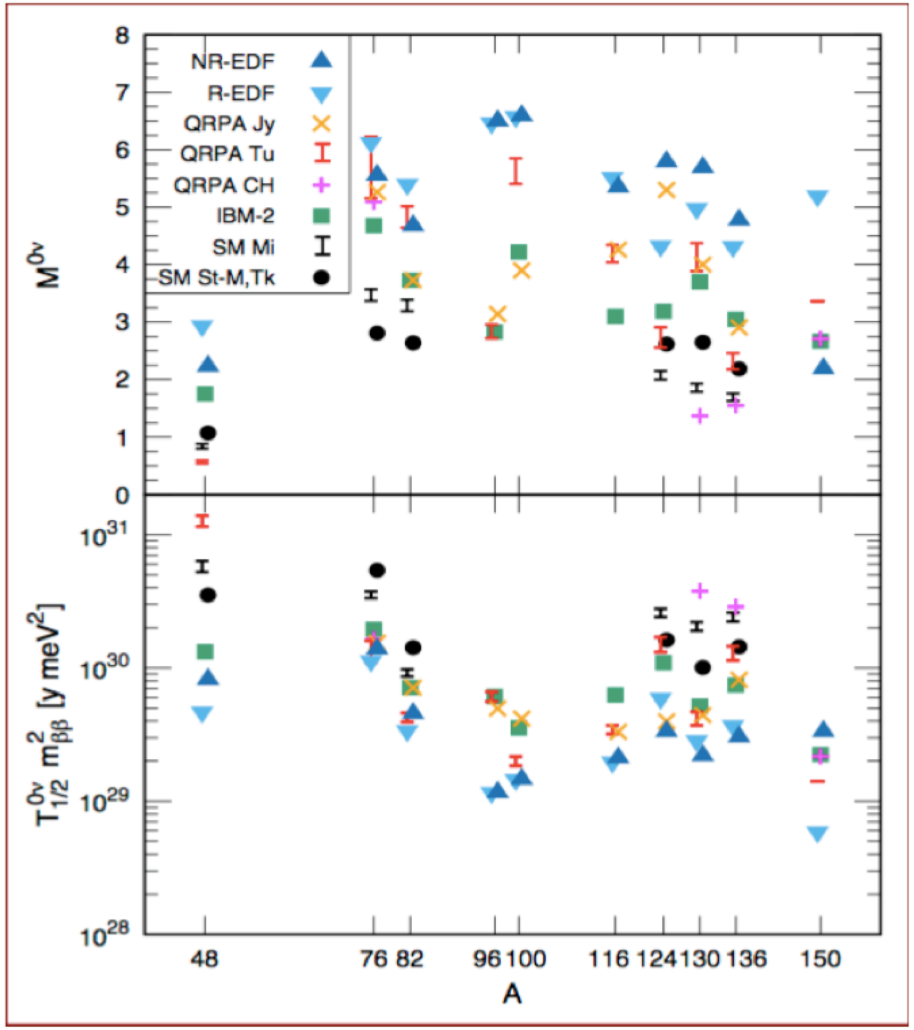
Effective Majorana mass for light neutrino exchange:

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

Nuclear matrix element: how the nuclear decay occurs (states of nucleons, nucleus shape, etc.)

Nuclear Matrix Elements

- Tell you how to translate between a measured rate and $m_{\beta\beta}$
- Used to compare experiments in different isotopes
- These are big nuclei. Hard to calculate!
- Some nuclei of interest can't be calculated at all in certain models.
- Spread between models is large
- Dependence on element is small
- All models leave out important physics
- Uncertainties are hard (or impossible) to quantify
- This situation is improving, but it'll take a while



The 0νββ Rate

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

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

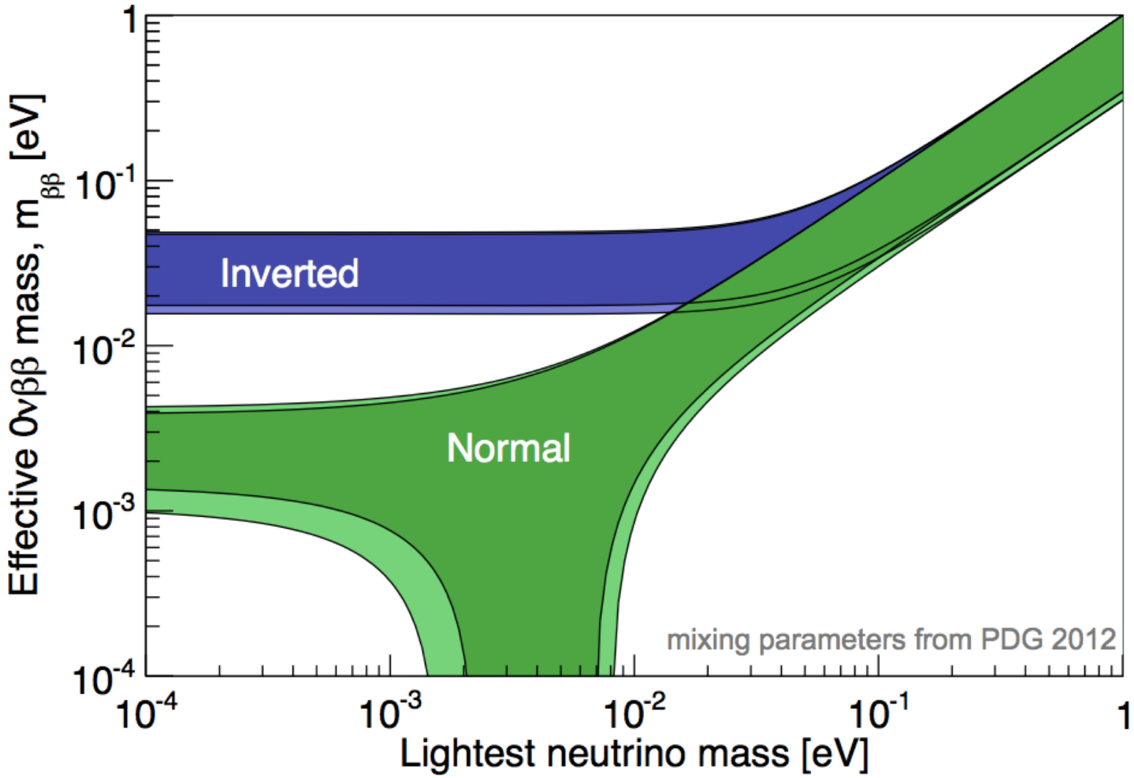


Figure courtesy of A. Schubert

Rate depends on mixing angles, neutrino mass, and mass hierarchy

Uncertainties in lightest ν mass, phases, hierarchy

0νββ and Neutrino Masses

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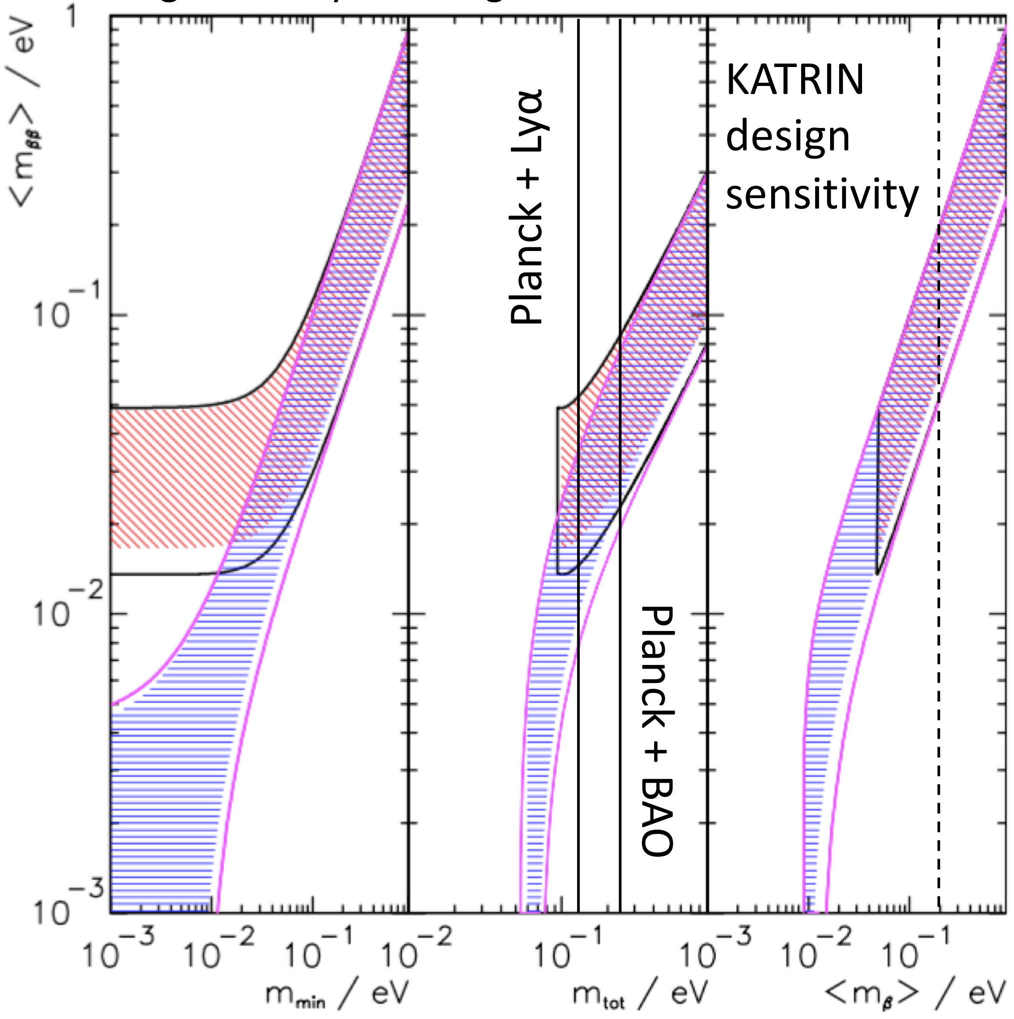
- In the usual picture, equal areas give the illusion of equal probability
- But $m_{lightest}$ is shown on a log scale and can go all the way to 0
- Mass measurements don't measure $m_{lightest}$: eventually they will measure something non-zero!
- Switching to this view also shows that there isn't a sudden jump between IH and NH allowed rates of 0νββ
- The situation for 0νββ is not as hopeless as it may first appear!
- Other neutrino experiments (NO/IO, mass measurements, mixing angles & phases) can tell you where to expect 0νββ for a given model

Fig. courtesy of P. Vogel



Usual picture

Cosmology perspective

Nuclear perspective

As a Probability Density

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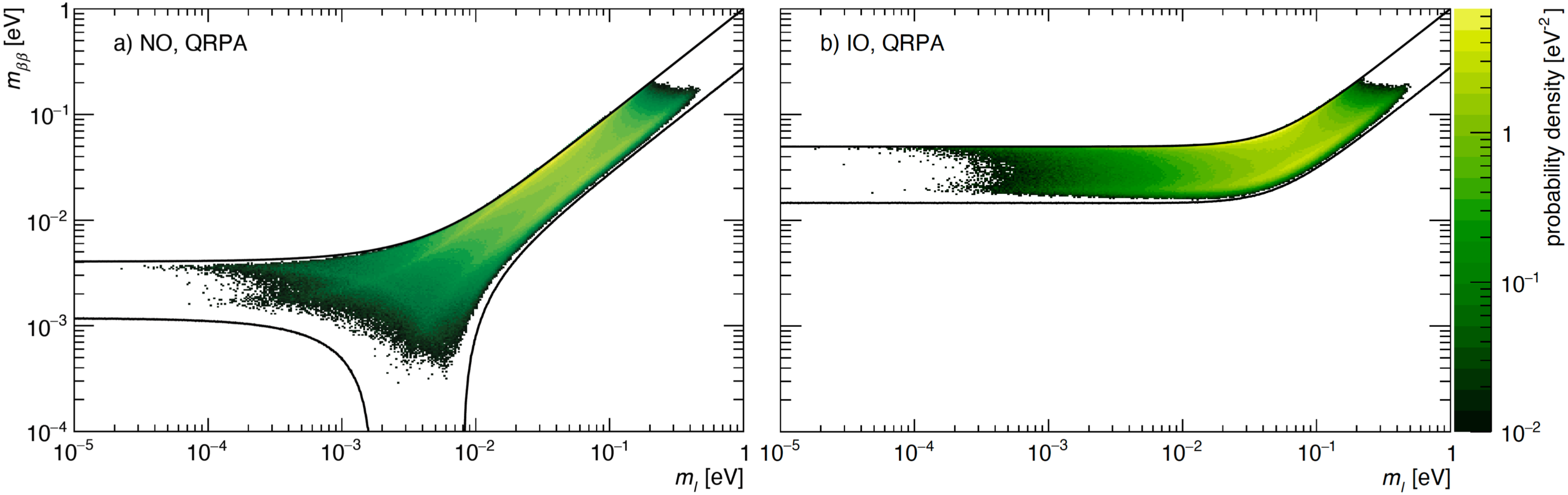
Bayesian framework gives us a way to analyze discovery probability in the "light neutrino exchange" minimal model



For the details of this analysis, see:
M. Agostini, G. Benato and J. A. Detwiler, Discovery probability of next-generation neutrinoless double-β decay experiments, Phys. Rev. D96 (Sep, 2017) 053001

What About the Unknown Unknowns?

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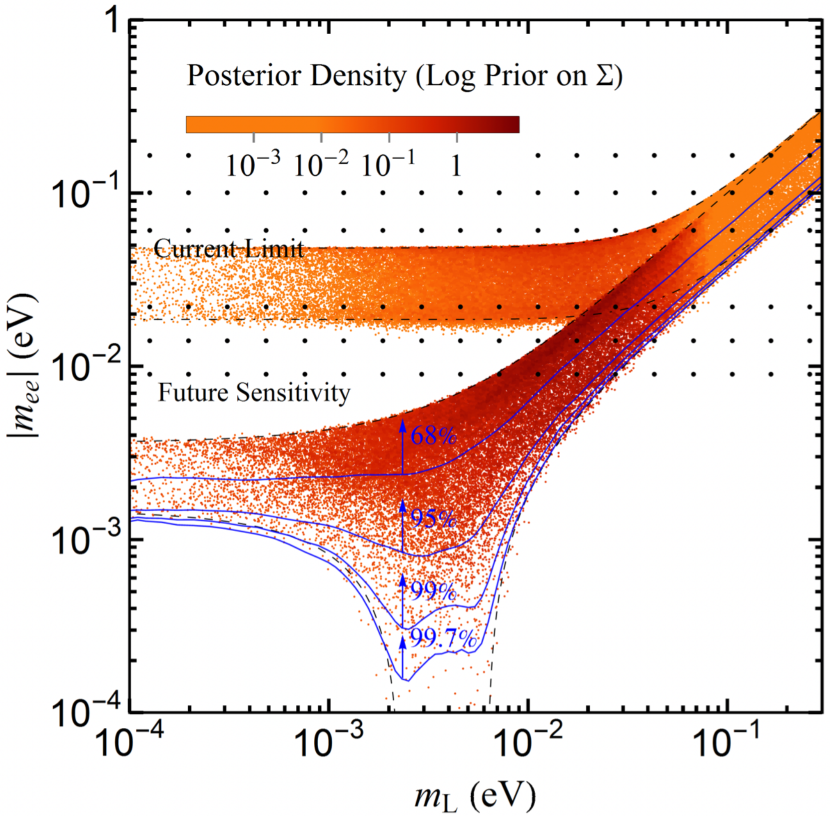
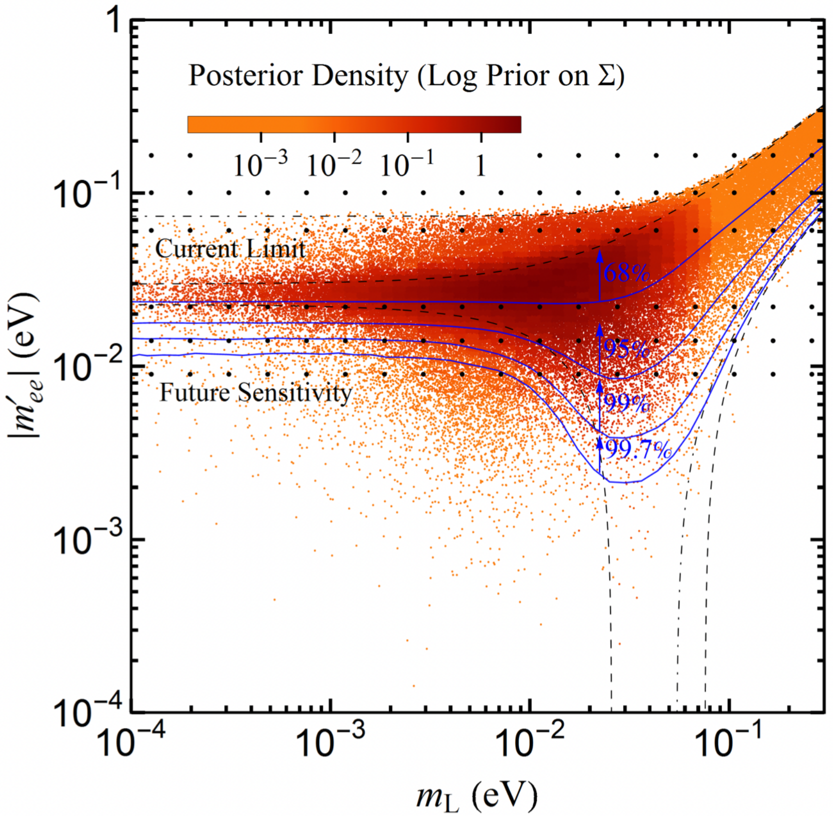


3ν mixing, flat prior on Σm

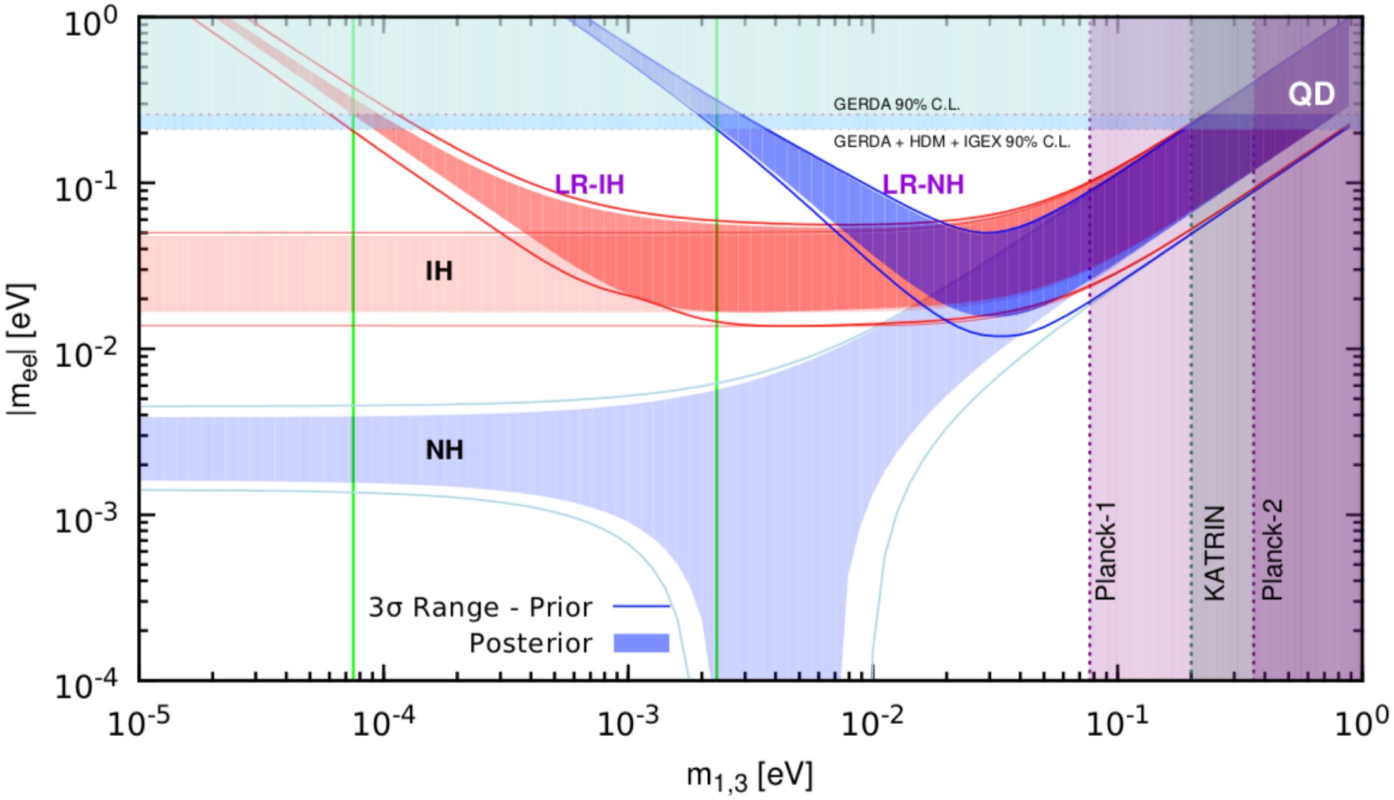


(3+1)ν mixing, flat prior on Σm
$\Delta m^2_{41} \equiv 1.7\ eV^2$ and $\sin^2\theta = 0.019$

- Adding sterile neutrinos also changes the expected rate
- The change depends on the sterile neutrino mass and its mixing

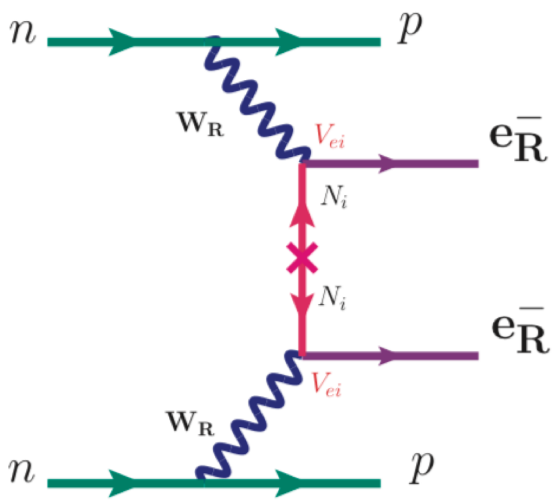
G. Huang, S. Zhou, arXiv: 1902.03839

What About the Unknown Unknowns?

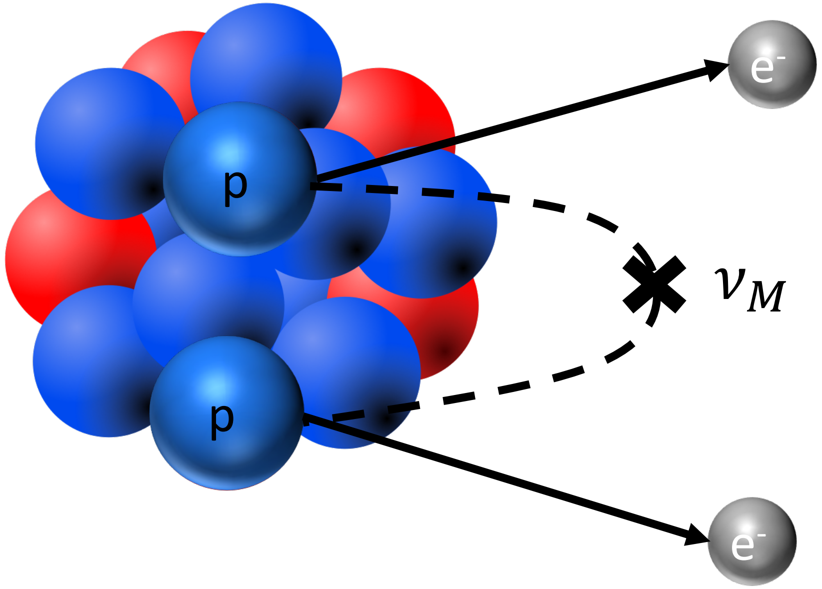


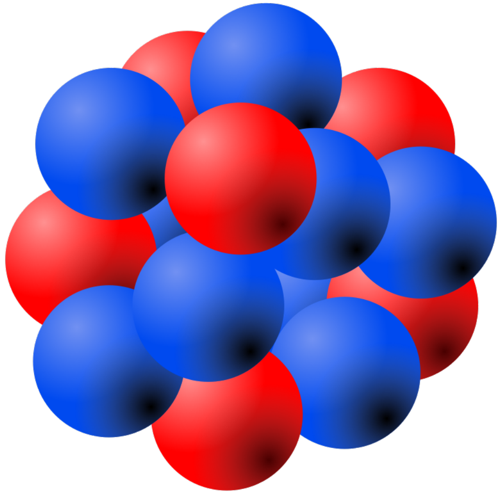
S.-F. Ge, M. Linder, and S. Patra, JHEP 1510 (2015) 077

- The situation changes significantly if new physics is at lower scales
- For instance, Type-II seesaw-dominated LRSM



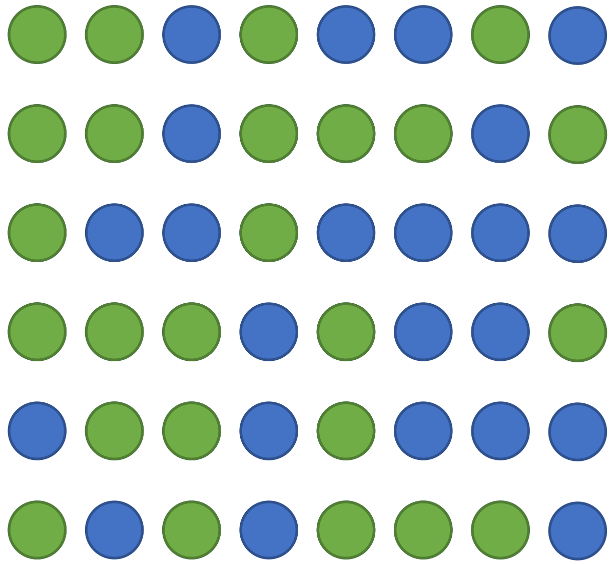
How rare is neutrinoless double beta decay?





Half life: how long it takes for half of the atoms to decay

How rare is neutrinoless double beta decay?



The age of the universe:

14 billion years = 1.4×10^{10} yrs

Two Neutrino Double Beta Decay:

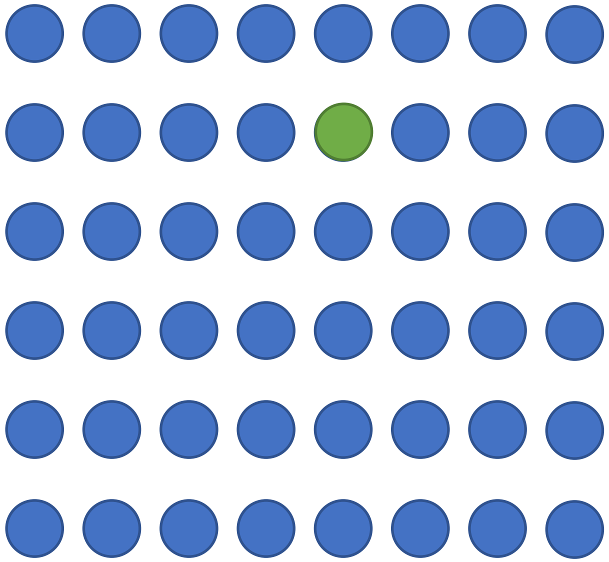
Half life = $\sim 10^{20}$ yrs

Neutrinoless Double Beta Decay:

Half life > 10^{26} yrs

Half life: how long it takes for half of the atoms to decay

How rare is neutrinoless double beta decay?



The age of the universe:

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Two Neutrino Double Beta Decay:

Half life = $\sim 10^{20}$ yrs

Neutrinoless Double Beta Decay:

Half life > 10^{26} yrs

Avogadro’s Number: 6×10^{23}

Don’t wait for half to decay, wait for 1 to decay!

If I watch 50 kg of atoms for 5 years, I’ll see 1 decay for a half-life of 10^{26} years

Detecting 0νββ

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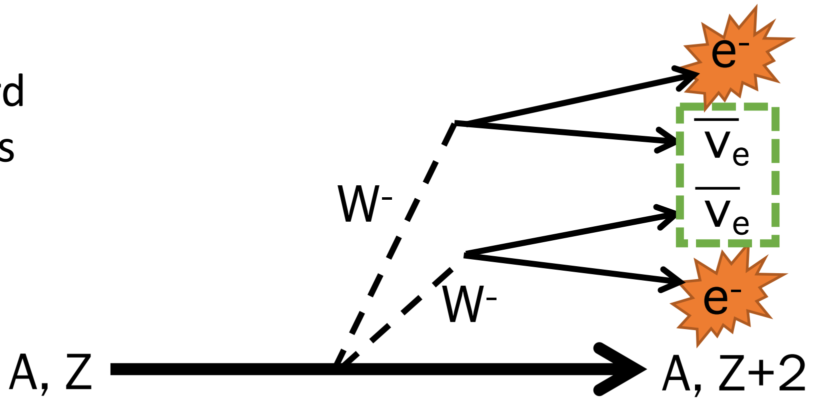
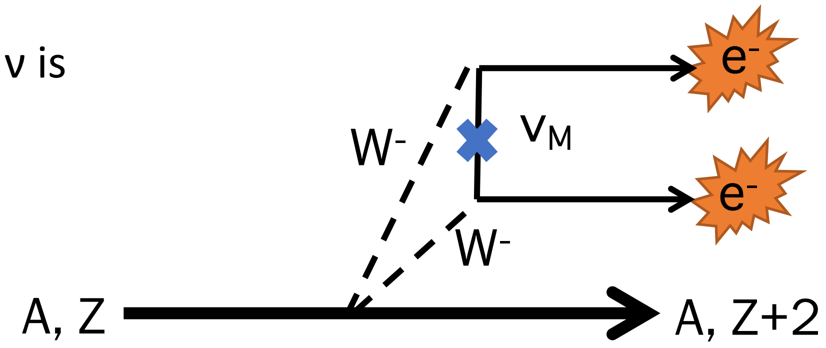
2νββ: Standard Model process



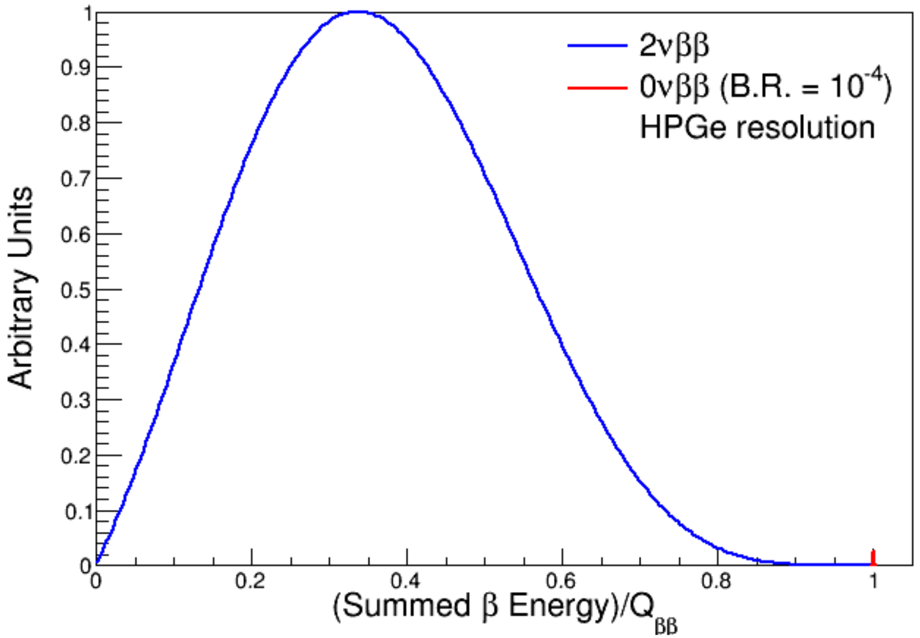
Missing energy

0νββ: Only if ν is Majorana



No missing energy

- **Don't detect neutrinos directly**
- Ignore the neutrinos, measure the rest of the energy



Discovery, Background, and Exposure

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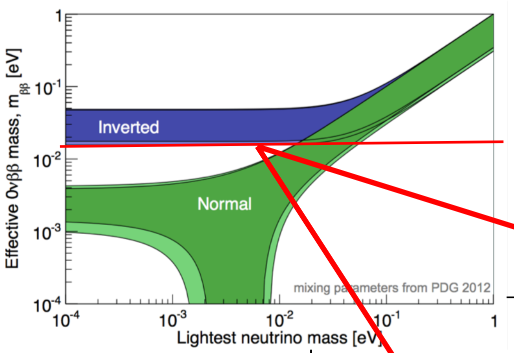
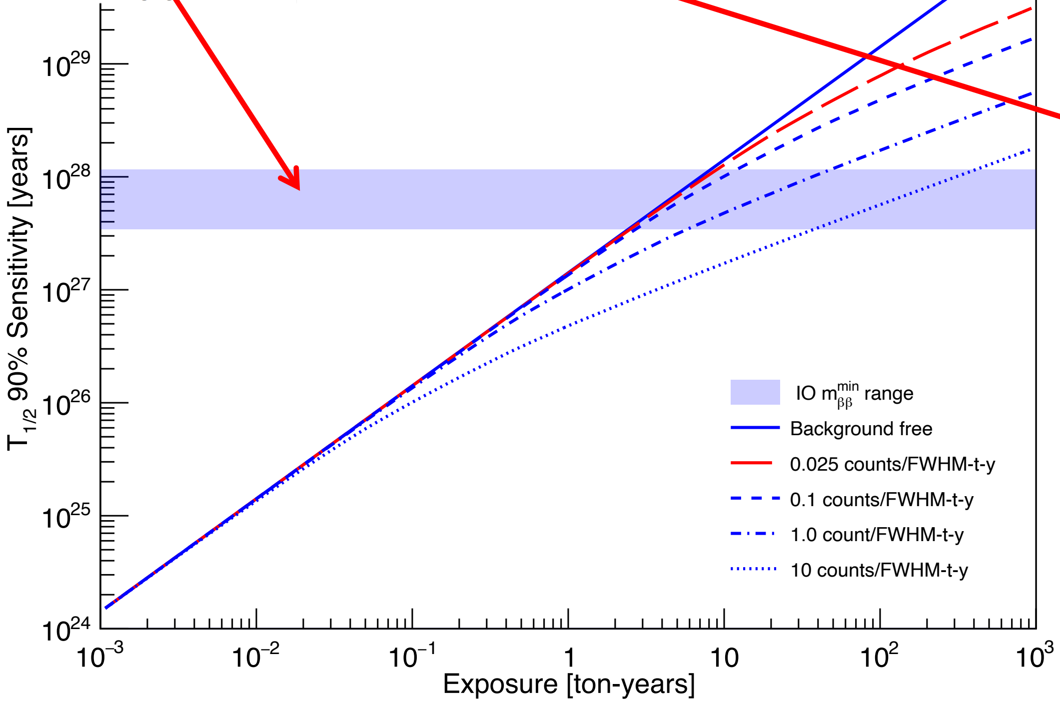
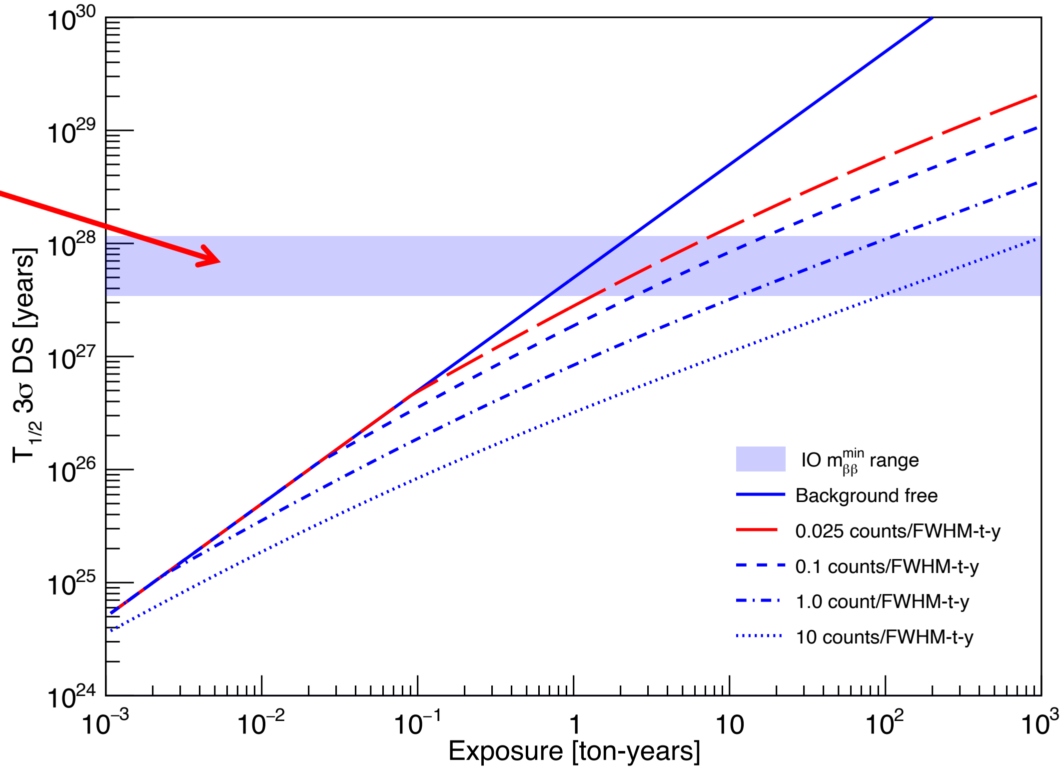


Setting a Limit



Discovery at 3σ



Designing a Search for 0νββ

If I want to see 1 atom of ~10^{25} or more decay (and be sure of what I saw), I need:

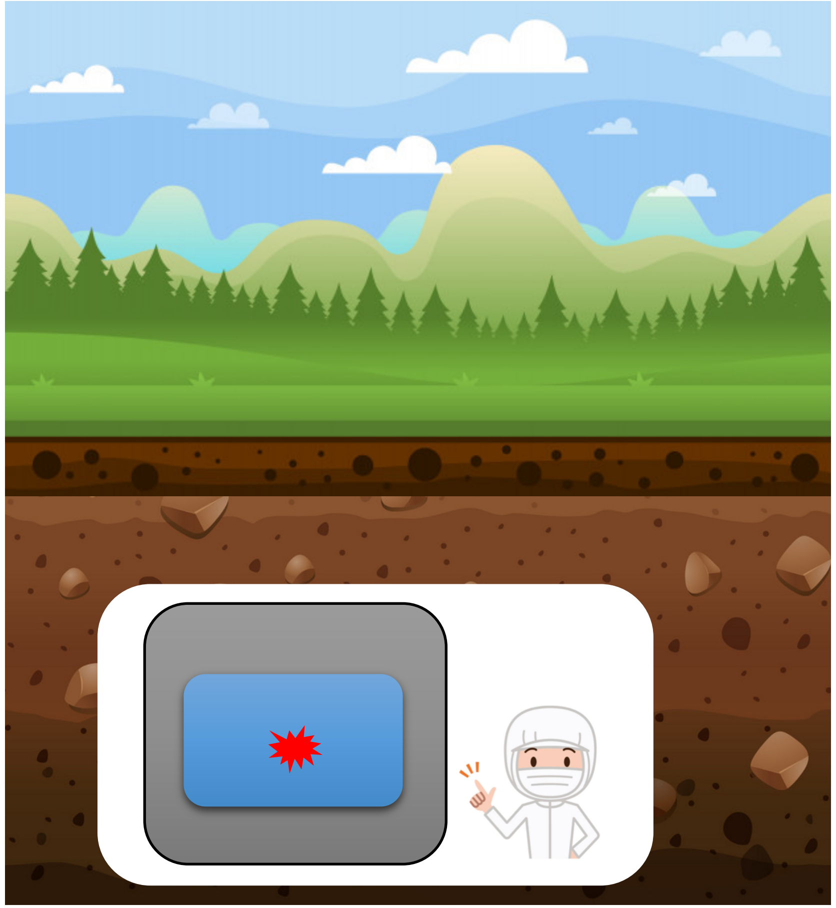
- Very high efficiency
- Very low rates of other kinds of events
- The best-possible energy resolution
- Ways to verify that my signal has the right properties

This is hard, the world is very radioactive!

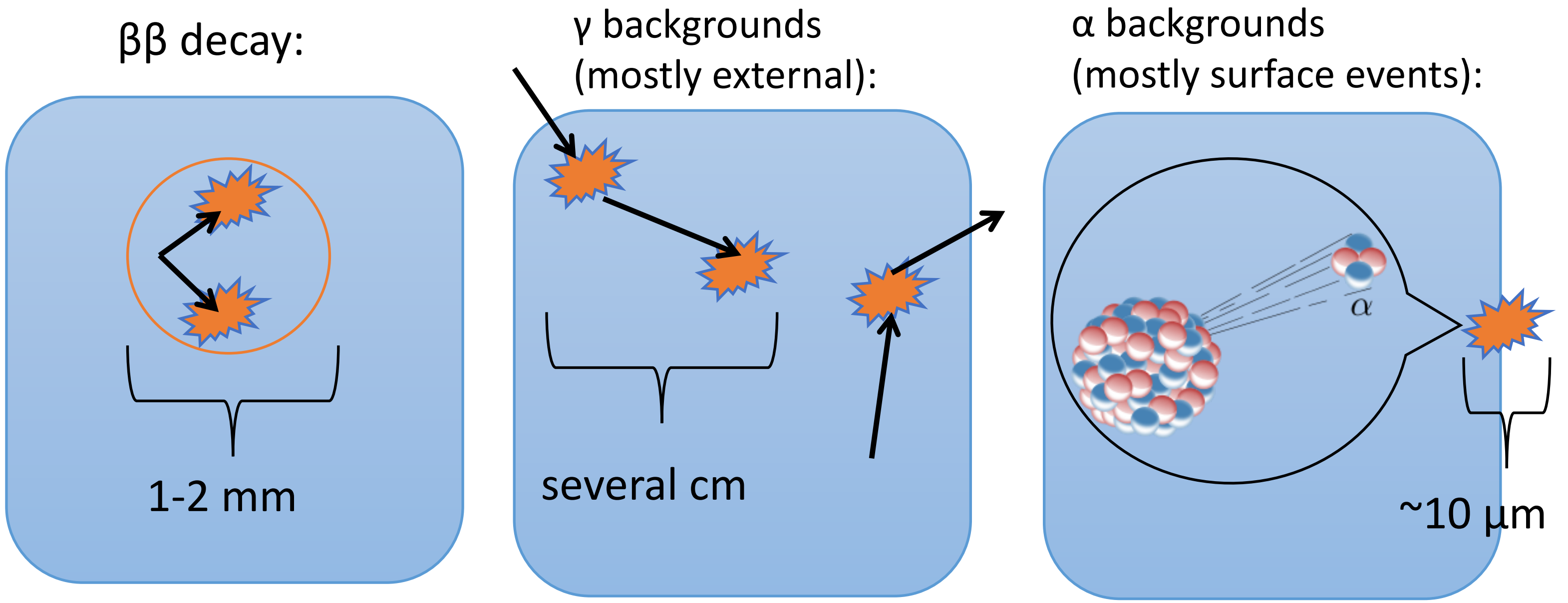
Lessons from other neutrino experiments:

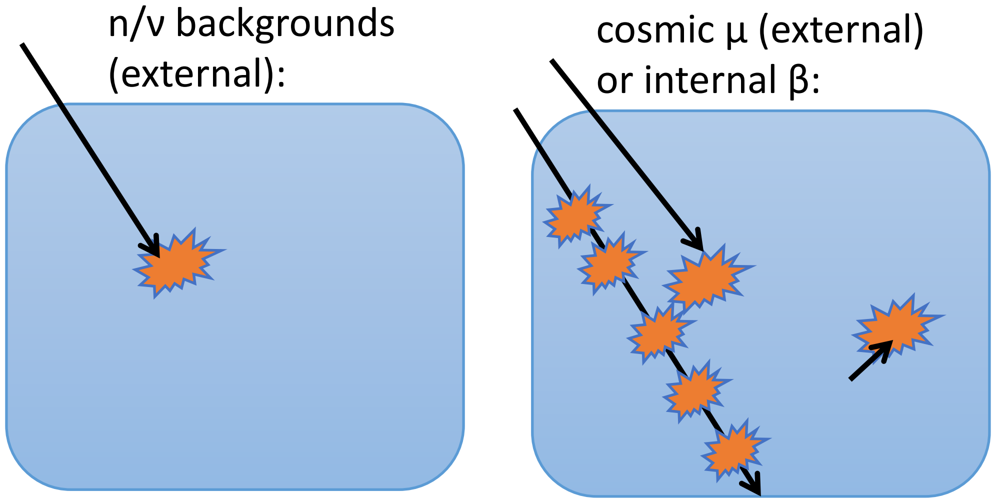
- Go underground
- Use a ”veto detector”
- Select clean materials
- Complexity is ok, if it helps you tag signals!

Most Experiments



Signal and Backgrounds





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

Techniques for background suppression:

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

The Experiments

A Caveat

- I won’t have time to go through all of the ongoing experiments, there are too many! I’ll cover the largest efforts.
- The materials in these slides are courtesy of the various experimental collaborations
- A portfolio review of the ton-scale efforts is underway, so there have been many very recent updates. Most are not reflected here.
- Thank you to all who all who I borrowed materials from!

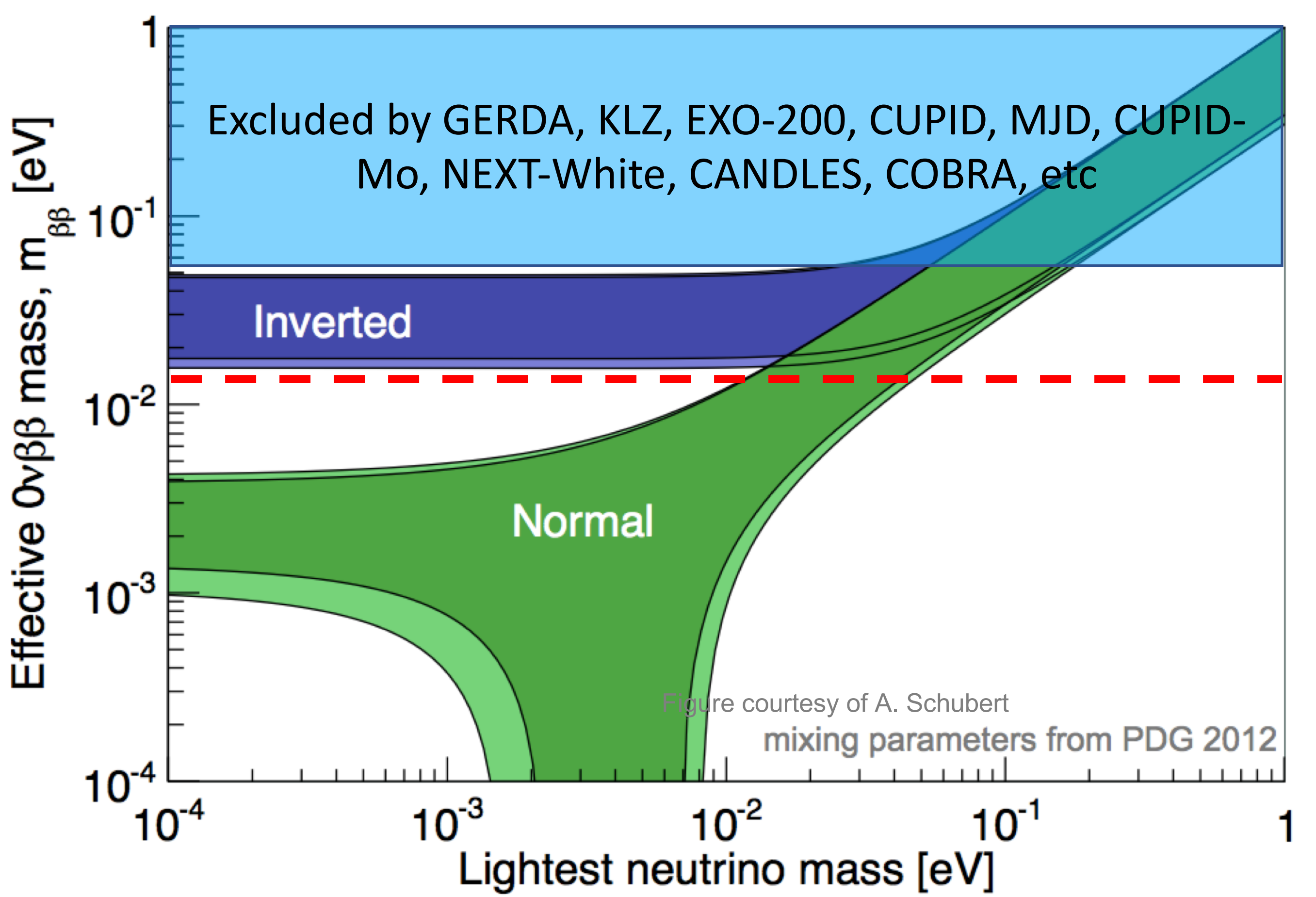
A Rich Experimental Landscape

Collaboration	Isotope	Technique	mass ($0\nu\beta\beta$ isotope)	Status
CANDLES	^{48}Ca	305 kg CaF_2 crystals - liq. scint	0.3 kg	Operating
CARVEL	^{48}Ca	$^{48}CaWO_4$ crystal scint.	16 kg	R&D
GERDA I	^{76}Ge	Ge diodes in LAr	15 kg	Complete
GERDA II	^{76}Ge	Point contact Ge in active LAr	44 kg	Complete
MAJORANA DEMONSTRATOR	^{76}Ge	Point contact Ge in Lead	30 kg	Operating
LEGEND 200	^{76}Ge	Point contact Ge in active LAr	200 kg	Construction
LEGEND 1000	^{76}Ge	Point contact Ge in active LAr	1 tonne	R&D
NEMO3	^{100}Mo/^{82}Se	Foils with tracking	6.9 kg/0.9 kg	Complete
SuperNEMO Demonstrator	^{82}Se	Foils with tracking	7 kg	Construction
SELENA	^{82}Se	Se CCDs	<1 kg	R&D
NvDEx	^{82}Se	SeF6 high pressure gas TPC	50 kg	R&D
AMoRE	^{100}Mo	CaMoO4 bolometers (+ scint.)	5 kg	Construction
CUPID	^{100}Mo	Scintillating Bolometers	250 kg	R&D
COBRA	^{116}Cd/^{130}Te	CdZnTe detectors	10 kg	Operating
CUORE-0	^{130}Te	TeO_2 Bolometer	11 kg	Complete
CUORE	^{130}Te	TeO_2 Bolometer	206 kg	Operating
SNO+	^{130}Te	0.3% ^{nat}Te in liquid scint.	800 kg	Construction
SNO+ Phase II	^{130}Te	3% ^{nat}Te in liquid scint.	8 tonnes	R&D
KamLAND-Zen 400	^{136}Xe	2.7% in liquid scint.	370 kg	Complete
KamLAND-Zen 800	^{136}Xe	2.7% in liquid scint.	750 kg	Operating
KamLAND2-ZEN	^{136}Xe	2.7% in liquid scint.	~tonne	R&D
EXO-200	^{136}Xe	Xe liquid TPC	160 kg	Complete
nEXO	^{136}Xe	Xe liquid TPC	5 tonnes	R&D
NEXT-WHITE	^{136}Xe	High pressure GXe TPC	~5 kg	Operating
NEXT-100	^{136}Xe	High pressure GXe TPC	100 kg	Construction
PandaX	^{136}Xe	High pressure GXe TPC	~tonne	R&D
DARWIN	^{136}Xe	Xe liquid TPC	3.5 tonnes	R&D
AXEL	^{136}Xe	High pressure GXe TPC	~tonne	R&D
DCBA	^{150}Nd	Nd foils & tracking chambers	30 kg	R&D

R&D Construction Operating Complete

From J. Wilkerson

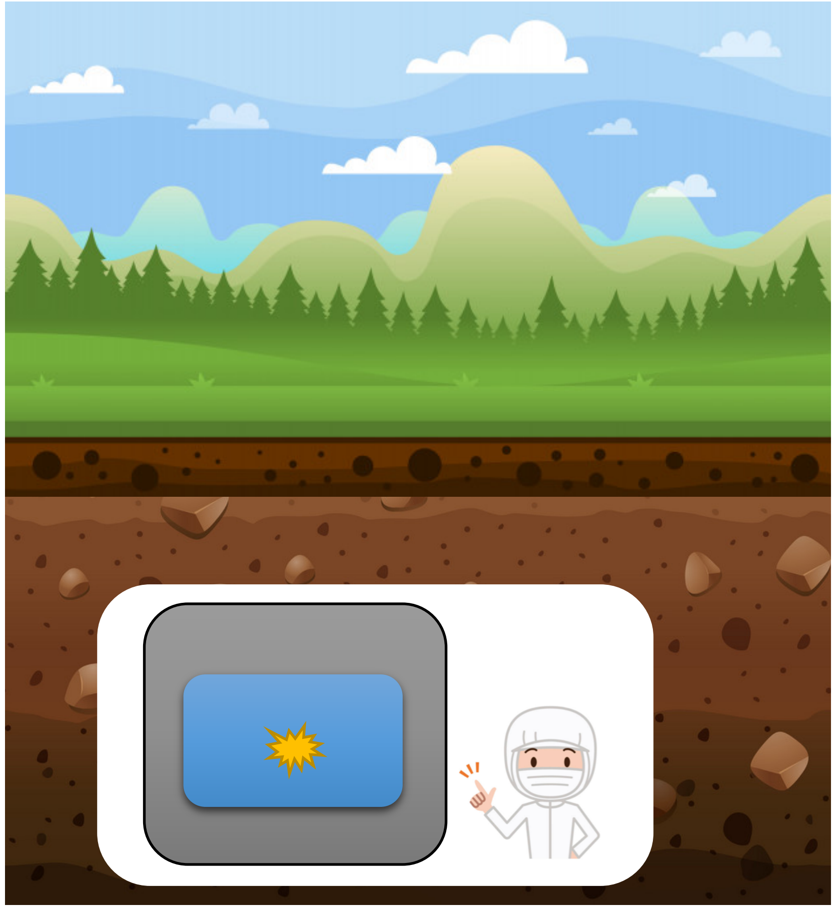
Setting Half-Life Goals for the Next Generation

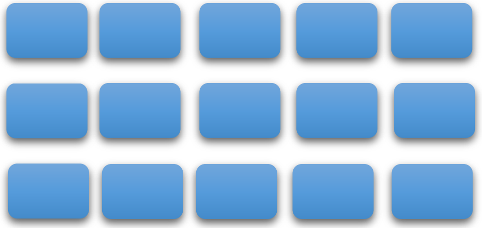


- Simple light neutrino exchange model is used to set goals for future experiments
- Currently-running experiments have reached half-life sensitivities of 10^{26} yrs
- Next generation plans to reach $m_{\beta\beta}$=18 meV, the value needed to cover the inverted ordering region

Experimental Techniques

Most Experiments

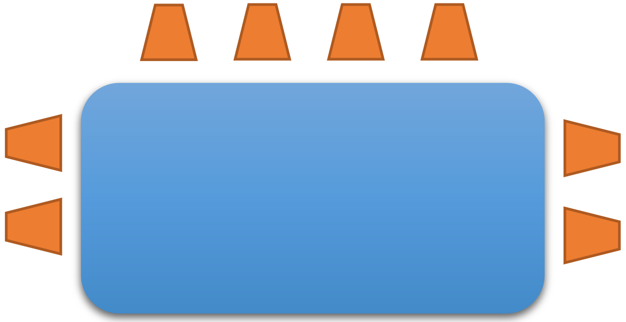




Advantages:
- Energy resolution
- Staging

Granular Detectors

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

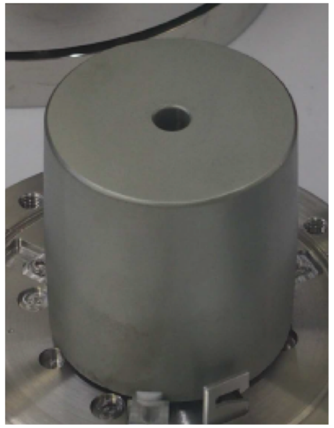


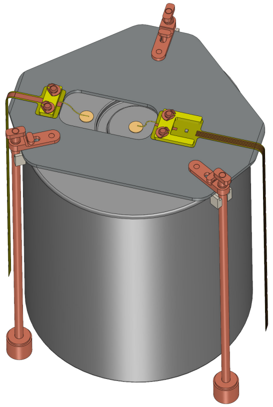
Advantages:
- Self-shielding
- Scalability

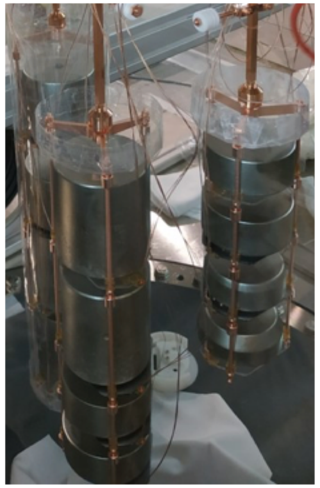
Monolithic Detectors

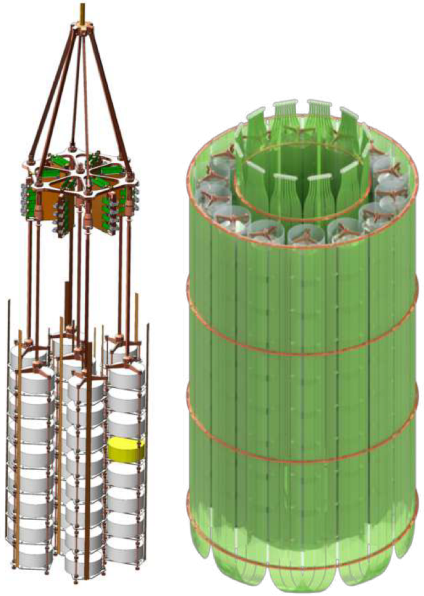
- Scintillators and TPCs
- E.g. KamLAND-Zen, SNO+, THEIA, nEXO, NEXT

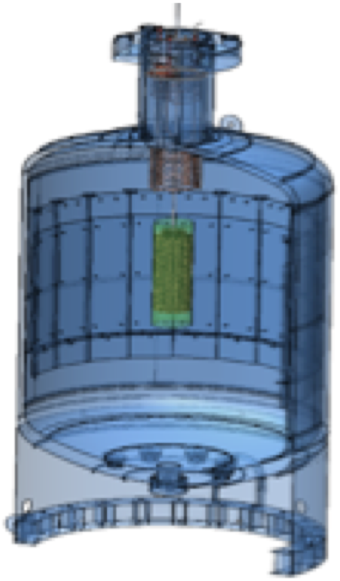
The LEGEND Concept





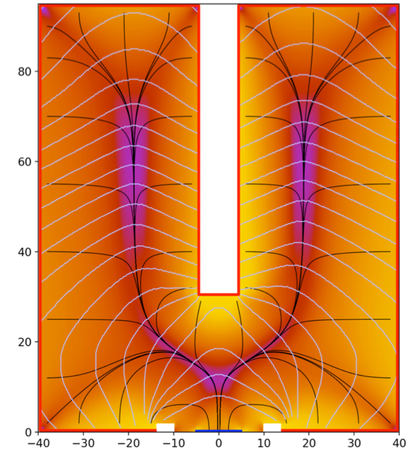






Point-contact Detector → Low-Mass Mount → String → Instrumented array → LAr cryostat → Water shield and μ veto

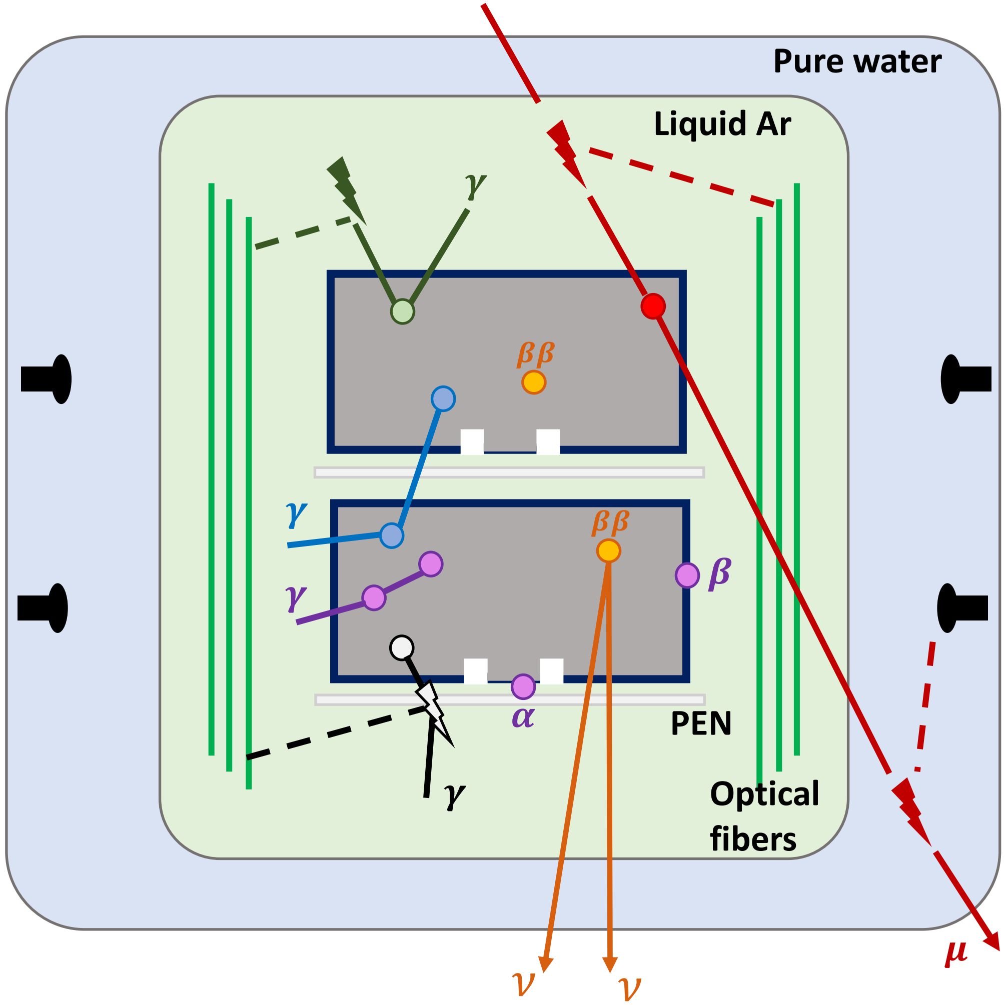
The LEGEND Concept



HPGe point-contact detectors:

- Event topology and fiducialization
- Excellent (~0.1%) energy resolution

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



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

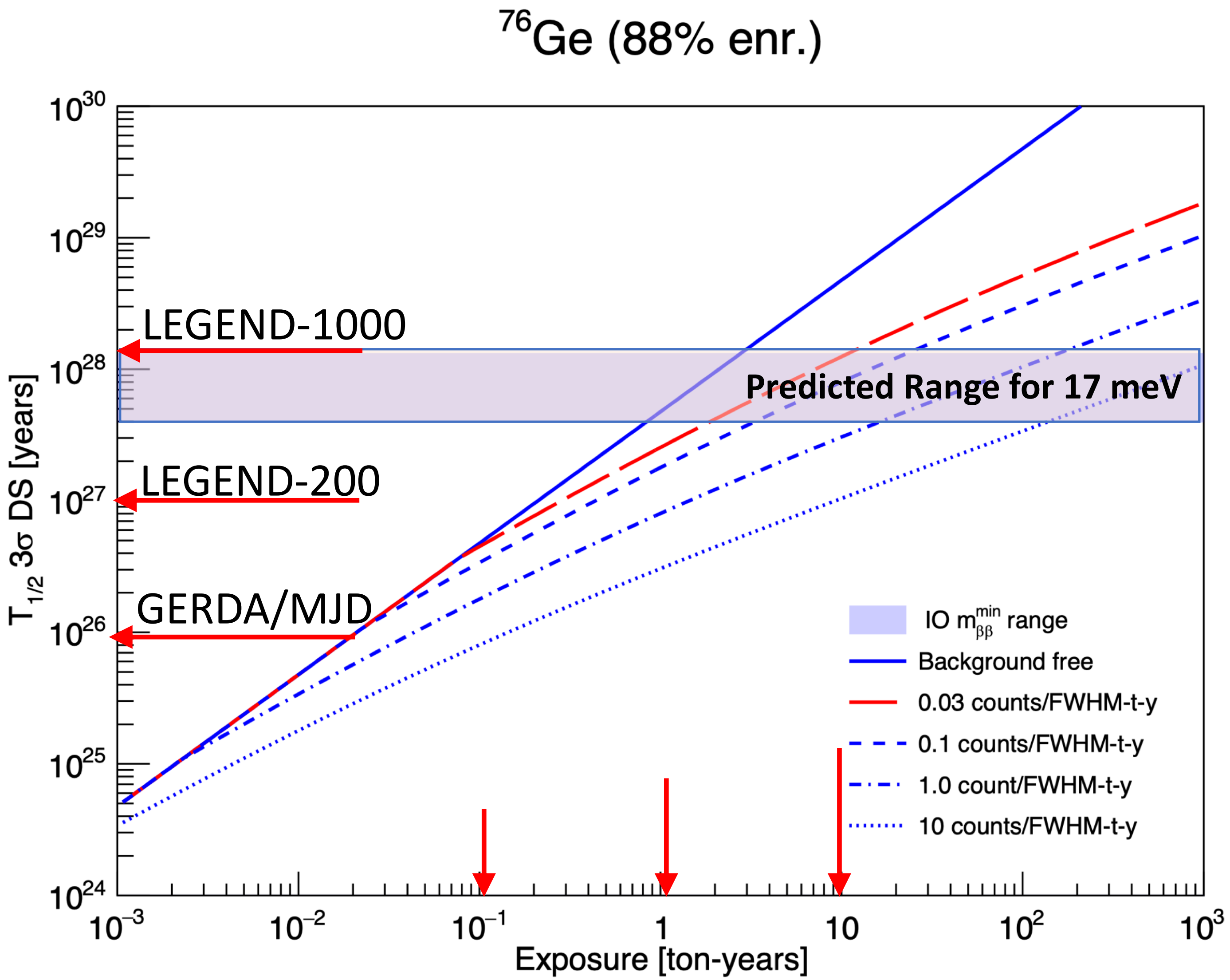
Ge detector anti-coincidence

Scintillating PEN plate holder

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

Muon veto based on Cherenkov light and plastic scintillator

LEGEND Background and Sensitivity Goals



Staged approach with 2 major phases

LEGEND-200:

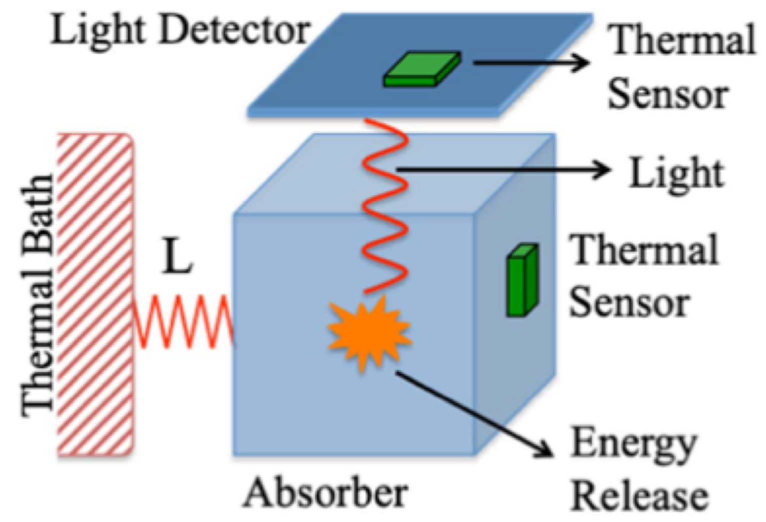
- 200 kg in upgrade of existing GERDA infrastructure at Gran Sasso
- Background goal <0.6 cts/(FWHM t yr) <2x10^{-4} cts/(keV kg yr)
- Data start ~2021

LEGEND-1000:

- 1000 kg, staged via individual payloads (300-500 detectors)
- Background goal <0.03 cts/(FWHM t yr),<1x10^{-5} cts/(keV kg yr)
- Location and timeline TBD

The CUPID Concept

- Tonne-scale bolometer approach demonstrated in CUORE
- Scintillating bolometer technique demonstrated in CUPID-Mo and other experiments
- Scintillation light allows for α rejection
- Mo-100 0νββ Q-value is higher in energy than most other backgrounds
- Switch from CUORE crystals to scintillating bolometers with light readout

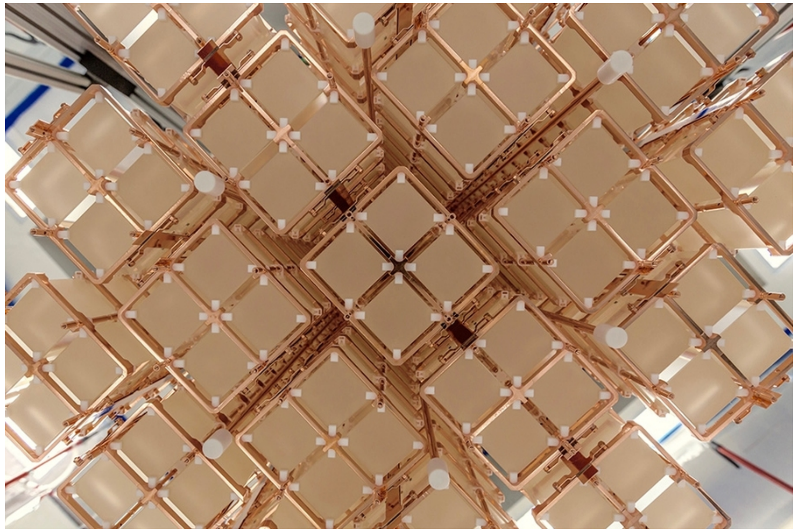


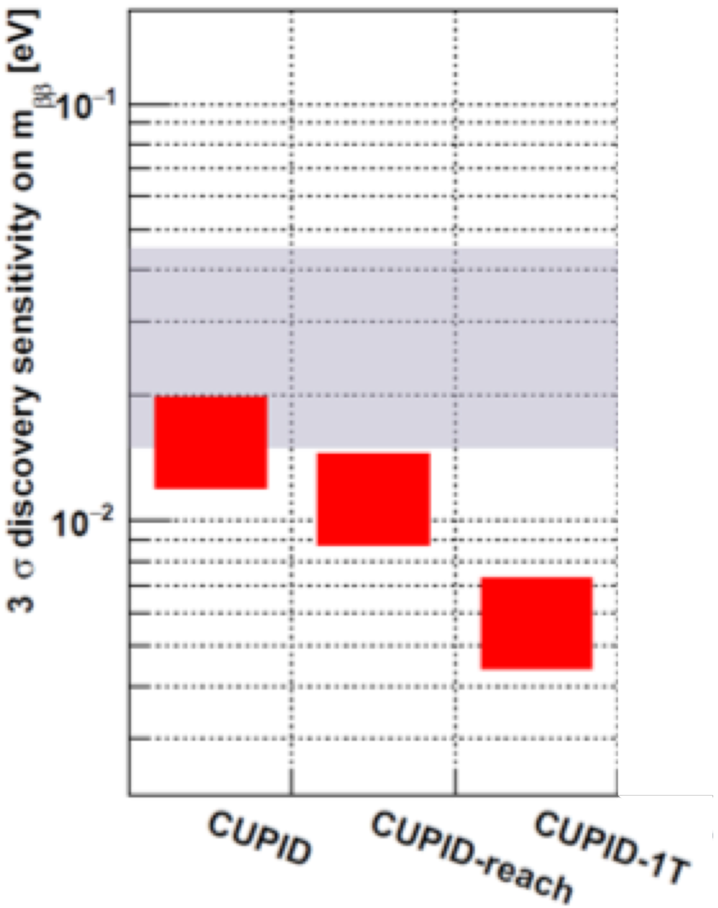
CUPID:

- *enrichment > 95% ⇒ ~250 kg of ^{100}Mo*
  - *~ 1500 crystals, ~300 g each*
  - *ΔE FWHM ~5 keV at $Q_{\beta\beta}$ ~3034 keV*
  - *alpha-particle rejection using light signal*

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

CUPID Background and Sensitivity Goals





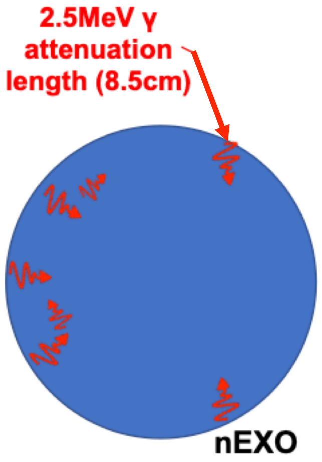
CUPID pre-CDR: exactly what we could start building today: 10^{-4} counts/keV/kg/yr

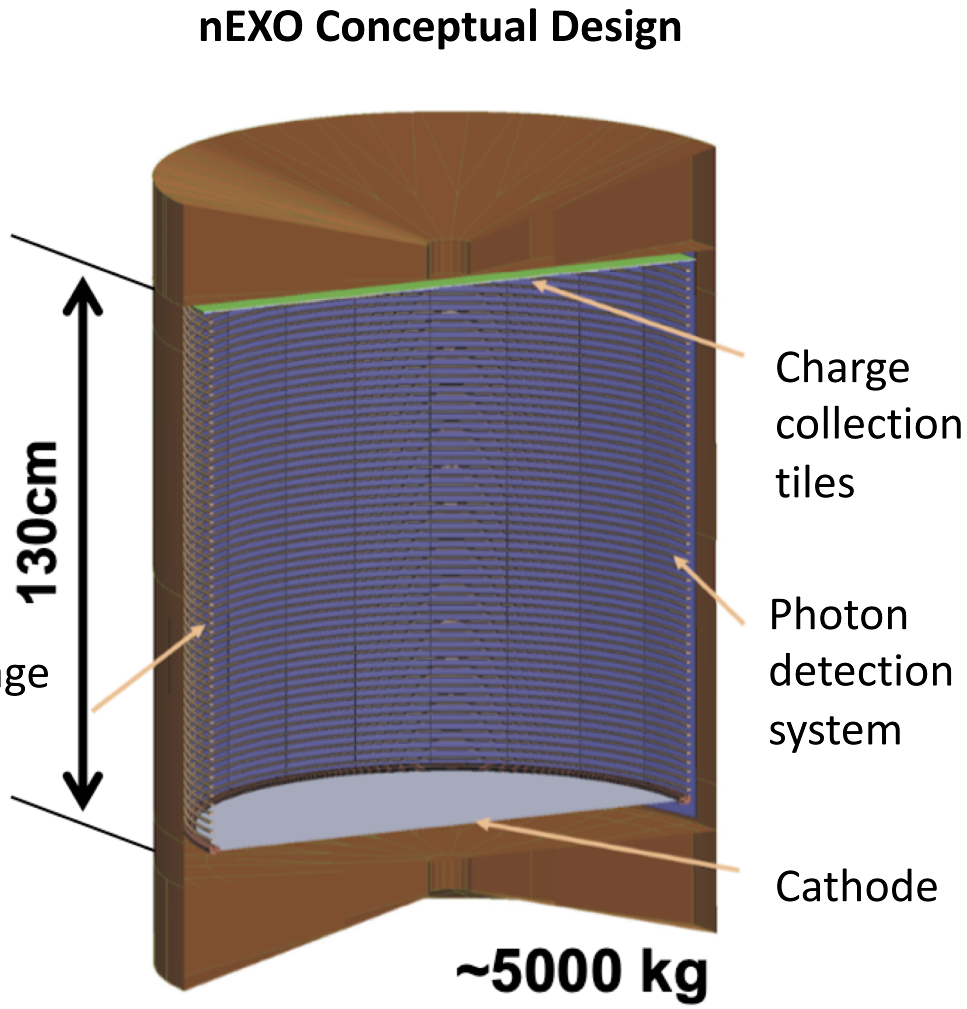
CUPID reach: assume improvement at reach before construction: $2{\cdot}10^{-5}$ counts/keV/kg/yr

CUPID 1Ton: new, 4 times larger (in volume) cryostat, 1 ton 100Mo : $5{\cdot}10^{-6}$ counts/keV/kg/yr

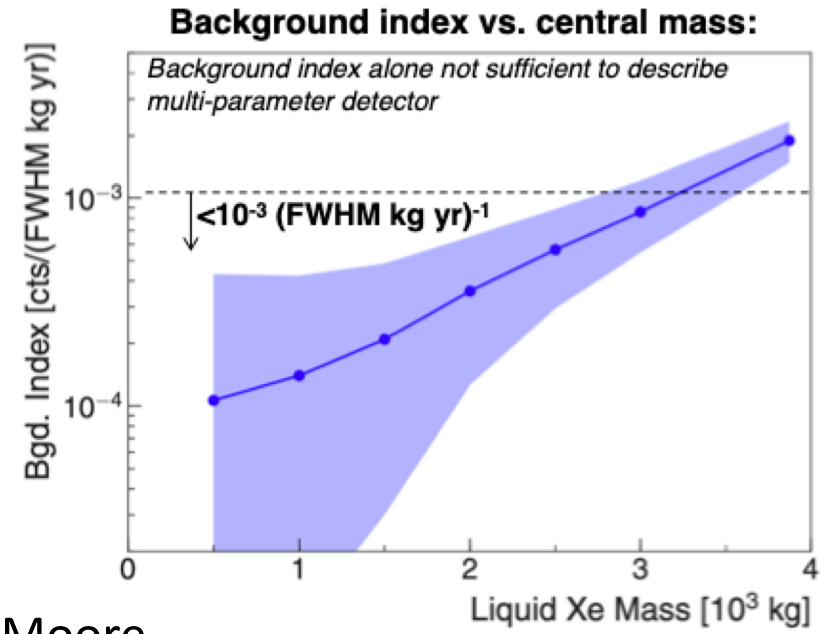
M. Pavan, CUPID Project Update 13 July 2020

The nEXO Concept





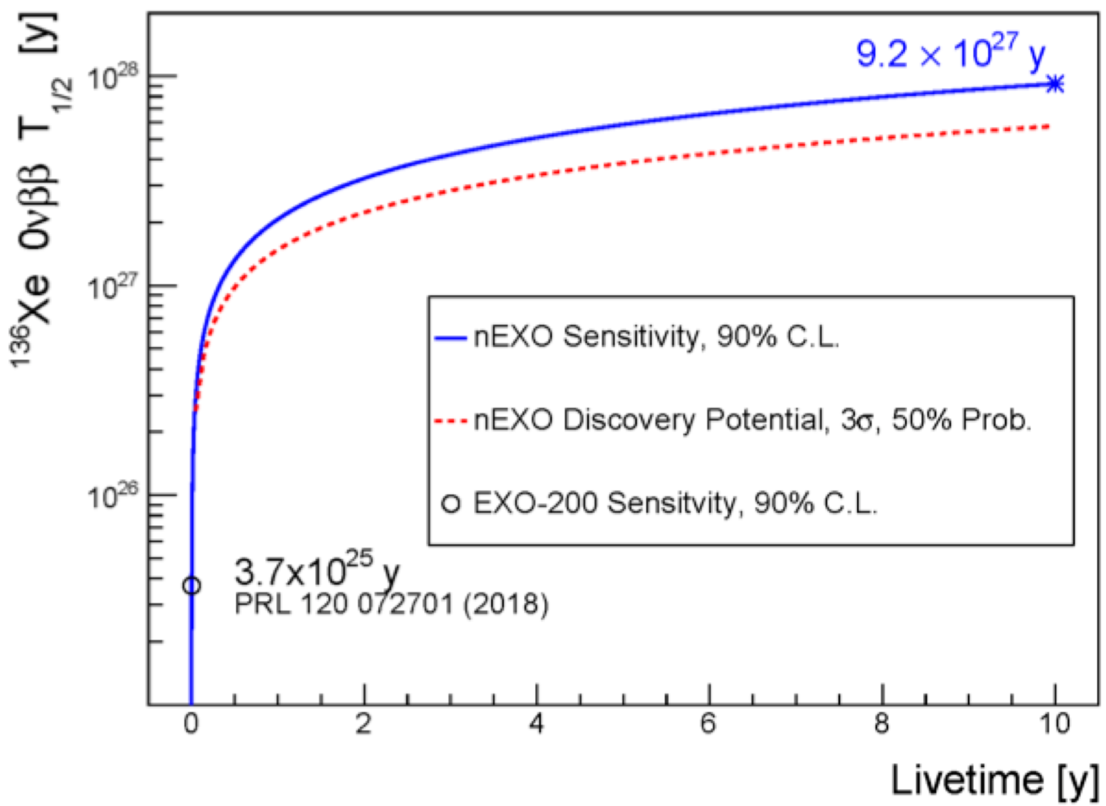
- Large single-phase LXe TPC
- Take advantage of self-shielding, (non-binary) fiducialization, and event topology information to reduce backgrounds



Slides provided by the EXO-200 and nEXO Collaborations, from D. Moore

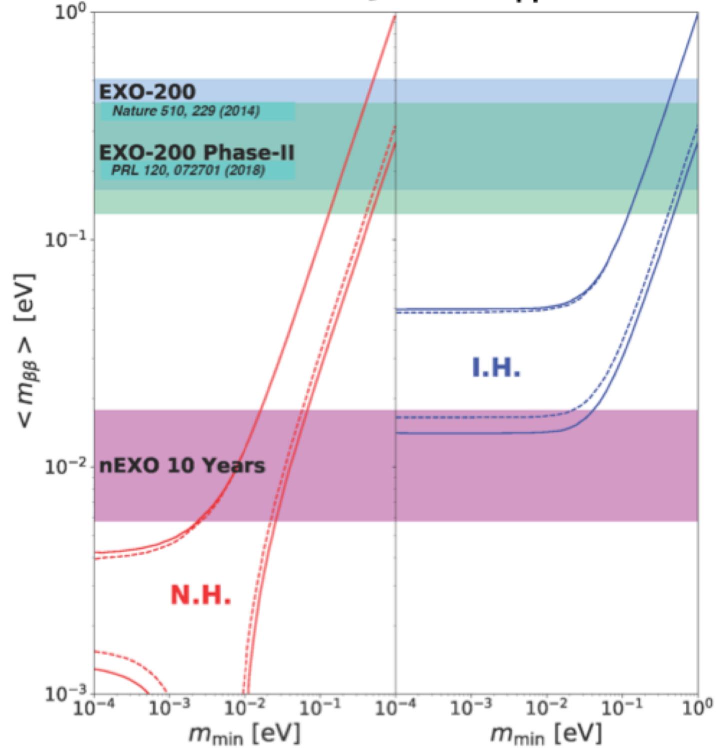
nEXO Sensitivity Goals

Projected half-life sensitivity vs. livetime:



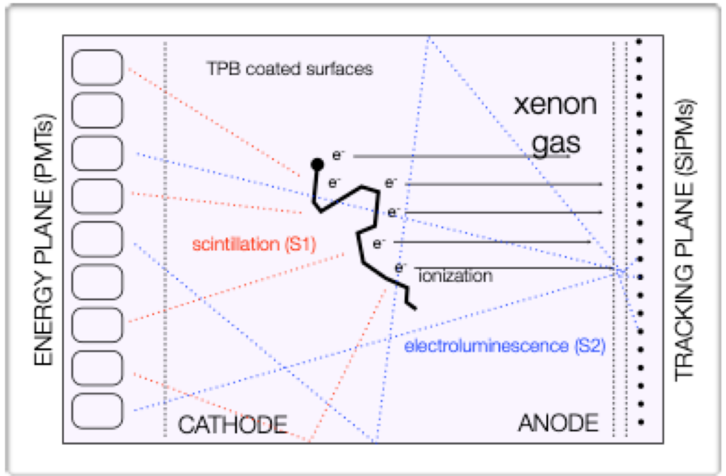
Phys. Rev. C 97, 065503 (2018), arXiv:1710.05075

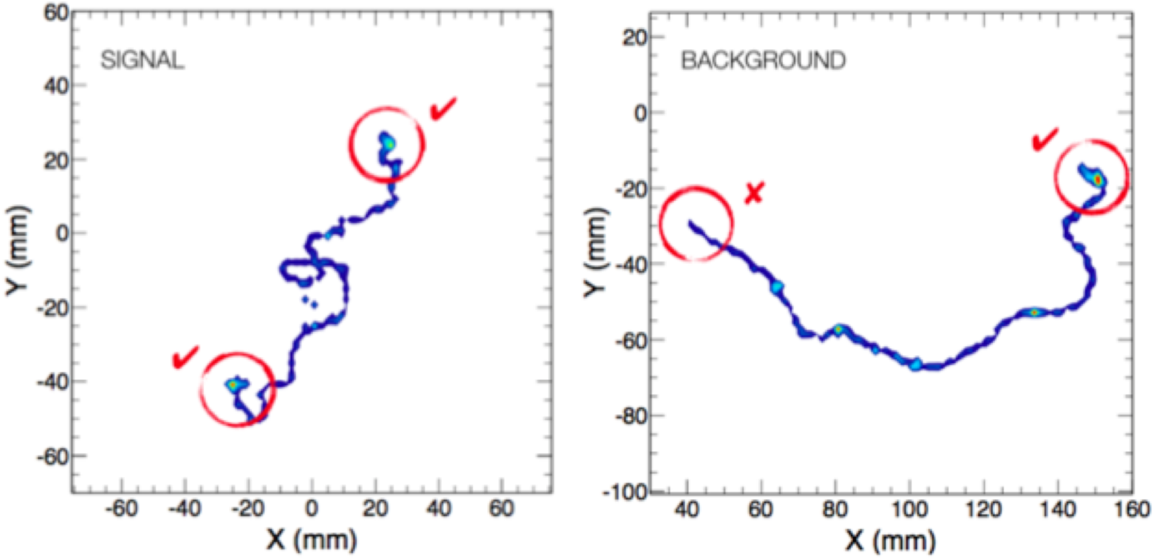
Sensitivity to ⟨$m_{\beta\beta}$⟩



- *Assumes $g_A = g_A^{free} = -1.27$*
- *Bands indicate the envelope of various NME calculations:*
  - *EDF: T.R. Rodríguez and G. Martínez-Pinedo, PRL 105, 252503 (2010)*
  - *ISM: J. Menendez et al., Nucl Phys A 818, 139 (2009)*
  - *IBM-2: J. Barea, J. Kotila, and F. Iachello, PRC 91, 034304 (2015)*
  - *QRPA: F. Šimkovic et al., PRC 87 045501 (2013)*
  - *SkyrmeQRPA: M.T. Mustonen and J. Engel PRC 87 064302 (2013)*

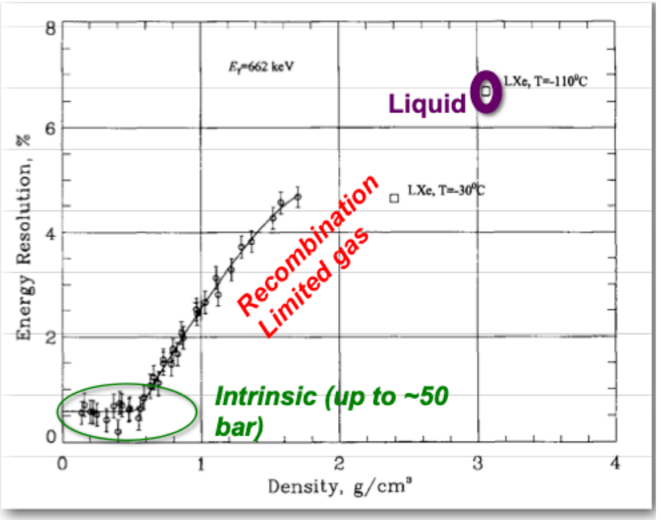
The NEXT Concept





High-pressure gas Xenon time projection chamber:

- High pressure reduces volume for a given mass
- Energy resolution is intrinsically better in gas
- Extensive event topology information, fiducialization, and particle ID

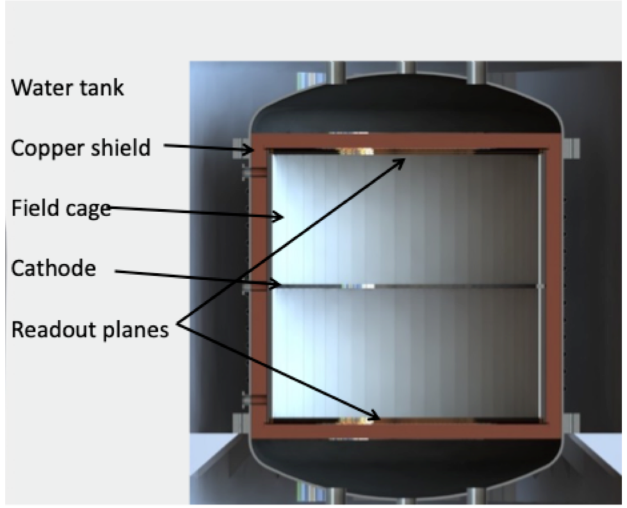


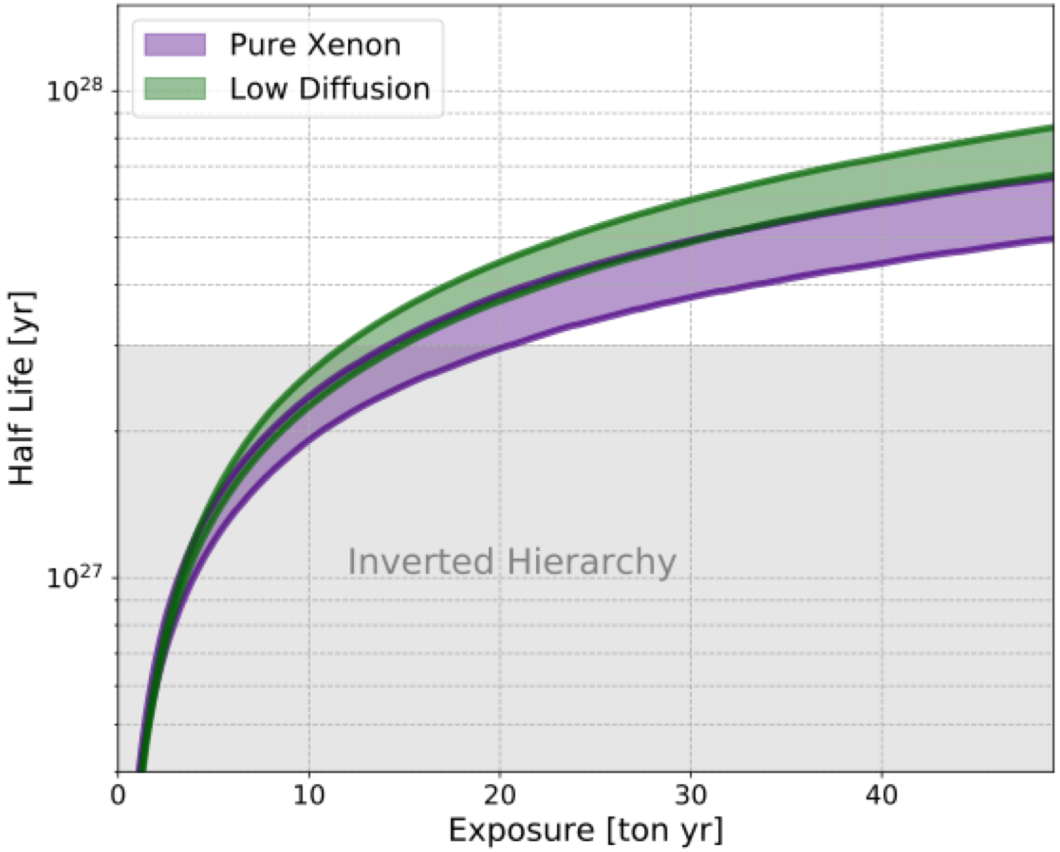
Bolotnikov and Ramsey. "The spectroscopic properties of high-pressure xenon."NIM A 396.3 (1997): 360-370

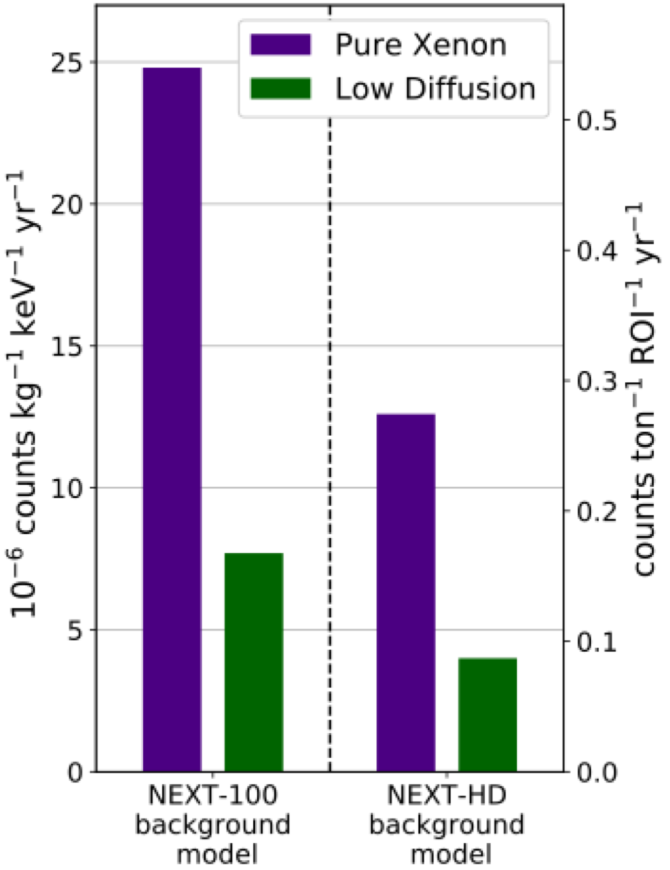
Slides courtesy of the NEXT Collaboration, from R. Guenette

NEXT Sensitivity Goals

- 1 ton module(s)
- Symmetric detector with 1.3m drift length
- SiPM readout







NEXT Collaboration, arXiv:2005.06467

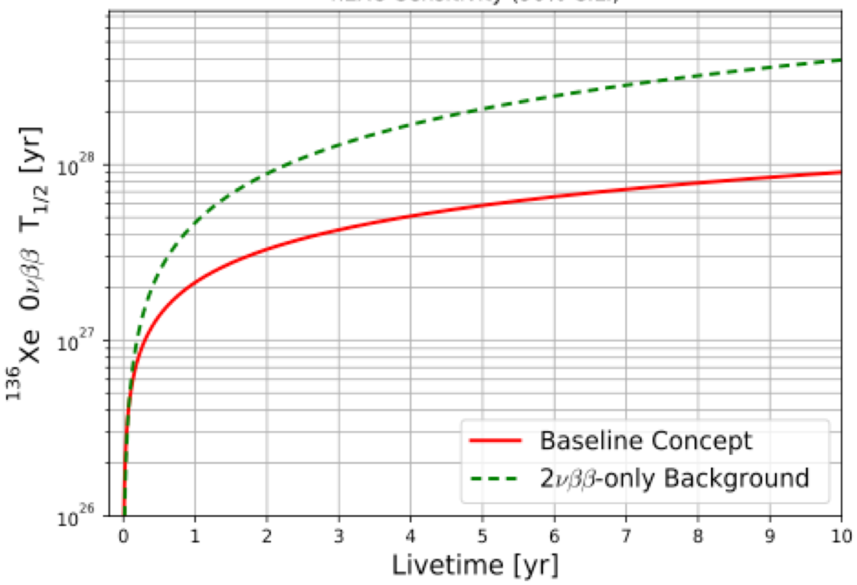
Barium Tagging: A Potential Path to NO

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

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

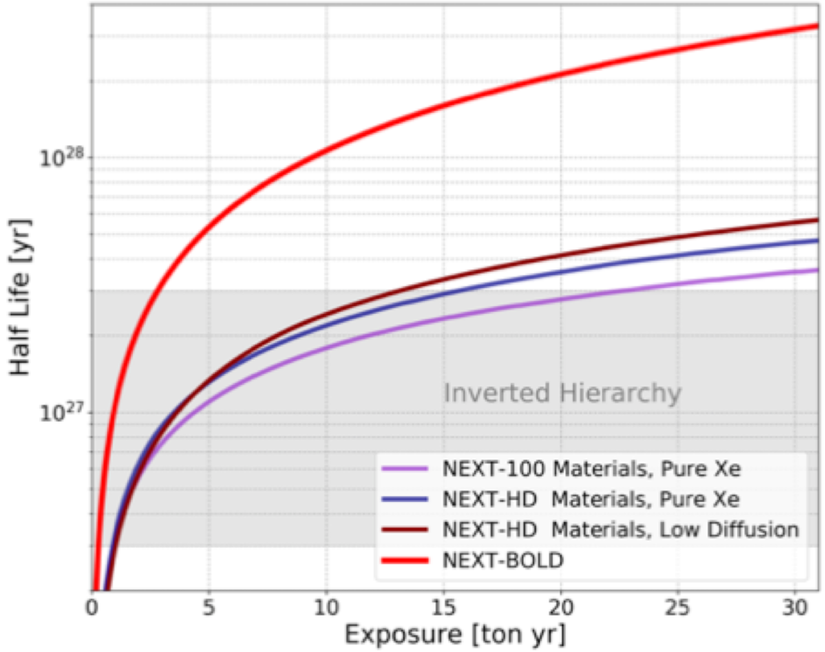
M. Moe, Phys. Rev. C 44, R931 (1991)

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

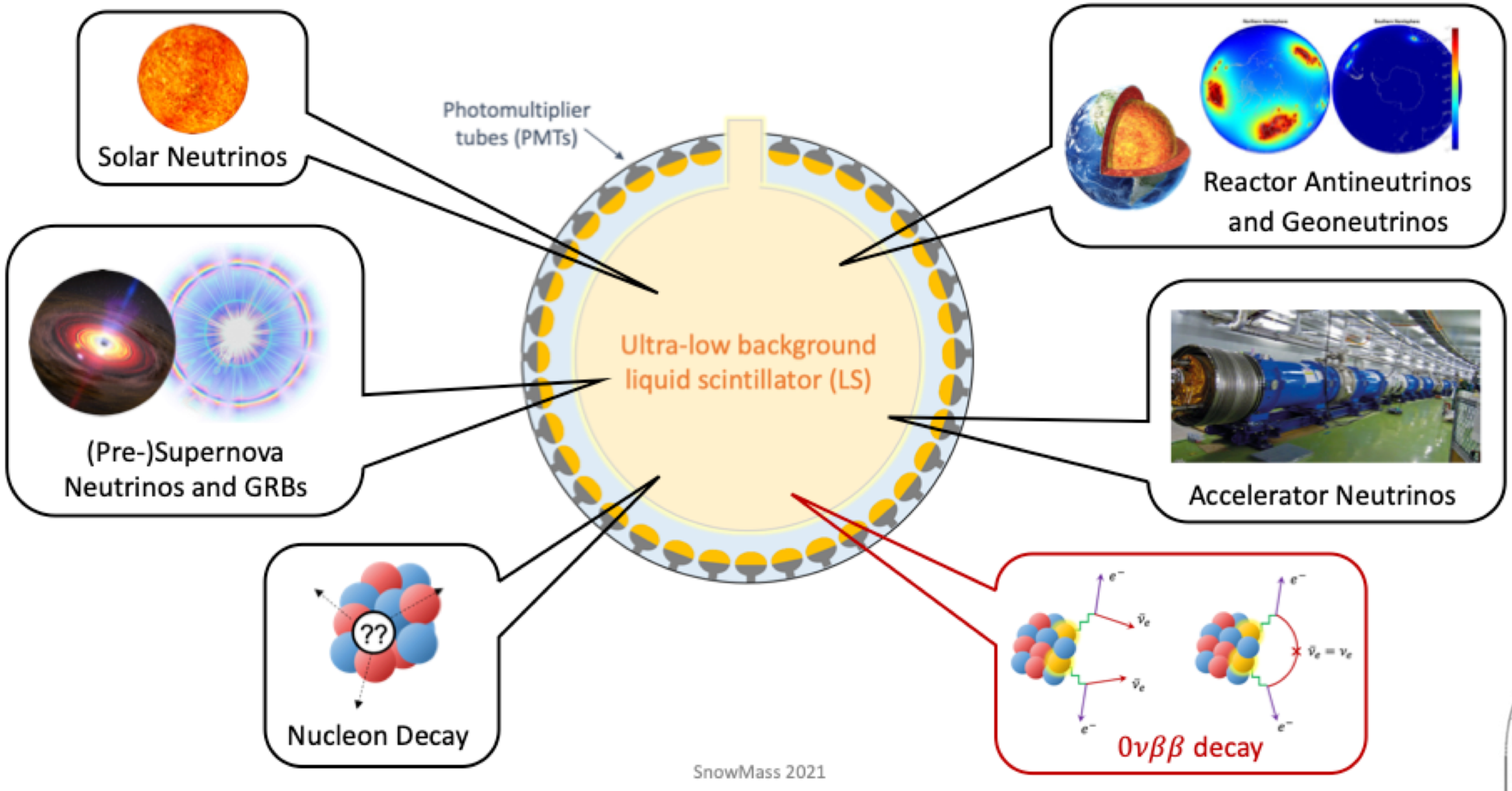


- NEXT and nEXO Collaborations are making progress on a variety of techniques
- Considered a possible upgrade path for the tonne-scale TPC experiments

Could extend sensitivity (further) into the normal ordering region!

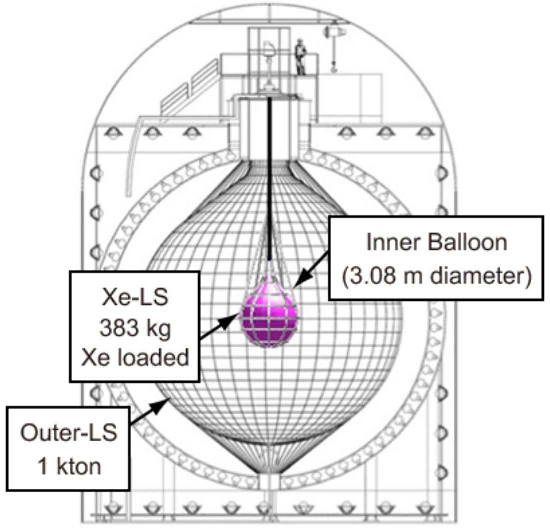
Slides courtesy of the NEXT and nEXO Collaborations, from B. Fairbank

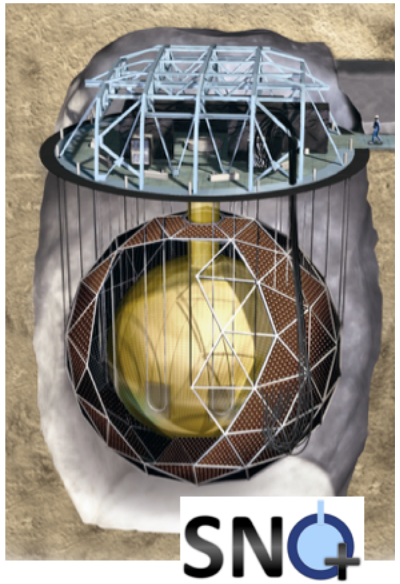
The Liquid Scintillator Concept: SNO+ and KLZ



- Self-shielding, fiducialization
- Interior materials can be made extremely pure
- Pursuing R&D for additional event topology and particle ID
- Multi-purpose detector
- Measurement with and without isotope is possible

KamLAND-Zen

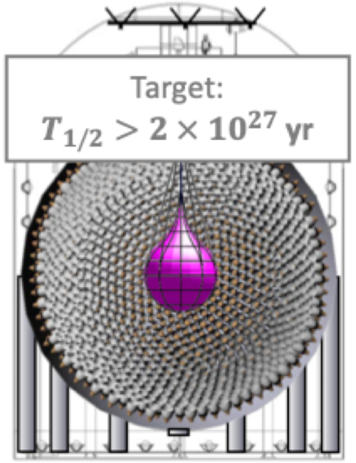




Slides courtesy of the SNO+, KamLAND-Zen, and Theia Collaborations, from C. Grant and R. Svoboda

Sensitivity of Future Liquid Scintillator Experiments

Future



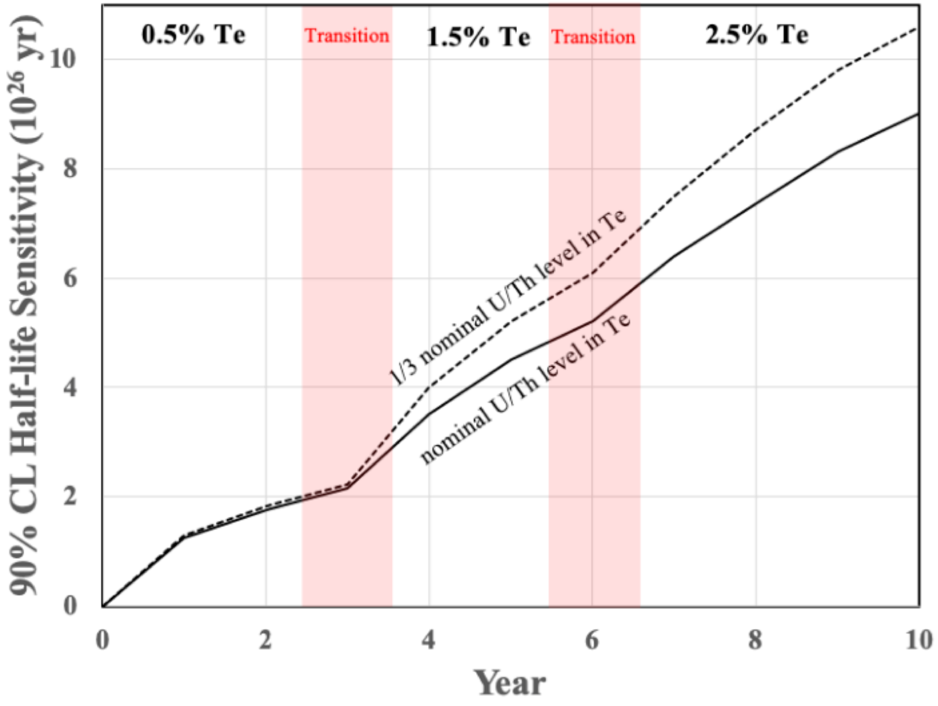
KamLAND2-Zen

Xenon mass ~ 1 ton

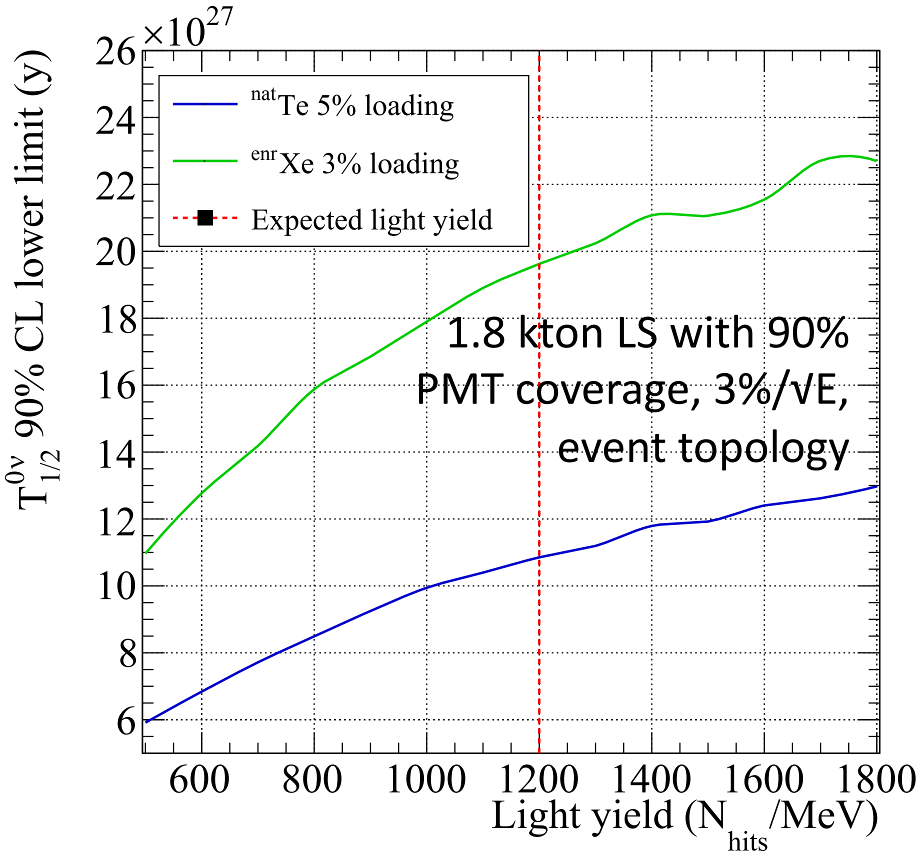
× 5 increase in light collection

Scintillation balloon film

SNO+ Phased Loading Plan
(no detector upgrades required)



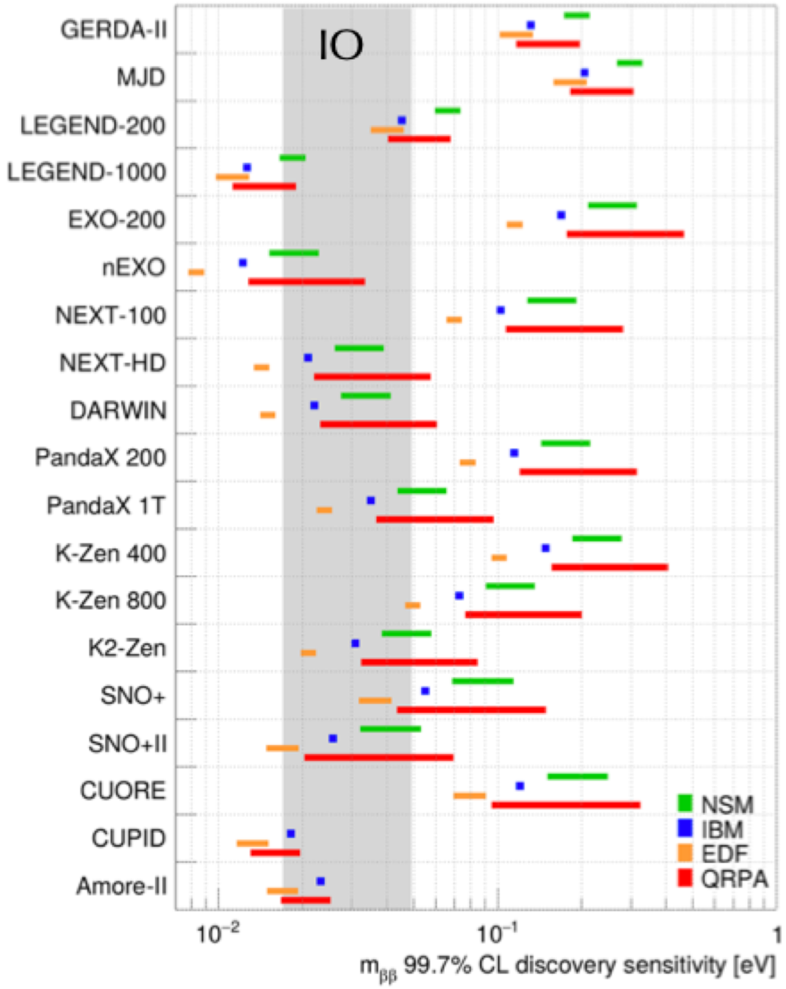
Theia Detector Concept

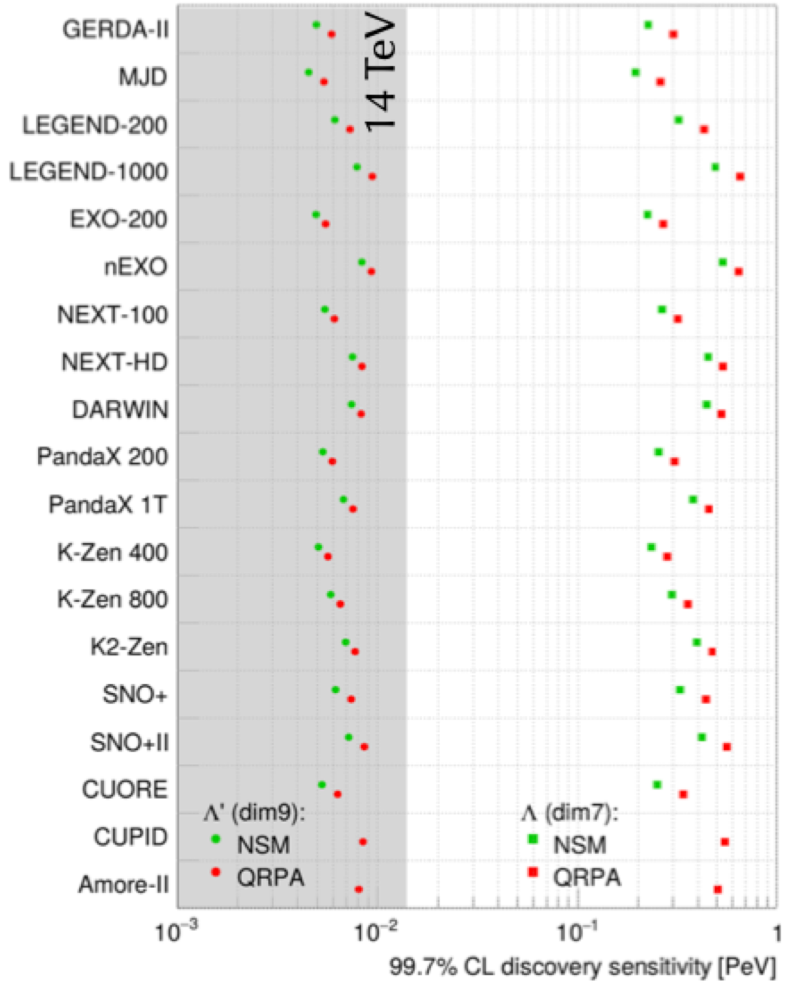


Eur. Phys. J. C (2020) 80:416

- Upgrades to KLZ and SNO+ will reach $T_{1/2} > 10^{27}$
- Theia concept could reach $m_{\beta\beta} < 10$ meV

The Future of 0νββ Searches





- 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 $m_{\beta\beta} \sim \mathcal{O}(1\text{meV})$
- Discovery could come at any time!

Agostini, Benato, Detwiler, Menendez, Vissani, paper in prep.

Conclusion

- Discovering $0\nu\beta\beta$ could lead to major insights into some of the biggest remaining mysteries of the Standard Model: neutrino mass and the matter/anti-matter asymmetry
- Searching for $0\nu\beta\beta$ requires big experiments with ultra-low backgrounds
- Many experimental efforts are underway, and more are hoping to begin soon
- Discovery could come at any time!

Questions?