UC San Diego

Neutrinoless Double Beta Decay

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CCEPP summer school
Lecture I, 8/23/2013

Lecture Outlines

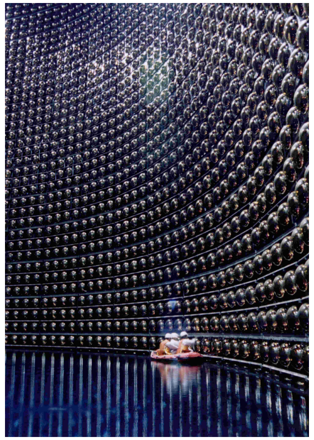
Lecture 1:

- **Brief review of theory of neutrino mass**
- **Majorana vs. Dirac neutrinos**
- **Experimental ideas to test Majorana neutrinos**
- **Neutrinoless double beta decay experiment overview**
- **Experimental sensitivity and background sources**

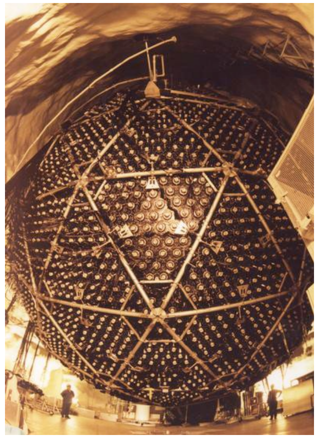
Lecture 2:

- Tracking detectors
- Bolometers
- Semiconductor
- Liquid Scintillators
- TPCs

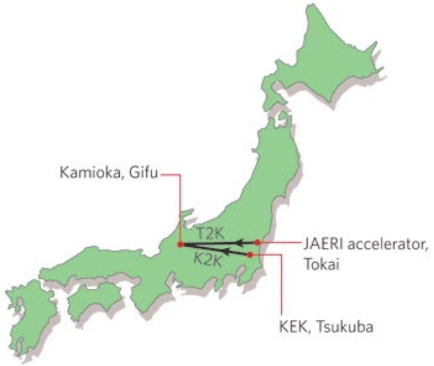
Neutrino Oscillation and Neutrino Mass



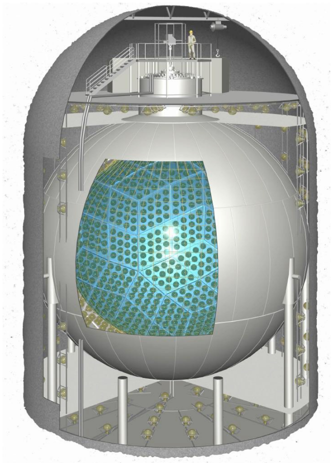
Super-K



SNO



K2K



KamLand

Super-K: atmospheric ν_μ neutrino oscillation

SNO: solar ν_e flavor transformation

K2K: accelerator ν_μ oscillation

Kamland: reactor $\overline{\nu}_e$ disappearance and oscillation

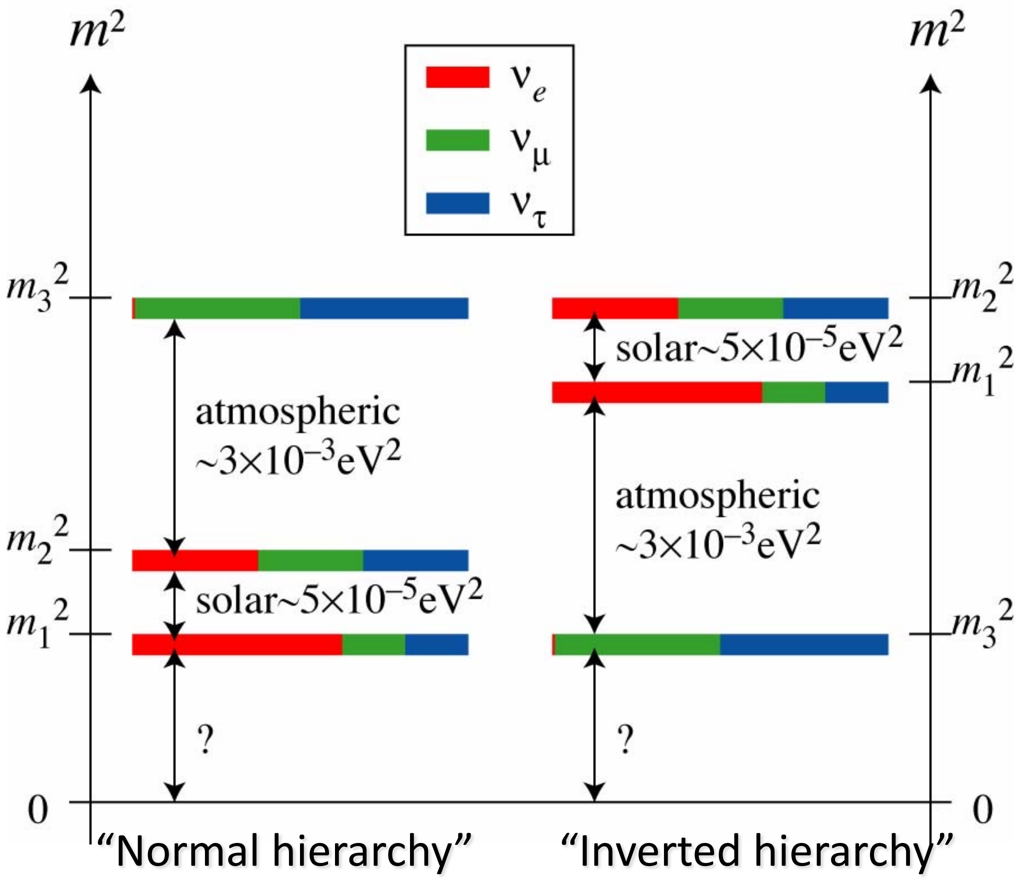
Neutrinos have Mass!!

Our first hints of physics beyond Standard Model…

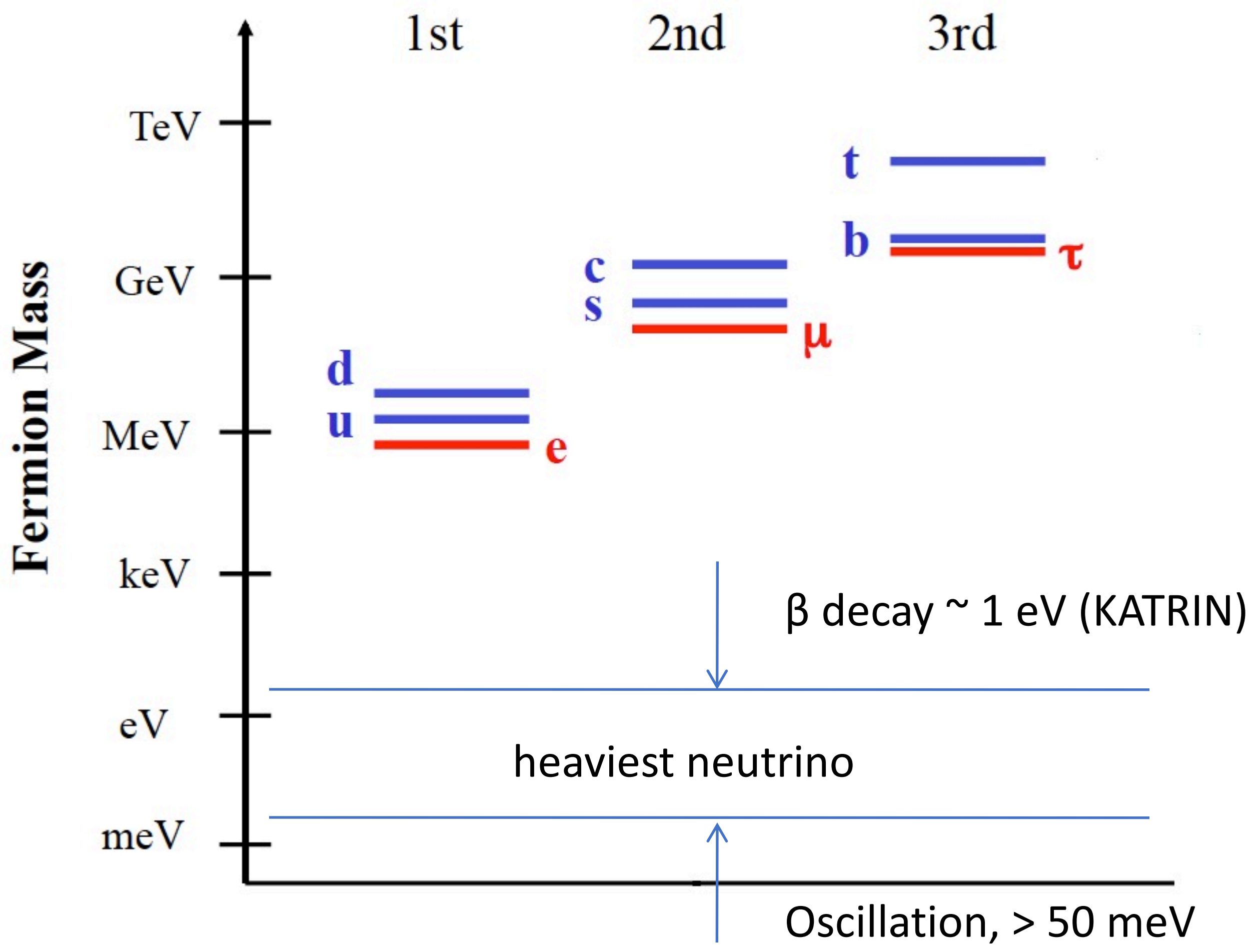
Unknown Properties of Neutrinos

Major Questions in Neutrino Physics

- Majorana particle, (i.e. its own antiparticle)
- Absolute mass scale of neutrinos.
- Mass hierarchy
- CP violation phase
- Anomalies (Sterile neutrinos?)



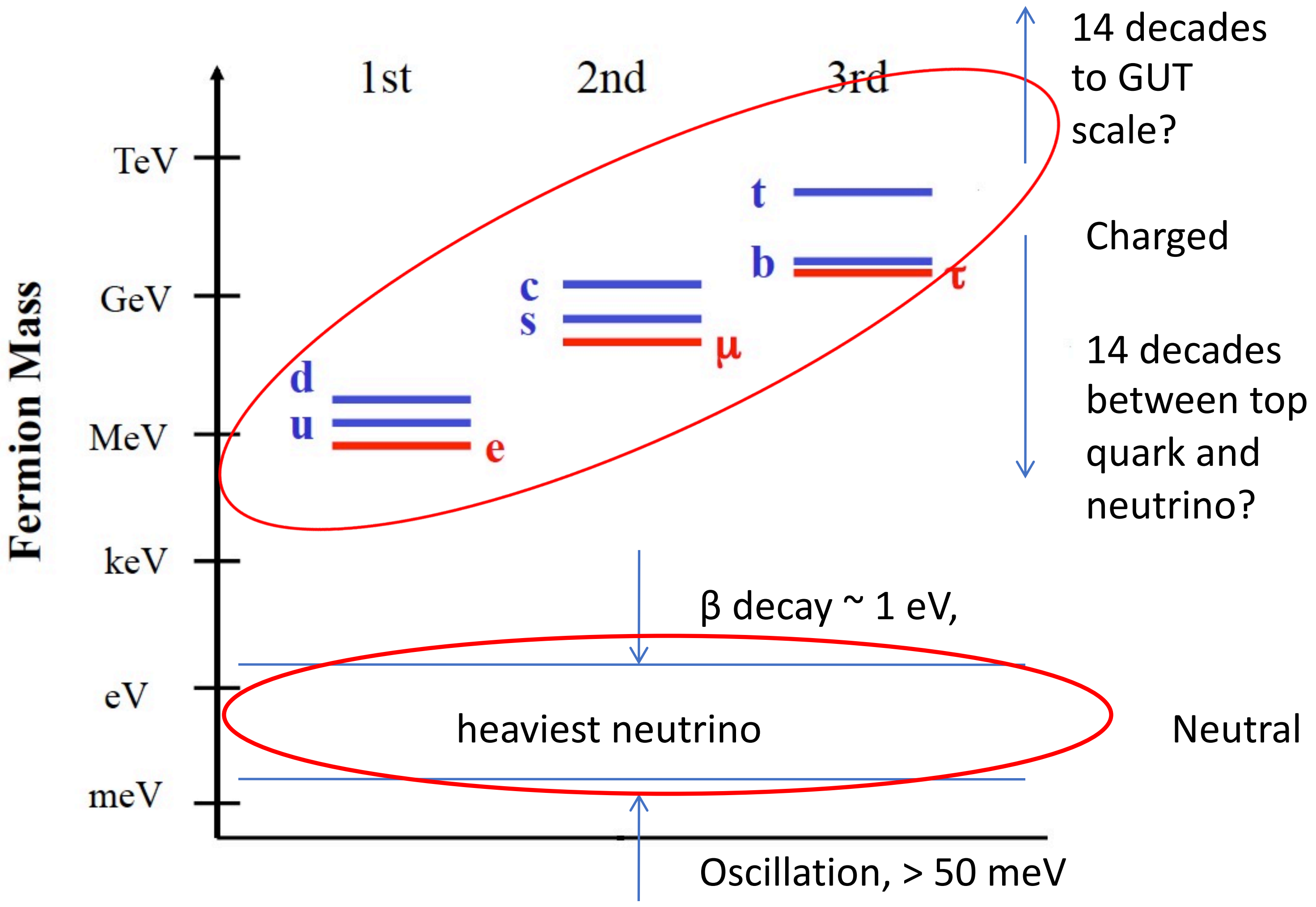
Spin 1/2 Fermion Mass Spectrum



- Quark sector has ~ 1 - 2 decade mass gap across doublet
- Lepton sector has 6+ decades mass gap across doublet

Why?

Spin 1/2 Fermion Mass Spectrum



Perhaps neutrinos are very different from other fermions, such as a Majorana particle?

Dirac vs. Majorana Particles

$$\nu^D = \begin{pmatrix} \nu_L \\ \bar{\nu}_L \\ \nu_R \\ \bar{\nu}_R \end{pmatrix}$$

$$(i\gamma^\mu \partial_\mu - m)\psi = 0$$

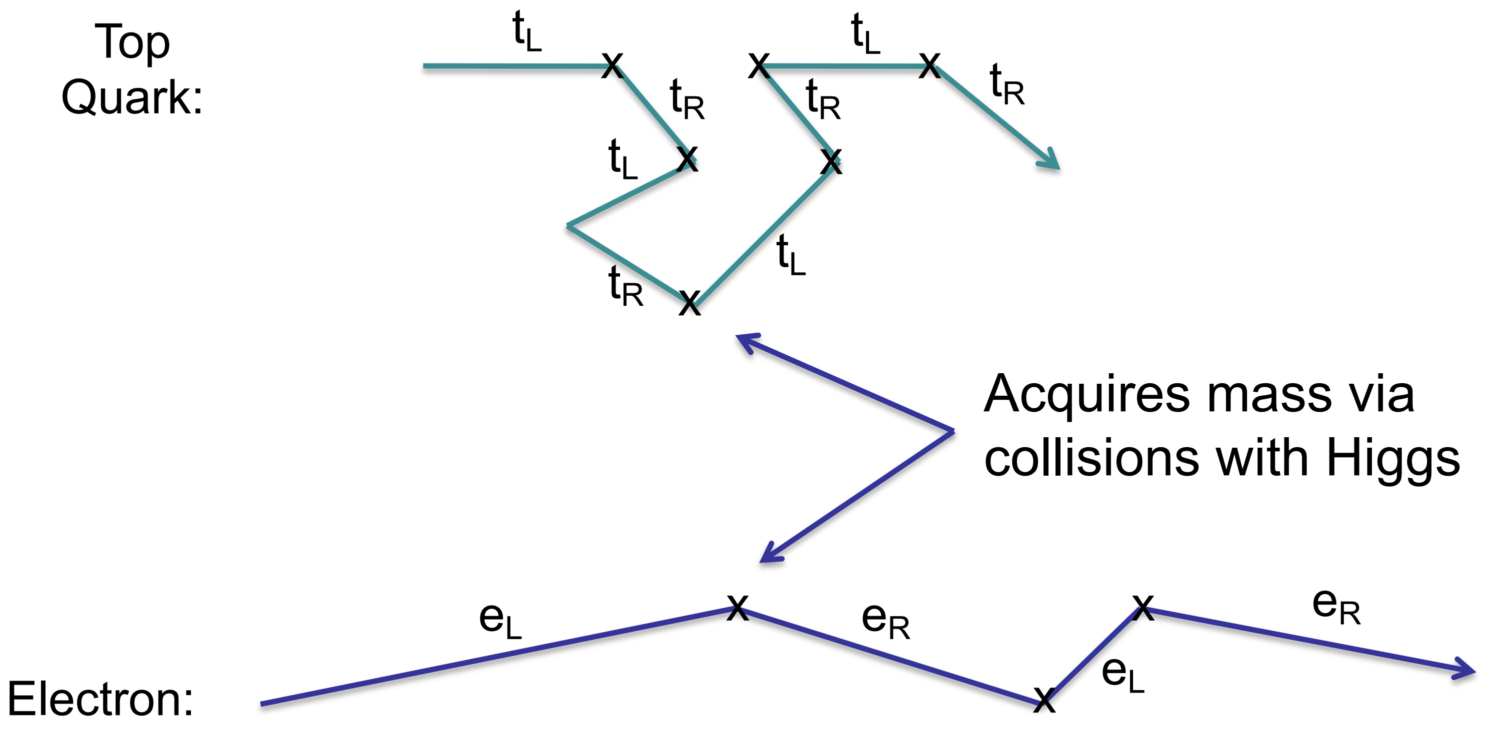
In 1928, Dirac wrote down his famous equation that describes the electrons. The solutions are complex fields, which means there are always a particle and antiparticle pairs.

$$\nu^M = \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

$$(i\tilde{\gamma}^\mu \partial_\mu - m)\tilde{\psi} = 0$$

In 1937, Majorana found a modified version of Dirac equation with a set of γ matrices that are purely imaginary, so the solutions to the equation are real fields.

Fermion Higgs Mechanism



Higgs interact with left and right handed fields

Higgs Mechanism — “Crowd Molasses”

ed.ted.com

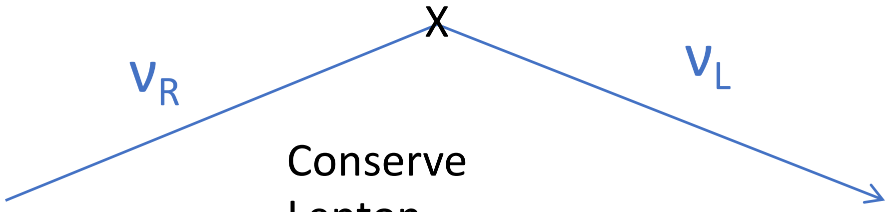
Crowd interacts differently with different people

Top Quark	⟷	Professor Higgs
Photon	⟷	Harry Potter in Invisibility Cloak
Neutrino	⟷	Cellophane Man?

Neutrino Mass Terms

Dirac Neutrino Mass:

$$-m_\nu(\bar{\nu}_R\nu_L + \mathrm{h.c.})$$

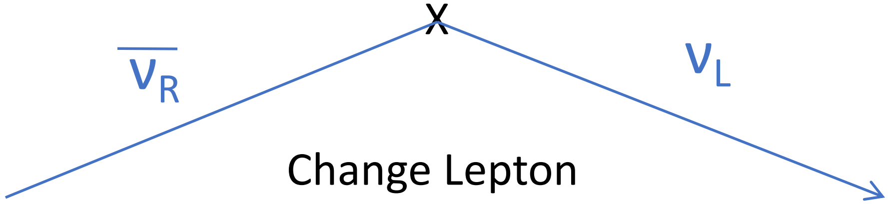


Conserve Lepton number

Neutrino mass can be generated by a “Yukawa” coupling to Higgs.

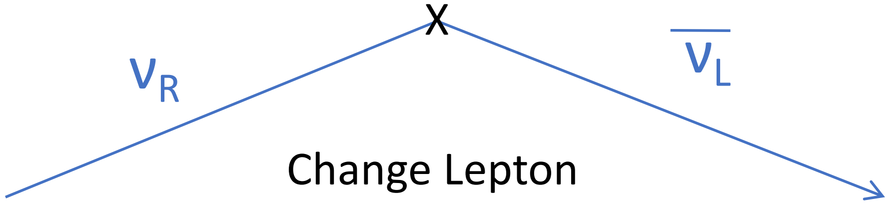
Majorana Neutrino Mass:

$$-\frac{1}{2}\nu_L^T M_{M,L} C^{-1} \nu_L$$



Change Lepton number by 2

“New Physics”



Change Lepton number by 2

$$-\frac{1}{2}\nu_R^T M_{M,R} C^{-1} \nu_R$$

See-Saw Mechanism

Light left-hand neutrino

Heavy right-hand neutrino

Generating the small neutrino mass via standard Higgs mechanism will require fine-tuning of the Yukawa coupling constants, (10^{-12} compared to top quark)

See-saw mechanism can generate the light neutrino mass in a natural way:

Suppose $m_{Dirac} \sim 100$ GeV, similar to top quark (due to Higgs)
$m_{Majorana} \sim 10^{15}$ GeV, (new physics at GUT scale)

Then we will would observe two Majorana neutrinos,

$$m_1 \approx m_D^2 / M_{GUT} \approx 10^{-2}\,\text{eV}$$
$$m_2 \approx M_{GUT}$$

See-saw Mechanism predicts that:

- Light Majorana neutrinos
- Heavy GUT scale neutrinos (possible source of leptogenesis)

Whether neutrinos are Majorana particles can only be answered experimentally!

Don’t we already know $\nu \neq \overline{\nu}$?

$$\overline{\nu}_e p \rightarrow e^+ n$$

Daya Bay
Antineutrino
Detector

Don’t we already know $\nu \neq \bar{\nu}$?

In fact, this is what people thought in 1956,

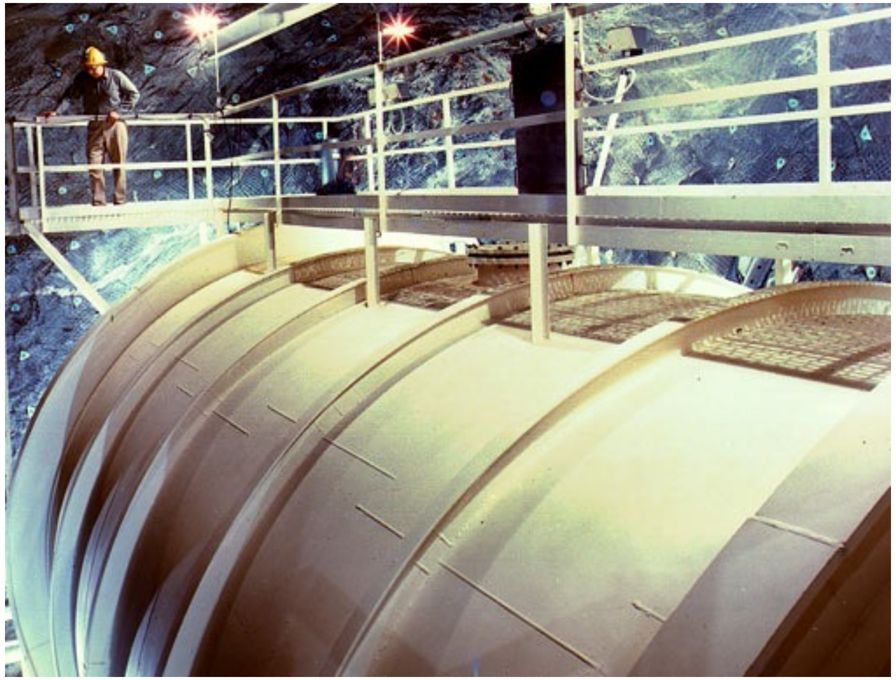
In 1952, Ray Davis found no evidence that anti-neutrinos from the reactor interacted with his Cl detector,

$$\bar{\nu}_e + {}^{37}_{17}Cl \rightarrow e^- + {}^{37}_{18}Ar$$

By 1956, it is known that only neutrino can interact with ^{37}Cl and produce an electron. The reaction Davie used in his famous solar neutrino experiment.

$$\nu_e + {}^{37}_{17}Cl \rightarrow e^- + {}^{37}_{18}Ar$$

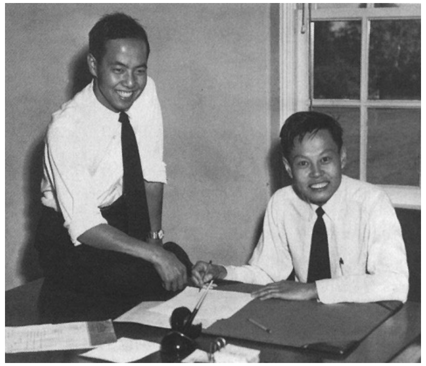
Ray Davis’ neutrino detector at Homestake Gold Mine



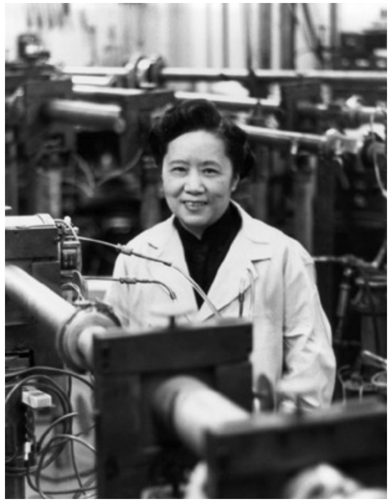
So, it was quite obvious to almost all physicists at the time that neutrinos must be a Dirac particle, not a Majorana particle.

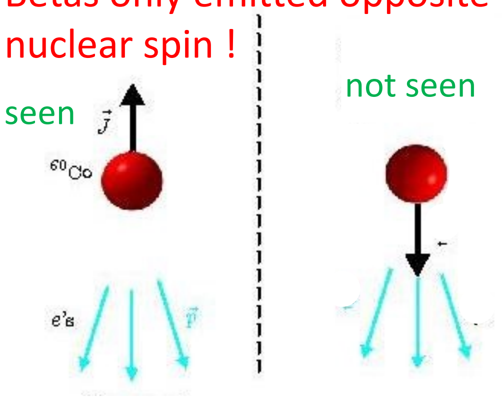
Not so fast ….

Discovery of Parity Violation

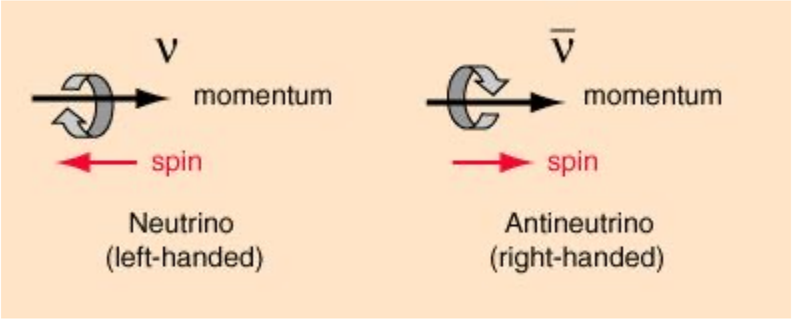


In 1956, when studying theta-tau puzzle, Lee and Yang proposed that parity could be violated in weak interaction.



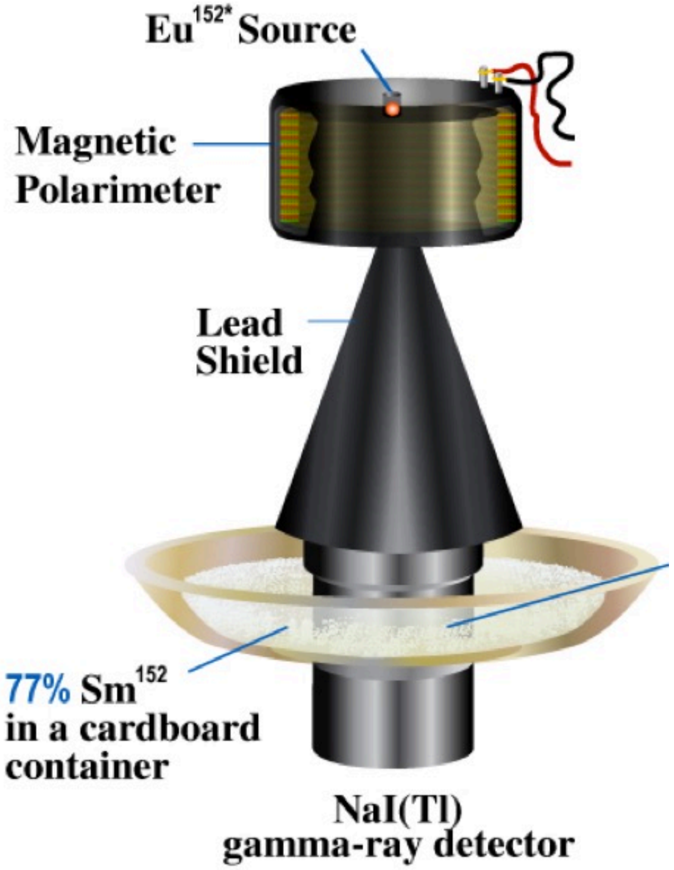


C.S. Wu's famous Co-60 experiment showed that parity is 100% violated.



It's soon realized that Davis' results could only distinguish the helicity of the particle, not whether or not they are Majorana particle.

Measurement of Neutrino Helicity (a digression)



Dr. Grodzins' talk at Neutrino 2010

M. Goldhaber, et. al., Phys. Rev., 109, 1015, (1958)

- Eu^{152} (I=0) undergoes electron capture. The helicity of the neutrino is transferred to the helicity of recoiling Sm^{152*}. (Eu + e = ν + Sm)

- Sm^{152*} decay quickly, emitting a 963 keV γ ray, and transfer the helicity. (Sm^{152*} = Sm^{152} + γ)

- How do we find out the momentum of the neutrino? Using resonance absorption, only γ ray emitting in the same direction of the recoiling Sm can be resonantly absorbed.

- How do we measure the gamma ray helicity? Use a magnetic analyzer.

One of the most beautiful experiment in the twentieth century.

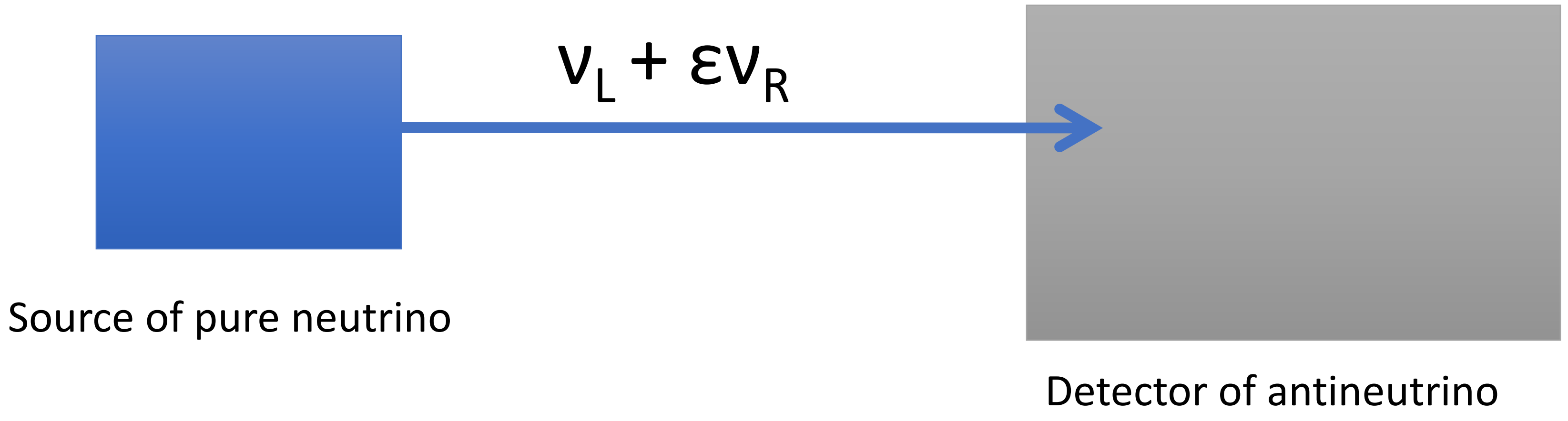
Dirac vs. Majorana Particles

$$\nu^D = \begin{pmatrix} \nu_L \\ \bar{\nu}_L \\ \nu_R \\ \bar{\nu}_R \end{pmatrix}$$

$$\nu^M = \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

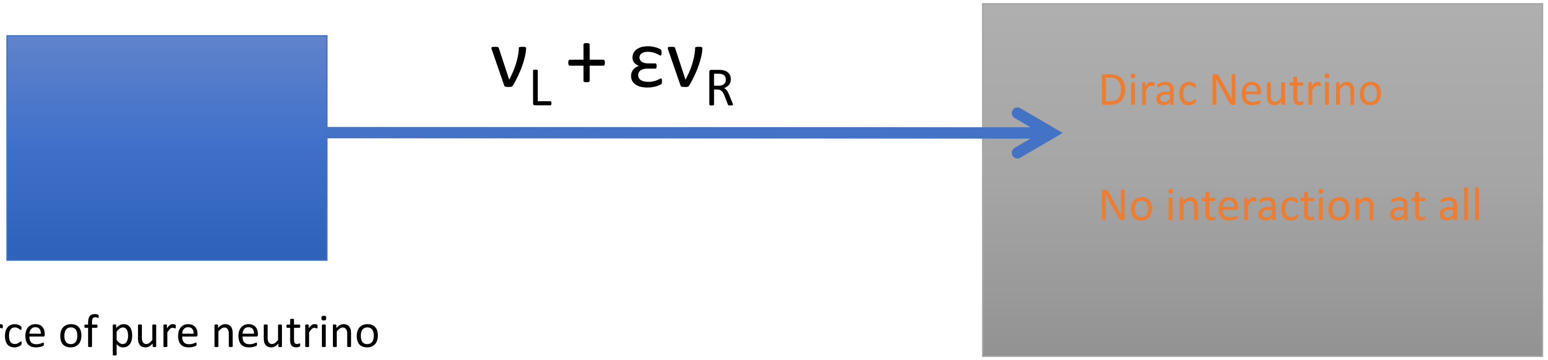
Weak interaction interacts with left-handed neutrinos and right-handed anti-neutrinos

Testing for Majorana Neutrino



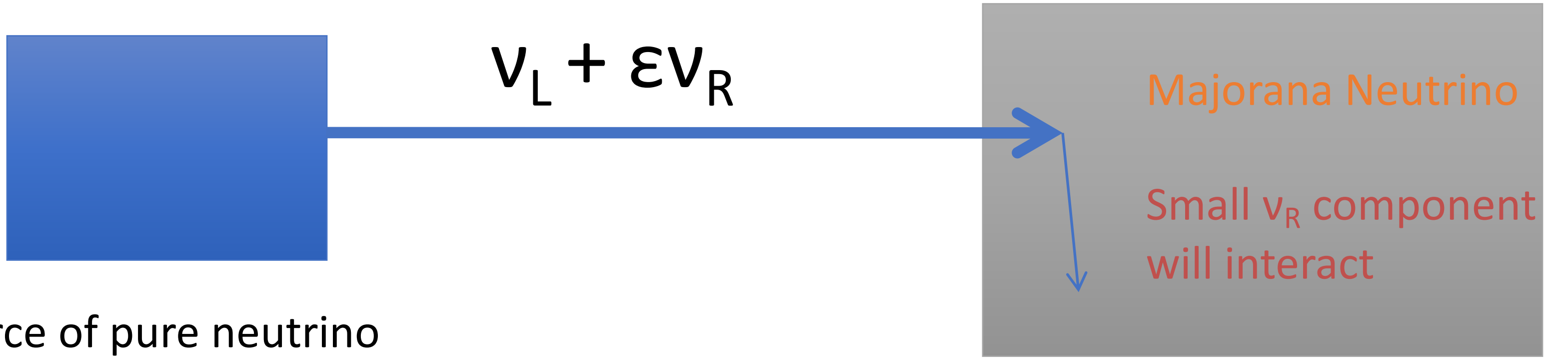
If neutrino is massless, the beam will be pure left handed neutrinos. However, we know that neutrino has mass, so a small amount of neutrinos are created with the wrong handedness (helicity).

Testing for Majorana Neutrino



Source of pure neutrino

Detector of antineutrino



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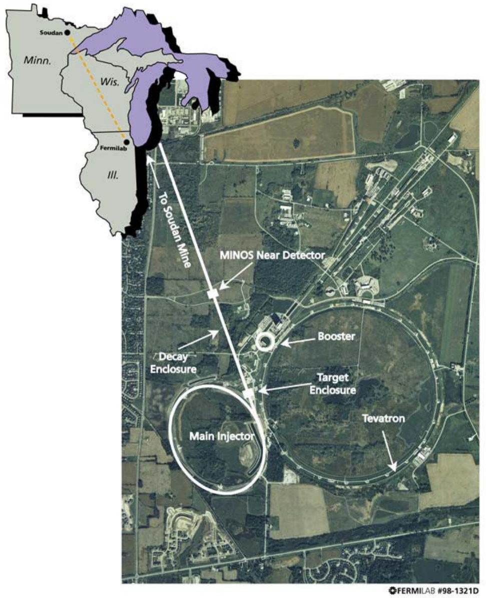
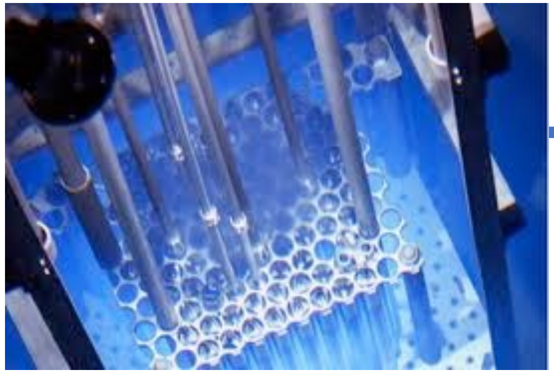


MINOS Beam

$$\pi^+ \rightarrow \mu^+ + \nu_L + \varepsilon\nu_R$$

- ν_L produces μ^- , ν_R if Majorana can produce μ^+
- $\varepsilon \sim m_\nu/E_\nu \sim 10^{-9}$
- μ^+ production is suppressed by $\varepsilon^2 \sim 10^{-18}$
- event rate and false positive are clear limitations

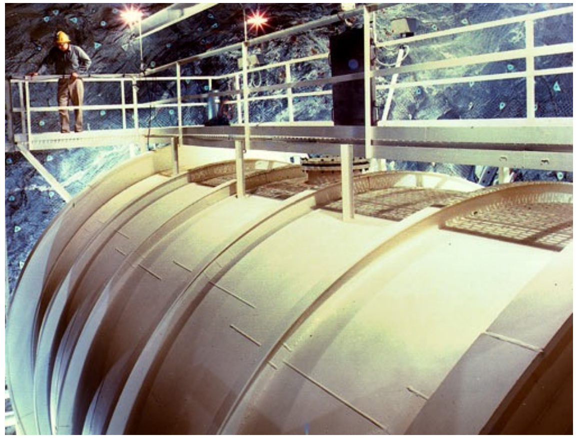
MINOS Detector, can measure muon charge



Reactor antineutrino

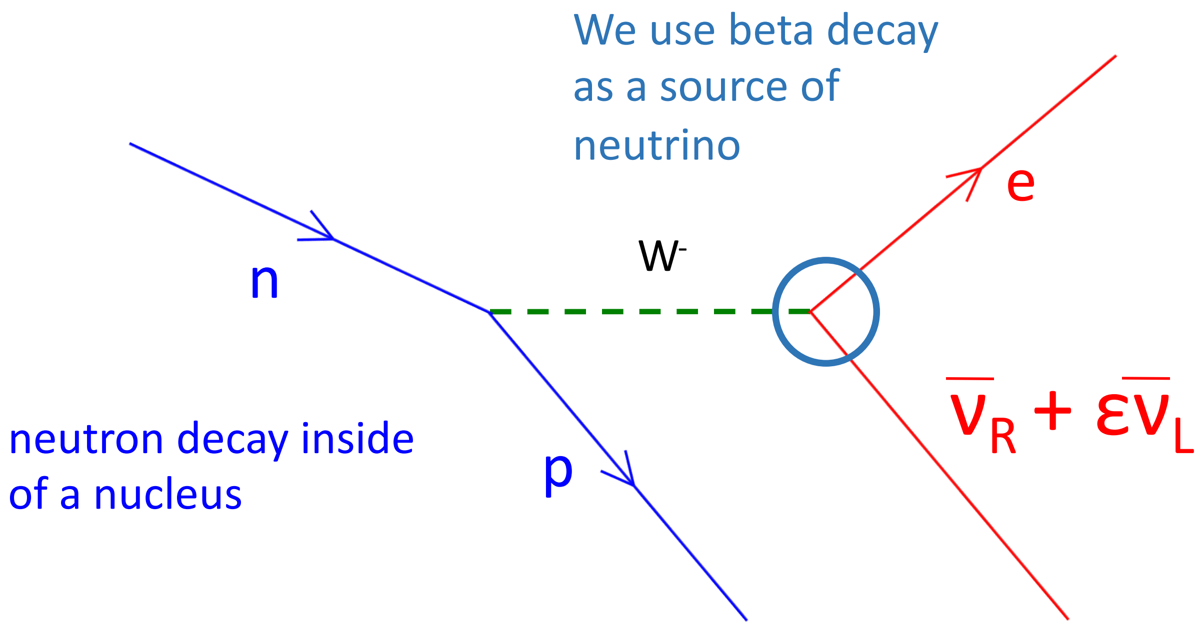
$$n \rightarrow p + e + \bar{\nu}_R + \varepsilon\bar{\nu}_L$$

- $\varepsilon \sim m_\nu/E_\nu \sim 10^{-6}$
- similar chiral suppression problems and solar neutrino background will dominate

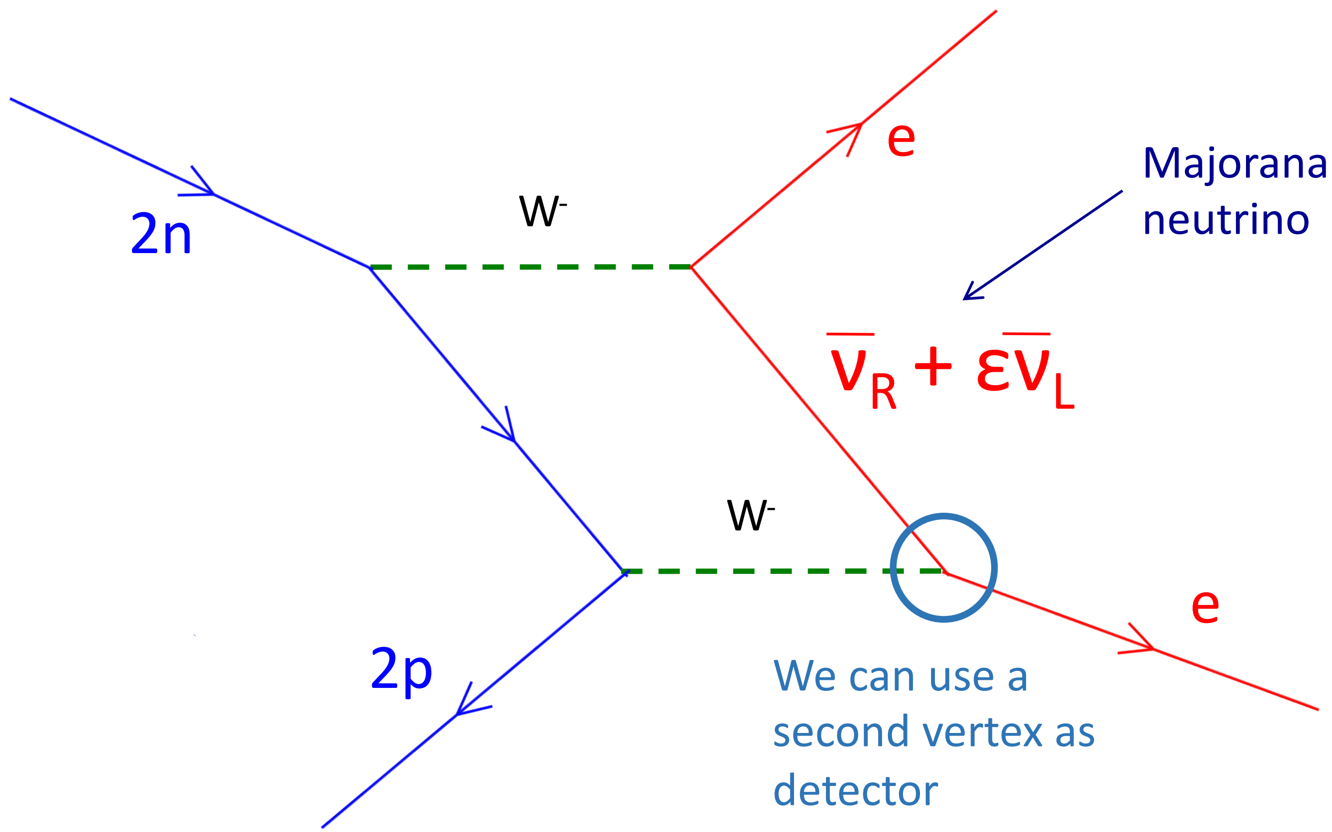


Davis' Cl detector

Neutrinoless Double Beta Decay

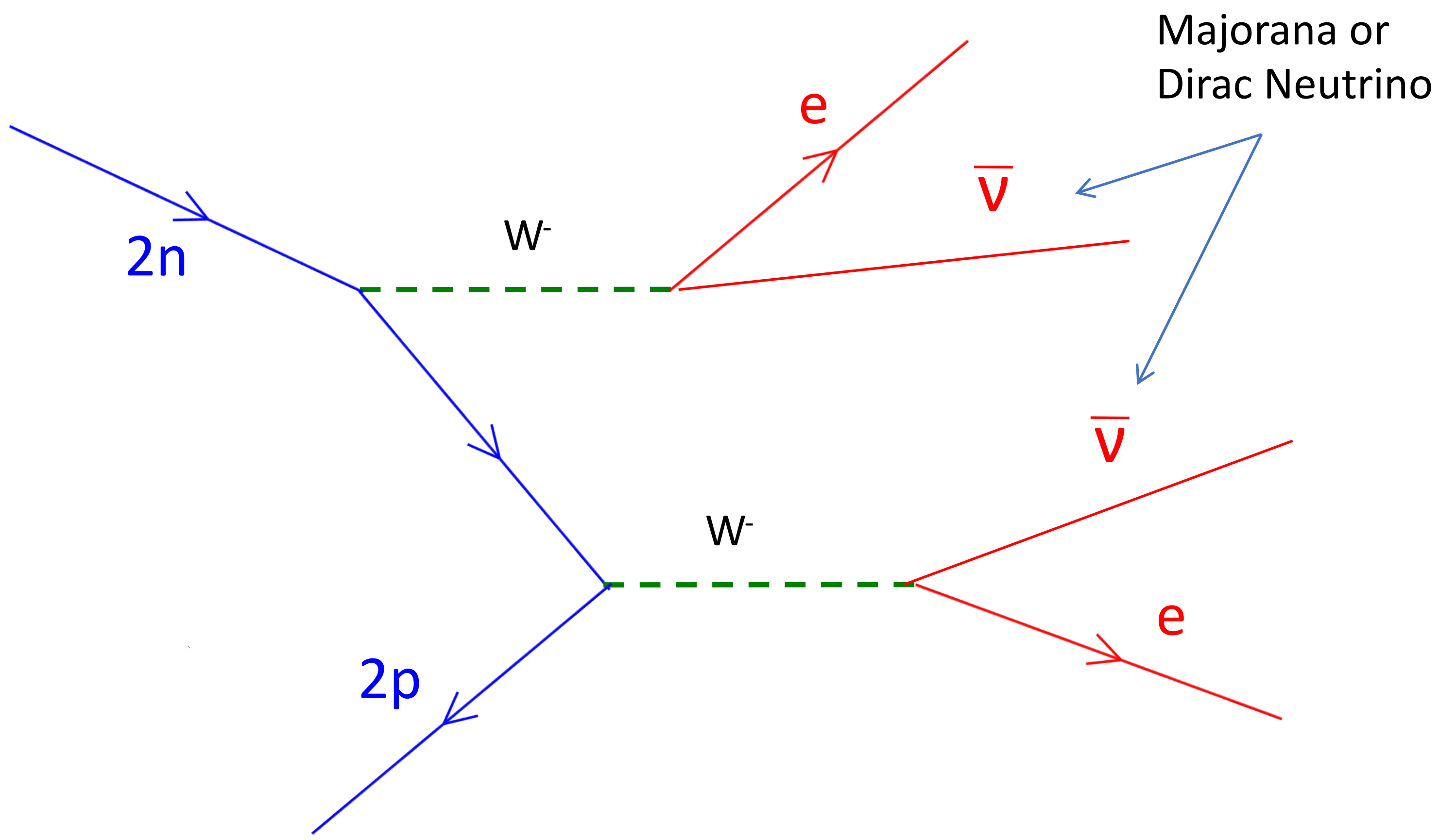


Neutrinoless Double Beta Decay



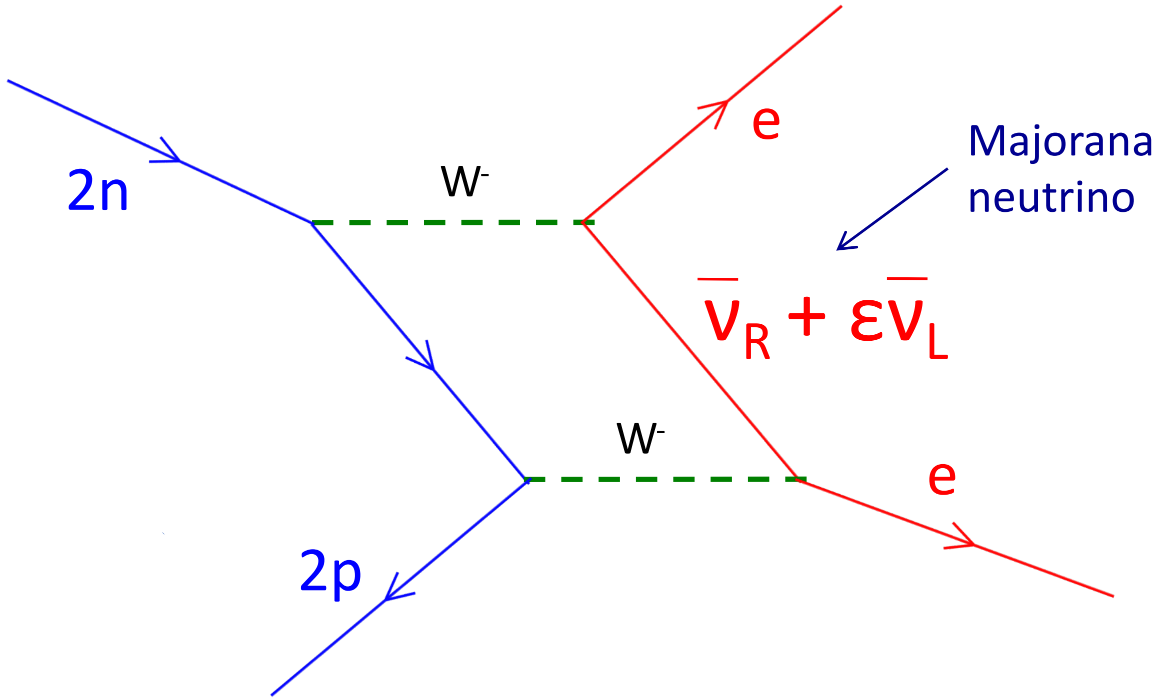
This process is only allowed if neutrino is a Majorana particle, and forbidden if neutrino is a Dirac particle.

Two Neutrino Double Beta Decay



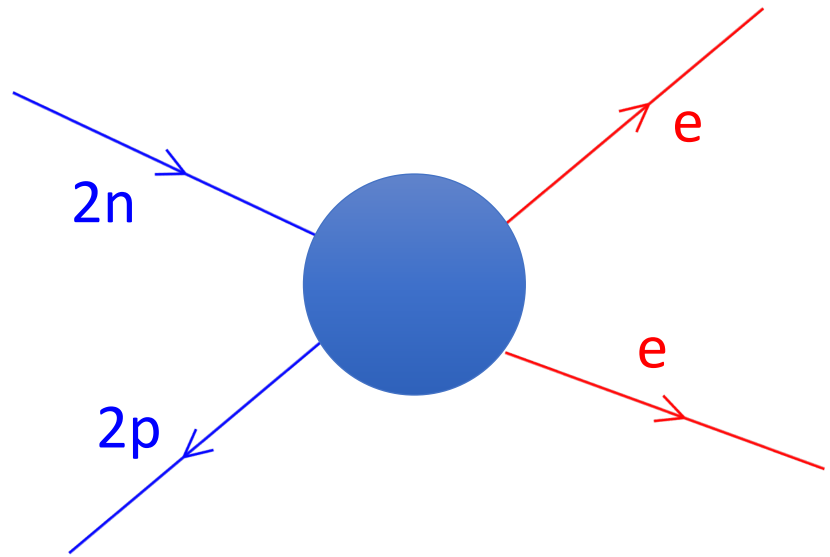
There is another kind of double beta decay process where two neutrinos gets emitted along with the two electrons. This process does not tell us whether or not neutrinos are Majorana or Dirac particles.

Why Neutrinoless Double Beta Decay Might Work?



- Eliminate the uninteresting events (10^{14}) where the neutrino would not interact with the second vertex.
- Chiral suppression still exists, and event rate is extremely low. Fortunately, Avogadro's number is large and every nucleus can both be the source and detector.
- Two neutrino double beta decay is a second order process, so rate is also low, therefore reducing background. False positive from radioactive background still an issue. (will be discussed later)

Other Mechanisms for Neutrinoless Double Beta Decay



There are many possible mechanisms for neutrinoless double beta decay, such as right handed weak current, leptoquark, supersymmetry, ect ..

Does the observation neutrinoless double beta decay necessarily prove that neutrinos are Majorana particles?

Black Box Theorem

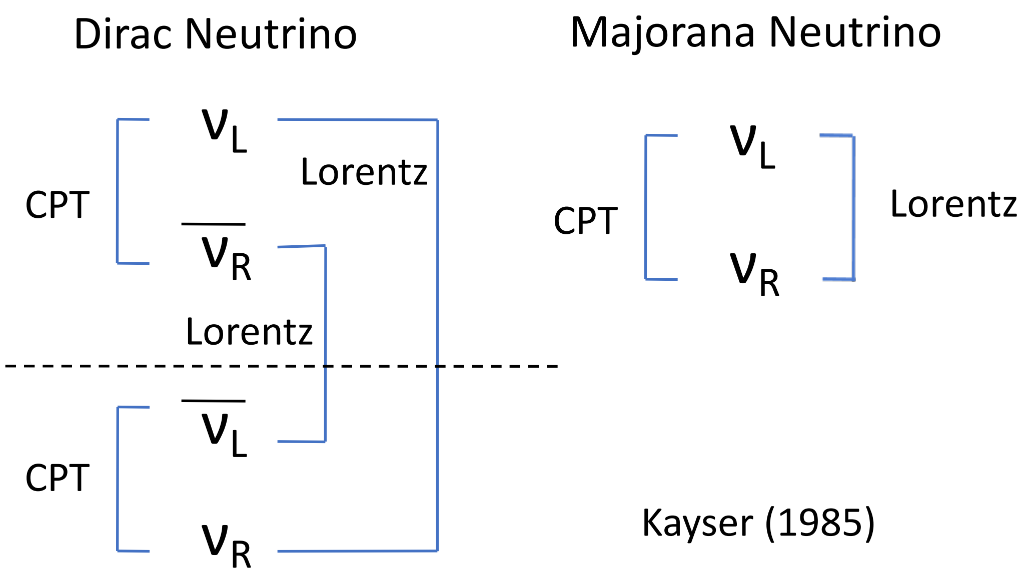
Schechter and Valle,82

No matter what underlying mechanism causes the $0\nu\beta\beta$, by adding standard model processes, we will get at Majorana mass term, therefore guaranteeing that neutrinos are massive Majorana particles.

Summary on Majorana/Dirac Measurements

• At first glance, it seems that it would be easy to distinguish Majorana and Dirac neutrinos, one has two distinct states and the other has four.

• However, parity violation and V-A weak interaction makes accessing the right hand neutrino difficult. In fact, if neutrinos are massless, the left hand and right hand neutrinos will be completely disconnected.



• Most experiments are unrealizable due to the chiral suppression and false positives.

• The smaller the neutrino mass, the more difficult to test Majorana/Dirac.

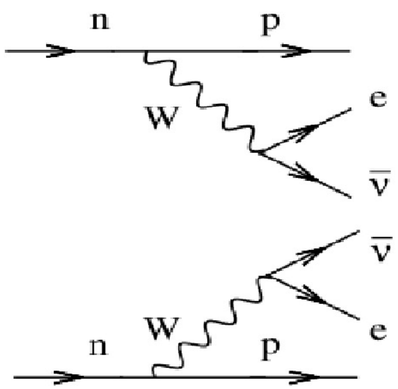
• Neutrinoless double beta decay is the most promising approach.

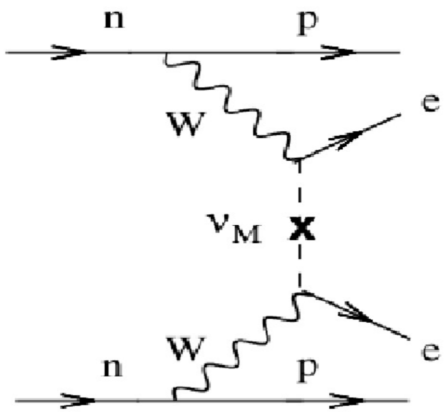
• See-saw mechanism favors Majorana neutrino, other theoretical ideas?

Double Beta Decay

Maria Goeppert Mayer

Ettore Majorana





Observation of 0νββ:

- Majorana neutrino
- Neutrino mass scale
- Lepton number violation

Two neutrino double beta decay

$$^{136}_{54}Xe \rightarrow ^{136}_{56}Ba^{++} + 2e^{-} + 2\bar{\nu}_e$$

1935 Maria Goeppert Mayer first proposed the idea of two neutrino double beta decay

1987 first direct observation in ^{82}Se by M. Moe

Neutrinoless double beta decay

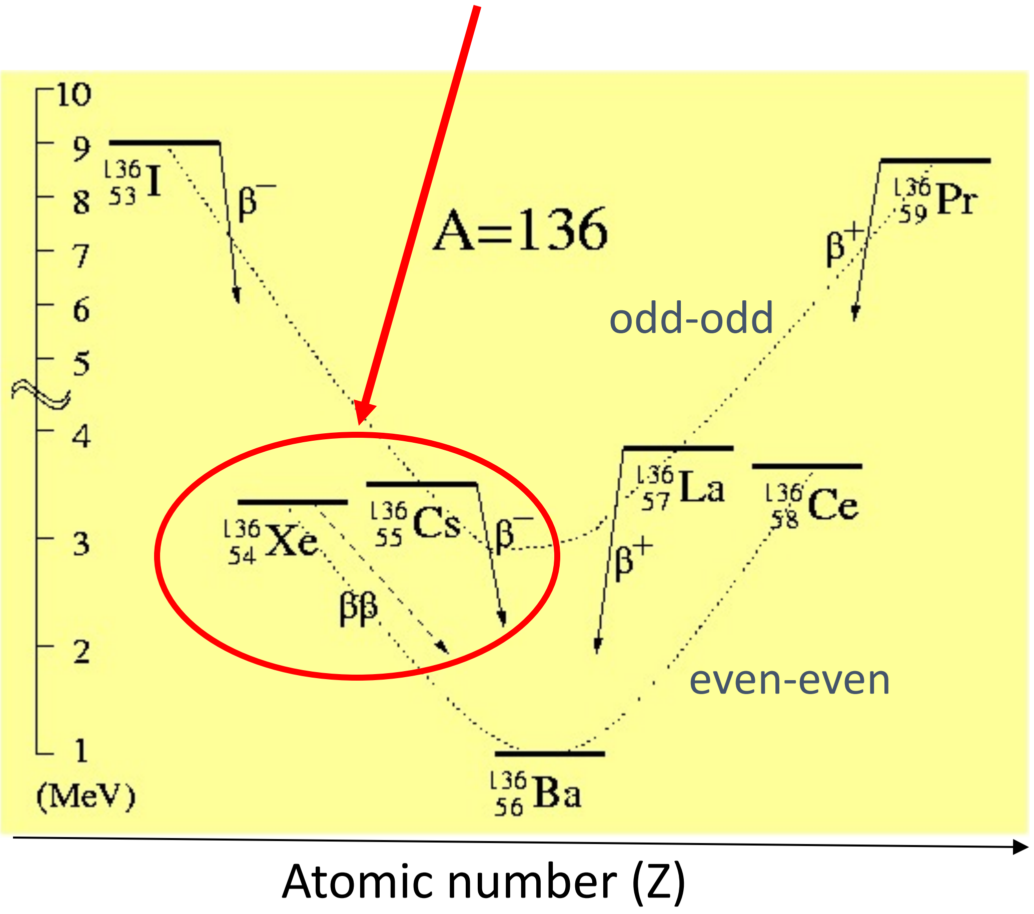
$$^{136}_{54}Xe \rightarrow ^{136}_{56}Ba^{++} + 2e^{-}$$

1937 Ettore Majorana proposed the theory of Majorana fermions

1939 Wendell Furry proposed neutrino less double beta decay

Double-beta Decay

a second-order process only detectable
if first order beta decay is energetically forbidden

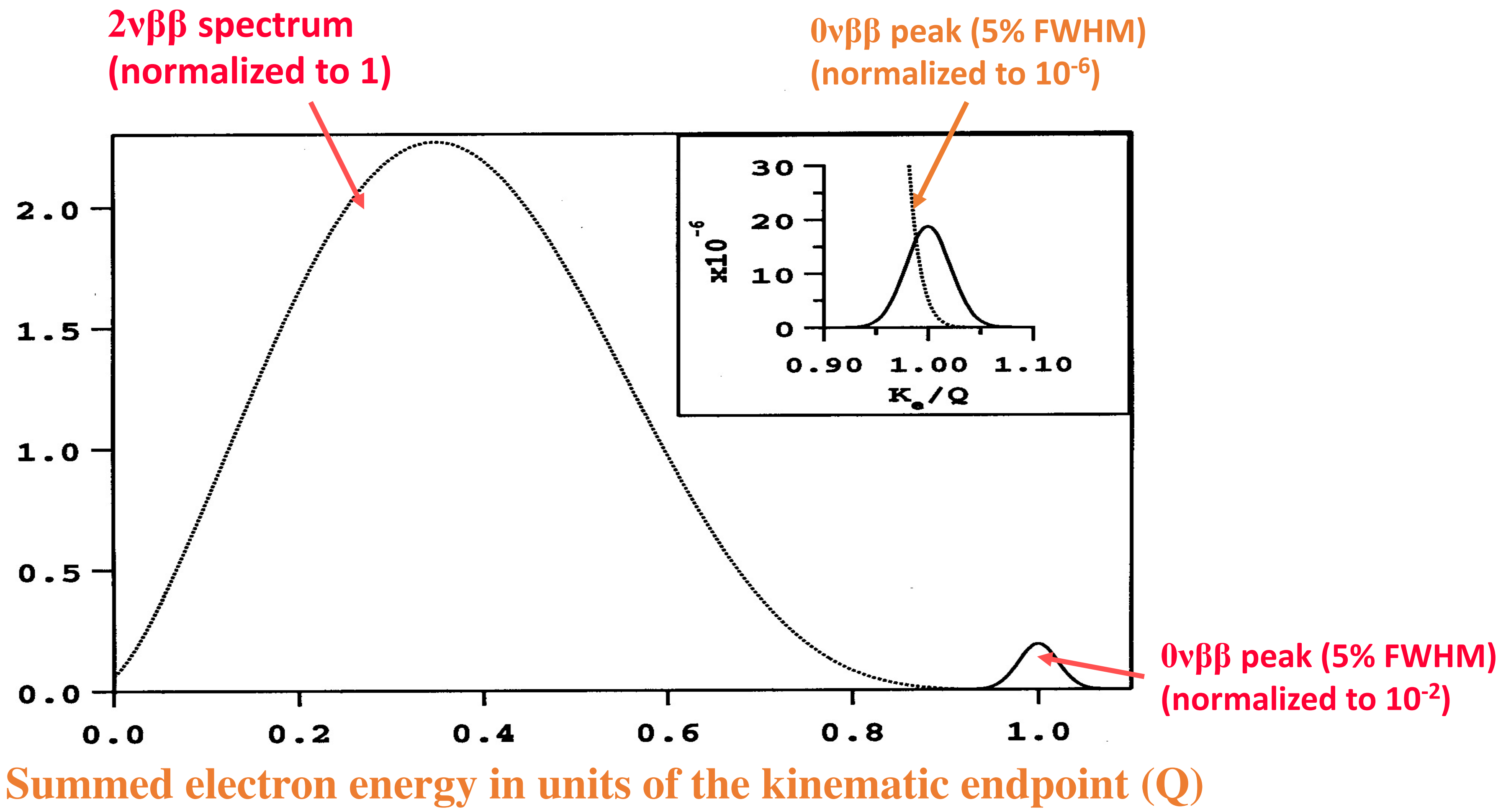


- For even atomic mass A, we get two mass curves, odd-odd and even-even.
- δ is a paring term, negative for Z even and positive for Z odd.
- Double beta decay candidates are always even-even, binding energy greater than two electron mass.
- How about $0\nu\beta^+\beta^+$, or double electron capture?

$$M_A(Z,A) = const + 2b_{sym}\frac{(A/2-Z)^2}{A^2} + b_{Coul}\frac{Z^2}{A^{1/3}} + m_e Z + \delta\,;$$

Semi-empirical mass formula

Double Beta Decay Energy Spectrum



2νββ and 0νββ can be separated in a detector with good energy resolution

Double Beta Decay Nuclei

Candidate	Q (MeV)	Abund.(%)
$^{48}Ca \rightarrow {}^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow {}^{76}Se$	2.040	7.8
$^{82}Se \rightarrow {}^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow {}^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow {}^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow {}^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow {}^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow {}^{124}Te$	2.228	5.64
$^{130}Te \rightarrow {}^{130}Xe$	2.533	34.5
$^{136}Xe \rightarrow {}^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow {}^{150}Sm$	3.367	5.6

Candidate nuclei with Q>2 MeV

- About 35 naturally occurring isotopes, but only dozen or so good neutrinoless double beta decay candidates

- Large Q means large phase space and larger abundance usually means cheaper source material, more on these comparisons later

$0\nu\beta\beta$ and Neutrino Mass

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}(Q,Z)\left|M^{0\nu}\right|^2 \langle m_{\beta\beta}\rangle^2$$

0νββ decay rate

Phase Space

Matrix Element

Effective Mass

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

Mixing matrix

mass eigenvalues

Majorana phase

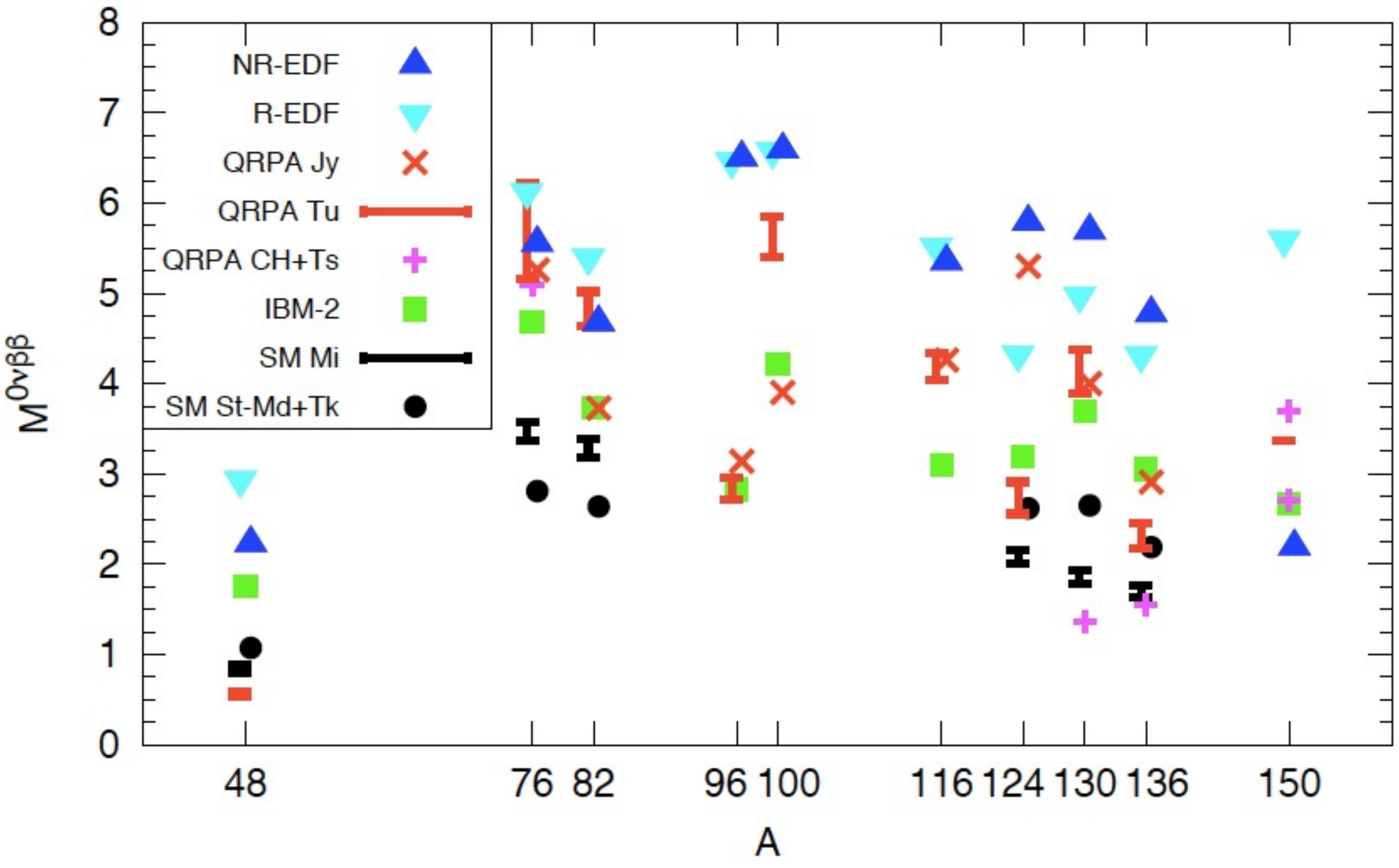
Three Caveats:

- Neutrino is a Majorana particle
- Light Majorana neutrino being the dominate decay mechanism
- reliable calculation of matrix elements

Effective Majorana mass is a coherent sum of neutrino mass eigenvalues, therefore cancellations are possible…

0νββ Matrix Elements

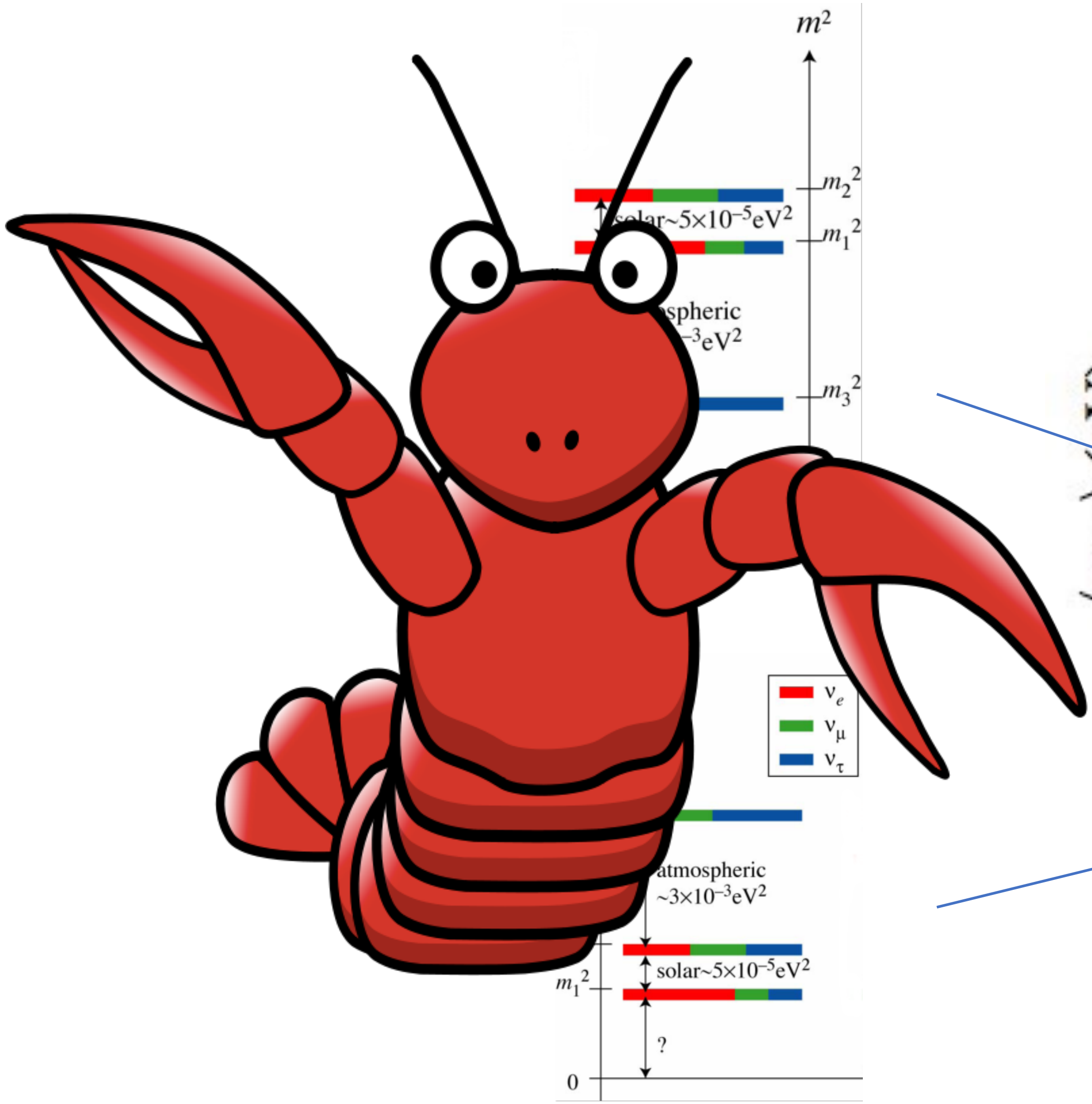
- Matrix element calculation is very difficult, in particular for big nuclei, most of the 0νββ candidates.
- Recent theoretical progress has narrowed the difference between models, but significant spread remains, difficult to estimate uncertainty

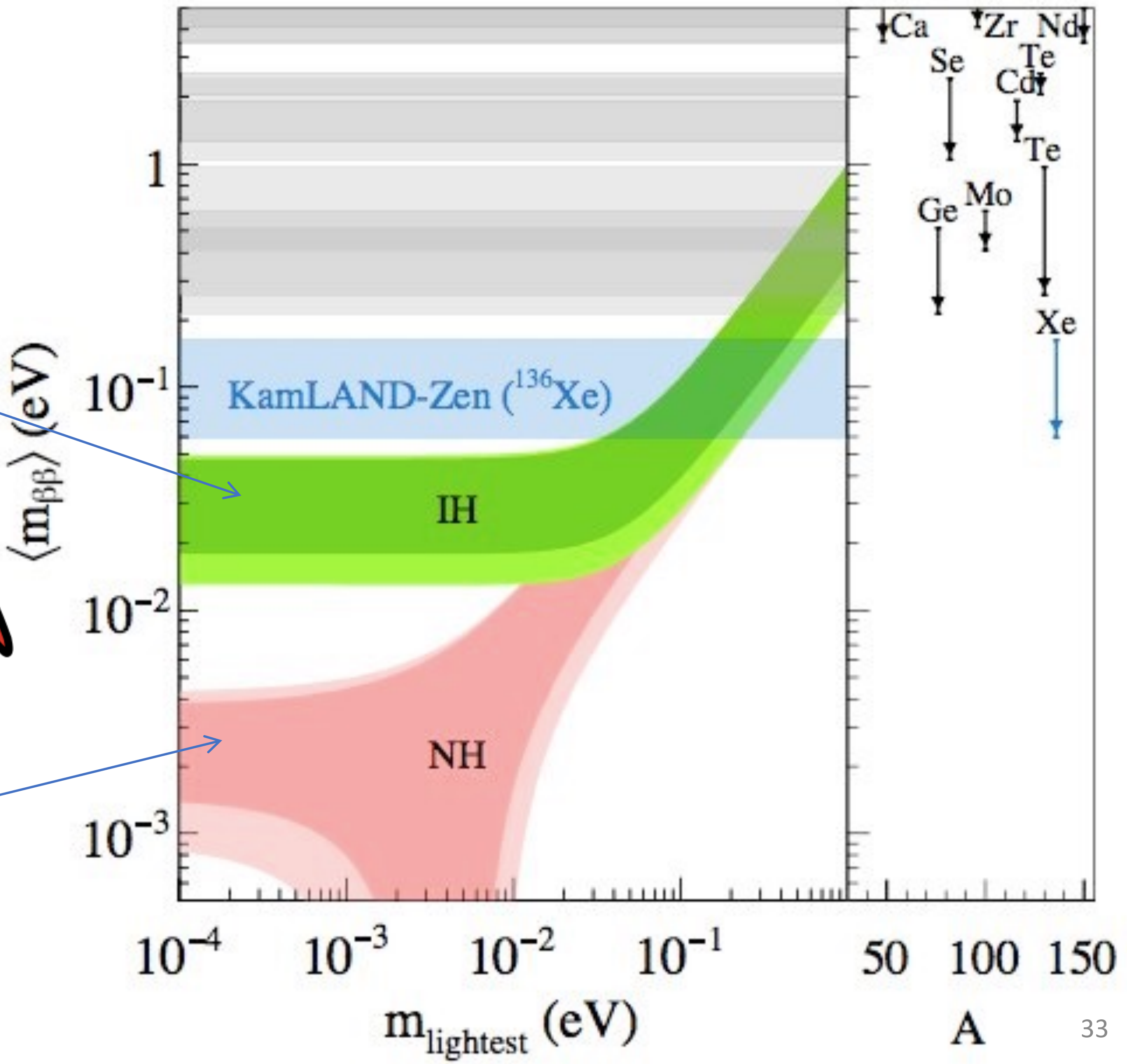


Rept.Prog. Phys. 80, 046301 (2017)

“Lobster Plot”

PRL 117, 082503 (2016)





PRL 117, 082503 (2016)

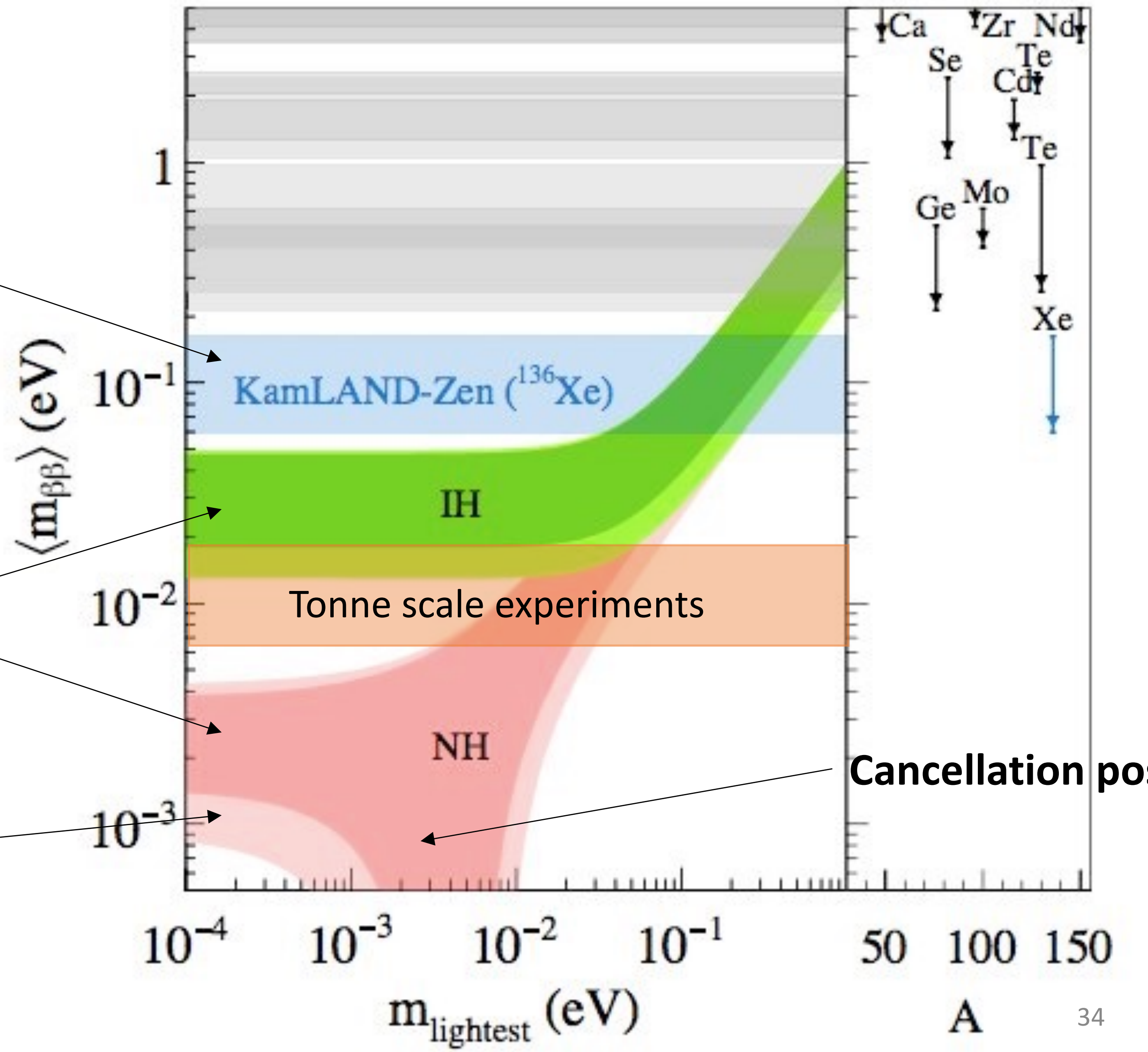
$$\langle m_{\beta\beta} \rangle = \left|\sum_{i=1}^{3} U_{ei}^2 m_i e^{i\alpha_i}\right|$$

Uncertainty in matrix elements

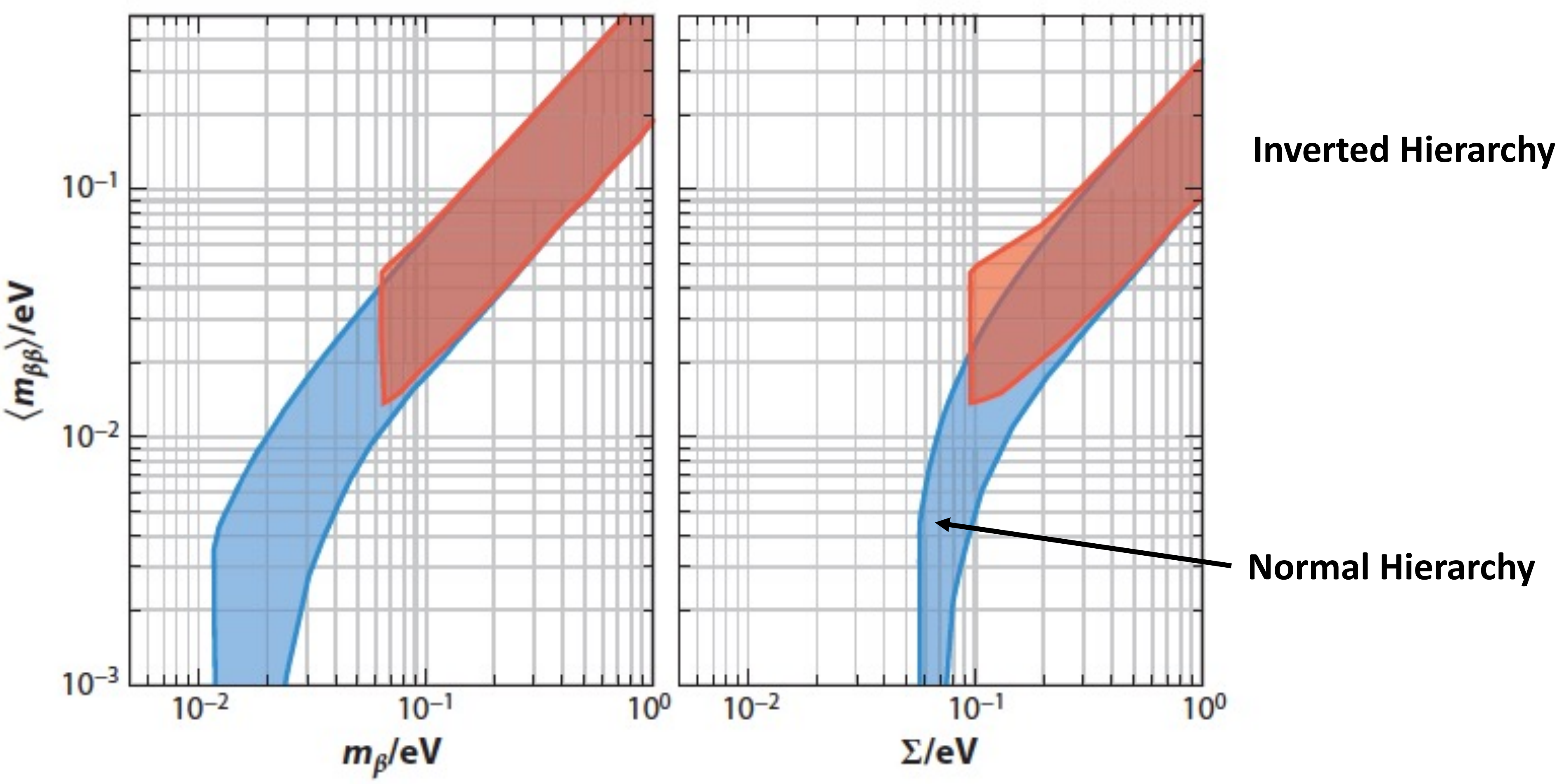
Unknown Majorana phases (dark)

Uncertainties in oscillation parameters (light)

Cancellation possible



Other Majorana Mass Plots



Electron Neutrino Mass

Sum of Neutrino Mass

Annu. Rev. Nucl. Part. Sci. 2019. 69:219–51

Experimental Sensitivity

The sensitivity of $T_{1/2}^{0v}$ is determined by the number of 0vββ events (N_{0v}) and the number of background (N_{bg}) events in the region of interest (ROI).

$$N_{0\upsilon} \propto \varepsilon \frac{a}{A} \frac{MT}{T_{1/2}^{0\upsilon}}$$

$$N_{bg} \propto MTB\Gamma$$

ε is efficiency
a is isotope abundance
A is atomic mass
M is source mass
T is live time
B is background index
Γ is resolution

For background free experiments,

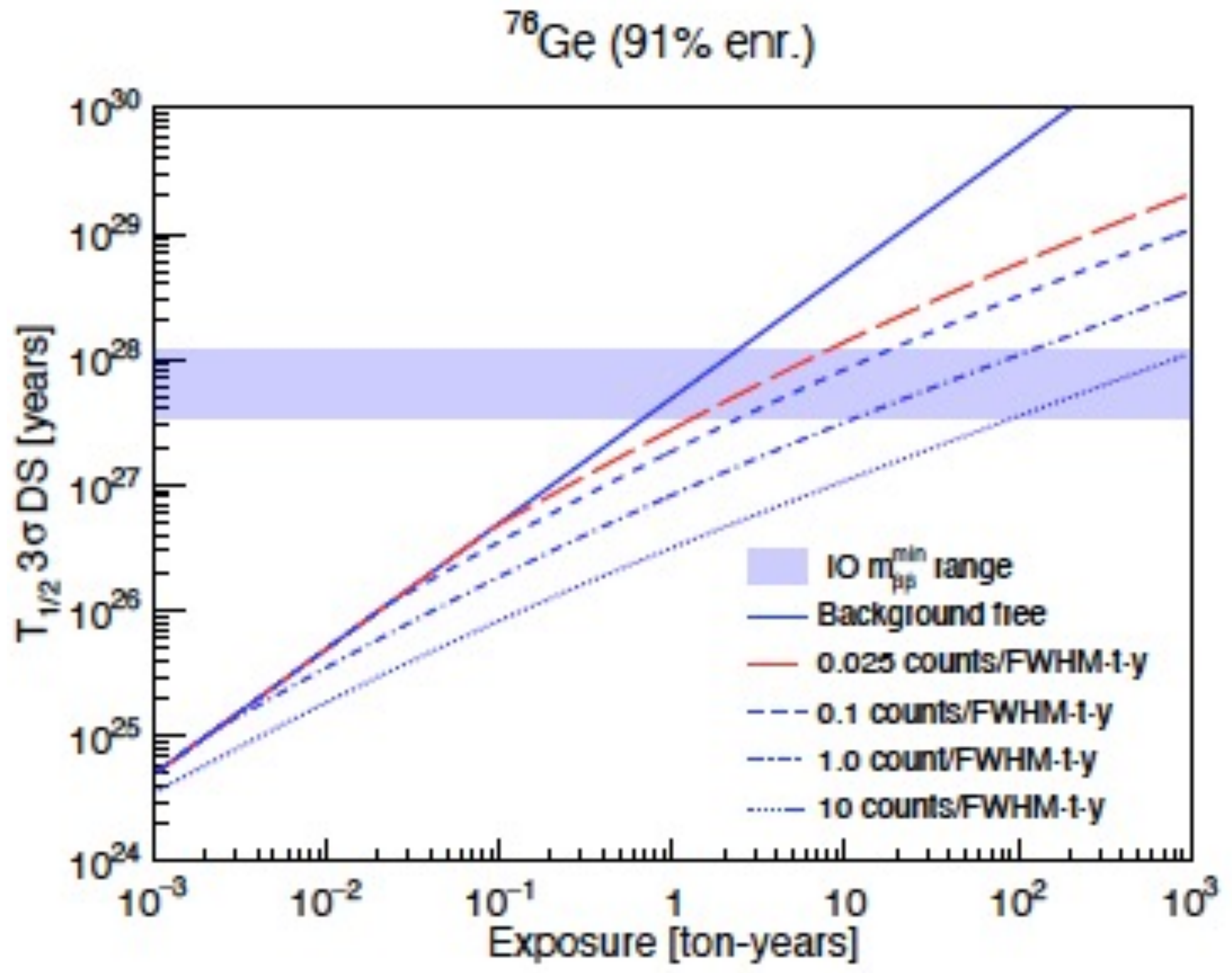
$$N_{0\upsilon} > 1 \quad \rightarrow \quad S_{1/2}^{0\upsilon} \propto \varepsilon \frac{a}{A} MT$$

For experiments with background,

$$N_{0\upsilon} > \sqrt{N_{bg}} \rightarrow S_{1/2}^{0\upsilon} \propto \frac{\varepsilon a}{A} \sqrt{\frac{MT}{B\Gamma}}$$

Note: for small number of N_{bg} (< ~ 6) , full statistical treatment is more complicated and will often require Monte Carlo simulations.

Experimental Sensitivity (Ge)



- 3σ discovery potential of the tonne scale Ge experiment depends strongly on the background

arXiv:2107.11462v1

LEGEND-1000 Preconceptual Design Report

Experimental Design Considerations

$$S_{1/2}^{0\nu} \propto \frac{\varepsilon a}{A}\sqrt{\frac{MT}{B\Gamma}} \qquad S_{m_{\beta\beta}}^{0\nu} \propto \frac{1}{\sqrt{G^{0\nu}}|M^{0\nu}|}\left[\frac{A}{\varepsilon}\right]^{\frac{1}{2}}\left[\frac{B\Gamma}{MT}\right]^{1/4}$$

ε is efficiency, *a* is isotope abundance, *A* is atomic mass, *M* is source mass, *T* is live time
B is background index, Γ is resolution, G^{0v} is phase space, M^{0v} is matrix element

To maximize sensitivity:

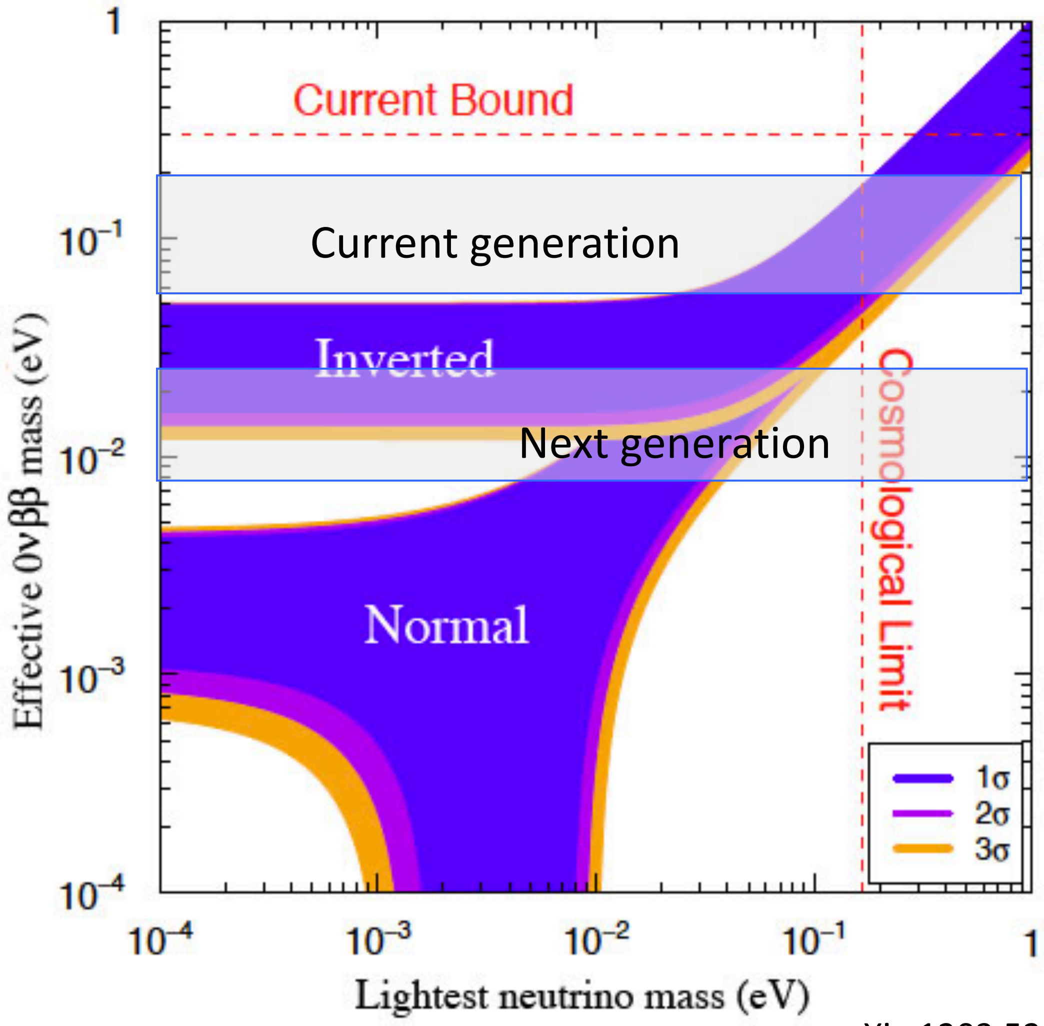
- Large isotope mass (10 – 100 kg now → 1-10 ton)
- High detection efficiency (~ 100 %)
  - source = detector?
- Good energy resolution
  - reduce flat background and resolve nearby background peaks
  - reduce 2νββ background
- Low background (10 – 100 cnts/yr/ton → 0.1 – 1 cnts/yr/ton)
  - underground detector to shield cosmic rays
  - clean material, passive and active shielding
  - discriminate against background events

Experimental Sensitivity to Neutrino Mass

Isotope Mass

10-100 kg

1-10 ton



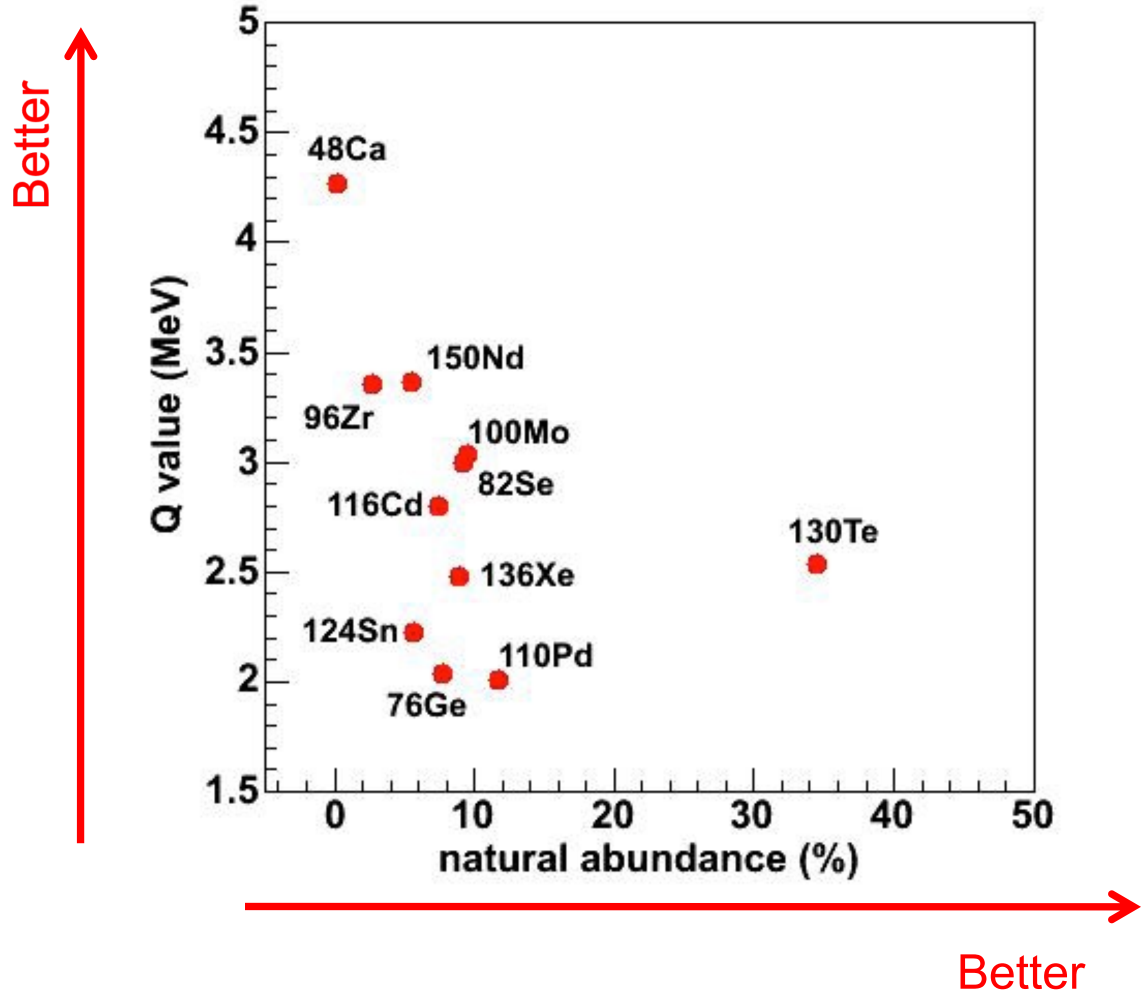
Background

10-100cts/yr/ton

0.1-1cts/yr/ton

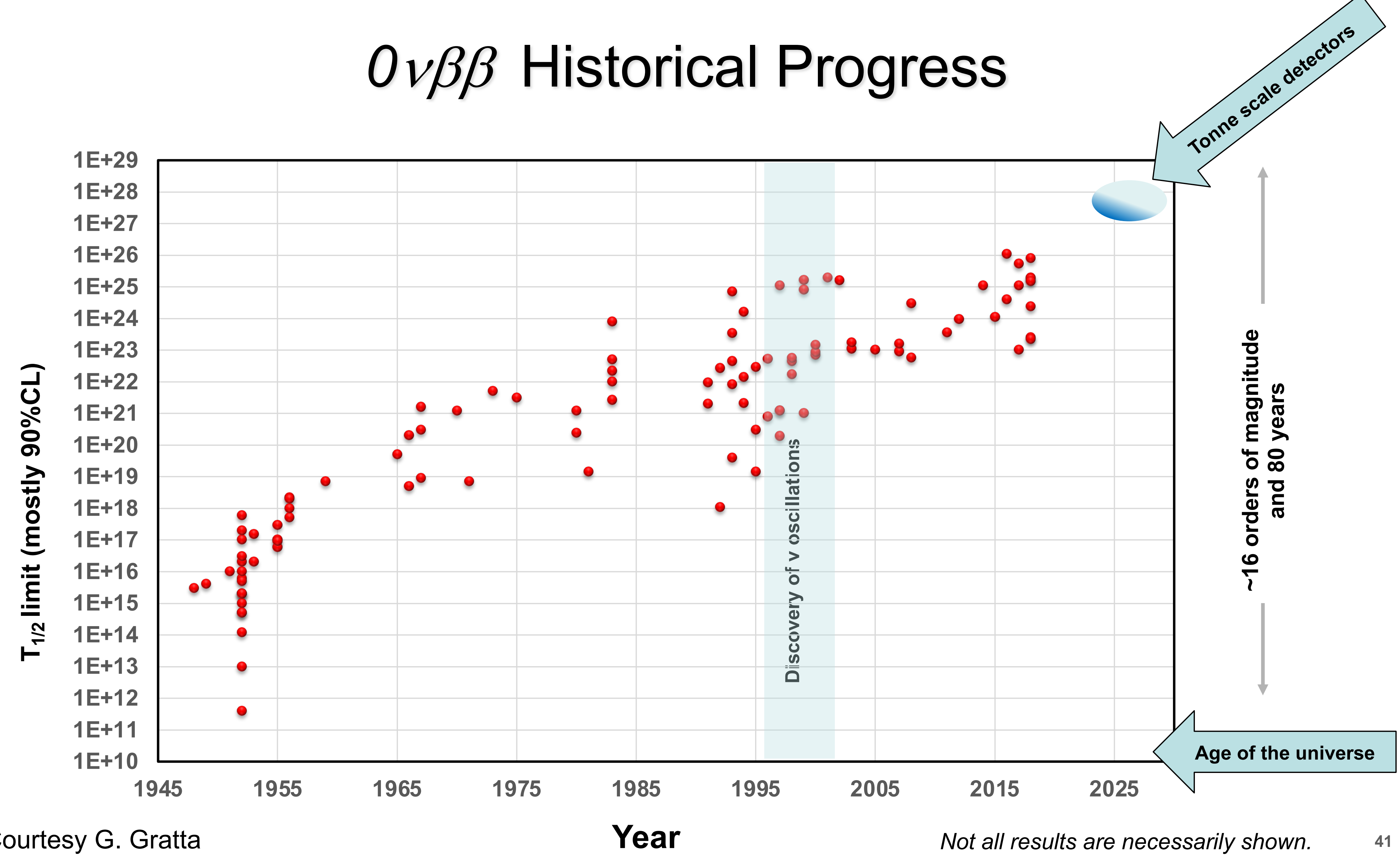
arXiv:1203.5250v1

Choice of Isotope



- High natural abundance means lower cost of enrichment
- Large Q value means lower background from natural radioactivity
- No golden element, detector technology and background reduction techniques are crucial considerations in isotope selection.
- More than one isotope likely needed to understand underlying mechanism.

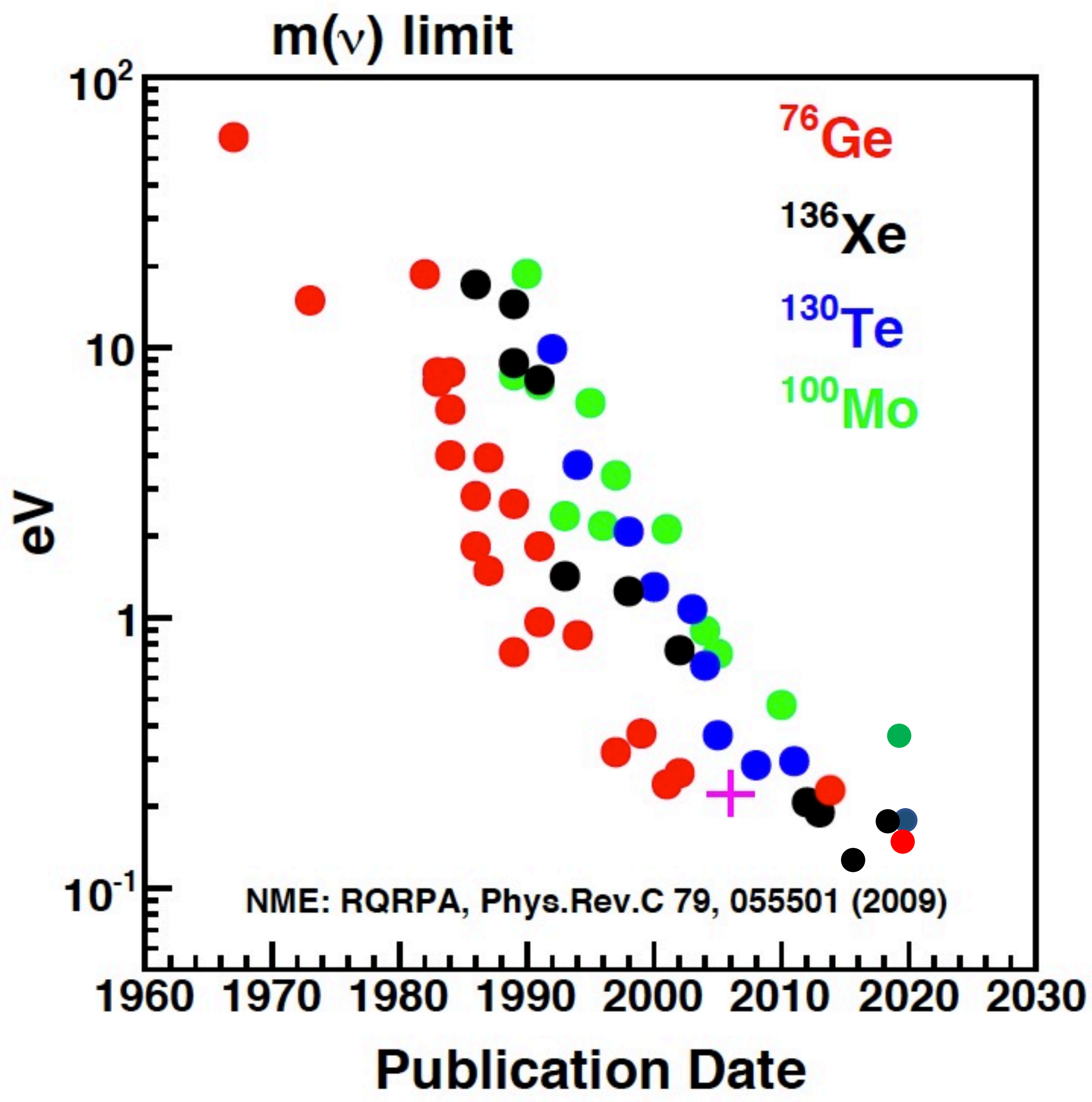
$0\nu\beta\beta$ Historical Progress



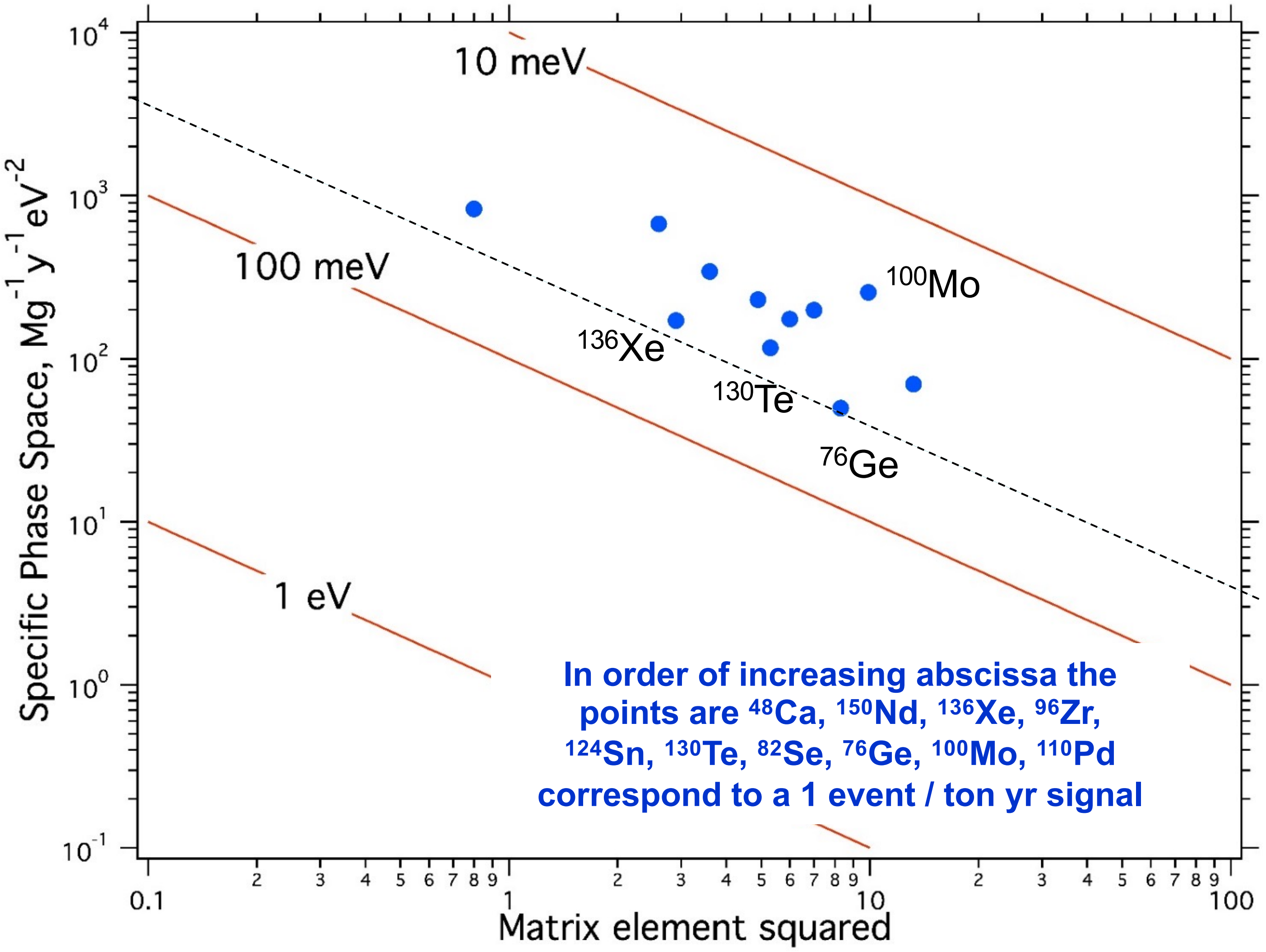
Courtesy G. Gratta

Not all results are necessarily shown.

$0\nu\beta\beta$ Historical Progress



Many isotopes have comparable sensitivities (at least in terms of rate per unit neutrino mass)



In order of increasing abscissa the points are ^{48}Ca, ^{150}Nd, ^{136}Xe, ^{96}Zr, ^{124}Sn, ^{130}Te, ^{82}Se, ^{76}Ge, ^{100}Mo, ^{110}Pd correspond to a 1 event / ton yr signal

R.G.H. Robertson, MPL A 28 (2013) 1350021

There is an "empirical" anticorrelation between phasespace and NME.

Current best $0\nu\beta\beta$ Limits

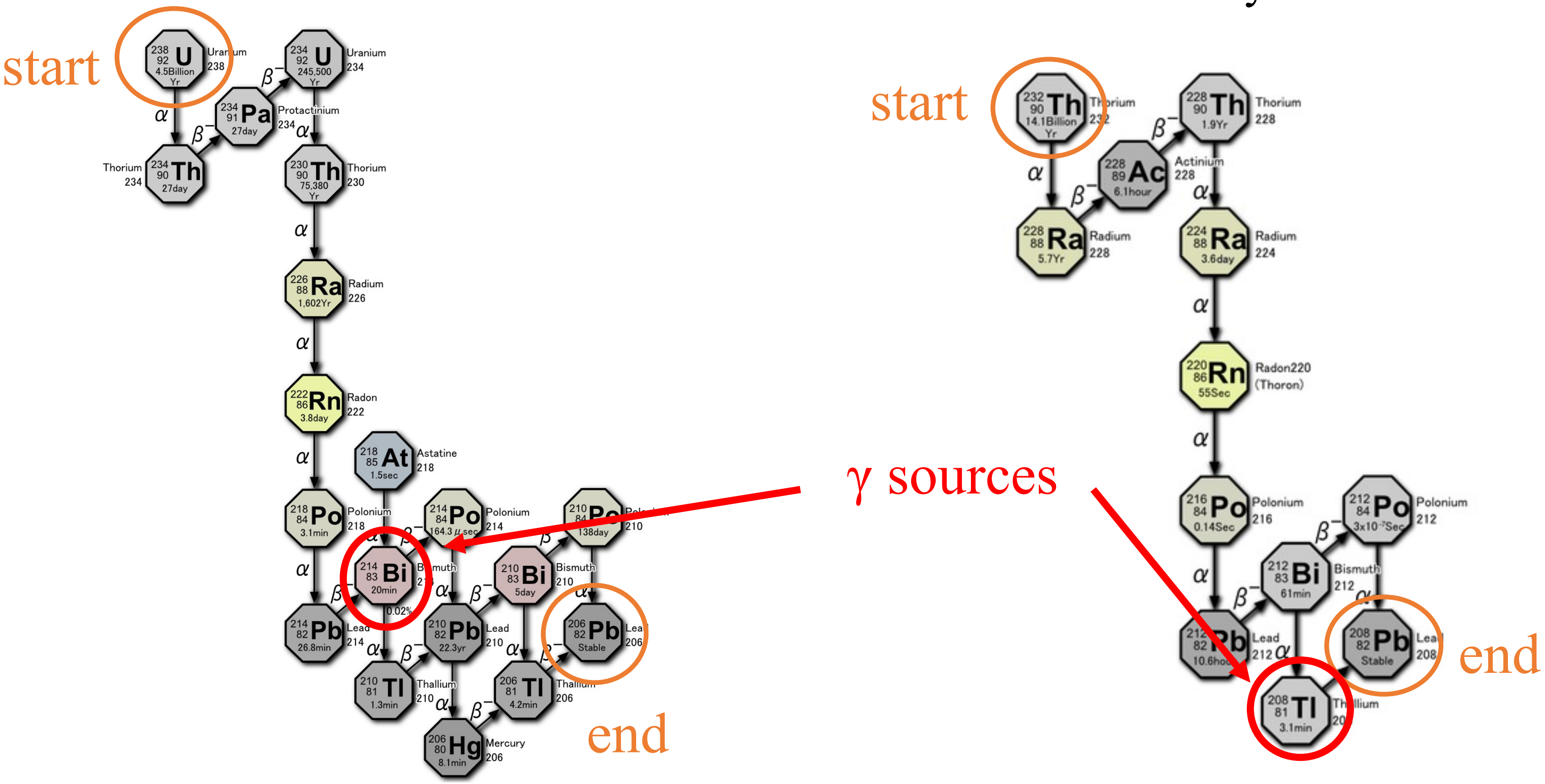
Isotope	Experiment	Isotope Exposure (kg yr)	Average half-life sensitivity (10^{25} y)	Half-life limit (10^{25} y) 90% C.L.	Effective mass limit (meV) Range from NME*	Reference
^{76}Ge	GERDA	127.2	18	> 18	< 79-180	M. Agostini et al., PRL **123**, 252502 (2020)
	MJD	29.7	4.8	> 2.7	< 200-433	Alvis et al. arXiv:1902.02299 (2019)
^{100}Mo	CUPID-Mo	1.17		> 0.15	< 310-540	Armengaud et al. PRL **126**, 181802 (2021)
^{130}Te	CUORE	358	2.8	> 2.2	< 90-305	Adams et al. arXiv:2104.06906 (2021)
^{136}Xe	EXO-200	234.1	5.0	> 3.5	< 93-286	Anton et al. PRL, **123**, 161802 (2019)
	KamLAND-ZEN	504	5.6	> 10.7	< 60-161	Gando et al., PRL **117**, 082503 (2016)

*Note that the range of NME is chosen by the experiments, and uncertainties related to g_A are not included.

Background from Natural Radioactivity

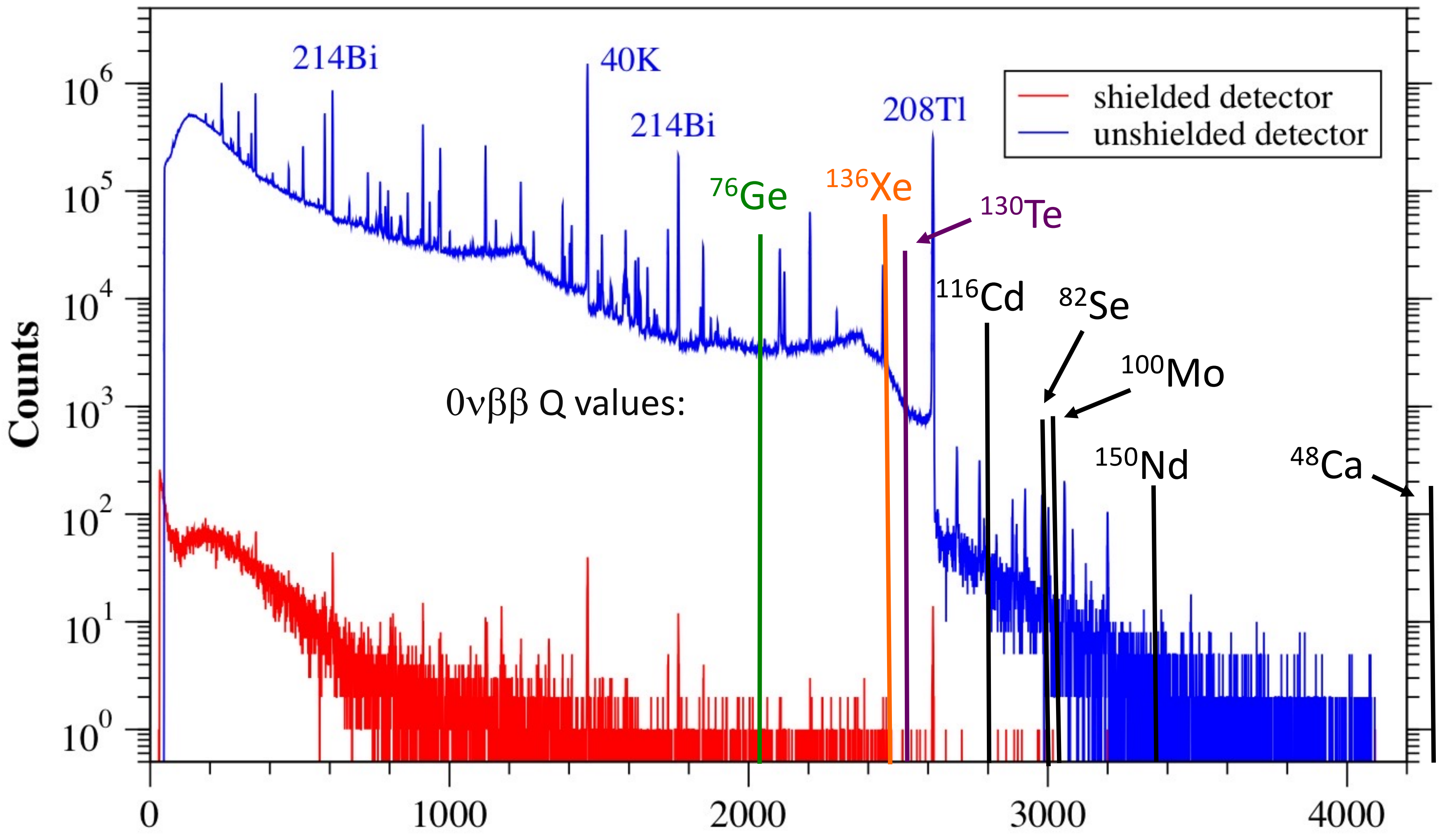
Uranium-238 decay chain

Thorium-232 decay chain



- Natural radioactivities on earth come from U, Th, ^{40}K (long decay lifetime ~ 10^9 yr), or cosmogenic activation, or human related activities.
- U and Th decay via a series α and β decays.
- Most troublesome background comes from high energy (~2MeV) γ rays.

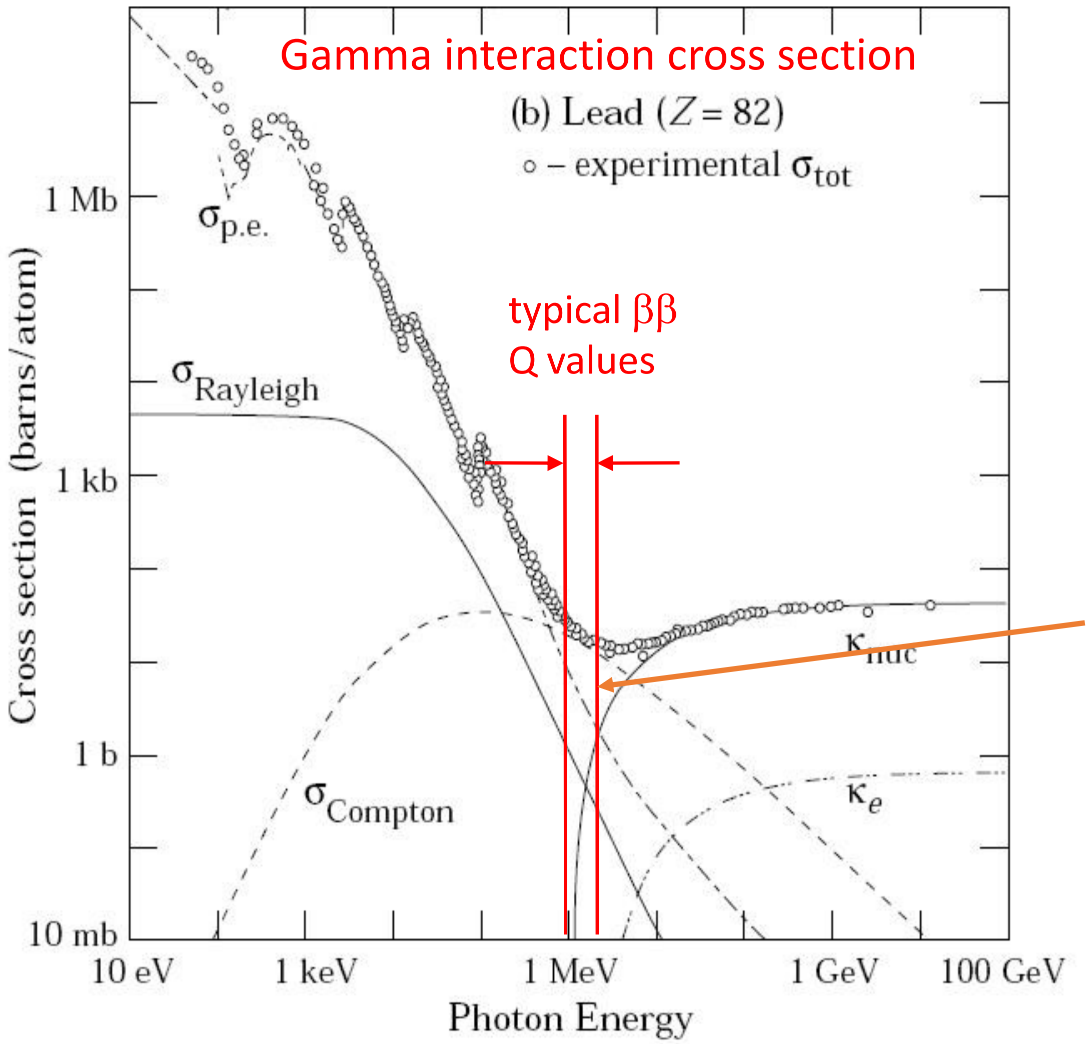
Energy Spectrum of Natural Radioactivity



Although ^{40}K decay energy is below most $0\nu\beta\beta$ Q values, gammas from U and Th are big background concerns.

Source: http://npgroup.pd.infn.it/luna/images/background.jpg
C. Hall, SnowMass premeting, 2013

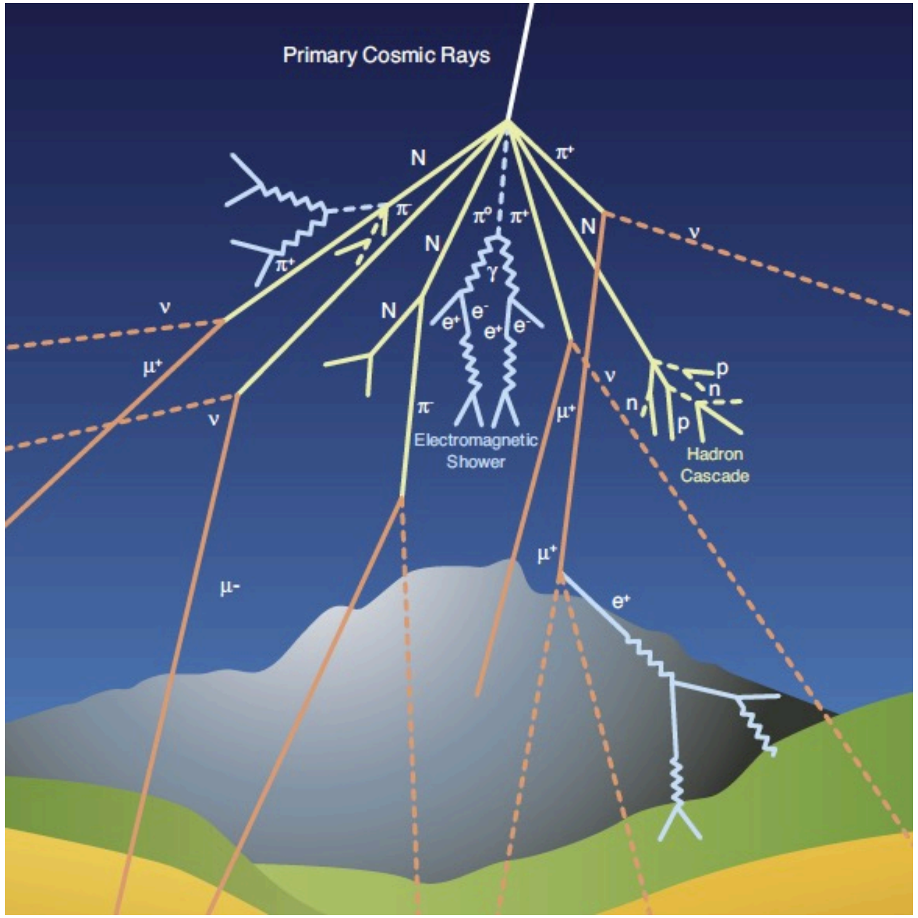
Shielding Difficulties



C. Hall, SnowMass premeting, 2013

- 1-3 MeV gamma rays are difficult to shield, so passive shielding or self shielding not very effective.
- It is critical to remove background form detector construction materials

Cosmic Ray Background



Source: CERN

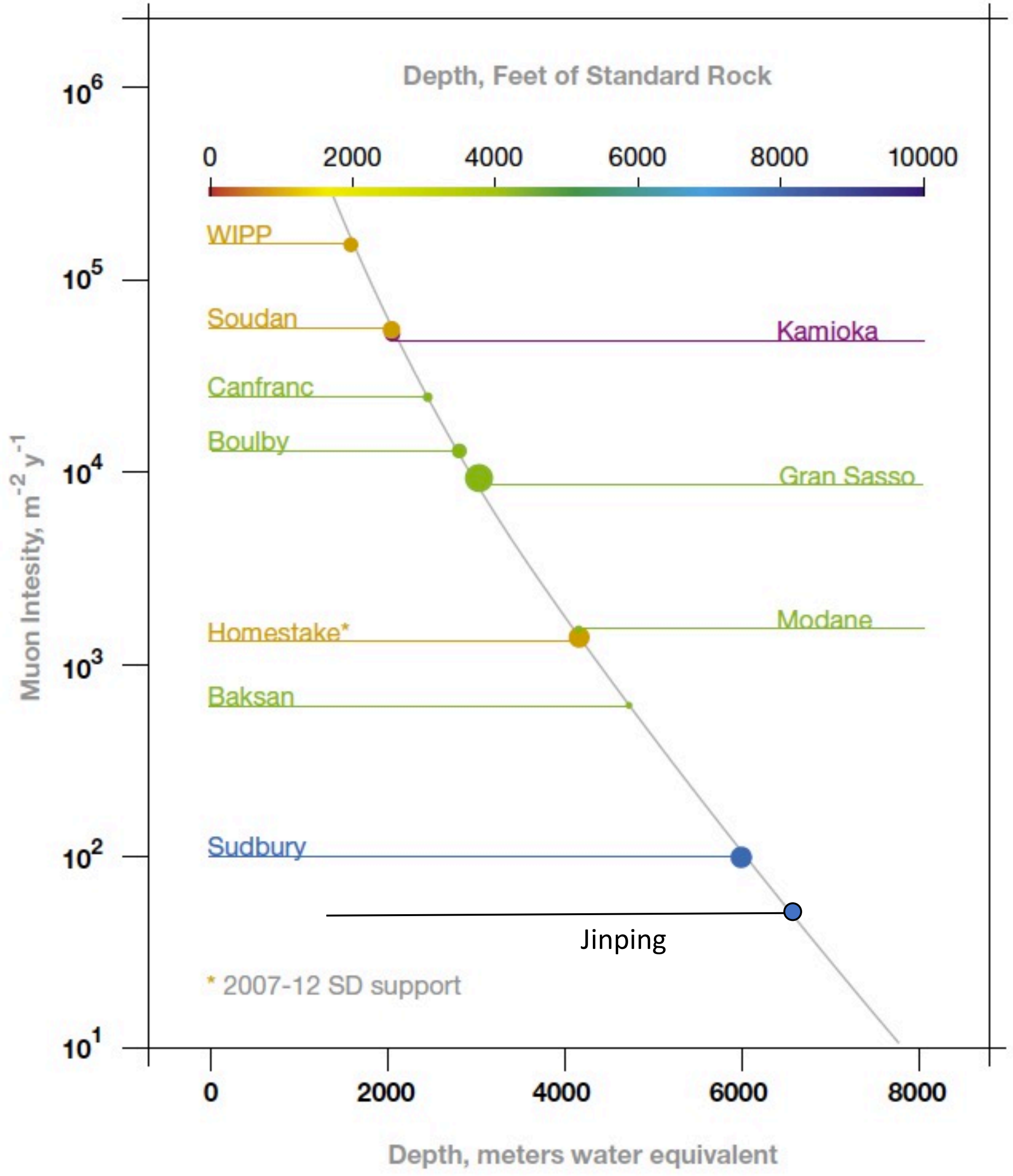
- Cosmic rays striking the upper atmosphere will create a shower of subatomic particles, including energetic muons,

- Cosmic muons can create radioactive isotopes via spallation, neutron activation and other nuclear processes.

- When muon goes through a detector, it can produce radioactive isotopes directly inside the detector.

- Muon can also produce secondary particles in material outside the detector such as fast neutrons, which later interact with the detector material.

Going Underground....



- By going to deeper underground lab, one can effectively shield against cosmic muons.

- At 6600 m.w.e., Jinping lab in Sichuan, China is the deepest underground lab, with a muon flux of ~50/m^2/yr, 9 order of magnitude reduction compared to sea level

- The muon angular and energy distribution depends on the depth, so Monte Carlo simulation is needed to understand the full background from the cosmic ray.

Underground Facilities

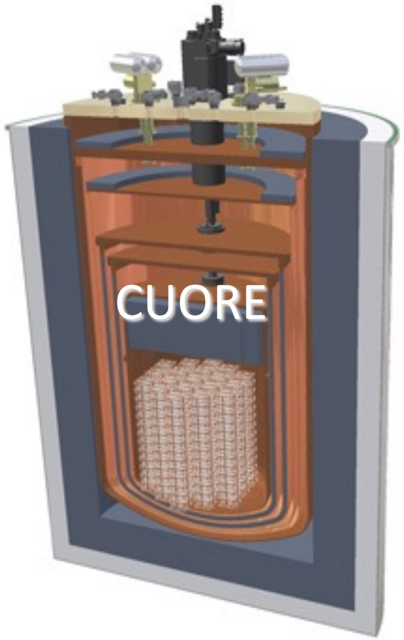
GERDA Experiment at Gran-Sasso

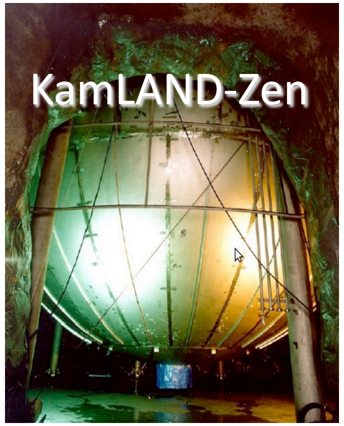
- The radioactivity in the underground cavern wall need to be shielded with ultra-clean water or lead.
- Radon purge system, additional neutron shielding, muon veto may also be required for the experiment.
- To minimize cosmogenic activation, detector material may need to produced or machined underground.

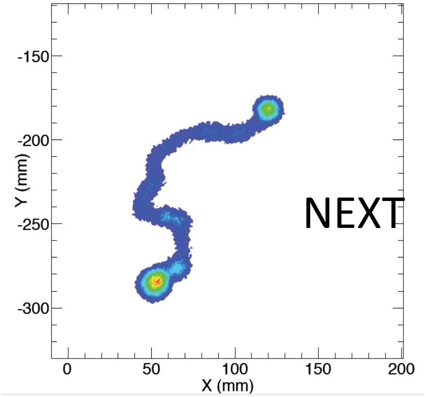
Facility	Depth [m.w.e.]	μ Flux [events / ($m^2 \cdot$year)]	Rock	^{238}U [Bq/kg]	^{232}Th [Bq/kg]	^{40}K [Bq/kg]
Jinping (PandaX)	6,600	66	marble	1.8 ± 0.2	< 0.27	< 1.1
Homestake	4,500	950	rhyolite	100	45	900
Grand Sasso – Hall B	3,500	8,030	dolomite	5.2	0.25	4.9

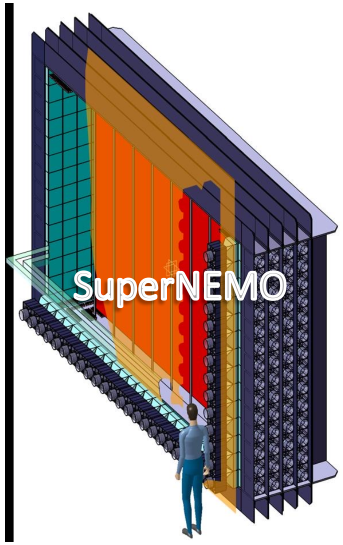
Underground lab rock radio-activity comparison

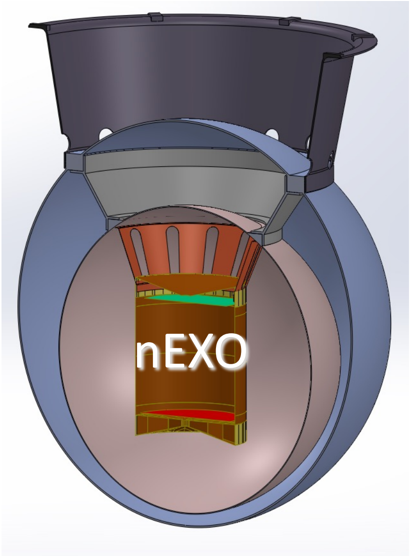
Diversity of 0νββ Experiments











Summary and Outlook

- $0\nu\beta\beta$ is the most powerful way to probe Majorana nature of neutrinos
- The extremely long lifetime challenges the experimenters to find creative ways to build large detectors and suppress the background
- We looked at some basics on experimental sensitivity and background sources
- We will delve deep into different experiment designs, study the current generation experiments, and look at the next generation experiment in the next lecture.