Ettore Majorana through the Looking-glass

J.J. Gómez-Cadenas
Instituto de Física Corpuscular (CSIC & UVEG)

CERN, January, 2013
Alice through the looking glass
Alice through the looking glass
Alice through the looking glass

Lewis Carroll: The world at the other side of the mirror is not just a dead reflection of ours but has rules of its own.
Neutrino through the looking glass

- In the Standard Model neutrinos are massless and left handed (antineutrinos are right handed)

- It would be possible to turn a left handed neutrino into a right handed neutrino by jumping in a reference frame that moves faster than the neutrino. But a massless neutrinos moves at the speed of light and cannot be overtaken
In the Standard Model neutrinos are massless and left handed (antineutrinos are right handed).

It would be possible to turn a left handed neutrino into a right handed neutrino by jumping in a reference frame that moves faster than the neutrino. But a massless neutrinos moves at the speed of light and cannot be overtaken.

Therefore we could live without right handed neutrinos and without left-handed antineutrinos. Standard model neutrinos do not reflect in the mirror!
Neutrino through the looking glass

- In the Standard Model neutrinos are massless and left handed (antineutrinos are right handed).

- It would be possible to turn a left handed neutrino into a right handed neutrino by jumping in a reference frame that moves faster than the neutrino. But a massless neutrinos moves at the speed of light and cannot be overtaken.

- Therefore we could live without right handed neutrinos and without left-handed antineutrinos. **Standard model neutrinos do not reflect in the mirror!**
But what if neutrinos are massive?

Reversing the argument, left-handed and right-handed neutrinos are guaranteed to exist. How does a massive neutrino reflects in the mirror?
But what if neutrinos are massive?

- Who is the right-handed neutrino state? How do we give neutrinos a mass?

- Reversing the argument, left-handed and right-handed neutrinos are guaranteed to exist. How does a massive neutrino reflect in the mirror?
Electrons through the looking glass
Electrons through the looking glass
Electrons through the looking glass
Electrons through the looking glass

left handed  parity  right handed
Electrons through the looking glass

left handed  parity  right handed
Electrons through the looking glass
Electrons through the looking glass

parity

left handed
right handed
Electrons through the looking glass
Electrons through the looking glass

- $e^-$
  - left handed
- $e^-$
  - right handed
- $e^-$
  - positive charge
- $e^-$
  - negative charge
- $e^+$

Parity

Charge
Electrons through the looking glass
Electron mass
Electron mass
Electron mass

left and right handed states bump against the Higgs field
left and right handed states bump against the Higgs field

\[ \mathcal{L}_D = \bar{e}_L m_e e_R + h.c. \]

\[ \lambda \bar{e}_R \phi e_L \rightarrow \lambda \nu \bar{e}_R e_L \]

\[ m_e = \lambda_e \nu \]
left and right handed states bump against the Higgs field

\[ \mathcal{L}_D = \bar{e}_L m_e e_R + h.c. \]

\[ \lambda \bar{e}_R \phi e_L \rightarrow \lambda \nu \bar{e}_R e_L \]

\[ m_e = \lambda_e \nu \]
left and right handed states bump against the Higgs field

\[ \mathcal{L}_D = \bar{e}_L m_e e_R + h.c. \]

\[ \lambda \bar{e}_R \phi e_L \rightarrow \lambda \nu \bar{e}_R e_L \]

\[ m_e = \lambda_e \nu \]

\[ e^- = e_L^- + e_R^- \]
Electron mass

left and right handed states bump against the Higgs field

\[ \mathcal{L}_D = \bar{e}_L m_e e_R + h.c. \]

\[ \lambda \bar{e}_R \phi e_L \rightarrow \lambda v \bar{e}_R e_L \]

\[ m_e = \lambda v \]

\[ e^- = e^-_L + e^-_R \]

\[ e^+ = e^+_L + e^+_R \]
Neutrino mass (Dirac recipe)
Neutrino mass (Dirac recipe)
Neutrino mass (Dirac recipe)

\[ \nu = \nu_L + \nu_R \]

\[ \nu^C = (\nu_L)^C + (\nu_R)^C \]
Neutrino mass (Dirac recipe)

\[ -\mathcal{L}_{\text{Dirac}} = \bar{\nu}_L m_\nu \nu_R + h.c. \]

\[ m_\nu = \lambda_\nu v \]

\[ \mathbf{\nu} = \nu_L + \nu_R \]

\[ \overline{\mathbf{\nu}} = \overline{\nu}_R + \overline{\nu}_L \]

\[ \nu^C = (\nu_L)^C + (\nu_R)^C \]
A deus ex machina  Latin: "god from the machine" is a plot device whereby a seemingly unsolvable problem is suddenly and abruptly solved with the contrived and unexpected intervention of some new event, character, ability, or object. Depending on usage, it can be used to move the story forward when the writer has "painted themselves into a corner" and sees no other way out, to surprise the audience, or to bring a happy ending into the tale.

The phrase comes from Horace's where he instructs poets that they must never resort to a god from the machine (mekhane) to solve their plots.
Nature has painted herself into a corner and sees no other way out to explain small neutrino masses than to resort to arbitrarily small coupling constant, that she lowers from the machine...

\[ \lambda_\nu << \lambda_e ? \]
“Because, you see, in the world there are various categories of scientists: people of a secondary or tertiary standing, who do their best but do not go very far. There are also those of high standing, who come to discoveries of great importance, fundamental for the development of science.

But then there are geniuses like Galileo and Newton. Well, Ettore was one of them. Majorana had what no one else in the world had”.

E. Fermi
Neutrino’s charge conjugation

Charge conjugation reverses the electric charge of the electron.

But the neutrino has no electric charge that needs to be conserved.
Majorana neutrinos

\[ \nu = \nu_L + \nu_R \]

\[ \nu^C = (\nu_L)^C + (\nu_R)^C \]

\[ \nu = \nu_L + \nu_L^C \]

\[ \nu^C = \nu \]

The neutrino is made, like in the Escher’s tableau of black and white chevaliers.
Neutrino mass (Majorana recipe)

\[ \nu_L = (\nu_R)^C \quad (\nu_L)^C = \nu_R \]

\(-\mathcal{L}_{\text{Majorana}} = \bar{\nu}_L m_\nu \nu_L^c + h.c.\)
Neutrino mass (Majorana recipe)

\[ \nu_L = (\nu_R)^C \quad (\nu_L)^C = \nu_R \]

\[ -\mathcal{L}_{\text{Majorana}} = \bar{\nu}_L m_\nu \nu_L^c + h.c. \]

\[ m_\nu \sim \lambda \frac{v^2}{\Lambda} \]
Effective theory (Fermi constant)

\[ G_F \sim \frac{1}{M_W^2} \]

Standard Model

Extension of Standard Model

\[ m_\nu = \frac{\alpha v^2}{\Lambda} \equiv Y_N^T \frac{v^2}{M_N} Y_N \]
See-saw models

\[ M_N = \text{GUT} \]

\[ m_\nu = \frac{\alpha v^2}{\Lambda} \equiv Y_N^T \frac{v^2}{M_N} Y_N \]

\[ M_N = \text{TeV} \]
The Big-Bang theory of the origin of the Universe requires matter and antimatter to be equally abundant at the very hot beginning.

What generated the asymmetry between matter and antimatter?
CP violation and Majorana neutrinos

If there is CP violation in the lepton sector, the heavy Majorana neutrino $N$ can violate CP too and decay with different rates to electrons and positrons. This results in an unequal number of leptons and antileptons in the early universe.

Leptonic asymmetry is later transferred to baryons, resulting in...
The Universe
The Universe

+
The Universe
The Universe
The Universe
What do we know about neutrino masses?
Neutrino oscillations
Neutrino oscillations

\[
\begin{pmatrix}
  \nu_e \\
  \nu_\mu \\
  \nu_\tau 
\end{pmatrix}
= U_{PMNS}(\theta_{12}, \theta_{23}, \theta_{13}, \delta, \ldots)
\begin{pmatrix}
  \nu_1 \\
  \nu_2 \\
  \nu_3 
\end{pmatrix}
\]
Neutrino oscillations

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= U_{PMNS}(\theta_{12}, \theta_{23}, \theta_{13}, \delta, \ldots)
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]
Neutrino oscillations

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= U_{PMNS}(\theta_{12}, \theta_{23}, \theta_{13}, \delta, \ldots)
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

Neutrino oscillation experiments measure two mass difference squared
Beta-decay of tritium

\[ m^2_\beta = \sum_{i=1}^{3} |U_{ei}|^2 m^2_i \]
Cosmological measurements

\[ m_{\text{cosmo}} = \sum_{i=1}^{3} m_i \]
Cosmological measurements

$\Lambda$CDM: Big-bang + Inflation (CMB)
Dark energy (73% of energy density), cold dark matter (23%)
ordinary matter (4.5%)

Light neutrinos can enter extensions of the $\Lambda$CDM model as "hot dark matter"

$$m_{\text{cosmo}} = \sum_{i=1}^{3} m_i$$
Are neutrino Majorana particles? To find out play...
Double or Nothing
Double beta decay

- Some nuclei, otherwise quasi stable can decay by emitting two electrons and two neutrinos by a second order process mediated by the weak interaction.

- This process exists due to nuclear pairing interaction that favors energetically the even-even isobars over the odd-odd ones.
Double beta decay

\[ \beta\beta 2\nu \]

SM-allowed process. Measured in several nuclei.

\[ T_{1/2} \sim 10^{18} - 10^{20} \text{ y} \]

\[ \beta\beta 0\nu \]

Lepton number violating process. Requires massive, Majorana neutrinos.

\[ T_{1/2} > 10^{25} \text{ y} \]
Majorana mass

\[ m_{\beta\beta} = \left| |U_{e1}|^2 m_1 + e^{i\alpha_1} |U_{e2}|^2 m_2 + e^{i\alpha_2} |U_{e3}|^2 m_3 \right| \]
In the $\nu_i$ is emitted \([RH + O{m_i/E_LH}\)]$. Thus, Amp $[\nu_i$ contribution] $\propto m_i$ $\quad A_{\nu_{\beta\beta}} \propto \sum m_i U_{e_i}^2 \equiv m_{\beta\beta} \quad U_{e_1} |U_{e_2}|^2 m_2 + e^{i\alpha_2} |U_{e_3}|^2 m_3$
$$m_{\beta\beta} = \left| |U_{e1}|^2 m_1 + e^{i\alpha_1} |U_{e2}|^2 m_2 + e^{i\alpha_2} |U_{e3}|^2 m_3 \right|$$
In the $\nu_i$ is emitted $[RH + O{m_i}/E]_{LH}$.

Thus, the Amp $[\nu_i$ contribution] $\propto m_i$ for each $\nu_i$.

$\mathcal{A} \propto m_i$ for each $\nu_i$.

The $U_{ei}$ terms are measured by neutrino oscillation experiments. Nothing is known about the two Majorana phases.
\[
(T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q, Z) |M^{0\nu}|^2 m_{\beta\beta}^2
\]

- Phase-space
- Nuclear matrix
- Majorana neutrino
Two protons decay simultaneously in a heavy isotope
Nuclear physics results in proportionality constants between
period and the inverse of the Majorana mass squared

\[
(T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q, Z) |M^{0\nu}|^2 m_{\beta\beta}^2
\]

phase-space
nuclear matrix
Majorana neutrino
The NME industry

http://arxiv.org/abs/1109.5515

\((T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q, Z) |M^{0\nu}|^2 m_{\beta\beta}^2\)
The NME industry

\[ (T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q, Z) |M^{0\nu}|^2 m_{\beta\beta}^2 \]

Phase space pretty democratic except for a few isotopes
Considerable spread between NME elements
In this talk: Use of PMR range.
The Majorana landscape

- Excluded by experiment
- Degenerated neutrinos
- Inverse hierarchy
- Normal hierarchy

The Majorana landscape

\[ m_{\beta\beta} \text{ (eV)} \]

\[ m_{\text{light}} \text{ (eV)} \]
Cosmological limits and limits from previous $bb0\nu$ experiments included in this plot.
The Majorana landscape

Cosmological limits and limits from previous $bb0nu$ experiments included in this plot.

Exploring the inverse hierarchy requires sensitivity to $mbb < 20$ meV
Cosmological limits and limits from previous bb0nu experiments included in this plot.

Exploring the inverse hierarchy requires sensitivity to $m_{bb} < 20$ meV

Normal hierarchy experimentally inaccessible (today)
News from Antarctica

arXiv:1210:7231
News from Antarctica

South Pole Telescope

arXiv:1210:7231
News from Antarctica

South Pole Telescope

SPT measures CMB in the region or large $l$.

arXiv:1210:7231
Adding SPT data

\[
\begin{align*}
\textbf{WMAP7} & \quad \textbf{SPT + WMAP7} \\
\hline
\text{ns} & \quad 0.98 \\
\hline
\Sigma m_\nu [\text{eV}] & \quad 0.0 \\
\hline
\end{align*}
\]

\[
\begin{align*}
\text{arXiv: 1212: 6267}
\end{align*}
\]
SPT alone prefers a lower value of \( \text{ns} \) relative to WMAP7, which causes the preferred value of \( \Sigma \text{m}_\nu \) to increase when SPT data are combined with WMAP 7.

\[ \text{arXiv: 1212: 6267} \]
Adding SPT data

SPT alone prefers a lower value of $n_s$ relative to WMAP7, which causes the preferred value of $\Sigma m_\nu$ to increase when SPT data are combined with WMAP7.

Low redshift data contribute to the constrains in $\Sigma m_\nu$.

arXiv: 1212: 6267
Majorana landscape revisited

\[ \sum_{i=1}^{3} m_i = 0.32 \pm 0.11 \]

\[ 26 \leq m_{\beta\beta} \leq 143 \]

\[ 28 \leq m_{\beta\beta} \leq 145 \]
Majorana landscape revisited

\[ \sum_{i=1}^{3} m_i = 0.32 \pm 0.11 \]

\[ 26 \leq m_{\beta\beta} \leq 143 \]

\[ 28 \leq m_{\beta\beta} \leq 145 \]

Cosmological measurement: very recent, to take cum grano salis. But it true, clear goal for $\beta\beta 0\nu$ experiments
Experimental challenges
Building an ideal experiment
How to build your $\beta\beta$0ν experiment

High X Isotope Enrichment

$\gamma$ has the best natural isotopic abundance

However, all next generation experiments will be isotopically enriched

Isotope Natural Abundance

$^{129m}$I, $^{85}$Se, $^{88}$Ge, $^{89}$Sr, $^{90}$Y, $^{96}$Zr, $^{98}$Mo, $^{107}$Pd, $^{110}$Cd, $^{113}$In, $^{120}$Te, $^{129}$Xe

Easiest to enrich are noble elements: $^{129}$Xe

Enrichment also provides purification against radioactive contaminants
How to build your $\beta\beta_{0\nu}$ experiment

- Get a large mass of double beta decay source.
- Almost all isotopes must be enriched.
- Easiest and cheapest: Xe-136 from Xenon
How to build your $\beta\beta0\nu$ experiment

$$T_{1/2} = \log 2 \frac{N_A M t}{A N_{\beta\beta}}$$

$$M = 100 \text{ kg}, \ A = 136, \ T_{1/2} = 10^{26} \text{ y} \ N_{\beta\beta} \sim 3$$

Thursday, January 17, 13
How to build your $\beta\beta0\nu$ experiment

• Get yourself a detector with perfect energy resolution
• Measure the energy of the emitted electrons and select those with $(T_1+T_2)/Q_{bb} = 1$
• Count the number of events and calculate the corresponding half-life.
• In Xe-136, a perfect detector of 100 kg observes 3 events for a lifetime of $10^{26}$ y.

$$T_{1/2} = \log 2 \frac{N_A}{A} \frac{M t}{N_{\beta\beta}}$$

$M = 100 \text{ kg}, \ A = 136, \ T_{1/2} = 10^{26} \text{ y} \ N_{\beta\beta} \sim 3$
How to build your $\beta\beta 0\nu$ experiment

![Graph showing exposure (kg year) vs. $m_{\beta\beta}$ (meV) for different isotopes.](image)

- Ge-76
- Se-82
- Te-130
- Xe-136
- Nd-150

exposure (kg year) $m_{\beta\beta}$ (meV)
How to build your $\beta\beta 0\nu$ experiment

- Compute $m_{\beta\beta}$ from $T^{0\nu}$
- In the absence of background improvement in period is proportional to the exposure (Mt) but improvement in $m_{\beta\beta}$ goes with the square root of exposure.
How to build your $\beta\beta 0\nu$ experiment

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

- Compute $m_{\beta\beta}$ from $T^{0\nu}$
- In the absence of background improvement in period is proportional to the exposure (Mt) but improvement in $m_{\beta\beta}$ goes with the square root of exposure.
Recipes for real bb0nu experiments
Energy resolution
Why Energy resolution?

- Even in the absence of other backgrounds, must separate $\beta\beta^{2\nu}$ from $\beta\beta^{0\nu}$
Why Energy resolution?

• Even in the absence of other backgrounds, must separate $\beta\beta 2\nu$ from $\beta\beta 0\nu$

• As the energy resolution worsens this becomes more difficult and limits, eventually the sensitivity.
Why Energy resolution?

• Even in the absence of other backgrounds, must separate $\beta\beta 2\nu$ from $\beta\beta 0\nu$

• As the energy resolution worsens this becomes more difficult and limits, eventually the sensitivity.
Why Energy resolution?
• But $\beta\beta2\nu$ is the least of our problems!
• Earth is a very radioactive planet. There are about 3 grams of U-238 and 9 grams of Th-232 per ton of rock around us.
• This is an intrinsic activity of the order of 60 Bq/kg of U-238 and 90 Bq/kg of Th-232.
• The lifetime of U-238 is of the order of $10^9$ y and that of Th-232 $10^{10}$ y. We want to explore lifetimes of $\beta\beta0\nu$ of the order of $10^{26}$ y.
Why Energy resolution?

- $10^{16}$: number of sand grains (1mm diameter) in a beach 1 km long, 1 km wide, 10 m deep.

- Unless the detector resolution is very good, background eats the signal.
Why Energy resolution?

- $10^{16}$: number of sand grains (1mm diameter) in a beach 1 km long, 1km wide, 10 m deep.

- Unless the detector resolution is very good, background eats the signal.
Other recipes
• Underground laboratory to reduce cosmic background (muons, cosmogenic activation, etc.)
Matrioska structure

• Lab walls shoot us $10^3$ gammas of high energy (direct background) per square meter or about 5,000 gammas into the detector.
• Stop them with a wall of 30 cm of radiopure lead (300 μBq/kg)
• Stop the gammas from the lead with ultra-radiopure copper inside the vessel (10 mBq/kg)
Radio purity

• Build everything out of extremely radiopure materials.
• Typical activities in detector material in the range of μBq/kg.
• We are way more radioactive than that (K-40 in our bones)

Everything is radioactive unless proven otherwise by screening.
Scalability

• Source must be equal to detector (dead fiducial law)
• Scale going to larger volume rather than replicating modules

= 100 kg ?!
Extra handles

TOPOLOGICAL signature of two electrons in a HPGXe (NEXT)
The experiment Rubik’s cube
The experiment Rubik’s cube
The experiment Rubik’s cube

- radio-purity
- scalability (mass, cost)
- control of background
- Resolution
- Volume/Surface
- extra handles
Figure of merit

\[ T_{1/2}^{-1} \propto a \cdot \epsilon \cdot \sqrt{\frac{Mt}{\Delta E \cdot B}} \]
Figure of merit

\[ T_{1/2}^{-1} \propto a \cdot \epsilon \cdot \sqrt{\frac{M t}{\Delta E \cdot B}} \]
Figure of merit

\[ T^{-1}_{1/2} \propto a \cdot \epsilon \cdot \sqrt{\frac{Mt}{\Delta E \cdot B}} \]
Figure of merit

\[ T_{1/2}^{-1} \propto a \cdot \epsilon \cdot \sqrt{\frac{Mt}{\Delta E \cdot B}} \]
Figure of merit

\[ T_{1/2}^{-1} \propto a \cdot \epsilon \cdot \sqrt{\frac{Mt}{\Delta E \cdot B}} \]
Figure of merit

\[ T_{1/2}^{-1} \propto a \cdot \epsilon \cdot \sqrt{\frac{M t}{\Delta E \cdot B}} \]
Figure of merit

\[ T_{1/2}^{-1} \propto a \cdot \epsilon \cdot \sqrt{\frac{Mt}{\Delta E \cdot B}} \]
Figure of merit

\[ T_{1/2}^{-1} \propto a \cdot \epsilon \cdot \sqrt{\frac{Mt}{\Delta E \cdot B}} \]
Figure of merit

\[ T_{1/2}^{-1} \propto a \cdot \epsilon \cdot \sqrt{\frac{Mt}{\Delta E \cdot B}} \]
Figure of merit

\[ T_{1/2}^{-1} \propto a \cdot \epsilon \cdot \sqrt{\frac{M t}{\Delta E \cdot B}} \]
Figure of merit

\[ T_{1/2}^{-1} \propto a \cdot \epsilon \cdot \sqrt{\frac{Mt}{\Delta E \cdot B}} \]
Figure of merit

\[ T_{1/2}^{-1} \propto a \cdot \epsilon \cdot \sqrt{\frac{Mt}{\Delta E \cdot B}} \]
Figure of merit

\[ T_{1/2}^{-1} \propto a \cdot \epsilon \cdot \sqrt{\frac{Mt}{\Delta E \cdot B}} \]

High X Isotope Enrichment

Natural Abundance

Ca, Ge, Se, Zr, Mo, Pd, Cd, Sn, Te, Xe

Isotope enrichment also provides purification against radioactive contaminants.

Source = Detector

2νββ

0νββ

Q value
Figure of merit

\[ T_{1/2}^{-1} \propto a \cdot \epsilon \cdot \sqrt{\frac{M t}{\Delta E \cdot B}} \]
Figure of merit

\[ T_{1/2}^{-1} \propto a \cdot \epsilon \cdot \sqrt{\frac{M t}{\Delta E \cdot B}} \]
Classical approach: Ge detectors

- **a**: expensive
- **ε**: > 80%
- **Mt**: Limited (≈100 kg)
- **ΔE**: Excellent (0.2 % FWHM)
- **b**: good to very good (10^{-2} to 10^{-3} cky)

\[
T_{1/2}^{-1} \propto a \cdot \epsilon \cdot \sqrt{\frac{Mt}{\Delta E \cdot B}}
\]
Xenon: the new kid in the block

High X Isotope Enrichment

Xenon has the best natural isotopic abundance. However, all next generation experiments will be isotopically enriched.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Natural Abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca</td>
<td>98.92%</td>
</tr>
<tr>
<td>Ge</td>
<td>7.02%</td>
</tr>
<tr>
<td>Se</td>
<td>17.3%</td>
</tr>
<tr>
<td>Zr</td>
<td>26.9%</td>
</tr>
<tr>
<td>Mo</td>
<td>95.9%</td>
</tr>
<tr>
<td>Pd</td>
<td>96.7%</td>
</tr>
<tr>
<td>Cd</td>
<td>99.7%</td>
</tr>
<tr>
<td>Sn</td>
<td>99.7%</td>
</tr>
<tr>
<td>Te</td>
<td>99.7%</td>
</tr>
</tbody>
</table>

Easiest to enrich are noble elements: Xe.
Xenon: the new kid in the block

• Xenon: cheap and easy to enrich (1/10 other isotopes).
• Good Qbb. No other radioactive isotopes.
• Noble gas: can be used to build HPXe or LXe. Can be dissolved in LSclnt.
• Fully active, scalable detectors.
LXe: EXO

Detail of the LAAPD read-out plane

Ground

-75kV

Avalanche Photodiodes

Detail of the LAAPD read-out plane
EXO

• **a**: Feasible (cheap)

• **ε**: 30-40% (self shielding)

• **Mt**: Scalable (∼multiton)

• **ΔE** moderate to poor (4 % FWHM)

• **b** good to very good ($10^{-3} - 10^{-4}$ cky)

\[
T_{1/2}^{-1} \propto a \cdot \epsilon \cdot \sqrt{\frac{Mt}{\Delta E \cdot B}}
\]
**LXe: Energy resolution**

Energy resolution: Anomalous in LXe. Much worse than in HPXe.

Energy resolution: 4% FWHM at Q, using anticorrelation between scintillation and ionization.
SciXe: KamLAND-Zen
• 320 kg of Xe-136 dissolved in 13 tons of liquid scintillator, held in an acrylic balloon (R~3 meter).
• Energy resolution is 10 % FWHM at Q
• Spacial resolution ~10 cm (1 sigma).
• Activity from external world including PMTs shielded by liquid scintillator.
• Activity from balloon shielded by fiducial volume cut (leaves about 100 kg of Xe-136 in fiducial volume)
• Currently dominated by “unexpected” isotopes Ag-110m
KamLAND-Zen

- Feasible (cheap)
- $\varepsilon$: 40% (fiducial cut)
- Mt: Scalable ($\approx$ multiton)
- $\Delta E$: poor (10% FWHM)
- b good to very good ($10^{-3}$ - $10^{-4}$ ckky)

$$T_{1/2}^{-1} \propto a \cdot \varepsilon \cdot \sqrt{\frac{Mt}{\Delta E \cdot B}}$$
136Xe-based experiments currently dominating the field (But KK will only be fully killed by Gerda...
THE THIRD WAY: next

• Neutrino Experiment with a Xenon high pressure (HPXe) gas TPC

• Very good energy resolution: ~0.5-0.7% FWHM @ Q

• Powerful background rejection using the event topological signature \(10^{-4}\) ckk

• Being built at the Laboratorio Subterráneo de Canfranc (LSC), under the Spanish Pyrenees.

• [http://next.ific.uv.es/next/](http://next.ific.uv.es/next/)
**HPGXe vs LXe**

![Graph showing comparison between HPGXe and LXe.](image)

- **V.~Alvarez et al. [NEXT Collaboration],** "Initial results of NEXT-DEMO, a large-scale prototype of the NEXT-100 experiment," arXiv:1211.4838 [physics.ins-det].
HPGXe has a topological signature (extra handle)
NEXT: An EL TPC

NEXT DEMO/DBDM

NEXT-DBDM at LBNL O(1 kg of gas). NEXT-DEMO at IFIC, O(5 kg of gas) St. Gottard!
**Gas System**

The role of the gas system (Figure 5) is to remove the gas impurities, in particular trace gases such as argon, \( \text{N}_2 \) and \( \text{CH}_4 \), as well as water vapor. This is achieved by continuously re-circulating the xenon gas through molecular traps called Getters. NEXT-DEMO is equipped with both “cold” and “hot” SAES Getters (MC500). All the gas piping, save for the inlet gas hoses and Getter fittings, are \( \frac{1}{2} \) inch diameter with VCR fittings. The re-circulation loop was powered, during the UVC, by a KNF diaphragm pump with a nominal flow of 100 standard liters per minute. At a 10 bar operating pressure of NEXT-DEMO this translates to an approximate flow of 10 liters per minute.
THE TRACKING PLANE

DBs made of Cuflon, hosting 64 PMTs per DB. In NEXT-100 there is about 110 DBs and 7000 channels. First Light pixel plane operating in a detector.
White through the looking glass
NEXT in blue
• \( a \): Feasible (cheap)

• \( \varepsilon \): moderate (30%)

• \( \text{Mt} \): Scalable (≈multiton)

• \( \Delta E \) good to very good (0.7% to 0.5% FWHM)

• \( b \) very good to excellent (\(10^{-4}\) ckky)

\[
T_{1/2}^{-1} \propto a \cdot \varepsilon \cdot \sqrt{\frac{\text{Mt}}{\Delta E \cdot B}}
\]
Sensitivity

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$M$ (kg)</th>
<th>$f$ (%)</th>
<th>$\varepsilon$ (%)</th>
<th>$\delta E$ (% FWHM)</th>
<th>$b$ ($10^{-3}$ cky)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXO-200</td>
<td>110</td>
<td>0.81</td>
<td>0.56</td>
<td>4.0</td>
<td>1.5</td>
</tr>
<tr>
<td>KamLAND-Zen</td>
<td>330</td>
<td>0.91</td>
<td>0.42</td>
<td>9.9</td>
<td>1.0</td>
</tr>
<tr>
<td>NEXT-100</td>
<td>100</td>
<td>0.91</td>
<td>0.30</td>
<td>0.7</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 2

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\varepsilon$ (%)</th>
<th>$\delta E$ (% FWHM)</th>
<th>$b \times 10^{-3}$ (ckky)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LXe</td>
<td>0.38</td>
<td>3.2</td>
<td>0.1</td>
</tr>
<tr>
<td>XeSci</td>
<td>0.42</td>
<td>6.5</td>
<td>0.1</td>
</tr>
<tr>
<td>HPXe</td>
<td>0.30</td>
<td>0.5</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Figure 6.2.4 Sensitivity

Figure 3, shows the expected performance of the three technologies, assuming the parameters described in Table 2, up to a total exposure of 10 ton year. Although we have used a reference year. This result is, of course, a reflection of the fact that the combination of the three experiments is 19 meV, fully covering the phase space, while the HPXe detector reaches 25 meV. Each one of the experiments covers a large fraction of the available phase space, with HPXe covering practically all the range of allowed values. The combination of HPXe and one of the other two is 21 meV.

Figure 4

Figure 4, shows the predicted sensitivity of future xenon–based neutrinoless double beta technologies after 10 ton exposure. Horizontal lines in blue show the one-sigma range even for the lower bound of the PMR (that is the ISM, which gives the lowest NME of the available models). Taking the central value of the PMR we find a sensitivity of 14 meV. Notice that the lower bound of the PMR we find a sensitivity of 25 meV for the combined limit, while taking the parameter space of the PMR (that is the ISM, which gives the lowest NME of the available models). This result is, of course, a reflection of the fact that the combination of HPXe and one of the other two is 21 meV.
If recent cosmological measurements are correct, xenon experiments (in particular NEXT) can make a major discovery.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\varepsilon$ (%)</th>
<th>$\delta E$ (% FWHM)</th>
<th>$b$ ($10^{-3}$ cky)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LXe</td>
<td>0.38</td>
<td>3.2</td>
<td>0.1</td>
</tr>
<tr>
<td>XeSci</td>
<td>0.42</td>
<td>6.5</td>
<td>0.1</td>
</tr>
<tr>
<td>HPXe</td>
<td>0.30</td>
<td>0.5</td>
<td>0.1</td>
</tr>
</tbody>
</table>

The combination of the three experiments is 19 meV, fully covering the phase space, while the HPXe detector reaches 25 meV. Each one of the experiments covers a large fraction of the available models.

This result is, of course, a lower bound of the PMR we find a sensitivity of 25 meV for the combined limit, while taking into account uncertainties in the values of the NME. Taking the limit for the three technologies, and use reasonable assumptions to predict their achievable background rate, which turns out to be, both very small and quite similar.

To determine the actual detector designs, the cost of enriched xenon and the total detector mass need to be done taking into account of the practical resolution near the expected sensitivity of current xenon–based experiments in 2020.
Summary and outlook

- Neutrino are being cornered. Cosmological measurements, direct measurements and neutrino oscillation experiments will reveal their mass spectrum in the next few years.

- Neutrinoless double beta decay experiments are coming to age. Exploring whether the neutrino is its own antiparticle may require detectors in the range of the (multi)ton isotope mass, with good efficiency and extremely good background rejection. Xenon experiments can provide all the above.

- In addition, HPXe can provide superb energy resolution. If the recent claim on the cosmological mass of the sum of the three neutrinos holds, the potential for discovery is very high.
Neutrino through the looking-glass
Neutrino through the looking-glass
Neutrino through the looking-glass

- Standard Model: The neutrino does not see her reflection in the mirror.
Neutrino through the looking-glass

• Standard Model: The neutrino does not see her reflection in the mirror.

• Ettore Majorana: When the neutrino goes through the looking-glass she finds herself.
Neutrino through the looking-glass

• Standard Model: The neutrino does not see her reflection in the mirror.

• Ettore Majorana: When the neutrino goes through the looking-glass she finds herself.
Ettore Majorana through the looking-glass
Majorana disappeared in the sea, in March 1938, aged 32. His body was never found. The reasons for his alleged suicide remain obscure.
Majorana disappeared in the sea, in March 1938, aged 32. His body was never found. The reasons for his alleged suicide remain obscure.
Ettore Majorana through the looking-glass

- Majorana disappeared in the sea, in March 1938, aged 32. His body was never found. The reasons for his alleged suicide remain obscure.
- Perhaps, like Alice, he managed to escape, through the looking-glass, to a better World.
Thanks for your attention