Ettore Majorana through the Looking-glass

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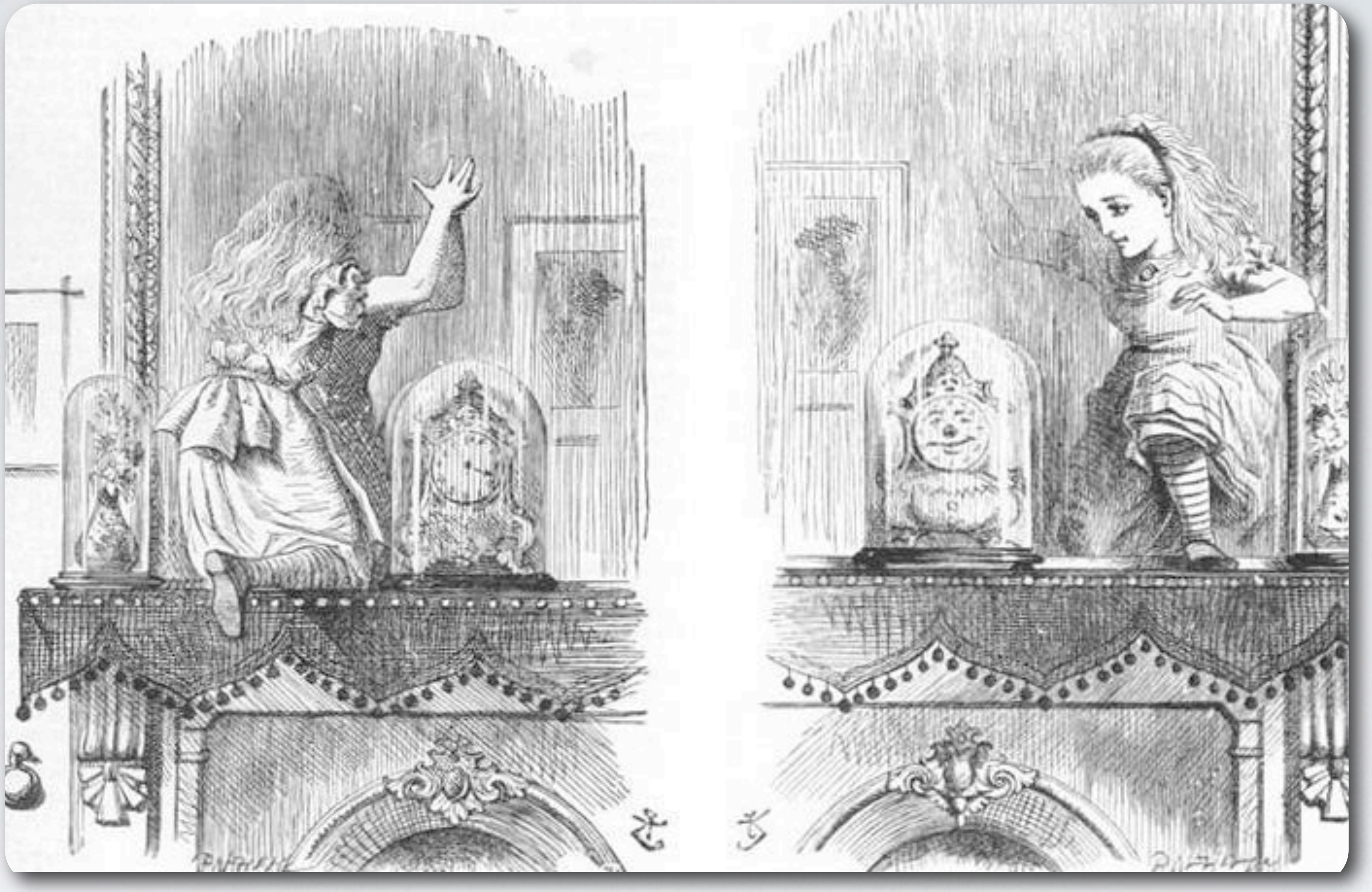
Instituto de Física Corpuscular (CSIC & UVEG)

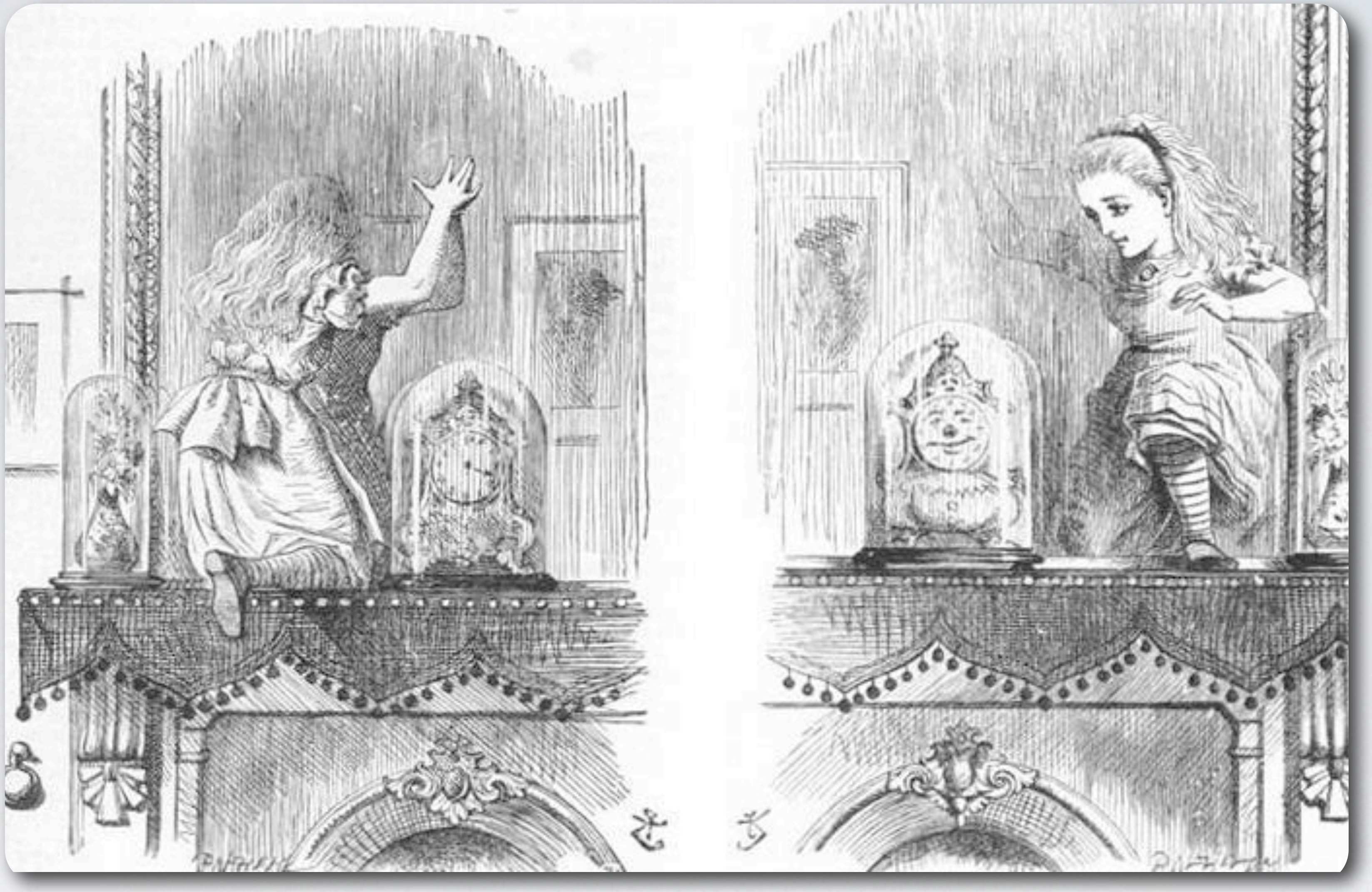
Fermilab, October, 2012

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.

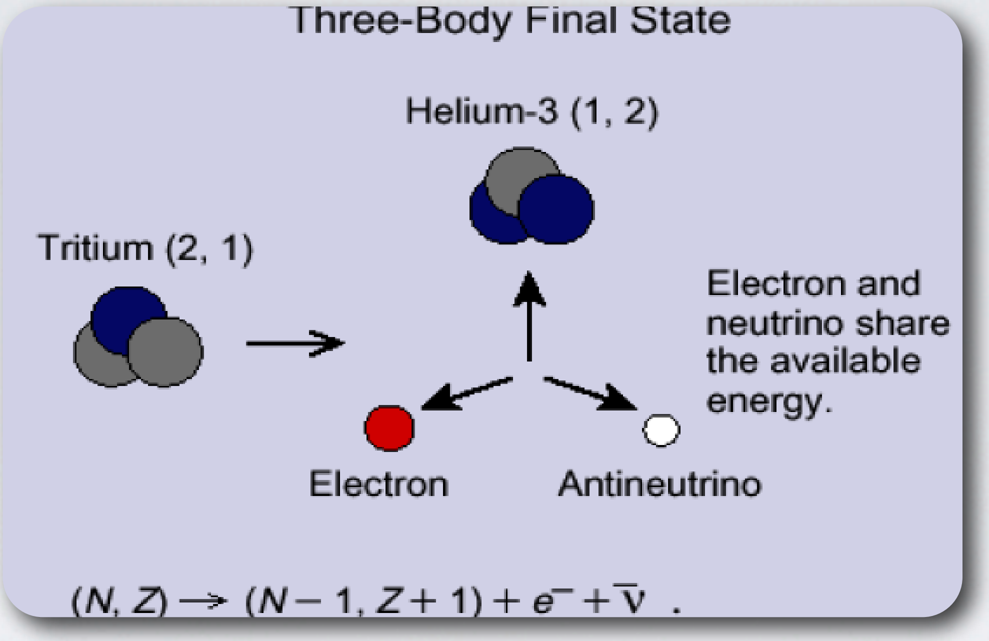
WILL TALK ABOUT...

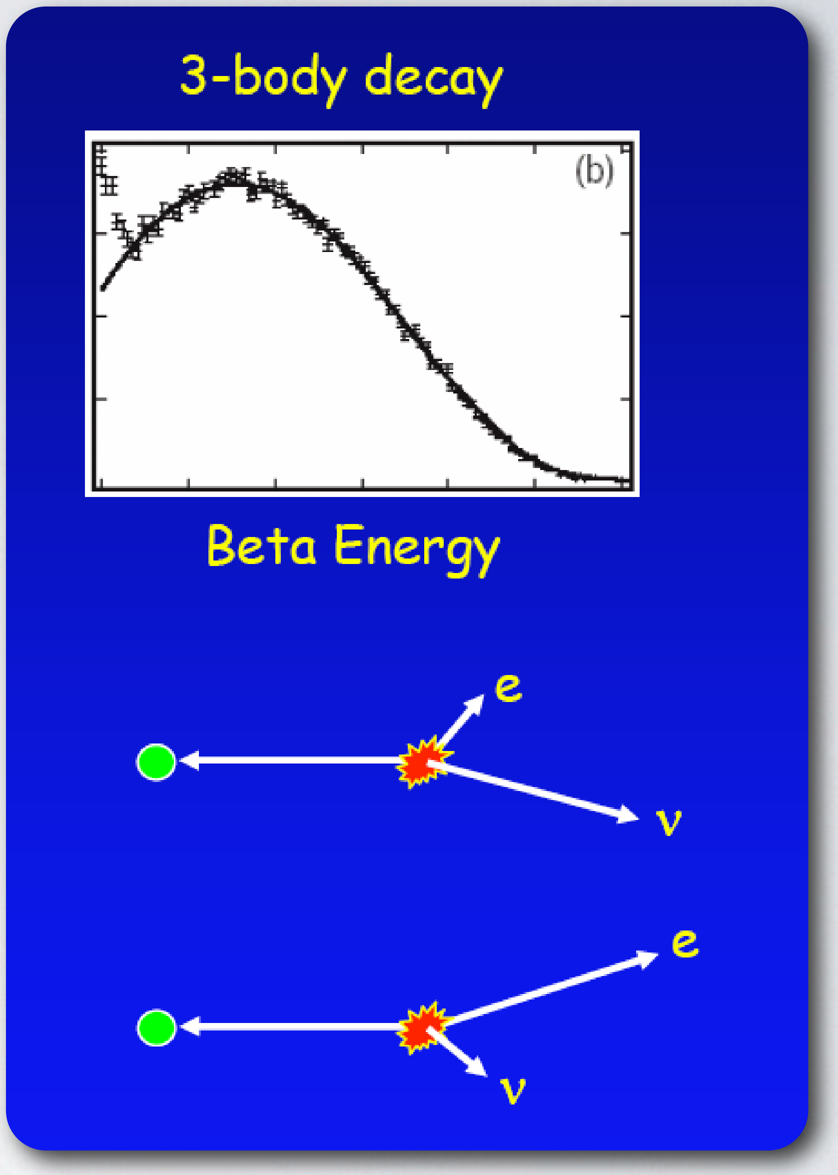
- Neutrinos, electrons, Majorana, and the mystery of the missing antimatter
- Are neutrinos Majorana particles? How to find out
- Experimental challenges
- A selection of experiments
- Ettore Majorana through the looking glass

Neutrinos, electrons, Majorana, and the mystery of the missing antimatter

Neutrinos

Meet the neutrino





Famously invented as a desperate remedy by W. Pauli

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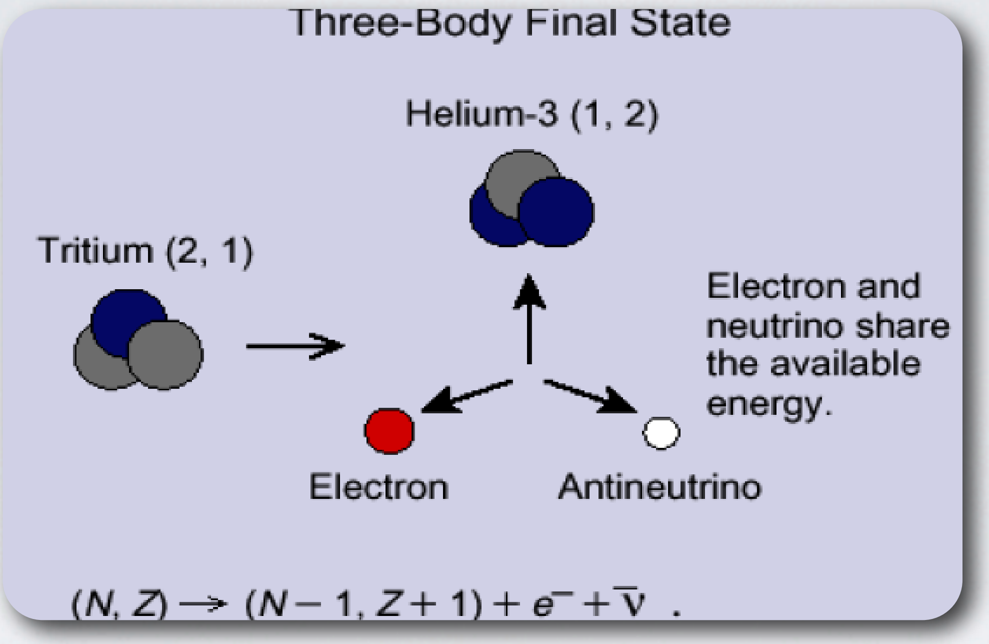
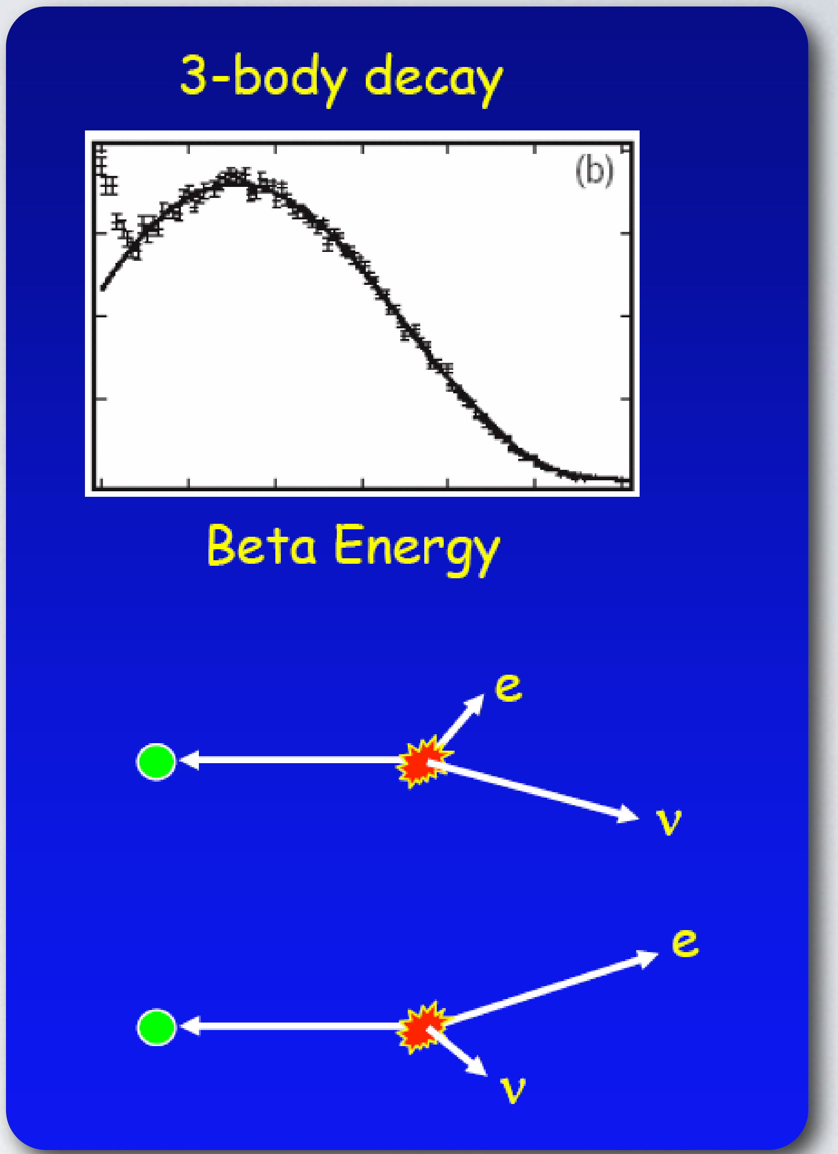
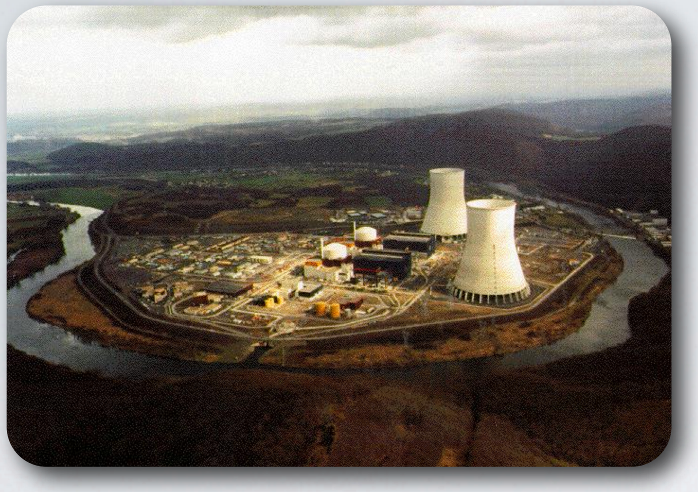




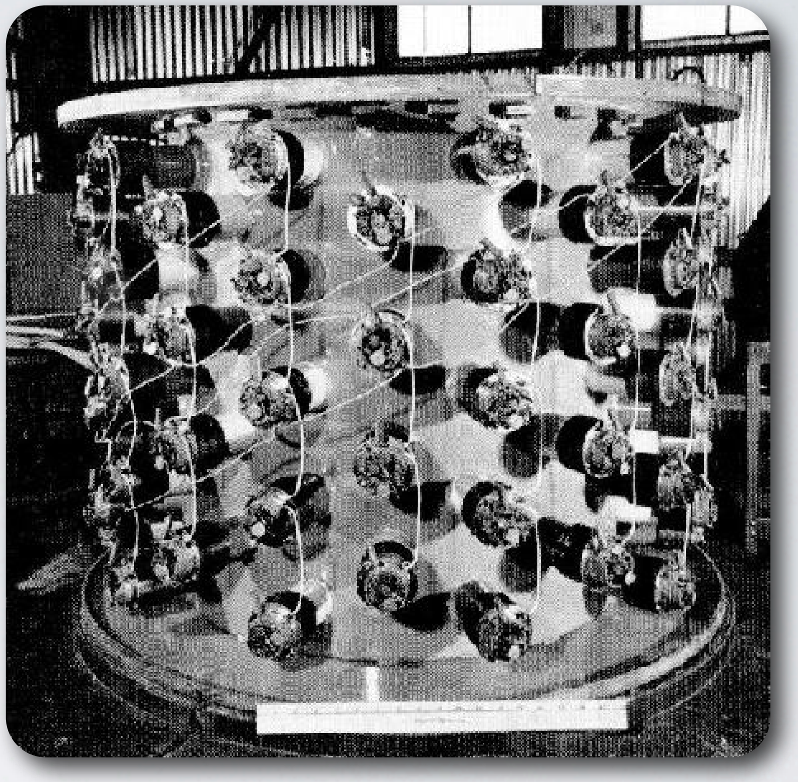
Famously invented as a desperate remedy by W. Pauli

I have done a terrible thing. Proposing a particle that cannot be detected. This is something that no theorist should ever do

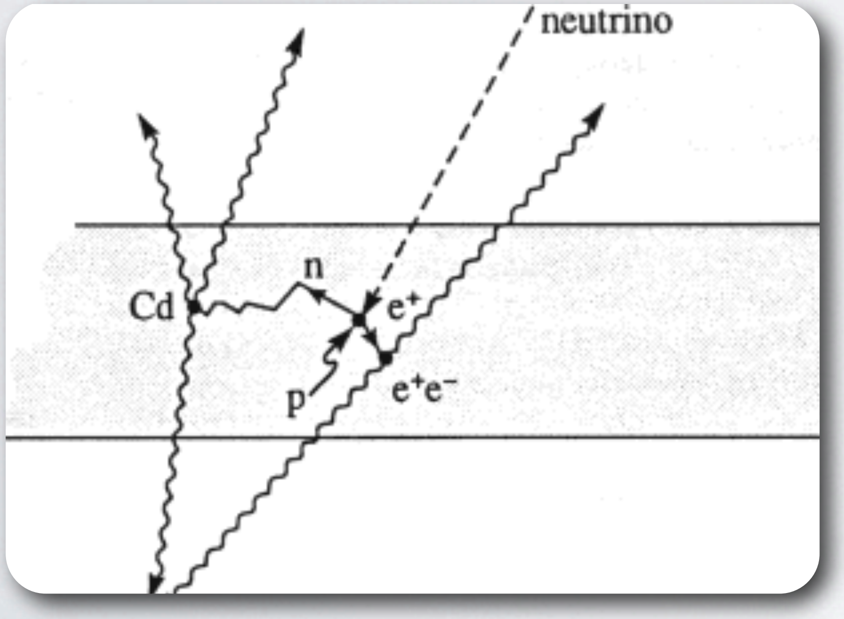
Meet the neutrino

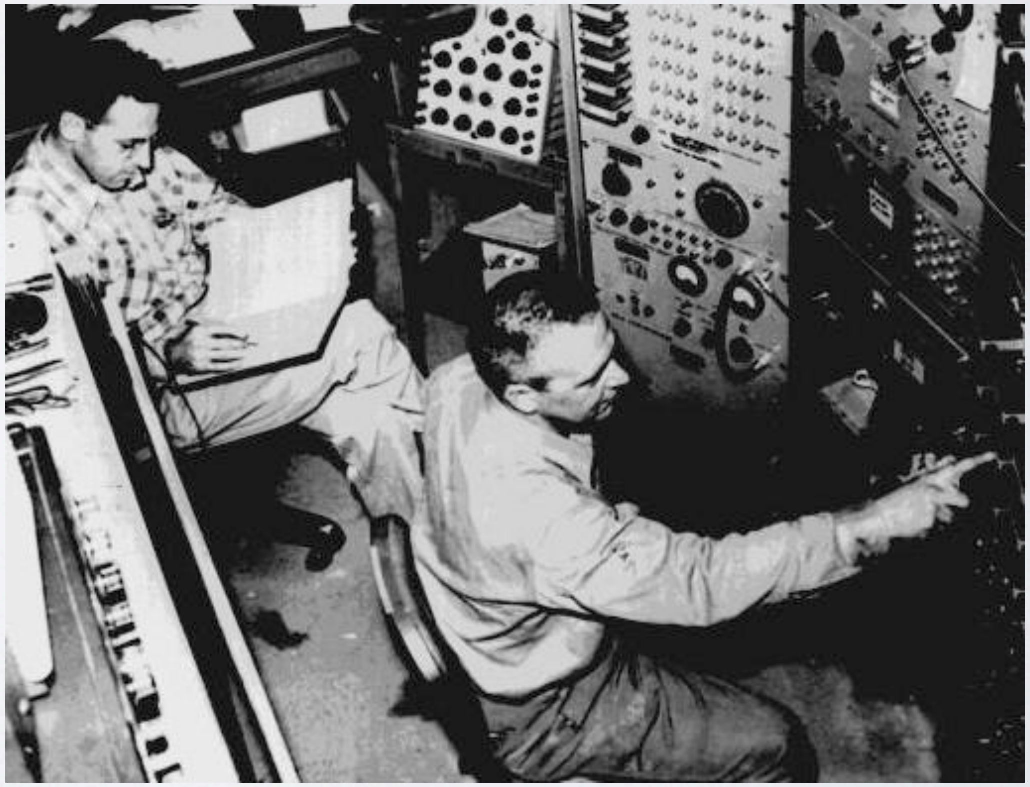


$\bar{\nu}_e$



First neutrino Observed by Reines & Cowan, 1953





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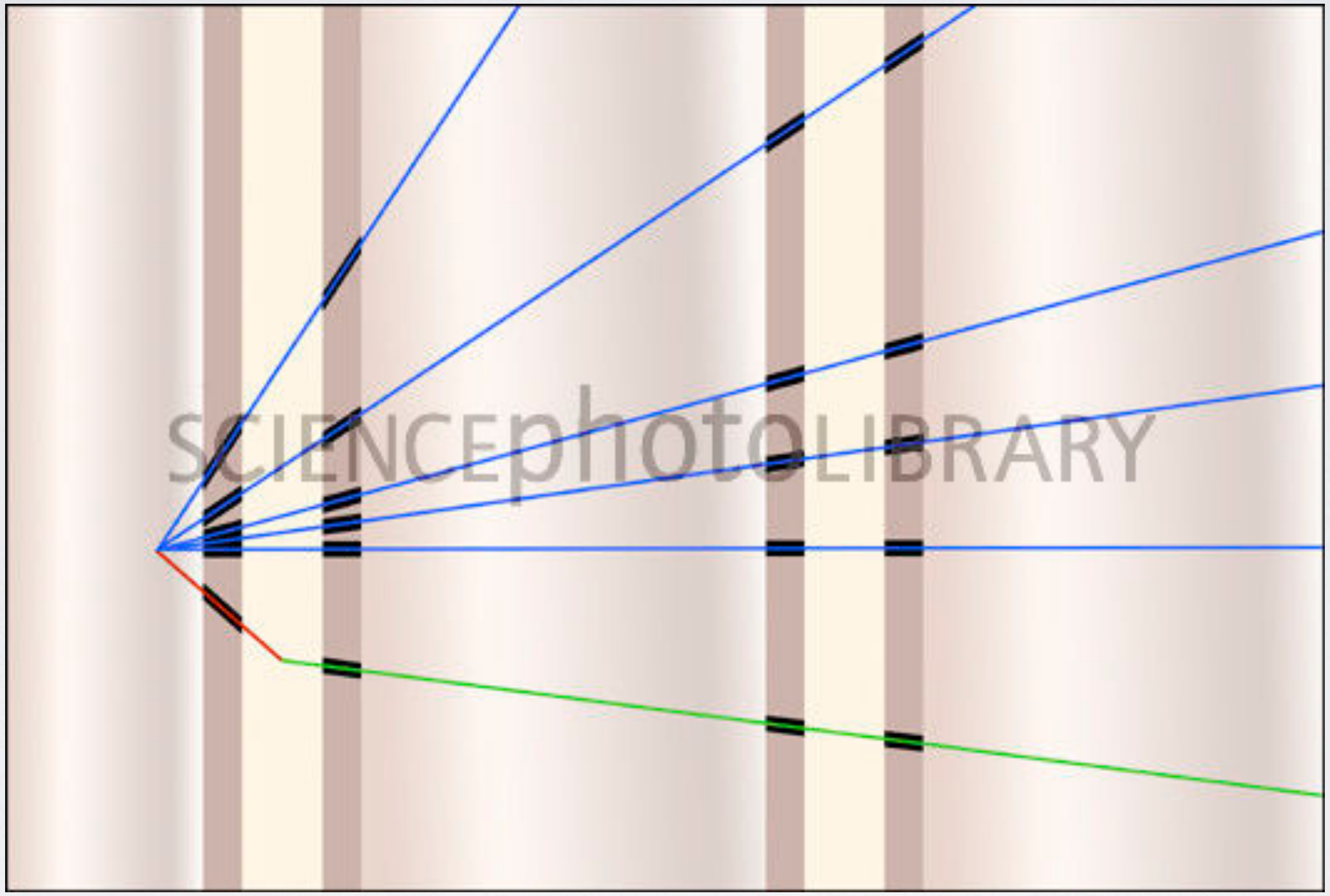
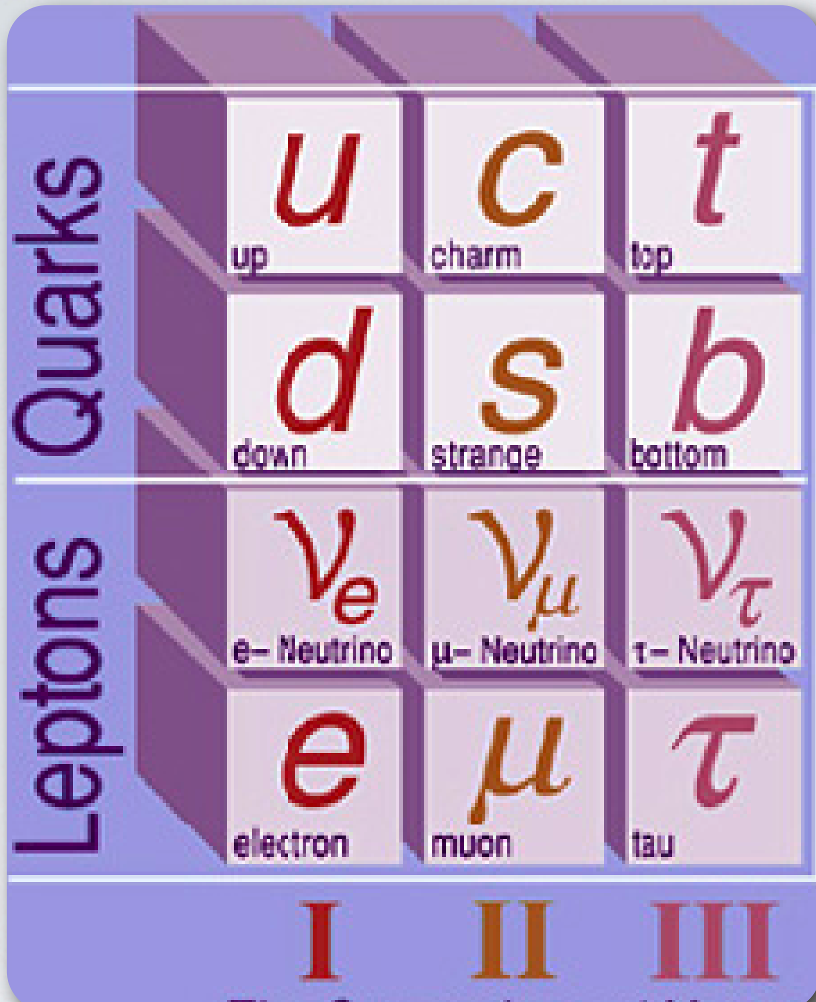
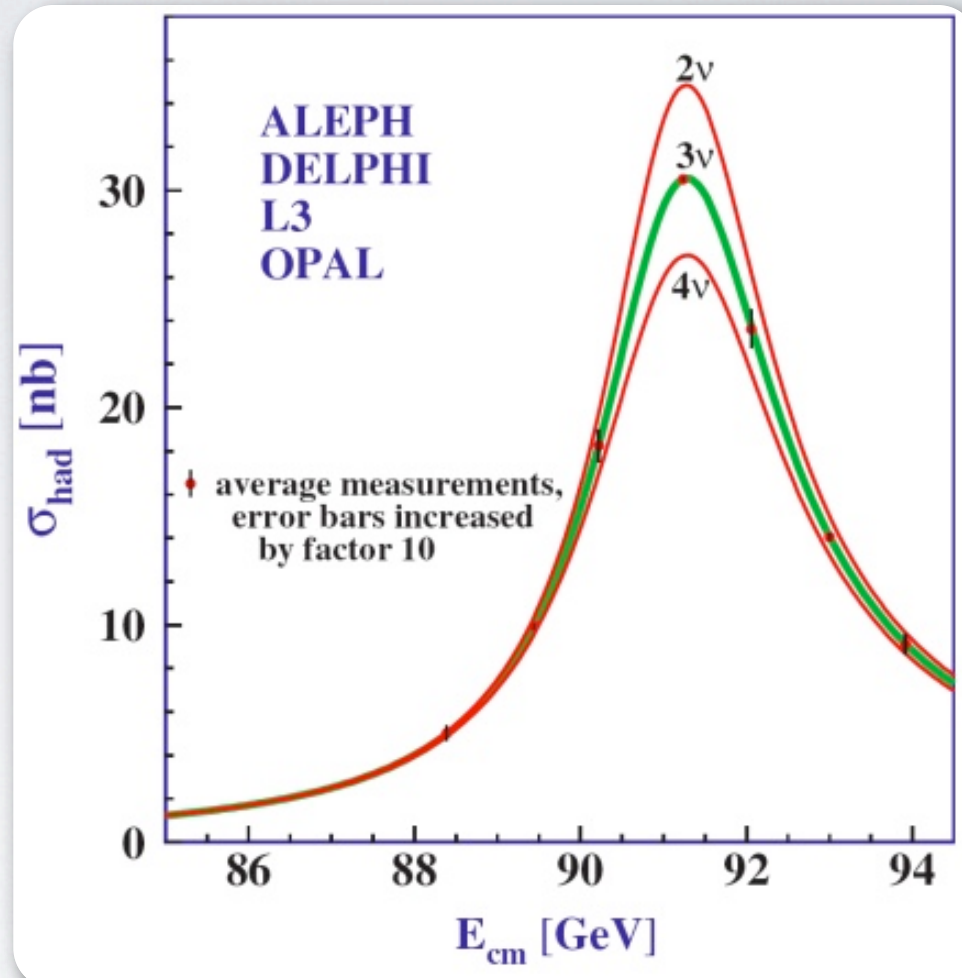


Last neutrino Observed by Donut experiment @ FNAL (2000)

Meet the neutrino





Three copies found by Mark-II and LEP experiments

Parity & Helicity

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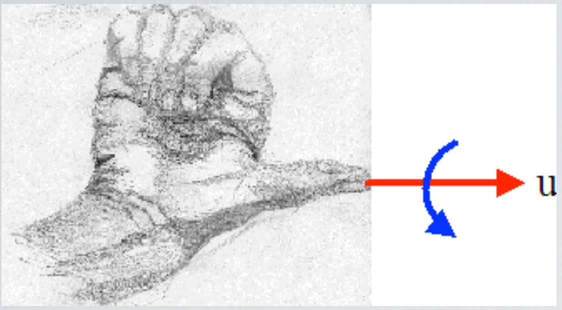
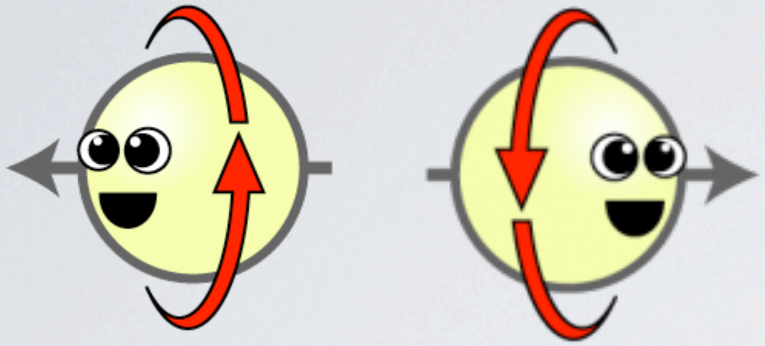
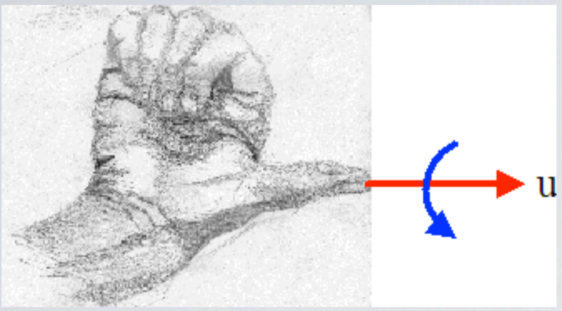




Right handed particle: spin (red arrow) and the direction of motion (gray arrow) define the same orientation as your right hand.



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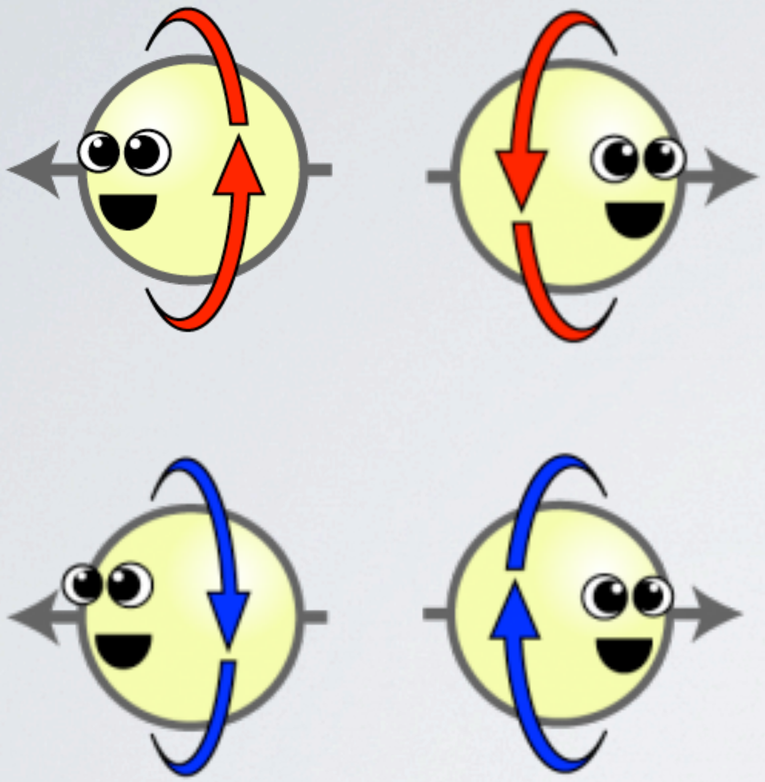

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A left handed particle spins in the opposite direction than a right handed particle.

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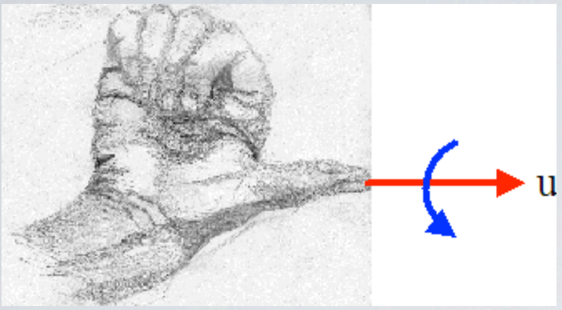

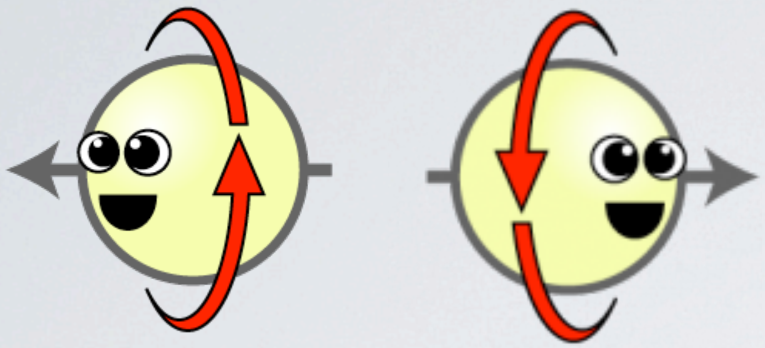

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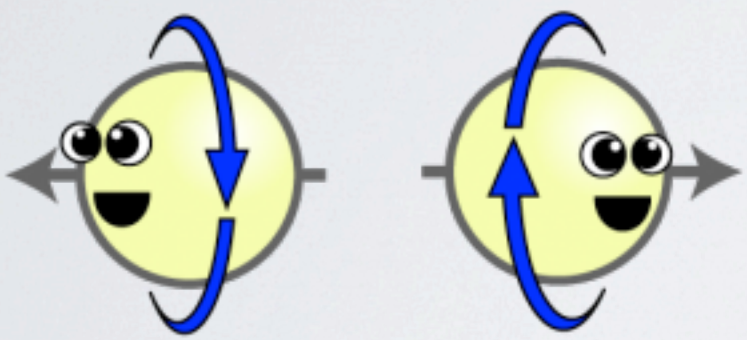

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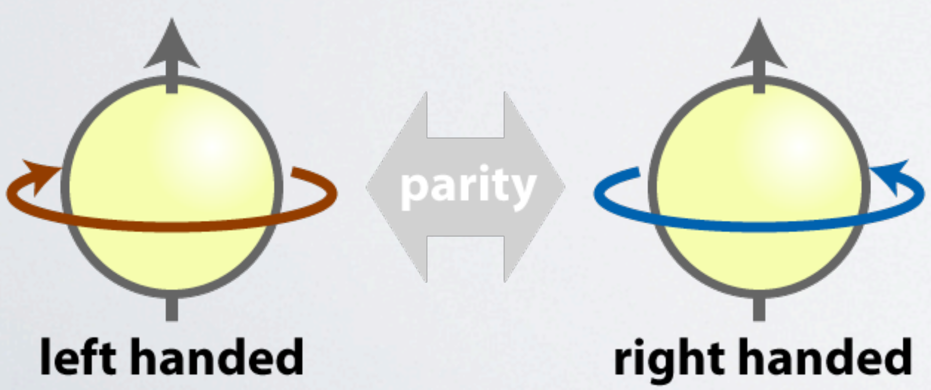
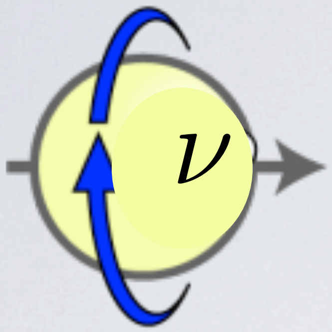


A parity operation (a mirror) transforms a left handed particle into a right handed particle.

Standard model neutrinos

Standard model neutrinos



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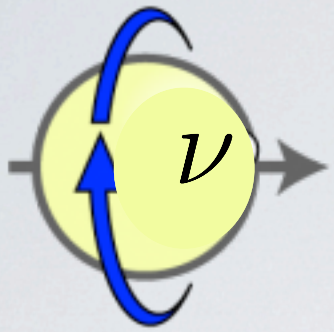

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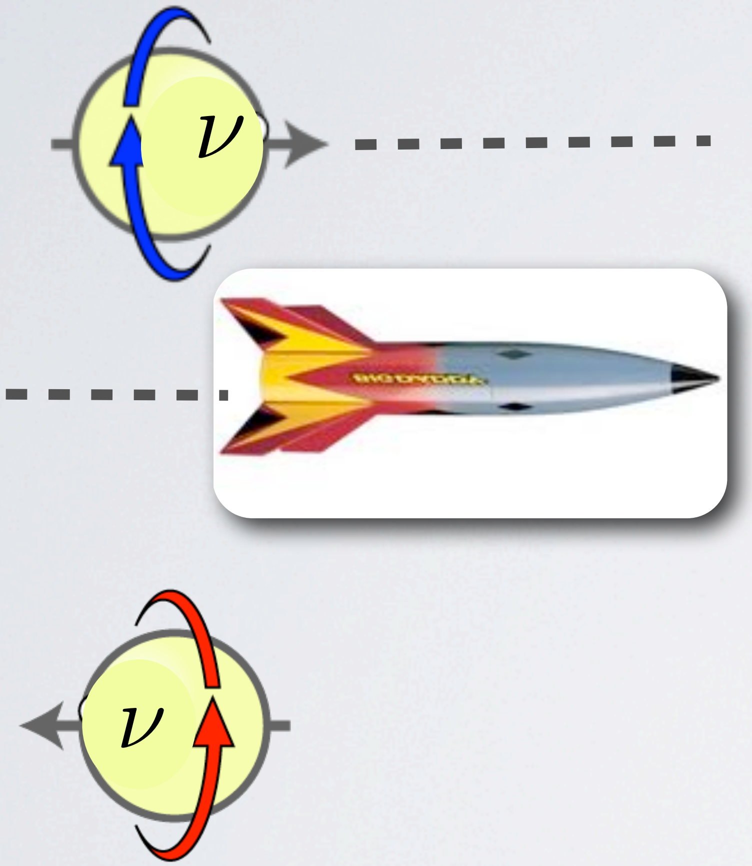

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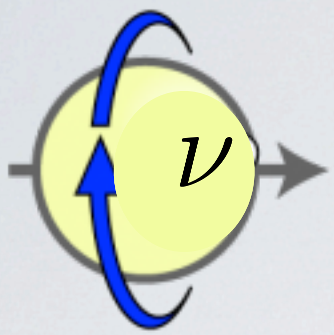

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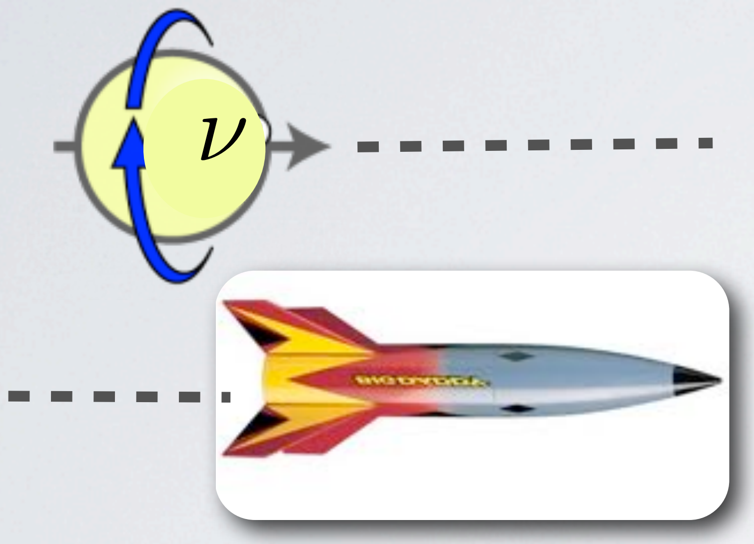

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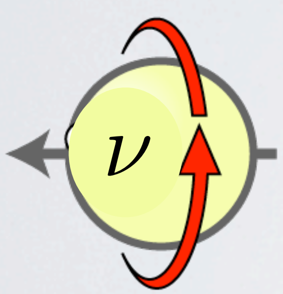
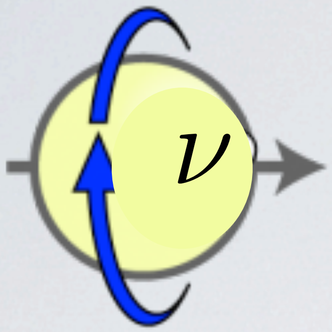


- Therefore there are no right handed neutrinos and no left-handed antineutrinos. Neutrinos do not reflect in the mirror! This is an extreme example of the mirror world being different!

Standard model neutrinos



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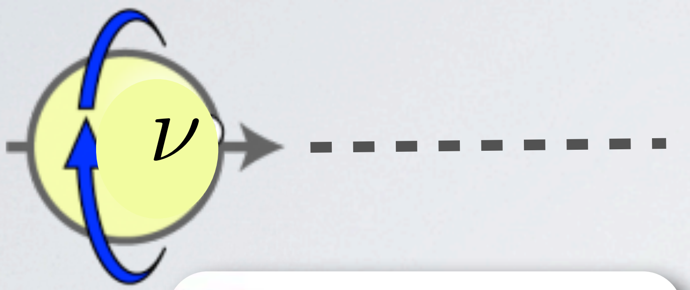

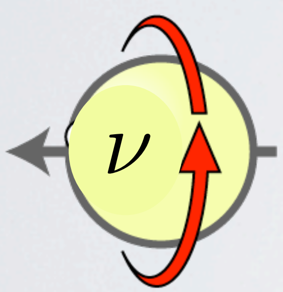

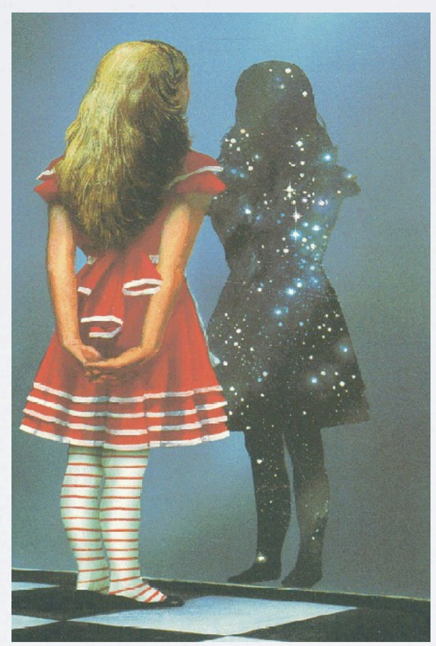

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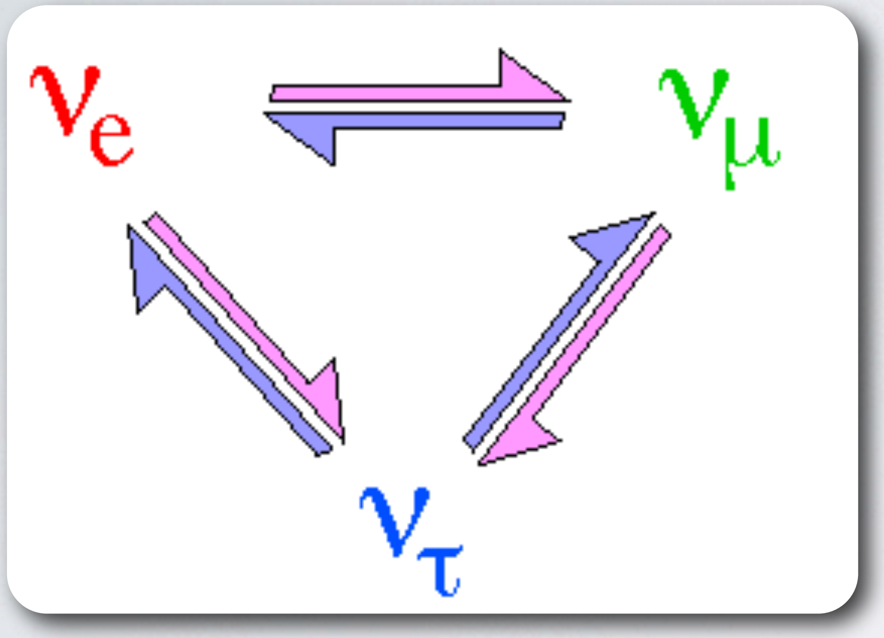

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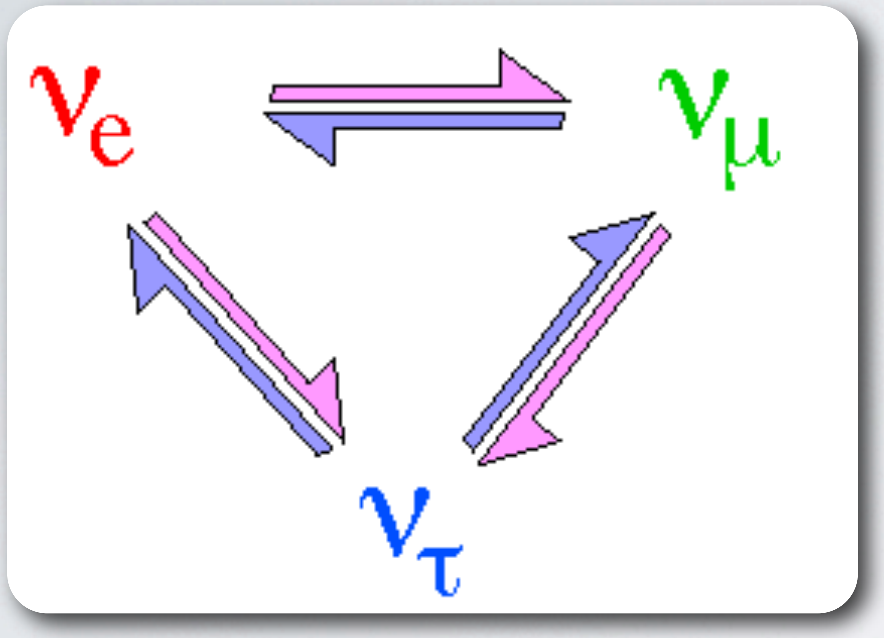

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS}(\theta_{12}, \theta_{23}, \theta_{13}, \delta, \ldots) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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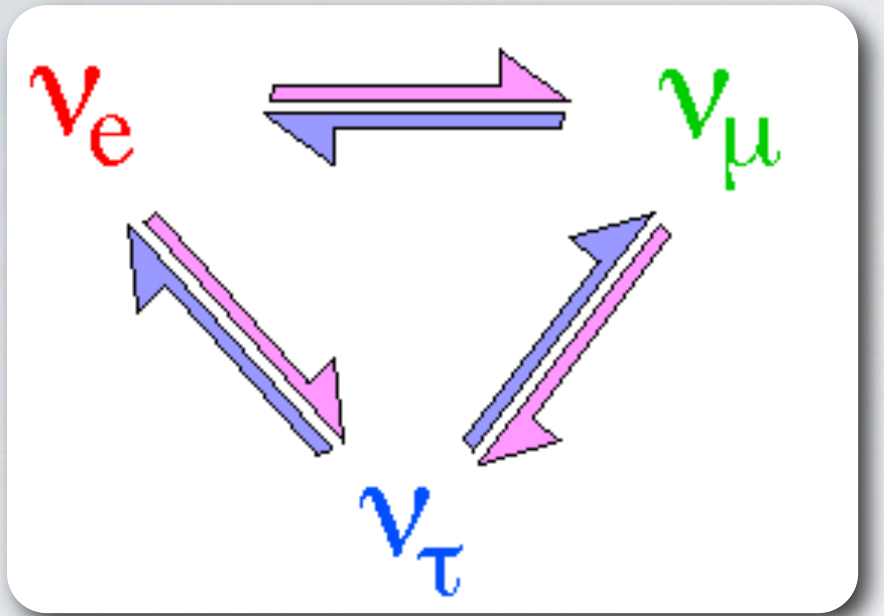

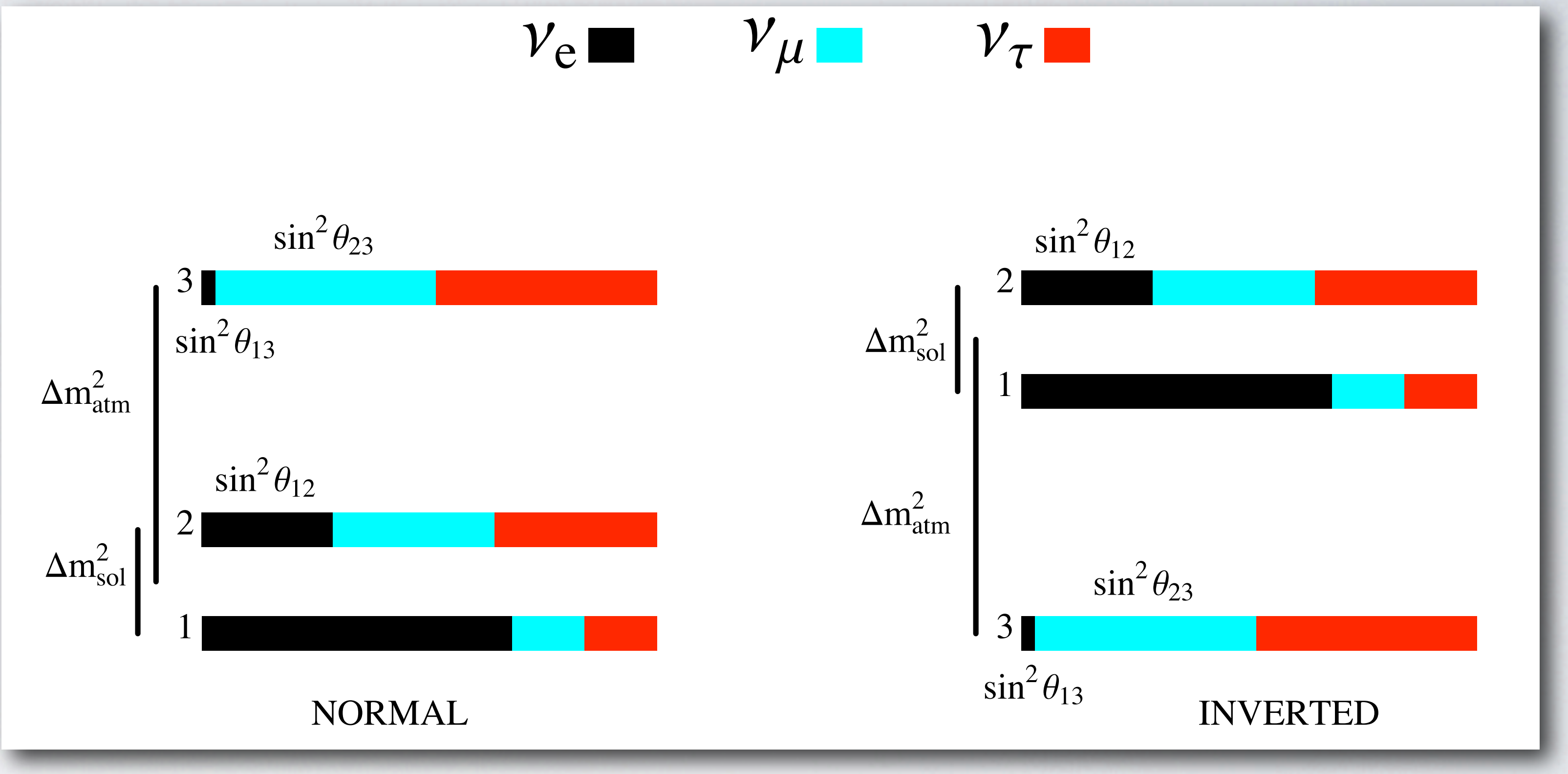

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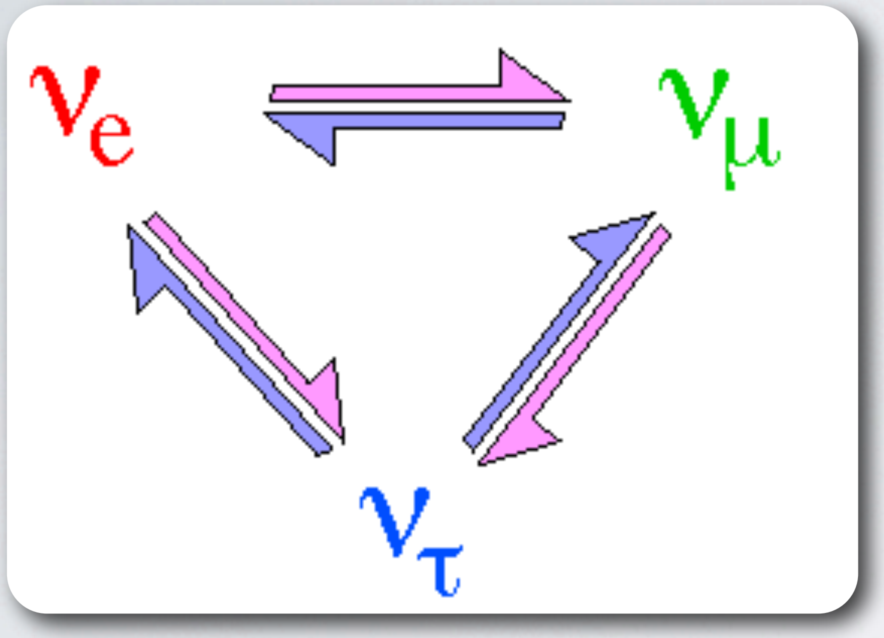

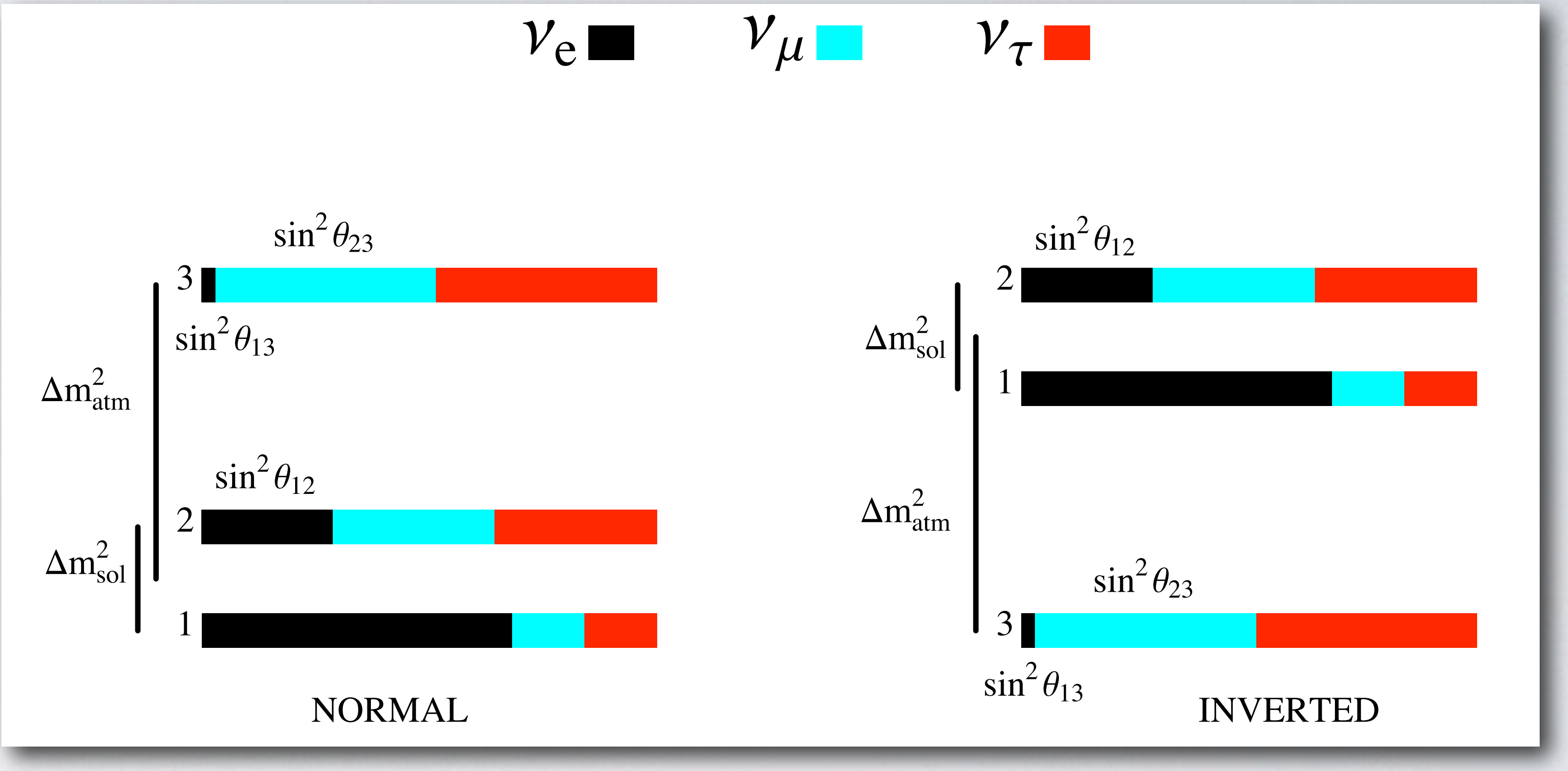

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How do we accommodate massive neutrinos in the Standard Model?

electrons

A (Dirac) electron

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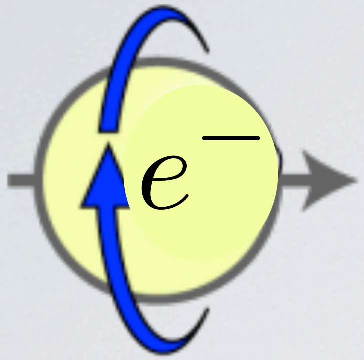

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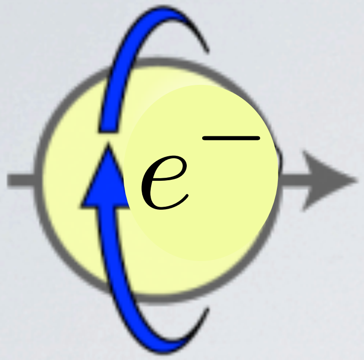

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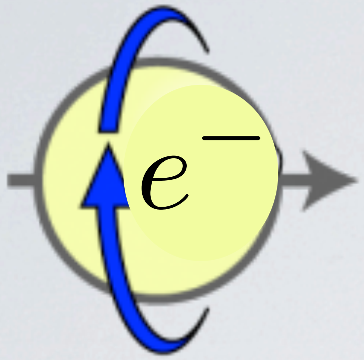

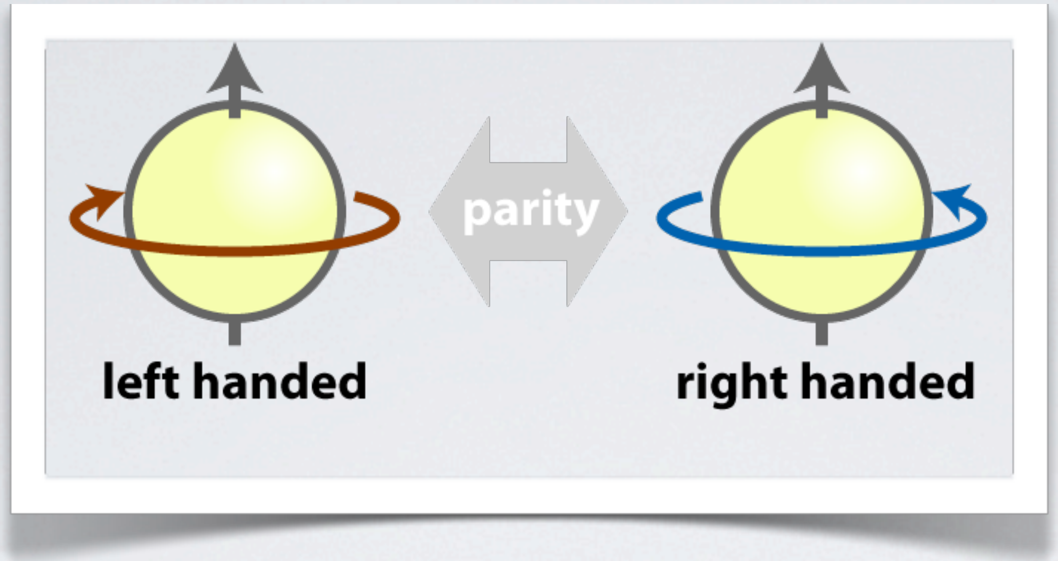

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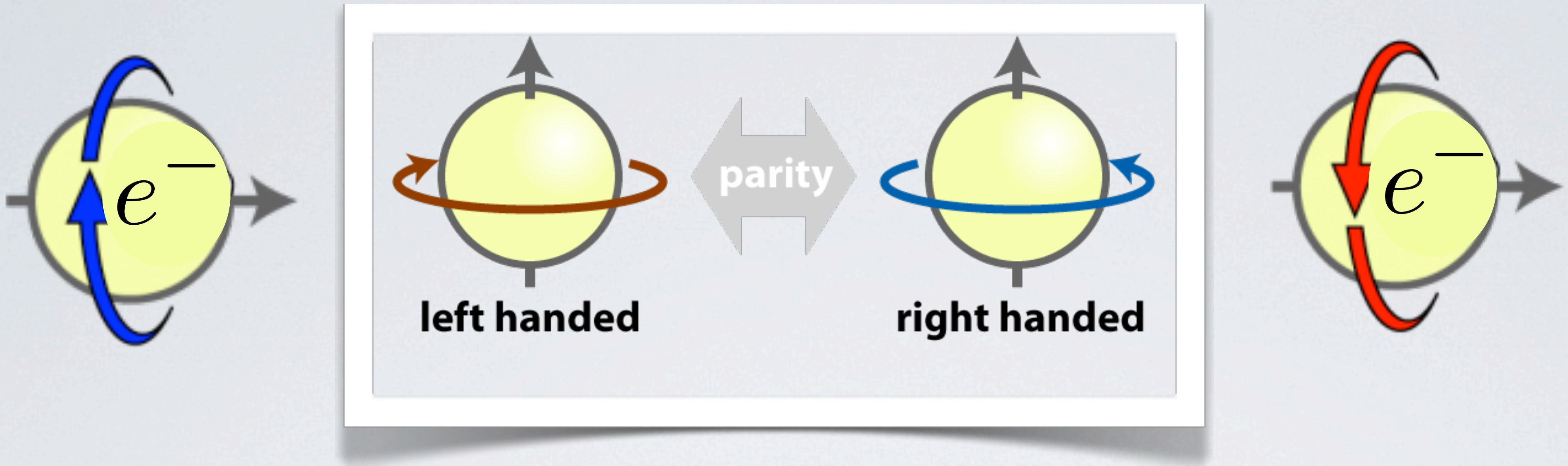

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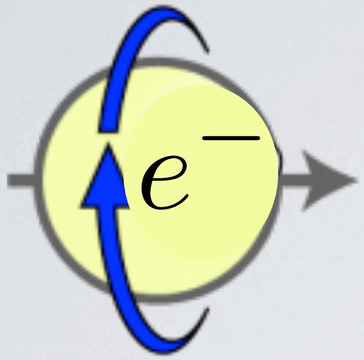

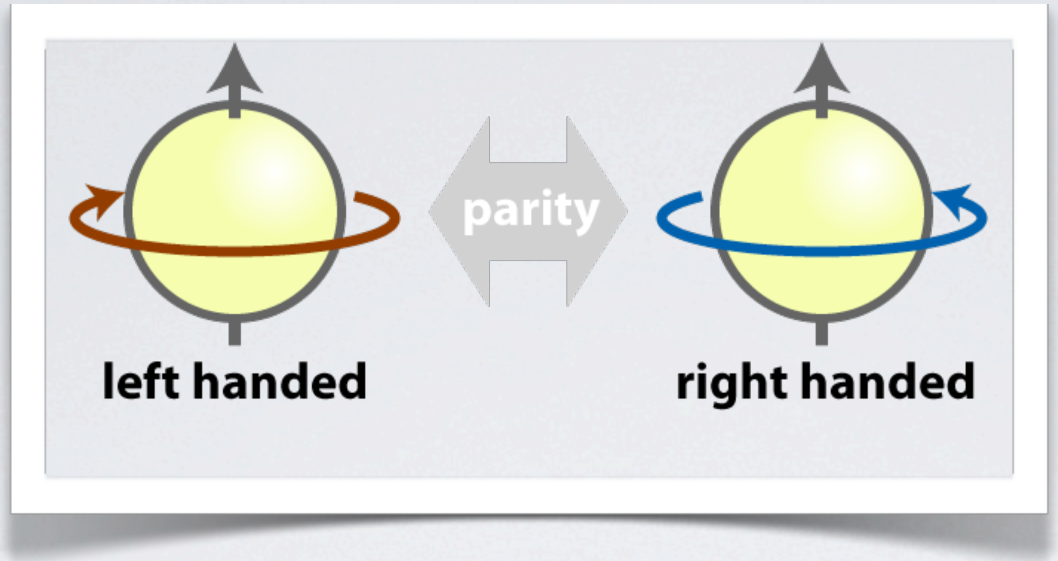

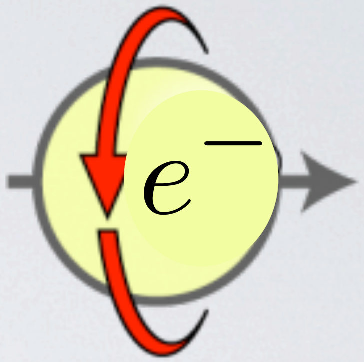

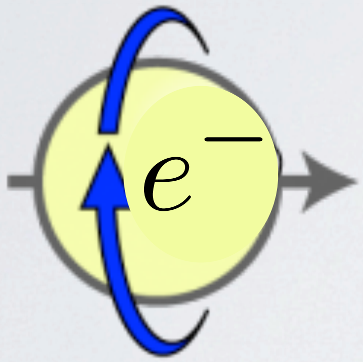

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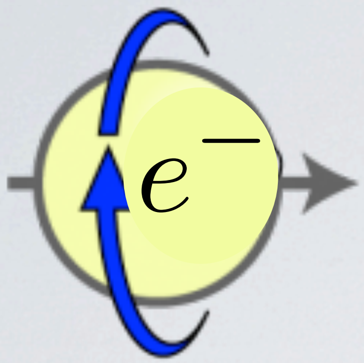

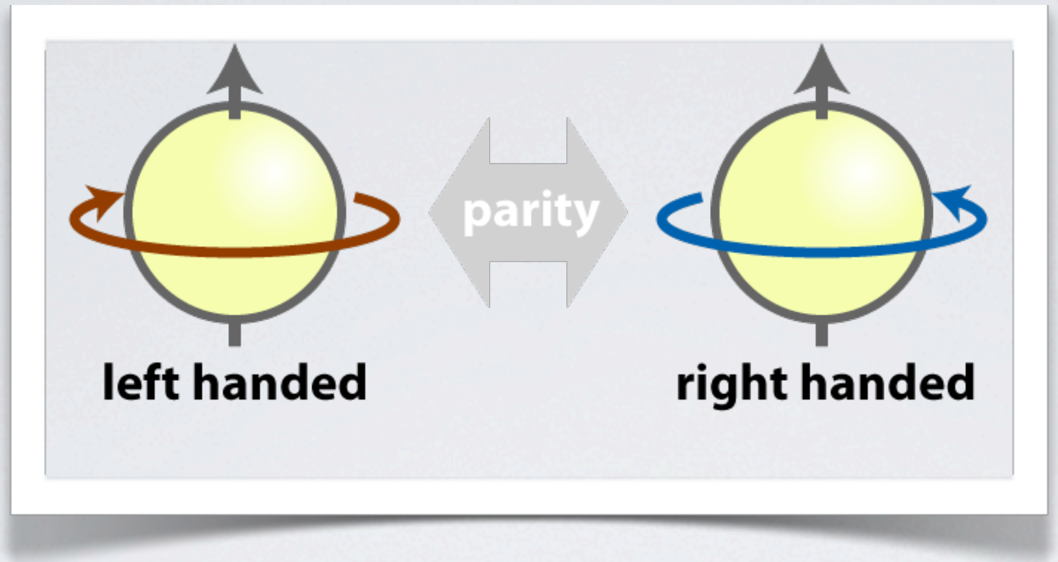

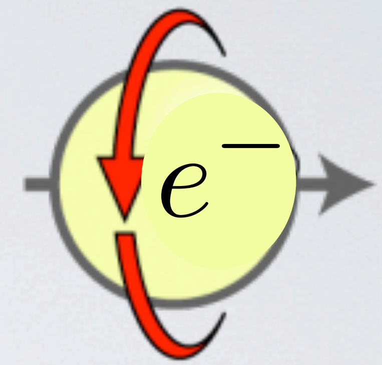

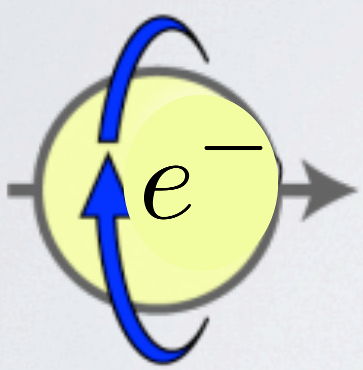

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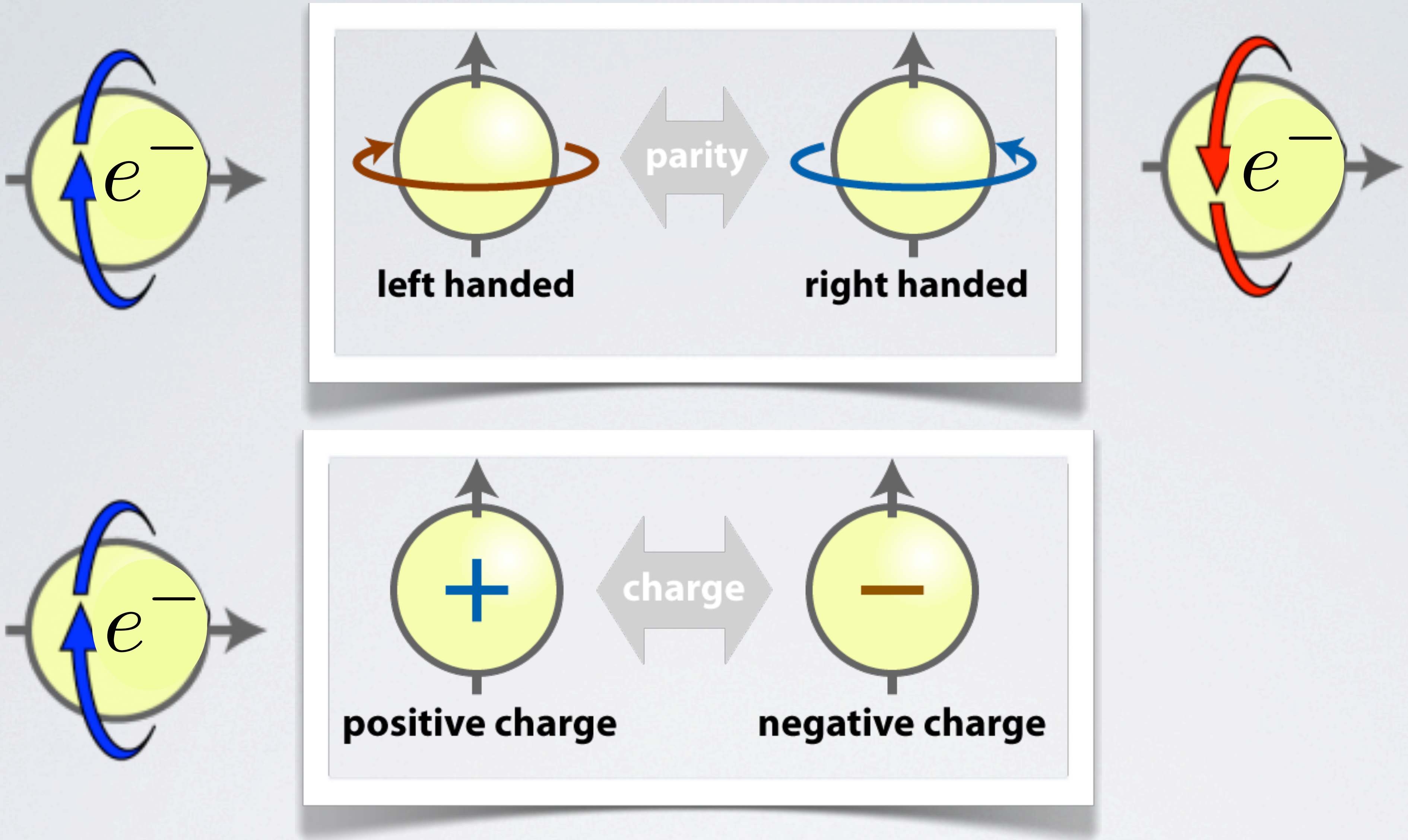

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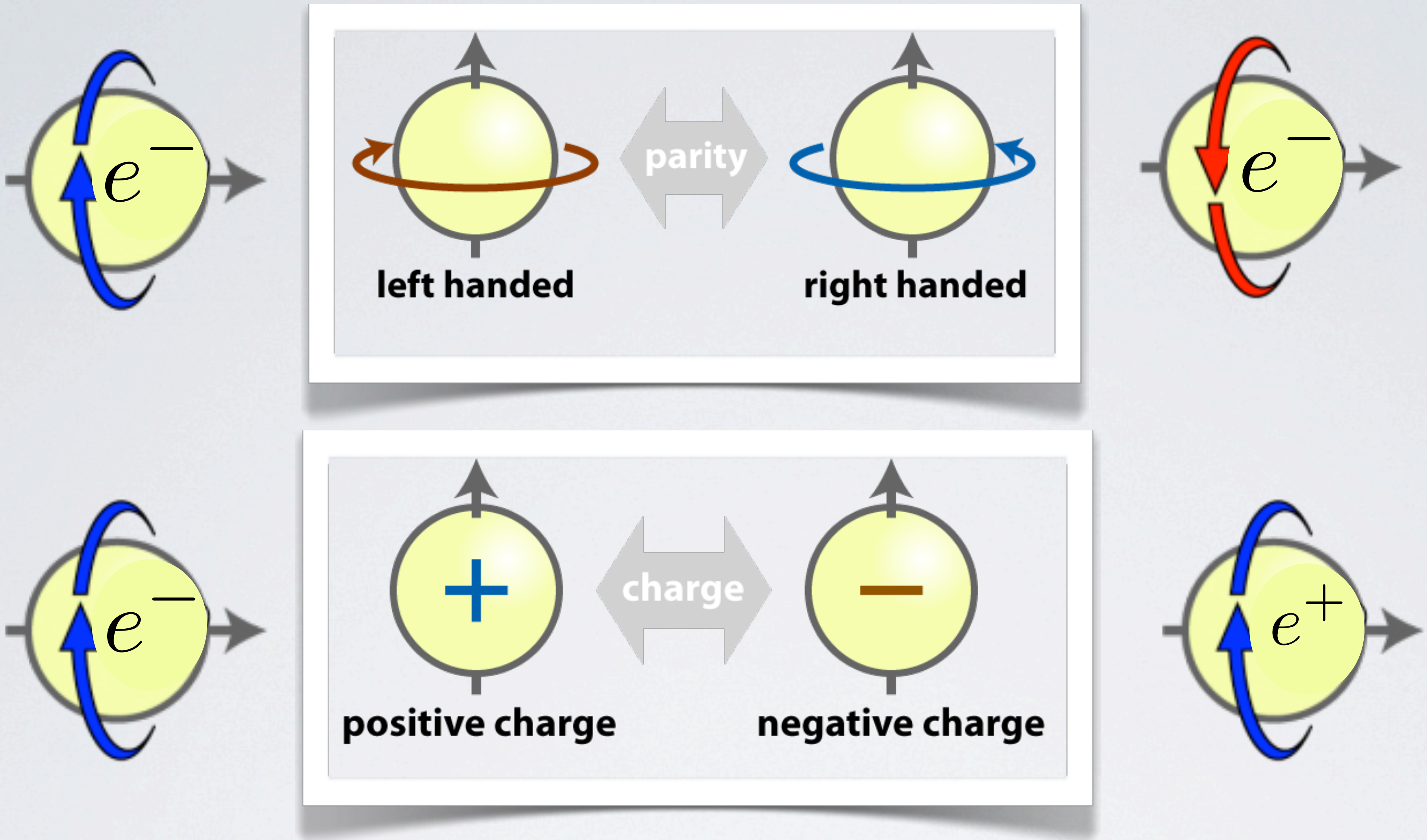

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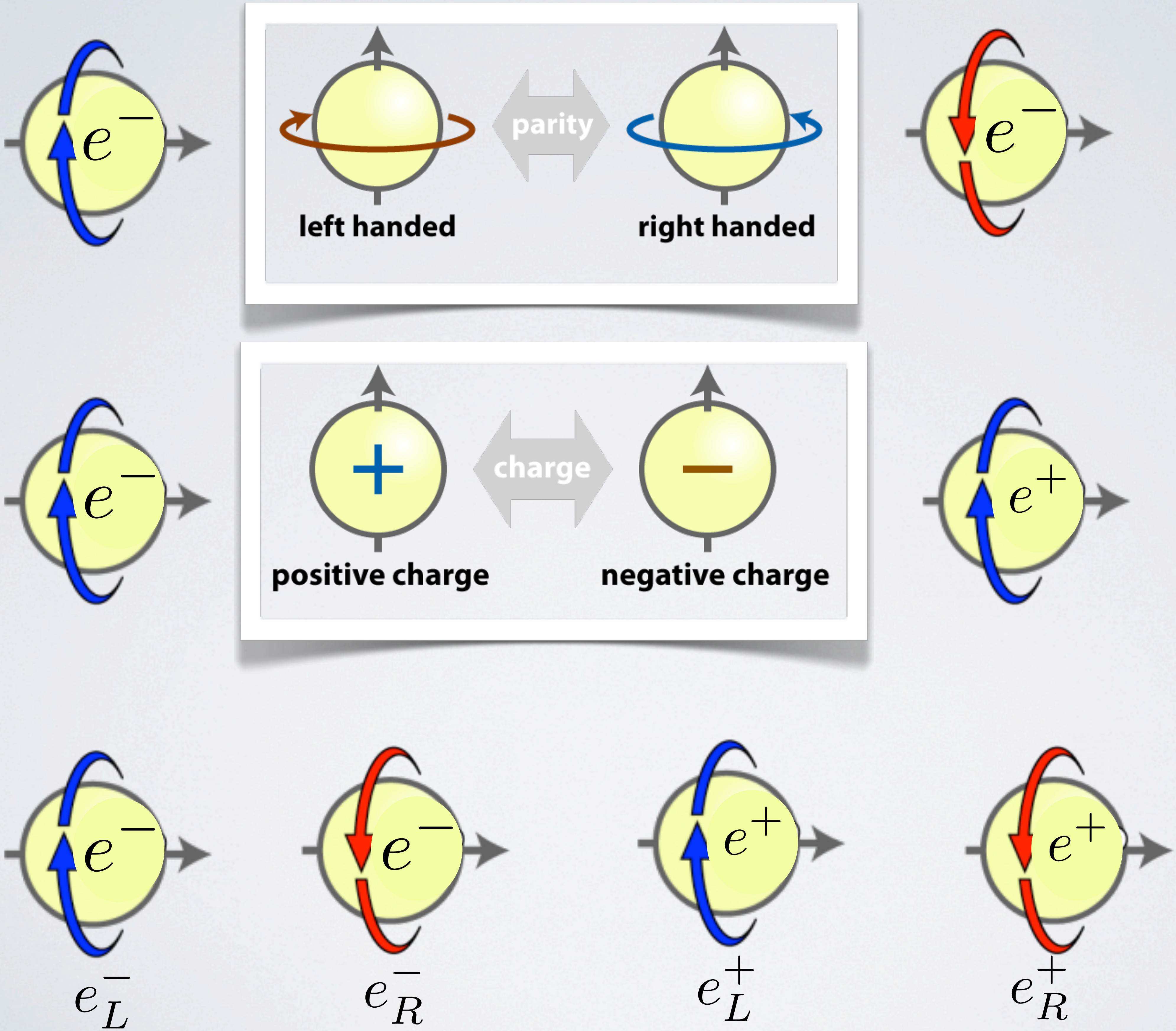

Electron mass

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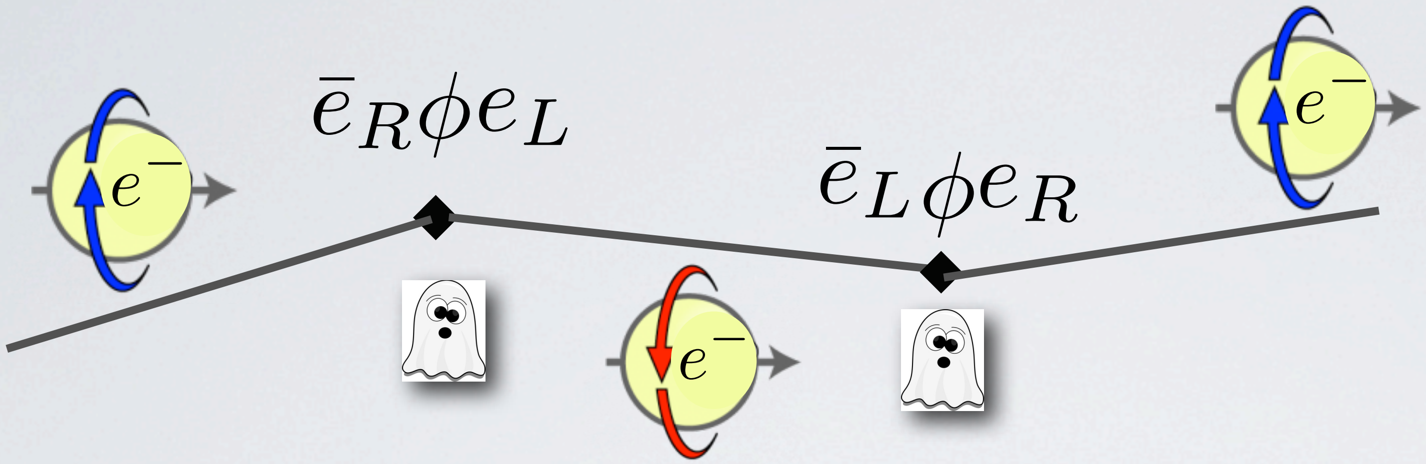

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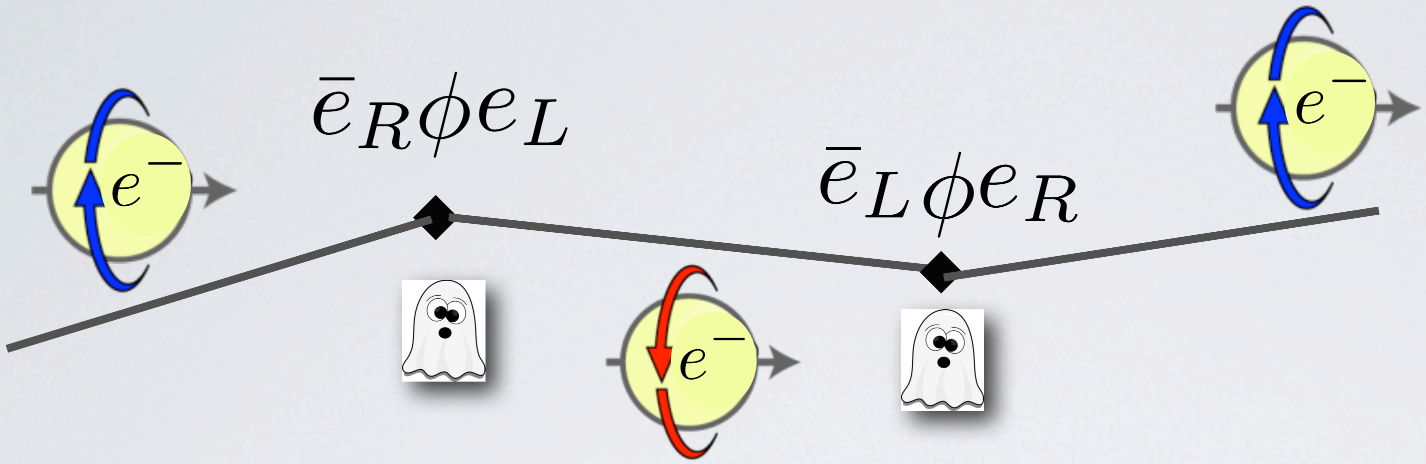

left and right handed states bump against the Higgs field

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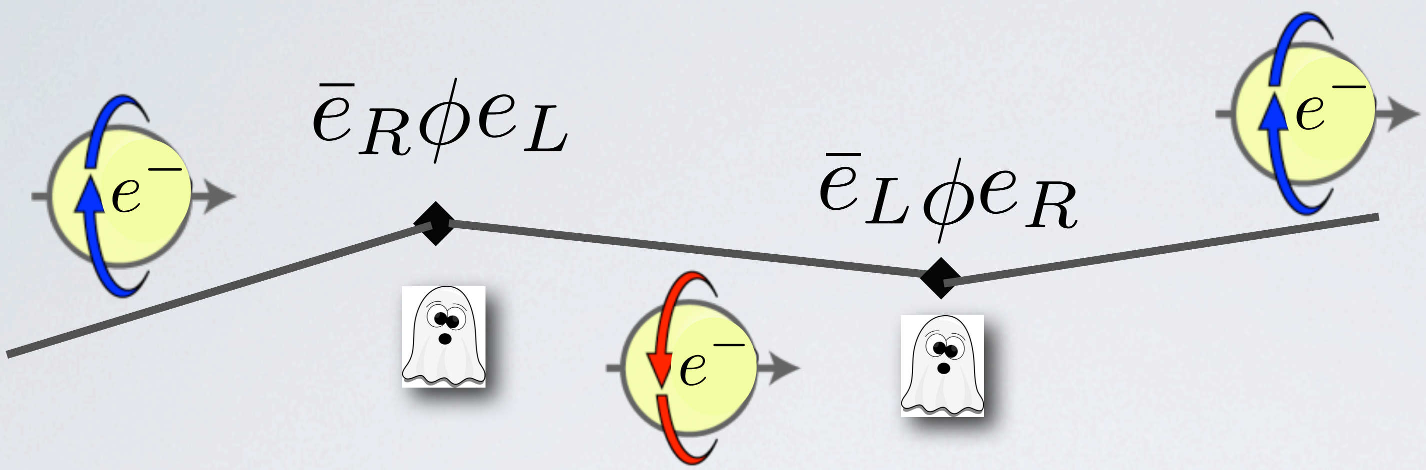

left and right handed states bump against the Higgs field

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

$$\lambda \bar{e}_R \phi e_L \rightarrow \lambda v \bar{e}_R e_L$$

$$m_e = \lambda_e v$$

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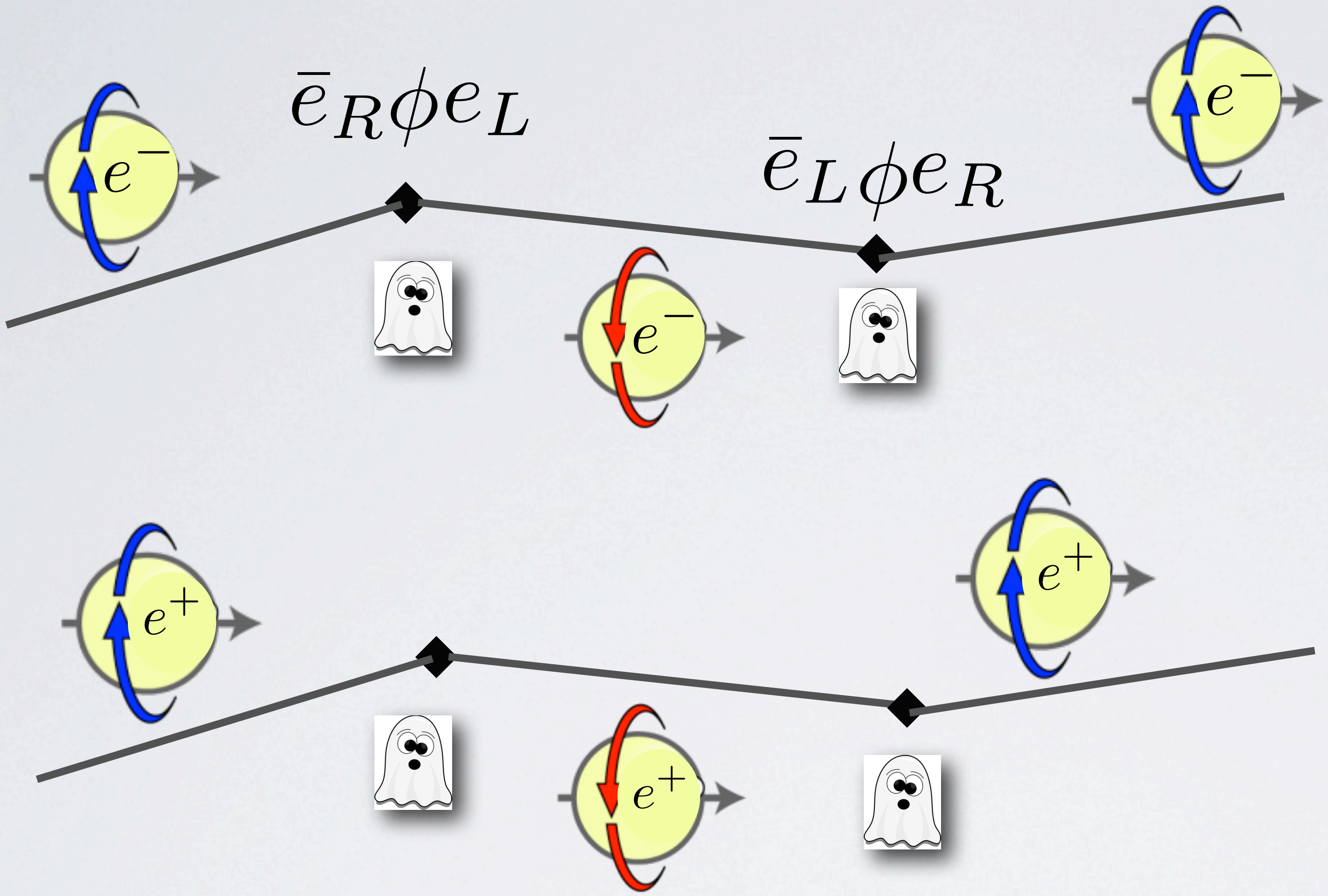

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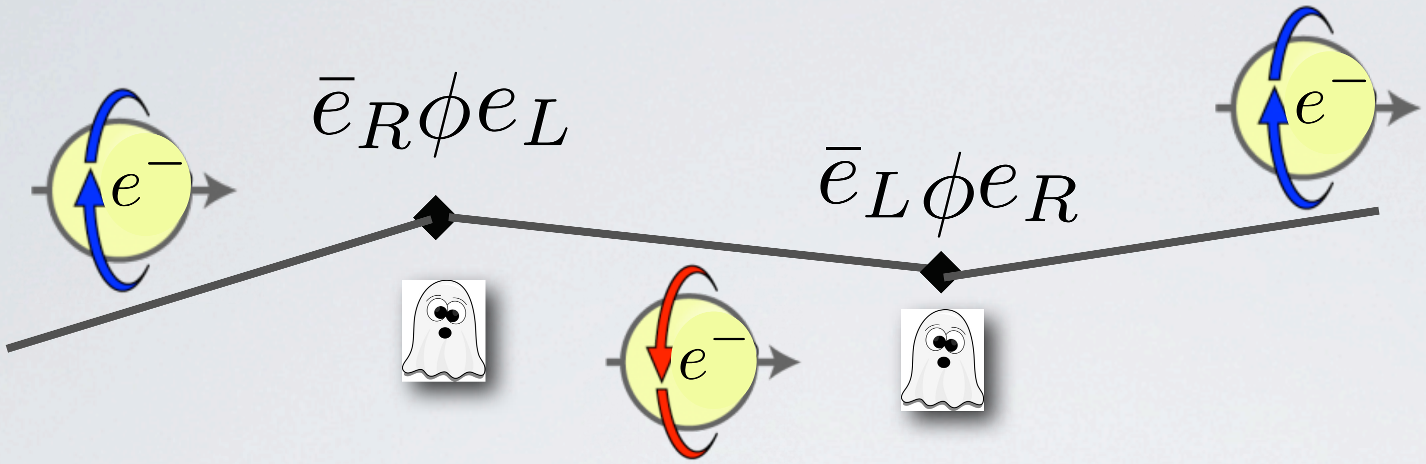

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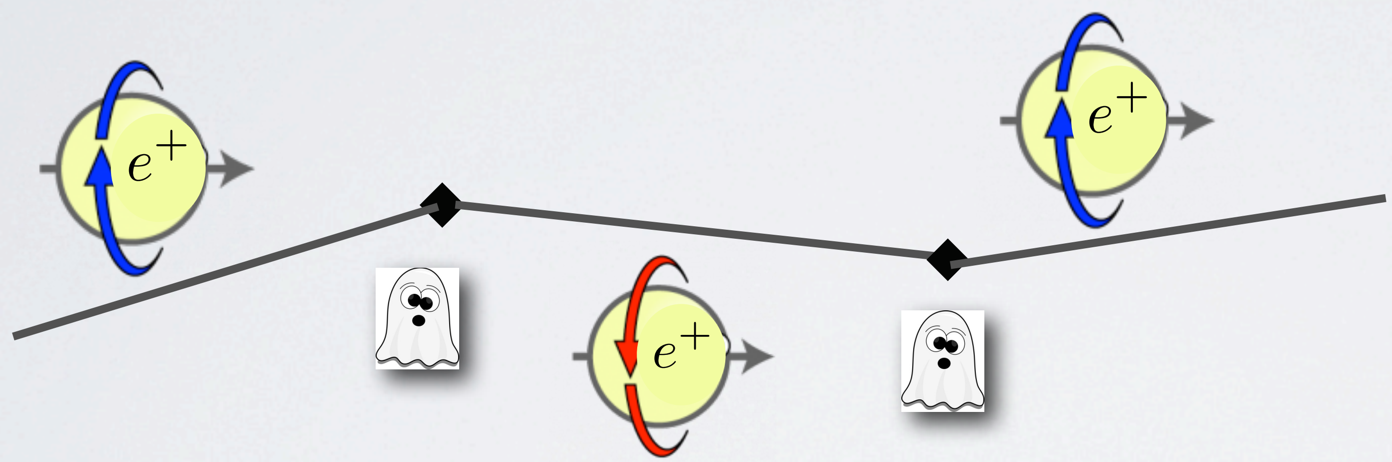

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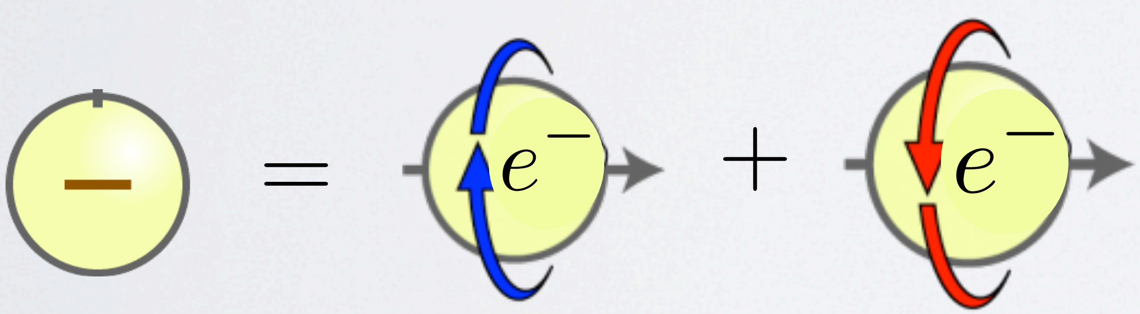
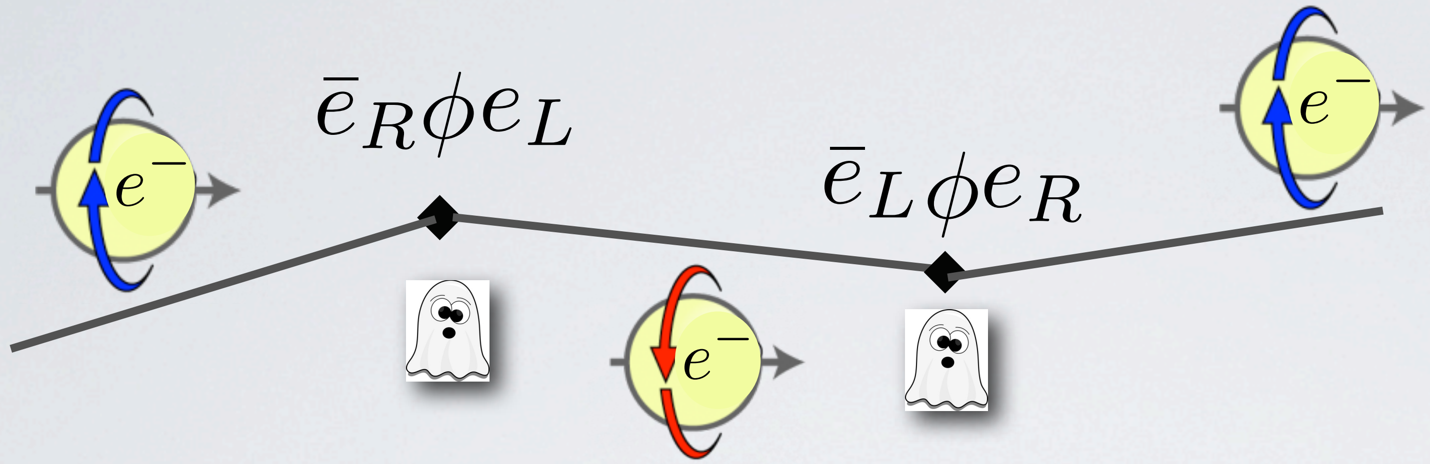


$$e^- = e_L^- + e_R^-$$

Electron mass



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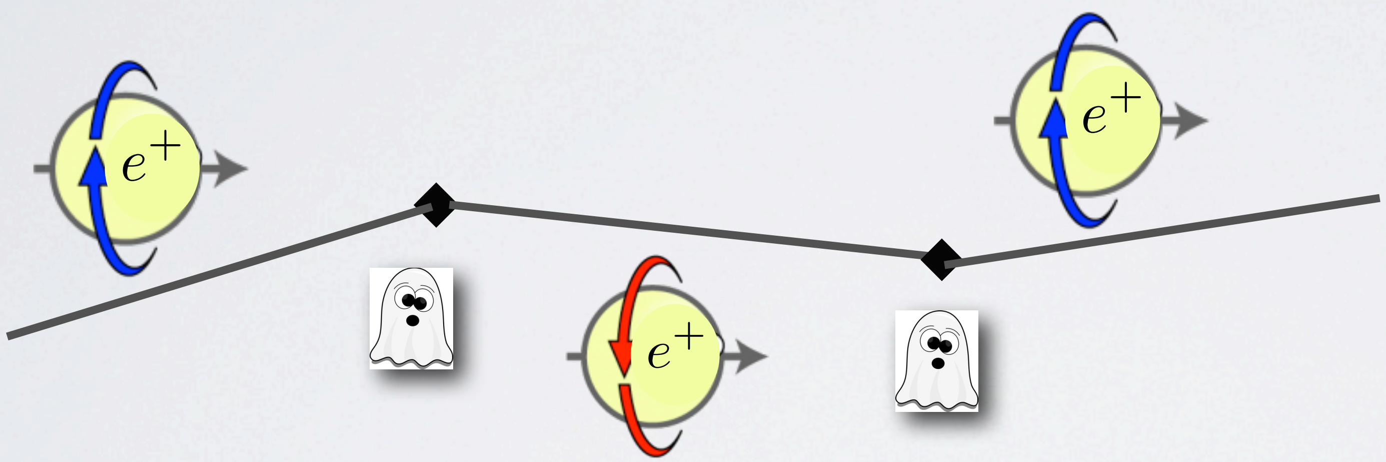

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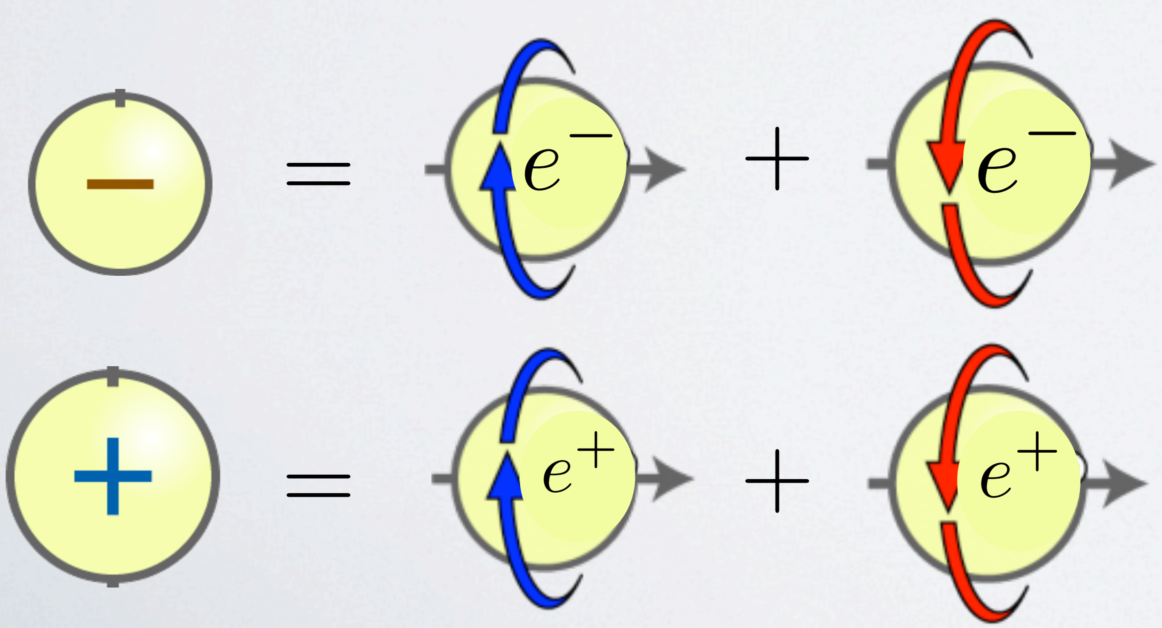

$$e^- = e^-_L + e^-_R$$

$$e^+ = e^+_L + e^+_R$$

Neutrino (Dirac) mass

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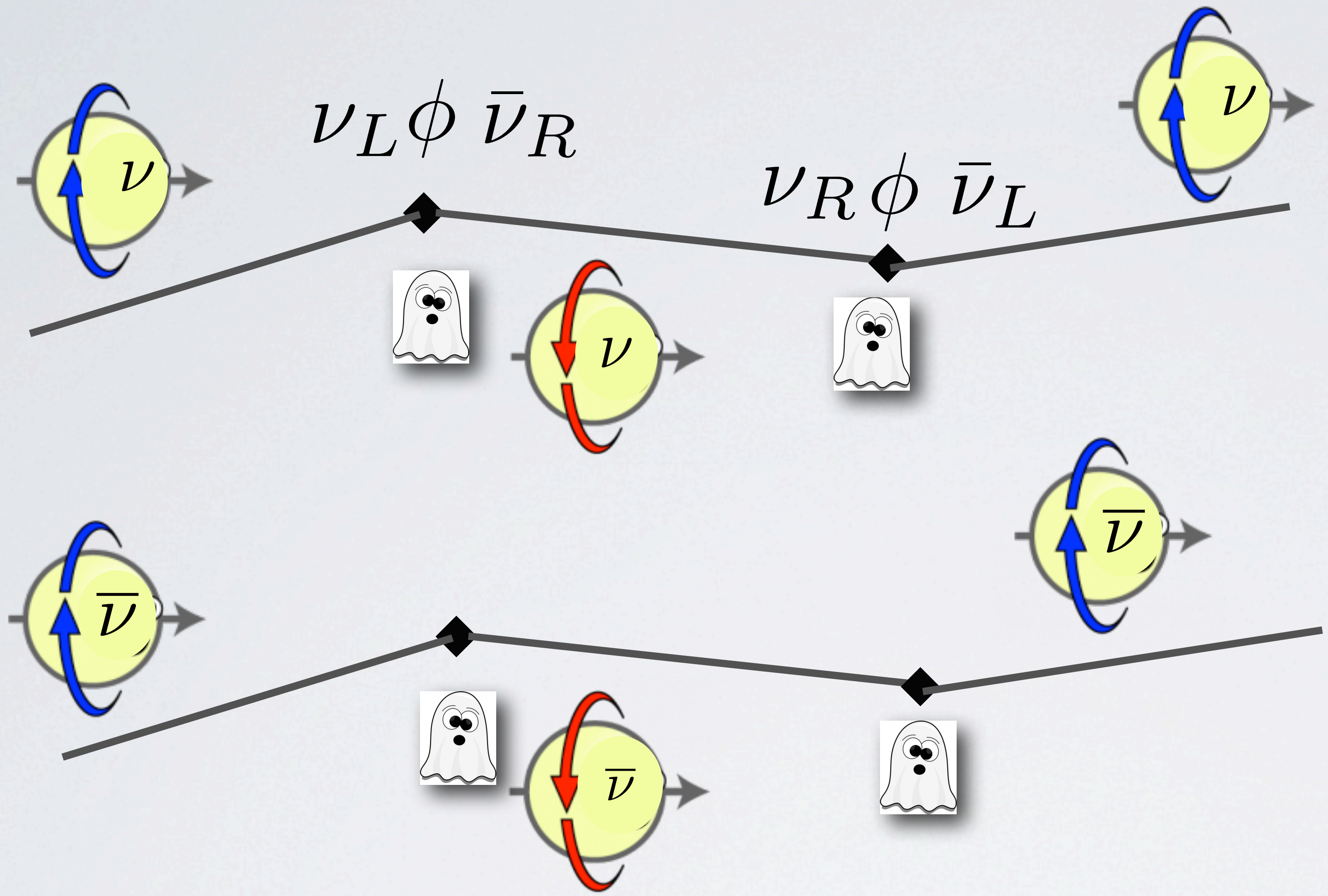
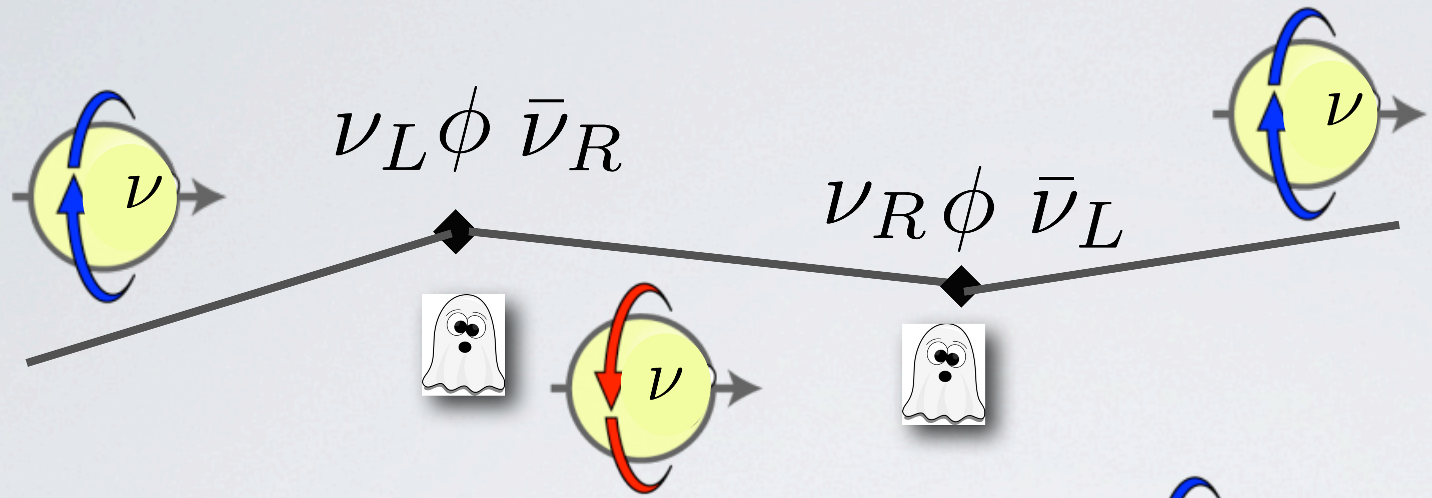
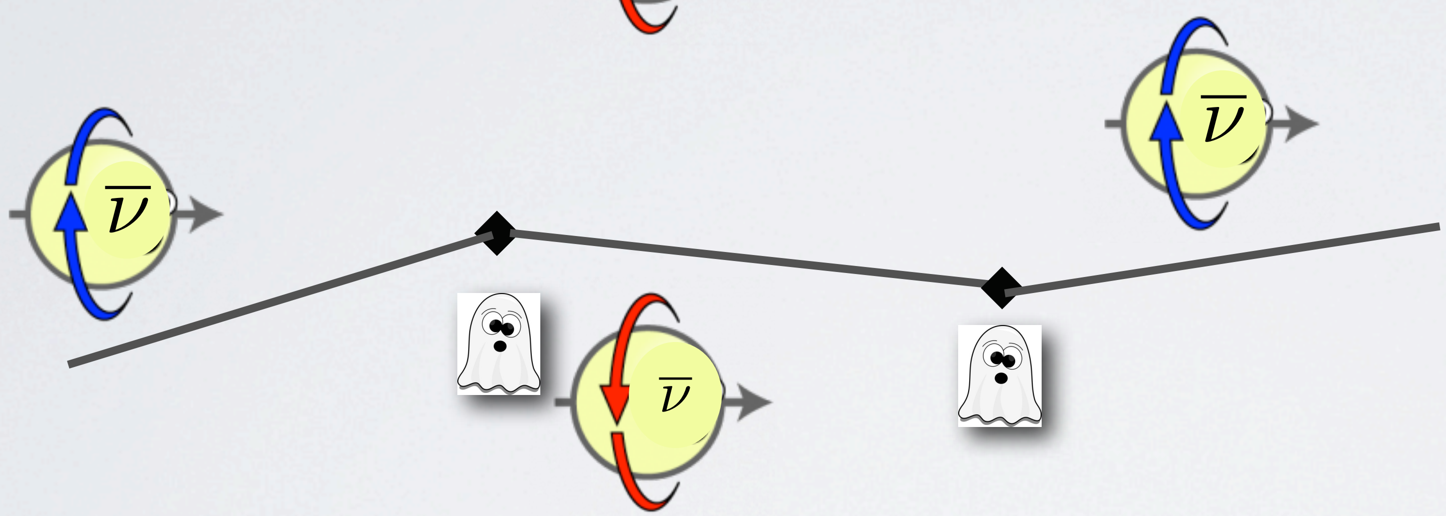
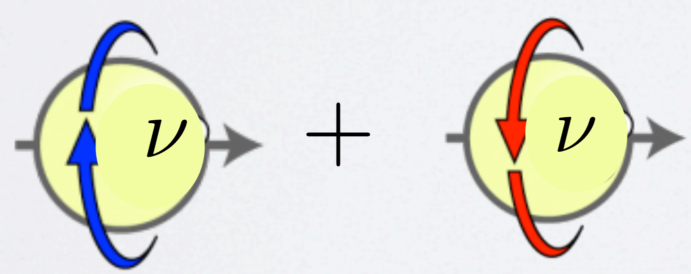


Neutrino (Dirac) mass





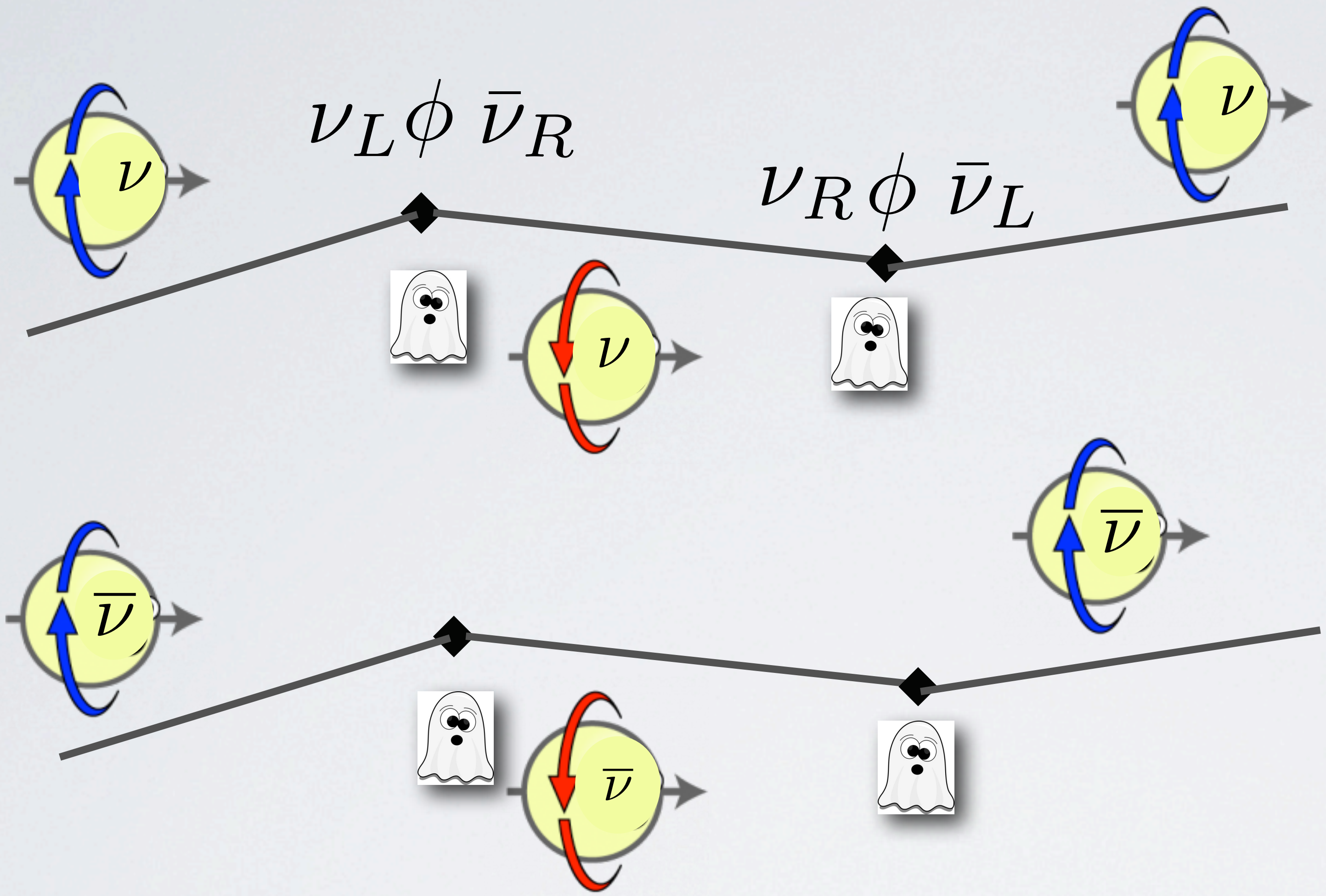
ν = 

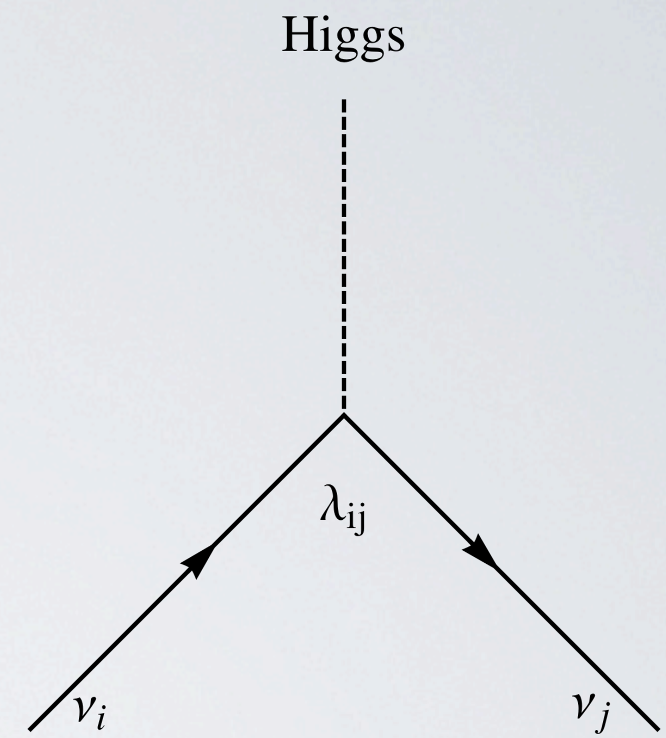
$$\nu = \nu_L + \nu_R$$

$\overline{\nu}$ = 

$$\nu^C = (\nu_L)^C + (\nu_R)^C$$

Neutrino (Dirac) mass

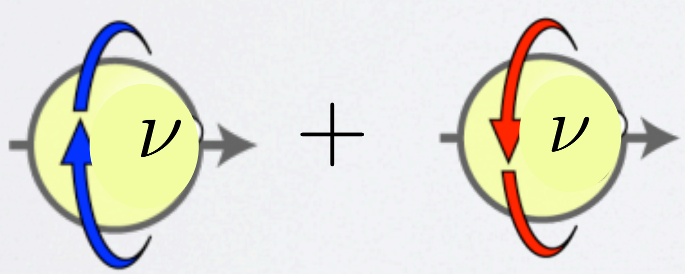




$$-\mathcal{L}_{\mathrm{Dirac}} = \bar{\nu}_L m_\nu \nu_R + h.c.$$

$$m_\nu = \lambda_\nu v$$

ν =

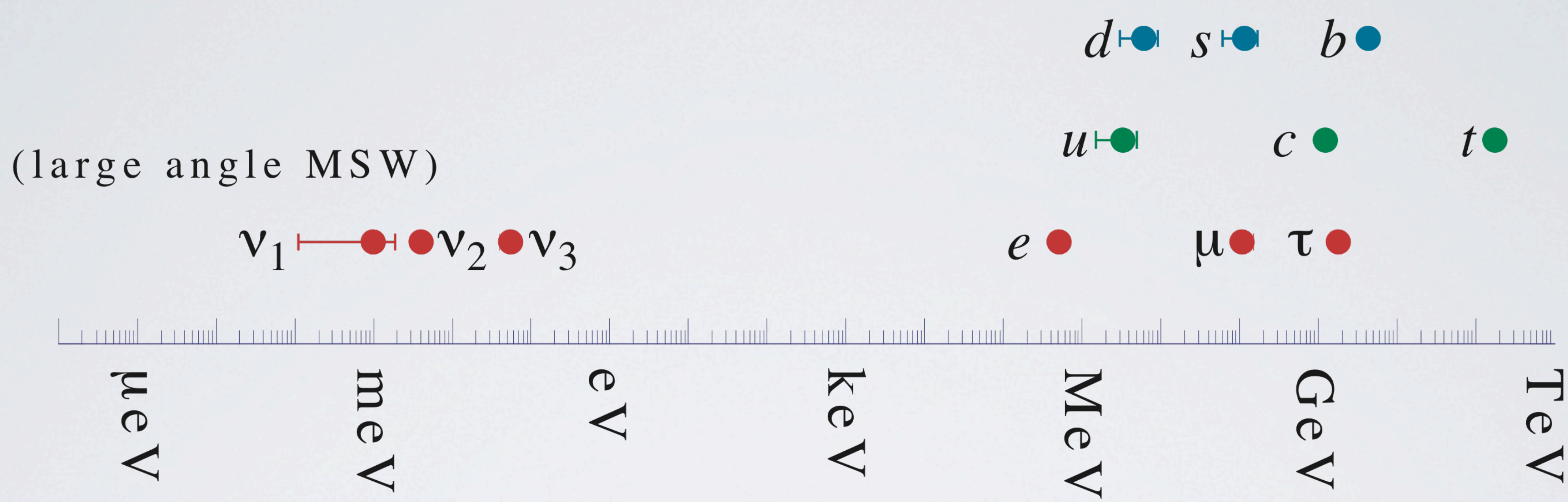


$$\nu = \nu_L + \nu_R$$

$\overline{\nu}$ =

$$\nu^C = (\nu_L)^C + (\nu_R)^C$$

Neutrino mass scale



Why are neutrino masses so small compared with the other fermions? Smaller Yukawas not very attractive explanation...

$$\lambda_\nu << \lambda_e?$$

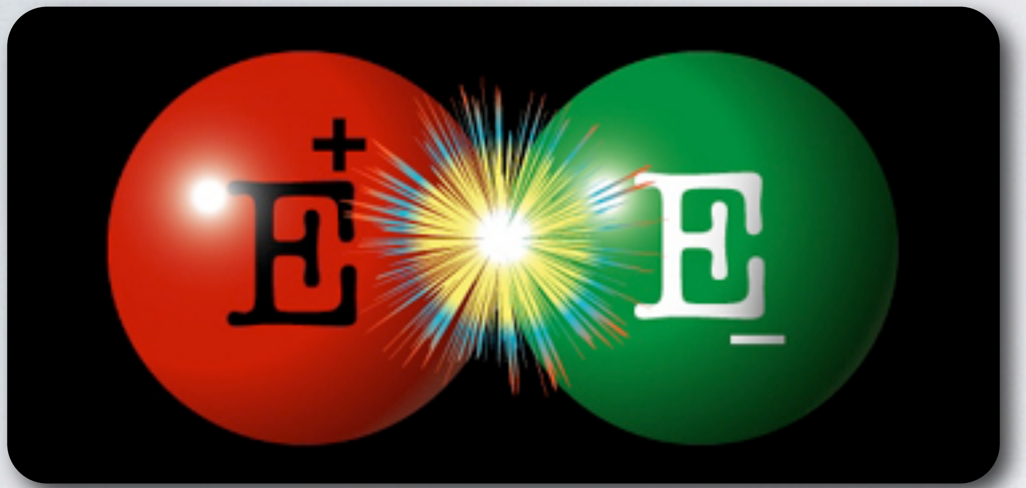
Majorana neutrinos

Neutrino charge conjugation

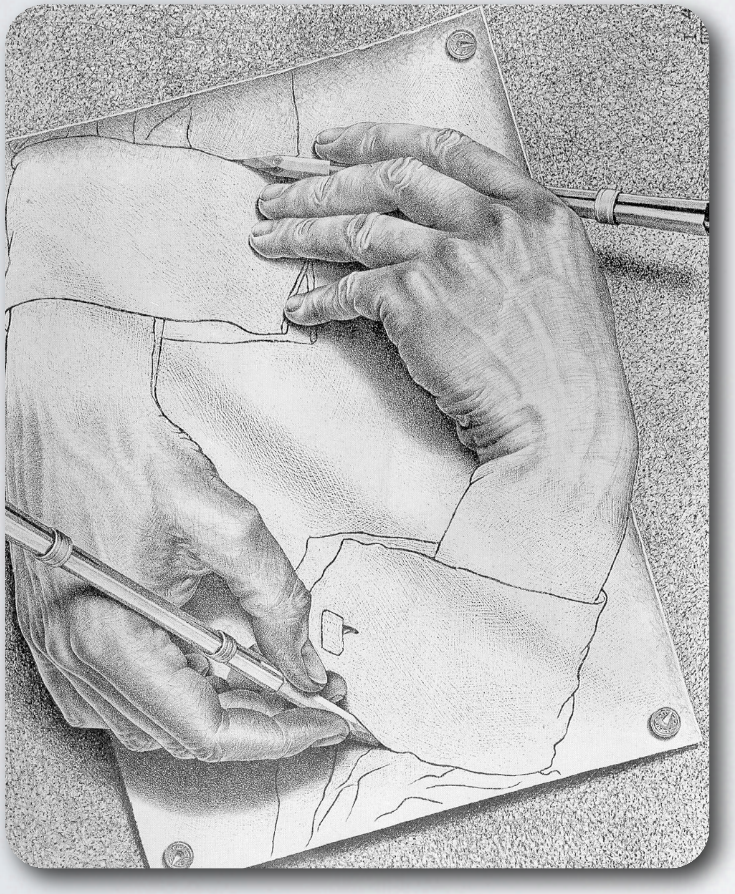
Neutrino charge conjugation

Charge conjugation reverses the electric charge of the electron.

Neutrino charge conjugation



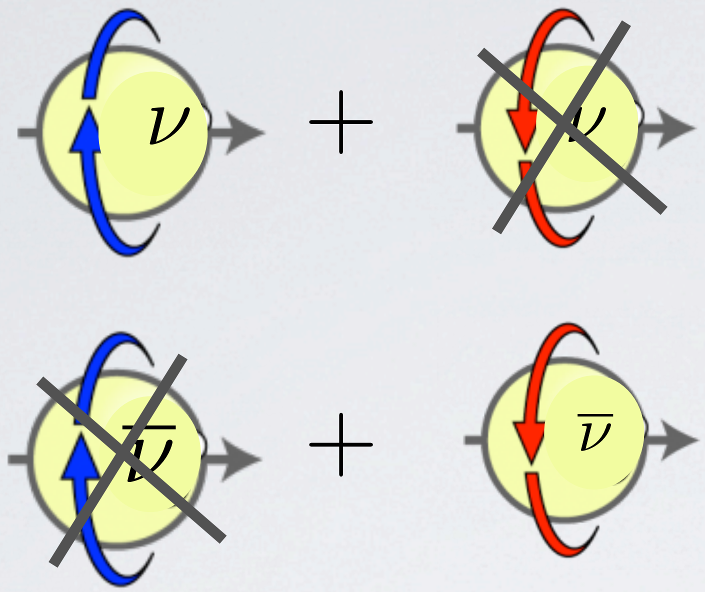
Charge conjugation reverses the electric charge of the electron.



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

Majorana neutrinos

$$\nu \quad =$$



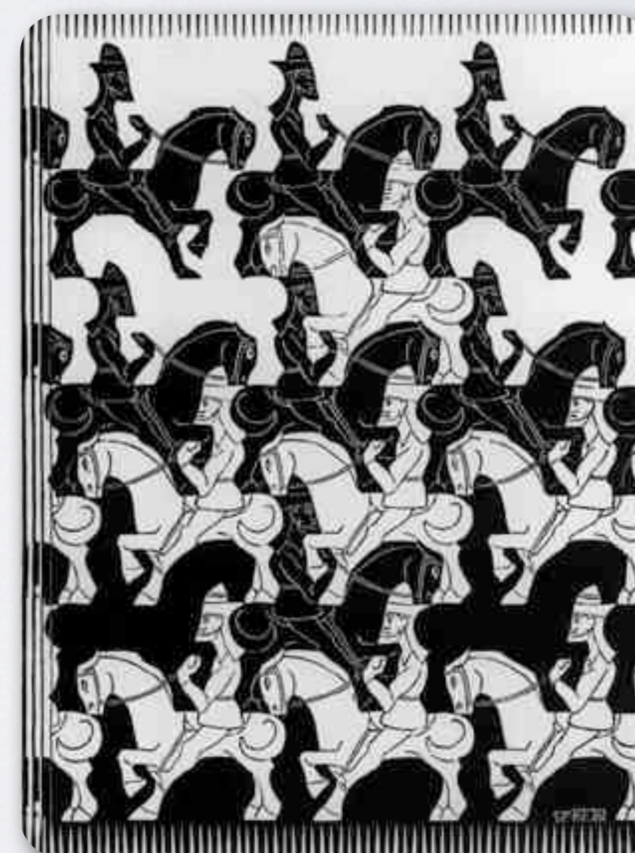
$$\nu = \nu_L + \cancel{\nu_R}$$

$$\nu^C = (\nu_L)^C + \cancel{(\nu_R)^C}$$

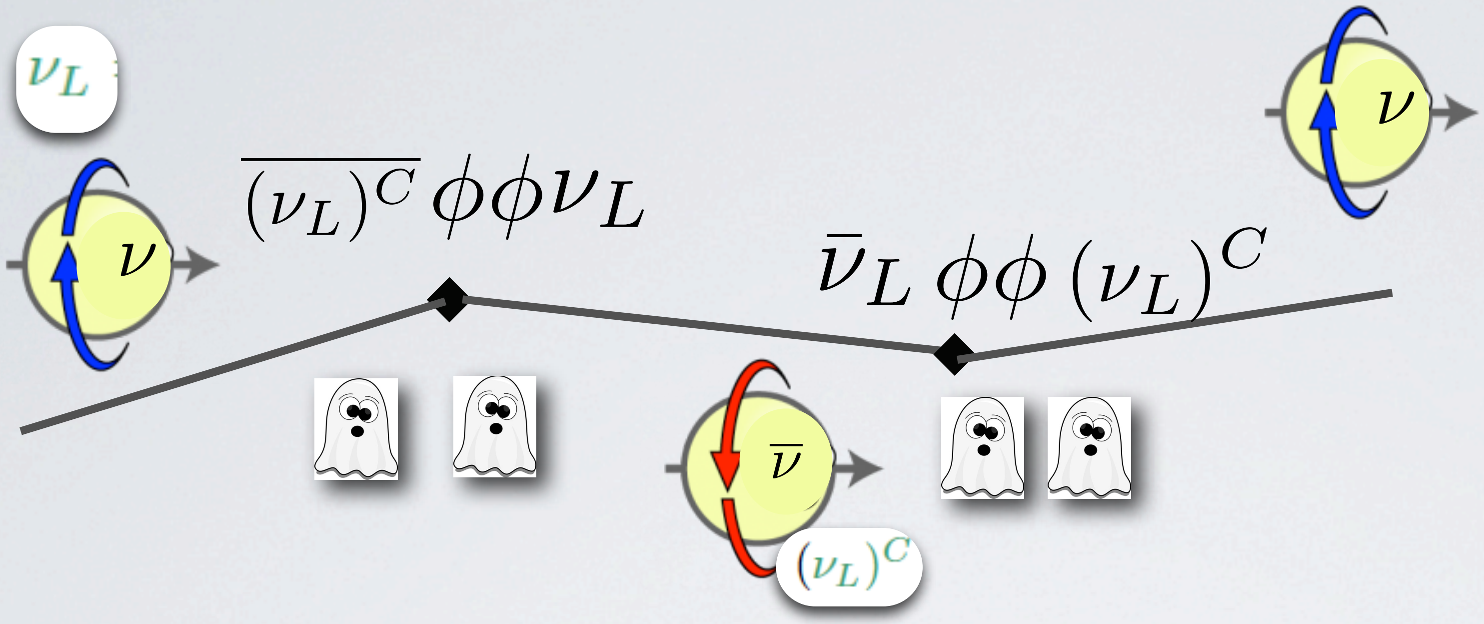
$$\nu = \bar{\nu}$$

$$\nu = \nu_L + \nu_L^C \qquad \nu^c = \nu$$

The neutrino is made, like in the Escher's tableau of black and white chevaliers.



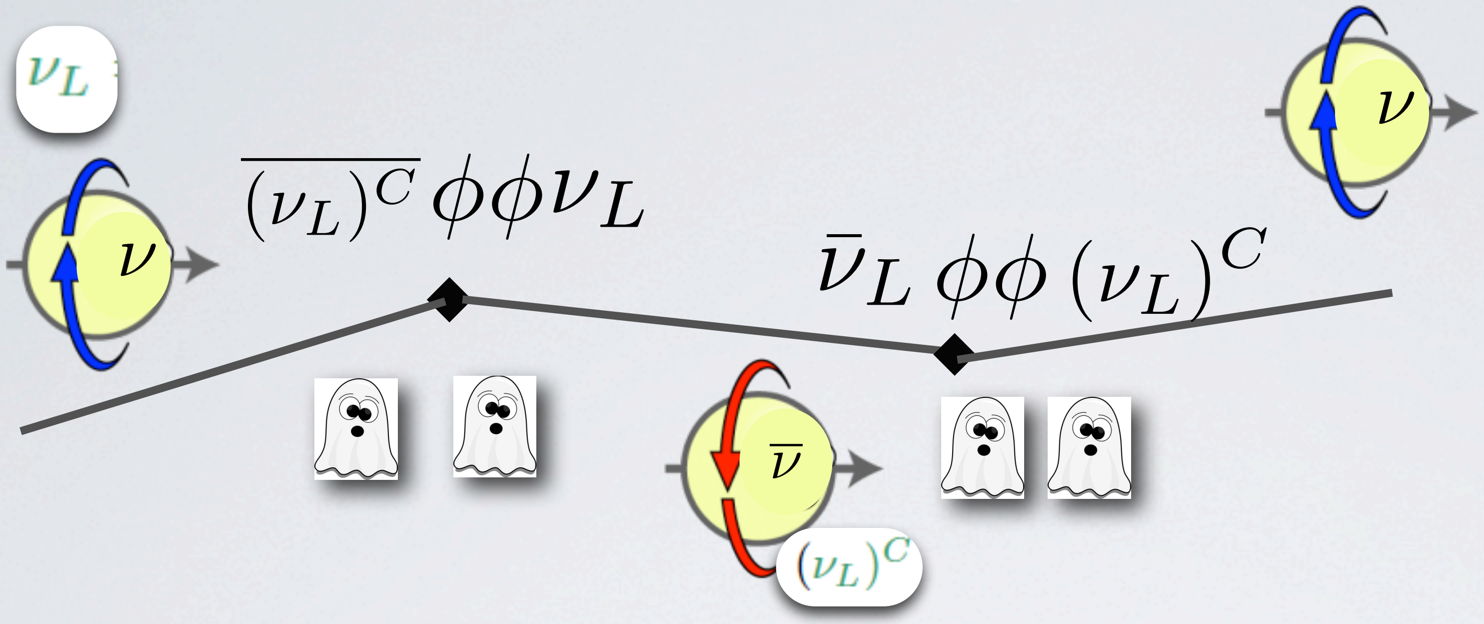
Neutrino (Majorana) mass



$$\nu_L = (\nu_R)^C \qquad (\nu_L)^C = \nu_R$$

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

Neutrino (Majorana) mass



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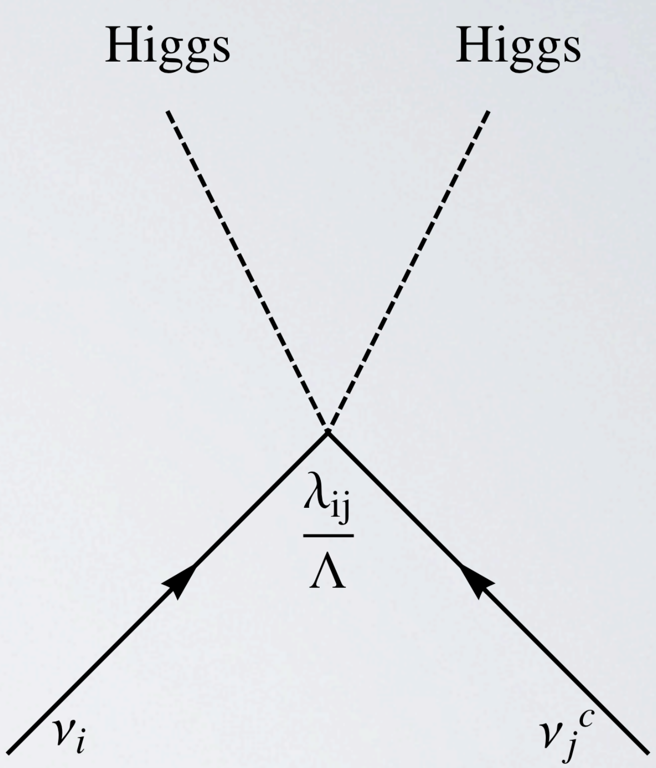
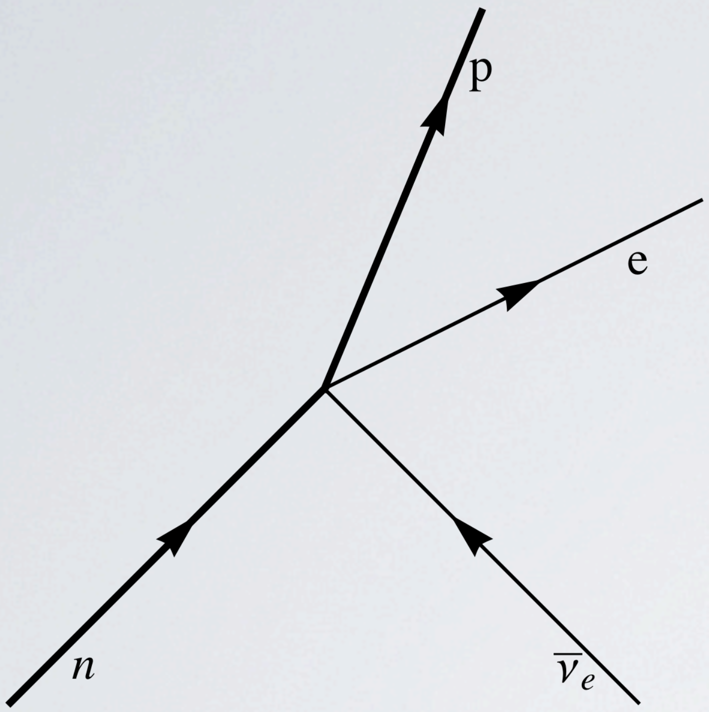


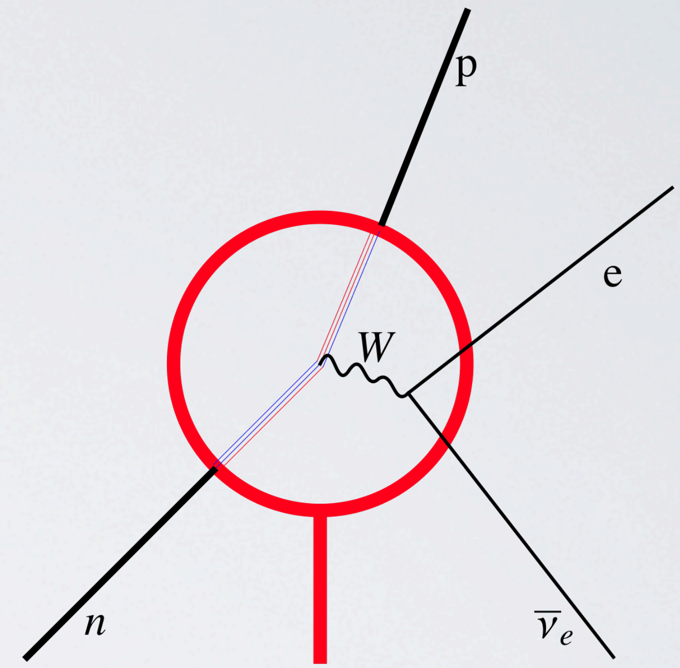
$$m_\nu \sim \lambda \frac{v^2}{\Lambda}$$

Effective theory (Fermi constant)

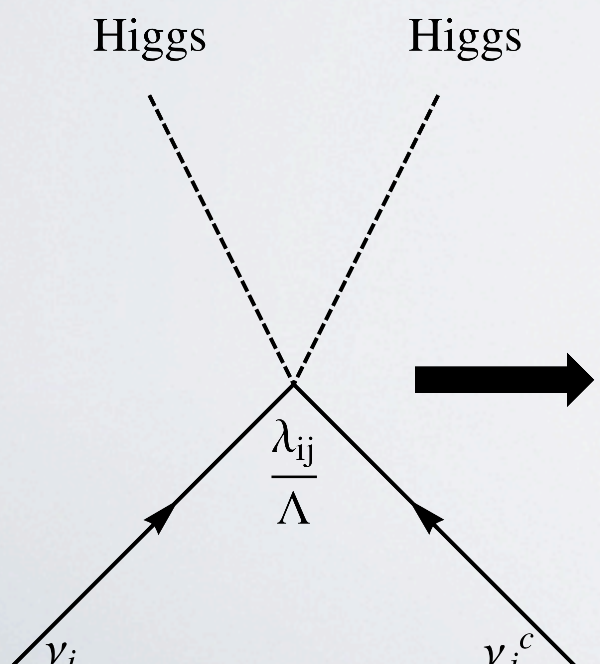


$$G_F \sim \frac{1}{M_W^2}$$

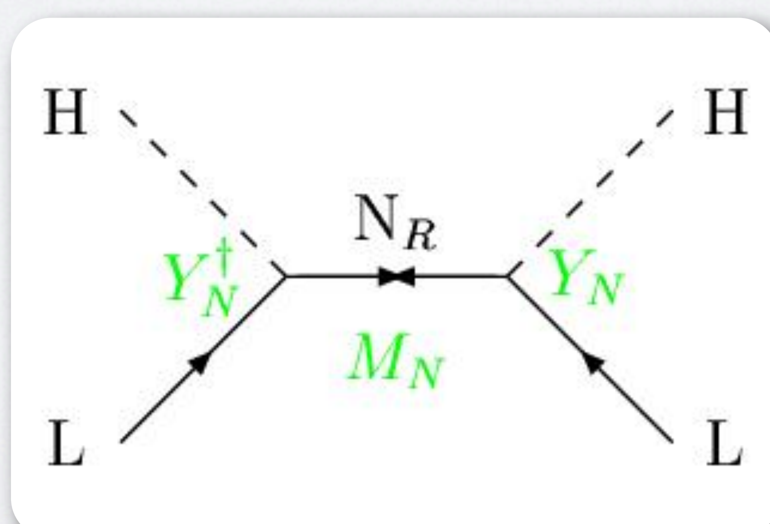
Standard Model



Effective theory (Λ)



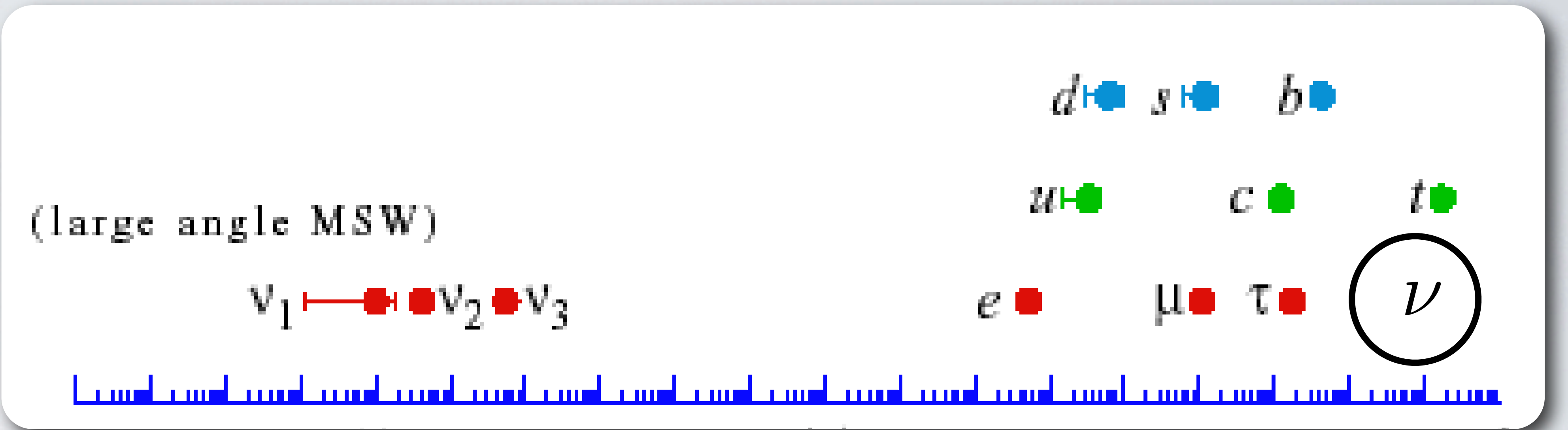
Extension of Standard Model



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

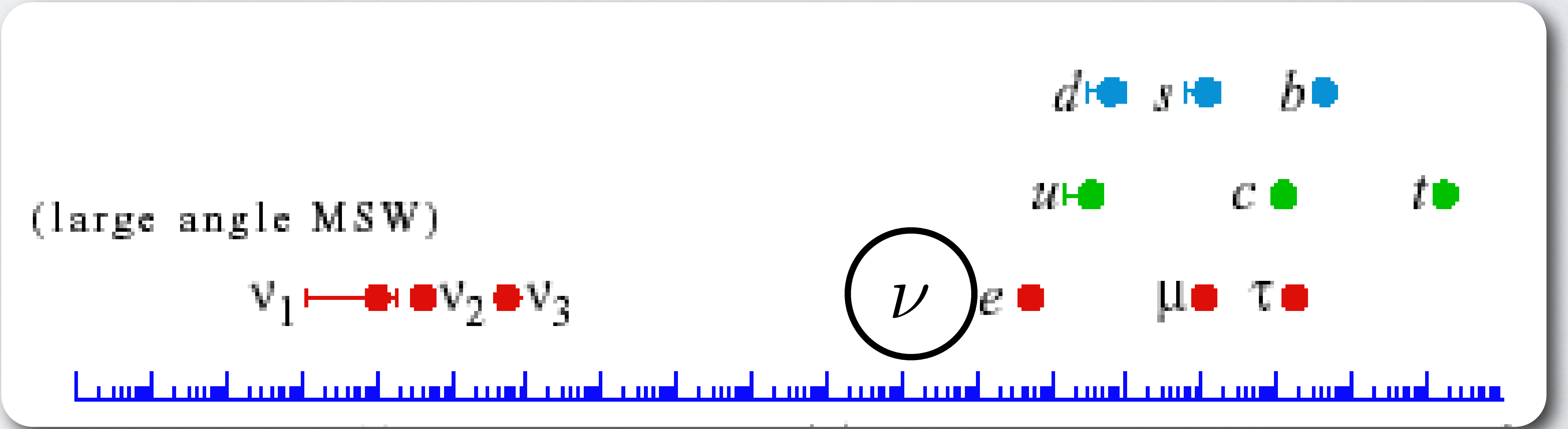
See-saw model & neutrino masses

M_N = GUT



Yukawa

M_N = TeV

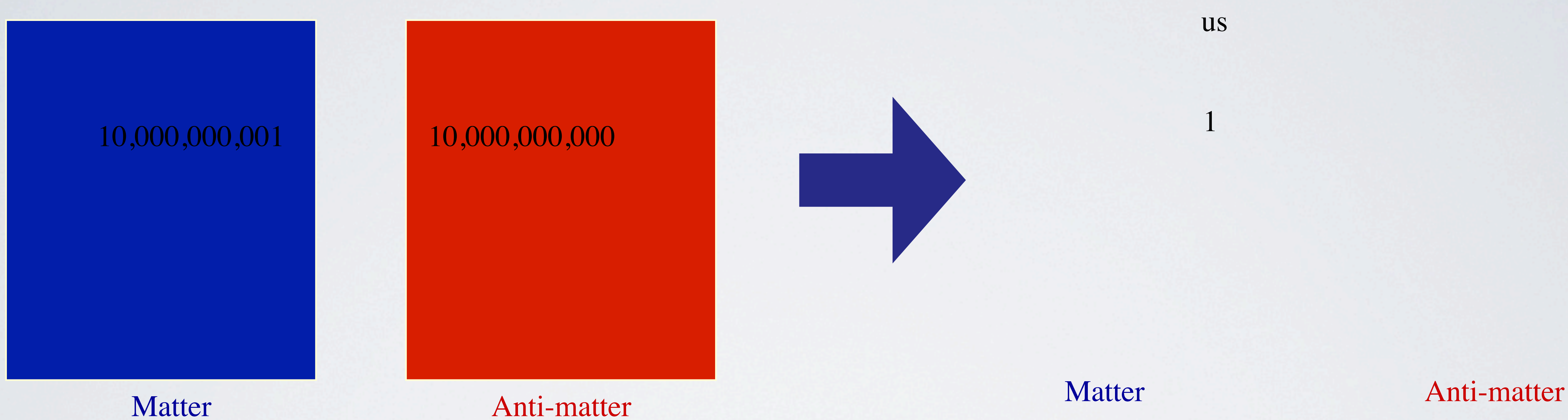


Yukawa

The mystery of the missing antimatter

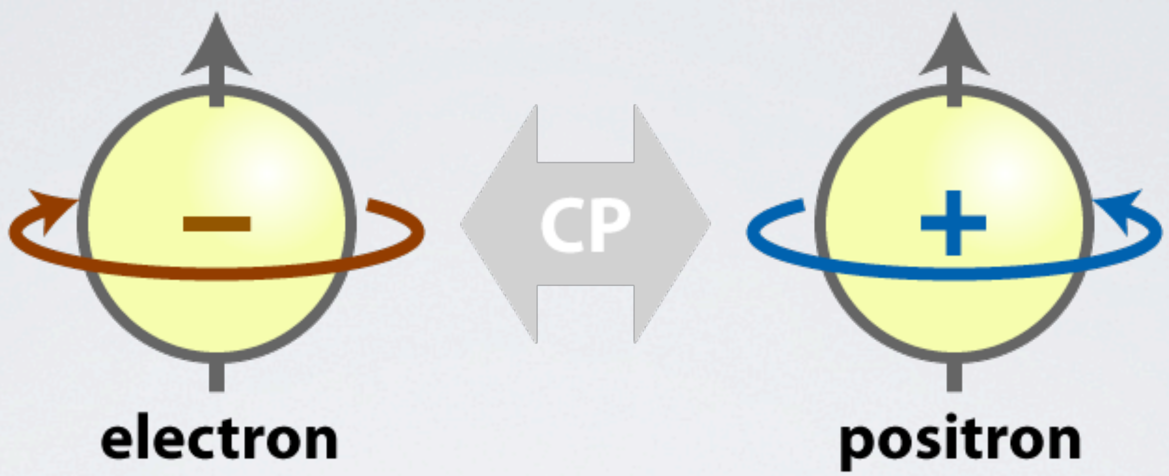
- The Big-Bang theory of the origin of the Universe requires matter and antimatter to be equally abundant at the very hot beginning

The great annihilation



What generated the asymmetry between matter and antimatter?

CP symmetry



- Nature violates CP conservation. We have experimental evidence of it in the quark sector. This means that the mirror world of antiparticles is not identical to the world of particles.

- Neutrinos could also violate CP, although this hast not yet been established experimentally.

CP violation and Majorana neutrinos

$$N \rightarrow e^- + H^+ \quad \text{and} \quad N \rightarrow e^+ + H^-$$

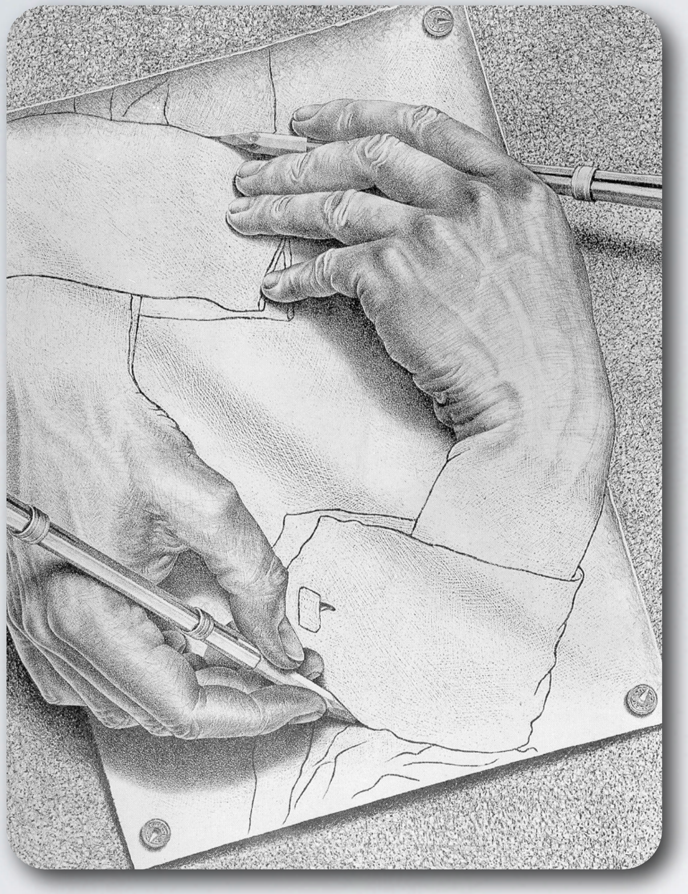
Standard-Model Higgs

- 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

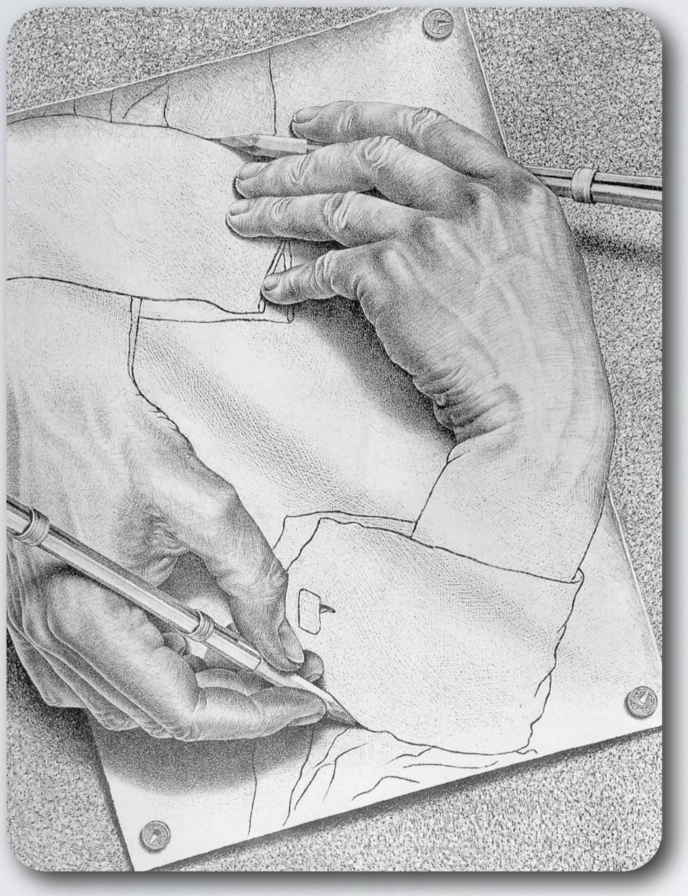
- Leptonic asymmetry is later transferred to baryons, resulting in...

The Universe

The Universe



The Universe



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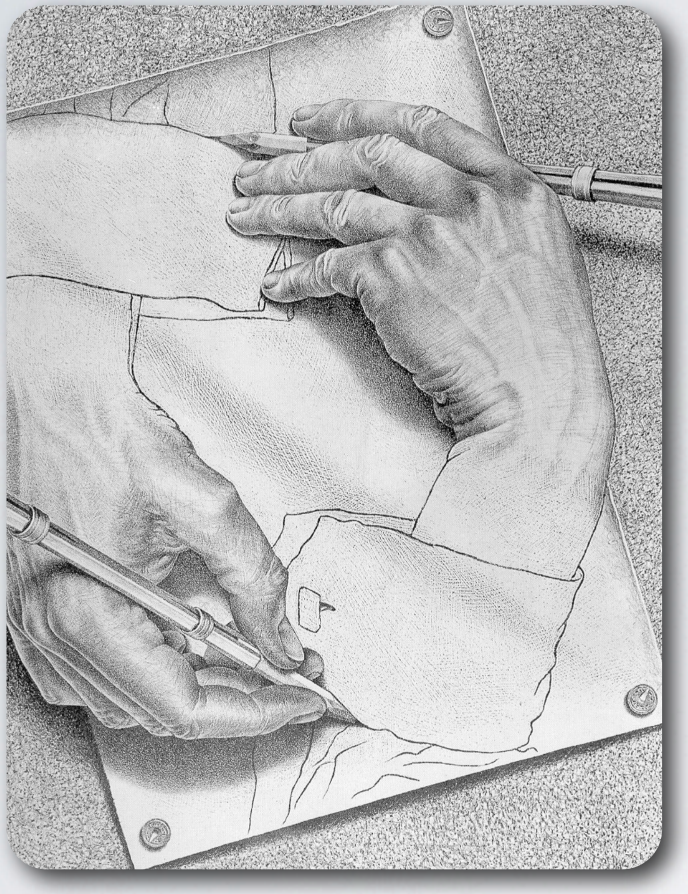
The Universe



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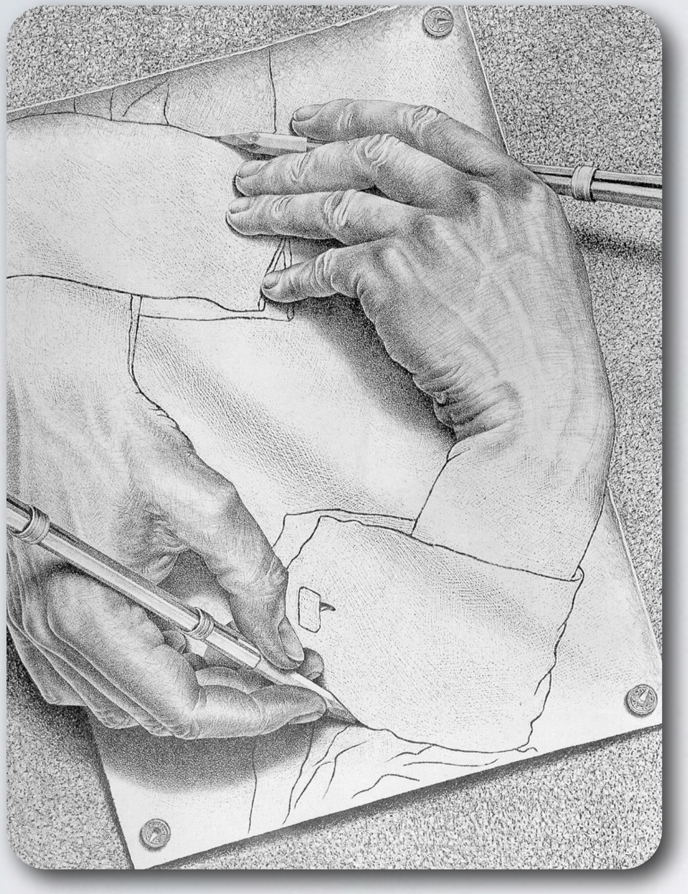
The Universe



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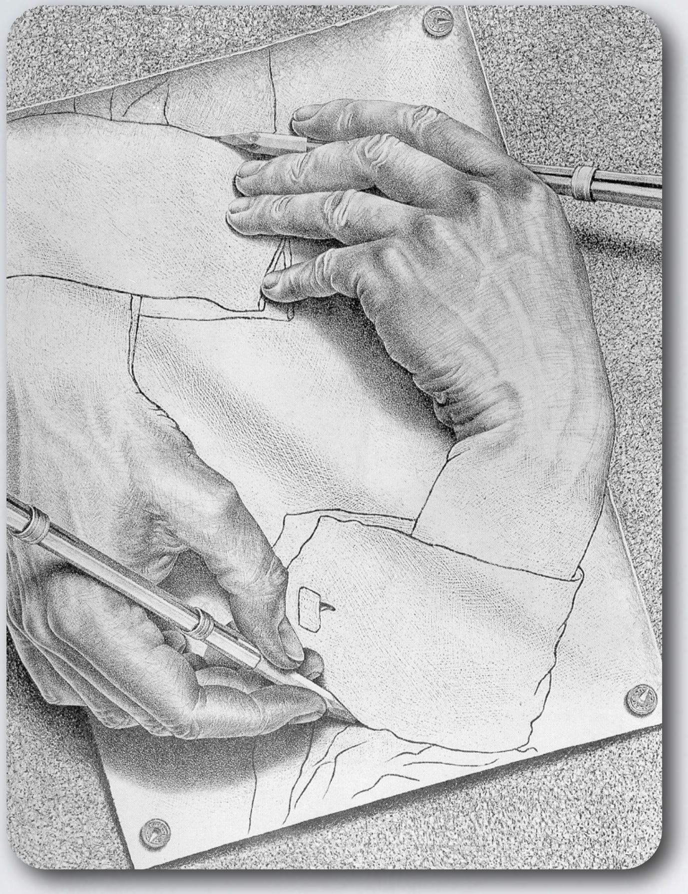
The Universe



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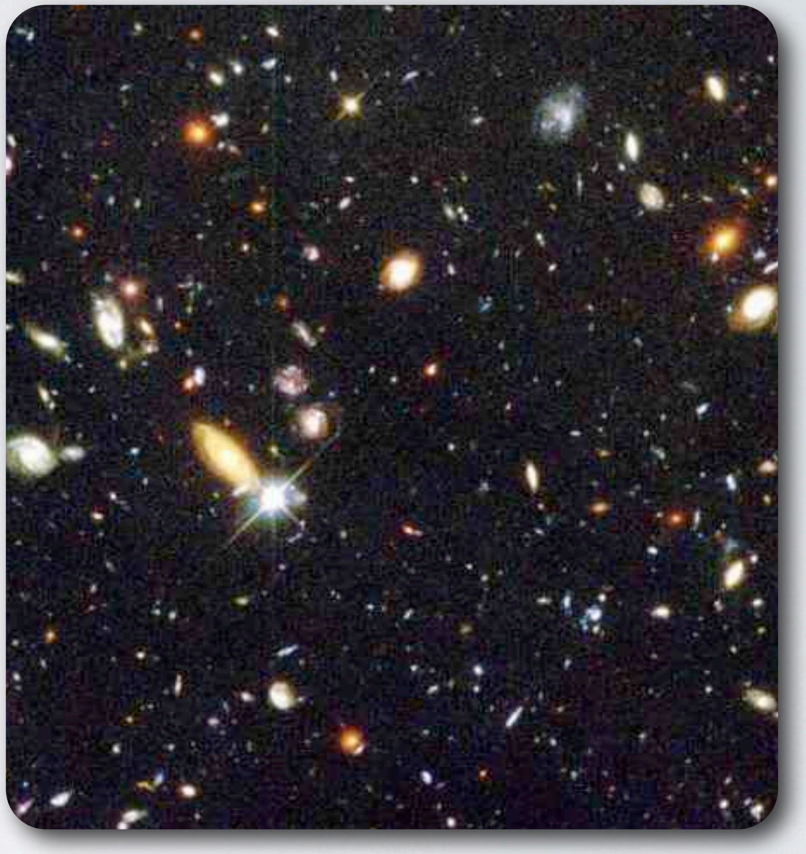
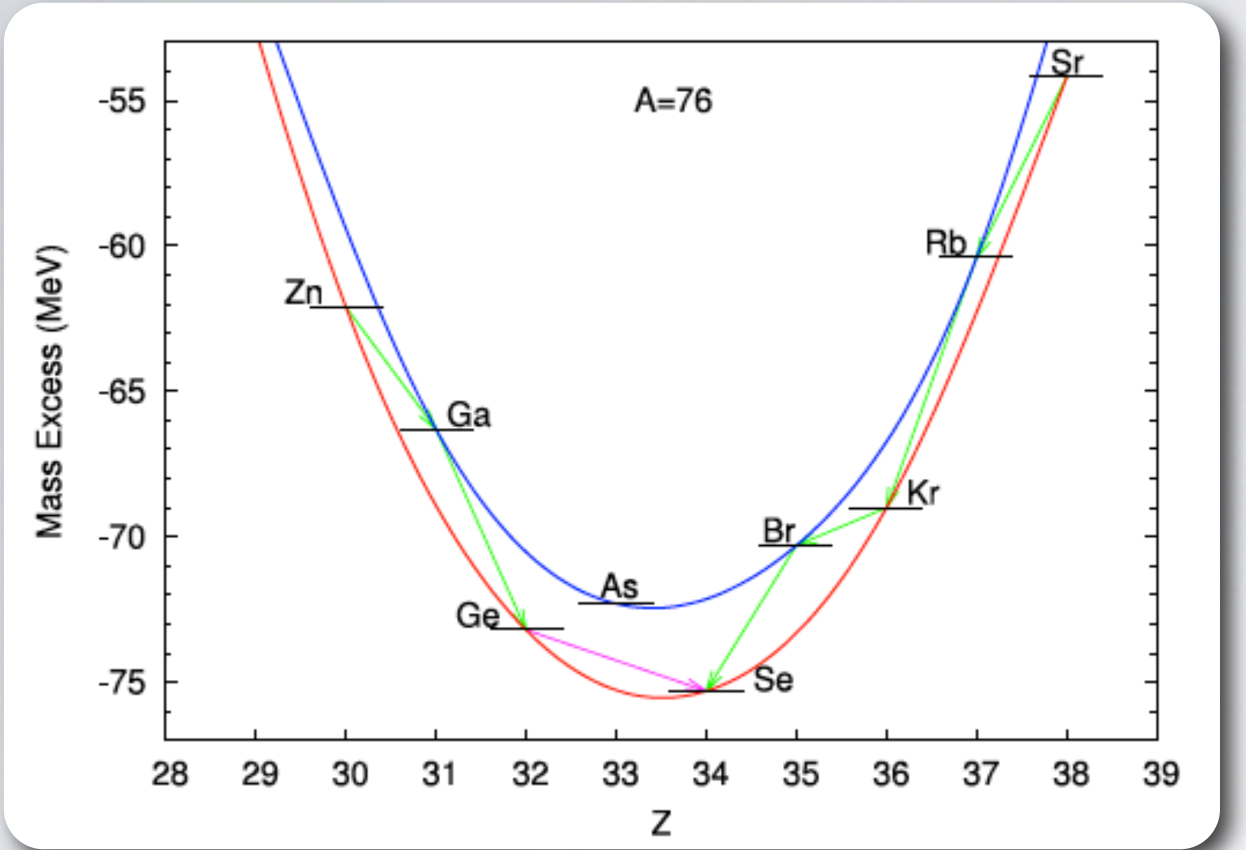
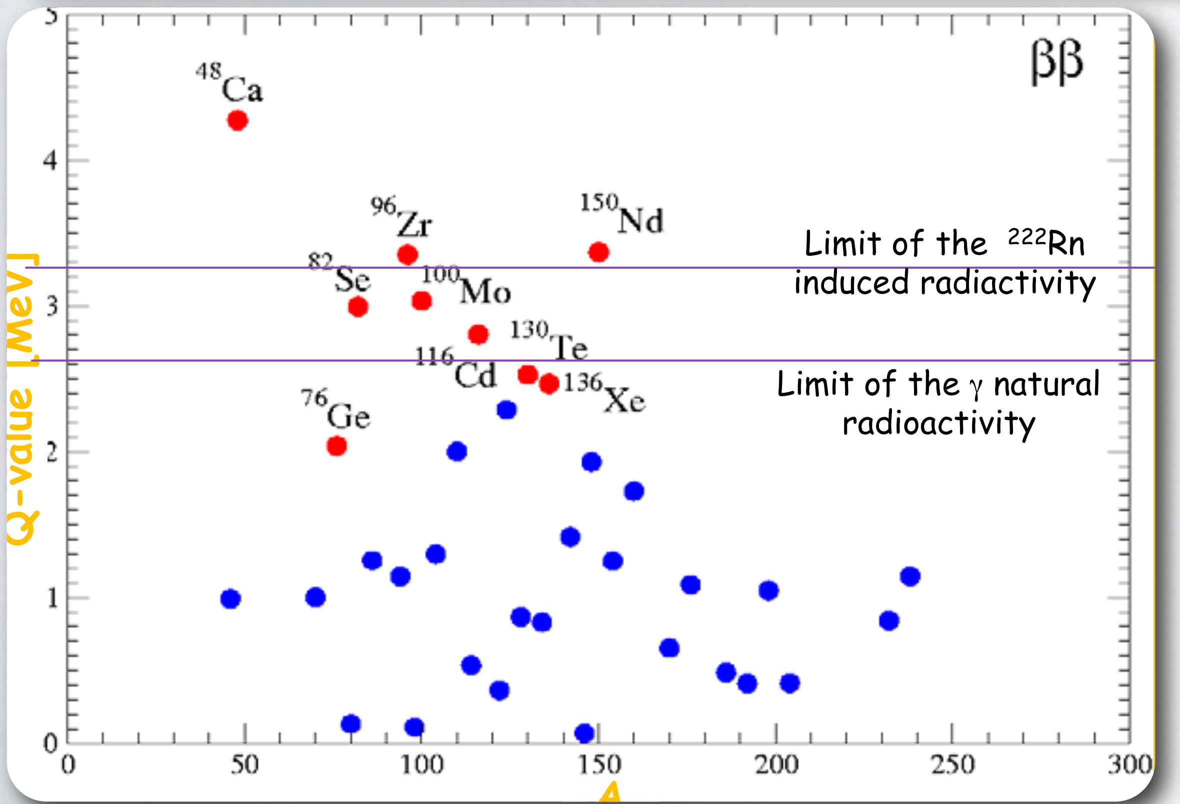


Are neutrino Majorana particles? How to find out


Reiner Knizia
Double
or
Nothing
OUT
überplay
Funagain.com

Double beta decay

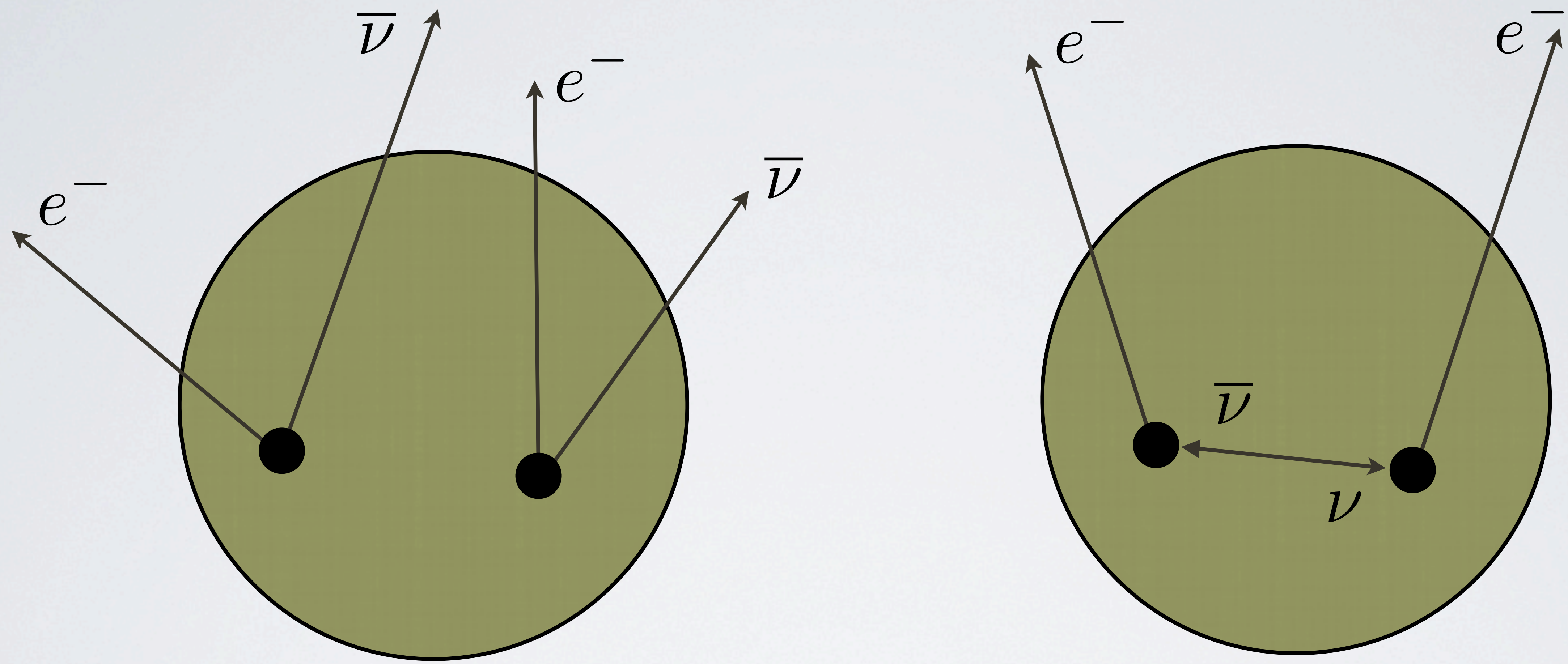




- Some nuclei, otherwise quasi stable can decay by emitting two electrons and two neutrinos by a second order process mediated by the weak interaction.

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

Double beta decay



$\beta\beta2\nu$

SM-allowed process.
Measured in several nuclei.

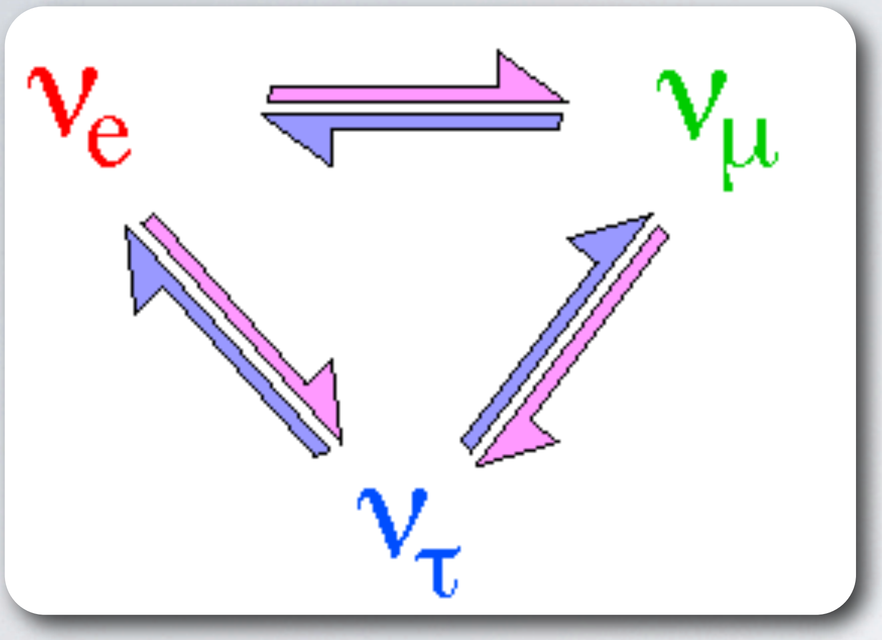
$$T_{1/2} \sim 10^{18} - 10^{20}\ \mathrm{y}$$

$\beta\beta0\nu$

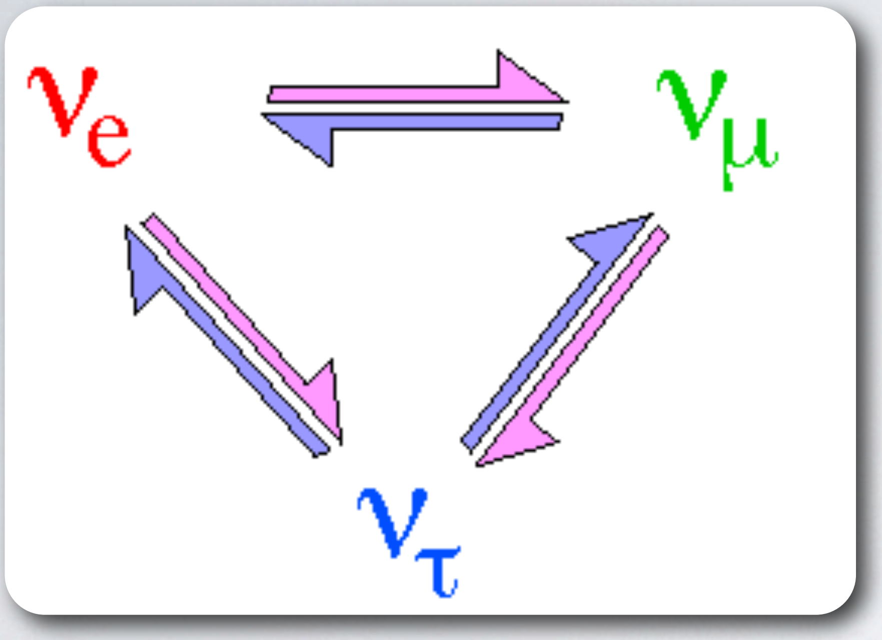
Lepton number violating process.
Requires massive, Majorana neutrinos.

$$T_{1/2} > 10^{25}\ \mathrm{y}$$

Neutrino oscillations

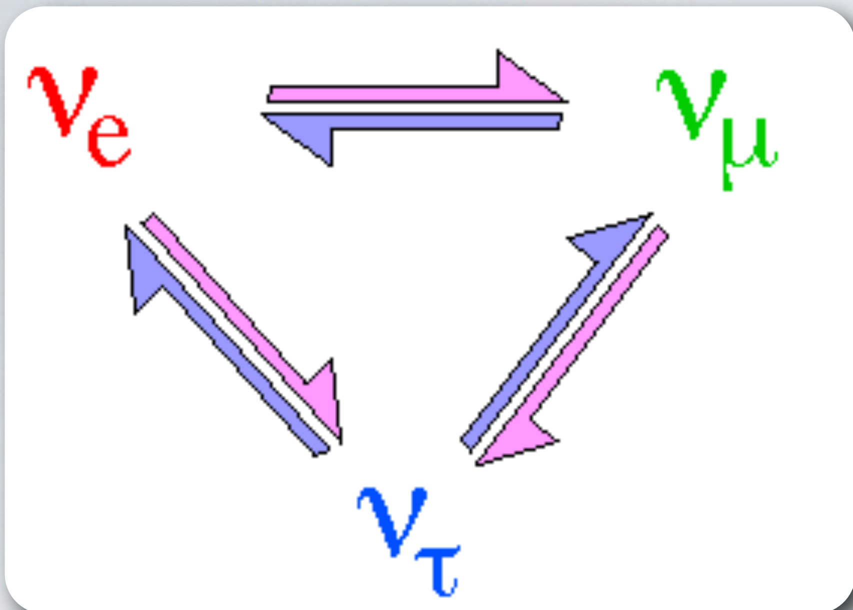


Neutrino oscillations



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

Neutrino oscillations

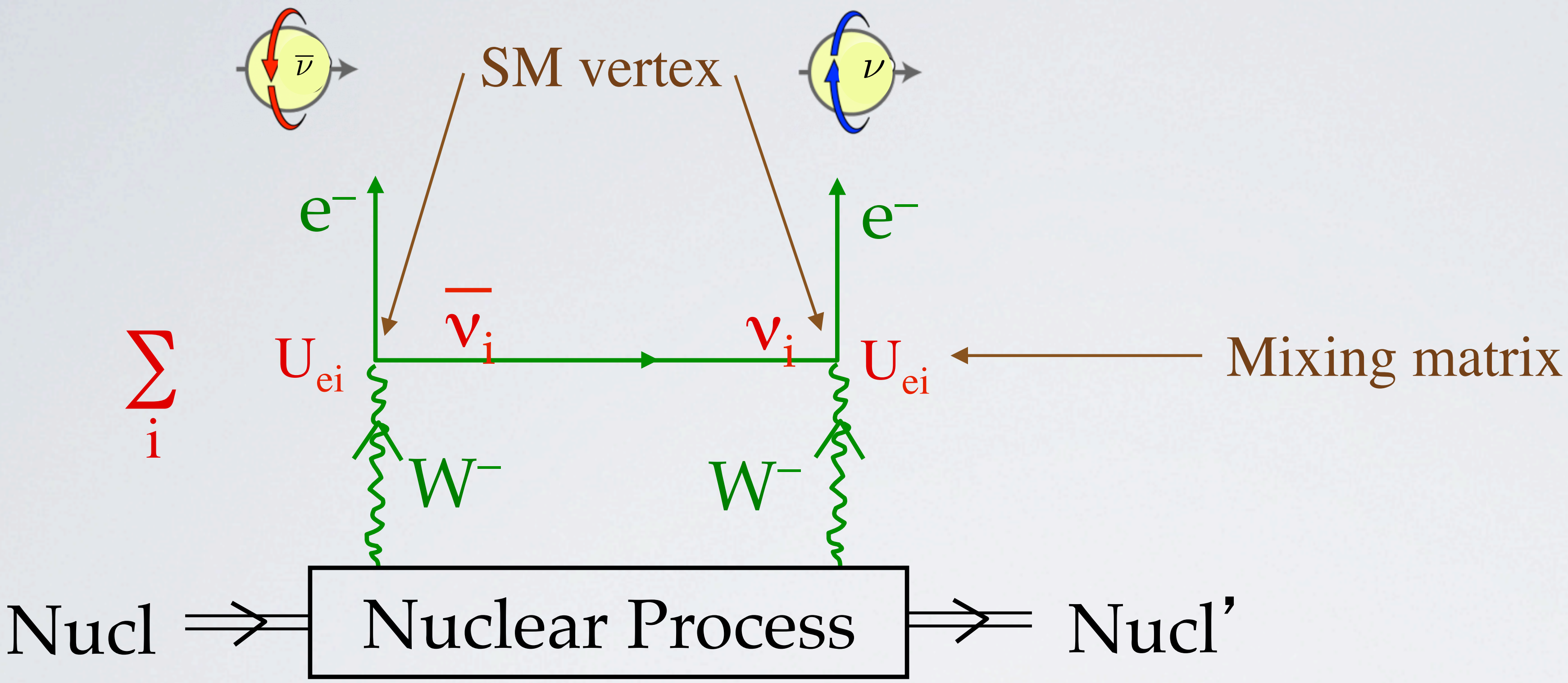


$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS}(\theta_{12}, \theta_{23}, \theta_{13}, \delta, ...) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\begin{aligned} U &= \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \\ &= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix} \\ &= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix} \end{aligned}$$

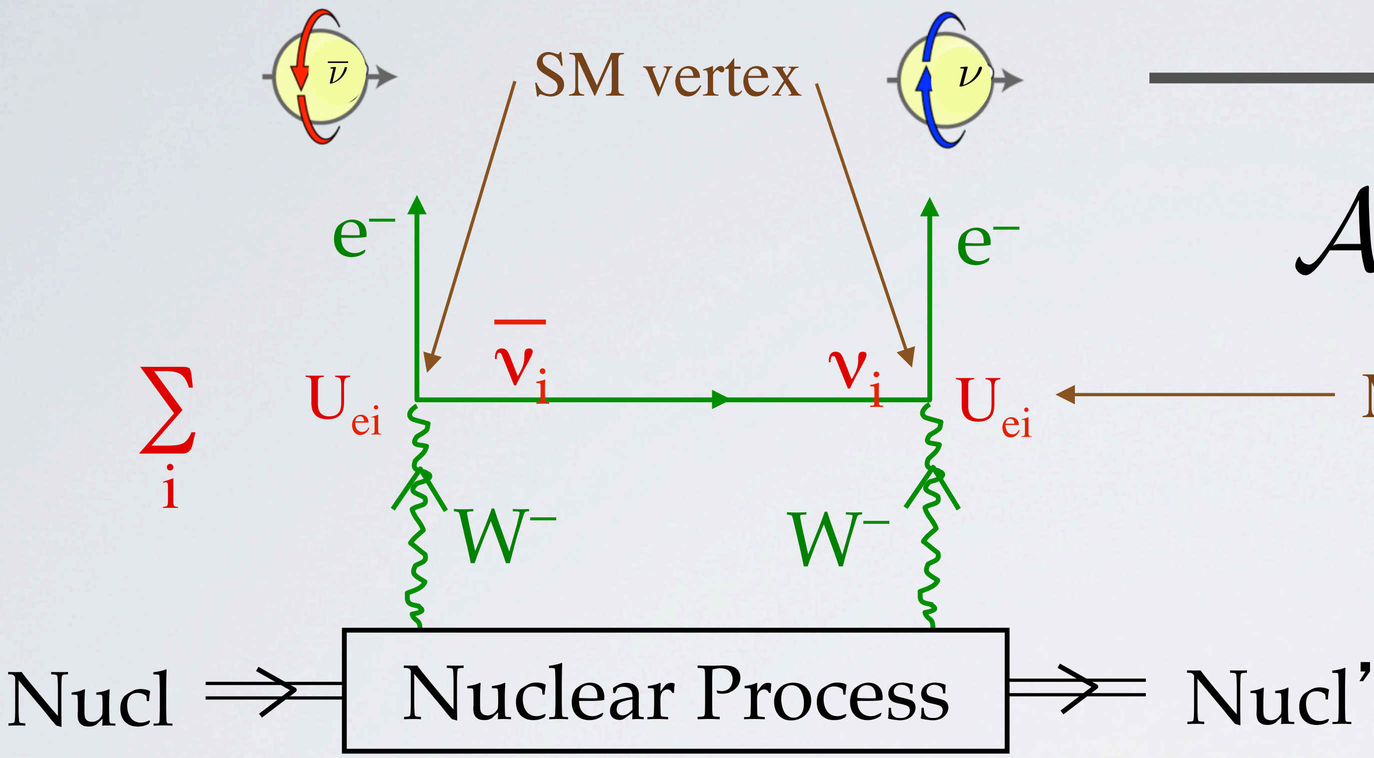
bb0nu decay

bb0nu decay



SM vertex
$\bar{\nu}$
ν
e^-
e^-
$\bar{\nu}_i$
ν_i
$\sum_i$
U_{ei}
U_{ei}
Mixing matrix
W^-
W^-
Nucl
Nuclear Process
Nucl'

bb0nu decay

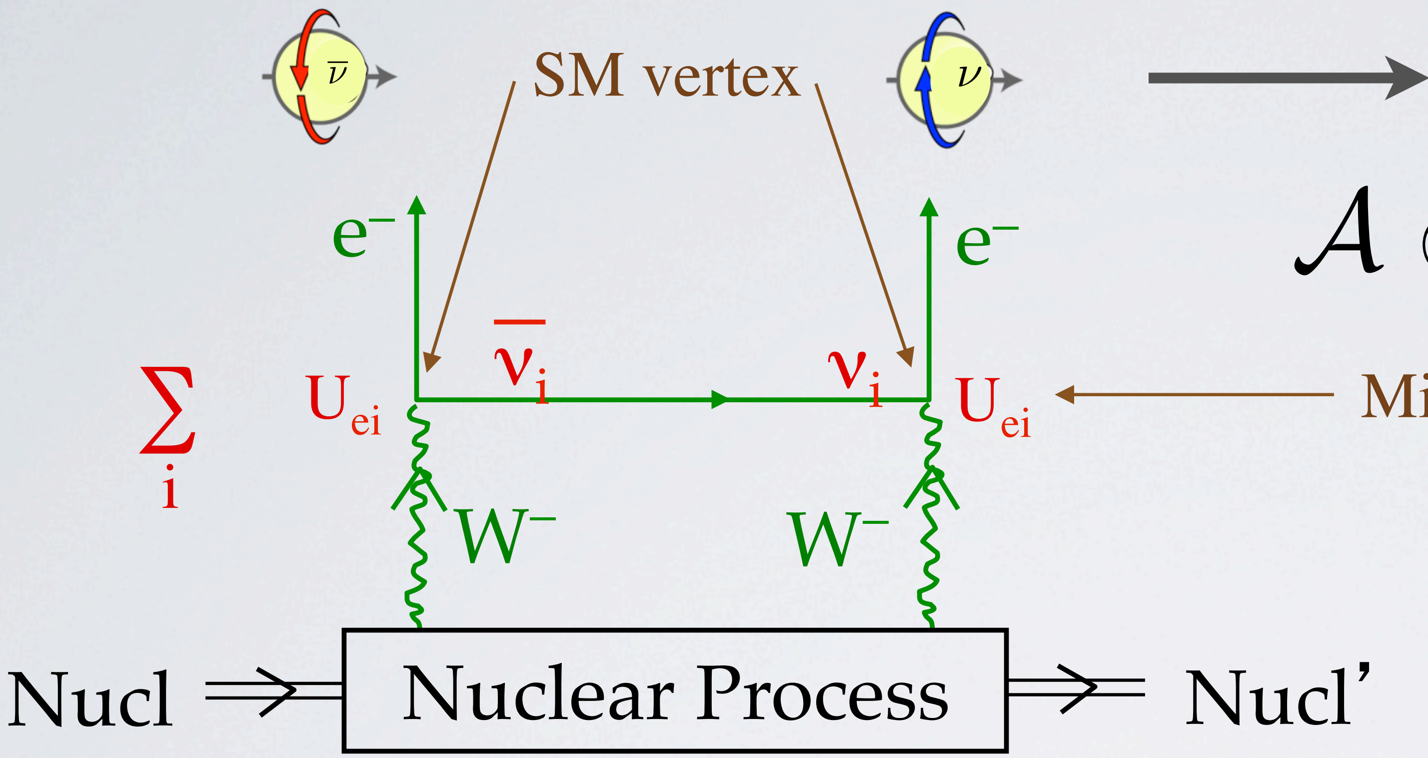


helicity flip $\propto \dfrac{m_i}{E}$

$\mathcal{A} \propto m_i$ **for each** ν_i

Mixing matrix

bb0nu decay



Mixing matrix

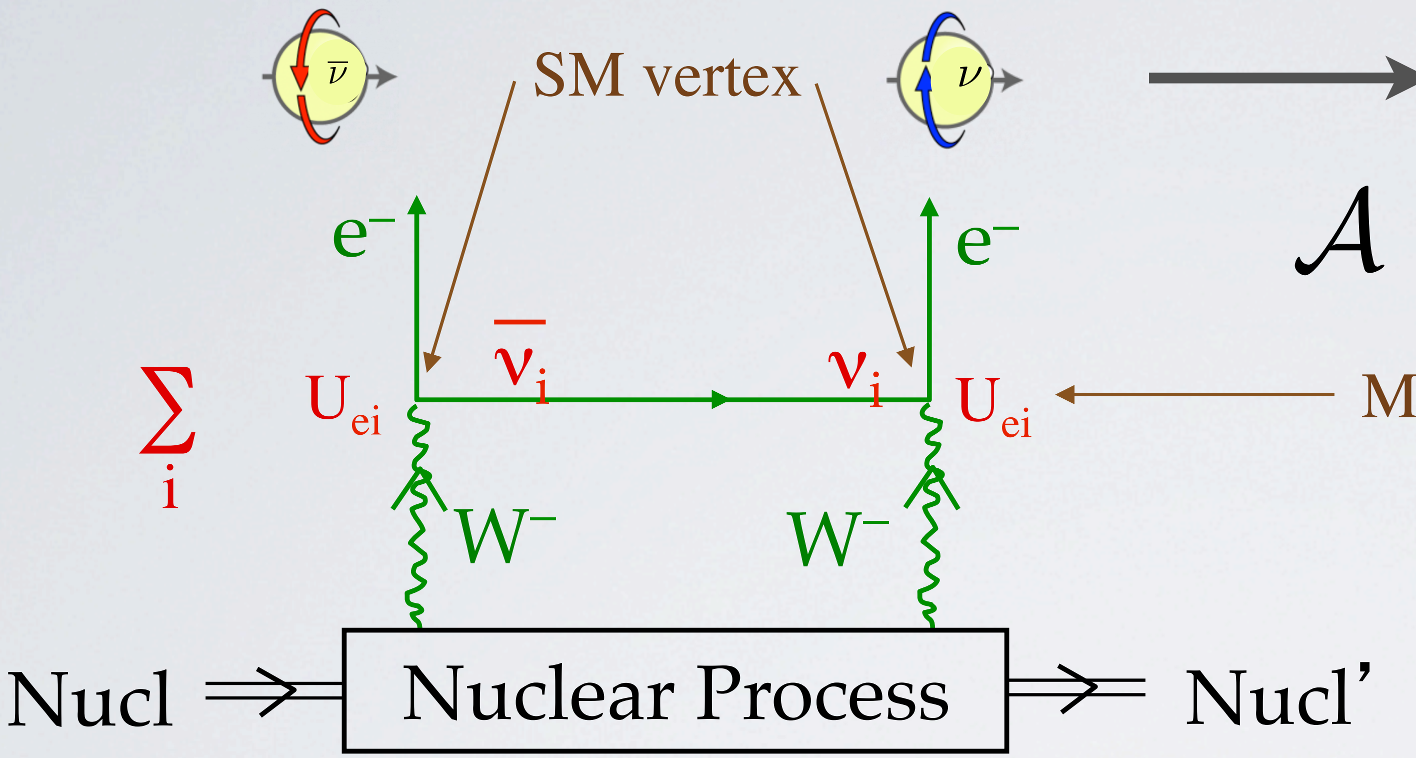
helicity flip $\propto \frac{m_i}{E}$

$\mathcal{A} \propto m_i$ **for each** ν_i

$$U_{MNSP} \sim \begin{pmatrix} 0.8 & 0.5 & 0.026 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

$$m_{\beta\beta} = ||U_{e1}|^2 m_1 + e^{i\alpha_1}|U_{e2}|^2 m_2 + e^{i\alpha_2}|U_{e3}|^2 m_3|$$

bb0nu decay



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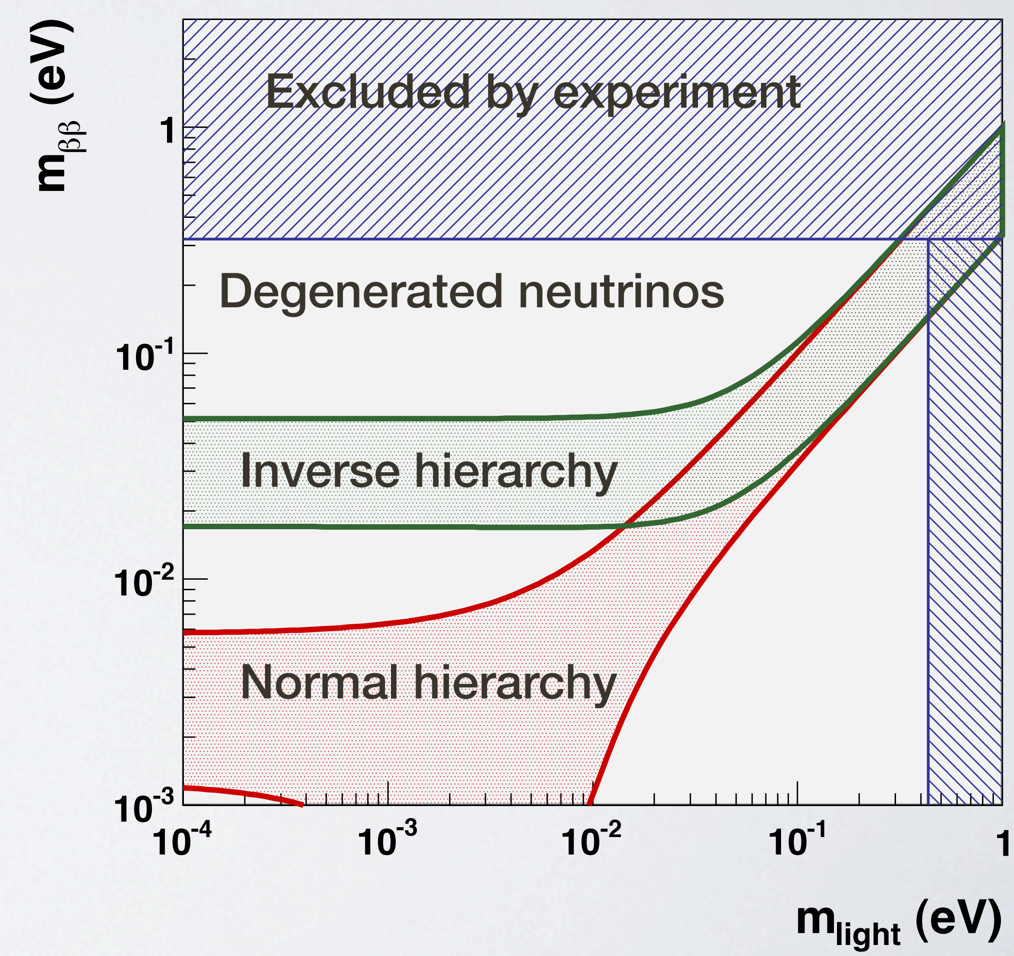
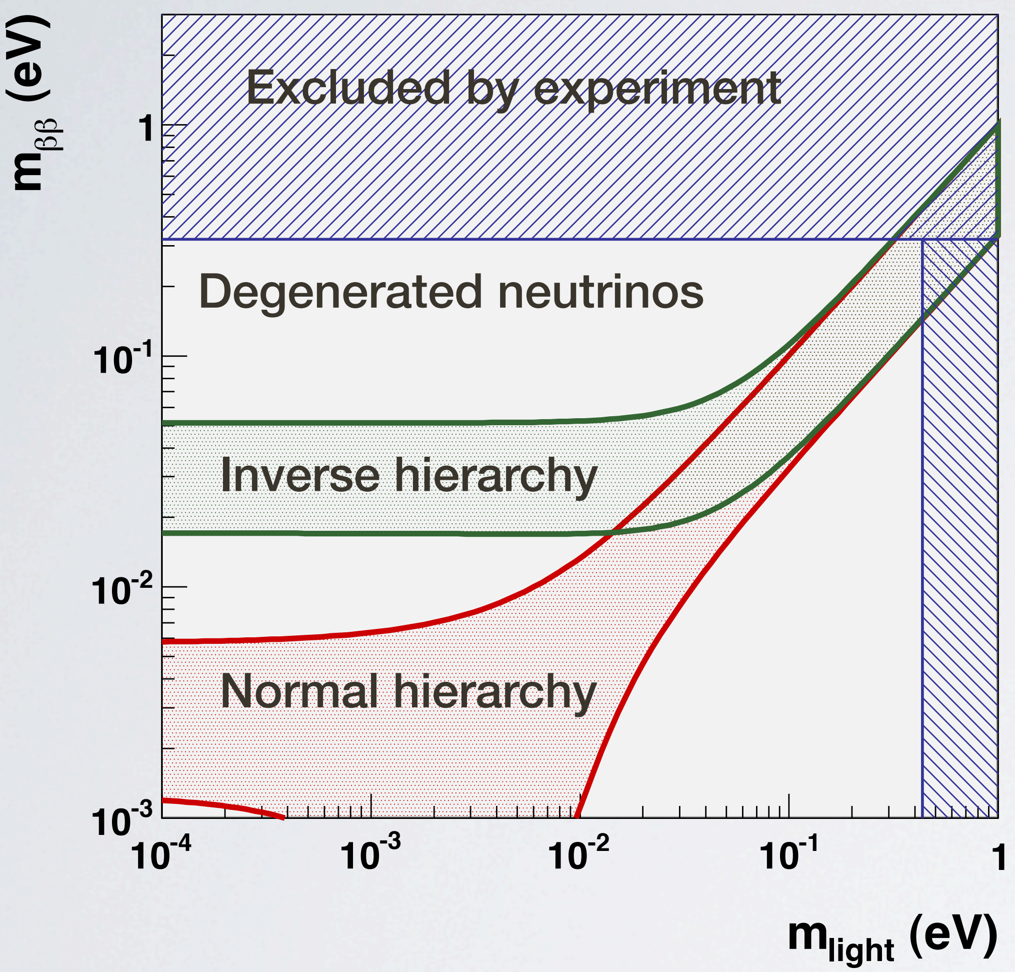


Effective neutrino mass



$$(T^{0\nu}_{1/2})^{-1} = \boxed{G^{0\nu}(Q,Z)}\,\boxed{|M^{0\nu}|^2}\,m^2_{\beta\beta}$$

phase-space

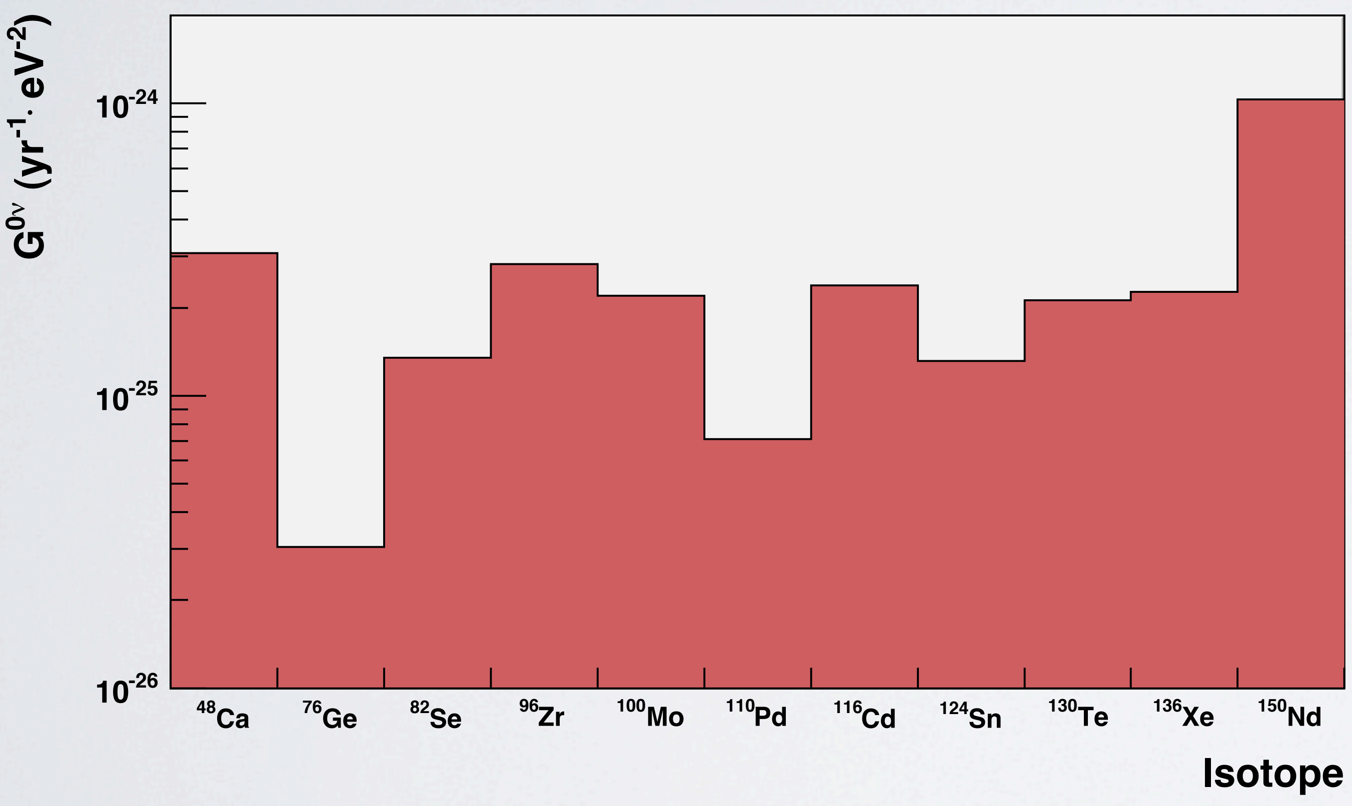
nuclear matrix

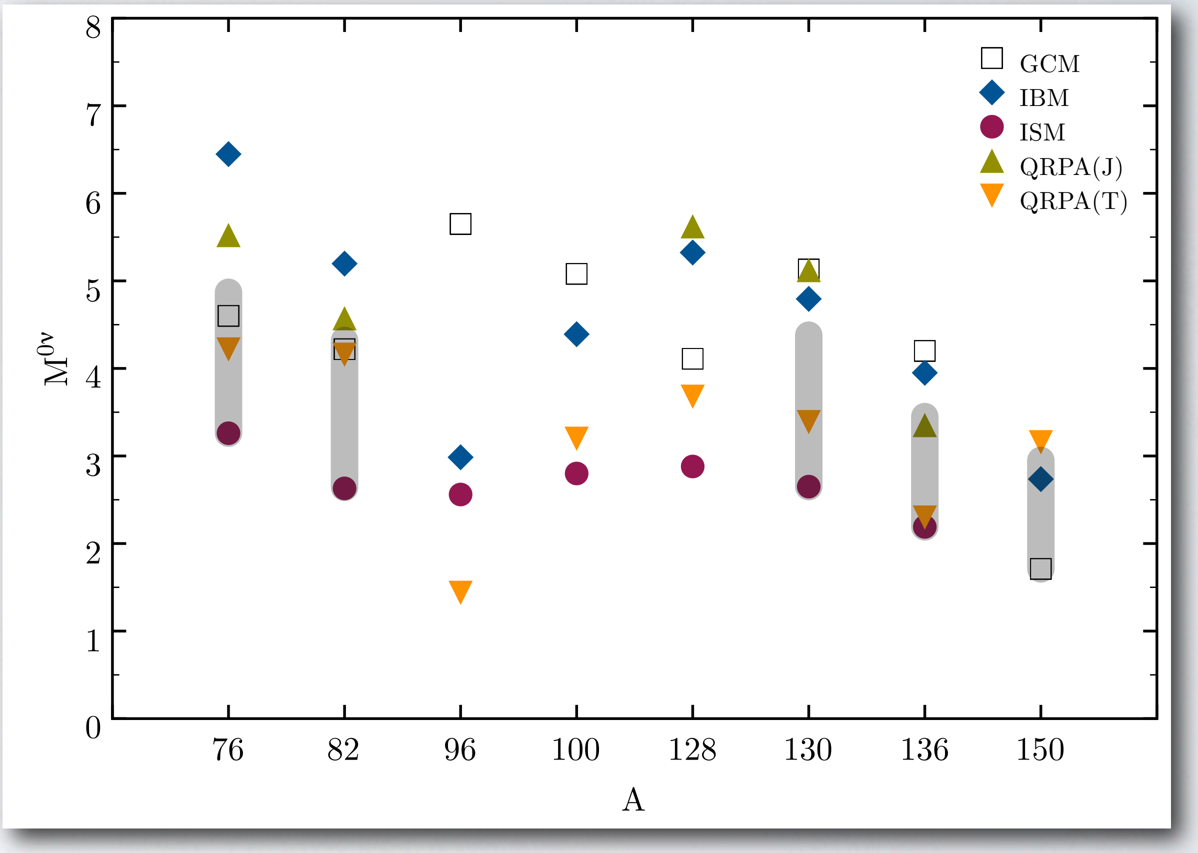
Majorana neutrino

$$m_{\beta\beta} = \Big|\sum_i m_i U^2_{ei}\Big|$$

Nuclear physics

$$(T^{0\nu}_{1/2})^{-1} = \boxed{G^{0\nu}(Q,Z)}\,\boxed{|M^{0\nu}|^2}\,m^2_{\beta\beta}$$



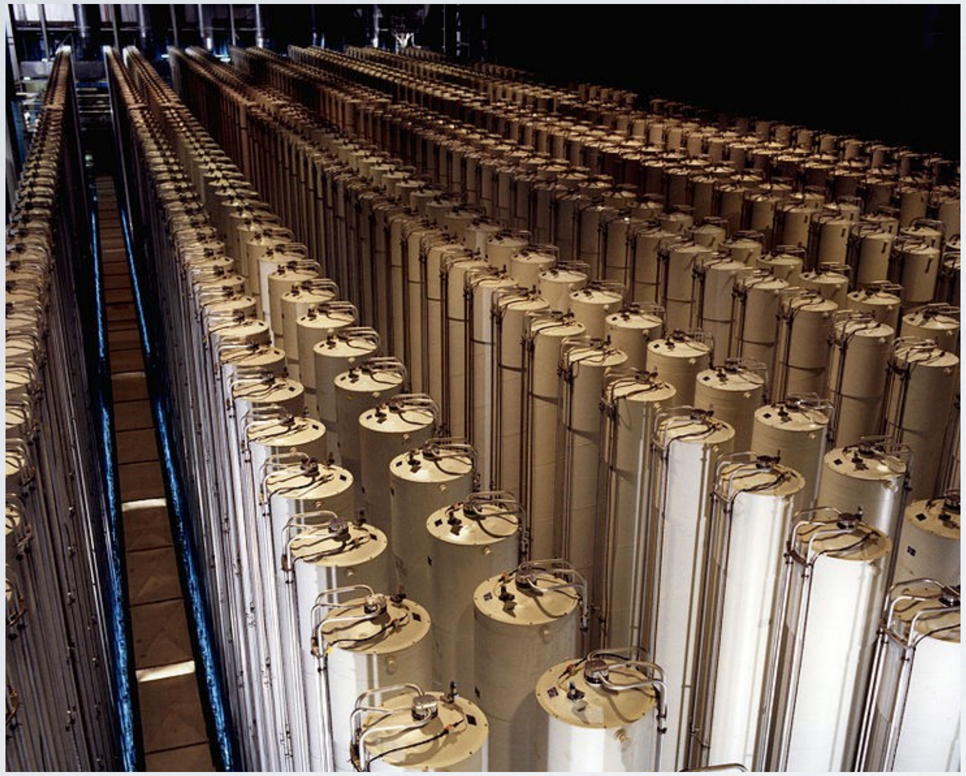


Experimental challenges

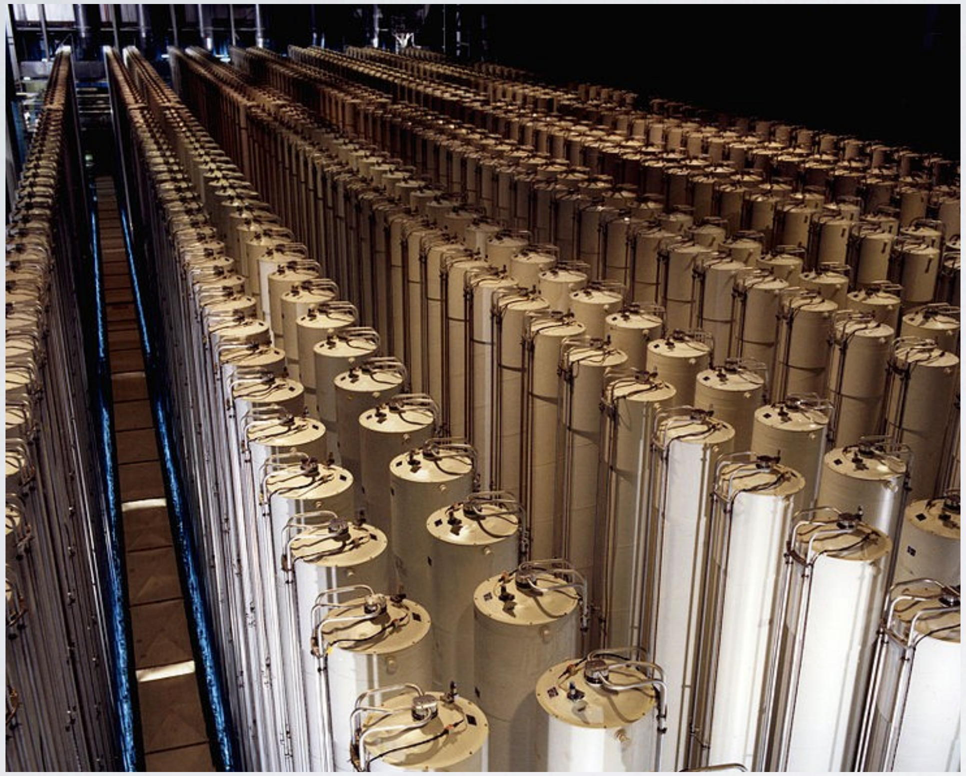
Building an ideal experiment

Photo by Nym Park

How to build your $\beta\beta0\nu$ *experiment*

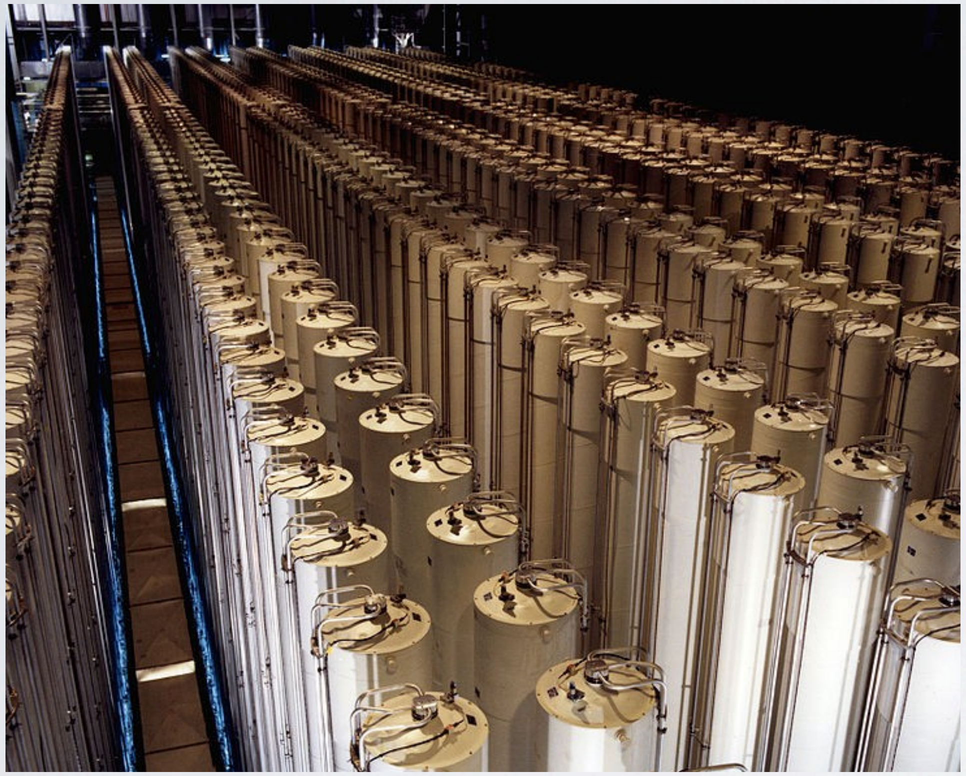


How to build your $\beta\beta 0\nu$ *experiment*



- Get a large mass of double beta decay source.
- Almost all isotopes must be enriched.
- Easiest: Xe-136 from Xenon

How to build your $\beta\beta0\nu$ *experiment*



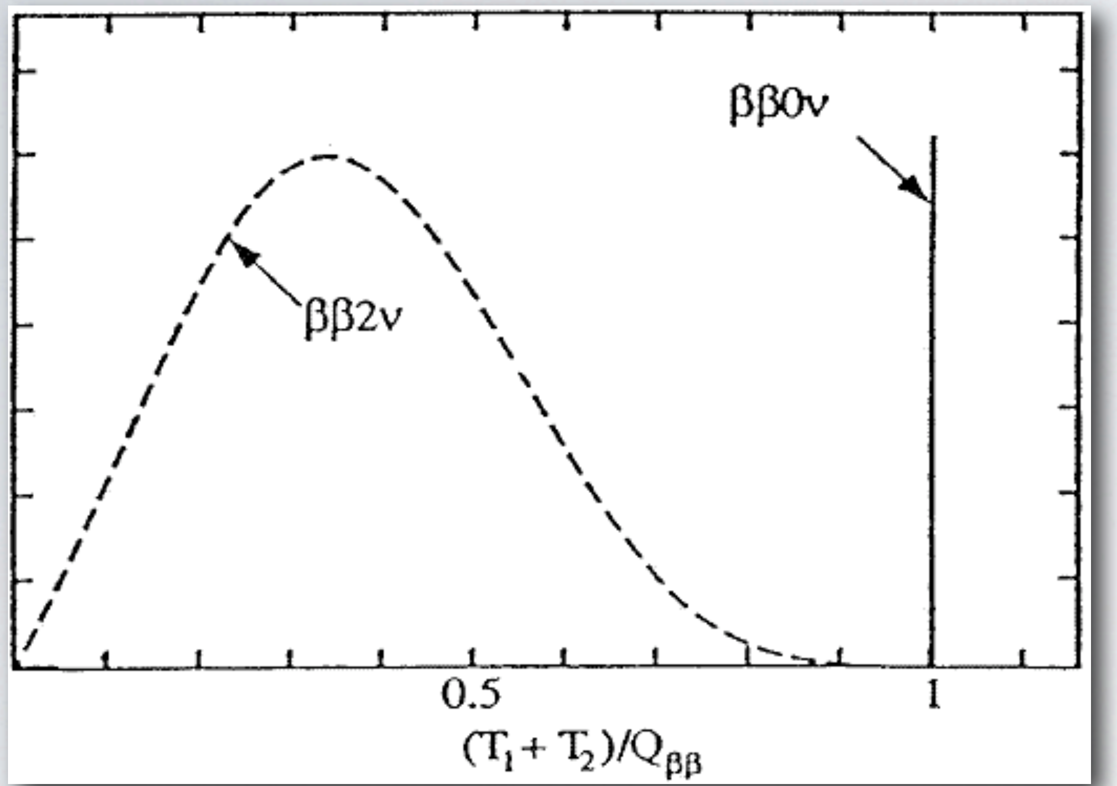
- Get a large mass of double beta decay source.
- Almost all isotopes must be enriched.
- Easiest: Xe-136 from Xenon

$$N = \frac{MtN_A}{A}$$

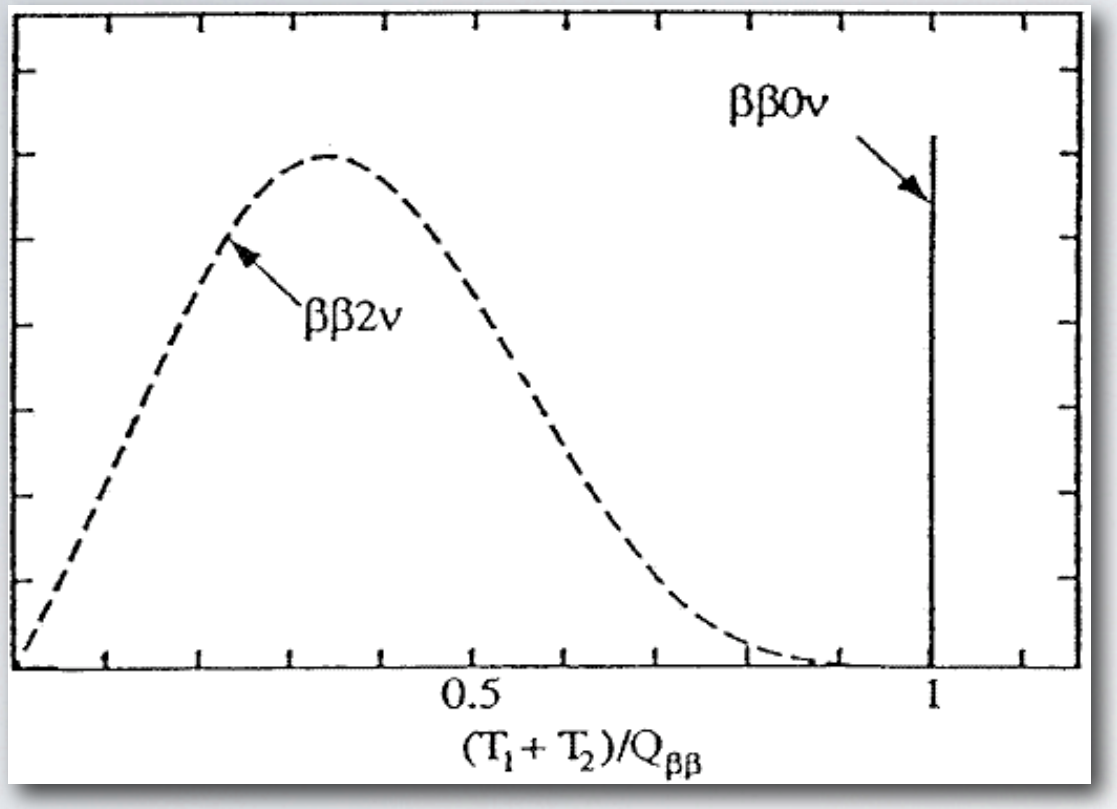
$$M = 100\ kg,\ \ A = 136$$

$$N = \frac{10^5 \cdot 6 \cdot 10^{23}}{136} = 4.4 \cdot 10^{26}$$

How to build your $\beta\beta0\nu$ *experiment*

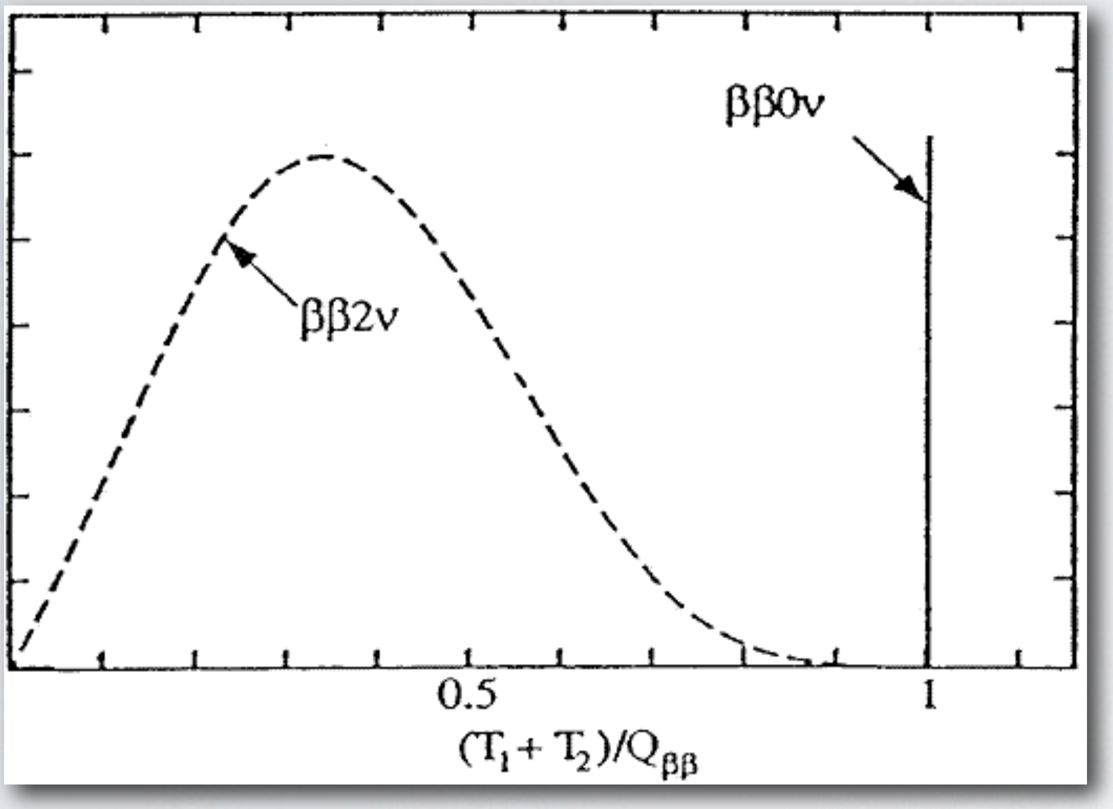


How to build your $\beta\beta0\nu$ *experiment*



- Get yourself a detector with perfect energy resolution
- Measure the energy of the emitted electrons and select those with (T1+T2)/Qbb = 1
- Count the number of events and calculate the corresponding half-life.
- In Xe-136, a perfect detector observes 3 events for a lifetime of 10^{26} y.

How to build your $\beta\beta0\nu$ *experiment*



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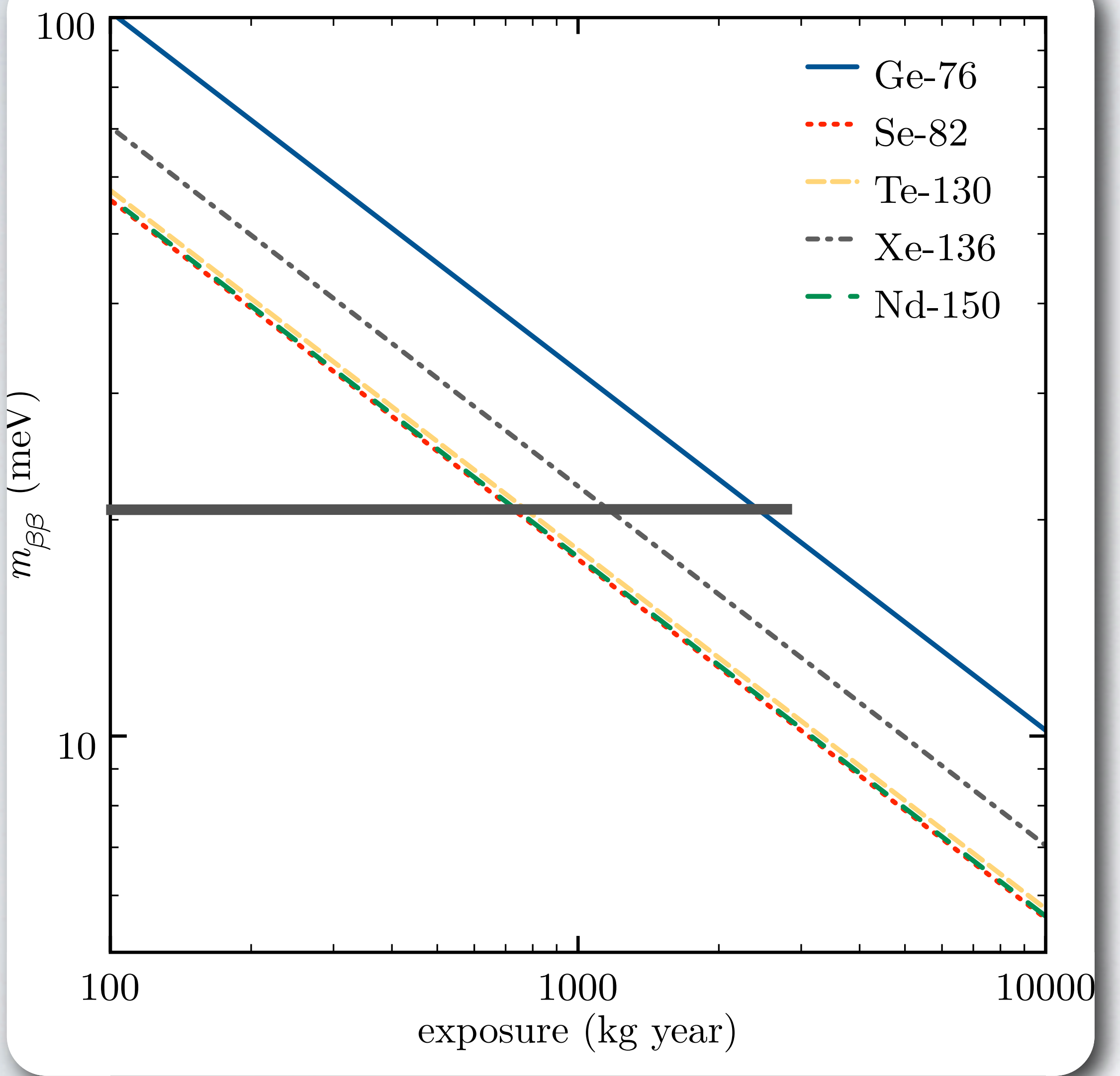
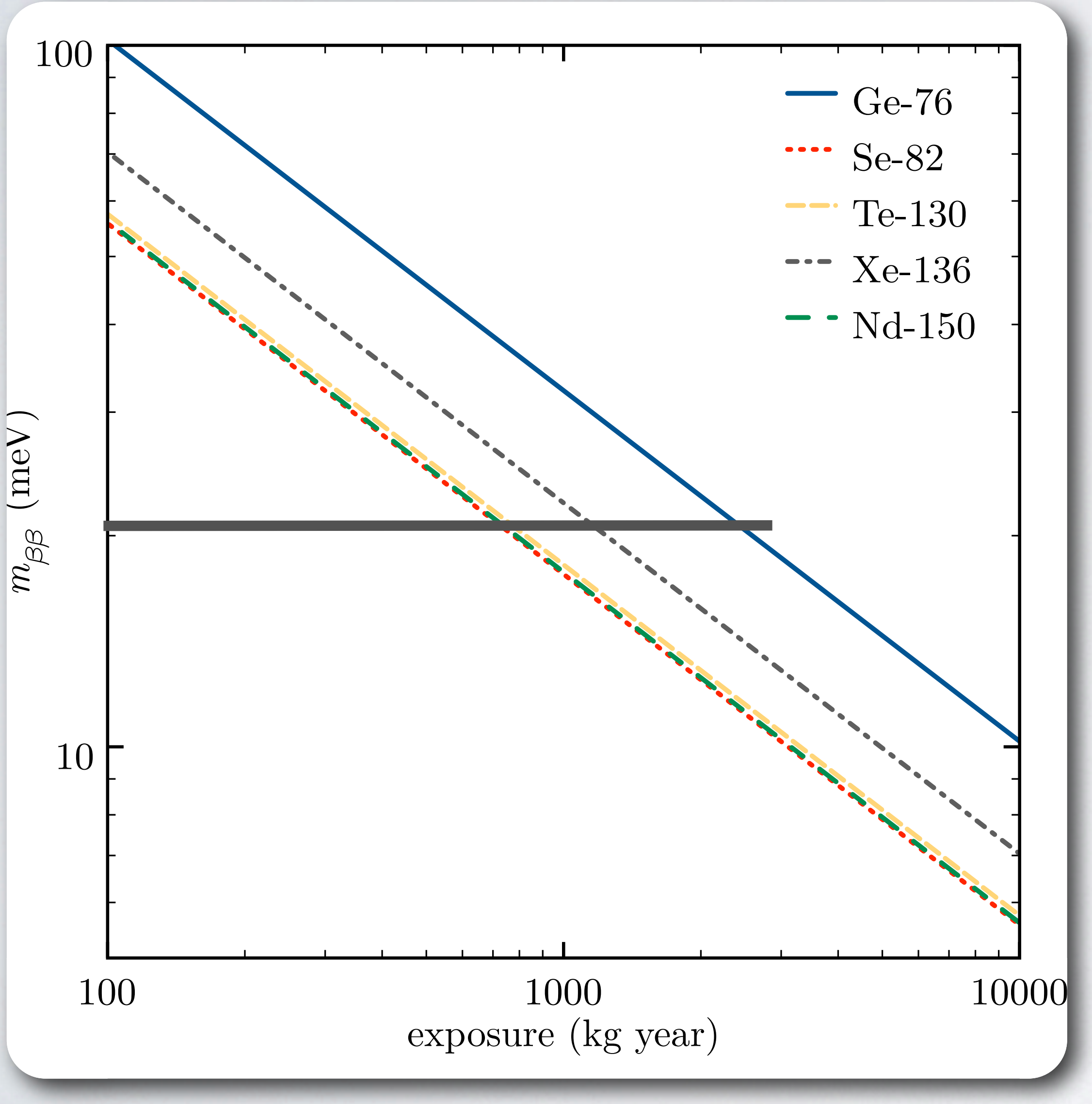
$$T_{1/2} = \log 2 \; \frac{N_A \; Mt}{A \; N_{\beta\beta}}$$

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

How to build your $\beta\beta0\nu$ *experiment*

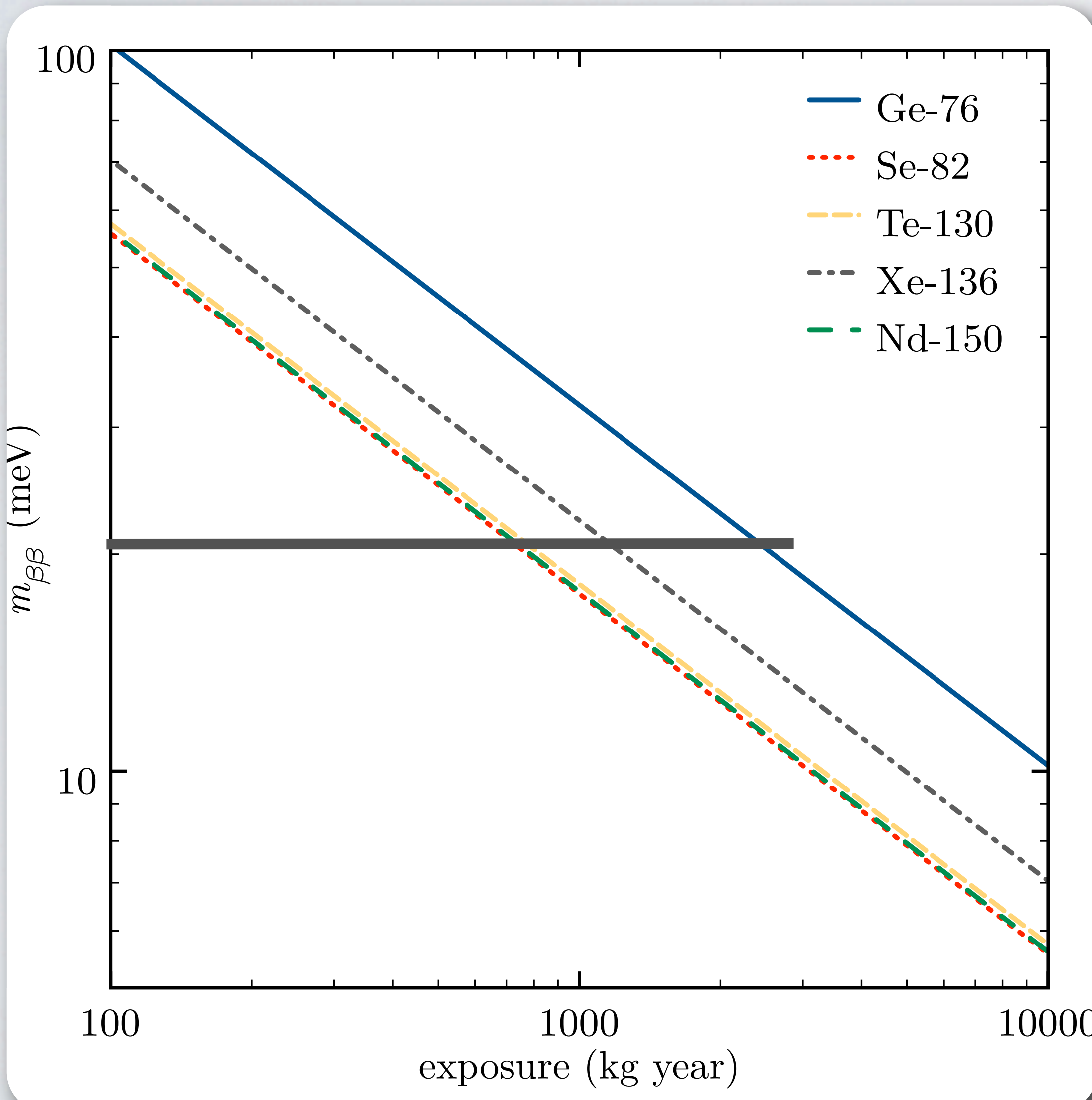


How to build your $\beta\beta0\nu$ *experiment*



- Compute mbb from T
- In the absence of background improvement in period is proportional to the exposure (Mt) but improvement in mbb goes with the square root of exposure.

How to build your $\beta\beta 0\nu$ experiment



$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\ |M^{0\nu}|^2\ m^2_{\beta\beta}$$

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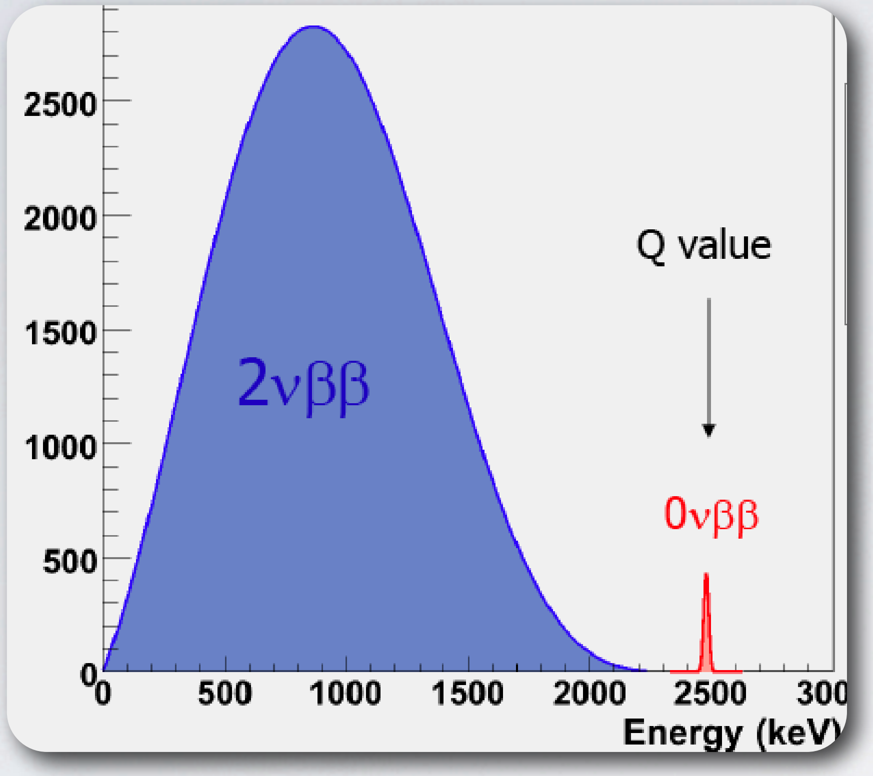
Recipes for real bb0nu experiments

Energy resolution

Why Energy resolution?



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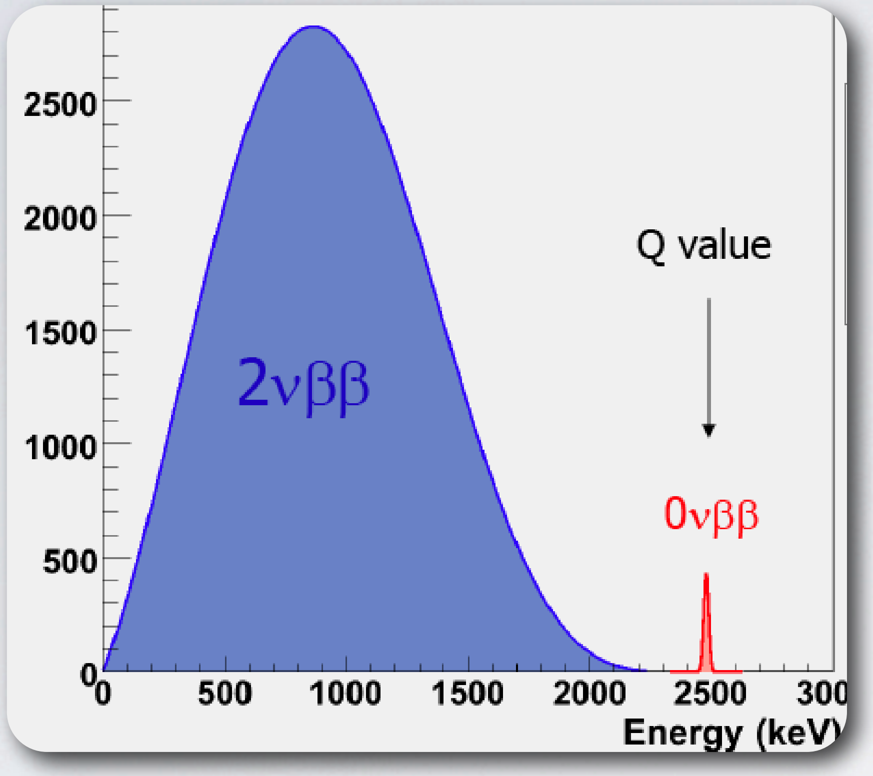

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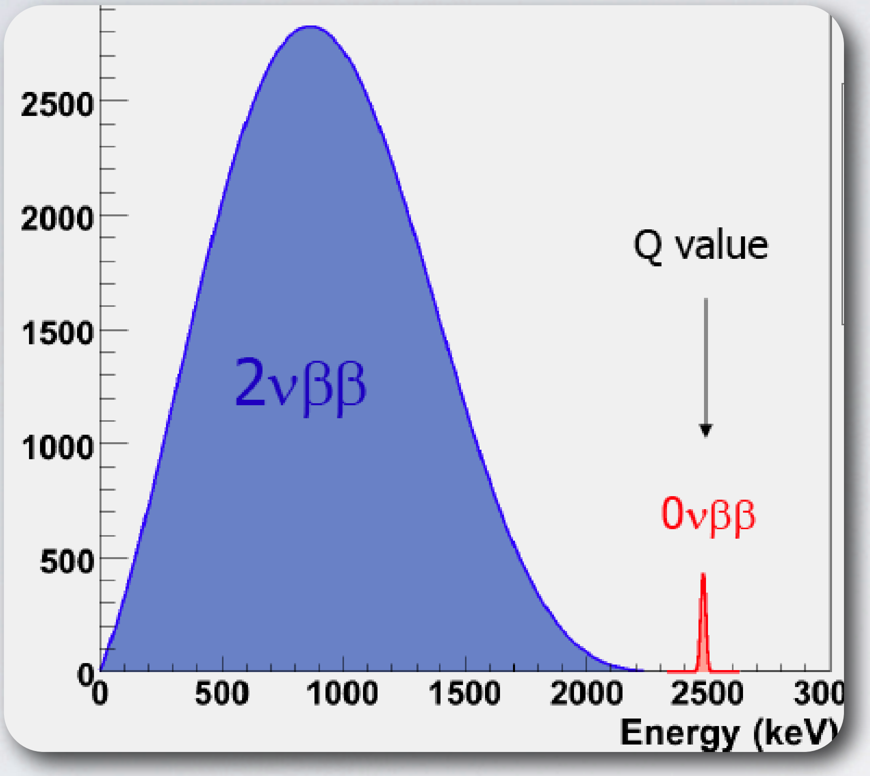

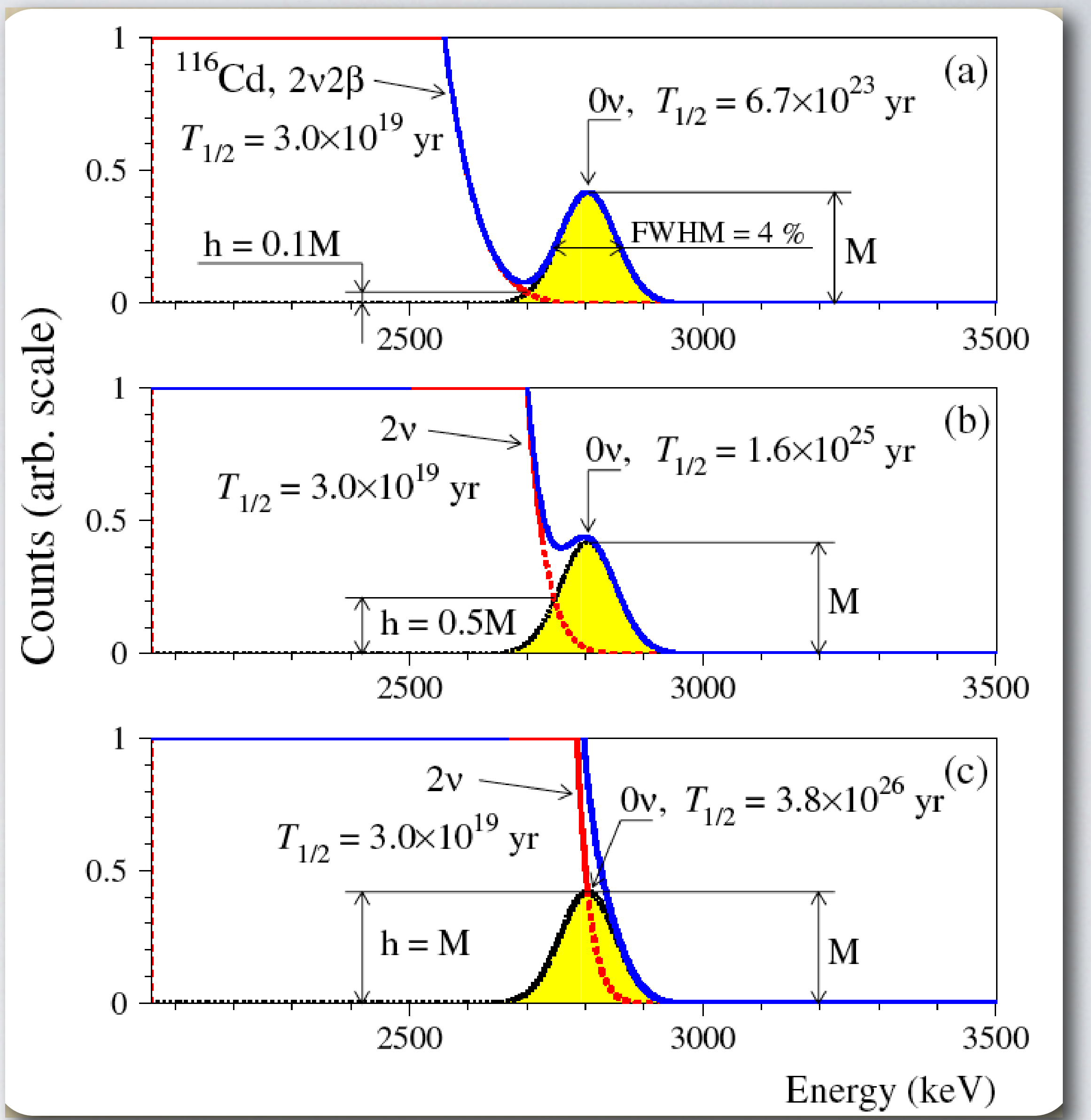

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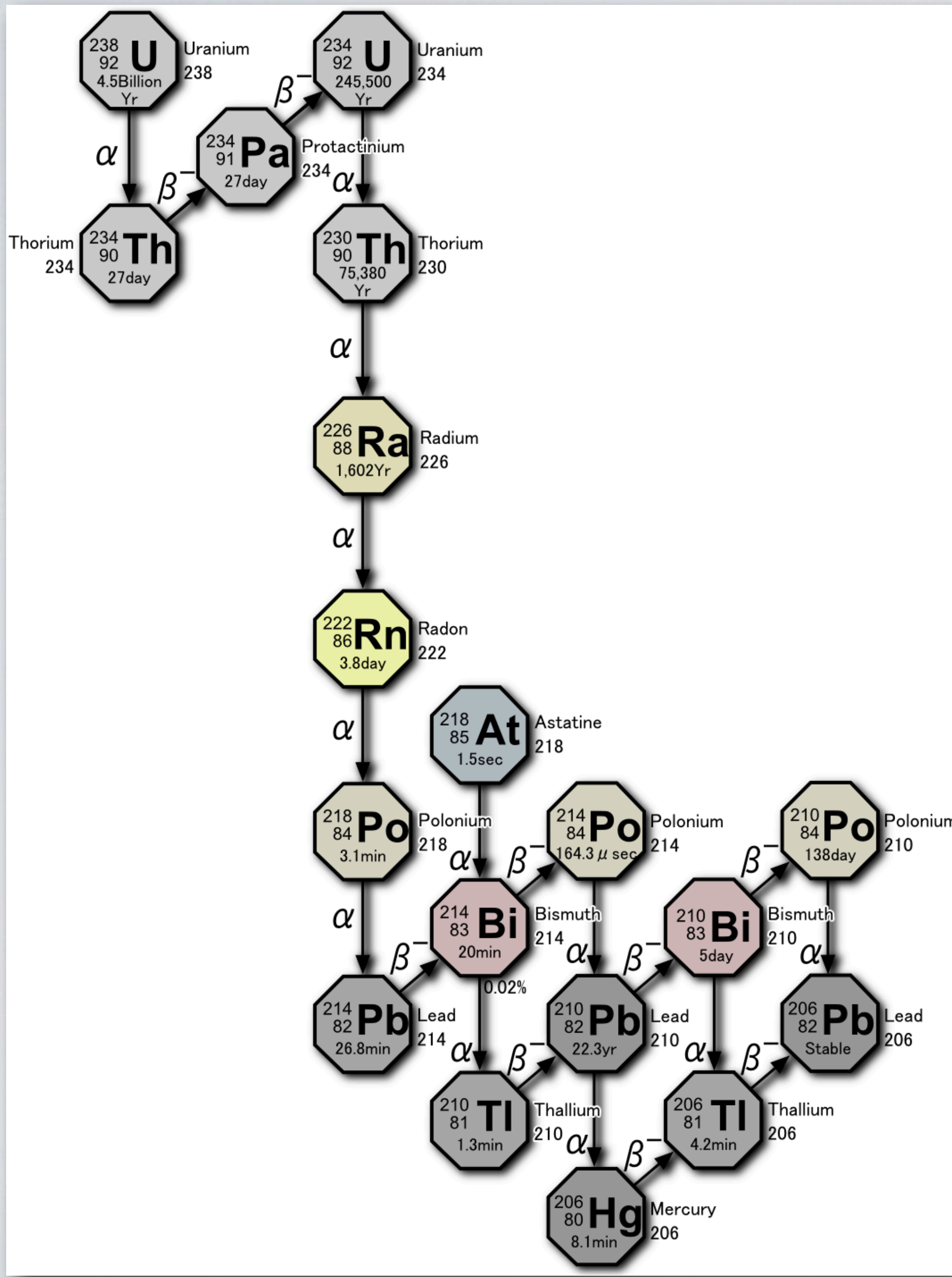

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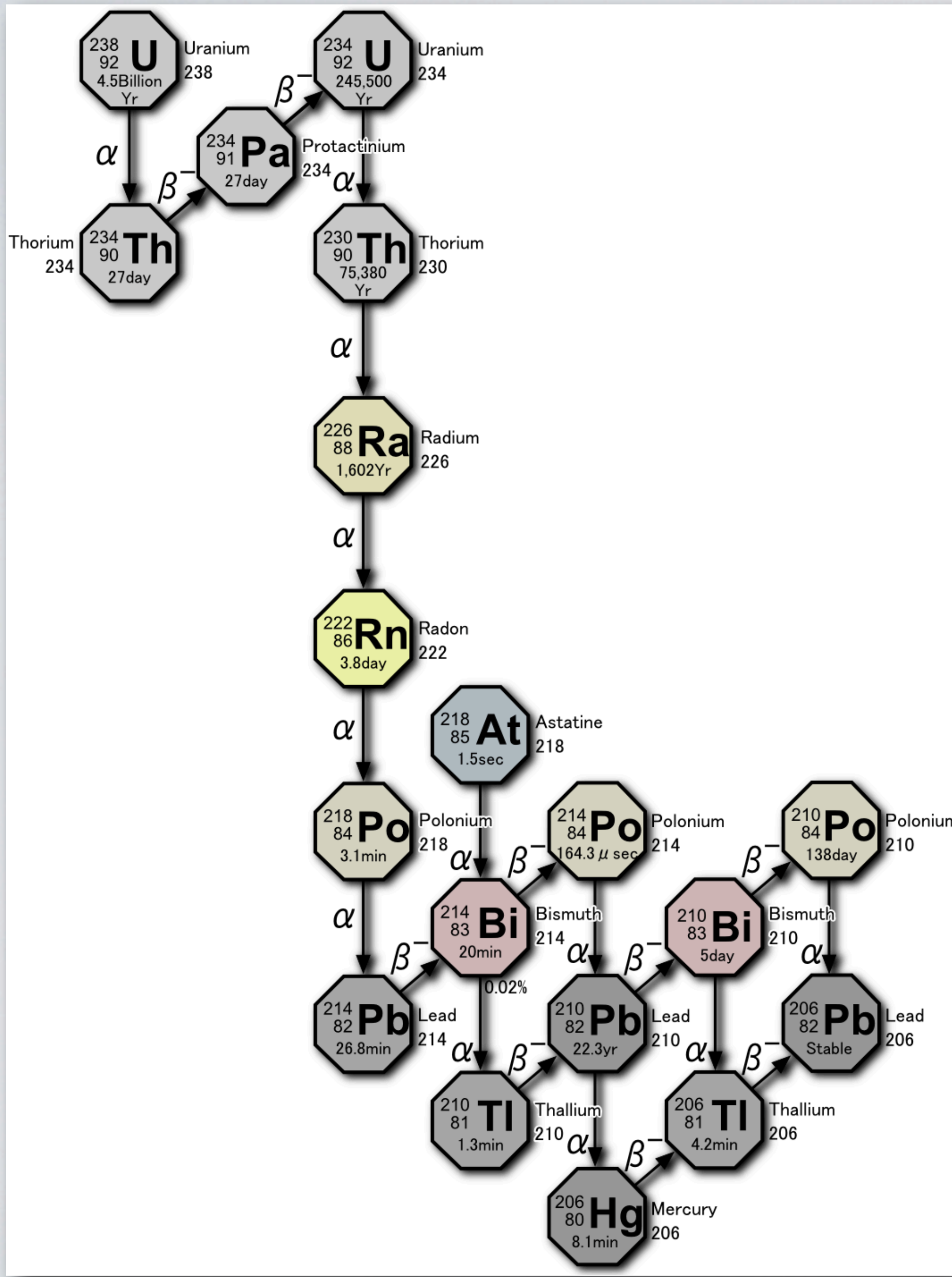
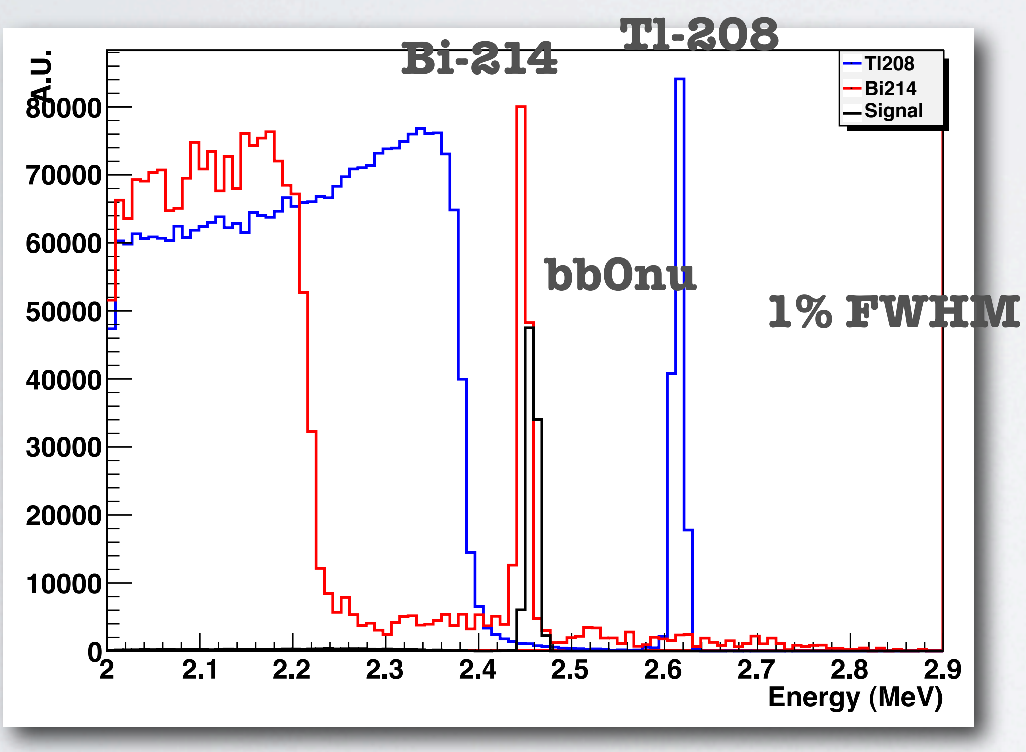
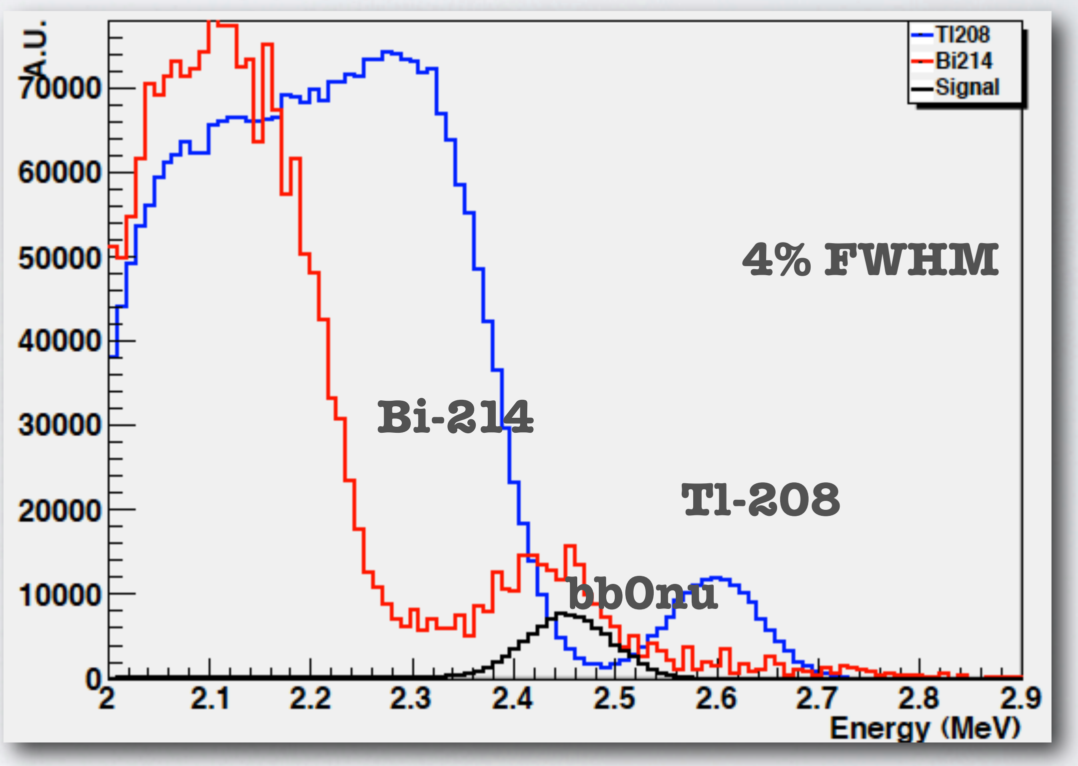


- But bb2nu is the least of our problems!
- Earth is a very radioactive planet. There are about 3 grams o U-238 and 9 grams of Th-232 per ton of rock around us.
- This is an intrinsic activity of the order of 60 Bq/kg of U-238 and 90 Bq/kg of Th-232.
- The lifetime of U-238 is of the order of 10^9 y and that of Th-232 10^{10} y. We want to explore lifetimes of bb0nu of the order of 10^{26} y.

Why Energy resolution?

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





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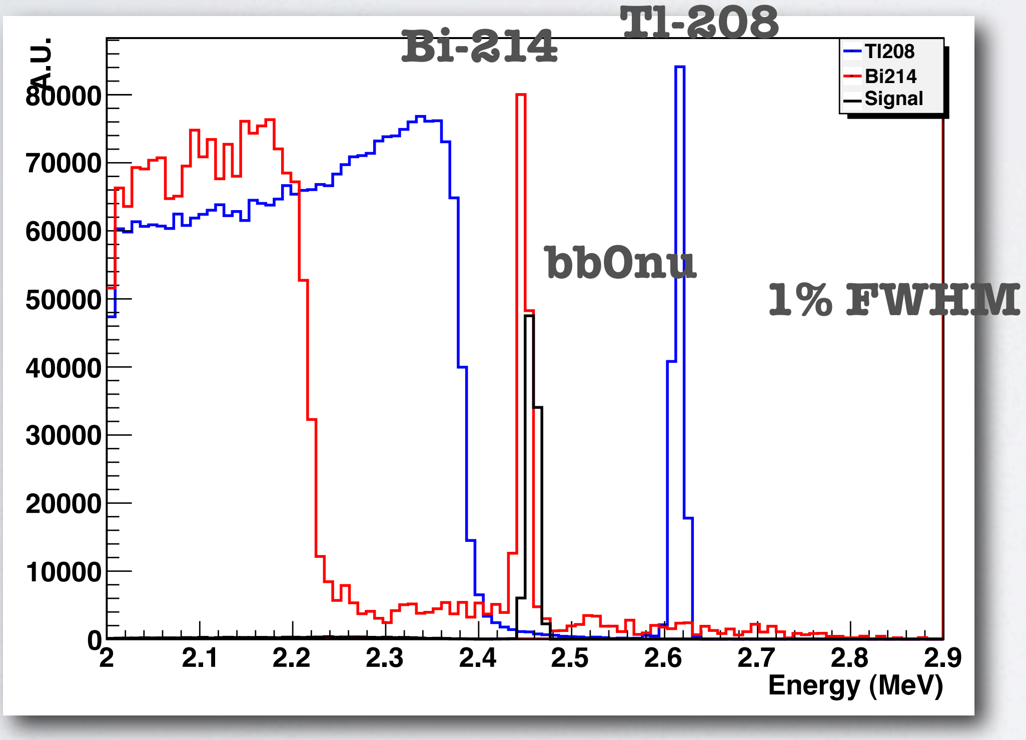

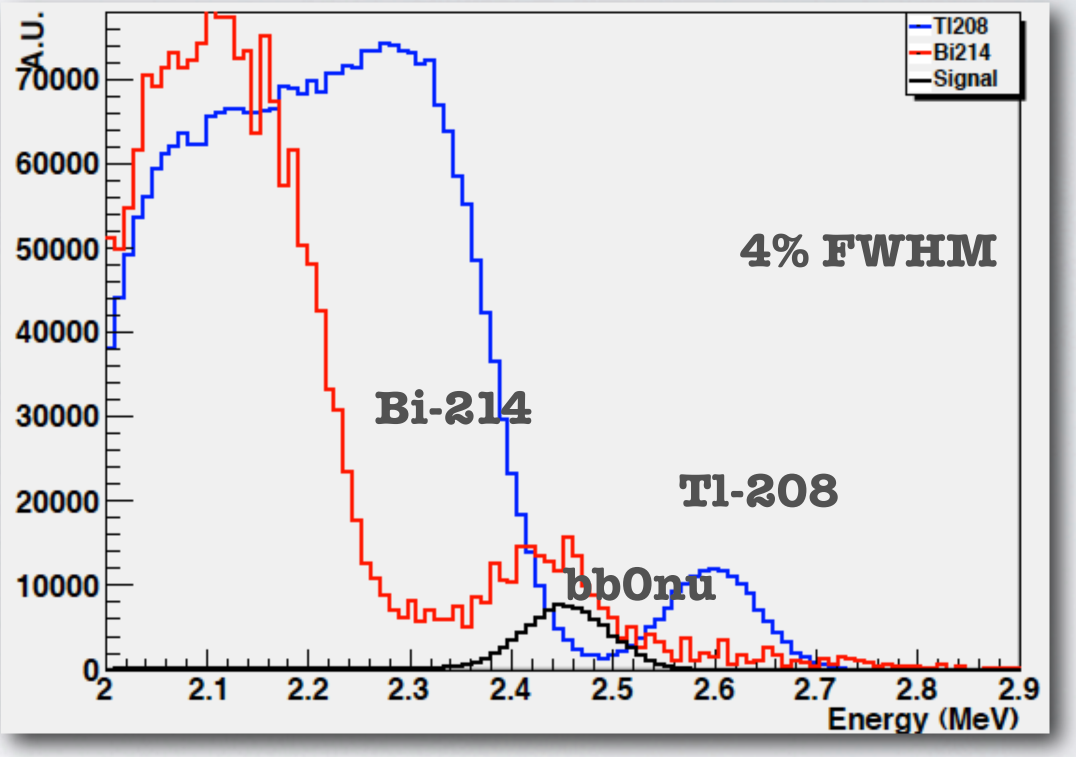

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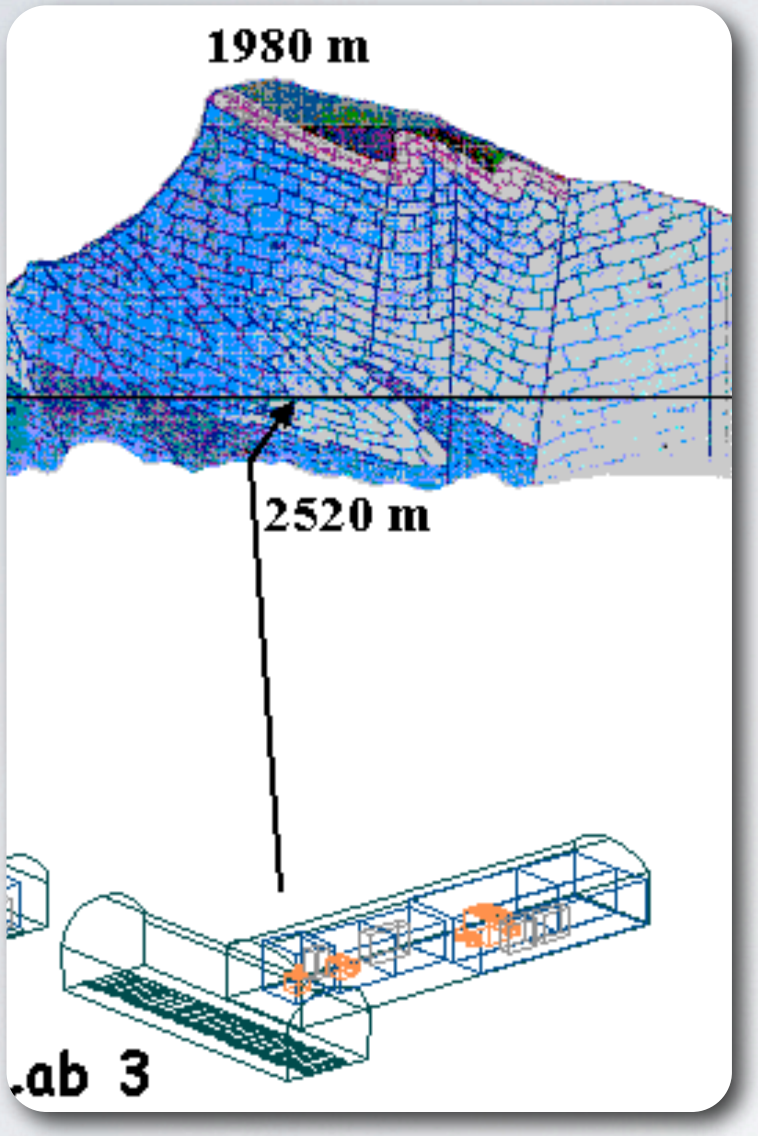
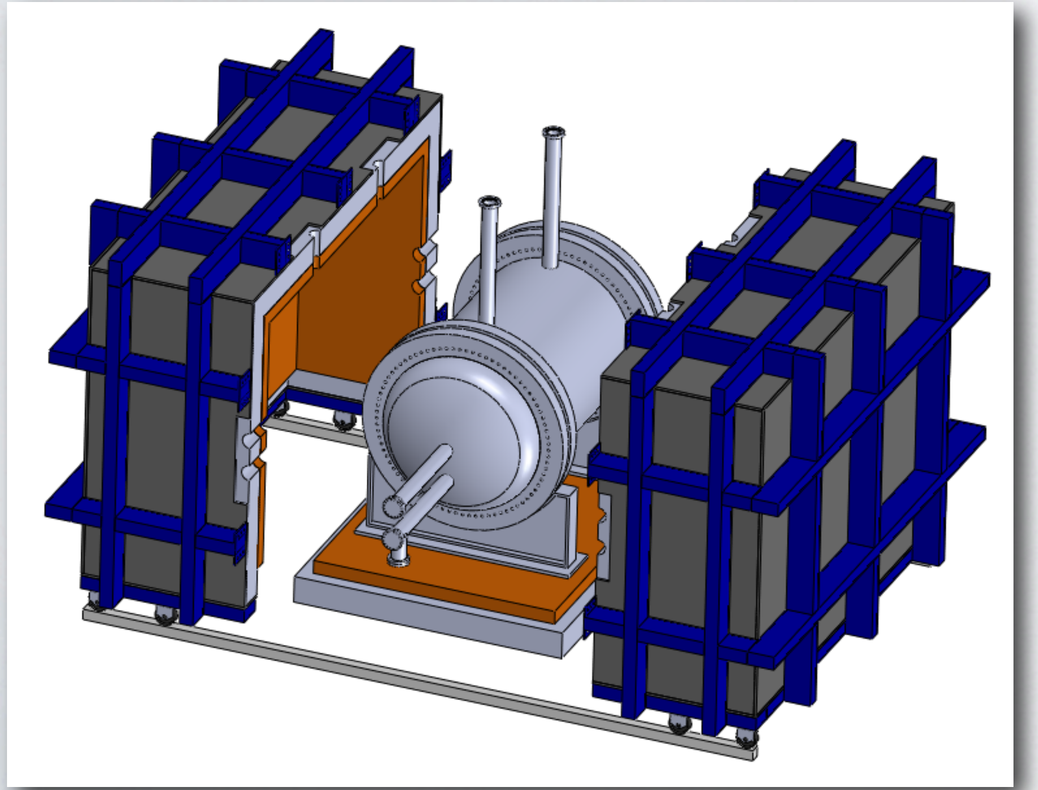
Other recipes

Recipes for real bb0nu experiments (Salt)



- Underground laboratory to reduce cosmic background (muons, cosmogenic activation, etc.): SHIELDING

Recipes for real bb0nu experiments (Mustard)



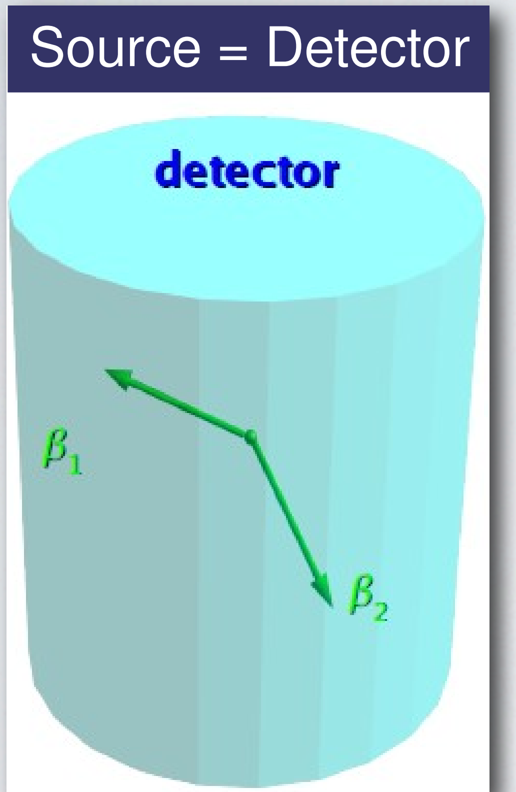
- Lab walls shoot us 10^3 gammas of high energy (direct background) per square meter or about 5,000 gammas into the detector.
- Stop them with a wall of 30 cm of radiopure lead (300 muBq/kg)
- Stop the gammas from the lead with ultra-radiopure copper inside the vessel (10 mqBq/kg): MATRIOSKA

Recipes for real bb0nu experiments (Rosemary & Pepper)

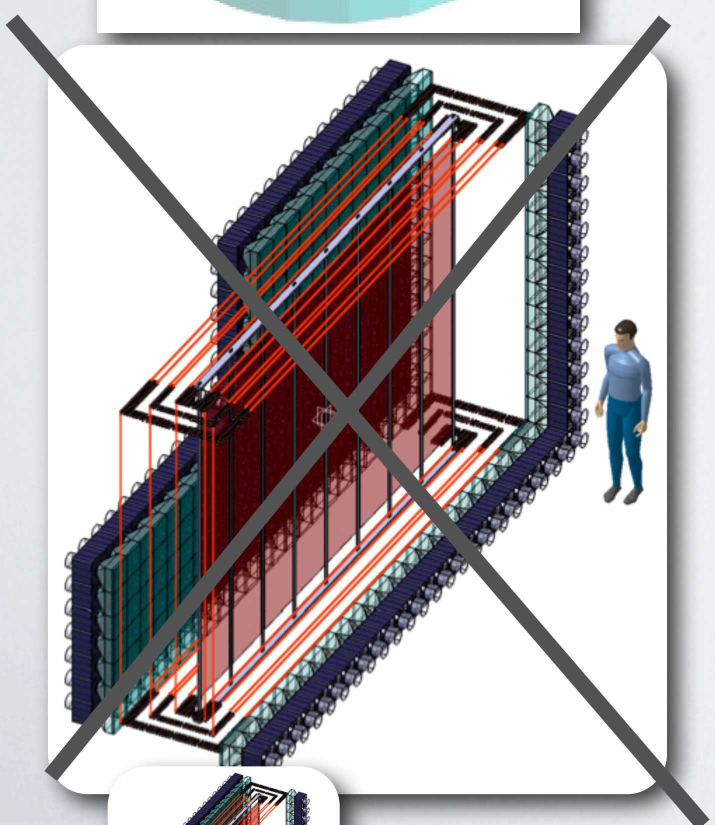
- Build everything out of extremely radiopure materials.
- Typical activities in detector material in the range of muBq/kg.
- We are way more radioactive than that (K-40 in our bones)

Everything is radioactive unless proven otherwise by screening. Radio PURITY

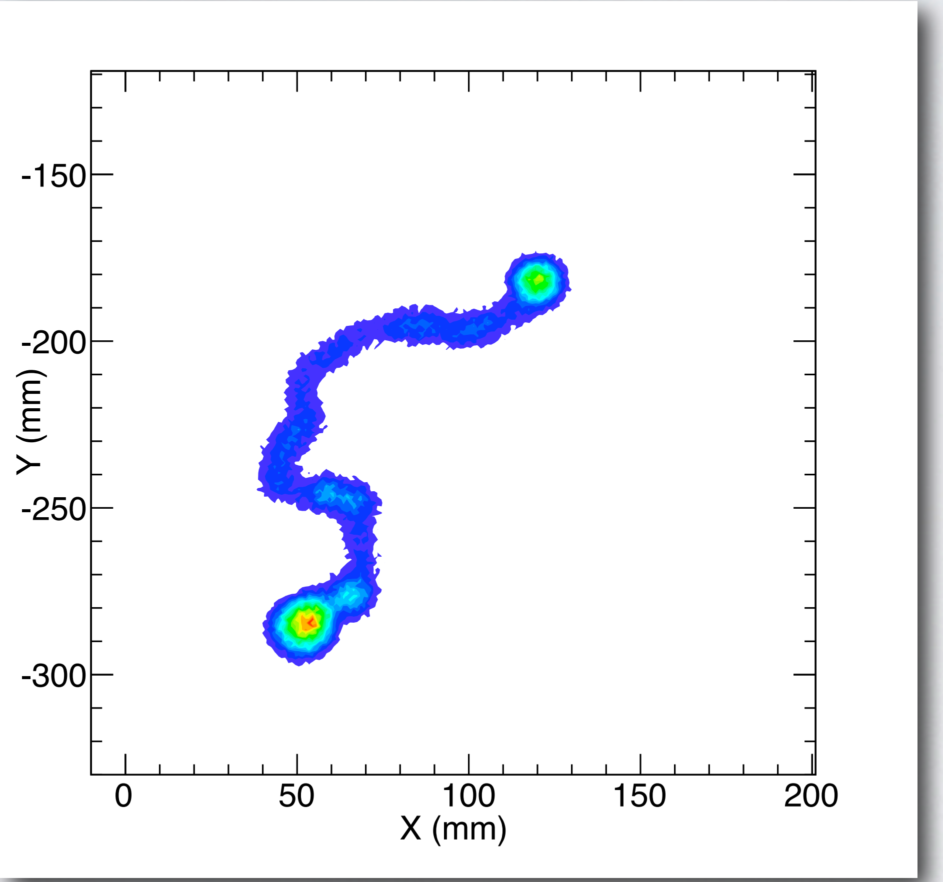
Recipes for real bb0nu experiments (Vinegar)



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



Recipes for real bb0nu experiments (Thyme)



TOPOLOGICAL signature of two electrons in a HPGXe (NEXT)

The experiment Rubik’s cube

The experiment Rubik's cube

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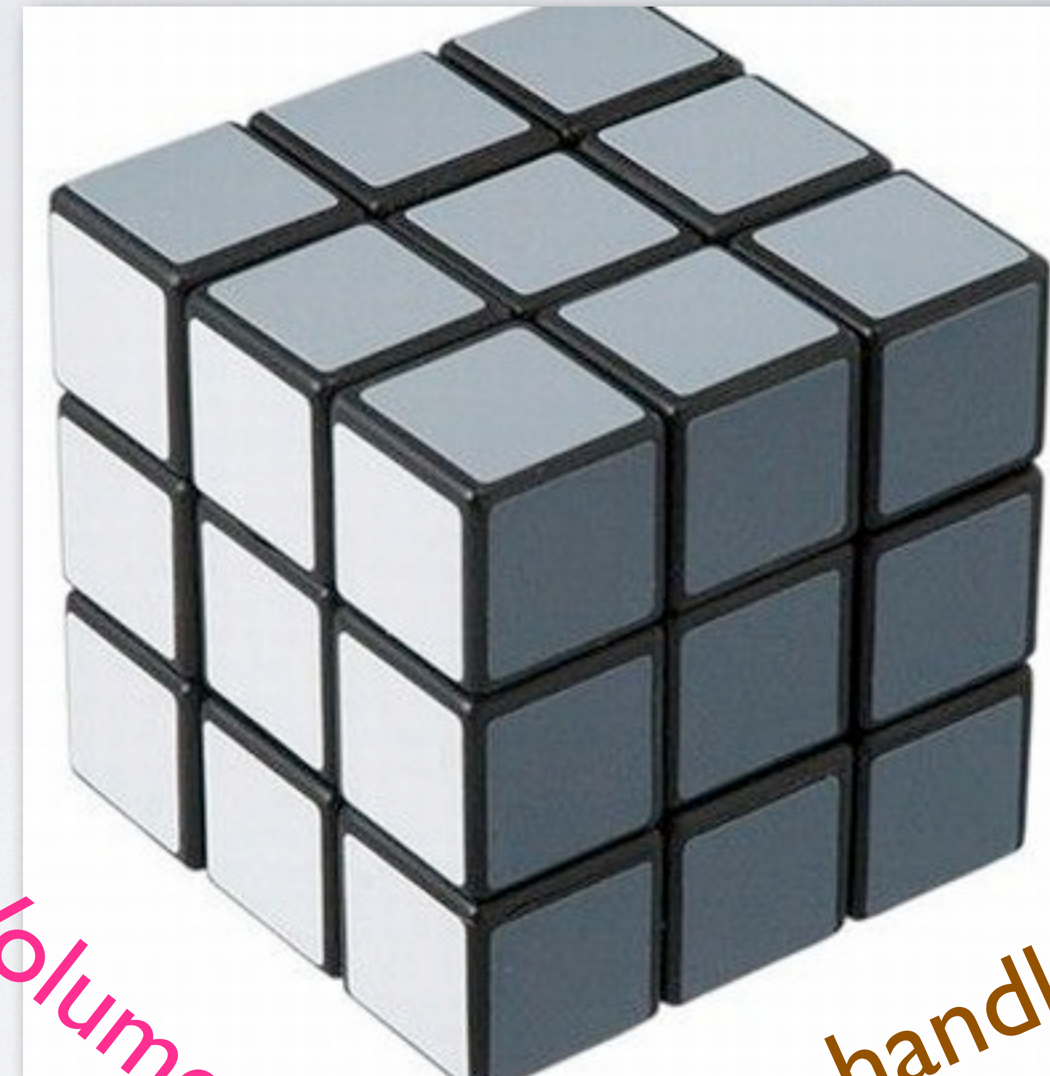
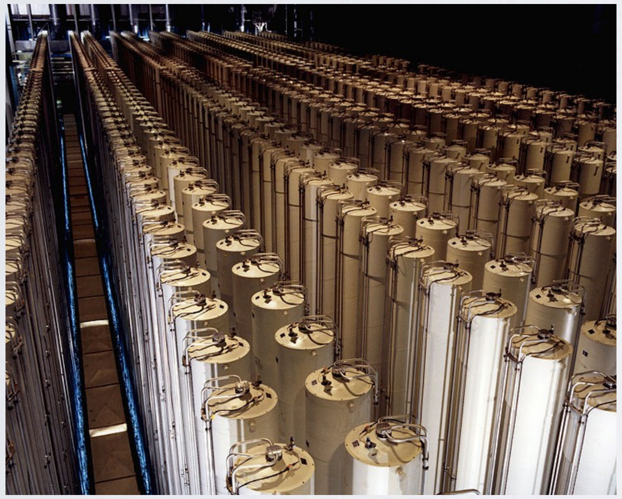
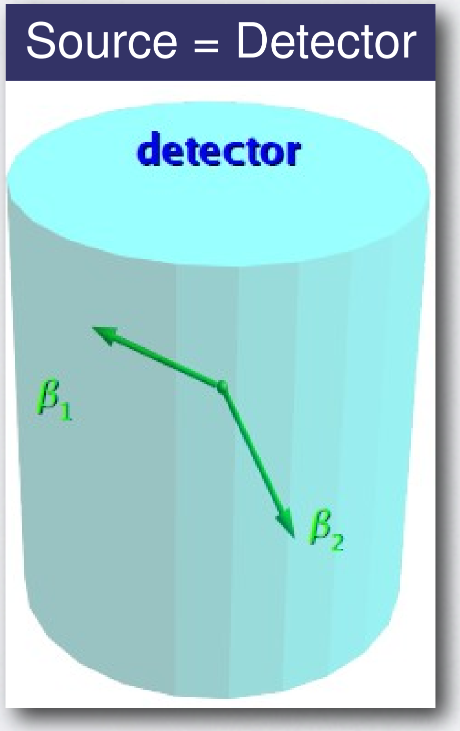
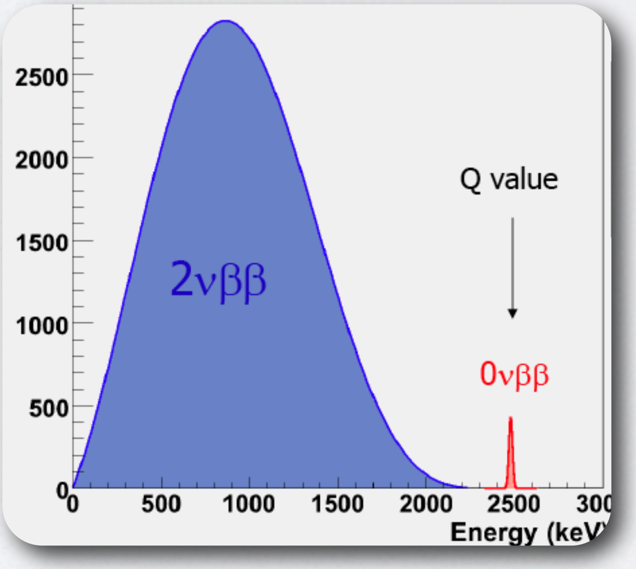


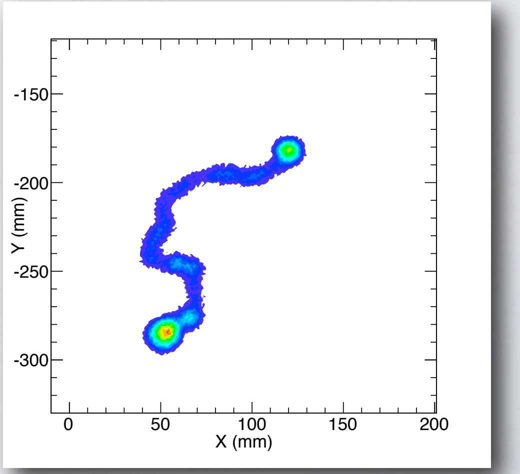
Figure of merit

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









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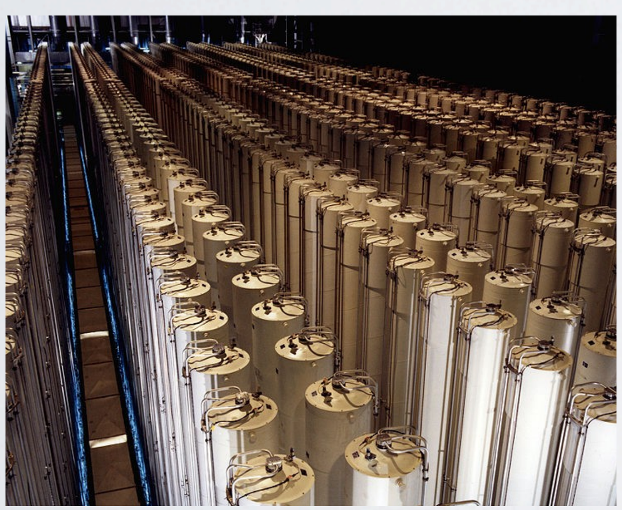

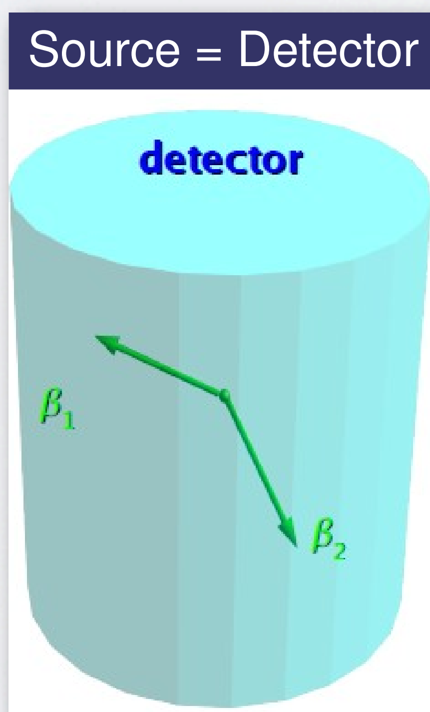

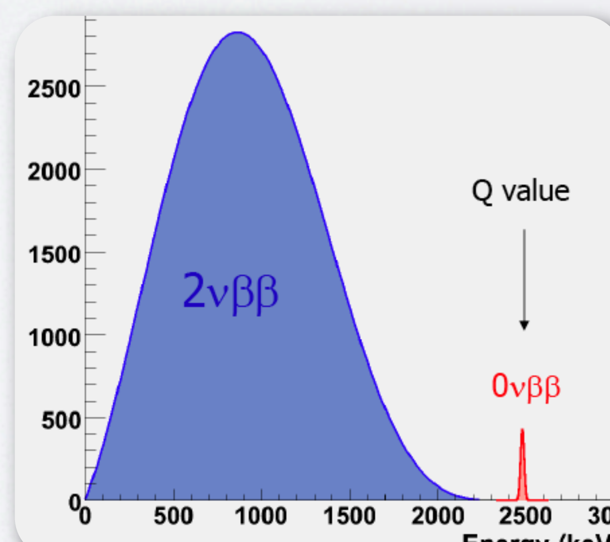

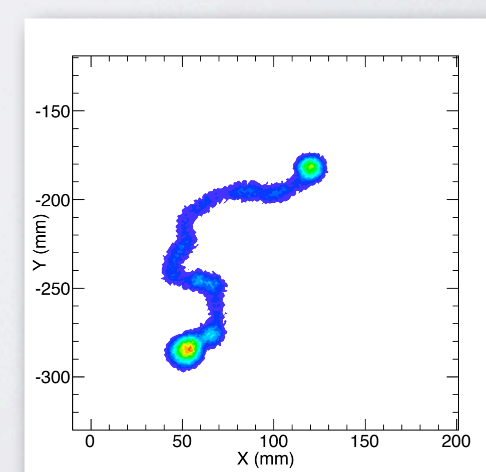

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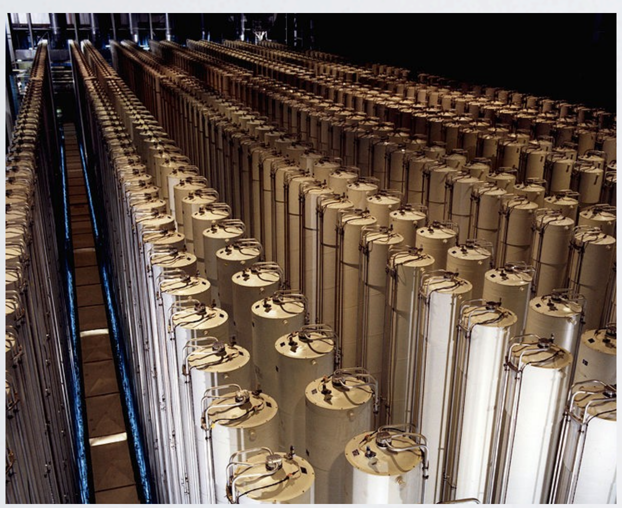

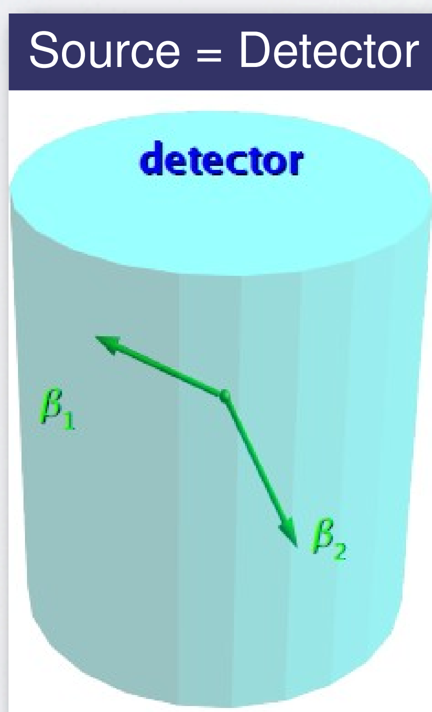

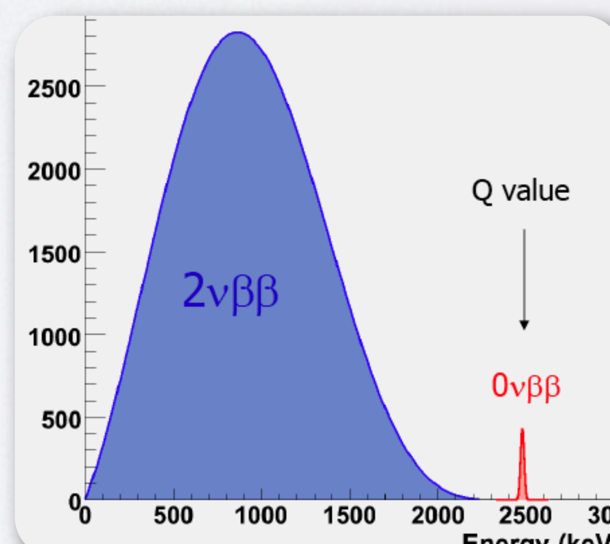

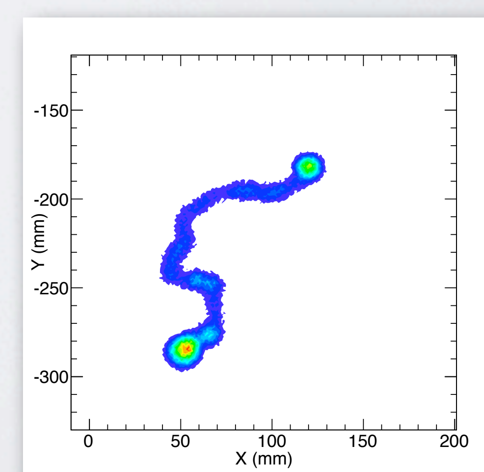

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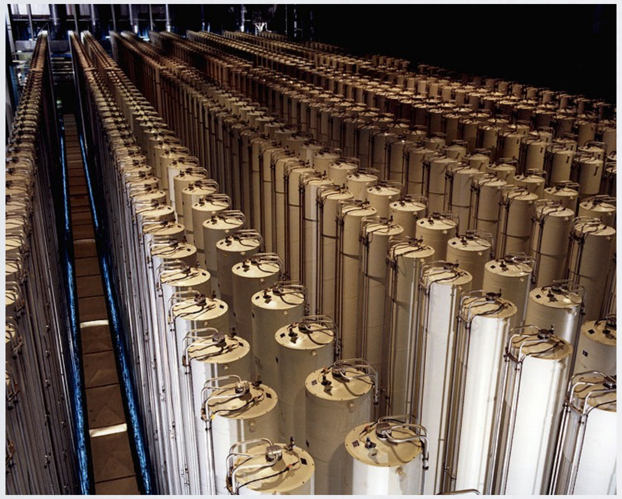

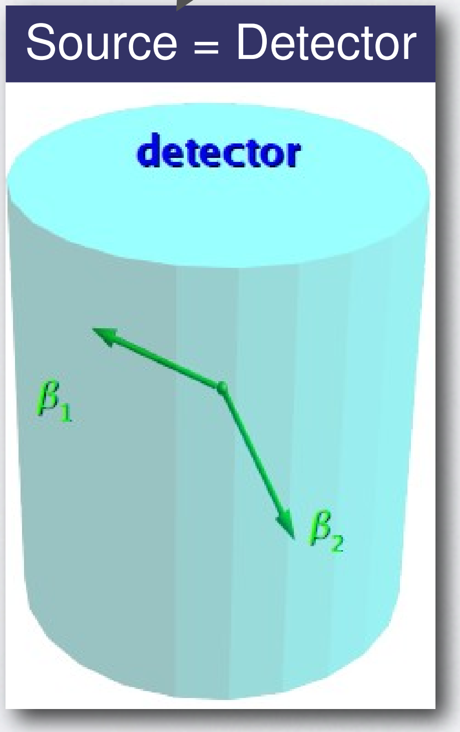

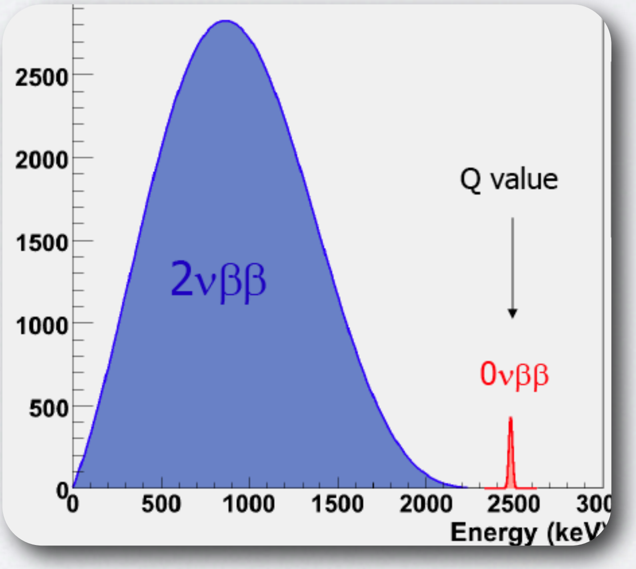

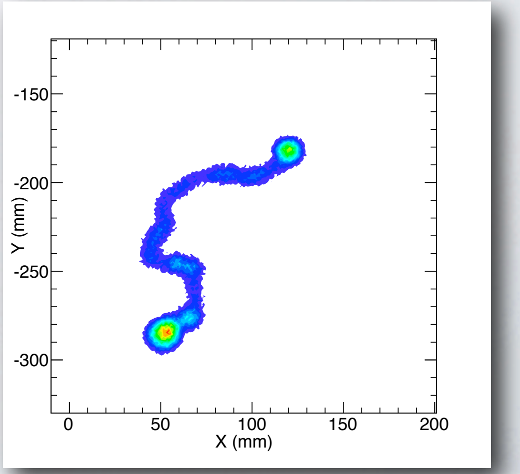

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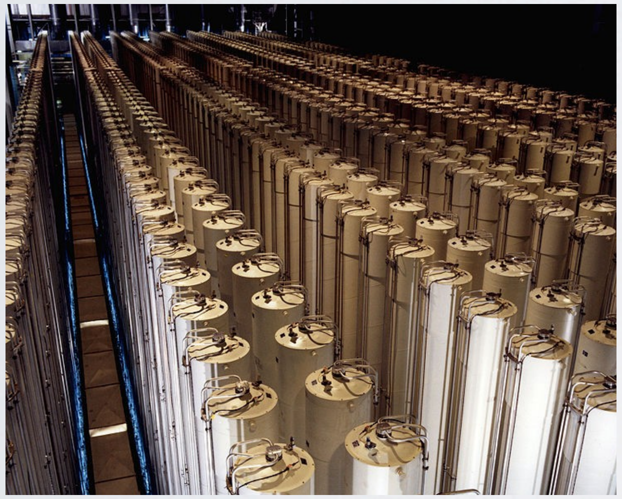

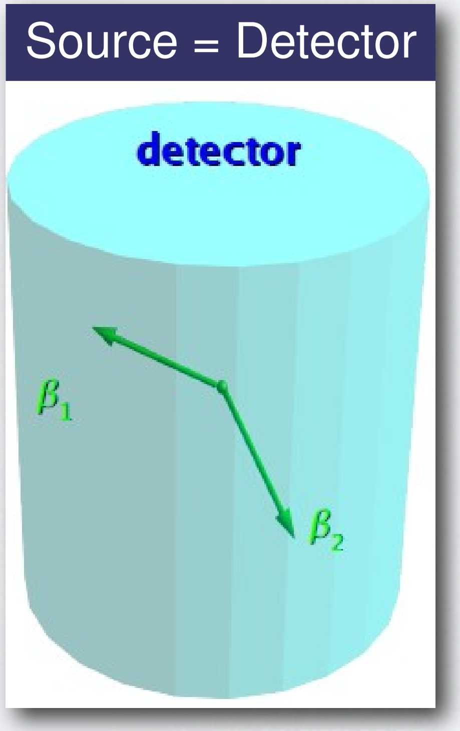

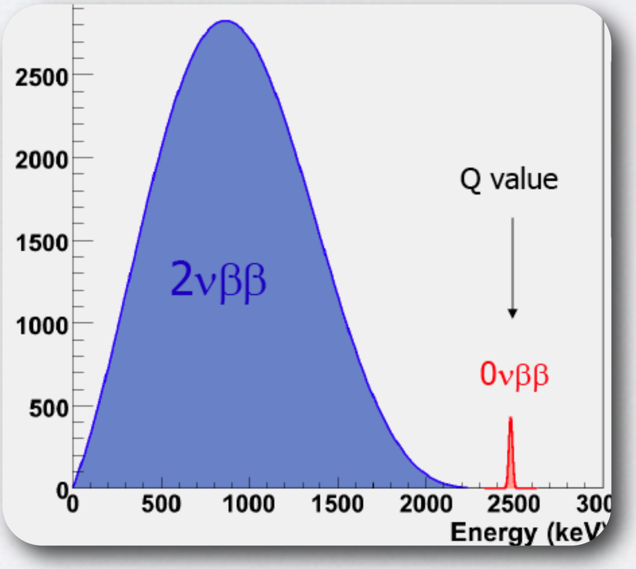

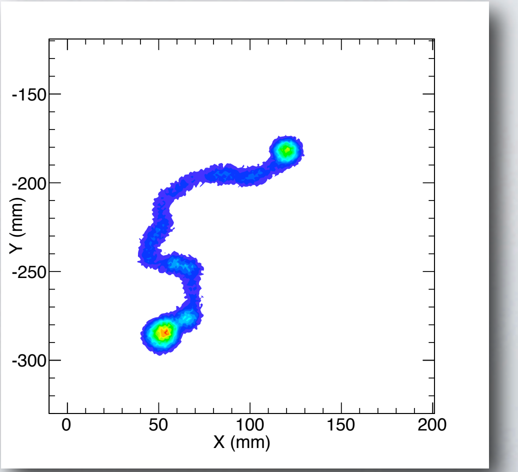

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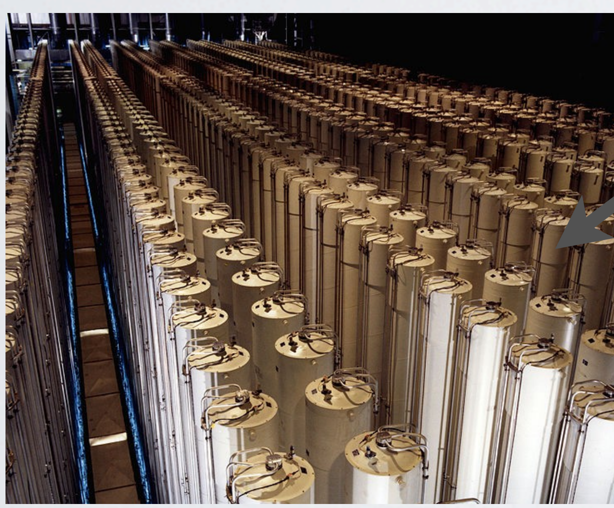

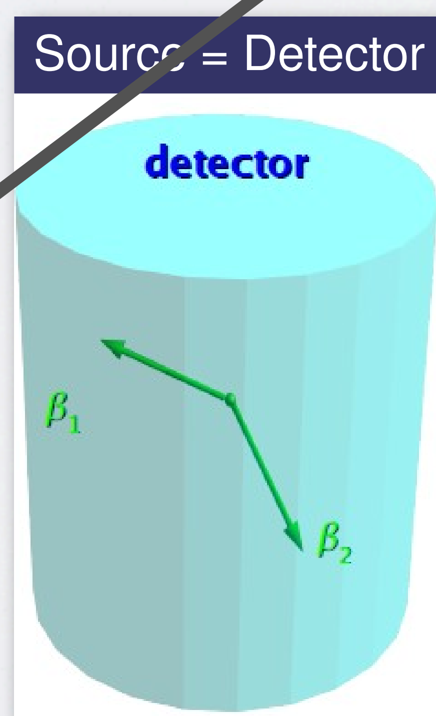

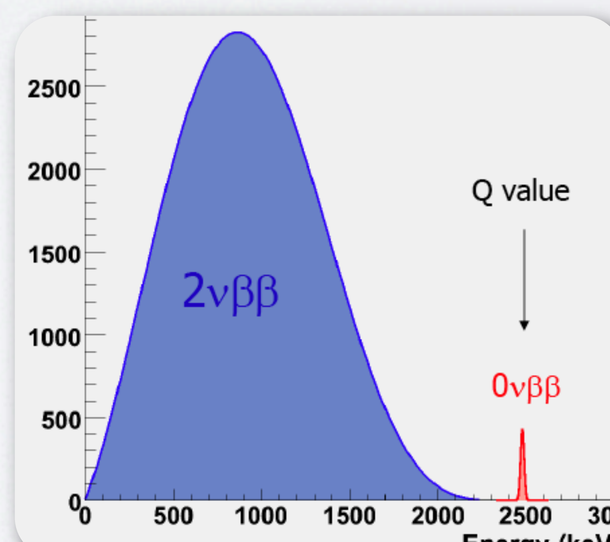

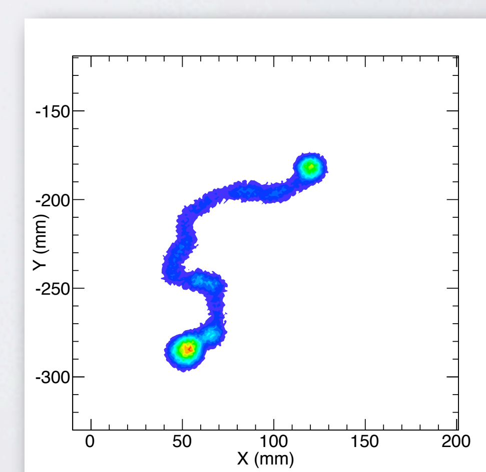

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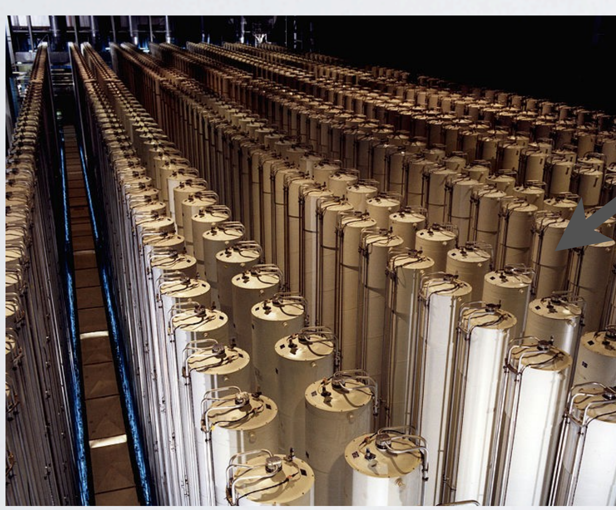

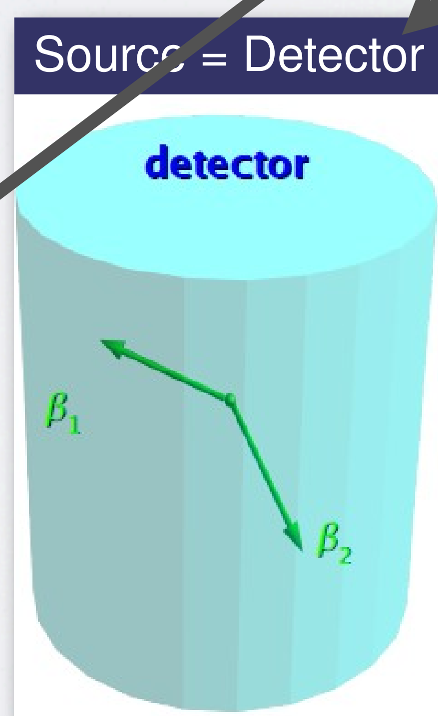

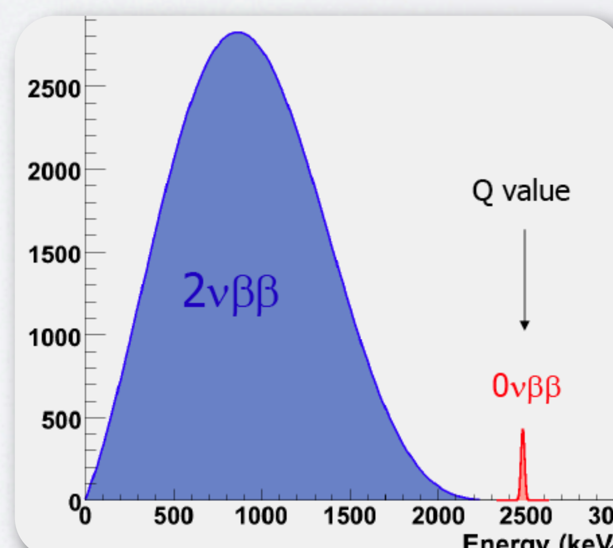

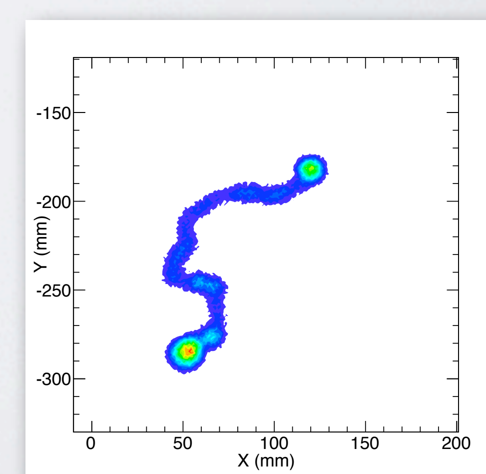

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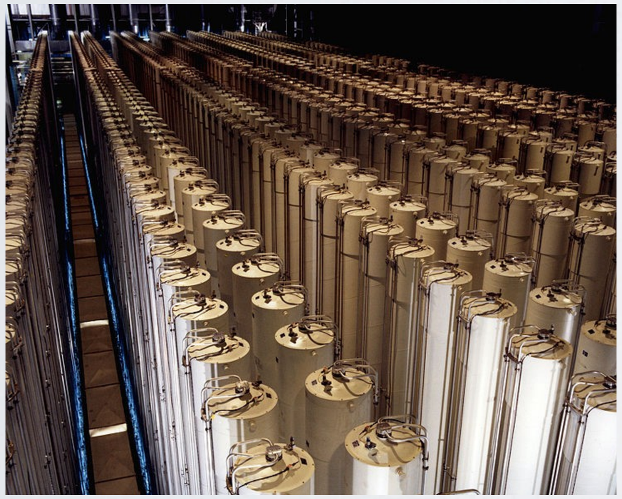

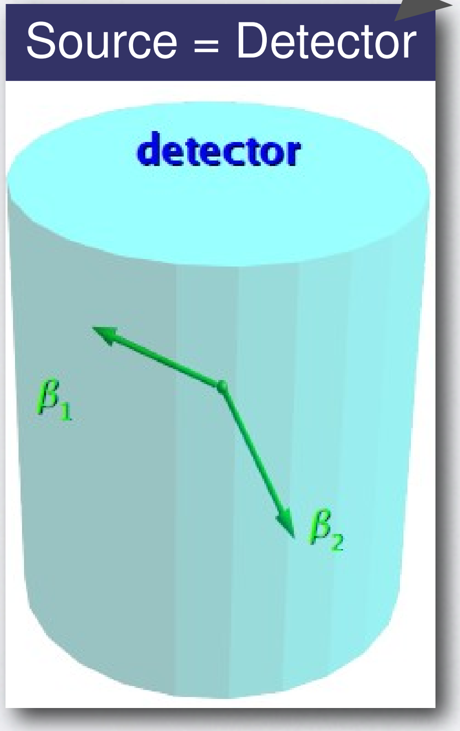

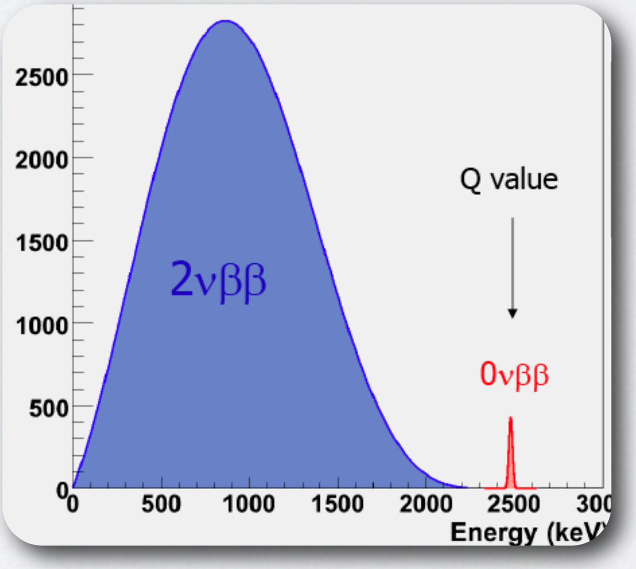

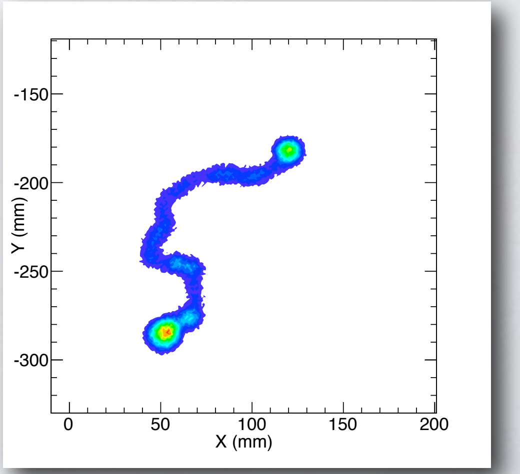

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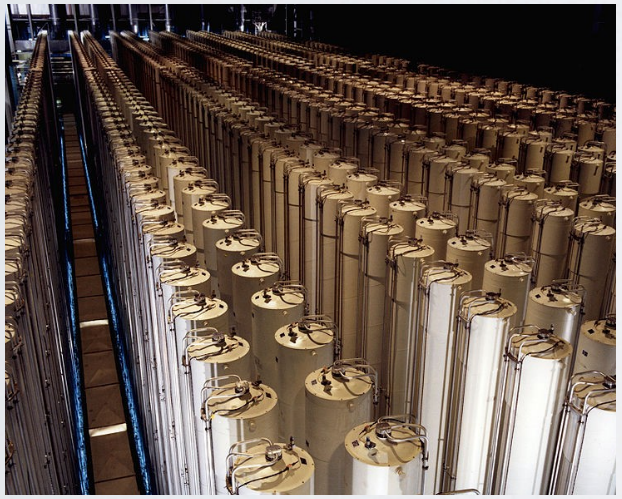

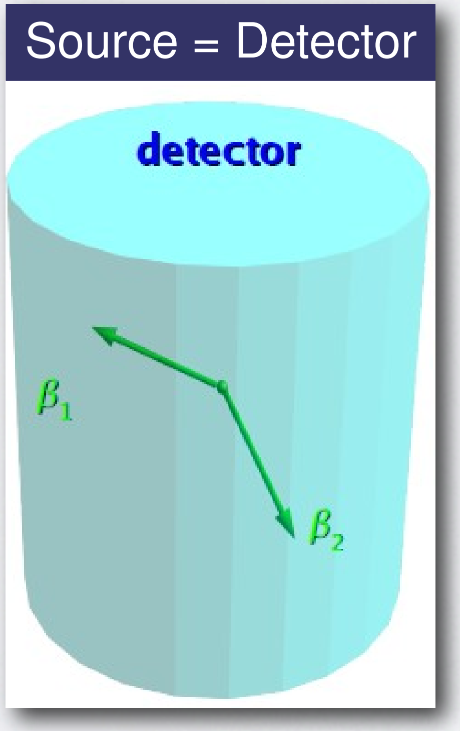

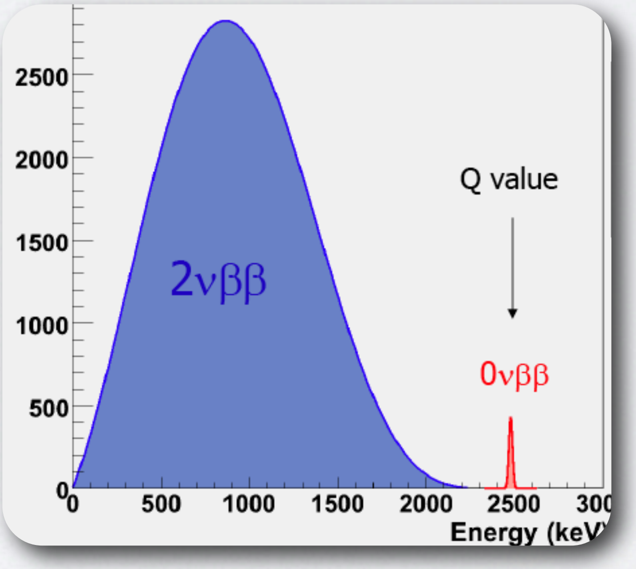

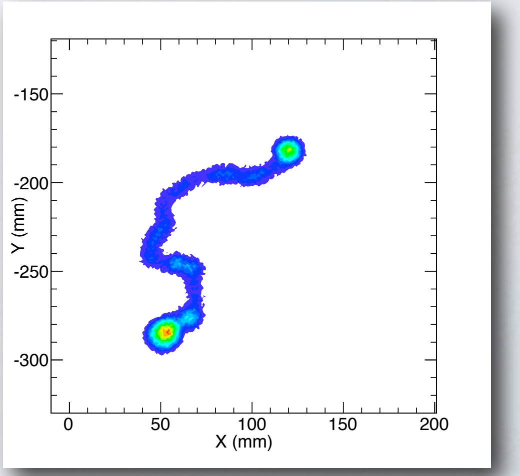

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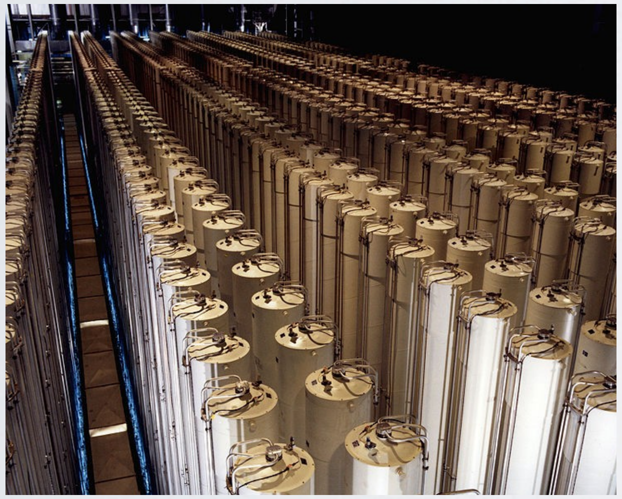

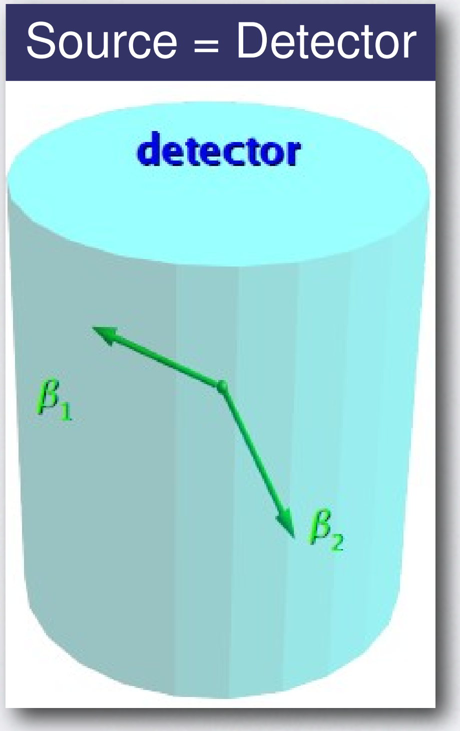

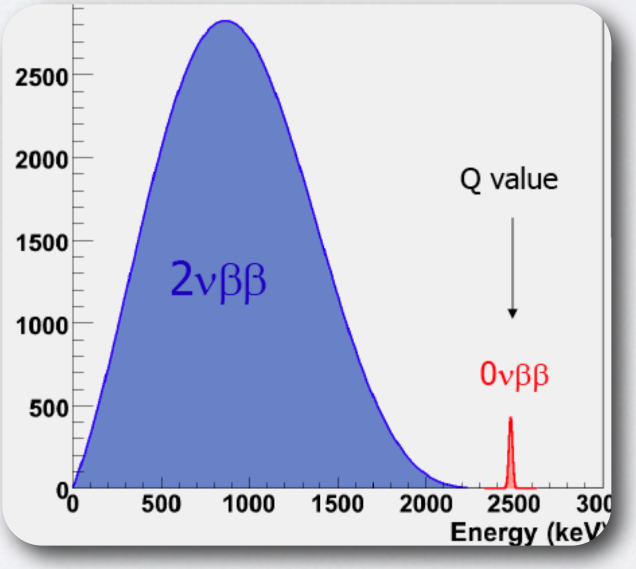

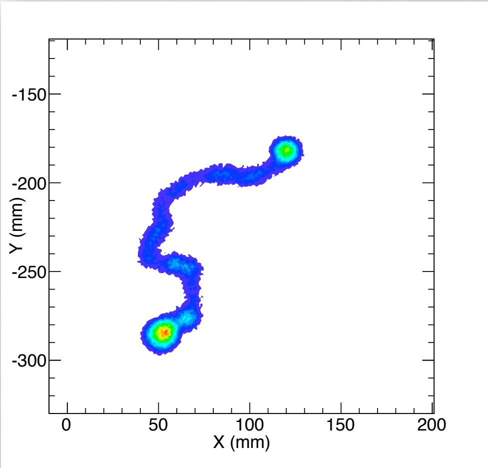

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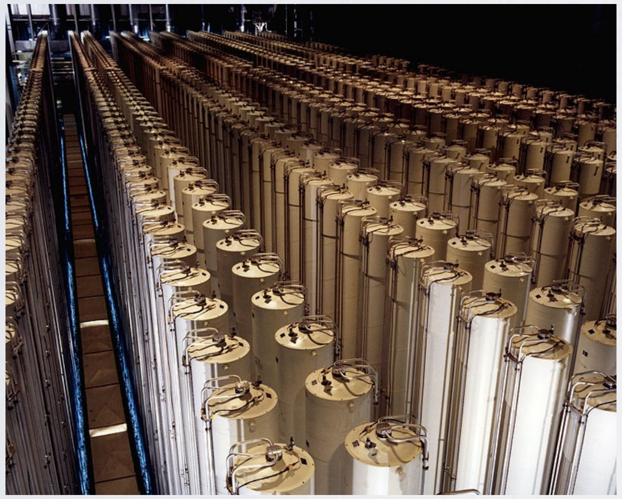

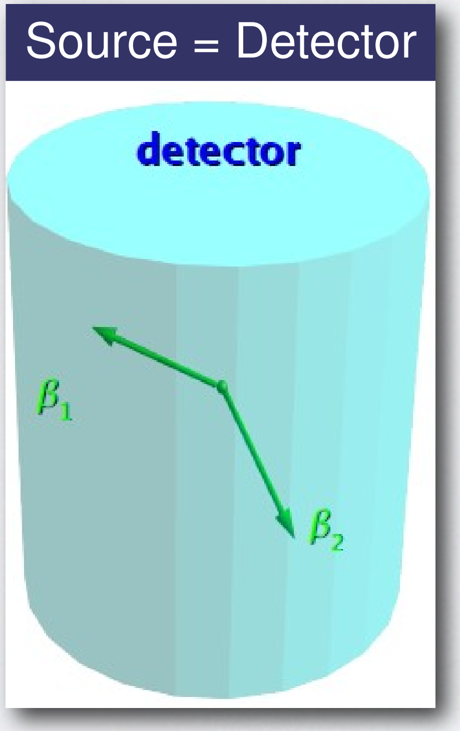

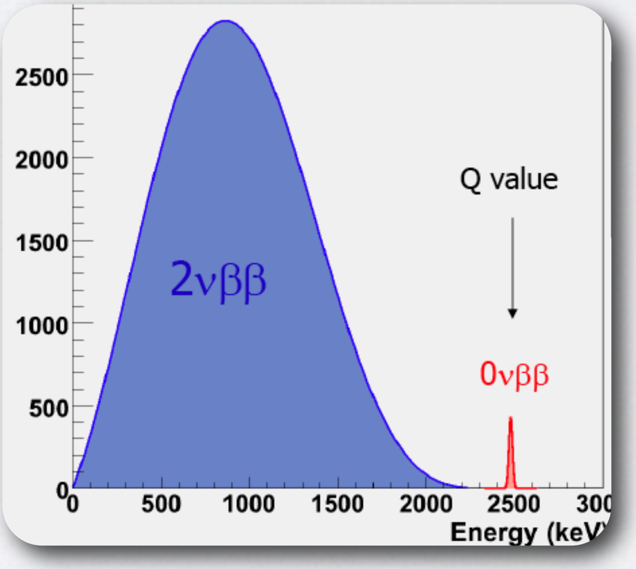

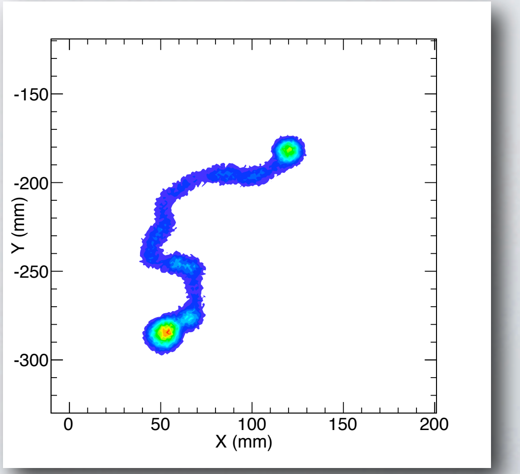

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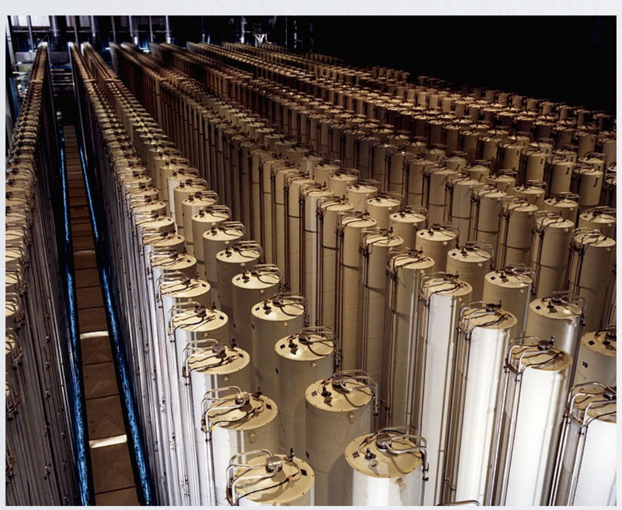
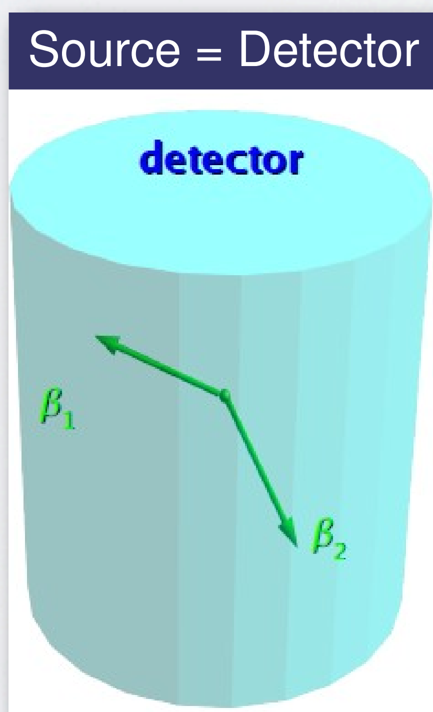
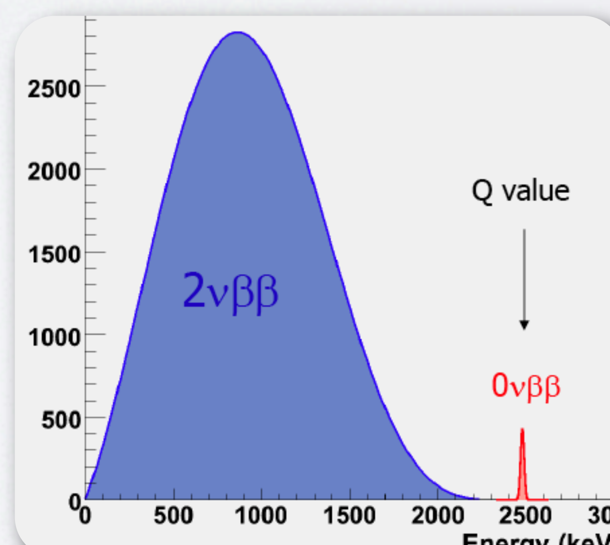






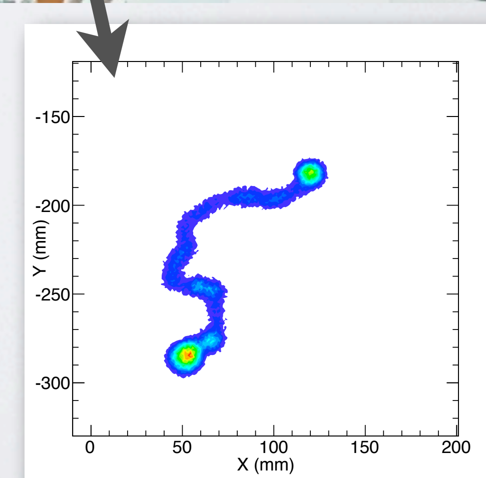
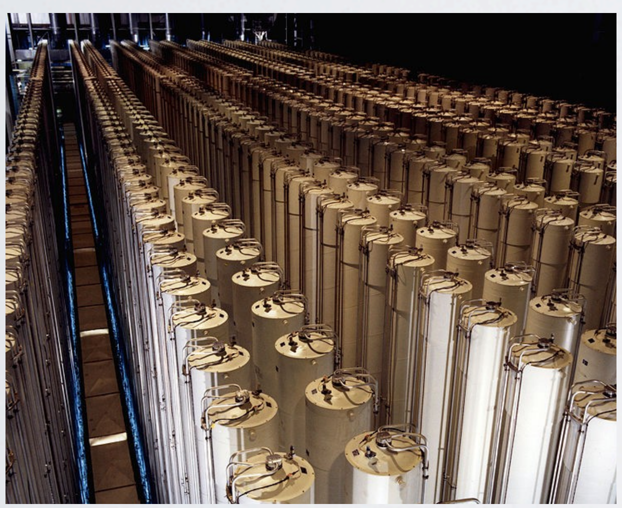
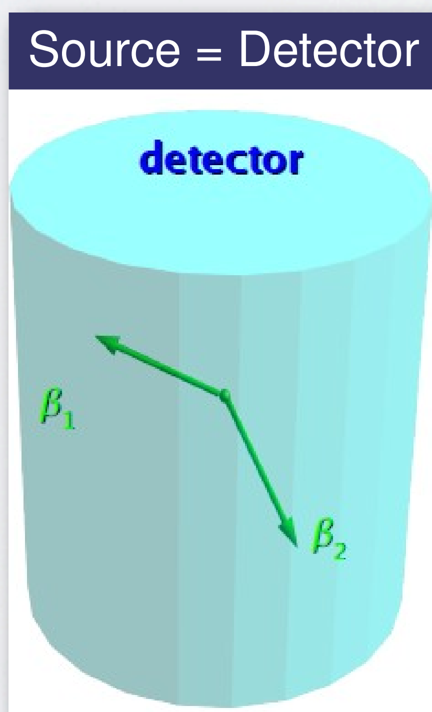
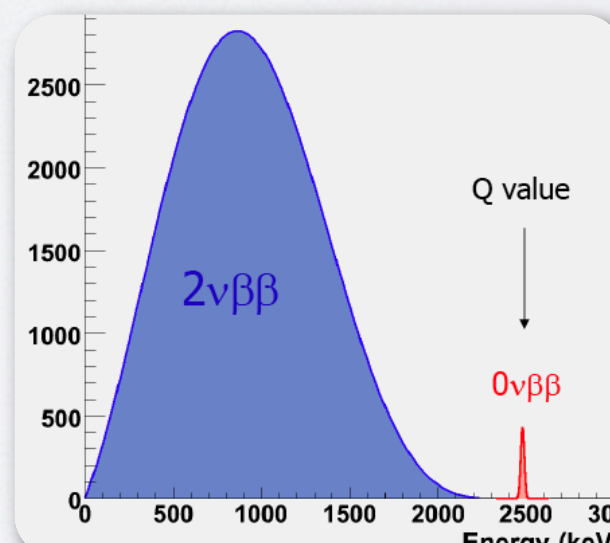


Figure of merit

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







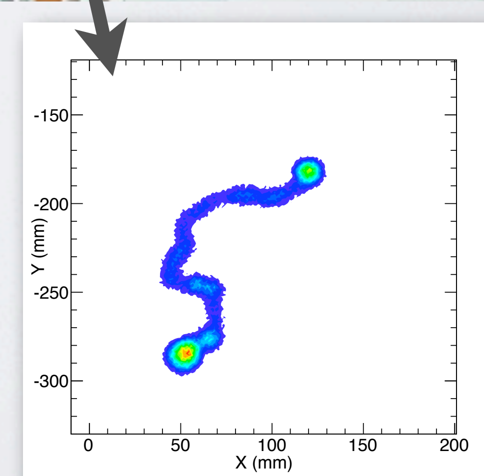
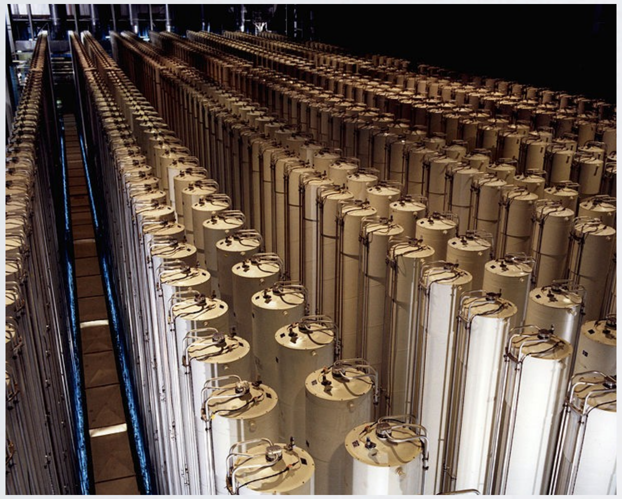
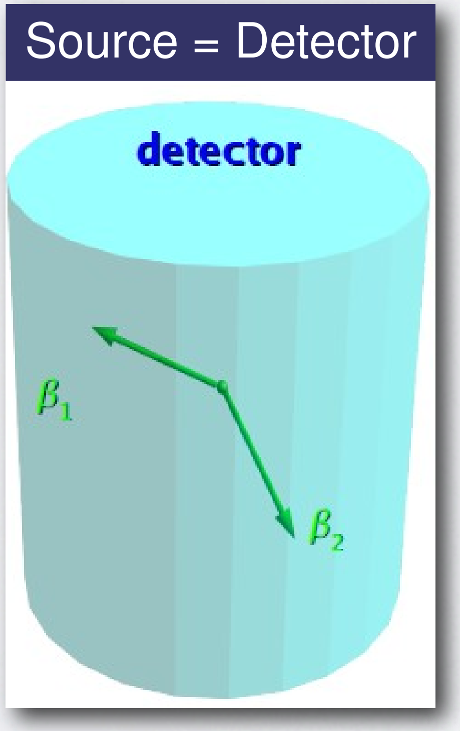
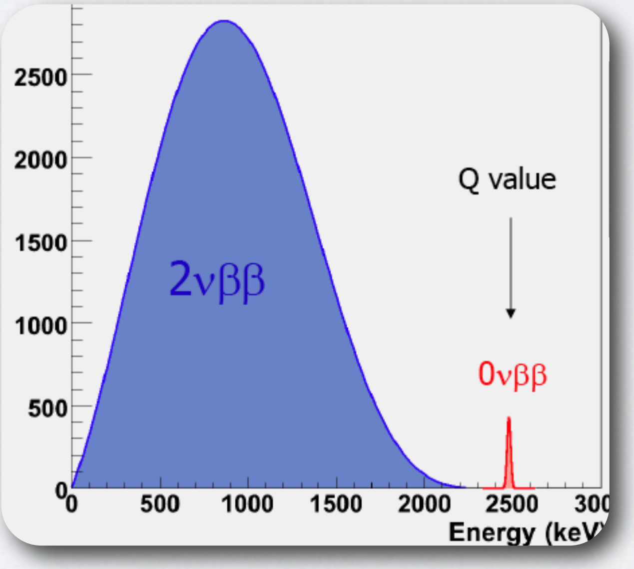


Figure of merit

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







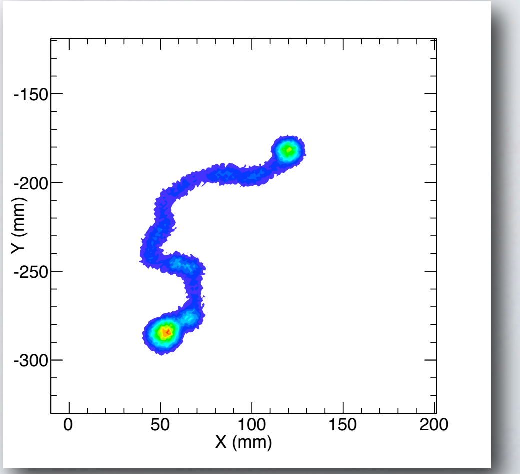
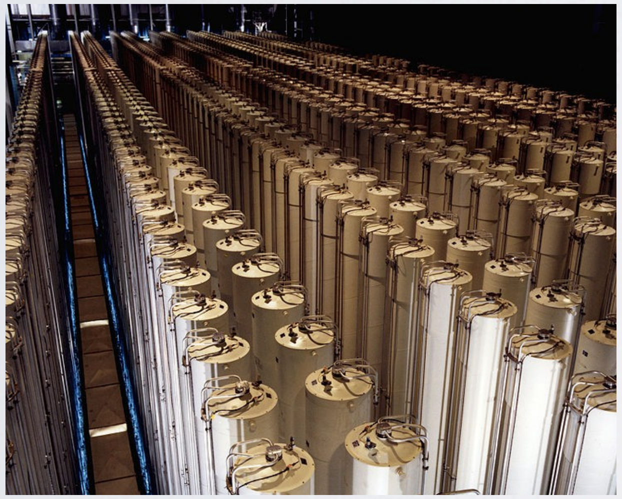
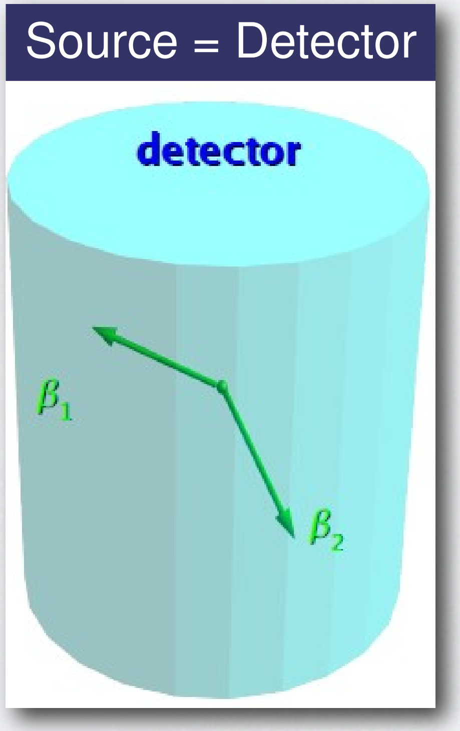
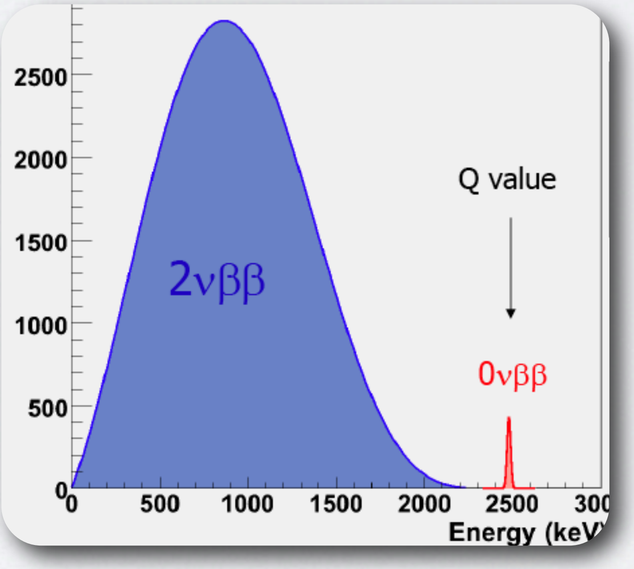


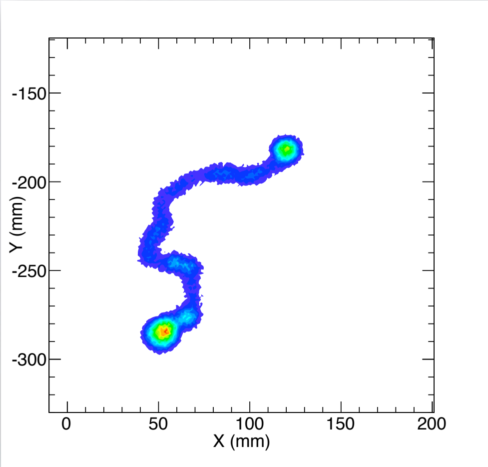
Figure of merit

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

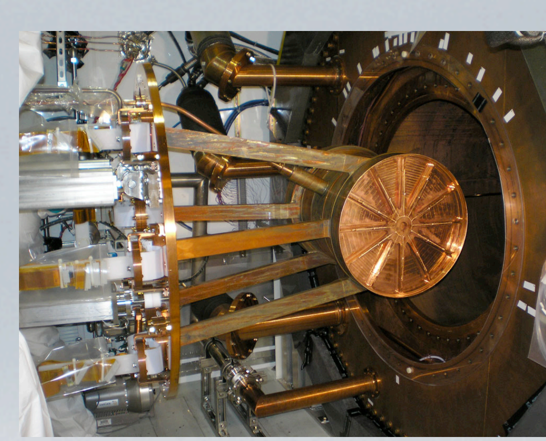


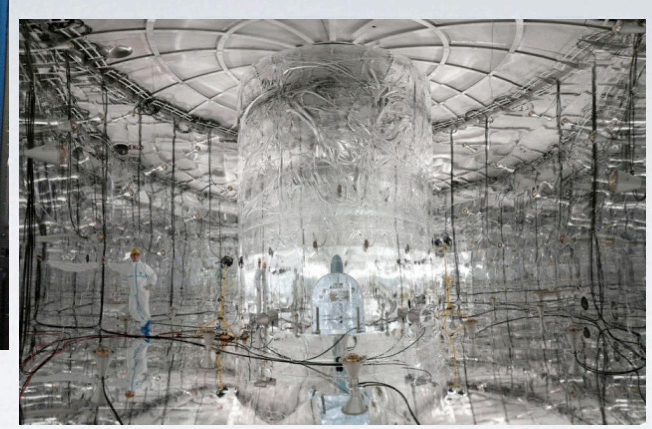




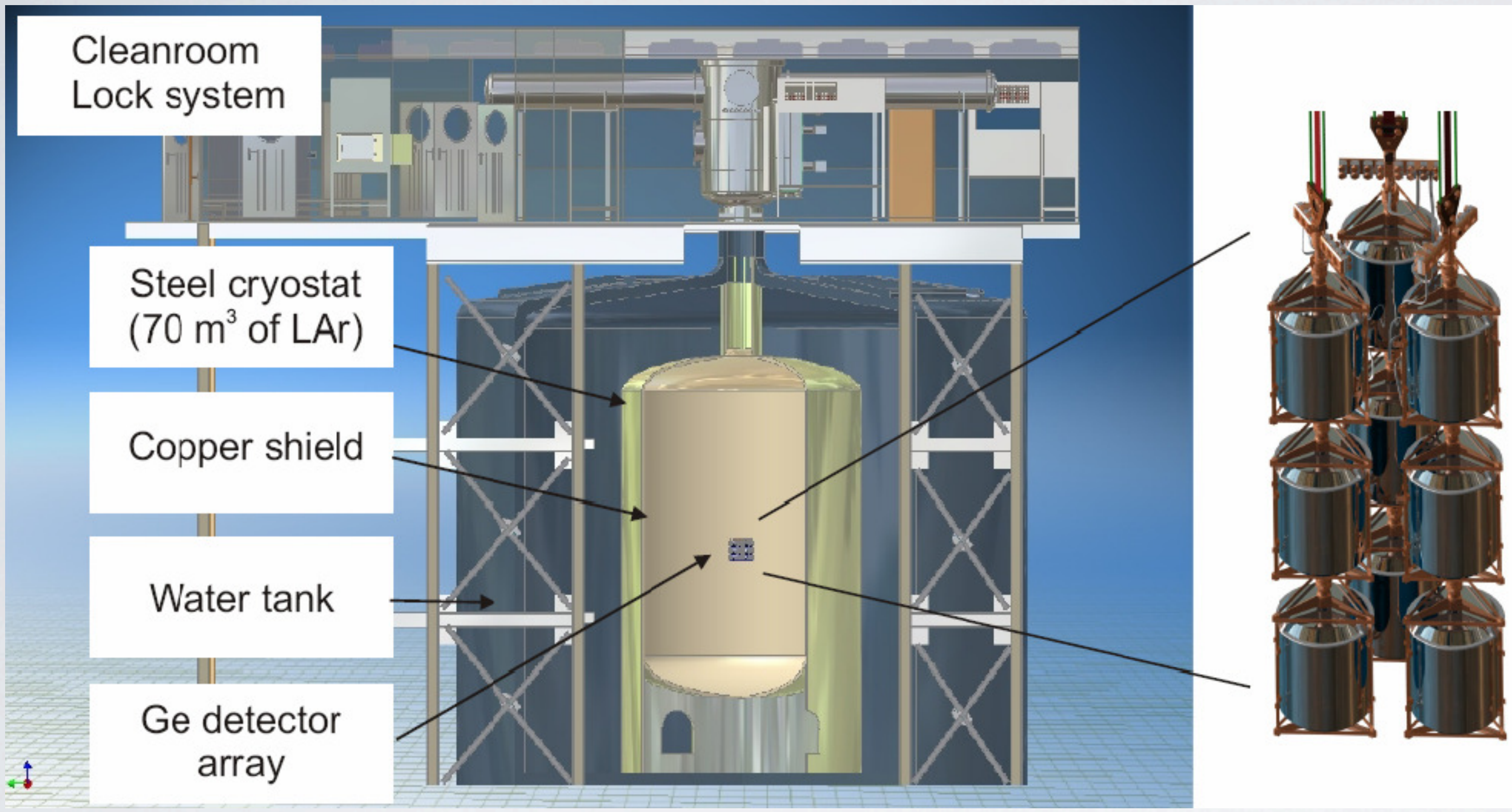


A selection of experiments





Example: Ge detectors



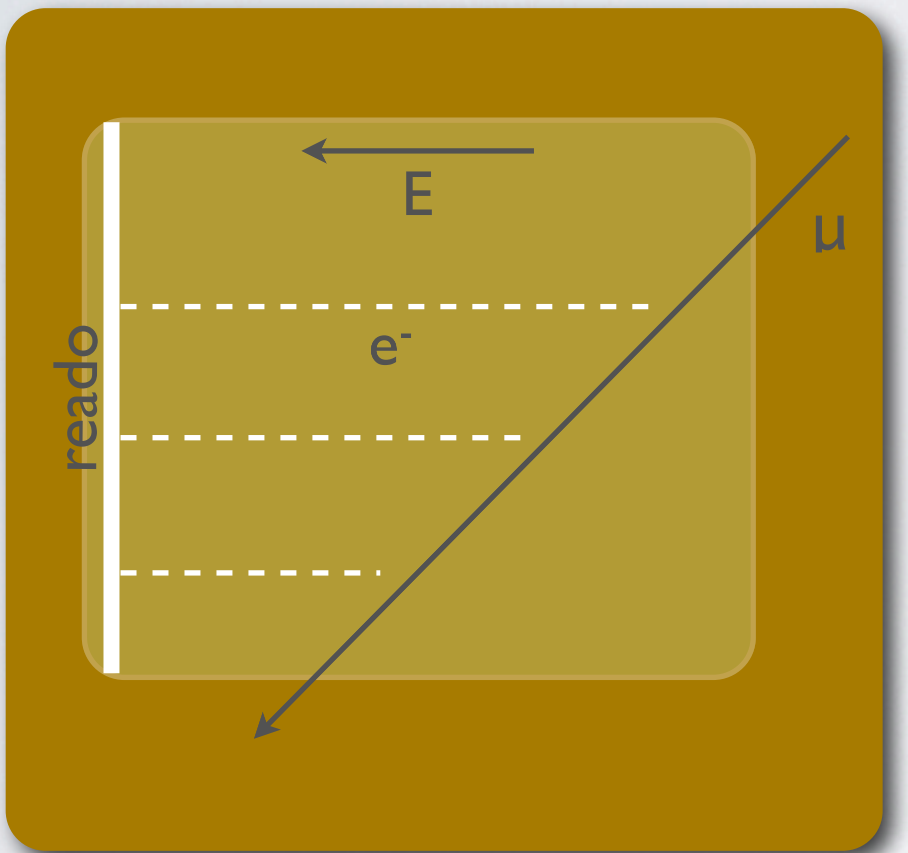
- **a**: expensive
- ε: > 80 %
- **Mt:** Limited (≈100 kg)
- ΔE Excellent (0.2 % FWHM)
- **b** good to very good (10^{-2} to 10^{-3} ckky)

- Excellent
- Very good
- Good
- Moderate
- Poor

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

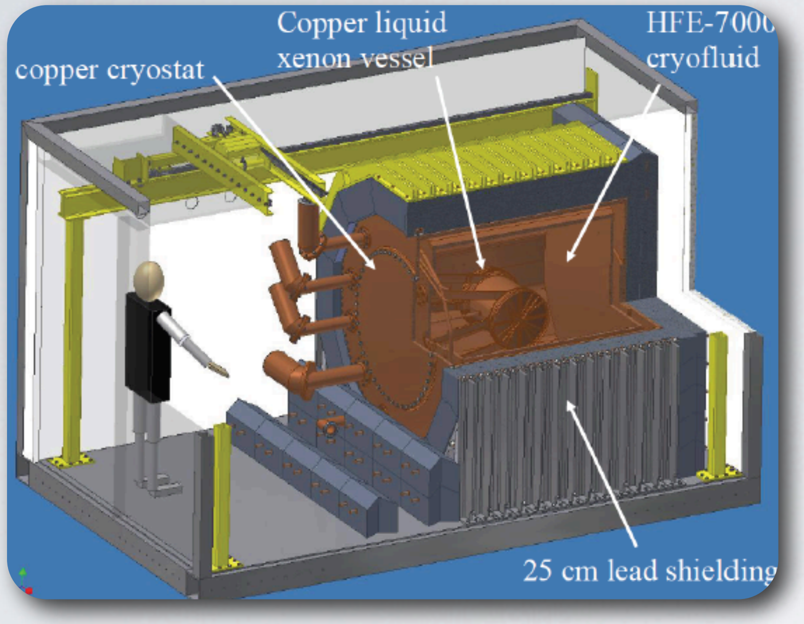
The TPC

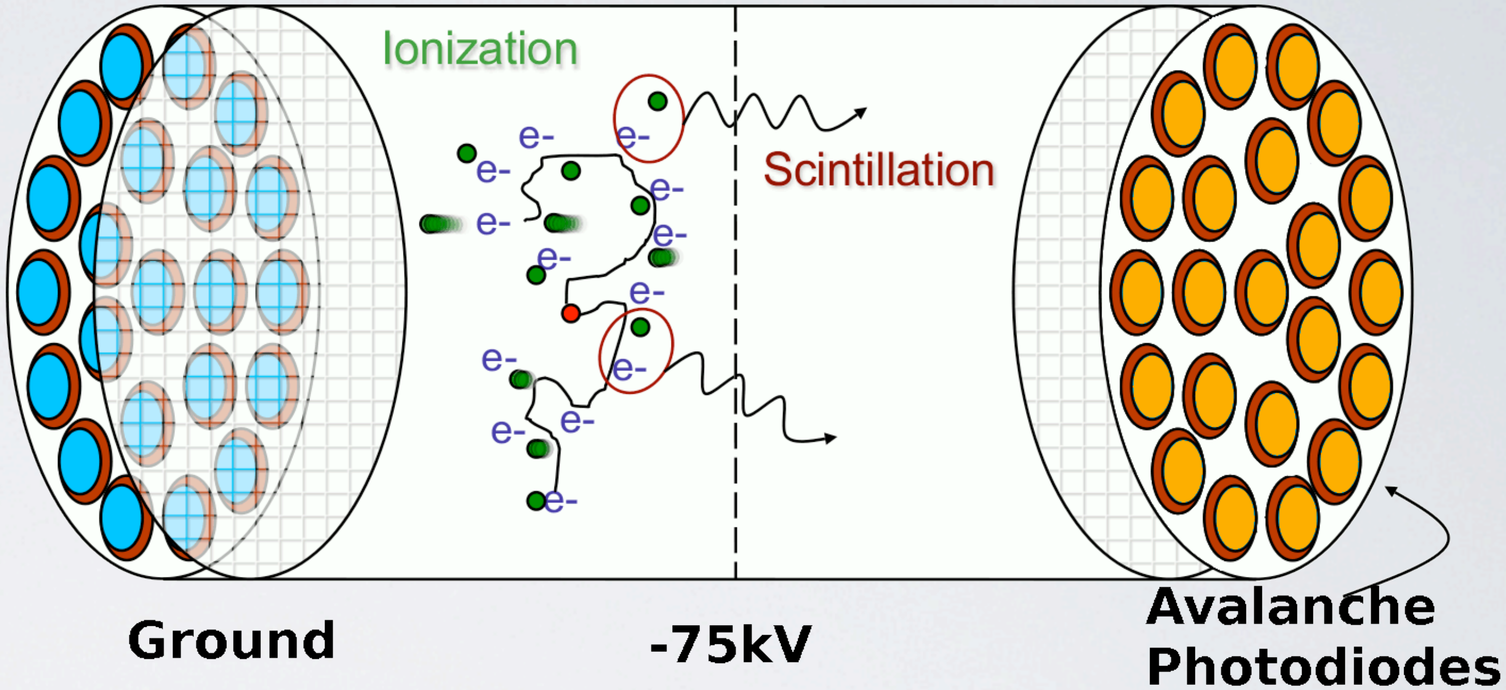
Time Projection Chamber: invented by D. Nygren in the 1970's.

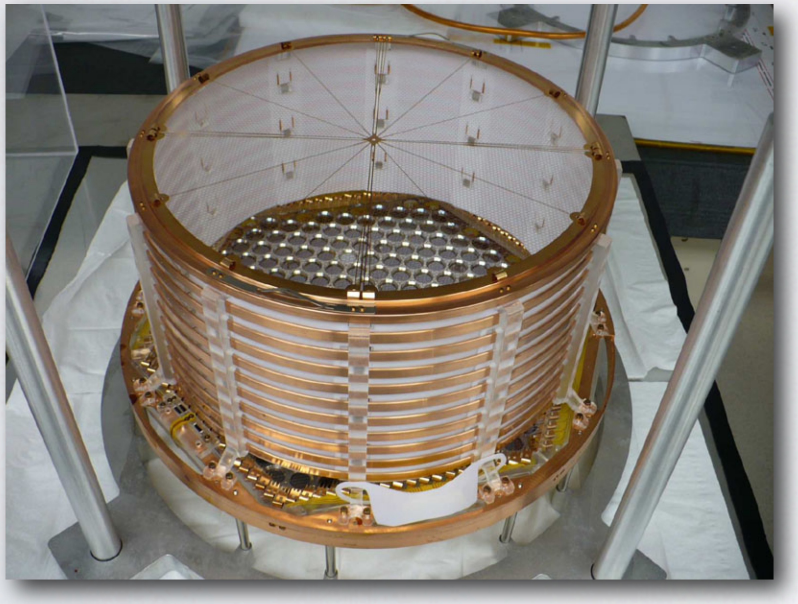


- charged particles traversing TPC ionize gas leaving a track
- If track stops inside TPC then its energy is calorimetrically measured (with good resolution)
- Large volume possible (thus large mass)
- Large V/S

LXe: EXO



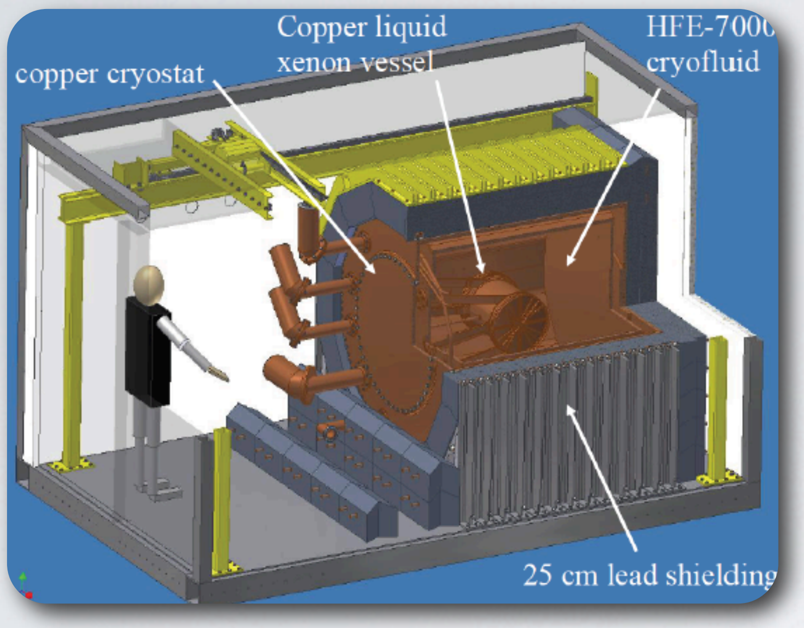




Detail of the LAAPD read-out plane

- Best sensitivity of all current experiments.
- First time Ge detectors are beaten

Example: EXO



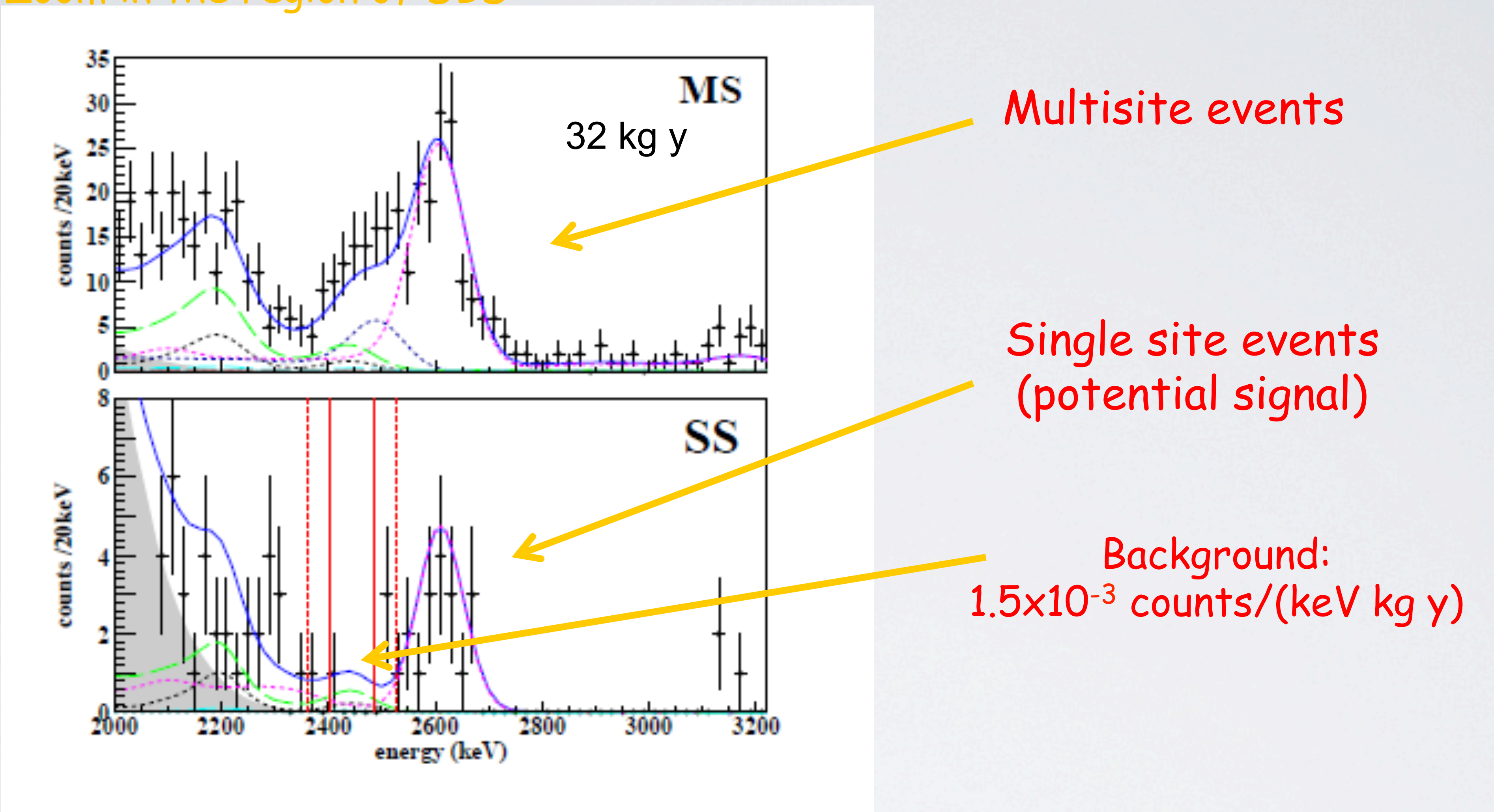
- **a**: Feasible (cheap)
- ε: 30-40% (self shielding)
- **Mt:** Scalable (≈multiton)
- Δ*E* moderate to poor (4 % FWHM)
- **b** very good (10^{-3} ckky)

- Excellent
- Very good
- Good
- Moderate
- Poor

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

EXO: Results

Zoom in the region of DBD



- Found 1 event of background, expected 4. Result is better than its sensitivity (only a 5% chance of getting such result)
- Good news. A nice limit: Bad news: more running can worsen result.

The law of diminished returns in bb0nu

$$\boxed{m_{\beta\beta} = K \ \sqrt{1/\varepsilon} \left(\frac{b \ \Delta E}{Mt}\right)^{1/4}}$$

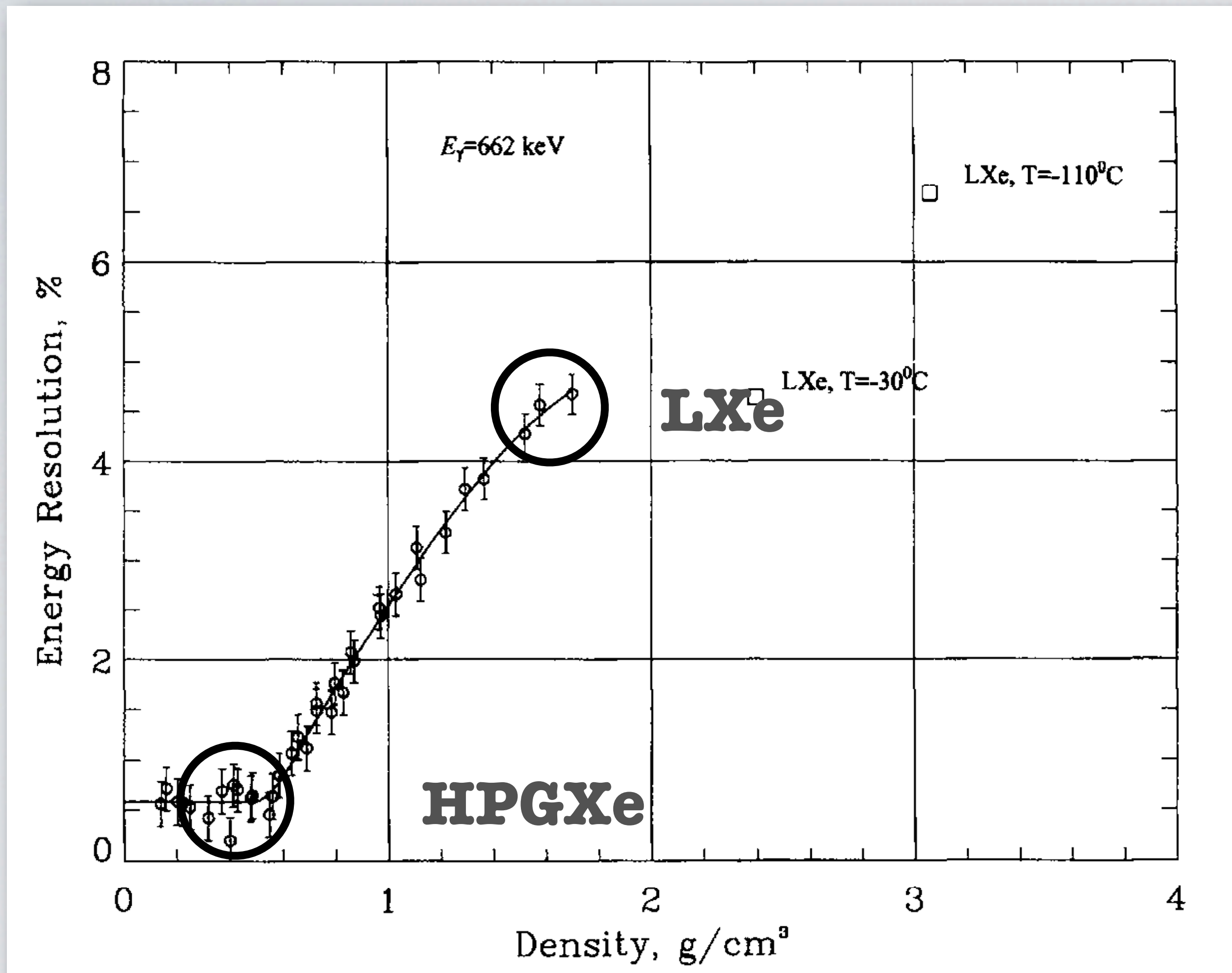
Today: ≈200 meV. Inverse: ≈ 20 meV

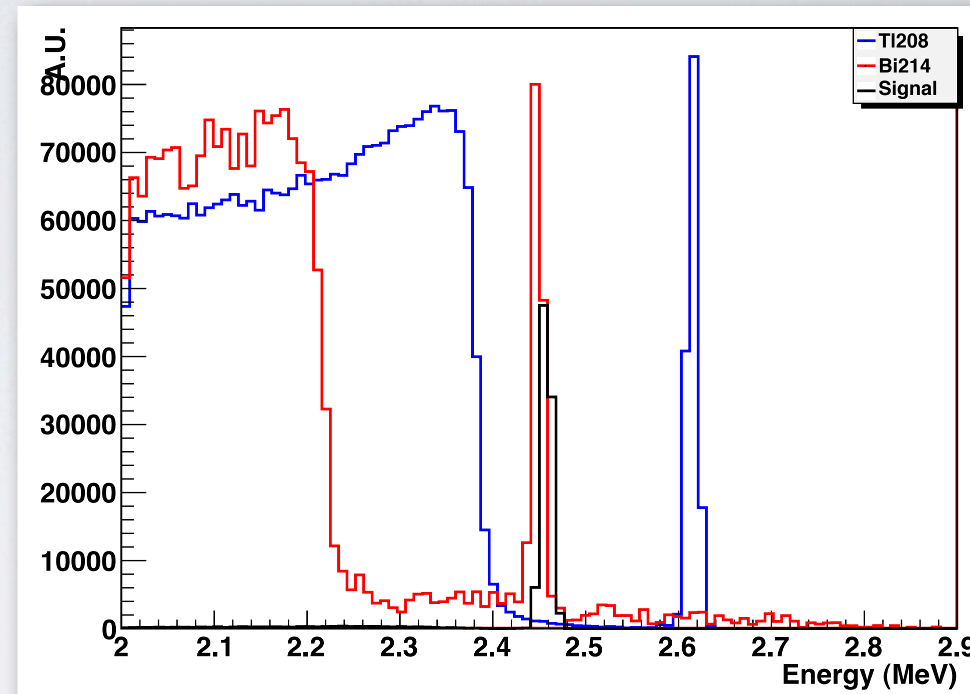
Need to Improve by 10^4!!! HOW??

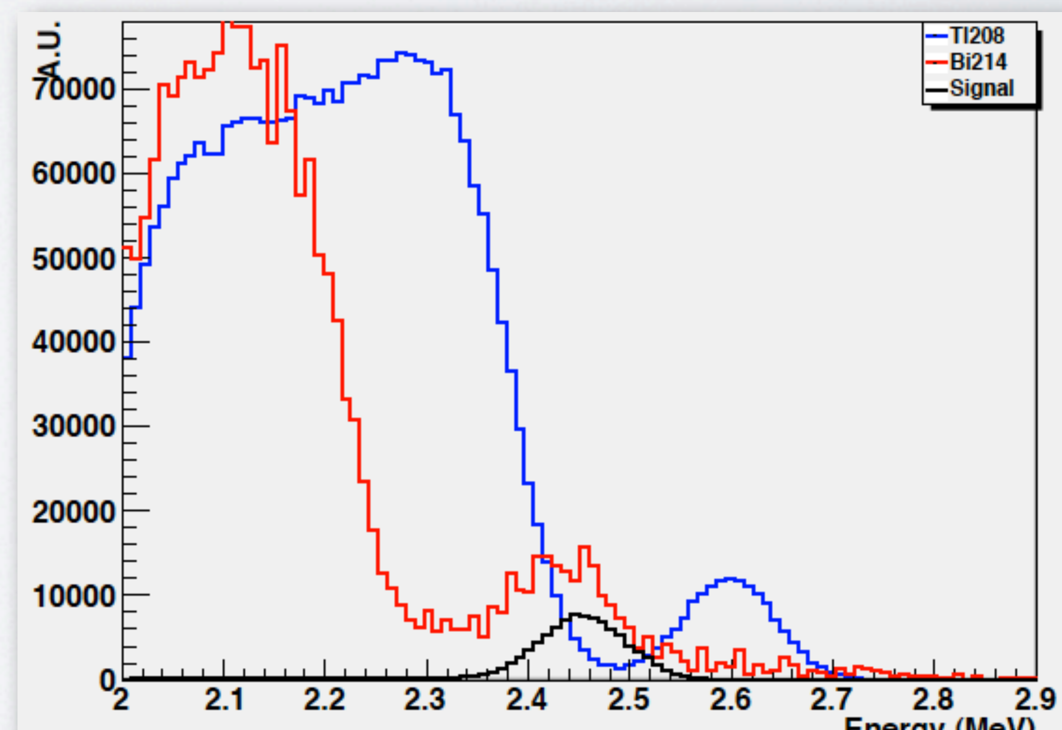
EXO: Mass could improve by 10^2 (30 kg y to 3 ton y). Resolution is fixed by the technology: Thus, a LXe detector needs to reduce background rate by 10^2 (from 10^{-3} ckky to 10^{-5} ckky)

VERY DIFFICULT

HPGXe vs LXe

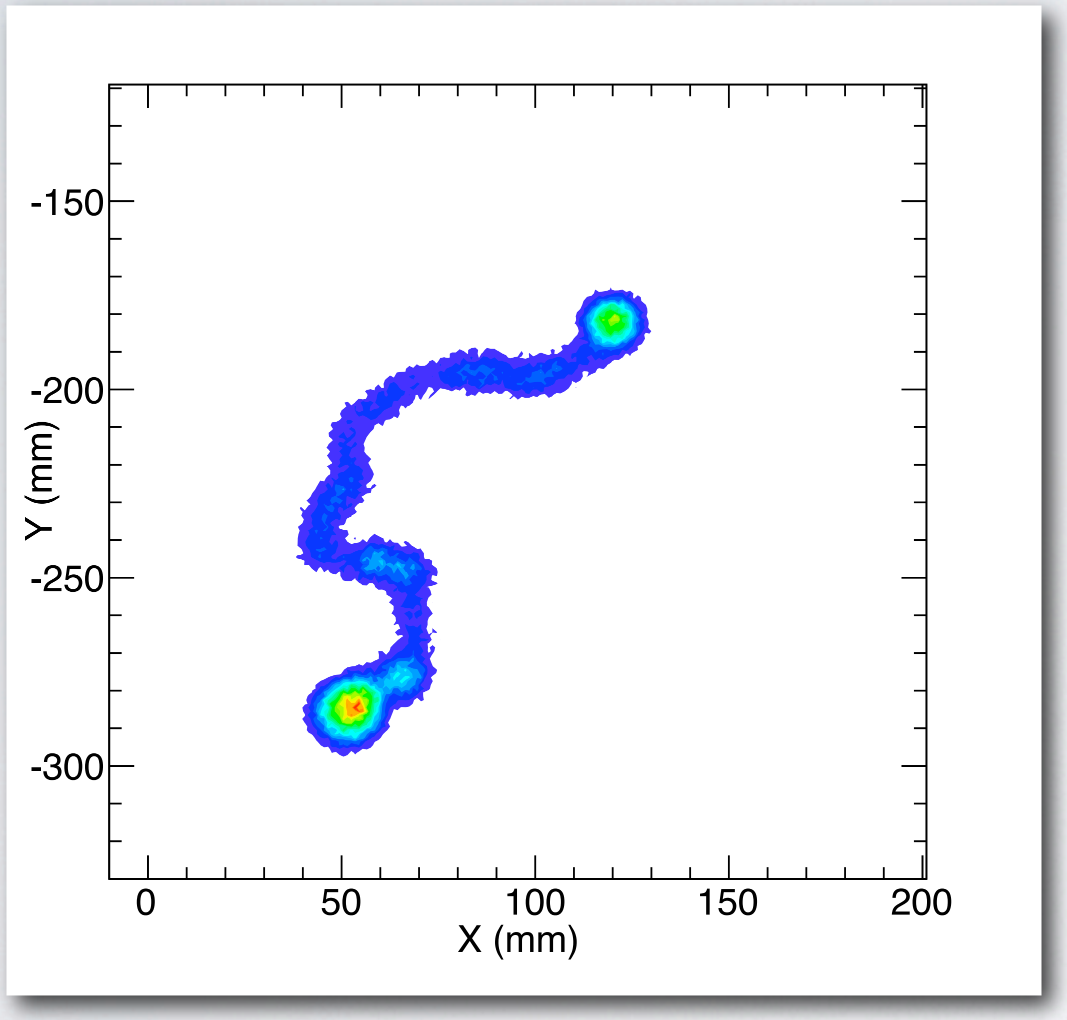


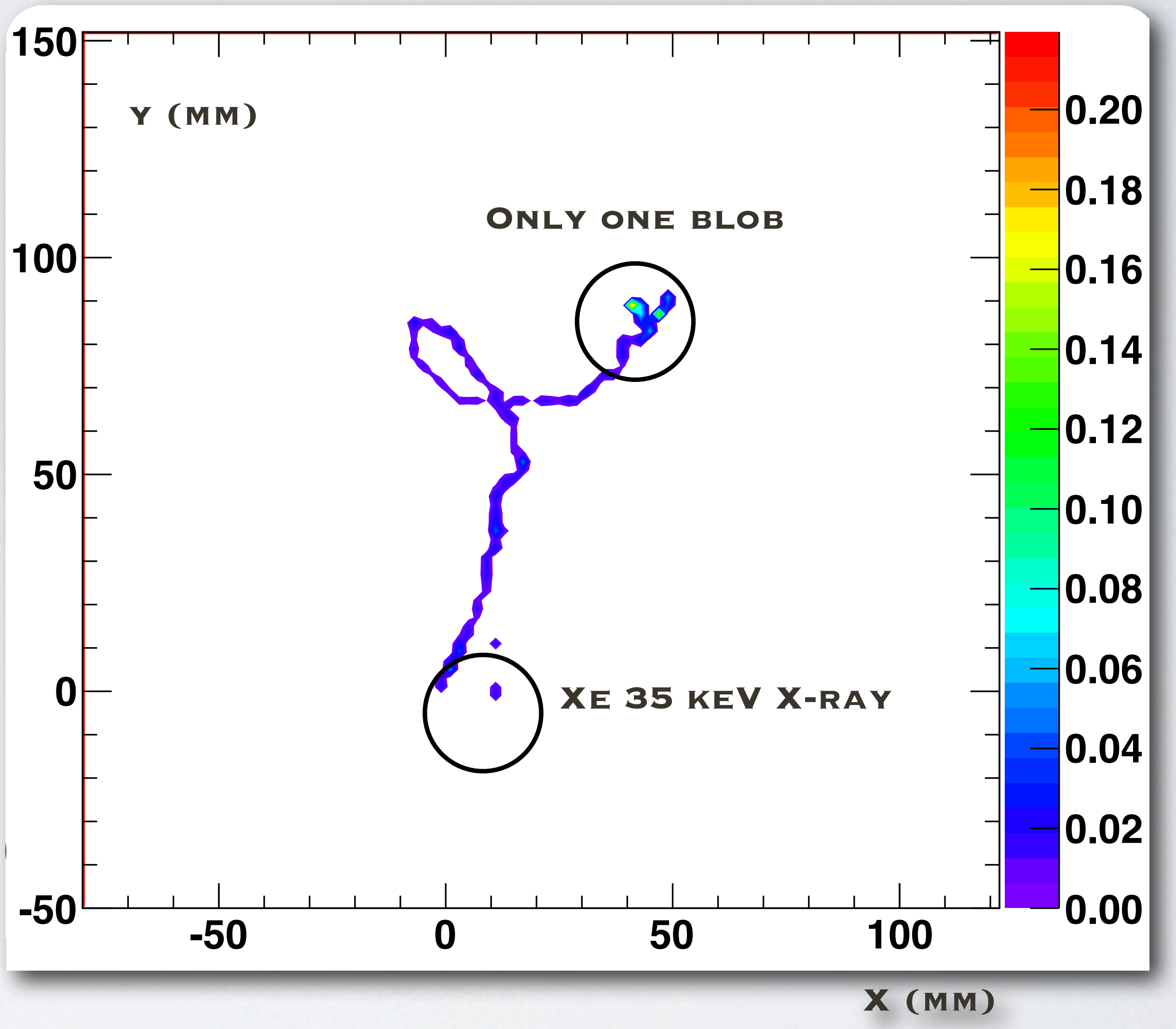




- **HPGXe can achieve a resolution 5 to 10 better than LXe. Essential!**

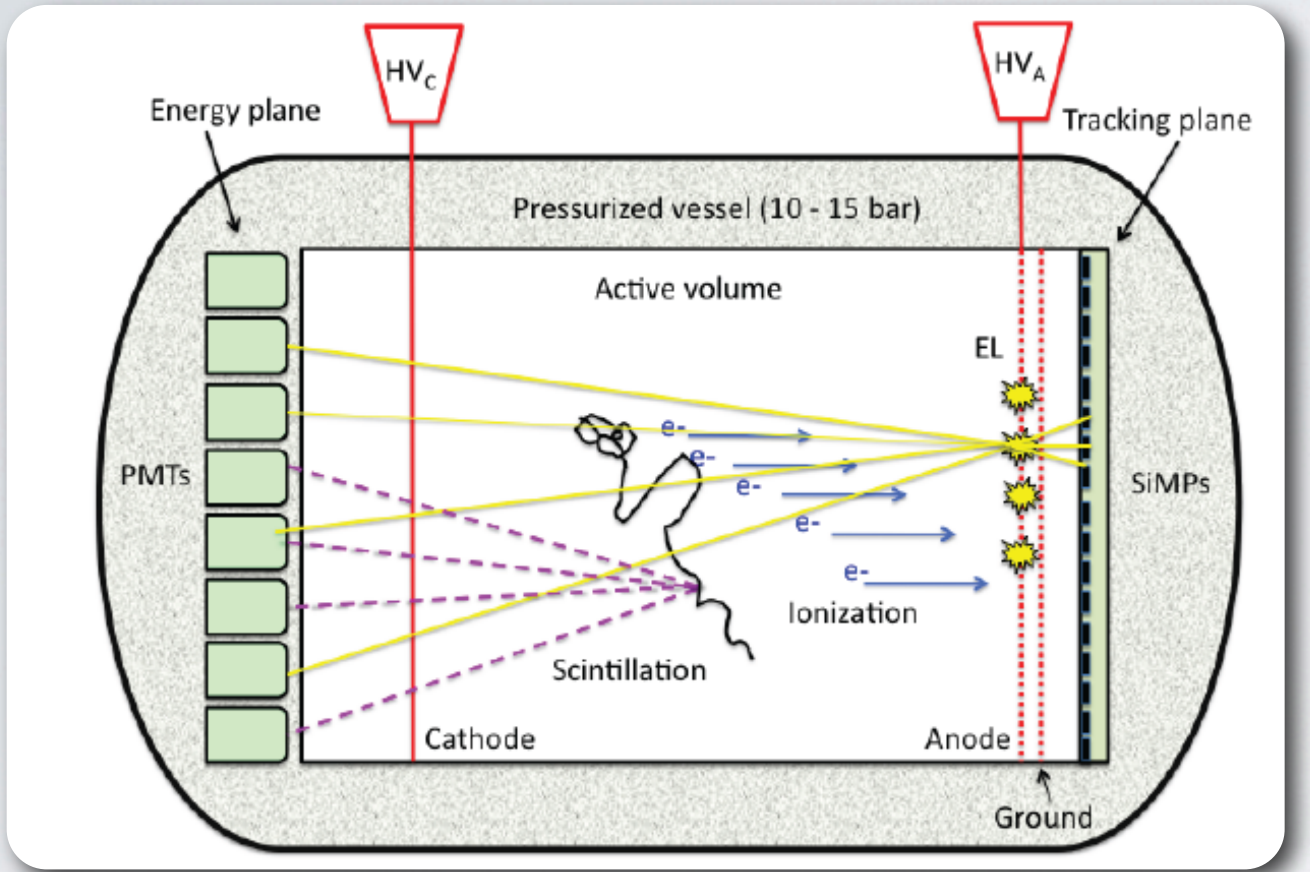
HPGXe has a topological signature (extra handle)

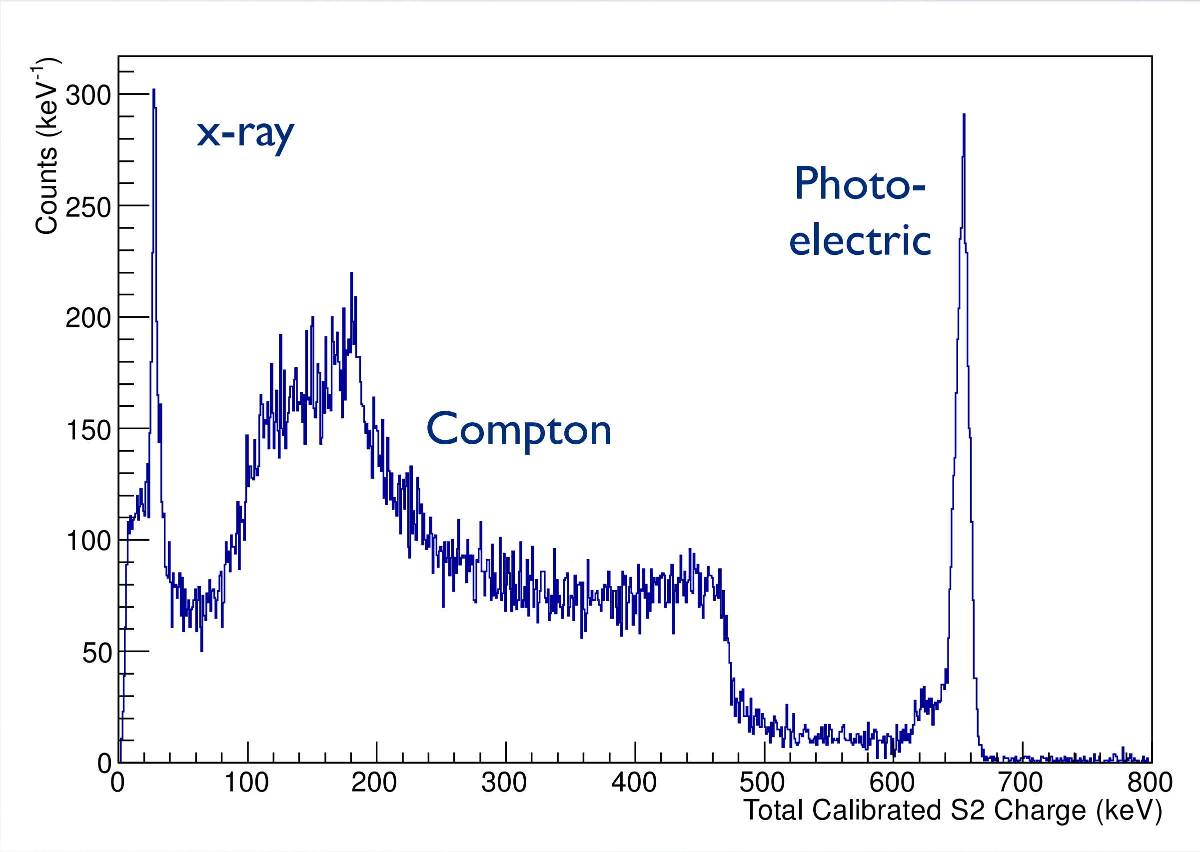


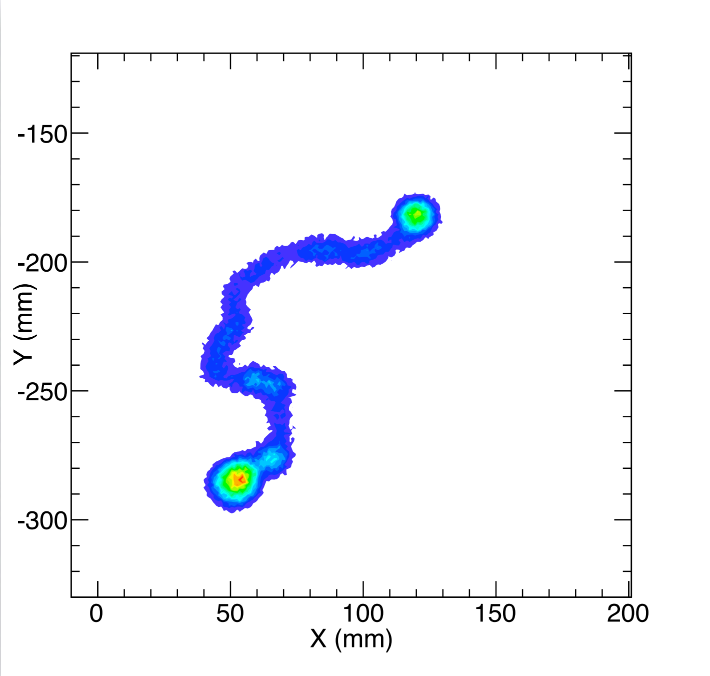


NEXT: Concept

Energy, 662 keV gammas from ^{137}Cs in NEXT-DBDM prototype

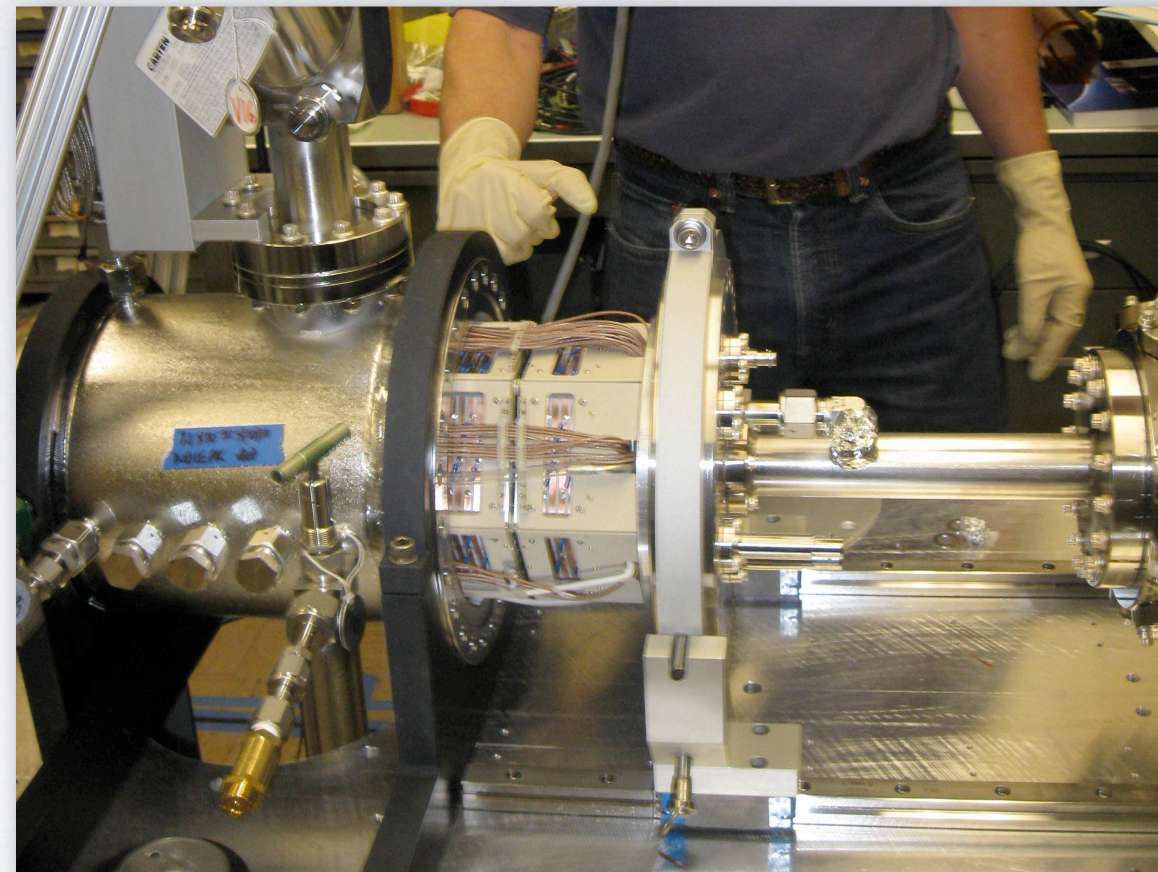






A HPGXe SOFT TPC

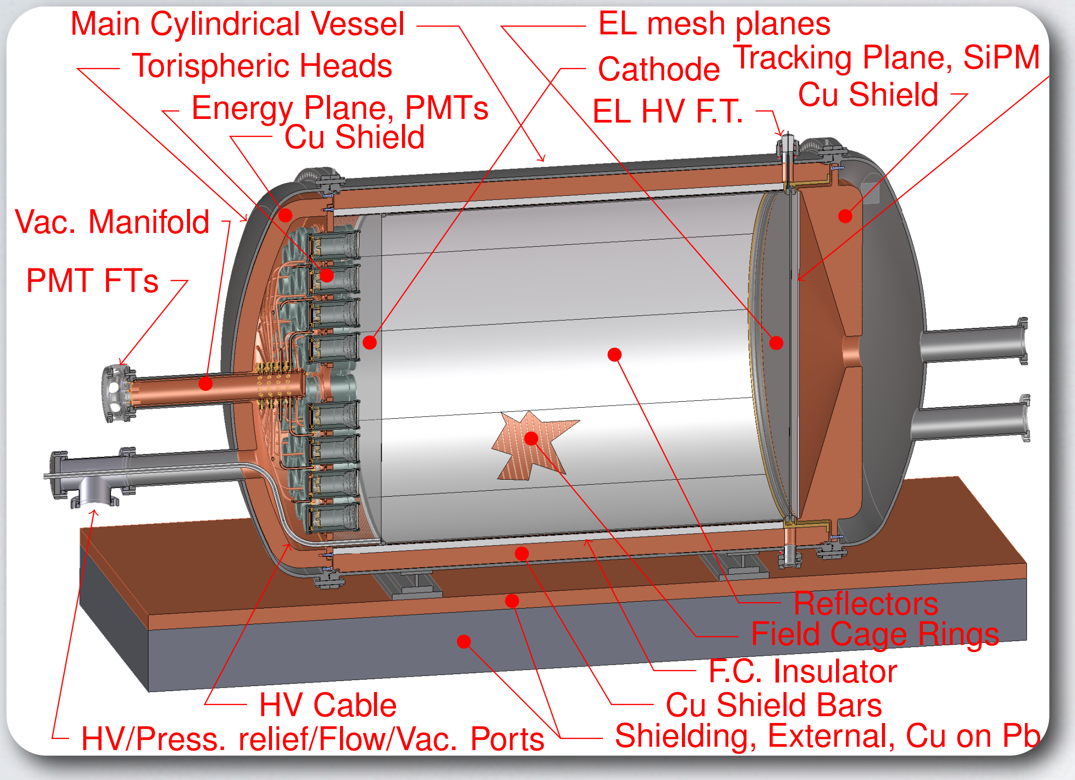
NEXT DEMO/ DBDM



Resolution: 0.5% FWHM in restricted region (LBNL). 1% in extended fiducial (DEMO). Tracking demonstrated

White through the looking glass

NEXT

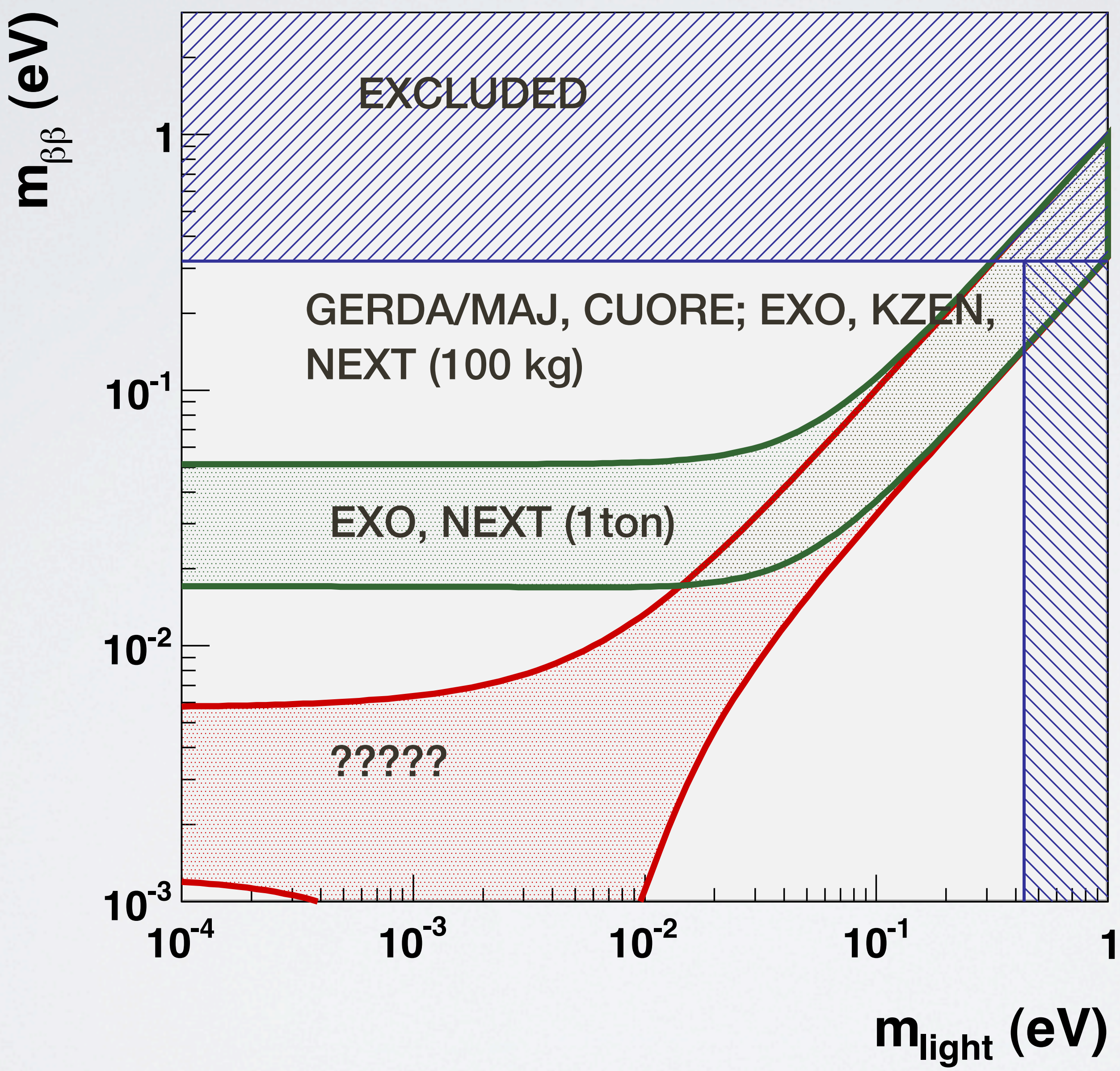


- **a**: Feasible (cheap)
- ε: moderate (30%)
- **Mt:** Scalable (≈multiton)
- ΔE good to very good (1% to 0.5% FWHM)
- **b** very good to excellent (10^{-4} ckky)

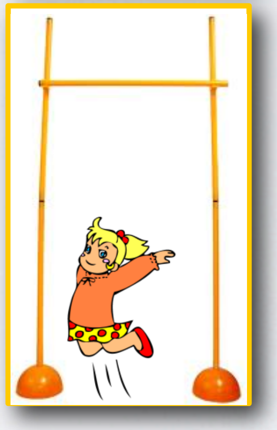
- Excellent
- Very good
- Good
- Moderate
- Poor

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

Prospect

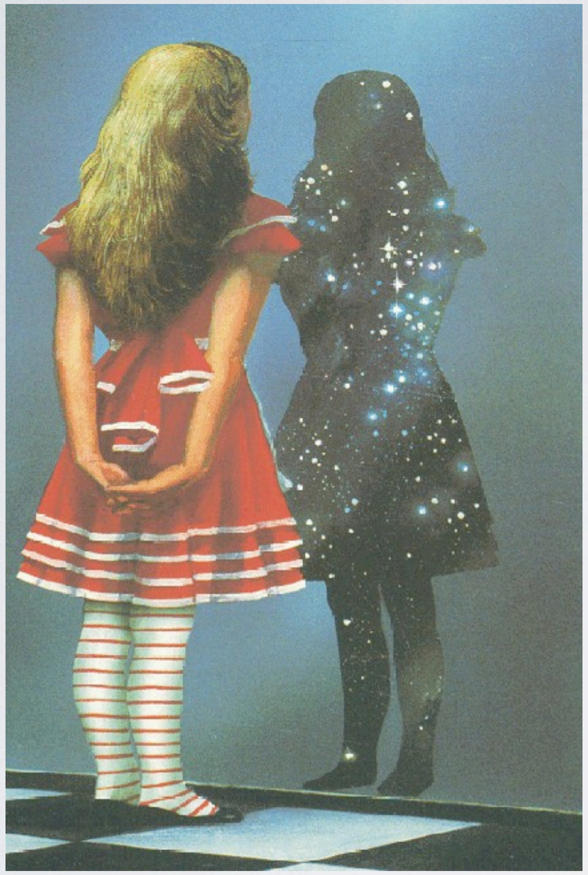


EXCLUDED
GERDA/MAJ, CUORE; EXO, KZEN,
NEXT (100 kg)
EXO, NEXT (1ton)
?????
$m_{\beta\beta}$ (eV)
m_{light} (eV)
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1

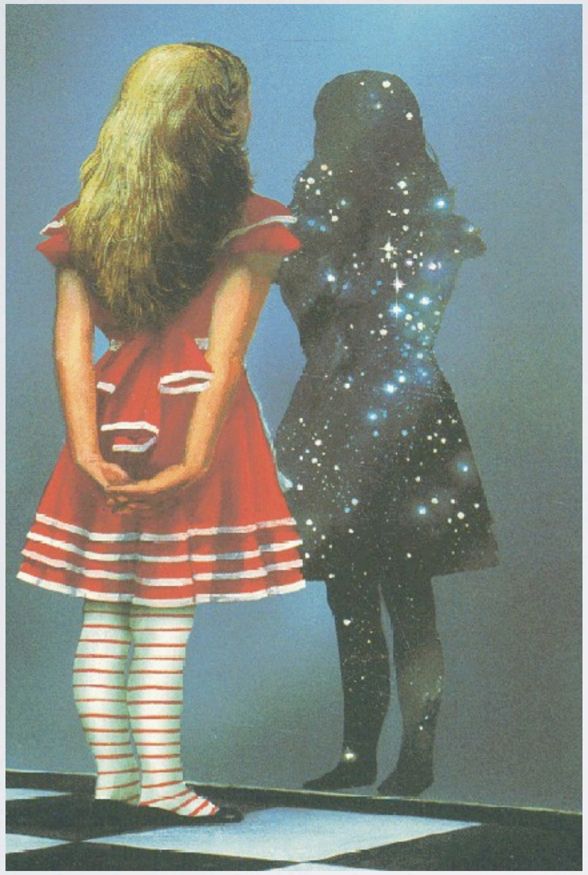


Ettore Majorana through the looking-glass

Ettore Majorana through the looking-glass

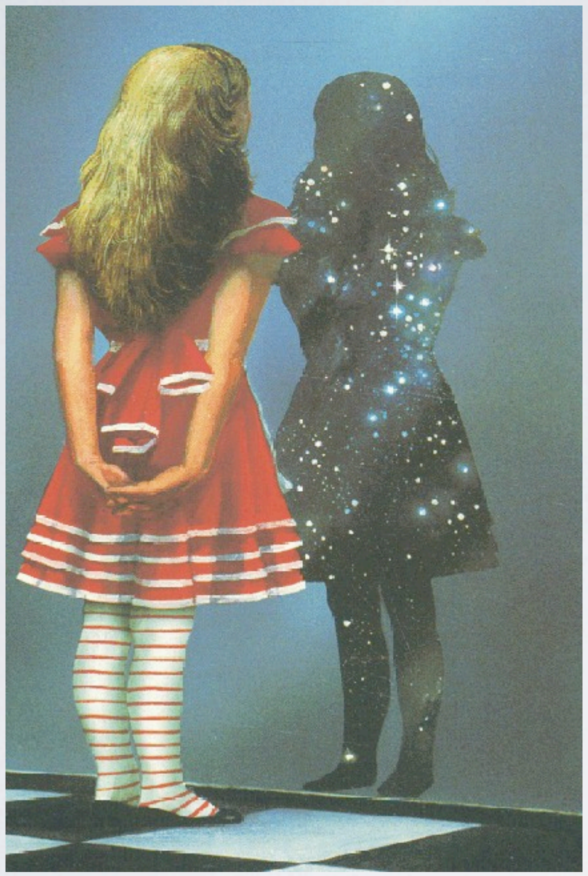


Ettore Majorana through the looking-glass



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

Ettore Majorana through the looking-glass



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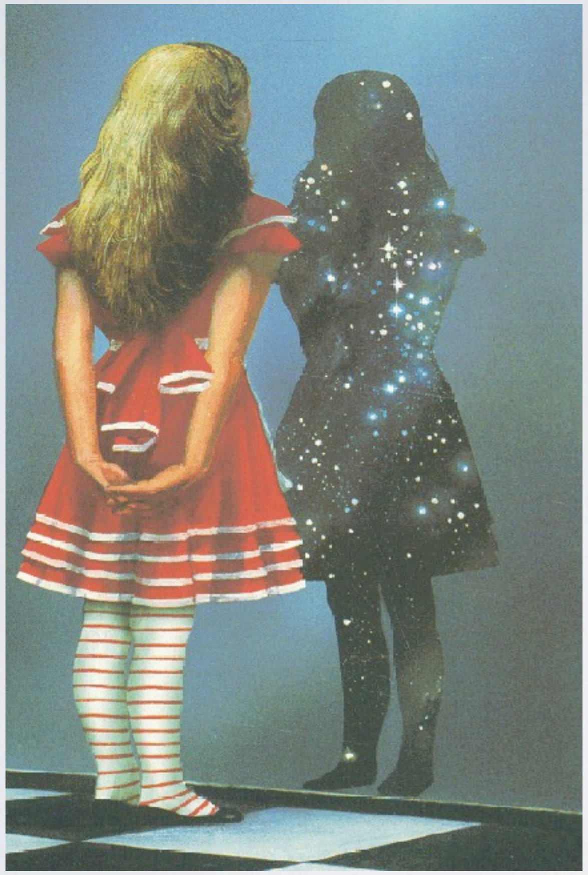
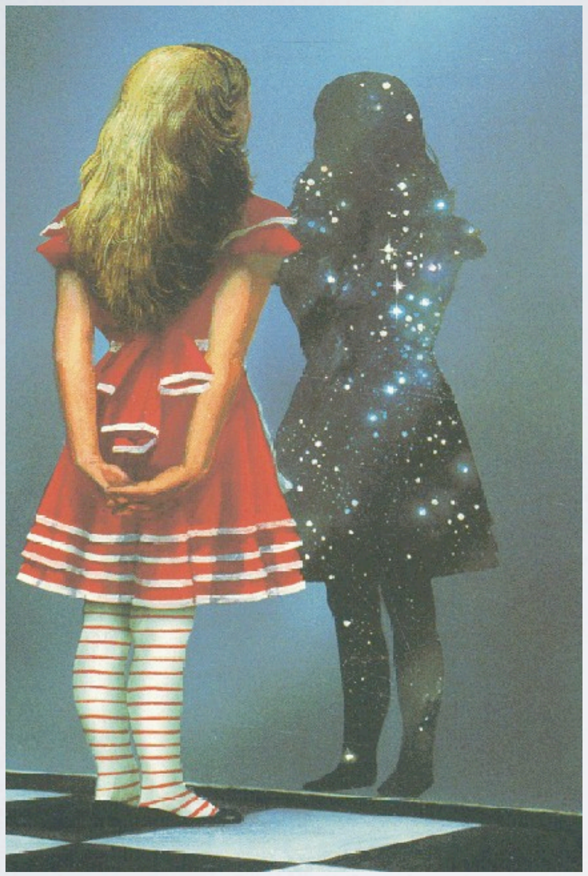
Ettore Majorana through the looking-glass

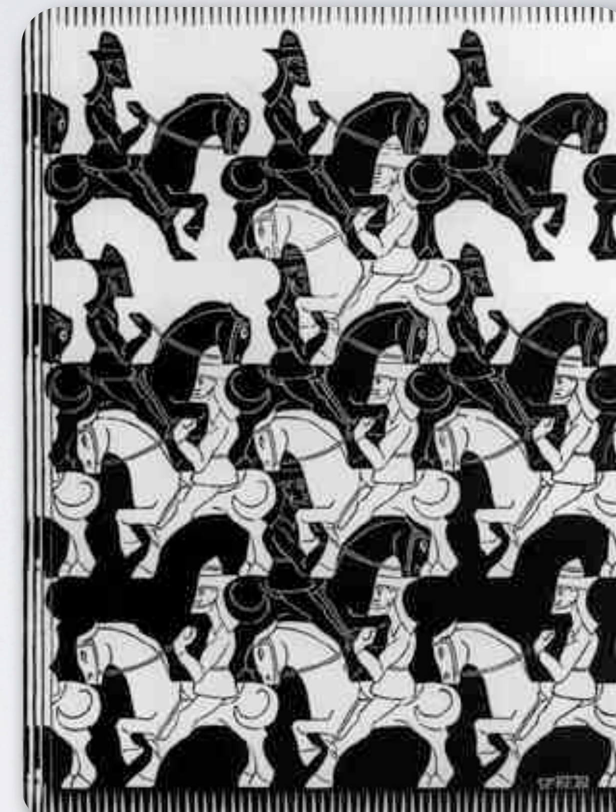


- Standard Model: The neutrino does not see her reflection in the mirror.

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

Ettore Majorana through the looking-glass





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thanks for your attention