Neutrinos physics

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- Introduction
- Neutrino oscillations
- The nature of the neutrino

Highly selective in terms of exp. results (and theoretical details …)

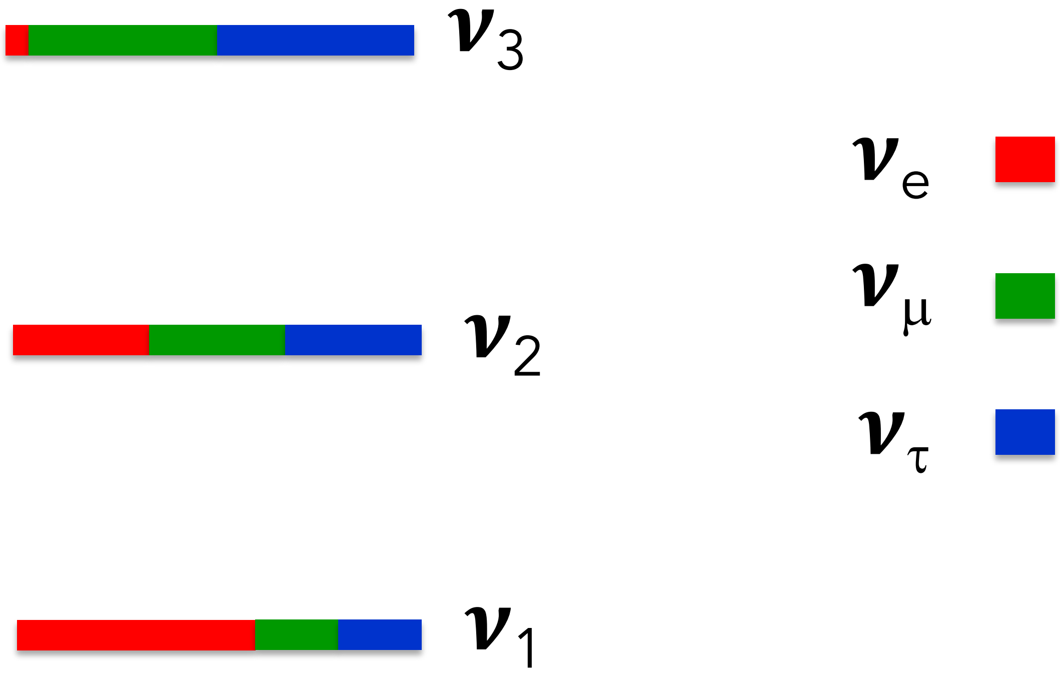
European Research Council
Established by the European Commission

The masses and the nature of the neutrinos

l'Élémentaire

What have we learnt from the oscillation experiments ?

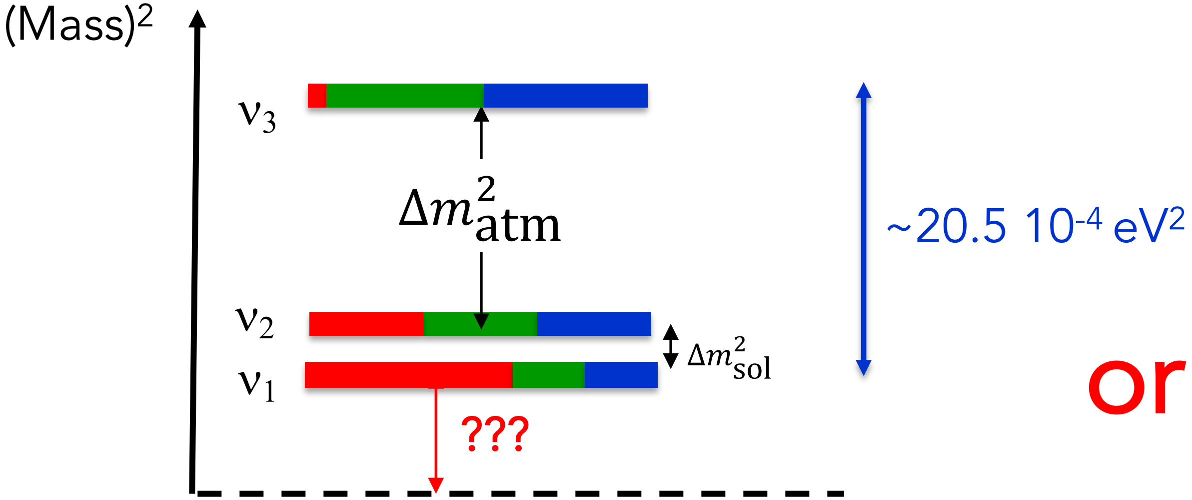
Two basis : mass eigenstates ($\boldsymbol{\nu}_i$) and the flavour eigenstates ($\boldsymbol{\nu}_e$, $\boldsymbol{\nu}_\mu$, $\boldsymbol{\nu}_\tau$)



The relative fractions are given by the mixing angles of the PMNS matrix

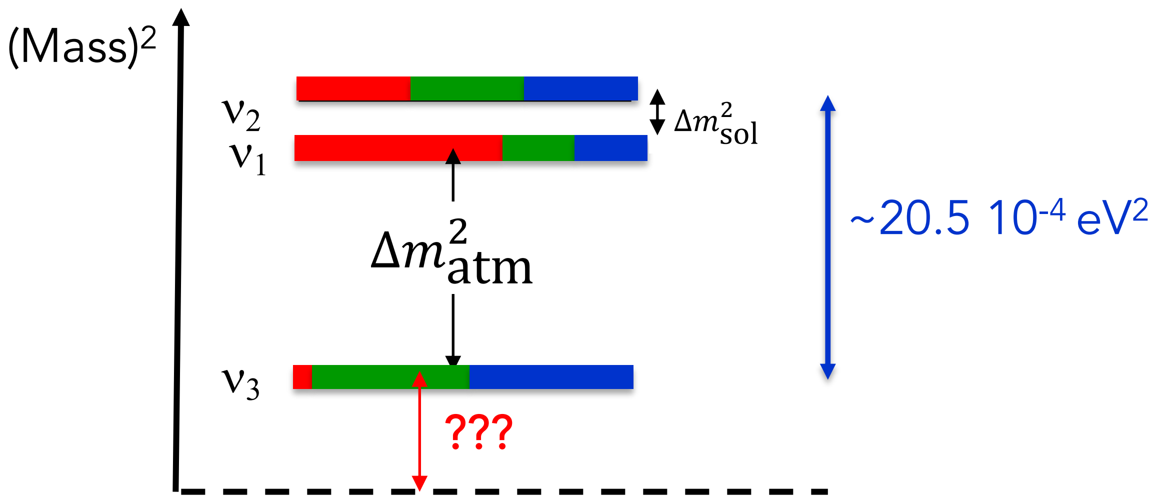
$$\begin{pmatrix} c_{12}\,c_{13} & s_{12}\,c_{13} & s_{13}\,e^{-i\delta_{\rm CP}} \\ -s_{12}\,c_{23} - c_{12}\,s_{13}\,s_{23}\,e^{i\delta_{\rm CP}} & c_{12}\,c_{23} - s_{12}\,s_{13}\,s_{23}\,e^{i\delta_{\rm CP}} & c_{13}\,s_{23} \\ s_{12}\,s_{23} - c_{12}\,s_{13}\,c_{23}\,e^{i\delta_{\rm CP}} & -c_{12}\,s_{23} - s_{12}\,s_{13}\,c_{23}\,e^{i\delta_{\rm CP}} & c_{13}\,c_{23} \end{pmatrix}$$

What have we learnt from the oscillation experiments ?



Normal ordering/hierarchy

or

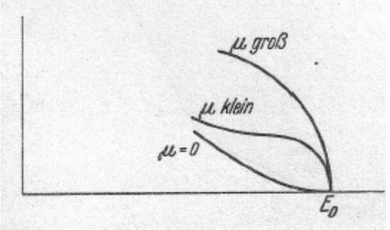


Inverted ordering/hierarchy

Neutrinos have a mass (at least one with m> 0.04 eV !)

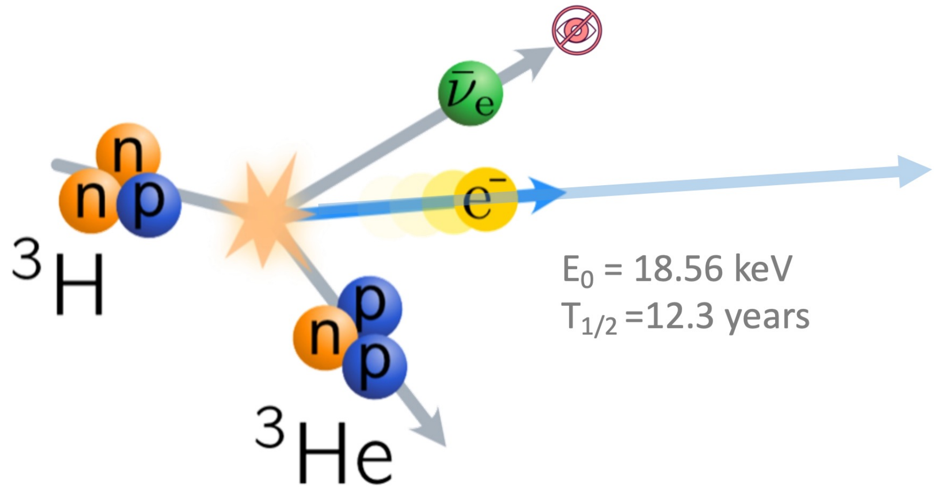
Neutrinos masses (direct) measurements :

Spectrum of electrons (Kurie Plot) emitted in **β** decay

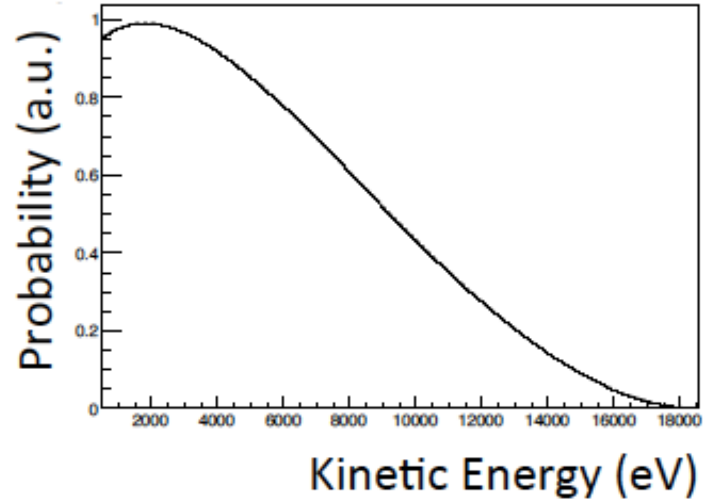


$$K(E) \propto (E_0 - E)\left[1 - \frac{m_\nu^2}{(E_0 - E)^2}\right]^{1/4}$$ for a massive neutrino

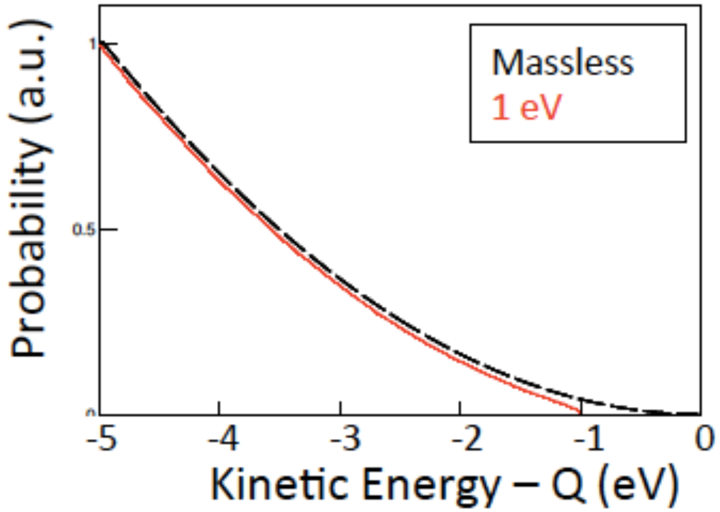
$n \rightarrow p\, e^- \,\overline{\boldsymbol{\nu}}$



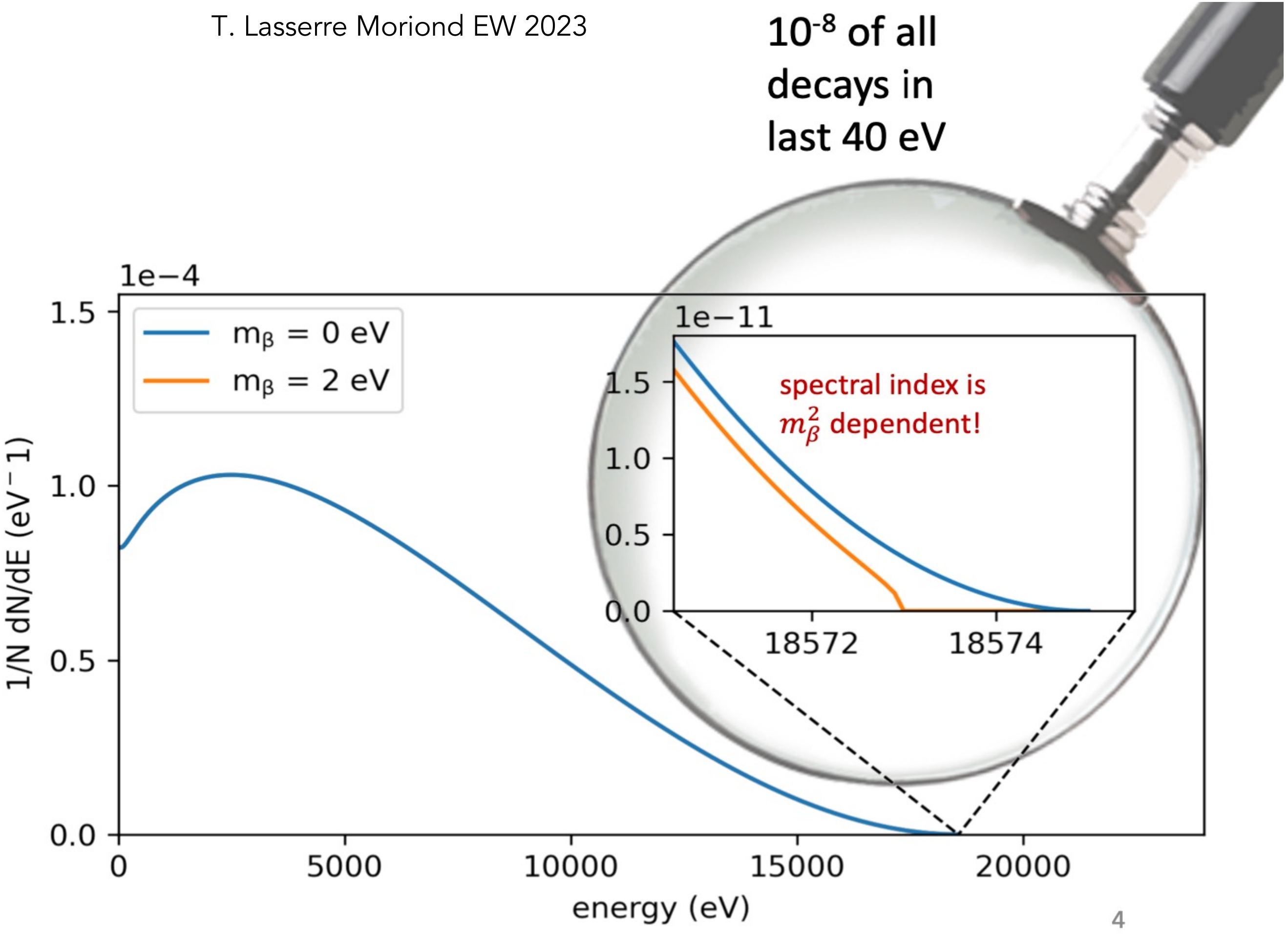
E_0 = 18.56 keV
$T_{1/2}$ =12.3 years



Shape of β spectrum near the end point



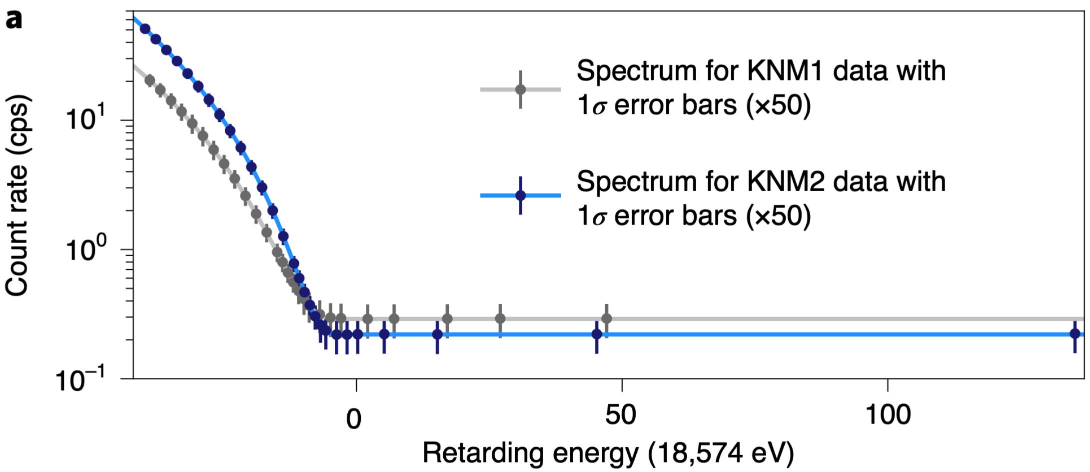
High intensity source (tritium 10^{11} decays/s)
Low background
Excellent energy resolution (1 eV)
High stability



T. Lasserre Moriond EW 2023

10^{-8} of all decays in last 40 eV

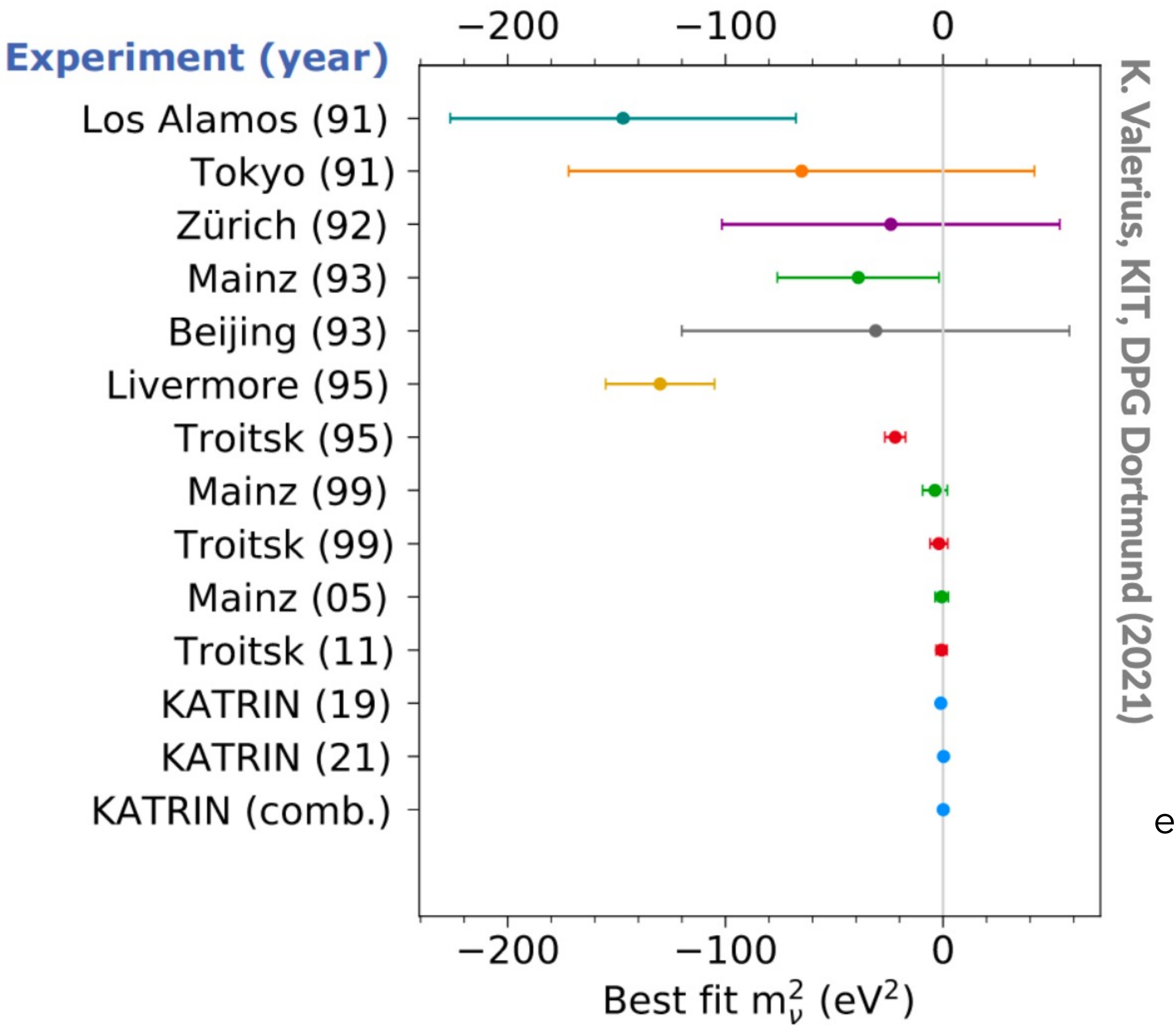
spectral index is m_β^2 dependent!



$m(\nu_e) < 0.8$ eV @ 90% CL

Ref

$$K(E) \propto (E_0 - E)\left[1 - \frac{m_\nu^2}{(E_0 - E)^2}\right]^{1/4}$$



K. Valerius, KIT, DPG Dortmund (2021)

expect to reach a limit of 0.2 eV

Using time of flight for a direct measurement of neutrino mass

Distance to Earth : 1.7 10^5 light years (d~1.5 10^{21}m)
A burst of $\bar{\nu}_e$

IMB@Brookhaven & Kamiokande in Japan

~10 neutrinos per detector
datasets cannot be merged due to no use of absolute time

$$\Delta t = d \times \left(\frac{1}{v_2} - \frac{1}{v_1} \right) = \frac{dm^2c^4}{2} \times \left(\frac{1}{E_2^2} - \frac{1}{E_1^2} \right)$$

$$m = E_1 E_2 \sqrt{\frac{2\Delta t}{d} \times c \times \frac{1}{E_1^2 - E_2^2}}$$

R. M. Bionta et al. Phys. Rev. Lett. 58, 1494 – Published 6 April 1987

TABLE III. Characteristics of the contained neutrino events recorded on 23 February.

Event No.[a]	Time (UT)	No. of PMT's	Energy[b] (MeV)	Angular distribution[c] (degrees)
33162	7:35:41.37	47	38	74
33164	7:35:41.79	61	37	52
33167	7:35:42.02	49	40	56
33168	7:35:42.52	60	35	63
33170	7:35:42.94	52	29	40
33173	7:35:44.06	61	37	52
33179	7:35:46.38	44	20	39
33184	7:35:46.96	45	24	102

[a] The event numbers are not sequential. Interspersed with the contained neutrino events are fifteen entering cosmic-ray muons.

[b] Error in energy determination is ± 25% (systematic plus statistical).

[c] Individual track reconstruction uncertainty is 15°. Note that this angular distribution will be systematically biased toward the source because of the location of the inoperative PMT's.

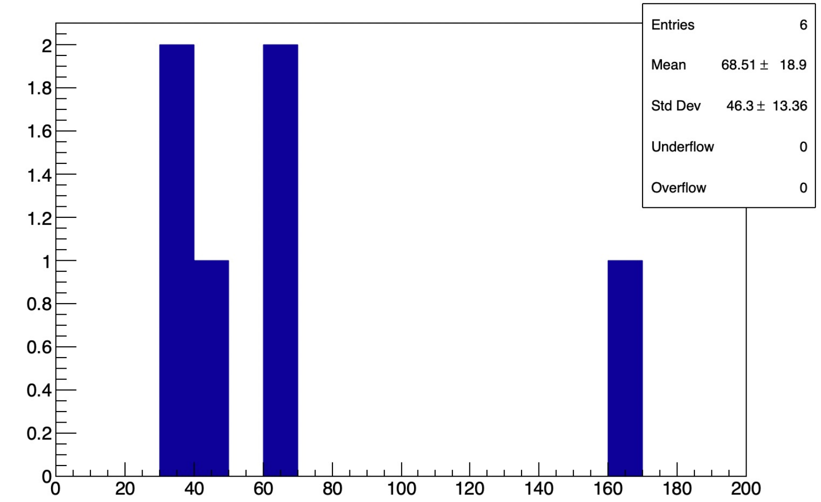
Our events and their proximity in time to the optical observation of the supernova 1987A are compelling evidence that neutrinos have been seen from a supernova collapse. It is clear that these data can be used to study fundamental properties of supernovae and neutrinos; further calculations are in progress.

$$m = E_1 E_2 \sqrt{\frac{2\Delta t}{d} \times c \times \frac{1}{E_1^2 - E_2^2}}$$

Use first & last:

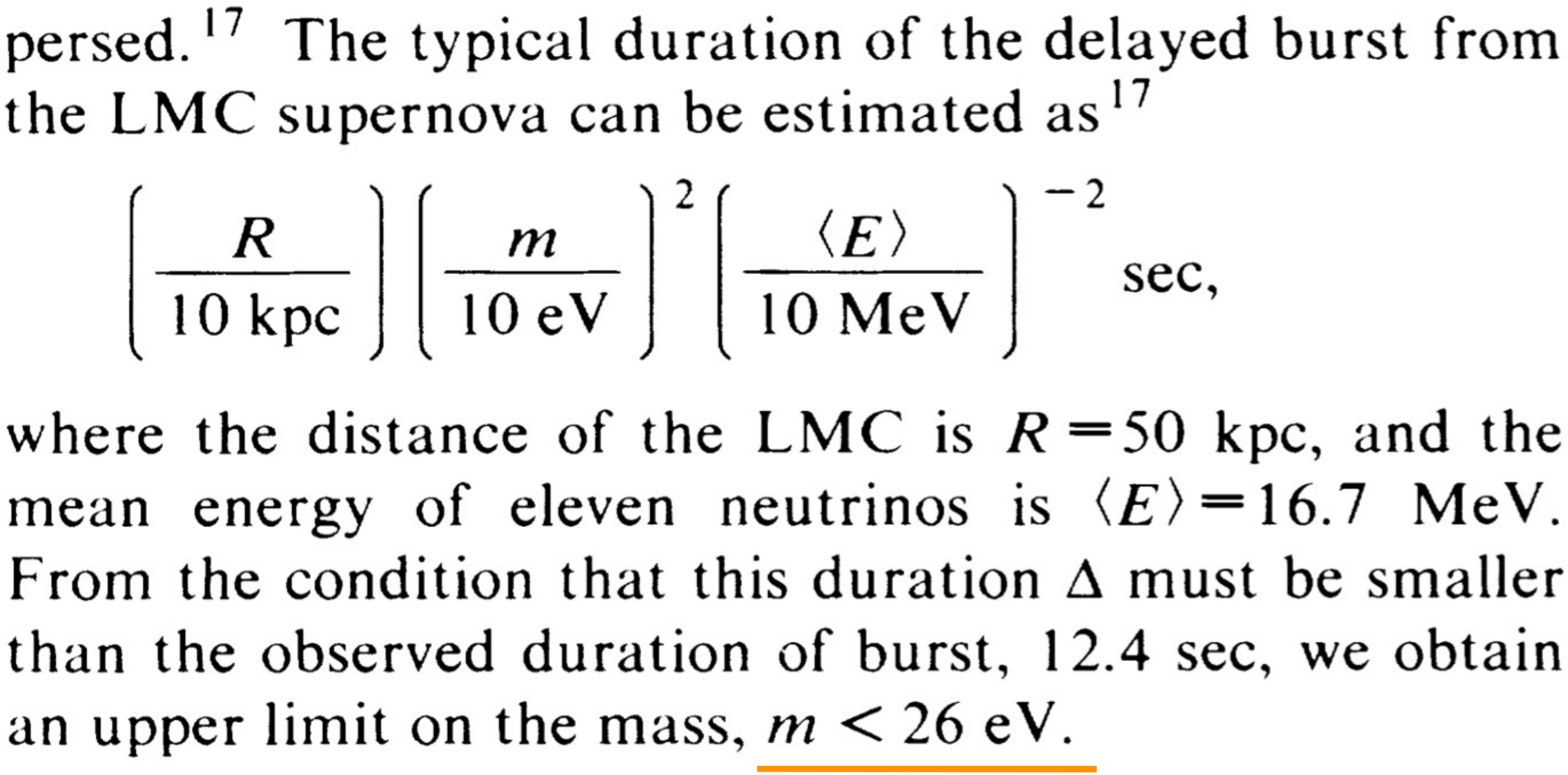
$m_\nu < 46$ eV

Use all (but #33167 ..):



Mean 68 eV

Kamiokande, Physical Review Letters, vol 58, p. 2722 (22 June 1987)



persed.[17] The typical duration of the delayed burst from the LMC supernova can be estimated as[17]

$$\left(\frac{R}{10\ \text{kpc}}\right)\left(\frac{m}{10\ \text{eV}}\right)^{2}\left(\frac{\langle E\rangle}{10\ \text{MeV}}\right)^{-2}\ \text{sec},$$

where the distance of the LMC is $R=50$ kpc, and the mean energy of eleven neutrinos is $\langle E\rangle=16.7$ MeV. From the condition that this duration Δ must be smaller than the observed duration of burst, 12.4 sec, we obtain an upper limit on the mass, $\underline{m < 26\ \text{eV}}$.

The other neutrinos :

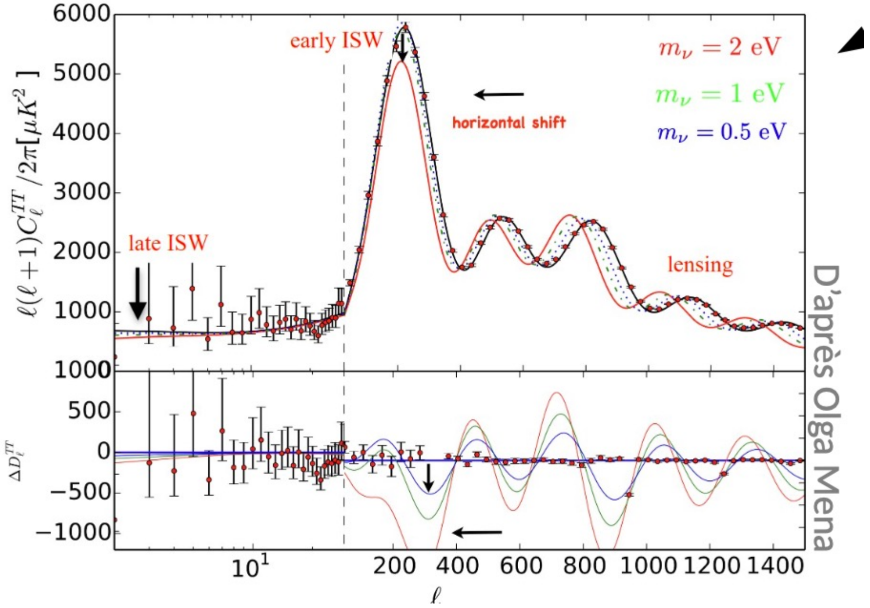
$$m^{\text{eff}}_{\nu_\mu} < 190\ \text{keV}\ (90\%\ \text{CL}) \qquad \text{from} \qquad \pi^- \to \mu^- + \bar{\nu}_\mu\,,$$

$$m^{\text{eff}}_{\nu_\tau} < 18.2\ \text{MeV}\ (95\%\ \text{CL}) \qquad \text{from} \qquad \tau^- \to n\pi + \nu_\tau\,.$$

LEP $Z^0 \to \boldsymbol{\tau\tau}$

Cosmological constraints on **Σ**m(**ν**)

- The neutrinos mass would modify the (delicate) balance between gravity and the Hubble expansion
- They would also have also affect on the structure formation …
- Small modifications in the Cosmological Microwave Background which is the fingerprint of what happended at the very beginning of the Universe



D'après Olga Mena

→ **Σ**m(**ν**)< ~ 0.1- 0.2 eV

PDG review

Neutrino mixing :
They have a mass
(at least one with m> 0.04 eV !)

Cosmological constraint:
$\boldsymbol{\Sigma} m(\boldsymbol{\nu}) < \sim 0.1\text{-}\ 0.2$ eV

In the framework with 3 neutrinos, the window for the mass of the heaviest one is not so wide …

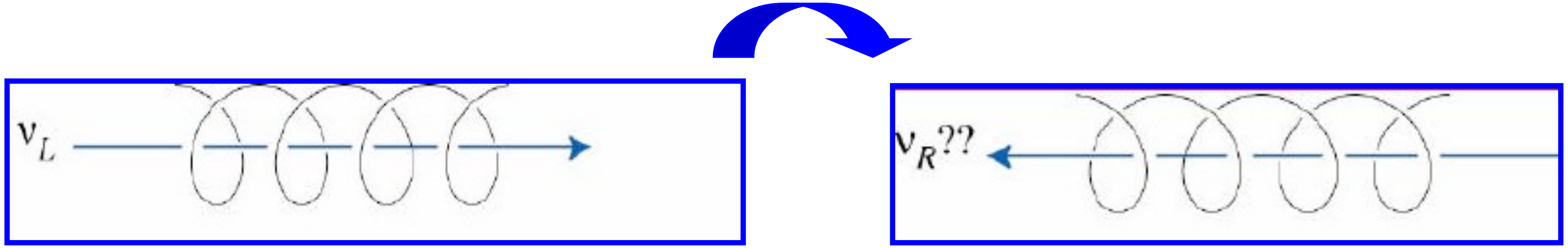
But the masses are tiny (few 10^{-2} eV) compared to 0.5 10^{6} eV for the electron and up to 10^{11} eV for the top quark … ?

In the Standard Model neutrinos are massless → no right-handed neutrino → no Dirac mass term

Suppose the neutrino has a tiny mass

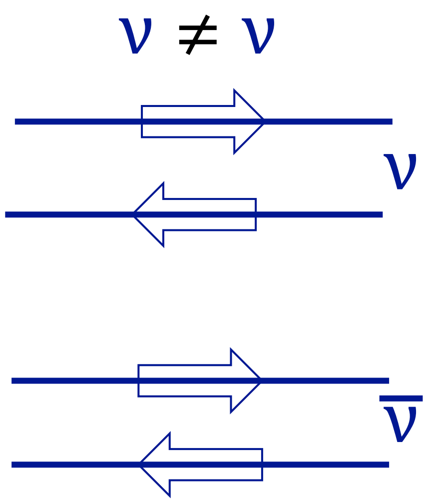
⇒ it cannot go at the speed of light

⇒ the neutrino can exist in two helicity states (jump into a reference system moving faster than ν to see its helicity flip)



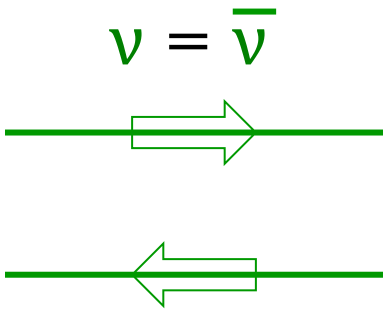
What is this ν_R state?

Dirac or Majorana neutrinos ?



Dirac

Majorana



$\boldsymbol{\nu}_R$ is a distinct state

$\begin{pmatrix} \boldsymbol{\nu}_L \\ \boldsymbol{\nu}_R \end{pmatrix}$ a Dirac spinor (like the other fermions)

But coupling to the Higgs 10^{-5} times smaller than those of the electron ?!

$\boldsymbol{\nu}_R$ is the $\boldsymbol{\nu}_L$ antineutrino

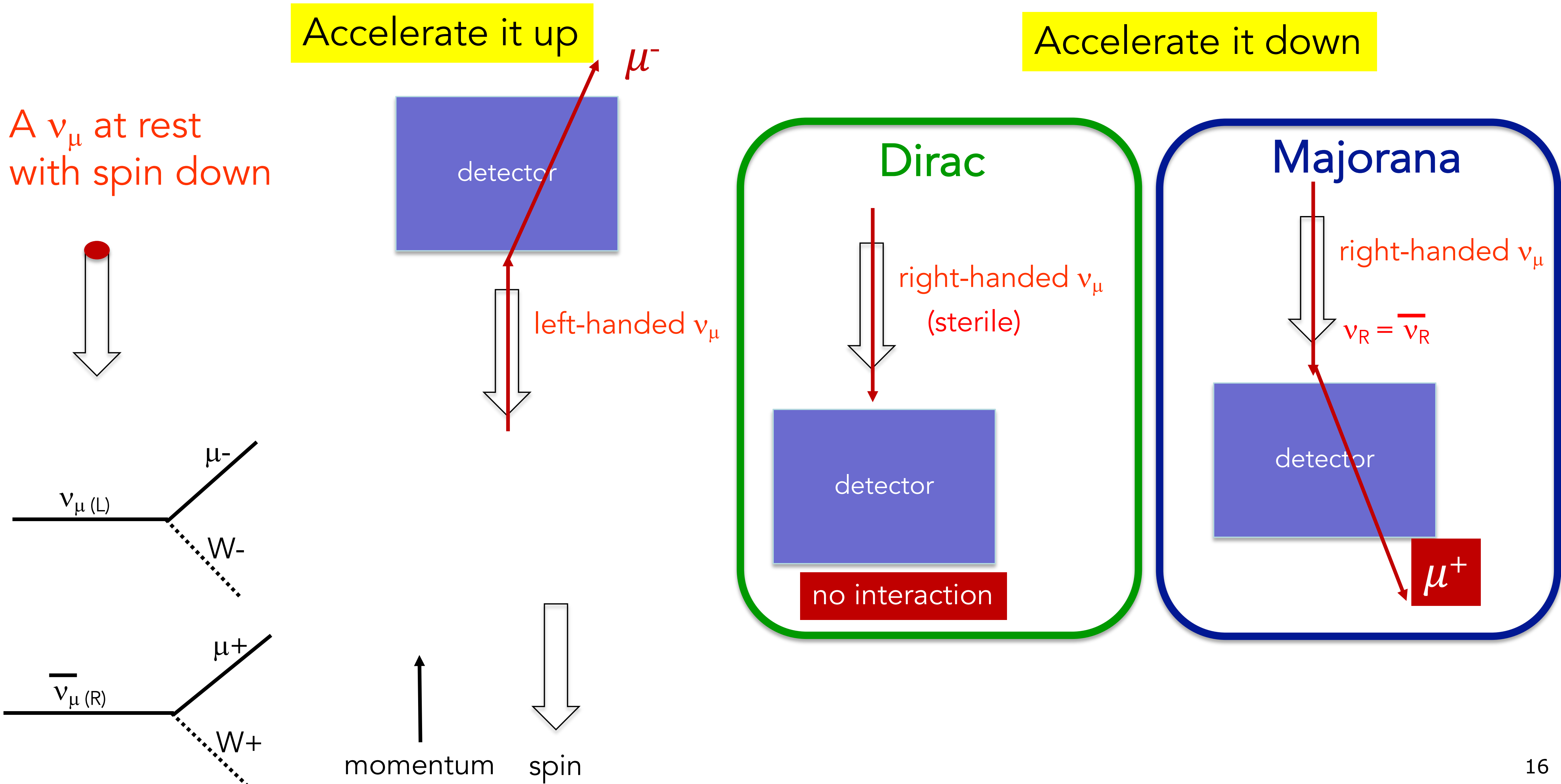
The neutrino cannot carry any charge (since particle and antiparticles carry opposite charges)

Neutrino and antineutrino are different polarizations of a unique particle which interacts mostly as a neutrino when its spin is anti-parallel to its momentum and as an antineutrino when its spin is parallel to its momentum

Violation of Lepton number

Dirac or Majorana ? A gedanken experiment

From Strumia-Vissani (hep/ph-0606054v2)



A ν_μ at rest
with spin down

$\nu_{\mu\,(L)}$

μ-

W-

$\overline{\nu}_{\mu\,(R)}$

μ+

W+

Accelerate it up

μ^-

detector

left-handed ν_μ

momentum

spin

Accelerate it down

Dirac

right-handed ν_μ
(sterile)

detector

no interaction

Majorana

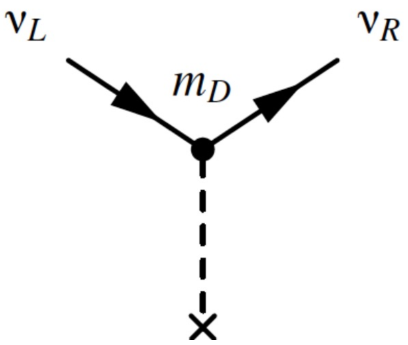
right-handed ν_μ

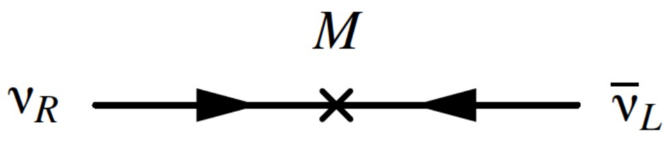
$\nu_R = \overline{\nu}_R$

detector

μ^+

See-saw mechanism (Majorana neutrinos)





most general form :
a Dirac term + a Majorana term

$$\mathcal{L} \sim -\frac{1}{2}\begin{pmatrix} \overline{\nu_L} & \overline{\nu_R^c} \end{pmatrix}\begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix}\begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

m_D ~ charged leptons & quarks
M very large

the physical "mass eigenstates" are those in the basis where the mass matrix is diagonal

$$m_\nu \approx \frac{m_D^2}{M}$$

light left-handed neutrino

$$m_N \approx M$$

heavy right-handed neutrino

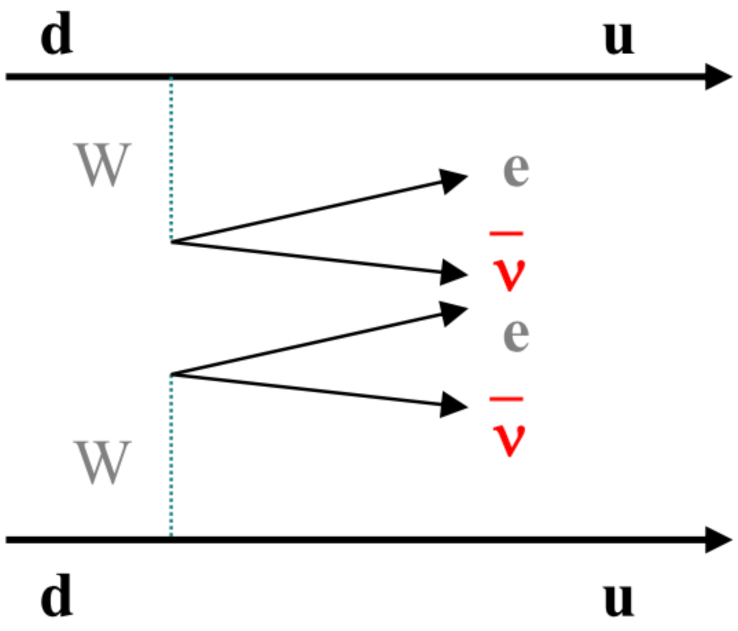
$$M \sim 10^{12} - 10^{16}\,\mathrm{GeV}$$

to match with current knowledge for charged fermions and neutrinos masses limits

Double β decay: 2β2**ν** or 2β0**ν** ?

$$(A,Z) \rightarrow (A,Z+2) + 2e^{-} + 2\overline{\nu}_e$$

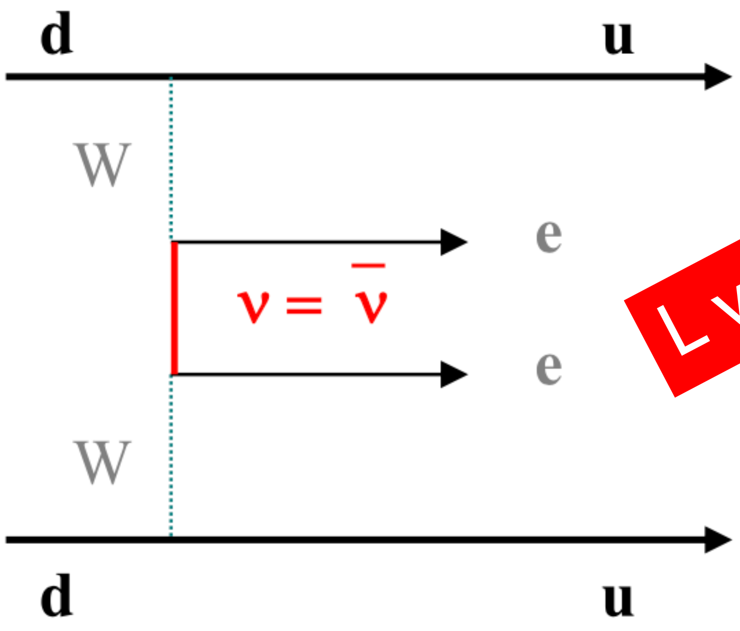
inside a nucleus



(2β2**ν**)

$$(A,Z) \rightarrow (A,Z+2) + 2e^{-}$$

inside a nucleus

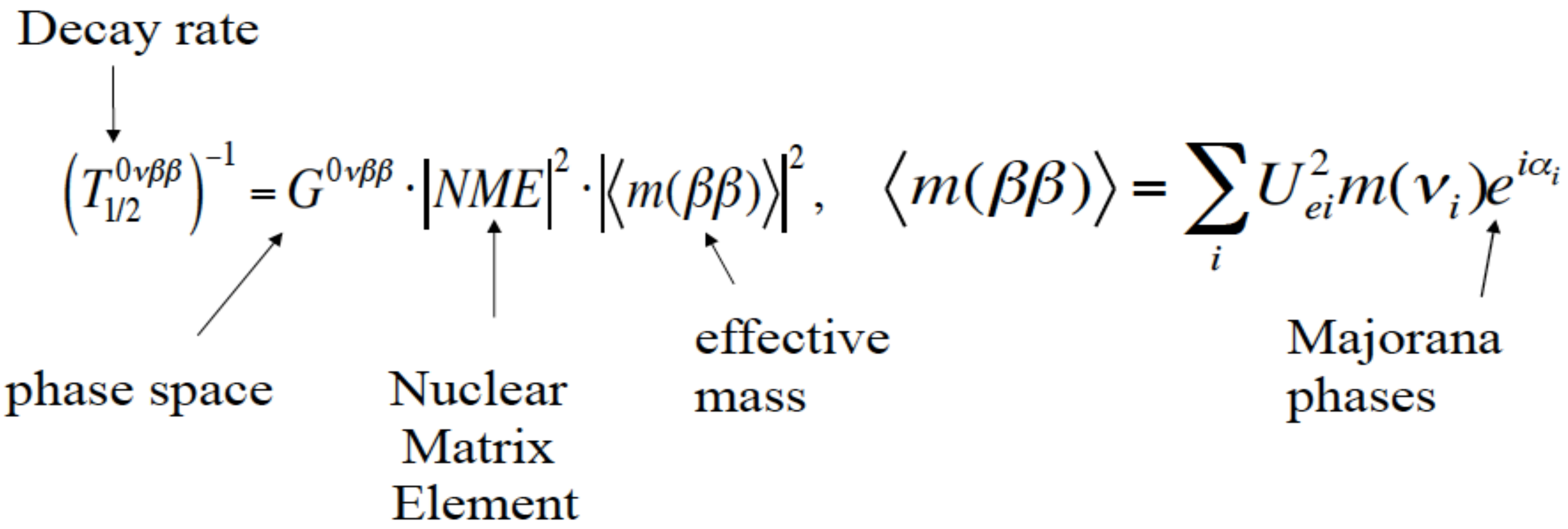


L violation

(2β0**ν**)

Probing the nature of the neutrino !

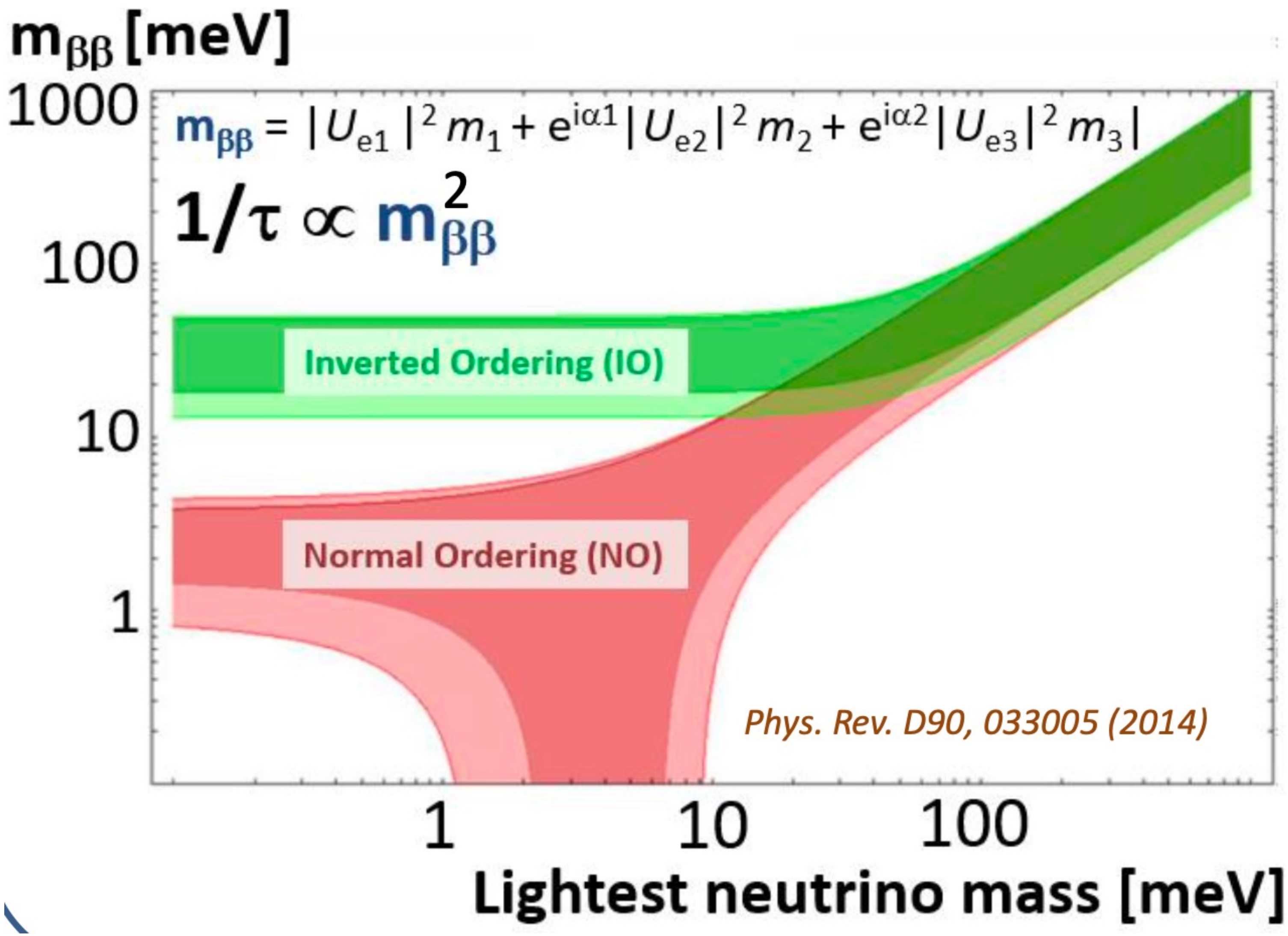
$2\boldsymbol{\beta}0\boldsymbol{\nu}$ half-life depends directly on m($\boldsymbol{\nu}$)



$$\left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} = G^{0\nu\beta\beta}\cdot\left|NME\right|^{2}\cdot\left|\left\langle m(\beta\beta)\right\rangle\right|^{2}, \quad \left\langle m(\beta\beta)\right\rangle = \sum_{i} U_{ei}^{2}\, m(\nu_i)\, e^{i\alpha_i}$$

Measurement of the lifetime allows to measure (or limit) the effective neutrinos mass

Search for 2β0ν

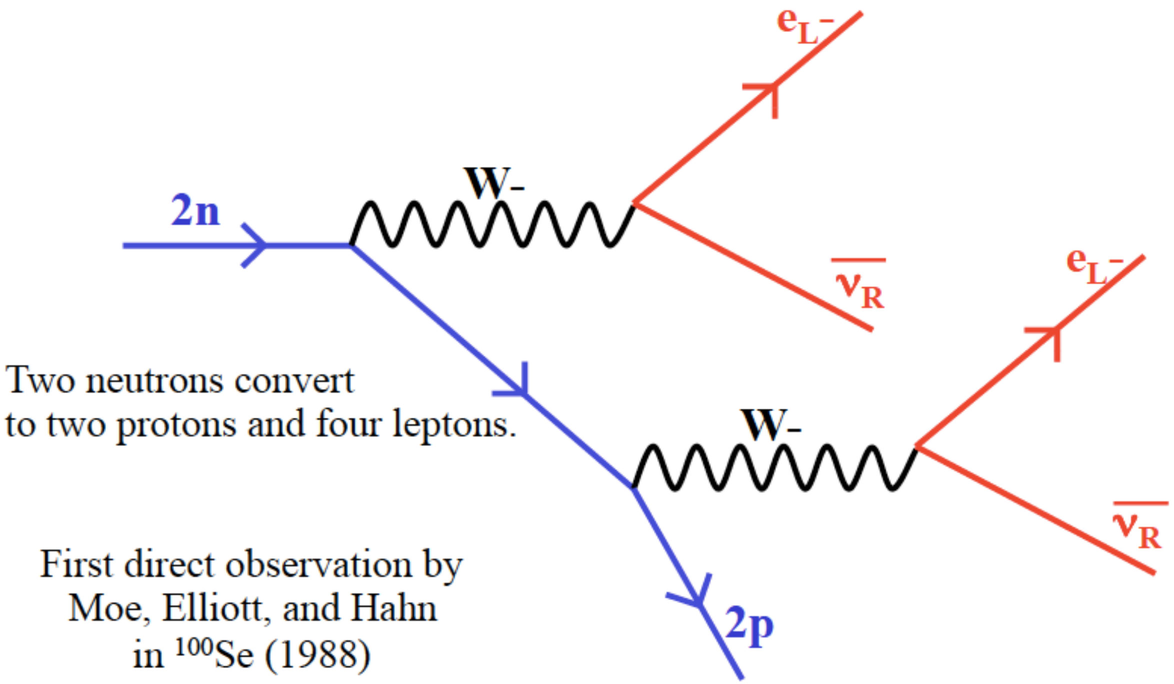


$$m_{\beta\beta} = |\,|U_{e1}|^2 m_1 + e^{i\alpha 1}|U_{e2}|^2 m_2 + e^{i\alpha 2}|U_{e3}|^2 m_3|$$

$$1/\tau \propto m_{\beta\beta}^2$$

Phys. Rev. D90, 033005 (2014)

Double β decay



Two neutrons convert
to two protons and four leptons.

First direct observation by
Moe, Elliott, and Hahn
in ^{100}Se (1988)

Allowed in the Standard Model with a very small decay rate :

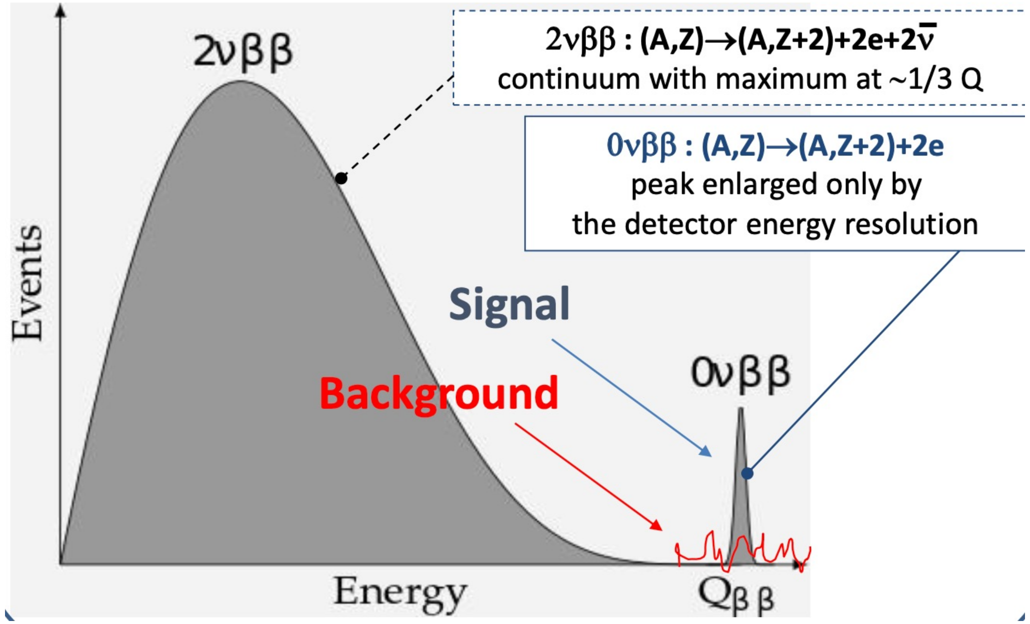
- small value of G_F
- large suppression of the phase-space factor (the small energy release must be shared by four leptons)

- Use nuclei where the **β** decay is forbidden
- Use nuclei where 2 **β** decay is possible

- Select those for which $Q_{\beta\beta}$ value is as far from backgrounds as possible

- Study the Kurie plot

Measurement of the sum of the 2 electrons energy



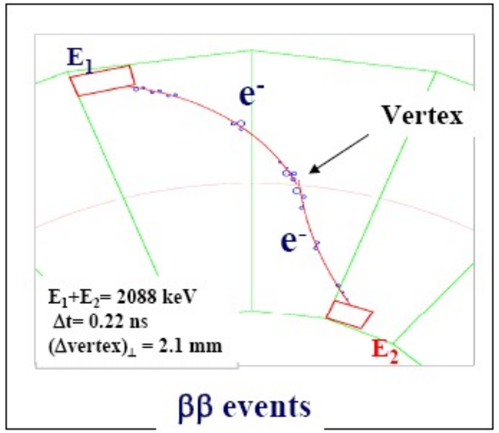
$$\frac{1}{\tau} = (\text{phase space}) \times \underbrace{g_A^4 \times (\text{Nuclear matrix element})^2}_{\text{uncertainties} \ldots} \times m_{\beta\beta}^2$$

$$m_{\beta\beta}^2 = \sum_i |U_{ei}|^2 \times m_i^2$$

Sensitivity ∝ Source Mass x Measurement Time

Source away from the detector

Tracking + calorimetry NEMO3 & co



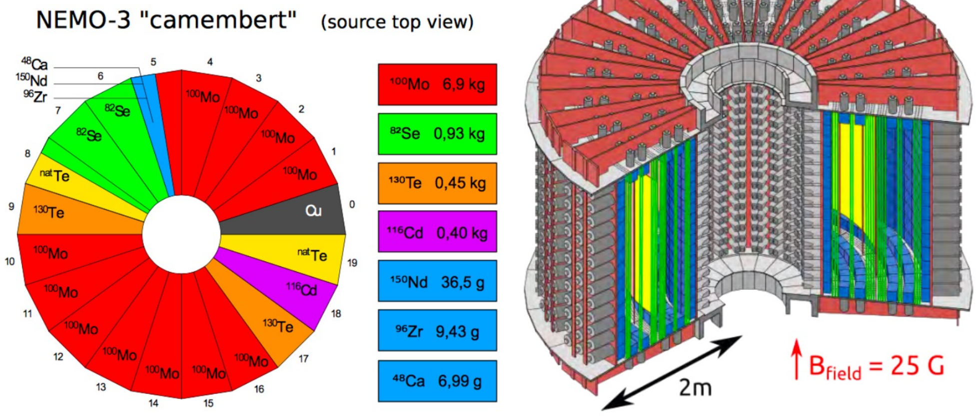
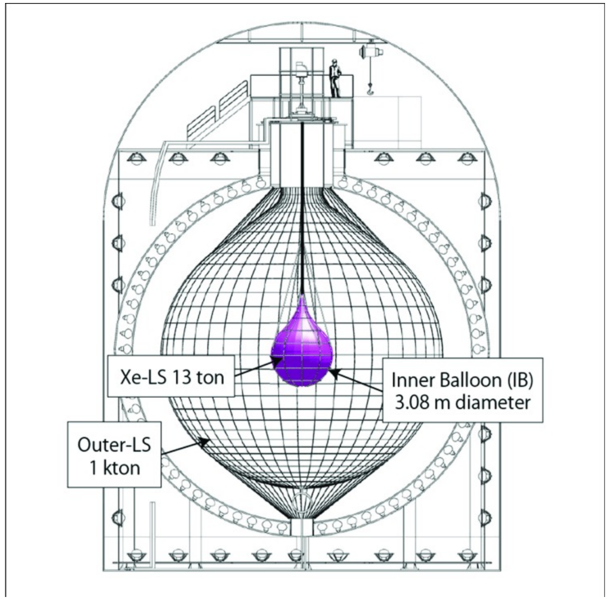


Figure 11. Right: distribution of isotopes in the NEMO experiment. Left: Schemetic representation of the experiment including the sources (yellow), the tracker (green) and the calorimeter (blue). Figures from the NEMO homepage.

Source embedded in the detector

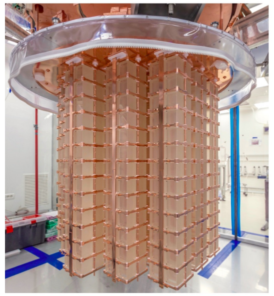
Liquid Scintillator
(large masses)

KamLAND Zen



Crystals
(granularity)

CUORE



GERDA

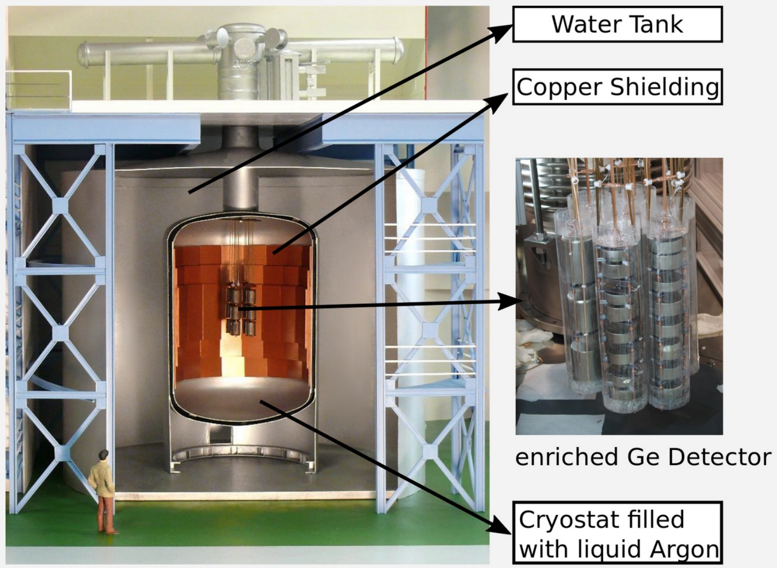
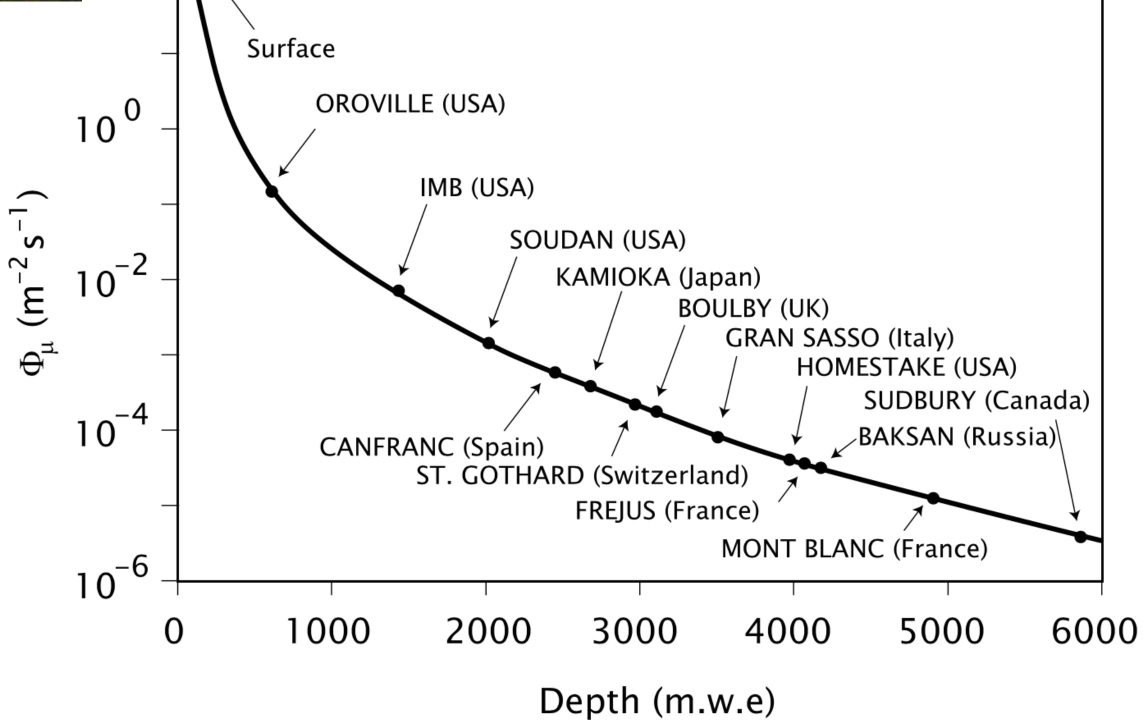
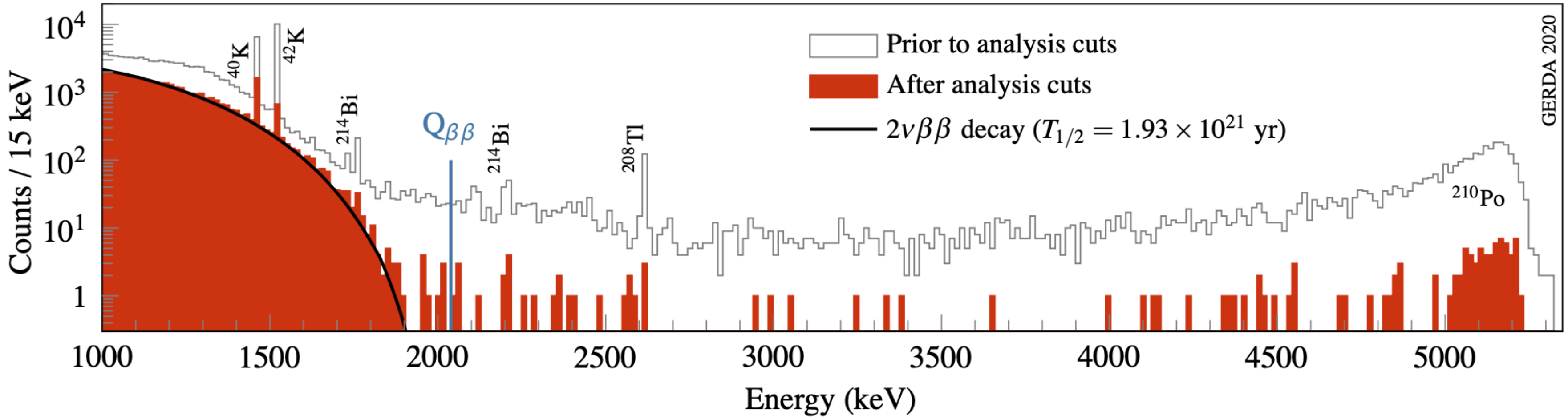


Fig.1: Illustration of GERDA. The Germanium diodes are protected by several layers of avtive an passive shieldings from external radiation.

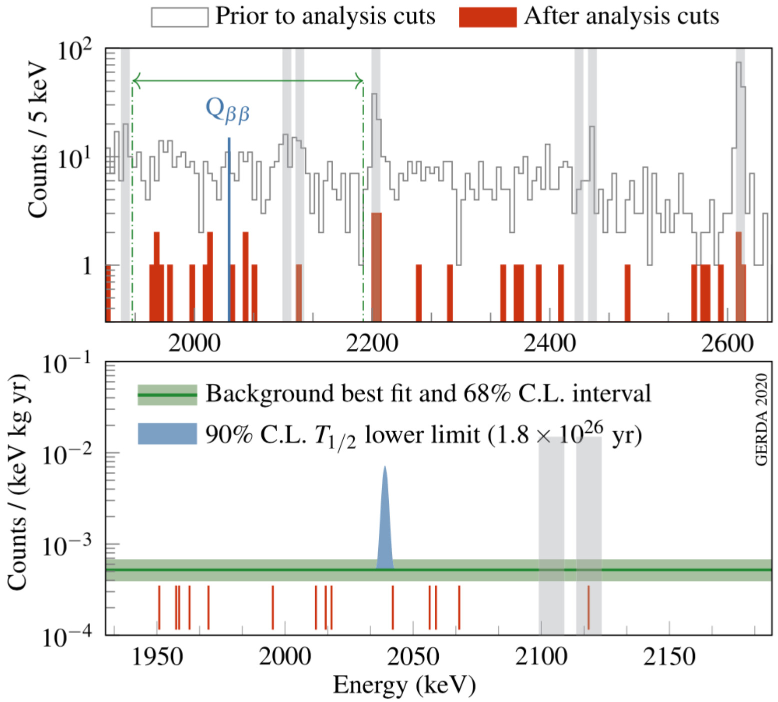
Gran Sasso


10^2
10^0
10^{-2}
10^{-4}
10^{-6}
Φ_μ ($m^{-2}s^{-1}$)
0
1000
2000
3000
4000
5000
6000
Depth (m.w.e)
Surface
OROVILLE (USA)
IMB (USA)
SOUDAN (USA)
KAMIOKA (Japan)
BOULBY (UK)
GRAN SASSO (Italy)
HOMESTAKE (USA)
SUDBURY (Canada)
BAKSAN (Russia)
CANFRANC (Spain)
ST. GOTHARD (Switzerland)
FREJUS (France)
MONT BLANC (France)

GERDA experiment



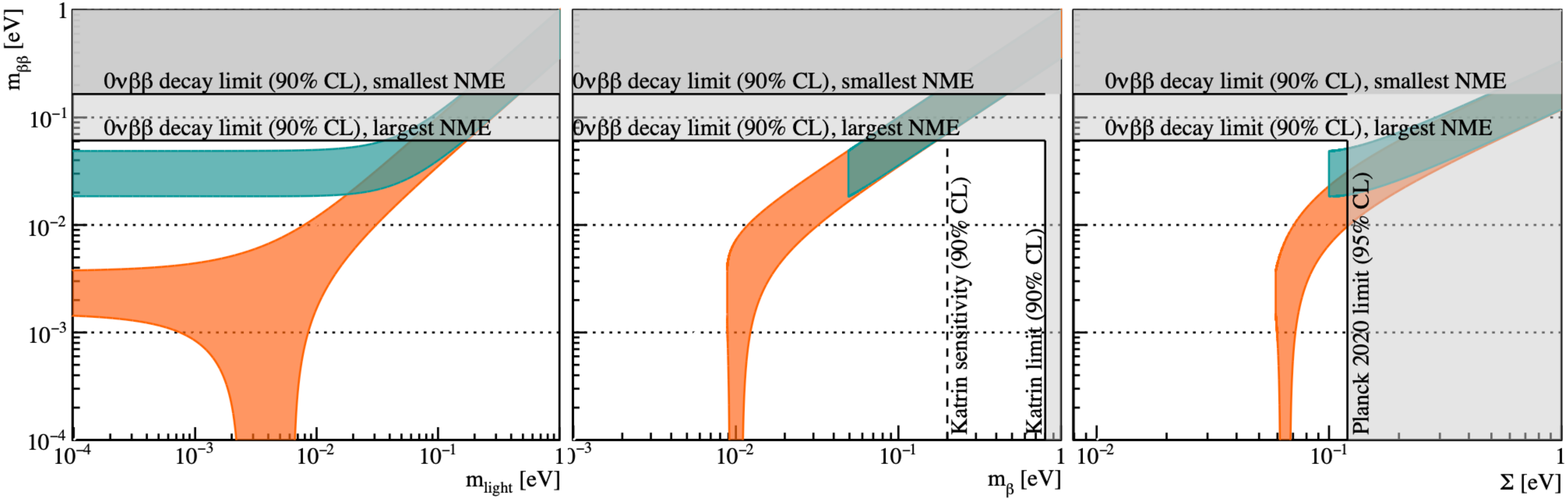
Phys. Rev. Lett. 125, 252502 (2020)



expected $\beta\beta0\nu$

$$T_{1/2} > 1.8 \times 10^{26} \text{ yr at } 90\% \text{ C.L.}$$

$m_{\beta\beta} < 0.079 – 0.180$ eV @ 90% CL arxiv:2202.01787



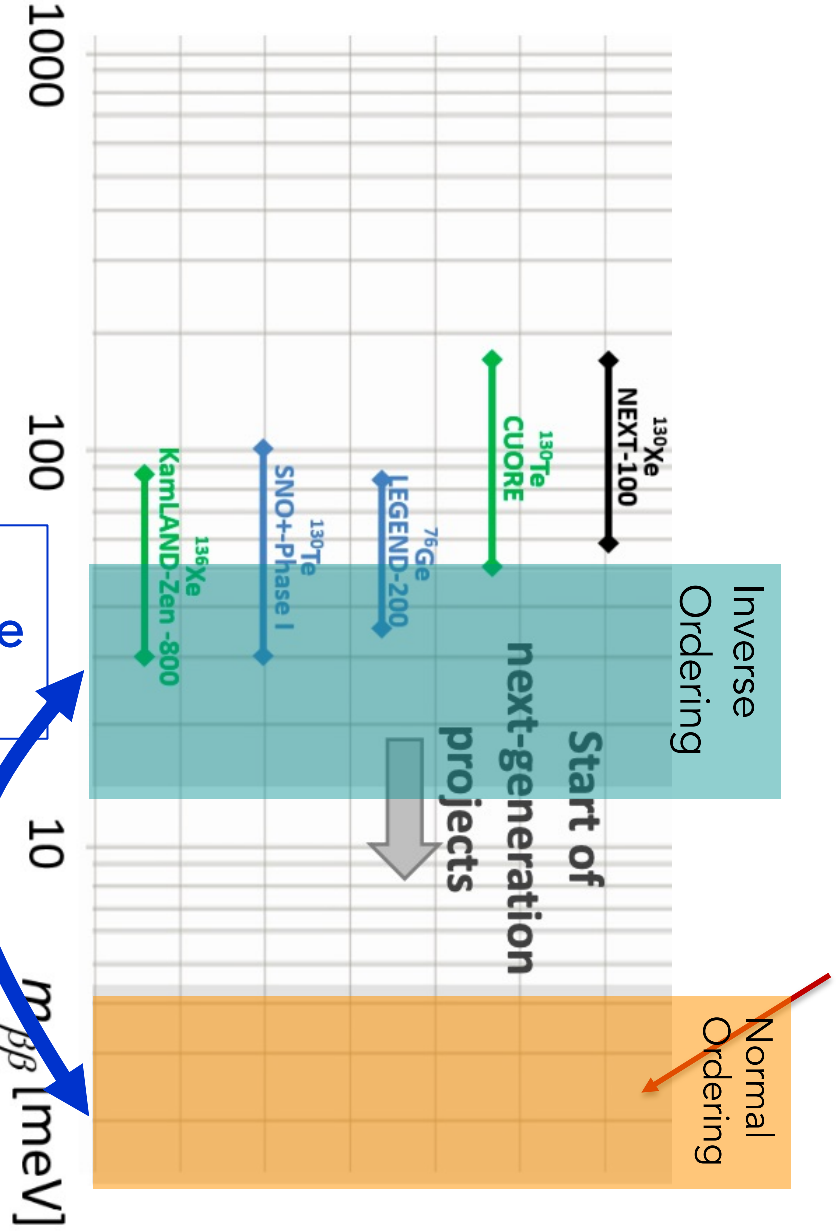
🟧 NO

🟦 IO

Getting into the interesting region

A lot of experimental (and theoretical) activities

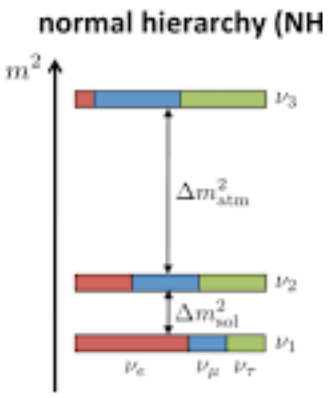
A. Giuliani @ TAUP21 "Possible scenario in 5 years"



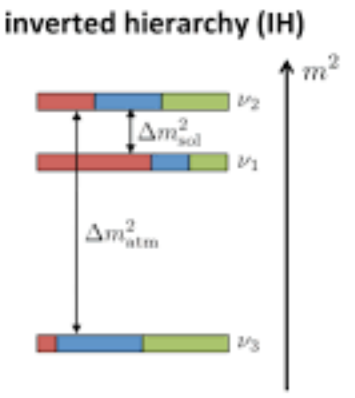
100 times more massive detectors

Extremely challenging to reach

- Limits on $T_{1/2}$ of $2\beta0\nu$:



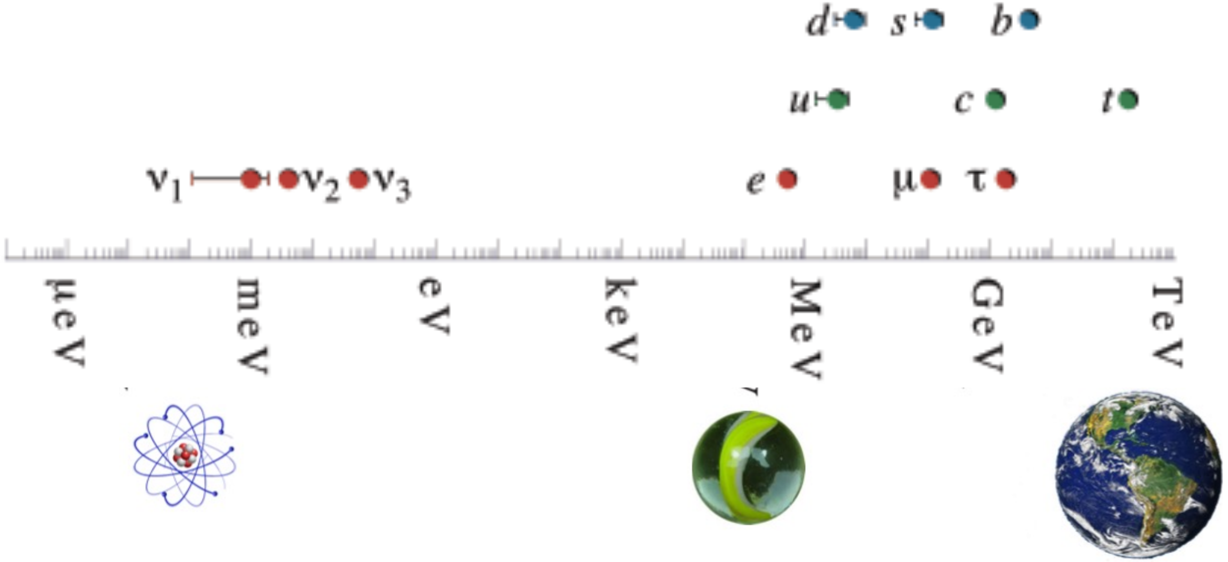
or



- Non observation of $2\beta0\nu$ would not prove that they are Dirac particles
- Observing $2\beta0\nu$ would prove that neutrinos are Majorana particles

Neutrino physics, a summary ?

At the interplay between collider physics and astroparticles & reactors
Origin of masses & problem of flavour



quarks

$$|V_{\rm CKM}| \sim \begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}$$

neutrinos

$$|U_{\rm PMNS}| \sim \begin{pmatrix} 0.8 & 0.5 & 0.1 \\ 0.5 & 0.6 & 0.7 \\ 0.3 & 0.6 & 0.7 \end{pmatrix}$$

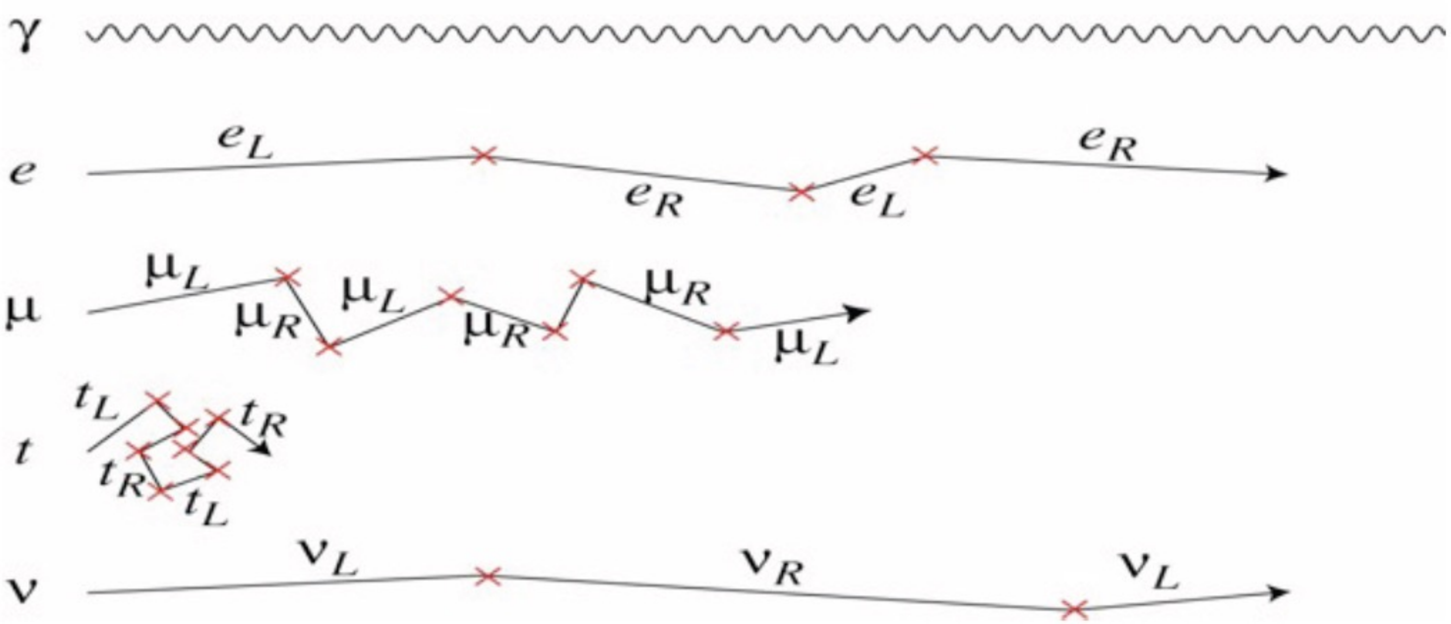
Dirac or Majorana ?

Explanation of the matter-antimatter asymmetry observed in the Universe ?

Back up slides

Masses extremely small …

If Dirac neutrinos



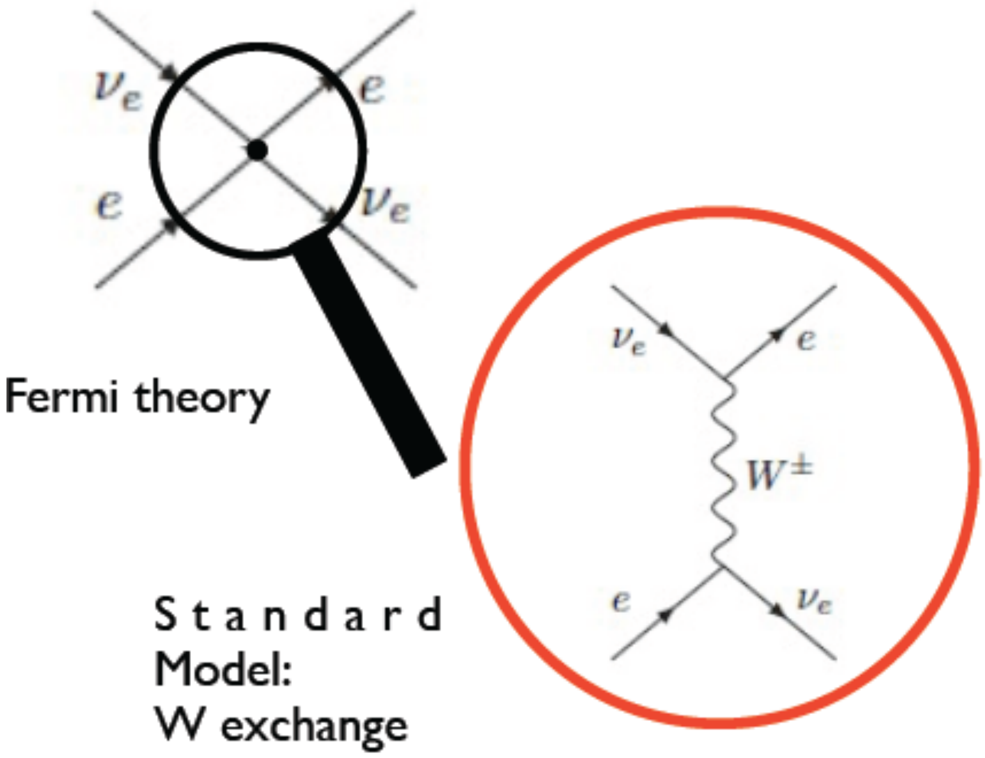
The couplings to the H are fixed : $m_\nu = \lambda v$

If m~ 0.1 eV since v ~ 250 GeV→ coupling λ= 4 10^{-13} !

If neutrinos are of Majorana type

The generation of the mass can arise as the low energy realisation of a higher energy theory (new mass scale!)

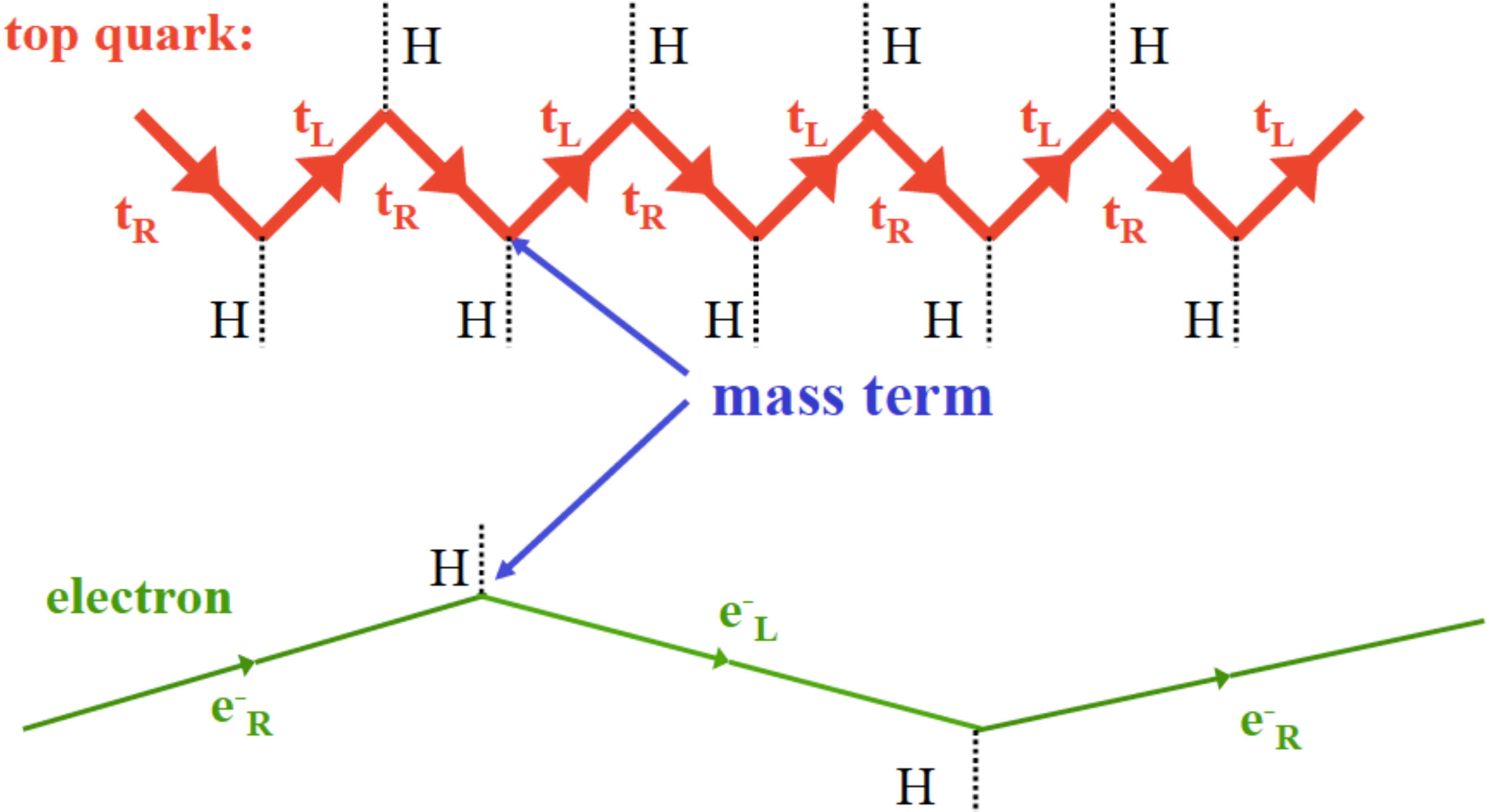
Remember Fermi's theory ?



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

λ similar to the coupling of other fermions but suppressed by a larger scale (new particle exchange)

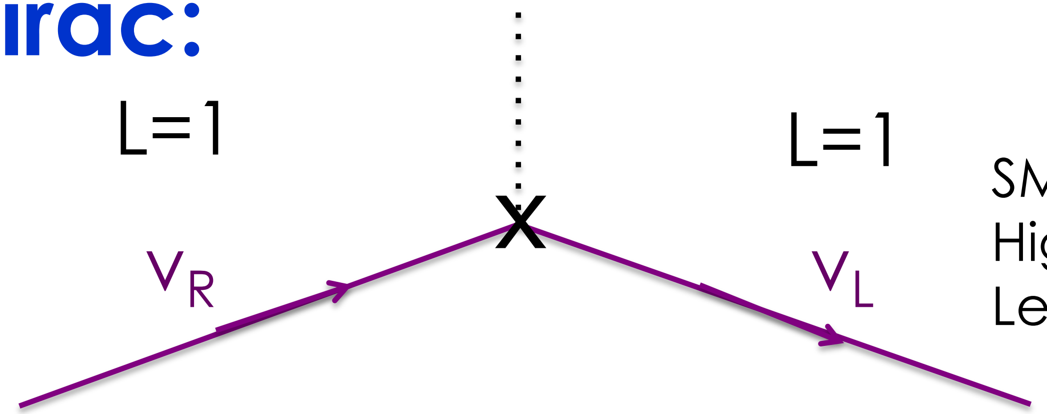
Remember the Higgs mechanism ?



Dirac mass term: conserves charge ($e^- \rightarrow e^-$)

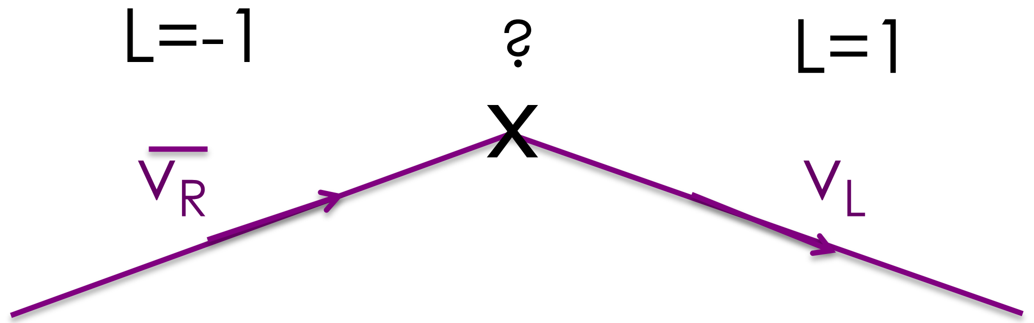
What about the neutrinos masses ?

Dirac:



SM
Higgs generates Dirac masses
Lepton number is conserved

Majorana:



Physics Beyond the SM
Lepton number violation !

Are the neutrinos of Majorana or Dirac type ?
Strong link with lepton number conservation

Helicity/Chirality :

Projection of the spin in the momentum direction

- Helicity: definition for the helicity operator : $H = \frac{\sigma . p}{|\vec{p}|}$ with $\sigma = \begin{pmatrix} \vec{\sigma} & 0 \\ 0 & \vec{\sigma} \end{pmatrix}$ 4×4

- Chirality:

  If ψ is a solution for the Dirac equation, on can write: $\psi = \psi_{CL} + \psi_{CR}$

  Definition: chirality operators *Left* ou *Right* (CL,CR) :

$$\boxed{\begin{aligned} P_{CL} &= \frac{1-\gamma_5}{2} = \begin{pmatrix} 0 & 0 \\ 0 & \mathbf{1} \end{pmatrix} \\ P_{CR} &= \frac{1+\gamma_5}{2} = \begin{pmatrix} \mathbf{1} & 0 \\ 0 & 0 \end{pmatrix} \end{aligned}}$$

$$\gamma_5 = \begin{pmatrix} \mathbf{1} & 0 \\ 0 & -\mathbf{1} \end{pmatrix} \quad 4 \times 4$$

(for the chiral representation)

Algebra :

$$P_{CL}^2 = P_{CL}, \quad P_{CR}^2 = P_{CR}, \quad P_{CL} + P_{CR} = 1, \quad P_{CL} P_{CR} = 0$$

$$\psi_{CL} = P_{CL}\psi \qquad \overline{\psi}_{CL} = \overline{\psi} P_{CR}$$

$$\psi_{CR} = P_{CR}\psi \qquad \overline{\psi}_{CR} = \overline{\psi} P_{CL}$$

$$P_{CL}\gamma^{\mu} = \gamma^{\mu} P_{CR} \qquad P_{CR}\gamma^{\mu} = \gamma^{\mu} P_{CL}$$

Link between helicity and chirality

- Chirality is the "correct" quantity (it appears in the Lagrangian and in addition the helicity in not Lorentz invariant) but what is measured in the processes is the helicity

- One can show that:

$$\psi_{CL} = \frac{a}{2}\psi_{HR} + \frac{b}{2}\psi_{HL}$$

$$\psi_{CR} = \frac{b}{2}\psi_{HR} + \frac{a}{2}\psi_{HL}$$

with

$$a = 1 - \frac{p}{E+m}$$

$$b = 1 + \frac{p}{E+m}$$

ψ_{CR}, ψ_{CL} are the eigenvectors of H

ψ_{CR} corresponds to the eigenvalue +1

ψ_{CL} corresponds to the eigenvalue -1

- for m<<E: a = 1 - β and b = 1 + β

  $\beta \sim 1$: a = 0 and b = 2

  and thus : $\psi_{CL}=\psi_{HL}$ and $\psi_{CR}=\psi_{HR}$

for E>>m : Helicity $\equiv$ Chirality

4.2 V-A structure:

Let's take an electromagnetic current : $\bar{\psi}\gamma^{\mu}\psi$:

(γ^{μ} is a vector, parity = -1)

$$\bar{\psi}\gamma^{\mu}\psi = \bar{\psi}\left(P_{CL} + P_{CR}\right)\gamma^{\mu}\left(P_{CL} + P_{CR}\right)\psi =$$

$$\bar{\psi}\cancel{P_{CL}\gamma^{\mu}P_{CL}}\psi + \bar{\psi}P_{CR}\gamma^{\mu}P_{CL}\psi + \bar{\psi}P_{CL}\gamma^{\mu}P_{CR}\psi + \bar{\psi}\cancel{P_{CR}\gamma^{\mu}P_{CR}}\psi =$$

$$\bar{\psi}_{CL}\gamma^{\mu}\psi_{CL} + \bar{\psi}_{CR}\gamma^{\mu}\psi_{CR}$$

$$\bar{\psi}\gamma^{\mu}\psi = \bar{\psi}_{CL}\gamma^{\mu}\psi_{CL} + \bar{\psi}_{CR}\gamma^{\mu}\psi_{CR}$$ selects ψ_{CL}, ψ_{CR}

⇒ for the electromagnetic interaction : ψ_{CL}- ψ_{CL} and ψ_{CR} - ψ_{CR} couplings

Let's take a weak coupling $\bar{\psi}\gamma^{\mu}(1-\gamma_5)\psi$:

$\gamma^{\mu}\gamma^{5}$ is vector-axial, parity +1
$\gamma^{\mu}(1-\gamma_5)$: V-A structure

$$\bar{\psi}\gamma^{\mu}\left(1-\gamma_5\right)\psi = \bar{\psi}\left(P_{CL} + P_{CR}\right)\gamma^{\mu}\left(1-\gamma_5\right)\left(P_{CL} + P_{CR}\right)\psi =$$

$$2\bar{\psi}\left(P_{CL} + P_{CR}\right)\gamma^{\mu}\left(P_{CL}^{2} + \cancel{P_{CL}P_{CR}}\right)\psi =$$

$$2\bar{\psi}P_{CL}\gamma^{\mu}P_{CL}\psi + 2\bar{\psi}P_{CR}\gamma^{\mu}P_{CL}\psi = 2\bar{\psi}\gamma^{\mu}\cancel{P_{CR}P_{CL}}\psi + 2\bar{\psi}_{CL}\gamma^{\mu}\psi_{CL}$$

$$\bar{\psi}\gamma^{\mu}\left(1-\gamma_5\right)\psi = 2\bar{\psi}_{CL}\gamma^{\mu}\psi_{CL}$$ ⇒ for the weak interaction : ψ_{CL}- ψ_{CL} coupling only

This form for the current leads to maximal parity violation
(the V-A structure allows only left handed neutrinos)

Validation of the $\gamma^{\mu}(1-\gamma_5)$ expression for the weak currents

Leptogenesis (Majorana neutrinos)

Very heavy
neutrino N

N can decay into ℓ^+ or ℓ^-

N created at the big bang time

$N \rightarrow \ell^+ \phi^-$

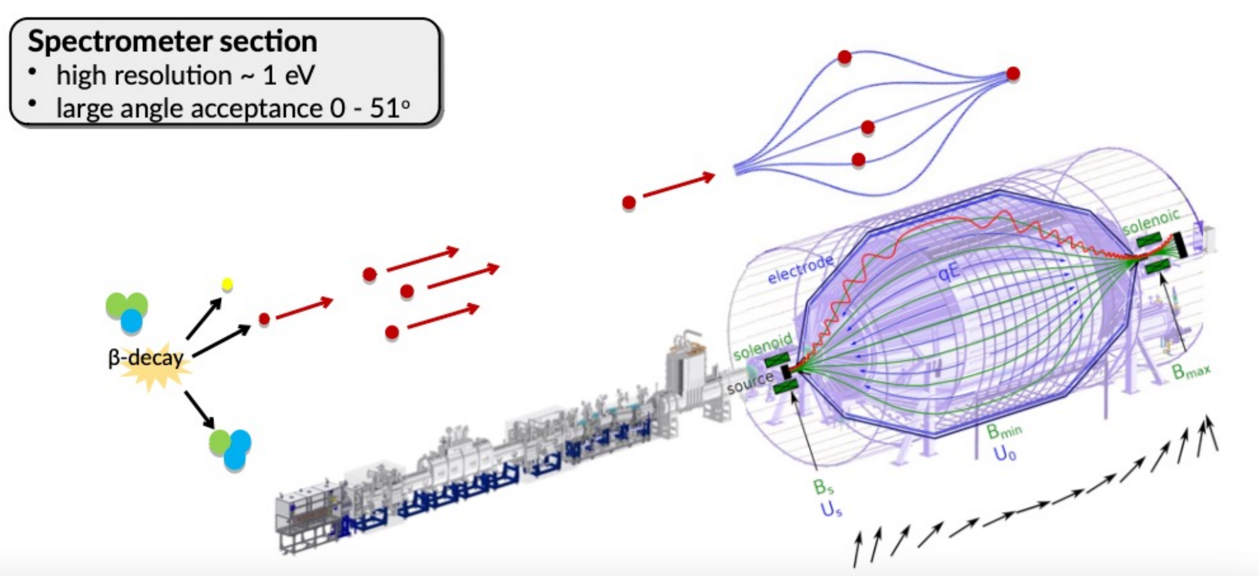
$N \rightarrow \ell^- \phi^+$

Higgs field before SSB $\begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$

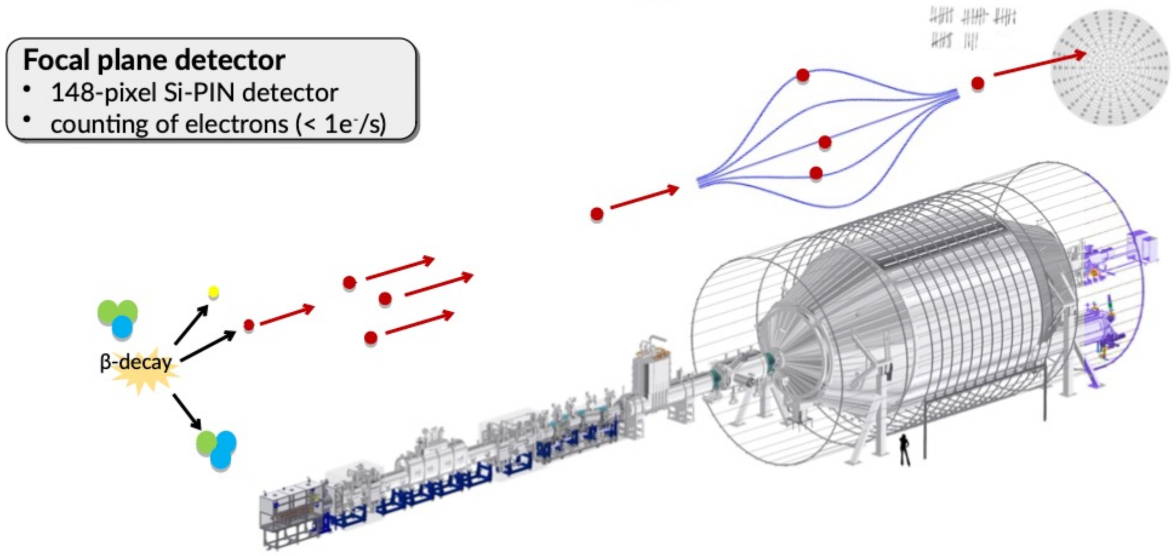
CP violation ⇒ $\Gamma(N \rightarrow \ell^+ \phi^-) \neq \Gamma(N \rightarrow \ell^- \phi^+)$

unequal amount of matter and antimatter in the leptonic sector

KATRIN spectrometer working principle



Spectrometer section
- high resolution ~ 1 eV
- large angle acceptance 0 - 51°



Focal plane detector
- 148-pixel Si-PIN detector
- counting of electrons (< $1e^-$/s)