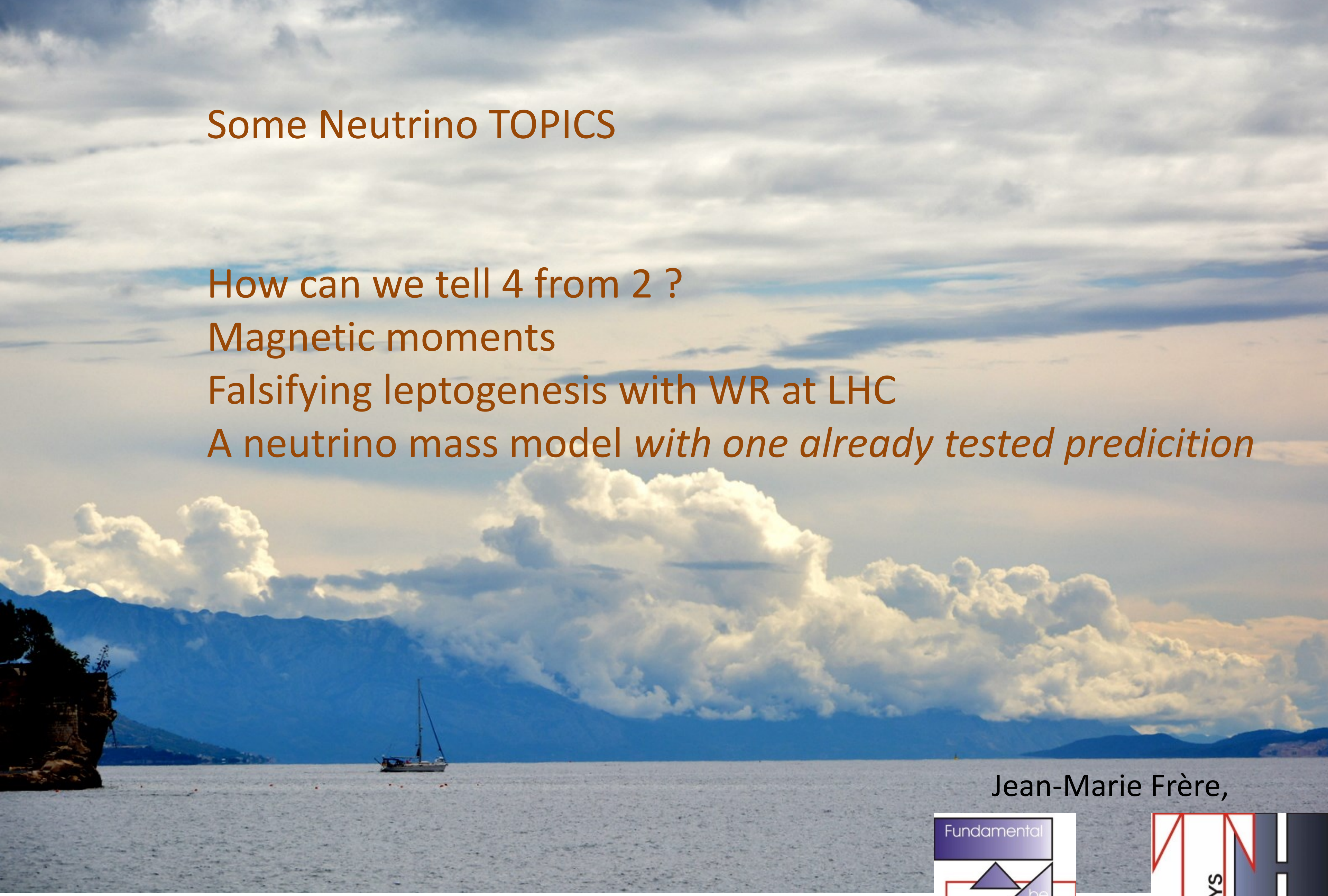


# Some Neutrino TOPICS

How can we tell 4 from 2 ?
Magnetic moments
Falsifying leptogenesis with WR at LHC
A neutrino mass model *with one already tested predicition*

Jean-Marie Frère,

Fundamental Interactions .be

PHYS

# Outline

- Neutrino masses: Majorana, Dirac …
- $\nu_R$ ?
- Magnetic moments ? - a new inequality
- R neutrinos put to use : leptogenesis – falsifiable by light $W_R$
- A model which predicted $\theta_{13}$

# Neutrinos ....

- Masses are very small (one could even vanish) ;
 we only know the differences of their squares.

•« Cabibbo » mixing is important, might even be more complicated
(extra phases if Majorana, mixing with steriles)

•We don’t even know the number of degrees of freedom (Majorana vs Dirac)

•They violate the ***separate*** conservation of electron, muon and tau numbers

Facts

- *They might violate the* ***global*** *lepton number (neutrinoless double beta)*

- *they could explain the Defeat of Antimatter (leptogenesis)*

- *They suggest (via See-Saw or other) the presence of new particles, new scales, and could even accomodate extra dimensions*

Conjectures

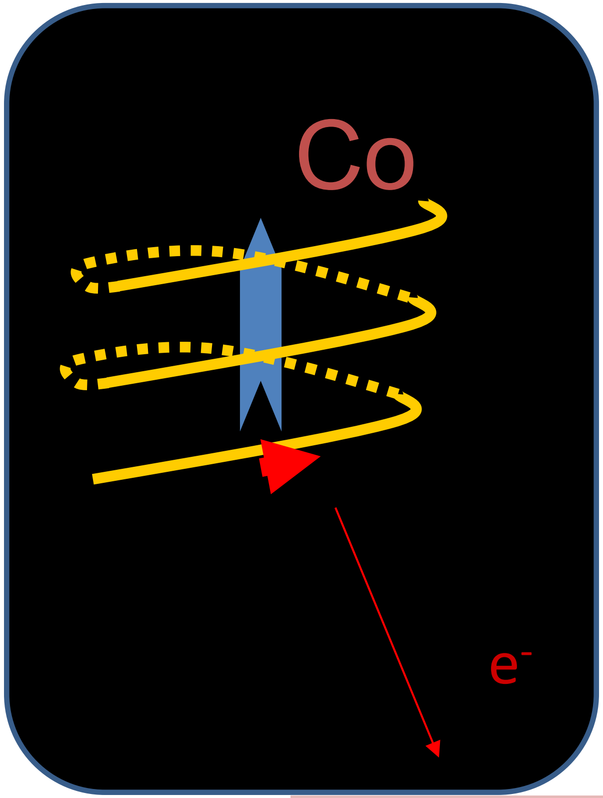
They pester us with re-learning about
Dirac, Majorana, degrees of freedom, oscillations, …

while the rest of the fermions seem so simple
by comparison!

# The lore of massless neutrinos in the Standard Model

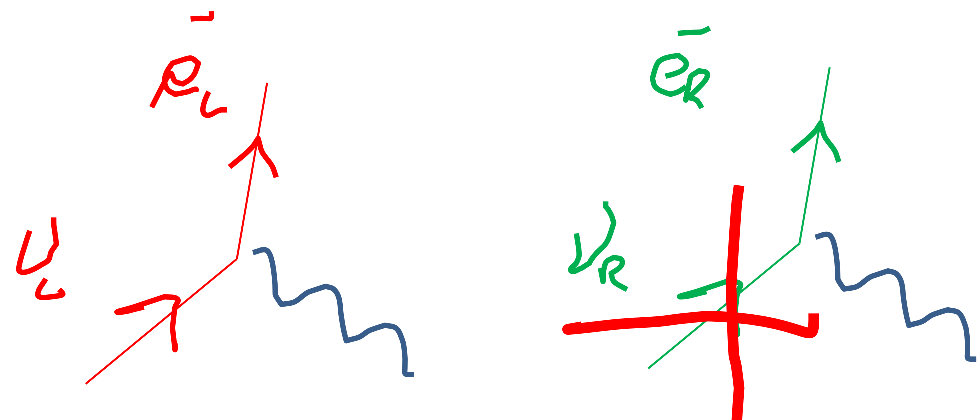
# Should neutrinos have been massless ?

*Once upon a time (has it completely ended? ) people used to blame P violation on the absence of right-handed neutrinos …*




P violation was clearly demonstrated in the Wu experiment ..

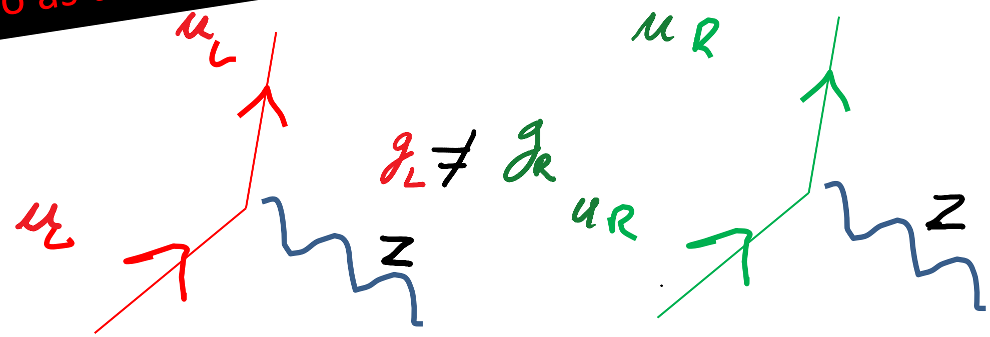
It is easy to explain if only left-handed electrons are produced in a charged vector current.




*Killing the right-handed neutrino allows for parity violation in charged currents, even if the coupling is pure vector*

*Killing the right-handed neutrino allows for parity violation in charged currents, even if the coupling is pure vector*

This was NEVER a solution …Assuming the whole world to be symmetrical under P, and taking the right-handed neutrino as the BAD GUY was NO SOLUTION.




- Not a solution today : we know the the Standard Model has neutral currents which violate P (parity violation in atoms, asymmetrical couplings of Z to quarks ..
- Even at the time of Wu's experiment, it was not a solution … this experiment was only a confirmation, a demonstration of P violation, known from the K→ 2 $\pi$ and K→ 3 $\pi$ (the $\Theta$ $\tau$ puzzle ) where neutrinos don't play!

*Still, in a way the doublet ($\nu_L$ $e_L$) was at the basis of the Standard Model, but the actual symmetry was experimentally found to be $SU(2)_L$ , applied to all known fermions, including quarks*

# From the «absence of $\nu_R$ » to « massless neutrinos »

The «absence of $\nu_R$ » meant that « ordinary » (Dirac) masses were excluded …

This fitted well the fact that very small neutrino masses (at least for the electron neutrino) were requested from $\beta$ decay kinematics.

…and this lead to the **LEGEND** that neutrinos had to be massless in the Standard Model
In fact, masses were simply omitted in the first version
(which also lacked quarks, families, CP violation..)

But .. Evidence for neutrino masses!

Gauge interactions,  Majorana and Dirac …

To be a bit provocative:

*(Dirac is a special of Majorana,*
*corresponding to 2 semi-spinors with masses m and –m )*

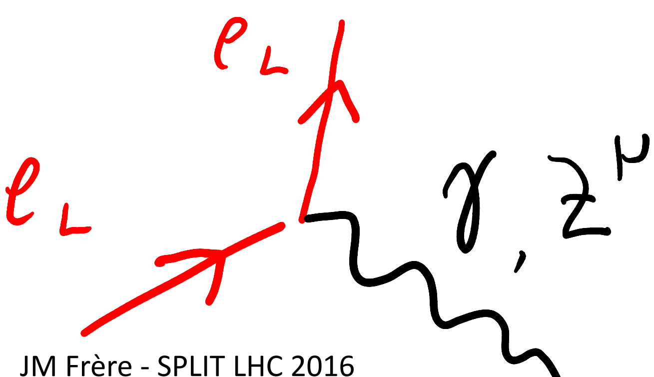
Even if we should keep in mind that interactions rather than masses can generate oscillations, let us now concentrate on masses.

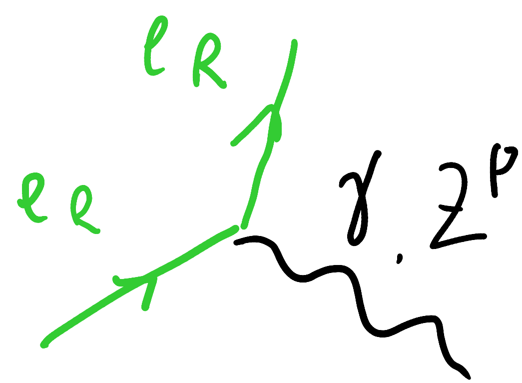
For questions of language, it is easier to speak of the electron + positron...

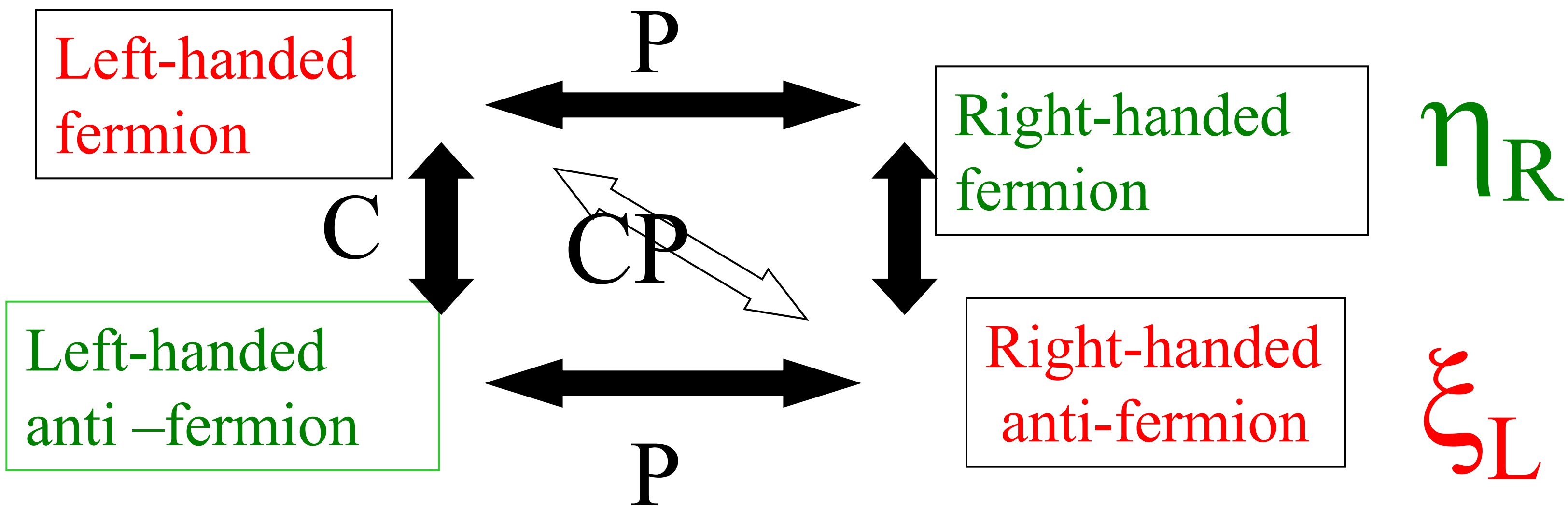
$$\begin{pmatrix} e_L \\ e_R \end{pmatrix} = \begin{pmatrix} e_{L1} \\ e_{L2} \\ e_{R1} \\ e_{R2} \end{pmatrix}$$

The Dirac spinor breaks down into 2 « Weyl » spinors, $\begin{pmatrix} \xi_L \\ \eta_R \end{pmatrix}$

Gauge interactions talk separately to the L (left-handed) and R (right -handed)

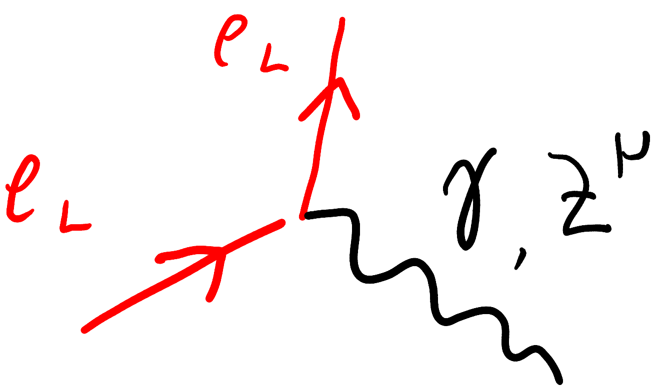





The simplest coupling only introduces the left-handed Weyl spinor,
C and P are violated, but CP is conserved : this is THE symmetry of gauge interactions,

$\xi_L$



# How can we write a mass term ?

A « mass » term must be invariant under proper Lorentz transformations (but we don't impose P or C, which are broken in the SM.

Equations of motion must lead to

$$p^2 = |m|^2$$

$$\begin{pmatrix} \psi_L \\ 0 \end{pmatrix} = \begin{pmatrix} \psi_{L1} \\ \psi_{L2} \\ 0 \end{pmatrix}$$

And,
in the
same way

$$\begin{pmatrix} \xi_L \\ 0 \end{pmatrix}$$

*W e introduce here 2 spinors,*
*We assume both to be L,*
*(if not, perform a CP transformation)*

The Lorentz invariant then reads

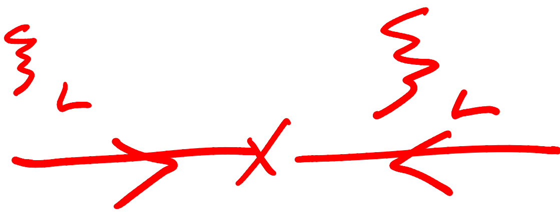
$$\psi_{L1}\xi_{L2} - \psi_{L2}\xi_{L1} = \epsilon_{ij} \;\; \psi_{Li}\xi_{Lj}$$

… if we limit ourselves to rotations, this is just the spin singlet !

This expression covers ALL cases!

$$\uparrow\downarrow - \downarrow\uparrow$$

$$\psi_{L1}\xi_{L2} - \psi_{L2}\xi_{L1} = \epsilon_{ij} \quad \psi_{Li}\xi_{Lj}$$




$$\psi_L = \xi_L$$

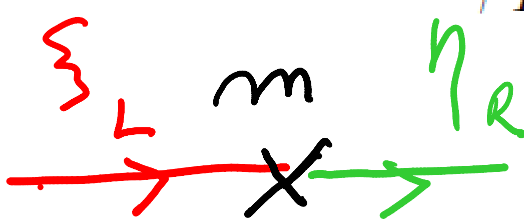
$$\epsilon_{ij}\xi_{Li}\xi_{Lj}$$

Creates (or destroys) 2 units of fermionic number :
« Majorana mass term»

2 special cases :

$$\psi_{Li} \quad = \quad \epsilon_{ik}\overline{\eta_{Rk}}$$

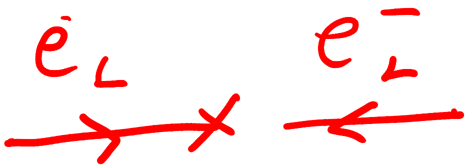
« Dirac mass term »

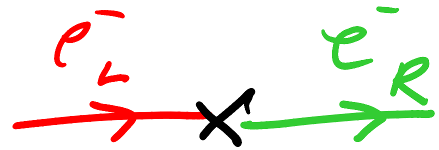



$$m \; \overline{\eta_{Rk}}\xi_{Lk}$$

If we can assign the same fermionic number to η and ξ,
Fermion number is now conserved

For the electron, only the « Dirac » mass term is allowed – the « Majorana » one does not even conserve electric charge!

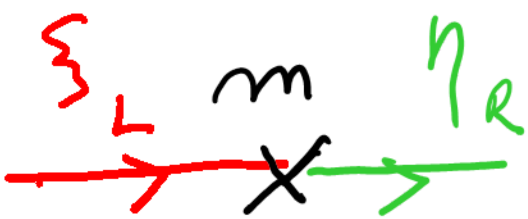



On the other hand, for the neutrino, charge is not a problem, and we can use the « Majorana » mass. It violates leptonic number, but if the mass is small enough, this escapes detection.

**It is thus possible to have Neutrino masses without introducing the right-handed neutrino**

# The sign (or phase) of the mass.


The parameter m in the Lagrangian is in general a complex number.
In the case of one family, in the Dirac case, we can always re-define m to be real, just by changing the sign of $\eta_R$, which does not couple to anyone.

This far we spoke of Weyl neutrinos, Majorana mass terms, but not of Majorana spinors…
In fact, they are not needed in 3+1 dim … just another (confusing) notation

$$\psi = \begin{pmatrix} \lambda \\ \rho \end{pmatrix}$$

Majorana or Weyl spinors ?

In 4-D : equivalent, Majorana is just a REDUNDANT way to write WEYL spinors

$$\psi^c = \psi$$

$$\Downarrow$$

$$\lambda_i = \epsilon_{ij} \; \rho^{+t}$$

$$\begin{pmatrix} \psi_L \\ (\psi_L)^c_R \end{pmatrix}$$

This is not true in more dimensions!


Can we tell 4 from 2?
Components

# Can we tell 4 from 2?

Components

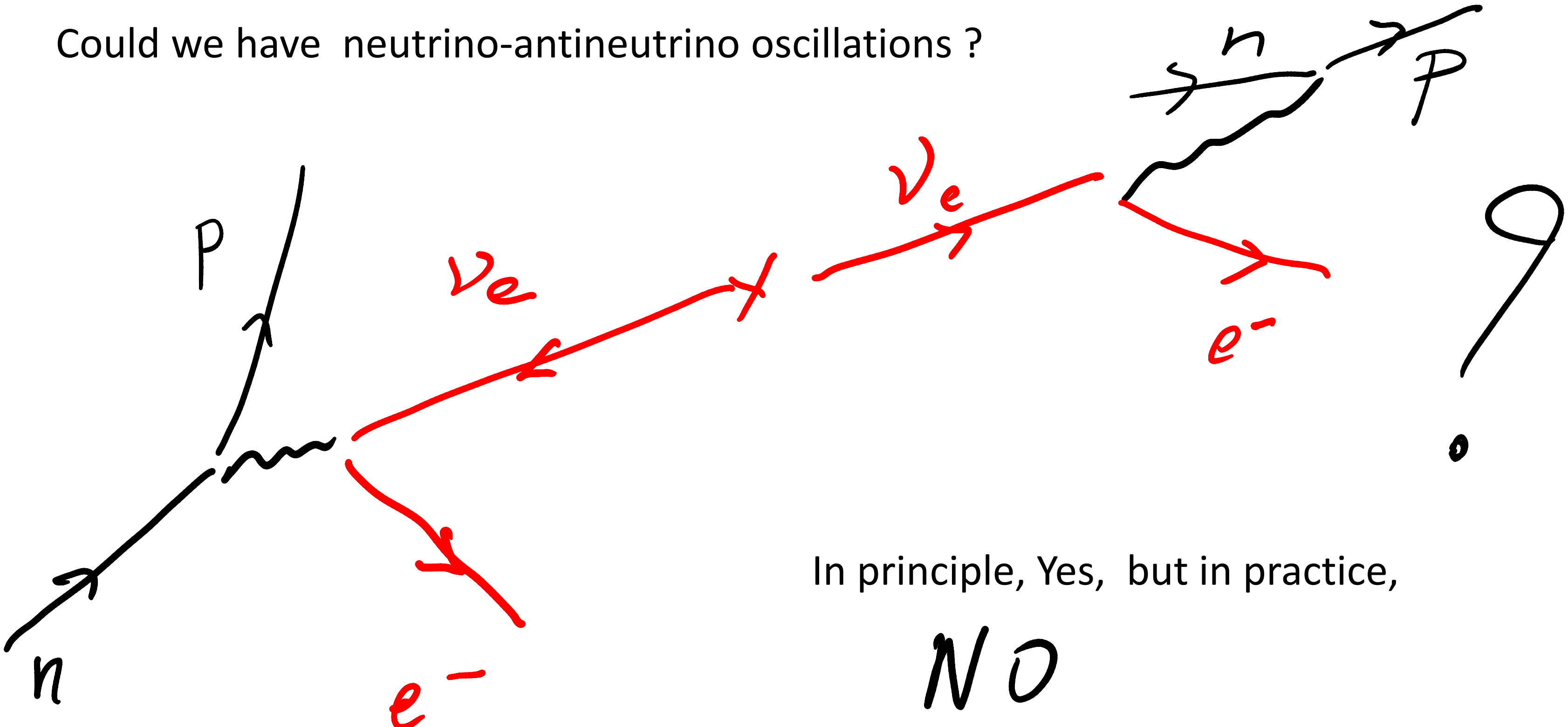
It is notoriously difficult to distinguish Weyl (Majorana) neutrinos from Dirac ones…

Why ? … outline …

- NO observable neutrino-antineutrino oscillations, even in Weyl-Majorana case
- Cosmology does not help
- Neutrinoless double beta decay : a possibility ! (but nuclear physics uncertainties)
- Magnetic moments ??

# Beyond the Neutrinoless Double beta decay,
# Can we probe the Majorana nature of neutrino masses?

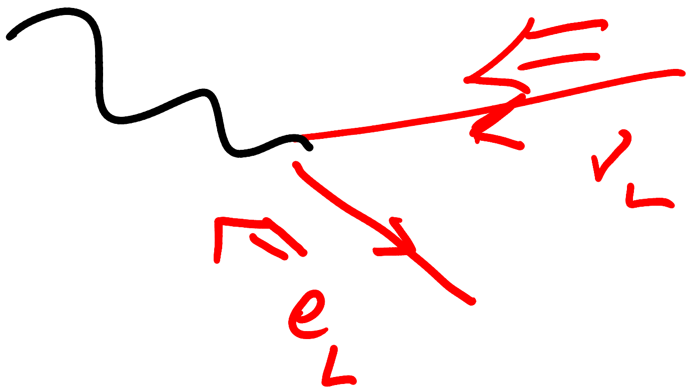
Could we have neutrino-antineutrino oscillations ?




In principle, Yes, but in practice,

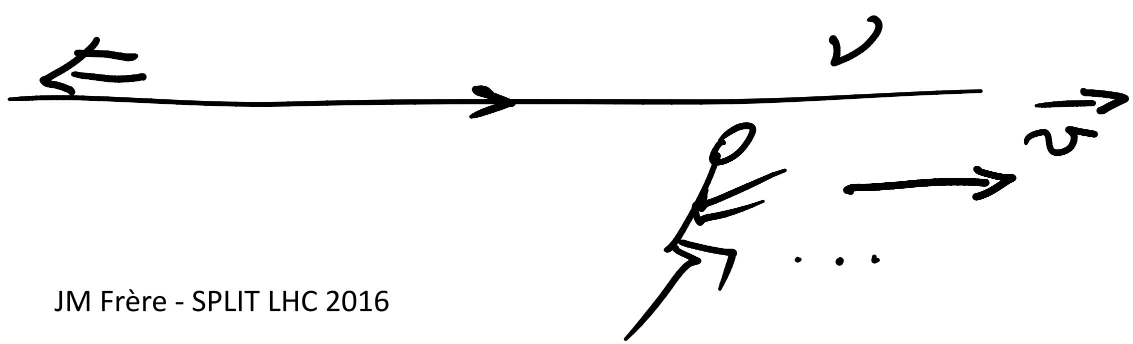
NO

Even though the lepton number is not conserved, angular momentum suppresses this reaction

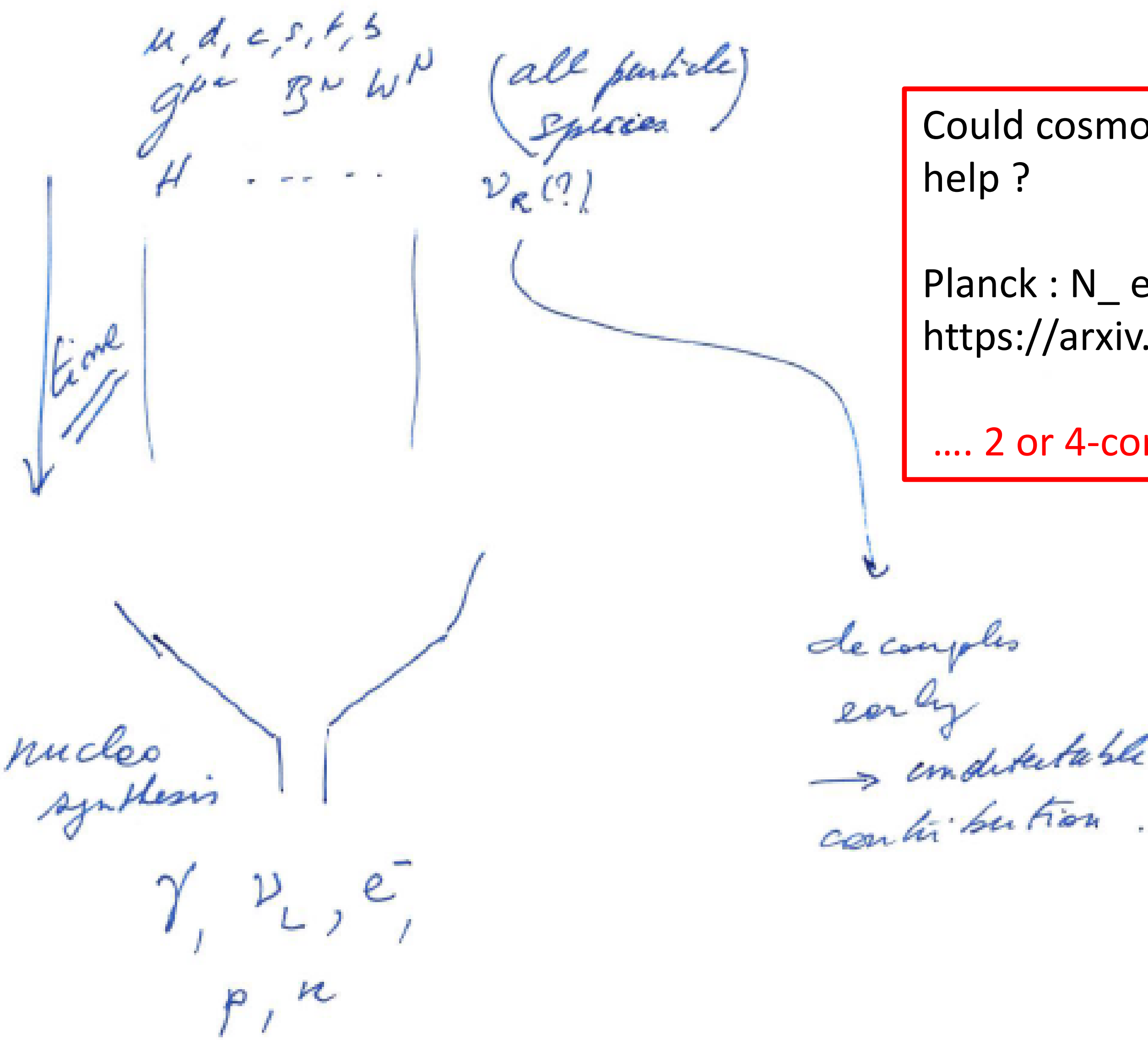



The $\nu_L$ stays linked to $e^-_L$, and not to $e^+_R$ by the W's in the SM

*As long as the detector and emitter don't have large relative speeds (in comparison to the neutrino), helicity is conserved up to factor of m/E in amplitude Even for 1MeV neutrinos, this gives a suppression of $10^{-12}$ in probability*



## Could the cosmological counting of neutrinos help us ?




Could cosmological neutrino counting help ?

Planck : N_ eff = 3.15 +/- 0.23
https://arxiv.org/abs/1502.01589

…. 2 or 4-components ? … not sensitive!

# Trying to sell Magnetic Monents

# Magnetic moments?

For ONE Weyl neutrino, a magnetic moment is forbidden by Fermi statistics ..

Is it a way to exclude Majorana masses? $\uparrow\uparrow$

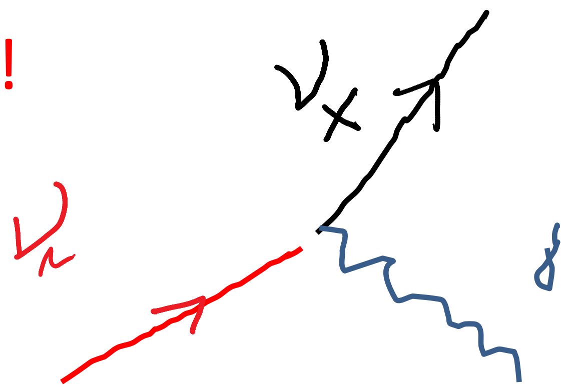
# Magnetic moments?

For ONE Weyl neutrino, a magnetic moment is forbidden by Fermi statistics ..

Is it a way to exclude Majorana masses? ↑↑

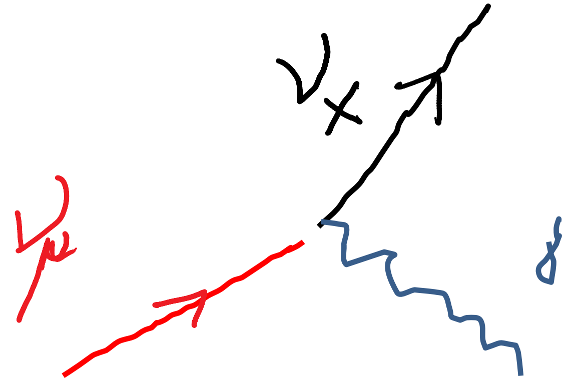
NO, TRANSITION magnetic moments are still allowed …

## and undistinguishable!



$$H_{\text{eff}} = \frac{\mu_{IJ}}{2} \overline{\nu_I^c} \sigma_{\alpha\beta} P_L \nu_J F^{\alpha\beta} + \text{h.c.},$$

In Weyl basis




$$\overbrace{\sqrt{|\mu_{e\mu}|^2 + |\mu_{\tau\mu}|^2}}^{\text{effective moment for } \nu_X} \left( \overline{\nu_X^c} \sigma_{\alpha\beta} \nu_\mu F^{\alpha\beta} \right),$$

$$\overline{\nu_X^c} \equiv \frac{\left( \mu_{e\mu} \overline{\nu_e^c} + \mu_{\tau\mu} \overline{\nu_\tau^c} \right)}{\sqrt{|\mu_{e\mu}|^2 + |\mu_{\tau\mu}|^2}}.$$

Effective electromagnetic moment for the muon neutrino
In WEYL (Majorana) case :

$$|\mu_{\nu_\mu}| \equiv \sqrt{|\mu_{e\mu}|^2 + |\mu_{\tau\mu}|^2}$$

Effective electromagnetic moment for the muon neutrino
In WEYL (Majorana) case :

$$|\mu_{\nu_\mu}| \equiv \sqrt{|\mu_{e\mu}|^2 + |\mu_{\tau\mu}|^2}$$

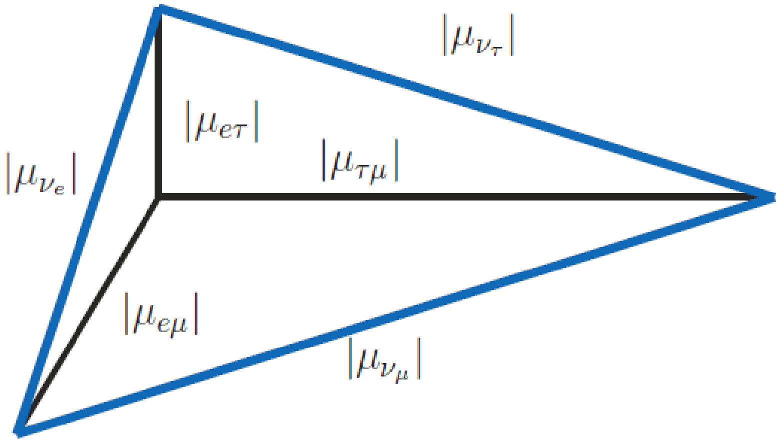



Figure 1: $|\mu_{\nu_J}|$ forms a right triangle with $|\mu_{IJ}|$ and $|\mu_{KJ}|$ (for $I \neq J \neq K$). $|\mu_{\nu_{I,J,K}}|$ thus also form a triangle (shown in thick blue), in general not with right angles.

JMF, J Heeck, S Mollet arXiv:1506.02964
Phys.Rev. D92 (2015), 053002

It is then easy to work out the inequalities ..

$$|\mu_{\nu_\tau}|^2 \leq |\mu_{\nu_e}|^2 + |\mu_{\nu_\mu}|^2 ,$$
$$|\mu_{\nu_\mu}|^2 \leq |\mu_{\nu_\tau}|^2 + |\mu_{\nu_e}|^2 ,$$
$$|\mu_{\nu_e}|^2 \leq |\mu_{\nu_\mu}|^2 + |\mu_{\nu_\tau}|^2 ,$$

= TEST for WEYL (Majorana) neutrinos

These are stronger than the more obvious « triangle inequalities »:
(none of the angles can be > 90°) $||\mu_{\nu_J}| - |\mu_{\nu_K}|| \leq |\mu_{\nu_I}| \leq |\mu_{\nu_J}| + |\mu_{\nu_K}|$

Current limits (terrestrial)

$$|\mu_{\nu_e}| < 2.9 \times 10^{-11} \mu_B , \qquad |\mu_{\nu_\mu}| < 6.8 \times 10^{-10} \mu_B , \qquad |\mu_{\nu_\tau}| < 3.9 \times 10^{-7} \mu_B .$$

Perspectives : SHiP (CERN SPS ) could improve considerably the τ neutrino limit …

Current limits (terrestrial)

$$|\mu_{\nu_e}| < 2.9 \times 10^{-11} \mu_B \, , \qquad |\mu_{\nu_\mu}| < 6.8 \times 10^{-10} \mu_B \, , \qquad |\mu_{\nu_\tau}| < 3.9 \times 10^{-7} \mu_B \, .$$

Current limits (astrophysics – in fact sum over all neutrinos)

$$4.5 \times 10^{-12} \mu_B$$

Hopeless for terrestrial mesurements?
NO …

if there is a 4th light (sterile) neutrino, with mass > keV,
astro limits don't apply
and a large electromagnetic moment could be observed … SHiP is in business !

Still --- complicated models needed for large magnetic moments !!!

# Update ….

Borexino brings interesting new bounds (from oscillated Solar neutrinos, in MASS basis )

tions, due to its robust statistics and the low energies observed, below 1 MeV. Our new limit on the effective neutrino magnetic moment which follows from the most recent Borexino data is $3.1 \times 10^{-11} \mu_B$ at 90% C.L. This corresponds to the individual transition magnetic moment constraints: $|\Lambda_1| \leq 5.6 \times 10^{-11} \mu_B$, $|\Lambda_2| \leq 4.0 \times 10^{-11} \mu_B$, and $|\Lambda_3| \leq 3.1 \times 10^{-11} \mu_B$ (90% C.L.), irrespective of any complex phase. Indeed, the incoherent admixture of neutrino mass eigenstates

Updating neutrino magnetic moment constraints
B.C. Canas, O.G. Miranda, A. Parada ,M. Tortola, Jose W.F. Valle Phys.Lett. B753 (2016) 191-198, Addendum: Phys.Lett. B757 (2016) 568-568   arXiv:1510.01684

Using these numbers, we have (if we saturate)
31.36 > 16 + 9.61   ….   is there hope to improve and get an actual check at the $10^{-11}$ level?


A hard sell …
if you want models !

**Still --- complicated models needed for large magnetic moments !!!
For instance ..**

**« Double see-saw »**

2 singlets

$$M_\nu = \begin{array}{c} \begin{array}{ccc} \nu_L & \nu_R & \nu_S \end{array} \\ \begin{pmatrix} 0 & m & 0 \\ m^{\mathrm{T}} & 0 & M^{\mathrm{T}} \\ 0 & M & m_\sigma \end{pmatrix} \end{array}$$

m = $\lambda$ v

$\lambda$ can then be large, and lead to observable effets, since the light neutrino mass is proportional to $m_\sigma$

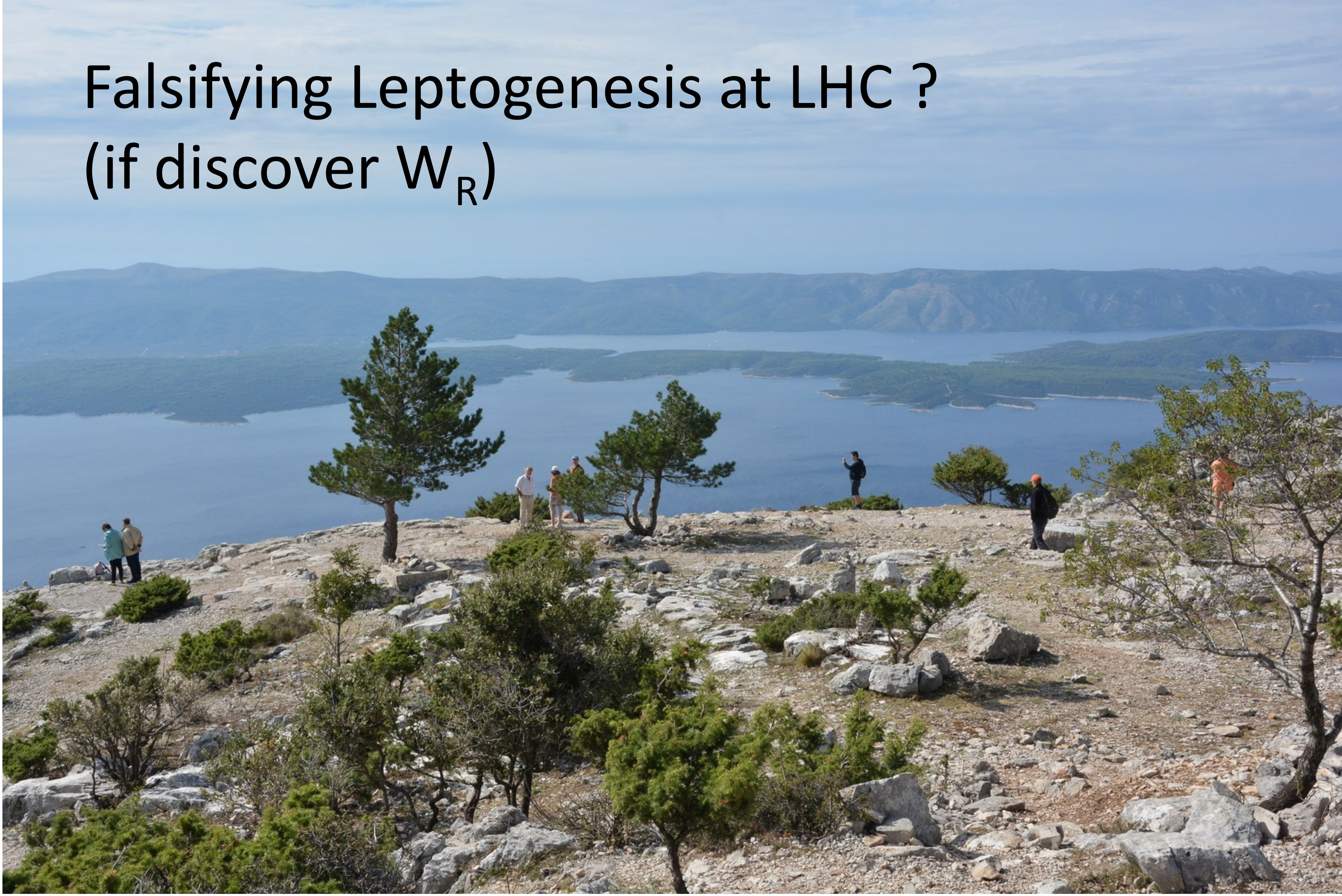
$$m_{\nu_1} \approx (m/M)^2 m_\sigma, \qquad m_{\nu_{2,3}} \approx M \pm m_\sigma/2,$$

*(remark : this is an example of « pseudo-Dirac »,*

*since $V_R + V_S$ act as a Dirac pair, whose contributions to the light neutrino compensate.*

*(an old idea, .. Langacker, Mohapatra, Antoniadis, 1986-88, jmf+Liu, recently revived…)*

# Falsifying Leptogenesis at LHC ? (if discover $W_R$)



# What are Right-handed neutrinos good for?

Baryogenesis via Leptogenesis

$\rightarrow$ The DEFEAT of antimatter

CP violating decay creates L<0,
converted into B>0 by an anomaly-related mechanism (instantons, sphalerons)

$$\nu_R \rightarrow N_R \quad \text{from now on}$$

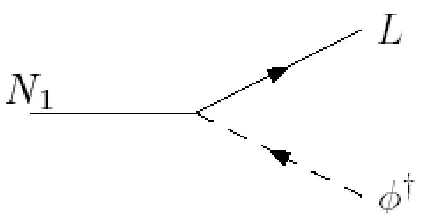
Notoriously robust and difficult to test … all particles could be at $10^{10}$ GeV or so..

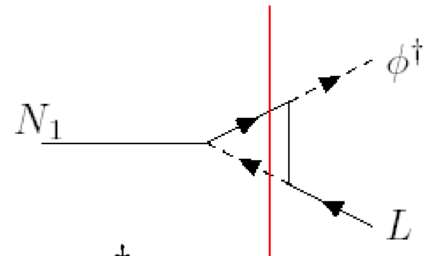
# How leptogenesis works….

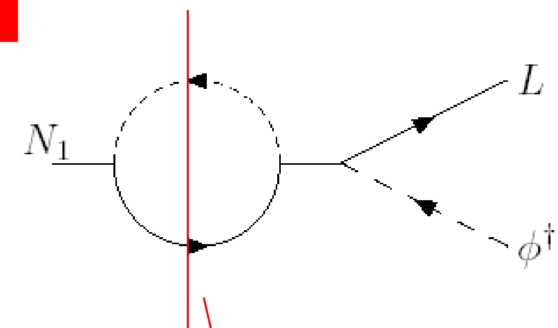
Assume that we have some population of heavy N particles…
*(either initial thermal population, or re-created after inflation) ; due to their heavy mass and relatively small coupling, N become easily relic particles.*

Generation of lepton number

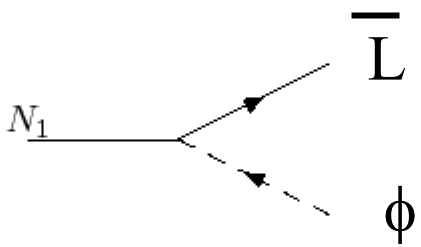
L =+1




N can decay to Lepton L + $\phi^\dagger$ as above, or to the opposite channel $\bar{L}\phi$




CP violation +
Interference term leads
to excess of L or anti-L

L =-1

Possible unitarity cuts

# Constraints:

Heavy neutrinos must decay out of equilibrium

$$\tau(X) >> H^{-1}$$

$H = \dot{a}/a$ is the Hubble constant,

$$\tau^{-1} = \Gamma \cong g^2 M$$

$$H = \sqrt{g^*}\frac{T^2}{10^{19} GeV}$$

$g^*$ is the number of degrees of freedom at the time

at decay : $T \approx M$ ,

Need enough CP violation;

for large splitting between neutrino masses, get

$$\varepsilon_i^{\phi} = -\frac{3}{16\pi}\frac{1}{\left[\lambda_\nu \lambda_\nu^\dagger\right]_{ii}}\sum_{j\neq i} \mathrm{Im}\left(\left[\lambda_\nu \lambda_\nu^\dagger\right]_{ij}^2\right)\frac{M_i}{M_j}.$$

Some rough estimations…

…What are the suitable values of $\lambda$ and M?

Assume there is only one generic value of $\lambda$ (in reality, a matrix)

$$\epsilon < \lambda^4/\lambda^2 \approx \lambda^2 > 10^{-8}$$

$$m_\nu = m^2/M \approx \lambda^2/M \approx .01eV$$

rough estimate of M scale (in GeV) needed…

similar to $\tau$ lepton →

At the difference of baryogenesis, the Yukawa matrix $\lambda$ leaves a lot of freedom

| $\lambda$ | light neutrino .01 eV M ~ | decay out of equil. M> | enough CP viol |
|---|---|---|---|
| .0000 1 | 10^7 | 10^8 | need tuning |
| .0001 | 10^9 | 10^10 | |
| .001 | 10^11 | 10^12 | |
| .01 | 10^13 | 10^14 | |
| .1 | 10^15 | 10^16 | |
| 1 | 10^17 | 10^18 | large |

# Can leptogenesis be falsified ?

In general, no, since most mass ranges are unaccessible.
But ..

Presence of $\nu_R$ suggest a larger symmetry, like SO(10 )

or $SU(2)_L \times SU(2)_R$

If so, gauge interactions dilute the lepton number asymmetry,
possibly below the requested number for the baryon number of the Universe..

# Can leptogenesis be falsified ?

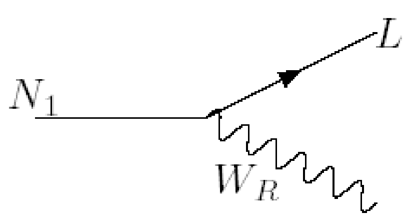
In general, no, since most mass ranges are unaccessible.
But .. Presence of $\nu_R$ suggest a larger symmetry, like SO(10 ) or SU(2)$_L$ X SU(2)$_R$

## with the gauge inclusion

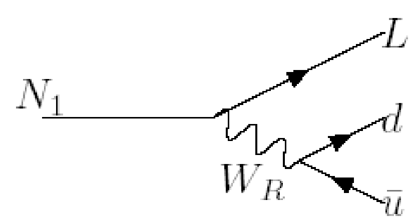
$$\epsilon_1 = \frac{\epsilon_1^0}{1+X}$$

diluted CP asymmetry

$\underline{M_{W_R} < M_{N_1}}$




$\underline{M_{W_R} > M_{N_1}}$

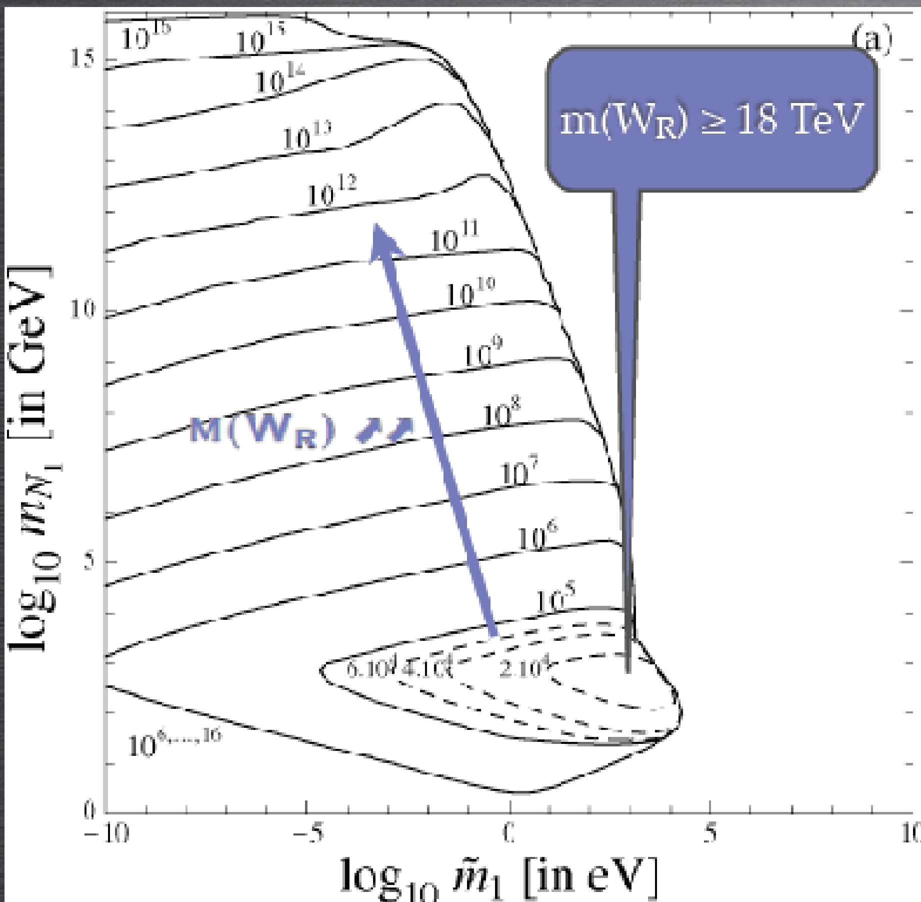



(competing effect : the presence of $W_R$ allows a faster build-up of the N population after inflation)

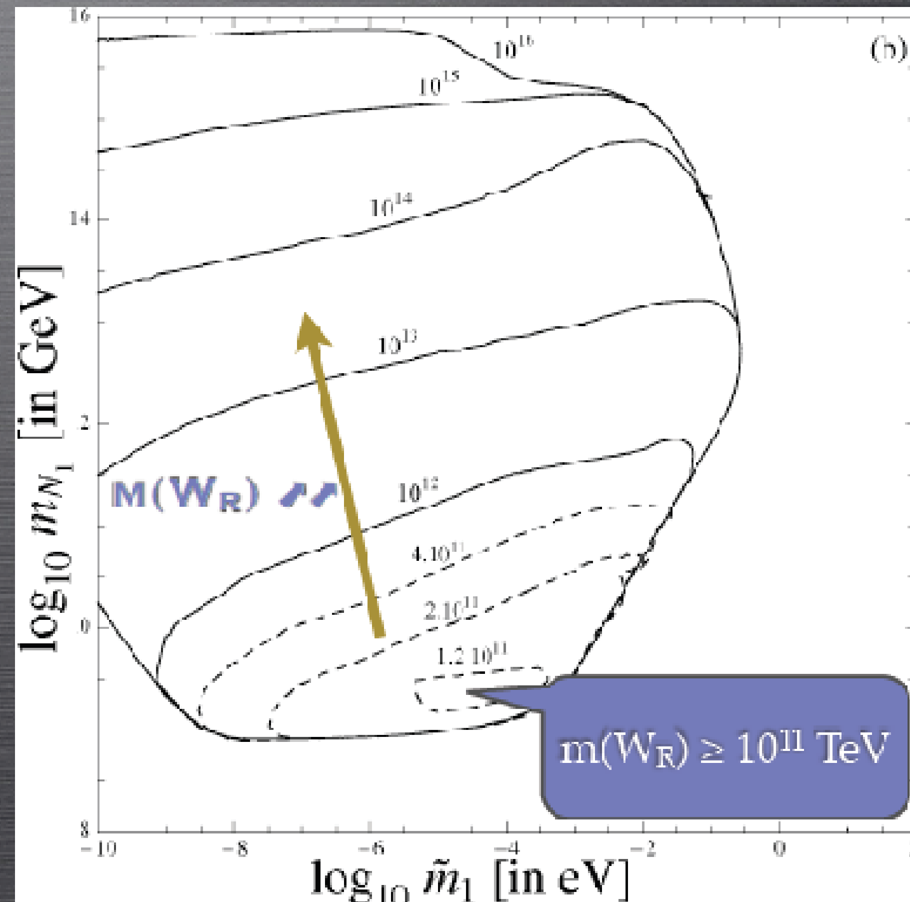
S Carlier, JMF, FS Ling **Phys.Rev. D60 (1999) 096003**
JMF, T Hambye, G Vertongen **JHEP 0901 (2009) 051**

# Bounds on $M(W_R)$ & $M(N_R)$

For $\varepsilon_{CP} = 1$




For $\varepsilon_{CP} = \varepsilon_{DI}$



Updates : see Dev, Lee, Mohapatra 2014 ..

Leptogenesis is by far the most attractive way to generate the current baryon asymmetry. It is extraordinarily sturdy and resilient, and the scale at which it happens makes it almost hopeless to CONFIRM.

Finding a $W_R$ at a collider near you would kill
at least the « vanilla » (most
straightforward) versions. … Probably the only realistic way to EXCLUDE leptogenesis!!!

*Ongoing work on bringing down the limit : the above limit is « generic »,*
*if one accepts tuning of the model (for instance large, comensating Yukawas, ..),*
*the limits could be brought down…however in that case close examination of the model*
*at hand would give the answer on leptogenesis :*

e.g. Leptogenesis Constraints on the Mass of Right-handed Gauge Bosons
P.S. Bhupal Dev (Chang-Hun Lee, R.N. Mohapatra **Phys.Rev. D90 (2014) , 095012**
arXiv:1408.2820 **has a > 3 TeV limit …**

# Mass models

Many attempts have been made at « predicting » or more often « postdicting » quark and lepton masses.

A frequent approach is based on « textures » , for instance imposing a certain number of vanishing elements in the mass matrices (hopefully in a basis-independent way), possibly via discrete symmetries (A3, A4,..)
Most have failed. (and nobody predicted the top quark in non-suspect time).

## A model inspired from extra dimensions

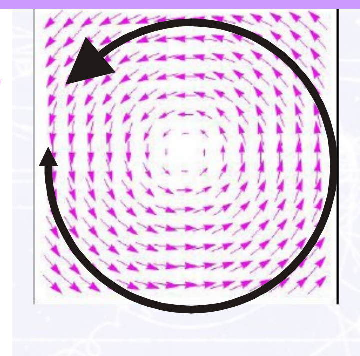

A neutrino mass model with one TESTED prediction

1family in 6D → 3 families in 4D

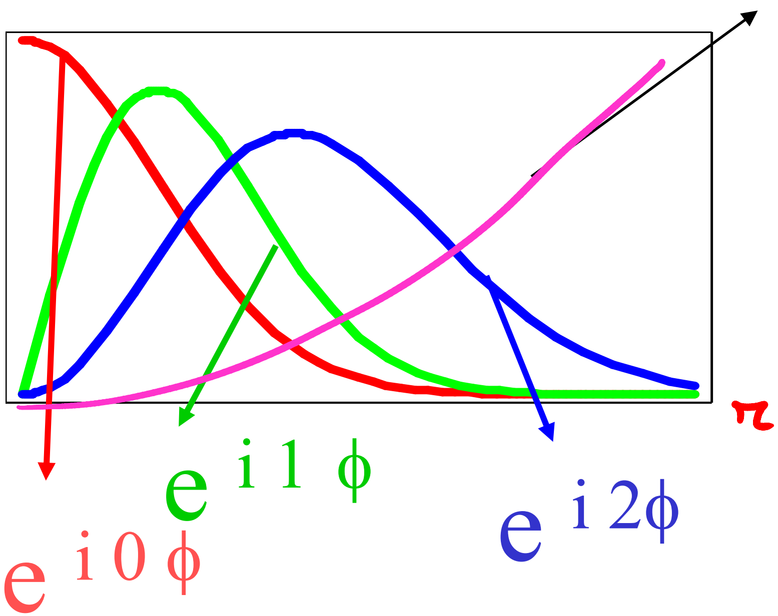
3+1 +2 dim

Vortex with winding number n localizes n chiral massless fermion modes in 3+1

Vortex Profile $e^{i\,3\,\phi}$



$$\Phi = e^{\,i\,n\varphi}$$




The 3 fermion modes have different shapes in r, and different winding properties in the extra dimension variable $\phi$

Generic prediction (quarks) :
- nearly diagonal mass matrices
- Strong hierarchy of masses linked to the overlaps at the origin

**Generic prediction (neutrinos) :**
- **large mixings,**
- **inverted hierarchy**
- **suppressed neutrinoless double beta decay**

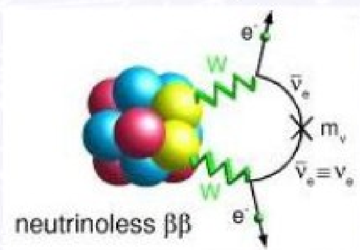
## Generic prediction : large mixings, inverted hierarchy suppressed neutrinoless double beta decay

# NEUTRINOS MASSES

$$M_\nu \sim \begin{pmatrix} \cdot & \cdot & \times \\ \cdot & \cdot & \cdot \\ \times & \cdot & \cdot \end{pmatrix}$$

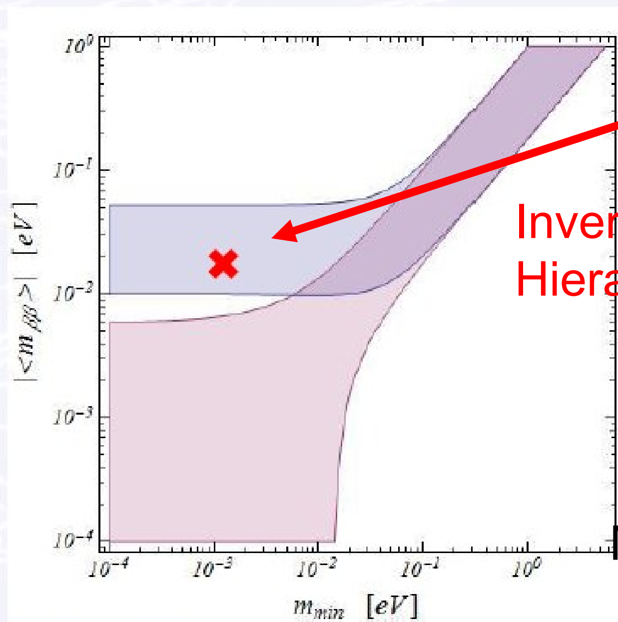
Automatically get

- Consequences of this structure
  - $0\nu\beta\beta$ decay




partial suppression

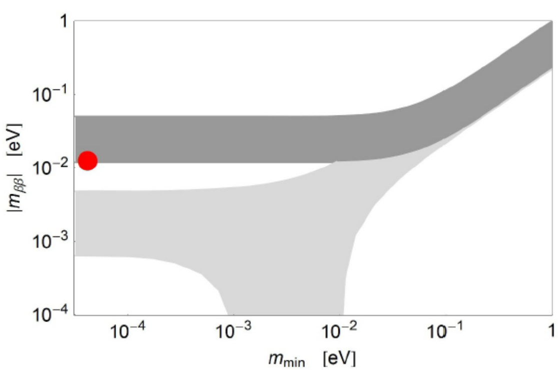
$$|\langle m_{\beta\beta}\rangle| \simeq \frac{1}{3}\sqrt{\Delta m^2_\oplus}$$




Inverted Hierarchy

Mass scale

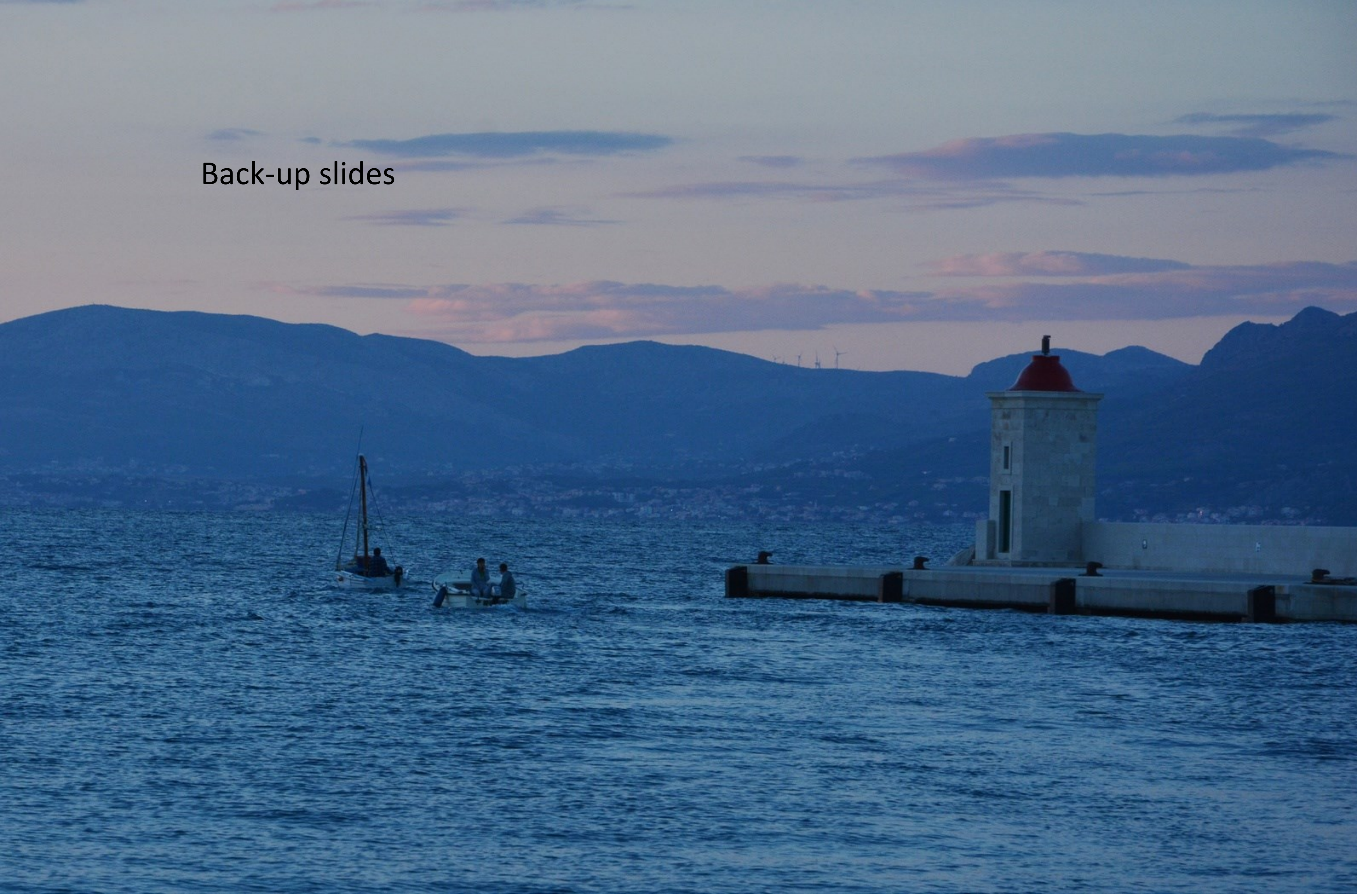
| | | |
|---|---|---|
| **Neutrino masses** | | |
| $m_1$ | $5.46 \cdot 10^{-2}\,\mathrm{eV}$ | — |
| $m_2$ | $5.53 \cdot 10^{-2}\,\mathrm{eV}$ | — |
| $m_3$ | $4.17 \cdot 10^{-5}\,\mathrm{eV}$ | — |
| $\Delta m^2_{21}$ | $7.96 \cdot 10^{-5}\ \mathrm{eV}^2$ | $(7.50 \pm 0.185) \cdot 10^{-5}\ \mathrm{eV}^2$ |
| $\Delta m^2_{13}$ | $2.98 \cdot 10^{-3}\ \mathrm{eV}^2$ | $(2.47^{+0.069}_{-0.067}) \cdot 10^{-3}\ \mathrm{eV}^2$ |
| **Lepton mixing matrix** | | |
| $\lvert U_{\mathrm{PMNS}}\rvert$ | $\begin{pmatrix} 0.76 & 0.63 & 0.13 \\ 0.39 & 0.58 & 0.72 \\ 0.52 & 0.52 & 0.68 \end{pmatrix}$ | $\simeq \begin{pmatrix} 0.795-0.846 & 0.513-0.585 & 0.126-0.178 \\ 0.205-0.543 & 0.416-0.730 & 0.579-0.808 \\ 0.215-0.548 & 0.409-0.725 & 0.567-0.800 \end{pmatrix}$ |
| $\langle m_{\beta\beta}\rangle$ | $0.013\,\mathrm{eV}$ | $\lesssim 0.3\,\mathrm{eV}$ [31] |
| J | $0.019$ | $\lesssim 0.036$ |
| $\theta_{12}$ | $39.7^\circ$ | $\simeq (31.09^\circ - 35.89^\circ)$ |
| $\theta_{23}$ | $46.5^\circ$ | $\sim (35.8^\circ - 54.8^\circ)$ |
| $\theta_{13}$ | $7.2^\circ$ | $\boxed{\simeq (7.19^\circ - 9.96^\circ)}$ |




*JMF,M Libanov, FS Ling, S Mollet, S Troitsky*

Note a non-vanishing $\theta_{13}$ was predicted (in previous version) *before observation*

Back-up slides



Why would be the propagation speed of neutrinos 1 and 2 differ?

It could be MASS,

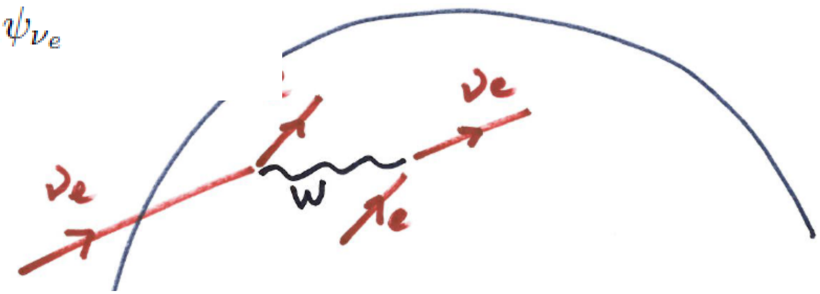
$$
\begin{aligned}
E^2 &= \vec{p}^{\,2} + m^2 \\
v &= |\vec{p}|/E \\
v &= \sqrt{1-(m/E)^2} \\
(v_1 - v_2)\, L &= \frac{(m_2^2 - m_1^2)\, L}{2E}
\end{aligned}
$$

*The effect is the same for neutrinos and antineutrinos, does not depend on the type of mass (Majorana or Dirac)*

But also any kind of interaction affecting differently 1 and 2
Well-known example : MSW effect

But also any kind of interaction affecting differently 1 and 2
Well-known example : MSW effect

$$Lagrangian \supset \overline{\psi_{\nu_e}}(p^0\gamma^0 - \vec{p}\,\vec{\gamma})\psi_{\nu_e} - V$$
$$V \supset \kappa G_F \overline{\psi_{\nu_e}}\gamma^\mu\psi_e\ \psi_e\gamma_\mu\psi_{\nu_e}$$




After Fierzing,

$$\kappa G_F \overline{\psi_{\nu_e}}\gamma^\mu\psi_e\ \psi_e\gamma_\mu\psi_{\nu_e} = \kappa' G_F \overline{\psi_{\nu_e}}\gamma^\mu L\psi_{\nu_e}\psi_e\ \psi_e\gamma_\mu L\psi_e$$
$$= \kappa'' \overline{\psi_{\nu_e}}\gamma^0 L\psi_{\nu_e} G_F \rho_e$$

matter.

$\nu_e$, $\nu_\mu$
$\nu$ sterile
have $\neq$ interactions
in matter.

This means that we simply replace $(p^0)^2 - \vec{p}^{\,2} = m^2$ by

$$p^0 \to p^0 - \kappa'' G_F \rho_e$$
$$E^2 - 2p^0\kappa'' G_F - \vec{p}^{\,2} = m^2$$

And get an effective mass ..
which differs for neutrino
and antineutrino (CPT violation …
we interact with MATTER

$$m^2 \to m^2 + 2p^0\kappa'' G_F \rho_e$$

$\nu$ $p^0 > 0$

$\bar{\nu}$ $p^0 < 0$

# Neutrinos masses in the Standard Model .. And a bit beyond...

The simplest...
Just treat them like other fermions,

Introduce $\nu_R$ and a Yukawa coupling $\lambda$

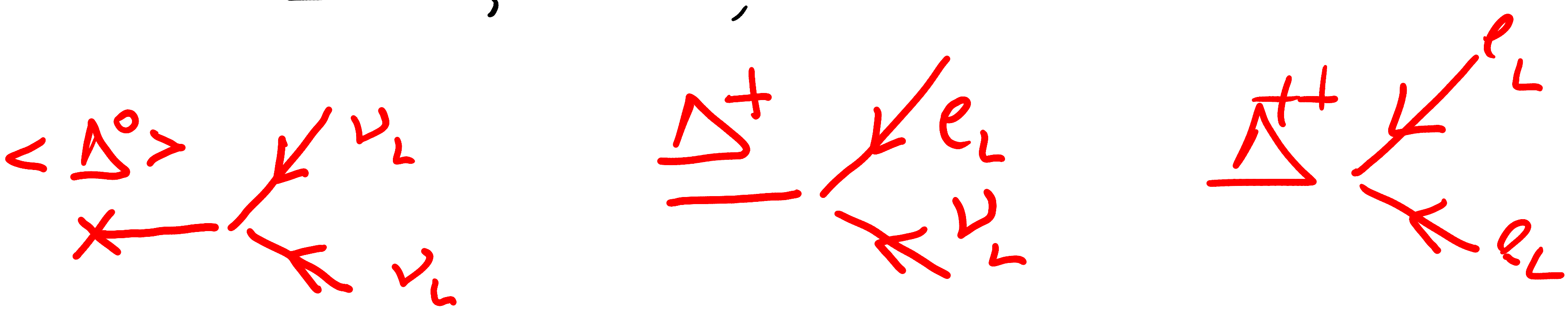
$\lambda < m_\nu / m_W < 10^{-11}$
A bit inelegant, but there are other large/small Yukawa ratios in the SM (top/ electron = 3 $10^{5)}$

In this context, the $\nu_R$ is all but unobservable, as its sole role is in giving mass .

We can also try to do without the $\nu_R$, and use a Majorana mass for the sole $\nu_L$

-- But such a term breaks SU(2) invariance, and we would need a scalar triplet, with a vev through spontaneous symmetry breaking.


$\Rightarrow \quad \Delta^{++}, \quad \Delta^{+}, \quad \Delta^{0}$



Such a breaking $V_L$ would upset the mass ratio W/Z

But is acceptable if small enough, for instance ..

$$\langle \Delta^0 \rangle = v_L < v/100 \qquad \frac{gv}{2} = m_W$$

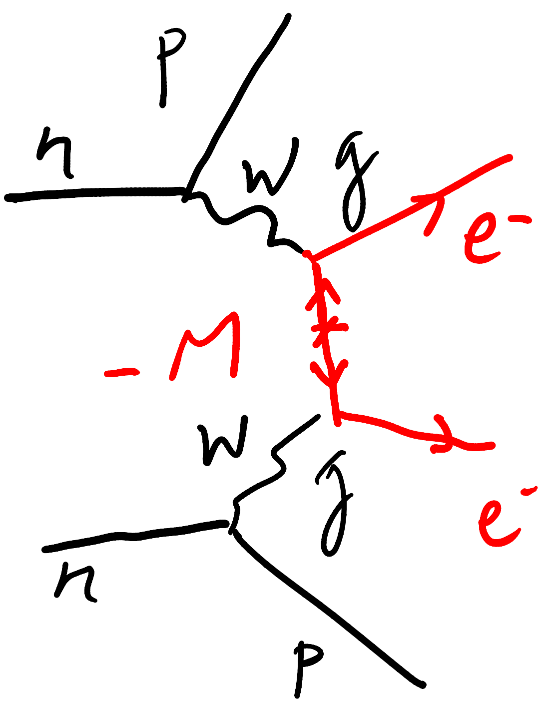
This solution is not more costly in terms of « degrees of freedom » than the introduction of right – handed neutrinos, … it deserves study at the LHC

## The sign of the fermion mass – Majorana case

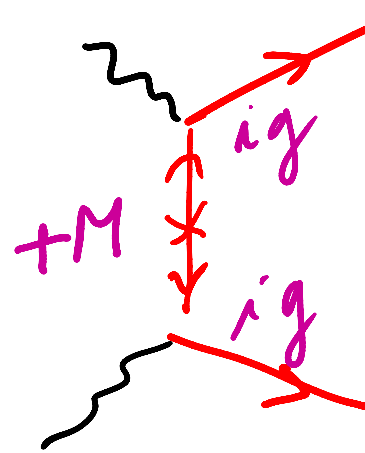
- M $\quad \epsilon_{ij}\xi_{Li}\xi_{Lj}$

Here, we cannot re-define the sign of the mass without affecting the interactions … we can bring m to be real by re-defining $\xi$-> i $\xi$

But in any case, the sign of the amplitude remains

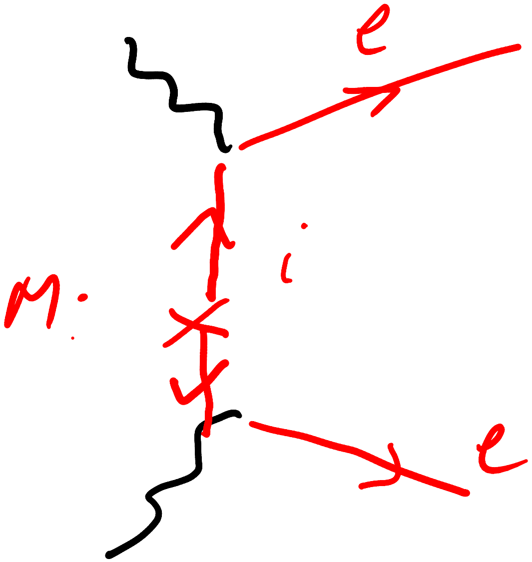



$\Longleftrightarrow$




$\Longleftrightarrow \quad \dfrac{-Mg^2}{q^2-M^2}$

Neutrinoless Double Beta decay is sensitive to the weighted sum of masses, including Majorana phases




$$\sum \left( \frac{M_i}{q^2 - M_i^2} \cdot g^2 V_{ei}^2 \right)$$

Special case : for one flavor,
Dirac can be seen as 2 semi-spinors with
equal but opposite masses and equal couplings

$$\sum M_i = 0$$

For later use : the cancellation occurs not in one family, but across families
« Pseudo-Dirac »

An aside : A Dirac spinor can indeed be seen as the sum of 2 Majorana spinors of equal and opposite masses ..

$$m\ \bar{\Psi}\ \Psi$$

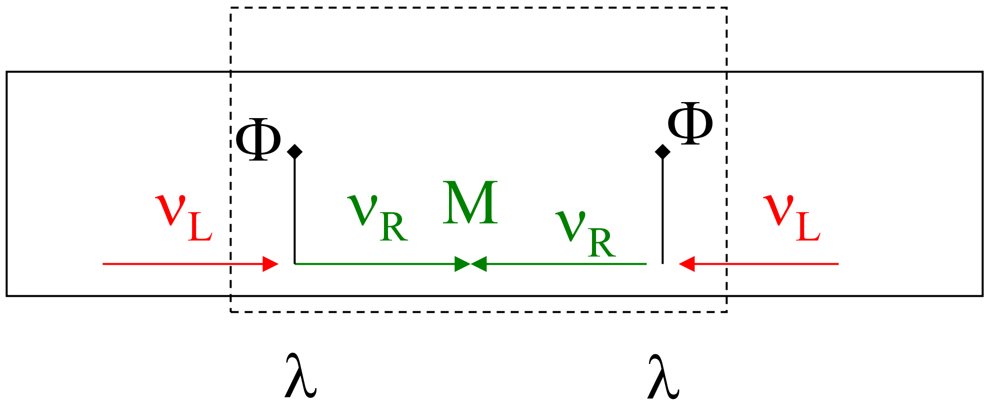
$$\chi = \frac{1}{\sqrt{2}}(\Psi + \Psi^c)$$

$$\lambda = i\frac{1}{\sqrt{2}}(\Psi - \Psi^c)$$

$$\frac{m}{2}\overline{\chi^c}\chi - \frac{m}{2}\overline{\lambda^c}\lambda$$

# A poor man's triplet

We can build an « effective triplet » from the Standard Model doublet, and, right-handed neutrinos ..




**After diagonalization,**
**2 Weyl spinors**
**SU(2) imposes $M_1 = 0$**
**For m= λ v <<$M_2$ =M we get**

$$|m_1| \approx m/M^2$$

$$|m_2| \approx M$$

| | $\xi_{Li}$ | $\epsilon_{ik}\eta^{+}_{Rk}$ |
|---|---|---|
| $\epsilon_{il}\xi_{Ll}$ | $M_1$ | $m$ |
| $\eta^{+}_{Ri}$ | $m$ | $M_2$ |

$$\lambda_1 \approx \xi_L - m/M \;\; \epsilon \cdot \eta_R^{+}$$

$$\lambda_2 \approx \eta_R + m/M \;\; \epsilon \cdot \xi_L^{+}$$

$$\lambda_1 \approx \xi_L - m/M \ \epsilon \cdot \eta_R^+$$

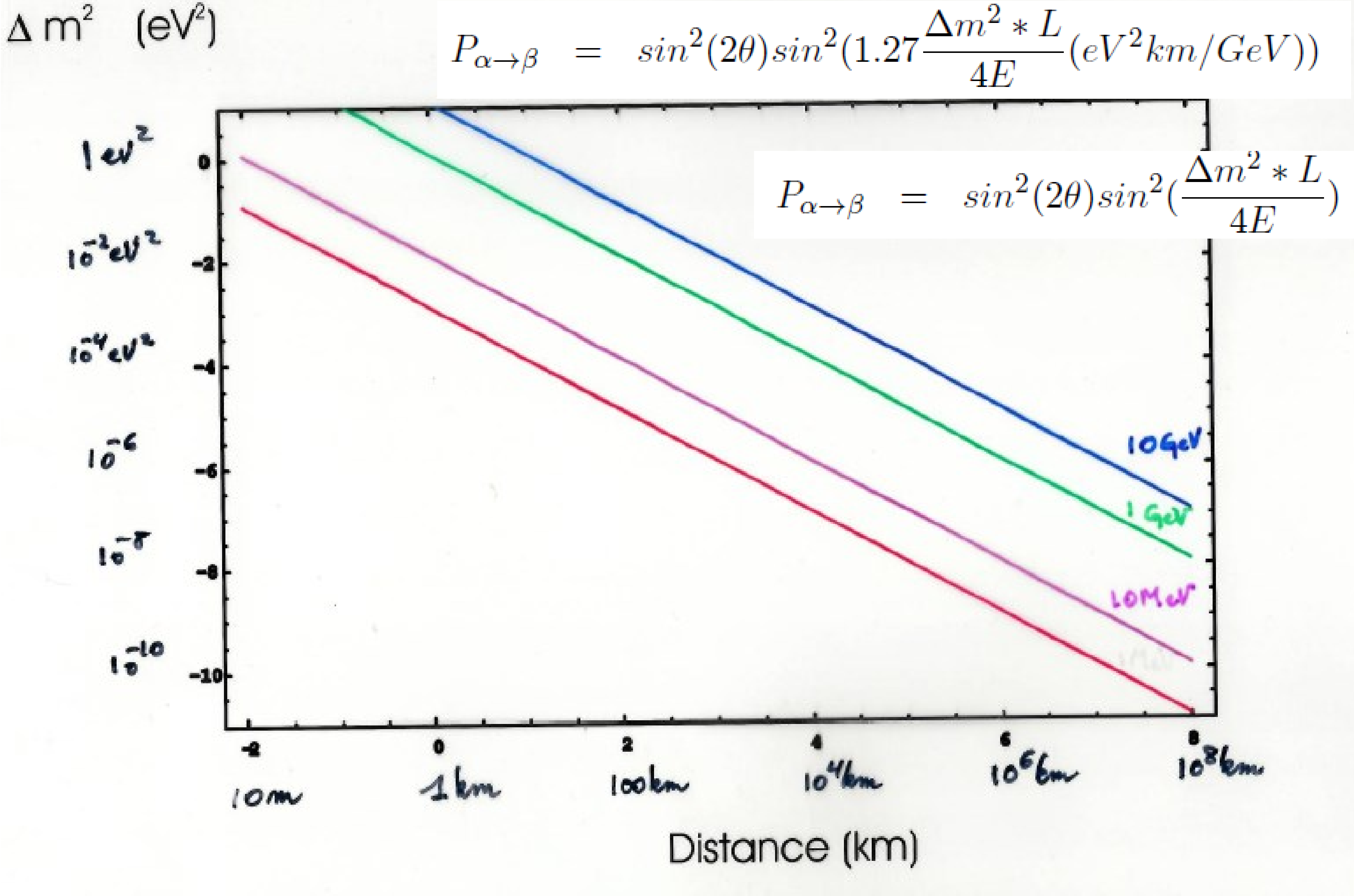
$$\lambda_2 \approx \eta_R + m/M \ \epsilon \cdot \xi_L^+$$

We end up with something close to a low Majorana mass left-handed neutrino, In principle, such schemes could be differentiated from the triplet by the small admixture of the R mode , which leads to a departure from unitarity in the mixing matrix .. However such effects are of order m/M and thus unobervable.

Some models may make this presence detectable, they tend however to be quite artificial … for instance :

$$P_{\alpha\to\beta} \;=\; sin^2(2\theta)sin^2(1.27\frac{\Delta m^2 * L}{4E}(eV^2km/GeV))$$

$$P_{\alpha\to\beta} \;=\; sin^2(2\theta)sin^2(\frac{\Delta m^2 * L}{4E})$$



# Short distance oscillations, « Reactor anomaly »

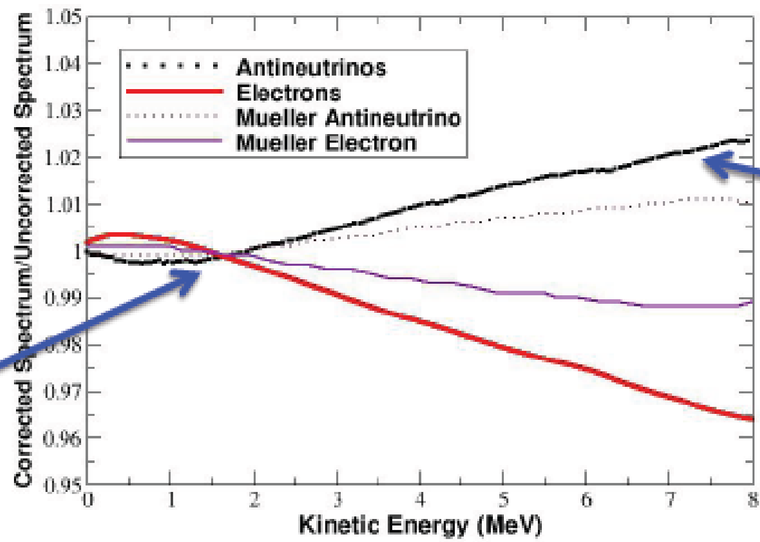
At short distance (or $\Delta m^2 = 1\ eV^2$) the situation is extremely confused, with contradictory claims from LSND, Mini-Boone, Karmen ..

More recently, a re-examination of neutrino fluxes from nuclear power plants has led to the claim of an « anomaly » (approx. 5% more neutrinos expected than from previous calculations, and above observations).

**In fact, it is not really the NUMBER of neutrinos which changes, but their energy distribution.**

The following is based on Anna Hayes 's talk at Moriond 2015
https://indico.in2p3.fr/event/10819/session/0/contribution/74/material/slides/0.pdf

## If all forbidden transitions are treated as allowed GT, the corrections lead to an anomaly – the $\nu_e$ spectrum is shifted to higher energy

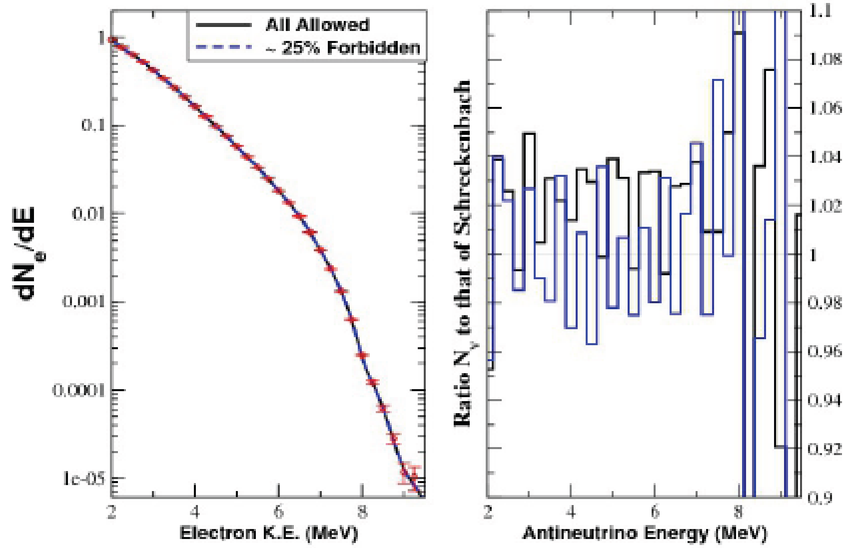



$$\bar{E}_0/2$$

$$\cong \frac{1}{2}\left[\frac{4(\mu_\nu - \frac{1}{2})}{6M_n g_A} - \frac{3Z\alpha R}{2\hbar c}\right]$$

Based on Anna Hayes ‘s talk at Moriond 2015
https://indico.in2p3.fr/event/10819/session/0/contribution/74/material/slides/0.pdf

# Fit to Schreckenbach’s beta spectrum




If all allowed:
⇒ +2.2% antineutrinos

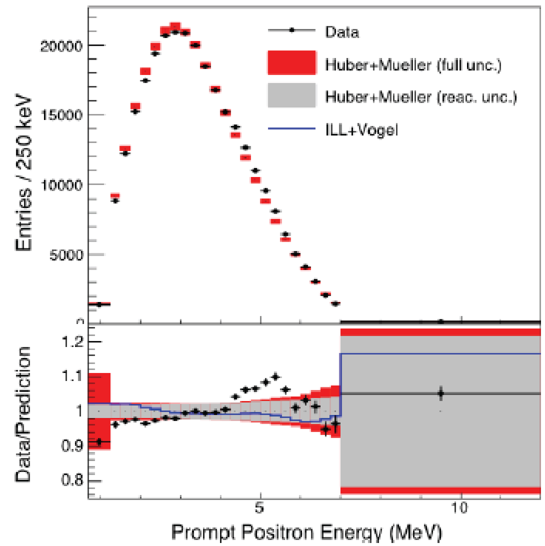
If 25% forbidden transitions
=> +0.06% antineutrinos

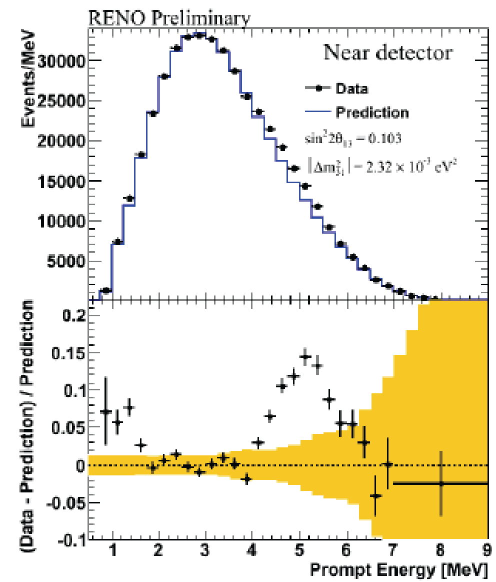
**Changes in the antineutrino spectrum range from 0-4%**
**Problem arises because of lack of knowledge on how to treat forbidden transitions**

Based on Anna Hayes 's talk at Moriond 2015
https://indico.in2p3.fr/event/10819/session/0/contribution/74/material/slides/0.pdf

**Significant Shoulder seen in the Near Detector at $E_{promt}$~4-6.5 MeV at both Dayabay and RENO. Also seen in the far detectors**

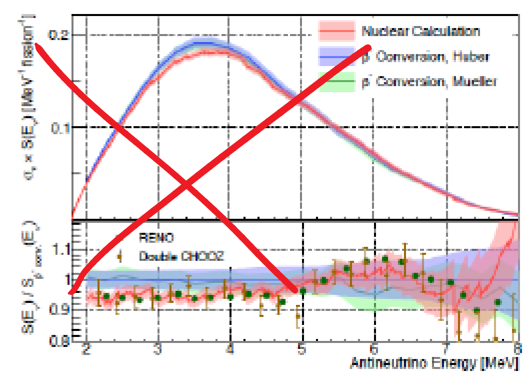
Not foreseen by the Muller and Huber calculations ..




~~Can be accounted for ..~~
~~Based on some data bases, but not others.~~
~~Dwyer+Langford, **arXiv:1407:1281**~~

See Hayes, Moriond 2016




The only way to know the neutrino flux measure it … (2 detectors experiments)

Can we test the « fast oscillations » scheme?

$$P_{\alpha\rightarrow\beta} = sin^2(2\theta)sin^2(\frac{\Delta m^2 * L}{4E})$$

$$P_{\alpha\rightarrow\beta} = sin^2(2\theta)sin^2(1.27\frac{\Delta m^2 * L}{4E}(eV^2m/MeV))$$

To get a suppression by 5% with unresolved oscillations, need
Sin2(2θ) > 0.1
Could we get very fast oscillations (say < 1m ) which could escape planned detectors?

Would need m> 10 eV … but with such large mixing, excluded by nucleosynthesis !

→ Currently built reactor experiments will tell us the answer !

## Massive Neutrinos as dark matter:

Could be constrained by Solar neutrino experiments …

DM has little momentum, but the mass of the heavy neutrino triggers the reaction.

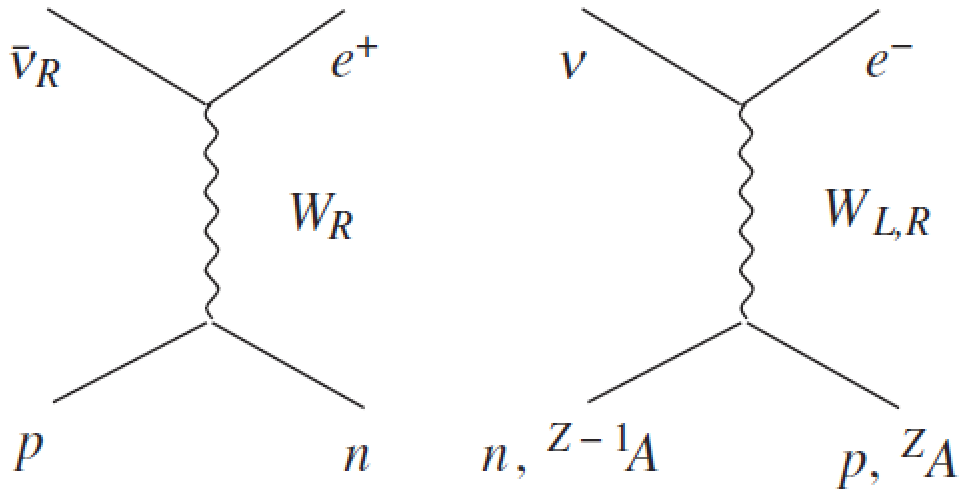
If light $W_R$ present and MeV « heavy neutrino »
Is a dark matter candidate,

we get limits from large underground detectors ..
Catalyse beta and betat+ decay

→ Limits .. For $m_R = 1$ MeV we obtain *MR/ML* > 10–20

JMF, L Lopez-Honorez, E Nezri, S Swillens, G Vertongen, **Phys.Rev. D75 (2007) 085017** hep-ph/0610240

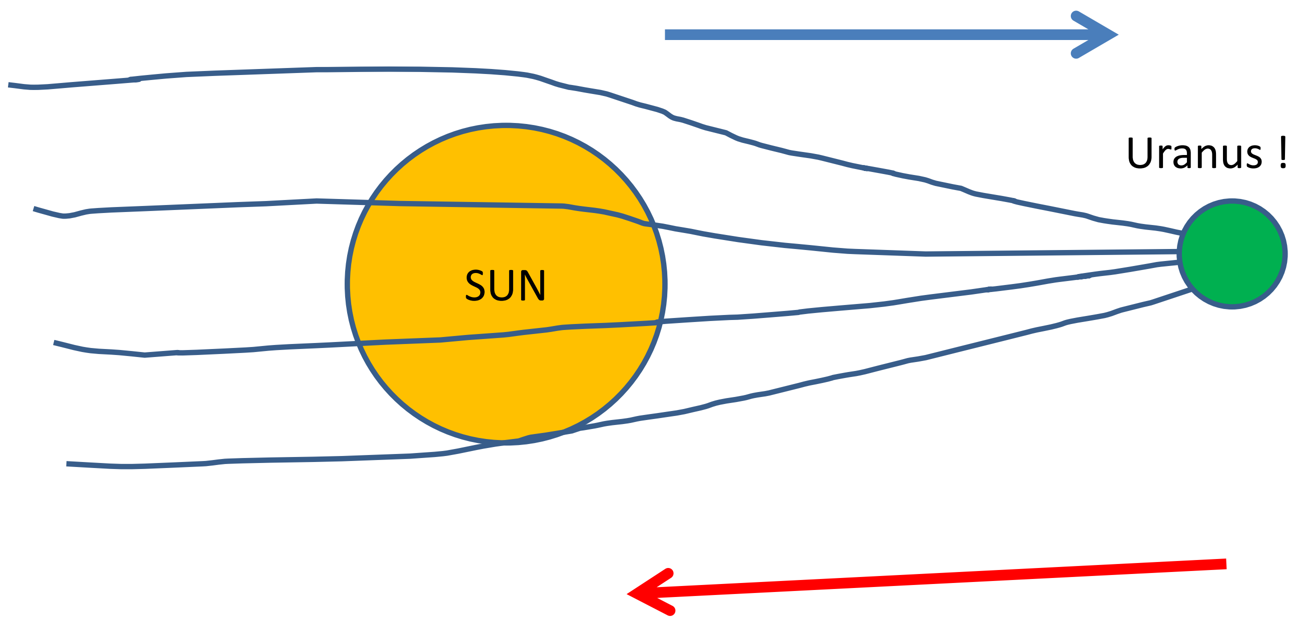
Exotica 1



Insights on neutrino lensing
R. Escribano jmf, D. Monderen, V. Van Elewyck (Brussels U.). **Phys.Lett. B512 (2001) 8-17**

# Just for the fun .. Neutrino lensing…

Stars are Gravitational lenses but bad lenses for light,
But can be good lenses for neutrinos !




Exotica2

*R. Escribano, J-M. F, D. Monderen, V. Van Elewyck*
*Phys.Lett. B512 (2001) 8-17*

Also binary star as « neutrino light house »