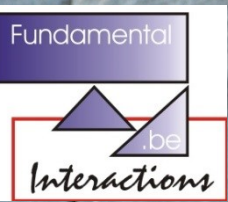


# Neutrino Magnetic moments vs Majorana

## Falsifying leptogenesis with $W_R$ (if time allows ...)



- 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

## Conjectures

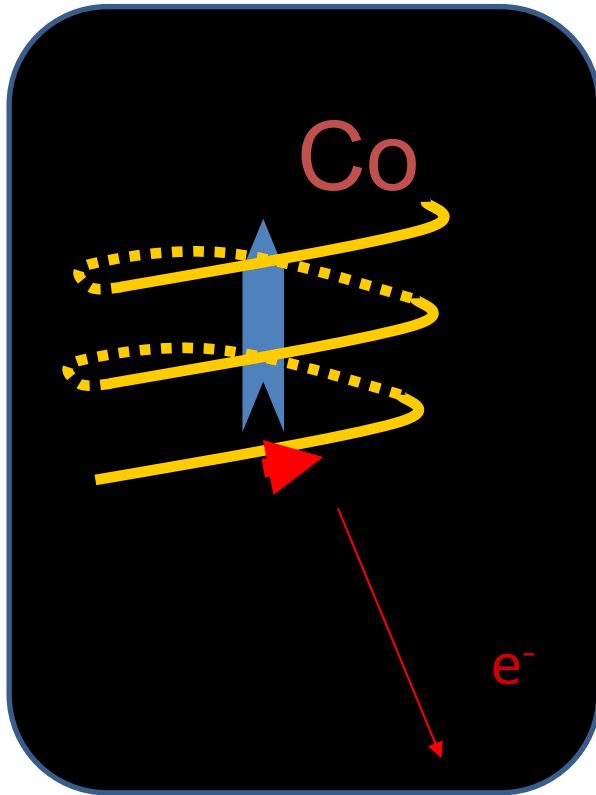
- *They might violate the **global** lepton number (neutrinoless double beta)*
- *they could explain the Defeat of Antimatter (leptogenesis)*
- *They suggest (via See-Saw or other) the presence of new particles, new scales, and could even accomodate extra dimensions*

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

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

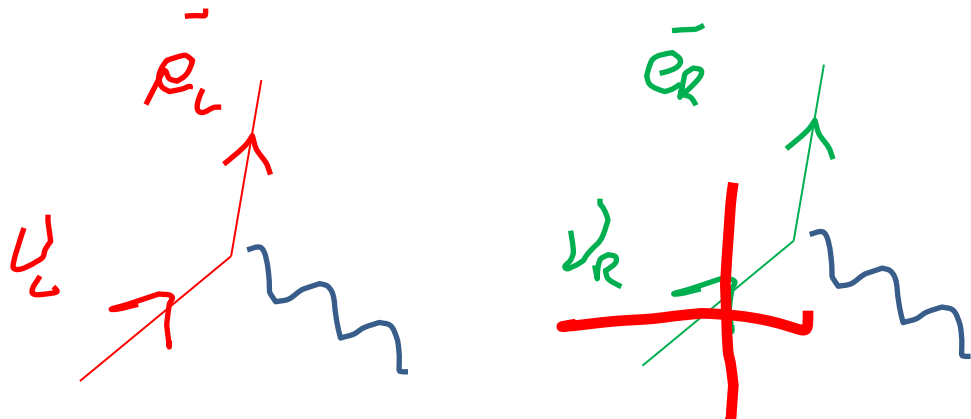
# Should neutrinos have been massless ?

*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 ..

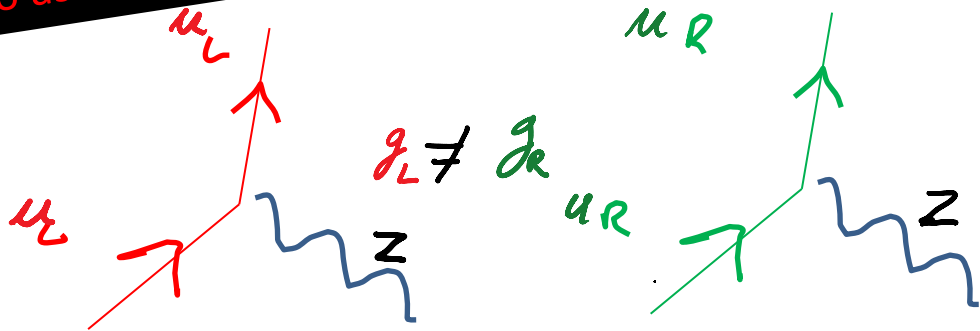
It is easy to explain if only left-handed electrons are produced in a charged vector current.



*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  $K \rightarrow 2 \pi$  and  $K \rightarrow 3 \pi$  (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!

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

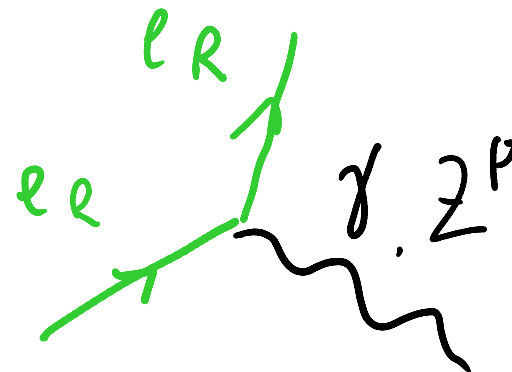
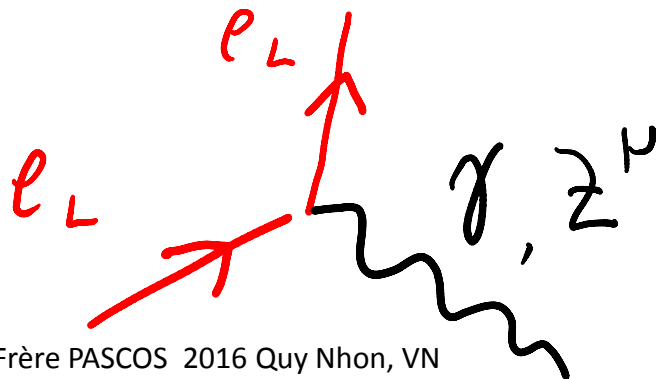
For questions of language, it is easier to speak of the electron + positron...

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

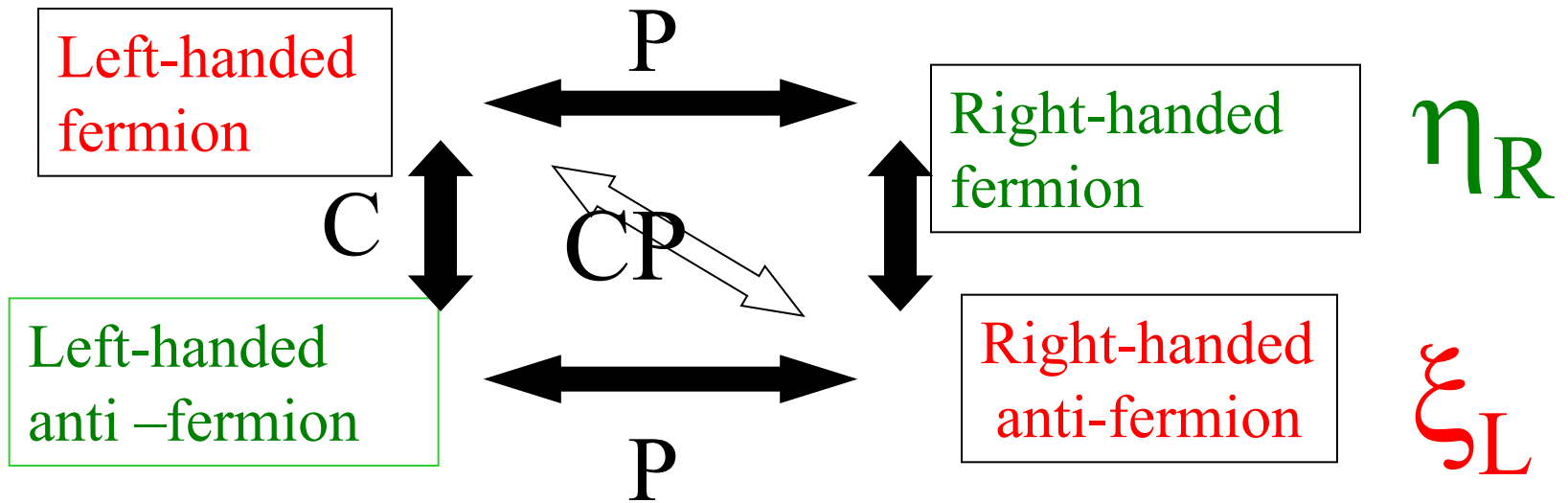
The Dirac spinor breaks down into 2 « Weyl » spinors,

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

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

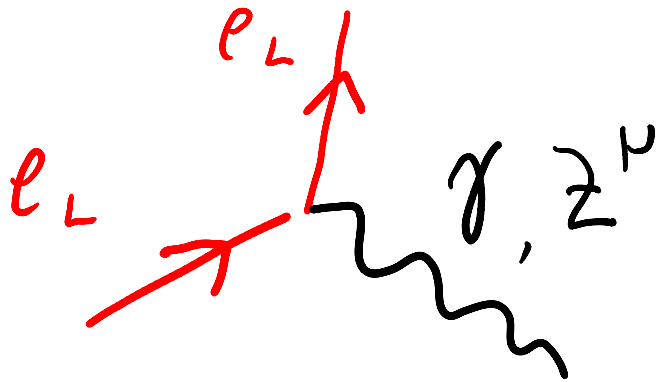






The simplest coupling only introduces the left-handed Weyl spinor, C and P are violated, but CP is conserved : this is THE symmetry of gauge interactions,

$\xi_L$



# 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

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

$$\begin{pmatrix} \Psi_L \\ 0 \end{pmatrix} = \begin{pmatrix} \Psi_{L1} \\ \Psi_{L2} \\ 0 \end{pmatrix} \begin{pmatrix} \xi_L \\ 0 \end{pmatrix}$$

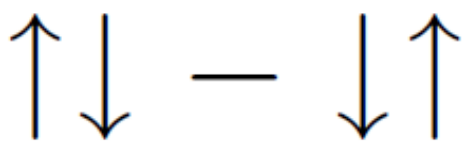
*We introduce here 2 spinors,  
We assume both to be L,  
(if not, perform a CP transformation)*

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!

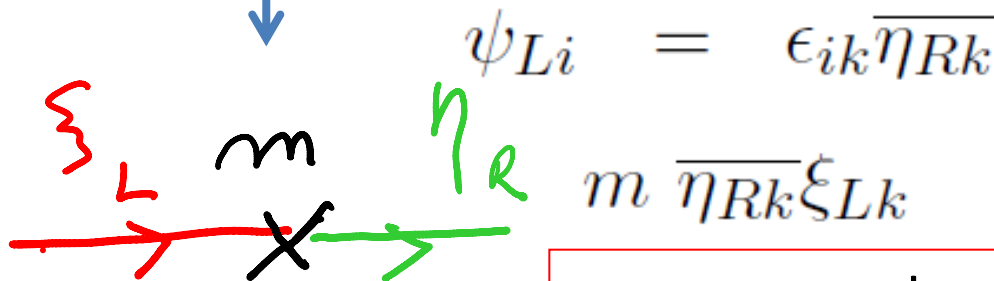


$$\psi_{L1}\xi_{L2} - \psi_{L2}\xi_{L1} = \epsilon_{ij} \psi_{Li}\xi_{Lj}$$



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

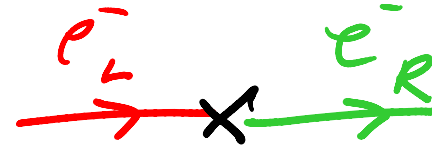
2 special cases :



« Dirac mass term »

If we can assign the same fermionic number to  $\eta$  and  $\xi$ ,  
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 neutrino, Majorana mass terms, but not of Majorana spinors...  
 In fact, they are not needed in 3+1 dim ... just another (confusing) notation

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

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

$$\psi^c = \psi$$



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

$$\begin{pmatrix} \psi_L \\ (\psi_L)_R^c \end{pmatrix}$$

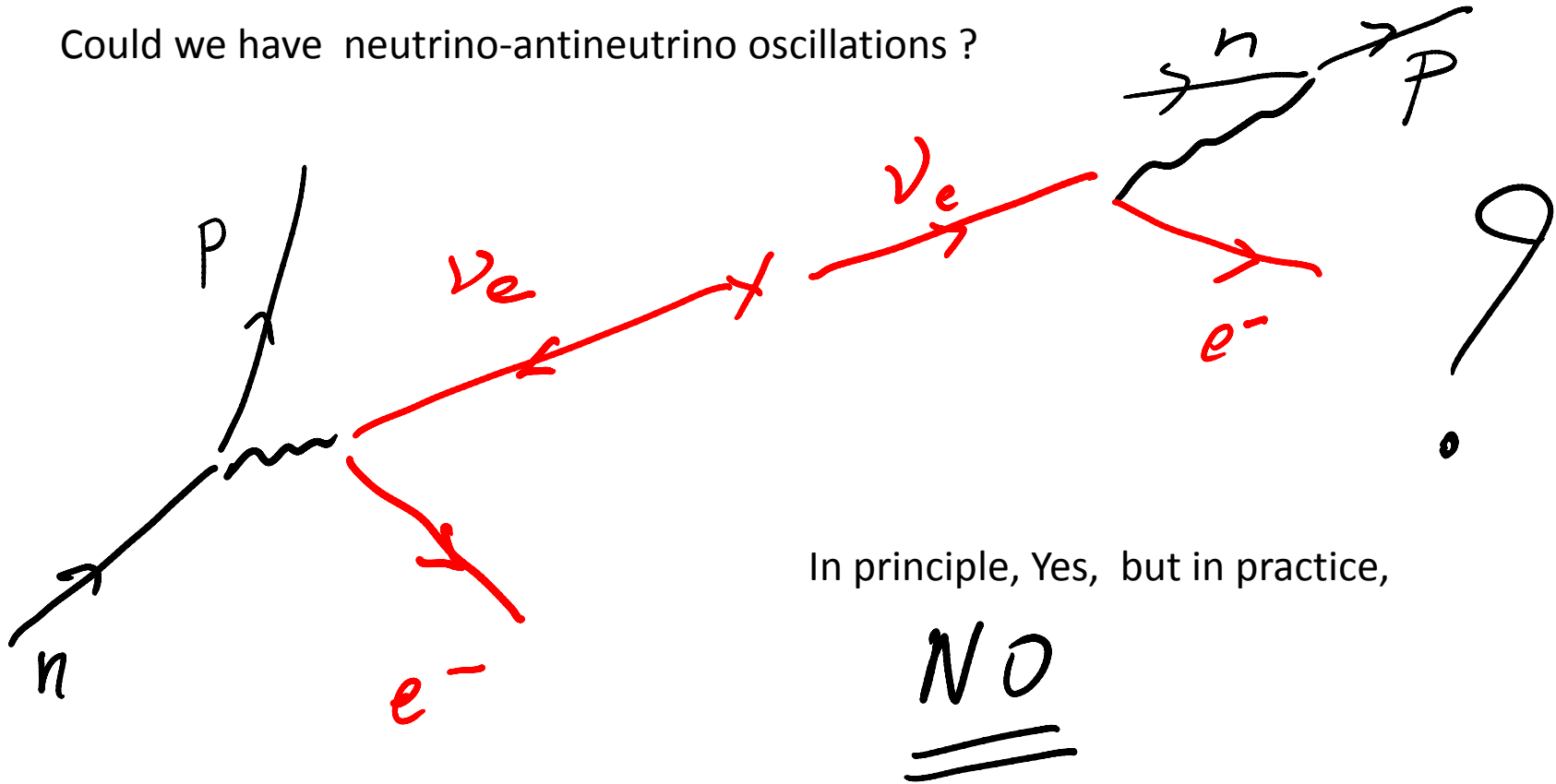
This is not true in more dimensions!

It is notoriously difficult to distinguish Weyl (Majorana) neutrinos from Dirac ones...  
Why ?

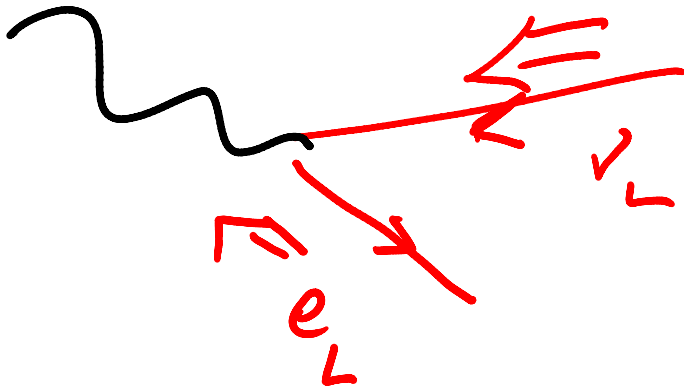
- NO observable neutrino-antineutrino oscillations, even in Weyl-Majorana case
- Cosmology does not help
- Neutrinoless double beta decay : a possibility ! (but nuclear physics uncertainties)
- Magnetic moments ??

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

Could we have neutrino-antineutrino oscillations ?

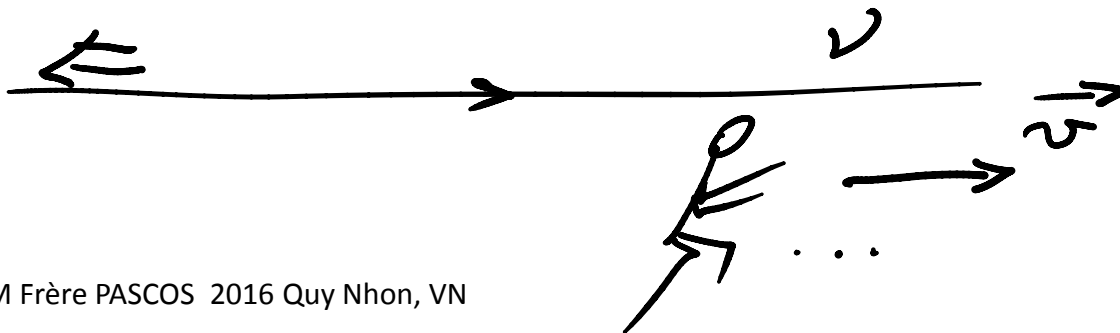


Even though the lepton number is not conserved, angular momentum suppresses this reaction

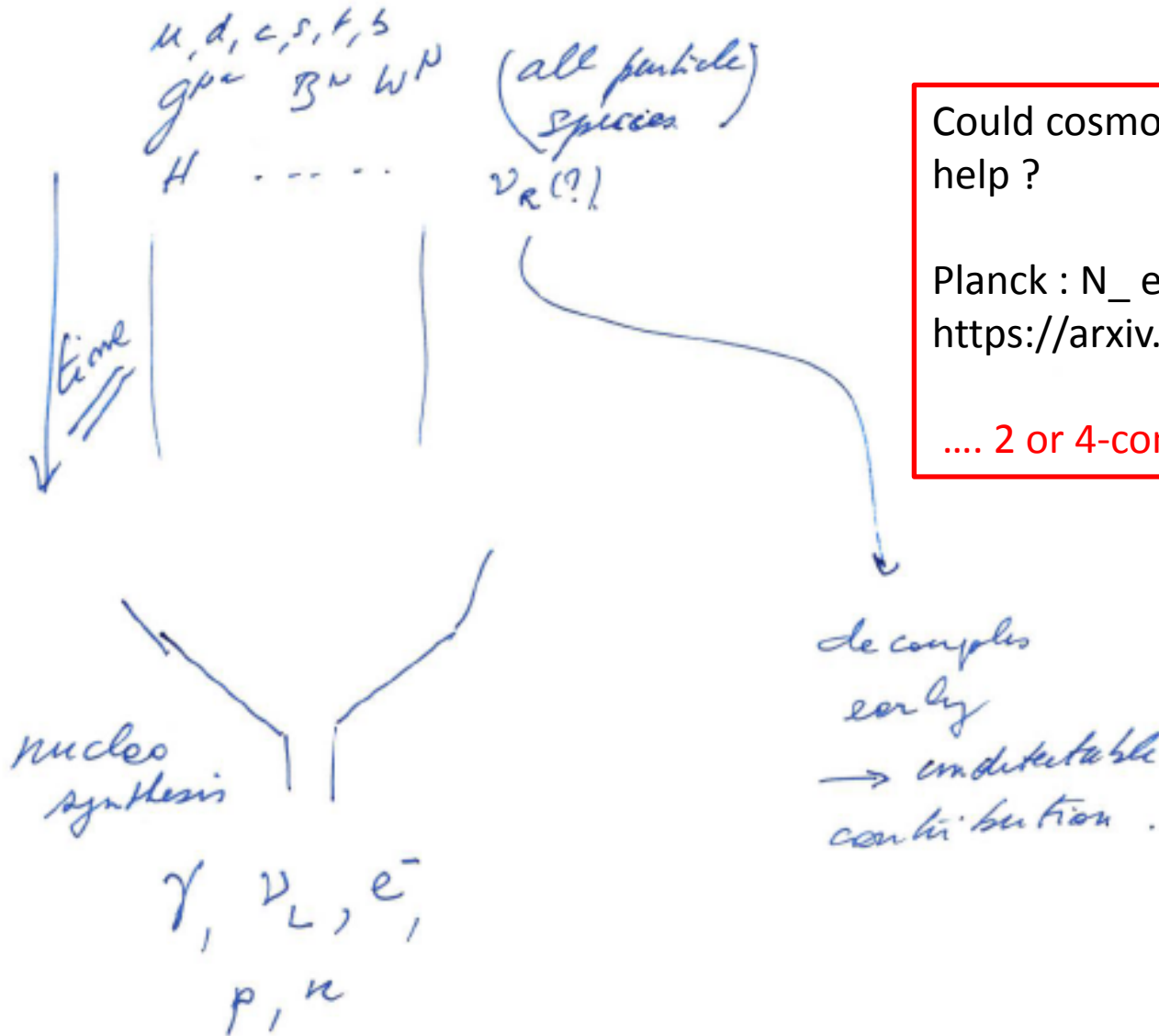


The  $\nu_L$  stays linked to  $e_L^-$ , and not to  $e_R^+$  by the  $W$ 's in the SM

*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 :  $N_{\text{eff}} = 3.15 \pm 0.23$

<https://arxiv.org/abs/1502.01589>

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

# Magnetic moments?

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

Is it a way to exclude Majorana masses?



# Magnetic moments?

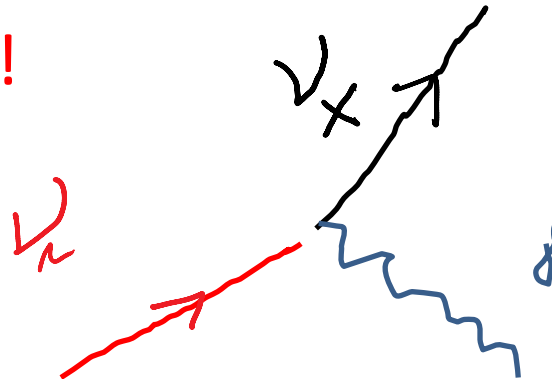
For ONE Weyl neutrino, a magnetic moment is forbidden by Fermi statistics ..

Is it a way to exclude Majorana masses?



**NO**, TRANSITION magnetic moments are still allowed ...

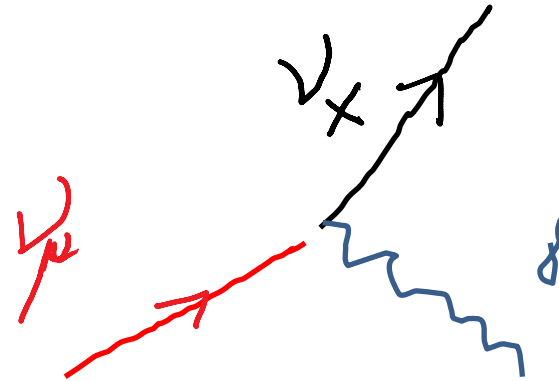
**and undistinguishable!**



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

In Weyl basis

effective  
moment  
for  $\nu_\mu$



$$\sqrt{|\mu_{e\mu}|^2 + |\mu_{\tau\mu}|^2} (\overline{\nu}_X^c \sigma_{\alpha\beta} \nu_\mu F^{\alpha\beta}),$$

$$\overline{\nu}_X^c \equiv \frac{(\mu_{e\mu} \overline{\nu}_e^c + \mu_{\tau\mu} \overline{\nu}_\tau^c)}{\sqrt{|\mu_{e\mu}|^2 + |\mu_{\tau\mu}|^2}}.$$

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  
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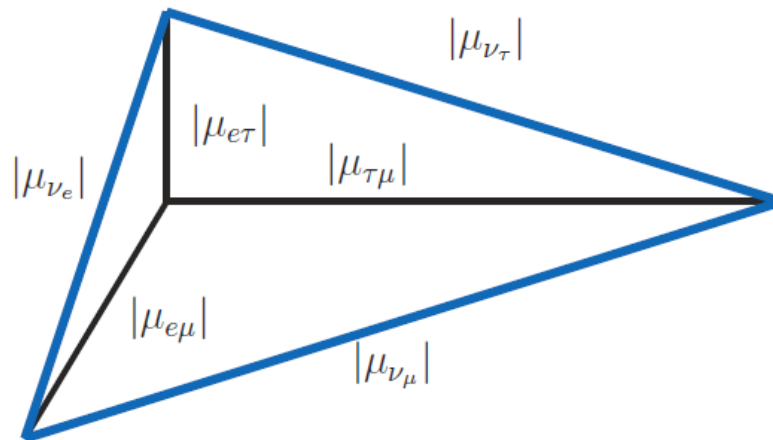


Figure 1:  $|\mu_{\nu_J}|$  forms a right triangle with  $|\mu_{IJ}|$  and  $|\mu_{KJ}|$  (for  $I \neq J \neq K$ ).  $|\mu_{\nu_{I,J,K}}|$  thus also form a triangle (shown in thick blue), in general not with right angles.

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  $> 90^\circ$ )  $||\mu_{\nu_J}| - |\mu_{\nu_K}|| \leq |\mu_{\nu_I}| \leq |\mu_{\nu_J}| + |\mu_{\nu_K}|$

Current limits (terrestrial)

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

Perspectives : SHiP (CERN SPS ) could improve considerably the  $\tau$  neutrino limit ...

## Current limits (terrestrial)

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

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

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

Hopeless for terrestrial measurements?

NO ...

if there is a 4th light (sterile) neutrino, with mass  $> \text{keV}$ ,  
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 !!!**

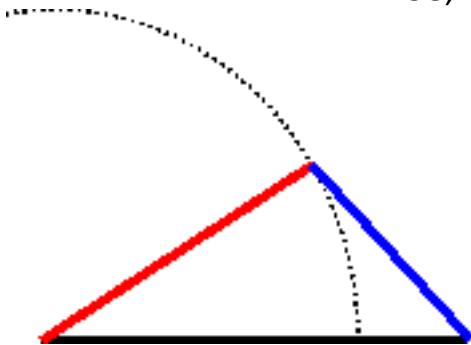
## Update ....

Borexino brings interesting new bounds (from « oscillated » Solar neutrinos)

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 the bounds)  $31.36 > 16 + 9.61$  .... is there hope to improve and get an actual check at the  $10^{-11}$  level?

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

« Double see-saw »

$$\mathbf{M}_\nu = \begin{pmatrix} \color{red}{\nu_L} & \color{green}{\nu_R} & \color{magenta}{\nu_S} \\ 0 & m & 0 \\ m^T & 0 & M^T \\ 0 & M & m_\sigma \end{pmatrix} \quad \xrightarrow{\text{2 singlets}}$$


$$m = \lambda v$$

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

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

*(remark : this is an example of « pseudo-Dirac »,  
 since  $\nu_R + \nu_S$  act as a Dirac pair, whose contributions to the light  
 neutrino compensate.)*

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

# What are Right-handed neutrinos good for?

## Baryogenesis via Leptogenesis



The DEFEAT of antimatter

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

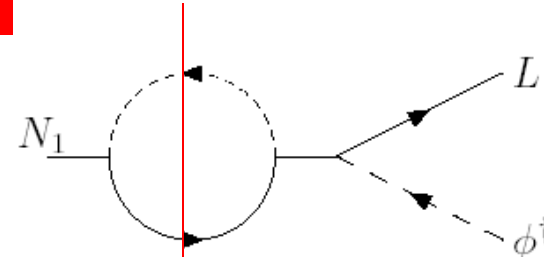
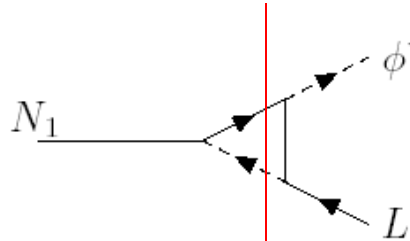
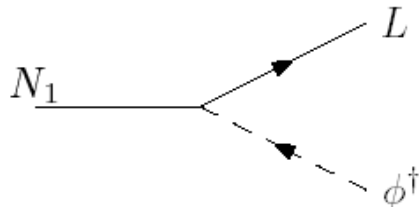
$\nu_R \rightarrow N_R$  from now on

# 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.*

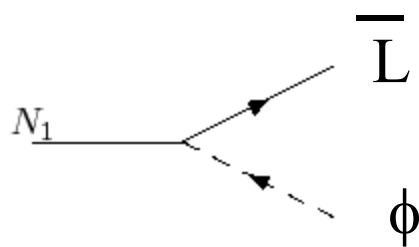
## Generation of lepton number

$L = +1$



$N$  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

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

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

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

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

$g^*$  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

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

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)

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

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

rough estimate of  $M$  scale  
(in GeV) needed...

similar to  $\tau$  lepton  $\longrightarrow$

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

$\lambda$	light neutrino .01 eV $M \sim$	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 inaccessible.

But ..

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

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

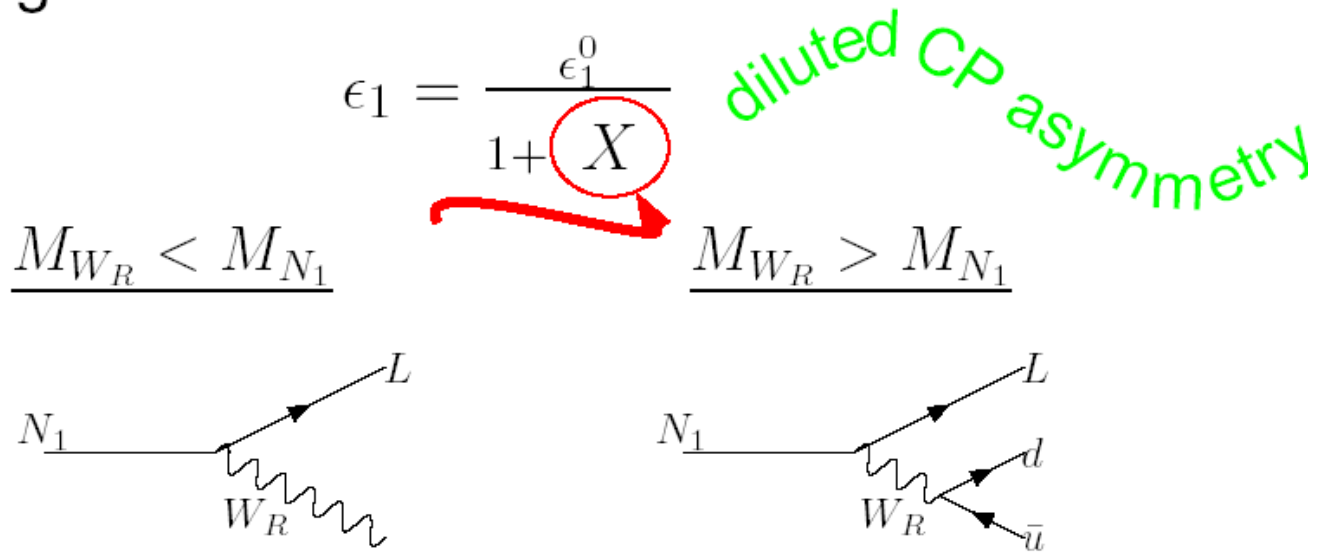
If so, gauge interactions dilute the lepton number asymmetry, possibly below the requested number for the baryon number of the Universe..

# Can leptogenesis be falsified ?

In general, no, since most mass ranges are inaccessible.

But .. Presence of  $\nu_R$  suggest a larger symmetry, like  $SO(10)$  or  $SU(2)_L \times SU(2)_R$

with the gauge inclusion



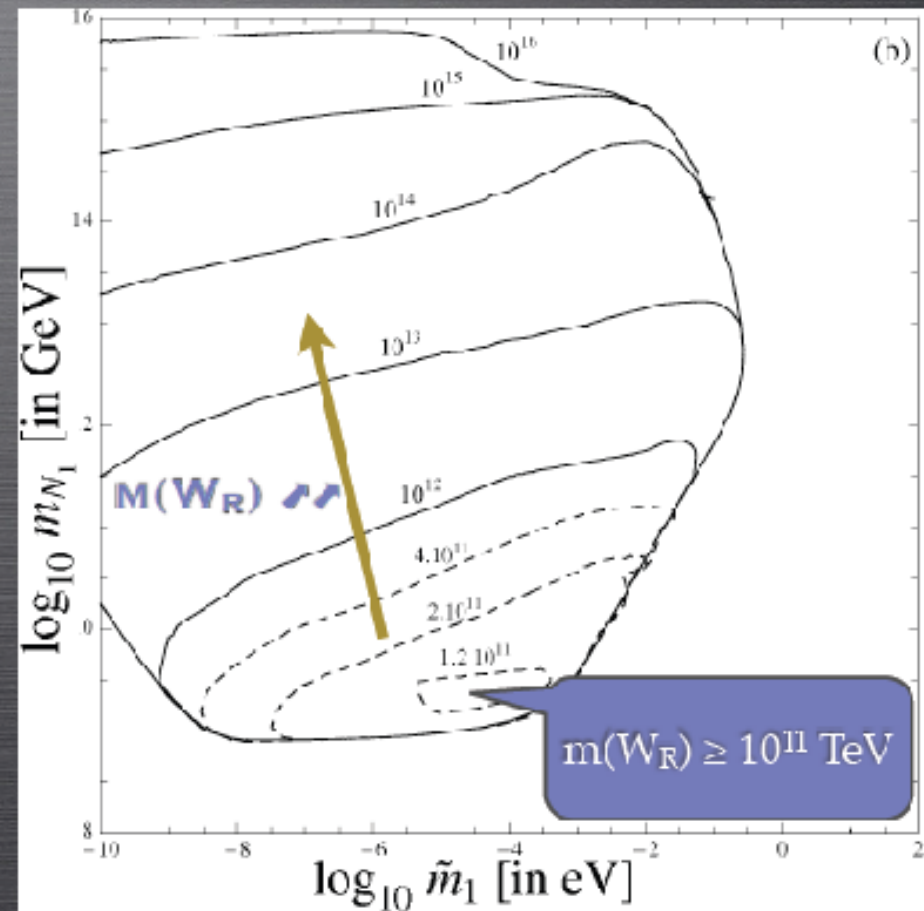
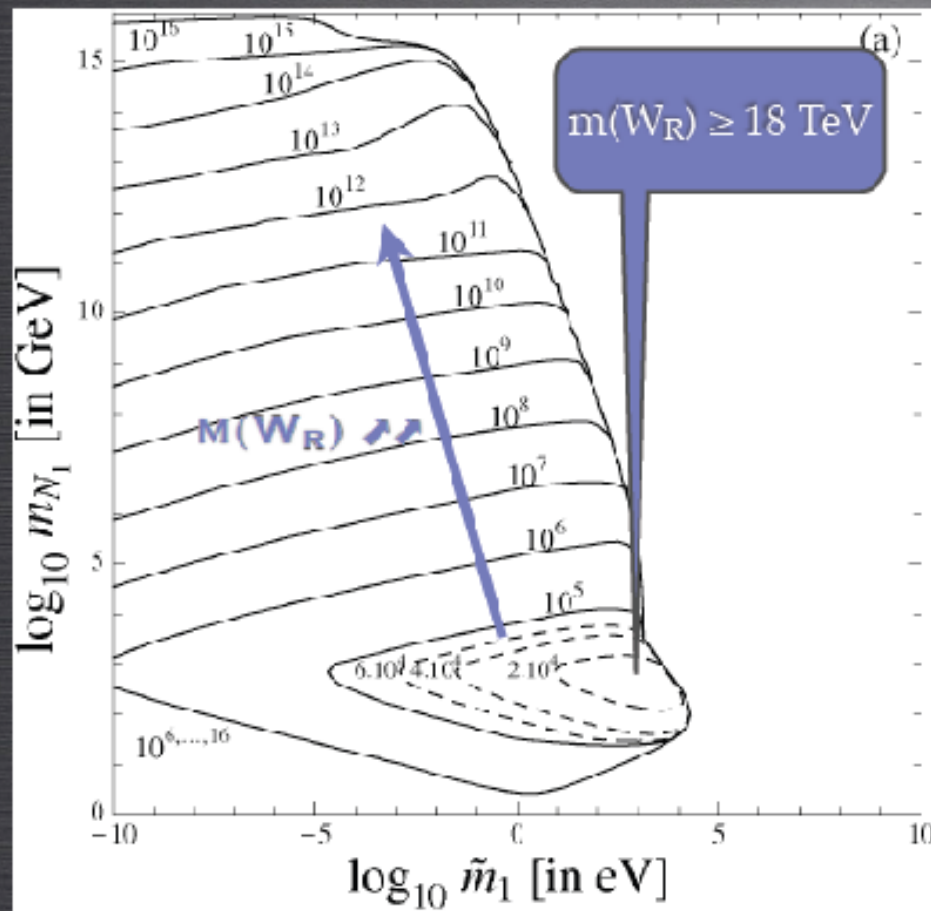
(competing effect : the presence of  $W_R$  allows a faster build-up of the N population after inflation)

S Carrier, 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  $\epsilon_{CP} = 1$

FOR  $\epsilon_{CP} = \epsilon_{DI}$



See T Hambye's talk

CAN LHC DISPROVE LEPTOGENESIS ?

Updates : see Dev, Lee, Mohapatra 2014 **Phys.Rev. D90 (2014) no.9, 095012**  
in case of strong cancellations, scales as low as 3 TeV could be accommodated  
**(but then, we can check for the presence of cancellations ...)**

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!!!

Back-up slides

## 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.

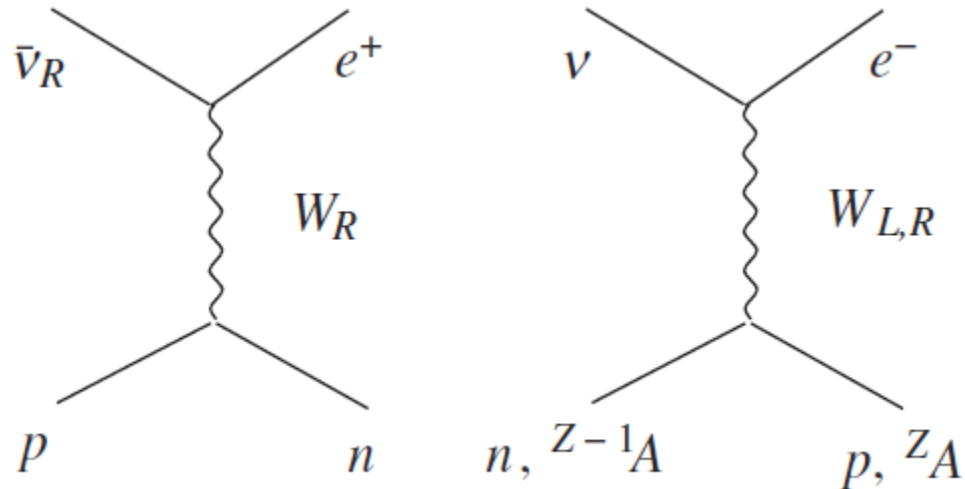
If light  $W_R$  present and  $\text{MeV} \ll \text{heavy neutrino}$   
Is a dark matter candidate,

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

→ Limits .. For  $m_R = 1 \text{ MeV}$  we obtain  $MR/ML > 10-20$

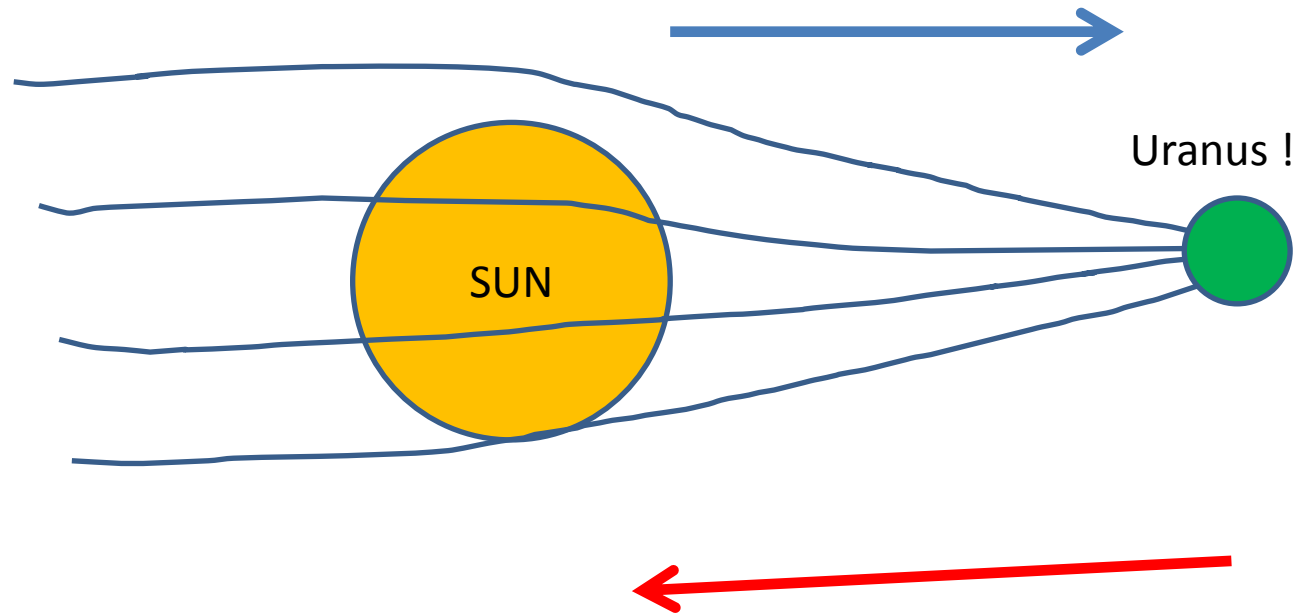
JMF, L Lopez-Honorez, E Nezri, S Swillens, G Vertongen, *Phys.Rev. D75 (2007) 085017* [hep-ph/0610240](https://arxiv.org/abs/hep-ph/0610240)

Exotica 1



## 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 »