Neutrinos and Leptogenesis in the Early Universe

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CERN

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Outline

1. The facts: neutrino masses and the baryon asymmetry

2. Neutrino masses and mixing

3. Leptogenesis

4. Low energy tests of leptogenesis ingredients

5. Is there a connection between low energy CPV and leptogenesis?

6. Conclusions

The facts

1. Neutrino oscillations (first evidence in 1998) imply: **neutrinos have mass and mix (CPV?)!**
This requires new physics BSM which might be lepton number violating.

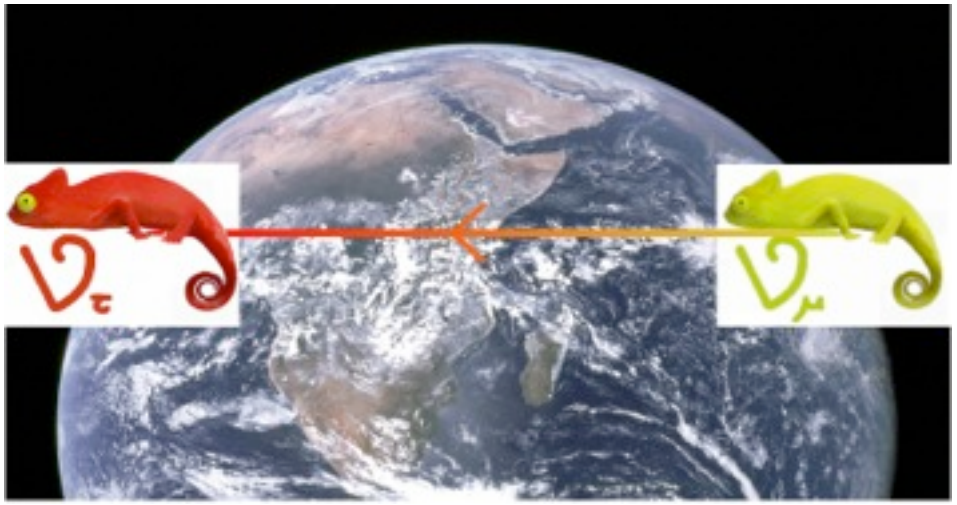
2. There is evidence of the baryon asymmetry:

$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.14 \pm 0.08) \times 10^{-10}$$

Planck, 1303.5076

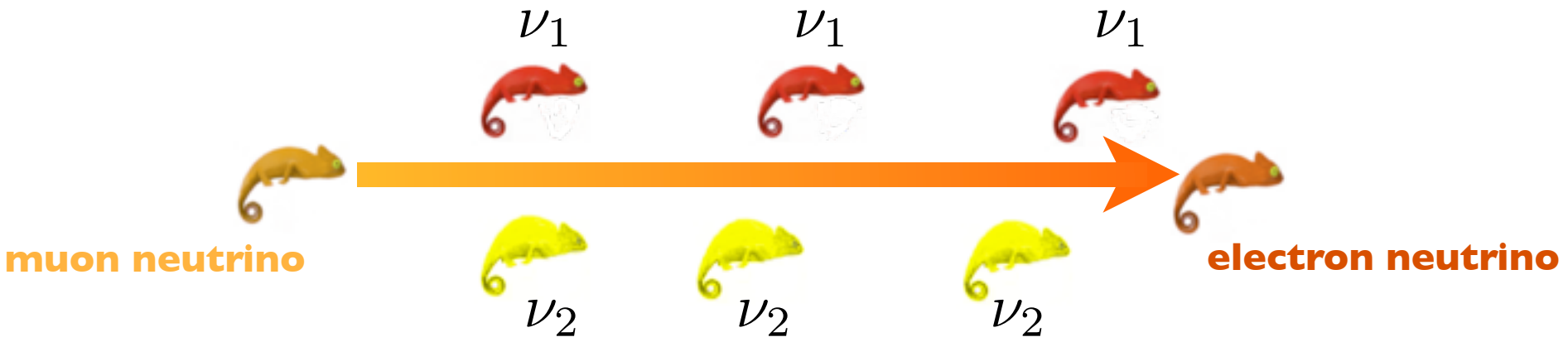
Is there a link between light neutrino physics and the baryon asymmetry?

Fact n. 1: Neutrinos oscillate



Contrary to what expected in the SM, neutrinos oscillate: after being produced, they can **change their "flavour"**. A flavour nu is a superposition of mass states.

Flavour states → $|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle$ ← Mass states



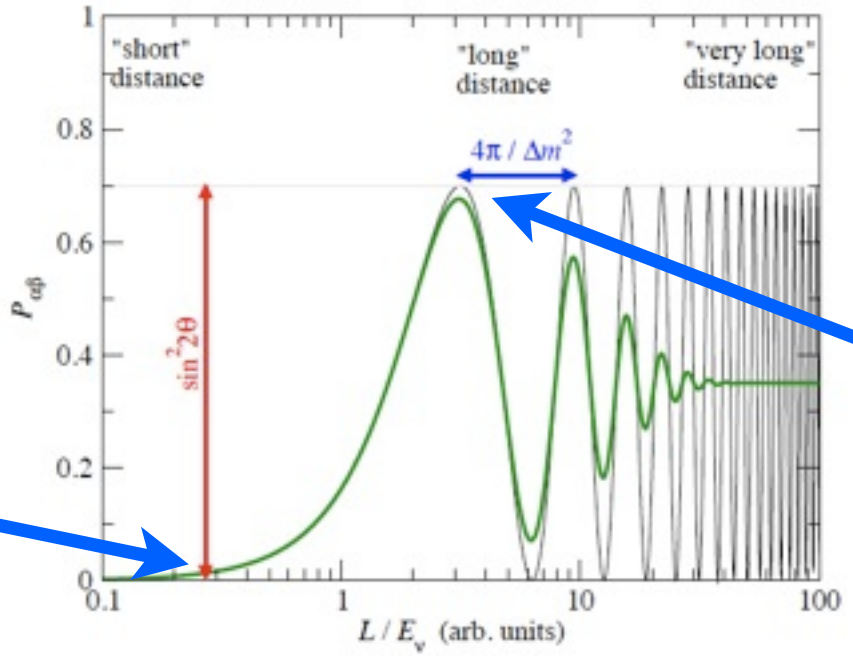
If their mass is different, they will evolve differently in time with their superposition corresponding to a different flavour neutrino.

The **probability** for a ν_μ to transform into a ν_e at a distance L from the source is:

$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta)\sin^2\frac{(m_2^2 - m_1^2)L}{4E}$$

Mixing angle between flavour and mass states

Neutrino masses



At small L no effect

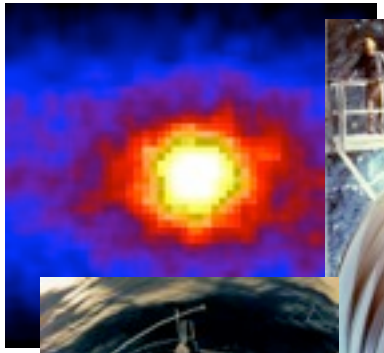
First oscillation maximum

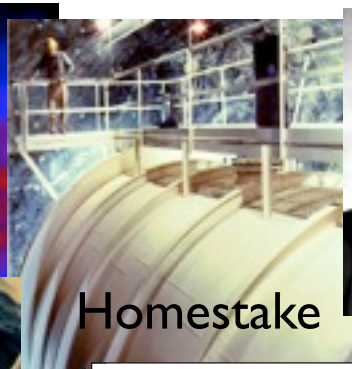
Thanks to T. Schwetz

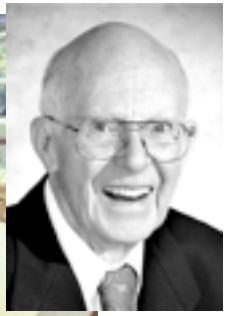
Neutrino oscillations imply that neutrinos have mass and they mix.
First evidence of physics beyond the SM.

A decade of exciting results

Solar neutrinos

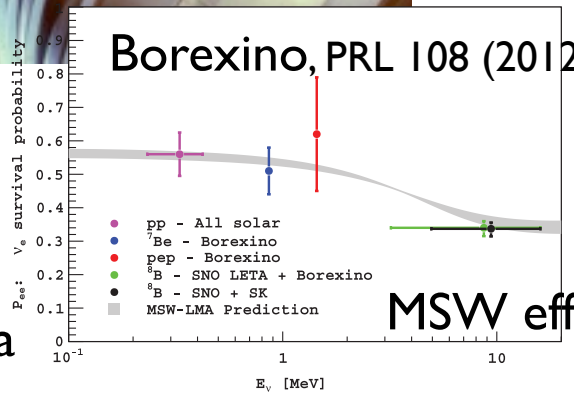






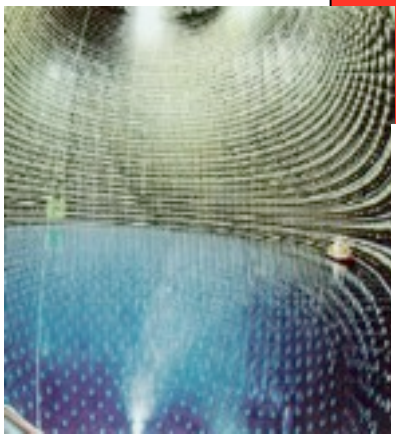
Homestake

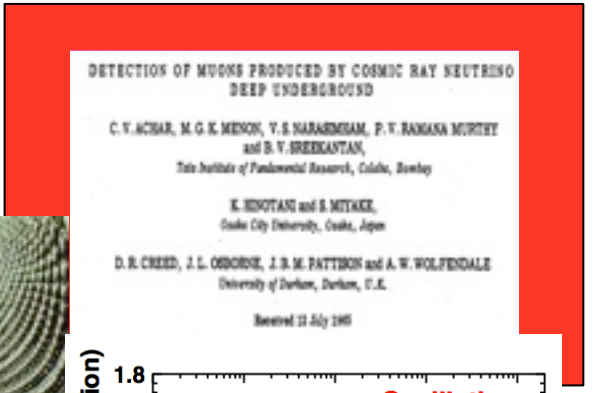
SNO, also Cl, Ga

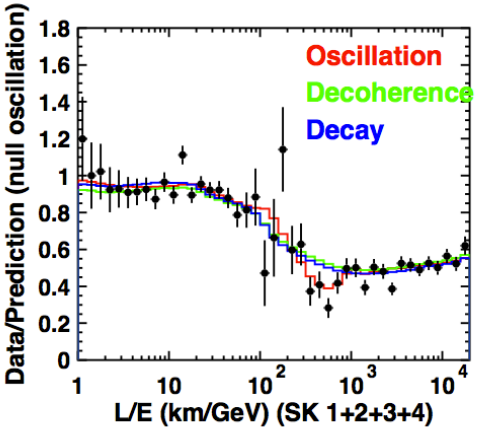


MSW effect

Atmospheric neutrinos

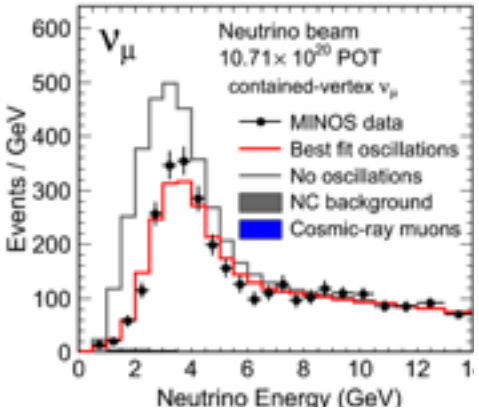


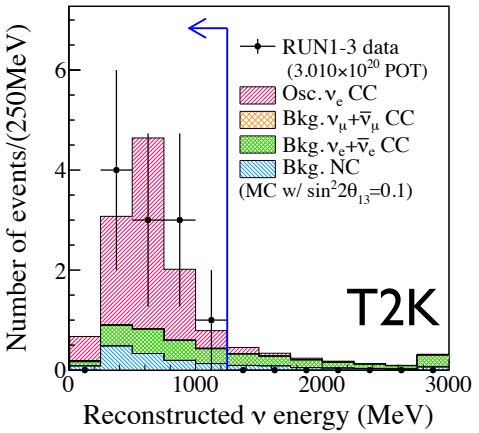




Super-Kamiokande, also MINOS

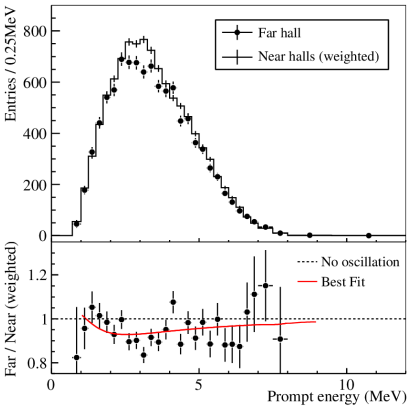
Accelerator neutrinos

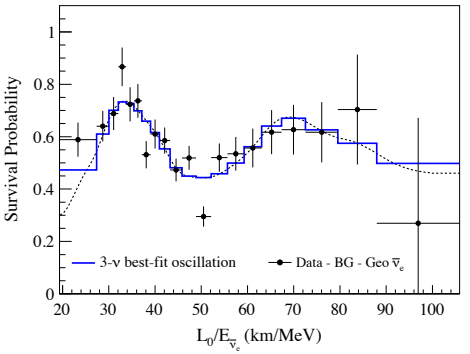




MINOS http://www-numi.fnal.gov

Reactor neutrinos

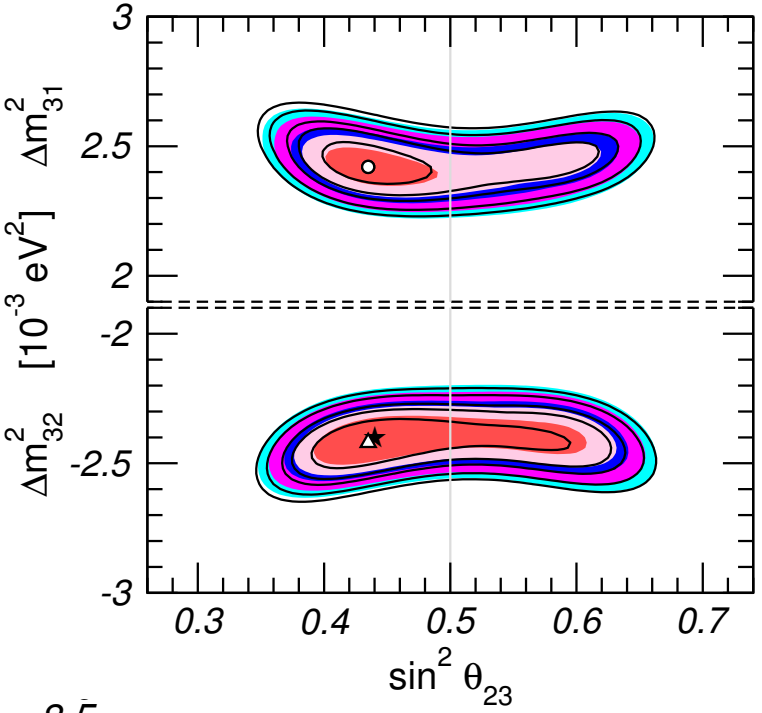


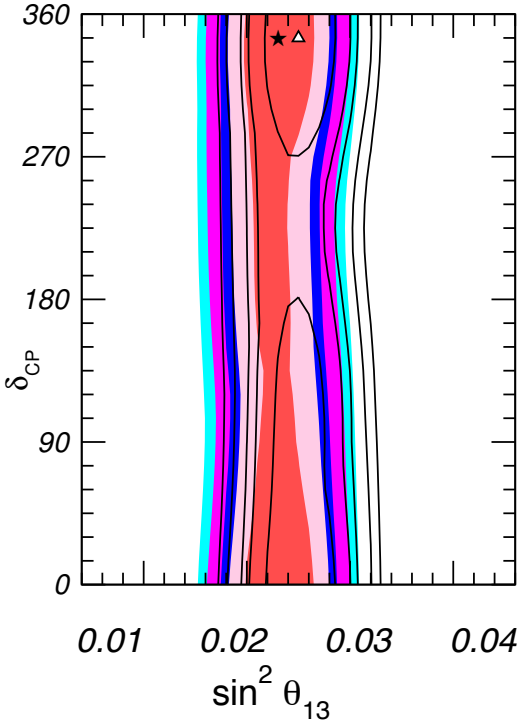


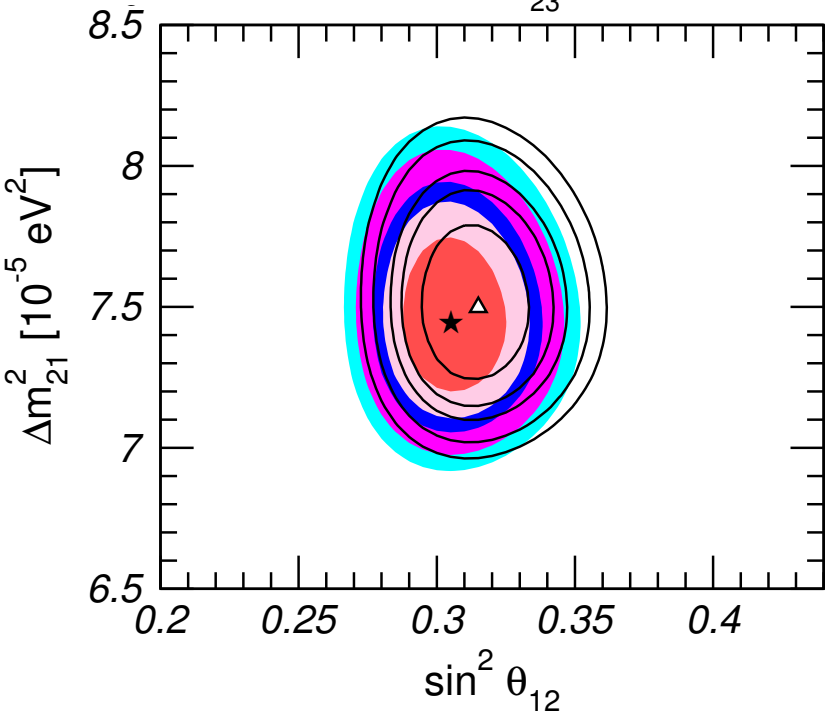
Daya Bay, PRL 108 (2012)
Also, RENO DoubleCHOOZ

KamLAND, 1303.4667

Current neutrino parameters







NuFit: M. C. Gonzalez-Garcia et al., 1209.3023

Global fit to neutrino oscillation data

www.invisibles.eu

All oscillation parameters are measured with good precision, except for the mass hierarchy and the delta phase. One needs to check the 3-neutrino paradigm (sterile neutrino?).

NuFIT 1.2 (2013)

	Free Fluxes + RSBL		Huber Fluxes, no RSBL	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.346$	$0.313^{+0.013}_{-0.012}$	$0.277 \to 0.355$
$\theta_{12}/^\circ$	$33.57^{+0.77}_{-0.75}$	$31.37 \to 36.01$	$34.02^{+0.79}_{-0.76}$	$31.78 \to 36.55$
$\sin^2\theta_{23}$	$0.446^{+0.008}_{-0.008} \oplus 0.593^{+0.027}_{-0.043}$	$0.366 \to 0.663$	$0.444^{+0.037}_{-0.031} \oplus 0.592^{+0.028}_{-0.042}$	$0.361 \to 0.665$
$\theta_{23}/^\circ$	$41.9^{+0.5}_{-0.4} \oplus 50.3^{+1.6}_{-2.5}$	$37.2 \to 54.5$	$41.8^{+2.1}_{-1.8} \oplus 50.3^{+1.6}_{-2.5}$	$36.9 \to 54.6$
$\sin^2\theta_{13}$	$0.0231^{+0.0019}_{-0.0019}$	$0.0173 \to 0.0288$	$0.0244^{+0.0019}_{-0.0019}$	$0.0187 \to 0.0303$
$\theta_{13}/^\circ$	$8.73^{+0.35}_{-0.36}$	$7.56 \to 9.77$	$9.00^{+0.35}_{-0.36}$	$7.85 \to 10.02$
$\delta_{CP}/^\circ$	266^{+55}_{-63}	$0 \to 360$	270^{+77}_{-67}	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.45^{+0.19}_{-0.16}$	$6.98 \to 8.05$	$7.50^{+0.18}_{-0.17}$	$7.03 \to 8.08$
$\frac{\Delta m^2_{31}}{10^{-3}\ \mathrm{eV}^2}$ (N)	$+2.417^{+0.014}_{-0.014}$	$+2.247 \to +2.623$	$+2.429^{+0.055}_{-0.054}$	$+2.249 \to +2.639$
$\frac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2}$ (I)	$-2.411^{+0.062}_{-0.062}$	$-2.602 \to -2.226$	$-2.422^{+0.063}_{-0.061}$	$-2.614 \to -2.235$

2 mass squared differences

M. C. Gonzalez-Garcia et al., 1209.3023

Masses are much smaller than the other fermions.

There are two possible orderings:

normal (m1<m2<m3) and inverted (m3<m1<m2).

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3 sizable mixing angles

M. C. Gonzalez-Garcia et al., 1209.3023

Mixing is described by the Pontecorvo-Maki-Nakagawa-Sakata matrix, which enters in the CC interactions.

Mixing angles are much larger than in the quark sector.

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M. C. Gonzalez-Garcia et al., 1209.3023

CP-violation? This phase enters in neutrino oscillations.

There are 2 other phases, if neutrinos are Majorana.

Fact n. 2: the baryon asymmetry. The theory

In order to generate dynamically a baryon asymmetry, the Sakharov's conditions need to be satisfied:

- B (or L) violation;

- C, CP violation;

- departure from thermal equilibrium.

See also, Mohapatra's, Pilaftsis', Sarkar's, Mukhopadhyay's talks

Fact n. 2: the baryon asymmetry. The theory

In order to generate dynamically a baryon asymmetry, the Sakharov's conditions need to be satisfied:

- B (or L) violation;

In the SM also L is violated at the non-perturbative level. A lepton asymmetry is converted into a baryon asymmetry by sphaleron effects.

If neutrinos are Majorana particles, L is violated.

See-saw models require L violation (typically the Majorana mass of a heavy right-handed neutrino).
In SUSY models without R-parity, L can be violated and neutrino masses generated.

Fact n. 2: the baryon asymmetry. The theory

In order to generate dynamically a baryon asymmetry, the Sakharov's conditions need to be satisfied:

- C, CP violation;

If C were conserved:

$$\Gamma(X^c \to Y^c + B^c) = \Gamma(X \to Y + B)$$

and no baryon asymmetry generated:

$$\frac{dB}{dt} \propto \Gamma(X^c \to Y^c + B^c) - \Gamma(X \to Y + B)$$

We have observed CPV in quark sector (too small) and we can search for it in the leptonic sector.

Fact n. 2: the baryon asymmetry. The theory

In order to generate dynamically a baryon asymmetry, the Sakharov's conditions need to be satisfied:

- out of equilibrium

In equilibrium

$$\Gamma(X \to Y + B) = \Gamma(Y + B \to X)$$

A generated baryon asymmetry is cancelled exactly by the antibaryon asymmetry.
When particles get out of equilibrium, this does not happen.

$$T < M_X$$

A successful model of baryogenesis:

Leptogenesis in models at the origin of neutrino masses

Neutrino masses BSM

Neutrino Masses in the Standard Model

In the SM, neutrinos do not acquire a mass and mixing:

- like the other fermions as there are no right-handed neutrinos.

$$m_e \bar{e}_L e_R \qquad\qquad m_\nu \bar{\nu}_L \nu_R$$

Solution: Introduce ν_R for Dirac masses

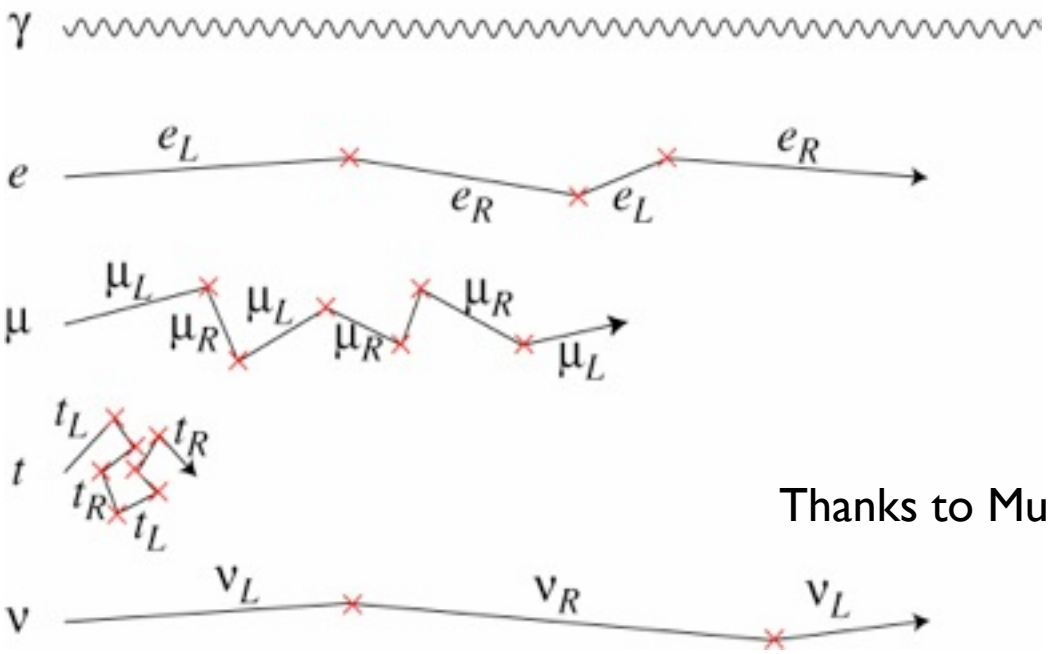
- they do not have a Majorana mass term

$$M \nu_L^T C \nu_L$$

as this term breaks the SU(2) gauge symmetry.
Solution: Introduce an SU(2) scalar triplet or gauge invariant non-renormalisable terms (D>4).

Dirac Masses

Neutrino masses in the sub-eV range cannot be explained naturally within the SM. If neutrinos had the same interactions with the Higgs as the top quark, they would be **100000000000** times heavier!



Thanks to Murayama

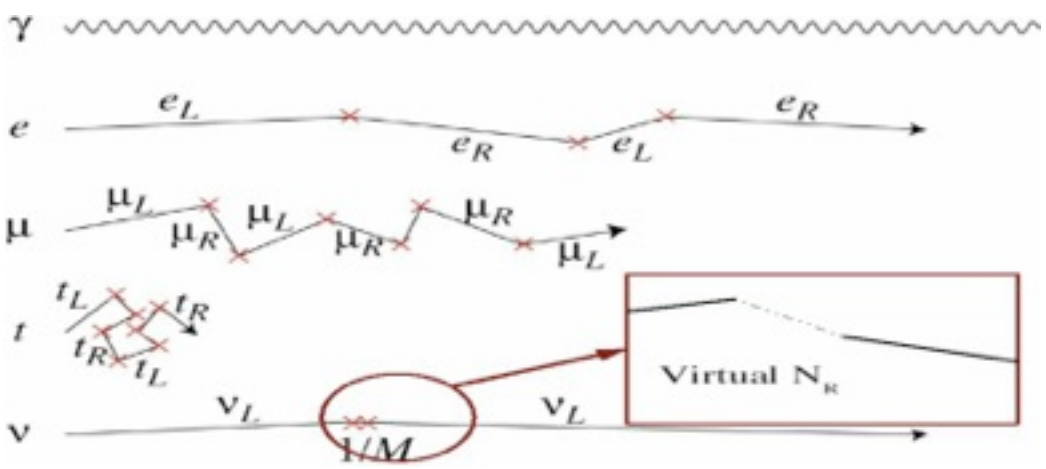
$$\mathcal{L} = -y_\nu \bar{L} \cdot \tilde{H} \nu_R + \text{h.c.}$$

$$y_\nu \sim \frac{\sqrt{2} m_\nu}{v_H} \sim \frac{0.2 \text{ eV}}{200 \text{ GeV}} \sim 10^{-12}$$

Many theorists consider this explanation of neutrino masses unnatural, unless an explanation can be given for the extreme smallness of the coupling.

Majorana Masses

In order to have an SU(2) invariant mass term for neutrinos, it is necessary to introduce a Dimension 5 operator (or to allow for new scalar fields, e.g. a scalar triplet):



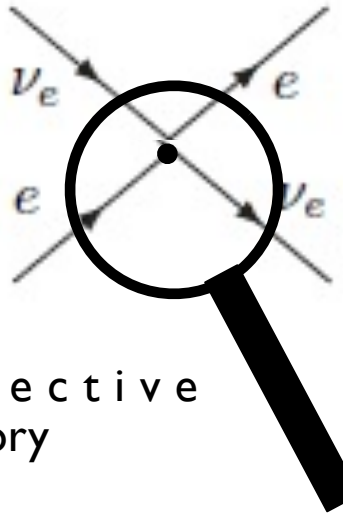
Thanks to
H. Murayama

D=5 term

$$-\mathcal{L} = \lambda \frac{\nu_L H \, \nu_L H}{M} = \frac{\lambda v^2}{M} \nu_L^T C \nu_L$$

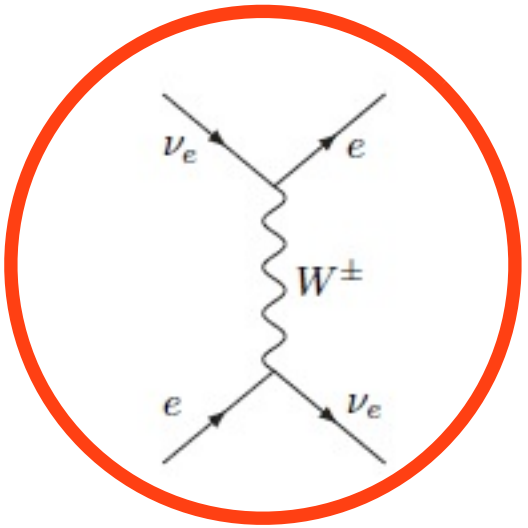
Lepton number violation!

If neutrino are Majorana particles, a **Majorana mass** can arise as the **low energy realisation of a higher energy theory (new mass scale!)**.



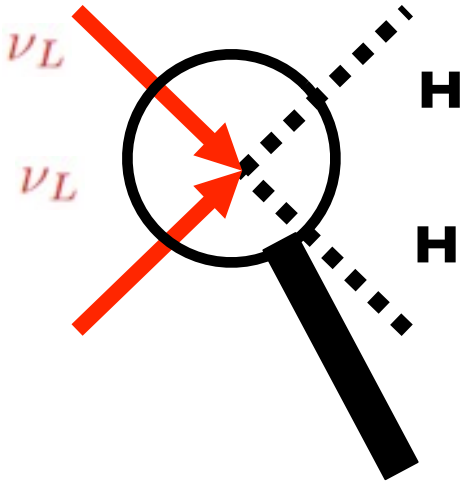
effective theory

$$\mathcal{L} \propto G_F(\bar{e}_L\gamma_\mu\nu_L)(\bar{\nu}_L\gamma^\mu e_L)$$



Standard Model: W exchange

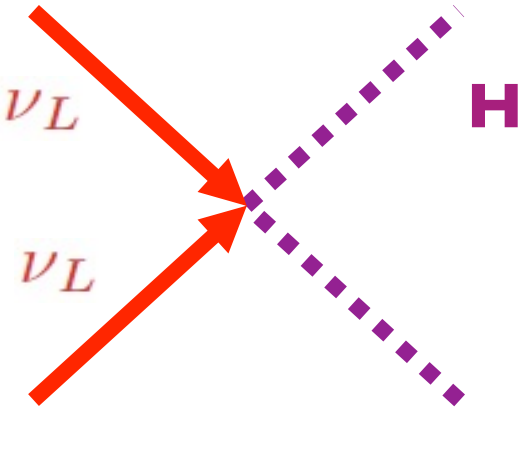
$$\mathcal{L}_{SM} \propto g\bar{\nu}_L\gamma^\mu e_L W_\mu \Rightarrow G_F \propto \frac{g^2}{m_W^2}$$



Neutrino mass

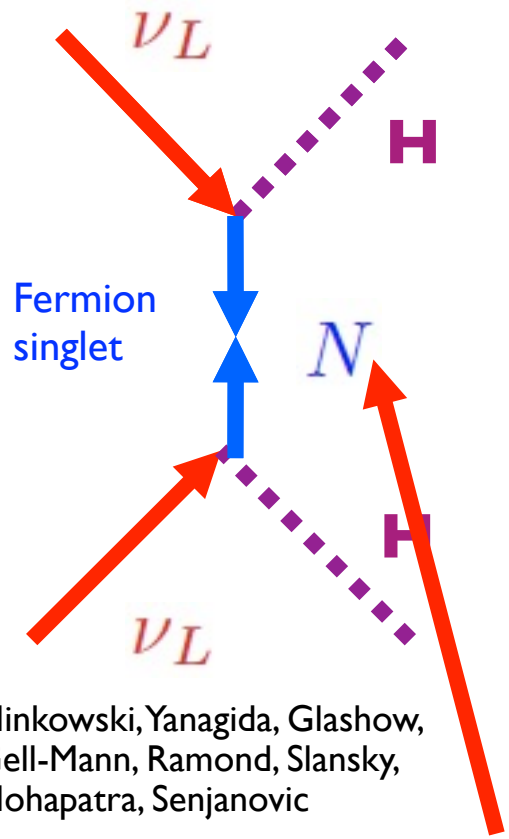
$$-\mathcal{L} = \lambda\frac{\nu_L H\,\nu_L H}{M} = \frac{\lambda v^2}{M}\nu_L^T C\nu_L$$

New theory: new particle exchange with mass M



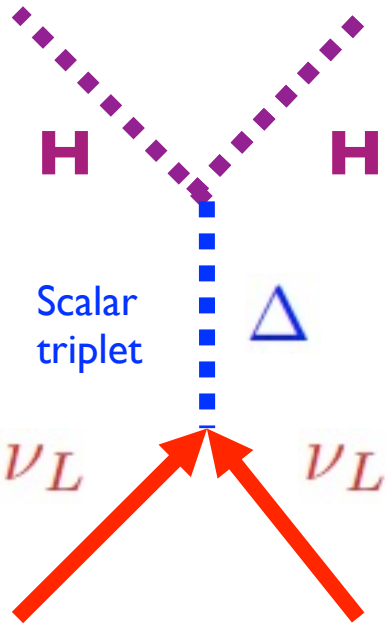
$$\frac{\nu_L H\ \nu_L H}{\Lambda}$$

See-saw Type I



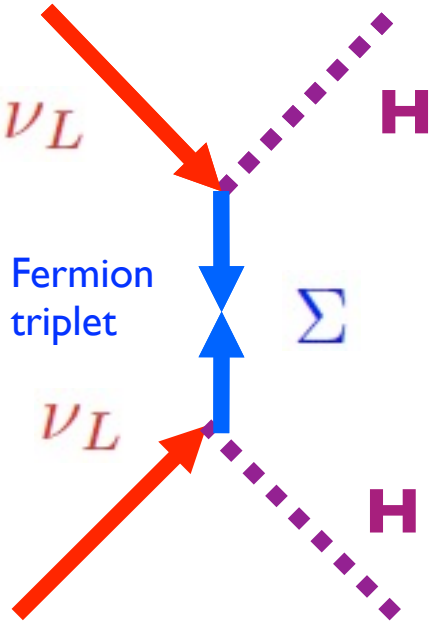
Minkowski, Yanagida, Glashow, Gell-Mann, Ramond, Slansky, Mohapatra, Senjanovic

See-saw Type II



Magg, Wetterich, Lazarides, Shafi. Mohapatra, Senjanovic, Schecter, Valle

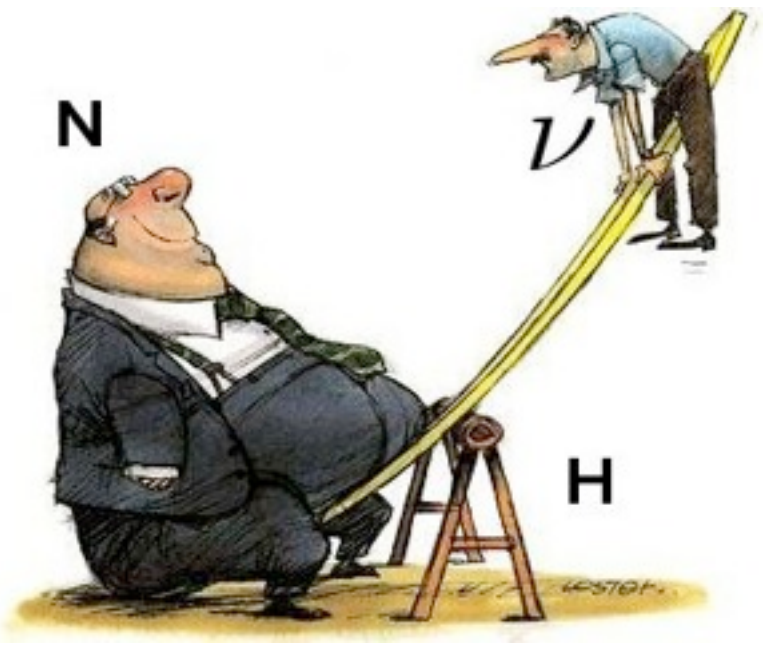
See-saw Type III



Ma, Roy, Senjanovic, Hambye

Sterile neutrino

The simplest see saw mechanism: type I



- Introduce a right handed neutrino **N (sterile neutrino)**
- Couple it to the Higgs and left handed neutrinos

$$\mathcal{L} = -Y_\nu \bar{N} L \cdot H - 1/2 \bar{N}^c M_R N$$

When the Higgs gets a vev:

$$\mathcal{L} = \left(\nu_L^T N^T\right) \begin{pmatrix} 0 & m_D \\ m_D^T & M \end{pmatrix} \begin{pmatrix} \nu_L \\ N \end{pmatrix}$$

$$m_\nu \simeq \frac{m_D^2}{M} \sim \frac{1\,\mathrm{GeV}^2}{10^{10}\,\mathrm{GeV}} \sim 0.1\,\mathrm{eV}$$

The light neutrino acquires a tiny mass!

Leptogenesis

At T>M, the right-handed neutrinos N are in equilibrium thanks to the processes which produce and destroy them:

$$N \leftrightarrow \ell H$$

When T<M, N drops out of equilibrium

$$N \rightarrow \ell H$$

A lepton asymmetry can be generated if

$$\Gamma(N \rightarrow \ell H) \neq \Gamma(N \rightarrow \ell^c H^c)$$

Sphalerons convert it into a baryon asymmetry.

Fukugita, Yanagida, PLB 174; Covi, Roulet, Vissani; Buchmuller, Plumacher; Abada et al., ...

In order to compute the baryon asymmetry:

1. evaluate the CP-asymmetry

$$\epsilon \equiv \frac{\Gamma(N \to \ell H) - \Gamma(N^c \to \ell^c H^c)}{\Gamma(N \to \ell H) + \Gamma(N^c \to \ell^c H^c)}$$

2. solve the Boltzmann equations to take into account the wash-out of the asymmetry

$$Y_L = k\epsilon$$

3. convert the lepton asymmetry into the baryon one

$$Y_B = \frac{k}{g^*} c_s \epsilon \sim 10^{-3} - 10^{-4} \epsilon$$

For T < 10^{12} GeV, flavour effects are important.

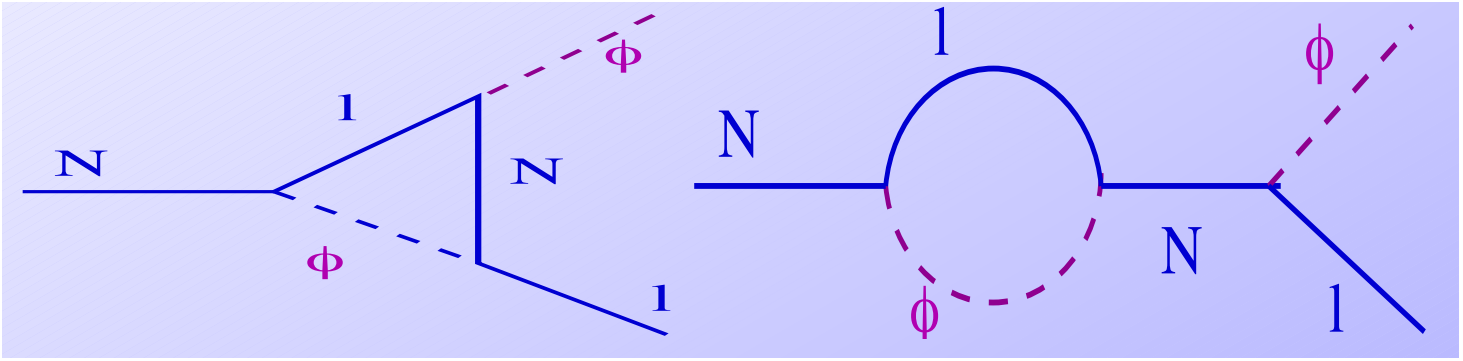
See also Pilaftsis' talk

Leptogenesis at the TeV scale

It is possible to lower the scale of leptogenesis.

Resonant leptogenesis in see saw type I

If the right-handed neutrinos are nearly degenerate, there is a resonant enhancement of the asymmetry.



Flanz et al.; Pilaftsis, Underwood.....

Leptogenesis in see-saw type II

The asymmetry comes from the scalar triplet decays.

Can we test Leptogenesis?

First of all, we can look for the ingredients needed:

- L violation

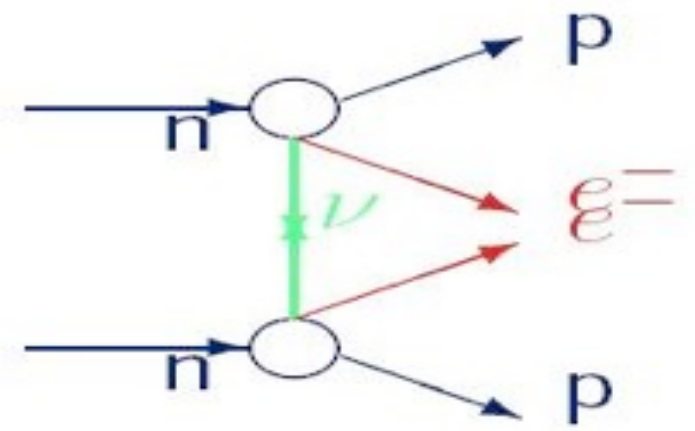
- CP violation

- out of equilibrium V

expansion of the Universe

Lepton number violation?

- At low energy, **neutrinoless double beta decay,** (A, Z) → (A, Z+2) + 2 e



- LNV tau and meson decays (requires masses in the 100s MeVs-GeV range)

- LNV at colliders (if masses in the 10s GeV-TeV range)

Neutrinoless double beta decay

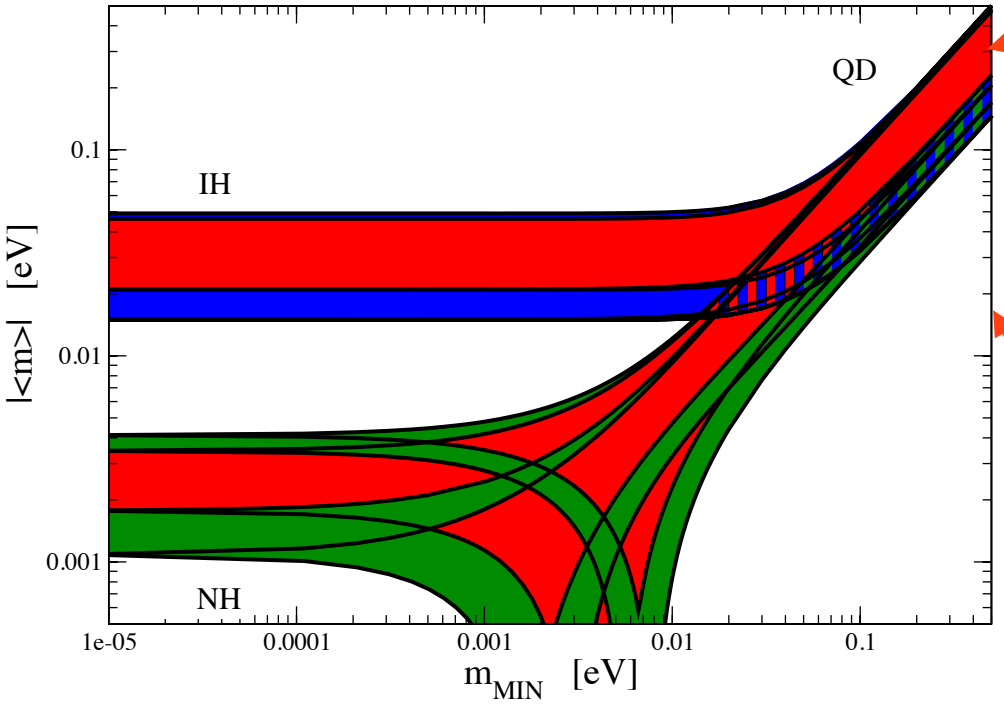
The half-life time depends on neutrino properties

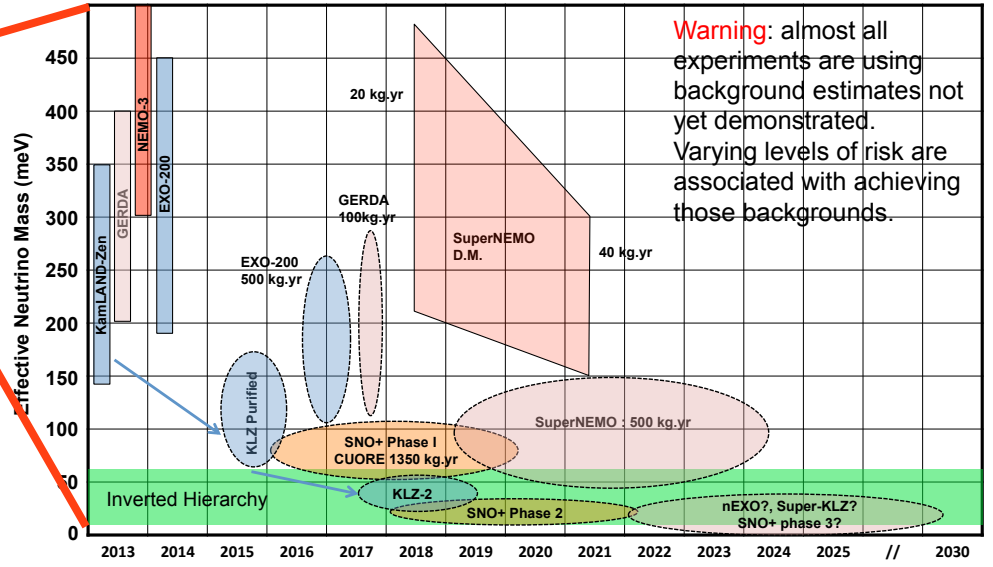
$$\left[T^{1/2}_{0\nu}(0^+ \rightarrow 0^+)\right]^{-1} \propto |M_F - g_A^2 M_{GT}|^2 \, |<m>|^2$$

$$|\langle m \rangle| \sim |m_1 \cos^2\theta_{12} + m_2 \sin^2\theta_{12} e^{i\alpha_{21}} + m_3 \sin^2\theta_{13} e^{i\alpha_{31}}|$$

Mixing angles (mostly known)

CPV phases (unknown)

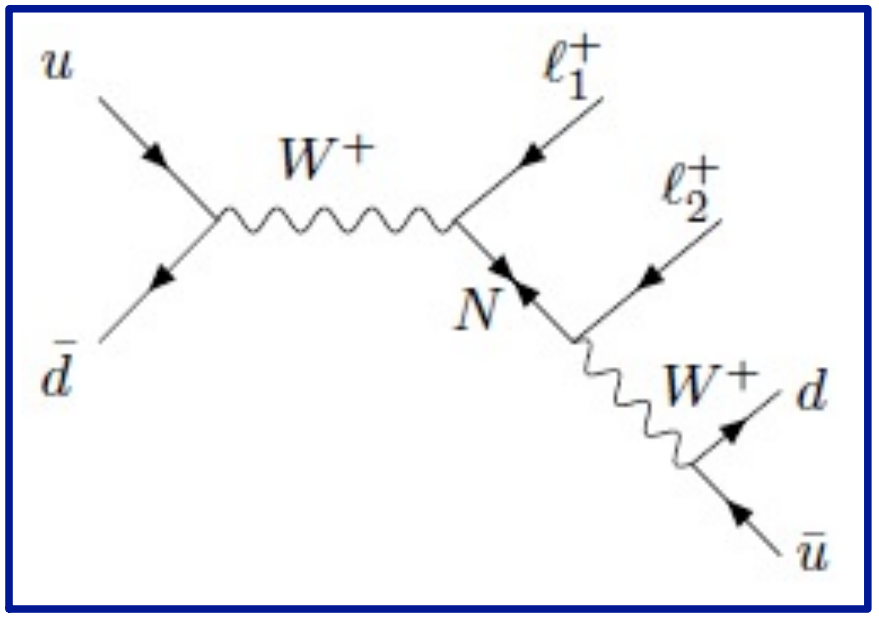


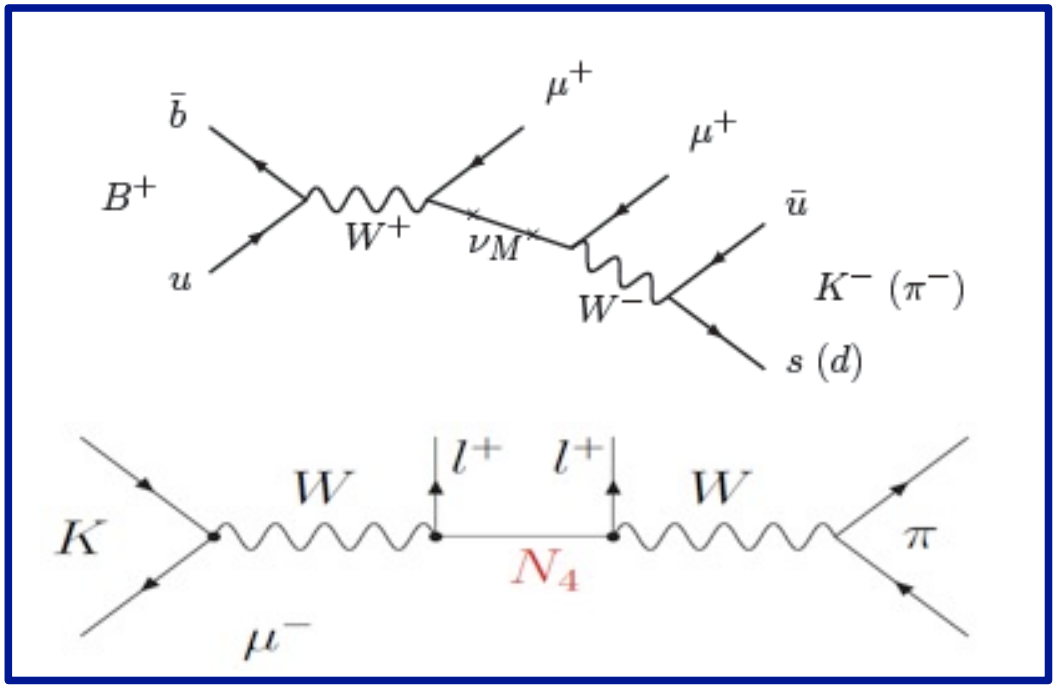


J. Hartnell, IOP meeting

SP 2014, from Nakamura, Petcov review in PDG

Searches for LNV at colliders and in rare meson/tau decays





At colliders, same-sign leptons and no missing E_T.
CMS and ATLAS searches have reported no signal.

Tau and Meson LNV decays.
They get resonantly enhanced for M~ 100 MeV - few GeV.

Channel	Observed 95% CL
$K^+\mu^-\mu^-$	5.4×10^{-8}
$D^+\mu^-\mu^-$	6.9×10^{-7}
$D^{*+}\mu^-\mu^-$	2.4×10^{-6}
$\pi^+\mu^-\mu^-$	1.3×10^{-8}
$D_s^+\mu^-\mu^-$	5.8×10^{-7}
$D^0\pi^+\mu^-\mu^-$	1.5×10^{-6}

LHC-b
PRL 108 and PRD 85.

@Silvia Pascoli

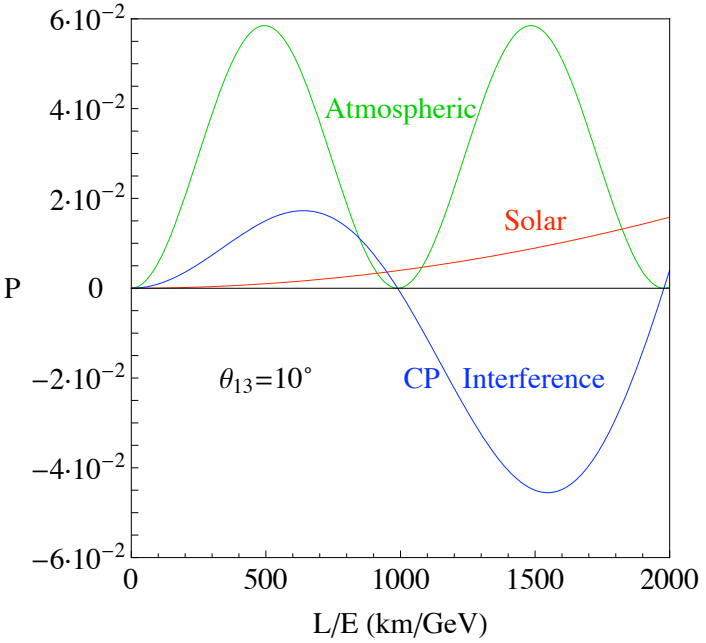
CP-violation in LBL experiments

CP-violation will manifest itself in neutrino oscillations, due to the delta phase. The CP-asymmetry:

$$P(\nu_\mu \to \nu_e; t) - P(\bar{\nu}_\mu \to \bar{\nu}_e; t) =$$

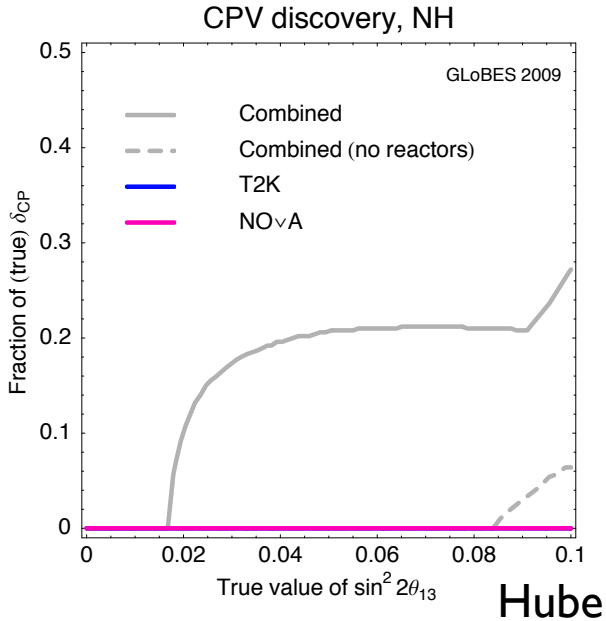
$$= 4 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \left[\sin\left(\frac{\Delta m^2_{21} L}{2E}\right) + \sin\left(\frac{\Delta m^2_{23} L}{2E}\right) + \sin\left(\frac{\Delta m^2_{31} L}{2E}\right) \right]$$

- CP-violation requires all angles to be nonzero.
- It is proportional to the sine of the delta phase.
- Problem of degeneracies.

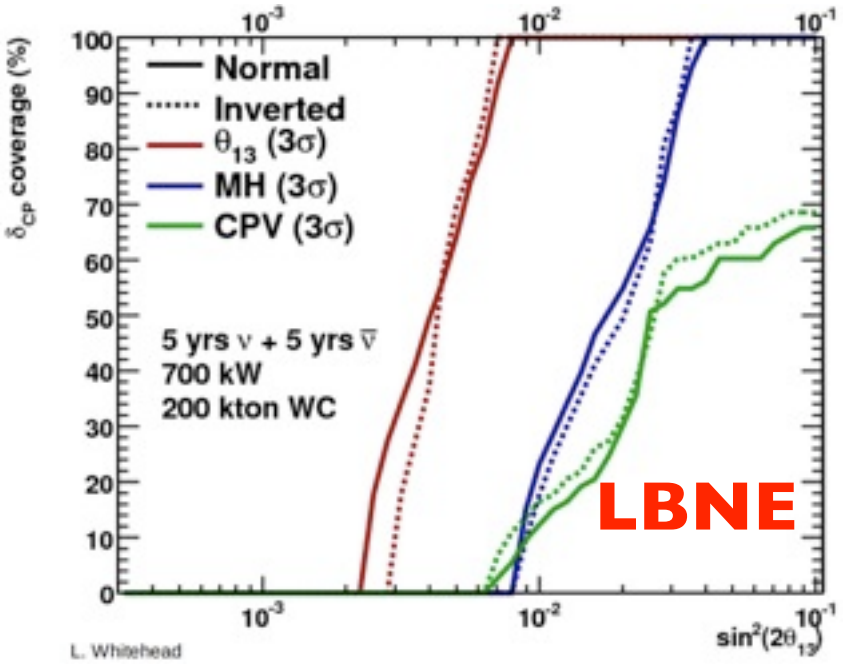


Coloma and Fernandez-Martinez, 2011

T2K and NOvA



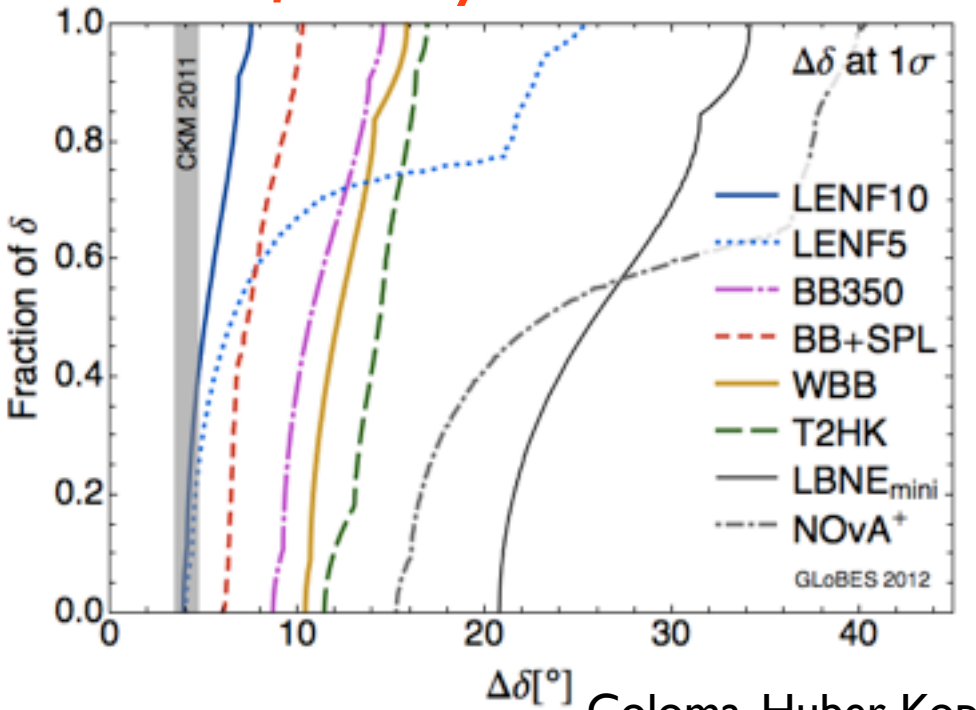
Huber at al., 2009



LBNE

Superbeams

Neutrino factory



Coloma, Huber, Kopp, Winter, 1209.5973

Current generation (T2K, NOvA) goals: get some information about the mass hierarchy and open the hunt for CP-violation.

Next generation (LBNE, T2HK and LBNO) goals: CPV and matter effects.

Future (neutrino factory): best reach for CPV and precision measurement.

Is there a connection between low energy CPV and the baryon asymmetry?

The general picture

ϵ depends on the CPV phases in Y_ν

$$\epsilon \propto \sum_j \Im(Y_\nu Y_\nu^\dagger)^2_{1j} \frac{M_j}{M_1}$$

One flavour approximation

and in the U mixing matrix via the see-saw formula.

$$m_\nu = U^* m_i U^\dagger = -Y_\nu^T M_R^{-1} Y_\nu v^2$$

Let's consider see-saw type I with 3 NRs.

High energy		
M_R	3	0
Y_ν	9	6

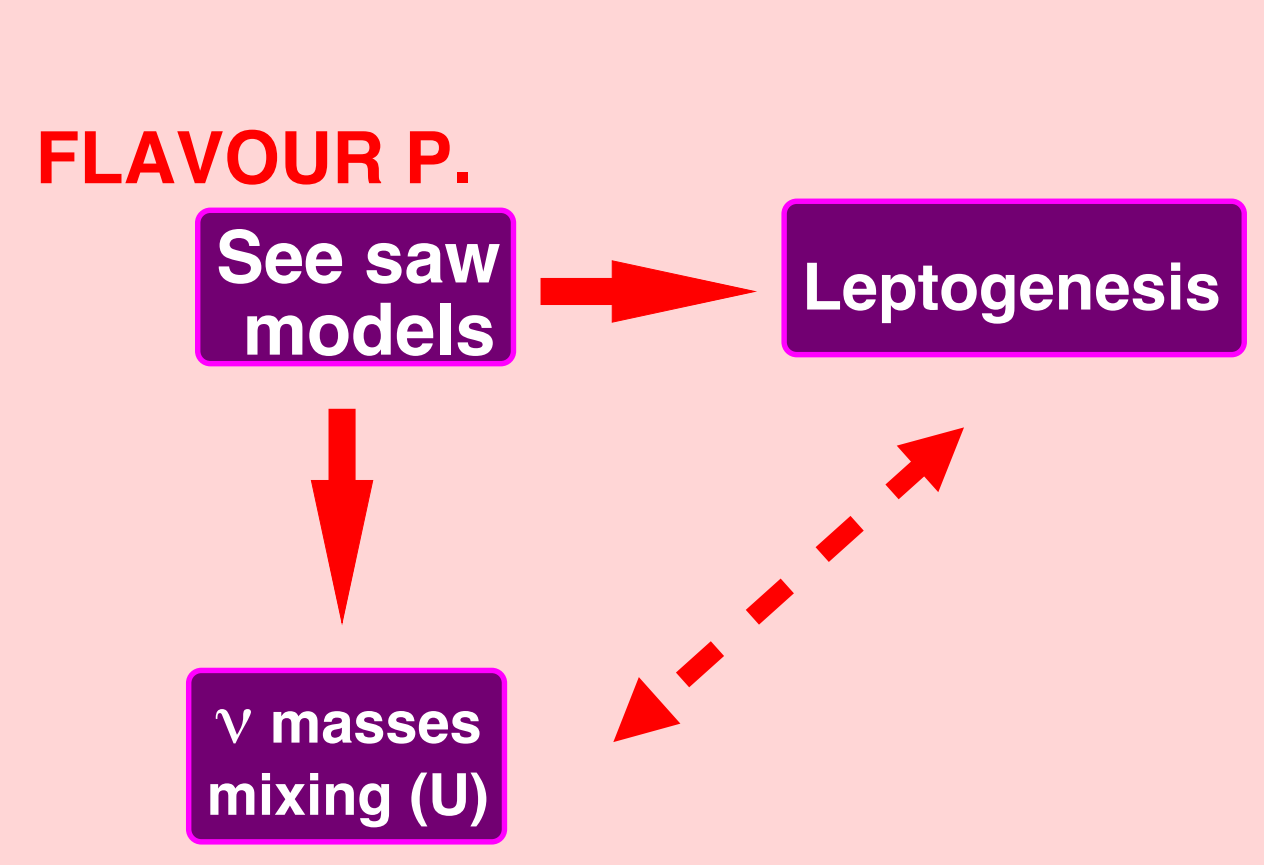
Low energy		
m_i	3	0
U	3	3

3 phases missing!

Specific flavour models

In understanding the origin of the flavour structure, the see-saw models have a reduced number of parameters.

It may be possible to predict the baryon asymmetry from the Dirac and Majorana phases.



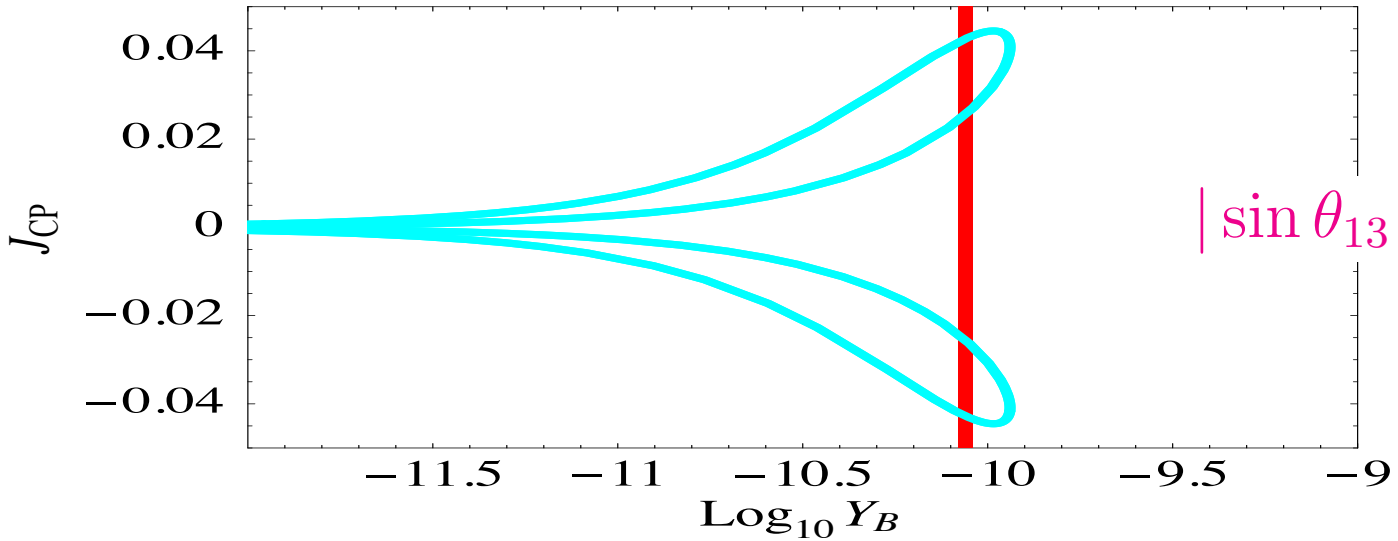
Does observing low energy CPV imply a baryon asymmetry?

It has been shown that, thanks to flavour effects, the low energy phases enter directly the baryon asymmetry.

In see-saw type I, even if this is the only source of CPV,

$$\epsilon_\tau \propto M_1 f(R_{ij}) \left[c_{23} s_{23} c_{12} \sin\left(\frac{\alpha_{32}}{2}\right) - c_{23}^2 s_{12} s_{13} \sin\left(\delta - \left(\frac{\alpha_{32}}{2}\right)\right)\right]$$

M1<<M2<<M3, for NH spectrum



$$|\sin\theta_{13}\ \sin\delta| \gtrsim 0.11$$

SP, Petcov, Riotto, PRD and NPB 2007

Large theta13 implies that delta can give an important (even dominant) contribution to the baryon asymmetry.

Conclusions

- Leptogenesis requires
  - L violation (nu-less double beta decay, colliders...)
  - C/CPV (LBL and nu-less double beta decay (?))
  - out-of-equilibrium (expansion of the Universe)

The observation of L violation and of CPV in the lepton sector would be a strong indication (even if not a proof) of leptogenesis as the origin of the baryon asymmetry.