Introduction to leptogenesis

Marco Zito

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Warning: not an introduction to
- Majorana neutrinos
- Sphalerons (?)
- Boltzmann equations
- GUT
- Flavor leptogenesis
- ...

Reading material

- P. Di Bari arxiv:1206.3168
- S. Davidson, E. Nardi, Y. Nir arxiv:0802.2962
- M. Chen hep-ph/0703087
- Slides by Y. Nir and his notes
  http://pontecorvosch.jinr.ru/2010/Lectures/Nir_lg_notes.pdf

La question de Leibniz (1646,1716)

Pourquoi il y a plutôt quelque chose que rien ? Car le rien est plus simple et plus facile que quelque chose. De plus, supposé que des choses doivent exister, il faut qu'on puisse rendre raison pourquoi elles doivent exister ainsi, et non autrement. (Leibniz, Principes de la nature et de la grâce 1714)

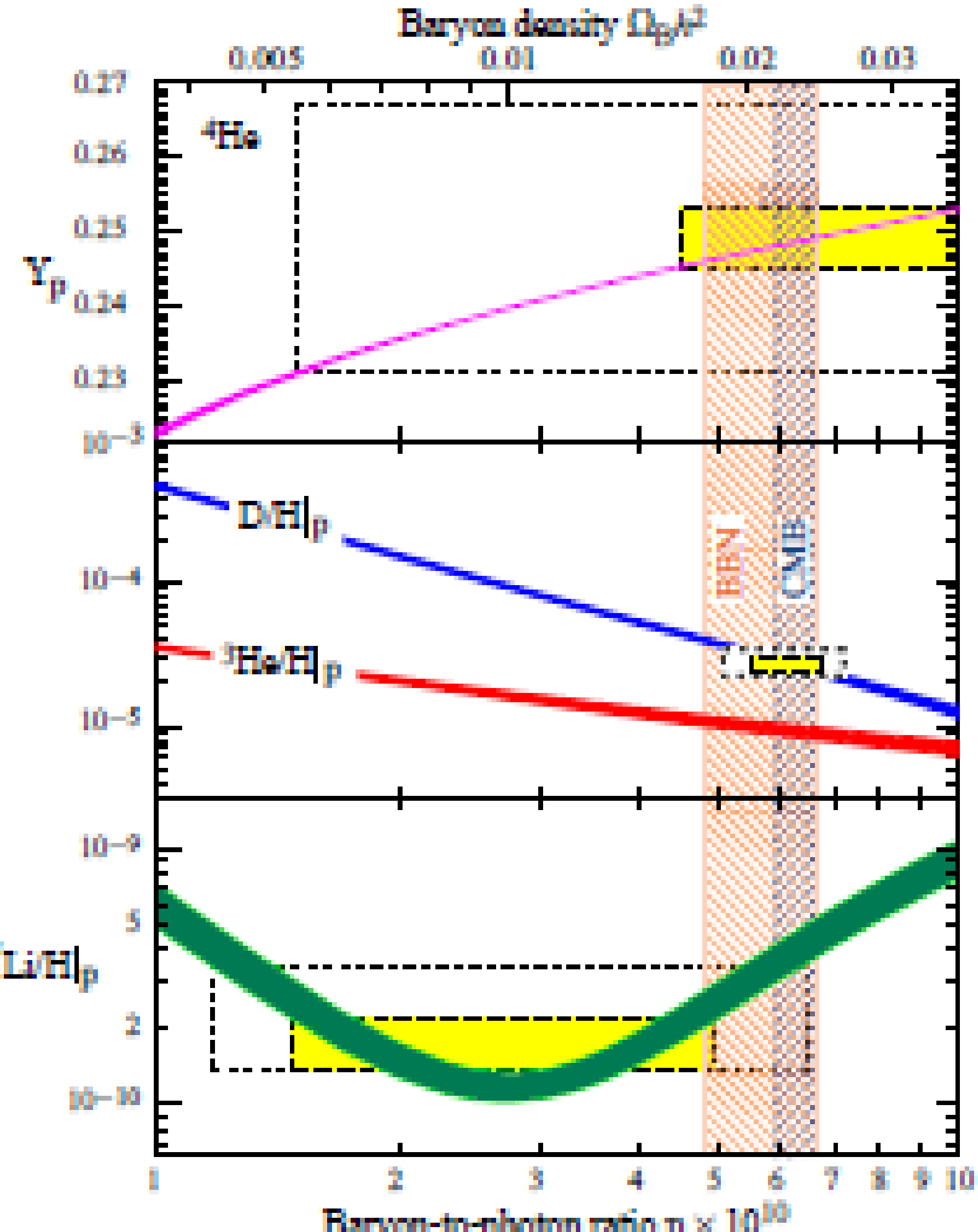
Outline

1) Baryonic asymmetry
2) Dynamic generation
3) Sakharov conditions
4) Leptogenesis: storytelling
5) Sphalerons
6) See saw lagrangian
7) Evolution equations
8) Constraints
9) Predictivity
10) Current status

The baryon asymmetry

- ΛCDM -> hot initial stage of the Universe. Presumably symmetric in the baryon number
- Today : no primordial anti-matter observed
- Baryon asymmetry: η=(n(B)-n(Bbar)/n(γ)
- BBN : $\eta=(5.9\pm0.5)\ 10^{-10}$
- CMB : $\eta=(6.2\pm0.15)\ 10^{-10}$
- NB: the two measurements are not at the same time (BBN ~1-300s, CMB 4 10**5 y)

Baryon asymmetry from BBN and CMB



PDG

Dynamic generation of the baryon asymmetry

Why is this not just a problem of an initial value for η ?

- Fine tuning: 10^{-6}
- Inflation: dilution of any initial asymmetry. The universe starts empty plus the inflaton vacuum energy

A. D. Sakharov, Pisma Zh. Eksp. Teor. Fiz. 5, 32 (1967) [JETP Lett. 5, 24 (1967)].

Sakharov conditions

Conditions for dynamically generating a baryon asymmetry

1) Baryon number violation

2) C and CP violation

$$X \to Y + B : \Gamma\left(X \to Y + B\right) = \Gamma\left(\bar{X} \to \bar{Y} + \bar{B}\right)$$

3) Out of equilibrium

According to CPT symmetry, the mass M of a particle and of an antiparticle are equal. In thermal equilibrium, the number of particles is governed by the Boltzmann factor exp(-M/KT), same as for an antiparticle.

SM and baryogenesis

- The three Sakharov conditions are fulfilled by the SM with
  - B violation = sphalerons (see later)
  - C, CP : CKM CP violation
  - Out of eq.: the EW phase transition
- But numerically this does not work. It would have required a low Higgs mass mH<40 GeV
- Plus the amount of CP violation from CKM insufficient
- $J_{CP} \equiv (m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)(m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2) s_{12} s_{23} s_{13} c_{12} c_{13} c_{23} s_\gamma \neq 0.$

$J_{CP}/T_c^{12} = 10^{-20}$ → New sources of CP violation

Sphalerons

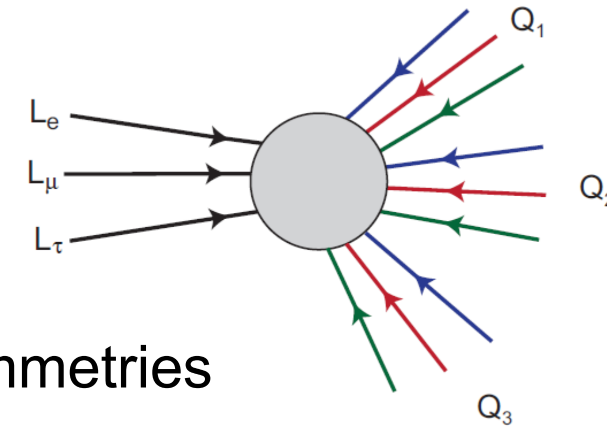


FIG. 5: A $B+L$ violating process due to non-perturbative SM effects.

- In the SM the L and B number are accidental symmetries
- At the quantum level they are violated by the triangular anomalies
- The divergence of the current is related to interactions with the gauge fields (W, B)
- This process is strongly suppressed today but was at the equilibrium for $E > E_{EW}$
- The process violates B+L but conserves B-L. It does not lead to the proton decay
- In GUT, other processes give B violation (and proton decay)

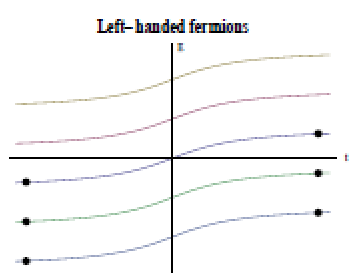


Figure 3.1: Evolution with time of the energy eigenstates of chiral fermions in a gauge field background with $F\tilde{F} \neq 0$.

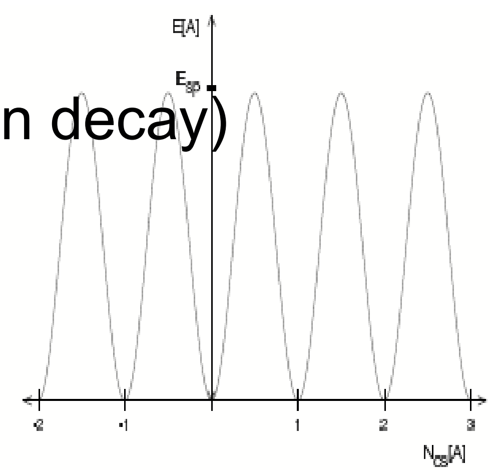
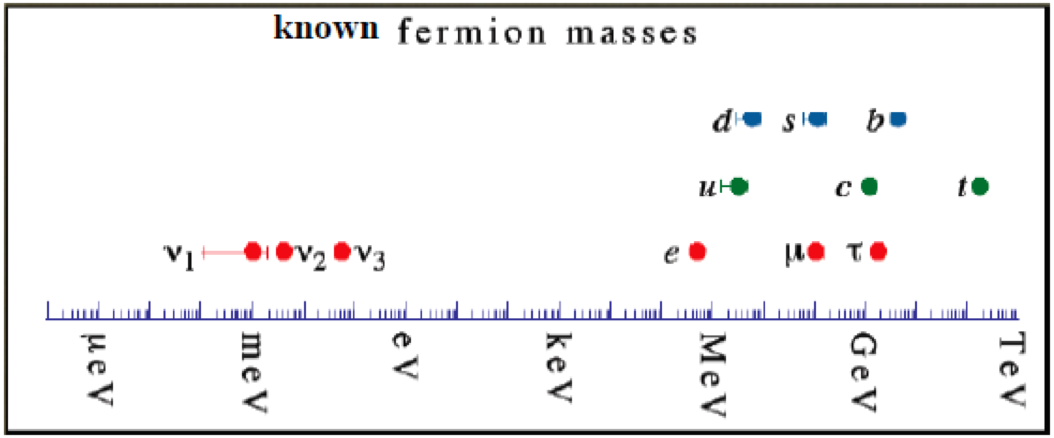


Fig. 1.3. The energy dependence of the gauge configurations A as a function of the Chern-Simons number, $N_{cs}[A]$. Sphalerons correspond to the saddle points, *i.e.* maxima of the potential.

Signals/hints of New Physics

- Dark Matter
- Missing ingredients for Baryogenesis
- Neutrino masses

Leptogenesis: Solving these two problems at once



Leptogenesis : the story

1) Inflation
2) Reheating at a large T (~10^{15} GeV)
3) Thermal production of new heavy neutral leptons N
4) N decay out of equilibrium
5) With CP violation → generation of B-L
6) Partial wash out by inverse reactions
7) Sphalerons convert B-L into B asymmetry
8) B (we) survives until now

See saw lagrangian-1

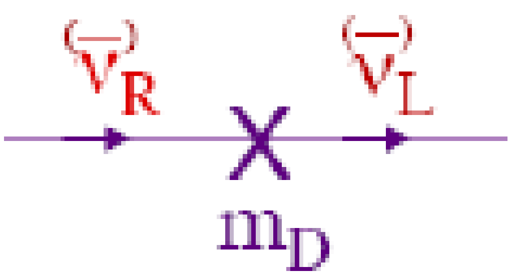
The observation of neutrino oscillations (solar, atmospheric) requires a mass term for the neutrinos

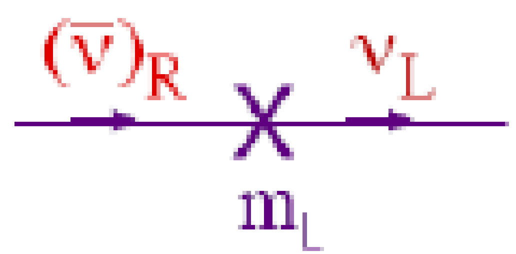
$$m_D \bar{\nu}_L \nu_R$$

A Dirac mass term for the neutrino. Requires a new state ν_R, a singlet under the SM gauge group.

$$m_M \overline{\nu^c}_R \nu_R$$

No symmetry of the SM prevents this Majorana mass term to appear. Nothing constraints this term to be at the EW scale.



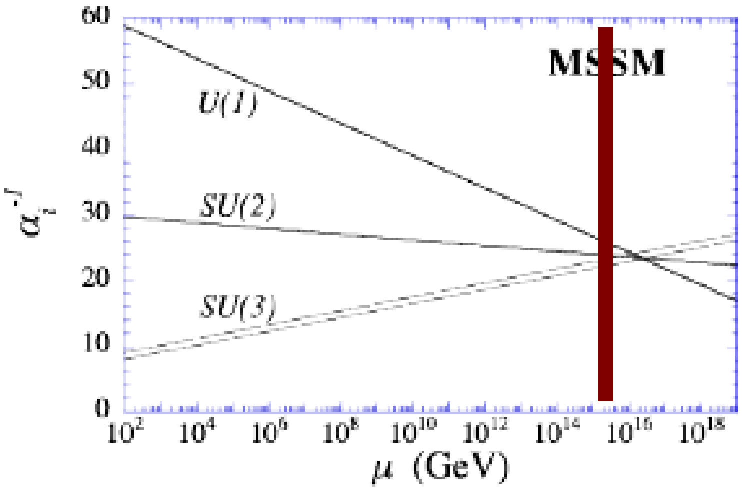


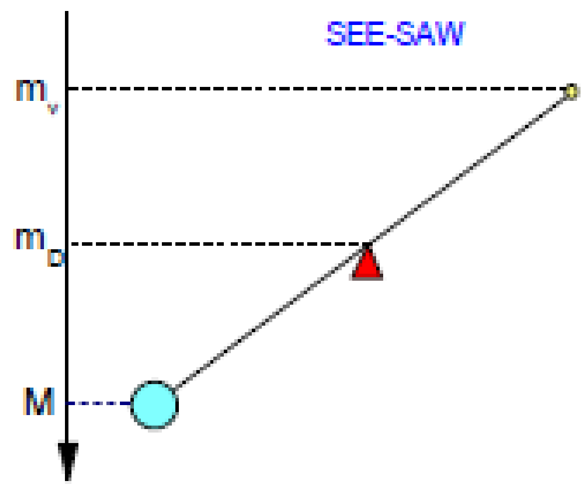
See saw lagrangian-2

$$L = (\bar{\nu}_L, \bar{N}_R^c) \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N_R \end{pmatrix}$$

Yielding these eigenvalues: $m_1 \approx M_R \quad m_2 = m_D^2 / M_R$

$M_R \sim 10^{15}$ GeV for $m_\nu \sim 0.1$ eV





See saw lagrangian/leptogenesis 1

L = YNHL + MNN

This is a Yukawa term for Higgs (**H**), Lepton doublet (**L**), **N**. It generates an off-diagonal mass term and an interaction term N-> H l

Majorana mass term for the heavy neutrinos **N.** Assume there are 3 of them, but could work with 2

Seesaw : $m_\nu = Y^2 v/M$ ie M/Y^2 ~10**14 GeV

See saw lagrangian/leptogenesis 2

L = YNHL + MNN

The “predictivity” of leptogenesis comes from the fact that Y parametrizes both neutrino masses and (light+heavy neutrino+Higgs interactions

Number of degrees of freedom: 18 (Y is a 3x3 complex matrix) – 3 (redefinition of lepton doublet phase) +3 (heavy neutrino masses)=18. Can also be seen as 6 (mixing light)+3(masses light)+(3 masses heavy+ Gamma+3CP asymmetries)

Y->h in the paper by Di Bari

The relevant parameters

Ignoring flavor, the final Y_B depends on four parameters:

- ϵ, the CP asymmetry;
- M_1, the mass of the lightest N;
- $\tilde{m}_1 \equiv \frac{(Y^\dagger Y)_{11} v^2}{M_1}$, the effective neutrino mass;
- $\bar{m}^2 = m_1^2 + m_2^2 + m_3^2$, the sum of light neutrino mass-squared.

Successful baryogenesis requires

- $\boxed{M_1 \gtrsim 10^9 \text{ GeV } (\Longrightarrow T_{RH} \gtrsim 10^9 \text{ GeV})}$
  With supersymetry: gravitino problem?
- No model-independent bound on low energy phases

N1 decays and H

- We need to compare the decay rate (width) of N_1 to the expansion rate of the Universe (at a temperature ~ their mass)

$$\Gamma_N \propto M \left(Y Y \right)_{11}$$

$$\Gamma_N < H \left(T = M \right) \Rightarrow \tilde{m}_1 = \frac{\left(Y Y \right)_{11} v^2}{M_1} < 10^{-3}\, eV$$

Two different regimes

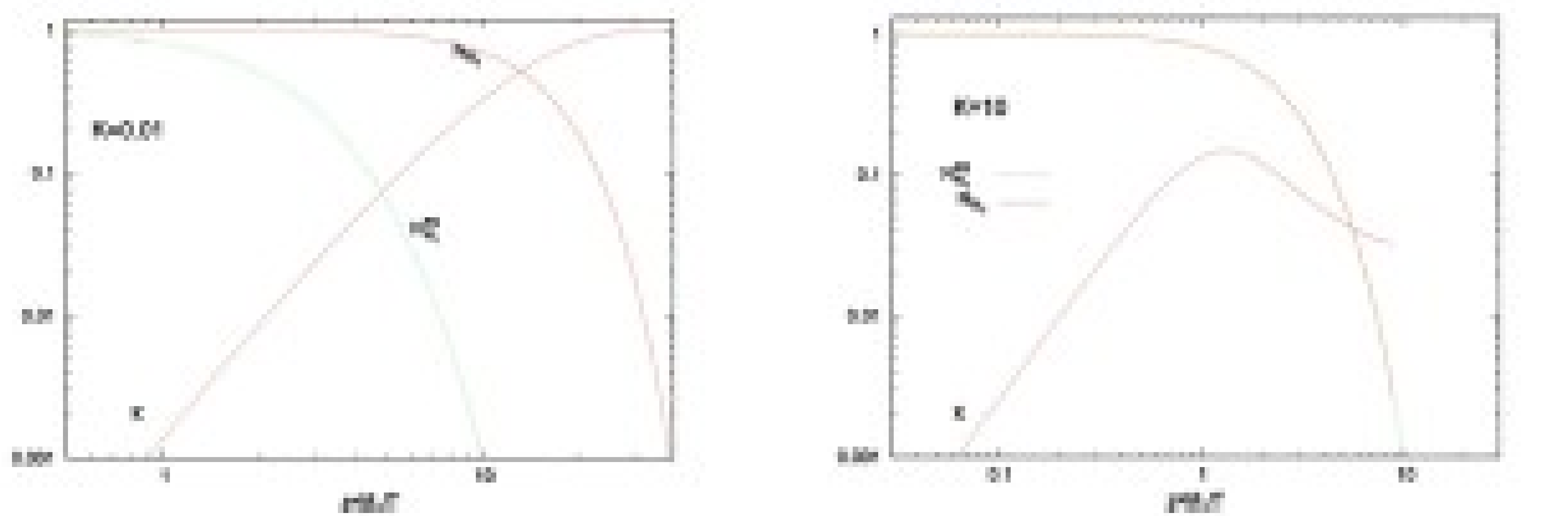
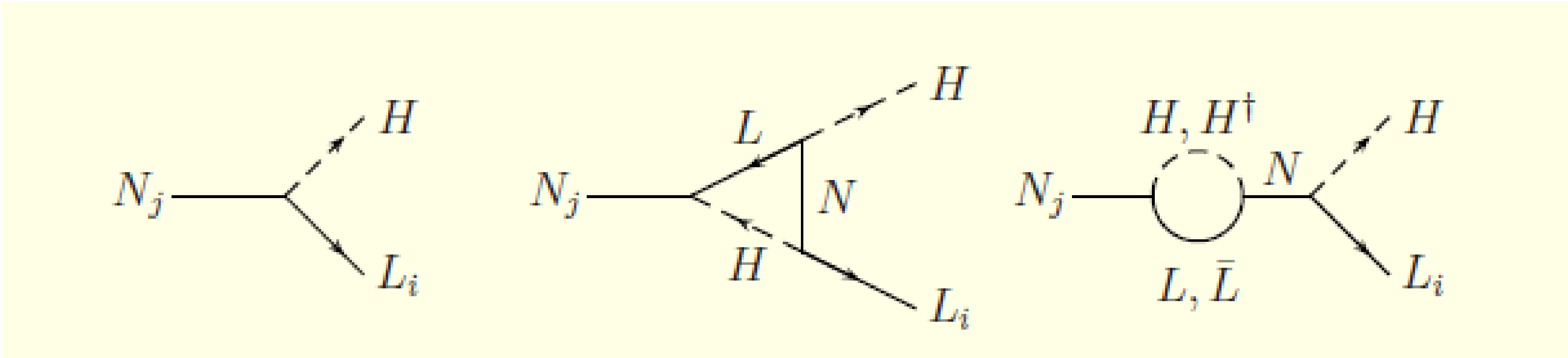


Figure 2. Evolution of the RH neutrino abundance N_{N_1} (red line) and of the efficiency factor κ (red line) with the temperature for two different values of the decay parameter K_1: (left) $K_1 = 0.01$ and (right) $K_1 = 10$. The green dotted line is the thermal equilibrium abundance $N_{N_1}^{eq}$: in the right panel it is hardly visible since it is closely tracked by N_{N_1}.

K <1 Decay out of equilibrium, weak wash-out. Fully efficient, but depends on initial conditions.

K >1 Strong wash-out. Low efficiency, independent on initial conditions. NB effect of heavier N will be completely washed-out

CP violation

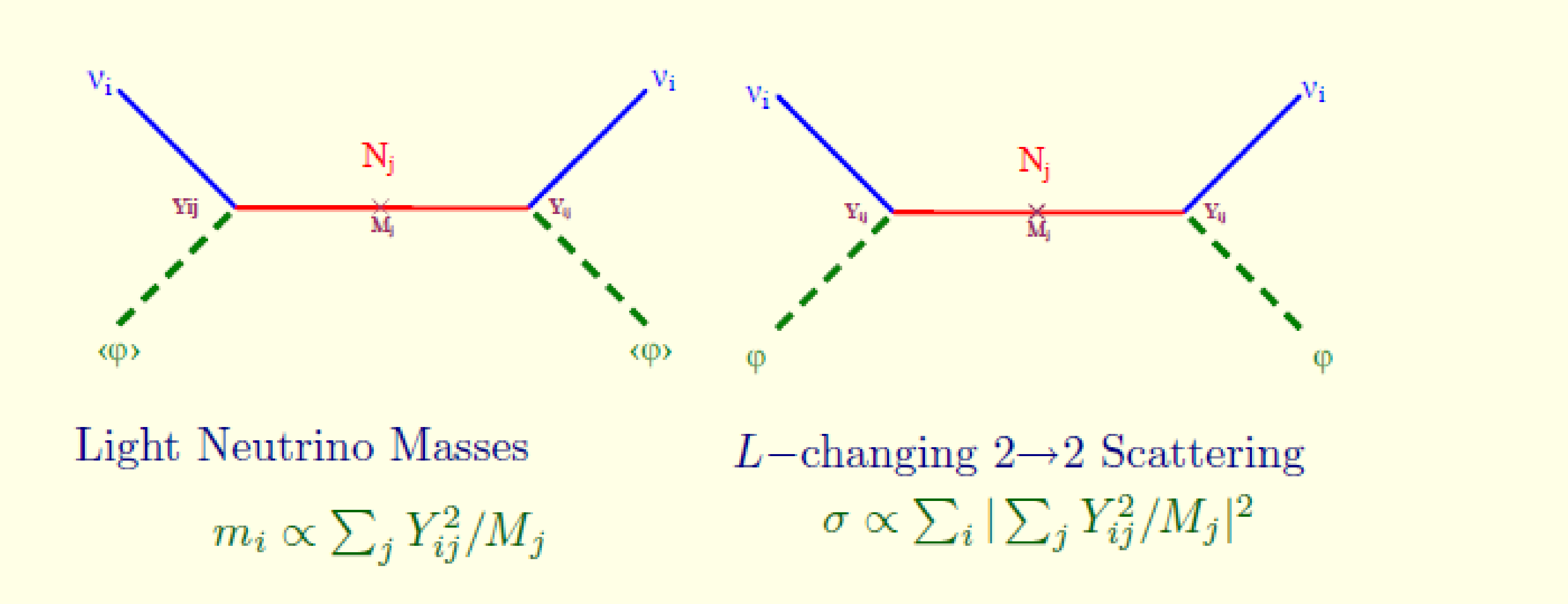


$$\epsilon \equiv \frac{\Gamma(N \to LH) - \Gamma(N \to \overline{L}H^\dagger)}{\Gamma(N \to LH) + \Gamma(N \to \overline{L}H^\dagger)} = \frac{1}{8\pi} \sum_k \frac{\mathcal{I}m[(Y^\dagger Y)^2_{k1}]}{(Y^\dagger Y)_{11}} \times f\left(\frac{M_k^2}{M_1^2}\right)$$

- Lepton number violation at the tree level if for instance Γ(N1->H-l+) ne Γ(N1->H+l-)
- Direct CP violation at one loop
- Requires at least 2 heavy neutrinos N

Wash out

- Depending on the see-saw parameters, there is some dilution (wash-out) of the lepton asymmetry given by the inverse decays and by other diagrams



Boltzmann equations

- A rigorous treatment requires to solve the two coupled Boltzmann equations

$$\frac{dN_{N_i}}{dz} = -D_i\left(N_{N_i} - N_{N_i}^{\rm eq}\right),$$

$$\frac{dN_{B-L}}{dz} = \sum_{i=1}^{3} \varepsilon_i\, D_i\left(N_{N_i} - N_{N_i}^{\rm eq}\right) - N_{B-L}\left[\Delta W(z) + \sum_i W_i^{\rm ID}(z)\right],$$

Putting it all together

$$\eta = a_{sph} k_1(K_1) \epsilon_1$$

$$K_1 \sim m_{sol,atm} / 10^{-3} eV \gg 1$$

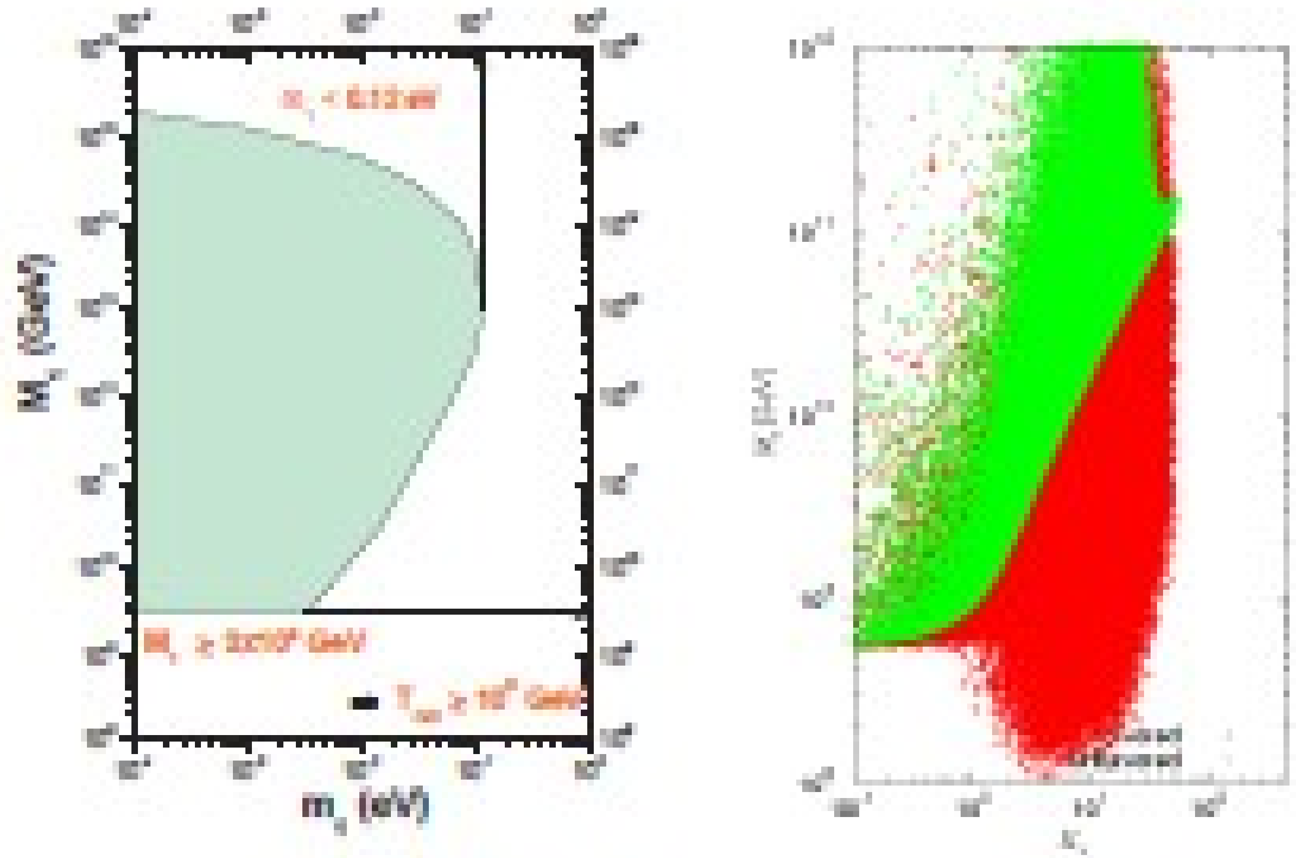
The strong wash-out regime is typically realised

$$\epsilon_1 < 10^{-6} \frac{M_1}{10^{10} GeV} \frac{m_{atm}}{m_1 + m_3}$$

Bounds on m_1 and M_1

$$m_1 < 0.12\, eV \qquad M_1 > 3\, 10^9\, GeV$$

Bounds



(a) (b)

Figure 5. Left: Neutrino mass bounds in the vanilla scenario. Right: Relaxation of the lower bound on M_1 thanks to additional unbounded flavoured CP violating terms.

PMNS measurements and leptogenesis

If all CPV necessary for the generation of the BAU is due to δ (PMNS phase) a necessary condition is (Pascoli Petcov Riotto, 2006)

$$\left|\sin\theta_{13}\sin\delta\right| > 0.1$$

Daya Bay $\sin(\theta_{13}) \sim 0.15$

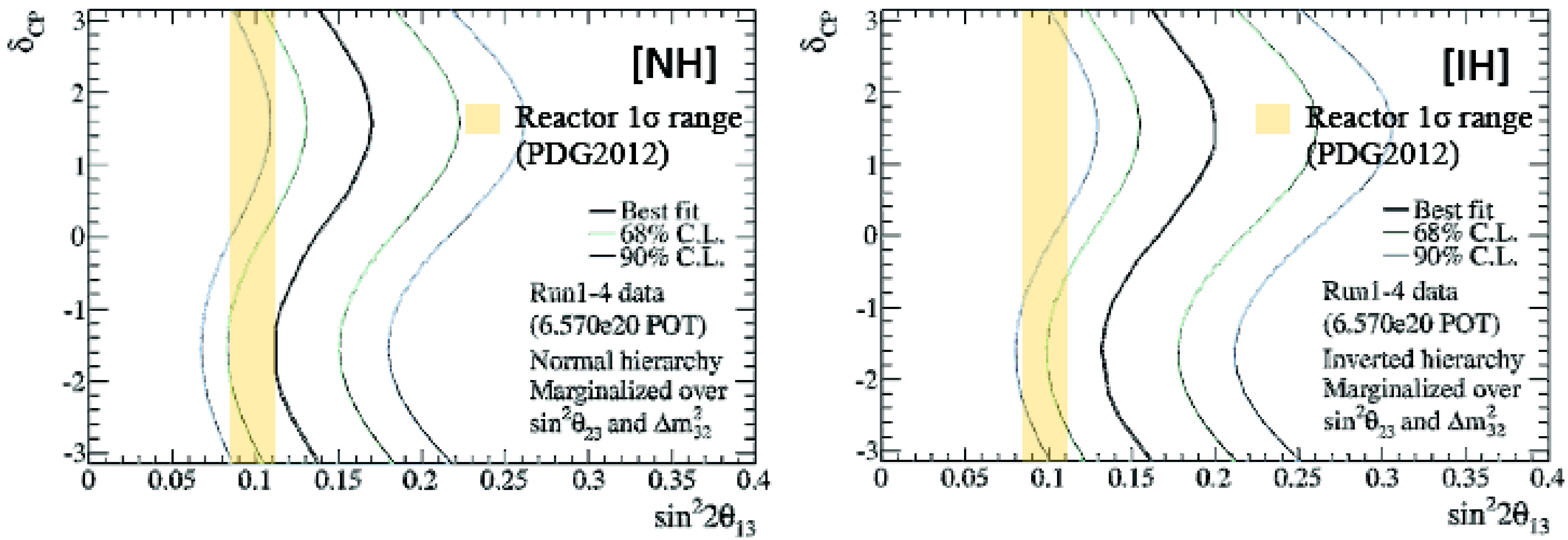
T2K : δ could be close to 3/2 π

[NH] Normal hierarchy, [IH] Inverted hierarchy

T2K 2014

Results of ν_e appearance analysis

Allowed region of $\sin^2 2\theta_{13}$ for each value of δ_{CP}



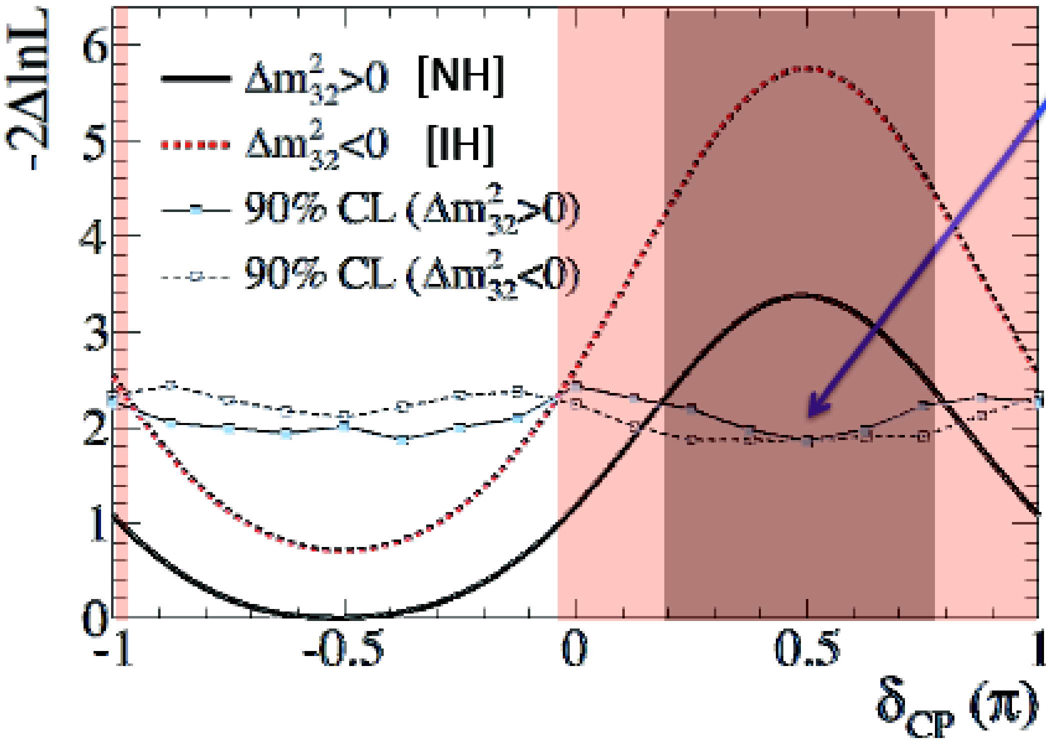
Note

- These are 1D contours for values of δ_{CP}, not 2D contours in δ_{CP}-θ_{13} space

[NH] Normal hierarchy, [IH] Inverted hierarchy

Results of ν_e appearance analysis

Combination of T2K + Reactor ($\sin^2 2\theta_{13}$=0.098±0.013 from PDG2012)



90% C.L. limits by Feldman-Cousins

90% C.L. excluded region

[NH]: 0.19π ~ 0.80π

[IH]: -0.04π ~ 1.03π

- Best fit is found at very interesting point, δ_{CP} ~ -π/2.
- If it is true, severe competition w/ NOνA.

Very important to increase statistics ASAP.