… a personal review on

Leptogenesis

Isabella Masina (CERN)

TH-Institute on Flavor, CERN, 08/05/08

Based on some works with:

V.Cirigliano, A.De Simone, G.Isidori, F.R. Joaquim, A.Riotto, C.A.Savoy

FOR A RECENT GENERAL REVIEW: Davidson Nardi Nir, arXiv:0802.2962

…leptogenesis is maybe the most promising mechanism to explain B-asymmetry

BUT WHY A TALK ABOUT IT IN A *"FLAVOR AS A WINDOW TO NEW PHYSICS AT LHC"* WORKSHOP?

New Physics

necessary because (even postponing the problem of unification with gravity) **it must account for:**

astro

- baryon asymmetry
- dark matter
- dark energy
- ….

particle

- ν masses&mixings
- hierarchy problem (th)
- flavour&CP problem (th)
- ….

esp'lly if
NP@TeV!!!

→ leptogenesis and flavor are both related to New Physics bSM, so that flavor might play an important role in the generation of B-asymmetry

PLAN

1- What is and how to measure the B asymmetry

2- Dynamical mechanisms for Baryogenesis (beyond SM) → leptogenesis

3- Various leptogenesis → seesaw type I, II, III, ...

4- Leptogenesis via type I seesaw
    a- effects: flavor, resonant, quantum
    b- related phenomenology
        i- connection with CPV in ν masses
        ii- range of RH ν masses
        iii- embedding in susy: gravitino problem
        iv- embedding in susy: LFV, EDM, ….
        v- embedding in GUT/flavor models: 2 examples

5- Conclusions

Baryon asymmetry of the universe

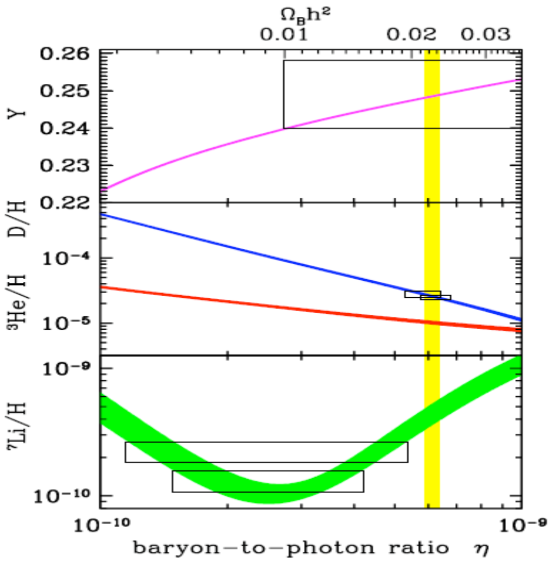
n_X= # density of X

$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} = 274 \times 10^{-10} \Omega_B h^2 = (6.21 \pm .16) \times 10^{-10}$$

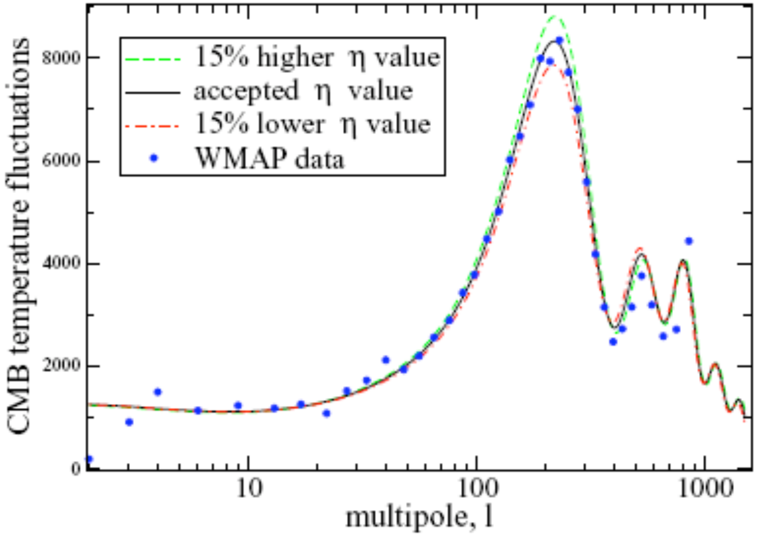
@68%

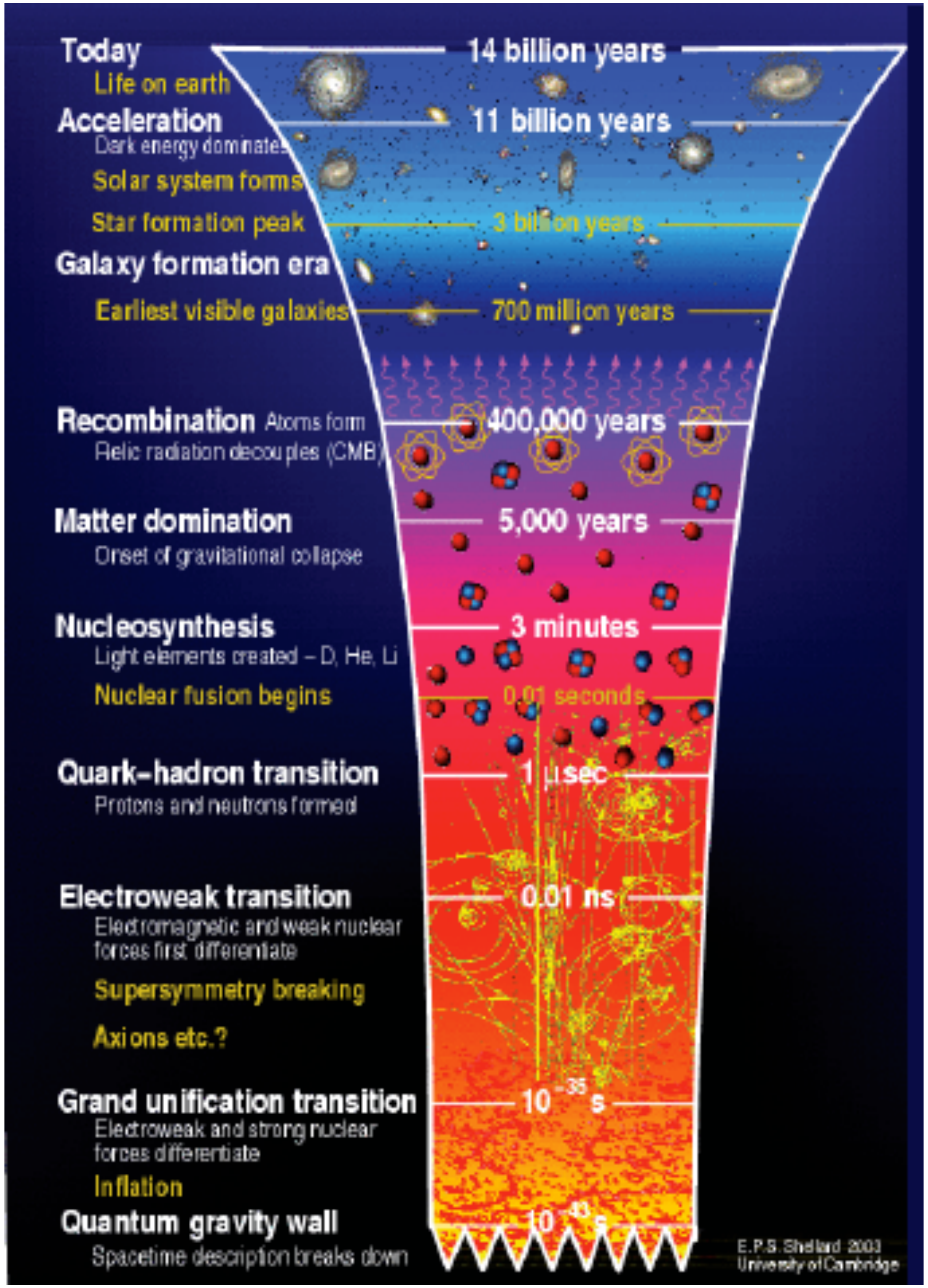
How to measure?

BBN - Historically



CMB - At present more precise





← Today

← CMB

← BBN

A NAIVE estimation of the B asymmetry of the universe TODAY

$$1.5 \times 10^{79} \text{ Hatoms in observed universe} =$$

$$\underbrace{1.25\ 10^{11} \text{ galaxies}}_{\text{Hubble Space Telescope}} \times \underbrace{10^{11} \text{ stars/galaxy}}_{\text{as in our galaxy}} \times \underbrace{1.2\ 10^{57} \text{ Hatoms/star}}_{\text{as in the Sun}}$$

$$\frac{2\times10^{30} \text{ kg/star}}{1.67\times10^{-27} \text{ kg/Hatom}}$$

$$3.6 \times 10^{80}\ m^3 = \text{volume of observed universe}$$

$$\frac{\text{Hatom density} = 4.2 \times 10^{-2}\ /m^3}{\text{number density of gas of photons in th eq at } T=2.73K = 4.1 \times 10^{8}\ /m^3} = 10^{-10}$$

Baryon asymmetry of the universe

A **non-trivial** value! If the universe were B-antiB symmetric

$$\frac{n_B}{n_\gamma} = \frac{n_{\bar{B}}}{n_\gamma} \sim 10^{-20}$$

….annihilation catastrophe!

From **fine-tuned** ($1/10^9$) initial conditions?

No: with inflation, any preexisting B-asymm is diluted to a negligible value, due to entropy production during reheating

Need a dynamical mechanism to generate B-asymmetry after inflation!

Baryogenesis

Sakharov's 3 conditions ['67] to dynamically create the asymmetry

1- B Violation

2- C & CP Violations

3- out of thermal equil'm

Baryogenesis

Sakharov's 3 conditions ['67] to dynamically create the asymmetry

1- B Violation → **at quantum-level** (triangle anomaly)

2- C & CP Violations → **maximal & TOO tiny**

3- out of thermal equil'm → **NOT so STRONG 1° EWPT**

SM

possess all ingredients but does not work...

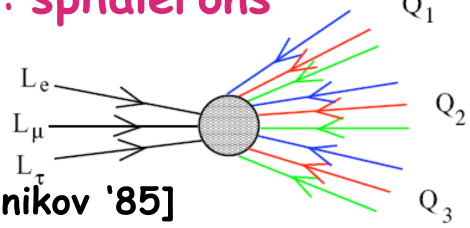
[Gavela Hernandez Orloff Pene]

Topological trans'n: **sphalerons**

B-L conserved:

$$\Delta_B = \Delta_L = \pm 3$$

[Kuzmin Rubakov Shaposhnikov '85]



Mechanisms for Baryogenesis

Sakharov's 3 conditions ['67] to dynamically create the asymmetry

1- B Violation

2- C & CP Violations

3- out of thermal equil'm

bSM

A) out of eq decay (3-) of heavy particles whose int's violate C, CP (2-) and B-L (1-) so that SM sphalerons do not erase the B asymmetry :

GUT leptoquarks ; RH neutrinos ; etc

GUT baryogenesis **leptogenesis**

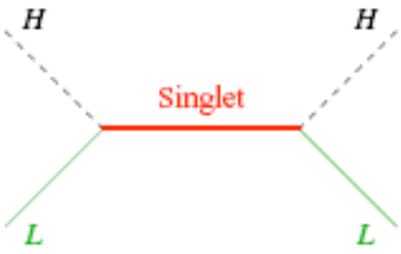
B) OTHERS: EW baryogenesis (modification of EWPT): 2HDM, MSSM; **spontaneous baryogenesis; Affleck-Dine; gravitational leptogenesis; etc**

Various Leptogensis

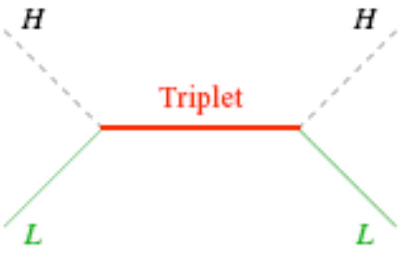
…according to type of seesaw inducing

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{(LH)^2}{2\Lambda_L}$$

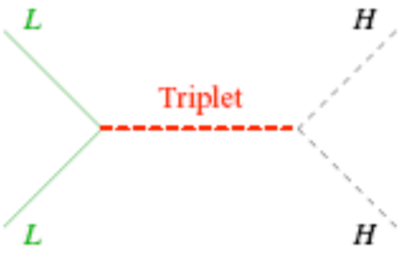
The neutrino Majorana mass operator $(LH)^2$ *can be mediated by tree level exchange of:*



I) *a fermion singlet ('see-saw');*



II) *a fermion triplet;*



III) *a scalar triplet.*

from now on

The seesaw (I)

[P.Minkowski '77]

Dirac-Yukawa
if complex → CPV

Majorana-mass
ΔL=2

$$\mathcal{L}_{ss} = \bar{\nu}_R Y_\nu \nu_L H + \bar{\nu}^c_R M_\nu \nu_R + h.c.$$

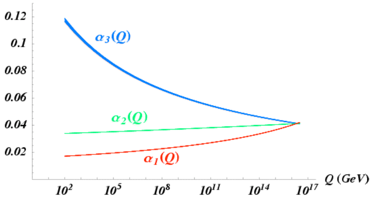
Mass eigenstates:

Heavy: $N \approx \nu_R$ **with** $M_\nu = (M_1, M_2, M_3)$ (where $M_1 < M_2 < M_3$)

Light: $\nu \approx \nu_L$ **with** $m_\nu = U^* m^d_\nu U^\dagger = Y_\nu^T M_R^{-1} Y_\nu v^2$

MNS mixing matrix

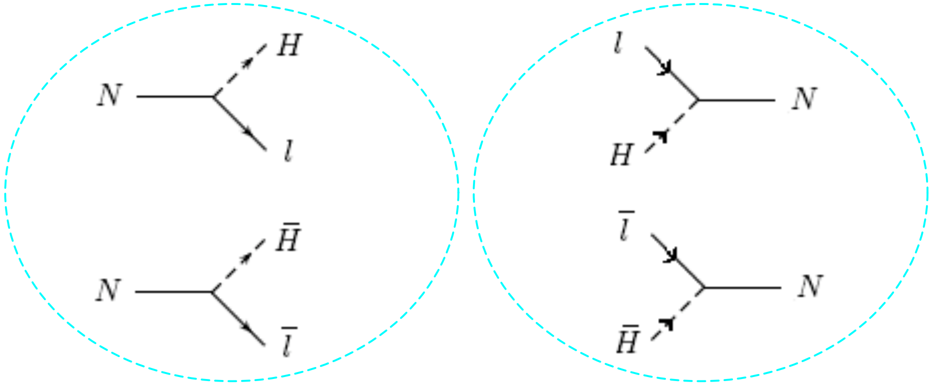
m_ν =O(eV) → M_ν = O(10^{15}GeV) , near SUSY g.c.u.!



Leptogenesis

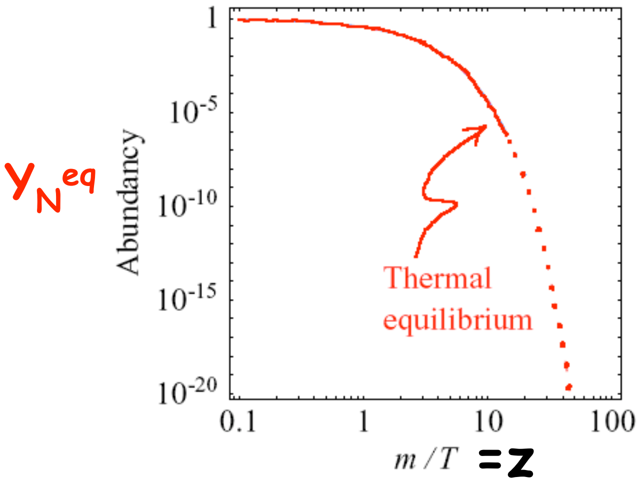
[Fukugita Yanagida '86]

0. In the thermal bath with $\Gamma(N \to \ell H, \bar{\ell}\bar{H}) > H(T)$ ← **tipically T>M_R**



decays & inverse decays

are in thermal equilibrium



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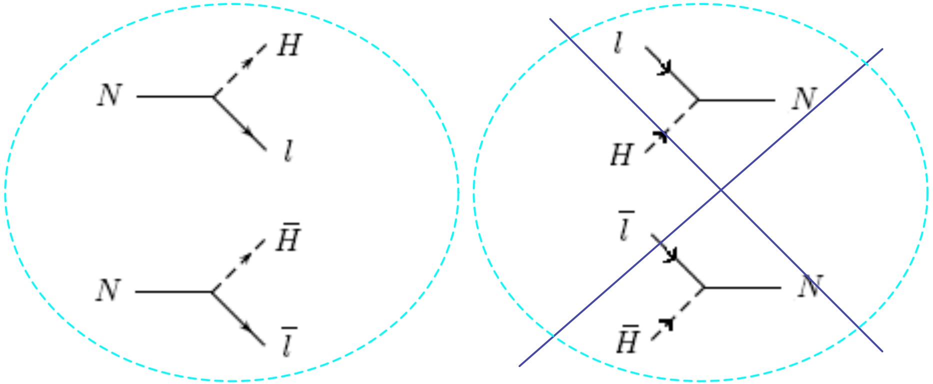


decays & **inverse decays**

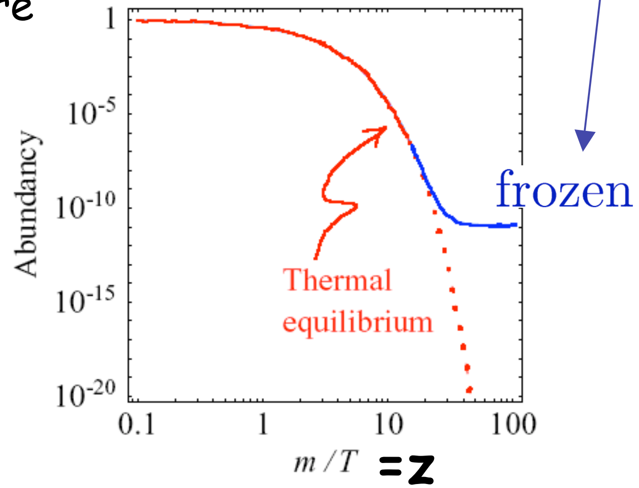
are no more effective in diluting Y_N

go out of equilibrium!

sooner (i.e. N's more abundant) the more

$$K = \Gamma/H(T = M_R) < 1$$

Y_N



=z

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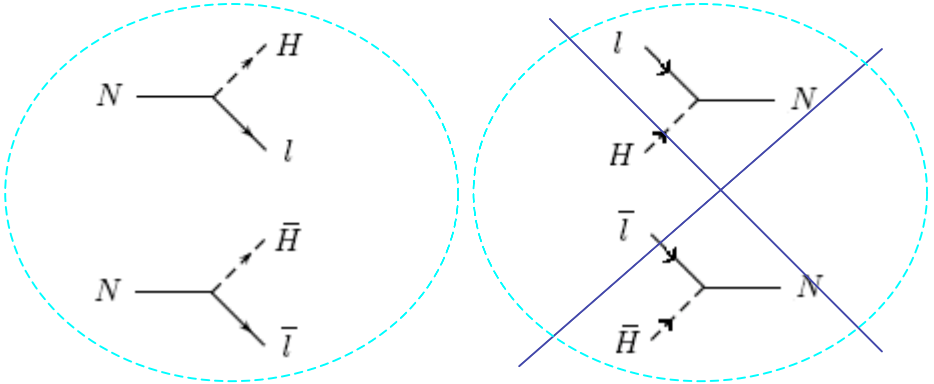

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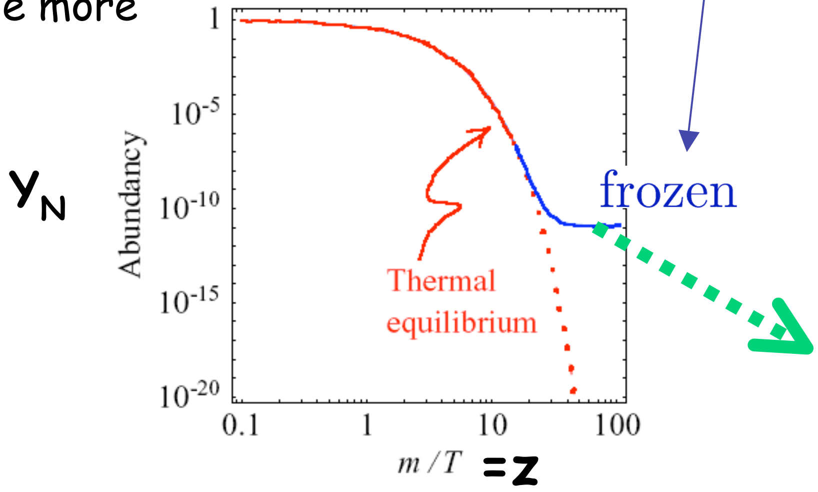


HOWEVER: later **N's decay**

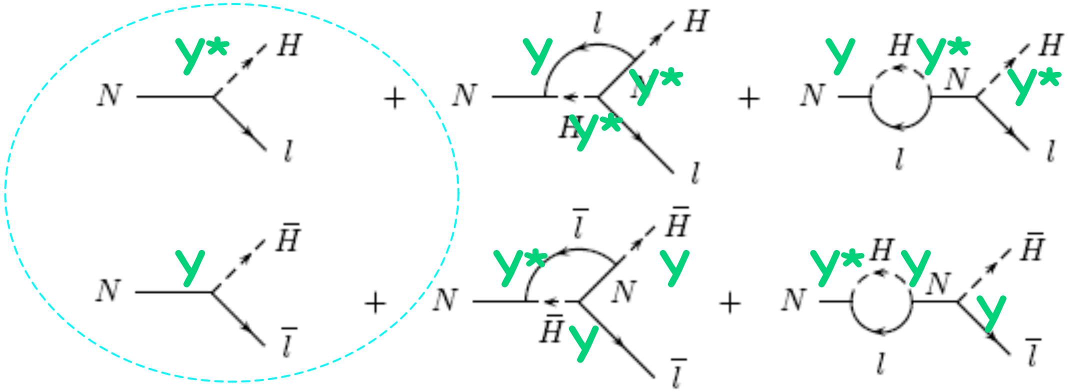
$$\boxed{\frac{dY_{N_i}}{dz} = -D_i \left(Y_{N_i} - Y_{N_i}^{eq}\right)}$$

Boltzmann eq'n

Leptogenesis

[Fukugita Yanagida '86]

2. Violating **C&CP**



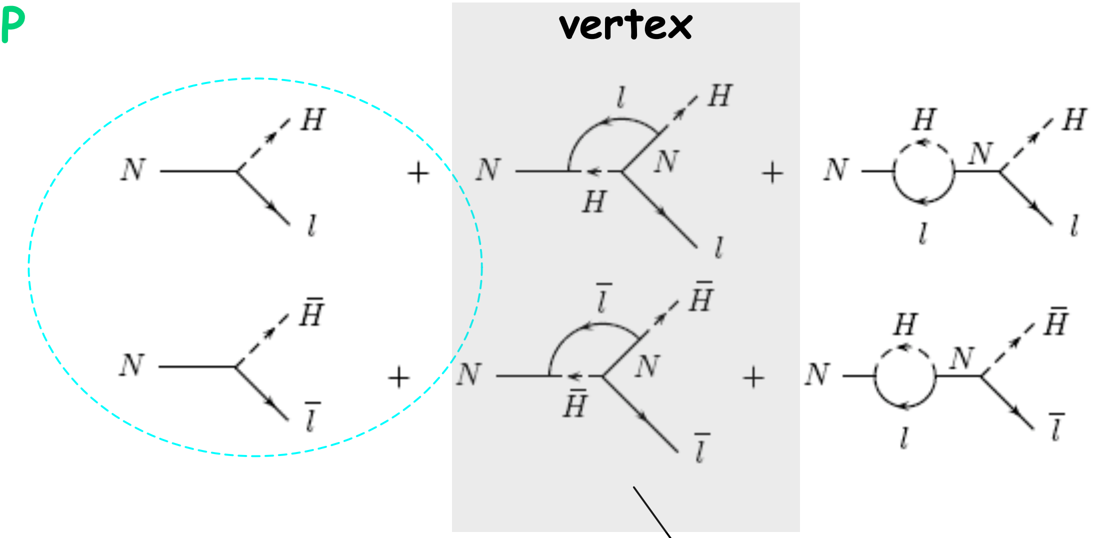
lepton asymm

$$\epsilon_{i\alpha} \equiv \frac{\Gamma(N_i \to \ell_\alpha \bar{H}) - \Gamma(N_i \to \bar{\ell}_\alpha H)}{\Gamma(N_i \to \ell_\alpha \bar{H}) + \Gamma(N_i \to \bar{\ell}_\alpha H)} = \sum_{j \neq i} \frac{1}{8\pi} \frac{\mathrm{Im}\left[(\lambda_\nu)_{i\alpha}(\lambda_\nu)^\dagger_{\alpha j}(\lambda_\nu \lambda_\nu^\dagger)_{ij}\right]}{\left(\lambda_\nu \lambda_\nu^\dagger\right)_{ii}} \left(g_V^{(j,i)} + g_S^{(j,i)}\right)$$

Leptogenesis

[Fukugita Yanagida '86]

2. Violating *C&CP*



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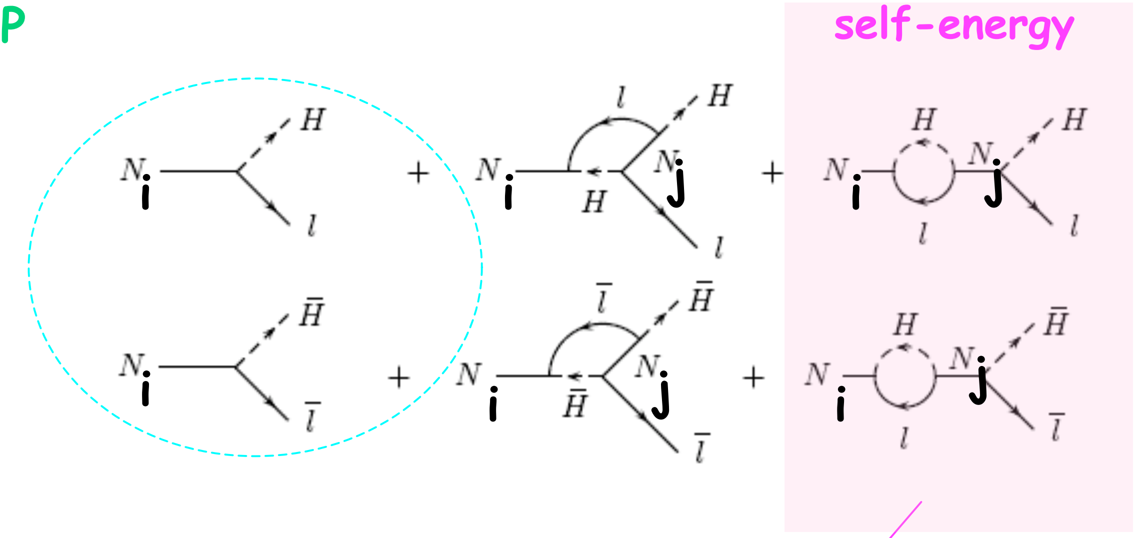
most important for hierarchical RH ν's
→ lower limit on M_1

Leptogenesis

2. Violating **C&CP**



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resonantly enhanced for

$$\Delta M_{ij} = M_i - M_j \lesssim \Gamma_j$$

(i-decays, j-internal)

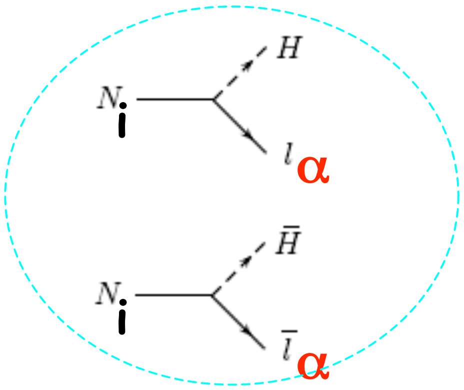
Resonant effects

[Pilaftsis, Covi Roulet,Flanz… '97]

relevant for nearly deg RH ν's

→ M_1 as low as TeV

Leptogenesis



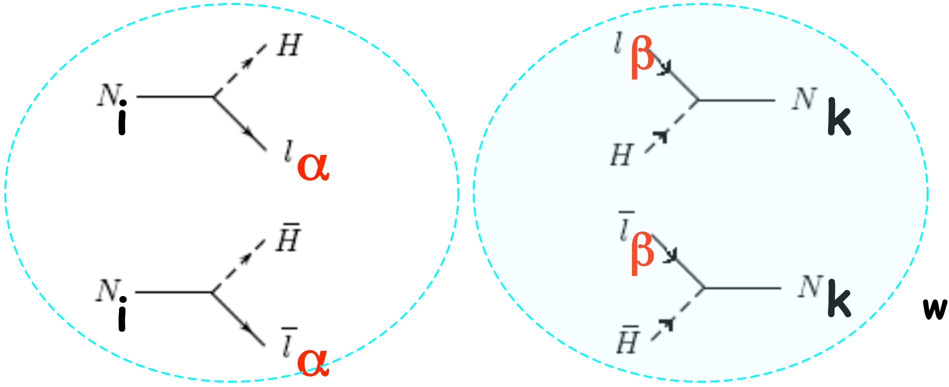
lepton asymm

$$\varepsilon_{i\alpha} \equiv \frac{\Gamma(N_i \to \ell_\alpha \bar{H}) - \Gamma(N_i \to \bar{\ell}_\alpha H)}{\Gamma(N_i \to \ell_\alpha \bar{H}) + \Gamma(N_i \to \bar{\ell}_\alpha H)} = \sum_{j \neq i} \frac{1}{8\pi} \frac{\mathrm{Im}\left[(\lambda_\nu)_{i\alpha}(\lambda_\nu)^\dagger_{\alpha j}(\lambda_\nu \lambda_\nu^\dagger)_{ij}\right]}{\left(\lambda_\nu \lambda_\nu^\dagger\right)_{ii}} (g_V^{(j,i)} + g_S^{(j,i)})$$

3. BV- Sphaleron conserve $Y_{\Delta\alpha}=B/3-L_\alpha$

$$\eta_B \frac{n_\gamma}{s} = Y_B = \frac{12}{37} \sum_\alpha Y_{\Delta\alpha}(z \to \infty)$$

Leptogenesis



inverse decays

wash out $\varepsilon_{i\alpha}$ only if $\beta=\alpha$

lepton asymm

$$\varepsilon_{i\alpha} \equiv \frac{\Gamma(N_i \to \ell_\alpha \bar{H}) - \Gamma(N_i \to \bar{\ell}_\alpha H)}{\Gamma(N_i \to \ell_\alpha \bar{H}) + \Gamma(N_i \to \bar{\ell}_\alpha H)} = \sum_{j \neq i} \frac{1}{8\pi} \frac{\mathrm{Im}\left[(\lambda_\nu)_{i\alpha}(\lambda_\nu)^\dagger_{\alpha j}(\lambda_\nu \lambda_\nu^\dagger)_{ij}\right]}{\left(\lambda_\nu \lambda_\nu^\dagger\right)_{ii}} \left(g^{(j,i)}_{\text{ʊ}} + g^{(j,i)}_{S}\right)$$

3. **BV- Sphaleron conserve $Y_{\Delta\alpha}=B/3-L_\alpha$**

Boltzmann eq'n:
$$\frac{dY_{\Delta\alpha}}{dz} = -\sum_i \varepsilon_{i\alpha} D_i \left(Y_{N_i} - Y^{eq}_{N_i}\right) - W_\alpha |A_{\alpha\alpha}| Y_{\Delta\alpha}$$

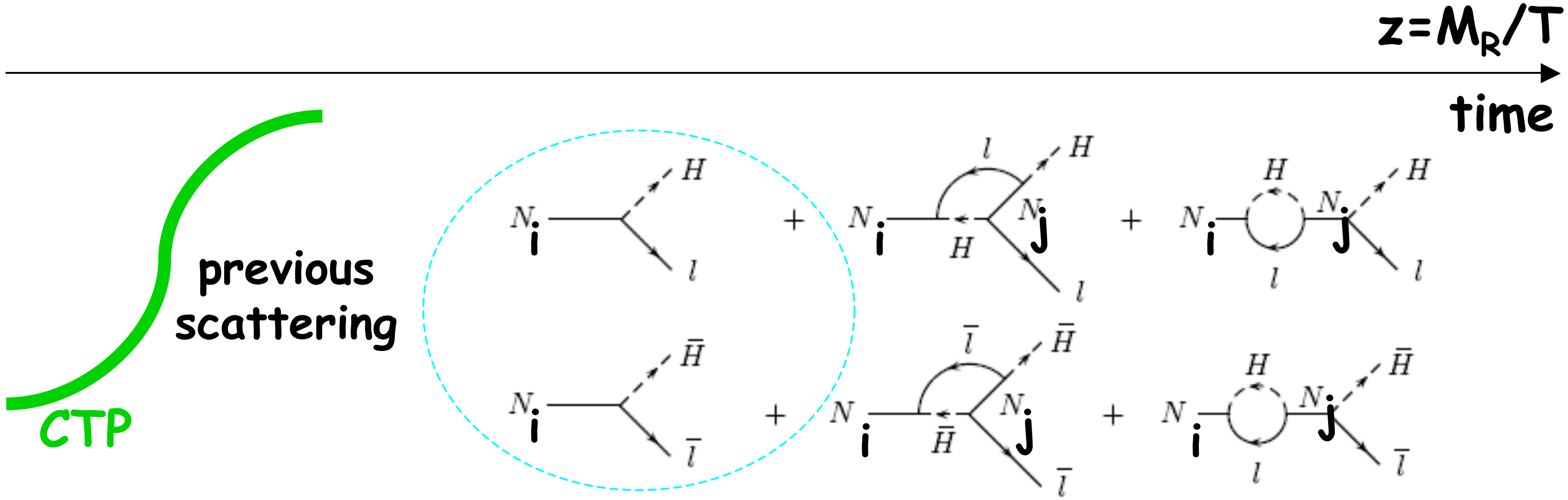
$$\eta_B \frac{n_\gamma}{s} = Y_B = \frac{12}{37} \sum_\alpha Y_{\Delta\alpha}(z \to \infty)$$

Flavor effects

[Barbieri et al; Abada et al;...]

$A_{\alpha\alpha}$ depend on which $Y_{\text{ch.lept}}$ inter'ns are in equil'm

Leptogenesis



$z=M_R/T$

time

previous scattering

CTP

lepton asymm

from solving quantum Boltzmann eq'n

$$\varepsilon_{i\alpha}(z) \equiv \frac{\Gamma(N_i \to \ell_\alpha \bar{H}) - \Gamma(N_i \to \bar{\ell}_\alpha H)}{\Gamma(N_i \to \ell_\alpha \bar{H}) + \Gamma(N_i \to \bar{\ell}_\alpha H)} = \sum_{j \neq i} \frac{1}{8\pi} \frac{\mathrm{Im}\left[(\lambda_\nu)_{i\alpha}(\lambda_\nu)^\dagger_{\alpha j}(\lambda_\nu \lambda_\nu^\dagger)_{ij}\right]}{\left(\lambda_\nu \lambda_\nu^\dagger\right)_{ii}} \left(g_{\mathrm{v}}^{(j,i)} + g_{\mathrm{S}}^{(j,i)}\right) m^{(i,j)}(z)$$

$$2\ \sin^2\left(\frac{1}{2}\frac{M_j - M_i}{2H(M_1)} z^2\right) - \frac{\Gamma_j}{M_j - M_i}\ \sin\left(\frac{M_j - M_i}{2H(M_1)} z^2\right)$$

typical timescale $1/\Delta M_{ij}$

Quantum effects

[De Simone & Riotto '07]

relevant if t'scale-$\varepsilon_{i\alpha}$> t'scale-Y_{Ni}

namely $\Delta M_{ij} = M_i - M_j \lesssim \Gamma_i$

Leptogenesis-related phenomenology

I-Connection with CPV in ν masses

From seesaw: given M_R, reconstruction of Y_ν ambiguous up to R
(^=diag)

$$m_\nu = U^* \hat{m}_\nu U^\dagger = \underbrace{Y_\nu^T \hat{M}_R^{-1} Y_\nu}_{R^T R = 1} v^2$$

Casas-Ibarra parameterization

$$Y_\nu = \sqrt{\hat{M}_R} R \sqrt{\hat{m}_\nu} U^\dagger / v$$

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Casas-Ibarra parameterization

$$Y_\nu = \sqrt{\hat{M}_R} R \sqrt{\hat{m}_\nu} U^\dagger / v$$

(hierarchical case)

Neglecting flavor:

$$\epsilon_1 = -\frac{3M_1}{16\pi v^2} \frac{\mathrm{Im}\left(\sum_\rho m_\rho^2 R_{1\rho}^2\right)}{\sum_\beta m_\beta \left|R_{1\beta}\right|^2}$$

function of R and m_ν only!

[Davidson Ibarra, Branco IM et al, etc]

Including flavor:

$$\epsilon_\alpha = -\frac{3M_1}{16\pi v^2} \frac{\mathrm{Im}\left(\sum_{\beta\rho} m_\beta^{1/2} m_\rho^{3/2} U_{\alpha\beta}^* U_{\alpha\rho} R_{1\beta} R_{1\rho}\right)}{\sum_\beta m_\beta \left|R_{1\beta}\right|^2}$$

introduce dep on U

[Davidson, Ibarra, Petcov et al, etc]

II-Range for RH ν masses

Neglecting flavor:_

efficiency
factor κ<0.1

$$6 \times 10^{-10} \approx \eta_B \approx 10^{-2} \epsilon\, \kappa \lesssim 10^{-3} \epsilon \quad \rightarrow \quad \boxed{\epsilon \gtrsim 10^{-6}}$$

II-Range for RH ν masses

Neglecting flavor:_

efficiency
factor κ<0.1

$$6 \times 10^{-10} \approx \eta_B \approx 10^{-2} \epsilon\, \kappa \lesssim 10^{-3} \epsilon \quad \rightarrow \quad \boxed{\epsilon \gtrsim 10^{-6}}$$

Hierarchical (enough)

[Davidson Ibarra '02]

$$|\epsilon| < \frac{3}{16\pi} \frac{(m_{\max} - m_{\min}) M_1}{v_u^2}$$

$$\Downarrow$$

$$10^9 \mathrm{GeV} \lesssim M_1 \lesssim T_{RH}$$

Nearly degenerate

$$|\epsilon_{N_1}(\text{resonance})| \simeq \frac{1}{2} \frac{|\mathcal{I}m[(\lambda^\dagger\lambda)_{12}^2]|}{(\lambda^\dagger\lambda)_{11}(\lambda^\dagger\lambda)_{22}} . < O(1)$$

$$\Downarrow$$

$$\mathrm{TeV} \lesssim M_1 \lesssim T_{RH}$$

Including flavor: lower bound on M_1 relaxed in general by O(2)_

III-Embedding in SUSY: gravitinos

T_{RH} has to be small enough to avoid overproduction of gravitinos during reheating. Being only gravitationally coupled to MSSM particles, they decay late destroying successful BBN. [Moroi, etc]

For $m_{3/2} \approx 10^2 - 10^3\mathrm{GeV}$

gravitino bound

$$\boxed{T_{RH} \lesssim 10^5 - 10^7\mathrm{GeV}}$$

Tension with lower bound on M_1 for hier RH ν's

$$\boxed{10^9\mathrm{GeV} \lesssim M_1}$$

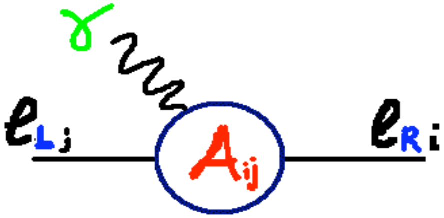
→**thermal production of RH ν's is inefficient**

<u>WAYS OUT</u>:

non-thermal production, e.g. via flat directions in scalar potential [Giudice etc];

stable gravitinos (but then model dependence); **resonant leptogenesis; etc etc**

IV-Embedding in SUSY: LFV & EDM



Loops w/ Sleptons
& Gauginos

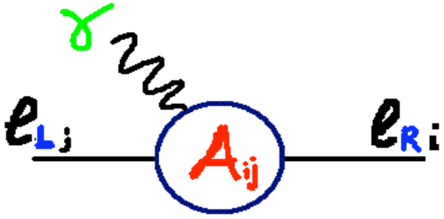
LFVdecays

$$BR(\ell_i \to \ell_j \gamma) \propto |A_{ij}|^2 = f_{LL}\,|\delta^{LL}_{ji}|^2 + f_{RR}\,|\delta^{RR}_{ji}|^2 + f_{LR}\,|\delta^{LR}_{ji}|^2 + f_{RL}\,|\delta^{RL}_{ji}|^2 + \ldots$$

EDMs

$$d_{\ell_i} = Im A_{ii} \;\; = f_a m_{\ell_i} Im a_i + f_{LLRR} Im(\delta^{LL} m_\ell \delta^{RR})_{ii} + \ldots$$

IV-Embedding in SUSY: LFV & EDM



Loops w/ Sleptons
& Gauginos

From **mSUGRA** at M_{Pl}, susy seesaw
induce FV and CPV at l.e. via **RGE**

$$C^k_{ij} = Y^*_{\nu\,ki} Y_{\nu\,kj} \ln \frac{M_{Pl}}{M_k}$$

[BorzumatiMasiero '86]

$$-\frac{1}{(4\pi)^2}\frac{6m_0^2+2a_0^2}{\bar{m}_L^2}\sum_k C^k_{ij}$$

LFVdecays

$$BR(\ell_i \to \ell_j \gamma) \propto |A_{ij}|^2 = f_{LL}\,|\delta^{LL}_{ji}|^2 + f_{RR}\,|\delta^{RR}_{ji}|^2 + f_{LR}\,|\delta^{LR}_{ji}|^2 + f_{RL}\,|\delta^{RL}_{ji}|^2 + \ldots$$

EDMs

$$d_{\ell_i} = Im A_{ii} \quad = \quad f_a m_{\ell_i} Im a_i + f_{LLRR} Im(\delta^{LL} m_\ell \delta^{RR})_{ii} + \ldots$$

FC

FV

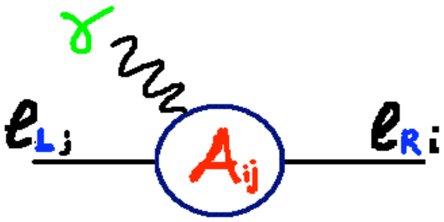
$$\frac{8a_0}{(4\pi)^4}\sum_{k>k'}\frac{\ln^k_{k'}}{\ln^{\rm Pl}_{k'}}\,{\rm Im}(C^k C^{k'})_{ii}$$

[EllisHisanoLolaRaidalShimizu '01]

$$\frac{8m_{\ell_i}}{(4\pi)^6}\frac{(6m_0^2+2a_0^2)(6m_0^2+3a_0^2)}{\bar{m}_L^2\bar{m}_R^2}\frac{m_\tau^2\tan^2\beta}{v^2}\sum_{k>k'}\cdot\widetilde{\ln}^k_{k'}\,{\rm Im}\left(C^k\frac{m_\ell^2}{m_\tau^2}C^{k'}\right)_{ii}$$

[IM '03]

IV-Embedding in SUSY: LFV & EDM



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$$C^k_{ij} = Y^*_{\nu\,ki} Y_{\nu\,kj} \ln \frac{M_{Pl}}{M_k}$$

at present (future)

LFVdecays BR(μ→e γ) < **10^{-11}**$^{(-13)}$ → $C_{21} < 10^{-1(-2)}$

strong impact on
see-saw models

[Buchmuller et al; Sato, Tobe, Yanagida; Casas Ibarra;
King et al; Lavignac I.M. Savoy; Masiero et al; ....]

EDMs $d_e <$ **10^{-27}**$^{(-30)}$ e cm → seesaw contribution to d_e observable in future only if tgβ large, RH ν's are Hi and various yukawas are O(1) [IM'04]

e.g.

$$Y_\nu = \begin{pmatrix} \lesssim 10^{-2} & \lesssim 10^{-2} & \lesssim 10^{-2} \\ \mathcal{O}(1) & \approx 0 & \mathcal{O}(1) \\ \mathcal{O}(1) & \approx 0 & \mathcal{O}(1) \end{pmatrix}$$

Th leptogenesis & observable
seesaw-induced d_e → $M_1 > 10^{11}$ GeV
→ can't explain both with seesaw

[IM Riotto Joaquim, ph/0701270]

V-Embedding in flavor models/GUTs

To look for correlations among observables:

2 examples with A) hierarchical B) degenerate RH ν's

A $SU(5)XU(1)_F$ with $q>0$ [Froggatt Nielsen]

$$\begin{cases} \eta_B : & M_1 = O(10^{11}) \text{ GeV} \\ \mu \to e\,\gamma : & M_3 \leq 5\text{x}10^{12\text{-}13} \text{ GeV} \end{cases}$$

x 1/30 in future

→ WHOLE CLASS could be TESTED!! [IM Savoy '05]

B Minimal Lepton Flavor Violation

Quantum effects [DeSimone Riotto Blanchet DiBari Raffelt]

might be as large as $O(10^3)$ [Cirigliano De Simone Isidori IM Riotto '07]

…despite "Minimal", not a very predictive model for η_B

Conclusions

New TeV-scale physics should not Violate too much F&CP

New physics must explain B-asymmetry → e.g. via leptogenesis

New Phys = seesaw

As happens for leptogenesis

(and depending on the details of the model),

the flavor structure of New Physics

can play a significant role in the generation of the B-asymmetry