GUT & leptogenesis

a predictive class of models

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MF, P.Hosteins, S.Lavignac and A.Romanino, NPB 806 (2009) 84

L.Calibbi, MF, S.Lavignac and A.Romanino, JHEP 0912 (2009) 057

Galileo Galilei Institute
Indirect searches for new physics at the time of LHC
Arcetri, March 10, 2010

GUT motivations (theory)

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- Supersymmetric Grand Unification (SUSY GUTs) may account for
  - the hierarchy problem, if the supersymmetry is realized close to the electroweak scale
  - the relative values of the Standard Model (SM) gauge couplings
  - the charge quantization, since the gauge group is simple
  - the gauge quantum numbers of the SM fermions
  - the mass relations between quarks and leptons
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  - ✤ the charge quantization, since the gauge group is simple
  - ✤ the gauge quantum numbers of the SM fermions
  - ✤ the mass relations between quarks and leptons
  - ✤ the chiral anomaly cancellation
- SUSY Grand Unification should then be realized at some level. We adopt here the traditional picture, with low energy SUSY, four spacetime dimensions and gravity effects negligible below M_{Planck}

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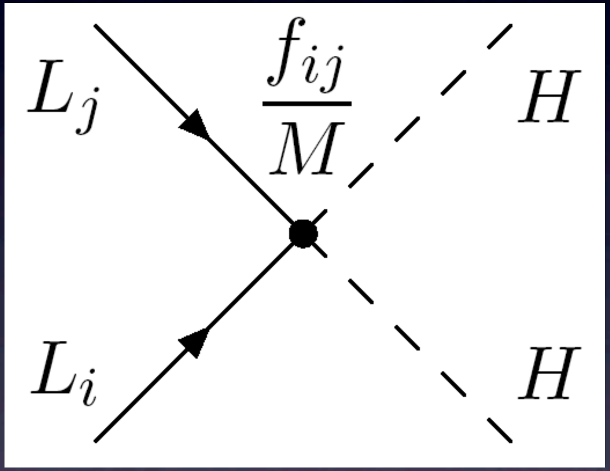
Neutrino mass & GUT scale

$$\frac{1}{M}\mathcal{L}_{D=5} = \frac{f_{ij}}{M} L_i L_j H H$$

the only dimension-5
operator that can be added
to the Standard Model



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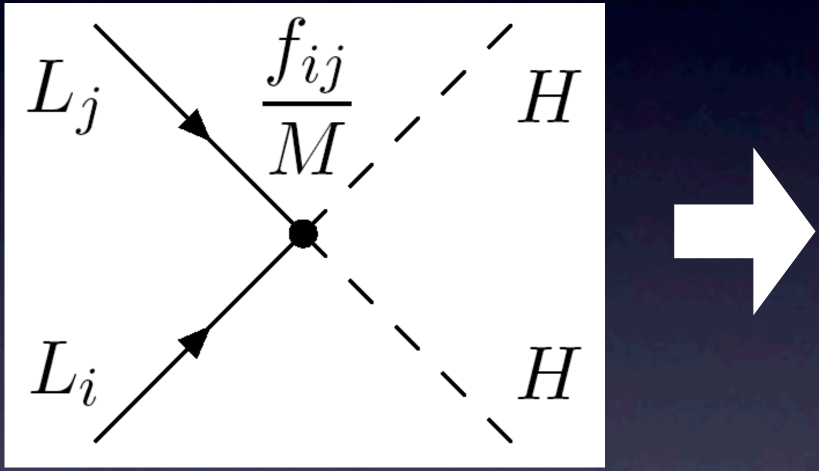
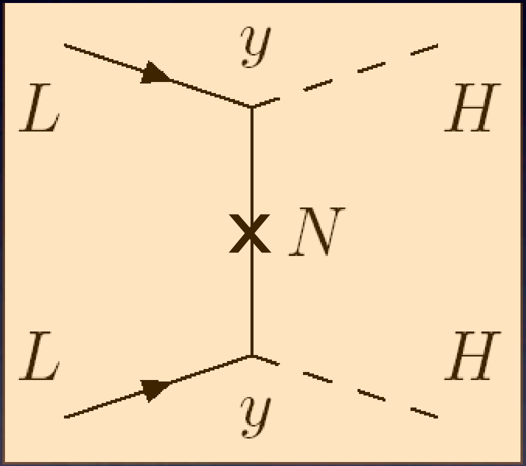
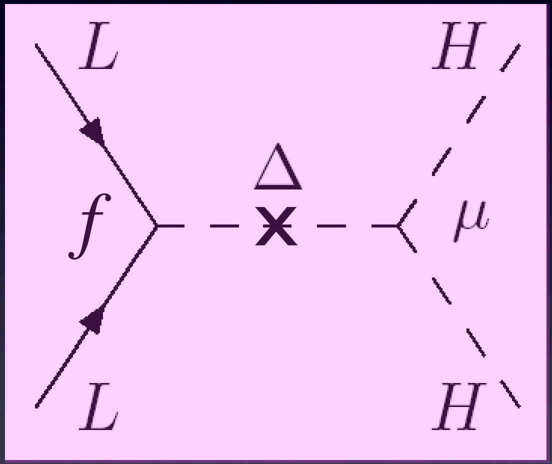




type I



type II

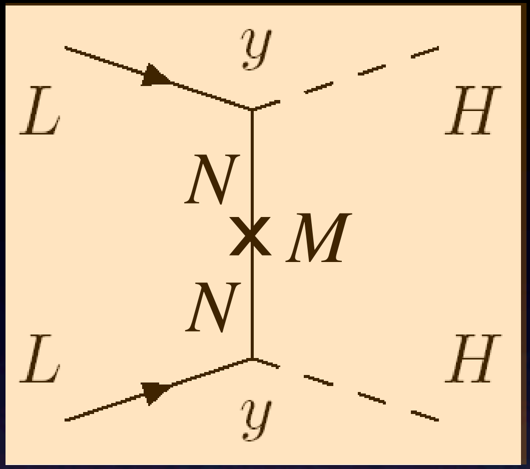
$$(m_\nu)_{ij}\nu_i\nu_j = \frac{f_{ij}\langle H^0\rangle^2}{M}\nu_i\nu_j$$

Seesaw mechanism:
exchange of superheavy
(<10^{15} GeV) particles
induces tiny Majorana
neutrino masses

Lepton flavour structure

In type I seesaw, light neutrinos couple through y_{ij} to gauge singlets N's, which have heavy Majorana masses M_{ij} : there are two sets of flavour parameters

$$m_{ij} = y_{ik} M^{-1}_{kl} y_{jl} v^2$$



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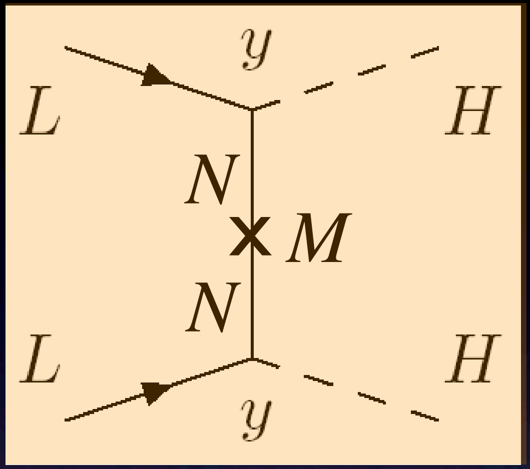
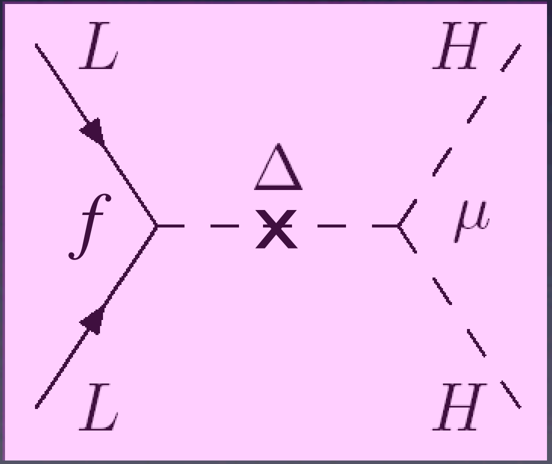


In type II seesaw, light neutrinos couple to the $SU(2)_L$ triplet Δ, with couplings f_{ij}

$$m_{ij} = \frac{\mu v^2}{M_\Delta^2} f_{ij}$$



The unique set of flavour parameters is the low energy one, that is, the light neutrino mass matrix m_{ij}

Baryogenesis via leptogenesis

$$\boxed{\frac{n_B}{s} \approx 0.9\ 10^{-10}}$$

WMAP

Sakharov

3 necessary conditions to generate the matter-antimatter asymmetry:

(i) violation of B-L symmetry: M_N

(ii) violation of CP symmetry: y

(iii) epoch out of thermal equilibrium

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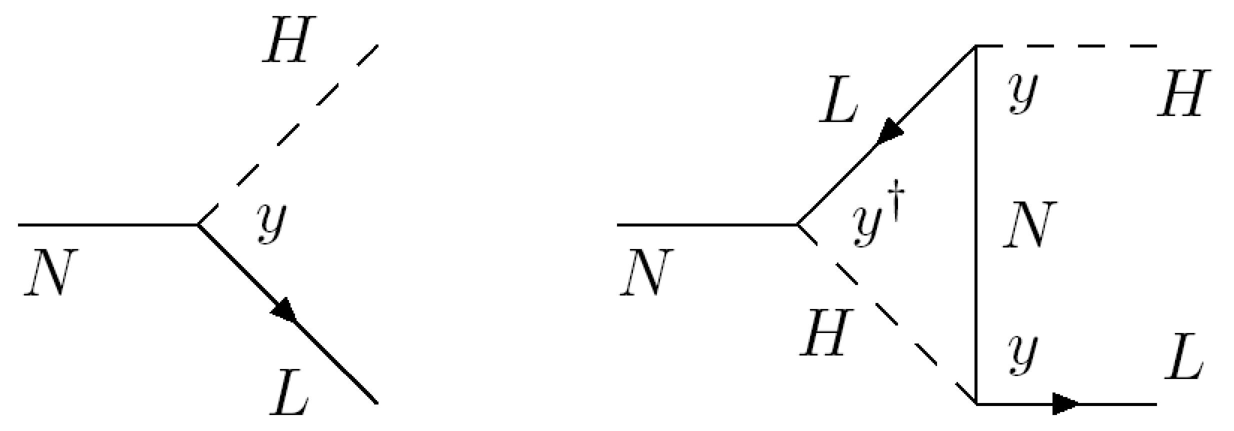
In the early Universe the heavy particles may decay out-of-equilibrium into leptons



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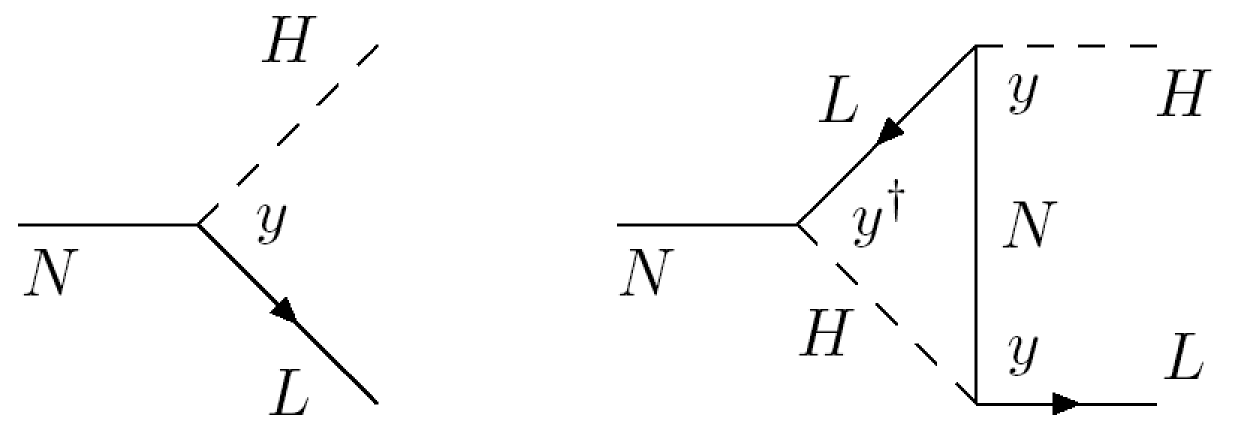
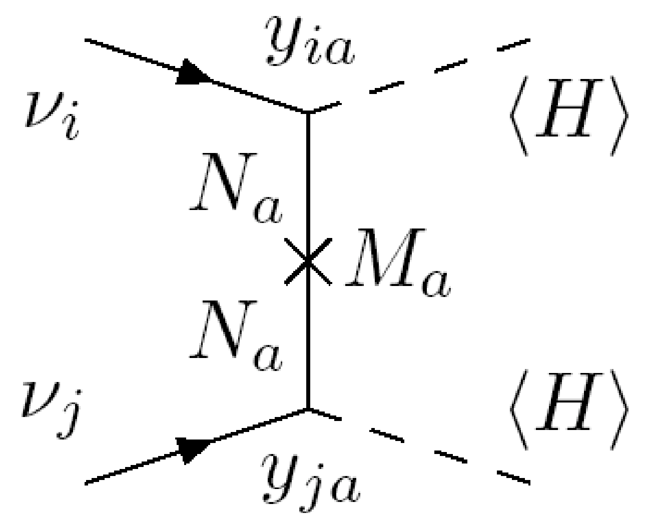


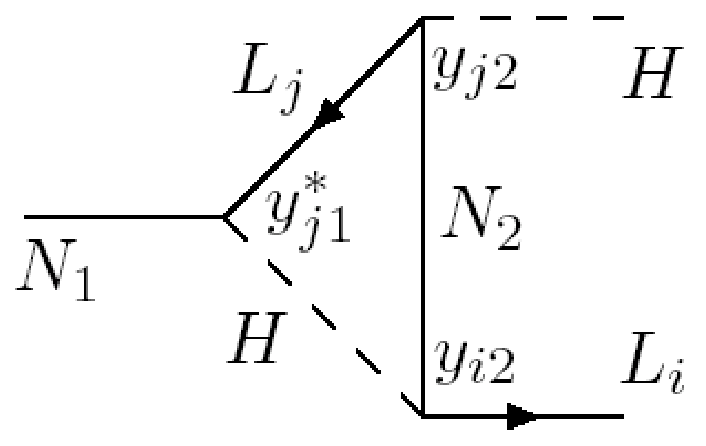
Asymmetry suppressed by (i) large number of d.o.f. (ii) a loop factor (iii) dilution effects

$$\boxed{\frac{n_B}{s} \approx 10^{-3} \epsilon_L \eta \overset{obs}{\approx} 10^{-10}}$$

Is leptogenesis testable? Flavour

$$m_{ij} = -\sum_a y_{ia} \frac{v^2}{M_a} y^T_{aj}$$





$$\epsilon_L = \frac{3}{8\pi} \frac{M_1}{M_2} \frac{\mathrm{Im}[(y^\dagger y)_{12} (y^\dagger y)_{12}]}{(y^\dagger y)_{11}}$$

$\varepsilon_L \equiv [\, \Gamma(N \to LH) - \Gamma(N \to L^* H^*) \,] / \Gamma_{tot}$

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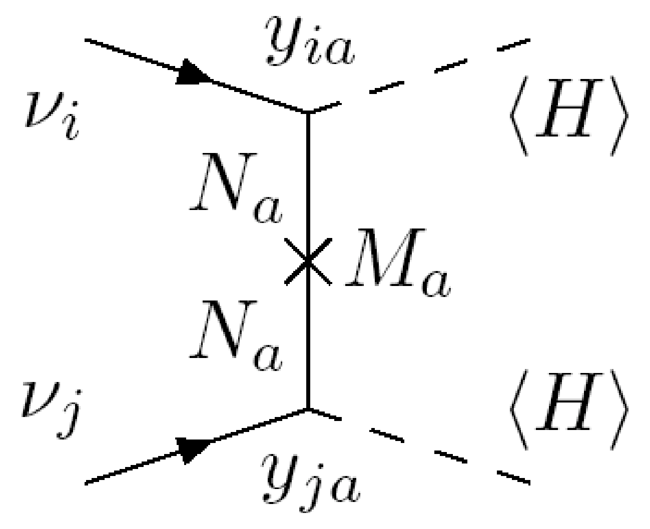

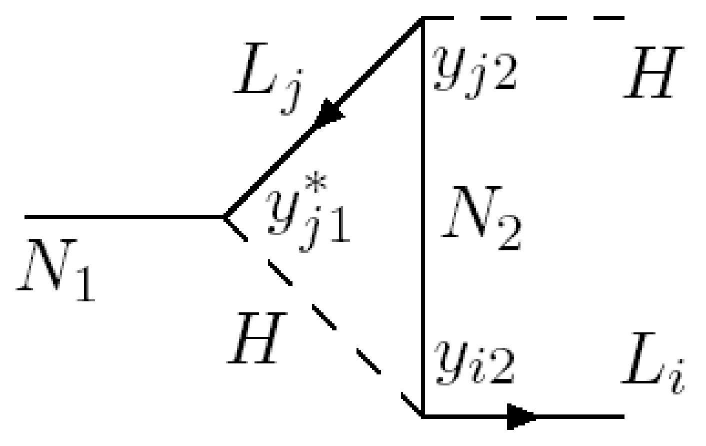

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✏ the couplings y_{ia} are not directly accessible at low energy

✏ N_1 and N_2 (at least) with different couplings are needed

✏ the outcome depends on several high energy flavour parameters

(minimal GUT models partially constrain y_{ia} and are more predictive)

Outline

- Type I SO(10) unification vs type II SO(10) unification: a class of models with no unknown flavour parameters at GUT scale
  - ✤ some model building ...
- Baryogenesis via leptogenesis in type II SO(10)
  - ✤ the CP asymmetry, the efficiency factor, the constraints on light neutrino parameters
- mSUGRA flavour & CP violating effects in type II SO(10)
  - ✤ the prediction for BR($\mu \to e\gamma$) waiting for the MEG experiment results

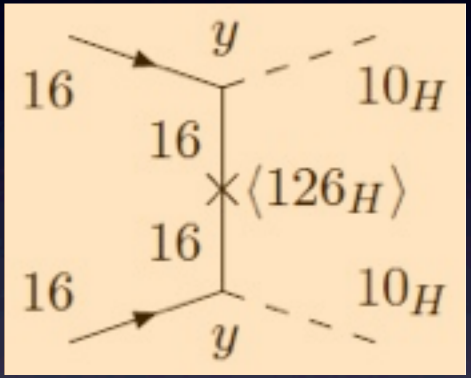
Neutrino masses in SO(10)

In usual SO(10) one entire family sits in a spinor representation:

$$16 = (1 + \overline{5} + 10)_{SU(5)} = N^c + (L, d^c) + (Q, u^c, e^c)$$

Neutrino Yukawa couplings lead to type I seesaw:

$$y\ 16\ 16\ 10_H \supset y\ L\ N^c\ H_u$$



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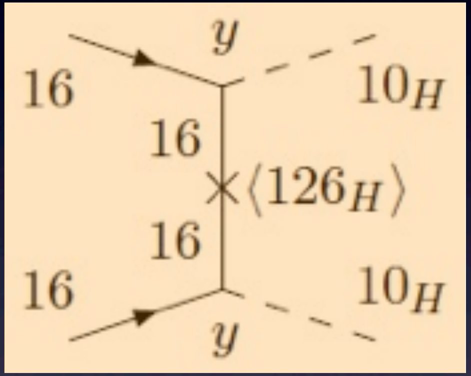
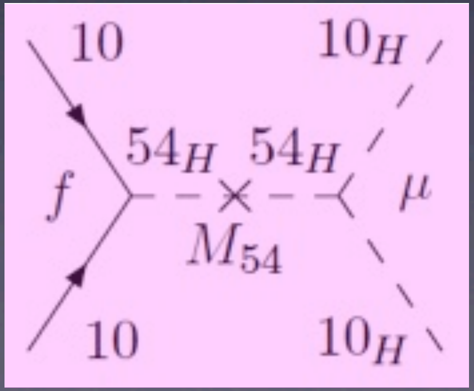


$$y\ 16\ 16\ 10_H \supset y\ L\ N^c\ H_u$$

The fundamental representation also contains L and d^c states:

$$10 = (5 + \overline{5})_{SU(5)} = (L^c,\ d) + (L,\ d^c)$$

These L states have no Yukawas to N^c, but:



$$f\ 10\ 10\ 54_H \supset f\ L\ L\ \Delta$$

Light & heavy matter fields

If both 16 and 10 matter fields exist, the light lepton doublet L is in general a linear combination of L^{16} and L^{10}.

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When SO(10) is broken to SU(5) by the VEV of a dim-16 Higgs, the states $(L, d^c)^{16}$ acquire a mass of order M_{GUT} :

$$Y^D 16\ 10\ 16_D \supset Y^D \left(\boxed{\bar{5}^{16}\ \ 5^{10}}\, \langle 1_D^{16} \rangle + 10^{16}\ \bar{5}^{10}\ \ \langle \bar{5}_D^{16} \rangle \right) .$$

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The light L and d^c states belong to the 10 multiplets.

Y^D generates also down quark & charged lepton masses.

Charged fermion masses

In other words, type II SO(10) is a different route to embed the flexible SU(5) unification into the more constrained SO(10) unification:

SU(5)

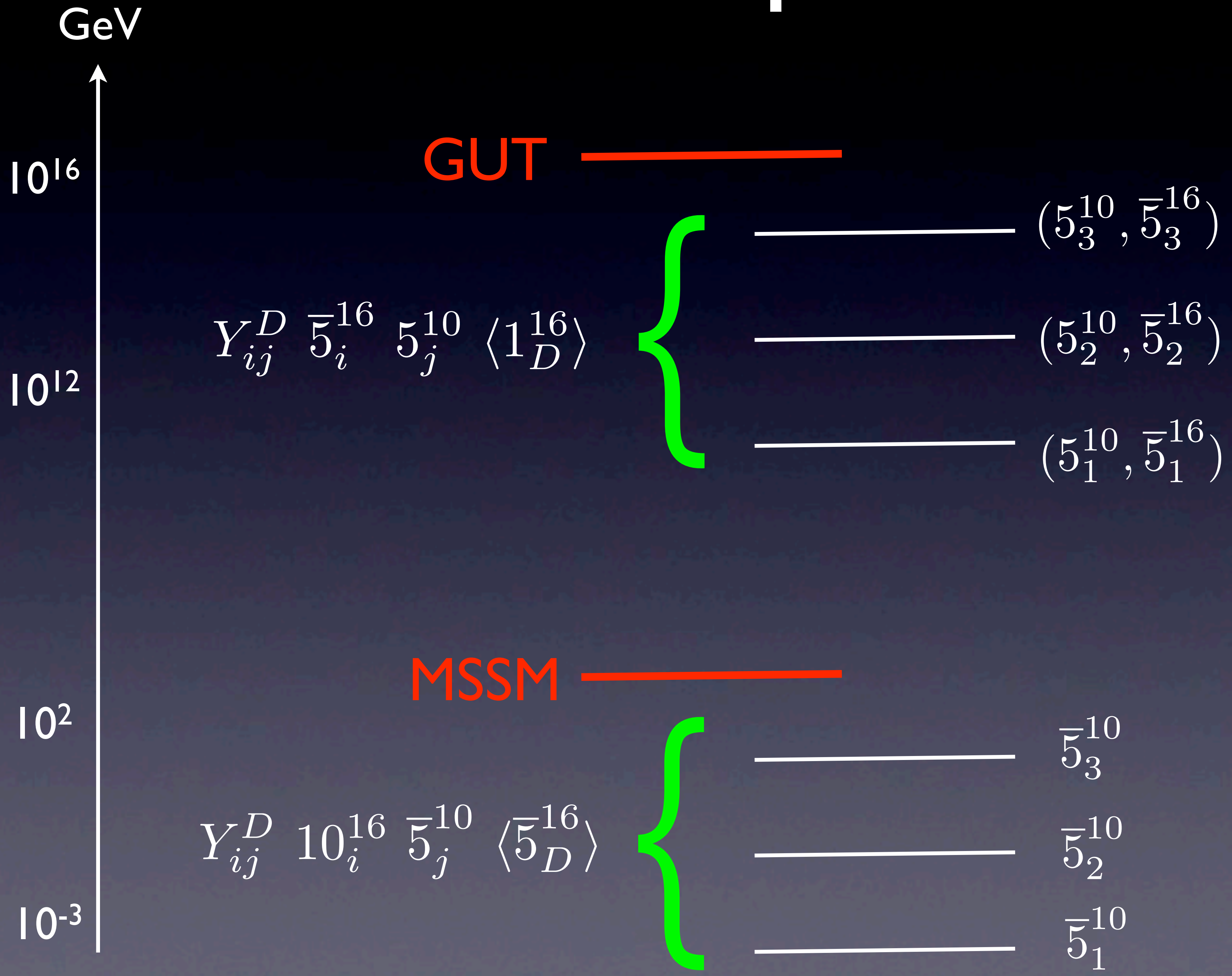
$$\begin{tikzcd}
\boxed{Y^U_{ij}\ 10_i\ 10_j\ 5_U + Y^D_{ij}\ 10_i\ \bar{5}_j\ \bar{5}_D} \arrow[r, "\text{type I}", "\text{SO(10)}"'] \arrow[d, "\text{type II}"', "\text{SO(10)}"] & \begin{array}{r} Y^U_{ij}\ 16_i\ 16_j\ 10_U \\ +Y^D_{ij}\ 16_i\ 16_j\ 10_D \end{array} \\
Y^U_{ij}\ 16_i\ 16_j\ 10_U + Y^D_{ij}\ 16_i\ 10_j\ 16_D &
\end{tikzcd}$$

$$\boxed{\begin{array}{l} 16 = (1 + \bar{5} + 10)_{SU(5)} \\ 10 = (\bar{5} + 5)_{SU(5)} \end{array}}$$

The up-type Higgs doublet resides in 10_U, as usual.

The down-type Higgs doublet resides in 16_D, which is needed anyway.

The mass spectrum

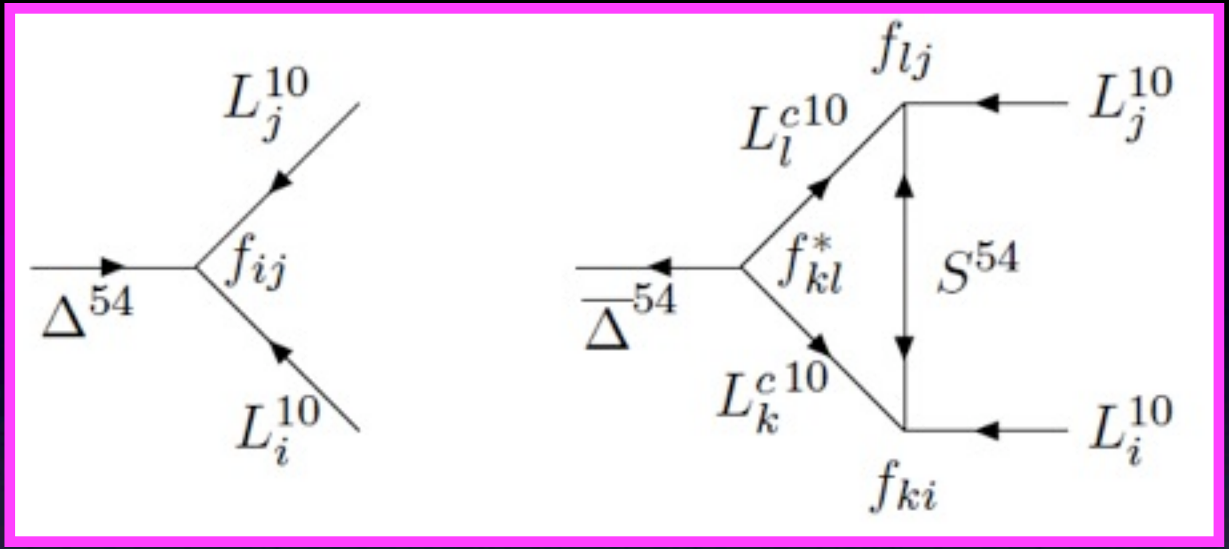


Model-building issues

- SO(10) is broken to the SM in one step by an appropriate choice of W_{GUT}, involving extra fields with mass M_{GUT}
- Natural doublet-triplet splitting: the MSSM Higgs doublets ($H_U \subset 10_U$ & $H_D \subset 16_D$) are kept light by the 'missing VEV' mechanism
- Dim-5 operators contribute to p-decay through T_U - T_D mixing: this needs to be tuned down to about $10^{-2}\, M_{GUT}$, similarly to minimal SU(5)
- Dim-6 operators contribute to p-decay through the (X,Y) gauge bosons as in SU(5): the present bound is $M_{GUT} > 5\ 10^{15}$ GeV

Type II SO(10) leptogenesis

$$\begin{aligned} W_{SO(10)} &\supset f_{ij}\ 10_i\ 10_j\ 54 \\ &\supset f_{ij}\ L_i\ L_j\ \Delta \\ &+ f_{ij}\ L_i^c\ L_j^c\ \overline{\Delta} \\ &+ f_{ij}\ L_i\ L_j^c\ S \end{aligned}$$



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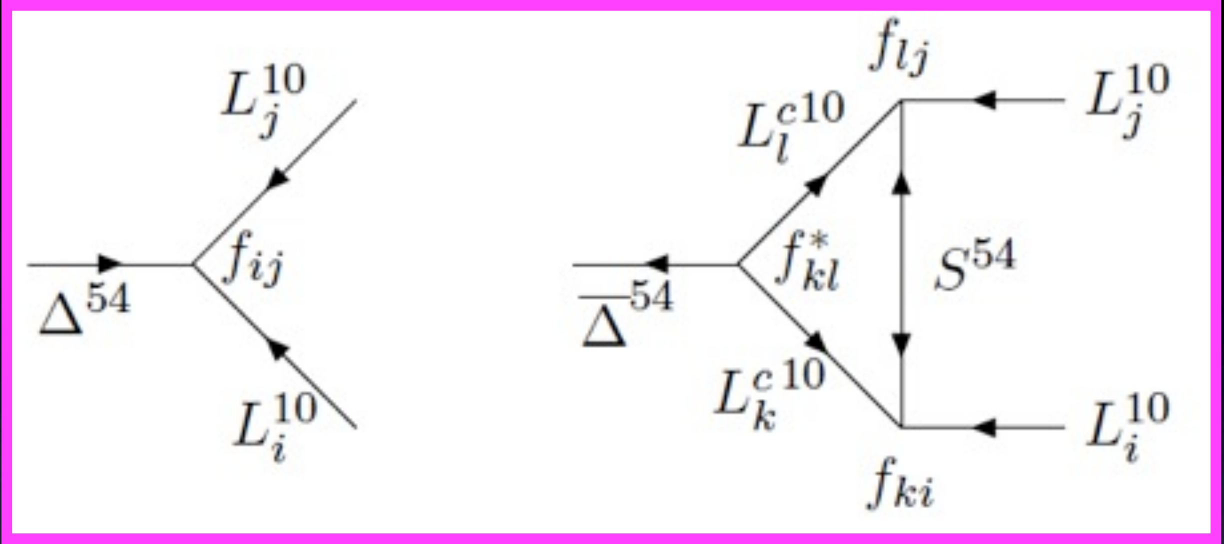

A lepton asymmetry is produced by the couplings f_{ij} only

$$m_\nu = \frac{\sigma_u v_u^2}{2M_\Delta} f$$

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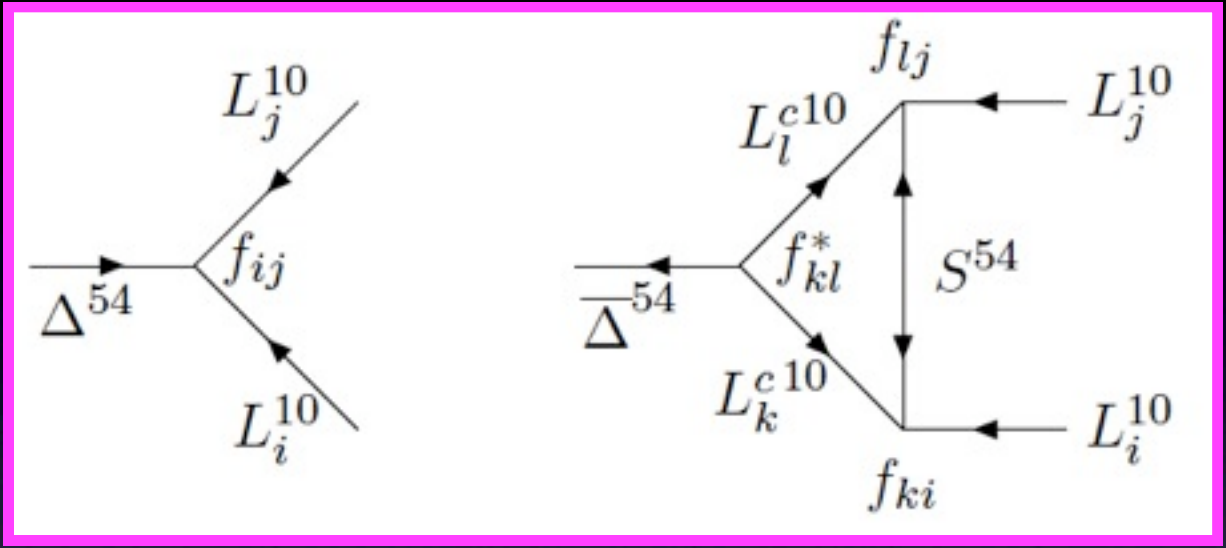

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The leptons L^c in the loop are heavy, with masses $M_{1,2,3} \approx y_{e,\mu,\tau} M_{GUT}$. In the case $M_1 << M_\Delta < M_2$ one finds

$$\epsilon_L \approx \frac{\mathrm{Tr}(f^* f)}{10\pi} \frac{M_\Delta}{M_S} \frac{\mathrm{Im}[m_{11}(m^* m m^*)_{11}]}{(\sum_{i=1}^3 m_i^2)^2}$$

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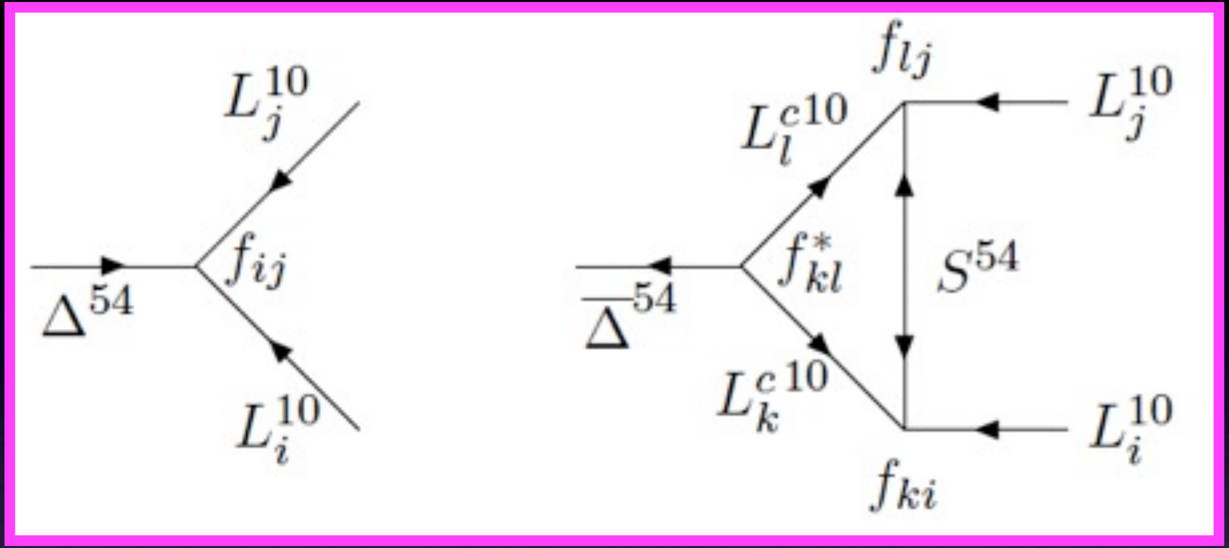

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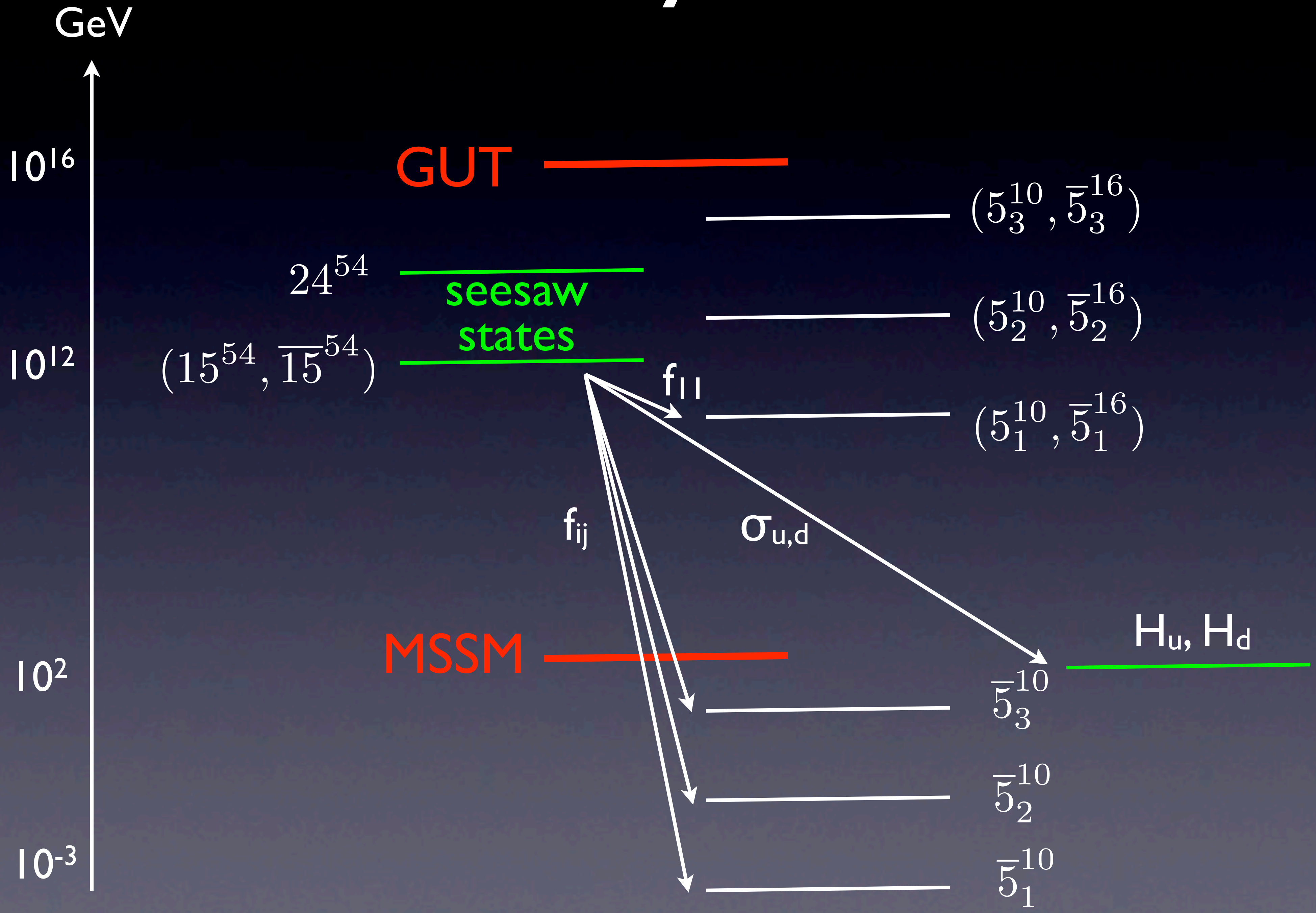
Baryogenesis from the same CP phases observable in the lepton sector !

The decay channels



GeV

10^{16}

GUT

$(5_3^{10},\bar{5}_3^{16})$

24^{54}

seesaw states

$(5_2^{10},\bar{5}_2^{16})$

10^{12}

$(15^{54},\overline{15}^{54})$

f_{11}

$(5_1^{10},\bar{5}_1^{16})$

f_{ij}

$\sigma_{u,d}$

H_u, H_d

MSSM

10^2

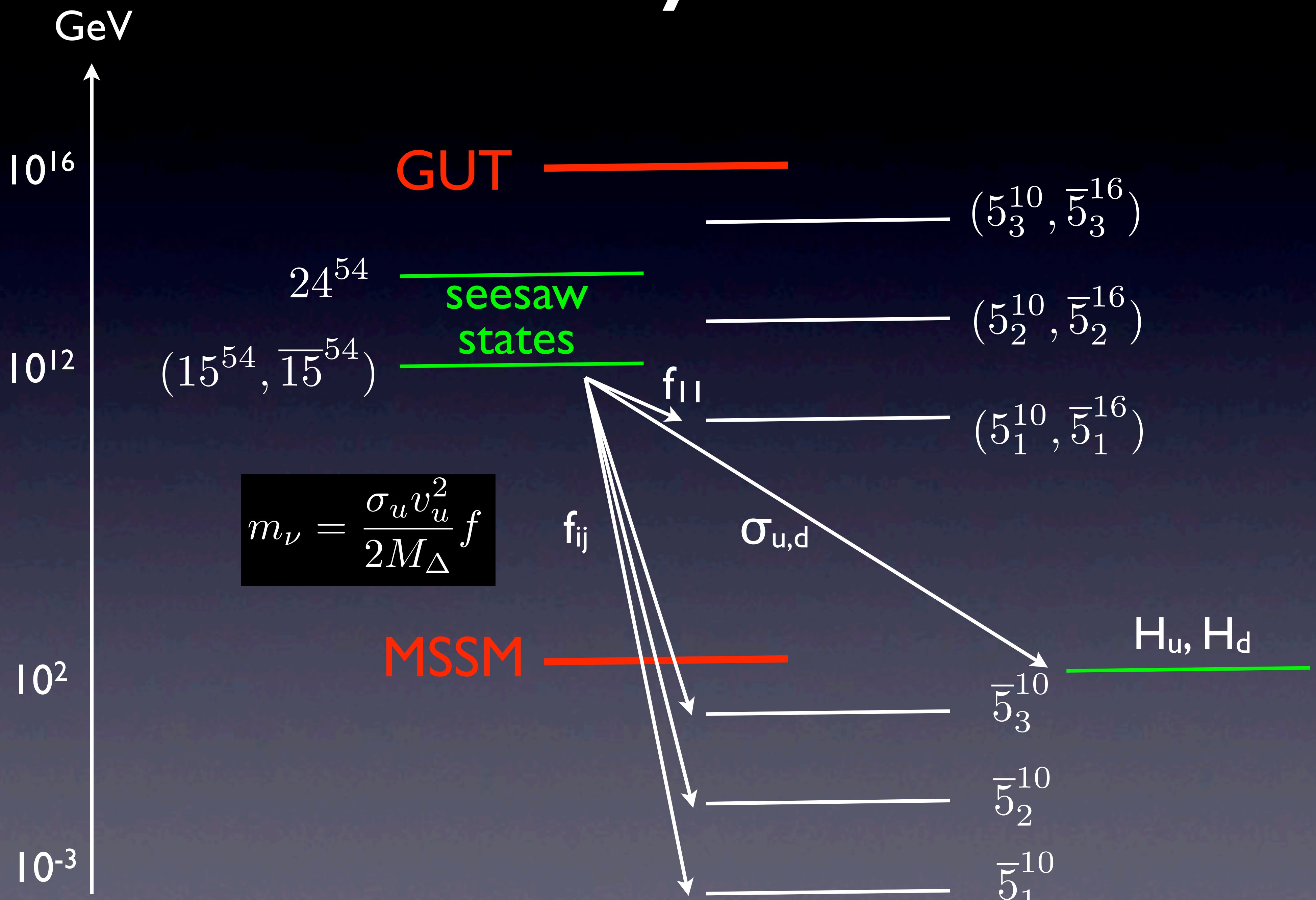
$\bar{5}_3^{10}$

$\bar{5}_2^{10}$

10^{-3}

$\bar{5}_1^{10}$

The decay channels



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seesaw
states

$(15^{54}, \overline{15}^{54})$

$(5_3^{10}, \bar{5}_3^{16})$

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f_{11}

f_{ij}

$\sigma_{u,d}$

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MSSM

H_u, H_d

$\bar{5}_3^{10}$

$\bar{5}_2^{10}$

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Efficiency of leptogenesis

$$\frac{n_B}{s} = 7.6 \times 10^{-3}\ \epsilon_L\ \eta \overset{obs}{=} 0.9 \times 10^{-10}$$

$$\boxed{(\epsilon_L)_{max} \approx 0.1\ \sqrt{\frac{\Delta m^2_{12}}{\Delta m^2_{23}} s^2_{13}}\,\Bigg|_{max} \approx 10^{-3}}$$

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The efficiency parameter η is determined by the Boltzmann equations for the decays of Δ in the three channels LL, L^{c}L^c and HH

$$\Gamma_{tot}(\Delta) = \frac{M_\Delta}{32\pi}\left[\lambda^2_L + \lambda^2_{L^c} + \lambda^2_H\right] \qquad K_a \equiv \frac{\Gamma(\Delta \to aa)}{H(M_\Delta)} \overset{?}{<} 1$$

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Large (order one) efficiency η is obtained when Γ$_{tot}$ is larger than Hubble, but one decay channel is out-of-equilibrium

Hambye, Raidal, Strumia

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$$\frac{n_B}{s} = 7.6 \times 10^{-3}\ \epsilon_L\ \eta \overset{obs}{=} 0.9 \times 10^{-10}$$

$$\boxed{(\epsilon_L)_{max} \approx 0.1 \sqrt{\frac{\Delta m^2_{12}}{\Delta m^2_{23}} s^2_{13}}\Bigg|_{max} \approx 10^{-3}}$$

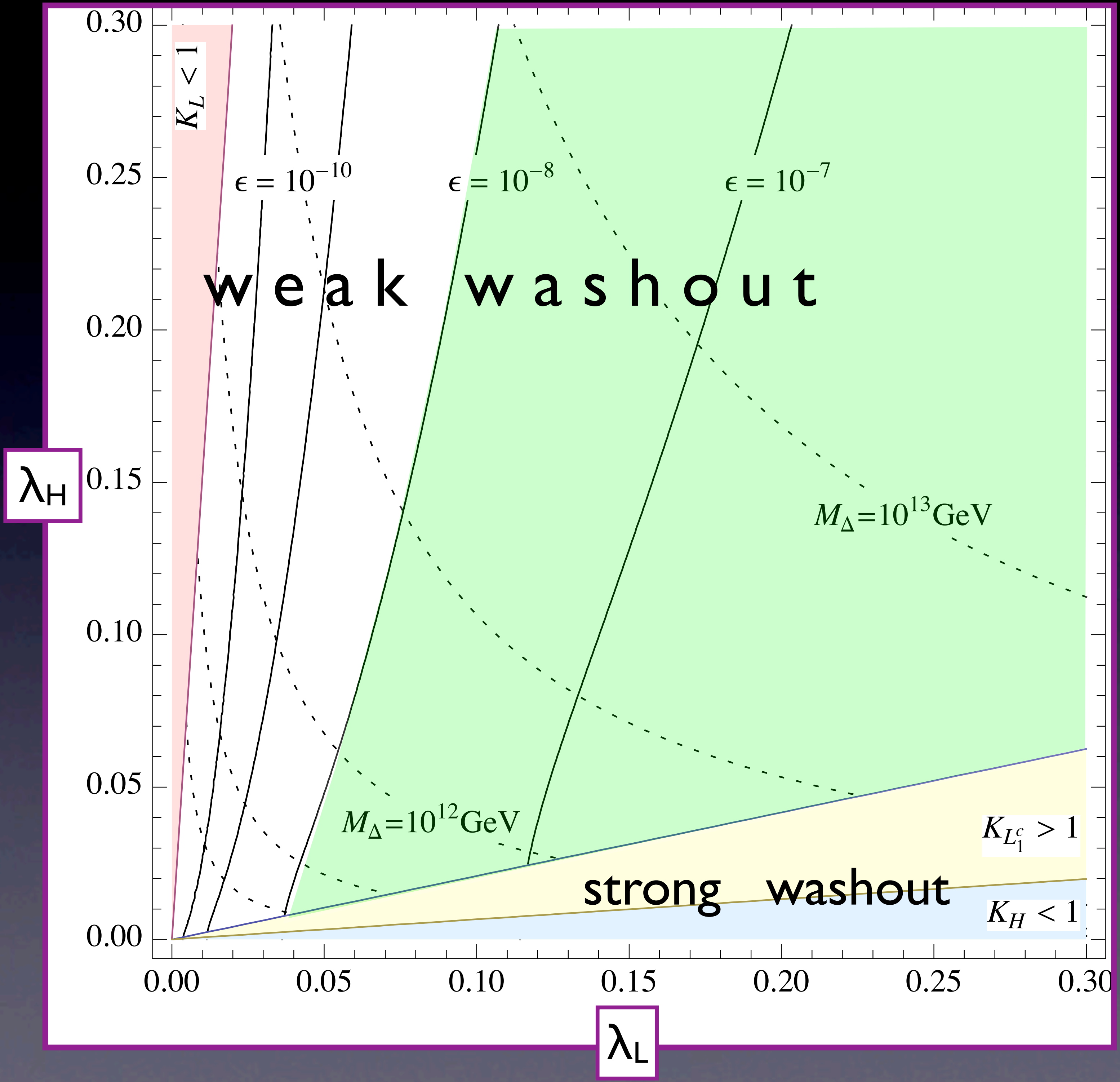
The efficiency parameter η is determined by the Boltzmann equations for the decays of Δ in the three channels LL, L^cL^c and HH

$$\Gamma_{tot}(\Delta) = \frac{M_\Delta}{32\pi}\left[\lambda_L^2 + \lambda_{L^c}^2 + \lambda_H^2\right] \qquad K_a \equiv \frac{\Gamma(\Delta \to aa)}{H(M_\Delta)} \overset{?}{<} 1$$

Large (order one) efficiency η is obtained when Γ_{tot} is larger than Hubble, but one decay channel is out-of-equilibrium

Hambye, Raidal, Strumia

- The neutrino mass scale fixes $K_L K_H = 220 (\Sigma_i m_i^2) / \Delta m^2_{23} >> 1$
- A good efficiency requires $K_{L^c} = |m_{ee}|^2 / (\Sigma_i m_i^2) K_L << 1$



Define $Y_p = (n_p - n_{p^*})/s$ for each species p.

At the end of baryogenesis epoch we find $Y_{L^c} = Y_L - Y_H \neq 0.$

Later L^c's decay and asymmetry in light leptons is left.

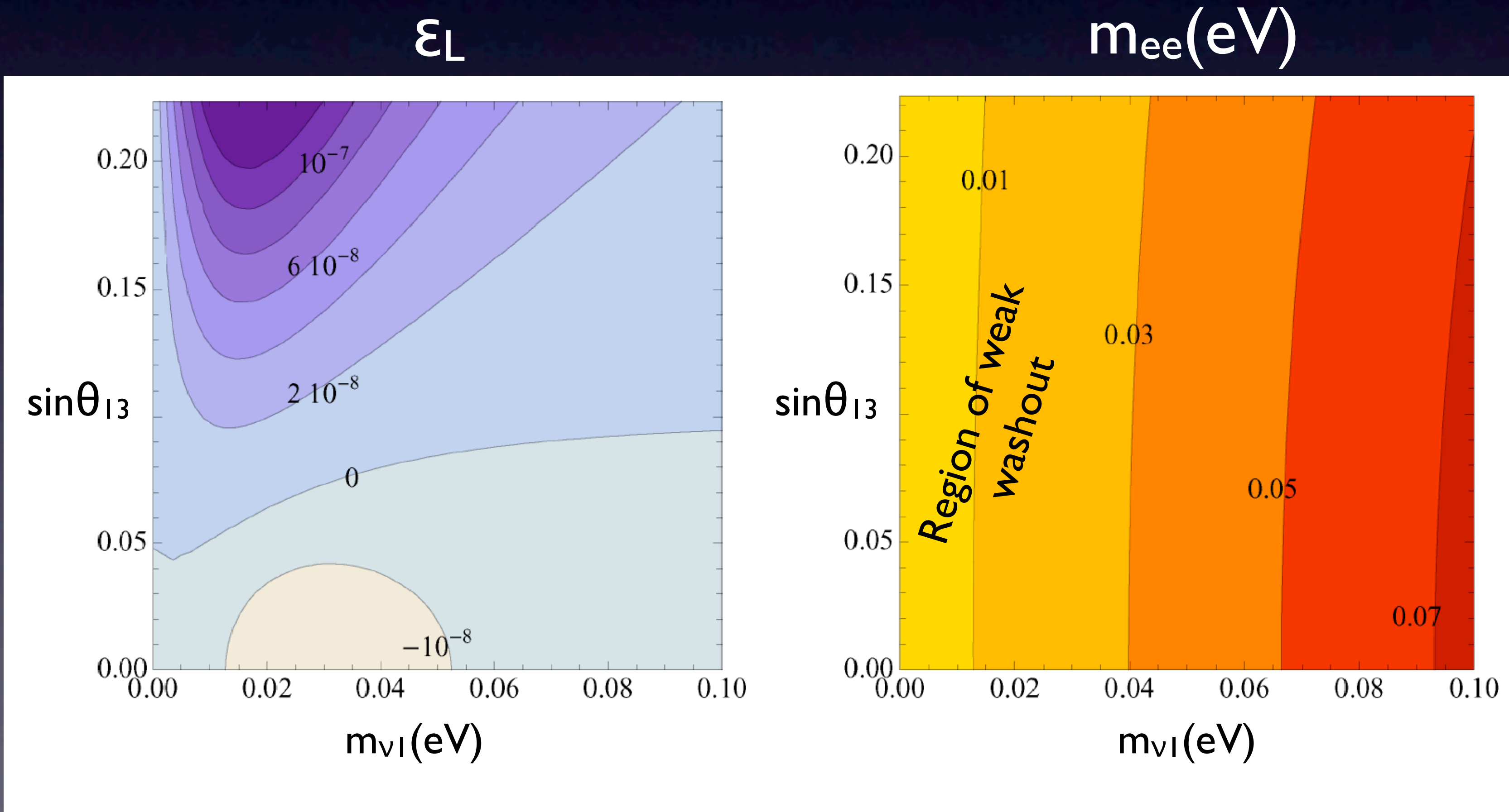
Constraints on ν parameters

The washout may be weak & the CP asymmetry sufficiently large for $M_\Delta > 10^{11}$GeV and specific ν parameters. If one takes $M_\Delta = 10^{12}$ GeV, successful leptogenesis requires: (i) suppression of 0ν2β decays (ii) normal ν mass hierarchy (iii) sin θ_{13} close to the upper bound ≈ 0.2

Baryon asymmetry above 10^{11}GeV

↕

Neutrinoless 2β decay of heavy nuclei

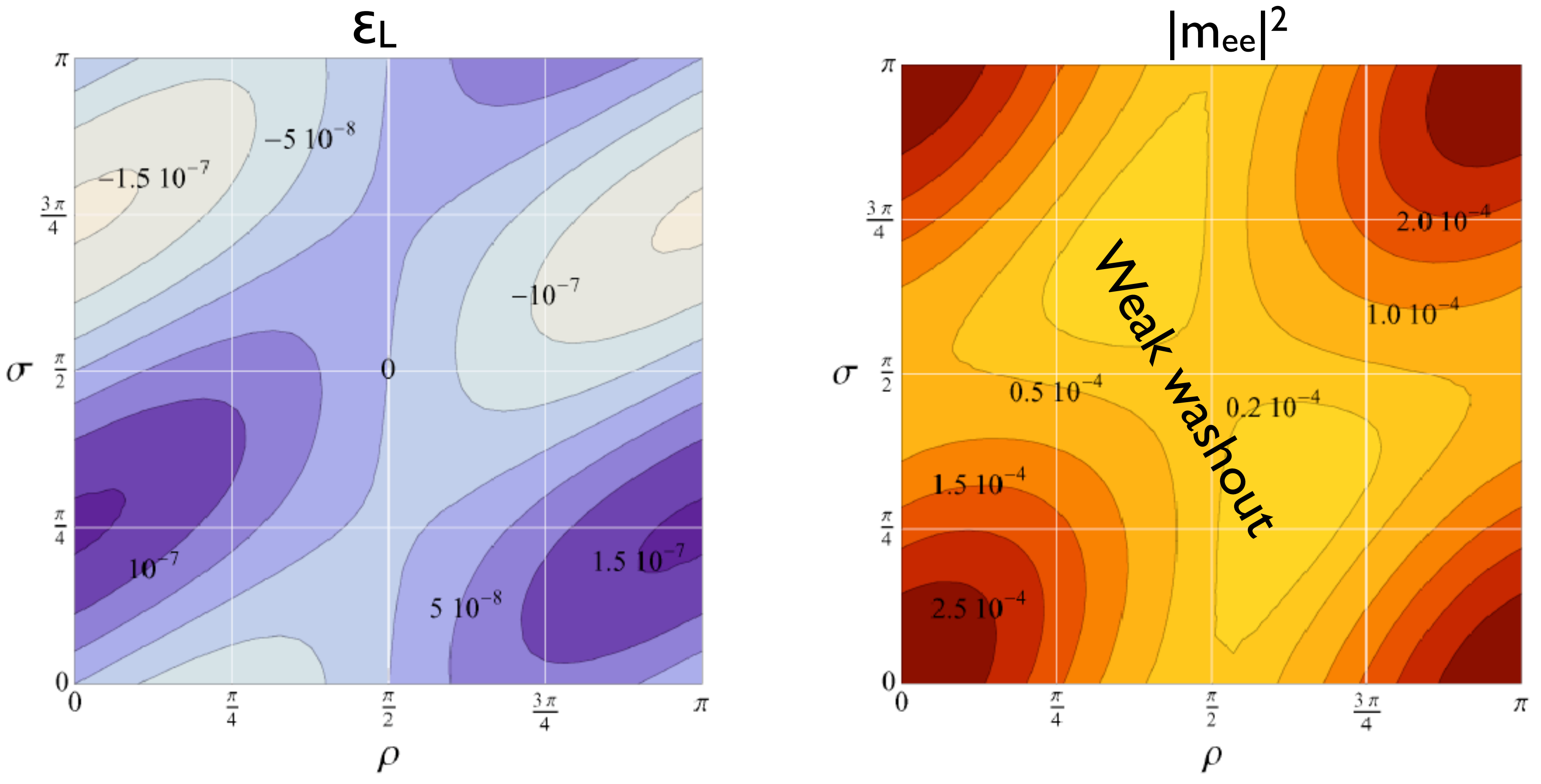


Constraints on ν parameters

Successful leptogenesis implies also non-zero

Majorana-type CP violating phases, ρ and σ.

They are the same phases entering 0ν2β decay.



Unfortunately weak washout requires $|m_{ee}| < 10^{-2}$ eV

Soft SUSY breaking parameters

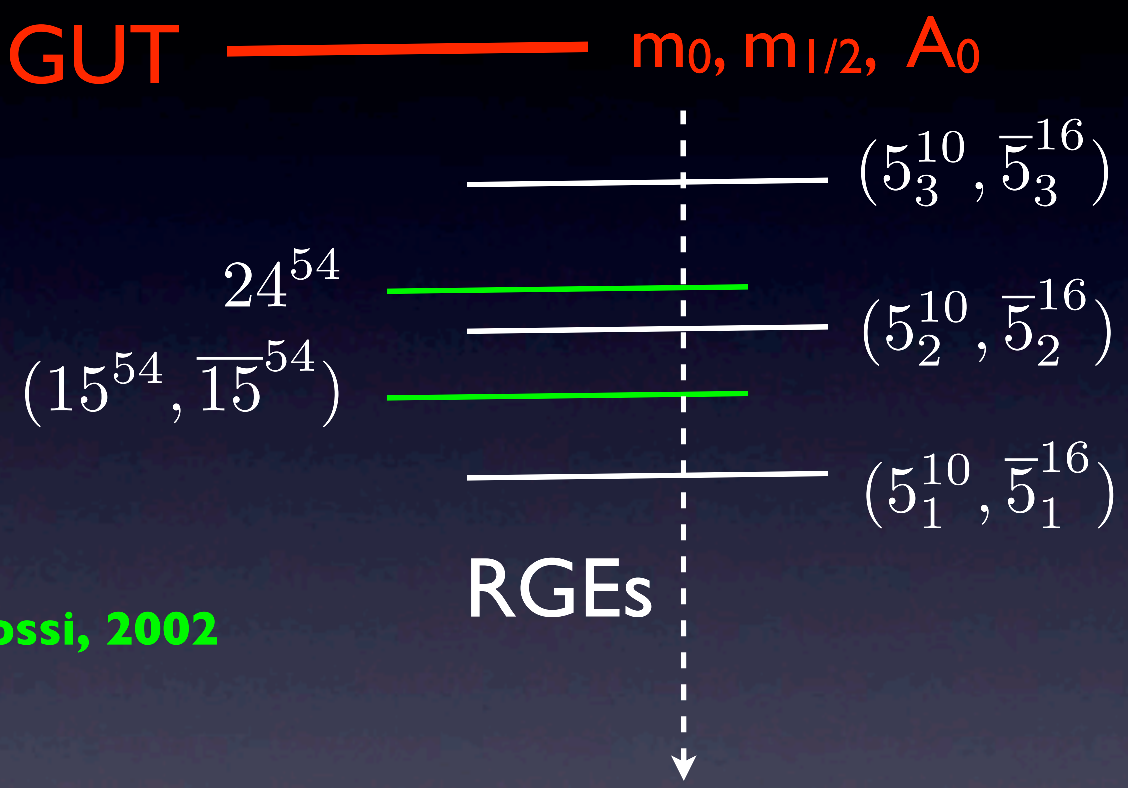
Flavour universal
SUSY breaking mediation

GUT —— $m_0, m_{1/2}, A_0$

Soft SUSY breaking parameters

Flavour universal
SUSY breaking mediation

Flavour and CP
violating thresholds
determined by Yukawa
couplings related to
seesaw & leptogenesis



GUT

m0, m1/2, A0

$(5_3^{10}, \bar{5}_3^{16})$

24^{54}

$(5_2^{10}, \bar{5}_2^{16})$

$(15^{54}, \overline{15}^{54})$

$(5_1^{10}, \bar{5}_1^{16})$

RGEs

Borzumati & Masiero, 1986; Rossi, 2002

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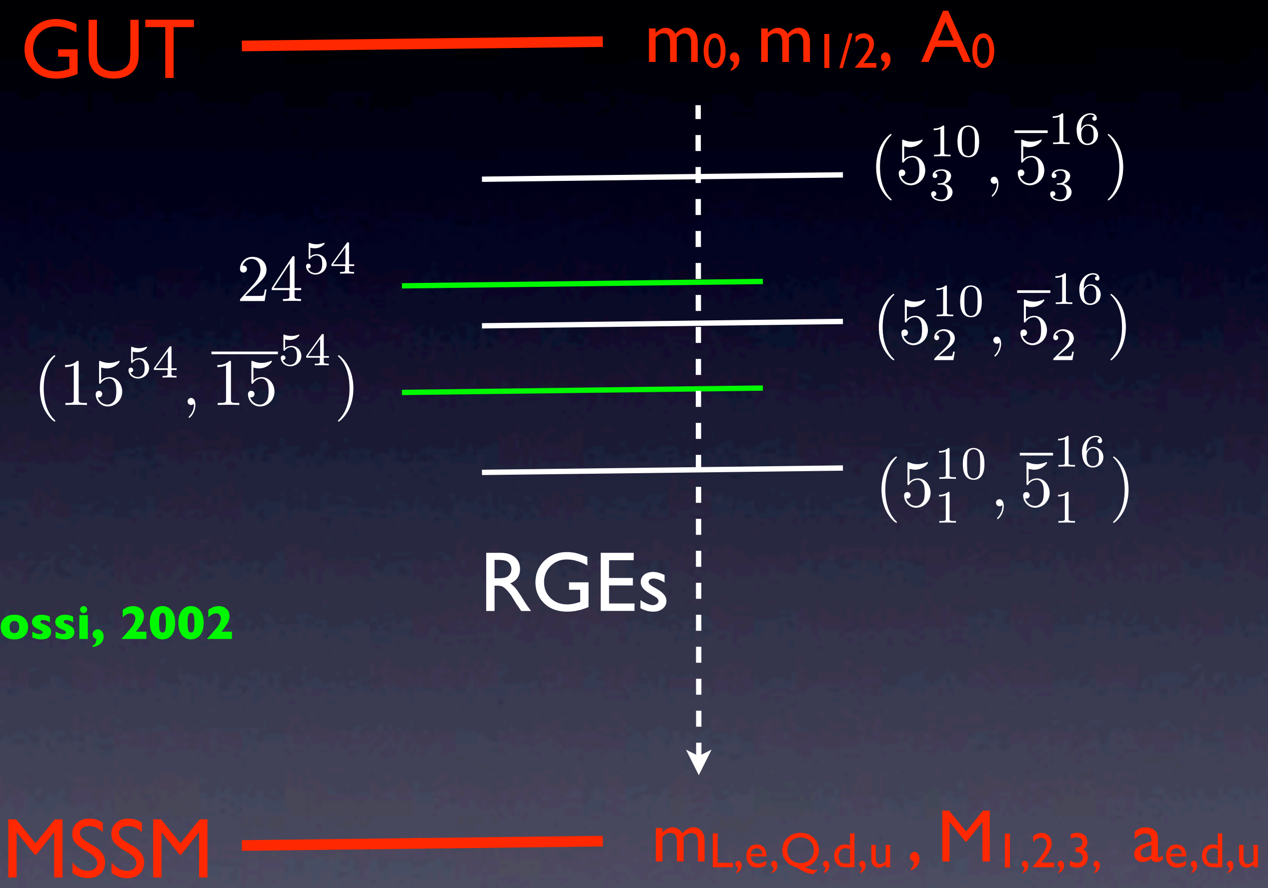

GUT — $m_0, m_{1/2}, A_0$

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$(5_1^{10}, \overline{5}_1^{16})$

RGEs

MSSM — $m_{L,e,Q,d,u}$, $M_{1,2,3}$, $a_{e,d,u}$

TeV scale SUSY
spectrum

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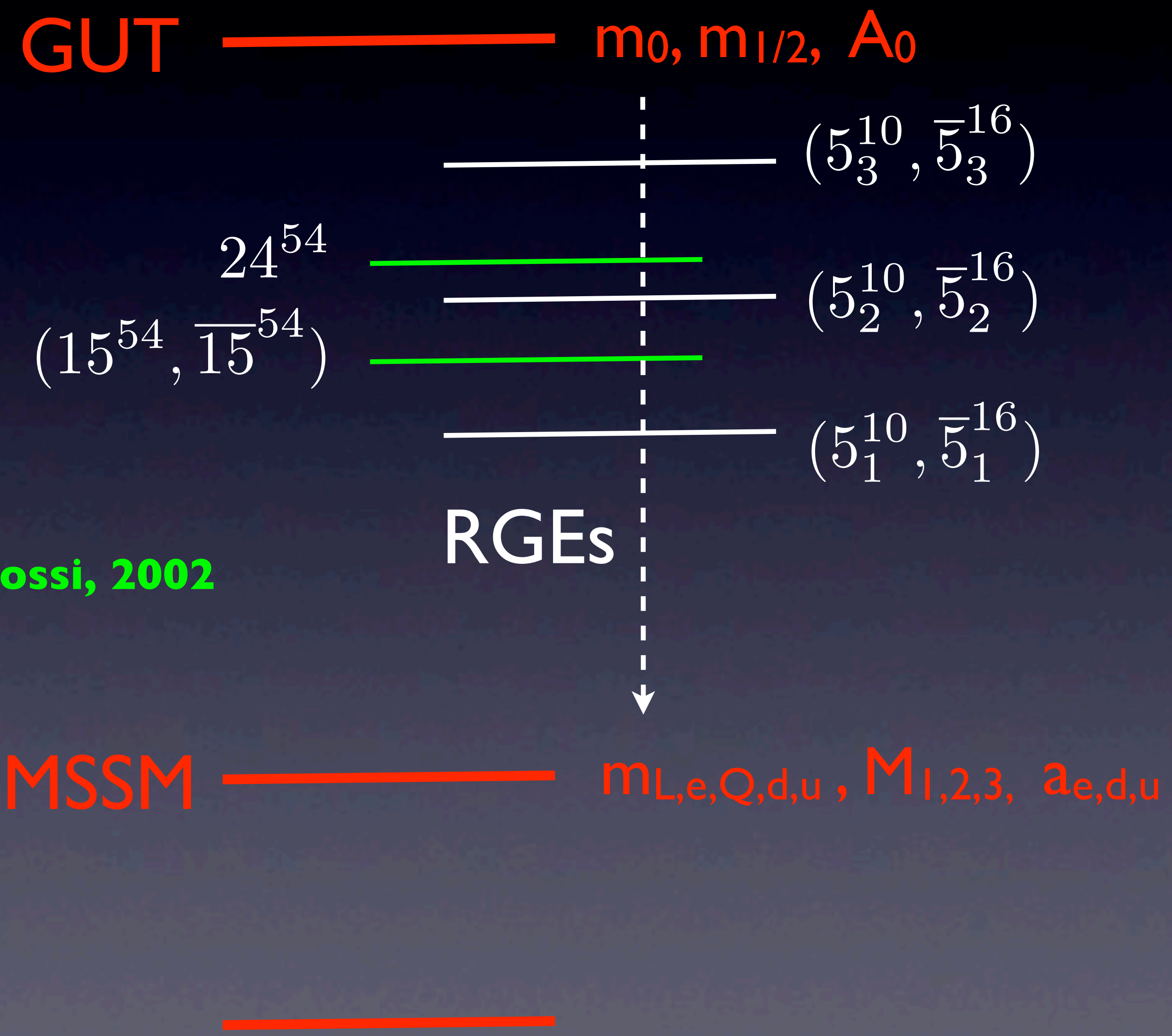

GUT — $m_0, m_{1/2}, A_0$

$(5^{10}_3, \bar{5}^{16}_3)$

24^{54}

$(5^{10}_2, \bar{5}^{16}_2)$

$(15^{54}, \overline{15}^{54})$

$(5^{10}_1, \bar{5}^{16}_1)$

RGEs

MSSM — $m_{L,e,Q,d,u}$, $M_{1,2,3}$, $a_{e,d,u}$

TeV scale SUSY
spectrum

Flavour and CP violating
rare processes

Sfermion masses

Taking mSUGRA boundary conditions at MGUT:

$$\boxed{(\tilde{m}_L^2)_{ij}} \approx \boxed{(\tilde{m}_{d^c}^2)_{ji}} \approx \frac{3m_0^2 + A_0^2}{16\pi^2} \sum_{a=1,2,3} f_{ia}^* \left[6 \log \frac{M_\Delta}{M_{GUT}} + \frac{24}{5} \log \frac{M_S + M_a}{M_{GUT}} \right] f_{aj}$$

type II seesaw à la SU(5)

$$\boxed{(\tilde{m}_{e^c}^2)_{ij}} \approx \frac{3m_0^2 + A_0^2}{16\pi^2} \sum_{a=1,2,3} 4|\alpha_d|^2 y_{ia}^* \log \frac{M_a}{M_{GUT}} y_{aj}$$

3 heavy matter families from SO(10) breaking

MSSM like effects

$$\boxed{(\tilde{m}_Q^2)_{ij}} \approx \frac{3m_0^2 + A_0^2}{16\pi^2} \sum_{a=1,2,3} y_{ia}^* \left[2|\alpha_u|^2 \log \frac{M_{SUSY}}{M_{GUT}} + 2|\alpha_d|^2 \log \frac{M_a}{M_{GUT}} \right] y_{aj}$$

Sfermion masses

Taking mSUGRA boundary conditions at M_{GUT}:

$$\boxed{(\tilde{m}^2_L)_{ij}} \approx \boxed{(\tilde{m}^2_{d^c})_{ji}} \approx \frac{3m_0^2+A_0^2}{16\pi^2}\sum_{a=1,2,3} \enclose{circle}{f^*_{ia}} \left[6\log\frac{M_\Delta}{M_{GUT}} + \frac{24}{5}\log\frac{M_S+M_a}{M_{GUT}}\right] \enclose{circle}{f_{aj}}$$

type II seesaw à la SU(5)

$$\boxed{(\tilde{m}^2_{e^c})_{ij}} \approx \frac{3m_0^2+A_0^2}{16\pi^2}\sum_{a=1,2,3} 4|\alpha_d|^2 \enclose{circle}{y^*_{ia}} \log\frac{M_a}{M_{GUT}} \enclose{circle}{y_{aj}}$$

3 heavy matter families from SO(10) breaking

MSSM like effects

$$\boxed{(\tilde{m}^2_Q)_{ij}} \approx \frac{3m_0^2+A_0^2}{16\pi^2}\sum_{a=1,2,3} \enclose{circle}{y^*_{ia}} \left[2|\alpha_u|^2\log\frac{M_{SUSY}}{M_{GUT}} + 2|\alpha_d|^2\log\frac{M_a}{M_{GUT}}\right] \enclose{circle}{y_{aj}}$$

After RGE evolution, ***flavour violations are "minimal" both for quarks and leptons*** (CP violation depends also on 5 high energy phases)

Lepton flavour & CP violations

Masina, Savoy, ’03; Paradisi, ’05; Ciuchini et al. , ’07; ...

Choosing (i) a heavy mass spectrum compatible with unification, (ii) the parameters leading to leptogenesis, (iii) approximatively equal superpartner masses, we roughly estimate:

$$BR(\mu \to e\gamma) \sim 10^{-12} \left(\frac{\tan\beta}{10}\right)^2 \left(\frac{500\ \mathrm{GeV}}{M_S}\right)^4 \frac{\sin^2\theta_{13}}{0.05}$$

The MEG experiment is taking data:

from 10^{-11} (already last summer) to 2 10^{-13} (three years data taking)

Strong correlations with $\tau \to \mu\gamma, e\gamma$ (*A.Rossi*)

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The MEG experiment is taking data:
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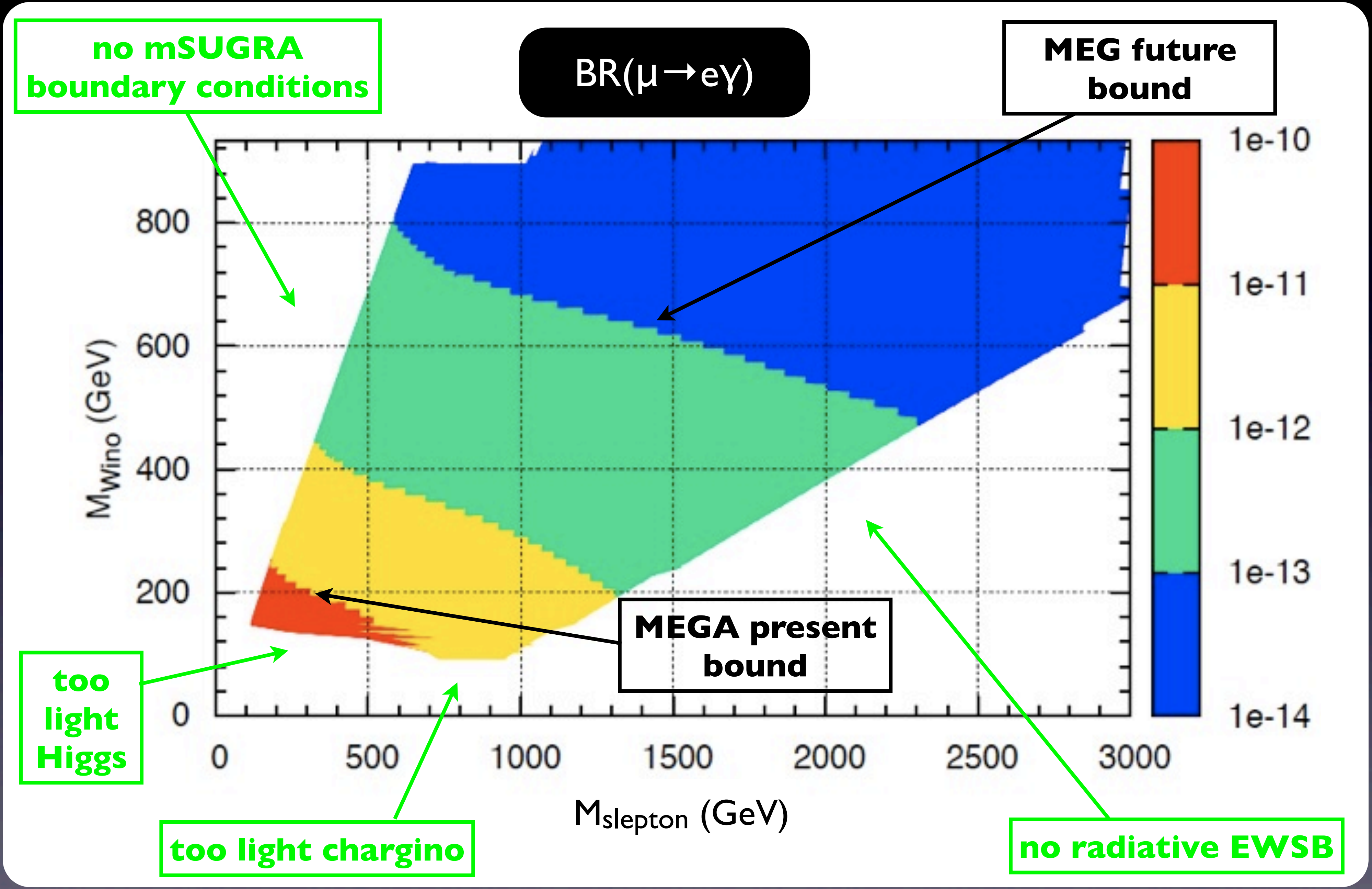
Strong correlations with $\tau \to \mu\gamma, e\gamma$ *(A.Rossi)*

$$EDM_e \sim 10^{-33} \mathrm{e\ cm}\ \frac{\tan\beta}{10} \left(\frac{500\ \mathrm{GeV}}{M_S}\right)^2 \left(\frac{\sin^2\theta_{13}}{0.05}\right)^{1/2} \sin\arg(U_{13}V_{31}^*)$$

The present bound is 7 10^{-28} e cm, prospects to reach 10^{-30} : out of reach

parameters leading to successful leptogenesis at 10^{12} GeV, tan β = 10



no mSUGRA boundary conditions

MEG future bound

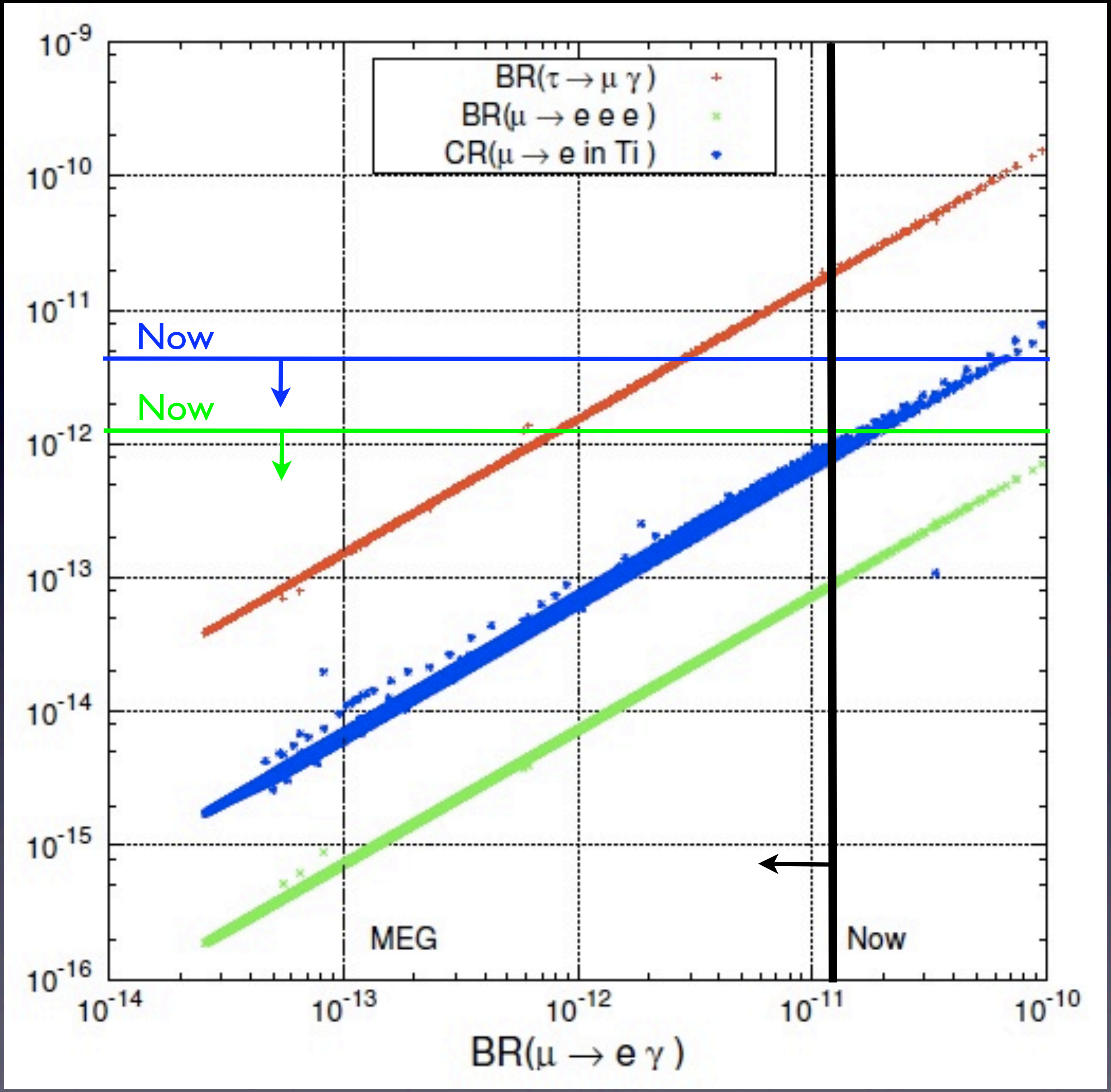
MEGA present bound

too light Higgs

too light chargino

no radiative EWSB

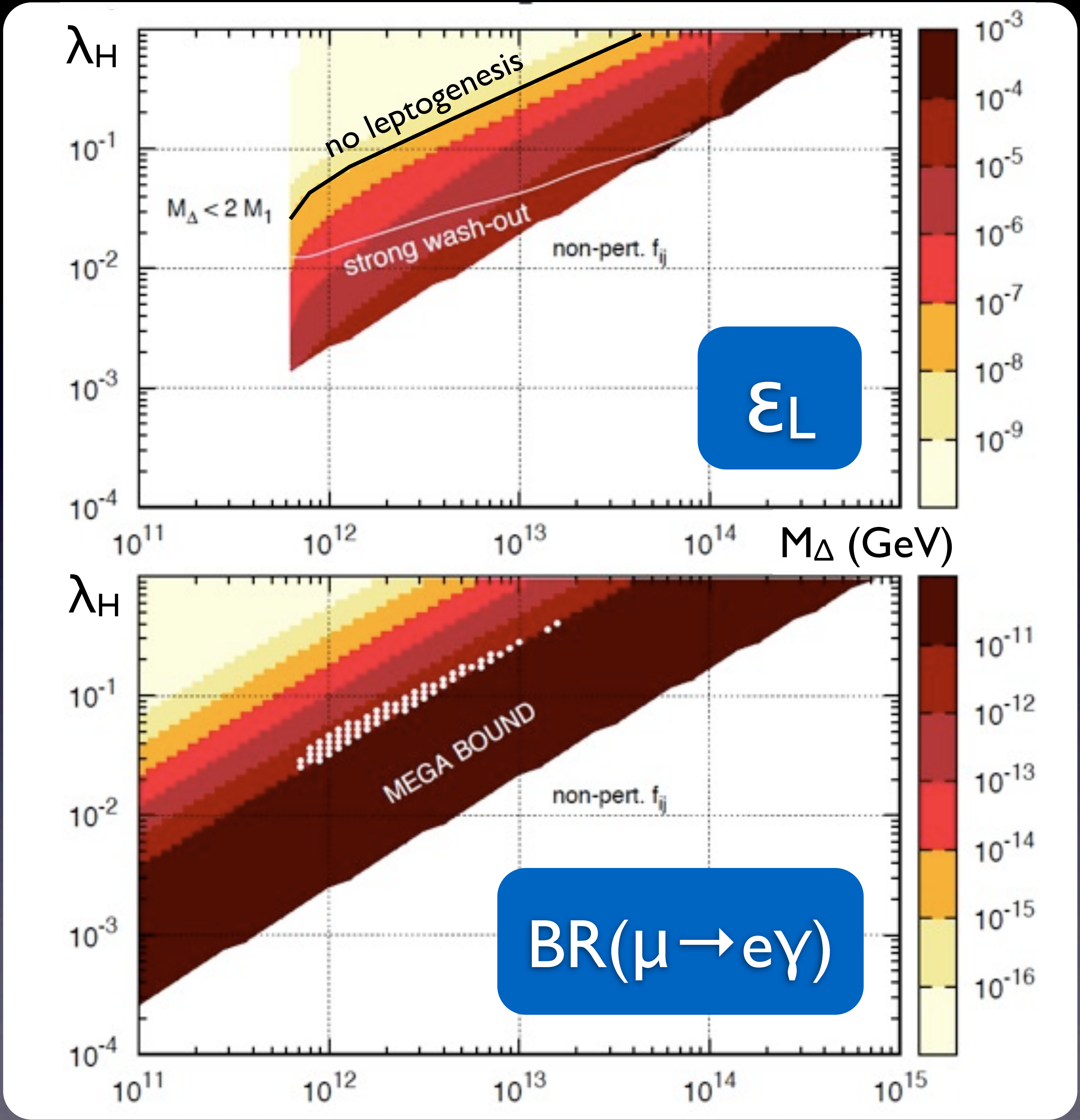
L.Calibbi, MF, S.Lavignac, A.Romanino, JHEP 0912 (2009) 057 same parameters as before, scanning over m_0 and $m_{1/2}$



μ to e conversion on Titanium could be probed down to 10^{-16} (Mu2e) or 10^{-18} (PRISM)

mSUGRA
parameters fixed
to $\tan\beta = 10$
$m_0 = 700$ GeV
$m_{1/2} = 700$ GeV

the slope of the
contours (λ_H / M_Δ)
is fixed by the size
of neutrino masses

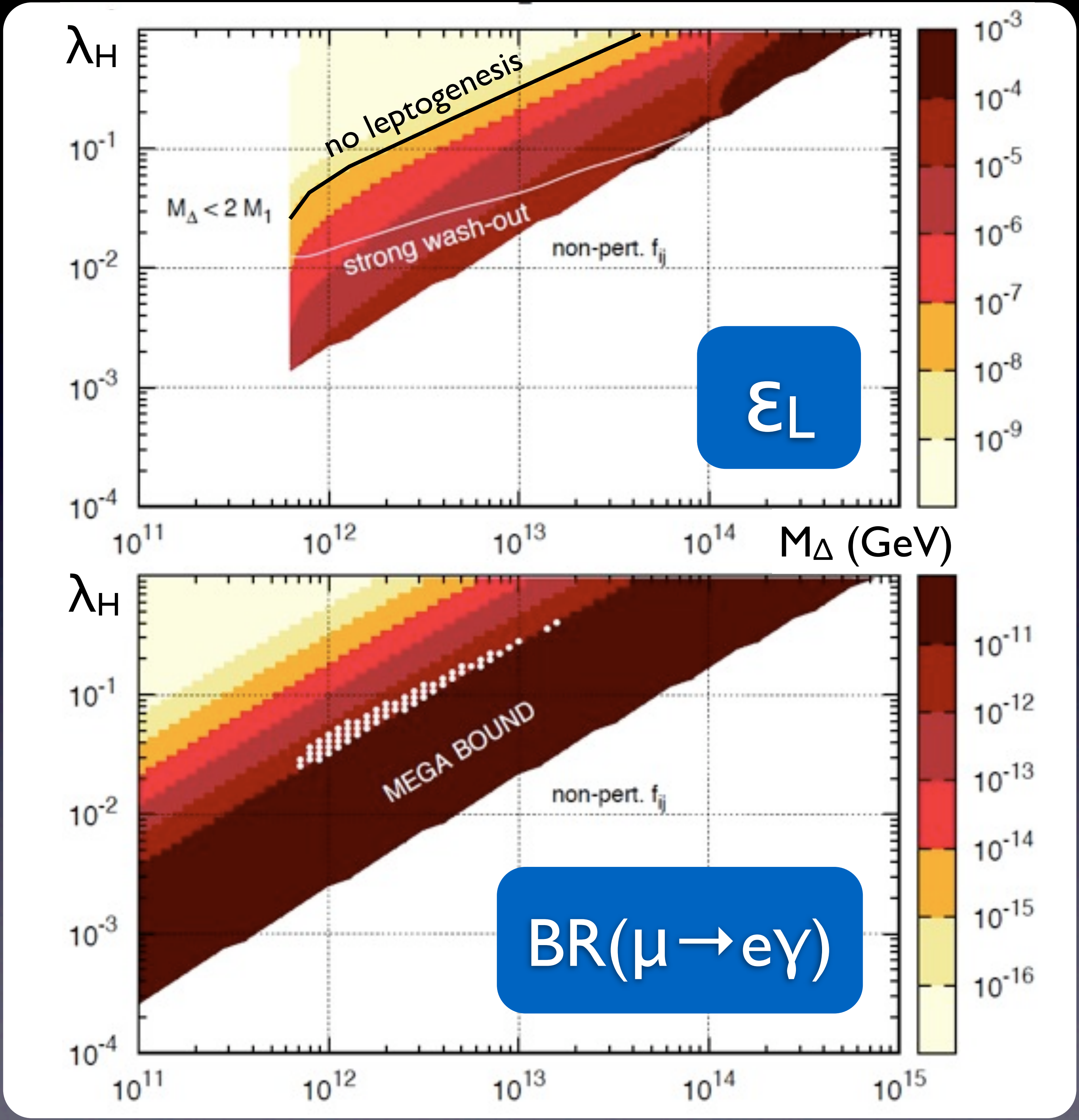


mSUGRA parameters fixed to tan β = 10
m_0 = 700 GeV
$m_{1/2}$ = 700 GeV

the slope of the contours (λ_H / M_Δ) is fixed by the size of neutrino masses

Leptogenesis dynamics is constrained by LFV bounds: no strong washout

Requiring leptogenesis determines the overall size of LFV



mSUGRA parameters fixed to

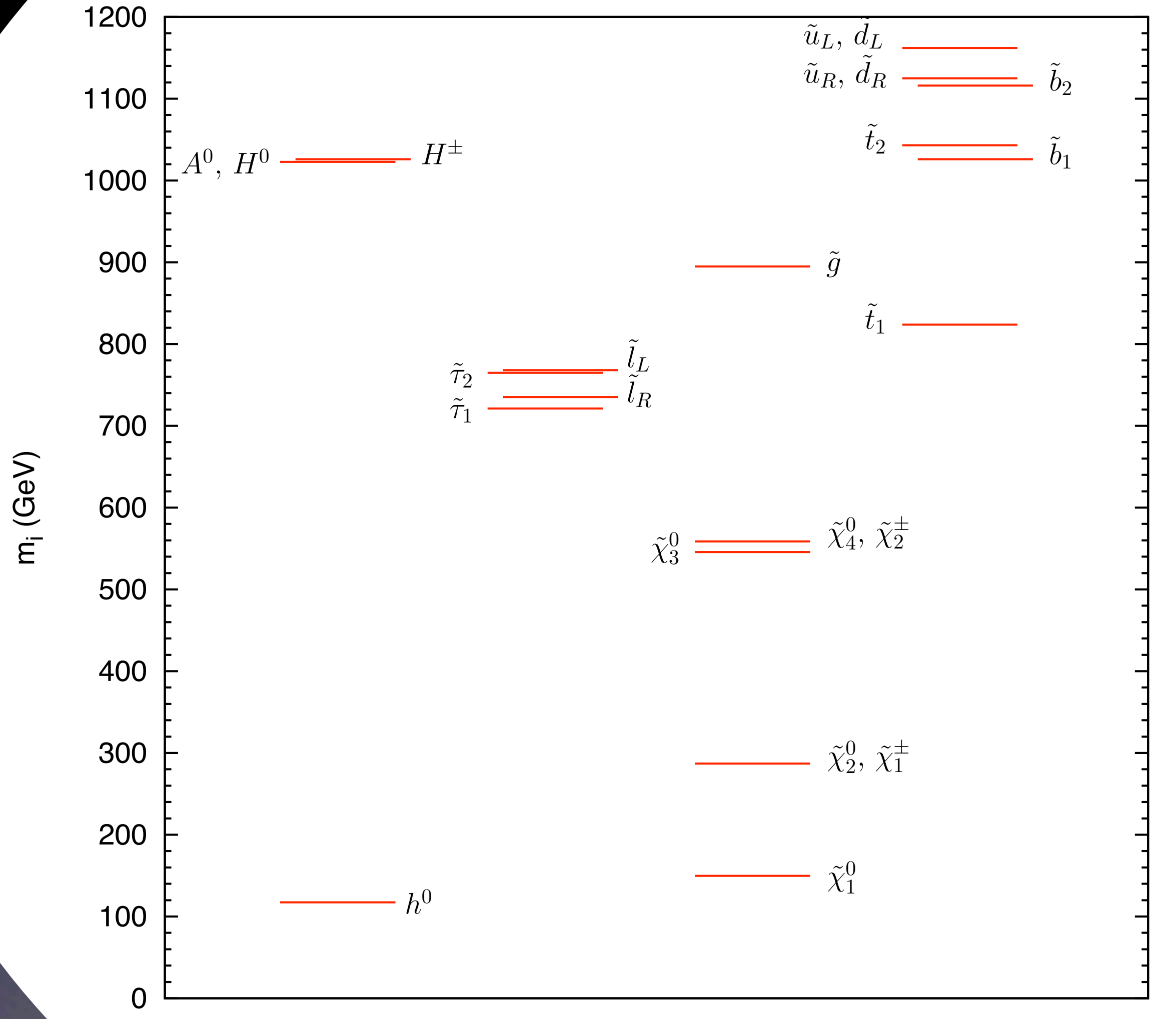
tan β = 10

m_0 = 700 GeV

$m_{1/2}$ = 700 GeV

A_0 = 0

μ > 0



large unified gauge coupling makes all sfermions heavier than all neutralinos and charginos; never stau LSP

Quark flavour & CP violations

Correlated analysis of the hadronic observables gives weaker constraints.

Most noticeable difference with the MSSM is $\delta^{RR}_d \neq 0$ at leading log.

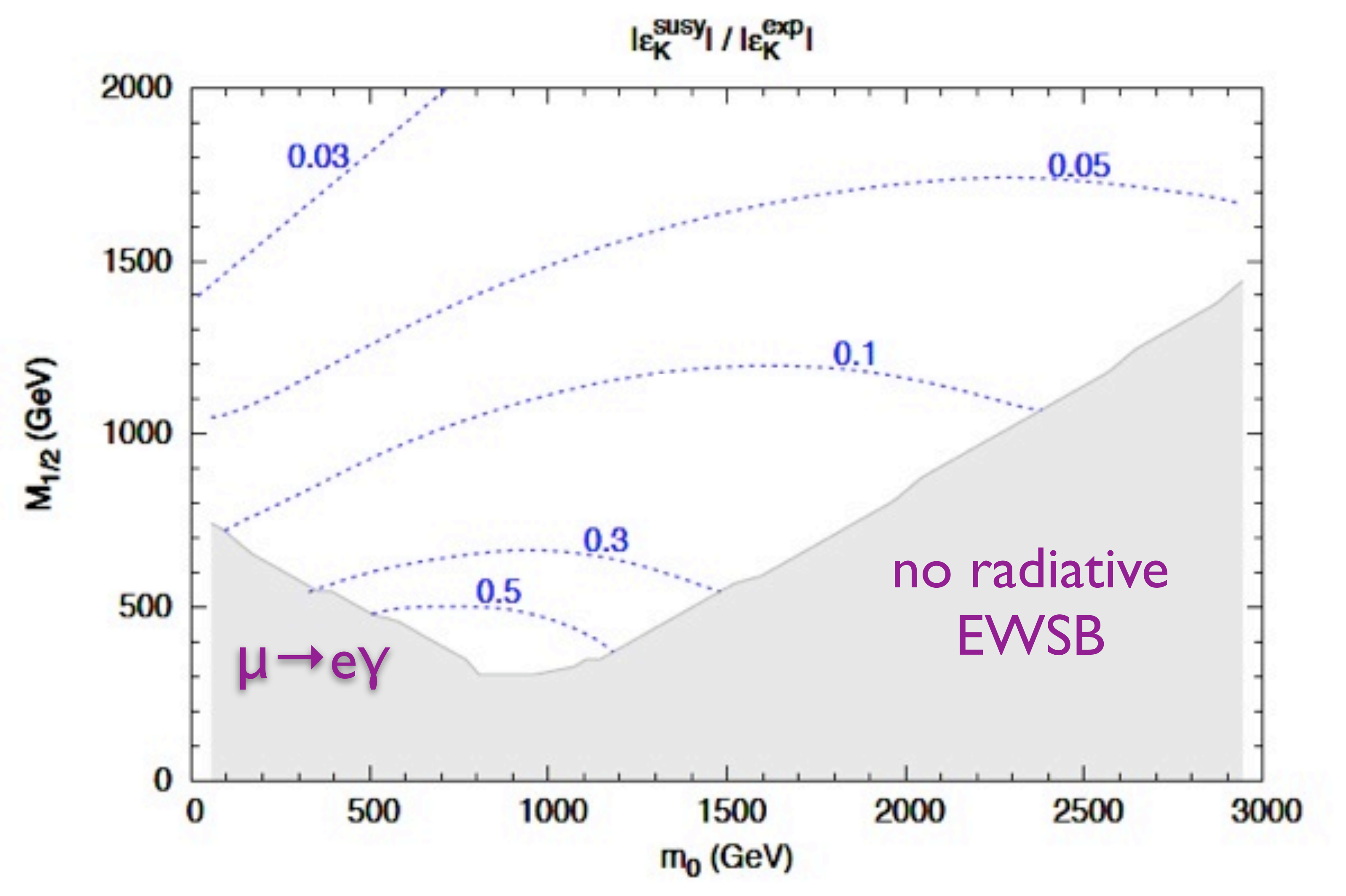
$$\begin{aligned} BR(b \to s\gamma)|_{\tilde{g}} \quad \sim & \quad \left(\frac{100\ \text{GeV}}{M_S}\right)^4 \left[(3.9 \cdot 10^{-6})_{LL} + (1.9 \cdot 10^{-7})_{RR}\right] \\ + & \quad \left(\frac{100\ \text{GeV}}{M_S}\right)^2 \left[(5.4 \cdot 10^{-7})_{LR} + (1.2 \cdot 10^{-8})_{RL}\right] \end{aligned}$$

The presently allowed range is $(1.8 - 4.3)\ 10^{-4}$.
RR and RL contributions can be enhanced by the factor $(f_{ij} / 0.05)^4$.

Other constraints from CP violating observables as ε_K or EDM$_n$.
They are sensitive to both low and high energy CP phases.

$\epsilon_K^{exp} = (2.23 \pm 0.01)10^{-3}$

SM may account only for 80-90% of this measured value (**Buras, Guadagnoli**) *but hadronic uncertainties large*



$\arg(\delta_d^{RR})_{12} = 0.5$ arbitrary choice of a CP violating phase

Conclusions

- Several upcoming experiments will provide new severe & complementary tests of SUSY GUTs

- In type II SO(10) models, the low energy fermion masses & mixing angles are the only flavour parameters of the full theory

- Baryogenesis via leptogenesis & neutrino masses are determined by the same Yukawa coupling matrix, and significantly constrain the parameters of this scenario

- A specific pattern is predicted for SUSY flavour violating effects, the strongest constraint coming from the present & near future bounds on BR($\mu \to e\gamma$)

BACKUP SLIDES

The model: Yukawa sector

$$h\left(L^{16}L^{c}\langle 1_H^{16}\rangle + e^{c}L^{10}\langle H_d\rangle\right)$$

heavy lepton & d-quark masses: $M_E = M_D^T = h\,V_{GUT}$

light lepton & d-quark masses: $m_e = m_d^T = h\,v_d$

$$W_Y = \frac{1}{2}\,y_{ij}\,\mathbf{16}_i\mathbf{16}_j\mathbf{10} + h_{ij}\,\mathbf{16}_i\mathbf{10}_j\mathbf{16} + \frac{1}{2}\,f_{ij}\,\mathbf{10}_i\mathbf{10}_j\mathbf{54}$$

$$y\,Qu^{c}\langle H_u\rangle$$

up quarks: $m_u = y\,v_u$

no neutrino Dirac mass!

$$\frac{1}{2} f L^{10}L^{10}\langle\Delta\rangle$$

54 is needed to make neutrinos massive (type II seesaw): $m_\nu = f\,v_\Delta$

Type I versus type II SO(10)

The most general superpotential for dim-10 and dim-16 multiplets:

$$W_Y = \frac{1}{2} y 16_M 16_M 10_H + h 16_M 10_M 16_H + \frac{1}{2} M_{10} 10_M 10_M$$

The singlet VEV in 16_H mixes the (L, d^c) states in 16_M and 10_M :

$$W_Y \supset 5^{10}_M \left(\langle 1^{16}_H \rangle \, \bar{5}^{16}_M + M_{10} \, \bar{5}^{10}_M \right)$$

The orthogonal combination defines the light (L,d^c) states

In general $L^{light} = \cos\theta \, L^{10} + \sin\theta \, L^{16}$:

Type I SO(10) limit is $\theta = \pi/2$; type II scenario is $\theta = 0$ (it occurs for $M_{10} = 0$; notice that DT splitting requires $M_H \, 10_H \, 10_H$ to be forbidden)

SO(10) breaking to the SM

To break SO(10), besides 16 one may use 45 and 54 Higgs multiplets, acquiring a GUT scale VEV

To align a 45 VEV along $T_{B\text{-}L}$ one needs a non-generic W_{GUT}

$$\begin{aligned} W_{GUT} &= \tfrac{1}{2}\sigma_1 54' 45_{3R} 45_{3R} + (\lambda_{12} S + \sigma_{12} 54') 45_{B-L} 45_{3R} \\ &+ \tfrac{1}{3}\lambda 54' 54' 54' + \overline{16}(M_{16} + g 45_{3R}) 16 \end{aligned}$$

In this way SO(10) is broken in one step (at M_{16}) to the SM, with the correct VEV alignment required by DT-splitting

All (un)eaten fields in W_{GUT} get mass at the GUT scale ~ M_{16}

DT-splitting and p-decay

$$W_{DT} = \alpha 10\ 45_{B-L}\ 10' + M\ 10'\ 10' + \eta\ \overline{16}\ \overline{16}\ 10 + g\overline{16}\ 45_{B-L}\ 16$$

Doublet-Triplet splitting by the missing VEV mechanism (Dimopoulos-Wilczek), but with the down Higgs partly in 16:

$$M_D = \begin{pmatrix} 0 & 0 & \eta V_1 \\ 0 & M_{10} & 0 \\ 0 & 0 & gV_{B-L} \end{pmatrix}$$

$$\boxed{\begin{aligned} H_u &= H_u^{10} \\ H_d &= cH_d^{10} + sH_d^{16} \end{aligned}}$$

$$M_T = \begin{pmatrix} 0 & \alpha V_{B-L} & \eta V_1 \\ -\alpha V_{B-L} & M_{10} & 0 \\ 0 & 0 & gV_{B-L} \end{pmatrix}$$

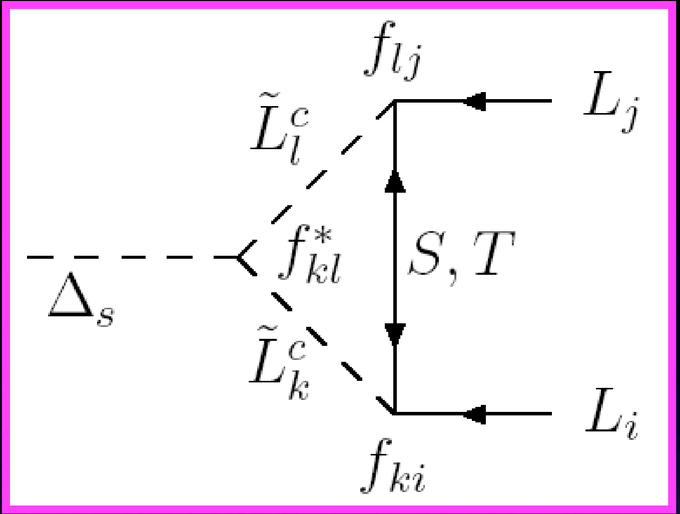
$$\boxed{\frac{\eta V_1 M_{10}}{\alpha^2 g V_{B-L}^3} \ll \frac{1}{M_{GUT}}}$$

Due to the type II SO(10) structure,
the D=5 p-decay can be mediated only through T^{10} - T^{16} mixing

Full computation of ε_L

$$\epsilon^{\Delta}_{B-L} = 2\cdot\frac{\Gamma(\Delta\to L^*L^*)-\Gamma(\Delta^*\to LL)}{\Gamma_{tot}(\Delta^*)+\Gamma_{tot}(\Delta)}$$

The loop contains 2 heavy sleptons with masses M_l and M_k, and a Higgsino from 54, either $S \sim (1,1,0)_{SM}$ or $T \sim (1,3,0)_{SM}$



$$\boxed{\epsilon^{\Delta}_{B-L} = \frac{1}{16\pi}\sum_{R=S,T} c_R \sum_{k,l=1}^{3} F\left(\frac{M_R}{M_\Delta},\frac{M_k}{M_\Delta},\frac{M_l}{M_\Delta}\right)\frac{Im[f^*_{kl}(f f^* f)_{kl}]}{Tr(f^* f)+\ldots}}$$

$$F(x,x_k,x_l) = \Theta(1-x_k-x_l)\,x\log\left[\frac{1+2x^2-x_k^2-x_l^2+\sqrt{\lambda(1,x_k^2,x_l^2)}}{1+2x^2-x_k^2-x_l^2-\sqrt{\lambda(1,x_k^2,x_l^2)}}\right]$$

F is the imaginary part of the loop integral

$$\boxed{\begin{array}{ll} M_k+M_l\to 0 & F\approx\frac{M_R}{M_\Delta}\log\left(1+\frac{M_\Delta^2}{M_R^2}\right) \\ & F_{max}\approx 0.8 \quad \text{for} \quad \frac{M_R}{M_\Delta}\approx 0.5 \\ M_k+M_l\to M_\Delta & F\to 0 \\ M_k+M_l> M_\Delta & F=0 \end{array}}$$

The gravitino problem

In our scenario, at least in the weak washout region,
thermal leptogenesis requires $M_\Delta \geq 10^{11\text{-}12}$ GeV

In SUGRA, if $m_{3/2}$ is close to the electroweak scale, the gravitino overproduction bound on the reheating temperature is $T_{RH} < 10^{9\text{-}10}$ GeV (much stronger bounds from BBN, but more model-dependent)

Ways out :

- ➡ Non-supersymmetric scenario, with a real 54 Higgs
- ➡ Gravitino very heavy ($m_{3/2} >> 100$ TeV), e.g. significantly split SUSY
- ➡ Gravitino very light ($m_{3/2} < 100$ eV), e.g. some gauge-mediation models
- ➡ Non-thermal production of Δ's even for $T_{RH} << M_\Delta$

Leptogenesis in type I SO(10)

- In SO(10) models with type I seesaw, further suppression of ε_L comes from small Yukawa couplings: $y = y_{up}$

$$\boxed{\frac{n_B}{s} \approx 10^{-3} \epsilon_L \eta \overset{obs}{\approx} 10^{-10}}$$

$\varepsilon_L \sim [\, \Gamma(N \to LH) - \Gamma(N \to L^*H^*) \,]$

- Some tuning of parameters is needed to enhance the asymmetry:
  - quasi-degeneracy of two decaying states N_1 & N_2
  - interplay with type II seesaw
  - N_2 decays plus flavour effects

$$\boxed{\epsilon_L = \frac{3}{8\pi} \frac{M_1}{M_2} \frac{\mathrm{Im}[(M_u^\dagger M_u)_{12}]^2}{v^2 (M_u^\dagger M_u)_{11}}}$$

Flanz, Paschos, Sarkar, Weiss; Covi, Roulet, Vissani; Pilaftsis, Underwood; Akhmedov, MF, Smirnov

Joshipura, Paschos, Rodejohann; Hambye, Senjanovic; Hosteins, Lavignac, Savoy, Abada, Josse-Michaux

Di Bari; Vives; Riotto