Leptogenesis and the Flavour Structure of the Seesaw

based on:
hep-ph/0609038 (JCAP 0611 (2006) 011) with S.F. King, A. Riotto
hep-ph/0611232 (JCAP 0702 (2007) 024) with A.M. Teixeira
arXiv:0704.1591 (Phys. Rev. D76 (2007) 023512)

Seminar @ MPIK, January 28, 2008

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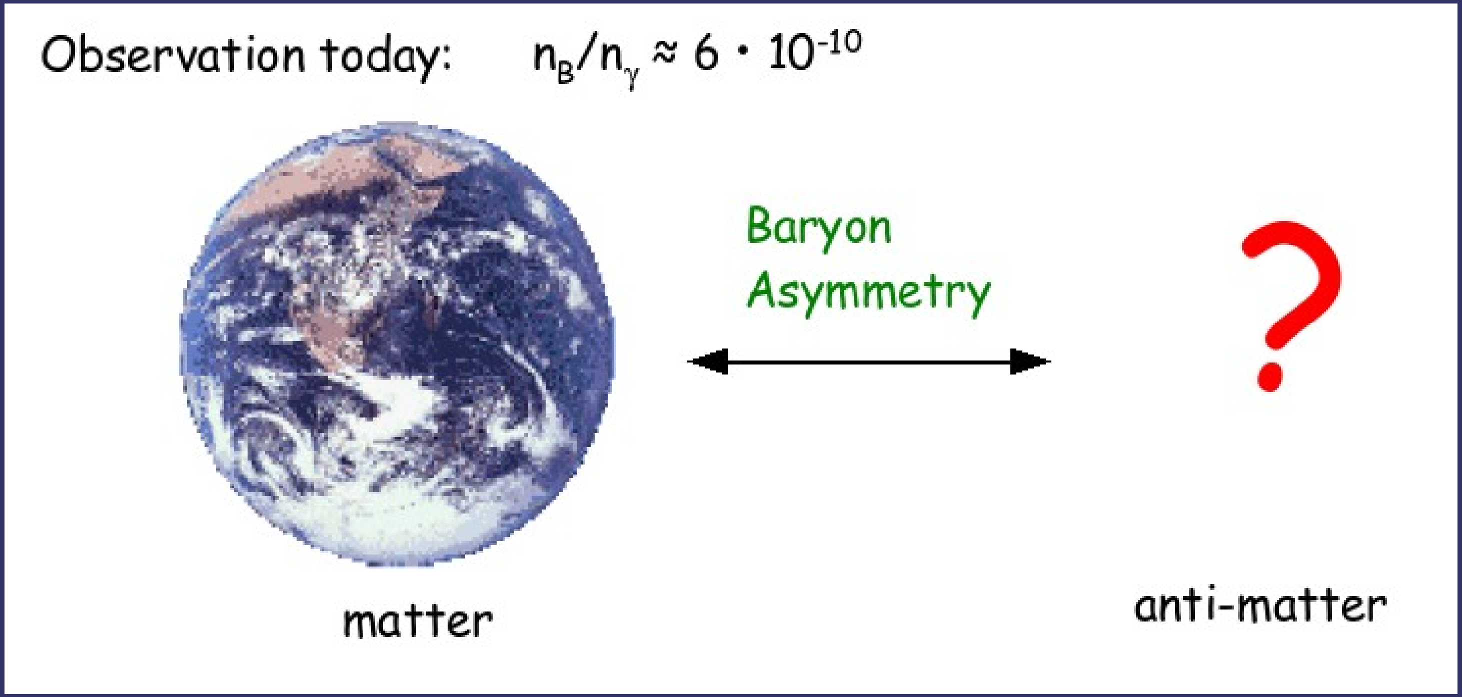
Problem in Cosmology: The baryon asymmetry of the universe



- How was the observed baryon asymmety of the universe (BAU) generated?

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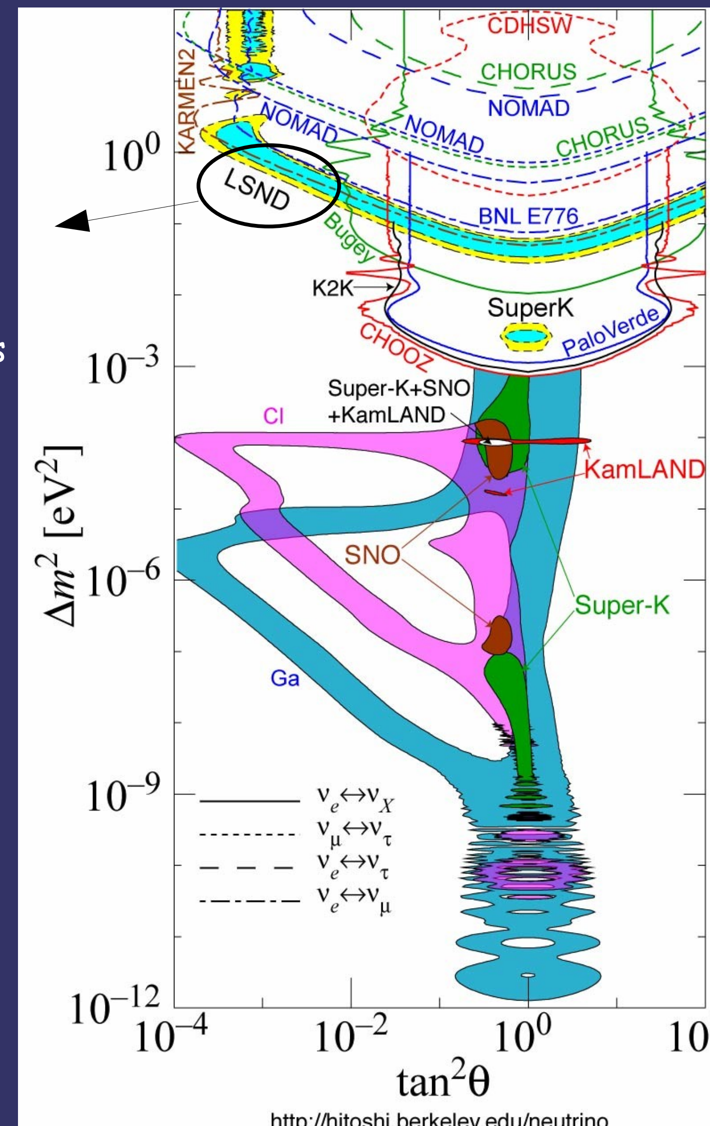
Problem in Particle Physics: Origin of neutrino masses

LSND:
if correct, not
from ν-oscillations
(MiniBooNE)



- Strong evidence for neutrino oscillations:

Neutrinos have mass
⇒ The SM has to be extended!

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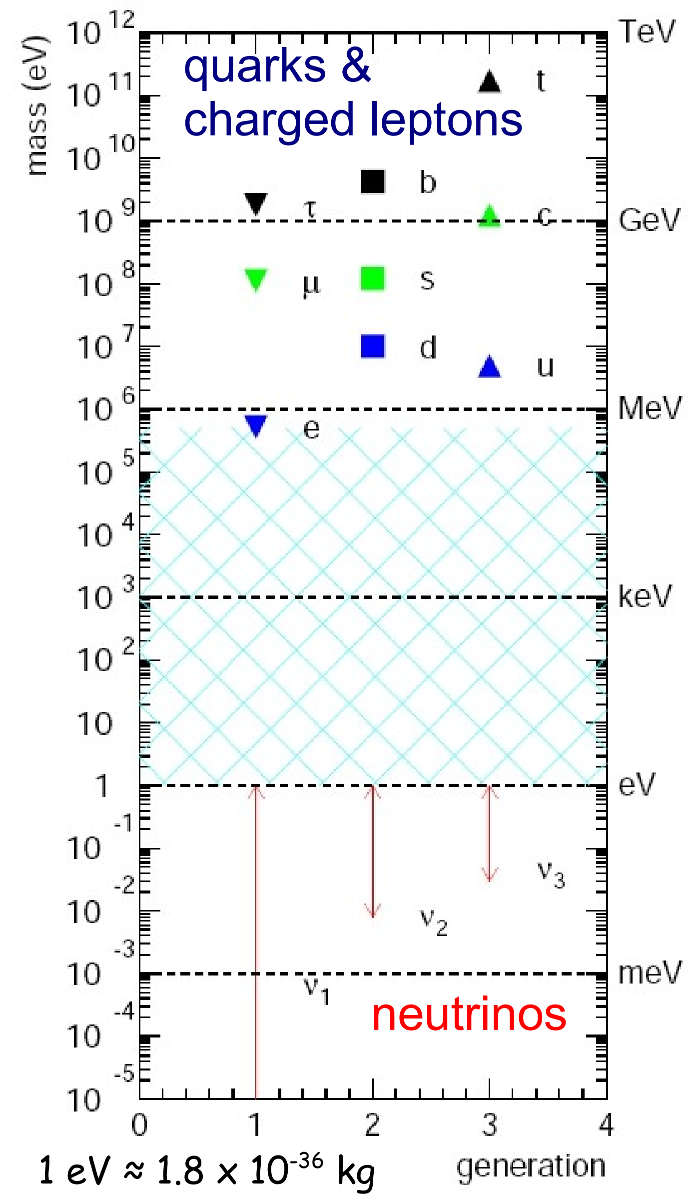
Summary: Present knowledge on neutrino masses & mixing



	Best-fit value	Range	C.L.
θ_{12} [°]	33.2	29.3 – 39.2	99% (3σ)
θ_{23} [°]	45.0	35.7 – 55.6	99% (3σ)
θ_{13} [°]	–	0.0 – 11.5	99% (3σ)
Δm^2_{21} [eV^2]	$7.9 \cdot 10^{-5}$	$7.1 \cdot 10^{-5} - 8.9 \cdot 10^{-5}$	99% (3σ)
$\lvert\Delta m^2_{31}\rvert$ [eV^2]	$2.6 \cdot 10^{-3}$	$2.0 \cdot 10^{-3} - 3.2 \cdot 10^{-3}$	99% (3σ)

- Two mixing angles large (θ_{23} close to maximal)
- Constraints from 0νββ-decay, Tritium β-decay & cosmology: $m_{\nu i}$ below about 0.5 eV
- Open questions: CP violation, mass scale & ordering, θ_{13}, ...

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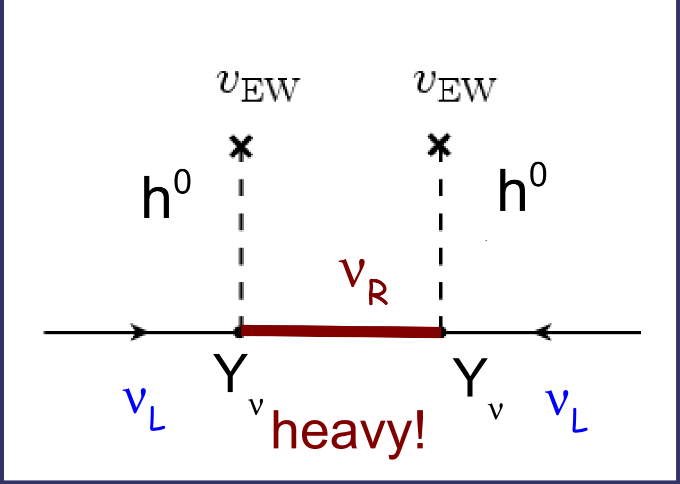
A possible solution to both problems: Type I & II seesaw mechanism

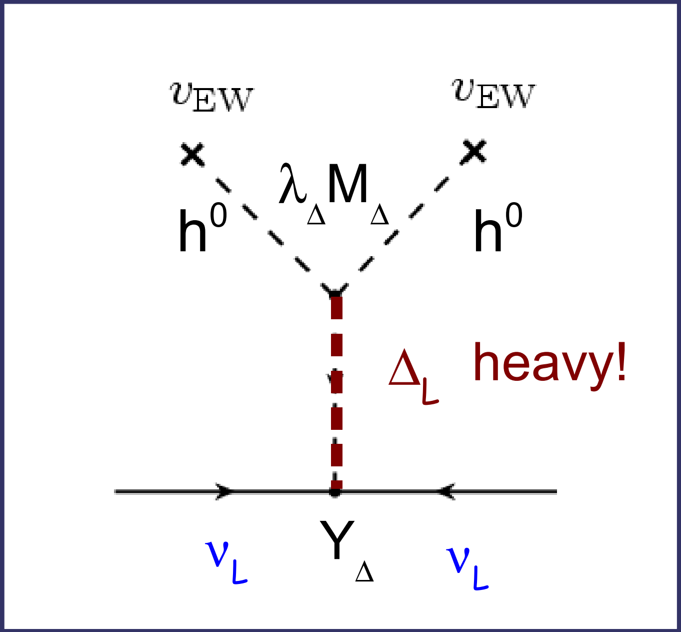
- Type I Seesaw



$$m_{\rm LL}^{\rm I} \approx -\frac{v_u^2}{2} Y_\nu^T M_{\rm RR}^{-1} Y_\nu$$

P. Minkowski (1977), Gell-Mann, Glashow, Mohapatra, Ramond, Senjanovic, Slanski, Yanagida (1979/1980)

- Type I + Triplet Seesaw = Type II Seesaw



$$m_{\rm LL}^{\rm II} \approx \lambda_\Delta Y_\Delta \frac{v_u^2}{M_\Delta}$$

Lazarides, Magg, Mohapatra, Schechter, Senjanovic, Shafi, Valle, Wetterich (1981)

The 6x6 neutrino mass matrix and the seesaw

$$\mathscr{L}_{M_\nu} = -\frac{1}{2}\begin{pmatrix} \overline{\nu^f_{\mathrm{L}}} \\ \overline{\nu^{\mathrm{C}i}_{\mathrm{R}}} \end{pmatrix}^T \begin{pmatrix} (m^{\mathrm{II}}_{\mathrm{LL}})_{fg} & (m_{\mathrm{LR}})_{fj} \\ (m^T_{\mathrm{LR}})_{ig} & (M_{\mathrm{RR}})_{ij} \end{pmatrix} \begin{pmatrix} \nu^{\mathrm{C}g}_{\mathrm{L}} \\ \nu^j_{\mathrm{R}} \end{pmatrix} + \mathrm{h.c.}$$

(3 left-handed and
3 right-handed neutrinos)

- Approximate block-diagonalization for heavy right-handed neutrinos:

Effective mass matrix of the light neutrinos

$$\mathscr{L}_{M_\nu} \approx -\frac{1}{2}\begin{pmatrix} \overline{\nu'^f_{\mathrm{L}}} \\ \overline{\nu'^{\mathrm{C}i}_{\mathrm{R}}} \end{pmatrix}^T \begin{pmatrix} (m^{\nu}_{\mathrm{LL}})_{fg} & 0 \\ 0 & (M_{\mathrm{RR}})_{ij} \end{pmatrix} \begin{pmatrix} \nu'^{\mathrm{C}g}_{\mathrm{L}} \\ \nu'^j_{\mathrm{R}} \end{pmatrix} + \mathrm{h.c.}$$

$\nu'^f_{\mathrm{L}} \approx \nu^f_{\mathrm{L}}$ $\nu'^{\mathrm{C}i}_{\mathrm{R}} \approx \nu^{\mathrm{C}i}_{\mathrm{R}}$

Type II contribution

$$m^{\nu}_{\mathrm{LL}} \approx m^{\mathrm{II}}_{\mathrm{LL}} + m^{\mathrm{I}}_{\mathrm{LL}} = m^{\mathrm{II}}_{\mathrm{LL}} - m_{\mathrm{LR}}\, M^{-1}_{\mathrm{RR}}\, m^T_{\mathrm{LR}}$$

- (Type II) Seesaw formula

Type I mass matrix

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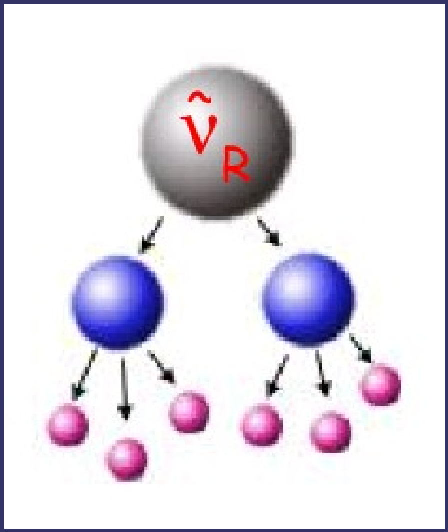
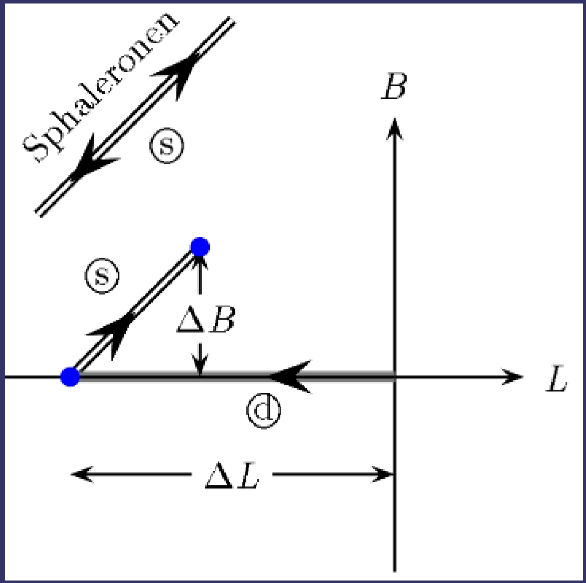
Leptogenesis: The mechanism

- Out-of-equilibrium decay of heavy RH neutrinos in the early universe
  $\Rightarrow$ lepton asymmetries ΔL_α Fukugita, Yanagida ('86)



- Sphaleron processes (conserve B - L) within SM (MSSM) partly convert lepton asymmetries into baryon asymmetry ΔB



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Motivation

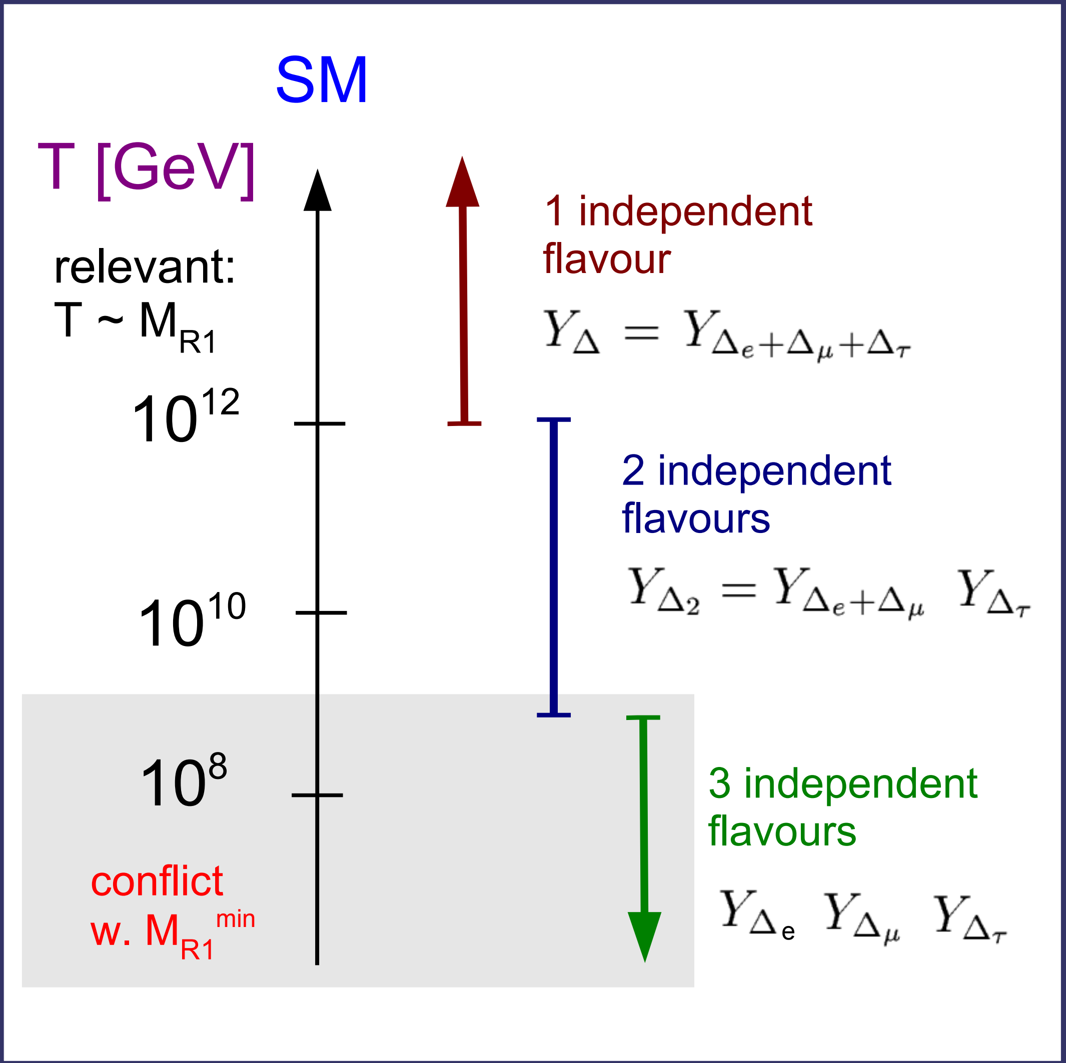
- Leptogenesis is an attractive mechanism, intensively studied ...
- New aspect got attention (~ 2 years ago): Flavour-dependence!
- Consequence: Several issues have to be revisited:
  - Bounds on $\varepsilon_{1,\alpha}$, M_{R1}, T_{RH}, ν-mass scale (?)
  - How does the seesaw flavour structure affect thermal leptogenesis?
  - How does leptogenesis in type I seesaw compare to leptogenesis in type II?
- Typically people consider leptogenesis in the context of the SM ...
- However: Leptogenesis operates at very high energies >> M_{EW}
  $\rightarrow$ hierarchy problem (new physics @ leptogenesis scale(s) scales)
- Possible solution: low energy supersymmetry
- Question: Flavour-dependent leptogenesis in MSSM $\leftrightarrow$ SM?

Outline

- Part 1: Computation of the baryon asymmetry via leptogenesis:
  Restrictions: thermal leptogenesis via ν_{R1}-decay; $M_{R1} \ll M_{R2}, M_{R3}, M_{\Delta}$
  Include: type I and type II seesaw; flavour-dependent treatment; MSSM & SM; effects of reheating temperature
  - Flavour-dependent decay asymmetries $\varepsilon_{1,\alpha}$
  - Flavour-dependent Boltzmann equations $\rightarrow$ efficiency factor η_{α}
- Part 2: General Bounds ($\varepsilon_{1,\alpha}$, M_{R1}, T_{RH}, m_{ν} (?))
- Part 3: Impact of the flavour structure of the (type I) seesaw on the producede BAU from thermal leptogenesis
  - Classes of models: 'Sequential RH neutrino Dominance (SD)'
  - Fully general, model independent (R-matrix parametersation)
- Summary & Conclusions

When does flavour matter ... ?

- If flavour matters depends on whether the charged lepton Yukawa interactions are in/out of thermal equilibrium.
- For which T is y_α in thermal equillibrium? Compare $\Gamma_{y\alpha} \approx 5 \times 10^{-3}\, y_\alpha^{\,2}\, T$ with $H(T) \propto T^2$
- Flavour-independent approximation (considered in most studies until recently) only appropriate for $T > 10^{12}$ GeV !



Barbieri et al ('99), Abada et al ('06), Nardi et al ('06)

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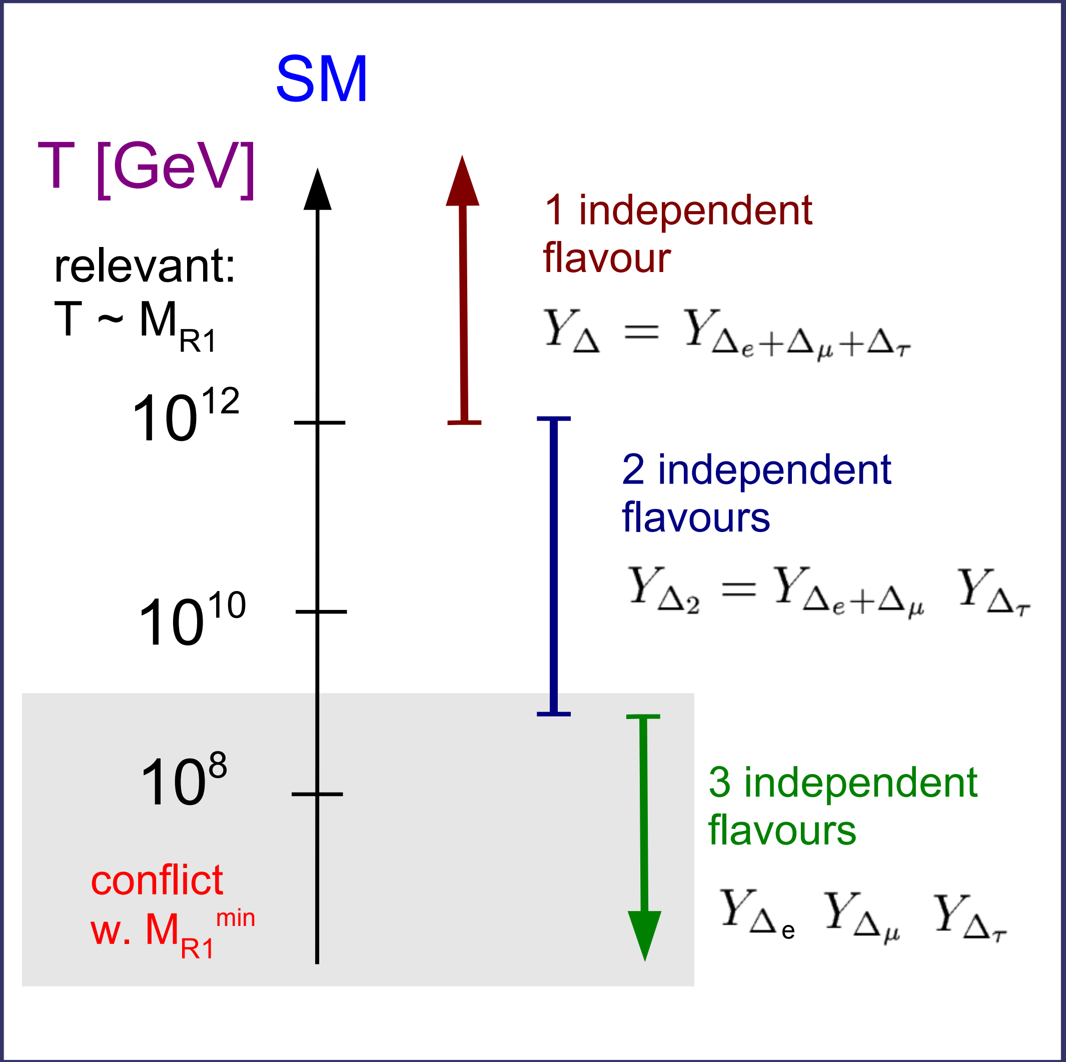
When does flavour matter ... ?

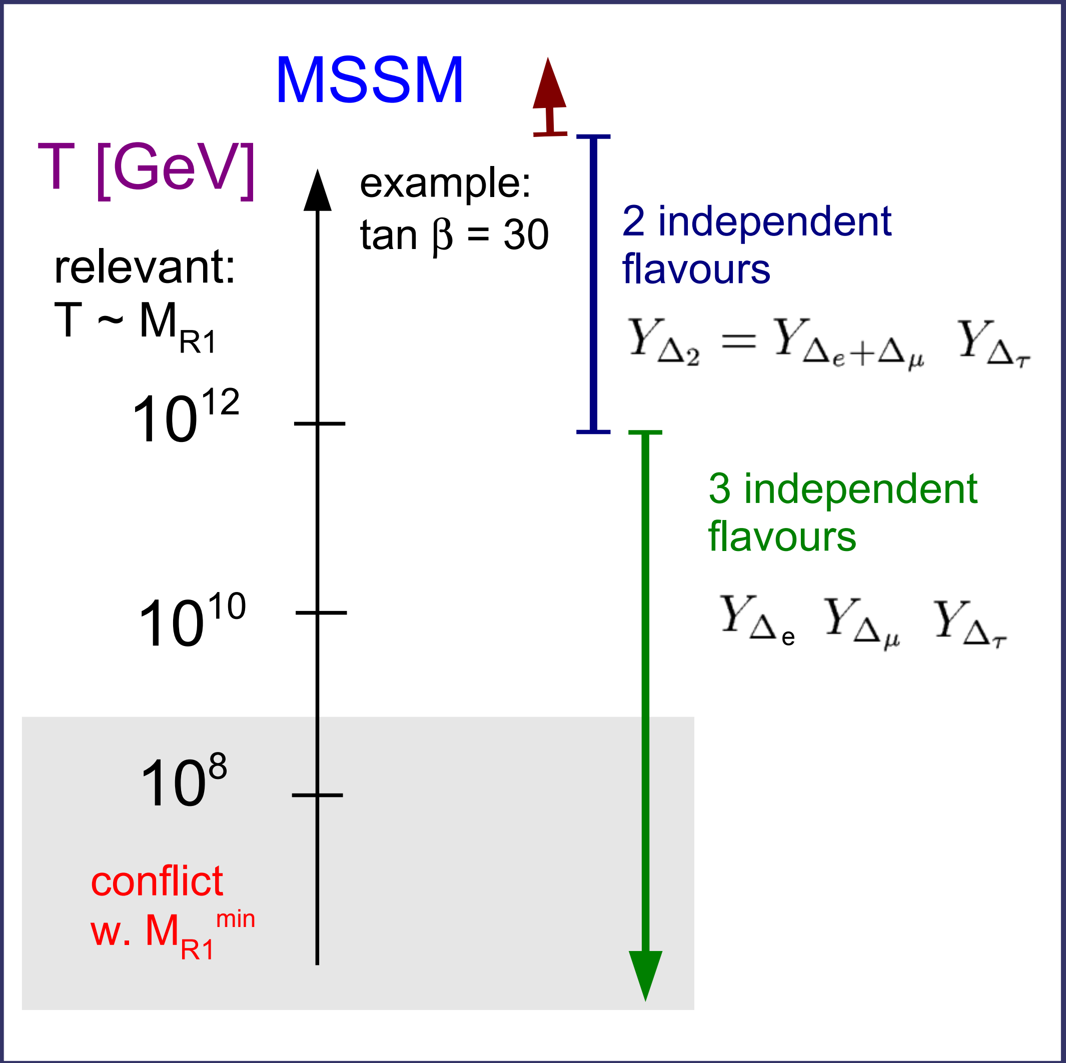
- In the SM:
  - below ≈ 10^{12} GeV, interaction mediated by y_τ in thermal eqilibrium
  - below ≈ 10^{9} GeV, interaction mediated by y_τ & y_μ in thermal equilibrium
- As we will see: last case in conflict with bounds on M_{R1}
  SM: 1 or 2 independent flavours



Barbieri et al ('99), Abada et al ('06), Nardi et al ('06)

When flavour matters: MSSM

- Important difference in the MSSM: for e, μ, τ
  $y^{MSSM} = y^{SM} (1+\tan^2\beta)^{1/2}$
  Consequence: relevant T by changes by x $(1+\tan^2\beta)$!
- In the MSSM: (e.g. $\tan\beta = 30$)
  - below ≈ 10^{15} GeV, interaction mediated by y_τ in th. eq.
  - below ≈ 10^{12} GeV, interaction mediated by y_τ & y_μ in th. eq.
- In the many interesting cases in the MSSM (T_{RH} constraints), 3 independent flavours !



S.A., S.F. King, A. Riotto ('06)

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Flavour-dependent Boltzmann equations

- Differential equations for the number densities of the lightest RH neutrino (Y_{N1}) and for the independent B/3 – L_α asymmetries ($Y_{\Delta\alpha}$)

$A_{\alpha\beta}$: induces a coupling between the diff. Eqs. for the asymmetries $Y_{\Delta\alpha}$

γ_D: production and decay of RH neutrinos

($z = M_1 / T$)

$$\frac{\mathrm{d}Y_{N_1}}{\mathrm{d}z} = \frac{-z}{sH(M_1)}(\gamma_D + \gamma_{S,\Delta L=1})\left(\frac{Y_{N_1}}{Y_{N_1}^{\mathrm{eq}}} - 1\right),$$

$$\frac{\mathrm{d}Y_{\Delta_\alpha}}{\mathrm{d}z} = \frac{-z}{sH(M_1)}\left[\varepsilon_{1,\alpha}(\gamma_D + \gamma_{S,\Delta L=1})\left(\frac{Y_{N_1}}{Y_{N_1}^{\mathrm{eq}}} - 1\right) - \left(\frac{\gamma_D^\alpha}{2} + \gamma_{W,\Delta L=1}^\alpha\right)\frac{\sum_\beta A_{\alpha\beta} Y_{\Delta_\beta}}{Y_\ell^{\mathrm{eq}}}\right]$$

$\varepsilon_{1,\alpha}$: decay asymmetries (into L_α + H)

γ_D^α: inverse decays and scattering processes which 'wash out' asymmetries in flavour α, but are also essential for their generation

$$Y_B^{\mathrm{SM}} = \frac{12}{37}\sum_\alpha Y_{\Delta_\alpha}^{\mathrm{SM}}$$

SM: Barbieri et al ('99), Abada et al ('06), Nardi et al ('06)
MSSM: S.A., S.F. King, A. Riotto ('06)

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The produced BAU (SM)

$Y_{\Delta\alpha}$: B/3 – L_α asymmetries

$\varepsilon_{1,\alpha}$: decay asymmetries (into L_α + H)

$$Y_{\Delta_\alpha}^{\rm SM} = \eta_\alpha^{\rm SM} \varepsilon_{1,\alpha}^{\rm SM} Y_{N_1}^{\rm eq}(z \ll 1)$$

η_α: efficiency factors

$$Y_B^{\rm SM} = \frac{12}{37} \sum_\alpha Y_{\Delta_\alpha}^{\rm SM}$$

sphaleron conversion

- Two ingredients:
  - the decay asymmetries $\varepsilon_{1,\alpha}$ for the independent flavours
  - the 'efficiency factor' η_α with which the asymmetries $Y_{\Delta\alpha}$ are generated (numerically, from flavour-dependent Boltzmann equations)

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The produced BAU (SUSY case)

total B/3 – L_α asymmetries (particle + sparticle!)

$\varepsilon_{1,\alpha}$: decay asymmetries (into L_α + H)

$$\hat{Y}^{\mathrm{MSSM}}_{\Delta_\alpha} = \eta^{\mathrm{MSSM}}_\alpha \varepsilon^{\mathrm{MSSM}}_{1,\alpha} \left[Y^{\mathrm{eq}}_{N_1}(z \ll 1) + Y^{\mathrm{eq}}_{\widetilde{N}_1}(z \ll 1) \right]$$

η_α: efficiency factors

$$Y^{\mathrm{MSSM}}_B = \frac{10}{31} \sum_\alpha \hat{Y}^{\mathrm{MSSM}}_{\Delta_\alpha}$$

sphaleron conversion

- Note: The above ansatz uses already $\varepsilon^{\mathrm{MSSM}}_{1,\alpha} = \varepsilon^{\mathrm{MSSM}}_{1,\widetilde{\alpha}} = \varepsilon^{\mathrm{MSSM}}_{\widetilde{1},\alpha} = \varepsilon^{\mathrm{MSSM}}_{\widetilde{1},\widetilde{\alpha}}$, where:

$$\varepsilon_{1,\alpha} = \frac{\Gamma_{N_1 \ell_\alpha} - \Gamma_{N_1 \bar{\ell}_\alpha}}{\sum_\alpha (\Gamma_{N_1 \ell_\alpha} + \Gamma_{N_1 \bar{\ell}_\alpha})}\,, \quad \varepsilon_{1,\widetilde{\alpha}} = \frac{\Gamma_{N_1 \widetilde{\ell}_\alpha} - \Gamma_{N_1 \widetilde{\ell}^*_\alpha}}{\sum_\alpha (\Gamma_{N_1 \widetilde{\ell}_\alpha} + \Gamma_{N_1 \widetilde{\ell}^*_\alpha})}$$

$$\varepsilon_{\widetilde{1},\alpha} = \frac{\Gamma_{\widetilde{N}^*_1 \ell_\alpha} - \Gamma_{\widetilde{N}_1 \bar{\ell}_\alpha}}{\sum_\alpha (\Gamma_{\widetilde{N}^*_1 \ell_\alpha} + \Gamma_{\widetilde{N}_1 \bar{\ell}_\alpha})}\,, \quad \varepsilon_{\widetilde{1},\widetilde{\alpha}} = \frac{\Gamma_{\widetilde{N}_1 \widetilde{\ell}_\alpha} - \Gamma_{\widetilde{N}^*_1 \widetilde{\ell}^*_\alpha}}{\sum_\alpha (\Gamma_{\widetilde{N}_1 \widetilde{\ell}_\alpha} + \Gamma_{\widetilde{N}^*_1 \widetilde{\ell}^*_\alpha})}$$

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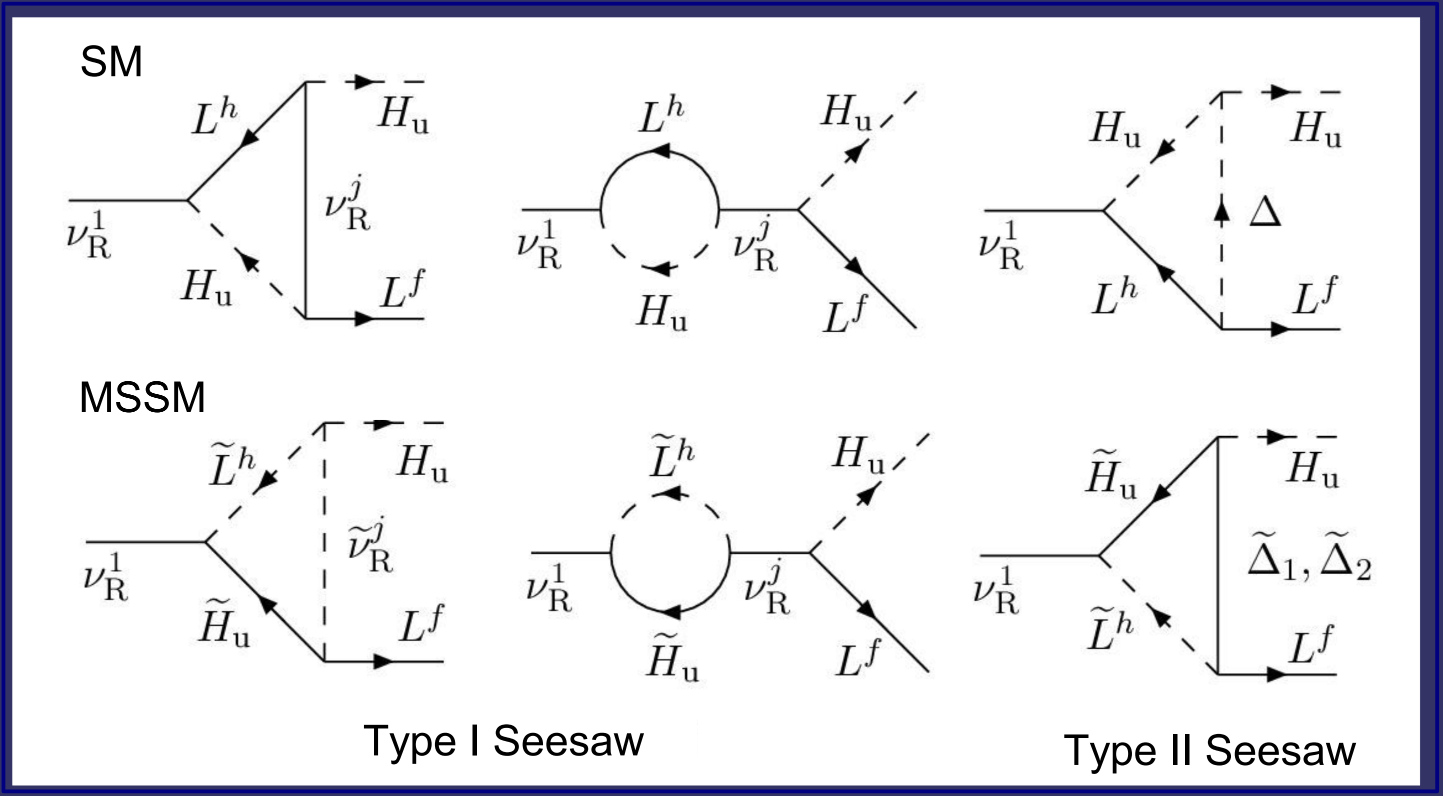
Step 1: Decay asymmetries

➲ Decay of the lightest RH neutrino ($\nu_R^1 \rightarrow L^f H_u$): Tree-level $\leftrightarrow$ 1-loop



Type I: L. Covi, E. Roulet, F. Vissani ('96)

Type II: S.A., S.F. King ('04)

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Step 1: Decay asymmetries

- Results: in the limit $M_{R1} \ll M_{R2} \ll M_{R3}$ and $M_{R1} \ll M_{\Delta}$
  - in the SM: (Y_e diagonal)

$$\varepsilon_{1,f}^{\mathrm{SM}} = \frac{3}{16\pi} \frac{M_{\mathrm{R1}}}{v_{\mathrm{u}}^2} \frac{\sum_{fg} \mathrm{Im}\,[(Y_\nu^*)_{f1}(Y_\nu^*)_{g1}(m_{\mathrm{LL}}^{\mathrm{I}} + m_{\mathrm{LL}}^{\mathrm{II}})_{fg}]}{(Y_\nu^\dagger Y_\nu)_{11}}$$

  - in the MSSM: (Y_e diagonal)

$$\varepsilon_{1,f}^{\mathrm{MSSM}} = \frac{3}{8\pi} \frac{M_{\mathrm{R1}}}{v_{\mathrm{u}}^2} \frac{\sum_{fg} \mathrm{Im}\,[(Y_\nu^*)_{f1}(Y_\nu^*)_{g1}(m_{\mathrm{LL}}^{\mathrm{I}} + m_{\mathrm{LL}}^{\mathrm{II}})_{fg}]}{(Y_\nu^\dagger Y_\nu)_{11}}$$

link to the (type I + type II) neutrino mass matrix

proportional to the mass of ν_{R1}

dependence on the Yukawa couplings to ν_{R1}

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Step 2: Computation of the flavour-dependent efficiency factor

- From solving the Boltzmann equations ...

S.A., S.F. King, A. Riotto ('06)

Efficiencies depend mainly on flavour-dependent washout parametrer

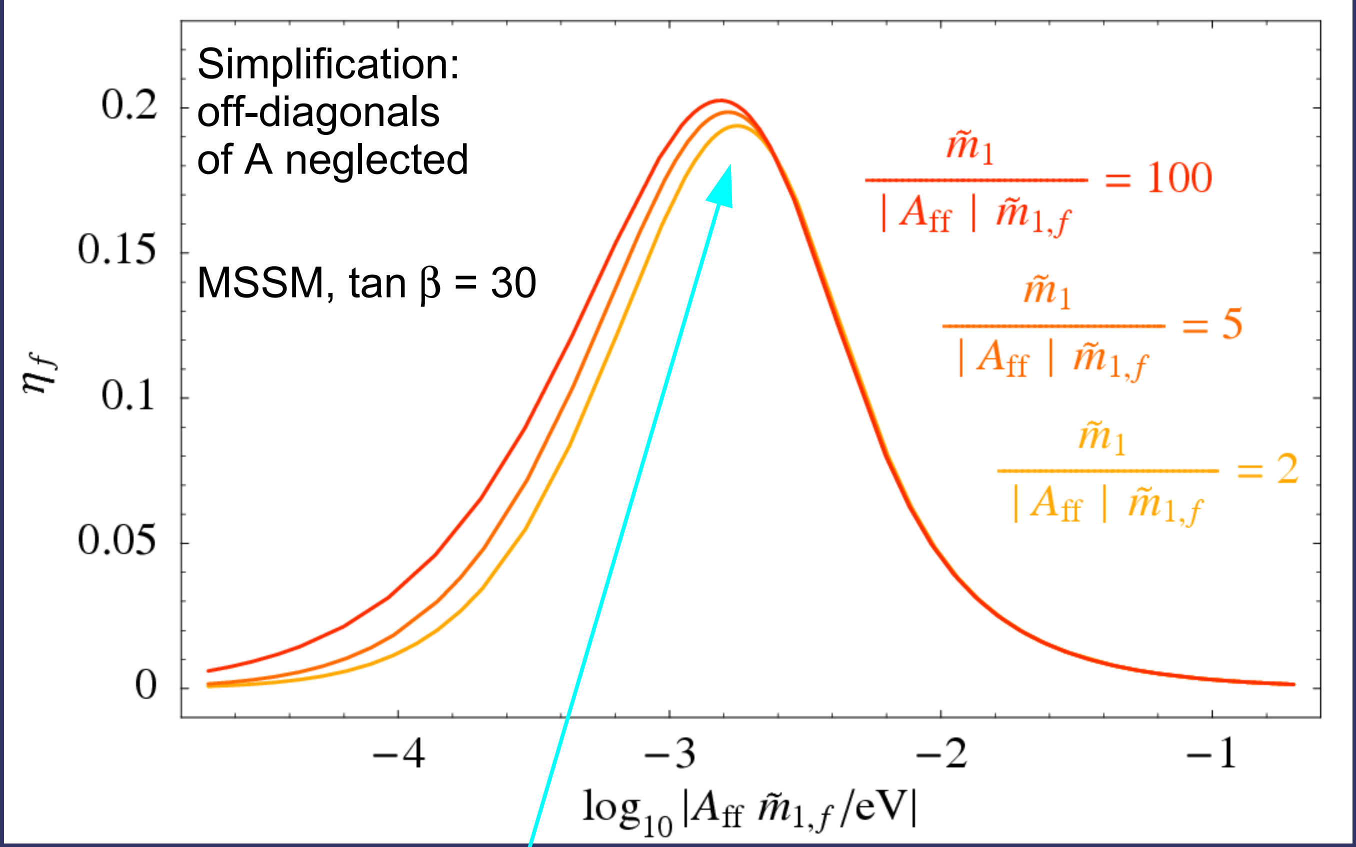
$$\widetilde{m}_{1,f} = \frac{v_u^2 \, |(Y_\nu)_{f1}|^2}{M_{R1}}$$

on the sum

$$\widetilde{m}_1 = \sum_f \widetilde{m}_{1,f}$$

and on the matrix A

$$A^{\rm MSSM} = \begin{pmatrix} -93/110 & 6/55 & 6/55 \\ 3/40 & -19/30 & 1/30 \\ 3/40 & 1/30 & -19/30 \end{pmatrix}$$



Note: $A_{\alpha\alpha} = O(1)$

Optimal efficiency for washout parameter ~

$$m^*_{\rm MSSM} \approx \sin^2(\beta) \times 1.58 \times 10^{-3} \text{ eV}$$

Main difference: Flavour-dependent vs. flavour-independent treatment

Correct flavour-dependent:

$$\sum_\alpha \varepsilon_{1,\alpha}\eta_{\alpha}$$

Flavour-dep. $\varepsilon_{1,\alpha}$ weighted by flavour-dep. efficiency η_α !

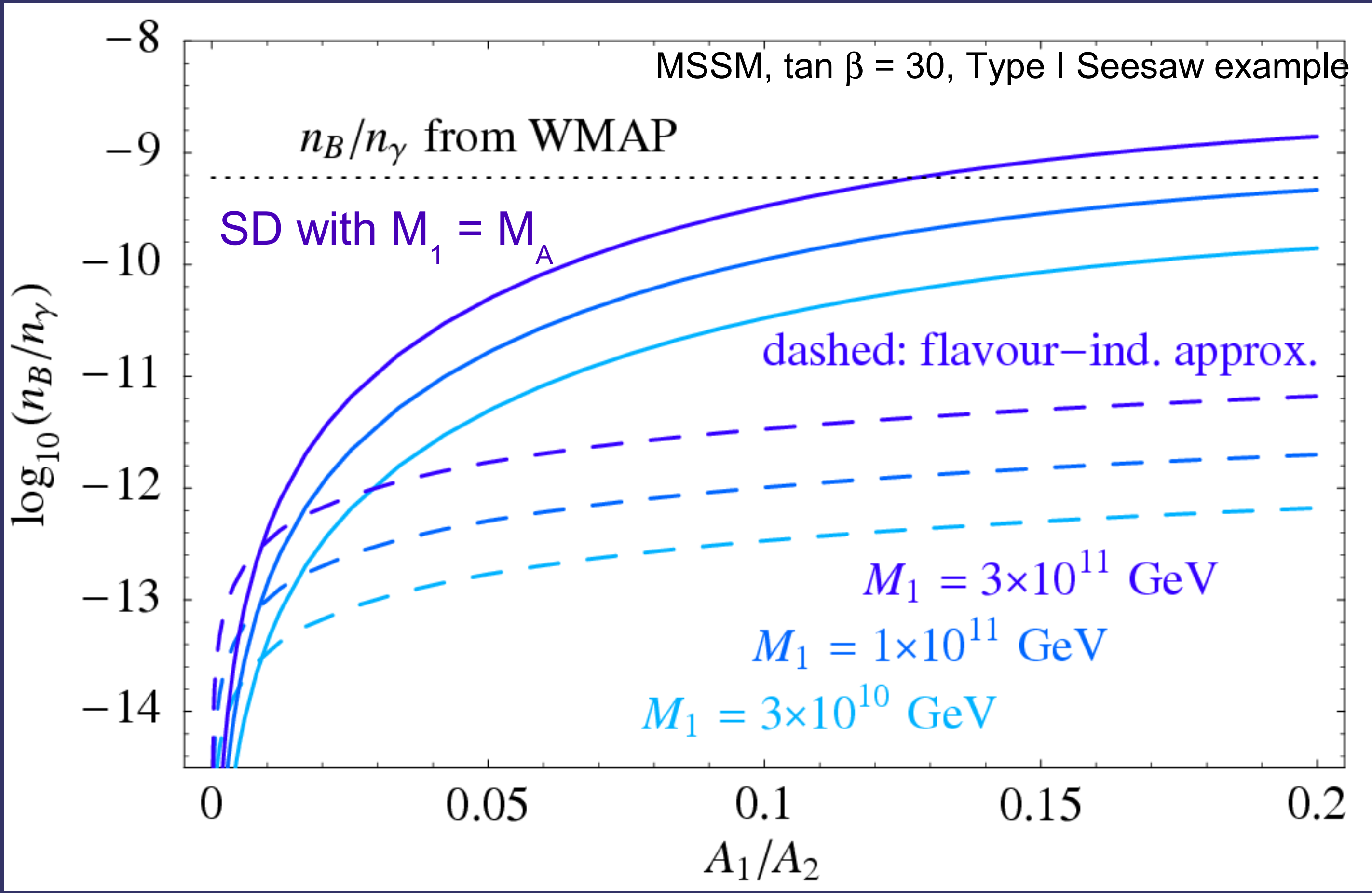
Flavour-independent approximation:

$$\left(\sum_\alpha \varepsilon_{1,\alpha}\right) \times \eta^{\mathrm{ind}}\left(\sum_\beta \widetilde{m}_{1,\beta}\right)$$

- This affects the produced BAU from thermal leptogenesis with a given seesaw flavour structure ...

Example: Flavour-dependent vs. flavour independent

S.A., S.F. King, A. Riotto ('06)



Correct flavour-dependent treatment:

$$Y_B \propto \sum_\alpha \varepsilon_{1,\alpha} \eta_\alpha$$

vs.

Flavour-independent approximation:

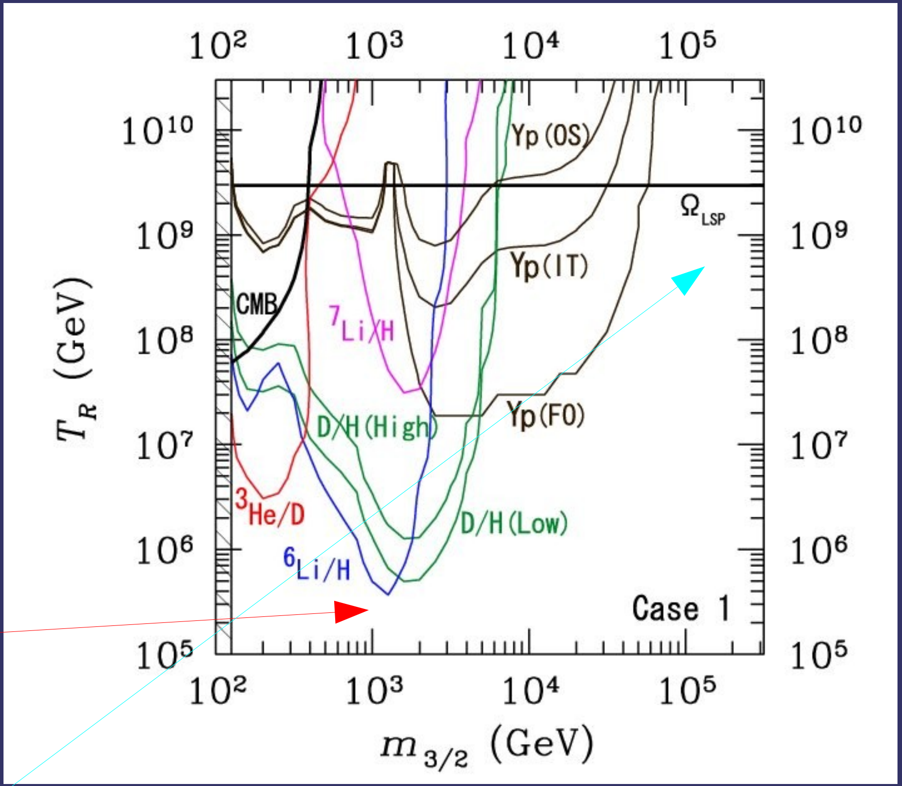
$$Y_B \propto \left(\sum_\alpha \varepsilon_{1,\alpha}\right) \times \eta^{\text{ind}} \left(\sum_\beta \widetilde{m}_{1,\beta}\right)$$

Constraints on T_{RH}

- The role of T_{RH} for leptogenesis:
  - ... for thermal leptogenesis high temperatures are required in order to produce RH neutrinos in the thermal bath (naively $T \sim M_{R1}$)
  - ... realised after inflation ($\rightarrow T_{RH}$)
- Typical problems of high T_{RH}: (thermal prod. of long lived particles)
  - i) BBN gravitino problem:
    $\Rightarrow$ constraints on reheating T_{RH}, depending on gravitino mass $m_{3/2}$!

    Here: $m_{3/2}$ free parameter $\rightarrow$ heavy

example in SUGA model (maybe not fully up-to-date):



Kohri, Moroi, Yotsuyanagi ('05)

Note: stable gravitinos $\rightarrow$ problems with long lived NLSPs; possible solutions if e.g. R-parity violated, ...

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Constraints on T_{RH}

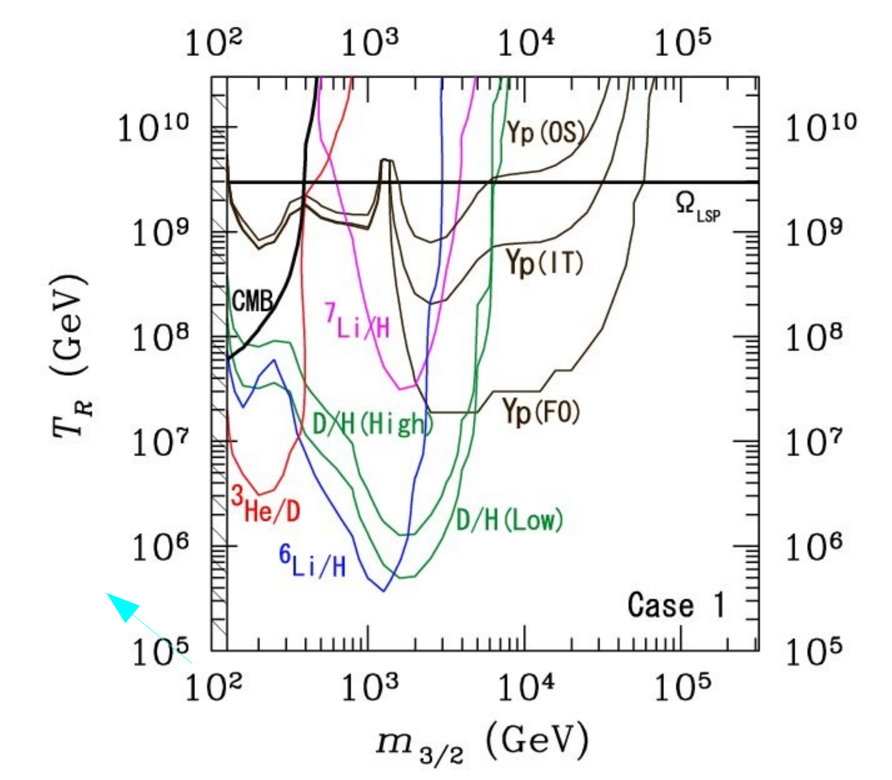
- Typical problems of high T_{RH}:
  - ii) Gravitino decay $\Rightarrow$ LSP
    (R-parity assumed, neutralino LSP)
    LSPs produced non-thermally from gravitino decays. From $\Delta\Omega_{LSP} < \Omega_m$
    $\Rightarrow$ constraints on reheating T_{RH}

$\rightarrow$ $T_{RH} \lesssim 2 \times 10^{10}$ GeV
for neutralino mass 100 ...150 GeV

$$\Delta\Omega_{\rm LSP} h^2 \simeq 0.054 \times \left(\frac{m_{\chi_1^0}}{100\ \rm GeV}\right)\left(\frac{T_{\rm R}}{10^{10}\ \rm GeV}\right)$$

has to be <~ 0.13 WMAP

example in SUGA model (maybe not fully up-to-date):



Kohri, Moroi, Yotsuyanagi ('05)

- Consequence: constraints on leptogenesis ($\rightarrow$ flavour structure)

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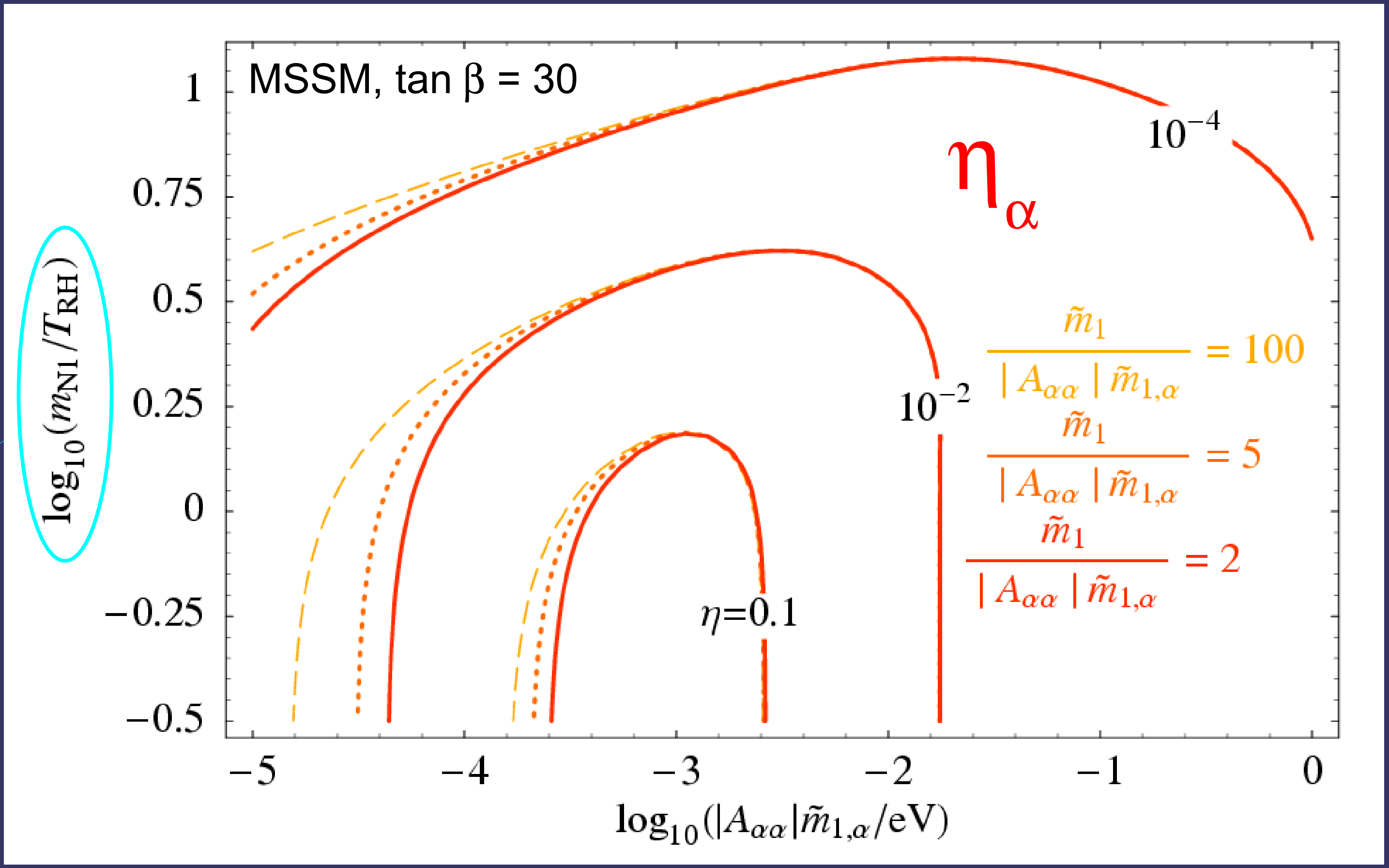
Leptogenesis efficiency and T_{RH}

- Assuming that the decays of the inflaton reheat only MSSM particles (Note: non-th. ν_{R1}-prod. (gravitino prod.) can improve η_α (lower T_{RH}^{max})):



strong dependence!

Note: $A_{\alpha\alpha}$ = O(1)

S.A., A. Teixeira ('06)

- Results (Mathematica function!) available!

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General considerations: Bounds on the decay asymmetries

- Type I seesaw:

Abada et al. ('06)

$$|\varepsilon_{1,f}^{\mathrm{I,MSSM}}| \leq \frac{3}{8\pi}\frac{M_{\mathrm{R1}}}{v_{\mathrm{u}}^2} m^{\nu}_{\mathrm{max}} \left(\frac{\widetilde{m}_{1,f}}{\widetilde{m}_1}\right)^{\frac{1}{2}}$$

proportional to the mass of ν_{R1}

proportional to the absolute neutrino mass scale

supression for quasi-degenerate neutrino masses if optimal flavoured washout parameter (~ 10^{-3} eV)

note: only in type I

$$\widetilde{m}_1 \geq m^{\nu}_{\mathrm{min}}$$

- Type II seesaw:

S.A., S.F. King ('04) S.A. ('07)

$$|\varepsilon_{1,f}^{\mathrm{MSSM}}| \leq \frac{3}{8\pi}\frac{M_{\mathrm{R1}}}{v_{\mathrm{u}}^2} m^{\nu}_{\mathrm{max}}$$

no supression for quasi-degenerate neutrino masses
$\rightarrow$ leptogenesis more efficient if $m_\nu \uparrow$

- Observation: For $m_\nu \uparrow$, type I bound stronger (below ~ 0.5 eV, for optimal efficiency/washout) whereas type II bound relaxed!

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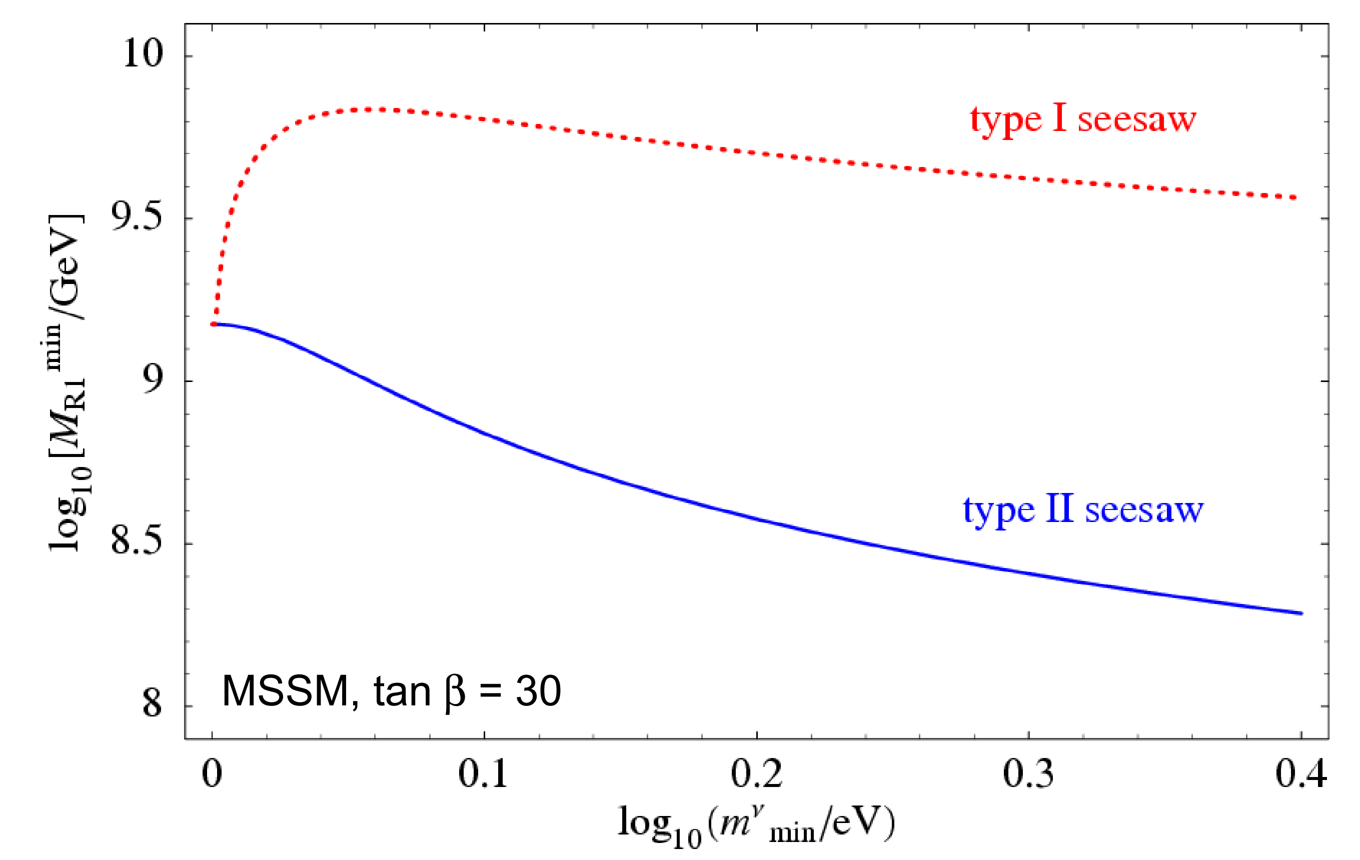
General considerations: Bounds on the decay asymmetries

- Using the bounds on $\varepsilon_{1,\alpha}$, and results for η_α, we obtain a bound for M_{R1}!

$$\hat{Y}^{\mathrm{MSSM}}_{\Delta_\alpha} = \eta^{\mathrm{MSSM}}_\alpha \, \varepsilon^{\mathrm{MSSM}}_{1,\alpha} \left[Y^{\mathrm{eq}}_{N_1}(z \ll 1) + Y^{\mathrm{eq}}_{\widetilde{N}_1}(z \ll 1) \right]$$

S.A. ('07)



Note: for hierarchical neutrinos, almost unchanged compared to flavour-independent approximation; changes for m_ν ↑

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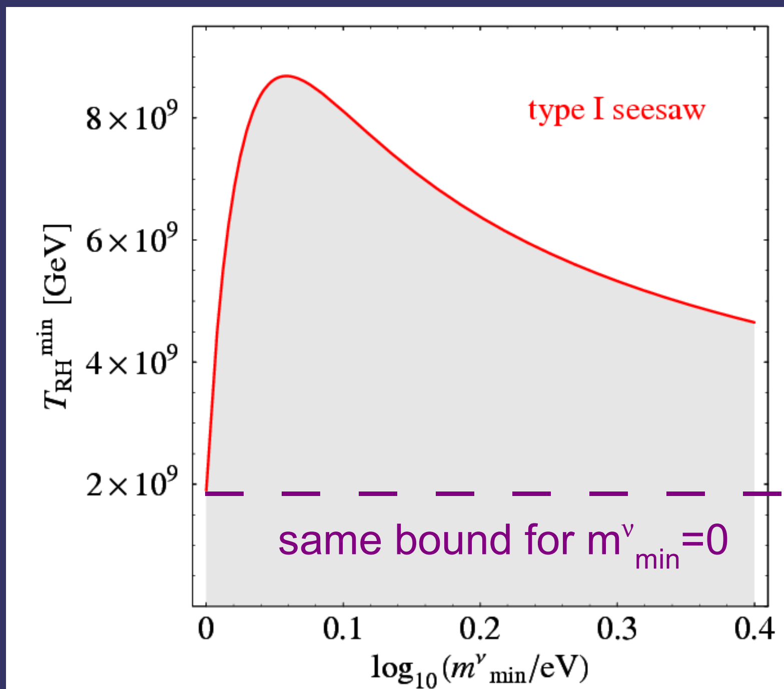
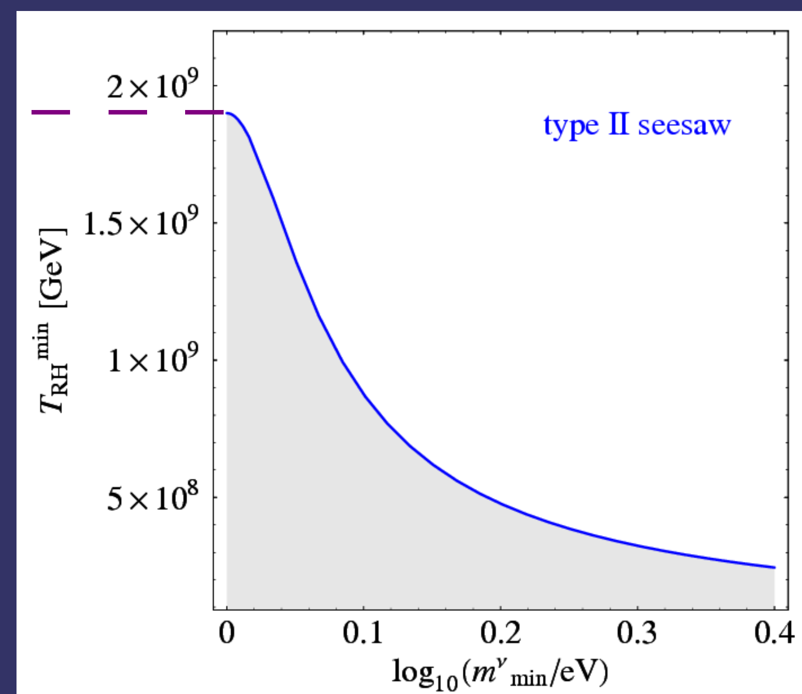
Constraints on T_{RH} and on m_ν



S.A. ('07)

- Type I Seesaw:
  $m^\nu{}_{min} \uparrow \Rightarrow T^{min}{}_{RH} \uparrow$

MSSM, tan β = 30



- Type II Seesaw:
  $m^\nu{}_{min} \uparrow \Rightarrow T^{min}{}_{RH} \downarrow$

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Sequential RH neutrino dominance

- Mass matrix of RH neutrinos (diagonal)
  (Note: within type I seesaw !)

$$M_{\mathrm{RR}} = \begin{pmatrix} M_A & 0 & 0 \\ 0 & M_B & 0 \\ 0 & 0 & M_C \end{pmatrix}$$

- Neutrino Yukawa matrix (Y_e diagonal,LR conv.)
  Note: permuations A ↔ B ↔ C possible!

$$Y_\nu = (\vec{A} \;\; \vec{B} \;\; \vec{C})$$

- Low energy: neutrino mass operator ('Seesaw formula')

$$\mathcal{L}^{\nu}_{eff} = \frac{(\nu_i^T A_i)(A_j^T \nu_j)}{M_A} + \frac{(\nu_i^T B_i)(B_j^T \nu_j)}{M_B} + \frac{(\nu_i^T C_i)(C_j^T \nu_j)}{M_C}$$

- Sequential dominance condition:

S.F. King ('98,'02)

$$\frac{A_i A_j}{M_A} \gg \frac{B_i B_j}{M_B} \gg \frac{C_i C_j}{M_C}$$

'subsubdominant RH neutrino' (mass M_C) gives smallest contribution (hierarchical ν-masses, ↔ $m_{\nu 1}$)

Leading contribution to m_ν from 'dominant RH neutrino' (mass M_A)

Sub-leading contribution to m_ν from 'subdominant RH neutrino' (mass M_B)

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SD and neutrino masses and mixing angles

Yukawa couplings of dominant RH neutrino — Yukawa couplings of subdominant RH neutrino

- Defining $A_\alpha = |A_\alpha| e^{i\phi_{A_1}}, \; B_\alpha = |B_\alpha| e^{i\phi_{B_1}}, \; C_\alpha = |C_\alpha| e^{i\phi_{C_1}}$
- MNS mixing angles

$$\tan\theta_{23} \approx \frac{|A_2|}{|A_3|},$$

Almost maximal $\theta_{23} \Rightarrow |A_2| \approx |A_3|$

Small $\theta_{23} \Rightarrow |A_1| << |A_2|, |A_3|$

$$\tan\theta_{12} \approx \frac{|B_1|}{c_{23}|B_2|\cos\tilde{\phi}_2 - s_{23}|B_3|\cos\tilde{\phi}_3},$$

Large $\theta_{12} \Rightarrow |B_1| \approx |B_2|$ &/or $|B_3|$

$$\theta_{13} \approx e^{i(\tilde{\phi}+\phi_{B_1}-\phi_{A_2})} \frac{|B_1|(A_2^* B_2 + A_3^* B_3)}{[|A_2|^2+|A_3|^2]^{3/2}} \frac{M_A}{M_B} + \frac{e^{i(\tilde{\phi}+\phi_{A_1}-\phi_{A_2})}|A_1|}{\sqrt{|A_2|^2+|A_3|^2}}$$

$O(m_2/m_3)$

- Neutrino masses

$$m_3 \approx \frac{(|A_2|^2+|A_3|^2)v^2}{M_A},$$

$$m_2 \approx \frac{|B_1|^2 v^2}{s_{12}^2 M_B},$$

$$m_1 \approx \mathcal{O}(|C|^2 v^2/M_C).$$

- CP phases (+ conditions θ_{12}, θ_{13} real $\Rightarrow \delta$)

$$\tilde{\phi}_2 \equiv \phi_{B_2} - \phi_{B_1} - \tilde{\phi} + \delta,$$

$$\tilde{\phi}_3 \equiv \phi_{B_3} - \phi_{B_1} + \phi_{A_2} - \phi_{A_3} - \tilde{\phi} + \delta$$

Decay asymmetries and washout factors in SD (3 classes of models)

Type of SD	$\varepsilon_{1,\alpha}$	$\widetilde{m}_{1,\alpha}$
$M_1 = M_A$	$-\frac{3M_1}{16\pi}\left\{\frac{\mathrm{Im}\left[A^*_\alpha B_\alpha (A^\dagger B)\right]}{M_B\,(A^\dagger A)} + \frac{\mathrm{Im}\left[A^*_\alpha C_\alpha (A^\dagger C)\right]}{M_C\,(A^\dagger A)}\right\}$	$\frac{\lvert A_\alpha\rvert^2 v_\mathrm{u}^2}{M_1}$
$M_1 = M_B$	$-\frac{3M_1}{16\pi}\left\{\frac{\mathrm{Im}\left[B^*_\alpha A_\alpha (B^\dagger A)\right]}{M_A\,(B^\dagger B)} + \frac{\mathrm{Im}\left[B^*_\alpha C_\alpha (B^\dagger C)\right]}{M_C\,(B^\dagger B)}\right\}$	$\frac{\lvert B_\alpha\rvert^2 v_\mathrm{u}^2}{M_1}$
$M_1 = M_C$	$-\frac{3M_1}{16\pi}\left\{\frac{\mathrm{Im}\left[C^*_\alpha A_\alpha (C^\dagger A)\right]}{M_A(C^\dagger C)} + \frac{\mathrm{Im}\left[C^*_\alpha B_\alpha (C^\dagger B)\right]}{M_B(C^\dagger C)}\right\}$	$\frac{\lvert C_\alpha\rvert^2 v_\mathrm{u}^2}{M_1}$

M_1: lightest RH neutrino

leading contribution

subleading (suppressed) contribution

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Ideal conditions for leptognesis?

S.A., S.F. King, A. Riotto ('06)

- Decay asymmetries:

Type of SD	relation for $\varepsilon_{1,e}$	relation for $\varepsilon_{1,\mu}$	relation for $\varepsilon_{1,\tau}$
$M_1 = M_A$	$\ll \mathcal{O}(\frac{m_2}{m_3})\varepsilon^{\max}$	$\lesssim \mathcal{O}(\frac{m_2}{m_3})\varepsilon^{\max}$	$\lesssim \mathcal{O}(\frac{m_2}{m_3})\varepsilon^{\max}$
$M_1 = M_B$	$\ll \varepsilon^{\max}$	$\lesssim \varepsilon^{\max}$	$\lesssim \varepsilon^{\max}$
$M_1 = M_C$	$\lesssim \mathcal{O}(\frac{m_2}{m_3})\varepsilon^{\max}$	$\lesssim \varepsilon^{\max}$	$\lesssim \varepsilon^{\max}$

Can in general be optimal, but potential cancellation in $\varepsilon_{1,\alpha}$ if θ_{12} close to tri-bimaximal via A = (0,-1,1), B = (1,1,1)!

- Washout parameters:

Type of SD	washout by $\widetilde{m}_{1,e}$	washout by $\widetilde{m}_{1,\mu}$	washout by $\widetilde{m}_{1,\tau}$
$M_1 = M_A$	weak/optimal	strong, $\widetilde{m}_{1,\mu} \approx \frac{1}{2} m_3$	strong, $\widetilde{m}_{1,\tau} \approx \frac{1}{2} m_3$
$M_1 = M_B$	optimal, $\widetilde{m}_{1,e} \approx s_{12}^2 m_2$	$\lesssim \mathcal{O}(m_2)^*$	$\lesssim \mathcal{O}(m_2)^*$
$M_1 = M_C$	weak/optimal	weak/optimal	weak/optimal

*(At least) one of them is $O(m_2)$; optimal washout possible ...

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MNS CP phase δ and leptogenesis

S.A., S.F. King, A. Riotto ('06)

- 3 characteristic cases:
  - $M_1 = M_A$ and 2 texture zeros: ⇒ strong δ MNS ↔ leptogenesis link!

$$Y_\nu = \begin{pmatrix} 0 & B_1 & C_1 \\ A_2 & B_2 & C_2 \\ A_3 & 0 & C_3 \end{pmatrix}$$

$$Y_B \propto -\sin(\delta)$$

$$Y_\nu = \begin{pmatrix} 0 & B_1 & C_1 \\ A_2 & 0 & C_2 \\ A_3 & B_3 & C_3 \end{pmatrix}$$

$$Y_B \propto \sin(\delta)$$

  - $M_1 = M_B$ and 2 texture zeros: ⇒ strong δ MNS ↔ leptogenesis link!

$$Y_\nu = \begin{pmatrix} B_1 & 0 & C_1 \\ B_2 & A_2 & C_2 \\ 0 & A_3 & C_3 \end{pmatrix}$$

$$Y_B \propto \sin(\delta)$$

$$Y_\nu = \begin{pmatrix} B_1 & 0 & C_1 \\ 0 & A_2 & C_2 \\ B_3 & A_3 & C_3 \end{pmatrix}$$

$$Y_B \propto -\sin(\delta)$$

  - $M_1 = M_C$: ⇒ no MNS ↔ leptogenesis link!

R-matrix parameterisation of the seesaw degrees of freedom

➲ Completely model-independent:

- Start with seesaw equation: $m_\nu = -v_u^2 Y_\nu M_{RR}^{-1} Y_\nu^T$ (basis: $Y_e = Y_e^{diag}$)
  (Note: here type I !)
  low energy: 12 parameters
  high energy: 21 parameters

- Strategy: find $m_D = v_u Y_\nu$ with $(M_{RR})_{ij} = (M_{RR})_{ij}^{diag}$

- Solution can be expressed in terms of complex orthogonal matrix R

$$m_D^T = i\sqrt{M_{RR}^{diag}} R \sqrt{m_\nu^{diag}} U_{MNS}^\dagger \qquad R = R^T \quad \text{(R orthogonal, complex)}$$

$$R = \begin{pmatrix} c_2 c_3 & -c_1 s_3 - s_1 s_2 c_3 & s_1 s_3 - c_1 s_2 c_3 \\ c_2 s_3 & c_1 c_3 - s_1 s_2 s_3 & -s_1 c_3 - c_1 s_2 s_3 \\ s_2 & s_1 c_2 & c_1 c_2 \end{pmatrix}$$

Casas, Ibarra ('01)

$c_i = \cos\theta_i$, $s_i = \sin\theta_i$, $\theta_{1,2,3}$ complex

R-matrix vs. Sequential Dominance

- $M_1 = M_A$:
  - $Y_\nu = (A,B,C)$ $\leftrightarrow$ $(\theta_1,\theta_2,\theta_3) \approx (\pi/2,0,\pi/2)$
  - $Y_\nu = (A,C,B)$ $\leftrightarrow$ $(\theta_1,\theta_2,\theta_3) \approx (\pi/2,\pi/2,0)$
- $M_1 = M_B$:
  - $Y_\nu = (B,A,C)$ $\leftrightarrow$ $(\theta_1,\theta_2,\theta_3) \approx (0,0,\pi/2)$
  - $Y_\nu = (B,C,A)$ $\leftrightarrow$ $(\theta_1,\theta_2,\theta_3) \approx (\pi/2,\pi/2,\pi/2)$
- $M_1 = M_C$:
  - $Y_\nu = (C,A,B)$ $\leftrightarrow$ $(\theta_1,\theta_2,\theta_3) \approx (\pi/2,0,0)$
  - $Y_\nu = (C,B,A)$ $\leftrightarrow$ $(\theta_1,\theta_2,\theta_3) \approx (0,0,0)$

- Other angles interpolate between SD cases!

Decay asymmetries and washout factors in R-matrix parameterisation

- Decay asymmetries

$$\varepsilon_{1,\alpha} = -\frac{3\, m_{N_1}}{8\,\pi\, v_2^2} \frac{\mathrm{Im}\left[\sum_{\beta\rho} m_{\nu_\beta}^{1/2}\, m_{\nu_\rho}^{3/2} (U_{\mathrm{MNS}})^*_{\alpha\beta} (U_{\mathrm{MNS}})_{\alpha\rho}\, R_{1\beta}\, R_{1\rho}\right]}{\sum_\delta m_{\nu_\delta} |R_{1\delta}|^2}$$

- Washout parameters

$$\widetilde{m}_{1,\alpha} = \left|\sum_\beta \sqrt{m_{\nu_\beta}} R_{1\beta} (U^\dagger_{\mathrm{MNS}})_{\beta\alpha}\right|^2$$

dependence on
R-matrix angles
and RH ν-masses

dependence on $m_{\nu i}$
and U_{MNS}

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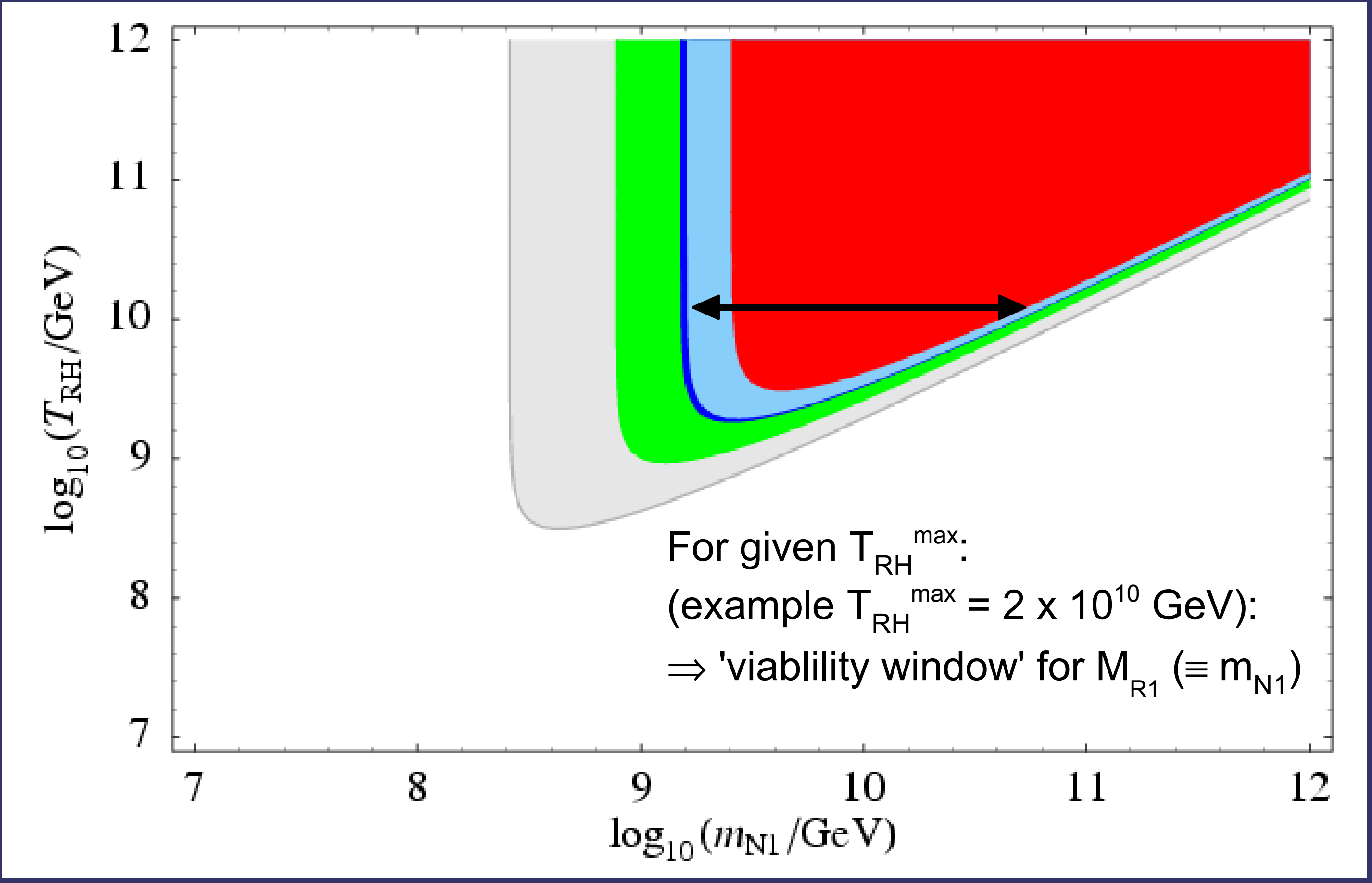
Leptogenesis bounds on T_{RH} and M_{R1}

- In type I seesaw (using the upper bound for $\varepsilon_{1,\alpha}$ (& $\Sigma\, \varepsilon_{1,\alpha}$) and optimal η_α):

→ maximally possible BAU (type I seesaw)

<u>Here and in the following:</u>
MSSM case, tan β = 30,
type I seesaw,
normal ν-mass hierarchy
$m_{\nu 1} = 10^{-3}$ eV

<u>Colour code:</u>
grey: WMAP x [1/5,1/2]
green: WMAP x [1/2,1]
dark blue: WMAP range
light blue: ~ WMAP x [1,2]
red: >~ WMAP x 2



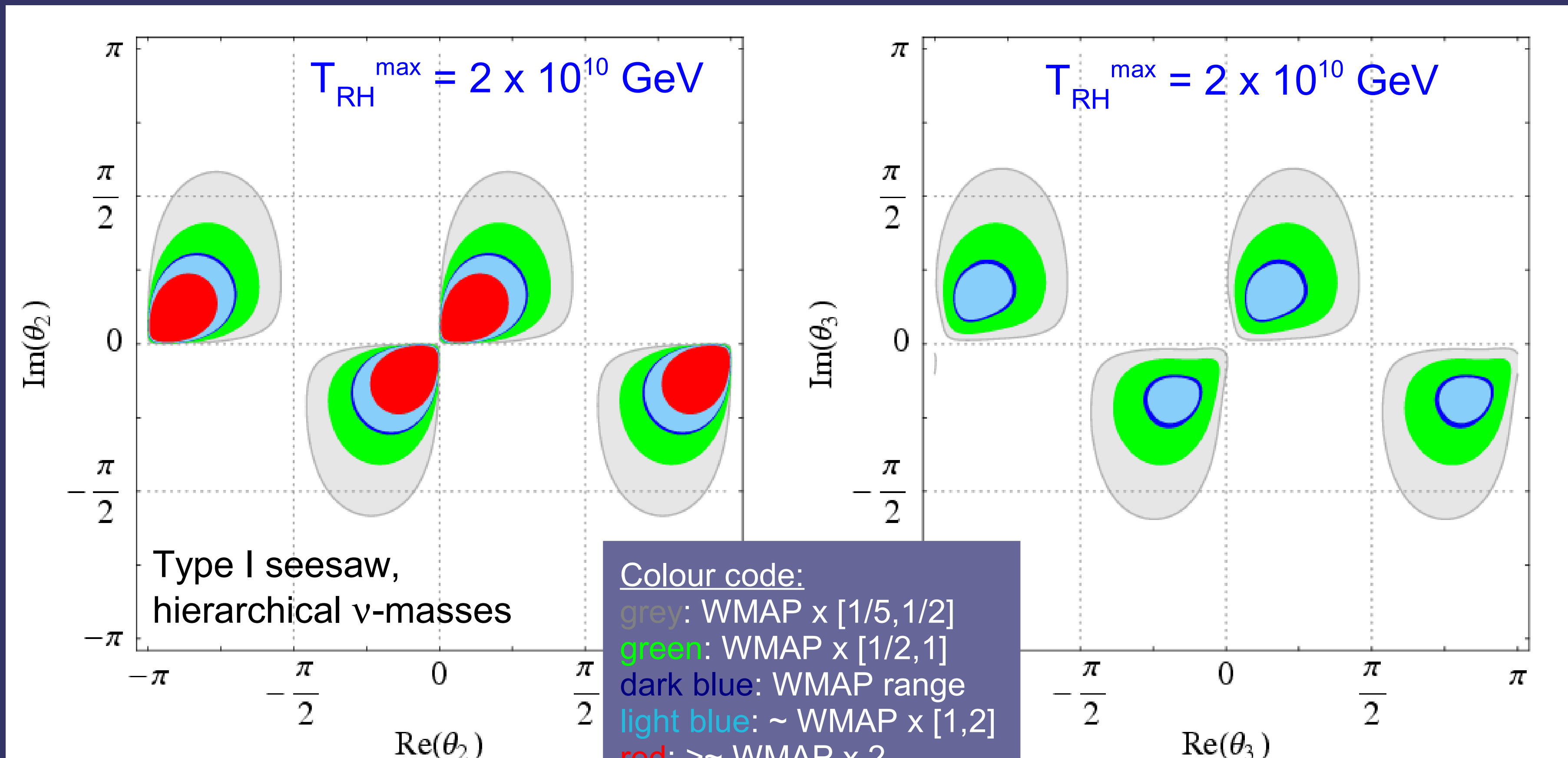
S.A., A. Teixeira ('06)

- Next: Flavour structure compatible with $T_{RH}^{max} = 2 \times 10^{10}$ GeV

Leptogenesis constraints on See-saw parameters (MSSM)

- Constraints on R matrix angles θ_2 and θ_3

S.A., A. Teixeira ('06)



(a) $T_{\rm RH} \leq 2 \times 10^{10}$ GeV, $\theta_{13} = \delta = \varphi_1 = \varphi_2 = 0°$

$T_{\rm RH} \leq 2 \times 10^{10}$ GeV, $\theta_{13} = \delta = \varphi_1 = \varphi_2 = 0°$

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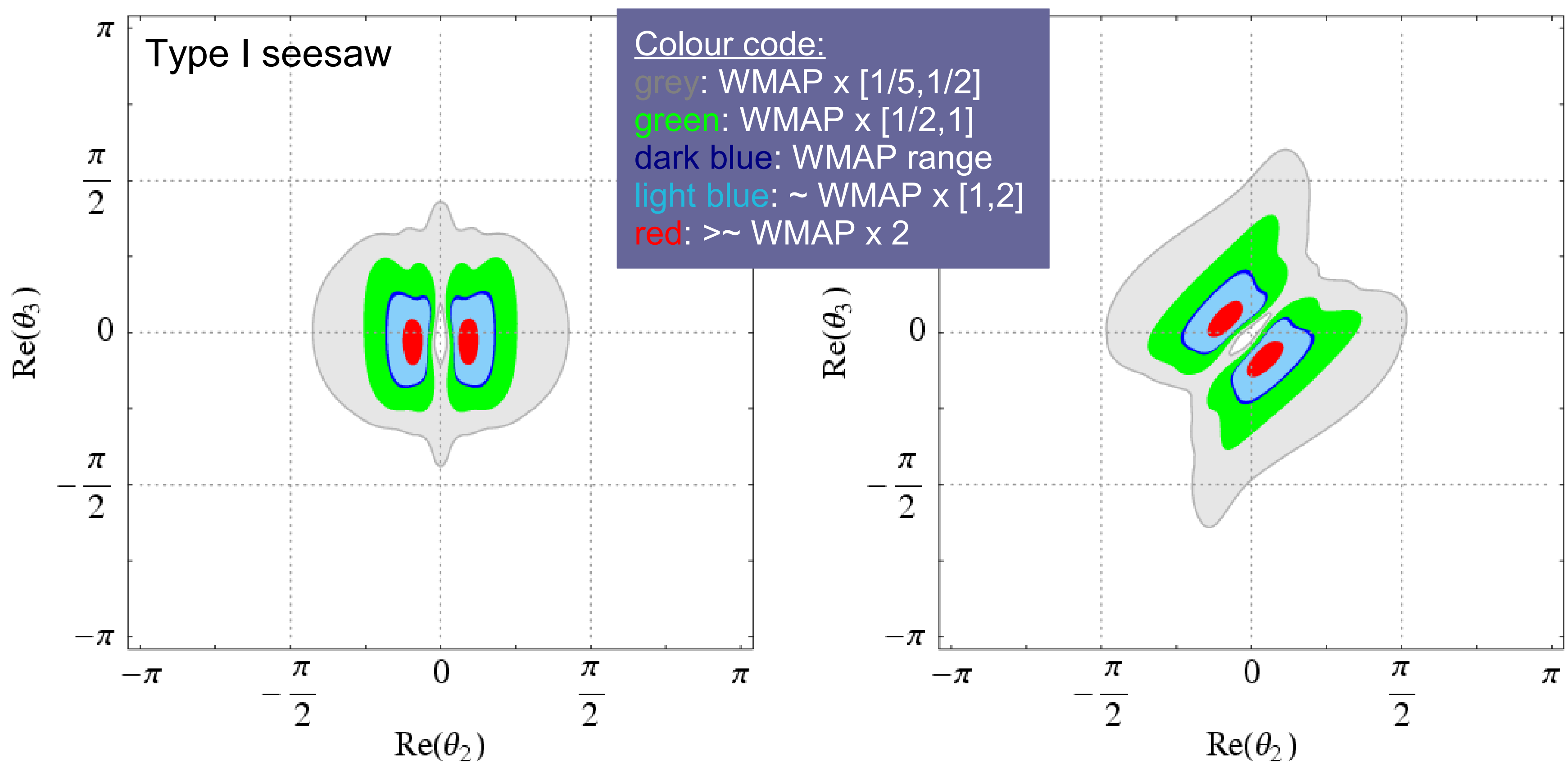
Leptogenesis constraints on See-saw parameters (MSSM)

- The role of the R matrix angle θ_1



(a) $T_{\mathrm{RH}} \leq 5 \times 10^9$ GeV, $\arg(\theta_2, \theta_3) = \pi/4$, $\theta_1 = 0$

(b) $T_{\mathrm{RH}} \leq 5 \times 10^9$ GeV, $\arg(\theta_2, \theta_3) = \pi/4$, $|\theta_1| = \pi/4$, $\arg(\theta_1) = 0$

Note: 'interpolates' between Y_ν = (C,A,B) ↔ Y_ν = (C,B,A)

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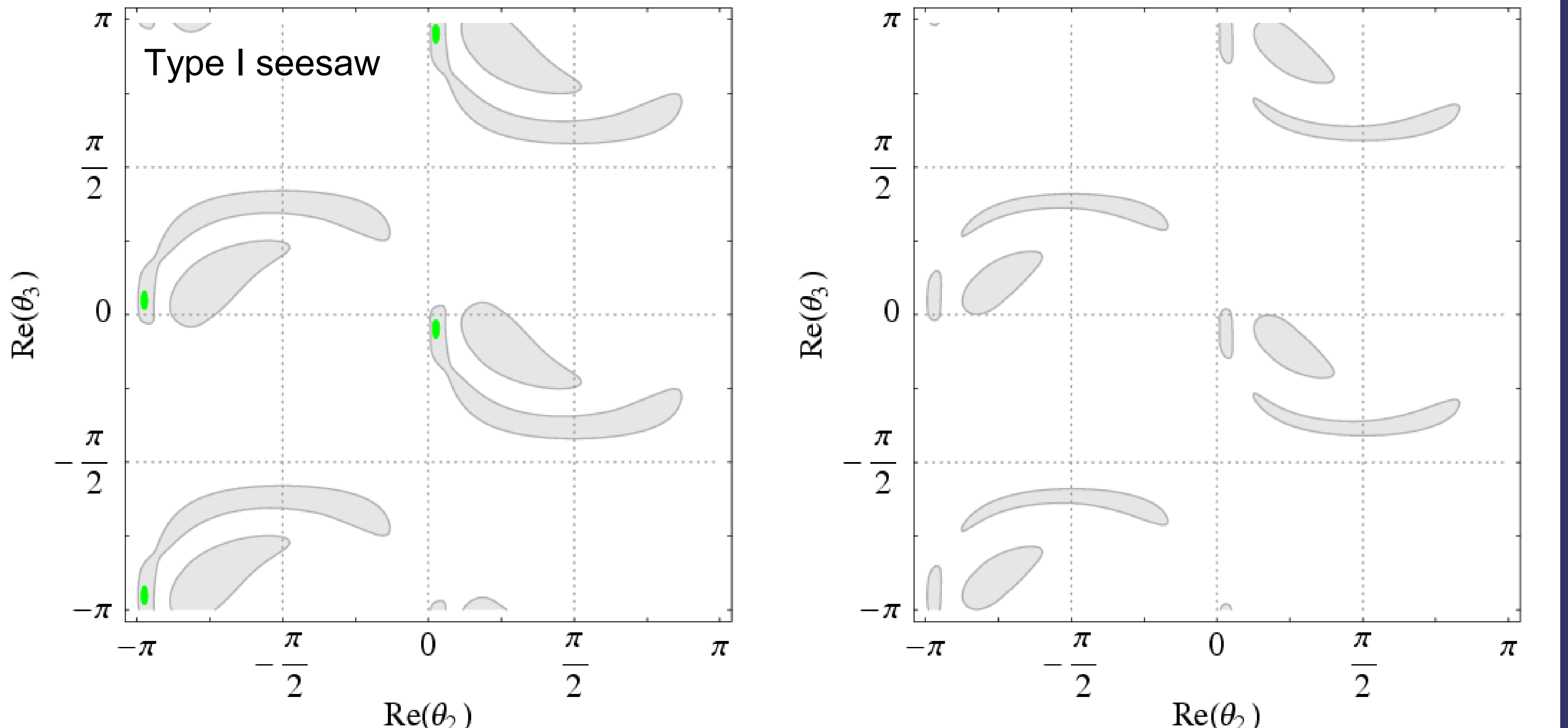
Leptogenesis constraints on See-saw parameters (MSSM)

- The case of real R matrix: CP violation only from δ_{MNS} ?



(a) $T_{\rm RH} \leq 2 \times 10^{10}$ GeV, $\theta_{13} = 11.5°, \delta = 90°$ (b) $T_{\rm RH} \leq 2 \times 10^{10}$ GeV, $\theta_{13} = 7.5°, \delta = 90°$

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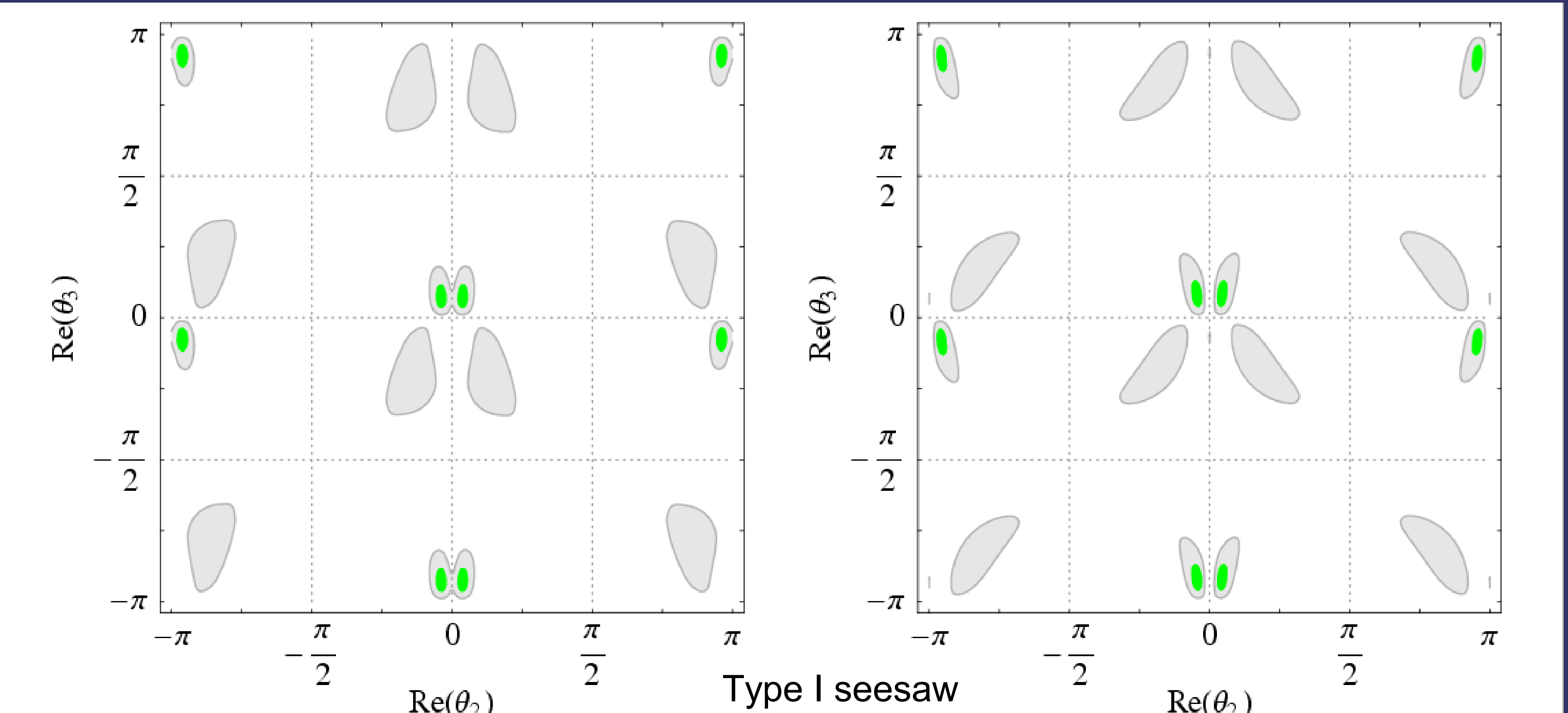
Leptogenesis constraints on See-saw parameters (MSSM)

- Real R matrix case: CP violation from Majorana phases ?



(a) $T_{\mathrm{RH}} \leq 2 \times 10^{10}$ GeV, $\varphi_2 = 180°$, $\theta_{13} = \delta = \varphi_1 = 0°$

(b) $T_{\mathrm{RH}} \leq 2 \times 10^{10}$ GeV, $\varphi_1 = 180°$, $\theta_{13} = \delta = \varphi_2 = 0°$

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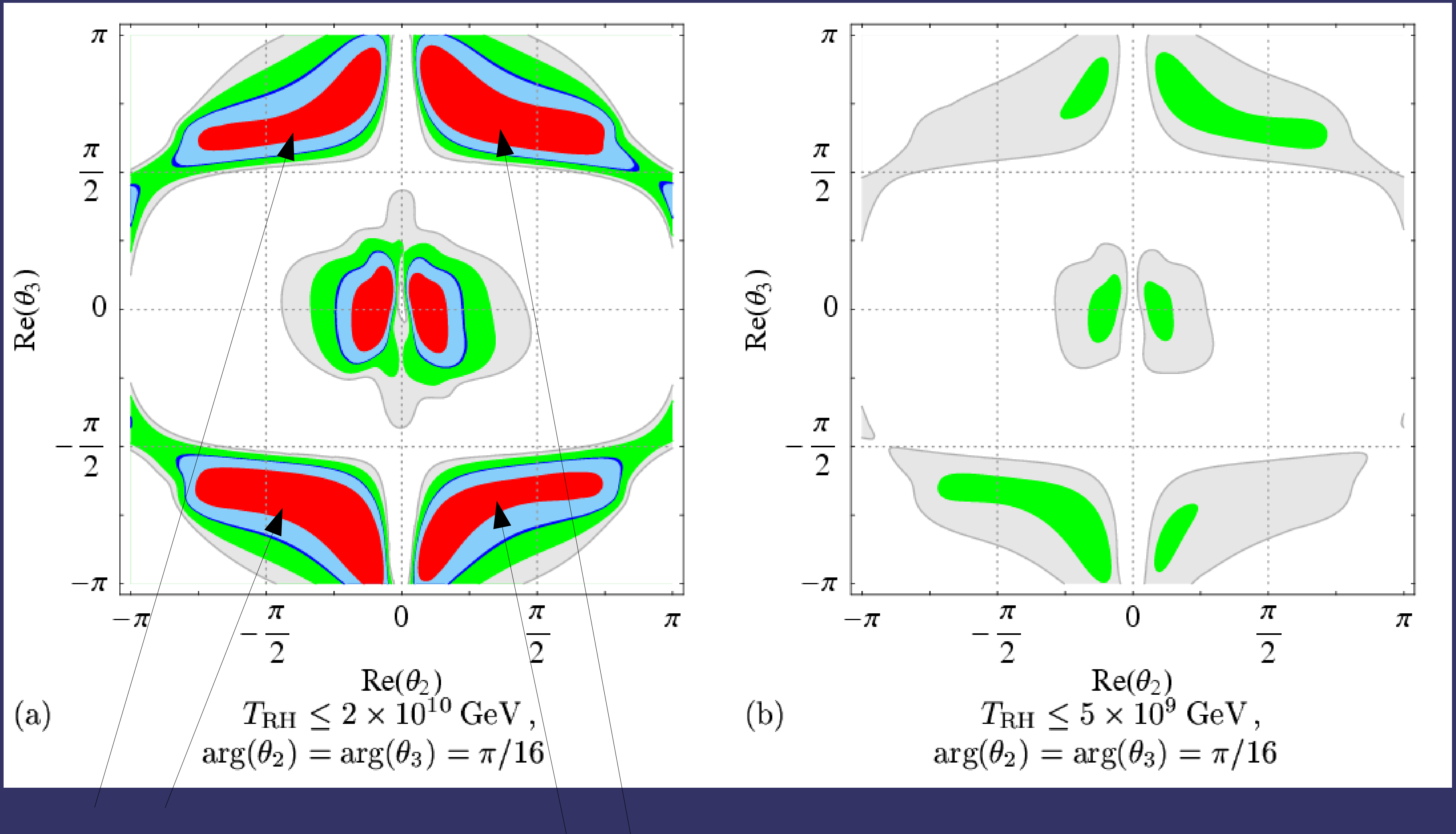
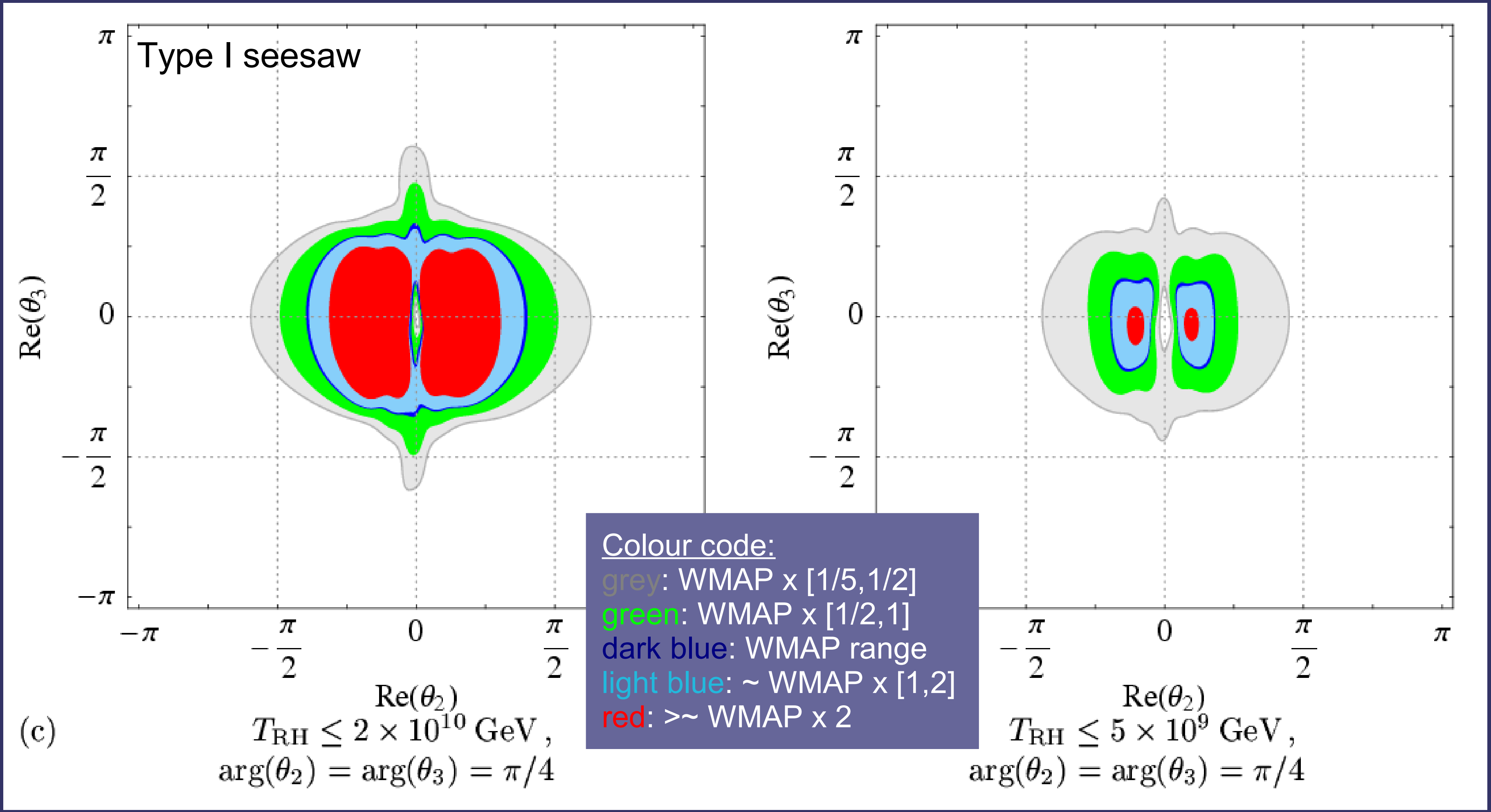
Leptogenesis constraints on See-saw parameters



- New allowed regions due to flavour-dependent effects (large complex θ_2, θ_3) ↔ in SD: within/ interpolation between classes $M_1 = M_B$ & $M_1 = M_A$!

Which region of SUSY Seesaw parameters is most favoured?

- Most favoured by thermal leptogenesis: small and complex θ_2 (and θ_3)



- Sequential Dominance: correspond to $M_1 = M_C$

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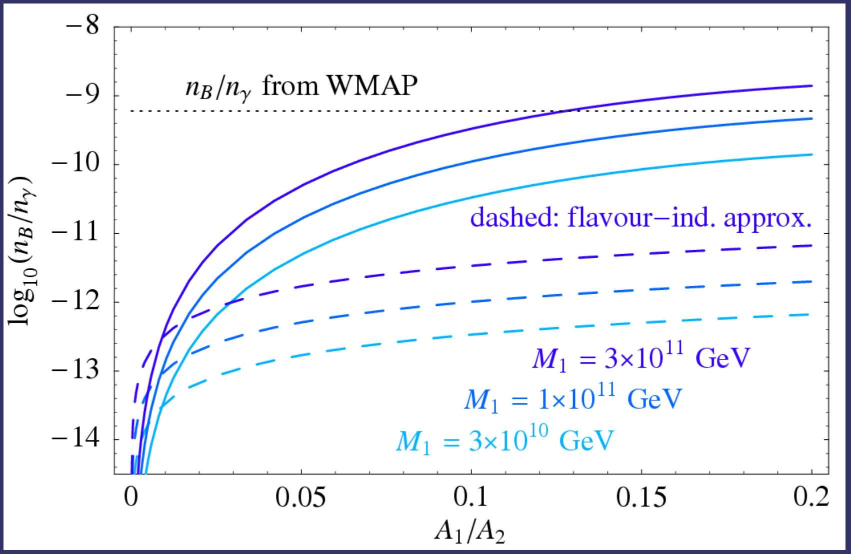
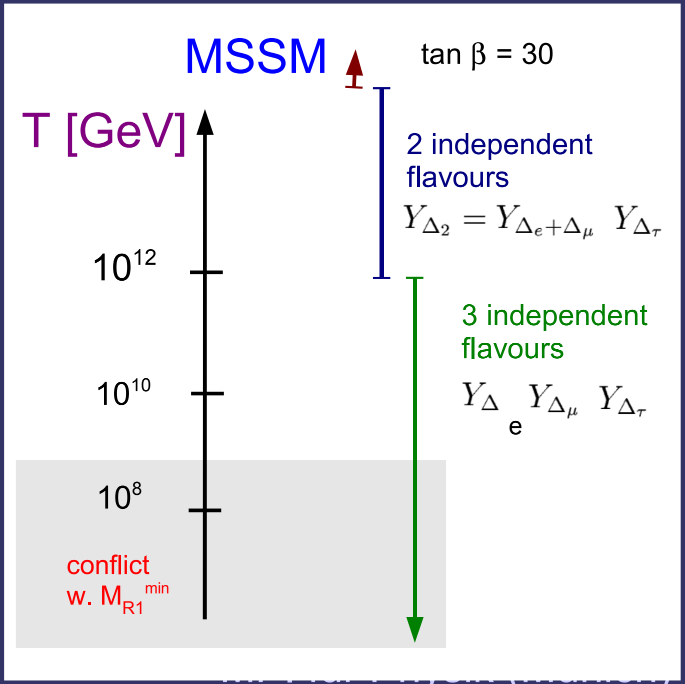
Summary and Conclusions (I)

- Flavour-dependent effects have important impact on the produced baryon asymmetry
  Main difference to flavour-in. approx.:
  $\Sigma\, \varepsilon_{1,\alpha}\, \eta_\alpha(\tilde{m}_{1,\alpha}) \leftrightarrow (\Sigma\, \varepsilon_{1,\alpha})$ x $\eta_{ind}(\Sigma\, \tilde{m}_{1,\alpha})$
  (correct, fl. dep.) (flavour-ind.)



- Temperature where flavour-effects are relevant differs in SM and MSSM (MSSM: typically 3 or 2 independent flavours, SM: only 2 or 1)

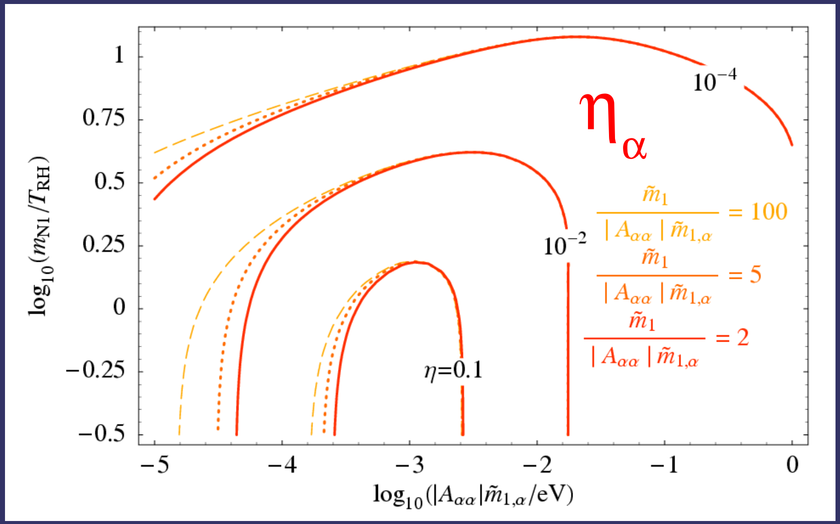


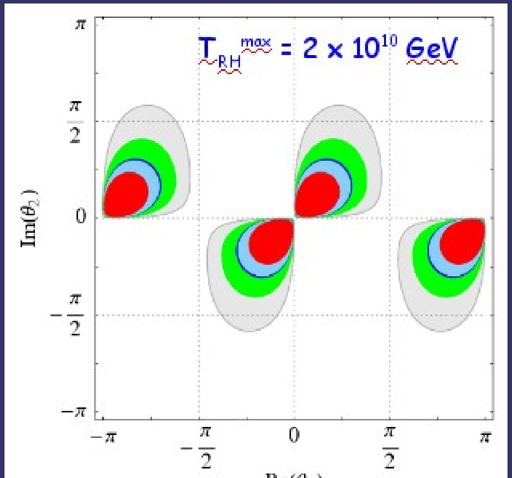
Summary and Conclusions (II)

- Leptogenesis in SUSY: constrained but *not* ruled out. Quite robust bound (local SUSY) $T_{RH}^{max} = 2 \times 10^{10}$ GeV

- To analyse T_{RH}-constraints on thermal leptogenesis:
  Flavour-dependent efficiency factor (incl. T_{RH}) public → S.A., A. Teixeira ('06)

- Produced baryon asymmetry from thermal leptogenesis depends strongly on the flavour structure of the seesaw! (best: LG via *e* and/or μ flavours; R-matrix → small θ_2,θ_3; SD → $M_1 = M_C$)





(a) $T_{RH} \leq 2 \times 10^{10}$ GeV, $\theta_{13} = \delta = \varphi_1 = \varphi_2 = 0°$

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