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# LFV and Leptogenesis in a minimally flavor violating world


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# Outline

- LFV, CPV & Leptogenesis: overview
- Leptonic "Minimal Flavor Violation"

  - Charged LFV
    - Observable ?
    - Testable ?
  - Leptogenesis
    - Viable ?
    - Correlation with CLFV ?

# Introduction: LFV, CPV & Leptogenesis

# LFV, CPV, BAU: what's the connection?

See-saw mechanism for $m_\nu$ (Type I)

$$\mathcal{L} \supset \frac{1}{2} (M_R)_{ij} \, \nu_R^{Ti} \, C \, \nu_R^j - \lambda_\nu^{ij} \, \bar{\nu}_R^i \, (H_c^\dagger \, L_L^j) + \mathrm{h.c.}$$

Heavy $\nu_R$
($M_R >> v_{ew}$)

$M_R$ : L violation
$\lambda_\nu$ : CP and $L_i$ violation

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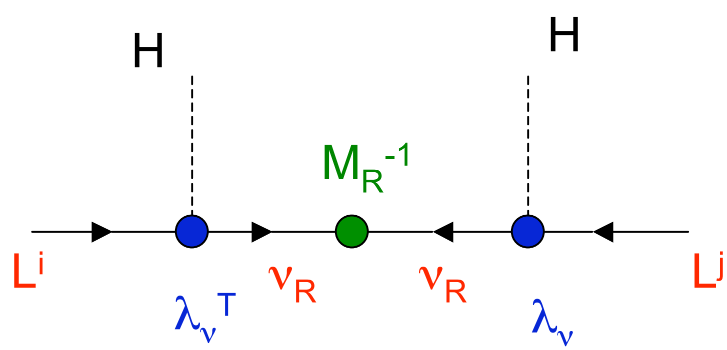


$m_\nu \sim v_{ew}^2\; \lambda_\nu^T\, M_R^{-1}\, \lambda_\nu$

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1) $\not{C}$P and $\not{L}$ out-of-equilibrium decays of $N_i$ ($T \sim M_R$) $\Rightarrow n_L$

$$\Gamma(N_i \to l_k \, H^*) \neq \Gamma(N_i \to \bar{l}_k \, H)$$

2) B+L violation (sphalerons) $\Rightarrow$

$$\eta_B \equiv \frac{n_B}{n_\gamma} \neq 0$$

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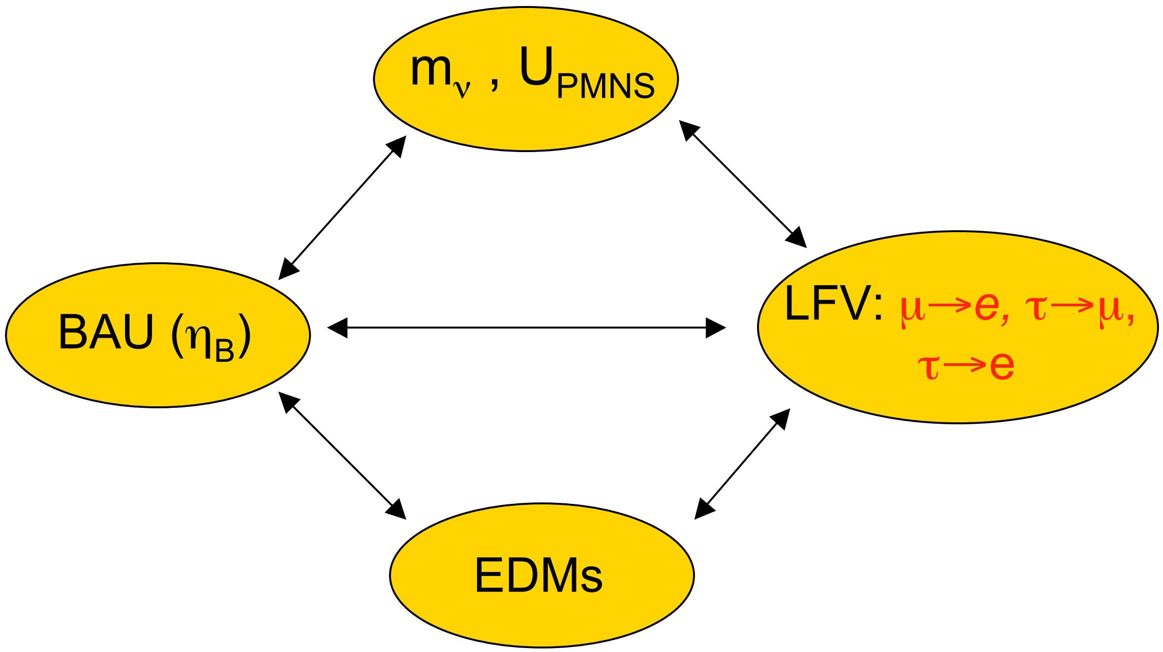
If CP & $L_i$ violation is communicated to particles with mass $\Lambda$~TeV

Observable LFV

Observable lepton EDMs

- Key issue: can we identify signatures for the see-saw scenario?




- Quite hard in general. In this talk, I discuss correlations emerging in the context of a specific scenario, MFV

# Minimal Flavor Violation

# MFV hypothesis in the lepton sector

- MFV hypothesis: all flavor-breaking structures are aligned with fermion mass matrices

- Introduced in the quark sector to “explain” absence of large non-standard FCNC from TeV scale physics.

Georgi-Chivukula ‘87

- Can be formulated in the EFT language, insensitive to UV details of the underlying model

D’ambrosio-Isidori-Giudice-Strumia ‘02

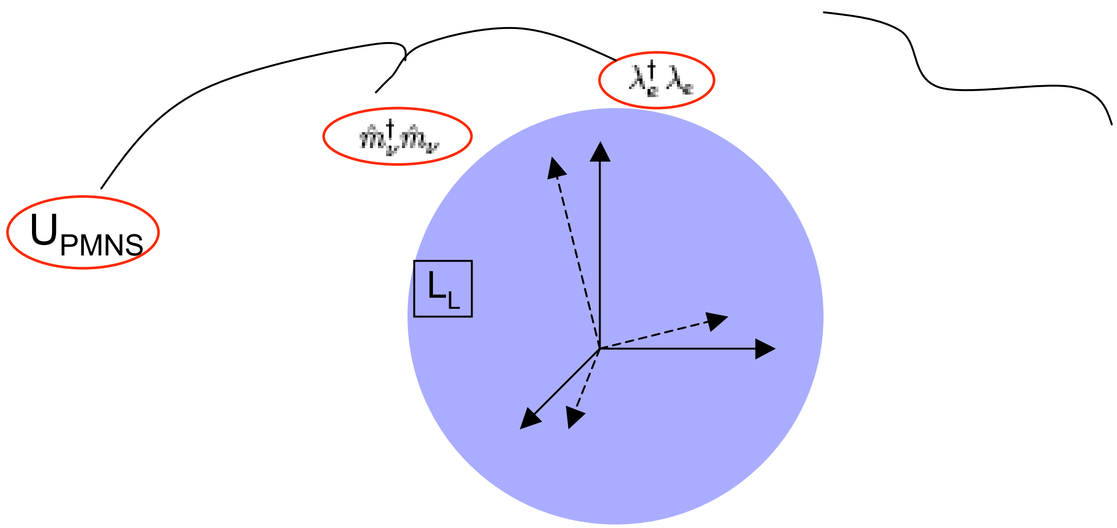
- Its extension to leptons defines a *constrained* class of models.
Tool to investigate nature / structure of flavor breaking sources

VC-Grinstein-Isidori-Wise ‘05

# MFV hypothesis in the lepton sector

- MFV hypothesis: all flavor-breaking structures are aligned with fermion mass matrices

- $m_\nu$ and $m_e$ ($\lambda_e$) select two eigen-bases in $L_L$ space (related by $U_{PMNS}$)




$$L_L^i = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}^i$$

i=1,2,3

- MFV($\ell$): BSM flavor structures are "aligned" with $m_\nu$ or $m_e$ in $L_L$ space
  - → do not select new eigen-bases
  - → FCNC are controlled by lepton masses and $U_{PMNS}$

# MFV in models with heavy $\nu_R$

- Spurions in $L_L$ space: $\lambda_e^\dagger \lambda_e \quad m_\nu^\dagger m_\nu \quad \lambda_\nu^\dagger \lambda_\nu$

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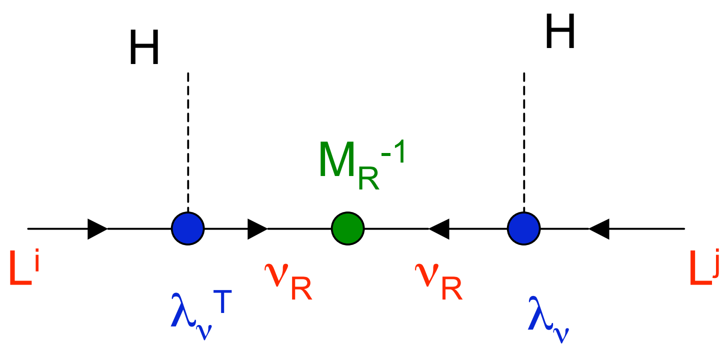
$$m_\nu \; = \; v^2 \, \lambda_\nu^T \, \hat{M}_R^{-1} \, \lambda_\nu \quad \longleftrightarrow \quad \lambda_\nu = \frac{1}{v} \, \hat{M}_R^{1/2} \, R \, \hat{m}_\nu^{1/2} \, U^\dagger$$

Casas-Ibarra '01

Complex orthogonal matrix



# MFV in models with heavy $\nu_R$

- Spurions in $L_L$ space: $\lambda_e^\dagger \lambda_e \quad m_\nu^\dagger m_\nu \quad \lambda_\nu^\dagger \lambda_\nu$

$$m_\nu = v^2 \lambda_\nu^T \hat{M}_R^{-1} \lambda_\nu \quad \longleftrightarrow \quad \lambda_\nu = \frac{1}{v} \hat{M}_R^{1/2} R \, \hat{m}_\nu^{1/2} U^\dagger$$

- Strict MFV definition (alignment of $m_\nu^\dagger m_\nu$ and $\lambda_\nu^\dagger \lambda_\nu$ ) $\Rightarrow$

$$\hat{M}_R = M_\nu \cdot I$$

*and*

$$R = I$$

- Flavor broken only by Yukawas: $\lambda_e$ and $\lambda_\nu$ [with constrained CP structure].

- In this minimal framework (R=I), we investigate the following issues:

LFV decays:
$\mu \to e\gamma$, $\tau \to \mu\gamma$, $\tau \to e\gamma$

- What is the overall normalization of CLFV rates ?
  Does MFV($\ell$) alleviate the lepton FCNC problem ?

- What pattern of LFV decays is predicted?
  Can we test it?

↕

Leptognesis

- Is thermal leptogenesis viable in such a constrained framework ?

- Does successful leptogenesis constrain rate & pattern of LFV decays ?

# Phenomenology of $\ell_i \to \ell_j \gamma$

- Effective coupling governing $\ell_i \to \ell_j$ transitions

$$H_{\text{eff}} = \frac{C_W}{\Lambda^2}\, H^\dagger\, \bar{e}^i_R\, \sigma^{\mu\nu}\, ( \quad ?\,? \quad )^{ij}\, L^j_L\, F_{\mu\nu}$$

~ TeV

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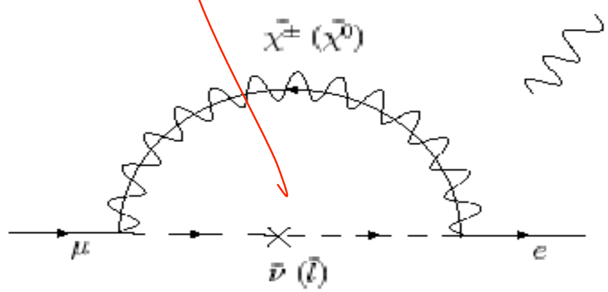
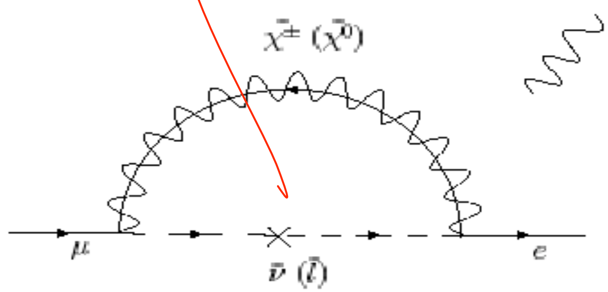


# Phenomenology of $\ell_i \to \ell_j \gamma$

- Effective coupling governing $\ell_i \to \ell_j$ transitions $\propto \quad \lambda_\nu^\dagger \lambda_\nu \; = \; \frac{M_\nu}{v^2} \, U \, \hat{m}_\nu \, U^\dagger$

$$H_{\rm eff} = \frac{C_W}{\Lambda^2} \, H^\dagger \, \bar{e}_R^i \, \sigma^{\mu\nu} \, \left(\lambda_e \, \lambda_\nu^\dagger \, \lambda_\nu\right)^{ij} \; L_L^j \; F_{\mu\nu}$$

~ TeV



# Phenomenology of $\ell_i \to \ell_j \gamma$

$$B_{\ell_i \to \ell_j \gamma} = \frac{v^2 M_\nu^2}{\Lambda^4} \times |b_{ij}(U_{\rm PMNS}; m_{\rm min}; \Delta m_\nu^2)|^2 \times |c_{RL}^{(1-2)}|^2 \, I_{PS}$$

(i) Overall normalization controlled by $\frac{v^2 M_\nu^2}{\Lambda^4}$. Signals within reach of future searches (MEG, Mu2e, …) if:

$$M_\nu \sim 10^{9-10} \, \mathrm{GeV} \times (\Lambda / 1 \, \mathrm{TeV})^2$$

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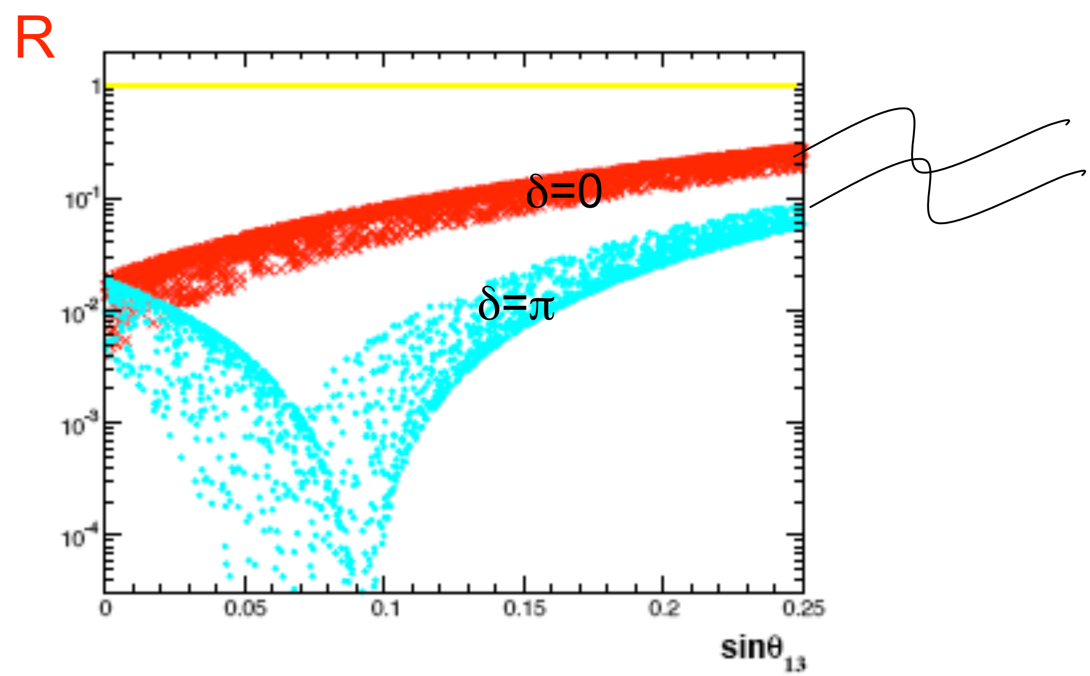
(ii) Signatures: MLFV *predicts* ratios of $B(\ell_a \to \ell_b \gamma)$ in terms of $U_{\rm PMNS}$ and mass splittings with pattern:

$$B(\tau \to \mu\gamma) >> B(\tau \to e\gamma) \sim B(\mu \to e\gamma)$$

(with $\mu \to e / \tau \to \mu$ suppression increasing as $s_{13} \to 0$)

# Illustration: R= B(μ → e γ)/B(τ→μγ)




Pattern entirely determined by:

- $\Delta m^2_{atm} \gg \Delta m^2_{sol}$
- $\theta_{atm}, \theta_{sol} \gg \theta_{13}$

↕

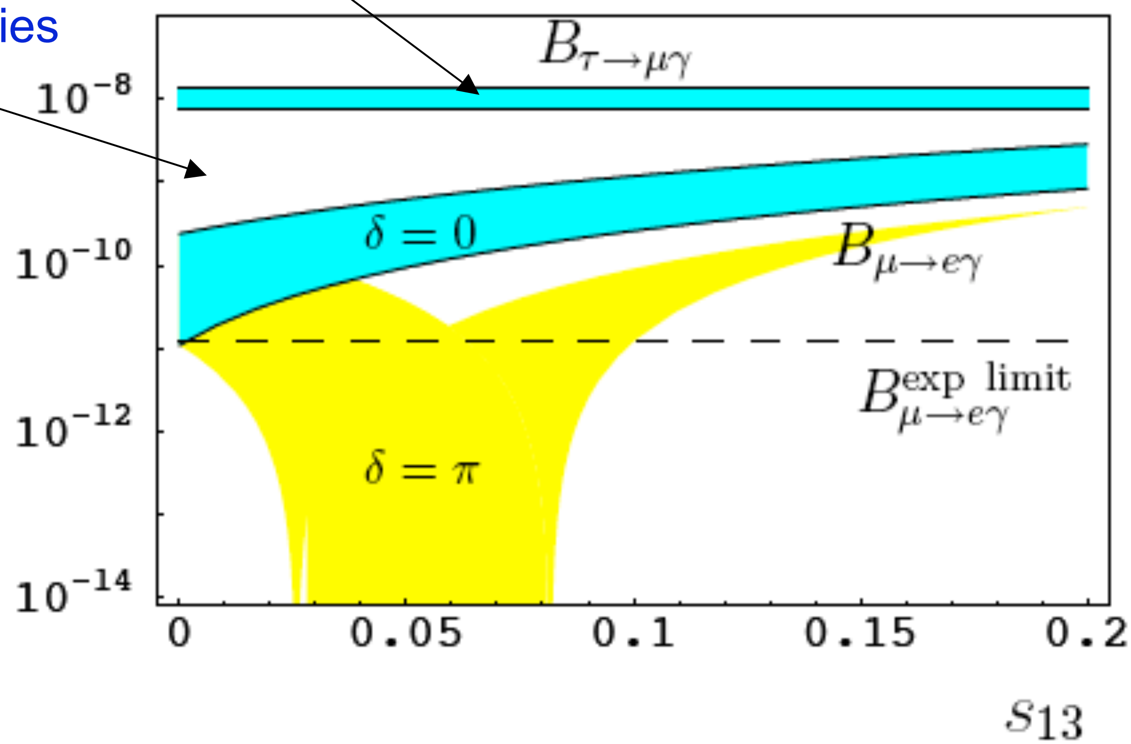
$$b_{ij} = \left(U \frac{m_\nu}{v_{ew}} U^+\right)_{ij}$$

# This framework can be tested !

- If $s_{13} \geq 0.08$, limits on $B(\mu \to e\gamma)$ preclude observing $\tau \to \mu\gamma$ at B factories
- If $\tau \to \mu\gamma$ is observed at B factories then $s_{13} < 0.08$

Reach of B factories

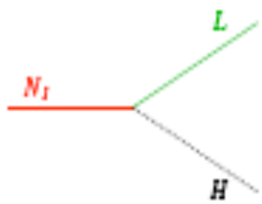
Reach of Super-B factories

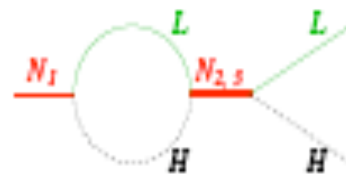


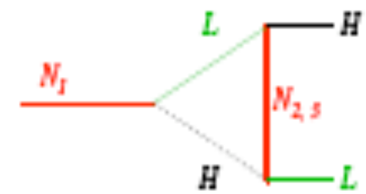
# How does leptogenesis work ?

Leptogenesis accounts for $\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.3 \pm 0.3) \times 10^{-10}$ through:

- Out of equilibrium decays of $N_i$ in presence of CPV $\Rightarrow n_L \neq 0$
- EW sphalerons (B+L violation) convert $n_L \leftrightarrow n_B$




Dominant if $\Delta M_{ij} \sim \Gamma_j$
("resonant leptogenesis")

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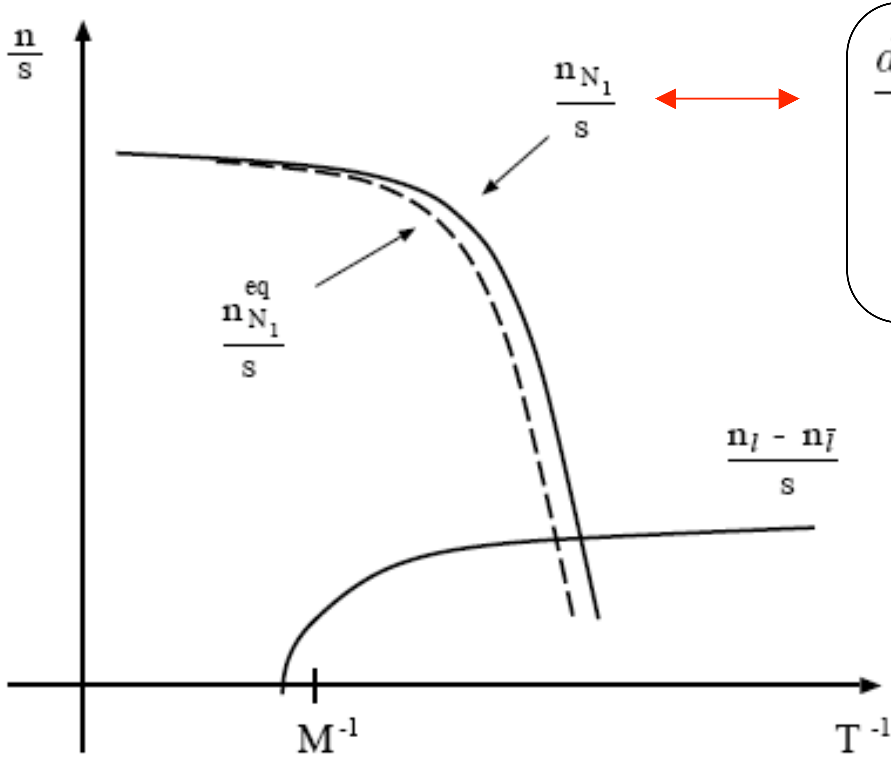


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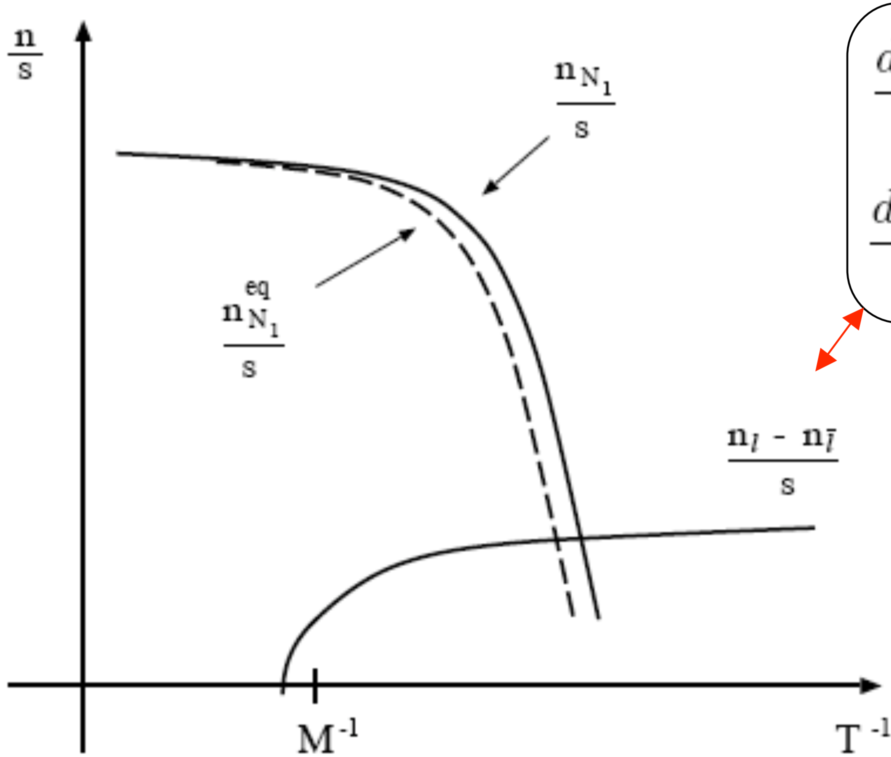


$$\frac{dn_{N_i}}{dz} = -D_i \left(n_{N_i} - n_{N_i}^{eq}\right),$$

$$\frac{dn_{L_\alpha}}{dz} = -\sum_i \epsilon_{i\alpha} D_i \left(n_{N_i} - n_{N_i}^{eq}\right) - W_\alpha n_{L_\alpha}$$

$$\epsilon_{i\alpha} \equiv \frac{\Gamma(N_i \to \ell_\alpha \bar{H}) - \Gamma(N_i \to \bar{\ell}_\alpha H)}{\Gamma(N_i \to \ell_\alpha \bar{H}) + \Gamma(N_i \to \bar{\ell}_\alpha H)}$$

# Relevance of “Flavor Effects”

Abada, Davidson, Josse-Michaoux, Losada, Riotto ‘06 Nardi, Nir, Roulet, Racker ‘06

- For $T < T_{fl}$ , interactions mediated by Yukawa couplings come in equilibrium $\Rightarrow$ project lepton asymmetry onto individual flavors

$$N_1 \rightarrow \ell_1 \, H^* \qquad \ell_1 \to \ell_{\tau,\mu,e}$$

$T_\tau \sim 10^{12}$ GeV

$T_\mu \sim 10^9$ GeV

$$\Gamma_\alpha \sim 10^{-3} \lambda_\alpha^2 \; T$$

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$T_\mu \sim 10^{9}$ GeV

- Key consequences:
  - Washout via inverse decays is typically less effective
  - CP asymmetries $\varepsilon_{i\alpha}$ are sensitive to CPV phases of $U_{PMNS}$

$$\epsilon_{i\alpha} = \sum_{j\neq i} \frac{1}{8\pi} \frac{\mathrm{Im}\left[(\lambda_\nu)_{i\alpha}(\lambda_\nu)^\dagger_{\alpha j}(\lambda_\nu\lambda_\nu^\dagger)_{ij}\right]}{\left(\lambda_\nu\lambda_\nu^\dagger\right)_{ii}} \left(g_s^{(j,i)} + g_v^{(j,i)}\right)$$

Functions of $\nu_R$ masses

# MFV leptogenesis

- Can happen only in the “flavored-regime”: $M_\nu < 10^{12}$ GeV

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- MFV highly constraints the structure of the $\nu_R$ mass matrix …

$$M_R = M_\nu \Big[ 1 + c^{(1)} (h_\nu + h_\nu{}^T) + c_1^{(2)} ((h_\nu)^2 + (h_\nu{}^T)^2) + c_2^{(2)} h_\nu h_\nu{}^T + c_3^{(2)} h_\nu{}^T h_\nu + c_4^{(2)} (h_e + h_e{}^T) + .... \Big]$$

$$h_\nu = \lambda_\nu \lambda_\nu{}^\dagger \qquad h_e = \lambda_\nu \lambda_e{}^\dagger \lambda_e \lambda_\nu{}^\dagger$$

Structures are fixed by MFV hypothesis (generated by radiative corrections)

Coefficients depend on underlying model. Typically one expects $c^{(1)} \sim \log(\Lambda_{GUT}/M_R)$

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Coefficients depend on underlying model.
Typically one expects $c^{(1)} \sim \log(\Lambda_{GUT}/M_R)$

- … and hence the CP asymmetries: $\epsilon_{i\alpha} \leftrightarrow \mathrm{Im}\left[(\lambda_\nu)_{i\alpha}(\lambda_\nu)^\dagger_{\alpha j}(\lambda_\nu \lambda_\nu^\dagger)_{ij}\right]$

Yukawa couplings in basis in which $M_\nu$ is diagonal

- Analytic dependence of CP asymmetries on underlying parameters is understood with EFT + symmetry considerations.

  But coefficients $c^{(1)}$ and $c^{(2)}$ are determined by UV details

VC-DeSimone-Isidori-Masina-Riotto '07

- Numerical analysis with RGE equations

Branco-Buras-Jager-Uhlig-Weiler '06

Uhlig '07

Boundary conditions: $M_R = M_\nu \times I$ and $R=I$ @ $\Lambda_{GUT}$

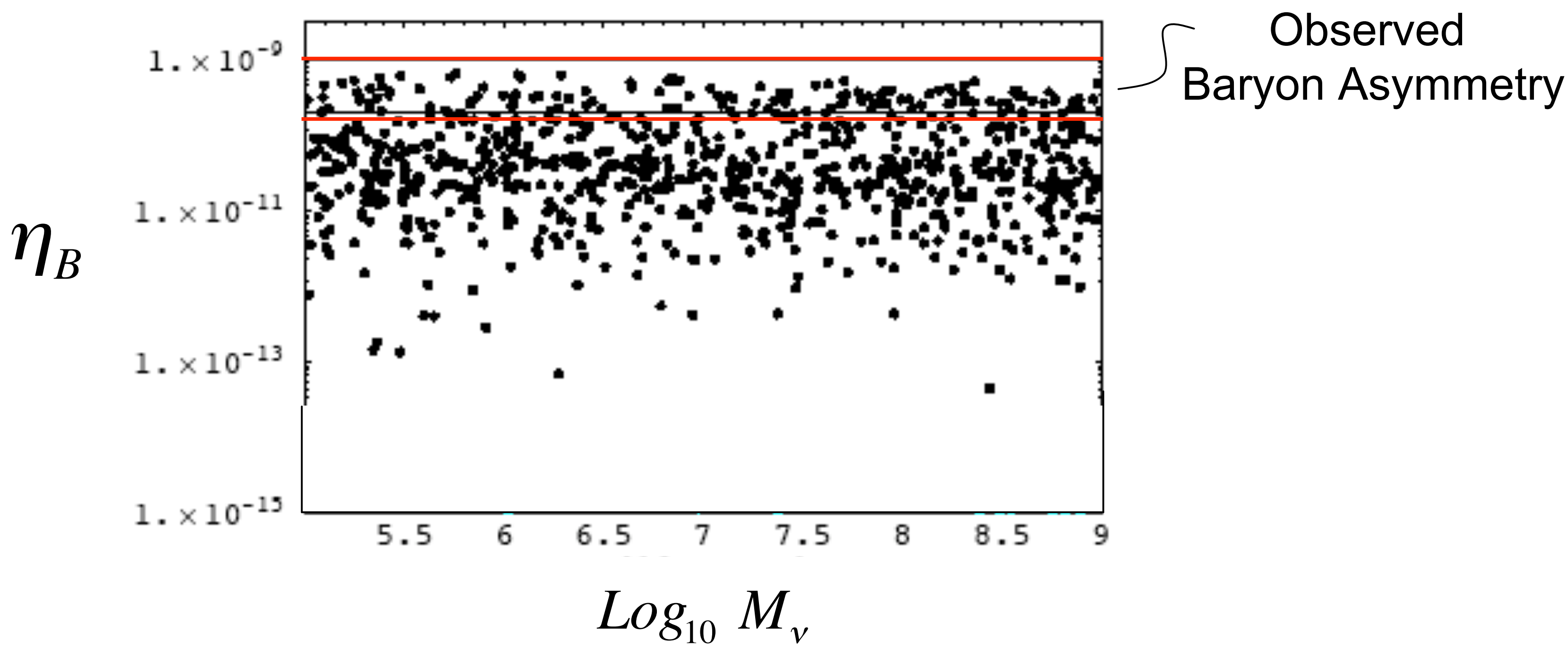
Parameter space scan:

- $M_\nu \in [10^5, 10^9]$ GeV
- $m_\nu^{min} \in [0, 0.2]$ eV, NH & IH
- $\mathrm{Sin}(\theta_{13}) \in [0, 0.2]$
- PMNS phases: $\delta \in [0, 2\pi]$; $\alpha_M, \beta_M \in [0, \pi]$

Results are valid for $\tan(\beta) \sim O(1)$, but keep in mind that $\eta_B \propto [\tan(\beta)]^2$

- Highlights of numerical analysis (Uhlig '07)

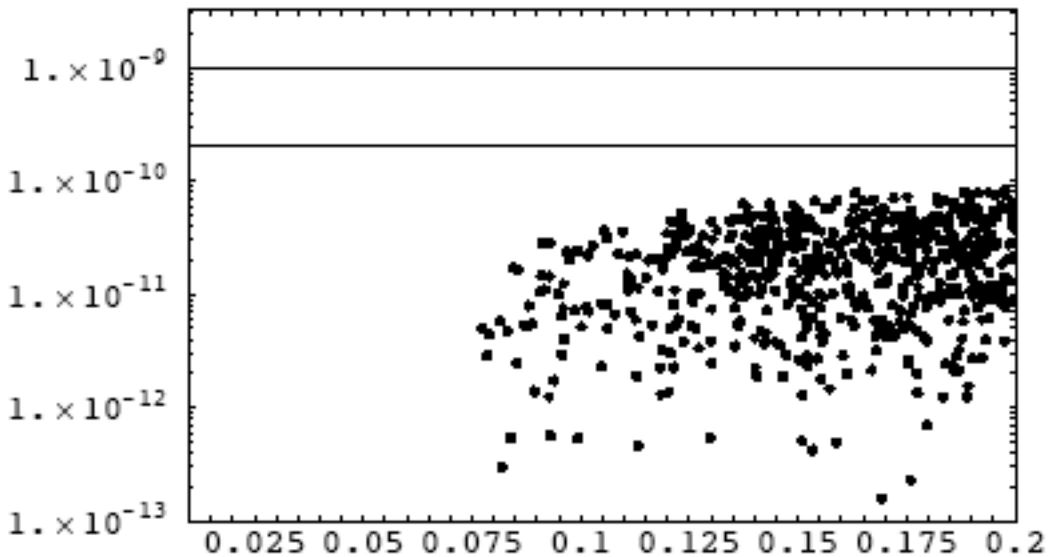
  - Leptogenesis is viable in this setup !! (for NH of light ν spectrum)
  - "Flat" dependence on $M_\nu$



- Highlights of numerical analysis (Uhlig '07)

  - Leptogenesis *not viable* for IH of light ν spectrum

    (due to stronger washout)



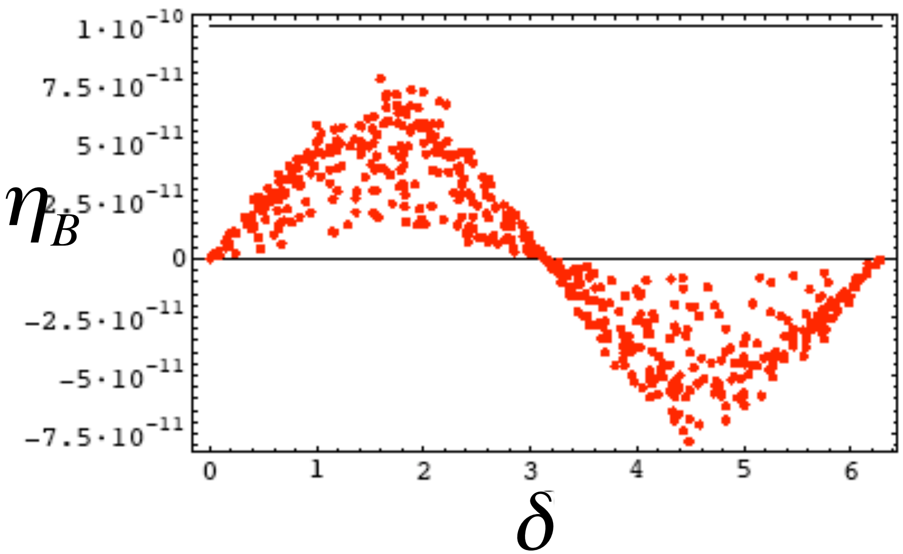

$\eta_B$

$Sin(\vartheta_{13})$

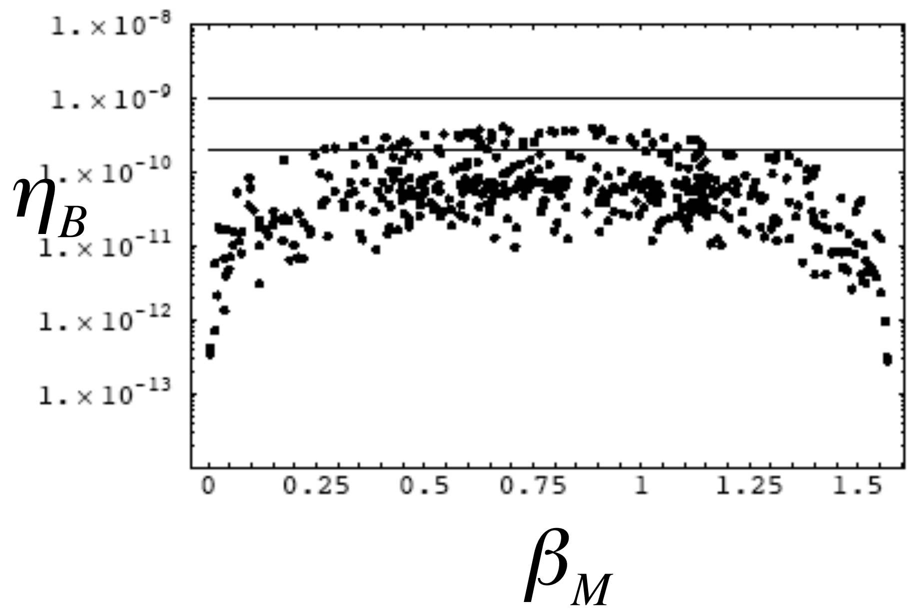
- Highlights of numerical analysis (Uhlig '07)

  - CPV with a single PMNS phase ?

Dirac phase: no!




Majorana phase: yes!




(understood in terms of $\theta_{13}$ suppression)

- Impact on CLFV rates ? [through handle on the scale $M_\nu$ ]

  - Successful MFV-Leptogenesis requires in principle $M_\nu < 10^{12}$ GeV (need to be at least in the 2-flavor regime)

  - Numerical analysis was performed in the 3-flavor regime $M_\nu < 10^9$ GeV

$$B(\mu \to e\gamma) \sim 10^{-14} \times \left( \frac{M_\nu}{10^9\, GeV} \right)^2 \left( \frac{1TeV}{\Lambda} \right)^4$$

↓

Leptogenesis constraint implies signal within reach of MEG ($\mu \to e\,\gamma$ @ $10^{-13}$ level) for $\Lambda \leq$ TeV

# Conclusions

- The notion of MFV can be introduced in models with heavy $\nu_R$ :
  $M_R$ is flavor blind and CPV occurs only through $U_{PMNS}$

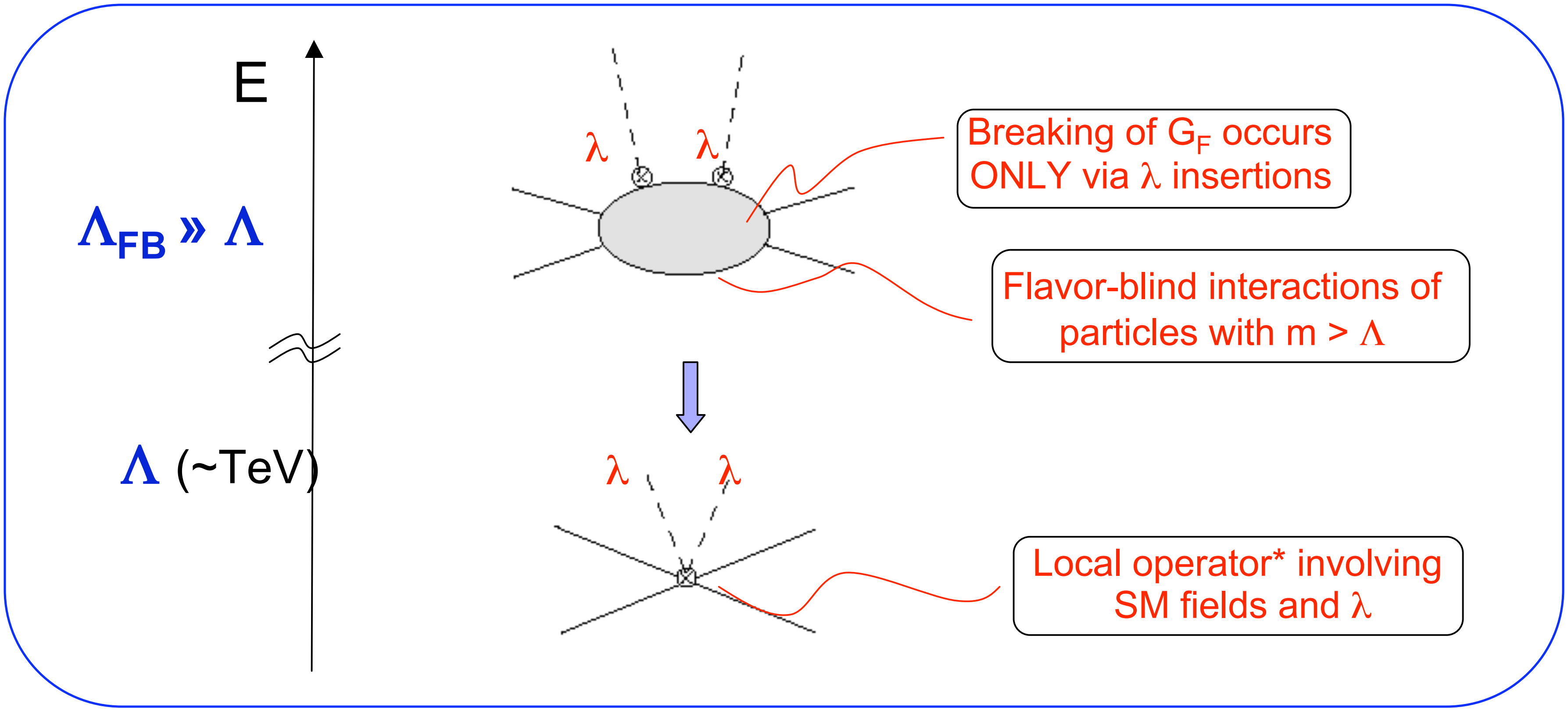
- CLFV Phenomenology:
  - normalization of rates depends on $(vM_\nu)^2/\Lambda^4$
  - pattern of predictions for ratios of LFV transitions $\mu \to e/\tau \to \mu$, … is governed by measured leptonic mass matrices and mixing angles

- Leptogenesis is viable in this scenario ("radiative resonant leptogenesis")
  - Only in the flavored regime $M_\nu < 10^{12}$ GeV
  - This implies $\mu \to e\gamma$ rate within reach of MEG if $\Lambda \leq$ TeV

# Additional Material

# MFV Effective Theory

- Flavor symmetry of $\mathcal{L}_{Gauge}$ $[G_F = SU(3)^5]$ broken *only* by $\lambda$ 's




Group Theory + Effective Field Theory ⇒ investigate consequences of MFV hypothesis in great generality

# Washout factors

$$K_{i\alpha} \equiv \frac{\Gamma(N_i \to \ell_\alpha \bar{H})}{H(T = M_i)}$$

$$K_\alpha = \sum_i K_{i\alpha}$$

$$\begin{aligned}
K_e &= (m_1 c_{12}^2 + m_2 s_{12}^2 + m_3 s_{13}^2)/m_* \quad , \\
K_\mu &= (m_1 c_{23}^2 s_{12}^2 + m_2 c_{12}^2 c_{23}^2 + m_3 s_{23}^2)/m_* \\
K_\tau &= (m_1 s_{12}^2 s_{23}^2 + m_2 c_{12}^2 s_{23}^2 + m_3 c_{23}^2)/m_*
\end{aligned}$$

$$m_* \approx 10^{-3} \text{ eV}$$

# Memory Effects

De Simone - Riotto '07

- Quantum Boltzmann eqs: "collision" term depends on history of the system

$$\frac{\partial n_{\mathcal{L}_i}(X)}{\partial t} = -\int d^3z \int_0^t dt_z \,\mathrm{Tr}\left[\Sigma^{>}_{\ell_i}(X,z)G^{<}_{\ell_i}(z,X) - G^{>}_{\ell_i}(X,z)\Sigma^{<}_{\ell_i}(z,X) + G^{<}_{\ell_i}(X,z)\Sigma^{>}_{\ell_i}(z,X) - \Sigma^{<}_{\ell_i}(X,z)G^{>}_{\ell_i}(z,X)\right].$$

- Key consequence:
  - CP asymmetries depend on $z=M_1/T$ (time variable)

$$\varepsilon_1(z) = \varepsilon_1^{(0)}\left[2\sin^2\left(\frac{(M_2-M_1)z^2}{4H(M_1)}\right) - \frac{\Gamma_2}{M_2-M_1}\sin\left(\frac{(M_2-M_1)z^2}{2H(M_1)}\right)\right]$$

  - Effect is important if $1/\Delta M_{12} > 1/\Gamma_N \sim 1/H\ (T=M_1)$

# Impact of memory effects

VC-DeSimone-Isidori-Masina-Riotto

- "Memory" effects are controlled by condition

$$\Delta M_{ji} < \Gamma_i \quad \xleftrightarrow{\text{MFV}} \quad 16\pi\, c^{(1)} \frac{\Delta \mathrm{m}_{ji}}{\mathrm{m}_i} < 1$$