Susy SeeSaw: from EDM to Leptogenesis

Isabella Masina (CERN)

Meeting on Particle Physics Phenomenology, CERN, 29/06/07

Y_B from Y_L ⟵ SeeSaw (SS) for m_ν ⟶ d_e^{SS} if susy at l.e.

Potentially accessible by planned exp's!

Q: if observed, is d_e^{SS} compatible with thermal leptogenesis?

[F.R.Joaquim, IM and A.Riotto, hep-ph/0701270]

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A:
- ☐ yes
- ☒ no

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OUTLINE:

Y_B vs d_e // th leptg // d_e^{SS} // Method // A: ☐ yes ☒ no // Conclusions

$Y_B = n_B/s$ vs d_e

macroscopic cosmological observable
(n_B=baryon number asymm, s=entropy density)

property of elementary particle
(like mass, spin, charge, MDM)

Need 3 Sakharov's:

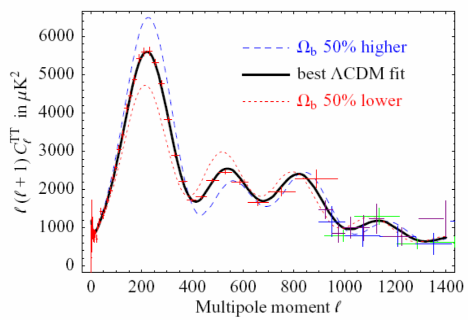
i) dev th eq, ii) BV, iii) CV, **CPV**

In common

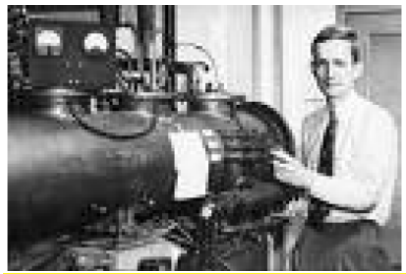
Need:

CPV, PV

Determined by WMAP-CMB (& BBN)



Lab exp searches in progress since 50's!



Norman Ramsey
Separated Oscillator Beam Resonance
Nobel Prize 1989 ***STANDARD OF TIME***

$Y_B = (8.7 \pm 0.3) \times 10^{-11}$

$d_e < 1.6 \times 10^{-27}$ e cm

A Permanent EDM Violates both T & P Symmetries:

$$H = -d\vec{\sigma}\cdot\vec{E} \xrightarrow{\mathbf{T}} H = -d(-\vec{\sigma})\cdot\vec{E} = d\vec{\sigma}\cdot\vec{E}$$

$$H = -d\vec{\sigma}\cdot\vec{E} \xrightarrow{\mathbf{P}} H = -d\vec{\sigma}\cdot\left(-\vec{E}\right) = d\vec{\sigma}\cdot\vec{E}$$

MDMs are Allowed…

$$H = -\mu\vec{\sigma}\cdot\vec{B} \xrightarrow{\mathbf{T}} H = -\mu(-\vec{\sigma})\cdot\left(-\vec{B}\right) = -\mu\vec{\sigma}\cdot\vec{B}$$

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$Y_B = n_B/s$ vs d_e

$Y_B = n_B/s$	d_e
macroscopic cosmological observable (n_B=baryon number asymm, s=entropy density)	property of elementary particle (like mass, spin, charge, MDM)
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In common: CPV

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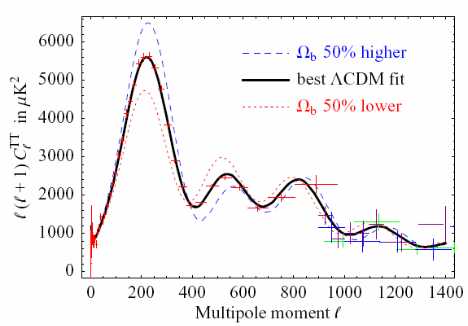

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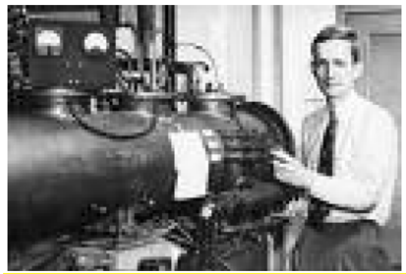

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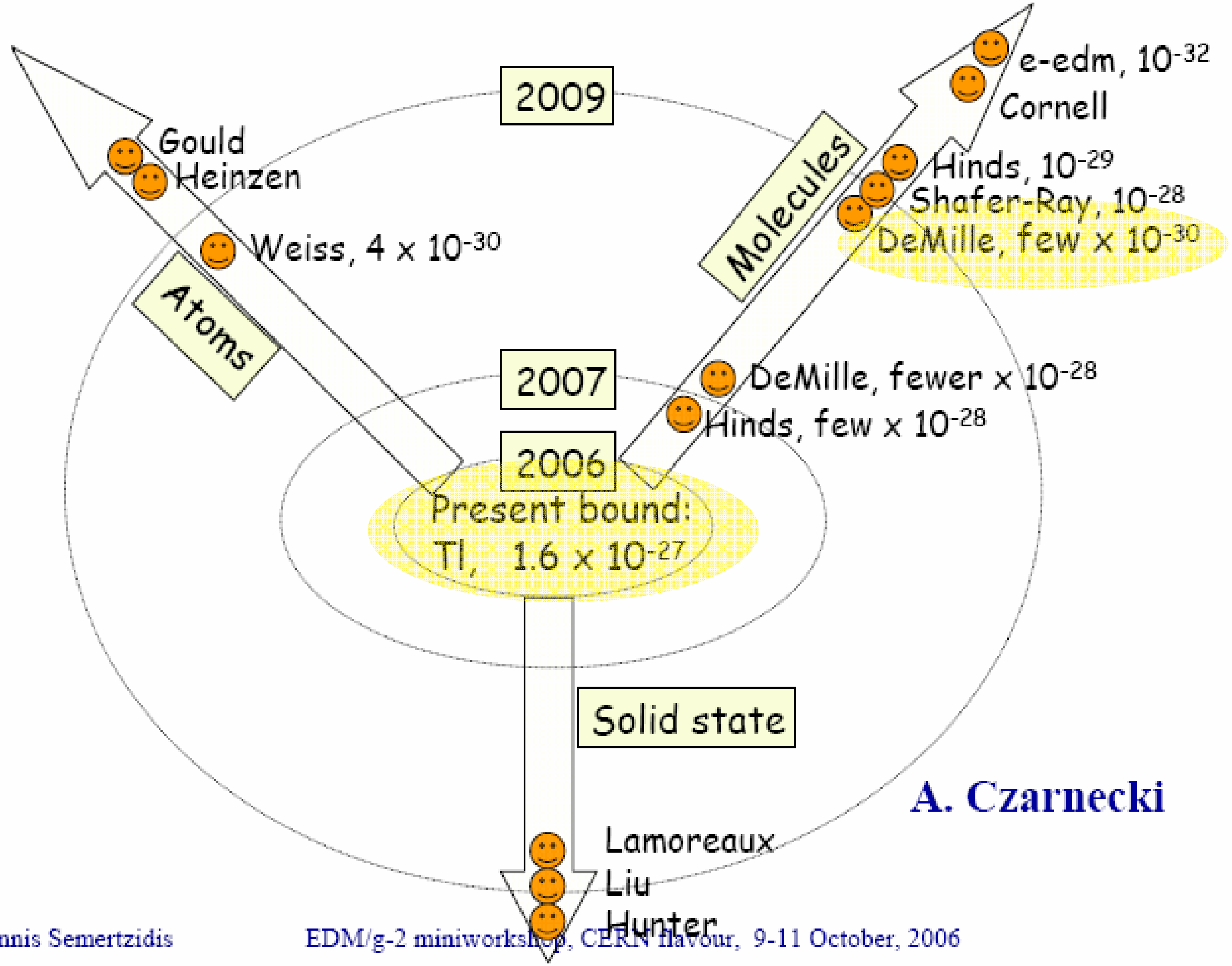
A forecast: electron EDM



A. Czarnecki

$Y_B = n_B/s$ vs d_e

Need 3 Sakharov's:

i) dev th eq, ii) BV, iii) CV, CPV

too suppressed

by quark masses

Need:

CPV, PV

$d_e \neq 0$ only at 4-loop

but **too small** to be detected

SM CANNOT DO THE JOB

$Y_B = n_B/s$ vs d_e

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STRONG CP PROBLEM:

$$\mathcal{L}_{d\leq 4} \supset \bar{\theta} \frac{g_s^2}{32\pi^2} G^a \tilde{G}^a$$

(θ =0 with PQ symm)

$d_n < 1.5 \times 10^{-26}$ e cm $\rightarrow$ $\theta < 10^{-10}$, hence

$$d_{Tl} = -585\, d_e + d(\theta)$$

($d(\theta) < 10^{-30}$ e cm)

If d_{Tl} is measured, it is actually d_e!

$Y_B = n_B/s$ vs d_e

Need 3 Sakharov's:

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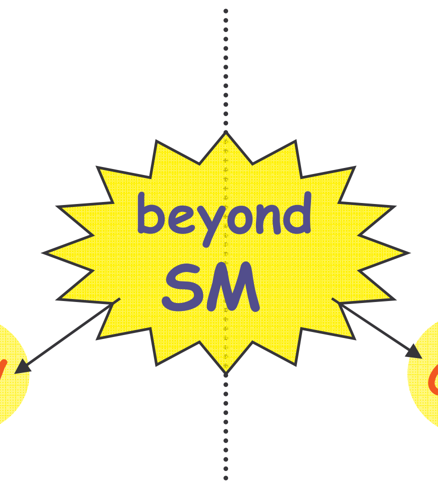


Need:

CPV, PV

New physics is required to explain

$$m_\nu = U^* \, m_\nu^d \, U^+$$

Spectrum: NH or IH?

MNS: 2 large angles and **3 CPV phases**

$Y_B = n_B/s$ vs d_e

Need 3 Sakharov's:

i) dev th eq, ii) BV, iii) CV, CPV

beyond SM

Need:

CPV, PV

Simplest: try with **seesaw** yukawas ! [P.Minkowski '77]

The seesaw [P.Minkowski '77]

In addition to SM: take **3** RH neutrinos **N** and **allow** L_{tot} V

(nicely fit into 16 of SO(10))

(like other ch fermions) **Dirac-Yukawa**

(L_{tot} viol) **Majorana-mass**

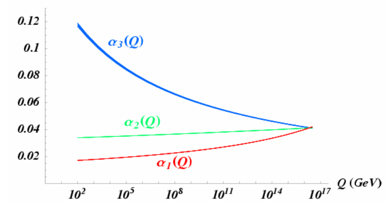
(3x3 matrices)

h.e. $L_{SS} = N\, Y_\nu\, \nu\, H_u + N\, M_R\, N$ with $M_1 < M_2 < M_3$

l.e. $= \nu\, \underbrace{Y_\nu^T\, M_R^{-1}\, Y_\nu\, v_u^2}_{m_\nu}\, \nu$

m_ν ← diag'd by U_{MNS}

$m_\nu = O(eV)$ → $M_R = O(10^{15} GeV)$, near SUSY g.c.u.!



$Y_B = n_B/s$ vs d_e

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Need 3 Sakharov's:

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Need: **CPV**, PV

Simplest: try with **seesaw** yukawas ! [P.Minkowski '77]

$$\mathcal{L}_{SS} = N\, Y_\nu\, \nu\, H_u + N\, M_R\, N \;\rightarrow\; \underbrace{\nu\, Y_\nu^T\, M_R^{-1}\, Y_\nu\, v_u^2\, \nu}_{m_\nu = U^* m_\nu^d U^+}$$

[Casas Ibarra '01]

$R^T R = 1$

R as dominance matrix

[Lavignac IM Savoy'02]

E.g.

$$R = \begin{array}{c} \\ M_1 \\ M_2 \\ M_3 \end{array} \begin{array}{c} m_1 \quad m_2 \quad m_3 \\ \begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{pmatrix} \end{array}$$

$M_{1,2,3} \rightleftharpoons m_{3,2,1}$

$Y_B = n_B/s$ vs d_e

beyond SM

Need 3 Sakharov's:

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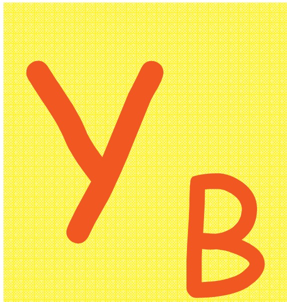
[Casas Ibarra '01]

$R^T R = 1$

$$m_\nu = U^*\, m_\nu^d\, U^+$$

$$\epsilon_1^\ell \propto M_1 \frac{Im(\sum_{\beta\rho} m_\beta^{1/2} m_\rho^{3/2} U_{\ell\beta}^* U_{\ell\rho} R_{1\beta} R_{1\rho})}{\sum_\beta m_\beta |R_{1\beta}|^2}$$

$$C_{ij}^k = Y_\nu^*{}_{ki} Y_{\nu kj} \ln \frac{M_{Pl}}{M_k}$$


Y_B

Y_B

Flavored (ℓ=e,μ,τ) th leptogenesis

[Fukugita Yanagida '86]

At T~M_1 decays of (the lighest) $N_1 \to L_\ell H$

out of eq if $\Gamma_1 < H(M_1)$: CV,CPV in Y_ν generate ΔL_ℓ : later converted to ΔB by SM sphalerons

$$\epsilon_1^\ell \propto M_1 \frac{Im(\sum_{\beta\rho} m_\beta^{1/2} m_\rho^{3/2} U^*_{\ell\beta} U_{\ell\rho} R_{1\beta} R_{1\rho})}{\sum_\beta m_\beta |R_{1\beta}|^2}$$

$$\frac{n_B}{n_\gamma} \approx \Sigma_\ell \frac{\varepsilon_1^\ell \, \eta_\ell}{g_{SM}}$$

efficiency factor (N_1 inverse decays tend to maintain th eq)

ℓ in eq. (susy case)

- μ,τ: $(1+\tan^2\beta)\, 10^5 < M_1\,[GeV] < (1+\tan^2\beta)\, 10^9$
- τ: $(1+\tan^2\beta)\, 10^9 < M_1\,[GeV] < (1+\tan^2\beta)\, 10^{12}$
- none (1-flav OK): $M_1\,[GeV] > (1+\tan^2\beta)\, 10^{12}$

Y_B

Flavored (ℓ=e,μ,τ) th leptogenesis

[Fukugita Yanagida '86]

$$\epsilon_1^\ell \propto M_1 \frac{Im(\sum_{\beta\rho} m_\beta^{1/2} m_\rho^{3/2} U^*_{\ell\beta} U_{\ell\rho} R_{1\beta} R_{1\rho})}{\sum_\beta m_\beta |R_{1\beta}|^2}$$

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For hier RH N's and thermal initial abundance

$$M_1 > \frac{5}{O(2)} \times 10^8 GeV$$

including flavor - but very mod dep

Efficient generation of N_1 only if

$$T_{RH} > M_1$$

Y_B — Flavored ($\ell = e, \mu, \tau$) th leptogenesis

[Fukugita Yanagida '86]

$$\epsilon_1^\ell \propto M_1 \frac{Im(\sum_{\beta\rho} m_\beta^{1/2} m_\rho^{3/2} U^*_{\ell\beta} U_{\ell\rho} R_{1\beta} R_{1\rho})}{\sum_\beta m_\beta |R_{1\beta}|^2}$$

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For hier RH N's and thermal initial abundance

$$M_1 > \frac{5}{O(2)} \times 10^8 GeV$$

including flavor - but very mod dep

Efficient generation of N_1 only if

"10^{10} GeV" > T_{RH} > M_1

To avoid overproduction of gravitinos during reheating (their late decays destroy BBN)

including flavor: **milder tension** with T_{RH}

d_e

Introduction first....

All from DIPOLE OPERATOR bSM

$$\mathcal{L}_{d=5} = \frac{1}{2}\,\bar{\psi}_{Ri}\,A_{ij}\,\psi_{Lj}\,\sigma^{\mu\nu}F_{\mu\nu} + h.c.$$

NewPhys

	$F^{\mu\nu}$, $\bar{\psi}\sigma^{\mu\nu}\psi$	$i\bar{\psi}\sigma^{\mu\nu}\gamma_5\psi$
C	−	−
P	+	−
T	−	+

LFVdecays

$$BR(\ell_i \to \ell_j \gamma) \propto |A_{ij}|^2$$

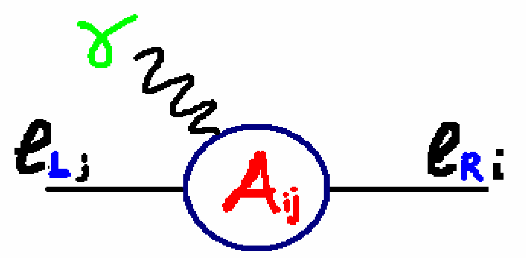
MDMs

$$\delta a_{\ell_i} = Re A_{ii}$$

EDMs

$$d_{\ell_i} = Im A_{ii}$$

P&T V



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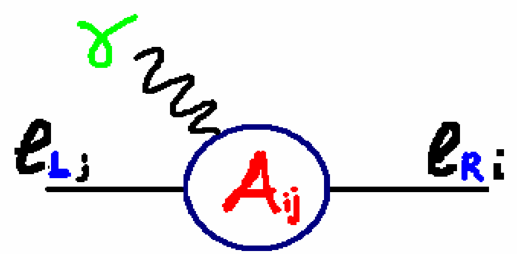


$$\approx \frac{e\, m_i}{(4\pi)^2} \frac{\Gamma_{ij}}{M^2}$$

- ≈ : 1-loop NP
- e : e.m.charge
- m_i : chir flip
- $(4\pi)^2$: loop factor
- Γ_{ij} : adim coupl of NP with lept, encodes F&CP violations
- M^2 : NP mass scale

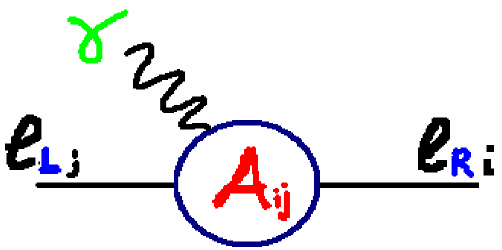
Which **NP scales and couplings are** to be probed?

		present	planned	at present M_{NP} >	planned
EDM	d_e [e cm]	1.6×10^{-27}	10^{-30}	$(\mathrm{Im}\Gamma_{ee})^{1/2} \times 6$ TeV	-> 250 TeV
	d_μ [e cm]	10^{-19}	10^{-24}	$(\mathrm{Im}\Gamma_{\mu\mu})^{1/2} \times 10$ GeV	-> 3 TeV
MDM	δa_e	6×10^{-11}		$(\mathrm{Re}\Gamma_{ee})^{1/2} \times 30$ GeV	
	δa_μ	$\approx(1-3)\times10^{-9}$		$\approx(\mathrm{Re}\Gamma_{\mu\mu})^{1/2} \times 0.2$ TeV	th?
LFV	BR($\mu \to e\gamma$)	10^{-11}	10^{-14} (PSI)	$\lvert\Gamma_{\mu e}\rvert^{1/2} \times 4$ TeV	-> 20 TeV
	BR($\tau \to \mu\gamma$)	10^{-6}	10^{-8} (LHC)	$\lvert\Gamma_{\tau\mu}\rvert^{1/2} \times 0.1$ TeV	-> 0.5 TeV

$$BR(\ell_i \to \ell_j \gamma) \propto |A_{ij}|^2$$

$$\delta a_{\ell_i} = Re A_{ii}$$

$$d_{\ell_i} = Im A_{ii}$$



$$\approx \frac{e\, m_i}{(4\pi)^2} \frac{\Gamma_{ij}}{M^2}$$

adim coupl of NP with lept
encodes F&CP violations

NP mass scale

if Γ^{NP} = O(1) -> probe **now** M_{NP}=O(TeV) , in future O(10 TeV)

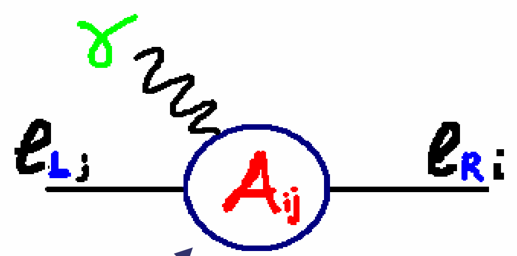
Relevant for l.e. susy

SUSY

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

$$\delta a_{\ell_i} = Re A_{ii} \;=\; f_\mu\, m^2_{\ell_i}\; Re\mu + \ldots$$

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



Loops w/ Sleptons & Gauginos

$$\approx \frac{e\, m_i}{(4\pi)^2} \frac{\Gamma_{ij}}{M^2_{SUSY}}$$

lep-slept misalignment

$$(\tilde{L}_e^* \, \tilde{L}_\mu^* \, \tilde{L}_\tau^*)\, \mathcal{M}^2_{\tilde{L}} \begin{pmatrix} \tilde{L}_e \\ \tilde{L}_\mu \\ \tilde{L}_\tau \end{pmatrix} + (\tilde{e}_R^* \, \tilde{\mu}_R^* \, \tilde{\tau}_R^*)\, \mathcal{M}^2_{\tilde{e}_R} \begin{pmatrix} \tilde{e}_R \\ \tilde{\mu}_R \\ \tilde{\tau}_R \end{pmatrix} + \left[(\tilde{e}_L^* \, \tilde{\mu}_L^* \, \tilde{\tau}_L^*)\, \mathcal{M}^2_{LR} \begin{pmatrix} \tilde{e}_R \\ \tilde{\mu}_R \\ \tilde{\tau}_R \end{pmatrix} + h.c. \right]$$

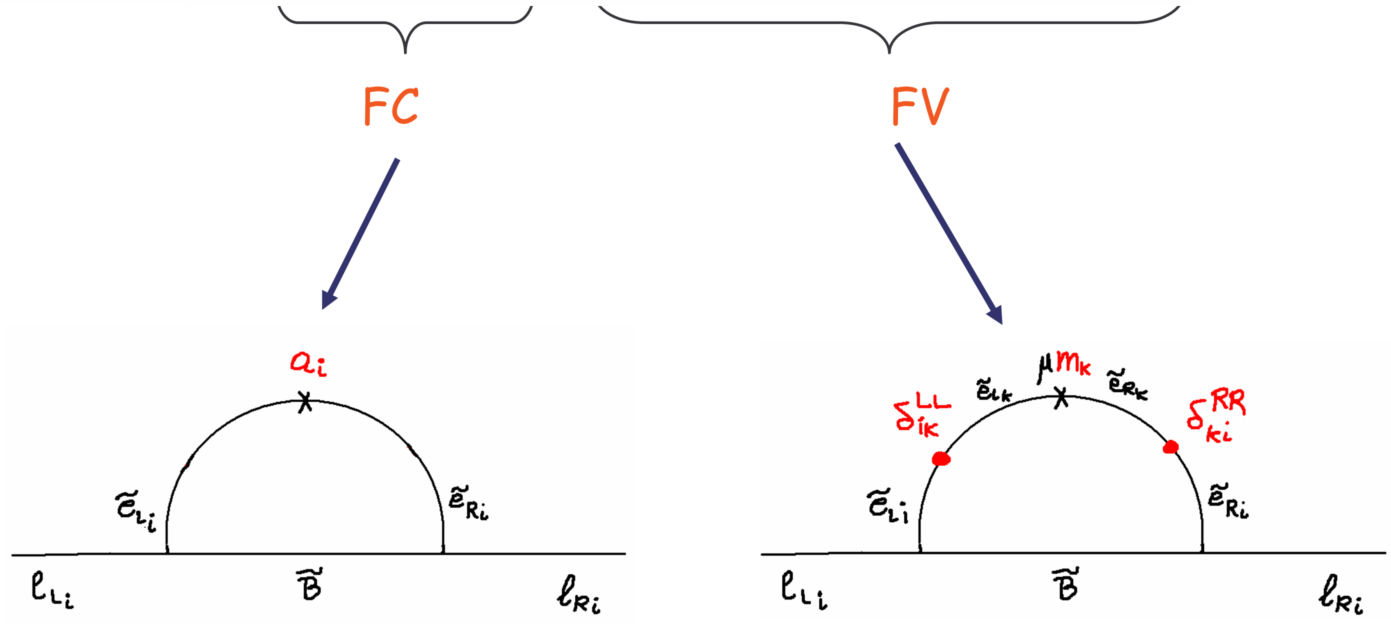
$$\mathcal{M}^2_{\tilde{L}} = \overline{m}^2_L (1\!\!1 + \delta^{LL}) \qquad \mathcal{M}^2_{\tilde{e}_R} = \overline{m}^2_R (1\!\!1 + \delta^{RR}) \qquad \mathcal{M}^2_{LR} = \hat{m}_e (\hat{a}_e^* - \mu\, t_\beta) + \overline{m}_L \overline{m}_R\, \delta^{LR}$$

Mass Insertion:
assume real μ-term

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

$$\delta a_{\ell_i} = Re A_{ii} = f_\mu\, m^2_{\ell_i}\, Re\mu + \ldots$$

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



d_e

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]

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

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

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

FC

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

[EllisHisanoLolaRaidalShimizu '01]

FV

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

[IM '03]

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[EllisHisanoLolaRaidalShimizu '01]

FV

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[IM '03]

FC&FV vanish if RH N's are deg

With O(1) yuk & hier RH, (only) d_e^{SS} is significant for experiments

FV generically dominant for tanβ > 10

Q: if observed, is d_e^{SS} compatible with thermal leptogenesis?

Work it out...

...by exploiting the fact that

$$Y_\nu = \begin{pmatrix} & \nu_e & \nu_\mu & \nu_\tau \\ N_1 & \lesssim 10^{-2} & \lesssim 10^{-2} & \lesssim 10^{-2} \\ & & & \\ & & & \end{pmatrix}$$

← For M_1 to be in the interesting range for leptogenesis

⇓

C^1 negligible, only **$C^{2,3}$ matter** for LFV and d_e

⇓

the splitting M_2/M_3 is crucial for d_e

#1: Largeness of d_e^{SS}

Taking here for definiteness $P = (\tilde{M}_1, \bar{m}_R) = (200, 500)\,\mathrm{GeV}$, the limit on $\ell_i \to \ell_j \gamma$ constrains:

(k=2,3) $\sum_k C_{21}^k < 5 \times 10^{-3} \frac{50}{\tan\beta}$ $\qquad \sum_k C_{32}^k < 0.8 \frac{50}{\tan\beta}$ $\qquad \sum_k C_{31}^k < \frac{50}{\tan\beta}$ =C

very small

$$d_e^{SS} \approx (f_{FC} + f_{FV})\, \underbrace{Im(C_{31}^{2*} C_{31}^3)}_{<|CC|}\, \ln\frac{M_3}{M_2} < d_e^{\tau \to e\gamma} \approx (10^{-2} - 10^{-1})\, d_e^{exp}$$

barring canc's

But even allowing for cancellations in $|C^2+C^3|_{13}$ the bound is safe

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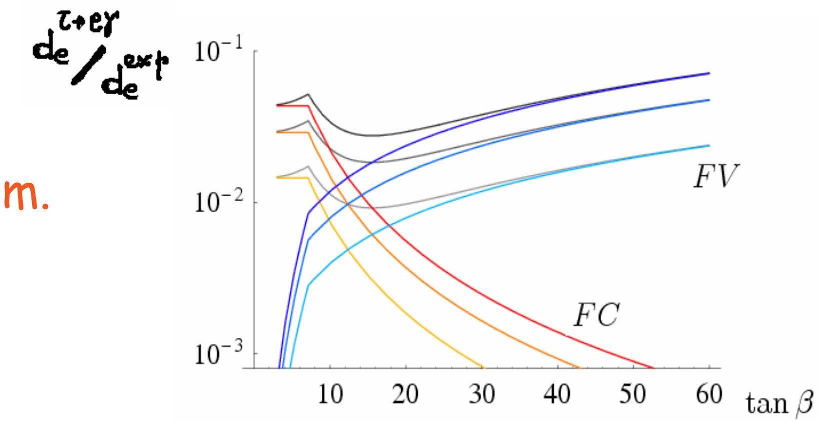
barring canc's

But even allowing for cancellations in $|C^2+C^3|_{13}$ the bound is safe

Exp improvement by 2 o.o.m. needed to test d_e^{ss}



: $M_2 = 5\times 10^{14}$ GeV and, from top to bottom lines, $M_3/M_2 = 10^3, 10^2, 10.$

#2. The class of textures maximizing d_e^{SS}

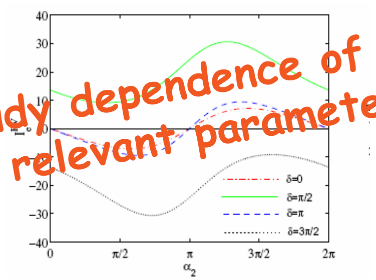
$M_3 >> M_2$ &

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

For M_1 in the interesting range for leptogenesis

Only possible structure allowing large d_e
and enough suppressed $\mu \to e\gamma$
(clearly, $\tau \to e\gamma$ is close to its bound)

→ explore parameter space



learning e.g. that

$$M_2 \approx \frac{v_u^2}{m_h} \qquad m_e \approx \frac{v_u^2}{M_3}$$

cannot vanish!

#3. Estimate of Y_L

This class of textures corresponds to very specific **R** structures, which depend on light ν-**spectrum**, **U** and $\chi \ll 1$

$$R^{NH} = \begin{pmatrix} \chi & \bar{c} & \bar{s} \\ 0 & \bar{s} & -\bar{c} \\ -1 & \chi\bar{c} & \chi\bar{s} \end{pmatrix}$$

where

$$\bar{t} = \sqrt{\frac{m_3}{m_2}}\frac{U^*_{23}}{U^*_{22}}$$

$$R^{IH} = \begin{pmatrix} \tilde{s} & \tilde{c} & \chi \\ -\tilde{c} & \tilde{s} & 0 \\ \tilde{s}\chi & \chi\tilde{c} & -1 \end{pmatrix}$$

where

$$\tilde{t} = \sqrt{\frac{m_1}{m_2}}\frac{U^*_{21}}{U^*_{22}}$$

In terms of [S.F.King's] "dominance" : $M_1 - m_{heavy}$ $M_3 - m_{light}$

Due to the particular form of R_{1j} , a sufficiently large $\epsilon_1^\ell \propto M_1 \frac{Im(\sum_{\beta\rho} m_\beta^{1/2} m_\rho^{3/2} U^*_{\ell\beta} U_{\ell\rho} R_{1\beta} R_{1\rho})}{\sum_\beta m_\beta |R_{1\beta}|^2}$ **requires** for both NH and IH

$M_1 > 10^{11}$ GeV

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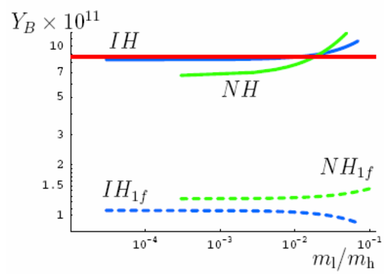
$M_1 > 10^{11}$ GeV

...despite flavor effects ARE large: O(10) !



2 examples with successful Y_B

#3. Estimate of Y_L

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$M_1 > 10^{11}$ **GeV**

definitely too large w.r.t. "bound on T_{RH}" → th prod of N_1 unlikely

Conclusions

Observing d_e^{SS} is possibile BUT REQUIRES

specific class of textures and some relations to hold → $m_\ell \approx \frac{v_u^2}{M_3}$

This determines R_{1j} → $M_1 > 10^{11}$GeV for th lept (even with flavor effects)

strong tension with gravitino bound on $T_{RH} <$ "10^{10}GeV"

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Observing d_e^{SS} is possibile BUT REQUIRES

specific **class of textures** and some **relations** to hold → $m_\ell \approx \frac{v_u^2}{M_3}$

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strong tension with gravitino bound on $T_{RH} <$ "10^{10}GeV"

THEN... in case d_e were mesured:

keep d_e^{SS} → non-thermal production of N_1 **OR** abandon leptogenesis

keep **th leptog** → d_e from a different source of CPV bSM than susy-ss
many candidates, e.g. GUT's triplet Yukawas

CPV-related observables are useful guides for theories beyond the SM

$p \to K^+ \nu$ VS d_e

From d=5 op generated by TRIPLET exchange
['82: Weinberg, Sakai, Yanagida, ...]

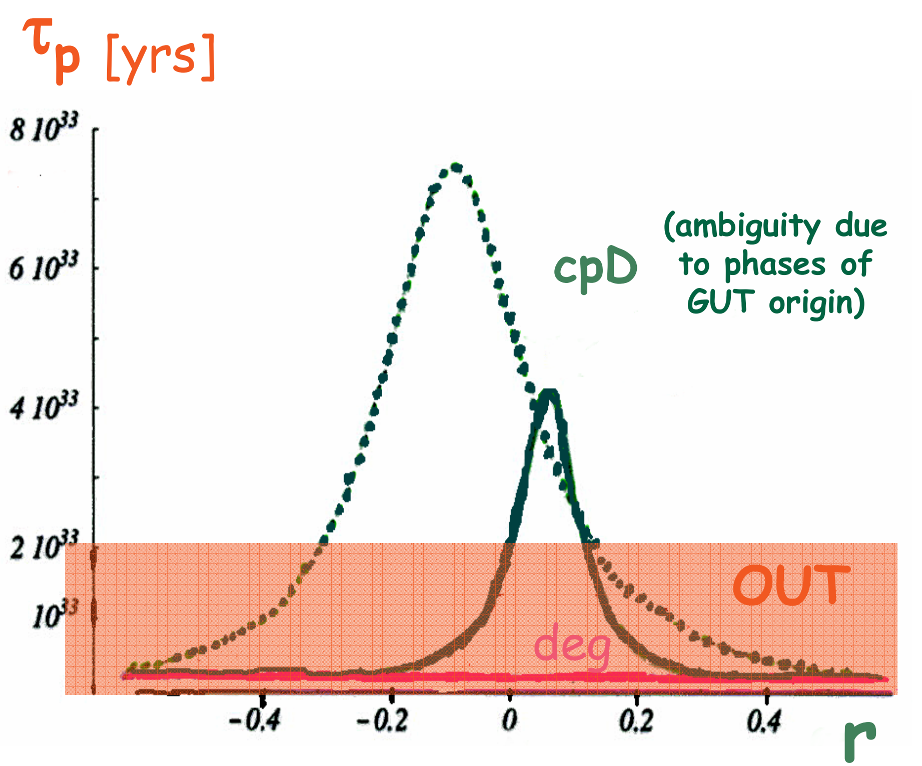
τ_p **depends A LOT on M_T-structure**

deg: KO cpD: SAFE

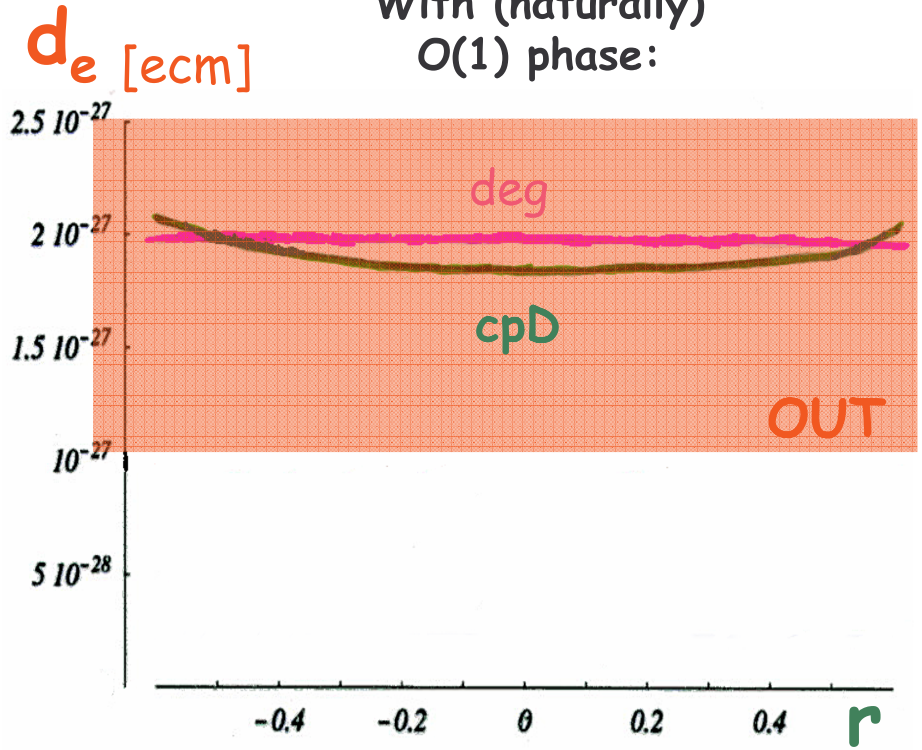
From RGE where contributions of the many heavy states sum up

d_e **INSENSITIVE to M_T-structure**

g_μ region& $tg\beta=3$



With (naturally) O(1) phase:



Complementary in constraining SUSY GUTs

Susy Seesaw & dipole operator

Basic idea:

seesaw yukawas induce via **RGE** flavor & CP V in slepton masses

→ coeff of dipole op is linked to seesaw

& turns out to be exp relevant!

Caveat:

to isolate just the seesaw contribution to dipole operator, better to suppress other potential flavor & CP V sources

→ assume real and universal soft masses at M_{Planck} : **mSugra**