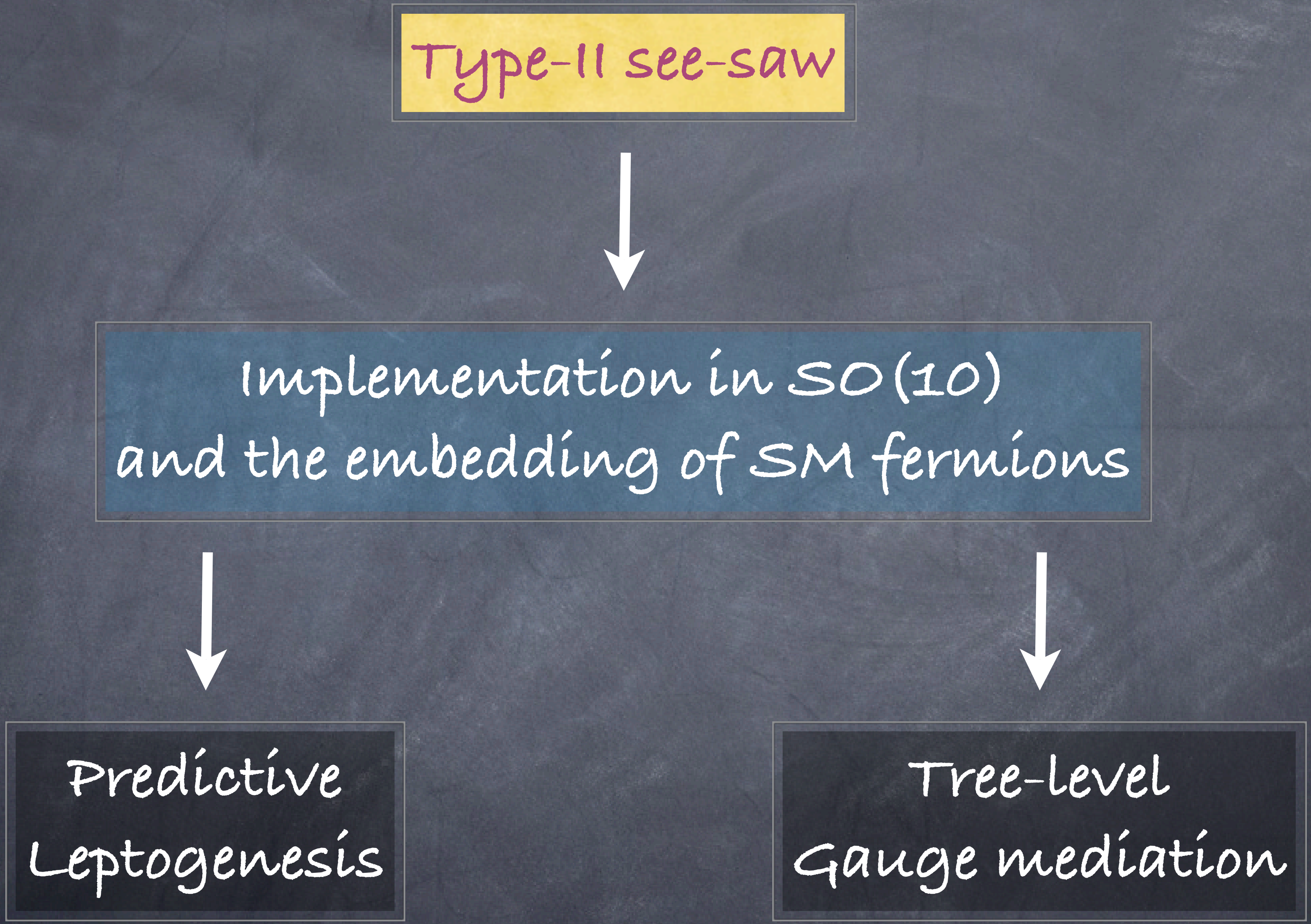
From type-II see-saw to a new mechanism of supersymmetry breaking

Andrea Romanino
SISSA

GoranFest, Split

From type-II see-saw to supersymmetry breaking

???


Type-II see-saw
Implementation in SO(10) and the embedding of SM fermions
Predictive Leptogenesis
Tree-level Gauge mediation

Type-II see-saw

(pure) type-II see-saw

[Mohapatra Senjanović
Lazarides Shafi Wetterich]

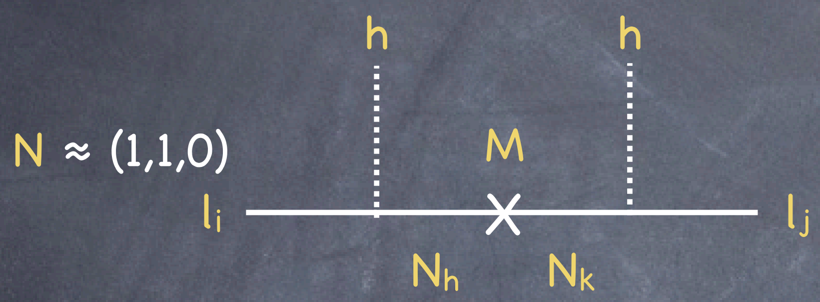
$$\mathcal{L} = \Delta\, l^2 + \frac{M^2}{2}\Delta^2 + \alpha M h_u^2 \Delta^*$$

$\Delta \approx (1,3,1)$

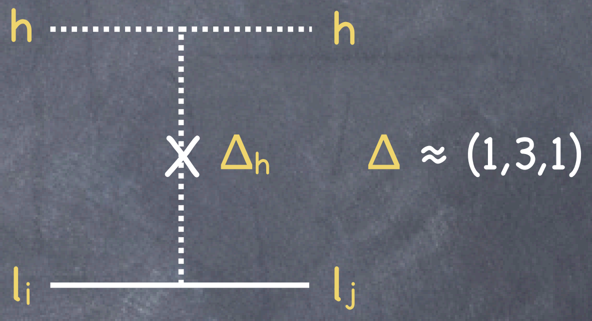
$$\langle \Delta \rangle = -\alpha \frac{\langle h_u \rangle^2}{M} \quad \Rightarrow \quad m_\nu = \alpha \frac{\langle h_u \rangle^2}{M}$$

Type-II see-saw

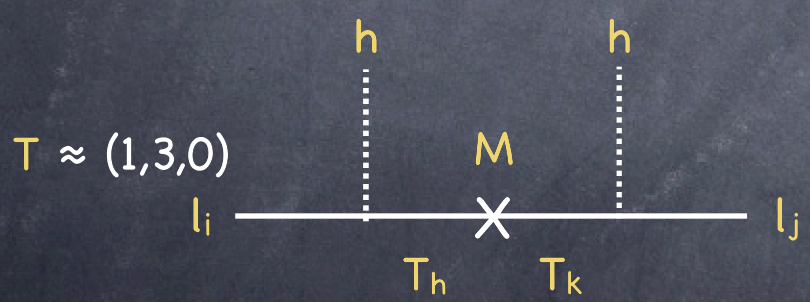
$$\mathcal{L}^{\rm eff}_{E\ll\Lambda} = \mathcal{L}^{\rm ren}_{\rm SM} + \frac{a_{ij}}{2\Lambda}(h\,l_i)(h\,l_j) + \dots$$



See-saw type I



See-saw type II



See-saw type III

(Any number of N_h, T_h, Δ_h)

$(SU(3)_c, SU(2)_L, Y)$

(Comparison with see-saw type-I)

- Relevant interactions: $\lambda^E_{ij} e^c_i l_j h_d + \lambda^N_{ij} N_i l_j h_u + \frac{M_{ij}}{2} N_i N_j \quad \left[m_\nu = -v_u^2 \, \lambda_N^T \frac{1}{M} \lambda_N \right]$
- Overall size of neutrino Yukawa couplings

$$\begin{matrix} \lambda_N \to k\,\lambda_N \\ M \to k^2 M \end{matrix} \Rightarrow \begin{matrix} m_\nu \to m_\nu \\ \mathrm{BR}(e_i \to e_j \gamma) \to k^4 \log k \, \mathrm{BR}(e_i \to e_j \gamma) \end{matrix}$$

- Unknown flavour structure

$v_d \lambda_E,\ v_u \lambda_N,\ M$ — 21 physical parameters

$m_e\, m_\mu\, m_\tau,\ m_{\nu_1}\, m_{\nu_2}\, m_{\nu_3},\ U$ — 12 known or measurable parameters

e.g. $v_u \lambda_N = v_u \lambda_N^{\mathrm{diag}} V_N$ or M^{diag},

$R = 1/\sqrt{M^{\mathrm{diag}}}\, v_u \lambda_N\, U^\dagger / \sqrt{M^{\mathrm{diag}}}$

9 unknowns = 3 masses + 3 angles + 3 phases

- Type-II: LFV more predictive [Rossi 02], leptogenesis as well in SO(10)

also

[Bajc Senjanović Vissani]

- Possibility to link b-τ unification to large atmospheric neutrino mixing

$$M_U = Y_{10} v_{10}^u + Y_{126} v_{126}^u$$
$$M_D = Y_{10} v_{10}^d + Y_{126} v_{126}^d$$
$$M_E = Y_{10} v_{10}^d - 3 Y_{126} v_{126}^d$$
$$M_N = Y_{126} \langle (3,1,10)_{126} \rangle$$

$$M_N \propto Y_{126} \propto M_D - M_E$$

A simple Implementation of type-II see-saw in SO(10)

The embedding of the SM fermions

- Reminder: SU(5) embedding

  $l + d^c = \bar{5}_{SU(5)}$ $\quad$ $q + u^c + e^c = 10_{SU(5)}$

- Usually

  $16_{SO(10)} = (\bar{5}_{SU(5)}, 10_{SU(5)}, 1_{SU(5)})$ $\quad$ (and $10_{SO(10)} = (5_{SU(5)}, \bar{5}_{SU(5)})$)

- Here

  $16_{SO(10)} = (\bullet, 10_{SU(5)}, \bullet)$ $\quad$ $10_{SO(10)} = (\bullet, \bar{5}_{SU(5)})$ $\quad$ ($\bullet$ = heavy)

Type-II see-saw in SO(10)

- $\Delta \approx (1,3,1) \subset 15_{SU(5)}$ $\Delta + \bar{\Delta} \subset 54_{SO(10)}$ $= 15_{SU(5)} + \overline{15}_{SU(5)} + 24_{SU(5)}$ (or $\subset 126 + \overline{126}$ or > 500)
- Note: $10 \times 10 = 1_s + 45_a + 54_s$ $54 < 252$ (perturbativity)
- 54 does not couple to 16×16
- But it does couple to 10×10, and $10 \supset \bar{5}_{SU(5)} \supset l$
- Hence the need of the embedding of $\bar{5}_{SU(5)}$ in $10_{SO(10)}$

A predictive model of leptogenesis

Frigerio Hosteins Lavignac R, arXiv:0804.0801 (NPB)
Calibbi Frigerio Lavigac R, arXiv:0910.0377 (JHEP)

The see-saw lagrangian

- $10_{i\,SU(5)} \subseteq 16_{i\,SO(10)}$, $\bar{5}_{i\,SU(5)} \subseteq 10_{i\,SO(10)}$

- $$W \supseteq \frac{y_{ij}}{2} 16_i 16_j 10 + h_{ij} 16_i 10_j 16 + \frac{f_{ij}}{2} 10_i 10_j 54 + \frac{\sigma}{2} 10\,10\,54 + W_{\text{vev+NR}}$$

- $$\begin{cases} m^U_{ij} = v_u\, y_{ij} \\ m^E_{ij} = v_d\, h_{ij} \\ m^\nu_{ij} = \sigma \dfrac{v_u^2}{2M_\Delta} f_{ij} \quad \text{(pure type II)} \end{cases}$$

$$h_{ij} 16_i 10_j 16 \to V_{16}\, h_{ij} \bar{5}^{16}_i 5^{10}_j = V_{16}\, h_{ij} (\bar{L}_i L_j + \bar{D}^c_i D^c_j)$$

<16> pairs up the spare components in 16_i 10_i

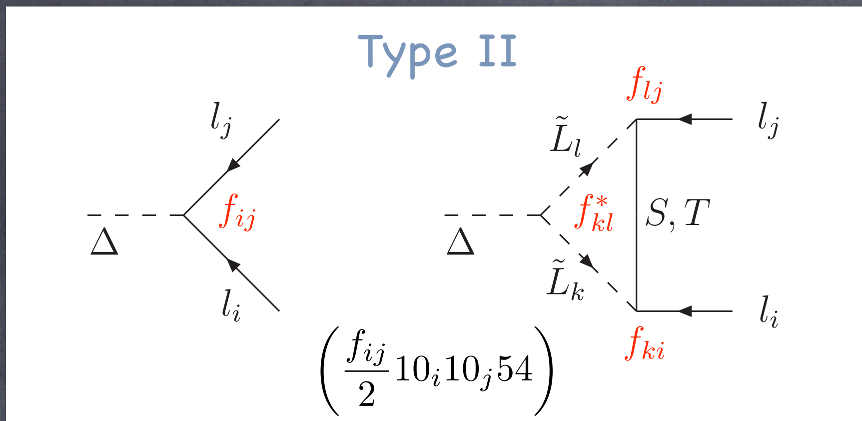
- W is R_P invariant, generic up to mass terms; no type-I

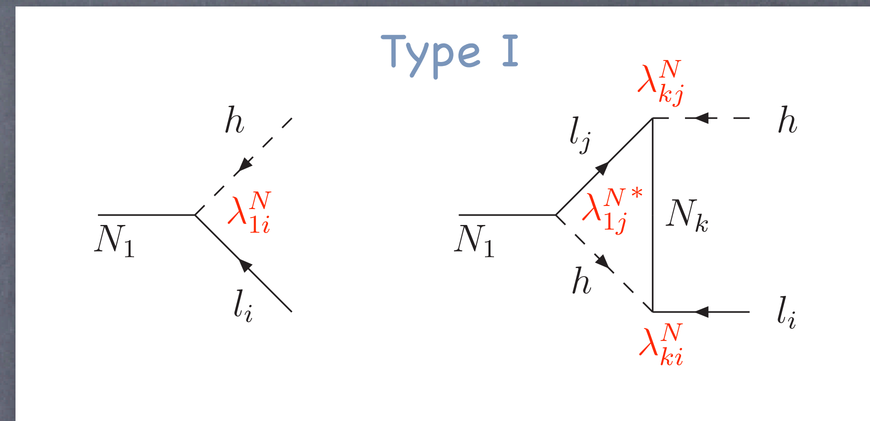
- Below M_{GUT}: MSSM + $(5_i+\bar{5}_i)$ + $(15+\overline{15}+24)$ (+ N_i)
  LNV from Δ (and N_i) $\quad M_\Delta = M_{15} < M_{24}\ M_N$

- The presence of the heavy L, D^c (+ conj) leads to
  - leptogenesis (1-loop diagrams giving rise to CP asymmetry)
  - LFV effects (radiative effects on soft terms)

- Flavour parameters known (up to mild model dependence)
- Flavour-blind parameters unknown (triplet mass, its coupling to h_u..)

Leptogenesis



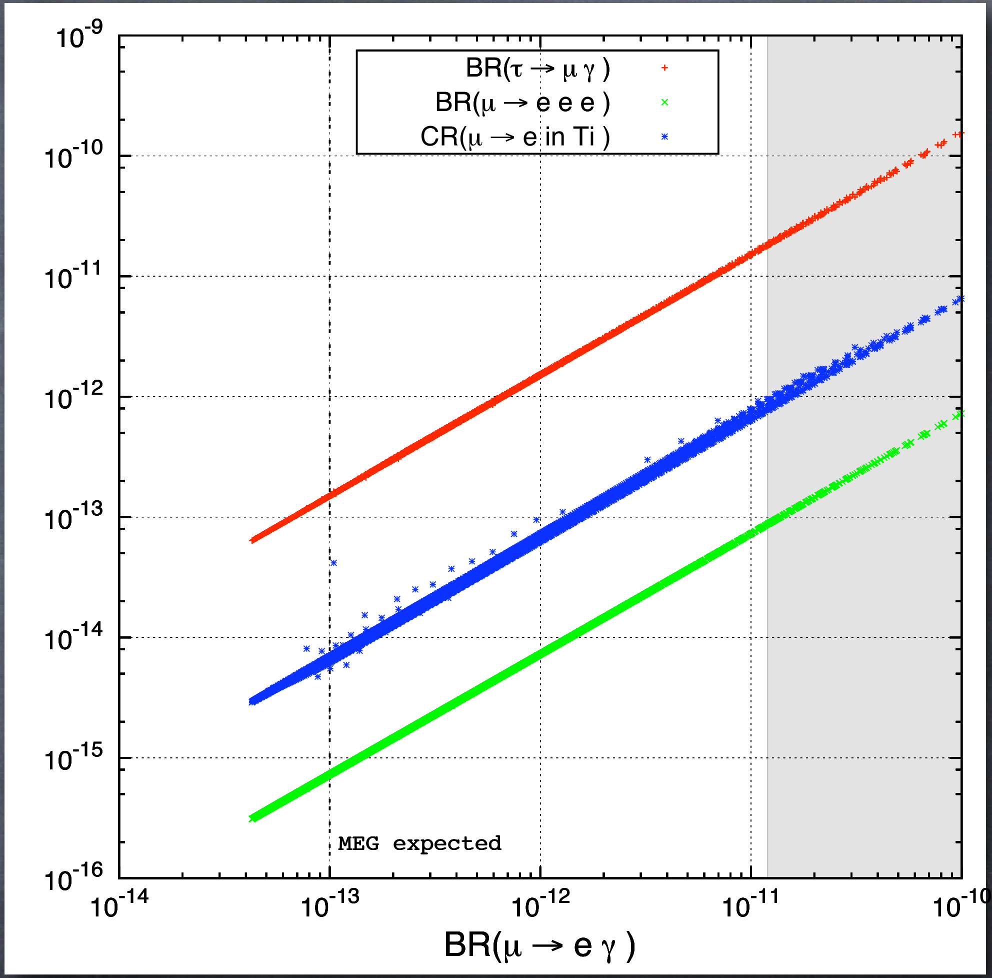


- f_{ij}, M^L_{ij} from m_ν, m_E (up to overall factors, W_{NR})
- L_1 lighter than $M_\Delta/2$? $M_{L_1} \sim h_1 V_{16} \sim \frac{0.5 \cdot 10^{11}\,\text{GeV}}{\cos\beta} \left(\frac{V_{16}}{2 \cdot 10^{16}\,\text{GeV}}\right)$ ✓
- $M_{L1} < M_\Delta < M_{L2}$, M_{24}: $\epsilon \approx \frac{1}{10\pi} \frac{M_\Delta}{M_{24}} \frac{\lambda_l^4}{\lambda_l^2 + \lambda_h^2} \frac{\text{Im}[m^*_{11}(mm^*m)_{11}]}{(\sum_i m_i^2)^2}$

(in the diagonal m_E basis)

$$\left(\begin{array}{c} \lambda_l^2 \equiv \sum_{ij} |f_{ij}|^2, \quad \lambda_h^2 \equiv |\sigma|^2 \\ \epsilon \equiv 2 \frac{\Gamma(\Delta \to l^* l^*) - \Gamma(\Delta^* \to ll)}{\Gamma_\Delta + \Gamma_{\Delta^*}} \end{array} \right)$$

LFV

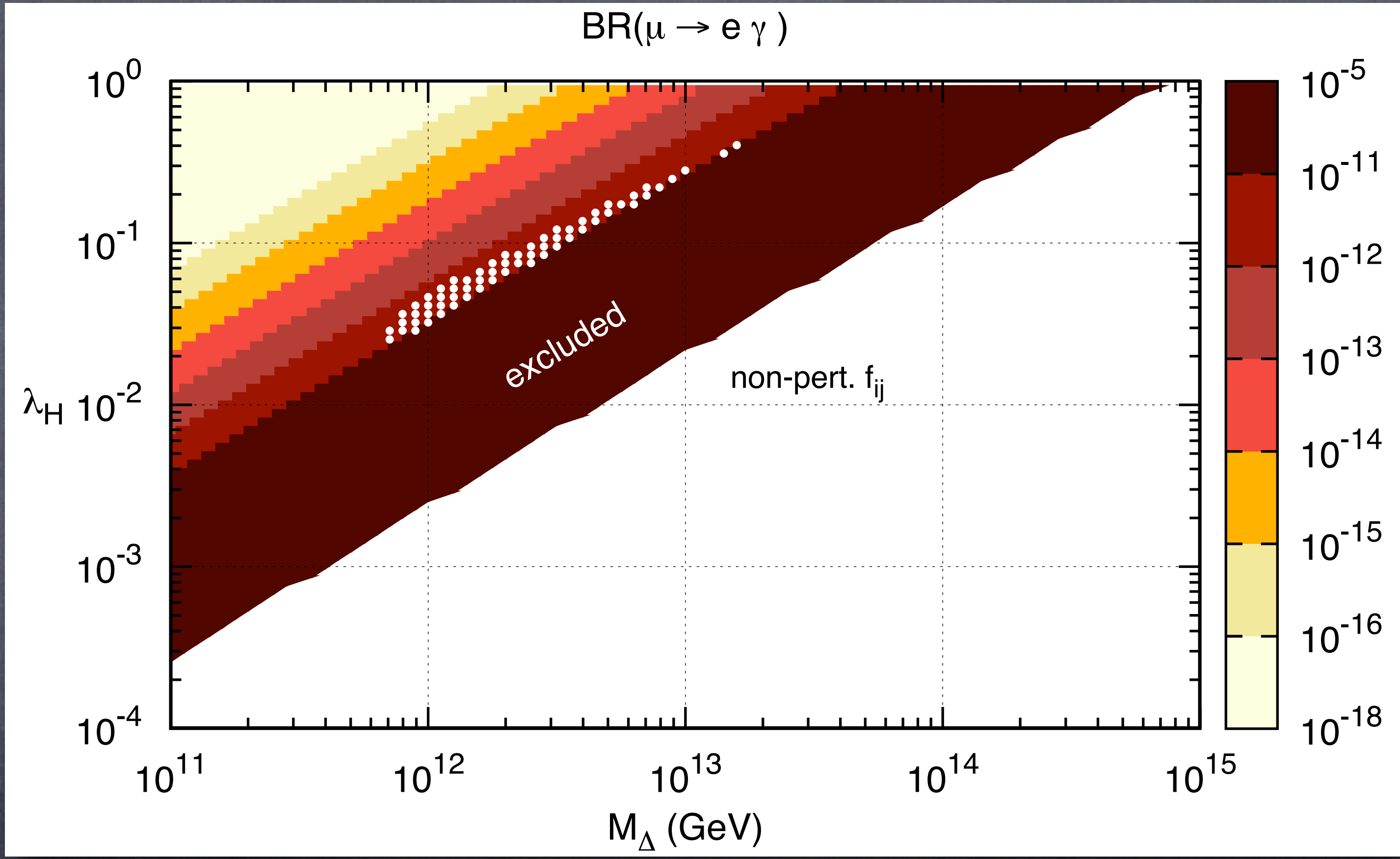


$m_1 = 0.005$ eV
$\sin^2\theta_{13} = 0.05$

- Similar to A. Rossi, 02 but with additional effects from the heavy fields crucial for leptogenesis

Leptogenesis + LFV

- $\mu \to e\,\gamma$ predicted to be within MEG sensitivity



$m_0 = M_{1/2} = 700$ GeV

$A_0 = 0$ $\tan\beta = 10$ $\mu > 0$

$m_1 = 0.005$ eV $\sin^2\theta_{13} = 0.05$

Tree-level gauge mediation

with Nardecchia, Ziegler
arXiv:0909.3058 (JHEP)
arXiv:0912.5482 (JHEP)
and Monaco (in progress)

A wide class of models of supersymmetry breaking

[Polchinski Susskind,
Dine Fischler,
Dimopoulos Raby,
Barbieri Ferrara Nanopoulos]

SUSY breaking	?	MSSM
Hidden sector	⟷	**Observable sector**
Z chiral superfield $\langle Z \rangle = F\theta^2$ $F \gg (M_Z)^2$ SM singlet	M	Q chiral superfield

$$\int d^4\theta \, \frac{Z^\dagger Z \, Q^\dagger Q}{M^2} \quad \to m^2 \tilde{Q}^\dagger \tilde{Q}, \quad m^2 = \frac{F^2}{M^2}$$

A wide class of models of supersymmetry breaking

[Polchinski Susskind,
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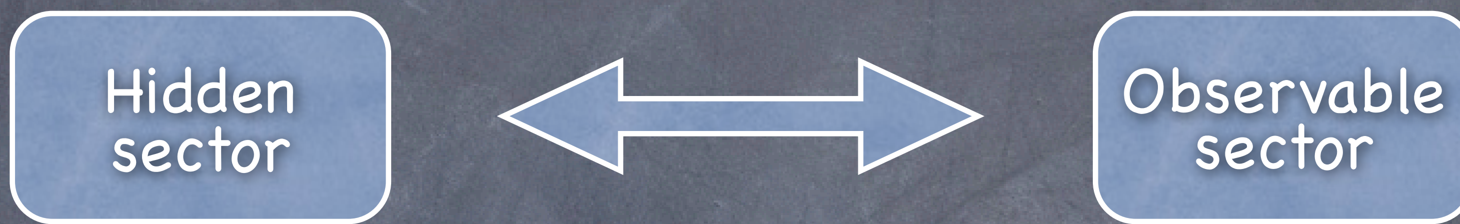
SUSY breaking

gravity
mediation

MSSM



Z chiral superfield
$\langle Z \rangle = F\theta^2$
$F \gg (M_Z)^2$
SM singlet

M

Q chiral superfield

$$\int d^4\theta \, \frac{Z^\dagger Z \, Q^\dagger Q}{M^2} \quad \to m^2 \tilde{Q}^\dagger \tilde{Q}, \quad m^2 = \frac{F^2}{M^2}$$

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SUSY breaking

gauge
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MSSM

Z chiral superfield
$\langle Z \rangle = F\theta^2$
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A wide class of models of supersymmetry breaking

[Polchinski Susskind,
Dine Fischler,
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Barbieri Ferrara Nanopoulos]

SUSY breaking

bulk
mediation

MSSM

Z chiral superfield
$\langle Z \rangle = F\theta^2$
$F \gg (M_Z)^2$
SM singlet

M

Q chiral superfield

$$\int d^4\theta \, \frac{Z^\dagger Z\, Q^\dagger Q}{M^2} \quad \to m^2 \tilde{Q}^\dagger \tilde{Q}, \quad m^2 = \frac{F^2}{M^2}$$

A wide class of models of supersymmetry breaking

[Polchinski Susskind,
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SUSY breaking

tree-level gauge mediation

MSSM

Z chiral superfield
$\langle Z \rangle = F\theta^2$
$F \gg (M_Z)^2$
SM singlet

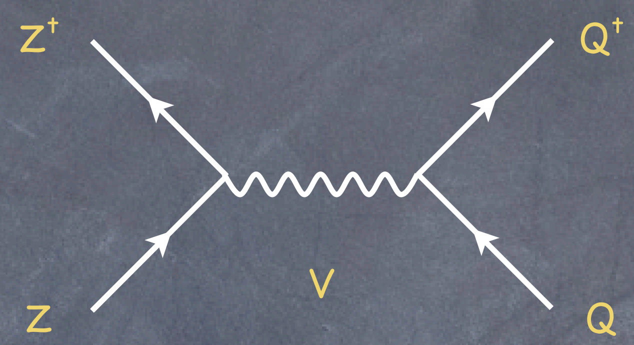
M

Q chiral superfield

$$\int d^4\theta \, \frac{Z^\dagger Z \, Q^\dagger Q}{M^2} \quad \to m^2 \tilde{Q}^\dagger \tilde{Q}, \quad m^2 = \frac{F^2}{M^2}$$

Tree level gauge mediation

$$\int d^4\theta \, \frac{Z^\dagger Z \, Q^\dagger Q}{M^2}$$



↑

heavy vector superfield
SM singlet
non-anomalous
assumed to part of a GUT

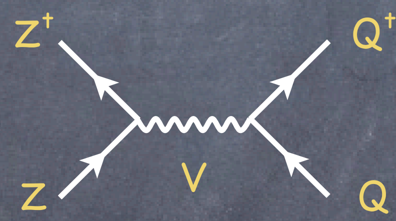
A concrete example

- G = SO(10) "minimal" GUT (V heavy SM singlet means rank ≥ 5)

- V associated to the SU(5)-invariant generator "X"

SO(10)		SU(5)		
16	=	$\bar{5}$ +	10 +	1
X		-3	1	5

SO(10)		SU(5)	
10	=	$\bar{5}$ +	5
X		2	-2

- 

gives $\tilde{m}^2_Q \propto X_Q X_Z$

- The (usual) embedding of a MSSM family in a single 16 does not work (whatever the sign of X_Z)

- The three MSSM families are embedded in $16_i + 10_i$, i=1,2,3 (needs $X_Z > 0$)

SO(10)		SU(5)				
16_i	=	$\bar{5}_i$	+	10_i	+	1_i
X		−3		1		5

SO(10)		SU(5)		
10_i	=	$\bar{5}_i$	+	5_i
X		2		−2

must be made heavy

- Does not require any effort! (SO(10) reps with d < 120)

SO(10) breaking needs $16 + \overline{16}$ with $\langle 16 \rangle = \langle \overline{16} \rangle = M \approx M_{GUT}$

$h_{ij}\, 16_i\, 10_j\, 16 \rightarrow M_{ij}\, 5_i\, 5_j$ when $16 \rightarrow \langle 16 \rangle$

(Reinforces the theoretical consistency)

- SUSY breaking: Z must be the singlet of a 16′ (gauge invariance: 16′ ≠ 16)

$$\tilde{m}_Q^2 = \frac{X_Q}{2X_Z}\frac{F^2}{M^2}$$

- Then $\tilde{m}_q^2 = \tilde{m}_{u^c}^2 = \tilde{m}_{e^c}^2 = \tilde{m}_{10}^2 = \frac{1}{10}\, m^2, \quad \tilde{m}_l^2 = \tilde{m}_{d^c}^2 = \tilde{m}_{\bar{5}}^2 = \frac{1}{5}\, m^2, \quad m = \frac{F}{M}$

- In particular

- all sfermion masses are positive

- sfermion masses are flavour universal, thus solving the supersymmetric flavour problem, and determined by a single parameter

- $\tilde{m}_{q,u^c,e^c}^2 = \frac{1}{2}\tilde{m}_{l,d^c}^2$ (at M)

Against common wisdom

- Supersymmetry breaking masses (Z*ZQ*Q) are obtained at the tree level from spontaneous SUSY breaking in a renormalizable theory

- Two arguments seem to prevent this possibility

1. the supertrace formula

$$0 = (\mathrm{Str}\, M^2)_{f,tot} = \underbrace{(\mathrm{Str}\, M^2)_{f,MSSM}}_{>0} + \underbrace{(\mathrm{Str}\, M^2)_{f,extra}}_{<0}$$

$$(\tilde{m}^2_{\text{lightest ``squark''}} \leq m_d^2 \text{ or } m_u^2 \quad \text{if no additional U(1)'s})$$

2. small gaugino masses [Arkani-Hamed Dimopoulos Giudice R]

$$\tilde{m}_f \sim 100\, M_2 \gtrsim 10\,\mathrm{TeV} \quad \Rightarrow \quad \tilde{m}_f \sim 10\, M_2 \cdot \eta \gtrsim 1\,\mathrm{TeV} \cdot \eta$$

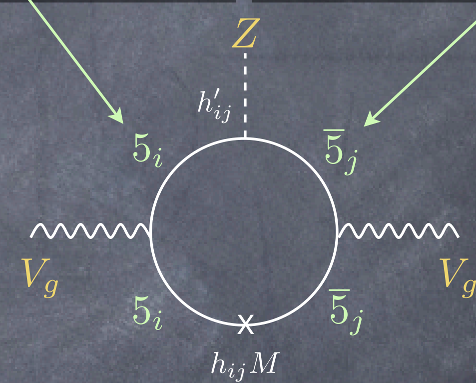
Gaugino masses

- Arise at one-loop because of a built-in ordinary gauge mediation structure

SO(10)		SU(5)				
16_i	=	$\bar{5}_i$	+	10_i	+	1_i
X		−3		1		5

SO(10)		SU(5)		
10_i	=	5_i	+	$\bar{5}_i$
X		2		−2

- ($W = h_{ij}\, 16_i\, 10_j\, 16 + h'_{ij}\, 16_i\, 10_j\, 16'$)



- $$\left.\frac{M_2}{\tilde{m}_t}\right|_{M_{\rm GUT}} = \frac{3\sqrt{10}}{(4\pi)^2}\,\lambda, \quad \lambda = \frac{g^2\,{\rm Tr}(h' h^{-1})}{3}$$

- O(100) hierarchy → O(10): $\tilde{m}_t$ > O(1 TeV) x model dep factor λ

How general are the predictions?

- They assume:
  - Minimal GUT implementation (SO(10))
  - Only SO(10) reps with d < 120
  - Pure embeddings of SM multiplets in 1 type of SO(10) reps (guarantees the solution of the SUSY flavour problem), or no matter mass terms
- Non minimal GUTs?
  - A natural option is E_6
  - $27_i = 16_i + 10_i + 1_i$ under SO(10)

Miscellaneous

- A new D=3 solution of the μ problem
  D=4 (NMSSM) and D=5 (Giudice-Masiero) can also work
- Sugra contamination smaller than in loop gauge mediation (M_{GUT} OK)
- LSP is the gravitino
- Higgs soft terms bounded in predicted interval
- Up and down Yukawas decoupled despite SO(10)
- Neutrino masses through type-I, type-II, or hard susy breaking operators
- Type-II leptogenesis possible

In conclusion..

Happy Birthday Goran!