Non-Universal SUSY-GUTS, DM and the LHC

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Dedicated to IOANNIS BAKAS

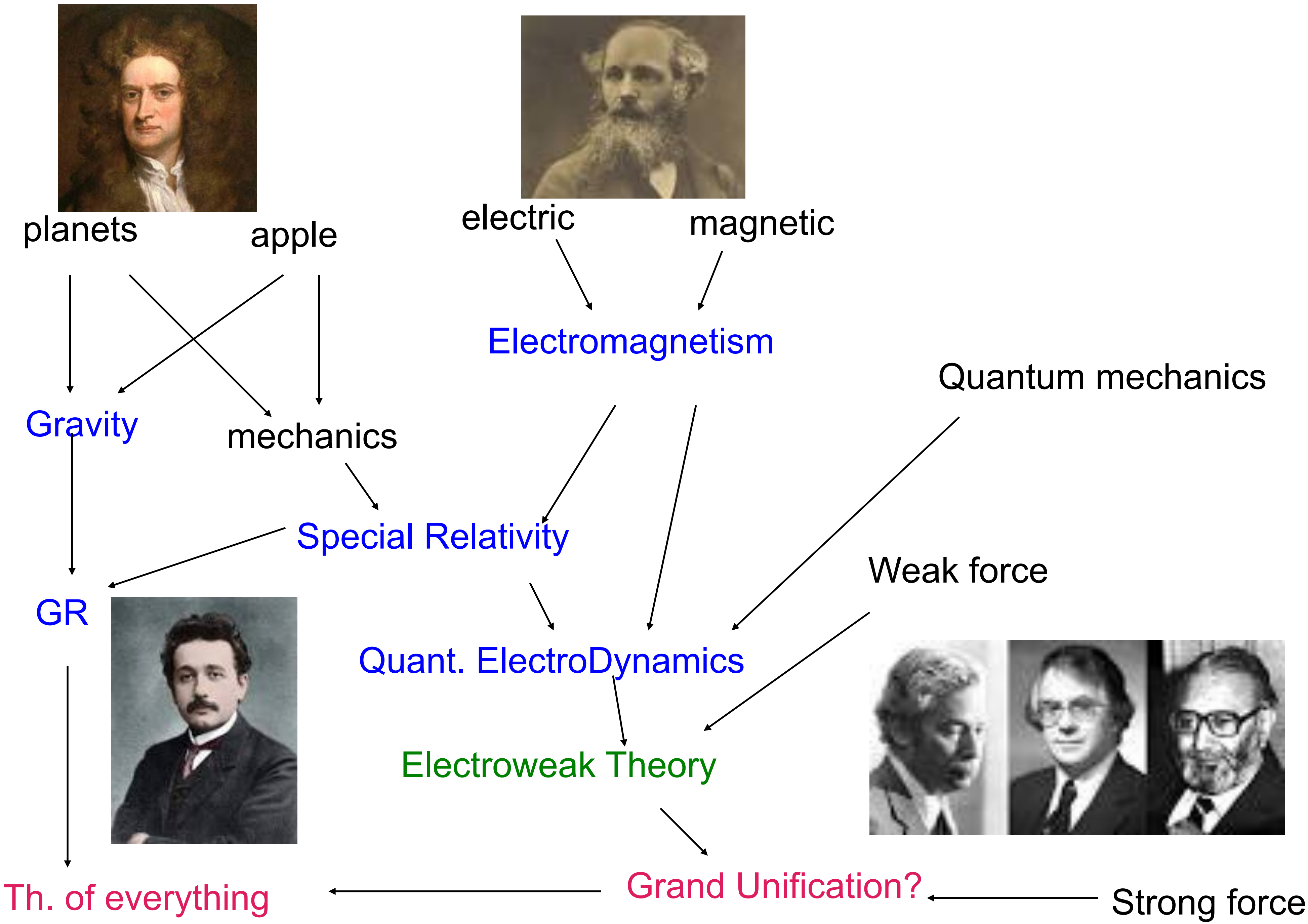
Motivation

- Higgs discovery but no SUSY signal at the LHC
  Severe constraints on at least the simplest realisations of susy
- Still, we need to go beyond the SM, due to
  - Neutrino masses & mixing
  - Baryon asymmetry in the universe
  - Origin of dark matter
  - Large number of arbitrary parameters (mostly in mass sector)
  - Hierarchy problem, **especially if further unification exists**

In this respect, SUSY GUTs have very attractive features
(see lectures by G.G. Ross)

- Non-minimal SUSY extensions
  - **Break unification conditions of minimal schemes** &/or
  - add new particles and interactions *(softer fitting constraints)*

Success of Unification



Contents

- Relevant aspects of GUTs, SUSY, Flavour Symmetries
- Different predictions in various GUTs

  SO(10), SU(5), Flipped SU(5)
- Can we distinguish them at the LHC

  Several constraints from DM considerations
- **MAIN QUESTION:** What can the LHC tell us on the underlying symmetries?

  How can we explicitly distinguish different scenarios?

SUSY – new particles and interactions
(refer to lectures by W. Hollik & H.P. Nilles)

particle		spin	sparticle		spin
quark	q	1/2	squarks	$\tilde{q}_{L,R}$	0
charged lepton	l	1/2	charged sleptons	$\tilde{l}_{L,R}$	0
neutrino	ν	1/2	sneutrino	$\tilde{\nu}$	0
gluon	g	1	gluino	$\tilde{g}$	1/2
photon	γ	1	photino	$\tilde{\gamma}$	1/2
	Z^0	1	zino	$\tilde{Z}$	1/2
neutral higgses	h, H, A	0	neutral higgsinos	$\tilde{H}^0_{1,2}$	1/2
	$W^\pm$	1	wino	$\tilde{W}^\pm$	1/2
charged higgs	$H^\pm$	0	charged higgsino	$\tilde{H}^\pm$	1/2
graviton	G	2	gravitino	$\tilde{G}$	3/2

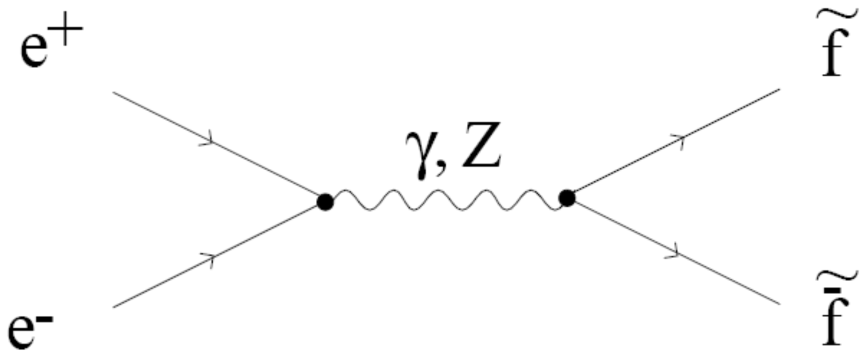
$\tilde{W}^\pm$,$\tilde{H}^\pm$ mix to form 2 chargino mass eigenstates $\chi_1^\pm$,$\chi_2^\pm$

$\tilde{\gamma}$, $\tilde{Z}$, $\tilde{H}^0{}_{1,2}$ mix to form 4 neutralino mass eigenstates $\chi_1^0, \chi_2^0, \chi_3^0, \chi_4^0$

$\tilde{t}_L, \tilde{t}_R$ (and $\tilde{b}, \tilde{\tau}$) mix to form the mass eigenstates $\tilde{t}_1, \tilde{t}_2$

Minimal SUSY Lagrangian– very simple rule: all SM interactions
+ those where 2 particles are substituted by antiparticles

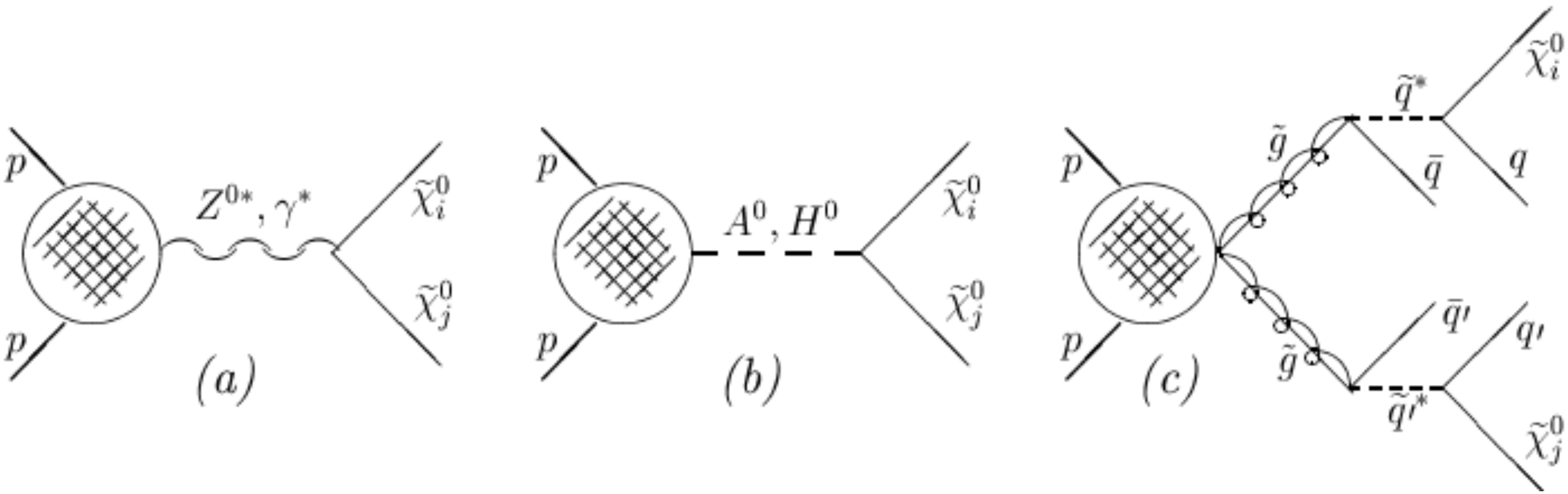
i.e.



Simplest SUSY models:

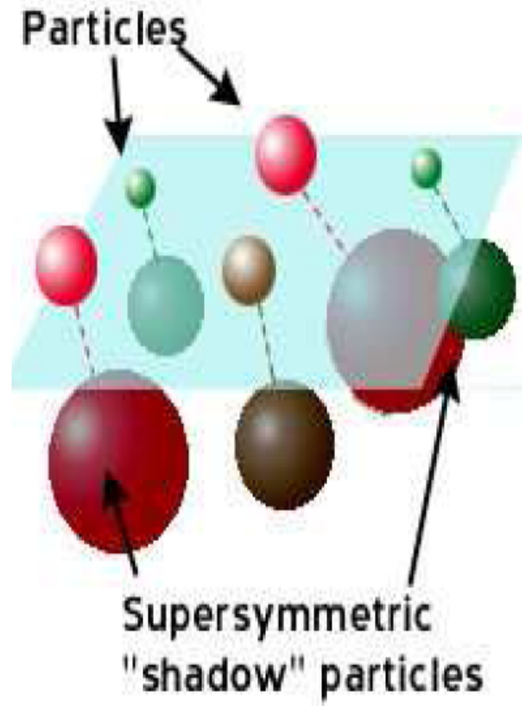
- Missing Energy Signature

- LSP as Dark Matter (one of our basic requirements)



Soft SUSY breaking terms

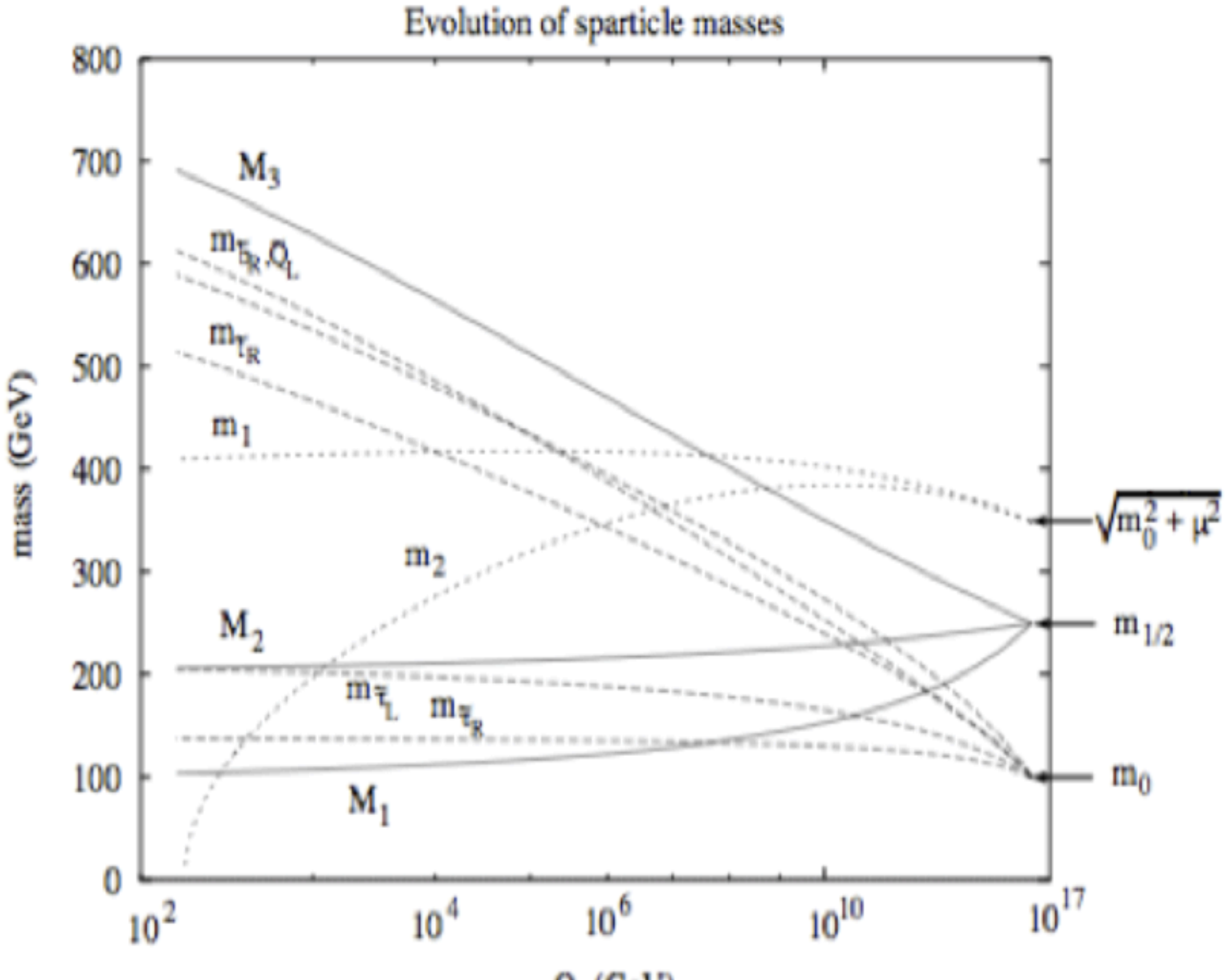
$$-\mathcal{L}_{\text{soft}} = -\frac{1}{2}\left(M_3 \lambda_{\tilde{g}}^a \lambda_{\tilde{g}}^a + M_2 \lambda_{\tilde{W}}^i \lambda_{\tilde{W}}^i + M_1 \lambda_{\tilde{B}} \lambda_{\tilde{B}} + \text{h.c.}\right)$$
$$+ M_L^2 \tilde{L}^\dagger \tilde{L} + M_Q^2 \tilde{Q}^\dagger \tilde{Q} + M_U^2 \tilde{U}^* \tilde{U} + M_D^2 \tilde{D}^* \tilde{D} + M_E^2 \tilde{E}^* \tilde{E} +$$
$$m_{H_d}^2 \tilde{H}_d^\dagger \tilde{H}_d + m_{H_u}^2 H_u^\dagger H_u - \left(B\mu \tilde{H}_d^T H_u + \text{h.c.}\right)$$
$$+ \left(y_\ell A_\ell H_d^\dagger \tilde{L}\tilde{E} + y_d A_d H_d^\dagger \tilde{Q}\tilde{D} - y_u A_u H_u^T \tilde{Q}\tilde{U} + \text{h.c.}\right),$$



Inspired from supergravity assume universal soft breaking, $\mathcal{L}_{\text{soft}}$:

$$\sum_{f,H} m_0^2 \tilde{f}\tilde{f} + \sum_{\lambda} m_{\frac{1}{2}} \lambda\lambda + \sum_{f} A_0 Y_f \tilde{f}\tilde{F} H_f + B\mu H_u H_d$$

$m_0,\ m_{\frac{1}{2}},\ A_0,\ \tan\beta,\ \text{sign}(\mu)$



Evolution of sparticle masses
mass (GeV)
800
700
600
500
400
300
200
100
0
10^2
10^4
10^6
10^{10}
10^{17}
M_3
m_1
m_2
M_2
M_1
$\sqrt{m_0^2 + \mu^2}$
$m_{1/2}$
m_0

The simplest models may be too restrictive

To search for/exclude SUSY unification need to first consider several alternative possibilities

Vast number of models
How to distinguish between them?

Try to address at the same time the origin of mass, combining GUT and flavour symmetries

Fermion hierarchies from flavour symmetries

(i.e. Why the top quark mass so much larger?)

A family symmetry generates the observed hierarchies

	Q_i	$\bar{U}_i$	$\bar{D}_i$	L_i	$\bar{E}_i$	H_2	H_1
$U(1)$	a_i	a_i	a_i	b_i	b_i	$-2a_3$	wa_3

Charges such that only 3 generation masses allowed
(0 flavour charges for 3rd generation)
The rest of the terms appear once the symmetry is broken

Frogatt-Nielsen mechanism

$$Q_i \bar{U}_j H_2 (< \theta > / M)^n$$

Similarly for other fermions, including neutrinos

- Up-mass matrix:

Top coupling $Q_3\bar{U}_3H_2$ 0 charge $\Rightarrow$ allowed

All other couplings forbidden

$$M^{up} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Suppose singlets θ with non-0 flavor-charges

(singlets expected in realistic models)

Then: invariant terms $Q_i\bar{U}_jH_2(<\theta>/M)^n$

n depending on flavour charges

- Hierarchical mass structures generated for ALL fermions

$SU(5)$

(i) Assume the family symmetry is combined with $SU(5)$

(ii) Use the GUT structure ONLY to constrain $U(1)$ charges

Under this group we have the following relations:

$$Q_{(q,u^c,e^c)_i} = Q_i^{10}$$
$$Q_{(l,d^c)_i} = Q_i^{\bar{5}}$$
$$Q_{(\nu_R)_i} = Q_i^{\nu_R}$$

- M_{up} symmetric
- $M_{\ell^\pm} = M_{down}^T$
- L lepton mixing $\approx$ R down-quark one

$$Q_{1,2,3} = \bar{E}_{1,2,3} = 3, 2, 0$$
$$\bar{D}_{1,2,3} = L_{1,2,3} = 1, 0, 0$$

SL, Ross

$$\frac{M_u}{m_t} = \begin{pmatrix} \bar\epsilon^6 & \bar\epsilon^5 & \bar\epsilon^3 \\ \bar\epsilon^5 & \bar\epsilon^4 & \bar\epsilon^2 \\ \bar\epsilon^3 & \bar\epsilon^2 & 1 \end{pmatrix}, \frac{M_{down}}{m_b} = \begin{pmatrix} \bar\epsilon^4 & \bar\epsilon^3 & \bar\epsilon^3 \\ \bar\epsilon^3 & \bar\epsilon^2 & \bar\epsilon^2 \\ \bar\epsilon & 1 & 1 \end{pmatrix}$$

$$\frac{M_\ell}{m_\tau} = \begin{pmatrix} \bar\epsilon^4 & \bar\epsilon^3 & \bar\epsilon \\ \bar\epsilon^3 & \bar\epsilon^2 & 1 \\ \bar\epsilon^3 & \bar\epsilon^2 & 1 \end{pmatrix}, m_{eff} \propto \begin{pmatrix} \bar\epsilon^2 & \bar\epsilon & \bar\epsilon \\ \bar\epsilon & 1 & 1 \\ \bar\epsilon & 1 & 1 \end{pmatrix}$$

$SO(10)$

- All L- and R-handed fermions in the 16 of $SO(10)$
- Both MSSM Higgs fields fit in a single 10 of $SO(10)$ $\Downarrow$

For all fermions, *L-R symmetric textures*, similar structure

(different expansion parameters due to Higgs mixing)

Flipped $SU(5)$

$$Q_{(q,d^c,\nu^c)_i} = Q_i^{10}, \quad Q_{(l,u^c)_i} = Q_i^{\bar{5}}, \quad e^c \text{ singlet of } SU(5)$$

- Symmetric M_{down}
- $m_\nu^D = M_{up}^T$

MINIMAL MODIFICATIOS:

Non Universal SO(10)

$$W_{SO(10)} = \lambda_{ij}^{u} 16_i 10^u 16_j + \lambda_{ij}^{d} 16_i 10^d 16_j$$

$$Q_L, D, U, L, E, N \subseteq 16$$

$$H_u \subset 10^u ; H_u \subset 10^u$$

The soft term masses are taken at GUT as:

$$m_{16} = m_0 ; m_u = x_u m_0 ; m_d = x_d m_0 ;$$

Equivalent to NUHM

Trilinear terms:

$$A_0 = a_0 m_0$$

Non Universal SU(5)

$$W_{SU(5)} = Y_u^{ij} 10_i 10_j 5^u + Y_d^{ij} 10_i \bar{5}_j \bar{5}^d$$

$$(Q_L, U, E) \subseteq 10$$

$$H_u \subset 5^u ; H_d \subset \bar{5}^d$$

$$(D, L) \subseteq \bar{5}$$

The soft terms are taken at GUT as:

$$m_{10} = m_0 ;$$
$$m_5 = x_5 \cdot m_{10} ;$$
$$m_u = x_u \cdot m_{10} ;$$
$$m_d = x_d \cdot m_{10.}$$

$$A_{10,5} = a_0 \cdot m_{0,}$$

Okada, Shafi, Raza

Phys.Rev. D90 (2014)

Flipped SU(5) - versus SU(5)

SU(5) $(Q, u^c, e^c)_i \in \mathbf{10}_i\,,\ (L, d^c)_i \in \bar{\mathbf{5}}_i\,,\ \nu_i^c \in \mathbf{1}_i\,.$

Flipped SU(5) $(Q, d^c, \nu^c)_i \in \mathbf{10}_i\,,\ (L, u^c)_i \in \bar{\mathbf{5}}_i\,,\ e_i^c \in \mathbf{1}_i\,.$

$$m_{10} = m_0, \quad m_5 = x_5 \cdot m_{10} \quad m_R = x_R \cdot m_{10}$$

$$m_{H_u} = x_u \cdot m_{10} \quad m_{H_d} = x_d \cdot m_{10} ;$$

Different field assignment in representations – different predictions

(i.e. more freedom with stop masses as compared to SO(10), SU(5))

Could have gone even further *(model dependent)*
Flavour symmetries determine soft SUSY terms

$$\mathcal{L}_{m^2} = m_0^2(\phi_1^*\phi_1+\phi_2^*\phi_2+\phi_3^*\phi_3+\left(\frac{\langle\theta\rangle}{M_{\rm fl}}\right)^{q_2-q_1}\phi_1^*\phi_2+\left(\frac{\langle\theta\rangle}{M_{\rm fl}}\right)^{q_3-q_1}\phi_1^*\phi_3+\left(\frac{\langle\theta\rangle}{M_{\rm fl}}\right)^{q_3-q_2}\phi_2^*\phi_3+\text{h.c.}).$$

L-R symmetric

$$\begin{pmatrix} 1 & \tilde{\epsilon}^{|a+2b|} & \tilde{\epsilon}^{|a+b|} \\ \tilde{\epsilon}^{|a+2b|} & 1 & \tilde{\epsilon}^{|b|} \\ \tilde{\epsilon}^{|a+b|} & \tilde{\epsilon}^{|b|} & 1 \end{pmatrix}$$

SU(5)

$$\mathbf{E}_L \sim \begin{pmatrix} 1 & \lambda^2 & \lambda^2 \\ \lambda^2 & 1 & 1 \\ \lambda^2 & 1 & 1 \end{pmatrix} \qquad \mathbf{E}_R \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

$$\begin{aligned} Q_{(q,u^c,e^c)_i} &= Q_i^{10} \\ Q_{(l,d^c)_i} &= Q_i^{\bar{5}} \\ Q_{(\nu_R)_i} &= Q_i^{\nu_R} \end{aligned}$$

$$\frac{M_\ell}{m_\tau} = \begin{pmatrix} \bar{\epsilon}^4 & \bar{\epsilon}^3 & \bar{\epsilon} \\ \bar{\epsilon}^3 & \bar{\epsilon}^2 & 1 \\ \bar{\epsilon}^3 & \bar{\epsilon}^2 & 1 \end{pmatrix}$$

L: (1,0,0)
R: (3,2,0)

Dark Matter –various possibilities

Higgsino χ_1^0:

$$h_f > 0.1, \quad |m_A - 2m_\chi| > 0.1\, m_\chi .$$

$$h_f \equiv |N_{13}|^2 + |N_{14}|^2 ,$$

A/H resonances:

$$|m_A - 2m_\chi| \leq 0.1\, m_\chi .$$

$\tilde{\tau}$ coannihilations:

$$h_f < 0.1, \quad (m_{\tilde{\tau}_1} - m_\chi) \leq 0.1\, m_\chi$$

$\tilde{\tau} - \tilde{\nu}_\tau$ coannihilations:

$$h_f < 0.1, \quad (m_{\tilde{\tau}_1} - m_\chi) \leq 0.1\, m_\chi , \quad (m_{\tilde{\mu}_1} - m_\chi) \leq 0.1\, m_\chi .$$

$\tilde{t}_1$ coannihilations:

$$h_f < 0.15, \quad (m_{\tilde{t}_1} - m_\chi) \leq 0.1\, m_\chi .$$

(refer tp lecture by M. Lindner

Set 1	SO(10)	SU(5)	FSU(5)
$100 \text{ GeV} \leq m_0 \leq 10 \text{ TeV}$	$0 \leq x_u \leq 2$	$0 \leq x_u \leq 2$	$0 \leq x_u \leq 2$
$50 \text{ GeV} \leq m_{1/2} \leq 10 \text{ TeV}$	$0 \leq x_d \leq 2$	$0 \leq x_d \leq 2$	$0 \leq x_d \leq 2$
$-10 \text{ TeV} \leq A_0 \leq 10 \text{ TeV}$		$0 \leq x_5 \leq 2$	$0 \leq x_5 \leq 2$
$2 \leq \tan\beta \leq 65$			$0 \leq x_R \leq 2$
Set 2	SO(10)	SU(5)	FSU(5)
$100 \text{ GeV} \leq m_0 \leq 2500 \text{ GeV}$	$0 \leq x_u \leq 1$	$0 \leq x_u \leq 1$	$0 \leq x_u \leq 1$
$50 \text{ GeV} \leq m_{1/2} \leq 2500 \text{ GeV}$	$0 \leq x_d \leq 2$	$0 \leq x_d \leq 2$	$0 \leq x_d \leq 2$
$-10 \text{ TeV} \leq A_0 \leq 10 \text{ TeV}$		$0 \leq x_5 \leq 2$	$0 \leq x_5 \leq 1$
$2 \leq \tan\beta \leq 65$			$1 \leq x_R \leq 2$

Parameter space scans with 2 sets:

Set 1 is broader, up to 10 TeV

Combined data accommodated easier with a heavy spectrum and Higgsino LSP

Set 2 zooms to the lower mass spectrum where co-annihilations are expected

Complex computations:

→ SUSY SEARCH: SuperBayeS, MultiNest

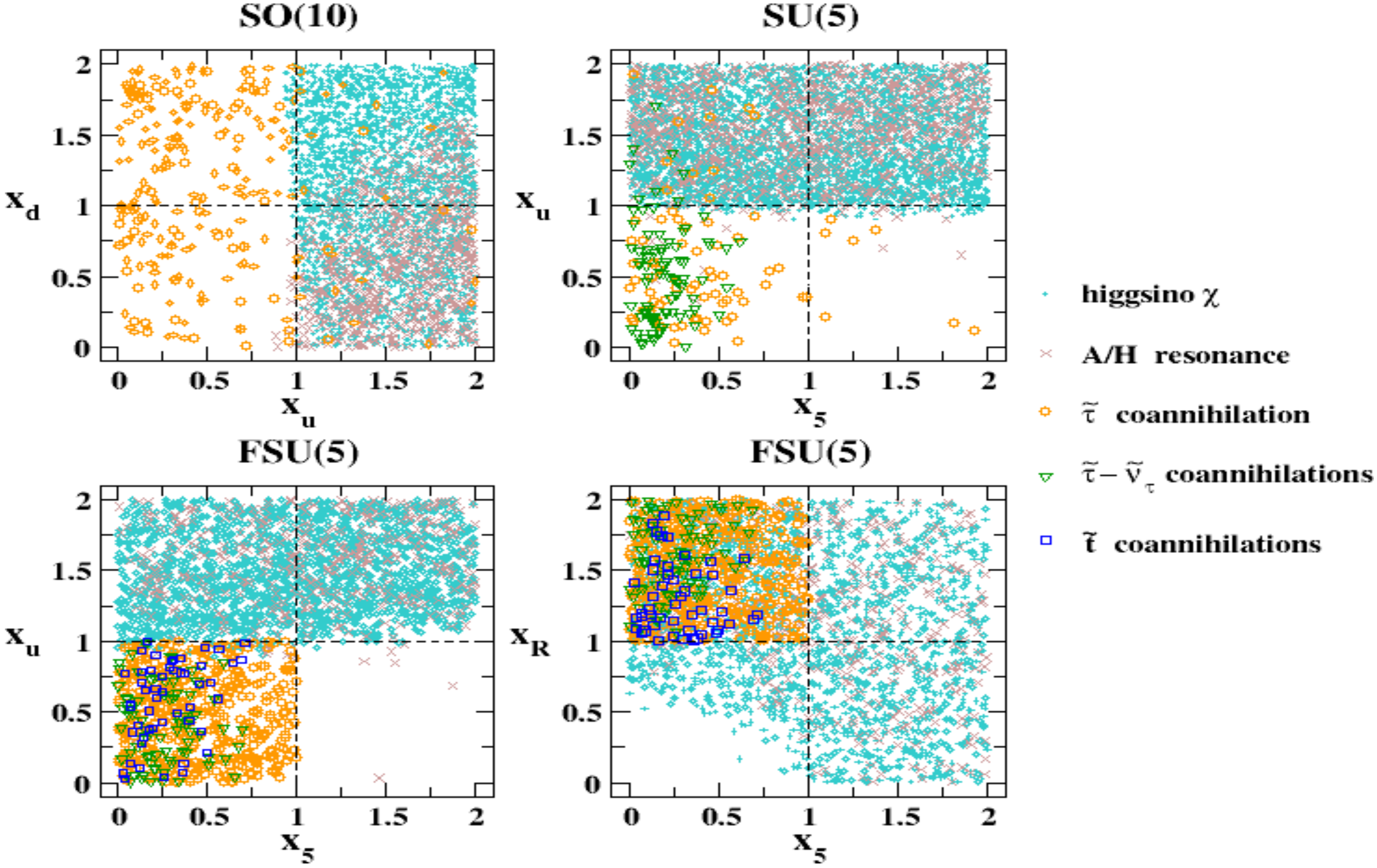
→ RGE's: SoftSusy

→ Relic Density: MicroOMEGAs

→ Direct DM detection: DarkSUSY

→ SusyBSG: B-Physics.

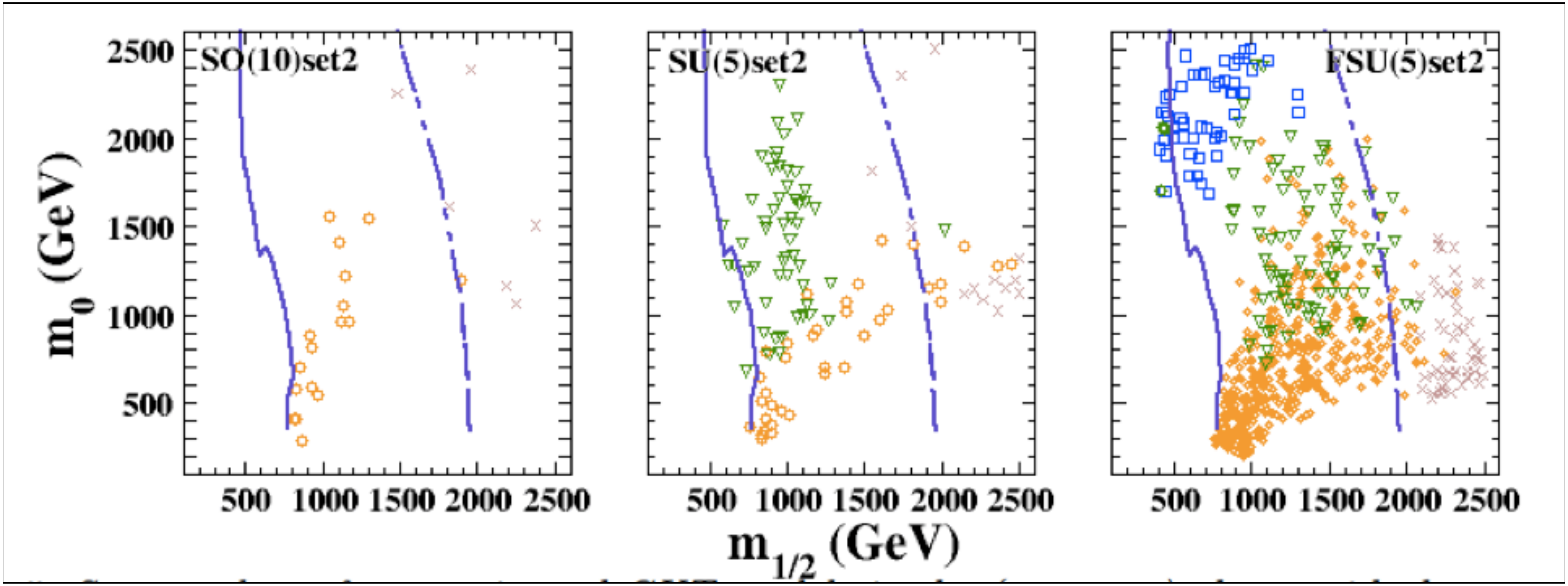
try to quantify some relatively expected results



Correlations between the non-universal soft scalar masses
and DM in different SUSY GUTS (set 1)

(CMSSM fpr xu,d,5,R = 1 / too restrictive)

Soft parameter correlations



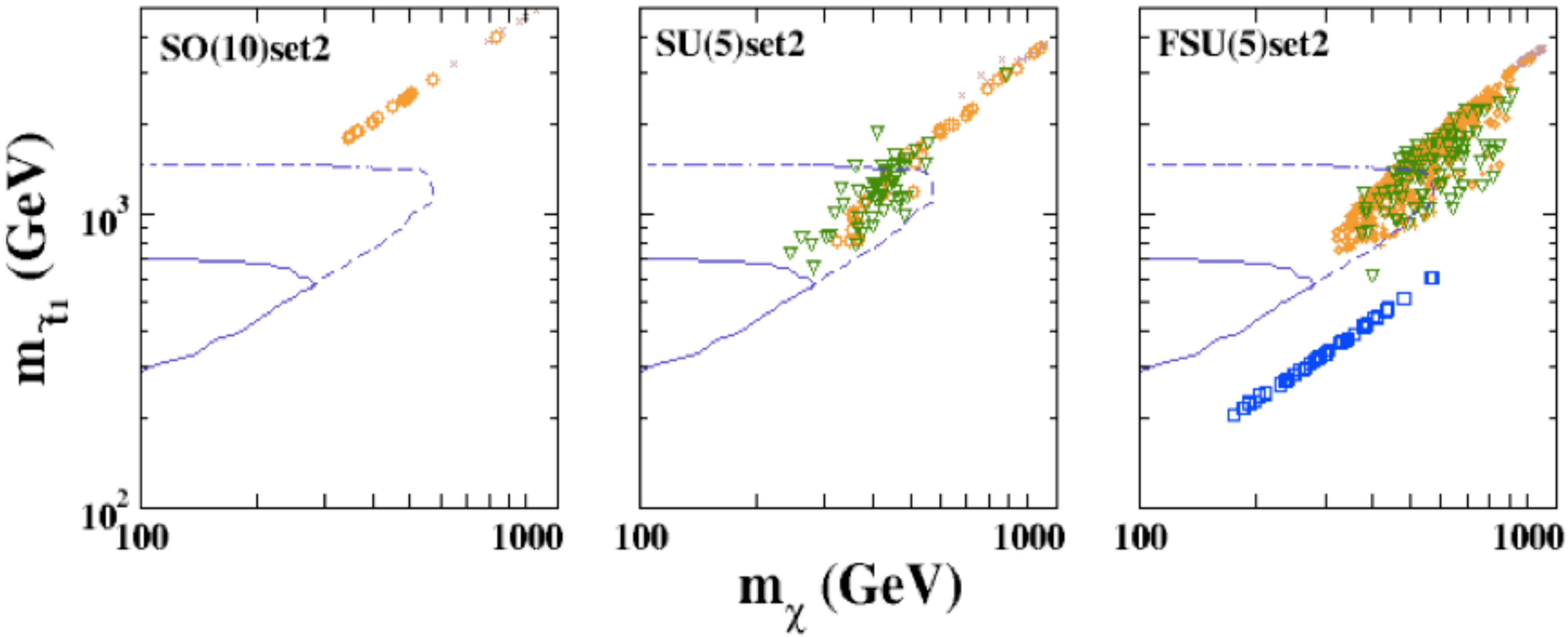
SO(10) very restrictive

SU(5) – significant enhancement of solutions

F-SU(5) many solutions / also allows stop coannihilations

Projected exclusion sensitivity to cover most of the parameter space

Sparticle correlations



SO(10), SU(5): stop mass mostly > 800 GeV

(pres. limits from stop->top neutralinonot yet there)

F-SU(5) stop-coannihilations possible for significantly lighter stop

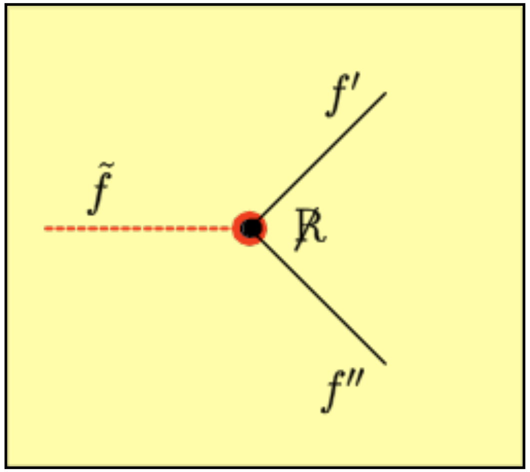
(not excluded directly / but part excluded indirectly by other mass bounds – see remaining sparticle correlation plots in JCAP 1603 (2016) no. 03)

For completeness: Some comments on R-violating SUSY

In addition to couplings generating fermion masses,

$$h_{ij} L_i H_1 \bar{E}_j \qquad h'_{ij} Q_i H_1 \bar{D}_j \qquad h''_{ij} Q_i H_2 \bar{U}_j$$

Also $\lambda_{ijk} L_i L_j \bar{E}_k \qquad \lambda'_{ijk} L_i Q_j \bar{D}_k \qquad \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$



VERY RICH FLAVOUR STRUCTURE

45 couplings *violating lepton or baryon number*

X Previous discussion: killed all couplings via R-parity *(Fayet)*
(SM: +1 , SUSY: -1) thus avoiding fast proton decay OR

✓ Can also allow subsets by baryon / lepton parities *(i.e. Ibanez, Ross)*
LSP: unstable *– lose (?) a dark matter candidate*
Colliders: Multi-lepton/jet events instead of missing energy
Single sparticle productions possible

Both possibilities open from theoretical point of view
(several viable models have been constructed)

Predictions for R-violating operators in different GUTS:

What type of processes favoured in different groups?

(proceed similarly to discussion for fermion mass terms)

L-R symmetric – SO(10):

similar LLE,LQD,UDD (only generation matters)

- Bounds on products of couplings, due to correlations, translated to individual bounds /very restrictive [Ellis, SL, Ross]

-1 coupling dominance disfavoured

- Single sparticle productions disfavoured over MSSM ones, with RPV decays

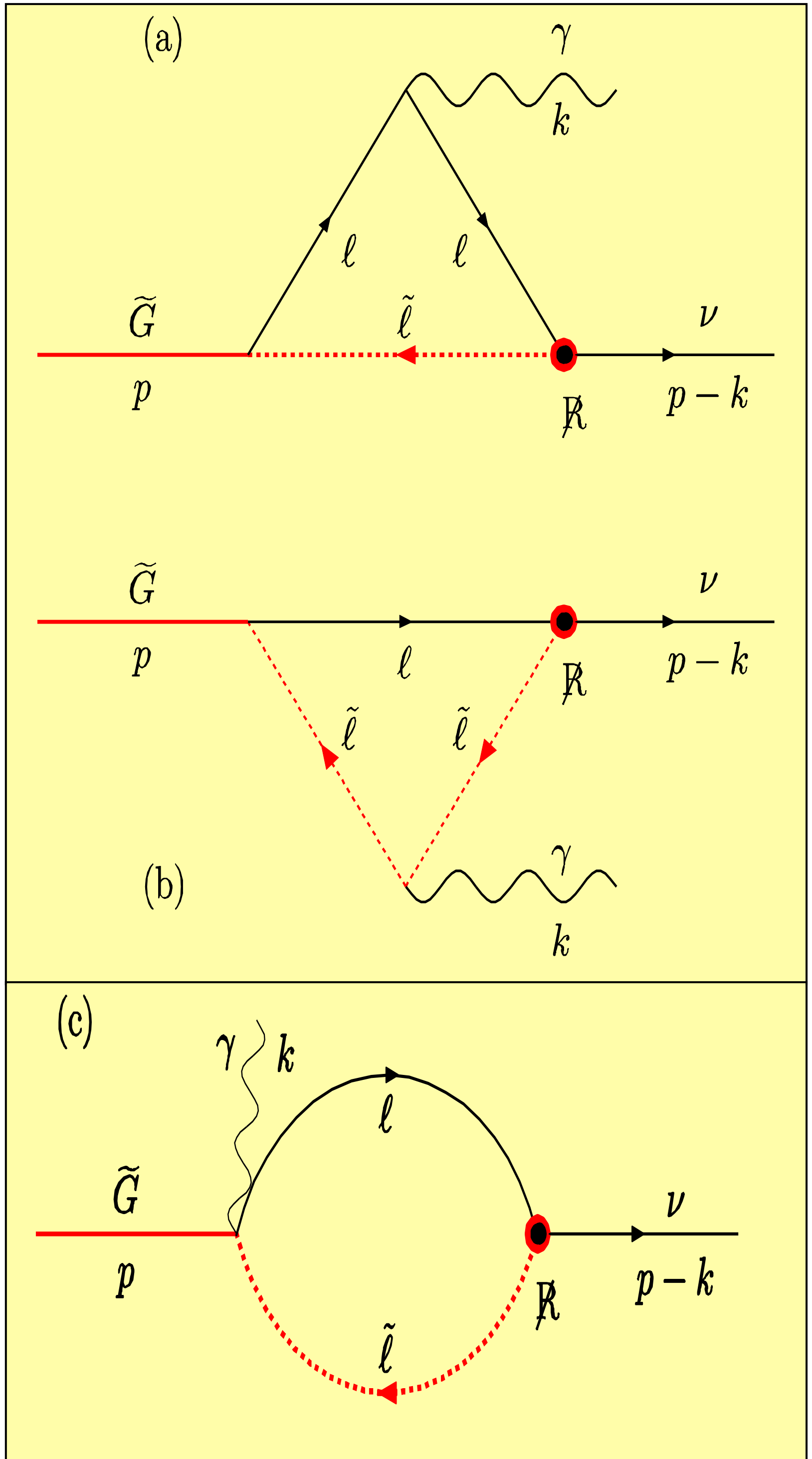
SU(5) – with U(1) charges chosen to match lepton data

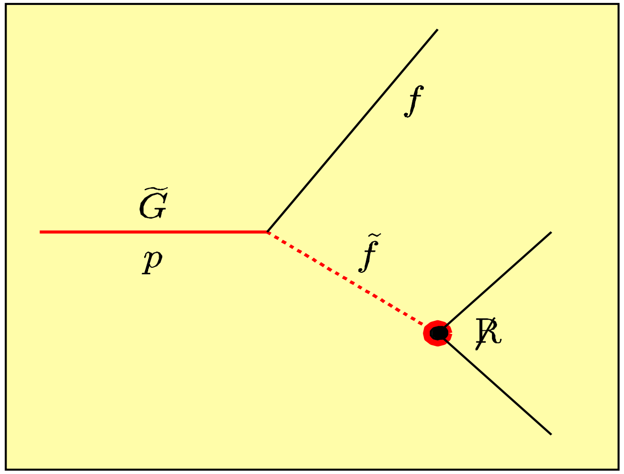
Very different expected correlations
Larger hierarchies and dominance of fewer couplings
Single sparticle productions better accommodated

Neutralinos-charginos couple to all 45 operators, thus are ideal channels to study simultaneously all hierarchies
[Bomark, Choudhury, Kvellestad, SL, Osland, Raklev]

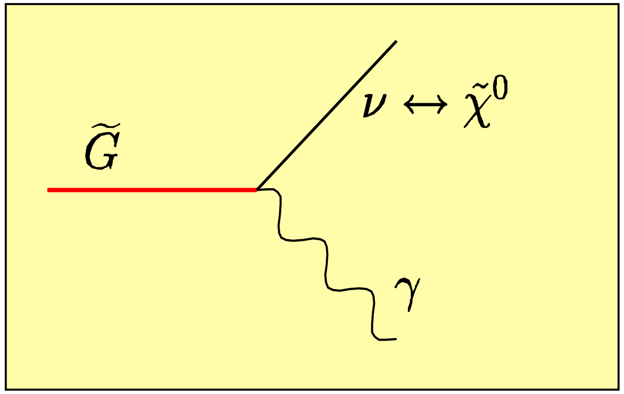
Gravitino Dark matter a viable possibility
RPV decays can be very suppressed

[SL, P. Osland, A. Raklev]





[Chemtob, Moreau]



[Takayama, Yamaguchi]
[Buchmuler, Covi, Hamaguchi, Ibarra, Yanagida]

Suppressed by:

- *Gravitino vertex (~1/Mp)*
- *Phase space (light gravitino)*
- *Loop factors (~ fermion mass)*
- *Neutrino- neutralino mixing*

Conclusions

- We identified different patterns of soft SUSY-breaking terms at the GUT scale, compatible with DM predictions and LHC spectra
- The models predict different spectra for the same LSP mass, connecting possible future observations with the structure of the underlying unified theory.
- In particular, SO(10), SU(5) and flipped SU(5) lead to very different predictions, and thus are distinguishable in future searches.
- Flipped SU(5) predicts stop-χi coannihilations that are absent in the other groups and can be explored by LHC searches.
- Equally interesting possibilities for DM and the LHC exist within the framework of R-violating SUSY