Supersymmetric Dark Matter

From Historical Foundations to Future Challenges

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Conference in memory of Veniamin Sergeyevich Berezinsky

GSSI, L'Aquila − October 2, 2024

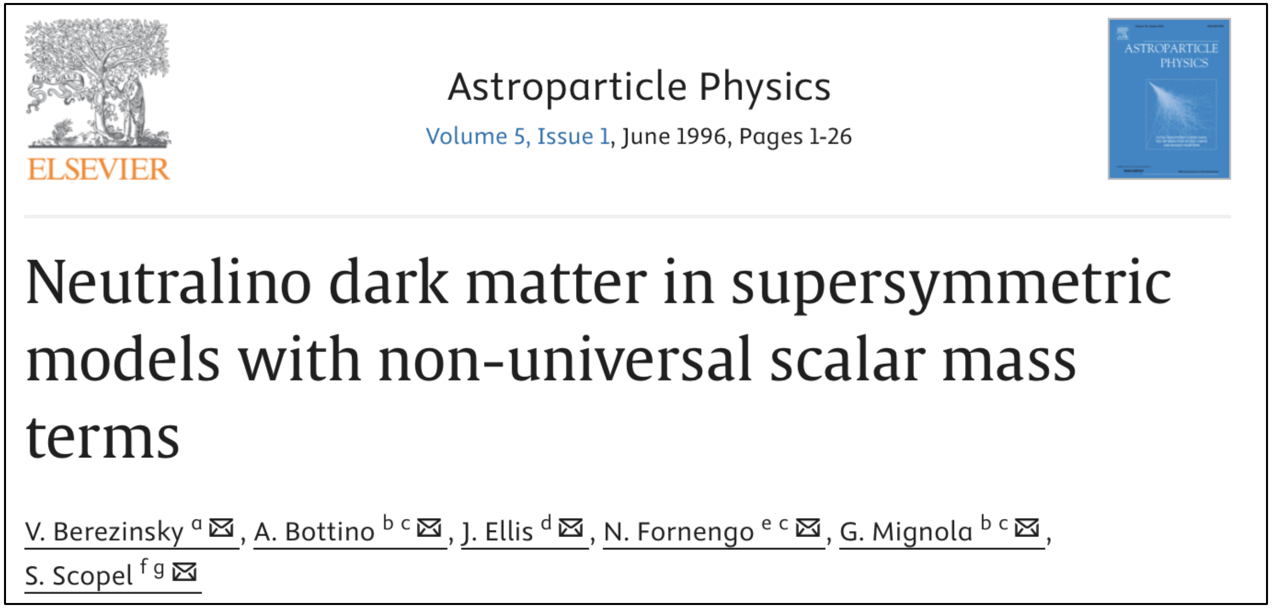
Supersymmetry

- Profound symmetry between fermions and bosons
- Extends spacetime symmetries
- Its local version contains a link to Gravity (SUGRA)
- Requires the introduction of new particles (superpartners + extended Higgs sector)
- Unfortunately, is broken

Dark Matter

- Overwhelming evidence
  - Rotational curves of spiral galaxies
  - Galaxy clusters dynamics
  - Gravitational lensing
  - Hydrodynamical equilibrium of hot gas in galaxy clusters
  - Large scale structure of the Universe
  - Energy budget of the Universe
  - Structure formation
- However: DM evidence is purely gravitational
- A new particle?

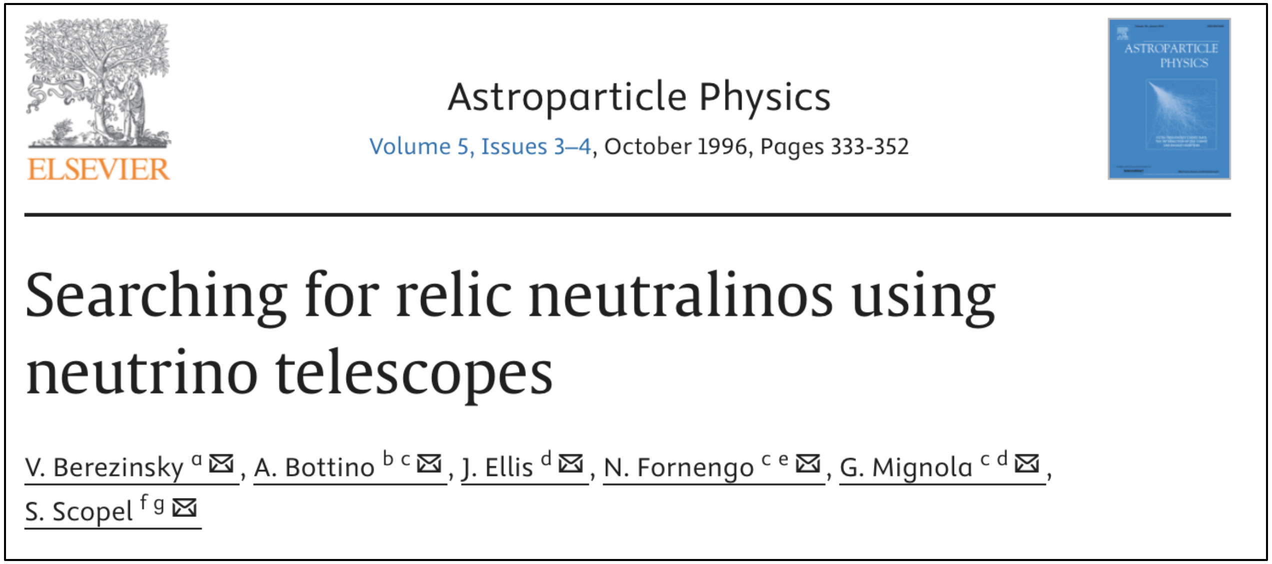
A mutual opportunity?



Astroparticle Physics
Volume 5, Issue 1, June 1996, Pages 1-26

Neutralino dark matter in supersymmetric models with non-universal scalar mass terms

V. Berezinsky [a] ✉, A. Bottino [b] [c] ✉, J. Ellis [d] ✉, N. Fornengo [e] [c] ✉, G. Mignola [b] [c] ✉, S. Scopel [f] [g] ✉



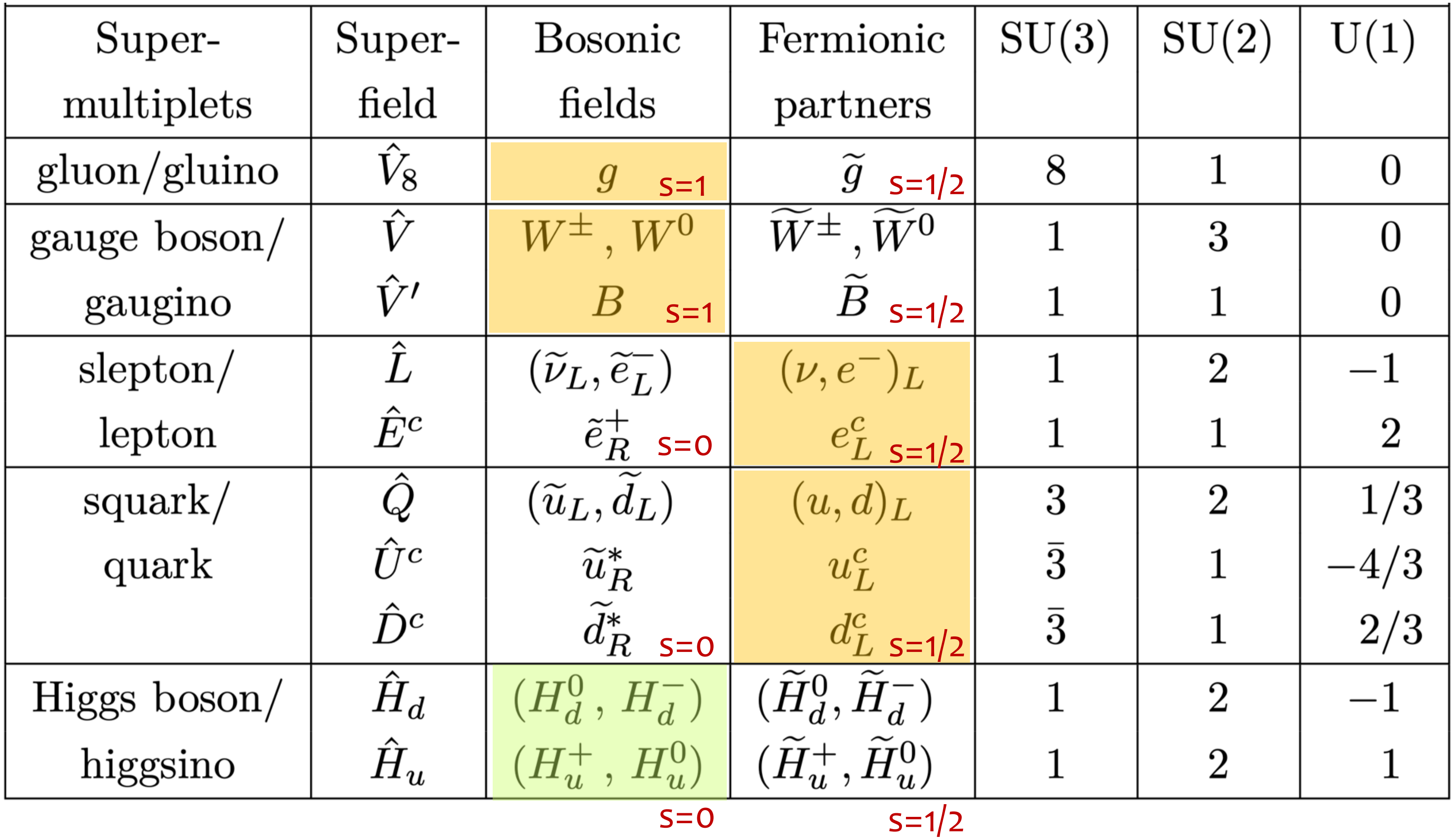
Astroparticle Physics
Volume 5, Issues 3–4, October 1996, Pages 333-352

Searching for relic neutralinos using neutrino telescopes

V. Berezinsky [a] ✉, A. Bottino [b] [c] ✉, J. Ellis [d] ✉, N. Fornengo [c] [e] ✉, G. Mignola [c] [d] ✉, S. Scopel [f] [g] ✉

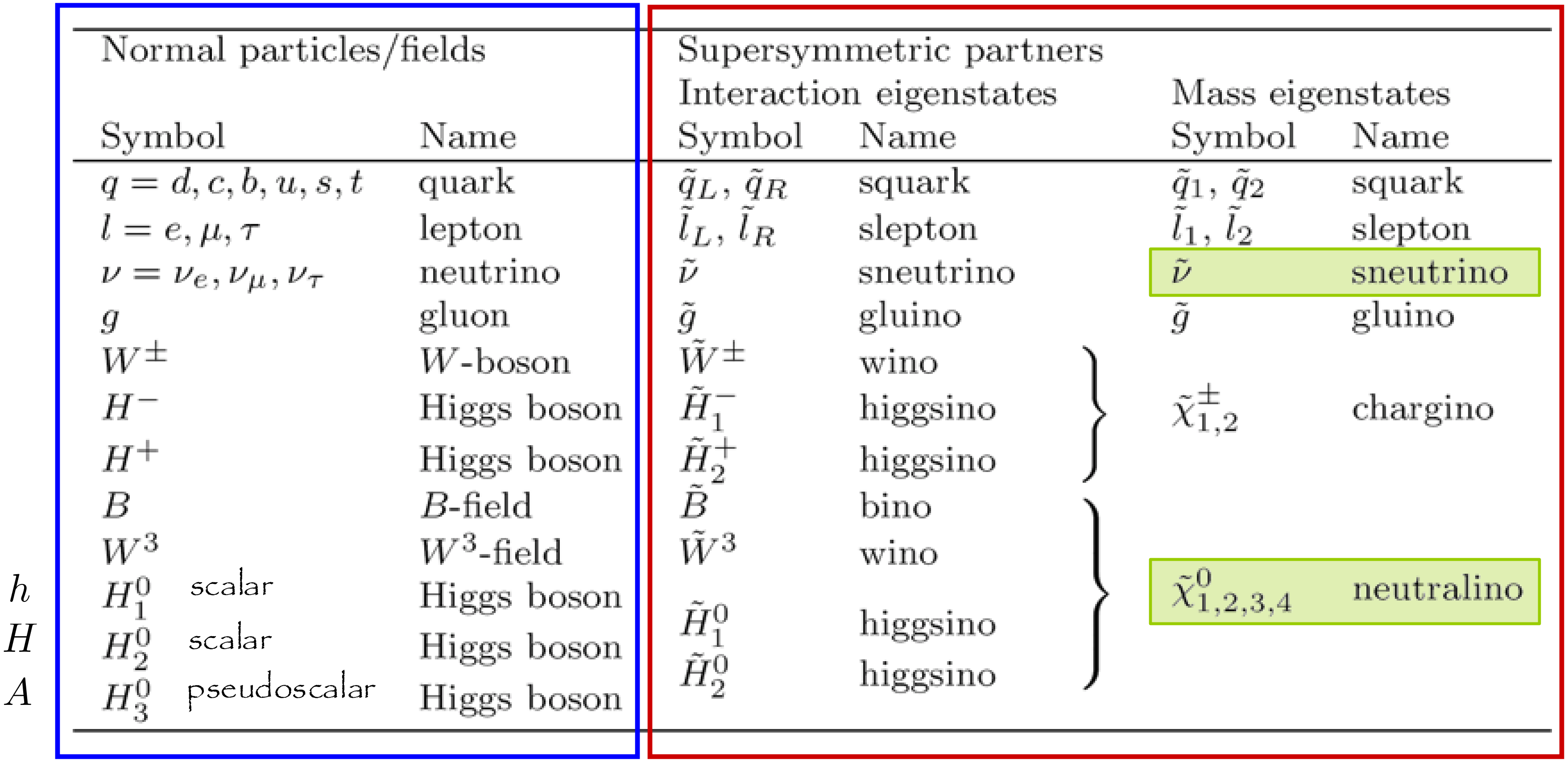
Minimal SUSY extension of the SM

Supersymmetry: Fermions ⟷ Bosons



Super-multiplets	Super-field	Bosonic fields	Fermionic partners	SU(3)	SU(2)	U(1)
gluon/gluino	$\hat{V}_8$	g s=1	$\widetilde{g}$ s=1/2	8	1	0
gauge boson/	$\hat{V}$	$W^\pm , W^0$	$\widetilde{W}^\pm , \widetilde{W}^0$	1	3	0
gaugino	$\hat{V}'$	B s=1	$\widetilde{B}$ s=1/2	1	1	0
slepton/	$\hat{L}$	$(\widetilde{\nu}_L, \widetilde{e}^-_L)$	$(\nu, e^-)_L$	1	2	-1
lepton	$\hat{E}^c$	$\widetilde{e}^+_R$ s=0	e^c_L s=1/2	1	1	2
squark/	$\hat{Q}$	$(\widetilde{u}_L, \widetilde{d}_L)$	$(u, d)_L$	3	2	$1/3$
quark	$\hat{U}^c$	$\widetilde{u}^*_R$	u^c_L	$\bar{3}$	1	$-4/3$
	$\hat{D}^c$	$\widetilde{d}^*_R$ s=0	d^c_L s=1/2	$\bar{3}$	1	$2/3$
Higgs boson/	$\hat{H}_d$	(H^0_d , H^-_d)	$(\widetilde{H}^0_d, \widetilde{H}^-_d)$	1	2	-1
higgsino	$\hat{H}_u$	(H^+_u , H^0_u)	$(\widetilde{H}^+_u , \widetilde{H}^0_u)$	1	2	1
		s=0	s=1/2			

Particle content



	Normal particles/fields		Supersymmetric partners			
			Interaction eigenstates		Mass eigenstates	
	Symbol	Name	Symbol	Name	Symbol	Name
	$q = d, c, b, u, s, t$	quark	$\tilde{q}_L, \tilde{q}_R$	squark	$\tilde{q}_1, \tilde{q}_2$	squark
	$l = e, \mu, \tau$	lepton	$\tilde{l}_L, \tilde{l}_R$	slepton	$\tilde{l}_1, \tilde{l}_2$	slepton
	$\nu = \nu_e, \nu_\mu, \nu_\tau$	neutrino	$\tilde{\nu}$	sneutrino	$\tilde{\nu}$	sneutrino
	g	gluon	$\tilde{g}$	gluino	$\tilde{g}$	gluino
	$W^\pm$	W-boson	$\tilde{W}^\pm$	wino	$\tilde{\chi}^\pm_{1,2}$	chargino
	H^-	Higgs boson	$\tilde{H}_1^-$	higgsino		
	H^+	Higgs boson	$\tilde{H}_2^+$	higgsino		
	B	B-field	$\tilde{B}$	bino	$\tilde{\chi}^0_{1,2,3,4}$	neutralino
	W^3	W^3-field	$\tilde{W}^3$	wino		
h	H_1^0 scalar	Higgs boson	$\tilde{H}_1^0$	higgsino		
H	H_2^0 scalar	Higgs boson	$\tilde{H}_2^0$	higgsino		
A	H_3^0 pseudoscalar	Higgs boson				

Neutral SUSY particles: sneutrinos, neutralinos [gravitinos]

Two required ingredients

- Supersymmetry breaking
  - “Super”-particles cannot have the same mass as their SM partners (not observed)
  - Large number of additional parameters (120+)

- R- parity
  - For a generic SUSY models, a sort of (B-L) symmetry need to be enforced to prevent too-fast proton decay

$$R = (-1)^{3(B-L)+2S}$$

  - This implies that the LSP is stable: if neutral, being massive and stable, it can be the DM

$$A + B \longrightarrow \tilde{X} + \tilde{Y}$$

$$\tilde{X} \longrightarrow \tilde{Y} + A + B$$

SUSY DM candidates

- Sneutrinos

$\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau \quad \longrightarrow \quad \tilde{\nu}_1, \tilde{\nu}_2, \tilde{\nu}_3$

The lightest of the three

- Neutralinos

$$\tilde{\gamma}, \tilde{Z}, \tilde{H}_1, \tilde{H}_2 \quad \longrightarrow \quad \chi_i = a_{1_i}\tilde{\gamma} + a_{2_i} + a_{3_i}\tilde{H}_1 + a_{4_i}\tilde{H}_2 \quad (i = 1, 2, 3, 4)$$

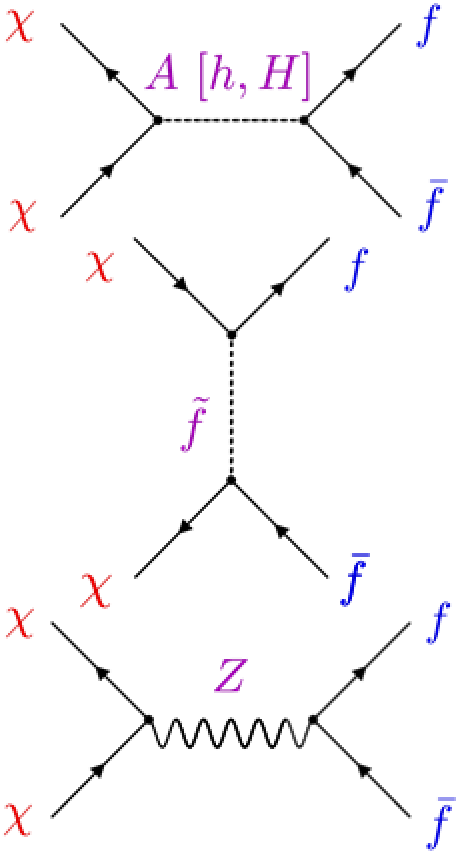
The lightest of the four

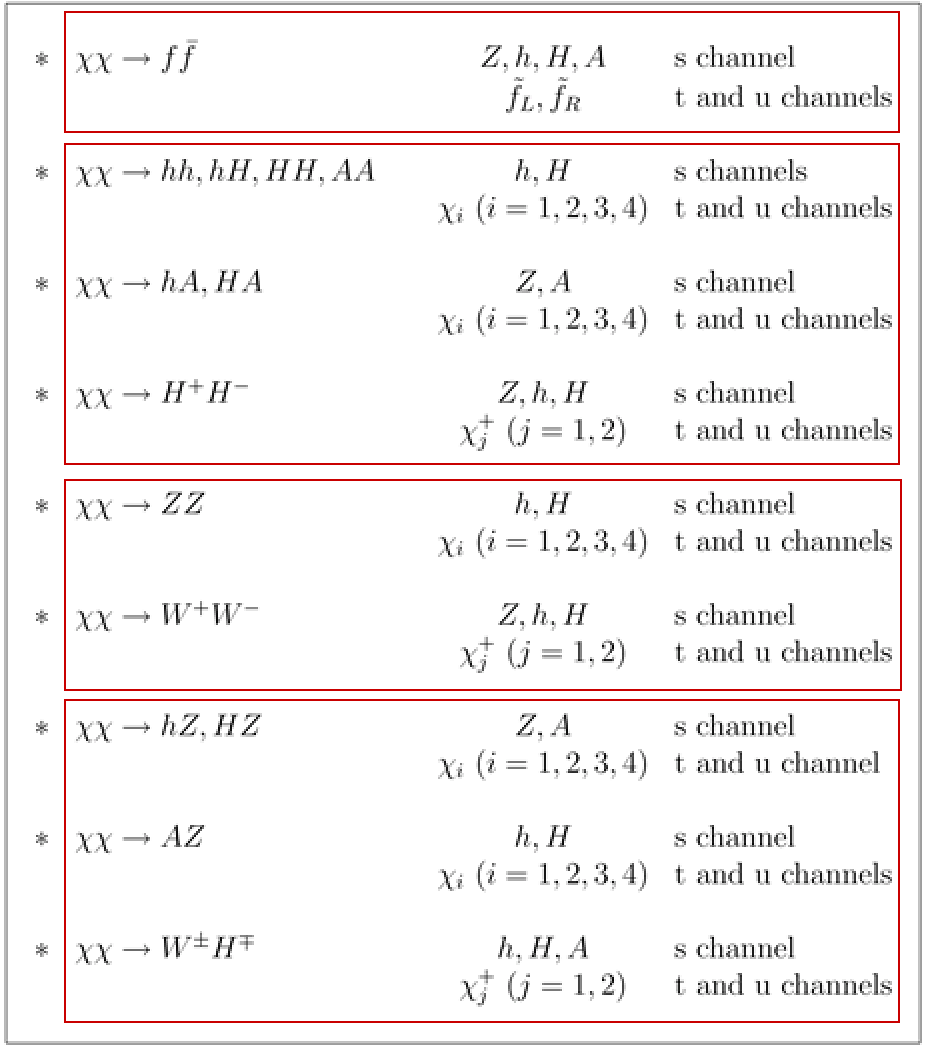
- Gravitino

$\tilde{g}$

Neutralino cosmology

$$\Omega h^2 \sim \langle \sigma_{\rm ann} v \rangle^{-1}$$





*	$\chi\chi \to f\bar{f}$	Z, h, H, A $\tilde{f}_L, \tilde{f}_R$	s channel t and u channels
*	$\chi\chi \to hh, hH, HH, AA$	h, H $\chi_i\ (i = 1,2,3,4)$	s channels t and u channels
*	$\chi\chi \to hA, HA$	Z, A $\chi_i\ (i = 1,2,3,4)$	s channel t and u channels
*	$\chi\chi \to H^+H^-$	Z, h, H $\chi_j^+\ (j = 1,2)$	s channel t and u channels
*	$\chi\chi \to ZZ$	h, H $\chi_i\ (i = 1,2,3,4)$	s channel t and u channels
*	$\chi\chi \to W^+W^-$	Z, h, H $\chi_j^+\ (j = 1,2)$	s channel t and u channels
*	$\chi\chi \to hZ, HZ$	Z, A $\chi_i\ (i = 1,2,3,4)$	s channel t and u channel
*	$\chi\chi \to AZ$	h, H $\chi_i\ (i = 1,2,3,4)$	s channel t and u channels
*	$\chi\chi \to W^\pm H^\mp$	h, H, A $\chi_j^+\ (j = 1,2)$	s channel t and u channels

which one is open depends on the neutralino mass

Higgs sector: 2HDB

$$V_0 = \left(M_{H_1}^2 + \mu^2\right)|H_1|^2 + \left(M_{H_2}^2 + \mu^2\right)|H_2|^2 - B\mu\left(H_1 H_2 + \text{ h.c. }\right)$$
$$+ \text{ quartic D terms.}$$

$$v_u^2 + v_d^2 = (246\,\text{GeV})^2$$
$$\tan\beta = v_u/v_d$$

$$\sin 2\beta = \frac{-2B\mu}{M_{H_1}^2 + M_{H_2}^2 + 2\mu^2}$$
$$M_Z^2 = 2\frac{M_{H_1}^2 - M_{H_2}^2 \tan^2\beta}{\tan^2\beta - 1} - 2\mu^2$$
$$M_A^2 = M_{H_1}^2 + M_{H_2}^2 + 2\mu^2 > 0$$

+ radiative corrections

Parameters:

$\tan\beta$

μ

$M_{H_1}^2$

$M_{H_2}^2$

Soft SUSY breaking

$$
\begin{aligned}
\mathcal{V}_{soft} &= \sum_i m_i^2 \left|\phi_i\right|^2 \\
&+ \left\{ \left[A^l_{ab} h'_{ab} \tilde{L}_a H_1 \tilde{R}_b + A^d_{ab} h^d_{ab} \tilde{Q}_a H_1 \tilde{D}_b + A^u_{ab} h^u_{ab} \tilde{Q}_a H_2 \tilde{U}_b + \text{ h.c. } \right] - B\mu H_1 H_2 + \text{ h.c. } \right\} \\
&+ \sum_i M_i \left(\lambda_i \lambda_i + \bar{\lambda}_i \bar{\lambda}_i \right)
\end{aligned}
$$

Parameters:

m_i	Scalar masses
M_i	Gaugino masses
A_{ab}	Trilinear couplings

SUSY Frameworks

- The number of free parameters is exceedingly large (124)

- Effective MSSM: a bunch of relevant phenomenological parameters are taken as independent at the EW scale

- SUGRA-inspired models: EW-scale parameters are obtained through RGE-evolution from a very limited set of parameters defined at the GUT or Planck scale. RGE-evolutions determines EWSB and all the low-energy phenomenology

mSUGRA/CMSSM

- High-scale parameters unification

$M_i(M_{GUT}) = m_{1/2}$

At low-energy, implies

$M_1 : M_2 : M_2 = \alpha_1 : \alpha_2 : \alpha_3$

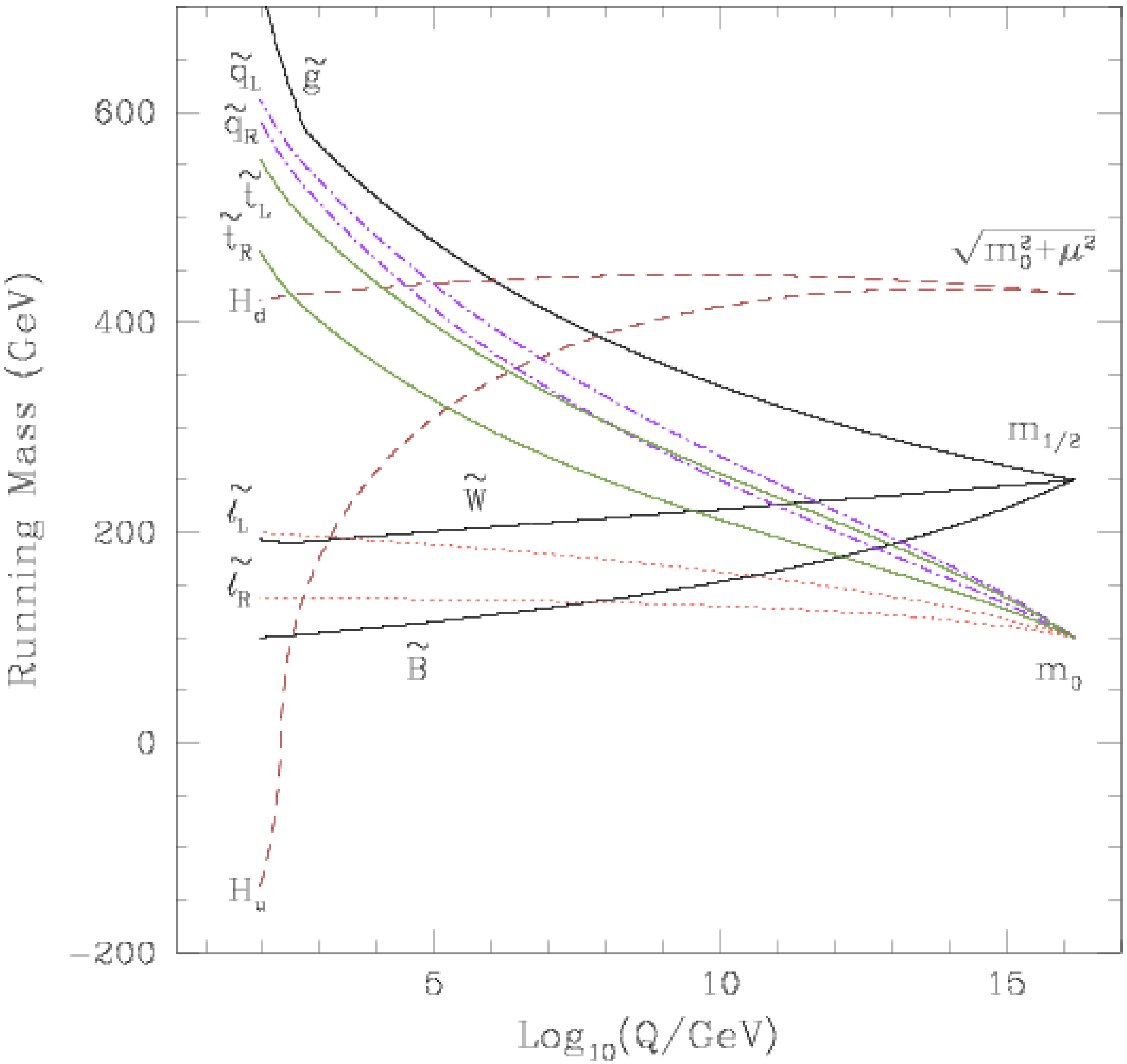
$$M^2_{H_1}(M_{GUT}) = M^2_{H_2}(M_{GUT}) = m_0^2$$
$$M^2_{\widetilde{L}}(M_{GUT}) = M^2_{\widetilde{E}}(M_{GUT}) = m_0^2\mathbf{1}$$
$$M^2_{\widetilde{Q}}(M_{GUT}) = M^2_{\widetilde{U}}(M_{GUT}) = M^2_{\widetilde{D}}(M_{GUT}) = m_0^2\mathbf{1}$$
$$A_U(M_{GUT}) = A_D(M_{GUT}) = A_E(M_{GUT}) = A_0\mathbf{1}$$

- Low-energy parameters

$|\mu|$

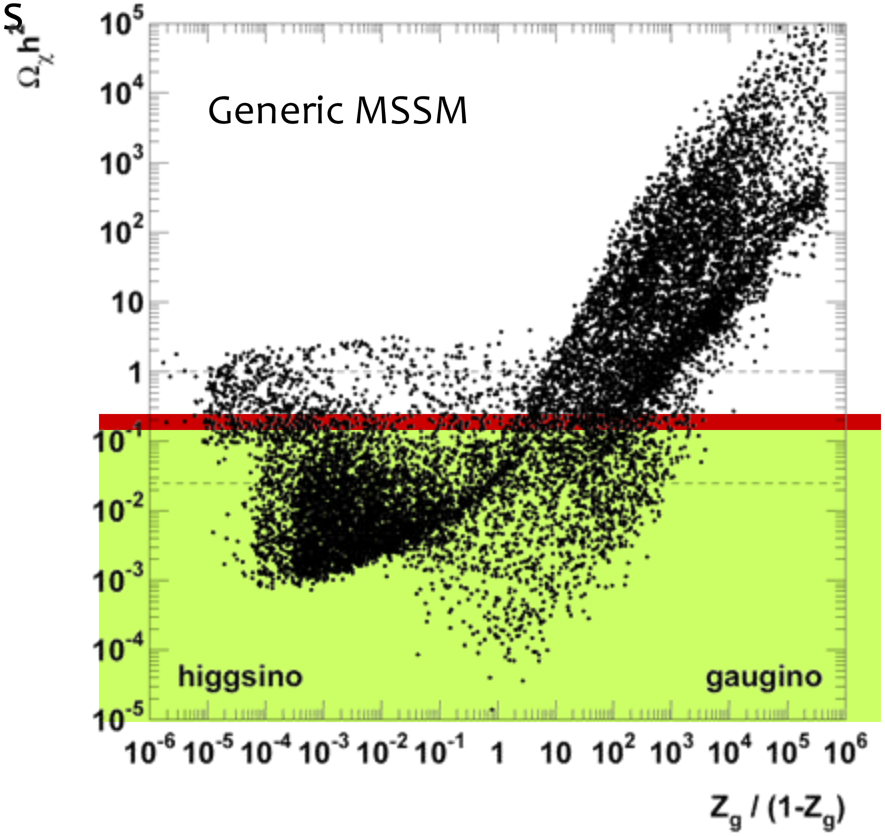
$\tan\beta$

RGE evolution



The most popular: mSUGRA/CMSSM

- Consequences for neutralino DM:
  - Neutralino is mostly a gaugino
  - Exceedingly large relic abundance
  - Suppressed DM detection rates



Caveats on mass universality

- Strict unification of mass parameters at the GUT scale (universality) is not at the same level of motivation as gauge coupling unification
- Threshold effects or evolution from Planck/string scale to the GUT scale can easily spoil mass universality

- Non-universality can alter neutralino DM phenomenology quite significantly through:
  - Change in the low-energy Higgs phenomenology (Higgs masses and couplings to matter and DM)
  - Change in the low-scale neutralino characteristics (flip from pure gaugino to a gagino-higgsino mix)

Papers with Venya

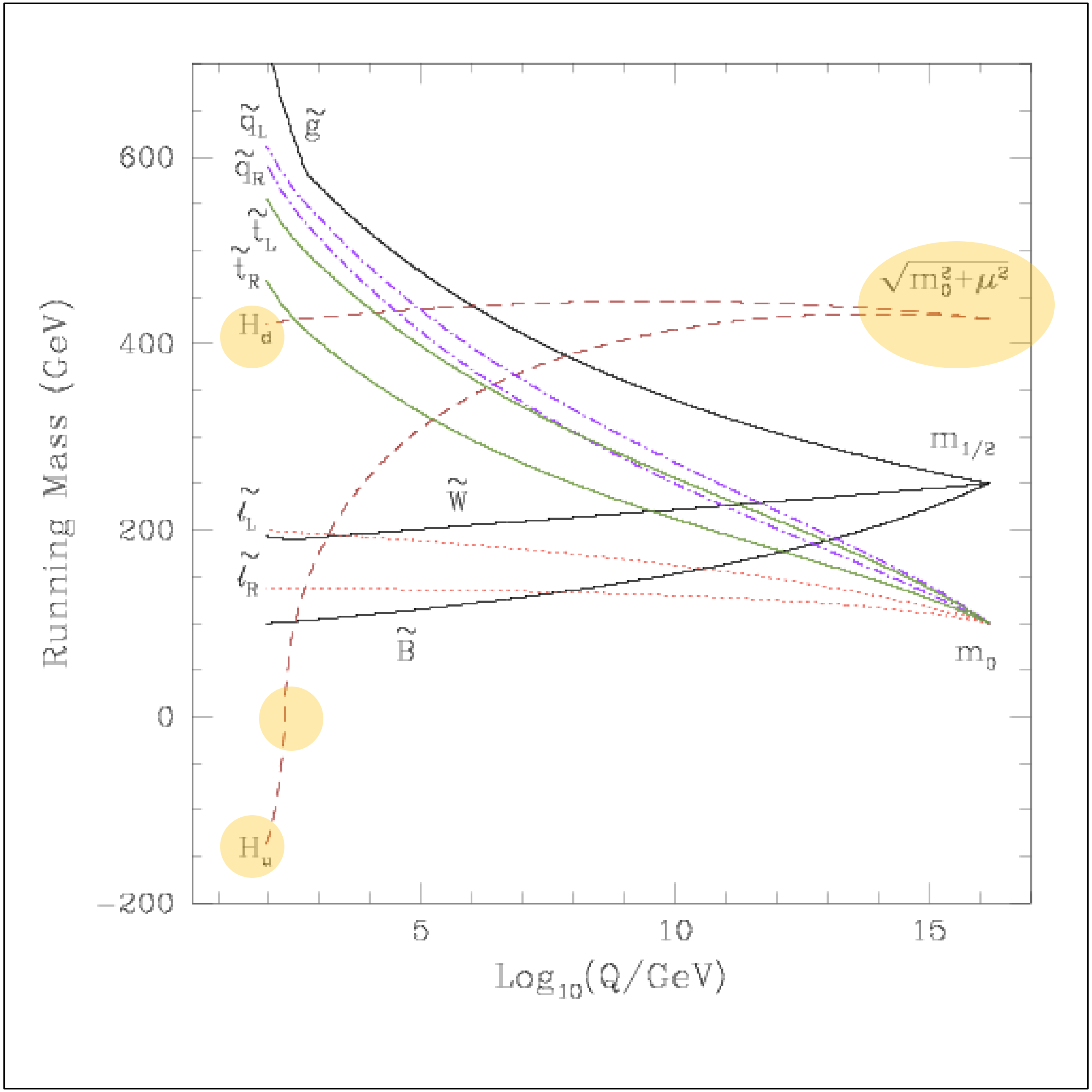
Non-universal-Higgs models

$$M^2_{H_i}\left(M_{GUT}\right) = m^2_0\left(1+\delta_i\right)$$

Split in the Higgs soft masses, while maintaining universality if the sleptons and squark sectors, as well as in the gaugino sector

This adds only 2 parameters to the model, but changes significantly the phenomenology, even with moderate non-universality, at the level of a few percent change

RGE evolution



Higgs sector

RGE evolution can be summarized in a dependence of the low energy parameters from the GUT-scale ones:

$$M_{H_i}^2 = a_i m_{1/2}^2 + b_i m_0^2 + c_i A_0^2 m_0^2 + d_i A_0 m_0 m_{1/2}$$

$$\mu^2 = J_1 m_{1/2}^2 + J_2 m_0^2 + J_3 A_0^2 m_0^2 + J_4 A_0 m_0 m_{1/2} - \frac{M_Z^2}{2}$$

$$M_A^2 = K_1 m_{1/2}^2 + K_2 m_0^2 + K_3 A_0^2 m_0^2 + K_4 A_0 m_0 m_{1/2} - M_Z^2$$

Higgs sector

Let's simplify and take A_0 = 0

$$M^2_{H_i} = a_i m^2_{1/2} + b_i m^2_0$$

$$\mu^2 = J_1 m^2_{1/2} + J_2 m^2_0 \qquad\qquad - \frac{M^2_Z}{2}$$

$$M^2_A = K_1 m^2_{1/2} + K_2 m^2_0 \qquad\qquad - M^2_Z$$

These parameters in front of m_0 acquire dependence from the non-universality parameters delta and alter the low-energy Higgs phenomenology, including EWSB.

In particular, the can lower the A-higgs mass (relevant for neutralino relic abundance and detections rates) and the mu-parameter (relevant also for gaugino/higgsino mixing)

Neutralino sector

gaugino

$$M_N \equiv \begin{pmatrix} M_1 & 0 & -\frac{1}{2}g'v_d & \frac{1}{2}g'v_u \\ 0 & M_2 & \frac{1}{2}gv_d & -\frac{1}{2}gv_u \\ -\frac{1}{2}g'v_d & \frac{1}{2}gv_d & 0 & -\mu \\ \frac{1}{2}g'v_u & -\frac{1}{2}gv_u & -\mu & 0 \end{pmatrix}$$

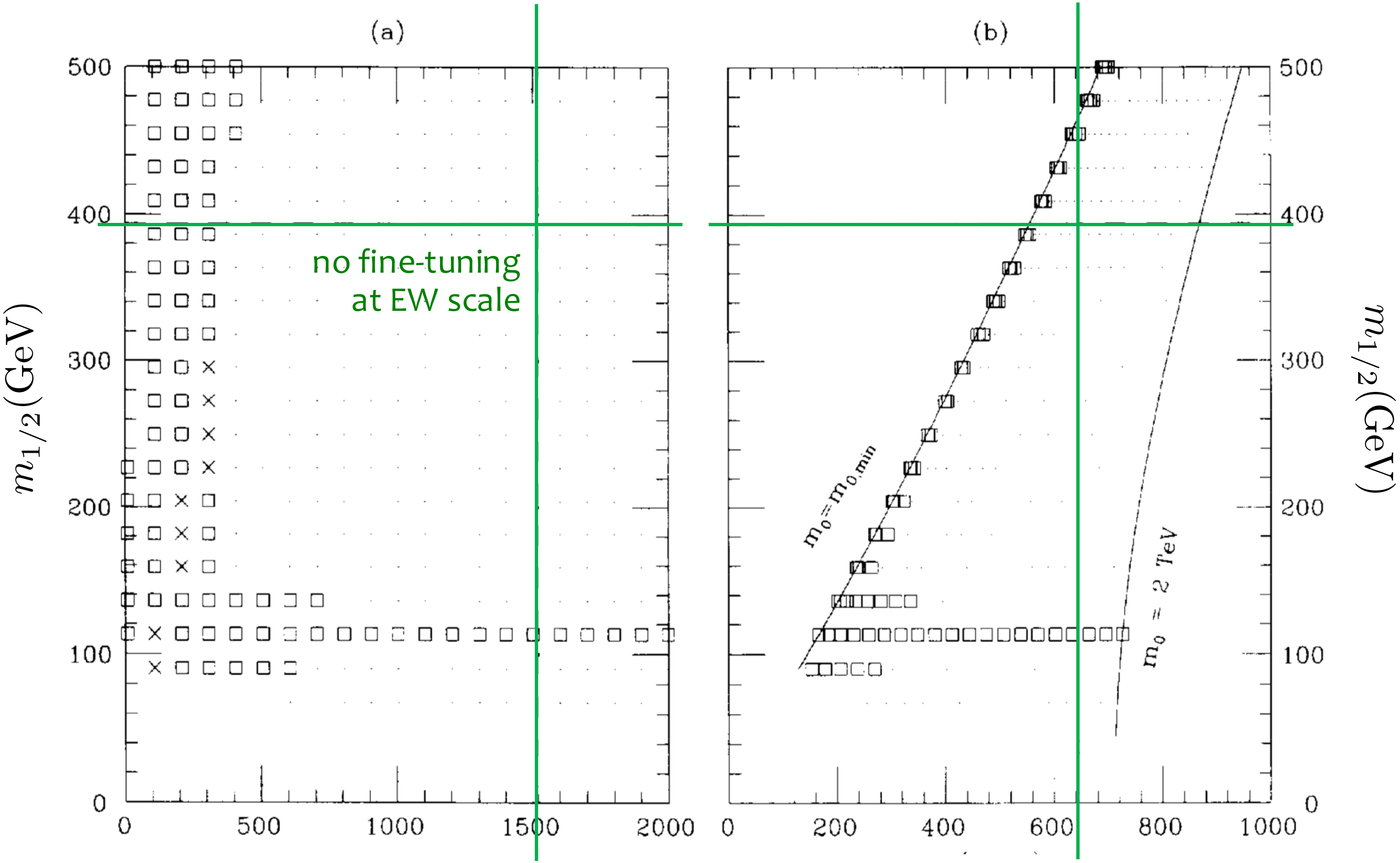
higgsino

With gaugino-mass unification:

$$M_1 : M_2 : M_3 = \alpha_1 : \alpha_2 : \alpha_3$$

$$M_1 = \frac{5}{3}\tan^2\theta_W M_2 \simeq 0.5 M_2$$

mSUGRA/CMSSM



$$\tan\beta = 8; \quad \delta_1 = 0; \quad \delta_2 = 0$$

No fine-tuning

The EW scale is obtained without excessive level of cancellations

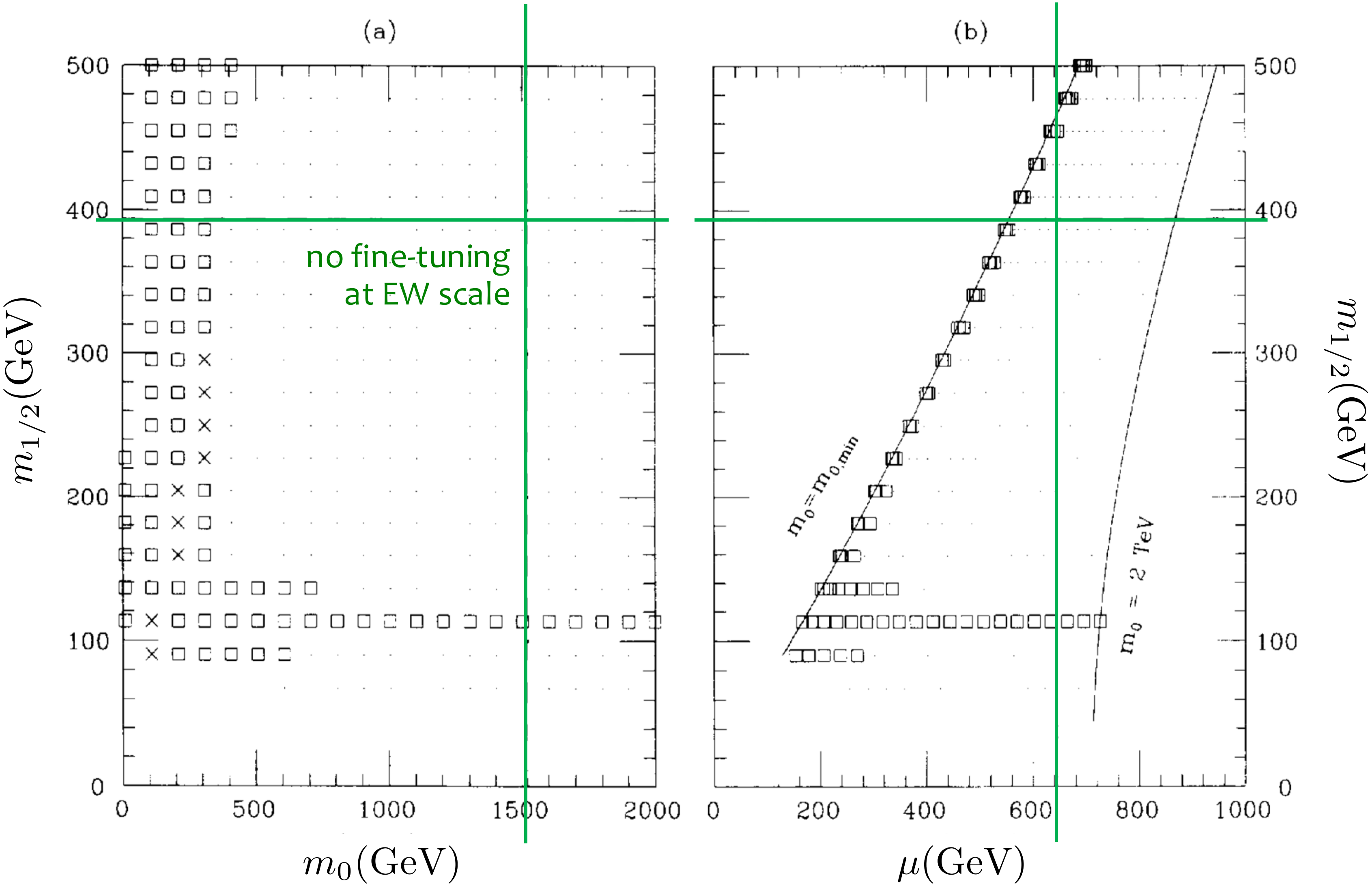
$$M_Z^2 = 2\left(J_1 m_{1/2}^2 + J_2 m_0^2 + J_3 A_0^2 m_0^2 + J_4 A_0 m_0 m_{1/2} - \mu^2\right)$$

$$\left|\frac{\Delta M_Z^2}{M_Z^2}\right| < \eta_f \left|\frac{\Delta x_i^2}{x_i^2}\right|$$

For A0 = 0

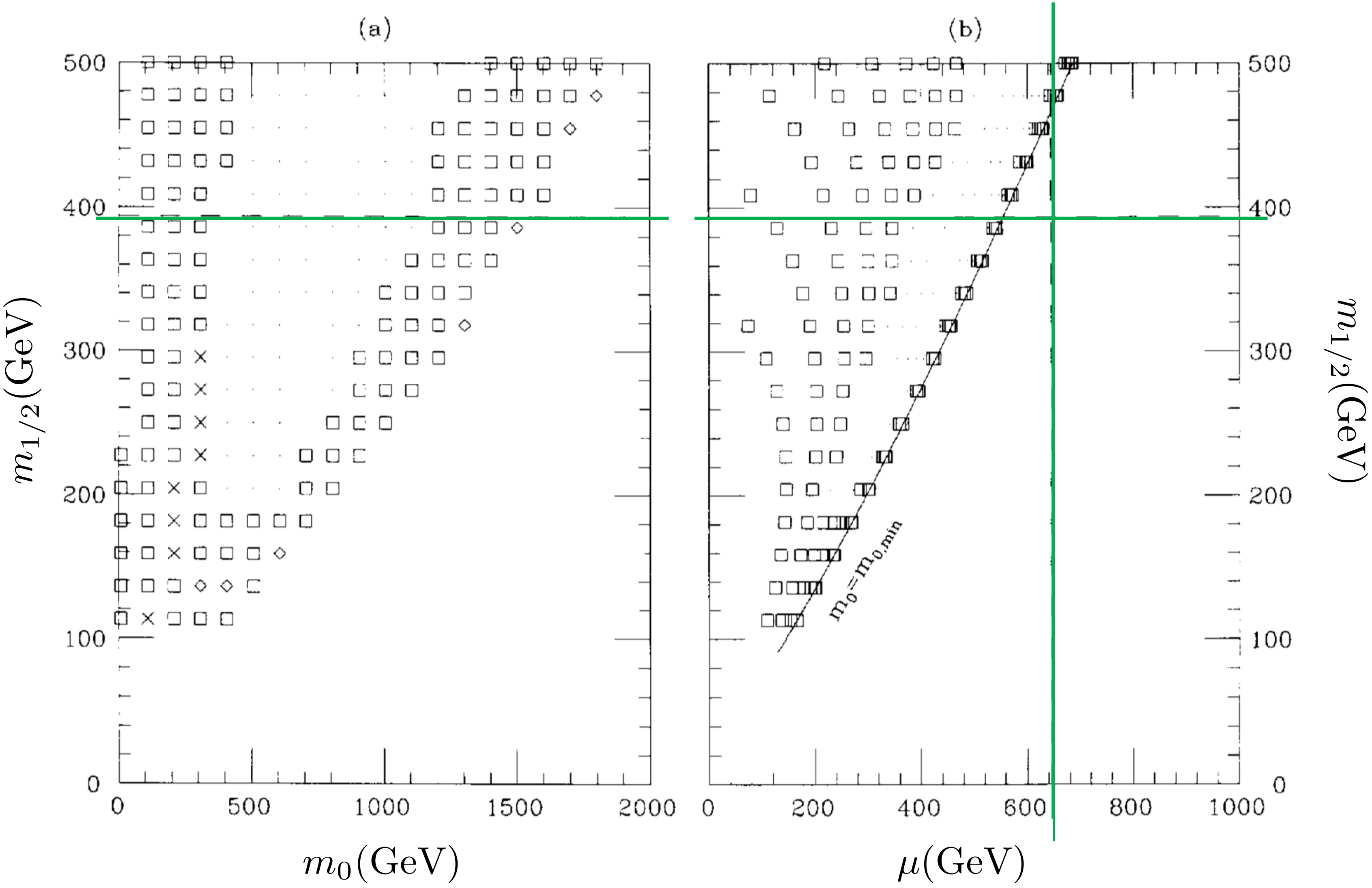
$$m_{1/2}^2 < \frac{\eta_f}{2\,|J_1|} M_Z^2, \quad m_0^2 < \frac{\eta_f}{2\,|J_2|} M_Z^2, \quad \mu^2 < \frac{\eta_f}{2} M_Z^2 \simeq (640\mathrm{GeV})^2$$

mSUGRA/CMSSM



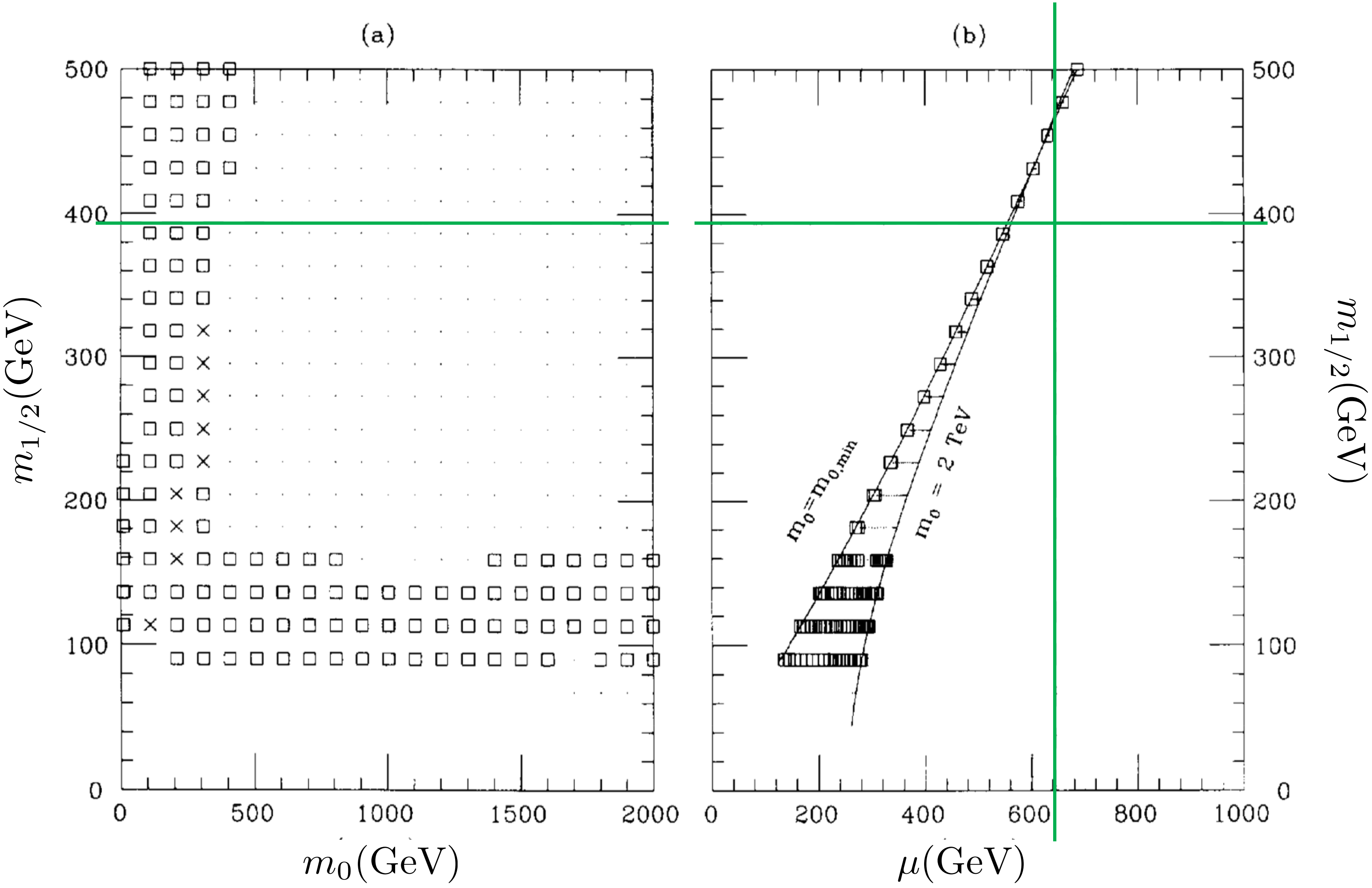
$$\tan\beta = 8; \quad \delta_1 = 0; \quad \delta_2 = 0$$

Non-universal model



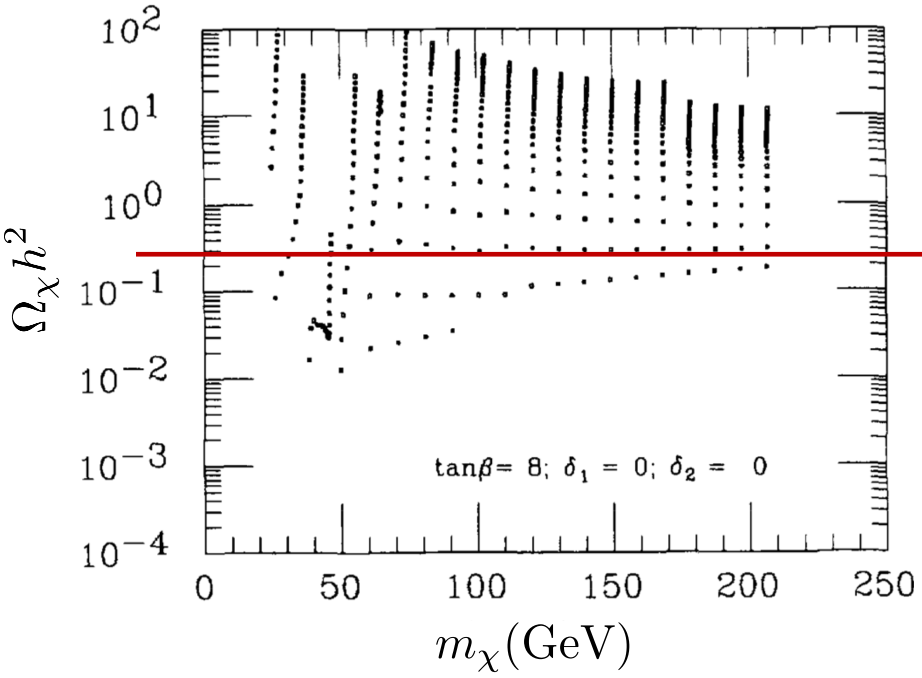
$$\tan\beta = 8; \quad \delta_1 = -0.2; \quad \delta_2 = 0.4$$

Non-universal model

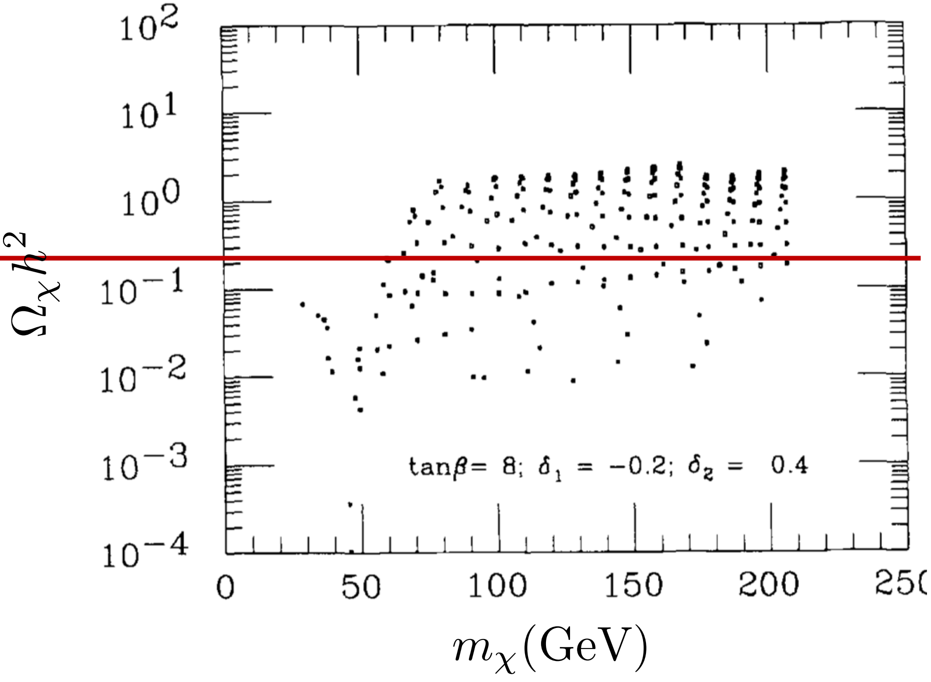


$$\tan\beta = 8; \quad \delta_1 = -0.8; \quad \delta_2 = 0.2$$

Neutralino relic abundance

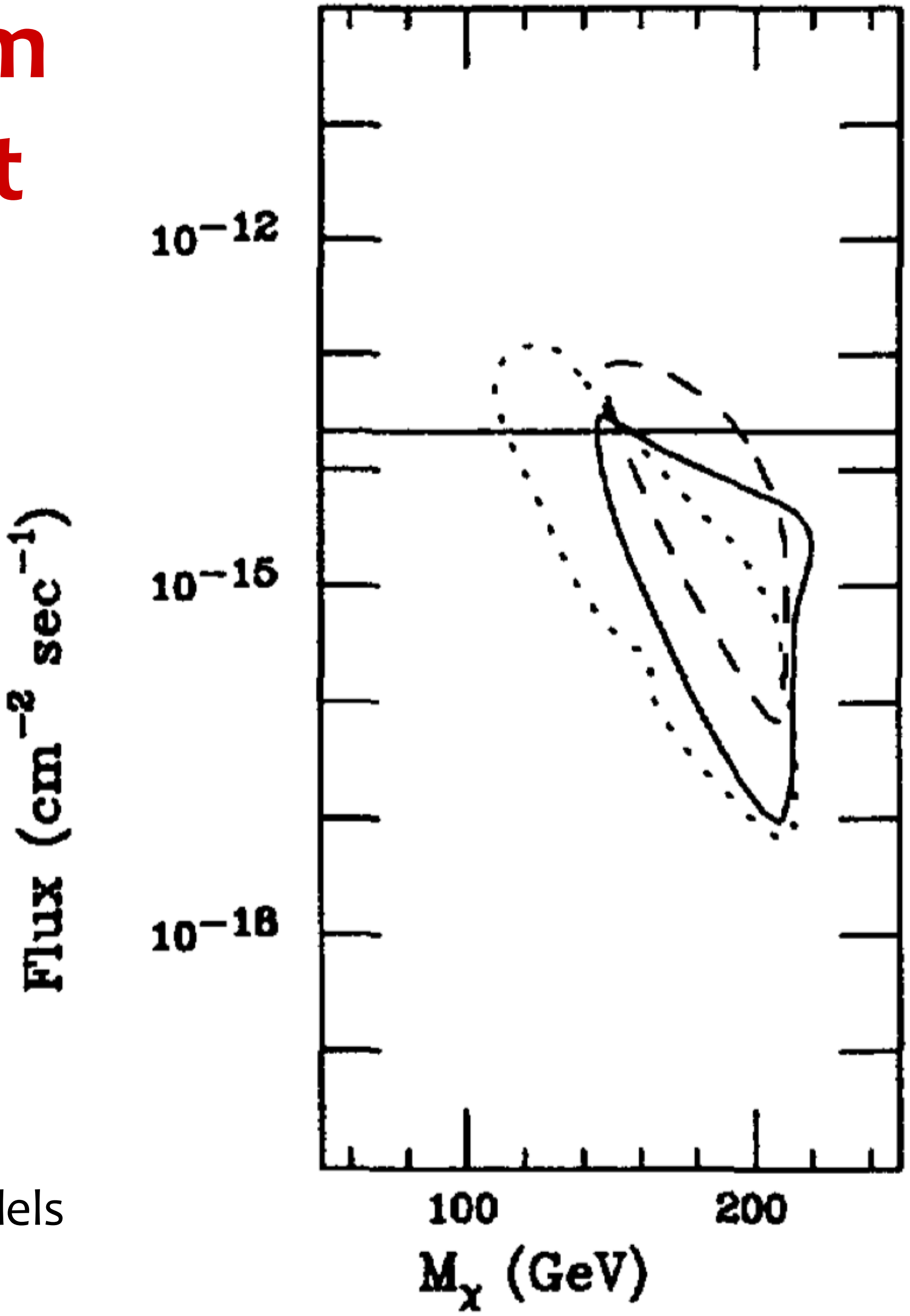


mSUGRA/CMSSM



Non-universal model

Neutrino flux from the Earth (indirect detection)



Solid: mSUGRA/CMSSM

Dashed, dotted: Non-universal models

Gaugino non-universality

PHYSICAL REVIEW D
Light relic neutralinos
A. Bottino, N. Fornengo, and S. Scopel
Phys. Rev. D **67**, 063519 – Published 28 March 2003

- By allowing non-universality in the gaugino sector, neutralino lighter than the “canonical” ones become possible, by evading the bound induced by the non-observation of the chargino at accelerators

Neutralino

$$M_N \equiv \begin{pmatrix} M_1 & 0 & -\frac{1}{2}g'v_d & \frac{1}{2}g'v_u \\ 0 & M_2 & \frac{1}{2}gv_d & -\frac{1}{2}gv_u \\ -\frac{1}{2}g'v_d & \frac{1}{2}gv_d & 0 & -\mu \\ \frac{1}{2}g'v_u & -\frac{1}{2}gv_u & -\mu & 0 \end{pmatrix}$$

Chargino

$$M_C \equiv \begin{pmatrix} M_2 & \frac{1}{\sqrt{2}}gv_u \\ \frac{1}{\sqrt{2}}gv_d & \mu \end{pmatrix}$$

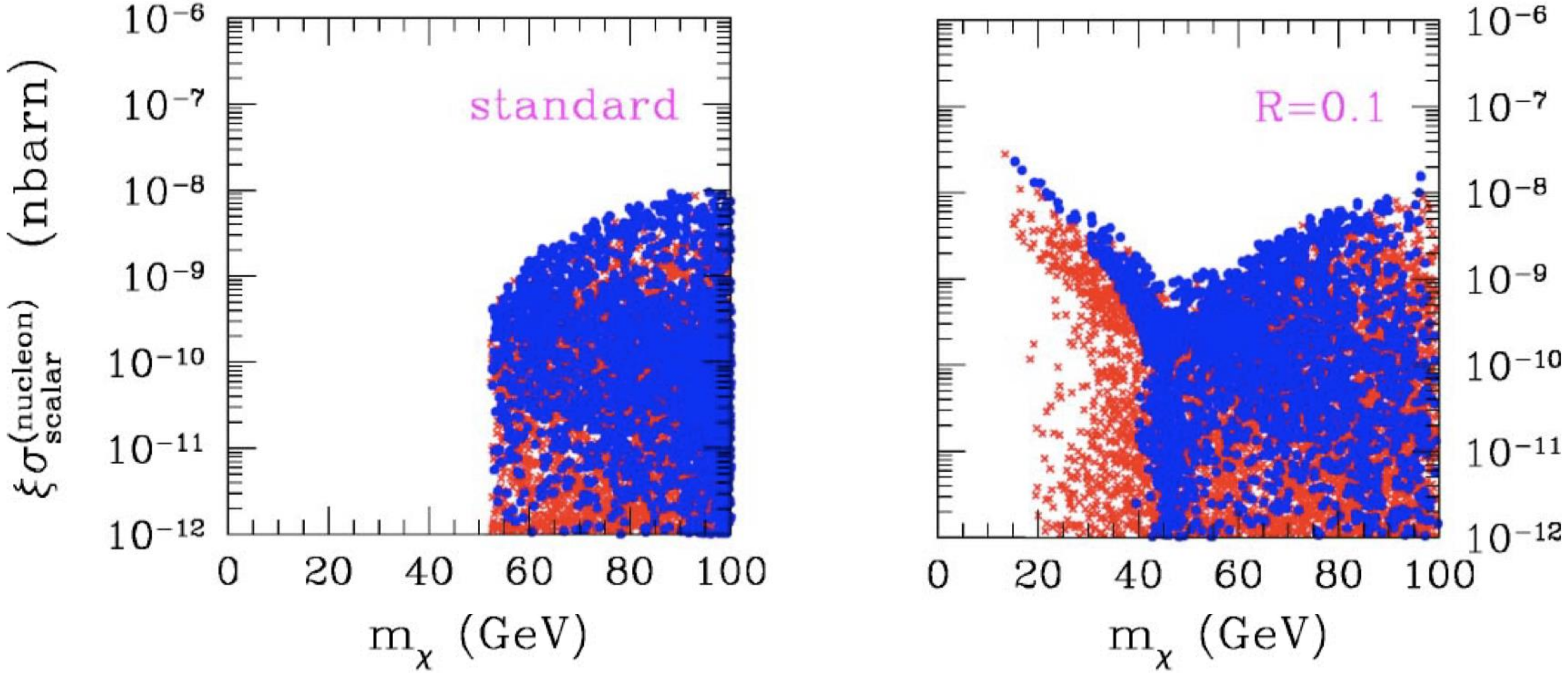
SUGRA inspired

$$M_1 : M_2 : M_3 = \alpha_1 : \alpha_2 : \alpha_3$$
$$M_1 = \frac{5}{3}\tan^2\theta_W M_2 \simeq 0.5 M_2$$

Gaugino non-universal

$$M_1 = R \times M_2$$

DM direct detection



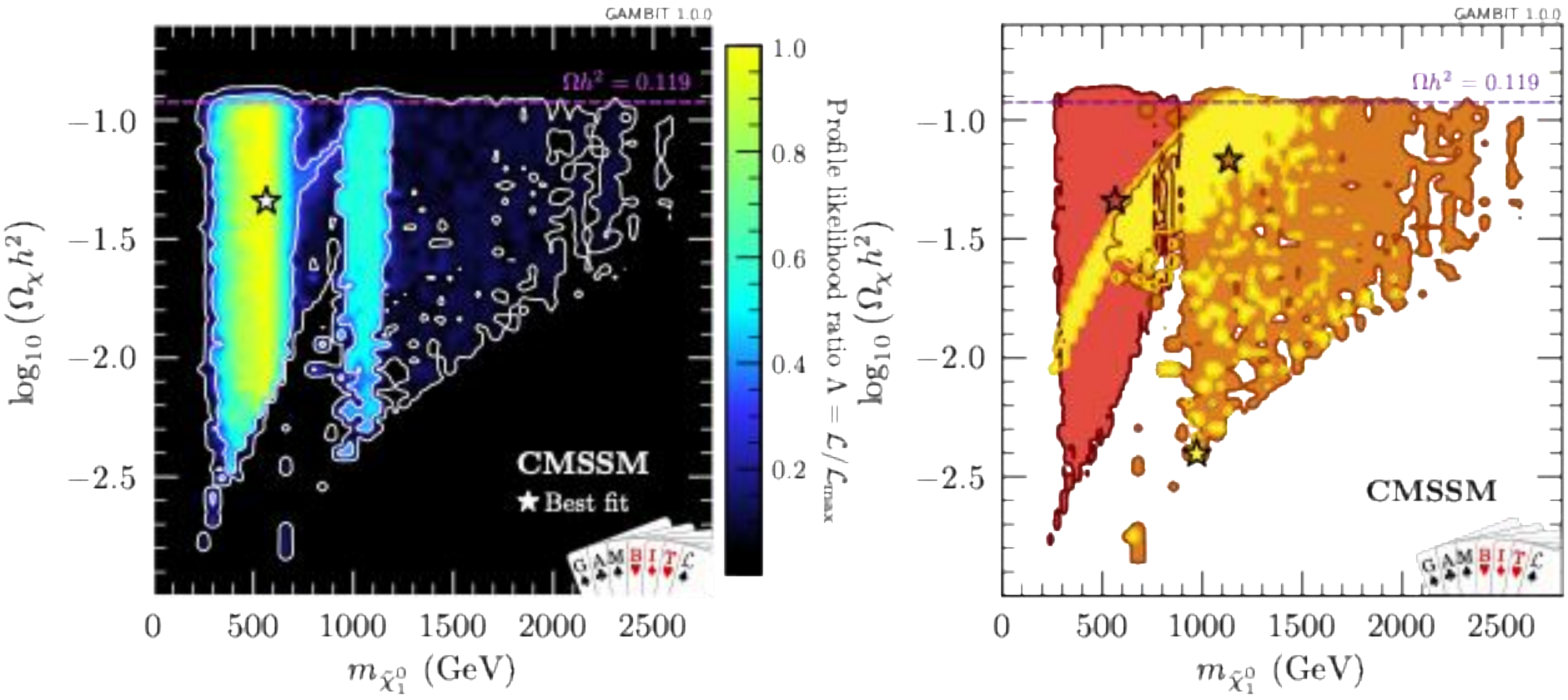
Fast forward 25+ years

- The Higgs boson has been discovered (this fixes the Higgs mass and its coupling to the SM particles): what about 2HDM?
- Plenty of new data from the LHC
- No evidence of SUSY has been found
  - Several SUSY frameworks have been investigated since 1996:

    mSUGRA/CMSSM
    NUHM1, NUHM2
    NMSSM
    pMSSM
    AMSB models
    GMSB models
    …

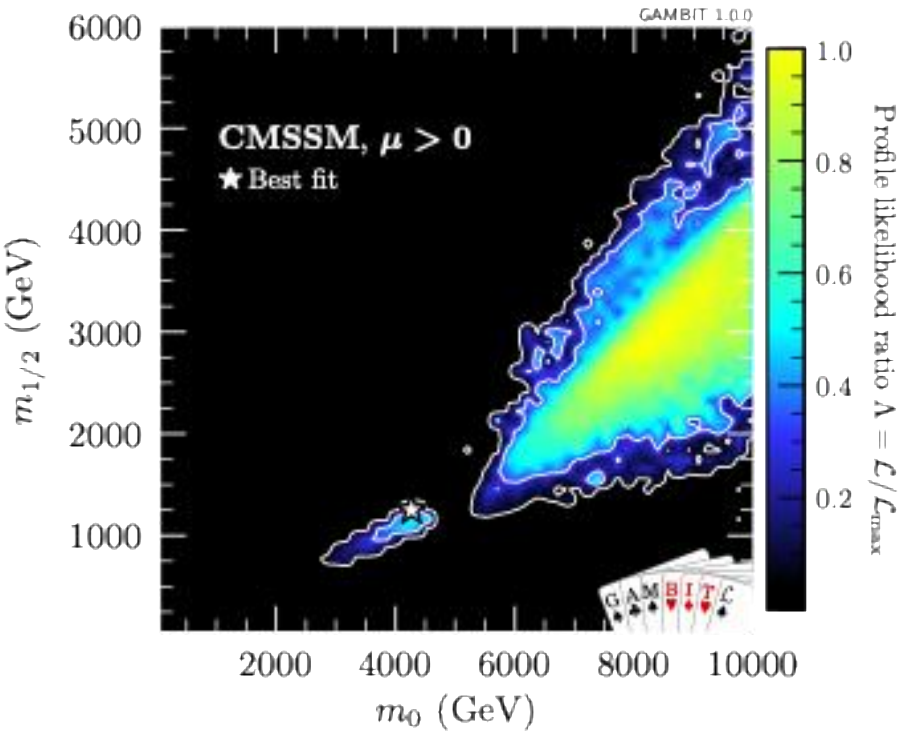
- Dark Matter remains an unsolved outstanding problem
- Significant improvements in sensitivity for both direct detection and indirect detection searches

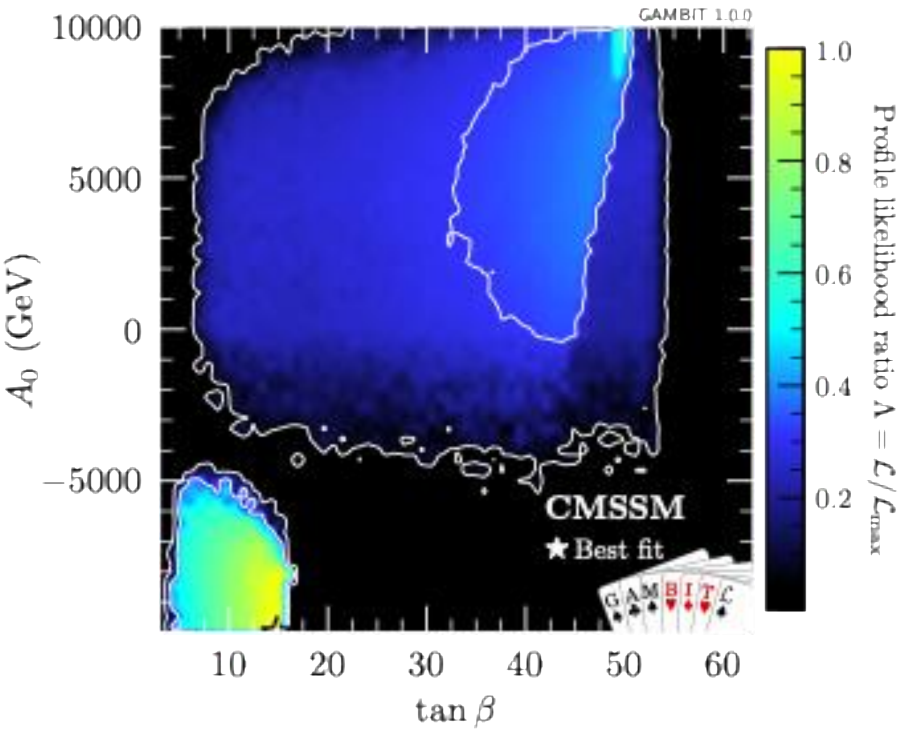
Constrained MSSM



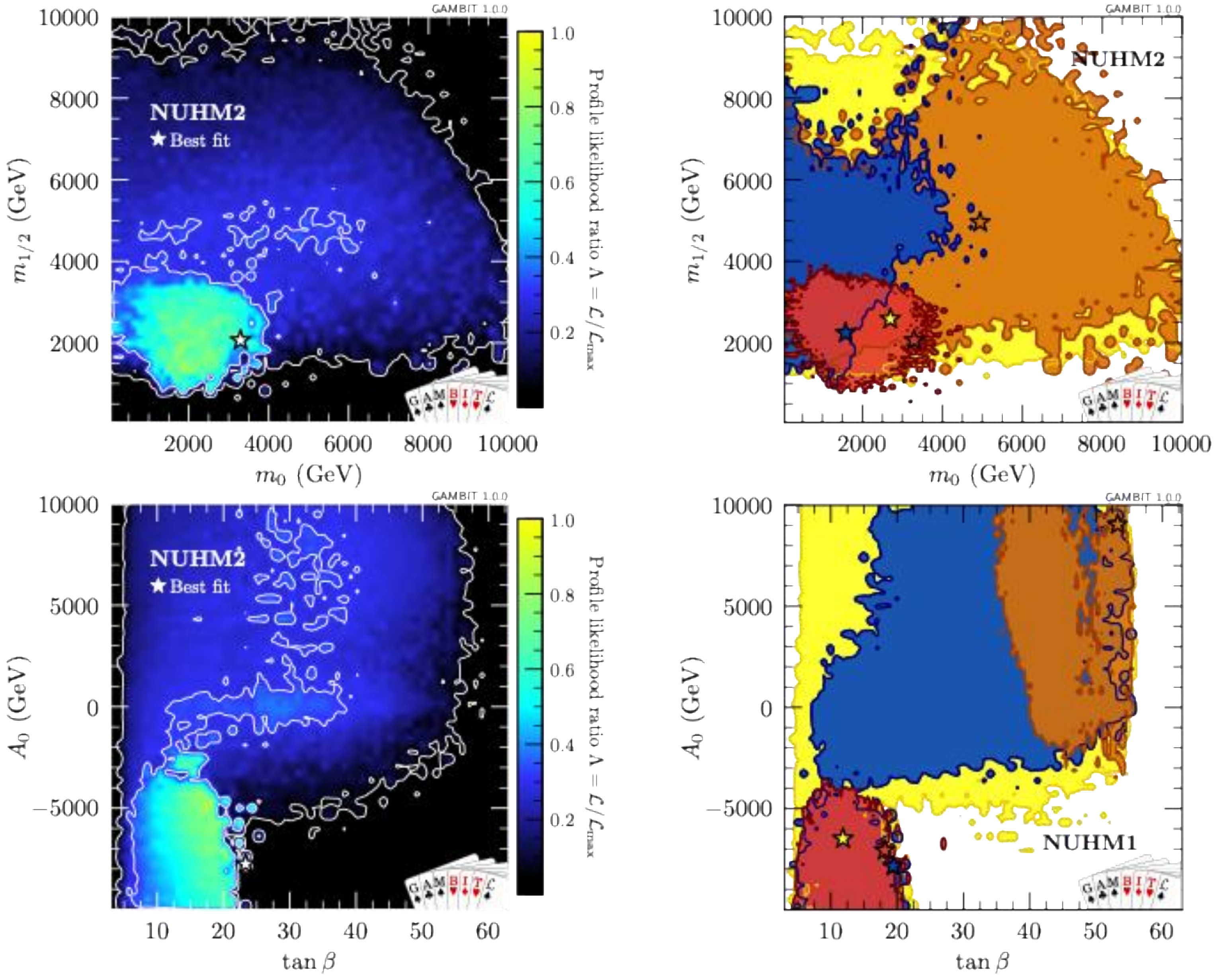
🟥 $\tilde{t}_1$ co-annihilation 🟧 A/H funnel 🟨 $\tilde{\chi}_1^\pm$ co-annihilation

Constrained MSSM





Non Universal Scalars (NUHM2)



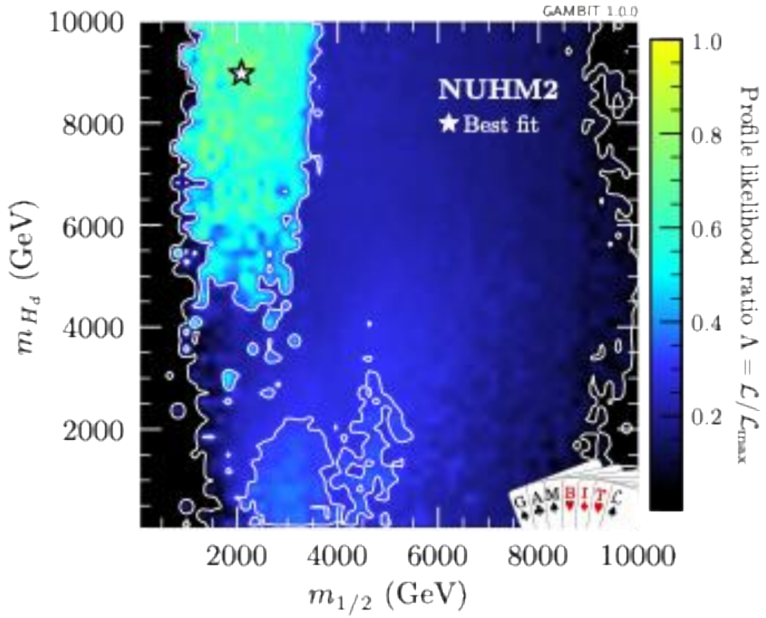
🟥 $\tilde{t}_1$ co-annihilation

🟧 A/H funnel

🟨 $\tilde{\chi}_1^\pm$ co-annihilation

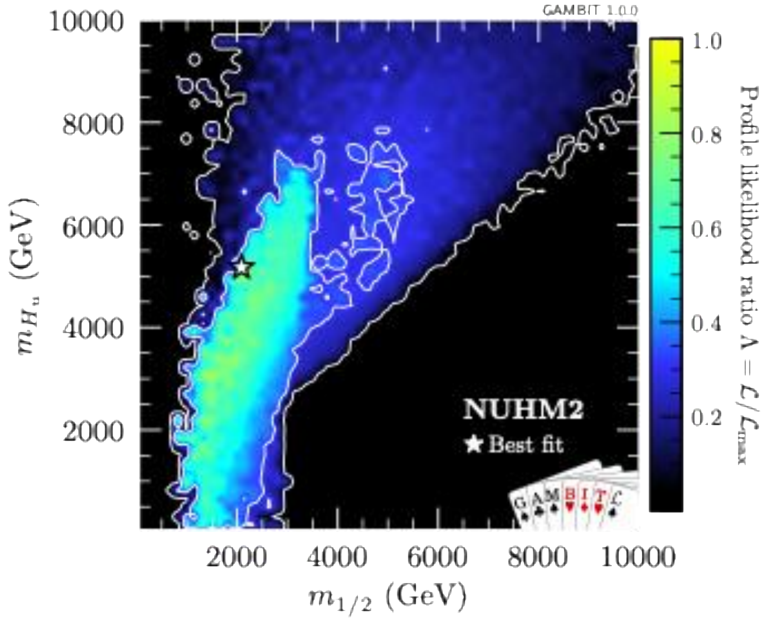
🟦 $\tilde{\tau}_1$ co-annihilation

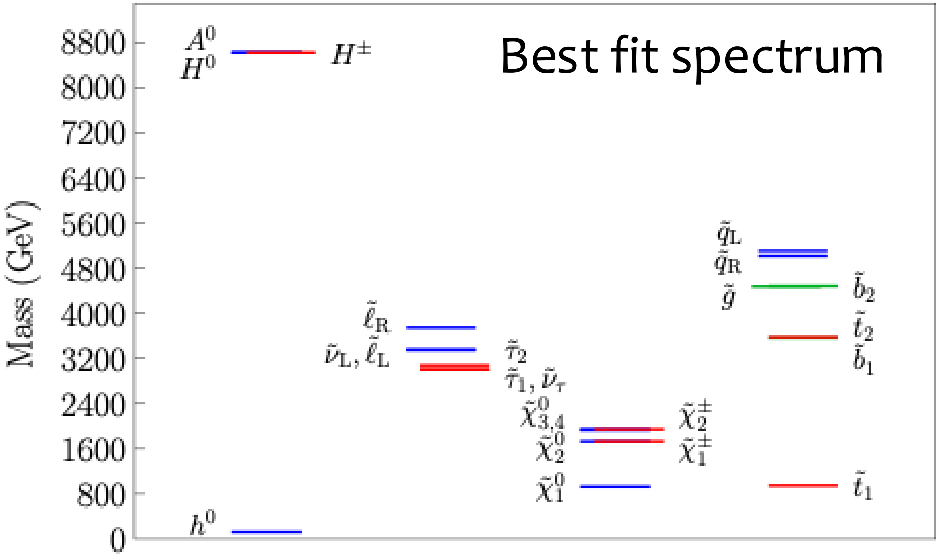
Non Universal Scalars (NUHM2)



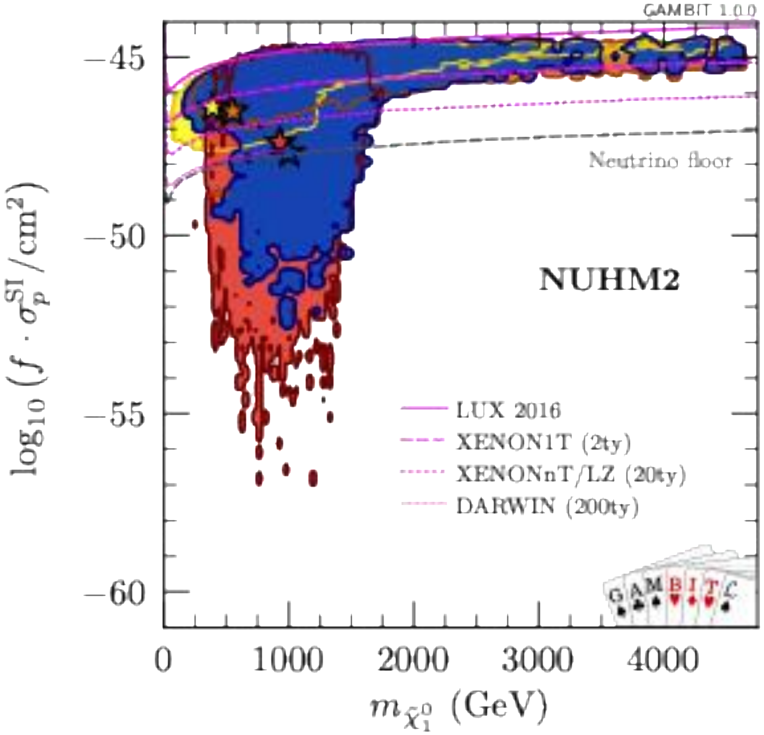
Models bounded by:

- Direct and indirect dark matter searches
- Electroweak precision and flavour observables
- Direct searches for supersymmetry at LEP and Runs I and II of the LHC
- Constraints from Higgs observables

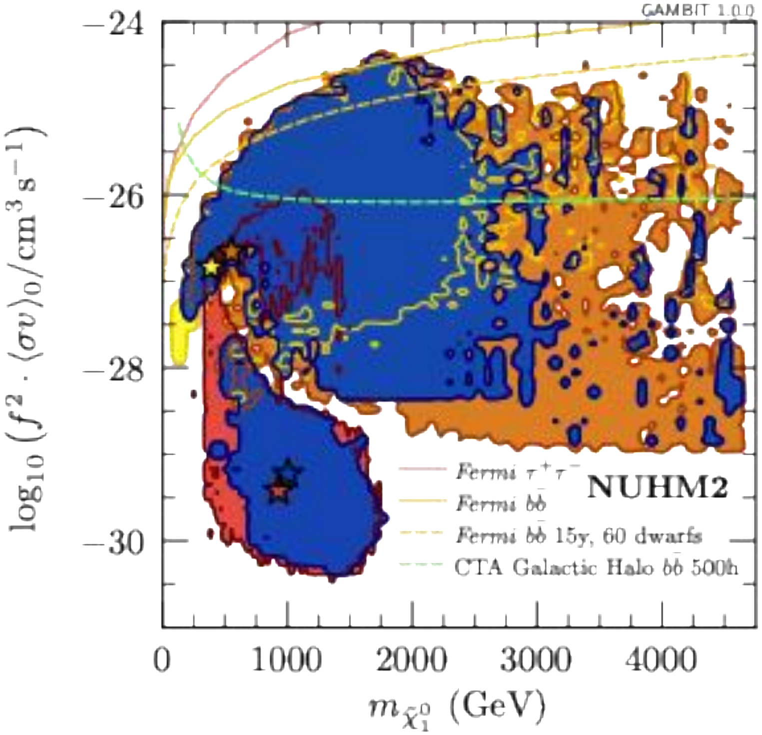



Best fit spectrum

Non Universal Scalars (NUHM2)



Direct DM searches



Indirect DM searches

Conclusions

Venya, as well as for cosmic rays, neutrinos and other astroparticle physics topics, has been a pioneer also in the study of dark matter, bringing new bright ideas both to theory and phenomenology

Small scale clumps and minihalos: 1405.2204, 1308.6742, 1107.2751, 1102.3445, 1002.3445, 1002.3444, 0712.3499, astro-ph/0511494, astro-ph/0301551

Superheavy DM: 0810.3012, astro-ph/0604311

Neutralino stars: astro-ph/9610060

DM annihilation in the galactic center: hep-ph/9402215

Majoron DM: hep-ph/9309214

DM distribution in the galaxy and implications for SUSY: PLB294(1992)221

Gamma-ray line from DM annihilation: PLB274(1992)122

Signatures of broken R-parity SUSY: PLB286(1991)382

Cosmology of gravitinos: PLB261(1991)71

It has been a privilege to work with Venya and to have the opportunity to learn so many things from his deep knowledge and understading of Physics!