SUPERSYMMETRY : AT WHICH SCALE ?

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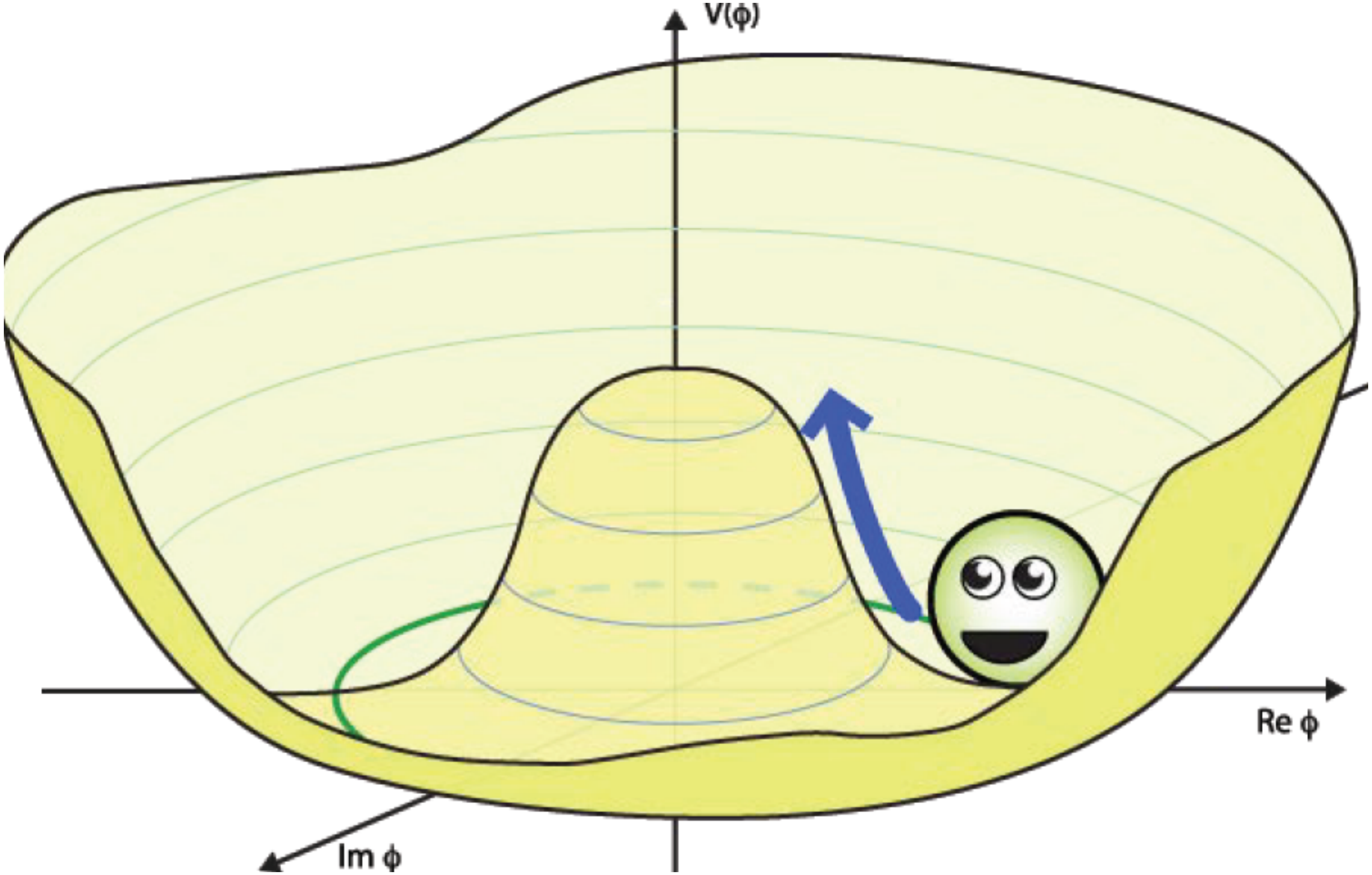
Outline

1) Why and which Supersymmetry ?
- The hierarchy problem : low-scale dynamics or UV intelligent completion ?
- Dark Matter
- Unification of gauge couplings
2) Nonlinear SUSY and cosmology
3) High-scale SUSY, Higgs mass, dark matter and inflation
4) SUSY perspectives ?

1) Why and which supersymmetry ?

- In july 2012, LHC discovered the Higgs boson. No signs of deviations in its couplings: maybe the first elementary scalar ?



- Are fundamental scalars required by fundamental symmetries or principles ?

YES, SUPERSYMMETRY

Fermions ⟷ Bosons

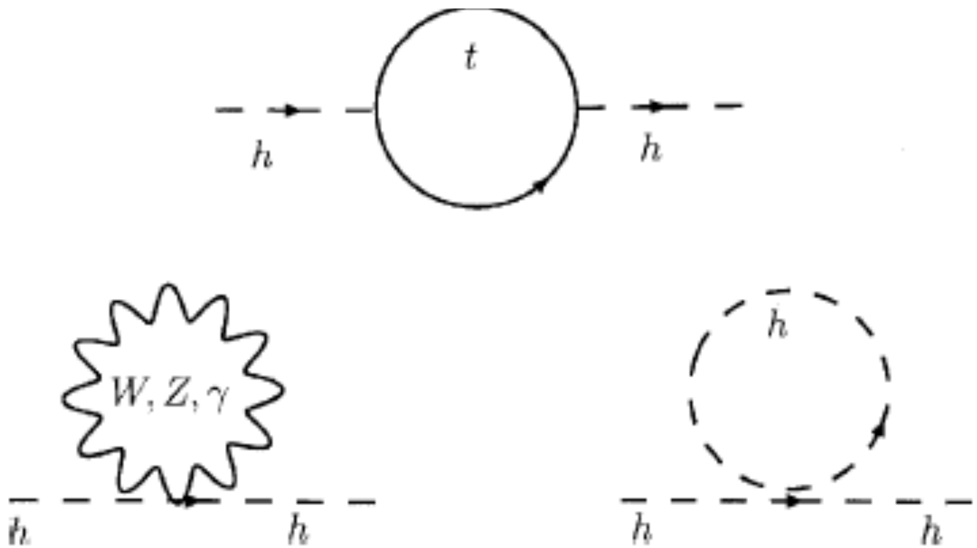
Unbroken SUSY ⟹ $m_F = m_B$

Broken SUSY, TeV splittings = Low-energy SUSY

Low-energy Supersymmetry naturally adresses some of the mysteries of the SM:

a) The **hierarchy problem** (mis?)guided BSM physics for the last 30 years. Quantum corrections to the Higgs mass in the SM are UV sensitive

$$\delta m_h^2 \simeq \frac{3\Lambda^2}{8\pi^2 v^2}(4m_t^2 - 4M_W^2 - 2M_Z^2 - m_h^2)$$

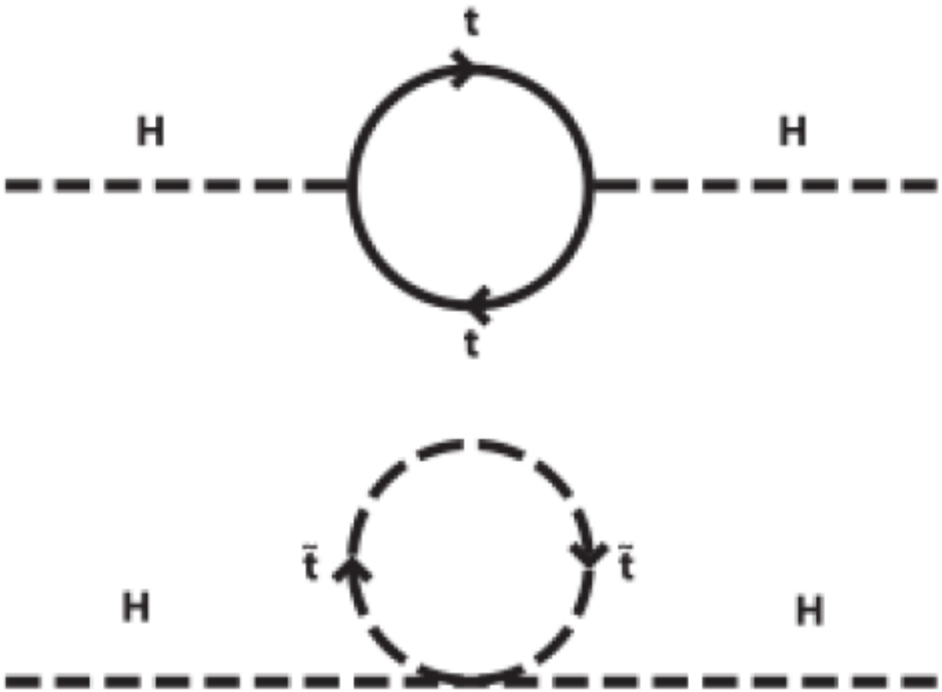


$\Lambda = 10^{16}\ GeV$

$\delta m_h^2 \sim 10^{32} m_h^2$

In SUSY models, cancelation between fermionic and bosonic loops removes the UV sensitivity

$$\text{SM} \; : \; \Delta M_h^2 \sim \frac{\Lambda^2}{16\pi^2} \; , \; \text{MSSM} \; : \; \Delta M_h^2 \sim \frac{m_t^2}{16\pi^2} \; \log \frac{m_{\tilde{t}}^2}{m_t^2}$$

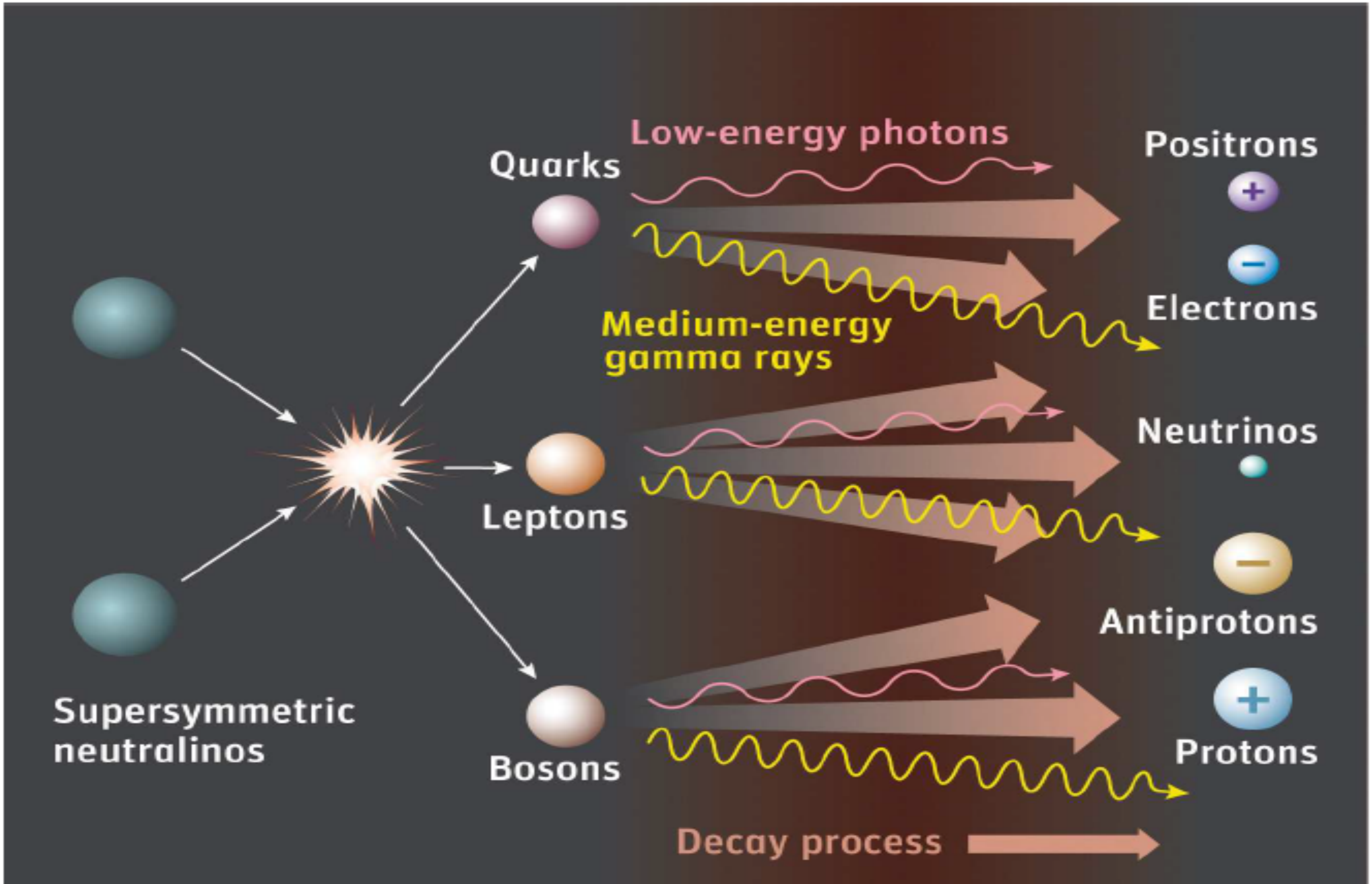


Most known solutions to the hierarchy problem:
SUSY, large Xtra dims, compositeness/technicolor,
imply low-energy dynamics
(notable exception : relaxion, models not fully convincing yet)

What if nothing is found at LHC ?

- We are unlucky, new physics still « around the corner », moderate unexplained tuning: heavier SUSY spectrum (mini-split), etc
- We were naive: no low-energy physics and anthropic/ landscape explanation for the electroweak scale
- Nature is subtle: intelligent UV completions explain the hierachy problem.

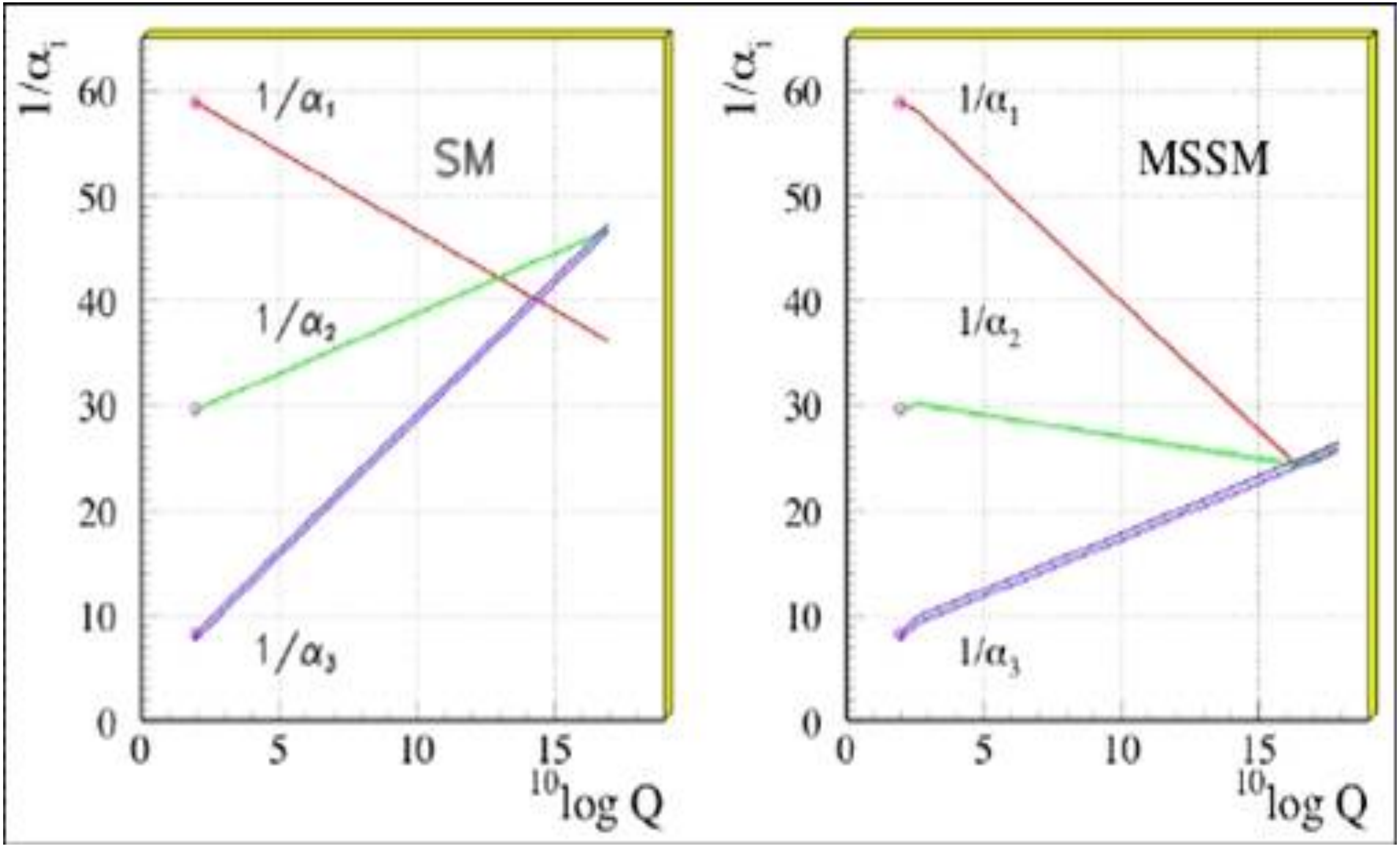
b) Dark Matter Candidate: LSP (=WIMP), protected by R-parity ?



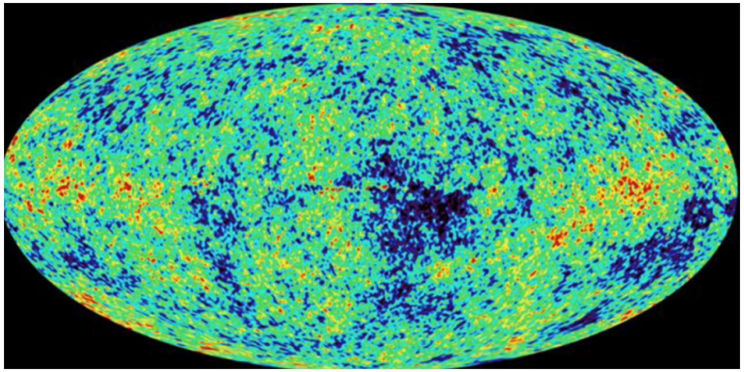
WIMP miracle still attractive possibility, but shaken more and more by direct DM constraints

Plethora of other possibilities: FIMP's, axions, SIMP's…
Early Cosmology could be very different.

c) Gauge coupling unification around 2×10^{16} GeV, close to the energy scale during inflation. Coincidence ?



2) Nonlinear supersymmetry and Cosmology



- Local supersymmetry implies Einstein gravity

- Inflation with super-Planckian field variations need an UV description ⇒ String Theory
- Supersymmetry crucial in String Theory, can ensure quantum stability of inflaton potential

- Some advantage of having certain type of high-scale SUSY breaking = Nonlinear SUSY in cosmology :

(less scalars fields, no inflatino, no Polony fields,etc)

Activity in the last 3 years on nonlinear realizations in supergravity, based on constrained superfields, from the viewpoint of:

- geometrical origin of the Volkov-Akulov model in SUGRA

$$X^2 = 0 \leftrightarrow (\mathcal{R} - \lambda)^2 = 0$$

gravitino

Chiral superfield; Goldstino
= spin ½ fermion, no scalar

Curvature superfield
Goldstino = $(1/\lambda)\gamma^{mn} D_m \Psi_n$
pure SUGRA (no matter)

- inflation, minimal models with SUSY breaking:

$$X(\Phi + \bar{\Phi}) = 0$$

Φ contains only the inflaton (real scalar), no inflatino, no scalar partner

- moduli stabilization: X as uplift in KKLT.

Disclamer:

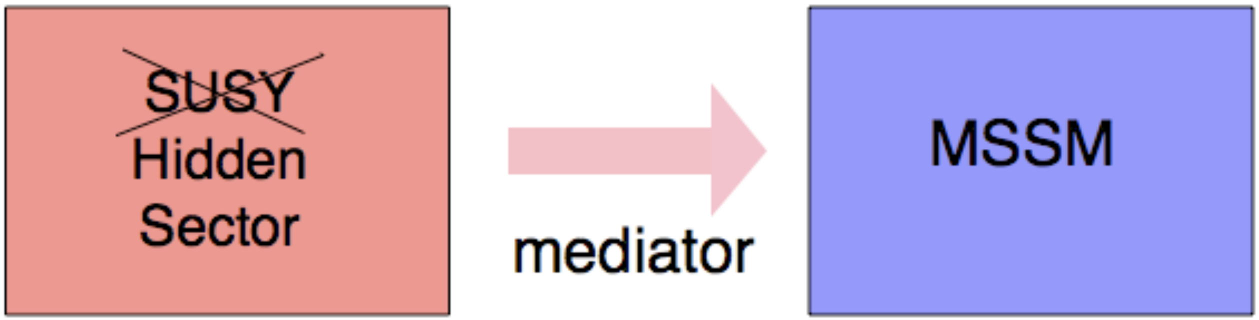
Low-energy SUSY is the only known framework naturally incorporating a), b) , c) , d) simultaneously,

but the SUSY breaking scale is unknown and superpartners denied to show up until now at LHC…

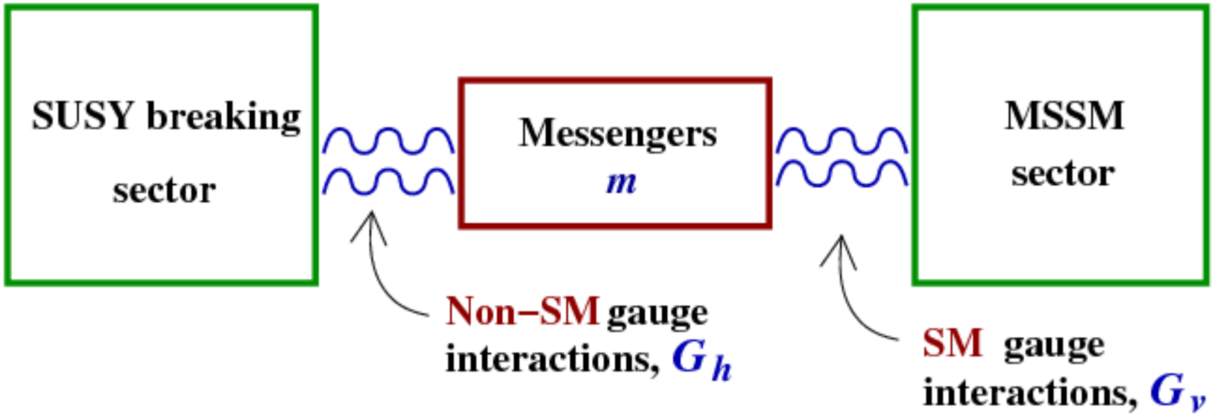
Supersymmetry breaking mistery

Supersymmetry breaking is the key question:
its origin and transmission to Standard Model fields:

- Is it Gravity Mediation ?

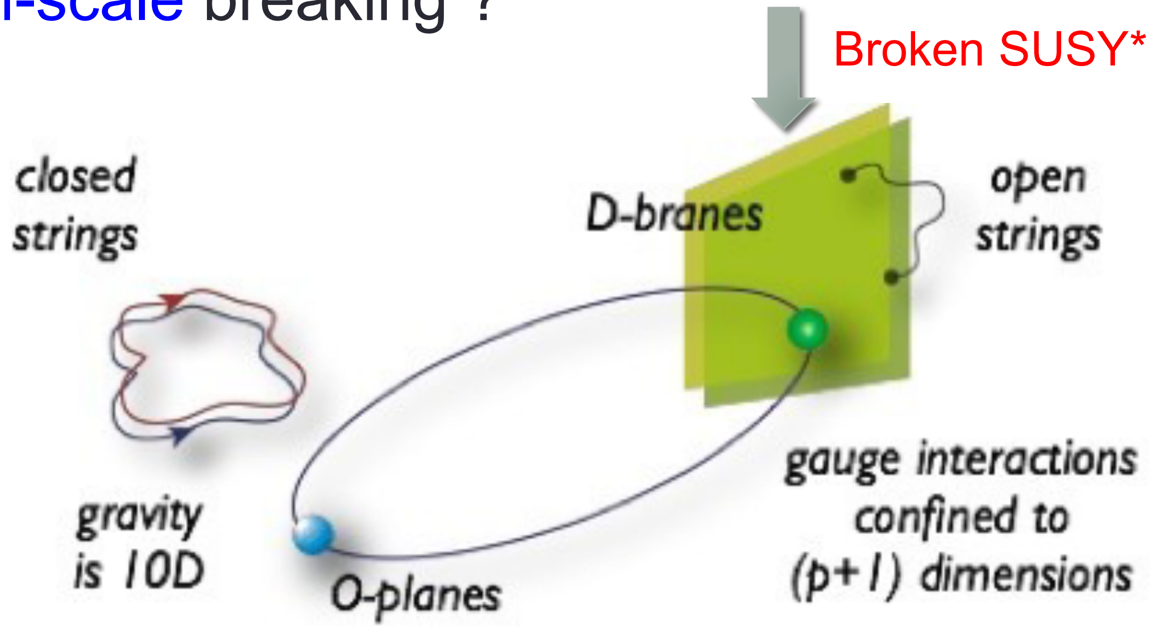


- Or gauge mediation ?



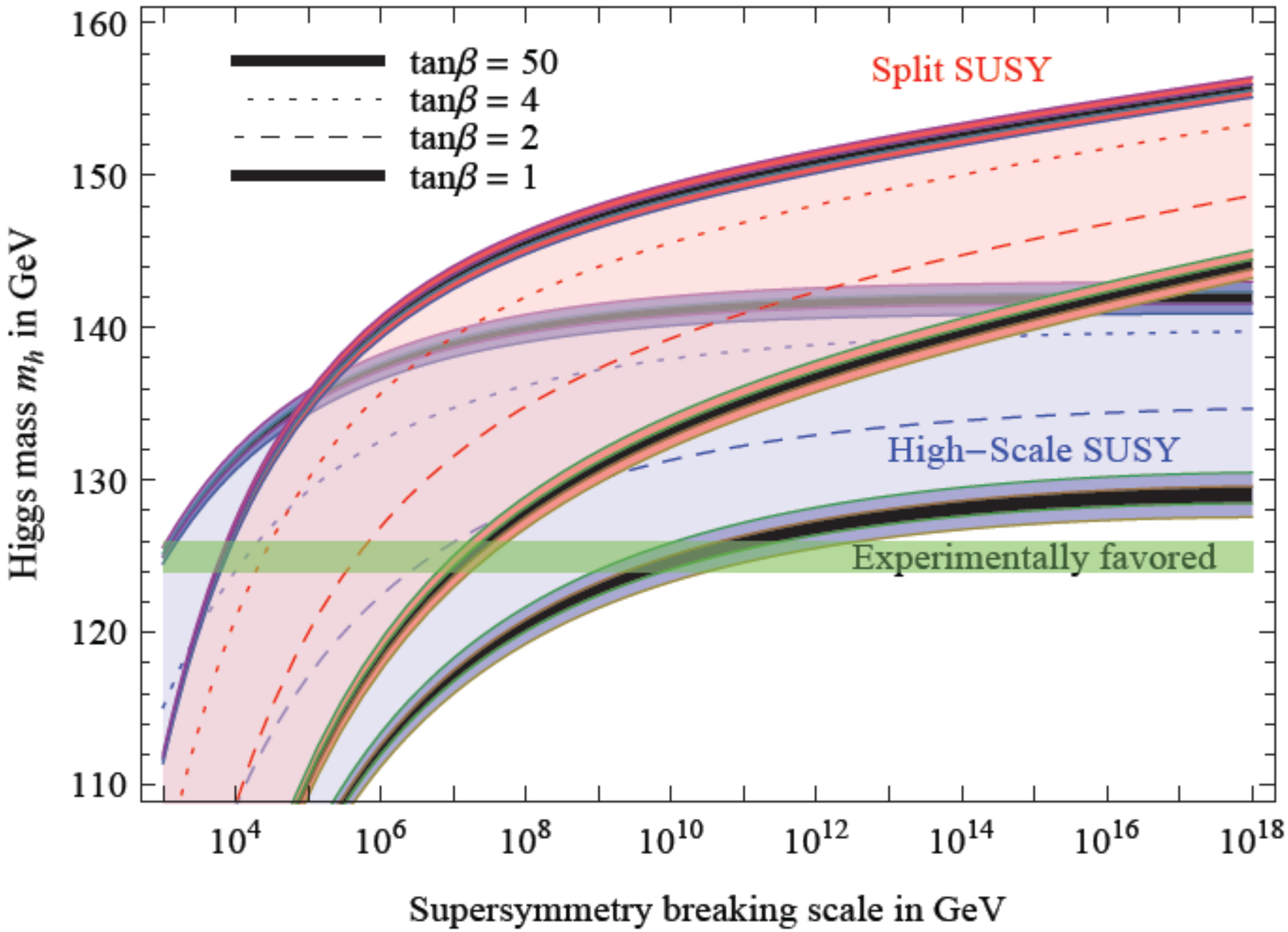
- or maybe a perturbative SUSY breaking in string theory

= high-scale breaking ?



There are various ways of breaking SUSY in string theory, most lead to high-scale SUSY breaking.

- *High-scale SUSY $TeV << m_{sparticles} \lesssim M_s$



Higgs scalar mass versus scalar masses in split and high-scale SUSY models (from Giudice-Strumia (2011))

With O(10-100) non-degeneracy, sparticles masses can be much heavier (S.Ellis, J. Wells, 2017).

2) High-scale SUSY, Higgs mass, dark matter and inflation

Do we necessarily give up all advantages of SUSY by breaking it at a high-scale ?

One potential example of Intelligent UV Completion:

SUSY theory with extra dimensions, with:

- magnetic fields in the internal space $F_{56} = B$

breaking SUSY due to the magnetic coupling

$$H = -\mu \mathbf{B} = -\frac{q}{m} \mathbf{SB} \Leftrightarrow M_{SUSY} \sim M_{GUT} \sim R^{-1}$$

Charged states turn KK states into Landau levels, mass

$$\delta M^2 = (2n+1)|qB| + 2qB\Sigma_{56}$$

Internal components of the gauge fields are massless at tree-level. At one-loop, an infinite tower of Landau levels contribute

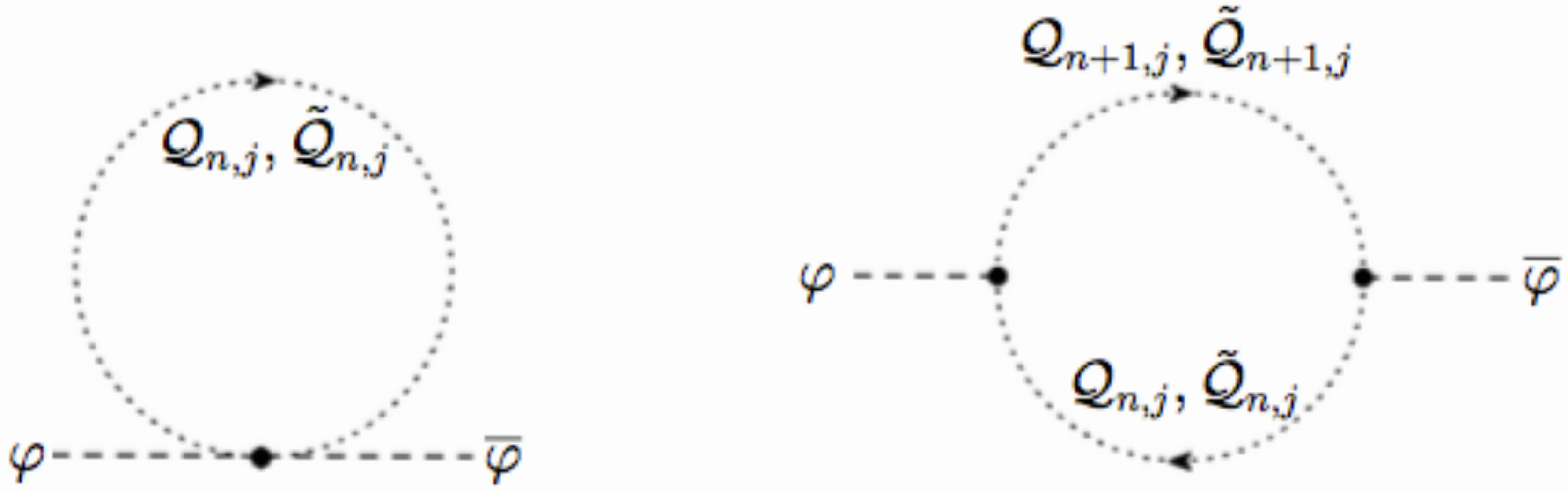


Figure 3: Bosonic contributions to the Wilson line mass with flux.

Although each contribution is quadratically divergent, scalar mass is protected by the magnetic field

$$m_h^2 = \frac{c}{16\pi^2} B \sim \frac{1}{16\pi^2 R^2}$$

The final 4d effective action for Landau levels is

FI term

$$S_4^* = \int d^4x \left[\int d^4\theta \left(\overline{\varphi}\varphi + \sum_{n,j} (\overline{Q}_{n,j} e^{2gqV_0} Q_{n,j} + \overline{\tilde{Q}}_{n,j} e^{-2gqV_0} \tilde{Q}_{n,j}) + 2fV_0 \right) \right.$$
$$+ \int d^2\theta \left(\frac{1}{4} \mathcal{W}_0^\alpha \mathcal{W}_{\alpha,0} \right.$$
$$\left. \left. + \sum_{n,j} \left(-i\sqrt{-2qgf(n+1)} \tilde{Q}_{n+1,j} Q_{n,j} + \sqrt{2} qg \tilde{Q}_{n,j}\, \varphi\, Q_{n,j} \right) \right) + \text{h.c.} \right]$$

Coupled mass terms

- SUSY broken like in the FI model, with an infinite number of fields. Truncation to a finite number inconsistent.

The total contribution to the mass is exactly zero

(W.Buchmuller,M.Dierigl, E.D.,J.Schweizer, 2017)

We believe this is not an accident: a higher-dimensional symmetry is spontaneously broken by the magnetic flux

→

The scalar is protected by a spontaneously broken higher-dimensional symmetry, invisible from four dimensions

- Coupling to gravity will break explicitly the global symmetry, and provide a Higgs mass

$$m_h << R^{-1} = M_{SUSY}$$

- It remains to be seen if this mechanism can work in realistic models…

Gravitino dark matter high-scale SUSY

- In various models with high-scale SUSY breaking, gravitino is parametrically lighter than other superpartners →

low-energy theory is Standard Model + gravitino,

+ effective interactions

$$L_{2G} = \frac{i}{2f^2}(G\sigma^\mu\partial^\nu\bar{G} - \partial^\nu G\sigma^\mu\bar{G})T_{\mu\nu}$$

Goldstino (longitudinal component gravitino) Matter energy-momentum tensor

$f = m_{3/2}M_P$ is the SUSY breaking scale

Such a gravitino is generically not in thermal equilibrium with SM particles

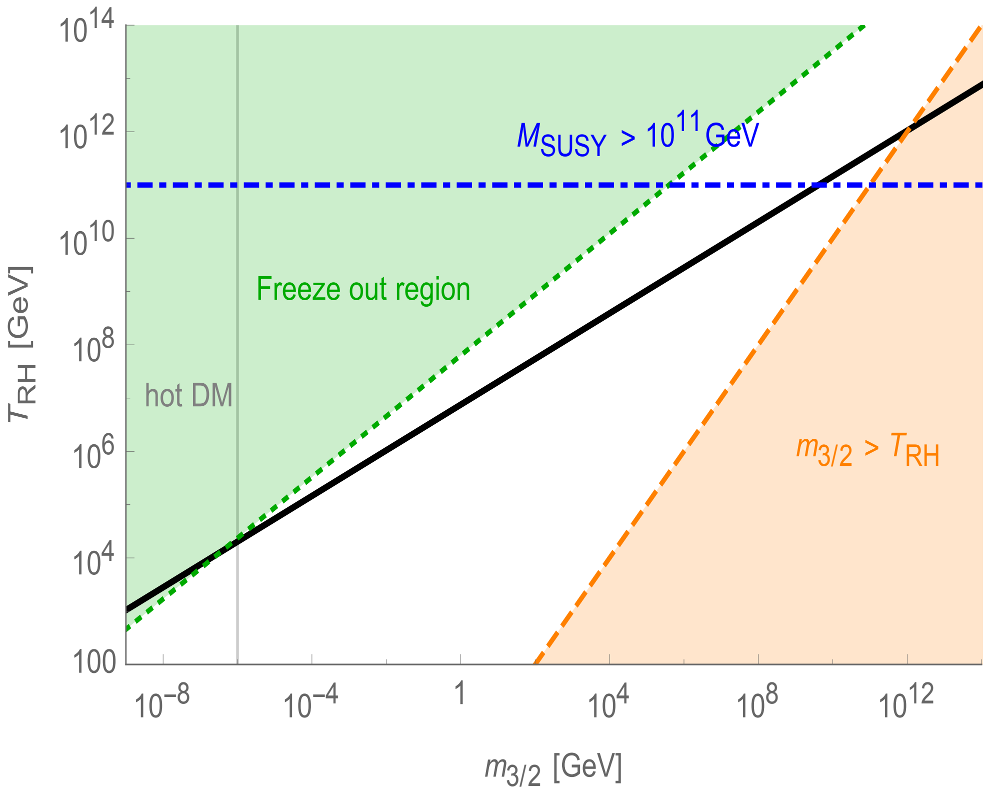
If gravitino not produced significantly during reheating, then it is produced from SM particles via effective interactions, freeze-in
(Benakli,Chen,E.D.,Mambrini, 2017)

$$\Omega_{3/2}h^2 \simeq 0.11 \left(\frac{0.1\ \text{EeV}}{m_{3/2}}\right)^3 \left(\frac{T_{RH}}{2.0\times 10^{10}\ \text{GeV}}\right)^7$$

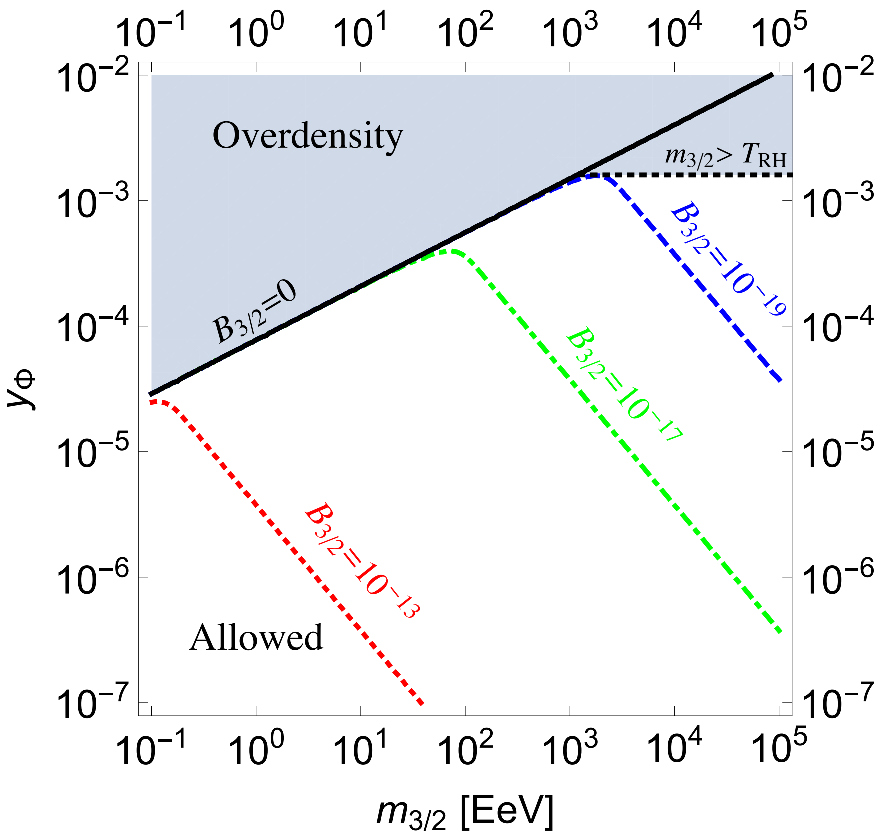
Possible to have models compatible with:
- relic density
- reheating to SM particles (superpartners masses > T_{RH}, m_ϕ)
- SUGRA models with inflation and SUSY breaking, if

$$m_{3/2} > \frac{m_\phi^2}{\sqrt{3}M_P} \simeq 0.2\text{EeV}$$

- EeV = 10^9 GeV gravitino mass optimal choice, without spoiling inflaton flatness (E.D.,Mambrini, Olive + Gherghetta, 2017)



T_{RH} [GeV]
$M_{SUSY} > 10^{11}$ GeV
Freeze out region
hot DM
$m_{3/2} > T_{RH}$
$m_{3/2}$ [GeV]



Overdensity
$m_{3/2} > T_{RH}$
$B_{3/2}=0$
$B_{3/2}=10^{-19}$
$B_{3/2}=10^{-17}$
$B_{3/2}=10^{-13}$
Allowed
y_Φ
$m_{3/2}$ [EeV]

Perspectives

- Low-energy SUSY still the best option nature has to address misteries of the Standard Model. Imaginative non-minimal SUSY extensions welcome

- SUSY seems a good bet at very high-energy: inflation,string theory, but scale of SUSY breaking unknown

- Worth checking if high-scale SUSY breaking destroys all nice features of SUSY constructions. Easier in string theory

- Intelligent UV completions are maybe possible, with no new particles at low-energy. DM could be a heavy gravitino.

- If high-scale SUSY, the big question is testability. Some hopes: « Cosmological collider » (Arkani-Hamed,Maldacena), high-energy events (ICECUBE)…

THANK YOU