SPLIT SUPERSYMMETRY AND DARK MATTER

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DESY Cosmology Workshop
Oct 1st, 2004

- Motivations for Split Supersymmetry
- Observational consequences and Dark Matter

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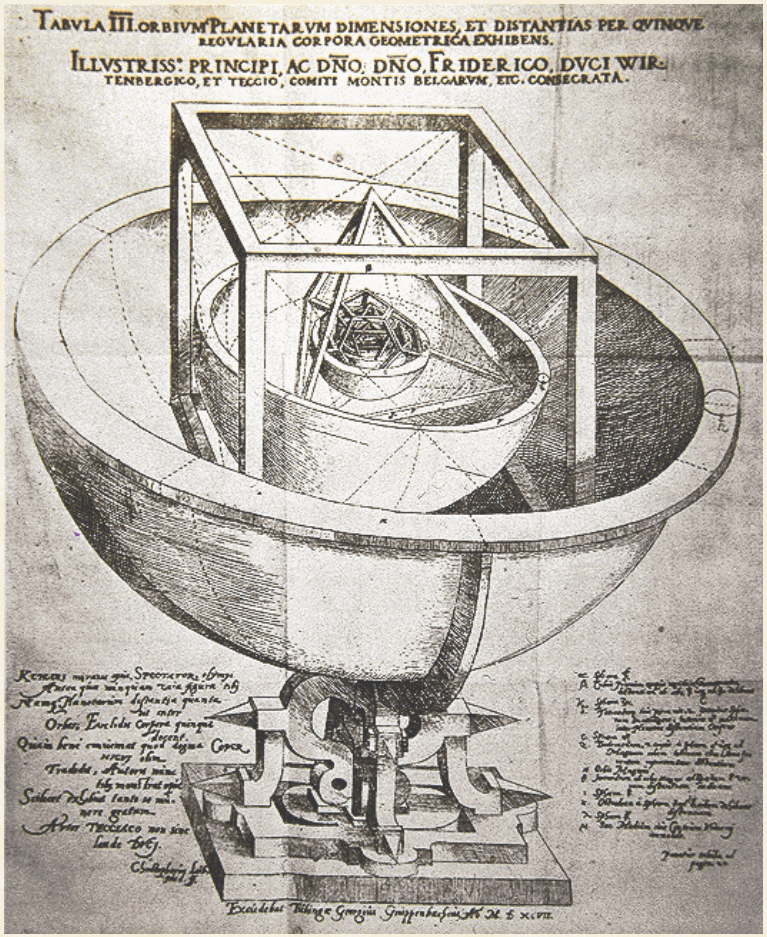
Role of fundamental physics is to extract the essential out of complexity

One critical step: identify fundamental (and not accidental) quantities/parameters and compute them in the context of a new theory (with deeper conceptual or symmetry principles)

In 1595 Kepler asked the question "Why are there 6 planets?" It seems a proper scientific question ("Why are there 3 quark families?")

"Mysterium Cosmographicum" gives a geometrical explanation

Planetary orbits lie within the only 5 Platonic solids that can be both circumscribed and inscribed within a sphere. It well matched planetary distances known at that time (within 10%).



Sphere
Saturn
Cube
Jupiter
Tetrahedron
Mars
Dodecahedron
Earth
Icosahedron
Venus
Octahedron
Mercury
Sphere

In "Harmonices Mundi", Kepler tried to understand the planetary velocities in terms of musical harmonies.

These theories are nonsense (but led to Kepler's law)

Now we know that the number of planets (9?) is an accident
Kepler's question was not fundamental

Earth-Sun distance is fixed by anthropic principle: it is the correct distance to allow for liquid water

Many astronomical properties are determined by anthropic arguments and not by fundamental principles

Earth's size: correct to retain large amounts of liquid water

Earth's age: biological evolution, convective dynamo necessary for magnetic field protecting from solar-wind erosion of atmosphere (not the case on Mars)

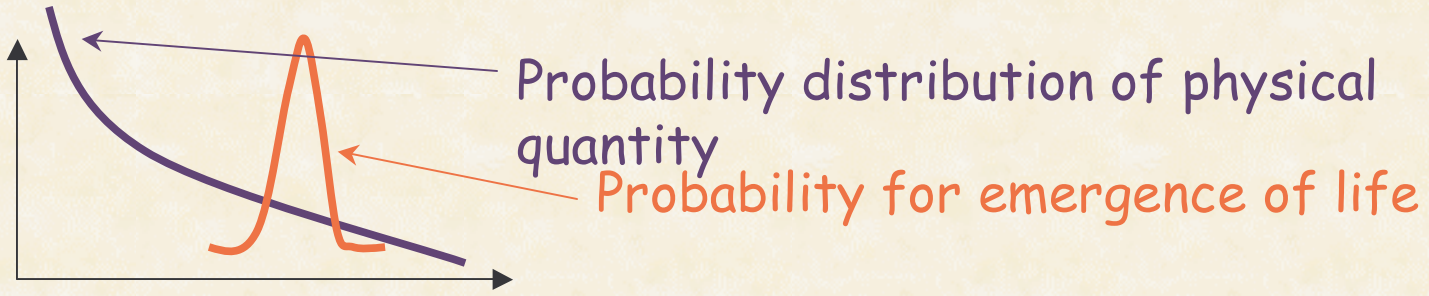
Sun's age: main-sequence lifetime allowing biological evolution

Solar system's orbit: unusually low eccentricity and small amplitude of vertical motion, tuned to reduce comet impacts

We are confident about the anthropic explanation because we observe a vast universe with a multitude of stars

We cannot fully predict its probability, but emergence of life is highly non-trivial and requires many fortuitous accidents: planet Earth is not an average place in the universe!

Suppose a dust cloud obscure the universe beyond solar system. If we exclude: 1) unlikely coincidences, 2) divine intervention, then we could infer the existence of a multitude of stars. Indeed, in our universe, the probability for life is of order unity.



Bias from the observer's point of view, or cosmic-variance problem

Applying to the anthropic principle is viewed with skepticism in the scientific world

"A physicist talking about the anthropic principle runs the same risk as a cleric talking about pornography: no matter how much you say you are against it, some people will think you are a little too interested" S. Weinberg

Two objections:

- Giving up fundamental explanation ⇨ you have asked the wrong question
- Lack of predictive power ⇨ negative answers; existence of ensemble

Understanding SM free parameters: good scientific question or similar to Kepler's attempt?

Belief in fundamental theory and power of symmetries. After relativity and quantum mechanics, many attempts to "calculate" c and $\hbar$. Should the fundamental theory be able to calculate α, m_q , θ_{QCD}?

GUT gives striking evidence for the "calculability" of α_i

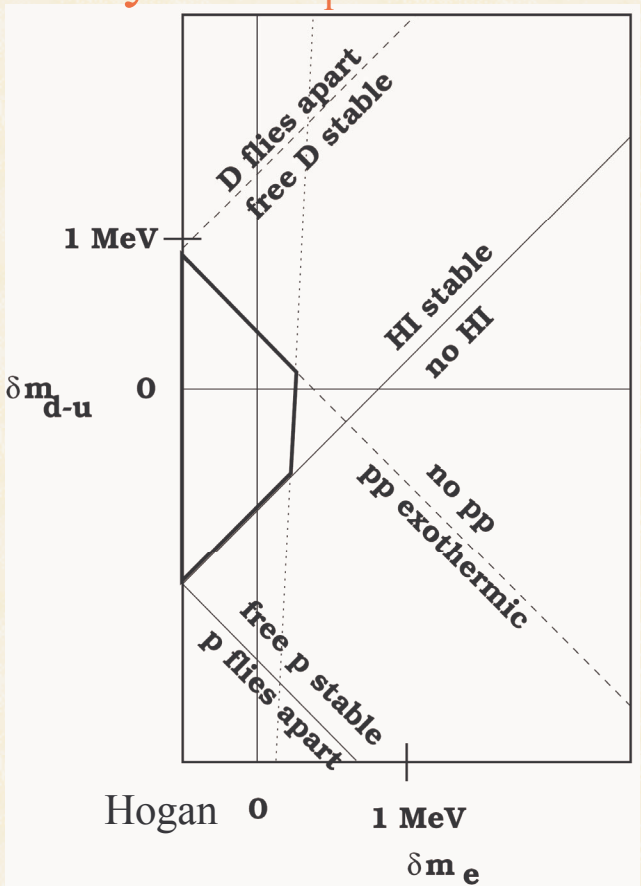
Quark masses show a "special" pattern

Hard to imagine that m_c, m_b, m_t, m_μ, m_τ, V_{ub}, V_{cb} are explained anthropically. However, small changes of m_u, m_d, m_e have catastrophic effects on life

$$m_N = m_q + m_{QCD} + m_{QED} \Rightarrow$$

$$m_n - m_p = m_d - m_u - 1.7\ \text{MeV} = 1.3\ \text{MeV}$$

No unlikely coincidences, no divine intervention, then …



SM dimensionful parameters

$$\mathcal{L} = \Lambda^4 \mathcal{L}_0 + \Lambda^2 \mathcal{L}_2 + \Lambda^0 \mathcal{L}_4 + \cdots$$

Cosmological constant $\Lambda = 10^{-3}$ eV

Higgs mass parameter $\Lambda = 10^2$ GeV

much smaller than M_{Pl} or other fundamental scales

From field-theory point of view, the two problems are deeply connected: are their solutions disconnected?

Cosmological constant

- no good theoretical explanation

Weinberg
Vilenkin

- vacuum energy does not prevent galaxy formation ⇨ $\Lambda <$ few 10^{-3} eV

Higgs mass parameter

- good theoretical proposals (after LEP2 all of them suffer from a certain amount of tuning)
- existence of non-trivial chemistry ⇨ v < few 10^2 GeV

Agrawal et al.

Why are Λ_{CC} and m_H much smaller than M_{Pl}: good scientific question or similar to Kepler's attempt?

PROS

- Λ_{CC} and m_H are the result of cancellations between large contributions
- the tuning is incredibly precise: $\Lambda_{CC}/M_{Pl} = 10^{-31}$, $m_H/M_{Pl} = 10^{-17}$

CONS

- Naturalness fails for CC, as there is no evidence for new physics at 10^{-3} eV
- No indications for new physics at LEP2 (entering fine-tuning territory)

I hope that Λ_{CC} and m_H are explained in terms of fundamental physics. However I cannot exclude that the solution to the hierarchy problem does not modify SM extrapolation beyond TeV

Multitude of theories, similar to multitude of stars?

Inflation ⇨ many universes

String theory ⇨ many vacua

~~Promise of string theory: it can predict everything~~

Success of string theory: it predicts nothing!

Abandon hierarchy problem (speculations on probability distributions of theories) and use only observational hints

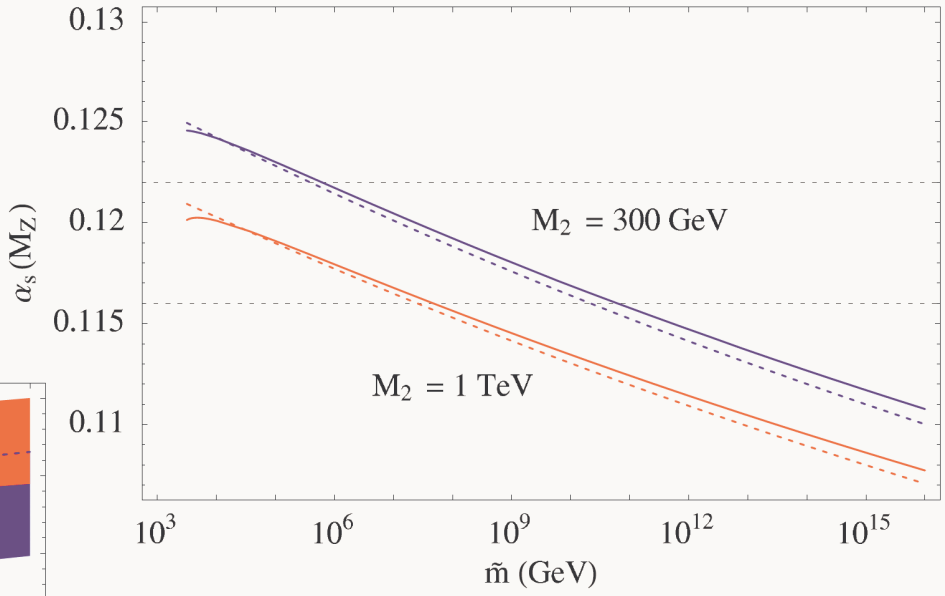
Gauge-coupling unification: motivated by theory that addresses fundamental structure of SM and by measurements on α_i

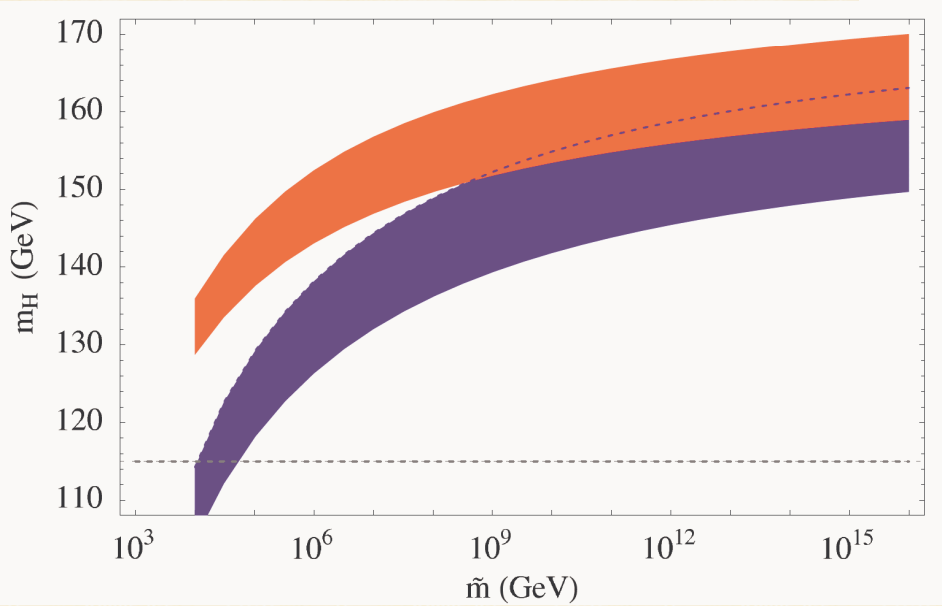
Dark matter: connection between weak scale and new particle masses

$$\Omega_{\mathrm{rel}} h^2 \approx \frac{0.1\,\mathrm{pb}}{\langle \sigma v \rangle}$$

Proposal of SPLIT SUPERSYMMETRY: retain at the weak scale only gauginos, higgsinos and one Higgs boson (squarks, sleptons and extra Higgs at the scale $\tilde{m}$)

Gauge-coupling unification as successful (or better) than in ordinary SUSY



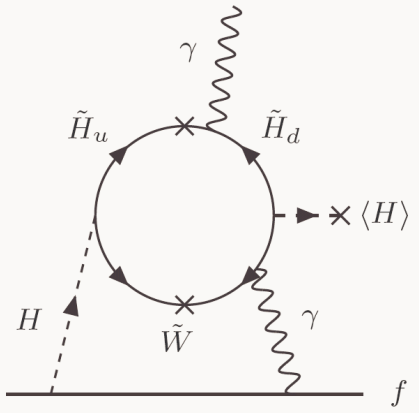


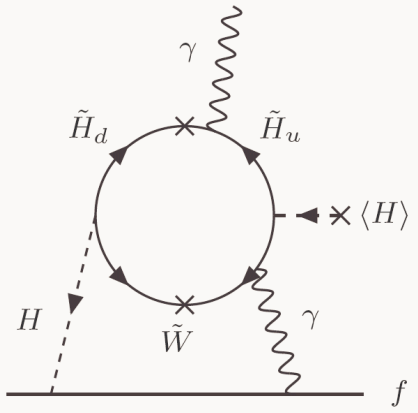
Higgs boson heavier than in ordinary SUSY

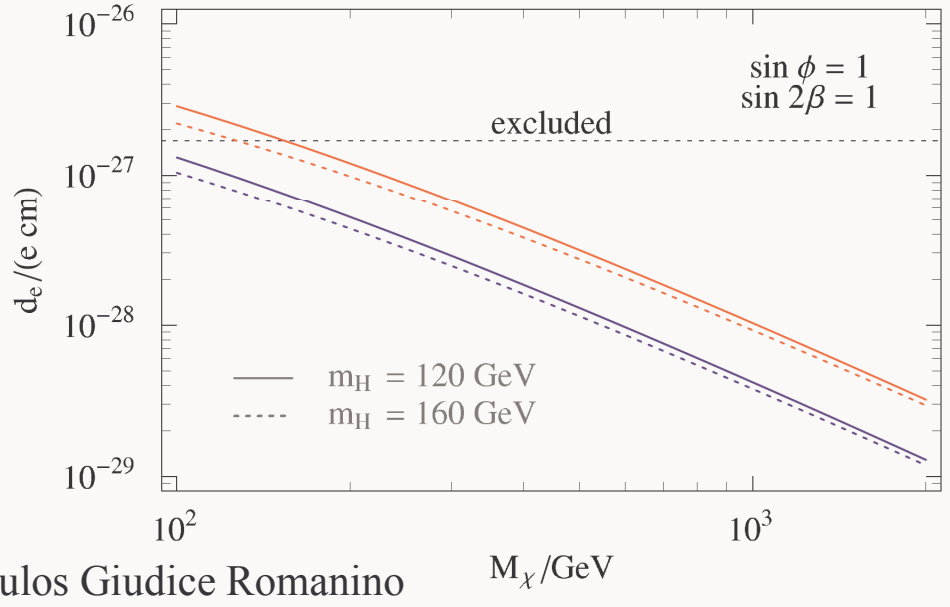
Giudice Romanino

Flavour, CP, proton stability problems are solved for large $\tilde{m}$

EDM just below experimental limit (for maximal phase)







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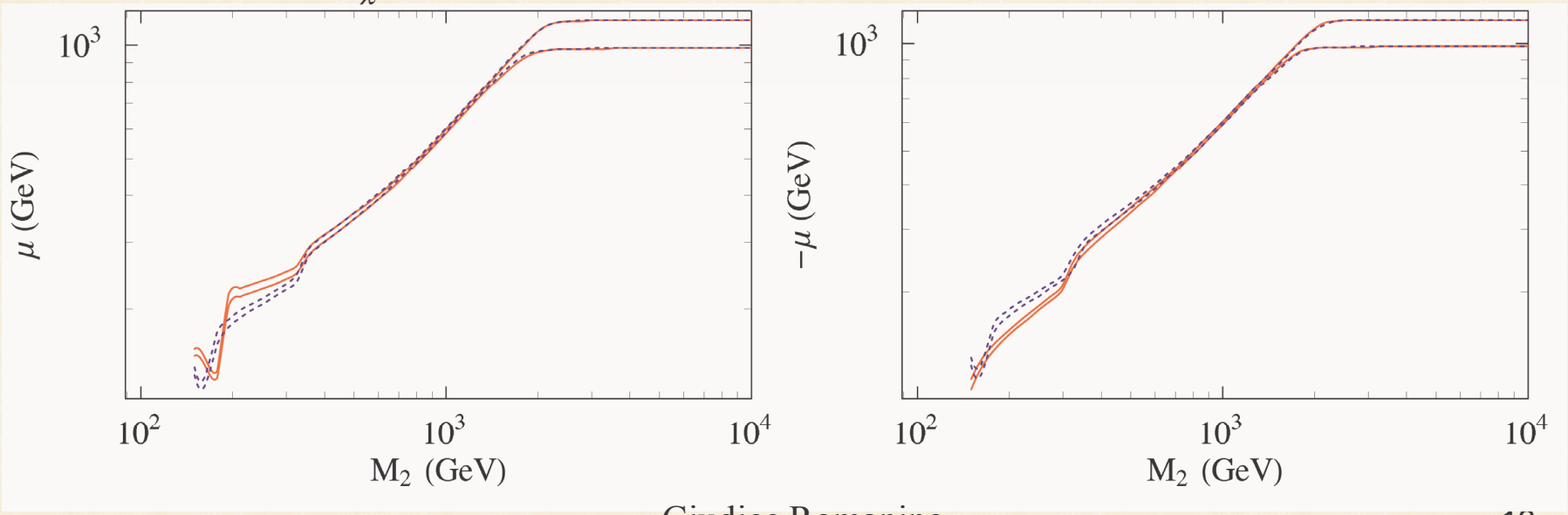
DARK MATTER IN SPLIT SUPERSYMMETRY

With respect to ordinary susy
- μ not determined by EWSB
- B only interacts with Higgs-Higgsino

- χ mixed state $\Omega_\chi h^2 \approx 0.1\,\mu^2\left(M_1^2+\mu^2\right)^2/\left(m_\chi\ \mathrm{TeV}\right)^4$
- χ Higgsino $\Omega_\chi h^2 \approx 0.09\left(\mu/\mathrm{TeV}\right)^2$ DM for $\mu = 1.0-1.2\ \mathrm{TeV}$
- χ Wino $\Omega_\chi h^2 \approx 0.02\left(M_2/\mathrm{TeV}\right)^2$ DM for $M_2 = 2.0-2.5\ \mathrm{TeV}$



The space of Split Supersymmetry is mapped by $(\tilde{m}, m_{3/2})$

$$\frac{dn_{3/2}}{dt} + 3Hn_{3/2} = \left(\gamma_{sc} + \gamma_{dec}\right)$$

$$\gamma_{sc} = C\frac{T^6}{M_{Pl}^2}$$

Bolz Brandenburg Buchmüller

$$\gamma_{dec} = C' e^{-\tilde{m}/T}\left(\tilde{m}^{13/2}T^{3/2}\right)\Big/\left(m_{3/2}^2 M_{Pl}^2\right)$$

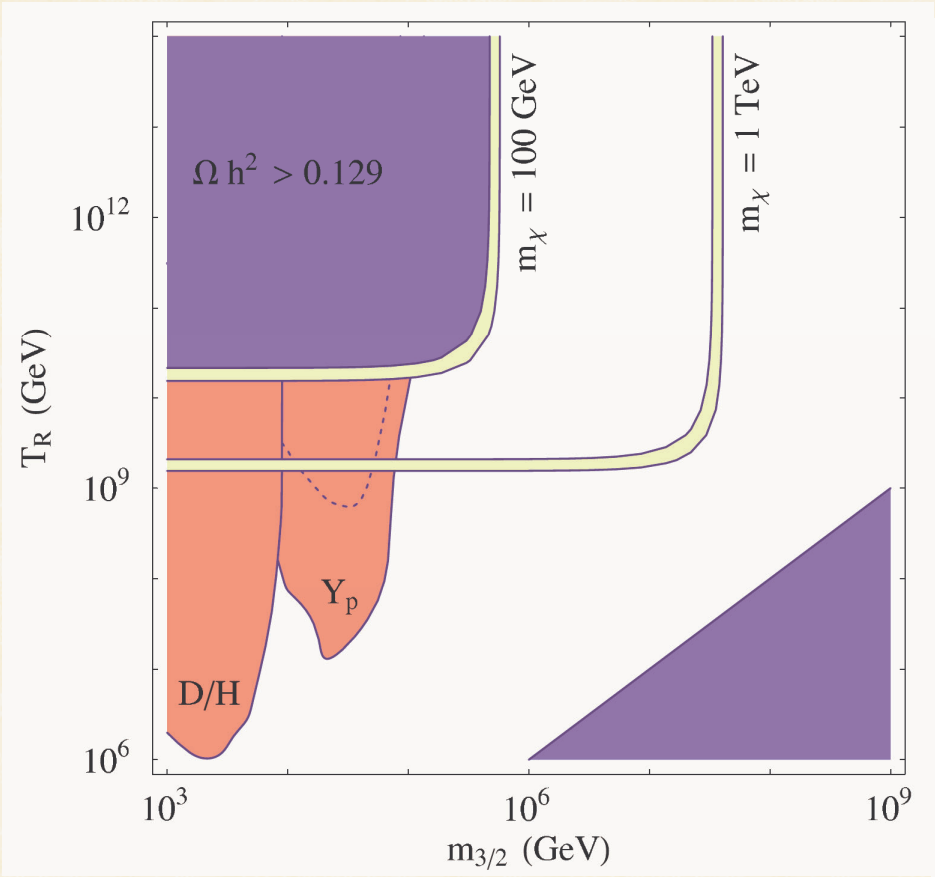
$$\frac{dY_{3/2}}{dT} = -\frac{\gamma_{sc} + \gamma_{dec}}{HTs} \quad \Rightarrow \quad Y_{3/2} = Y_{3/2}^{sc} + Y_{3/2}^{dec}$$

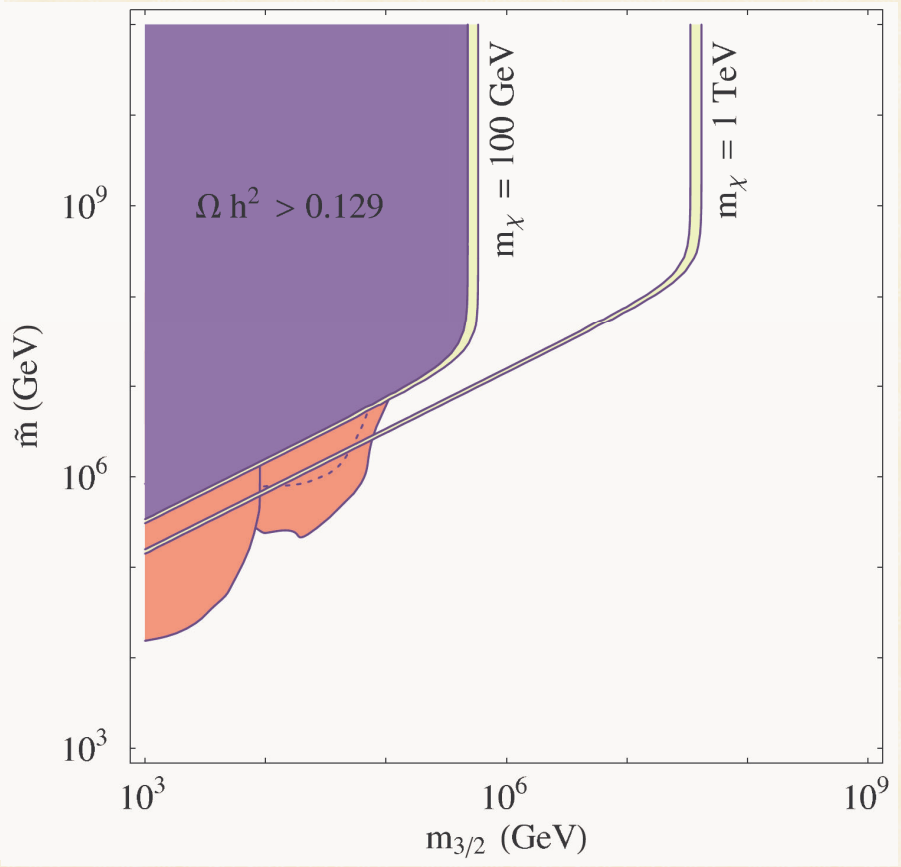
$$Y_{3/2}^{sc} = \left(\frac{T_R}{10^{10}\ \text{GeV}}\right) 10^{-12}$$ dominated by high T

$$Y_{3/2}^{dec} = \left(\frac{\tilde{m}}{10^{8}\ \text{GeV}}\right)^3 \left(\frac{10^{7}\ \text{GeV}}{m_{3/2}}\right)^2 10^{-12}$$ dominated by $T = \tilde{m}$

$$\text{If } T_{3/2} < T_f \Rightarrow m_{3/2} < \left(\frac{m_\chi}{\text{TeV}}\right)^{2/3} 4\times 10^7\ \text{GeV}$$

gravitino decay generates a non - thermal population of χ





$$\tilde{m} > T_R$$

$$T_R > \tilde{m} > \left(\frac{T_R}{10^{10}\,\mathrm{GeV}}\right)^{1/3} \times \left(\frac{m_{3/2}}{10^5\,\mathrm{GeV}}\right)^{2/3} 4\times 10^6\,\mathrm{GeV}$$

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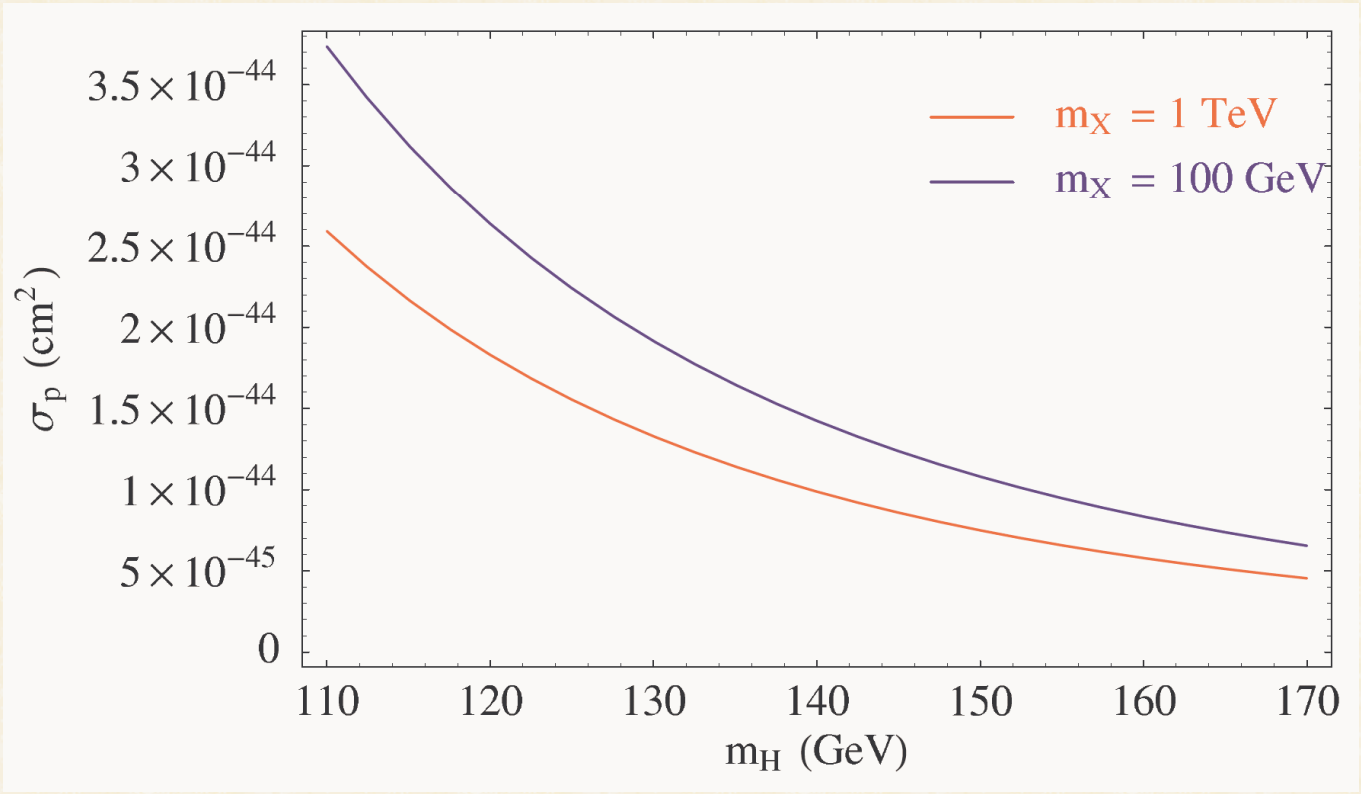
Upper bound on m_χ from thermal relic abundance retained also when gravitino decay contributes to DM

Spin-independent χ scattering cross section off protons is mediated by Higgs exchange



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Why Supersymmetry?

Gauge-coupling unification and DM do not nail new physics as much as the naturalness criterion

- Splitting of GUT irreps: in SpS Higgs doublet-triplet splitting is sufficient
- Light particles: R-symmetry protects fermion masses
- Existence and stability of DM: R-parity makes χ stable
- Instability of coloured particles: coloured particles are necessary, but they decay either by mixing with quarks (FCNC!) or by interactions with scale $< 10^{13}$ GeV
- Minimality: minimal field content at the weak scale consistent with gauge-coupling unification and DM

SpS not unique, but it has all the necessary features built in

Why Split Supersymmetry?

SpS Spectrum generated by R-symmetry with $R[H_u H_d]=0$

Whenever there is D-term (rather than F-term) susy breaking, only dim-2 soft terms are generated at leading order

$$\tilde{m}_Q, B_\mu \approx \tilde{m}$$

Dim-3 soft terms are generated by non-renormalizable operators

$$\mu, M_{\tilde{g}} \approx \tilde{m}^2 / M_*$$

Analogy with L-violation: in SM no m_ν at leading order, but

$$m_\nu \approx \mathrm{v}^2 / M_*$$

Indeed, in D-breaking, there is an accidental R-symmetry

CONCLUSIONS

- Failure of naturalness argument for CC casts doubts on the existence of a physical threshold at the weak scale
- Split Supersymmetry abandons hierarchy problem, but retains gauge-coupling unification and dark matter
- Not unique solution but, under certain assumption, it is the simplest option
- Certain patterns of susy breaking automatically lead to the spectrum of Split Supersymmetry
- Observational consequences for collider searches, EDM, dark matter and gravitino cosmology