Spread Supersymmetry

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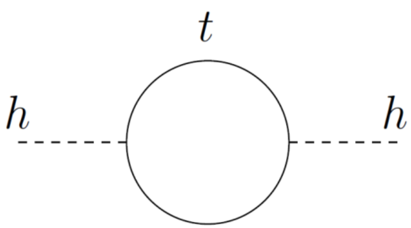
Is there a New Physics?

— if so, where is it?

Naturalness



… We "must" find $M_{New} \sim v_{EW}$

⟹ true?

Shocking news in 1998

Supernova cosmology project; Supernova search team

$$\Lambda \neq 0 \, !$$

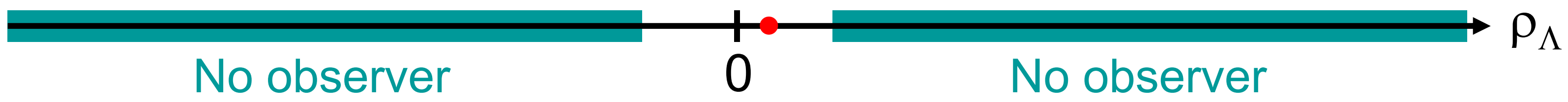
$\rho_{\Lambda,obs} \sim (10^{-3}\,\text{eV})^4 \ll M_{Pl}^{\,4}$ (or TeV^4)

- Naïve estimates $O(10^{120})$ too large
- There does not seem new gravitational physics at $L \sim (10^{-3}\,\text{eV})^{-1}$

More significantly, $\rho_\Lambda \sim \rho_{matter}$ — Why now?

Emerging picture

--- Environmental selection in multiple "universes" (the multiverse)



It is "natural" to observe $\rho_{\Lambda,obs}$, as long as different values of ρ_Λ are "sampled"

c.f. Weinberg ('87)

Also suggested by theory

- String landscape

  Compact (six) dimensions → huge number of vacua

- Eternal inflation

  Inflation is (generically) future eternal → populate all the vacua

Significant Impacts on the way we think about physics

- Fundamental theory

  Predictivity crisis / measure problem → A new view of spacetime and gravity

  … Quantum mechanics is important even at long distances   Multivere = Quantum Many Worlds

  c.f. Y.N., arXiv:1205.2675

- Implications for TeV physics

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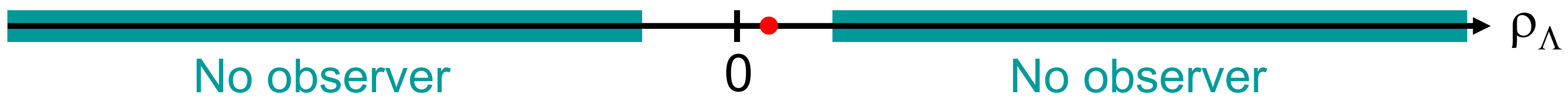

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⇒ • Implications for TeV physics

Spread Supersymmetry
(especially) with $\tilde{W}$ LSP

L.J.Hall and Y.Nomura, JHEP 01, 082 (‘12) [arXiv:1111.4519]
L.J.Hall, Y.Nomura, and S.Shirai, arXiv:1210.2395

Building upon

……

Giudice, Luty, Murayama, Rattazzi (‘98) … (unsequestered) anomaly mediation
Wells (‘03,’04) … scalar particles at PeV

……

Wino dark matter / collider: Gherghetta, Giudice, Wells; Moroi, Randall; Hisano, Matsumoto, Nagai, Saito, Semani; Hisano, Ishiwata, Nojiri, Saito; Ibe, Moroi, Yanagida; Buckley, Randall, Shuve; …

……

Arkani-Hamed, Dimopoulos (‘04) … “split supersymmetry”
Arkani-Hamed, Delgado, Giudice (‘06) … “the simplest model of split”

……

- What is the **simplest** scenario?
  (especially in the framework of the multiverse)
- What are the experimental **signals**?

Should the weak scale be natural?

--- No!

ex. Stability of complex nuclei Agrawal, Barr, Donoghue, Seckel ('97)

For fixed Yukawa couplings,

no complex nuclei for $v \gtrsim 2\, v_{obs}$ Damour, Donoghue ('07)

… The origin of the weak scale may very well be anthropic / environmental!

Does this mean that there is no weak scale supersymmetry?

--- No

The scale of superparticle masses determined by statistics

$$d\mathscr{N} \sim f(\tilde{m})\, \frac{v^2}{\tilde{m}^2}\, d\tilde{m} \qquad f(\tilde{m}) \sim \tilde{m}^{p-1}$$

For $p < 2$, weak scale SUSY results, but for $p > 2$, $\tilde{m}$ prefers to be large…

What is the simplest scenario in this case?

We assume the "simplest": MSSM + *R* parity

(I) The simplest high scale mediation

SUSY breaking mediated at the field-theoretic "cutoff" scale M_* ($\gtrsim M_{unif}$)
e.g. the string scale

--- no (need of) flavor symmetry, *CP*, sequestering, …

SUSY breaking field $X = \theta^2 F$ is **not** neutral

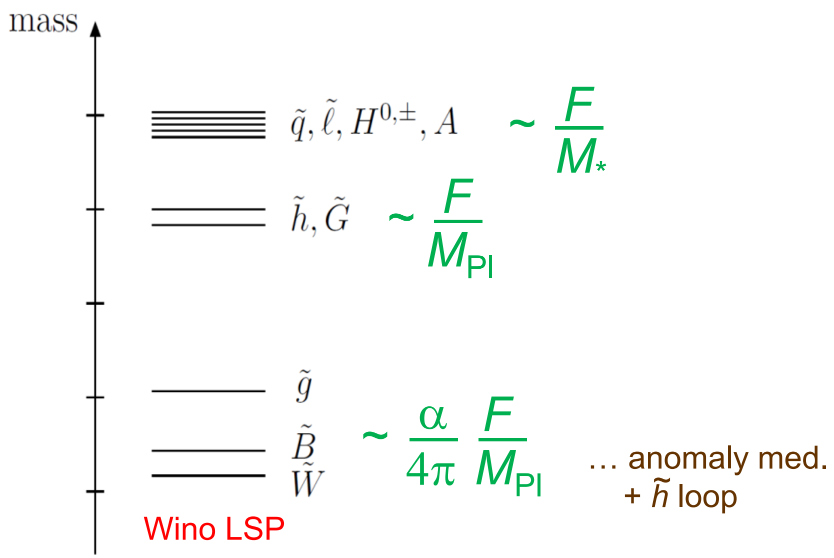
… scalar masses: $X^+X\,Q^+Q$, B_μ term: $X^+X\,H_uH_d$

~~gaugino mass: $XW^\alpha W_\alpha$~~, ~~A term: XQ^+Q~~, ~~μ term: $X^+H_uH_d$~~

… supergravity or loop effects

→ "Spread" in the superparticle spectrum

Write down all the possible terms
with $O(1)$ couplings in units of M_*,
including $K = H_uH_d$



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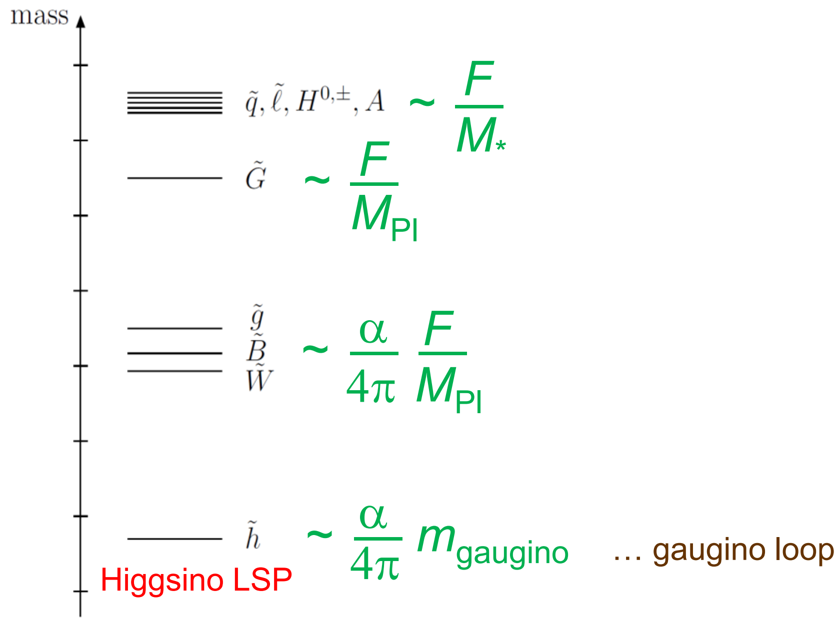

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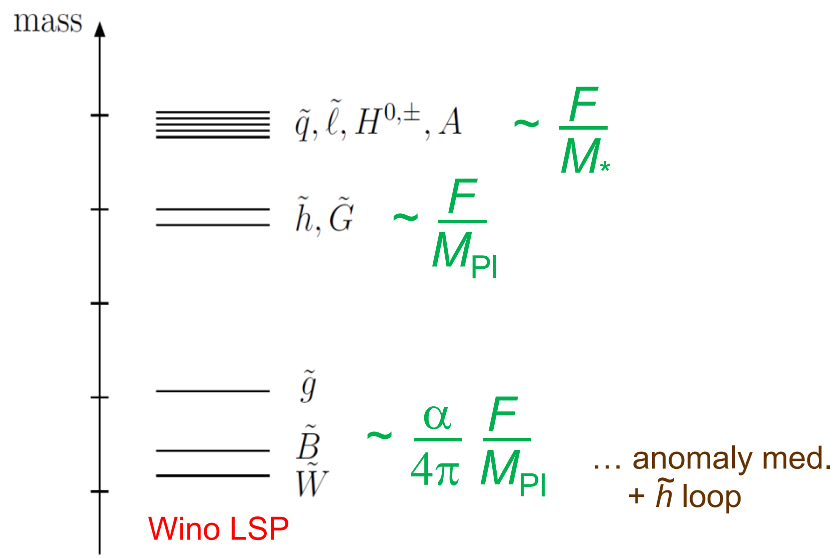
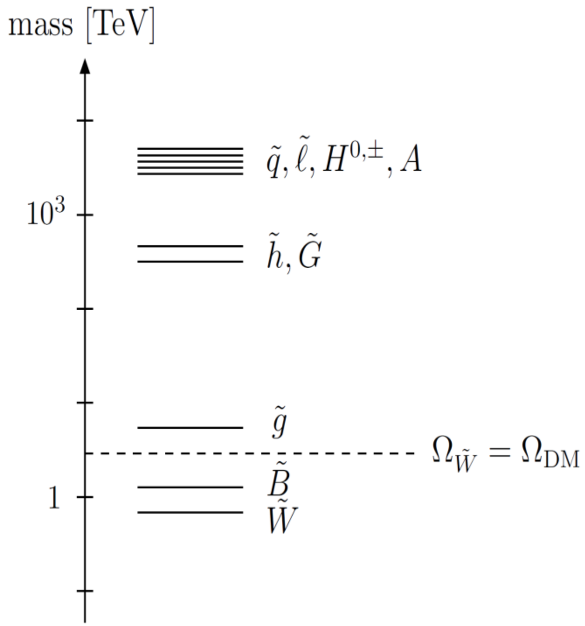


What stops "drifting-up" of the spectrum?

(II) The existence of the environmental boundary

$$\Omega_{DM} < \Omega_{DM,max}$$



If thermal & $\Omega_{\tilde{W}} = \Omega_{DM}$,
$M_{\tilde{W}} \sim 3$ TeV … generally **not** the case

Note: This is the same boundary used to argue for axion DM

Linde ('88); Tegmark, Aguirre, Rees, Wilczek ('05)

In general,

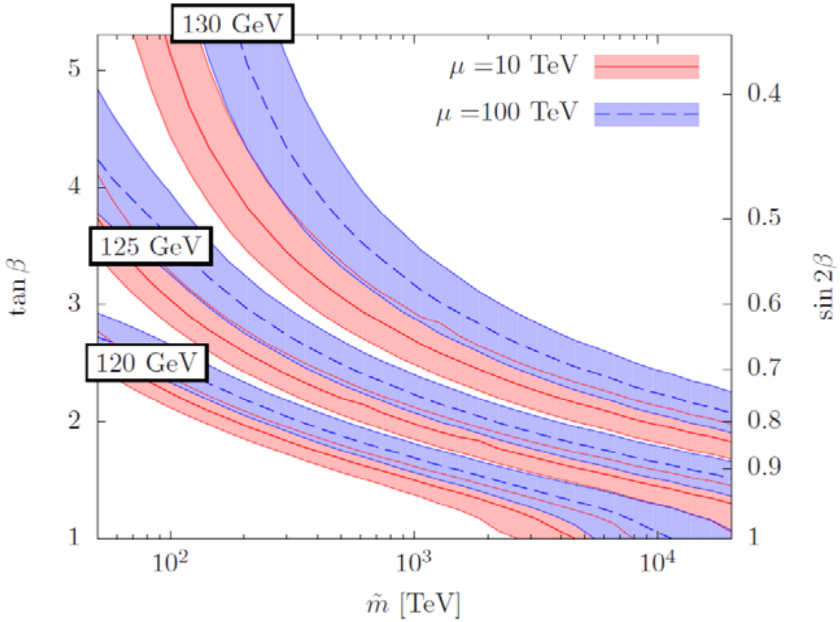
$$\Omega_a + \Omega_{WIMP} < \Omega_{DM,max} \longrightarrow$$ Multi-component DM !

Immediate gifts

The two-step hierarchy implies

$$\tilde{m} \sim (10^2 - 10^4)\ \text{TeV}$$

- Higgs boson mass



- Unsuppressed B_μ term
  → $\tan\beta \sim O(1)$
- $|A_t| \ll m_{\tilde{t}}$

- No SUSY flavor or *CP* problem (but still have a chance to see signals in the future)
- No gravitino problem ($m_{3/2} \sim 10 - 100$ TeV)

Experimental signatures

— depend on the gaugino spectrum & overall mass scale

(A) Gaguino spectrum

The gaugino masses arise from anomaly mediation and Higgsino-Higgs loops

$$M_1 = \frac{3}{5}\frac{\alpha_1}{4\pi}(11 m_{3/2} + L),$$
$$M_2 = \frac{\alpha_2}{4\pi}(m_{3/2} + L),$$
$$M_3 = \frac{\alpha_3}{4\pi}(-3 m_{3/2})(1 + c_{\tilde{g}}).$$

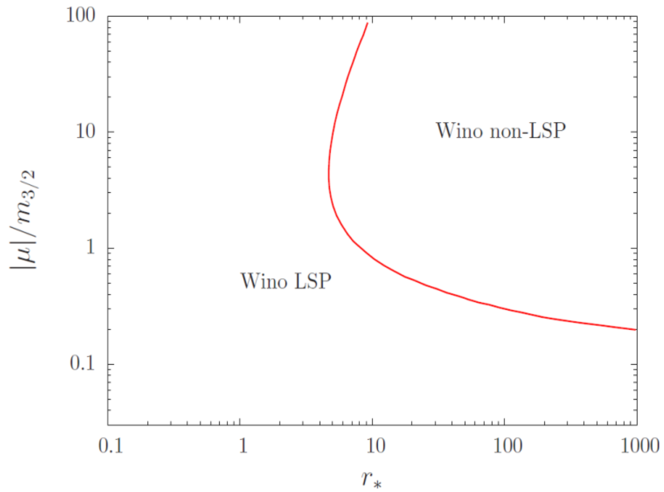
correction from heavy squarks

Here,

$$L = \mu \sin(2\beta)\frac{m_A^2}{|\mu|^2 - m_A^2}\ln\frac{|\mu|^2}{m_A^2} \sim 2\mu\sin(2\beta)\ln r_*$$

… from Higgsino/Higgs loops

$$r_* \equiv \frac{M_{Pl}}{M_*}$$



Wino LSP
in most parameter space

(B) The overall mass scale

— controlled by the dark matter abundance through condition $\Omega_{\rm DM} < \Omega_{\rm DM,max}$

There are three sources for the wino relic abundance

$$\Omega_{\tilde{W}} = \Omega_{\tilde{W}}^{\rm thermal} + \Omega_{\tilde{W}}^{\rm non-thermal}$$

from gravitino decay

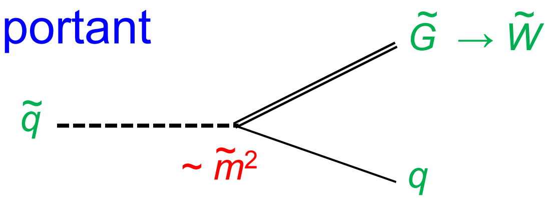
$$\Omega_{\tilde{W}}^{\rm thermal} h^2 \simeq 2 \times 10^{-4} \left(\frac{M_{\tilde{W}}}{100~{\rm GeV}} \right)^2$$

$$\Omega_{\tilde{W}}^{\rm non-thermal} = \frac{M_{\tilde{W}}}{m_{3/2}} \left(\Omega_{3/2}^{\rm freeze-in} + \Omega_{3/2}^{\rm UV} \right)$$

$$\Omega_{3/2}^{\rm freeze-in} h^2 \simeq 10^{-2} \sum_{i:\,{\rm thermalized}} d_i \left(\frac{\tilde{m}_i}{1000~{\rm TeV}} \right)^3 \left(\frac{100~{\rm TeV}}{m_{3/2}} \right)$$

$$\Omega_{3/2}^{\rm UV} h^2 \simeq 3.9 \left(\frac{T_R}{10^9~{\rm GeV}} \right) \left(\frac{m_{3/2}}{100~{\rm TeV}} \right)$$

Because of large $\tilde{m}$, the "freeze-in" contribution is important



… larger wino abundance

→ smaller wino (gaugino) mass

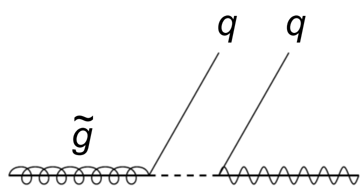
(even smaller mass if significant axion component)

⟹ **The gluino can be within LHC reach!**

Gluino signals

Because of large $\tilde{m}$, the gluino is "long-lived"

$$c\tau_{\tilde{g}} = O(1\ \mathrm{cm}) \left(\frac{M_{\tilde{g}}}{1\ \mathrm{TeV}}\right)^{-5} \left(\frac{\tilde{m}}{1000\ \mathrm{TeV}}\right)^{4}$$



… $r_* \gtrsim O(10)$ $\rightarrow$ long-lived (displaced) gluino signatures

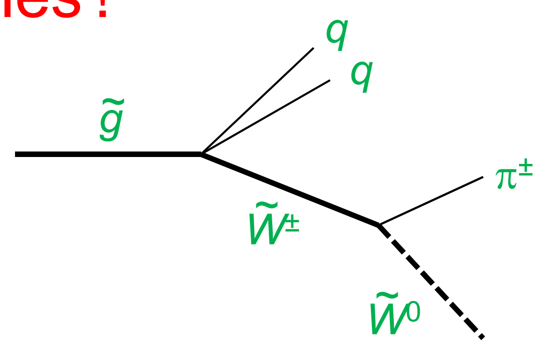
Winos are (nearly-degenerate) co-LSPs

$$M_{\tilde{W}^\pm} - M_{\tilde{W}^0} \simeq 160\ \mathrm{MeV} \longrightarrow c\tau_{\tilde{W}^\pm} = O(10\ \mathrm{cm})$$

(Tree-level contribution could give a correction)

⟹ Decay chain with two long-lived particles !

$$\tilde{g} \xrightarrow[\text{long-lived}]{} q\bar{q}(\tilde{W}^\pm \xrightarrow[O(10\ \mathrm{cm})]{} \tilde{W}^0\pi^\pm)$$



… allows us to measure masses & lifetimes of these particles

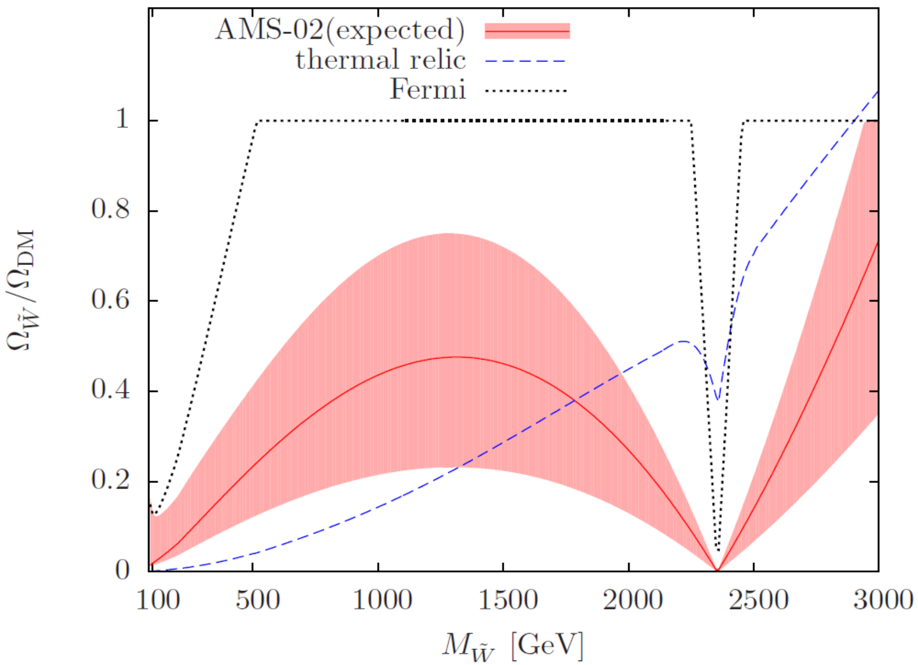
Measuring flavors of quarks from $\tilde{g}$ decay,
we can probe the flavor structure of the squark sector !

e.g. $\tilde{g} \rightarrow b\bar{s}\tilde{\chi}, t\bar{c}\tilde{\chi}$

Cosmic / astrophysical signals

Good prospect for indirect detection

because of relatively large wino annihilation section

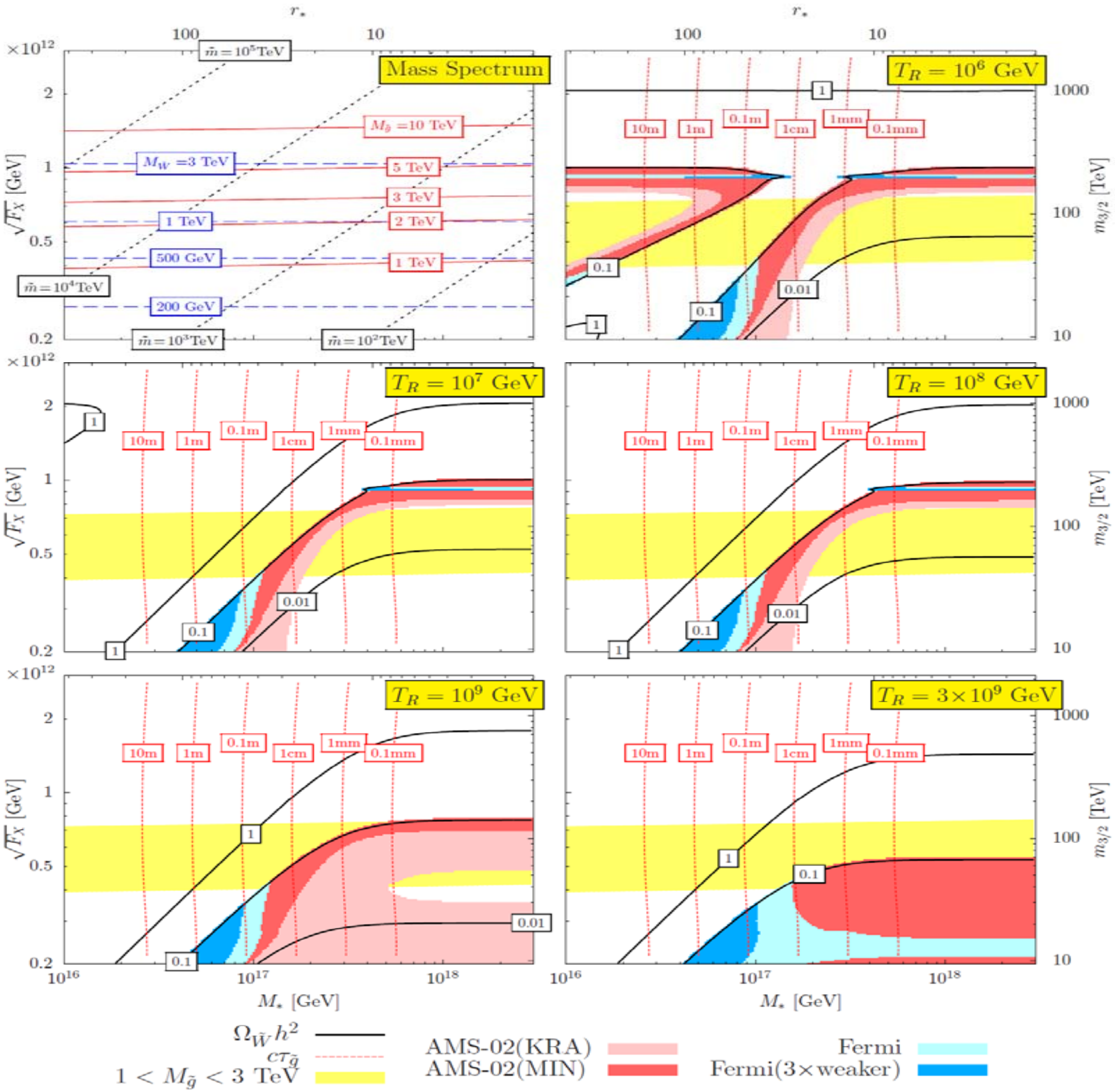


- Fermi gamma ray search already constrains the model
- AMS-02 antiproton search will probe significant parameter space

Direct detection is challenging

$$\sigma_{\rm SI} \simeq (0.6-2)\times 10^{-46}\ {\rm cm}^2\ \sin^2(2\beta)\left(\frac{|\mu|}{5\ {\rm TeV}}\right)^{-2}\left(\cos(\arg(M_2\mu))+\left|\frac{M_2}{\mu}\right|\right)^2$$

Current status (parameters: F_X, M_*, L, T_R for degenerate m)



$L \sim 3\, m_{3/2}$

(small $|M_3/M_2|$)

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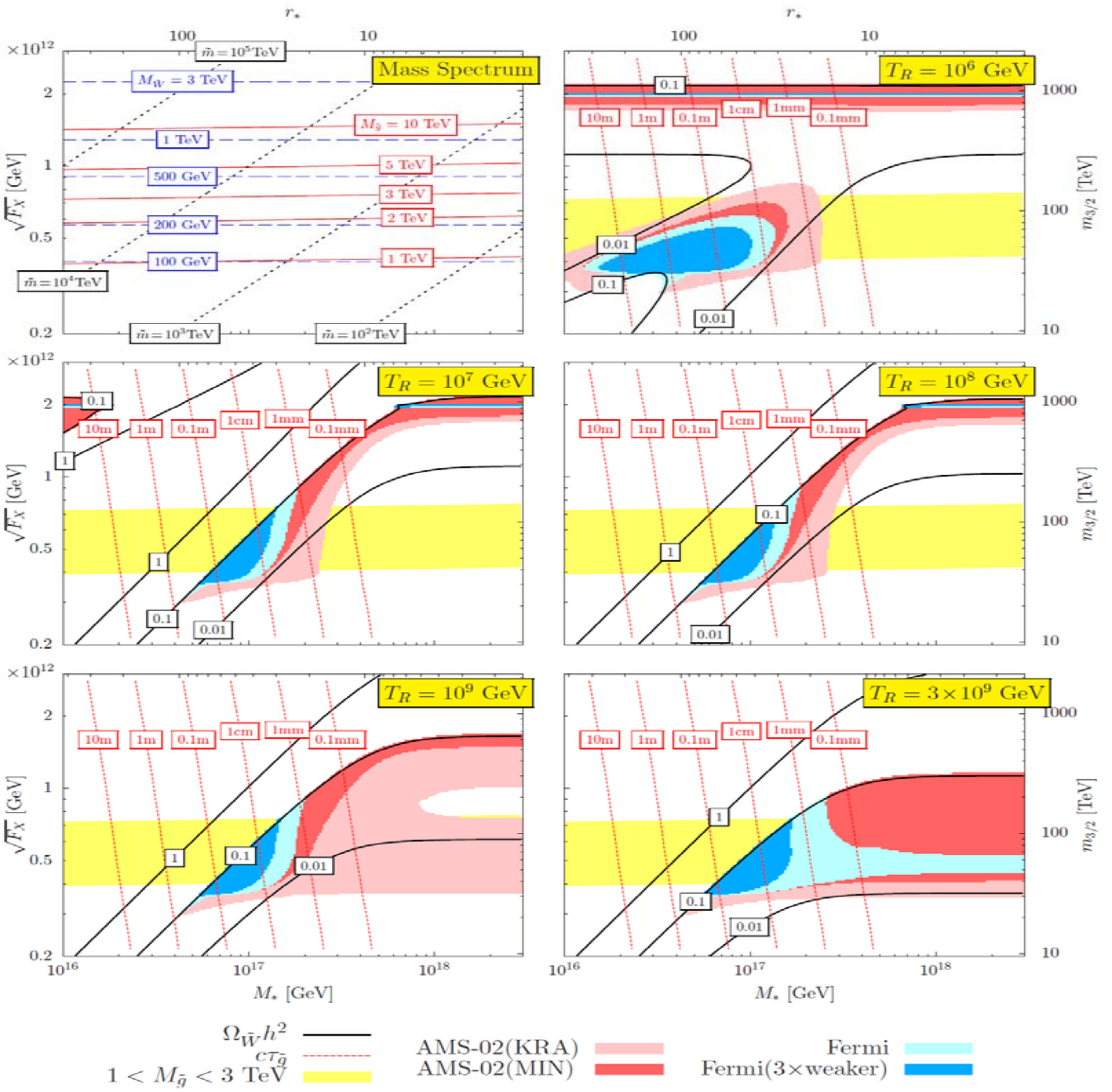


$L \sim 0$

(large $|M_3/M_2|$)

Future prospects

- AMS-02 will probe a significant portion of parameter space

- LHC has a great reach

  — gluino

  $c\tau_{\tilde{g}} \ll O(1\ \mathrm{mm})$ … missing energy + high P_T jets

  $c\tau_{\tilde{g}} \gtrsim O(0.1\ \mathrm{mm})$ … displaced decay

  — long-lived charged wino

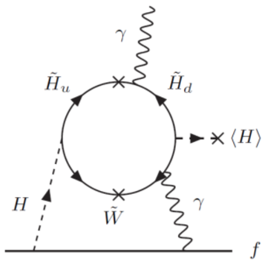
- CMB measurements (recombination history)

  … can probe the region

$$m_{\tilde{W}} \lesssim \left(\frac{\Omega_{\tilde{W}}}{\Omega_{\mathrm{DM}}}\right)^{2/3} \times \begin{cases} 230\ \mathrm{GeV} & (\mathrm{WMAP7}) \\ 460\ \mathrm{GeV} & (\mathrm{Planck\ forecast}) \\ 700\ \mathrm{GeV} & (\mathrm{cosmic\ variance\ with}\ \ell_{\max} = 2500) \end{cases}$$

Galli, Iocco, Bertone, Melchiorri ('09);
Slatyer, Padmanabhan, Finkbeiner ('09)

- Electric dipole moments



$$d_e \simeq 3 \times 10^{-29}\ e\ \mathrm{cm} \times \sin(2\beta)\,\sin(\arg(M_2\mu)) \left(\frac{|\mu|}{10\ \mathrm{TeV}}\right)^{-1} \left(\frac{M_{\tilde{W}}}{200\ \mathrm{GeV}}\right)^{-1} f(m_h^2/M_{\tilde{W}}^2)$$

Arkani-Hamed, Dimopoulos, Giudice, Romanino ('04)

current bound: $d_e < 1.05 \times 10^{-27}\ e\ \mathrm{cm}$, expected to become $d_e \sim 10^{-31}\ e\ \mathrm{cm}$

- Direct detection, Gravitational wave, …

Multiverse interpretation

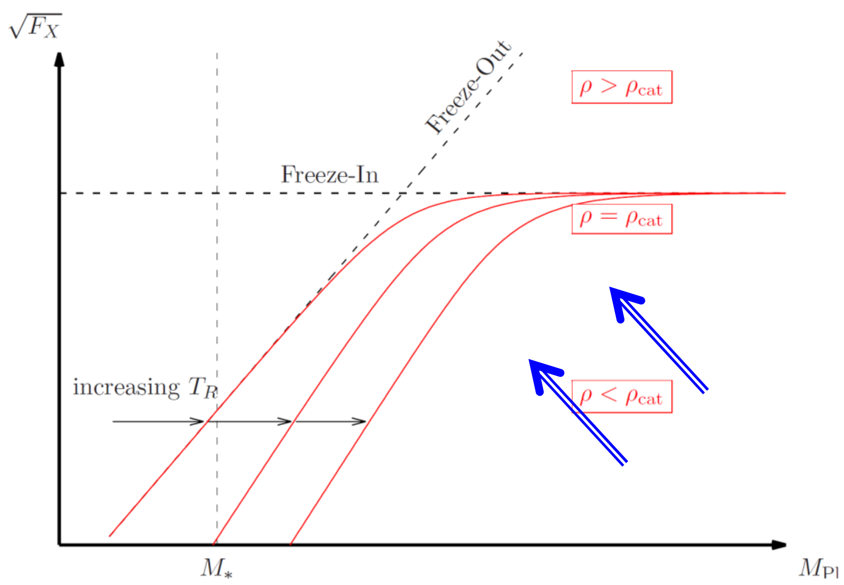
"Strange" coincidences: $\Omega_{\rm thermal} \sim \Omega_{\rm freeze\text{-}out} \sim \Omega_{\rm UV}$

$$(Ym)_{\tilde{W}}|_{\rm FO} \sim 10^{-10}\ {\rm GeV} \left(\frac{\sqrt{F_X}}{2 \times 10^{12}\ {\rm GeV}} \right)^4 \left(\frac{2 \times 10^{18}\ {\rm GeV}}{M_{\rm Pl}} \right)^3,$$

$$(Ym)_{\tilde{W}}|_{\rm FI} \sim 10^{-10}\ {\rm GeV} \left(\frac{\sqrt{F_X}}{2 \times 10^{12}\ {\rm GeV}} \right)^4 \left(\frac{3 \times 10^{17}\ {\rm GeV}}{M_*} \right)^3,$$

$$(Ym)_{\tilde{W}}|_{\rm UV} \sim 10^{-10}\ {\rm GeV} \left(\frac{T_R}{10^9\ {\rm GeV}} \right) \left(\frac{\sqrt{F_X}}{2 \times 10^{12}\ {\rm GeV}} \right)^2 \left(\frac{2 \times 10^{18}\ {\rm GeV}}{M_{\rm Pl}} \right)^2.$$

… understood in terms of "scanning" in the multiverse



→ Environmental determination of $M_{\rm Pl}/M_*$, F_x, and T_R

Summary

Weak scale supersymmetry

- Naturalness
- Gauge coupling unification
- WIMP dark matter

- SUSY flavor/*CP* (and μ) problems
- Cosmological gravitino problem
- ….

Summary

Weak scale supersymmetry

- ~~Naturalness~~ → Typicality
- Gauge coupling unification
- WIMP dark matter

- ~~SUSY flavor/*CP* (and μ) problems~~
- ~~Cosmological gravitino problem~~
- ~~….~~

– The simplest high scale mediation with non-singlet *X*
– Environmental selection on the dark matter abundance

⟹ Spread Supersymmetry

Plenty of experimental signatures

- AMS-02 antiproton search
- LHC probe of (displaced) gluino & charged wino decays (probing flavor)
- CMB, EDM measurements, …

→ (further) forces the revision of the concept of naturalness