Higgs and Supersymmetry In the Multiverse

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LHC 7 & 8

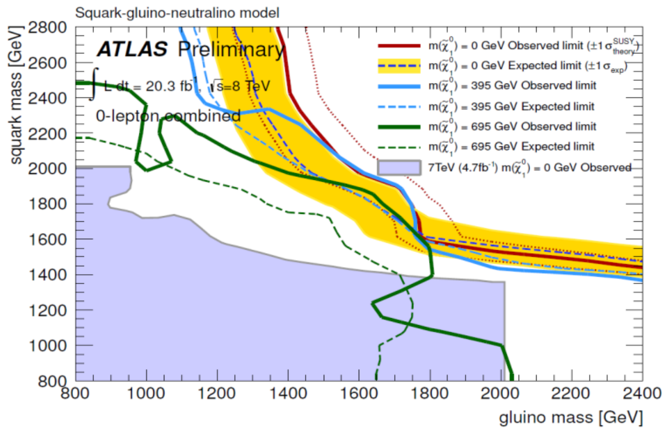
— Discovery of the Higgs boson with $M_H \sim 126$ GeV

— No new physics

- Great success of the Standard Model

- Nature seems to be fine-tuned

… (at least) at the level of $< 10^{-3}$–10^{-2}



ATLAS-CONF-2013-047

Can we do better than just the SM?

Do/Can we still expect new physics?

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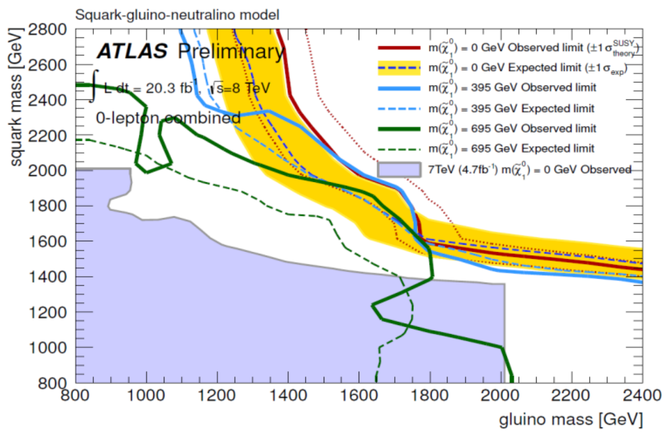

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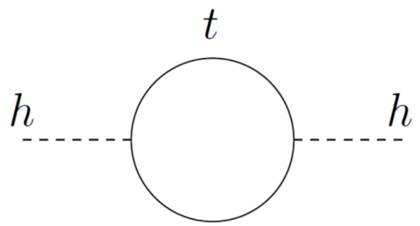
Can we do better than just the SM?

Do / Can we still expect new physics?

The conventional argument for new physics

— Naturalness



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

⟹ true?

Shocking news in 1998

Supernova cosmology project; Supernova search team

$$\Lambda \neq 0\ !$$

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

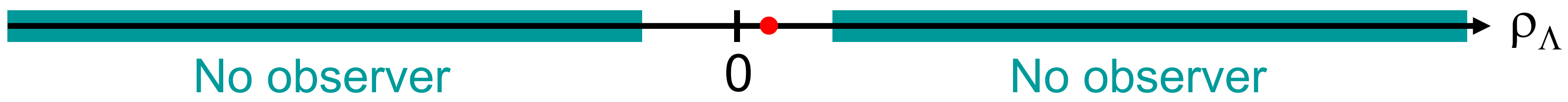
- Naïve estimates $O(10^{120})$ too large
- There does not seem new gravitational physics at $L \sim (10^{-3}\,\text{eV})^{-1}$

More significantly, $\rho_\Lambda \sim \rho_{\text{matter}}$

— Why now? … The statement is even time dependent!

Emerging picture

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



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

c.f. Weinberg ('87)

Also suggested by theory

- String landscape

  Compact (six) dimensions $\rightarrow$ huge number of vacua

- Eternal inflation

  Inflation is (generically) future eternal $\rightarrow$ populate all the vacua

Significant impacts on the way we think about physics

- Fundamental theory

  Predictivity crisis / measure problem $\rightarrow$ A new view of spacetime and gravity

  … Multiverse = Quantum many worlds

  Y.N., JHEP **11**, 063 ('11) [arXiv:1104.2324]

- Implications for TeV physics

Emerging picture

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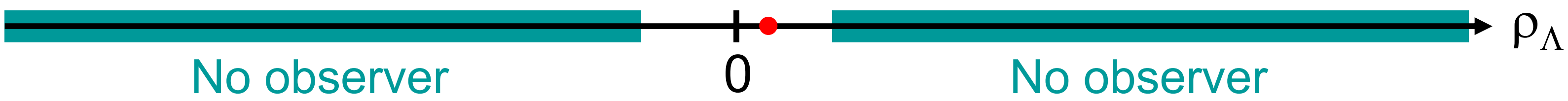

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$\Longrightarrow$ • Implications for TeV physics

Two possible scenarios that SUSY can appear at higher scales (than the naïve weak scale)

High Scale Supersymmetry ($\tilde{m}$ » weak scale)

L.J. Hall and Y. Nomura, JHEP **03** (2010) 076 [arXiv:0910.2235]

— M_H ~ 126 GeV obtained from supersymmetry at a very high scale

Spread Supersymmetry ($\tilde{m}$ ~ 10^2–10^4 TeV)

L.J. Hall and Y. Nomura, JHEP **01** (2012) 082 [arXiv:1111.4519]

— Gauge coupling unification, M_H ~ 126 GeV, (mixed) wino dark matter

… similar scenarios also (later) called mini-split, pure gravity mediation, simply unnatural, …

… depending on the statistics in the multiverse

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 $v \gtrsim 2\, v_{\rm obs}$ 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

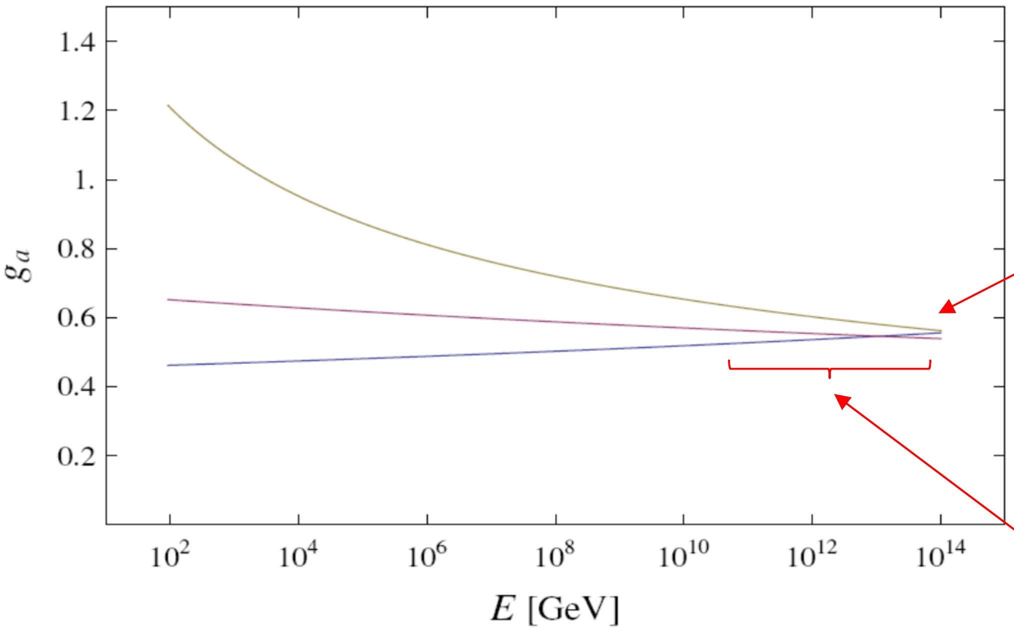
$$d\mathscr{N} \sim f(\tilde{m})\, \frac{v^2}{\tilde{m}^2}\, d\tilde{m} \qquad f(\tilde{m}) \sim \tilde{m}^{p-1}$$

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

Results from LHC may be suggesting this…

(I) What if $\tilde{m}$ shoots up?

Standard Model:



Unification ~ 10^{14} GeV

unification at the level of $\delta g_a^2 \sim 6\%$ at $E \sim 10^{14}$ GeV

~~SUSY~~ at a high scale

Dark matter can be axions — $\theta_{QCD} \ll 1$ … still need mechanism

Doesn't seem that bad…

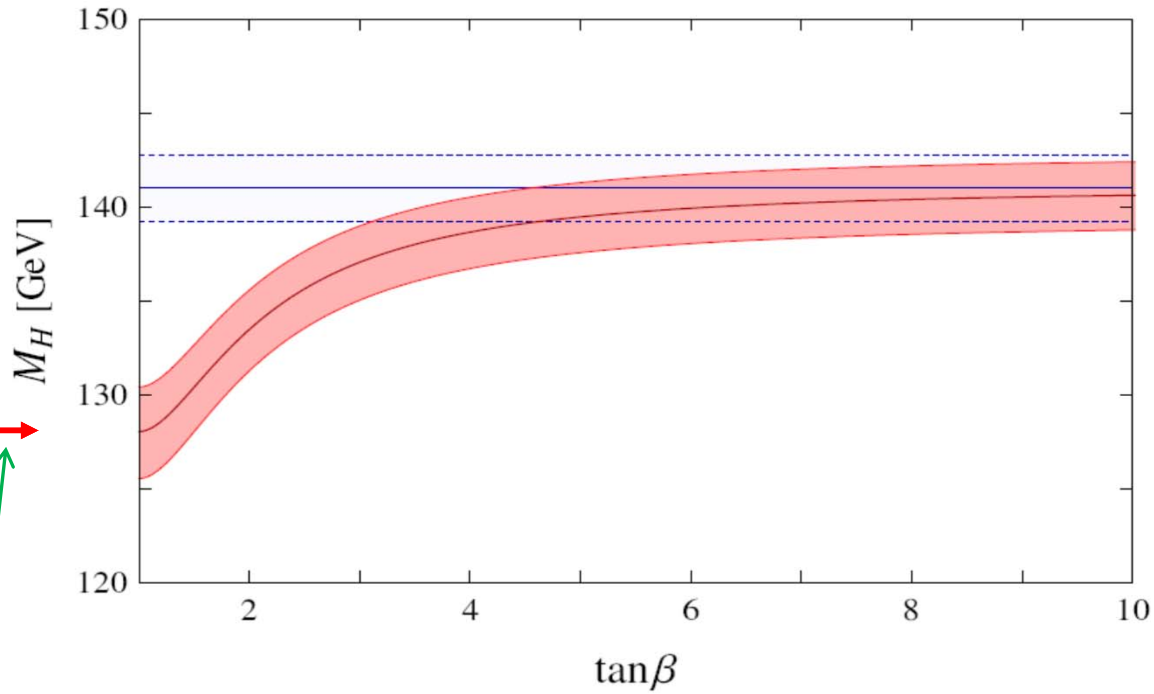
— nothing left at low energies?

High Scale Supersymmetry

Hall and Y.N., 0910.2235

$$\lambda(\tilde{m}) = \frac{g^2(\tilde{m}) + g'^2(\tilde{m})}{8} \cos^2 2\beta$$

$\lambda(m) \rightarrow \lambda(v) \rightarrow M_H$ prediction



$H_u \leftrightarrow H_d$

$m_t = 173.1 \pm 1.3$ GeV
$\alpha_s(M_Z) = 0.1176 \pm 0.002$

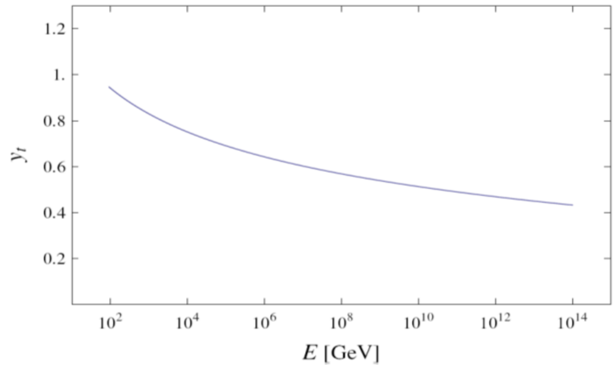
$M_H = (128 \pm 3 \pm 0.6 \pm 1.0)$ GeV

m_t, α_s $\tilde{t}$ loop $\tilde{m} = 10^{14\pm2}$ GeV

Model realizations:

shift symmetry: Hebecker, Knochel, Weigand, 1204.2551
cMSSM b.c.: Ibáñez, Valenzuela, 1301.5167
....

Lucky "accidents"



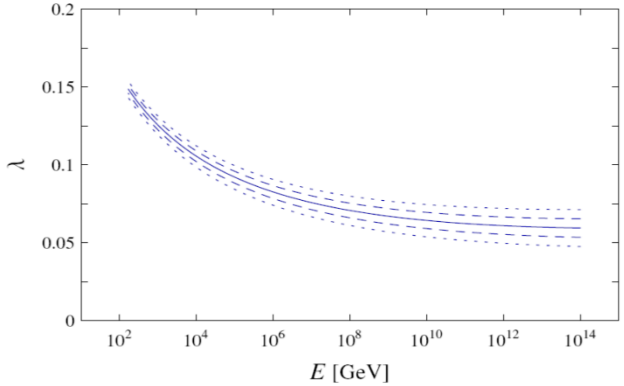
$y_t(\tilde{m}) \approx 0.5\, y_t(v)$

… very small stop loop corrections

(proportional to y_t^4)

- Small gauge and Yukawa couplings $\rightarrow$ extreme insensitivity to $\tilde{m}$
- Infrared convergence property

RGE for λ



Implications

- No new physics at LHC14
- No LSP dark matter (presumably axion dark matter)

(II) $\tilde{m}$ may not shoot up?

— Some environmental effect may stop runaway

For example

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

cf. Tegmark, Aguirre, Rees, Wilczek, astro-ph/0511774

- no disk fragmentation
- close encounter
- ….

$$\rightarrow \tilde{m} < \tilde{m}_{\rm max} \Longrightarrow m_{\rm LSP} \sim \alpha_{\rm eff}\sqrt{T_{\rm eq} M_{\rm Pl}} \sim \text{TeV}$$

…unnatural $\gtrsim$ TeV spectrum

$$X W^{\alpha} W_{\alpha}$$

exist → MSSM with multi-TeV superparticles (environmental MSSM)

not exist (e.g. X not neutral) → Gaugino masses at 1-loop

Anomaly mediation:

Giudice, Luty, Murayama, Rattazzi ('98)

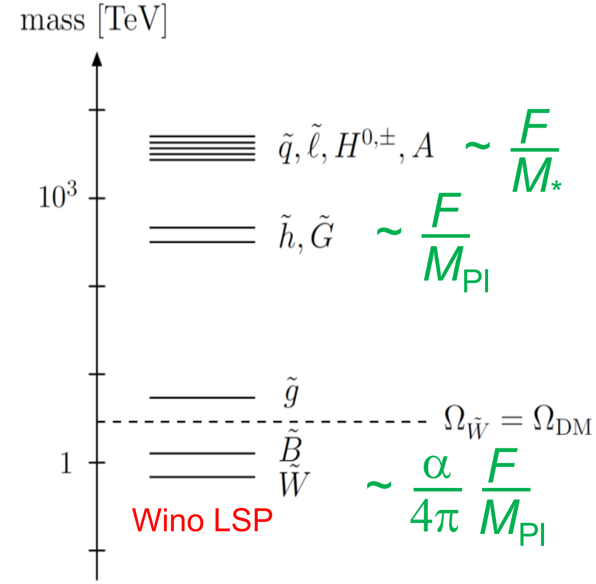
Wells ('03,'04) … PeV scalars

… Spread Supersymmetry

Gauge coupling unification as in the MSSM

Spread Supersymmetry

Hall and Y.N., 1111.4519



$\tilde{m}$ ~ (10^2 – 10^4) TeV

— can eliminate a need of flavor symmetry, *CP*, …

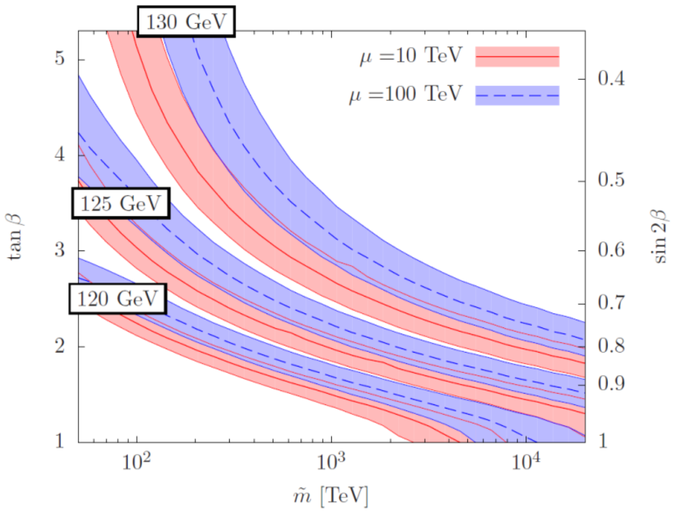
If thermal & $\Omega_W = \Omega_{DM}$,

M_W ~ 3 TeV … generally **not** the case

In general, $\Omega_a + \Omega_{WIMP} < \Omega_{DM,max}$

→ multi-component DM !

Higgs mass is "automatic"



c.f.

Spread

Hall, Nomura, 1111.4519

Pure gravity mediation

Ibe, Yanagida, 1112.2462

Mini-split

Arvanitaki, Craig, Dimopoulos, Villadoro, 1210.0555

Simply unnatural

Arkani-Hamed, Gupta, Kaplan, Weiner, Zorawski, 1212.6971

Experimental signatures

Hall, Y.N., Shirai, 1210.2395

— a lot !

(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

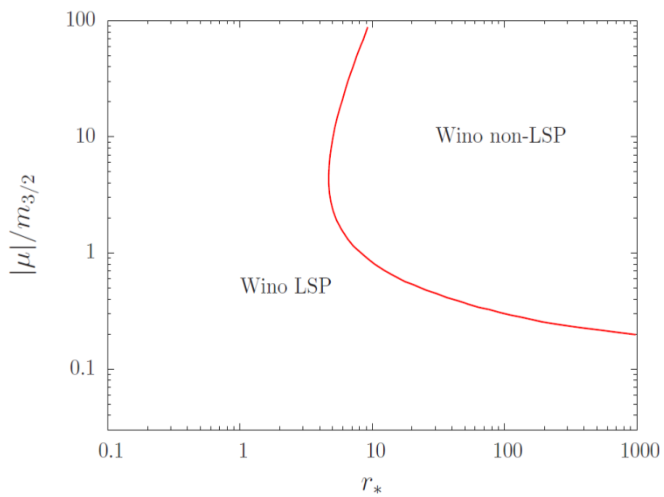
Here,

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

… from Higgsino/Higgs loops

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

⟹



Wino LSP
in most parameter space

(B) The overall mass scale

— determined 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

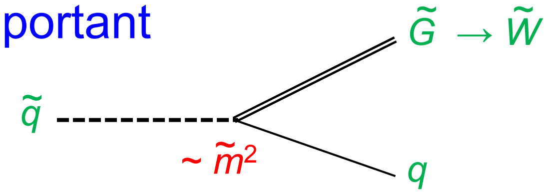
$$\Omega_{\tilde W}^{\rm thermal} h^2 \simeq 2\times 10^{-4} \left(\frac{M_{\tilde W}}{100~{\rm GeV}} \right)^2$$

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

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

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

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



… larger wino abundance

→ smaller wino (gaugino) mass

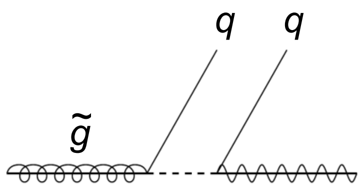
(even smaller mass if significant axion component)

⟹ The gluino may be within LHC reach!

Gluino signals

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

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



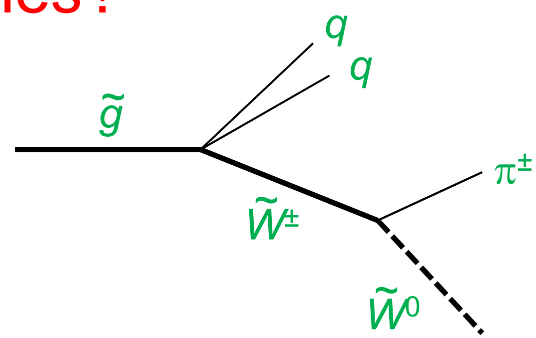
… $r_* \gtrsim O(10)$ → long-lived (displaced) gluino signatures

Winos are (nearly-degenerate) co-LSPs

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

⟹ Decay chain with two long-lived particles !

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

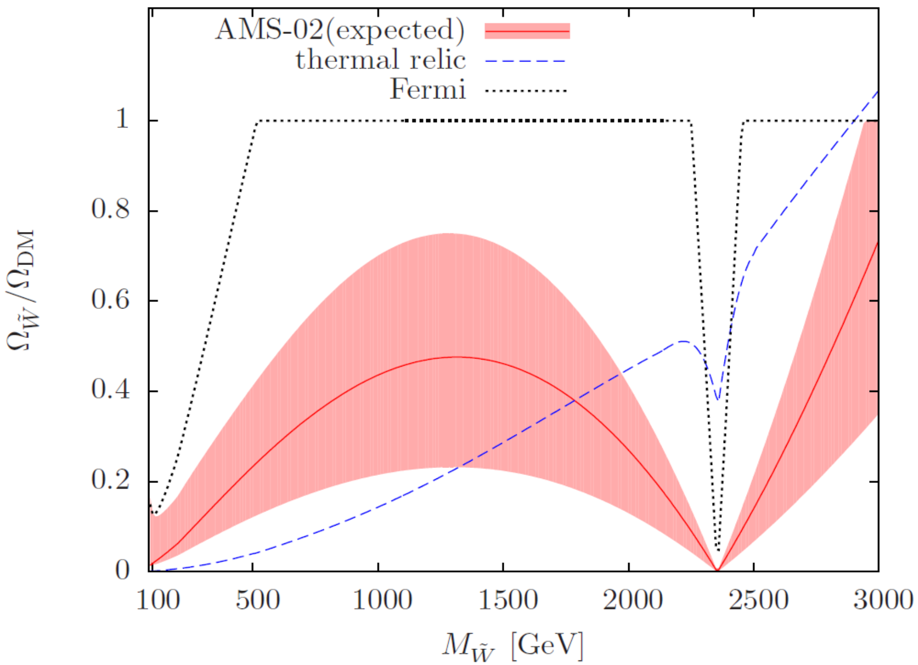


… allows us to measure masses & lifetimes of these particles

Measuring flavors of quarks from $\tilde{g}$ decay,
we can probe the flavor structure of the squark sector ! e.g. $\tilde{g} \to b\bar{s}\tilde{\chi}, t\bar{c}\tilde{\chi}$

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

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

Many things to expect/consider

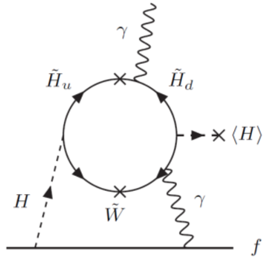
- CMB measurements (recombination history)

  … can probe the region

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

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

- Electric dipole moments



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

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

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

- Possible flavor / *CP* signatures

  flavor, CP: Moroi, Nagai, 1303.0668; Moroi, Nagai, Yanagida, 1303.7357; Altmannshofer, Harnik, Zupan, 1308.3653
  nuclear EDMs: McKeen, Pospelov, Ritz, 1303.1172
  flavor at colliders (from gluino decays):

- Proton decays

  d=5 in minimal SU(5): Hisano, Kobayashi, Kuwahara, Nagata, 1304.3651
  enhanced d=6: Hall, Y.N., 1111.4519

- Cosmological signatures

  gravitational wave: Saito, 1201.6589

Summary

Accelerated cosmic expansion, (eternal) inflation, string theory, etc suggest

~~Naturalness~~ ⟶ Typicality

Does this affect our considerations of TeV physics?

… depends on the distribution of parameters in the multiverse

The LHC results (so far) seem to suggest that it does.

This does **not** mean that we cannot make progress
or there is no new physics at the TeV scale

Supersymmetry may exist at scales higher than naïvely imagined

High scale supersymmetry

- $\tilde{m}$ » weak scale
- M_H ~ 126 GeV predicted
- axion dark matter

Spread supersymmetry

- $\tilde{m}$ ~ 10^2–10^4 TeV
- M_H ~ 126 GeV natural, gauge coupling unif.
- (mixed) wino dark matter, many signals, …

(Hopefully) experiments will guide us further