A Theoretical Perspective on Dark Matter

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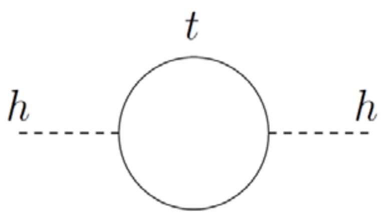
A dominant paradigm for dark matter

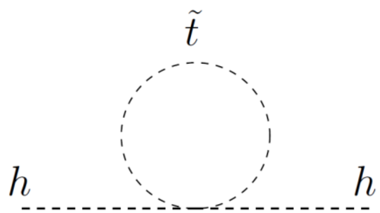
— Weakly interacting massive particle (WIMP)

EW stability



$\Longrightarrow$

New physics at ~ TeV



$\Longrightarrow$ Stable particle χ with $\langle\sigma v\rangle \sim \dfrac{1}{\text{TeV}^2}$ $\Longrightarrow$ $\Omega_{\text{DM}} \sim 0.2$

ex. Weak scale supersymmetry

Is it true that the EW scale must be natural?

If not, what can be the implications for DM?

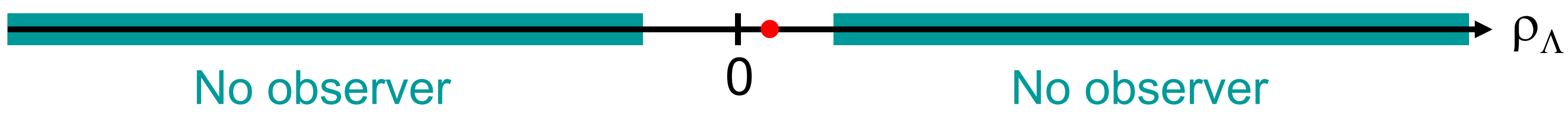
$\rho_{\Lambda,obs} \sim (10^{-3}\,\text{eV})^4 \ll M_{Pl}^4$ (or TeV^4)

- 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 … huge number of vacua
- Eternal inflation … populate all the vacua

Significant Impacts on the way we think about 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, JHEP 01, 036 ('13) [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"

……

See also, Ibe, Yanagida; Arvanitaki, Craig, Dimopoulos, Villadoro; Arkani-Hamed, Gupta, Kaplan, Weiner, Zorawski; …

- 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_* ($\gtrsim M_{\rm unif}$)   e.g. the string scale

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

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

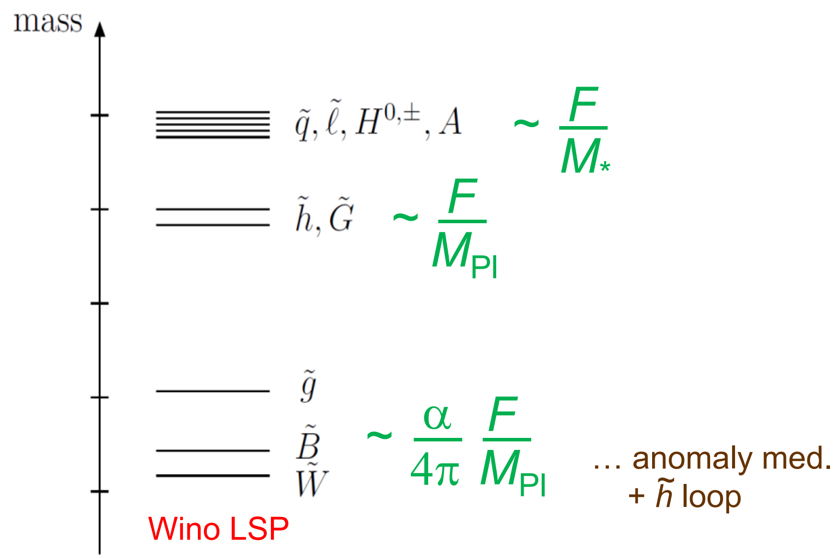
… scalar masses: $X^+X\, Q^+Q$, B_μ term: $X^+X\, H_uH_d$

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

… supergravity or loop effects

⟶ "Spread" in the superparticle spectrum

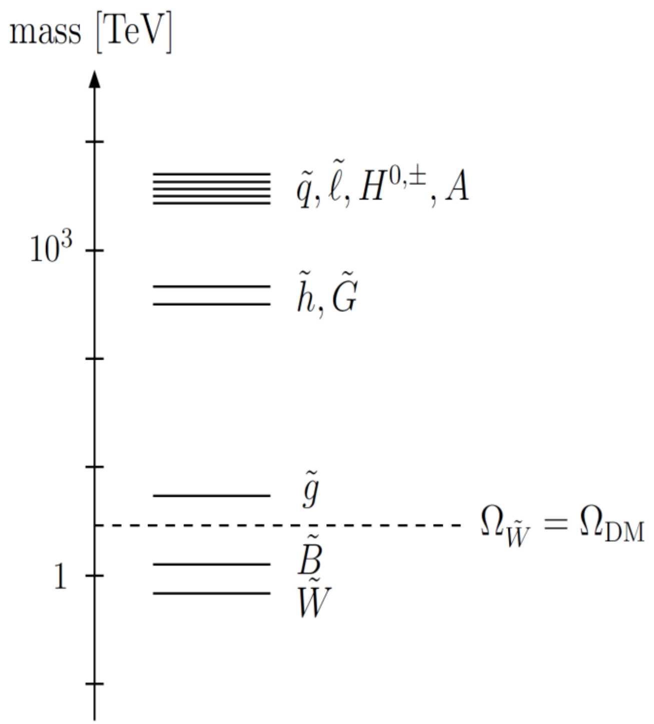
Write down all the possible terms
with $O(1)$ couplings in units of M_*,
including $K = H_uH_d$



What stops "drifting-up" of the spectrum?

(II) The existence of DM 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 that this is the same boundary used to argue for axion DM

Can anthropic explain *everything*? ⟹ **No !**

ex. Strong CP problem in QCD

θ_{QCD} already way too small ($< 10^{-10}$)

… mechanism needed → "axion"

(more "robust" problem than the hierarchy problem)

Implication for Dark Matter (DM)

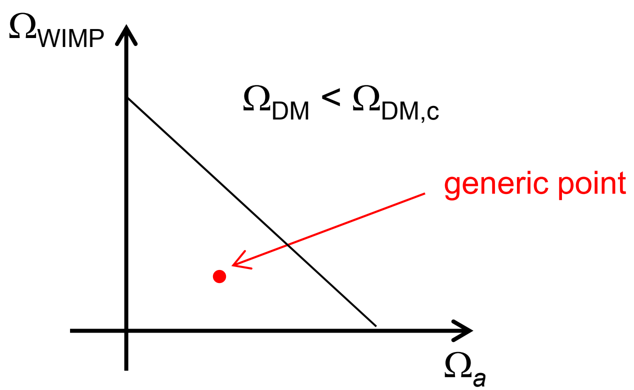
$f_a \sim M_{GUT}$ → overabundant → fine with $\theta_{init} \ll 1$

… forced by $\Omega_{DM} < \Omega_{DM,c}$

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

WIMP?

— possible



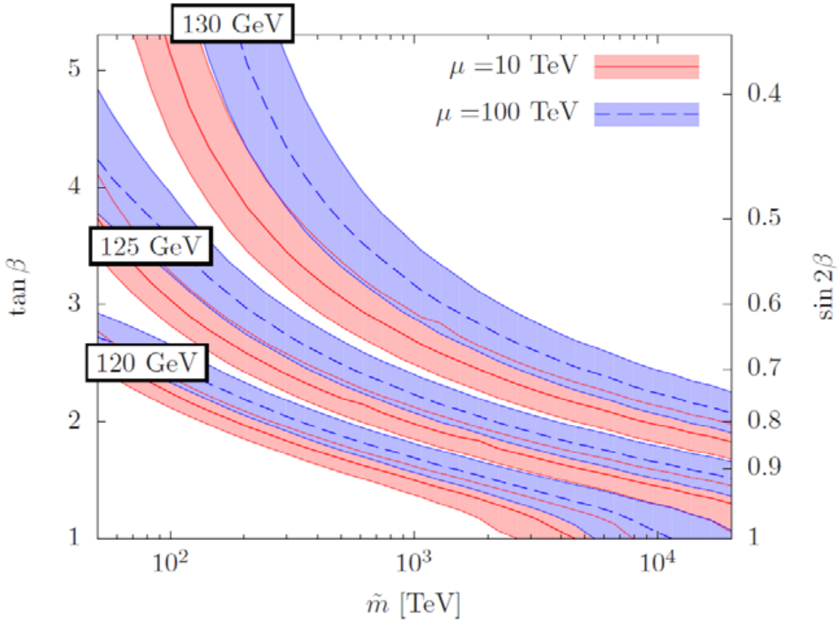
$\Omega_a + \Omega_{WIMP} < \Omega_{DM,max}$ ⟶ Multi-component DM !

Immediate gifts

The two-step hierarchy implies

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

- Higgs boson mass



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

- 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

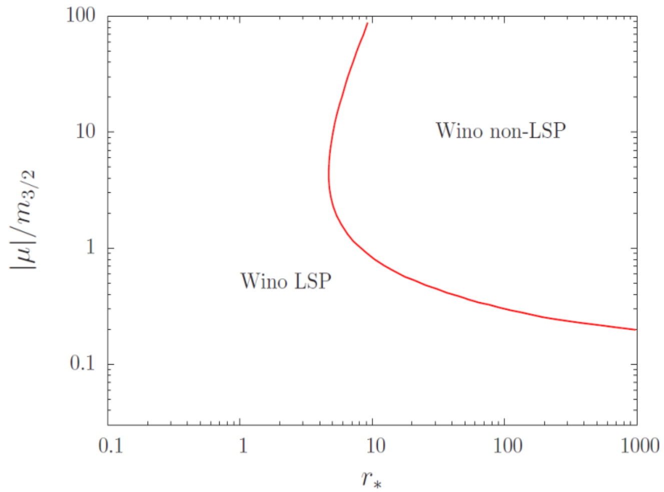
Here,

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

… 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 $\Omega_{DM} < \Omega_{DM,max}$

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

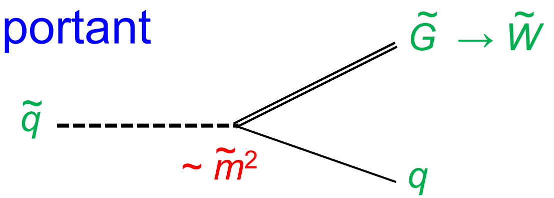
$$\Omega_{\tilde{W}}^{\rm thermal} h^2 \simeq 2 \times 10^{-4} \left(\frac{M_{\tilde{W}}}{100 \text{ GeV}} \right)^2$$

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

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

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

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



… larger wino abundance

$\rightarrow$ smaller wino (gaugino) mass

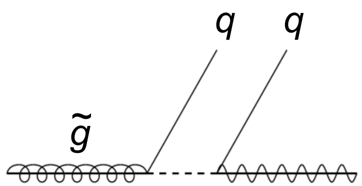
(even smaller mass if significant axion component)

$\Longrightarrow$ **The gluino can be within LHC reach!**

Gluino signals

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

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



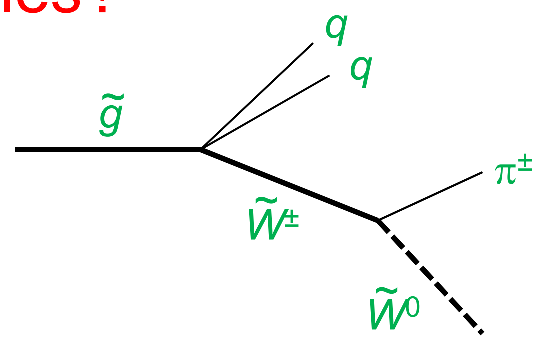
… $r_* \gtrsim O(10)$ → long-lived (displaced) gluino signatures

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 !

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



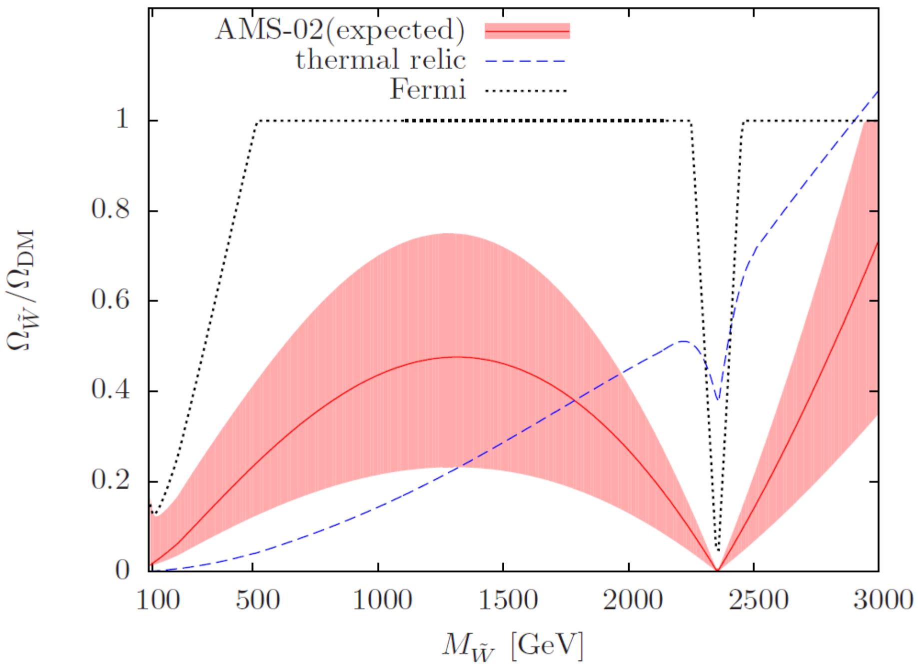
… allows us to measure masses & lifetimes of these particles

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

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

General lessons

- DM may very well be multi-components (thermal, non-thermal, …)

  — Coincidences are "general" features of the anthropic universe

  (The relative abundances, however, depend on the underlying statistics) c.f. $\Omega_{matter} \sim \Omega_{\Lambda}$

- The origin of $\Omega_{DM} \sim 0.2$ may look fine-tuning

  cf. $\theta_{init} \ll 1$, $\phi_{moduli} \ll M_{Pl}$, …

  — All the components may coexist

- Axion is likely one of the components

  … lack of the anthropic solution to the strong CP problem

$\Longrightarrow$ All possible searches

without limiting to $\Omega_{DM} = \Omega_{DM,obs}$, "natural" models, …

(axions, WIMPs with a wide range of masses, Q balls, slowly decaying moduli, …)