Split SUSY, Dark Matter, and Anthropics

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At TRIUMF, Dec. 11, 2013

Based on: JiJi Fan & MR “In Wino Veritas?” (1307.4400);
work in progress, in part with Josef Pradler

Outline

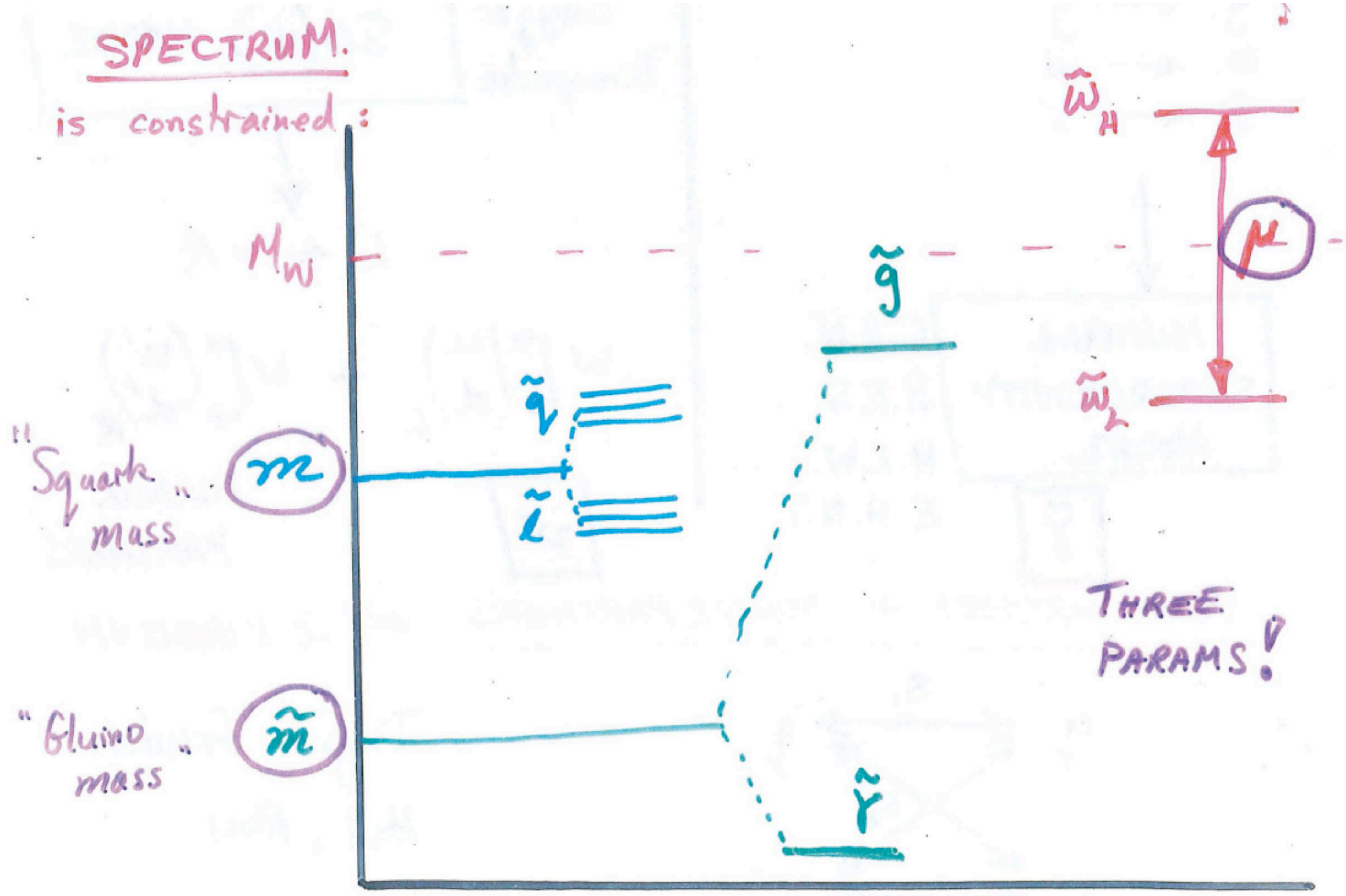
- SUSY is likely tuned.
- Moduli and light nonthermal wino DM.
- Nonthermal wino DM is dead.
- Cosmologies & anthropic stories.

The latter part of the talk is a sketch of some things I'm thinking about but far from having a complete answer to. Hopefully it will be thought-provoking even though very inconclusive so far.

Natural SUSY, 1984

A historical relic (from Lawrence Hall's talk at Savasfest).

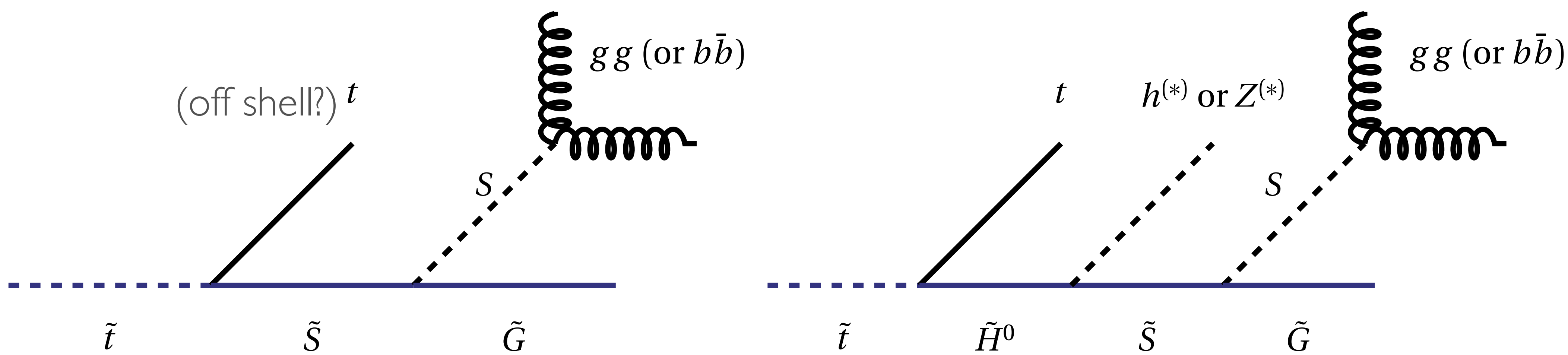
All the scalars, and the Higgs, should be at the weak scale!



The "anthropic" part of this talk will be: why don't we live in the SUSY universe as envisioned circa 1984?

Natural SUSY?

I’m still playing with scenarios where SUSY could be natural but hidden, e.g. with stealth SUSY stop decay chains:



It’s important to rule out these scenarios at colliders and make sure we’re not missing something.

But even the best case looks somewhat tuned.

The Higgs looks SM-like

The low-energy theorem tells us stops correct Higgs couplings to gluons or photons:

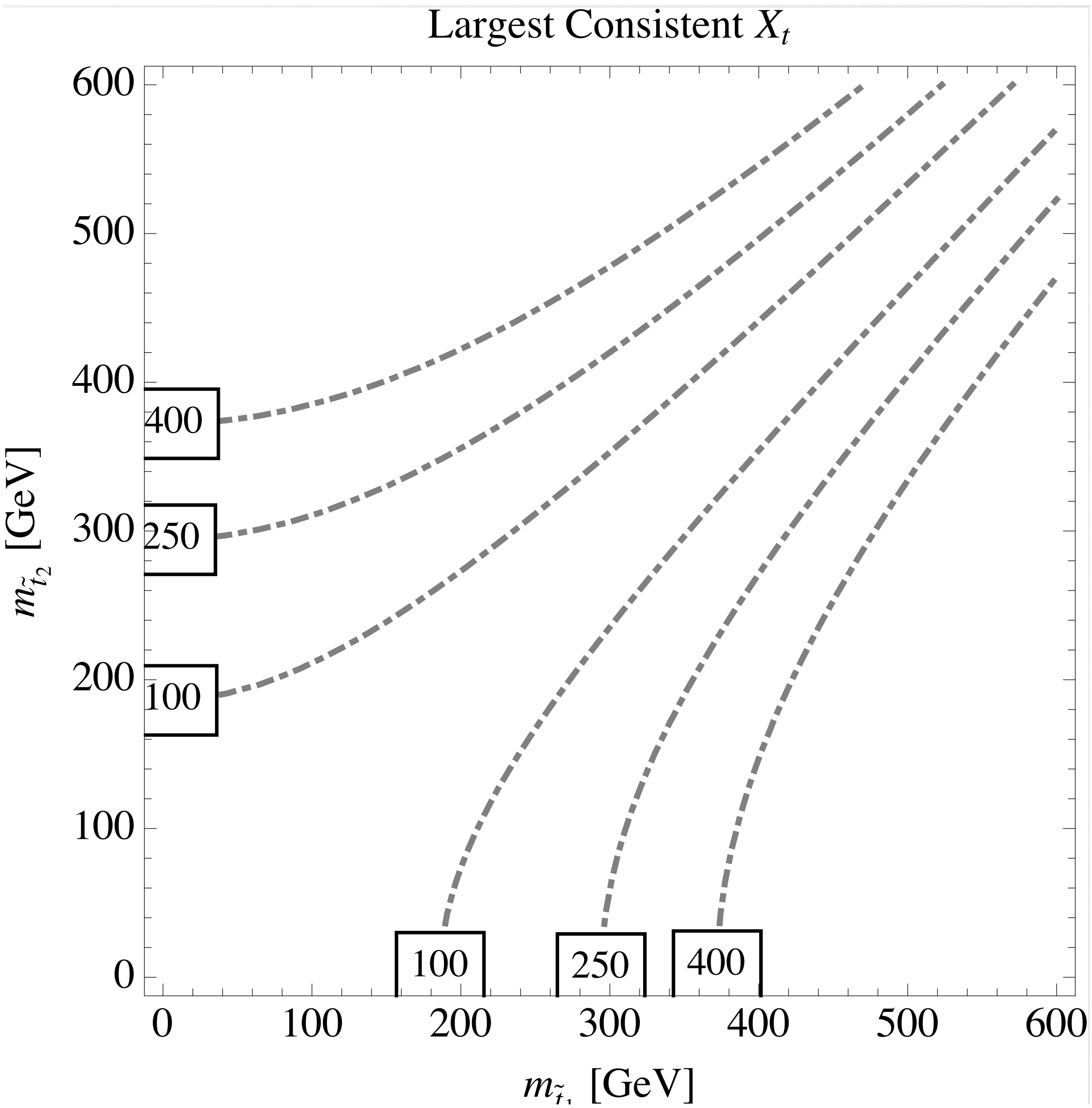
$$\mathcal{A}_{\tilde{t}-\mathrm{loop}}(gg \to h) \propto \frac{\partial \log \det M_{\tilde{t}}^2}{\partial v} \sim y_t m_t \frac{\tilde{m}_Q^2 + \tilde{m}_u^2 - X_t^2 \sin^2\beta}{\tilde{m}_Q^2 \tilde{m}_u^2 - X_t^2 m_t^2 \sin^2\beta}$$

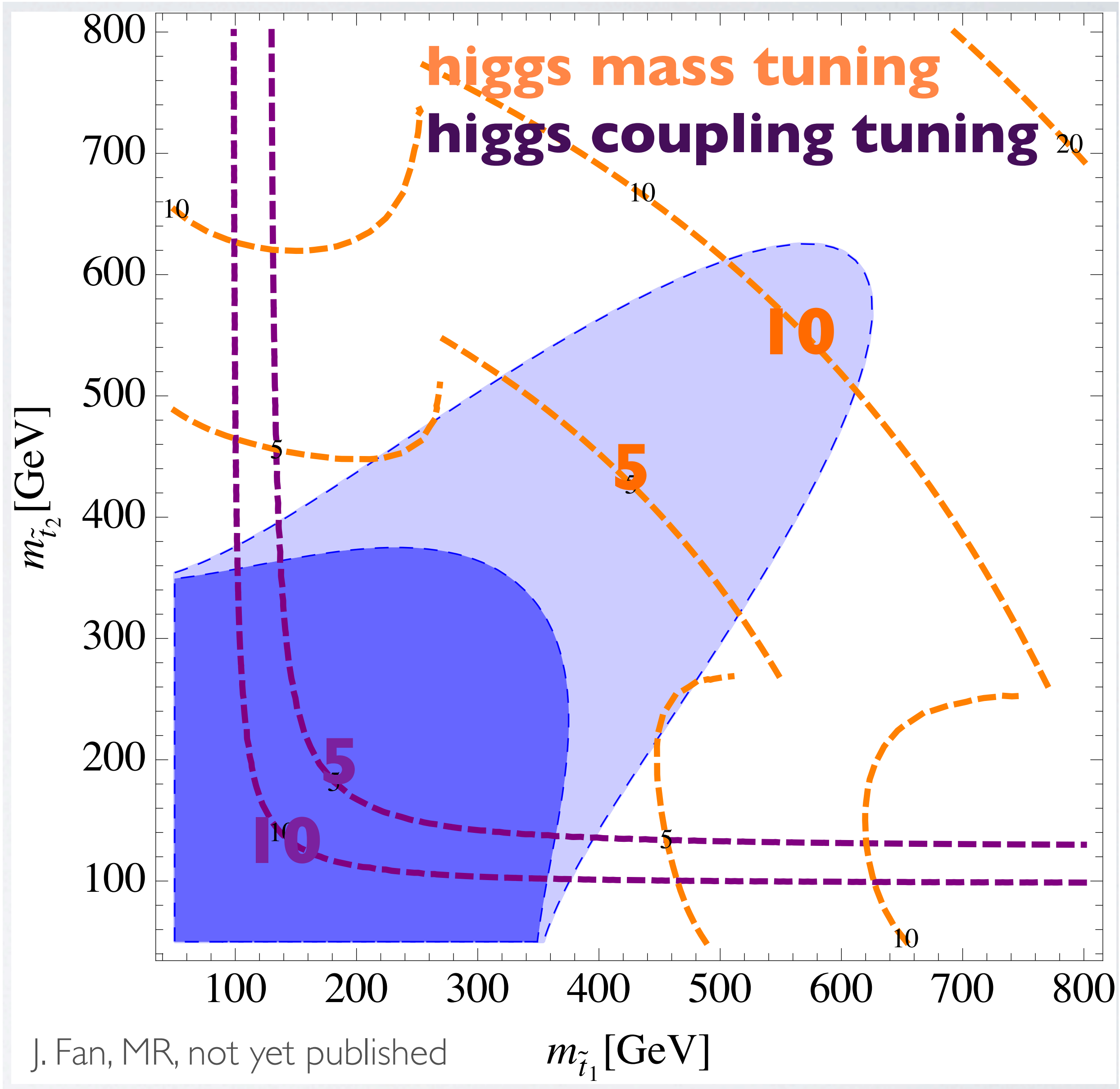
For light enough stops, can only avoid a big correction via a sizable mixing term X_t. Implies tuning of the coupling.

For any pair of *physical* stop masses, there's a *maximum* X_t. (On the diagonal, $X_t = 0$: symmetric matrix with off-diagonal term will *always* have two unequal eigenvalues.)

So: robust bound on light stops.

Stop constraints





Dead minimum factor of ~5 tuning, even without using direct stop searches, gluino searches, etc. "Stealth" can only help so much. Most models much worse.

More likely?

Despite continuing to work on stealth SUSY or other natural SUSY scenarios, what I really think now is:

Completely natural SUSY is probably dead. Most of the effort is just trying to ascertain how cold the body is.

So, in the rest of the talk I will assume the weak scale is (at least mildly) fine-tuned and sketch my evolving opinions on what tuned scenario is most plausible.

Moduli

String compactifications always have scalar fields coupling with gravitational strength, called “moduli.” Their VEVs determine couplings, e.g.

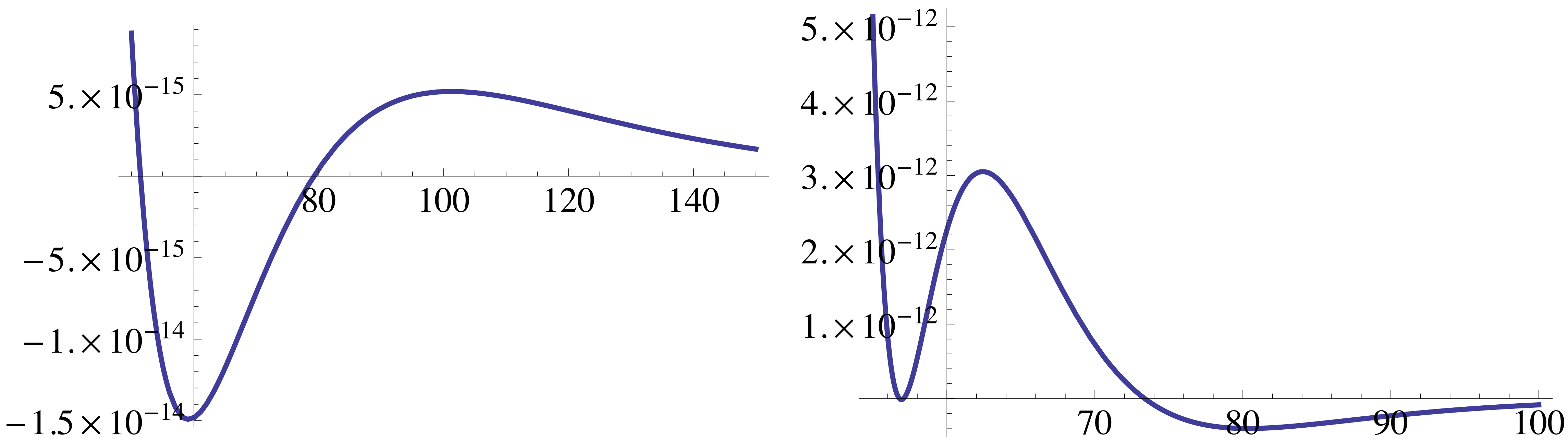
$$\mathcal{L} \supset c_\phi \frac{\phi}{M_{\rm Pl}} F_{\mu\nu} F^{\mu\nu}$$

In a SUSY theory, the imaginary part is an axion-like field. It has a shift symmetry and appears in *W* only in exponential terms.

These fields are often light: in fact, the natural scale for their masses is $m_{3/2}$. (Coughlan, Fischler, Kolb, Raby, Ross 1983; de Carlos, Casas, Quevedo, Roulet 1993).

Heavy Moduli are Tuned

Two potentials with a minimum at the same location and same depth, but very different mass around the minimum:



$$W_{tunable} = W_0 + \Lambda^3 e^{-bT} - \Lambda'^3 e^{-b'T}.$$

O'KKLT (Kallosh, Linde): strongly stabilized moduli can be heavy. But the left plot is much more generic than the right!

The Moduli Problem

- Moduli have long lifetimes due to Planck-suppressed couplings.
- They are generally displaced from the minimum of their potential in the early universe, so (like axions) they start to roll when Hubble ~ modulus mass.
- They overclose the universe or ruin BBN unless their masses are > 100 TeV.

Moduli Solutions

- Make them so heavy they don't matter at all. (E.g. recent work of Dudas, Linde, Mambrini, Mustafayev, Olive). Could be right. Looks tuned to me.
- Dilute them, e.g. thermal inflation. Old idea (Randall & Thomas, Lyth & Stewart). Tried to make a nice version of this using saxions (Fan, MR, Wang 2011). Strongly constrained and works marginally if at all.
- Put them at ~100 TeV so they reheat above BBN.

Moduli and split SUSY

Decay width $\Gamma_\phi = \frac{c}{4\pi}\frac{m_\phi^3}{M_{\rm Pl}^2}.$ Reheats to $T_{\rm RH} \equiv \left(\frac{90}{\pi^2 g_*(T_{\rm RH})}\right)^{1/4}\sqrt{\Gamma_\phi M_{\rm Pl}},$

so reheating above ~5 MeV for BBN leads to masses ~ 10 to 100 TeV (Moroi, Yamaguchi, Yanagida hep-ph/9409367).

This fits very well with *anomaly mediation* or other scenarios (including many moduli-mediated scenarios!) where gaugino masses are set by

$$m_\lambda \sim \frac{\alpha}{\pi} m_{3/2}$$

Without jumping through hoops (sequestering), in such a scenario scalars are ~ $m_{3/2}$ and the spectrum is split.

Triple coincidence?

- If gauginos are at the 100 GeV to 1 TeV scale (and we know they aren't much lighter…), AMSB puts the gravitino at ~10 to 100 TeV.

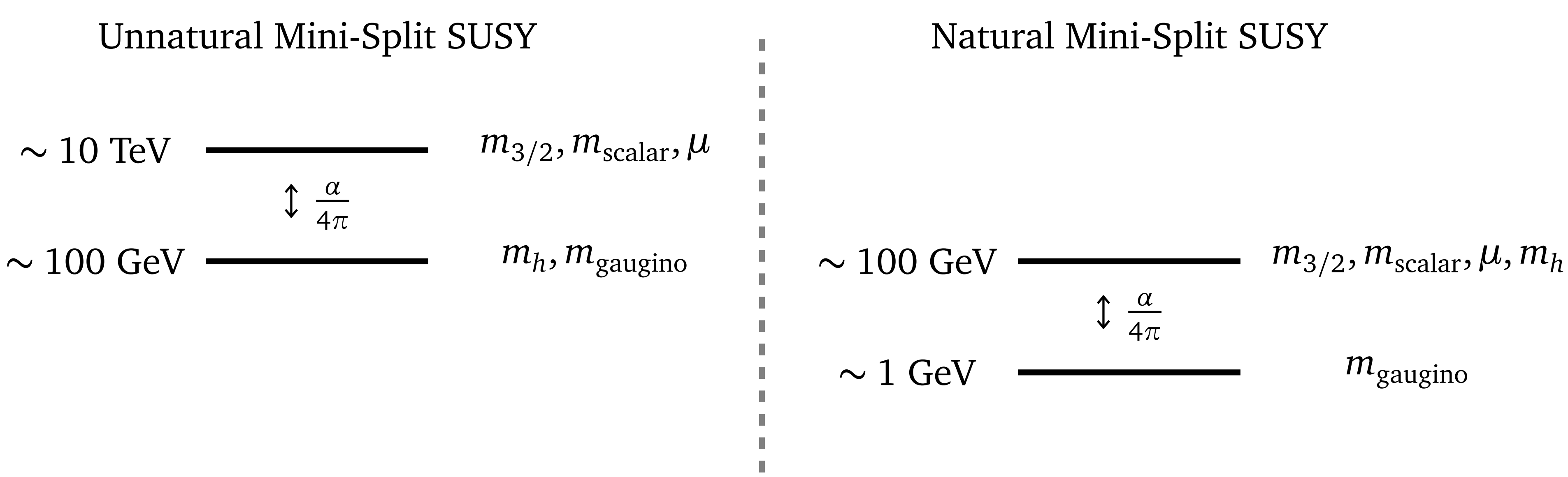
- If we want moduli to reheat above BBN, this picks out a scale ~10 to 100 TeV.

- If we want to raise the Higgs mass to 125 GeV without large *A*-terms, for moderate to large tan beta this picks out scalar masses ~ 10s of TeV.

- It's a nice story, aside from the fine-tuning.

A "mini-split" naturalness puzzle: why not both?

Moduli, a loop factor splitting, AMSB, etc… All could have been compatible with 1984-style natural SUSY!



Will come back to this later in the talk, but it should bother you. The universe on the right doesn't look like an obviously bad place to live, and it's much less tuned.

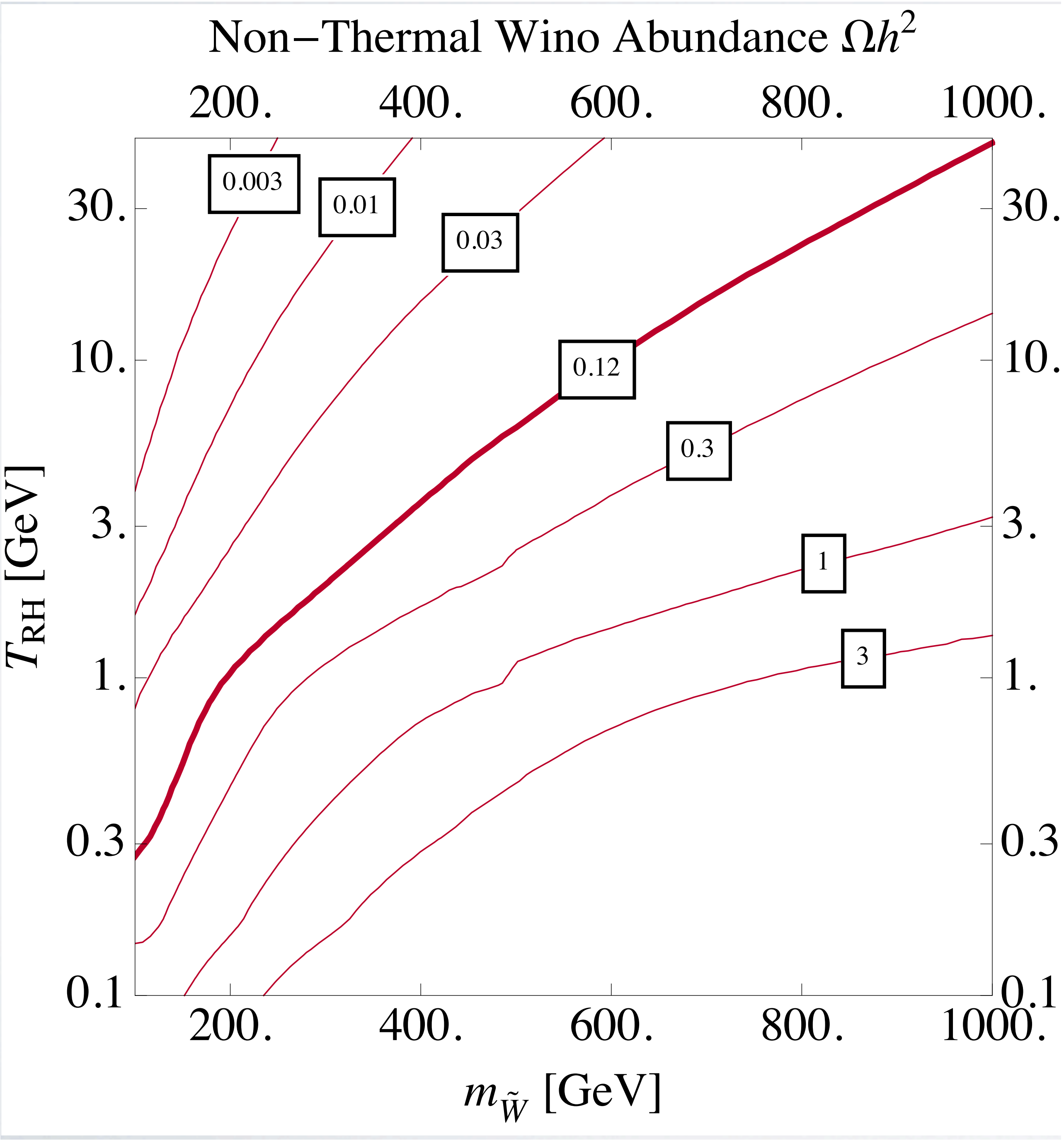
Dark matter in split SUSY

AMSB or related models often predict that the *wino* is the LSP. In thermal cosmologies this means not enough DM: winos annihilate away.

Moduli change this story by decaying (~ half the time) to *R*-odd particles, so they produce a lot of winos. (See: Moroi & Randall hep-ph/9906527; J. Kaplan, hep-ph/0601262; etc)

Roughly, enhance Ωh^2 by a factor of $T_{freezeout}/T_{reheat}$. Ideal for light wino dark matter.

Non-thermal abundances



Solve a set of Boltzmann equations:

$$\begin{aligned}
\frac{dn_{\tilde W}}{dt} + 3Hn_{\tilde W} &= -\langle \sigma_{\rm eff} v\rangle (n_{\tilde W}^2 - n_{\tilde W,{\rm eq}}^2) + N_{\tilde W}\Gamma_X n_X, \\
\frac{dn_X}{dt} + 3Hn_X &= -\Gamma_X n_X, \\
\frac{d\rho_{\rm rad}}{dt}\left(1+\frac{1}{3}\frac{\partial \ln g_*}{\partial \ln T}\right) &= (-4H\rho_{\rm rad} + q)\left(1+\frac{1}{4}\frac{\partial \ln g_*}{\partial \ln T}\right),
\end{aligned}$$

finding that 100 GeV winos are all the DM for reheating temperatures ~ 100 MeV (a bit higher than one would like.)

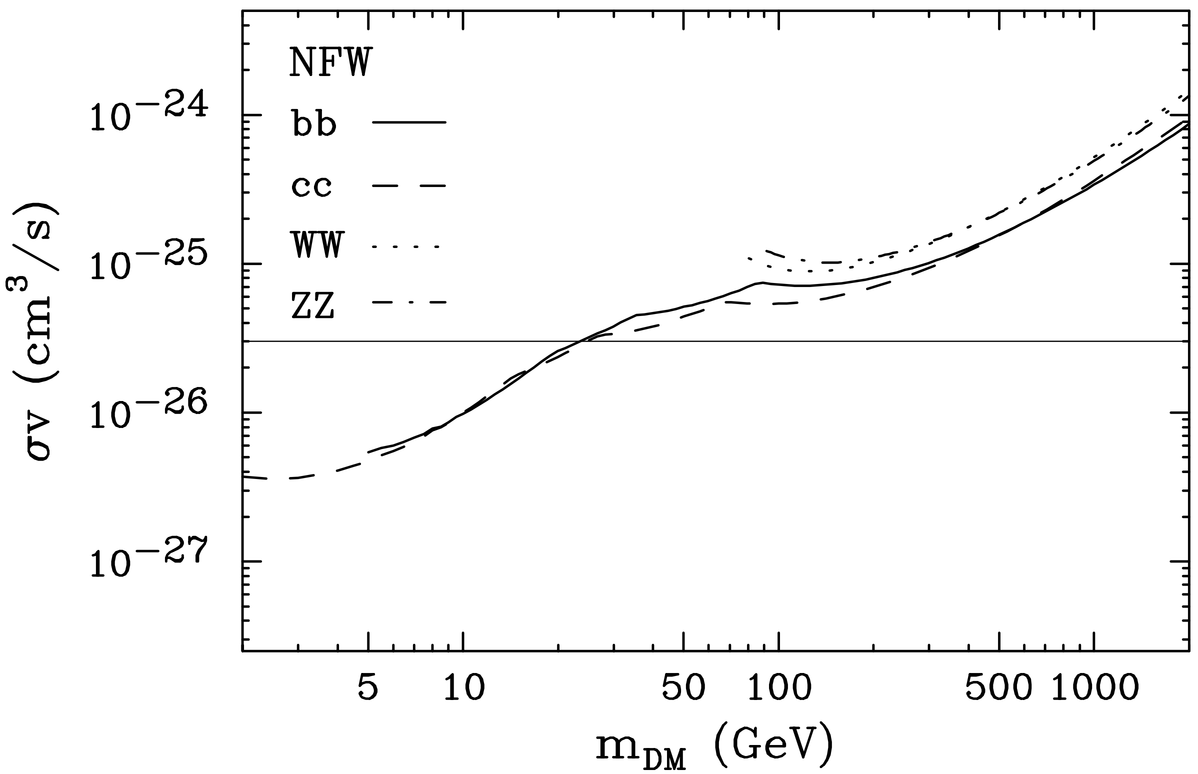
In Wino Veritas?

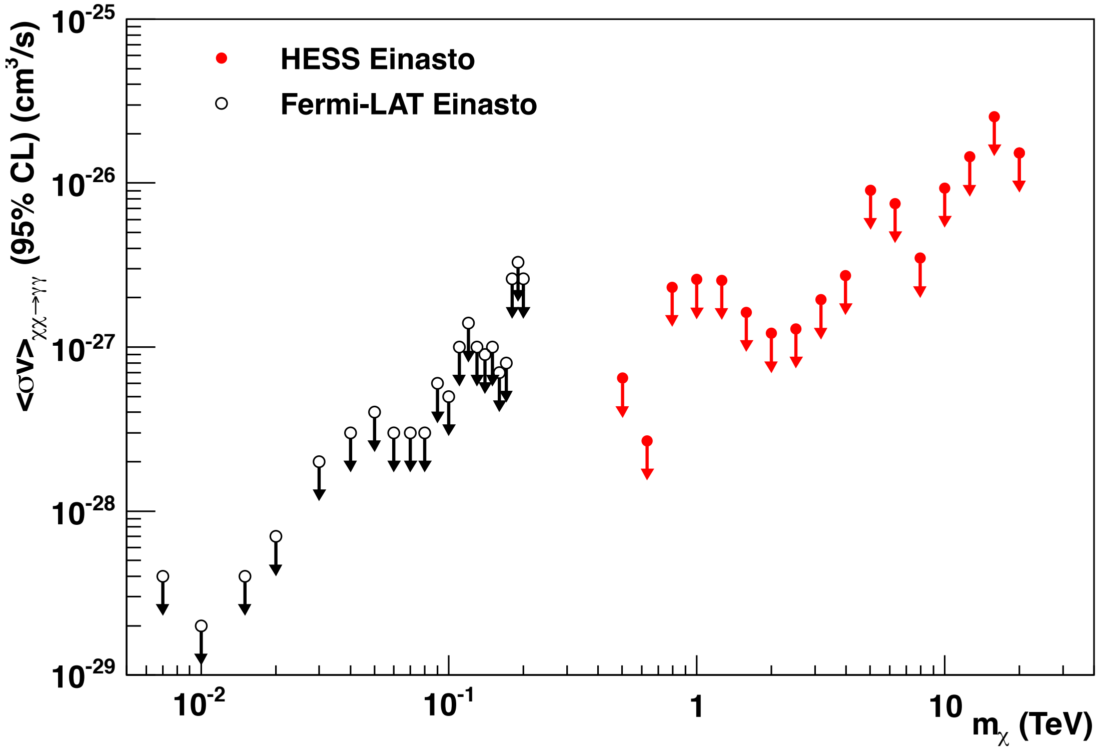
- Non-thermal wino DM has been discussed by many groups: Moroi & Randall, recently Gordy Kane & collaborators, Yanagida & collaborators, etc. It’s a compelling idea.

- But is it true?

- No: predicts too many gamma rays from dwarf galaxies & galactic center. (See also: Cohen, Lisanti, Pierce, Slatyer 1307.4082.)

Bounds from Fermi-LAT and HESS (Gamma Rays)



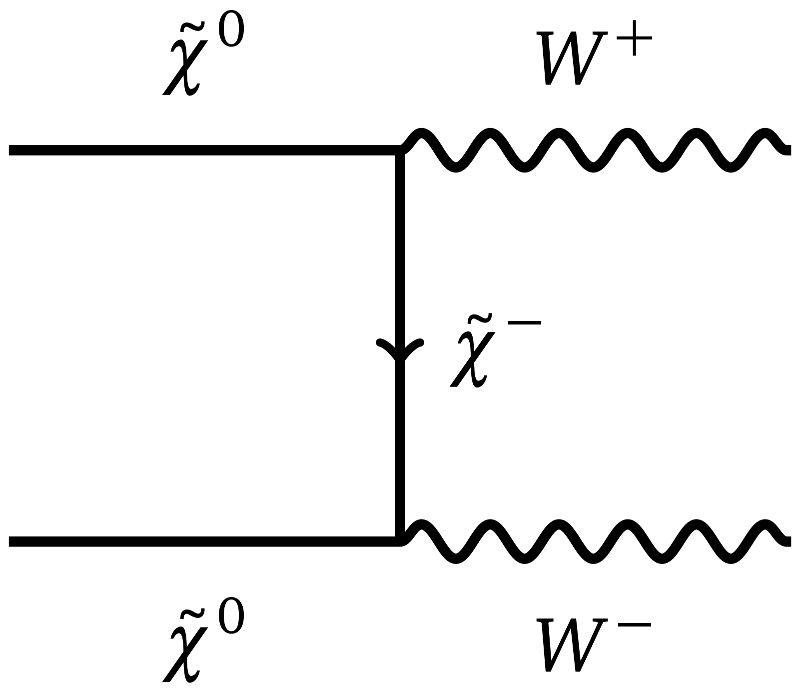


Galactic center continuum bound, Hooper et al.

HESS line search, 1301.1173

(dwarf bounds weaker)

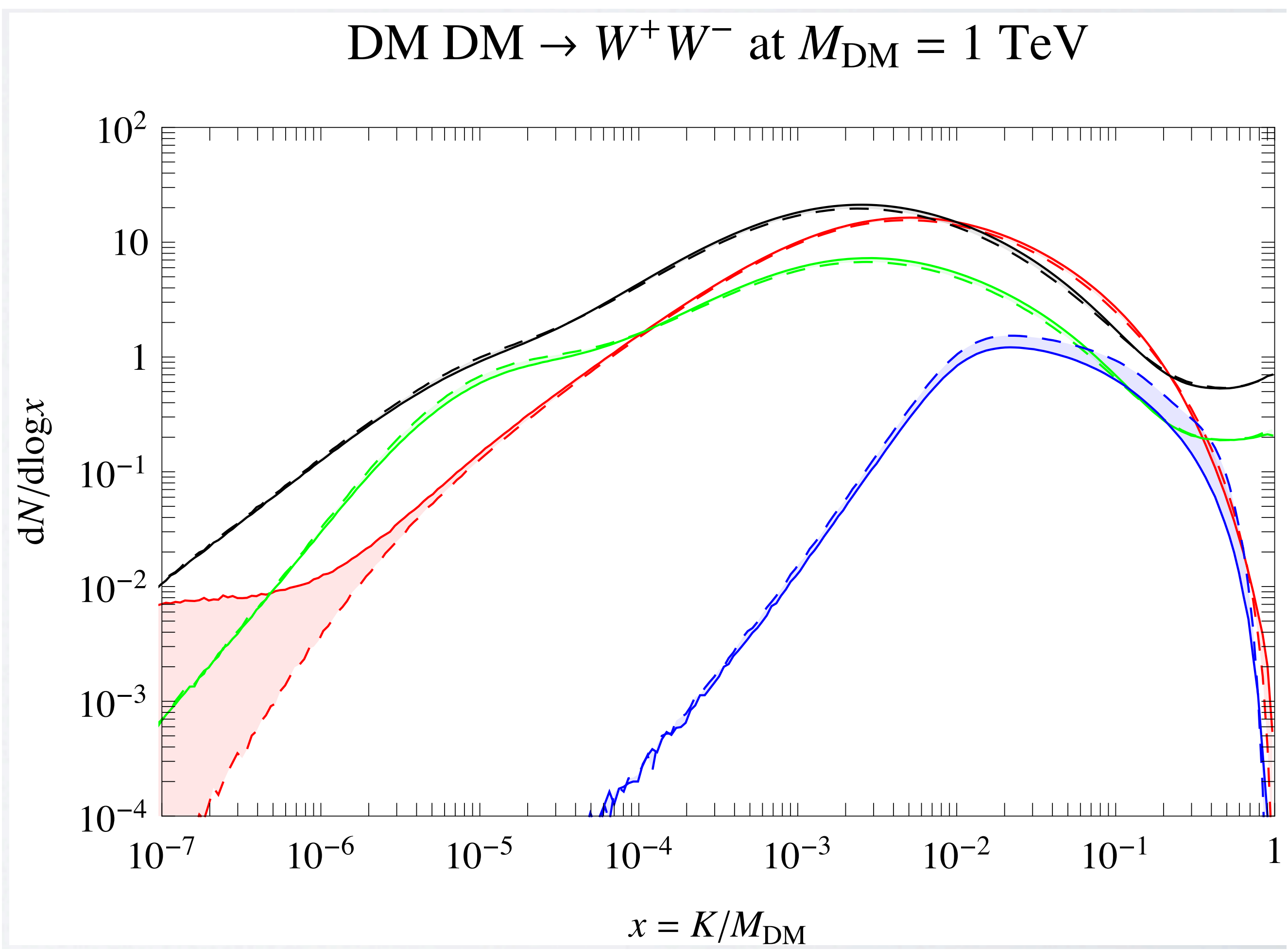
Wino Annihilation



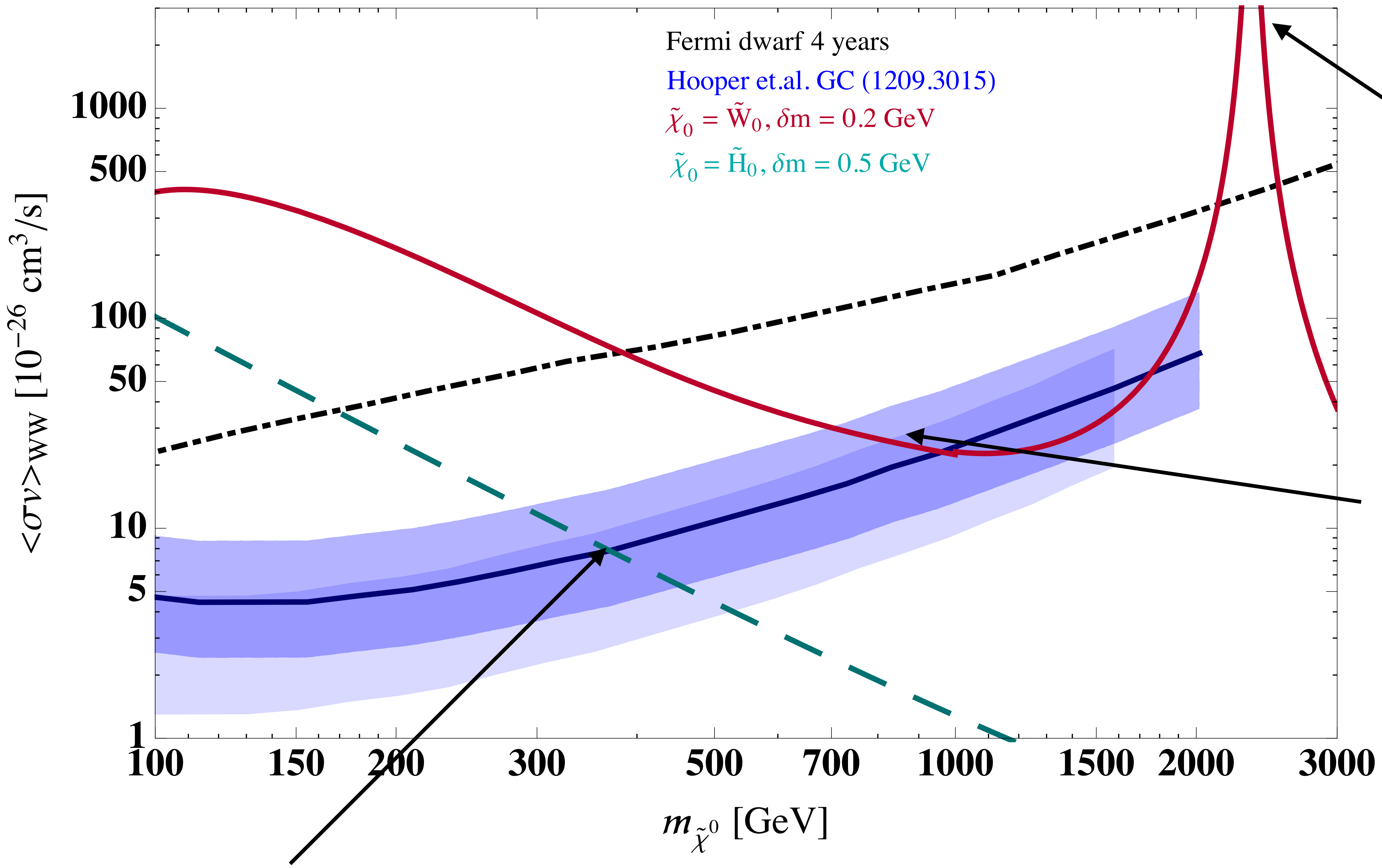
Winos annihilate through the weak interaction to *W* bosons. Gamma rays mostly from neutral pions.

Cirelli et al. 1012.4515: red curve is photons. Peak at energies ~ $M_{DM}/100$.

(black: neutrinos; green: e+e-; blue: antiprotons)



Continuum Bounds

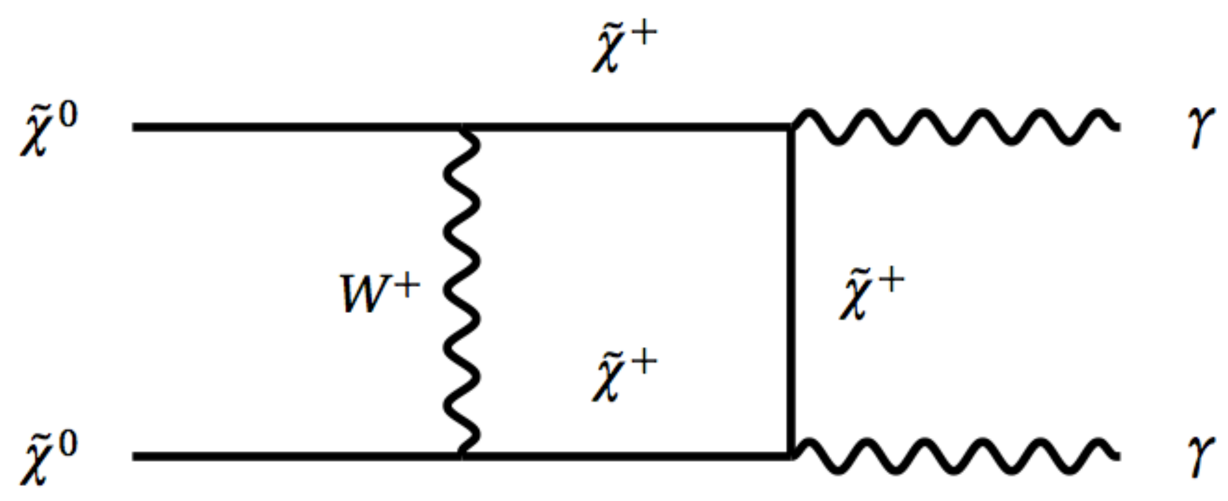


resonant peak (Sommerfeld)

winos excluded to ~ 700 GeV (if all the DM)

higgsinos excluded to ~ 300 GeV

Gamma Ray Lines

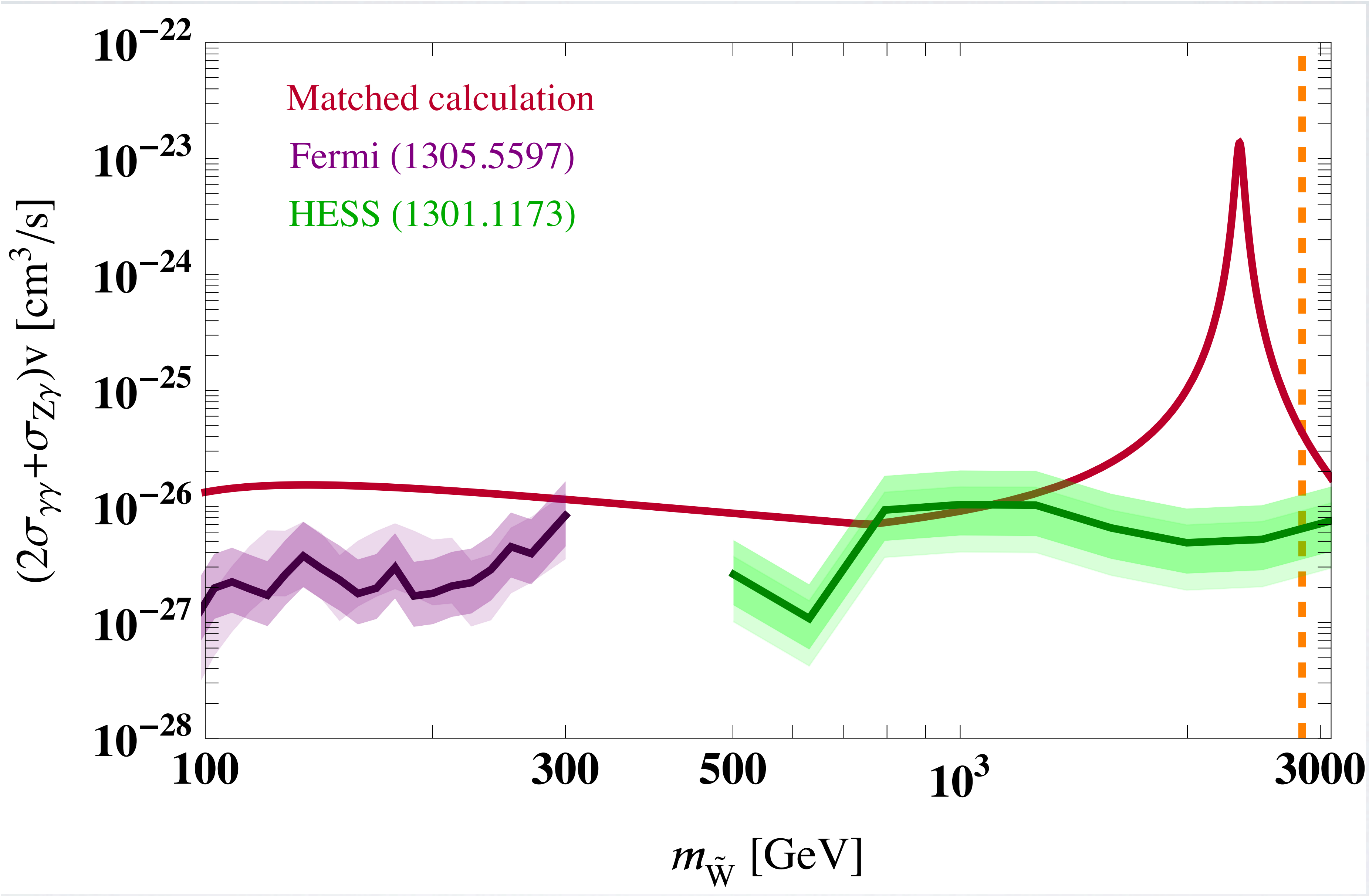


Naively, down by a loop factor, so less useful than continuum.

However, this diagram goes as $1/m_W^2$ rather than $1/m_{\mathrm{wino}}^2$ for large wino masses. (Related to Sommerfeld effect.)

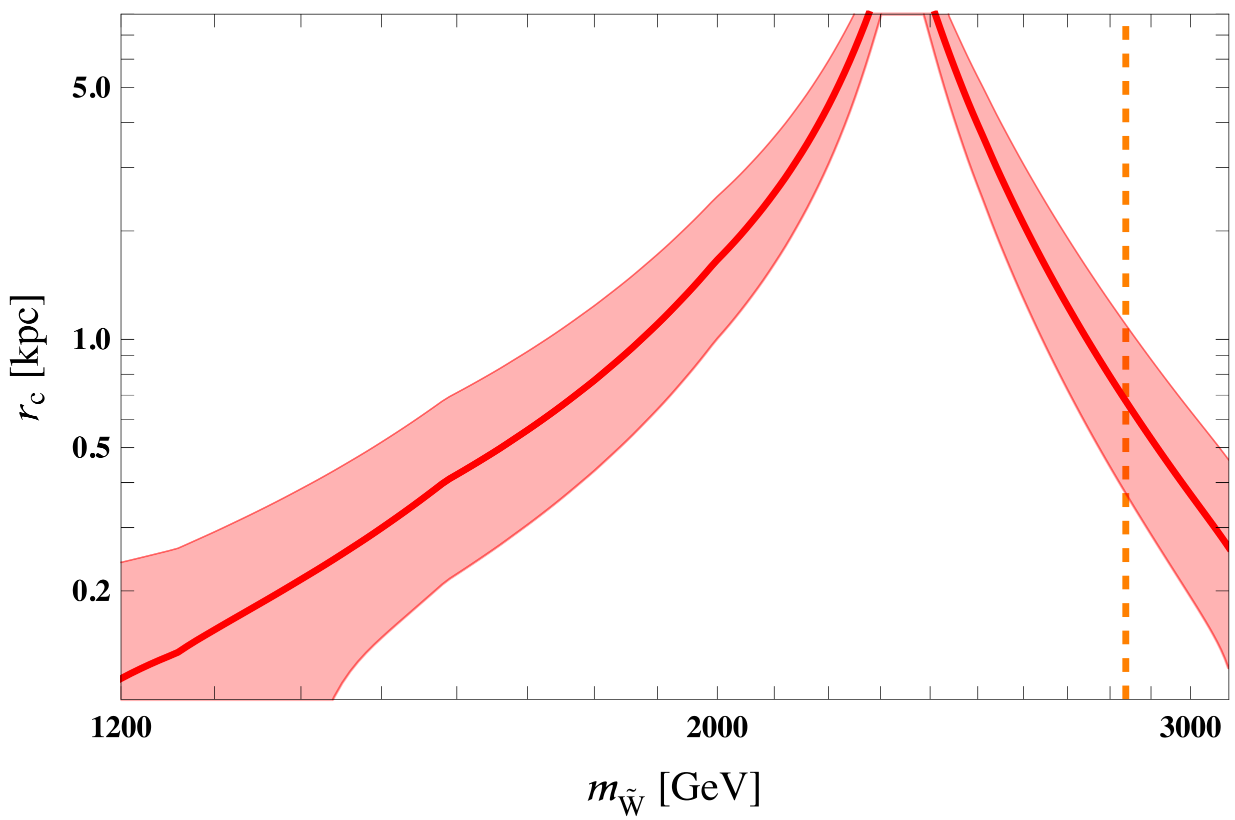
This makes line searches a very powerful probe of heavy winos.

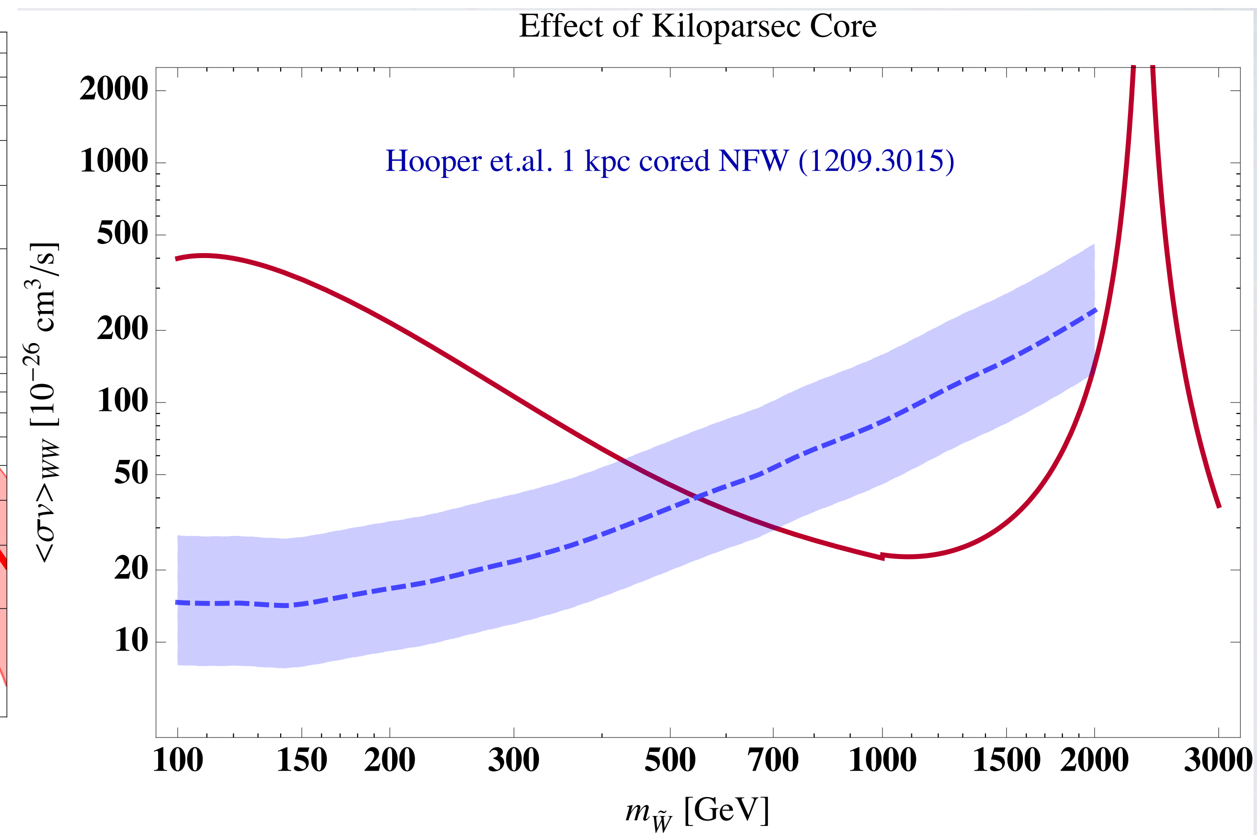
Line Bounds



HESS excludes most of the high-mass region (including thermal winos). Fermi excludes the low-mass region.

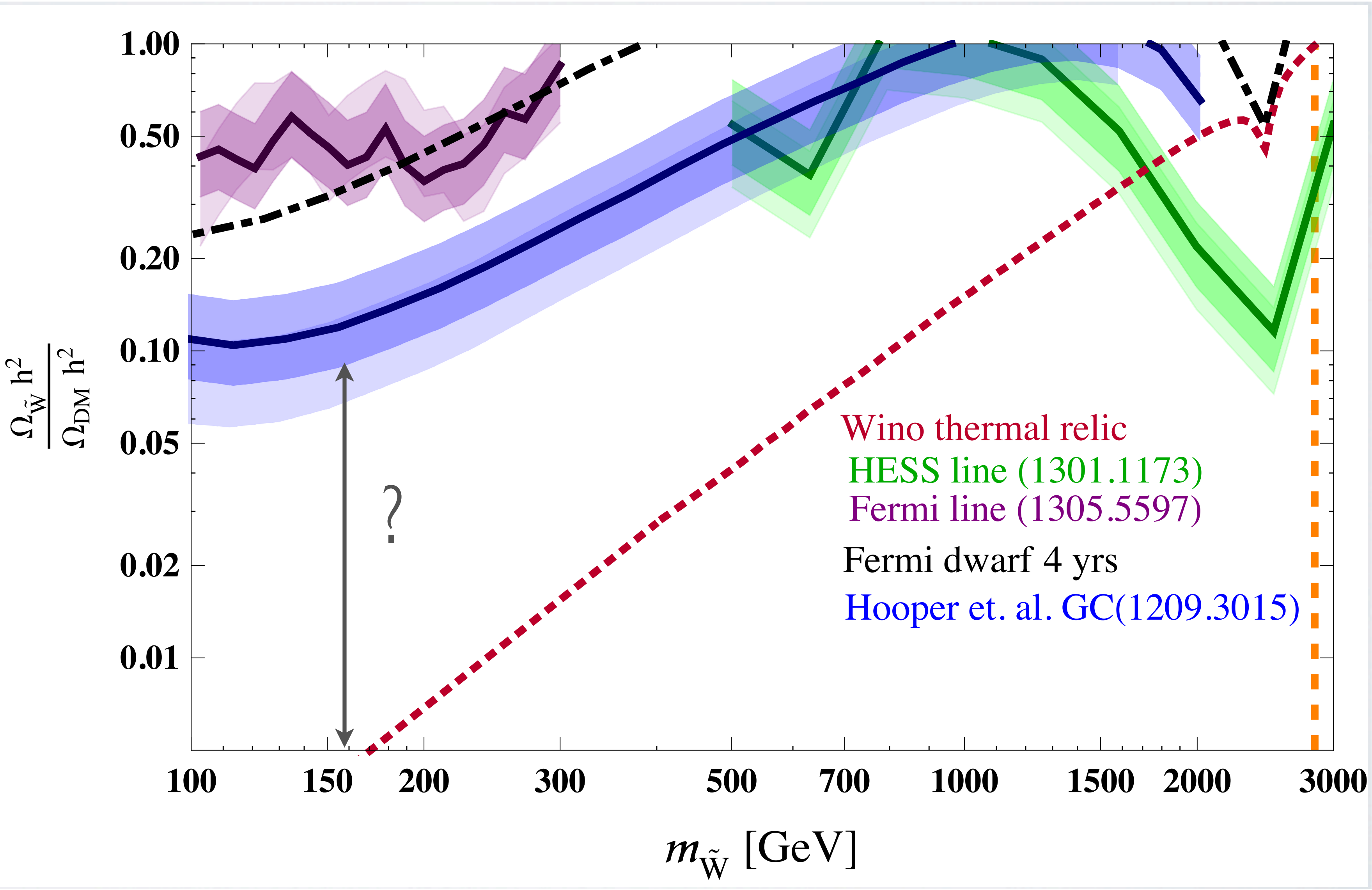
Limits with Cored Dark Matter Profiles





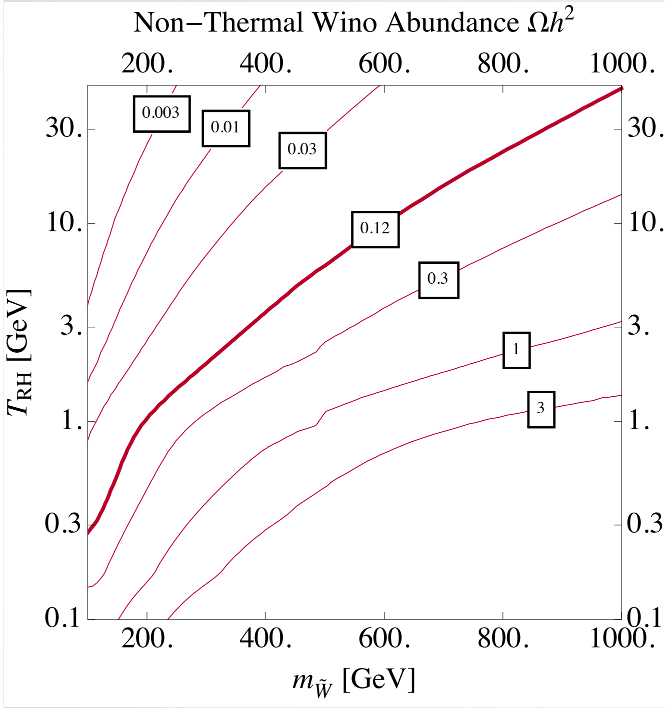
The thermal wino bound can be evaded with a ~kpc core. Even with such a core, light nonthermal winos remain strongly excluded.

Fraction of Allowed Wino Dark Matter

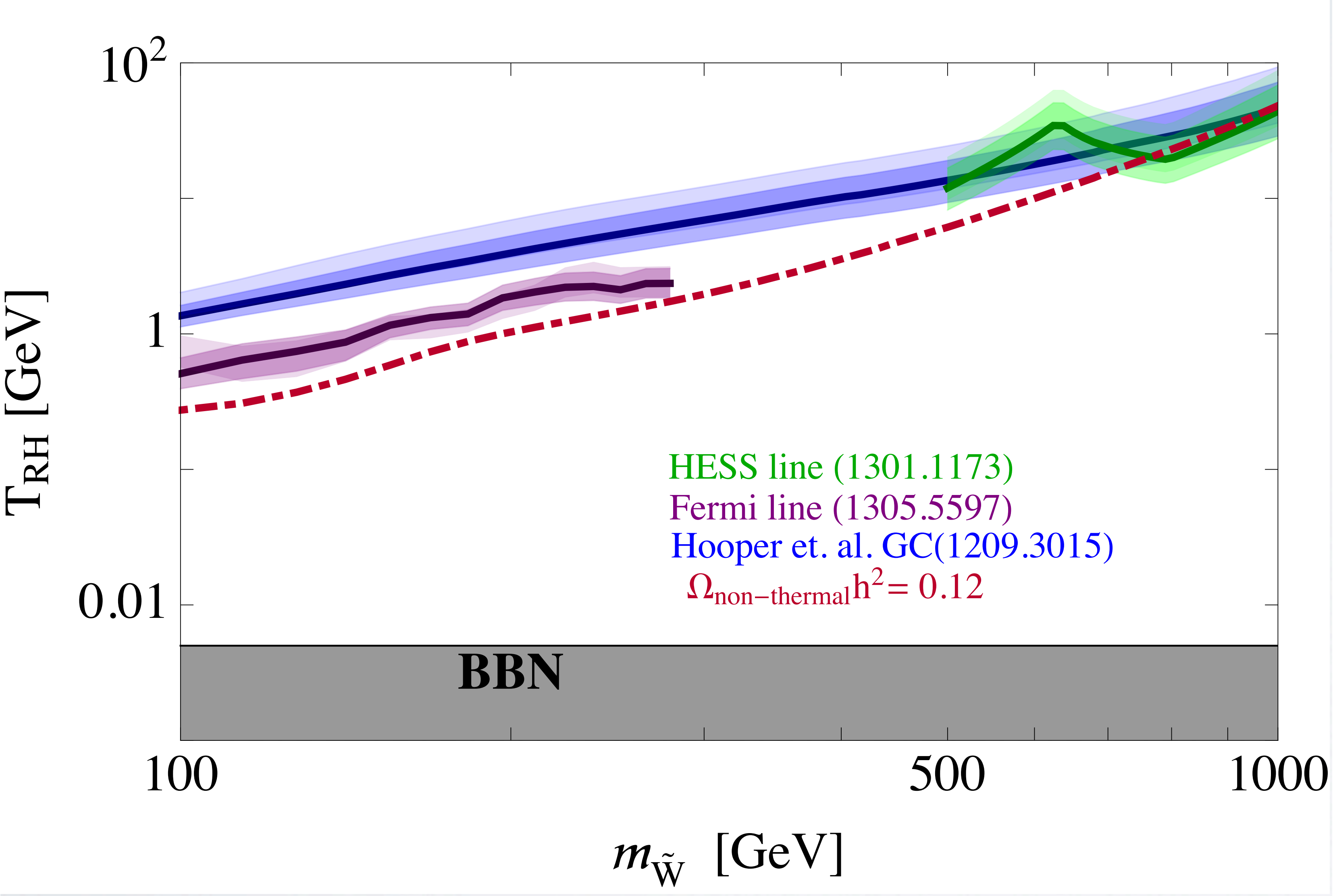


Still a long way to go to rule out a *subdominant* light thermal relic wino.

Interpret with:

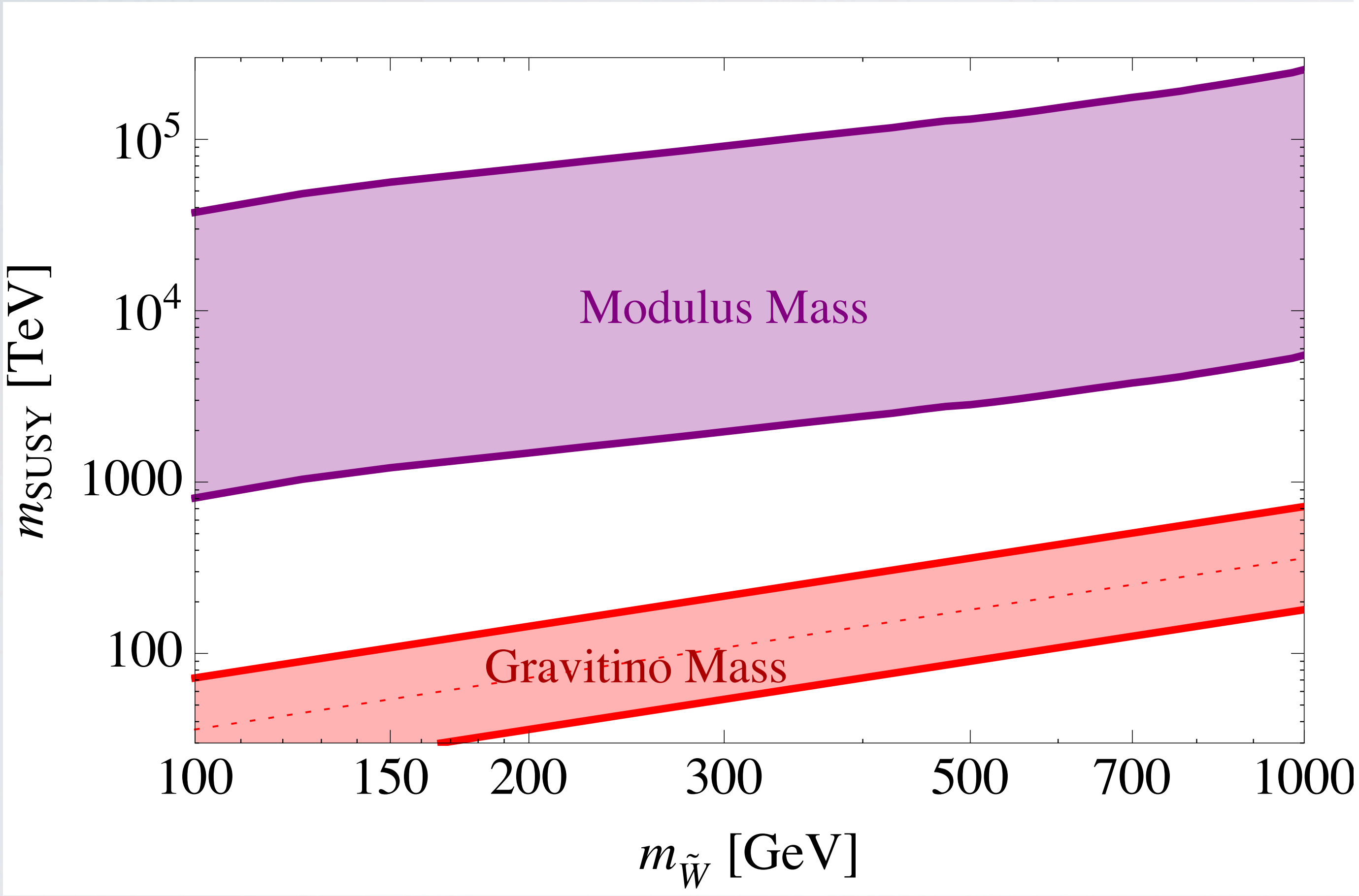


Bounds on the Reheating Temperature



Only reheating temperatures above about 1 GeV are allowed.

Trouble for Moduli Cosmology?



Purple band: allowed range of moduli masses assuming $\Gamma_\phi = \frac{c}{4\pi}\frac{m_\phi^3}{M_{\mathrm{Pl}}^2}.$

(Reasonable spread of choices for *c*.)

Red band: gravitino mass, if wino mass is ~ AMSB size.

Problem: moduli decays to gravitino are dangerous; gravitinos decay to an overabundance of winos.

The Moroi-Randall nonthermal wino scenario is dead.

Clarification: no chirality suppression

Moroi & Randall said moduli decays to gauginos were chirality suppressed. Has been advocated (e.g. Hooper 2013) as a way around constraints. But this is wrong:

$$\int d^2\theta \phi \mathcal{W}^\alpha \mathcal{W}_\alpha \Rightarrow \phi \lambda^\dagger i \partial_\mu \bar{\sigma}^\mu \lambda + F_\phi \lambda\lambda$$

The former gives a chirality-suppressed amplitude, but the latter does not: $F_\phi \sim m_\phi \phi$

So even without SUSY-breaking, get a substantial decay width to gauginos (J.Kaplan 2006, Nakamura & Yamaguchi 2006, various papers by Dine & collaborators, etc.)

What to keep, what to give up?

- Moduli seem generic to me given SUSY at any accessible scale. (*Especially* if we want an axion: the saxion must be stabilized by SUSY breaking.)
- The mini-split story with a loop factor seems very reasonable. Solve most of the hierarchy problem, get a Higgs at 125 GeV.
- For me, wino dark matter is the weak link. Let’s throw it out! Easy to do. Turn on RPV, for example.

R-parity violation

RPV has received a lot of attention recently in the context of natural SUSY (hiding superpartners from the LHC).

I think we should also be thinking about RPV *in the unnatural, mini-split SUSY context*. Produce winos, which decay. How do they decay?

$W_{RPV} = u^c d^c d^c$ has gotten a lot of recent attention (e.g. MFV RPV). Good for hiding from LHC searches (multi-jet signals).

I want to comment on an option that received less recent attention: bilinear RPV, with 2-body wino decays at the LHC.

(for older work: see hep-ph/9612447 by Mukhopadyaya and Roy; hep-ph/0410242 by Chun and Park)

Bilinear RPV

If we violate *R*-parity by violating lepton number, can add

$$W_{LNV} = \frac{1}{2}\lambda_{ijk}L_iL_jE_k + \lambda'_{ijk}L_iQ_jD_k + \epsilon_iL_iH_u$$

the bilinear term can be rotated away, but in general still have bilinear soft terms remaining:

$$\mathcal{L}_{LNV} \supset -\left(B_{L_i\mu}\mu\tilde{L}_iH_u + \tilde{m}^2_{H_d,L_i}\tilde{L}_iH_d^\dagger + \mathrm{h.c.}\right)$$

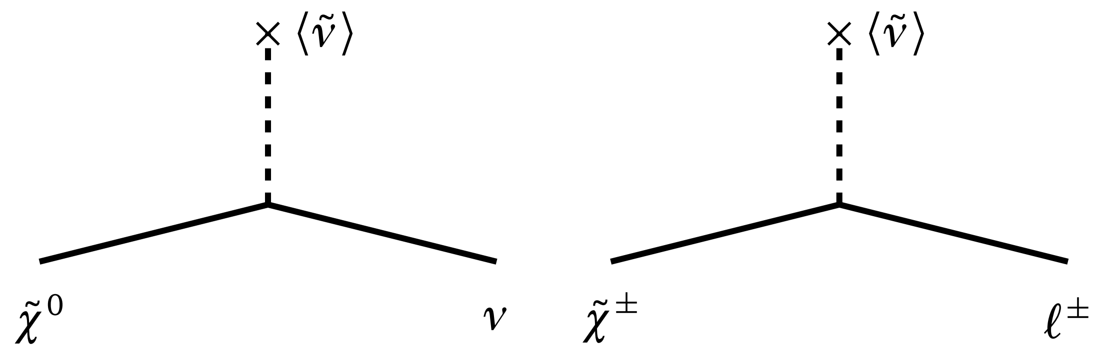
In the mini-split context would guess $B_{L_i\mu}\mu,\ \tilde{m}^2_{H_d,L_i} \sim \epsilon m^2_{3/2}$

Once the Higgs gets a VEV, these terms become sneutrino tadpoles, so the sneutrino gets a VEV:

$$\langle\tilde{\nu}\rangle \sim \epsilon v$$

Sneutrino VEVs

The sneutrino VEV has several interesting consequences.
Gauginos mix with leptons:



If winos are the LSPs, this will give them new decay modes:

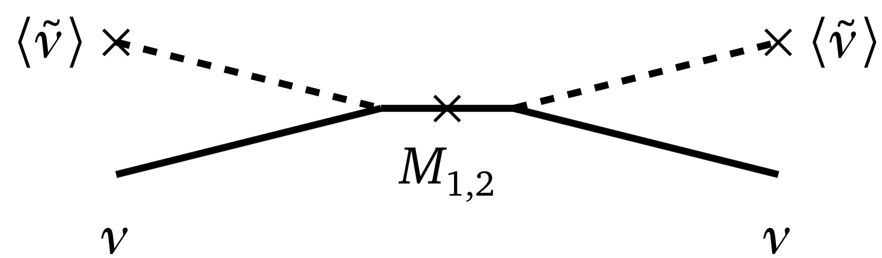
$$\tilde{W}^0 \to Z\nu, W^\pm\ell^\mp$$

$$\tilde{W}^\pm \to Z\ell^\pm, W^\pm\nu$$

This would be a worthwhile search channel at the LHC.
(Probably the lepton is mostly tau? Need flavor model.)

Bilinear RPV

Also get a contribution to neutrino masses:



$m_\nu \sim \epsilon^2 \frac{v^2}{M_{1,2}}$

This implies an upper bound $\epsilon \sim 10^{-6}$.

This gives a *lower* bound on the lifetime of the two-body wino decays, ~ 100 microns.* So should look for

$$\tilde{W}^0 \to Z\nu, W^\pm \ell^\mp$$
$$\tilde{W}^\pm \to Z\ell^\pm, W^\pm \nu$$

with displaced vertices! (Possibly macroscopically displaced; standard lepton ID may fail.)

* Disclaimer: I haven't plugged in all order-one factors; hope to study this more carefully soon.

Baryogenesis?

- Once we start talking about violating baryon or lepton number via RPV, we open up one connection to cosmology: RPV may play a role in baryogenesis.

- I have nothing new to say about that now, but see e.g. Haipeng An’s talk yesterday (1310.2608) and Yanou Cui’s recent paper (1309.2952)

What about dark matter?

It's very possible that DM is part of a hidden sector, consists of multiple particles, has nontrivial self-interactions and interactions with the SM. These are things I'm thinking about.

But for today I'll tell you a more conventional, minimal story:

Moduli-dominated cosmology is *much better* for axion DM than the conventional thermal cosmology!

(Kawasaki, Moroi, Yanagida hep-ph/9510461; Banks, Dine, Graesser hep-ph/0210256)

Axions & Moduli

Axions start to oscillate while moduli dominate, so the universe is matter-dominated, not radiation-dominated. Oscillation begins when $m_a(T) \sim H$; the energy density is $\sim m_a(T)^2 f_a^2 \sim H^2 f_a^2$, so they have $(f_a/M_{Pl})^2$ of the total energy density.

When moduli decay, their energy converts into radiation with a large entropy. After the dust clears, find:

$$\begin{aligned}\Omega_a h^2 &\simeq 3.1 \times 10^8 \mathrm{GeV}^{-1} T_R F_a^2 \theta^2 M^{-2} \xi(T_1)^{-1} \\ &\simeq 5.3 \left(\frac{T_R}{1\mathrm{MeV}}\right) \left(\frac{F_a \theta}{10^{16}\mathrm{GeV}}\right)^2 \xi(T_1)^{-1}.\end{aligned}$$

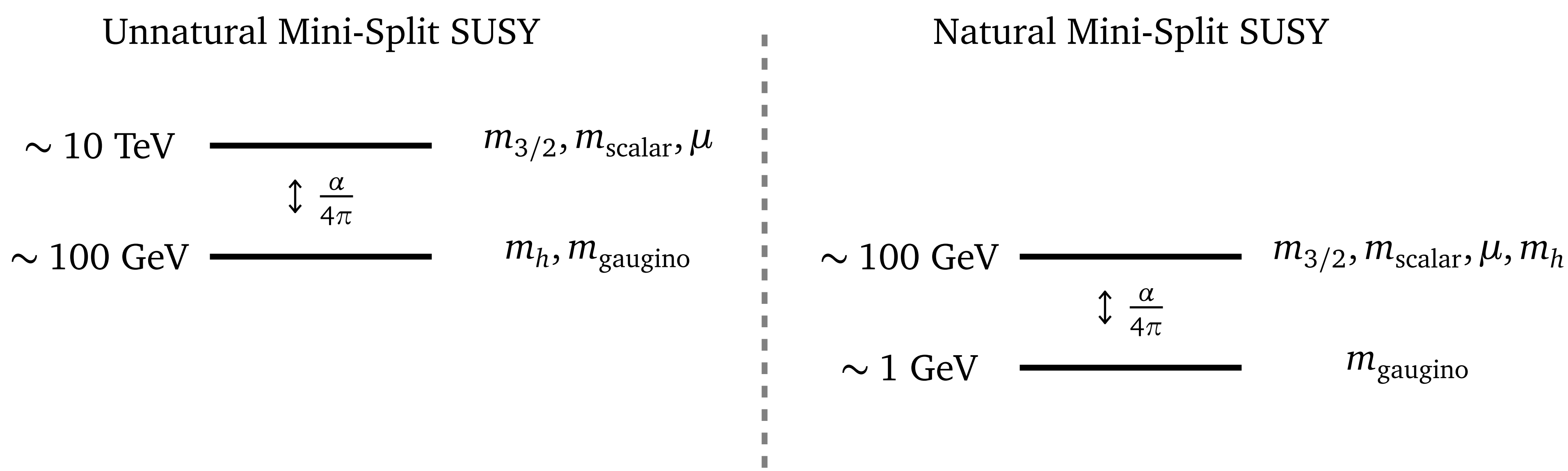
(Kawasaki et al 1995)

$\xi(T_1) \equiv m_a(T_1)/m_a \leq 1$

So, ~ string scale decay constants could be salvaged without tuning initial angle.

(See Svrcek, Witten 2006.)

The Anthropic Question



Is there a good reason why we might find ourselves living in the universe at left instead of the natural one at right?

There could be a reason tied to cosmology, if moduli are at the scale $m_{3/2}$. Work in (early) progress (with Josef Pradler). So the remaining slides are provisional.

The General Idea

If moduli have mass ~ $m_{3/2}$, then in the fully natural scenario where scalars are at 100 GeV, moduli decays reheat the universe to a temperature of ~1 keV.

Clearly this is not our universe. But: is it a universe we could have lived in, or not?

Many aspects of cosmology change and there are several possible anthropic problems with such a universe.

The Big Picture?

SUSY may solve most of the hierarchy problem. What we see conflicts with our notions of naturalness because we could not live in the natural world. Balance of two pressures:

GeV $\longrightarrow$ **We are here?** $\longleftarrow$ Planck scale

Anthropic pressure

Naturalness pressure

BBN?

In our universe, we begin with significantly fewer neutrons than protons due to the remarkable coincidence that weak interactions decouple at

$$T \sim \left(\frac{m_W^4}{M_{\rm Pl}}\right)^{1/3} \sim 1 \text{ MeV} \sim m_n - m_p.$$

If $T_{RH} < 1$ MeV this coincidence breaks. In "In Wino Veritas" we suggested this could lead to an anthropic argument related to having too much helium. But our argument was flawed. Moduli decays will break up bound states formed at early times. It seems most plausible that this leads to an all-hydrogen universe; not obviously a problem.

Diluting Matter?

If the abundance of some species of matter is set before moduli domination starts (plausible for baryon number), then the decays of moduli dilute the abundance.

When moduli *start* oscillating their number density dominates over the entropy in radiation:

$$Y_\phi \equiv \frac{n_\phi}{s} = \frac{1}{m_\phi}\frac{\rho_\phi}{\rho_{\rm rad}}\frac{3g_*}{4g_{*s}}T \sim \frac{T}{m_\phi}\cdot \sim \frac{\sqrt{HM_{\rm Pl}}}{m_\phi} \sim \sqrt{\frac{M_{\rm Pl}}{m_\phi}}.$$

Their decays then produce a large amount of entropy:

$$\frac{s_{\rm decay}}{s_{\rm before}} = \frac{\frac{2\pi^2}{45}g_{*s}T_{\rm RH}^3}{n_\phi(t_{\rm decay})/Y_\phi} = \frac{Y_\phi m_\phi}{T_{RH}}\frac{4g_{*s}}{3g_*} \sim \frac{M_{\rm Pl}}{m_\phi}.$$

Natural split SUSY moduli would lead to 1000x more dilution.

Baryon-to-Axion Ratio?

If axions are the DM, they start to oscillate during moduli domination. So they aren't diluted by entropy production in the same way that pre-existing matter is.

Neglecting for the moment temperature dependence of the axion mass, have:

$$\frac{n_a}{s} = \frac{\rho_a}{m_a s} \sim \left(\frac{f_a}{M_{\rm Pl}}\right)^2 \frac{T_{\rm RH}}{m_a}.$$

But $T_{RH} \sim (m_{\rm modulus})^{3/2}$, so for fixed decay constant, moduli are diluted more than baryons (which dilute as $m_{\rm modulus}/M_{\rm Pl}$).

So, have a **lower dark matter-to-baryon ratio.**

Cosmological Problems

We've seen that a fully natural scenario can dilute the amount of matter. This can be dangerous. Structure starts to grow when matter domination kicks in. If the *cosmological constant* takes over sooner, we lose structure formation. *Need*:

If all matter is diluted, $Y_m^{\text{before}} = Y_m^{\text{after}} \frac{M_{\text{Pl}}}{m_\phi} > \frac{M_{\text{Pl}}\Lambda}{m_{\text{matter}} m_\phi} \sim 1 \left(\frac{100\ \text{GeV}}{m_{\text{matter}}}\right)\left(\frac{100\ \text{TeV}}{m_\phi}\right).$

If dominantly axions, $f_a > 10^{14}\ \text{GeV}\left(\frac{100\ \text{TeV}}{m_\phi}\right)^{3/4}.$

These conditions may be difficult to satisfy. Having too many baryons relative to DM can also be problematic for growth of structure (e.g. due to Silk damping). Need to do more work, but plausible that a strong argument exists.

Changing QCD Scale?

In the natural split SUSY case, if we hold α_s fixed at a high scale, its running changes at low scales because the colored scalars and gauginos are lighter.

All else equal, this lowers the QCD scale by an order-one amount, and $m_{u,d}/\Lambda_{QCD}$ becomes larger.

This potential affects nuclear properties, BBN, etc., along the lines of older anthropic studies (e.g. Agrawal, Barr, Donoghue, Seckel hep-ph/9707380)

But is α_s at a high scale the right parameter to keep constant?

What to hold fixed?

Any anthropic argument tends to involve fixing some parameters and varying others. Holding α_s at a high scale fixed seems unlikely to be the right thing. α_s is related to VEVs of moduli, and we're changing moduli masses.

A toy model including moduli stabilization seems necessary to at least start to develop intuition about how the QCD scale will vary in conjunction with SUSY-breaking parameters.

This seems feasible but I don't have results to tell you about yet.

Status

Two ideas that seemed to work very well are now in serious trouble:

1. Natural SUSY is being squeezed by the LHC.
2. Nonthermal wino DM is in trouble from gamma rays.

But mini-split SUSY with 100 TeV scalars solves *most* of the hierarchy problem, gets the Higgs mass right, has gauge coupling unification, and might help with axion DM.

I suspect we can find an argument that the fully natural scenario is anthropically disfavored. Maybe live in a sweet spot between naturalness and anthropic pressures.

Try to link the anthropic argument with observable cosmology? It suggests a low T_{RH}. How could we confirm it?