Status of low-scale supersymmetry

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SUSY18, Barcelona

What can SUSY do for us?

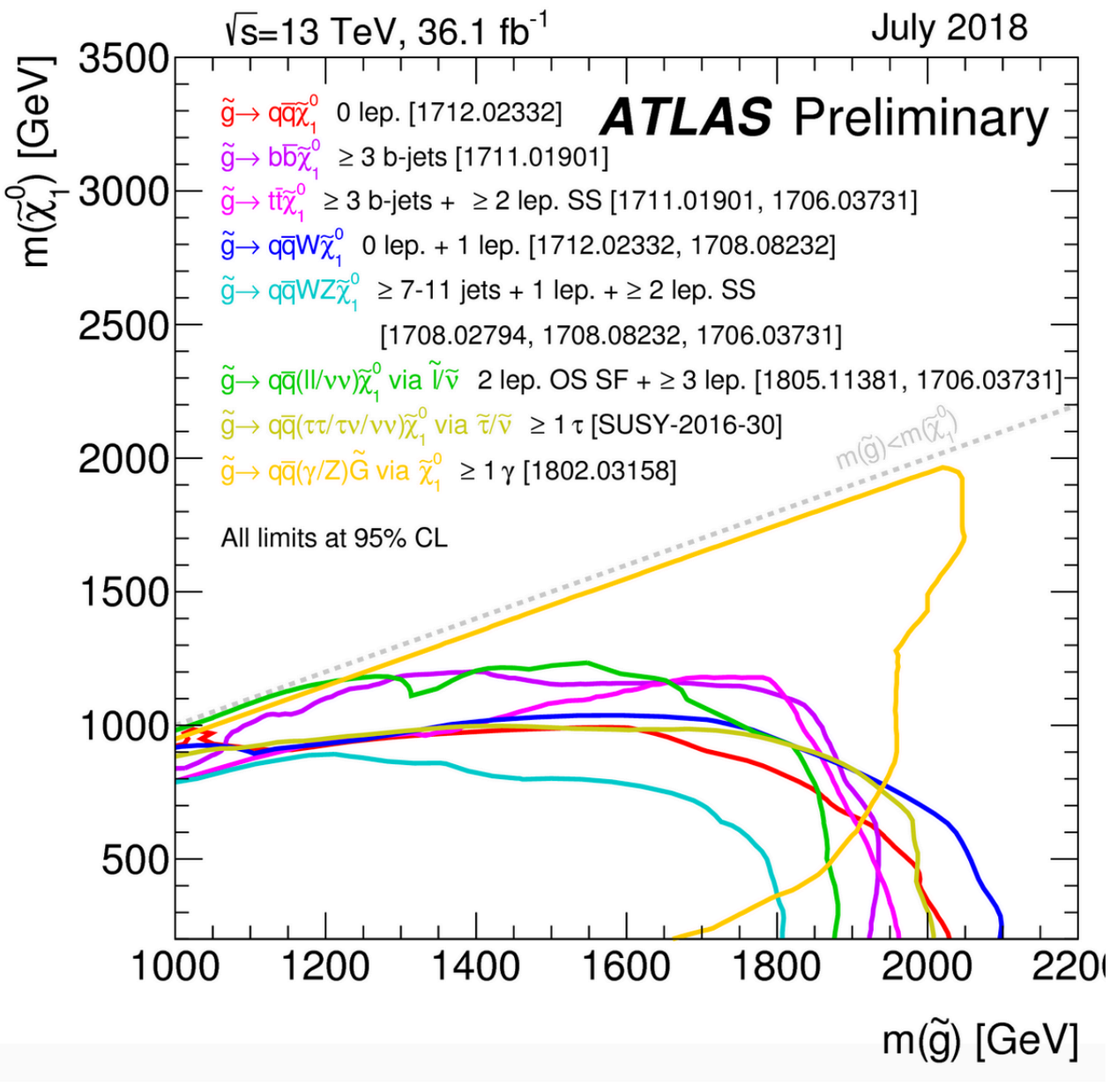
Current scorecard….

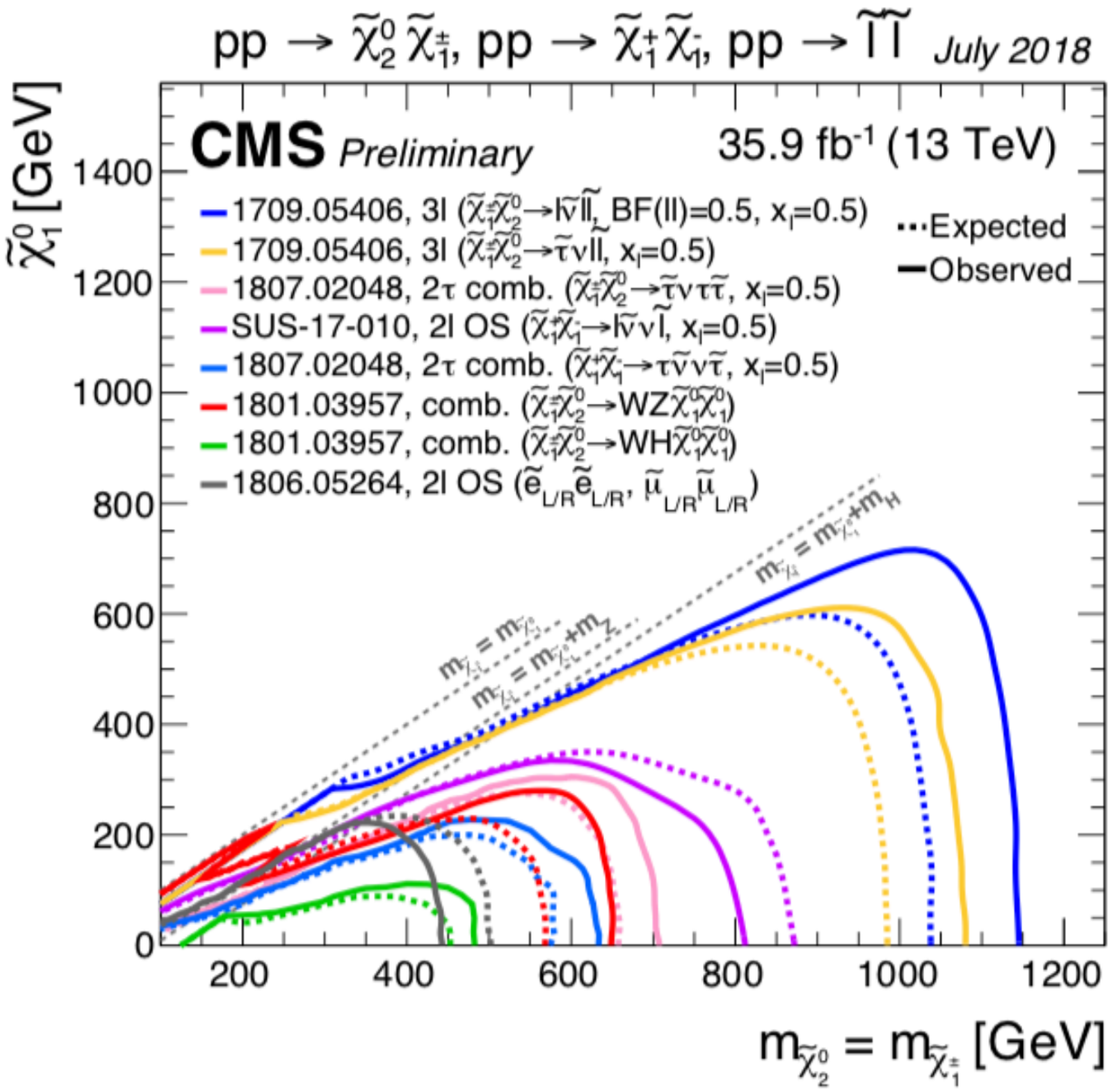
- Solve the “big” hierarchy problem 
- also the “little” hierarchy problem —fully natural EWSB  (depending on how “little”?)
- Precision gauge coupling unification 
- Provide a dark matter candidate 

This talk

- What is the LHC telling us so far?
- Less-explored corners
- SUSY dark matter
- SUSY, tuning, and cosmological dynamics
- Progress in electric dipole moment experiments

Where is SUSY?





No sign so far. Keep looking: compressed spectra, mixed branching ratios, electroweak production (without light sleptons)

Two Paths to 125 GeV

Higgs at 125 GeV

Beyond MSSM, *natural*

robust experimental connection

Stop search;
Higgs sector
(rates, decays)

Models?
(NMSSM, D-terms, compositeness....)

MSSM with heavy scalars

Gluino search

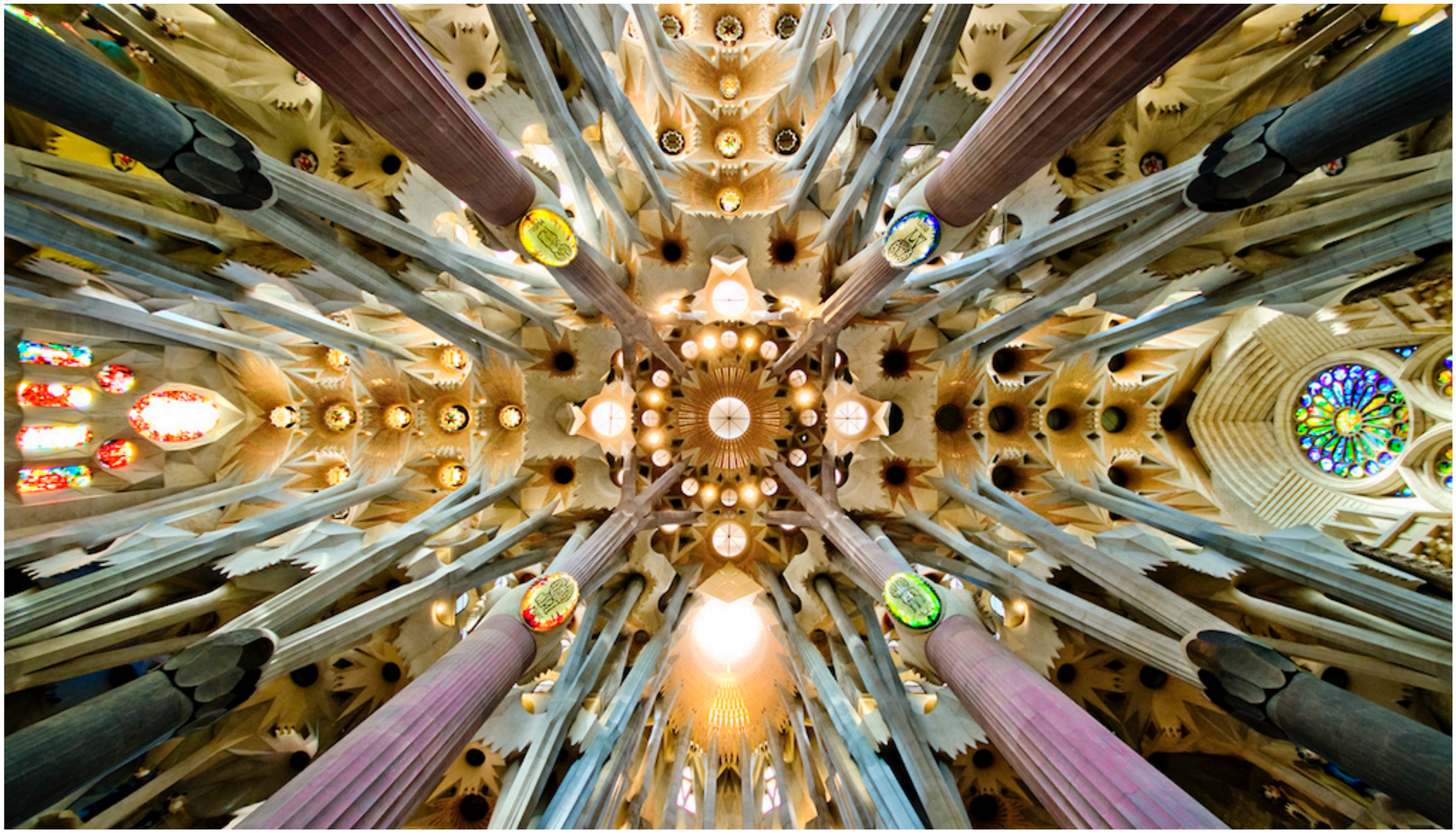
Top-down theory

Patience…

Fully constructing the theory of the weak scale may take longer than some expected

and some of the details may seem confusing

Symmetry

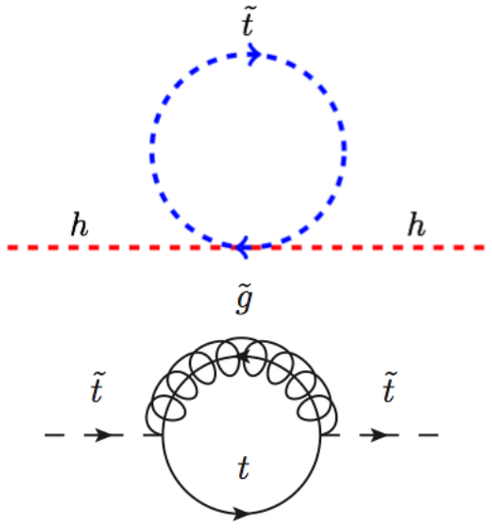


Nature may reward our patience by revealing beautiful structures and symmetries

How Tuned Is it?

Expect to find light higgsinos (tree-level tuning), stops (one-loop tuning, gluinos (two-loop tuning)

$$\text{higgsinos}: \quad \delta m_H^2 = |\mu|^2$$

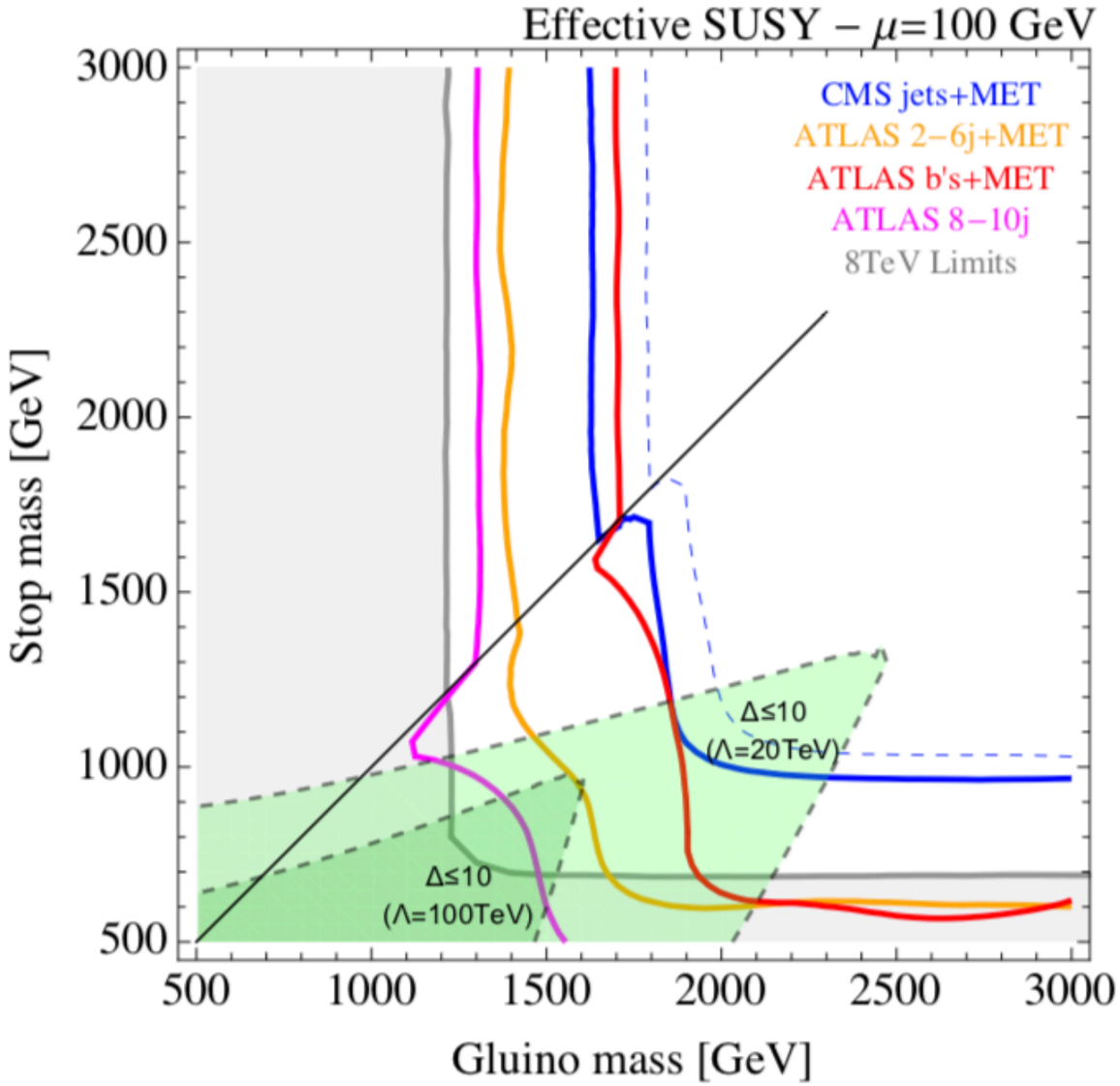


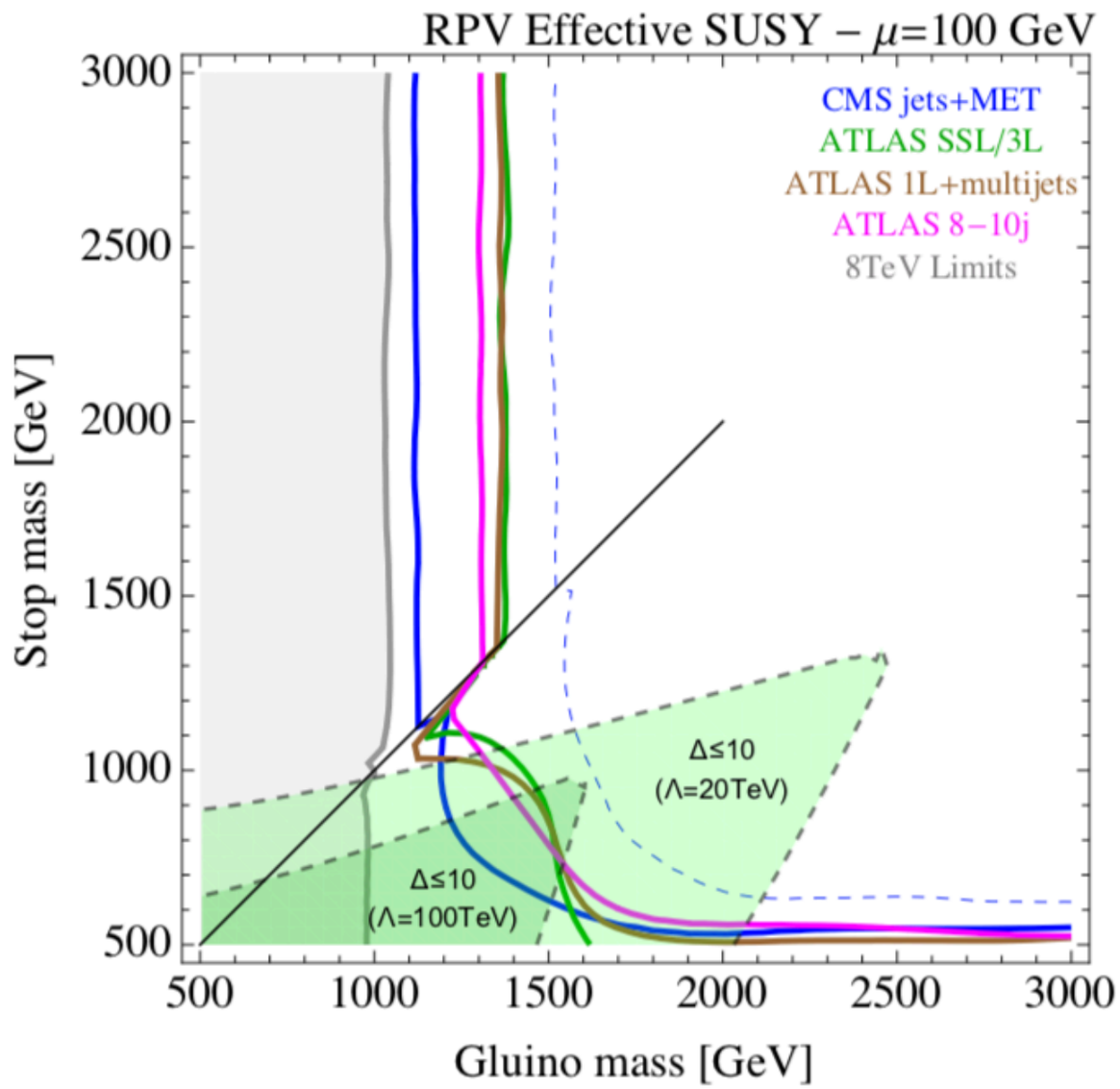
$$\text{stops}: \quad \delta m_H^2 \sim -\frac{3}{8\pi^2} y_t^2 (m_{Q_3}^2 + m_{U_3}^2) \log \frac{\Lambda}{Q}$$

$$\text{gluinos}: \quad \delta m_H^2 \sim -\frac{g_3^2 y_t^2}{4\pi^4} |M_3|^2 \log^2 \frac{\Lambda}{Q}$$

Taking care with the tuning measure, one finds that perhaps we've been overly pessimistic, due to threshold corrections and running effects. [Buckley, Monteux, Shih arXiv:1611.05873]. Could also have UV correlations reducing tuning [Baer et al.]

How Tuned Is it?

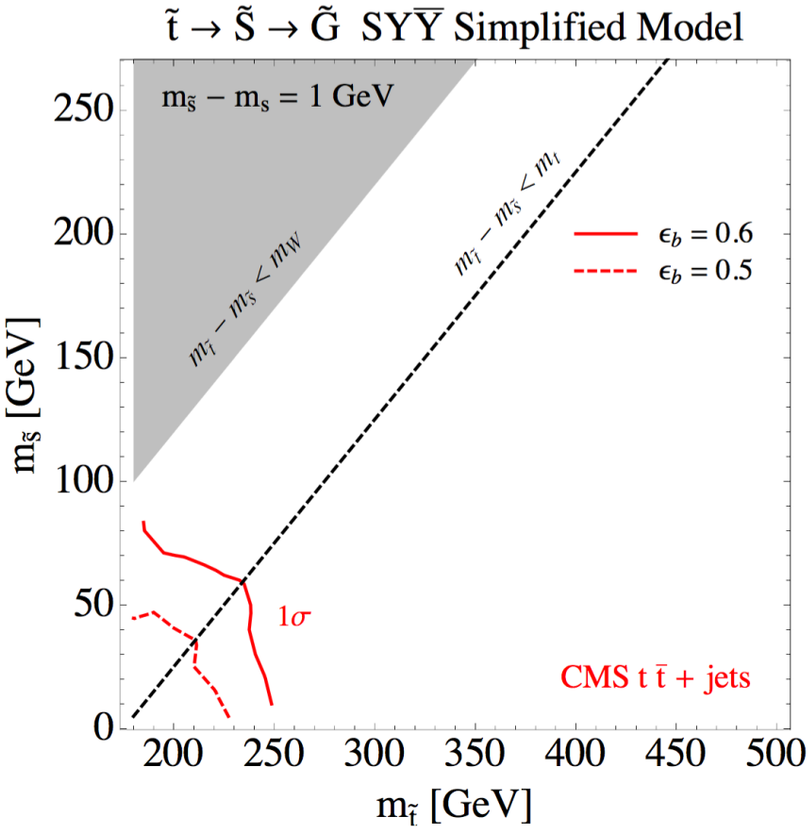


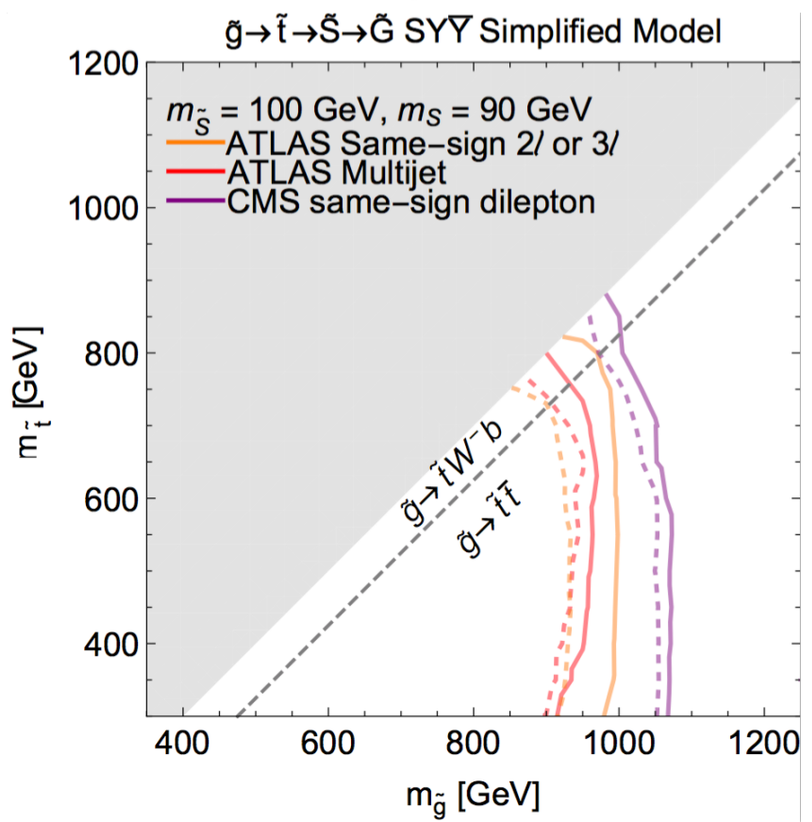


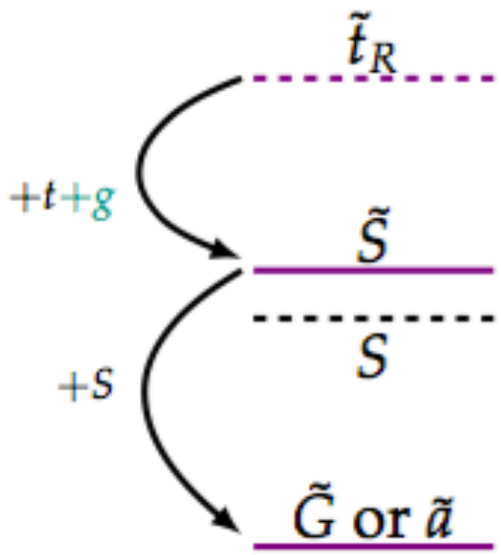
RPV/Hidden Valley (signals are mostly hadronic) + “Effective SUSY” (decouple 1st/2nd gen squarks) can weaken the bounds.

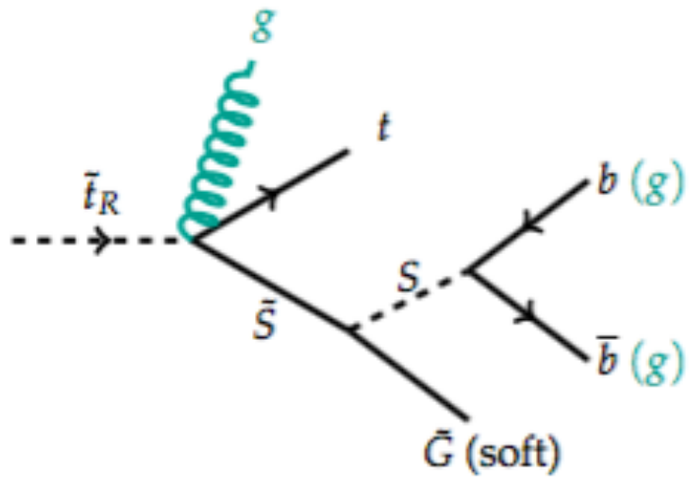
Buckley, Feld, Macaluso, Monteux, Shih 1610.08059

Stealth Supersymmetry



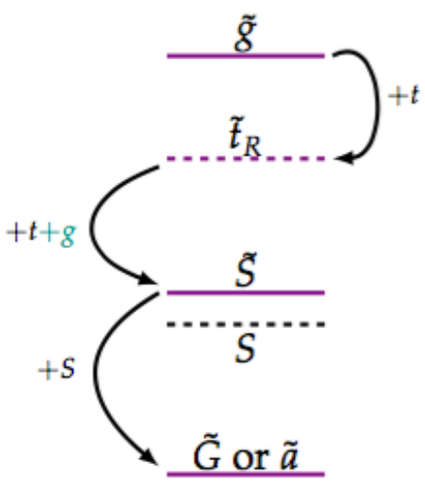


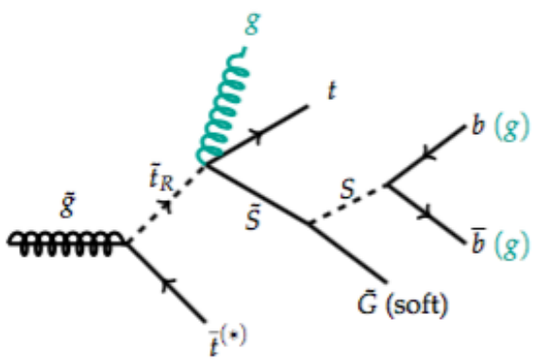




Decays through an **approximately supersymmetric hidden sector** can remove missing momentum from signal

Fan, Reece, Ruderman 2011
1512.05781 Fan, Krall, Pinner, Reece, Ruderman

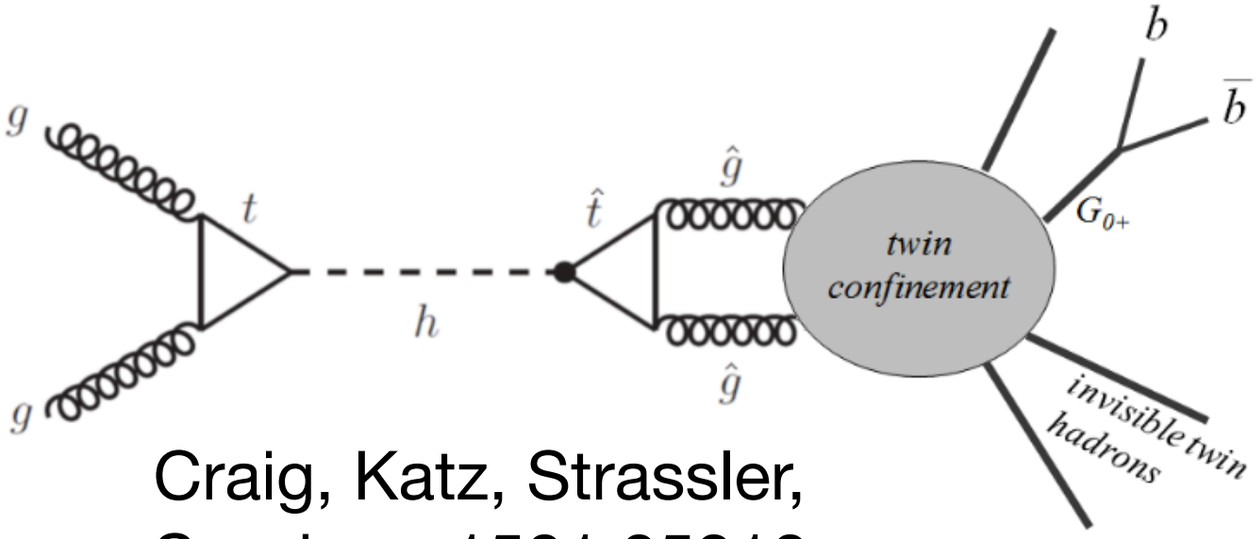




Gluinos still constrained (also see Evans et al. 1310.5758; Buckley et al. 1610.08059)

Neutral Naturalness

Revival of Twin Higgs (Chacko, Goh, Harnik hep-ph/0506256) and related ideas.



Craig, Katz, Strassler, Sundrum 1501.05310

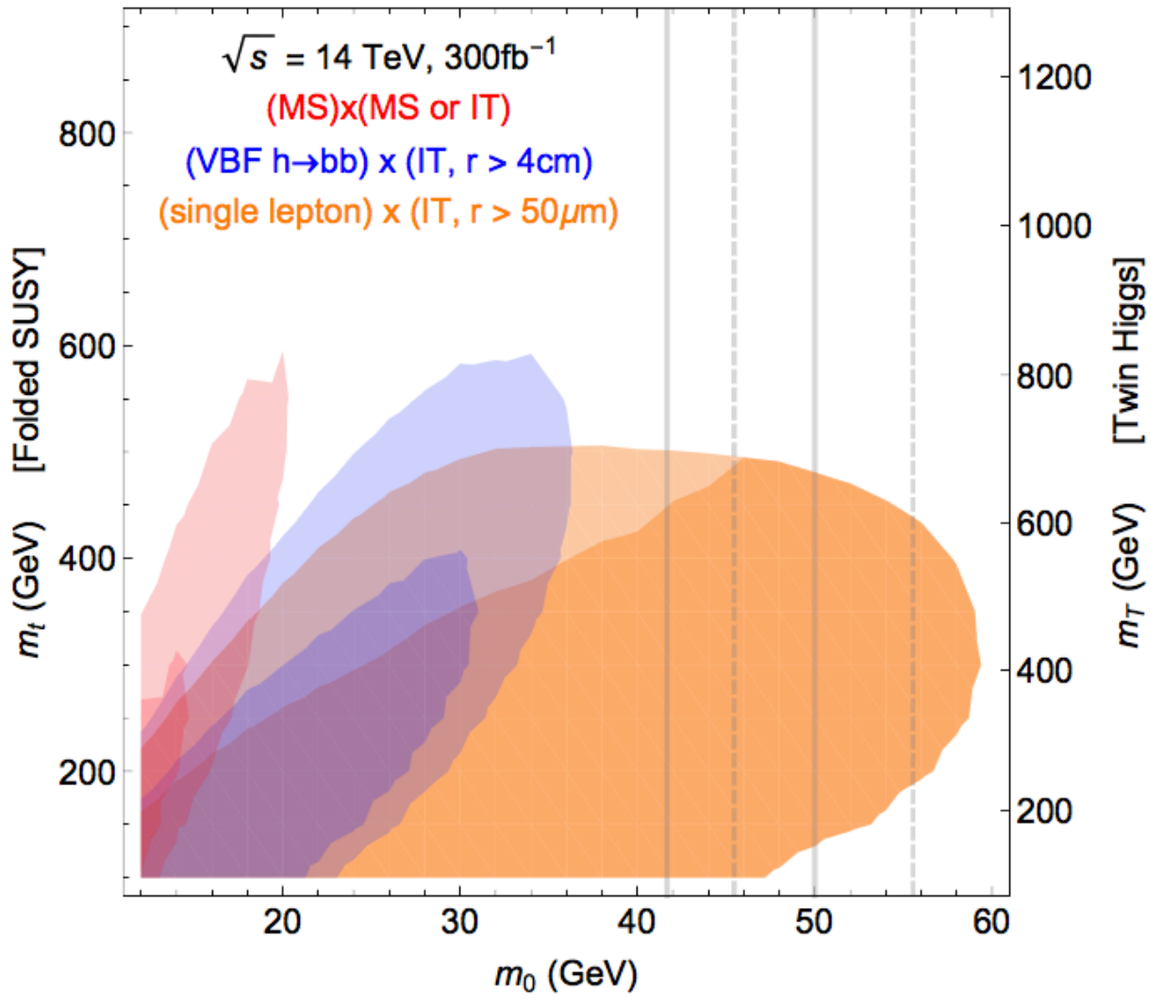
Constructed to solve only the little hierarchy problem; need UV completion.

Could fit together with SUSY as a solution to the “big” hierarchy problem.

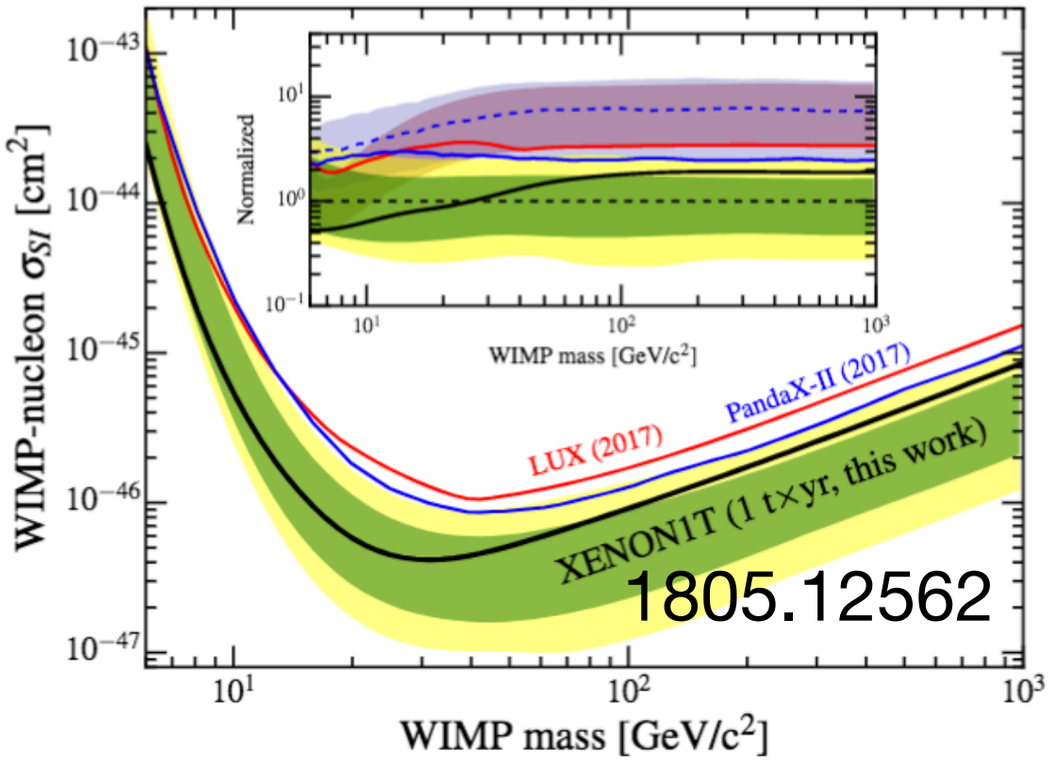
Interesting cosmological challenges.

Hidden Valley signatures: twin glueball a key particle

Curtin, Verhaaren 1506.06141



SUSY Dark Matter

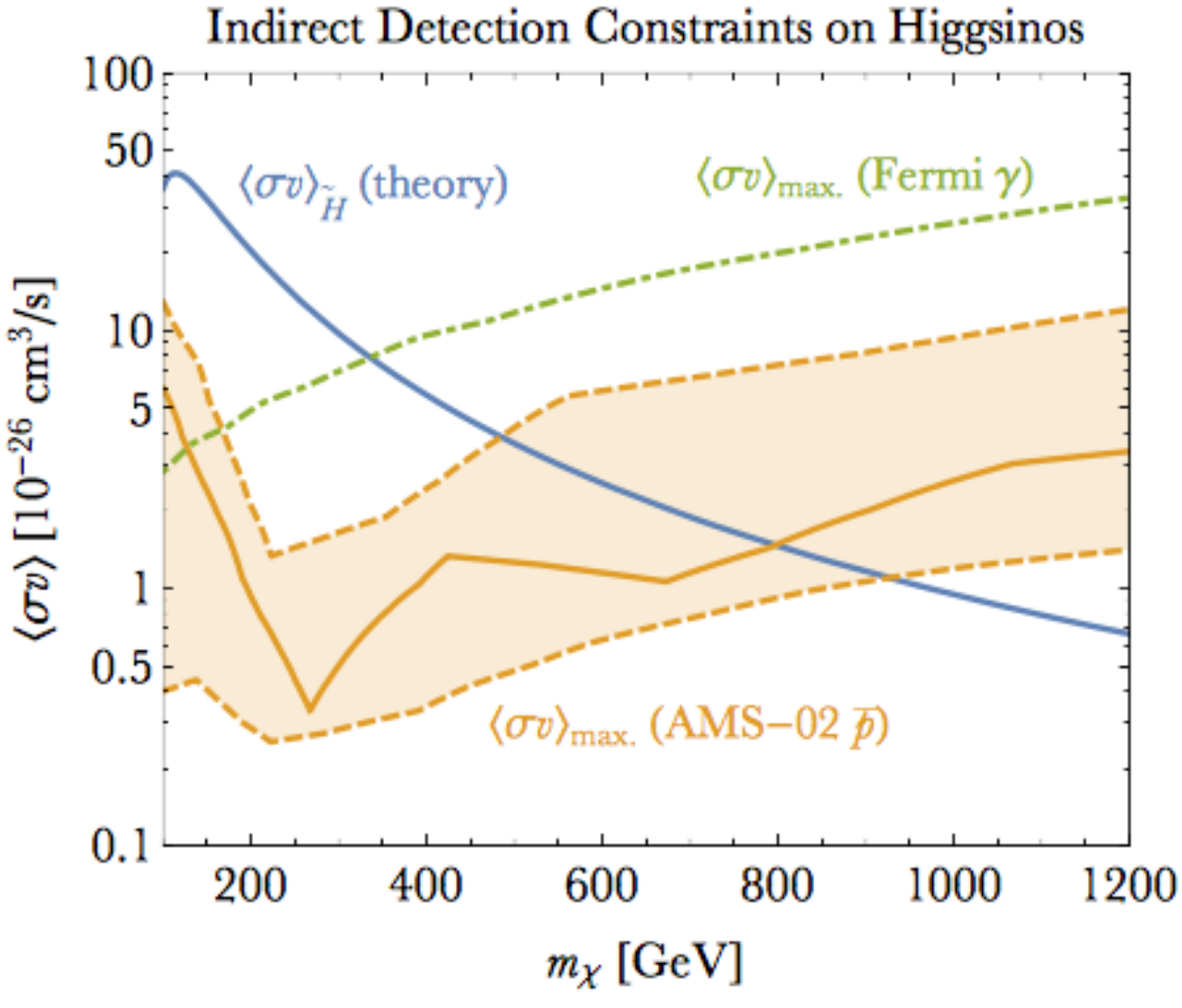


The xenon based experiments have strongly constrained WIMPs coupling to the Higgs boson.

WIMPs in pure SU(2) multiplets have

$$\tilde{\chi}^0\tilde{\chi}^0 \to W^+W^-$$

annihilation. Indirect detection severely constrains winos*; constrains ***higgsinos*** mildly.



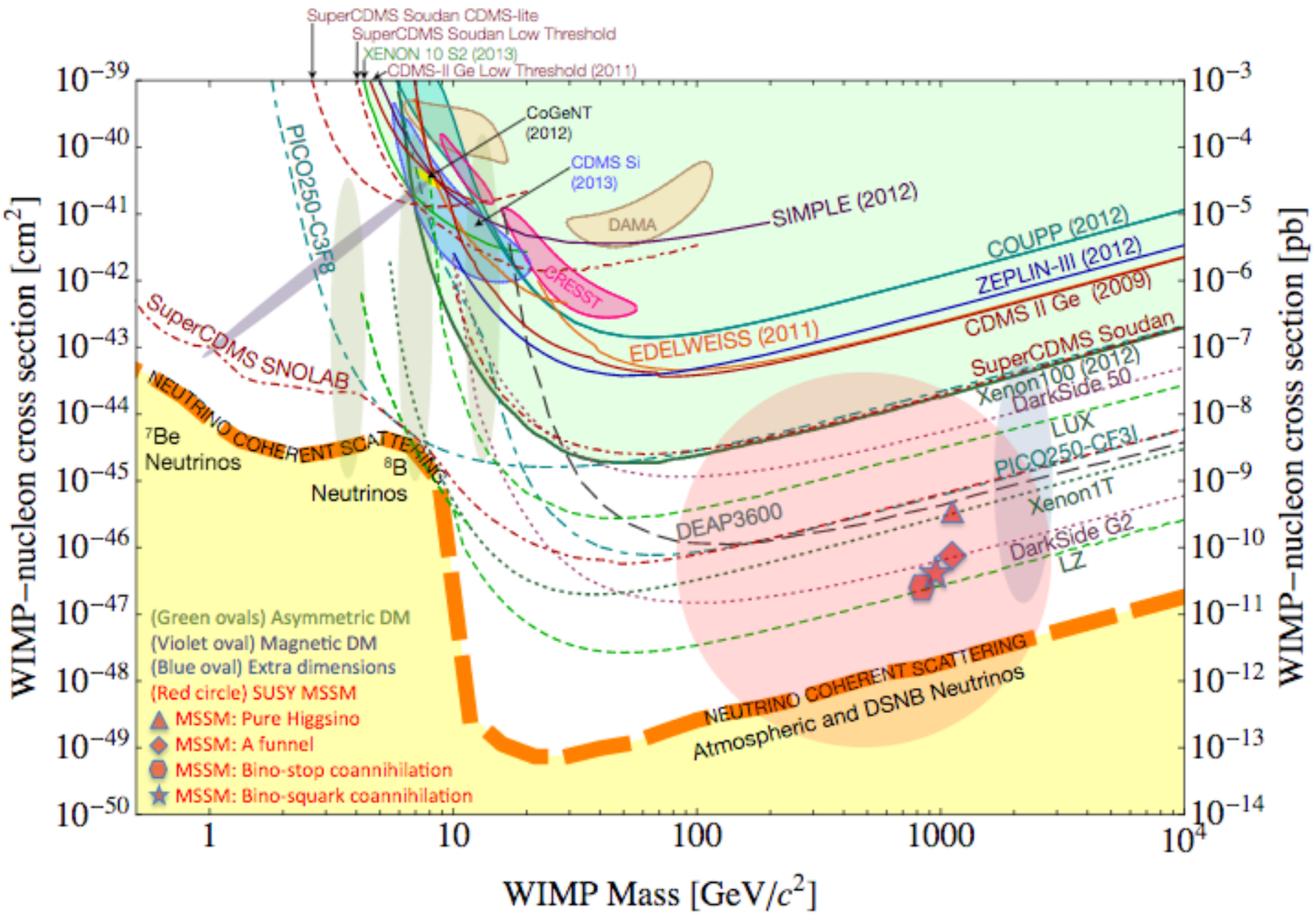
* Cohen, Lisanti, Pierce, Slatyer 1307.4082

* Fan, MR 1307.4400

Krall, MR 1705.04843, using work of Cuoco, Krämer, Korsmeier 1610.03071

Future Direct Detection

Snowmass: Cushman et al. 1310.8327



← *Z* exchange

← *h* exchange

← *W* loop (wino)

← *W* loop (higgsino)

SU(2) multiplets dominantly scattering through loops are a real challenge, beyond the next generation of experiments.

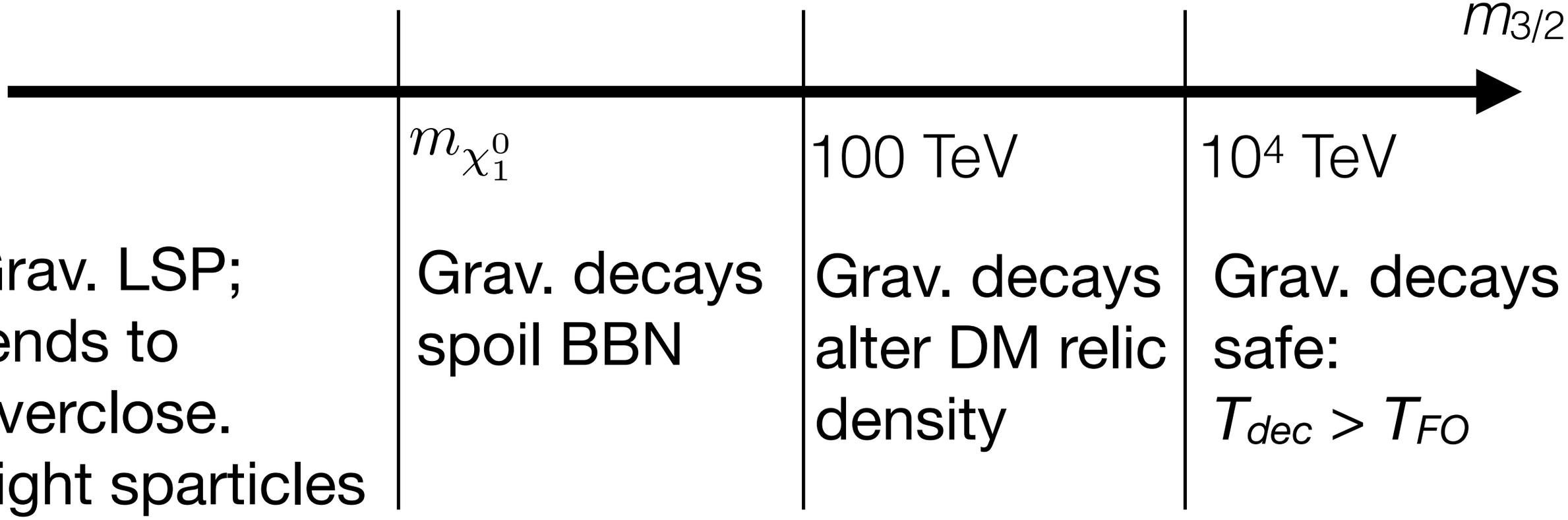
SUSY Cosmology: Is Thermal Equilibrium Expected?

Gravitino very weakly coupled, and so decays very late:

$$T_{dec} \approx 10 \text{ MeV} \left(\frac{m_{3/2}}{100 \text{ TeV}} \right)^{3/2}$$

(moduli, modulinos, saxions, axinos similar)

Regimes of gravitino mass:

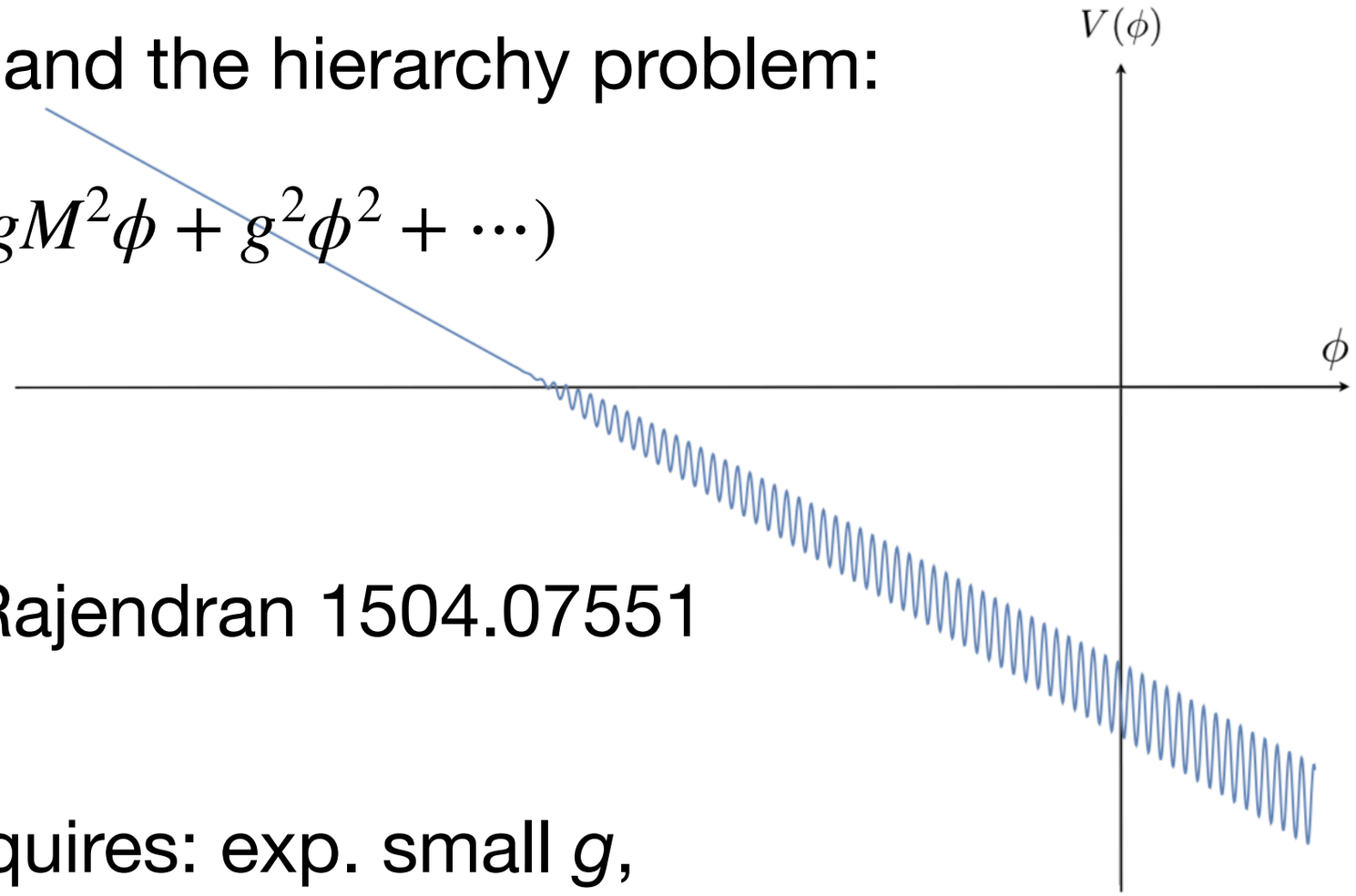


Relaxing the little hierarchy?

Axion monodromy and the hierarchy problem:

$$(-M^2 + g\phi)\,|h|^2 + (gM^2\phi + g^2\phi^2 + \cdots)$$

$$+\Lambda(h)^4\cos(\phi/f)$$



Graham, Kaplan, Rajendran 1504.07551

Original version requires: exp. small *g*,
exp. many e-folds, exp. large field range

Difficult to UV complete (McAllister, Schwaller, Servant, Stout, Westphal 1610.05320)

Relaxing Split SUSY

Batell, Giudice, McCullough 1509.00834
Relaxion chiral supermultiplet *S*. Relaxino as gravitino.

$$\mathscr{L} = \int d^4\theta \left[f^2 K(S+S^\dagger) + Z_i(S+S^\dagger)\,\Phi_i^\dagger e^V \Phi_i \right] + \left[\int d^4\theta\, U(S+S^\dagger)\, e^{-qS} H_u H_d \right.$$
$$\left. + \int d^2\theta \Big(C_a(S)\,\mathrm{Tr}\mathcal{W}_a\mathcal{W}_a + \mu_0\, e^{-qS} H_u H_d + \text{Yukawa int.} \Big) + \text{h.c.} \right]$$

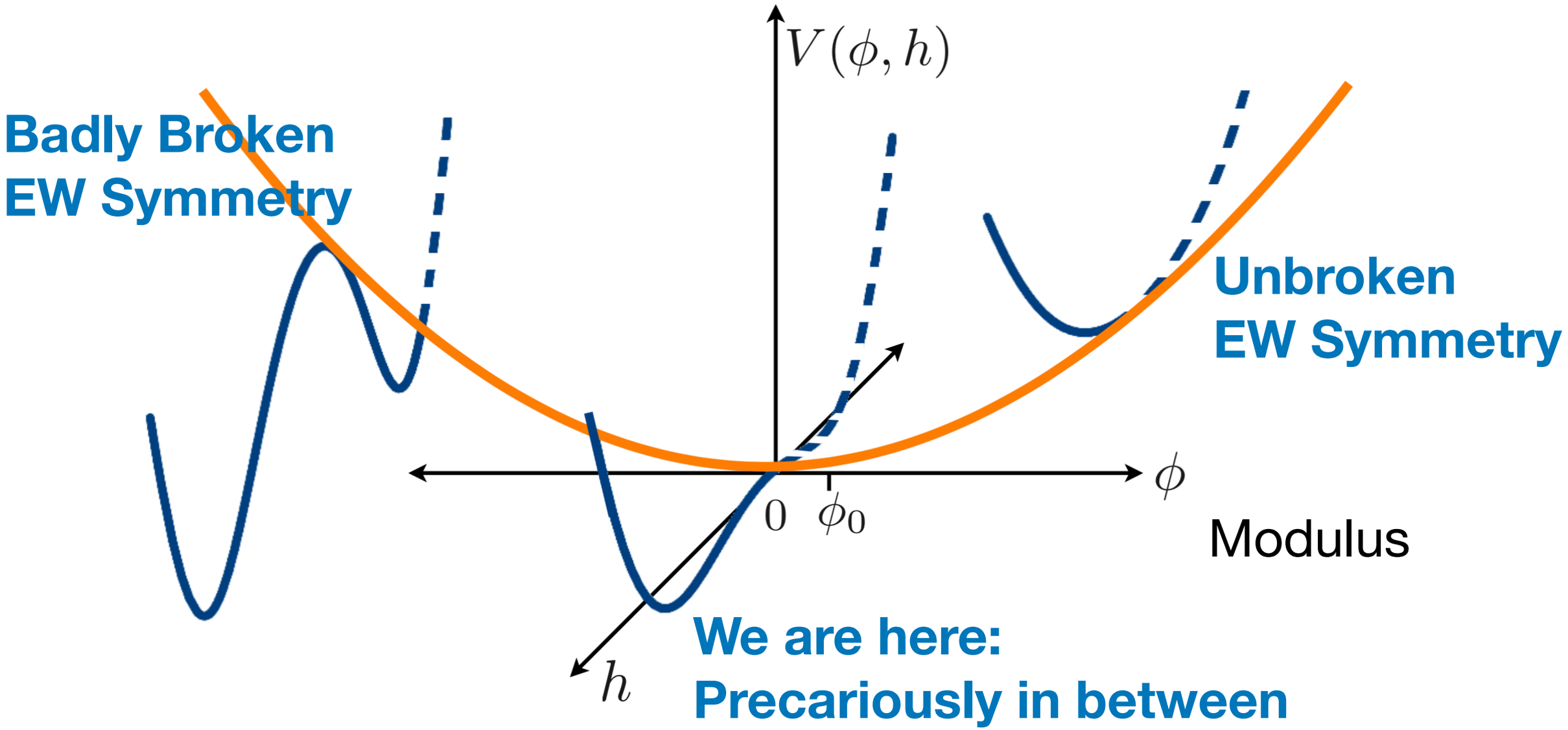
Split-SUSY like spectrum with little hierarchy explained dynamically.

Other interesting developments: alternative friction during relaxation from particle production (Hook, Marques Tavares 1607.01786; Fonseca, Morgante, Servant, 1805.04543)

$$\mathcal{L} \supset (\Lambda^2 - \epsilon\phi) h h^\dagger + \epsilon\phi\Lambda^2 + \Lambda_c^4 \cos\frac{\phi}{f'} - \frac{\phi}{f}(\alpha_Y B\tilde{B} - \alpha_2 W\tilde{W})$$

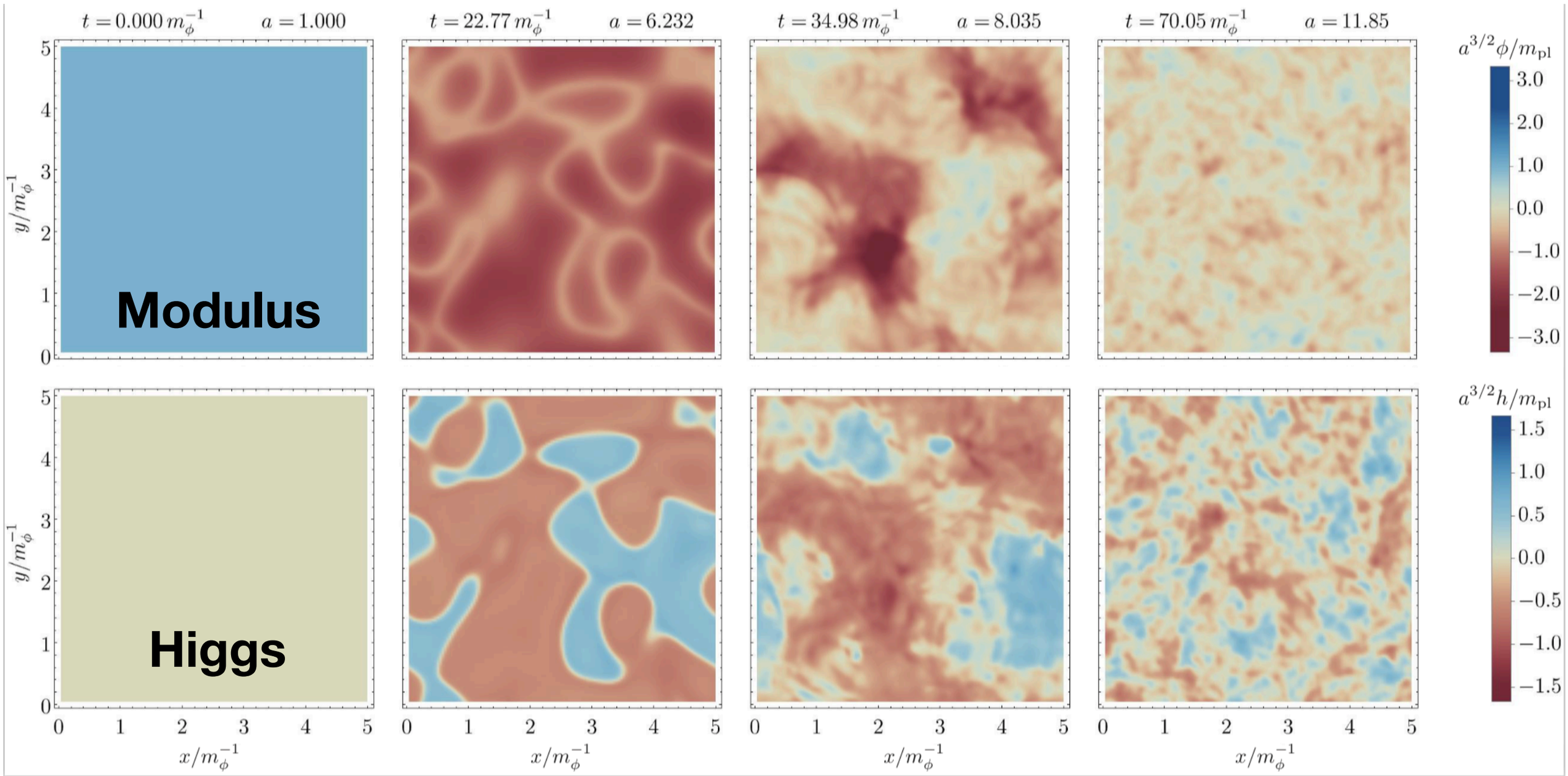
Smaller field range needed. Closer to plausibility?

Cosmological Signals of a Fine-Tuned Universe



[Amin, Fan, Lozanov, MR 1802.00444]

Higgscitement

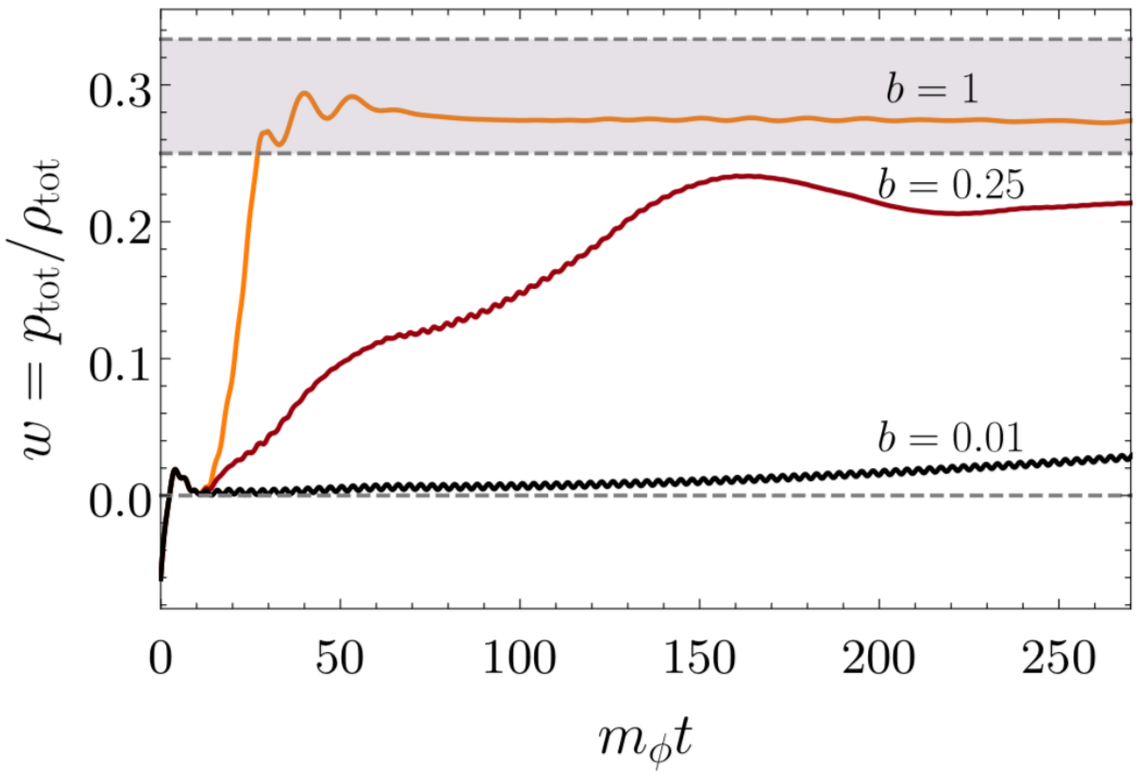


Fine-tuned Higgs ⇒ Violent dynamics fragment the modulus

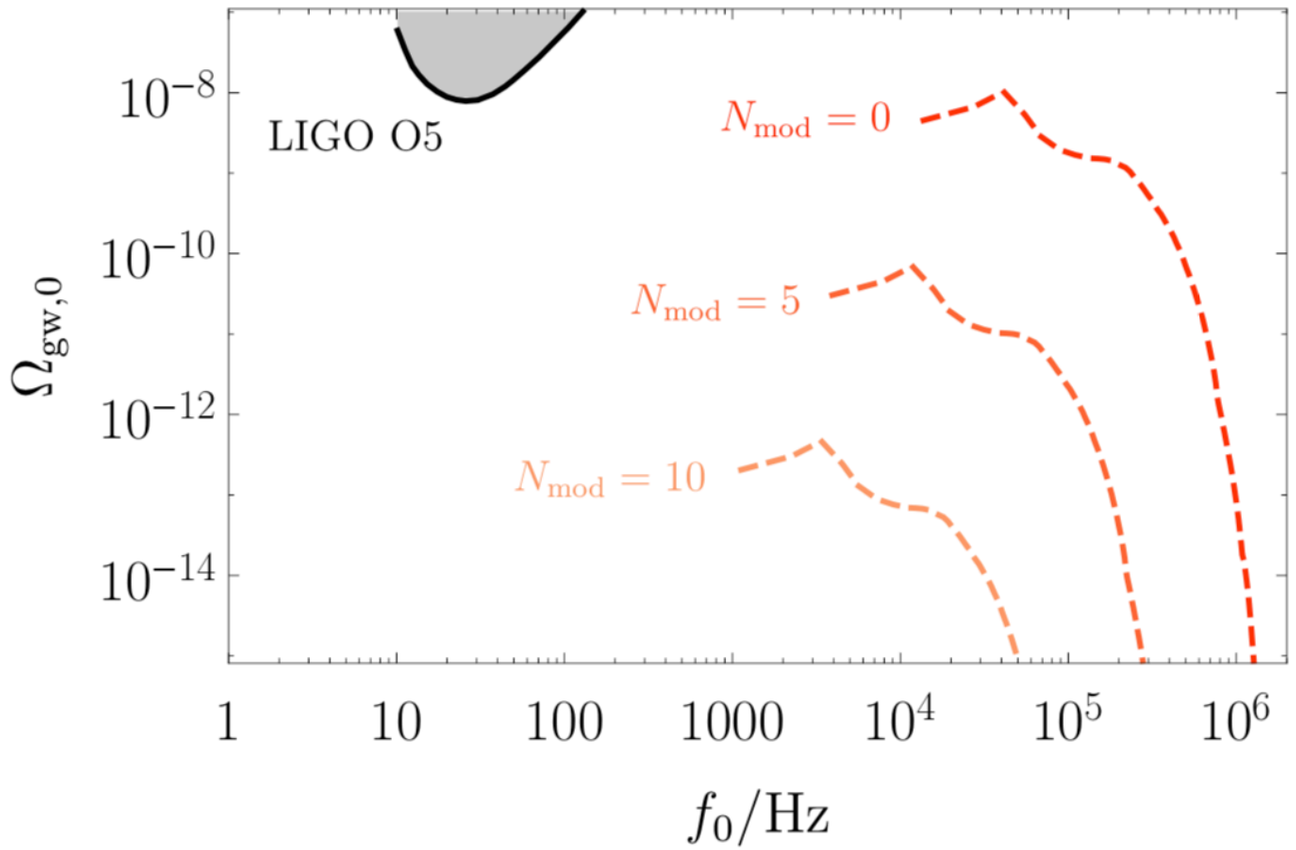
[Amin, Fan, Lozanov, MR 1802.00444]

Higgscitement

nontrivial equation of state



stochastic gravitational waves



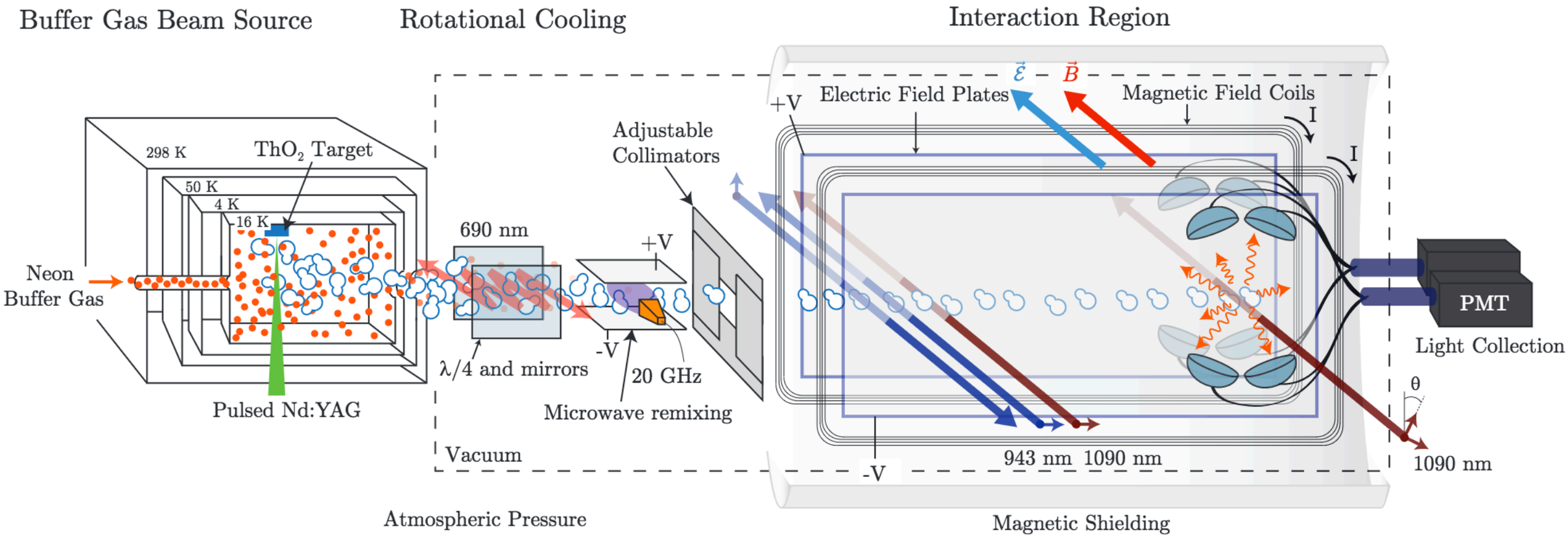
Fine-tuned dynamics *and* SUSY flat directions: far from a quiescent, modulus-dominated phase with equation of state $w = 0$.

[Amin, Fan, Lozanov, MR 1802.00444]

EDM Experiments

One of the most exciting recent experimental probes of SUSY comes from AMO physics: searches for the electron EDM.

ACME 2 (source: electronedm.org) DeMille, Doyle, Gabrielse and collaborators. New result expected very soon!



Electron EDM

We expect the upcoming ACME result to be somewhere in the neighborhood of $d_e \lesssim 1.0 \times 10^{-29}\, e\,\mathrm{cm}$

EDMs violate chirality, so putting in the electron mass a spurion, we expect an effect of order:

$$d_e \sim \delta_{\mathrm{CPV}} \left(\frac{\lambda}{16\pi^2}\right)^k \frac{m_e}{M^2}$$

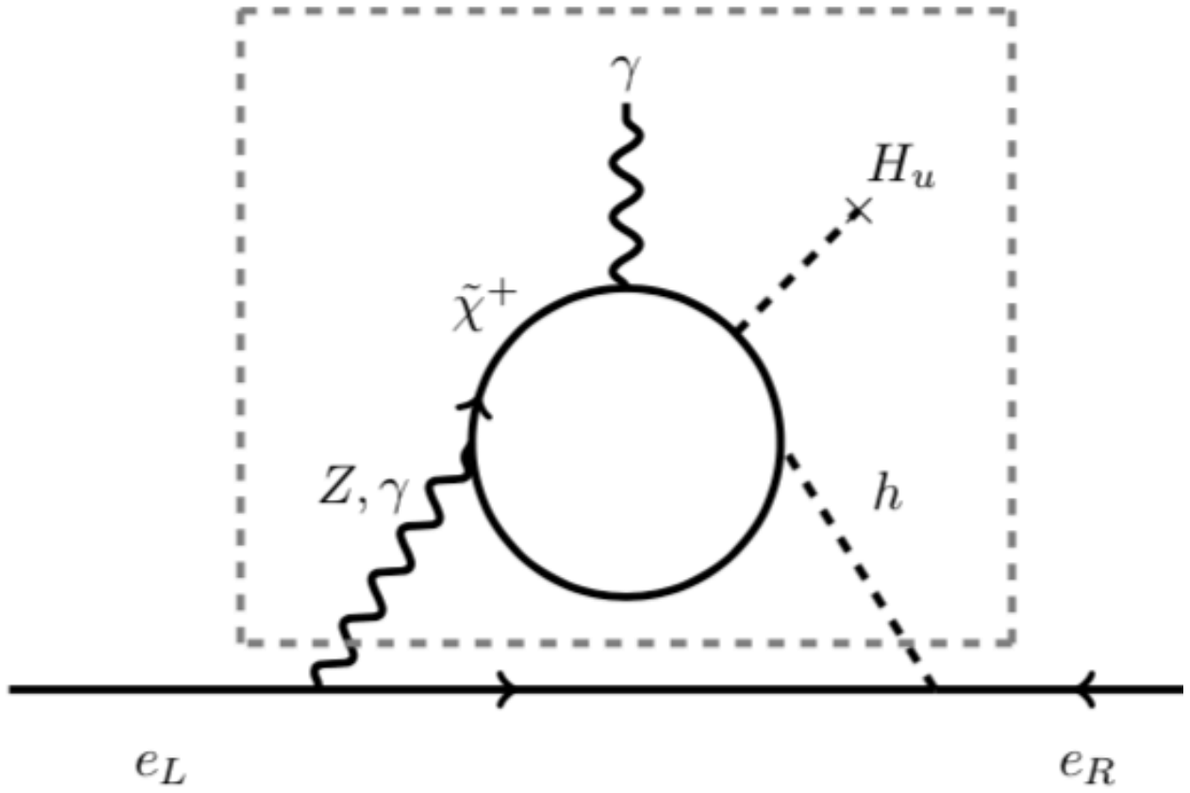
Then dimensional analysis tells us that the experiment probes masses **Preliminary: experimental result not yet known**

0-loop	1-loop	2-loop
800 TeV	40 TeV	2 TeV

for order-one CPV phases this often exceeds LHC reach!

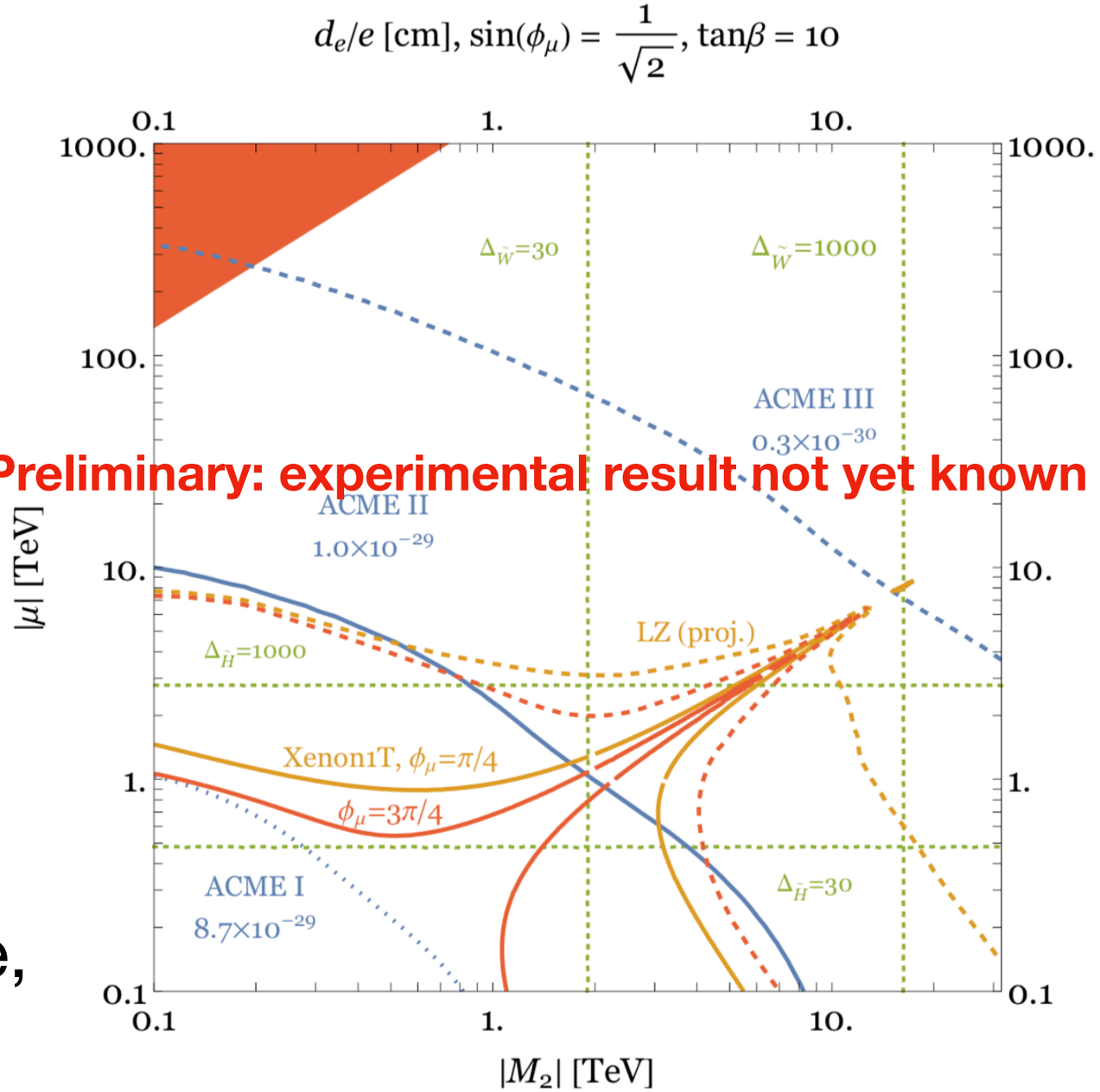
Electron EDMs

Quite generally, electroweak new physics coupling to the Higgs boson gives rise to an electron EDM (Barr-Zee).



[Cesarotti, Lu, Nakai, Parikh, Reece, to appear]

Powerful split SUSY constraints (forecast) from ACME 2!



Conclusions

No signs of superpartners have appeared so far.

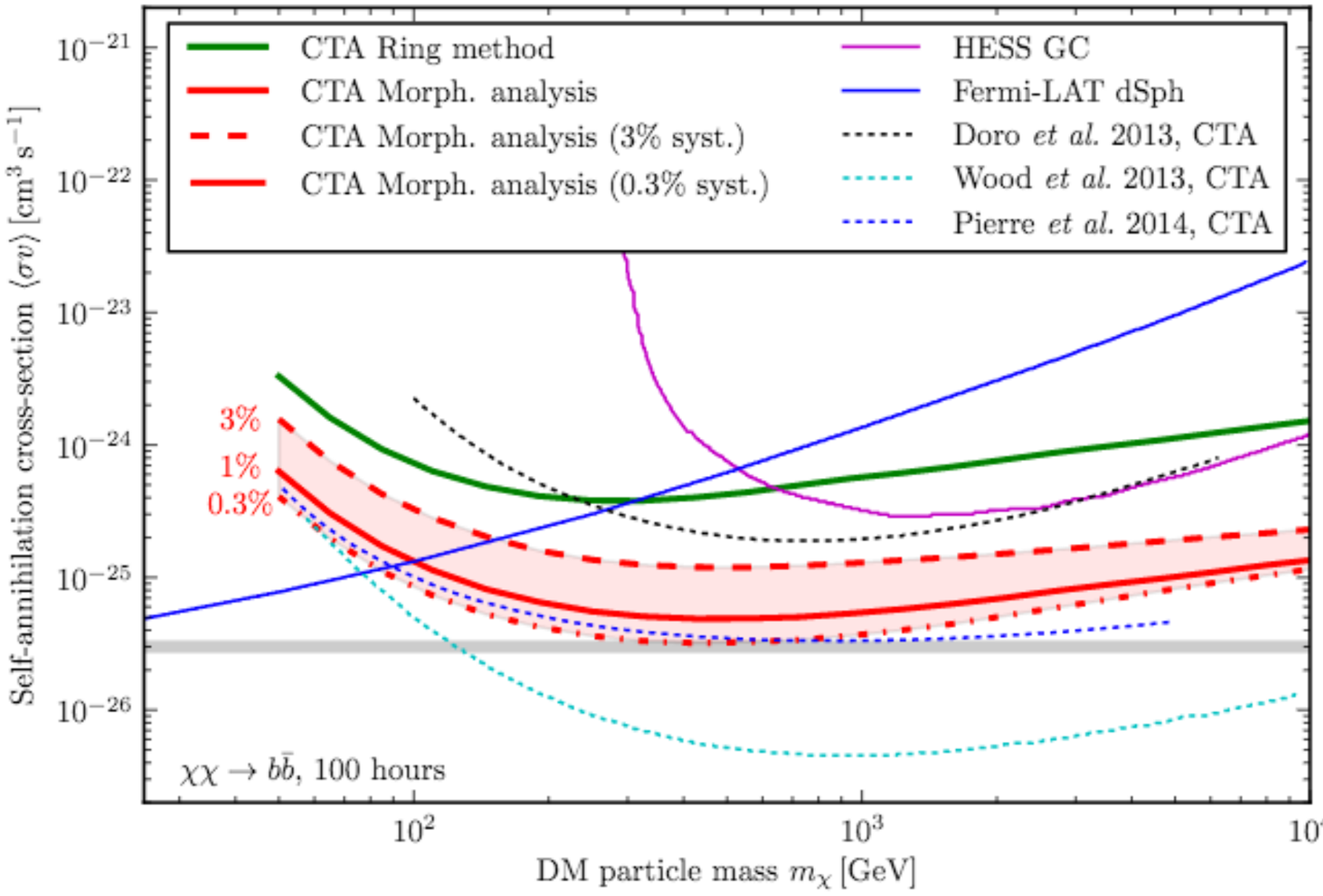
The Higgs fine-tuning puzzle is as puzzling as ever. Do we simply live in a (mildly?) fine-tuned universe? Or is there a subtle solution?

Themes of recent years: search for electroweak or neutral new particles at colliders to exhaust possibilities; intriguing possibilities for connections of the weak scale with cosmology.

Amazing landscape of experiments: LHC, dark matter, EDMs, flavor physics. New physics discovery could come at any time!

backup

Future Indirect Detection



1408.4131
Silverwood, Weniger, Scott, Bertone

CTA (Cherenkov Telescope Array) will get *close* to ruling out thermal relic dark matter over most of the hundreds-of-GeV range, but will likely not quite reach TeV higgsinos.

(Assuming no improvements do much better than these estimates)