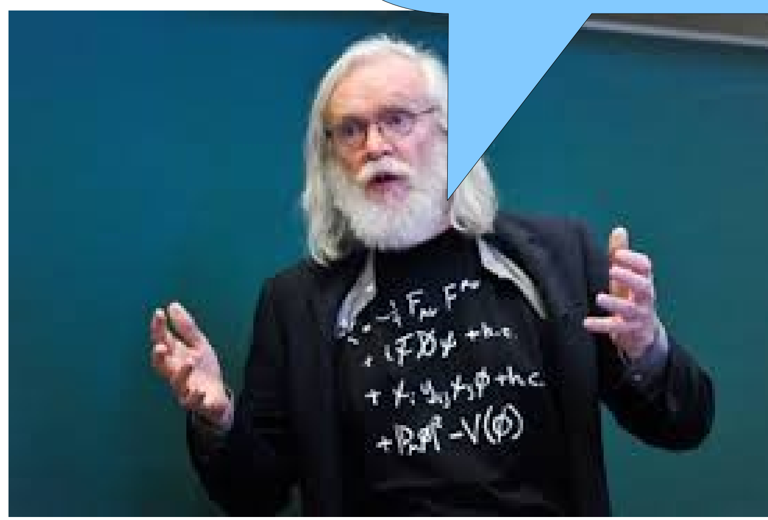
Revisiting fine-tuning in the MSSM.

...or thoughts about the SUSY WIMP...

Kai Schmidt-Hoberg



Largely based on

1603.09347
1701.03480

with G Ross and F Staub

Corfu Summer Institute

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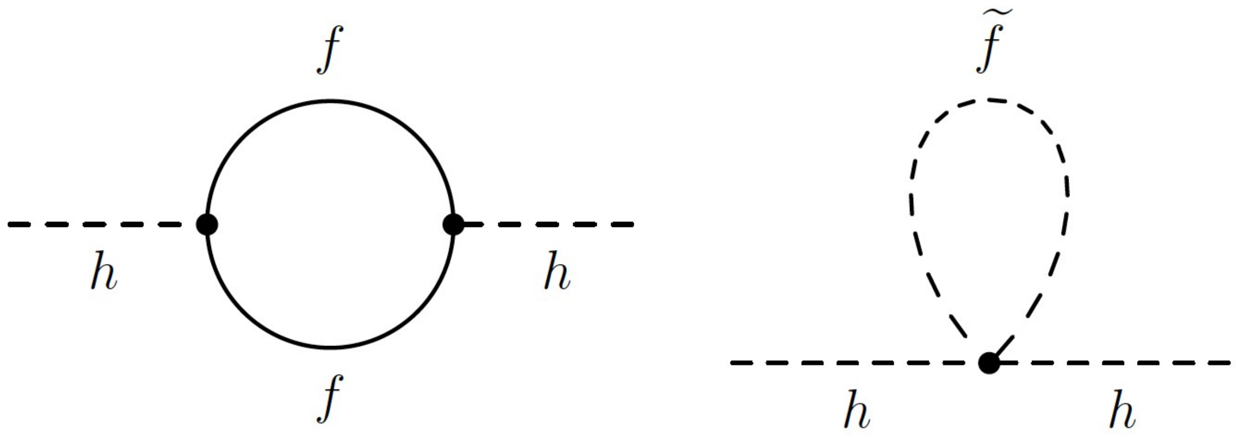
DESY

Why we like(d) SUSY

> Hierarchy problem: stabilizes the weak against the Planck scale



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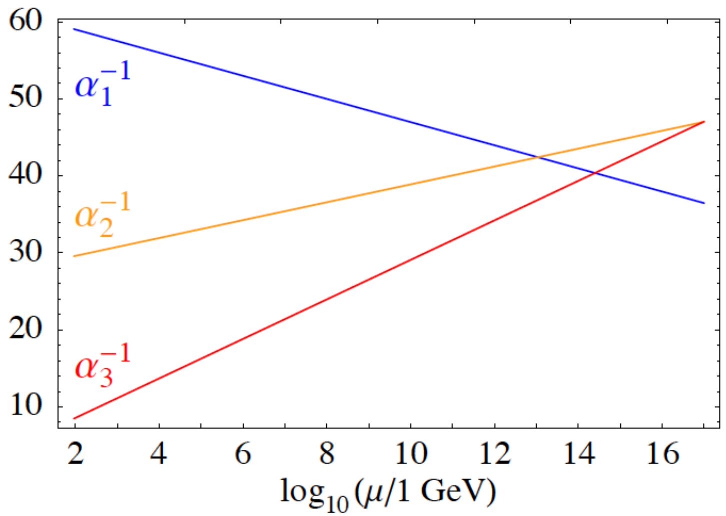

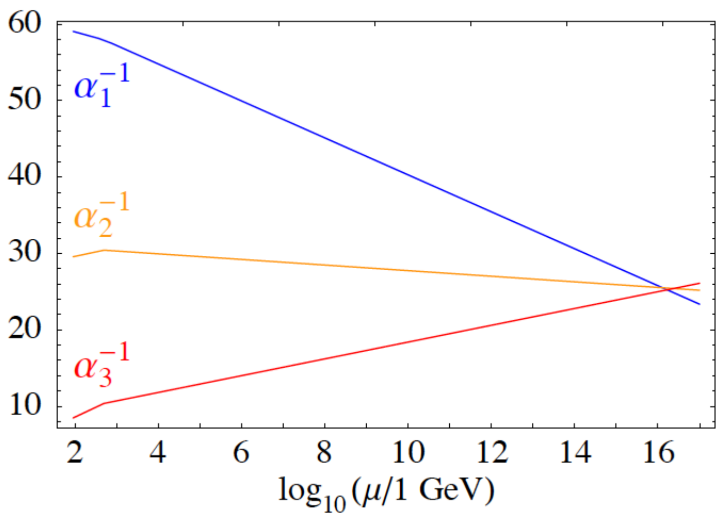

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- Hierarchy problem: stabilizes the weak against the Planck scale
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- A 125 GeV Higgs boson: Additional hint for SUSY?

...somebody still owes me...

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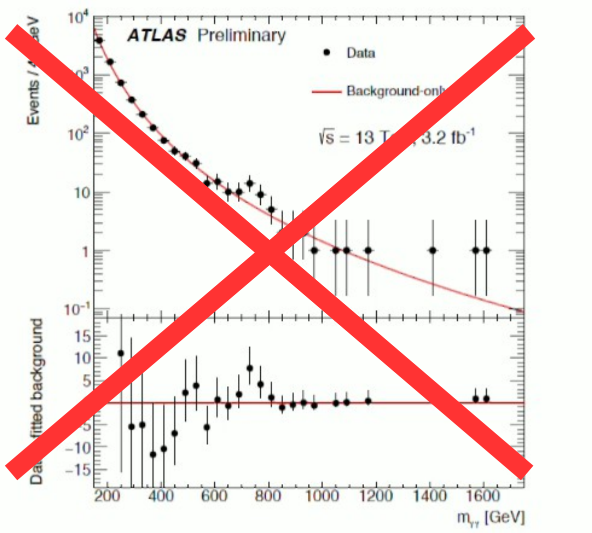
- Also hard to get 750 GeV diphoton excess ;-)



Congrats Jamie!

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- Hierarchy problem: stabilizes the weak against the Planck scale
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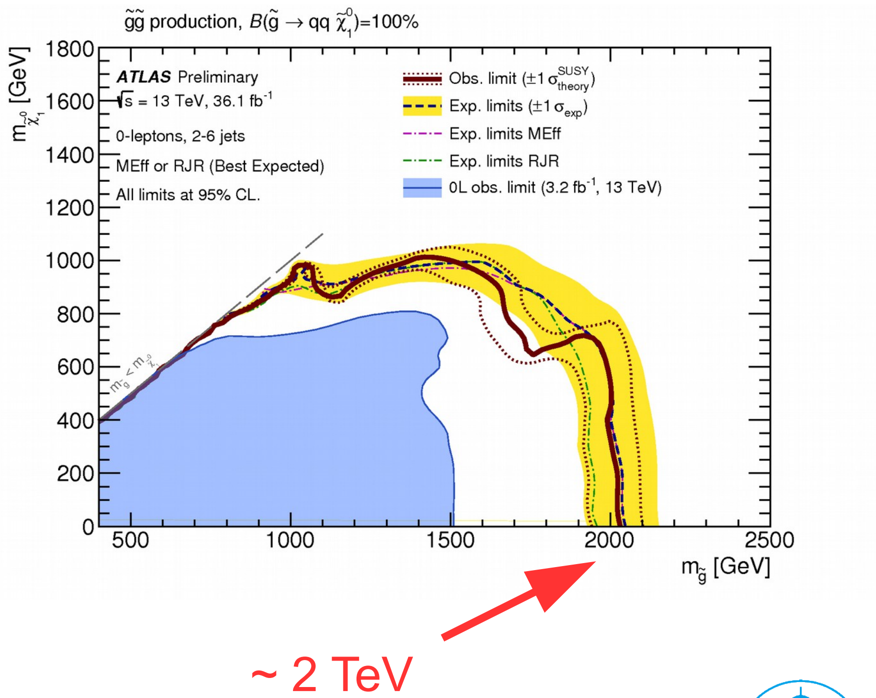
- So why do people get worried?



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NATURALNESS!

DM naturalness in the MSSM

- How naturally can the dark matter relic abundance be achieved?

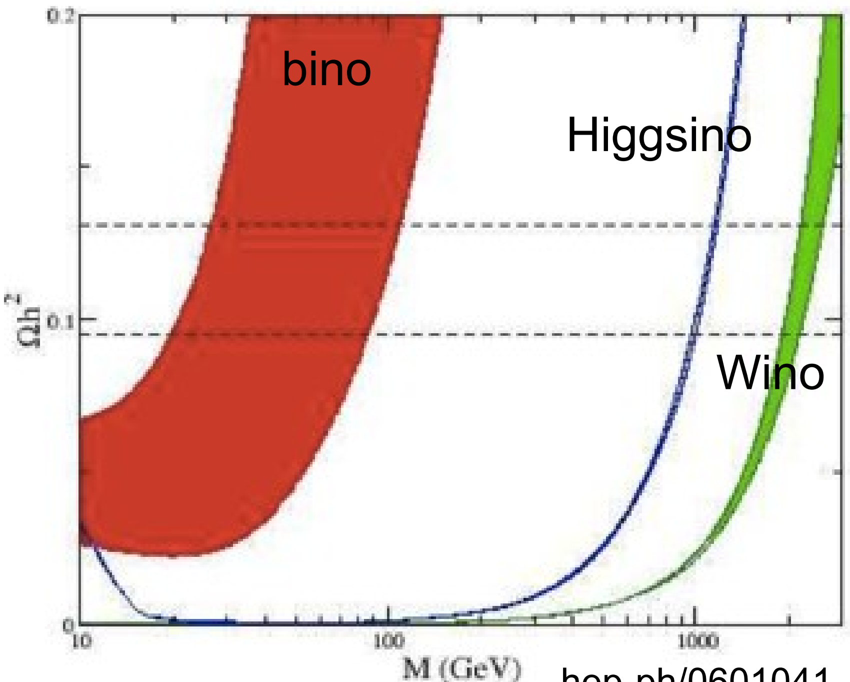
Often universal gaugino masses assumed at high scale, at low scale M3:M2:M1 ~ 6:2:1 → bino LSP

Bino: Typically need to finely tune relic density via coannihilations or resonances :-(

Crucially depends on assumption of SUSY breaking terms!
Other patterns possible...

2-3 TeV Wino challenged by ID
Mariengela Lisanti et al 1307.4082

1 TeV Higgsino looking good :-)



hep-ph/0601041

EW naturalness in the MSSM

- How naturally can we achieve the correct Higgs vev?
- Electroweak vev (or m_Z) determined by SUSY parameters (from minimization condition for scalar potential)

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - \mu^2 \simeq -m_{H_u}^2 - \mu^2$$

- Cancellation (tuning) needed for large SUSY masses
- How to quantify this?

$$\Delta_p \equiv \frac{\partial \ln v^2}{\partial \ln p} = \frac{p}{v^2}\frac{\partial v^2}{\partial p}$$ 'sensitivity measure'

- Large Δ implies large tuning

The usual story

- What does this tell us about a natural SUSY spectrum?
- μ is a superpotential parameter and hardly runs: $\mu_{EW} \sim \mu_{GUT}$

$$\Delta_\mu \sim \frac{2\mu^2}{M_Z^2}$$

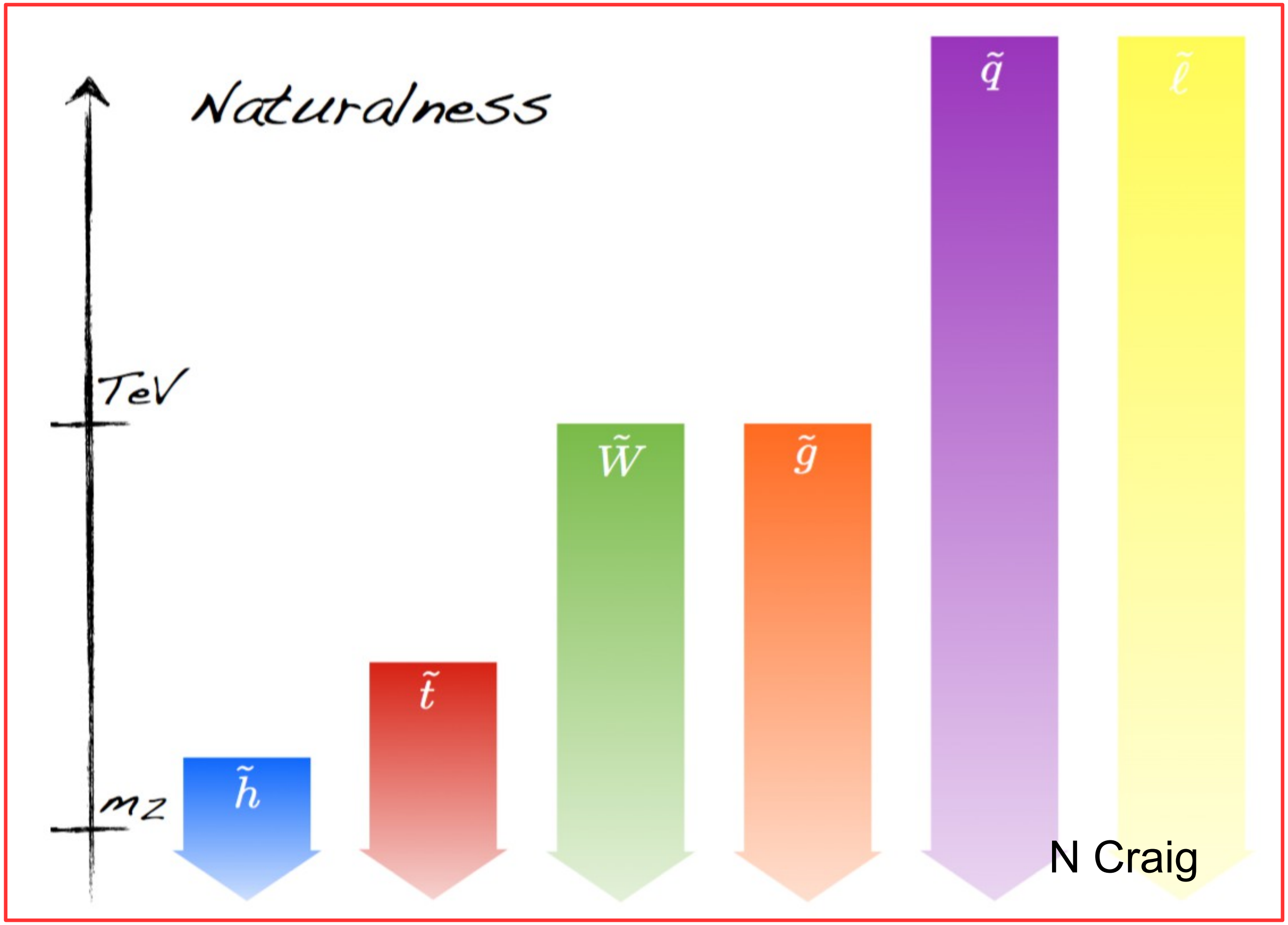
Higgsino mass ~ $\mu \sim 1$ TeV $\rightarrow$ $\Delta \sim 250$

- "Natural SUSY requires light Higgsino"
- What about the m_{Hu} part?
- Loop effects introduce a large sensitivity to stop and gluino masses

$$\delta m_{H_u}^2 = -\frac{3y_t^2}{4\pi^2} m_{\tilde{t}}^2 \ln\left(\Lambda/m_{\tilde{t}}\right)$$

$$\delta m_{\tilde{t}}^2 = \frac{2g_s^2}{3\pi^2} m_{\tilde{g}}^2 \ln\left(\Lambda/m_{\tilde{g}}\right)$$

The 'natural SUSY' spectrum



The 'natural SUSY' spectrum

EW naturalness in the MSSM – the GUT picture

- Starting from the high scale, all soft terms contribute to m_{Hu} and m_Z

$$
\begin{aligned}
m_Z^2 \simeq\ & -2.18\mu^2 + 3.84M_3^2 + 0.32M_3M_2 + 0.047M_1M_3 - 0.42M_2^2 \\
& +0.011M_2M_1 - 0.012M_1^2 - 0.65M_3A_t - 0.15M_2A_t \\
& -0.025M_1A_t + 0.22A_t^2 + 0.004M_3A_b \\
& -1.27m_{H_u}^2 - 0.053m_{H_d}^2 \\
& +0.73m_{Q_3}^2 + 0.57m_{U_3}^2 + 0.049m_{D_3}^2 - 0.052m_{L_3}^2 + 0.053m_{E_3}^2 \\
& +0.051m_{Q_2}^2 - 0.11m_{U_2}^2 + 0.051m_{D_2}^2 - 0.052m_{L_2}^2 + 0.053m_{E_2}^2 \\
& +0.051m_{Q_1}^2 - 0.11m_{U_1}^2 + 0.051m_{D_1}^2 - 0.052m_{L_1}^2 + 0.053m_{E_1}^2,
\end{aligned}
$$

- We don't just want m_{Hu} to be small, but every contribution to it. Assuming no correlations among the terms, need rather light stops and gluinos

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$m_i^2 = m_0^2$

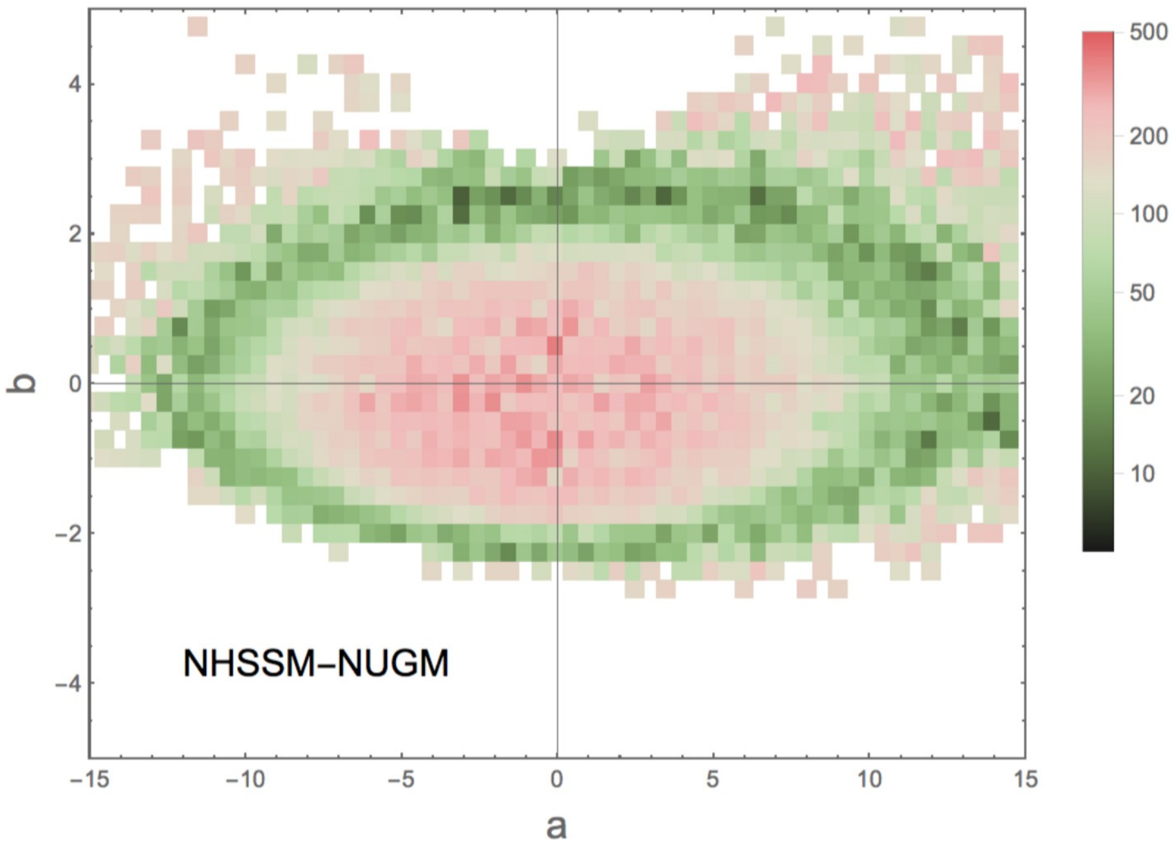
$\sim 0.01\ m_0^2$

- We don't just want m_{Hu} to be small, but every contribution to it. Assuming no correlations among the terms, need rather light stops and gluinos
- But we know correlations should be present…
- Example: the scalar focus point.

The gaugino focus point

- Assume fixed ratios of gaugino masses
- Possible also in GUTs Horton, Ross, 0908.0857

$$M_1 = a \cdot m_{1/2}$$
$$M_2 = b \cdot m_{1/2}$$
$$M_3 = m_{1/2}$$



Comment on loop corrections

- So far assumed tree-level relation for EWSB condition

Slide from F Staub

$$\left.\frac{\partial V^{(L)}}{\partial v_u}\right|_{\tan\beta\to\infty} \equiv 0 = (m_{h_u}^2 + \mu^2 + \frac{1}{8}(g_1^2 + g_2^2)v^2)v + \Sigma_u$$

How to parametrise Σ_u?

1. $\Sigma_u \equiv v\Sigma_{uu}$

$$\rightarrow \qquad \frac{1}{2}M_Z^2 = -|\mu|^2 - m_{H_u}^2 + \Sigma_{uu}$$

no change in FT; **only valid if Σ_{uu} is independent of v!**

2. $\Sigma_u \equiv \Sigma_1 v + \Sigma_2 v^2 + \Sigma_3 v^3$

$$\rightarrow \qquad \Delta_\mu = \frac{8\mu^2}{(g_1^2 + g_2^2 + 8\Sigma_3)v^2 + 4\Sigma_2 v}$$

Comment on loop corrections

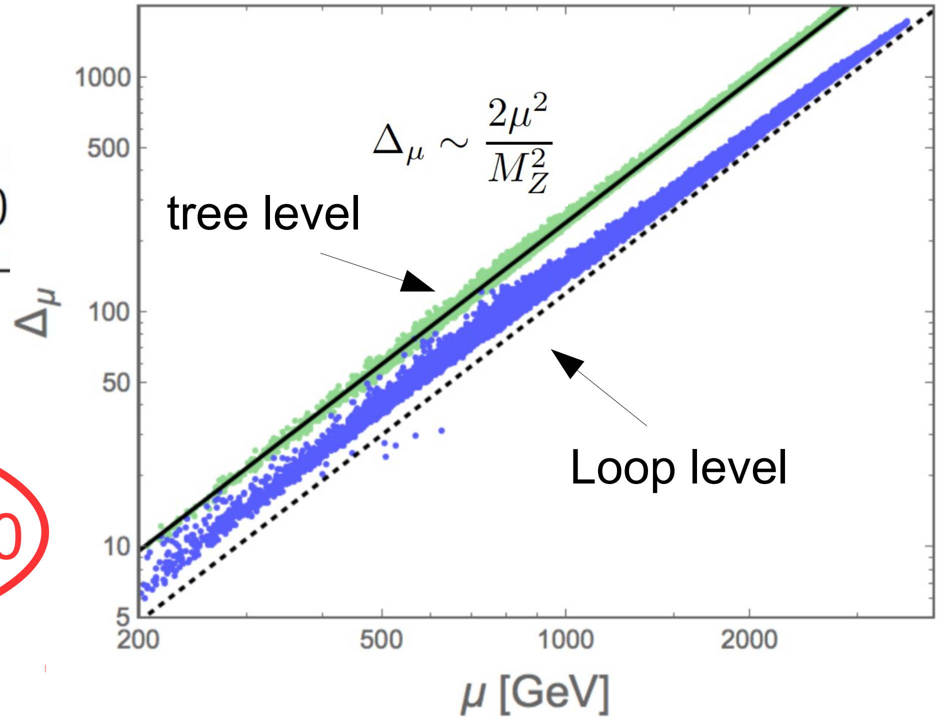
- Result for leading stop correction

$$\Sigma_1 = -\frac{3 m_{\tilde{t}}^2 Y_t^2 \left(-2\log\left(\frac{2m_{\tilde{t}}^2 + v^2 Y_t^2}{Q^2}\right) + 2 + \log(4)\right)}{32\pi^2}$$

$$\Sigma_2 = 0$$

$$\Sigma_3 = \frac{3 Y_t^4 \left(\log\left(\frac{2m_{\tilde{t}}^2 + v^2 Y_t^2}{Q^2}\right) - \log\left(\frac{v^2 Y_t^2}{Q^2}\right)\right)}{32\pi^2} \neq 0$$

$$r^{FT} \equiv \frac{\Delta_\mu^{\text{Loop}}}{\Delta_\mu^{\text{Tree}}} \simeq \left(1 + \frac{3}{4\pi^2}\frac{Y_t^4}{g_1^2 + g_2^2}\log\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right)\right)^{-1} \simeq \frac{1}{2}$$



See also Ghilencea, Ross +
0903.1115, 1001.3884

- Reduction of about ½ when including loop corrections

Comment on loop corrections

- Result for leading stop correction

$$3m_t^2 Y_t^2 \left(-2\log\left(\frac{2m_t^2+v^2Y_t^2}{Q^2}\right)+2+\log(4)\right)$$

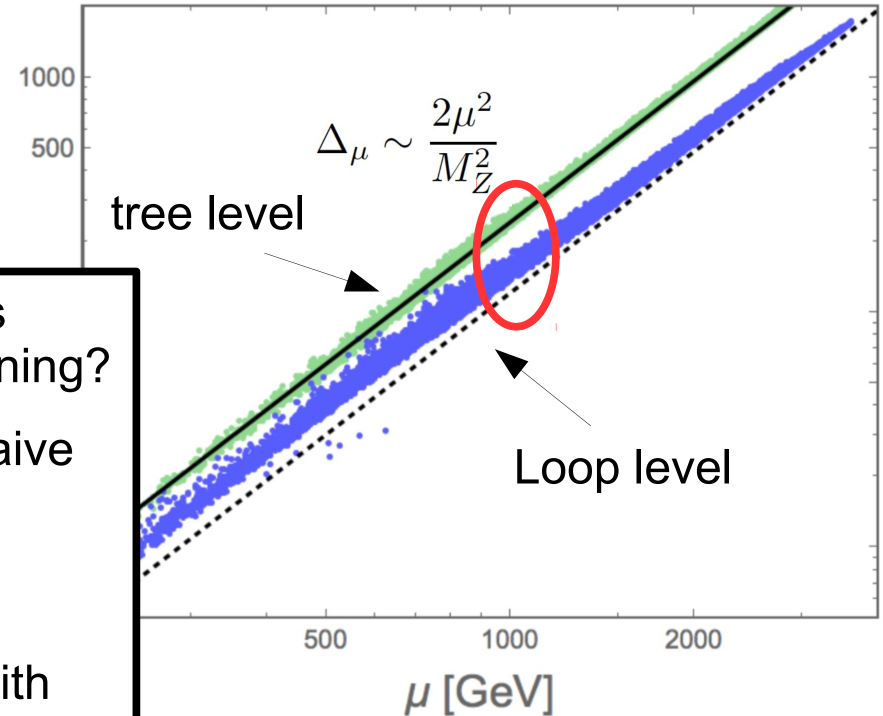
$\Sigma_1 = -$

$\Sigma_2 = 0$

$\Sigma_3 = $

$r^{FT} \equiv$

- So does a 1 TeV Higgsino always require significant electroweak tuning?
- Two possible ways beyond the naive FT arguments
- The μ-term could be correlated with the soft terms (→ μ problem)
- The Higgsino mass could arise from something beyond the μ-term



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- Reduction of about ½ when including loop corrections

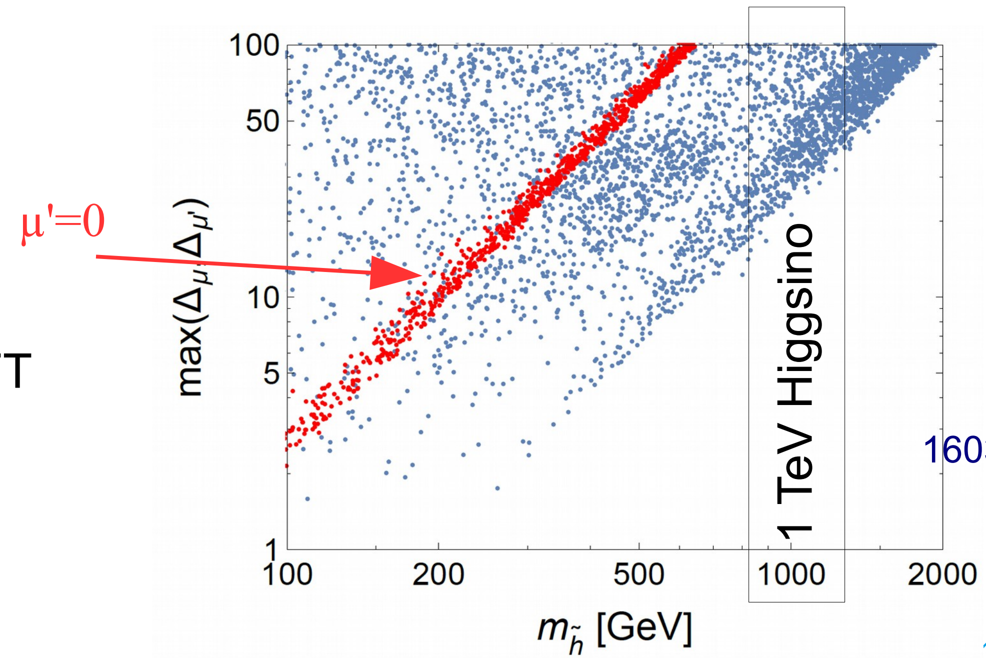
A new contribution to the Higgsino mass

- Non-standard SUSY breaking terms (in the classification of S Martin: 'maybe-soft')

$$\mathcal{L}_{NH} = \mu' \tilde{h}_d \tilde{h}_u + T'_{u,ij} h_d^* \tilde{u}^*_{R,i} \tilde{q}_j + T'_{d,ij} h_u^* \tilde{d}^*_{R,i} \tilde{q}_j + T'_{e,ij} h_u^* \tilde{e}^*_{R,i} \tilde{l}_j + \text{h.c.}$$

Girardello, Grisaru (1982)

- μ' contributes to the Higgsino mass ($m_h \sim \mu + \mu'$) but does not enter the scalar potential
- Can significantly reduce FT



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Embedding this into a model

- Studied different MSSM variants with GUT boundary conditions

	$m^2_{h_u}$	$m^2_{h_d}$	M_1	M_2	M_3	μ'	A'_0
CMSSM	m_0^2	m_0^2	$m_{1/2}$	$m_{1/2}$	$m_{1/2}$	-	-
MSSM-NUHM	$m^2_{h_u}$	$m^2_{h_d}$	$m_{1/2}$	$m_{1/2}$	$m_{1/2}$	-	-
MSSM-NUGM	m_0^2	m_0^2	$a \cdot m_{1/2}$	$b \cdot m_{1/2}$	$m_{1/2}$	-	-
CNHSSM	m_0^2	m_0^2	$m_{1/2}$	$m_{1/2}$	$m_{1/2}$	μ'	A'_0
NHSSM-NUHM	$m^2_{h_u}$	$m^2_{h_d}$	$m_{1/2}$	$m_{1/2}$	$m_{1/2}$	μ'	A'_0
NHSSM-NUGM	m_0^2	m_0^2	$a \cdot m_{1/2}$	$b \cdot m_{1/2}$	$m_{1/2}$	μ'	A'_0

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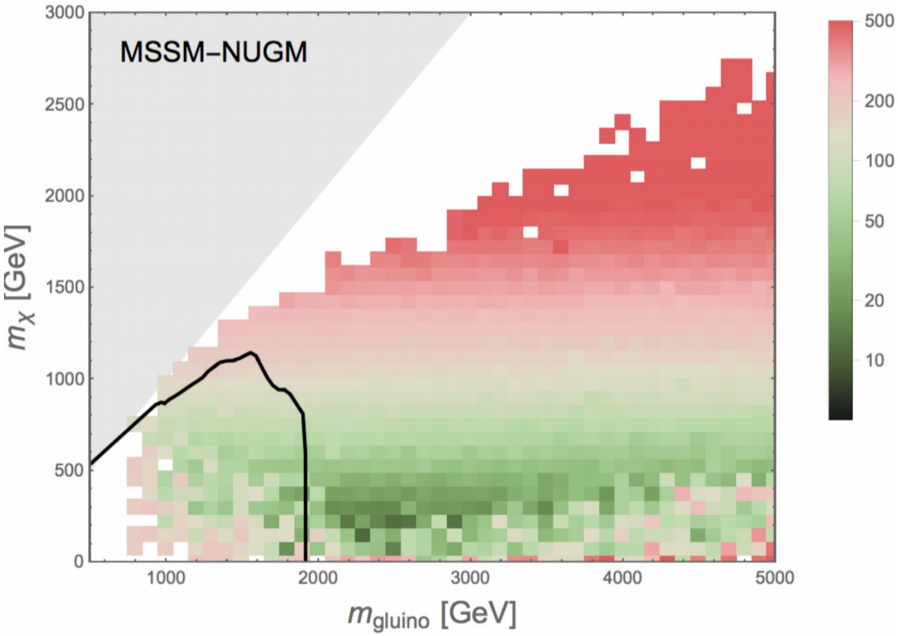
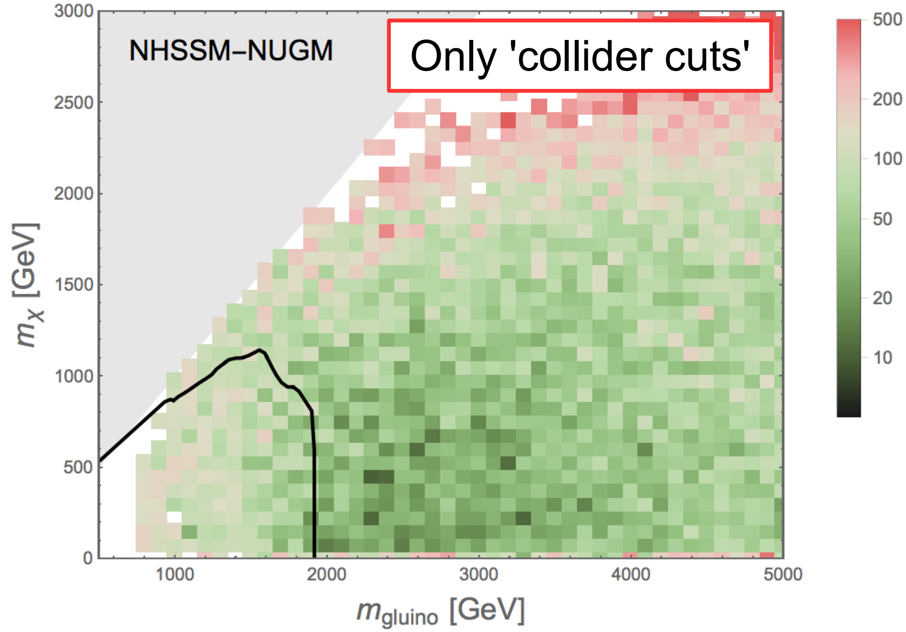
Results non-universal gaugino masses

> Region of small FT can be well beyond LHC reach

$\mu'=0$





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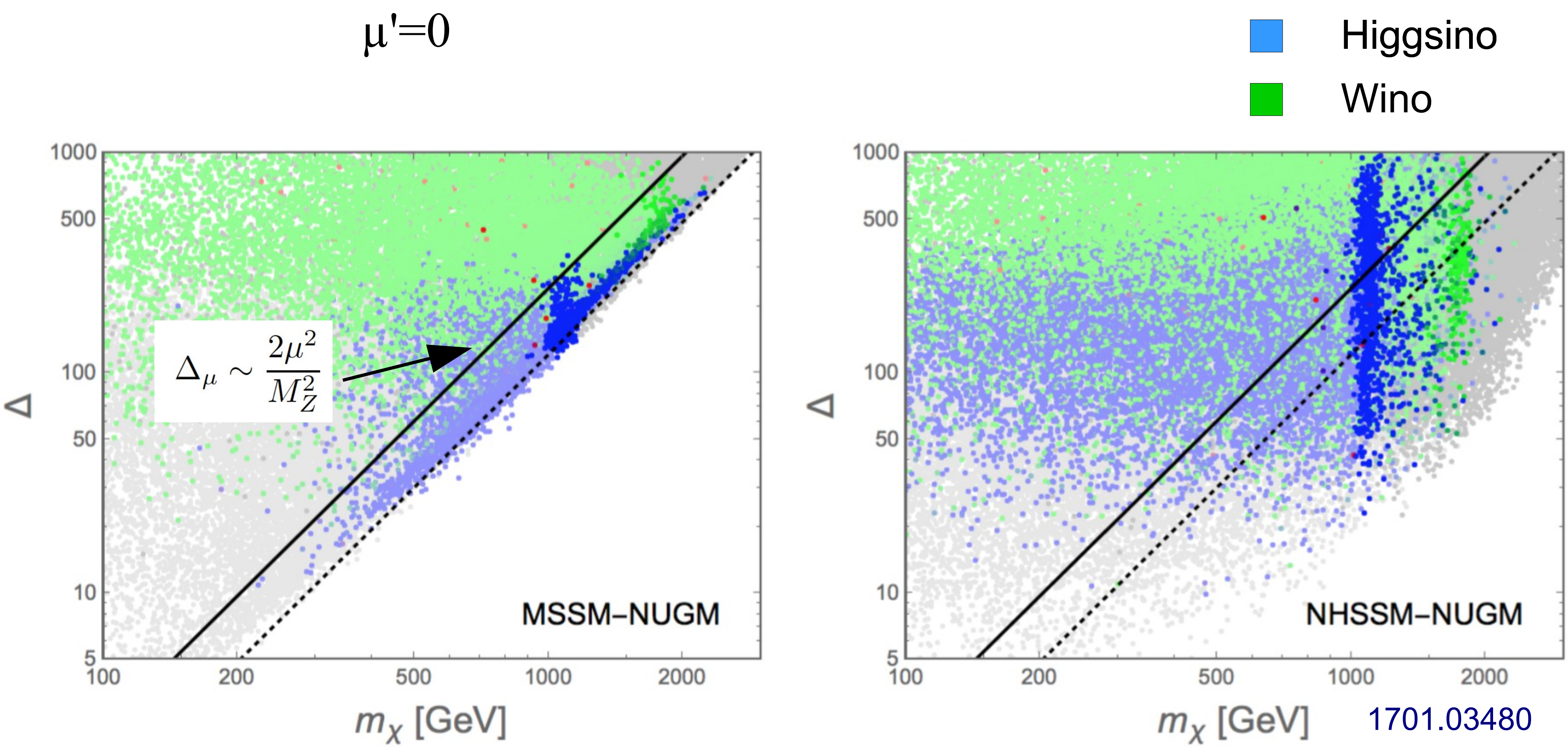
> Allowing for DM underabundance FT can be as small as 10.

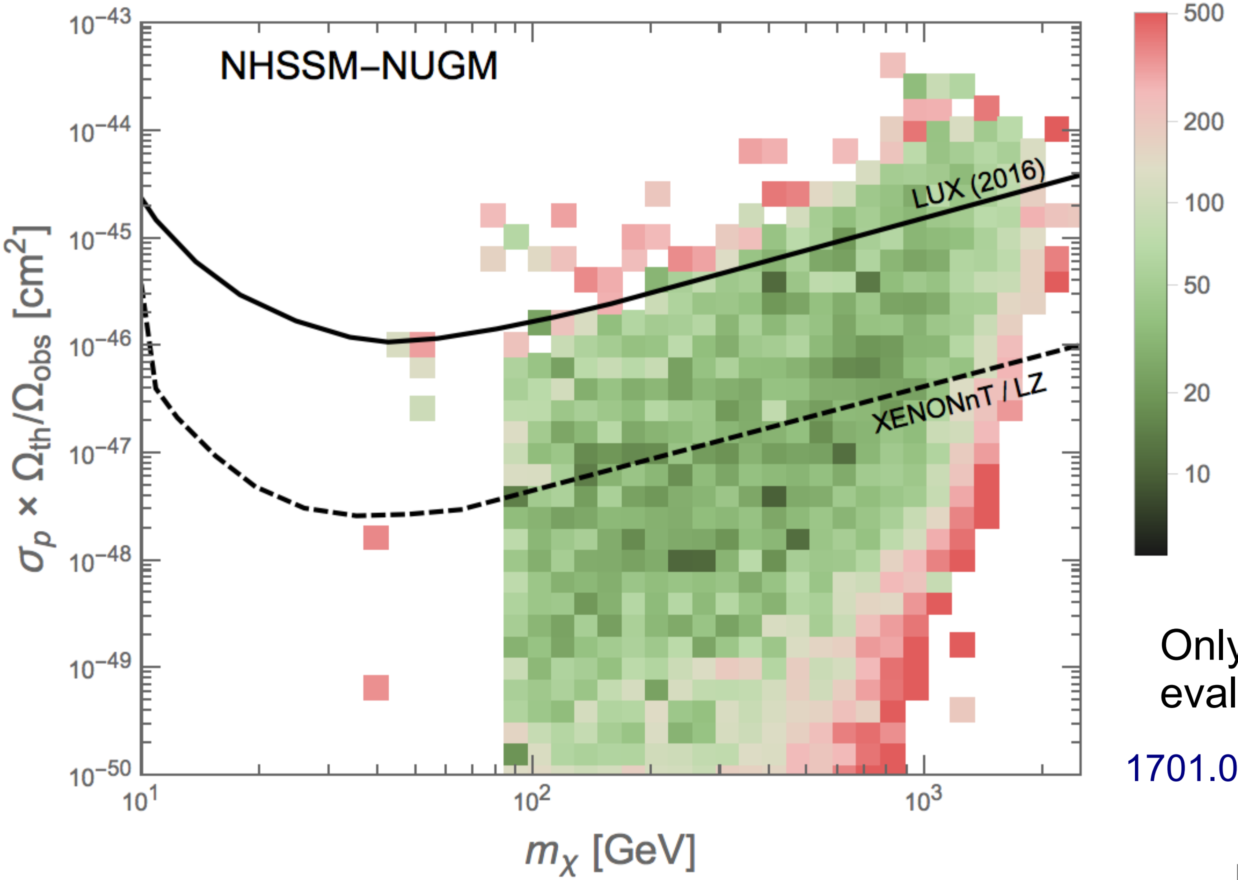
Results non-universal gaugino masses

- A 1 TeV Higgsino can be quite natural



Prospects for direct detection

- Prospects for direct detection
- No lower bound on relic abundance (and rescaled) – other DM component



Only tree-level evaluation

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Prospects for direct detection

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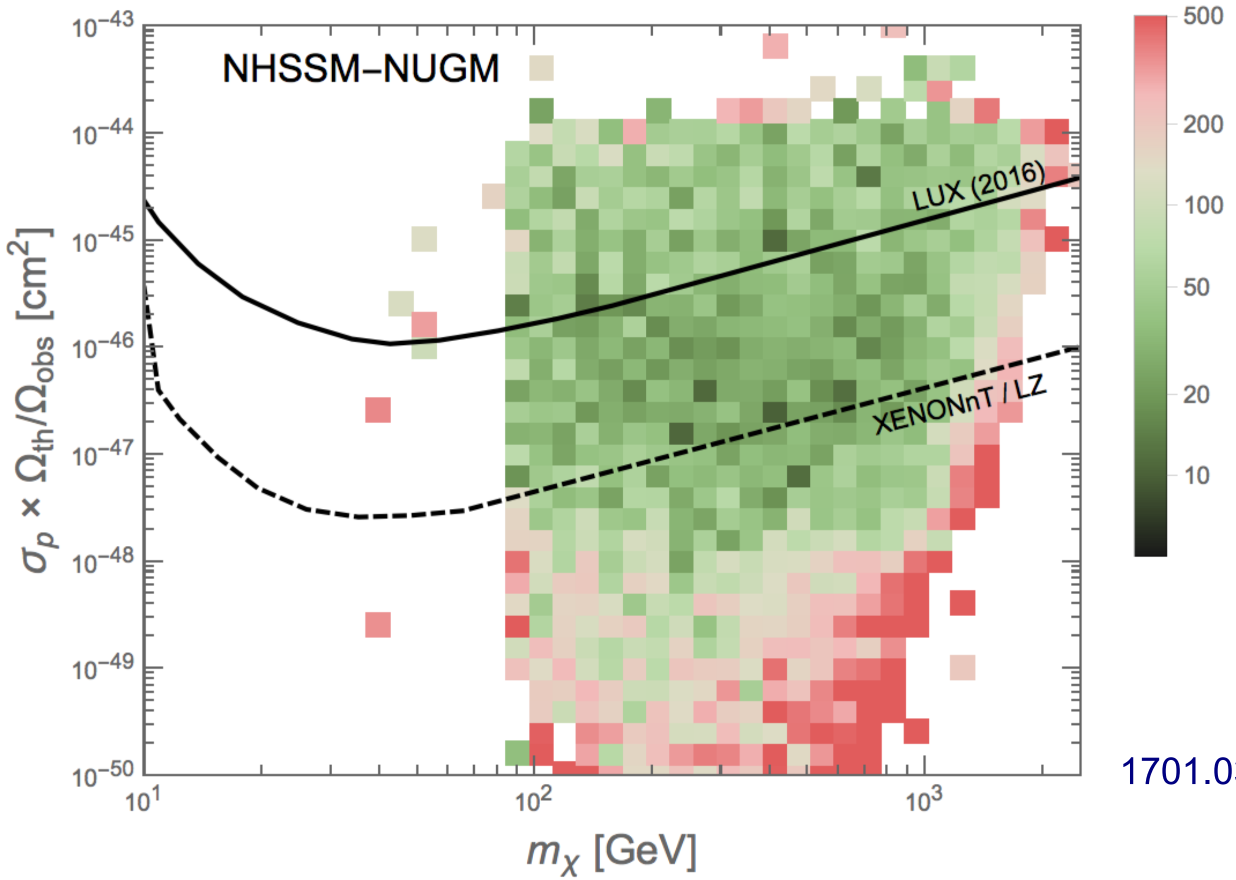
- No lower bound on relic abundance (not rescaled) – non-thermal production (gravitino decay)



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Prospects for direct detection

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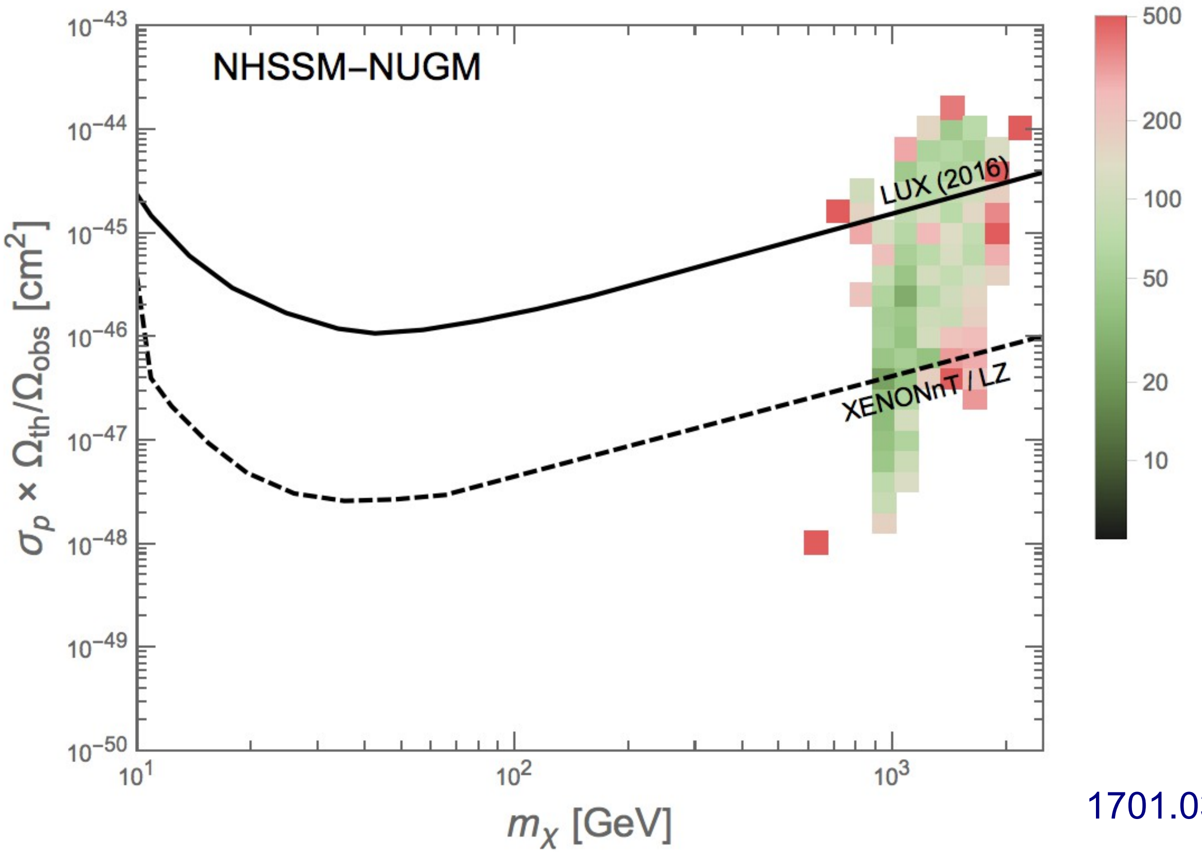
- Correct (thermal) relic abundance



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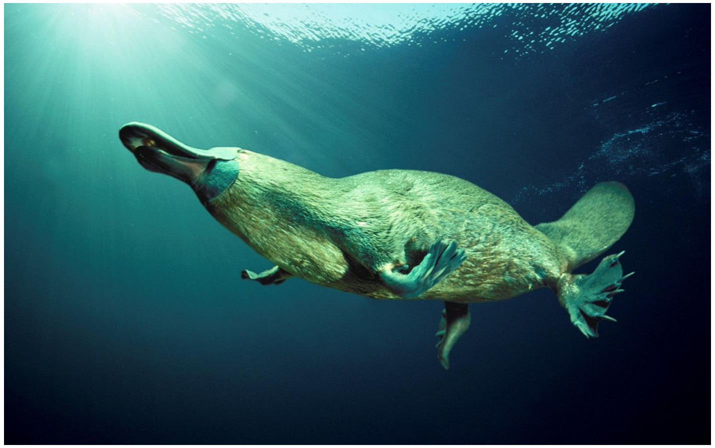
Summary

- What looks unnatural from an IR perspective **might** still look natural from the UV
- Extra Higgsino mass contribution μ' could help
- To do: build a UV model



- SUSY could well be beyond the LHC reach
- Good chances at direct detection experiments to find it

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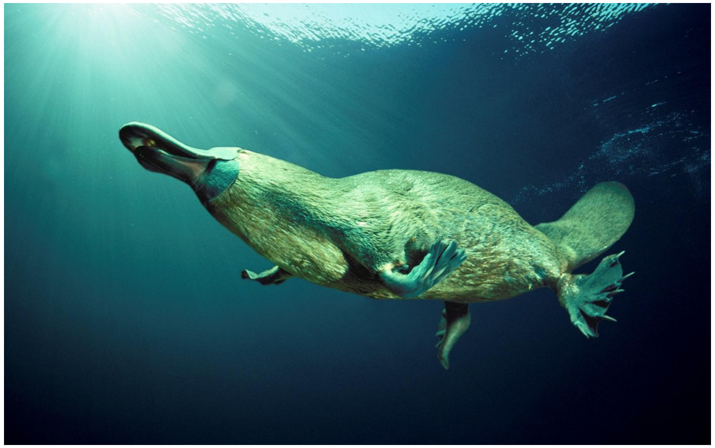
Thank you!



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