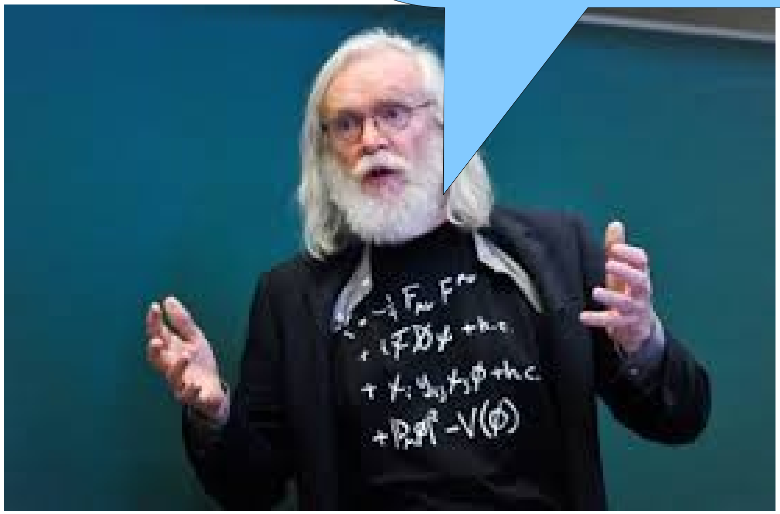
Thoughts about the SUSY WIMP.

...and the state of SUSY generally...

Kai Schmidt-Hoberg

"SUSY anywhere is better than SUSY nowhere!"



Largely based on

1603.09347
1701.03480

with G Ross and F Staub

MPIK theory seminar

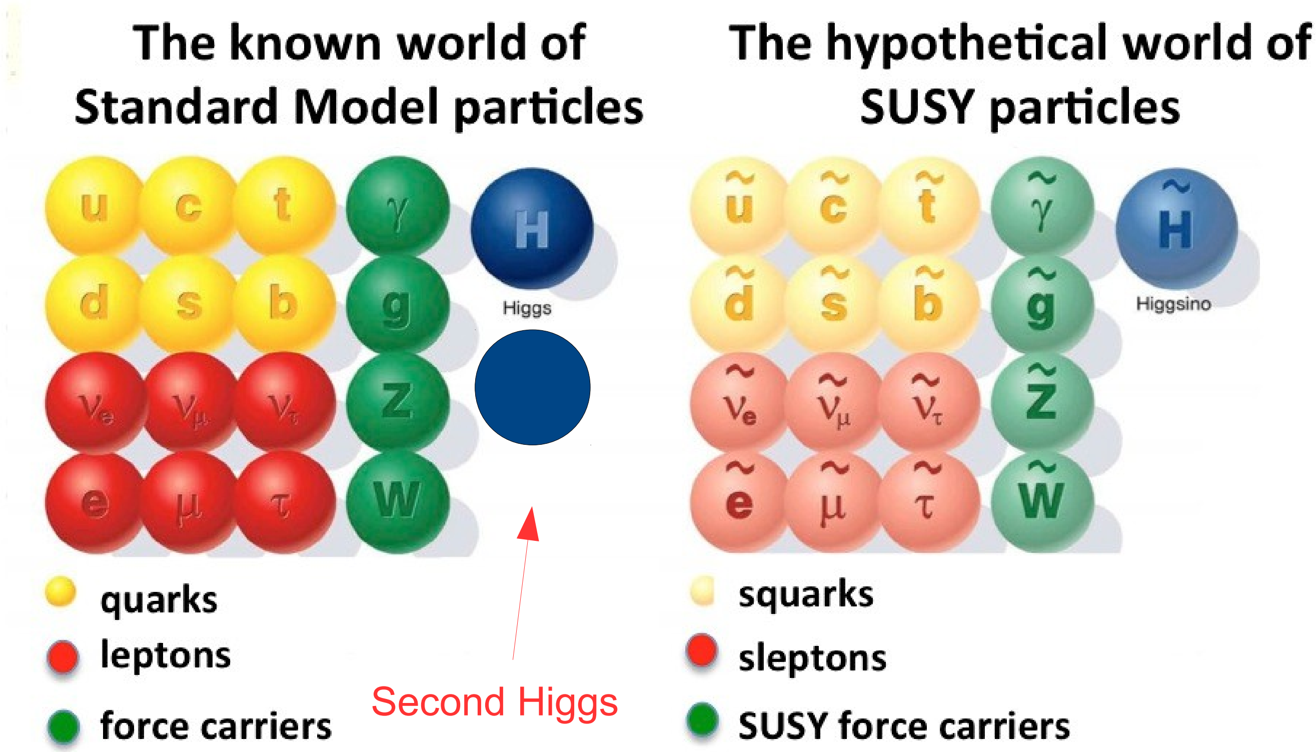
erc

HELMHOLTZ | ASSOCIATION

DESY

SUSY → MSSM (this talk)

> A SUSY partner for each SM particle with Δs=1/2 with **the same mass**



> SUSY broken in nature

> Breaking mechanism unknown, parameterized by soft terms

MSSM

- Field content fixed: theory specified by superpotential and soft terms

$$
\begin{aligned}
\mathcal{W} = \; & \mu H_u H_d + \kappa_i L_i H_u \\
& + Y_e^{ij} H_d L_i E_j^c + Y_d^{ij} H_d Q_i D_j^c + Y_u^{ij} H_u Q_i U_j^c \\
& + \lambda_{ijk}^{(0)} L_i L_j E_k^c + \lambda_{ijk}^{(1)} L_i Q_j D_k^c + \lambda_{ijk}^{(2)} U_i^c D_j^c D_k^c \\
& + \kappa_{ij}^{(0)} H_u L_i H_u L_j + \kappa_{ijk\ell}^{(1)} Q_i Q_j Q_k L_\ell + \kappa_{ijk\ell}^{(2)} U_i^c U_j^c D_k^c E_\ell^c
\end{aligned}
$$

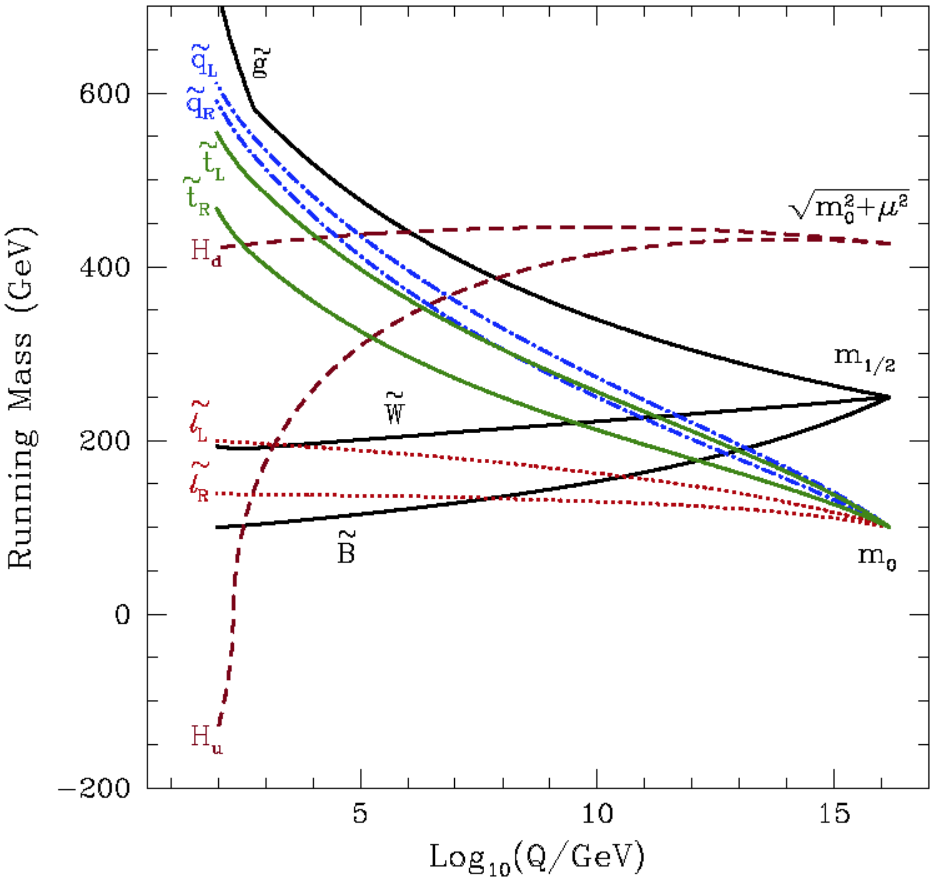
superfields

$$
\begin{aligned}
L_{SB} = \; & -\frac{1}{2}\sum_a M_a \bar{\lambda}_a \lambda_a - \sum_i m^2_{\tilde{\Phi}_i} |\tilde{\Phi}_i|^2 + \\
& T_u H_u \tilde{Q} \tilde{u} + T_d H_d \tilde{Q} \tilde{d} + T_e H_d \tilde{L} \tilde{e} + B_\mu H_u H_d
\end{aligned}
$$

- Many new parameters (>100) but likely not independent

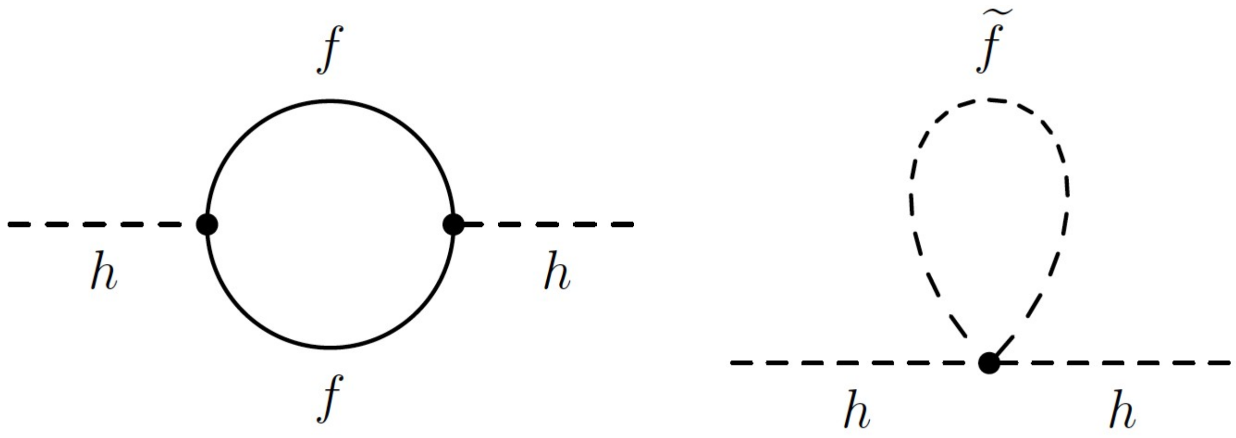
High scale SUSY

- In many models SUSY breaking at high scale in hidden sector
- Often some universality
- Take into account running to predict SUSY spectrum at the electroweak scale.



Why we like(d) SUSY

- Hierarchy problem: stabilizes the weak against the Planck scale



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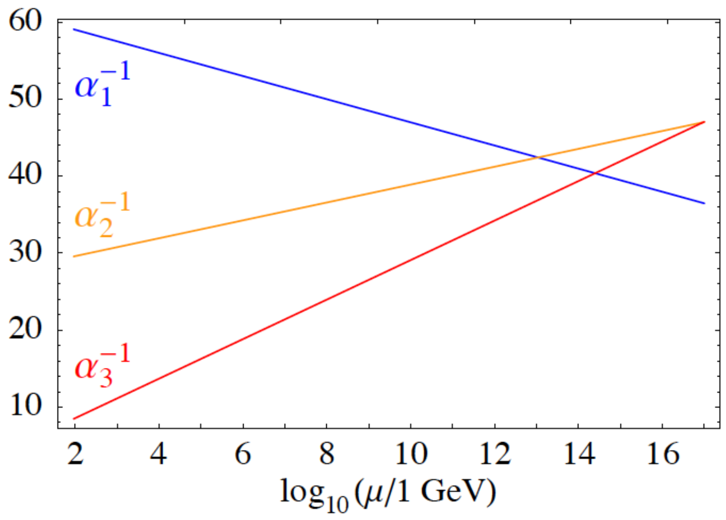

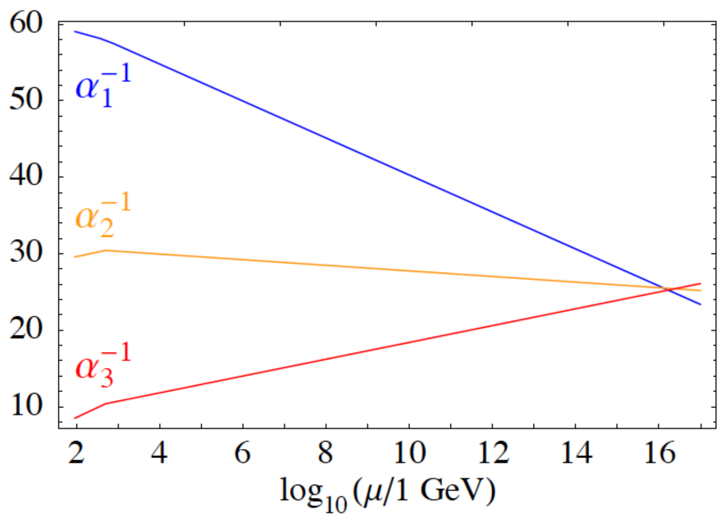

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- A 125 GeV Higgs boson: Additional hint for SUSY?

...a TC guy from Odense still owes me...

Why we like(d) SUSY

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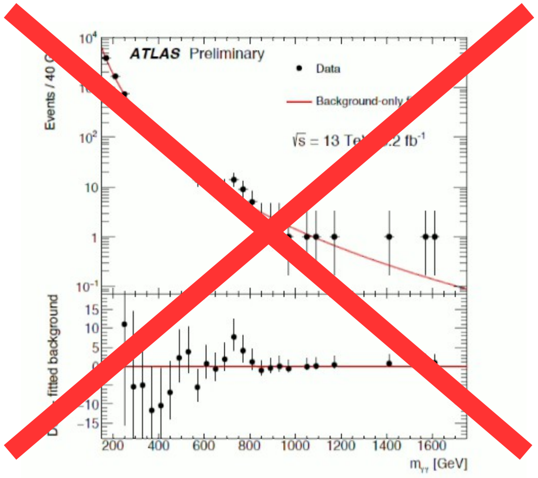
- A 125 GeV Higgs boson: Additional hint for SUSY?
- Also hard to get 750 GeV diphoton excess ;-)



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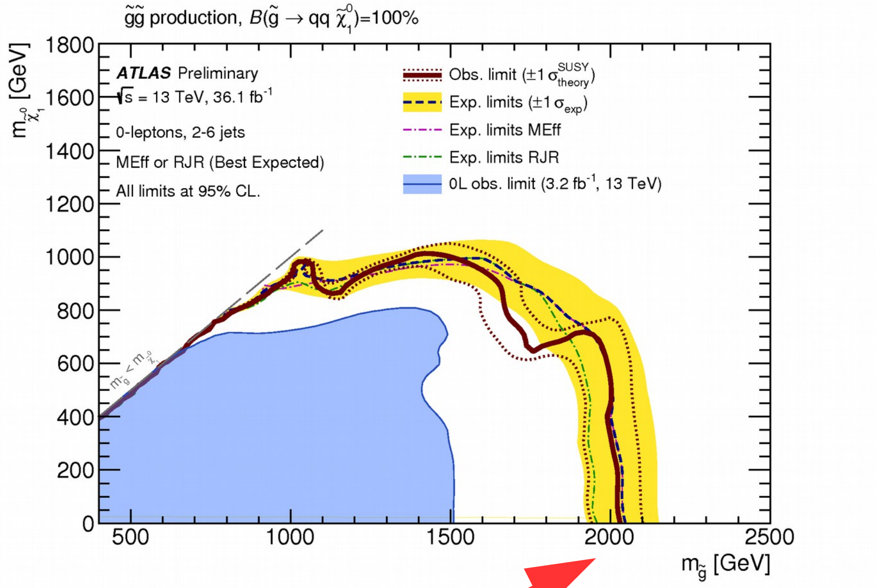
- So why do people get worried?



~ 2 TeV

Why we like(d) SUSY

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NATURALNESS!

The LSP – a DM candidate.

- Neutralinos are mixtures of bino, Wino and Higgsinos
- EM and colour neutral → potentially interesting dark matter candidates

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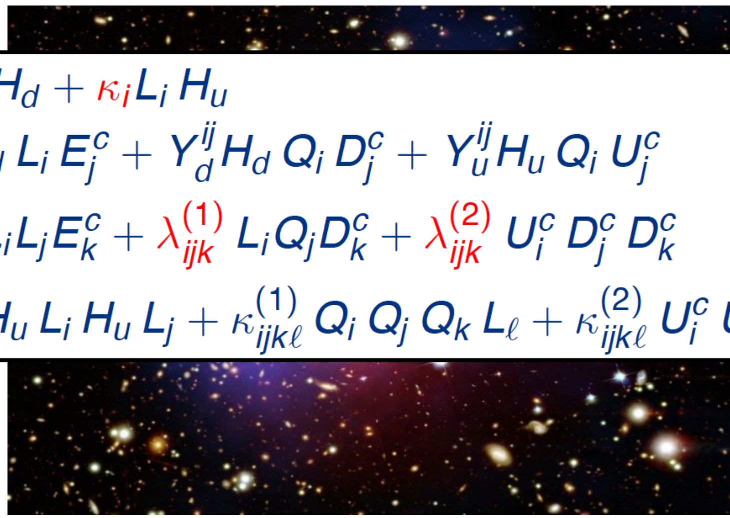

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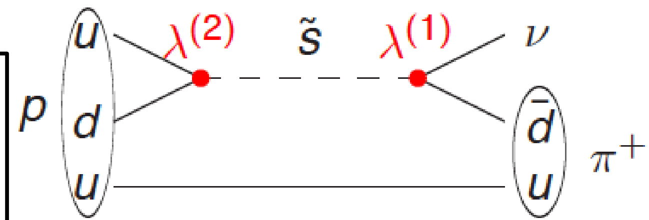
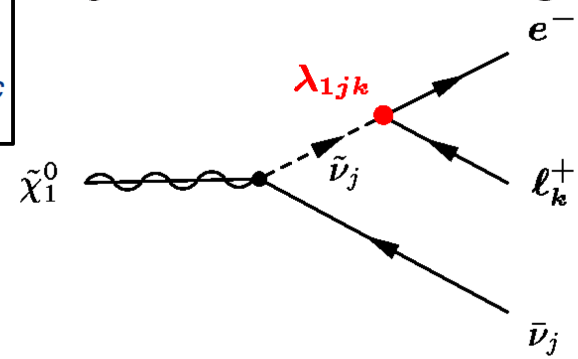




- With only SUSY and gauge invariance: extra terms leading to proton and dark matter decay → need additional symmetry.
- Standard assumption: R-parity conservation (good enough for dark matter – not good enough for the proton, need a better symmetry such as Z_4^R)

The relic abundance

> Neutralinos are produced in the early universe via thermal freeze out

(1) Neutralino X is initially in thermal equilibrium:

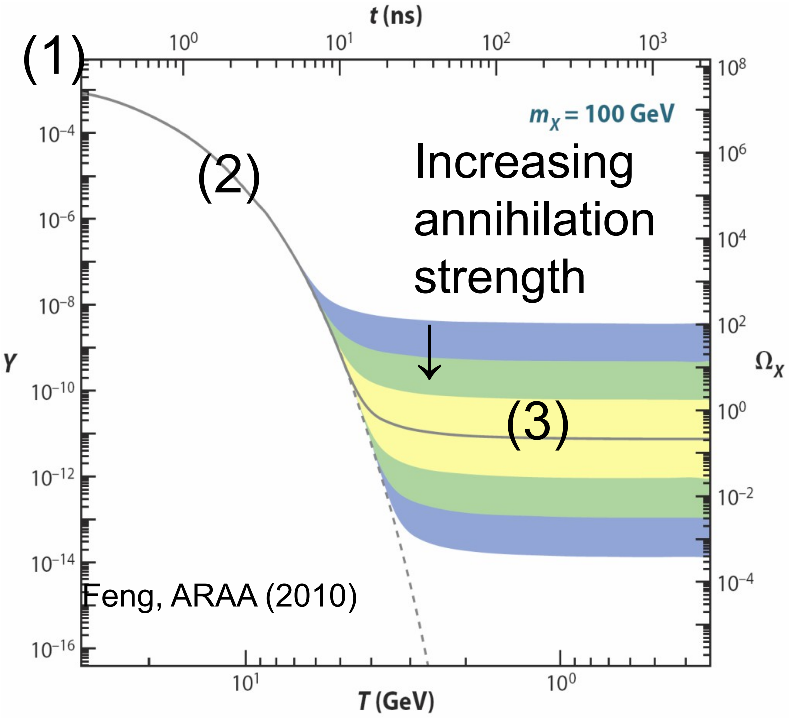
$$XX \leftrightarrow qq$$

(2) Universe cools:

$$XX \rightarrow qq$$

(3) Universe expands:

$$XX \quad qq$$



> Relic abundance depends on annihilation cross section

The relic abundance

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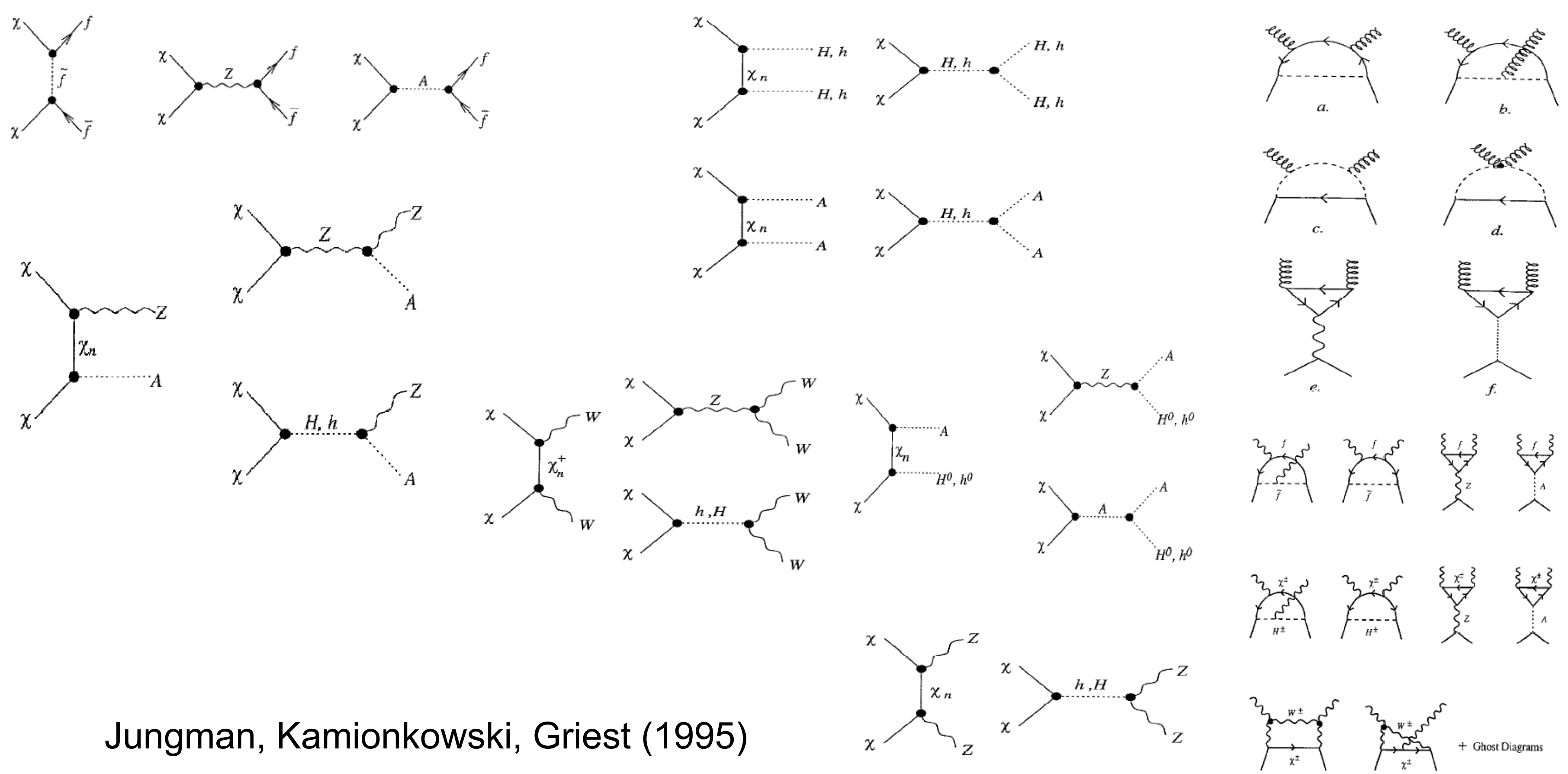


Jungman, Kamionkowski, Griest (1995)

DM naturalness in the MSSM

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

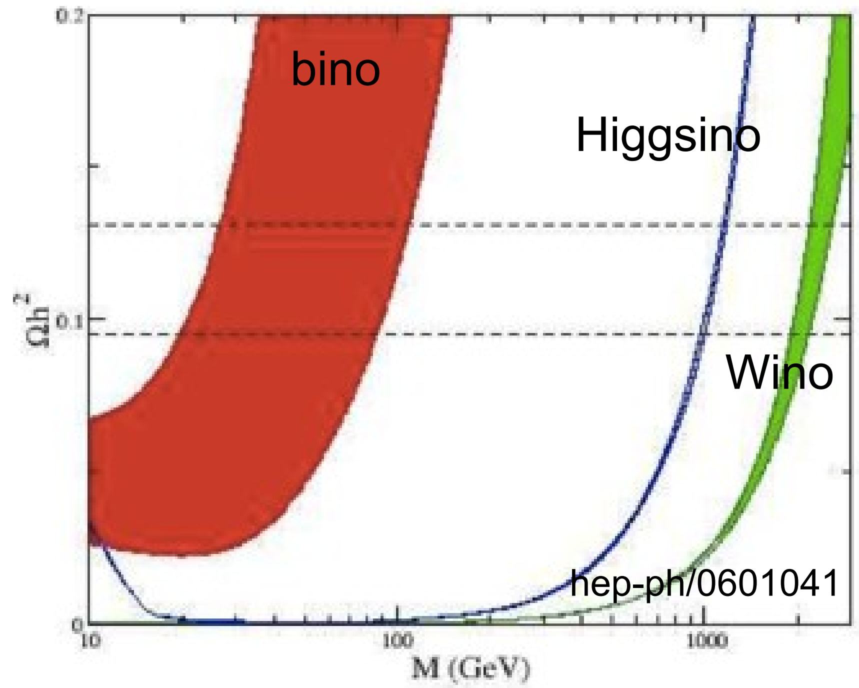
Often universal gaugino masses assumed at high scale, at low scale M3:M2:M1 ~ 6:2:1 → bino LSP

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 :-)



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

Caveats of the sensitivity measure

- What fundamental parameters should be included (and what are the fundamental parameters)?
- Also depends on parameterization of fundamental parameters
- At which scale?
- It measures sensitivity rather than 'tuning' – can be different
- The acceptable values Δ depends on taste – no absolute measure

→ **While for a given definition it can be calculated precisely, its physical interpretation is somewhat blurred**.

The usual story

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

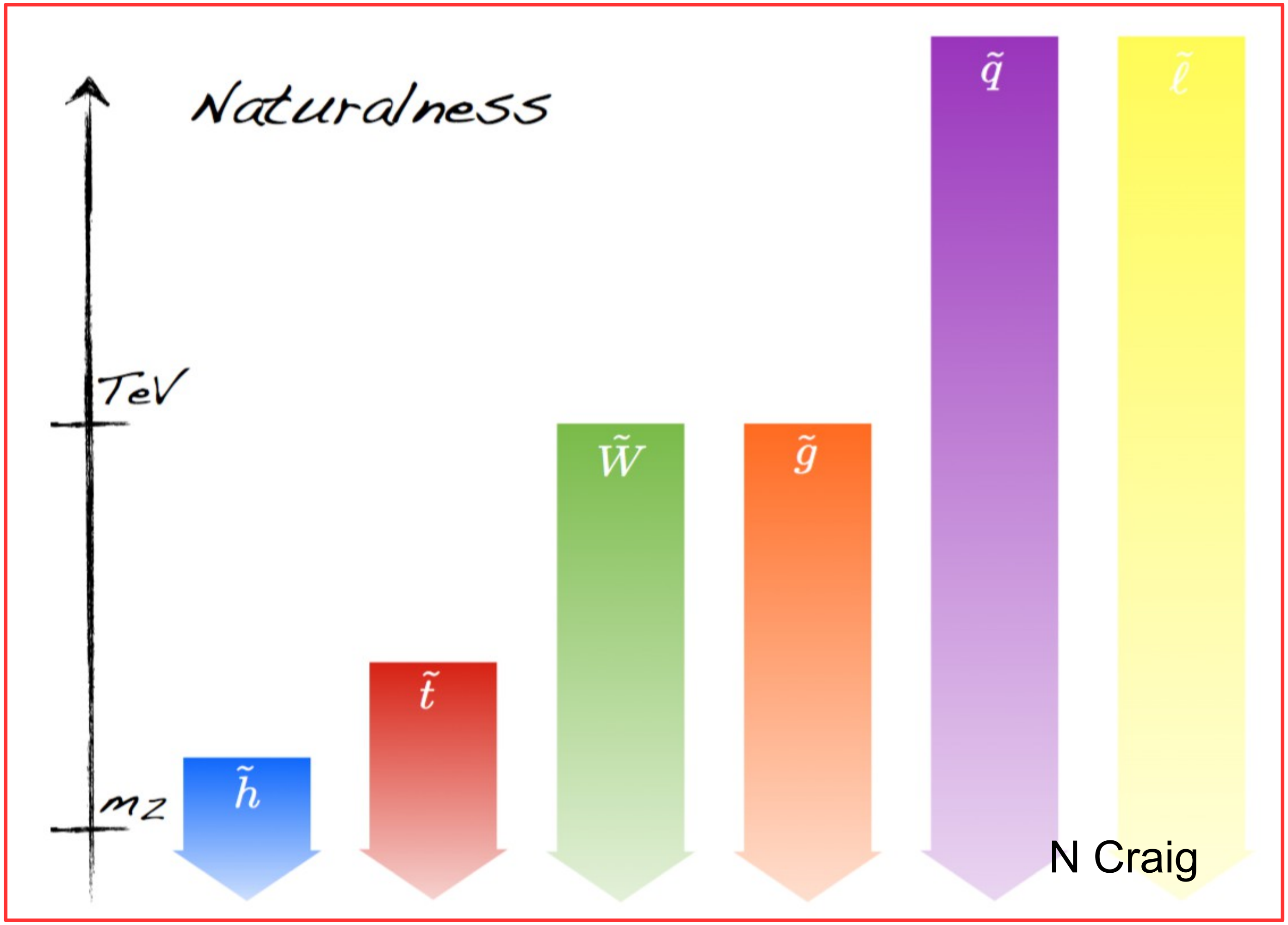
Higgsino mass ~ $\mu \sim 1$ TeV - $\Delta_\mu \sim \frac{2\mu^2}{M_Z^2} \sim 250$

- "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



EW naturalness in the MSSM

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

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

- 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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$$

$m_i^2 = m_0^2$

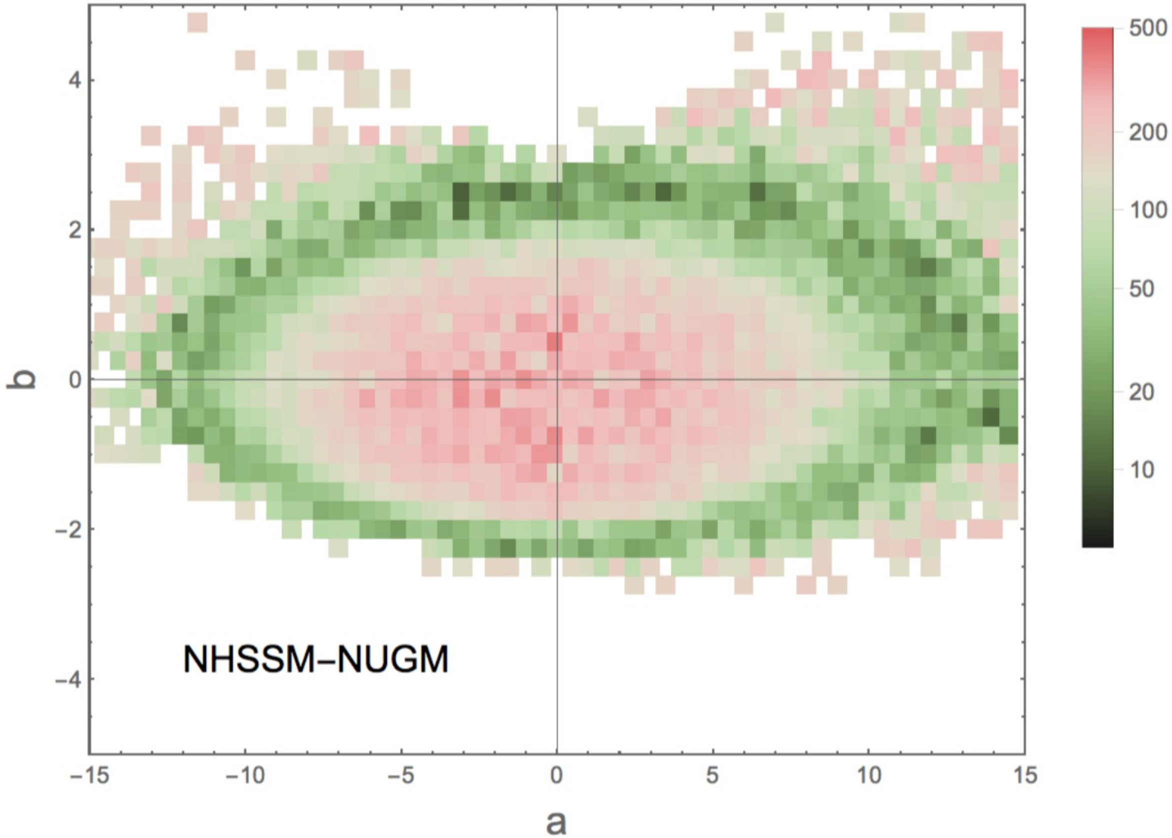
$\sim 0.01\ m_0^2$

- 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

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



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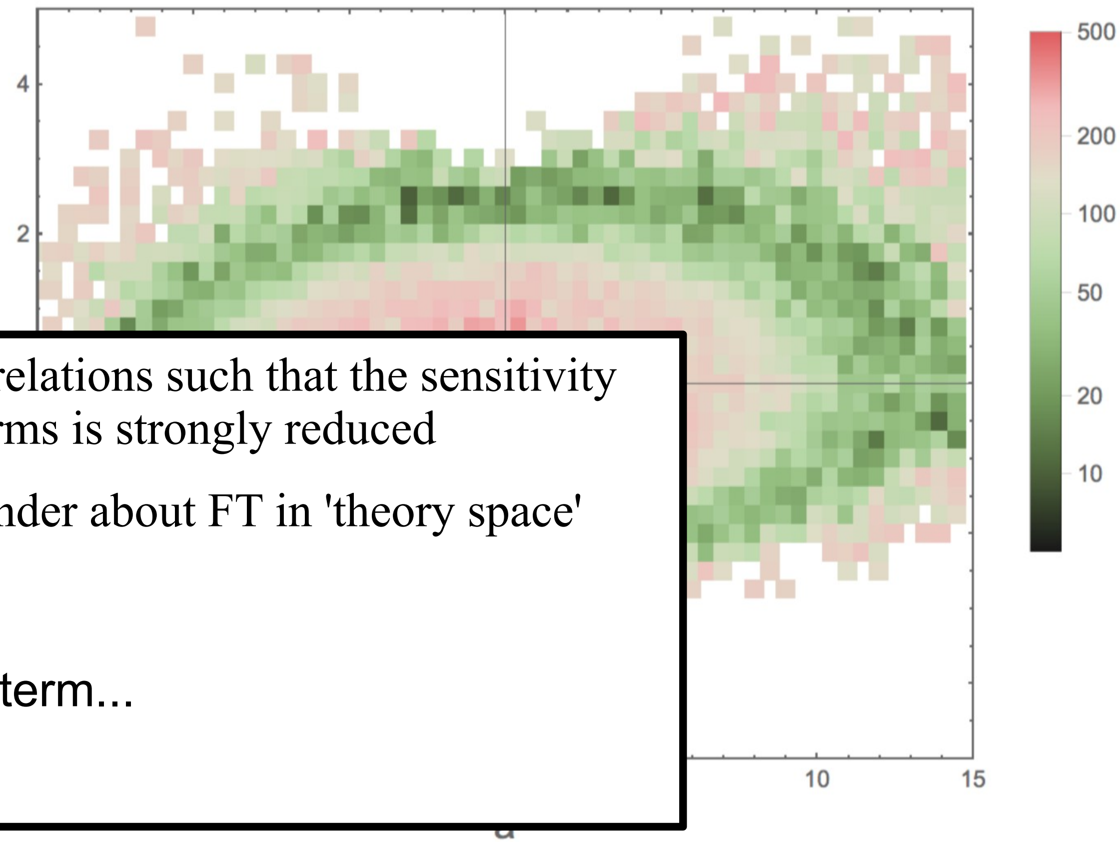

- Can find correlations such that the sensitivity to the soft terms is strongly reduced
- You may wonder about FT in 'theory space'
- μ not a soft term...

Comment on loop corrections

- So far assumed tree-level relation for EWSB condition

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

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!**

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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

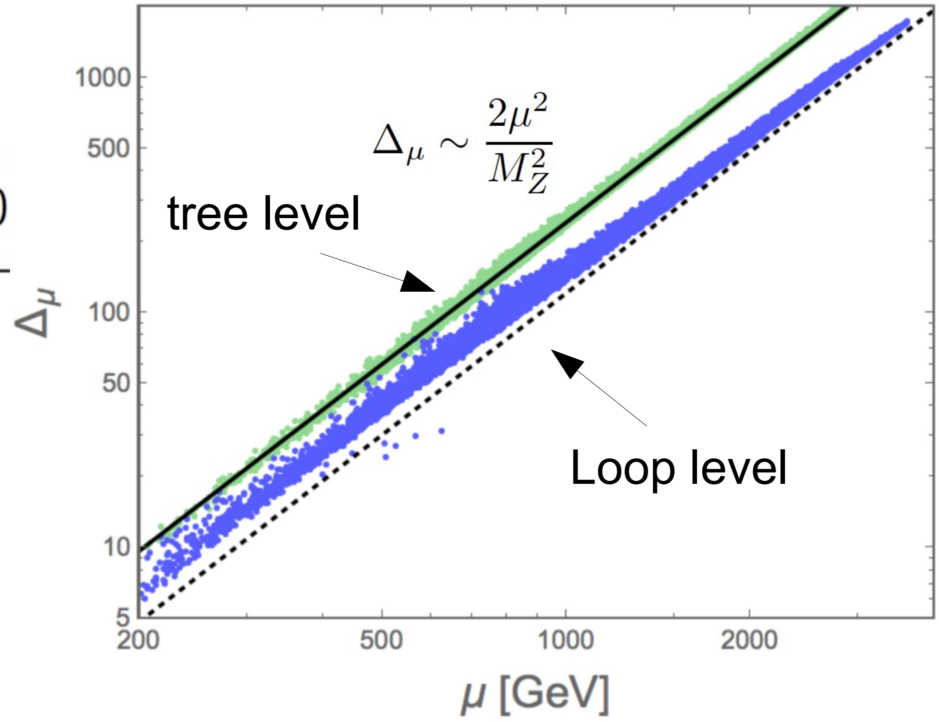
- Result for leading stop correction

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

$$\Sigma_2 = 0$$

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

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



- Reduction of about ½ when including loop corrections

Comment on loop corrections

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$$\Sigma_2 = 0$$

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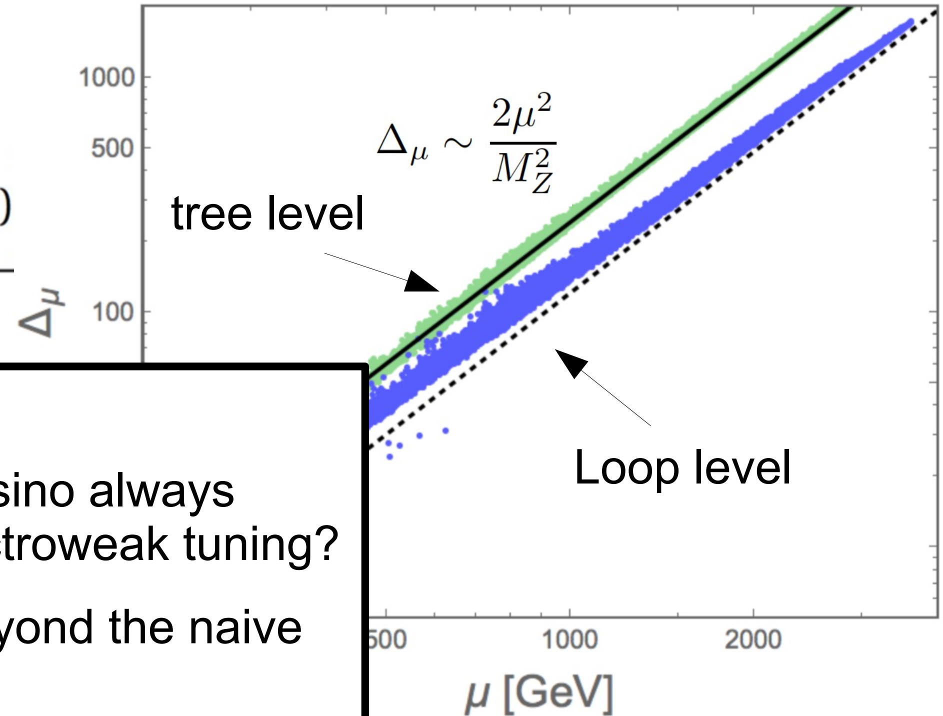
$$r^{FT} \equiv \frac{\Delta_\mu^{\text{Loop}}}{\Delta_\mu^{\text{Tree}}} \simeq \left(1 \ldots\right.$$

- Reduction c…

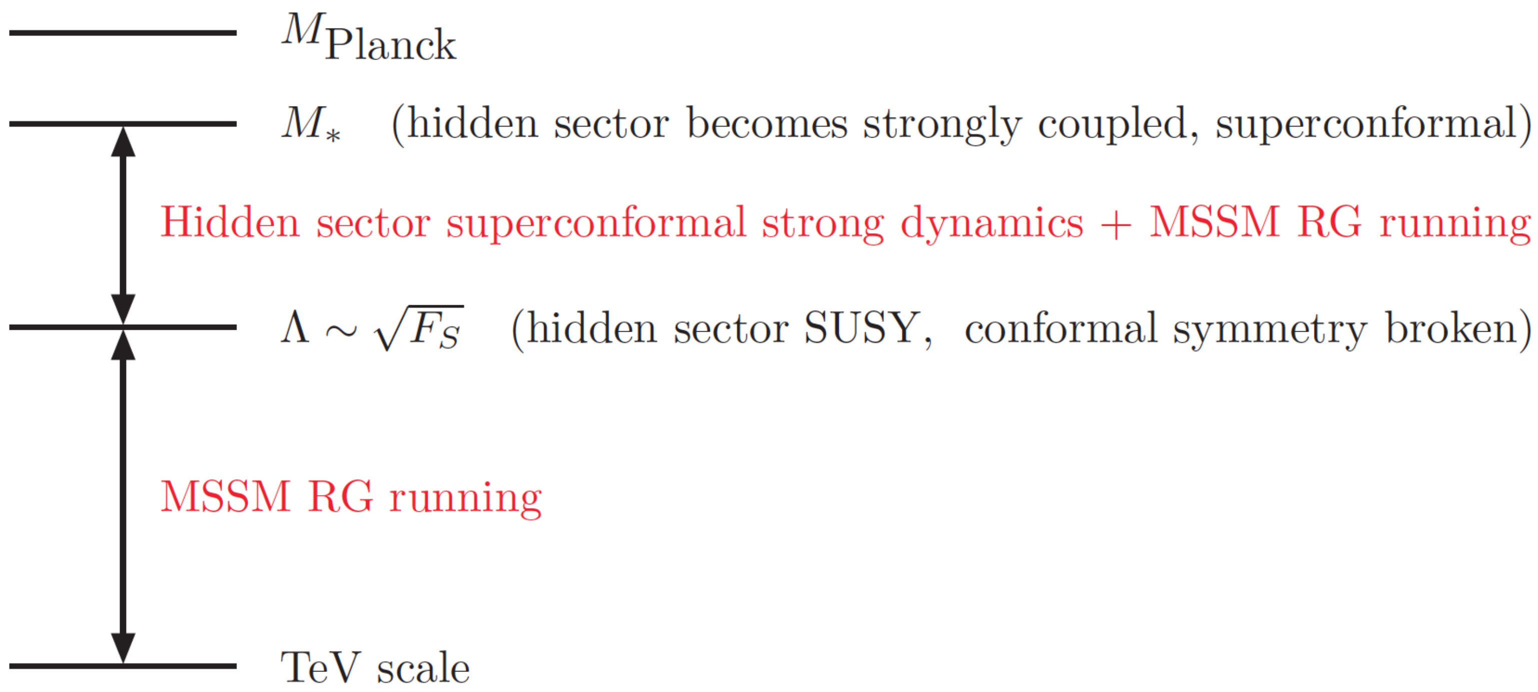


- µ not a soft term...
- So does a 1 TeV Higgsino always require significant electroweak tuning?
- Two possible ways beyond the naive FT arguments
- The µ-term could be correlated with the soft terms (→ µ problem)
- The Higgsino mass could arise from something beyond the µ-term

A further correlation

- The μ-term could be correlated with the soft terms

S Martin, 1712.05806



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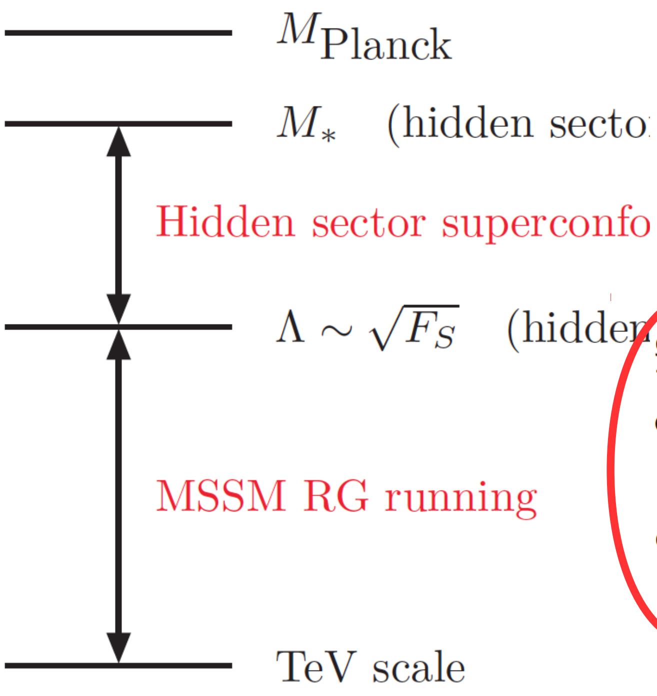
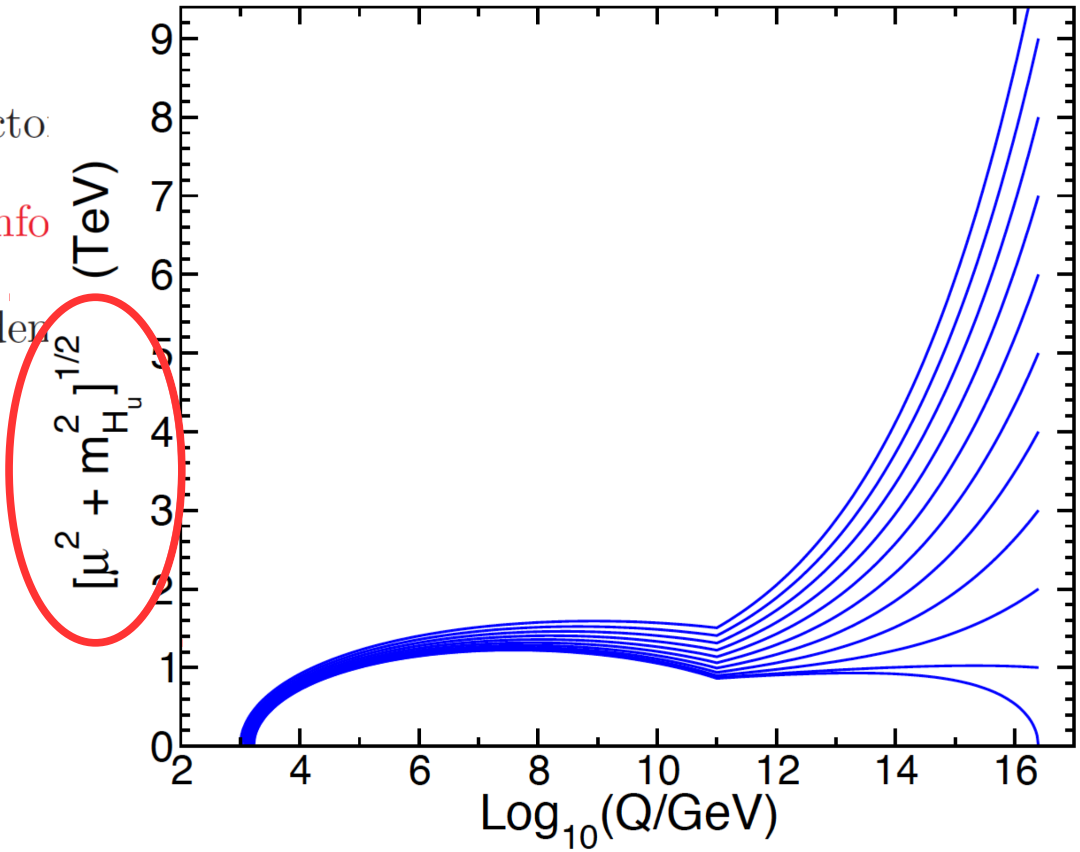




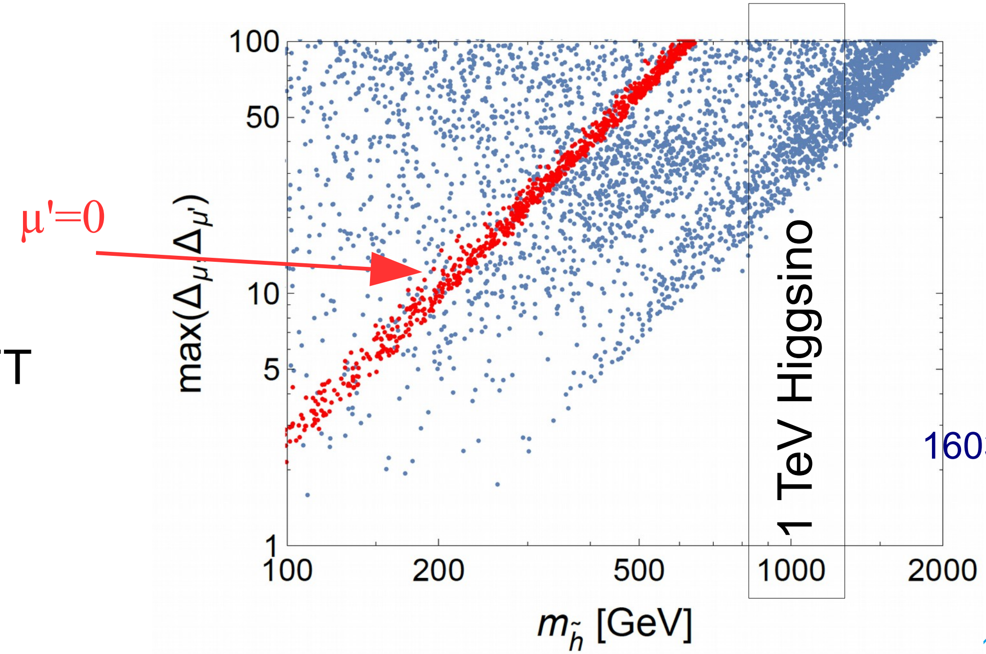
A new contribution to the Higgsino mass

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

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

- μ' contributes to the Higgsino mass ($m_h \sim \mu + \mu'$) but does not enter the tadpole equations

- Can significantly reduce FT



1603.09347

Embedding this into a model

> Studied different MSSM variants with GUT boundary conditions

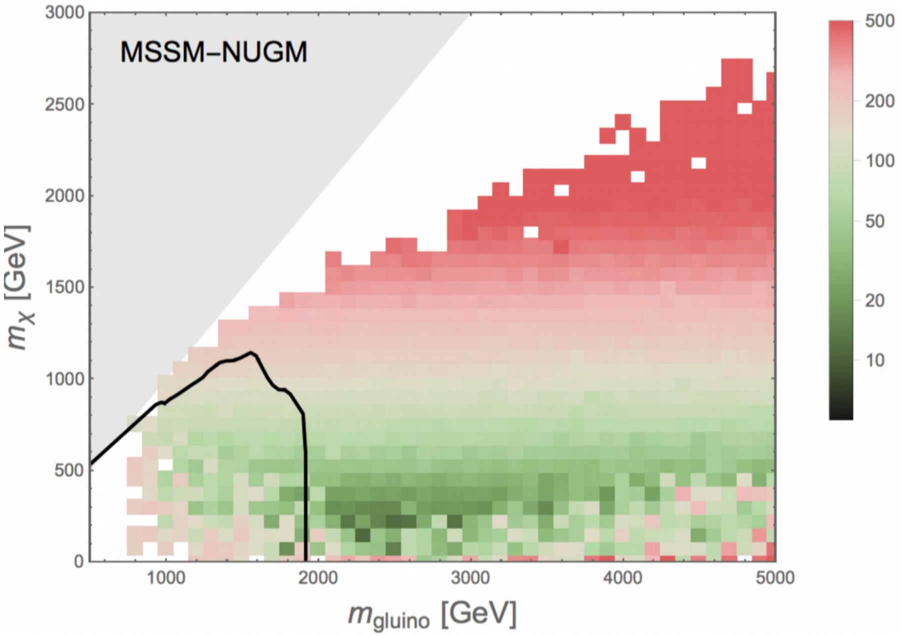
	$m_{h_u}^2$	$m_{h_d}^2$	M_1	M_2	M_3	μ'	A_0'
CMSSM	m_0^2	m_0^2	$m_{1/2}$	$m_{1/2}$	$m_{1/2}$	-	-
MSSM-NUHM	$m_{h_u}^2$	$m_{h_d}^2$	$m_{1/2}$	$m_{1/2}$	$m_{1/2}$	-	-
MSSM-NUGM	m_0^2	m_0^2	$a \cdot m_{1/2}$	$b \cdot m_{1/2}$	$m_{1/2}$	-	-
CNHSSM	m_0^2	m_0^2	$m_{1/2}$	$m_{1/2}$	$m_{1/2}$	μ'	A_0'
NHSSM-NUHM	$m_{h_u}^2$	$m_{h_d}^2$	$m_{1/2}$	$m_{1/2}$	$m_{1/2}$	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'

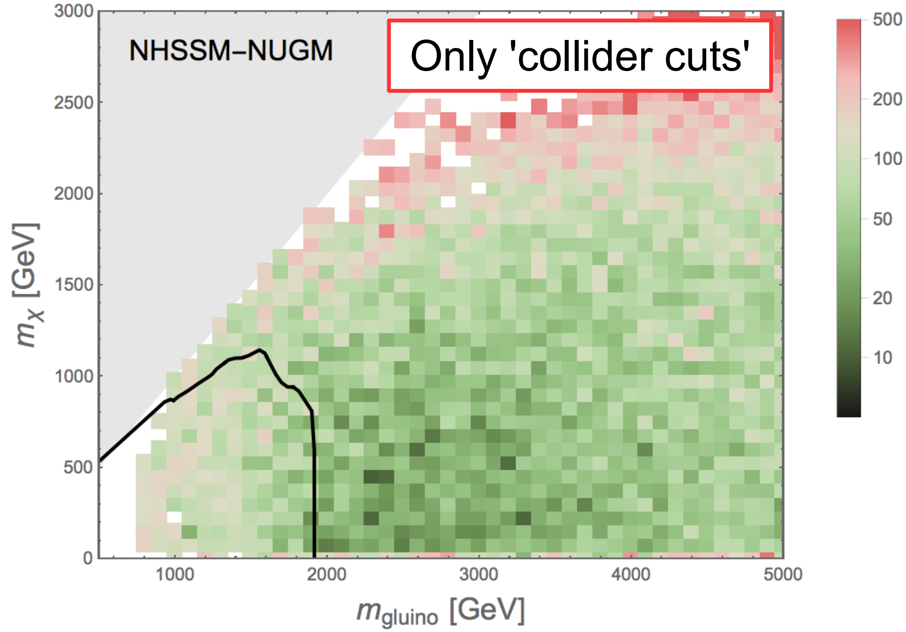
1701.03480

Results non-universal gaugino masses

- Region of small FT can be well beyond LHC reach

$\mu'=0$





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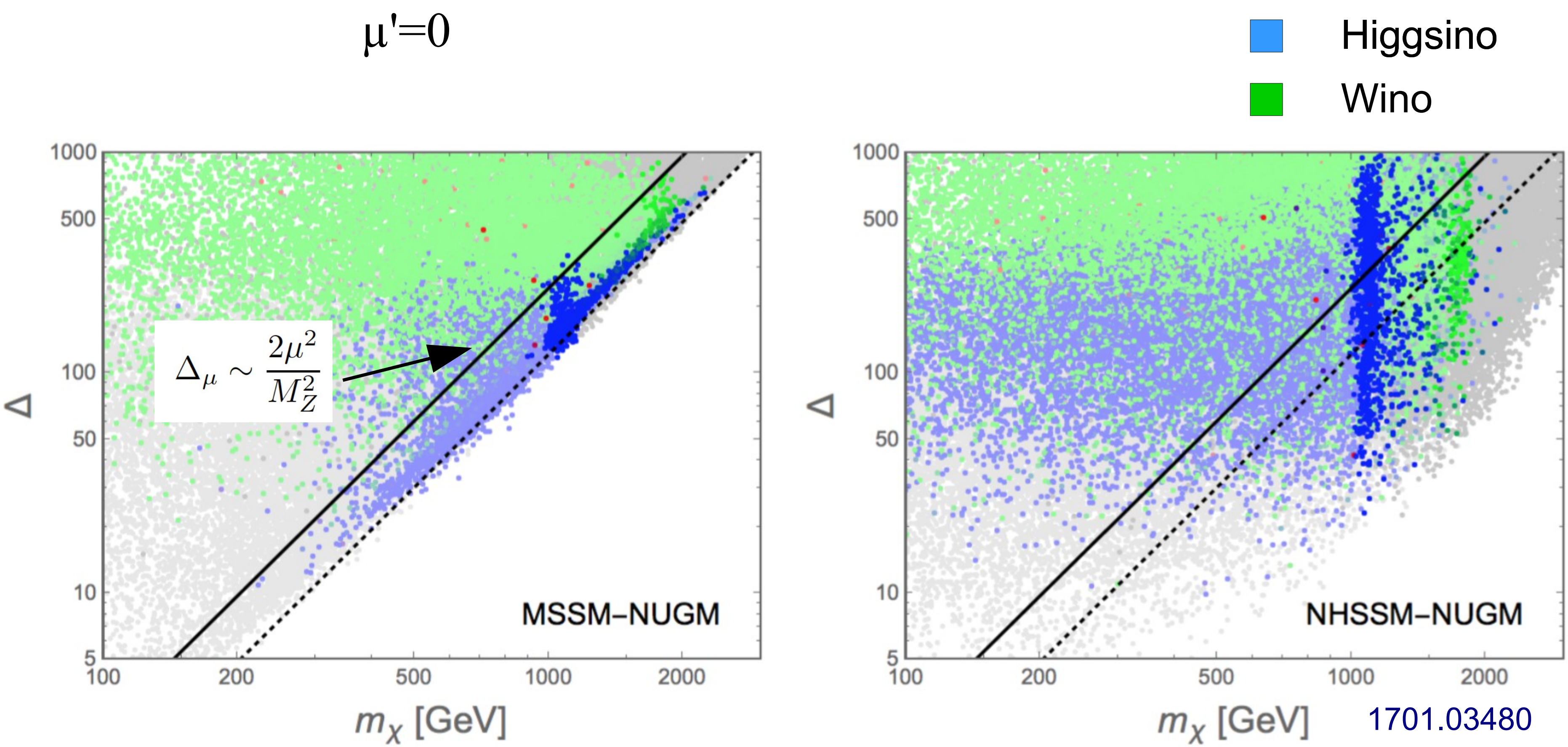
- Allowing for DM underabundance FT can be as small as 10.

Results non-universal gaugino masses

- A 1 TeV Higgsino can be quite natural



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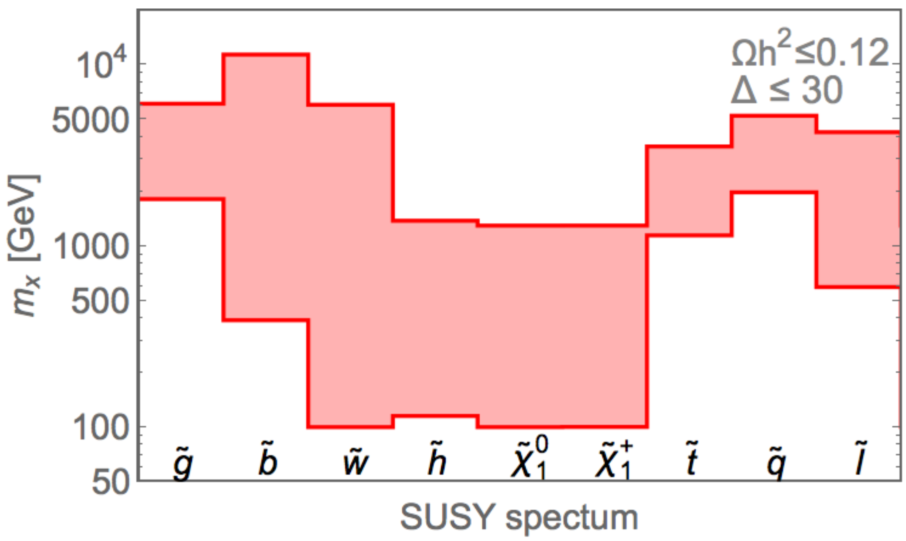
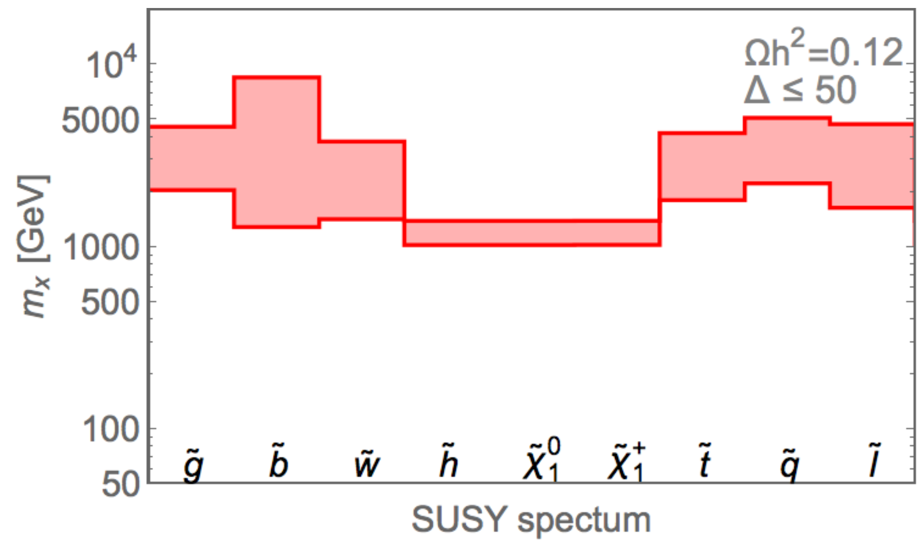
The SUSY spectrum

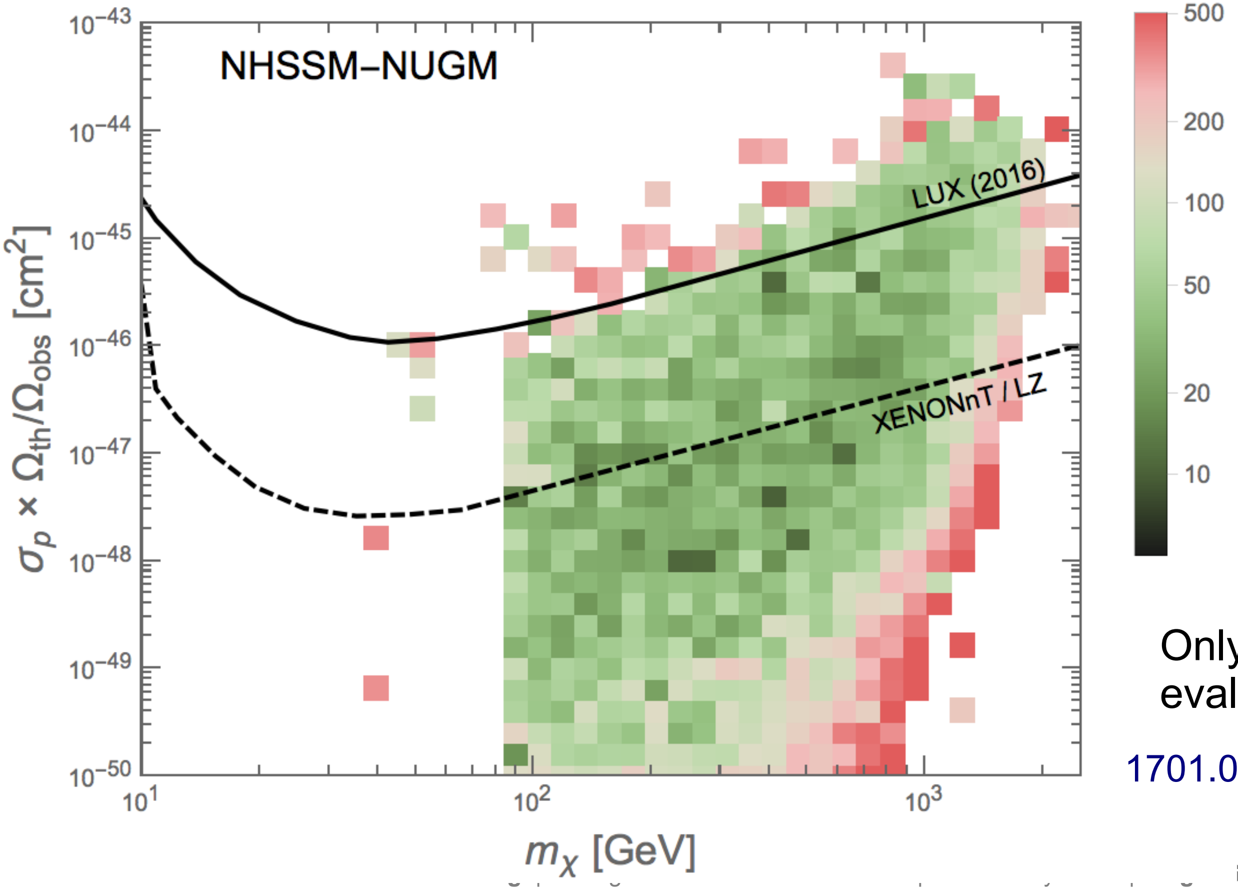
> What does the spectrum in the regions with low FT look like?





Prospects for direct detection

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

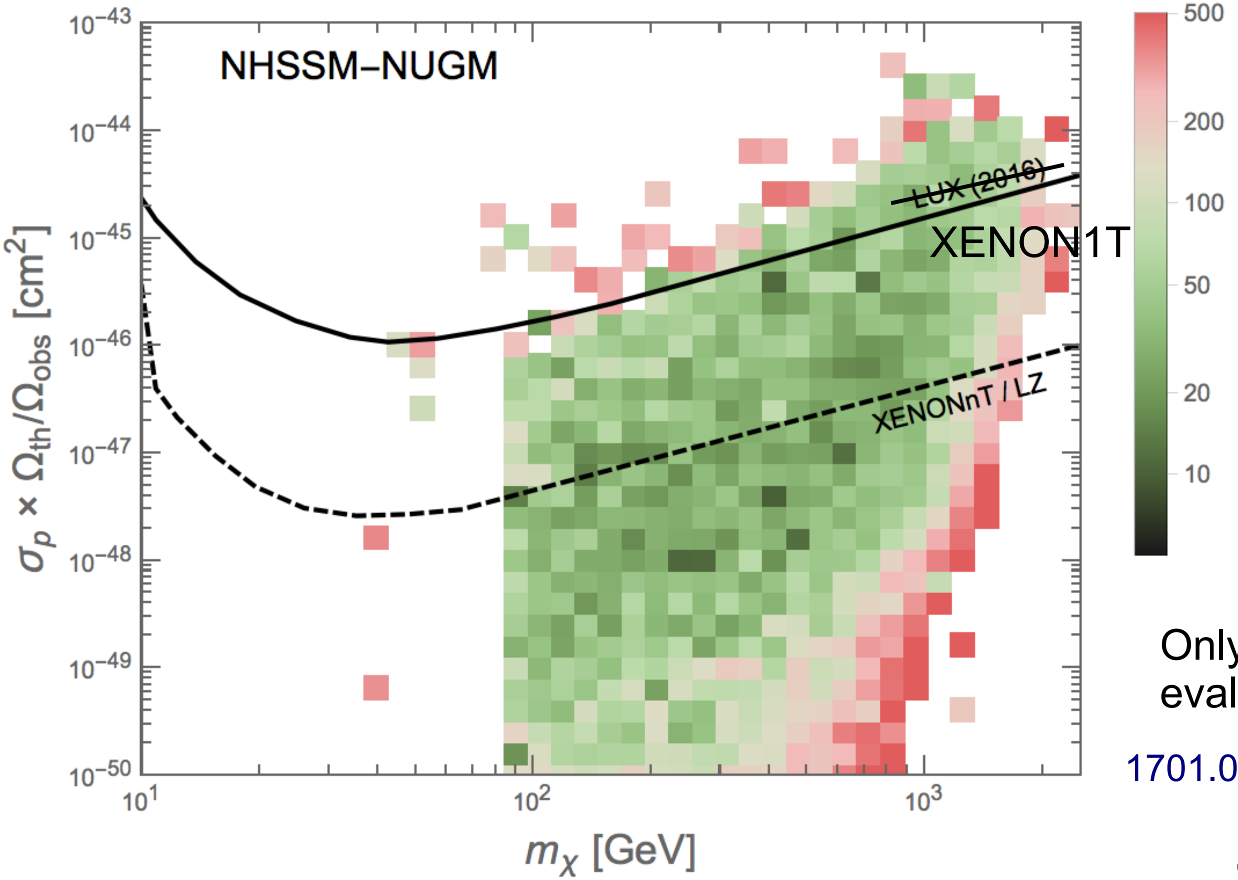


Only tree-level evaluation

1701.03480

Prospects for direct detection

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

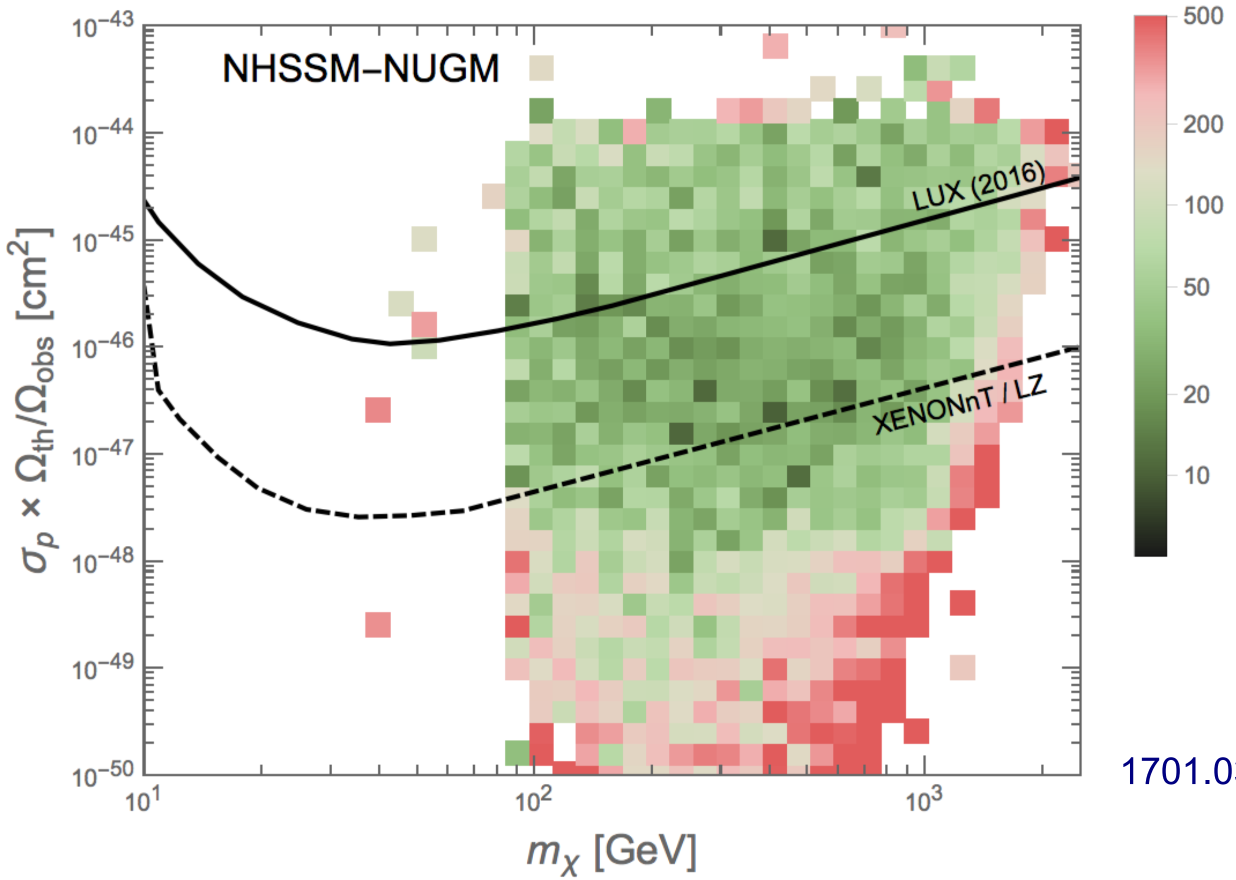


Only tree-level evaluation

1701.03480

Prospects for direct detection

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



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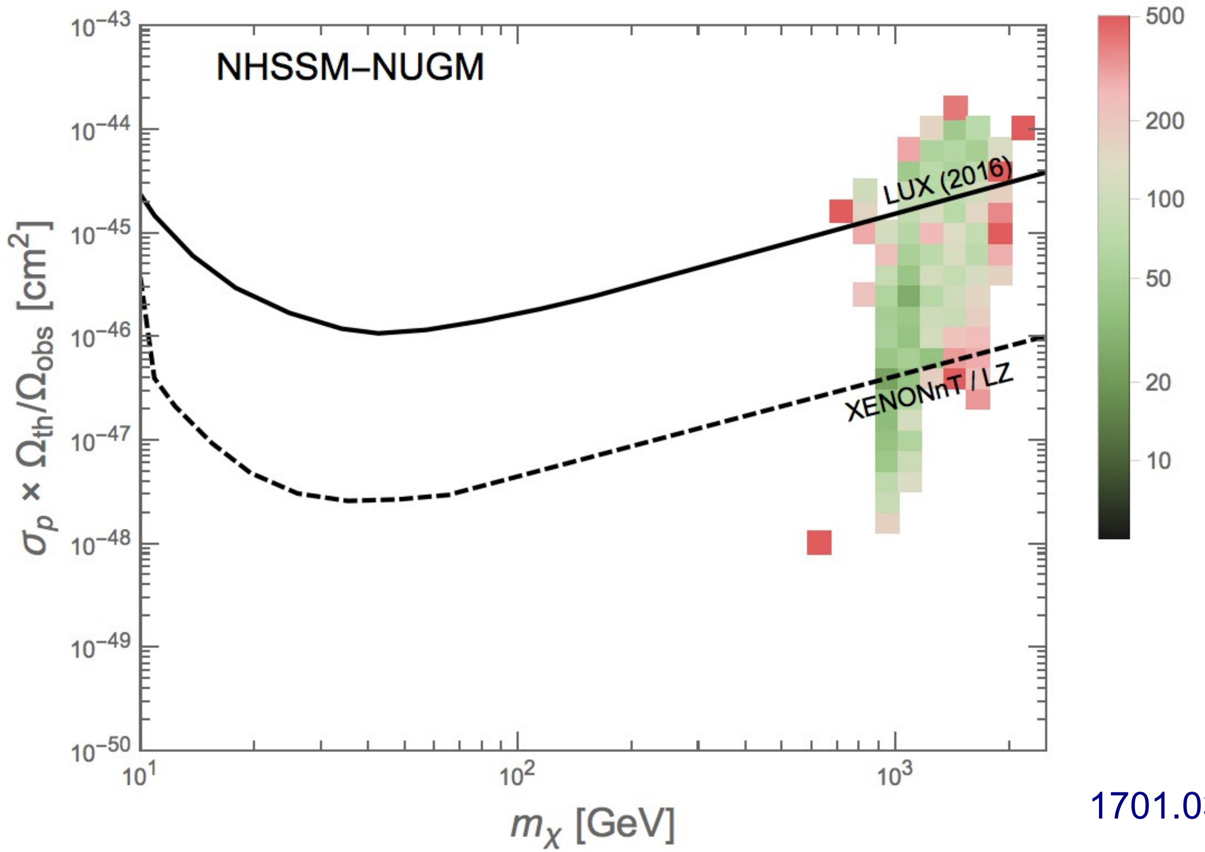
Prospects for direct detection

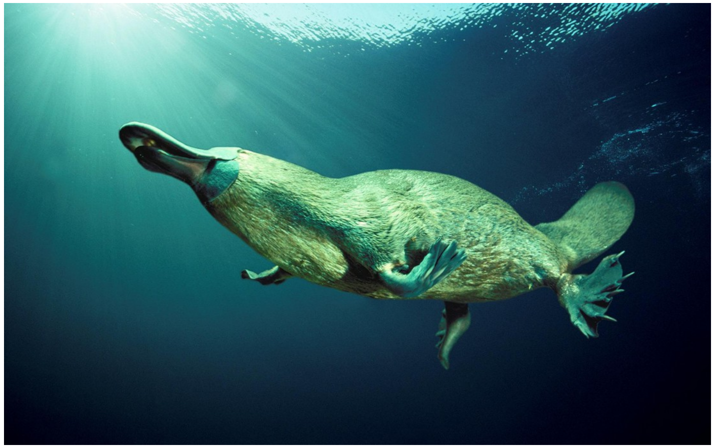
- Prospects for direct detection
- Correct (thermal) relic abundance



1701.03480

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



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- Good chances at direct detection experiments to find it

Summary

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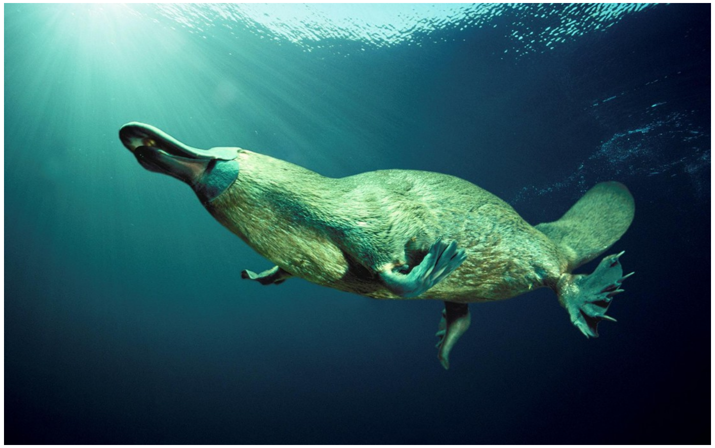
Thank you!



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