

The Dark Side of Naturalness Beyond the MSSM

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Belanger, CD, Goudelis: to appear

Motivations

Short distance motivation for SUSY:

- SM w/Higgs is a **complete** theory of EWSB (up to 10^{19} GeV?)
- But it is **highly unnatural**, ie. sensitive to UV dynamics:

$$\delta m_h^2 = \boxed{\text{Feynman diagram showing a loop of Higgs bosons (dashed) and top quarks (solid), with a W/Z boson loop (wavy) attached to the top quark line. The coupling to the Higgs loop is labeled } Y_t.} \sim -\frac{3Y_t^2}{8\pi^2}\Lambda^2$$

if $\Lambda \gg o(\text{TeV}) \rightarrow \text{Hierarchy problem}$

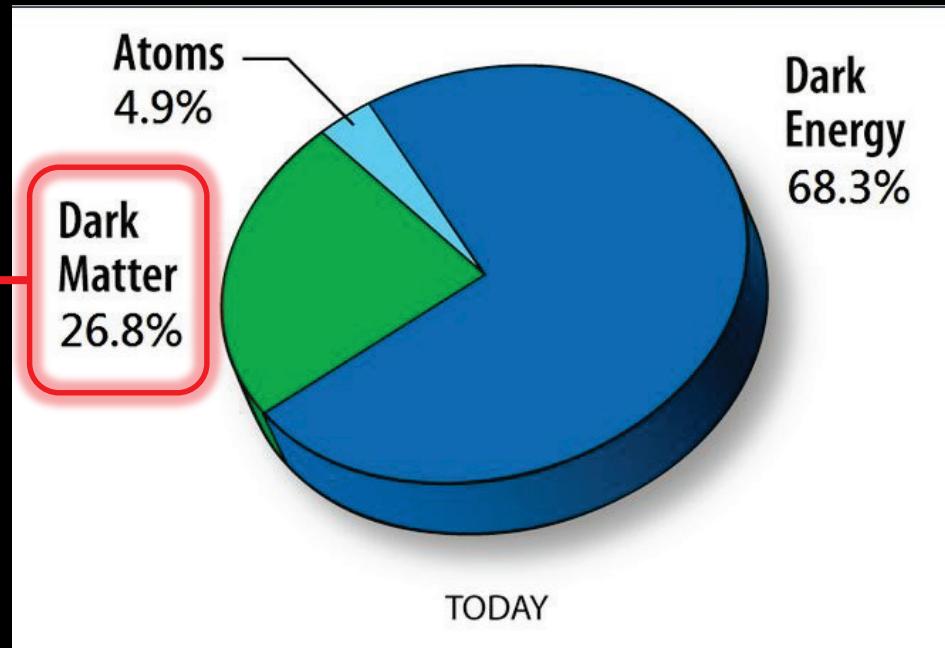
$$+ h^0 \text{---} \text{---} \tilde{t} \text{---} \text{---} Y_t \text{---} \text{---} + h^0 \text{---} \text{---} \tilde{t} \text{---} \text{---} \propto \log \frac{m_{\tilde{t}}}{m_t}$$

same coupling guaranteed by SUSY: $\int d^2\theta Y_t Q H_u \bar{U}$

Long distance motivation for SUSY:

Energy-density content
of our Universe:

neutral, long-lived, cold
→ no SM candidate



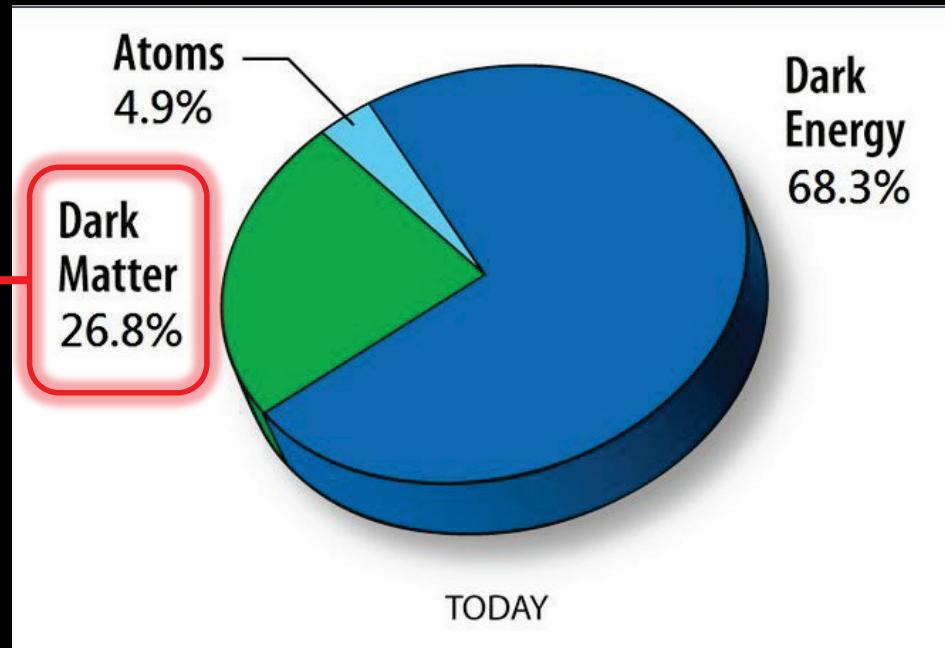
SUSY + unbroken (R) parity provides a DM candidate:

- EWino = lightest neutralino
- Gravitino
- RH sneutrino
- axino,...

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working assumption in this talk:

SUSY solves the hierarchy problem

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main agenda: how DM pressures naturalness?

$$-\frac{m_Z^2}{2} \approx |\mu|^2 + m_{H_u}^2$$

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stop (+sbottom+gluino)
searches at LHC

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DM observables
(better than LHC?)

stop (+sbottom+gluino)
searches at LHC

Main lesson from the Higgs discovery:

- $m_h \approx 125\text{GeV}$

MSSM : $m_h^2 < (m_Z \cos \beta)^2 + \delta_{loop}$

$\tan \beta \gg 1$: $(125\text{GeV})^2 \approx m_Z^2 + (87\text{GeV})^2$

\rightarrow need heavy and/or mixed stops

SUSY breaking

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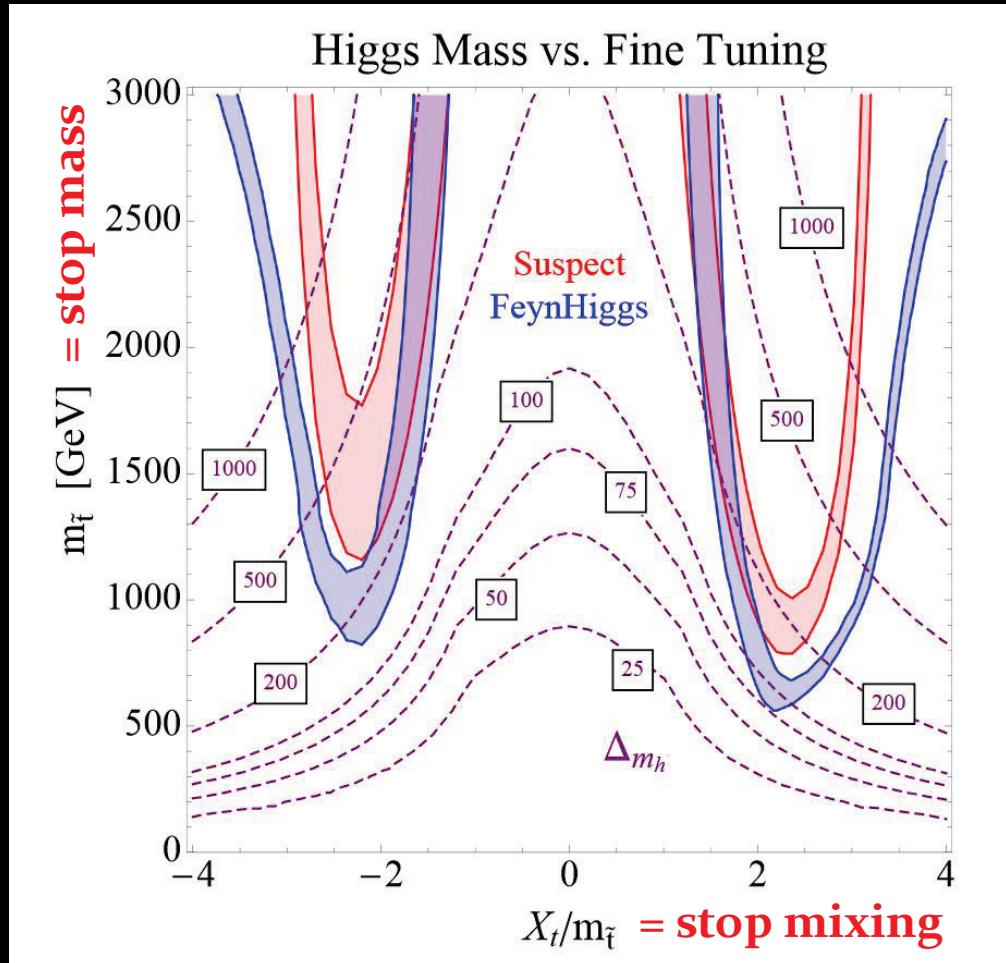
- fine-tuning bites back:

$$m_Z^2 \approx -2|\mu|^2 - 2(m_{H_u}^2 + \delta m_{H_u}^2)$$

$$\delta m_{H_u}^2 \approx -\frac{3Y_t^2}{8\pi^2} (m_{Q_3}^2 + m_{U_3}^2 + |A_t|^2) \log\left(\frac{\Lambda_{mess}}{m_{\tilde{t}}}\right)$$

Main lesson from the Higgs discovery:

MSSM :



Hall, Pinner,
Ruderman '11

$m_h \approx 125\text{GeV}$ requires *at least* 1% fine-tuning
→ need to go beyond the MSSM (?)

Lessons from (Nino) Dark matter searches:

- $\sigma_{\text{proton}}^{SI} \lesssim \mathcal{O}(10^{-45} \text{cm}^2)$ for DM~ $\sim \mathcal{O}(100 \text{GeV})$

LUX experiment '13

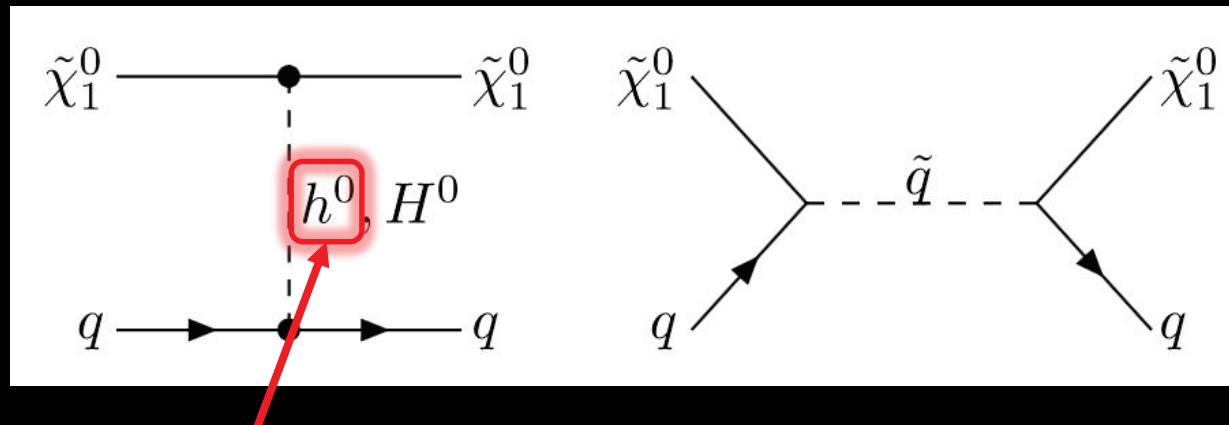
at odds with WIMP miracle: $\Omega_{DM} h^2 \approx 0.1 \left(\frac{10^{-36} \text{cm}^2}{\langle \sigma v \rangle} \right)$

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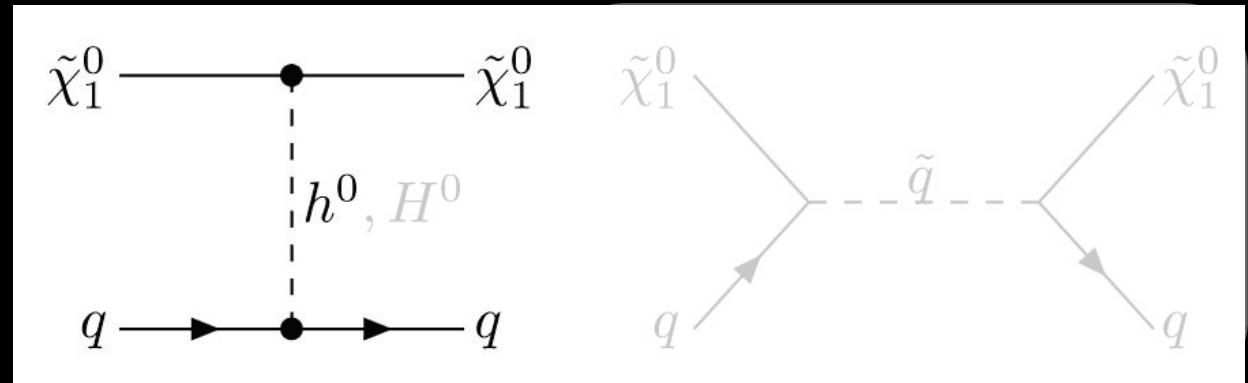
- Nino DM scatters off quarks through:



unavoidable (often dominant) contribution

Lessons from (Nino) Dark matter searches:

- MSSM:



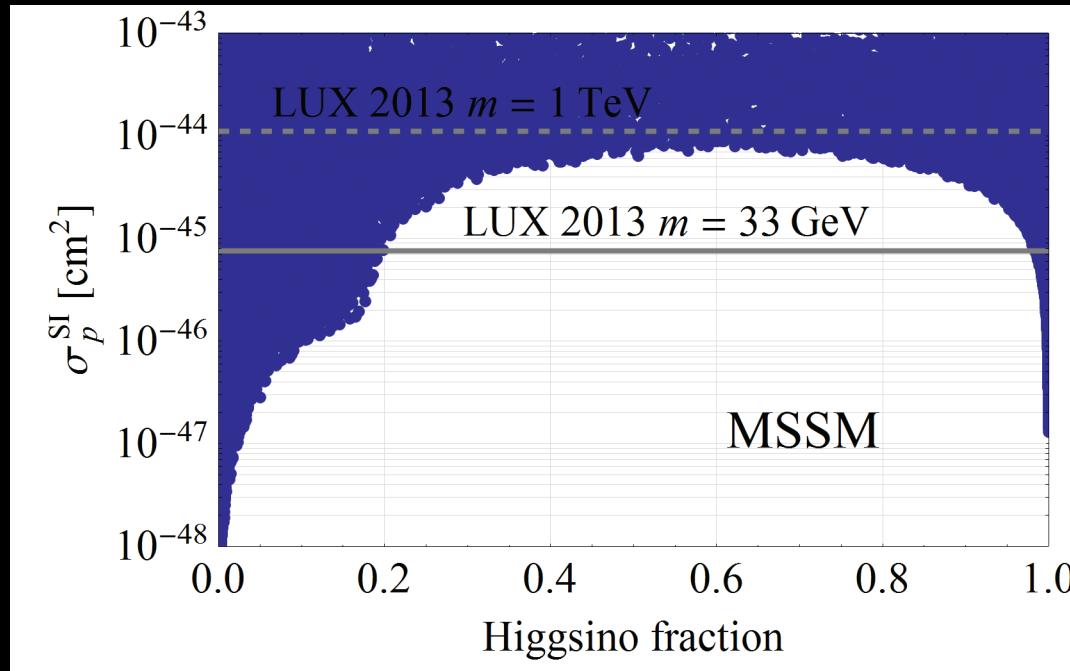
$$\chi_0 = N_{\chi_1} \widetilde{B}_Y + N_{\chi_2} \widetilde{W}_3 + N_{\chi_3} \widetilde{H}_d + N_{\chi_4} \widetilde{H}_u$$

$h\chi\chi$ arises from: $\int d^4\theta H_{u,d}^\dagger e^V H_{u,d} \rightarrow$ of the form $h\tilde{\lambda}\widetilde{H}$

- $h\chi\chi = g(\mathcal{N}_{\chi_2} - t_W \mathcal{N}_{\chi_1})(\mathcal{N}_{\chi_3} \sin \alpha + \mathcal{N}_{\chi_4} \cos \alpha)$

vanishes for pure Gaugino or Higgsino DM

Lessons from (Nino) Dark matter searches:



= update of original plot
from Perelstein,Shakya '11

scanning over MSSM parameters: $M_1, M_2, \mu, m_A, t_\beta$
(ignoring possible accidental cancelations with
resonance squark scattering)

→ DD forces nearly pure Gaugino or Higgsino DM

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«tree-level» source

$$\Delta_0 \equiv \sqrt{\sum_p \Delta_p^2} ,$$

$$\Delta_p \equiv \left| \frac{\partial \log m_Z^2}{\partial \log p} \right|$$

$$p = \mu, B_\mu, m_{H_u}^2, m_{H_d}^2 @\text{weak scale}$$

dominant source: $\Delta_\mu \approx \frac{4|\mu|^2}{m_Z^2}$

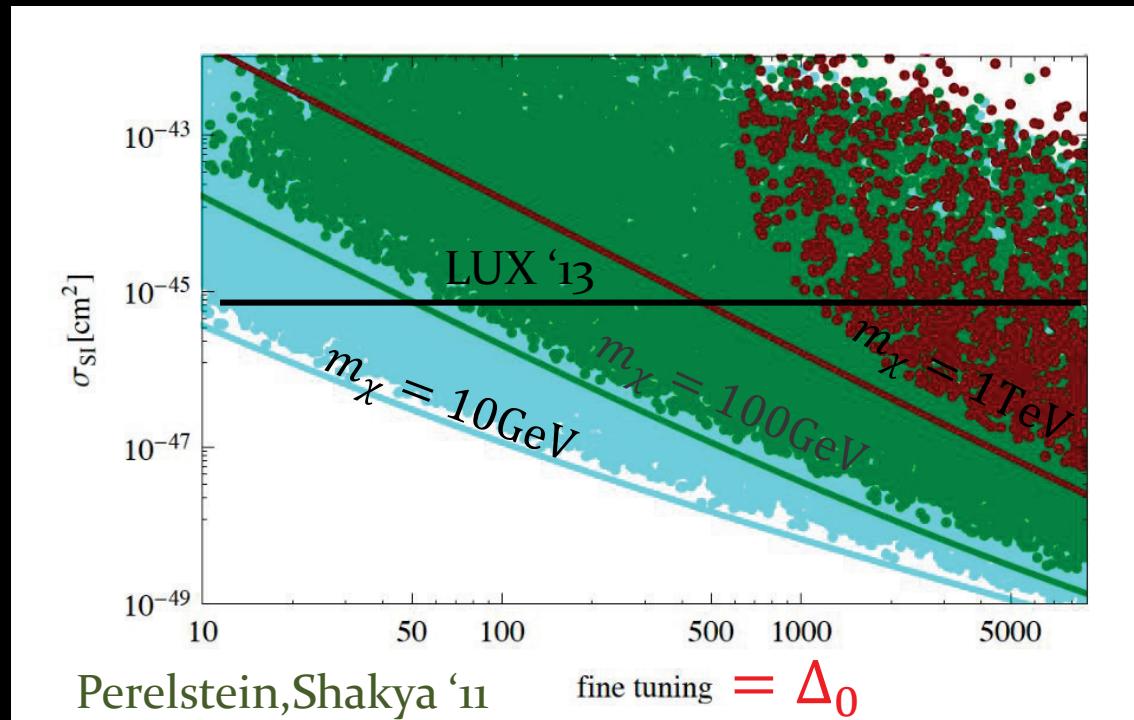
Lessons from (Nino) Dark matter searches:

- Gaugino DM:
 $\mu \gg M_1$ and/or M_2

example: for Bino DM
 to leading $\mathcal{O}(\frac{m_Z}{\mu - M_1})$



$$h\chi\chi \approx \frac{2g'm_Z s_W}{\mu} \left(\frac{1}{t_\beta} + \frac{M_1}{2\mu} \right)$$



\rightarrow for DM ~ 100 GeV
 Δ_0 is *at least* 1-2%

Lessons from (Nino) Dark matter searches:

- Higgsino DM: no tension w/ direct detection
 $\mu \ll M_{1,2}$ but efficient (co-)annihilation to VV significantly depletes the relic density unless DM is very sparsely distributed

$$\Omega_{\tilde{H}} h^2 \approx 0.1 \left(\frac{\mu}{1.2 \text{TeV}} \right)^2$$

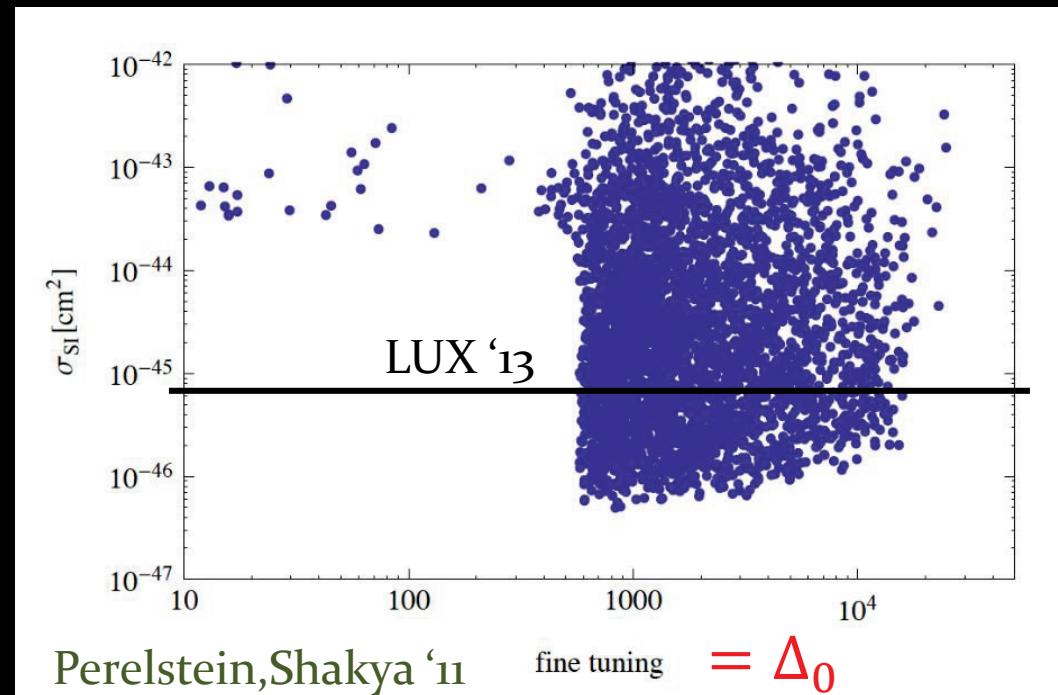
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Δ_0 at least
of order few %



→ need to go beyond the MSSM (?)

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- Heavy new sector \leftarrow this talk (BMSSM)
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BMSSM physics reviewed

BMSSM in a nutshell

Dine,Seiberg,Thomas '07

- Introduce a new scale $M \gtrsim \mu, m_{\text{soft}}$

$$\mathcal{W} = \mathcal{W}_{\text{MSSM}} + \frac{1}{M} (\lambda_1 + \lambda_2 X) (H_u H_d)^2$$

$$\mathcal{K} = \mathcal{K}_{\text{MSSM}} + \mathcal{O}\left(\frac{1}{M^2}\right)$$

F-term breaking spurion
 $X = \langle F \rangle / M_{\text{mess}} \theta^2$

- Other operators involve Higgs+fermions:

$$\frac{1}{M} \int d^4 \theta H_d^\dagger Q \bar{U}, \dots$$

yet, no effects on m_h , neutralino
 \rightarrow ignored

BMSSM in a nutshell

- $(H_u H_d)^2$ induces:
 - New (F-type) Higgs quartics:

$$2\epsilon_1(h_u \cdot h_d) (|h_u|^2 + |h_d|^2) + \epsilon_2(h_u \cdot h_d)^2 + \text{h.c.}$$

$$\epsilon_1 \equiv \frac{\lambda_1 \mu^*}{M}, \quad \epsilon_2 \equiv -\frac{\lambda_2 \langle F \rangle}{MM_{\text{mess}}}$$

- New Higgs-Higgsino interactions:

$$-\frac{\epsilon_1}{\mu^*} \left[2(h_u \cdot h_d)(\tilde{h}_u \cdot \tilde{h}_d) + 2(\tilde{h}_u \cdot h_d)(h_u \cdot \tilde{h}_d) + (h_u \cdot \tilde{h}_d)^2 + (\tilde{h}_u \cdot h_d)^2 \right] + \text{h.c.}$$

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→ shifts in m_h and Nino correlated thanks to SUSY!

BMSSM and the light Higgs mass

- m_h significantly shifted *classically*:

$$\delta m_h^2 = \boxed{2v^2 \left(\epsilon_2 - 2\epsilon_1 \sin 2\beta - \frac{2\epsilon_1 x \sin 2\beta + \epsilon_2 y \cos^2 2\beta}{\sqrt{y^2 + (x^2 - y^2) \sin^2 2\beta}} \right)}$$

$v \approx 174 \text{ GeV}$ $x \equiv m_A^2 + m_Z^2, \quad y \equiv m_A^2 - m_Z^2$

$$\simeq 16v^2 \left(-\frac{\epsilon_1}{t_\beta} + \frac{\epsilon_2}{2t_\beta^2} \right) + \mathcal{O}\left(\frac{m_Z^2}{m_A^2}, \frac{1}{t_\beta^3}\right)$$

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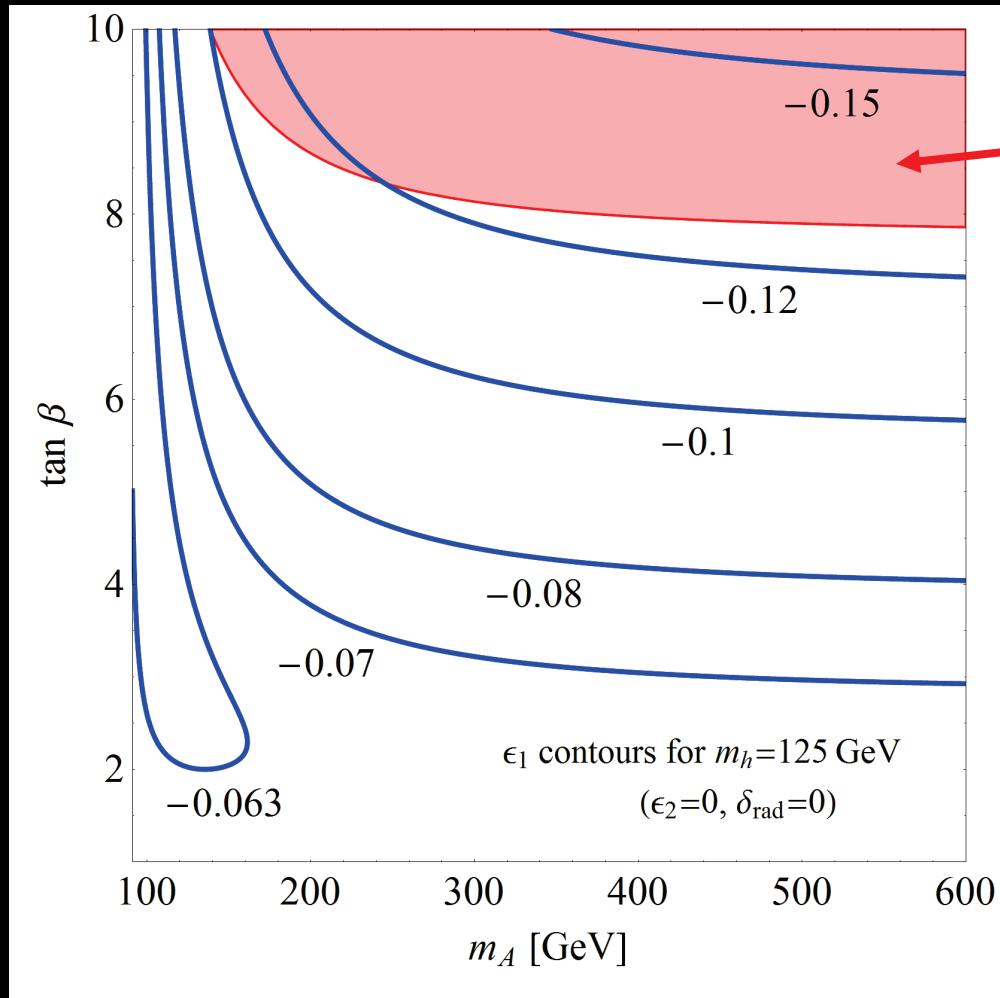
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- w/out stops, $\delta m_h^2 \approx (87 \text{ GeV})^2$

$$\rightarrow -\epsilon_1 \approx 0.05, t_\beta \approx 3 \quad i.e. M/\lambda_1 \approx 2 \text{ TeV} \left(\frac{\mu}{100 \text{ GeV}} \right)$$

BMSSM and the light Higgs mass



higher ϵ -orders
become relevant
 $\epsilon_1^2 \sim |\epsilon_1|/t_\beta$

good control over
EFT prediction of m_h
only for low $t_\beta \lesssim 8 - 10$

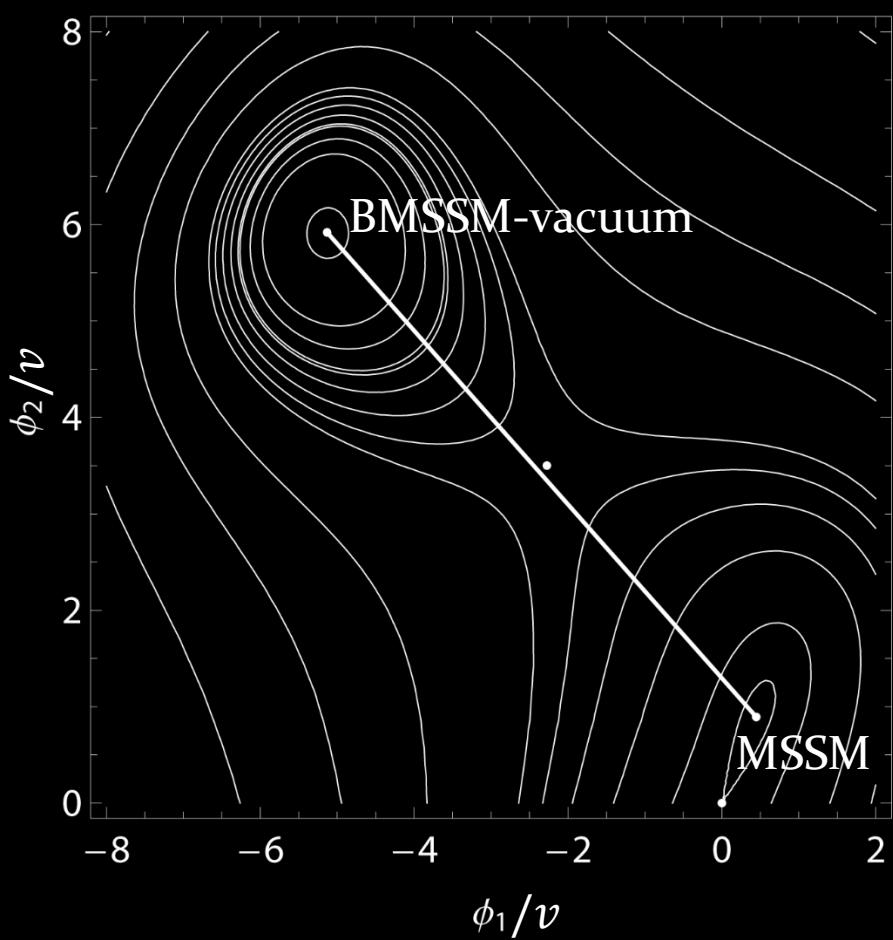
(see e.g. Antoniadis et al. '09
for effects of $1/M^2$ operators)

→ in this talk: $\epsilon_2 = 0, \epsilon_1$ set so $m_h = 125 \text{ GeV}$ classically.

BMSSM and vacuum stability

Blum,CD,Hochberg '09

- second vacuum dominated by $(H_u H_d)^2$

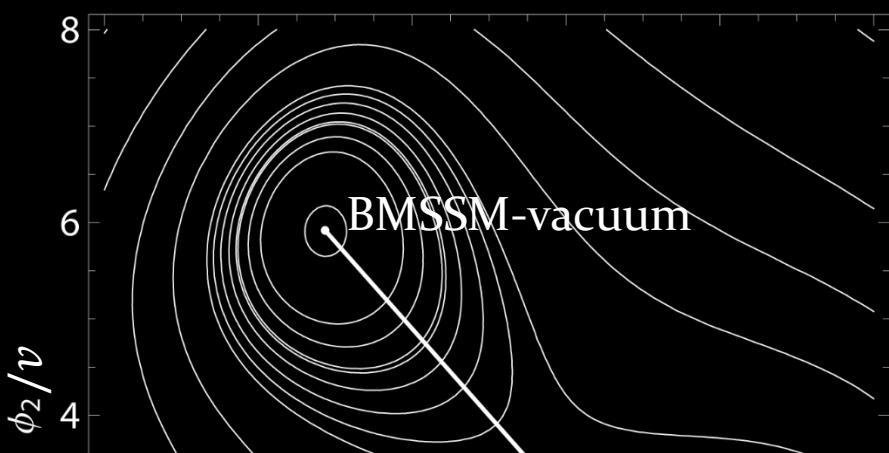


at $h_u \approx -h_d \approx \sqrt{\mu M} \ll M$

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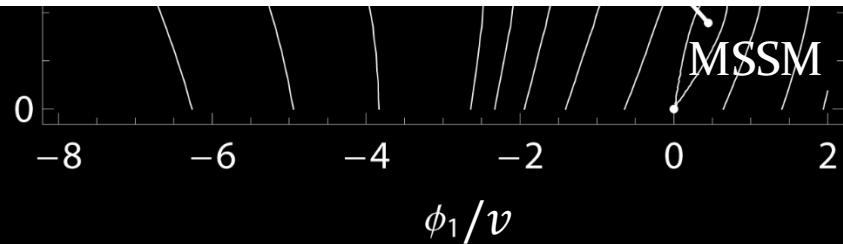
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approximate condition
for EW vacuum stability:

$$\mu \lesssim m_A \sqrt{\frac{1 + \sin 2\beta}{2}} \left[1 + \frac{8v^2}{m_A^2} \left(\frac{1 + 2 \sin 2\beta}{1 + \sin 2\beta} - \frac{3}{2} \right) \right]^{1/2}$$



slightly conservative
in practice (...tunneling)

BMSSM fine-tuning

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- Potential minimization yields:

$$m_Z^2 = \frac{|m_{H_d}^2 - m_{H_u}^2|}{\sqrt{1 - \sin^2 2\beta}} - m_{H_u}^2 - m_{H_d}^2 - 2\mu^2 + 4\epsilon_1 v^2 \sin 2\beta$$

$$\sin 2\beta = \frac{2b}{m^2} + \frac{4v^2}{m^2} \left[\epsilon_1 \left(1 + 4 \frac{b^2}{m^4} \right) \right] \quad m^2 \equiv m_{H_u}^2 + m_{H_d}^2 + 2\mu^2$$

- Fine-tuning measure:

$$\Delta \equiv \sqrt{\Delta_0^2 + \Delta_{\text{rad}}^2},$$

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stop source
 subdominant here if
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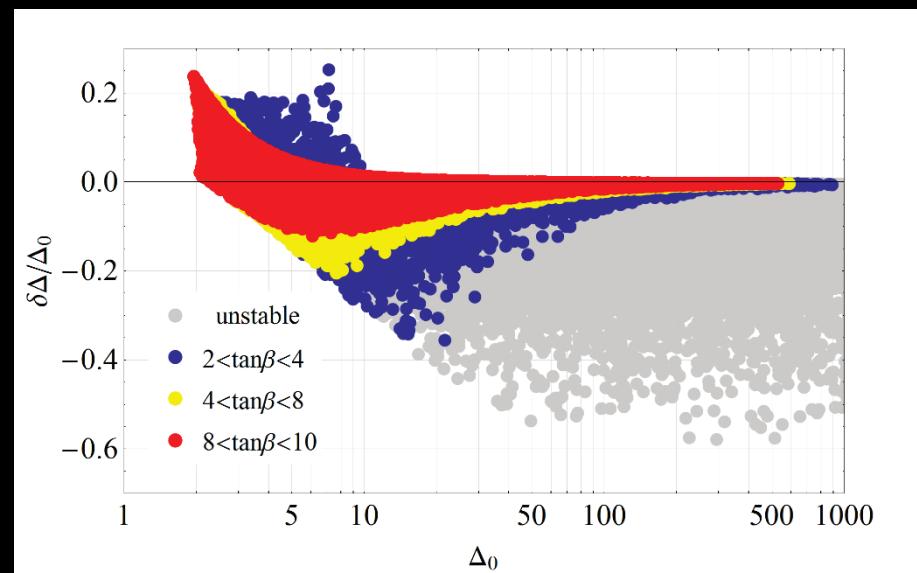
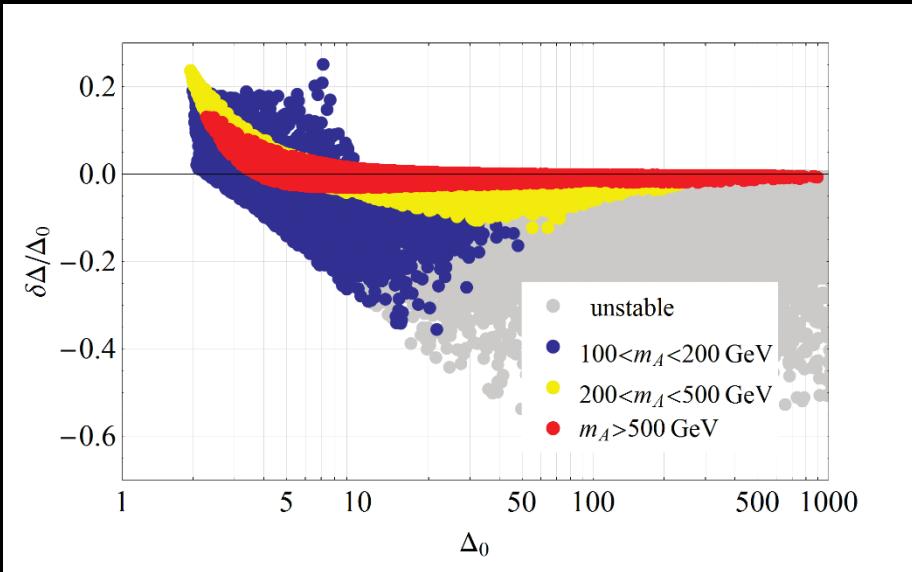
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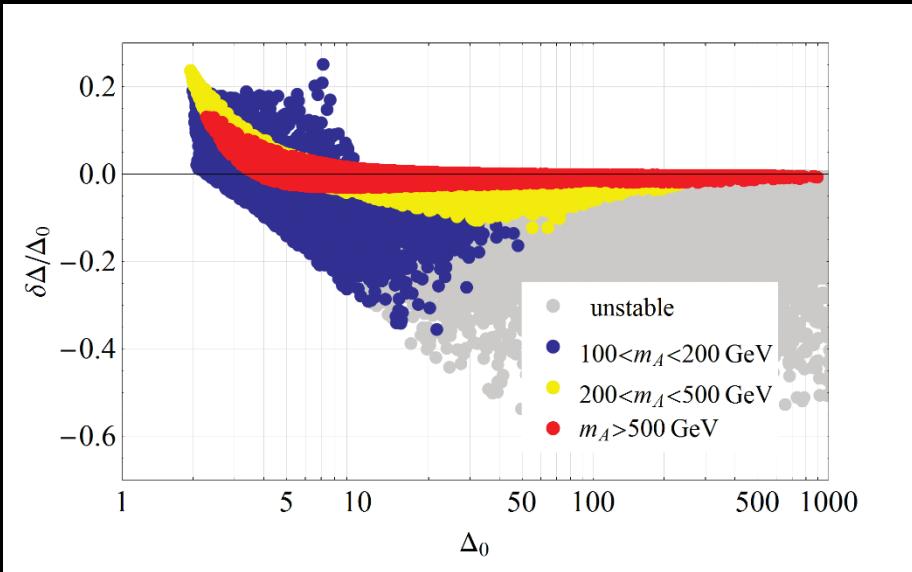
BMSSM tree-level fine-tuning

- FT relative to MSSM at fixed μ, m_A, t_β

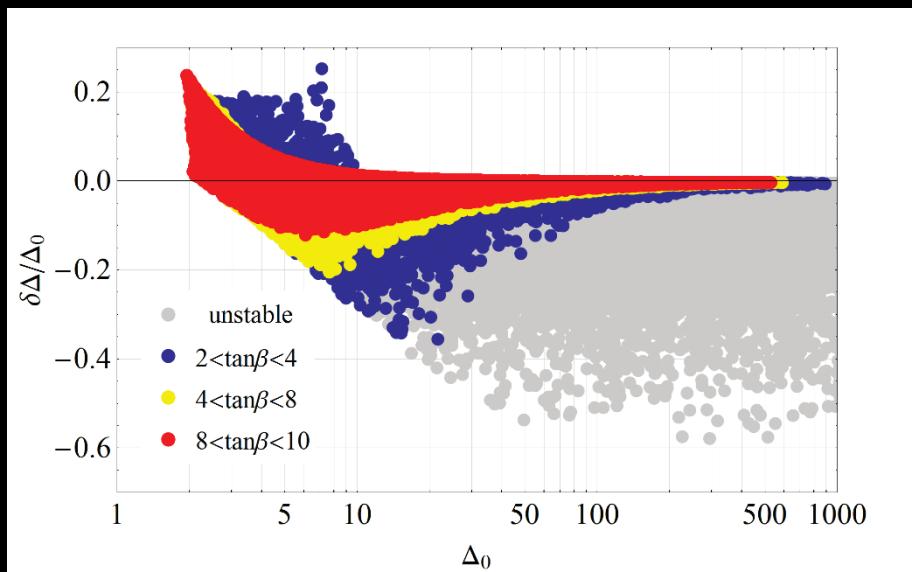


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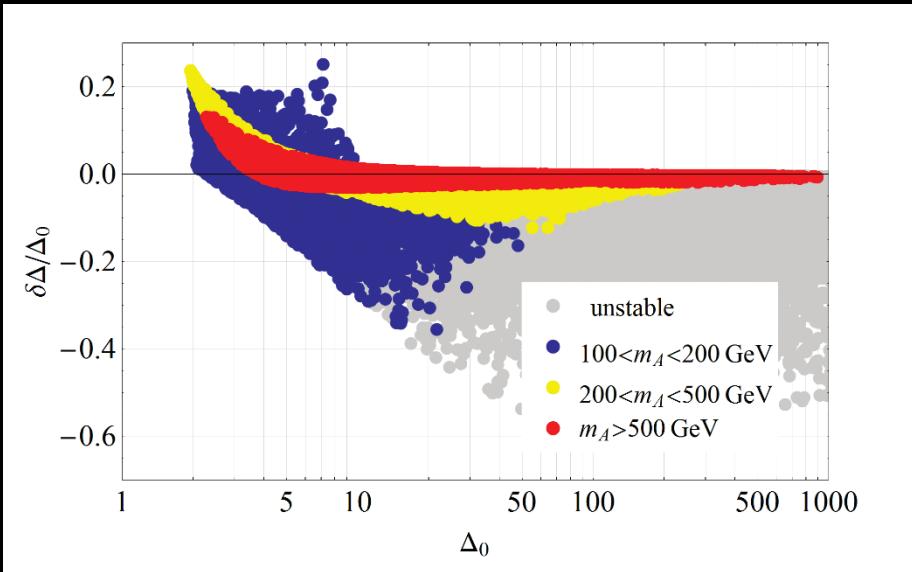


vacuum stability is relevant:
 $m_A \gtrsim \sqrt{2}\mu$



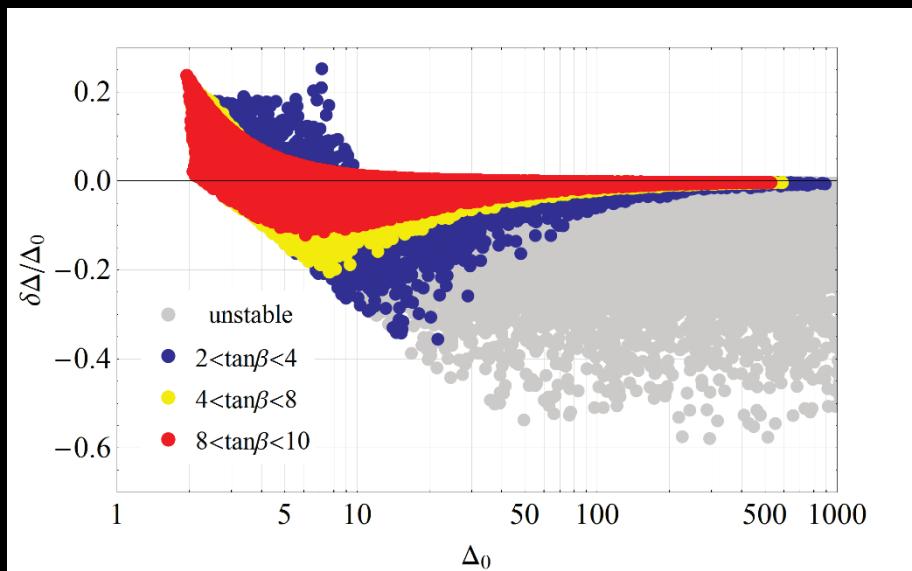
BMSSM tree-level fine-tuning

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Tree-level FT often reduced
in the BMSSM,
up to 40% for $m_A \lesssim 200$ GeV
and $t_\beta \lesssim 4$

vacuum stability is relevant:
 $m_A \gtrsim \sqrt{2}\mu$



BMSSM tree-level fine-tuning

- Dominant FT sources at large-ish $\tan \beta$:

$$\Delta_\mu \simeq \frac{4\mu^2}{m_Z^2} \left(1 + 8\eta \frac{\epsilon_1 v^2}{m_A^2} + \mathcal{O}(\eta^2) \right) \quad \eta \equiv 1/t_\beta$$

$$\Delta_{m_{H_u}^2} \simeq \left(1 + \frac{2\mu^2}{m_Z^2} \right) \left[1 + 4\eta \frac{\epsilon_1 v^2}{m_A^2} \left(1 - \frac{2m_A^2}{m_Z^2 + 2\mu^2} \right) + \mathcal{O}(\eta^2) \right]$$

also important,
if $m_A > m_Z t_\beta$

$$\Delta_b \simeq 2\Delta_{m_{H_d}^2} \simeq \frac{2\eta^2 m_A^2}{m_Z^2}$$

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$$\Delta_b \simeq 2\Delta_{m_{H_d}^2} \simeq \frac{2\eta^2 m_A^2}{m_Z^2}$$

$\epsilon_1 < 0$ always reduces Δ_μ
as well as $\Delta_{m_{H_u}^2}$ if m_A not too
large

Higgsino properties

BMSSM Higgsino sector:

- Neutralino mass matrix:

$$\mathcal{M}_{\chi_0} = \begin{pmatrix} M_1 & 0 & -m_Z s_W c_\beta & m_Z s_W s_\beta \\ 0 & M_2 & m_Z c_W c_\beta & -m_Z c_W s_\beta \\ -m_Z s_W c_\beta & m_Z c_W c_\beta & 2\epsilon_1 \frac{v^2}{\mu} s_\beta^2 & -\mu + 2\epsilon_1 \frac{v^2}{\mu} s_{2\beta} \\ m_Z s_W s_\beta & -m_Z c_W s_\beta & -\mu + 2\epsilon_1 \frac{v^2}{\mu} s_{2\beta} & 2\epsilon_1 \frac{v^2}{\mu} c_\beta^2 \end{pmatrix}$$

- Higgs-to-LSP coupling:

$$h\chi\chi = g(\mathcal{N}_{\chi 2} - t_W \mathcal{N}_{\chi 1})(\mathcal{N}_{\chi 3} \sin \alpha + \mathcal{N}_{\chi 4} \cos \alpha)$$

$$-2\sqrt{2}\frac{\epsilon_1 v}{\mu} [2 \cos(\alpha + \beta) \mathcal{N}_{\chi 3} \mathcal{N}_{\chi 4} + \cos \alpha \sin \beta \mathcal{N}_{\chi 3}^2 - \sin \alpha \cos \beta \mathcal{N}_{\chi 4}^2]$$

BMSSM Higgsino sector:

- Chargino mass matrix:

$$M_{\tilde{C}} = \begin{pmatrix} M_2 & \sqrt{2}m_W s_\beta \\ \sqrt{2}m_W c_\beta & \mu \end{pmatrix} - \frac{2\epsilon_1 m_W^2 s_{2\beta}}{\mu^* g^2} \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$$

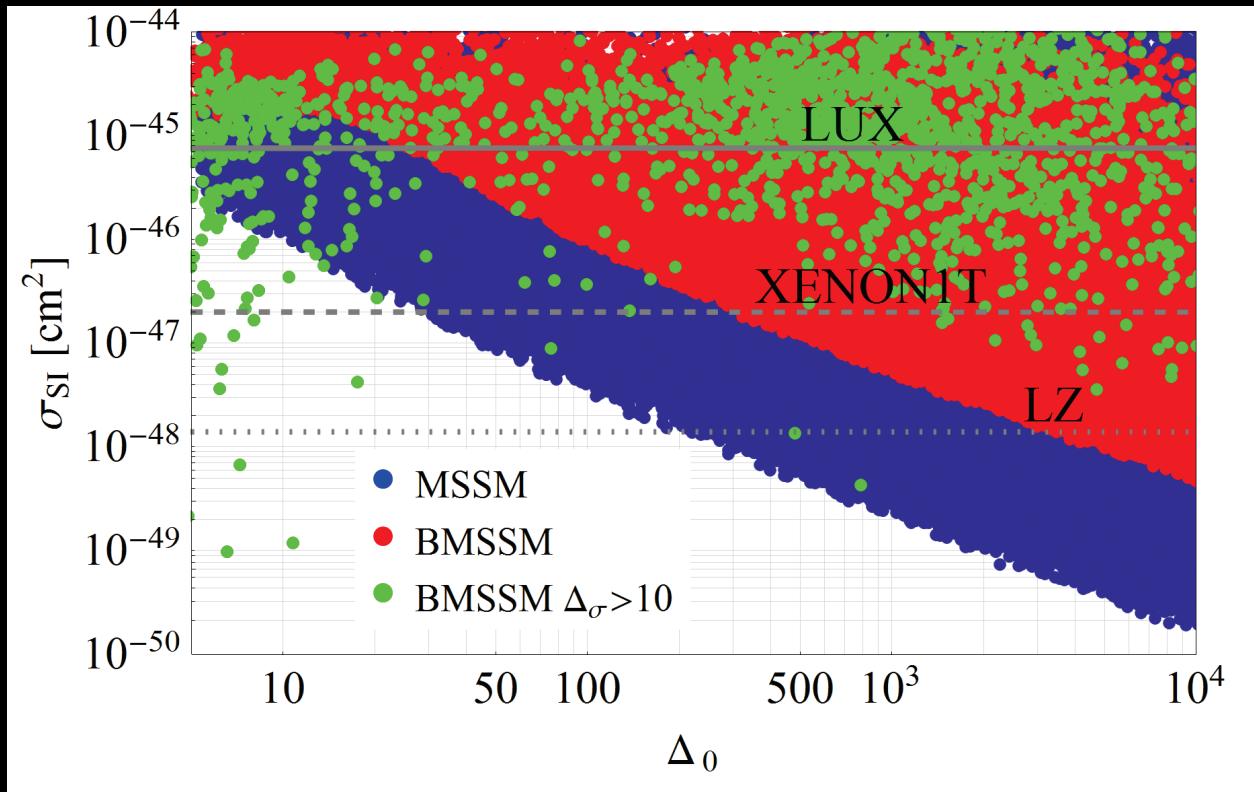
- Neutral-charged Higgsino mass splitting:

$$m_{\tilde{C}} - m_\chi = \left(-\frac{\epsilon_1 v^2}{\mu} + \frac{m_W^2}{2M_2} \right) (1 - s_{2\beta})$$

Gaugino Dark Matter

Gaugino DM

- tension between direct searches and light μ :



at fixed σ_p^{SI} , barring accidental cancellations,
BMSSM is significantly more fine-tuned than MSSM

Gaugino DM

- origin is the low- $\tan \beta$ required in BMSSM:

Example:
 $\chi \simeq \widetilde{B}_Y$

$$g_{h\chi\chi}^{\tilde{B}} \simeq \frac{2g'm_Z s_W}{\mu} \left(\frac{1}{t_\beta} + \frac{M_1}{2\mu} - \frac{\epsilon_1 v^2}{\mu^2} \right)$$

MSSM: $\tan \beta < 50$
BMSSM: $\tan \beta < 8 - 10$



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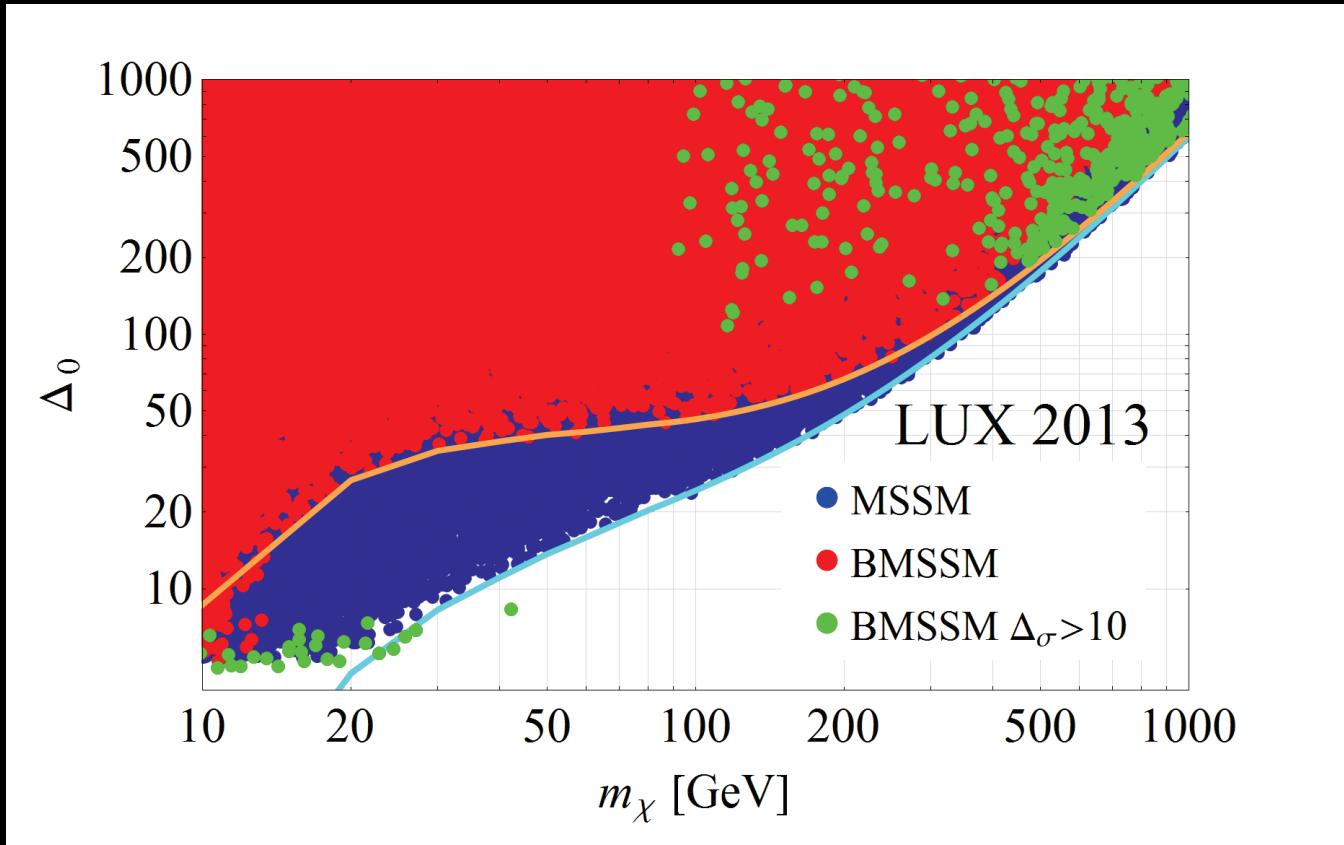
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- $\tan \beta$ difference irrelevant at large LSP mass

Gaugino DM

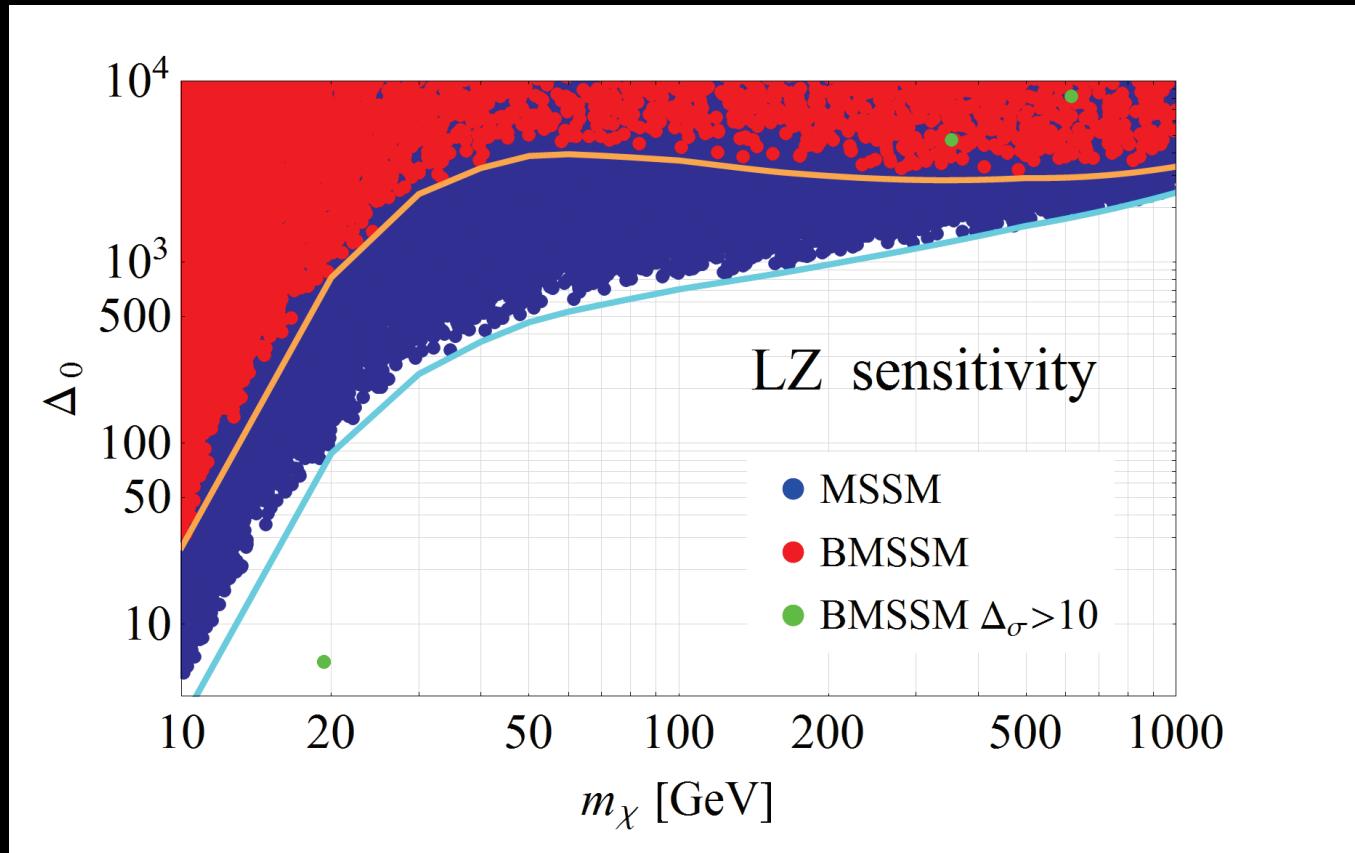
- Implication of current LUX limit



- BMSSM FT $\sim 4x$ larger for LSP $\sim 30\text{-}50\text{GeV}$

Gaugino DM

- Future LZ (LUX+ZEPLIN) projection:

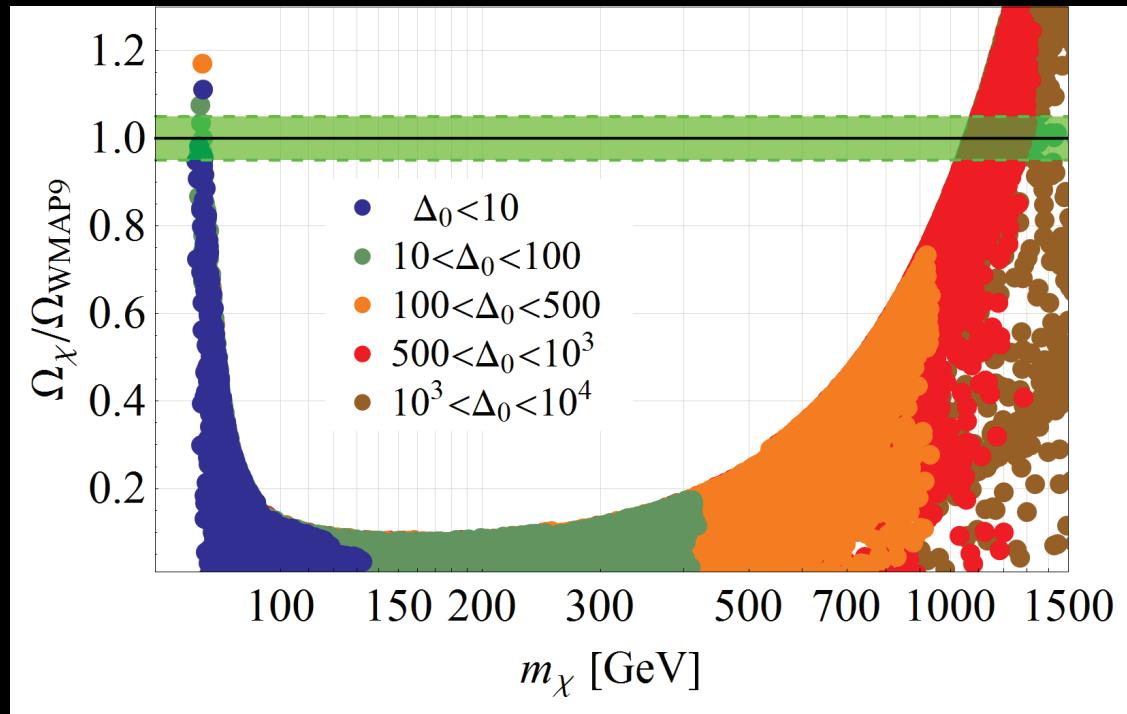


- BMSSM FT ~10x larger for LSP~50GeV

Higgsino Dark Matter

Higgsino DM

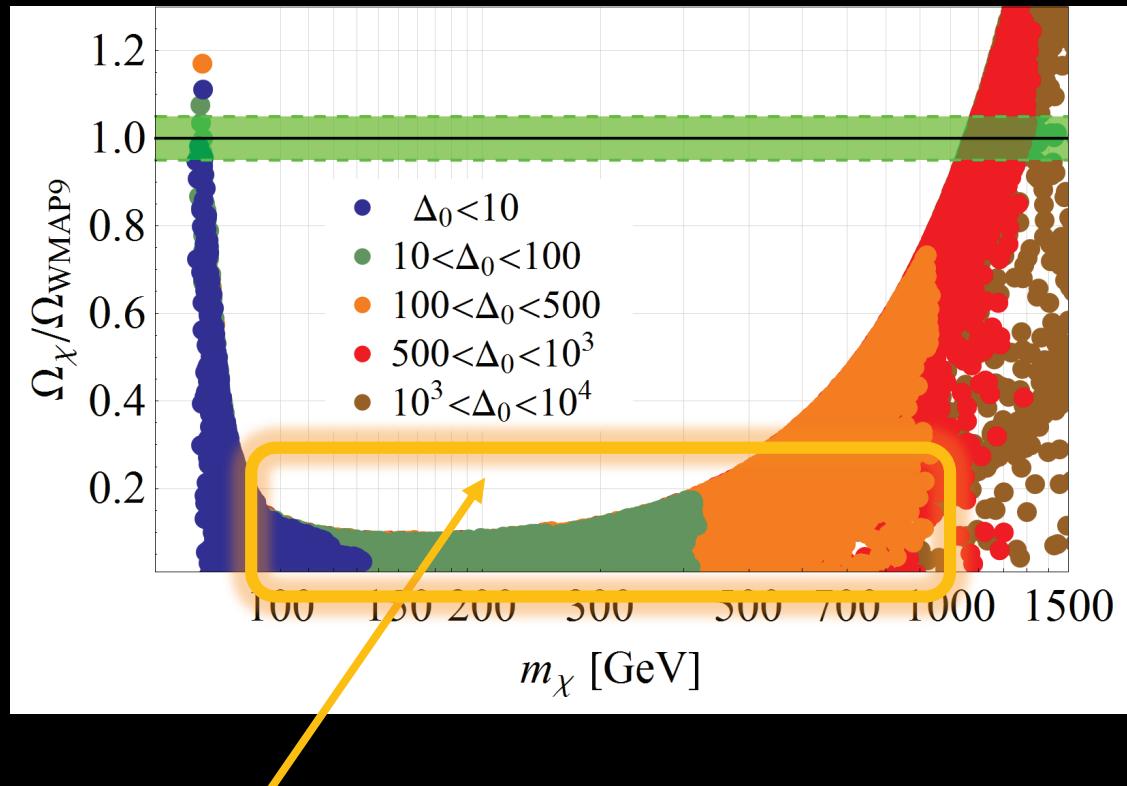
- BMSSM relic density prediction*:



*thanks to micrOmegas

Higgsino DM

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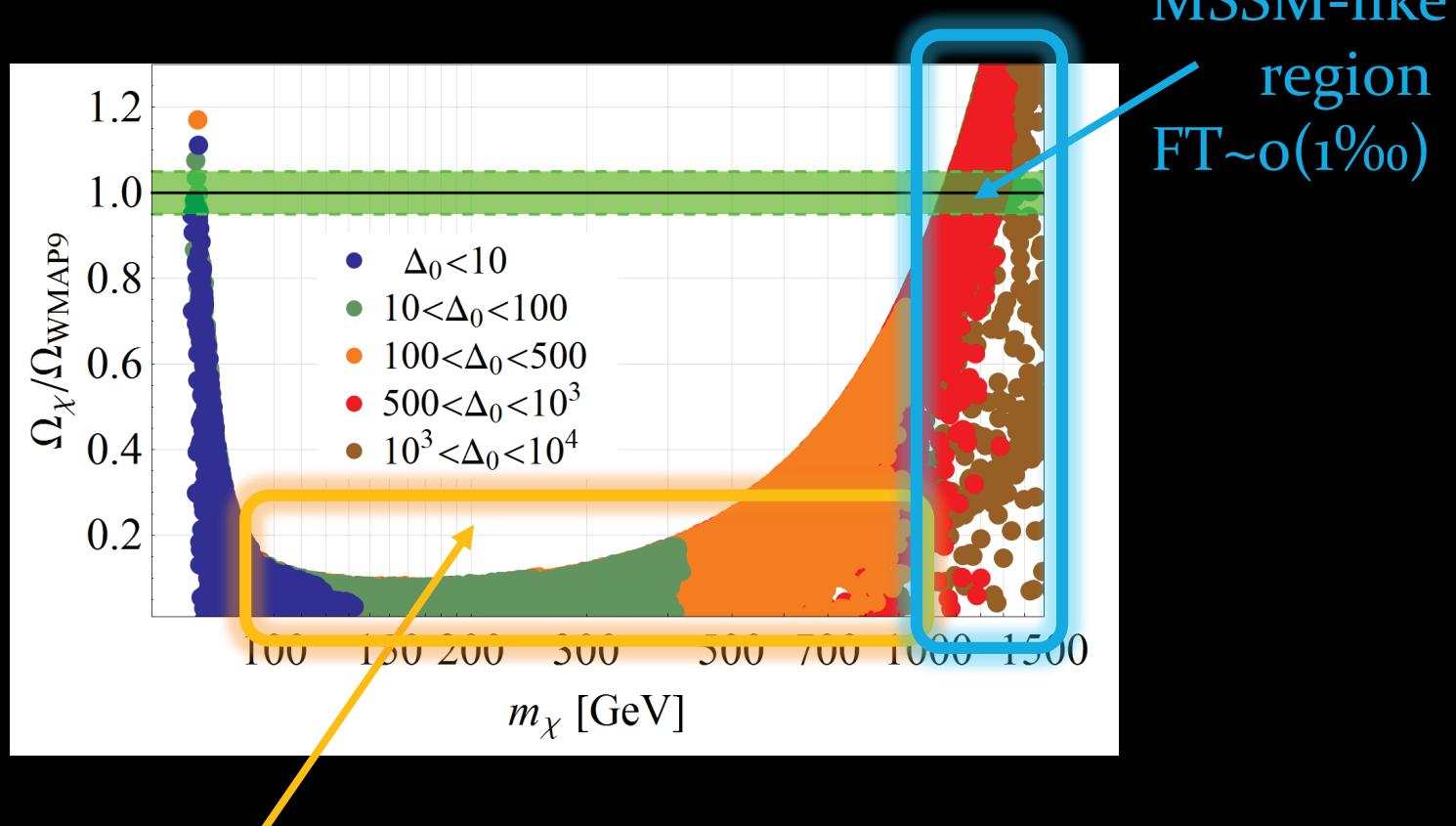


$\tilde{H}\tilde{H} \rightarrow VV + \text{coannihilation}$
overly efficient (as in MSSM)

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Higgsino DM

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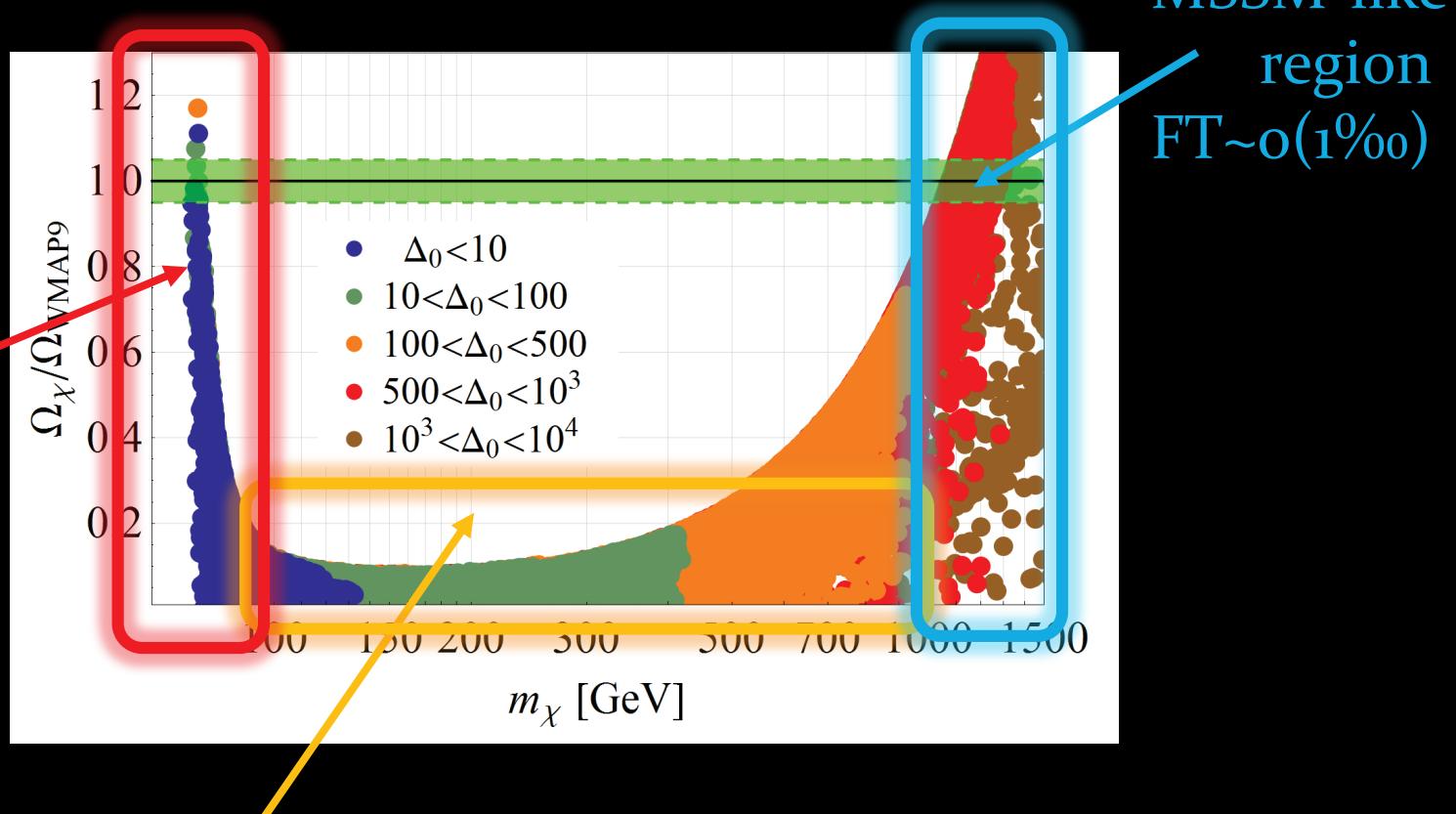
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Higgsino DM

- BMSSM relic density prediction*:

BMSSM
region,
below VV
threshold
FT 5-10%



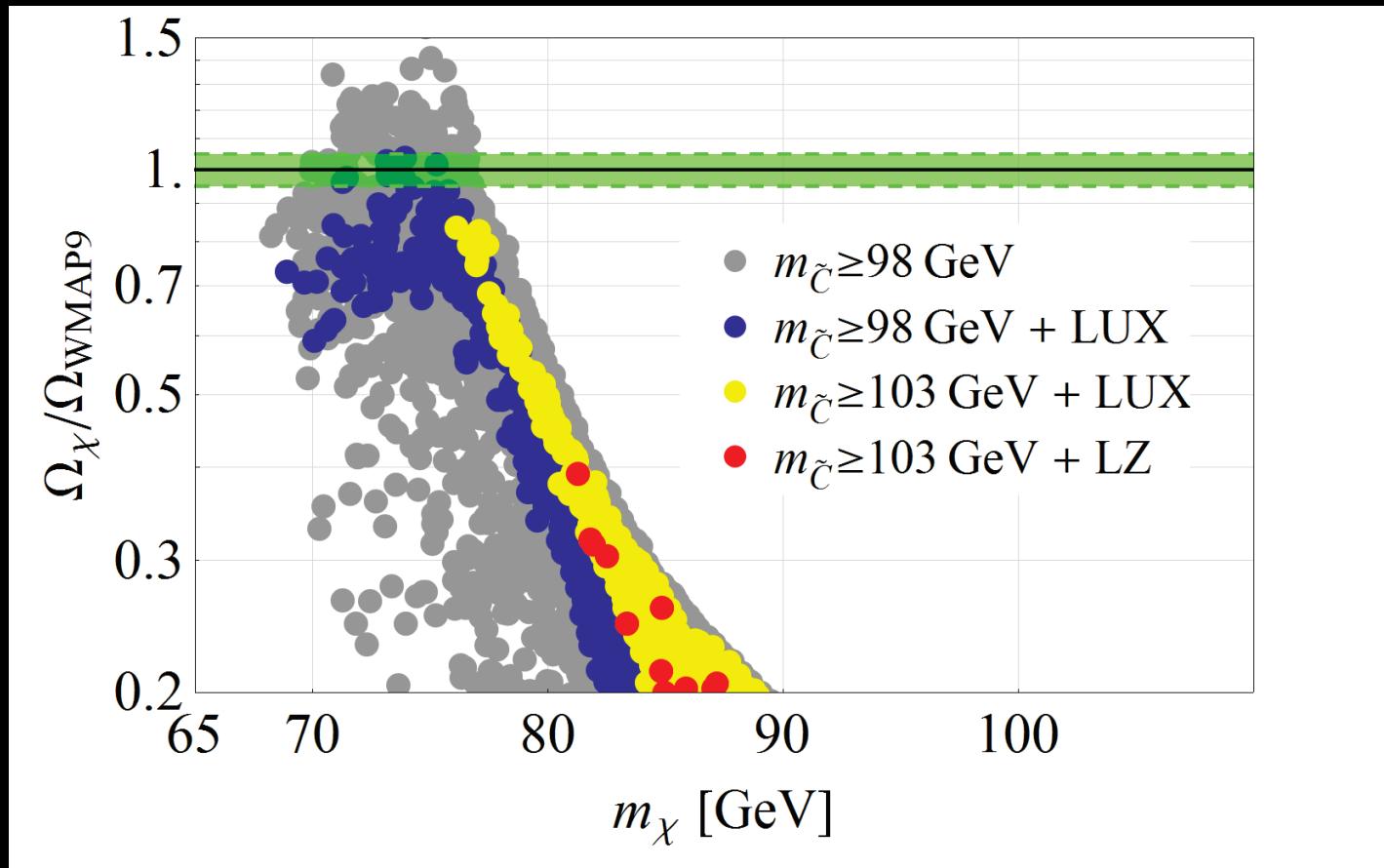
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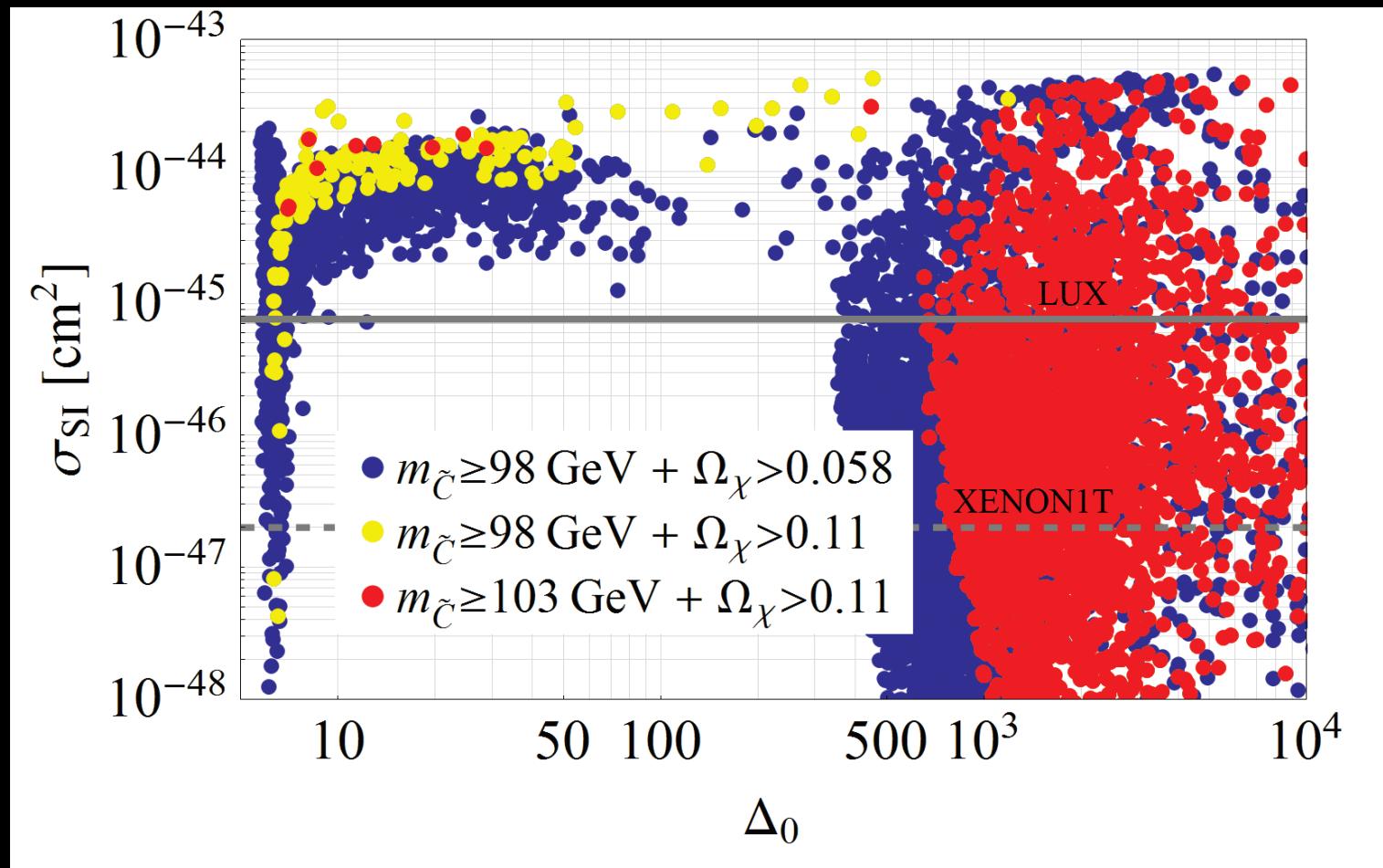
Natural island for Higgsino DM

- This naturalness island is fragile:
 - Chargino bound from LEP $m_{\tilde{C}} \gtrsim 103\text{GeV}$
→ pushes LSP above VV threshold, depleting $\Omega_{\tilde{H}}$
 - Direct detection bounds
→ decouple gauginos, reducing LSP/chargino splitting

Constraints on Higgsino DM



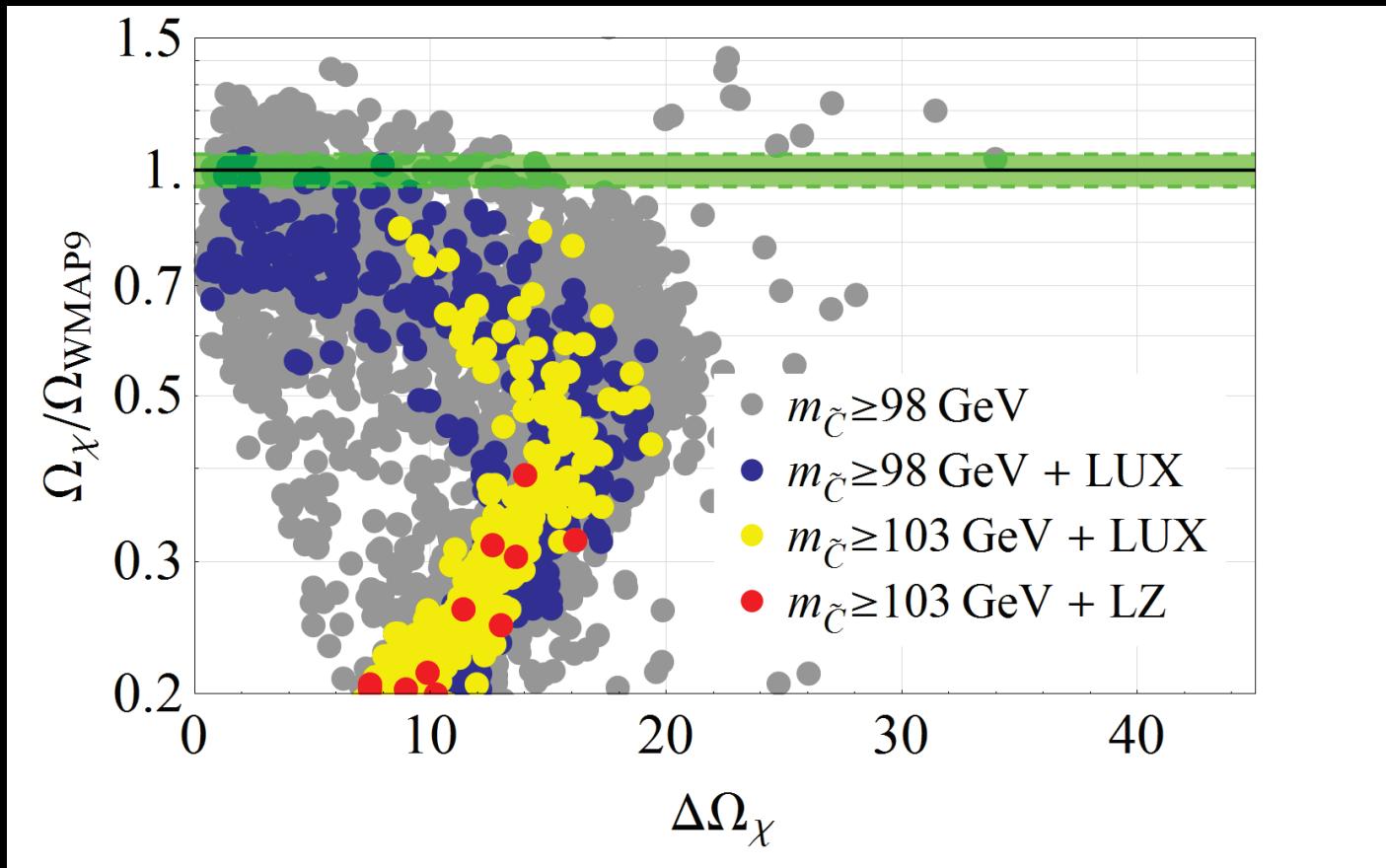
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 - Direct detection bounds
→ decouple gauginos, reducing LSP/chargino splitting
 - 10% sensitivity of relic to model parameters (μ, \dots)

Log-sensitivity of $\Omega_{\tilde{H}}$ for Higgsino DM



Concluding remarks

Take home:

- SUSY solves hierarchy problem, yet $m_h \approx 125\text{GeV}$ implies a severe fine-tuning in the MSSM, from 1% to 0.1%
- If DM=neutralino LSP, direct DM searches implies a similar fine-tuning level in the MSSM, through μ .
- both issues call for MSSM extensions

Take home:

- If the little hierarchy problem is solved by higher-dim operators (BMSSM), it implies:
 - Gaugino DM is parametrically more fine-tuned
 - Higgsino DM shows comparable fine-tuning, with the noteworthy exception of the marginally allowed natural island below the VV threshold. Improvement on chargino or direct DM searches would easily wipe it out.
- light MSSM extensions seem more favored.