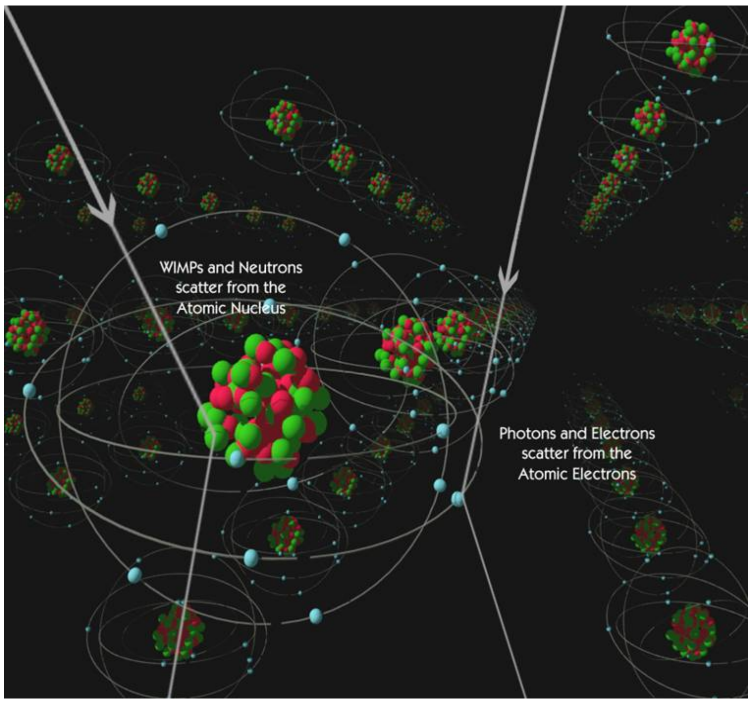
Direct Detection Implications for Supersymmetry Naturalness



Bibhushan Shakya

Cornell University

IDM 2012

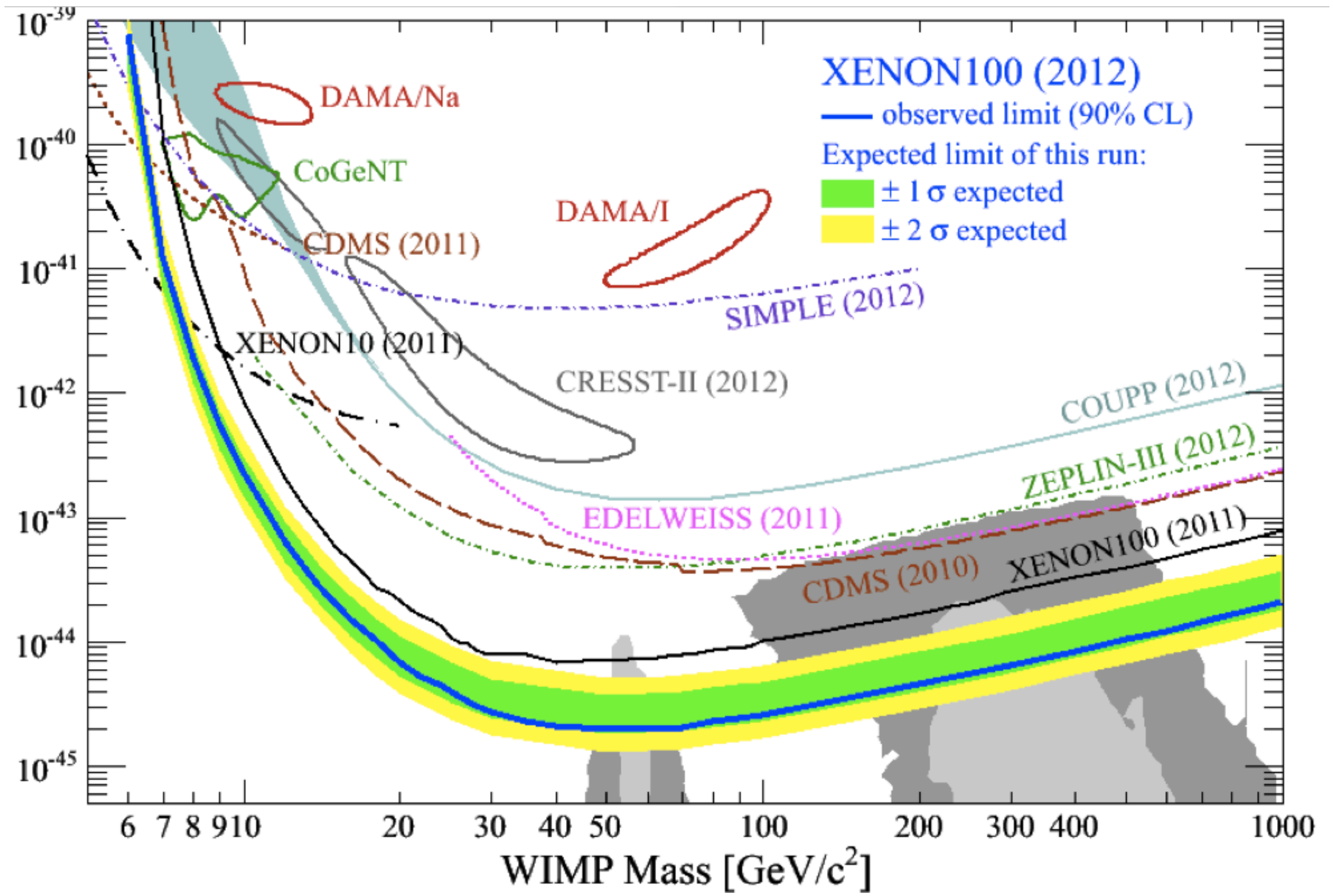
July 27, 2012

Based on
hep-ph : next.week?, 1107.5048
with Maxim Perelstein

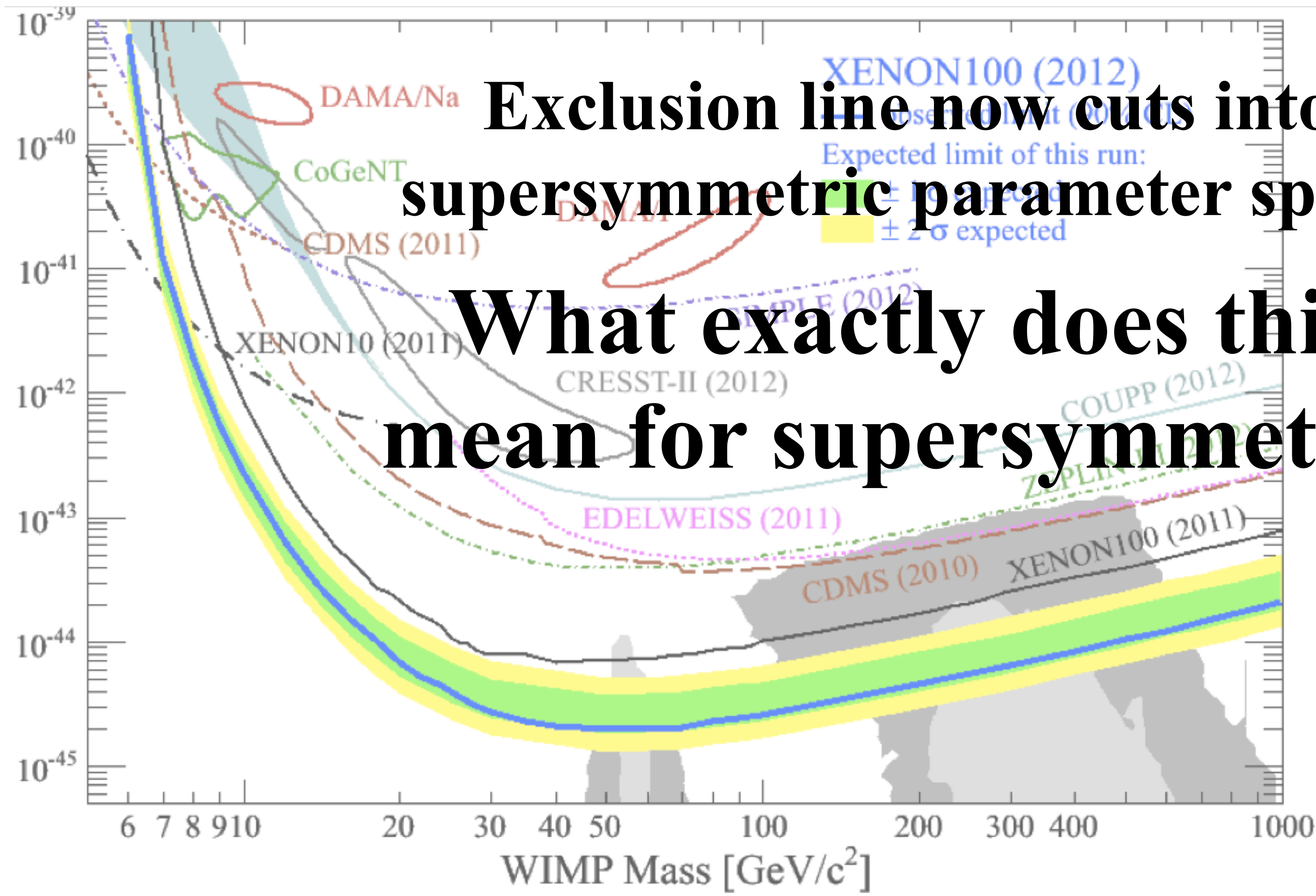
IDENTIFICATION OF DARK MATTER

IDM 2012 CHICAGO

Direct Detection vs Neutralino Dark Matter



Direct Detection vs Neutralino Dark Matter



Exclusion line now cuts into supersymmetric parameter space.

What exactly does this mean for supersymmetry?

Guiding Idea:

NATURALNESS

Natural SUSY: The LHC perspective

- No superpartners observed so far

SM-like Higgs at 125 GeV

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SM-like Higgs at 125 GeV

MSSM

- Tree level higgs mass lies below M_Z

$$m_h^2 = M_Z^2 \cos^2 2\beta + \delta_t^2$$

- need large corrections from stop loops to lift it to 125 GeV, *extremely* fine-tuned

Natural SUSY: The LHC perspective

- No superpartners observed so far

SM-like Higgs at 125 GeV

NMSSM

- Extend MSSM by a gauge singlet superfield S. Superpotential contains:

$$\lambda \hat{S} \hat{H}_u \cdot \hat{H}_d + \frac{\kappa}{3} \hat{S}^3$$

- Gives additional contribution to tree level higgs mass

$$m_h^2 \; = \; M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \delta_t^2$$

- Can get close to 125 GeV with large λ (~0.6), small tanβ (~2), only a small loop correction needed. VERY natural.

Natural SUSY: The LHC perspective

- No superpartners observed so far

SM-like Higgs at 125 GeV

λ-SUSY

- In NMSSM, $\lambda < 0.75$ to avoid Landau pole below GUT scale
- Can have $0.75 < \lambda < 2$ and accept Landau pole below GUT scale but above 10 TeV (inconsistent with precision electroweak below this)

$$m_h^2 = M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \delta_t^2$$

- Easy to get 125 GeV higgs at tree level
- Further suppresses fine-tuning (more later): stops >TeV very natural.

(Hall, Pinner, Ruderman; hep-ph 1112.2703)

Natural SUSY: The LHC perspective

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SM-like Higgs at 125 GeV

SUSY variations of interest after these LHC results:

- **MSSM**
- **NMSSM**
- **λ-SUSY**

Guiding Idea:

NATURALNESS

Can dark matter direct detection results
tell us anything about naturalness in
supersymmetry?

Quantifying (EWSB) Fine-tuning

- Tree level relation for m_Z :

$$m_Z^2 = -m_u^2 \left(1 - \frac{1}{\cos 2\beta}\right) - m_d^2 \left(1 + \frac{1}{\cos 2\beta}\right) - 2|\mu|^2$$

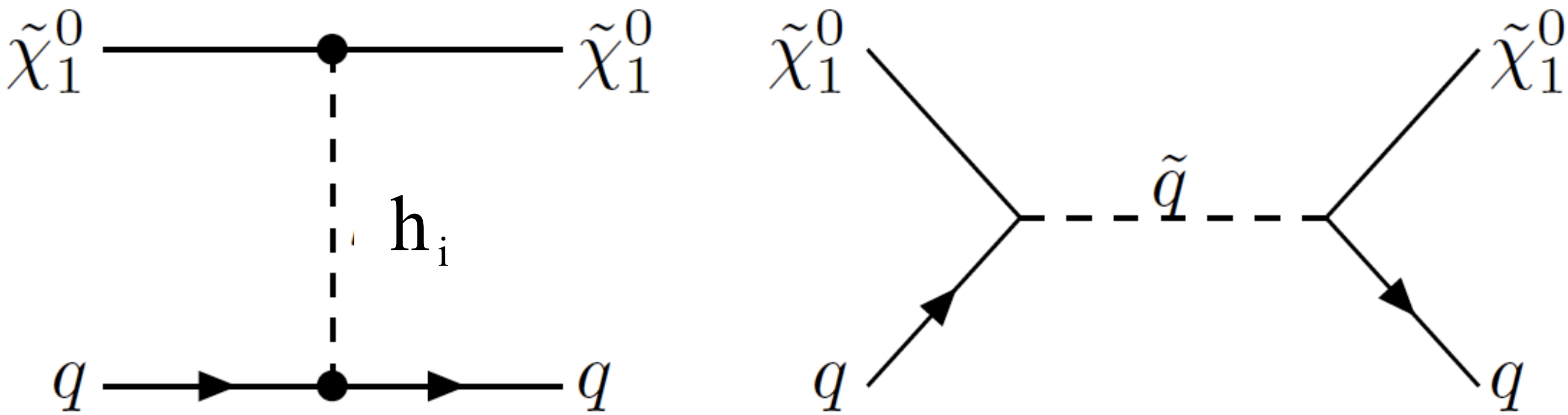
- If terms on r.h.s. are not ~100 GeV, need cancellations to make things work. Fine-tuning !

- Calculate sensitivity to small changes in Lagrangian parameters:

$$\delta(\xi) = \left|\frac{\partial \log m_Z^2}{\partial \log \xi}\right|$$

- **In general, larger μ gives greater fine-tuning.**

Spin independent scattering



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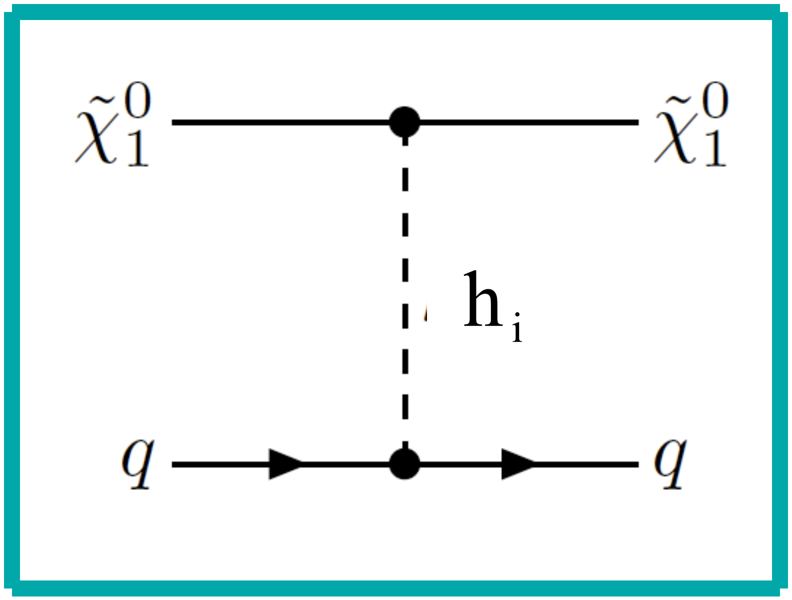
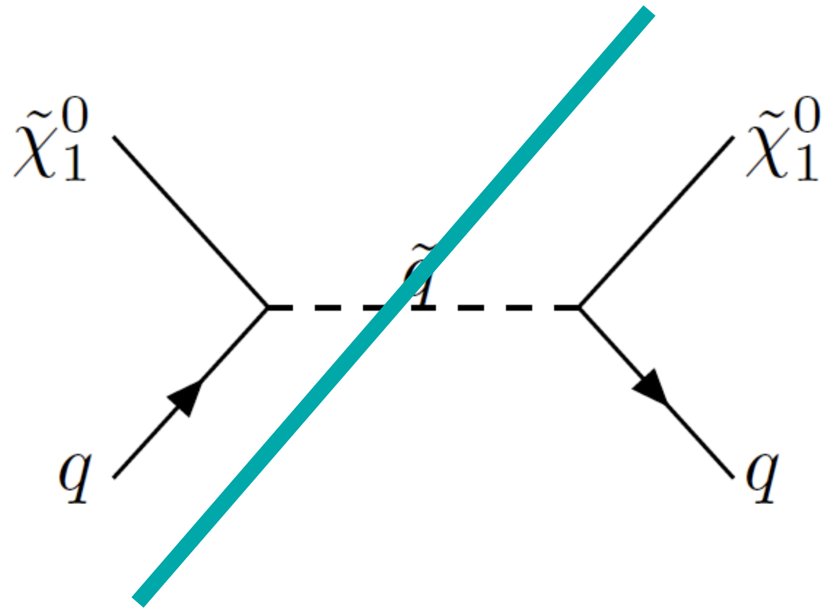


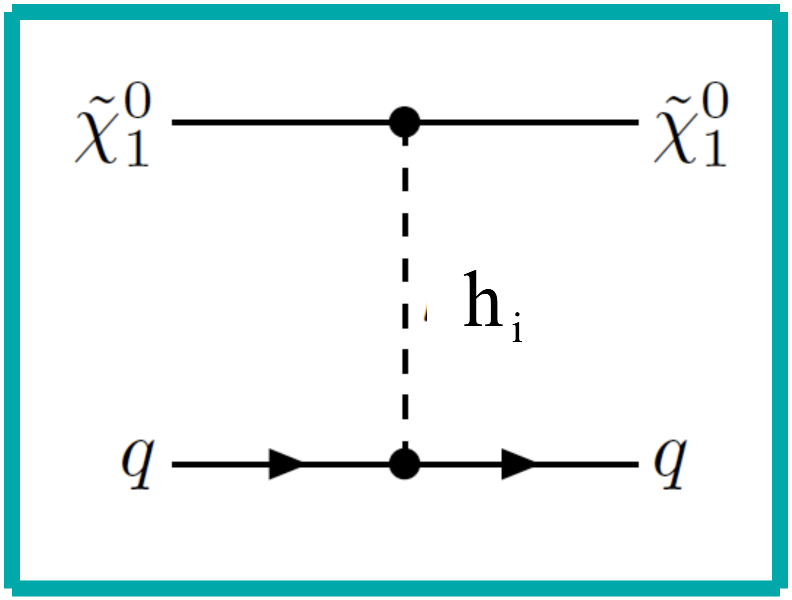


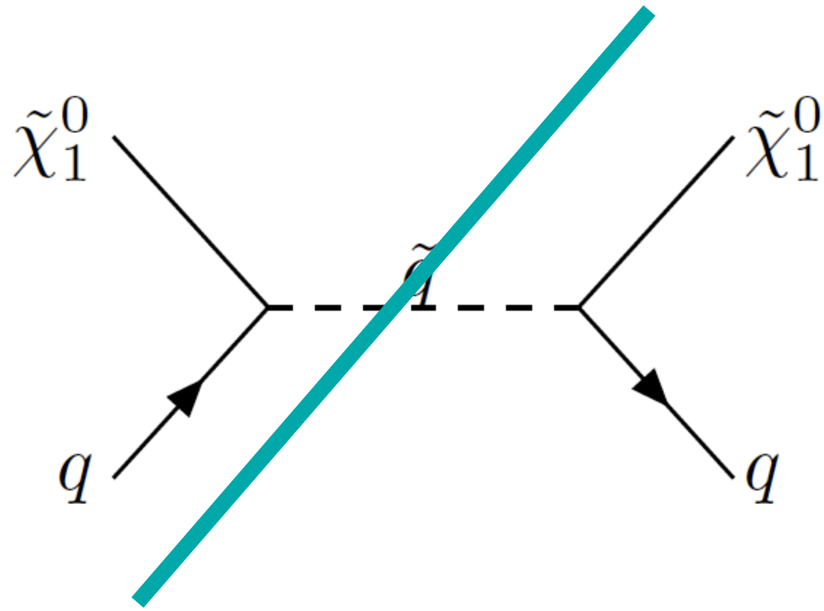
Ignore this contribution

(usually subdominant, only need an approximate lower bound for the cross section)

Direct detection cross section depends only on gaugino masses and parameters in the Higgs sector

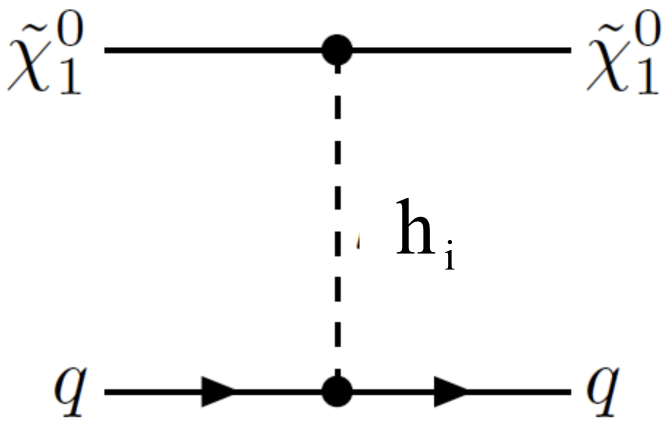
Spin independent scattering





Scan parameters:
MSSM: μ, m_A, M_1, M_2, $\tan\beta$
NMSSM, λ-SUSY: μ, M_1, M_2, $\tan\beta$, κ, λ, A_λ, A_κ

Spin independent scattering



"Typical" scattering cross section

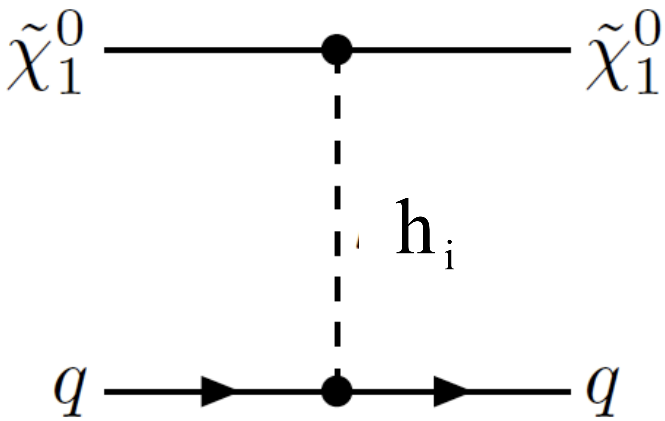
(MSSM, NMSSM, **λ**-SUSY):

$\sim 10^{-43}$ cm^2

Current XENON100 upper bound:

$\sim 10^{-45}$ -10^{-44} cm^2

Spin independent scattering



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Fine-tuning ???

The Approach

- **Define Lagrangian parameters independently at EW scale** (ie assume no relations such as unification), scan over parameters (allowed to be negative)

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- **Ignore relic density** (some exceptions)

The Approach

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- **Ignore accidental cancellations**: want to make general statements true in most of parameter space

- **Ignore relic density** (some exceptions)

- Other Requirements:

  neutralino LSP; charginos heavier than 103 GeV; light neutralinos satisfy experimental constraint on Z invisible width;

  Higgs sector:

  MSSM: set mass of lighter higgs to 125 GeV;

  NMSSM / λ-SUSY: require a non-singlet Higgs with tree-level mass 100-150 GeV, physical Higgs masses nontachyonic

  (no additional collider constraints imposed)

MSSM

$$\tilde{\chi}_1^0 = Z_{\chi 1}\tilde{B} + Z_{\chi 2}\tilde{W}^3 + Z_{\chi 3}\tilde{H}_d^0 + Z_{\chi 4}\tilde{H}_u^0$$

$$\begin{aligned} \tilde{\chi}^0\tilde{\chi}^0 h: &\quad (gZ_{\chi 2} - g' Z_{\chi 1})(\cos\alpha Z_{\chi 4} + \sin\alpha Z_{\chi 3}) \\ \tilde{\chi}^0\tilde{\chi}^0 H: &\quad (gZ_{\chi 2} - g' Z_{\chi 1})(\sin\alpha Z_{\chi 4} - \cos\alpha Z_{\chi 3}) \end{aligned}$$

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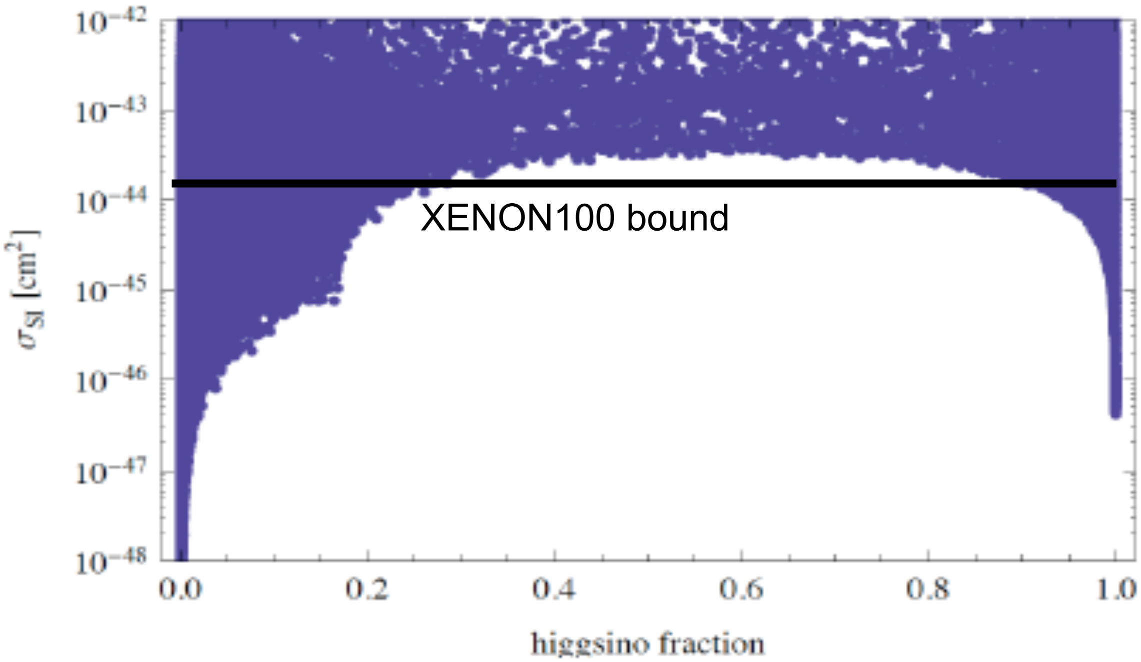

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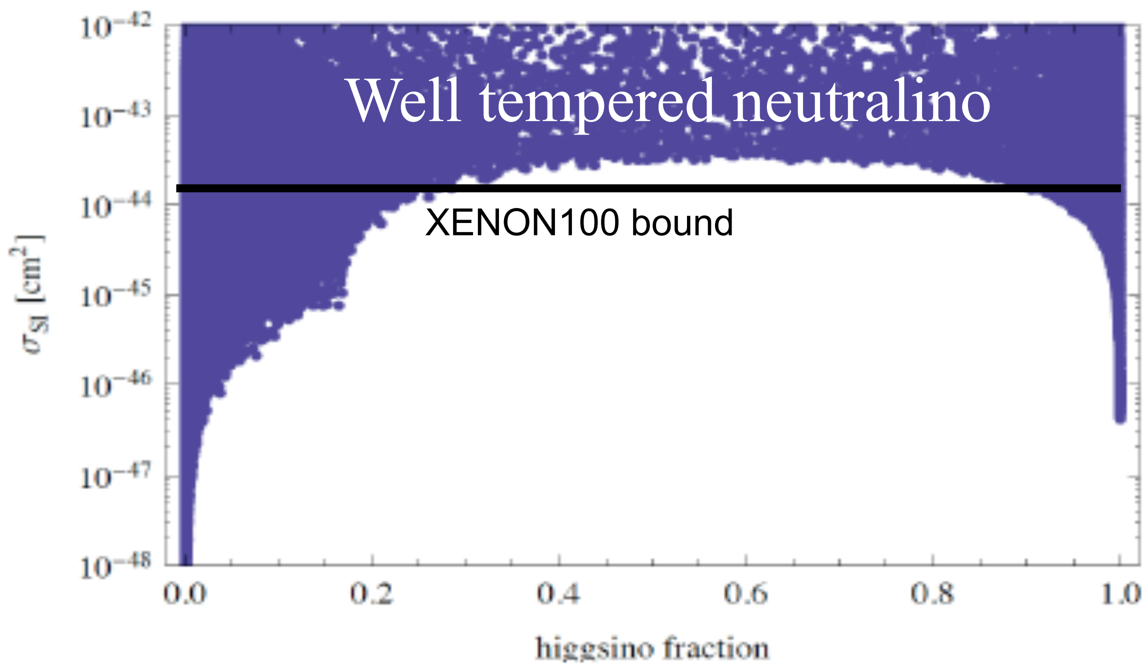

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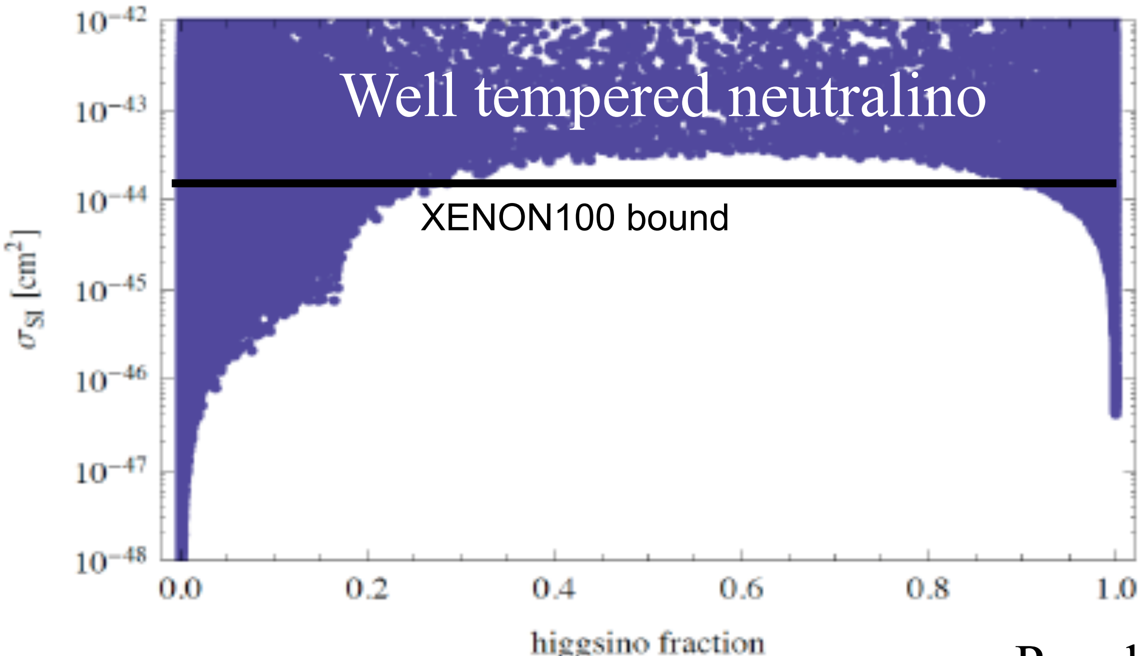

Pure higgsino:
Need mass ~ TeV to give the right relic density
➔ μ~TeV ➔ < 1% tuned!

MSSM

$$\tilde{\chi}_1^0 = Z_{\chi 1}\tilde{B} + Z_{\chi 2}\tilde{W}^3 + Z_{\chi 3}\tilde{H}_d^0 + Z_{\chi 4}\tilde{H}_u^0$$

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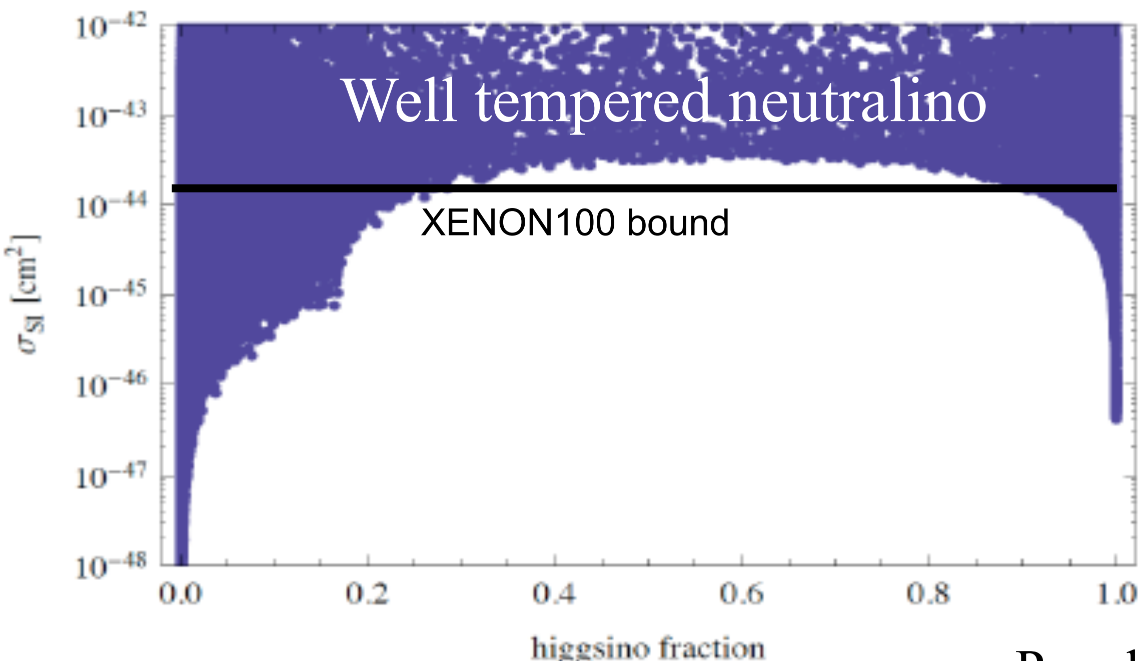
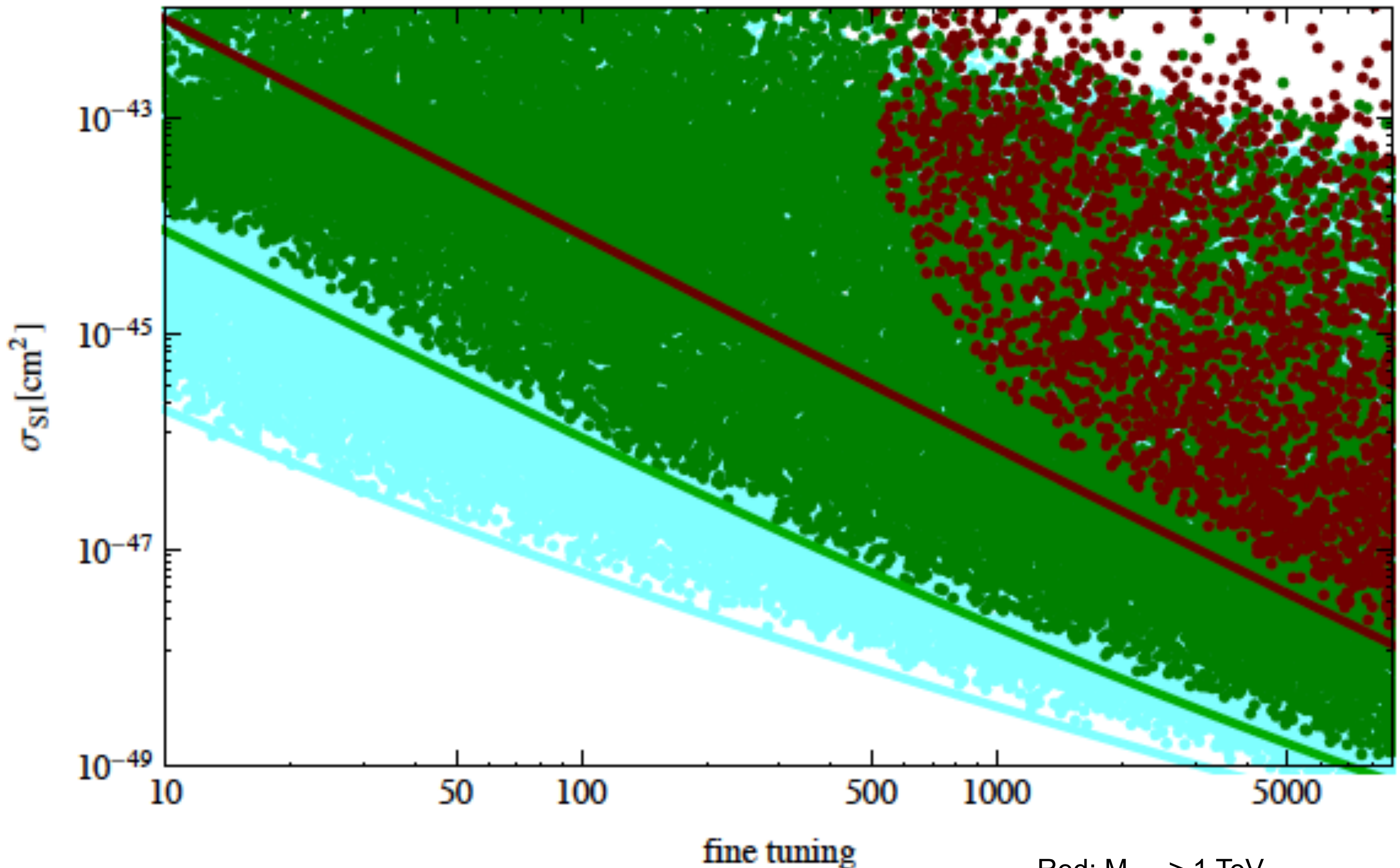


Pure gaugino:
requires μ to be raised relative to M_1 or M_2.
fine tuned!

Pure higgsino:
Need mass ~ TeV to give the right relic density
➔ μ~TeV ➔ < 1% tuned!

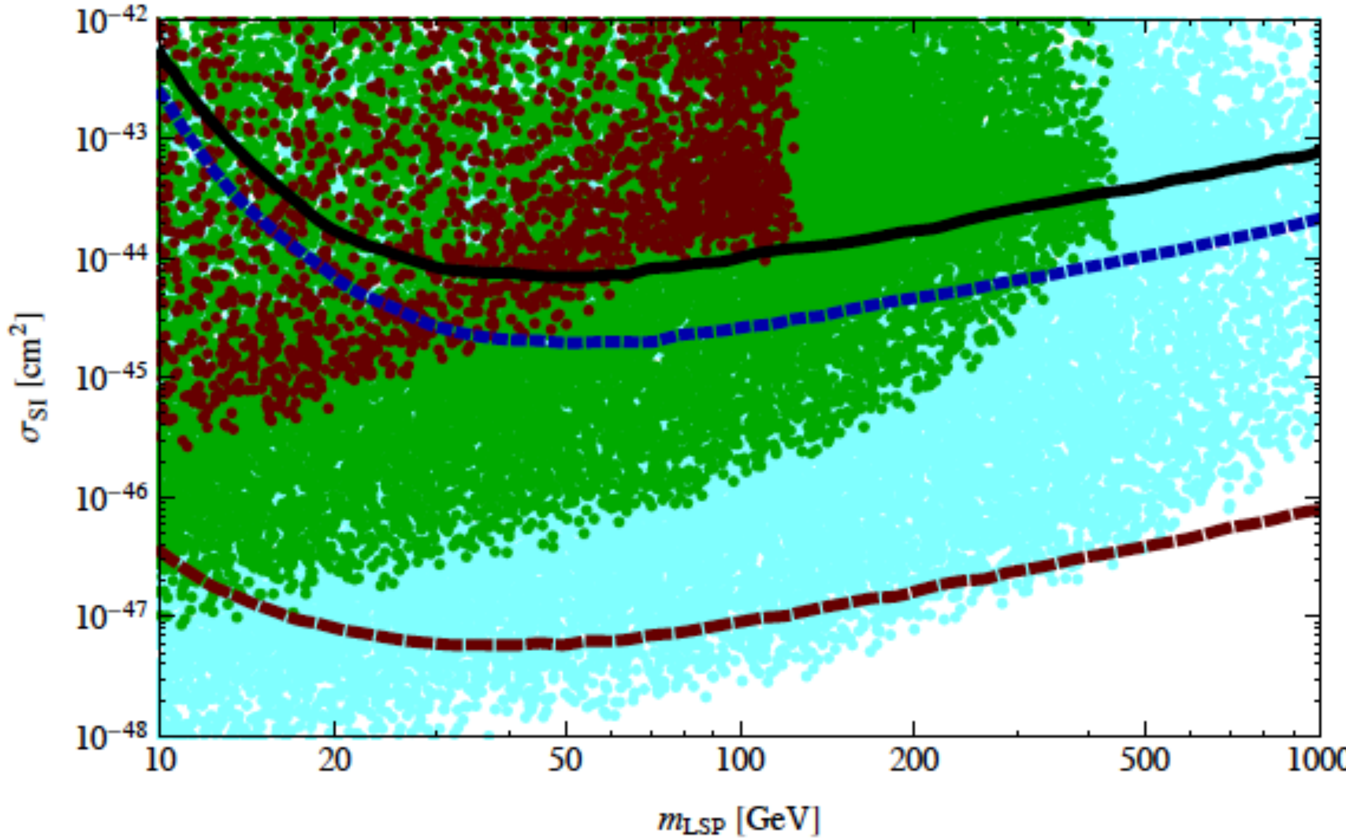
MSSM



Lines: analytic bounds (see 1107.5048)

Red: $M_{LSP} > 1$ TeV
Green: $M_{LSP} > 100$ GeV
Cyan: $M_{LSP} > 10$ GeV

MSSM



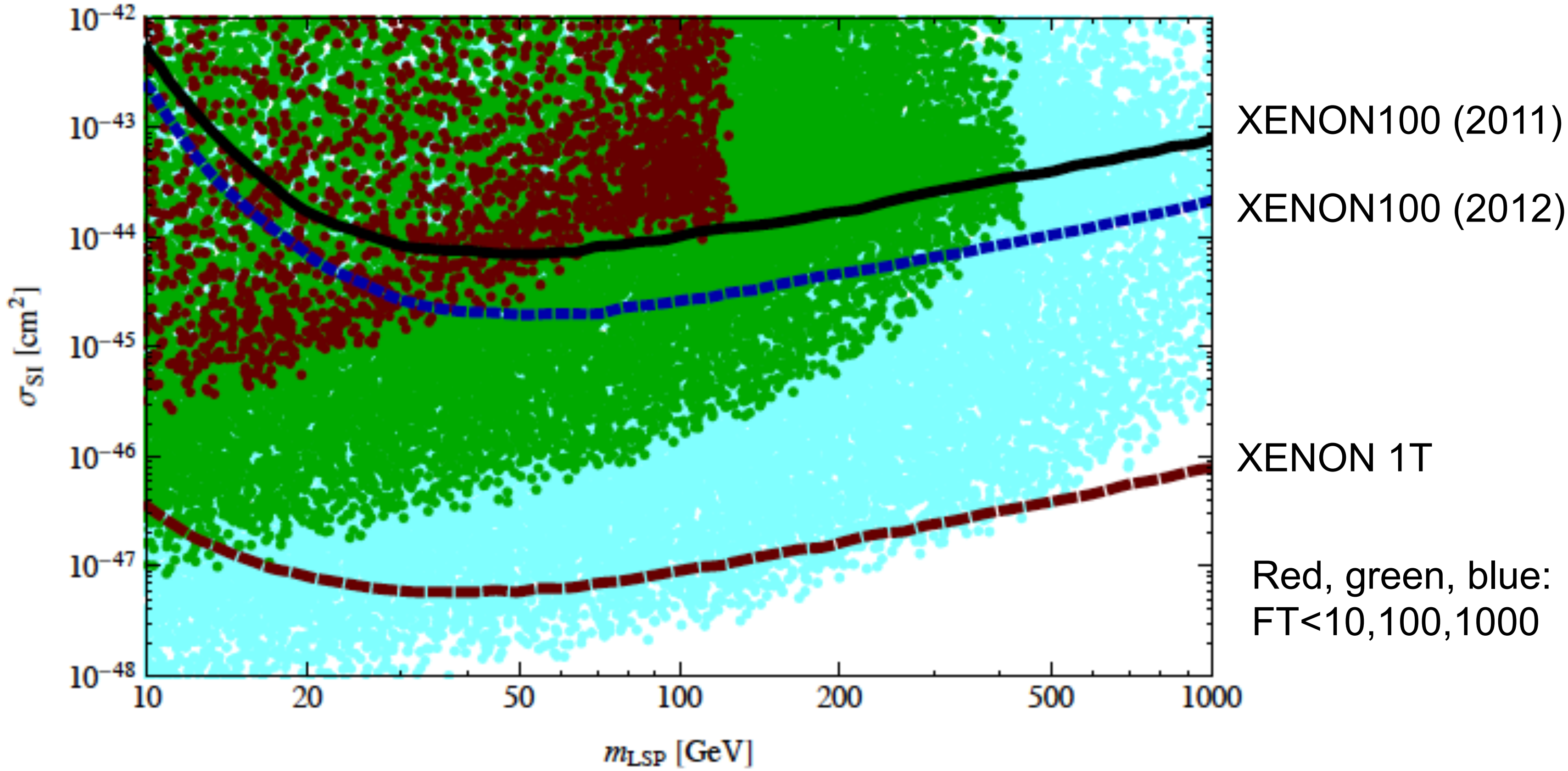
XENON100 (2011)

XENON100 (2012)

XENON 1T

Red, green, blue:
FT<10,100,1000

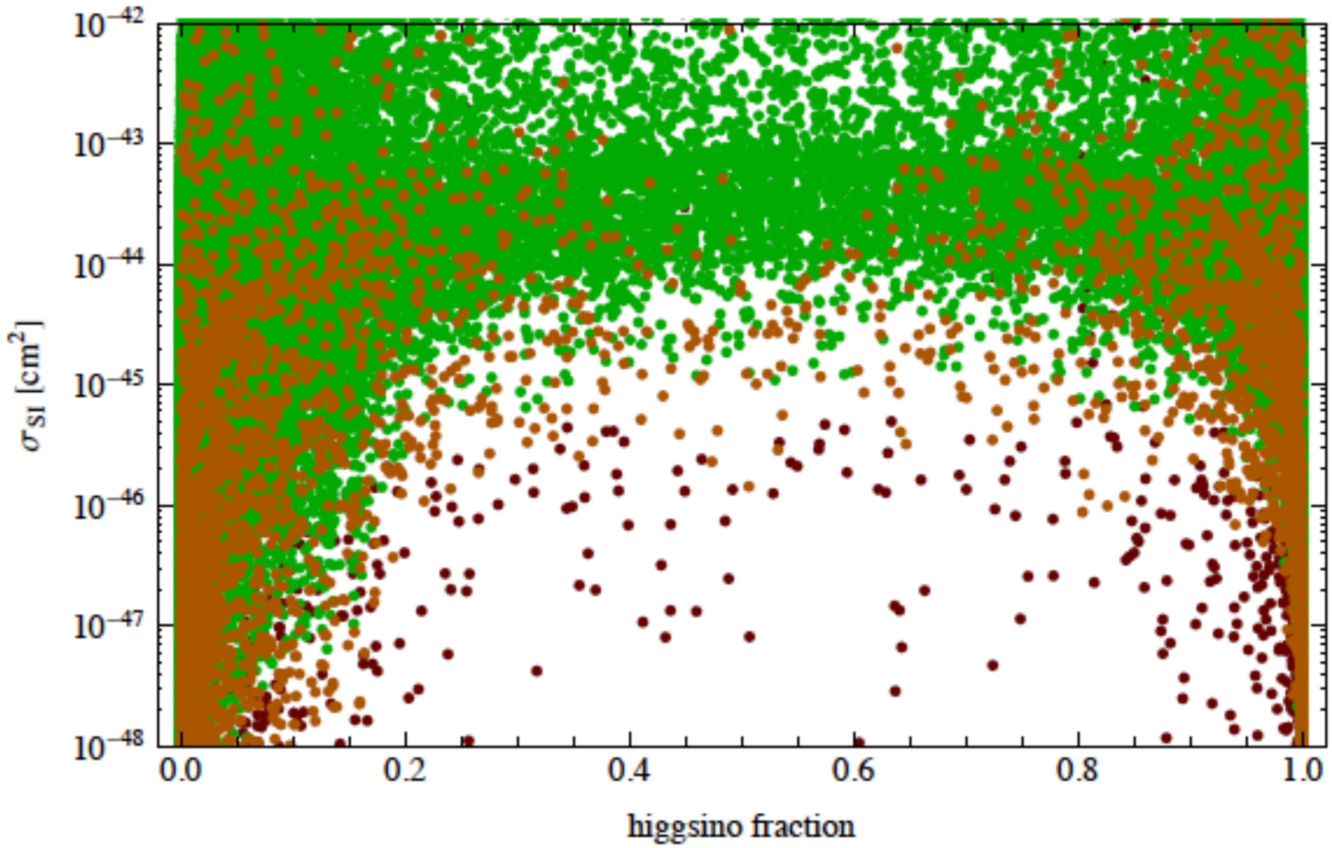
MSSM



M_{LSP} > 50 (400) GeV is worse than 10% (1%) fine-tuned.
XENON1T can probe entire MSSM parameter space down to 1% tuning

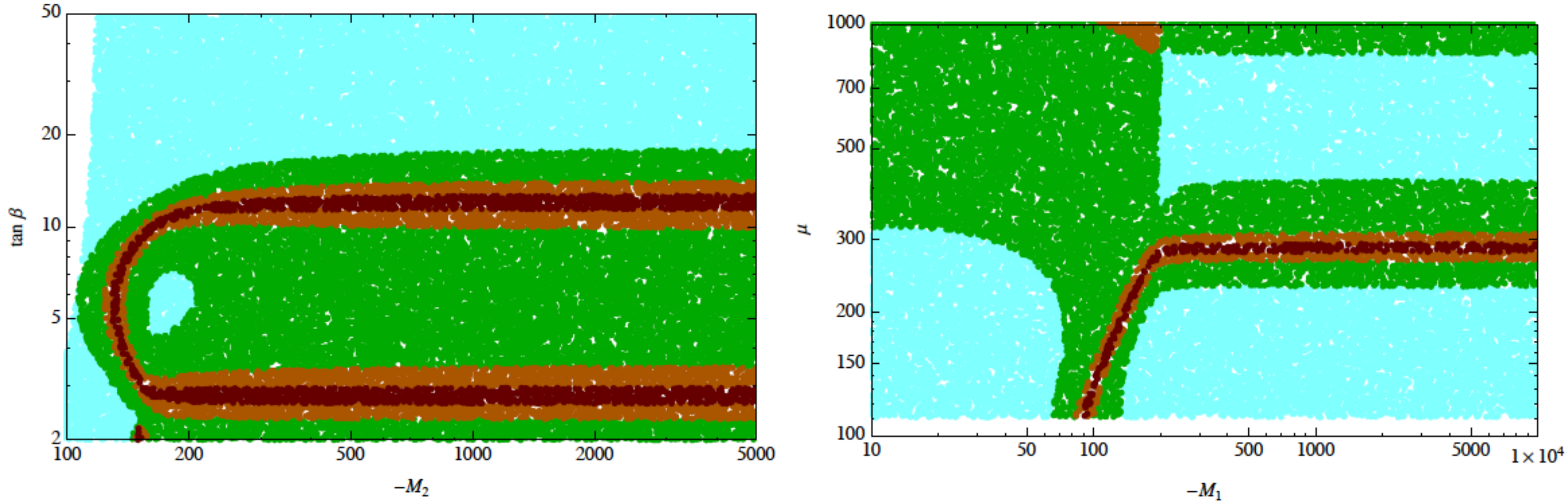
MSSM with negative/complex parameters

Can get cancellations, destroys aforementioned correlations



MSSM with negative/complex parameters

However, such cancellations are themselves ‘fine-tuned’.

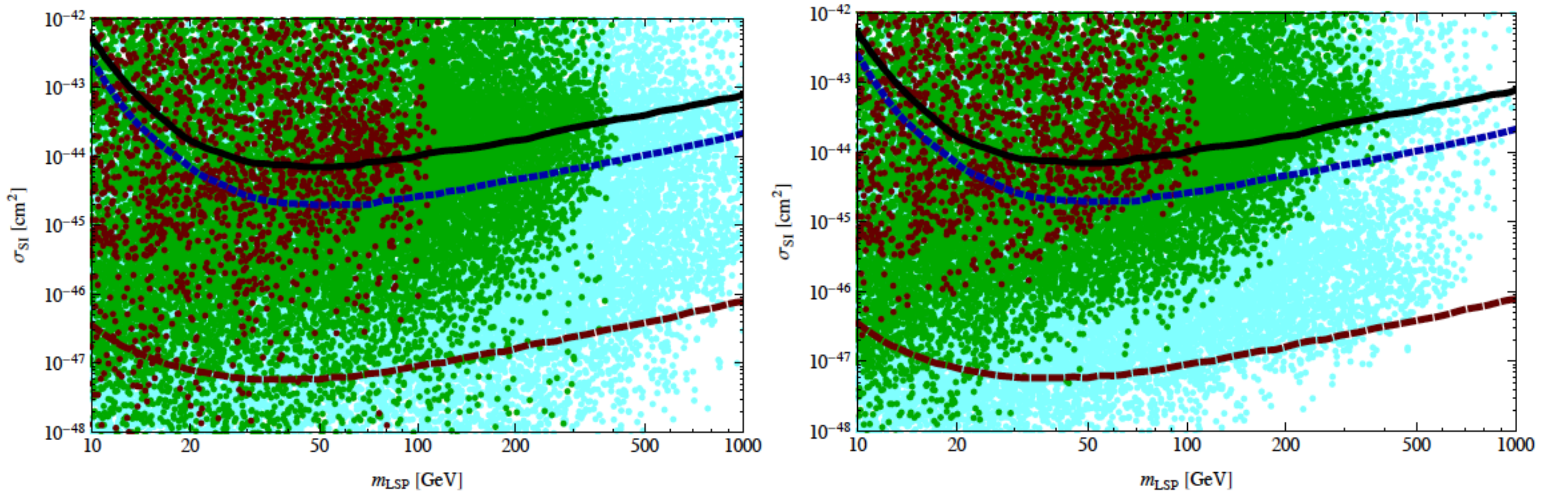


Red, orange, green, cyan: cross section < 10^-(47,46,45), above

Quantify these cancellations in the same way as EWSB fine-tuning

$$\mathrm{Acc} \equiv Max \left| \frac{\partial \log \sigma_{SI}}{\partial \log \xi_i} \right|$$

MSSM with negative/complex parameters



With (left) and without (right) points with accidental cancellations in the cross section. Correlation restored!

Dark Matter in NMSSM

New singlet superfield S.

$$\lambda \hat{S} \hat{H}_u \cdot \hat{H}_d + \frac{\kappa}{3} \hat{S}^3$$

Fermionic component of S gives an additional neutralino: singlino.
Mixes with the four MSSM neutralinos.

$$\begin{pmatrix} M_1 & 0 & -\frac{g_1 v_d}{\sqrt{2}} & \frac{g_1 v_u}{\sqrt{2}} & 0 \\ & M_2 & \frac{g_2 v_d}{\sqrt{2}} & -\frac{g_2 v_u}{\sqrt{2}} & 0 \\ & & 0 & -\mu_{\text{eff}} & -\lambda v_u \\ & & & 0 & -\lambda v_d \\ & & & & 2\kappa s \end{pmatrix}$$

$$= 2\kappa\mu_{\text{eff}}/\lambda$$

CP even singlet higgs: mixes with higgs doublet.

Dark Matter in NMSSM

$H_{physical} = s_j\, H_j$, $\quad H_j = \{H_u, H_d, S\}$

$\chi_{physical} = n_j\, \chi_j$, $\quad \chi_j = \{B, W_3, H_u^0, H_d^0, S\}$

$$
\begin{aligned}
h_i\chi\chi = & \frac{\lambda}{\sqrt{2}}(s_{H_d} n_{\tilde{H}_u} n_{\tilde{S}} + s_{H_u} n_{\tilde{H}_d} n_{\tilde{S}} + s_S n_{\tilde{H}_u} n_{\tilde{H}_d}) \\
& - \frac{\kappa}{\sqrt{2}} s_S n_{\tilde{S}} n_{\tilde{S}} \\
& + \frac{g_1}{2}(s_{H_d} n_{\tilde{B}} n_{\tilde{H}_d} - s_{H_u} n_{\tilde{B}} n_{\tilde{H}_u}) \\
& - \frac{g_2}{2}(s_{H_d} n_{\tilde{W}_0} n_{\tilde{H}_d} - s_{H_u} n_{\tilde{W}_0} n_{\tilde{H}_u})
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\end{aligned}
$$

125 GeV higgs must be mostly doublet

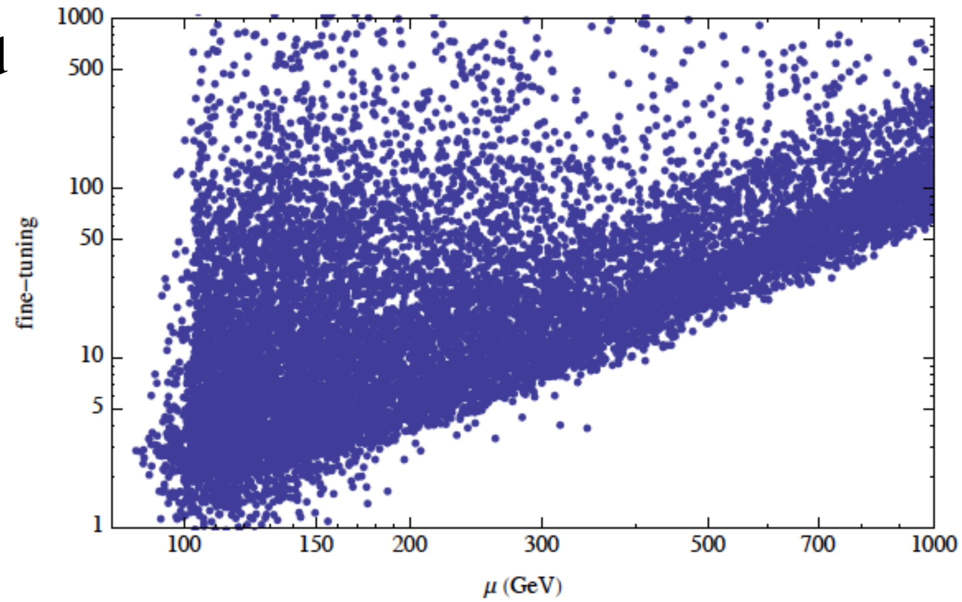
large cross section if gaugino-higgsino

$\lambda \sim 0.6$ for 125 GeV higgs, large contribution if higgsino-singlino

Are deviations from gaugino-higgsino or gaugino-singlino fine-tuned?

Dark Matter in NMSSM

Similar insight: large μ is fine-tuned



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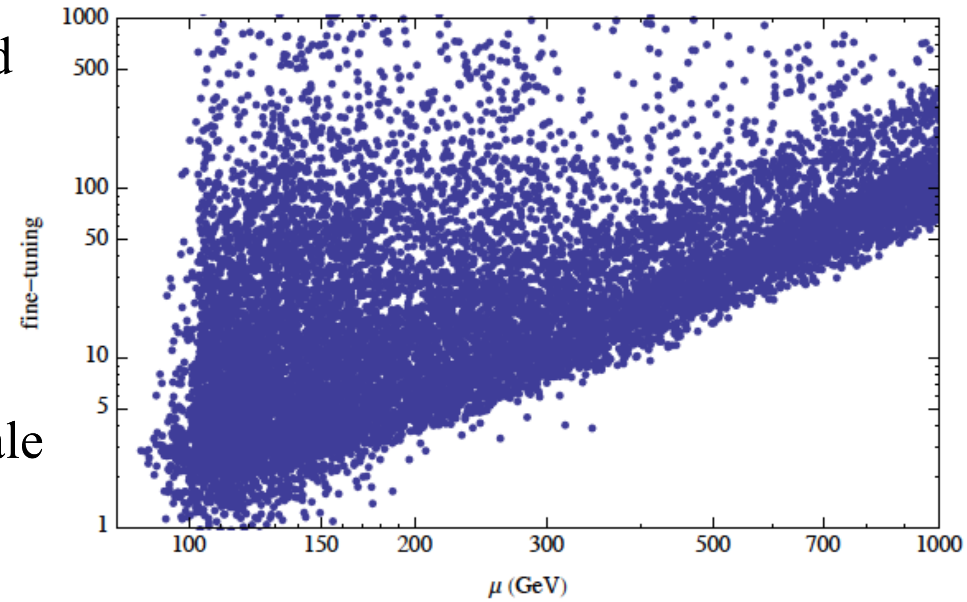
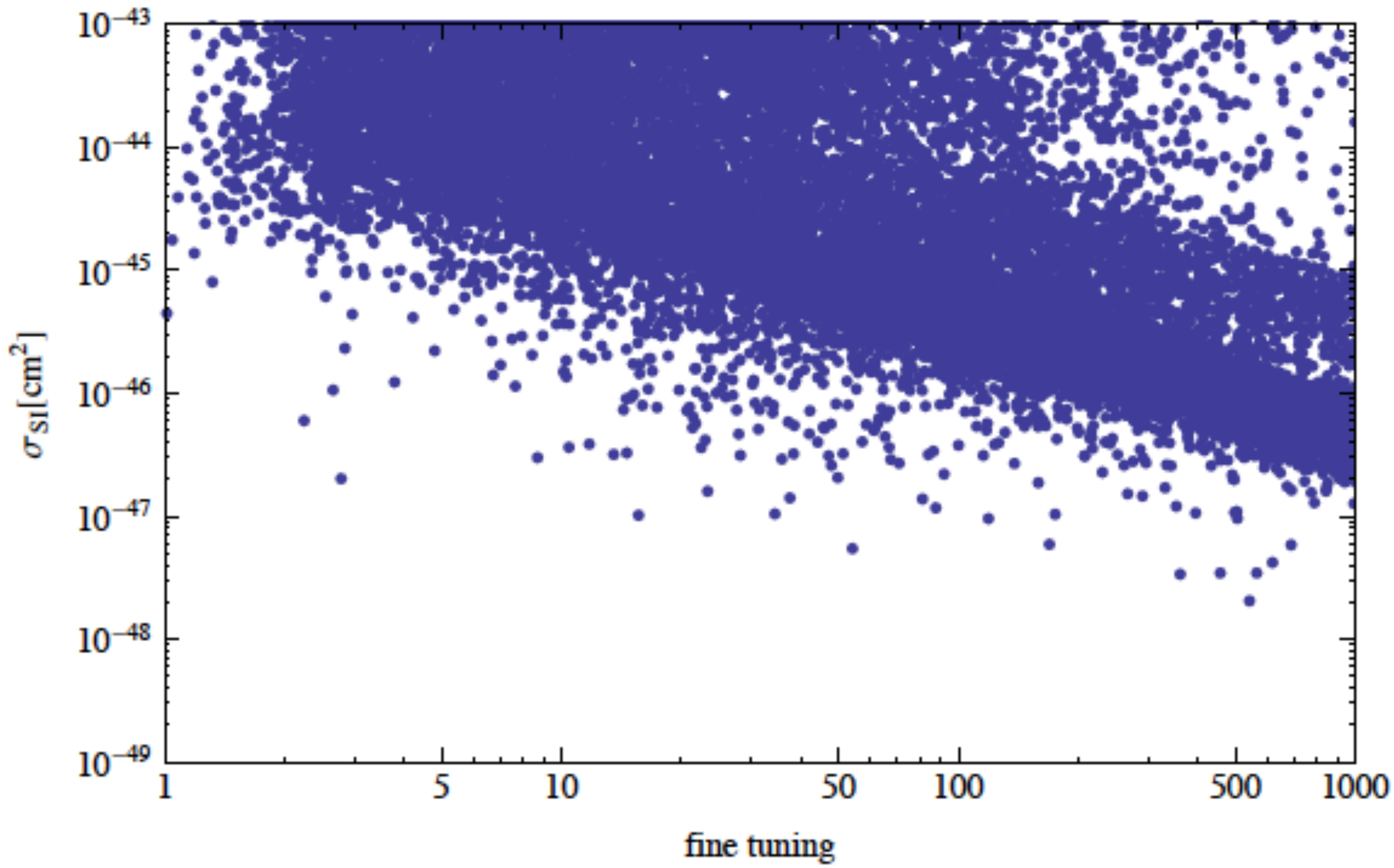


Pure gaugino or gaugino-singlino:
requires lifting μ far above M_1, M_2

Higgsino:
relic density too low unless TeV scale

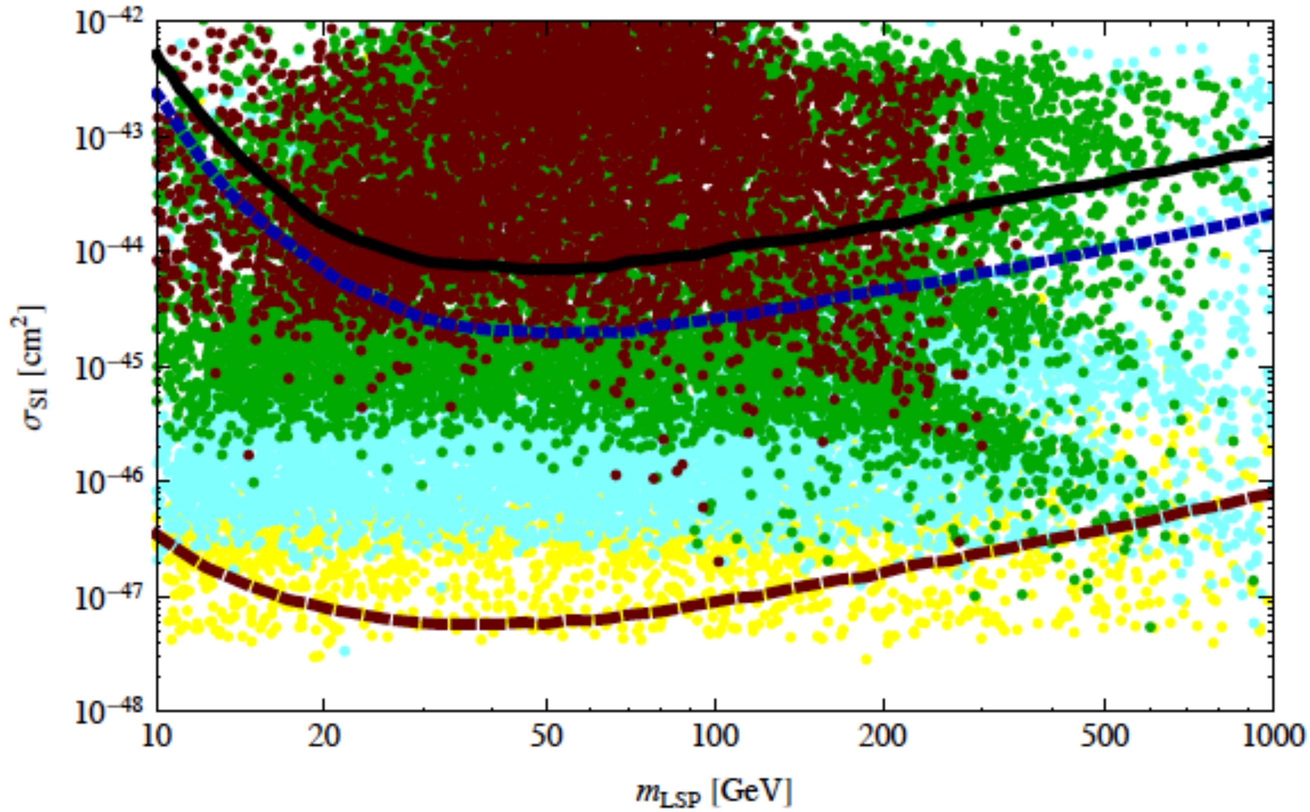
Singlino:
Large λ introduces large mixing between higgsinos and singlino. Beating this mixing by lifting the mass scales requires large μ and is fine-tuned.

Dark Matter in NMSSM



Again, a clear correlation between lower direct detection cross section and fine-tuning.

Dark Matter in NMSSM



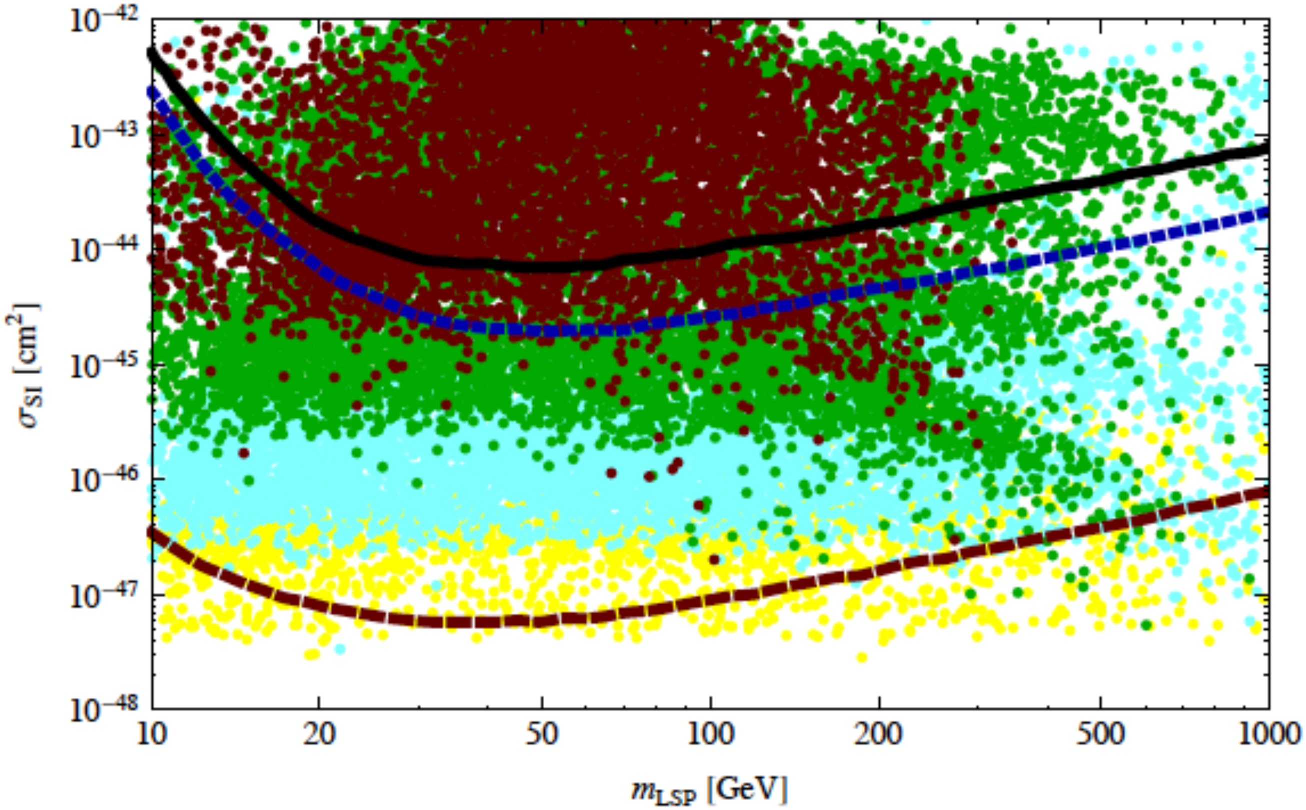
XENON100 (2011)

XENON100 (2012)

XENON 1T

Red, green, blue,yellow: FT<10,100,1000, worse

Dark Matter in NMSSM



XENON100 (2011)

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XENON 1T

Red, green, blue,yellow: FT<10,100,1000, worse

Current bound requires NMSSM to be tuned to 20% or worse
XENON1T will also probe NMSSM down to 1% level tuning

λ-SUSY

$$0.75 < \lambda < 2.$$

A different fine-tuning behavior:

$$m_Z^2 = -m_u^2\left(1-\frac{1}{\cos 2\beta}\right) - m_d^2\left(1+\frac{1}{\cos 2\beta}\right) - 2|\mu|^2 \qquad \delta(\xi) = \left|\frac{\partial \log m_Z^2}{\partial \log \xi}\right|$$

λ-SUSY

$$0.75 < \lambda < 2.$$

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$$m_Z^2 = -m_u^2\left(1 - \frac{1}{\cos 2\beta}\right) - m_d^2\left(1 + \frac{1}{\cos 2\beta}\right) - 2|\mu|^2 \qquad \delta(\xi) = \left|\frac{\partial \log m_Z^2}{\partial \log \xi}\right|$$

However, μ is not a fundamental Lagrangian parameter, but an output of the minimization conditions. Need to rewrite this relation in terms of fundamental parameters:

$$m_Z^2 = \frac{g^2}{\lambda^2} m_{H_u}^2 + \ldots$$

λ-SUSY

$$0.75 < \lambda < 2.$$

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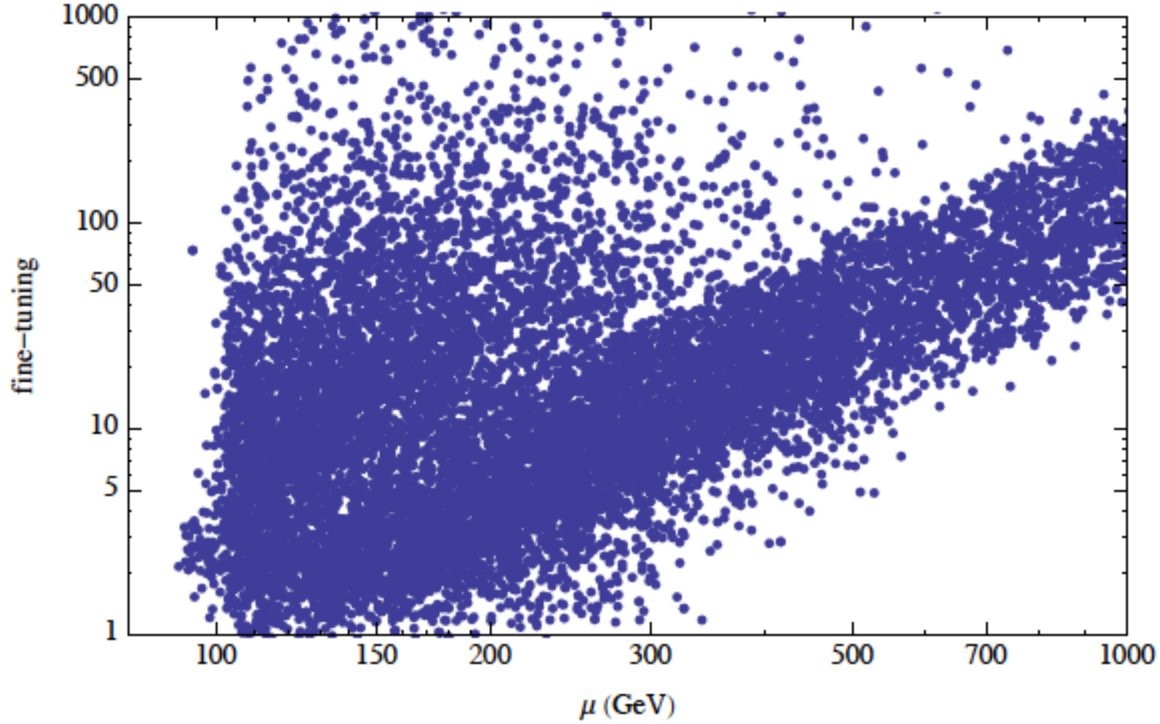
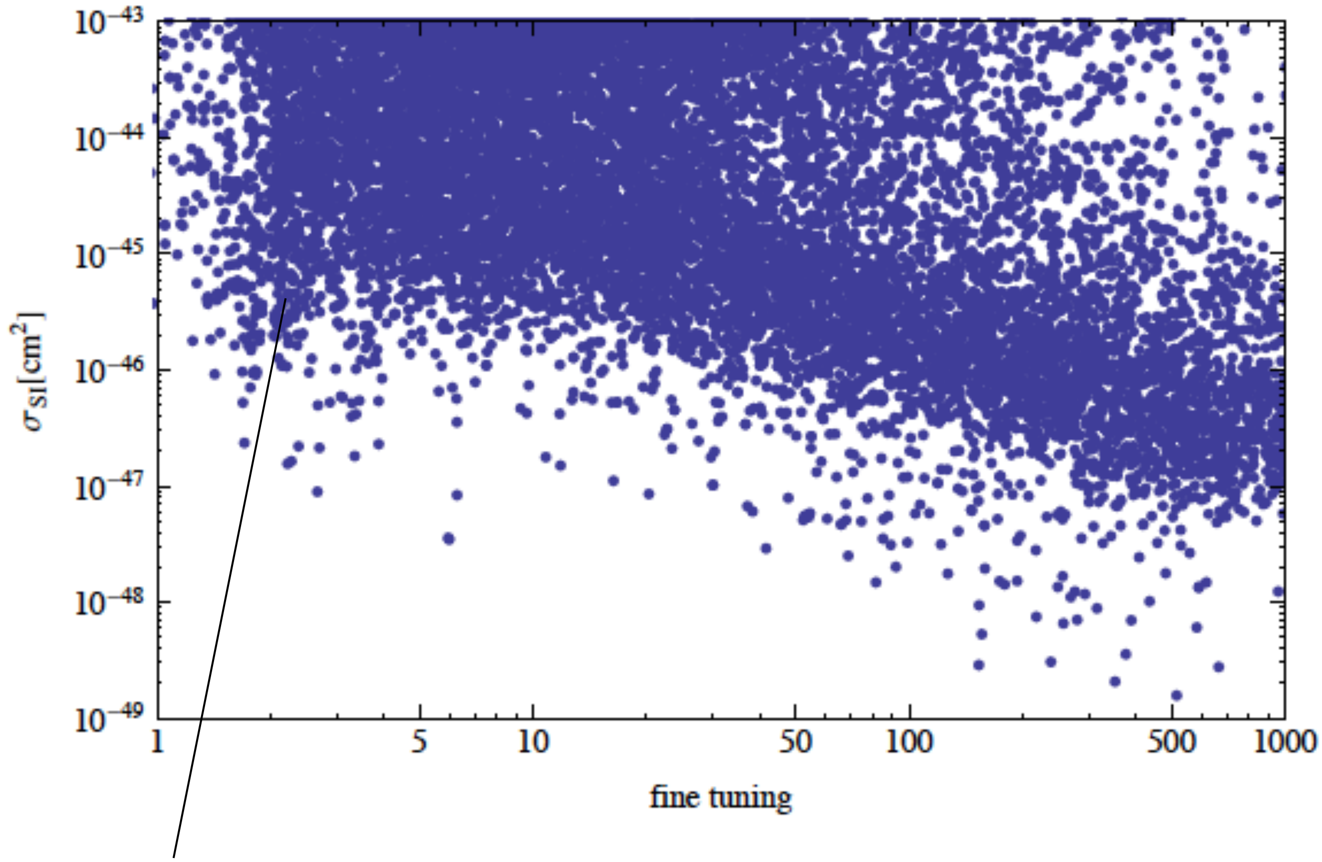
Fine-tuning improved by a factor of g/λ (stops, gluinos can naturally be heavier than TeV).

λ-SUSY



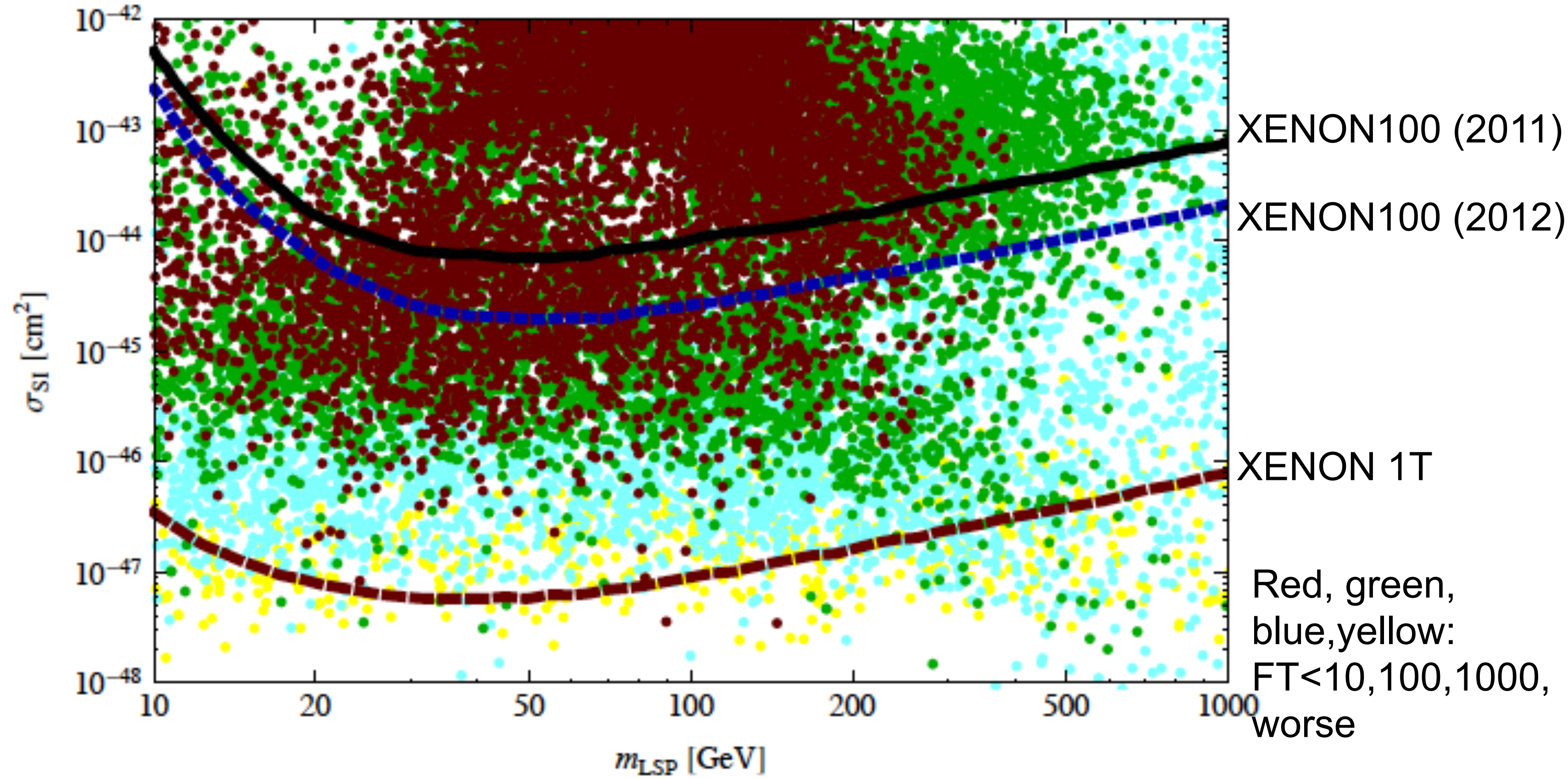
Higher mass scales (~400 GeV) still natural

λ-SUSY



Can get lowered cross sections with very small fine-tuning.
(Imagine points moving left by a factor of g/λ)

λ-SUSY



Very natural to evade current XENON100 bound
XENON1T can still probe it down to 1% level

Summary

Lower direct detection cross section is correlated with greater (EWSB)fine-tuning.

Null direct detection results (XENON100) can give meaningful constraints on naturalness of supersymmetry (especially after the discovery of a 125 GeV higgs)

A 'well-tempered' neutralino – higgsino mixed with gaugino or singlino – is strongly disfavored.

MSSM: ~10% tuned (but already greater tuning needed for 125 GeV higgs),
most natural surviving candidate: mostly bino, lighter than 50 GeV

NMSSM: ~20% tuned (probably a stronger constraint than from colliders),
most natural surviving candidate: mostly bino, < 40 GeV, or mostly gaugino, between 100 and 200 GeV.

λ-SUSY: very natural to evade XENON100 bounds

XENON1T will detect a signal if dark matter is a supersymmetric neutralino, and the theory is not worse than 1% tuned!

THANK YOU!