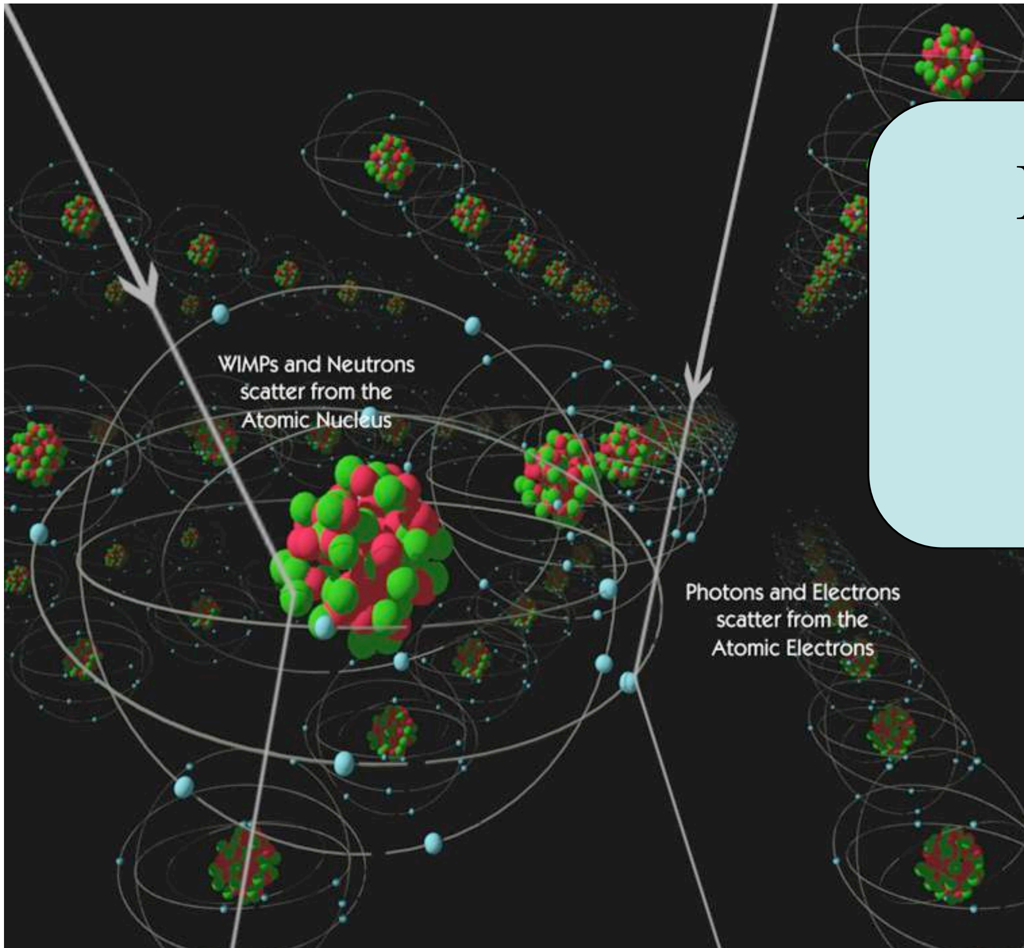
Naturalness in Supersymmetry and Dark Matter Direct Detection



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Based on
hep-ph:1107.5048, 1205.xxxx
with Maxim Perelstein

Natural SUSY: The LHC perspective

- No superpartners observed so far
- **SM-like Higgs at 125 GeV**
- **MSSM**: need large loop level correction, *extremely* fine-tuned

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

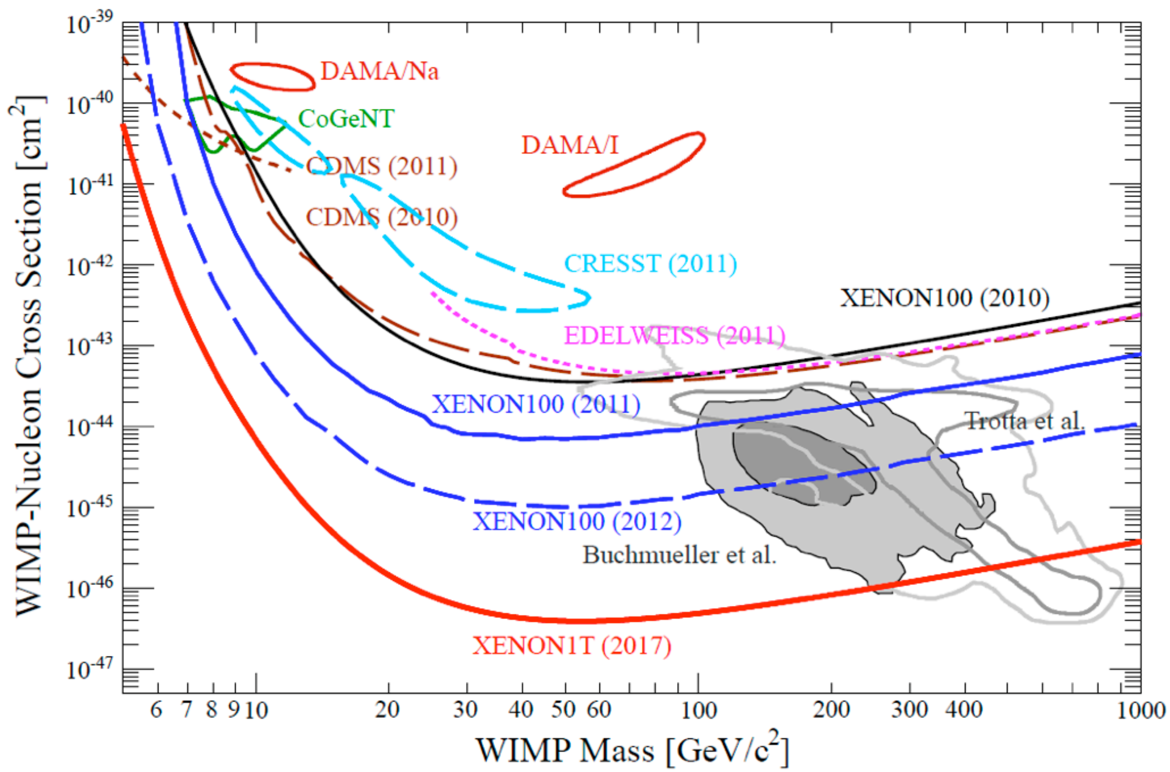
- **NMSSM**: additional tree level contribution, 125 GeV higgs natural with large λ (~0.6), small tanβ (~1)

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

- **λ-SUSY**: $0.75<\lambda<2$, Landau pole below GUT scale but satisfies all experimental constraints; can get 125GeV higgs at tree level, mass scales can be raised by a factor of λ/g, natural to have superpartners closer to TeV scale.

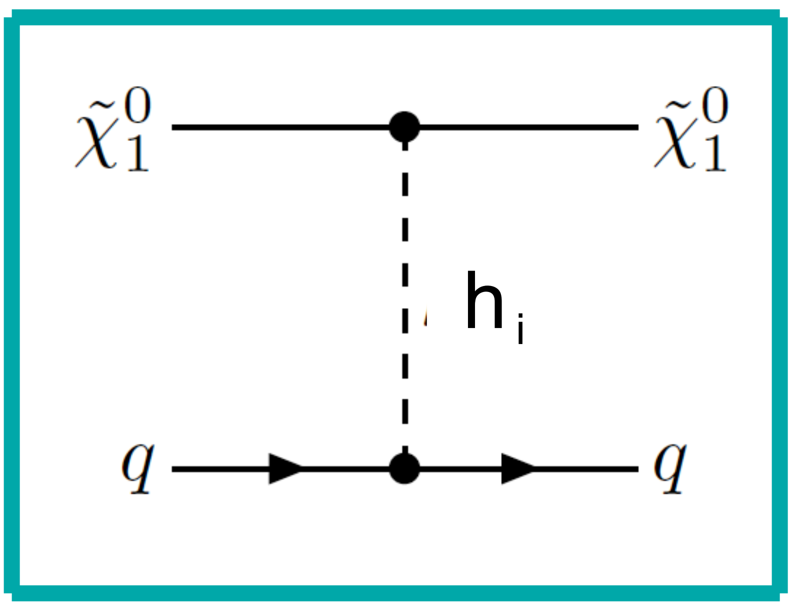
(Hall, Pinner ,Ruderman; hep-ph 1112.2703)

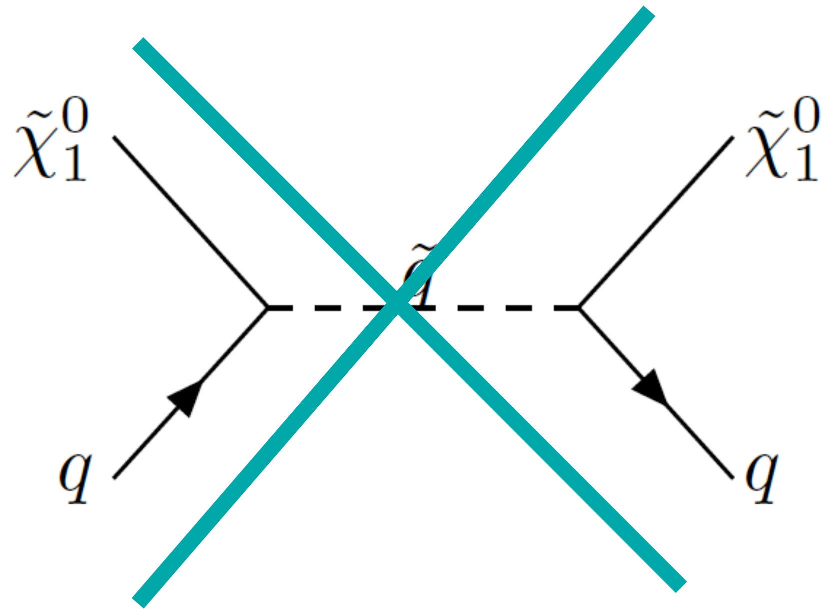
Another Probe: Dark Matter Direct Detection



- Lightest neutralino in supersymmetry: our favorite dark matter candidate
- Nothing at XENON100, update imminent, XENON1T planned
- Limits can give meaningful constraints on parameter space

Spin independent scattering

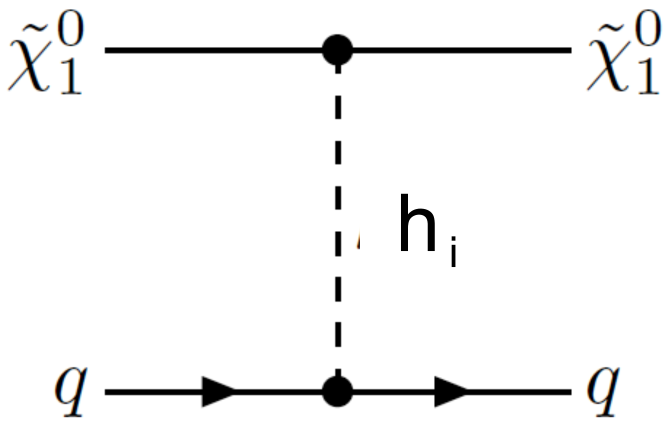




Ignore this contribution

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

Spin independent scattering



"Typical" scattering cross section

(MSSM and NMSSM):

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

Current XENON100 upper bound:

$\sim 10^{-44}\,\text{cm}^2$

Fine-tuning ???

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, large μ gives greater 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)

- **Relic density:**

  generally ignored (mild constraints for pure higgsinos and singlinos)

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

- Other Requirements:

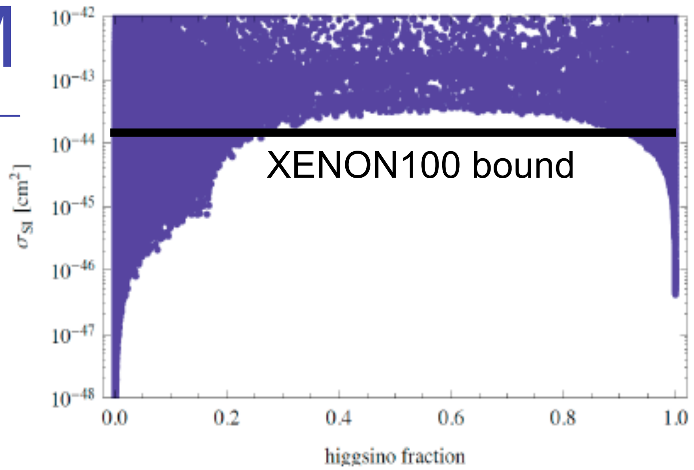
  neutralino LSP; charginos heavier than 103 GeV; light neutralinos satisfy experimental constraint on Z invisible width;

  Higgs sector: require tree level contribution to SM-like Higgs mass to exceed 100GeV, then fix at m_h=125 GeV. (physical) Higgs masses nontachyonic (no additional collider constraints imposed)

Briefly: Dark Matter in MSSM

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

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

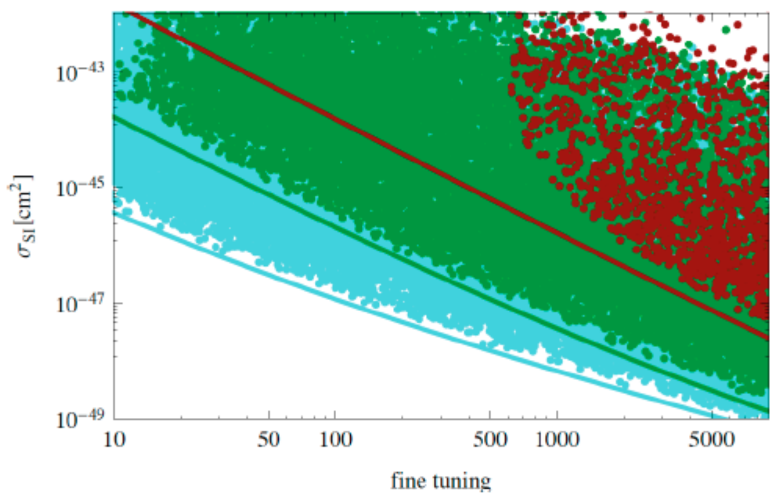


Gaugino-like: requires μ to be raised relative to M_1 or M_2

Higgsino-like: relic density too small unless TeV scale; μ~TeV

Recall: large μ is fine-tuned.

- Current XENON bound: More than 10% fine-tuning above 70 GeV
- Xenon 1T will probe regions with fine-tuning down to percent level.



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

Dark Matter in NMSSM

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

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

Generates an effective $\mu_{eff}=\lambda s$ when the singlet gets a vev s.

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

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

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

CP even singlet higgs: mixes with higgs doublet.
125 GeV SM-like (mostly doublet) higgs provides interesting constraints!

Dark Matter in NMSSM

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

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

Dark Matter in NMSSM

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

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

} large cross section if gaugino-higgsino

λ~0.6 for 125 GeV higgs, large contribution if higgsino-singlino

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

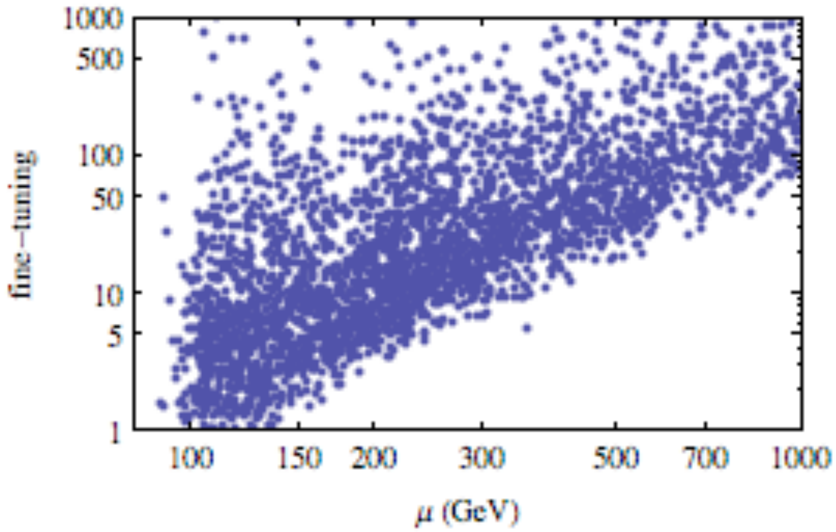
Dark Matter in NMSSM

Similar insight: large μ is fine-tuned

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

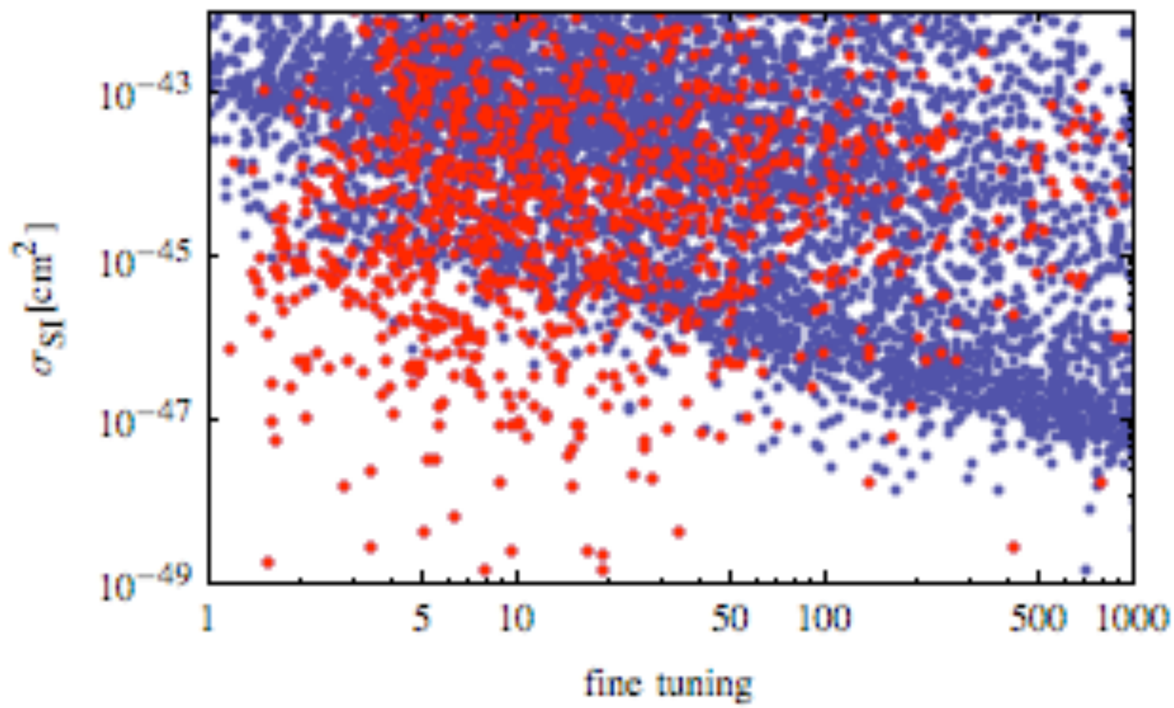
Higgsino:
relic density too low unless TeV scale

Singlino:
requires $\kappa \ll \lambda$; no significant coupling to anything, relic density too high



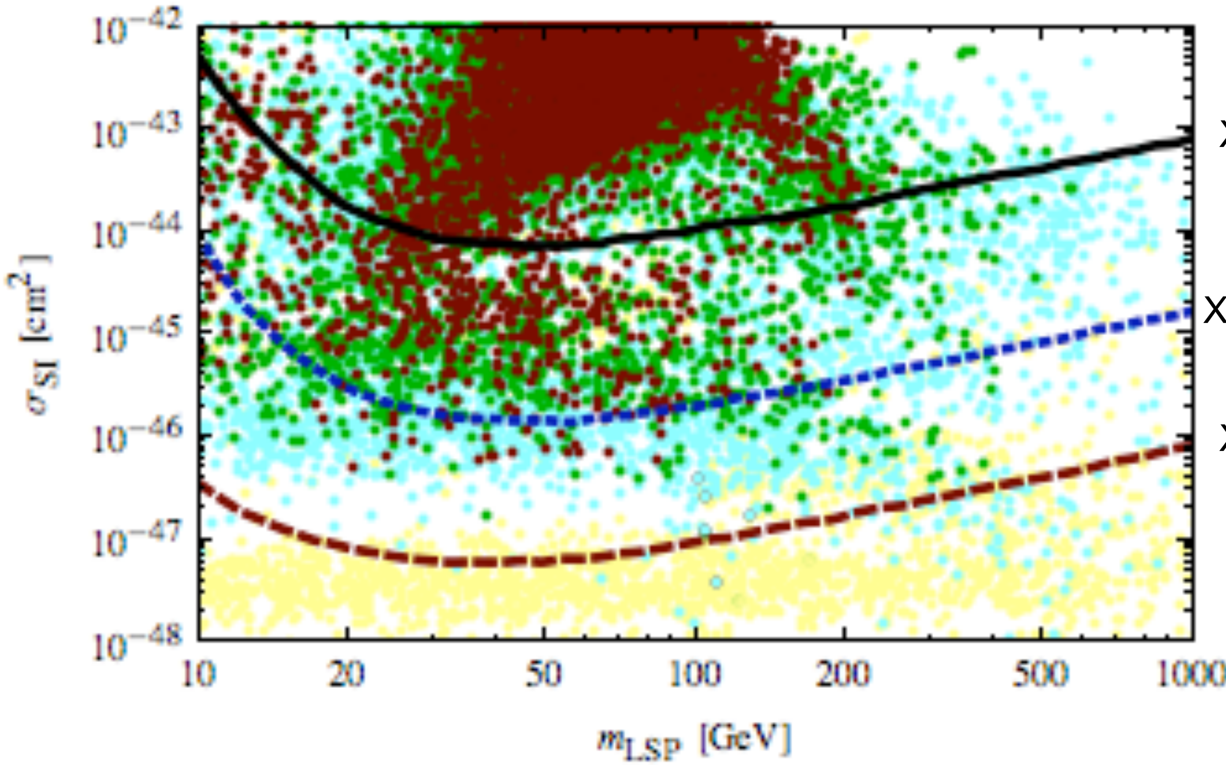
Lower direct detection cross section involves fine-tuning.

Dark Matter in NMSSM



Red: points with accidental cancellations (small change in input parameters changes cross-section by a huge amount)

Dark Matter in NMSSM



Points evading current XENON100 constraints but accessible to upcoming update: < 20% tuning, very natural!

Within reach of XENON1T: < 5% tuning.

λ-SUSY

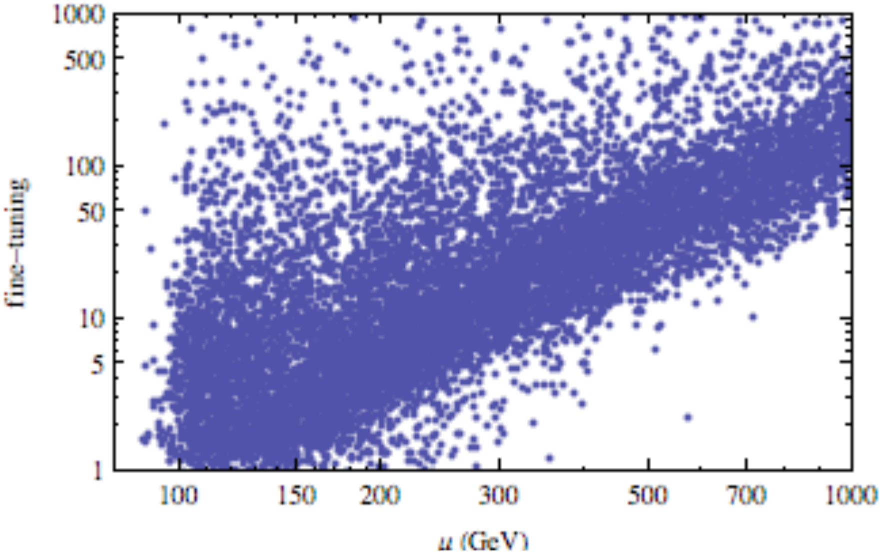
0.75<λ<2.

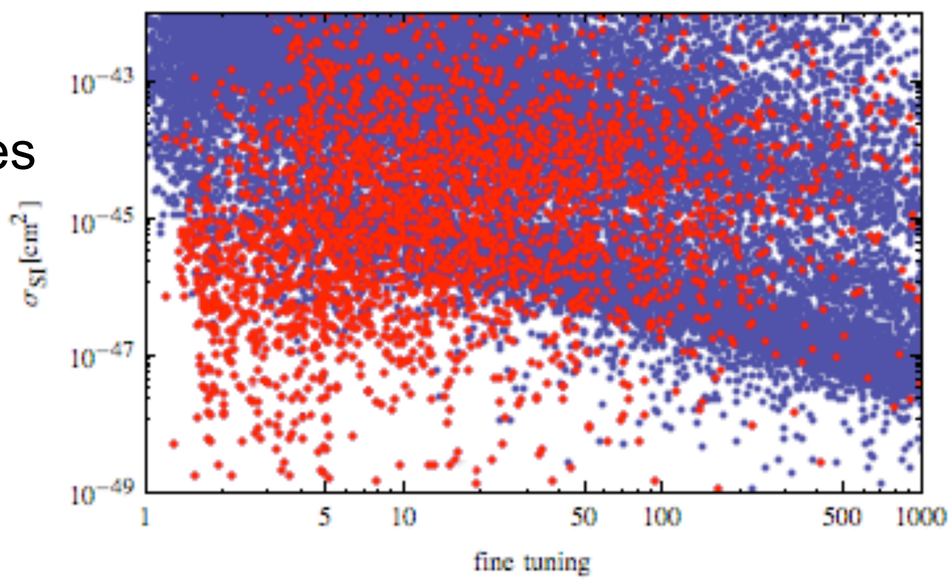
Mass scales can be raised by a factor of λ/g (ie fine-tuning better by this factor)

Singlino-gaugino component gives large cross sections because of large λ, need to suppress them further

Small cross section at low masses more natural.

XENON1T reach similar to NMSSM case (5-10%).





Summary

Dark matter considerations can give meaningful constraints on naturalness of supersymmetry

NMSSM (including λ-SUSY) with SM-like 125 GeV higgs

- Upcoming XENON100 update will probe a very natural (< 20% tuning) region of NMSSM, might see something!
- Lowering the direct detection cross section further requires some fine-tuning; XENON1T will probe NMSSM down to a tuning of ~5%.
- λ-SUSY: fine-tuning slightly alleviated. XENON1T will still probe it down to tuning of 5-10% level.

MSSM: >10% tuned from current XENON100 data, sub-percent level tuning with XENON1T. But already excessively tuned for 125GeV higgs.

THANK YOU!