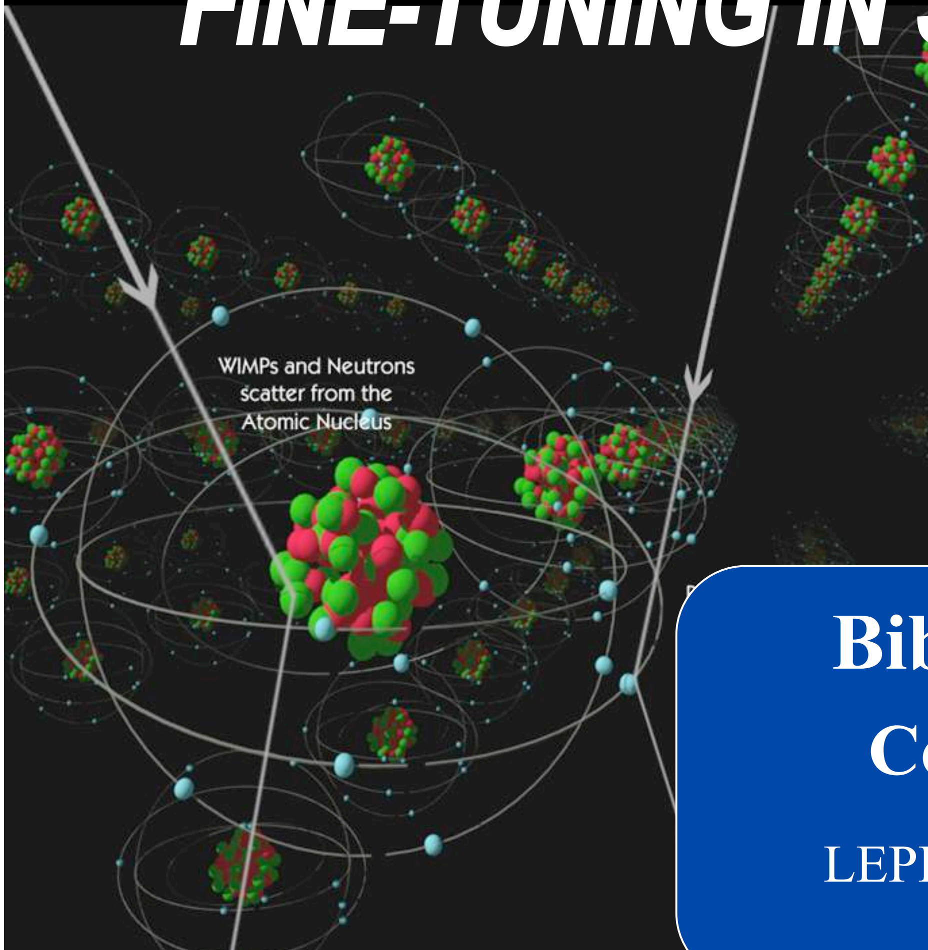
DIRECT DARK MATTER SEARCHES AND FINE-TUNING IN SUPERSYMMETRY



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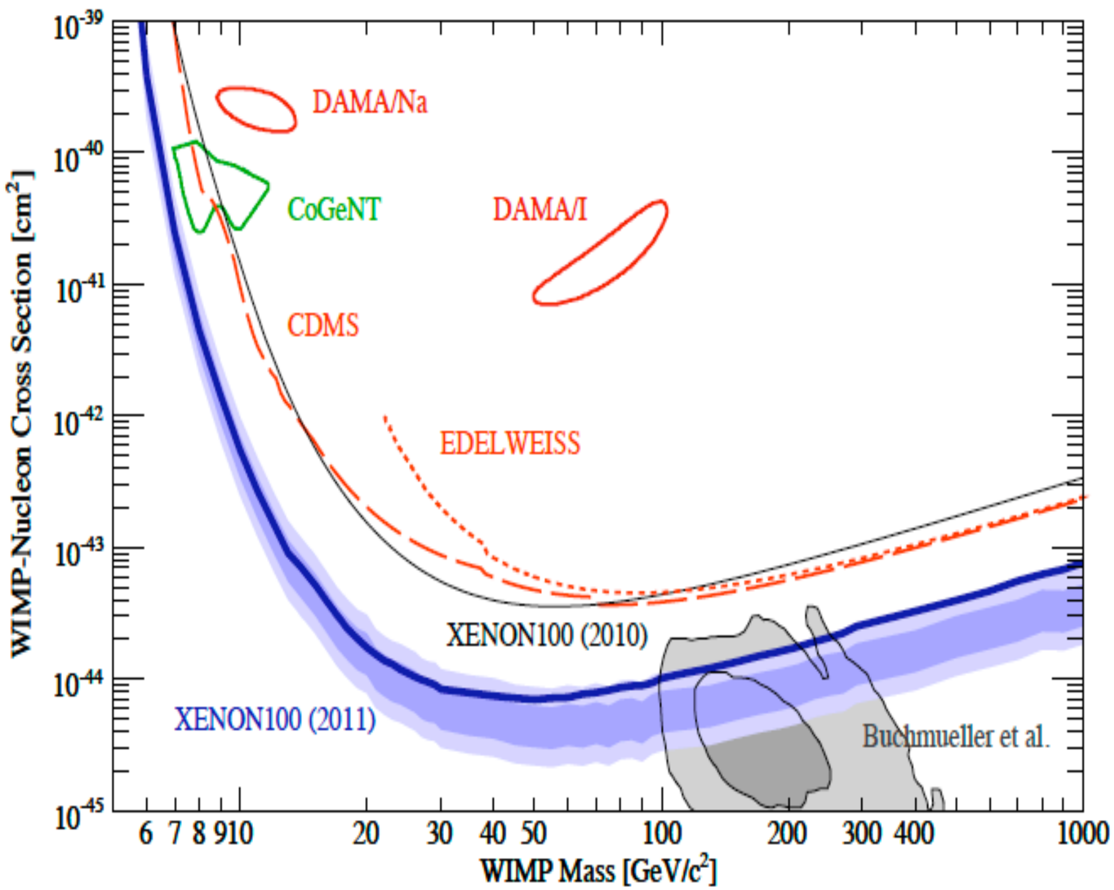
LEPP Particle Theory Seminar

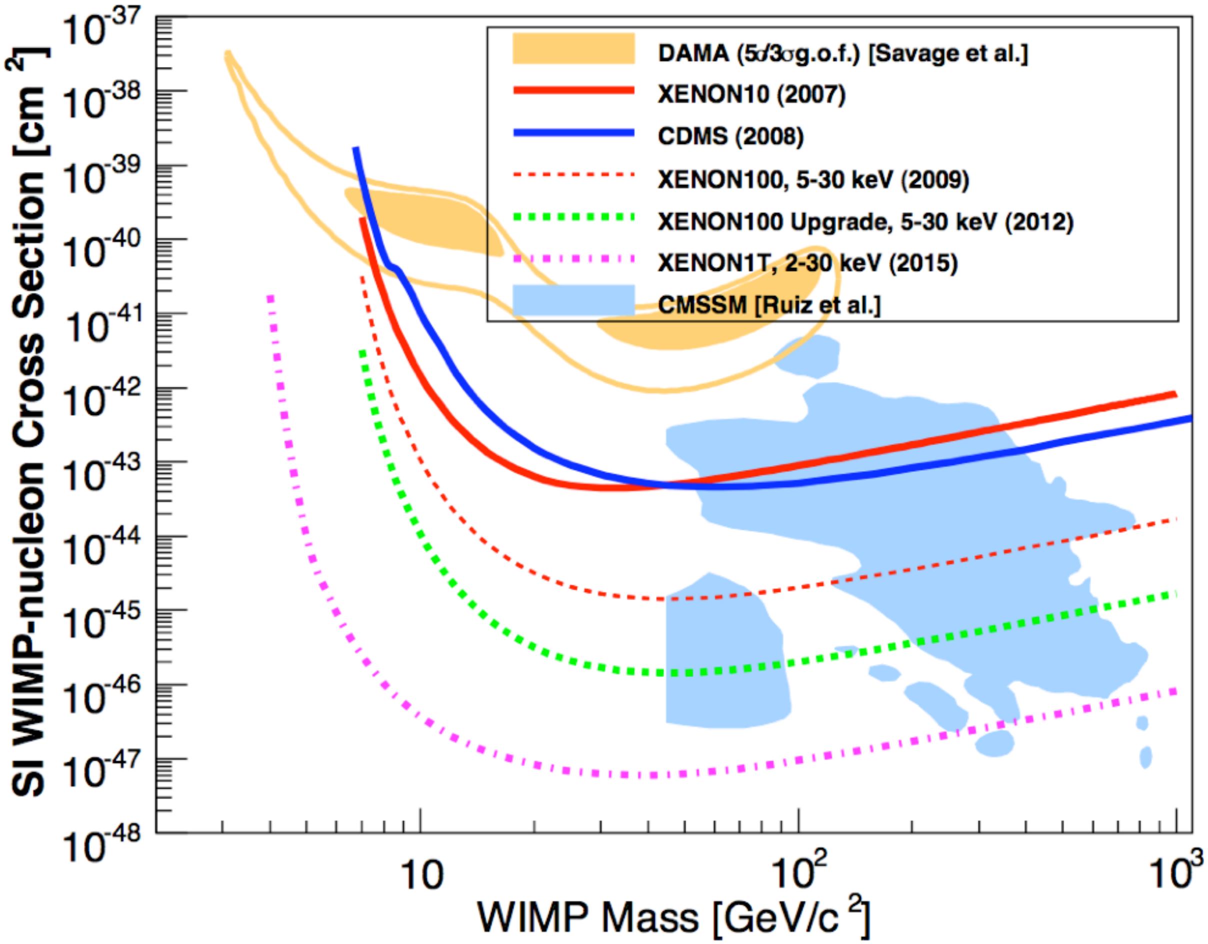
November 4, 2011

Based on arXiv:1107.5048 with Maxim Perelstein

Several direct detection experiments searching for dark matter; exciting times!



Recently beginning to probe interesting regions where SUSY predicts signals



Future upgrades will probe even lower cross sections

Uncertainties in Direct Detection Experiments

- Local dark matter density
- Velocity distribution
- Isospin symmetry of WIMP-nucleon couplings
- Nuclear formfactors (esp. that of the strange quark)
- Channeling…

Will not discuss these further,
assume they are known and properly incorporated,
bound on direct detection cross section as a function of
WIMP mass as starting point

Interpreting results in the context of MSSM

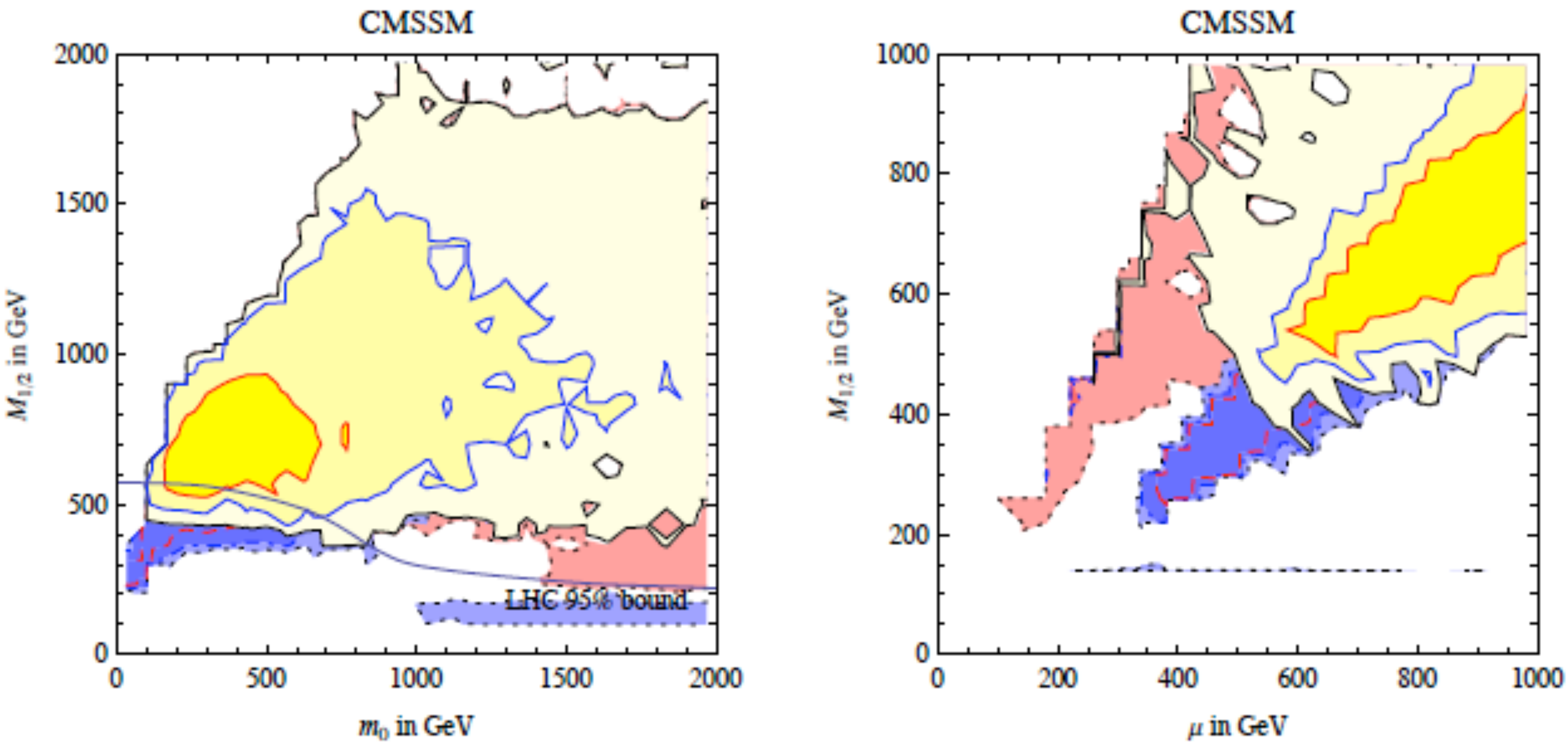
- Large number of free parameters (>100), allowed ranges highly uncertain

- Reduce parameter space via specific assumptions that relate otherwise independent parameters, e.g. high scale unification, specific model of SUSY breaking

- E.g. mSUGRA has only 5 parameters (but serious issues with FCNCs)

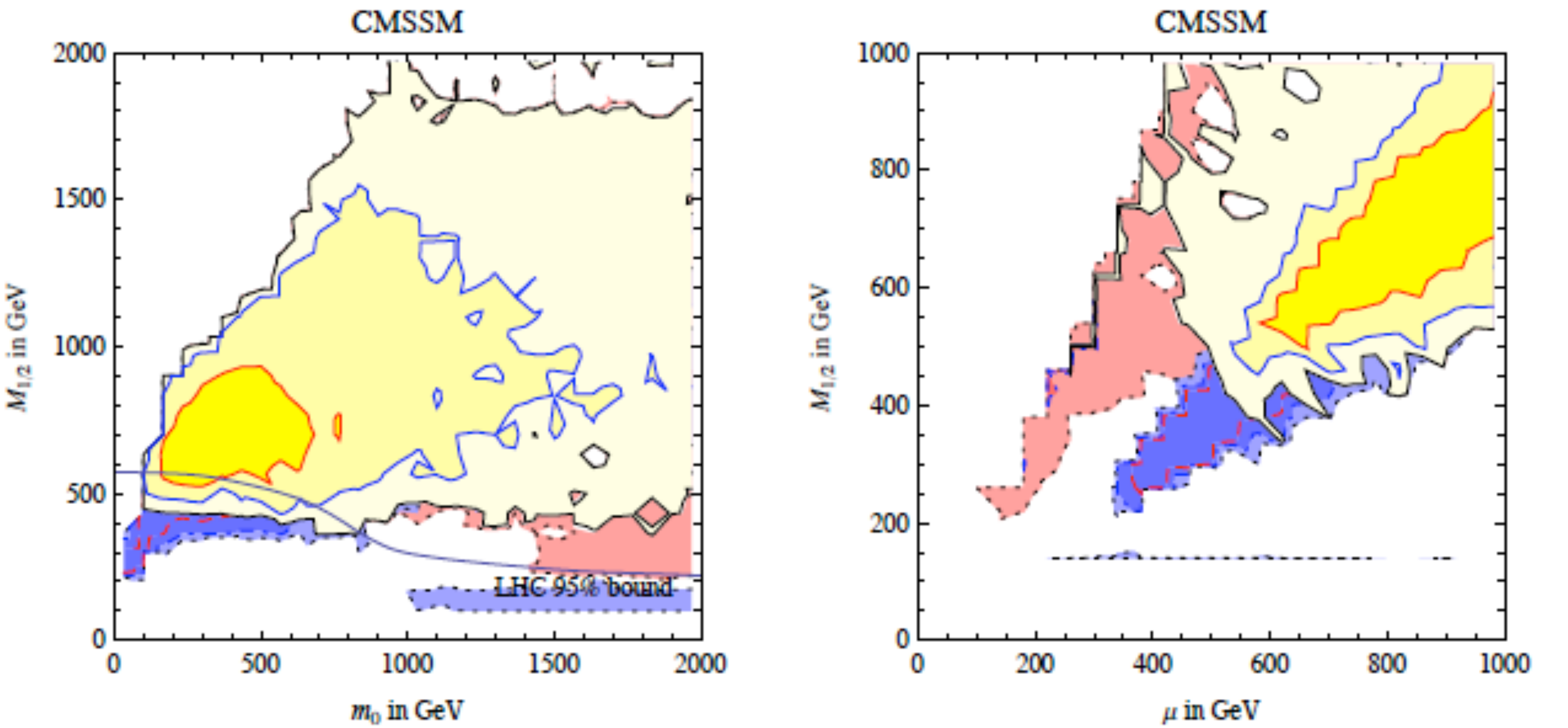
- Use results of direct detection to make exclusion plots on combinations of free parameters (while assuming specific values for free parameters not on the plot)

Null results ⟹ Bounds on parameter combinations



hep-ph 1104.3572

Null results ⟹ Bounds on parameter combinations



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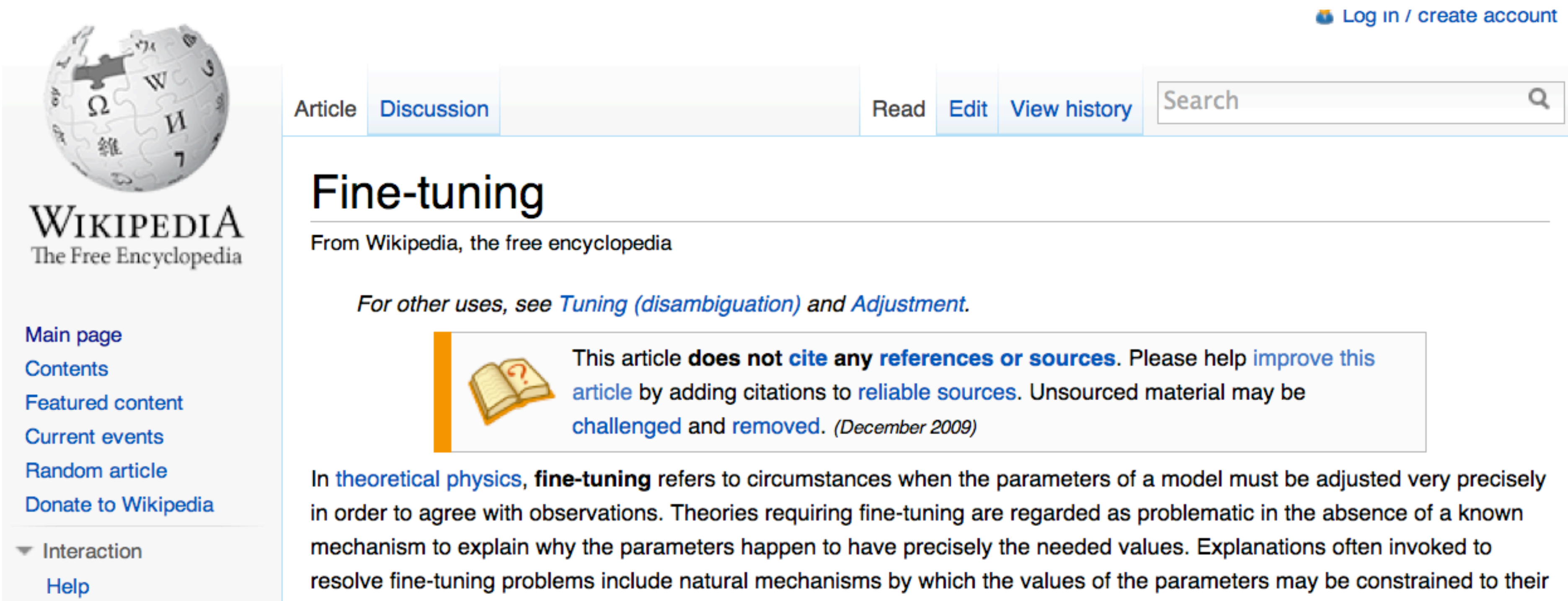
What is the most general take-away message ??

A meaningful measure:

Fine-tuning



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For other uses, see Tuning (disambiguation) and Adjustment.

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In theoretical physics, **fine-tuning** refers to circumstances when the parameters of a model must be adjusted very precisely in order to agree with observations. Theories requiring fine-tuning are regarded as problematic in the absence of a known mechanism to explain why the parameters happen to have precisely the needed values. Explanations often invoked to resolve fine-tuning problems include natural mechanisms by which the values of the parameters may be constrained to their

A meaningful measure:

Fine-tuning

The Question

In generic supersymmetry models, can one naturally get points that evade current and future direct detection constraints, without needing to fine-tune parameters?

Quantifying (EWSB) Fine-tuning

- In EW sector, MSSM parameters must reproduce the correct 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:

$$\delta(\xi) = \left|\frac{\partial \log m_Z^2}{\partial \log \xi}\right| \qquad \xi = m_u^2, m_d^2, b, \mu$$

- Add these in quadrature $\rightarrow$ a measure of EWSB fine-tuning

- Can write the final expression as a function of m_A, μ, tan β, m_Z

- For tan β >> 1, $\delta(\mu) \approx \frac{4\mu^2}{m_Z^2}, \quad \delta(b) \approx \frac{4m_A^2}{m_Z^2 \tan\beta}$
- Fine-tuned for large μ, to a smaller extent for small tan β, large m_A.

Our Approach

Work within (phenomenological) MSSM

Assume no relations between weak-scale MSSM parameters

No accidental cancellations

(ignore correlations that are true only on a measure zero hypersurface of the parameter space; want to make general statements valid in most of the parameter space)

The lightest neutralino is dark matter, and makes up all of the observed dark matter in the universe

Dark Matter in the MSSM

- Neutralino mass matrix:

$$\mathbf{M}_{\tilde{N}} = \begin{pmatrix} M_1 & 0 & -c_\beta\, s_W\, m_Z & s_\beta\, s_W\, m_Z \\ 0 & M_2 & c_\beta\, c_W\, m_Z & -s_\beta\, c_W\, m_Z \\ -c_\beta\, s_W\, m_Z & c_\beta\, c_W\, m_Z & 0 & -\mu \\ s_\beta\, s_W\, m_Z & -s_\beta\, c_W\, m_Z & -\mu & 0 \end{pmatrix}$$

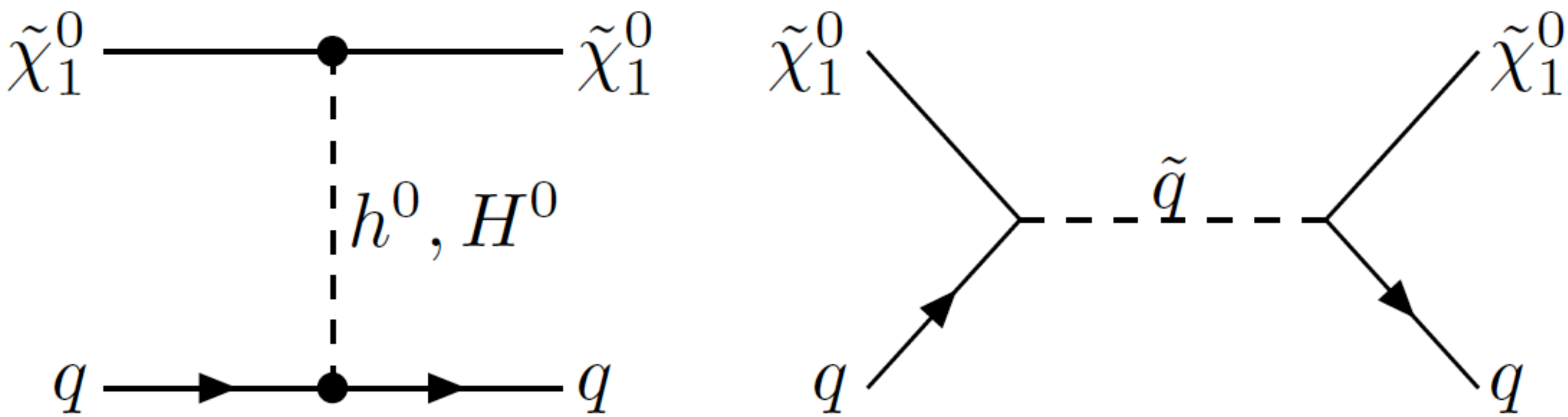
- The lightest neutralino (dark matter)

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

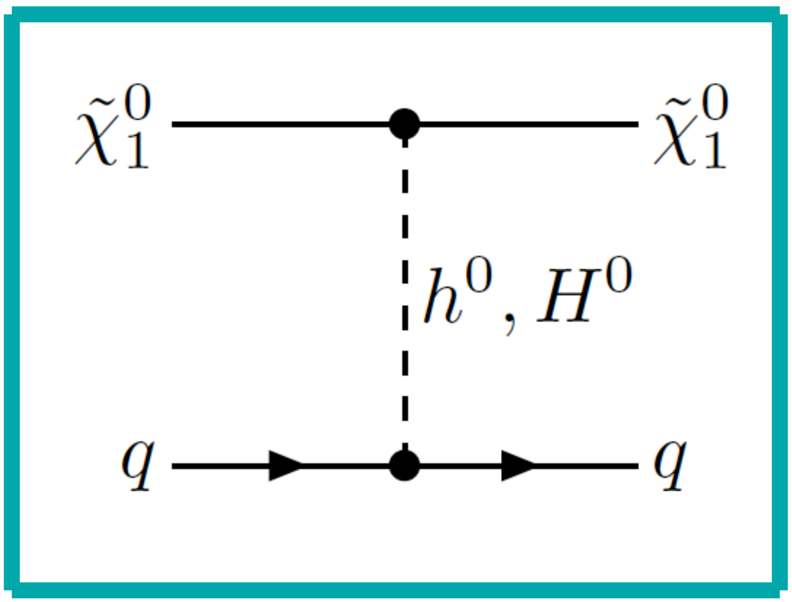
- The relative sizes of M_1, M_2, μ determine the content of the LSP neutralino

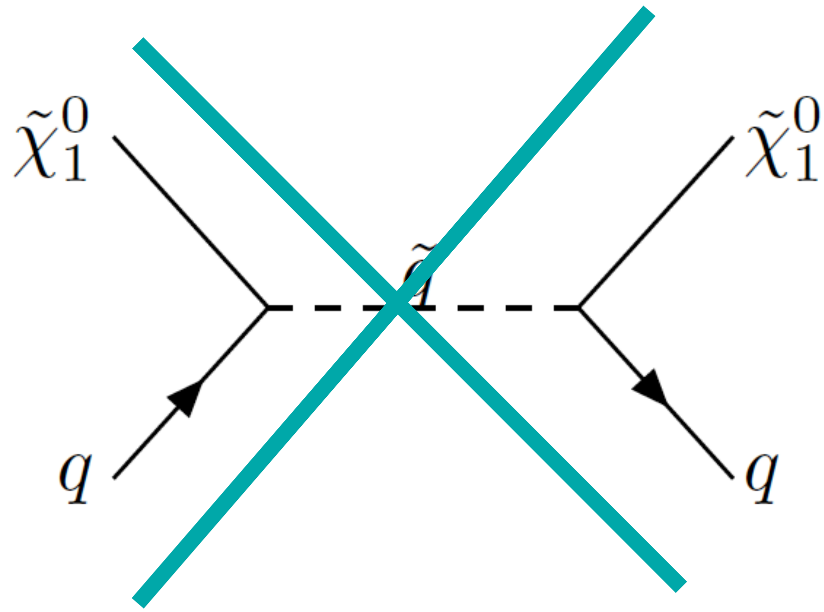
Spin independent scattering

(strongest bounds)



Spin independent scattering



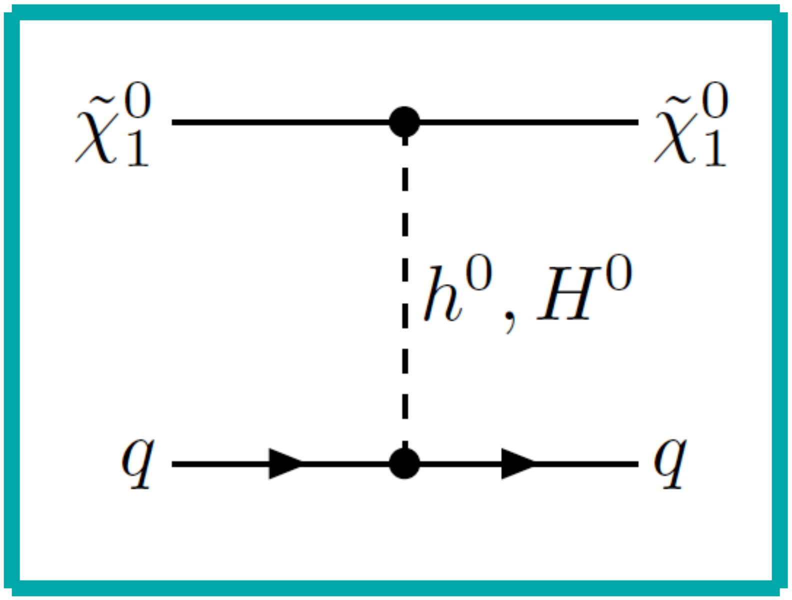


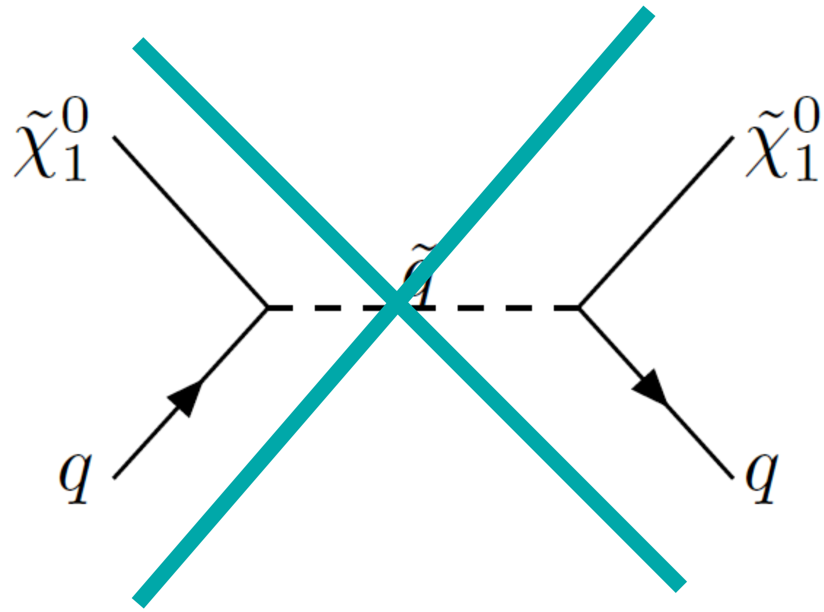
Ignore this contribution

Direct detection cross section depends only on

$$p_i = (M_1, M_2, \mu, \tan\beta, m_A)$$

Spin independent scattering





Ignore this contribution

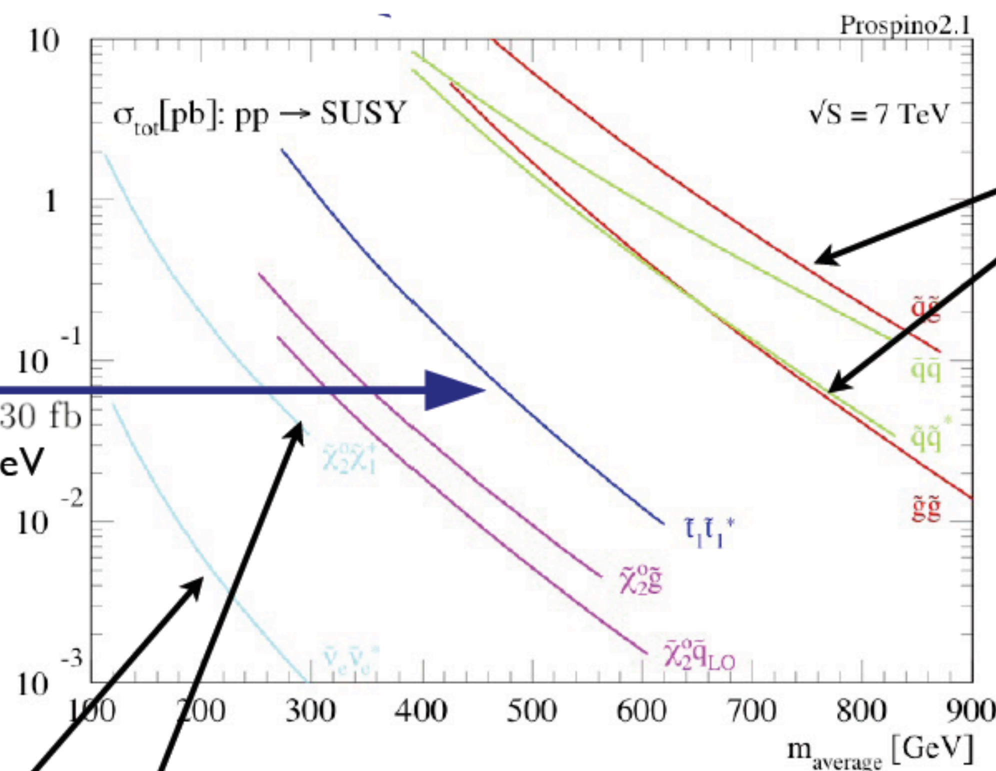
Direct detection cross section depends only on

$$p_i = (M_1, M_2, \mu, \tan\beta, m_A)$$

Both cross section and fine tuning determined by the same parameters!

(Reminder: fine tuning depends on m_A, μ, $\tan\beta$)

Aside: Why not do the same with LHC data?



$\sigma(\tilde{t}\tilde{t}^*) \approx 30$ fb at 500 GeV

All searches so far rely on producing gluinos and/or 1st, 2nd gen. squarks, different decay channels

Chargino/neutralino (e.g. higgsino) cross sections are also small

"No" impact on fine-tuning!

(3rd generation squarks enter at loop level, gluinos only relevant at two loops)

Plot credit: H. Bachacou talk at LP-11

The Procedure

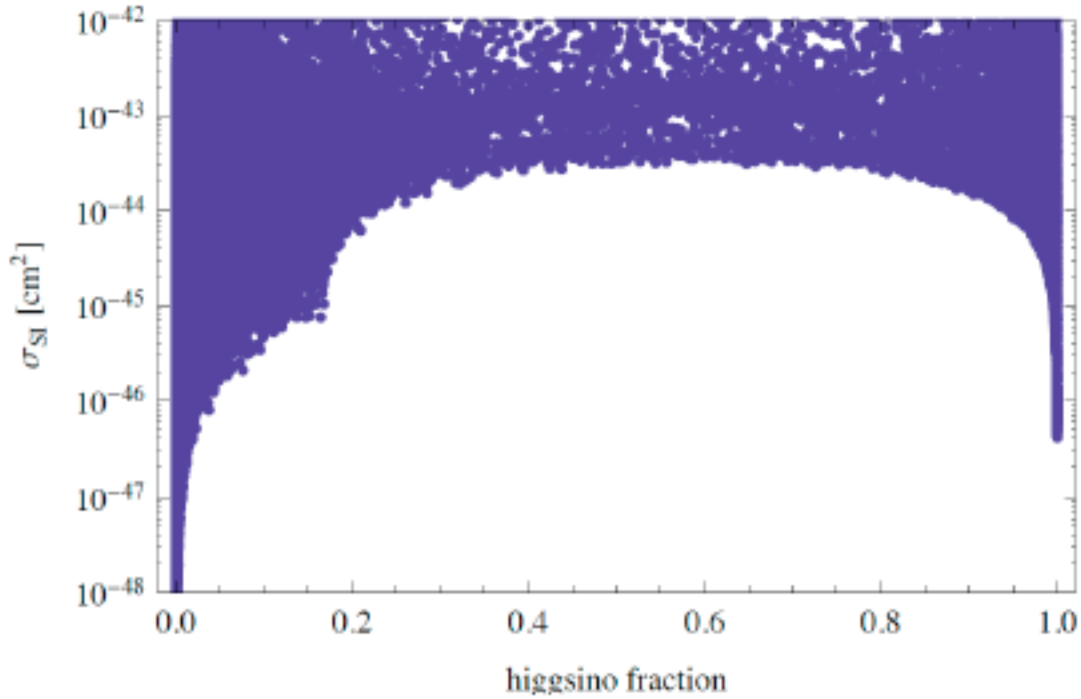
- Scan over parameters $p_i = (M_1, M_2, \mu, \tan\beta, m_A)$
- Fix Higgs mass at m_H=120 GeV

$$|M_1| \in [10, 10^4]\ \text{GeV}; \qquad |M_2| \in [80, 10^4]\ \text{GeV};$$
$$\mu \in [80, 10^4]\ \text{GeV}; \qquad m_A \in [100, 10^4]\ \text{GeV};$$
$$\tan\beta \in [2, 50]\,.$$

- Requirements:
  neutralino LSP, charginos heavier than 100 GeV
- Scan with all real, positive parameters (will look at cases with negative or complex parameters later)

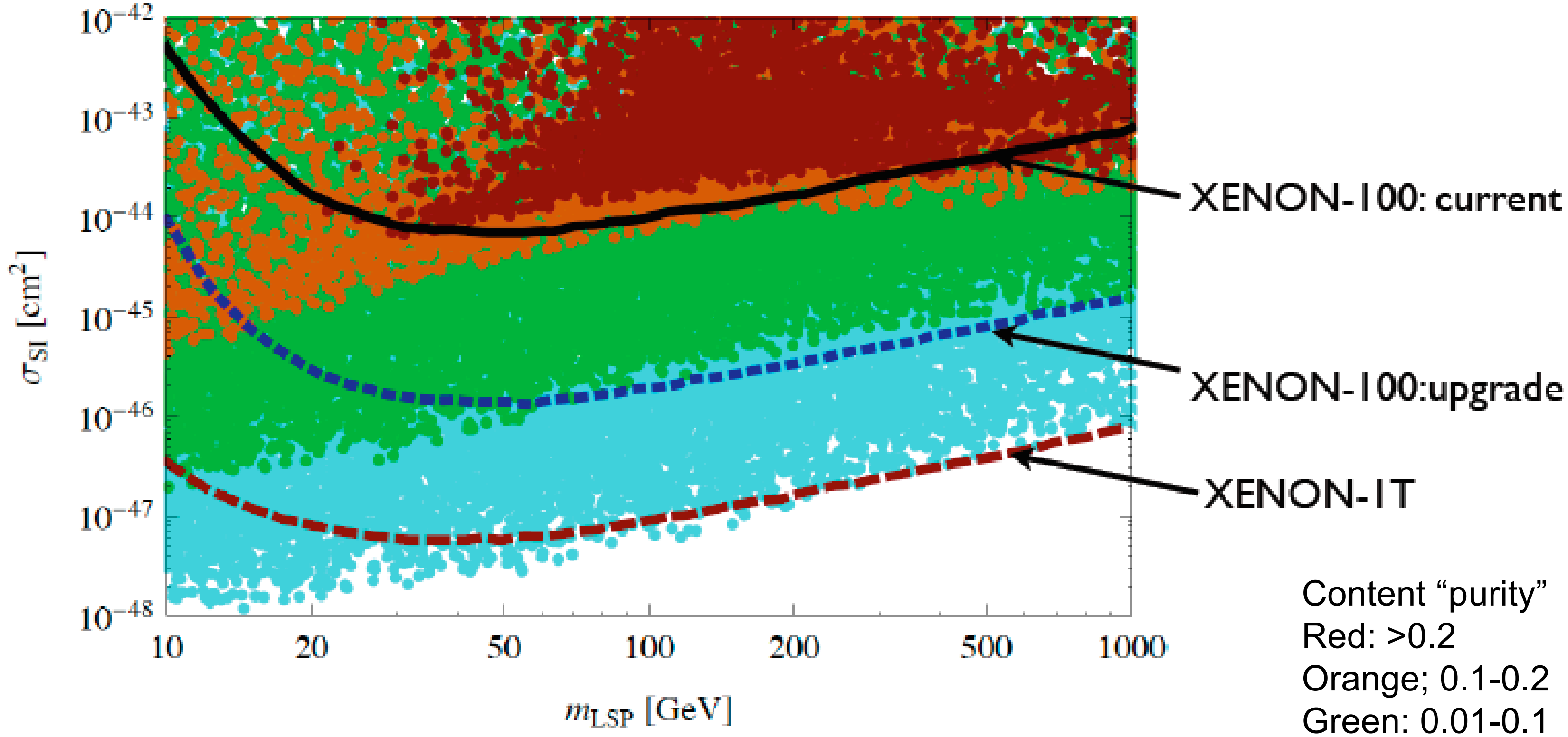
LSP Neutralino content

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



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

LSP Neutralino content



Content "purity"
Red: >0.2
Orange; 0.1-0.2
Green: 0.01-0.1
Cyan: 0.001-0.01

Xenon100 results are forcing us into pure gaugino or pure higgsino regions!

Gaugino Dark Matter and Fine-Tuning

$M_1 < \mu$ or $M_2 < \mu$

Can derive an approximate, analytic bound (for all real, positive parameters):

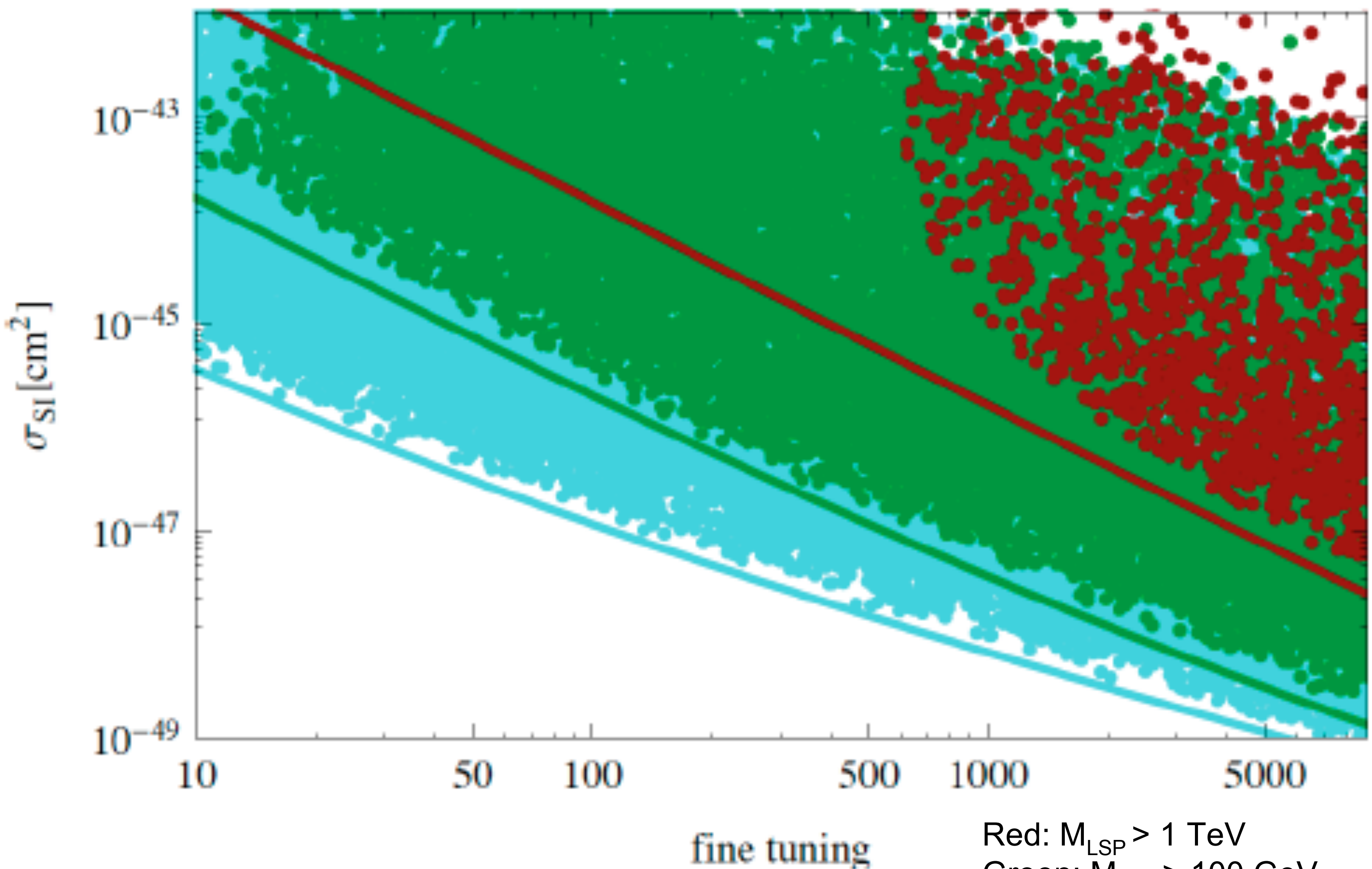
$$\sigma_{\min} = (1.2 \times 10^{-42}\ \mathrm{cm}^2) \left(\frac{120\ \mathrm{GeV}}{m_h}\right)^4 \frac{1}{\Delta} \left(\frac{1}{\tan\beta} + \frac{1}{\sqrt{\Delta}} \frac{M_{\mathrm{LSP}}}{m_Z}\right)^2$$

Also see hep-ph/0606134

$\Rightarrow$ For a given LSP mass, a lower cross section requires greater fine-tuning!

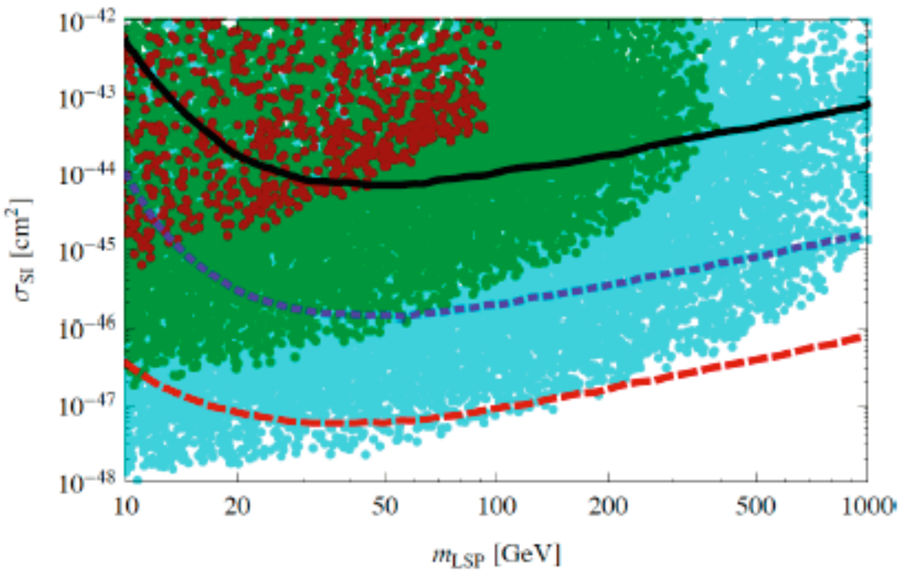
Makes sense: Smaller cross section $\rightarrow$ purer gaugino LSP $\rightarrow$ larger μ $\rightarrow$ more severely fine-tuned

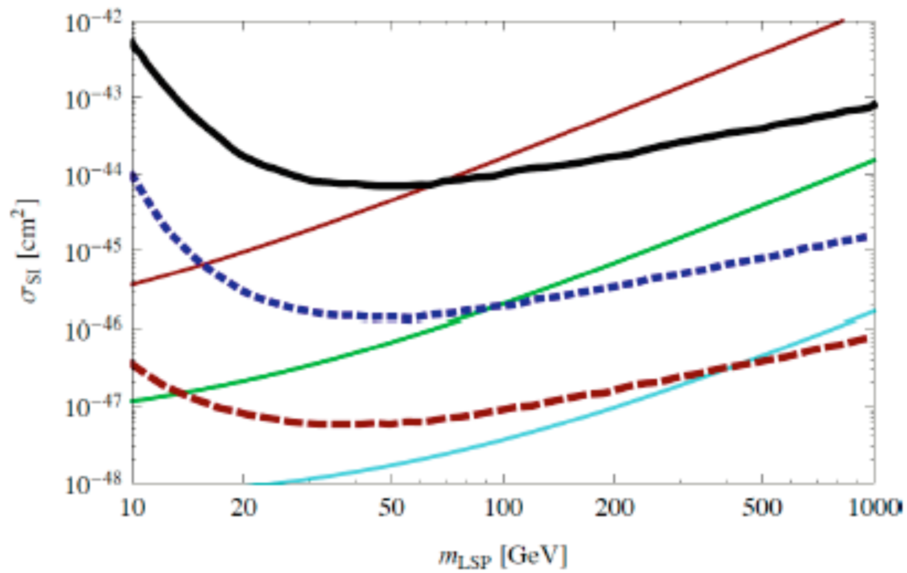
Gaugino Dark Matter and Fine-Tuning



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

Gaugino Dark Matter and Fine-Tuning





Fine-tuning: Red, green, cyan: >10,100,1000

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

Higgsino Dark Matter

$\mu < M_1, M_2$

Can keep μ small and avoid fine-tuning, but increase M_1, M_2 and suppress direct detection cross section

Higgsino Dark Matter

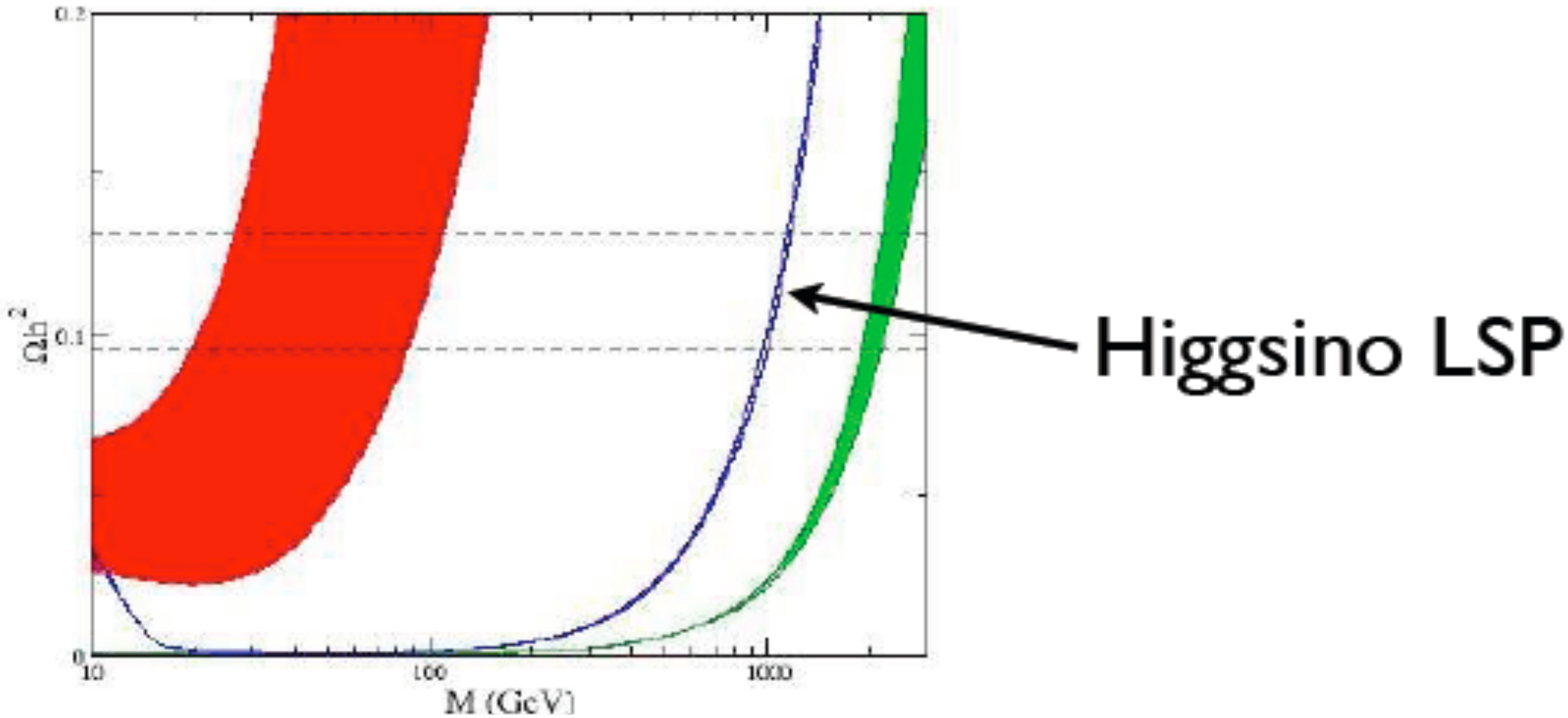
$\mu < M_1, M_2$

Can keep μ small and avoid fine-tuning, but increase M_1, M_2 and suppress direct detection cross section

Need additional constraint:
Invoke relic density!
Requirement: relic density equal/exceed observed relic density

(we are ignoring contributions from squarks, including them can lead to larger annihilation cross sections and lower relic density)

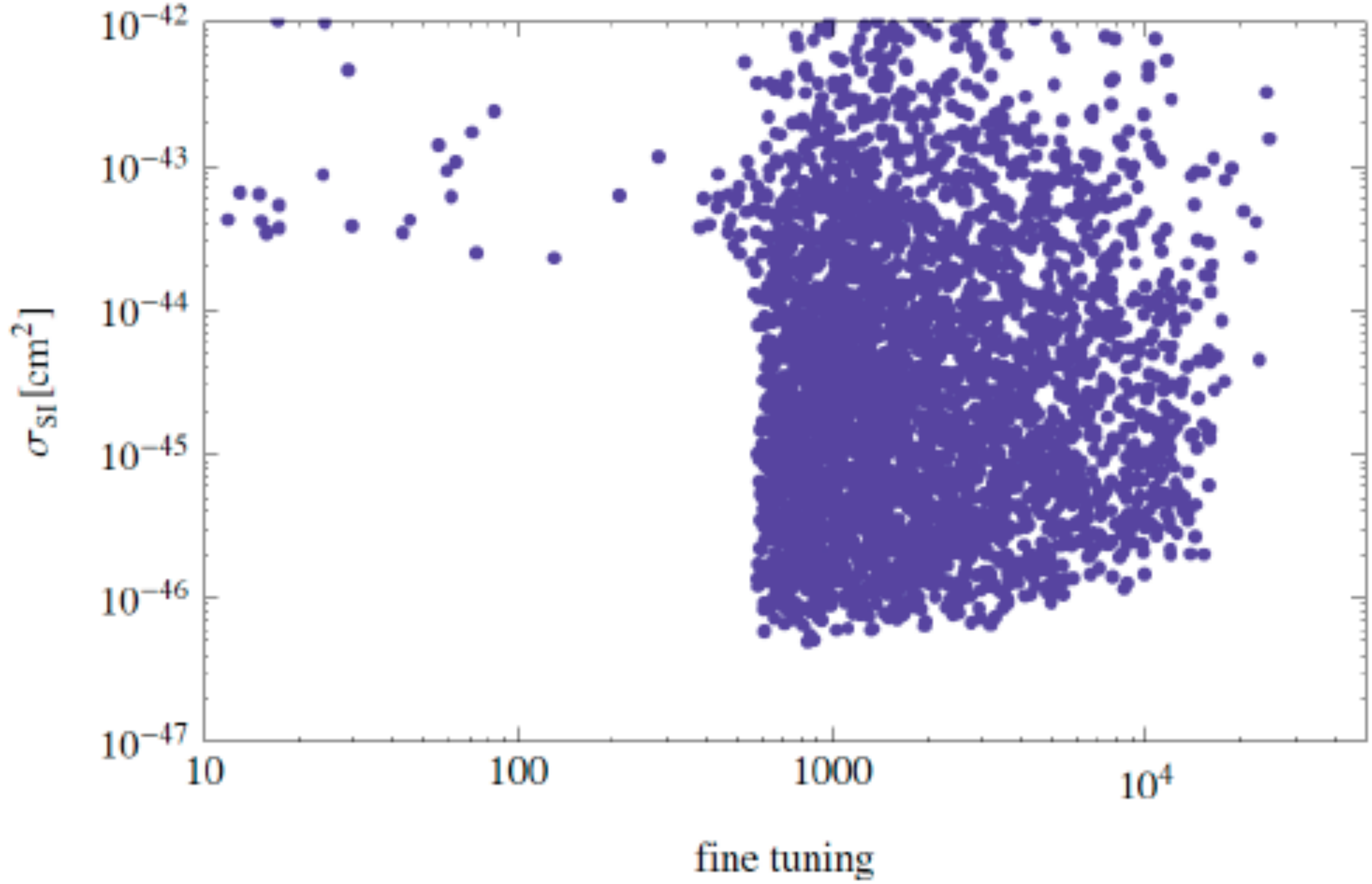
Higgsino Dark Matter



[Plot from Arkani-Hamed, Delgado, Giudice, hep-ph/0601041]

require relic density to equal/exceed observed relic density
$\rightarrow$ require $M_{LSP} \sim \mu >$ TeV $\rightarrow$ HUGE fine-tuning

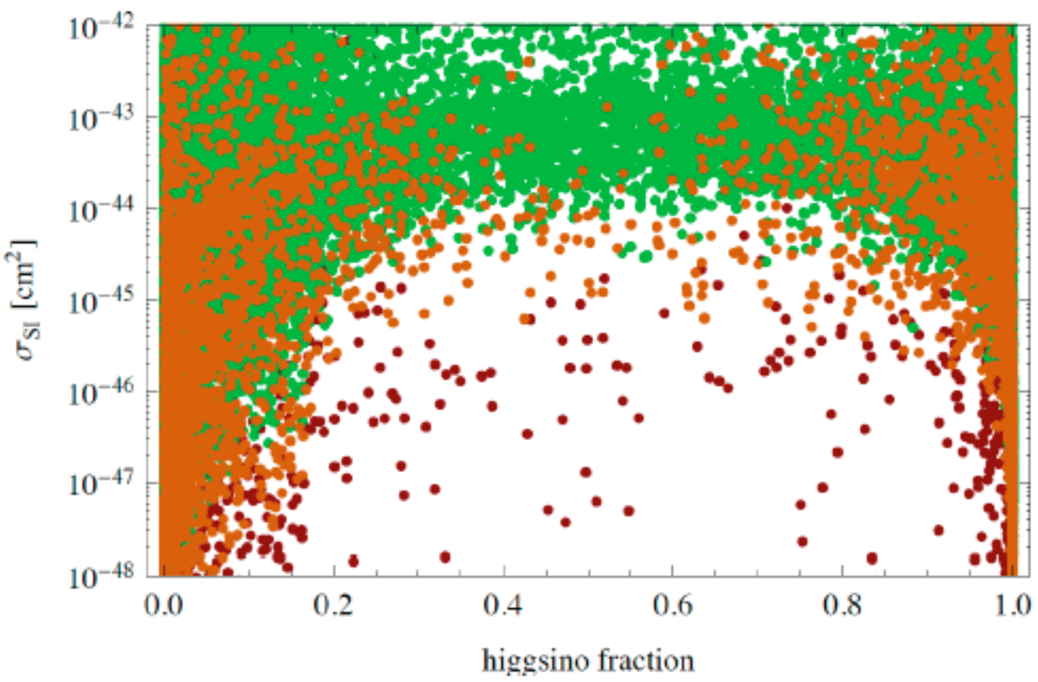
Higgsino Dark Matter



Negative/Complex Parameters

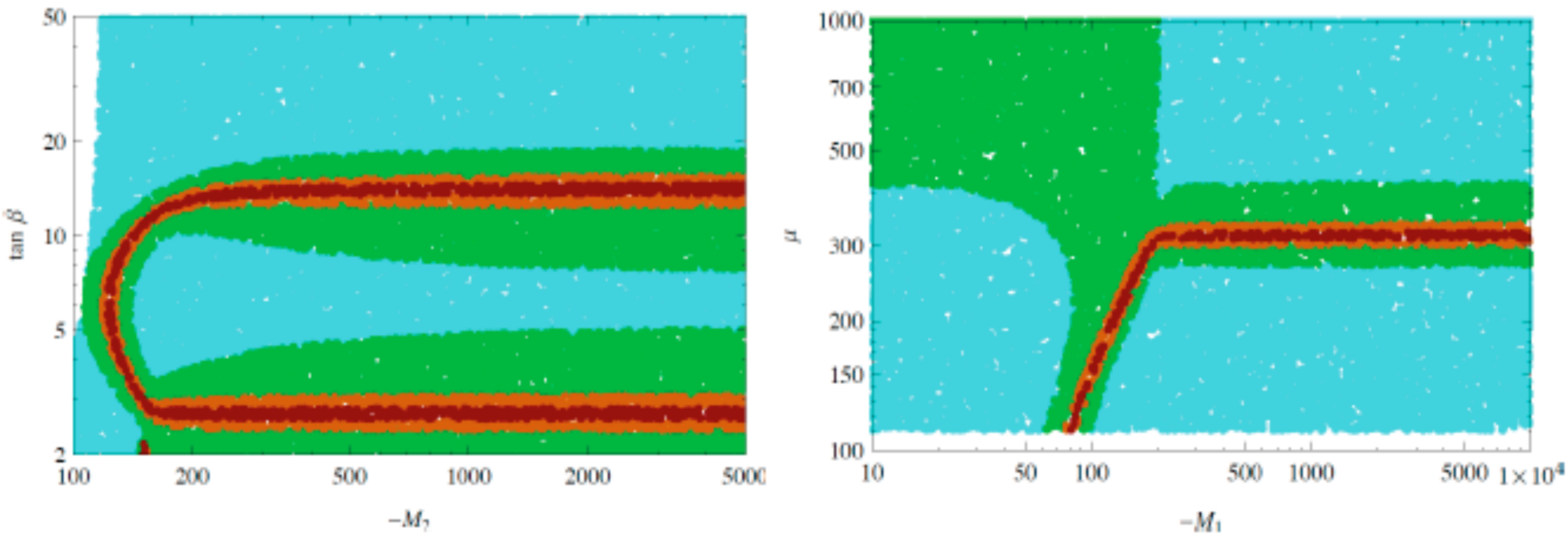
(Choose basis where M_1, M_2 can be negative/complex)

- Cancellations between contributions possible, aforementioned correlations no longer hold



Negative/Complex Parameters

However, such cases themselves require parameters to be tuned to achieve the right cancellation



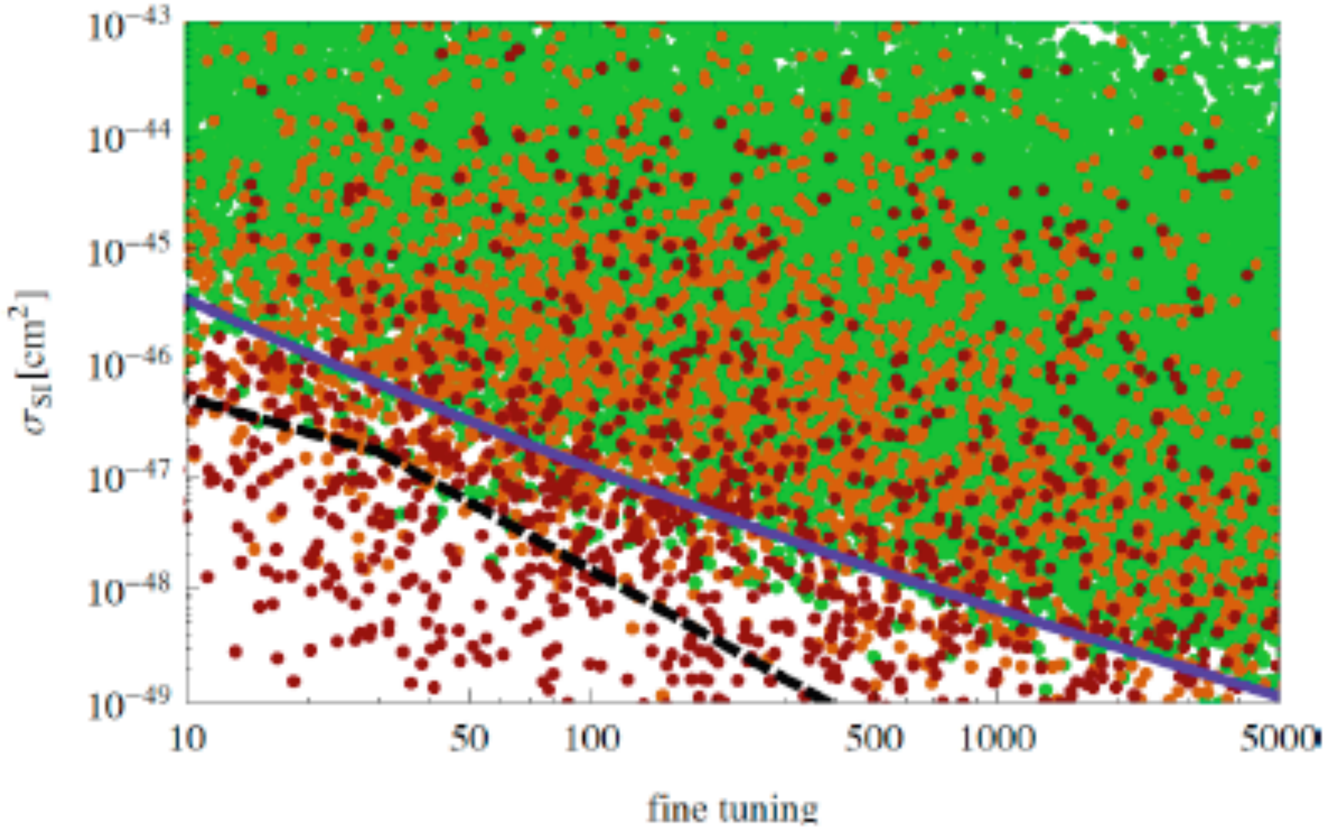
Red, orange, green, cyan: $\log_{10}\sigma$ < -47,-46,-45, and above

Quantify this accidental cancellation in the same way as fine-tuning in the EWSB sector:

$$\Delta_{\rm acc} \equiv \sqrt{\sum_{i=1}^{5}\left(\frac{\partial \log \sigma}{\partial \log p_i}\right)^2}$$

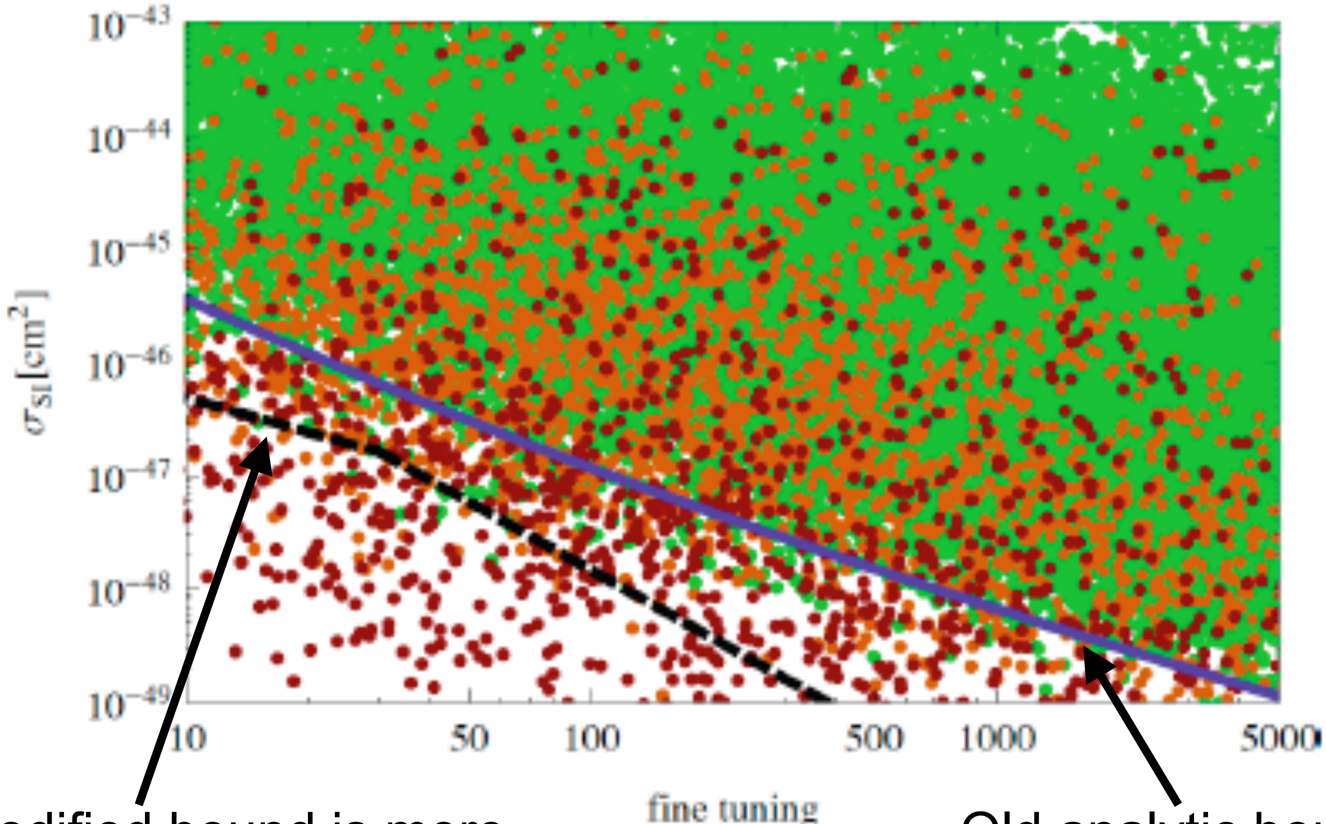
Negative/Complex Parameters

Red, orange, green: Δacc > 30,10, <10



Negative/Complex Parameters

Red, orange, green: Δacc > 30,10, <10

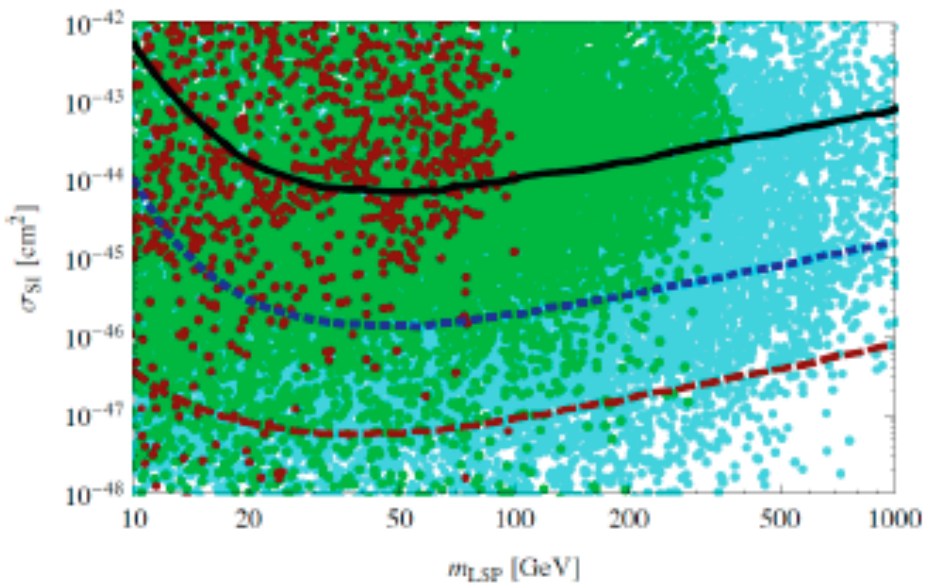


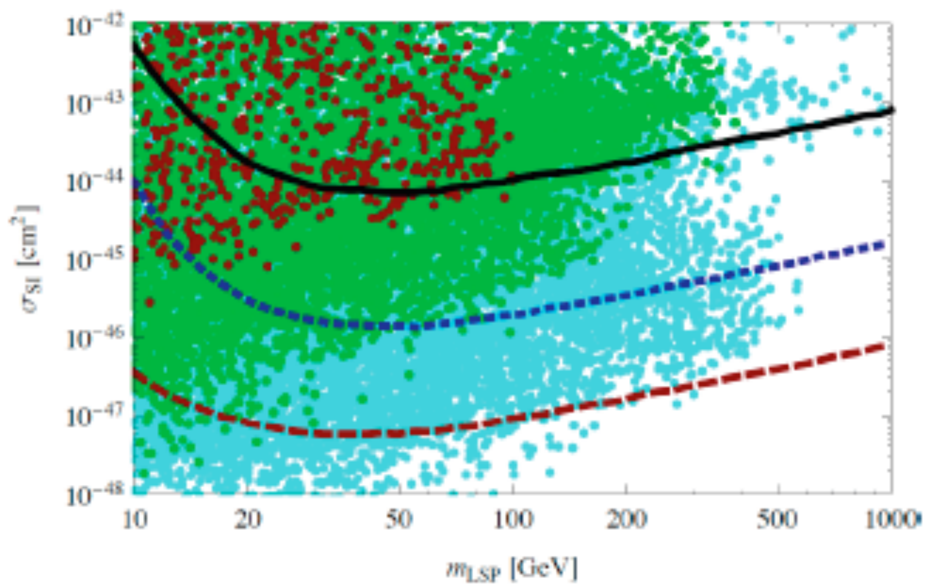
A modified bound is more satisfactory but not absolute

Old analytic bound no longer applicable

Negative/Complex Parameters

With (left) and without (right) points with accidental cancellations in direct detection cross section





Summary of MSSM implications

- Current Xenon100 bounds require pure gaugino or higgsino LSP
- Gaugino LSP: smaller direct detection cross sections correlate with stronger fine-tuning; current Xenon100 bounds already imply 10% or worse tuning for LSP heavier than 70 GeV
- Higgsino LSP: a mild relic density constraint already requires sub-percent level fine-tuning
- Xenon1T can probe regions with fine tuning down to percent level
- These statements apply in the most general MSSM, assuming only the absence of accidental cancellations

However, MSSM already suffers from naturalness problems:

- μ problem

The natural value of μ is order Plank scale, NOT weak scale

- Non observation of Higgs at LEP II

Tree level prediction: $m_H < m_Z$

LEP II bound: $m_H > 114$ GeV

Need to tune squark masses to get a large enough loop correction to push m_H above the LEP II bound

These problems evaded in extended models of supersymmetry

A representative case: **NMSSM**

extend MSSM by a single gauge-singlet superfield S

- μ problem

Effective μ term of right order generated when scalar component of S acquires a VEV of order SUSY breaking scale

- Non observation of Higgs at LEP II

Light Higgs with reduced couplings, can lie below the LEP II experimental bound

Additional field content in the NMSSM

- One additional neutralino: the singlino

  mixes with the four MSSM neutralinos; dark matter can have a singlino component

- One additional CP-even and one CP-odd neutral Higgs boson

  New channels available for scattering

- Direct detection picture can be very different!

Can we get small direct detection cross sections without fine-tuning in the NMSSM?

WORK IN PROGRESS…

BACKUP SLIDES

Direct Detection Cross Section

Spin independent, elastic DM-nucleon scattering at zero momentum exchange

$$\sigma = \frac{4m_r^2 f_p^2}{\pi} \qquad \frac{f_p}{m_p} = \sum_{q=u,d,s} f_{T_q}^{(p)} A_q + \frac{2}{27} f_{TG}^{(p)} \sum_{q=c,b,t} A_q. \qquad f_{TG}^{(p)} = 1 - \sum_{q=u,d,s} f_{T_q}^{(p)}.$$

$$f_{Tu}^{(p)} = 0.08, \quad f_{Td}^{(p)} = 0.037, \quad \underline{f_{Ts}^{(p)} = 0.34.}$$

$$\begin{aligned} A_i \;=\; & -\frac{g}{4m_W B_i}\Big[\left(\frac{D_i^2}{m_h^2} + \frac{C_i^2}{m_H^2}\right) \mathrm{Re}\left[\delta_{2i}(gZ_{\chi 2} - g' Z_{\chi 1})\right] \\ & + C_i D_i \left(\frac{1}{m_h^2} - \frac{1}{m_H^2}\right) \mathrm{Re}\left[\delta_{1i}(gZ_{\chi 2} - g' Z_{\chi 1})\right]\Big], \end{aligned} \qquad (6)$$

where for up-type quarks

$$B_u = \sin\beta\,, \quad C_u = \sin\alpha\,, \quad D_u = \cos\alpha\,, \quad \delta_{1u} = Z_{\chi 3}\,, \quad \delta_{2u} = Z_{\chi 4}\,; \qquad (7)$$

while for down-type quarks

$$B_d = \cos\beta\,, \quad C_d = \cos\alpha\,, \quad D_d = -\sin\alpha\,, \quad \delta_{1d} = Z_{\chi 4}\,, \quad \delta_{2d} = -Z_{\chi 3}\,. \qquad (8)$$

Derivation: Analytic bound for gaugino dark matter

Since g'<g, assume bino dark matter: $M_1 << \mu << M_2$
Decoupling limit $m_A >> m_Z$

From the resulting 3x3 matrix

$$Z_{\chi 3} \approx s_w \frac{m_Z}{\mu}\left(s_\beta + c_\beta \frac{M_1}{\mu}\right),$$

$$Z_{\chi 4} \approx s_w \frac{m_Z}{\mu}\left(-c_\beta - s_\beta \frac{M_1}{\mu}\right)$$

$$\Longrightarrow \quad A_u \approx A_d \approx \frac{\pi\alpha}{c_w^2}\frac{1}{m_h^2\mu}\left(\sin 2\beta + \frac{M_{\rm LSP}}{\mu}\right)$$

Large tan β limit

$$\Delta \approx \frac{4}{m_Z^2}\sqrt{\mu^4 + \frac{m_A^4}{\tan^2\beta}} \qquad \Delta \approx \frac{4\mu^2}{m_Z^2}$$

$$\Longrightarrow \quad A_u \approx A_d \approx \frac{4\pi\alpha}{c_w^2 m_Z m_h^2}\frac{1}{\sqrt{\Delta}}\left(\frac{1}{\tan\beta} + \frac{1}{\sqrt{\Delta}}\frac{M_{\rm LSP}}{m_Z}\right)$$