Here Be Dragons:

The Unexplored Continents of the CMSSM

Timothy Cohen
(SLAC)

with Jay Wacker

arXiv:1305.soon

SLAC ATLAS Jamboree
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Outline

I) Motivation

II) CMSSM Cartography

III) Dark Matter in the CMSSM

IV) Conclusions

MOTIVATION

The MSSM in the Era of Higgs Discovery

- A SM-like Higgs has been discovered at 125 GeV.

ATLAS [arXiv:1207.7214]; CMS [arXiv:1207.7235]

- This measurement is "consistent" with the MSSM (and its extensions).

$$m_h^2 \simeq m_Z^2 \cos^2 2\,\beta + \frac{3\,g^2\,m_t^4}{8\,\pi^2\,m_W^2}\left[\log\left(\frac{\widetilde{m}_{t_1}\,\widetilde{m}_{t_2}}{m_t^2}\right) + \frac{A_t^2}{\widetilde{m}_{t_1}\,\widetilde{m}_{t_2}}\left(1 - \frac{A_t^2}{12\,\widetilde{m}_{t_1}\,\widetilde{m}_{t_2}}\right)\right]$$

- Stops from O(100 GeV) to O(100 TeV) $\Rightarrow$ 4x heavier than pre discovery:

$$m_{h'} - m_h \simeq \frac{3\,g^2\,m_t^4}{16\,\pi^2\,m_h\,m_W^2}\log\frac{\widetilde{m}_{t'_1}\,\widetilde{m}_{t'_2}}{\widetilde{m}_{t_1}\,\widetilde{m}_{t_2}} \quad \Longrightarrow \quad \widetilde{m}_{t'_1}\,\widetilde{m}_{t'_2} \simeq \widetilde{m}_{t_1}\,\widetilde{m}_{t_2}\,2^{\frac{\Delta m_h}{5.6\text{ GeV}}}$$

- The motivation for weak-scale superpartners still stands:
  - Solves the hierarchy problem;
  - Explains the dark matter;
  - Predicts gauge coupling unification.

The MSSM in the Era of Higgs Discovery

- The parameter space of the MSSM is enormous.
  - The soft supersymmetry breaking Lagrangian includes more than 120 new dimensionful terms.
- How can we map out all possible signatures?
  - Simplified models: isolate particles for specific signature. Parameter space is tractable; only a few masses and branching ratios.
    Alwall, Le, Listanti, Wacker [arXiv:0809.3264]; Alwall, Schuster, Toro [arXiv:0810.3921]; LHC New Physics Working Group [arXiv:1105.2838]
  - pMSSM: phenomenologically motivated reduction to 19 parameters.
    Berger, Gainer, Hewett, Rizzo [arXiv:0812.0980]
  - CMSSM/mSUGRA: 4 parameters.
    Chamseddine, Arnowitt, Nath [PRL 49 (1982)]; Barbieri, Ferrara, Savoy [PLB (1982)]; Hall, Lykken, Weinberg [PRD (1983)]
- 4 parameters is potentially tractable.
- Can we understand all predictions of the CMSSM ansatz?

A Simple Ansatz - a wide range of dynamics

- The CMSSM is a four dimensional subspace of the *R*-parity conserving MSSM.
- It is defined at the GUT scale by the following (real) inputs:
  - The unified scalar soft mass, M_0 .
  - The unified gaugino mass: $M_{1/2}$.
  - The unified *A*-term: A_0 .
  - The ratio of the Higgs vevs: $\tan\beta$ (traded for the B_μ term).

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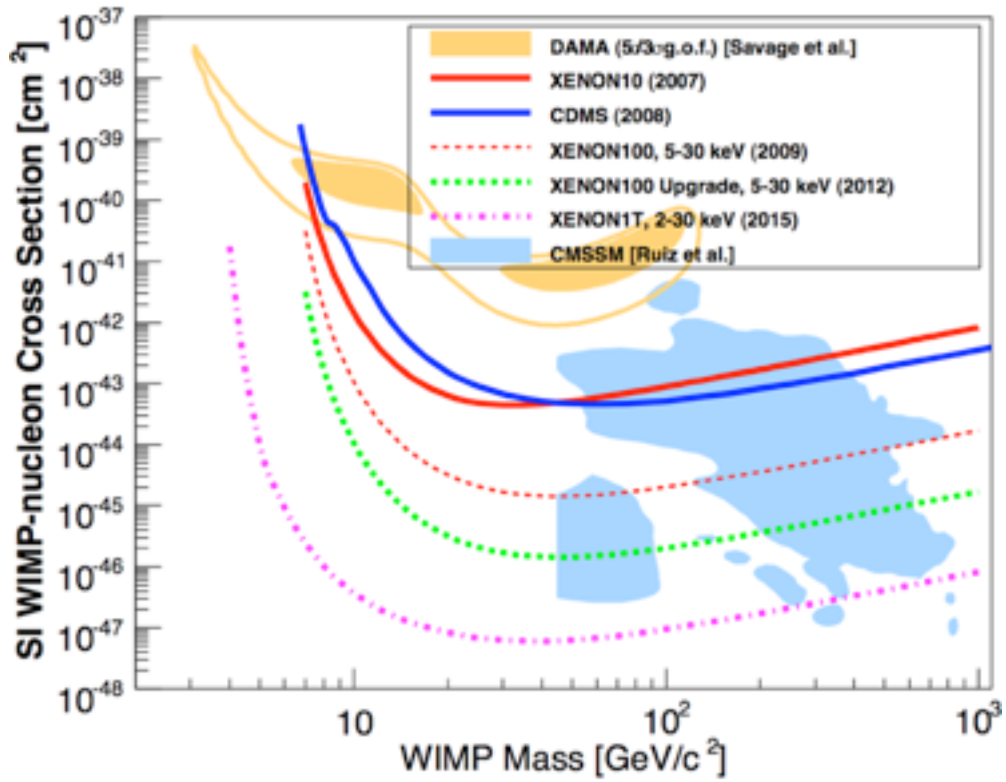
- Parameters are evolved to weak scale using RGEs.
- μ-term is determined by requiring $m_Z = 91$ GeV.
- 19 coupled RGEs integrated over 32 e-folds: relation between the inputs & low energy parameters is highly non-linear.

The State of the Art



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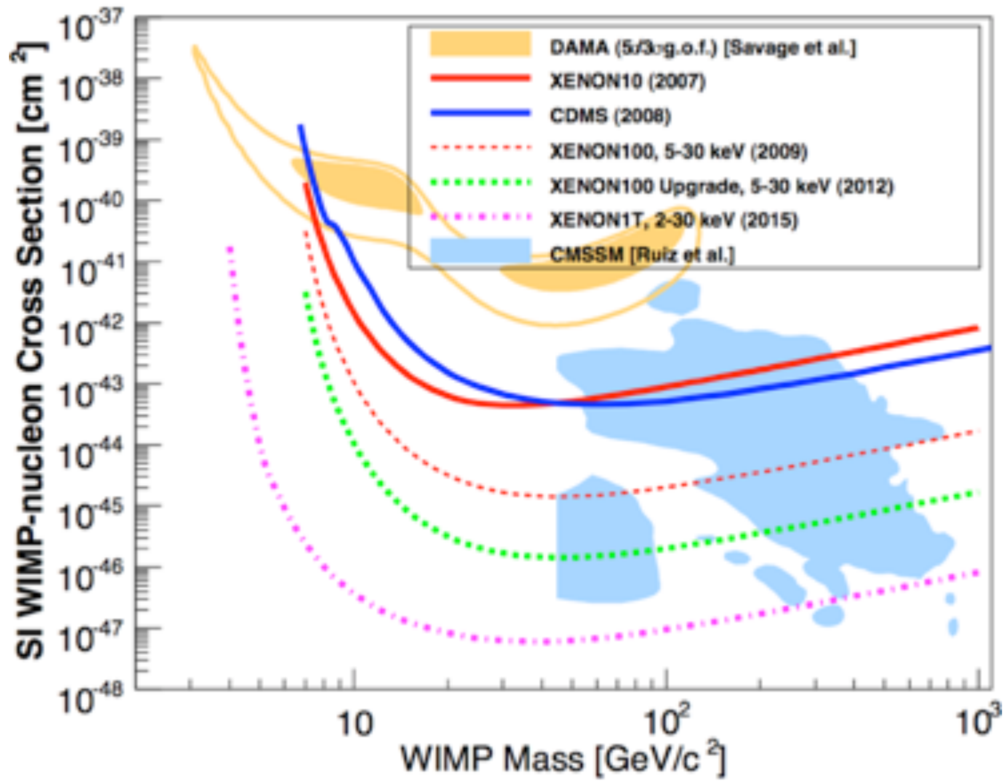

- What is the Higgs mass?
- Does the neutralino overclose the Universe?

Classification

- We will require that the Higgs mass is ~125 GeV and the neutralino comprises all of the dark matter.
- "Quadrants" are defined by the $\mathrm{sign}(A_0)$ and the $\mathrm{sign}(\mu)$.
- Schematically, the RGEs for *A* and *B* terms:

$$16\,\pi^2 \frac{d}{dt} A = A\,\left(|y|^2 - g^2\right) + y\,g^2\,M,$$
$$16\,\pi^2 \frac{d}{dt} B = B\,\left(|y|^2 - g^2\right) + \mu\,\left(A\,y^\dagger + g^2\,M\,\right),$$

- Very different low energy behavior depending on these signs.

Classification

- What process determines the relic abundance?
  - “light $\widetilde{\chi}^0$”: annihilation is dominated by the Z^0 and *h* poles.
  - “well-tempered”: annihilation via Higgsino/bino mixing to $W^+ W^-$.
  - “A^0 pole”: annihilation is dominated by an *s*-channel A^0 resonance.
  - “stau coannihilation”
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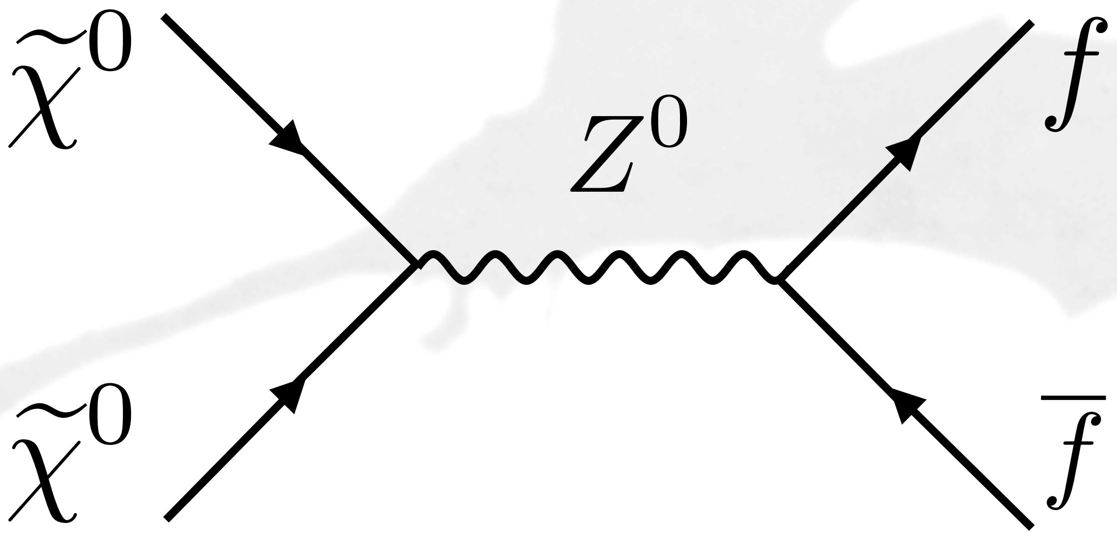

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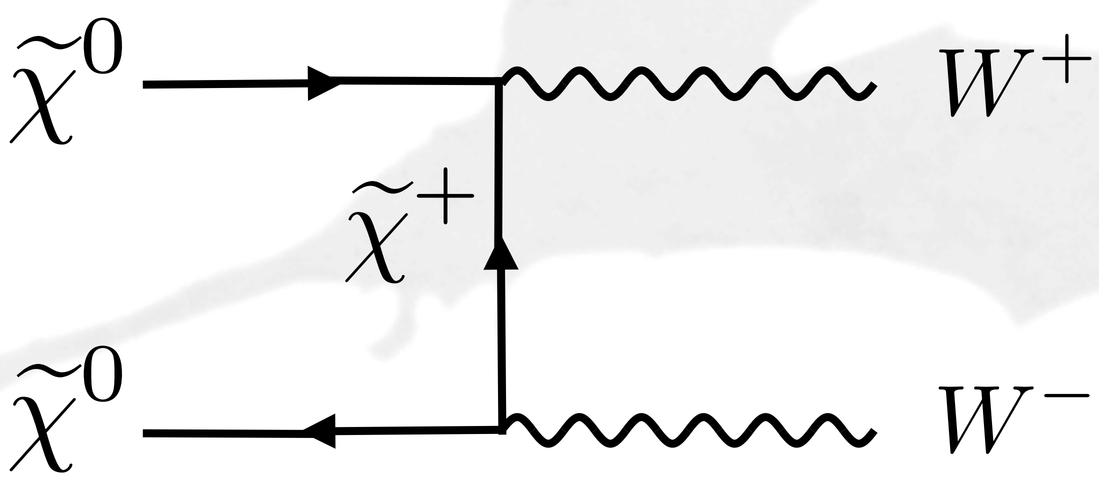

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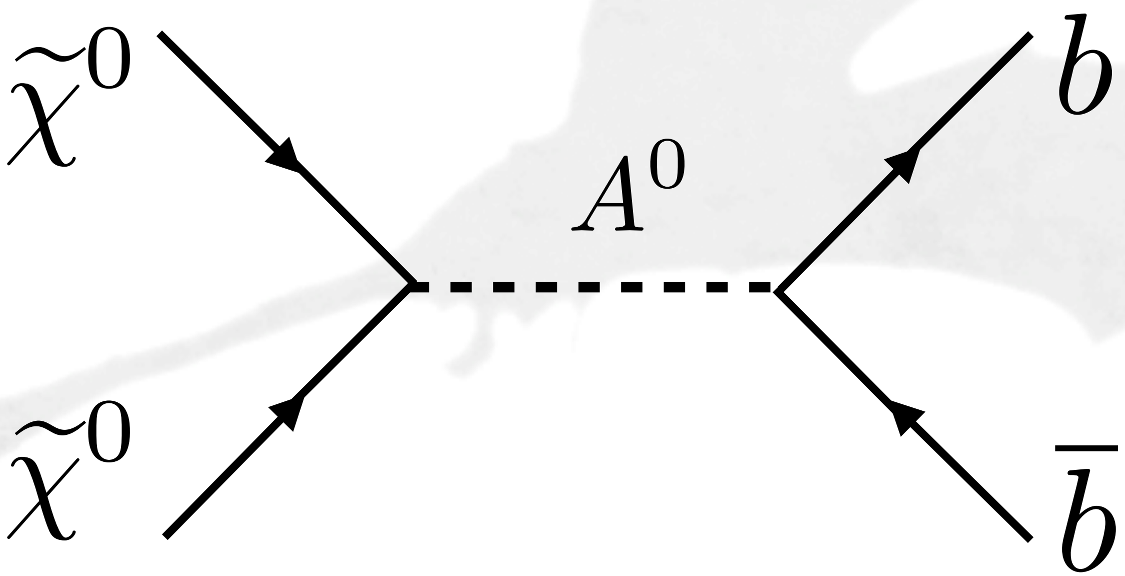

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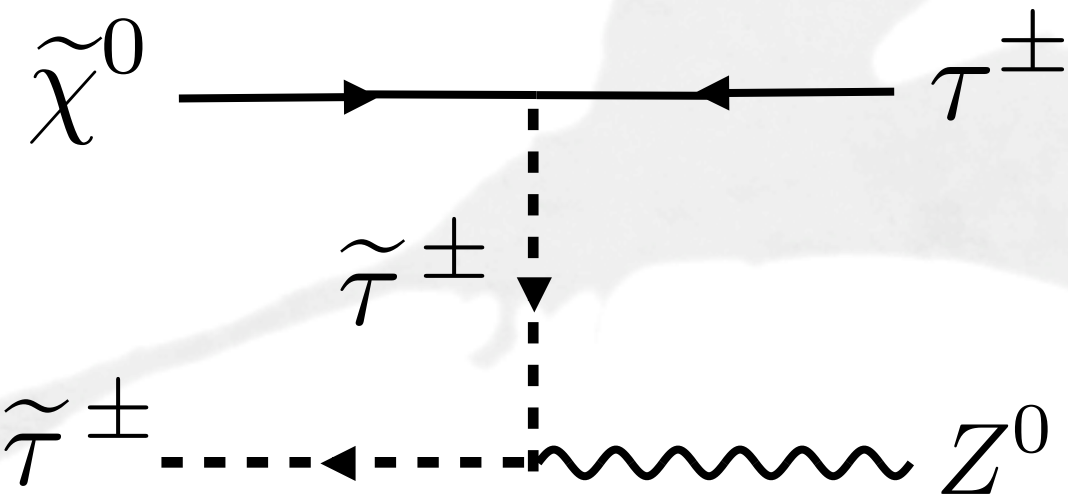

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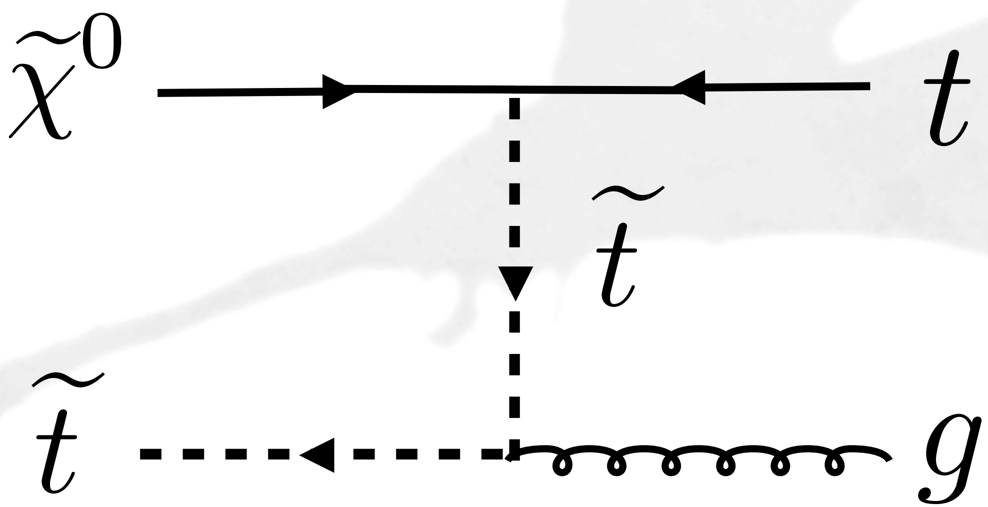

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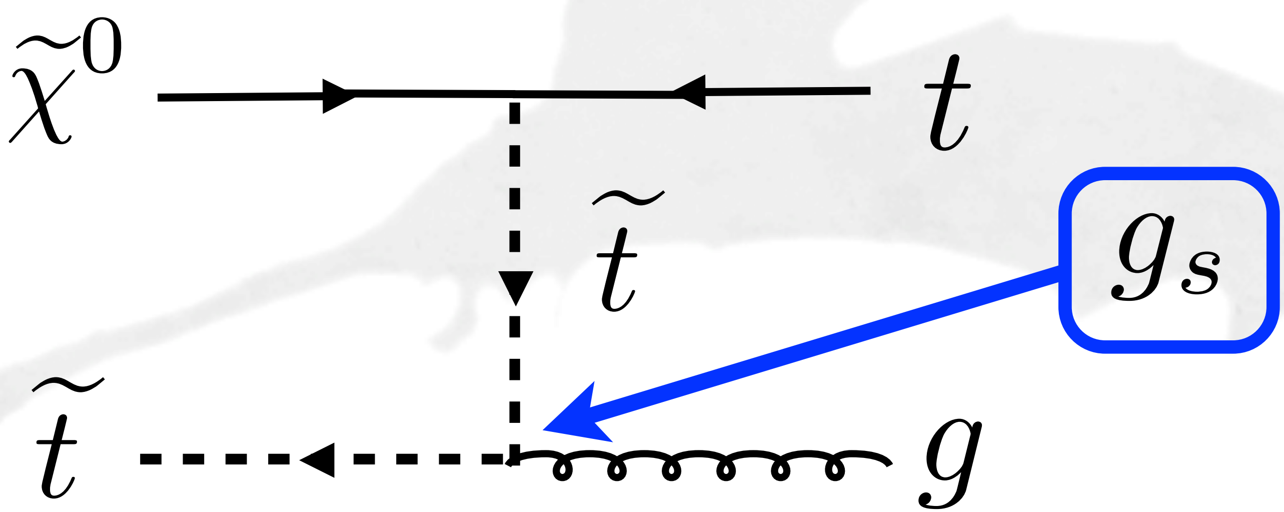

CMSSM Cartography

The CMSSM is Compact

- Higgs mass: $m_h = 125 \text{ GeV} \Longrightarrow M_0$ bounded.
- Relic density: not overclosing $\Longrightarrow m_\chi$ bounded.
- Lifetime of our vacuum longer than 14 Gyr $\Longrightarrow A_0$ bounded.
- Perturbativity of bottom Yukawa coupling $\Longrightarrow \tan\beta$ bounded.

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Consequence

The *entire* CMSSM is discoverable by human-buildable experiments

Tools

- SoftSUSY v3.3.7 computes the low energy spectrum from the CMSSM inputs. Allanach [arXiv:hep-ph/0104145]
  - The two loop MSSM RGEs (leading log decoupling is accounted for by the inclusion of all 1-loop finite terms).
  - The two loop contributions to the Higgs potential.
- DarkSUSY v5.1.1 computes the relic density and direct detection cross sections.
  - All 2-2 scattering processes are included.

  Gondolo, Edsjo, Ullio, Bergstrom, Schelke [arXiv:astro-ph/0406204]
- SUSY-HIT v1.3 computes the decay tables.

  Djouadi, Muhlleitner, Spira [arXiv:hep-ph/0609292]

Constraints

- 3 GeV error for the theoretical prediction of the Higgs mass:

$$122 \text{ GeV} < m_h < 128 \text{ GeV}$$

Allanach, Djuadi, Kneur, Porod, Slavich [arXiv:hep-ph/0406166]

- Require the relic density in the range:

$$0.08 < \Omega\, h^2 < 0.14$$

- Require that the lifetime for the vacuum to decay to charge/color breaking minimum be longer than 14 Gyr:

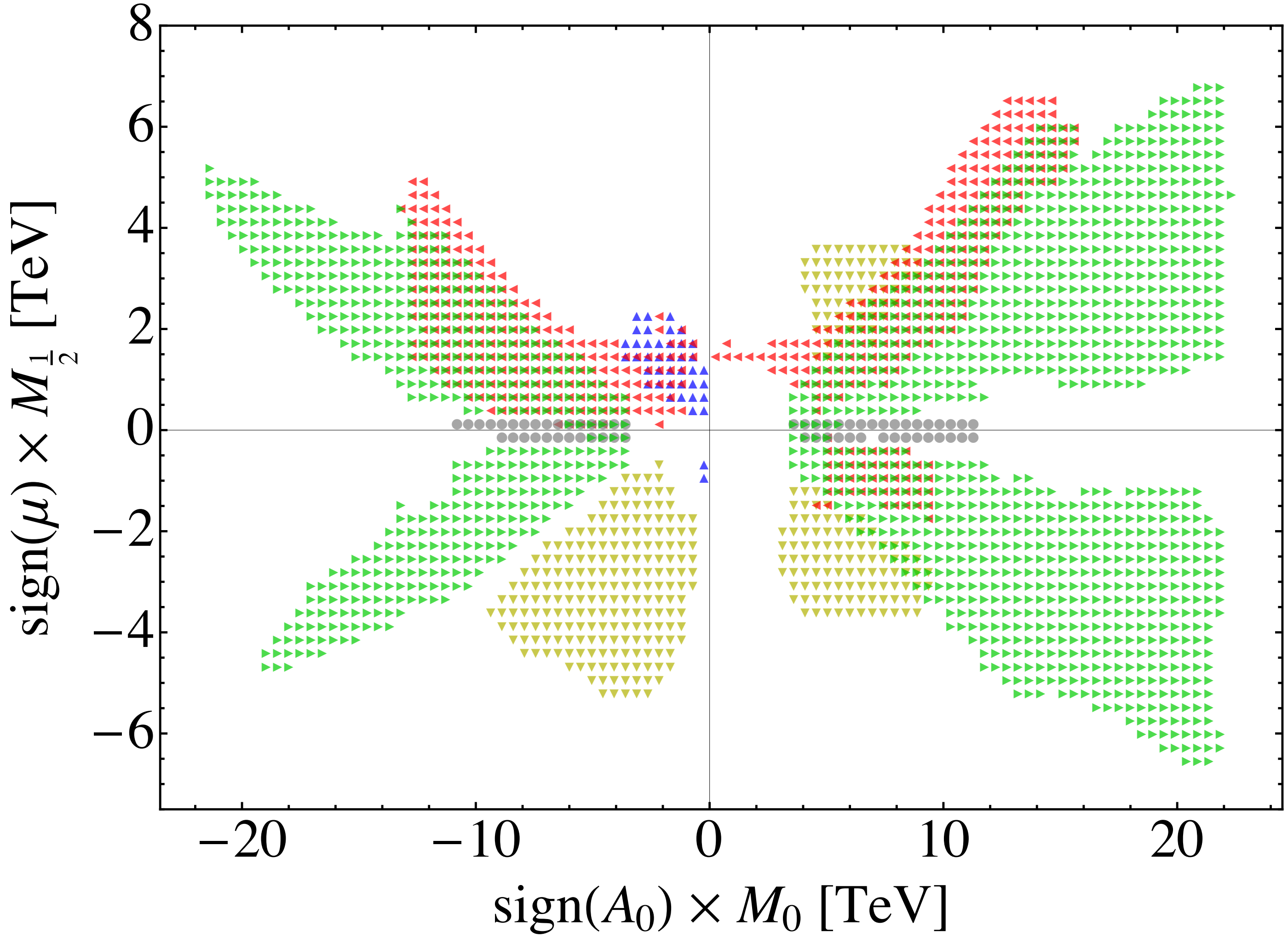
$$|a_t|^2 < (7.5\, m_{q_3}^2 + 7.5\, m_{u_3^c}^2 + 3\,(m_{H_u}^2 + |\mu|^2))$$

Kusenko, Langacker, Segre [arXiv:hep-ph/9602414]

- We require that the chargino mass satisfy a naive LEP bound:

$$\widetilde{m}_{\chi^+} > 100 \text{ GeV}$$

Charting the CMSSM



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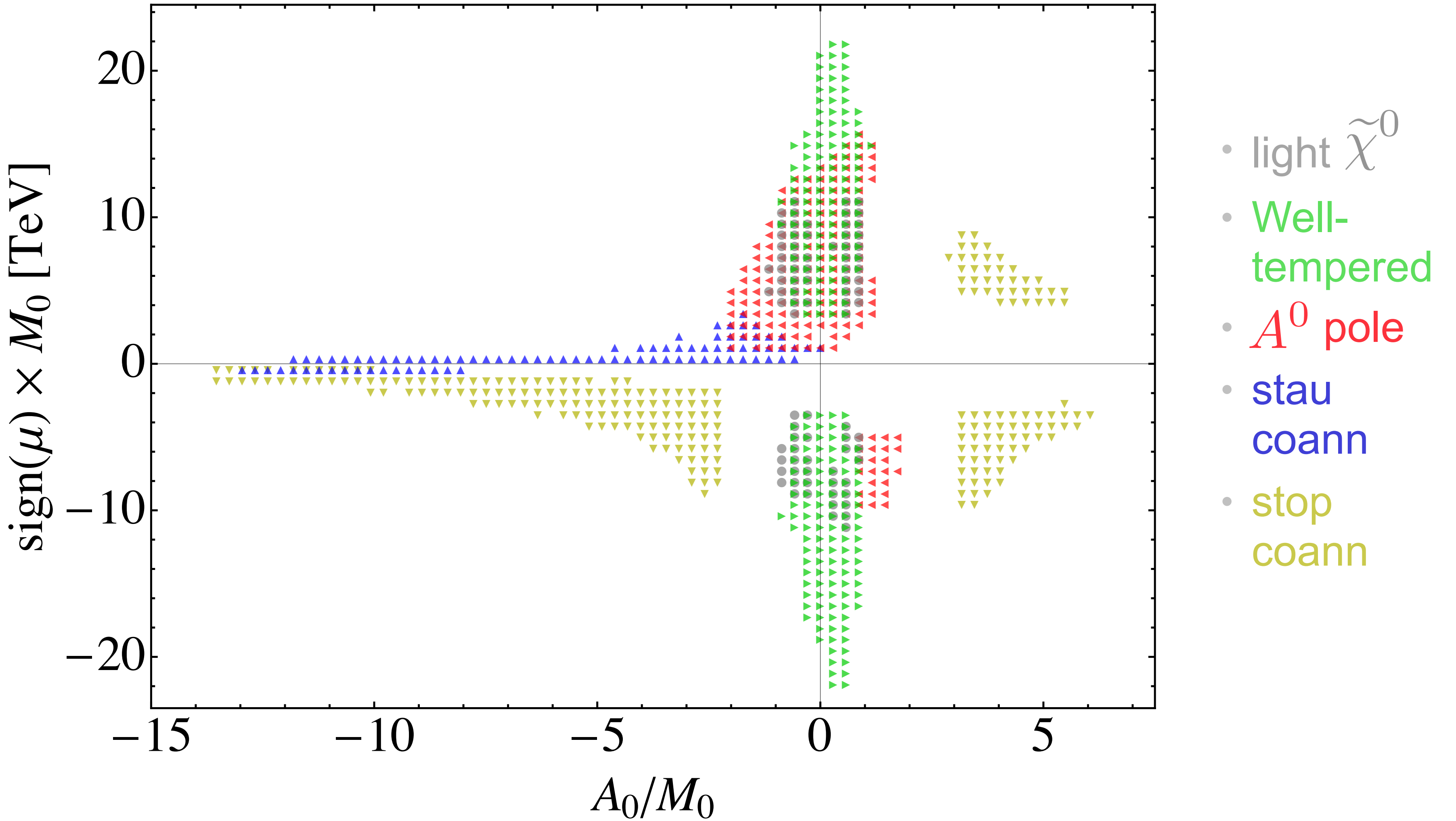

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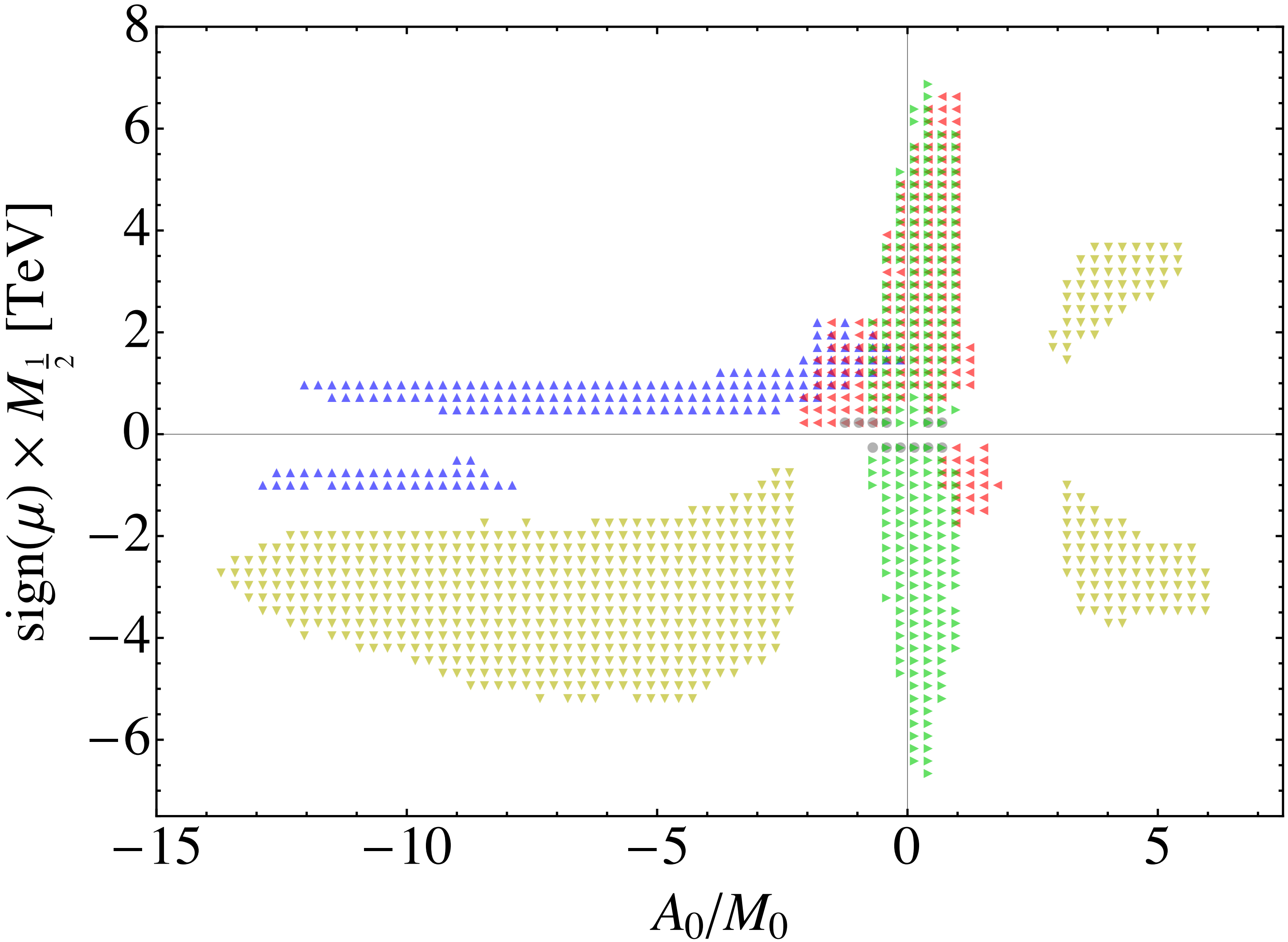

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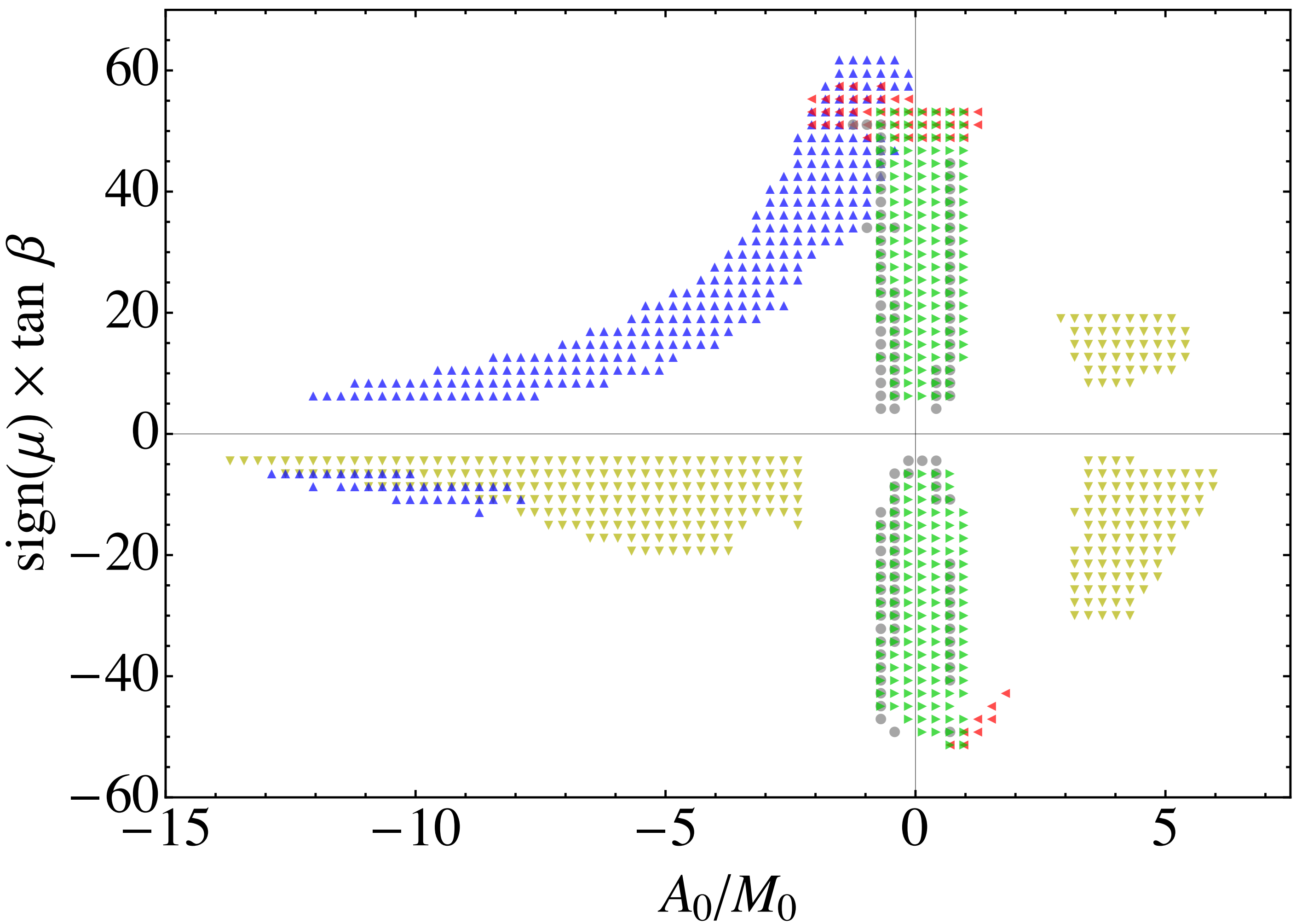

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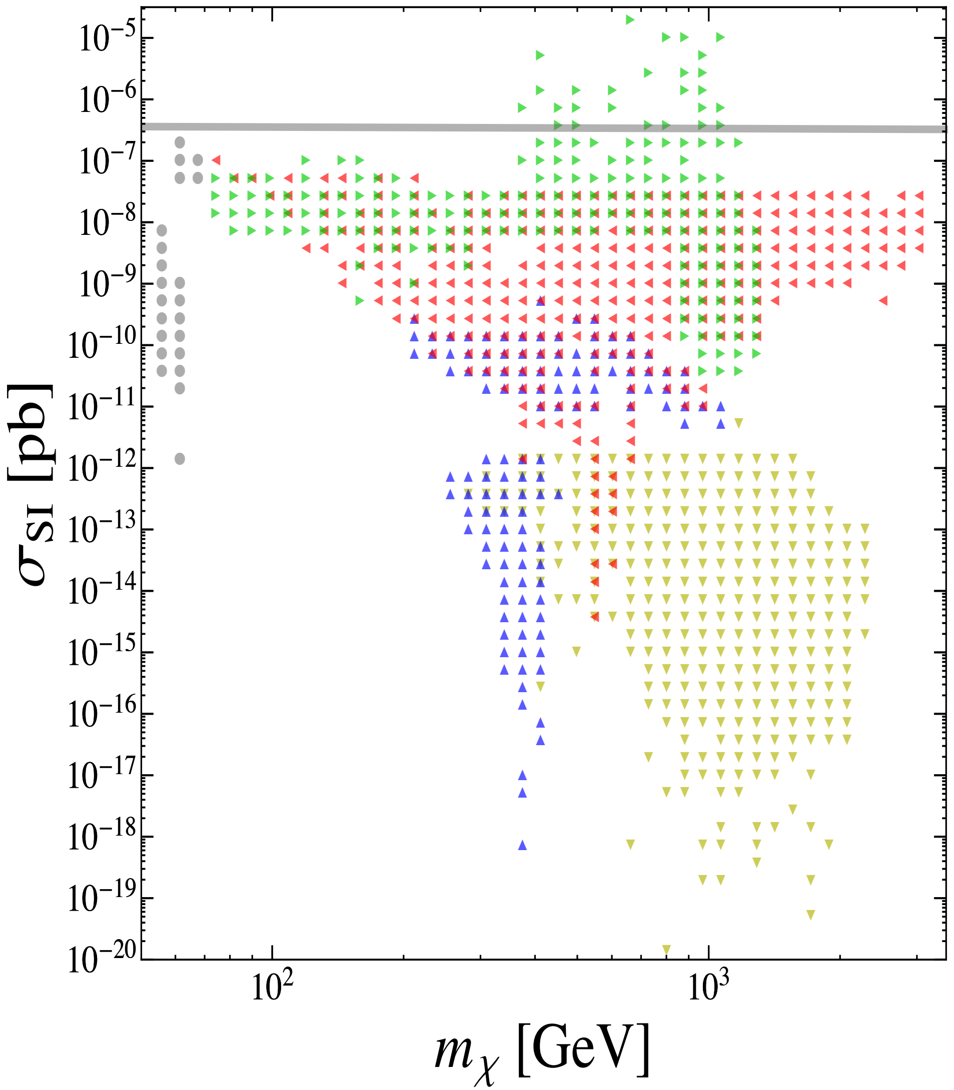
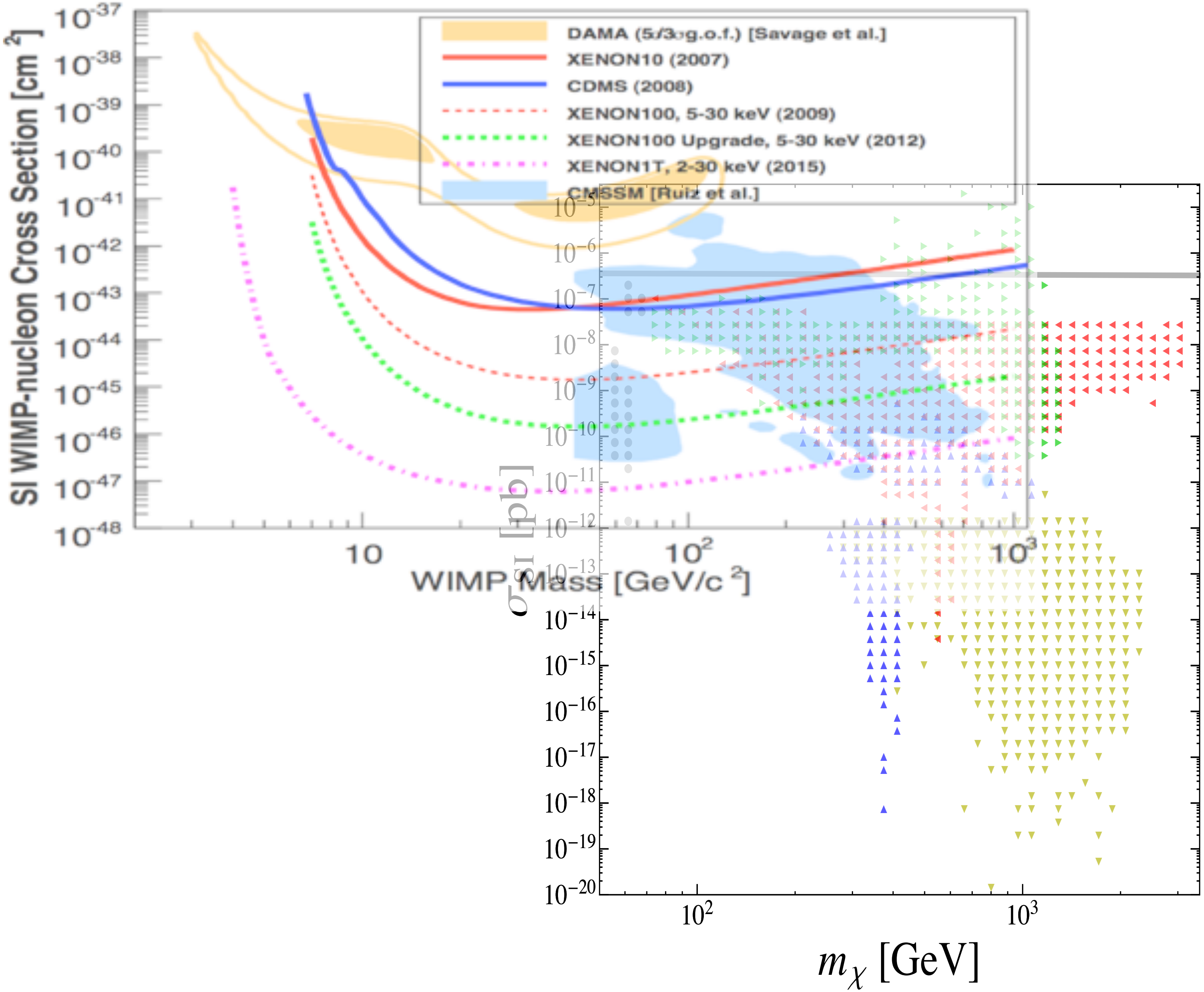
Dark Matter in the CMSSM

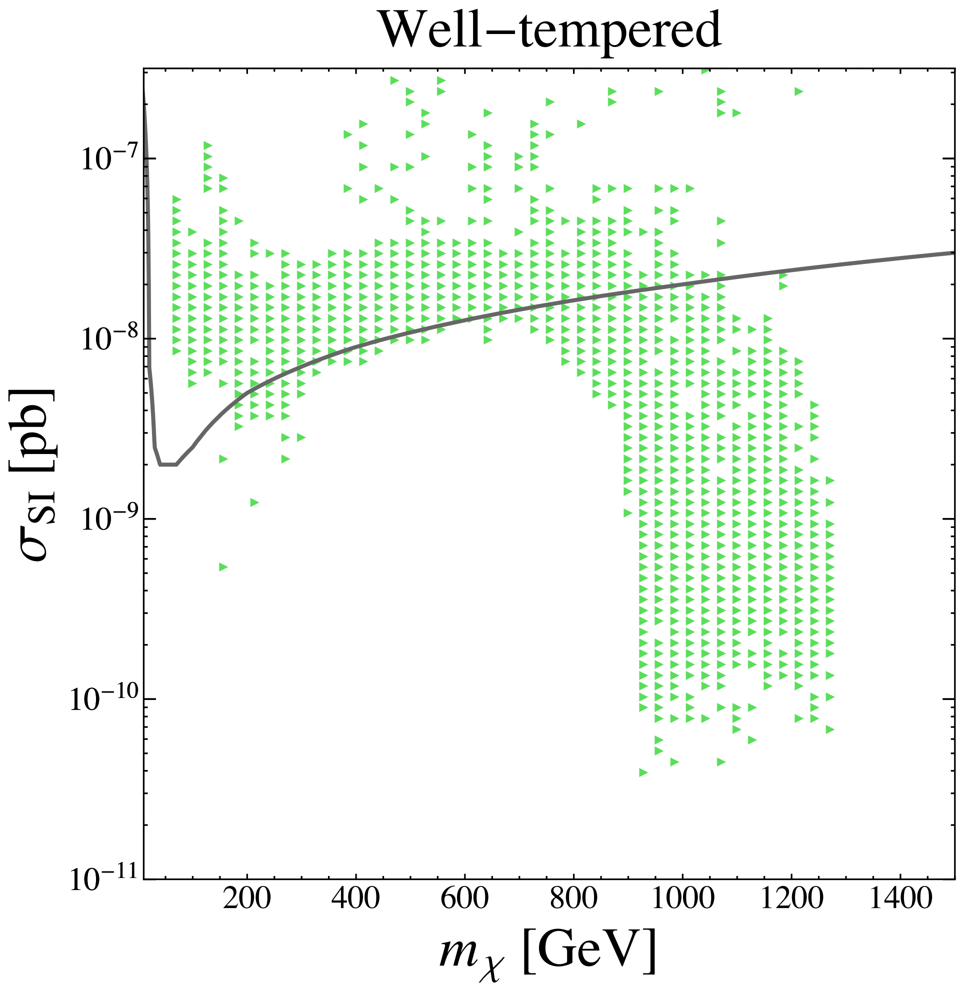
Direct Detection





SI WIMP-nucleon Cross Section [cm²]
WIMP Mass [GeV/c²]
DAMA (5σ/3σ g.o.f.) [Savage et al.]
XENON10 (2007)
CDMS (2008)
XENON100, 5-30 keV (2009)
XENON100 Upgrade, 5-30 keV (2012)
XENON1T, 2-30 keV (2015)
CMSSM [Ruiz et al.]
σ_SI [pb]
m_χ [GeV]

Will direct detection exclude well-tempered?



- A 1-ton Xenon experiment can reach spin-independent cross sections of $O(10^{-11}\ \text{pb})$ at 300 GeV.

Dark matter limit plotter [http://dmtools.brown.edu/]

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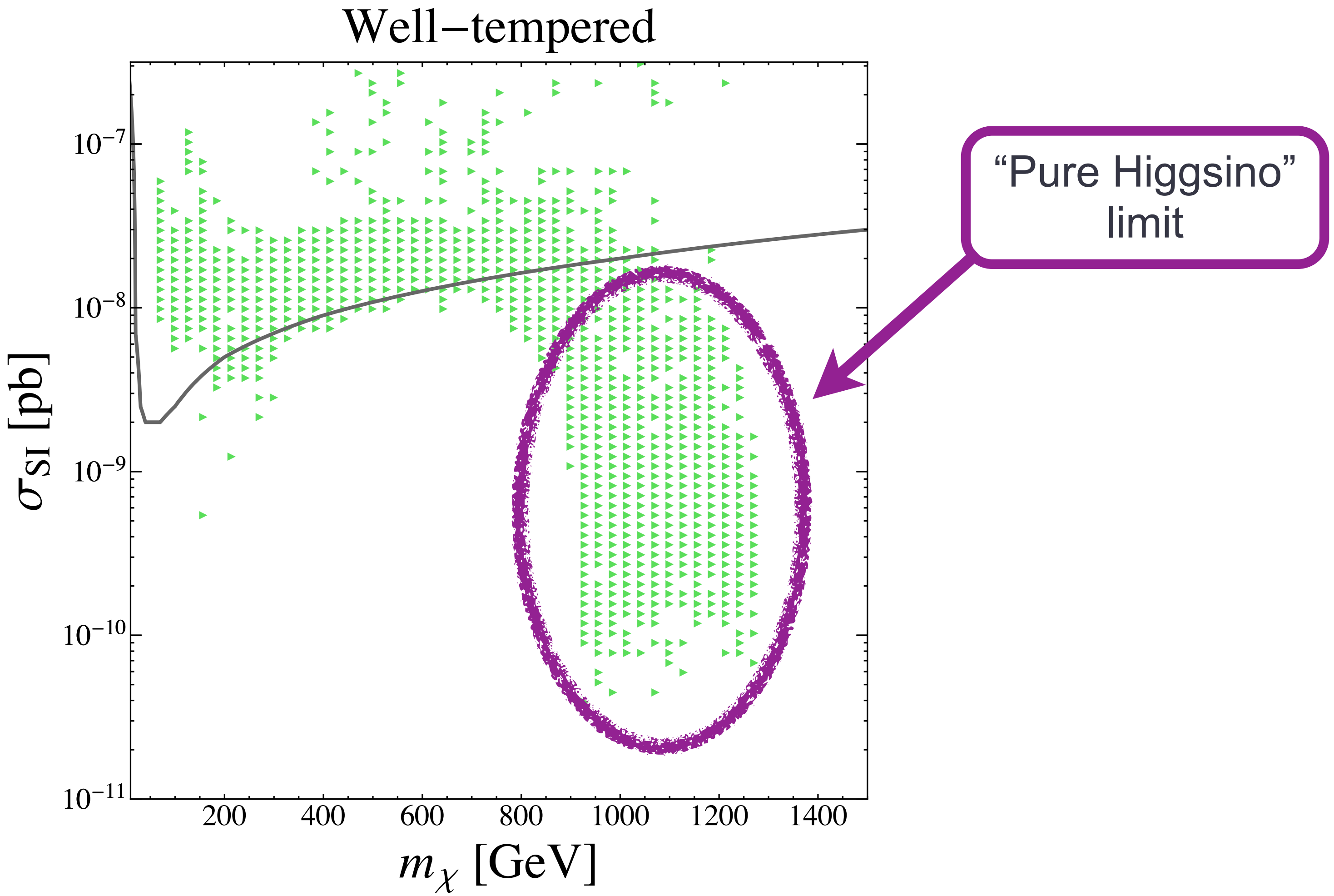

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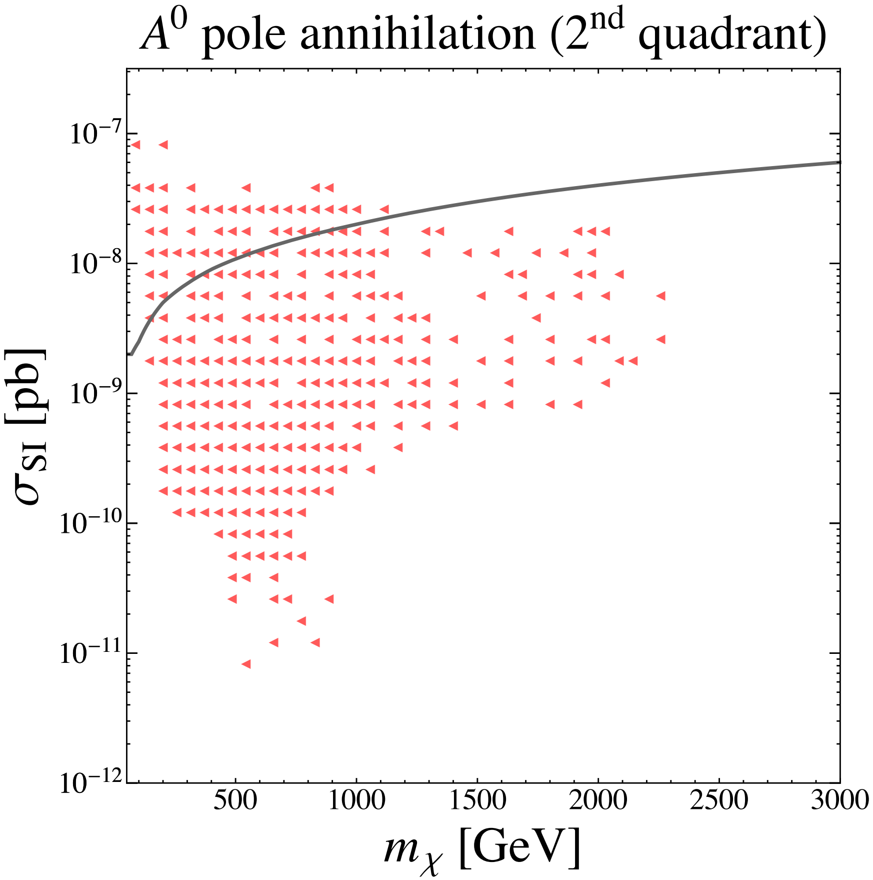
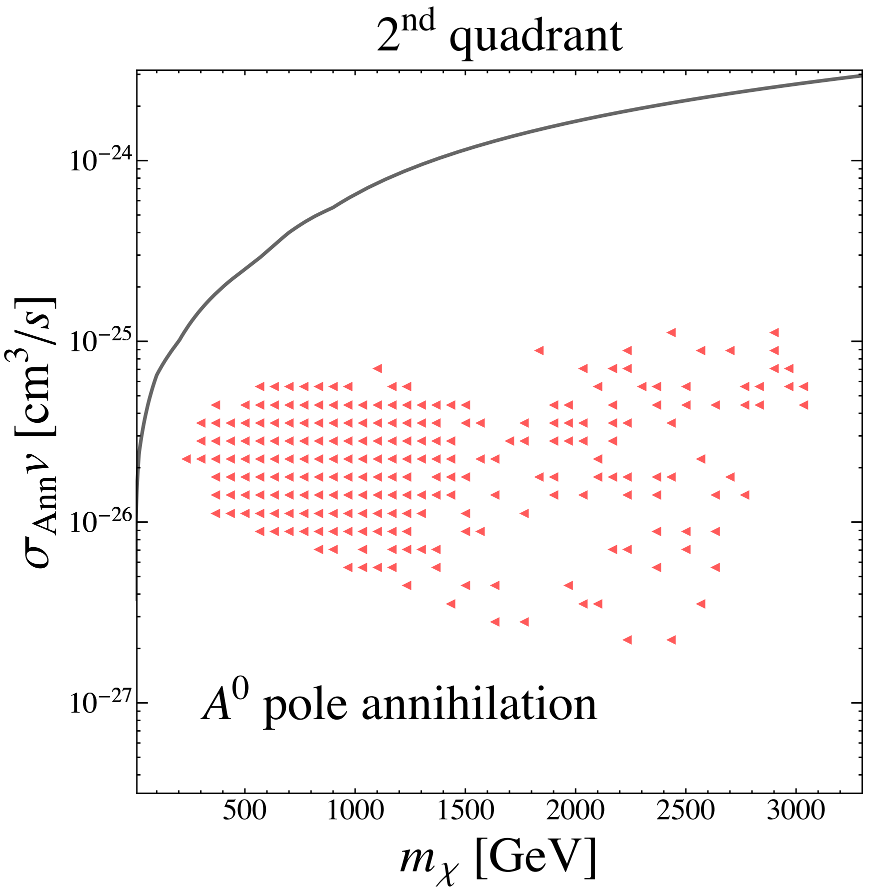
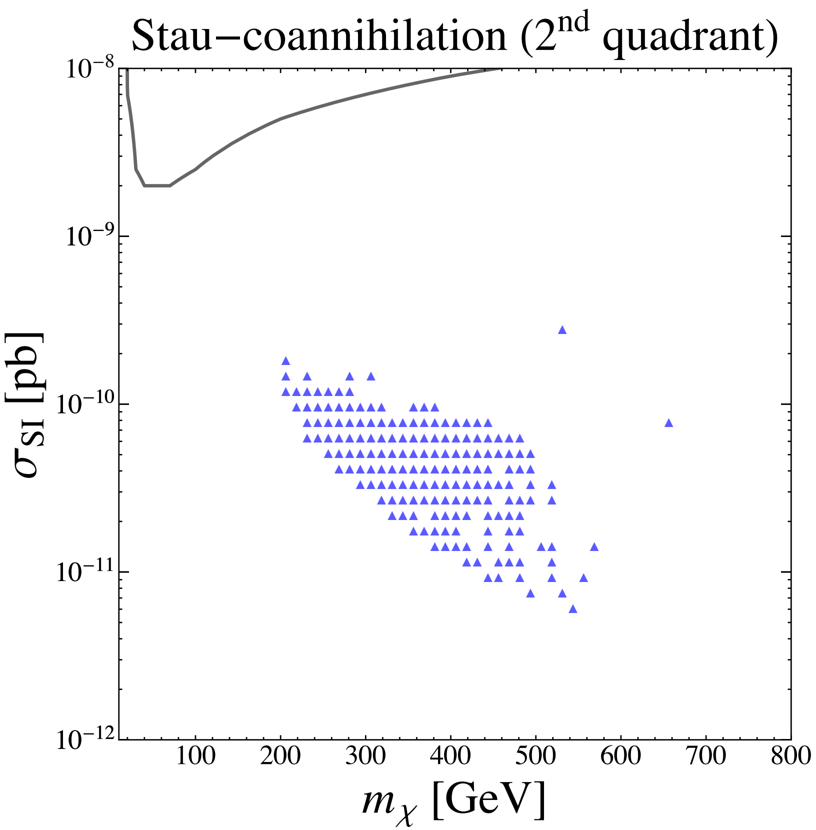
A-pole: Direct & Indirect Detection

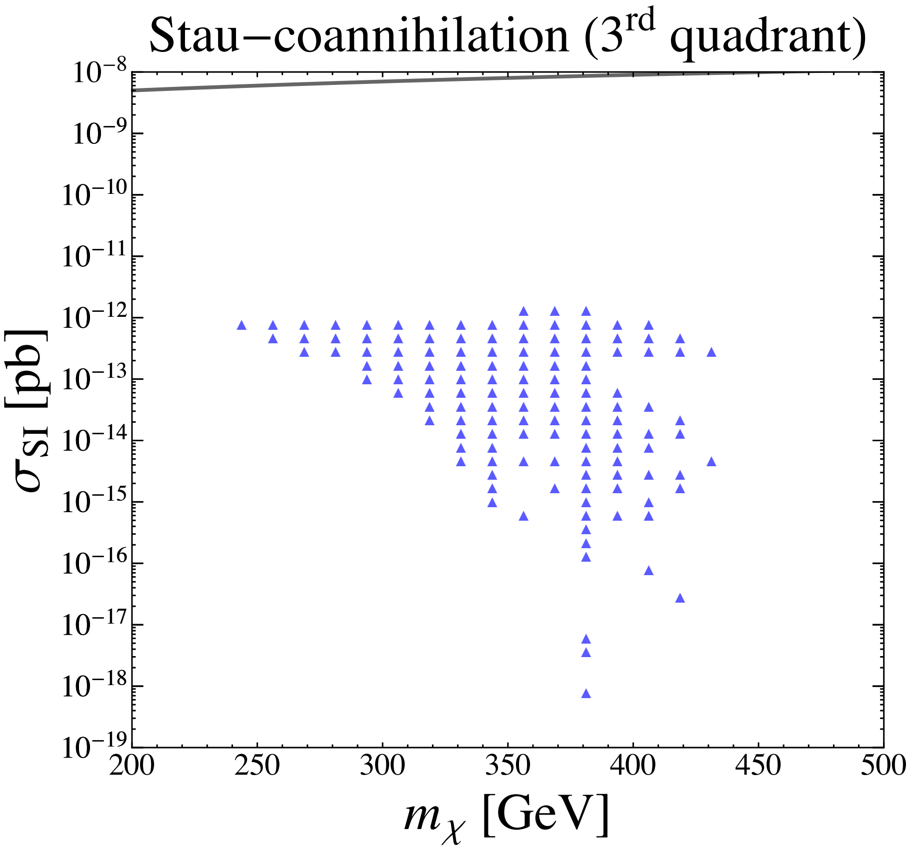




- 1st quadrant is similar but 4th quadrant extends below 10^{-14} pb .

Stau-coann: direct detection





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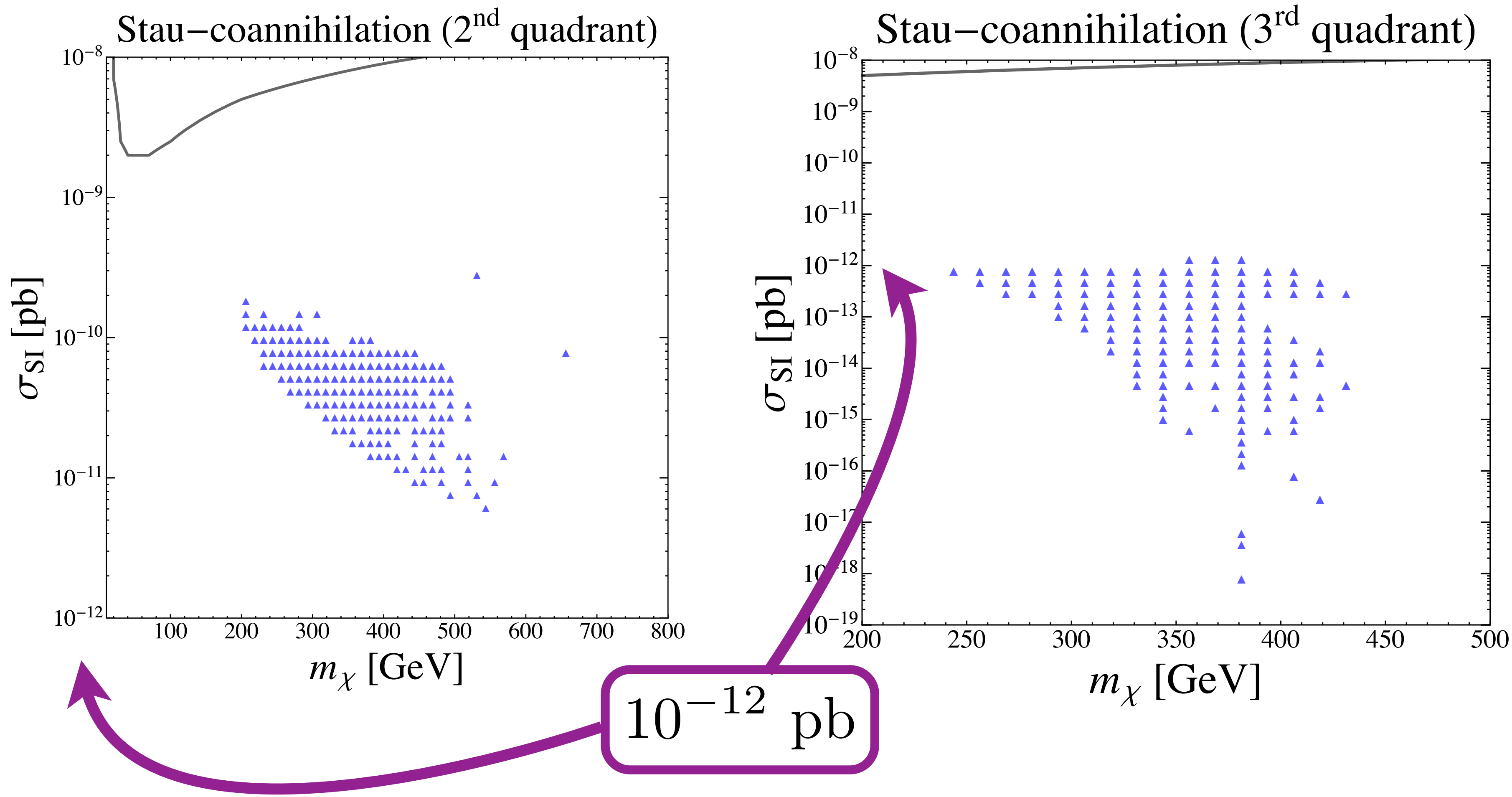
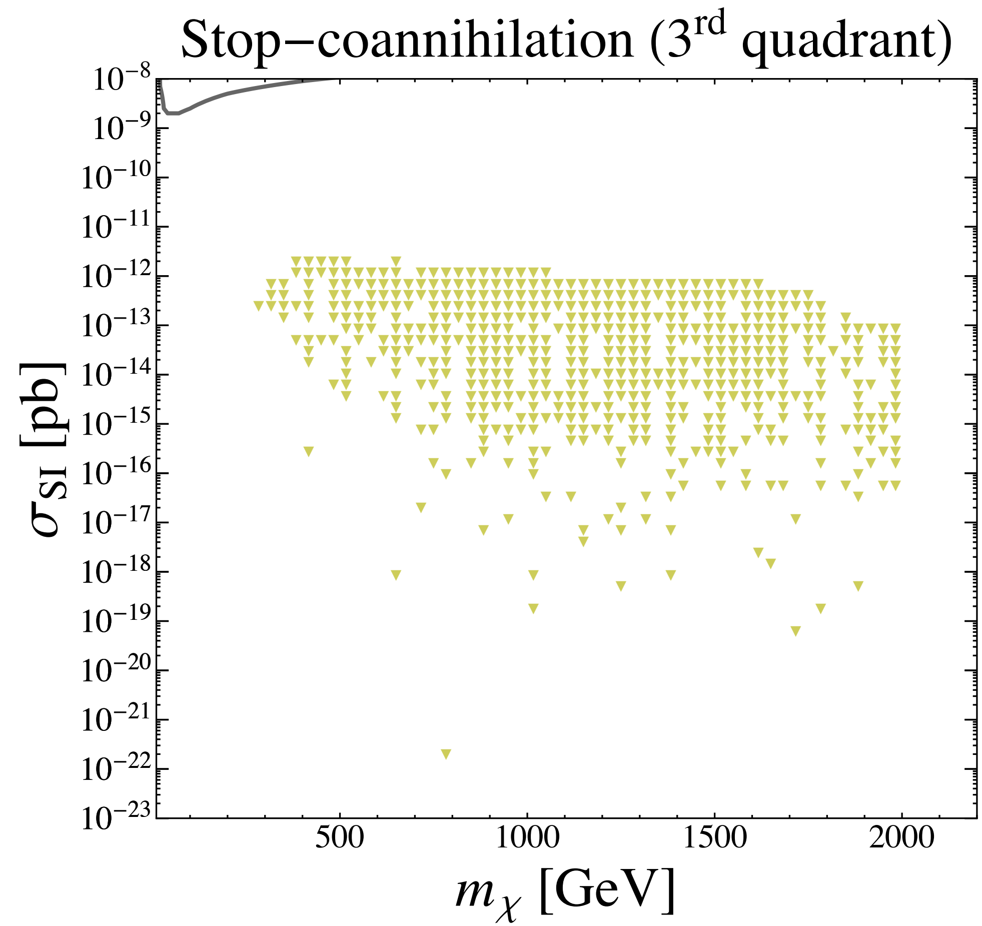


Stop-coannihilation: direct detection



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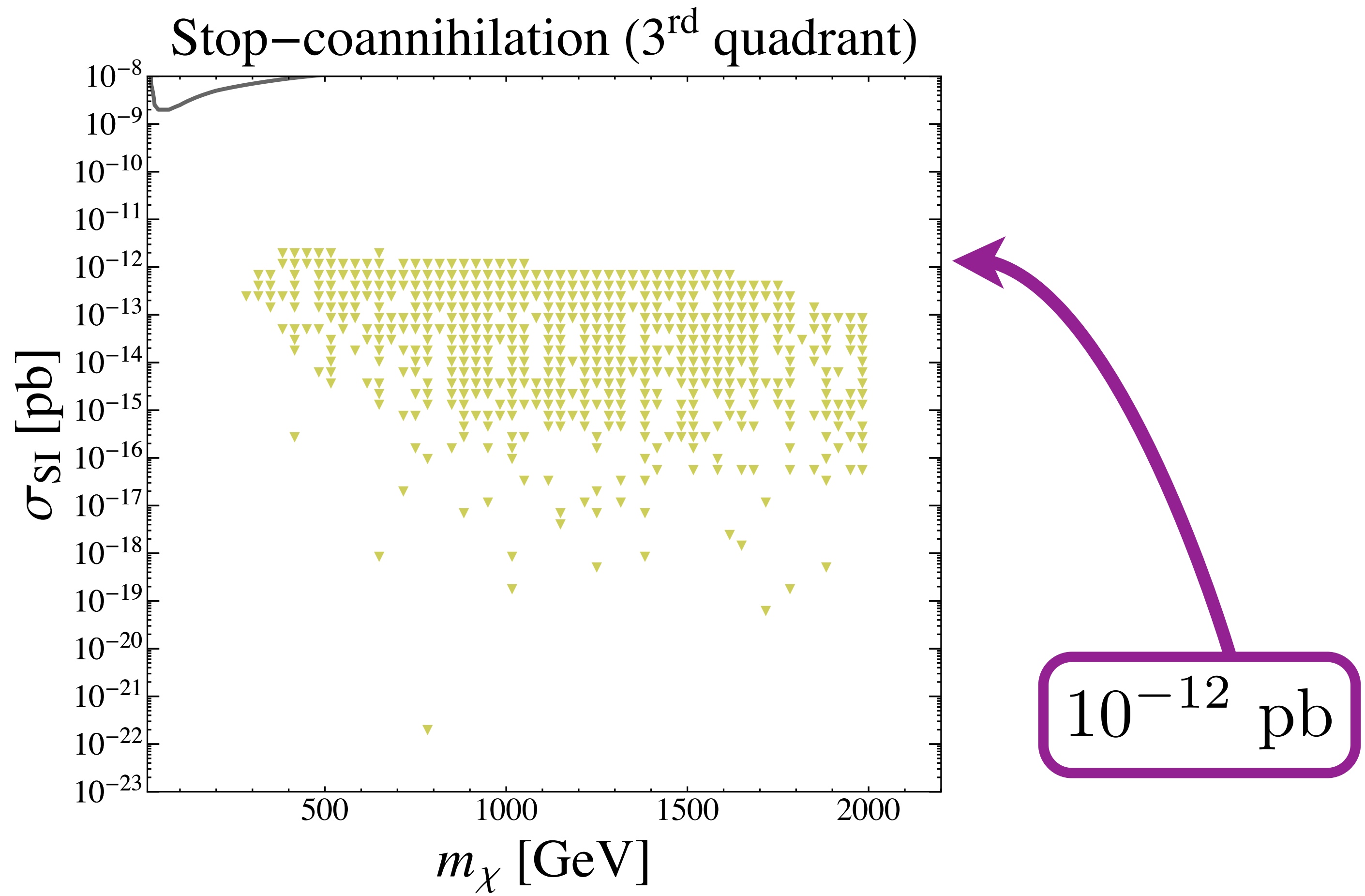
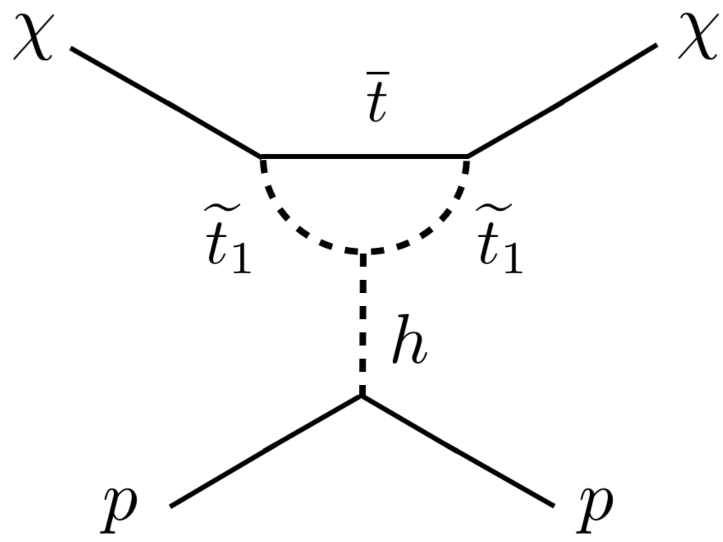


New contribution at 1-loop



- Possibly observable for large *A* terms.

$$\sigma_{\mathrm{SI}}^{1-\mathrm{loop}} \sim 3 \times 10^{-13}\ \mathrm{pb} \times \left(\frac{A_t}{m_{\tilde{t}_1}}\right)^2$$

Almost Home

Conclusions

Conclusions

- CMSSM provides tractable ansatz & allows study of full parameter space.
- Provided a map of the CMSSM consistent with Higgs mass & thermal dark matter.
- Demonstrated that parameter space is compact.
- Regions will remain unconstrained after LHC13 and Ton scale spin-independent direct detection?
    - A^0-pole annihilation
    - Stop coannihilation
- LHC, direct and indirect detection necessary to explore all parameter space.