Light Neutralino Dark Matter

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Mitchell Workshop

Texas A&M

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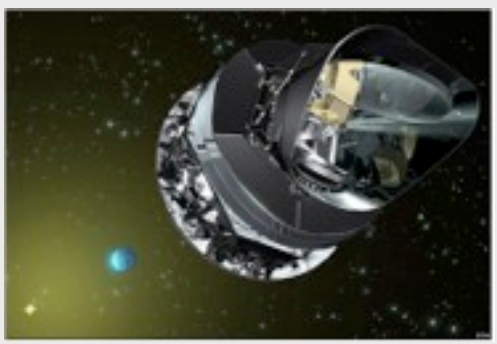
T. Han, Z. Liu and SS, to appear

Outline

- Introduction/Motivation
- Light neutralino dark matter
  - A_1/H_1 funnel region
  - sbottom coannihilation
  - stau coannihilation
- Direct and indirect detections
- LHC observables
- Nearly degenerate sfermion signals at the ILC
- Conclusion

Dark Matter

Dark Matter



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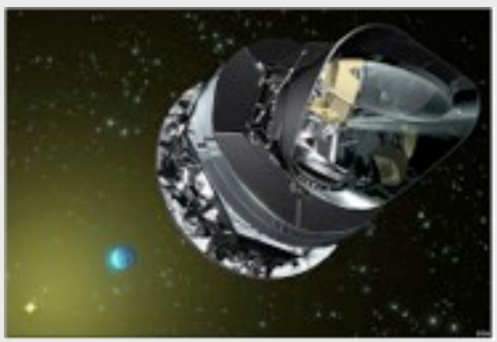

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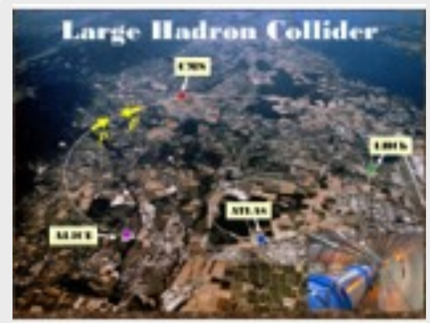

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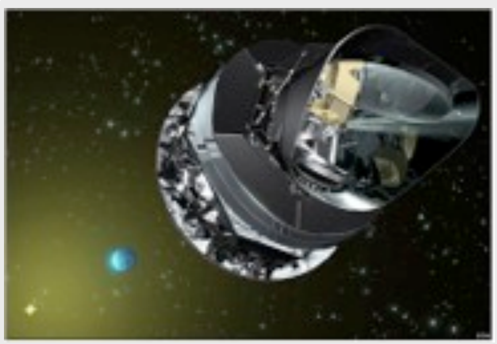
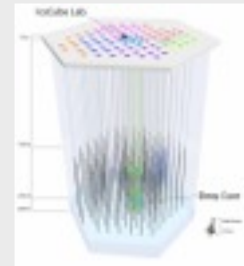


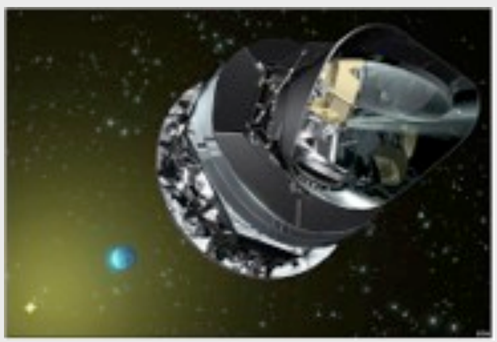
Dark Matter

LUX

Dark Matter







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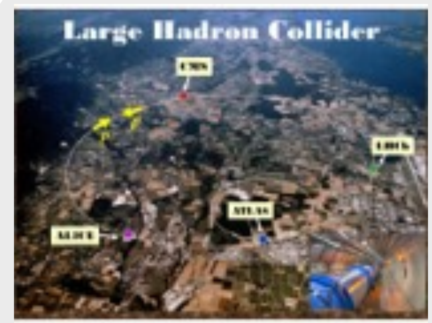

LUX

WIMP

- Relic density

$$M_{\text{WIMP}} \lesssim \frac{g^2}{0.3}\, 1.8\ \text{TeV}$$

- Connection of WIMP dark matter to TeV scale new physics

- DM mass, coupling, relic density: model dependent

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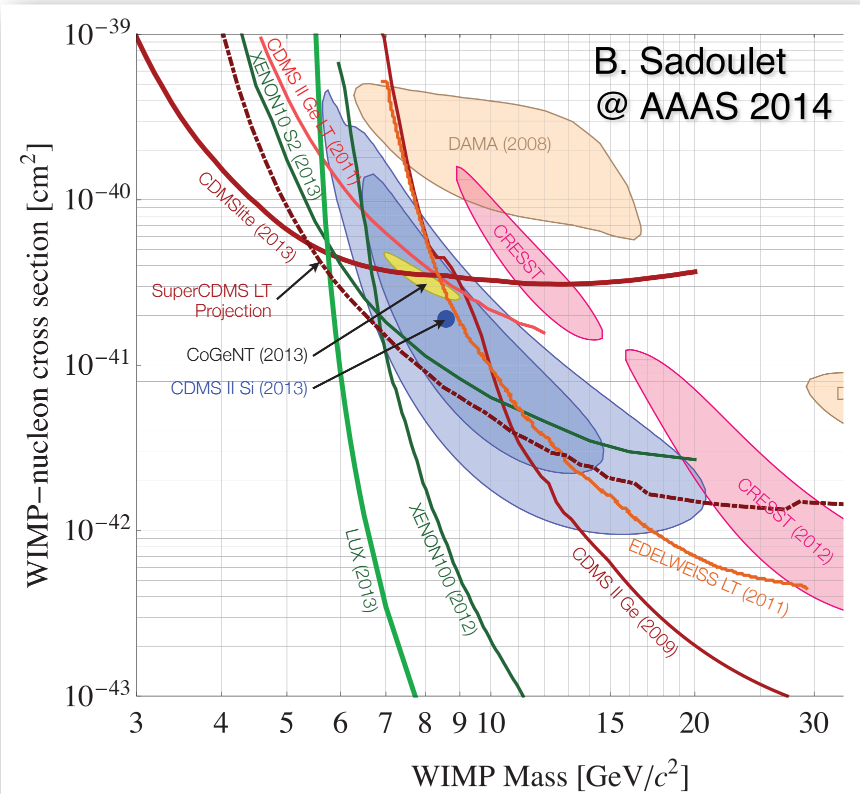
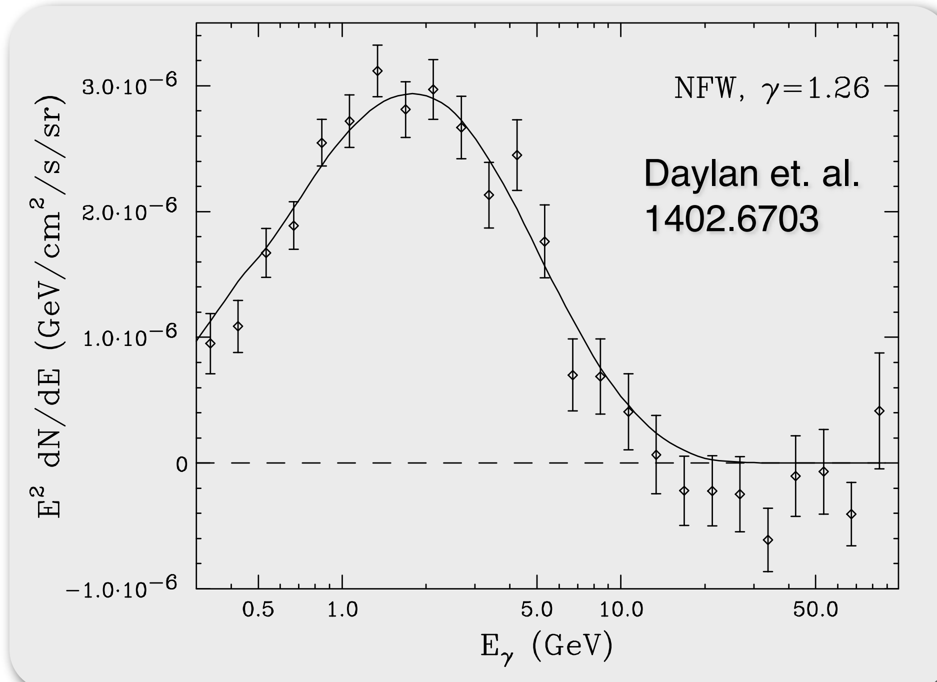
- How light a WIMP dark matter can be?
  - preserve WIMP DM properties
  - satisfy current experimental constraints

Light Dark Matter

- Direct detection

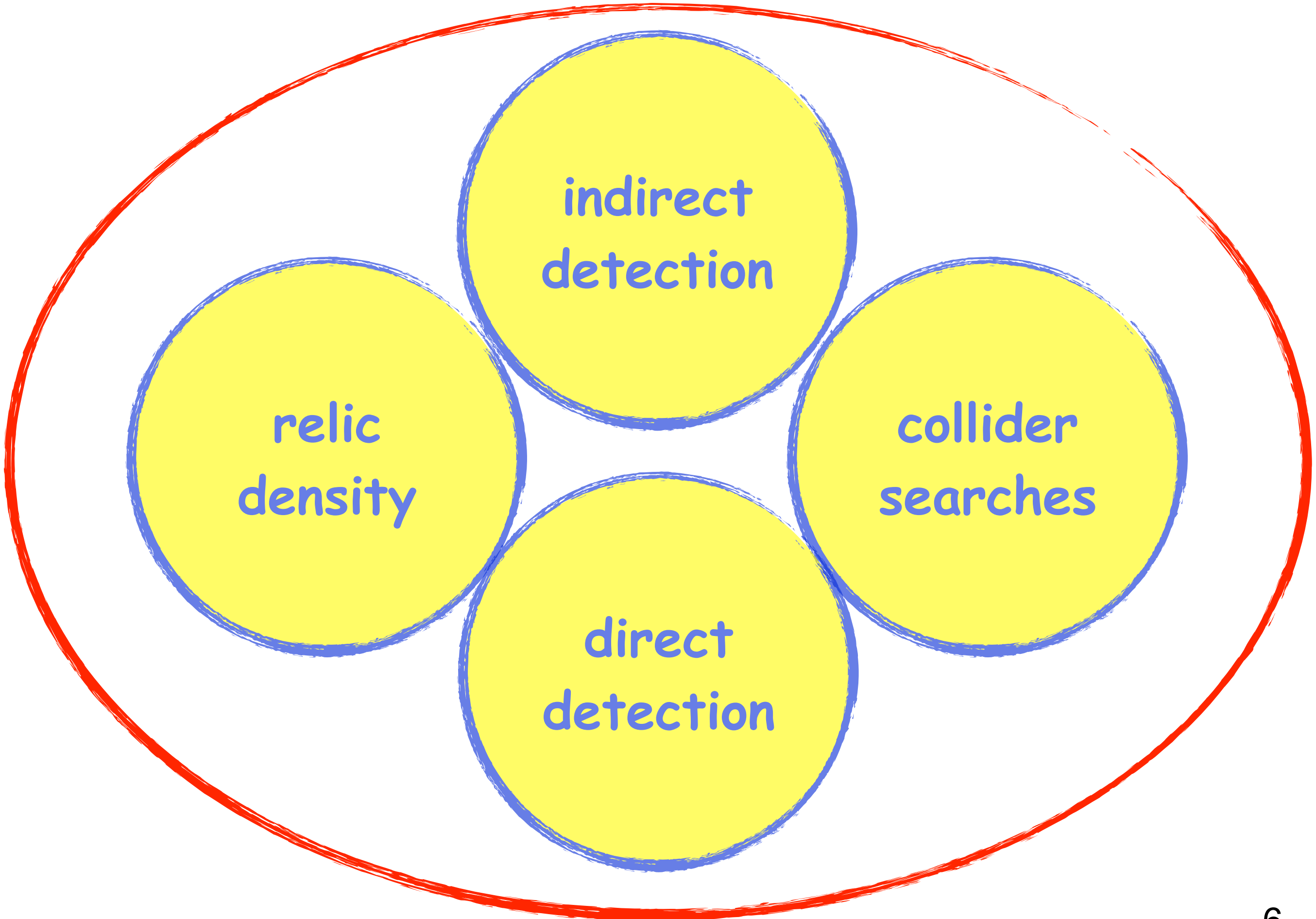


- Galactic center γ ray excess



Complementarity

- consistent observations among all approaches



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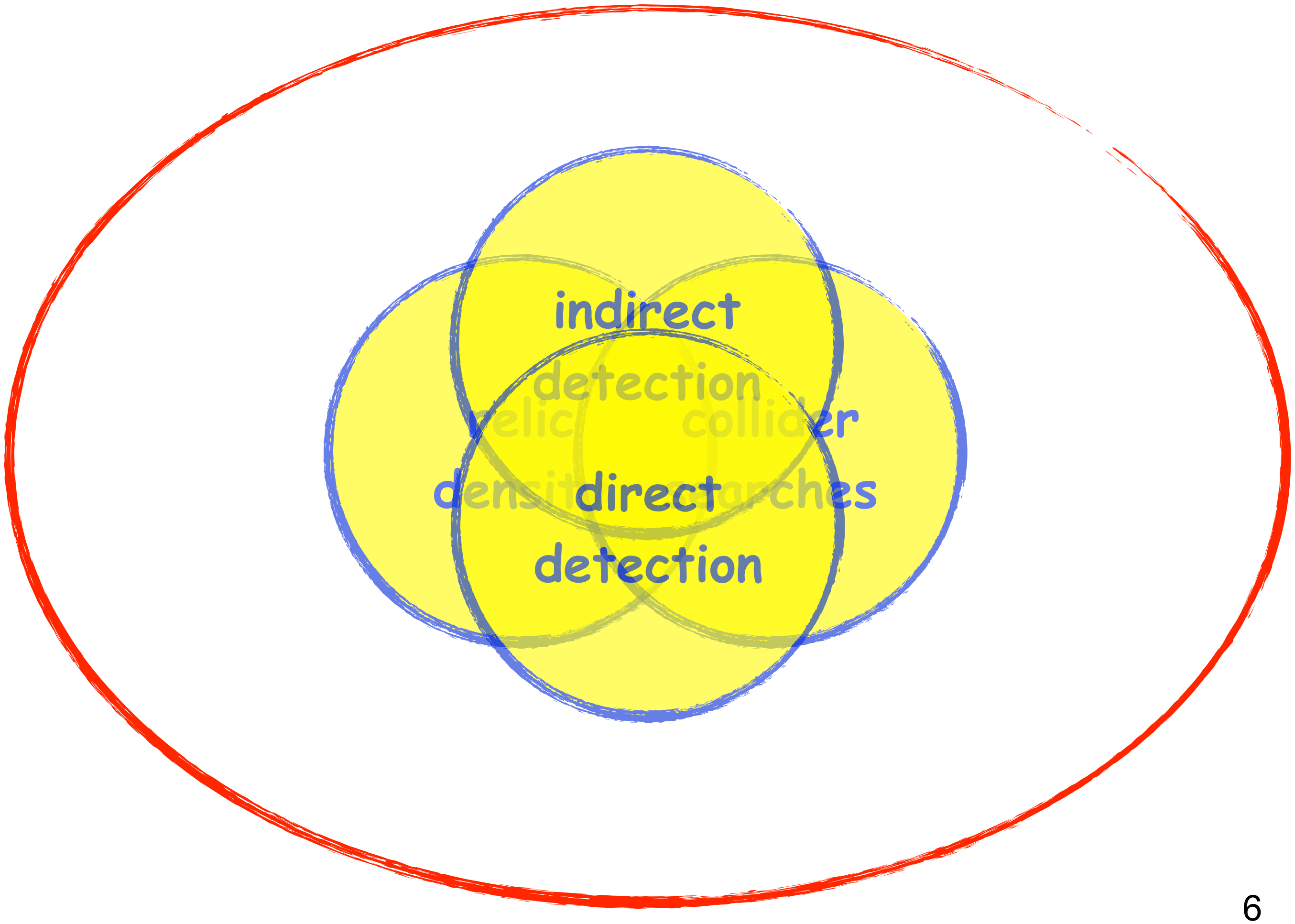

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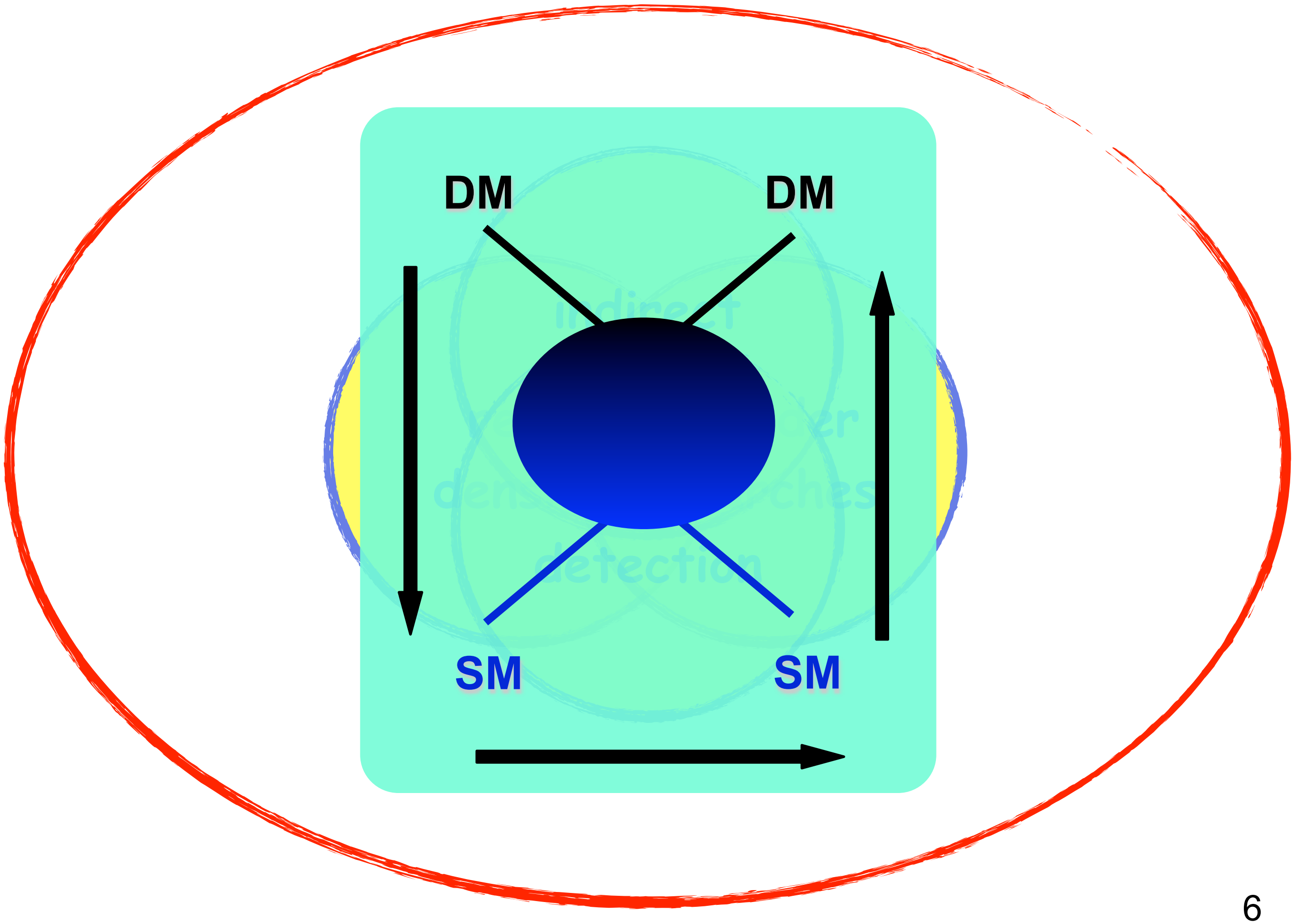

Neutralino Dark Matter @ MSSM

- Gauginos and Higgsinos
  - Neutral ones: Bino, Wino, $\tilde{H}_u^0$, $\tilde{H}_d^0$
  - charged ones: Winos, $\tilde{H}_u^+$, $\tilde{H}_d^-$
- Parameters: M_1, M_2, μ, $\tan\beta$

→ Neutralinos and charginos

$$M_{\tilde{N}^0} = \begin{pmatrix} M_1 & 0 & -g_1\frac{v_d}{\sqrt{2}} & g_1\frac{v_u}{\sqrt{2}} \\ & M_2 & g_2\frac{v_d}{\sqrt{2}} & -g_2\frac{v_u}{\sqrt{2}} \\ & & 0 & -\mu \\ & * & & 0 \end{pmatrix}$$

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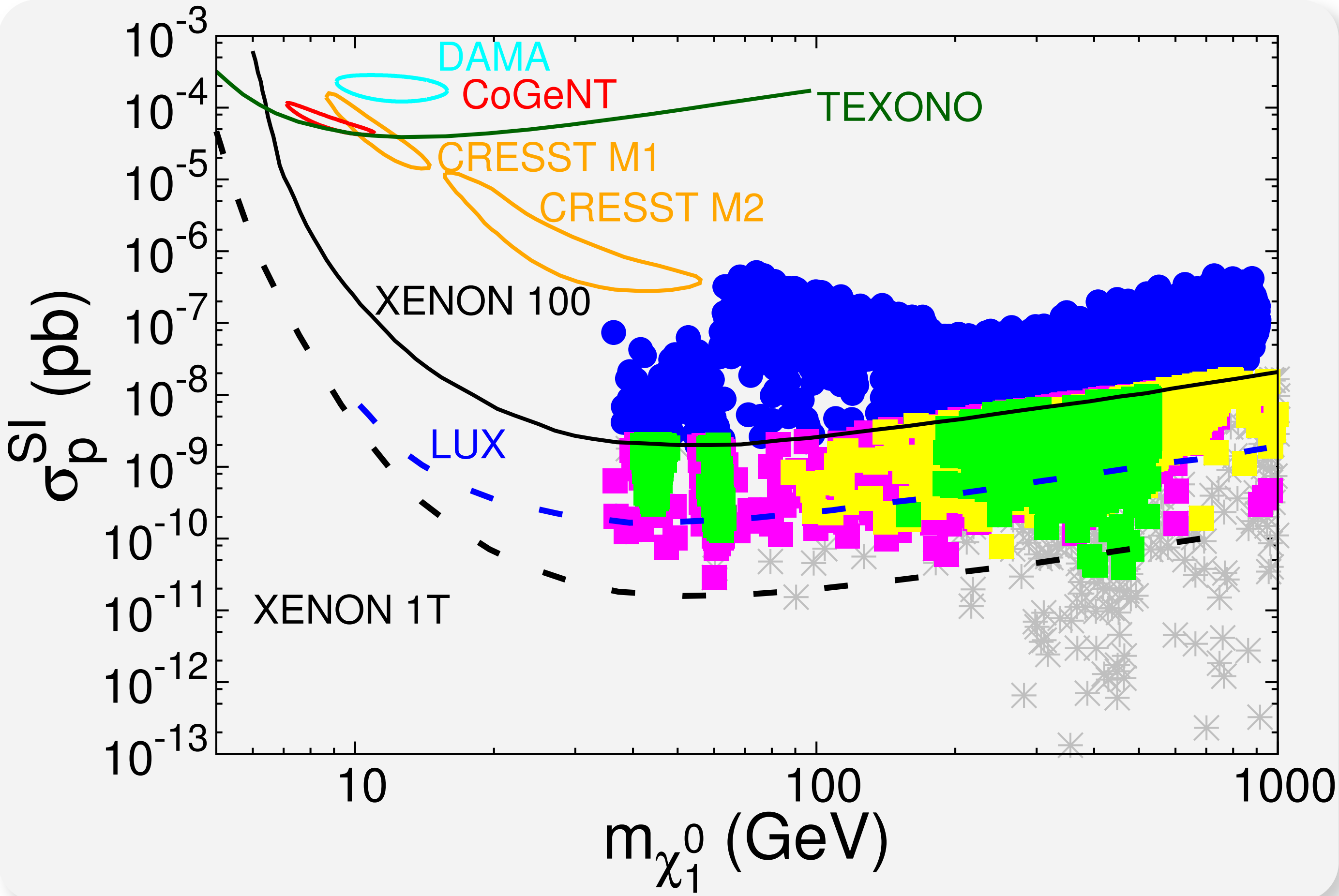
Dark Matter in MSSM

- lightest neutralino LSP in MSSM as good dark matter candidate



Han, Liu and Natarajan , 1303.3040

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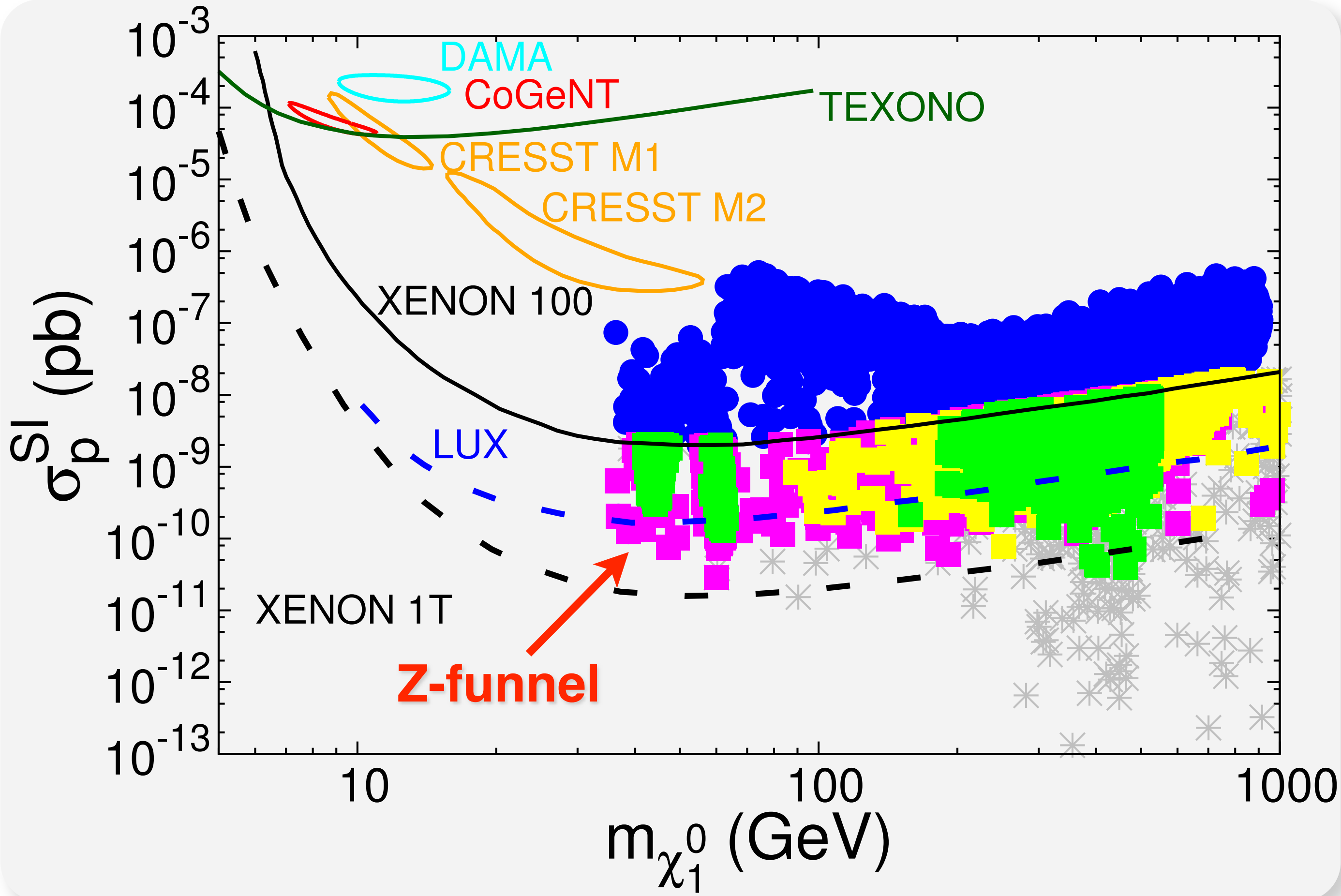

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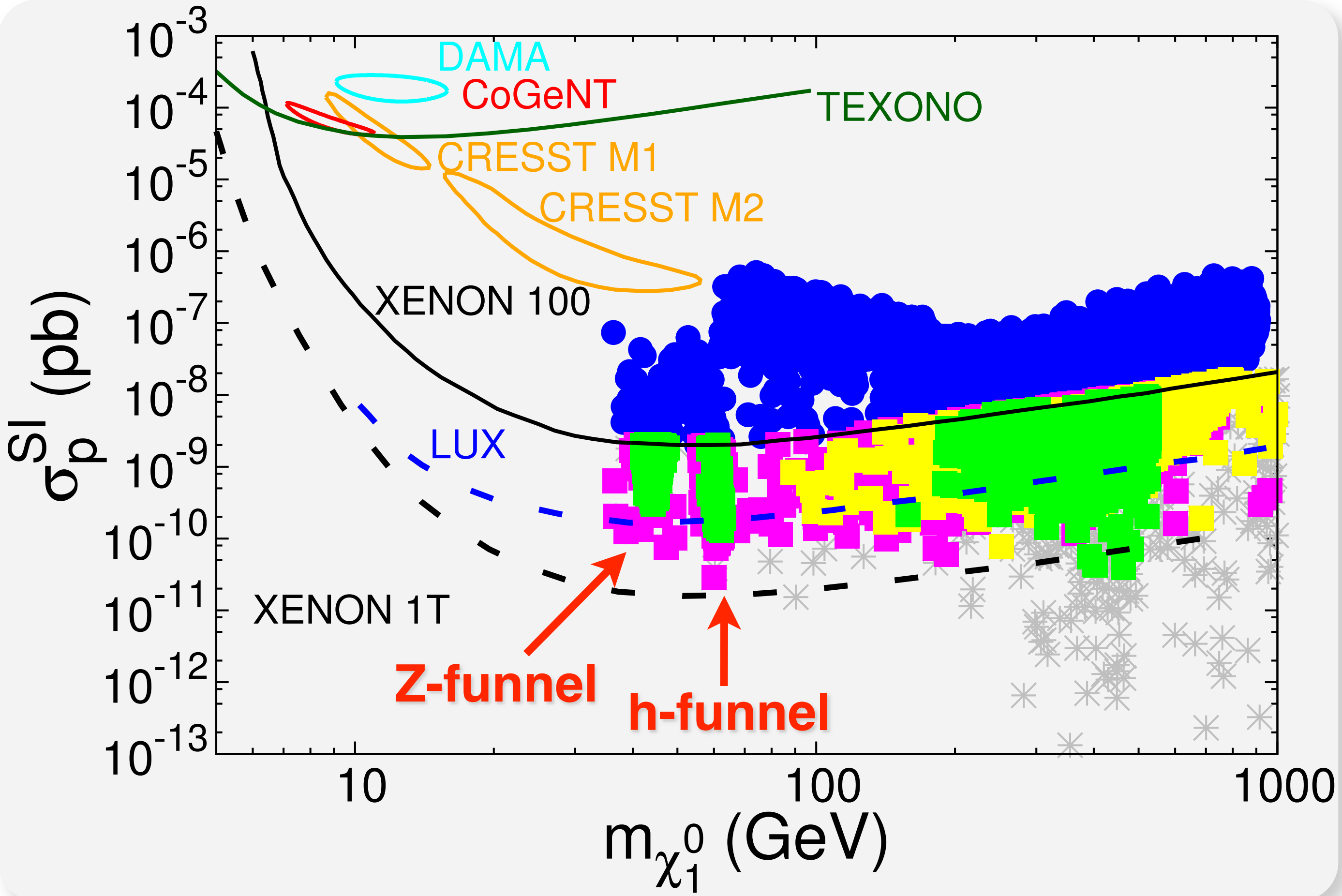

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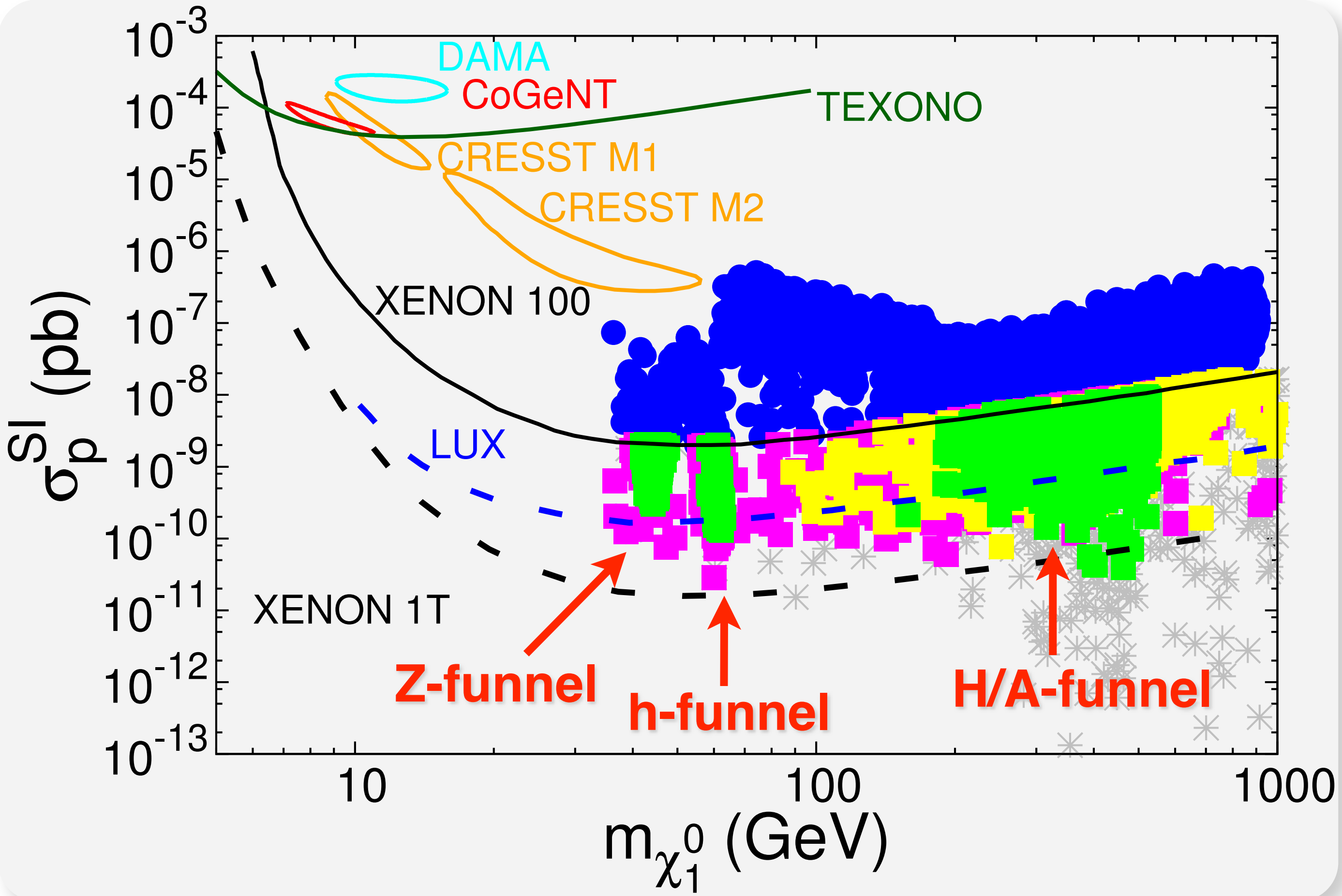

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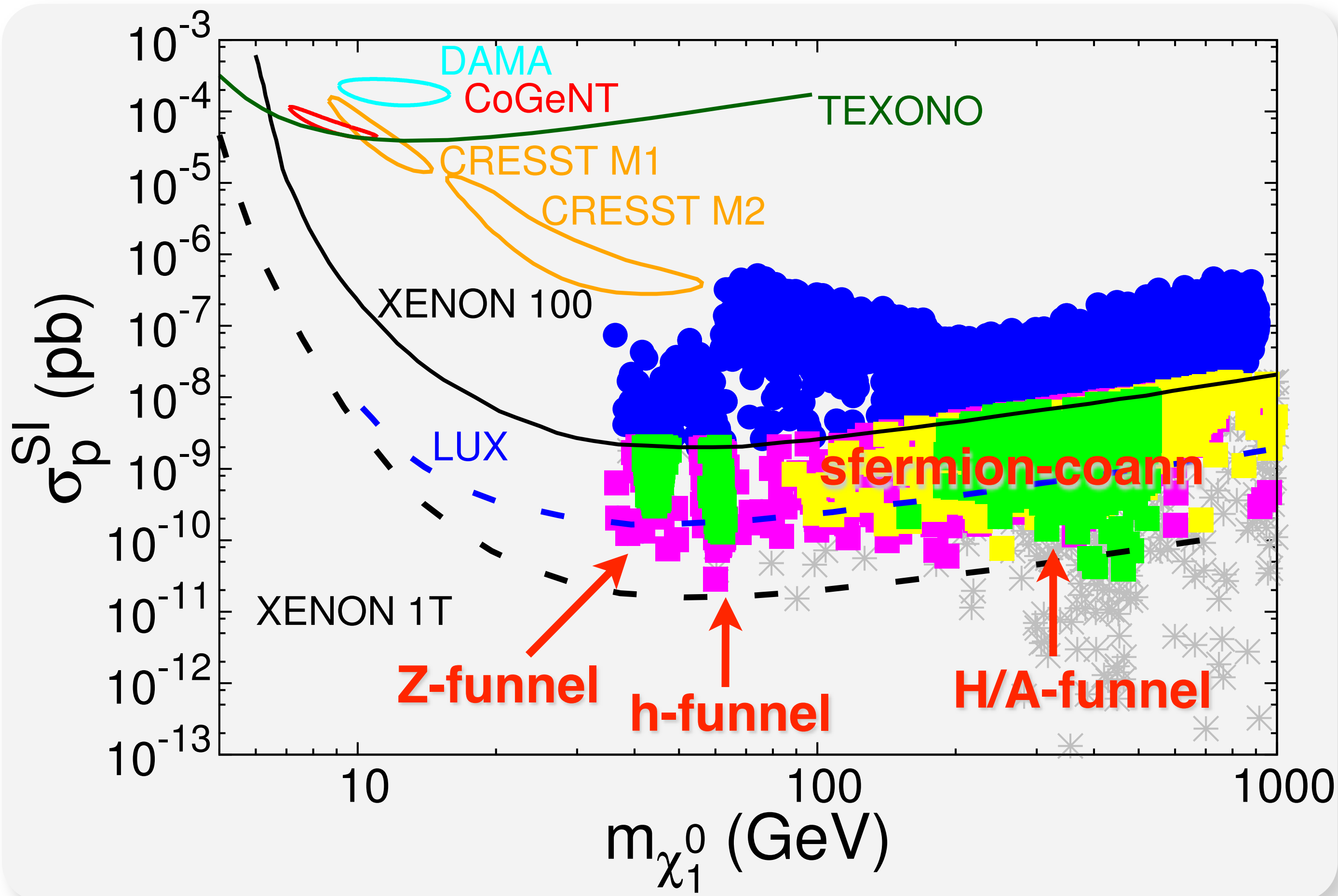

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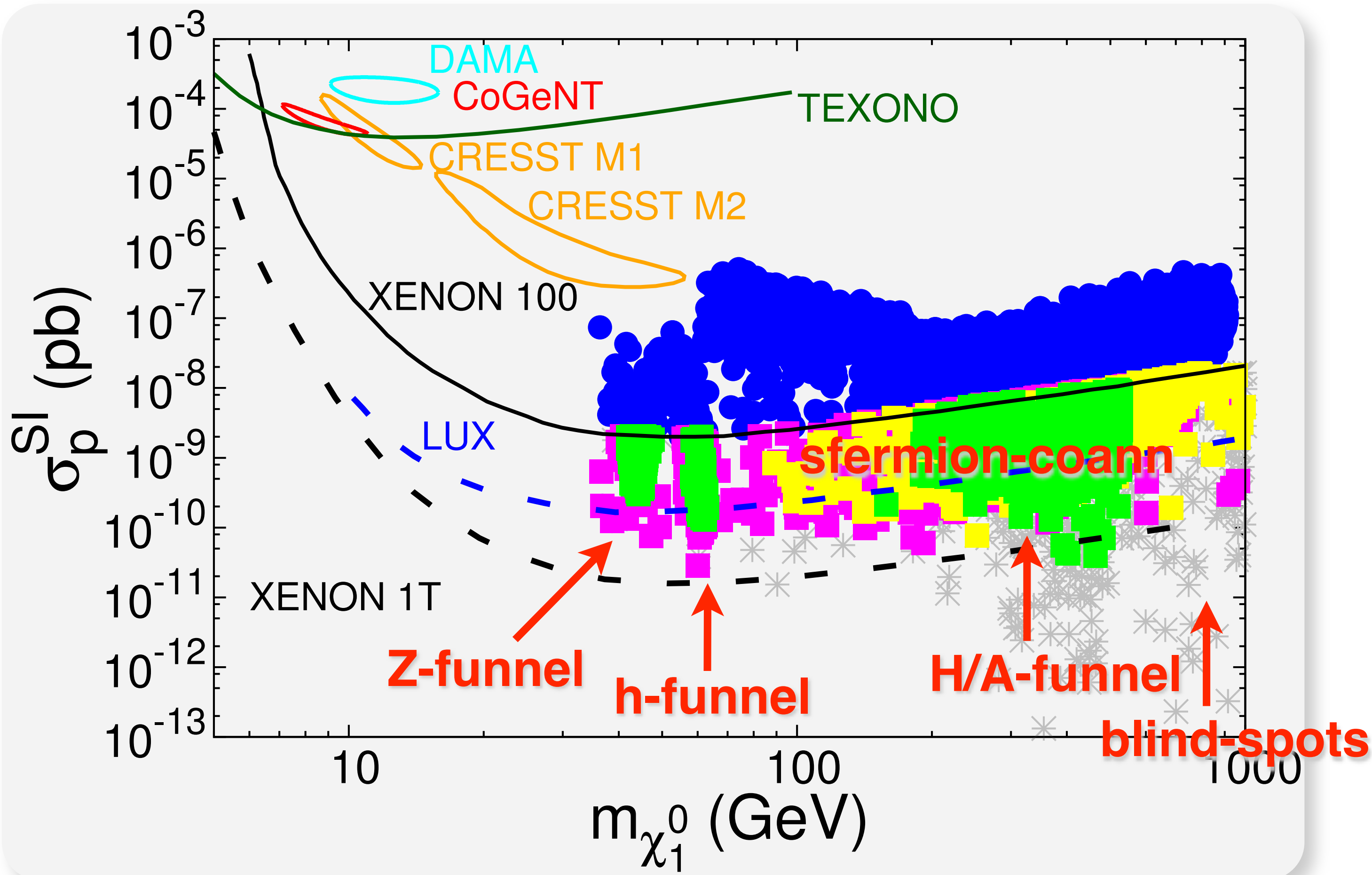

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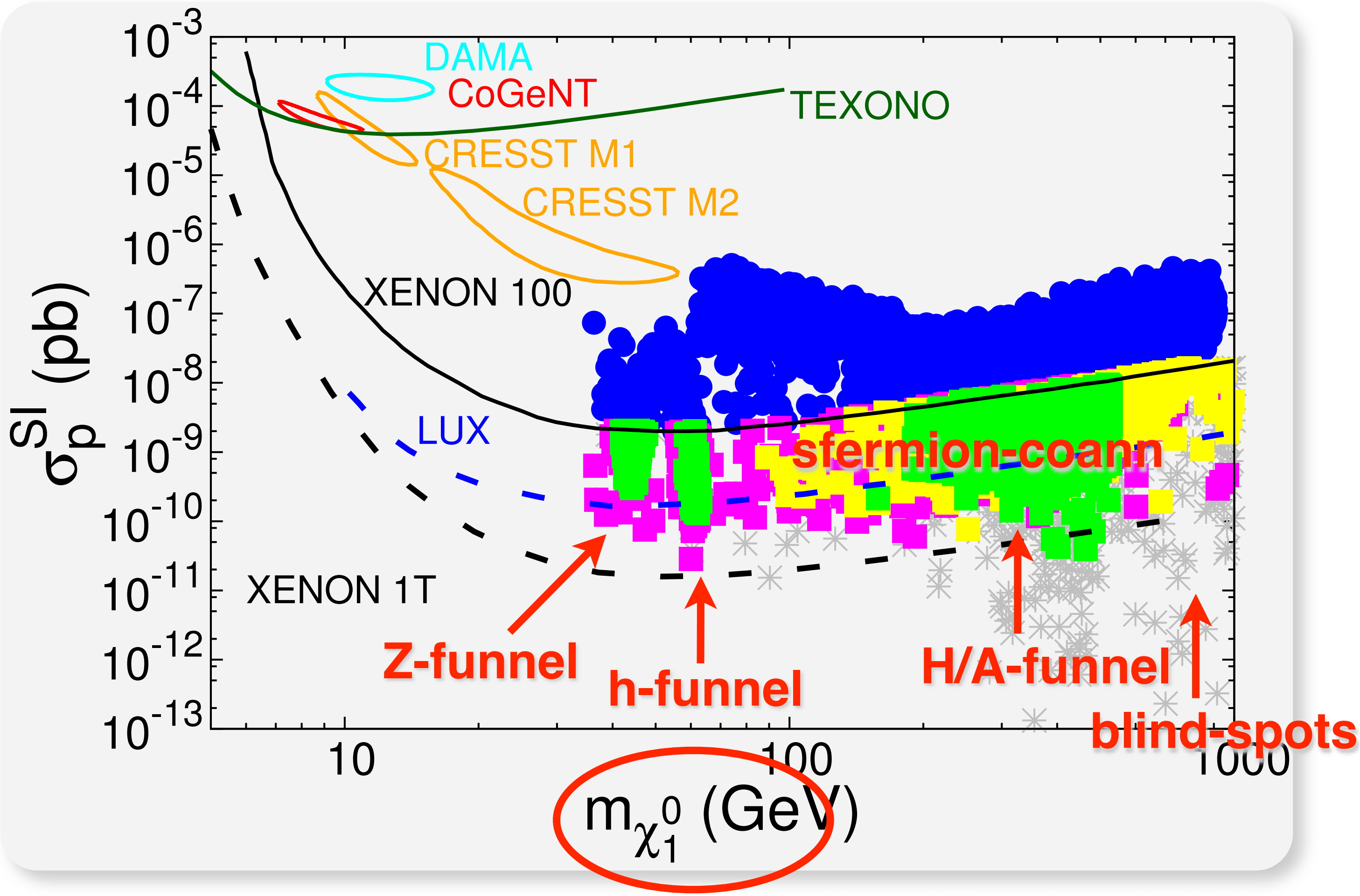

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Bino-like with Higgsino component

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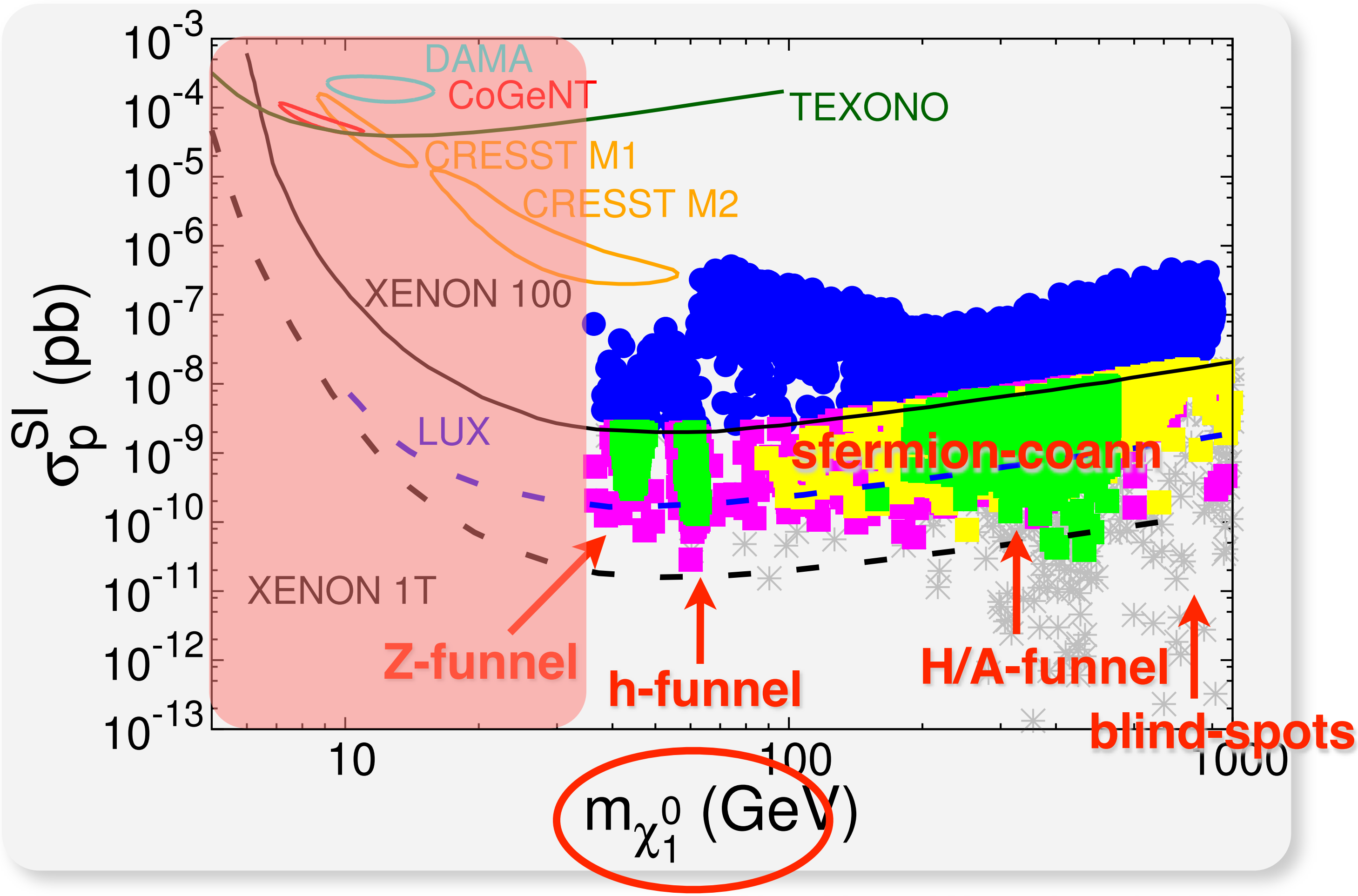

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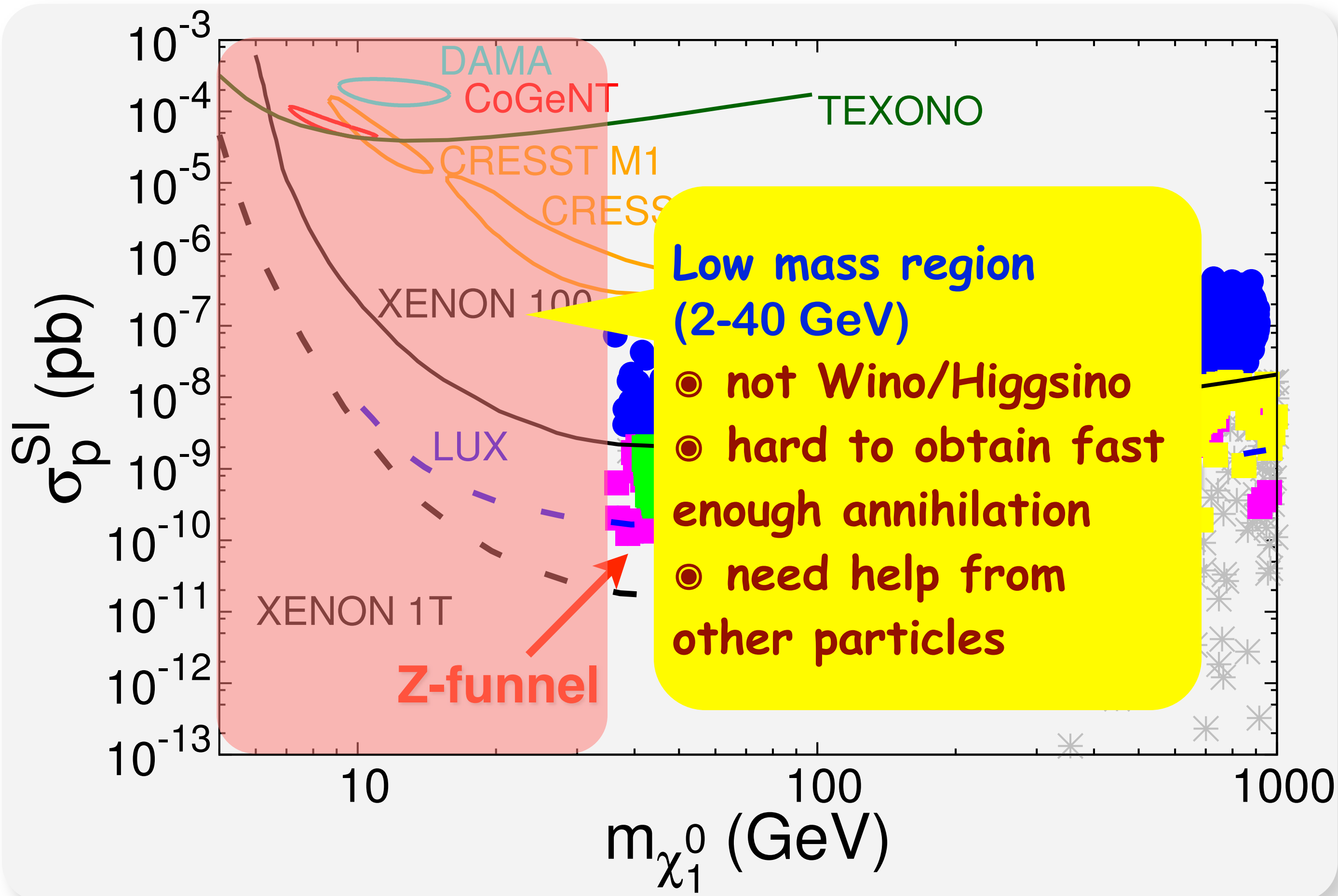

Han, Liu and Natarajan , 1303.3040

Light Neutralino DM @ NMSSM

Draper et. al. , 1009.3963
Arbey et. al. , 1205.2557,...

Co-ann
Funnel

Models	DM (< 40 GeV)	Annihilation
MSSM & NMSSM	Bino/Singlino	$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to f\bar{f};\ \tilde{\chi}_1^0\tilde{f} \to Vf;\ \tilde{f}\tilde{f}' \to ff'$
NMSSM	Singlino/Bino	$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to a_1, h_1 \to SM$

- Study properties of those solutions
- Direct and indirect detection
- Observational aspects at colliders
  - via SM-like Higgs
  - light Higgses
  - light sfermion

NMSSM Higgs Sector

- Type II Two Higgs Doublet Model plus singlet S

$$W_{\rm NMSSM} = Y_u \hat{u}^c \hat{H}_u \hat{Q} + Y_d \hat{d}^c \hat{H}_d \hat{Q} + Y_e \hat{e}^c \hat{H}_d \hat{L} + \lambda \hat{S} \hat{H}_u \hat{H}_d + \frac{1}{3}\kappa \hat{S}^3$$

$$V_{H,Soft} = m_{H_u}^2 H_u^\dagger H_u + m_{H_d}^2 H_d^\dagger H_d + M_S^2 |\mathcal{S}|^2 + \left(\lambda A_\lambda (H_t^T \epsilon H_d)\mathcal{S} + \frac{1}{3}\kappa A_\kappa \mathcal{S}^3 + c.c. \right)$$

- SSB

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}, \quad H_u^0 \to v_u/\sqrt{2} \qquad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}, \quad H_d^0 \to v_d/\sqrt{2} \qquad S \to v_s/\sqrt{2} \quad (\mu = \lambda v_s/\sqrt{2})$$

$$v_u^2 + v_d^2 = v^2 = (246\text{GeV})^2$$
$$\tan\beta = v_u/v_d$$

after EWSB, 7 physical Higgses

CP-even Higgses: H_1, H_2, H_3

CP-odd Higgs: A_1, A_2

Charged Higgses: $H^\pm$

Neutralinos @ NMSSM

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- **Bino-like LSP**

$$N_{11} \approx 1, \quad N_{15} \approx 0,$$

$$N_{13} \approx \frac{m_Z s_W}{\mu} s_\beta, \quad N_{14} \approx -\frac{m_Z s_W}{\mu} c_\beta.$$

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- **Singlino-like LSP**

$$N_{11} \approx 0, \quad N_{15} \approx 1$$

$$N_{13} \approx -\frac{\lambda v}{\mu} c_\beta, \quad N_{14} \approx -\frac{\lambda v}{\mu} s_\beta$$

Parameter Scan

NMSSMTools4

	General	Sbottom	Stau	$H_1,\ A_1$-funnel
$m_{A_{\rm tree}}$	[0,3000]	—	—	—
$\tan\beta$	[1,55]	—	—	—
μ	[100,500]	—	—	—
$\|A_\kappa\|$	[0,1000]	—	—	—
λ	[0,1]	—	—	[0.01,0.6]
κ	[0,1]	either $\kappa \in [2,30]\lambda/(2\mu)$		
$\|M_1\|$	[0,500]	or $M_1 \in [2,30]$, or both		
$M_{Q3},\ M_{U3}$	[0,3000]	—	—	—
$\|A_t\|$	[0,4000]	—	—	—
M_{D3}	[0,3000]	[0,80]	3000	
$\|A_b\|$	[0,4000]	—	0	
M_{L3}, M_{E3}	[0,3000]	3000	[0,500]	3000
$\|A_\tau\|$	[0,4000]	0	[0,2000]	0

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$\|A_b\|$	[0,4000]	—	0	
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$M_{Q3},\ M_{U3}$	[0,3000]	—	—	—
$\lvert A_t\rvert$	[0,4000]	—	—	—
M_{D3}	[0,3000]	[0,80]	3000	
$\lvert A_b\rvert$	[0,4000]	—	0	
M_{L3}, M_{E3}	[0,3000]	3000	[0,500]	3000
$\lvert A_\tau\rvert$	[0,4000]	0	[0,2000]	0

Parameter Scan

NMSSMTools4

	General	Sbottom	Stau	$H_1,\ A_1$-funnel
$m_{A_{\rm tree}}$	[0,3000]	—	—	—
$\tan\beta$	[1,55]	—	—	—
μ	[100,500]	—	—	—
$\|A_\kappa\|$	[0,1000]	—	—	—
λ	[0,1]	—	—	[0.01,0.6]
κ	[0,1]	either $\kappa \in [2,30]\lambda/(2\mu)$		
$\|M_1\|$	[0,500]	or $M_1 \in [2,30]$, or both		
$M_{Q3},\ M_{U3}$	[0,3000]	—	—	—
$\|A_t\|$	[0,4000]	—	—	—
M_{D3}	[0,3000]	[0,80]	3000	
$\|A_b\|$	[0,4000]	—	0	
M_{L3}, M_{E3}	[0,3000]	3000	[0,500]	3000
$\|A_\tau\|$	[0,4000]	0	[0,2000]	0

Experimental Constraints

- Theoretical constraints such as Vacuum stability.
- Collider Higgs search limits from the LEP, the Tevatron and the LHC.
- LEP, Tevatron and LHC constrains on searches of supersymmetric particles, such as charignos, leptons and squarks;
- 2σ window of the SM-like Higgs boson mass: 122.7 – 128.7 GeV (including linearly added estimated theoretical uncertainties of ± 2 GeV).
- 2σ window of the SM-like Higgs bosons cross sections for $\gamma\gamma$, ZZ, W^+W^-, $\tau^+\tau^-$ and $b\bar{b}$ different production modes.
- Z boson invisible width and hadronic width as in Eq. (2.11) and Eq. (2.12).
- B-physics constrains, including $b \to s\gamma$, $B_s \to \mu^+\mu^-$, $B \to \chi_s\mu^+\mu^-$ and $B^+ \to \tau^+\nu_\tau$, as well as Δm_s, Δm_d, $m_{\eta_b(1S)}$ and $\Upsilon(1S) \to a\gamma, h\gamma$.

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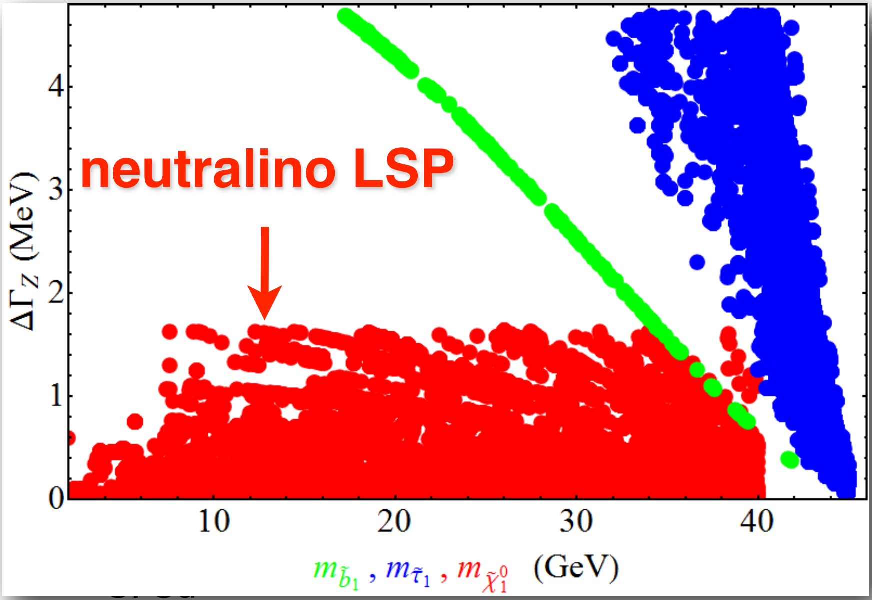
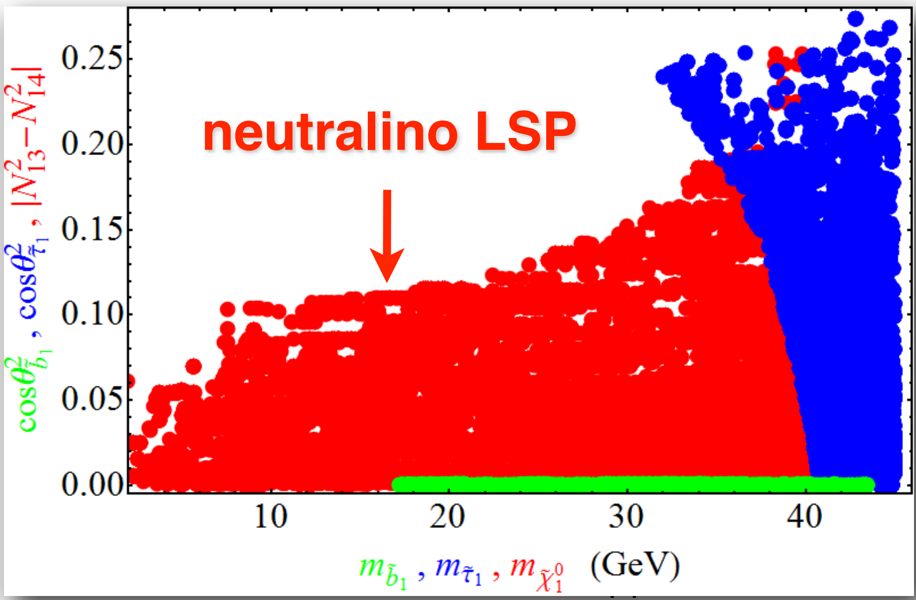
Constraints for Low Mass

- **Light neutralino LSP: invisible Z decay with** $\Delta\Gamma_{\rm inv} < 2.0\ \text{MeV}$

$$Z\tilde{\chi}_1^0\tilde{\chi}_1^0 \text{ coupling}, \quad N_{14}^2 - N_{13}^2$$

- Bino LSP: μ > 140 GeV
- Singlino LSP: μ/λ > 540 GeV





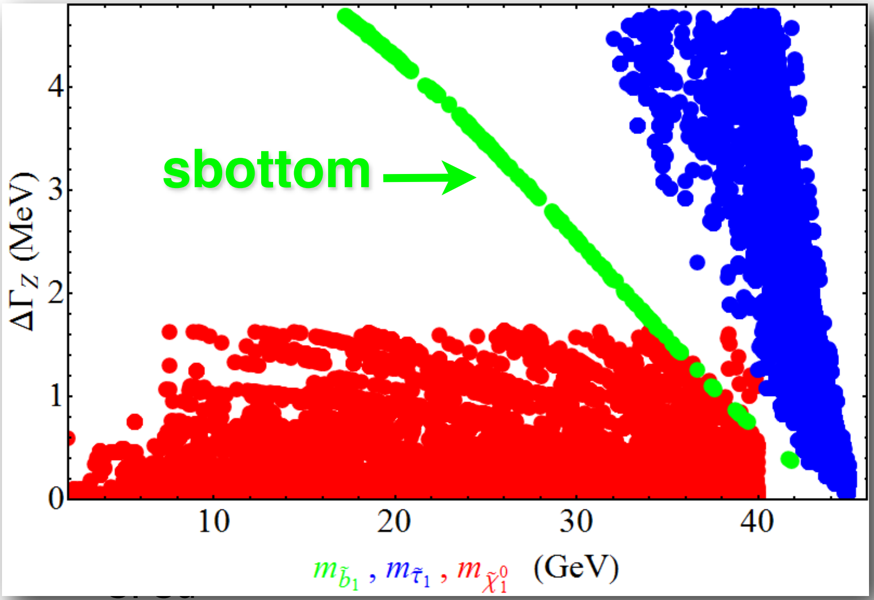
Constraints for Low Mass

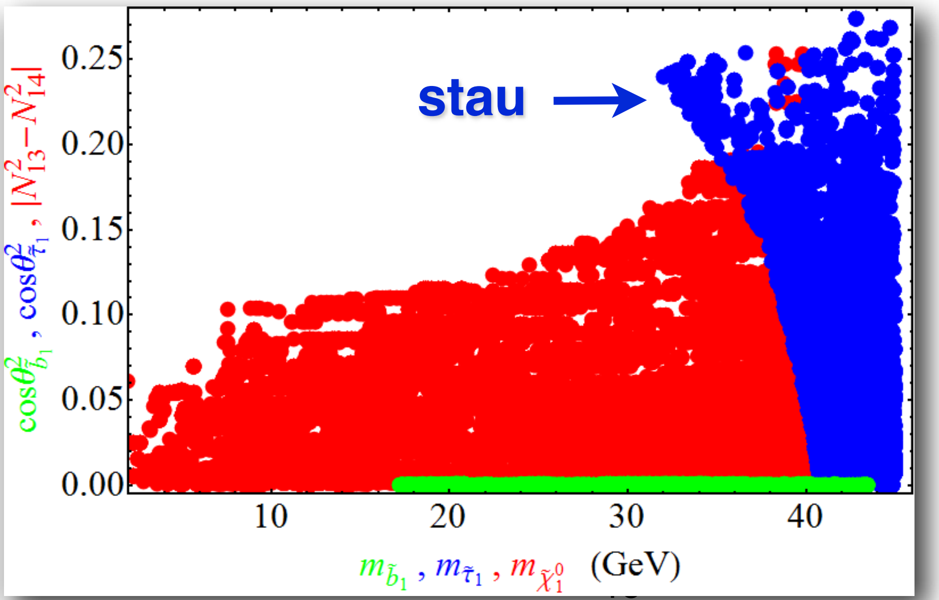
- Light sfermion: total Z decay width

$$\Delta\Gamma_{\rm tot} < 4.7 \ \ {\rm MeV}$$

$$Z\tilde{f}_1\tilde{f}_1 : g_f^L \cos^2\theta_{\tilde{f}} + g_f^R \sin^2\theta_{\tilde{f}} \qquad \tan^2\theta_{\tilde{f}}^{min} = -g_f^L/g_f^R$$

  - sbottom: mostly right-handed
  - stau: even mixture of left and right-handed

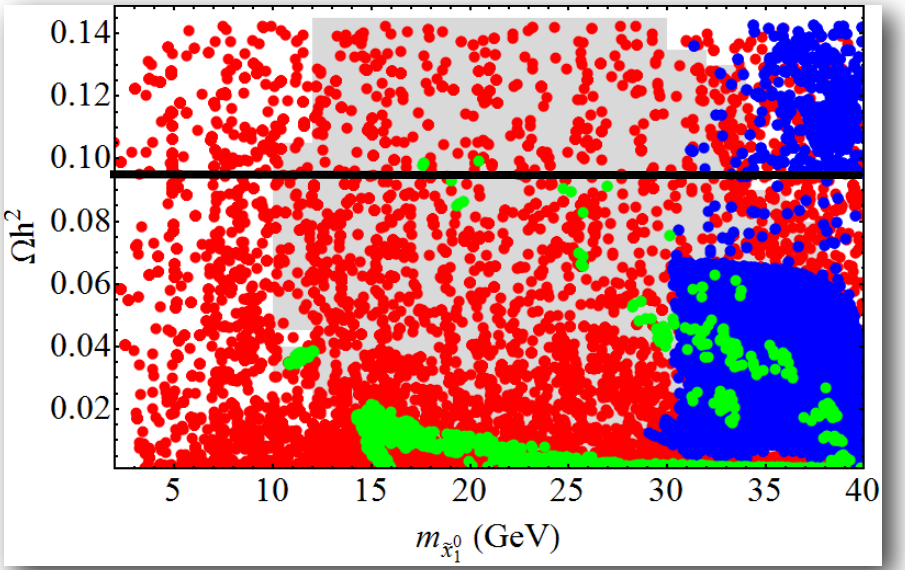




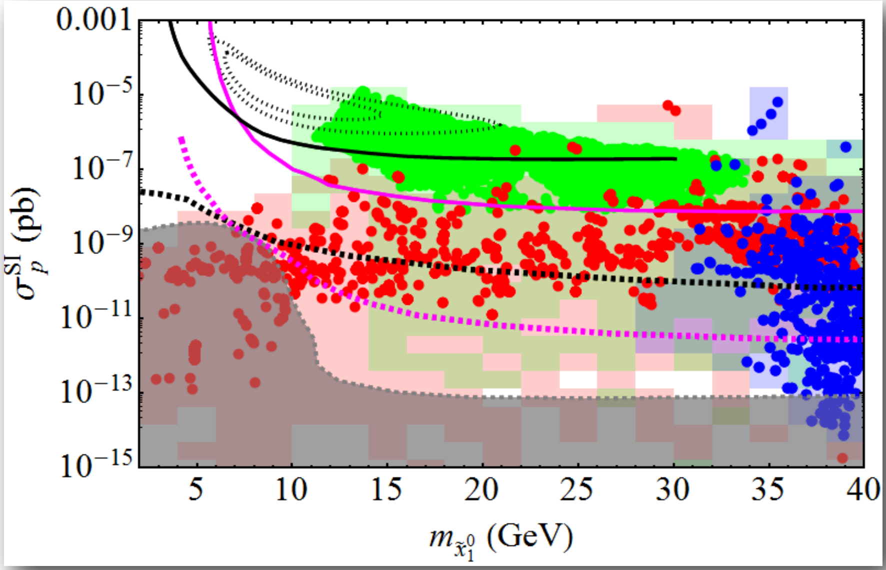
Dark Matter Properties

$$0.0947\ (0.001) < \Omega_{\tilde{\chi}_1^0} h^2 < 0.142,$$

- Relic density



- Direct detection



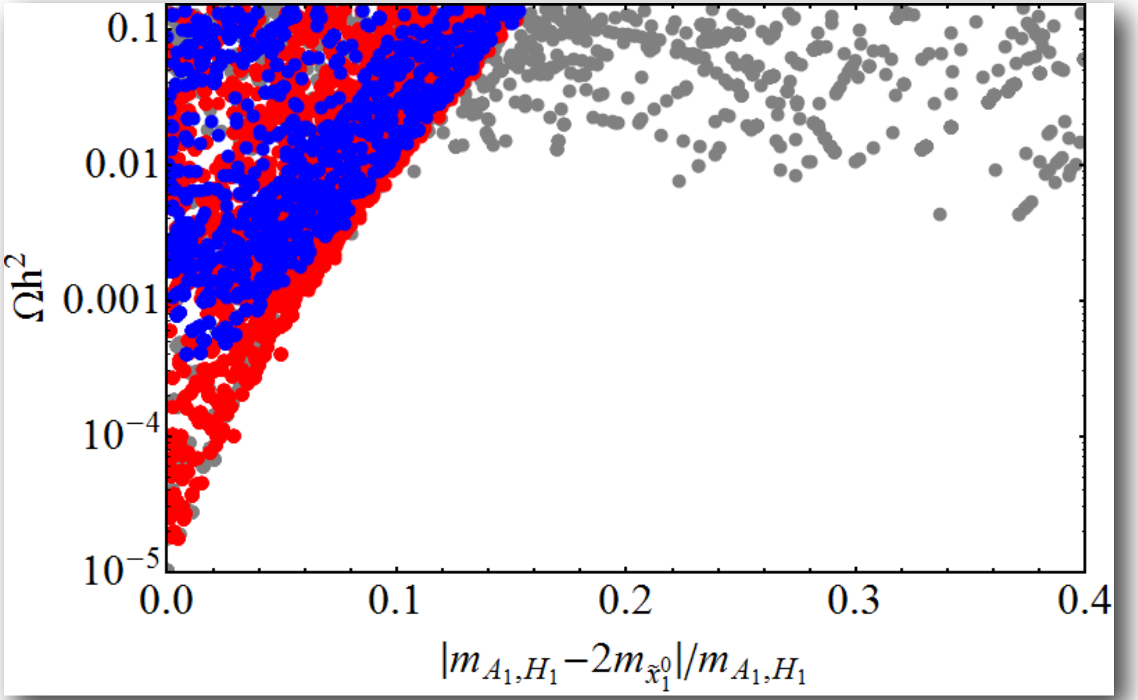
funnel

sb-coann

stau-coann

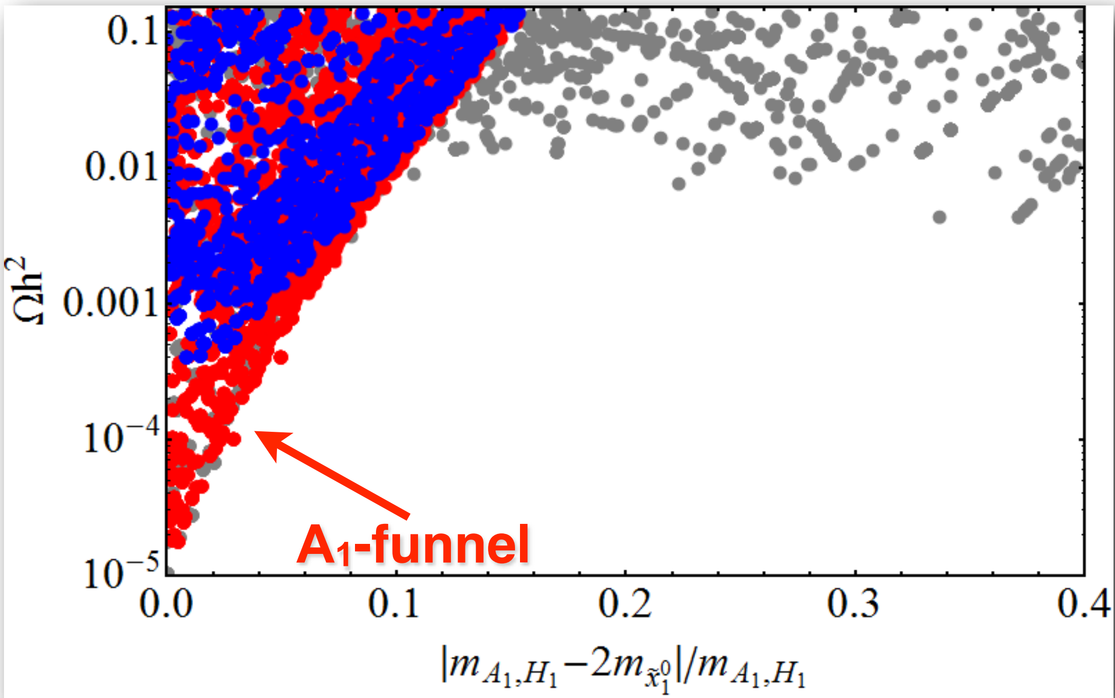
DM Properties

- A_1/H_1 funnel



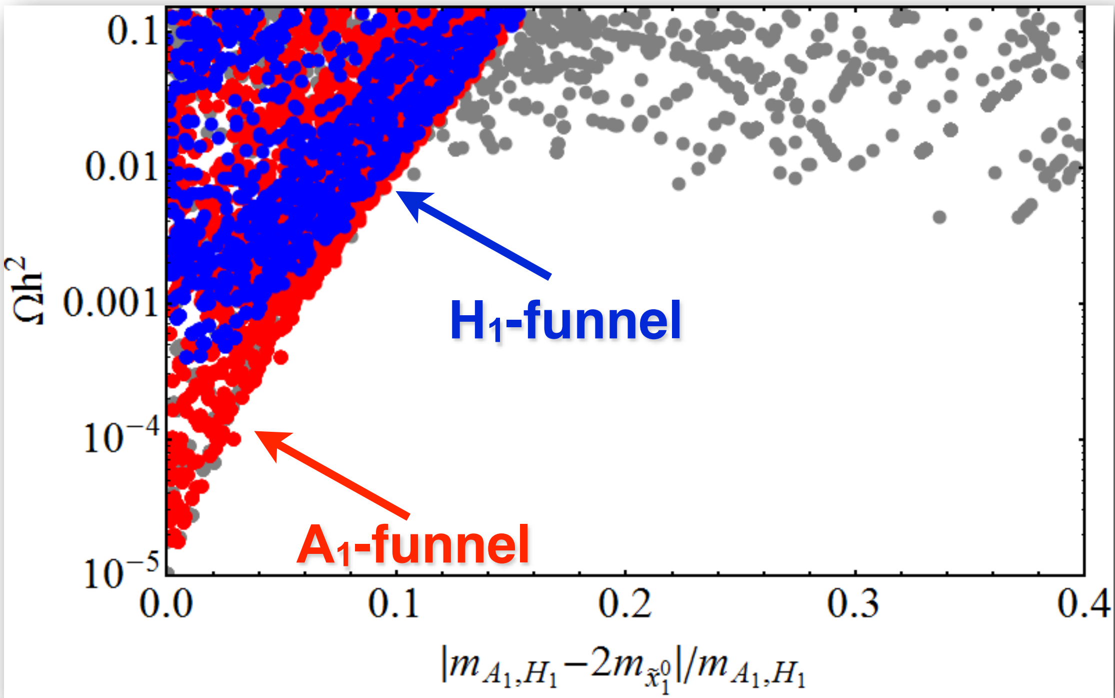
DM Properties

- **A_1 /H_1 funnel**



DM Properties

- A_1 /H_1 funnel



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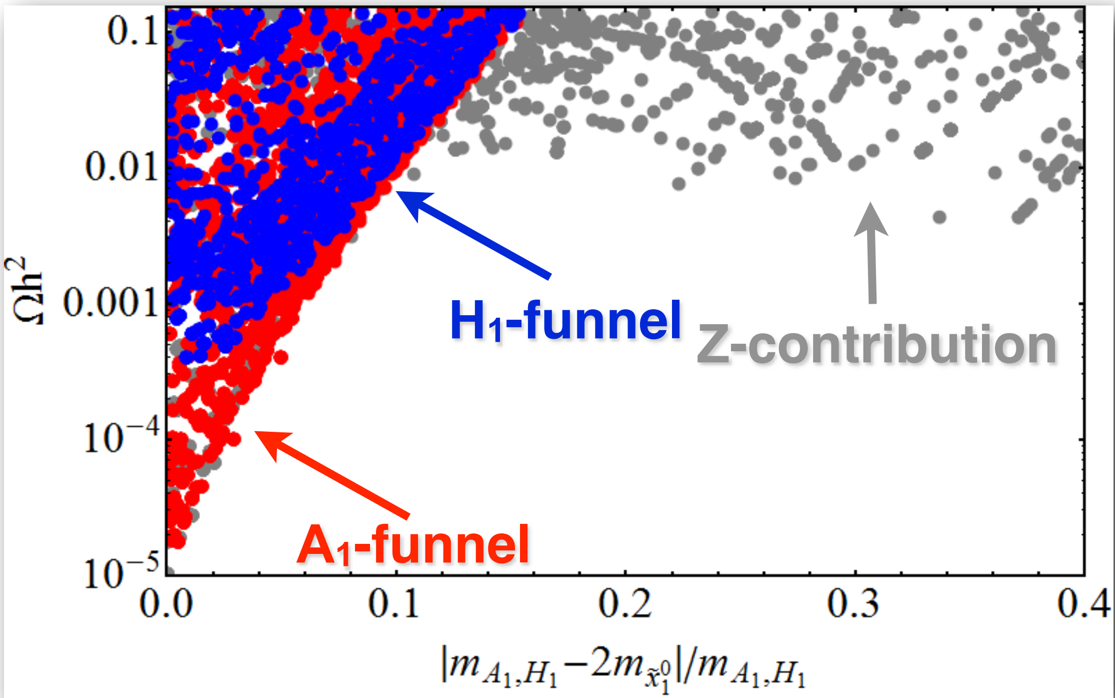
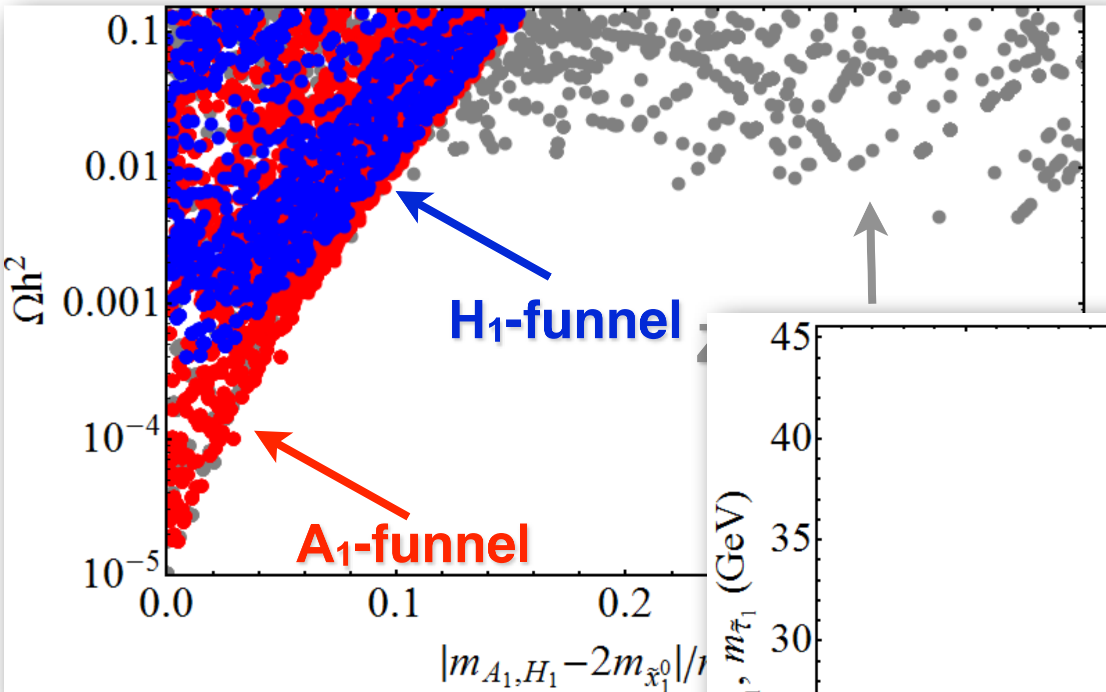
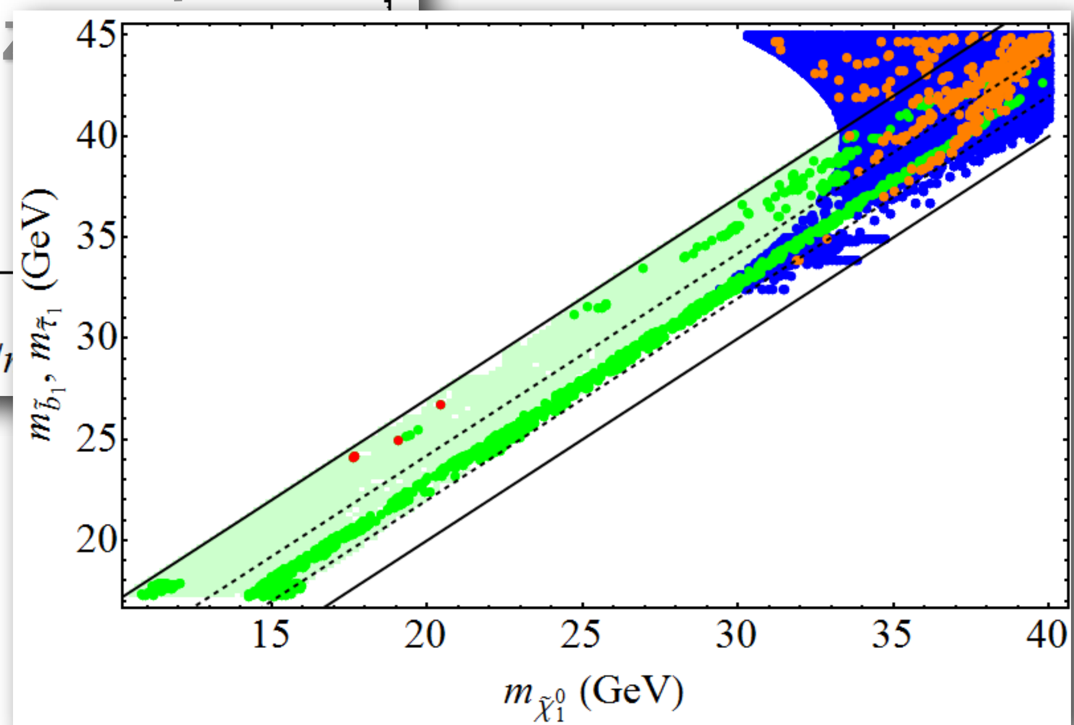


DM Properties

- A_1 /H_1 funnel



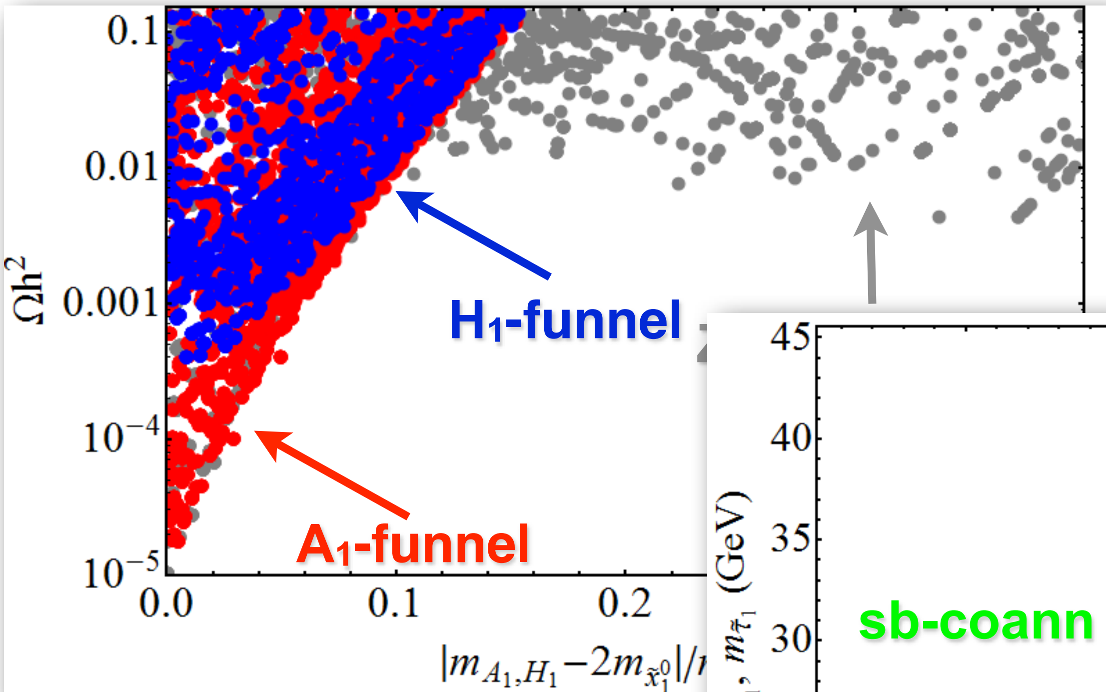
- coannihilation



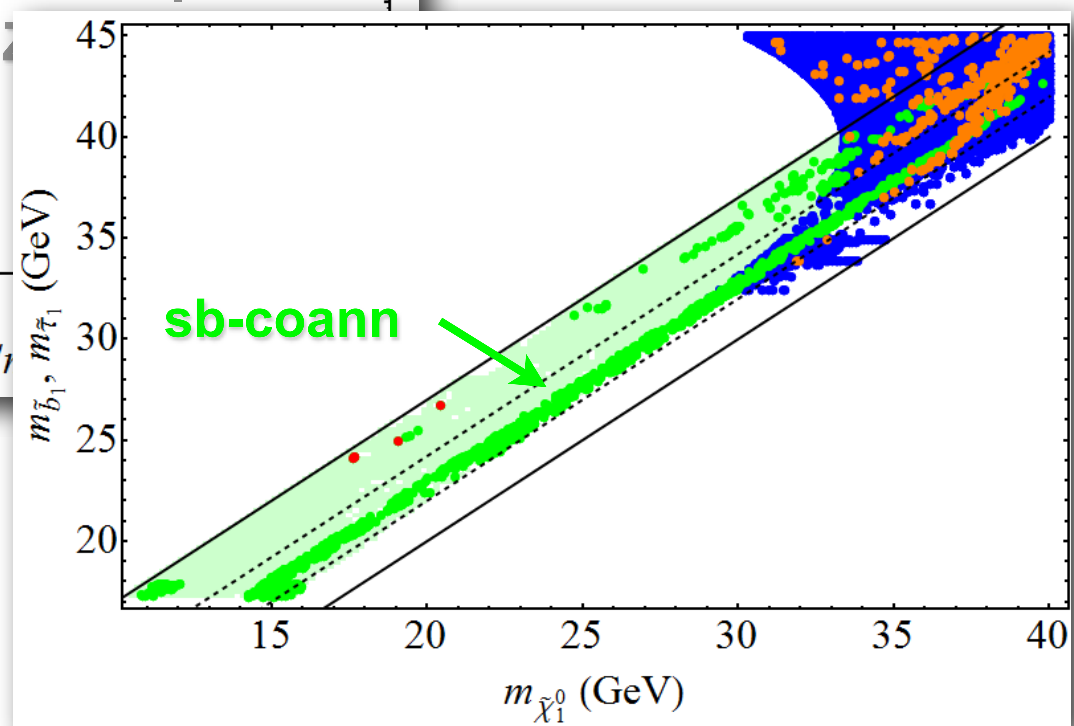
S. Su

DM Properties

- A_1/H_1 funnel



- coannihilation



S. Su

DM Properties

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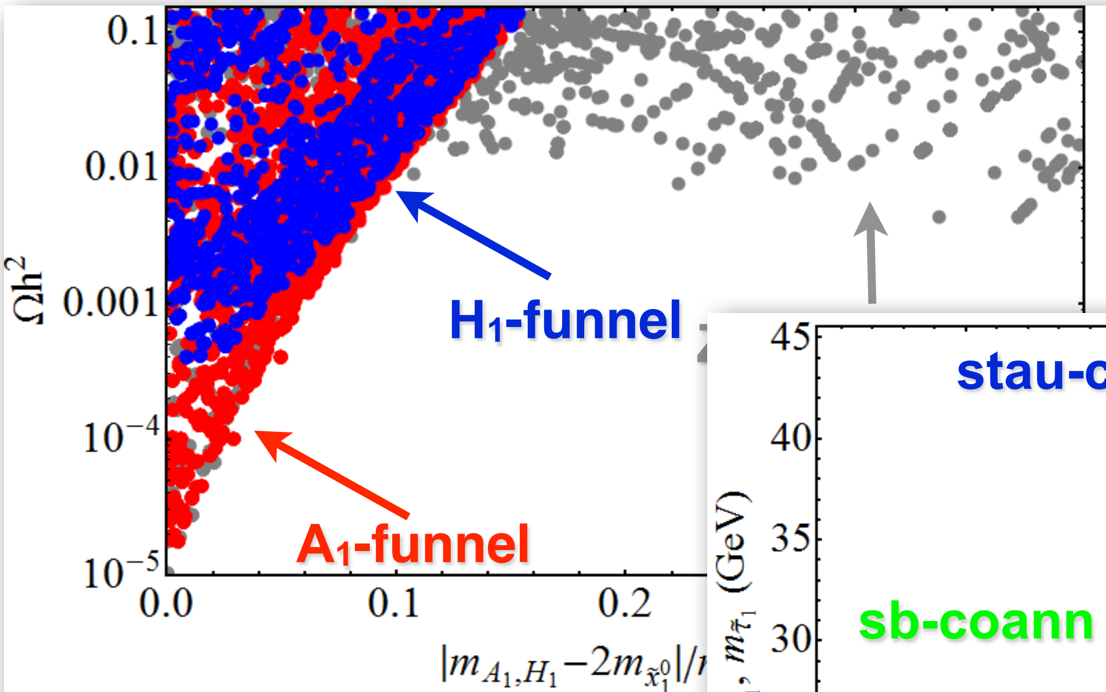
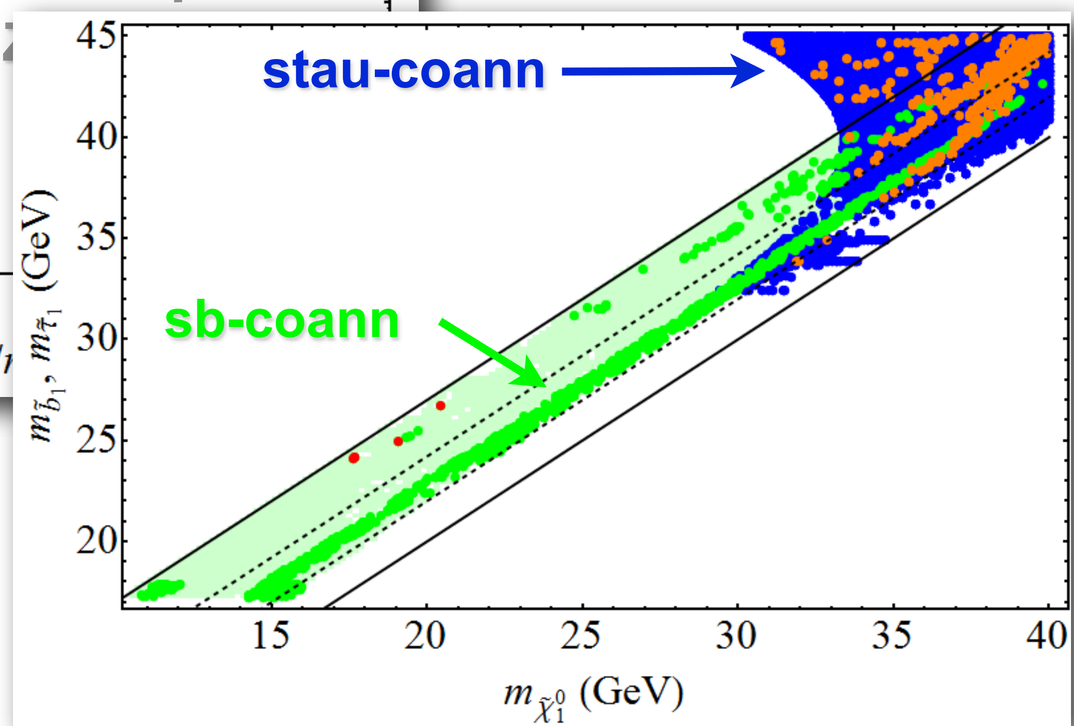
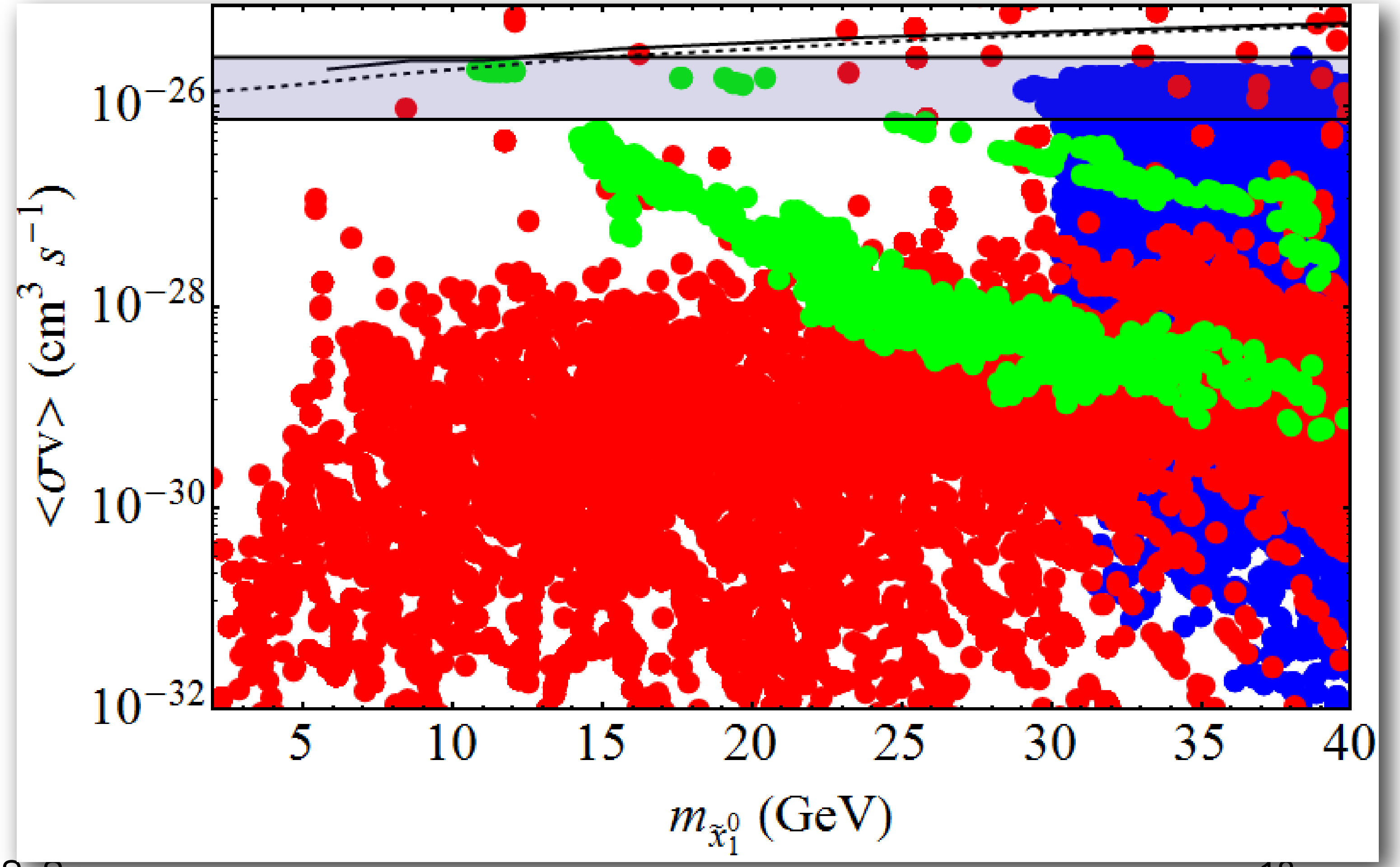


- coannihilation



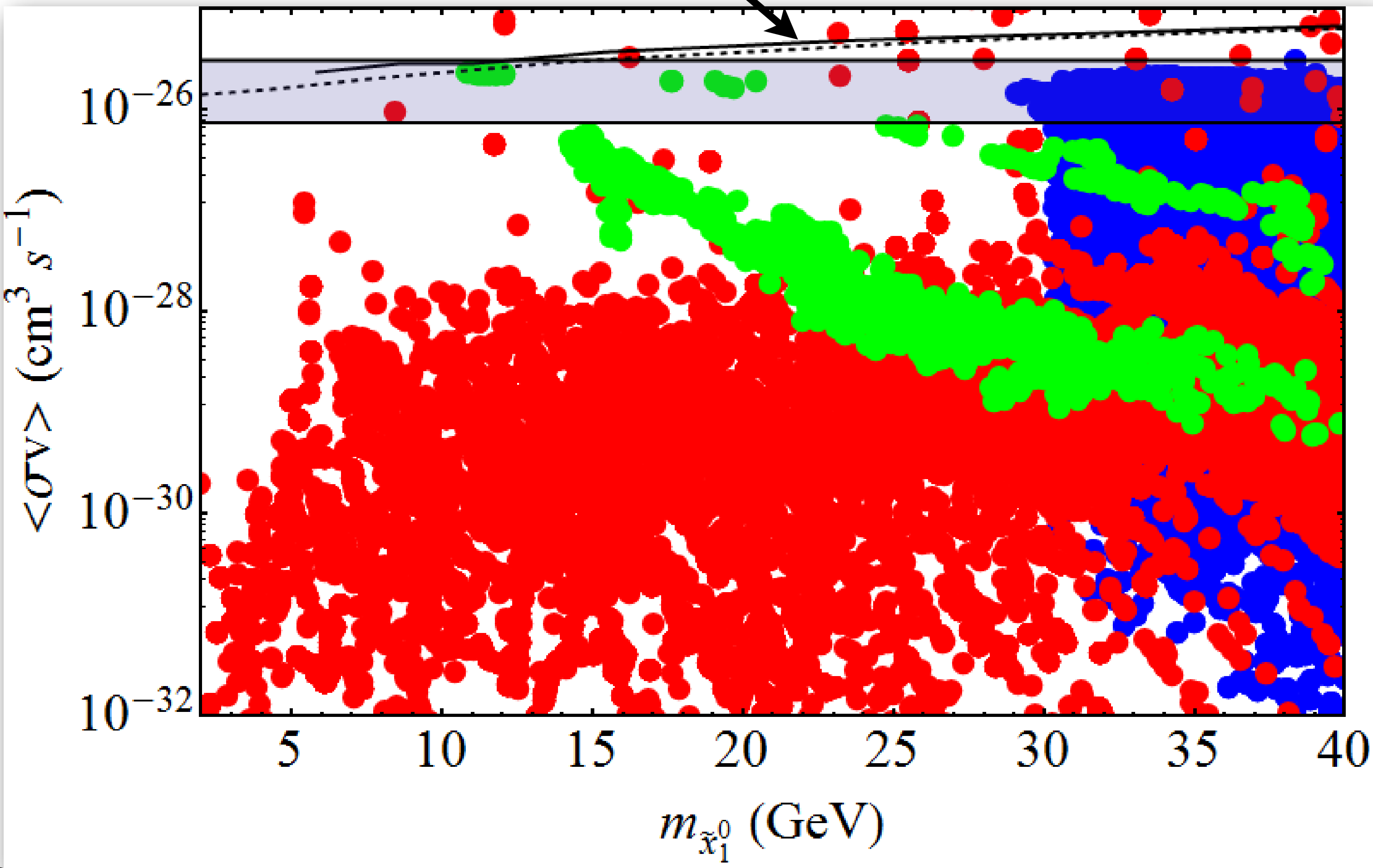
S. Su

Indirect Detection

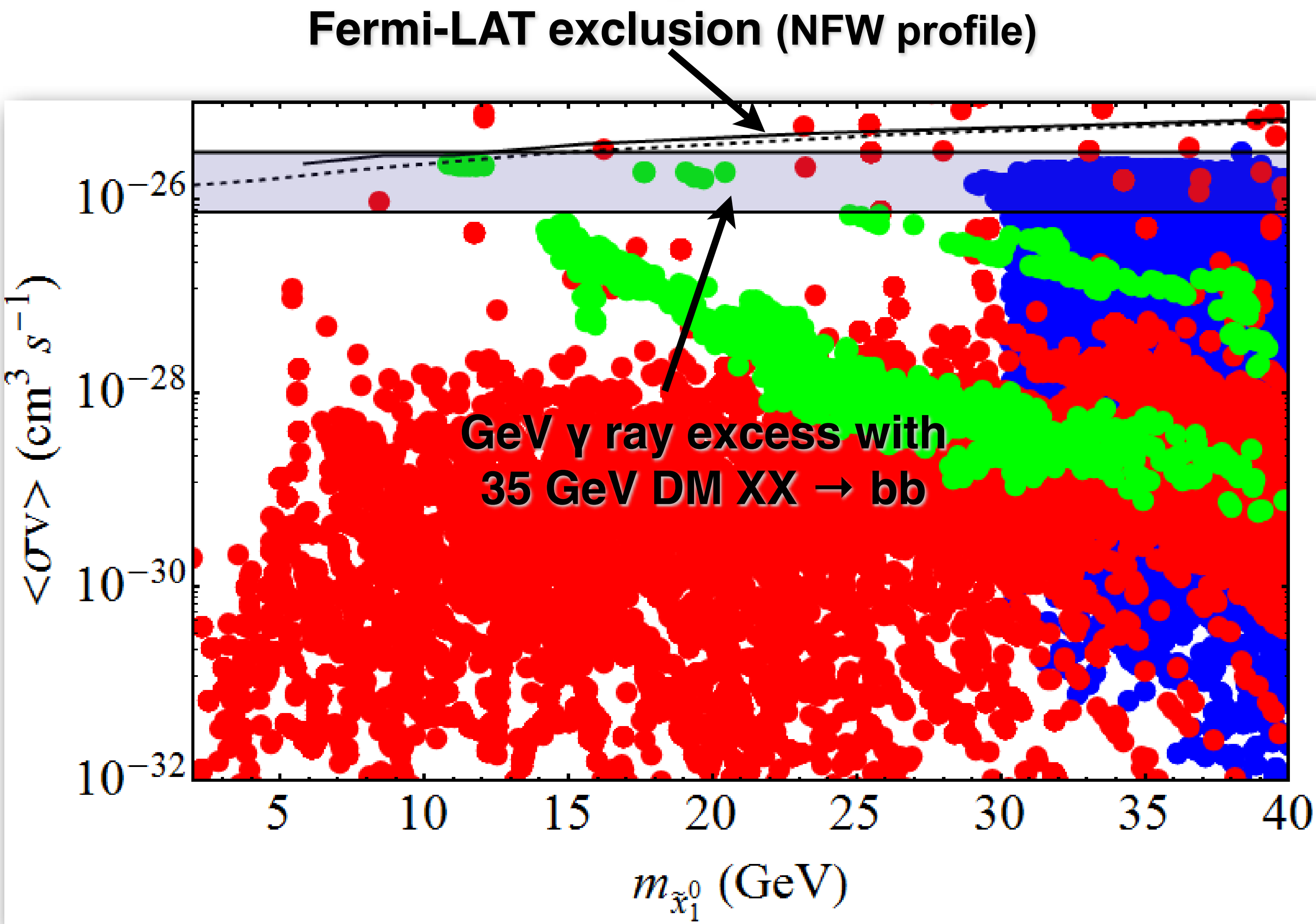


Indirect Detection

Fermi-LAT exclusion (NFW profile)

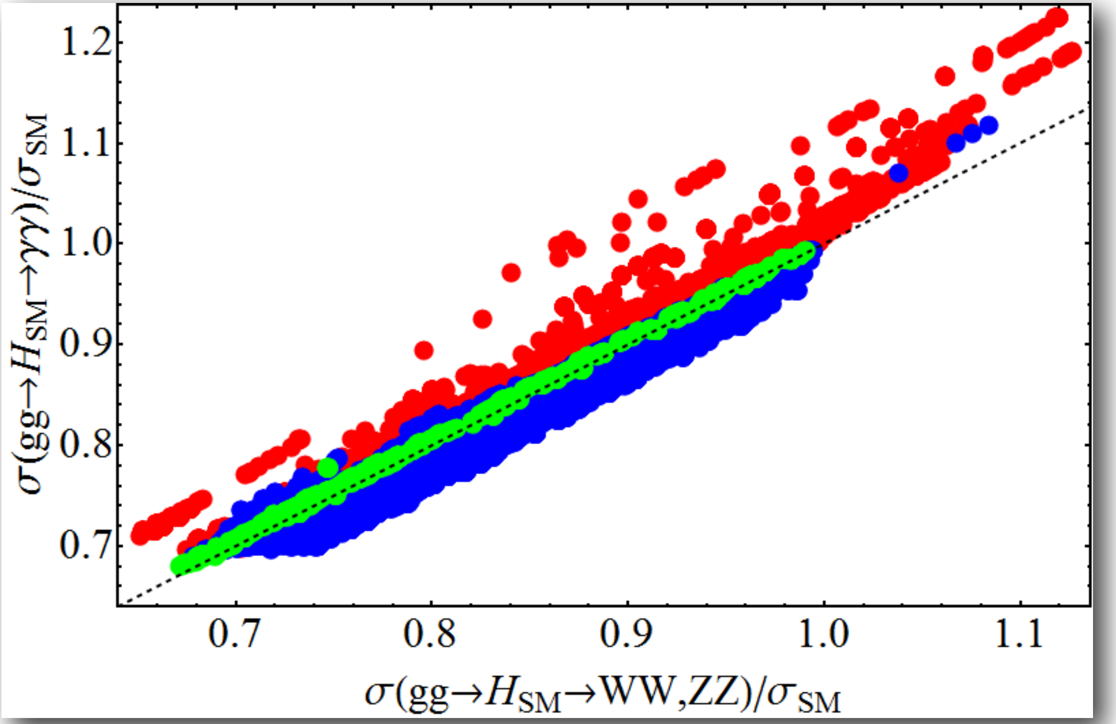


Indirect Detection

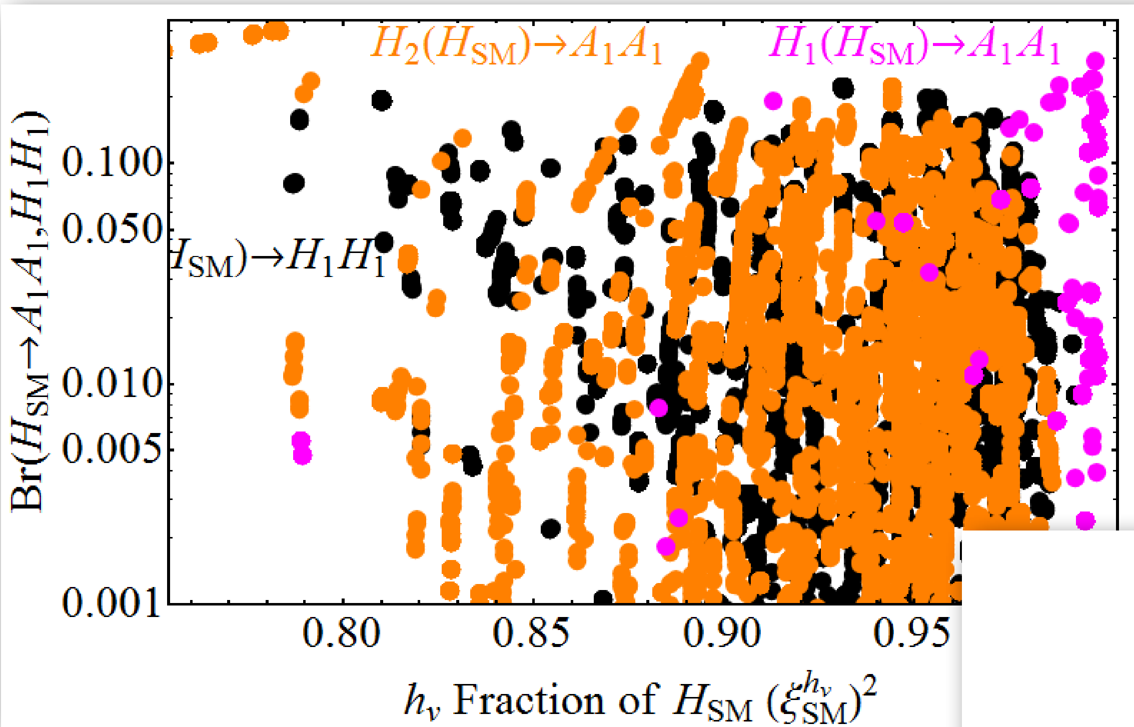


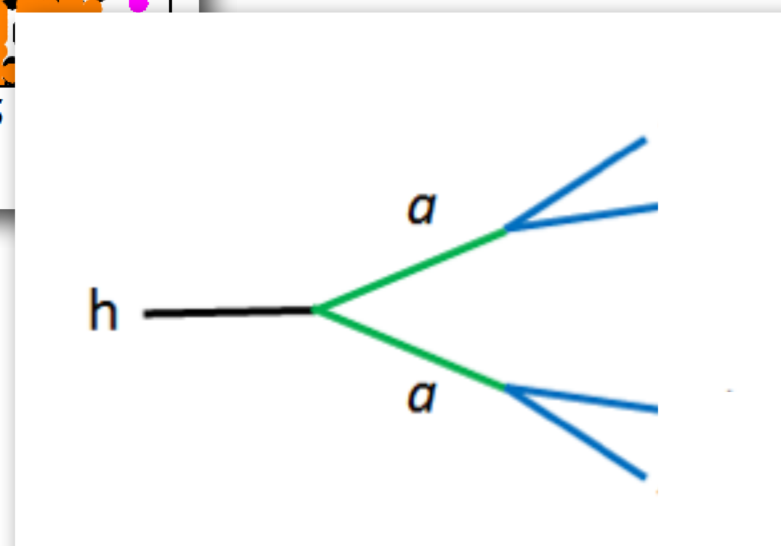
SM Higgs

- Observation of a SM-like Higgs poses strong constraints
  - mixture from other Higgses
  - new decay modes open: $\tilde{\chi}_1^0\tilde{\chi}_1^0$, A_1A_1, H_1H_1, $\tilde{\tau}_1^+\tilde{\tau}_1^-$ and $\tilde{b}_1\tilde{b}_1^*$
  - light sbottom/stau appears in Hgg, Hγγ

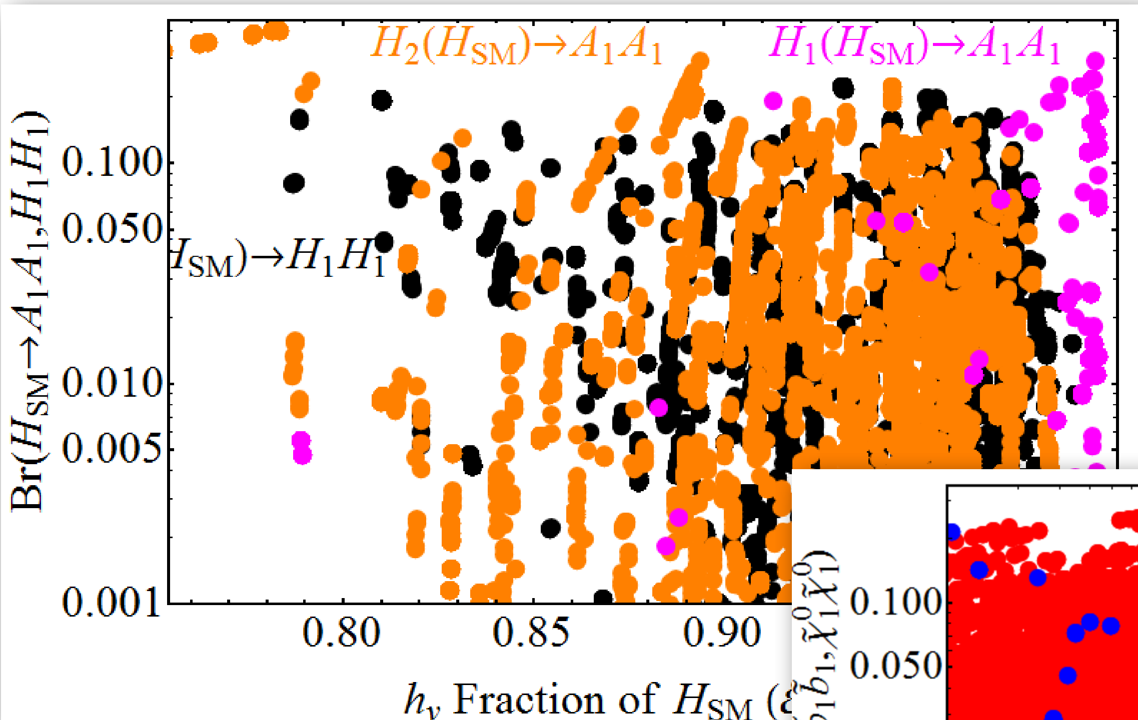


SM Higgs

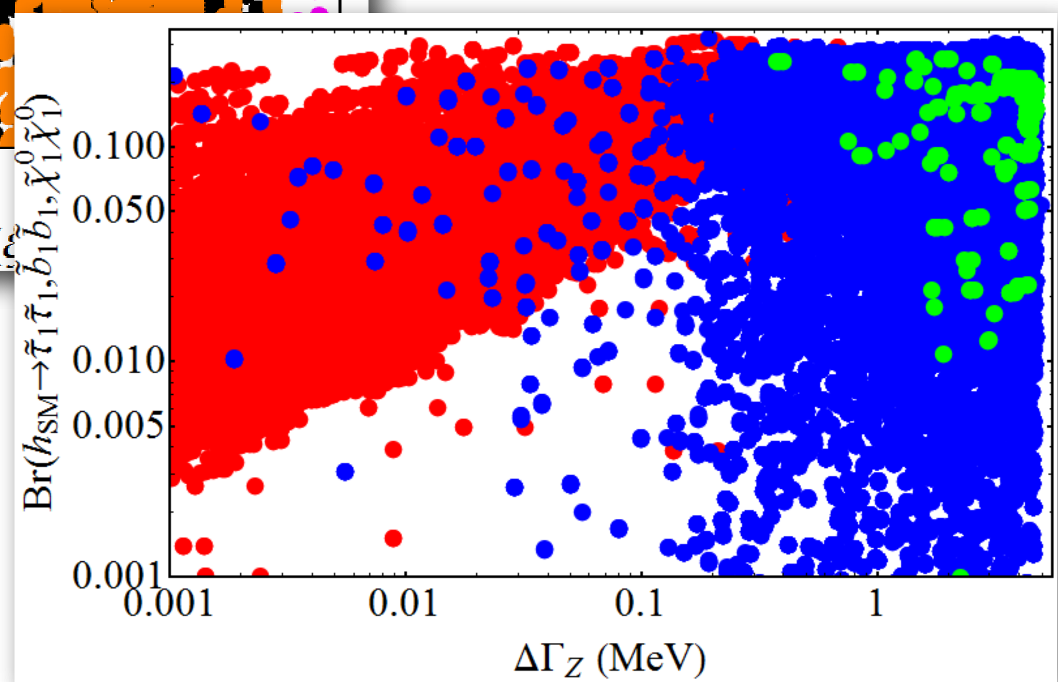

H2(HSM)→A1A1
H1(HSM)→A1A1
HSM)→H1H1
Br(HSM→A1A1,H1H1)
0.100
0.050
0.010
0.005
0.001
0.80
0.85
0.90
0.95
hv Fraction of HSM (ξSM^hv)^2


h
a
a

SM Higgs



$H_2(H_{SM})\to A_1A_1$
$H_1(H_{SM})\to A_1A_1$
$H_{SM})\to H_1H_1$
$Br(H_{SM}\to A_1A_1, H_1H_1)$
0.100
0.050
0.010
0.005
0.001
0.80
0.85
0.90
h_v Fraction of H_{SM}



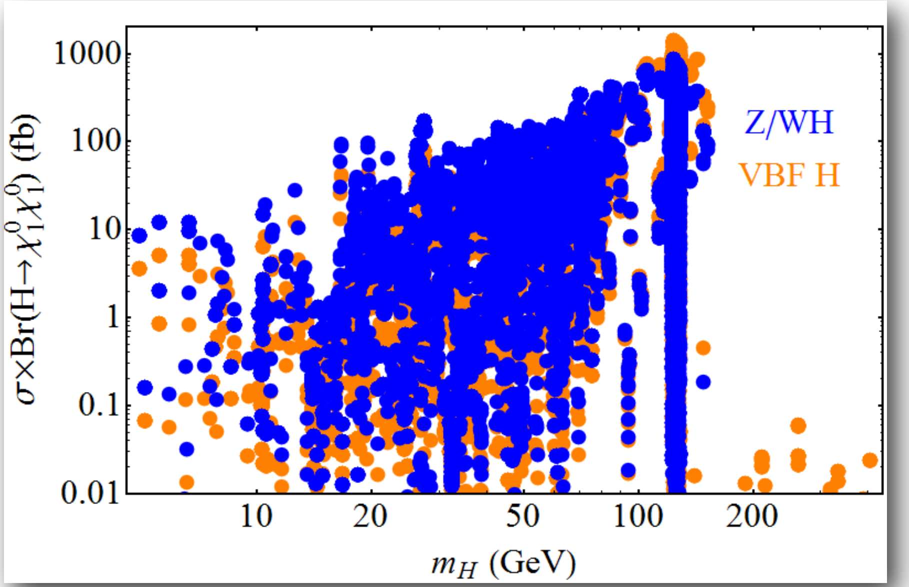
$Br(h_{SM}\to\tilde{\tau}_1\tilde{\tau}_1, \tilde{b}_1\tilde{b}_1, \tilde{\chi}_1^0\tilde{\chi}_1^0)$
0.100
0.050
0.010
0.005
0.001
0.001
0.01
0.1
1
$\Delta\Gamma_Z$ (MeV)

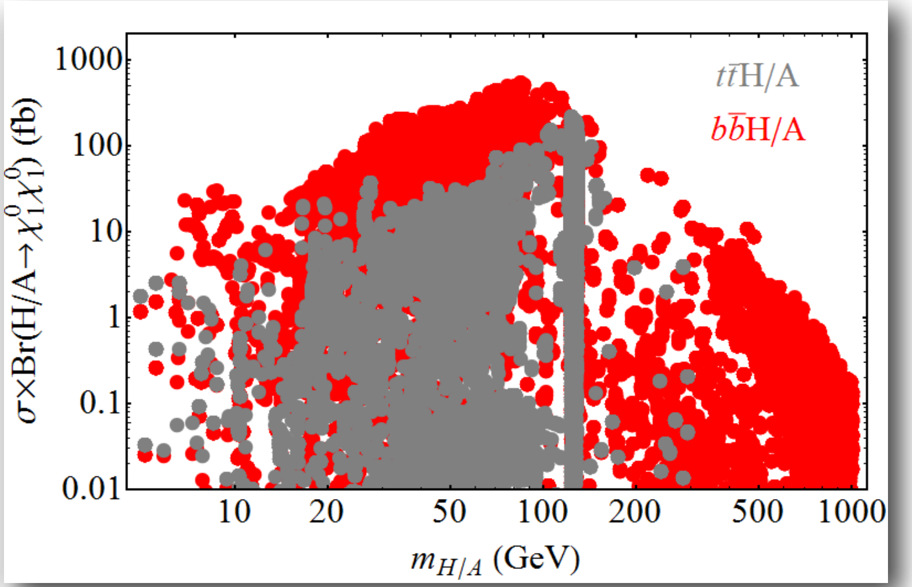
S. Su

Higgs Portal

- Dark matter production via Higgs portal

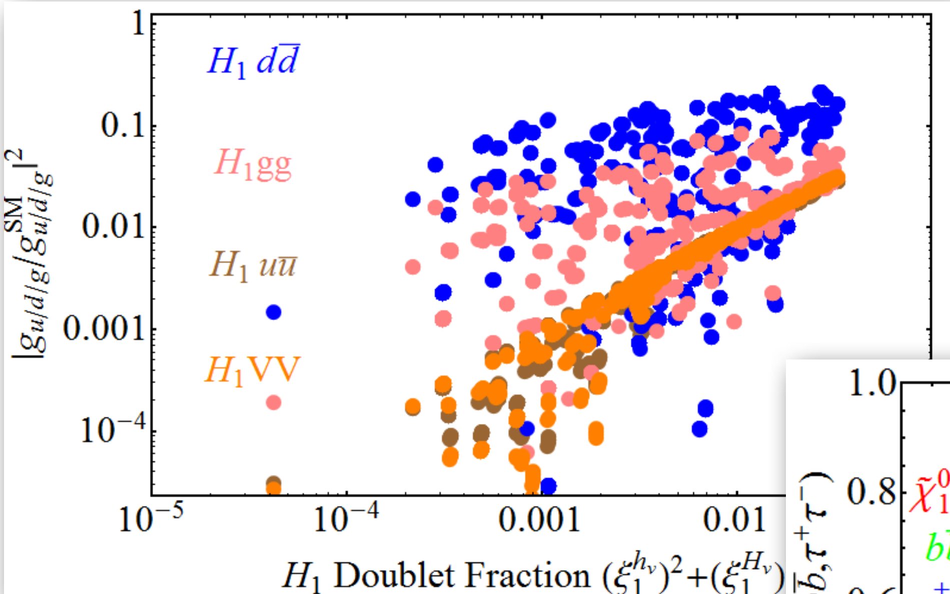
H → XX

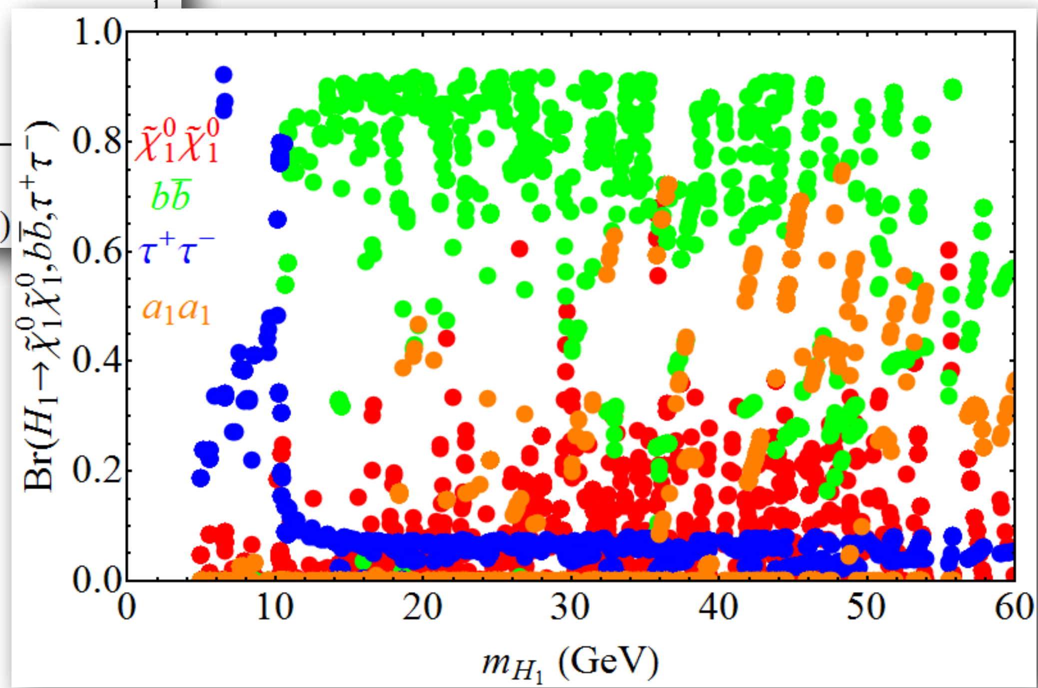




Light A_1/H_1

- Coupling and Decay: singlet like





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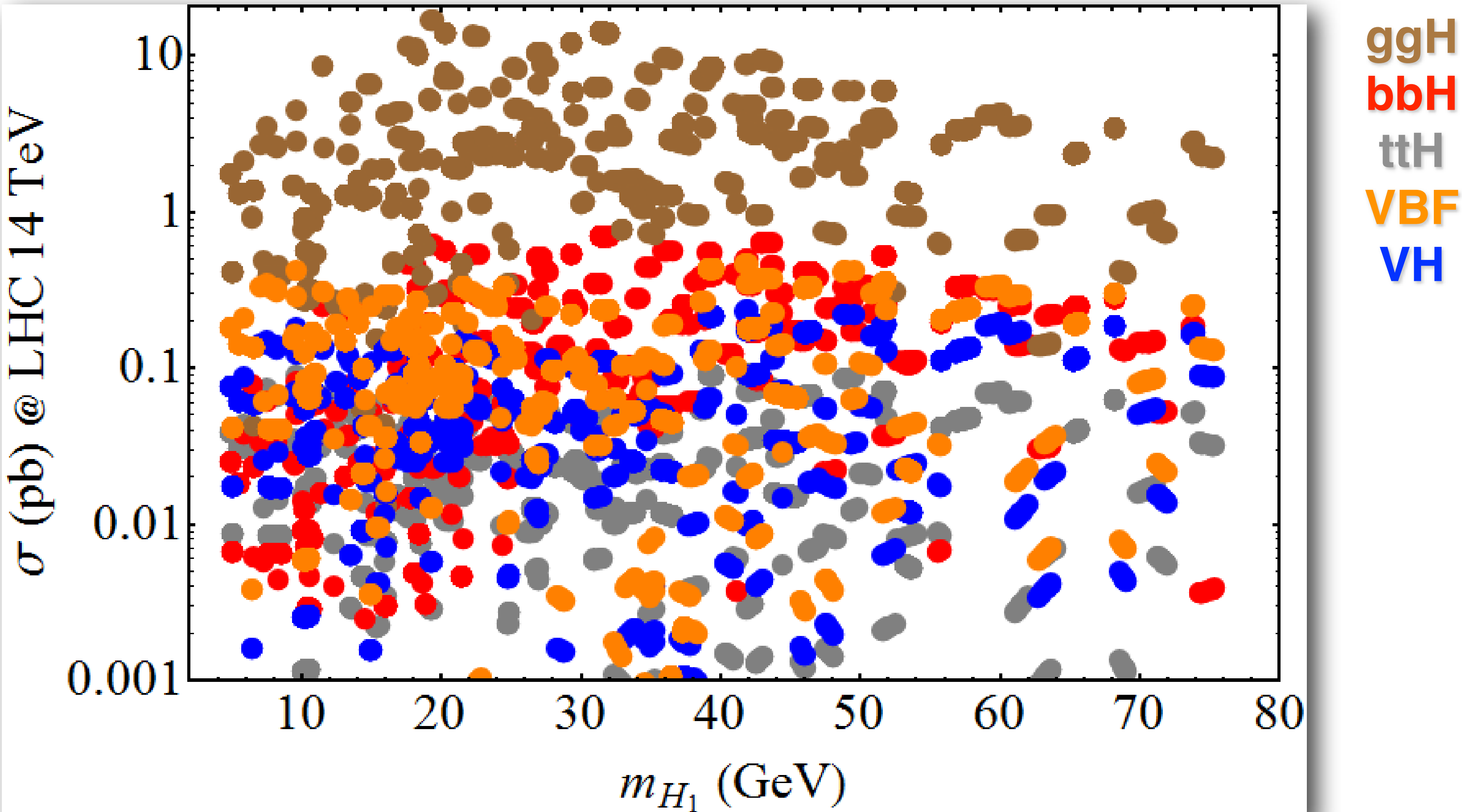
Light A_1/H_1

- Production: < 10% SM rate



Light Sbottom

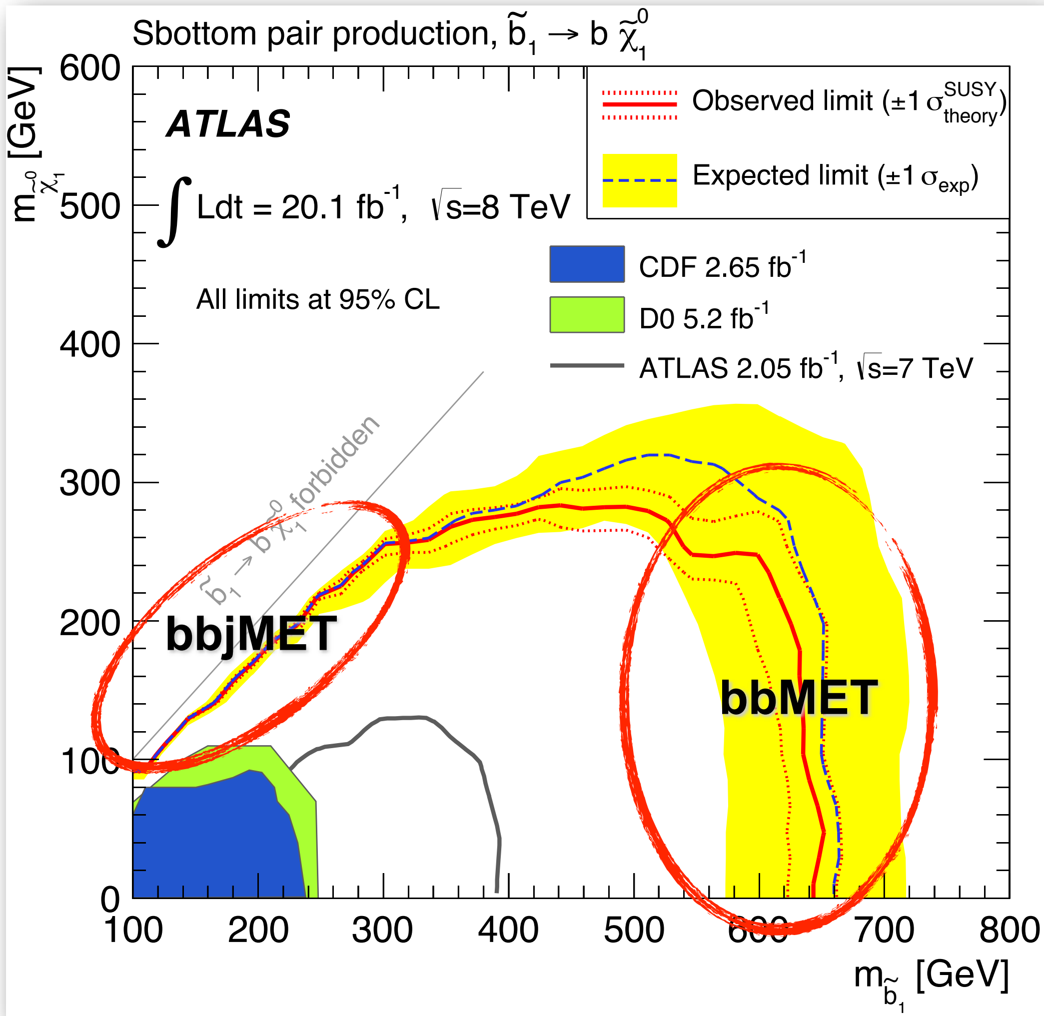
- Light sbottom with compressed spectrum: small Δm
  - $\Delta m > m_b$: prompt sbottom decay
  - $\Delta m < m_b$: prompt, displaced vertex, R-hadron, ...
    depend on the flavor structure

- LEP limits

$\tilde{f}$	m_{min}(GeV)	Ref.	Condition
$\tilde{b}$	76	DELPHI [50]	$\tilde{b} \to \tilde{\chi}^0 b$, all $\theta_{\tilde{b}}$, $\Delta m > 7$ GeV
	89	ALEPH [48]	$\tilde{b} \to \tilde{\chi}^0 b$, all $\theta_{\tilde{b}}$, $\Delta m > 10$ GeV
	$390 \sim 645$	ATLAS [51, 52]	$\tilde{b} \to \tilde{\chi}_1^0 b$, simplified, $m_{\tilde{\chi}_1^0} < 60$ GeV for $m_{\tilde{b}} > 100$ GeV

Light Sbottom

- ATLAS limits: 2b+MET,bbj+MET



Light Sbottom

- recast ATLAS sbottom search results for light sbottom
  m_{sb}=20 GeV, m_χ=14 GeV, prompt decay

	SRA bbMET			SRB bbjMET
	Lepton veto			
$\not{E}_T$	> 150 GeV			> 250 GeV
$P_T(j_1)$	> 130 GeV			> 150 GeV
$P_T(j_2)$	> 50 GeV			> 30 GeV
$P_T(j_3)$	veto if > 50 GeV			> 30 GeV
$\Delta\phi(\not{E}_T, j_1)$	—			> 2.5
b tagging	tagged b jet j_1, j_2			j_2, j_3
$\Delta\phi_{min}$	> 0.4			> 0.4
$\not{E}_T/m_{eff}(k)$	$\not{E}_T/m_{eff}(2) > 0.25$			$\not{E}_T/m_{eff}(3) > 0.25$
m_{bb}	> 200 GeV			—
$H_{T,3}$	—			< 50 GeV
m_{CT}	≥ 250 GeV	≥ 300 GeV	≥ 350 GeV	
95% C.L. upper limit σ_{vis} (fb)	0.45	0.37	0.26	1.3
σ_{sig} (fb)	0.20	0.19	0.17	137

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$P_T(j_3)$	veto if > 50 GeV			> 30 GeV
$\Delta\phi(\not{E}_T, j_1)$	—			> 2.5
b tag				$j_2,\ j_3$
$\Delta\phi_{min}$				> 0.4
$\not{E}_T/m_{eff}$				$\not{E}_T/m_{eff}(3) > 0.25$
m_{bb}	> 200 GeV			—
$H_{T,3}$	—			< 50 GeV
m_{CT}	≥ 250 GeV	≥ 300 GeV	≥ 350 GeV	
95% C.L. upper limit σ_{vis} (fb)	0.45	0.37	0.26	1.3
σ_{sig} (fb)	0.20	0.19	0.17	137

- $\Delta m > m_b$ (prompt sb decay): ruled out
- $\Delta m < m_b$: depends on the decay life time

Light Stau

- **LEP limit**

$\tilde{\tau}$	81.9	DELPHI [50]	$\Delta m > 15$ GeV, all $\theta_{\tilde{\tau}}$, $\tilde{\tau} > 45$ GeV
	$35 \sim 45$	ALEPH [53, 54]	$Z \to \ell\ell$ (acoplanar), right-handed, $\Delta m > 2 \sim 5$ GeV
	35	ALEPH [53, 54]	$Z \to$ invisible, right-handed, all Δm
	$20 \sim 44$	ALEPH [53, 54]	Z-decoupling, $\Delta m > 2 \sim 15$ GeV

- **LHC limit with stau from neutralino/chargino decay**

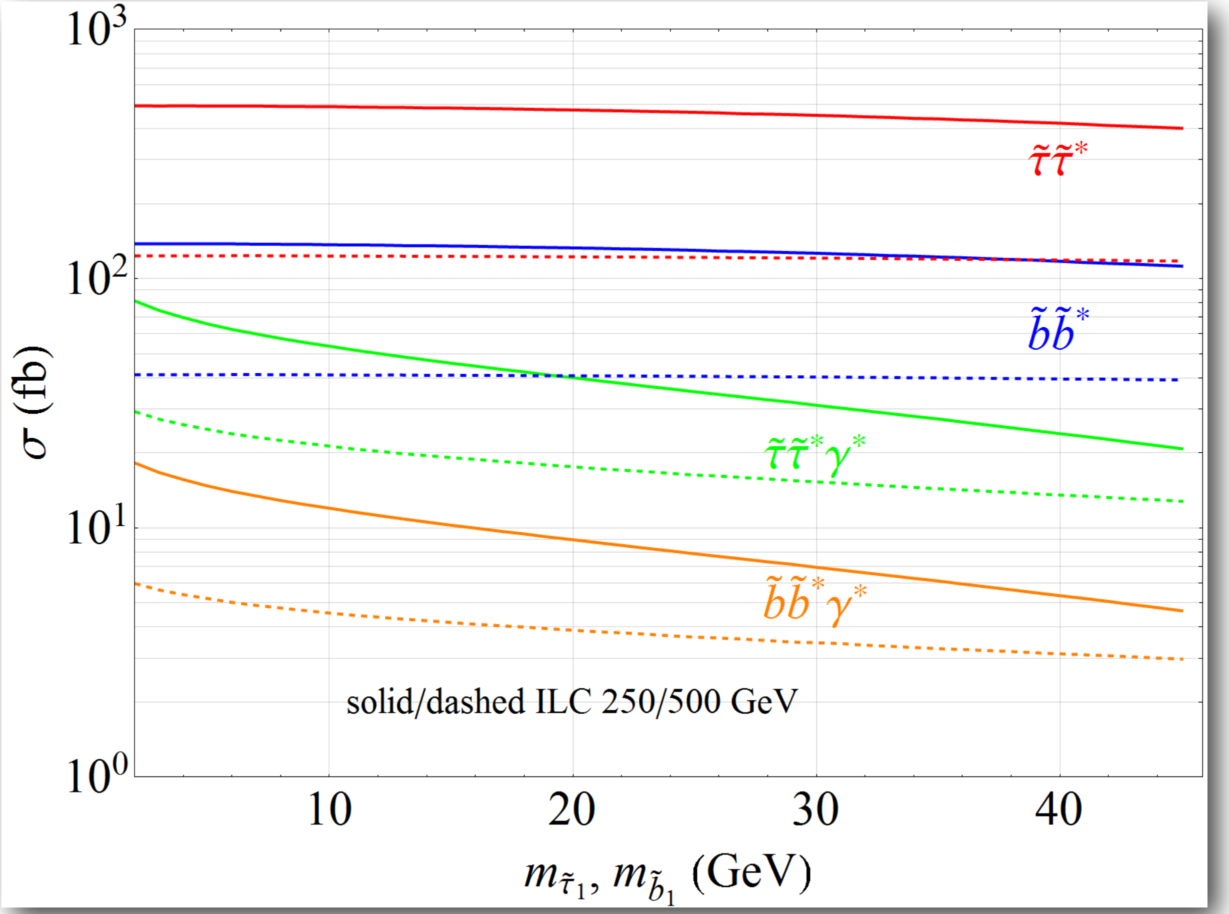
  not applicable with large MT2 cut of 90-110 GeV

- **ττ(j) + MET search difficult with WW(j)+MET background.**

light stau difficult at LHC as well.

Light Sfermion @ ILC

- bbγ+MET, ττγ+MET



Conclusion

light neutralino dark matter (2 - 40 GeV)

	A_1/H_1 funnel	sb-coann	stau-coann
DM	Bino/Singlino	Bino	Bino/Singlino
light particle	$m_{A1/H1}\sim 2m_\chi$ singlet-like	$m_{sb}\sim m_\chi$ $\Delta m < m_b$	$m_{stau}\sim m_\chi$ $m_{stau}>30$ GeV
relic	✓	✓	✓
direct detection	✓		✓
indirect detection	✓	✓	✓
via SM Higgs	✓	✓	✓
LHC	✓	✗	✗
ILC	✓	✓	✓