SUSY Implications from WIMP Annihilation into scalars at the Galactic Center

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[1502.xxxx]
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CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

THE UNIVERSITY OF MELBOURNE

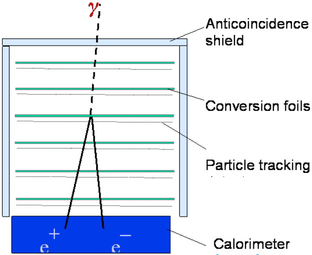
Fermi Satellite Experiment


fermi.gsfc.nasa.gov

- launched 11 June 2008
- running 5 - 10 years

Fermi-LAT

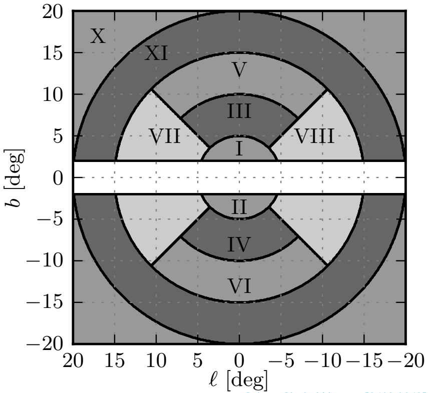
- Observation of γ-rays
- $E = 30\text{MeV} - 500\text{GeV}$
- High energy resolution: $< 15\%$ at energies > 100 MeV
- large field of view 2.4 sr



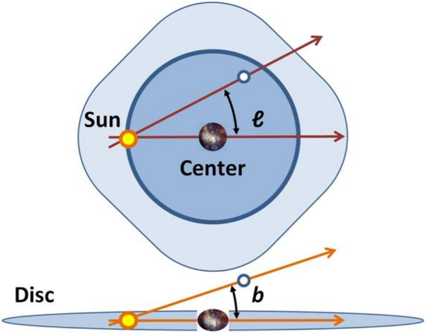
fermi.gsfc.nasa.gov

Analysis of γ-rays from Galactic Centre

- Recent analysis Calore,Cholis,Weniger [1409.0042]
- $|l| < 20°, 2° < |b| < 20°$
- galactic disk removed
- using 284 weeks of data



Calore,Cholis,Weniger [1409.0042]

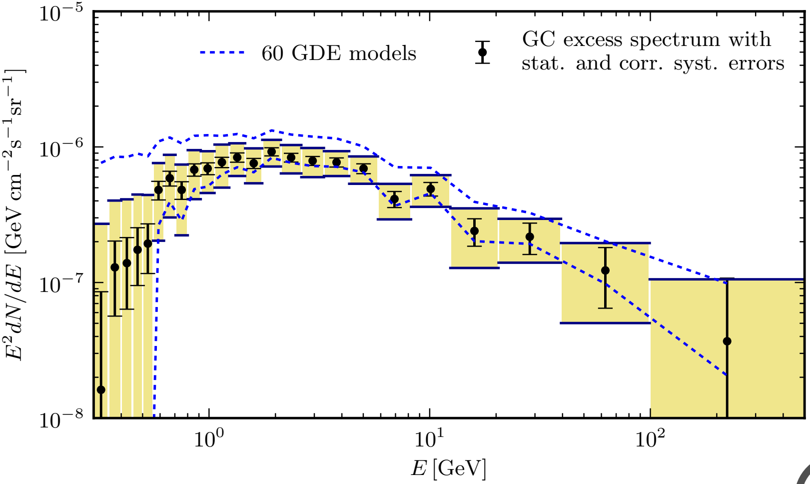


Wikipedia

- Study of sub-regions
- Excess above what?

Astrophysical Background and Foregrounds

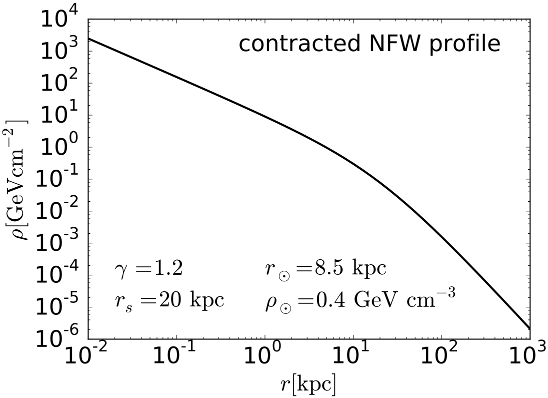
- point and extended sources
- galactic diffuse emission
- Cosmic rays generating π^0's
- CR e^-: Bremsstrahlung, ICS



Dark Matter Interpretation of Fermi GeV Excess

DM $$\frac{dN}{dE} = \sum_f \frac{\langle \sigma v \rangle_f}{8\pi m_\chi^2} \frac{dN_\gamma^f}{dE} \int_{l.o.s.} ds\, \rho^2(r(s,\psi))$$

Generalized NFW profile $$\rho(r) = \rho_\odot \left(\frac{r}{r_\odot}\right)^{-\gamma} \left(\frac{1 + r_\odot/r_s}{1 + r/r_s}\right)^{3-\gamma}$$



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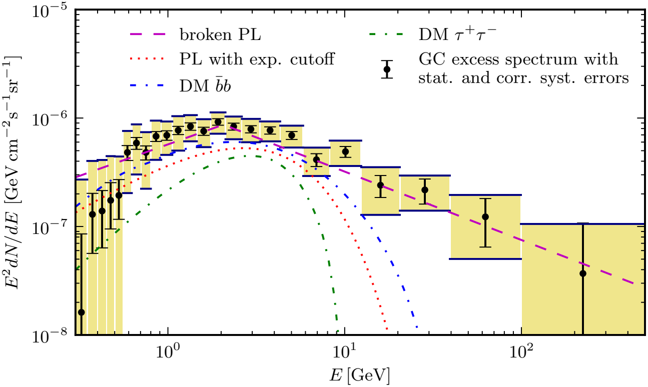


p-values

broken PL
$p = 0.47$

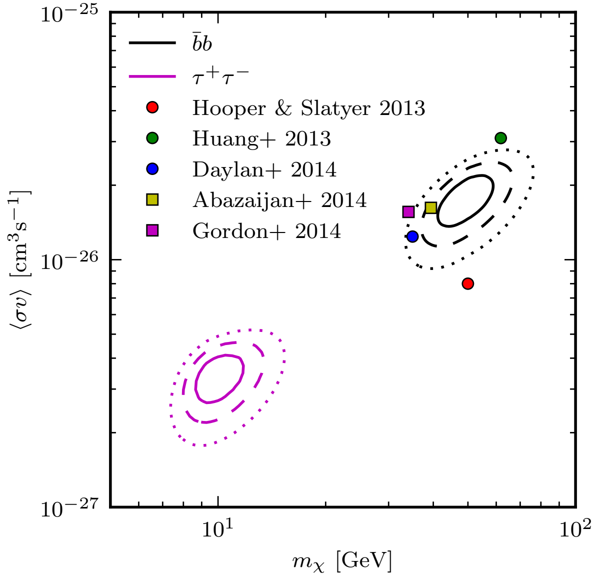
exp cutoff
$p = 0.16$

DM $b\bar{b}$
$p = 0.43$

DM $\tau^+\tau^-$
$p = 0.065$

Calore, Cholis, Weniger [1409.0042]

Other Analyses of Dark Matter Interpretation



Calore, Cholis, Weniger [1409.0042]

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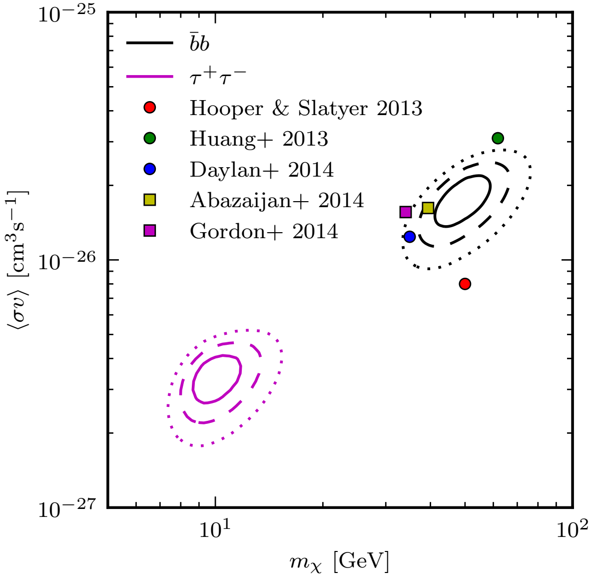


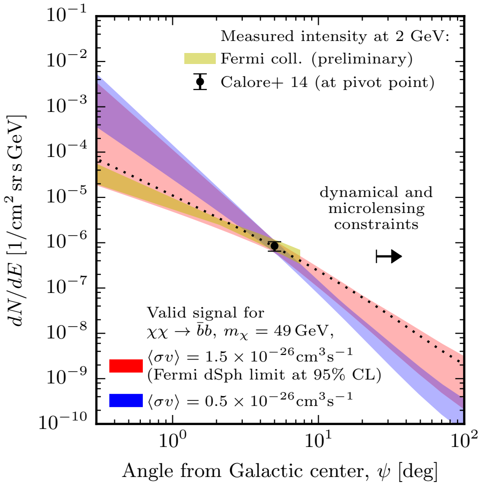
Calore, Cholis, Weniger [1409.0042]

- Fermi-LAT Collaboration recently confirmed excess
- but analysis still preliminary

Dwarf Spheroidal Limits for annihilation into $b\bar{b}$

- $\langle \sigma_{b\bar{b}} v \rangle_0 < 5(7.91) \times 10^{-26} \text{cm}^3/\text{s}$ for $m_{DM} = 25(50)$ GeV Fermi Collaboration 2013
- Preliminary Fermi limit $\langle \sigma_{b\bar{b}} v \rangle_0 \lesssim 1.5 \times 10^{-26} \text{cm}^3/\text{s}$ for $m_{\tilde{\chi}} = 49$ GeV

Andersen, Talk at Fermi Symposium 2014



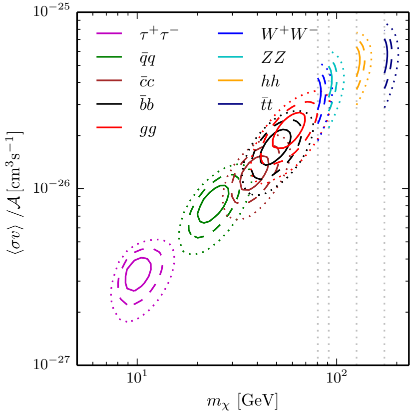
Calore, Cholis, McCabe, Weniger [1411.4647]

Already mild tension

- Large uncertainties in Milky Way and dwarf spheroidal halo profile
- Signal at $\psi = 5^\circ$ relatively independent of profile
- Generate large sample of Milky Way halo profiles
- Envelope shows possible signal as function of ψ

$\Rightarrow$ Tension alleviated if uncertainties properly taken into account

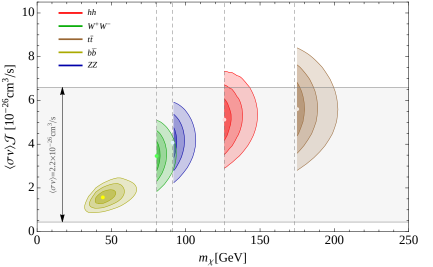
DM Fits: 3σ Regions



Calore, Cholis, McCabe, Weniger [1411.4647]

	$\langle\sigma v\rangle$	m_χ	$\chi^2_{\min}$	p-value
$\bar{b}b$	$1.75^{+0.28}_{-0.26}$	$48.7^{+6.4}_{-5.2}$	23.9	0.35
$\bar{t}t$	$5.8^{+0.8}_{-0.8}$	$173.3^{+2.8}_{-0}$	43.9	0.003
hh	$5.33^{+0.68}_{-0.68}$	$125.7^{+3.1}_{-0}$	29.5	0.13
W^+W^-	$3.52^{+0.48}_{-0.48}$	$80.4^{+1.3}_{-0}$	36.7	0.026
ZZ	$4.12^{+0.55}_{-0.55}$	$91.2^{+1.53}_{-0}$	35.3	0.036

Calore,Cholis,McCabe,Weniger [1411.4647]



Agrawal, Batell, Fox, Harnik [1411.2592]

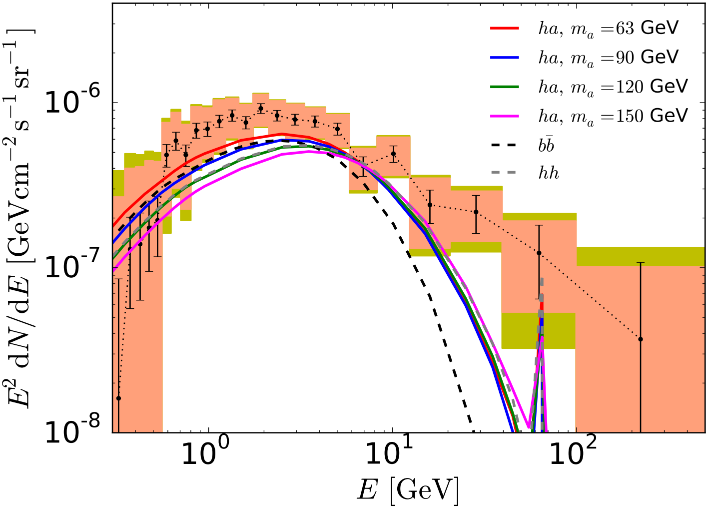
Uncertainties in DM halo

$\mathcal{A} = [0.17, 5.3]$ ($\mathcal{J} = [0.19, 3]$)

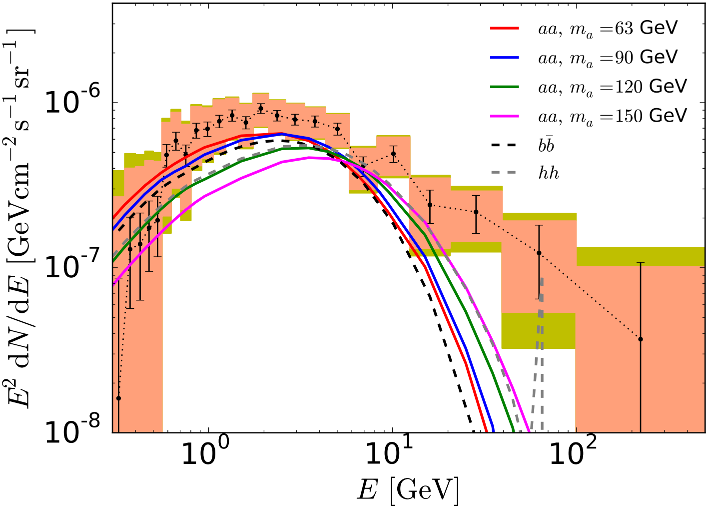
Annihilation into ha and aa in type II 2HDM

- Independent of additional scalar singlets (includes the NMSSM).
- Fits with a Higgs at 125 GeV with SM couplings and setting $\tan\beta = 3$.
- Consider the dominant decay channels $b\bar{b}$, $\tau^+\tau^-$, $c\bar{c}$, $\gamma\gamma$ and gg and simulate the prompt photon spectra using `PYTHIA 8.201`.
- For intermediate $\tan\beta \Rightarrow$ $\mathrm{Br}(a \to \gamma\gamma)/\mathrm{Br}(h_{\mathrm{SM}} \to \gamma\gamma) \sim 1/(10 \times \tan^4\beta)$.
- Spectral line from $a \to \gamma\gamma$ barely distinguishable from the continuum for $m_a \sim 150$ GeV and $\tan\beta \sim 1$ using Fermi-LAT resolution.
- 2-peak structure in ha may be detectable in future experiments.

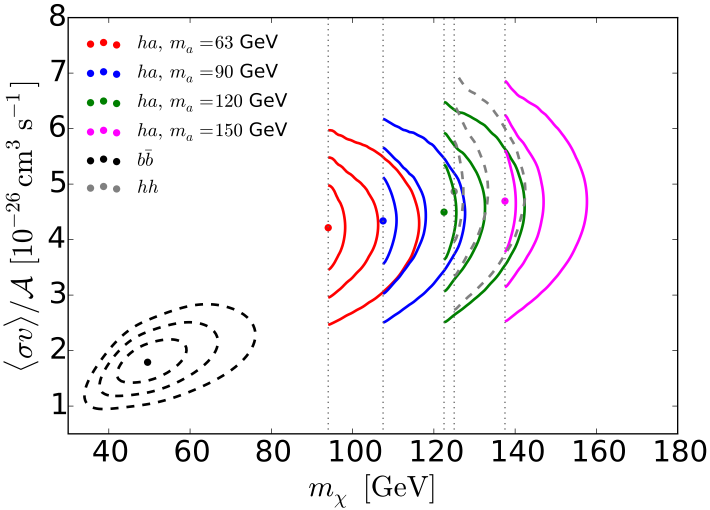
Spectral Fit for ha



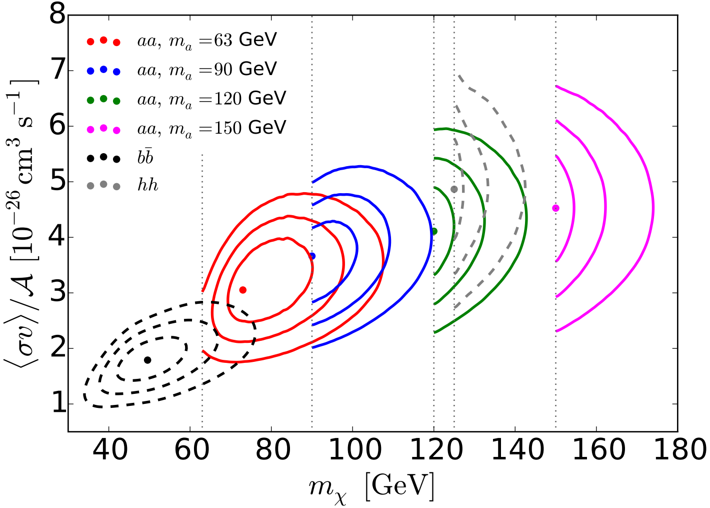
Spectral Fit for aa



Best fit regions for ha



Best fit regions for aa

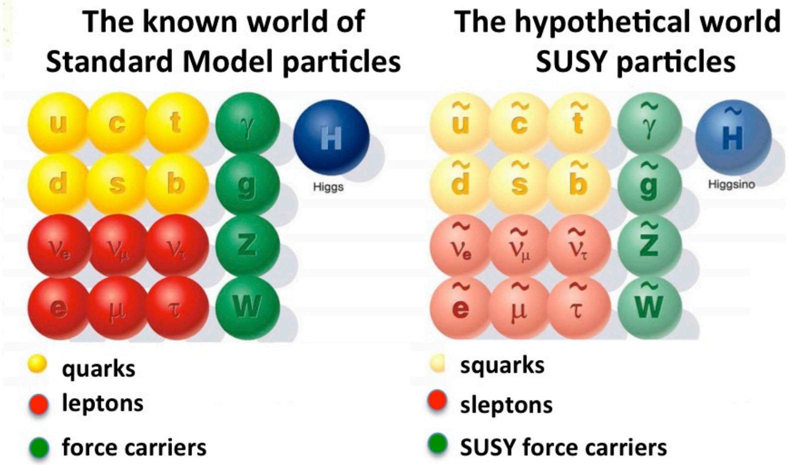


channel	m_a [GeV]	$m_{\rm DM}$ [GeV]	$\langle\sigma v\rangle_0\,[10^{-26}{\rm cm}^3/{\rm s}]$	$\chi^2_{\rm min}$	p-value
$b\bar{b}$		$49.5^{+8.1}_{-6.3}$	$1.8^{+0.3}_{-0.3}$	24.5	0.32
hh		$125.0^{+2.3}_{0.0}$	$4.9^{+1.0}_{-0.9}$	30.0	0.12
ha	63	$94.0^{+4.2}_{0.0}$	$4.2^{+0.8}_{-0.8}$	22.4	0.43
	90	$107.5^{+3.4}_{0.0}$	$4.3^{+0.8}_{-0.8}$	25.3	0.28
	120	$122.5^{+3.0}_{0.0}$	$4.5^{+0.9}_{-0.9}$	30.3	0.11
	150	$137.5^{+2.7}_{0.0}$	$4.7^{+1.0}_{-1.0}$	36.0	0.03
aa	63	$73.0^{+15.4}_{-10.0}$	$3.1^{+0.6}_{-0.6}$	24.3	0.33
	90	$90.0^{+10.9}_{0.0}$	$3.7^{+0.5}_{-0.8}$	24.4	0.33
	120	$120.0^{+4.9}_{0.0}$	$4.1^{+0.8}_{-0.8}$	31.0	0.10
	150	$150.0^{+4.4}_{0.0}$	$4.5^{+1.0}_{-1.0}$	41.4	0.01

INTERESTING TO STUDY WELL-MOTIVATED DM MODELS IN WHICH THESE CHANNELS NATURALLY ARISE.

SUSY COMES TO MIND . . .

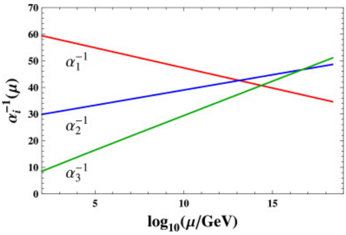
Minimal Supersymmetric SM (MSSM)



QuantumDiaries

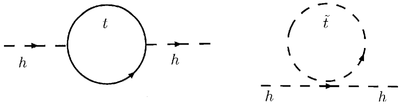
SUperSYmmetry (SUSY)

- The MSSM contains the minimal supersymmetric particle content compatible with the Standard Model (SM), $\mathcal{N}=1$ SUSY (one SUSY charge generator).
- Gauge couplings unify in the MSSM $\Longrightarrow$ strong hint towards GUT theories.
- If R-parity is conserved: avoid proton decay constraints, SUSY particles produced in pairs and LSP is stable $\Longrightarrow$ DM.



SUperSYmmetry (SUSY)

- SUSY avoids quadratically divergent quantum corrections to the Higgs mass involving a physical cut-off Λ (If softly broken).



- Quantum corrections still generate large logarithms $\sim \log(\Lambda/m_{\tilde{t}}) \Rightarrow$ Summed up via RGE (β-functions).
- Finite corrections via effective action,

$$\mathcal{S}_{eff} = \int d^4x \left\{ \sum_{n=0}^{\infty} Z_i^n \partial_\mu \phi_i^\dagger \partial^\mu \phi_i - \sum_{n=0}^{\infty} V_n \right\}$$

- At one-loop we recover the Coleman-Weinberg formula which in the $\bar{DR}$ scheme is

$$V_1 = \frac{1}{64\pi^2} \, \mathrm{STr}\, M^4 \left[\ln\left(\frac{M^2}{\mu_r^2}\right) - \frac{3}{2} \right]$$

Energy scales involved:

Λ ———— Scale at which SUSY breaking is transmitted from hidden sector to visible sector

m_{soft} ———— Scale at which EWSB happens

$m_h \sim v_{EW}$ ———— Pole Higgs mass

- In the best fit regions for the annihilation channels $b\bar{b}$, ha and aa imply a somewhat light $m_a \lesssim 150$ GeV $\Rightarrow$ Hard to accomplish in the MSSM for $m_h \approx 125$ GeV and constrained by LEP and LHC measurements (particularly $h, a \to \tau^+\tau^-$).
- Also in tension with flavour physics (B-meson decays) due to light charged Higgs.

FURTHERMORE . . .

Higgs Mass in MSSM

Rely on loop corrections to Higgs mass from (s)top sector

$$m_h^2 = m_Z^2 \cos^2 2\beta \left(1 - \frac{3}{8\pi^2} y_t^2 t\right) + \frac{3}{4\pi^2} y_t^2 \left[\frac{1}{2} X_t + t + \dots\right]$$

with $t = \ln \frac{m_{\tilde{t}}^2}{M_t^2}$, $X_t = \frac{2(A_t - \mu \cot\beta)^2}{m_{\tilde{t}}^2} \left(1 - \frac{(A_t - \mu \cot\beta)^2}{12 m_{\tilde{t}}^2}\right)$,
$m_{\tilde{t}} = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$

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Large contribution to $m_{H_u}^2$ from RG evolution in the supersymmetric theory

$$m_{H_u}^2(m_{\tilde{t}}) = m_{H_u}^2(\Lambda) - \frac{3y_t^2}{8\pi^2}\left[m_{Q_3}^2(\Lambda) + m_{u_3}^2(\Lambda) + A_t^2(\Lambda)\right] \ln\left[\frac{\Lambda}{m_{\tilde{t}}}\right] + \ldots$$

Tree-level minimisation conditions

$$m_Z^2 = \frac{m_{H_u}^2 - m_{H_d}^2}{\cos 2\beta} - m_{H_u}^2 - m_{H_d}^2 - 2\mu^2$$

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Tree-level minimisation conditions ⇒ Cancellation Required!!

$$m_Z^2 = \frac{m_{H_u}^2 - m_{H_d}^2}{\cos 2\beta} - m_{H_u}^2 - m_{H_d}^2 - 2\mu^2$$

Fine tuning in the MSSM

One way to quantify the tuning is with the measure Ellis, Barbieri, Giudice,...

$$\Sigma^v \equiv \max_{\xi_i} \left| \frac{\partial \ln v^2}{\partial \ln \xi(\Lambda)} \right|$$

- How much does v change when infinitesimally moving the independent parameters at the high scale Λ.
- In the MSSM
  $\xi_i = (m^2_{H_u}, m^2_{H_d}, \mu, b, m^2_{Q_3}, m^2_{u_3}, m^2_{d_3}, A_t, A_b, M_1, M_2, M_3)$.
- Using the chain rule,

$$\Sigma^v = \max_i \left| \sum_j \frac{\xi_i(\Lambda_{mess})}{v^2} \frac{dv^2}{d\xi_j(m_{\tilde{t}})} \frac{d\xi_j(m_{\tilde{t}})}{d\xi_i(\Lambda_{mess})} \right|$$

$$\simeq \left| \frac{3y_t^2}{8\pi^2 v^2}(m^2_{Q_3} + m^2_{u_3} + A_t^2) \log\left[\frac{\Lambda_{mess}}{m_{\tilde{t}}}\right] \times \frac{dv^2}{dm^2_{H_u}(m_{\tilde{t}})} \right|$$

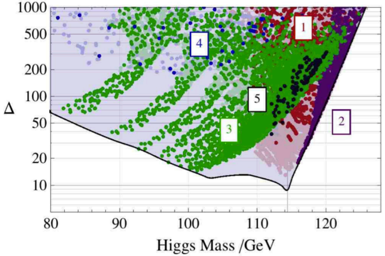
Fine tuning in the MSSM

- Neglecting the Coleman-Weinberg corrections in the MSSM and in the regime $\tan\beta \gg 1$

$$\frac{dv^2}{dm_{H_u}^2(m_{\tilde{t}})} \simeq -\frac{2v^2}{m_Z^2} + \mathcal{O}\left(\frac{1}{\tan\beta}\right)$$

$\therefore$ NO FREEDOM TO SUPPRESS DERIVATIVE AND REDUCE TUNING!

- In the CMSSM with current experimental constraints and $m_h \approx 126$ GeV, $\Sigma^v \gtrsim 1000$.



Scale Invariant NMSSM

- Introduce a gauge singlet chiral superfield S in addition to the MSSM superfield content.
- No mass scale in the new superpotential piece ($\mathbb{Z}_3$ symmetry):

$$W_{NMSSM} = \lambda S H_d H_u + \frac{\kappa}{3} S^3$$

- Soft breaking terms:

$$\begin{aligned} V_{soft} &= m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2 \\ &+ \left(\lambda A_\lambda S H_d H_u + \frac{\kappa A_\kappa}{3} S^3 + h.c \right) \end{aligned}$$

Notice from W_{NMSSM} that:

1. If $\langle s \rangle \sim v$ for $\lambda \sim 1 \Rightarrow$ solve the μ-problem found in the MSSM.
2. Contributions to the Higgs potential of the form $F_S F_S^*$ generate a quartic coupling at tree-level proportional to λ^2.

Scale Invariant NMSSM

- CP-conserved Higgs-singlet sector $\Rightarrow$ 3 CP-even states, 2 CP-odd states and 1 charged Higgs.
- Neutral components: $H_u^0 = v_u + (h_u + ih_{u,I})/\sqrt{2}$, $H_d^0 = v_d + (h_d + ih_{d,I})/\sqrt{2}$ and $S = v_s + (s + is_I)/\sqrt{2}$.
- CP-even sector useful to rotate to the basis

$$\begin{pmatrix} h \\ H \\ s \end{pmatrix} = \begin{pmatrix} \sin\beta & \cos\beta & 0 \\ -\cos\beta & \sin\beta & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} h_u \\ h_d \\ s \end{pmatrix}$$

only $\langle h \rangle = v \neq 0$ (besides $\langle s \rangle = v_s \neq 0$) and $m_{hh}^2 = m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta$.

- $\tan\beta \approx 1$ to increase the tree-level Higgs mass (upper bound on the tree-level Higgs mass).
- If lightest eigenstate is mostly h, mixing with either H or s pulls mass down (level repulsion).

Scale Invariant NMSSM

- We take the best case scenario for tuning:
  1. Keep only 3^{rd} generation squarks and gauginos light. All other sparticles have masses $\tilde{m} \sim \Lambda$.
  2. Take a low "messenger" scale (physical cutoff) $\Lambda = 20$ TeV, 100 TeV, 1000 TeV.

- Largest regions of parameter space consistent with low fine tuning satisfying collider and flavor constraints.
- Low cutoff $\Rightarrow$ large value of $\lambda(m_{\tilde{t}}) \gtrsim 1$ (if $\Lambda = M_{GUT} \Rightarrow \lambda(m_{\tilde{t}}) \lesssim 0.65$).
- Models of λ-SUSY Barbieri, Hall, Nomura, Ruderman, . . .
  $\therefore$ Loop corrections from Higgs-singlet sector become very important and should be included.

Large λ helps

- Minimization conditions for the scale invariant NMSSM

$$
\begin{aligned}
m_Z^2 =& \frac{m_{H_u}^2 - m_{H_d}^2}{\cos 2\beta} - m_{H_u}^2 - m_{H_d}^2 - 2\lambda^2 v_s^2. \\
\lambda^2 v^2 =& \frac{2(\lambda A_\lambda v_s + \lambda\kappa v_s^2)}{\sin 2\beta} - m_{H_u}^2 - m_{H_d}^2 - 2\lambda^2 v_s^2 \\
m_s^2 =& \lambda\kappa v^2 \sin 2\beta - 2\kappa^2 v_s^2 - \lambda^2 v^2 - \frac{\lambda A_\lambda v^2}{2 v_s} \sin 2\beta - \kappa A_\kappa v_s
\end{aligned}
$$

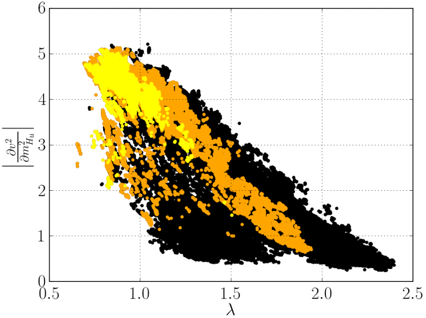
- In this case we find

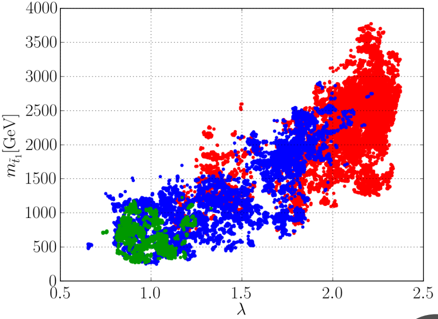
$$\frac{dv^2}{dm_{H_u}^2(m_{\tilde{t}})} = \frac{\kappa}{\lambda^3} \cot 2\beta + \mathcal{O}\left(\frac{1}{\lambda^4}\right)$$

$\therefore$ Large λ seems to help allowing for smaller tuning and/or larger stop masses.

Large λ hurts

- All plots have 5 % vev tuning or better. For large λ: $\lambda v \sin 2\beta > m_h \Rightarrow$ cancellation required!
- Dominantly cancelled by loop corrections from Higgs-singlet sector.
- New tuning measure $\Sigma^h \equiv \max_{\xi_i} |d \log m_h^2 / d \log \xi_i|$ and combined tuning $\Sigma^v \times \Sigma^h$.





Neutralino LSPs

Superpotential

$$W_{NMSSM} = W_{MSSM,Y} + \lambda S H_d H_u + \frac{\kappa}{3} S^3$$

Neutralino $(\tilde{B}, \tilde{W}^3, \tilde{h}_u^0, \tilde{h}_d^0, \tilde{s})$

$$M_{\tilde{\chi}} = \begin{pmatrix} M_1 & 0 & \frac{g_1}{\sqrt{2}} v \sin\beta & -\frac{g_1}{\sqrt{2}} v \cos\beta & 0 \\ . & M_2 & -\frac{g_2}{\sqrt{2}} v \sin\beta & \frac{g_2}{\sqrt{2}} v \cos\beta & 0 \\ . & . & 0 & -\mu_{\text{eff}} & -\lambda v \cos\beta \\ . & . & . & 0 & -\lambda v \sin\beta \\ . & . & . & . & 2\kappa v_s \end{pmatrix}$$

Lightest Supersymmetric Particle (LSP) is stable

$$\tilde{\chi} = N_{1\tilde{B}} \tilde{B} + N_{1\tilde{W}} \tilde{W}^3 + N_{1\tilde{h}_u^0} \tilde{h}_u^0 + N_{1\tilde{h}_d^0} \tilde{h}_d^0 + N_{1\tilde{s}} \tilde{s}$$

Neutralino LSPs

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$$W_{NMSSM} = W_{MSSM,Y} + \lambda S H_d H_u + \frac{\kappa}{3} S^3$$

Neutralino $(\tilde{B}, \tilde{W}^3, \tilde{h}_u^0, \tilde{h}_d^0, \tilde{s})$

$$M_{\tilde{\chi}} = \begin{pmatrix} M_1 & 0 & \frac{g_1}{\sqrt{2}} v \sin\beta & -\frac{g_1}{\sqrt{2}} v \cos\beta & 0 \\ . & M_2 & -\frac{g_2}{\sqrt{2}} v \sin\beta & \frac{g_2}{\sqrt{2}} v \cos\beta & 0 \\ . & . & 0 & -\mu_{\text{eff}} & -\lambda v \cos\beta \\ . & . & . & 0 & -\lambda v \sin\beta \\ . & . & . & . & 2\kappa v_s \end{pmatrix}$$

Lightest Supersymmetric Particle (LSP) is stable

$$\tilde{\chi} = N_{1\tilde{B}} \tilde{B} + N_{1\tilde{W}} \tilde{W}^3 + N_{1\tilde{h}_u^0} \tilde{h}_u^0 + N_{1\tilde{h}_d^0} \tilde{h}_d^0 + N_{1\tilde{s}} \tilde{s}$$

Neutralino LSPs

Superpotential

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Mediators for LSP annihilation into $b\bar{b}$

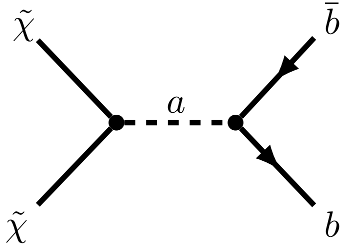
- Annihilation into fermions via CP-even Higgs sector is $p-$wave suppressed
- Annihilation into fermions via Z is helicity-suppressed in the $s-$wave, however $p-$wave contribution can be important during freeze-out near resonance Zurek et al. (2014).
- CP-odd Higgs scalars suitable mediators ($s-$wave contribution),

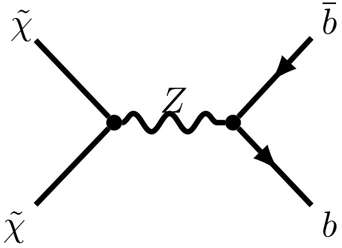
$$M^2_{CP\text{-odd}} = \begin{pmatrix} m_A^2 & \lambda v(A_\lambda - 2\kappa v_s) \\ . & \lambda\, v^2 \sin 2\beta \left(\frac{A_\lambda}{2v_s} + 2\kappa\right) - 3\kappa A_\kappa v_s \end{pmatrix},$$

where $m_A^2 \equiv 2\lambda v_s(A_\lambda + \kappa v_s)/\sin 2\beta$. We write the lightest CP-odd state as $a = \cos\theta_A H_I + \sin\theta_A s_I$. A light singlet-like scalar is now attainable!.

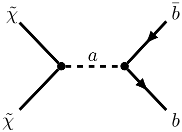
Dark Matter Annihilation in the NMSSM

- $\tilde{\chi}\tilde{\chi} \to b\bar{b}$ Annihilation





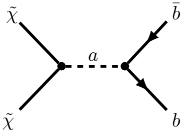
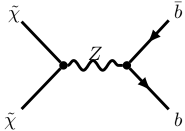
Annihilation to Bottom Quarks



Today	Early Universe
✓	×

- $m_{\tilde{\chi}_1^0} = 30 - 70$ GeV
- $\langle \sigma v \rangle = [1,5] \cdot 10^{-26} \frac{\text{cm}^3}{\text{sec}}$
- Dominantly Bino LSP
- If annihilation today at resonance $\Rightarrow$ not related to annihilation cross section in the Early Universe
- p-wave suppressed cross sections can be relevant in Early Universe

Annihilation to Bottom Quarks

Diagram	Today	Early Universe
	$\checkmark$	$\times$
	$\times$	$\checkmark$

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Constraints [assuming $m_{\tilde{\chi}} = 40$GeV]

Invisible Width of Higgs

$$\Gamma_{h\to\tilde{\chi}\tilde{\chi}} = |c_{h\tilde{\chi}\tilde{\chi}}|^2 \frac{m_h}{16\pi}\left(1-\frac{4m_{\tilde{\chi}}^2}{m_h^2}\right)^{\frac{3}{2}}$$

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$\Rightarrow |c_{h\tilde{\chi}\tilde{\chi}}| \lesssim 0.04$

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$$f_p = m_p\Big(\sum_{q=u,d,s} f_{T_q}^p \frac{a_q}{m_q} + \frac{2}{27} f_{T_G}^p \sum_{q=c,b,t}\frac{a_q}{m_q}\Big)$$

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Pure bino LSP: $|N_{13}| \lesssim c_{max}/g_1\cos\beta$, $|N_{14}| \lesssim c_{max}/g_1\sin\beta$.
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Bounds alleviated for $\mu < 0$ due to cancellations Cheung,Hall,Pinner,Ruderman (2012)

Relic Density

$$\langle \sigma v \rangle_0 \approx 2 \times 10^{-26} \, \frac{\text{cm}^3}{\text{s}} \left| \frac{c_{ab\bar{b}}}{y_b} \right|^2 \left| \frac{c_{a\tilde{\chi}\tilde{\chi}}}{0.5} \right|^2 \left(\frac{m_{\tilde{\chi}}}{40\,\text{GeV}} \right)^2 \left(\frac{(120\,\text{GeV})^2 - 4(40\,\text{GeV})^2}{m_a^2 - 4m_{\tilde{\chi}}^2 + m_a^2 \Gamma_a^2} \right)^2$$

- $\langle \sigma v \rangle_T \approx \langle \sigma v \rangle_0$
- Rough estimate for SM-like Higgs, $S_{13} \ll 1$. In absence of accidental cancellations and $\tan\beta = 3$, for Bino

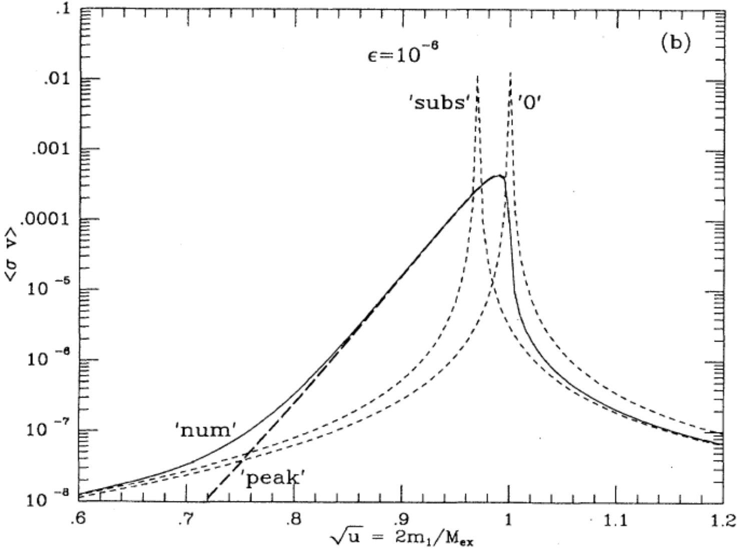
$$\left| \frac{c_{ab\bar{b}}}{y_b} \right|^2 \left| \frac{c_{a\tilde{\chi}\tilde{\chi}}}{0.5} \right|^2 \lesssim \begin{cases} 0.3 & \text{for } \cos\theta_A \approx 1 \\ (0.3 + 1.6 \times 10^{-2}\,\lambda)^2 & \text{for } \cos\theta_A \approx 1/\sqrt{2}\,. \end{cases}$$

and singlino,

$$\left| \frac{c_{ab\bar{b}}}{y_b} \right|^2 \left| \frac{c_{a\tilde{\chi}\tilde{\chi}}}{0.5} \right|^2 \lesssim \begin{cases} 0.3 & \text{for } \cos\theta_A \approx 1 \\ (0.3 + 3\,|\kappa| + 8 \times 10^{-3}/\lambda)^2 & \text{for } \cos\theta_A \approx 1/\sqrt{2}\,. \end{cases}$$

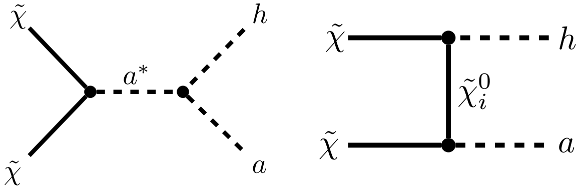
$\Rightarrow$ It is not possible to achieve the required cross section off-resonance.

Thermal Broadening of Resonances $\epsilon = \left(\frac{\Gamma_{ex}}{M_{ex}}\right)^2$



Griest,Seckel (1991)

Annihilation to Higgs and Pseudo-Scalar



- Cross section can be large off-resonance: $\langle \sigma v \rangle_0 \sim \langle \sigma v \rangle_{T_F}$
- t/u-diagram $p-$wave suppressed for CP-even final state pair.
- Defining $\delta \equiv (2m_{\tilde{\chi}} - (m_a + m_h))/2m_{\tilde{\chi}}$, $s-$wave contribution,

$$\langle \sigma_{ha} v \rangle_0 \approx \frac{1}{8\pi} \left(\frac{m_h}{m_{\tilde{\chi}}} \right)^{1/2} \left(1 - \frac{m_h}{2m_{\tilde{\chi}}} \right)^{1/2}$$

$$\times \left[\frac{c_{aah} c_{a\tilde{\chi}\tilde{\chi}}}{m_h(4m_{\tilde{\chi}} - m_h)} + \frac{c_{a_2ah} c_{a_2\tilde{\chi}\tilde{\chi}}}{4m_{\tilde{\chi}}^2 - m_{a_2}^2 + m_{a_2}\Gamma_{a_2}} + 2\sum_{k=1}^{5} \frac{c_{a\tilde{\chi}\tilde{\chi}_k} c_{h\tilde{\chi}\tilde{\chi}_k}}{m_h + m_{\tilde{\chi}_k} - m_{\tilde{\chi}}} \right]^2$$

Annihilation to Higgs and Pseudo-Scalar

- All channels contribute to the cross-section to accommodate the GCE signal.
- For t/u-channel with $\tilde{\chi}_k \neq \tilde{\chi}$, $c_{h\tilde{\chi}\tilde{\chi}_k}$ can be much larger than those allowed by direct detection ($\tilde{\chi}_k = \tilde{\chi}$) $\Rightarrow$ for $m_{\tilde{\chi}_k} \gtrsim m_{\tilde{\chi}}$, seizable cross sections can be accomplished.
- Happens for a Bino-like LSP $\tilde{\chi}$ and Higgsino-like 2^{nd}-lightest neutralino $\tilde{\chi}_2$, with $c_{h\tilde{\chi}\tilde{\chi}_2}$ and $c_{a\tilde{\chi}\tilde{\chi}_2}$ dominated by g_1 . $\therefore$ Could potentially also work in the MSSM!
- Light doublet-like a is highly constrained from LEP, LHC and B-physics.

Numerical Grid Scan

- NMSSMTools 4.4.0 Ellwanger et al. (2005)
- micrOMEGAs 3.0 Belanger et al. (2005)

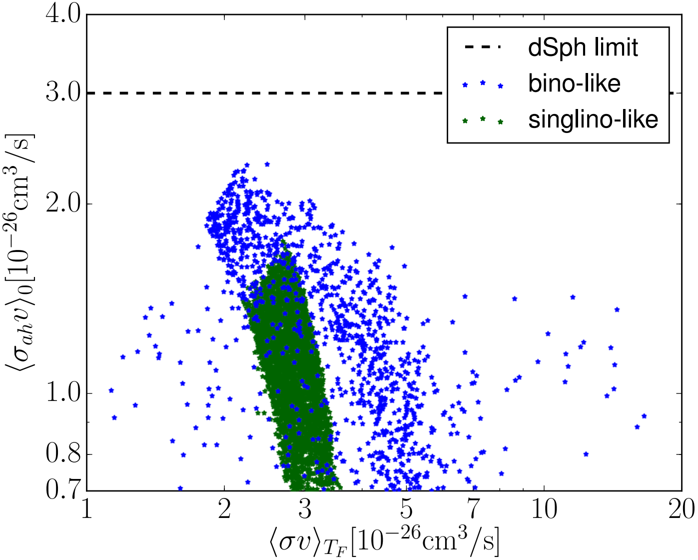
For ha, with $A_\kappa \in [-100, 100]$ GeV, fix A_λ such that h is SM-like, choose $\mu < 0$ to avoid direct detection.

	ΔA_λ [GeV]	$\mu_{\rm eff}$ [GeV]	M_1 [GeV]	λ	κ	$\tan\beta$
bino-like	[-50,50]	[-300,-100]	[60,170]	[0.6,1.4]	[0.1,1.6]	[2,5]
singlino-like	[-50,50]	[-600,-200]	2000	[0.6,1.4]	[0.05,0.5]	[2,5]

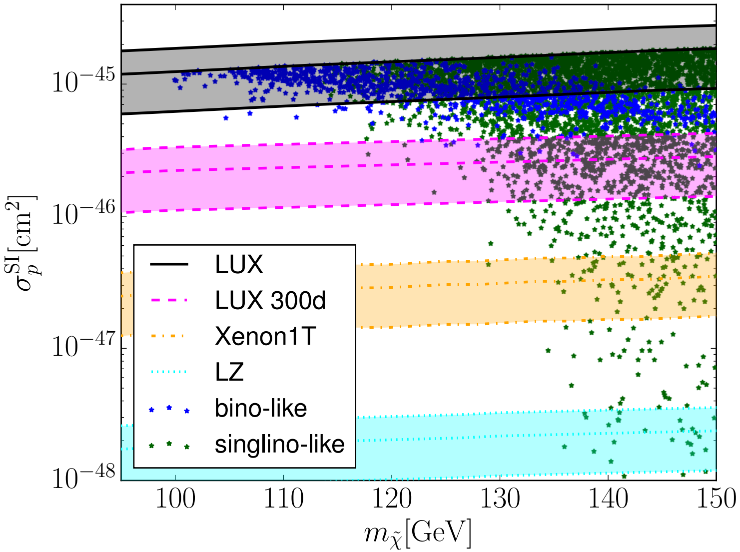
For $b\bar{b}$,

	A_λ [GeV]	A_κ [GeV]	$\lvert\mu_{\rm eff}\rvert$ [GeV]	M_1 [GeV]	λ	κ	$\tan\beta$
range	[-1000,1000]	[-300,300]	[300,600]	[30,50]	[0.8,1.4]	[0.8,1.4]	[1,4]
step	10	1	100	1	0.05	0.05	1

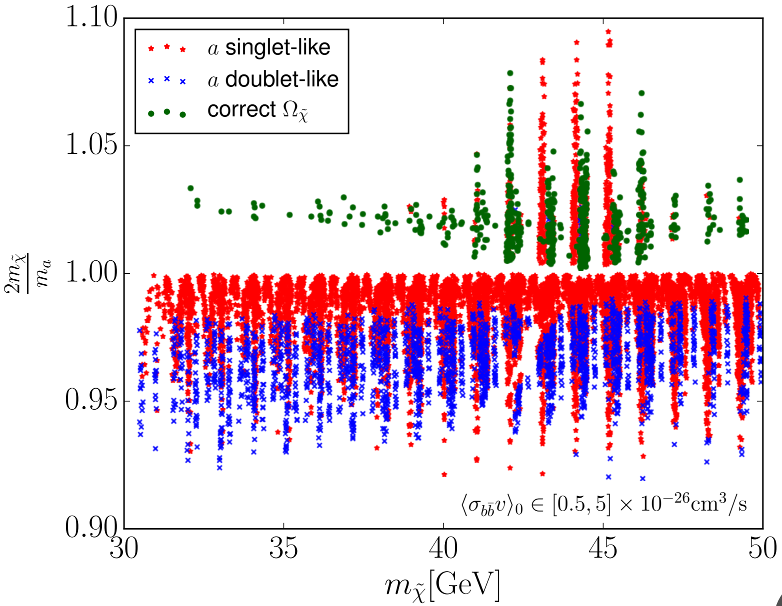
Early and late time cross sections for ha case



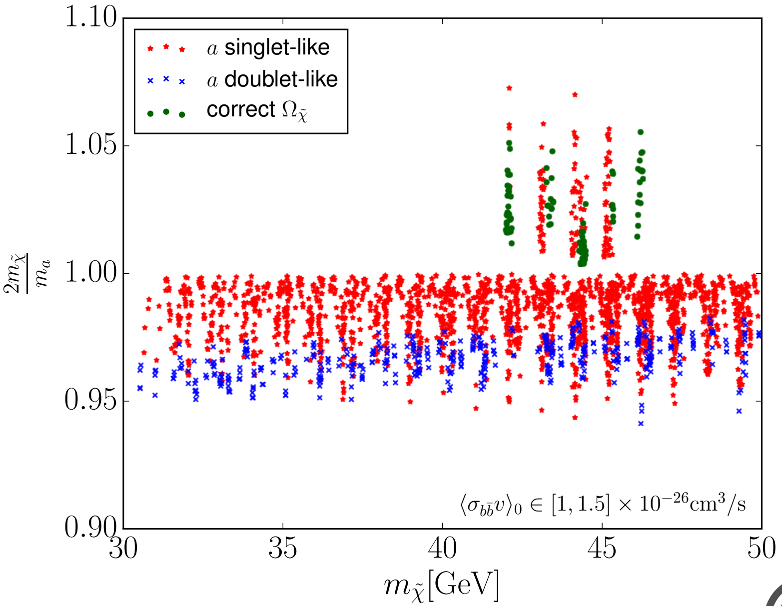
Direct Detection for ha case



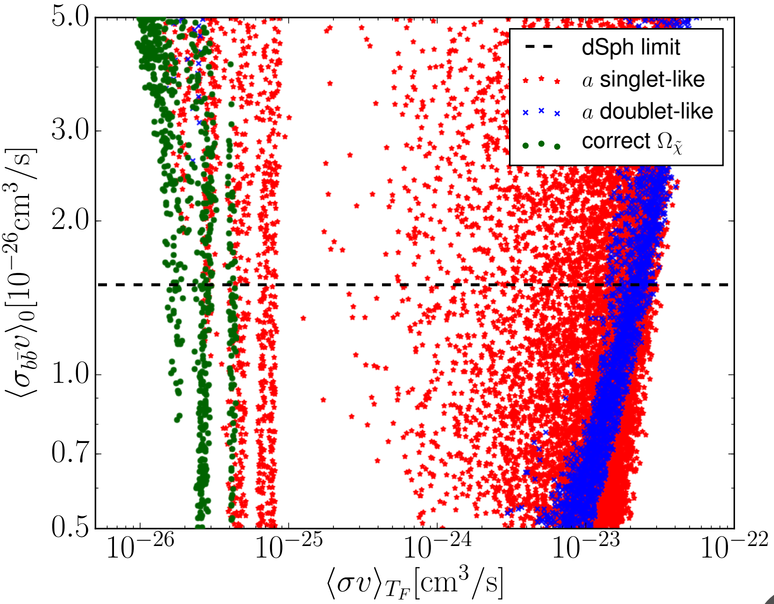
Resonance Condition for $b\bar{b}$ case



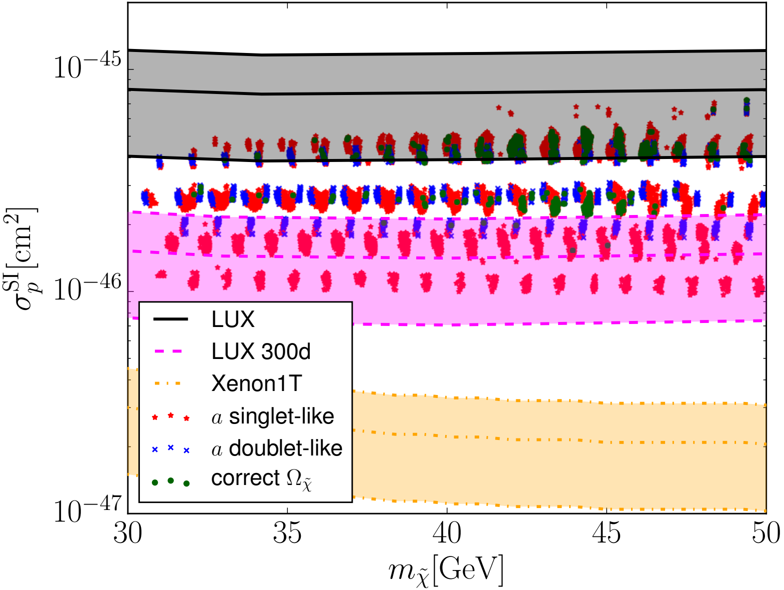
Resonance Condition for $b\bar{b}$ case with DSph bounds



$\langle\sigma v\rangle$ today and at freeze-out for bb case



Direct Detection and Invisible decay for $b\bar{b}$ case



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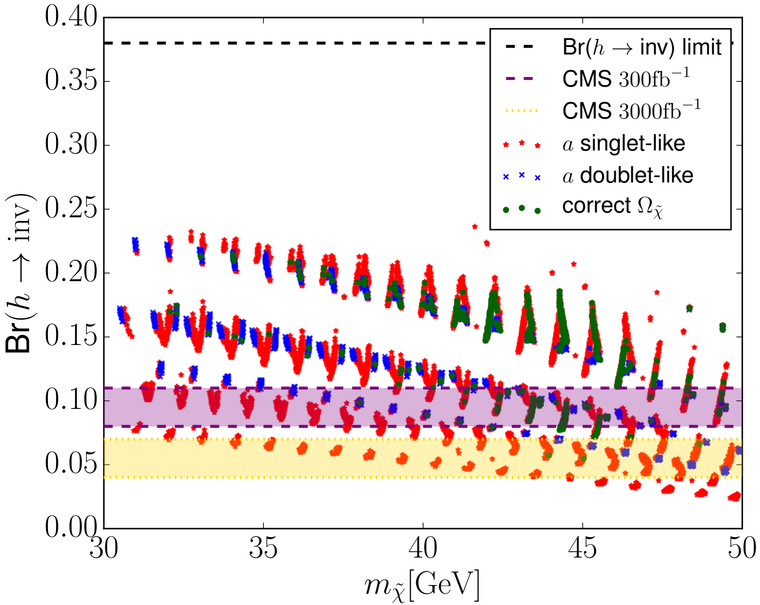

Thermal sneutrino DM annihilation into aa

- Introduce three right-handed neutrino superfields

$$W = W_{NMSSM} + \lambda_N SNN + y_N LNH_u$$

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- Majorana masses $m_N = 2\lambda_N v_s$ and $m_\nu \approx y_N \lambda_N^{-1} y_N^T \times v^2 \sin^2\beta/(2v_s) \Rightarrow |y_N| \lesssim 10^{-6}$.

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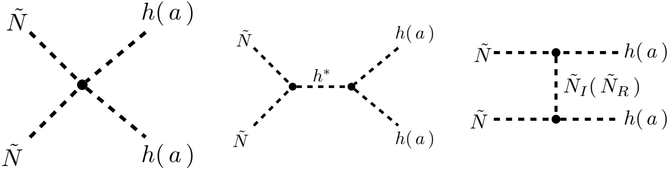
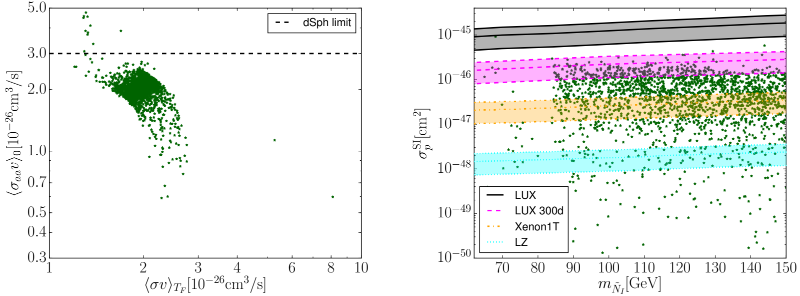
- Similar bound from dominant annihilation into hh or aa.



A_λ [GeV]	A_κ [GeV]	$\lvert\mu_{\rm eff}\rvert$ [GeV]	λ	κ
[-100,100]	[-10,10]	[200,500]	[0.5,1.5]	[0.2,1.4]

$\tan\beta$	$\Delta m_{\tilde{N}_I}$ [GeV]	λ_N	$m_{\tilde{N}_R}$ [GeV]
[1.2,4]	[0,30]	[-0.1,0.1]	[$m_{\tilde{N}_I}$,400]



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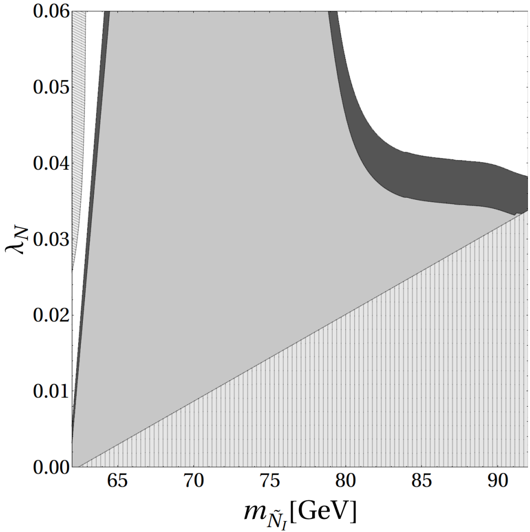
- The final DM abundance is given by

$$\Omega_{\rm DM} = \frac{m_{\tilde{\chi}_1^0}}{m_{\tilde{N}}} \Omega_{\tilde{N}} + \Omega'_{\tilde{\chi}_1^0}$$

Parameter Space for $(m_{\tilde{\chi}}, m_a) = (63, 88)$ GeV



dark gray: correct DM abundance

Conclusions

- Fermi GeV Excess stands all tests
- Dark matter annihilations to $b\bar{b}$ as well as hh close to threshold provide a good fit
- We showed that annihilations to ha (and aa) also provide a good fit and are naturally present in NMSSM
- Required dark matter abundance can be generated non-thermally via late sneutrino decays