The Reach of
Thermal Supersymmetric Dark Matter

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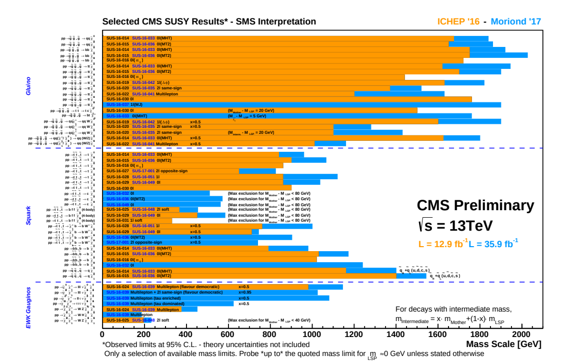
Outline

- Motivations
- SUSY Dark Matter
- Coannihillation
  - Gluino Coannihilation
  - Stop Coannihilation

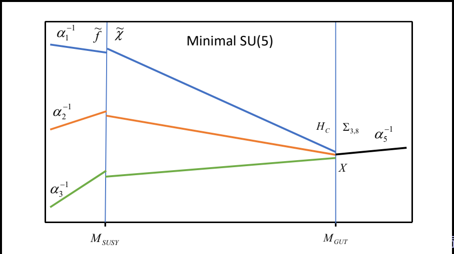
Where We Are So Far

- SUSY is most likely somewhat tuned
  - $\Delta_{BG} \sim M_{SUSY}^2 / m_Z^2$
- Is it time to let that ship sink?
  - We worry because we can detect it



Unification and Thresholds

- Gauge couplings unify in SUSY
- M_{GUT} affects on Unification
  - M_{GUT} thresholds $\rightarrow$ unification
- Unification $\rightarrow$ upper limit on M_{SUSY}
  - $\beta(\alpha_i)$ change at M_{SUSY}
  - $\mu, M_i \gg m_W \rightarrow$ no unification



SUSY Well Tempered Neutralinos

- WIMP miracle
  - Weak scale masses/interactions give correct density
- Netralinos: the perfect WIMP ($r = M_1^2/m_{\tilde{e}_R}^2 \rightarrow 0.25$)
  - density only depends on scattering cross section

$$\langle \sigma_{\tilde{B}} v \rangle = \frac{3 g^3 t_w^3 r (1 + r^2)}{2\pi m_{\tilde{e}_R}^2 x (1 + r)^4} \qquad \langle \sigma_{\mathrm{eff}_{\tilde{H}}} v \rangle \simeq \frac{21 g^4}{512 \pi \mu^2} \qquad \langle \sigma_{\mathrm{eff}_{\tilde{W}}} v \rangle = \frac{3 g^4}{16 \pi M_2^2}$$

$$\Omega h^2 \simeq 0.12 \left(\frac{m_{\tilde{e}_R}}{100 \text{ GeV}} \right)^2 \qquad \Omega_{\tilde{H}} h^2 \simeq 0.1 \left(\frac{\mu}{1 \text{ TeV}} \right)^2 \qquad \Omega_{\tilde{W}} h^2 \simeq 0.13 \left(\frac{M_2}{2.5 \text{ TeV}} \right)^2$$

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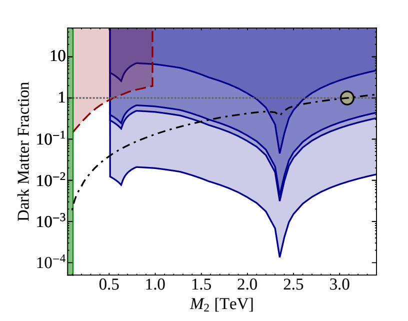

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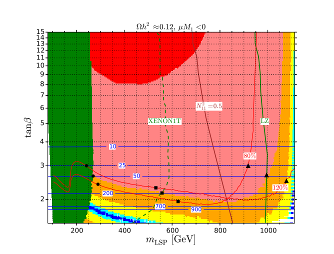
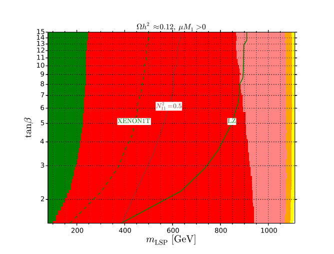
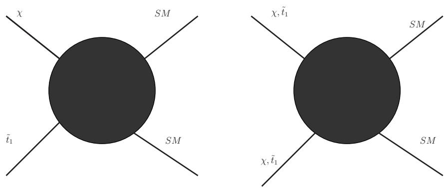
- Simple thermal relics all but gone (Badziak, Olechowski, Szczerbiak)

Red: LUX(SI), Green: LUX(SD), Orange: (XENON1T), Yellow: (LZ)





Beyond the Well Tempered Neutralino: Coannihilation



- Reaction rates

$$n_\chi n_{\tilde{t}_1} \sigma_{\chi \tilde{t}_1} \sim T^3 m_\chi^{3/2} m_{\tilde{t}_1}^{3/2} \sigma_{\chi \tilde{t}_1} e^{\left[-\frac{m_\chi + m_{\tilde{t}_1}}{T}\right]}$$

$$n_\chi n_{SM} \sigma_{\tilde{t}_1 SM} \sim T^{9/2} m_\chi^{3/2} \sigma_{\chi SM} e^{\left[-\frac{m_\chi}{T}\right]}$$

$$R = \left(\frac{T}{m_{\tilde{t}_1}}\right)^{3/2} \exp\left[\frac{m_{\tilde{t}_1}}{T}\right]$$

- $(m_{NLSP} - m_{LSP})/m_{LSP} \ll 1 \rightarrow$ Coannihilation
  - Thermal Fluctuations convert LSP to NSLP
- As $\tilde{t}_1$ annihilates, replenished by SM scattering
  - $n_{\tilde{t}_1 eq} \simeq n_{\chi eq} \rightarrow$ enhances $\sigma_{\chi\chi eff}$.
- Scattering of coannihilation partner determines density

Gluino Coannihilation

- Gluino coannihilation largest Sommerfeld enhancement
  - Final states: singlet, octet, and 27_s for $C_j = 0, 3, 8$
  - Stronger binding energy more enhancement

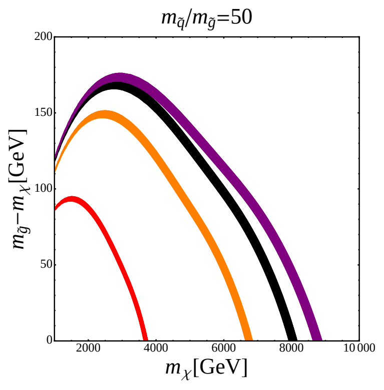
$$V = \frac{\alpha_s}{2r}\left[C_f - C_i - C_i'\right]$$

- Boundstate formation important
  - R hadron production enhances $\tilde{g}\tilde{g}$ annihilation rate
  - $\langle \Gamma \rangle_{\tilde{R}} \gg \langle \Gamma \rangle_{dis}$ enhanced coannihilation

$$\langle \sigma v \rangle_{\tilde{g}\tilde{g}\to gg, q\bar{q}} \to \langle \sigma v \rangle_{\tilde{g}\tilde{g}\ incl.\ \tilde{R}} \equiv \langle \sigma v \rangle_{\tilde{g}\tilde{g}\to gg, q\bar{q}} + \langle \sigma v \rangle_{bsf} \frac{\langle \Gamma \rangle_{\tilde{R}}}{\langle \Gamma \rangle_{\tilde{R}} + \langle \Gamma \rangle_{dis}},$$

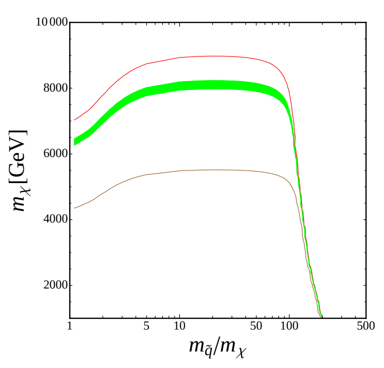
Dependence of Gluino Coannihilation

- Relative importance of Sommerfeld and Bound state
  - No Som/Boun (red) Som only (Orange)
  - All (Black) Boun×2 (Purple)



Dependence of Gluino Coannihilation

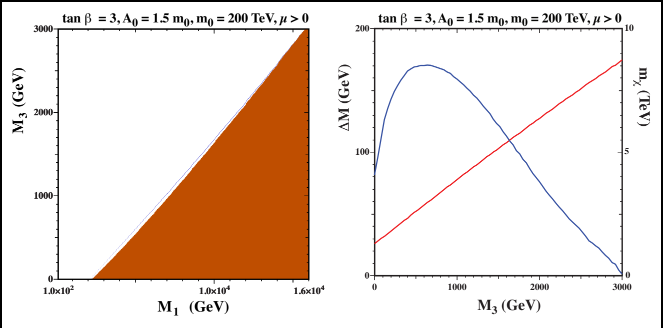
- Relative importance of Sommerfeld and Bound state
- Somewhat insensitive to squark mass
  - Squark mass control conversion of $\tilde{\chi} \leftrightarrow \tilde{g}$



Non-Universal CMSSM

- Non-universal input gauginos $\rightarrow$ gluino coannihilation
  - Gluino coannihilation extends to $m_\chi \sim 8.5$ TeV

$$M_1 = M_2,\ M_3,\ m_0,\ \tan\beta,\ A_0$$



Pure-Gravity Mediation with Vector Multiplets

- Pure-Gravity Mediation
  - GM term $\rightarrow$ linearly independent $B, \mu \rightarrow$ free $\tan\beta$

$$m_0, \qquad \tan\beta$$

- Gauginos mass anomaly mediated

$$M_i = b_i \frac{g_i^2}{16\pi^2} m_{3/2} \qquad b_i = \left\{ \frac{33}{5}, 1, -3 \right\}$$

- Additional $10 + \bar{1}0$ mass from GM term
  - Additional 10 can couple to $H_u \rightarrow$ larger $\tan\beta$, m_h

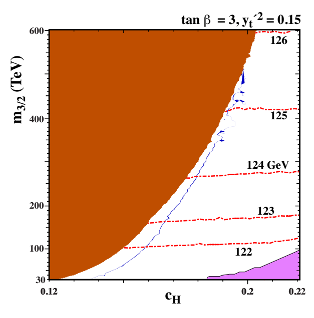
$$K \supset c_H 10\bar{1}0 + h.c \qquad W \supset y_t' H_u Q' U' + ..$$

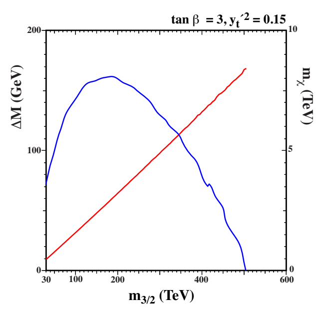
  - Gaugino mass do not decouple
  - Gluino mass purely from thresholds

$$M_1 = \frac{48}{5} \frac{g_1^2}{16\pi^2} m_{3/2} \qquad M_2 = \frac{g_2^2}{4\pi^2} m_{3/2} \qquad M_3 = 0$$

Gluino Coannihilation in PGM with Vector Multiplets

- Gluino coannihilation extends to $m_\chi \sim 8.5$ TeV
  - For smaller c_H gluino thresholds small and $\tilde{g}$ is LSP



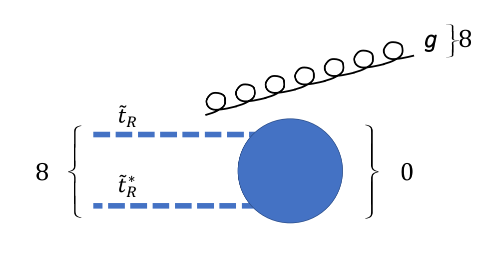


Stop Coannihilation

- Stop coannihilation is also Sommerfeld enhanced
  - Final states: singlet or octet for $C_f = 0, 3$
  - Less enhanced compared to gluino case ($C_3 = \frac{4}{3}$)

$$V = \frac{\alpha_s}{2r}\left[C_f - C_i - C_i'\right]$$

- Boundstate formation important
  - Octet $\tilde{t}_R \tilde{t}_R^*$ forms bound state from gluino emission



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Goldstone Boson Enhancements

- Goldstone Boson Equivalence Theorem (GBET)
  - W_L/Z_L remember origins
- GBET leads to enchanced $t \to Wb$ decay rate
  - Goldstone couples via top Yukawa ($y_t > g_2$)

$$\Gamma_t \simeq \frac{g_2^2}{64\pi}\frac{m_t^3}{m_W^2} = \frac{y_t^2}{32\pi} m_t$$

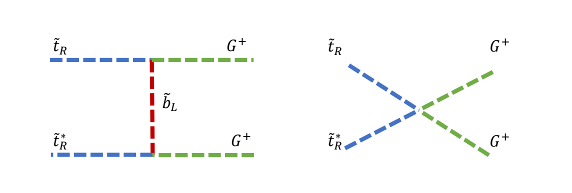
- In SUSY stops couple to goldstone via A-terms
  - $A_t \gg M_{SUSY}$, large enhancement to W_L/Z_L couplings
  - Goldston predominantly in the H_u, only A_t matters

$$\mathcal{L} \supset -y_t(A_t H_u + \mu H_d^\dagger)\tilde{Q}_L \tilde{t}_R - |y_t|^2 \left(|\tilde{Q}_L|^2 |H_u|^2 + |\tilde{t}_R|^2 |H_u|^2|\right)$$

Stop Coannihilation to Goldstone Boson

- In Feynman gauge goldstone boson are manifest
  - $\tilde{t}_R \tilde{t}_R^* \to W^+ W^- \quad \simeq \quad \tilde{t}_R \tilde{t}_R^* \to G^+ G^-$

$$\mathcal{L} \supset -y_t X_t \sin\beta G^+ \tilde{b}_L \tilde{t}_R - |y_t|^2 \sin^2\beta |\tilde{t}_R|^2 |G^+|^2$$



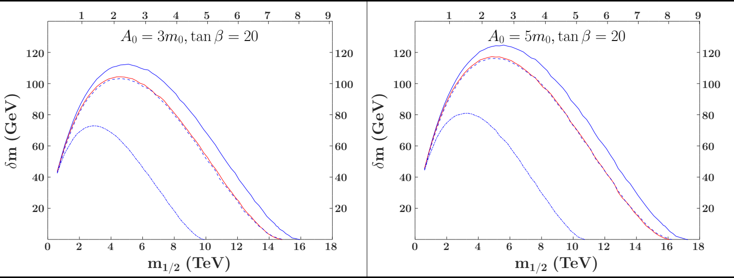
- s-wave annihillation two sources of enhancement
  - $y_t > g_2$ and $A_t > \sqrt{m_{\tilde{t}_R}^2 + m_{\tilde{t}_L}^2}$
  - For $A_t / \sqrt{m_{\tilde{t}_R}^2 + m_{\tilde{t}_L}^2} \gtrsim g_3 / y_t$, most important mode

$$\langle \sigma v \rangle_{\tilde{t}\tilde{t}^* \to W^+ W^-} \simeq \frac{g_2^4}{128\pi m_{\tilde{t}_R}^2} \left(\frac{m_t}{m_W} \right)^4 \left(\frac{(A_t + \mu \cot\beta)^2 - m_{\tilde{t}_R}^2 - m_{\tilde{t}_L}^2}{m_{\tilde{t}_R}^2 + m_{\tilde{t}_L}^2} \right)^2$$

Stop Coannihilation in the CMSSM

- For large A_t, $m_\chi \sim 8$ TeV (Similar to gluino case)
  - m_0 chosen to give relic density

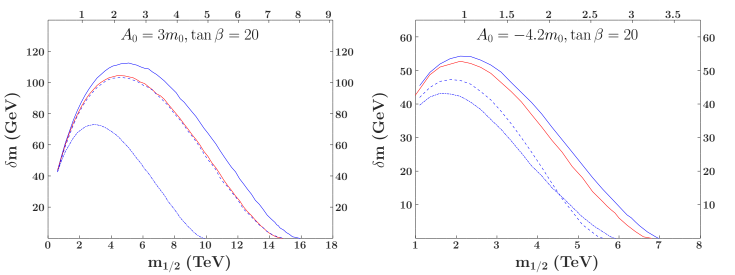
Solid (All) | Dashed (No BS) | Dash-Dot (No GS) | Solid ($\mu < 0$)



Stop Coannihilation in the CMSSM

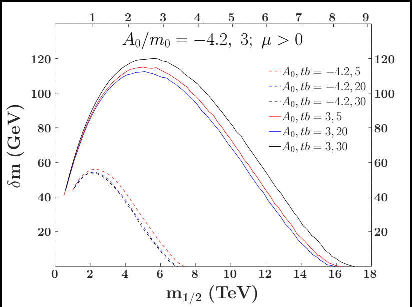
- For large A_t, $m_\chi \sim 8$ TeV (Similar to gluino case)
- $A_t < 0$, $m_\chi \sim 3$ TeV
  - $|A_t(M_{SUSY})| \ll M_{SUSY}$ due to RG running

Solid (All) | Dashed (No BS) | Dash-Dot (No GS) | Solid ($\mu < 0$)



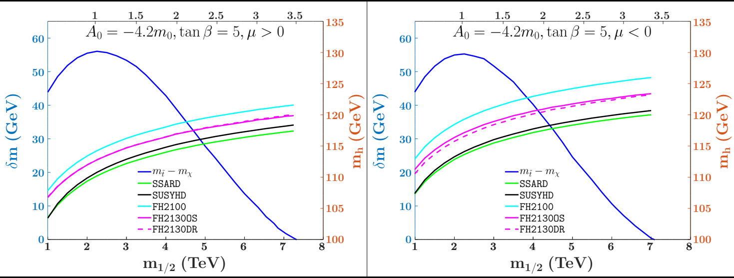
Stop Coannihilation in the CMSSM

- For large A_t, $m_\chi \sim 8$ TeV (Similar to gluino case)
- $A_t < 0$, $m_\chi \sim$ TeV (Similar to gluino case)
  - $|A_t(M_{SUSY})| \ll M_{SUSY}$ due to RG running
- Little dependence on $\tan\beta$
  - Some enhancement from μ for small $\tan\beta$



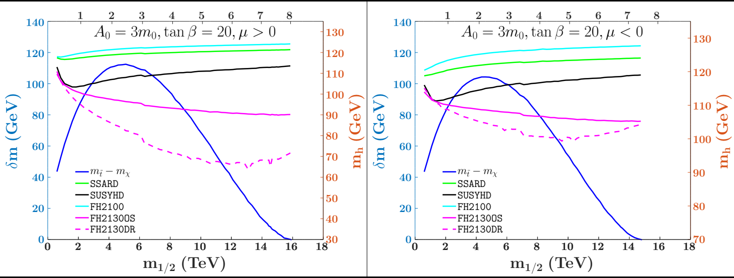
Constraints on the Stop Coannihilation Strip

- Higgs mass constrain coannihilation strip
  - $A_0 < 0$, $|A_t|$ is small and Higgs mass resonable



Constraints on the Stop Coannihilation Strip

- Higgs mass constrain coannihilation strip
  - $A_0 > 0$ and A_t large, Higgs mass calculation unstable



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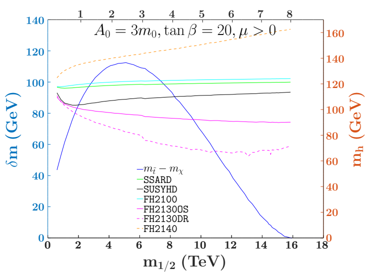
- Higgs mass constrain coannihilation strip
  - FeynHiggs 2.14.0 makes things worse



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m_h along
stop coannihilation strip
not reliable!!!!

Higgs Mass and Stop Coannihilation Strip

- Corrections to Higgs quartic coupling (Mass)
  - Higgs mass suppressed for very large A_t

$$\Delta\lambda \supset \frac{|y_t|^4}{8\pi^2}\left(\tilde{X}_t \tilde{F}_1\left(\frac{m_{\tilde{t}_L}}{m_{\tilde{t}_R}}\right) - \frac{1}{12}\tilde{X}_t^2 \tilde{F}_2\left(\frac{m_{\tilde{t}_L}}{m_{\tilde{t}_R}}\right)\right) \qquad \tilde{X}_t = \frac{A_t + \mu \cot\beta}{m_{\tilde{t}_R} m_{\tilde{t}_L}}$$

- Coannihilation leading contribution
  - Coannihilation strip extended for large A_t

$$\langle \sigma v \rangle_{\tilde{t}\tilde{t}^* \to W^+ W^-} \simeq \frac{g_2^4}{128\pi m_{\tilde{t}_R}^2}\left(\frac{m_t}{m_W}\right)^4 \left(\frac{(A_t + \mu\cot\beta)^2 - m_{\tilde{t}_R}^2 - m_{\tilde{t}_L}^2}{m_{\tilde{t}_R}^2 + m_{\tilde{t}_L}^2}\right)^2$$

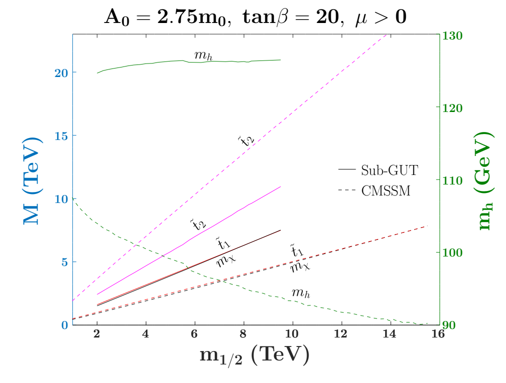
- Length of stop strip maximized for $m_{\tilde{t}_R} = m_{\tilde{t}_L}$

Sub-GUTS and the Stop Coannihilation Strip

- Supersymmetry input scale may be below M_{GUT}
  - Mirage mediation $\rightarrow$ apparent sub-GUT spectrum
- Smaller M_{in} leads to less RG running
  - Stop masses less split
  - Higgs mass less suppressed
  - Coannihilation strip extended
- Use FeynHiggs 2.13.0 OS for Higgs mass calculation
  - Most recent available code at the time
  - FeynHiggs 2.14.0 now available but seems worse

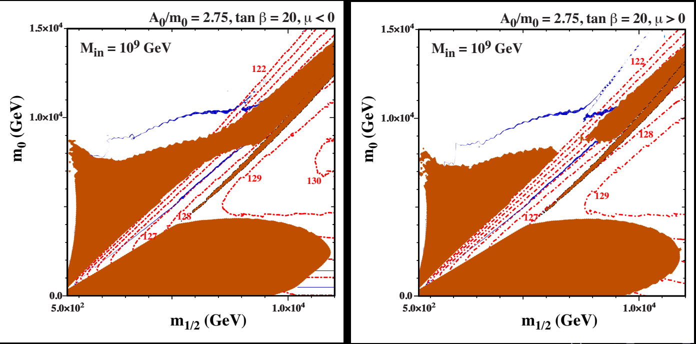
Sub-GUT Plane

- Sub-GUT models very different from CMSSM planes
  - Stop masses more split
  - Higgs mass much better



Sub-GUT Plane

- Sub-GUT models very different from CMSSM planes
- Sub-GUT plane
  - Stop LSP region limited
  - Coannihilation region much less tuned



Conclusions

- Naturalness somewhat strained
  - But not dead
- Gauge coupling unification still good
  - Upper limit on SUSY breaking scale $\sim 10^6$ GeV
- Thermal dark matter still alive
  - Gluino coannihilation extends to $m_\chi \lesssim 8.5$ TeV
  - Stop coannihilation may extends to $m_\chi \lesssim 8.5$ TeV
  - Sub-GUT models give more natural coannihilation
    - $m_\chi \lesssim 7$ TeV