Supersymmetric Super-GUT Models

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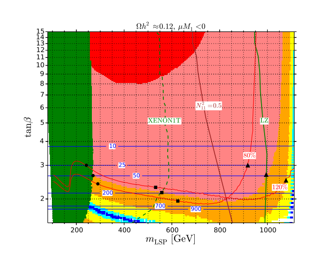
Ellis, JLE, Mustafayev, Nagata,Olive Eur. Phys. J. C **76**, no. 11, 592 (2016)
Ellis, JLE, Nagata, Nanopoulos, Olive Eur. Phys. J. C **77**, no. 4, 232 (2017)

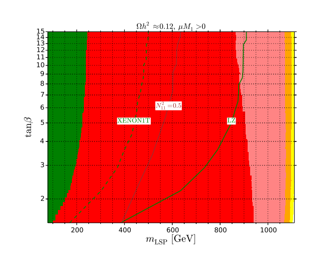
Outline

SUSY

- SUSY still relatively Natural ($M_{SUSY} \ll M_{GUT}$)
  - Strict naturalness strained but still better
- Simple thermal relics strained but not gone

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

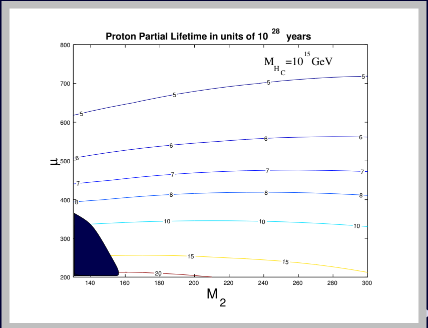




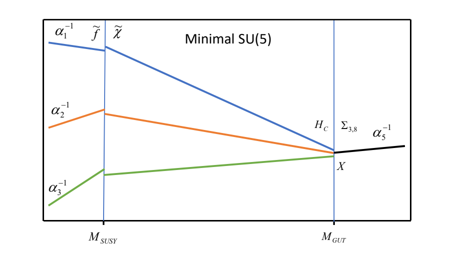
Badziak, Olechowski, Szczerbiak

SUSY

- SUSY still relatively Natural ($M_{SUSY} \ll M_{GUT}$)
  - Strict naturalness strained but still better
- Simple thermal relics strained but not gone
- Gauge Coupling Unification
  - Proton Decay problematic ? (Pierce Murayama)



Unification and Thresholds



- M_{SUSY} affects on Unification
  - $\beta(\alpha_i)$ change at M_{SUSY}
  - $\mu, M_i \gg m_W \to$ no unification
- M_{GUT} affects on Unification
  - M_{GUT} thresholds $\to$ unification
- M_{H_C}, M_Σ and M_X constrained by imperfect unification
  - Third condition determines $g_5(M_{GUT})$

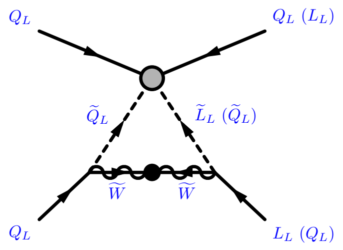
$$\frac{3}{g_2^2(M_{GUT})} - \frac{2}{g_3^2(M_{GUT})} - \frac{1}{g_1^2(M_{GUT})} = -\frac{3}{10\pi^2}\ln\left(\frac{M_{GUT}}{M_{H_C}}\right)$$

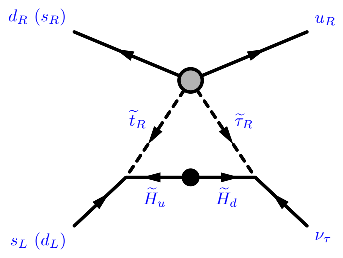
$$\frac{5}{g_1^2(M_{GUT})} - \frac{3}{g_2^2(M_{GUT})} - \frac{2}{g_3^2(M_{GUT})} = -\frac{3}{2\pi^2}\ln\left(\frac{M_{GUT}^3}{M_X^2 M_\Sigma}\right)$$

Proton Decay

- H_C mediates proton decay
  - Integrate out H_C at M_{GUT}
  - RG run Wilson coefficeints to M_{SUSY}
  - Integrate out SUSY particles
  - Then run down to hadronic scale

$$W_5 = (h_{\mathbf{10}})_{ij}\, \epsilon_{\alpha\beta\gamma\delta\zeta} \Psi_i^{\alpha\beta} \Psi_j^{\gamma\delta} H^{\zeta} + (h_{\bar{\mathbf{5}}})_{ij}\, \Psi_i^{\alpha\beta} \Phi_{j\alpha} \overline{H}_{\beta}$$





- Approximate low-scale WC of proton decay

$$C_{LL} \simeq \frac{2\alpha_2^2}{\sin 2\beta} \frac{m_t m_b M_2}{m_W^2 M_{H_C} M_{\mathrm{SUSY}}^2} V_{ub}^* V_{td} V_{ts} e^{i\phi_3} \left(1 + e^{i(\phi_2 - \phi_3)} \frac{m_c V_{cd} V_{cs}}{m_t V_{td} V_{ts}}\right)$$

$$C_{RL} \simeq -\frac{\alpha_2^2}{\sin^2 2\beta} \frac{m_t^2 m_d m_\tau \mu}{m_W^4 M_{H_C} M_{\mathrm{SUSY}}^2} V_{tb}^* V_{ud} V_{ts} e^{-i(\phi_2 + \phi_3)}$$

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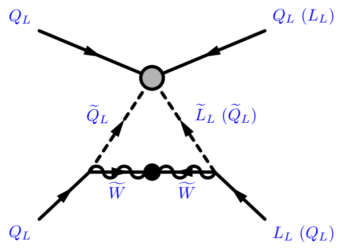
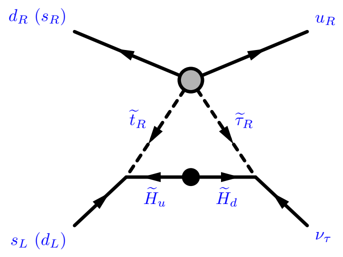




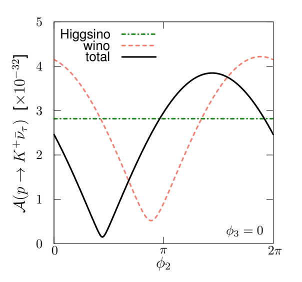
- Respective $\tau(p \to K\nu)$ for $\phi_{2,3} = 0$
  - $\tau(p \to K\nu) > 6.6 \times 10^{33}$ yr

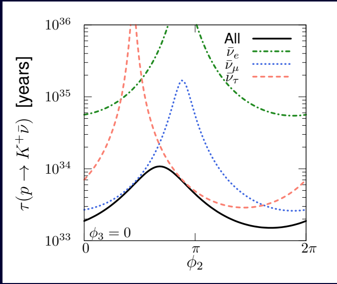
$$\Gamma_{\tilde{W}} \simeq 3.3 \times 10^{31}\ \mathrm{yr} \left(\frac{M_{H_C}}{7 \times 10^{16}\ \mathrm{GeV}}\right)^2 \left(\frac{M_{SUSY}}{11\ \mathrm{TeV}}\right)^4 \left(\frac{3.5\ \mathrm{TeV}}{M_2}\right)^2$$

$$\Gamma_{\tilde{h}} \simeq 2.8 \times 10^{31}\ \mathrm{yr} \left(\frac{M_{H_C}}{7 \times 10^{16}\ \mathrm{GeV}}\right)^2 \left(\frac{M_{SUSY}}{11\ \mathrm{TeV}}\right)^4 \left(\frac{12\ \mathrm{TeV}}{\mu}\right)^2$$

Phase Dependence of Proton Decay

- Matrix elements for Higgsino and wino similar size
  - Varying phase leads to cancellations





What Does This Mean for The CMSSM?

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  - Interplay between dark matter and proton decay

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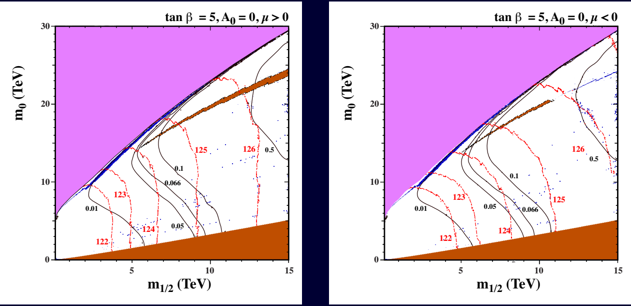

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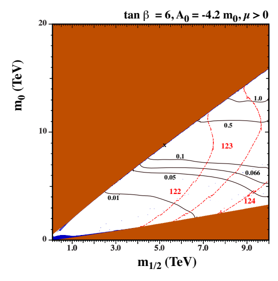
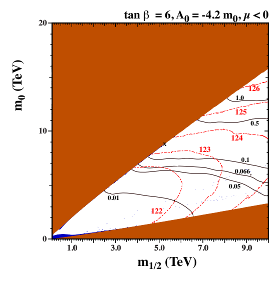
- Proton decay in the CMSSM
  - Interplay between dark matter and proton decay
- Focus point: RG running leads to small Higgsino mass
  - Small Higgsino mass suppresses cancellation
- Stop Coannihilation: Stop and LSP nearly degenerate
  - Coannihilation strip only extends so far





Minimal SU(5) Super-GUT Model

- SUSY breaking unifies beyond M_{GUT}

$$W_5 = \mu_\Sigma \mathrm{Tr}\Sigma^2 + \frac{1}{6}\lambda' \mathrm{Tr}\Sigma^3 + \mu_H \overline{H} H + \lambda \overline{H}\Sigma H$$
$$+ (h_{\mathbf{10}})_{ij}\, \epsilon_{\alpha\beta\gamma\delta\zeta} \Psi_i^{\alpha\beta}\Psi_j^{\gamma\delta} H^\zeta + (h_{\overline{\mathbf{5}}})_{ij}\, \Psi_i^{\alpha\beta}\Phi_{j\alpha}\overline{H}_\beta$$

Minimal SU(5) Super-GUT Model

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  - CMSSM like boundary conditions at $M_{in} > M_{GUT}$

$$m_{\bar{\mathbf{5}}} = m_{\mathbf{10}} = m_{\mathbf{5}_H} = m_{\bar{\mathbf{5}}_H} = m_0 \qquad A_{\mathbf{10}} = A_{\bar{\mathbf{5}}} = A_0$$

$$M_5 = m_{1/2} \qquad \tan\beta \qquad sgn(mu)$$

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- RG run to M_{GUT} and match onto MSSM
  - Higgs parameters matching non-trivial

$$\mu = \mu_H - 3\lambda V \left[1 + \frac{A_{\lambda'} - B_\Sigma}{2\mu_\Sigma} \right]$$

$$B = B_H + \frac{3\lambda V \Delta}{\mu} + \frac{6\lambda}{\lambda' \mu} \left[(A_{\lambda'} - B_\Sigma)(2B_\Sigma - A_{\lambda'} + \Delta) - m_\Sigma^2 \right]$$

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  - Higgs parameters matching non-trivial
  - $\Delta = A_{\lambda'} - B_{\Sigma} - A_{\lambda} + B_H \lesssim M_{SUSY}^2 / M_{GUT}$

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- SUSY breaking unifies beyond M_{GUT}
  - CMSSM like boundary conditions at $M_{in} > M_{GUT}$
- RG run to M_{GUT} and match onto MSSM
  - Higgs parameters matching non-trivial
  - $\Delta \lesssim M_{SUSY}^2 / M_{GUT}$
- Planck Suppressed operators alter coupling matching
  - M_{H_C} becomes free parameter

$$\frac{3}{g_2^2(Q)} - \frac{2}{g_3^2(Q)} - \frac{1}{g_1^2(Q)} = -\frac{3}{10\pi^2} \ln\left(\frac{Q}{M_{H_C}}\right) - \frac{96cV}{M_P}$$

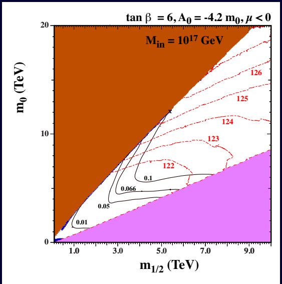
$$\frac{5}{g_1^2(Q)} - \frac{3}{g_2^2(Q)} - \frac{2}{g_3^2(Q)} = -\frac{3}{2\pi^2} \ln\left(\frac{Q^3}{M_X^2 M_\Sigma}\right)$$

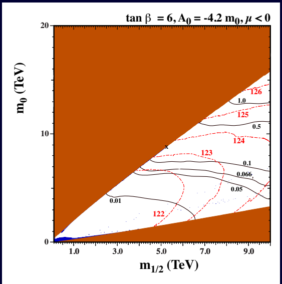
Super-GUT vs. CMSSM

- No focus point region

Super-GUT vs. CMSSM

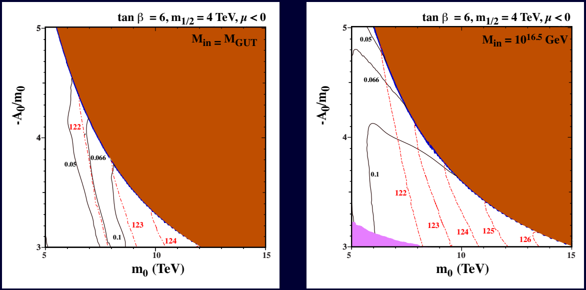
- No focus point region
- Stop coannihilation
  - Tachyonic stop shift to larger m_0
  - Tachyonic stau replaced by no EWSB (B matching)
  - Higgs mass better





Stop Coannihilation for Super-GUTS

- Stop Mass larger for given *A*-term
  - Super-GUT running supported by gaugino contribution
  - A-term smaller for Sub-GUT running



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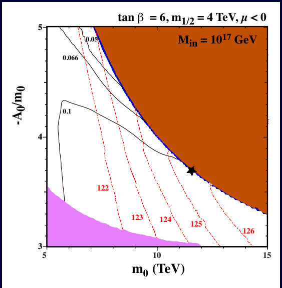
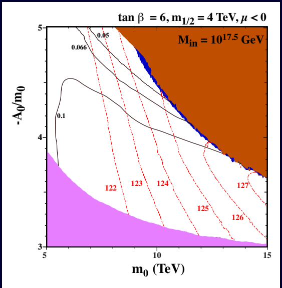




Conclusions

- Naturalness somewhat strained
  - Scalar masses are getting larger
- Dark matter more complicated
  - Well Tempered neutralino all but gone
- Minimal SU(5) proton decay better
  - Larger SUSY masses suppress proton decay
  - Heavier neutralinos lead to larger M_{H_C}
- Phases in Yukawas in Minimal SU(5) suppress $p \to K\nu$
  - Phases need not be too tuned
  - Other nucleon decay still subdominant

Gravity Corrections to Unification

- Gravity corrections to unification important
  - $V/M_P \sim 1/(16\pi^2)$

$$W_{\mathrm{eff}}^{\Delta g} = \frac{c}{M_P} \mathrm{Tr}\left[\Sigma \mathcal{W} \mathcal{W}\right]$$

- M_{H_C} becomes free parameter
  - λ and λ' now independent
  - λ' can be taken small $\rightarrow$ large M_{H_C}

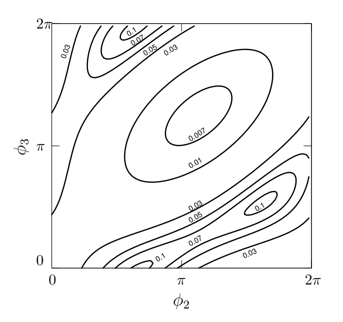
$$M_{H_C} = \lambda \left(\frac{2}{\lambda' g_5^2} \right)^{\frac{1}{3}} \left(M_X^2 M_\Sigma \right)^{\frac{1}{3}}$$

- Gaugino mass affected by Planck suppressed operator
  - For stop coannihillation A-term large

$$\Delta M_1 = \frac{4 c g_1^2 V (A_{\lambda'} - B_\Sigma)}{M_P} \qquad \Delta M_2 = \frac{12 c g_2^2 V (A_{\lambda'} - B_\Sigma)}{M_P} \qquad \Delta M_3 = -\frac{8 c g_3^2 V (A_{\lambda'} - B_\Sigma)}{M_P}$$

Phase Dependence of Proton Decay

- Matrix elements for Higgsino and wino similar size
  - Varying phases leads to cancellations
- Is the amount of tuning reasonable?



Phase Dependence of Proton Decay

- Matrix elements for Higgsino and wino similar size
  - Varying phases leads to cancellations
- Is the amount of tuning unreasonable?
- Other nucleon decays modes
  - $p \to \pi^+ \nu$ and $n \to \pi^0 \nu$ depend on similar combinations of parameters
  - Different tuning need to suppress these modes