Supersymmetric Super-GUT Models

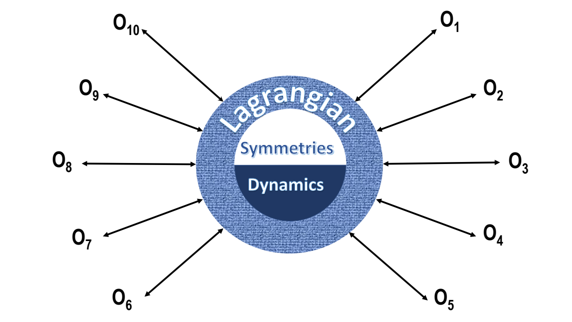
Jason L. Evans

Korea Institute for Advanced Study

Physics is About Correlations

- Science explains correlation
  - Naturalness: correlation between weak scale and Λ

    Theory does not explain correlation, counter terms
    Symmetries like (SUSY) explain correlation
    Dynamics relaxion field explain correlation



Physics is About Correlations

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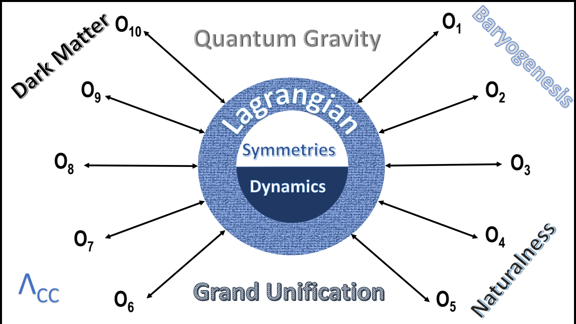
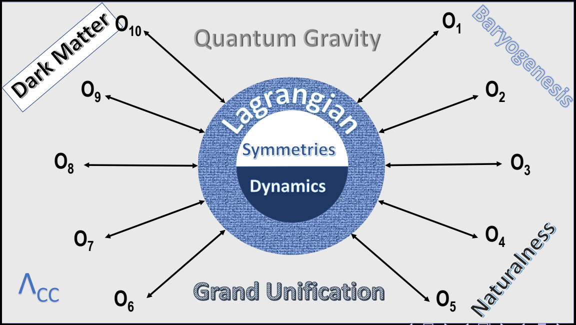
- Many correlations unknown



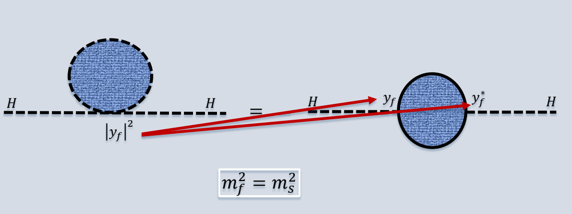
Physics is About Correlations

- Science explains correlation
- Many correlations unknown
- Good BSM explains more than one observable



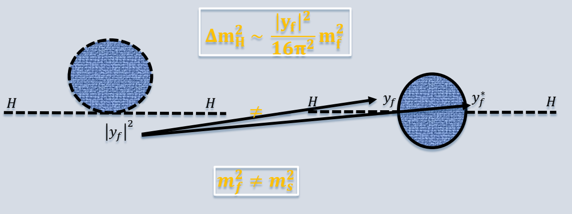
Three Triumphs of SUSY: Naturalness

- SUSY enforces relationships among parameters



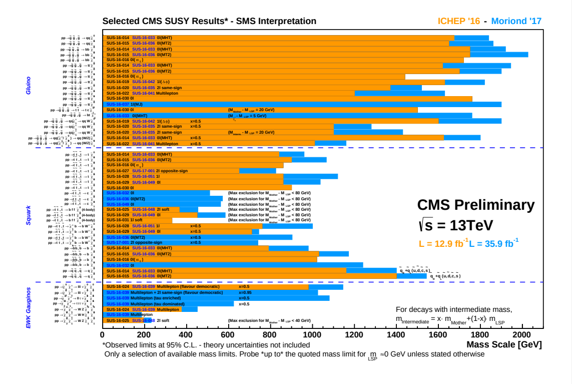
Three Triumphs of SUSY: Naturalness

- SUSY enforces relationships among parameters
- Experiment tells us SUSY must be broken
  - If breaking too large $\rightarrow$ unnatural



Three Triumphs of SUSY: Naturalness

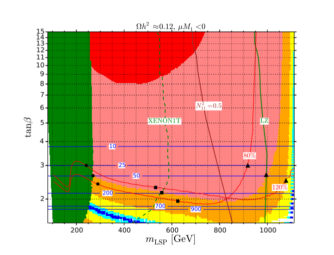
- SUSY enforces relationships among parameters
- Experiment tells us SUSY must be broken
- Not perfect but not so bad?
  - $\Delta_{BG} \sim M_{SUSY}^2 / m_Z^2$

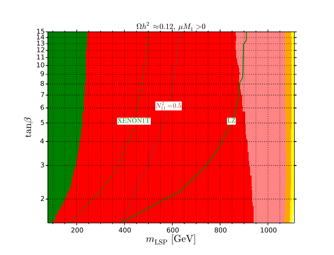


Three Triumphs of SUSY: Dark Matter

- SUSY has many dark matter candidates
  - Some are ruled out

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





Badziak, Olechowski, Szczerbiak

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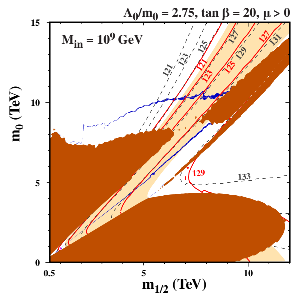

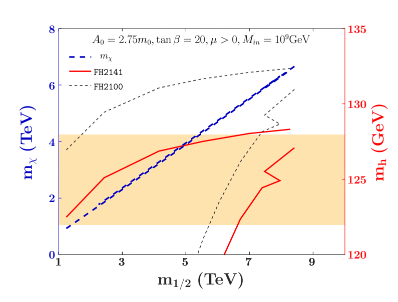

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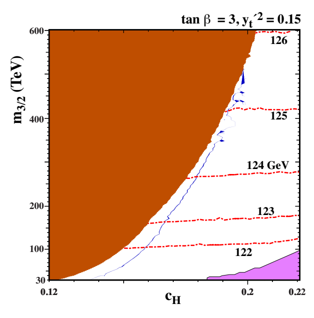

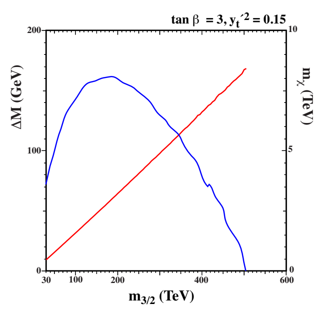

Three Triumphs of SUSY:Grand Unification

- Gauge couplings unify well in SUSY
- Quality of unification depends on μ, m_i

$$g_i^{-2}(m_Z) = g_5^{-2}(M_{GUT}) + \frac{1}{8\pi^2}\left(\beta_{SM_i} \ln\left(\frac{m_Z}{M_{GUT}}\right) + \frac{1}{3}\left(N_{\bar{5}} + 3N_{10}\right) \ln\left(\frac{M_{GUT}}{M_{SUSY}}\right) + \beta_{\mu_i} \ln\left(\frac{M_{GUT}}{\mu}\right) + \beta_{m_i} \ln\left(\frac{M_{GUT}}{m_i}\right)\right)$$

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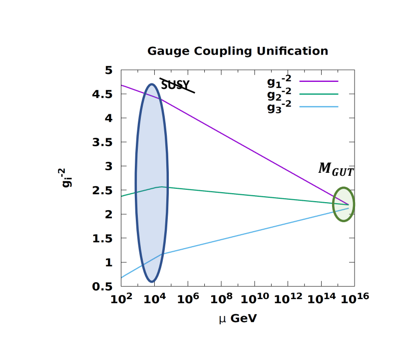
CMSSM with $m_0 = 20$ TeV



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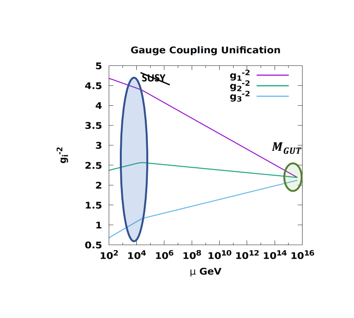
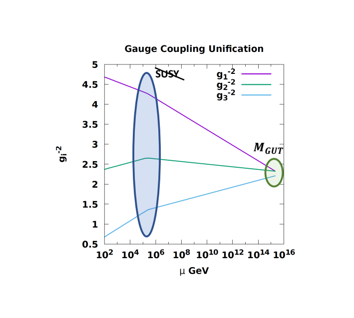
  - CMSSM with $m_0 = 20$ TeV vs $m_0 = 200$ TeV





Unification, Thresholds, and Low-Scale Observables

- Minimal Supersymmetric SU(5)

$$\Psi = \mathbf{10} \supset Q_L, \bar{U}, \bar{E} \qquad \overline{\Phi} = \mathbf{5} \supset L, \bar{D} \qquad (\textbf{and} 1 \supset N)$$

$$W_5 = \mu_\Sigma \mathrm{Tr}\Sigma^2 + \frac{1}{6}\lambda' \mathrm{Tr}\Sigma^3 + \mu_H \overline{H} H + \lambda \overline{H} \Sigma H$$
$$+ (h_{\mathbf{10}})_{ij}\, \epsilon_{\alpha\beta\gamma\delta\zeta} \Psi_i^{\alpha\beta} \Psi_j^{\gamma\delta} H^\zeta + (h_{\overline{\mathbf{5}}})_{ij}\, \Psi_i^{\alpha\beta} \Phi_{j\alpha} \overline{H}_\beta \,,$$
$$\left[+ (h_1)_{ij} \overline{H}^\alpha \Phi_{i\alpha} N_j + \frac{1}{2} M_{ij} N_i N_j \right]$$

Unification, Thresholds, and Low-Scale Observables

- Minimal Supersymmetric SU(5)
- Threshold corrections $\rightarrow$ unification of couplings

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

$$\frac{5}{g_1^2(M_{GUT})} - \frac{3}{g_2^2(M_{GUT})} - \frac{2}{g_3^2(M_{GUT})} = -\frac{9}{2\pi^2} \ln\left(\frac{M_{GUT}}{(M_X^2 M_\Sigma)^{\frac{1}{3}}}\right)$$

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$$\frac{3}{\bar{g}_2^2(M_{GUT})} + \Delta_{SUSY_2} - \frac{2}{g_3^2(M_{GUT})} - \frac{1}{g_1^2(M_{GUT})} = -\frac{3}{10\pi^2} \ln\left(\frac{M_{GUT}}{M_{H_C}}\right)$$

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- Minimal Supersymmetric SU(5)
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  - SUSY breaking determines/constraints M_{H_C}, M_X, M_Σ
- Color Higgs $\rightarrow$ B, L violating interactions
  - This leads to nucleon decay

$$\mathcal{L}|^{\Delta B=1}_{\text{eff.}} = C^{ijkl}_{5L} \int d^2\theta \, \frac{1}{2}(Q_i Q_j)(Q_k L_l) + C^{ijkl}_{5R} \int d^2\theta \, \overline{U}_i \overline{E}_j \overline{U}_k \overline{D}_l + \text{h.c.}$$

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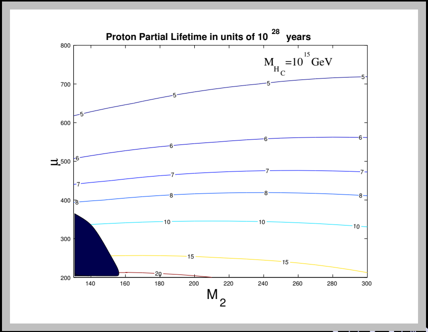
- Proton decay determined M_{H_C} and so constrains SUSY

$$C^{ijkl}_{5L} = -\frac{1}{M_{H_C}} f^u_i e^{i\varphi_{u_i}} \delta^{ij} V^*_{kl} f^d_l \qquad C^{ijkl}_{5R} = -\frac{1}{M_{H_C}} f^u_i V_{ij} V^*_{kl} f^d_l e^{-i\varphi_{u_k}}$$

Gauge Coupling Unfication: Proton Decay

- Murayama and Pierce claim minimal SU(5) excluded
  - Non-minimal models needed(Pierce Murayama)



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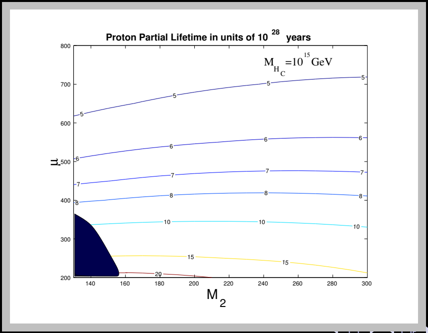
$$m_{\tilde{f}_3} = 1\text{TeV} \qquad m_{\tilde{f}_{2,3}} = 10\text{TeV} \qquad \mu \in (100, 1000)\text{GeV} \qquad M_2 \in (100, 400)\text{GeV}$$



Details of Proton Decay Amplitude

- Amplitudes for proton decay

$$\mathcal{A}(p \to K^+ \bar{\nu}_i) = C_{RL}(usd\nu_i)\langle K^+|(us)_R d_L|p\rangle$$
$$+C_{RL}(uds\nu_i)\langle K^+|(ud)_R s_L|p\rangle$$
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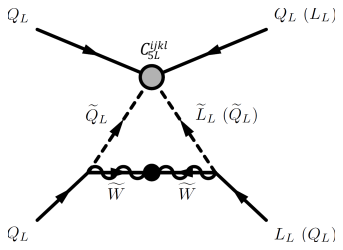

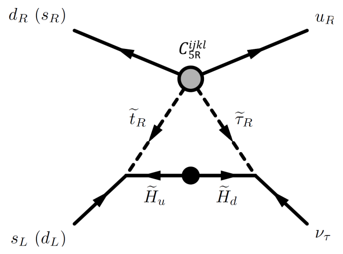

- Approximate low-scale WC of proton decay

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

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

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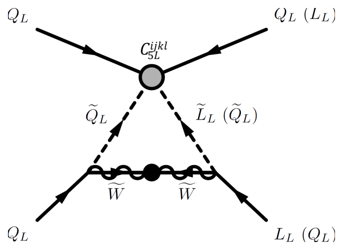

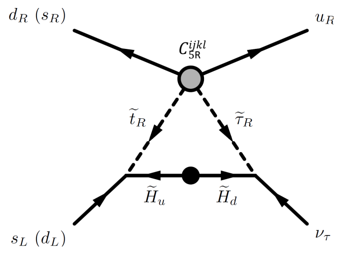

- Respective $\tau(p \to K\nu)$ for $\phi_{2,3} = 0$
  - $\tau(p \to K\nu) > 6.6 \times 10^{33}$ yr

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

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

Proton Decay and Low-scale SUSY

- Large soft masses will help
- PGM/mini-split models give sufficient suppression
  - Strong Moduli Stabilization

$$\frac{\langle Z \rangle}{M_P} \ll 1 \qquad \frac{F_Z}{M_P} \sim m_{3/2}$$

Proton Decay and Low-scale SUSY

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  - Z not a singlet suppressed in gauge kinetic function

$$h_{\alpha\beta} = \frac{Z^n}{M_P^n} \quad \rightarrow \quad m_{1/2} \sim \left(\frac{\langle Z \rangle}{M_P}\right)^{n-1} m_{3/2} \ll m_{3/2}$$

Proton Decay and Low-scale SUSY

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  - Z not a singlet suppressed in gauge kinetic function
  - Gauginos are generated by anomalies

$$M_a = \frac{b_a g_a^2}{16\pi^2} m_{3/2} \qquad b_a = (-33/5, -1, 3)$$

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  - A-terms are also suppressed

$$K = \frac{Z^\dagger Z}{M_P^2} H_u^\dagger H_u \quad \rightarrow \quad \frac{Z^\dagger}{M_P} \frac{F_Z}{M_P} H_u F_{H_u}^\dagger$$

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  - Strong Moduli Stabilization
  - Z not a singlet suppressed in gauge kinetic function
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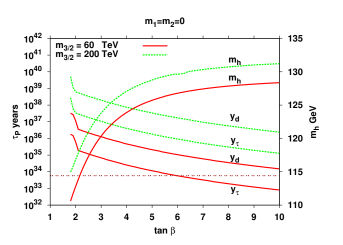
  - A-terms are also suppressed
  - Scalar masses the same as mSUGRA

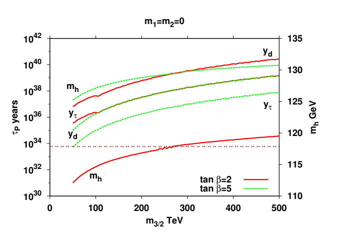
$$m_0 = m_{3/2}$$

Proton Decay and Low-scale SUSY

- Large soft masses will help
- PGM/mini-split models give sufficient suppression

$$m_{\tilde{f}} = m_{3/2} \qquad m_i = \beta_i m_{3/2} \qquad A_0 = 0 \qquad (\mu \sim m_{\tilde{f}})$$





Proton Decay and Low-scale SUSY

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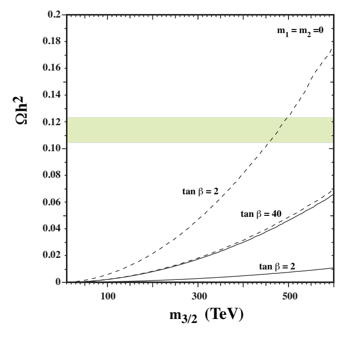
- PGM/mini-split models give sufficient suppression
  - $m_{3/2} \lesssim 400$ TeV, DM not viable



Proton Decay and CMSSM

- What about CMSSM like models?
  - M_{SUSY} is low

$$\Gamma_{\tilde{W}} \sim 10^{31}\ \mathrm{yr}\left(\frac{M_{H_C}}{7\times 10^{16}\ \mathrm{GeV}}\right)^2\left(\frac{M_{SUSY}}{11\ \mathrm{TeV}}\right)^4\left(\frac{3.5\ \mathrm{TeV}}{M_2}\right)^2 \qquad \Gamma_{\tilde{h}} \sim 10^{31}\ \mathrm{yr}\left(\frac{M_{H_C}}{7\times 10^{16}\ \mathrm{GeV}}\right)^2\left(\frac{M_{SUSY}}{11\ \mathrm{TeV}}\right)^4\left(\frac{12\ \mathrm{TeV}}{\mu}\right)^2$$

- Contributions can add destructively

$$\mathcal{A}(p\to K^+\bar{\nu}_i) = C_{RL}(usd\nu_i)\langle K^+|(us)_R d_L|p\rangle + C_{RL}(uds\nu_i)\langle K^+|(ud)_R s_L|p\rangle$$

$$+C_{LL}(usd\nu_i)\langle K^+|(us)_L d_L|p\rangle + C_{LL}(uds\nu_i)\langle K^+|(ud)_L s_L|p\rangle$$

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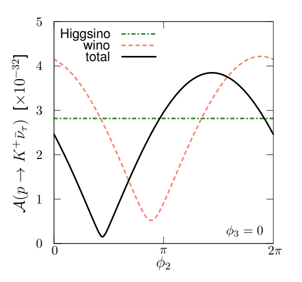
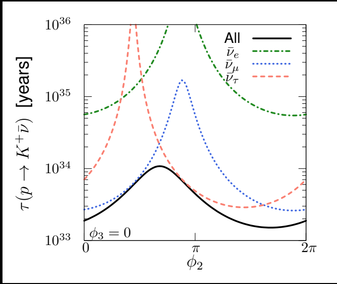
$$C_{RL} \simeq -\frac{\alpha_2^2}{\sin^2 2\beta}\,\frac{m_t^2 m_d m_\tau \mu}{m_W^4 M_{H_C} M_{\mathrm{SUSY}}^2}\,V_{tb}^* V_{ud} V_{ts} e^{-i(\phi_2+\phi_3)}$$

Phase Suppresion of Proton Decay

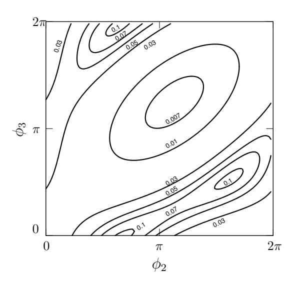
- Significant suppression afforded by phases
  - Misalignment of decay to different generations limits suppression

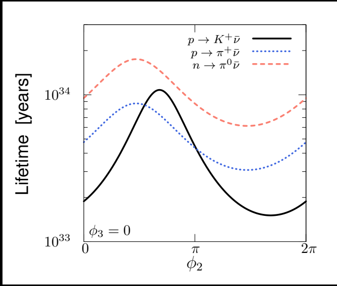




Phase Suppresion of Proton Decay

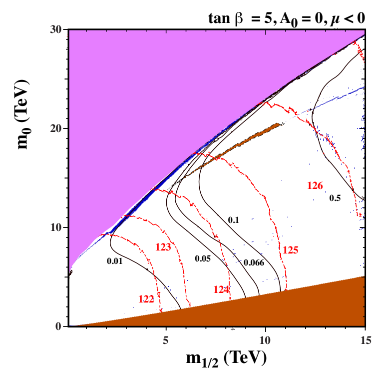
- Significant suppression afforded by phases
  - Misalignment of decay to different generations limits suppression
- Suppression not so tuned in phase
- Other nucleon lifetimes also enhanced

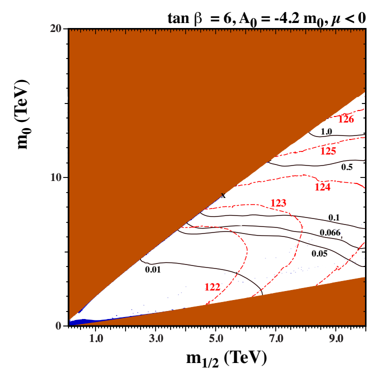




CMSSM with Phase Suppressed Proton Decay

- Phase Suppression sufficient for viable dark matter





Super-GUT Models

- SUSY breaking mediated at some scale $M_{in} > M_{GUT}$
  - Parameters at M_{in} for CMSSM

$$m_0 \qquad m_{1/2} \qquad \tan\beta \qquad A_0 \qquad \mathrm{sgn}(mu)$$

Super-GUT Models

- SUSY breaking mediated at some scale $M_{in} > M_{GUT}$
  - Some matching conditions have consequences

$$B = B_H + \frac{3\lambda V\Delta}{\mu} + \frac{6\lambda}{\lambda'\mu}\left[(A_{\lambda'} - B_\Sigma)(2B_\Sigma - A_{\lambda'} + \Delta) - m_\Sigma^2\right] \quad \rightarrow \quad A_{\lambda'} \gtrsim 8m_{\tilde{\Sigma}}^2$$

$$\frac{3}{g_2^2(Q)} - \frac{2}{g_3^2(Q)} - \frac{1}{g_1^2(Q)} = -\frac{3}{10\pi^2}\ln\left(\frac{Q}{M_{H_C}}\right) \quad \rightarrow \quad M_{H_C} \sim 10^{15}\mathrm{GeV}$$

$$\frac{5}{g_1^2(Q)} - \frac{3}{g_2^2(Q)} - \frac{2}{g_3^2(Q)} = -\frac{3}{2\pi^2}\ln\left(\frac{Q^3}{M_X^2 M_\Sigma}\right) \quad \& \quad M_{H_C} = \lambda\left(\frac{2}{\lambda' g_5^2}\right)^{\frac{1}{3}}\left(M_X^2 M_\Sigma\right)^{\frac{1}{3}}$$

$\lambda \propto \lambda'$ & $\lambda' \sim 1$ $\rightarrow$ **Proton Decays too Quickly**

Super-GUT Models

- SUSY breaking mediated at some scale $M_{in} > M_{GUT}$
  - Some matching conditions have consequences
- Add higher dimensional operators

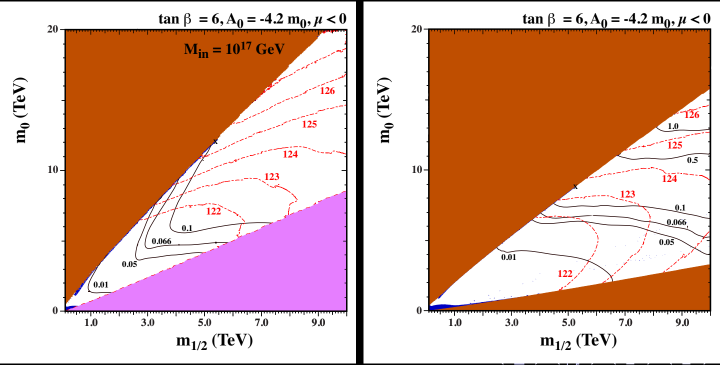
$$W_{\mathrm{eff}}^{\Delta g} = \frac{c}{M_P} \mathrm{Tr}\left[\Sigma \mathcal{W}\mathcal{W}\right]$$

  - Alters matching condition $\rightarrow$ M_{H_C} Free

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

Super-GUT Models

- SUSY breaking mediated at some scale $M_{in} > M_{GUT}$
  - Some matching conditions have consequences
- Add higher dimensional operators
- Super-GUT CMSSM versus CMSSM ($\lambda = 0.6, \lambda' = 10^{-4}$)



Minimal SU(5) + Right-Handed Neutrinos

- Neutrino seemingly benign interactions
  - Leptongenesis is viable

$$W_5 = (h_1)_{ij} \overline{H}^{\alpha} \Phi_{i\alpha} N_j + \frac{1}{2} M_{ij} N_i N_j$$

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- Neutrino seemingly benign interactions

$$W_5 = (h_1)_{ij}\overline{H}^{\alpha}\Phi_{i\alpha}N_j + \frac{1}{2}M_{ij}N_iN_j$$

- Physical degrees of freedom in the Yukawa's
  - We will assume $M_R = \delta_{ij}M_{R_i}$

$$f^u_{ij} = f^u_i e^{i\varphi_{u_i}}\delta_{ij} \qquad f^d_{ij} = f^d_i V^*_{ij} \qquad f^{\nu}_{ij} = f^{\nu}_j e^{i\varphi_{d_i}} U^*_{ij} \qquad (M_R)_{ij} = e^{i\varphi_{\nu_i}} W_{ik}(M^D_R)_k e^{2i\overline{\varphi}_{\nu_k}} W_{jk} e^{i\varphi_{\nu_j}}$$

Minimal SU(5) + Right-Handed Neutrinos

- Neutrino seemingly benign interactions

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$$(M_R)_{ij} = e^{i\varphi_{\nu_i}} W_{ik}(M^D_R)_k e^{2i\overline{\varphi}_{\nu_k}} W_{jk} e^{i\varphi_{\nu_j}}$$

- PMNS has large CP violation and large flavor mixing

$$\sin^2\theta_{12} = 0.297\,, \quad \sin^2\theta_{23} = 0.425\,, \quad \sin^2\theta_{31} = 0.0214\,, \quad \delta_{CP} = 1.38\pi$$

Kaon Mixing From Right-Handed Neutrinos

- Beta function of $\Phi_i, \overline{H}$ affected by h_1 (N_i GUT Yukawa)
  - Leading-log approximation for affected soft masses

$$(m^2_{\tilde{d}})_{ij} \quad \simeq -\frac{1}{8\pi^2}[f^\nu f^{\nu\dagger}]_{ij}(3m_0^2 + A_0^2)\ln\frac{M_*}{M_{GUT}}\,, \qquad (i \neq j)$$

Kaon Mixing From Right-Handed Neutrinos

- Beta function of $\Phi_i, \overline{H}$ affected by h_1
- Mixing in down-squark soft masses $\rightarrow$ kaon mixing

$$\mathcal{H}_{\text{eff.}}^{\Delta S=2} \simeq -\frac{\alpha_S^2}{36 m_{\tilde{q}}^2}\left(\Delta_{12}^{(R)}\right)^2 F_1\left(\frac{m_{\tilde{g}}^2}{m_{\tilde{q}}^2}\right)\overline{d}_R^\alpha \gamma_\mu s_R^\alpha \overline{d}_R^\beta \gamma^\mu s_R^\beta - \frac{\alpha_S^2}{3 m_{\tilde{q}}^2}\Delta_{12}^{(L)}\Delta_{12}^{(R)} F_2\left(\frac{m_{\tilde{g}}^2}{m_{\tilde{q}}^2}\right)\overline{d}_L^\alpha s_R^\alpha \overline{d}_R^\beta s_R^\beta - \frac{\alpha_S^2}{9 m_{\tilde{q}}^2}\Delta_{12}^{(L)}\Delta_{12}^{(R)} F_3\left(\frac{m_{\tilde{g}}^2}{m_{\tilde{q}}^2}\right)\overline{d}_L^\alpha s_R^\beta \overline{d}_R^\beta s_R^\alpha$$

$$(m_{\tilde{d}}^2)_{12} \simeq -\frac{1}{8\pi^2} e^{i(\varphi_{d_1}-\varphi_{d_2})} U_{1k} (f_k^\nu)^2 U_{2k}^* (3m_0^2 + A_0^2) \ln\frac{M_{\text{in}}}{M_{\text{GUT}}}$$

SUSY contributions

$$\Delta m_K^{\text{SUSY}} = 2\text{Re}\left\langle \overline{K}^0 \right| \mathcal{H}_{\text{eff.}}^{\Delta S=2} \left| K^0 \right\rangle ,$$

$$\epsilon_K^{\text{SUSY}} = \frac{1}{\sqrt{2}\Delta m_K}\text{Im}\left\langle \overline{K}^0 \right| \mathcal{H}_{\text{eff.}}^{\Delta S=2} \left| K^0 \right\rangle$$

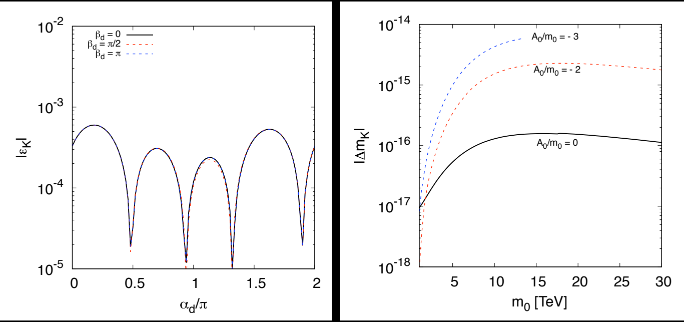
Hadron matrix elements:

SM op.: [FLAG average '16]

BSM ops.: [SWME collaboration '15]

Kaon Mixing From Right-Handed Neutrinos

- Beta function of $\Phi_i, \overline{H}$ affected by h_1
- Mixing in down-squark soft masses $\rightarrow$ kaon mixing
- Irreducible contributions to Kaon mixing ($\alpha_d = \phi_{d_1} - \phi_{d_2}$)



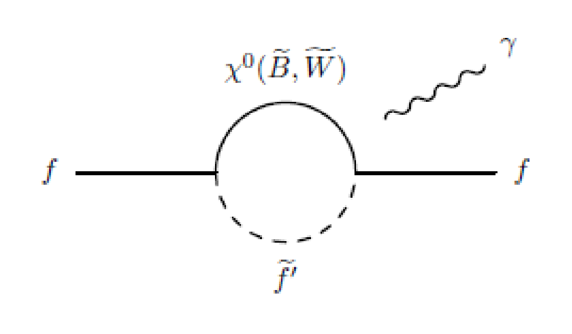
eEDM From Right-Handed Neutrinos

- Right-handed neutrino Yukawa's also affect leptons
  - Super-GUT RG running enhances FV+CP violation
  - Effect maximized for $Y_\nu \sim 1 \rightarrow M_{N_R} \sim 10^{15}$

$$(m^2_{\tilde{L}})_{ij} \simeq -\frac{1}{8\pi^2} \sum_k \hat{f}^\nu_{ik} (\hat{f}^{\nu\dagger})_{kj} (3m_0^2 + A_0^2) \ln \frac{M_*}{(M_R^D)_k} , \qquad (i \neq j)$$

eEDM From Right-Handed Neutrinos

- Right-handed neutrino Yukawa's also affect leptons
- Generated FV+CP violation lead to eEDM's



eEDM From Right-Handed Neutrinos

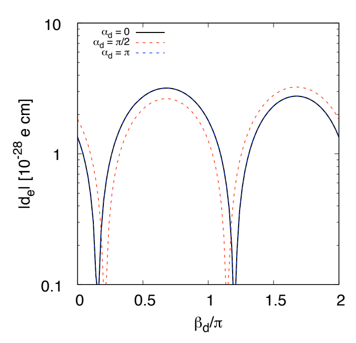
- Right-handed neutrino Yukawa's also affect leptons
- Generated FV+CP violation lead to eEDM's

$$\frac{d_e}{e} \sim \frac{g_Y^2}{32\pi^2}\frac{m_\tau}{m_{\tilde{l}}^2}\frac{\mu M_1}{m_{\tilde{l}}^2}\mathrm{Im}[(\Delta_l^{(L)})_{13}(\Delta_l^{(R)})_{31}]f(x)$$

$$(\Delta_l^{(L)})_{ij} \equiv \frac{(m_{\tilde{L}}^2)_{ij}}{m_{\tilde{l}}^2}, \qquad (\Delta_l^{(R)})_{ij} \equiv \frac{(m_{\tilde{e}}^2)_{ij}}{m_{\tilde{l}}^2}$$

eEDM From Right-Handed Neutrinos

- Right-handed neutrino Yukawa's also affect leptons
- Generated FV+CP violation lead to eEDM's
- Irreducible contribution to eEDM ($\beta_d = \phi_{d_1} - \phi_{d_3}$)



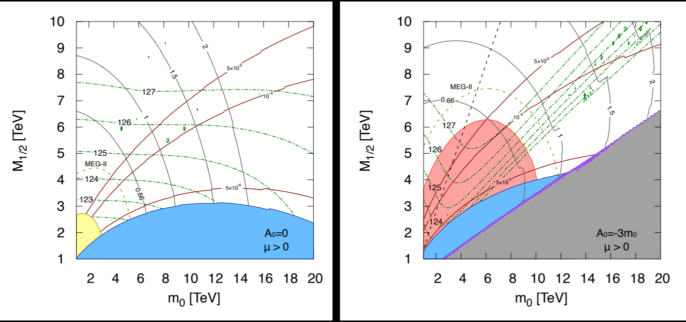
Consequences for Super-GUT Models

- Super-GUT CMSSM with right-handed neutrinos

$$m_0 \quad m_{1/2} \quad A_0 \quad \tan\beta \quad \mathrm{sgn}(\mu) \quad M_{in} \quad M_R \quad \lambda \quad \lambda' \quad \phi_{u_i} \quad \phi_{d_i}$$

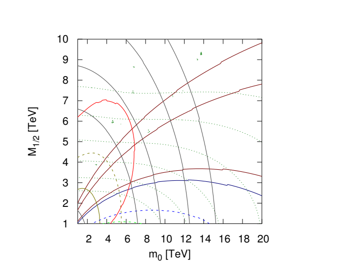
Consequences for Super-GUT Models

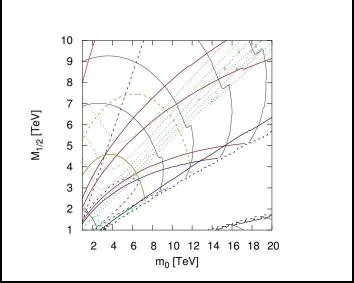
- Super-GUT CMSSM with right-handed neutrinos
  - yellow: $\mu \to e\gamma$ Cyan: eEDM(9.3×10^{-29}) Red: ε_K



Consequences for Super-GUT Models

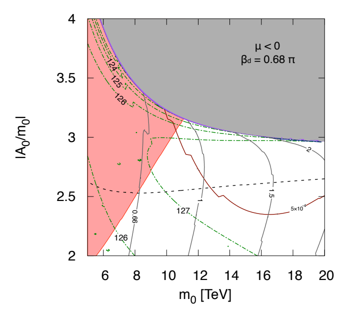
- Super-GUT CMSSM with right-handed neutrinos
  - yellow: $\mu \to e\gamma$ Cyan: eEDM(1.1×10^{-29}) Red: ε_K

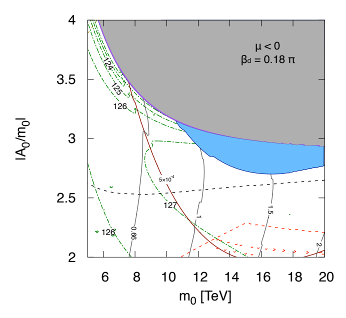




Consequences for Super-GUT Models

- Super-GUT CMSSM with right-handed neutrinos
- Constraints depend on β_d
  - Cyan: eEDM(9.3×10^{-29}) Red: ε_K





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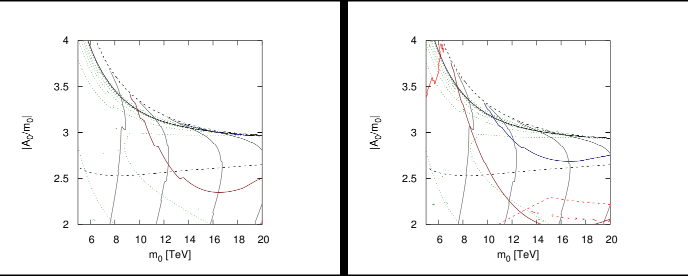


Super-GUT PGM

- CMSSM required Planck suppressed operators
  - M_{H_C} was required to be too small

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

Super-GUT PGM

- CMSSM required Planck suppressed operators
- PGM proton decay is suppressed by soft masses
  - M_{H_C} is relatively unconstrained
  - No Planck Suppressed operators needed

$$\Gamma_{\tilde{W}} \sim 10^{31}\ \mathrm{yr} \left(\frac{M_{H_C}}{7 \times 10^{16}\ \mathrm{GeV}}\right)^2 \left(\frac{M_{SUSY}}{11\ \mathrm{TeV}}\right)^4 \left(\frac{3.5\ \mathrm{TeV}}{M_2}\right)^2 \qquad \Gamma_{\tilde{h}} \sim 10^{31}\ \mathrm{yr} \left(\frac{M_{H_C}}{7 \times 10^{16}\ \mathrm{GeV}}\right)^2 \left(\frac{M_{SUSY}}{11\ \mathrm{TeV}}\right)^4 \left(\frac{12\ \mathrm{TeV}}{\mu}\right)^2$$

Super-GUT PGM

- CMSSM required Planck suppressed operators
- PGM proton decay is suppressed by soft masses
- PGM restricts $\tan\beta$
  - soft masses larger guagino small
  - Stop masses driven lighter
  - More difficult to drive Higgs mass negative

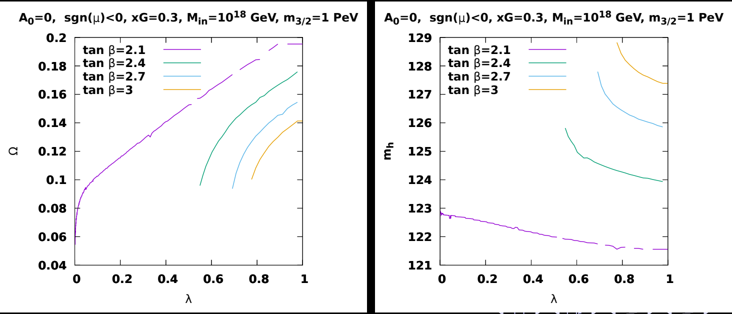
Super-GUT PGM

- CMSSM required Planck suppressed operators
- PGM proton decay is suppressed by soft masses
- PGM restricts $\tan\beta$
- Super-GUT RG running allows for larger $\tan\beta$

$$W_5 \supset \lambda \bar{H} \Sigma H \qquad \rightarrow \qquad \Delta\beta_{m^2_{H_u}} = \frac{|\lambda|^2}{8\pi^2}\left(m^2_\Sigma + m^2_{\bar{H}} + m^2_H + |A_\lambda|^2\right)$$

Super-GUT PGM

- CMSSM required Planck suppressed operators
- PGM proton decay is suppressed by soft masses
- PGM restricts $\tan\beta$
- Super-GUT RG running allows for larger $\tan\beta$
  - Wino dark matter with acceptable density



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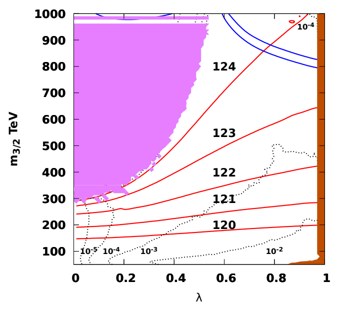

Non-Renormalizeable Operators in Super-GUT PGM

- Supersymmetric Non-Renormalizable operators

$$W_{\rm eff}^{\Delta g} = \frac{c}{M_P} {\rm Tr}\left[\Sigma \mathcal{W}\mathcal{W}\right] \qquad \rightarrow \qquad \lambda' \textbf{ Free Parameter}$$

- Heavy gauge bosons can be suppressed

$$\frac{5}{g_1^2(M_{GUT})} - \frac{3}{g_2^2(M_{GUT})} - \frac{2}{g_3^2(M_{GUT})} = -\frac{9}{2\pi^2} \ln\left(\frac{M_{GUT}}{(M_X^2 M_\Sigma)^{\frac{1}{3}}}\right) \qquad M_\Sigma = \frac{5}{2}\lambda' V$$

- Large sfermion masses allow for large λ'
  - Dim-6 proton decay enhanced

$P \to \pi e$ in Minimal Supersymmetric SU(5)

- Heavy gauge bosons violate B,L

$$\mathcal{L}_{\text{int}} = \frac{g_5}{\sqrt{2}} \left[-\overline{d^c_{Ri}} \not{X} L_i + e^{-i\varphi_i} \overline{Q_i} \not{X} u^c_{Ri} + \overline{e^c_{Ri}} \not{X} (V^\dagger)_{ij} Q_j + \text{h.c.} \right]$$

- Amplitudes for $P \to \pi e$

$$\mathcal{A}_L(p \to \pi^0 e^+) = -\frac{g_5^2}{M_X^2} \cdot A_1 \cdot \langle \pi^0 | (ud)_R u_L | p \rangle \,,$$

$$\mathcal{A}_R(p \to \pi^0 e^+) = -\frac{g_5^2}{M_X^2} (1 + |V_{ud}|^2) \cdot A_2 \cdot \langle \pi^0 | (ud)_R u_L | p \rangle \,,$$

$P \to \pi e$ in Minimal Supersymmetric SU(5)

- Heavy gauge bosons violate B,L

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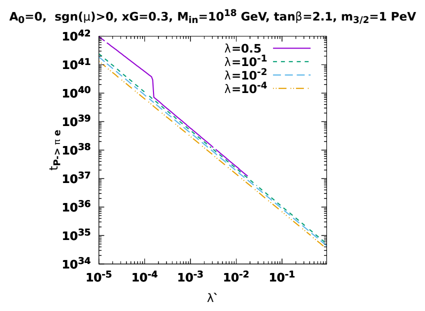
Planck Corrections to Gauge Kinetic Terms

- For lager λ' Dim-6 Proton decay most important
  - Dim-5 suppressed by larger sfermion masses.



SUSY Breaking Planck Suppressed operators

- Planck Suppressed operators and SUSY breaking field

$$\Delta W = \frac{Z}{\sqrt{3}M_P}\mu\Phi\Psi + \frac{Z}{\sqrt{3}M_P}\Phi\Psi X \qquad \Delta K = \kappa_i \frac{Z}{\sqrt{3}M_P}|\Phi_i|^2 + \frac{Z}{\sqrt{3}M_P}\Phi\Psi$$

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- Shift symmetry on Z restricts allowed operators

SUSY Breaking Planck Suppressed operators

- Planck Suppressed operators and SUSY breaking field
- Shift symmetry on Z restricts allowed operators
- A-terms and B-terms get corrections of order $m_{3/2}$

$$\Delta A = (\kappa_1 + \kappa_2 + \kappa_3) m_{3/2} \qquad \Delta B = (\kappa_1 + \kappa_2) m_{3/2}$$

$$W = \mu \phi_1 \phi_2 + y \phi_1 \phi_2 \phi_3$$

SUSY Breaking Planck Suppressed operators

- Planck Suppressed operators and SUSY breaking field
- Shift symmetry on Z restricts allowed operators
- A-terms and B-terms get corrections of order $m_{3/2}$

$$\Delta A = (\kappa_1 + \kappa_2 + \kappa_3) m_{3/2} \qquad \Delta B = (\kappa_1 + \kappa_2) m_{3/2}$$

- A and B-terms give large corrections to gaugino masses

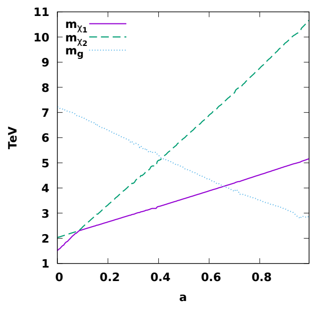
$$M_1 = \frac{g_1^2}{g_5^2} M_5 - \frac{g_1^2}{16\pi^2}\left[10 M_5 - 10(A_{\lambda'} - B_\Sigma) - \frac{2}{5} B_H\right] - \frac{4 c g_1^2 V (A_{\lambda'} - B_\Sigma)}{M_P}$$

$$M_2 = \frac{g_2^2}{g_5^2} M_5 - \frac{g_2^2}{16\pi^2}\left[6 M_5 - 6 A_{\lambda'} + 4 B_\Sigma\right] - \frac{12 c g_2^2 V (A_{\lambda'} - B_\Sigma)}{M_P}$$

$$M_3 = \frac{g_3^2}{g_5^2} M_5 - \frac{g_3^2}{16\pi^2}\left[4 M_5 - 4 A_{\lambda'} + B_\Sigma - B_H\right] + \frac{8 c g_3^2 V (A_{\lambda'} - B_\Sigma)}{M_P}$$

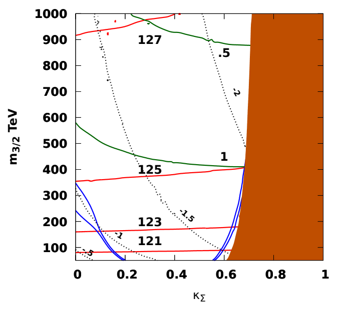
Dark Matter in PGM

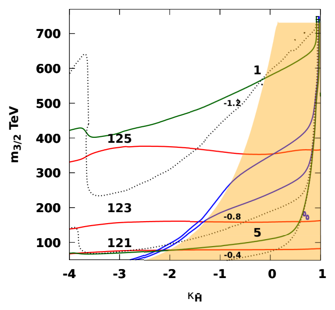
- Guaginos change so much that LSP changes



Dark Matter in PGM

- Guaginos change so much that LSP changes
- Gluino and Wino Coannihilation with Bino arises





Conclusions

- Science is about interrelating parameters
- Supersymmetric models are still true to goals of science
- Gauge couplings unify in SUSY
  - Important guided for BSM
- Min-SUSY SU(5) models have low-scale consequences
  - Proton decay requires large soft masses
  - Matching conditions prefer large A-terms
- Right-handed neutrinos lead to additional constraints
  - Generated mixing in $m^2_{\tilde{d}}$ can lead to large ε_K
- Right-handed neutrinos also leads to additional signals
  - Irreducible FV+CPV lead to future detectable eEDM's
- Higher Dim Operators can have important Consequences