PQ Symmetric Pure Gravity Mediation

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Outline

Why SUSY

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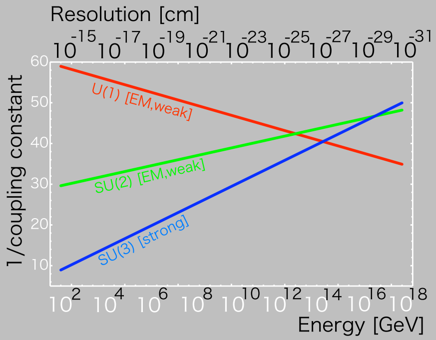
Grand unification in the SM

add many new $SU(2)$ doublets/ another copy of SM



Why SUSY

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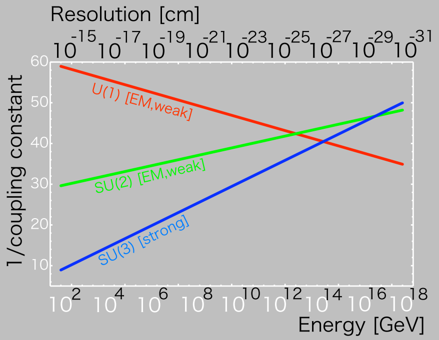
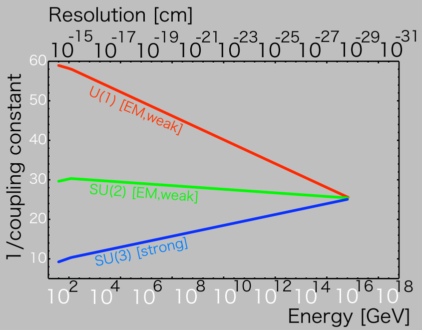


Why SUSY

- Grand unification in the MSSM
  - Needs $M_{SUSY} \lesssim 1000$ TeV



Why is the SUSY Breaking Scale So High?

- Flavor violation suppressed for larger scalar masses
- Gravitinos decays tend to be much less problematic
  - Gravitino decays early enough if $m_{3/2} \gtrsim 10$ TeV

$$\tau = \frac{1}{\Gamma_{3/2}} \sim \frac{M_P^3}{m_{3/2}^2} \sim s \left(\frac{10\textbf{TeV}}{m_{3/2}} \right)^3$$

- Reheat temperature also large enough if $m_{3/2} \gtrsim 10$ TeV

$$T_{3/2} = \left(\frac{\pi^2 g_*}{90} \right)^{-1/4} \sqrt{M_P \Gamma_{3/2}} \sim \textbf{MeV} \left(\frac{m_{3/2}}{M_P} \right)^{3/2}$$

$$\tilde{G} \to \tilde{\chi}\gamma$$

Pure Gravity Mediation

- Strongly stabilized SUSY breaking sector

$$K = |Z|^2 - \frac{|Z|^4}{\Lambda^2} \qquad W = Z\mu^2$$

- *A*-terms are also suppressed

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

- Supersymmetry is broken dynamical (i.e. no Singlets)

$$h_{\alpha\beta} = \frac{Z^\dagger Z}{M_P^2} \sim \frac{\Lambda^2}{M_P^2} \frac{F_Z}{M_P}$$

Pure Gravity Mediation: Continued

- Gauginos are generated by anomalies

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

- Scalar masses the same as mSUGRA

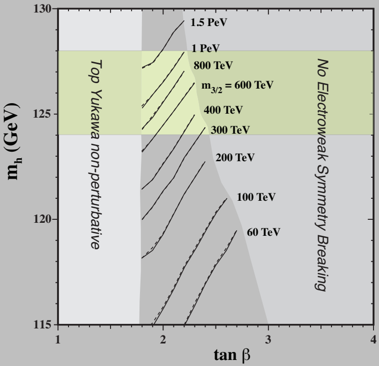
$$m_0 = m_{3/2}$$

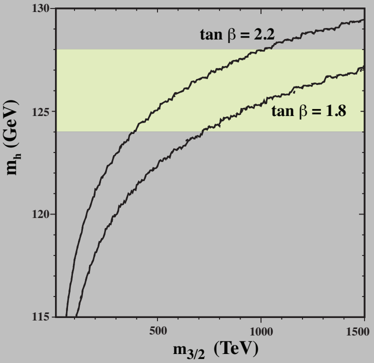
- Single parameter $m_{3/2}$
  - μ and $\tan\beta$ determined by minimization condition
- Radiative EWSB doesn't work
- Adding Giudice-Masiero term frees $\tan\beta$ for successful EWSB
  - Two free parameters

$$m_0 \qquad \tan\beta$$

Lightest Higgs Boson Mass

- $m_{3/2} = 300 - 1500$ TeV gives $m_h = 124 - 128$ GeV





Non-Universal Higgs Masses

- Universal Case, $\tan\beta \lesssim 2.7$ so that $m^2_{H_u} < 0$
- Non-universal Higgs masses relax $\tan\beta$ constraint
- Generic non-universalities from corrections to Kähler

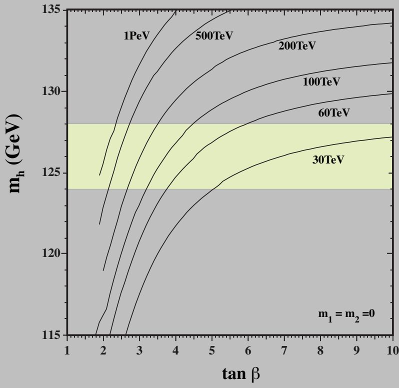
$$K^{(H)} = \left(1 + a\frac{ZZ^*}{M_P^2}\right) H_1 H_1^* + \left(1 + b\frac{ZZ^*}{M_P^2}\right) H_2 H_2^*$$

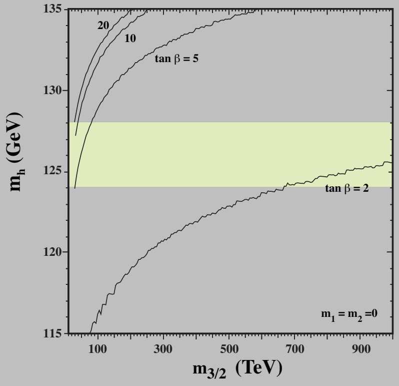
- Higgs masses free parameters

$$m_1^2 = (1 - 3a)m_{3/2}^2 \qquad m_2^2 = (1 - 3b)m_{3/2}^2$$

Higgs Mass Constraints

- $\tan\beta$ is a free parameter
- Higgs mass constraint on $m_{3/2}$ relaxed





Peccei-Quinn Symmetry

- PQ symmetry forbids tree-level μ term
- μ regenerated from PQ breaking field

$$W \supset k \frac{P^2}{M_P} H_1 H_2$$

- If dark matter is the axion

$$\Omega_a h^2 = 0.18 \left[\theta^2 + \left(\frac{H_I}{2\pi F^I_{PQ}} \right)^2 \right] \left(\frac{F_{PQ}}{10^{12}\,\mathrm{GeV}} \right)^{1.19} \left(\frac{\Lambda}{400\,\mathrm{MeV}} \right)$$

- PQ breaking scale (10^{12} GeV) sets Higgs bilinear mass

$$\mu = k \frac{\langle P \rangle^2}{M_P} \sim k\, \mathcal{O}(100)\ \mathrm{TeV}$$

Why is the SUSY Scale $\mathcal{O}(100)$ TeV

- Higgs soft breaking terms set by $m_{3/2}$
  - $m^2_{H_u} \sim -m^2_{\tilde{t}} \sim -m_{3/2}$
  - B-term also set by $m_{3/2}$, $B \sim m_{3/2}$
- EWSB determined by $\mathbf{Det}(m^2_H) < 0$.

$$\mathbf{Det}(m^2_H) \sim (m^2_{H_u} + \mu^2)(m^2_{H_d} + \mu^2) - (B\mu)^2$$

- Two ways to get EWSB
  - $m^2_{H_u} \sim \mu^2$ with no constraint on $B\mu$
  - $\mu^2 \gg m^2_{H_u}$ and $B\mu \sim \mu^2$
- Either way, $m_{3/2} \gtrsim \mu$

PQ breaking Before or After Inflation

- PQ Breaking after inflation
  - Cosmic strings formed
  - Domain walls formed
- PQ breaking before inflation
  - Cosmic strings and domain walls inflated away
  - Isocurvature perturbations

Isocurvaure Perturbations

- During inflation vevs of scalars are non-zero

$$\langle \phi^2 \rangle = \left(\frac{H_I}{2\pi} \right)^2$$

- Hubble during inflation determined by BICEP2

$$H_I \simeq 6 \times 10^{14}$$

- During inflation axion massless

$$\langle a^2 \rangle = \left(\frac{H_I}{2\pi} \right)^2$$

- Large H_I means large axion perturbations

Isocurvaure Perturbations: Continued

- Large axion perturbations $\rightarrow$ isocurvature perturbations

$$\left[\theta^2 + \left(\frac{H_I}{2\pi F^I_{PQ}}\right)^2\right]\left(\frac{H_I}{2\pi F^I_{PQ}}\right)^2\left(\frac{F_{PQ}}{10^{12}\mathrm{GeV}}\right)^{2.38} < 3.6\times 10^{-11}$$

- Axion field fluctuations are large

$$\frac{\langle a^2\rangle}{(F^I_{PQ})^2} = \left(\frac{H_I}{2\pi F^I_{PQ}}\right)^2 \sim 10^4$$

- Suppressing quantum fluctuations
  - If $F^I_{PQ} \gg F_{PQ}$ quantum fluctuations suppresed

Generating Large F^I_{PQ}

- PQ breaking sector

$$W = \lambda X(PQ - \Lambda^2)$$

- Giudice-Masiero like term in Kähler potential

$$K = |P|^2 + |Q|^2 - c_{PQ}(PQ + P^\dagger Q^\dagger)$$

- During inflation SUSY breaking masses generated

$$\mathcal{L}_{soft} \supset c_I H^2 \left(|P|^2 + |Q|^2 - c_{PQ}(PQ + P^\dagger Q^\dagger) \right)$$

- $c_{PQ} > 1$ and $\lambda \lesssim 10^{-4} \to F^I_{PQ} \sim M_P$

Generating Large F^I_{PQ}: Continued

- Strong dynamics break PQ symmetry, $g_0(M_P) \sim 4\pi$

$$f = \frac{1}{g_0^2} + \phi$$

- During inflation $\phi \sim 0$

$$F^I_{PQ} = \Lambda_{PQ} \sim M_P$$

- After inflation $\phi \sim 1$

$$\Lambda_{PQ} \sim F_{PQ}$$

- Simple theory for ϕ

$$W_\phi = \lambda' Y(\lambda'' \phi^2 - M_P^2)$$

PQ Symmetric Pure Gravity Mediation

- PQ symmetry forbids Giudice-Masiero term

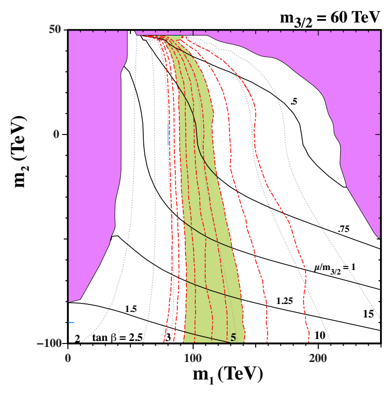
$$\mu = k\frac{\langle P\rangle^2}{M_P} \qquad B\mu = -m_{3/2}\mu$$

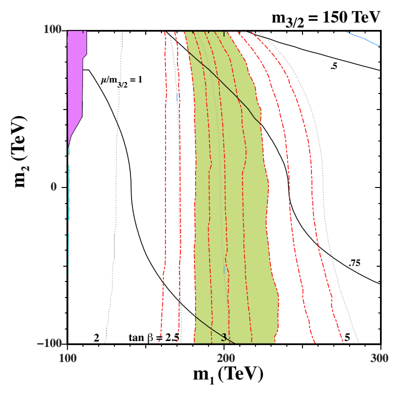
- GM term needed for universal mass but forbidden
- Non-universal Higgs masses sufficient

$$m_{3/2} \qquad m_1 \qquad m_2$$

PQPGM Parameter Sapce

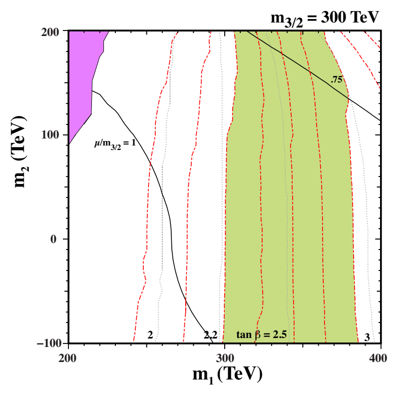
- Higgs mass consistent with PQPGM

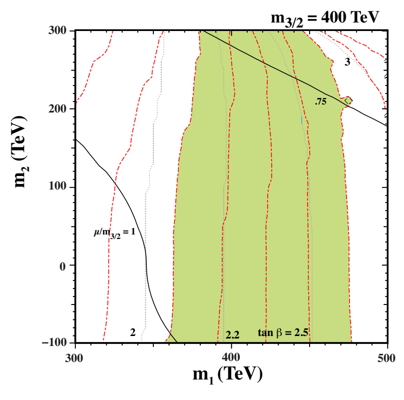




PQPGM Parameter Sapce: Continued

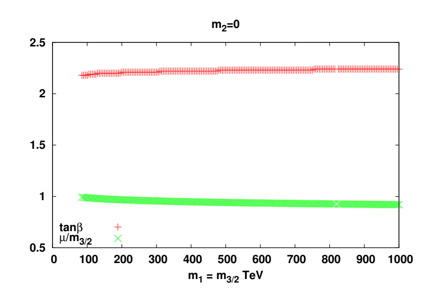
- Higgs mass good for broad range of $m_{3/2}$

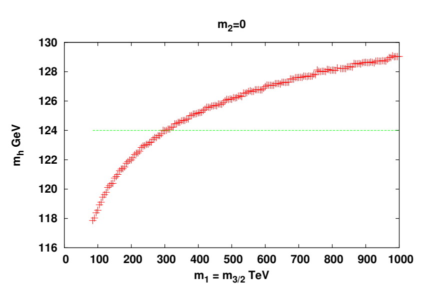




Single Parameter PQPGM

- For partial no scale or pNGM, one parameter needed





Conclusions

- Still motivations for SUSY (GUT, Higgs Mass, etc)
- Higgs Mass suggest we loosen views on naturalness
- No singlets in SUSY breaking sector fixes Polonyi problem
- No singlets gives hierarchy between gauginos and scalars.
- Large sfermion masses explain Higgs mass
- Higgs bilinear can be forbidden by PQ symmetry
- If axion is dark matter $\mu \sim 100$ TeV
- EWSB requires $\mu \sim m_{3/2}$
- Single parameter theory can explain everything