Stabilizing the Axion by Strong Dynamics

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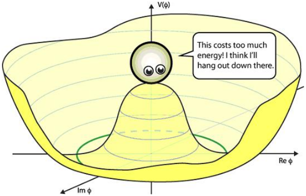
Virtues and Deficiencies of the Peccei-Quinn Mechanism



Why (oh why) is the strong nuclear force *CP*-conserving?

- Nothing wrong with, e.g., larger neutron EDM,
  $d_n \simeq \mathcal{O}(1) \times 10^{-16}\,\bar{\theta}\,\mathrm{e\,cm} \lesssim 3 \times 10^{-26}\,\mathrm{e\,cm}$
- Expectation $\bar{\theta} \sim 1$ vs. observation $\bar{\theta} \lesssim 10^{-10}$!?

Promising approach: Promote $\bar{\theta}$ to a dynamical field, the axion! [Peccei & Quinn '77; Weinberg '78; Wilczek '78]

- PNGB of spontaneously broken global $U(1)_{\mathrm{PQ}}$ with QCD instanton-induced potential

$$V_{\mathrm{eff}} \simeq \Lambda_{\mathrm{QCD}}^4 \left[1 - \cos\left(\bar{\theta} - \frac{a}{f_a}\right)\right] \quad \Rightarrow \quad \langle a \rangle = f_a\,\bar{\theta} \quad \Rightarrow \quad \left(\bar{\theta} - \frac{a}{f_a}\right) \frac{\alpha_s}{8\pi}\, G\tilde{G} \rightarrow 0\,. \qquad ☺$$

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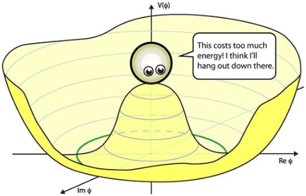

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However, not the end of the story! [Kamionkowski & March-Russell '92; Holman et al. '92; Barr & Seckel '92; Dobrescu '97]

1. $U(1)_{\mathrm{PQ}}$ must be of excellent quality! BUT gravity breaks all global symmetries! ☹
2. Axion decay constant $10^9\,\mathrm{GeV} \lesssim f_a \lesssim 10^{12}\,\mathrm{GeV}$. WHY SSB at intermediate scale?

Embedd PQ mechanism into grander framework! This talk: Dynamical SUSY breaking!

Outline

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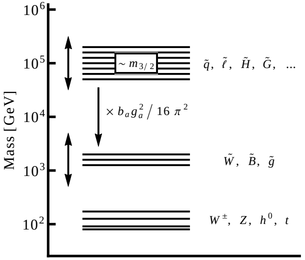
Connection to Spontaneous SUSY Breaking!?

Observation: $\Lambda_{\rm PQ} \sim 10^{11\cdots12}\,\rm GeV$ similar to $\Lambda_{\rm SUSY}$ in models of intermediate scale ~~SUSY~~!

Conjecture: ~~SUSY~~ by strong dynamics, $\Lambda_{\rm SUSY}$ generated via dimensional transmutation.

$$\Lambda_{\rm SUSY} \sim \Lambda \sim \Lambda_{\rm PQ} \sim 10^{11\cdots12}\,\rm GeV\,, \quad \Lambda:\ \text{dynamical scale of strong interactions}$$

- Hierarchy $\Lambda \ll M_{\rm Pl}$, since $\Lambda = M_{\rm Pl}\exp\left[-8\pi^2/b/g(M_{\rm Pl})\right]$ pure quantum effect. ✓
- Consistent w/ pure gravity mediation (PGM). [Ibe, Moroi, Yanagida '07; Ibe & Yanagida '12, Arkani-Hamed et al. '12]



Gravity mediation + anomaly-mediated gauginos masses

[See also Hall & Nomura '12 (spread SUSY); Arvanitaki et al. '13 (mini-split SUSY)]

- Stop loops → Higgs boson mass of $126\,\rm GeV$. ☺
- Gauge coupling unification at $\Lambda_{\rm GUT} \sim 10^{16}\,\rm GeV$. ☺
- LSP (wino typically) good WIMP DM candidate. ☺
- No Polonyi, gravitino, FCNC or ~~CP~~ problems. ☺

Goal: DSB model with $m_{3/2} \sim 100\,\rm TeV$ and $\Lambda_{\rm PQ} \sim \Lambda$.

IYIT Model of Dynamical SUSY Breaking [Izawa & Yanagida '96; Intriligator & Thomas '96]

Simplest realization of DSB in vector-like gauge theories: $Sp(N)$ with $N_f = N + 1$ flavors.

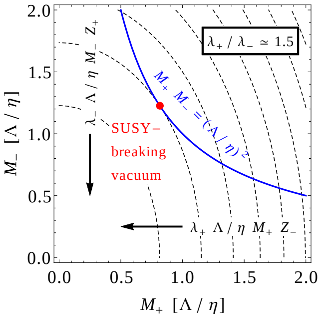
Flat moduli space at low energies [Seiberg '94; Luty '98]

- $Sp(1) \cong SU(2)$ with $2\,N_f = 4$ fundamentals Ψ^i.
- Low-energy EFT in terms of composite mesons,

$$M^{ij} \simeq \frac{1}{\eta}\frac{\langle \Psi^i \Psi^j \rangle}{\Lambda}\,, \quad \eta \sim 4\pi \quad \text{(from NDA)}$$

- Instanton-induced (deformed) moduli constraint,

$$\mathrm{Pf}\left(M^{ij}\right) \simeq \left(\frac{\Lambda}{\eta}\right)^2$$



Lift flat directions by means of Yukawa interactions

- Coupling to singlets in tree-level superpotential,

$$W_{\text{tree}} = \tfrac{1}{2}\lambda_{ij} Z_{ij} \Psi^i \Psi^j \;\to\; W_{\text{eff}} \simeq \tfrac{1}{2}\lambda_{ij} \Lambda Z_{ij} M^{ij}$$

- Global axial $U(1)_A$ associated with Ψ^i rotation,

$$\left[\Psi^1\right] = \left[\Psi^2\right] = +\tfrac{1}{2}\,, \quad \left[\Psi^3\right] = \left[\Psi^4\right] = -\tfrac{1}{2}$$

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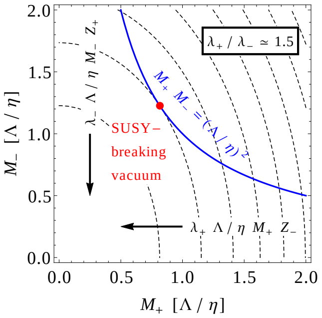


SUSY- & $U(1)_A$-breaking vacuum:

- Assume $\lambda_+\lambda_- < \lambda_1\lambda_4, \lambda_2\lambda_3$.

$$\left\langle M_\pm \right\rangle \simeq \sqrt{\frac{\lambda_\mp}{\lambda_\pm}}\frac{\Lambda}{\eta}\,, \quad \left\langle M_0^a \right\rangle = 0\,.$$

Identify $U(1)_A \rightarrow U(1)_{\text{PQ}}$!

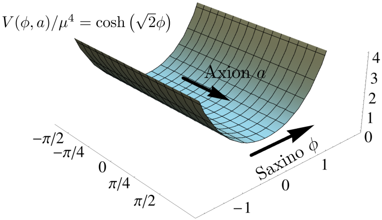
Identification and Couplings of the Axion Multiplet

Implement moduli constraint into effective superpotential via Lagrange multiplier X

$$W_{\rm eff} \simeq \kappa\,\eta\,X \left[M_+ M_- - \left(\frac{\Lambda}{\eta}\right)^2\right] + \frac{\Lambda}{\eta}\left(\lambda_+ M_+ Z_- + \lambda_- M_- Z_+\right)$$

- SUSY-breaking IYIT superpotential $\rightarrow$ basis for SUSY axion model à la KSVZ. ✓
- Axion multiplet A $\rightarrow$ fluctuations of $M_\pm$ along flat direction $M_+ M_- = \text{const.}$

$$M_\pm = \langle M_\pm \rangle\, e^{\pm A}\,, \quad S_0 = \frac{1}{\sqrt{2}}\left(Z_+ + Z_-\right), \quad S_1 = \frac{1}{\sqrt{2}}\left(Z_+ - Z_-\right)$$



Axion superpartners stabilized by ~~SUSY~~

[Same story in a different context: Domcke, KS, Yanagida '14]

- $W \supset \mu^2 S_0 - m\,A\,S_1 + m^2/(2\mu^2)\,A^2 S_0$.
- S_0 is the goldstino field, $\mu^2 \simeq \lambda\,(\Lambda/\eta)^2$.
- Axino $\tilde{a}$ and saxino ϕ mix w/ DOFs in S_1.

$$m_\phi^2 = 2\,m^2\,, \quad m_{\tilde{a}}^2 = m^2 \simeq \lambda^2\,(\Lambda/\eta)^2.$$

~~SUSY~~ sum rule: $m_\phi^2 + m_a^2 = 2\,m_{\tilde{a}}^2\,, \quad m_a^2 = 0.$ ✓

Next: Operators such $M_{\rm Pl}^{-1}\,(\Psi\Psi)^2$ break the $U(1)_{\rm PQ}$ *explicitly*! How do we avoid this?

Outline

Dangerous Higher-Dimensional Operators

Problem: Nothing forbids (Planck-suppressed) PQ symmetry-breaking operators!

$$W_{\text{eff}} \simeq W_{\text{eff}}^{\text{ren}} \quad + \quad \frac{\Lambda^2}{M_{\text{Pl}}} M_\pm^2 \, , \quad \frac{\Lambda^3}{M_{\text{Pl}}^3} M_\pm^3 \, , \quad X Z_\pm^2 \, , \quad Z_\pm^3 \, , \quad \cdots$$

If present in the EFT, PQ mechanism easily spoiled!

- QCD axion potential gets distorted,

$$V_{\text{eff}} \rightarrow V_{\text{eff}} + M^4 \cos\left(\frac{a}{f_a}\right)$$

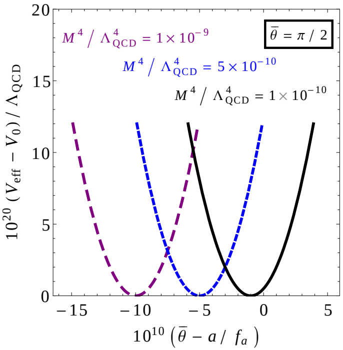
- Shift in the axion VEV re-introduces $\bar{\theta} \neq 0$,

$$\Delta\bar{\theta} \sim M^4/\Lambda_{QCD}^4 \lesssim 10^{-10}$$

- Tight bound on the scale of explicit ~~PQ~~,

$$M \lesssim 700\,\text{keV} \quad (\sim m_e)$$

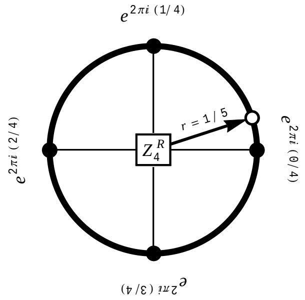
- Each operator $\rightarrow$ constraint on f_a, $m_{3/2}$, ...



Idea: $U(1)_{\text{PQ}}$ is approximate *accidental* symmetry. Protected by exact gauge symmetry!

Many models in the literature: continuous groups, discrete groups, string compactifications, ...

Discrete *R* Symmetries in SUSY Model Building



Technicalities and conventions:

- Chiral superfield $\Phi = (\phi, \psi) \to \left(\exp\left(\frac{2\pi i}{N} r\right)\phi, \exp\left(\frac{2\pi i}{N}(r-1)\right)\psi\right)$.
- R charges normalized such that $[\theta]_R = -1$ and thus $[W]_R = 2$.
- Restrict to generation-independent charges commuting with $SU(5)$.

Well motivated choice in SUSY context:
Discrete R symmetry. [Harigaya, Ibe, KS, Yanagida '13]

Advantages for pheno and model building

[Weinberg '82; Sakai & Yanagida '82] [Giudice & Masiero '88; Inoue et al. '92] [Izawa & Yanagida '97]

- No proton decay via dim-5 operators.
- μ term $W_\mu = \mu\, H_u H_d$ forbidden.
- No large $\langle W \rangle$, that is, negative CC.

Suited to protect global symmetries

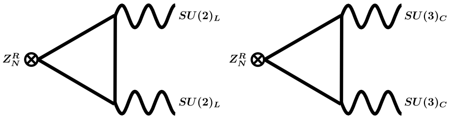
[Imamura, Watari, Yanagida '01; Kappl et al. 11; Dine & Monteux '14]

- Possibly remanant of continuous symmetry in higher dimensions.
- Remnant Z_N^R then gauged and not broken by gravitational interactions.

Which Z_N^R symmetry does the best job!?

Anomaly Constraints and Extra Matter Mulitplets

[Krauss & Wilczek '89; Ibanez & Ross '91, '92; Banks & Dine '92; Ibanez '93] [Green & Schwarz '84]



Z_N^R in general anomalous in the MSSM

- Color & weak anomaly coeffcients

$$\mathcal{A}_R^{(C)} \overset{(N)}{=} \mathcal{A}_R^{(L)} \overset{(N)}{=} -6$$

Extend MSSM to render Z_N^R anomaly-free

- String theory $\rightarrow$ Green-Schwarz mechanism.
- We stick to field theory $\rightarrow$ new matter fields.
- Complete $SU(5)$ reps to preserve unification,

$$Q_i \sim \mathbf{5}\,, \quad \bar{Q}_i \sim \mathbf{5}^*\,, \quad i = 1, 2, \cdots, k$$

- R charges such that $\Delta\mathcal{A}_R^{(C)} \overset{(N)}{=} \Delta\mathcal{A}_R^{(L)} \overset{(N)}{=} +6$,

$$k \times \left(r_Q + r_{\bar{Q}} - 2\right) \overset{(N)}{=} +6$$

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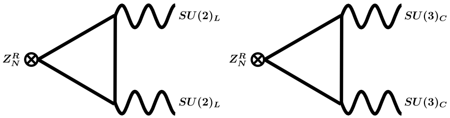

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Masses from coupling to ~~SUSY~~

- Couple $Q\bar{Q}$ to IYIT quarks,

$$W \supset \frac{c_Q}{M_{\rm Pl}} \Psi^1 \Psi^2 Q\bar{Q}$$

- In the EFT at low energies,

$$W_{\rm eff} \supset \frac{c_Q}{M_{\rm Pl}} \frac{\Lambda}{\eta} M_+ Q\bar{Q}$$

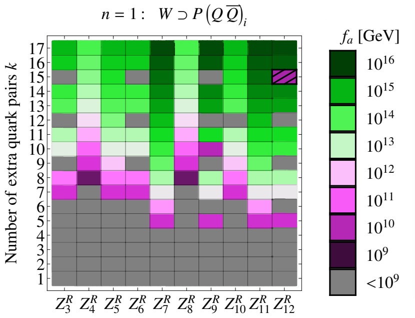
- Masses after ~~SUSY~~,

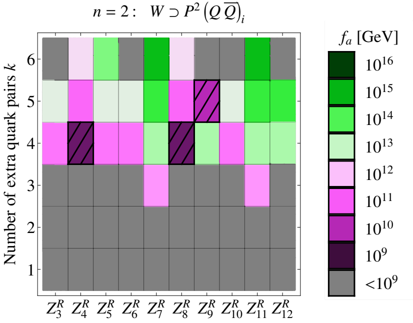
$$m_Q \simeq \frac{c_Q}{\eta^2} \frac{\Lambda}{M_{\rm Pl}} \Lambda \sim m_{3/2}$$

$\mathrm{PQ}\left[Q\bar{Q}\right] = -1 \to \mathcal{A}\left[U(1)_{\rm PQ}\text{–}SU(3)_C\text{–}SU(3)_C\right] = k \times (-1)$. KSVZ-like axion model!

Landscape of Possible Scenarios [Harigaya, Ibe, KS, Yanagida '13]

Systematic study of the PQ quality for arbitrary Z_N^R symmetry and arbitrary # of extra multiplets





- Here, no connection to SUSY breaking. $m_{3/2} = 1\,\mathrm{TeV}$ and f_a free parameter.
- PQ-breaking fields ($M_\pm$) assumed to be elementary $\rightarrow$ different power counting.
- Masses for the extra matter fields either generated by $M_+\left(Q\bar{Q}\right)$ or by $M_+^2\left(Q\bar{Q}\right)$.

Without any connection to ~~SUSY~~: Viable scenarios for any Z_N^R! How about our case now?

A Unique Z_4^R Symmetry for Pure Gravity Mediation

PGM requires a μ term of $\mathcal{O}\left(m_{3/2}\right)$ generated via a Higgs bilinear in the Kähler potential

[Giudice & Masiero '88; Inoue et al. '92; Casas & Munoz '93] [Evans et al. 13]

$$K \supset c_H\, H_u H_d \quad \rightarrow \quad \mu = c_H\, m_{3/2}\,, \quad c_H \simeq \mathcal{O}(1)$$

- Renders μ and B_μ linearly independent in PGM $\rightarrow$ successful radiative EWSB.
- μ term result of R symmetry breaking (down to Z_2^R) required to set the CC to zero.
- Only allowed for $r_{H_u} + r_{H_d} = 0 \mod N$. Meanwhile, any anomaly-free Z_N^R requires

  [Kurosawa, Maru, Yanagida '01; see also Evans et al. '12 as well as Harigaya, Ibe, KS, Yanagida '13]

$$r_{H_u} + r_{H_d} \overset{(N)}{=} 4 \quad \rightarrow \quad N = 4 \quad \text{unique choice for PGM!} \quad (N = 2 \text{ actually non-}R)$$

Particularly symmetric R charge assignment possible for $k = 5$ pairs of extra matter fields

10	**5***	**1**	$H_{u,d}$	Q	$\bar{Q}$	$\Psi^{1,2}$	$\Psi^{3,4}$	$Z_\pm$	Z_0	X
$1/5$	$-3/5$	1	$2\mp 2/5$	$2+1/5$	$-3/5$	$2+1/5$	$2-1/5$	$2\pm 2/5$	2	2

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Most dangerous PQ-breaking higher-dimensional operators remaining in the EFT

$$M_{\rm Pl}^{3-2k} \Lambda^k M_\pm^k\,, \quad M_{\rm Pl}^{3-k} Z_\pm^k \;(\text{even } k)\,, \quad M_{\rm Pl}^{2-k} X\, Z_\pm^k \;(\text{odd } k) \quad \left(\langle M_\pm \rangle \sim \Lambda\,, \quad \langle Z_\pm \rangle \sim m_{3/2}\right)$$

Now we are all set! So, $f_a \sim 10^{9\cdots12}\,\text{GeV}$ and $m_{3/2} \sim 100\,\text{TeV}$ OK while $\Delta\bar{\theta} \lesssim 10^{-10}$!?

Outline

Perturbative Gauge Coupling Unification

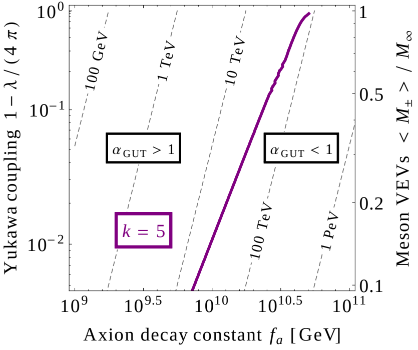
Extra **5**'s and **5***'s increase α_{GUT} at Λ_{GUT}

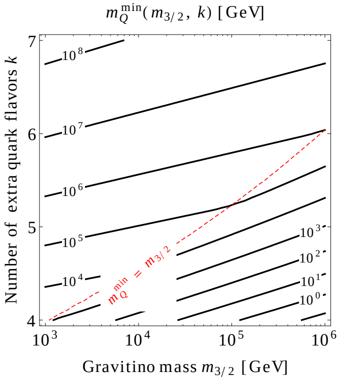
- For given k, lower bound on m_Q to ensure perturbative gauge coupling unification,

$$\alpha_{\mathrm{GUT}}\left(k, m_Q\right) \leq 1 \quad \text{for} \quad m_Q^{\min} \leq m_Q\,, \quad m_Q^{\min} = m_Q^{\min}\left(k, m_{3/2}\right)$$

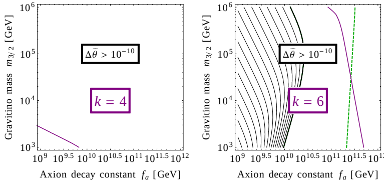
- Solve 2-loop RGEs for the SM gauge couplings; include SUSY thresholds

$$M_{\mathrm{gauginos}} \sim 1\,\mathrm{TeV}\,, \quad M_{\mathrm{heavy}} \sim m_{3/2}$$



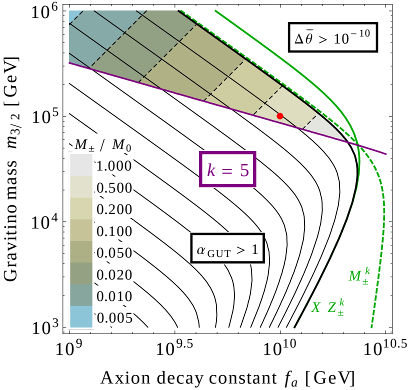


Constraints on Axion Decay Constant and Gravitino Mass



Unique number of extra multiplets!

- Only five **5**'s and **5***'s yield viable region in parameter space!
- $k \lesssim 4 \rightarrow$ PQ quality too bad.
- $k \gtrsim 6 \rightarrow$ Unification spoiled.



Rich phenomenology in the case $k = 5$

- Large Yukawa coupling required to suppress $M_\pm$ w.r.t. $M_0 \simeq \Lambda/\eta$,

$$M_\pm/M_0 \simeq \left[1 - (\lambda/4\pi)^2\right]^{1/2}$$

- For $m_{3/2} \sim 100\,\mathrm{TeV}$, one finds

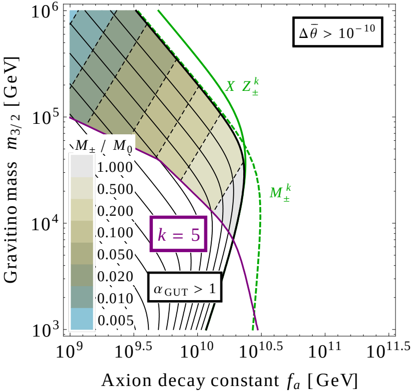
$$f_a \sim 10^{10}\,\mathrm{GeV}\,, \quad \Delta\bar{\theta} \sim 10^{-11}$$

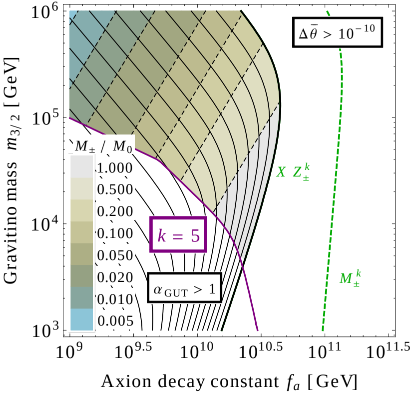
- SM rather strongly coupled around Λ_{GUT}. Hint at GUT dynamics!?
- DM mainly WIMPs (typically wino) plus subdominant axion contribution.

Uncertainties and Relaxed Parameter Constraints

$$m_Q \sim \frac{\Lambda^2}{M_{\rm Pl}} \to \frac{\Lambda^2}{\Lambda_{\rm GUT}}$$

$${M_{\rm Pl}}^{3-k}\mathcal{O}^k \to {M_*}^{3-k}\mathcal{O}^k\,, \quad M_* \gtrsim M_{\rm Pl}$$





- New GUT messengers $\Psi' \sim (\mathbf{5},\mathbf{2})$ under $G_{\rm SM} \times SU(2)$ with masses $M_{\Psi'} \sim \Lambda_{\rm GUT}$ and coupling $\Psi\Psi'\bar{Q}$.
- Effective cut-off scale M_* possibly $(8\pi)^{1/2} M_{\rm Pl}$ or $(4\pi)\, M_{\rm Pl}$ rather than reduced Planck mass $M_{\rm Pl} \sim 2 \times 10^{18}$.

Outline

Peccei-Quinn Mechanism from Dynamical SUSY Breaking

Shortcomings of the PQ mechanism: ① Quality of $U(1)_{\rm PQ}$!? ② Origin of $\Lambda_{\rm PQ}$!?

Idea: PQ related to dynamical ~~SUSY~~, $\Lambda_{\rm PQ} \sim \Lambda_{\rm SUSY} \sim \Lambda$, in the context of PGM.

- Minimal example: embed the PQ mechanism into the IYIT DSB model.
- Use anomaly-free Z_4^R to solve the μ problem and to protect the PQ symmetry.

Theoretical virtues:

- Pure gravity mediation (Higgs mass; unification; no Polonyi, gravitino, FCNC or ~~*CP*~~ problems); no dimensionful input scales; μ and strong *CP* problems solved; axion superpartners stabilized; no proton decay; VEV of the superpotential suppressed; ...

Phenomenlogical features:

- Axion decay constant $f_a \sim 10^{10}\,\mathrm{GeV}$, gravitino mass $m_{3/2} \sim 100\,\mathrm{TeV}$; $\Delta\bar{\theta}$ perhaps within experimental reach; mixed WIMP/axion dark matter; five new **5**'s and $\mathbf{5}^*$'s; ...

Next: DM / SUSY pheno; systematic study of Kähler corrections; other DSB models; ...

Appealing scenario that deserves further study and experimental scrutiny!

Thank you for your attention!