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Spontaneous CP violation and supersymmetry

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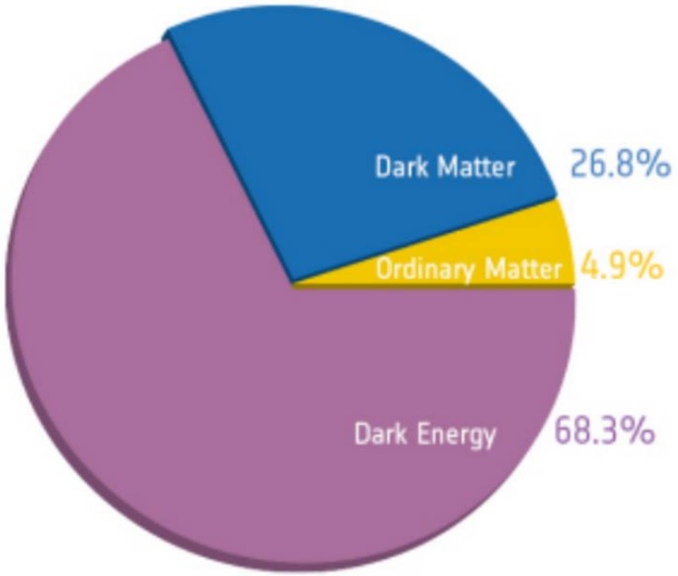
Problems in the Standard Model

- Dark matter
  - The most of the energy density of the matters come from unknown matter, called dark matter
    - Dark matter is stable, electrically neutral and non-relativistic when it decouples from the thermal bath
- Naturalness problem
  - Dark energy $\rho_\Lambda = \langle V_{\text{total}} \rangle \sim 10^{-120} M_{\text{PL}}^4$
  - The electroweak symmetry breaking scale $m_h^2 \sim 10^{-33} M_{\text{PL}}^2$
  - The strong CP problem $\bar{\theta} < \mathcal{O}(10^{-10}) \ll 1$
- Finite neutrino masses
- Baryon asymmetry of the universe



ESA and the Planck Collaboration

Strong CP problem

- The theta-parameter in QCD is required to be smaller than $O(10^{-10})$, which is clearly unnatural

$$\mathcal{L} = \frac{\bar{\theta}}{64\pi^2}\epsilon^{\mu\nu\rho\sigma}G_{\mu\nu}G_{\rho\sigma} \qquad \bar{\theta} = \theta_0 + \arg\det(m_u) + \arg\det(m_d)$$

expected to be $O(1)$

- Axion solution needs a UV completion beyond the commonly known models (KSVZ/DSFZ)
  - To solve the strong CP problem, the Peccei-Quinn symmetry must be broken at quantum level but it should be classically exact (even Planck suppressed operators are not allowed)
  - Classically exact global symmetry, which must be broken at quantum level, is a real symmetry?
  - It looks inconsistent with quantum gravity

- As another direction, spontaneous CP violation (SCPV) may be attractive
  - In supersymmetric theory, because there are no axino and saxion, SCPV may be easier to be realized from the view point of cosmology

Spontaneous CP violation (Nelson-Barr mechanism)

- The CP is exact symmetry (possibly from gauge symmetry)
  - $\theta_0 = 0$ and $\bar{\theta} = 0$ at the tree-level even after the CP symmetry is spontaneously broken

- The quark mass matrix is extended to include a heavy vector-like quark
  - The CKM phase is induced
  - $\det(m_d)$ is still real

- It needs supersymmetry (or something) to stabilize the potential for a new Higgs field, which breaks CP symmetry spontaneously
  - Otherwise the fine-tuning is severer than the tuning of $\bar{\theta} \approx 0$

[Nerson, 1984; Barr, 1984]

Bento-Branco-Parada model (non-supersymmetric)

- All the parameters in the Lagrangian are real
- The new Higgs field S has a complex VEV $\langle S \rangle = v_S e^{i\alpha}$
- The Lagrangian is controlled with additional Z_2 symmetry, where new fields (S, D_L, D_R) have odd charge

$$
\begin{aligned}
V \quad &= \quad V_0(H,S) + (\mu_S^2 + \lambda_1 |S|^2 + \lambda_2 |H|^2)\underbrace{(S^2 + S^{*2})}_{\propto \cos 2\alpha} \\
&+ \quad \lambda_3 \underbrace{(S^4 + S^{*4})}_{\propto \cos 4\alpha}
\end{aligned}
$$

α is non-zero in general and CP is spontaneously broken

Due to spontaneously broken Z_2 symmetry, the domain walls can be formed

$\Rightarrow$ upper-bound on the maximum temperature of the universe

[Bento, Branco, Parada, 1991]

Bento-Branco-Parada model

- The heavy quark ($SU(2)$ singlet) is introduced to generate the CKM phase

$$-\mathcal{L} \ni \left[\overline{Q_L^i} \underbrace{y_{ij} \langle H \rangle}_{m_{dij}} d_R^j + (\underbrace{f_i \langle S \rangle + f_i' \langle S^* \rangle}_{M_{Di}})\overline{D_L} d_R^i + \mu_D \overline{D_L} D_R\right] + h.c.$$

$$\mu_D \sim M_D \gg m_d$$

$$\mathcal{M}_d = \begin{pmatrix} m_d & 0 \\ M_D & \mu_D \end{pmatrix} \Rightarrow \det(\mathcal{M}_d) = \det(m_d)\mu_D = \text{real} \Rightarrow \bar{\theta} = 0$$

complex

$$U_L^\dagger \mathcal{M}_d U_R = \begin{pmatrix} \bar{m} & \\ & \bar{M} \end{pmatrix} \quad \bar{m} = \text{diag}(m_d, m_s, m_b) \qquad \bar{M} \sim \mu_D \sim M_D$$

$$U_L^\dagger \mathcal{M}_d \mathcal{M}_d^\dagger U_L = U_L^\dagger \left(\begin{array}{cc} m_d m_d^\dagger & m_d M_D^\dagger \\ M_D m_d^\dagger & \mu_D^2 + M_D M_D^\dagger \end{array} \right) U_L$$

$$\underline{\mu_D \sim M_D \gg m_d}$$

$$U_R^\dagger \mathcal{M}_d^\dagger \mathcal{M}_d U_R = U_R^\dagger \left(\begin{array}{cc} m_d^\dagger m_d + M_D^\dagger M_D & M_D^\dagger \mu_D \\ \mu_D M_D & \mu_D^2 \end{array} \right) U_R$$

$$U_L = \left(\begin{array}{cc} V_{\rm CKM} & \cdots \\ \cdots & \cdots \end{array} \right)$$

V_{CKM} is approximately unitary and has a complex phase
(U_R has a large mixing)

$$V_{CKM} \bar{m}^2 V_{CKM}^{-1} \approx m_d m_d^\dagger - \underbrace{m_d M_D^\dagger M_D m_d^\dagger / (\mu_D^2 + M_D M_D^\dagger)}_{\text{unsuppressed}}$$

Problems in BBP model

$$(k_S S^2 + k'_S S^{*2}) M_P^{-1} \overline{D_L} D_R$$

$$(h_i S + h'_i S^*) M_P^{-1} \overline{Q_L^i} H D_R \qquad M_P \approx 2.4 \times 10^{18}\,\mathrm{GeV}$$

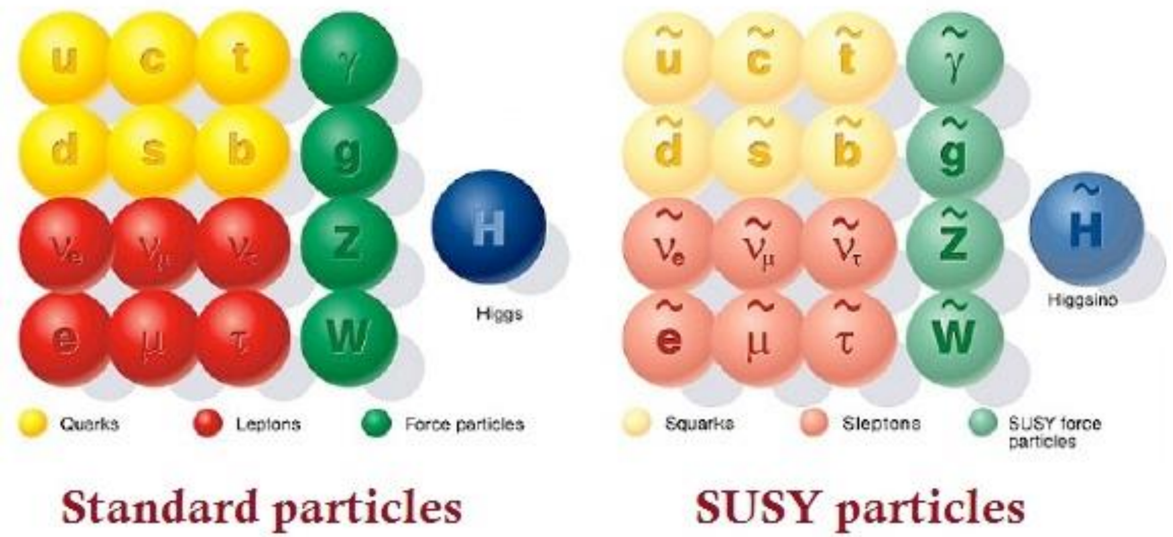
$\mathcal{M}_d$ is modified with the operators

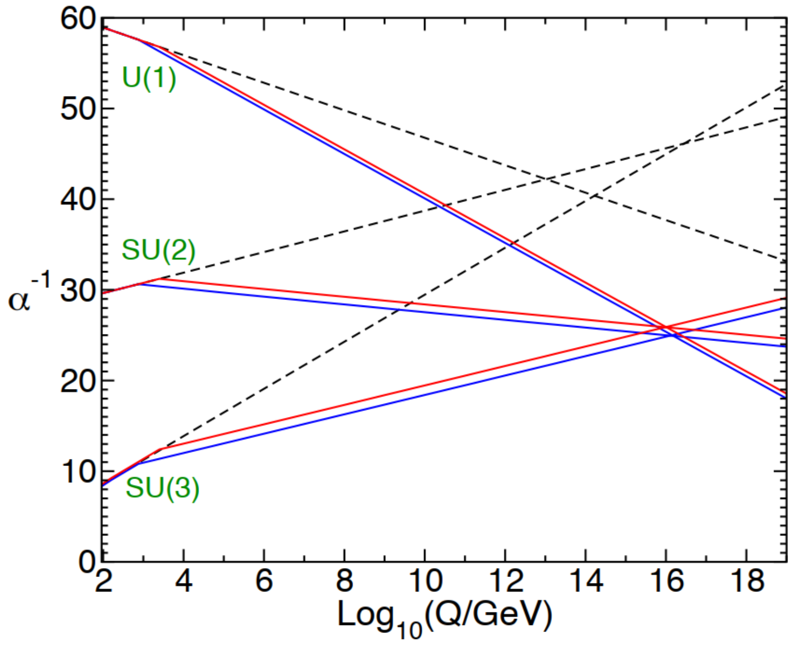
$$\Delta\bar{\theta} = \arg\det\mathcal{M}_d \lesssim 10^{-10} \quad \Rightarrow \quad \langle S \rangle \lesssim 10^8\,\mathrm{GeV}$$

- Hierarchy problem: $< H >^2 \ll < S >^2 \ll M_P^2$
- The maximal temperature should be smaller than 10^8 GeV to avoid the formation of the domain walls ⇒ tension with thermal leptogenesis

Supersymmetry

- It is an exchange symmetry between bosons and fermions
- Any hierarchy problems concerning scalar fields are solved
- Consistent with grand unified theories, explaining charge quantization





[A Supersymmetry Primer, Martin, 1997]

Supersymmetric model for SCPV

$$W = y_{ij} q_i H_d \bar{d}_j + Y_{\alpha,i} \eta_\alpha D \bar{d}_i + \mu_D D \bar{D}$$

$\alpha = 1, 2$

$\langle \eta_\alpha \rangle \sim \mu_D$ is assumed

To generate the CKM phase, we need two Higgs fields for spontaneous CP breaking (due to the holomorphy)

$$W_{CPV} = \lambda_1 Y_1 (\eta_1^2 - v_1^2) + \lambda_2 Y_2 (\eta_2^2 + v_2^2)$$

We introduce matter multiplets as SU(5) multiplets

$$\boxed{\mathbf{10}_i = (q_i,\, \bar{u}_i,\, \bar{e}_i) \qquad \overline{\mathbf{5}}_i = (\bar{d}_i,\, l_i)}$$

MSSM multiplets

$$\overline{\mathbf{5}}' = (\bar{D},\, L) \qquad \mathbf{5}' = (D,\, \bar{L})$$

[Evans, Han, Yanagida, **NY**, 2021]

To impose a non-anomalous discrete symmetry, we use a linear combination of $U(1)_Y$ and $U(1)_{B-L}$, $U(1)'$, with a charge

$$Q' = 5Q_{B-L} - 4Q_Y$$

$$Q'(\mathbf{10}_i) = 1,\ Q'(\bar{\mathbf{5}}_i) = -3,\ Q'(\bar{N}_i) = 5,\ Q'(H_u) = -2,\ Q'(H_d) = 2$$

For new fields, they are introduced as vector-like multiplets

$$Q'(\mathbf{5}') = 1,\ Q'(\bar{\mathbf{5}}') = -1 \quad Q'(\eta_1) = 2,\ Q'(\eta_2) = -2$$

Z_4 symmetry allows $\quad W_{CPV} = \lambda_1 Y_1(\eta_1^2 - v_1^2) + \lambda_2 Y_2(\eta_2^2 + v_2^2)$

The Majorana mass terms for the right-handed neutrinos are generated through

$\lambda_{\alpha,ij}\eta_\alpha \bar{N}_i \bar{N}_j \Longrightarrow$ seesaw and leptogenesis

[Leptogenesis: Fukugita, Yanagida, 1986]

Problematic operators

- We may forbid problematic operators

$$\frac{k_{\alpha\beta}\eta_\alpha\eta_\beta}{M_P} D\bar{D}, \quad \frac{k_{i\alpha}\eta_\alpha}{M_P} Q_i H_d \bar{D}$$

$\det \mathcal{M}_d$ is not real anymore. Therefore, it they exist

$$\arg\det \mathcal{M}_d \lesssim \mathcal{O}(10^{-10}) \quad \Rightarrow \quad \langle \eta_{1,2} \rangle \lesssim \mathcal{O}(10^8)\,\mathrm{GeV}$$

- One way is to just accept it. At least, supersymmetry protects $\langle H_{u,d} \rangle \ll \langle \eta_{1,2} \rangle \ll M_P$
- Or we can consider another symmetry to forbid the dangerous operators
  - Conceptually, the symmetry should be exact one, i.e., it should not have anomalies

Non anomalous discrete R-symmetry

- R-symmetry is a characteristic symmetry in supersymmetric theory
- It partly explains the smallness of the cosmological constant
- Non anomalous R-symmetry can be a real symmetry, which can be gauged

Non anomalous discrete R-symmetry

Non-anomalous discrete R-symmetry requires

$$Q_{Z_{NR}}(H_u) + Q_{Z_{NR}}(H_d) = 4 \quad \text{mod } N$$

[Kurosawa, Maru, Yanagida, 2001]

$$Q_{Z_{NR}}(D) + Q_{Z_{NR}}(\bar{D}) = 8 \quad \text{mod } N$$

Z_{NR} can be a gauge symmetry

It turns out Z_{4R} forbids problematic operators

$$\mu_D D\bar{D} = k_S \langle \Phi \rangle D\bar{D} \Leftarrow \langle W \rangle = \left\langle \mu_\Phi^2 \Phi - \frac{\lambda_\Phi}{3} \Phi^3 \right\rangle$$

Required to explain the small cosmological constant (dark energy)

Non anomalous discrete R-symmetry

Non-anomalous discrete R-symmetry requires

$$Q_{Z_{NR}}(H_u) + Q_{Z_{NR}}(H_d) = 4 \mod N$$

[Kurosawa, Maru, Yanagida, 2001]

$$Q_{Z_{NR}}(D) + Q_{Z_{NR}}(\bar{D}) = 8 \mod N$$

Z_{NR} can be a gauge symmetry

It turns out Z_{4R} forbids problematic operators

$$W \ni \mu H_u H_d = \lambda_H \langle \Phi_H \rangle H_u H_d$$

$$\left(W \ni \frac{\kappa}{3} \Phi_H^3 \right)$$

The Higgs sector should have a NMSSM like structure

Requirements for SUSY breaking mass parameters

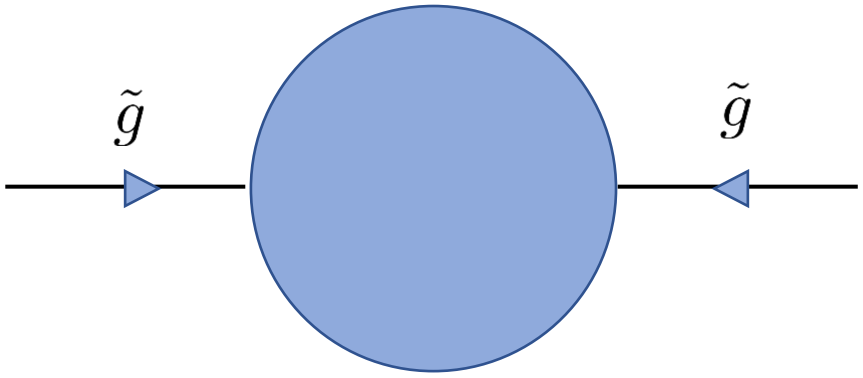
- We need to be careful about radiatively generated mass parameters for strongly interacting fermions
- It contributes to the theta parameter through chiral anomalies
- The complex arguments of mass parameters of strongly interacting fermions should be smaller than $O(10^{-10})$

the superpartner of the gluon

We need to check the quark mass matrix and gluino mass

Requirements for SUSY breaking mass parameters

For instance, the gluino mass receives a correction



$$\propto \sum_i \sum_{\alpha,\beta} Y_{i\alpha} \langle \eta_\alpha^* \rangle A_{i\beta} Y_{i\beta} \langle \eta_\beta \rangle$$ x loop factor

Soft SUSY breaking parameter

Without a special assumption, $A_{i1} \neq A_{i2}$

It gives a complex mass to the gluino

$\mathrm{Arg}(m_{\tilde{g}}) < \mathcal{O}(10^{-10})$ needs to be satisfied

An order parameter of SUSY breaking divided by M_P ~ gravitino mass

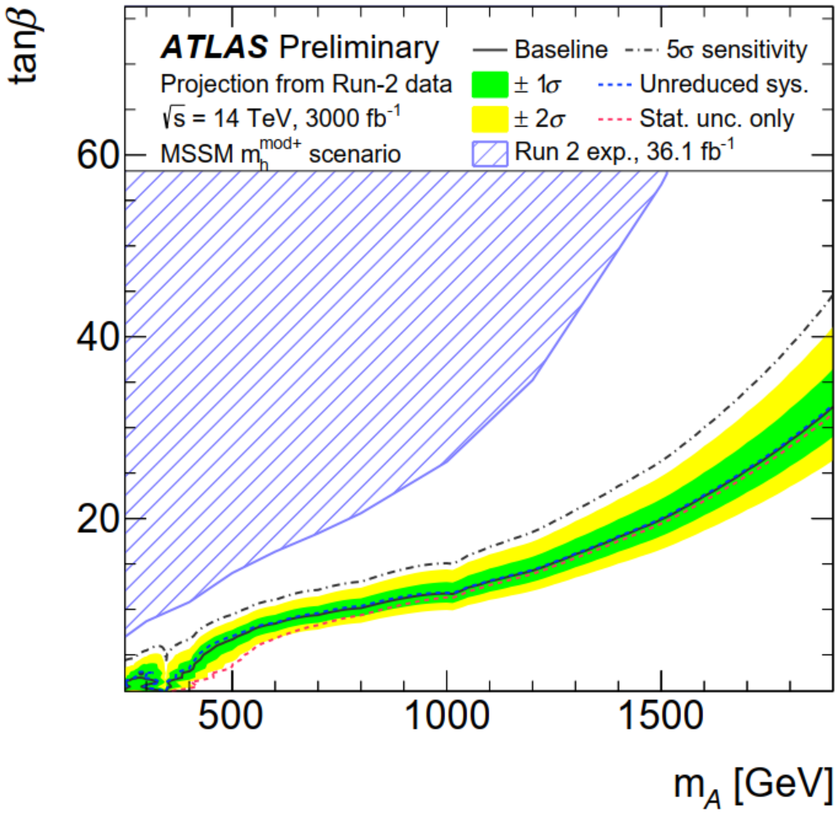
We focus on the case with the small gravitino mass: $m_{3/2} = \mathcal{O}(10)\,\mathrm{keV}$

The gravitino is a dark matter candidate

Heavy Higgs search

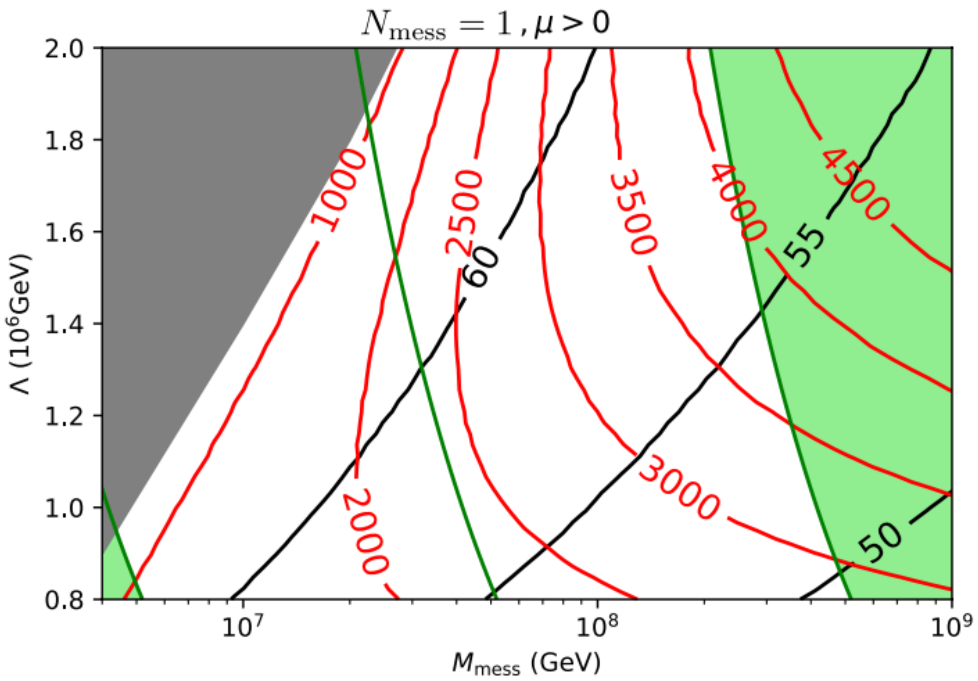
- With such a small gravitino mass, large tanβ and relatively light **heavy Higgs bosons** tend to be predicted

Prospect



[ATL-PHYS-PUB-2018-050 (ATLAS note)]

Prediction of the heavy Higgs mass



[Choi, Yanagida, NY, 2021]

Summary

- The strong CP problem is an important problem and the solutions can lead us to a more fundamental physics beyond the Standard Model
- The axion solution requires a unnatural chiral (PQ) symmetry: it should be classically exact but it needs to be broken at quantum level (by anomaly)
- The spontaneous CP violation is alternative way to solve the strong CP problem, which may be easier to understand
- Supersymmetric model of spontaneous CP violation leads to a robust framework
- The gravitino is a dark matter candidate
- The model can be checked at the LHC through heavy Higgs searches, even if other SUSY particles are too heavy