Axion properties in GUTs

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[Ernst, AR, Tamarit, arXiv:1801.04906; Di Luzio, AR, Tamarit, arXiv:1807.09769]
Motivation

- Non-observation of WIMPs at LHC and in direct detection dark matter (DM) experiments strong motivation to look into other DM candidates
- Axion strongly motivated since it solves in addition strong CP problem
- New experiments search for the axion in a wide mass range. Would profit very much if mass were known.

• However:
  • Solution of DM problem does not fix axion decay constant and thus not the mass
  • Axion solves strong CP problem for any decay constant and thus any mass
  • Strong motivation to consider UV completions of the SM in which decay constant predicted
  • Here: Non-SUSY Grand Unified Theories (GUTs)
Axion in non-SUSY SO(10) GUT

The virtue of imposing a Peccei-Quinn symmetry

- Gauge coupling unification needs at least one intermediate scale; often discussed SSB chain:

\[
SO(10) \xrightarrow{M_{V}} SU(4)_C \times SU(2)_L \times SU(2)_R \\
\xrightarrow{M_{BL}} SU(3)_C \times SU(2)_L \times U(1)_Y \\
\xrightarrow{M_Z} SU(3)_C \times U(1)_{em}
\]

[Ernst, AR, Tamarit, arXiv:1801.04906]

[Di Luzio ’11]
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The virtue of imposing a Peccei-Quinn symmetry

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  \[
  SO(10) \xrightarrow{M_{12}^{210H}} SU(4)_C \times SU(2)_L \times SU(2)_R
  \]
  \[
  \xrightarrow{M_{12}^{126H}} SU(3)_C \times SU(2)_L \times U(1)_Y
  \]
  \[
  \xrightarrow{M_{12}^{10H}} SU(3)_C \times U(1)_{em}
  \]

- SO(10) GUT with three copies of $16_F$: automatically features
  - neutrino masses and mixing
  - baryogenesis via leptogenesis

| SO(10)     | $4C^2_{2L}2_R$ | $4C^2_{2L}1_R$ | $3C^2_{1L}1_R1_B$ | $3C^2_{1L}1_Y$ | scale |
|------------|---------------|---------------|-------------------|---------------|-------|
| $16_F$     | (4, 2, 1)     | (4, 2, 0)     | (3, 2, 0, $\frac{1}{2}$) | (1, 2, 0, $-\frac{1}{2}$) | $M_Z$ |
| $4_{1,2}$  | (4, 1, 2)     | (3, 1, $\frac{1}{2}$) | (1, 1, $\frac{1}{2}$) | (1, 1, $-\frac{1}{2}$) | $M_Z$ |
| $16_F$     | (4, 1, $-\frac{1}{2}$) | (3, 1, $-\frac{1}{2}$) | (1, 1, $-\frac{1}{2}$) | (1, 1, 0) | $M_{E_L}$ |

- Most general Yukawas:
  \[
  \mathcal{L}_Y = 16_F \left( Y_{10}10^H_H + \tilde{Y}_{10}10^*_{\tilde{H}} + Y_{126126_H} \right) 16_F
  \]

- SSB vevs:
  \[
  v_L \equiv \langle (10, 3, 1)_{126} \rangle, \quad v_R \equiv \langle (10, 1, 3)_{126} \rangle,
  \]
  \[
  v_{u,d}^{10} \equiv \langle (1, 2, 2)_{u,d}^{10} \rangle, \quad v_{u,d}^{126} \equiv \langle (15, 2, 2)_{u,d}^{126} \rangle
  \]

- Fermion masses/mixing:
  \[
  M_u = Y_{10}v_{u}^{10} + \tilde{Y}_{10}v_{d}^{10*} + Y_{126}v_{u}^{126},
  \]
  \[
  M_d = Y_{10}v_{d}^{10} + \tilde{Y}_{10}v_{u}^{10*} + Y_{126}v_{d}^{126},
  \]
  \[
  M_e = Y_{10}v_{d}^{10} + \tilde{Y}_{10}v_{u}^{10*} - 3Y_{126}v_{d}^{126},
  \]
  \[
  M_D = Y_{10}v_{u}^{10} + \tilde{Y}_{10}v_{d}^{10*} - 3Y_{126}v_{u}^{126},
  \]
  \[
  M_R = Y_{126}v_R,
  \]
  \[
  M_L = Y_{126}v_L.
  \]
Axion in non-SUSY SO(10) GUT

The virtue of imposing a Peccei-Quinn symmetry

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  \[ SO(10) \rightarrow SU(4)_C \times SU(2)_L \times SU(2)_R \]
  \[ \rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y \]
  \[ \rightarrow SU(3)_C \times U(1)_{em} \]
  
- SO(10) GUT with three copies of \( 16_F \) automatically features
  - neutrino masses and mixing
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- PQ extension adds
  - predictivity of fermion masses/mixing
  - solution of strong CP problem
  - DM candidate: axion

\[ [\text{Bajc et al. 06; Altarelli,Meloni 13; Babu,Khan 15}] \]

- PQ symmetry imposed:
  \[ 16_F \rightarrow 16_F e^{i\alpha} , \]
  \[ 10_H \rightarrow 10_H e^{-2i\alpha} , \]
  \[ \overline{126}_H \rightarrow \overline{126}_H e^{-2i\alpha} , \]
  \[ 210_H \rightarrow 210_H e^{4i\alpha} \]

- Most general Yukawas:
  \[ \mathcal{L}_Y = 16_F \left( Y_{10}^{10H} + Y_{126}^{126H} \right) 16_F + \text{h.c.} \]

- SSB vevs:
  \[ v_L \equiv \langle (10,3,1)_{126} \rangle , \quad v_R \equiv \langle (10,1,3)_{126} \rangle , \]
  \[ v_{u,d}^{10} \equiv \langle (1,2,2)_{u,d}^{10} \rangle , \quad v_{u,d}^{126} \equiv \langle (15,2,2)_{u,d}^{126} \rangle \]

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  \[ M_d = Y_{10} v_d^{10} + Y_{126} v_d^{126} , \]
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Axion in non-SUSY SO(10) GUT

Axion predictions and experimental prospects

- Axion decay constant:
  \[ f_A \simeq \frac{1}{3} \frac{M_U}{g_U} \]

- From gauge coupling unification, assuming minimal scalar threshold corrections:
  \[ m_A \equiv \frac{\sqrt{\lambda}}{f_A} \simeq 0.74 \text{ neV} \]

\[ M_U = 1.4 \times 10^{16} \text{ GeV}, \quad \alpha_U(M_U)^{-1} = 33.6 \]

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- Taking into account scalar threshold corrections and constraints from black hole superradiance and proton decay:
  \[ 0.02 \text{ neV} < m_A < 2.2 \text{ neV} \]

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[Ernst 18; CASPER prospects from Kimball et al. 17]
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[Ernst 18; ABRACADABRA prospects from Kahn, Safdi, Thaler 16]
Axion in non-SUSY SU(5) GUT

A minimal GUT

- Original non-SUSY SU(5) model comprised of [Georgi, Glashow 74]
  - three copies of $10_F$ and $\bar{5}_F$, representing chiral SM matter fermions
  - $24_H$ and $5_H$, representing Higgs bosons
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  - Neutrinos massless
  - No gauge coupling unification

[Georgi, Glashow 74]

[StackExchange]
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fails phenomenologically:

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- Simple solution: add a $24_F$ [Bajc, Senjanovic 07]

  - Mixture of type-I and type-III seesaw from electroweak fermion singlets and triplets, $S_F = (1, 1, 0)_F$ and $T_H = (1, 3, 0)$
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  - Gauge coupling unification: electroweak fermion and scalar triplets, $T_F = (1, 3, 0)$ and $T_H = (1, 3, 0)$, delay meeting of $\alpha_1$ and $\alpha_2$
  - Clean correlation between effective electroweak triplet mass $m_3$ and unification scale $M_G$

\[
m_3 = \left( m_{TF}^4 m_{TH} \right)^{1/5}
\]
Axion in non-SUSY SU(5) GUT

Axion in minimal GUT and experimental prospects

- Require that $24_H$ complex and add $5'_H$
- Impose PQ symmetry:
  \[
  \begin{align*}
  \bar{5}_F & \to e^{-i\alpha/2}\bar{5}_F, \\
  10_F & \to e^{-i\alpha/2}10_F, \\
  5_H & \to e^{i\alpha}5_H, \\
  5'_H & \to e^{-i\alpha}5'_H, \\
  24_H & \to e^{-i\alpha}24_H, \\
  24_F & \to e^{-i\alpha/2}24_F
  \end{align*}
  \]
- Axion decay constant:
  \[f_A \approx \frac{1}{11} \sqrt{\frac{6}{5}} \frac{M_G}{g_5}\]
- Gauge coupling unification, taking into account LHC and Superkamiokande constraints:
  \[m_A \in [4.8, 6.6] \text{ neV}\]

[Di Luzio, AR, Tamarit, arXiv:1807.09769]
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  10_F \rightarrow e^{-i\alpha/2} 10_F, \\
  5_H \rightarrow e^{i\alpha} 5_H, \\
  5'_H \rightarrow e^{-i\alpha} 5'_H, \\
  24_H \rightarrow e^{-i\alpha} 24_H, \\
  24_F \rightarrow e^{-i\alpha/2} 24_F
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- Window can be explored by axion DM experiments

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- Require that $24_H$ complex and add $5'_H$
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  \[ 10_F \rightarrow e^{-i\alpha/2}10_F, \]
  \[ 5_H \rightarrow e^{i\alpha}5_H, \]
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Axion in non-SUSY SU(5) GUT

Minimal GUT SMASH?

- PQ symmetry has to be broken during and after inflation to avoid
  - SU(5) monopole problem
  - axion DM overabundance
- DM abundance depends not only on mass, but also on the initial value of $\theta_i = \Lambda_i/f_A$ inside causally connected region which is inflated to observable universe
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- DM abundance depends not only on mass, but also on the initial value of $\theta_i = A_i/f_A$ inside causally connected region which is inflated to observable universe:

$$\Omega_a h^2 = 0.12 \left( \frac{5.0 \text{ meV}}{m_a} \right)^{1.165} \left( \frac{\theta_i}{1.6 \times 10^{-2}} \right)^2$$

[Image of graph showing the relationship between $f_A$ and $\Omega_A > \Omega_{CDM}$ vs $m_A$, with pre-inflation misalignment range and post-inflation misalignment range marked]

[Borsanyi et al. '16]
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  \]
- Non-minimal chaotic \( 24_H \) inflation
  \[
  S \supset - \int d^4x \sqrt{-g} \xi_{24_H} \text{Tr}(24^2_H) R
  \]
  - For small enough quartic and Yukawa couplings, PQ symmetry after inflation may be avoided
  - Isocurvature constraints avoided if \( \xi_{24_H} \gtrsim 0.01 \)

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**SM * Axion * See-saw * Higgs portal inflation**

[Ballesteros, Redondo, AR, Tamarit '16]
Conclusions and outlook

- Realistic non-SUSY $SO(10) \times U(1)_{PQ}$ and $SU(5) \times U(1)_{PQ}$ models addressing both neutrino masses and gauge coupling unification predict the axion mass in a window which is accessible in the upcoming axion DM direct detection experiments (ABRACADABRA, CASPER-Electric)

- Precise determination of axion mass would lead to direct determination of GUT scale, possibly discriminating different GUT models and setting target for proton decay measurements

- Intriguing possibility that the Higgs field required for GUT breaking may be responsible for inflation, realizing non-minimal chaotic inflation, making the $SO(10) \times U(1)_{PQ}$ and $SU(5) \times U(1)_{PQ}$ model a potential candidate for a GUT SMASH variant, aiming at a self-contained (but highly fine-tuned) description of particle physics, from the electroweak scale to the Planck scale, and cosmology, from inflation to today
Back Up: Axion/ALP bounds from BH superradiance

- If ALP Compton wavelength of order black hole size:
  - Bound states around BH nucleus formed
  - Occupation numbers grow exponentially by extracting rotational energy and angular momentum from the ergosphere
  - Forming rotating Bose-Einstein condensate emitting gravitational waves
  - For BH lighter than $10^7$ solar masses, accretion cannot replenish spin
- Existence of bosonic WISPs leads to gaps in mass vs. spin plots of rapidly rotating BHs

[Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell 10]
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  • For BH lighter than 10^7 solar masses, accretion can not replenish spin
• Existence of bosonic WISPs leads to gaps in mass vs. spin plots of rapidly rotating BHs
• Stellar BH spin measurements exclude

\[ 6 \times 10^{-13} \text{ eV} < m_A < 2 \times 10^{-11} \text{ eV} \]

[Arvanitaki et al. 14]