Axion properties in GUTs

Andreas Ringwald
Corfu Summer Institute
Workshop on the Standard Model and Beyond
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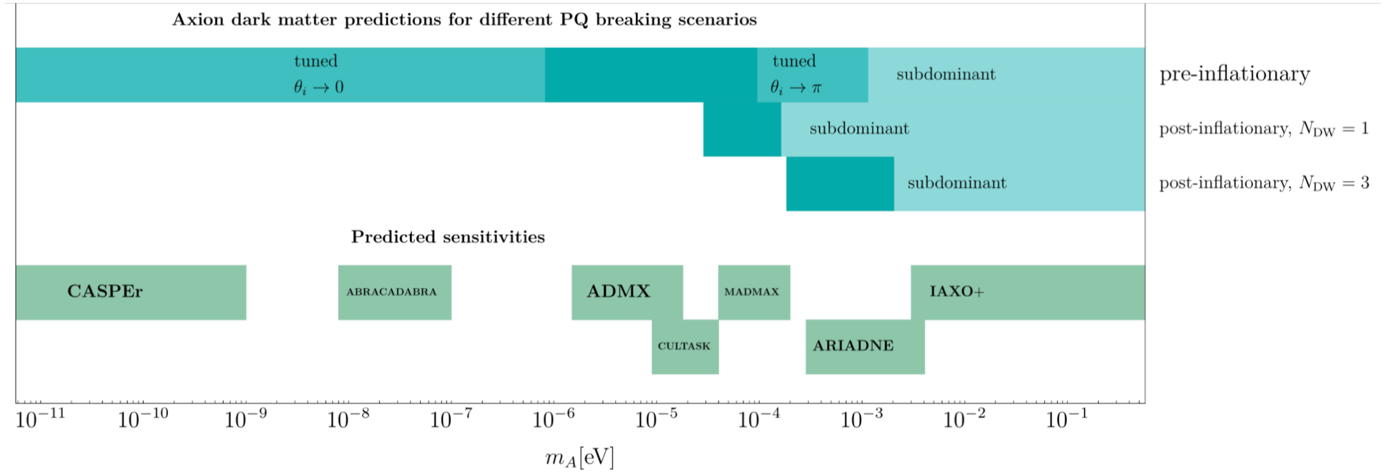
[Ernst, AR, Tamarit, arXiv:1801.04906; Di Luzio, AR, Tamarit, arXiv:1807.09769]

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

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

$$m_A = 57.0(7)\left(\frac{10^{11}\,\mathrm{GeV}}{f_A}\right)\mu\mathrm{eV}$$

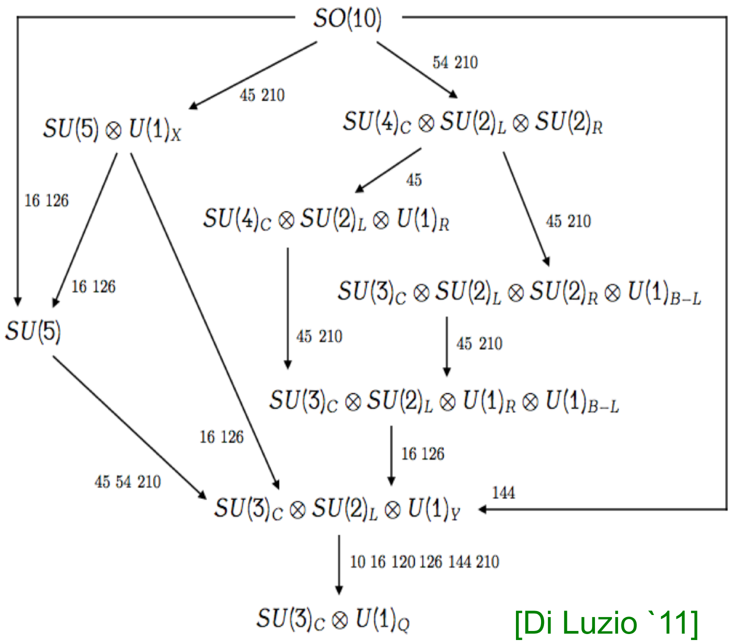
- Strong motivation to consider UV completions of the SM in which decay constant predicted
- Here: Non-SUSY Grand Unified Theories (GUTs)

Axion in non-SUSY SO(10) GUT

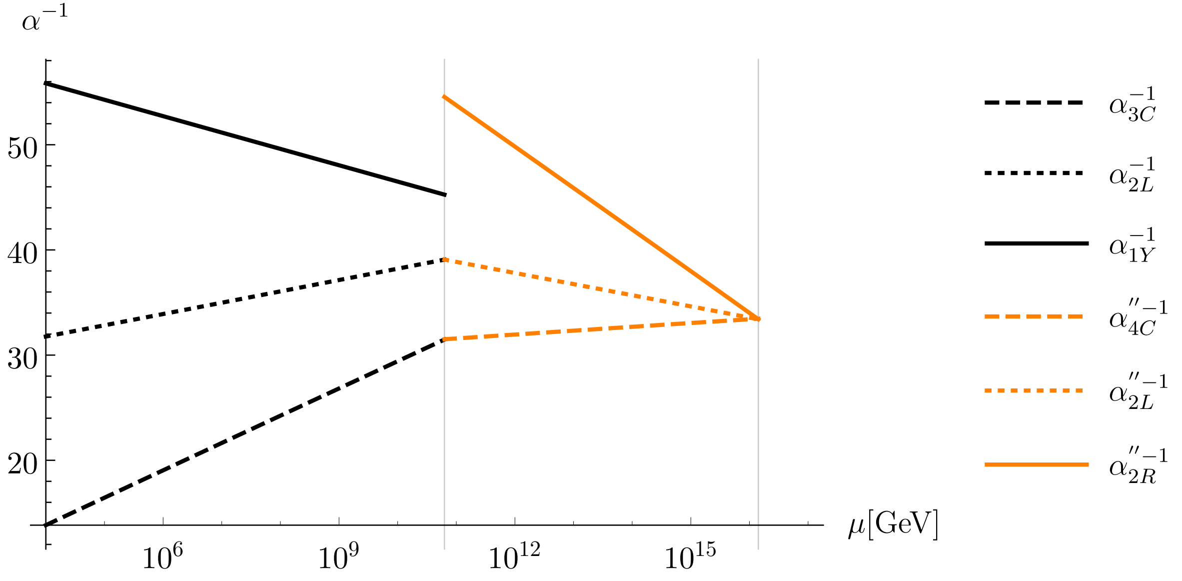
The virtue of imposing a Peccei-Quinn symmetry

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

$$\begin{aligned} SO(10) &\xrightarrow{M_{\mathrm{U}}-210_H} SU(4)_C \times SU(2)_L \times SU(2)_R \\ &\xrightarrow{M_{\mathrm{BL}}-126_H} SU(3)_C \times SU(2)_L \times U(1)_Y \\ &\xrightarrow{M_Z-10_H} SU(3)_C \times U(1)_{\mathrm{em}} \end{aligned}$$



[Di Luzio `11]



[Ernst, AR, Tamarit, arXiv:1801.04906]

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

$SO(10)$	$4_C 2_L 2_R$	$4_C 2_L 1_R$	$3_C 2_L 1_R 1_{B-L}$	$3_C 2_L 1_Y$	scale
16_F	$(4,2,1)$	$(4,2,0)$	$(3,2,0,\frac{1}{3})$	$(3,2,\frac{1}{6}) := Q$	M_Z
			$(1,2,0,-1)$	$(1,2,-\frac{1}{2}) := L$	M_Z
	$(\bar{4},1,2)$	$(\bar{4},1,\frac{1}{2})$	$(\bar{3},1,\frac{1}{2},-\frac{1}{3})$	$(\bar{3},1,\frac{1}{3}) := d$	M_Z
			$(1,1,\frac{1}{2},1)$	$(1,1,1) := e$	M_Z
		$(\bar{4},1,-\frac{1}{2})$	$(\bar{3},1,-\frac{1}{2},-\frac{1}{3})$	$(\bar{3},1,-\frac{2}{3}) := u$	M_Z
			$(1,1,-\frac{1}{2},1)$	$(1,1,0) := N$	$M_{\rm BL}$

- Most general Yukawas:

$$
\mathcal{L}_Y = 16_F \left(Y_{10} 10_H + \tilde{Y}_{10} 10_H^* + Y_{126} \overline{126}_H \right) 16_F
$$

- SSB vevs:

$$
v_L \equiv \langle (\overline{10},3,1)_{126} \rangle \,, \qquad v_R \equiv \langle (10,1,3)_{126} \rangle \,,
$$

$$
v_{u,d}^{10} \equiv \langle (1,2,2)_{u,d}^{10} \rangle \,, \qquad v_{u,d}^{126} \equiv \langle (15,2,2)_{u,d}^{126} \rangle
$$

- Fermion masses/mixing:

$$
\begin{aligned}
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^*} - 3 Y_{126} v_d^{126} \,, \\
M_D &= Y_{10} v_u^{10} + \tilde{Y}_{10} v_d^{10^*} - 3 Y_{126} v_u^{126} \,, \\
M_R &= Y_{126} v_R \,, \\
M_L &= Y_{126} v_L \,.
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- SO(10) GUT with three copies of 16_F automatically features
  - neutrino masses and mixing
  - baryogenesis via leptogenesis
- PQ extension adds
  - predictivity of fermion masses/mixing
  - solution of strong CP problem
  - DM candidate: axion

[Bajc et al. 06; Altarelli,Meloni 13; Babu,Khan 15]

- PQ symmetry imposed:

$$\begin{aligned} 16_F &\to 16_F e^{i\alpha}, \\ 10_H &\to 10_H e^{-2i\alpha}, \\ \overline{126}_H &\to \overline{126}_H e^{-2i\alpha}, \\ 210_H &\to 210_H e^{4i\alpha} \end{aligned}$$

- Most general Yukawas:

$$\mathcal{L}_Y = 16_F \left(Y_{10} 10_H + Y_{126} \overline{126}_H \right) 16_F + \text{h.c.}$$

- SSB vevs:

$$v_L \equiv \left\langle (\overline{10},3,1)_{126} \right\rangle , \qquad v_R \equiv \left\langle (10,1,3)_{126} \right\rangle ,$$
$$v^{10}_{u,d} \equiv \left\langle (1,2,2)^{10}_{u,d} \right\rangle , \qquad v^{126}_{u,d} \equiv \left\langle (15,2,2)^{126}_{u,d} \right\rangle$$

- Fermion masses/mixing:

$$\begin{aligned} M_u &= Y_{10} v_u^{10} + Y_{126} v_u^{126} , \\ M_d &= Y_{10} v_d^{10} + Y_{126} v_d^{126} , \\ M_e &= Y_{10} v_d^{10} - 3 Y_{126} v_d^{126} , \\ M_D &= Y_{10} v_u^{10} - 3 Y_{126} v_u^{126} , \\ M_R &= Y_{126} v_R , \\ M_L &= Y_{126} v_L . \end{aligned}$$

Axion in non-SUSY SO(10) GUT

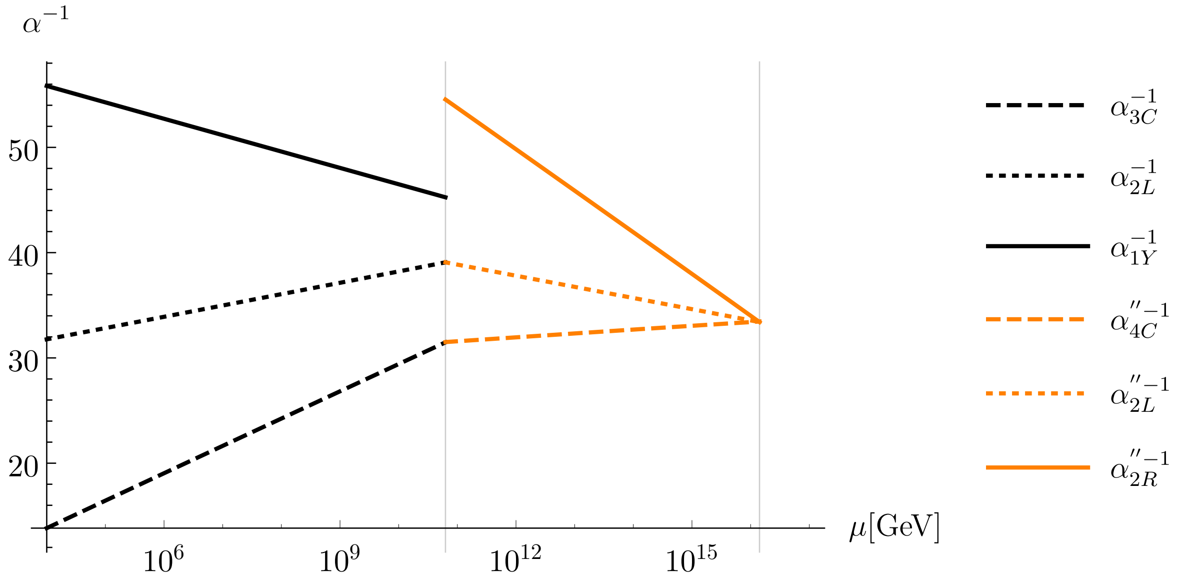
Axion predictions and experimental prospects

- Axion decay constant:

$$f_A \simeq \frac{1}{3}\frac{M_U}{g_U}$$

- From gauge coupling unification, assuming minimal scalar threshold corrections:

$$m_A \equiv \frac{\sqrt{\chi}}{f_A} \simeq 0.74\,\mathrm{neV}$$



[Ernst, AR, Tamarit, arXiv:1801.04906]

$$M_{\mathrm{U}} = 1.4\times 10^{16}\,\mathrm{GeV},\;\; \alpha_{\mathrm{U}}(M_{\mathrm{U}})^{-1} = 33.6$$

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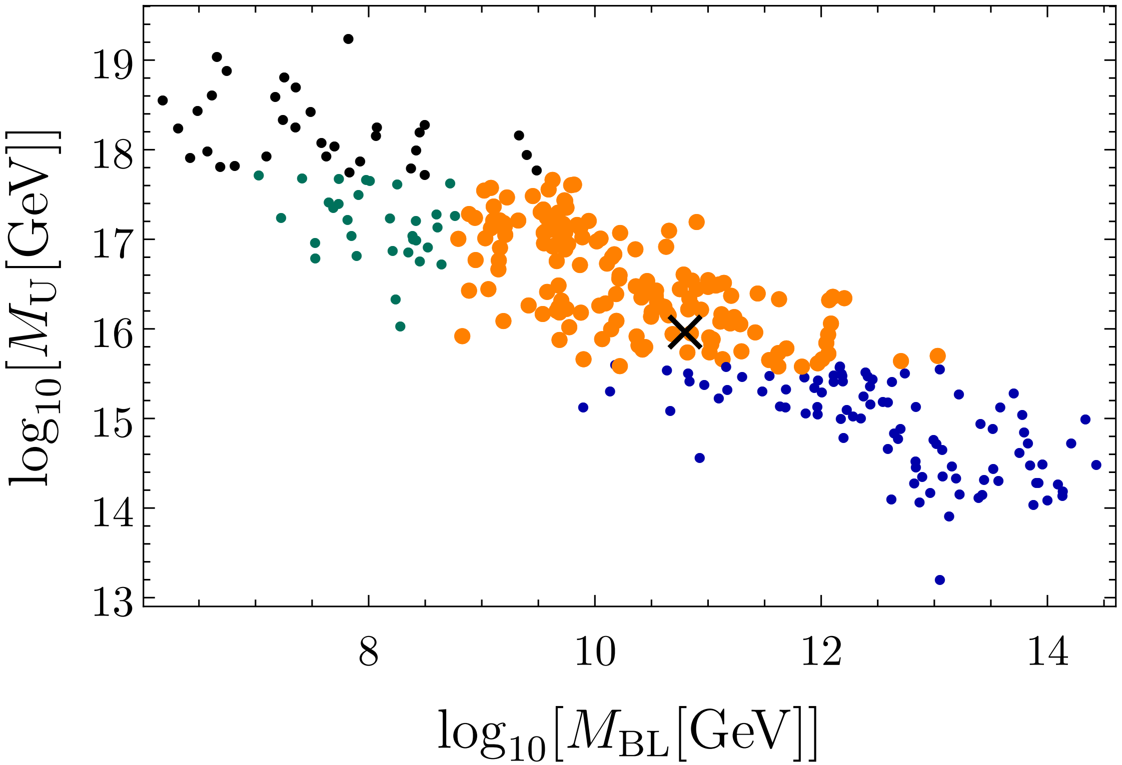
- Taking into account scalar threshold corrections and constraints from black hole superradiance and proton decay:

$$0.02\,\mathrm{neV} < m_A < 2.2\,\mathrm{neV}$$

$10^9\,\mathrm{GeV} < v_{\mathrm{BL}}$



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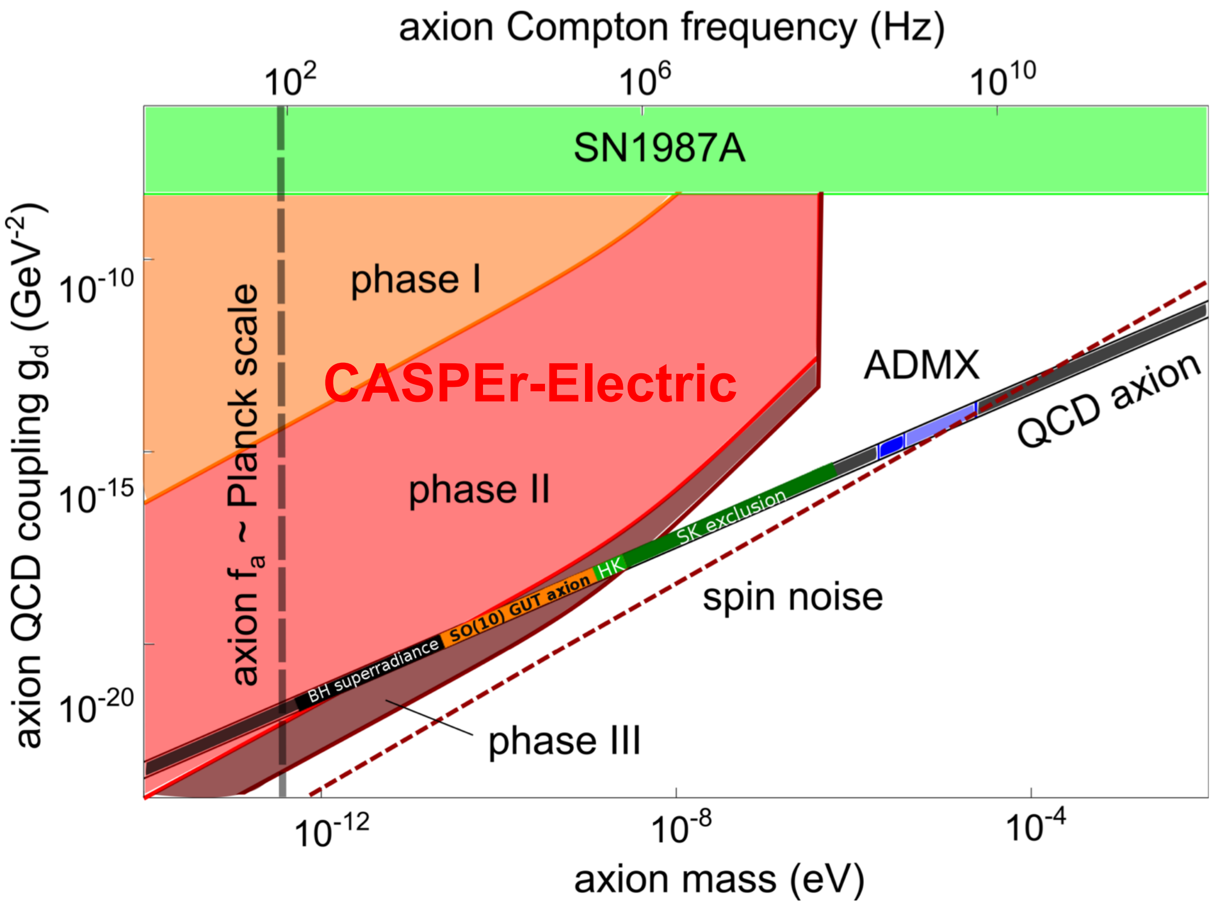

[Ernst 18; CASPEr prospects from Kimball et al. 17]

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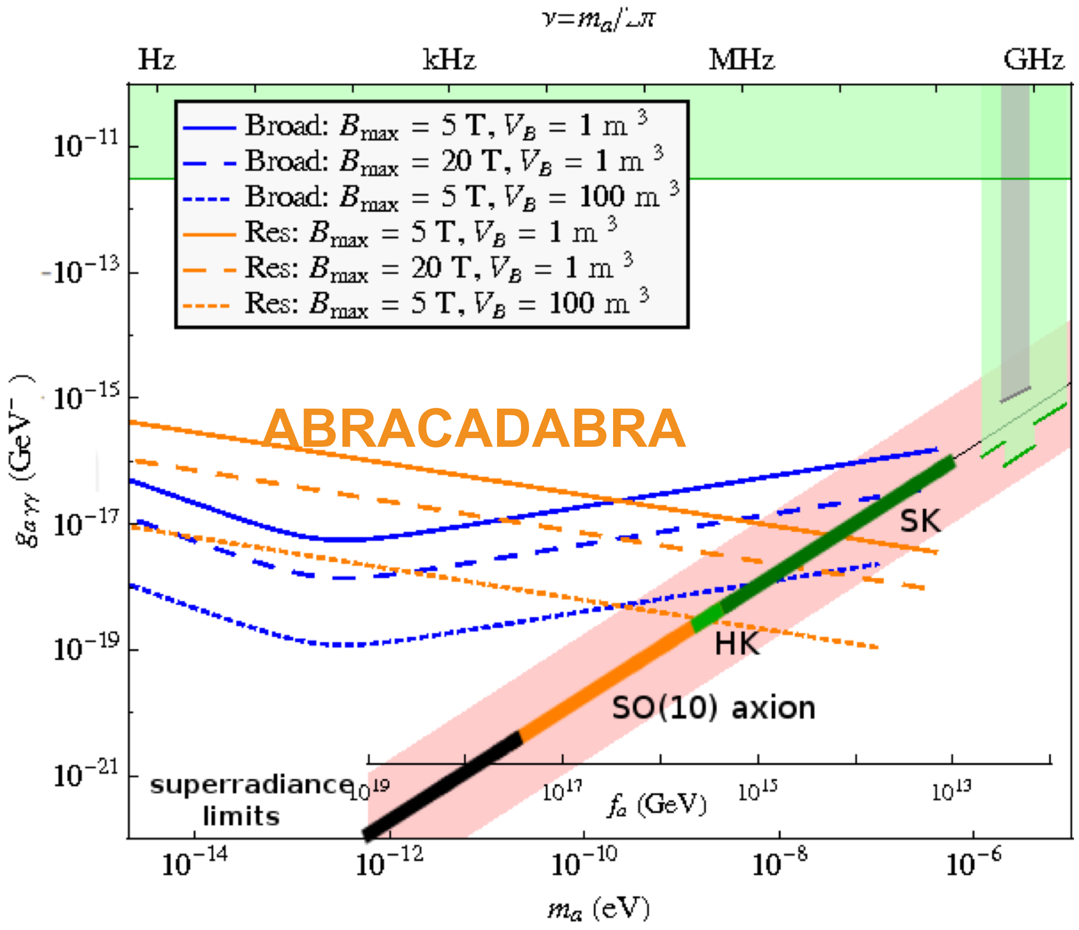

[Ernst 18; ABRACADABRA prospects from Kahn,Safdi,Thaler 16]

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

$$10_F = \underbrace{\left(\bar{3}, 1, -\frac{2}{3}\right)_F}_{u^c} \oplus \underbrace{\left(3, 2, +\frac{1}{6}\right)_F}_{q} \oplus \underbrace{(1, 1, +1)_F}_{e^c},$$

$$\bar{5}_F = \underbrace{\left(\bar{3}, 1, +\frac{1}{3}\right)_F}_{d^c} \oplus \underbrace{\left(1, 2, -\frac{1}{2}\right)_F}_{\ell},$$

$$\begin{aligned} 24_H = {} & \underbrace{(1, 1, 0)_H}_{S_H} \oplus \underbrace{(1, 3, 0)_H}_{T_H} \oplus \underbrace{(8, 1, 0)_H}_{O_H} \\ & \oplus \underbrace{\left(3, 2, -\frac{5}{6}\right)_H}_{X_H} \oplus \underbrace{\left(\bar{3}, 2, +\frac{5}{6}\right)_H}_{\bar{X}_H}, \end{aligned}$$

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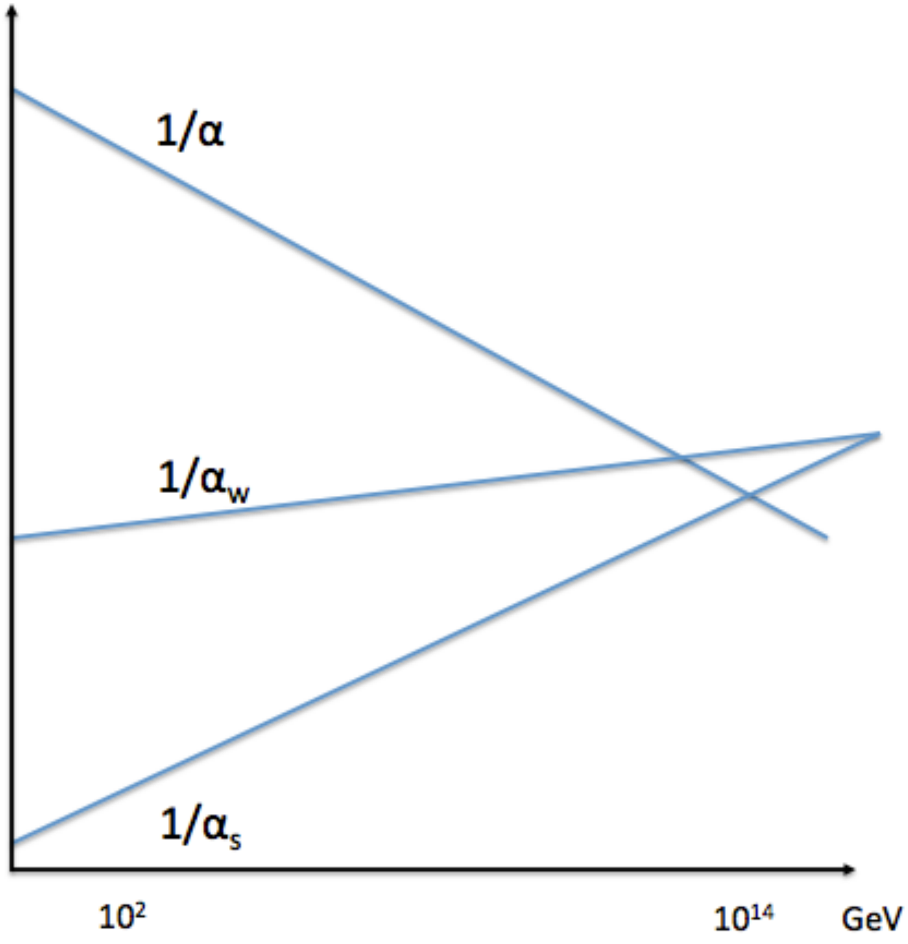

[StackExchange]

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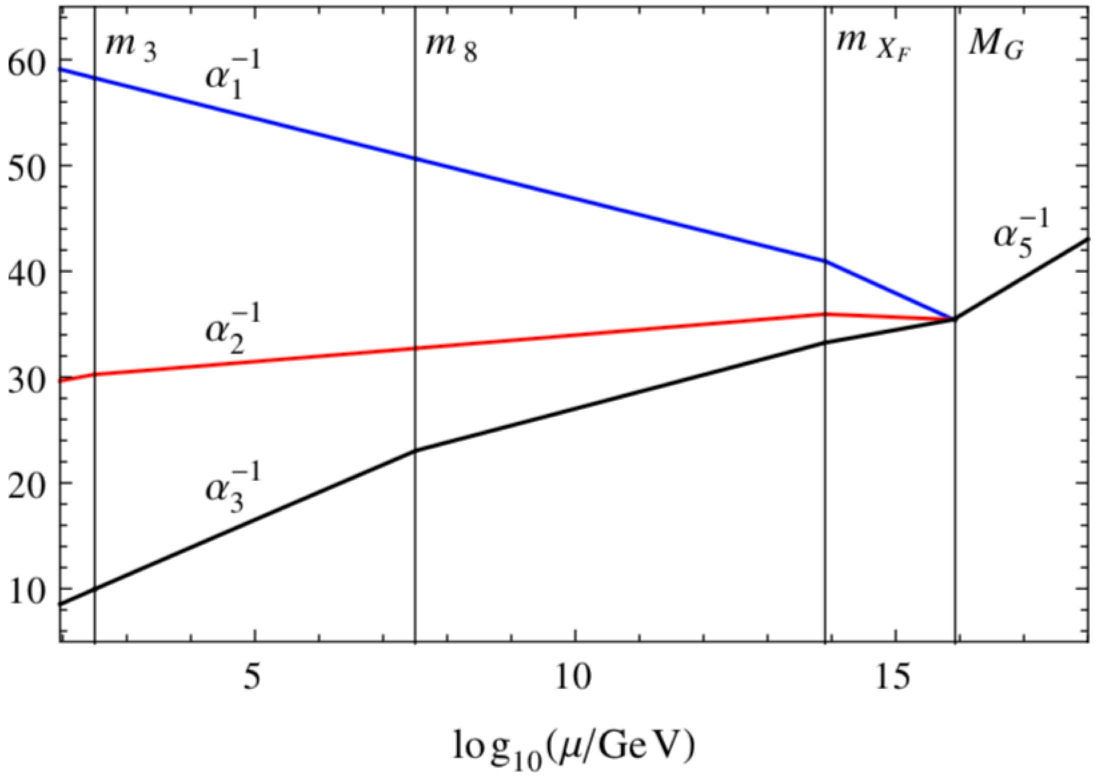

[Di Luzio, Mihaila 13]

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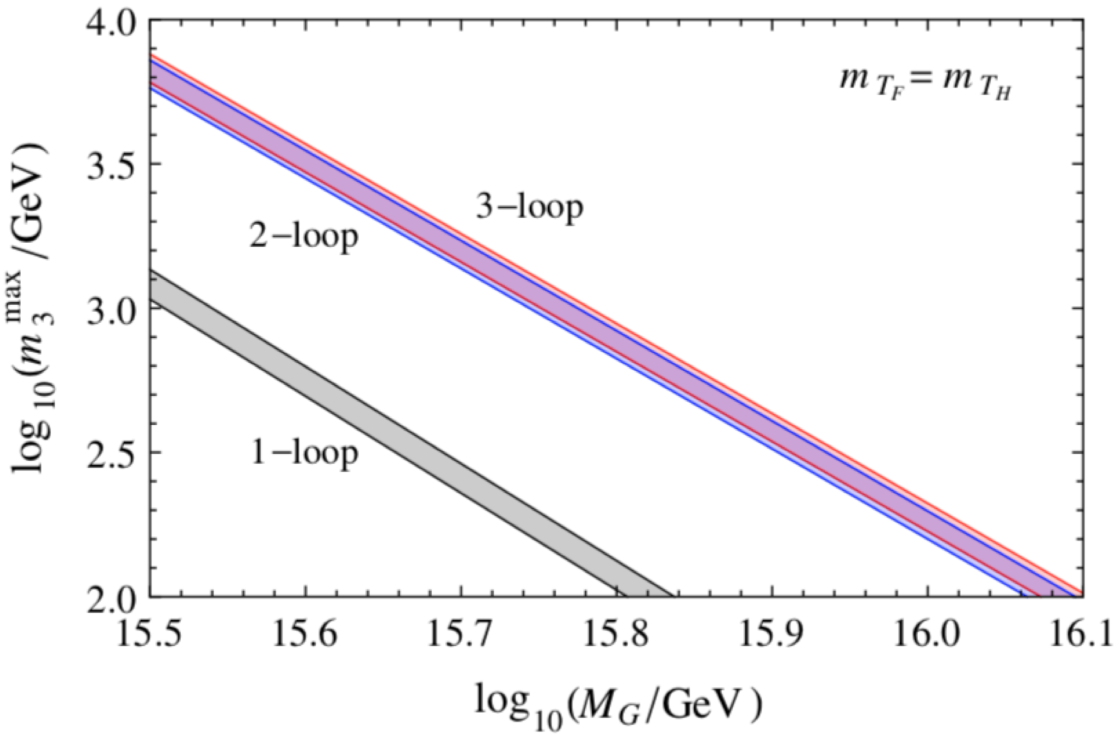
    - Clean correlation between effective electroweak triplet mass m_3 and unification scale M_G



[Di Luzio, Mihaila 13]

$$m_3 = \left(m_{T_F}^4 m_{T_H}\right)^{1/5}$$

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:

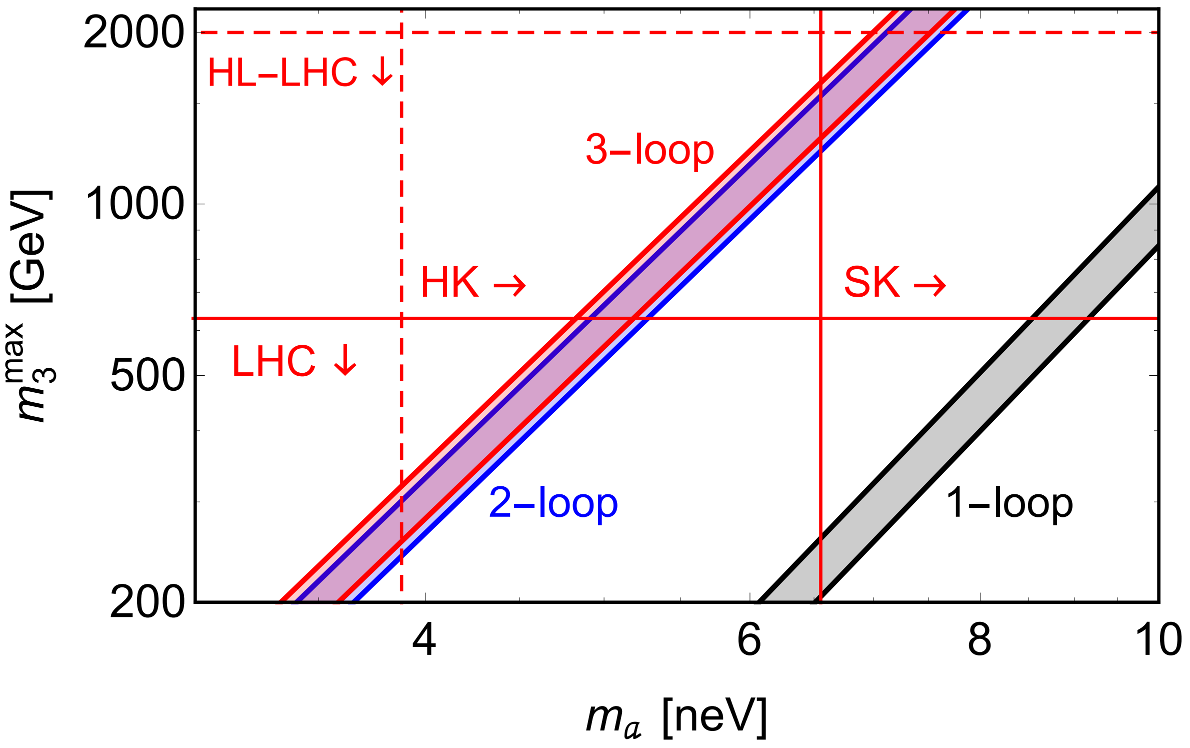
$$\begin{aligned}\bar{5}_F &\to e^{-i\alpha/2}\bar{5}_F,\\ 10_F &\to e^{-i\alpha/2}10_F,\\ 5_H &\to e^{i\alpha}5_H,\\ 5'_H &\to e^{-i\alpha}5'_H,\\ 24_H &\to e^{-i\alpha}24_H,\\ 24_F &\to e^{-i\alpha/2}24_F\end{aligned}$$

- Axion decay constant:

$$f_A \simeq \frac{1}{11}\sqrt{\frac{6}{5}}\frac{M_G}{g_5}$$

- Gauge coupling unification, taking into account LHC and Superkamiokande constraints:

$$m_A \in [4.8, 6.6]\ \mathrm{neV}$$



[Di Luzio, AR, Tamarit, arXiv:1807.09769]

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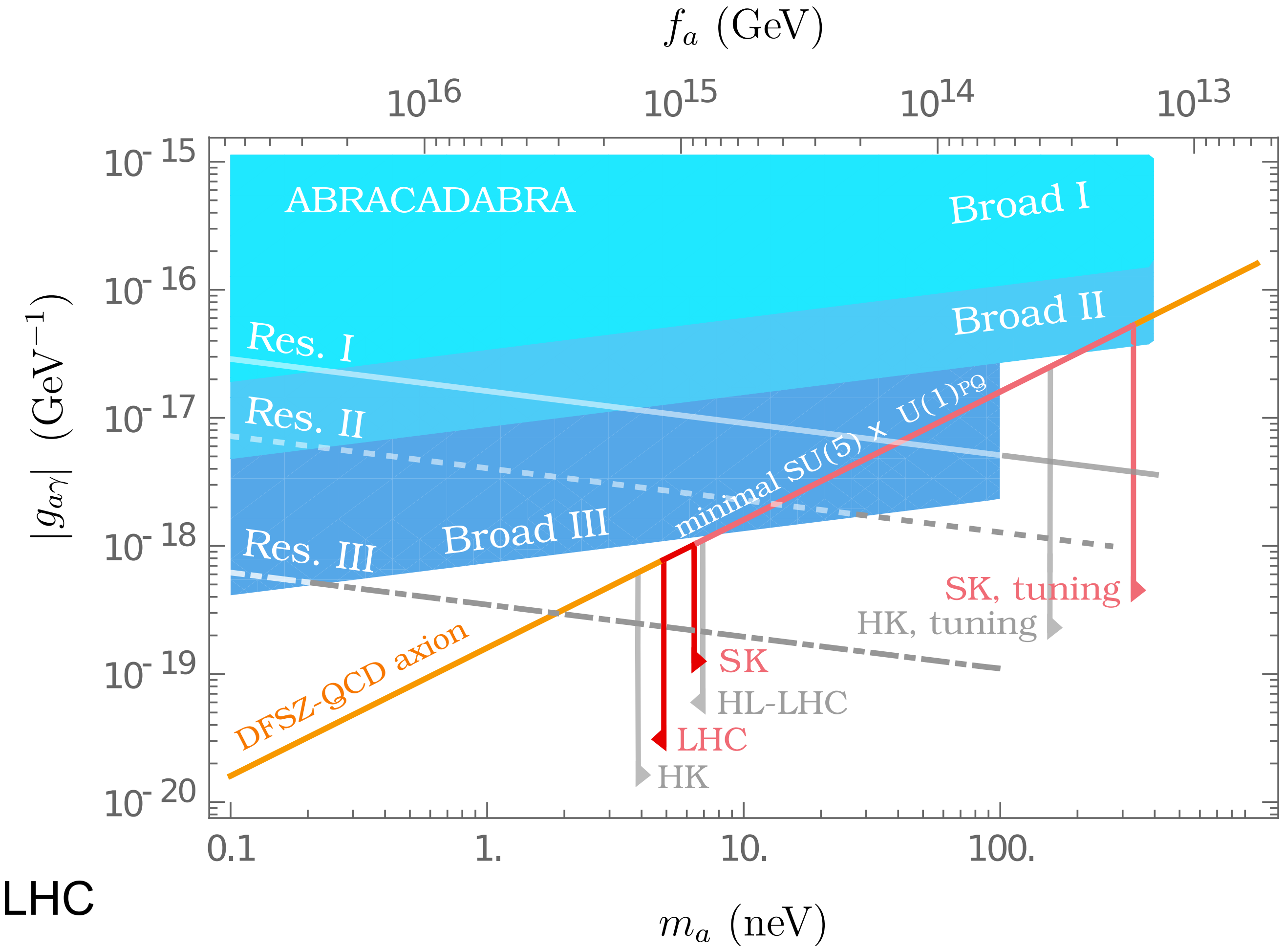
- Window can be explored by axion DM experiments



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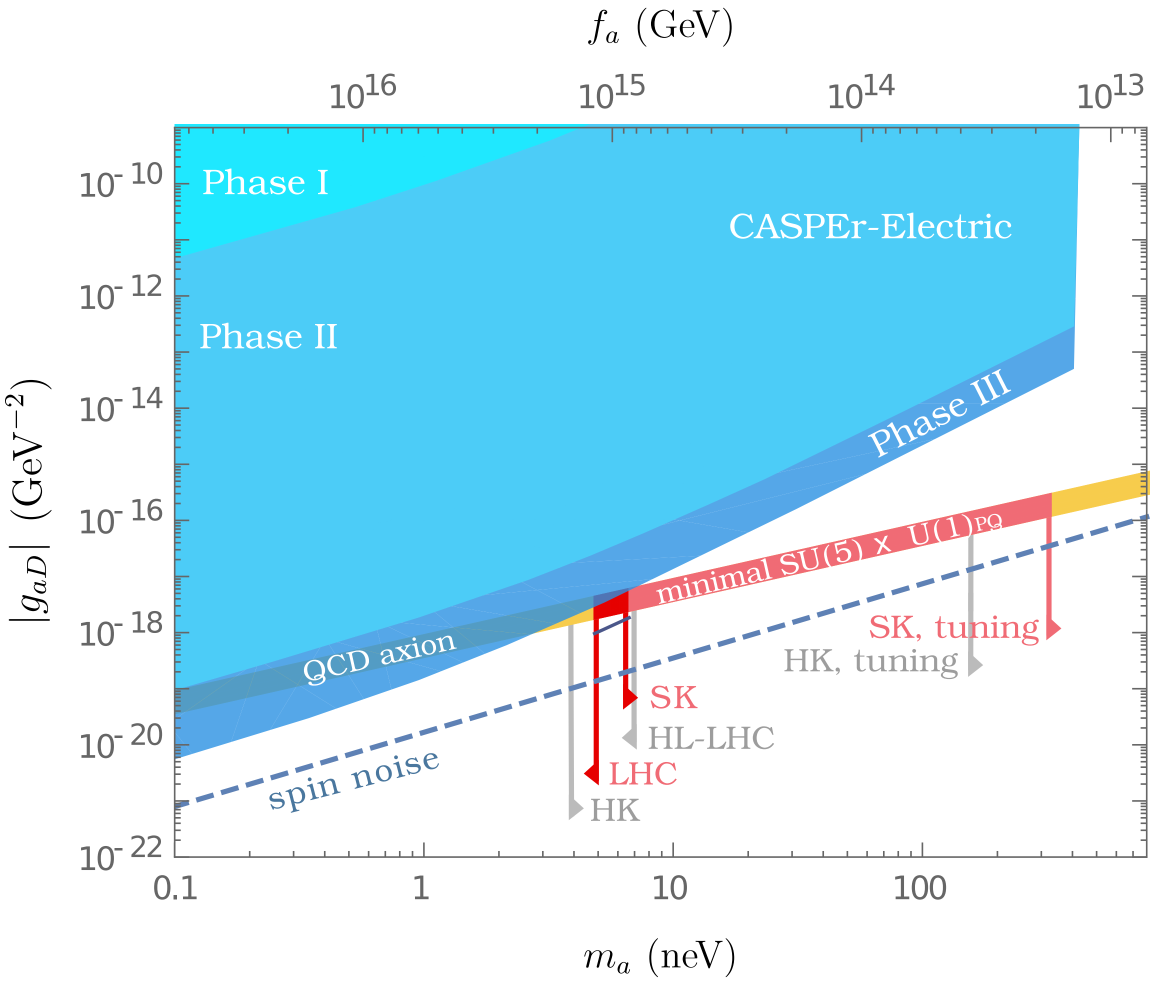

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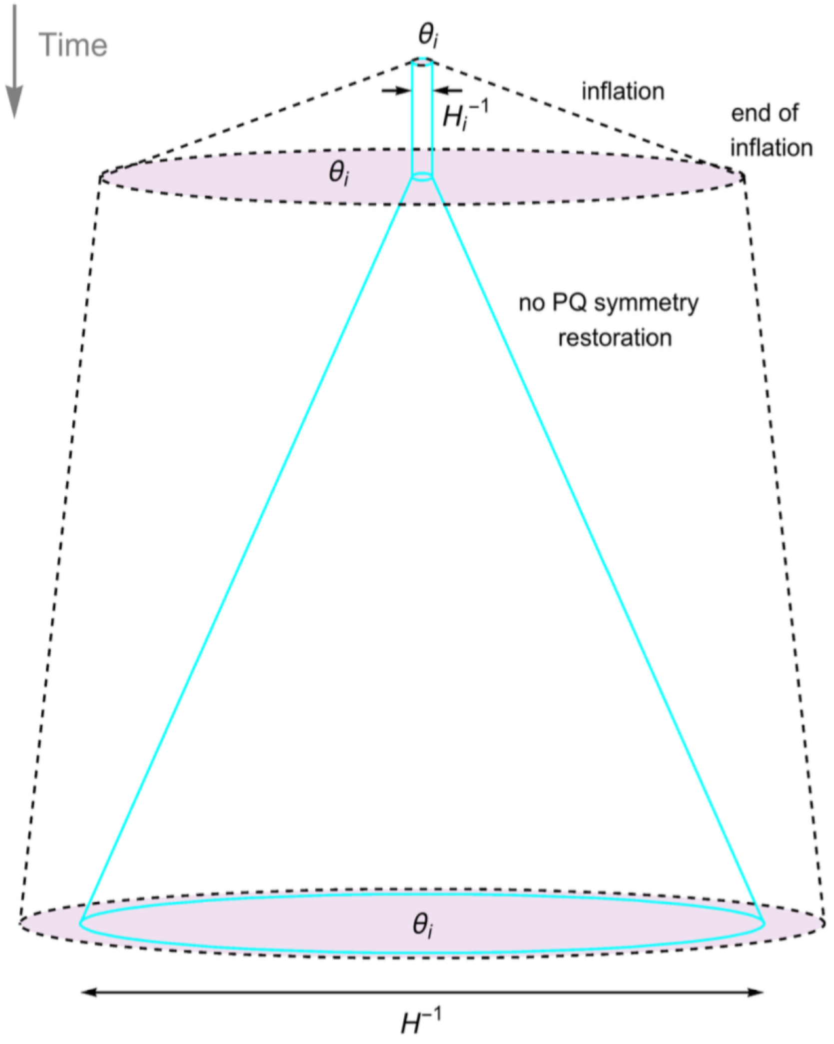
Axion in non-SUSY SU(5) GUT

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 $\theta_i = A_i/f_A$ inside causally connected region which is inflated to observable universe

Pre–inflationary PQ symmetry breaking scenario



[Saikawa]

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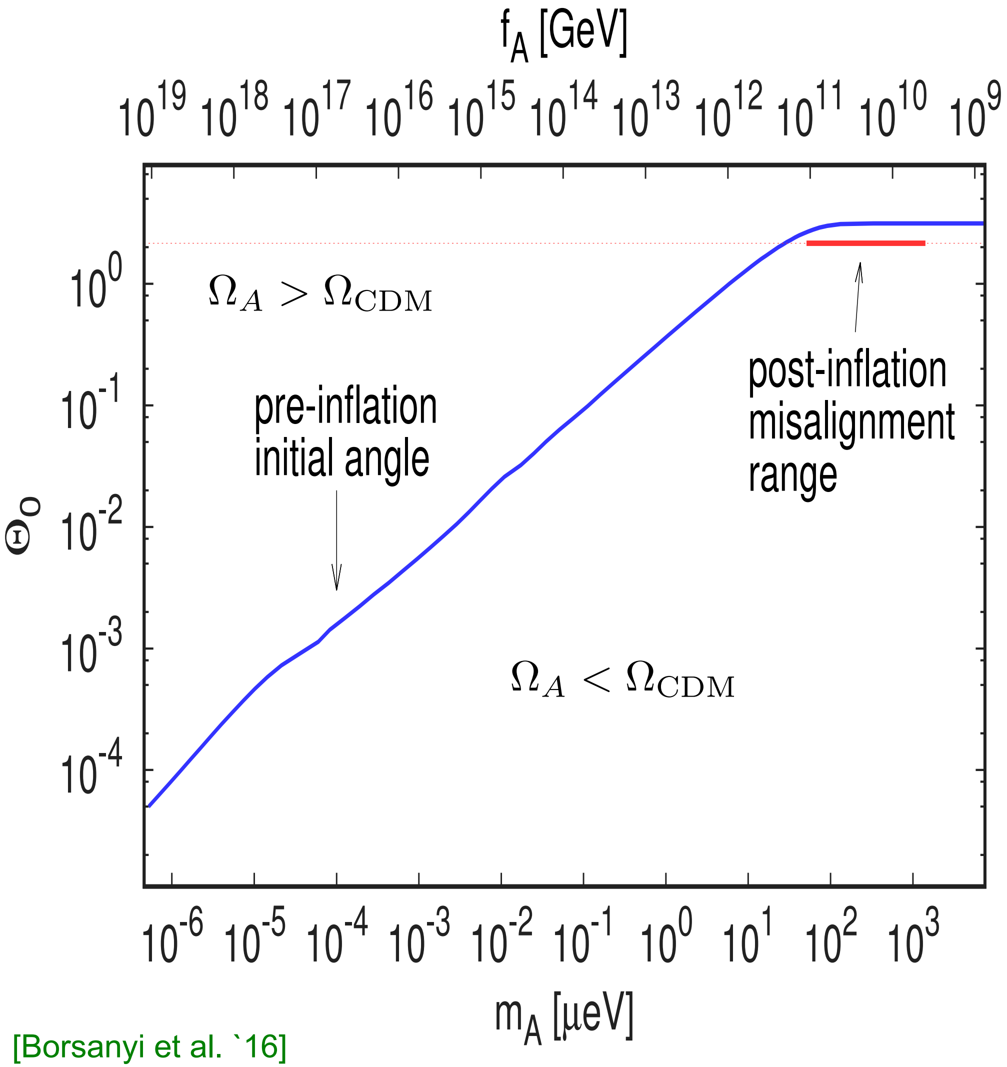
$$\Omega_a h^2 = 0.12 \left(\frac{5.0\ \mathrm{neV}}{m_a}\right)^{1.165} \left(\frac{\theta_\mathrm{i}}{1.6\times 10^{-2}}\right)^2$$



[Borsanyi et al. `16]

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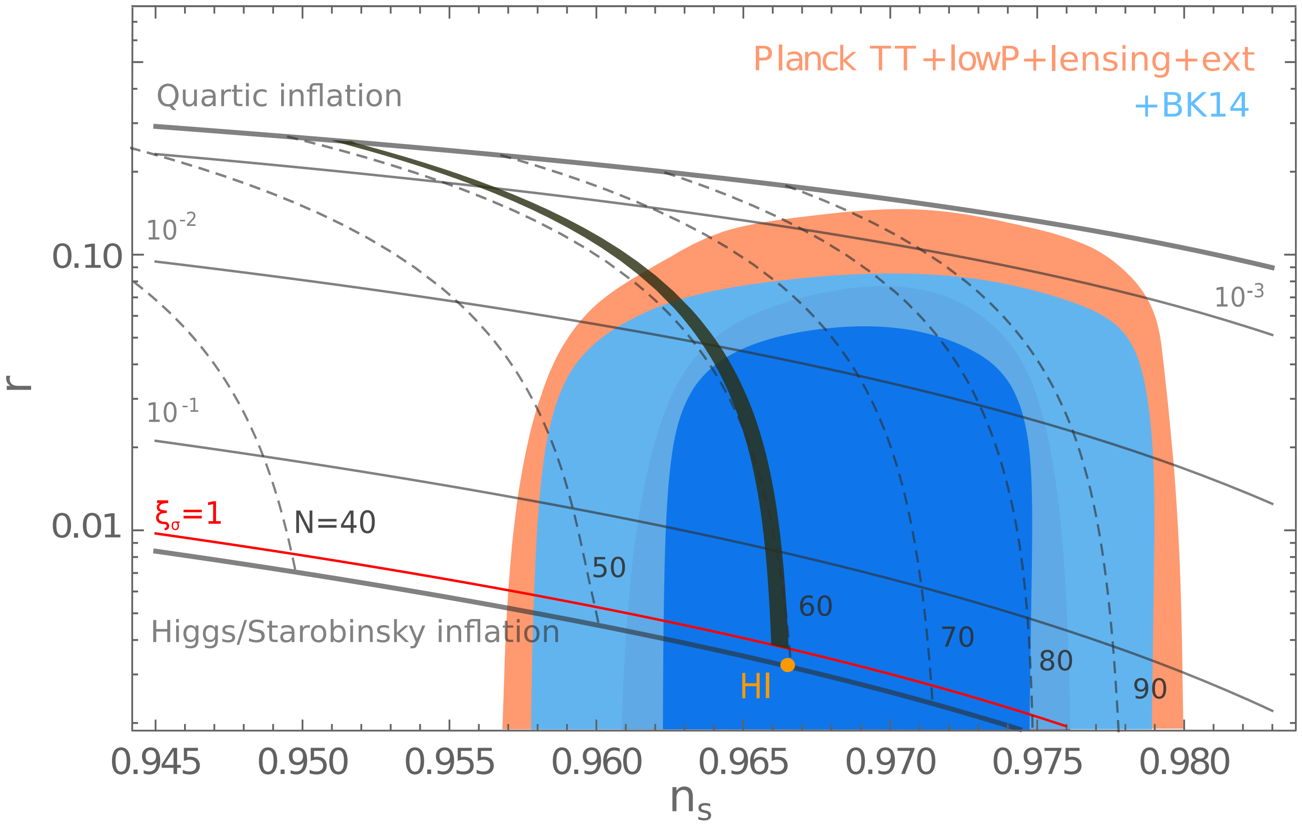
- Non-minimal chaotic 24_H inflation

$$S \supset -\int d^4x\,\sqrt{-g}\,\xi_{24_H}\,\mathrm{Tr}(24_H^2)R$$

  - For small enough quartic and Yukawa couplings, PQ symmetry after inflation may be avoided
  - Isocurvature constraints avoided if $\xi_{24_H} \gtrsim 0.01$

SM * Axion * See-saw * Higgs portal inflation



[Ballesteros,Redondo, AR,Tamarit `16]

Conclusions and outlook

- Realistic non-SUSY $\mathrm{SO}(10) \times \mathrm{U}(1)_{\mathrm{PQ}}$ and $\mathrm{SU}(5) \times \mathrm{U}(1)_{\mathrm{PQ}}$ 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 $\mathrm{SO}(10) \times \mathrm{U}(1)_{\mathrm{PQ}}$ and $\mathrm{SU}(5) \times \mathrm{U}(1)_{\mathrm{PQ}}$ 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 can not replenish spin
- Existence of bosonic WISPs leads to gaps in mass vs. spin plots of rapidly rotating BHs

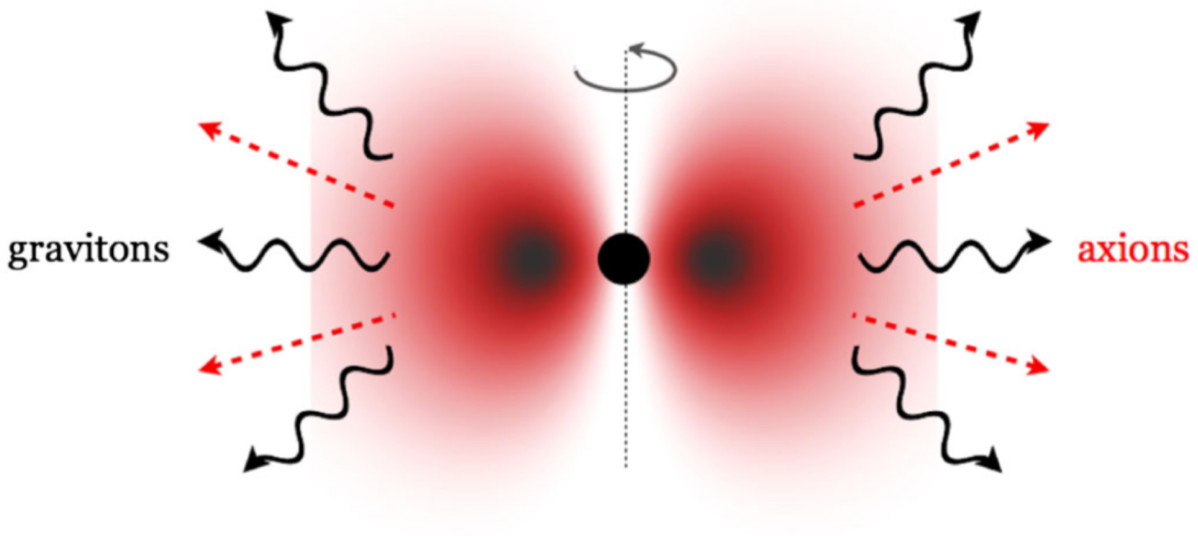


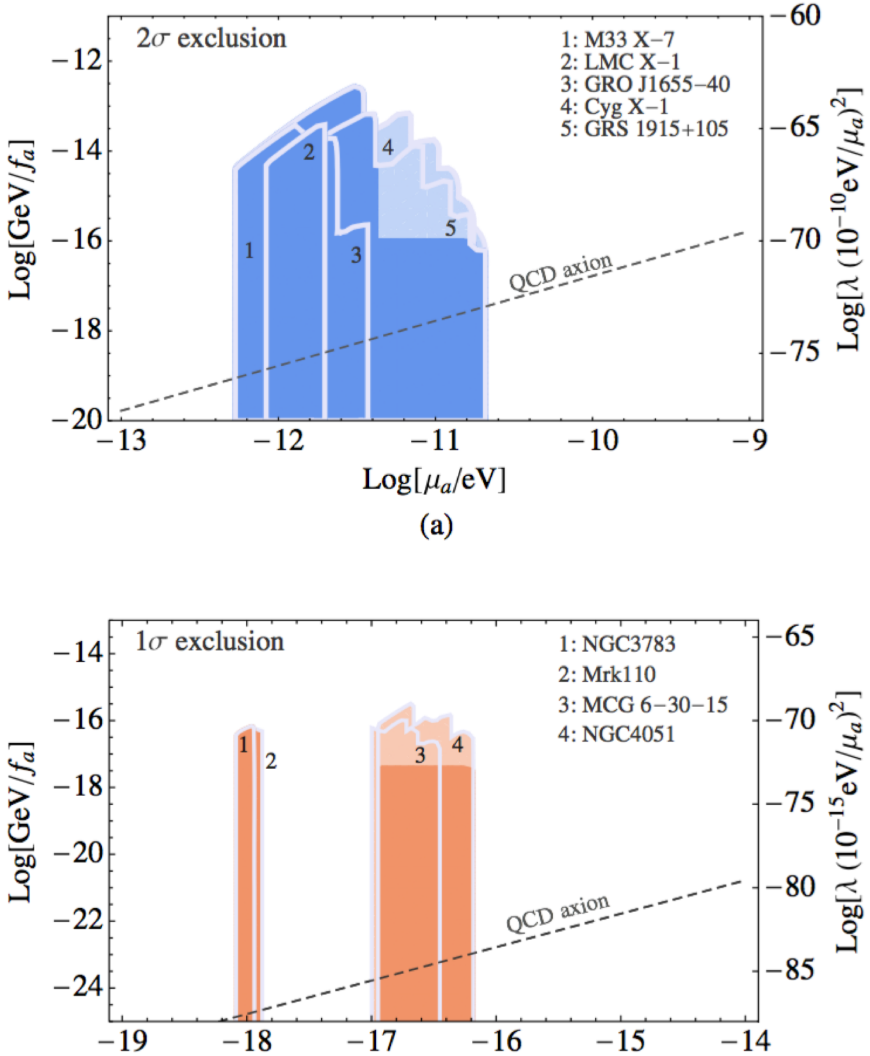
FIG. 1 (color online). *Axionic Black Hole Atom:* The spinning black hole "feeds" superradiant states forming an axion Bose-Einstein condensate. The resulting bosonic atom will emit gravitons through axion transitions between levels and annihilations and will emit axions as a consequence of self-interactions in the axion field.

[Arvanitaki,Dimopoulos,Dubovsky,Kaloper,March-Russell 10]

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 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

$$6 \times 10^{-13}\,\mathrm{eV} < m_A < 2 \times 10^{-11}\,\mathrm{eV}$$



(a)

(b)

[Arvanitaki et al. 14]