Axions

General Theory

Andreas Ringwald
Axions in Stockholm - Reloaded
Quantum Connections Session 5
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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Strong CP Problem

Theta term in QCD

- Most general gauge invariant Lagrangian of QCD: [Belavin et al. `75;´t Hooft 76;Callan et al. `76;Jackiw,Rebbi `76]

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu} + \overline{q}\,(i\gamma_\mu D^\mu - \mathcal{M}_q)\,q - \frac{\alpha_s}{8\pi}\,\overline{\theta}\,G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}$$

  - Parameters: strong coupling α_s, quark masses $\mathcal{M}_q = {\rm diag}(m_u, m_d, \ldots)$ and theta angle $\overline{\theta}$

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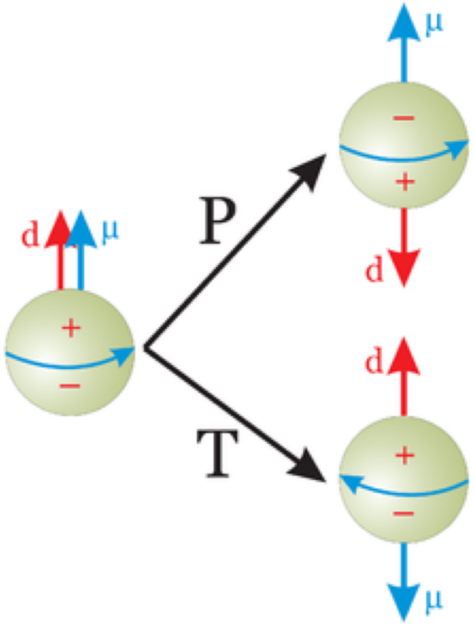
- Topological theta term $\propto G^a_{\mu\nu}\tilde{G}^{a,\mu\nu} \propto \mathbf{E}^a \cdot \mathbf{B}^a$ violates P and T, and thus CP

- Most sensitive probe of P and T violation in flavor conserving interactions: electric dipole moment of neutron



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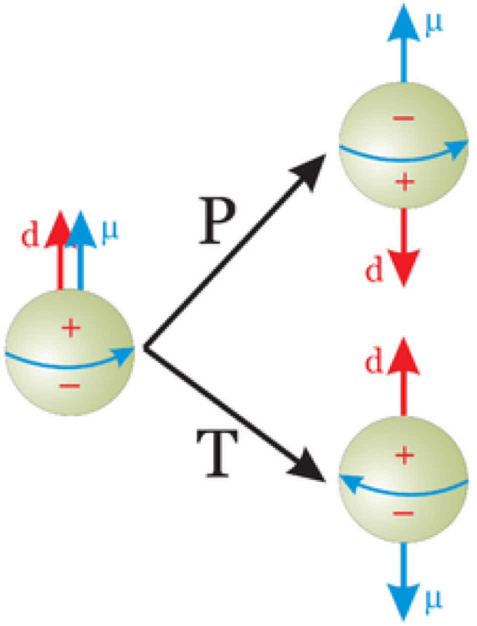
$$d_n(\overline{\theta}) = 2.4(1.0) \times 10^{-16}\,\overline{\theta}\,e\,{\rm cm}$$

- Experiment: [Baker et al. 06]

$$|d_n| < 2.9 \times 10^{-26}\,e\,{\rm cm} \Rightarrow |\overline{\theta}| < 10^{-10}$$



Axionic Solution of Strong CP Puzzle

In a nutshell …

- Add to SM Nambu-Goldstone field, $\theta(x) \equiv A(x)/f_A \in [-\pi, \pi]$, respecting a non-linearly realized $U(1)_{\rm PQ}$ symmetry ($\theta(x) \to \theta(x) + {\rm const.}$), broken by coupling to gluonic topological charge density: [Peccei,Quinn 77]

$$\mathcal{L} \supset -\theta(x)\, q(x)\,; \qquad q(x) \equiv \frac{\alpha_s}{8\pi}\, G^b_{\mu\nu}(x)\tilde{G}^{b,\mu\nu}(x)$$

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  - Can eliminate QCD $\overline{\theta}$-parameter

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi}\left[\overline{\theta} + \theta(x)\right] G^b_{\mu\nu}\tilde{G}^{b,\mu\nu}$$

    by shift $\theta(x) \to \theta(x) - \overline{\theta}$

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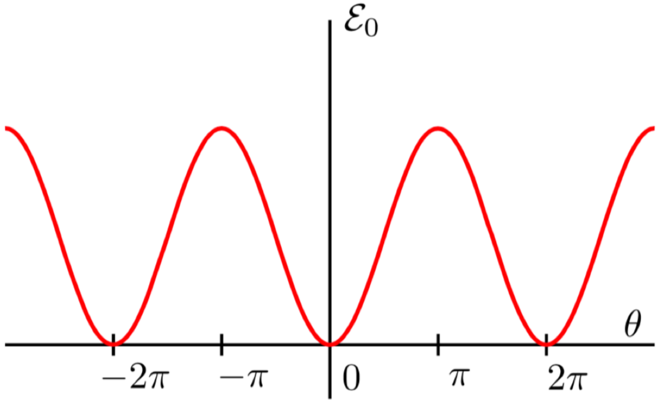
  - Effective potential at energies below $\Lambda_{\rm QCD}$ has absolute minimum at $\theta = 0$ and thus predicts vanishing vev, $\langle\theta(x)\rangle = 0$
    No strong CP violation in vacuum [Vafa,Witten 84]



$$V(\theta) = \Sigma\,(m_u + m_d)\left(1 - \frac{\sqrt{m_u^2 + m_d^2 + 2 m_u m_d \cos\theta}}{m_u + m_d}\right)$$

$$\Sigma \equiv -\langle \bar{u} u\rangle = -\langle d d\rangle$$

[Di Vecchia,Veneziano `80; Leutwyler,Smilga 92]

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    No strong CP violation in vacuum [Vafa,Witten 84]
  - Particle excitation: pseudo Nambu-Goldstone boson "axion" [Weinberg 78; Wilczek 78]
  - Topological susceptibility in QCD, $\chi \equiv \int d^4x \langle q(x) q(0)\rangle$, determines mass in units of decay constant: $m_A = \sqrt{\chi}/f_A$
  - Recent precise determination (ChPT; lattice QCD):

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

[Grilli di Cortona et al. \`16; Borsanyi et al. \`16]

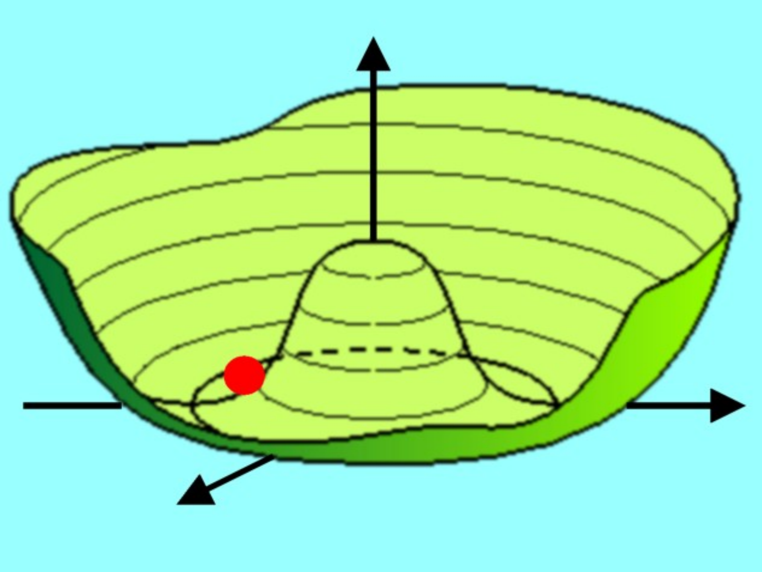
Peccei-Quinn Extension of Standard Model

UV completions of SM yielding axion

- A singlet complex scalar field σ, featuring a global $U(1)_{\rm PQ}$ symmetry, is added to SM
- Symmetry is broken by vev $\langle|\sigma|^2\rangle = v_{\rm PQ}^2/2$

$$\sigma(x) = \frac{1}{\sqrt{2}}\left(v_{\rm PQ} + \rho(x)\right) {\rm e}^{iA(x)/v_{\rm PQ}}$$

  - Excitation of modulus: $m_\rho \sim v_{\rm PQ}$
  - Excitation of phase: NGB $m_A = 0$



[Raffelt]

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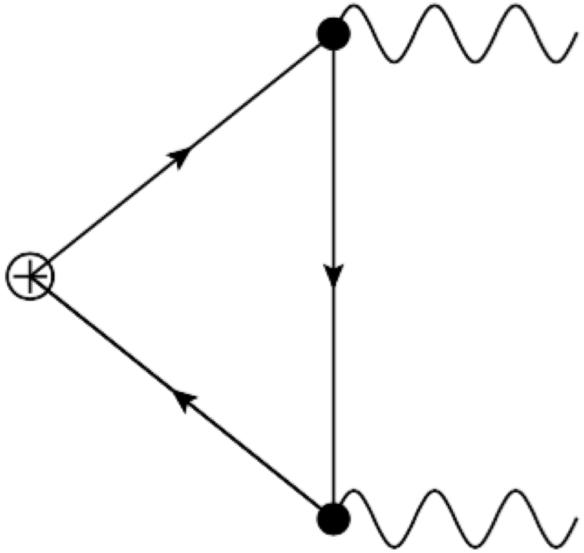
- Colored fermions (SM or extra) carry PQ charges such that $U(1)_{\rm PQ}$ is broken due to gluonic triangle anomaly:

$$\partial_\mu J^\mu_{U(1)_{\rm PQ}} \supset -\frac{\alpha_s}{8\pi} N\, G^b_{\mu\nu}\tilde{G}^{b,\mu\nu}$$



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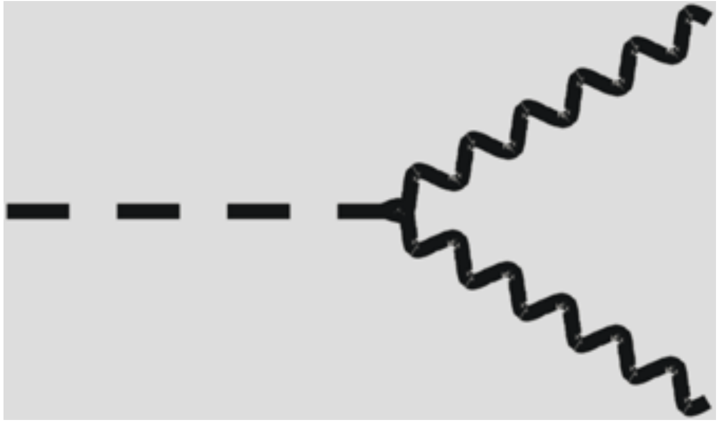
- Low energy effective field theory at energies above $\Lambda_{\rm QCD}$ but below $v\ (\ll v_{\rm PQ})$: [Peccei,Quinn 77; Weinberg 78; Wilczek 78]

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi}\,\theta(x)\, G^b_{\mu\nu}\tilde{G}^{b,\mu\nu}\,; \qquad \theta(x) = A(x)/f_A\,; \qquad f_A = v_{\rm PQ}/N$$

[Kim 79;Shifman,Vainshtein,Zakharov 80;Zhitnitsky 80;Dine,Fischler,Srednicki 81;...]



Peccei-Quinn Extension of Standard Model

Axion couplings to SM at energies below QCD scale

$$\mathcal{L}_A \supset -\frac{i}{2}\frac{C_{AD}}{f_A}\,A\,\overline{\Psi}_N\sigma_{\mu\nu}\gamma_5\Psi_N F^{\mu\nu} - \frac{\alpha}{8\pi}\frac{C_{A\gamma}}{f_A}\,A\,F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{2}\frac{C_{Af}}{f_A}\,\partial_\mu A\,\overline{\Psi}_f\gamma^\mu\gamma_5\Psi_f$$

- „Invisible axion“: couplings to SM suppressed by inverse power of $f_A = v_{\rm PQ}/N \gg v = 246\,{\rm GeV}$

[Kim 79;Shifman,Vainshtein,Zakharov 80;Zhitnitsky 80;Dine,Fischler,Srednicki 81;...]

- EDM coupling: $C_{AD} = 2.4(1.0)\times 10^{-16}\,e\,{\rm cm}$ [Pospelov,Ritz `00]
- Photon coupling: $C_{A\gamma} = \frac{E}{N} - 1.92(4)$ [Kaplan 85;Srednicki `85; Grilli di Cortona et al. `16]
- Nucleon couplings:

$$\begin{aligned} C_{Ap} &= -0.47(3) + 0.88(3)C_{Au} - 0.39(2)C_{Ad} - 0.038(5)C_{As} \\ &\qquad - 0.012(5)C_{Ac} - 0.009(2)C_{Ab} - 0.0035(4)C_{At}\,, \\ C_{An} &= -0.02(3) + 0.88(3)C_{Ad} - 0.39(2)C_{Au} - 0.038(5)C_{As} \\ &\qquad - 0.012(5)C_{Ac} - 0.009(2)C_{Ab} - 0.0035(4)C_{At} \end{aligned}$$

- Electron coupling very model-dependent
- Strong CP problem solved for any value of f_A (m_A)!

Axion Dark Matter

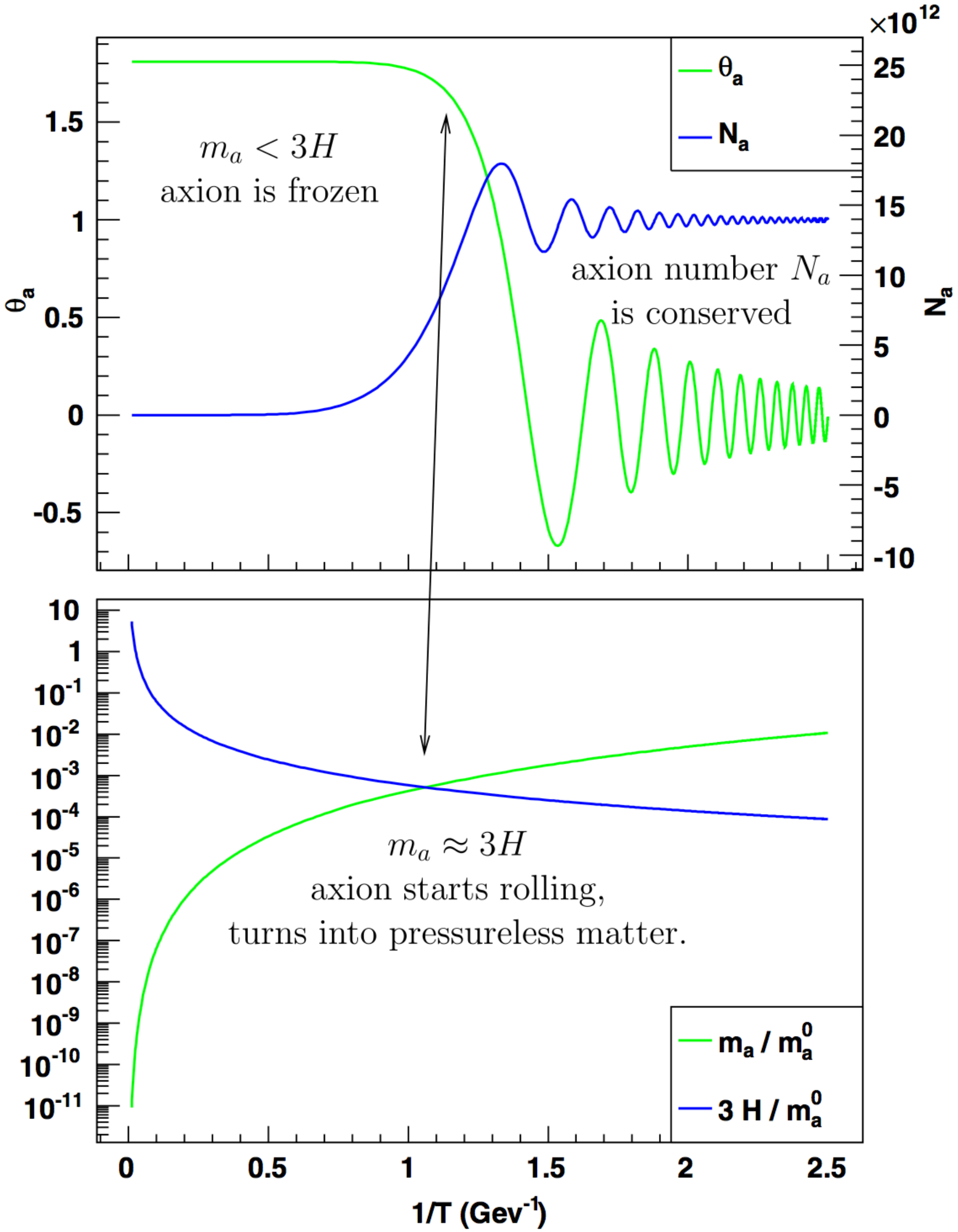
Vacuum re-alignment mechanism

- PQ phase transition takes place at

$$T \lesssim T_c^{\mathrm{PQ}} \sim v_{\mathrm{PQ}} = N f_A$$

- Axion takes random initial values in causally connected domains
- Later when $H(T) \sim m_A(T)$, axion field starts to oscillate around minimum of potential; behaves like cold dark matter: $w_A = p_A/\rho_A \simeq 0$

[Preskill,Wise,Wilczek 83; Abbott,Sikivie 83; Dine,Fischler 83,....]



[Wantz,Shellard `09]

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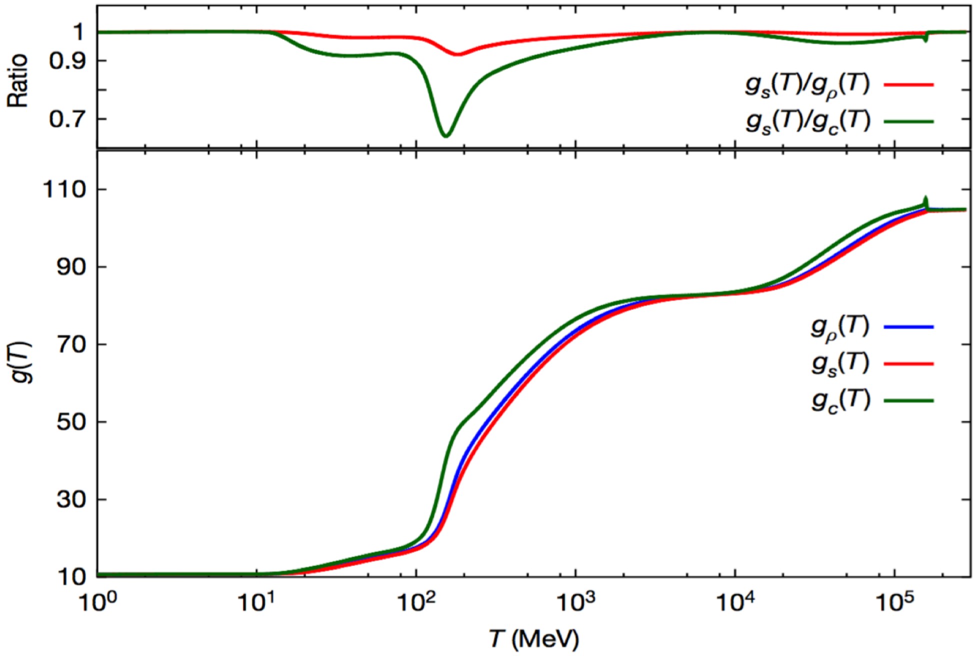
- QCD input from lattice:
  - Equation of state $\Rightarrow H(T)$



[Borsanyi et al., Nature `16 [1606.0794]]

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- QCD input from lattice:
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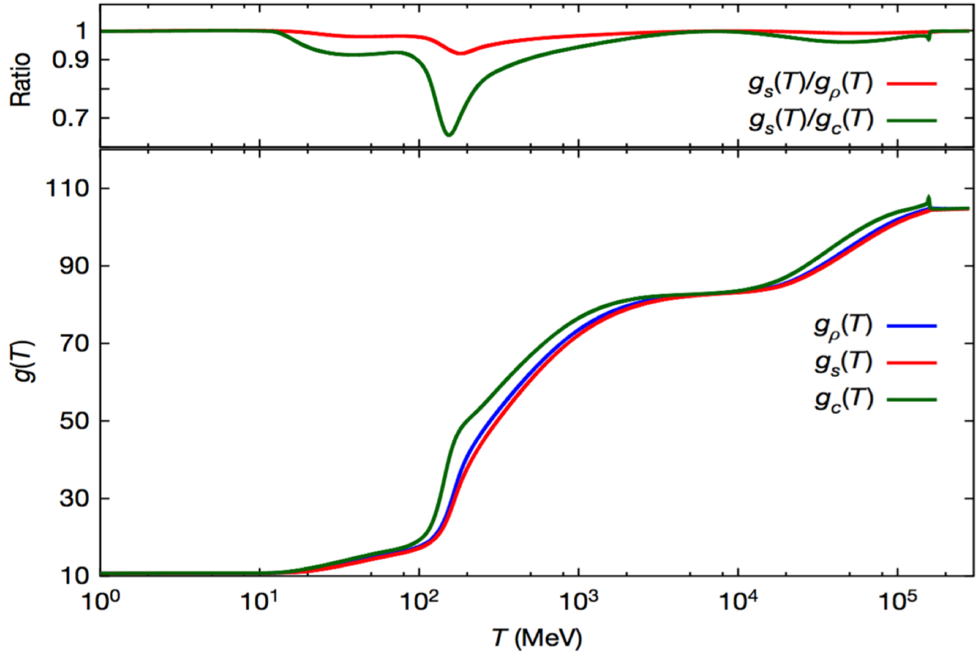
  - Topological susceptibility $\Rightarrow m_A(T) = \dfrac{\sqrt{\chi(T)}}{f_A}$



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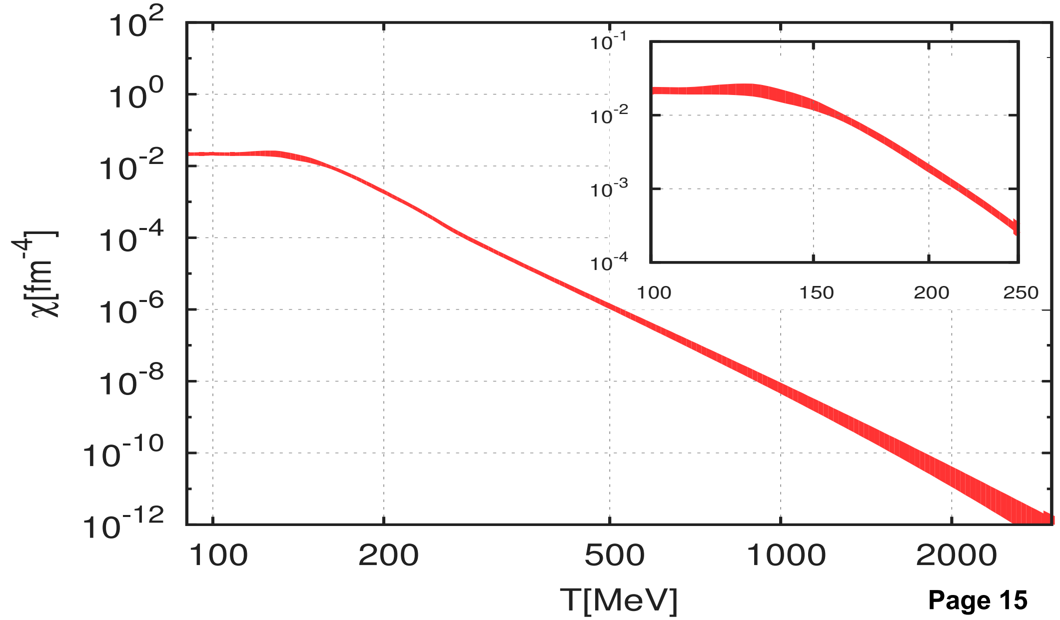
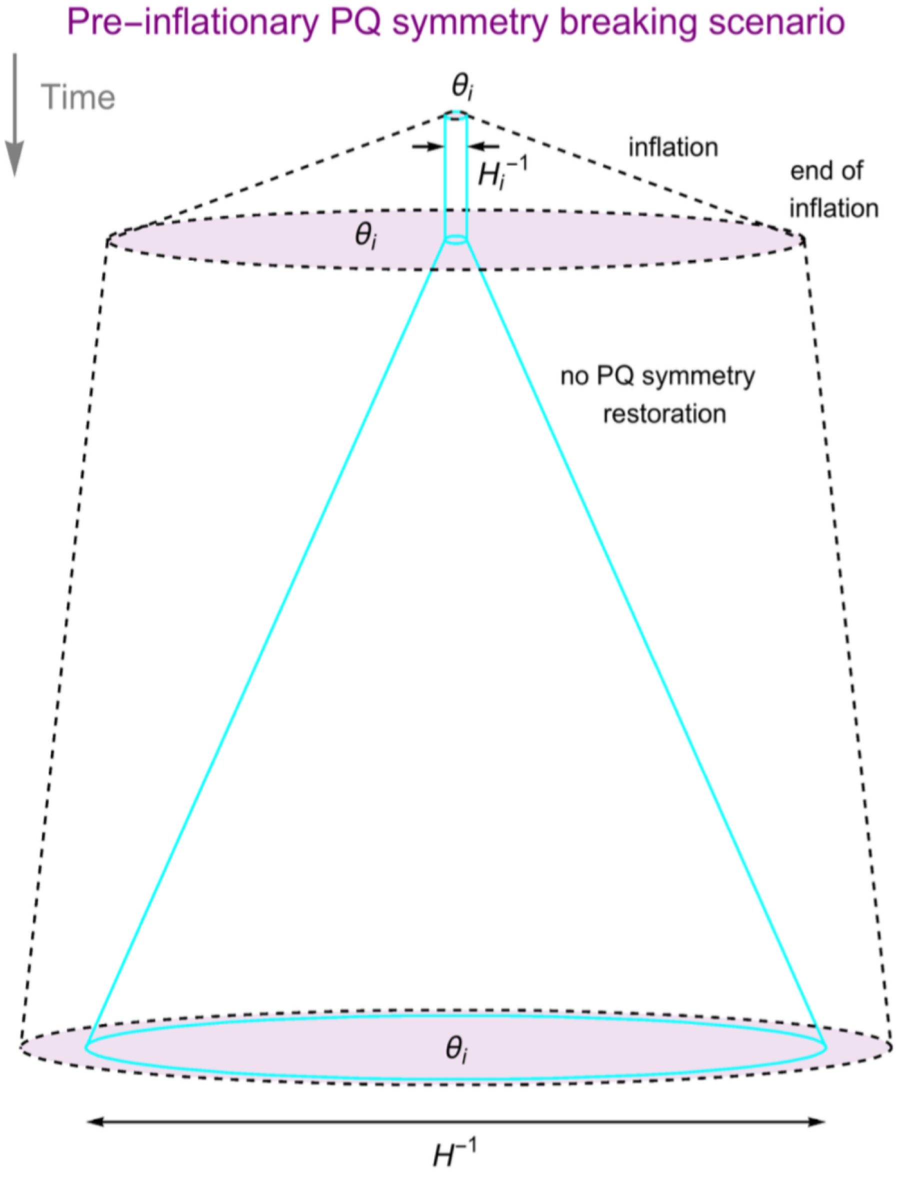


Axion Dark Matter

Pre-inflationary PQ SSB scenario

- If PQ symmetry broken before or during inflation $(f_A > H_I/(2\pi))$ and not restored afterwards
  - Axion CDM density depends on single initial value in patch which becomes observable universe and f_A

$$\Omega_A^{\rm vr} h^2 \approx 0.12 \left(\frac{f_A}{9\times 10^{11}\ {\rm GeV}}\right)^{1.165} \theta_{\rm i}^2$$
$$\approx 0.12 \left(\frac{6\ \mu{\rm eV}}{m_A}\right)^{1.165} \theta_{\rm i}^2\,,$$



[Saikawa]

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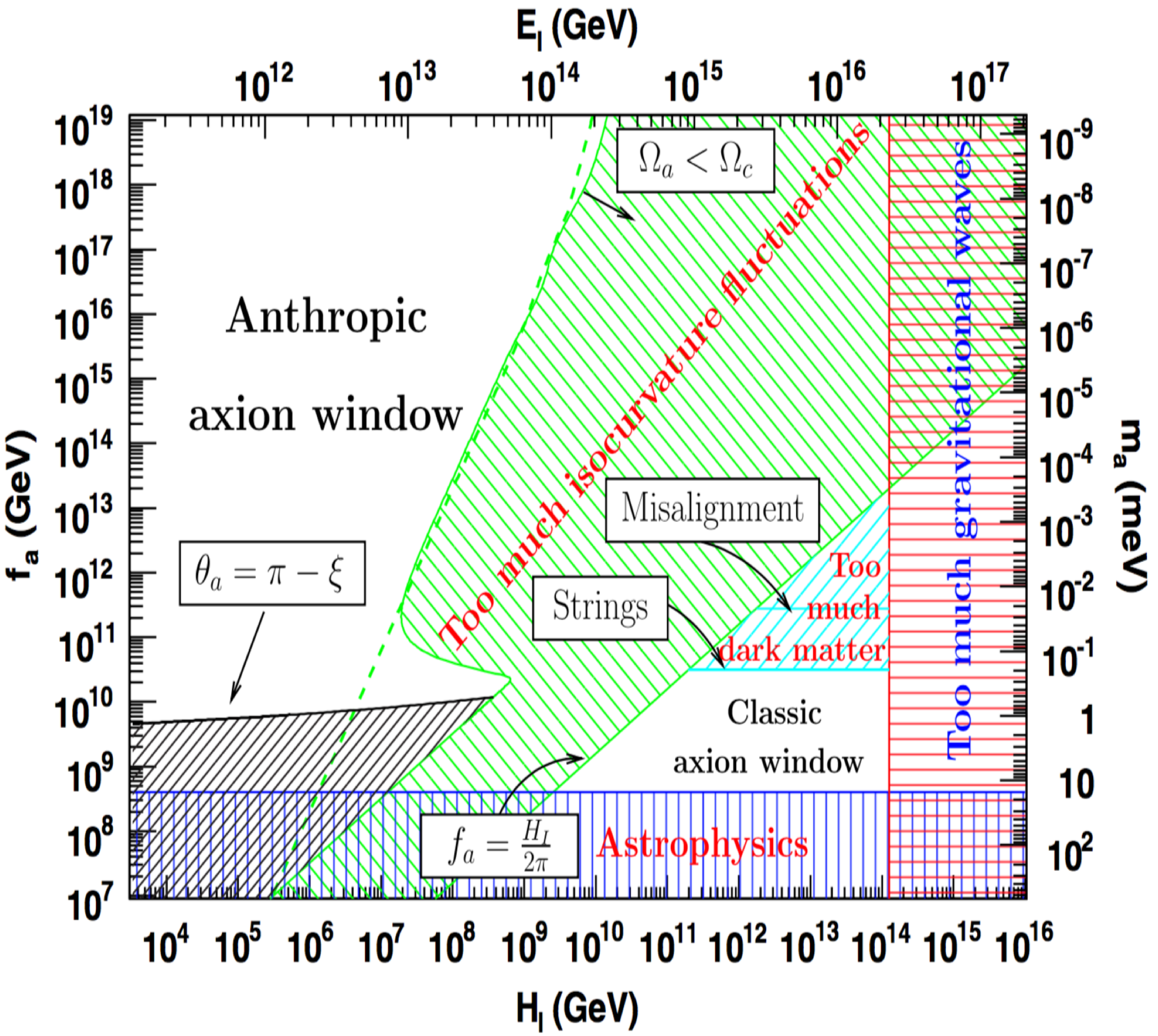
  - Upper bound on scale of inflation from isocurvature fluctuations produced by the axion during inflation and not erased afterwards:

$$H_I < 5.7\times 10^8\,{\rm GeV} \left(\frac{5.0\,{\rm neV}}{m_a}\right)^{0.4175}$$



[Wilczek,Turner `91; Beltran et al. 06; Hertzberg,Tegmark,Wilczek 08; Visinelli,Gondolo 09; Hamann et al. 09; **Wantz,Shellard 09**]

Axion Dark Matter

Post-inflationary PQ SSB scenario

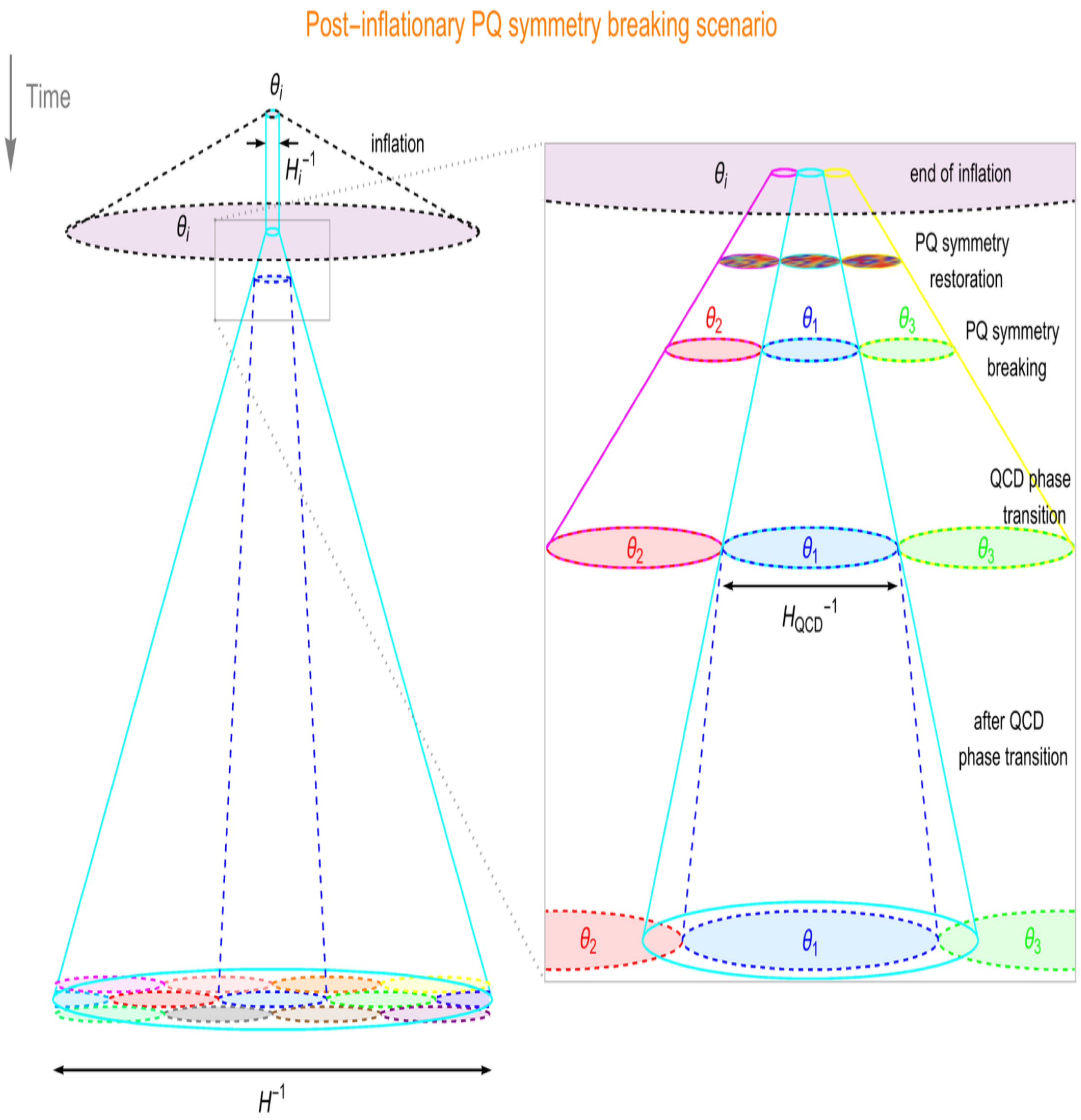
- Averaging over random initial axion field values

$$\Omega_A^{(\mathrm{VR})} h^2 = (3.8 \pm 0.6) \times 10^{-3} \left(\frac{f_A}{10^{10}\,\mathrm{GeV}} \right)^{1.165}$$

- Does not exceed observed CDM abundance for

$$m_A > 28(2)\,\mu\mathrm{eV}$$

[Borsanyi et al., Nature `16 [1606.0794]]



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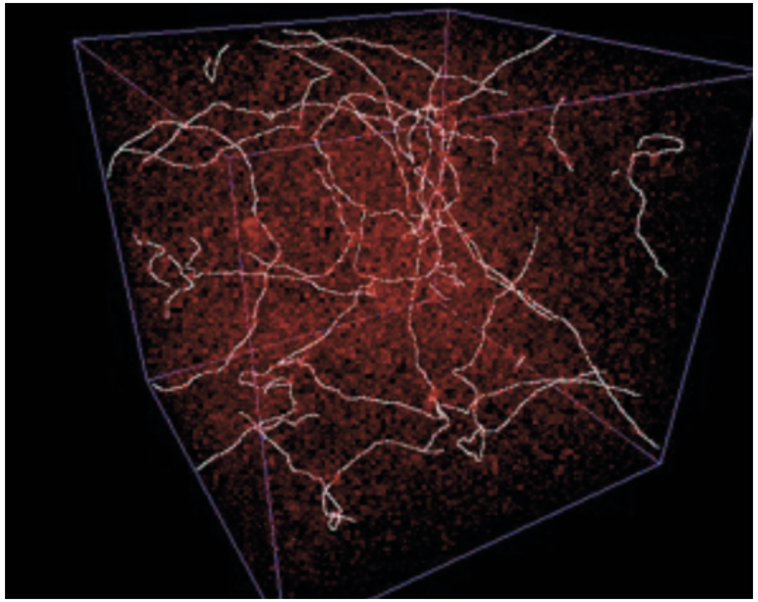
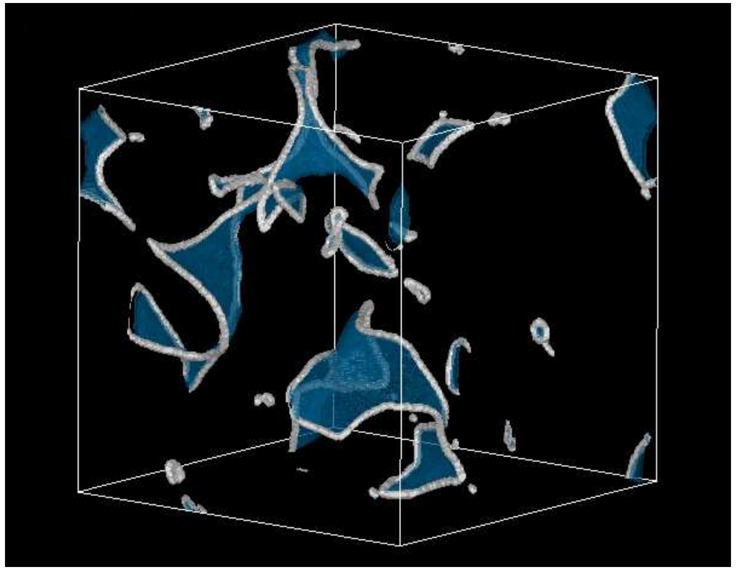
- Axions also produced by collapse of network of topological defects – strings and domain-walls –
  - Need field theoretic simulations to determine their contribution to dark matter



[Hiramatsu et al.]



Axion Dark Matter

Post-inflationary PQ SSB scenario

- For $N = 1$, exploiting results from field theoretic lattice simulations, updated to latest determination of topological susceptibility, find CDM explained for

[Hiramatsu et al. 11,12,13; Kawasaki,Saikawa,Segikuchi 15; Borsanyi et al. 16; Ballesteros et al. 16]

$$f_A \approx (3.8 - 9.9) \times 10^{10}\,\text{GeV} \quad \Leftrightarrow \quad m_A \approx (58 - 150)\ \mu\text{eV}$$

  - Still large unknown theoretical error because simulations can be done only at unrealistic values of string tension
  - Result from new simulation technique designed to work directly at high string tension: [Klaer,Moore `17]

$$m_A = (26.2 \pm 3.4)\,\mu\text{eV}$$

  - Evolution of axion spectrum crucial for reliable estimate of axion abundance from strings [Gorghetto,Hardy,Villadoro `18]

- For $N > 1$, domain wall problem can be avoided if PQ symmetry explicitely broken, e.g. by Planck suppressed operators, $\mathcal{L} \supset g M_{\rm P}^4 \left(\sigma/M_{\rm P}\right)^{\mathcal{N}} + \text{h.c.}$, for $\mathcal{N} = 9, 10$,

$$4.4 \times 10^7\,(1.3 \times 10^9)\,\text{GeV} < f_A < 1 \times 10^{10}\,\text{GeV} \;\Leftrightarrow\; 0.56\,\text{meV} < m_A < 130\,(4.5)\,\text{meV}$$

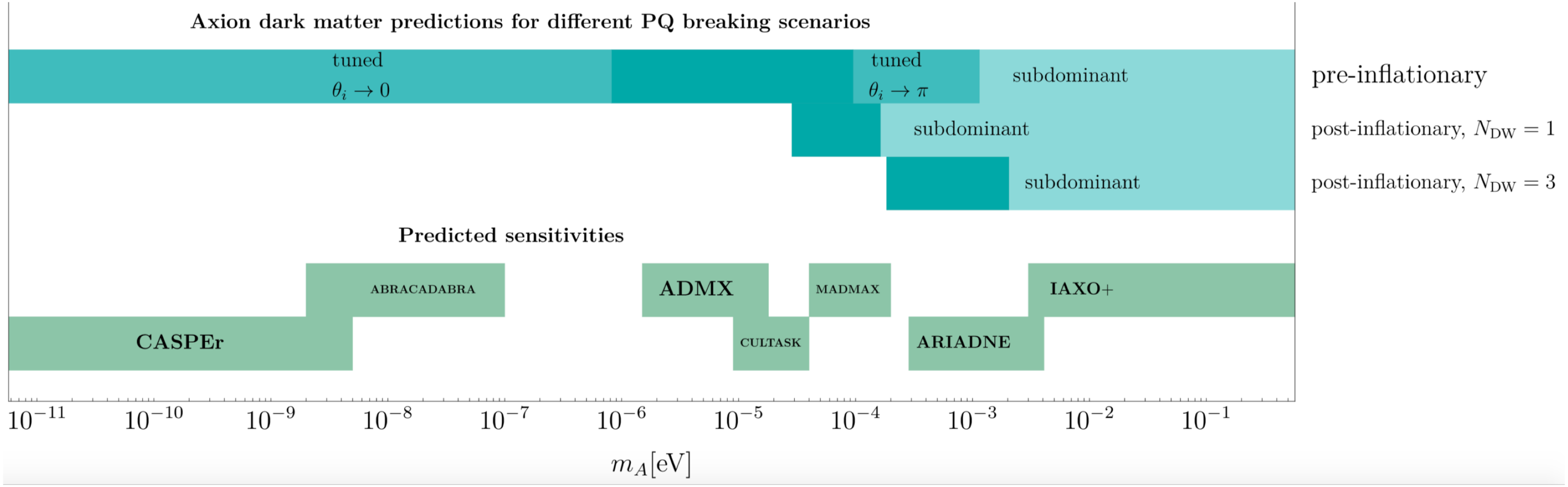
[Kawasaki,Saikawa,Sekiguchi `15; AR,Saikawa `16]

  - May postulate discrete symmetry to forbid lower dimensional operators e.g. [Dias et al. `14]
  - A DFSZ axion ($N = 6$) in this mass range explains excessive stellar energy losses [Giannotti,Irastorza,Redondo,AR,Saikawa`17]

Axion Dark Matter

Summary

- Dark-matter axion mass spans a huge range:



- Particularly well-motivated range: No Tuning

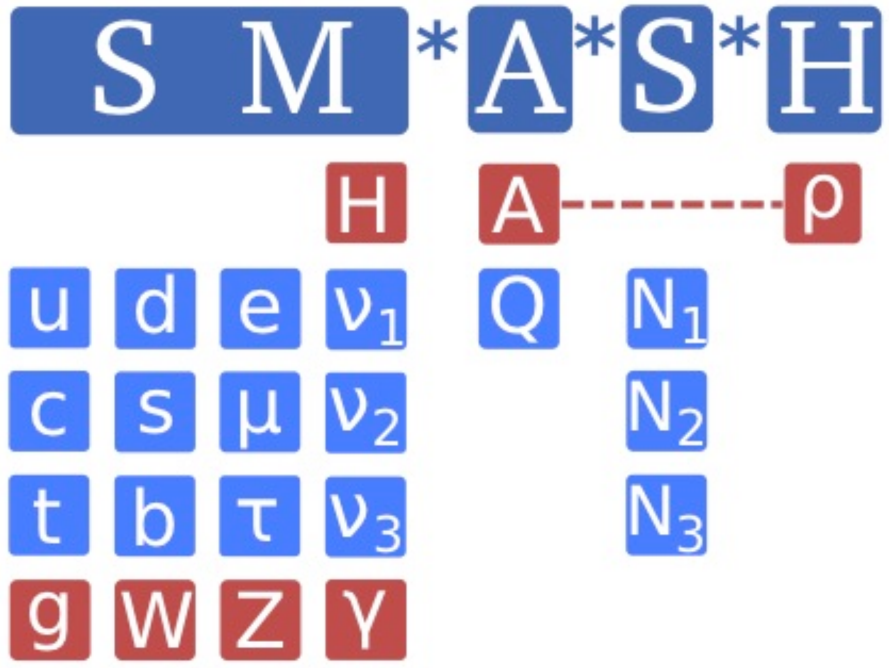
Minimal SMASH

Reminder ...

- KSVZ-type extension of SM plus three SM singlet neutrinos, getting their Majorana masses also through PQ vev $v_\sigma = f_A$
  - no strong CP problem
  - dark matter
  - inflation
  - neutrino masses and mixing
  - baryogenesis via leptogenesis

[Shin `88 ; Dias et al. `14; Ballesteros et al. `16]

SM***A**xion***S**eesaw***H**iggs Portal Inflation



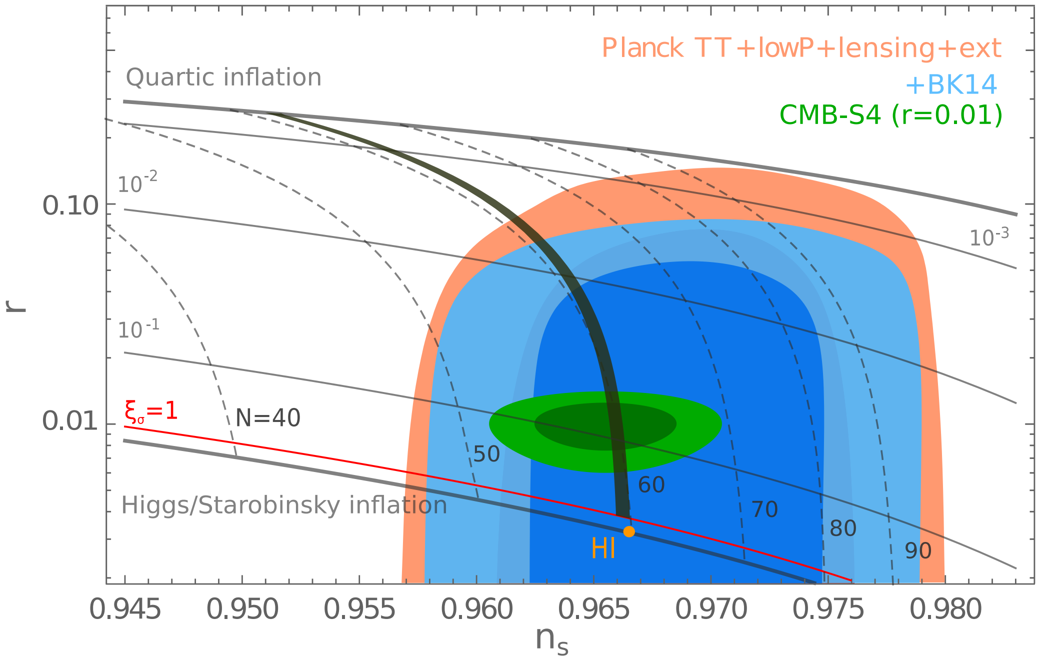
Minimal SMASH

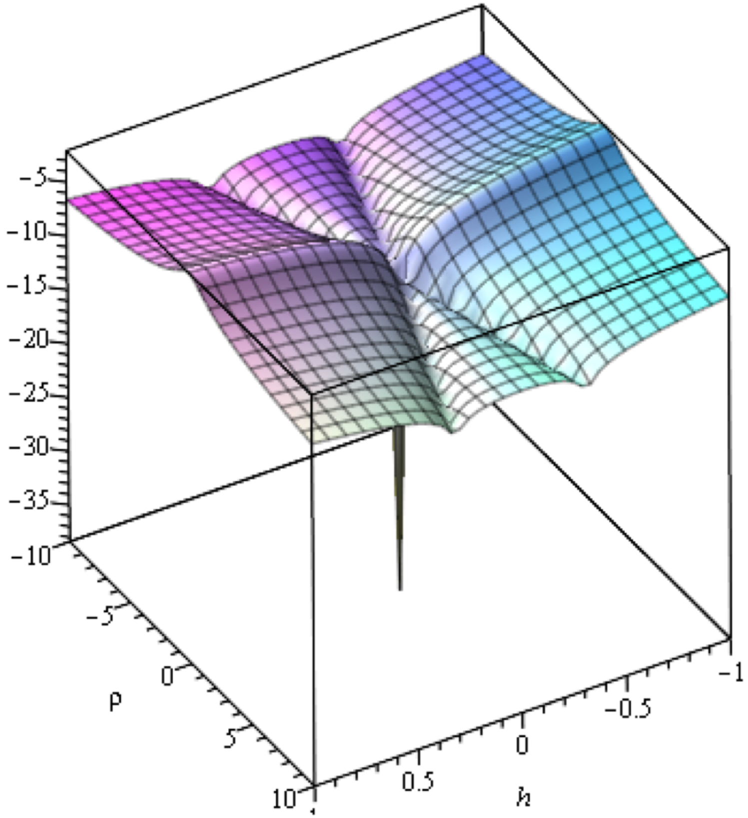
Non-Minimal Chaotic PQ Modulus Inflation

- Mixture of PQ modulus, $|\,\sigma\,| = \rho/\sqrt{2}$, with Higgs modulus is viable inflaton candidate, if it has non-minimal coupling to gravity, [Ballesteros et al. `16]

$$S \supset -\int d^4x\sqrt{-g}\;\xi_\sigma\,\sigma^*\sigma R$$

with $\xi_\sigma \simeq 2\times 10^5\sqrt{\lambda_\sigma} > \xi_H$ $\qquad \lambda_{H\sigma} < 0$





[Ballesteros,Redondo, AR,Tamarit `16]

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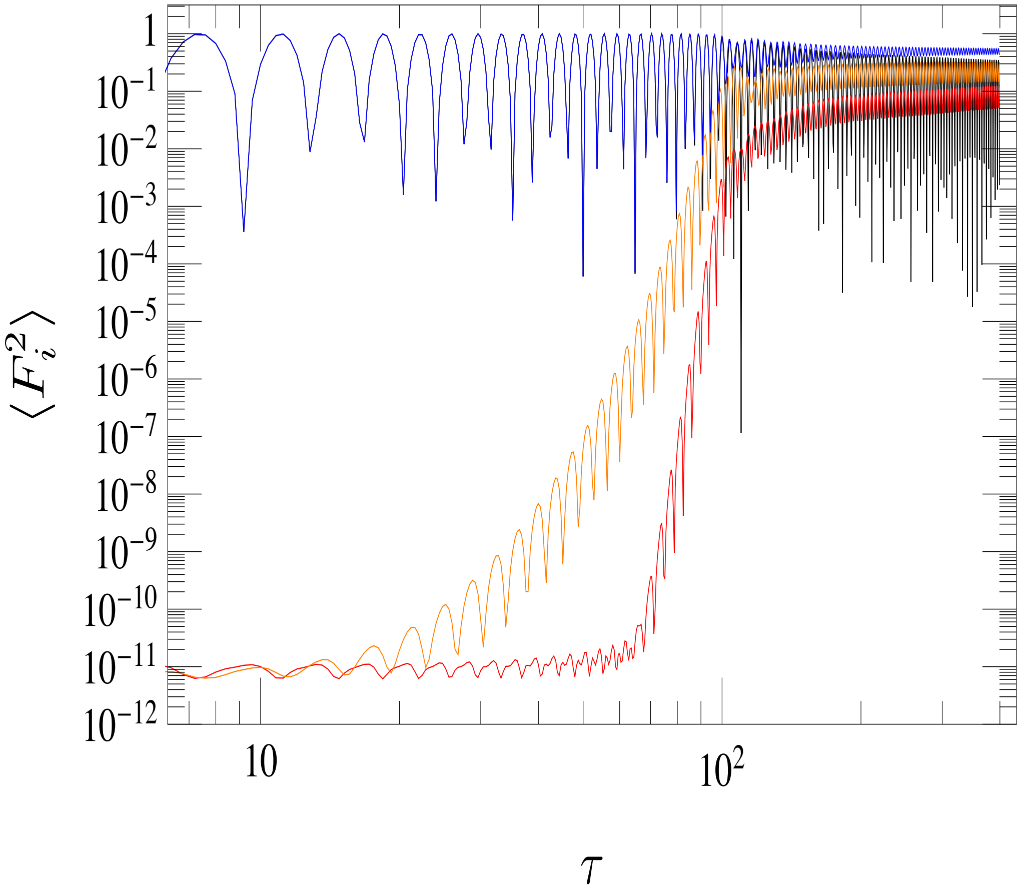
- Very predictive reheating:
  - For $f_A \lesssim 10^{16}\,\mathrm{GeV}$, PQ symmetry restored after inflation already in preheating stage
    - Dark-matter axion mass: $m_A \gtrsim 30\,\mu\mathrm{eV}$



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Minimal SMASH

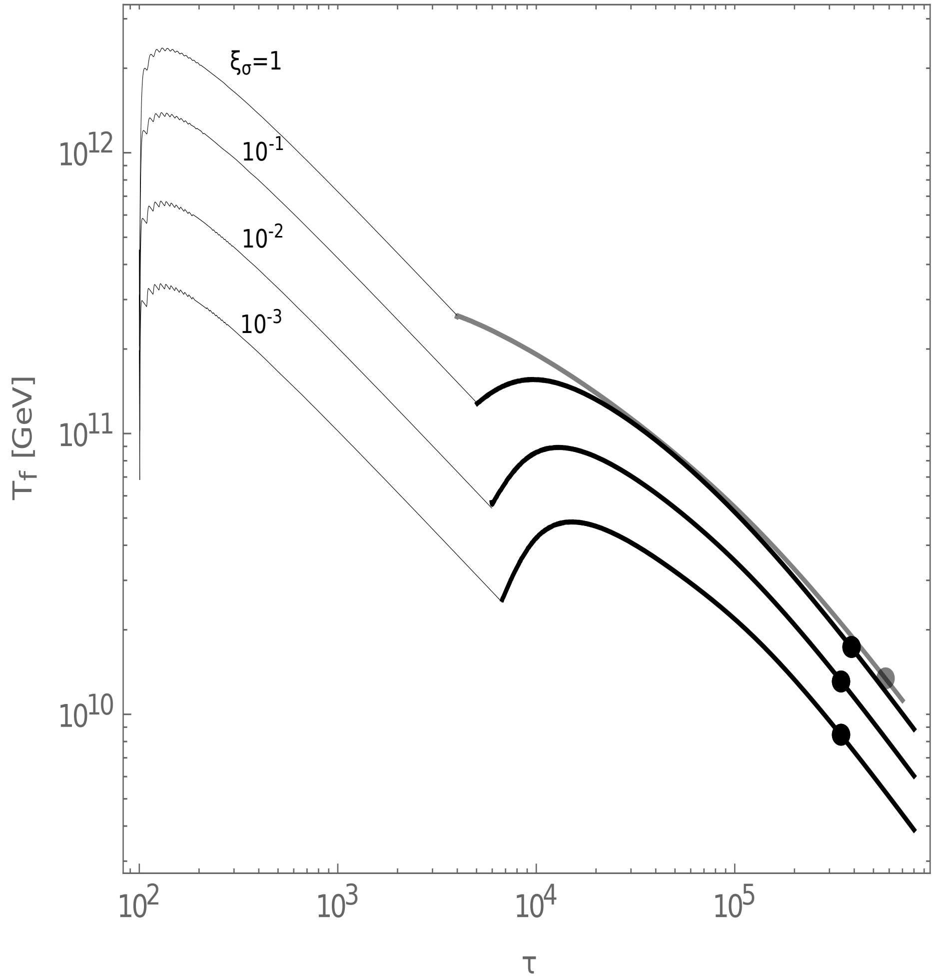
Non-Minimal Chaotic PQ Modulus Inflation

- Mixture of PQ modulus, $\mid \sigma \mid = \rho/\sqrt{2}$, with Higgs modulus is viable inflaton candidate, if it has non-minimal coupling to gravity, [Ballesteros et al. `16]

$$S \supset - \int d^4x \sqrt{-g}\, \xi_\sigma\, \sigma^* \sigma R$$

with $\xi_\sigma \simeq 2 \times 10^5 \sqrt{\lambda_\sigma} > \xi_H$ $\lambda_{H\sigma} < 0$

- Very predictive reheating:
  - For $f_A \lesssim 10^{16}\,\mathrm{GeV}$, PQ symmetry restored after inflation already in preheating stage
    - Dark-matter axion mass: $m_A \gtrsim 30\,\mu\mathrm{eV}$
  - Higgs component of inflaton allows for production of SM gauge bosons, resulting in large reheating temperature: $T_R \sim 10^{10}\,\mathrm{GeV}$
    - Axion dark radiation: $\Delta N_\nu^{\mathrm{eff}} \simeq 0.0268 \left(\frac{427/4}{g_{*s}(T_A^{\mathrm{dec}})} \right)^{4/3}$



[Ballesteros,Redondo, AR,Tamarit `16]

Axion in Non-SUSY SO(10) GUT

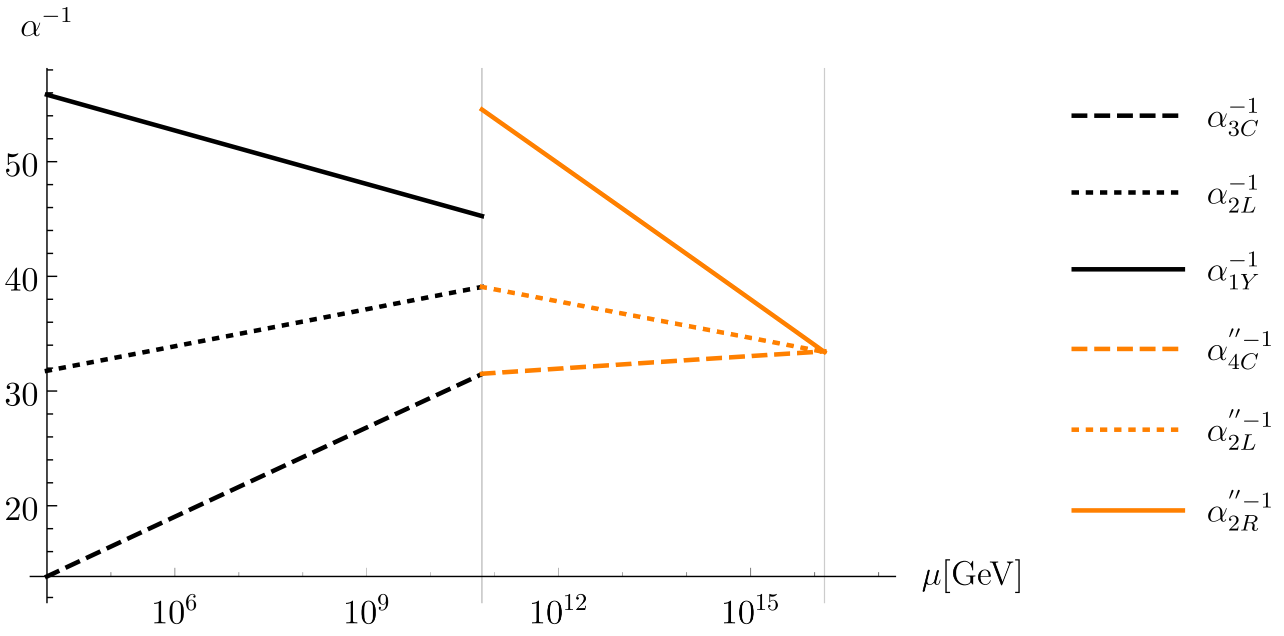
The virtue of imposing a Peccei-Quinn symmetry

- SO(10) GUT with three copies of 16_F automatically features
  - neutrino masses and mixing
  - baryogenesis via leptogenesis
- Gauge coupling unification needs at least one intermediate scale; often discussed SSB chain:

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

$SO(10)$	$4_C 2_L 2_R$	$4_C 2_L 1_R$	$3_C 2_L 1_R 1_{B-L}$	$3_C 2_L 1_Y$	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_{BL}

[Ernst, AR, Tamarit, arXiv:1801.04906]



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$$SO(10) \overset{M_{\rm U}-210_H}{\longrightarrow} SU(4)_C \times SU(2)_L \times SU(2)_R \overset{M_{\rm BL}-126_H}{\longrightarrow} SU(3)_C \times SU(2)_L \times U(1)_Y \overset{M_Z-10_H}{\longrightarrow} SU(3)_C \times U(1)_{\rm em}$$

- 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:

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

- Fermion masses/mixing:

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

Axion in Non-SUSY SO(10) GUT

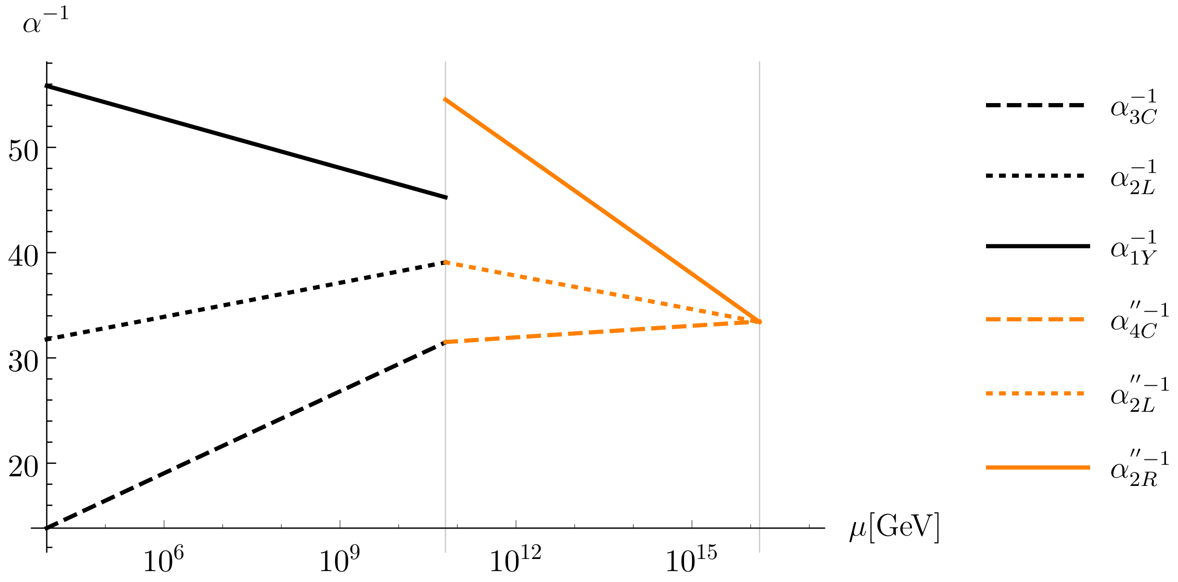
Axion predictions and experimental prospects

- Axion decay constant:

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

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

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



[Ernst, AR, Tamarit, arXiv:1801.04906]

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

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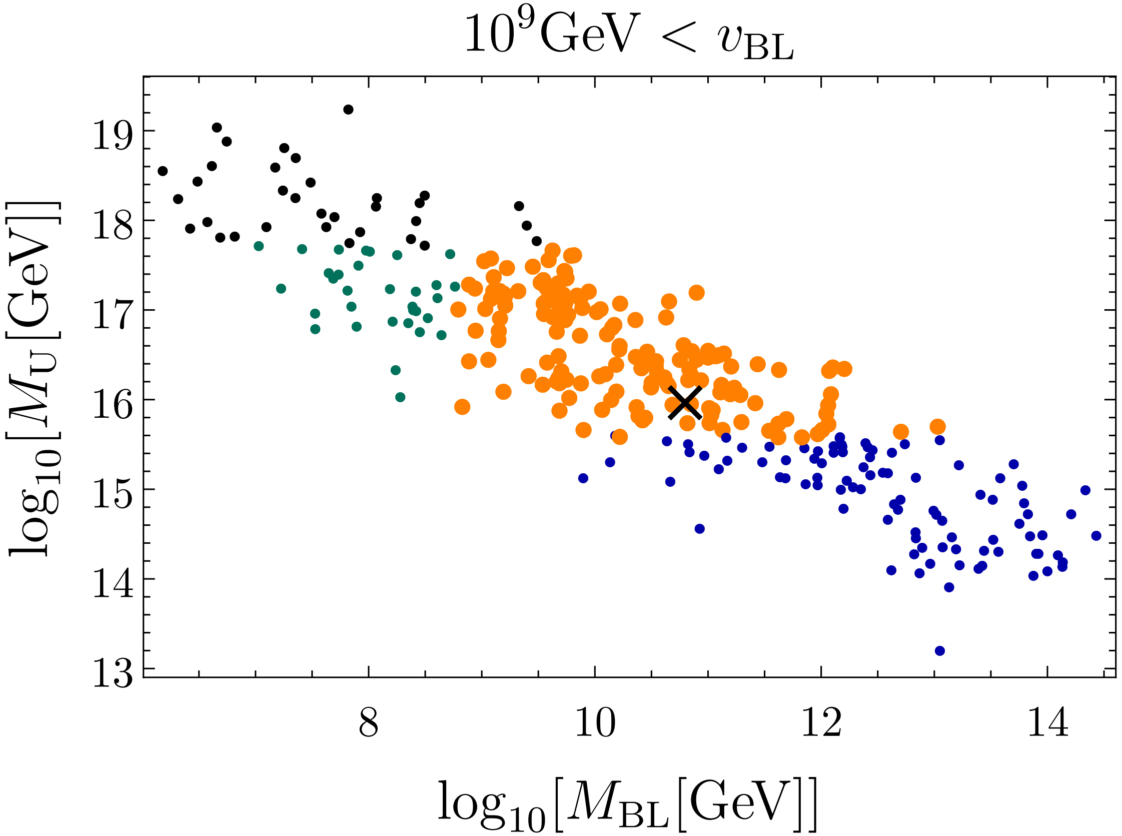

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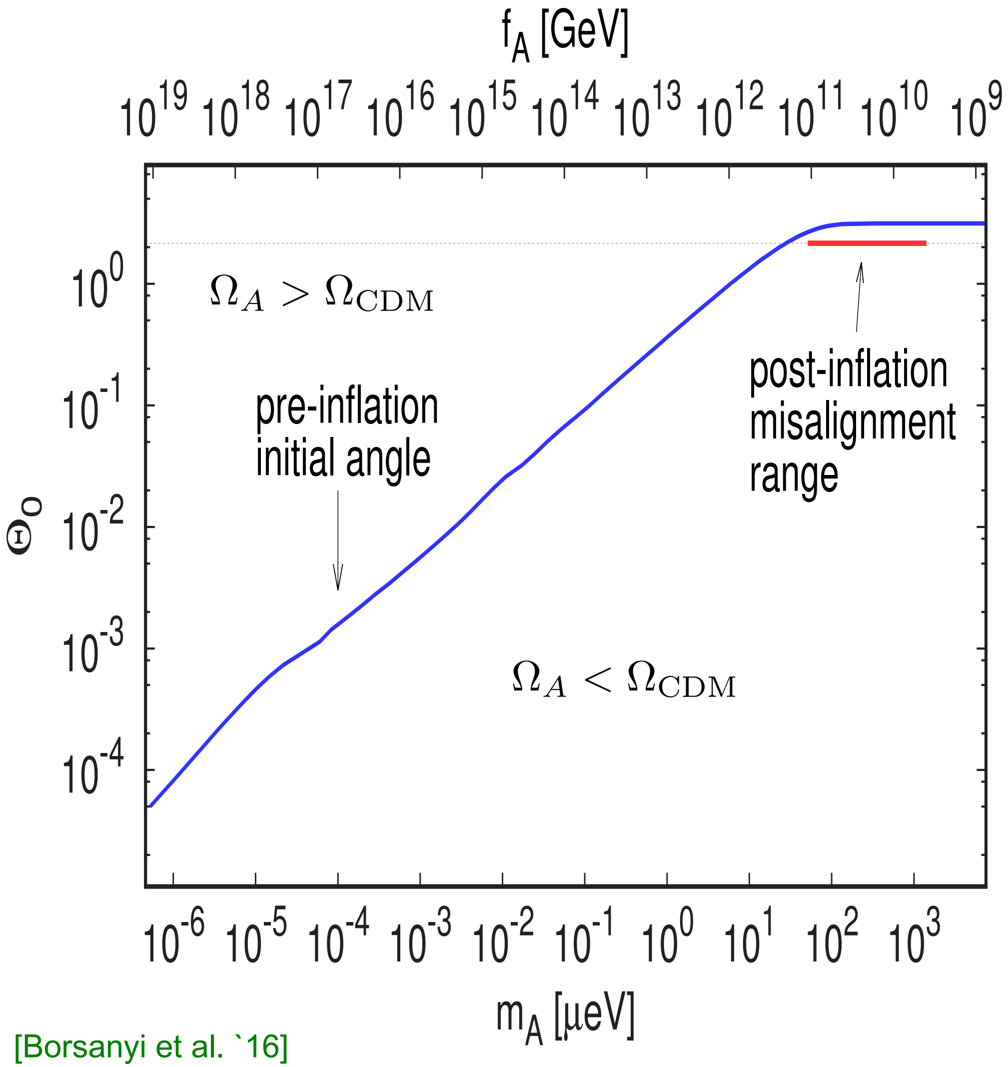
$$\Omega_a h^2 = 0.12\left(\frac{5.0\ \mathrm{neV}}{m_a}\right)^{1.165}\left(\frac{\theta_\mathrm{i}}{1.6\times10^{-2}}\right)^2$$



[Borsanyi et al. `16]

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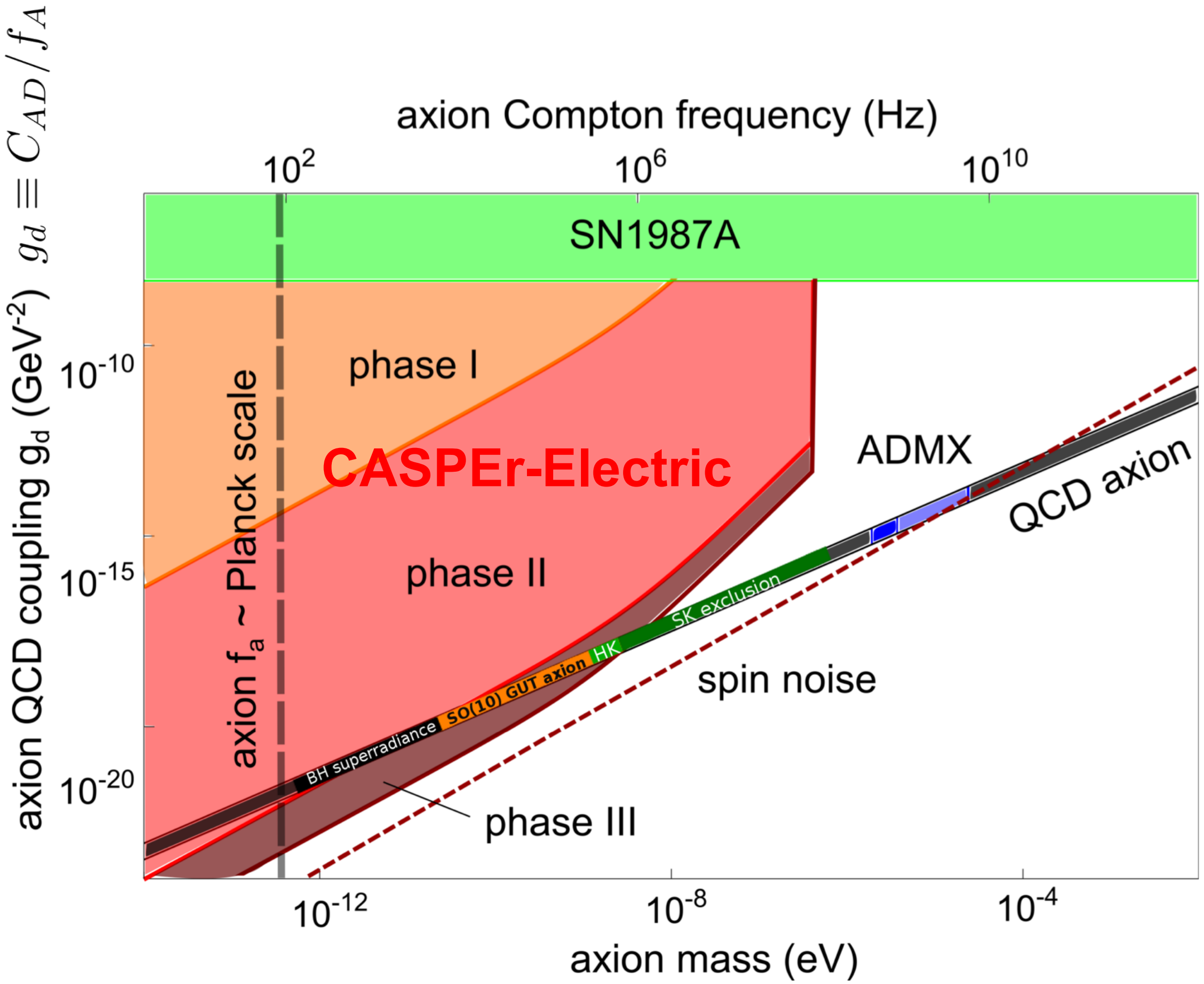

[Ernst 18; CASPEr prospects from Kimball et al. 17]

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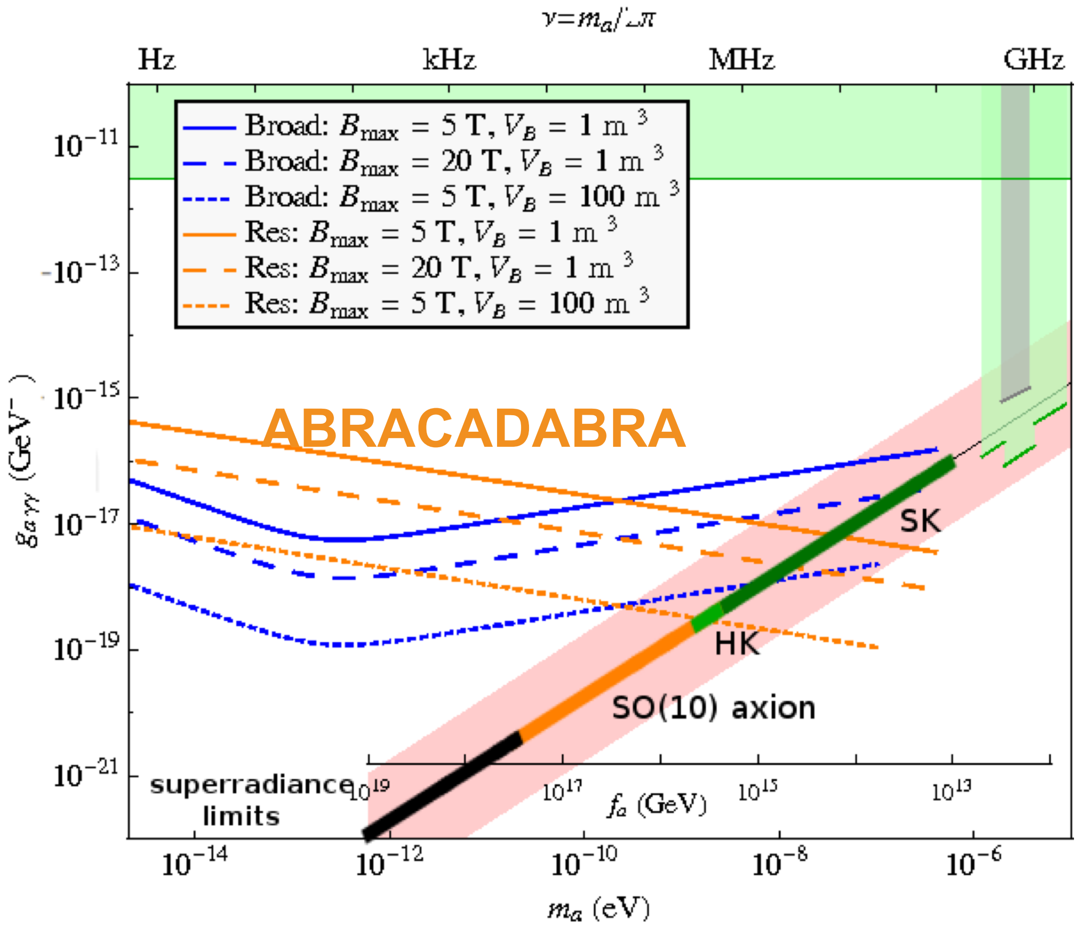

[Ernst 18; ABRACADABRA prospects from Kahn,Safdi,Thaler 16]

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

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

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

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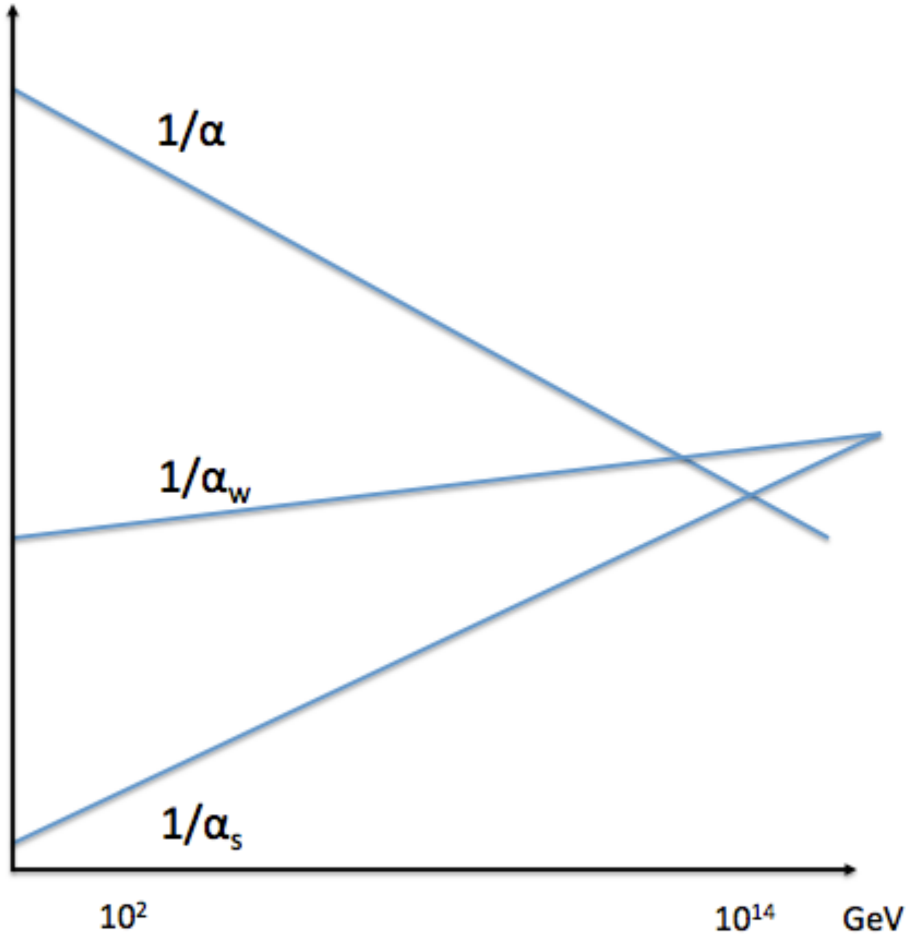

[StackExchange]

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  - Mixture of type-I and type-III seesaw from electroweak fermion singlets and triplets, $S_F = (1,1,0)_F$ and $T_F = (1,3,0)$

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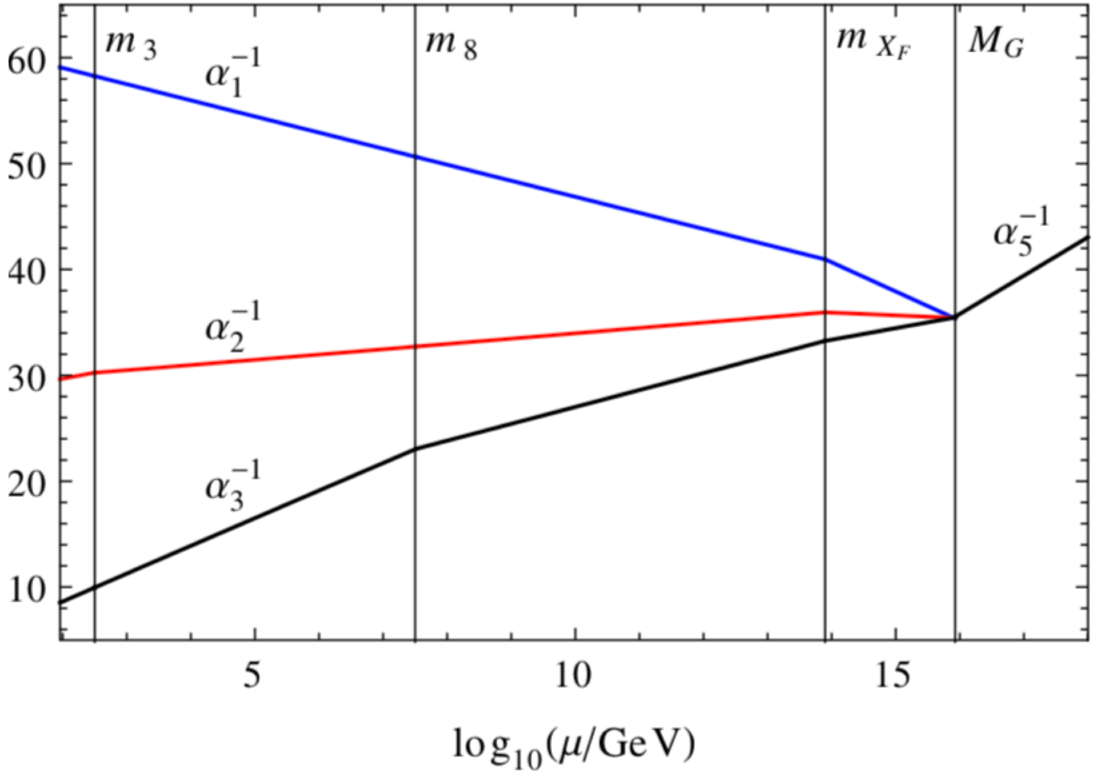

[Di Luzio, Mihaila 13]

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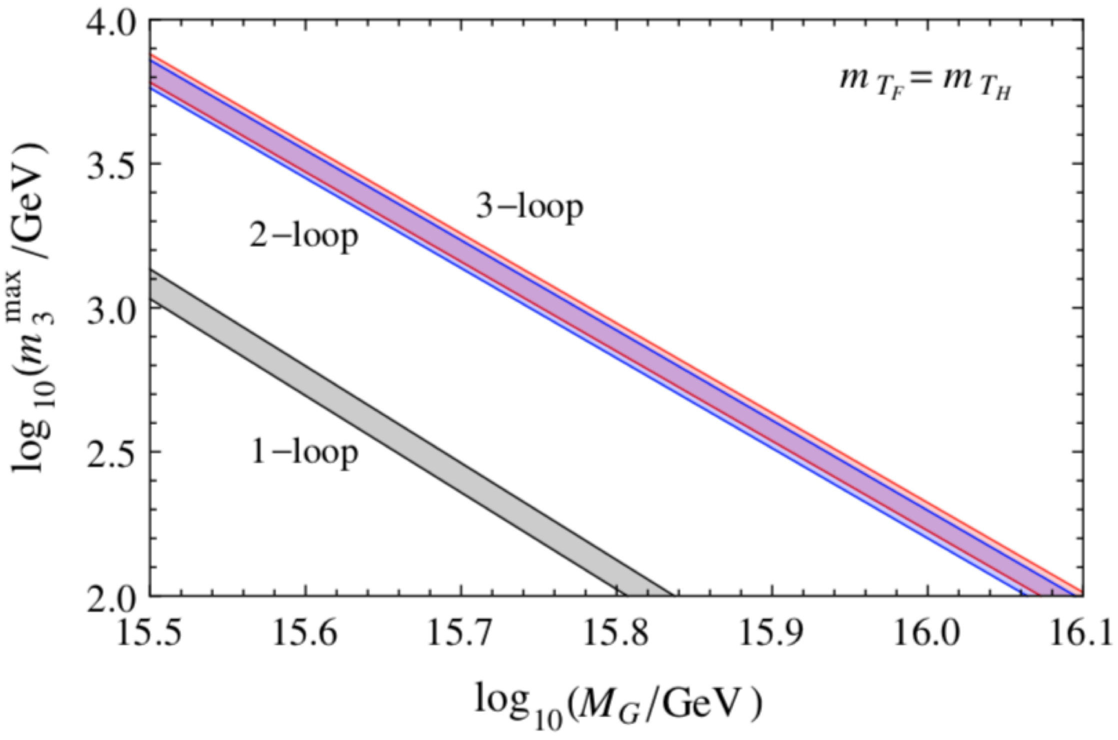
    - Clean correlation between effective electroweak triplet mass m_3 and unification scale M_G



[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:

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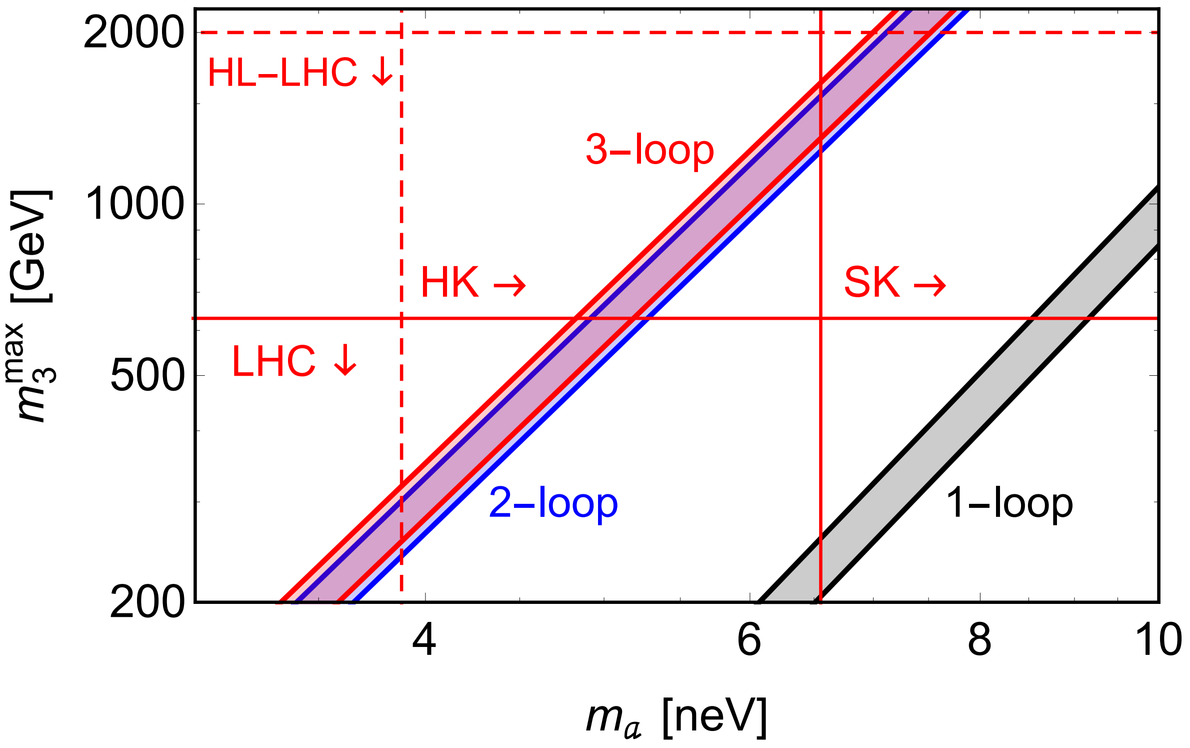
- Axion decay constant:

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

- 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]

Axion in Non-SUSY SU(5) GUT

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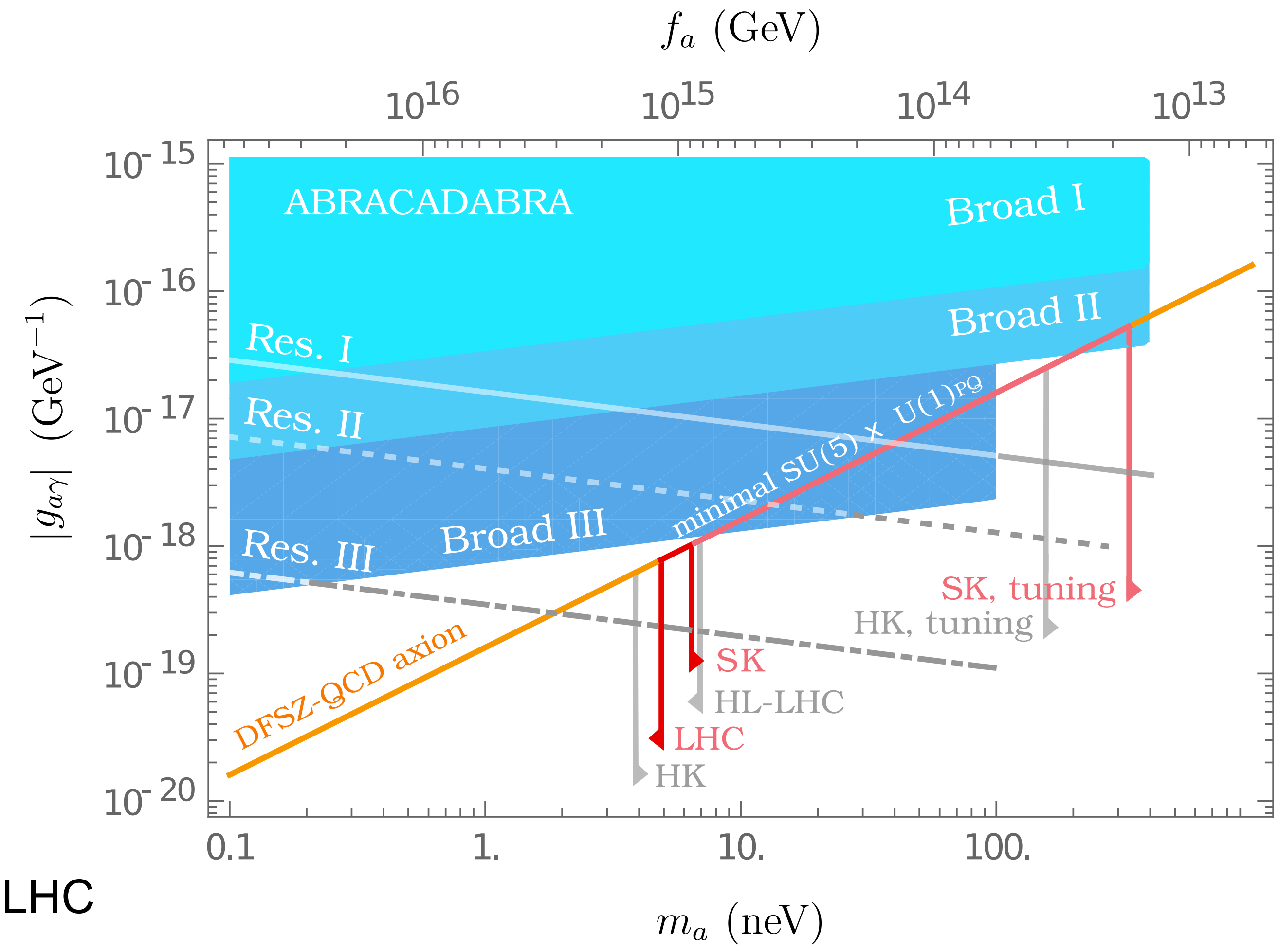

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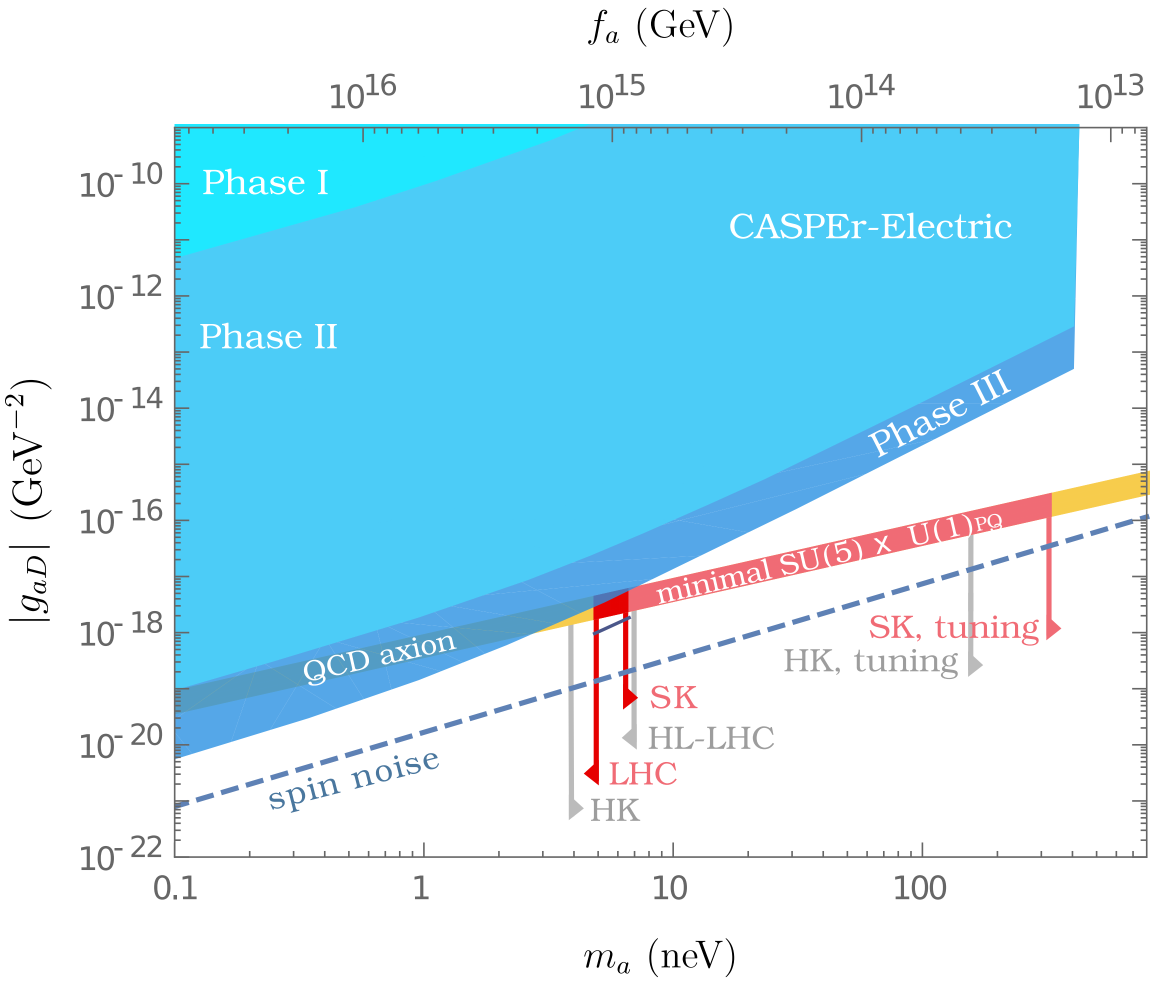


[Di Luzio, AR, Tamarit, arXiv:1807.09769]

Axion in Non-SUSY SU(5) GUT

GUT SMASH?

- PQ symmetry has to be broken during and after inflation to avoid
  - SU(5) monopole problem
  - axion DM overabundance

  and isocurvature constraints have to be obeyed

- In case of non-minimal chaotic inflation along one of the components of 24_H, exploiting

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

  - Isocurvature constraints can disappear completely since lightest fluctuations orthogonal to inflaton can have masses above H_I as long as non-minimal coupling $\xi_{24_H} \gtrsim 0.01$. In this case isocurvature fluctuations exponentially suppressed
  - PQ and GUT symmetry not restored if quartic and Yukawa couplings of 24_H sufficiently small

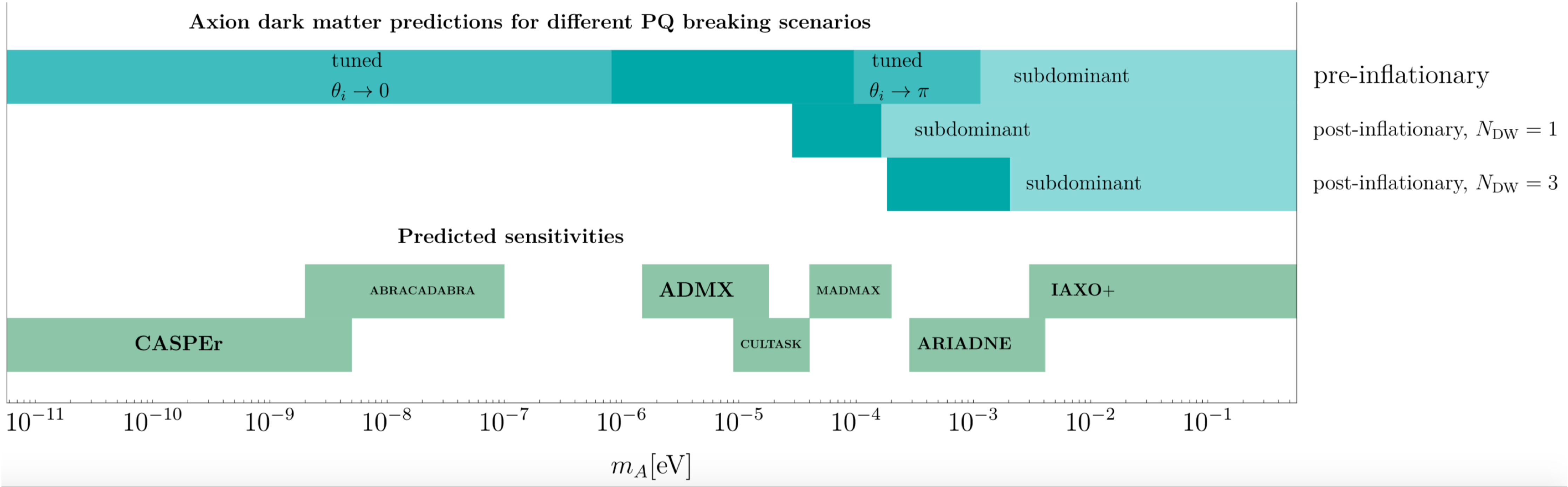
[Di Luzio, AR, Tamarit, arXiv:1807.09769 and in process]

Summary

- PQ extensions of SM very attractive:
  - Axion solves strong CP puzzle
  - Axion is dark matter candidate (for $f_A \gtrsim 10^8\,\mathrm{GeV} \;\Leftrightarrow m_A \lesssim 60\,\mathrm{meV}$)
  - PQ field/Higgs is non-minimal chaotic inflaton candidate (for $1 \gtrsim \xi_\sigma \simeq 2\times 10^5\sqrt{\lambda_\sigma} \gtrsim 10^{-3}$)

Summary

- Theoretically particularly well-motivated axion mass ranges:



GUT SMASH

Minimal SMASH

Back-Up: Topological Susceptibility

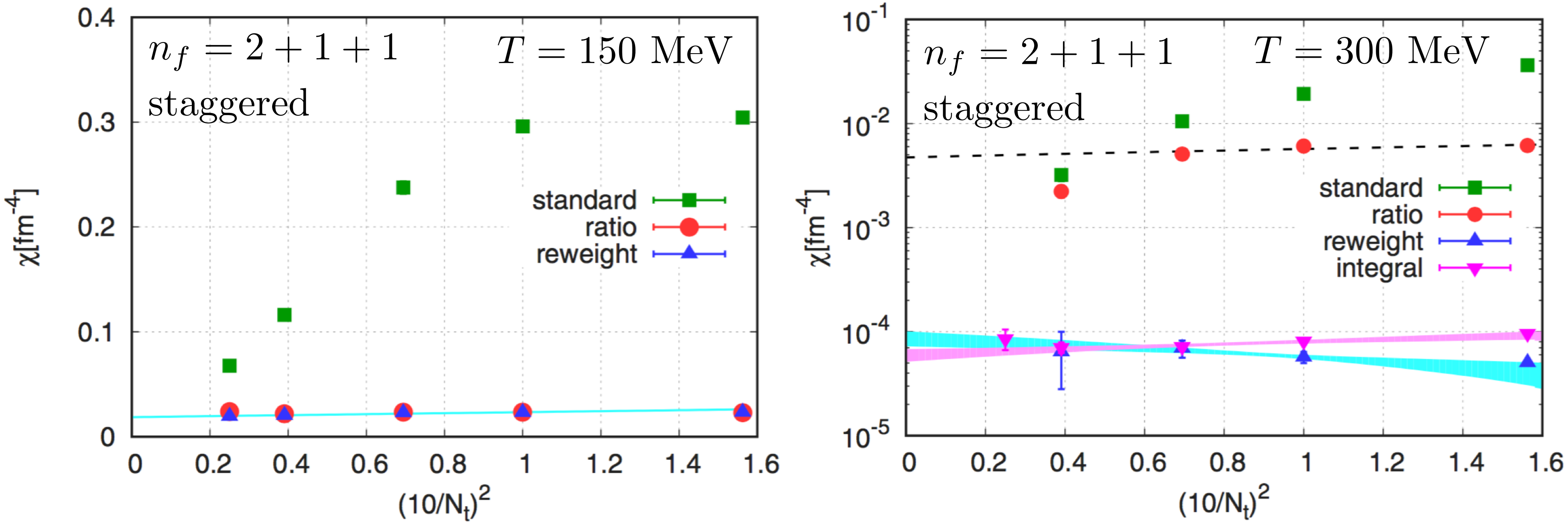
- Topological susceptibility notoriously difficult to calculate on lattice
  1. Large cutoff effects when exploiting action with non-chiral quarks to calculate topo-logical observables
  2. Tiny topological susceptibility needs extremely long simulation threads to observe enough changes of topological sectors
- Solutions of these problems:

[Borsanyi et al. `16]

  1. Eigenvalue reweighting technique: Substitute topology related eigenvalues of non-chiral quark Dirac operator with its corresponding eigenvalues in continuum
  2. Fixed sector integral technique: Measure logarithmic differential of topological sus-ceptibility which is related to quantities to be measured in fixed topological sectors. Then integrate.

Back-Up: Topological Susceptibility

- Comparison of lattice spacing dependence of topological susceptibility determined via different methods:



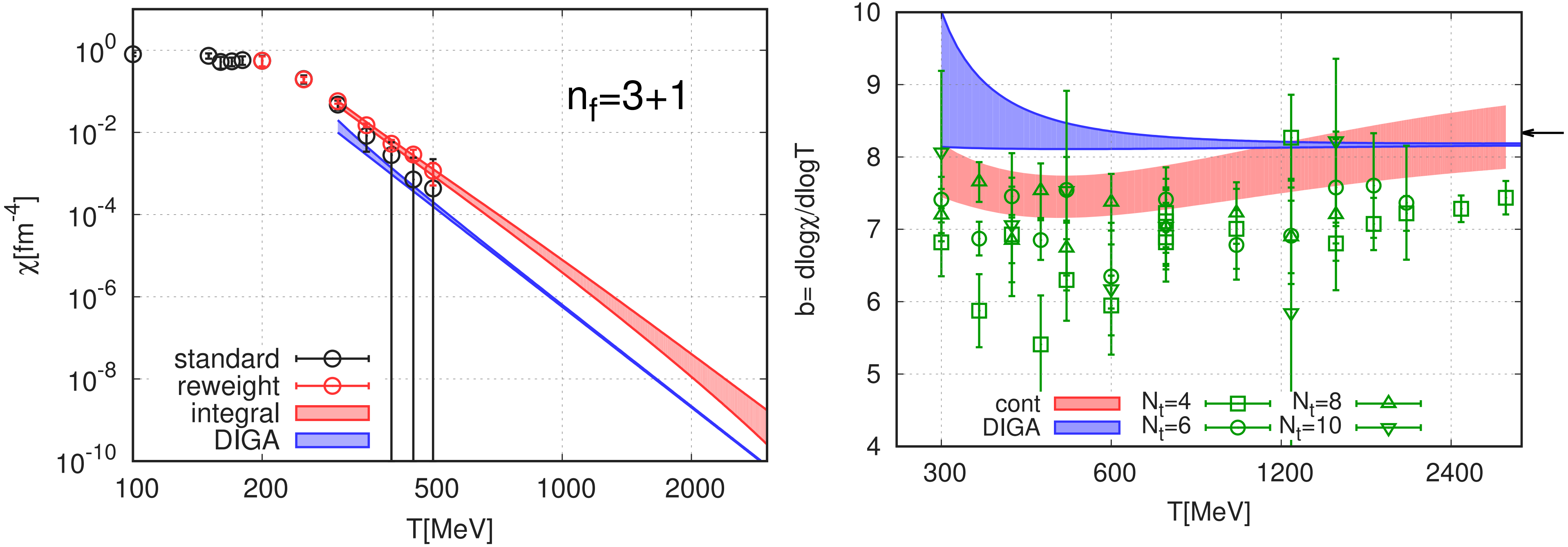
[Borsanyi et al. `16]

- At high temperatures, brute force („standard“) method and ratio method suffer from strong cutoff effects

Back-Up: Topological Susceptibility

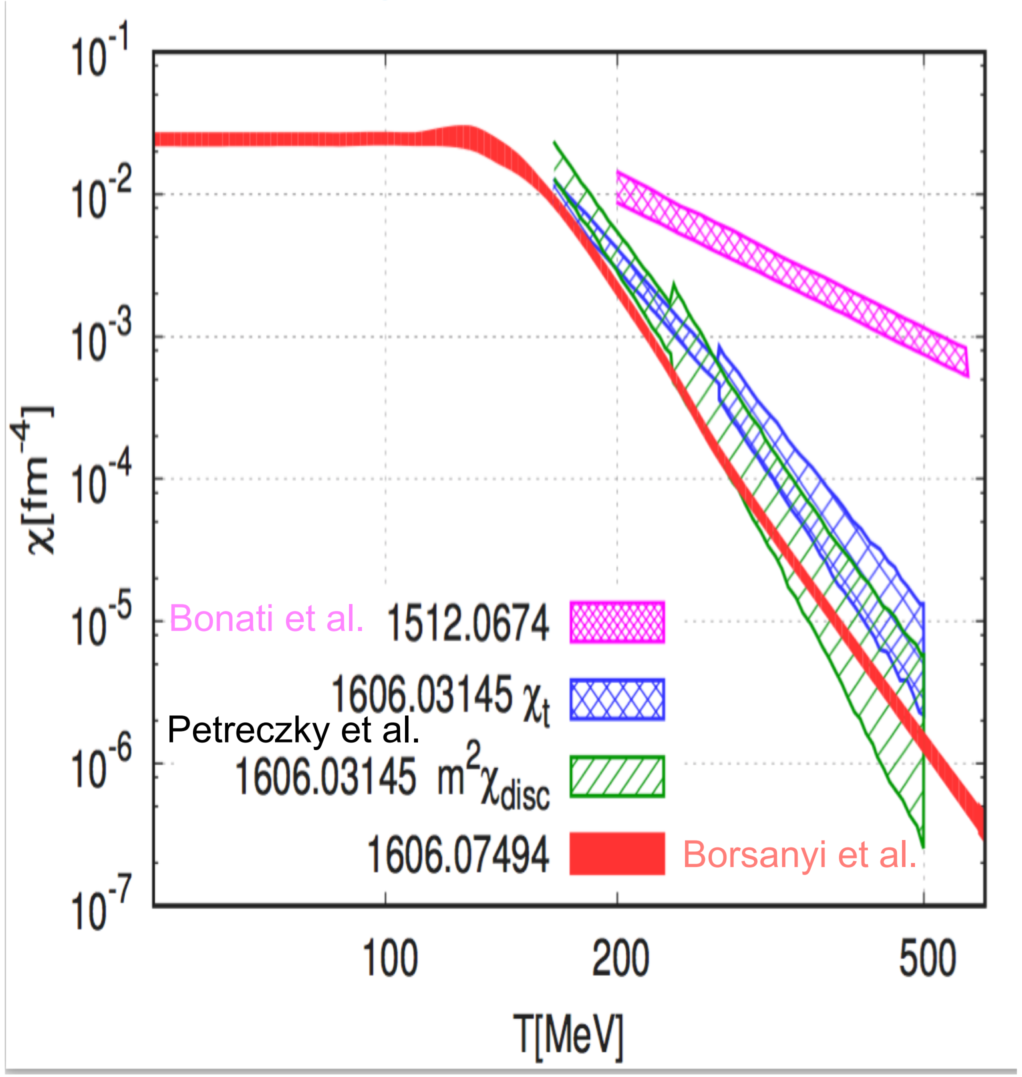
- Result:

[Borsanyi et al. `16]

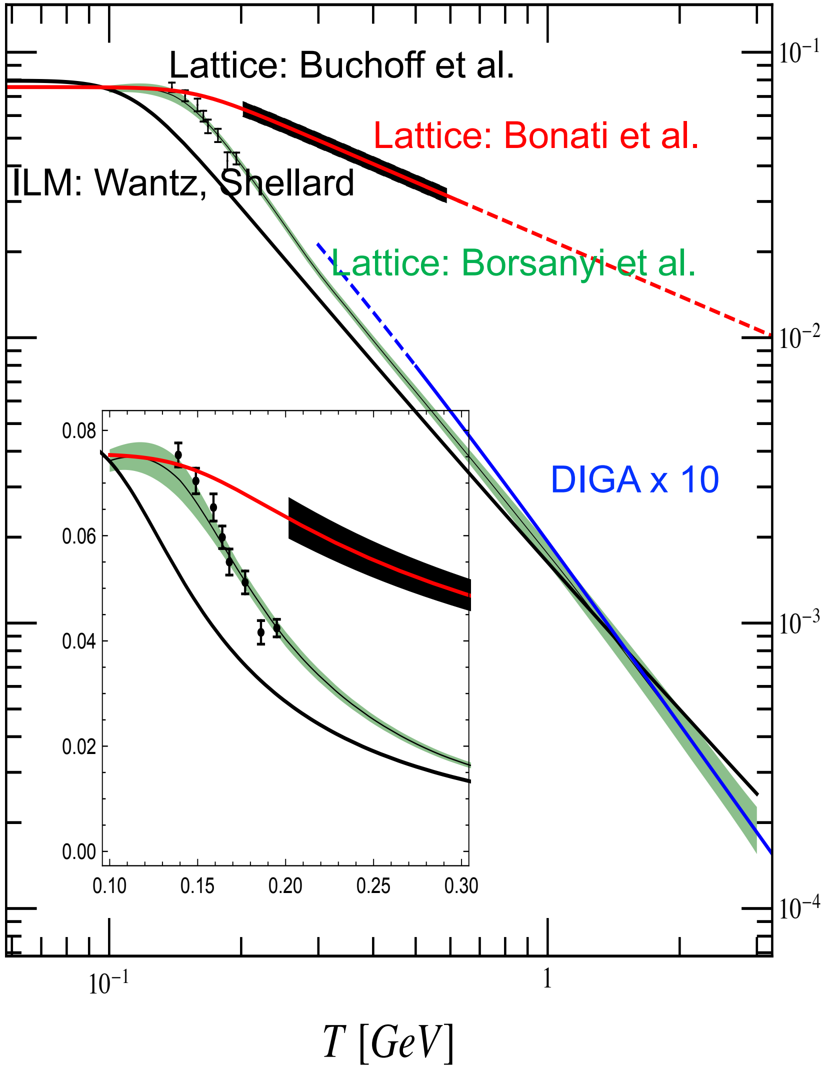


- Temperature slope close to dilute instanton gas approximation (DIGA)
- DIGA underestimates topological susceptibility by overall normalization „K factor“ of order ten (should be improved in two-loop DIGA)

Back-Up: Topological Susceptibility



[Borsanyi `16]



[Ballesteros,Redondo, AR,Tamarit `16]

Back-Up: DM Axion Mass in Post-Inflationary PQ SB Scenario

- For $\kappa \gg 1$, string‘s interactions with the long range PQ field ($\propto f_A^2$) become less important relative to string evolution under tension ($\propto f_A^2\kappa$)
- For $\kappa \gg 1$, string behavior should approach that of infinitely thin, i.e. local Nambu-Goto strings
- New method: exploit UV extension of PQ field theory, with additional comp-lex scalar and additional local U(1) symmetry, [Klaer,Moore `17]

$$T_{\rm str} = \pi f_A^2 \kappa$$
$$\kappa = \ln(\sqrt{2\lambda_\sigma} f_A/H)$$

$$\begin{aligned}
\mathcal{L} &= \mathcal{L}_{\rm NG} + \mathcal{L}_{\rm GS} + \mathcal{L}_{\rm KR}\,,\\
\mathcal{L}_{\rm NG} &= \bar\kappa \pi f_A^2 \int d\sigma \sqrt{y'^2(\sigma)(1-\dot y^2(\sigma))}\,,\\
\mathcal{L}_{\rm GS} &= f_A^2 \int d^3x\; \partial_\mu\theta \partial^\mu\theta\,,\\
\mathcal{L}_{\rm KR} &= \int d^3x\; A_{\mu\nu} j^{\mu\nu}\,,\\
H_{\mu\nu\alpha} &= f_A \epsilon_{\mu\nu\alpha\beta}\partial^\beta\theta = \partial_\mu A_{\nu\alpha} + \text{cyclic}\,,\\
j^{\mu\nu} &= -2\pi f_A \int d\sigma\, \left(v^\mu y'^\nu - v^\nu y'^\mu\right) \delta^3(x-y(\sigma))
\end{aligned}$$

$$\begin{aligned}
-\mathcal{L}(\varphi_1,\varphi_2,A_\mu) = {}& \frac{1}{4e^2} F_{\mu\nu}F^{\mu\nu} + \Big|(\partial_\mu - iq_1 A_\mu)\varphi_1\Big|^2 + \Big|(\partial_\mu - iq_2 A_\mu)\varphi_2\Big|^2\\
& + \frac{m_1^2}{8v_1^2}\left(2\varphi_1^*\varphi_1 - v_1^2\right)^2 + \frac{m_2^2}{8v_2^2}\left(2\varphi_2^*\varphi_2 - v_2^2\right)^2 + \frac{\lambda_{12}}{2}\left(2\varphi_1^*\varphi_1 - v_1^2\right)\left(2\varphi_2^*\varphi_2 - v_2^2\right)
\end{aligned}$$

Back-Up: DM Axion Mass in Post-Inflationary PQ SB Scenario

- Exploiting lattice results on topological susceptibility of [Borsanyi et al. `16] :

$$m_A = 26.2 \pm 3.4\,\mu\mathrm{eV}$$ [Klaer,Moore `17]

- Axion production efficiency smaller than angle-average of ``realignment'' mechanism

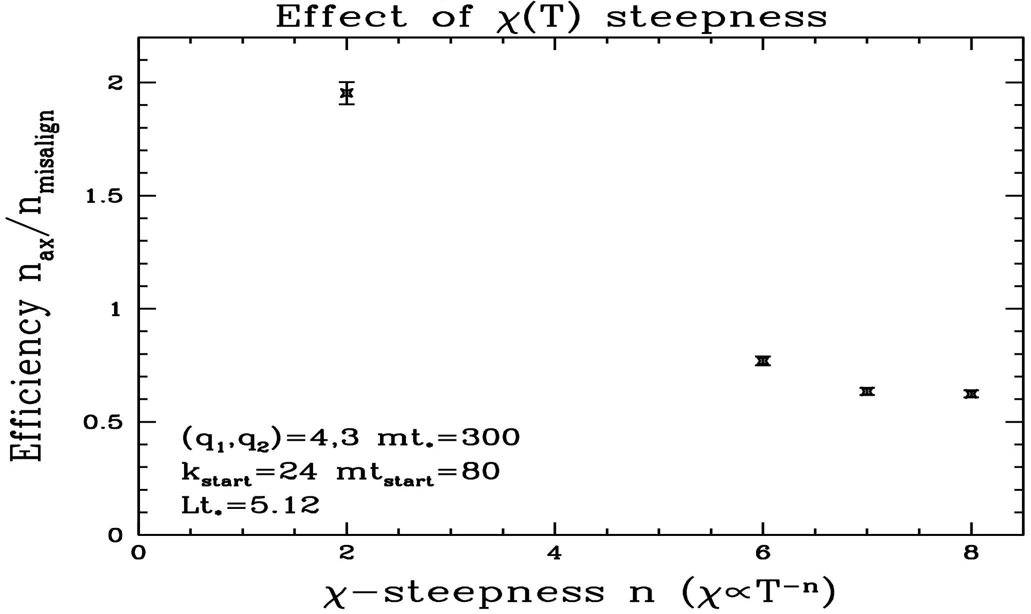
$$\Omega_A^{\rm vr} h^2 = 0.12 \left(\frac{29.7\ \mu\mathrm{eV}}{m_A} \right)^{1.165}$$

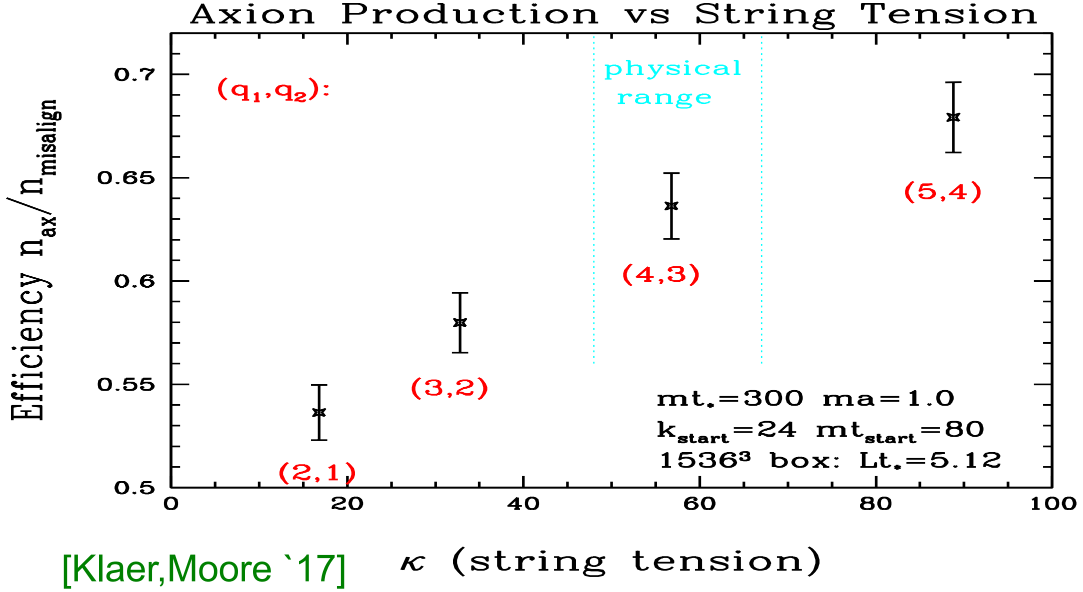
  - Simple sum

    $$\Omega_A^{\rm tot} = \Omega_A^{\rm vr} + \Omega_A^{\rm string+wall}$$

    double counts

    - Energy in domain walls is the energy of field misalignment, from values $\theta \sim \pi$





[Klaer,Moore `17]

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

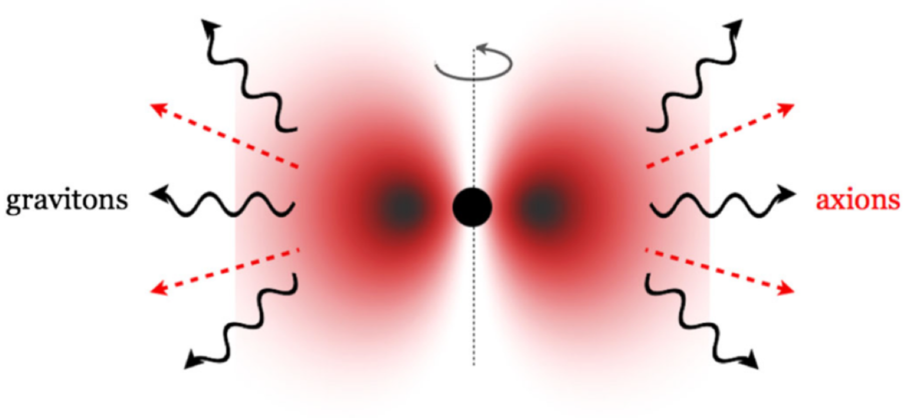


FIG. 1 (color online). *Axionic Black Hole Atom:* The spinning black hole "feeds" superradiant states forming an axion Bose-Einstein condensate. The resulting bosonic atom will emit gravitons through axion transitions between levels and annihilations and will emit axions as a consequence of self-interactions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

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

Back Up: Axion/ALP bounds from BH superradiance

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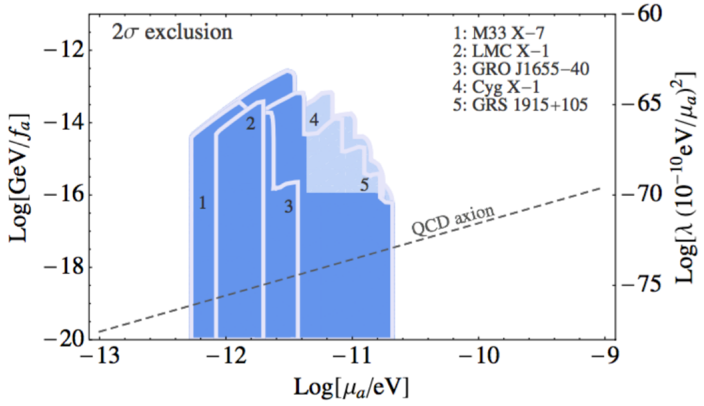
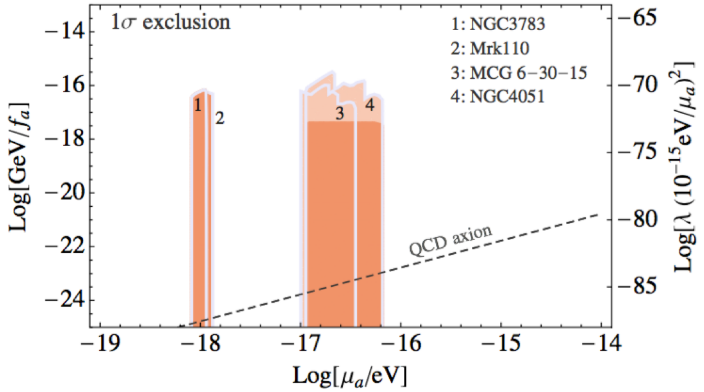
> Stellar BH spin measurements exclude

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



(a)

[Arvanitaki et al. 14]



(b)