Unifying Inflation with the Axion, Dark Matter, Baryogenesis, and the Seesaw Mechanism.

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Astroteilchenseminar
Max-Planck-Institut für Kernphysik
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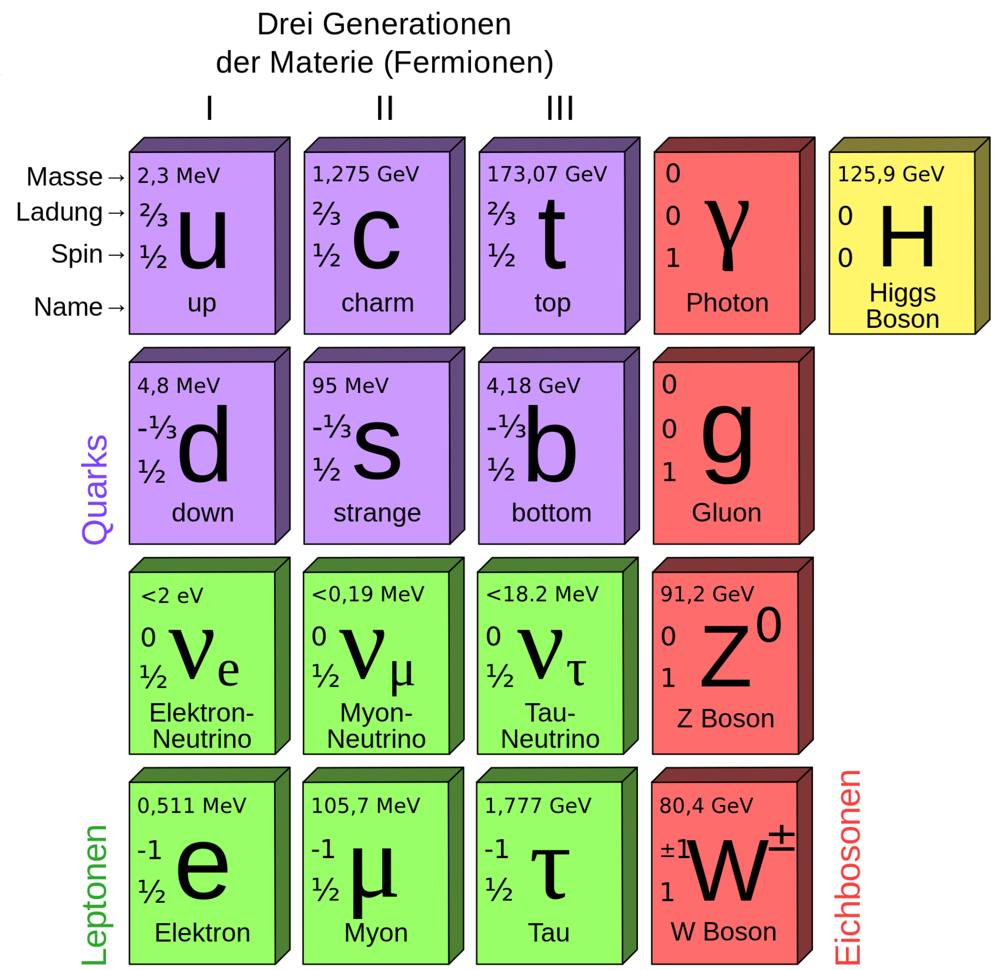
[Guillermo Ballesteros, Javier Redondo, AR, Carlos Tamarit, 1608.05414; 1610.01639]

HELMHOLTZ ASSOCIATION

DESY

Fundamental Problems

- Standard Model (SM) describes interactions of all known particles with remarkable accuracy



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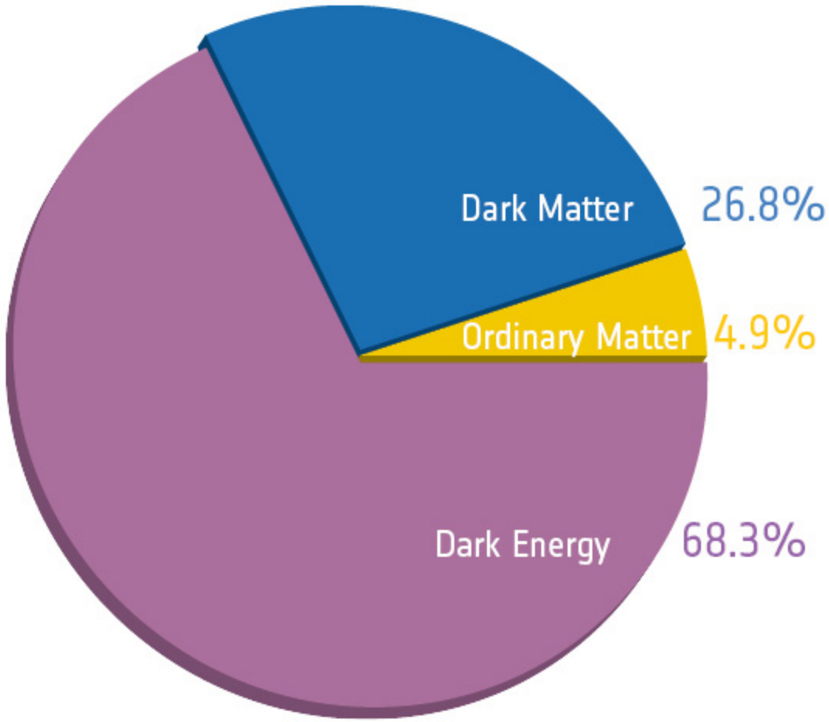
  - Dark matter
  - Neutrino masses and mixing
  - Baryon asymmetry
  - Inflation
  - Strong CP problem



[PLANCK]

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- Big fundamental problems in particle physics and cosmology seem to require new physics
  - Dark matter
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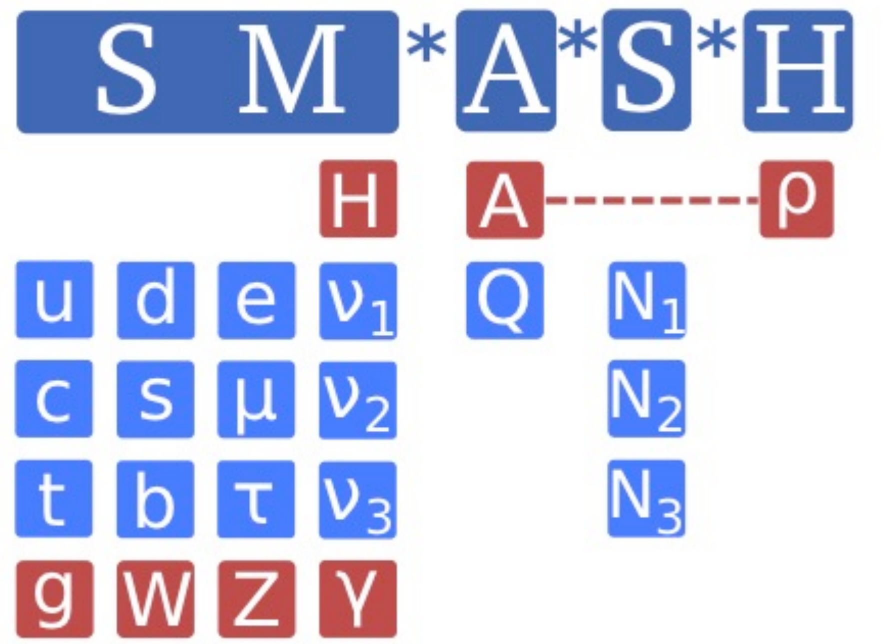
  - Inflation
  - Strong CP problem
- These problems may be intertwined in a minimal way, with a solution pointing to a new physics scale around $10^{11}\,\mathrm{GeV}$



[Ballesteros,Redondo,AR,Tamarit, 1608.05414; 1610.01639]

Strong CP Problem

> Most general gauge invariant Lagrangian of QCD:

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

- Parameters: strong coupling α_s, quark masses $\mathcal{M}_q = \mathrm{diag}(m_u, m_d, \ldots)$ and theta angle θ [Belavin et al. `75;´t Hooft 76;Callan et al. `76;Jackiw,Rebbi `76]

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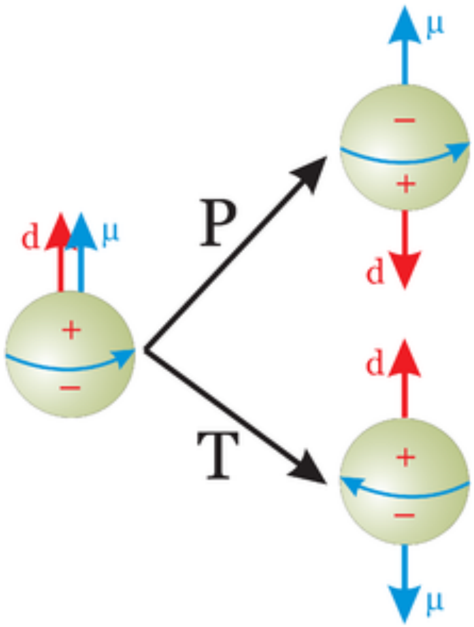

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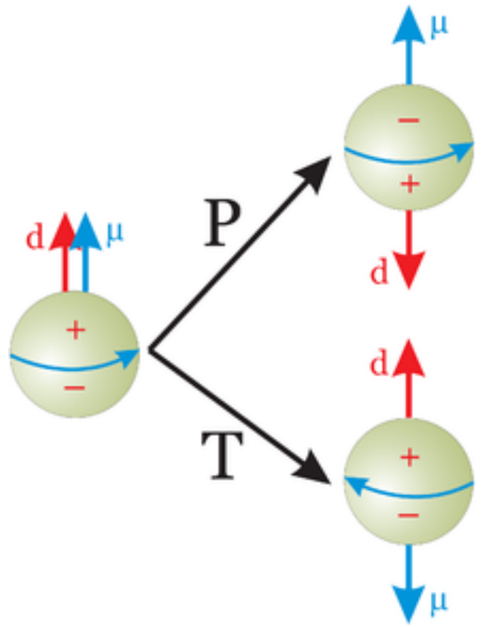
$$d_n \sim \frac{1}{m_n^2}\frac{m_u m_d}{m_u + m_d}\,\theta\, e \sim 6\times 10^{-17}\ \theta\ e\,{\rm cm}$$



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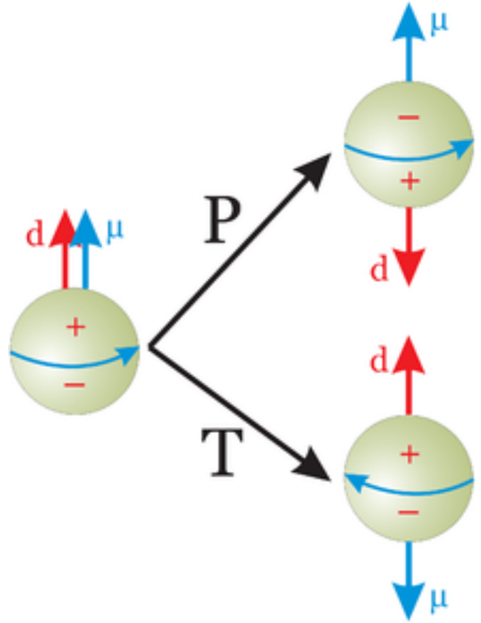
- Experiment: [Baker et al. 06]

$$|d_n| < 2.9 \times 10^{-26}\ e\,{\rm cm} \Rightarrow |\theta| < 10^{-9}$$

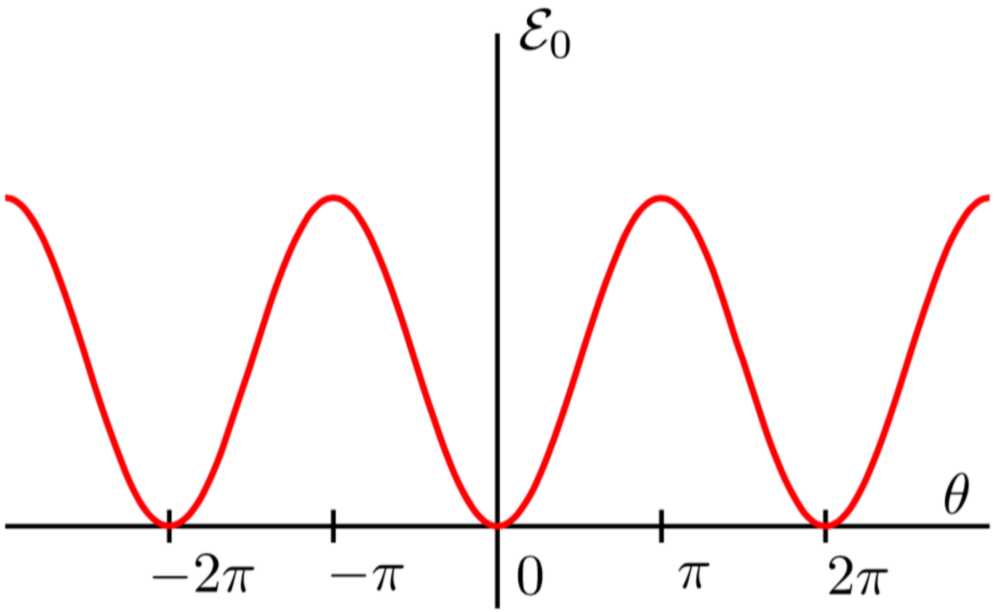


Axionic Solution of Strong CP Problem

- Peccei-Quinn (PQ) solution of strong CP problem based on observation that the vacuum energy in QCD, inferred from chiral effective field theory, has localised minimum at $\theta = 0$:

$$\epsilon_0(\theta) \simeq m_\pi^2 f_\pi^2 \left[1 - \frac{\sqrt{m_u^2 + m_d^2 + 2 m_u m_d \cos\theta}}{m_u + m_d} \right]$$

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



[Aguado,Asorey 10]

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- If θ were a dynamical field, its vev would be zero

- Add to SM angular field $\theta_A(x) \equiv A(x)/f_A$, respecting a shift symmetry $\theta_A(x) \to \theta_A(x) + \mathrm{const.}$, broken only by coupling to topological charge,

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

  - Can eliminate θ by shift $\theta_A(x) \to \theta_A(x) - \theta$; effective potential $V(\theta_A) \equiv \epsilon_0(\theta_A)$ predicts vanishing vev, $\langle \theta_A(x) \rangle = 0$, i.e. P, T, and CP conserved [Peccei,Quinn 77]
  - Particle excitation of A: Nambu-Goldstone boson "axion" [Weinberg 78; Wilczek 78]
  - Mass

$$m_A \simeq \frac{m_\pi f_\pi}{f_A} \frac{\sqrt{m_u m_d}}{m_u + m_d} \simeq 6 \text{ meV} \left(\frac{10^9 \text{ GeV}}{f_A} \right)$$

and strength of its interactions with SM controlled by decay constant f_A

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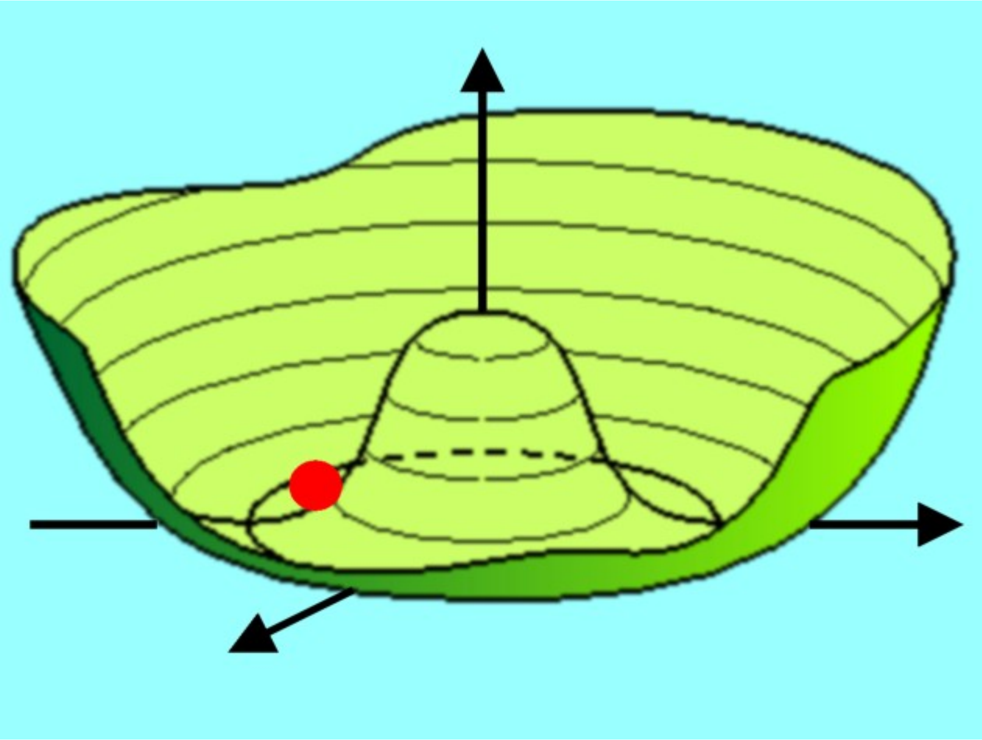
- Extend SM by singlet complex scalar field σ featuring global $U(1)_{\rm PQ}$
- Symmetry broken by vev, $\langle\sigma\rangle = v_\sigma/\sqrt{2}$



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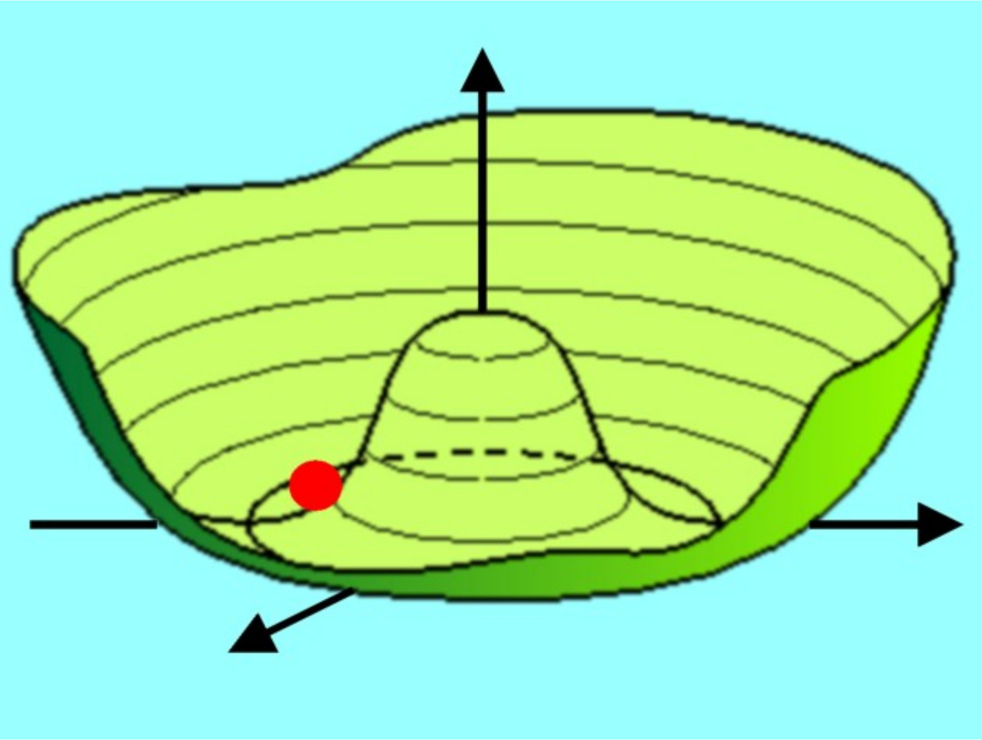
  - Excitation of modulus: $m_\rho \propto v_\sigma$ (saxion)
  - Excitation of argument: $m_A = 0$



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- Extend particle content further by vector-like quark Q with chiral assignment of PQ charges (KSVZ) [Kim 79;Shifman,Vainshtein,Zakharov 80]

q	u	d	Q	$\tilde{Q}$	σ
$1/2$	$-1/2$	$-1/2$	$-1/2$	$-1/2$	1

$$\mathcal{L} \supset -\left[Y_{u\,ij} q_i \epsilon H u_j + Y_{d\,ij} q_i H^\dagger d_j + y\,\tilde{Q}\sigma Q + y_{Q_d\,i}\sigma Q d_i + h.c.\right],$$

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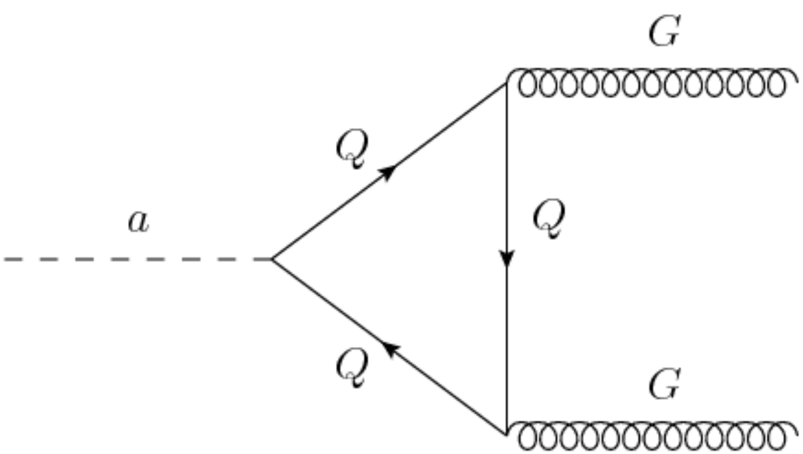

- Color triangle anomaly induces low energy coupling of A in form of θ term

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi}\frac{A(x)}{f_A} G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu}; \qquad f_A = v_\sigma$$

- θ term can be eliminated by shift; shifted field has zero vev [Peccei,Quinn 78]
- Particle excitation, axion: [Weinberg 79; Wilczek 79]

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

Saxion as Inflaton

- Take into account non-minimal coupling of Higgs and PQ field to gravity,

$$S \supset -\int d^4x\sqrt{-g}\left[\frac{M^2}{2} + \xi_H\, H^\dagger H + \xi_\sigma\, \sigma^*\sigma\right] R; \qquad M_P^2 = M^2 + \xi_H v^2 + \xi_\sigma v_\sigma^2$$

  - Generated anyway radiatively even if set to zero at some scale [Fairbairn,Hogan,Marsh `14]

- Non-minimal couplings stretch scalar potential in Einstein frame; makes it convex and asymptotically flat at large field values

$$\tilde{V}(h,\rho) = \frac{1}{\Omega^4(h,\rho)}\left[\frac{\lambda_H}{4}\left(h^2 - v^2\right)^2 + \frac{\lambda_\sigma}{4}\left(\rho^2 - v_\sigma^2\right)^2 + \frac{\lambda_{H\sigma}}{2}\left(h^2 - v^2\right)\left(\rho^2 - v_\sigma^2\right)\right]$$

$$\tilde{g}_{\mu\nu} = \Omega^2(h,\rho)\, g_{\mu\nu} \qquad\qquad \Omega^2 = 1 + \frac{\xi_H(h^2 - v^2) + \xi_\sigma(\rho^2 - v_\sigma^2)}{M_P^2}$$

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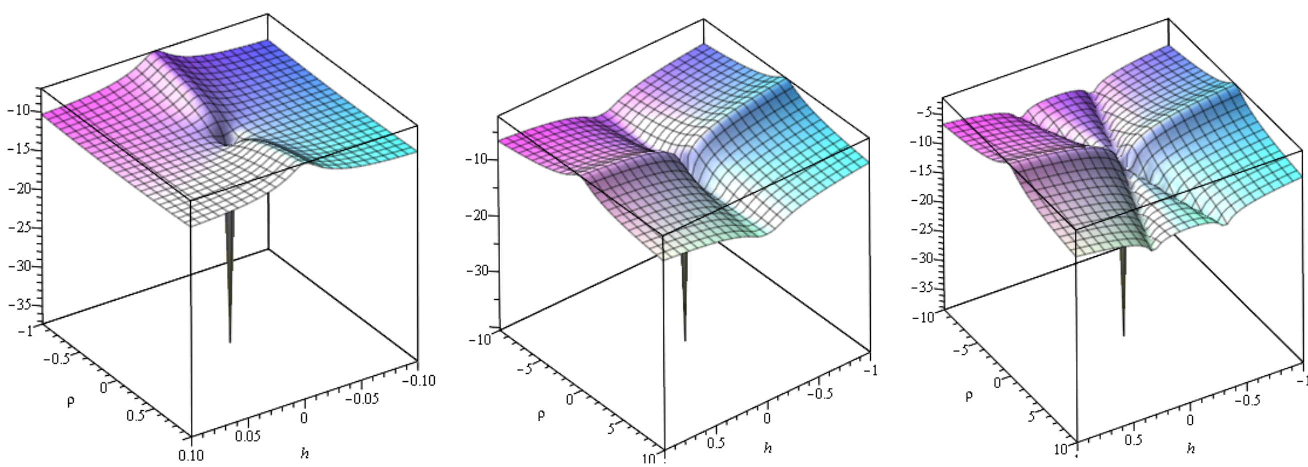
- Potential has valleys = attractors for Higgs Inflation (HI), Hidden Scalar Inflation (HSI) or mixed Higgs Hidden Scalar Inflation (HHSI), depending on relative signs of $\kappa_H \equiv \lambda_{H\sigma}\xi_H - \lambda_H\xi_\sigma\,, \quad \kappa_\sigma \equiv \lambda_{H\sigma}\xi_\sigma - \lambda_\sigma\xi_H$



sign(κ_H)	sign(κ_σ)	Inflation
$+$	$-$	HI
$-$	$+$	HSI
$-$	$-$	HHSI

[Ballesteros,Redondo, AR,Tamarit, 1610.01639]

Saxion as Inflaton

- CMB observables

$$A_s = (2.20 \pm 0.08) \times 10^{-9}\,,$$
$$n_s = 0.967 \pm 0.004\,,$$
$$r < 0.07$$

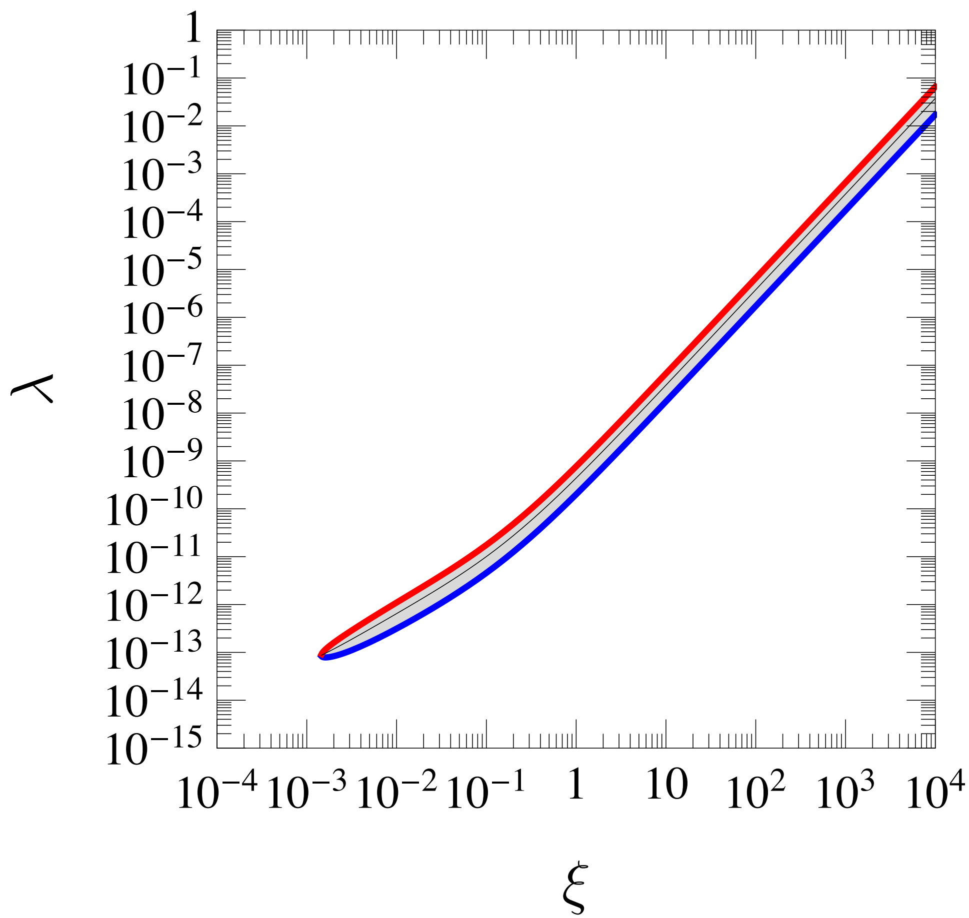
fit by

$$\xi \simeq 2 \times 10^5 \sqrt{\lambda} \gtrsim 10^{-3}$$

where

$$\xi \equiv \begin{cases} \xi_H\,, & \text{for HI,} \\ \xi_\sigma\,, & \text{for HSI,} \\ \xi_\sigma\,, & \text{for HHSI} \end{cases}$$

$$\lambda \equiv \begin{cases} \lambda_H\,, & \text{for HI,} \\ \lambda_\sigma\,, & \text{for HSI,} \\ \lambda_\sigma \left(1 - \frac{\lambda_{H\sigma}^2}{\lambda_\sigma \lambda_H}\right)\,, & \text{for HHSI} \end{cases}$$



[Ballesteros,Redondo, AR,Tamarit, 1610.01639]

Saxion as Inflaton

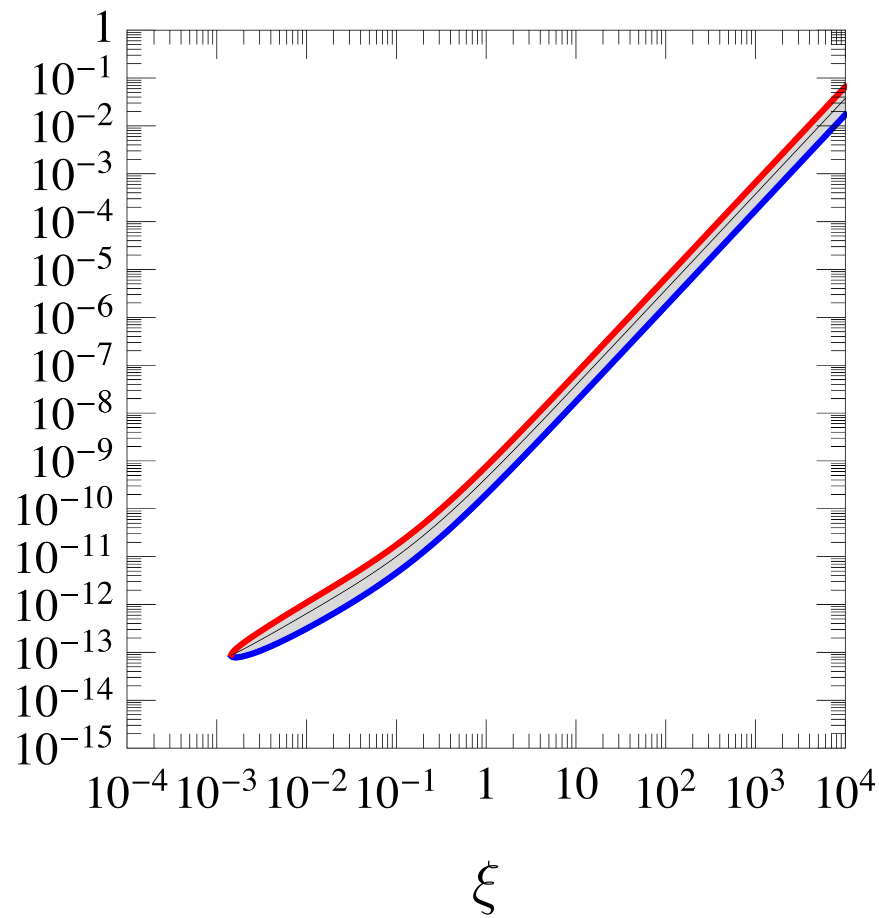
- HI requires huge non-minimal coupling of the Higgs:

$$\xi_H \sim 2 \times 10^5 \sqrt{\lambda_H(\sim M_P)} \sim 2 \times 10^4$$

- Perturbative unitarity lost in HI

$$\Lambda_U \sim \frac{M_P}{\xi_H} \sim 10^{14}\,\mathrm{GeV} \ll \tilde{V}^{1/4}(h_I) \sim 10^{16}\,\mathrm{GeV}$$

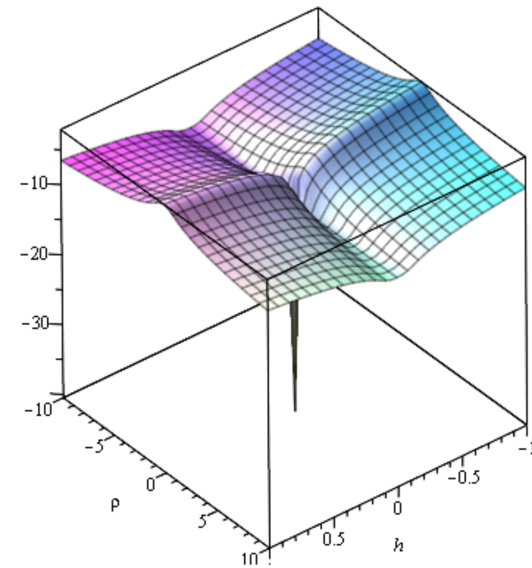
- No unitarity problem in HSI/HHSI, if $\lambda_\sigma, \tilde{\lambda}_\sigma \lesssim 10^{-10}$, since then $\xi_\sigma \lesssim 1$

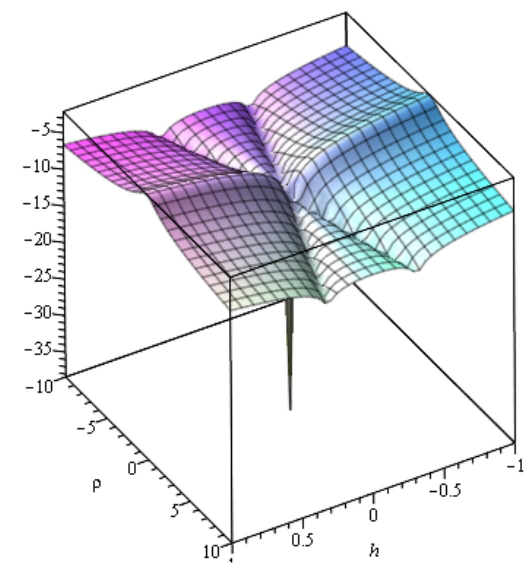


[Ballesteros,Redondo, AR,Tamarit, 1610.01639]

Saxion as Inflaton

- Both in HSI and HHSI with $\xi_\sigma \lesssim 1$, slow-roll inflation ends at a value of $\rho \sim \mathcal{O}(M_P)$
- Inflaton starts to undergo Hubble-damped oscillations in a quartic potential, with Universe expanding as in a radiation-dominated era





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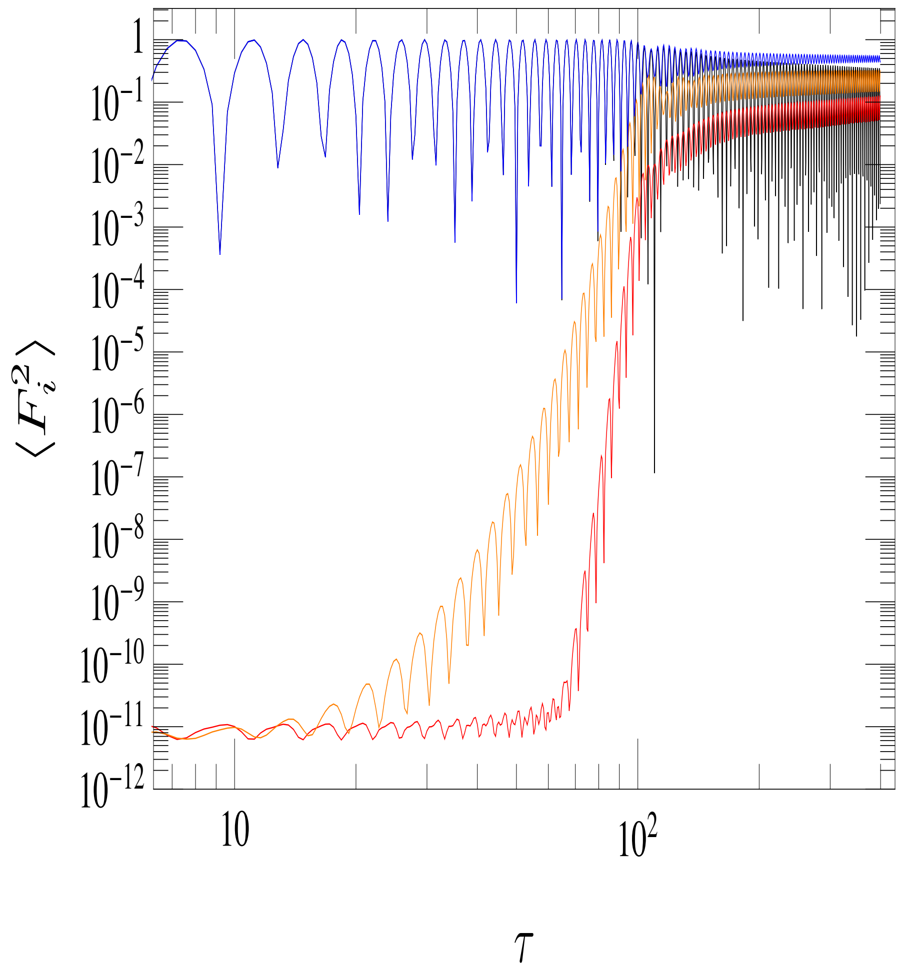
- PQ symmetry restored after inflation already in preheating stage when PQ field undergoes Hubble damped oscillations in quartic potential



[Ballesteros,Redondo, AR,Tamarit `16]

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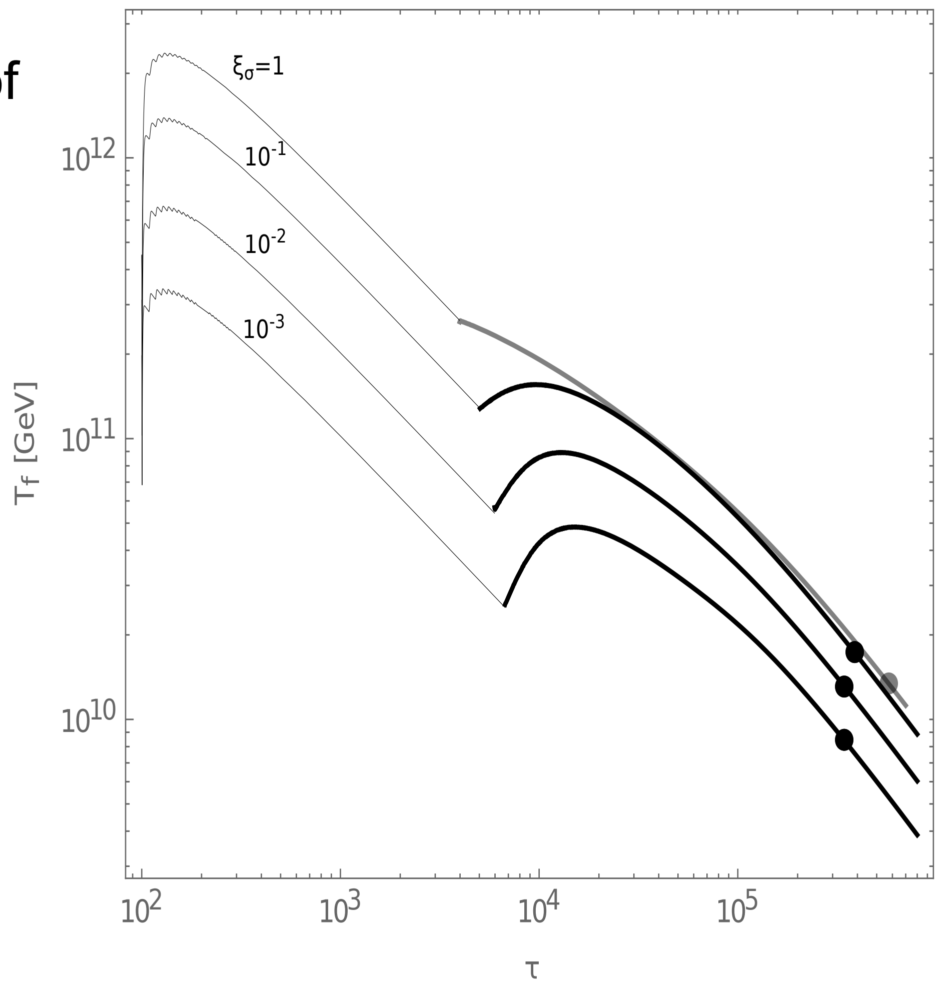
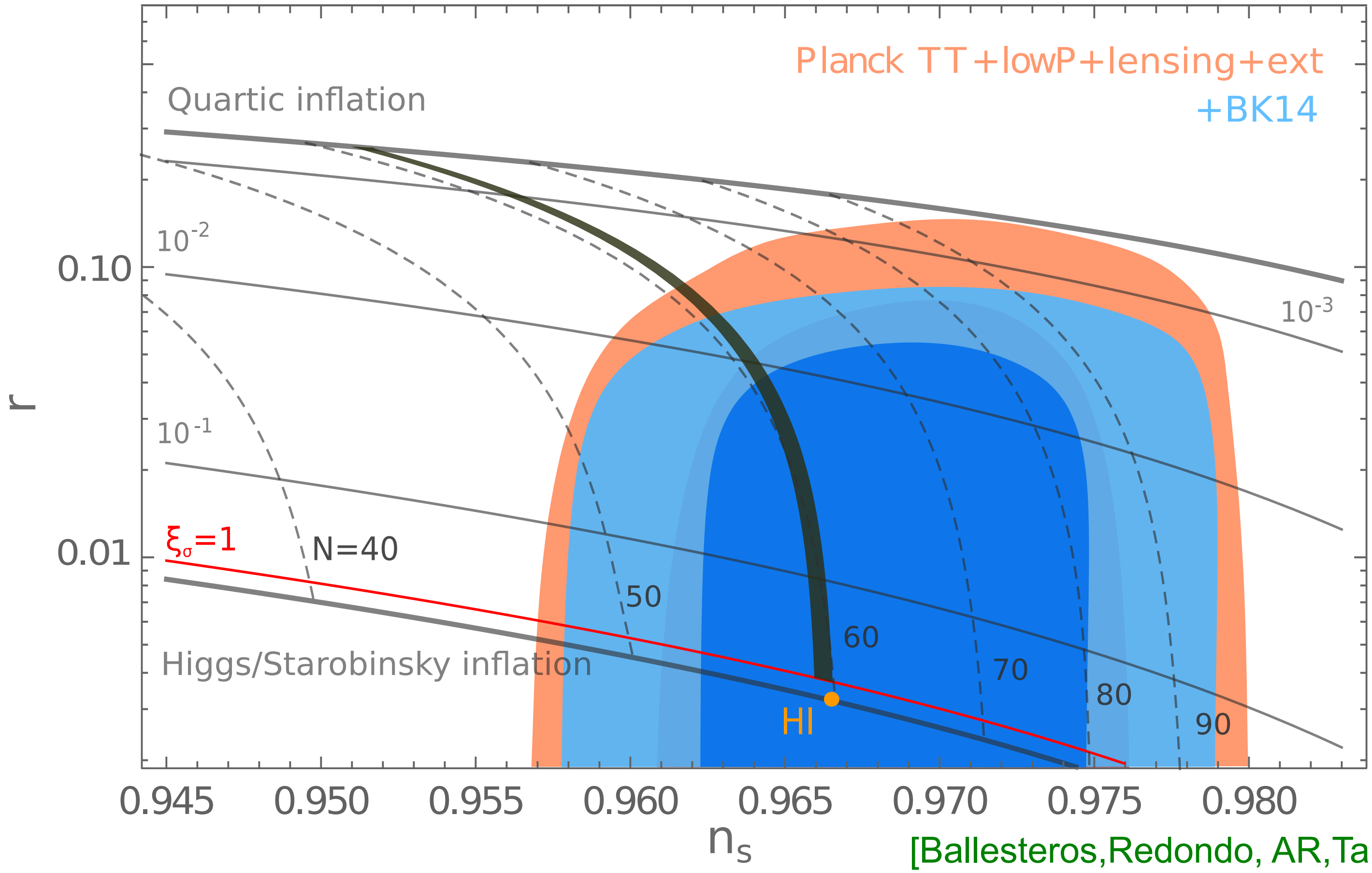
- PQ symmetry restored after inflation already in preheating stage when PQ field undergoes Hubble damped oscillations in quartic potential
- Large reheating temperature
  - $10^{10}\,\mathrm{GeV}$ for mixed PQ scalar/Higgs inflation $(\lambda_{H\sigma} < 0)$
- Axion dark radiation: $\Delta N_\nu^{\rm eff} \simeq 0.03$



[Ballesteros,Redondo, AR,Tamarit `16]

Saxion as Inflaton

- Sharp prediction of r vs n_s for fixed pivot scale, e.g. $k_0 = 0.002\ \mathrm{Mpc}^{-1}$



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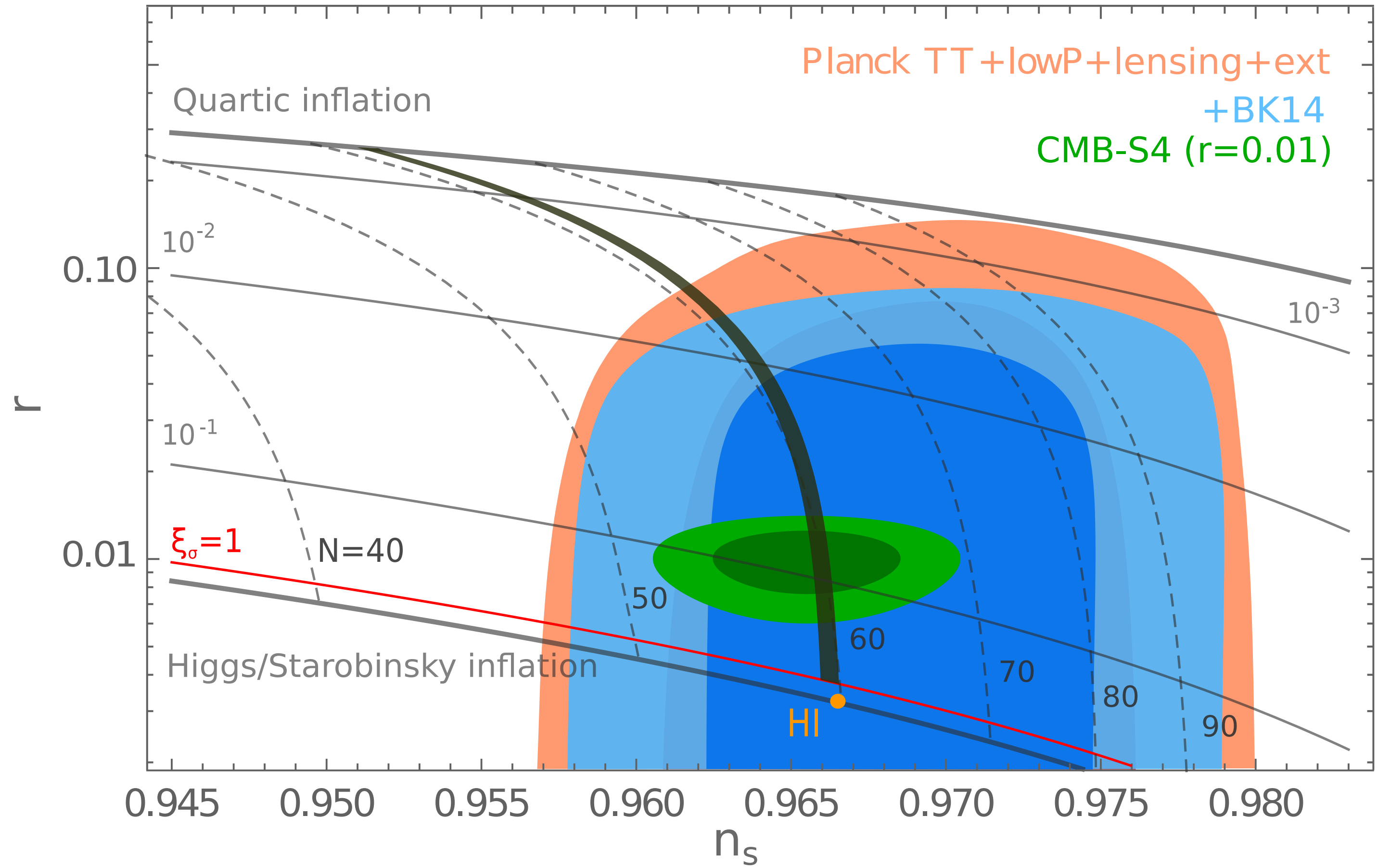
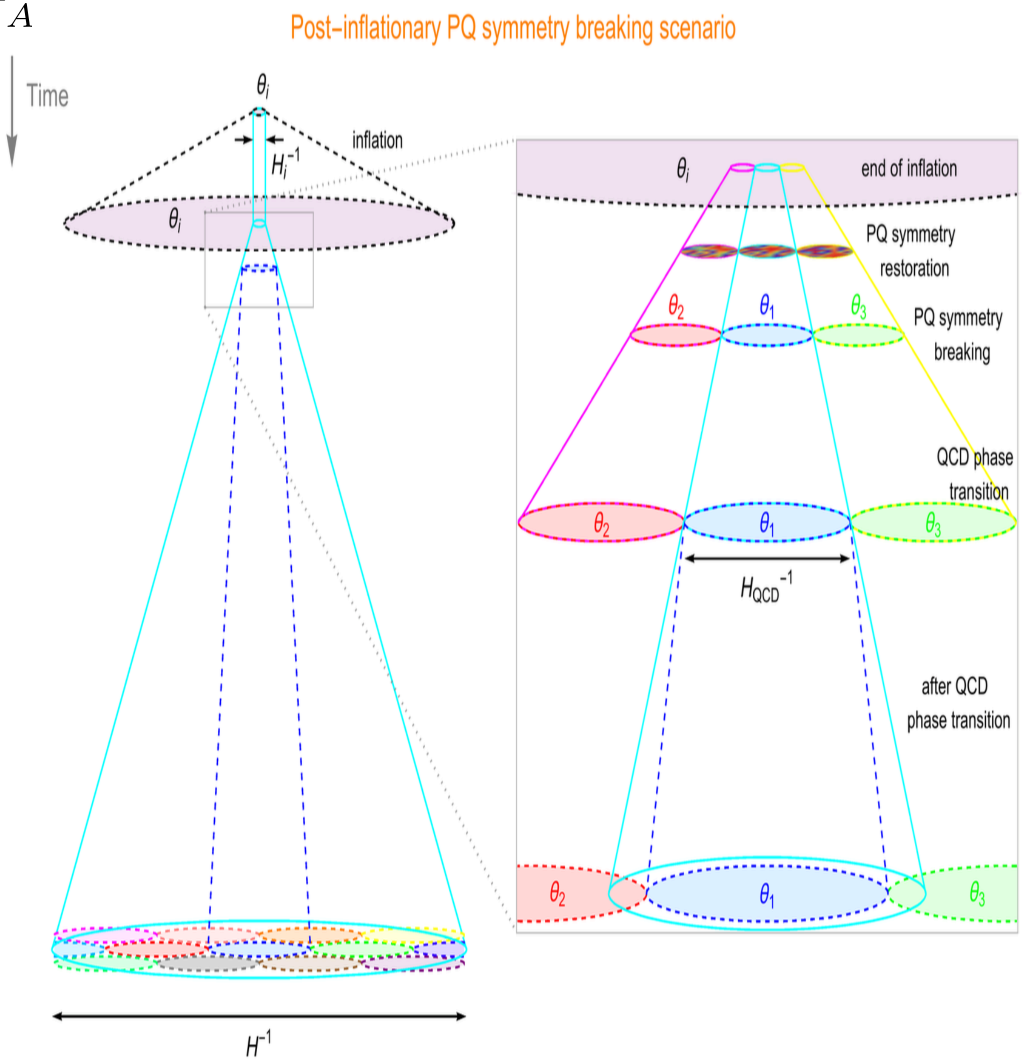


[Tamarit]

- Can be probed by next generation CMB experiments (e.g. CMB-S4)

Saxion as Inflaton and Axion as Dark Matter

- After PQ SSB, $T \lesssim T_c^{\rm PQ} \sim v_\sigma = f_A$
  - Present universe consists of many causally disconnected patches with random initial values of axion field



[Saikawa]

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  - In any of these regions, axion frozen at initial value
  - Later when $H(T) \sim m_A(T)$, axion field starts to oscillate around zero; behaves like cold dark matter:

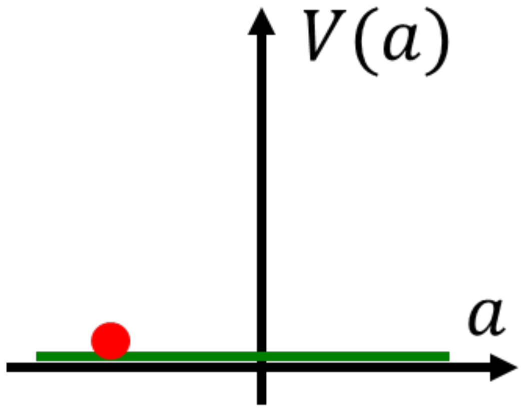
$$w_A = p_A/\rho_A \simeq 0$$

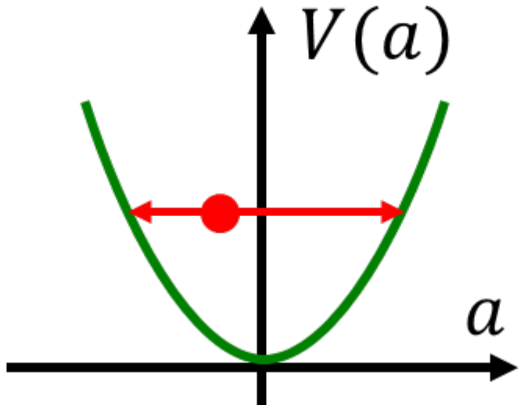
[Preskill,Wise,Wilczek 83; Abbott,Sikivie 83; Dine,Fischler 83,....]

  - Naive average over patches, ignoring inhomogeneities at boundaries

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

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





[Raffelt]

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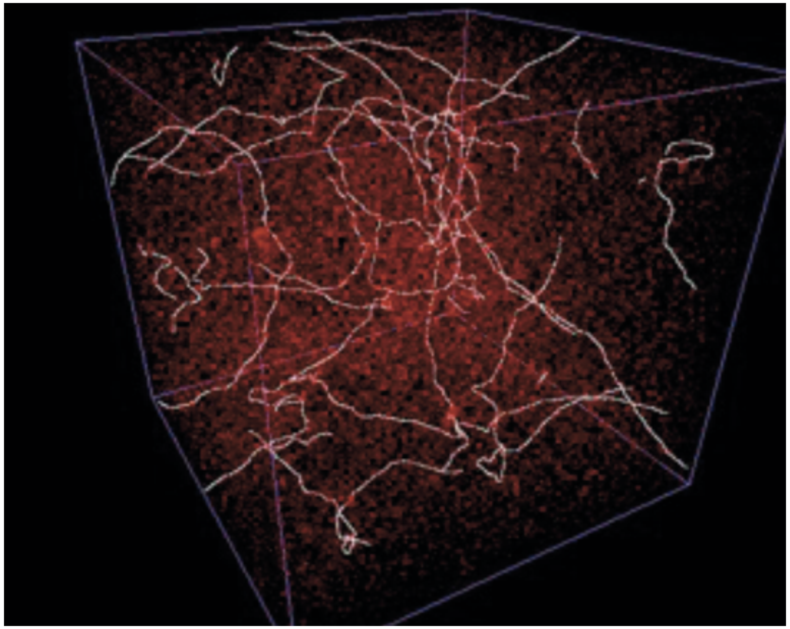
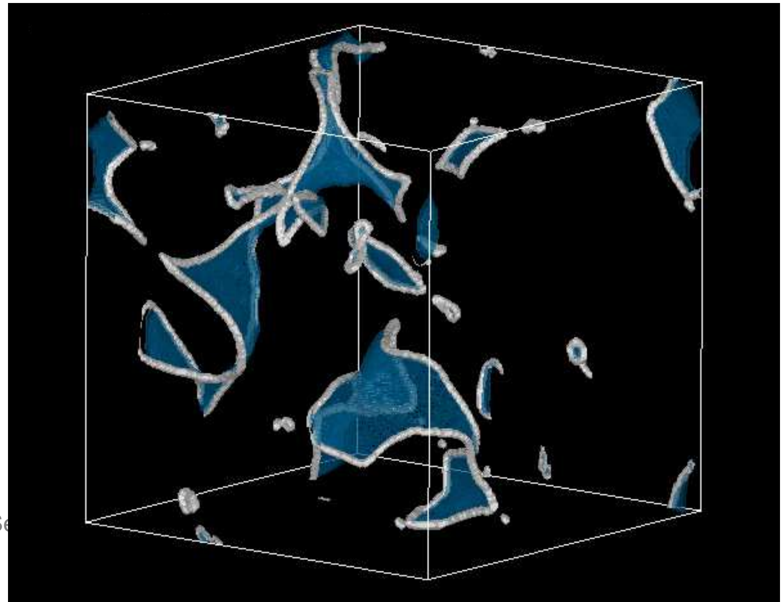
  - Non-negligible inhomogeneities at boundaries: cosmic strings and domain walls [Sikivie `82; Davis `86; Lyth `92]
  - Axion 100% dark matter, if

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

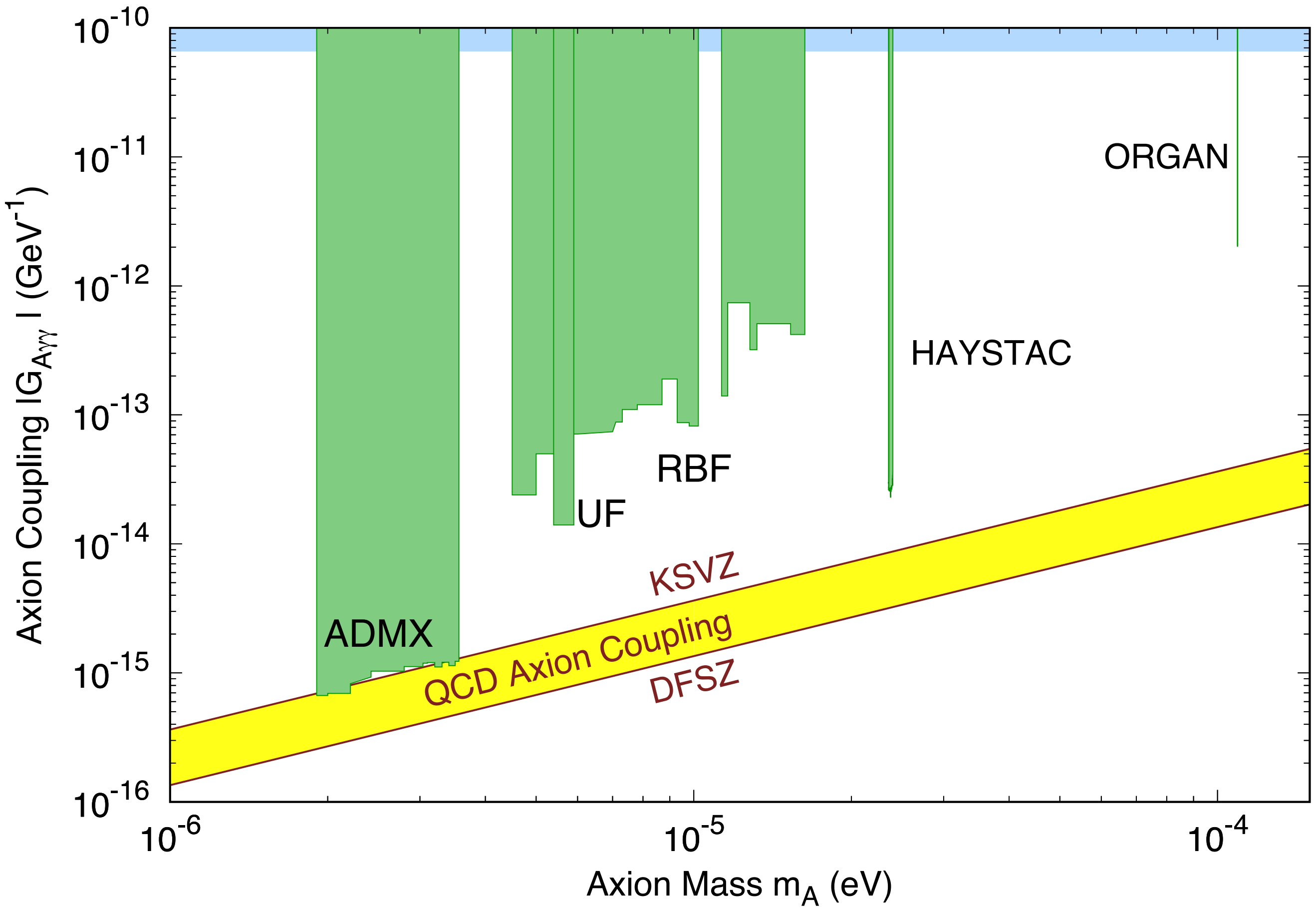


[Hiramatsu et al.]



Dark-Matter Axion Mass in Post-inflationary PQ SB Scen.

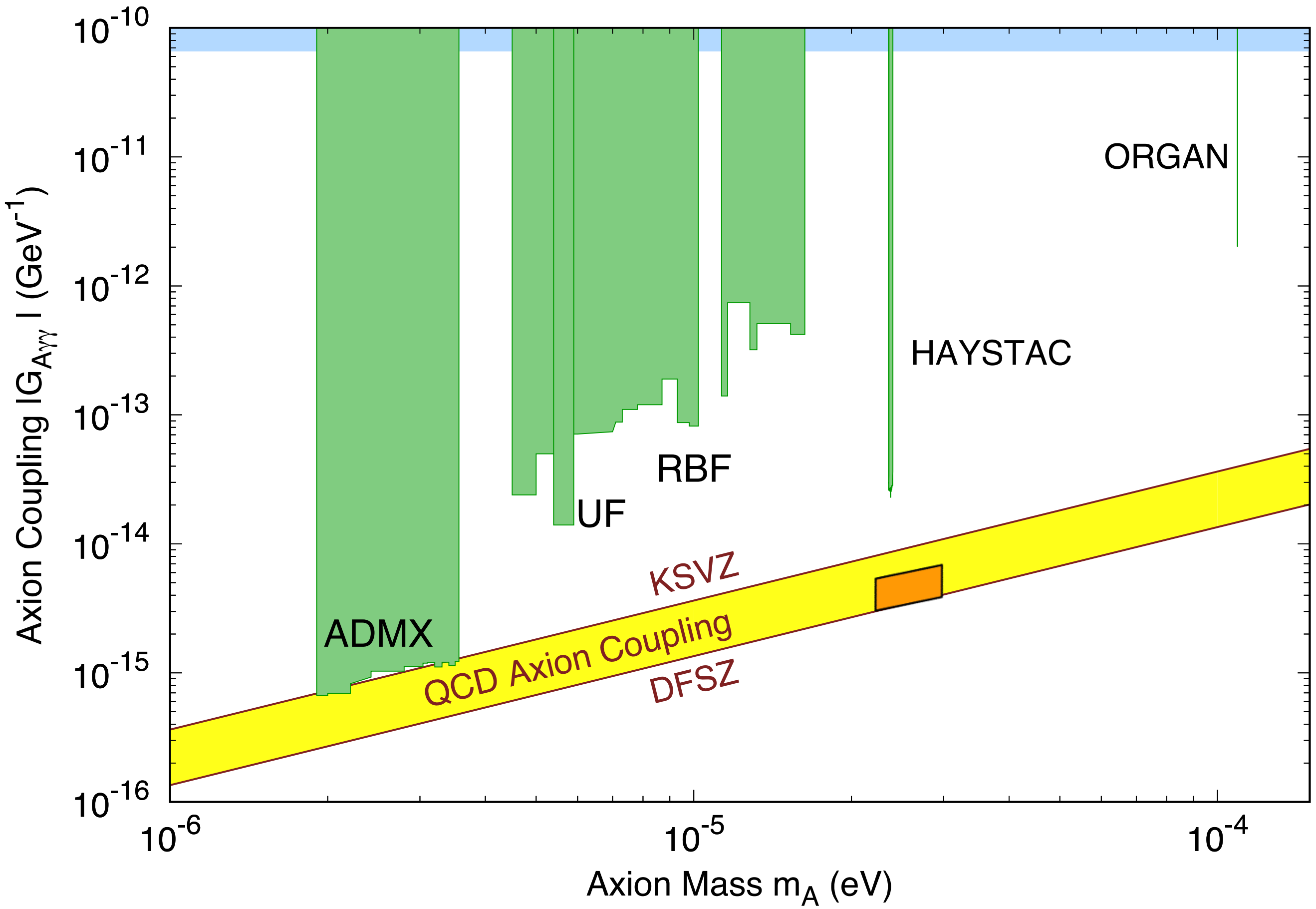
- Current experimental bounds:



[AR,Rosenberg,Rybka (RPP) `17]

Dark-Matter Axion Mass in Post-inflationary PQ SB Scen.

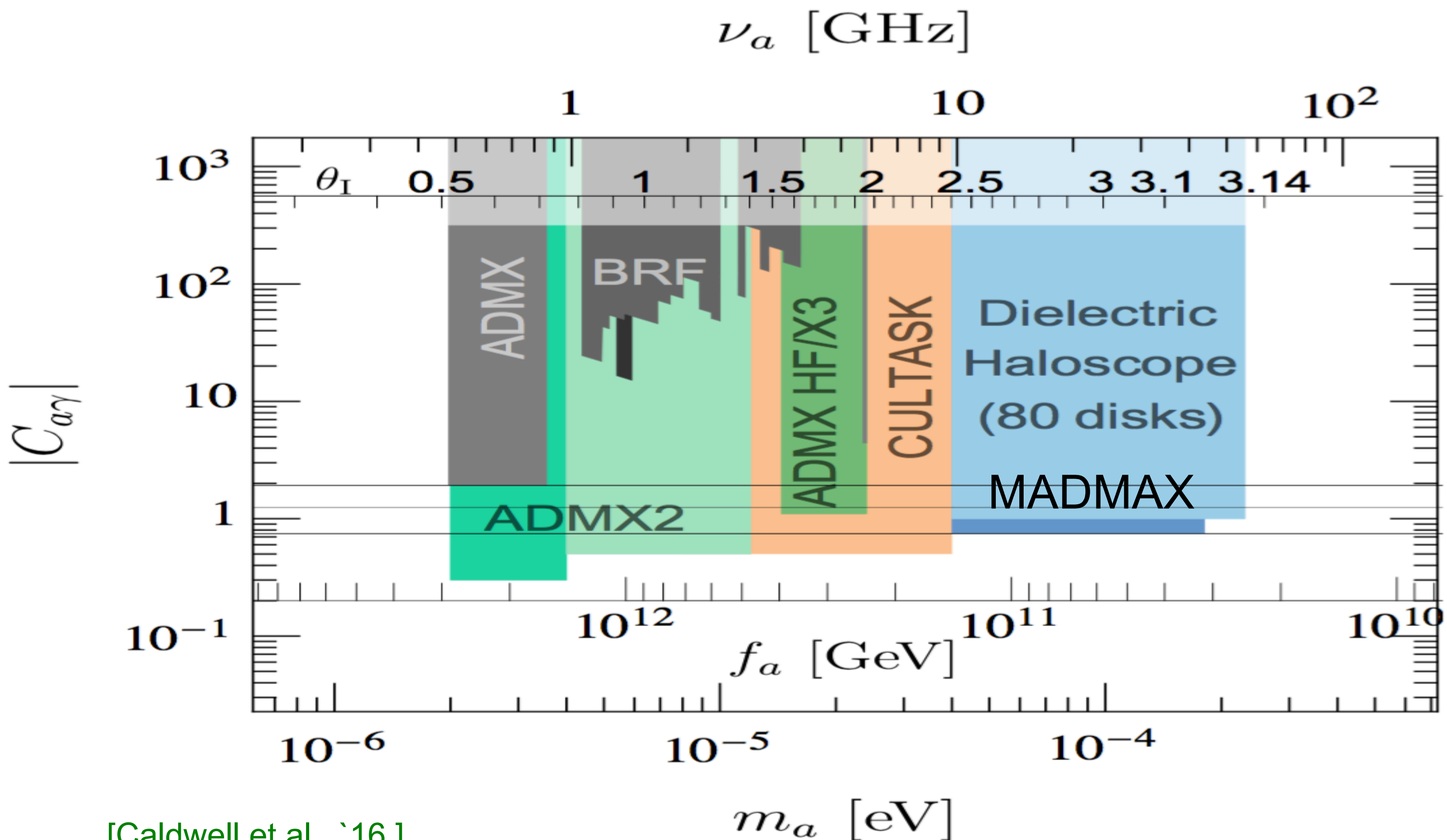
- Current experimental bounds vs. prediction:



[AR,Rosenberg,Rybka (RPP) `17]

Saxion as Inflaton and Axion as Dark Matter

> Projected experimental sensitivities:



[Caldwell et al. `16]

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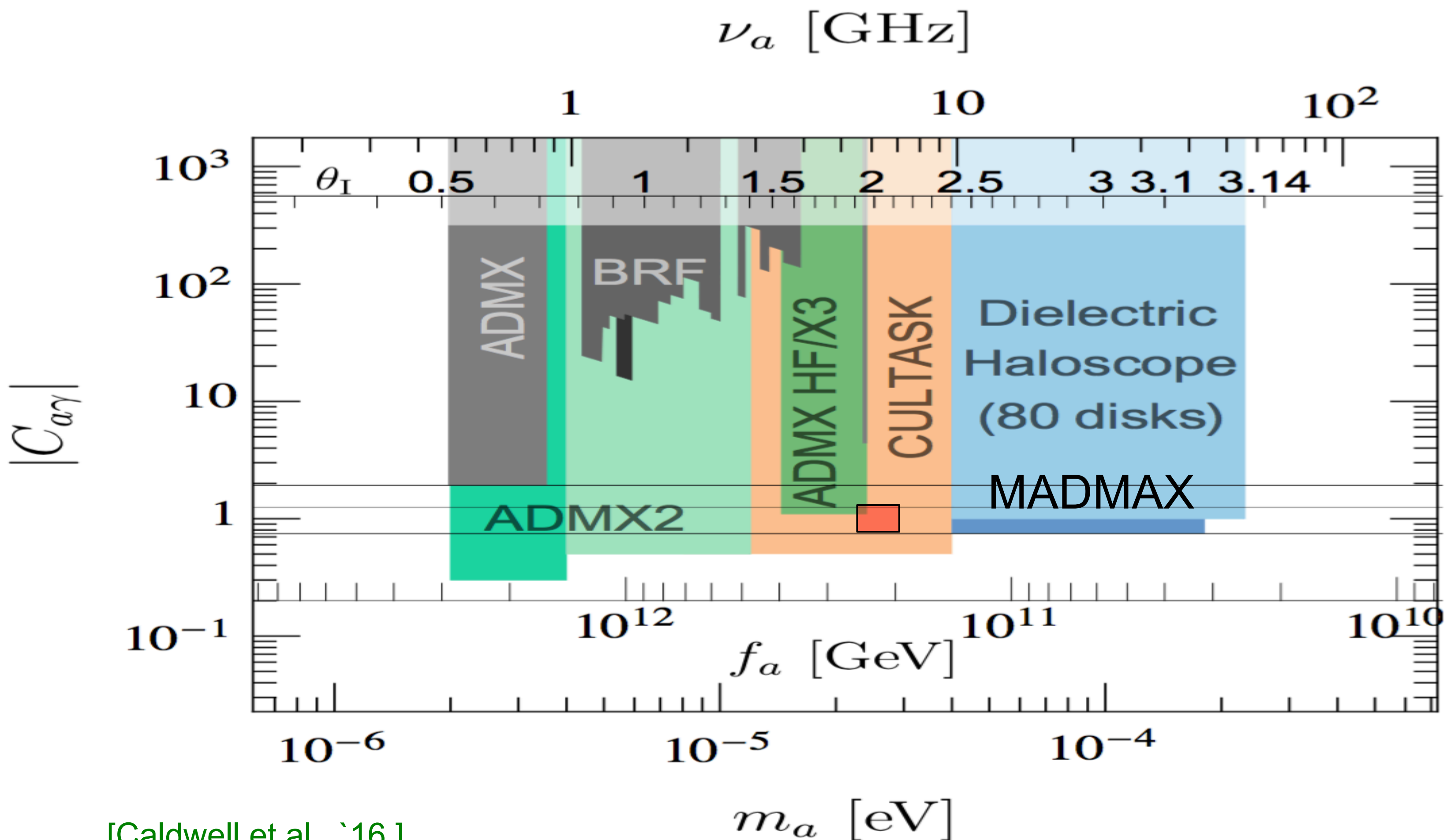


[Caldwell et al. `16]

Unifying Inflation, Dark Matter, and Seesaw with PQ Field

- Unify $U(1)_{\rm PQ}$ symmetry with lepton symmetry: give also the SM leptons and the right-handed neutrinos PQ charges [Shin 88; Dias et al. 14; Ballesteros et al. 16]

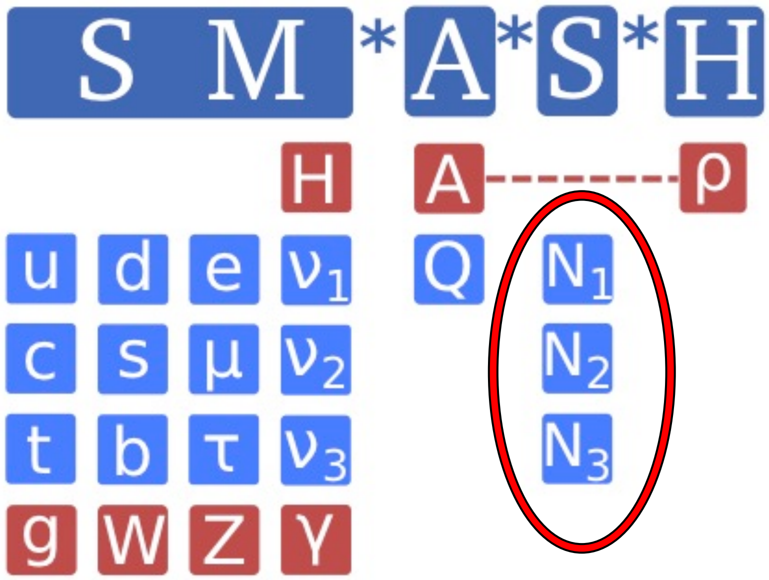
q	u	d	L	N	E	Q	$\tilde{Q}$	σ
$1/2$	$-1/2$	$-1/2$	$1/2$	$-1/2$	$-1/2$	$-1/2$	$-1/2$	1

$U(1)_{\rm PQ}$

$$\mathcal{L} \supset -\left[Y_{uij} q_i \epsilon H u_j + Y_{dij} q_i H^\dagger d_j + G_{ij} L_i H^\dagger E_j + F_{ij} L_i \epsilon H N_j + \frac{1}{2} Y_{ij} \sigma N_i N_j + y\,\tilde{Q}\sigma Q + y_{Q_{d}i}\sigma Q d_i + h.c.\right]$$

SM * Axion * See-saw * Higgs portal inflation

[Ballesteros,Redondo, AR,Tamarit, 1608.05414; 1610.01639]



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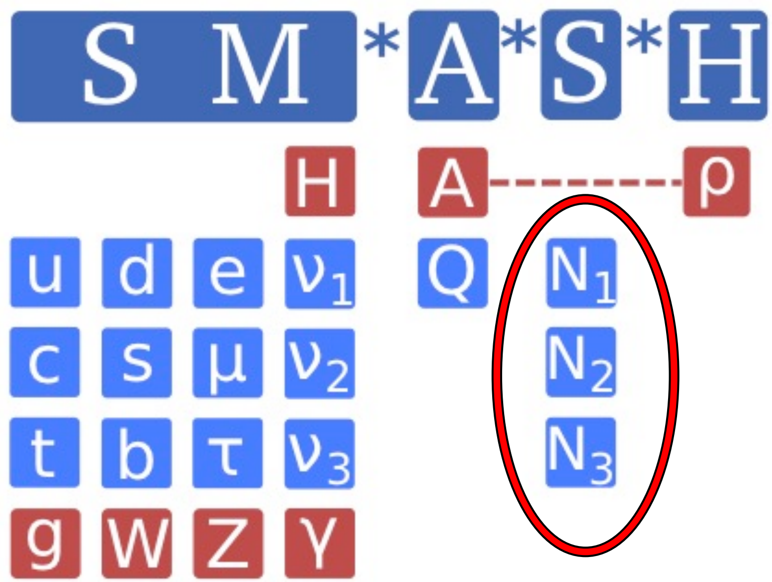
- Field content suffices to solve five problems in one stroke:

1. Strong CP problem
2. Dark matter
3. Inflation
4. Neutrino masses and mixing
5. Baryogenesis



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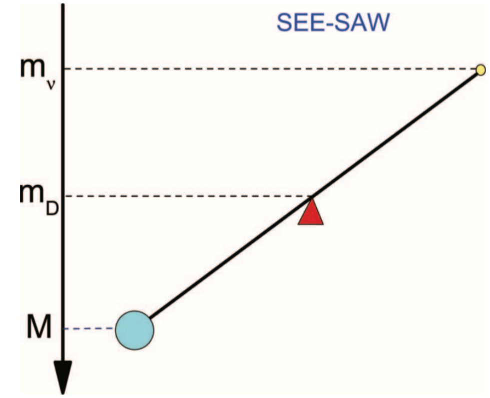

$$m_\nu = 0.04\,{\rm eV} \left(\frac{10^{11}\,{\rm GeV}}{v_\sigma}\right) \left(\frac{-F\,Y^{-1}\,F^T}{10^{-4}}\right)$$

Unifying Inflation, Dark Matter, and Seesaw with PQ Field

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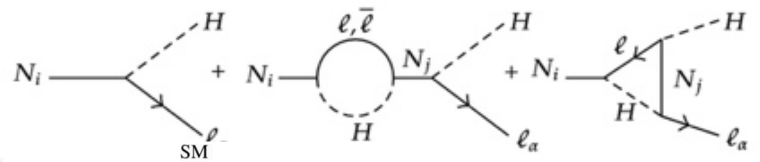
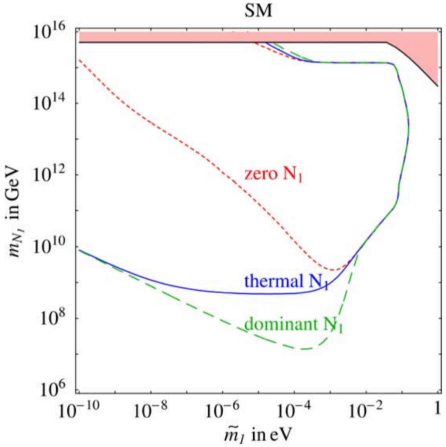
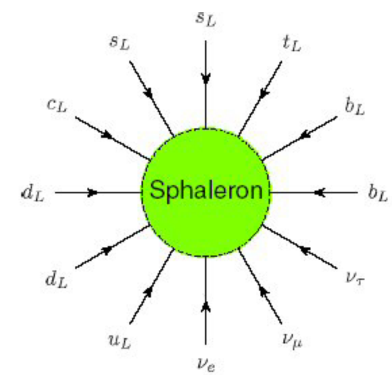
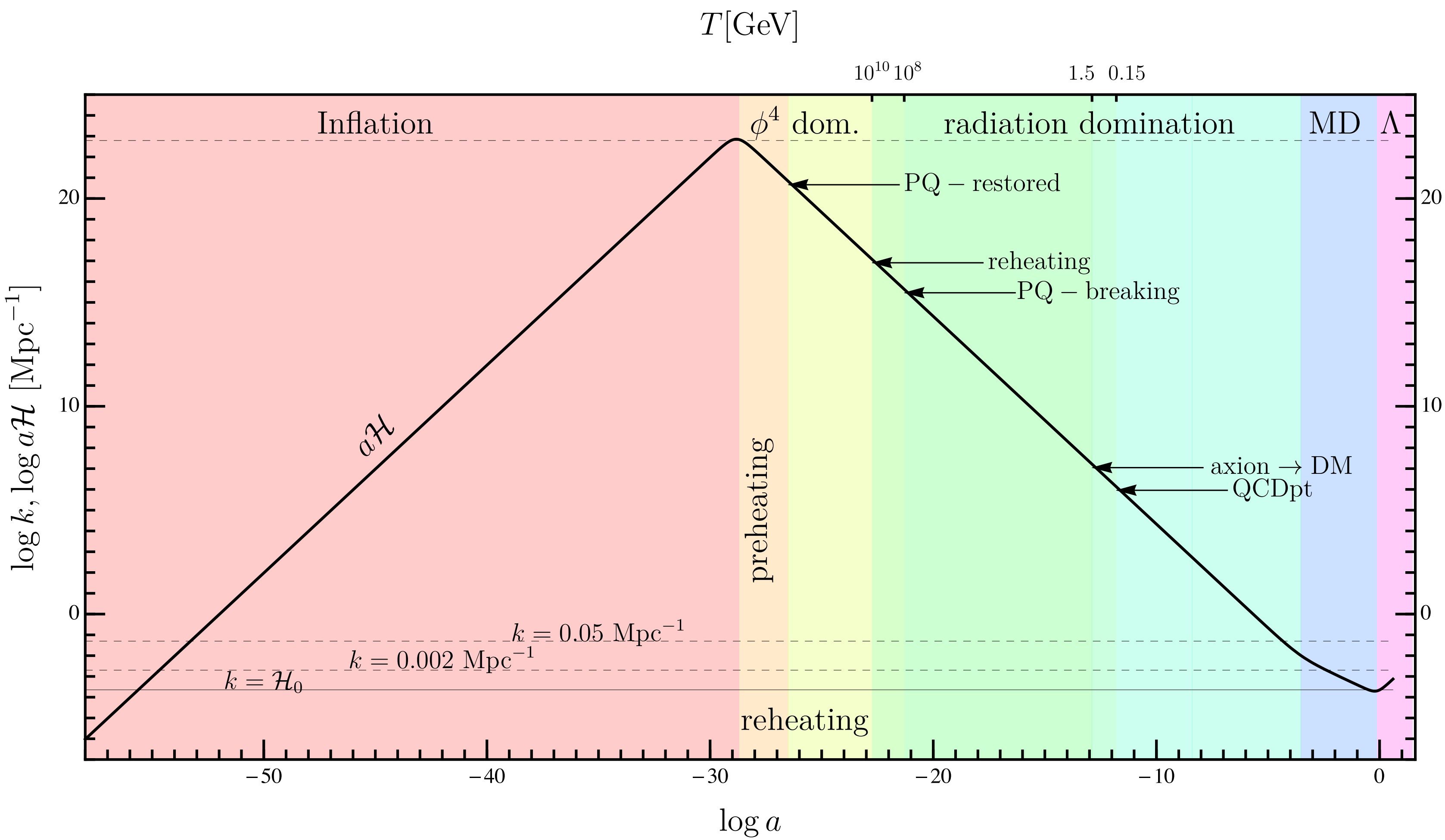






Unifying Inflation, Dark Matter, and Seesaw with PQ Field

- Complete and consistent history of the universe from inflation to now



[Ballesteros,Redondo, AR,Tamarit, 1610.01639]

Towards a GUT SMASH

- In non-SUSY SO(10), gauge coupling unification needs at least one intermediate scale; often discussed SSB chain:

$$SO(10) \overset{M_{\rm U} - 210_H}{\longrightarrow} SU(4)_C \times SU(2)_L \times SU(2)_R$$

$$\overset{M_{\rm BL} - 126_H}{\longrightarrow} SU(3)_C \times SU(2)_L \times U(1)_Y$$

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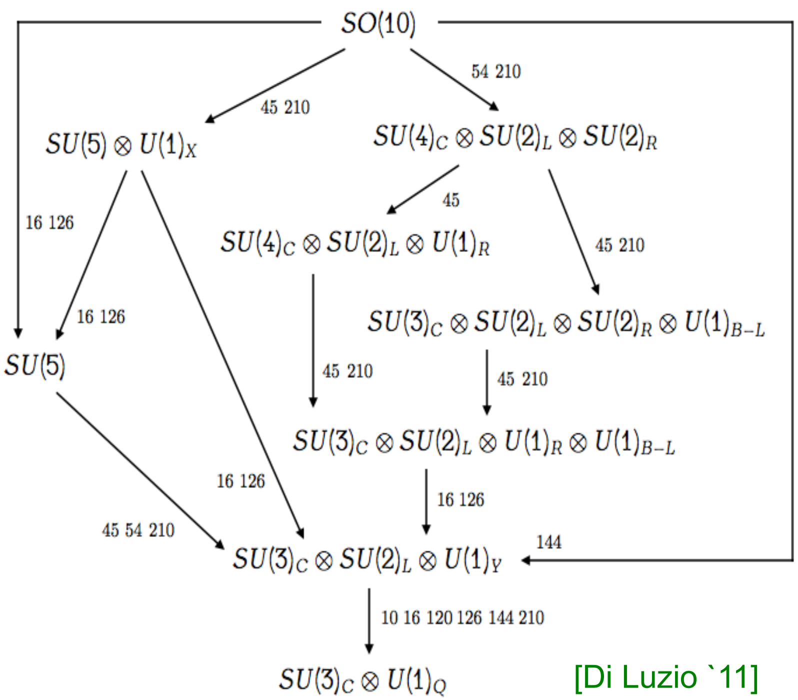

[Di Luzio `11]

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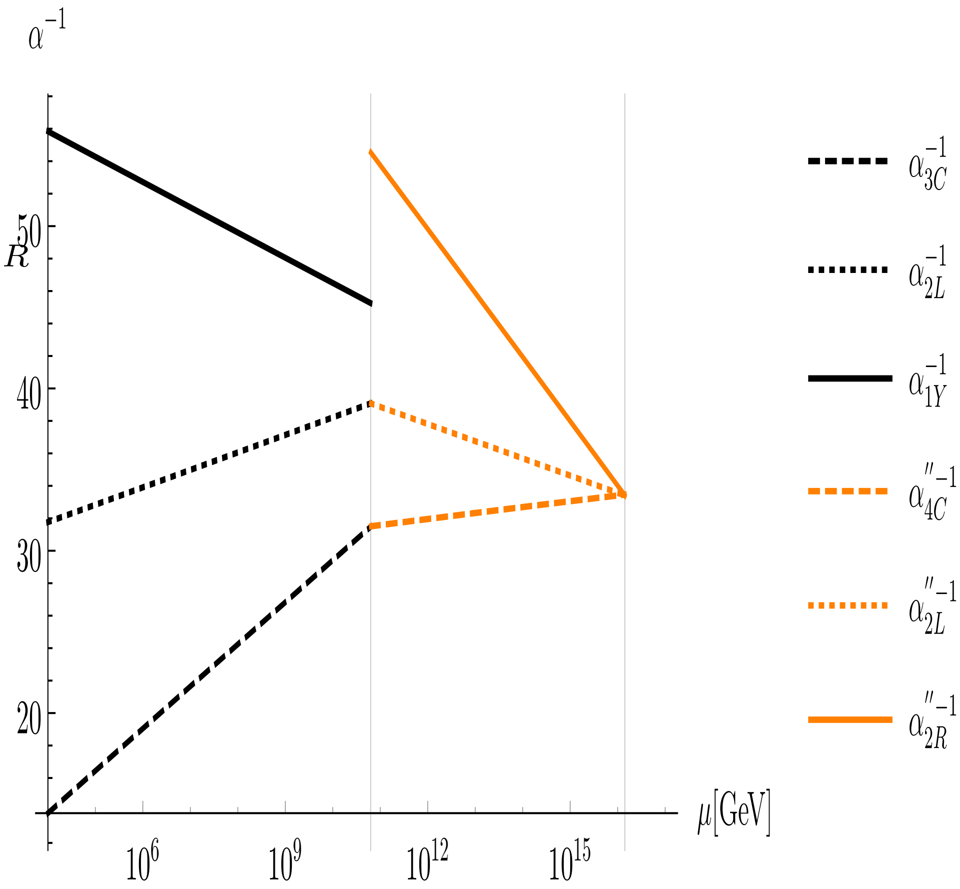

[Ernst,AR,Tamarit in prep.]

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- SO(10) GUT automatically features:
  - Neutrino masses and mixing
  - Baryogenesis via leptogenesis

$SO(10)$	$4_C2_L2_R$	$4_C2_L1_R$	$3_C2_L1_R1_{B-L}$	$3_C2_L1_Y$	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:

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

- Fermion masses/mixing:

$$M_u = Y_{10}v_u^{10} + \tilde{Y}_{10}v_d^{10^*} + Y_{126}v_u^{126}\,,$$
$$M_d = Y_{10}v_d^{10} + \tilde{Y}_{10}v_u^{10^*} + Y_{126}v_d^{126}\,,$$
$$M_e = Y_{10}v_d^{10} + \tilde{Y}_{10}v_u^{10^*} - 3Y_{126}v_d^{126}\,,$$
$$M_D = Y_{10}v_u^{10} + \tilde{Y}_{10}v_d^{10^*} - 3Y_{126}v_u^{126}\,,$$
$$M_R = Y_{126}v_R\,,$$
$$M_L = Y_{126}v_L\,.$$

Towards a GUT SMASH

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- SO(10) GUT automatically featu-res:
  - Neutrino masses and mixing
  - Baryogenesis via leptogenesis
- PQ extension adds [Bajc et al. 06; Altarelli,Meloni 13; Babu,Khan 15]
  - Predictivity of fermion masses/mixing
  - Solution of strong CP problem
  - Axion dark matter

- PQ symmetry imposed:

$$16_F \to 16_F e^{i\alpha},$$
$$10_H \to 10_H e^{-2i\alpha},$$
$$\overline{126}_H \to \overline{126}_H e^{-2i\alpha}$$

- 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:

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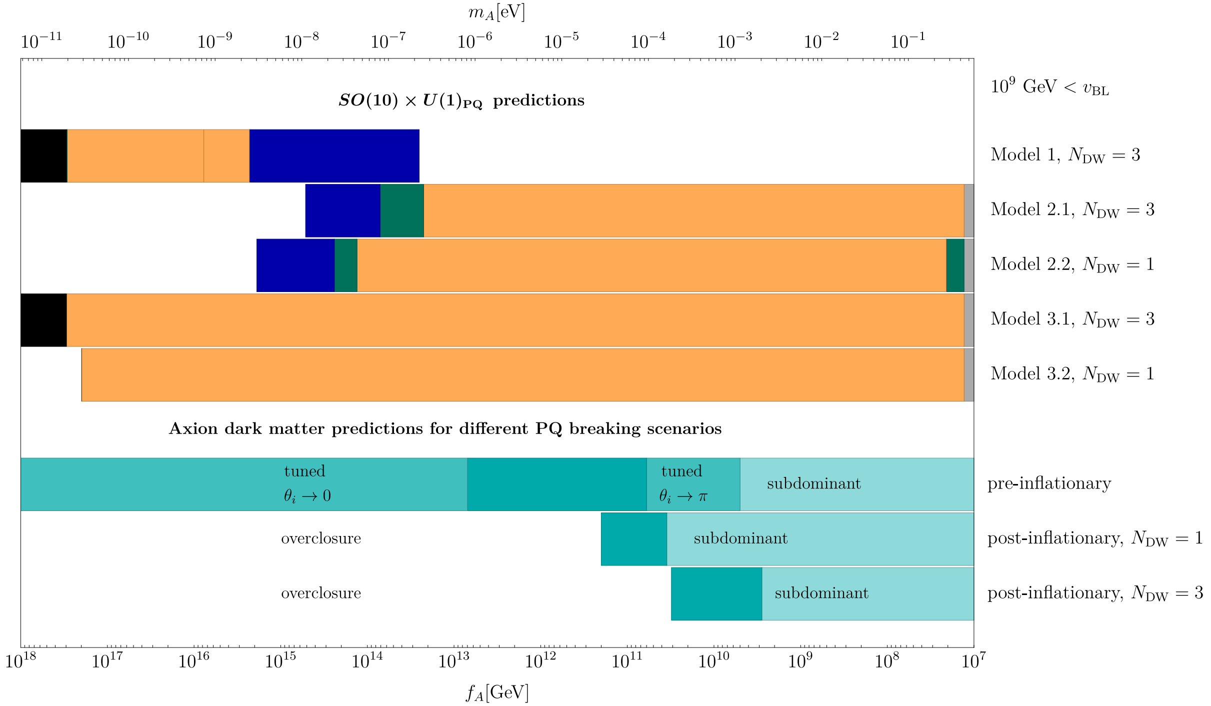
$$M_L = Y_{126} v_L \,.$$

Towards a GUT SMASH

- Various $SO(10) \times U(1)_{\rm PQ}$ models:
  [Ernst,AR,Tamarit in prep.]

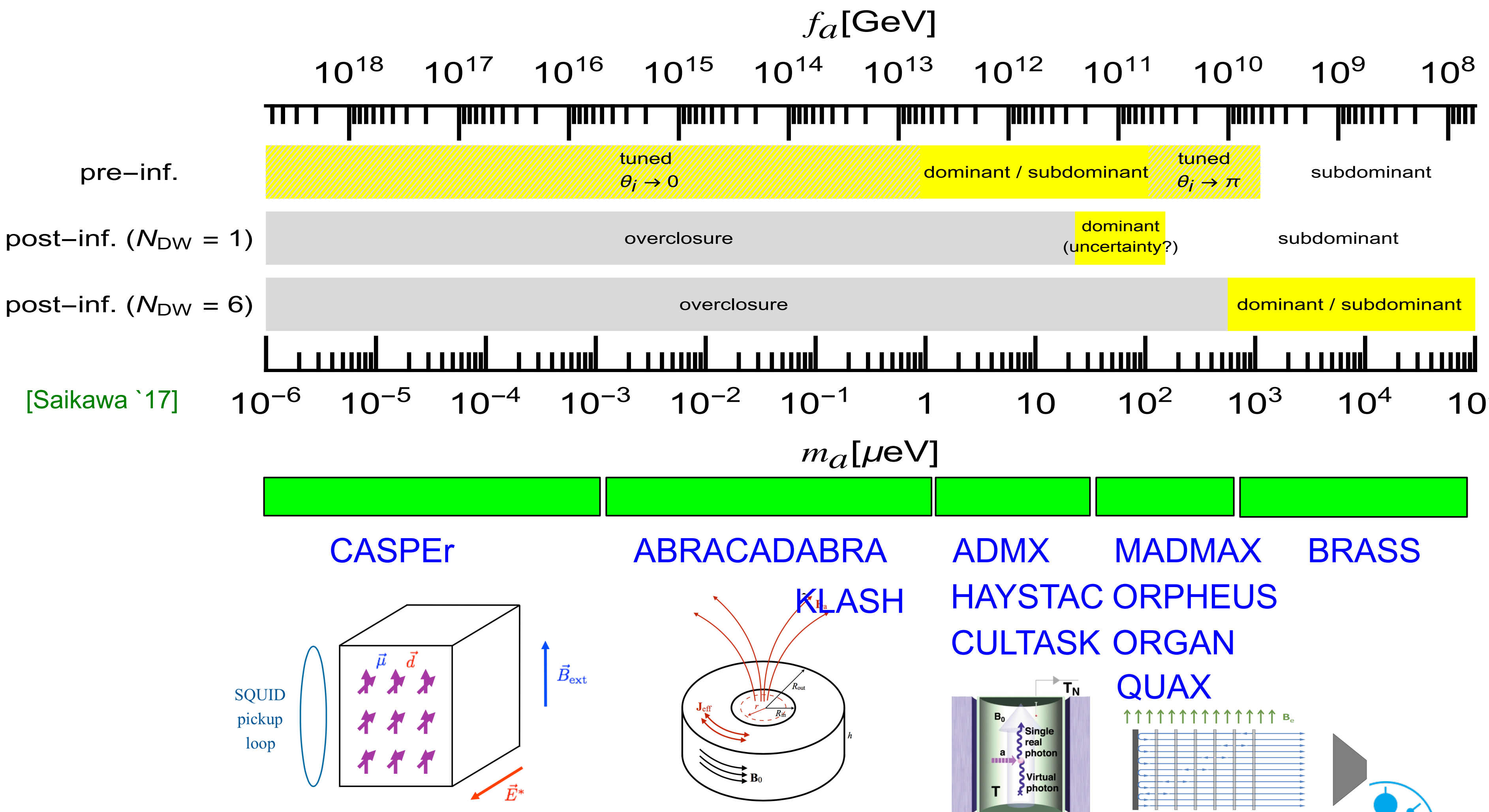
	16_F	$\overline{126}_H$	10_H	210_H	45_H	S	10_F
Model 1	1	-2	-2	4	–	–	–
Model 2.1	1	-2	-2	0	4	–	–
Model 2.2	1	-2	-2	0	4	–	-2
Model 3.1	1	-2	-2	0	–	4	–
Model 3.2	1	-2	-2	0	–	4	-2

- Axion predictions, taking into account constraints from unification, proton decay, seesaw scale, stellar cooling, superradiance of black holes:



Axion Dark Matter Direct Detection Experiments

- Upcoming generation of axion dark matter direct detection experiments can probe entire mass range:

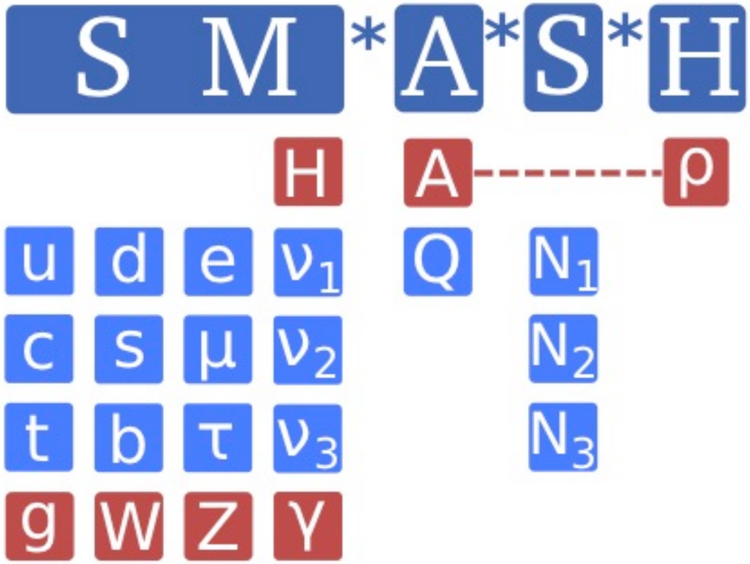


DESY

Summary

- Remarkably simple extension of SM involving just one new dimension-ful scale provides solution of five fundamental problems

  1. Neutrino oscillations
  2. Baryon asymmetry
  3. Dark matter
  4. Inflation
  5. Non-observation of strong CP violation



$$\mathcal{L} = \mathcal{L}_{\rm kin} + \mathcal{L}_{\rm yuk}^{SM}$$

INFLATION

$$-\left[\frac{M^2}{2} + \xi_H\, H^\dagger H + \xi_\sigma\, |\sigma|^2\right] R$$

$$-\lambda_H \left(H^\dagger H - \frac{v^2}{2}\right)^2$$

STABILITY

$$- 2\lambda_{H\sigma}\left(H^\dagger H - \frac{v^2}{2}\right)\left(|\sigma|^2 - \frac{v_\sigma^2}{2}\right)$$

CP PROBLEM

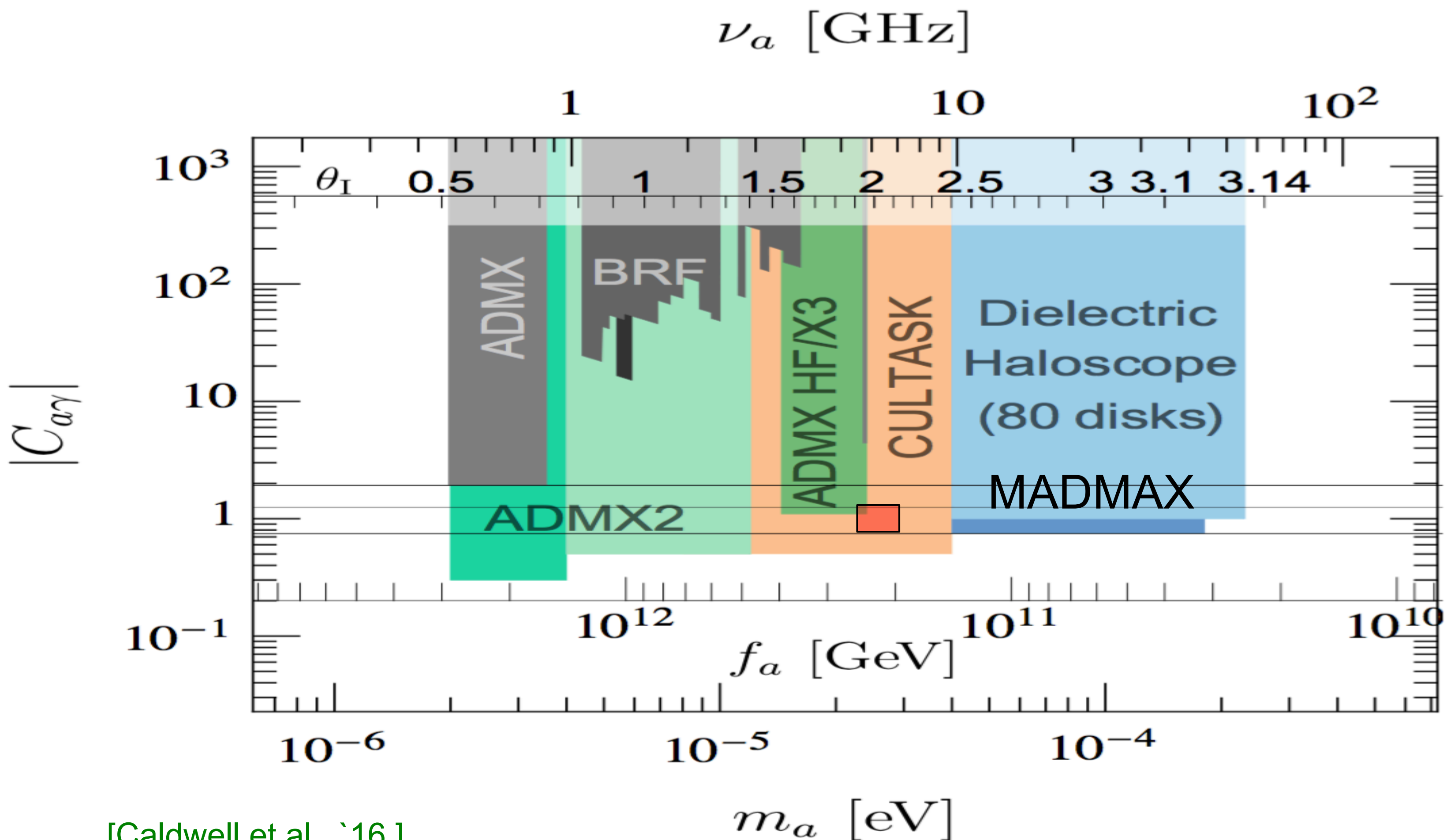
$$-\lambda_\sigma\left(|\sigma|^2 - \frac{v_\sigma^2}{2}\right)^2 - [y\sigma\tilde{Q}Q + y_{Q_{d_i}}\sigma Q d_i + c.c]$$

SEESAW AND LEPTOGENESIS

$$-[F_{ij}L_i\epsilon H N_j + \frac{1}{2}Y_{ij}\sigma N_i N_j + c.c.]$$

Summary

> Firm predictions in reach of upcoming experiments:



[Caldwell et al. `16]

Summary

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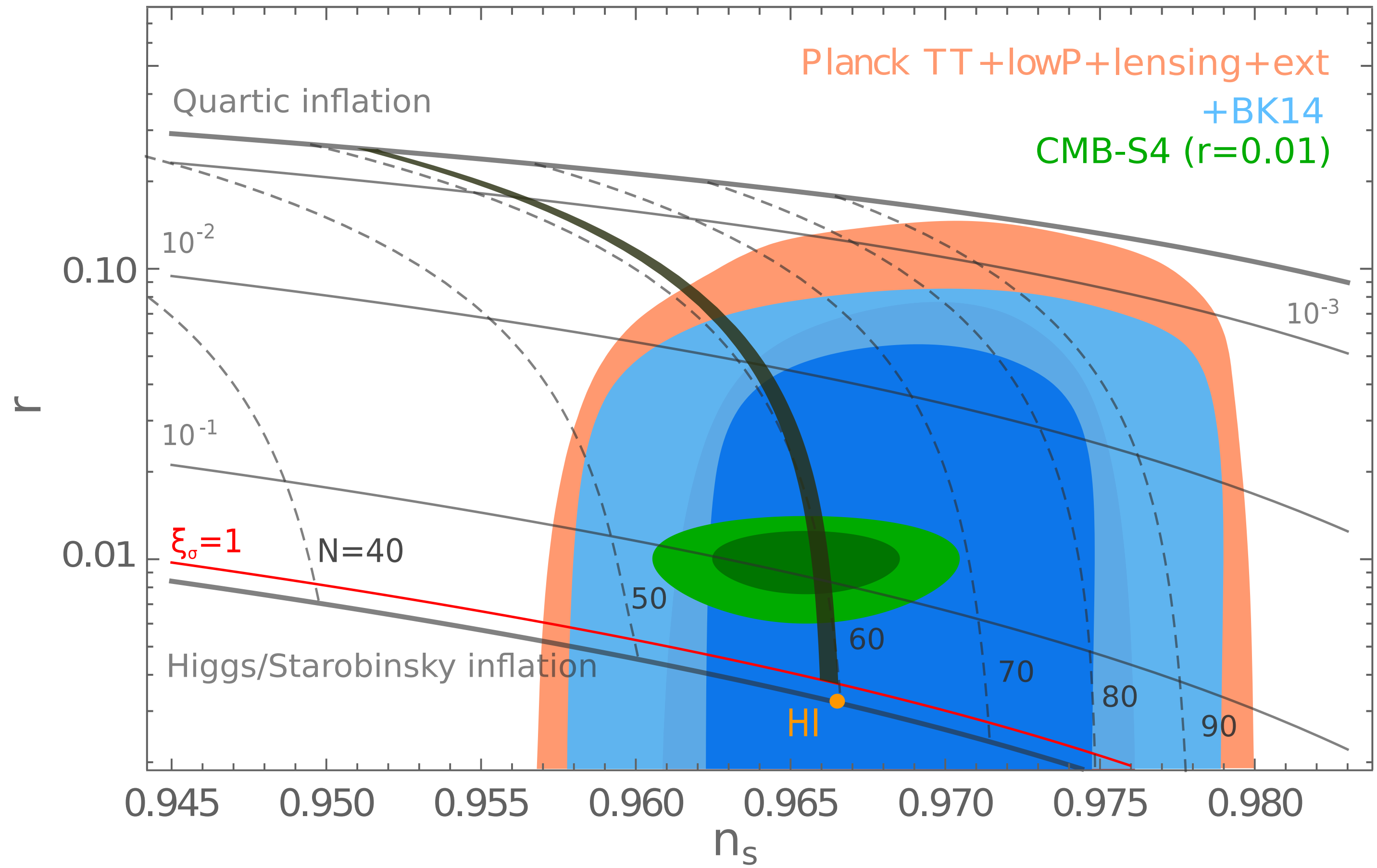

[Ballesteros,Redondo, AR,Tamarit `16]

Outlook

- Variants of SMASH
  - Embedding into non-supersymmetric SO(10) in progress
  - Other variants of see-saw mechanism?
  - Relaxation mechanism to solve naturalness problems (hierarchy problem, cosmological constant problem) inherent to SMASH?
- Ultraviolet completion of SMASH including quantum gravity?
  - Embedding in string theory?

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

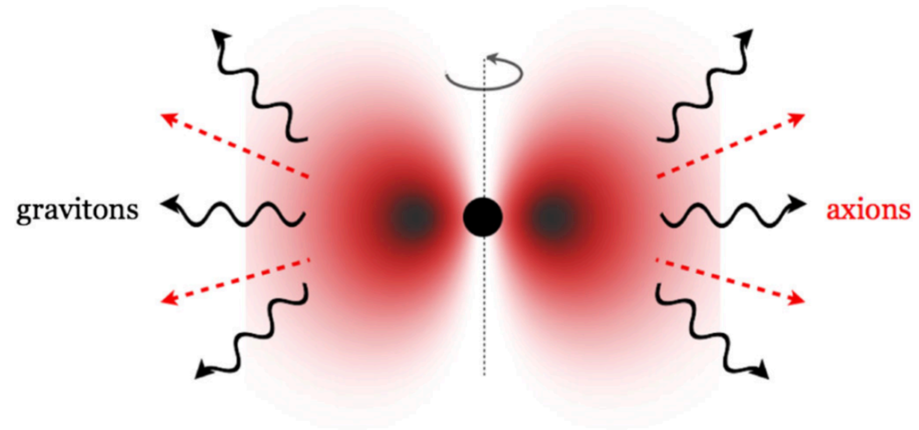

FIG. 1 (color online). *Axionic Black Hole Atom:* The spinning black hole "feeds" superradiant states forming an axion Bose-Einstein condensate. The resulting bosonic atom will emit gravitons through axion transitions between levels and annihilations and will emit axions as a consequence of self-interactions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

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

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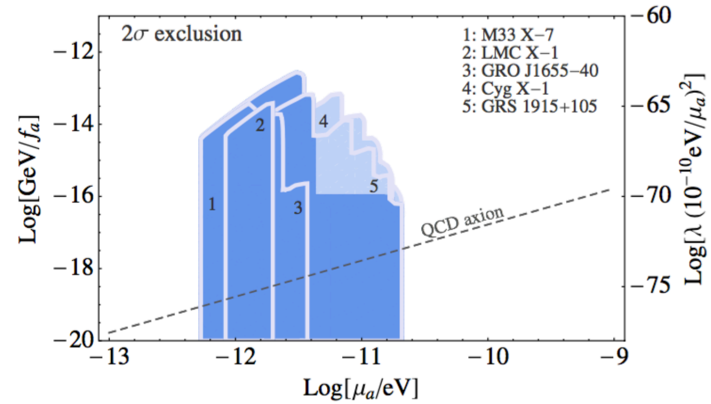
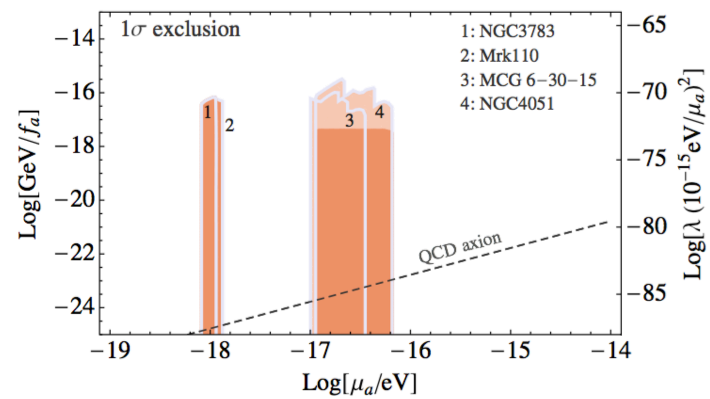
- Stellar BH spin measurements exclude

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



(a)

[Arvanitaki et al. 14]



(b)

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

- In $N=1$ post-inflationary PQ breaking scenario:
- Exploiting results from field theoretic lattice simulations, updated to latest determination of topological susceptibility, and artificially separating

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

find

$$\Omega_{A,{\rm tot}} h^2 \approx 1.6^{+1.0}_{-0.7} \times 10^{-2} \times \left(\frac{f_A}{10^{10}\,{\rm GeV}}\right)^{1.165}$$

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

CDM explained for

$$m_A \approx (50\text{–}200)\,\mu{\rm eV}$$

- Large uncertainty to account for errors due to extrapolation of string tension $T_{\rm str} = \pi f_A^2 \kappa$, with $\kappa = \ln(\sqrt{2\lambda_\sigma} f_A/H)$, from the values affordable in the simulations, $\kappa \lesssim$ to physical values, $\kappa \in [48, 67]$
- New simulation method allows to simulate at physical string tension

[Klaer,Moore `17]

Back Up: DM Axion Mass in Post-Infl. 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 [Klaer,Moore `17]

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

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- For $\kappa \gg 1$, string behavior should approach that of infinitely thin, i.e. local Nambu-Goto strings [Klaer,Moore `17]
- New method: exploit UV extension of PQ field theory, with additional complex scalar and additional local U(1) symmetry,

$$
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\end{aligned}
$$

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

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

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

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

[Klaer,Moore `17]

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

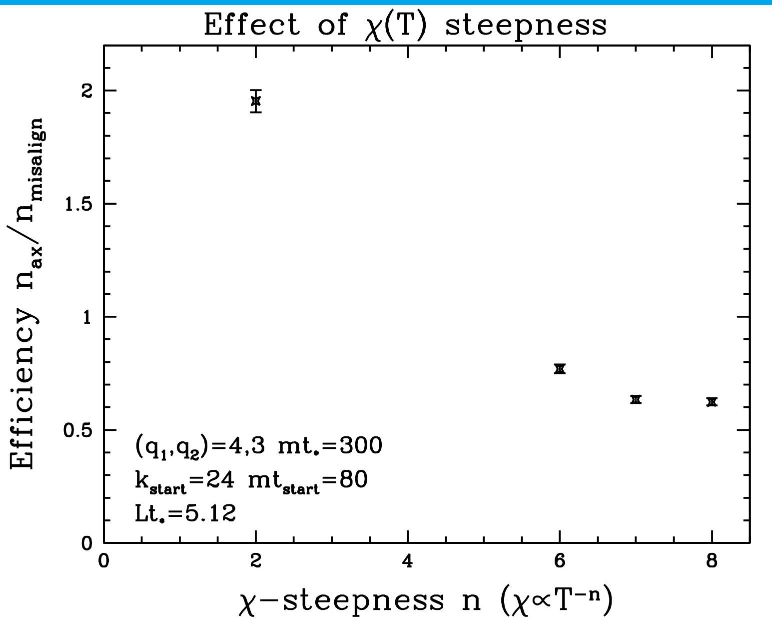
$$\Omega_A^{\rm vr} h^2 = 0.12 \left(\frac{29.7\ \mu\text{eV}}{m_A}\right)^{1.165}$$

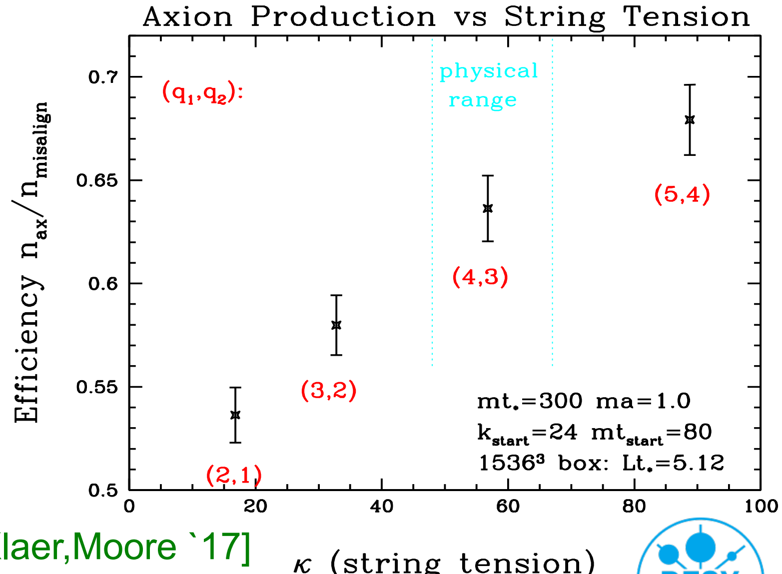
  - Simple sum

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

    double counts

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





[Klaer,Moore `17]