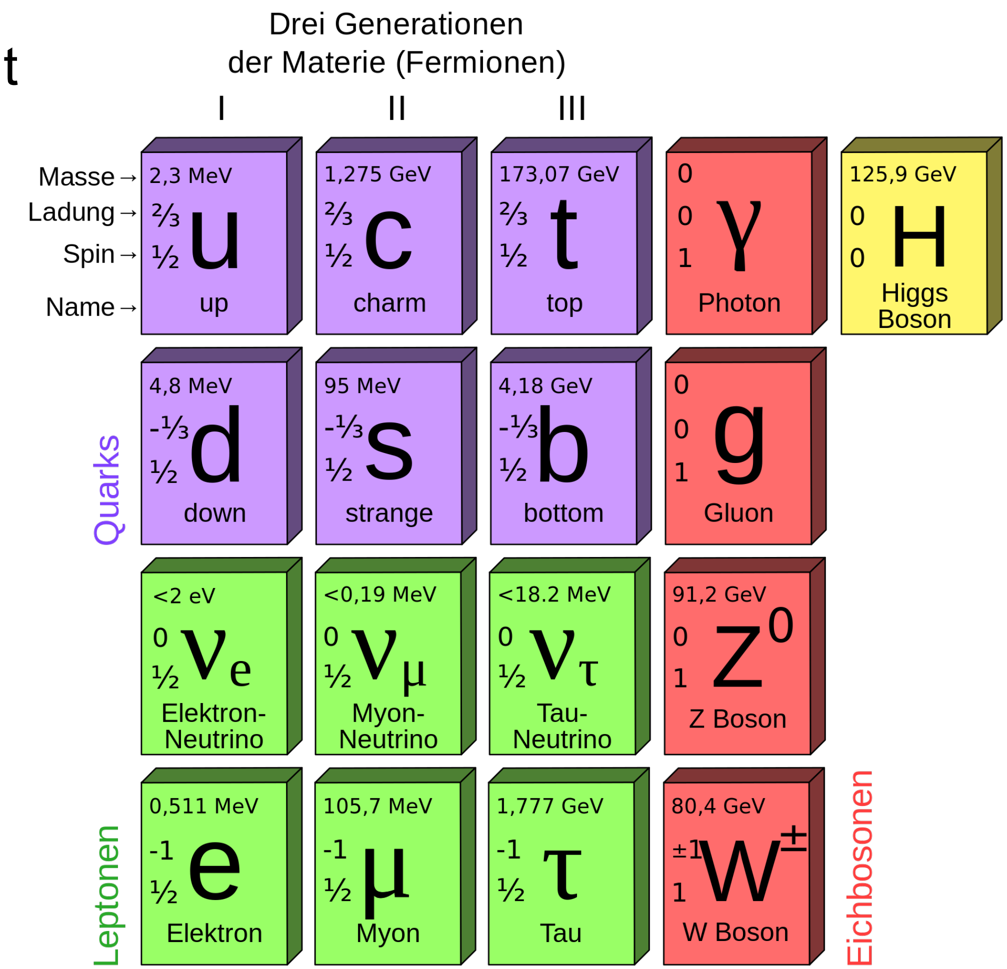
Axions in Particle Physics.

Andreas Ringwald

Annual Retreat of GRK and PRISMA
Kloster Johannisberg, D
20 September 2017

Strong Case for Physics Beyond the Standard Model

- Discovery of Higgs boson marks completion of SM particle content



[wikipedia]

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- Strong case for physics beyond SM (BSM) suggested by observations in particle physics, astrophysics and cosmology
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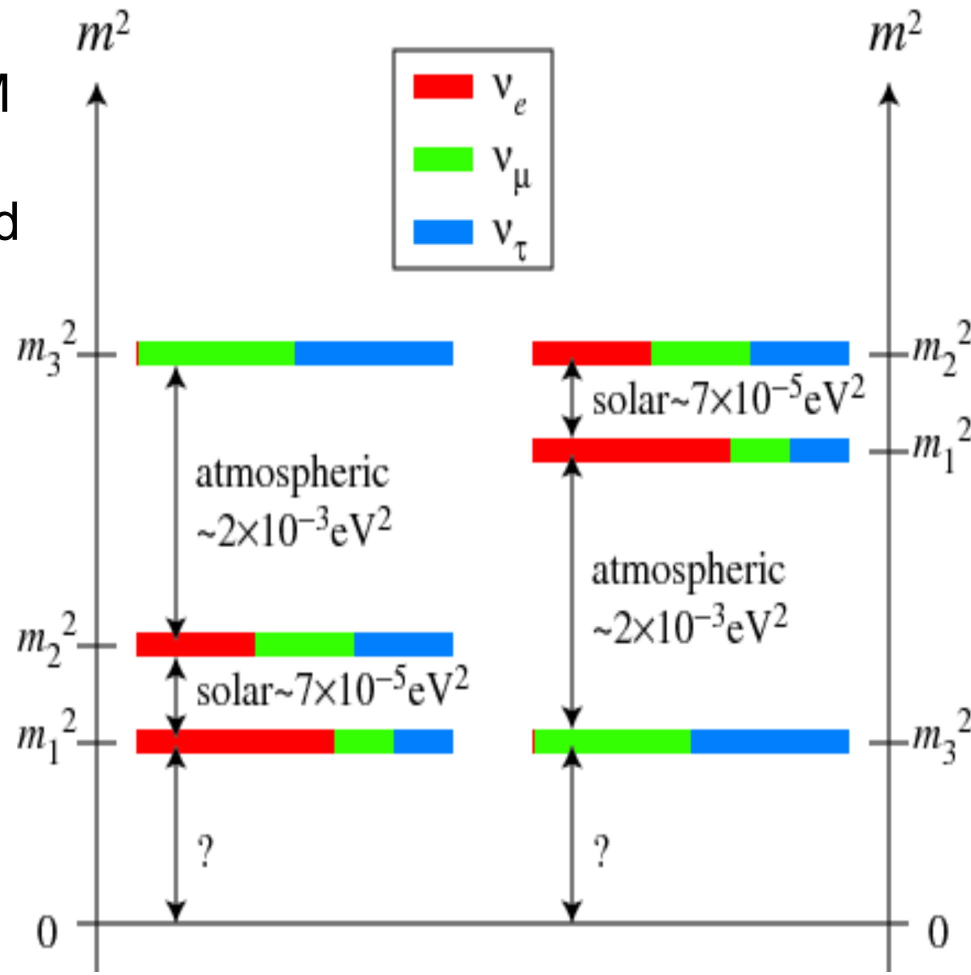

[King et al. 13]

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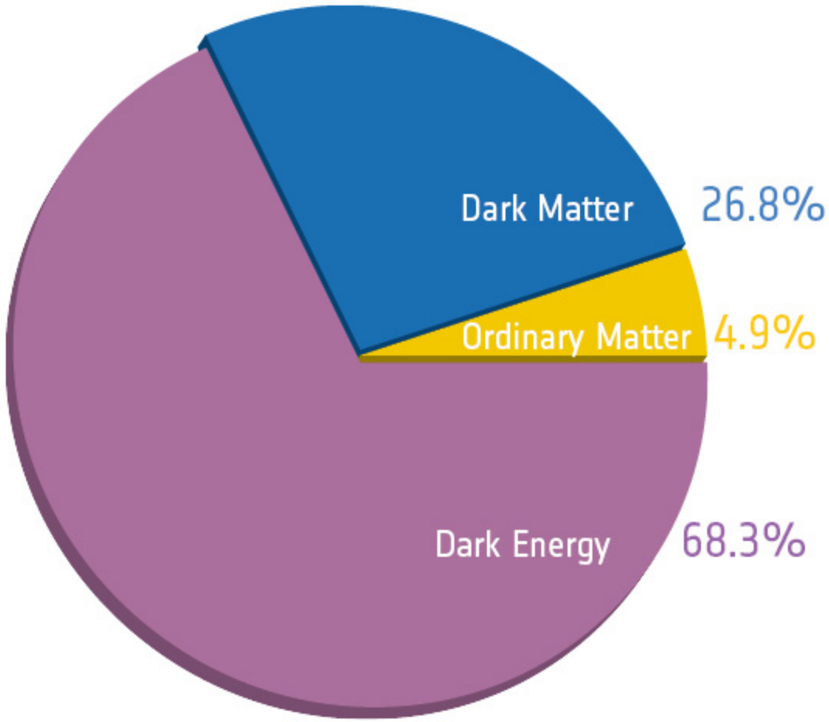

[PLANCK]

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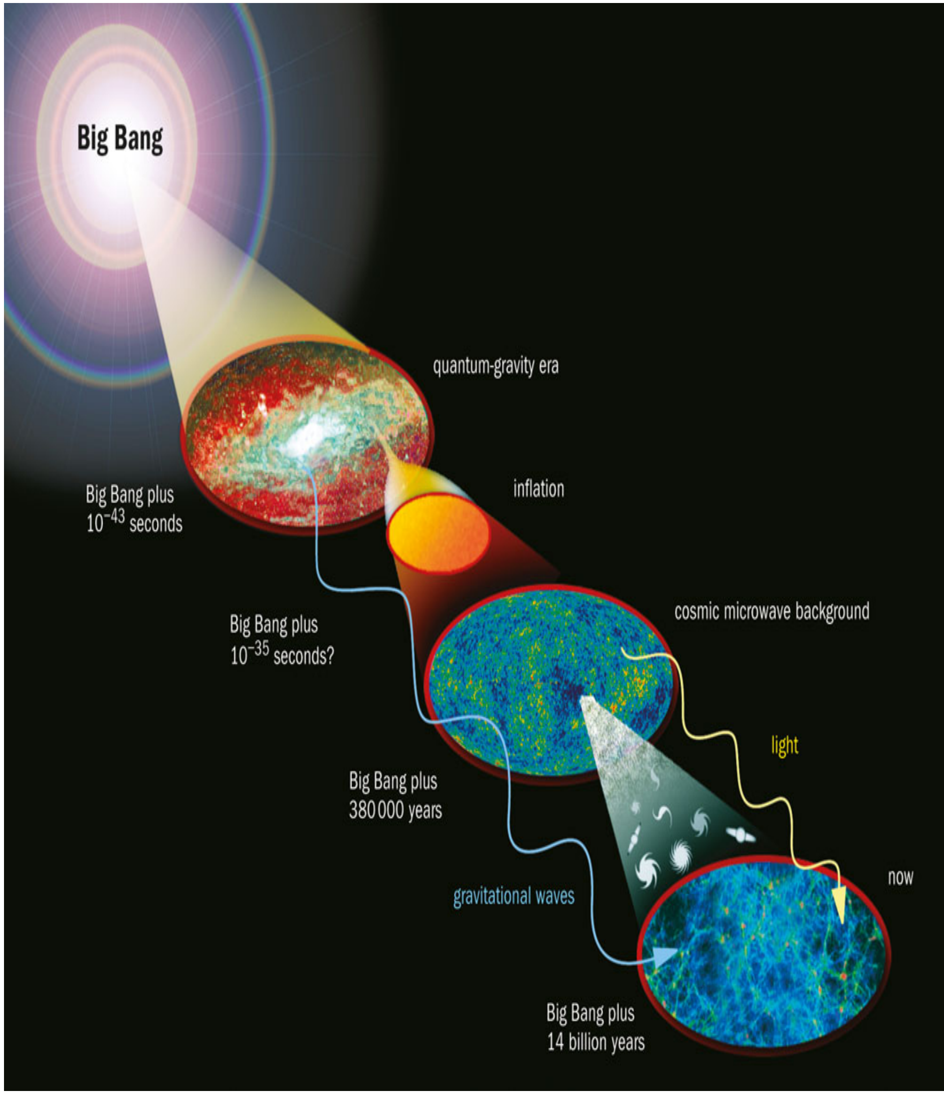

[physicsworld.com]

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  - Dark matter
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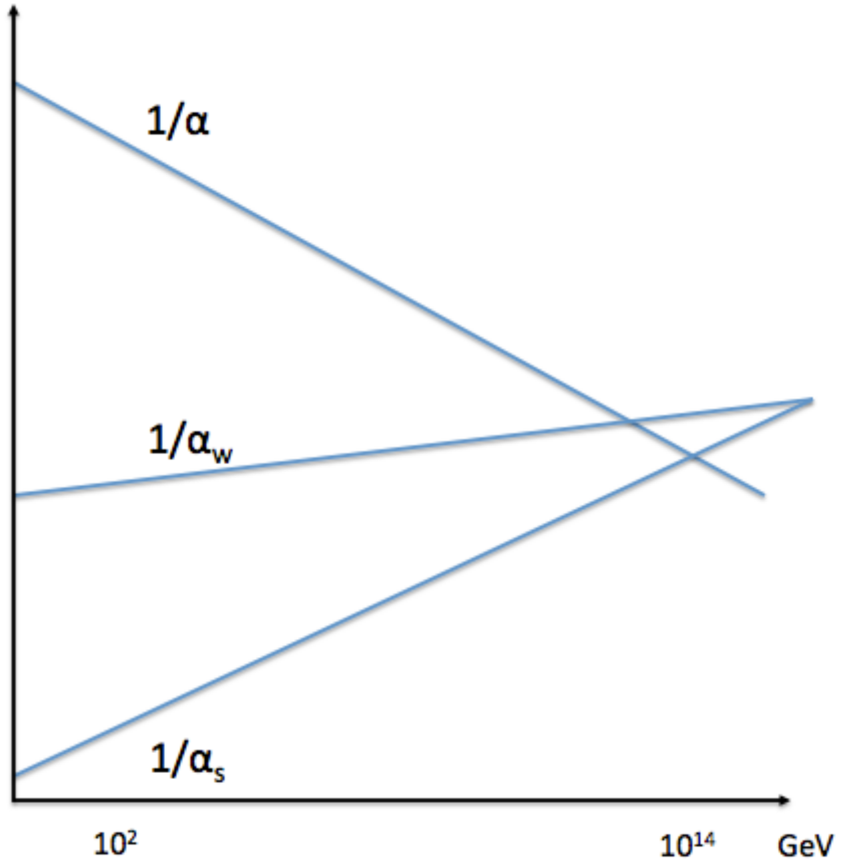
  - Baryon asymmetry
  - Unification?
  - Naturalness?
    - Cosmological constant (dark energy)
    - Hierarchy between weak scale and Planck scale
    - Non-observation of strong CP violation



[StackExchange]

Topological Theta Term and 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 $\mathcal{M}_q = {\rm diag}(m_u, m_d, \ldots)$ and theta angle θ [Belavin et al. `75;´t Hooft 76;Callan et al. `76;Jackiw,Rebbi `76]

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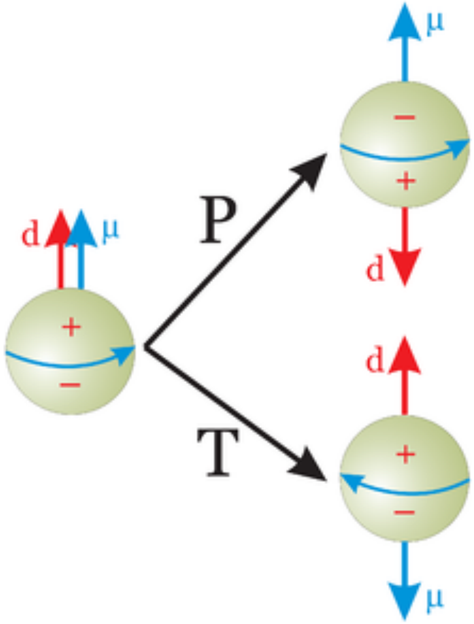

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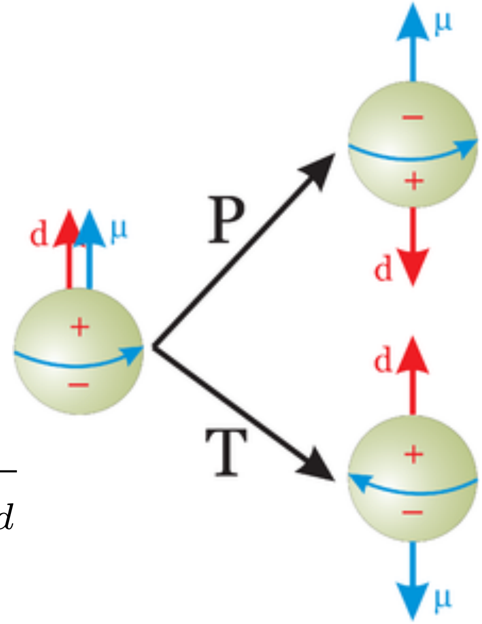
$$d_n \sim e\theta\, \frac{m_*}{m_n^2} \sim 6 \times 10^{-17}\ \theta\ e\,{\rm cm}; \qquad m_* = \frac{m_u m_d}{m_u + m_d}$$



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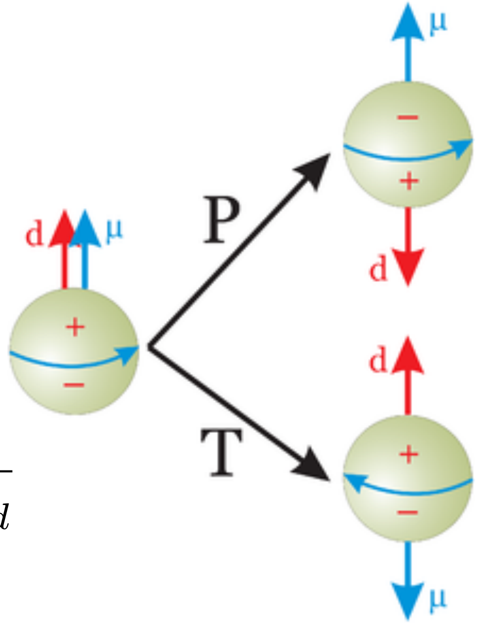
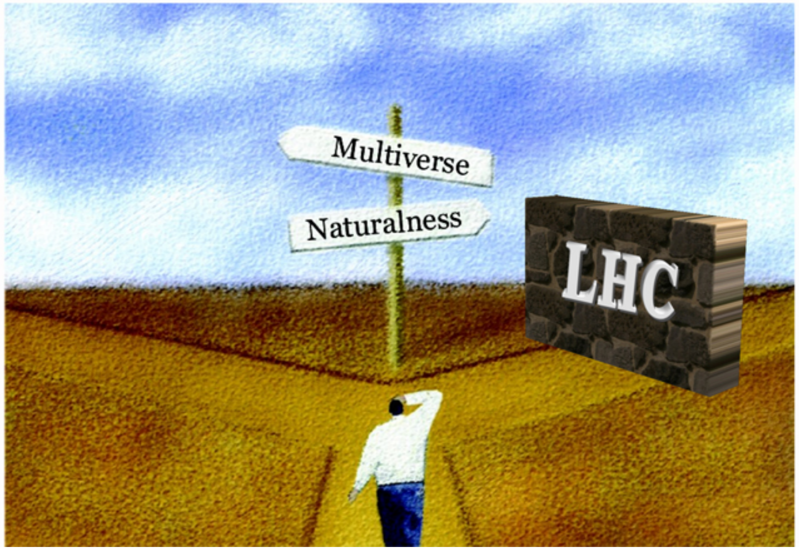


- Experiment: [Baker et al. 06]

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

Topological Theta Term and Strong CP Problem

- Naturalness?
  1. Cosmological constant (dark energy)
  2. Hierarchy between weak scale and Planck scale
  3. Non-observation of strong CP violation
- 1. and 2. can be „solved“ by anthropic selection in multiverse
- Fails for 3.!
  - No anthropic argument for $|\theta| < 10^{-9}$
- Dynamical solution of 3. most required!



[Quantamagazine]

Topological Theta Term and Strong CP Problem

- If θ were a dynamical field, its vacuum expectation value would be zero. Correspondingly: strong CP problem solved
  - Partition function in terms of Fourier series of Euclidean path integrals over gauge fields with fixed topological charge

$$Z(\theta) = \sum_{Q=-\infty}^{+\infty} \exp[i\theta Q] Z_Q, \qquad Q = \int d^4x \, \frac{\alpha_s}{8\pi} G^b_{\mu\nu} \tilde{G}^{b,\mu\nu} \equiv \int d^4x \, q(x)$$

$$Z_Q = \int_Q [dG][dq][d\bar{q}] \exp\left[- \int d^4x \left\{ \frac{1}{4} G^a_{\mu\nu} G^a_{\mu\nu} + i\bar{q}\gamma_\mu D_\mu q - \bar{q}_R \mathcal{M} q_L - \bar{q}_L \mathcal{M}^\dagger q_R \right\} \right]$$

  - Z_Q positive
  - Vacuum energy density in QCD

$$\epsilon_0(\theta) \equiv -\frac{1}{\mathcal{V}} \ln \left[\frac{Z(\theta)}{Z(0)} \right], \qquad -\pi \le \theta \le \pi$$

has absolute minimum at $\theta = 0$

[Vafa,Witten ´84]

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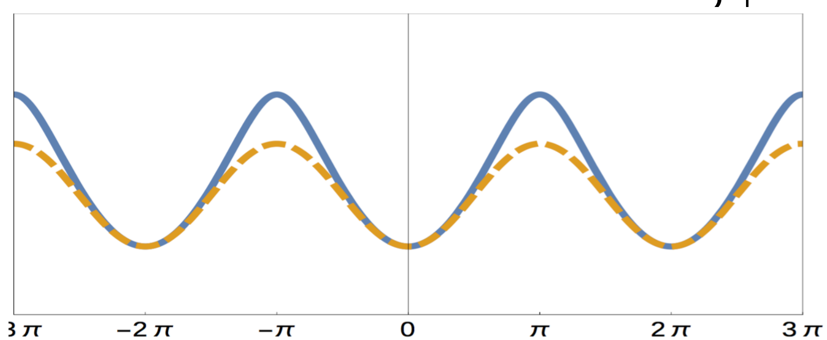


> Chiral EFT allows to calculate vacuum energy density: [Grilli di Cortona et al. `16]

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

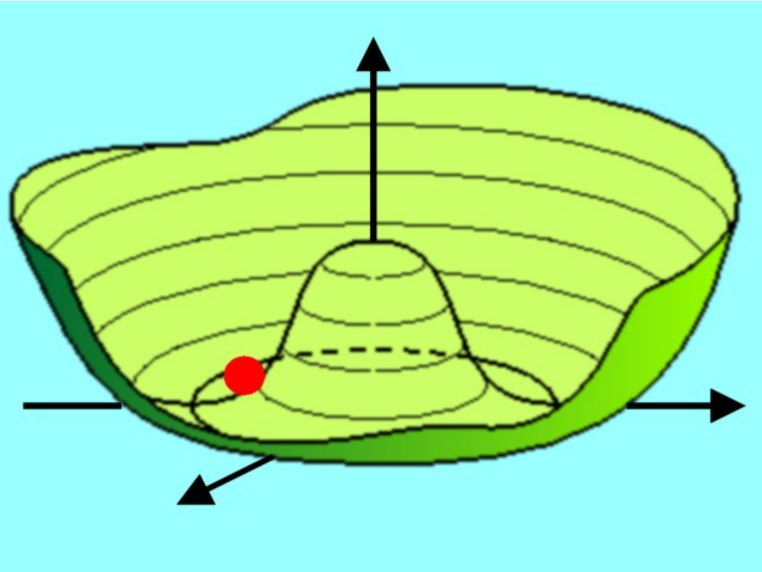
[Di Vecchia,Veneziano `80]

Axionic Solution of Strong CP Problem

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

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

  - Excitation of modulus: $m_\rho \sim v_{\rm PQ}$
  - Excitation of angle: NGB $m_A \ll v_{\rm PQ}$



[Raffelt]

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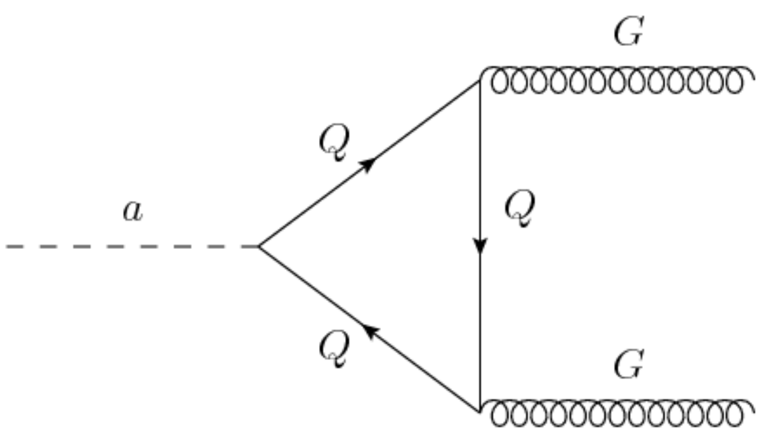
- Quarks (SM or extra) carry PQ charges such that $U(1)_{\rm PQ}$ is anomalously broken due to gluonic triangle anomaly

$$\partial_\mu J^\mu_{U(1)_{\rm PQ}} = -\frac{\alpha_s}{8\pi}\, N\, G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu} - \frac{\alpha}{8\pi}\, E\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$



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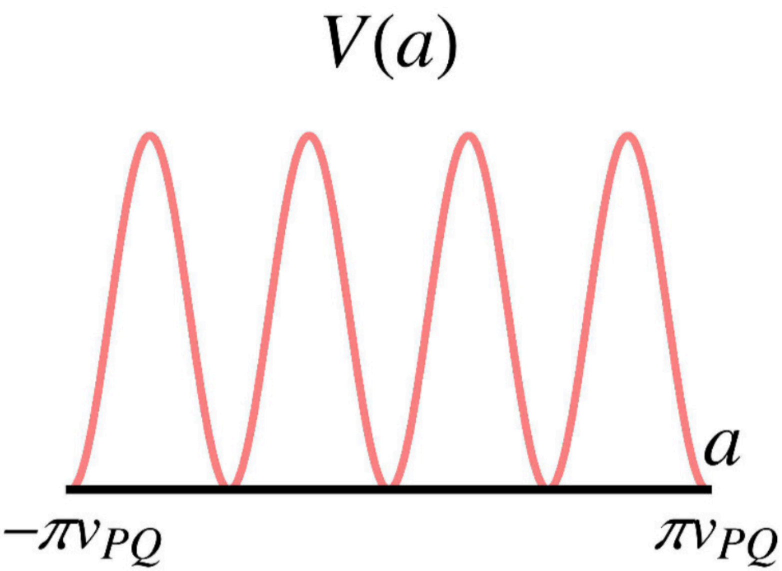

$$V(A) \simeq m_\pi^2 f_\pi^2 \left[1 - \frac{\sqrt{m_u^2 + m_d^2 + 2 m_u m_d \cos(NA/v_{\rm PQ})}}{m_u + m_d}\right]$$

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- No strong CP problem, since NGB field acts as x-dependent theta parameter:

[Peccei,Quinn 77; Weinberg 78; Wilczek 78]

A ... Axion

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi}\frac{A(x)}{f_A} G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu} - \frac{\alpha}{8\pi}\frac{E}{N}\frac{A(x)}{f_A} F_{\mu\nu}\tilde{F}^{\mu\nu}; \qquad f_A = v_{\rm PQ}/N$$

QCD dynamics: $\langle A(x)\rangle = 0$

Axion Couplings to SM at Energies Below QCD Scale

$$\mathcal{L} = \frac{1}{2}\partial_\mu A \partial^\mu A - \frac{1}{2} m_A^2 A^2 - \frac{\alpha}{8\pi}\frac{C_{A\gamma}}{f_A} A\, F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\frac{C_{Af}}{f_A}\partial_\mu A\, \overline{\psi}_f \gamma^\mu \gamma_5 \psi_f$$

- Axion mass: $m_A = 57.0(7) \left(\frac{10^{11}\,\mathrm{GeV}}{f_A}\right) \mu\mathrm{eV}$ [Weinberg ´78; ... Borsanyi et al. `16]

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$$f_A = v_{\rm PQ}/N \gg v = 246\,\mathrm{GeV}$$

rendering the axion „invisible“

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

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- Photon coupling: $C_{A\gamma} = \frac{E}{N} - 1.92(4)$ [Kaplan 85;Srednicki \`85]
- Nucleon couplings: [Grilli di Cortona et al. \`16]

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

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- Nucleon couplin[g]: model-independent [Grilli di Cortona et al. `16]

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- Electron coupling very model-dependent

Axion-Like Particles (ALPs)

- Extending the SM by further well-motivated global symmetries may lead to even more Nambu-Goldstone bosons:
  - Global lepton number symmetry: Majoron [Chikashige et al. 78; Gelmini,Roncadelli 80]
  - Global family symmetry: Familon [Wilczek 82; Berezhiani,Khlopov 90]

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi}\frac{C'_{ig}}{f_{a'_i}}\, a'_i\, G^b_{\mu\nu}\tilde{G}^{b,\mu\nu} - \frac{\alpha}{8\pi}\frac{C'_{i\gamma}}{f_{a'_i}}\, a'_i\, F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\frac{C'_{a'_i f}}{f_{a'_i}}\,\partial_\mu a'_i\, \overline{\psi}_f\gamma^\mu\gamma_5\psi_f$$

- Then the particle corresponding to the excitation of the field combination

$$\frac{A(x)}{f_A} \equiv \frac{C'_{ig}}{f_{a'_i}}\, a'_i(x)$$

  is the axion

- Particle excitations of the fields orthogonal to this field combination are called Axion-Like-Particles (ALPs)

- String theory suggests a plenitude of ALPs [Witten 84; Conlon 06; Arvanitaki,Dimopoulos,Dubovsky,Kaloper,March-Russell 10; Cicoli,Goodsell,AR 12]

A Minimal Model of Particle Physics and Cosmology

- Unify PQ U(1) symmetry with lepton symmetry: add vector-like quark and three right-handed SM-singlet neutrinos to SM [Shin 87; Dias et al. `14]

$$\mathcal{L} \supset -\Big[Y_{uij} q_i \epsilon H u_j + Y_{dij} q_i H^\dagger d_j + G_{ij} L_i H^\dagger E_j + F_{ij} L_i \epsilon H N_j + \frac{1}{2} Y_{ij} \sigma N_i N_j$$

$$+ y\, \tilde{Q} \sigma Q + y_{Q_d\,i} \sigma Q d_i + h.c. \Big]$$

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

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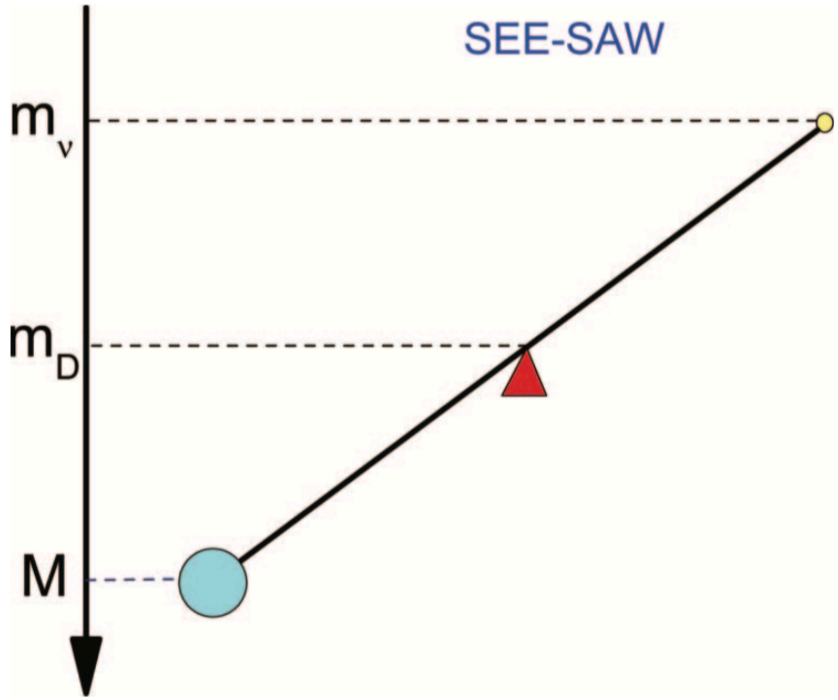
1. No strong CP problem
2. See-saw explanation of active neutrino masses

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



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> Unify PQ U(1) symmetry with lepton symmetry: add vector-like quark and three right-handed SM-singlet neutrinos to SM [Shin 87; Dias et al. `14]

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

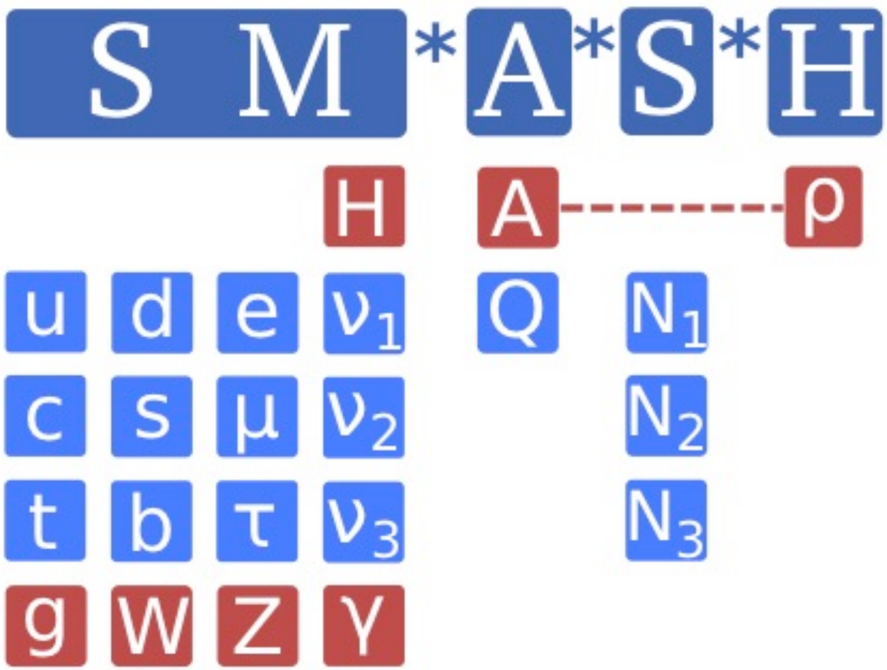
SM * Axion * See-saw * Higgs portal inflation

[Ballesteros,Redondo, AR,Tamarit, 1608.05414]

1. No strong CP problem
2. See-saw explanation of active neutrino masses

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

3. Axion dark matter
4. Explains matter-antimatter asymmetry by thermal leptogenesis
5. Higgs portal inflation



Axion in SO(10) GUT

- SO(10) GUT automatically features right-handed sterile neutrinos
  - Neutrino masses and mixing
  - Baryogenesis via leptogenesis
- PQ extension of non-SUSY SO(10) GUT provides in addition
  - Predictivity of fermion masses/mixing
  - Solution of strong CP problem
  - Axion dark matter

$$Q = \begin{pmatrix} u_1 & u_2 & u_3 & \nu \\ d_1 & d_2 & d_3 & e \end{pmatrix} ,$$

$$Q^c = \begin{pmatrix} d_1^c & d_2^c & d_3^c & e^c \\ -u_1^c & -u_2^c & -u_3^c & -\nu^c \end{pmatrix}$$

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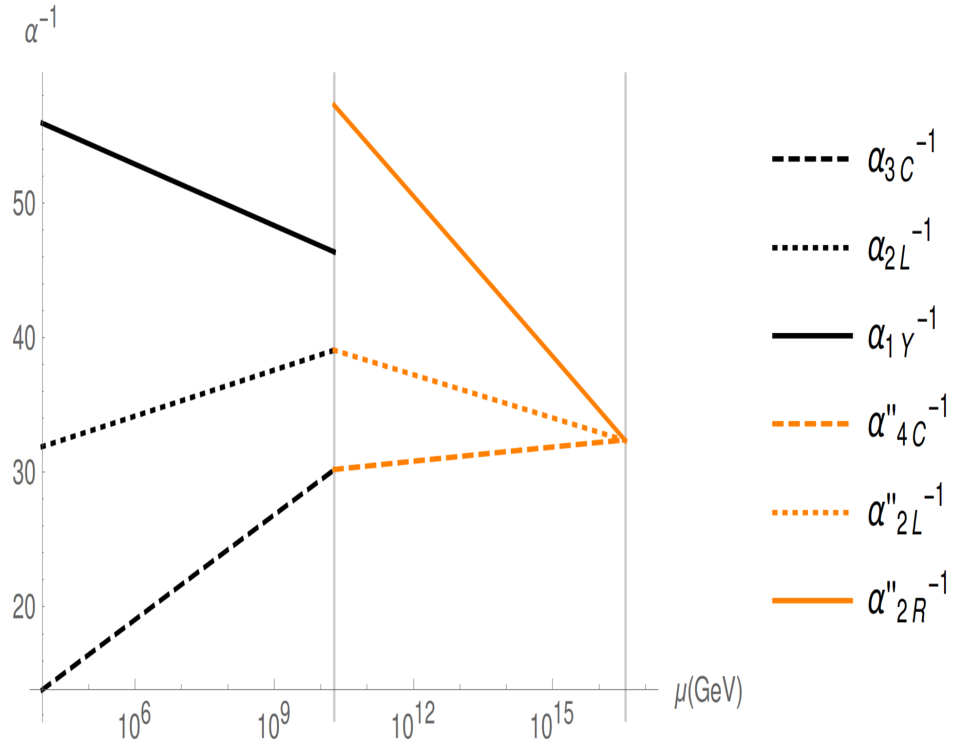
- Intermediate SSB step required:



[Ernst,AR,Tamarit in prep.]

$$SO(10) \stackrel{M_U - 210_H}{\longrightarrow} SU(4)_C \times SU(2)_L \times SU(2)_R \stackrel{M_I - 126_H}{\longrightarrow} SU(3)_C \times SU(2)_L \times U(1)_Y \stackrel{M_Z - 10_H}{\longrightarrow} SU(3)_C \times U(1)_Y$$

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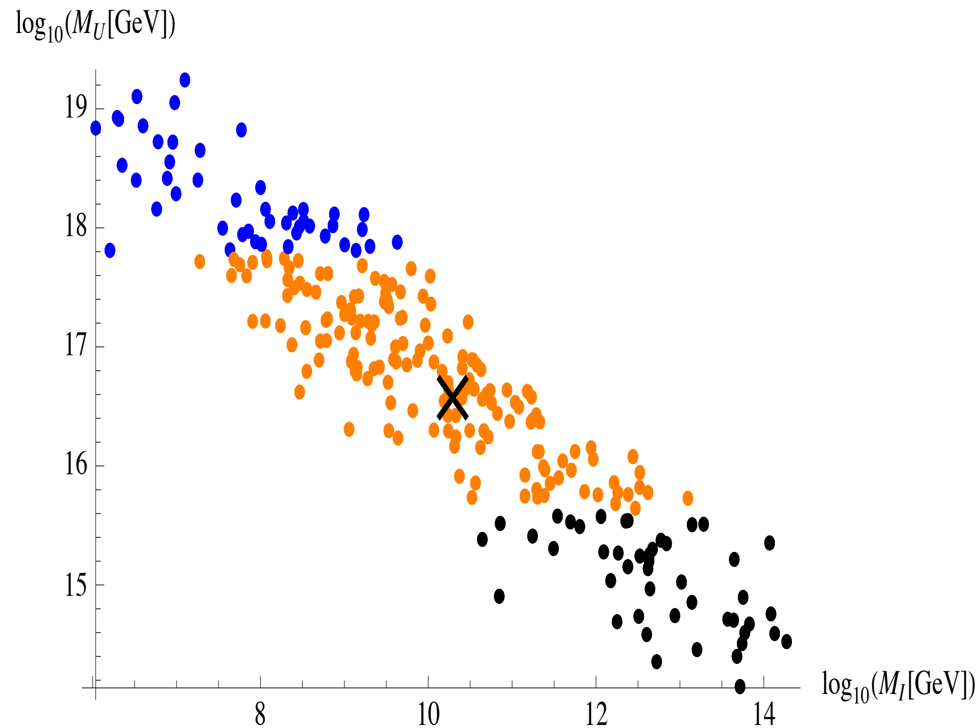

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- Imposing PQ symmetry,

[Ernst,AR,Tamarit in prep.]

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

predicts $1.9 \times 10^{-11}\mathrm{eV} < m_A < 2.2 \times 10^{-9}\mathrm{eV}$

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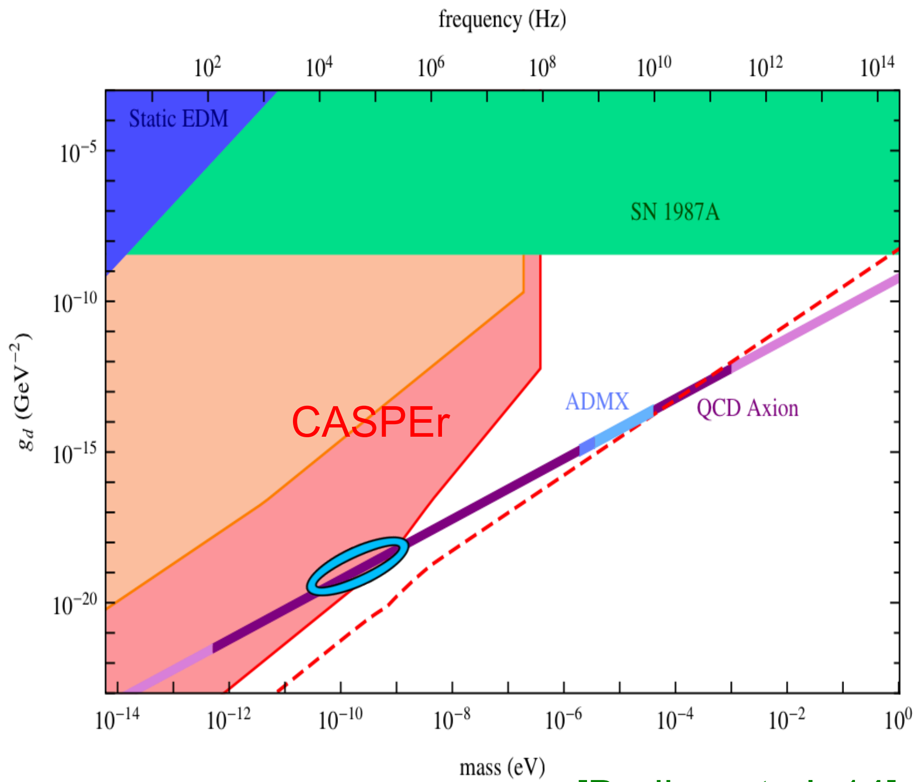


[Budker et al. 14]

- Intermediate SSB step required:

$$SO(10) \xrightarrow{M_U - 210_H} SU(4)_C \times SU(2)_L \times SU(2)_R \xrightarrow{M_I - 126_H} SU(3)_C \times SU(2)_L \times U(1)_Y \xrightarrow{M_Z - 10_H} SU(3)_C \times U(1)_Y$$

- Imposing PQ symmetry,

[Ernst,AR,Tamarit in prep.]

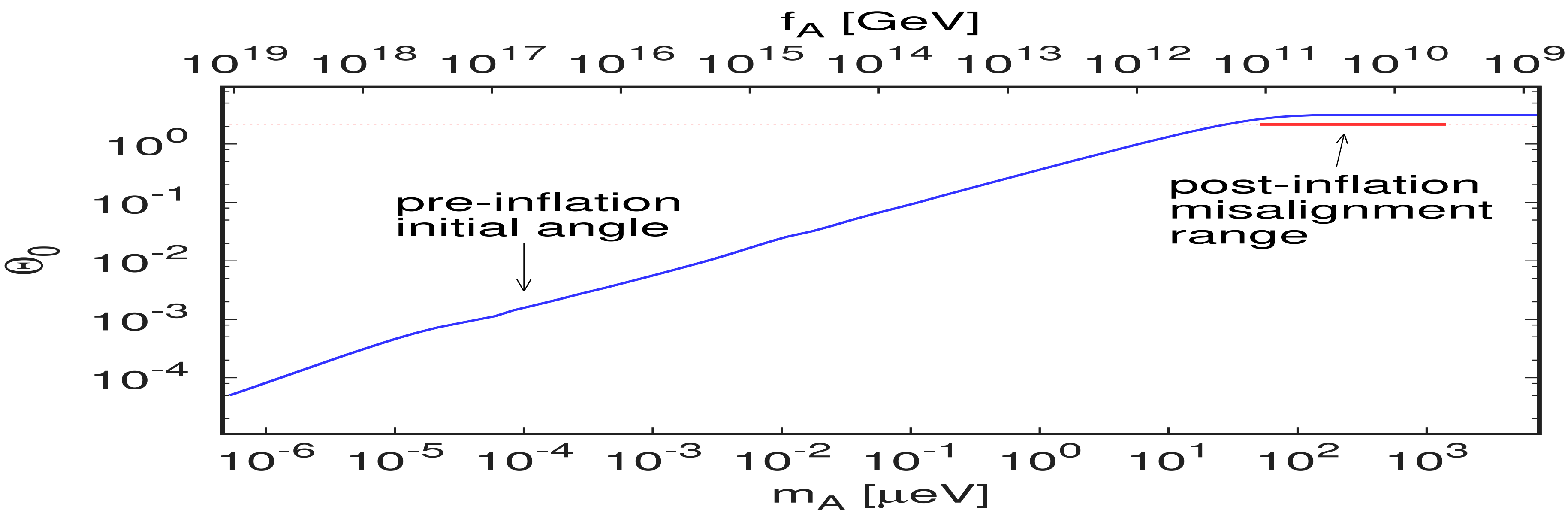
$$16_F \to 16_F e^{i\alpha},\ 10_H \to 10_H e^{-2i\alpha},\ \overline{126}_H \to \overline{126}_H e^{-2i\alpha},\ 210_H \to 210_H e^{4i\alpha}$$

predicts $1.9 \times 10^{-11}\text{eV} < m_A < 2.2 \times 10^{-9}\text{eV}$

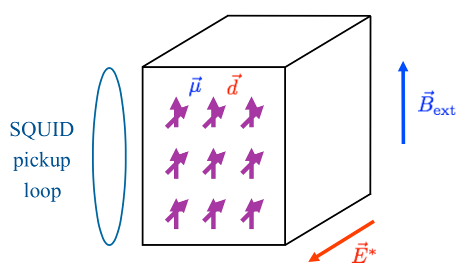
Axion in SO(10) GUT

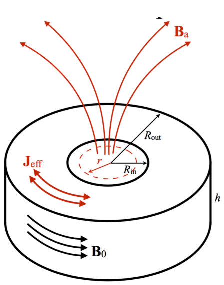
- Adding singlet S and imposing PQ symmetry predicts $m_A \gtrsim 10^{-11}$ eV

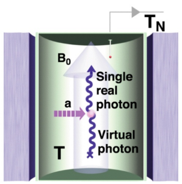
$$16_F \to 16_F e^{i\alpha},\ 10_H \to 10_H e^{-2i\alpha},\ \overline{126}_H \to \overline{126}_H e^{-2i\alpha},\ 210_H \to 210_H\,, S \to S e^{4i\alpha}$$

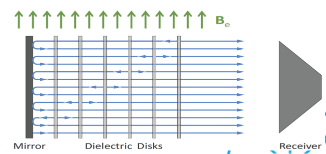


CASPEr | ABRACADABRA | ADMX HAYSTACK CULTASK | MADMAX ORPHEUS ORGAN QUAX | BRASS









DESY

Summary

- Unlike other naturalness problems (cosmological constant, weak scale), smallness of theta can not be justified by anthropic reasoning
- Plenty of UV extensions of SM can provide an axionic solution of the strong CP problem
- Strong CP problem solved for any value of decay constant
- Axion mass in terms of decay constant very well determined
- Couplings to photons and nucleons somewhat, to electrons strongly model-dependent
- Tomorrow: Axions in Astrophysics and Cosmology
- Suggest phenomenologically interesting ranges for decay constant