The Case for the Axion.

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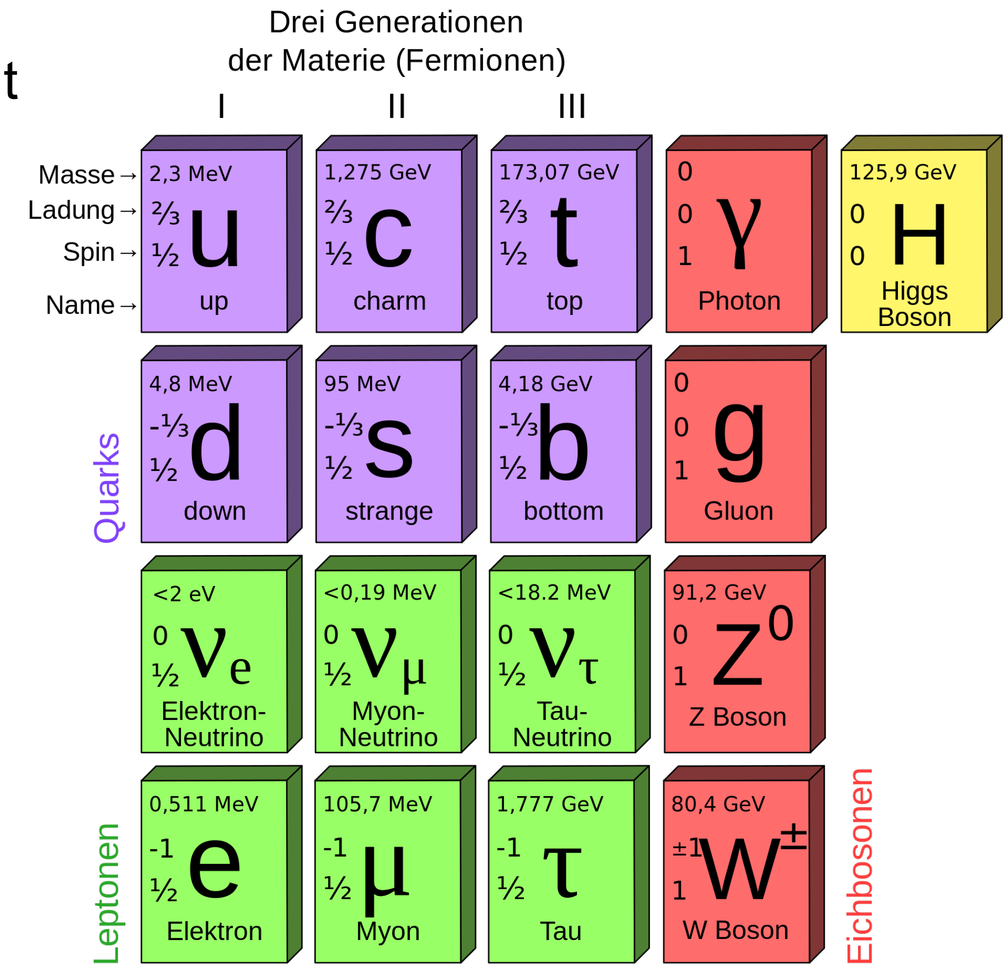
DESY

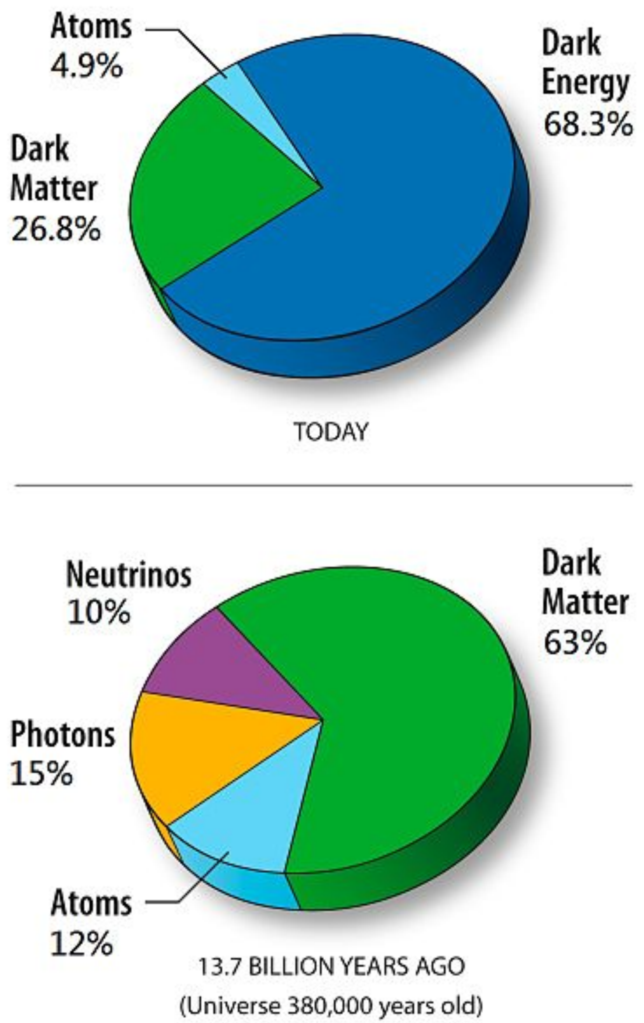
- Discovery of Higgs boson marks completion of SM particle content



[wikipedia]

Strong Case for Particles Beyond the Standard Model

- Discovery of Higgs boson marks completion of SM particle content
- Observations in particle physics, astrophysics and cosmology point to existence of BSM particles
  - Dark matter (DM)
  - Neutrino flavour oscillations
  - Non-observation of strong CP violation



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Strong Case for Particles Beyond the Standard Model

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- Observations in particle physics, astrophysics and cosmology point to existence of BSM particles
  - Dark matter (DM)
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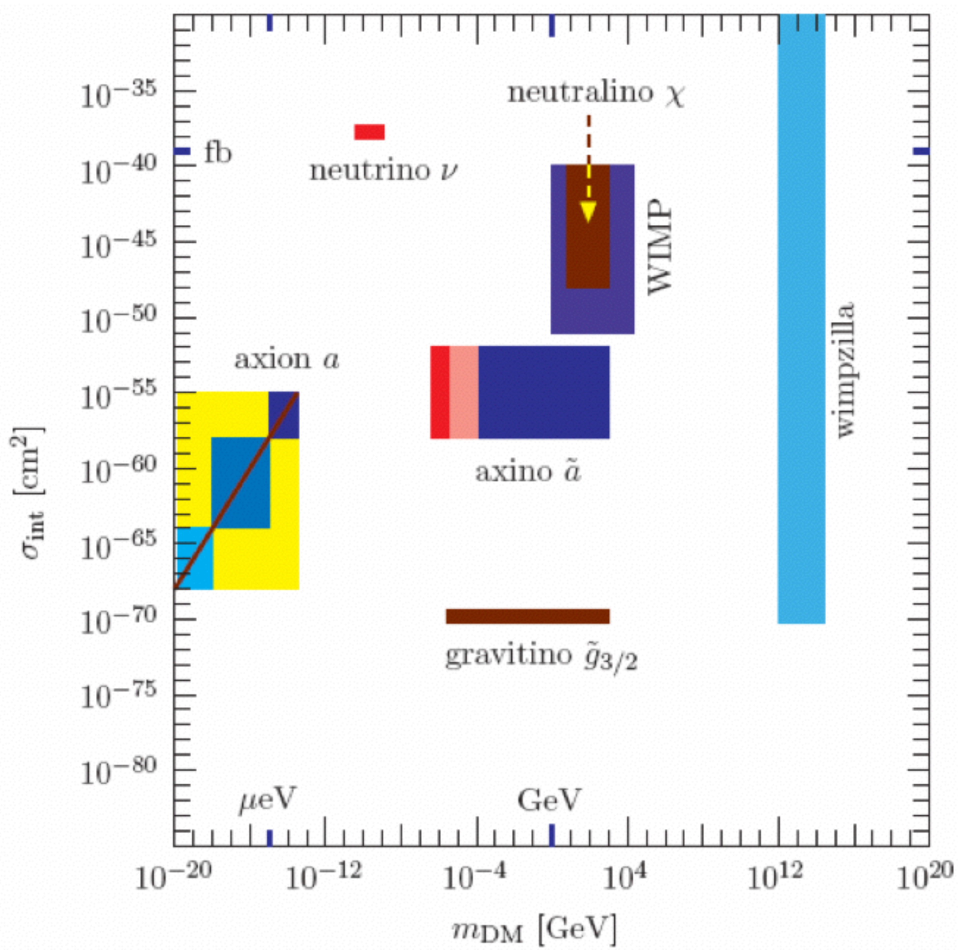
  - Non-observation of strong CP violation
- Plenitude of DM candidates, e.g.:
  - Weakly Interacting Massive Particles (WIMPs), such as neutralinos
  - Very Weakly Interacting Slim (=ultra-light) Particles (WISPs), such as axions



[Kim,Carosi 10]

Topological Theta Term and Strong CP Problem

> Most general gauge invariant Lagrangian of QCD:

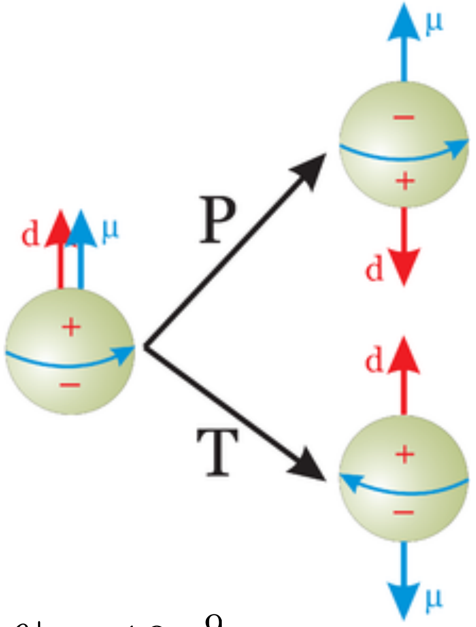
$$\mathcal{L}_{\rm QCD} = -\frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu} + \overline{q}\,(i\gamma_\mu D^\mu - \mathcal{M}_q)\,q - \frac{\alpha_s}{8\pi}\,\theta\,G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}$$

- 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]

> 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; experimentally

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



> Strong CP problem:

$$d_n(\theta) \sim e\,\theta \frac{m_u m_d}{(m_u + m_d) m_n^2} \sim 6 \times 10^{-17}\ \theta\ e\,{\rm cm} \Rightarrow |\theta| < 10^{-9}$$

Topological Theta Term and Strong CP Problem

- Theta dependence of vacuum energy density in QCD,

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

- Partition function in terms of Fourier series of Euclidean path integrals over gauge fields with fixed topological charge

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

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

- Since Z_Q positive, the vacuum energy density has absolute minimum at $\theta = 0$ [Vafa,Witten ´84]

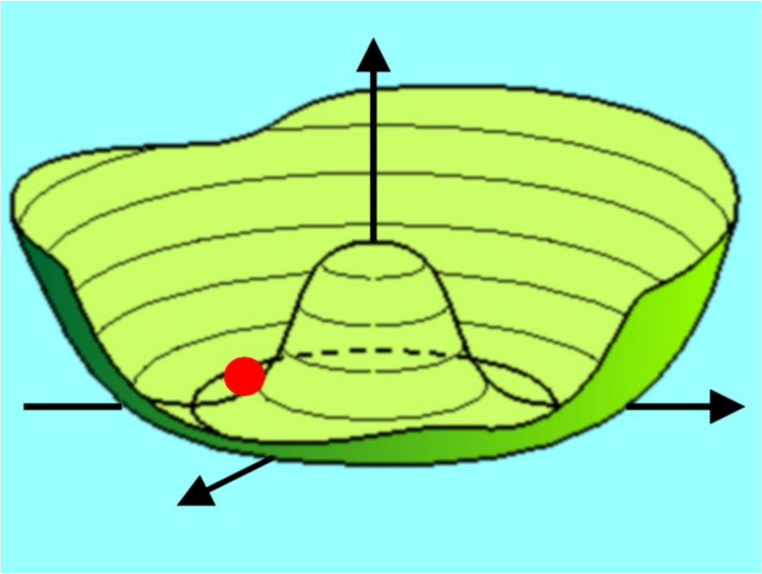
- If theta were a dynamical field, its vacuum expectation value would be zero: strong CP problem solved

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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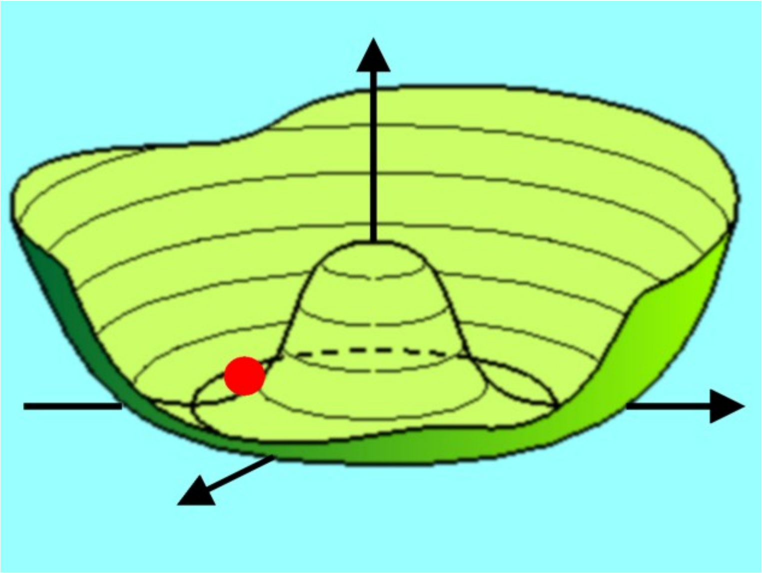
- $U(1)_{\rm PQ}$ charges of quarks (SM or extra) are such that $U(1)_{\rm PQ}\times SU(3)_C \times SU(3)_C$ has chiral anomaly: NGB is called axion

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



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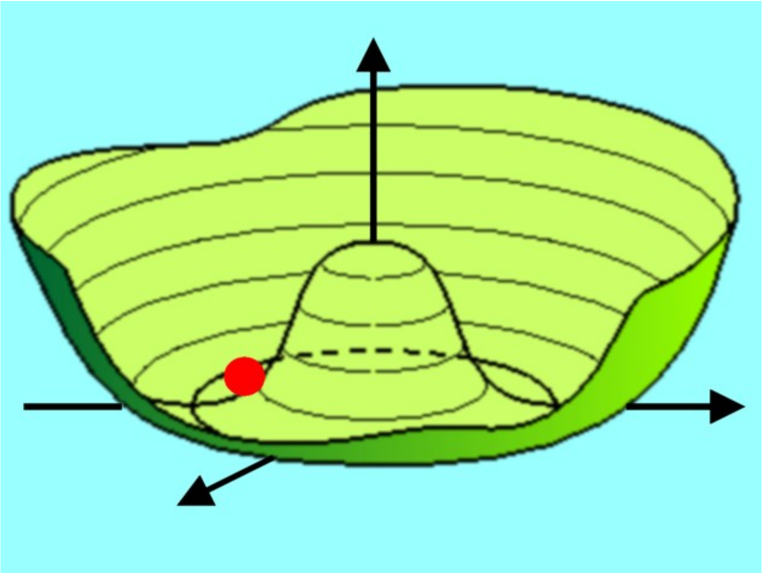


[Raffelt]

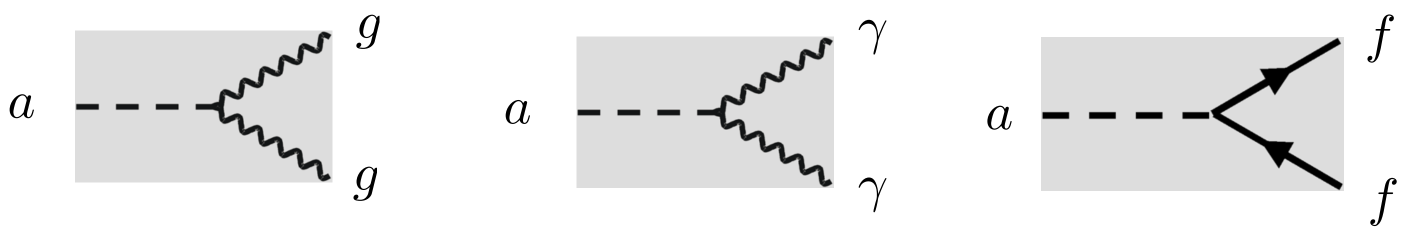
- No strong CP problem, since axion field acts as x-dependent theta parameter

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi}\frac{A(x)}{f_A} G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu}; \qquad f_A = v_{\rm PQ}/N_{\rm DW}; \qquad N_{\rm DW} = \#\ \text{quarks with PQ charge}$$

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

Axion Couplings to SM

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



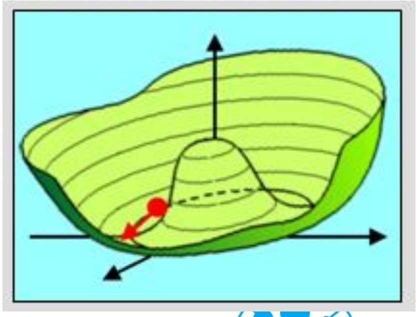
> Couplings of axion to SM suppressed by powers of

$$f_A = v_{\rm PQ}/N_{\rm DW} \gg v = 246\ {\rm GeV}$$

rendering the axion „invisible“ [Kim 79;Shifman,Vainshtein,Zakharov 80;Zhitnitsky 80;Dine,Fischler,Srednicki 81;...]

> Axion acquires a small mass from gluonic topological fluctuations: [Weinberg ´78; Wilczek `78; ... Borsanyi et al. `16]

$$m_A = \frac{\sqrt{\int d^4x \langle q(x) q(0)\rangle}}{f_A} \equiv \frac{\sqrt{\chi_0}}{f_A} = 57.0(7)\left(\frac{10^{11}{\rm GeV}}{f_A}\right)\mu{\rm eV}$$

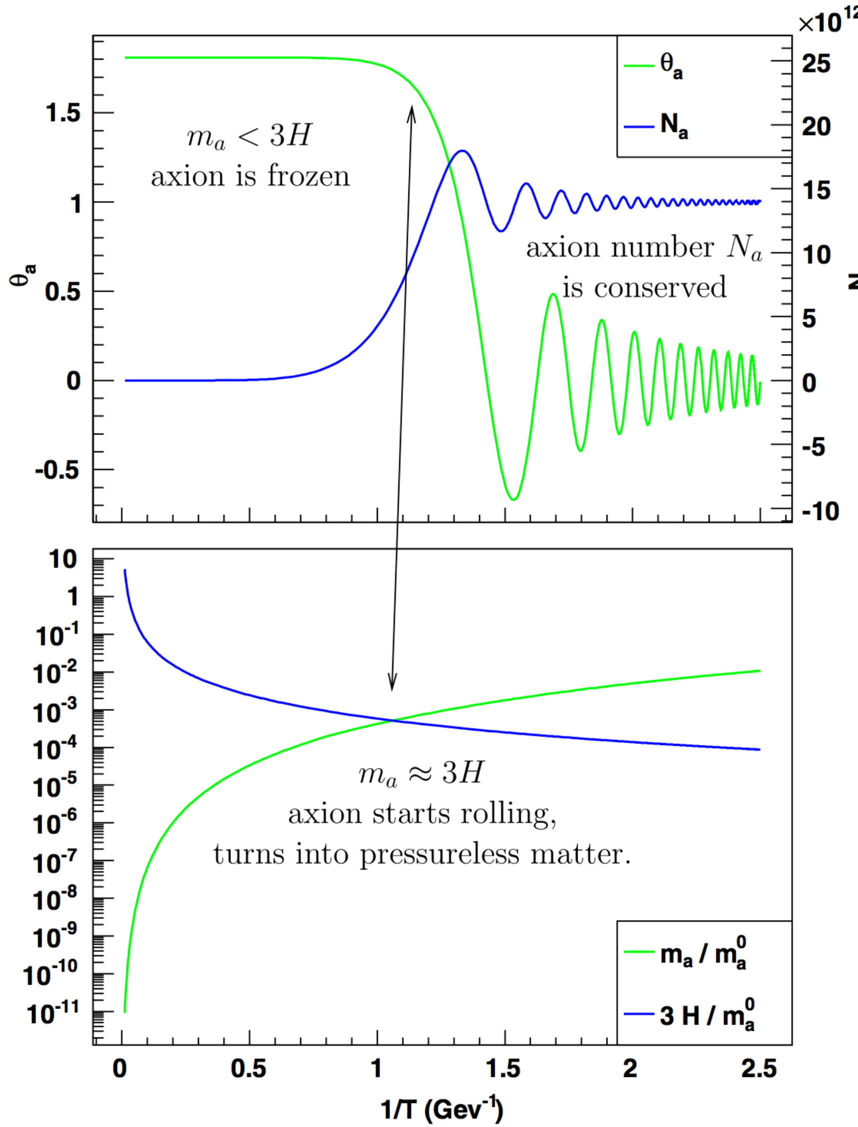


Axion Dark Matter

> DM from vacuum realignment:

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

- In early universe, axion frozen at random initial value
- Later, field feels pull of mass towards zero and oscillates around it
- Spatially uniform oscillating classical field = coherent state of many, extremely non-relativistic particles = CDM



[Wantz,Shellard `09]

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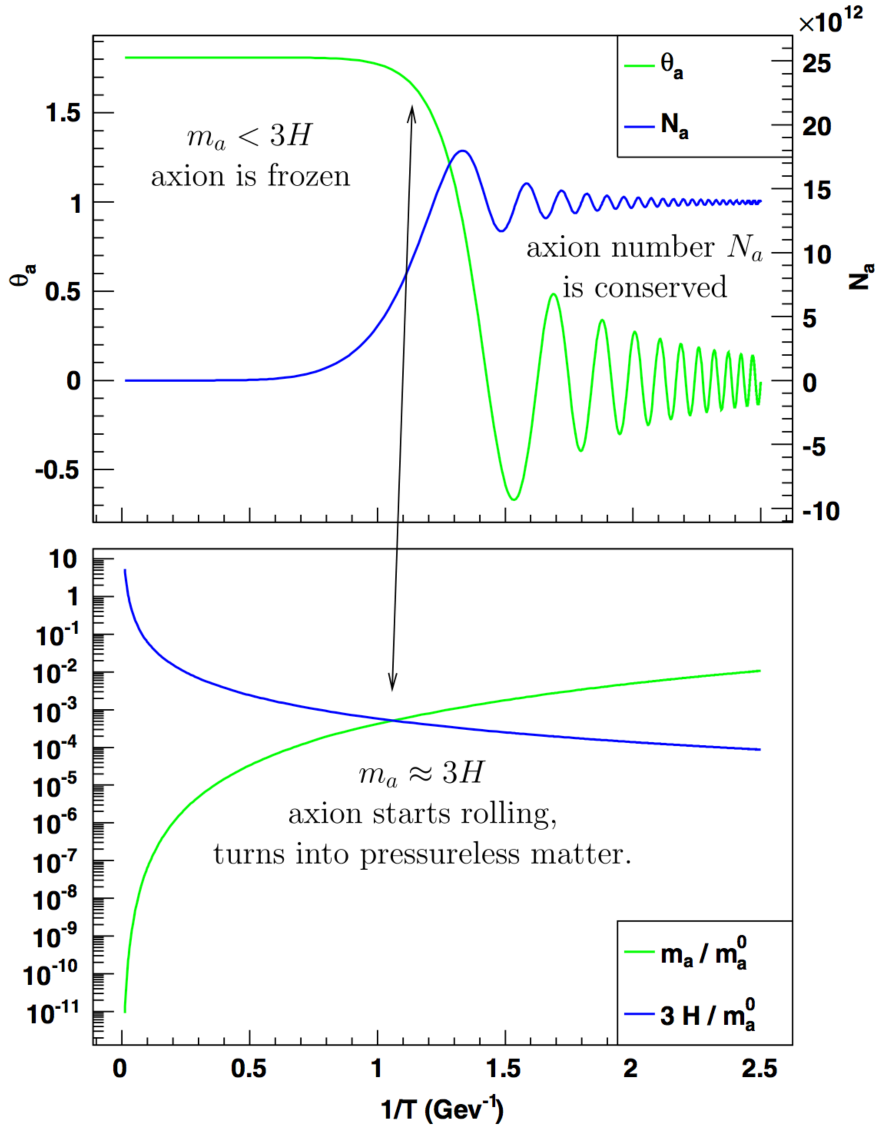
> Crucial QCD input for prediction of axion DM abundance:

- Equation of state at temperatures around 1 GeV: determines $H(T)$
- Topological susceptibility:

$$\chi(T) \equiv \int d^4x \langle q(x) q(0) \rangle_T$$

determines $m_A^2(T) = \chi(T)/f_A^2$



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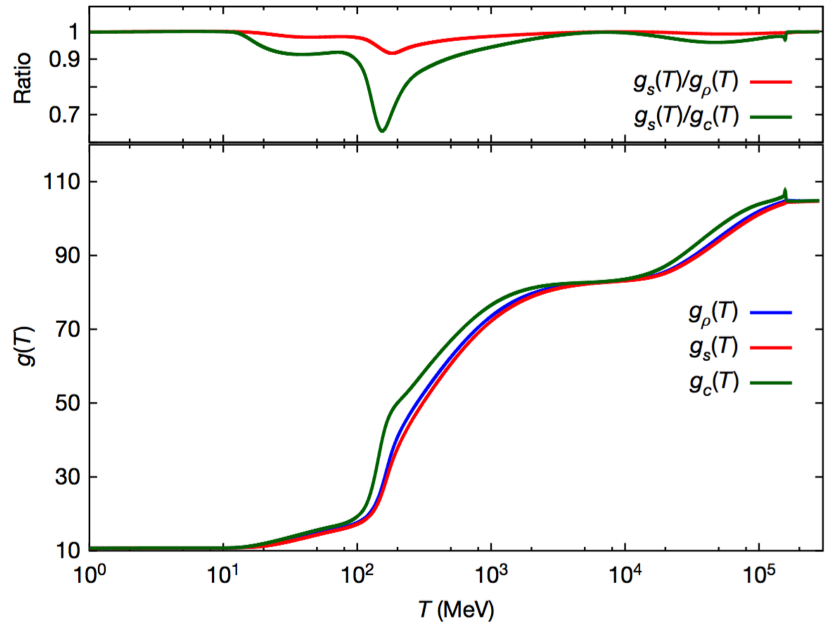

[Borsanyi et al., Nature `16 [1606.0794]]

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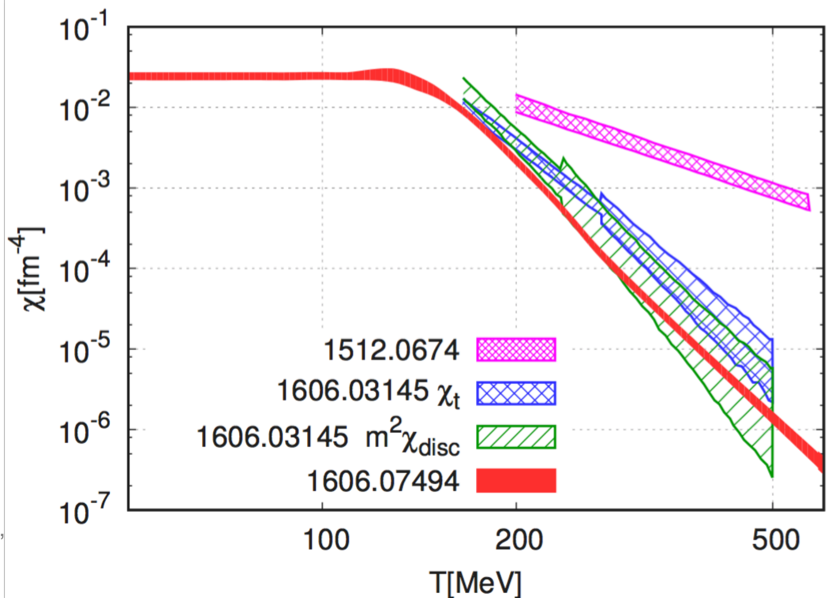

Axion Dark Matter

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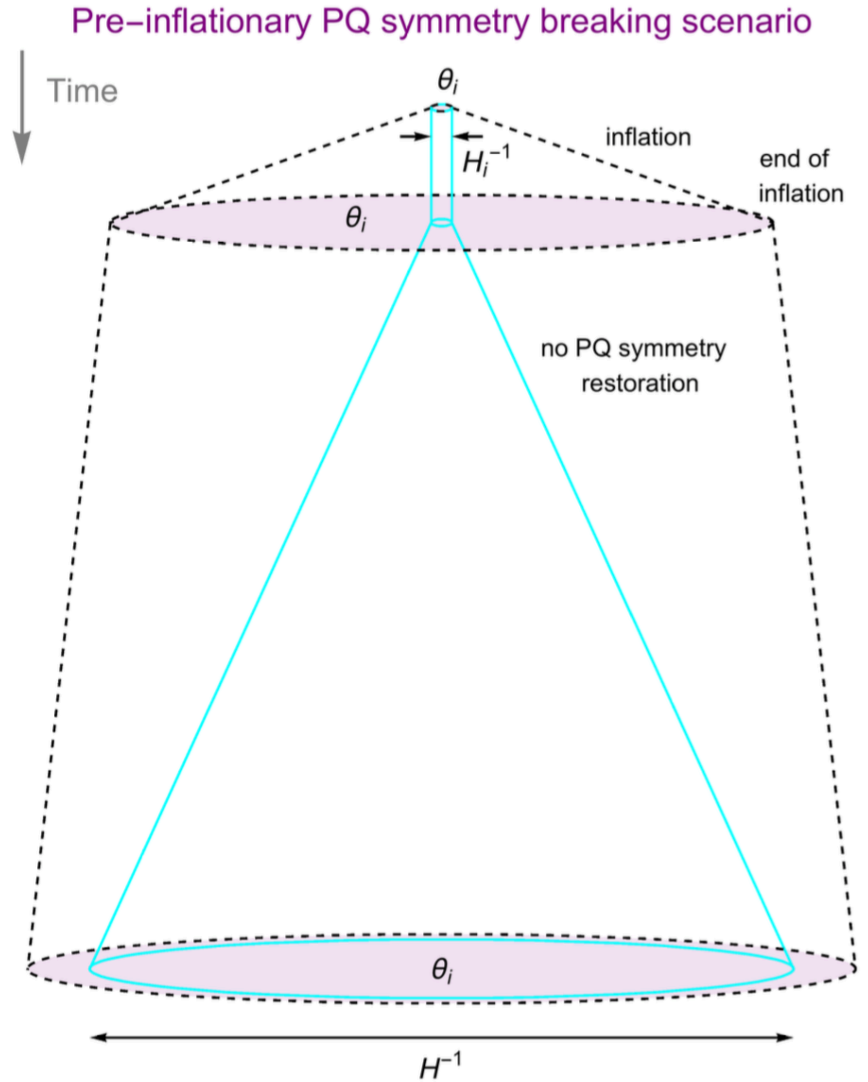
  - Axion CDM density depends on sing-le initial angle during inflation and f_A



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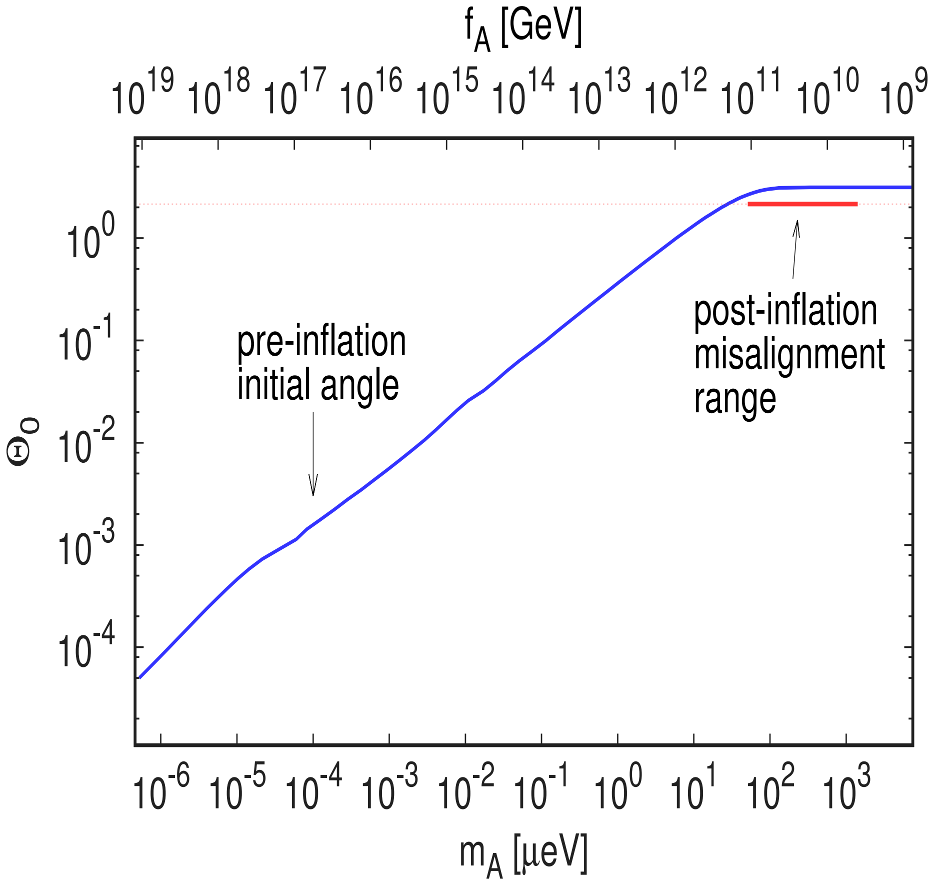

[Borsanyi et al. `16]

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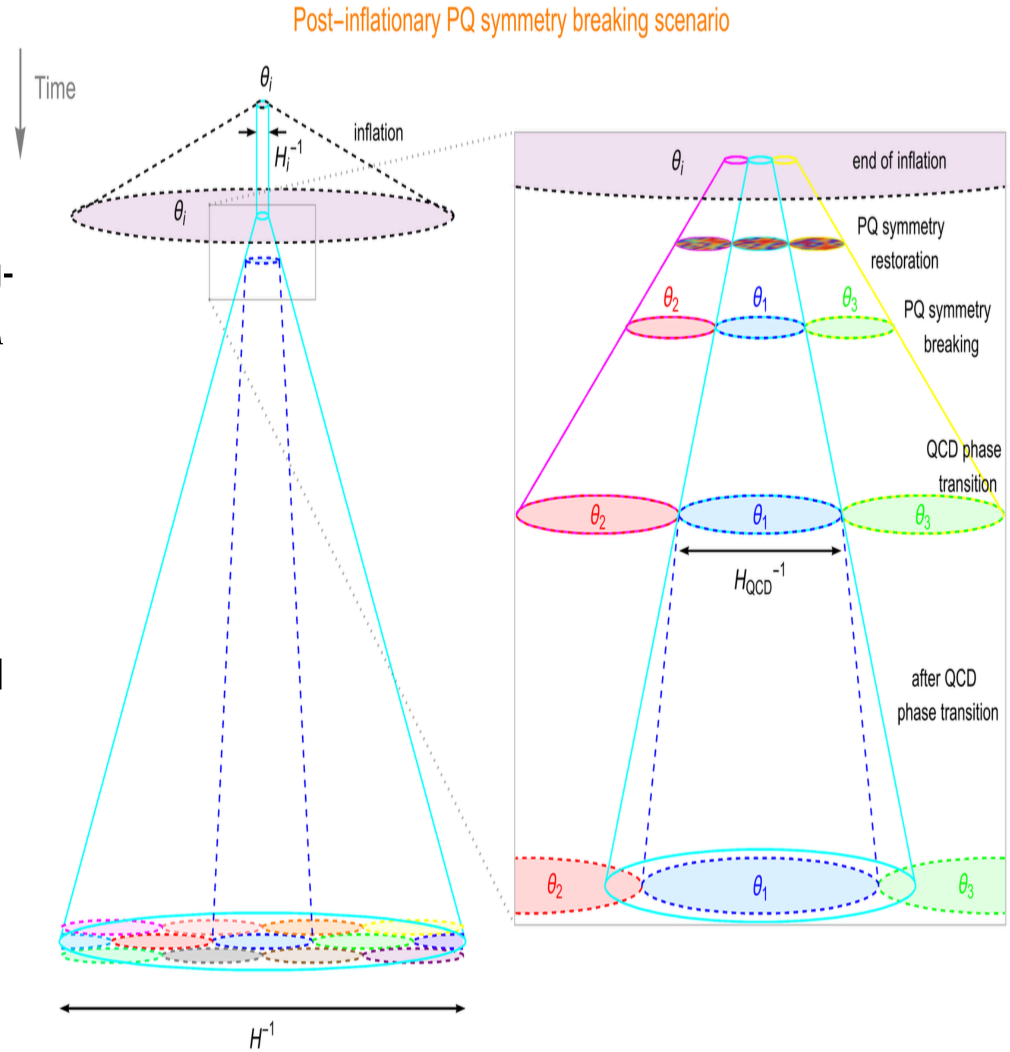

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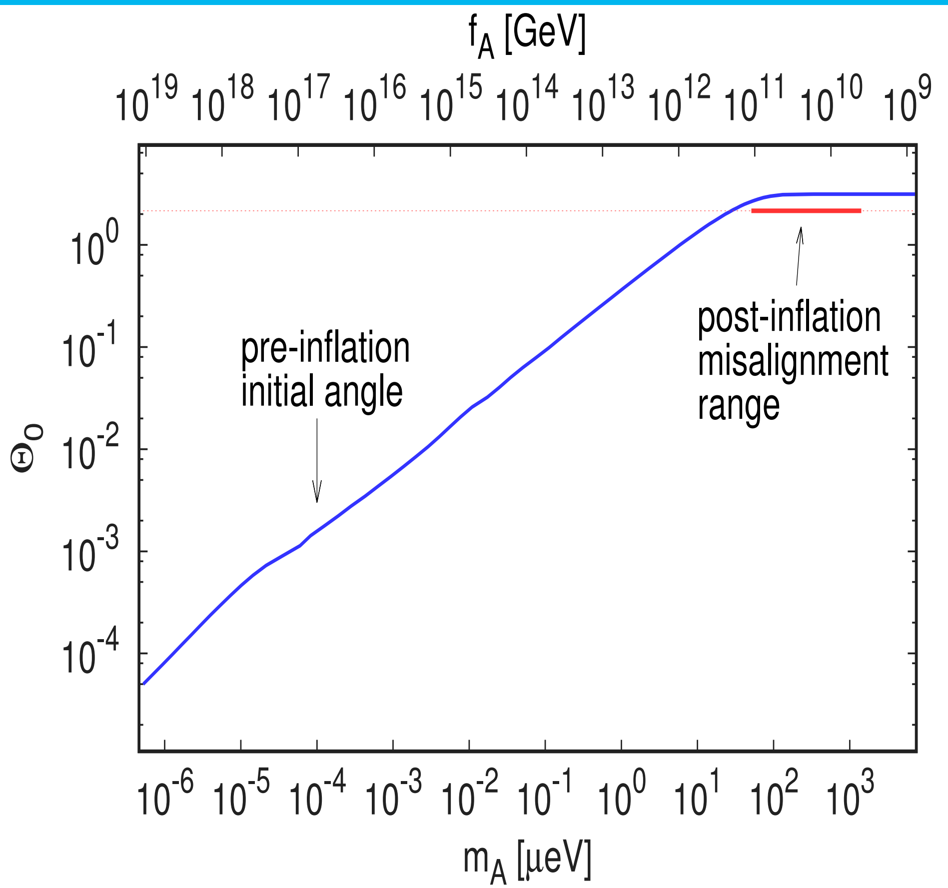
$$m_A > 28(2)\ \mu\text{eV}$$



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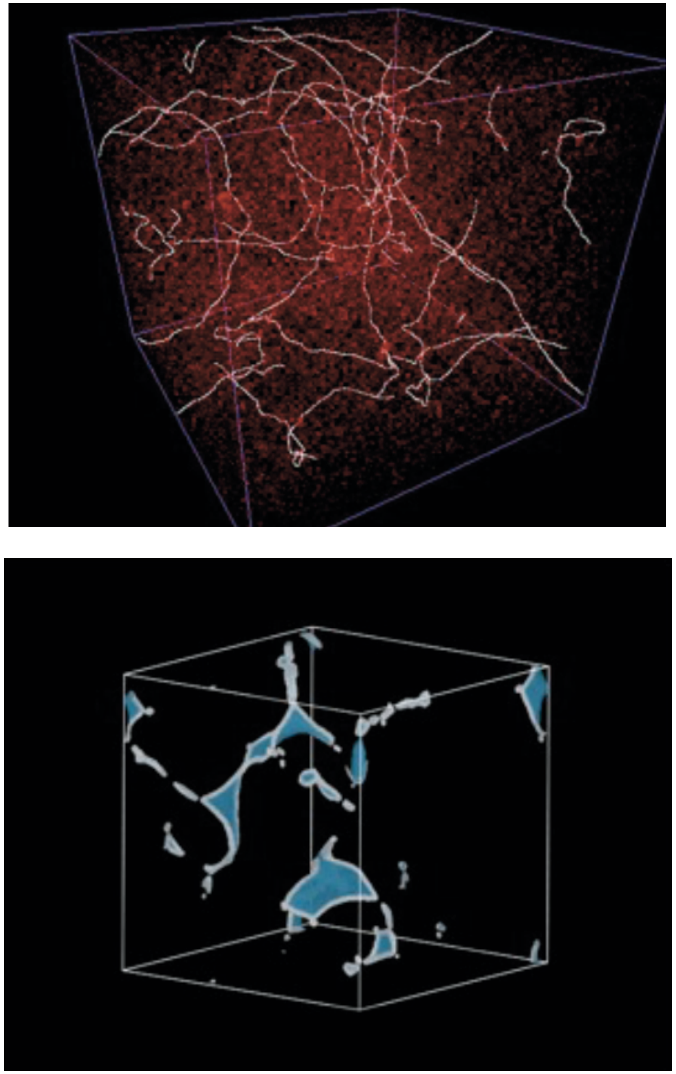
  - Additional contributions arise from decay of topological defects



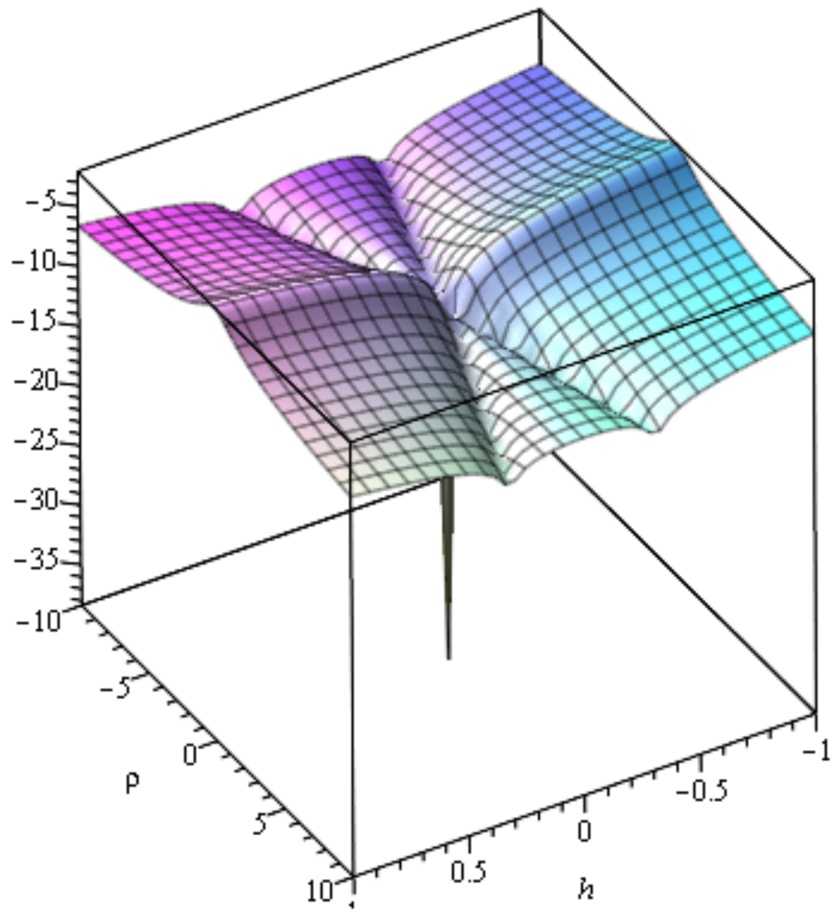
[Hiramatsu et al. 12]

One SM*A*S*H to rule them all ...

- $|\sigma| = \rho/\sqrt{2}$ or mixture with Higgs modulus may play role of inflaton, if it has non-minimal coupling to gravity, [Fairbairn et al. `14]

$$S \supset - \int d^4x \sqrt{-g} \left[\frac{M^2}{2} + \xi_\sigma \, \sigma^* \sigma \right] R$$

  - no strong CP problem
  - dark matter
  - inflation



[Ballesteros,Redondo, AR,Tamarit, 1610.01639]

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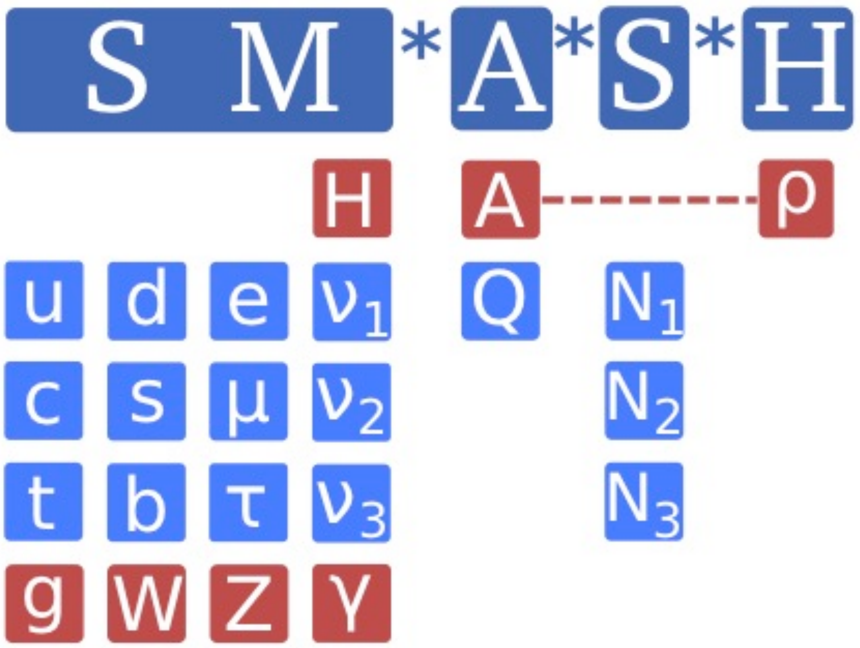
- Augmenting axion models with three RH singlet neutrinos, getting their Majorana masses also through the vev v_σ
  - no strong CP problem
  - dark matter
  - inflation
  - neutrino masses and mixing
  - baryogenesis via leptogenesis

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



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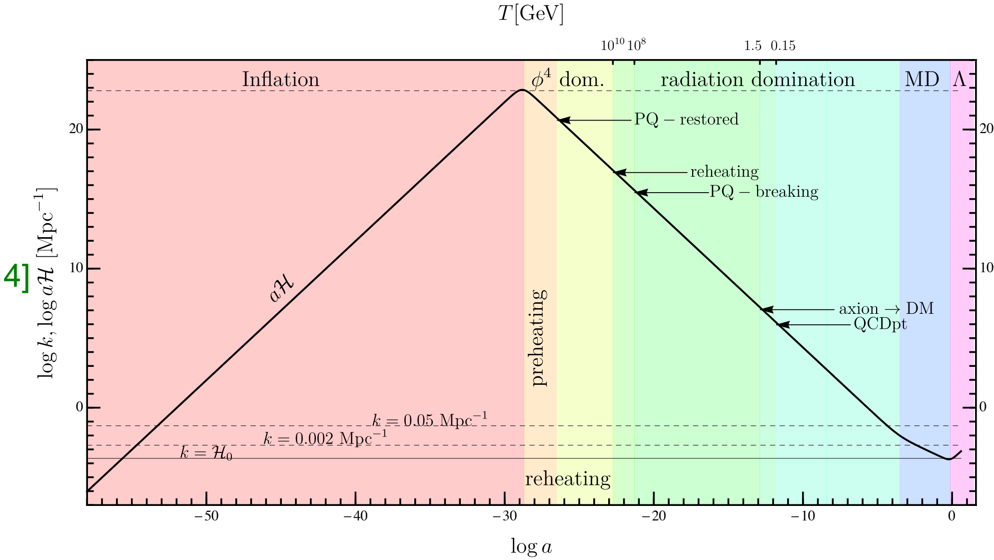

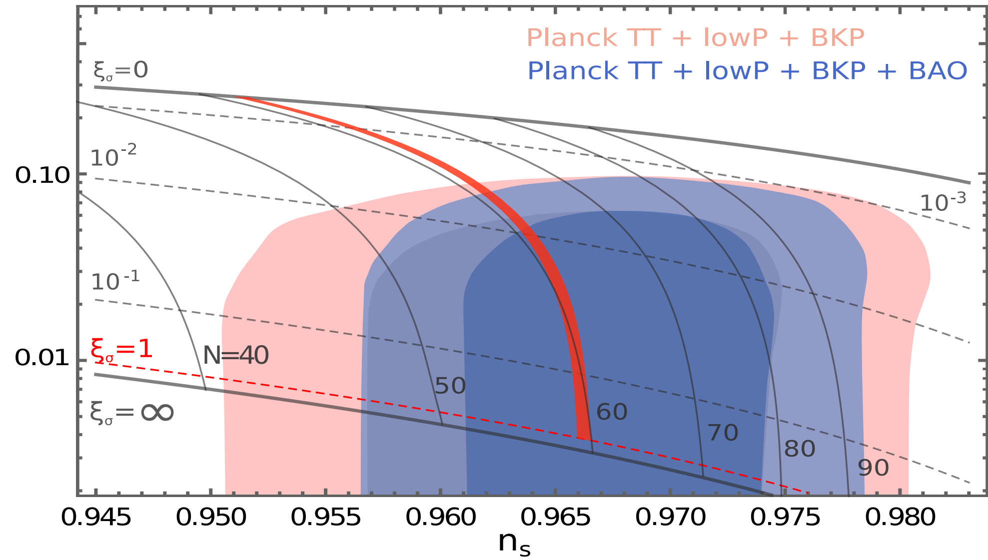

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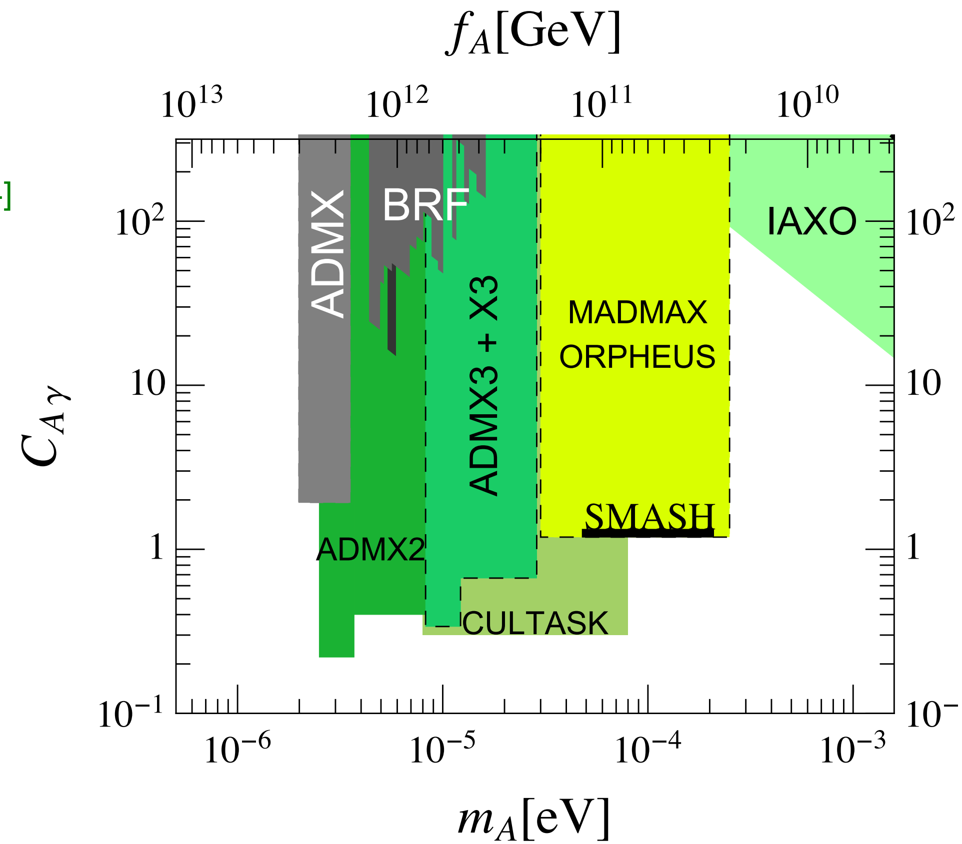

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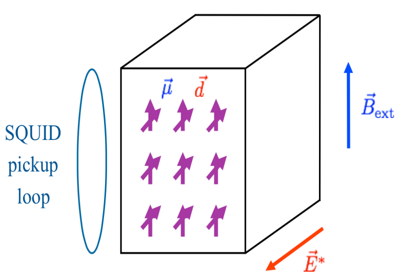
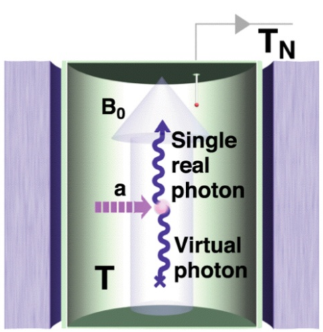
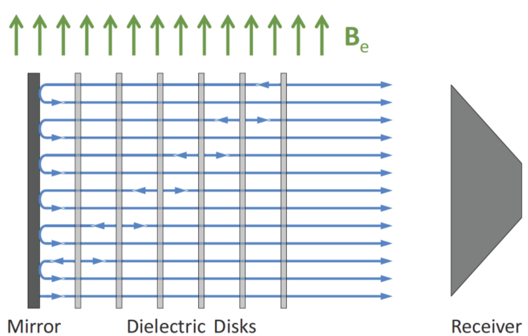
Axion Dark Matter Experiments

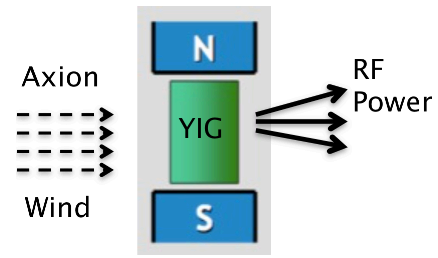
> Upcoming generation of axion dark matter experiments can probe sizeable portion of axion mass range relevant for DM:

- $m_A \ll \mu\mathrm{eV}$: searches for oscillating nuclear electric dipole moments exploiting nuclear magnetic resonance techniques (CASPEr); searches via LC circuit (ABRACADABRA)
- $\mu\mathrm{eV} \lesssim m_A \lesssim 0.1\,\mathrm{meV}$: searches for excitations of electromagnetic resonances due to axion photon conversion in microwave cavities in superconducting solenoids (ADMX, X3, CULTASK, ...)
- $30\,\mu\mathrm{eV} \lesssim m_A \lesssim 0.3\,\mathrm{meV}$: searches for electromagnetic excitation in open dielectric/ Fabry-Perot resonator in a strong magnetic field (MADMAX/ORPHEUS, ...)
- $0.3\,\mathrm{meV} \lesssim m_A \lesssim 10\,\mathrm{meV}$: searches exploiting dish antenna or electron spin pre-cession in galactic axion wind (QUAX)



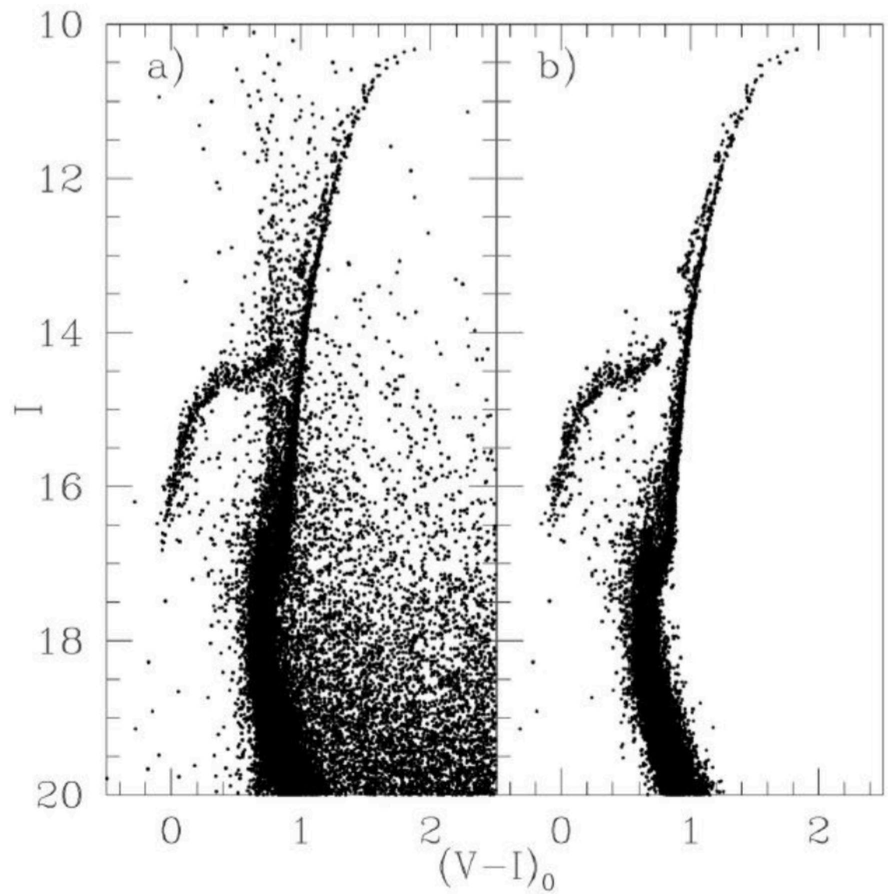






Astro-Hints for the Axion: Energy Losses of Stars?

- RG cooling excess: Brightness of tip of RG branch in color-magnitude diagram of globular cluster [Viaux et al. 13]



[Viaux et al. 13]

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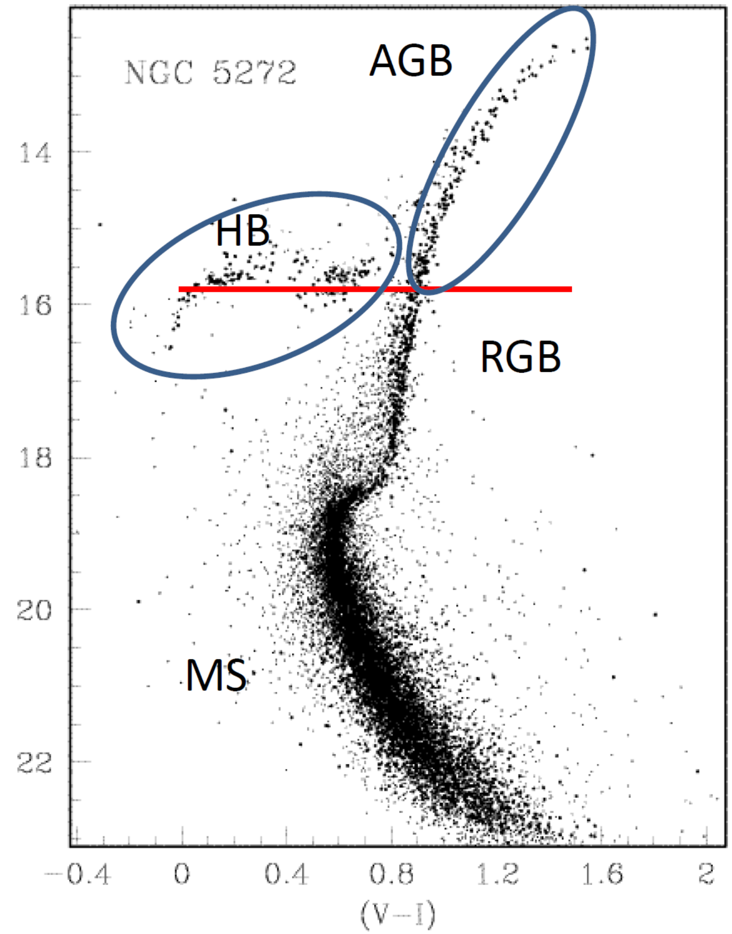
- HB cooling excess: Number of HB stars vs. number of RGs in color-magnitude diagram of globular cluster [Ayala et al. 14]



[Giannotti `16]

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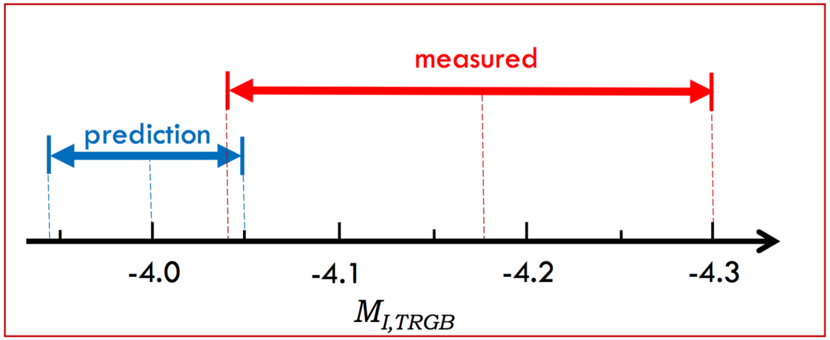

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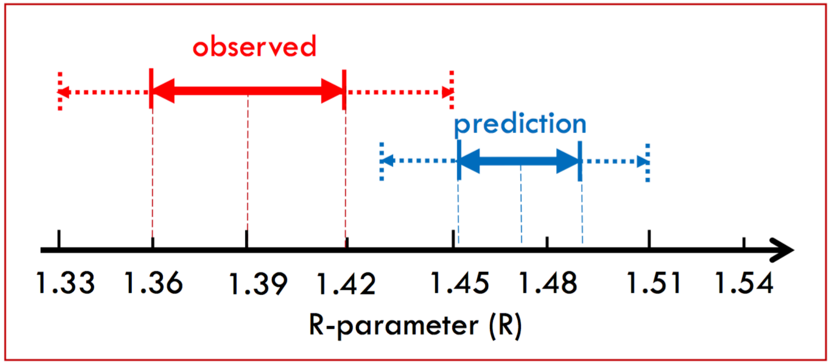

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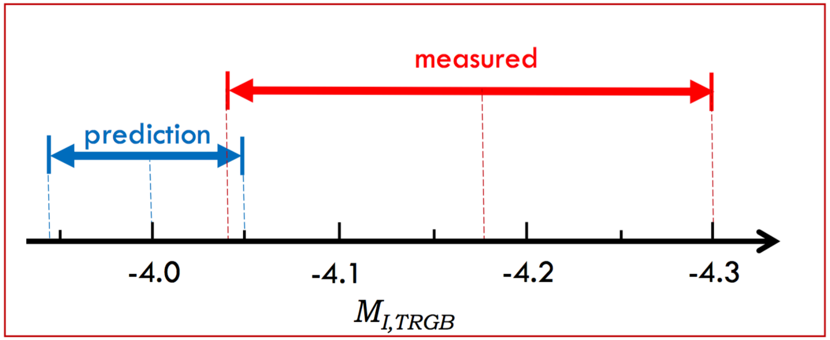

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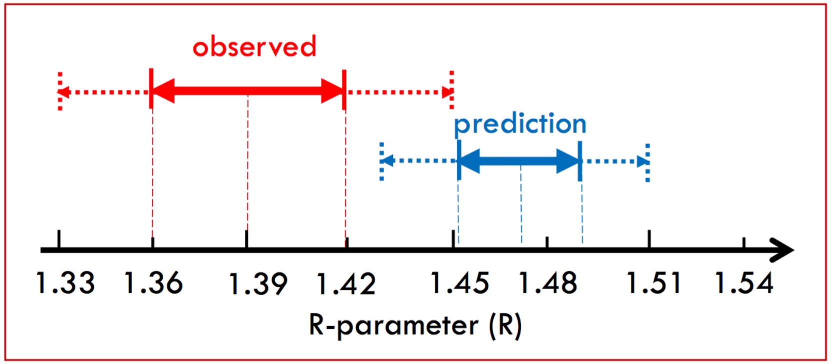
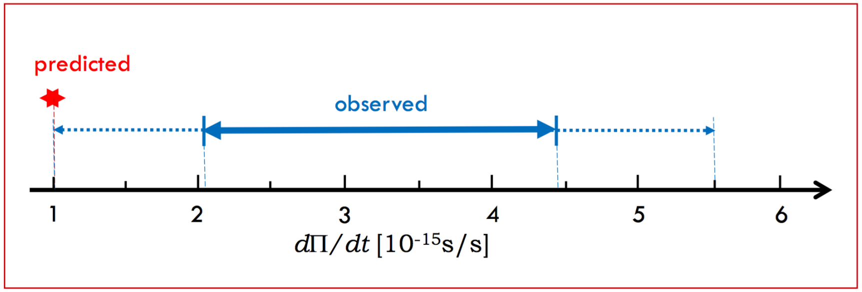


- WD cooling excess:
  - Period decrease of variable WDs [Kepler et al. 91,...]



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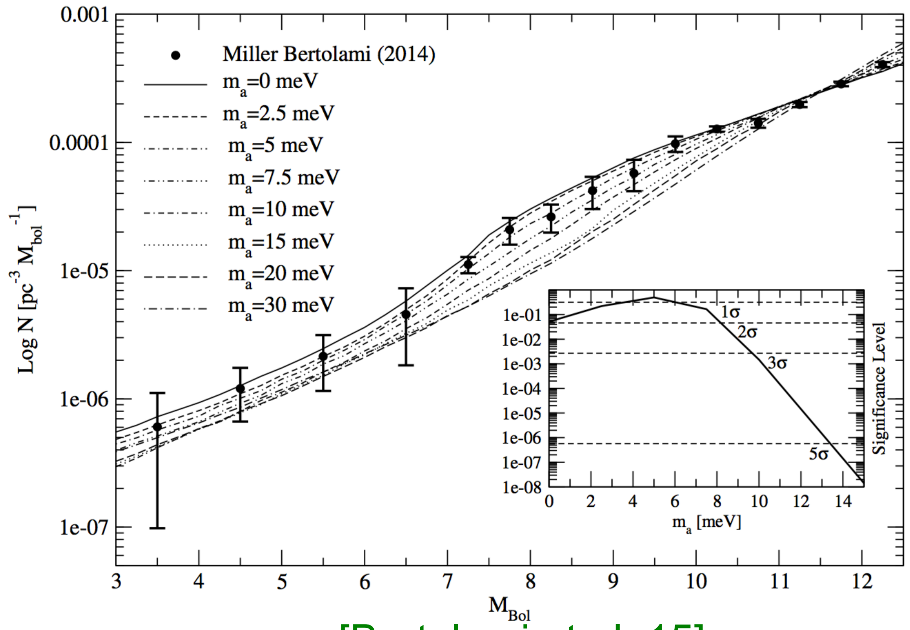
Astro-Hints for the Axion: Energy Losses of Stars?

- RG cooling excess: Brightness of tip of RG branch in color-magnitu-de diagram of globular cluster [Viaux et al. 13]

- HB cooling excess: Number of HB stars vs. number of RGs in color-magnitude diagram of globular cluster [Ayala et al. 14]

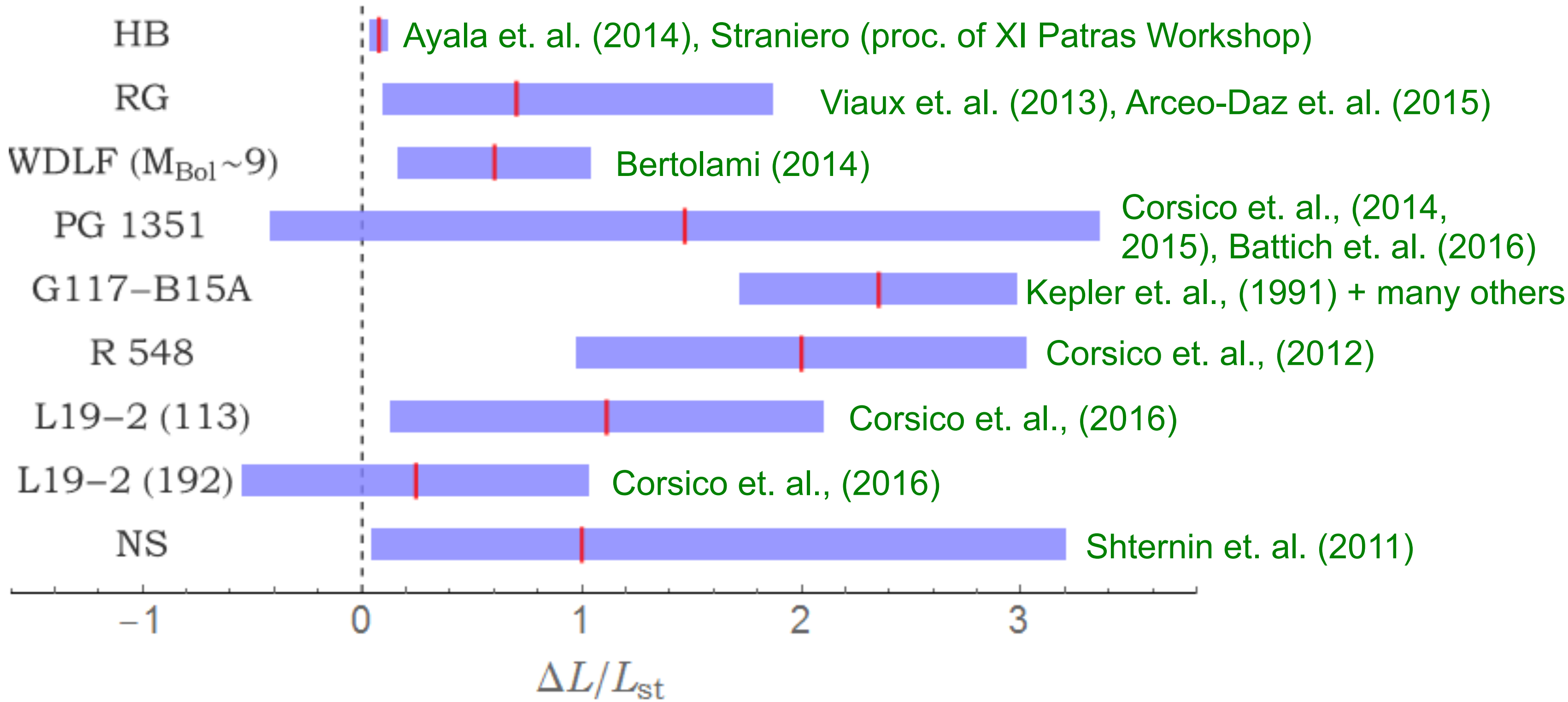
- WD cooling excess:
  - Period decrease of variable WDs [Kepler et al. 91,...]
  - White dwarf luminosity function (WDLF) [Isern et al. 08-12]



[Bertolami et al. 15]

Astro-Hints for the Axion: Energy Losses of Stars?

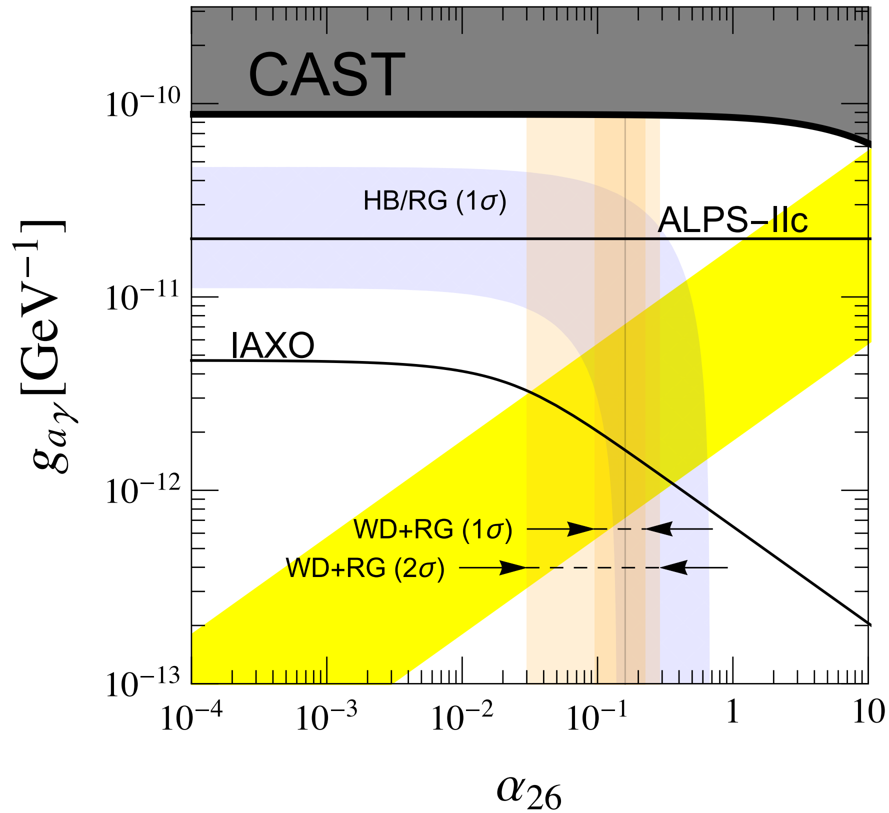
- Practically every stellar systems seems to be cooling faster than predicted by models



[Giannotti, Irastorza, Redondo, AR (2015); Giannotti, Irastorza, Redondo, AR (in preparation)]

Astro-Hints for the Axion: Energy Losses of Stars?

- Excessive energy losses of HBs, RG, WDs can be explained at one stroke by production of axion/ALP with coupling to photons and electrons and probed by photon regeneration experiments (ALPS II,IAXO):



$$g_{a\gamma} = C_{a\gamma}\alpha/(2\pi f_a)$$

$$\gamma + Ze \to Ze + a$$

$$g_{ai} = C_{ai} m_i / f_a$$

$$e + Ze \to Ze + e + a$$

$$\alpha_{26} = g_{ae}^2/(4\pi)/10^{-26}$$

[Giannotti,Irastorza,Redondo,AR `16]

Astro-Hints for the Axion: Energy Losses of Stars?

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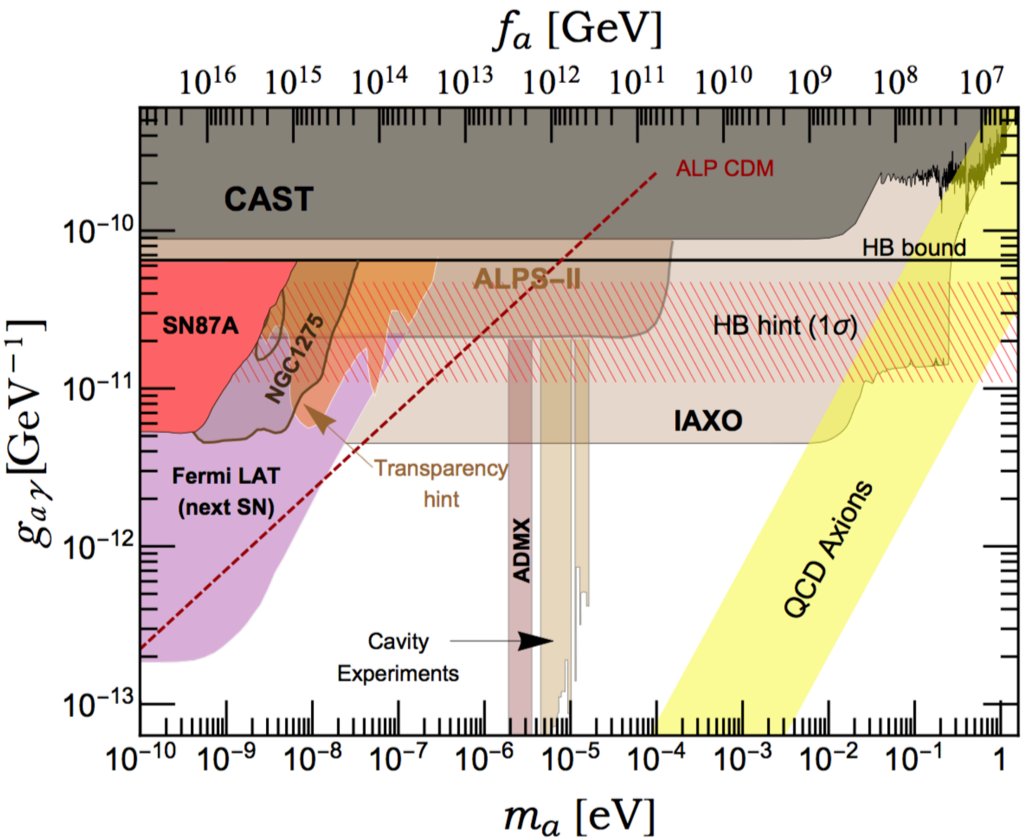

[Giannotti,Irastorza,Redondo,AR, in preparation]

Conclusions

- Strong physics case for the axion:
  - Solution of strong CP problem
  - Candidate for dark matter
  - Explanation of astrophysical hints on excessive energy losses of stars
- Strong motivation for experimental searches of the axion