Axion Dark Matter

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DARKWIN
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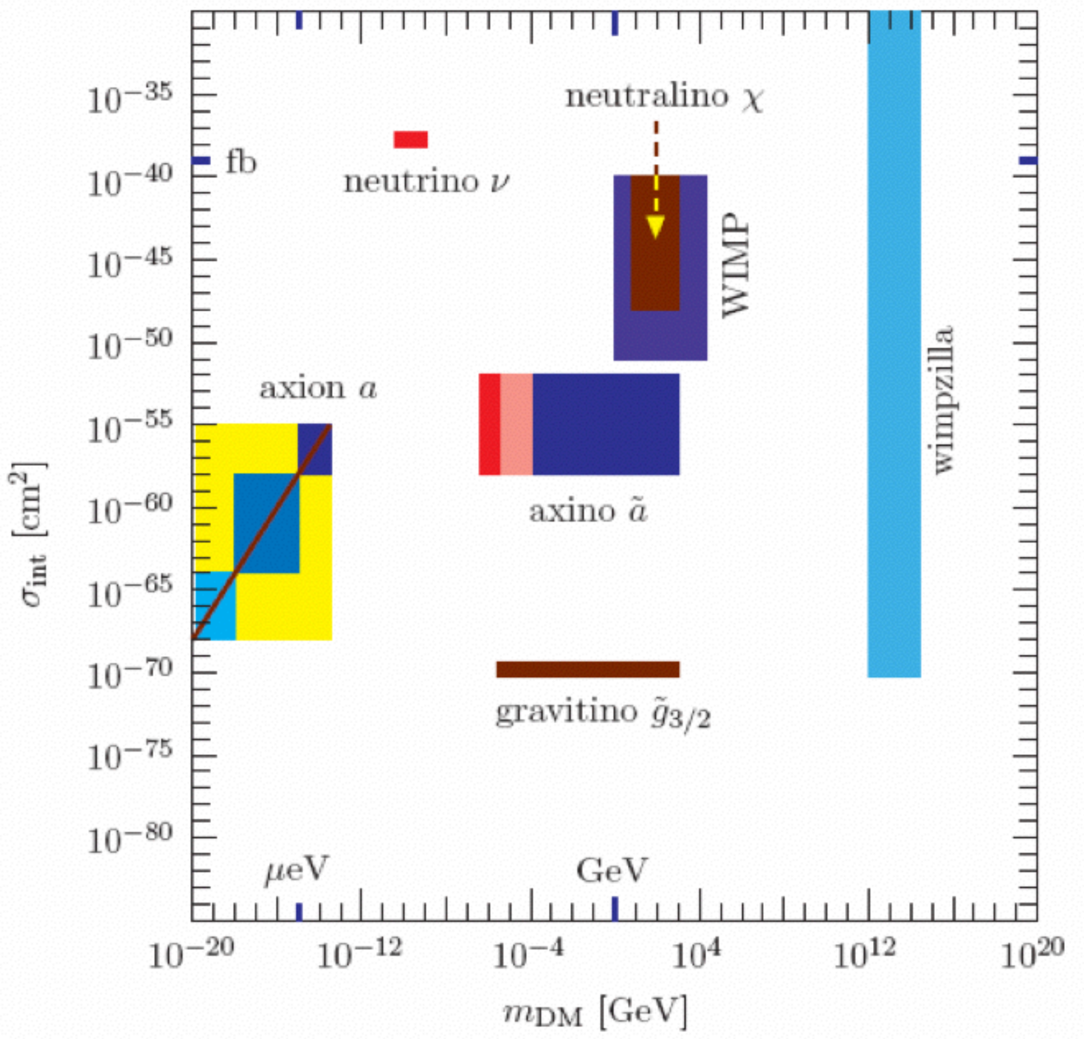
Motivation

- Unraveling nature of dark matter (DM) most urgent problem of particle physics and cosmology
- Non-observation of Weakly Interacting massive Particles (WIMPs) at LHC and in direct detection DM experiments strong motivation to focus also on alternative candidates, in particular to very Weakly Interacting Slim Particles dubbed WISPs

  [Preskill,Wise,Wilczek 83; Abbott,Sikivie 83; Dine,Fischler 83,...; Arias et al. 12]

- Particularly well motivated WISPs: Nambu-Goldstone bosons arising from the breaking of global symmetries introduced to solve other problems, e.g.
  - Axion – breaking of Peccei-Quinn symmetry – solves strong CP problem [Peccei,Quinn 77; Weinberg 78; Wilczek 78]
  - Majoron – breaking of lepton symmetry – solves neutrino mass problem [Chikashige et al. 78; Gelmini,Roncadelli 80]
  - Flavon – breaking of flavor symmetry – solves flavor puzzles [Wilczek 82; Berezhiani,Khlopov 90]



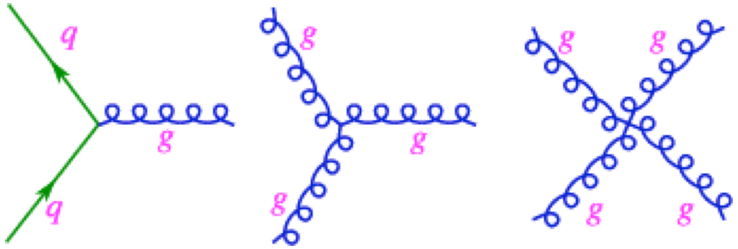
[Kim,Carosi 10]

Strong CP Puzzle

Theta term in Quantum Chromodynamics

- Quantum Chromodynamics (QCD): [Gross,Wilczek 73;Politzer 73; Fritzsch,Gell-Mann,Leutwyler 73]

$$S_{\mathrm{QCD}} = \int d^4x \left\{ \overline{q}\left(i\gamma_\mu D^\mu - \mathcal{M}_q\right) q - \frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu} \right\}$$



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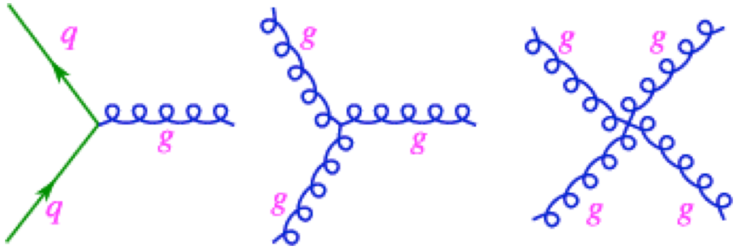

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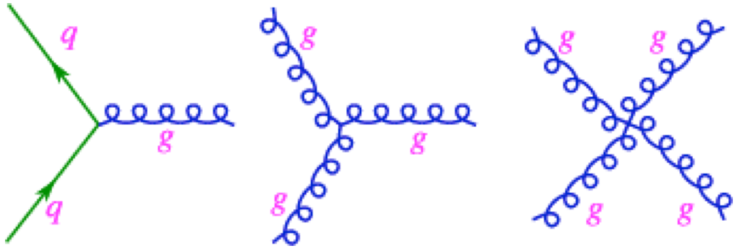

$$\int d^4x\,\partial_\mu J^\mu_{\rm CS} = 0, \pm 1, \pm 2, \ldots$$

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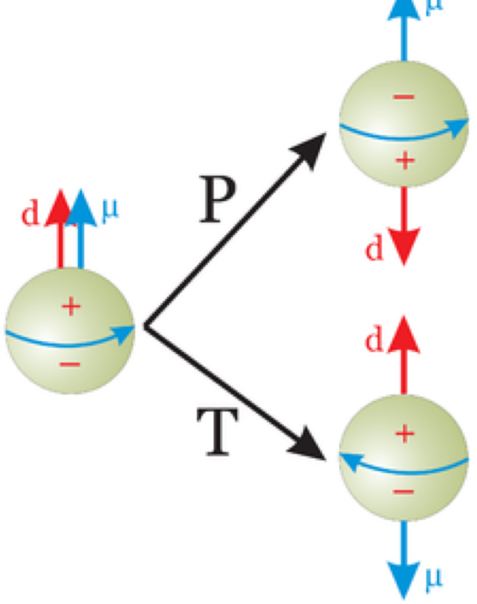
- Most sensitive probe of T and P violation in flavor conserving interactions: electric dipole moment of neutron



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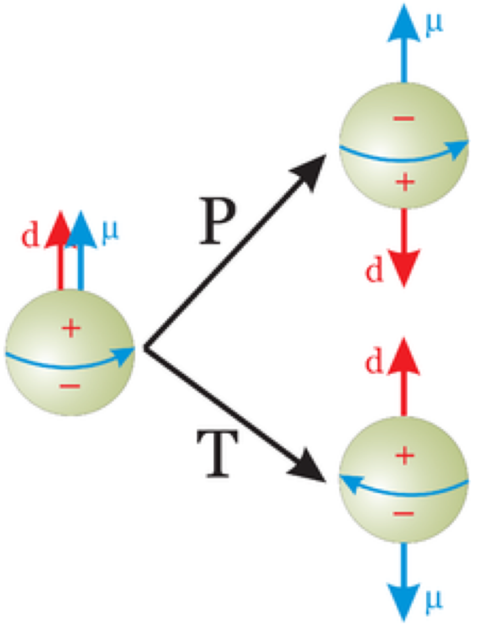
$$d_n(\overline{\theta}) = 2.4(1.0) \times 10^{-16}\, \overline{\theta}\, e\, {\rm cm}$$



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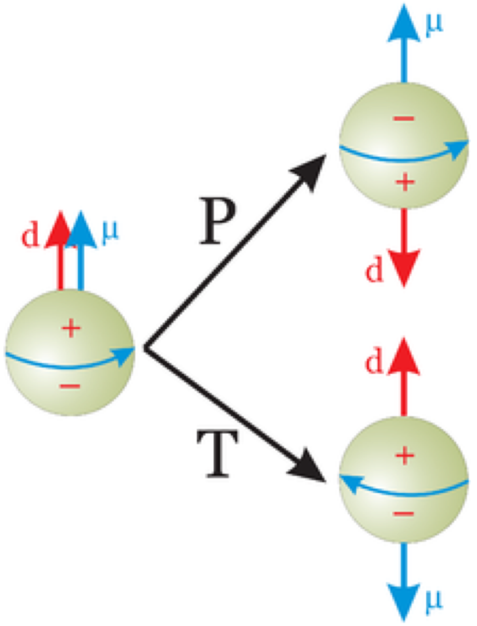
- Experiment: [Baker et al. 06]

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



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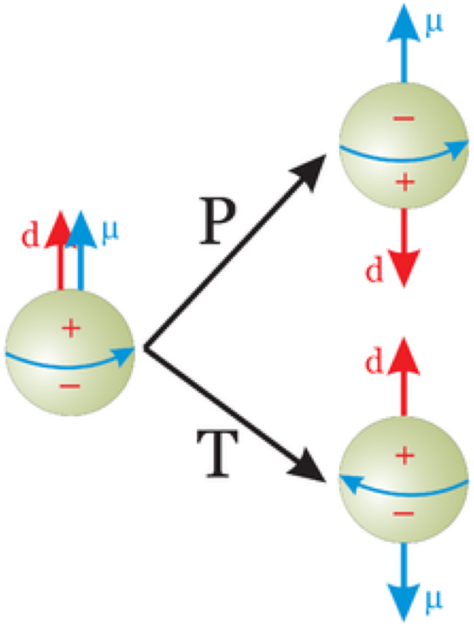
$$\Rightarrow |\overline{\theta}| < 10^{-10}$$



Axionic Solution of Strong CP Puzzle

In a nutshell: replace theta parameter by dynamical theta field

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

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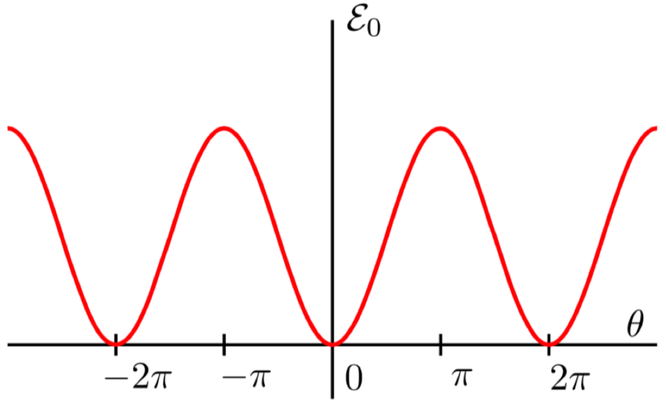
    No strong CP violation in vacuum [Vafa,Witten 84]



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

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

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

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  - 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):

$$m_A = 5.691(51)\left(\frac{10^9\ {\rm GeV}}{f_A}\right) {\rm meV}$$

[Grilli di Cortona et al. `16; Borsanyi et al. `16; Gorghetto, Villadoro `19]

Peccei-Quinn Extension of Standard Model

Simple way to get dynamical theta field

- A singlet complex scalar field σ, featuring a spontaneously broken global $U(1)_{\rm PQ}$ symmetry
- Particle excitations:

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

  - Mass of particle excitation of modulus: $m_\rho \sim v_{\rm PQ}$
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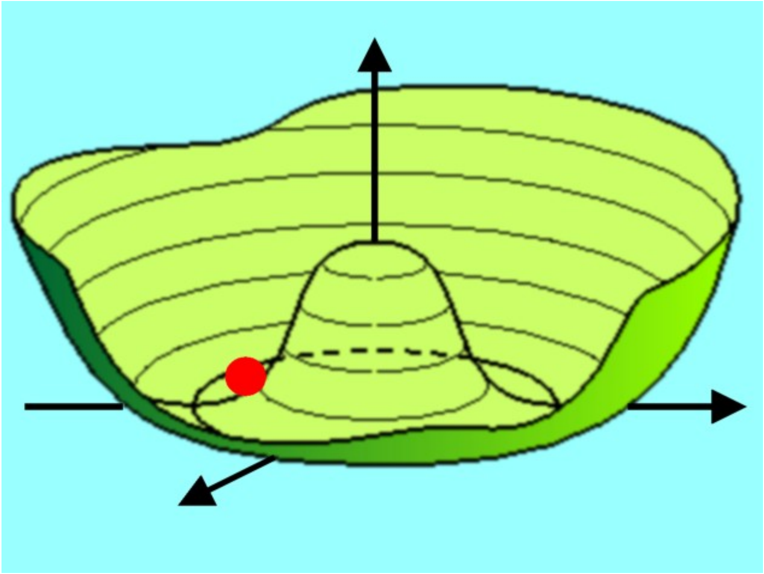

[Raffelt]

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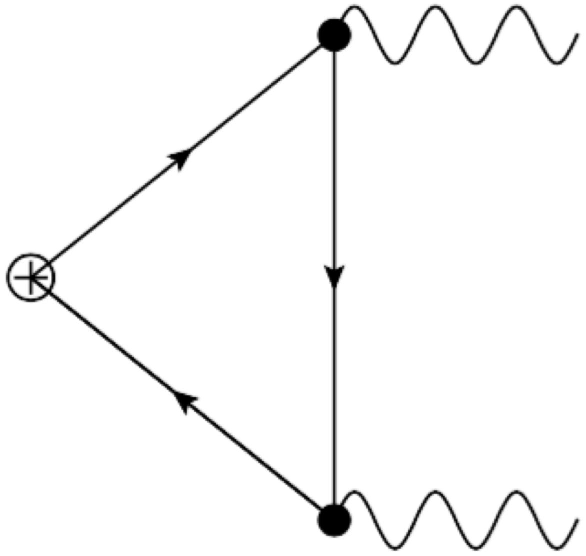
$$\partial_\mu J^\mu_{U(1)_{\rm PQ}} \supset -\frac{\alpha_s}{8\pi} N\, G^b_{\mu\nu}\tilde{G}^{b,\mu\nu}$$



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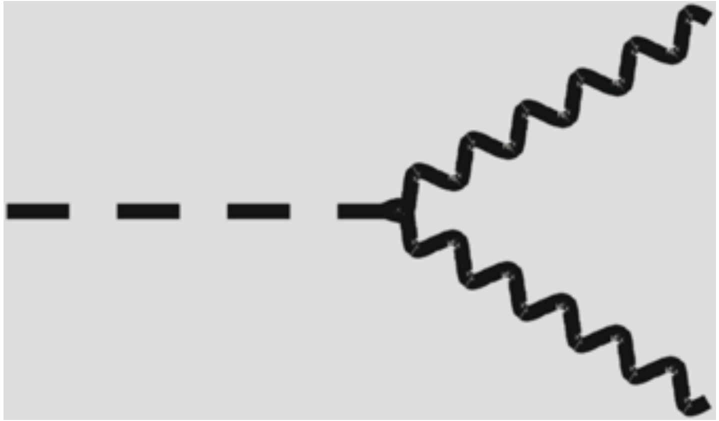
- Low energy effective field theory at energies above $\Lambda_{\rm QCD}$ but below v ($\ll v_{\rm PQ}$): [Peccei,Quinn 77; Weinberg 78; Wilczek 78]

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

[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

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

- Axion mass: $m_A = 5.691(51) \left(\frac{10^9\,\mathrm{GeV}}{f_A}\right) \mathrm{meV}$

[Grilli di Cortona et al. \`16 ; Borsanyi et al. \`16; Gorghetto,Villadoro \`19]

- Couplings of axion to SM suppressed by powers of

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

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

rendering the axion „invisible“

- Photon coupling: $C_{A\gamma} = \frac{E}{N} - 1.92(4)$

[Kaplan 85;Srednicki \`85]

- Nucleon couplings:

[Grilli di Cortona et al. \`16]

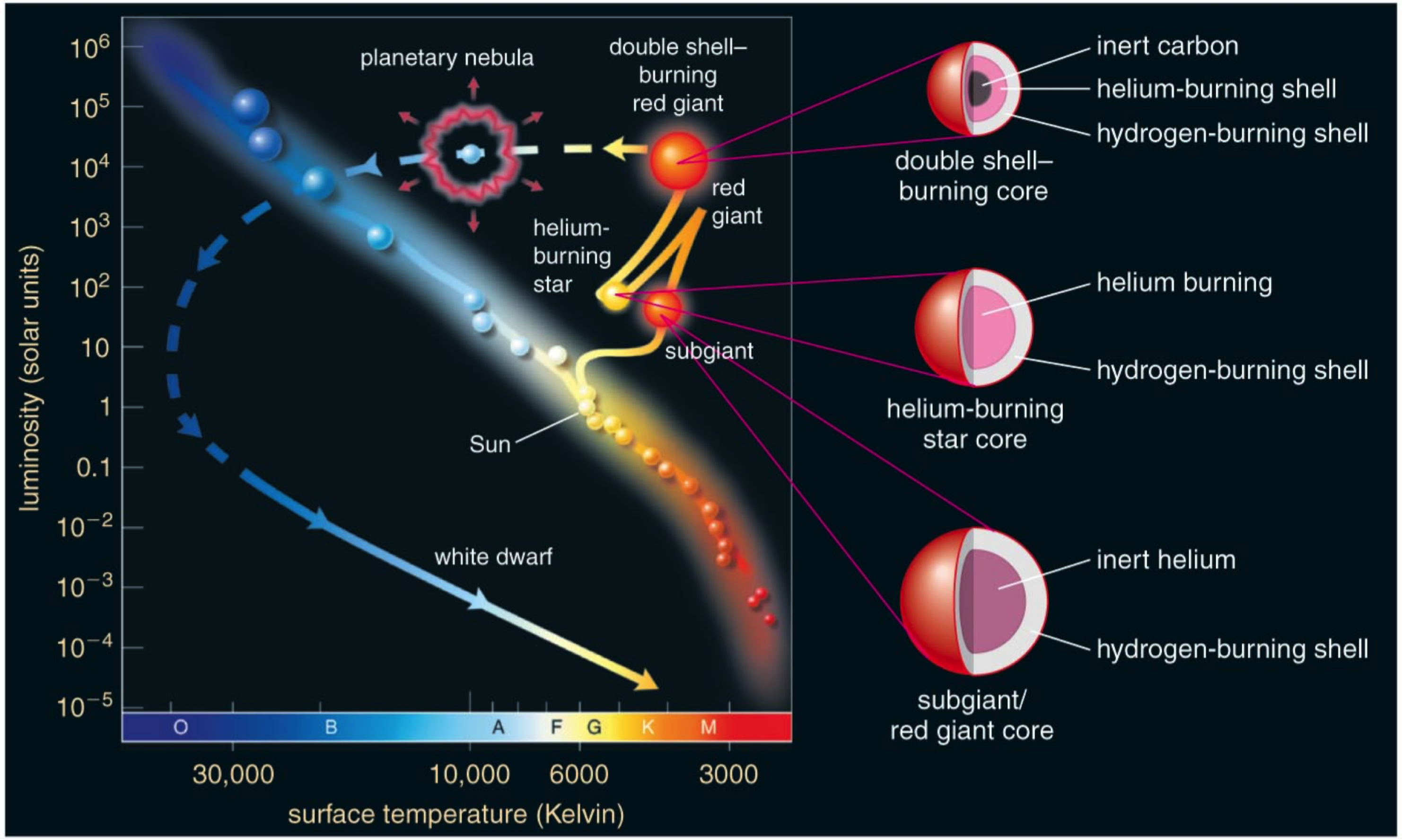
$$\begin{aligned} C_{Ap} &= -0.47(3) + 0.88(3) C_{Au} - 0.39(2) C_{Ad} - 0.038(5) C_{As} \\ &\quad - 0.012(5) C_{Ac} - 0.009(2) C_{Ab} - 0.0035(4) C_{At}\,, \\ C_{An} &= -0.02(3) + 0.88(3) C_{Ad} - 0.39(2) C_{Au} - 0.038(5) C_{As} \\ &\quad - 0.012(5) C_{Ac} - 0.009(2) C_{Ab} - 0.0035(4) C_{At} \end{aligned}$$

- Electron coupling very model-dependent

Astrophysical Axion Bounds

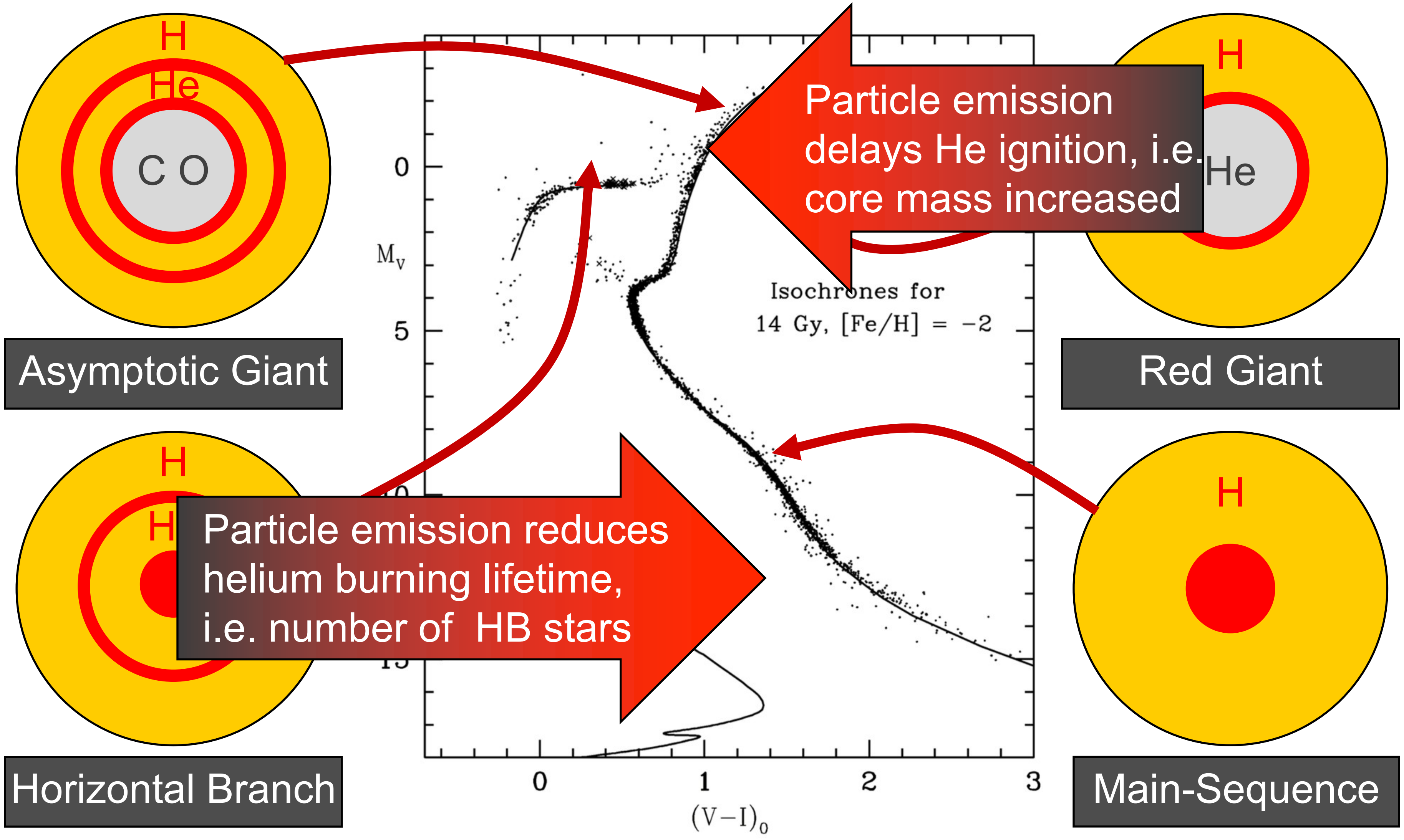
Stellar energy loss constraints

- Evolution of stars (Main Sequence – Red-Giant (RG) – Helium Burning (HB) – White Dwarf (WD)) sensitive to additional energy losses



[Copyright Addison Wesley]

Astrophysical Axion Bounds



[Raffelt 14]

Astrophysical Axion Bounds

Stellar energy loss constraints

- RG cooling rate: Brightness of tip of RG branch in color-magnitude diagram of globular cluster

$$|g_{Aee}| \equiv \frac{m_e}{f_A}|C_{Ae}| < 4.3 \times 10^{-13}$$

[Viaux et al. 13]

- HB cooling rate: Number of HB stars vs. number of RGs in color-magnitude diagram of globular cluster

$$|g_{A\gamma\gamma}| \equiv \frac{\alpha}{2\pi f_A}|C_{A\gamma}| < 6.6 \times 10^{-11}\,\mathrm{GeV}^{-1}$$

[Ayala et al. 14]

- WD cooling rate: White dwarf luminosity function (WDLF)

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[Isern et al. 08-12]

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- Axion is a WISPy Dark Matter candidate: very light and very weakly interacting, since

$$m_A = 5.691(51)\left(\frac{10^9\,\mathrm{GeV}}{f_A}\right)\mathrm{meV}$$

$$f_A = 5.1 \times 10^9\ |C_{Ae}|\left(\frac{10^{-13}}{|g_{Aee}|}\right)\mathrm{GeV}$$
$$= 1.2 \times 10^8\ |C_{A\gamma}|\left(\frac{10^{-11}\,\mathrm{GeV}^{-1}}{|g_{A\gamma\gamma}|}\right)\mathrm{GeV}$$

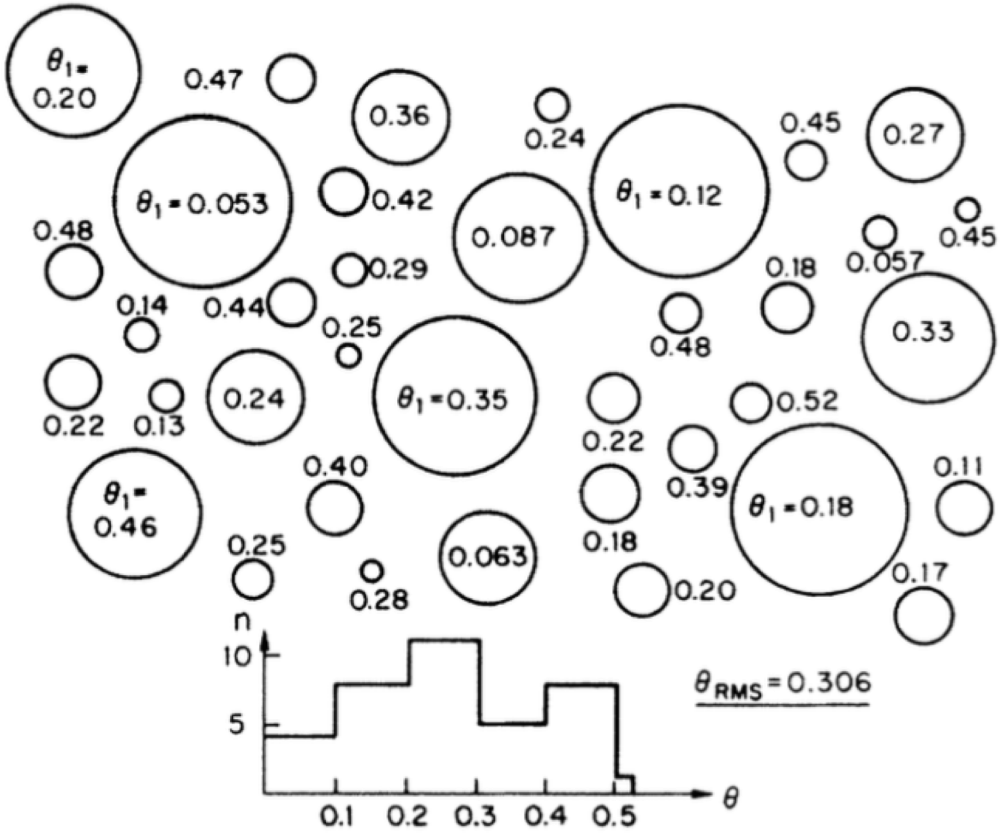
Axion Dark Matter

Vacuum re-alignment mechanism

- PQ phase transition takes place at

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

- Axion takes random initial values in causally connected domains



[Turner `86]

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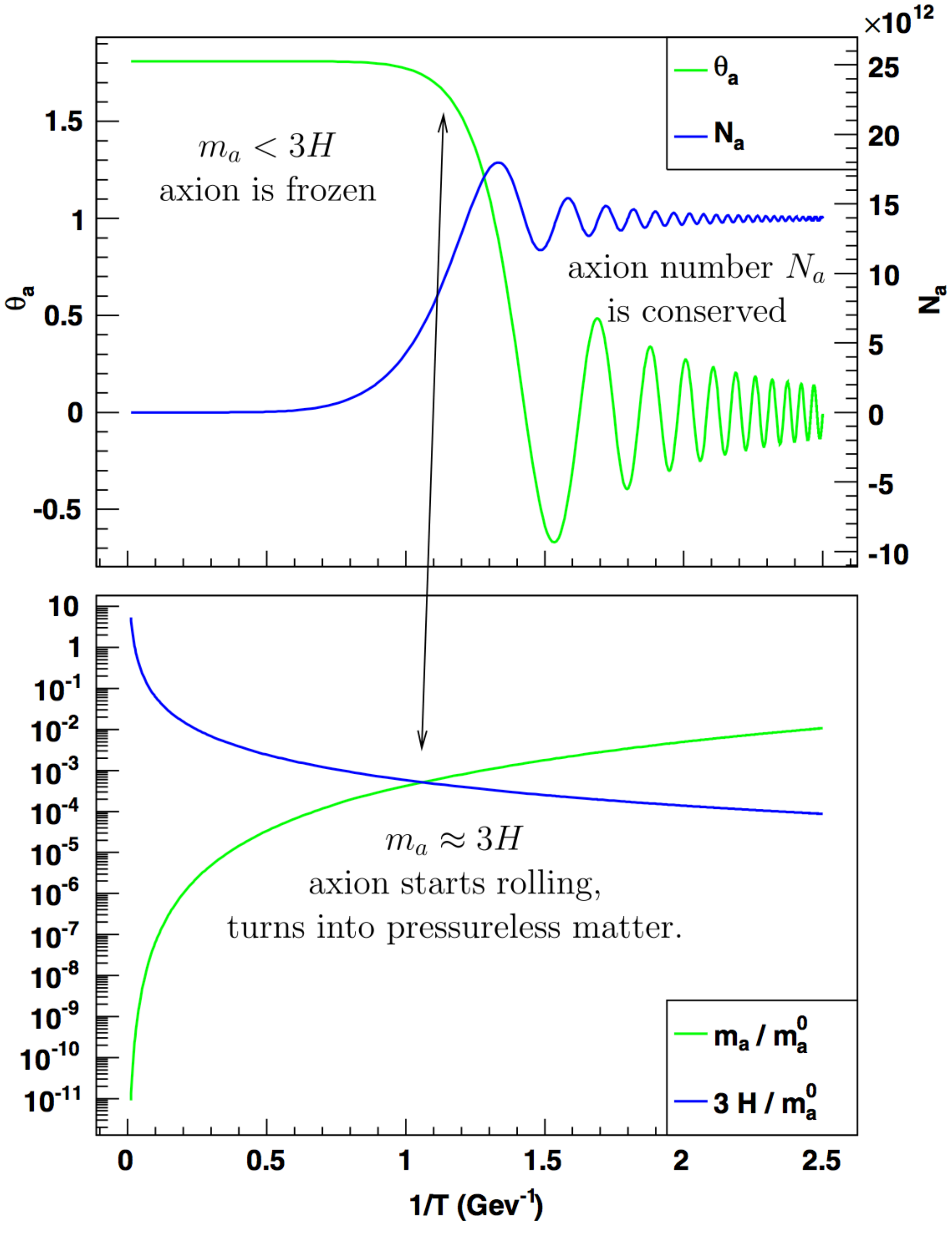
[Preskill,Wise,Wilczek 83; Abbott,Sikivie 83; Dine,Fischler 83,....]



[Wantz,Shellard `09]

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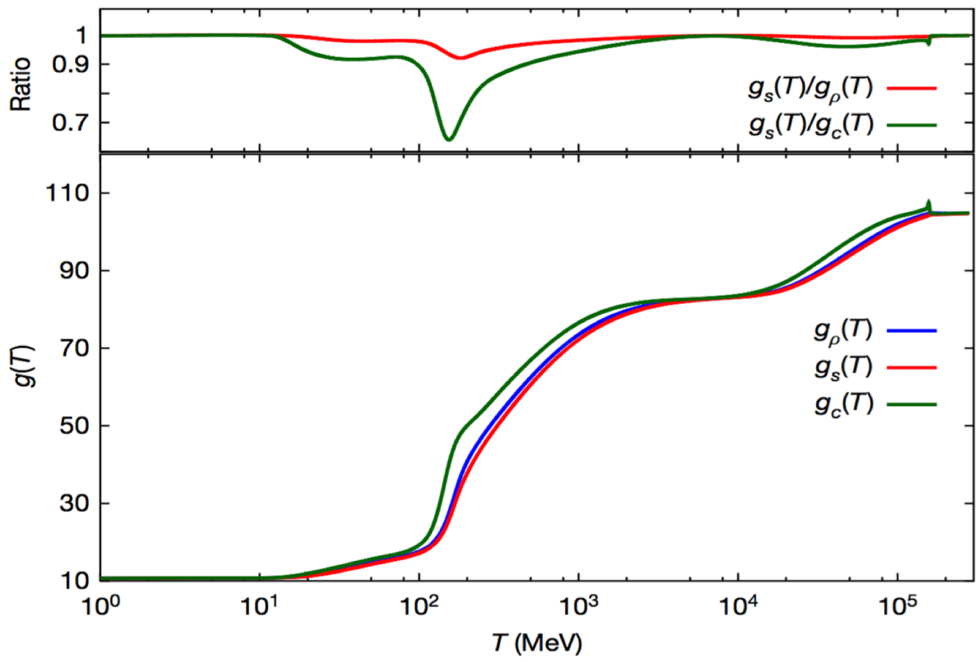
- QCD input from lattice:
  - Equation of state $\Rightarrow H(T)$



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

Axion Dark Matter

Vacuum re-alignment mechanism

- PQ phase transition takes place at

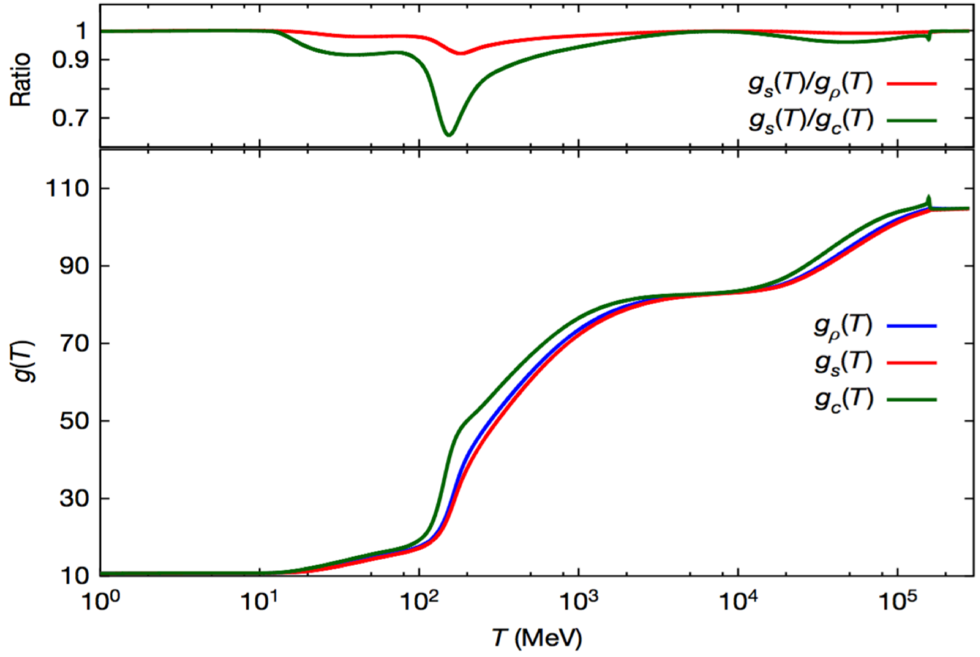
$$T \lesssim T_c^{\rm PQ} \sim v_{\rm PQ} = N f_A$$

- Axion takes random initial values in causally connected domains

- 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,....]

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



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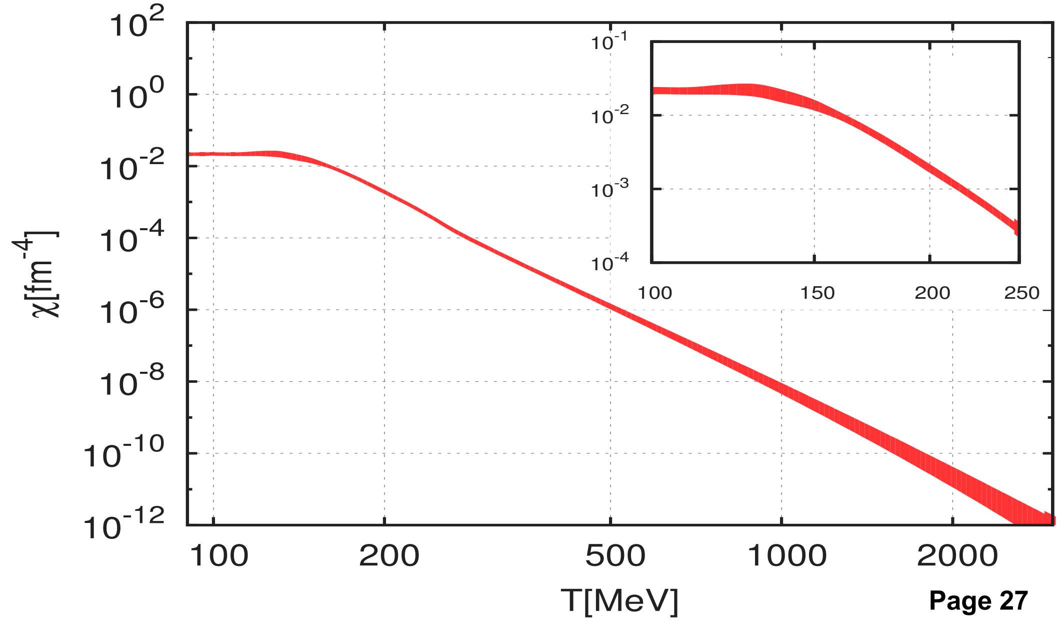
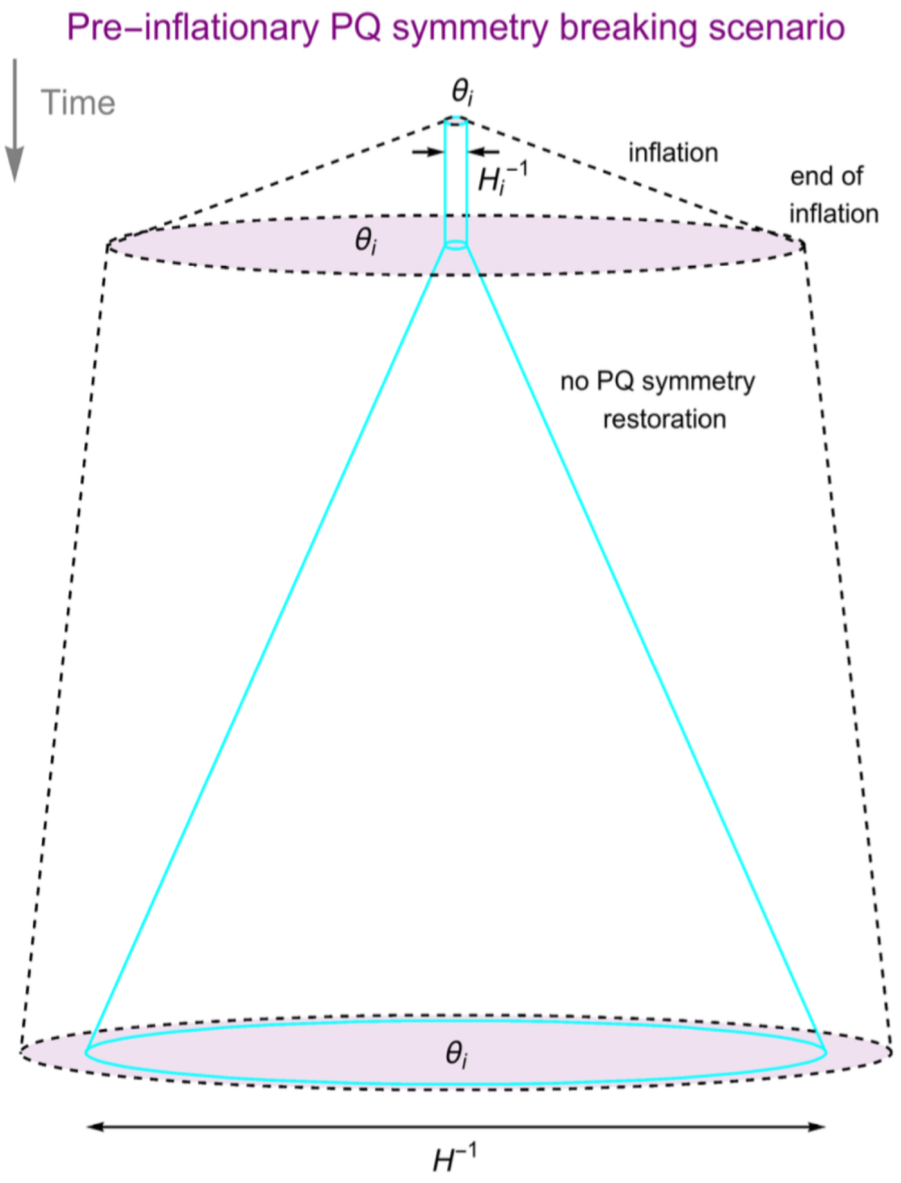


Axion Dark Matter

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



[Saikawa]

Axion Dark Matter

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

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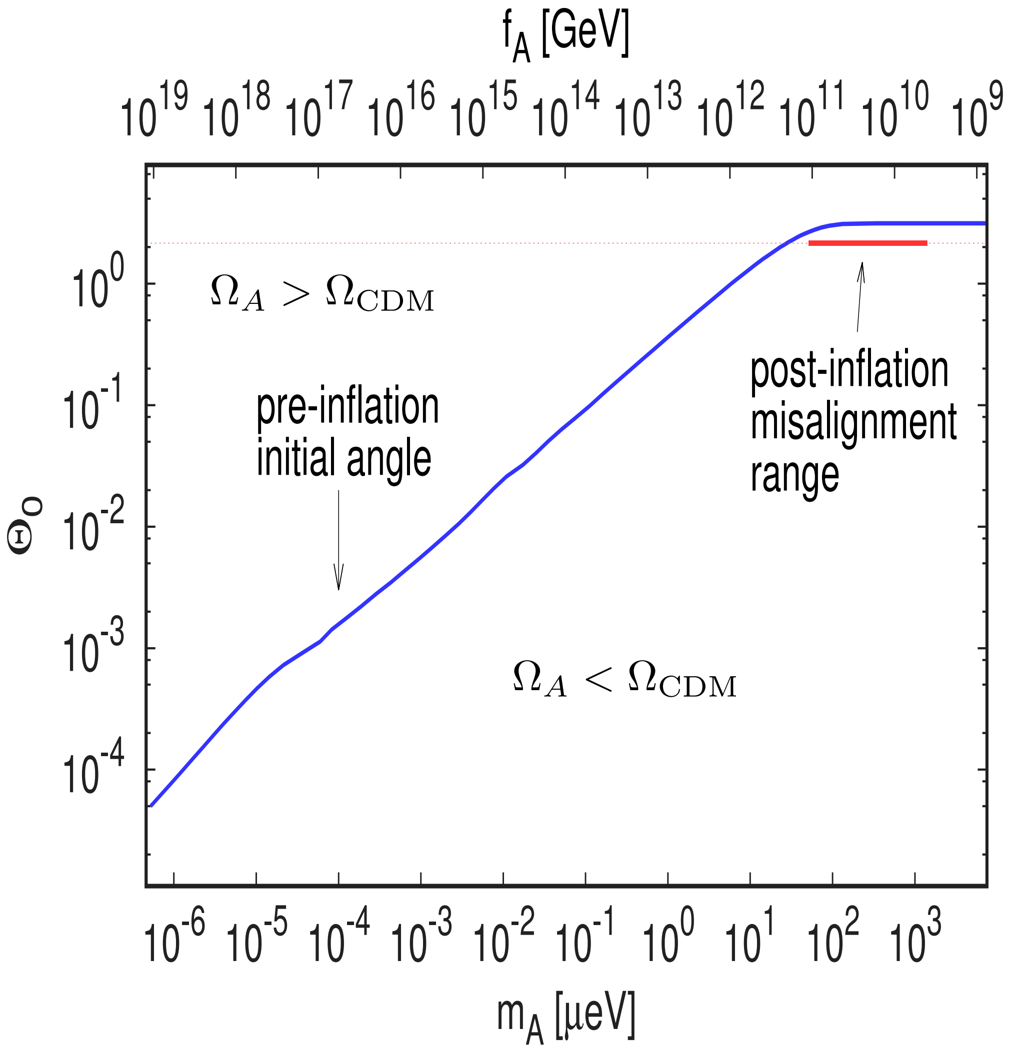

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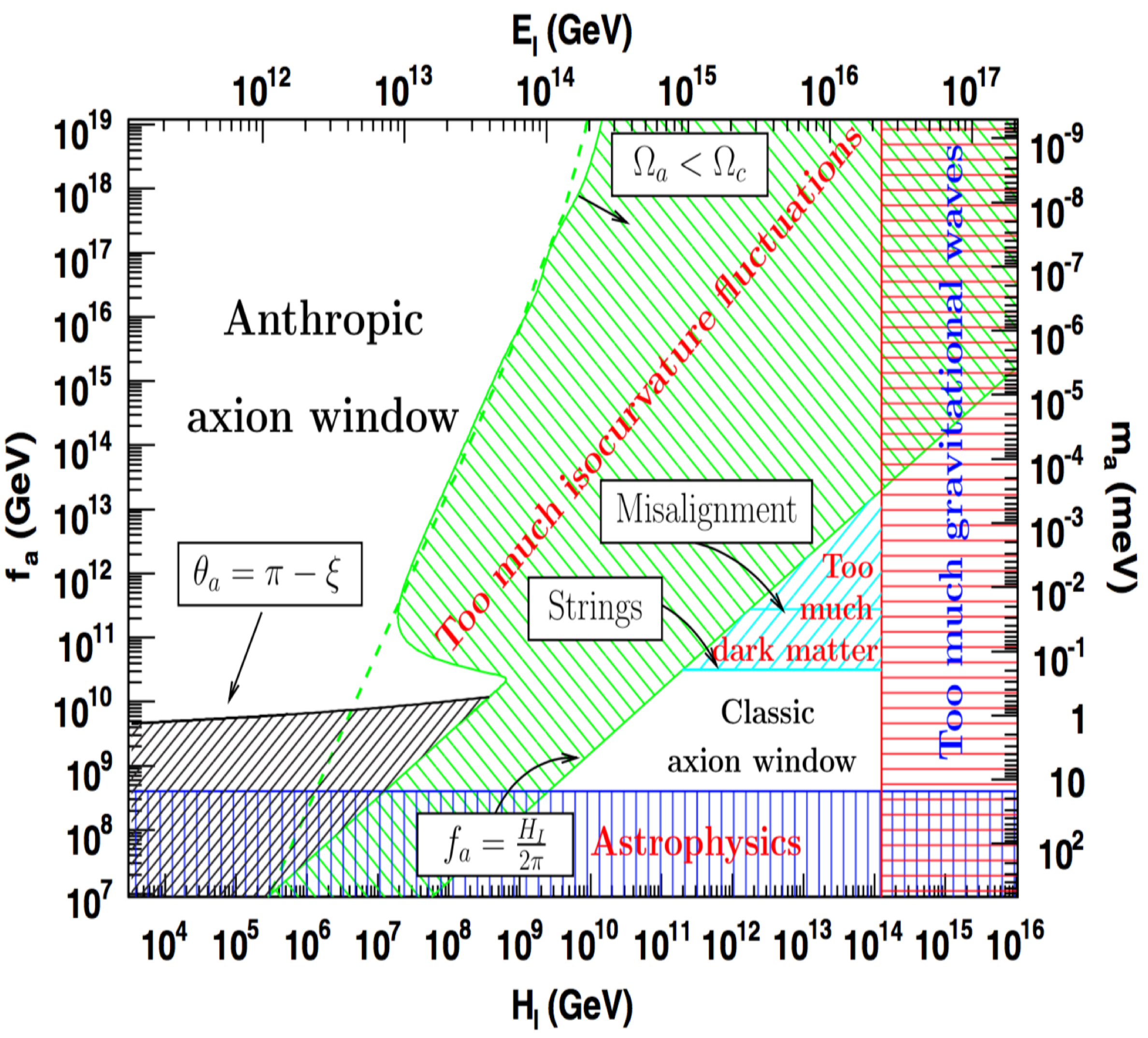
  - Upper bound on scale of inflation from isocurvature fluctuations produced by the axion during inflation and not erased afterwards:

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

  - VR works also for ALP (mass ind. of decay const.):

$$\Omega_A^{\rm vr} h^2 \approx 0.12 \left(\frac{m_A}{\mathrm{neV}} \right)^{1/2} \left(\frac{f_A}{4.7\times 10^{13}\,\mathrm{GeV}} \right)^2 \theta_i^2$$



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

Axion Dark Matter

Post-inflationary PQ SSB scenario

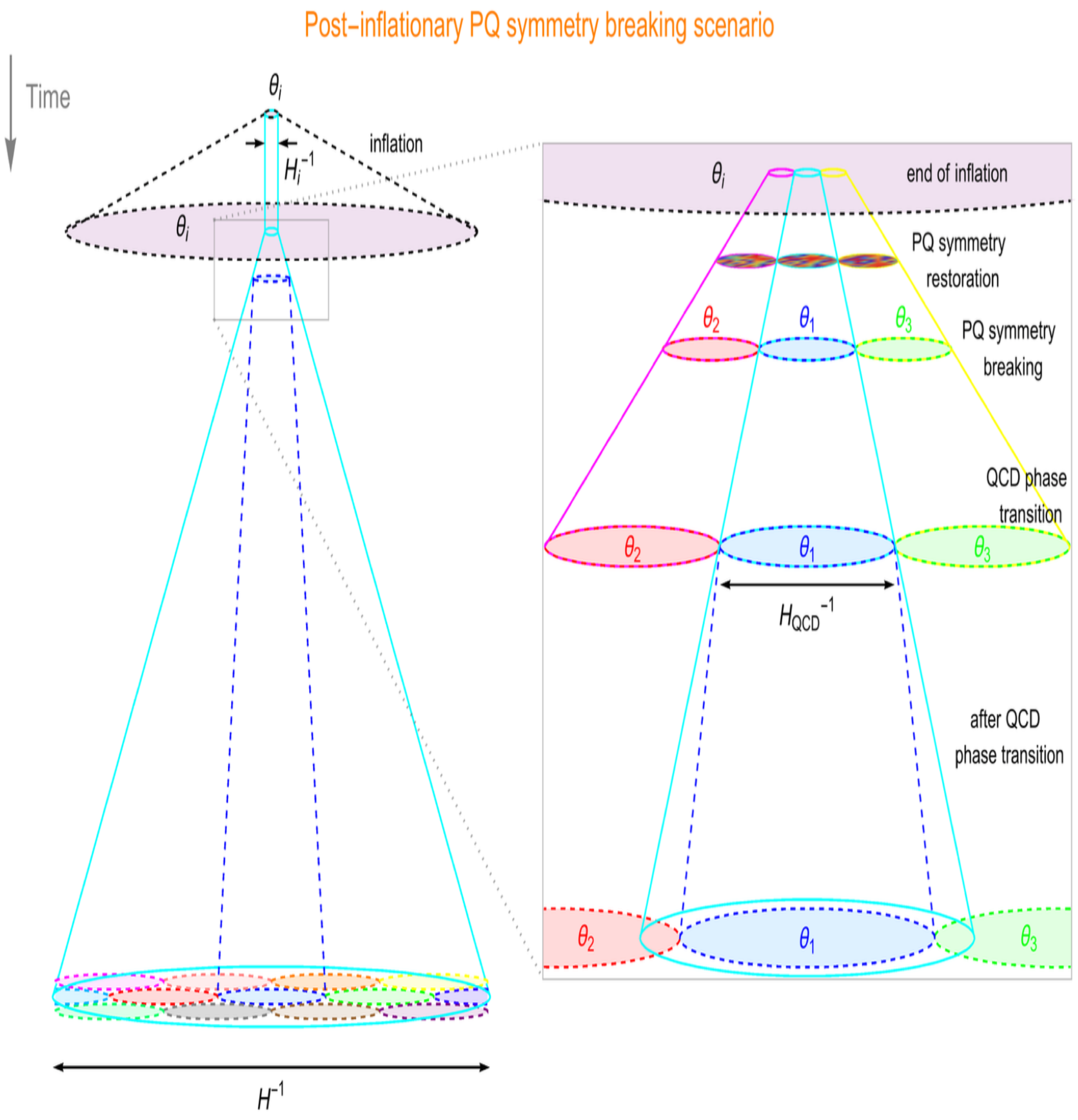
- Averaging over random initial axion field values

$$\Omega_A^{\rm vr} h^2 \approx 0.12 \left(\frac{30\ \mu{\rm eV}}{m_A}\right)^{1.165}$$

- Does not exceed observed CDM abundance for

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

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



[Saikawa]

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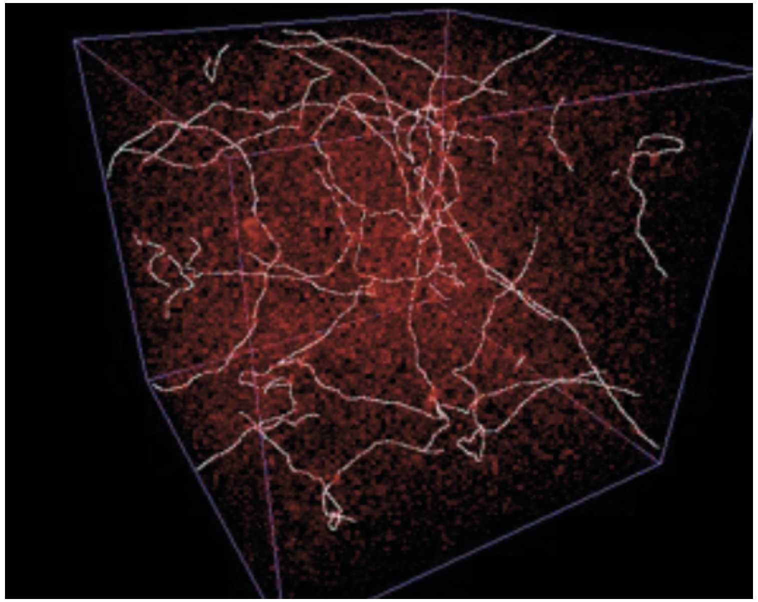
[Borsanyi et al., Nature `16 [1606.0794]]

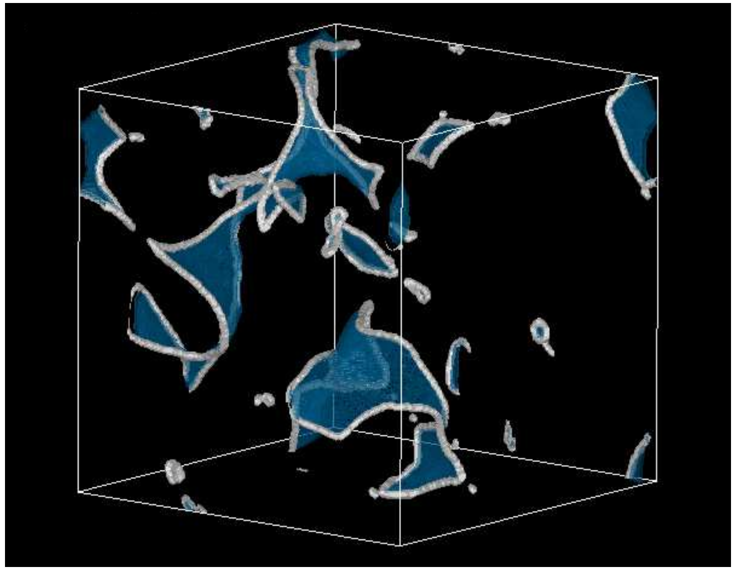
- Axions also produced by collapse of network of topological defects – strings and domain-walls –
- Axion can be 100% of DM for

$$m_A \approx 25\ \mu{\rm eV} - 4.4\ {\rm meV}$$

[Hiramatsu et al. 11,12,13;
Kawasaki,Saikawa,Segikuchi 15;
Ballesteros et al. 16;
AR,Saikawa `16;
Klaer,Moore `17;
Gorghetto,Hardy,Villadoro `18;
Buschmann et al. 19;
Hindmarsh 19]

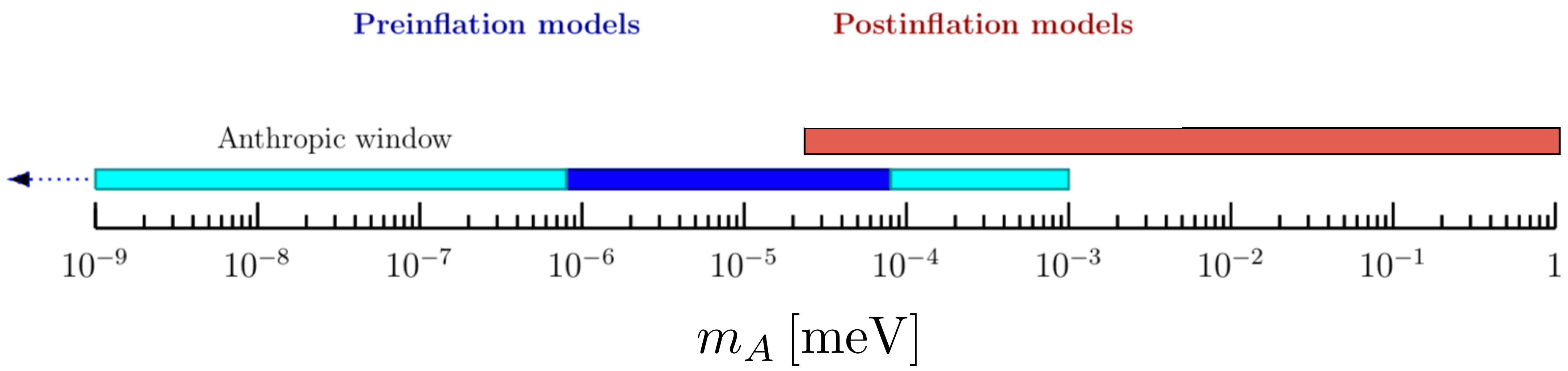


[Hiramatsu et al.]



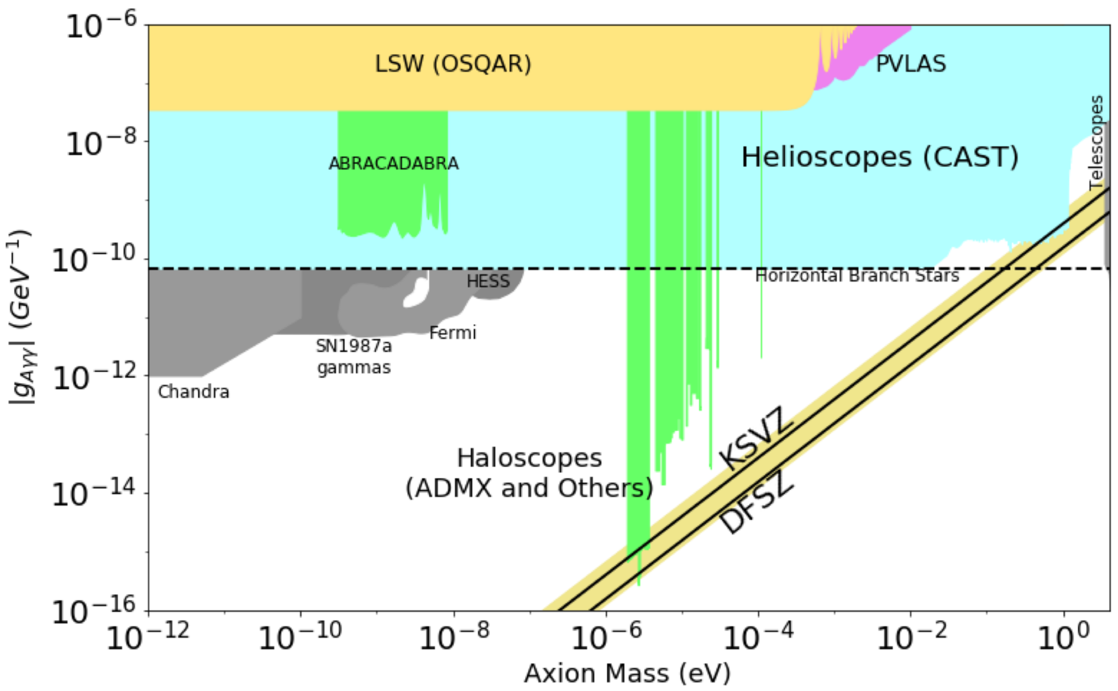
Summary

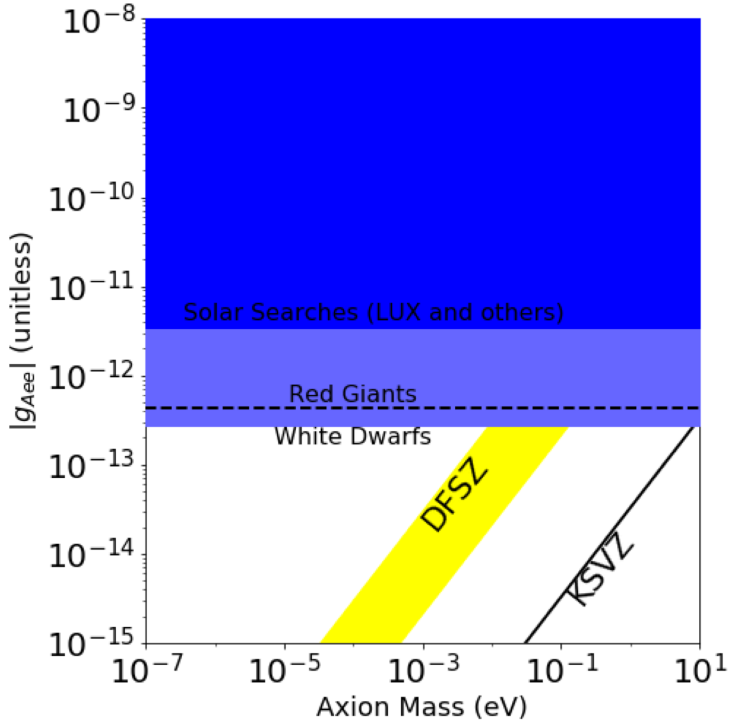
- DM axion mass spans a huge range:



Summary

- “Axion revelation“: DM axion mass starts right at border of stellar energy loss exclusion bounds:





- Many experiments are running/planned which probe a large region of relevant DM parameter space