Thermal production of axions

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UNIVERSITÀ DEGLI STUDI DI PADOVA

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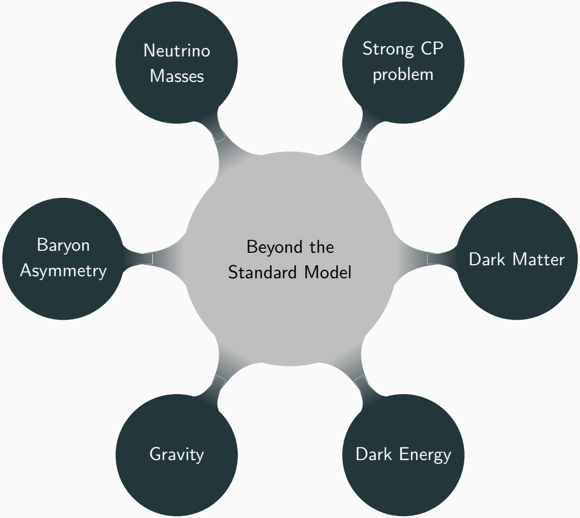
Motivations



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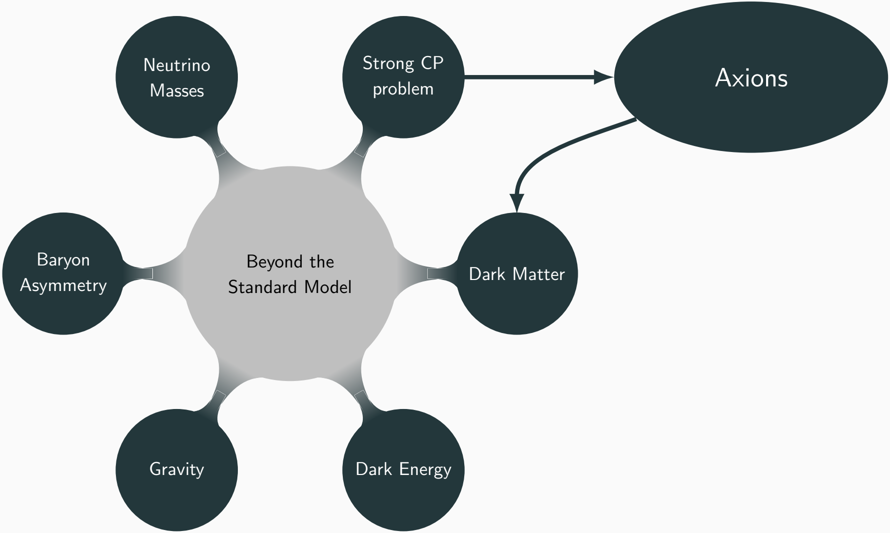

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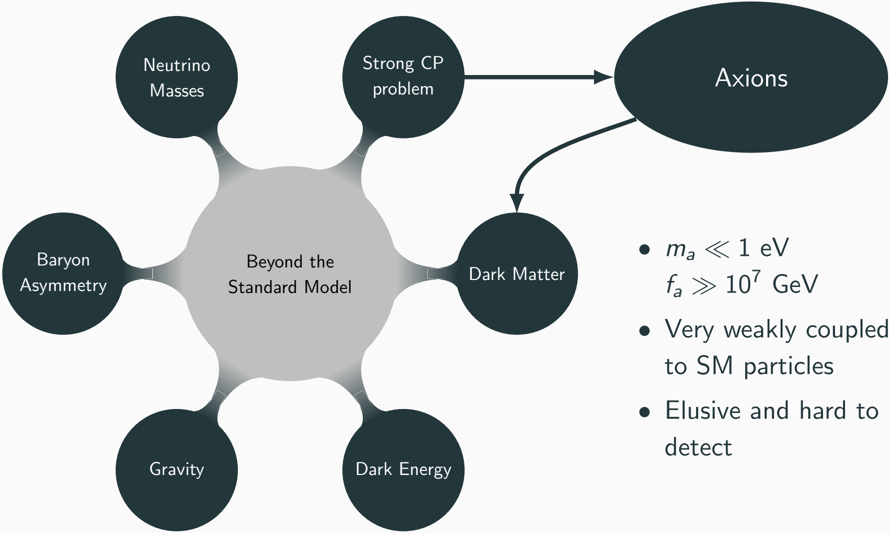

- $m_a \ll 1$ eV
  $f_a \gg 10^7$ GeV
- Very weakly coupled to SM particles
- Elusive and hard to detect

Outline

The QCD axion

Cosmological populations

Results in thermal production

The QCD axion

The strong CP problem

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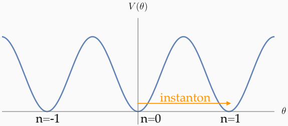
- Physical parameter $\bar{\theta} = \theta + N_f \theta_Y$



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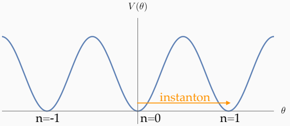
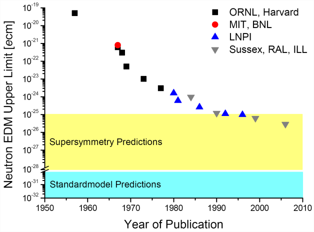
- Physical parameter $\bar{\theta} = \theta + N_f \theta_Y$
- Neutron EDM induced $d_N = \bar{\theta} \times 10^{-16}$ e cm
- Experimentally never observed

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

$$|\bar{\theta}| < 10^{-10}$$





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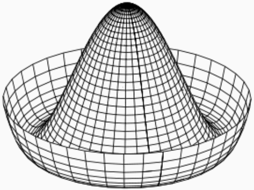
- Spontaneously broken by the vacuum

$E \sim f_a$

$$V(\varphi) = \lambda \left(|\varphi|^2 - \frac{f_a^2}{2} \right)^2 \quad \varphi(x) = \rho(x) e^{i\phi(x)/f_a}$$



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$$\mathscr{L}_\phi = \frac{1}{2} \partial_\mu \phi \partial^\mu \phi + \frac{\phi(x)}{f_a} \frac{\alpha_s}{8\pi} G \tilde{G} + \mathscr{L}_{int}$$

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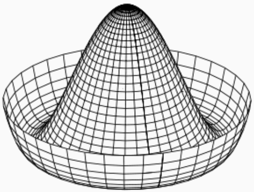

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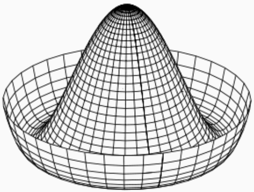

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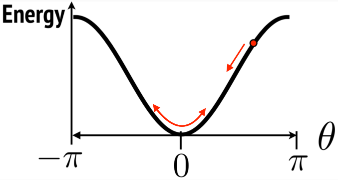
$E \sim \Lambda_{QCD} \ll f_a$

- Explicitly broken (at quantum level) by $G\tilde{G}$ and instantons at Λ_{QCD}



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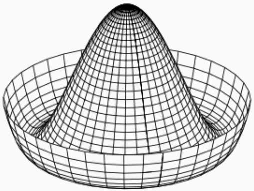
- Explicitly broken (at quantum level) by $G\tilde{G}$ and instantons at Λ_{QCD}
- $\bar{\theta} \to \bar{\theta}(x) = \phi(x)/f_a$
  Minimum is CP conserving

$E \sim f_a$



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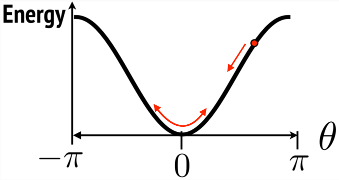

The QCD potential sources a mass term for low E, below Λ_{QCD}:

$$m_a^2 \simeq \frac{m_\pi^2 f_\pi^2}{f_a^2}, \quad m_a \sim 6 \text{ meV} \frac{10^9 \text{ GeV}}{f_a}$$

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I) DFSZ model

- Two Higgs doublets model H_u, H_d
- SM fermions carry PQ charge c_ψ

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II) KSVZ model

- New heavy quarks $Q^\star$
- The new quarks carry PQ charge

$$\frac{\partial_\mu \phi}{2f_a} c_{Q^\star} \bar{Q}^\star \gamma^\mu \gamma_5 Q^\star$$

Cosmological populations

- Thermal axions
- Non-thermal axions: misalignment and topological defects
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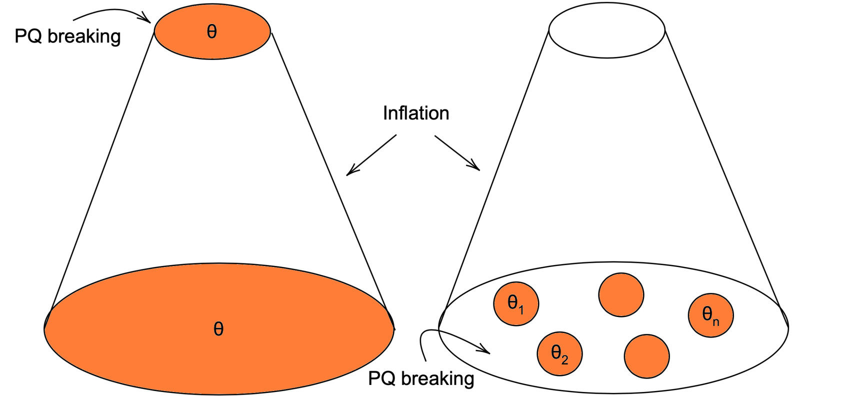


Vacuum realignment

We study the evolution of the ϕ field

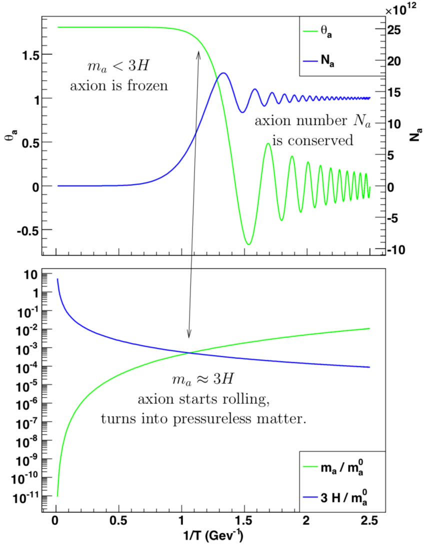
$$\ddot{\phi} + 3H\dot{\phi} + m_a^2\phi = 0$$

- At high T the axion field has a random initial value, and is *frozen*
- When $m_a(T_{osc}) \approx 3H(T_{osc})$ it starts oscillating

$$T_{osc} = 1.18 \left(\frac{10^{12}\ \text{GeV}}{f_a}\right)^{0.185} \quad \text{GeV}$$

- The field coherently oscillates producing a non-relativistic population of axions

$$\rho_\phi \propto R^{-3}$$



Hot axions: dark radiation

- Thermal production: $x_1 + x_2 \leftrightarrow x_3 + \phi$
- Solve Boltzmann equation
- Axions contribute to $N_{\rm eff}$

$$\frac{dn_\phi}{dt} + 3Hn_\phi = \Gamma(n_\phi^{eq} - n_\phi) \qquad \Delta N_{\rm eff} = N_{\rm eff} - N_{\rm eff}^{\rm (SM)} \propto \frac{\rho_\phi}{\rho_\gamma}$$

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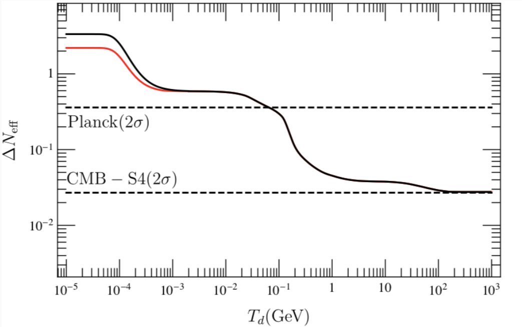
- $\Delta N_{\text{eff}} \propto g_{*s}^{-4/3}$
- We focus on $T_d \sim T_{EW}$
- CMB-S4 will reach sensitivity $\Delta N_{\text{eff}} \sim 0.01$



Axion cosmology

Cold axions

- Non-thermal production mechanisms

$$\Omega_a h^2 \sim 0.15 \left(\frac{f_a}{10^{11}\ \text{GeV}} \right)^{1.18} \bar{\theta}_i^2$$

Scenario A: $f_a > T_R$

$f_a \gtrsim 10^{10}$ GeV

Scenario B: $f_a < T_R, \quad \langle \bar{\theta}_i \rangle \sim \mathcal{O}(1)$

$10^9\ \text{GeV} \lesssim f_a \lesssim 10^{11}$ GeV

Hot thermal axions

- Production in our DFSZ and KSVZ models

Results in thermal production

Production at the EW scale in DFSZ

$$\mathscr{L} = \mathscr{L}_{SM} + \frac{1}{2}(\partial_\mu \phi)^2 + \frac{\phi}{f_a}\sum_X \frac{\alpha_X}{8\pi} C_{XX} \mathrm{tr} X_{\mu\nu}\tilde{X}^{\mu\nu} + \frac{\partial_\mu \phi}{2 f_a}\sum_\psi c_\psi \bar{\psi}\gamma^\mu \gamma_5 \psi$$

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Axion couplings

- Model independent $\phi G \tilde{G}$ operator, subdominant w.r.t. y_t
- Derivative $\rightarrow$ Yukawa

$$\frac{i c_\psi m_\psi}{f_a}\phi \bar{\psi}\gamma_5 \psi$$

- Leading top-axion operator at the EW scale $tX \rightarrow t\phi$

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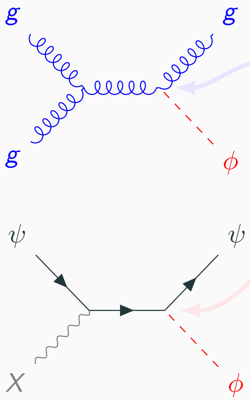

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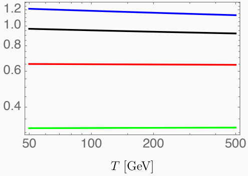
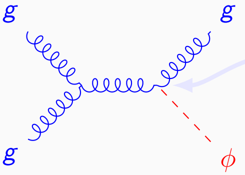
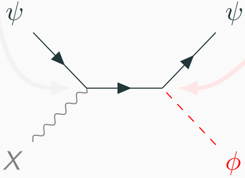
SM couplings

- $X = \{g, \gamma, W^\pm, Z, h\}$
- $g_s > y_t > g_W > e$



- $tg \to t\phi$ + EW corr.





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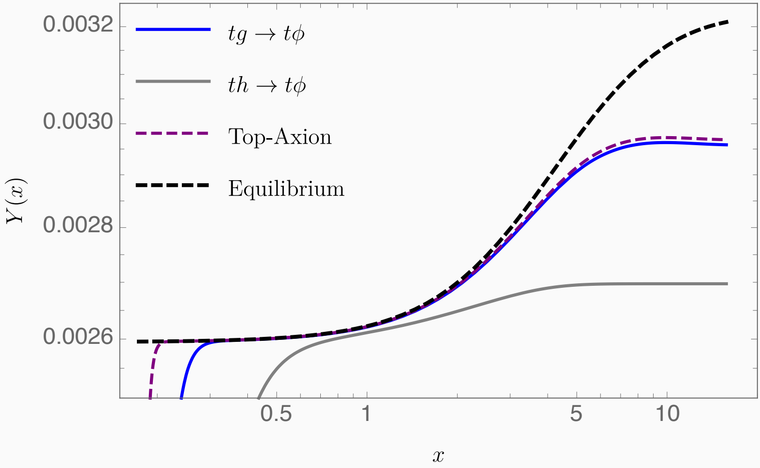
Numerical results

Comoving axion abundances for $f_a/c_t = 10^8$ GeV:



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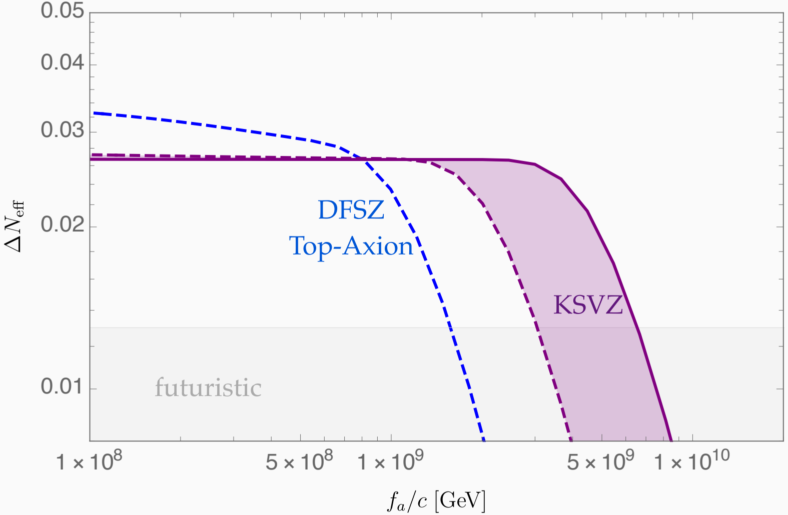
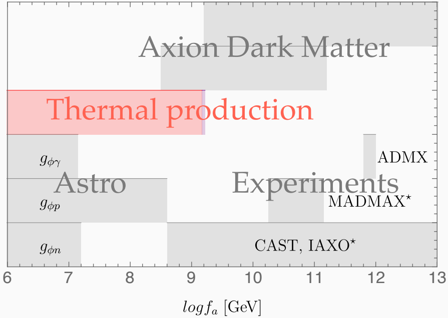
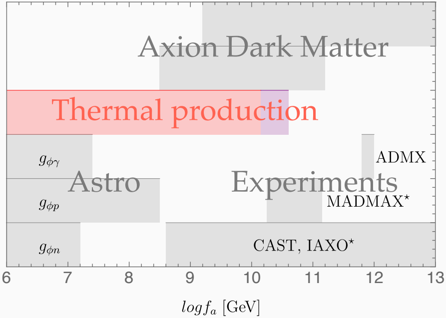


Axion parameter space

DFSZ model



KSVZ model

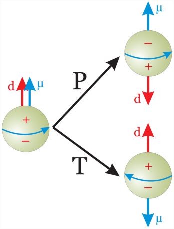


$$6 \times 10^8 \text{ GeV} \lesssim f_a^{\text{DFSZ}} \lesssim 2 \times 10^9 \text{ GeV}$$

$$5 \times 10^8 \text{ GeV} \lesssim f_a^{\text{KSVZ}} \lesssim 2 \times 10^{10} \text{ GeV}$$

Backup slides: nEDM

- The nEDM is a measure for the distribution of positive and negative charge inside the neutron
- Under T, μ_N changes its direction, whereas d_N stays unchanged
- Under P, the d_N changes its direction but not μ_N



- Measurable with Larmor precession of the neutron spin inside a parallel and anti-parallel **E** and **B** fields

$$h\nu = 2\mu_N B \pm 2 d_N E, \qquad d_n = \frac{h\Delta\nu}{4E}$$

Backup slides: axion CDM

Scenario A: $f_a > T_R$

- Only vacuum realignment contribution
- Crucially depends on the initial angle

$$\Omega_a h^2 \sim 0.15 \left(\frac{f_a}{10^{11}\ \text{GeV}} \right)^{1.18} \bar{\theta}_i^2$$

- Wide range of possible scales: $f_a \gtrsim 10^{10}$ GeV

Scenario B: $f_a < T_R$

- Vacuum realignment and topological defects contributions
- The initial angle value is averaged over different causal patches

$$\Omega_a h^2 \sim 0.7 \left(\frac{f_a}{10^{11}\ \text{GeV}} \right)^{1.18}$$

- Limited window: 10^9 GeV $\lesssim f_a \lesssim 10^{11}$ GeV