The Niels Bohr International Academy

APCTP Asia Pacific Center for Theoretical Physics

2nd NBIA-APCTP Workshop on Cosmology and Astroparticle Physics

Axion Cold Dark Matter with High Scale Inflation

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Outline

- The Strong CP problem & the axion solution.
- Astro and cosmological properties of the axion.
- BICEP2 implications on the axion CDM.

EJC, arXiv: 1404.4284

Strong CP problem

- QCD θ parameter allowed in SM violates CP:

$$\mathcal{L} = \theta \frac{g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a \;\Rightarrow\; \theta\, \mathbf{E} \cdot \mathbf{B}$$

- And leads to EDM $d_n \approx 2 \times 10^{-16} \theta\, ecm$
- Current measurement requires $\theta < 10^{-10}$
- Note) weak CP: $\delta_{\mathrm{CKM}} \sim 1$
- Why is θ so small?
- One of hierarchy problems in SM:

$m_W \sim m_h \sim m_t << M_{Pl}$,

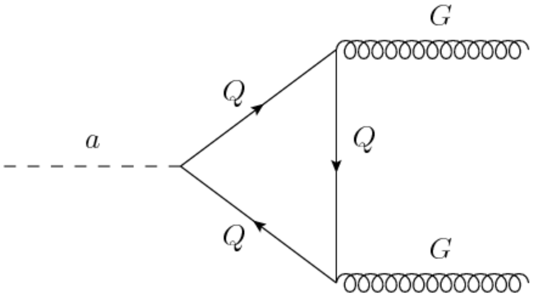
$m_\nu : m_e : m_t \sim 10^{-12} : 10^{-6} : 1$

Peccei-Quinn Mechanism

- Introduce a QCD-anomalous global U(1) symmetry which is spontaneously broken → axion

$$S = \frac{v_{PQ}}{\sqrt{2}} e^{ia/v_{PQ}}$$

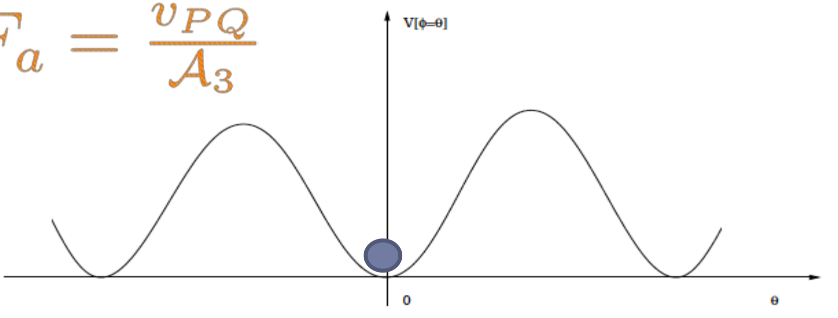
$$\mathcal{L} = \mathcal{A}_3 \frac{a}{v_{PQ}} \frac{g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a$$



- QCD phase transition below 1 GeV develops an axion potential dynamically settling down θ_{eff} to zero:

$$\mathcal{L} = m_\pi^2 f_\pi^2 \left[1 - \cos \frac{a}{F_a} \right] \qquad F_a = \frac{v_{PQ}}{\mathcal{A}_3}$$

$$\Rightarrow \left\langle \frac{a}{F_a} \right\rangle = 0$$



Axion models

- **K**im-**S**hifman-**V**ainshtein-**Z**akharov: $(\mathcal{A}_3 = N_{Q'})$

$$\mathcal{L}_{KSVZ} = \lambda_Q SQQ^c + h.c.$$

1 0 -1

- **D**ine-**F**ischler-**S**rednicki-**Z**hitinitski: $(\mathcal{A}_3 = 2N_g)$

$$\mathcal{L}_{DFSZ} = y_u q u^c H_u + y_d q d^c H_d + \lambda_H S^2 H_u H_d + h.c.$$

0 1 -1 0 1 -1 2 -1 -1

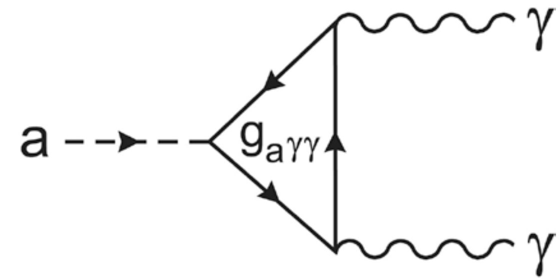
- $\mathcal{A}_3$ = Domain Wall number:

N_{DW} = 1 (6) for KSVZ (DFSZ)

Axion physics

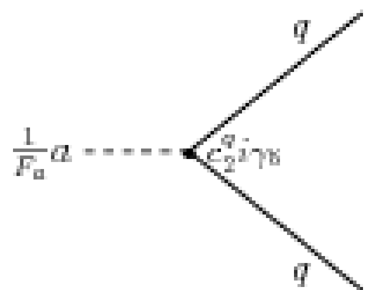
- Axion mass: $m_a \sim \frac{m_\pi f_\pi}{F_a} \sim 10 \left(\frac{10^{12}\mathrm{GeV}}{F_a} \right) \mu\mathrm{eV}$

- Axion couplings:



$$g_{a\gamma\gamma} \sim 10^{-15} \left(\frac{10^{12}\mathrm{GeV}}{F_a} \right) \mathrm{GeV}^{-1}$$

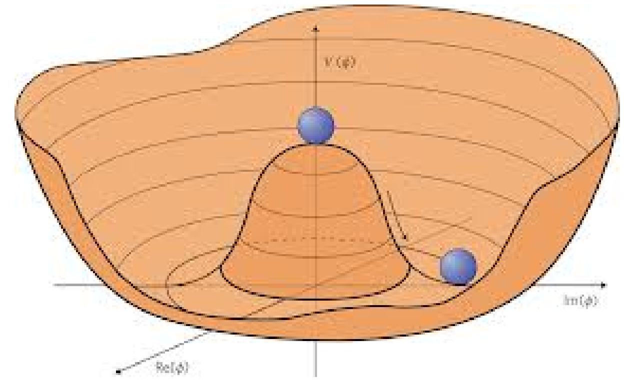
$$g_{aff} \sim \frac{m_f}{F_a}$$



- Lower bound on F_a from stellar evolution: $F_a > 10^{9-10}\mathrm{GeV}$

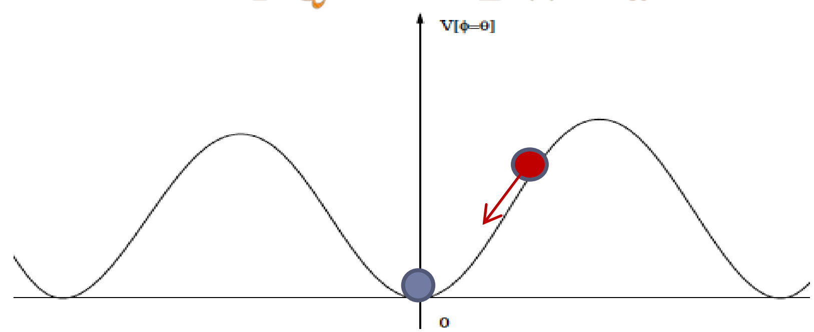
Axion Cold Dark Matter

- Being a Goldstone boson, axion has no potential after PQ symmetry breaking at v_{PQ} .
- As the axion potential develops at the QCD phase transition, θ oscillates starting from its mis-aligned value θ_0 → a stable oscillating scalar field forms cold dark matter.
- Distinct θ vacua: 0, 1, …, $N_{DW}-1$



$$a = [0, 2\pi v_{PQ}]$$

$$v_{PQ} = N_{DW} F_a$$



$$\theta \equiv a/F_a = [0, 2\pi]$$

Domain Wall problem

- If $N_{DW} > 1$, there exits $N_{DW} - 1$ distinguishable vacua and thus domain walls connecting them can be formed to overclose the universe.
- If the PQ symmetry is broken during inflation, this problem can be evaded as domain walls are washed away by inflation.
- If the PQ symmetry is broken after inflation, $N_{DW}=1$ is required.

Axion Cold Dark Matter

- Axion relic abundance:

$$\Omega_a h^2 \approx 0.18\,[\theta_0^2\,\alpha_{t.d.} + \delta\theta^2]\left(\frac{F_a}{10^{12}\mathrm{GeV}}\right)^{1.19}$$

Includes axions produced from the axionic string and domain walls. $\alpha_{t.d.} \sim 1 - 100$

Quantum fluctuation of the initial mis-alignment during inflation. $\delta\theta \equiv \frac{H_I}{2\pi F_a}$

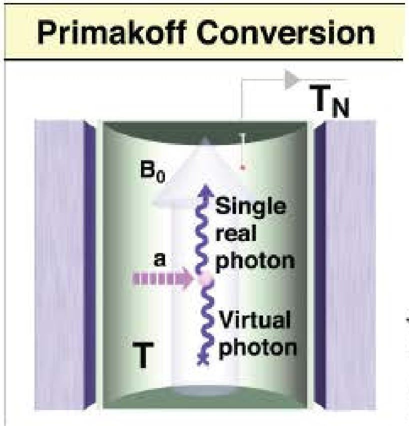
- PQ symmetry breaking during inflation:

$$\theta_0 = \mathrm{arbitrary} \qquad \alpha_{t.d.} = 1 \qquad \delta\theta = H_I/2\pi F_a$$

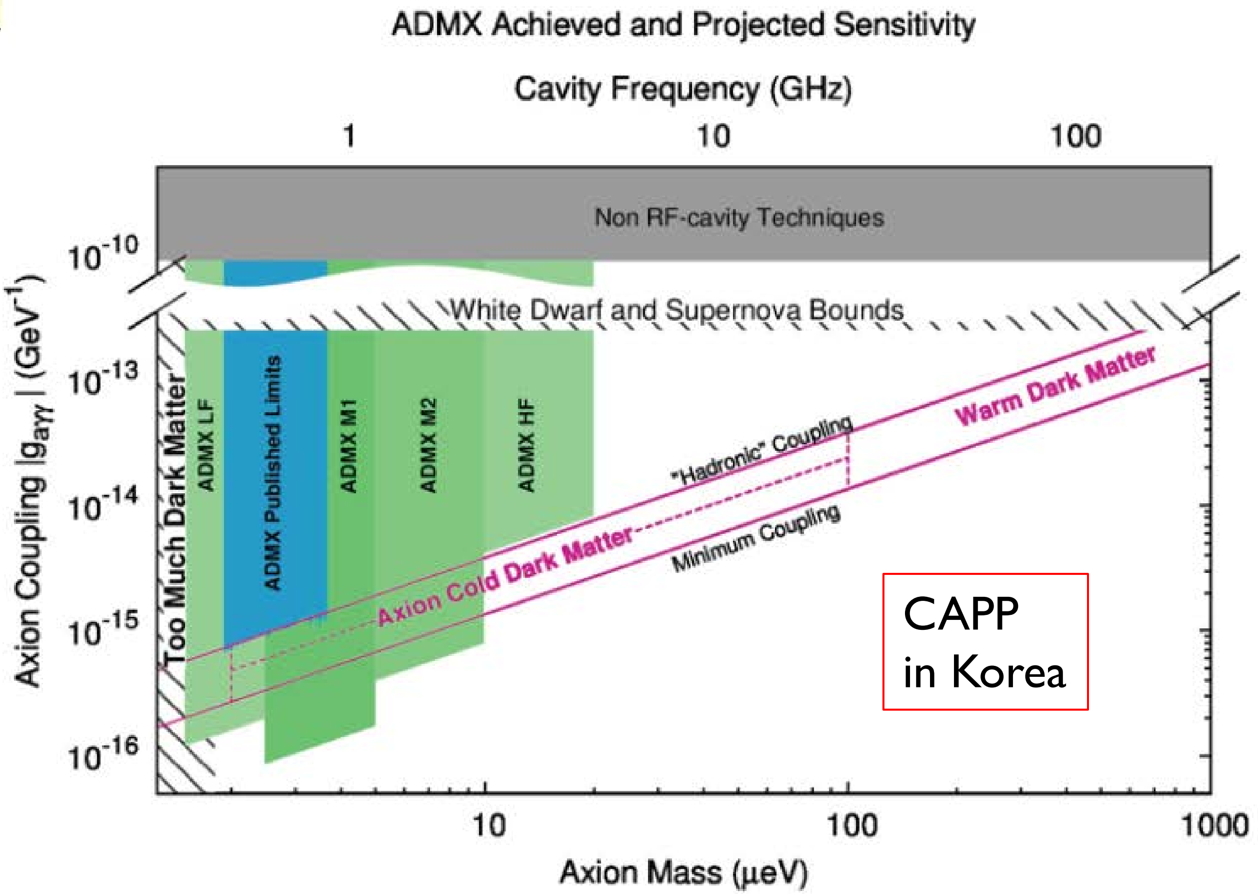
- PQ symmetry breaking after inflation:

$$\theta_0^2 = \langle\theta_i^2\rangle \approx 2\pi^2/3 \qquad \alpha_{t.d.} \sim 1 - 100 \qquad \delta\theta = 0$$

Axion detection



Rybka's Talk at Cosmic Frontier 2013



$F_a(\mathrm{GeV}) \approx 10^{12}$ $\quad 10^{11} \quad 10^{10}$

BICEP2

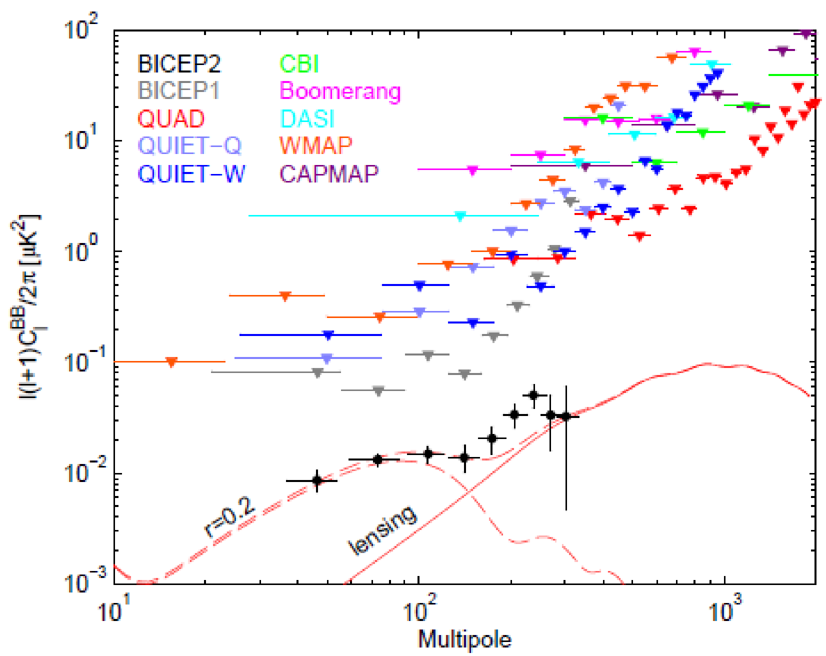
- Measurement of B (curly) mode CMB polarization at low multipole → primordial gravitational (tensor) perturbation → determine the inflation scale.

$$r \equiv \frac{\mathcal{P}_T}{\mathcal{P}_S} = \frac{16 H_I^2}{\pi \mathcal{P}_S M_P^2}$$

$$r = 0.16,\ \mathcal{P}_S = 2.2 \times 10^{-9}$$

$$\Rightarrow \quad H_I = 10^{14}\mathrm{GeV}$$

$$V_I^{1/4} = 2 \times 10^{16}\mathrm{GeV}$$



Implications on axion CDM

- Axion CDM limit:

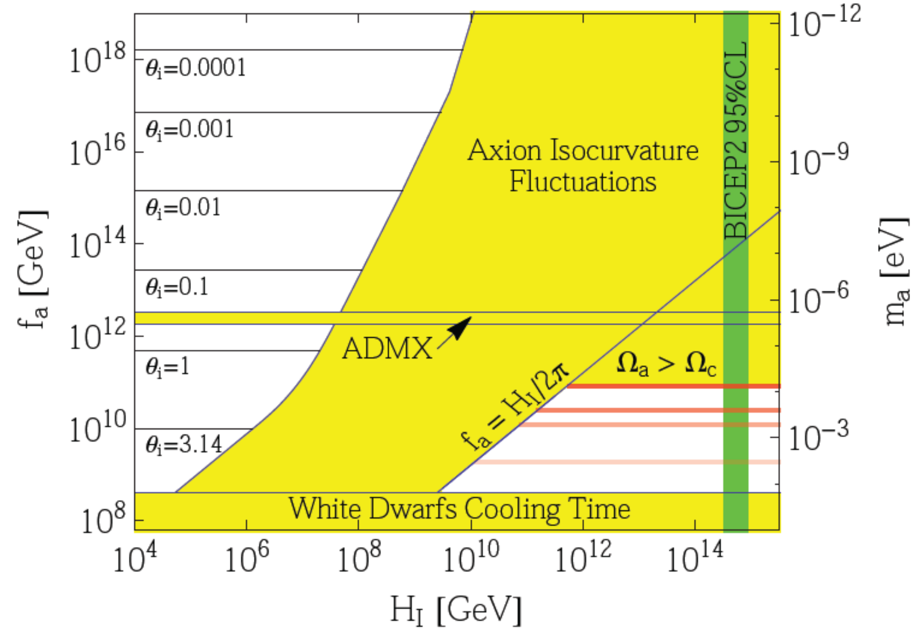
$$\Omega_a h^2 \approx 0.18\,[\theta_0^2\,\alpha_{t.d.} + \delta\theta^2]\left(\frac{F_a}{10^{12}\mathrm{GeV}}\right)^{1.19}$$
$$\leq 0.12$$

- Isocurvature perturbation constraint:

$$\mathcal{P}_a = 4\left(\frac{\Omega_a}{\Omega_{\rm CDM}}\right)^2 \frac{H_I^2}{(2\pi F_a\theta_0)^2 + H_I^2}$$

$$< 0.04\mathcal{P}_S$$

Marsh, et.al., 1403.4216
Visinelli-Gondolo, 1403.4594



PQ symmetry breaking during inflation

- The axion scale during inflation may be different from the one at present: F_a vs. F_I .
- Generalized constraints:

$$\Omega_a h^2 \approx 0.18\,[\theta_i^2 + \delta\theta^2]\left(\frac{F_a}{10^{12}\mathrm{GeV}}\right)^{1.19} \leq 0.12$$

$$\mathcal{P}_a = 4\left(\frac{\Omega_a}{\Omega_{\rm CDM}}\right)^2 \frac{H_I^2}{(2\pi F_I\theta_i)^2 + H_I^2} < 0.04\mathcal{P}_S$$

i) $F_I\,\theta_i < H_I/2\pi$:

$$\Omega_a < 4.7\times 10^{-6}\,\Omega_{\rm CDM}$$

$$F_I > 9\times 10^{15} F_{a,12}^{0.6}\,\mathrm{GeV}$$

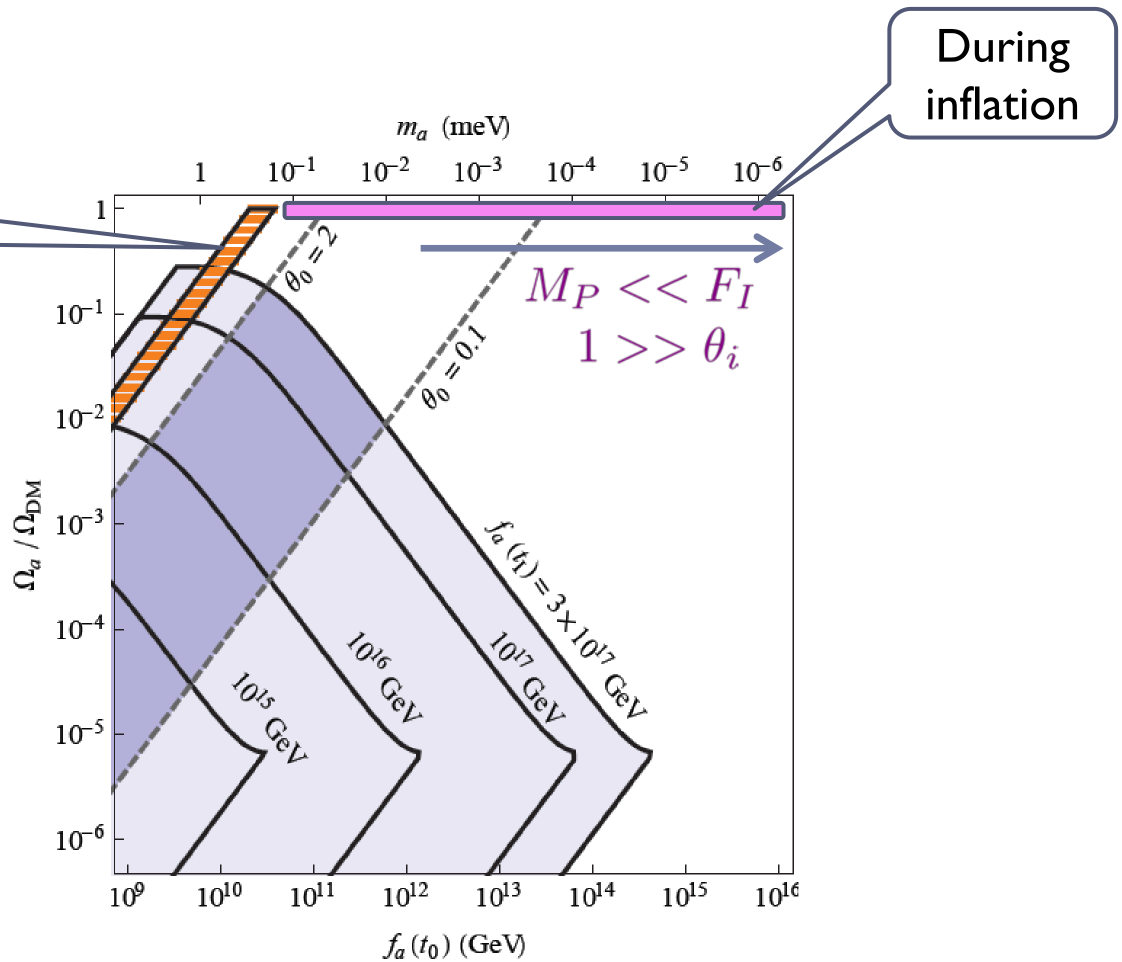
$$\theta_I < 0.0018 F_{a,12}^{-0.6}$$

ii) $F_I\,\theta_i > H_I/2\pi$:

$$\Omega_a/\Omega_{\rm CDM} = \left(\frac{\theta_i}{0.82}\right)^2 F_{a,12}^{1.2}$$

$$F_I > 1.7 M_P \left(\frac{\Omega_a h^2}{0.12}\right)^{1/2} F_{a,12}^{0.6}\,\mathrm{GeV}$$

Two allowed axion windows



K.Choi, et.al., 1404.3880

Dynamical generation of the axion scale

- Consider a supersymmetric extension of SM with the PQ sector

$$W_{PQ} = \lambda \frac{P^{n+2}Q}{M_P^n}$$

- Including soft SUSY breaking, the scalar potential may have the form

$$V = \lambda^2 \frac{|P|^{2n+4}}{M_P^{2n}} - m_P^2 |P|^2$$

- It leads to PQ symmetry breaking at the scale

$$F_a \sim \langle P \rangle \sim \left(\frac{m_P M_P^n}{\lambda} \right)^{1/n+1}$$

- The resulting axion scale is

$$F_a \sim 10^{11}, 10^{14}, 10^{15}\mathrm{GeV} \text{ for } n = 1, 2, 3$$

Supersymmery breaking during inflation

- The inflaton field χ has a generic Kahler term

$$\delta K \sim \frac{1}{M_P^2} \chi^\dagger \chi \, \phi^\dagger \phi$$

- If χ dominates the energy density of the Universe

$$\rho = 3H^2 M_P^2 \approx \left\langle \int d^4\theta \, \chi^\dagger \chi \right\rangle$$

Dine, Randall, Thomas, 1995

- Giving the effective mass to ϕ: $\delta V \sim -H^2 \phi^\dagger \phi$
- Thus, during inflation and inflaton oscillation period, there's an additional soft SUSY breaking by the Hubble parameter H.

Dynamical PQ symmetry breaking during and after inflation

- Consider a representative PQ sector

$$W_{PQ} = \frac{\lambda}{n+3} \frac{\phi^{n+3}}{M_P^n}$$

- Including the SUSY breaking effect by inflaton,

$$V = \lambda^2 \frac{|\phi|^{2n+4}}{M_P^{2n}} + \left[\frac{\lambda(C_A H + A)}{n+3} \frac{\phi^{n+3}}{M_P^n} + h.c. \right] - (C_m H^2 + m_\phi^2)|\phi|^2$$

- It leads to the time-dependent axion scale:

$$\langle \phi \rangle \sim \begin{cases} (H_I M_P^n)^{1/n+1} \sim F_I & \text{during inflation} \\ (\mathrm{Max}[\mathrm{H}, \mathrm{m}_\phi] \mathrm{M_P^2})^{1/\mathrm{n}+1} & \text{after inflation} \\ (m_\phi M_P^n)^{1/n+1} \sim F_a & \text{after reheating} \end{cases}$$

EJC, Dimopoulos, Lyth, 2004

PQ symmetry non-restoration

- For the PQ symmetry to be kept broken, the Hubble parameter at reheating should be smaller than m$_\phi$:

$$\rho_R = 3H_R^2 M_P^2 = \frac{\pi^2}{30} g_* T_R^4$$

$$H_R < m_\phi \quad \Rightarrow \quad T_R < 10^{10} \left(\frac{m_\phi}{200\mathrm{GeV}}\right)^{1/2} \mathrm{GeV}$$

- Independently of n, we have

$$\frac{F_I}{F_a} = \sqrt{\frac{C_m H_I}{m_\phi}} \qquad F_I > 1.7 M_P \left(\frac{\Omega_a h^2}{0.12}\right)^{1/2} F_{a,12}^{0.6}\,\mathrm{GeV}$$

- It requires

$$C_m > 3 \left(\frac{\Omega_a h^2}{0.12}\right) \left(\frac{m_\phi}{100\mathrm{GeV}}\right) \left(\frac{10^{13}\mathrm{GeV}}{F_a}\right)^{0.8}$$

$$\lambda < 10^{-6} \ \ \text{for} \ \ n = 2$$

Summary

- If BICEP2 is right , interpreting it as a primordial tensor perturbation determines the inflation scale $H_I = 10^{14}$ GeV.
- It has a significant implication on the axion CDM.
- In the conventional scenario, the axion CDM is ruled out due to isocurvature perturvations if PQ symmetry is broken during inflation. If PQ symmetry is broken after inflation, required is $F_a \sim 3x10^{10}$ GeV ($m_a \sim$ meV) with $N_{DW}=1$.
- However, the axion scale can be time-dependent as is generic in supersymmetric models.
- In this case, the axion CDM is consistent with PQ symmetry breaking during inflation (allowing $N_{DW} > 1$) for $F_a \sim 10^{12}$ GeV and $F_I \sim M_P$.