The Instanton Interference Effect: axion models without domain wall problem

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Outline

1) Topological defects: monopoles, strings and walls

2) The Domain Wall problem

3) The QCD axion case

4) The instanton interference effect (IIE)

FORMATION OF TOPOLOGICAL DEFECTS [See: Vilenkin, Phys.Rept. 121 (1985) 263-315]

- Cooling of the Universe ⟶ different phase transitions.

$$G \to H \to \cdots \to SU(3) \times SU(2) \times U(1) \to SU(3) \times U(1)_{em}$$

- Spontaneous breaking of symmetries leads to the formation of topological defects. **[Kibble mechanism]**

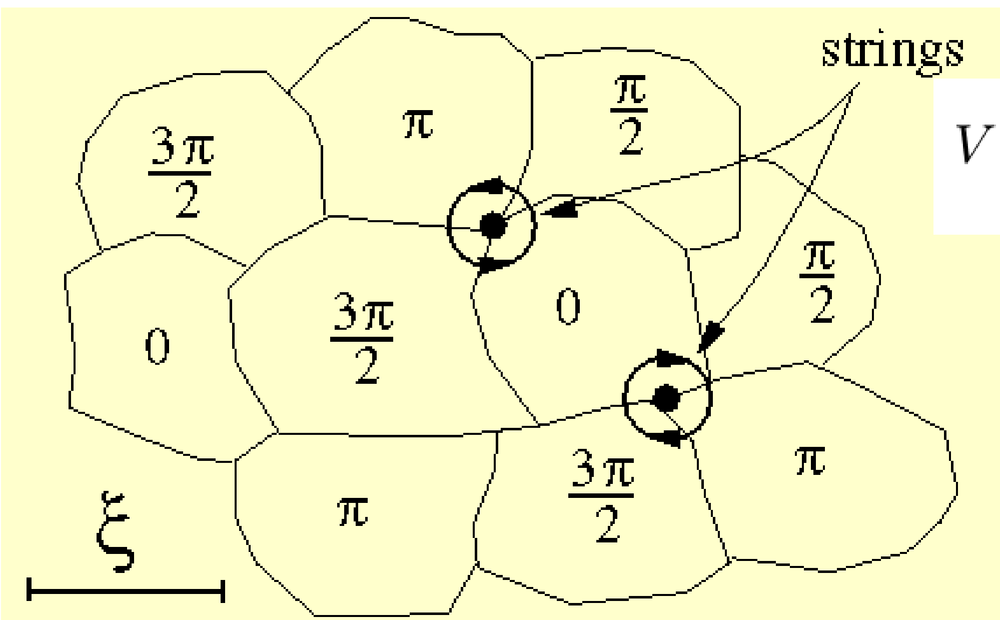
- Different topological defects: monopoles, strings, domain walls. Also hybrid configurations: walls bounded by strings, monopoles connected by strings…

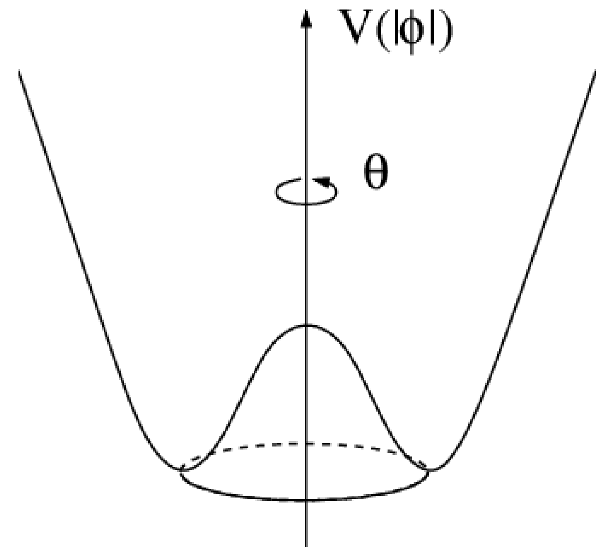
- Monopoles and domain walls lead to cosmological catastrophe.

COSMIC STRINGS (tubes of false vacuum)

- U(1) symmetric potential $V = \frac{\lambda}{2}\left(\phi^\dagger\phi - v^2\right)^2 \longrightarrow \langle\phi\rangle = e^{i\theta}v$
- The phase θ is not defined at $\langle\phi\rangle = 0$

$$V(0) = \frac{\lambda}{2}v^4$$

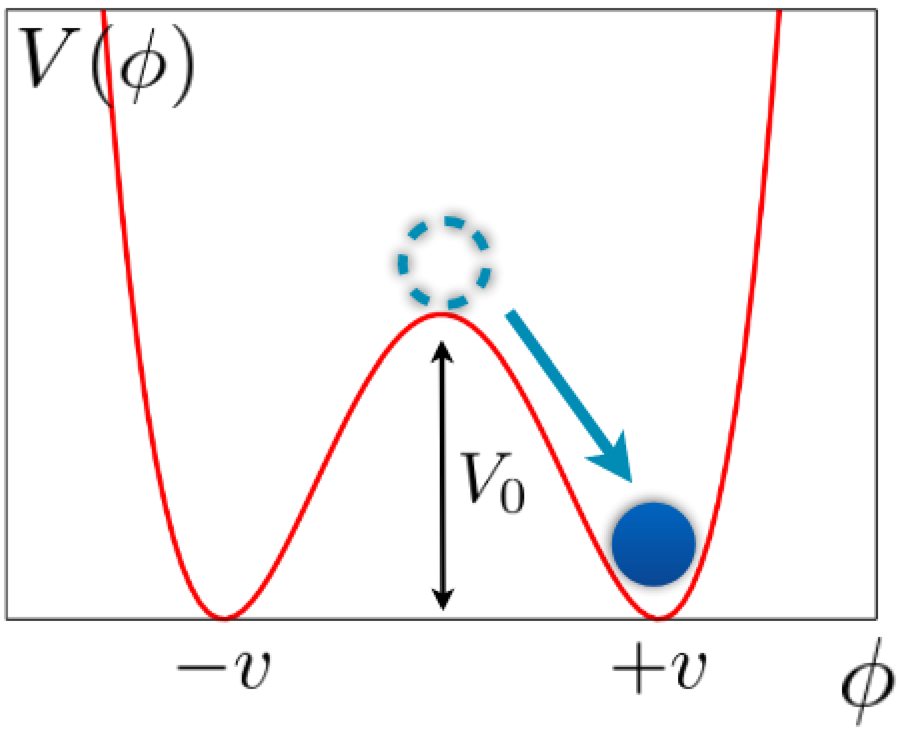


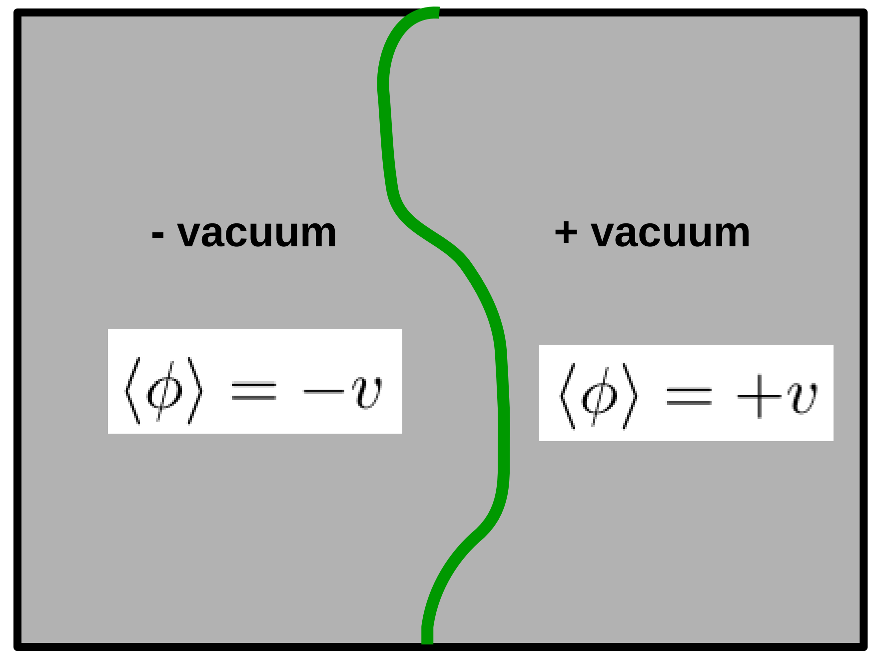


Unlike DW, cosmic strings **NEVER dominate the Universe**.
They are cosmologically safe. [Vilenkin, '85]

DOMAIN WALLS

Scalar field: $V = \frac{\lambda}{2}\left(\phi^2 - v^2\right)^2$ ← Z_2 symmetric





Real space

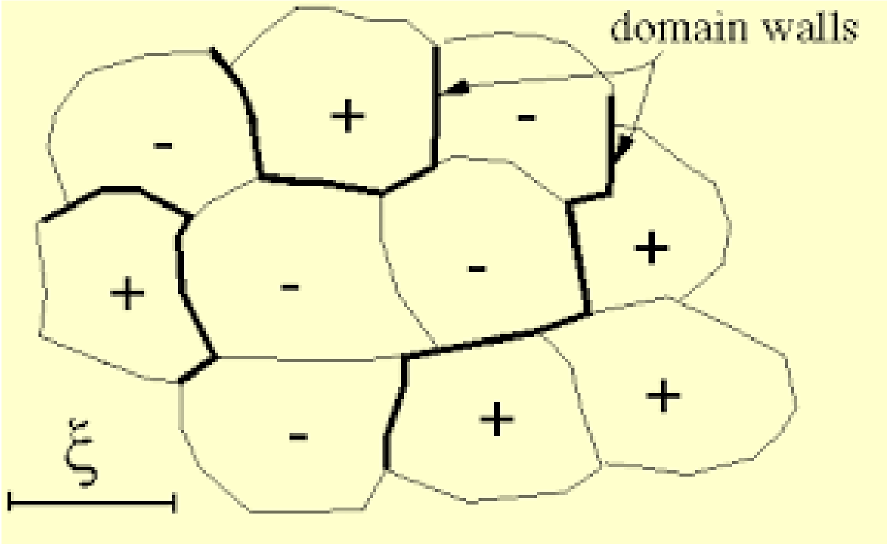
Width of the wall: $\delta \sim m_\phi^{-1} \sim 1/(\sqrt{\lambda}v)$

Surface tension: $\sigma \sim \delta V(0) = \sqrt{\lambda}v^3$

THE DOMAIN WALL PROBLEM

- Average: one DW per Hubble volume.
- Energy density:

$$\rho_{DW} \propto a^{-2}$$



- Evolve **SLOWER** than radiation or matter:

$$\rho_{rad} \propto a^{-4} \qquad \rho_{matter} \propto a^{-3}$$

- **Tend to dominate the energy density of the Universe:**

DOMAIN WALL PROBLEM

THE QCD AXION AND TOPOLOGICAL DEFECTS

THE STRONG CP PROBLEM

$$\Delta\mathcal{L}_{QCD} = \theta \frac{g^2}{32\pi^2} G^{\mu\nu}\tilde{G}_{\mu\nu} \qquad \theta \in [0, 2\pi[$$

- Generates a non-zero neutron EDM (electric dipole moment):

$$d_n \approx \theta \frac{e\, m_q}{M_n^2} \leq 10^{-26}\, e\, cm$$

$$\theta \rightarrow \bar{\theta} = \theta + Arg[\det M_q] \leq 10^{-11}$$

PURELY QCD

PURELY EW

STRONG CP PROBLEM:
WHY IS THIS COMBINATION SO SMALL???

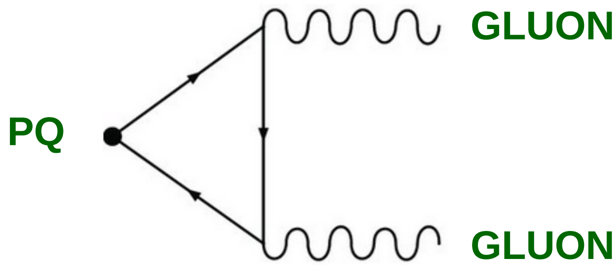
THE AXION SOLUTION

(Peccei, Quinn, '77 ; Wilczek '78 ; Weinberg '78)

- Introduce a (spontaneously broken) chiral U(1) symmetry

Nambu-Goldstone field: **the axion** $$a(x) \to a(x) + \alpha\, f_{PQ}$$

- QCD anomaly induces an effective coupling to gluons



$$\Delta\mathcal{L}_{QCD} = (\theta + \frac{a(x)}{f_{PQ}})\frac{g^2}{32\pi^2}G^{\mu\nu}\tilde{G}_{\mu\nu}$$

Shift $a(x) \to a(x) - \bar{\theta}$

$$\Delta\mathcal{L}_{QCD} = \frac{a(x)}{f_{PQ}}\frac{g^2}{32\pi^2}G^{\mu\nu}\tilde{G}_{\mu\nu}$$

- Non-perturbative effects induce a potential for the axion

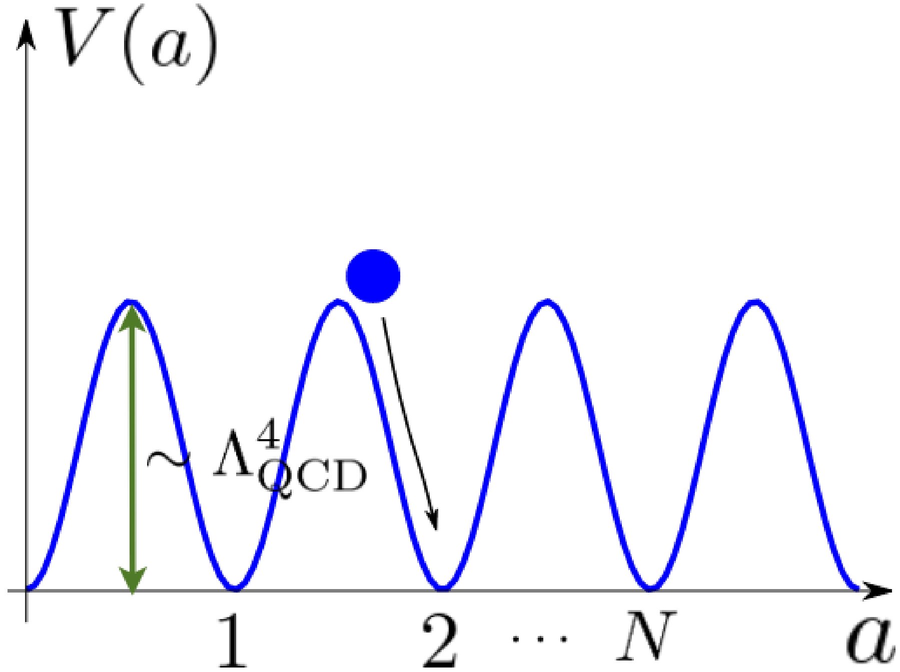
THE AXION POTENTIAL

- Axion potential (from QCD instantons):

$$N = \sum_R q_R t_R$$

$$V_{QCD}(a) = -m_\pi^2 f_\pi^2 \frac{\sqrt{m_u^2 + m_d^2 + 2 m_u m_d \cos\left(N \frac{a}{f_a}\right)}}{(m_u + m_d)}$$

$$\frac{\langle a \rangle}{f_a} = 0 + \frac{2\pi k}{N}$$

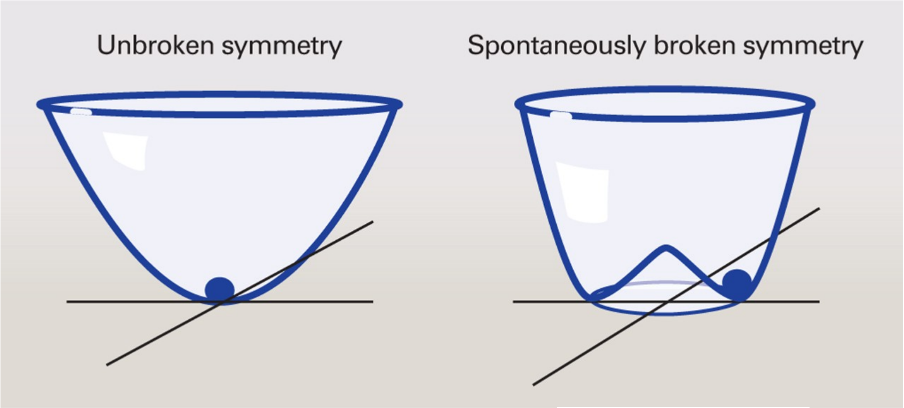


N degenerate (CP conserving) minima

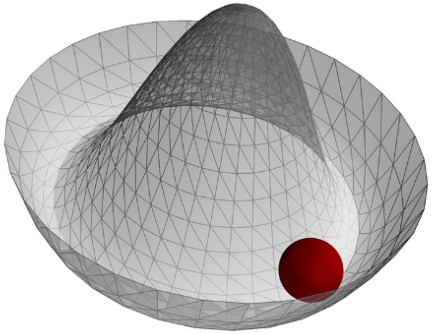
QCD AXION SUFFERS FROM DOMAIN WALL PROBLEM

COSMOLOGICAL HISTORY OF THE AXION

- As the Universe cools down there are two different phase transitions:



Explicit breaking by QCD instantons



$T \geq f_a$ $\qquad$ $T \leq f_a$ $\qquad$ $T \sim \Lambda_{QCD} \ll f_a$

Cosmic Temperature

- T dependence of axion mass

$$m_a^2(T) \approx m_a^2(1\,GeV)\left(\frac{GeV}{T}\right)^8$$

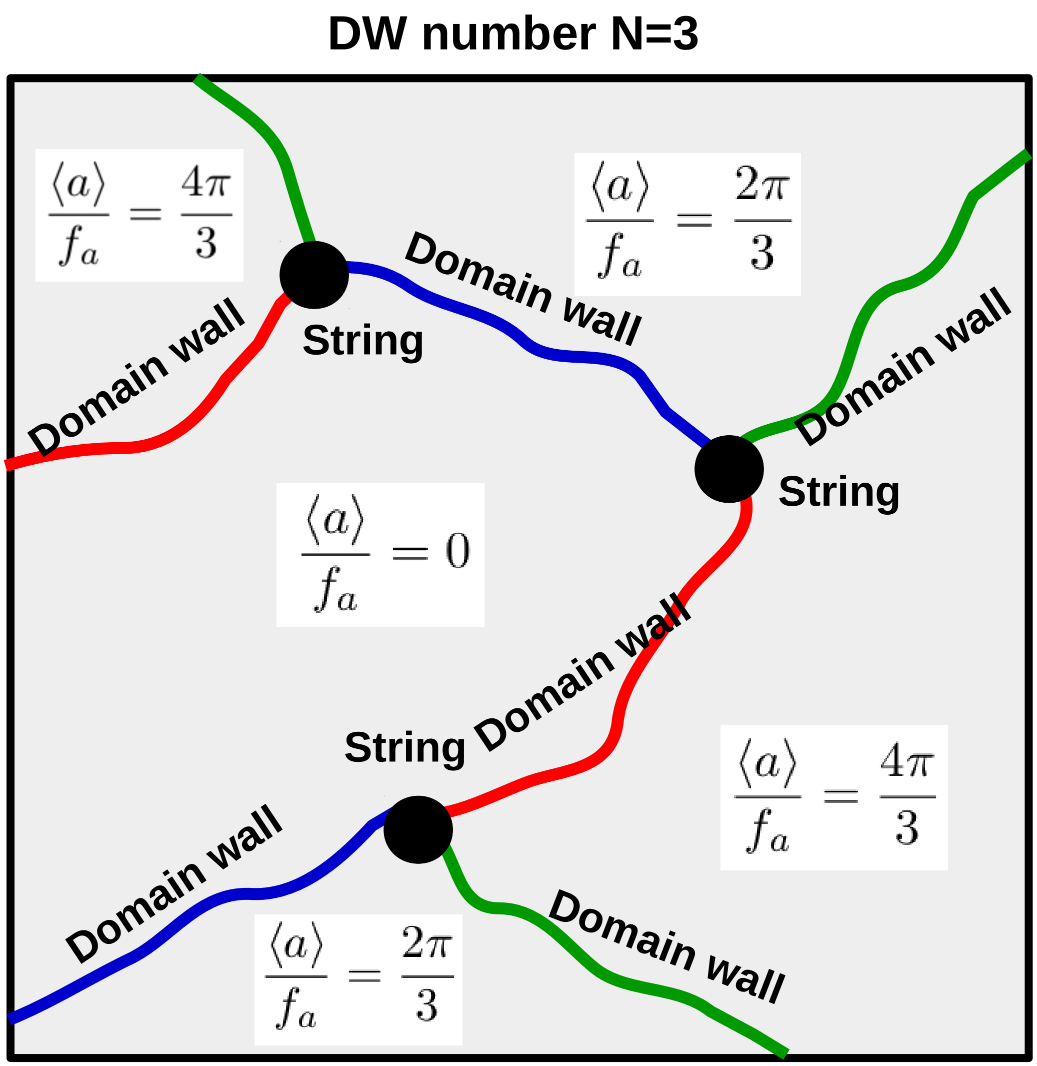
THE QCD AXION CASE

- Two different phase transitions

  1) At $T \sim \langle \phi \rangle = f_a$ strings form.

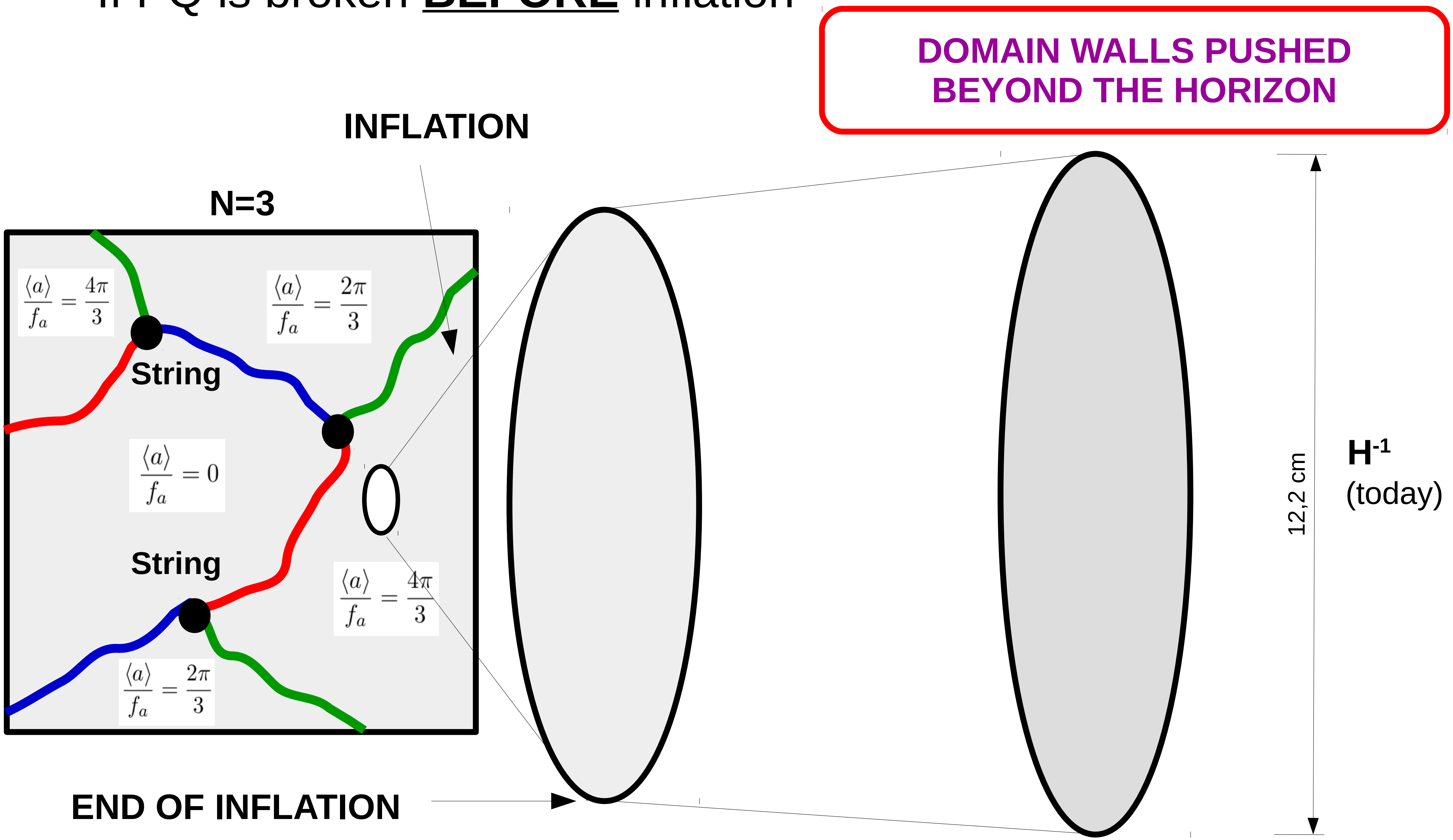
  2) At $T \sim \Lambda_{QCD}$ the domain walls form.

- **Strings form the boundaries of the walls.**



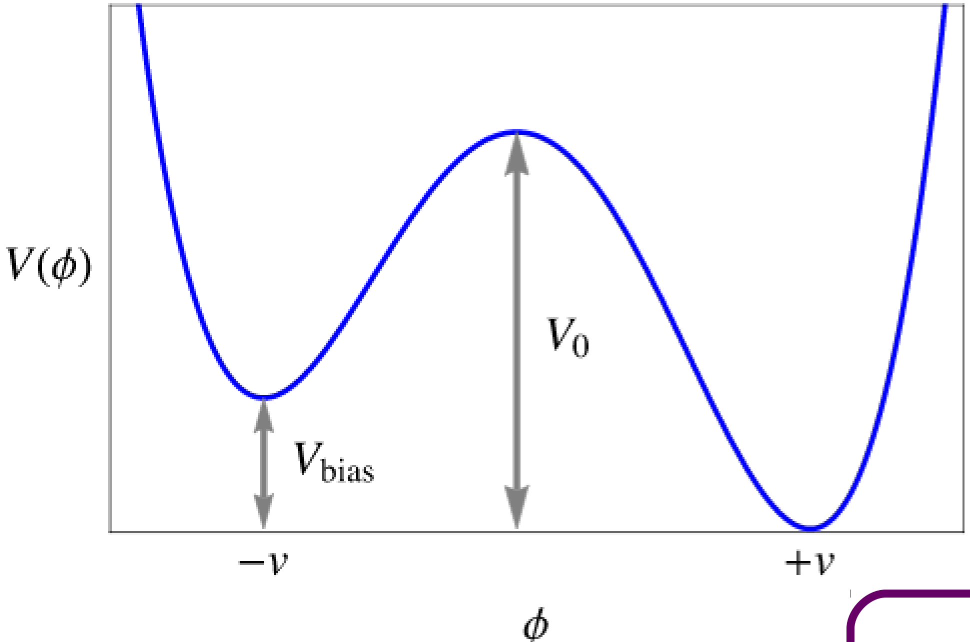
SOLUTIONS (I): COSMIC INFLATION

- If PQ is broken **BEFORE** inflation



SOLUTIONS (II): POST-INFLATION
The bias term solution

- Explicit PQ breaking removes physical degeneracy of the vacua:



$$\Delta\mathcal{L} = \frac{c}{M_P^{N-4}}\phi^N\,, \;\; N = 9, 10$$

$$\theta_{eff} \sim c\left(\frac{f_a}{M_P}\right)^N\left(\frac{M_P}{\Lambda_{QCD}}\right)^4 \leq 10^{-11}$$

- DW are unstable and decay.

- **Can spoil PQ solution to strong CP problem if N is small.**

SOLUTIONS (III): POST-INFLATION SCENARIO

- Instantons from a new confining interaction remove degeneracy of the vacua: **INSTANTON INTERFERENCE EFFECT (IIE)**

$$G \times U(1)_{PQ} \times SM$$

- G and QCD instantons break explicitly PQ symmetry:

$$[SU(3)_C]^2 \times U(1)_{PQ} \xrightarrow{\text{Explicit breaking}} Z_{N_{QCD}}$$

$$[G_{HC}]^2 \times U(1)_{PQ} \xrightarrow{\text{Explicit breaking}} Z_{N_{HC}}$$

ONLY COMMON SUBGROUP SURVIVES

Example:

$N_{HC} = 1$ and $N_{QCD} = 3$

No comon subgroup:
SOLVES DOMAIN WALL PROBLEM

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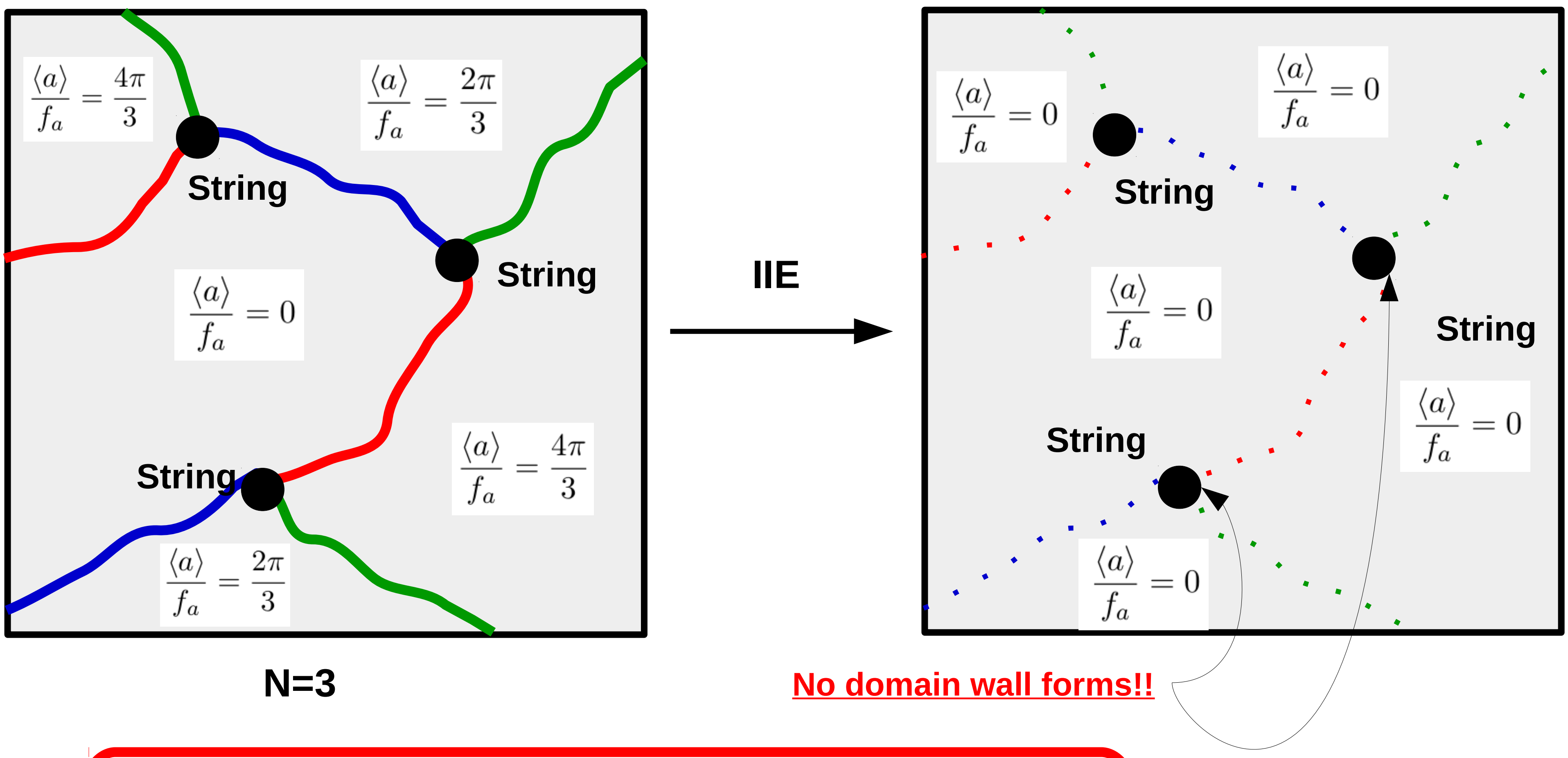
See also:
Barr & Kim, 1407.4311

Cosmological picture of Instanton Interference Effect (IIE)



IIE forces the vacuum to be the same everywhere:
<u>NO DOMAIN WALL PROBLEM!!</u>

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See also:
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IIE: solving the heavy relic problem

- New confining interactions usually bring associated stable bound-states.

$$G \times U(1)_{PQ} \times SM$$

- **SU(N) interaction**: U(1) symmetry protects baryon-like state composed by N fermions (in the fundamental N representation).

- **SO(N) interaction**: Z_2 symmetry can protect the lightest bound state.

- If stable, heavy bound states can overclose the Universe:

Upper bound confinement scale: $$\Lambda_{HC} \leq 240 \text{ TeV}$$ **[Griest, Kamionkowski; '90]**

IIE: solving the heavy relic problem

- New confining interaction:

$$G = SO(10)_{HC} \rightarrow \langle\psi\psi\rangle \sim \Lambda_{HC}^3 \rightarrow \Lambda_{HC} \equiv f_a \gg v_{EW}$$

PQ SSB SCALE

AXION NATURALLY INVISIBLE

- If fermions reside in spinor 16 representation, only bound states with even number of spinors.

$$SO(10) \rightarrow SO(9)$$
$$16 \rightarrow 16\,.$$
$$\rightarrow (16 \times 16)^k = 1 + \ldots$$

BOUND STATES ARE ALWAYS Z_2 SINGLETS!

- Lightest bound state: η'_{HC}, decay through the anomaly

$$\propto \eta'_{HC} F\tilde{F}$$

CONCLUSIONS

- The PQ mechanism: attractive solution of the strong CP problem giving QCD axion DM for free.
- QCD axion models (may) suffer from domain walls.
- If PQ is broken AFTER inflation: DW problem is theoretically challenging.
- IIE is a compelling post-inflation solution to DW problem.

Back-up slides

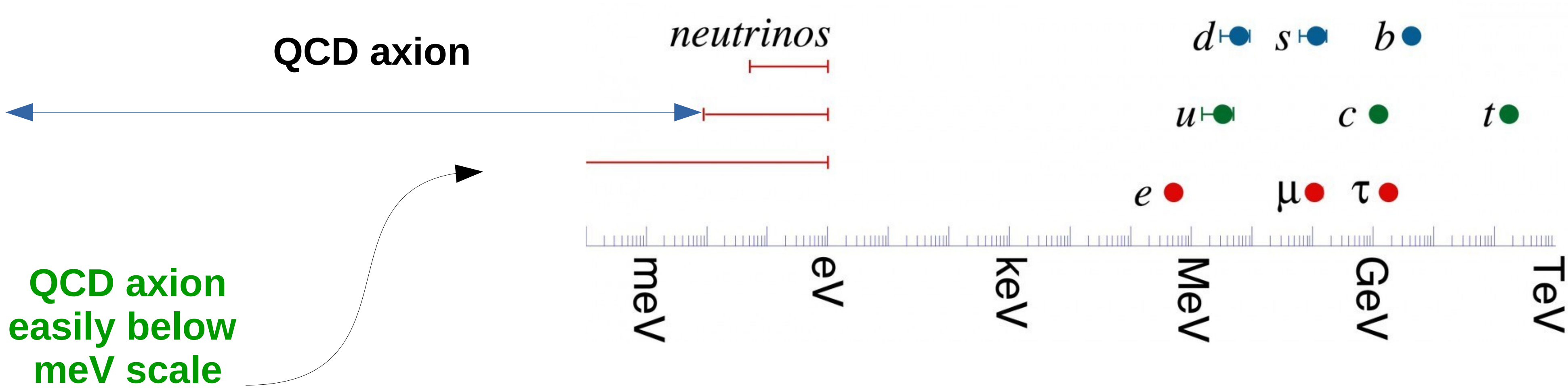
AXION PROPERTIES: THE AXION MASS

- Taking derivatives of the previous potential:

$$m_a^2 = \frac{d^2}{da^2} V_{QCD}(a) = \frac{m_\pi^2 f_\pi^2}{f_a^2} \frac{m_u m_d}{(m_u + m_d)^2}$$

$$m_a = 5.70(7)\mu\text{eV} \left(\frac{10^{12}\,\text{GeV}}{f_a} \right)$$

- Completely new scale:



THE ORIGINAL: THE PQWW AXION

Related to the $U(1)_A$ problem!

- In the early days pq was associated to $U(1)_A$

(Peccei, Quinn, '77 ; Wilczek '78 ; Weinberg '78)

$$\mathfrak{L}_{\text{int}} = g_1 (\overline{ud})_L \varphi_1 u_R + g_2 (\overline{ud})_L \tilde{\varphi}_2 d_R + \\ + \mathrm{H.c.} + V(\varphi_1, \varphi_2)$$

- Axion with mass around 25 KeV and coupling proportional to $1/v_{EW}$.

$$m_a \sim \frac{f_\pi m_\pi}{v_{EW}} \sim 25\, KeV$$

- Original axion models where soon ruled out from the non-observation of the decay

$$K^+ \to \pi^+ + a$$

INVISIBLE AXION: DFSZ & KSVZ

- Original axion models with f_a at EW scale ruled out soon.

H^u , H^d
quarks carry PQ

Exotic quarks with PQ
SM quarks don't carry PQ

- Invisible axion models **DFSZ** & **KSVZ**: PQ broken by SM singlet condensate

(Dine, Fischler, Sredniki, '81; Zhitnitsky, '80 / Kim, '79; Shifman, Vainshtein, Zakharov, '80)

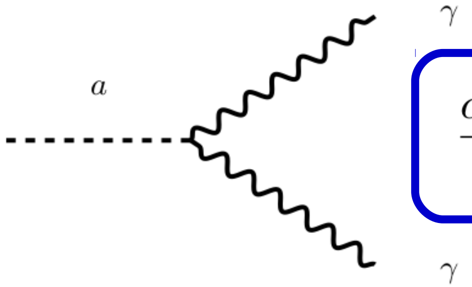
- Invisible axion is a **good DM candidate**

(Preskill, Wise, Wilczek; Abott, Sikivie; Dine, Fischler, '81)

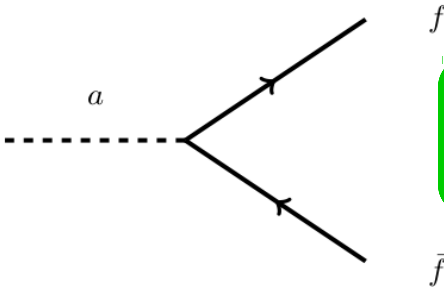
Note: Goldstone boson coupling strength is inversely proportional to the SSB scale!

AXION COUPLINGS TO MATTER (DFSZ case)

- Quarks carry PQ. We need two higgs doublets: H_u and H_d.



$$\frac{\alpha_{EM}}{8\pi}\frac{(E/N-1.92(4))}{f_a/N}F_{\mu\nu}\tilde{F^{\mu\nu}}$$



$$\frac{m_e}{f_a}a\bar{e}i\gamma_5 e$$

- Helioscopes and haloscopes to constrain axion-photon coupling.

- Strong constraints from stellar cooling

(Raffelt, '06)

$$f_a \geq 4\times 10^9\ \text{GeV}$$

COHERENT OSCILLATIONS: AXION DARK MATTER

(Preskill, Wise, Wilczek; Abott, Sikivie; Dine, Fischler, '81)

- Evolution of the axion field:

$$\ddot{a} + 3H\dot{a} + \frac{\partial V(a)}{\partial a} = 0$$

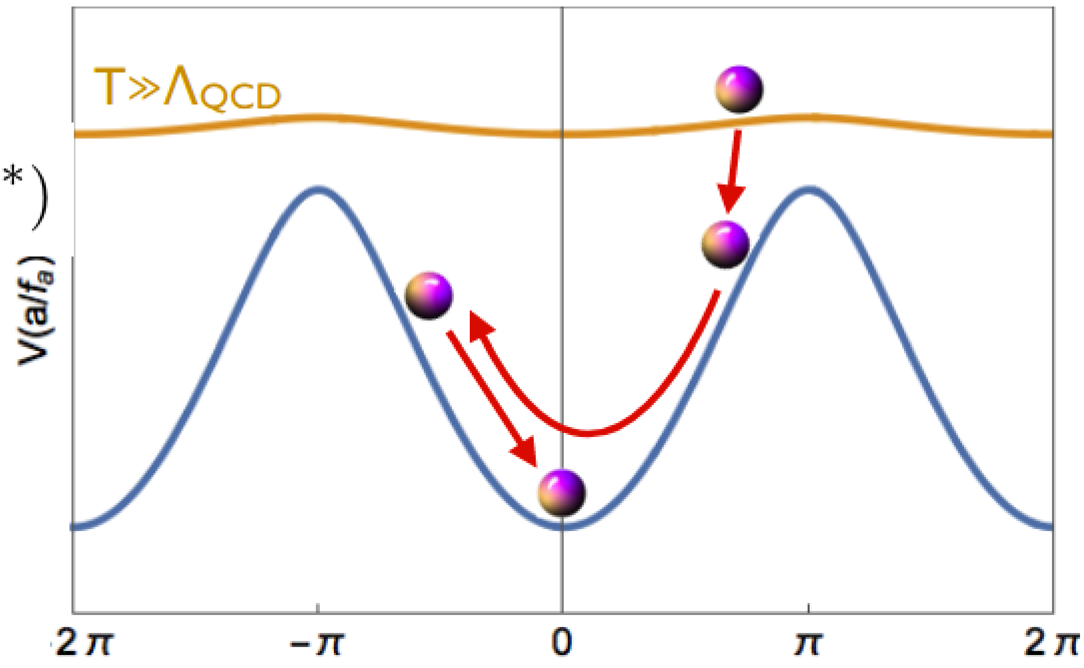
- At the time $3H(T^*) = m_a(T^*)$ the axion starts oscillating. Behaves as cold DM:

$$w_a = p_a/\rho_a \approx 0$$

- Energy density of axions:

$$\Omega_a h^2 \sim 0.01\theta_i^2 \left(\frac{f_a}{10^{11}GeV}\right)^{1.19}$$

- If axions are 100% DM: $f_a \sim 10^{12}\, GeV$



[Figure: Grilli di Cortona, 16']

Turning off the potential V_{HC}

$$V(a) = V_{QCD}(a) + V_{HC}(a)$$
$$\sim \Lambda^4_{QCD}\left(1 - \cos\left(\theta_{QCD} - \frac{a}{f_a}\right)\right) + \Lambda^4_{HC}\left(1 - \cos\left(\theta_{HC} - \frac{a}{f_a}\right)\right)$$

- V_{HC} might spoil the PQ solution:

(Barr & Kim, '14)

$$\frac{\langle a \rangle}{f_a} = \theta_{HC} \rightarrow \boxed{\bar{\theta}_{phys} = \theta_{QCD} - \theta_{HC}}$$

- Need a massless fermion in the HC sector:

$$\mathcal{L}_{HC} = y_1 \bar{\psi}_1{}^c H_1^\dagger \psi_1 + y_2 \bar{\psi}_2{}^c H_2^\dagger \psi_2 \longrightarrow \langle H_2 \rangle = 0\ ,\ \ T \leq T_c$$

Inverted phase transition

TOPOLOGICAL SUSCEPTIBILITY VANISHES WITH MASSLESS FERMION AND THE POTENTIAL FROM HC INSTANTONS BECOMES FLAT: PQ MECHANISM OPERATES AND SOLVES STRONG CP PROBLEM