

Lecture 3

Axions &

ALPs

1. CP-Violation in QCD

• QCD Lagrangian

$$\mathcal{L} \sim \sum_q \bar{q} (i \not{D} - m_q e^{i\theta_1 \gamma_5}) q + \frac{1}{4} G_{\mu\nu}^2 + \theta \frac{g_s^2}{32\pi^2} G_{\mu\nu}^2$$

$\sim \bar{q} \gamma_5 \gamma_\mu \gamma_\nu \gamma_\rho \gamma_\sigma q$
↓
 $\sim G_{\mu\nu}^2$

• use chiral rotation $q \rightarrow q e^{i\alpha \gamma_5}$
we shift

$$\theta_1 \rightarrow \theta_1 - \alpha \quad \theta \rightarrow \theta + \alpha$$

• CPV encoded in $\bar{\theta} = \theta + \arg \det(m_q)$

• is Θ physical?

- if $m_g = 0$ then Θ_g is unphysical

- in QED $\vec{F}\vec{F}$

$$S \sim \int d^4x \vec{F}\vec{F} = \int d^4x \vec{E}\vec{B} = \int d^4x \vec{\nabla}\phi\vec{B}$$

$$\approx \int d^4x [\nabla(\phi\vec{B}) - \cancel{\phi\vec{\nabla}\vec{B}}] = \int d^4x \nabla(\phi\vec{B})$$

$$\approx \int_S \cancel{\vec{d}x} \phi\vec{B} = 0$$

$$S = \int d^4x \sqrt{-g} \approx \int d^4x \partial_\mu \chi^\mu = \frac{g s^2}{32\pi} N$$

- effect on vacuum energy:

$$V \sim \Lambda^4 (1 - \cos \theta)$$

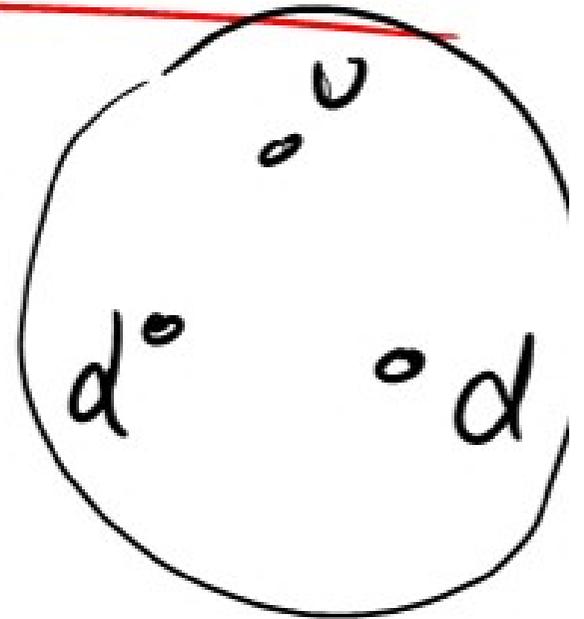
See Surjeet Rajendran's ICTP 2015
summer school for intuitive
derivation

② Strong CP Problem and Neutron EDM

• naive neutron EDM

size $\sim f_{\pi} \sim 10^{-13}$ cm, q_{ne}

$$\rightarrow d_n \sim 10^{-13} \text{ cm} \cdot e$$



• precise prediction

$$\rightarrow d_n \sim 5 \cdot 10^{-16} \text{ e} \cdot \text{cm} \times \bar{\theta}$$

• measurement

$$d_n < 3 \cdot 10^{-26} \text{ cm} \cdot e$$

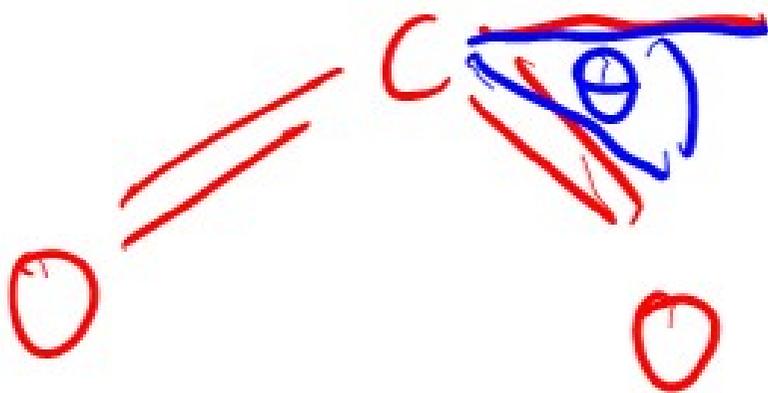
$$\Rightarrow \bar{\theta} \leq 10^{-10}$$

"Strong CP Problem"



- anthropic argument doesn't work
- massless quarks disfavored
- dynamical solution

$$0 = C = 0$$



θ is variable
ground state at
 $\theta = 0$

→ same idea for QCD
 $\bar{\theta} \rightarrow \bar{\theta} + \frac{a}{f_a} \leftarrow \text{QCD axion}$
 $f_a \leftarrow \text{axion scale}$

$$\mathcal{L} \sim -\frac{g^2}{32\pi^2} \left(\bar{\theta} + \frac{a}{f_a} \right) \text{G} \tilde{\text{G}}$$

$$V \sim \Lambda_{\text{QCD}}^4 \left(1 - \cos \left(\bar{\theta} + \frac{a}{f_a} \right) \right)$$

$$d_n = 0$$

← minimum at $a = -\bar{\theta} f_a$

③ Axions Models

° Idea: make $U(1)_A$ good symmetry?
→ $U(1)_{PQ}$

$\mathcal{L} \sim \Phi \bar{Q}_R Q_L$ the invariant
under $\Phi \rightarrow e^{i\alpha} \Phi$ $Q \rightarrow e^{i\alpha/2} Q$

if Φ has a vacuum exp. value

$$\Phi \rightarrow \frac{f_a}{\sqrt{2}} e^{i \frac{Q}{f_a}}$$

rotation of quark $Q \rightarrow Q e^{i\frac{\alpha}{2f_a} \gamma_5}$

$$\mathcal{L} \sim \frac{f_a}{R} \bar{Q}_L Q_L + h.c. - \frac{g^2}{32\pi f_a} G_{\mu\nu}^2$$

$$+ i \frac{\partial_\mu \alpha}{2f_a} \bar{Q} \gamma^\mu \gamma_5 Q$$

- Can $\mathbb{D} = H_{SM}?$ → No X
- PQWW → h_1 and h_2 X
- DSFE \hookrightarrow LSVE

④ ALB

1. assume global symmetry $U(1)_P Q$
at scale f_a

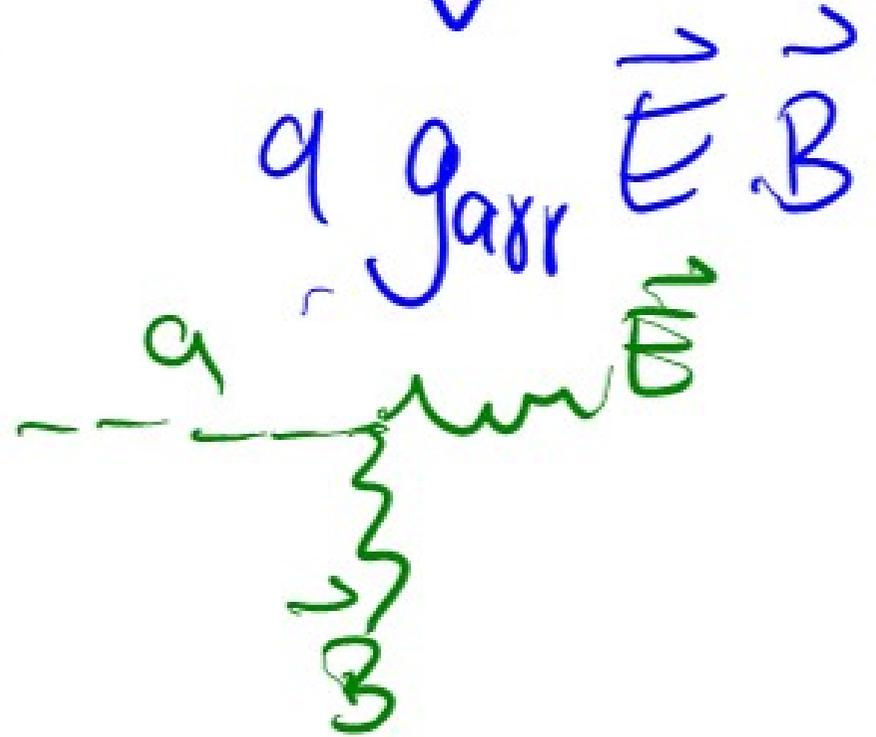
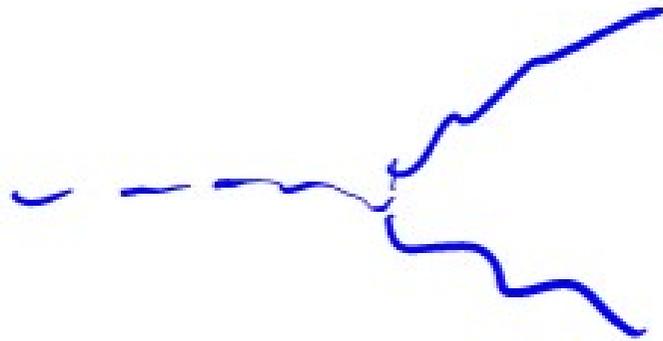
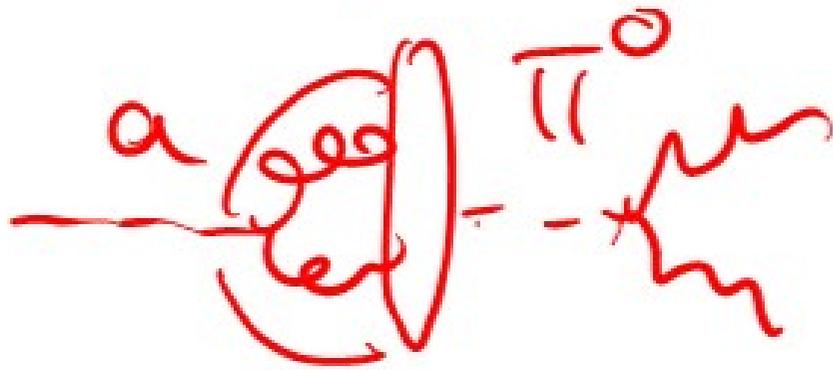
2. Symmetry is broken: goldstone boson

→ weakly broken → light boson

ALP

⑤ ACP Parameterspace

$$a \quad L_2 \quad \frac{a}{f_a} \quad G \quad S_2$$

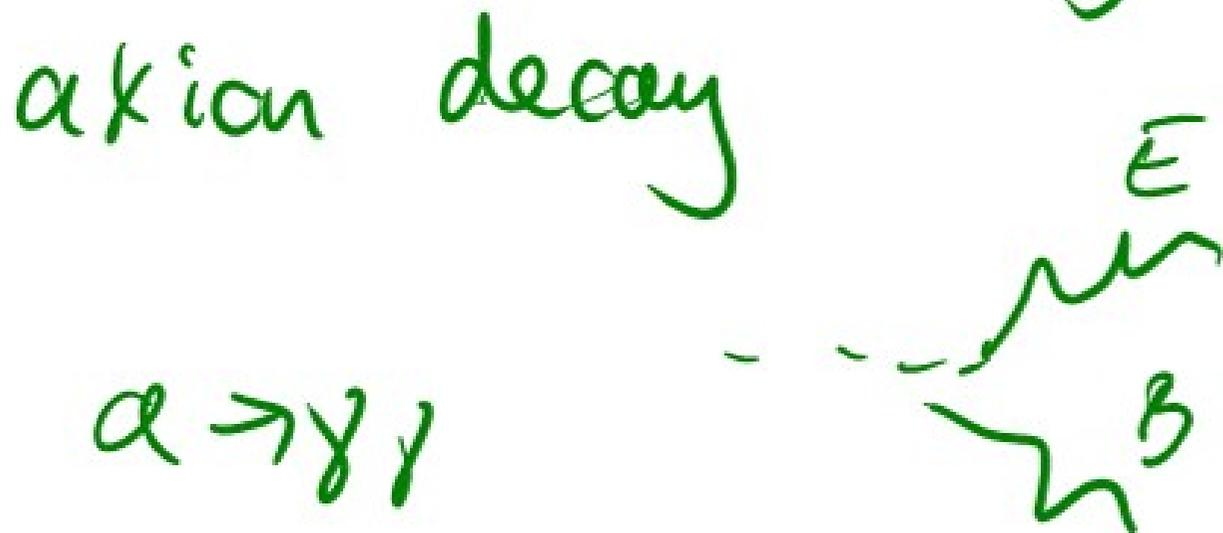




$$E + \gamma \rightarrow a$$



$$a + B \rightarrow E$$



$$\Gamma \sim \frac{m_a^3}{f_a^2}$$

QCD axion: $m_a f_a = m_\pi \cdot f_\pi \sim 100^2$

