Axions

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Overview

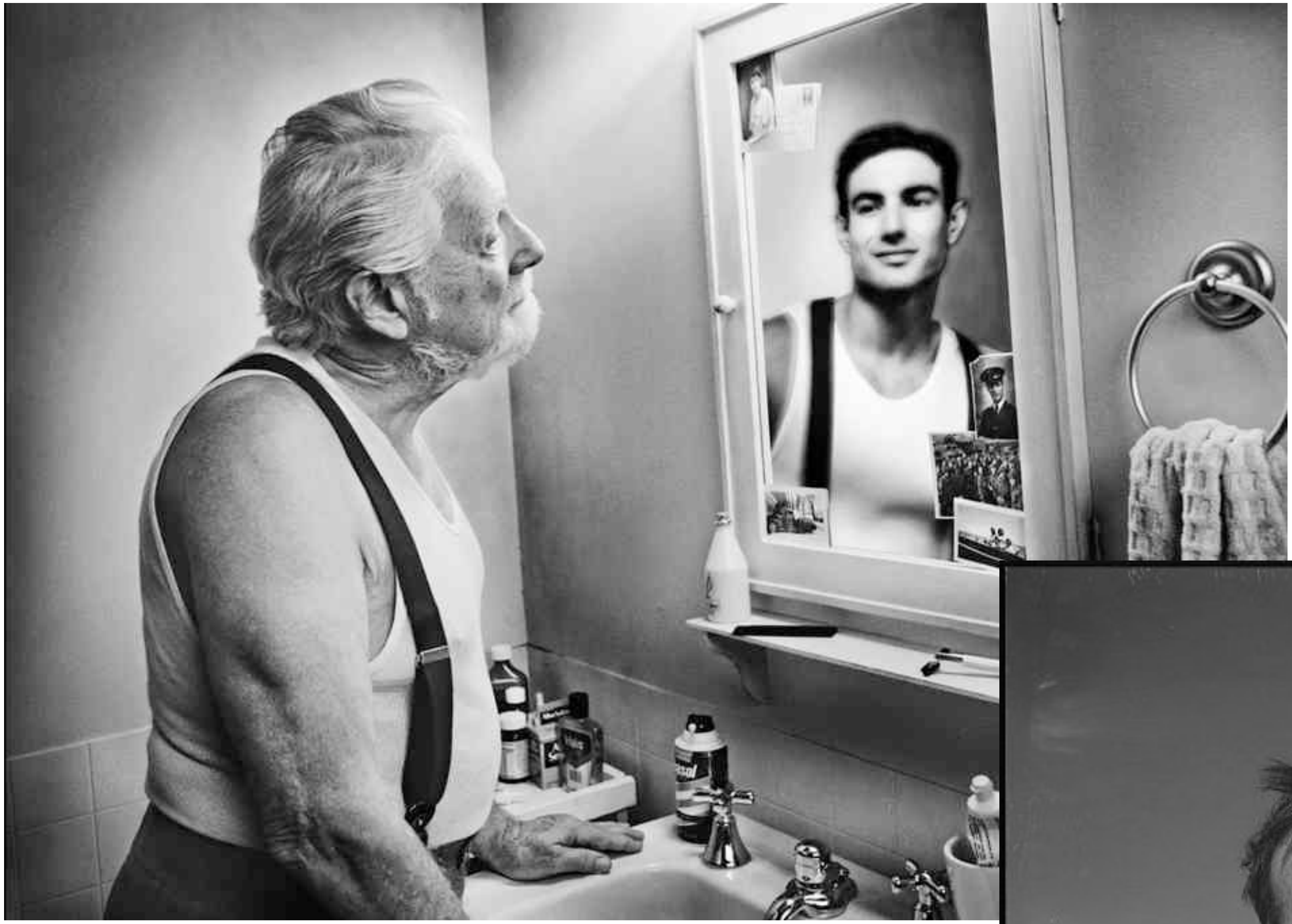
- Strong CP problem

- Axions

- Axion Dark matter

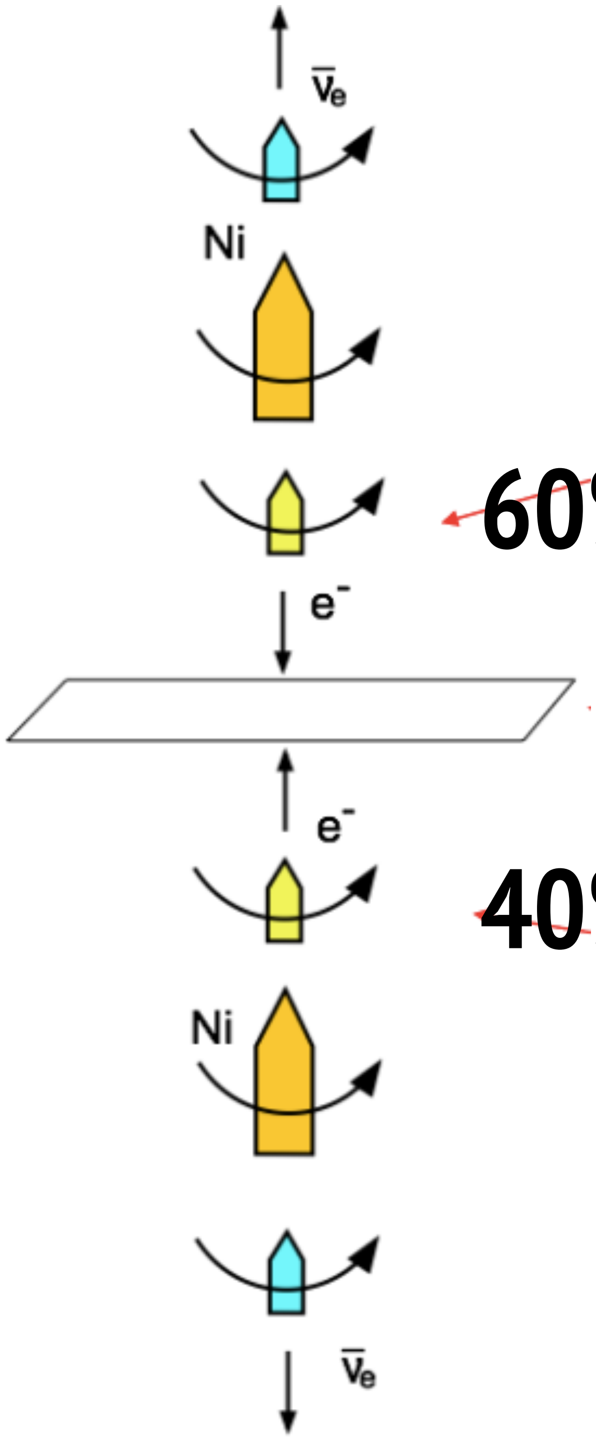
- Searching for axions in the sky in the lab

Parity and Time reversal



in particle physics (electroweak interactions)

P-violation (Wu 56)

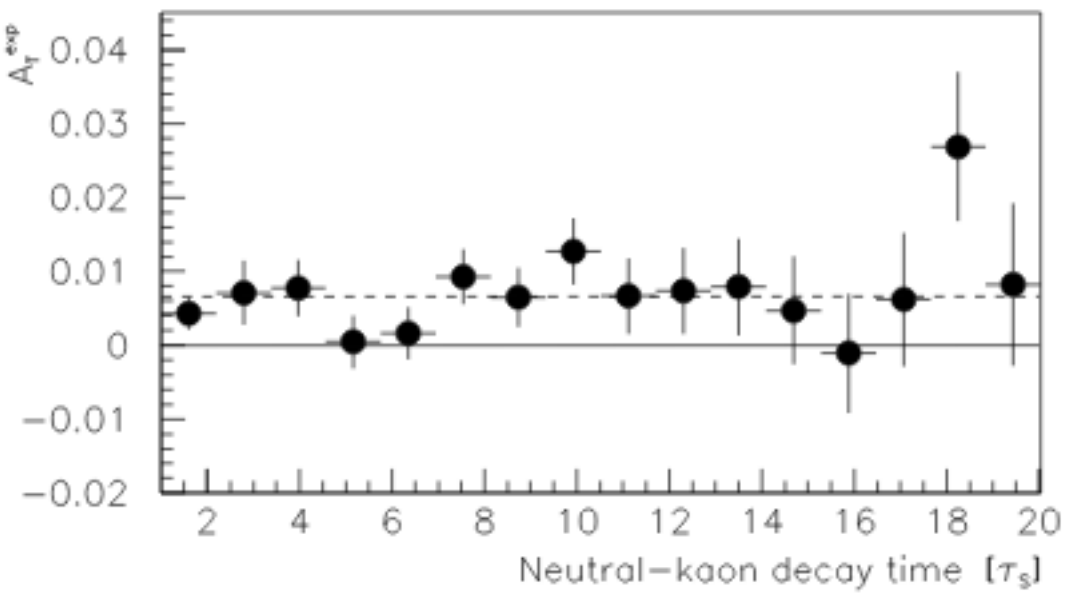


60%

40%

T-violation (CPLEAR 90's)

$$\frac{R(\bar{K}^0 \to K^0) - R(K^0 \to \bar{K}^0)}{R(\bar{K}^0 \to K^0) + R(K^0 \to \bar{K}^0)}$$

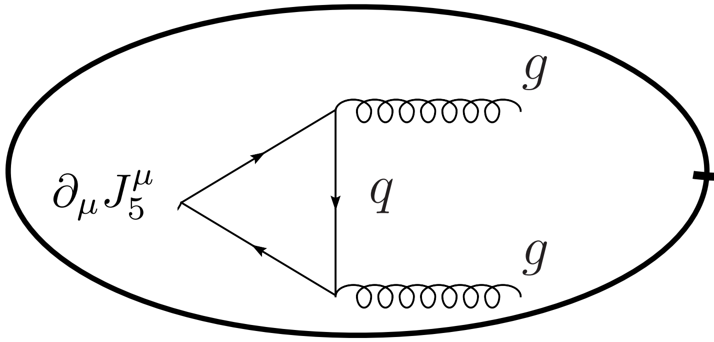


… but not in the strong interactions

The strong CP "issue"

- **CP violation in QCD sector: CKM angle** $\delta_{13} = 1.2 \pm 0.1\,\mathrm{rad}$ **AND flavour-neutral phase** $\theta = \theta_{\rm QCD} + N_f \delta$

$$\mathcal{L}_{\rm SM} \in -\bar{q}_L \begin{pmatrix} m_u e^{i\delta/2} & 0 & \dots \\ 0 & m_d e^{i\delta/2} & \dots \\ 0 & 0 & \dots \end{pmatrix} \begin{pmatrix} u \\ d \\ \dots \end{pmatrix}_R - \frac{\alpha_s}{8\pi} G\widetilde{G}\theta_{\rm QCD}$$



quark phase redefinition shifts between quark mass phase and QCD vacuum because of the axial anomaly

$$G\widetilde{G} = \sum_a \frac{1}{2}\epsilon^{\mu\nu\alpha\beta} G^a_{\mu\nu} G^a_{\alpha\beta}$$

Gluon field strength tensor $G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g_s \epsilon^{abc} A^b_\mu A^c_\nu$

can be also written as $$G\widetilde{G} = \sum_a (\epsilon^{0123} G^a_{01} G^a_{23} + \dots) \equiv \sum_a (-4\vec{E}^a \cdot \vec{B}^a)$$

transformation under parity $\mathrm{P}x \to -x$ **and time-reversal** $\mathrm{T}t \to -t$

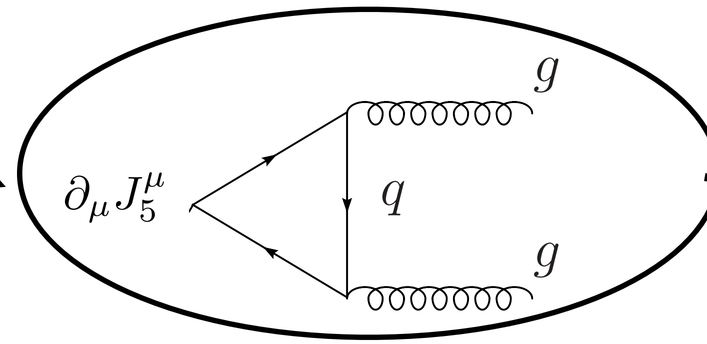
$$G\widetilde{G} \to \mathrm{P} \to -G\widetilde{G}$$
$$\partial_x \partial_y \partial_z \to (-1)^3 \partial_x \partial_y \partial_z$$

$$G\widetilde{G} \to \mathrm{T} \to -G\widetilde{G}$$
$$\partial_t \to -\partial_t$$

The strong CP "issue"

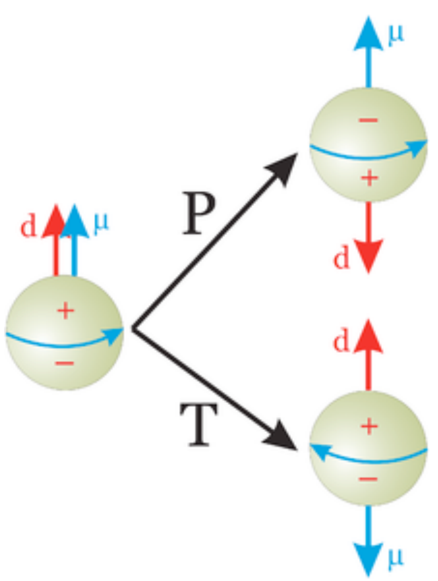
- **CP violation in QCD sector: CKM angle** $\delta_{13} = 1.2 \pm 0.1\,\mathrm{rad}$ **AND flavour-neutral phase** $\theta = \theta_{\mathrm{QCD}} + N_f \delta$

$$\mathcal{L}_{\mathrm{SM}} \in -\bar{q}_L \begin{pmatrix} m_u e^{i\delta/2} & 0 & \dots \\ 0 & m_d e^{i\delta/2} & \dots \\ 0 & 0 & \dots \end{pmatrix} \begin{pmatrix} u \\ d \\ \dots \end{pmatrix}_R - \frac{\alpha_s}{8\pi} G\widetilde{G}\theta_{\mathrm{QCD}}$$



quark phase redefinition shifts between quark mass phase and QCD vacuum because of the axial anomaly

- **The** θ**-angle produces flavour-neutral CP violation like Electric Dipole Moments ... never observed!**



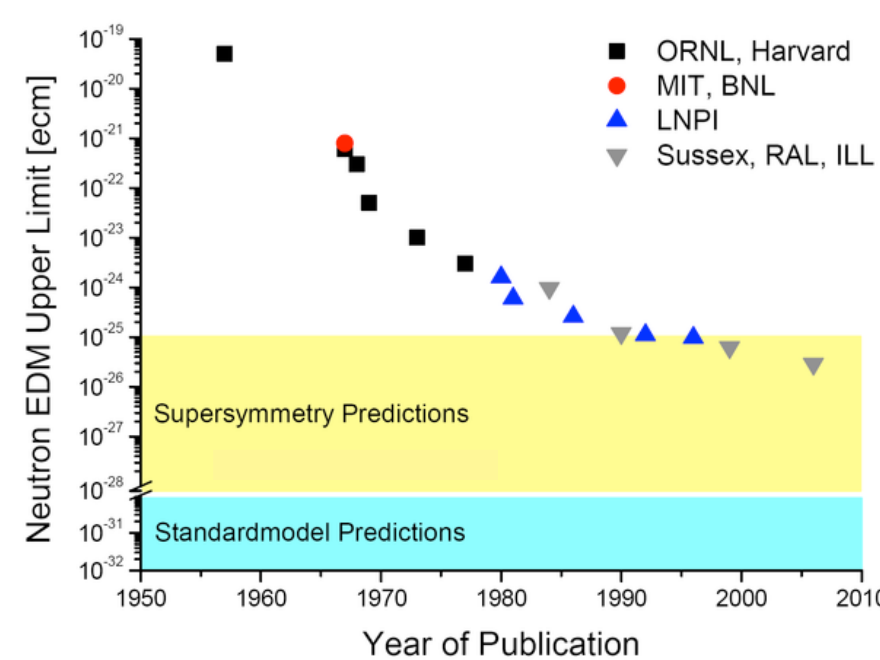
- **Neutron EDM** (Pospelov 9908508)

$$d_n = (2.4 \pm 1.0)\theta \times 10^{-3}\,\mathrm{e\,fm}$$

- **Experimental upper limit** (Grenoble hep-ex/0602020)

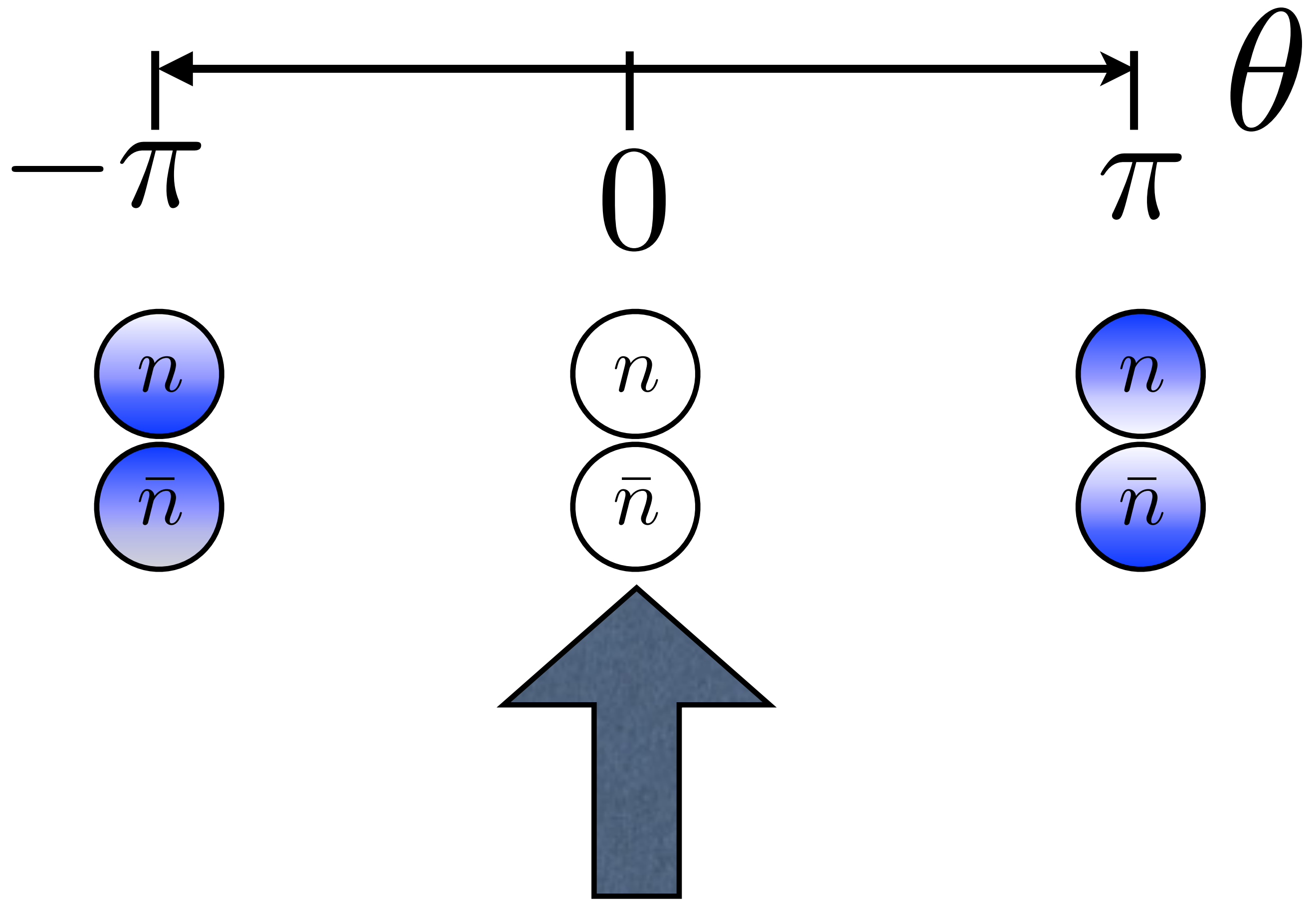
$$|d_n| < 3 \times 10^{-13}\,[\mathrm{e\,fm}]$$

- **Why is** $\theta < 10^{-10}$ **?**



The theta angle of the strong interactions

- The value of θ controls P,T violation in QCD



Measured today $|\theta| < 10^{-10}$ **(strong CP problem)**

Roberto Peccei and Helen Quinn 77

CP Conservation in the Presence of Pseudoparticles*

R. D. Peccei and Helen R. Quinn†
Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305
(Received 31 March 1977)

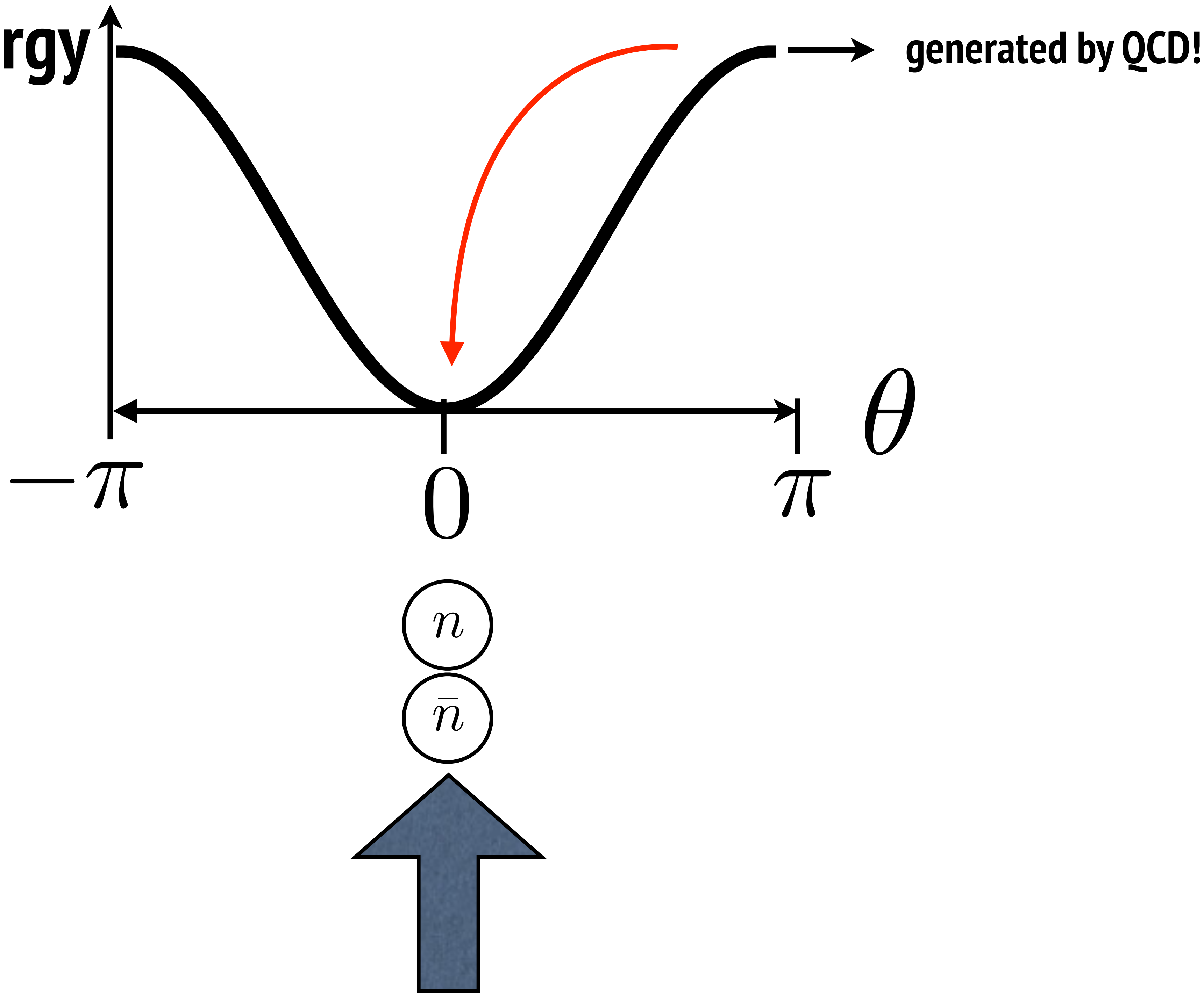
We give an explanation of the *CP* conservation of strong interactions which includes the effects of pseudoparticles. We find it is a natural result for any theory where at least one flavor of fermion acquires its mass through a Yukawa coupling to a scalar field which has nonvanishing vacuum expectation value.

It is experimentally obvious that we live in a

grangian.

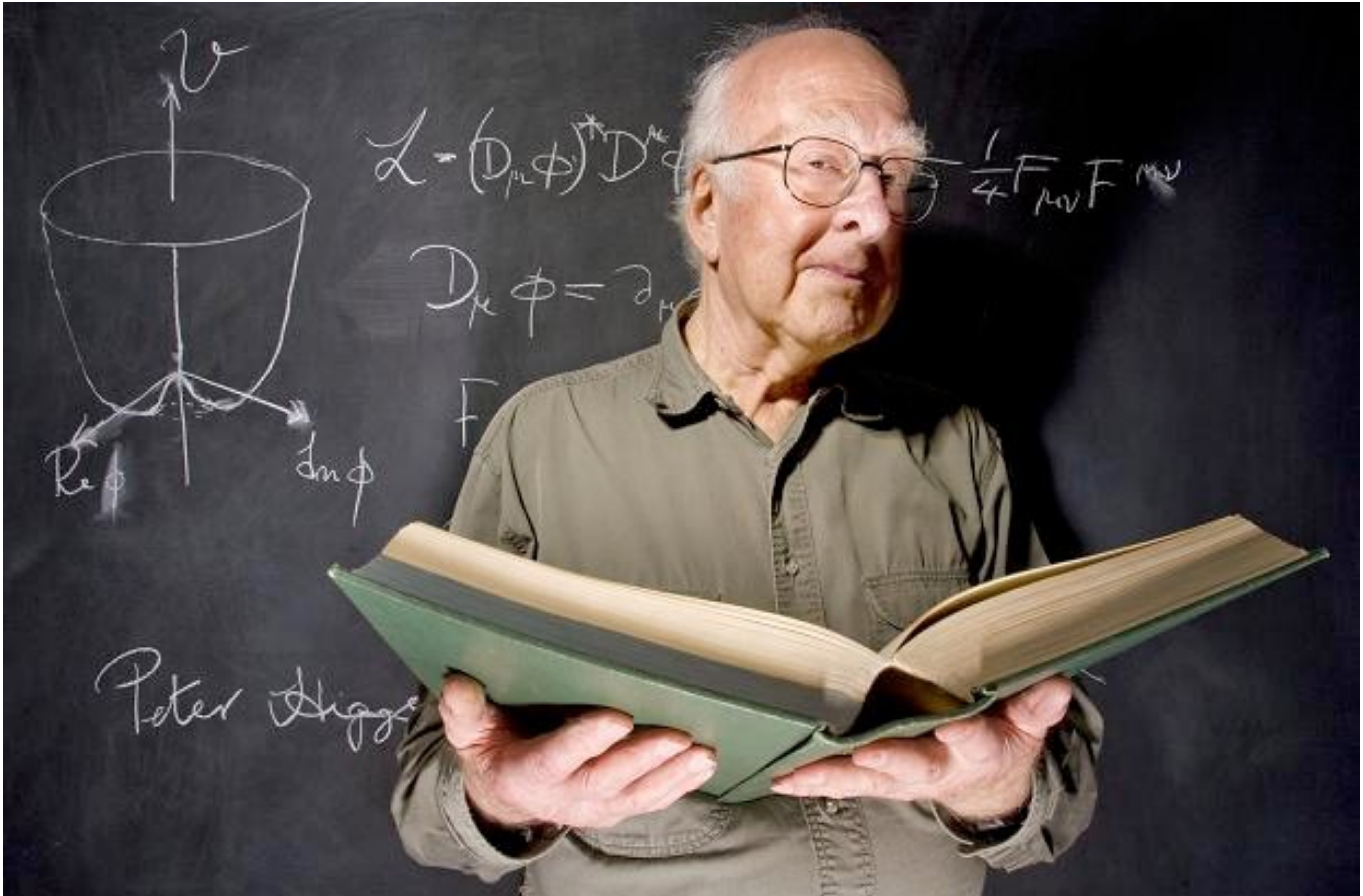
QCD vacuum energy minimised at theta = 0

- ... if $\theta(t, \mathbf{x})$ is dynamical field, relaxes to its minimum



Measured today $|\theta| < 10^{-10}$ (strong CP problem)

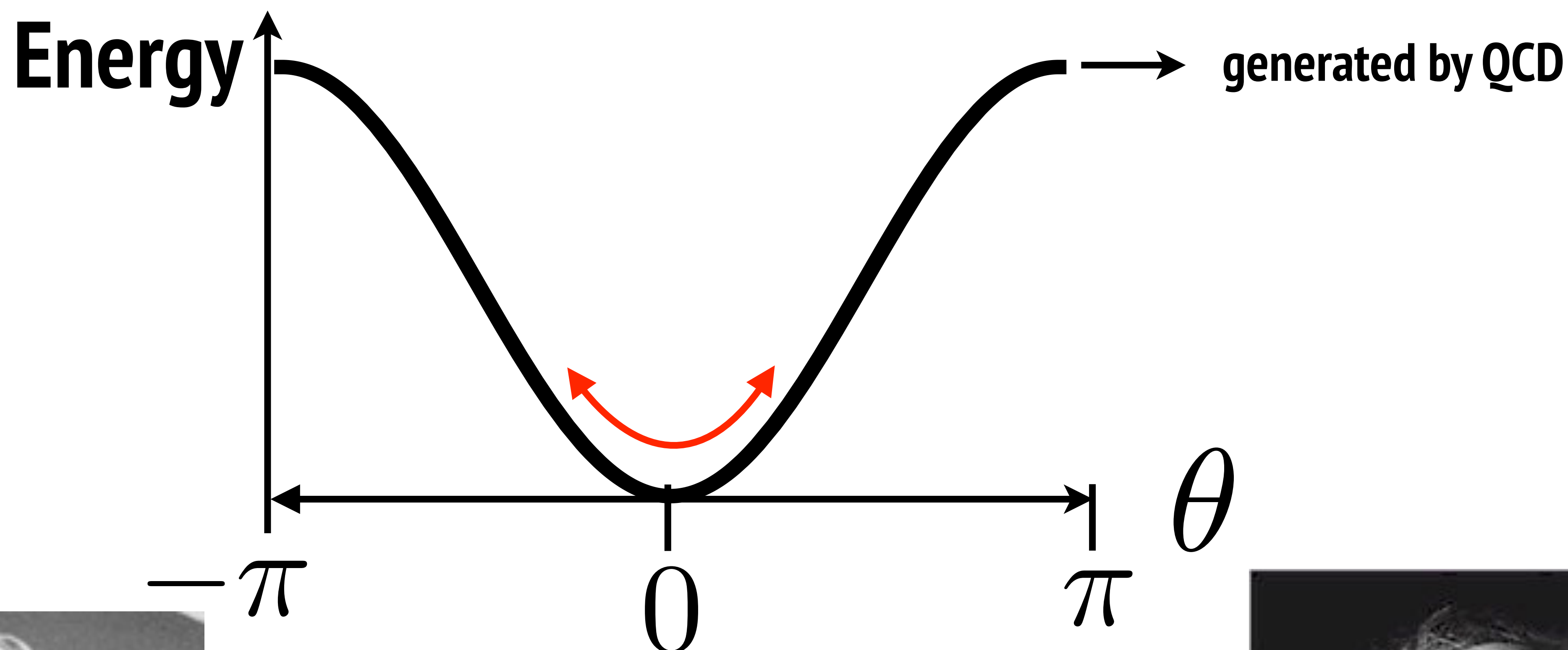
ain’t you forgetting something?



P. Higgs

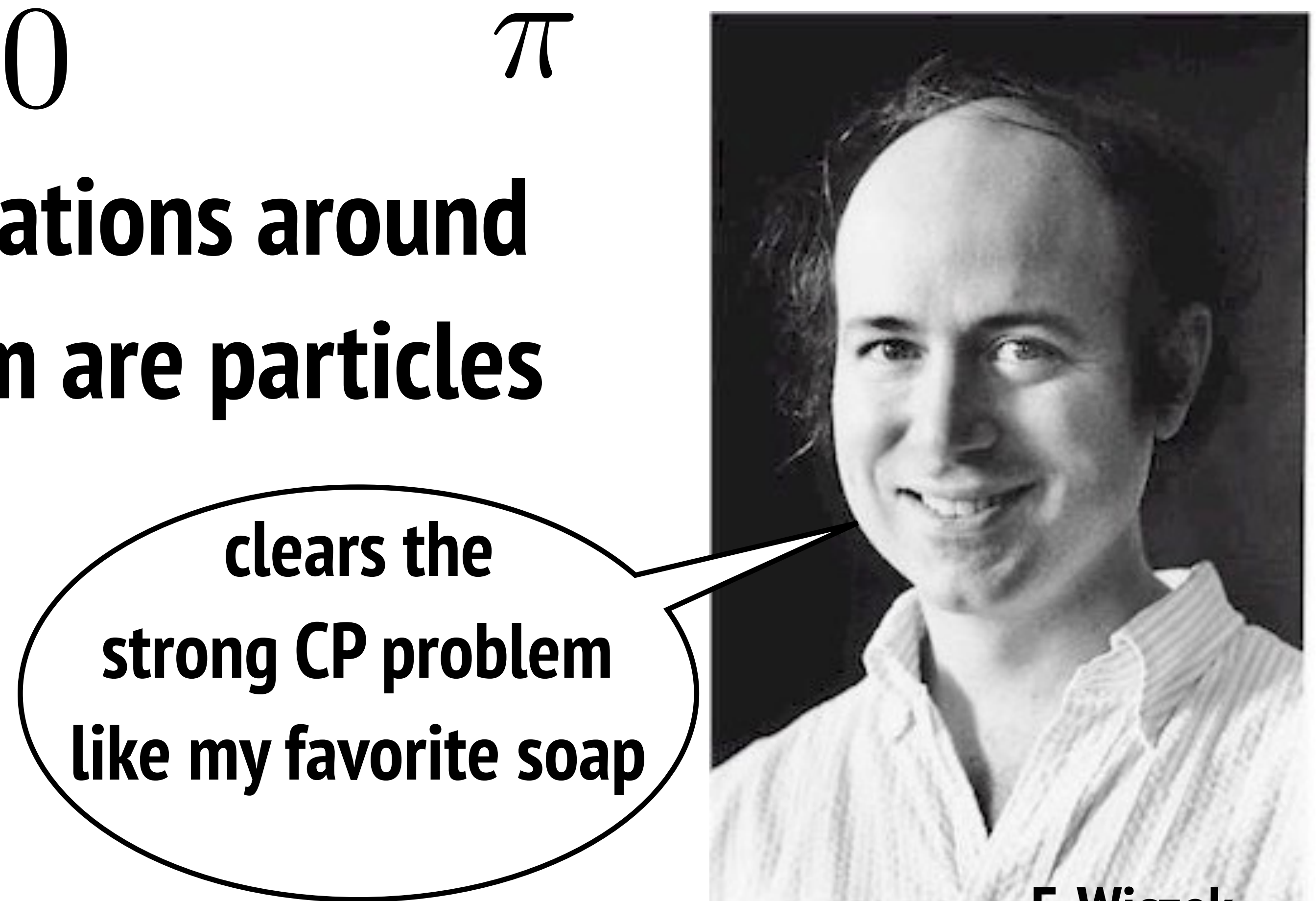
and a new particle is born ...

- if $\theta(t, \mathbf{x})$ is dynamical field



Field Excitations around the vacuum are particles

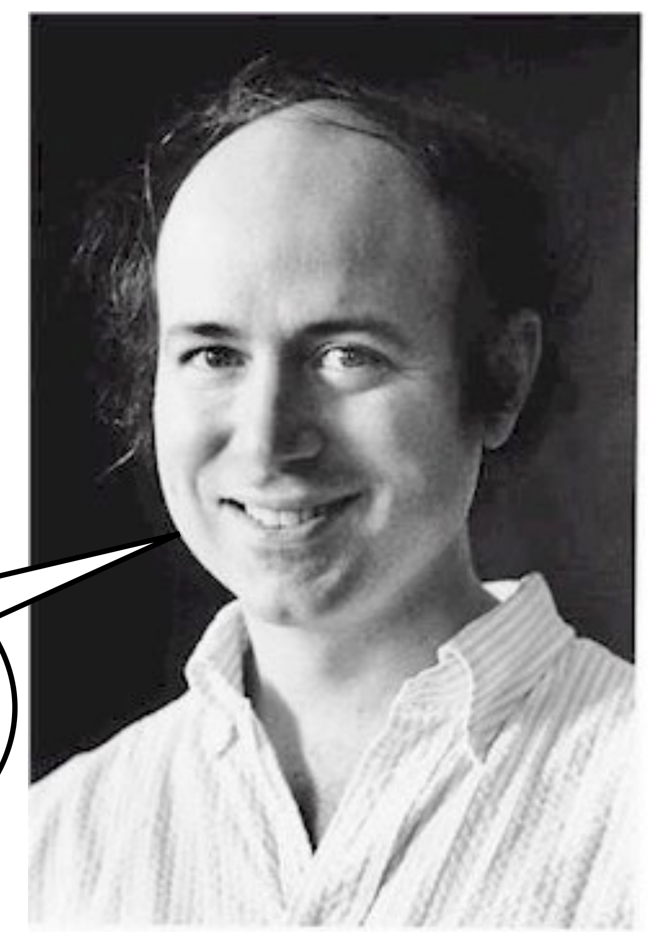
S. Weinberg



F. Wiczek

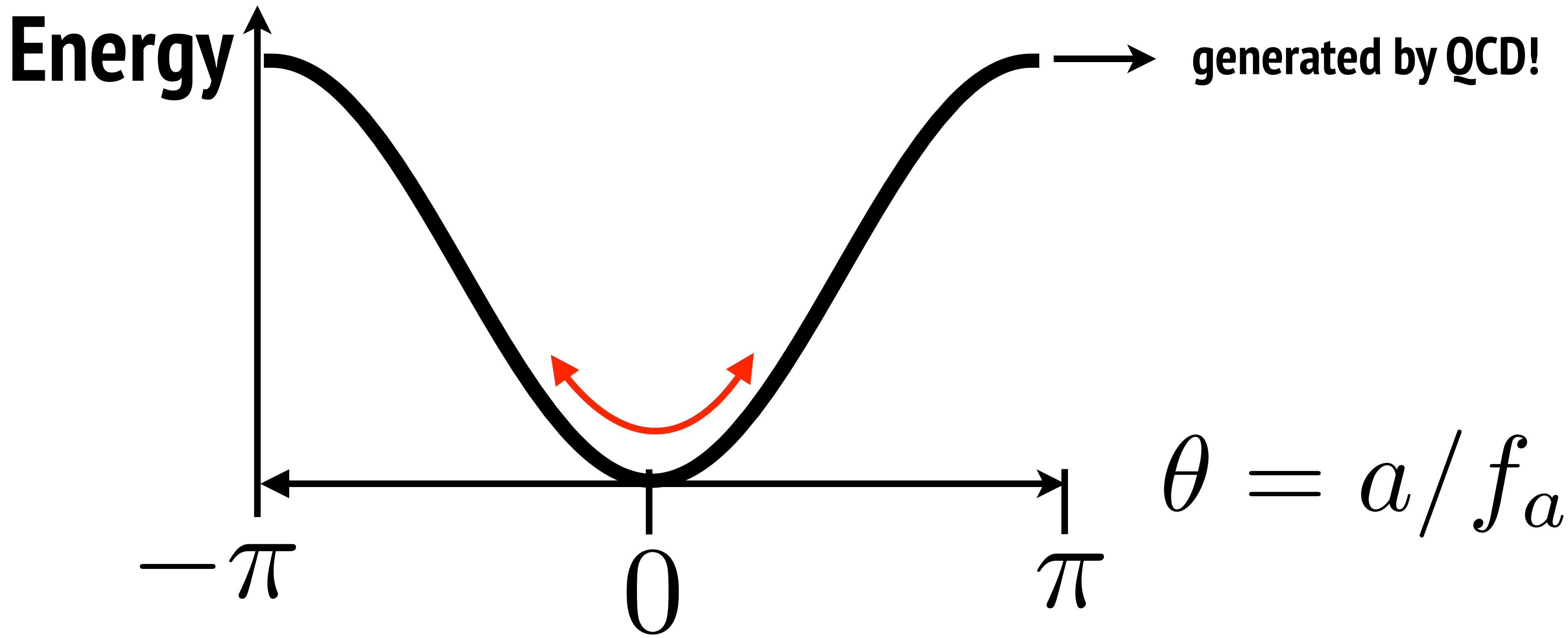
and a new particle is born ... the axion

- if $\theta(t, \mathbf{x})$ is dynamical field



and a new scale sets the game, fa

- kinetic term for θ requires a new scale



$$\theta = a/f_a$$

$$\mathcal{L}_\theta = \frac{\alpha_s}{8\pi} G_{\mu\nu a} \widetilde{G}_a^{\mu\nu} \theta + \frac{1}{2} (\partial_\mu \theta)(\partial^\mu \theta) f_a^2$$

$$\mathcal{L}_\theta = \frac{\alpha_s}{8\pi} G_{\mu\nu a} \widetilde{G}_a^{\mu\nu} \frac{a}{f_a} + \frac{1}{2} (\partial_\mu a)(\partial^\mu a)$$

Start again

Phase shifts

- **QCD with 2 flavors of quarks** $u = (u, d)$,

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a + i\bar{q}\gamma_\mu D^\mu q - (\bar{q}_L M_q q_R + \text{h.c.}) - \frac{\alpha_s}{4\pi} G\widetilde{G}\theta_{\text{QCD}}$$

- **quark phase redefinitions ... U(2)_A = U(1)_A x SU(2)_A transformations**

$$q_R \to e^{i(\theta_0 + \theta.\sigma)} q_R \quad ; \quad q_L \to e^{-i(\theta_0 + \theta.\sigma)} q_L, \quad \text{or} \quad q \to e^{i\gamma_5(\theta_0 + \vec{\theta}_\pi \cdot \vec{\sigma})} q$$

1 - are classical symmetries of QCD in the limit $m_q \to 0$

2 - they are not symmetries! so they can be used to eliminate all phases from M_q

3 - the common phase of M requires a U(1)_A shift, which is SPECIAL

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a + i\bar{q}\gamma_\mu D^\mu q - (\bar{q}_L m_q e^{i\theta_Y} q_R + \text{h.c.}) - \frac{\alpha_s}{4\pi} G\widetilde{G}\theta_{\text{QCD}} \qquad m_q = \text{diag}\{m_u, m_d\}$$

$$q \to e^{-i\gamma_5 \frac{\theta_Y}{2}} q$$

$$-(\bar{q}_L m_q q_R + \text{h.c.}) \quad -\frac{\alpha_s}{4\pi} G\widetilde{G}(\theta_{\text{QCD}} + N_f \theta_Y)$$

- **Note that all CP violation is now in GGtilde and only one phase remains:** $\theta = \theta_{\text{QCD}} + \arg\{\text{Det} M_q\}$

Axial Anomaly (nutshell)

Noether theorem (global symmetry = conserved current)

$$\phi \to \phi + \alpha\Delta\phi$$

$$\mathcal{L}' - \mathcal{L} = \partial_\mu \left((\alpha\Delta\phi) \frac{\partial \mathcal{L}}{\partial(\partial_\mu \phi)} \right) \equiv \partial_\mu \left(\alpha J^\mu \right)$$

Gell-Mann Levy trick, $\partial_\mu J^\mu$ from $\alpha(x)$

$$\partial_\mu J^\mu = \frac{\partial \mathcal{L}'}{\partial \alpha(x)} \qquad J^\mu = \frac{\partial \mathcal{L}'}{\partial(\partial \alpha(x))}$$

local symmetry transformations help to compute properties of global symmetries

Applied to U(1)_A (exercise...)

$$\mathcal{L}' = \mathcal{L} - (\partial_\mu \alpha)\bar{q}\gamma^\mu\gamma^5 q - (\alpha) 2 m_q i \bar{q}\gamma^5 q$$

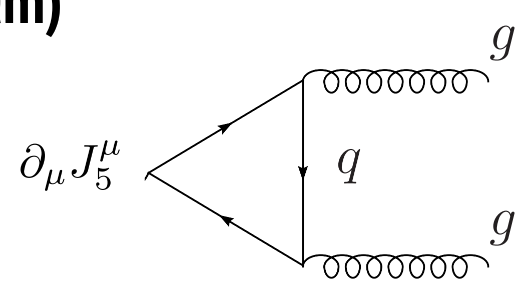
And we obtain an equality that should be always be valid (operator level) $\quad j^{5\mu} = -J^\mu = \bar{q}\gamma^\mu\gamma^5 q$

$$\partial_\mu \left(\bar{q}\gamma^\mu\gamma^5 q \right) = 2 m_q (i\bar{q}\gamma^5 q)$$

(The Axial current is NOT conserved if $m_q \neq 0$)

Adler-Bell-Jackiw anomaly, the equality is violated at the quantum level (triangle diagram)

$$\partial_\mu \left(\bar{q}\gamma^\mu\gamma^5 q \right) = 2 m_q (i\bar{q}\gamma^5 q) - 2 N_f \frac{\alpha_s}{4\pi} G\widetilde{G}$$



-The U(1) Axial current is NOT conserved even if $m_q \neq 0$

-U(1) Axial transformations shift quark phases into $G\widetilde{G}$ -term*

$$\mathcal{L}' = \mathcal{L} + \alpha \partial_\mu J^\mu = \mathcal{L} - 2\alpha m_q (i\bar{q}\gamma^5 q) - 2\alpha N_f \frac{\alpha_s}{4\pi} G\widetilde{G}$$

*extra term in the Lag. from path integral measure (Fujikawa)

* many inf. transformation $\int \alpha = \theta_0 \ \ldots \ \bar{q} m_q e^{i\gamma^5\theta_Y}(1 + i\gamma^5\alpha) q \to \bar{q} m_q e^{i\gamma^5(\theta_Y + \theta_0)} q$

U(1)_A anomaly

The axial anomaly does NOT allow to reabsorb θ_Y from Yukawas (mass)

$\theta_{\rm QCD}$ from QCD vacuum

but allows to cancel one of them, leaving $\theta = \theta_{\rm QCD} + \arg\{{\rm Det} M_q\}$ as the only source of P,T violation in WCD

... baring cancelations, we expect QCD to violate P, T, CP

... but no violation ever found

Meson masses: U(1) problem

Low energy QCD, chiPT meson lagrangian

- In the limit $m_q \to 0$ U(2)_A are global symmetries*
- Are spontaneously broken by quark condensate $\langle \bar{u}u \rangle = \langle \bar{d}d \rangle = -v^3$
- Goldstone theorem predicts 4 massless Goldstone bosons in the symmetric limit. (pions! and... ?) corresponding to shifts along the symmetric-flat directions

Consider now the redefinition, with $\theta_0 = \theta_0(x) = \dfrac{\eta_0(x)}{f_\pi}, \vec{\theta}_\pi = \vec{\theta}_\pi(x) = \dfrac{\vec{\pi}(x)}{f_\pi},$

$$q_R = e^{+i(\theta_0 + \vec{\theta}_\pi \cdot \vec{\sigma})/2} \tilde{q}_R \quad ; \quad q_L = e^{-i(\theta_0 + \vec{\theta}_\pi \cdot \vec{\sigma})/2} \tilde{q}_L \quad \text{or} \quad q = e^{i\gamma_5(\theta_0 + \vec{\theta}_\pi \cdot \vec{\sigma})/2} \tilde{q}$$

kinetic term $\frac{1}{2}(\partial_\mu U^\dagger)(\partial^\mu U) + \ldots \qquad U = e^{i\gamma_5(\theta_0 + \vec{\theta}_\pi \cdot \vec{\sigma})}$

- Explicit breaking terms give Goldstone bosons a mass (exercise?)

charged sector, set $\theta_0, \theta_3 = 0$

$$\bar{q}_L m_q q_R + \text{h.c.} \to -(m_u + m_d) v^3 \cos(\sqrt{\theta_- \theta_+}) = (m_u + m_d) v^3 + \frac{(m_u + m_d) v^3}{2 f_\pi^2} \pi_- \pi_+ \ldots$$

pion mass^2

neutral sector, set $\theta_\pm = \theta_1 \pm i\theta_2 = 0$

$$\bar{q}_L m_q q_R + \text{h.c.} \to -m_u v^3 \cos(\theta_0 + \theta_3) - m_d v^3 \cos(\theta_0 - \theta_3),$$

$$f_\pi \simeq f_\eta \to m_x^2 :: m_{\pi_0}^2 = m_u :: m_d \sim 1$$

Weinberg U(1)_A problem: no 4th light meson in nature!

$$\frac{m_\pi^2}{m_{\eta'}^2} \sim 50$$

Meson masses: U(1) solution

- U(1)_A is explicitly broken by anomaly!!! -> need a new term in the potential from GGtilde!

neutral sector, set $\theta_\pm = \theta_1 \pm i\theta_2 = 0$

$$\bar{q}_L m_q q_R + \text{h.c.} \to -m_u v^3 \cos(\theta_0 + \theta_3) - m_d v^3 \cos(\theta_0 - \theta_3) - \Lambda^4 \cos(\theta + 2\theta_0)$$

- The new term has to satisfy the following properties:

depends on $\theta + 2\theta_0$ **because a global U(1)_A transformation is now a shift of the field** θ_0 **and must shift** θ

It is periodic $\theta \to \theta + 2\pi$

it is minimum at $\theta = 0$

$$\equiv \theta + 2\langle\theta_0\rangle$$

$$V[\theta] \geq V[0]$$

Euclidean path integral ... $t \to -it$

$$e^{-\int d^4x_E V[\theta]} = \int \mathcal{D}A_{a\mu} e^{-S_E[A_{a\mu}] - i\theta \int d^4x_E \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \widetilde{G}^{\mu\nu}_a}$$

GGtilde is a total derivative, but ... QCD instantons contribute

$$\int d^4x \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \widetilde{G}^{\mu\nu}_a = \int d^4x \partial_\mu \mathcal{J}^\mu = \oint d\sigma_\mu \mathcal{J}^\mu = n \in Z$$

n is the topological charge of the A configuration

Vafa-Witten theorem*

$$e^{-\int d^4x_E V[\theta]} = \int \mathcal{D}A_{a\mu} e^{-S_E[A_{a\mu}]} e^{-i\theta n_A} \leq e^{-\int d^4x_E V[0]}$$

Meson masses: U(1) solution

- U(1)_A is explicitly broken by anomaly!!! -> need a new term in the potential from GGtilde!

neutral sector, set $\theta_\pm = \theta_1 \pm i\theta_2 = 0$

$$\bar{q}_L m_q q_R + \text{h.c.} \to -m_u v^3 \cos(\theta_0 + \theta_3) - m_d v^3 \cos(\theta_0 - \theta_3) - \Lambda^4 \cos(\theta + 2\theta_0)$$

- phase transformations are shifts of the Goldstones θ_0, θ_3
- absolute minimum of the potential would happen for $\theta = 0$ but θ is a constant to be measured

- Meson masses assuming $\Lambda^4 \gg m_q v^3$ (exercise*)

$$m_\eta'^2 \sim \frac{\Lambda^2}{f} + \mathcal{O}(mv^3/\Lambda^4) \qquad\qquad m_{\pi^0}^2 \simeq m_{\pi^\pm}^2$$

- P,T,CP violation $2\langle\theta_0\rangle + \theta \sim \dfrac{m_u m_d v^3}{\Lambda^4 (m_u + m_d)}\theta \sim \dfrac{m_u m_d}{(m_u + m_d)^2} \dfrac{m_\pi^2}{m_\eta'^2}\theta$

- Two VEVs, three terms in the potential cannot be taken to their minimum values! **->strong CP problem**

  eta' adjusts its VEV to cancel theta, but it cannot completely because it has the ~m terms (a compromise must be found)

- if any of the quark masses is zero, no CP violation (two VEVs, two terms to minimise, minimum energy achievable!)

  CP violation minimum when V is in absolute minimum $2\langle\theta_0\rangle + \theta = 0$

- if theta = 0, no CP violation
- CP violation is suppressed by a further small ratio m_pi/m_eta

The axion solution

- two VEVs cannot be adjusted to absolutely minimise 3 terms in the potential
- Postulate another Goldstone boson coupling to GGtilde ... its VEV also contributes to the "effective" theta!

$$\mathcal{L}_\phi = \frac{1}{2}(\partial_\mu \theta_\phi)(\partial^\mu \theta_\phi) f_a^2 - \frac{\alpha_s}{4\pi} G\widetilde{G}\theta_\phi$$

f_a new physics energy scale!

neutral sector potential

$$V_{\rm mesons} = -m_u v^3 \cos(\theta_0 + \theta_3) - m_d v^3 \cos(\theta_0 - \theta_3) - \Lambda^4 \cos(\theta + 2\theta_0 + \theta_\phi)$$

- minimisation of the potential gives VEVs ... $\langle \theta_\phi \rangle = -\theta, \theta_0 = \theta_3 = 0$ no CP violation!
- but a new meson-like particle is predicted! are we back to the U(1) mising meson problem???

f_a new physics energy scale!

The answer is yes, but this new meson, the AXION, can be veeery light and veeeery weakly interacting!

The axion mass and mixing with pion

neutral sector potential

$$V_{\rm mesons} = -m_u v^3 \cos(\theta_0 + \theta_3) - m_d v^3 \cos(\theta_0 - \theta_3) - \Lambda^4 \cos(\theta + 2\theta_0 + \theta_\phi)$$

- Introduce $\beta = f/2f_a$**, the mass matrix in the basis** $(\pi_3, \eta^0, \phi = \theta_\phi f_a)$

$$[m^2] = \begin{pmatrix} m_u + m_d & m_u - m_d & 0 \\ m_u - m_d & m_u + m_d & 0 \\ 0 & 0 & 0 \end{pmatrix} \frac{v^3}{f^2} + \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & \beta \\ 0 & \beta & \beta^2 \end{pmatrix} \frac{4\Lambda^4}{f^2}.$$

- Easier if we integrate out eta' $\eta'(x) = \eta^0(x) + \beta\phi(x) = 0$

$$V_{\rm meson} \sim -m_u v^3 \cos(\theta_3 - \theta_\phi/2) - m_d v^3 \cos(\theta_3 + \theta_\phi/2)$$

The relevant case is $\beta \ll 1$

$$\pi^0 = \pi_3 + \varphi_{a\pi}\phi \quad ; \quad m_\pi^2 = \frac{(m_u + m_d)v^3}{f^2} \qquad \varphi_{a\pi} = \frac{m_d - m_u}{2(m_u + m_d)} \frac{f}{f_a}$$

$$a = \phi - \varphi_{a\pi}\pi_3 \quad ; \quad m_a^2 = \frac{m_u m_d v^3}{(m_u + m_d) f_a^2} = \frac{m_u m_d}{(m_u + m_d)^2} \frac{m_\pi^2 f^2}{f_a^2},$$

Some axion couplings

- The axion model presented is the simplest, it is called HADRONIC because the axions gets all its couplings to the SM particles through the GGtilde term, and through it, by mixing with the mesons

- How does it work?

Any meson coupling in the axion-less theory converts into a coupling of meson+O(beta)axion

example:

$$\frac{\partial_\mu \pi^i}{f}\bar{N}\sigma^i\gamma^\mu\gamma^5 N \to \left(\frac{\partial_\mu \pi^i}{f} + \varphi_{a\pi}\frac{\partial_\mu a}{f}\right)\bar{N}\sigma^i\gamma^\mu\gamma^5 N$$

$$\frac{m_u - m_d}{m_u + m_c d}\frac{\partial_\mu a}{f_a}\bar{N}\sigma^i\gamma^\mu\gamma^5 N = C_{a\pi}\frac{\partial_\mu a}{f_a}\bar{N}\sigma^i\gamma^\mu\gamma^5 N$$

two photon coupling through eta' and pi: $\eta_0 \to \eta' - \beta a, \quad \pi_3 = \pi^0 - \varphi_{a\phi} a$

$$\mathcal{L} \ni \quad [6\left(\frac{2}{3}\right)^2 + 6\left(\frac{1}{3}\right)^2]\frac{\eta^0}{f}\frac{\alpha}{8\pi}F_{\mu\nu}\widetilde{F}^{\mu\nu} + [6\left(\frac{2}{3}\right)^2 - 6\left(\frac{1}{3}\right)^2]\frac{\pi_3}{f}\frac{\alpha}{8\pi}F_{\mu\nu}\widetilde{F}^{\mu\nu}$$

$$= \frac{10}{3}\frac{\eta^0}{f}\frac{\alpha}{8\pi}F_{\mu\nu}\widetilde{F}^{\mu\nu} + 2\frac{\pi_3}{f}\frac{\alpha}{8\pi}F_{\mu\nu}\widetilde{F}^{\mu\nu}$$

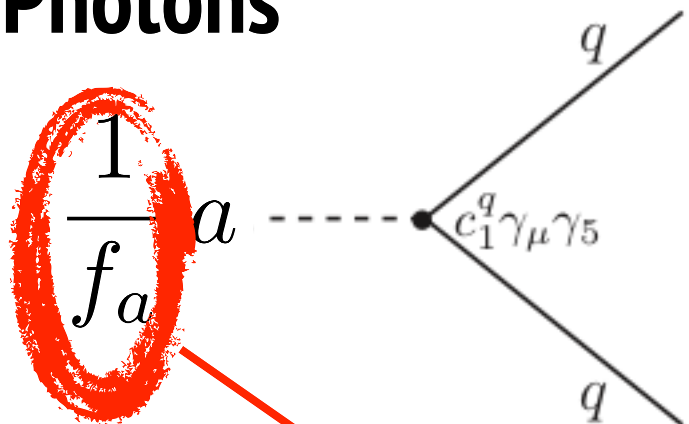
$$\left[-\frac{10}{3} - 2\frac{m_d - m_u}{2(m_u + m_d)}\right]\frac{a}{2f_a}\frac{\alpha}{8\pi}F_{\mu\nu}\widetilde{F}^{\mu\nu} = -\frac{2}{3}\frac{4m_d + m_u}{m_u + m_d}\frac{a}{f_a}\frac{\alpha}{8\pi}F_{\mu\nu}\widetilde{F}^{\mu\nu}$$

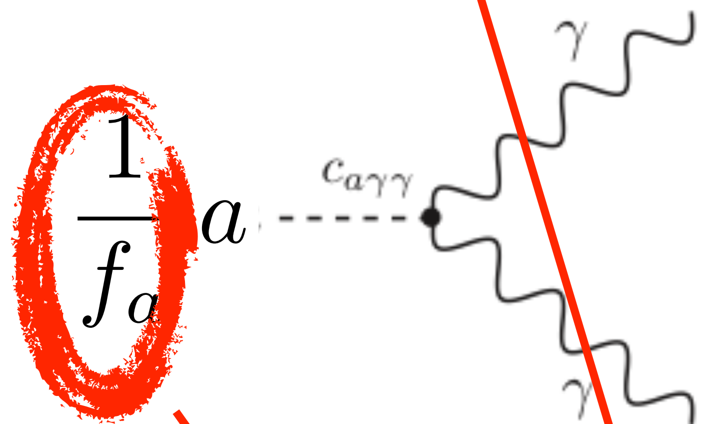
Axion mass and couplings

Mass

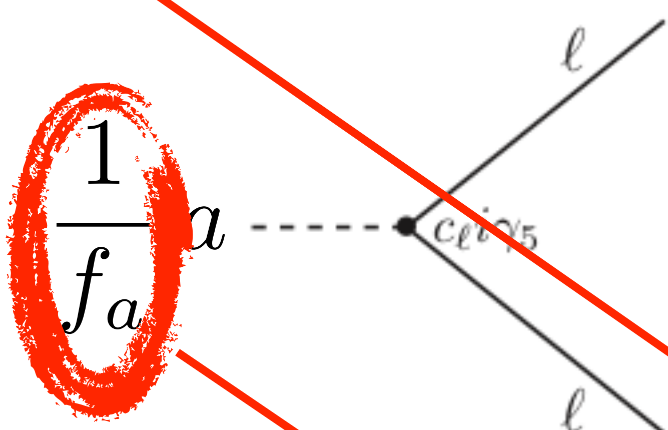
$$m_a \simeq m_\pi \frac{f_\pi}{f_a} \simeq 6\ \text{meV} \frac{10^9\,\text{GeV}}{f_a}$$

hadrons, Photons





Leptons (in some models)



The lighter the more weakly interacting

Spoiling the mechanism?

- two VEVs cannot be adjusted to absolutely minimise 3 terms in the potential
- Postulate another Goldstone boson coupling to GGtilde ... its VEV also contributes to the "effective" theta!

neutral sector potential

$$V_{\text{mesons}} = -m_u v^3 \cos(\theta_0 + \theta_3) - m_d v^3 \cos(\theta_0 - \theta_3) - \Lambda^4 \cos(\theta + 2\theta_0 + \theta_\phi)$$

- The axion must be the Goldstone boson of a U(1)_A symmetry spontaneously broken
  - Broken at the quantum level by the color anomaly
  - not explicitly broken by anything else!!!!

- Global symmetries tend to be broken one way or the other (Ultimately... quantum gravity? black hole no-hair?)

- How <u>small</u> or <u>fine-tuned</u> has to allow axions to solve strong CP ? exercise!

$$V_{\text{meson}} \sim -m_u v^3 \cos(\theta_3 - \theta_\phi/2) - m_d v^3 \cos(\theta_3 + \theta_\phi/2) - \Lambda'^4 \cos(\theta_\phi + \alpha')$$

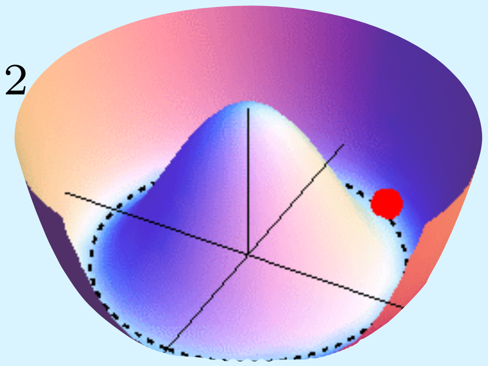
(almost already solved! is like the eta case with a different f!)

- Mechanisms to save the axion? Gauge symmetry, discrete symmetries, Dvalon?

Simple model (KSVZ)

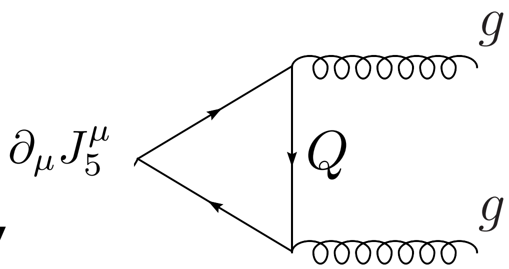
- Add one (heavy) quark Q and a new complex scalar with MH potential

$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\bar{Q}DQ + \frac{1}{2}(\partial_\mu\sigma)(\partial^\mu\sigma^*) - (y\bar{Q}_L Q_R\sigma + {\rm h.c}) - \lambda|\sigma|^4 + \mu^2|\sigma|^2$$



$$\sigma(x) = \rho(x)e^{i\frac{\phi(x)}{f_a}} \qquad f_a = \langle\rho\rangle = \sqrt{\mu^2/2\lambda}$$

<u>Exact</u> U(1)_A symmetry $\sigma \to e^{i\alpha}\sigma \quad , \quad Q \to e^{i\gamma^5\alpha/2}Q$ **(... but is color anomalous!)**



This is called a Peccei-Quinn symmetry and will imply an axion in the LOW ENERGY THEORY

kinetic term

$$\partial_\mu\sigma \ni \rho e^{i\theta_\phi}\partial_\mu\theta_\phi$$

Absorb. $\theta_\phi(x)$ **in Q (redefine new quark)**

$$Q \to e^{-i\gamma^5\theta_\phi/2}\tilde{Q}$$

$$\mathcal{L}' - \mathcal{L} \ni \partial_\mu\theta_\phi(i\bar{\tilde{Q}}\gamma^\mu\gamma^5\tilde{Q}) - \frac{\alpha_s}{4\pi}G\widetilde{G}\theta_\phi$$

integrate out heavy fields

$$\langle\rho\rangle = f_a, \tilde{Q} = 0$$

$$\mathcal{L}_\phi = \frac{1}{2}(\partial_\mu\theta_\phi)(\partial^\mu\theta_\phi)f_a^2 - \frac{\alpha_s}{4\pi}G\widetilde{G}\theta_\phi$$

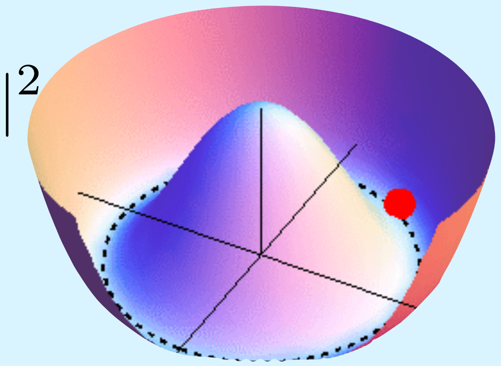
N heavy quarks

Simple model KSVZ

- Peccei-Quinn symmetry, color anomalous, spontaneously broken at f_a

$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\bar{Q}DQ + \frac{1}{2}(\partial_\mu\sigma)(\partial^\mu\sigma^*) - (y\bar{Q}_L Q_R\sigma + \text{h.c}) - \lambda|\sigma|^4 + \mu^2|\sigma|^2$$

$$\sigma(x) = \rho(x)e^{i\frac{a(x)}{f_a}} \qquad f_a = \sqrt{\mu^2/2\lambda}$$

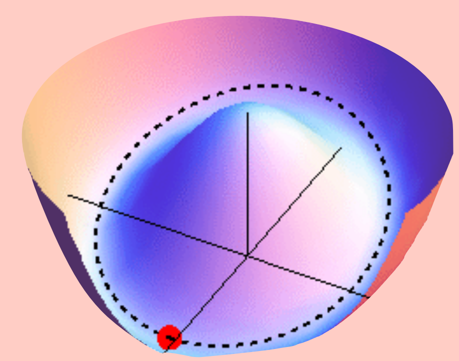


- At energies below f_a **(SSB)**

$$\mathcal{L} \in \frac{1}{2}(\partial a)^2 + \frac{\alpha_s}{8\pi}G\widetilde{G}\frac{a}{f_a}$$

- At energies below $\Lambda_{\rm QCD}$, $a - \eta' - \pi^0 - \eta - \ldots$ **mixing**

axion mass $m_a \simeq \frac{m_\pi f_\pi}{f_a} \sim 6\text{meV}\frac{10^9\text{GeV}}{f_a}$



couplings $\mathcal{L}_{a,I} = \sum_N c_{N,a}\bar{N}\gamma^\mu\gamma_5 N\frac{a}{f_a} + c_{a\gamma}\frac{\alpha}{2\pi}F_{\mu\nu}\widetilde{F}^{\mu\nu}\frac{a}{f_a} + \ldots$

nucleons ... photons ... mesons ...

ENERGY ~GeV ~f_a

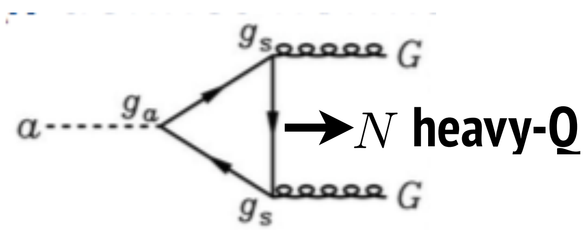
more on couplings

- **Shift symmetry** $\theta_\phi \to \theta_\phi + \alpha$ **allows some generic types of interactions allowed in HE theory**

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu \theta)(\partial^\mu \theta) f^2 + \sum_f c_f [\bar{f}\gamma^\mu \gamma_5 f]\partial_\mu \theta - E\frac{\alpha}{8\pi} F_{\mu\nu}\widetilde{F}^{\mu\nu}\theta$$

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) + \sum_f g_{af}[\bar{f}\gamma_5 f]a - \frac{g_{a\gamma}}{4} F_{\mu\nu}\widetilde{F}^{\mu\nu} a \quad \textbf{(canonically normalised)} \quad g \propto \frac{1}{f_A}$$

- **Colour anomaly breaks explicitly shift symmetry -> axion mass + interactions (EDM+...)**

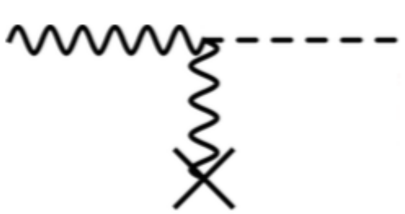


$$N\frac{\alpha}{8\pi}\left\{G_{\mu\nu}\widetilde{G}^{\mu\nu}\right\}\theta \equiv \frac{\alpha_s}{8\pi}\left\{G_{\mu\nu}\widetilde{G}^{\mu\nu}\right\}\frac{A}{f_A}$$

$$V(A) \sim \frac{1}{2}\chi_{\rm QCD}\left(\frac{A}{f_A}\right)^2 = \frac{1}{2}m_A^2 A^2$$

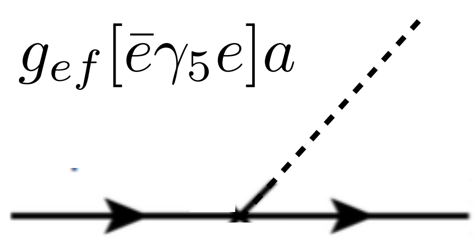
photon coupling

$$-\frac{g_{a\gamma}}{4}F_{\mu\nu}\widetilde{F}^{\mu\nu}a$$



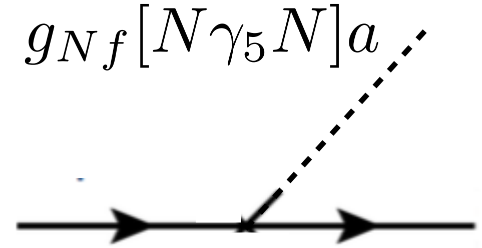
electron coupling

$$g_{ef}[\bar{e}\gamma_5 e]a$$



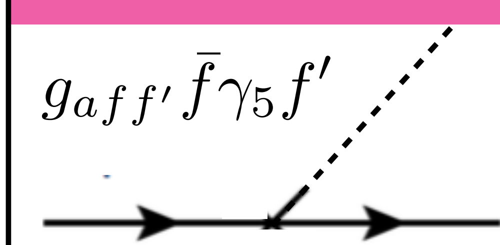
nucleon coupling

$$g_{Nf}[\bar{N}\gamma_5 N]a$$



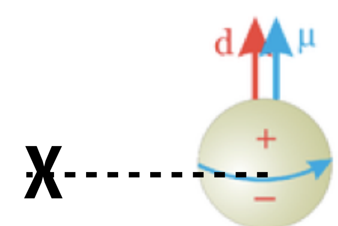
FCNC

$$g_{aff'}\bar{f}\gamma_5 f'$$



~~CP~~ Neutron electric dipole

$$\propto \frac{1}{m_n}[F_{\mu\nu}\bar{n}\sigma^{\mu\nu}\gamma_5 n]\frac{A}{f_A}$$



Models old and new, ALPs

- NGB models, hadronic, 2HDMs, families, axi-majorons…

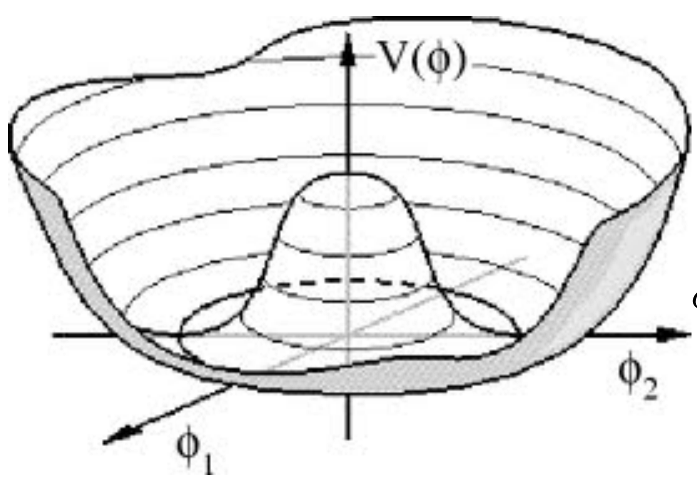
Model	$N_{\rm DW}$	High-E couplings: E/N	C_{Au}	C_{Ad}	C_{Ae}	Low-E couplings: $C_{A\gamma}$	C_{Ap}	C_{An}	C_{Ae}
PQWW	3	$8/3$	$c_\beta^2/3$	$s_\beta^2/3$	$s_\beta^2/3$	0.75	…	…	…
DFSZ I	6,3	$8/3$	$c_\beta^2/3$	$s_\beta^2/3$	$s_\beta^2/3$	0.75	(-0.2,-0.6)	(-0.16,0.26)	(0.024,⅓)
DFSZ II	6,3	$2/3$	$c_\beta^2/3$	$s_\beta^2/3$	$-c_\beta^2/3$	-1.25	(-0.2,-0.6)	(-0.16,0.26)	(-⅓,0)
KSVZ	1	0	g-loop	g-loop	0	-1.92	-0.47	-0.02(3)	$\sim 2\times10^{-4}$
Hadronic $1\mathcal{Q}$ [83]	1…20	$1/6 \ldots 44/3$	g-loop	g-loop	γ-loop	$-0.25 \ldots 12.7^\dagger$	-0.47	-0.02(3)	$(0.05 \ldots 5)\times10^{-3}$
SMASH [16]	1	$8/3,\ 2/3$	g-loop	g-loop	ν-loop	0.75,-1.25	-0.47	-0.02(3)	$(-0.16, 0.16)$
MFVA [91]	9	$2/3,\ 8/3$	0	$1/3$	$1/3$	$0.75, -1.25$	~ -0.6	~ -0.26	$\sim 1/3$
Flaxion/Axi-flavon [11, 12]	-	$8/3$	$\sim 10^{-5}$	$\sim 10^{-5}$	$\sim 10^{-6}$	(0.5,1.1)	-	-	-
Astrophobic M1,2 [93]	1,2	$2/3,\ 8/3$	$\sim 2/3$	$\sim 1/3$	~ 0	-1.25,0.75	$\sim 10^{-2}$	$\sim 10^{-2}$	~ 0
Astrophobic M3,4 [93]	1,2	$-4/3,\ 14/3$	$\sim 2/3$	$\sim 1/3$	~ 0	-3.3,2.7	$\sim 10^{-2}$	$\sim 10^{-2}$	~ 0

a recent selection from arXiv:1801.08127

- Axions and axion-like particles are generic in BSM (not necessarily guaranteed!)

pseudo Goldstone Bosons

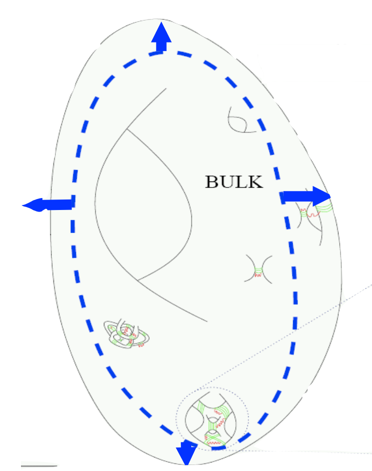
- Global symmetry spontaneously broken

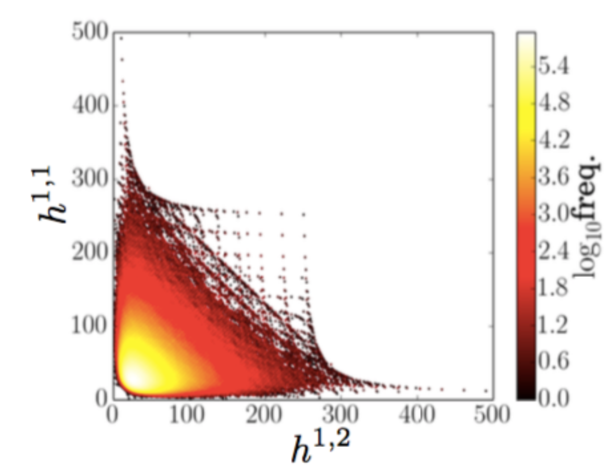


$$\phi(x) = \rho(x) e^{i\theta(x)}$$

stringy axions

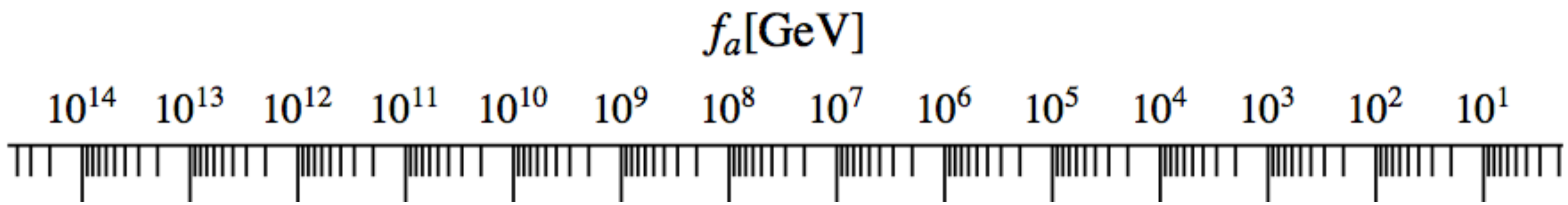
- Im parts of moduli fields (control sizes)





- O(100) candidates in typical compactifications
- masses from non-perturbative effects

Axion Landscape

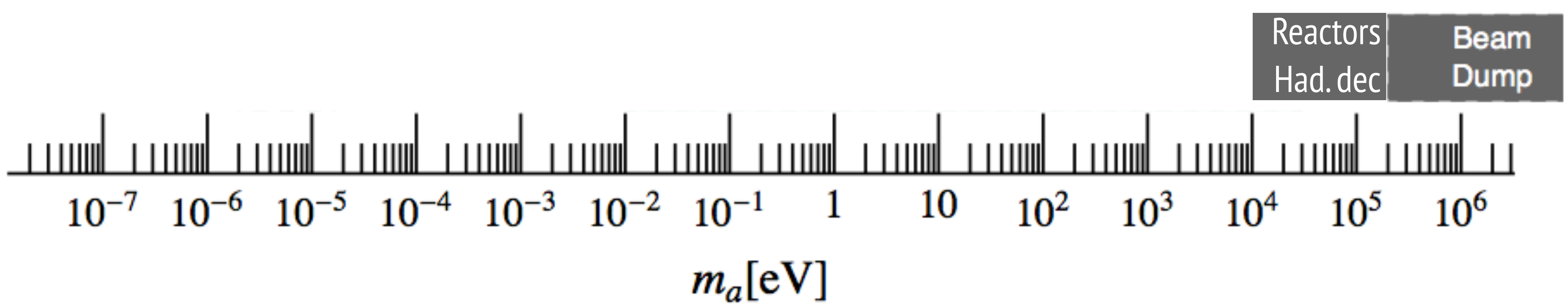


$f_a \gg v_{\rm EW}$

Invisible models

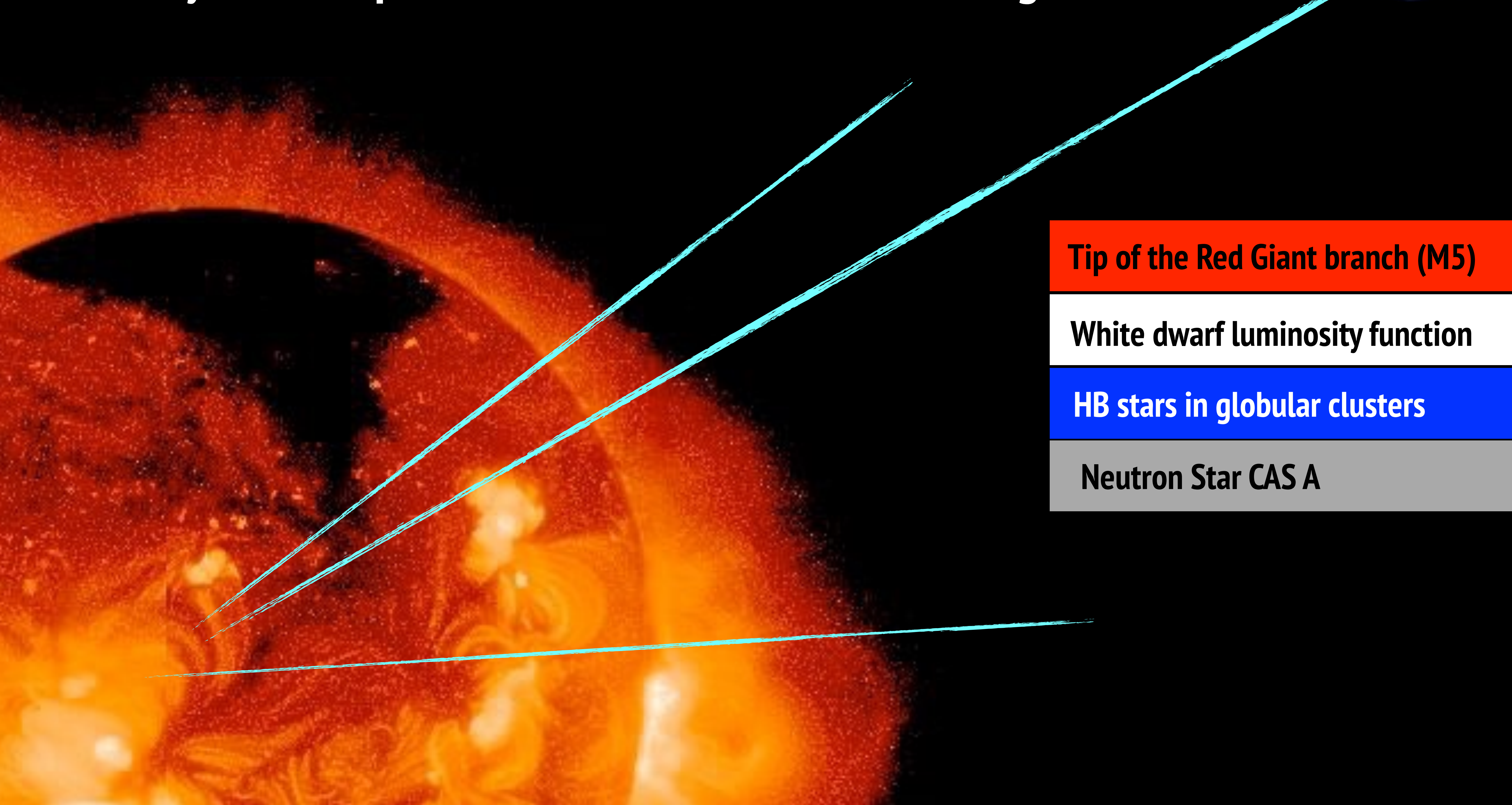
$f_a \sim v_{\rm EW}$

PQWW models

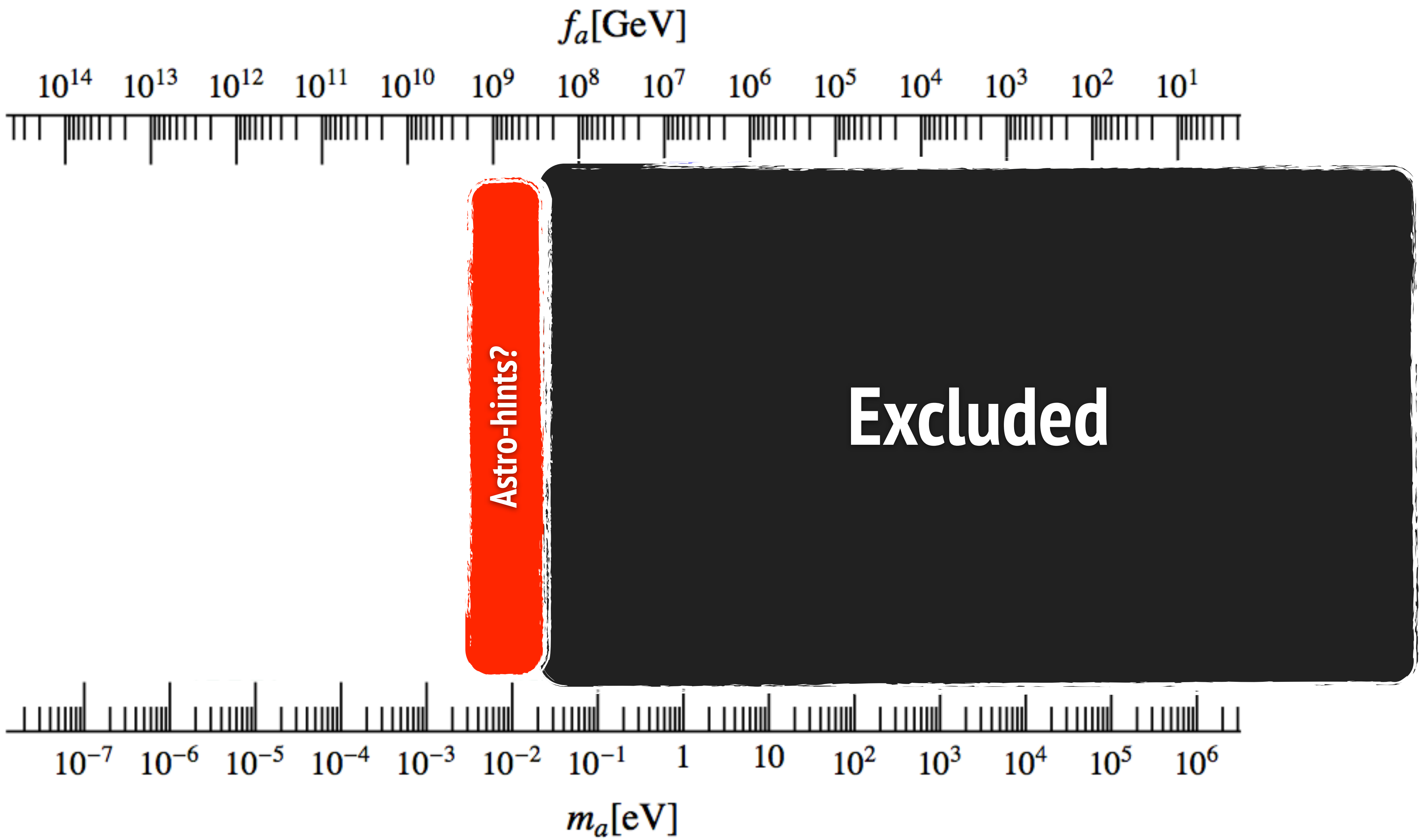


Bounds and hints from astrophysics

- Axions emitted from stellar cores accelerate stellar evolution
- Too much cooling is strongly excluded (obs. vs. simulations)
- Some systems improve with additional axion cooling!



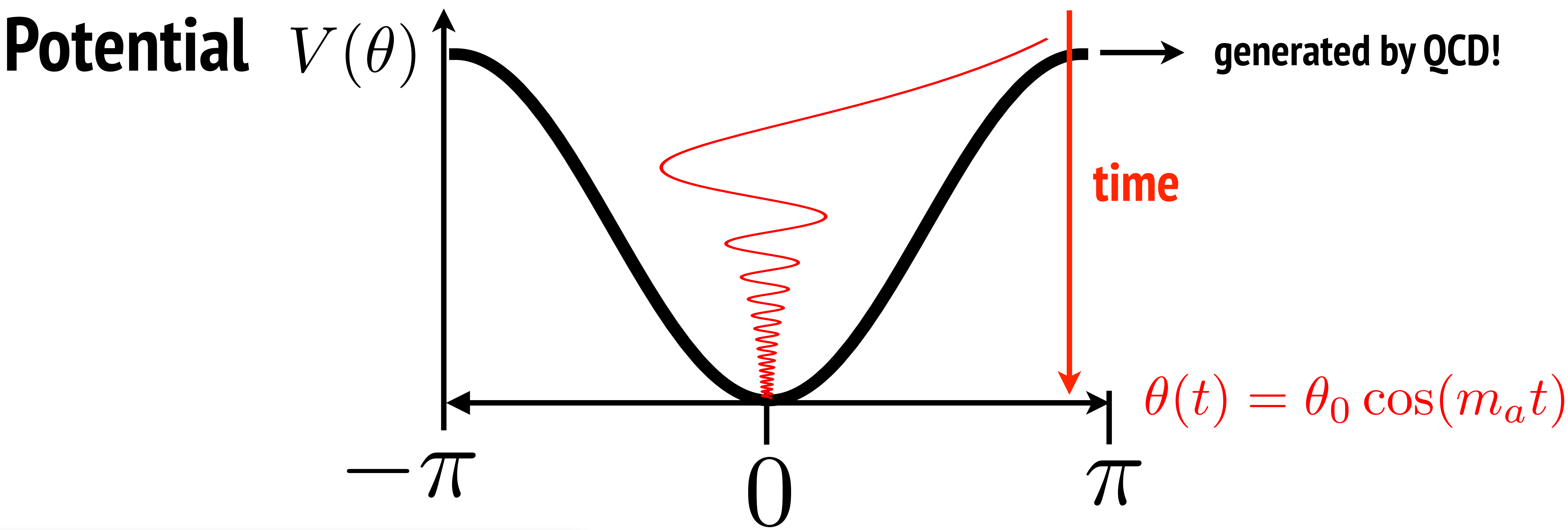
Axion Landscape

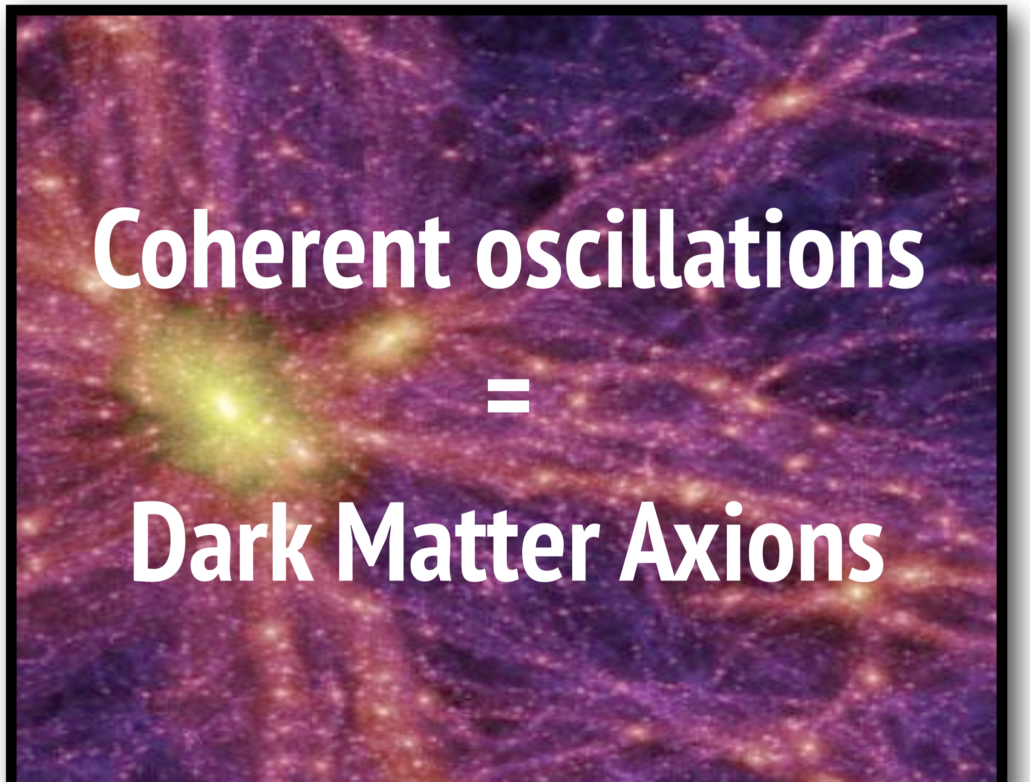


Dark Matters

Axions and dark matter

- axion field relaxes to minimum & oscillates (DARK MATTER!), damping due to expansion of the Universe





Oscillation frequency

$$\omega = m_a$$

Energy density (harm. oscillator)

$$\rho_{\mathrm{aDM}} = \frac{1}{2} m_a^2 f_a^2 \theta_0^2 = \frac{1}{2} (75\mathrm{MeV})^4 \theta_0^2$$