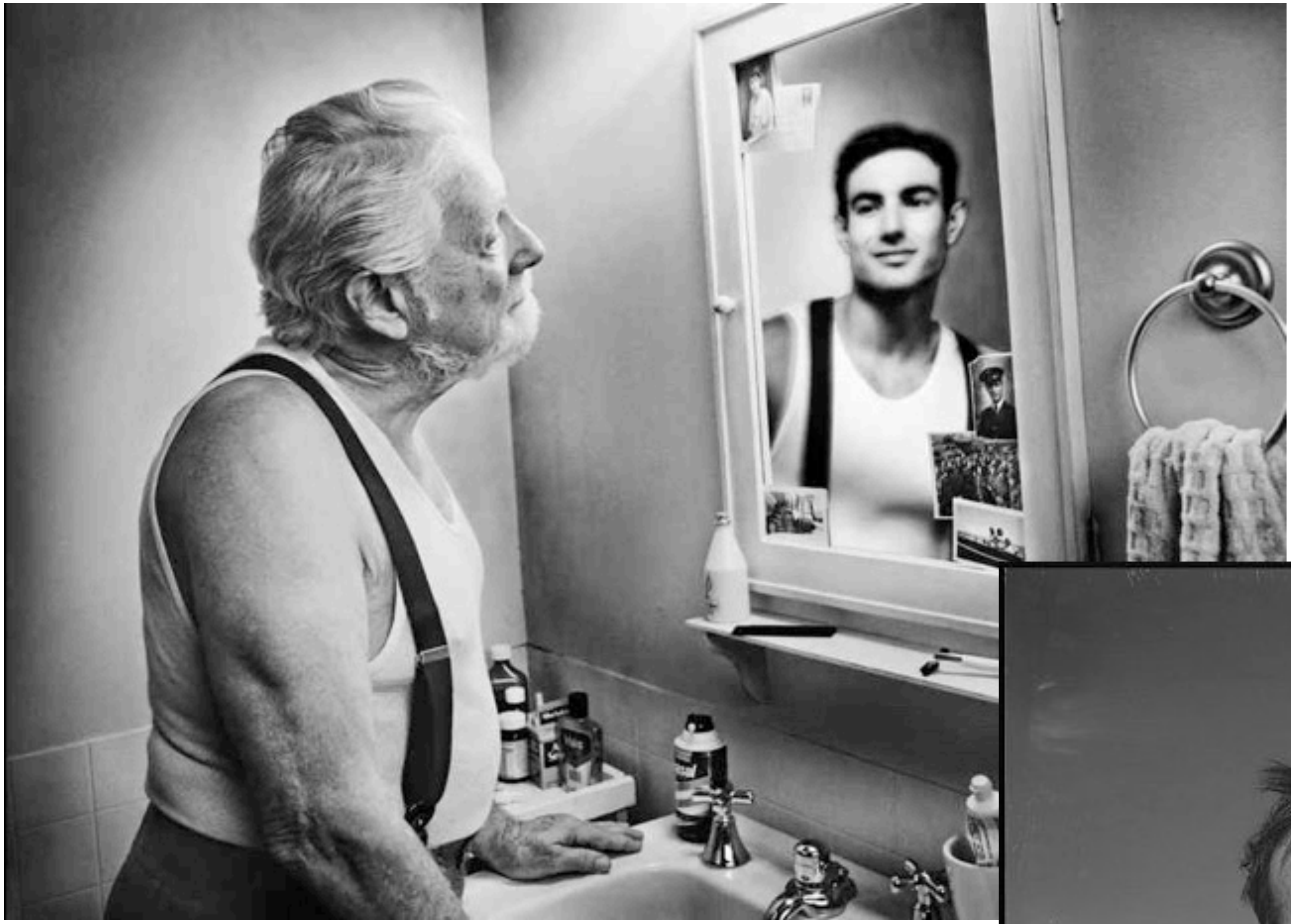
Axion Dark Matter

Javier Redondo
(Zaragoza U & MPP)

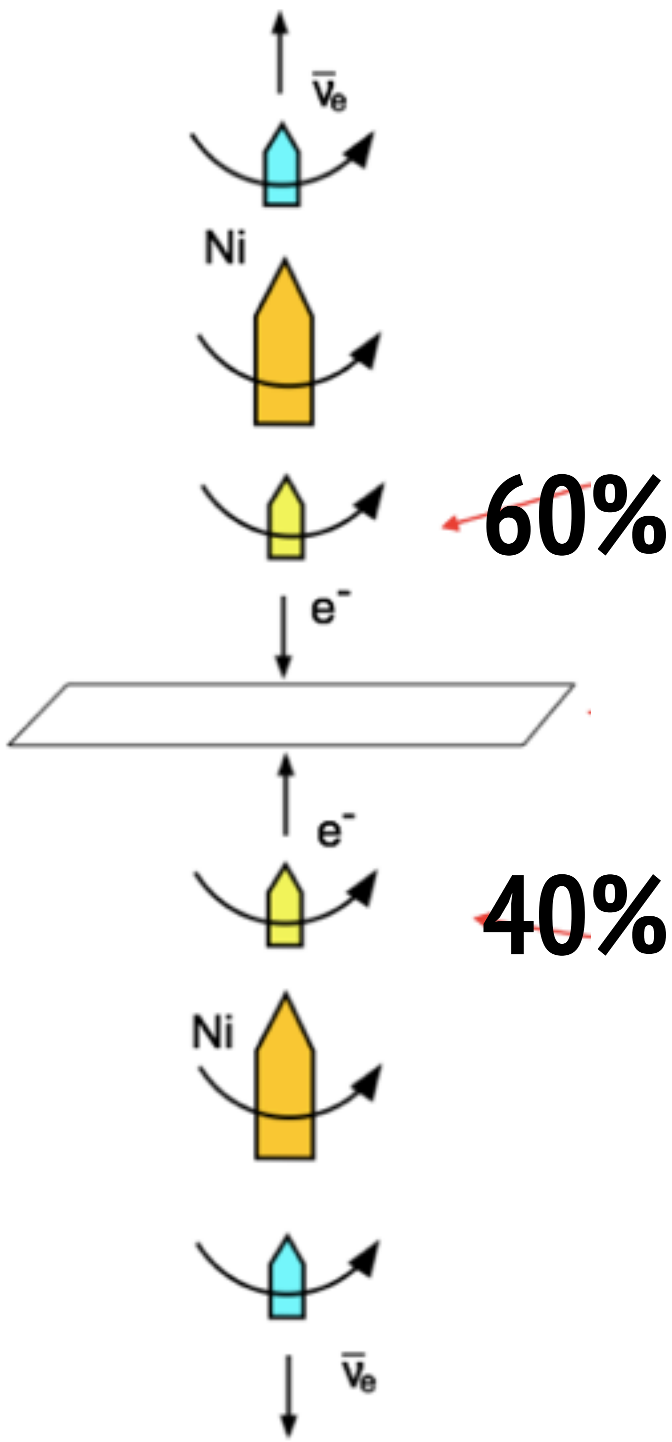
LACHEP 2016
Havanna 18-22 July 2016

Parity and Time reversal



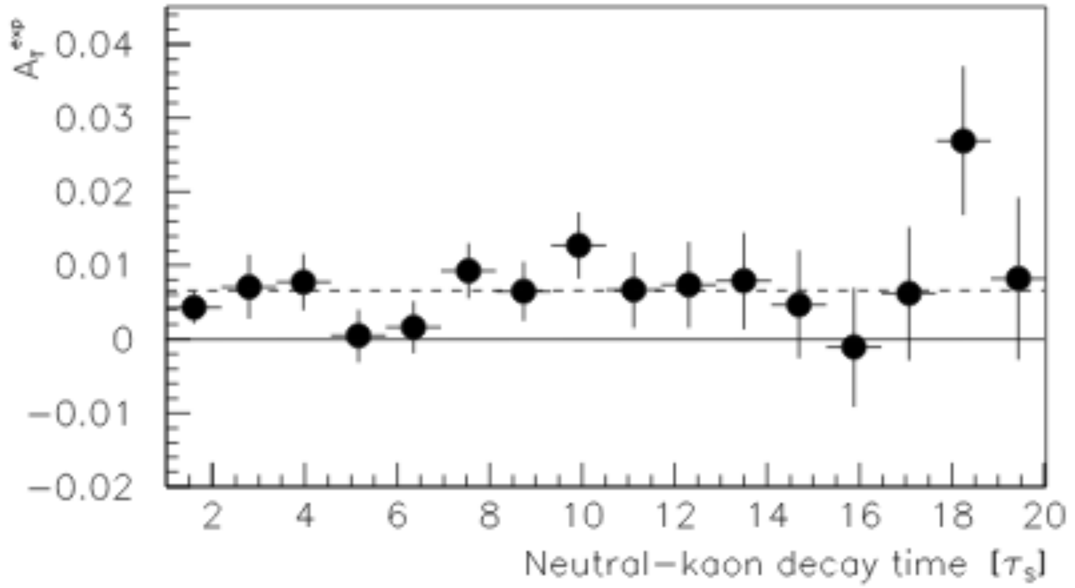
in particle physics (electroweak interactions)

P-violation (Wu 56)



T-violation (CPLEAR 90's)

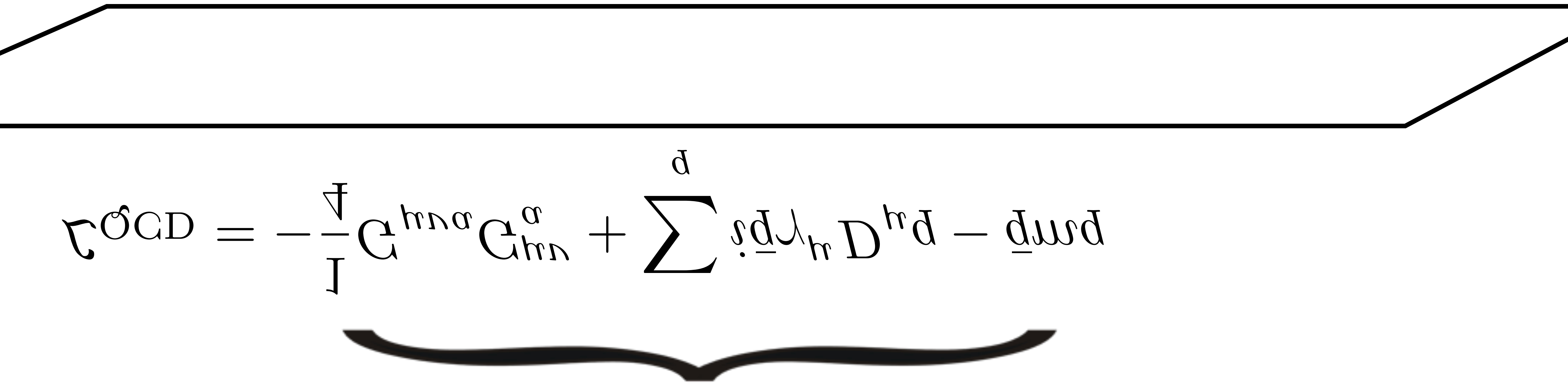
$$\frac{R(\bar{K}^0 \to K^0) - R(K^0 \to \bar{K}^0)}{R(\bar{K}^0 \to K^0) + R(K^0 \to \bar{K}^0)}$$



... but not in the strong interactions

Strong interactions SU(3)c (QCD)

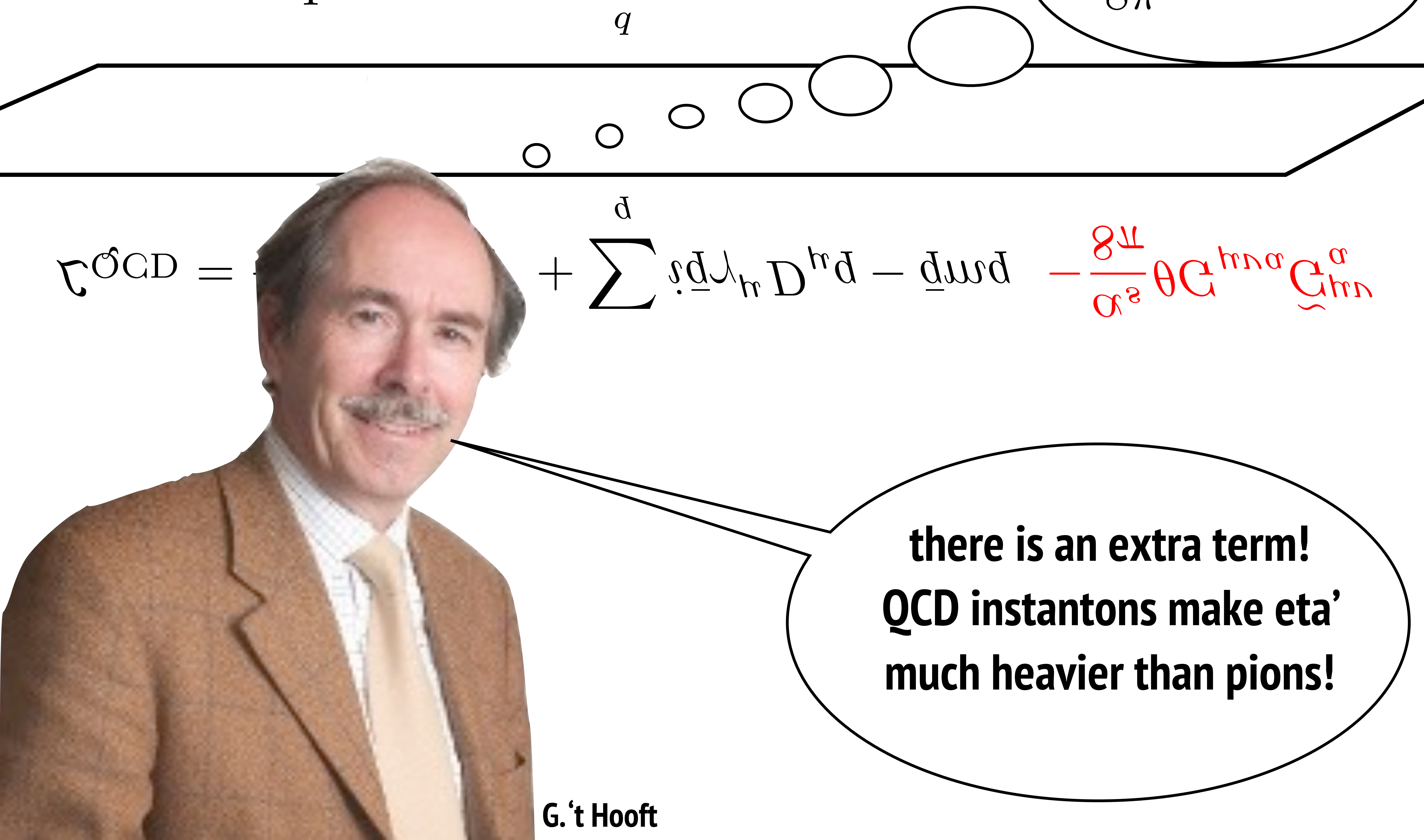
$$\mathcal{L}_{\rm QCD} = -\frac{1}{4} G_{\mu\nu a} G^{\mu\nu}_a + \sum_q i\bar{q}\gamma^\mu D_\mu q - \bar{q} m q$$



P,T equivalent by construction

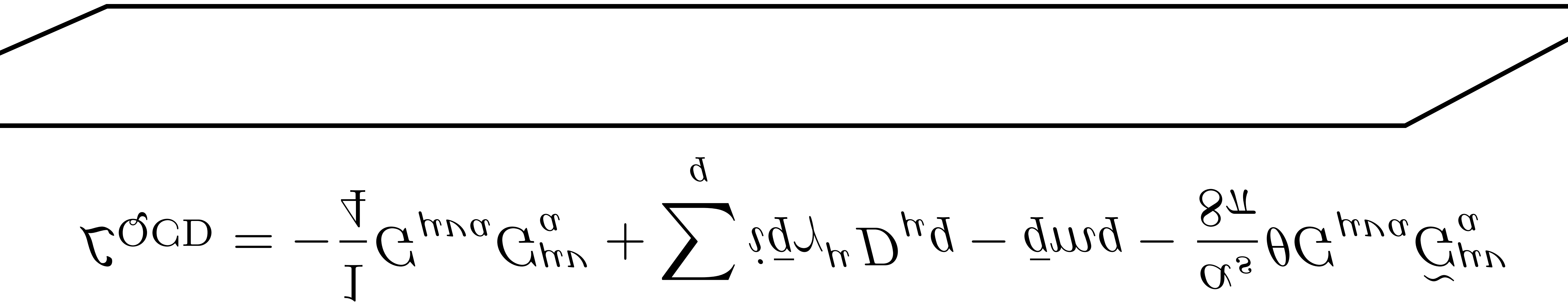
Strong interactions SU(3)c (QCD)

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4} G_{\mu\nu a} G^{\mu\nu}_{a} + \sum_q i\bar{q}\gamma^\mu D_\mu q - \bar{q} m q \quad + \frac{\alpha_s}{8\pi} \theta G_{\mu\nu a} \widetilde{G}^{\mu\nu}_{a}$$



Strong interactions SU(3)c (QCD)

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4} G_{\mu\nu a} G^{\mu\nu}_{a} + \sum_q i\bar{q}\gamma^\mu D_\mu q - \bar{q} m q + \frac{\alpha_s}{8\pi}\theta G_{\mu\nu a}\widetilde{G}^{\mu\nu}_{a}$$

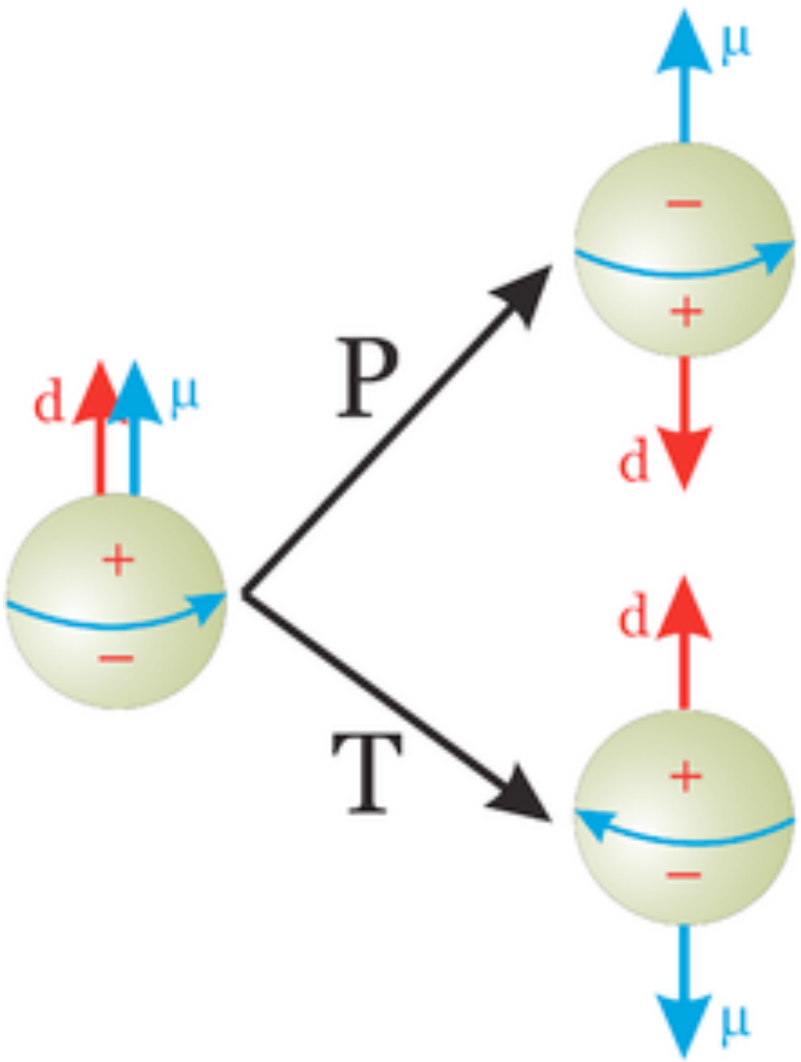


$$\frac{\alpha_s}{8\pi}\theta G_{\mu\nu a}\widetilde{G}^{\mu\nu}_{a}$$ **induces P and T (CP) violation** $\propto \theta$

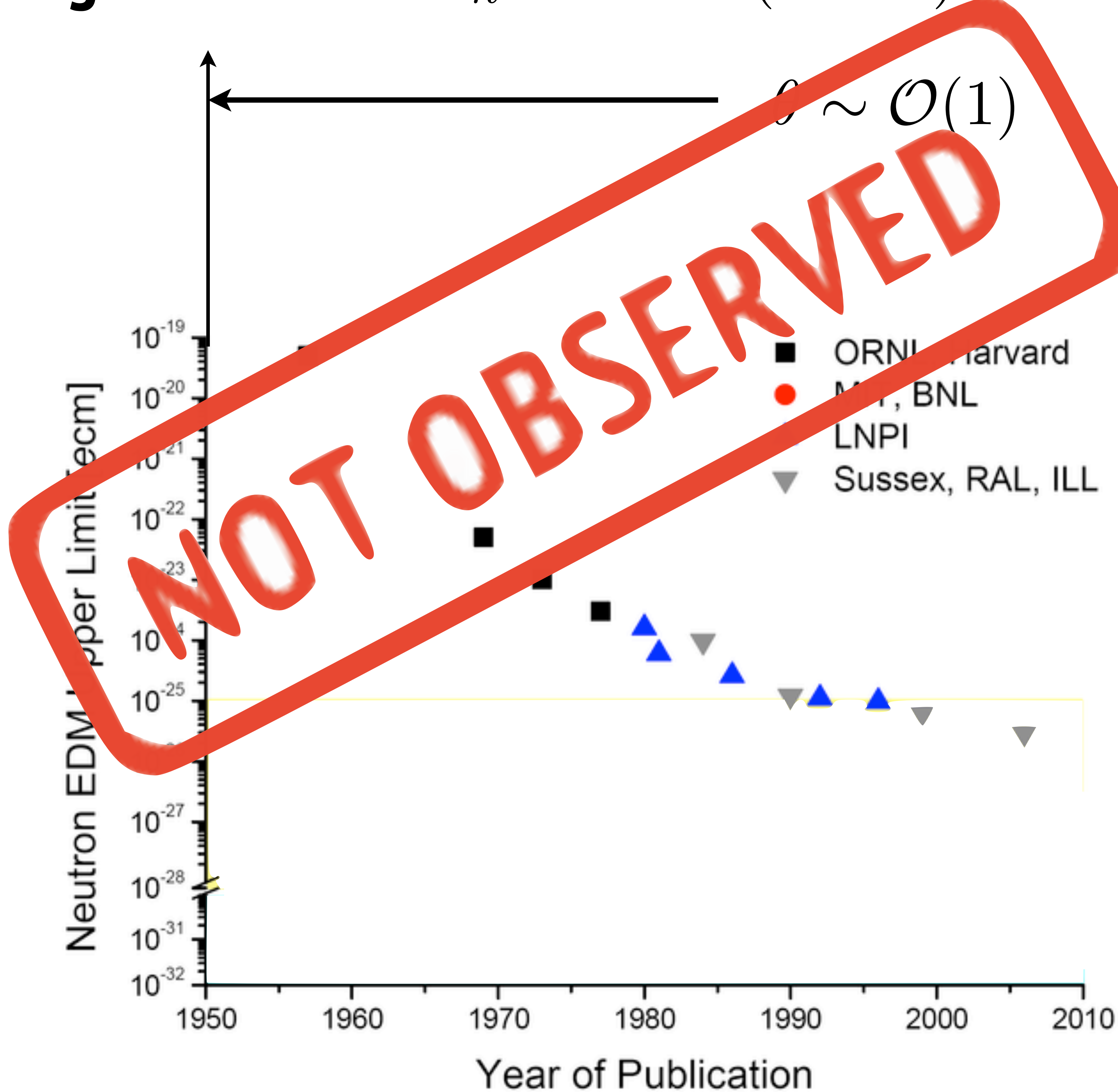
$\theta \in (-\pi, \pi)$ **infinitely versions of QCD... all are P,T violating**

Neutron EDM

Most important P, T violating observable $d_n \sim \theta \times \mathcal{O}(10^{-15})\mathrm{e\,cm}$

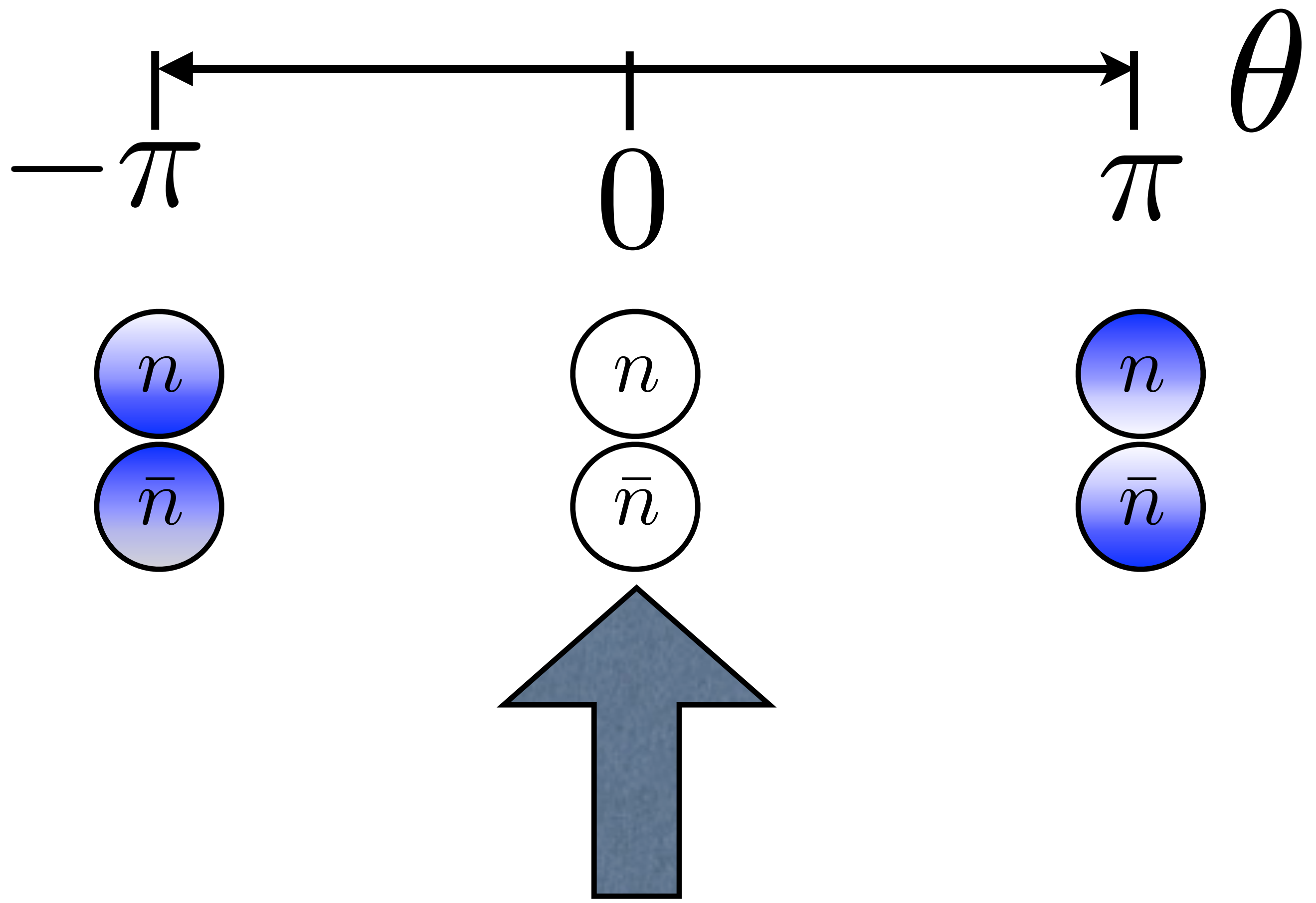


EDM violates P,T



The theta angle of the strong interactions

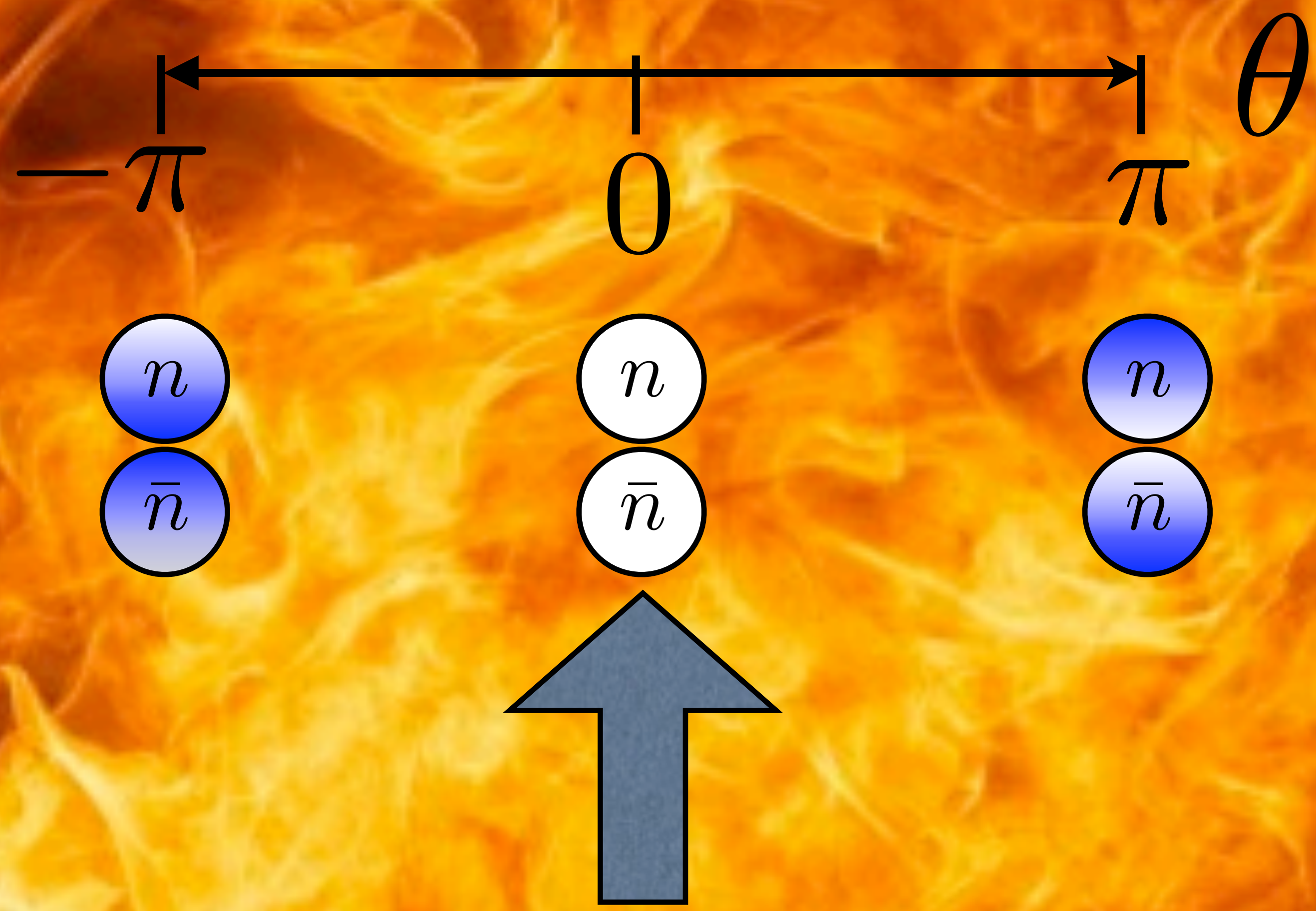
- The value of θ controls P,T violation in QCD



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

is there any preferred value for θ ?

no preferred value at high Temperature ($T > \Lambda_{\rm QCD}$)



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.

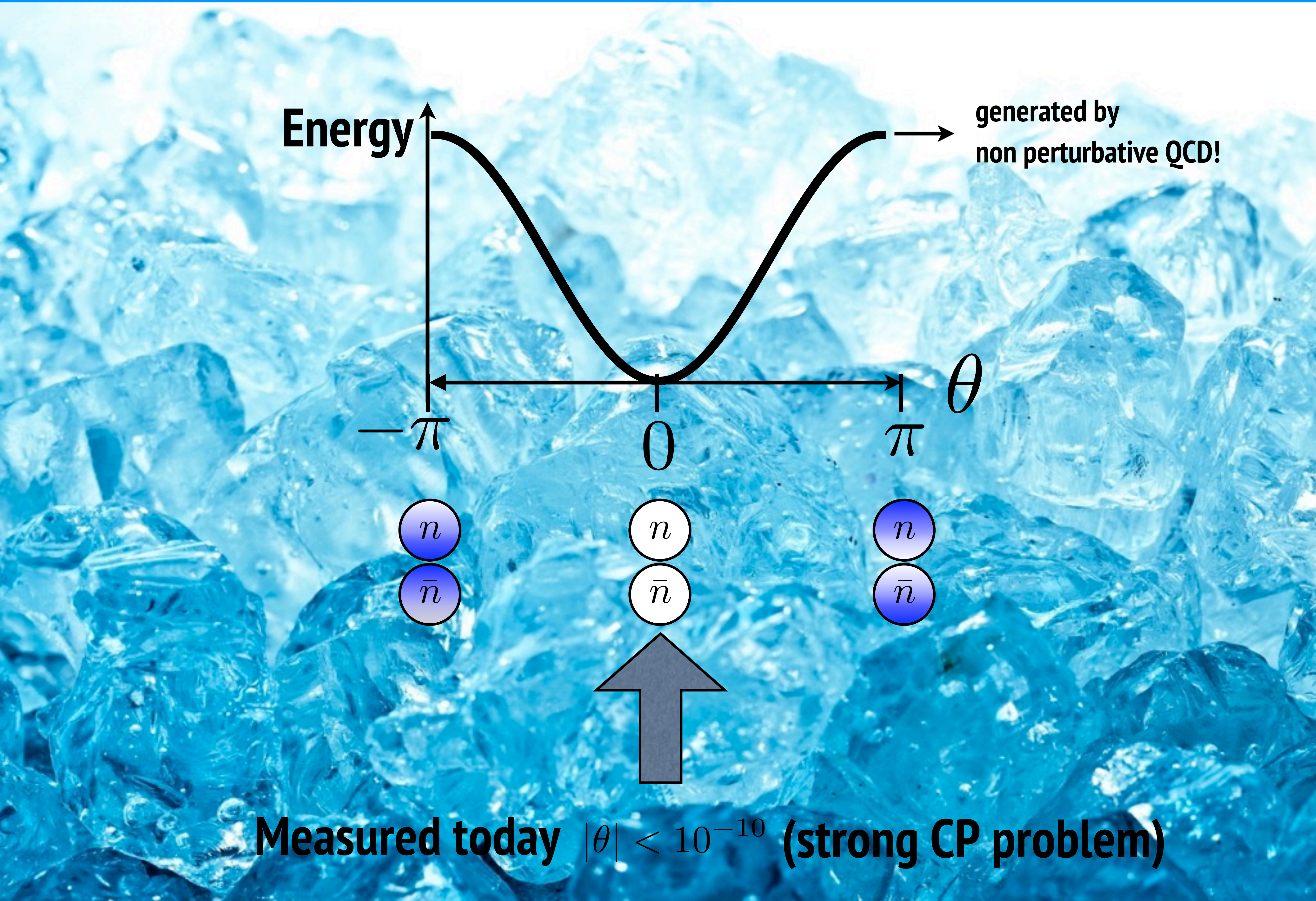
If all fermions which couple to the non-Abelian

(1)

(2)

(3)

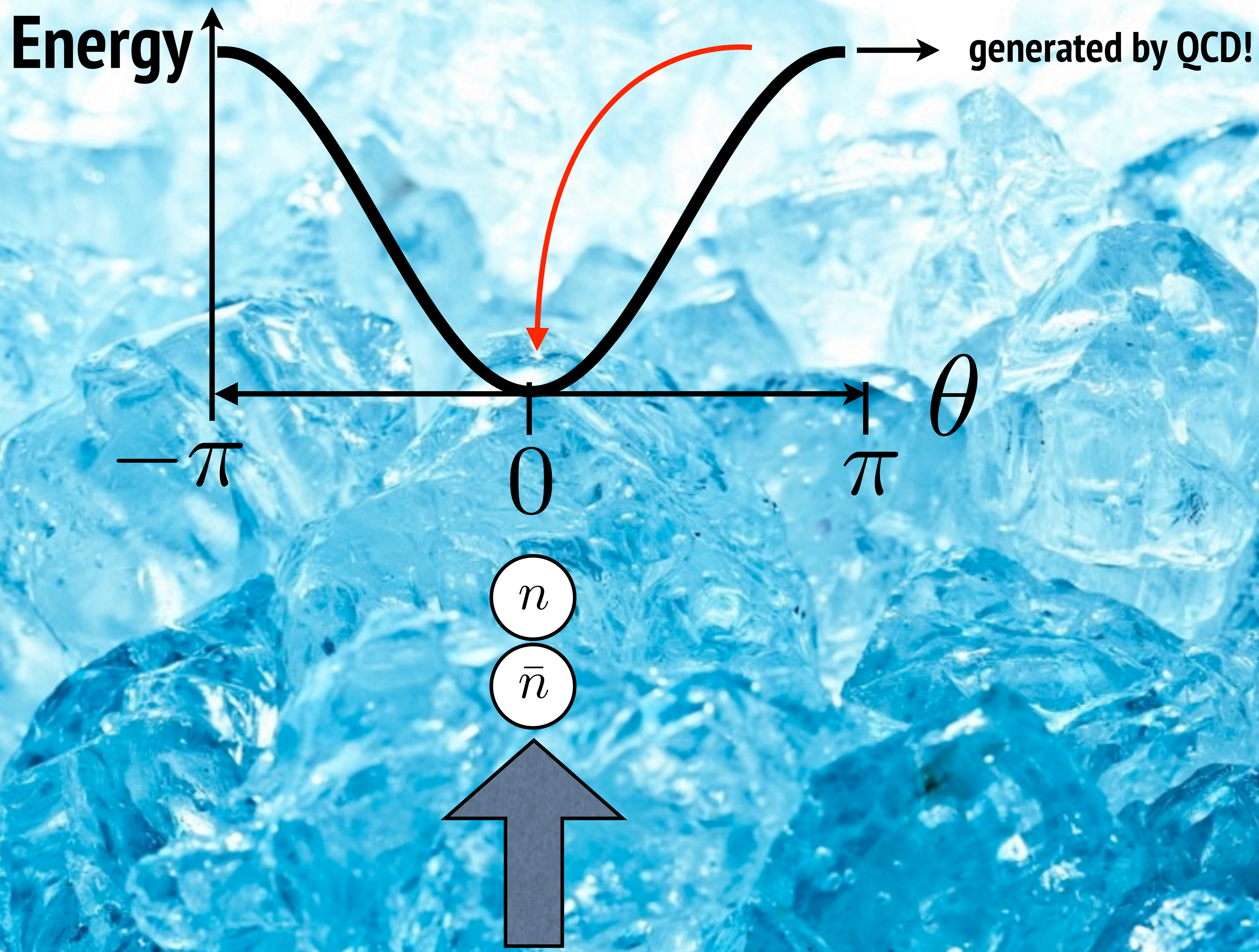
below confinement, theta = 0 minimises vacuum energy!



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

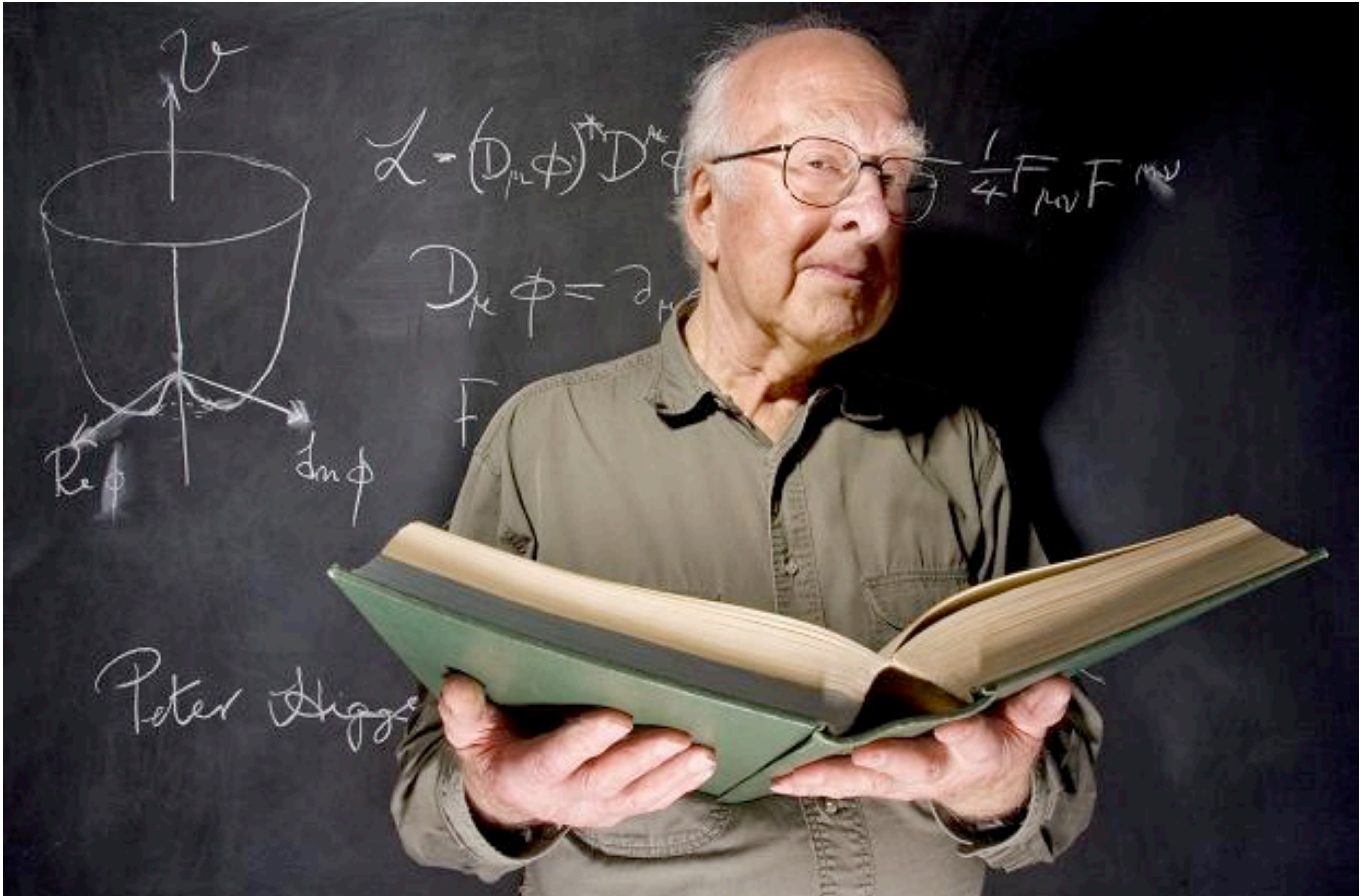
QCD vacuum energy minimised at theta = 0

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



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

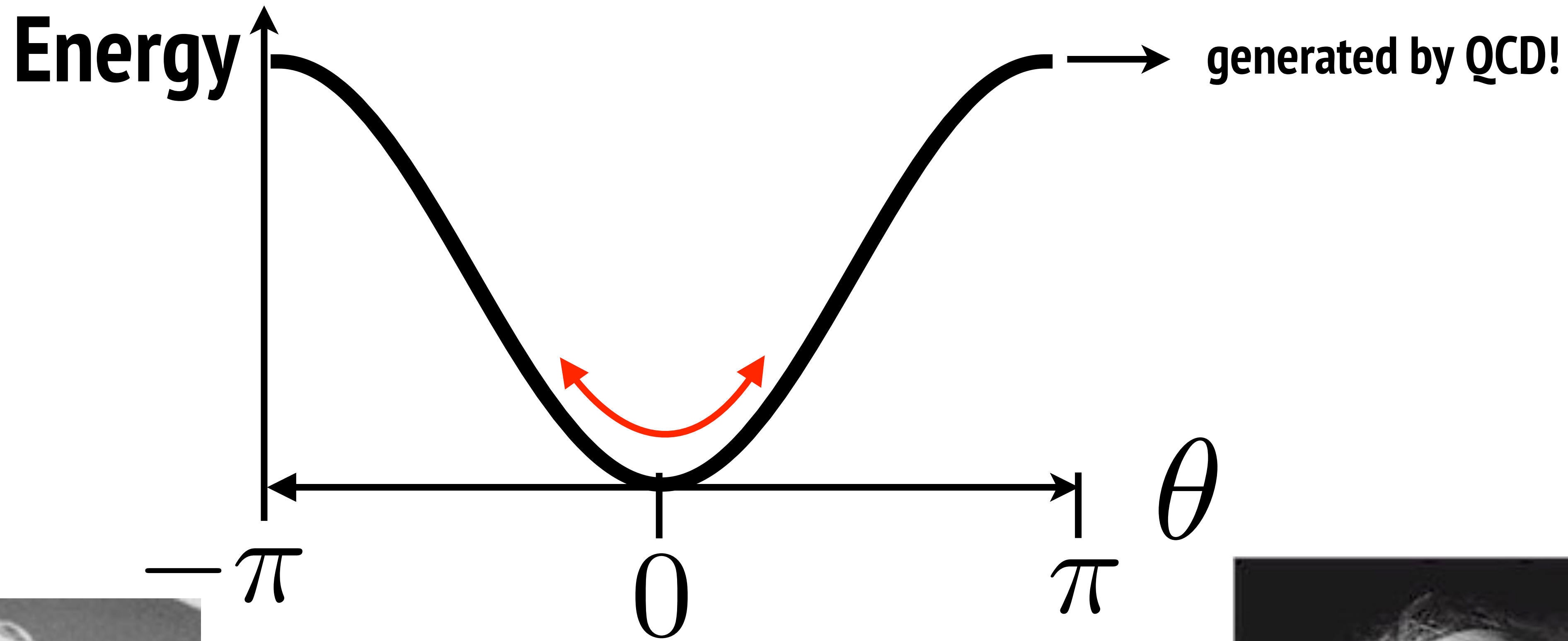
ain’t you forgetting something?



P. Higgs

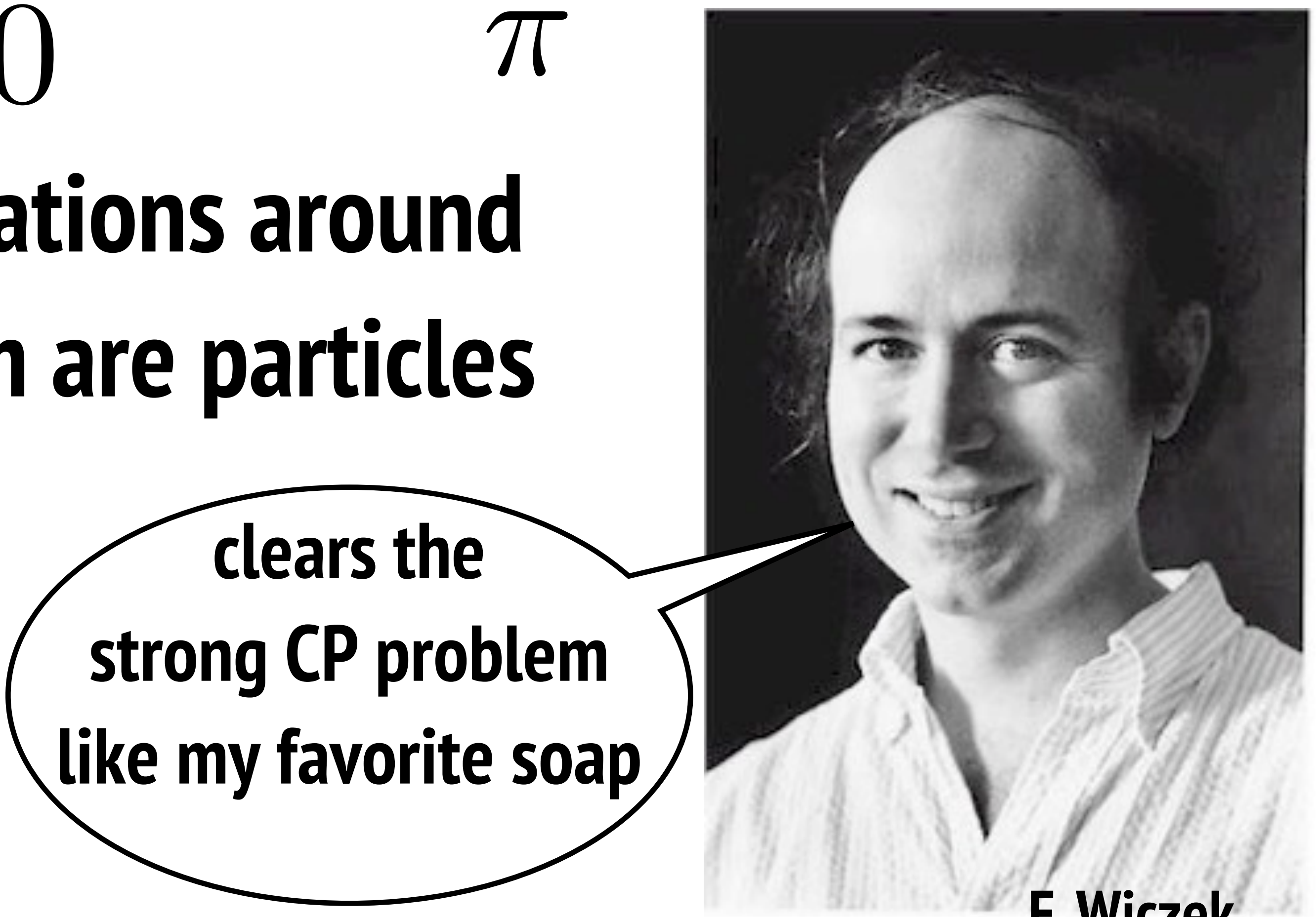
and a new particle is born ...

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



Field Excitations around the vacuum are particles

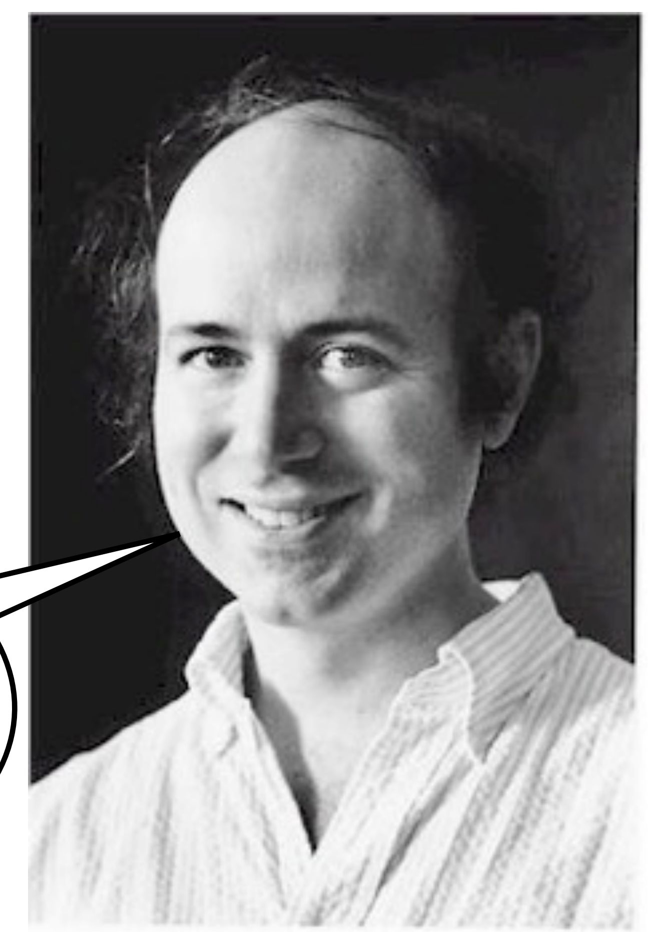
S. Weinberg



F. Wiczek

and a new particle is born ... the axion

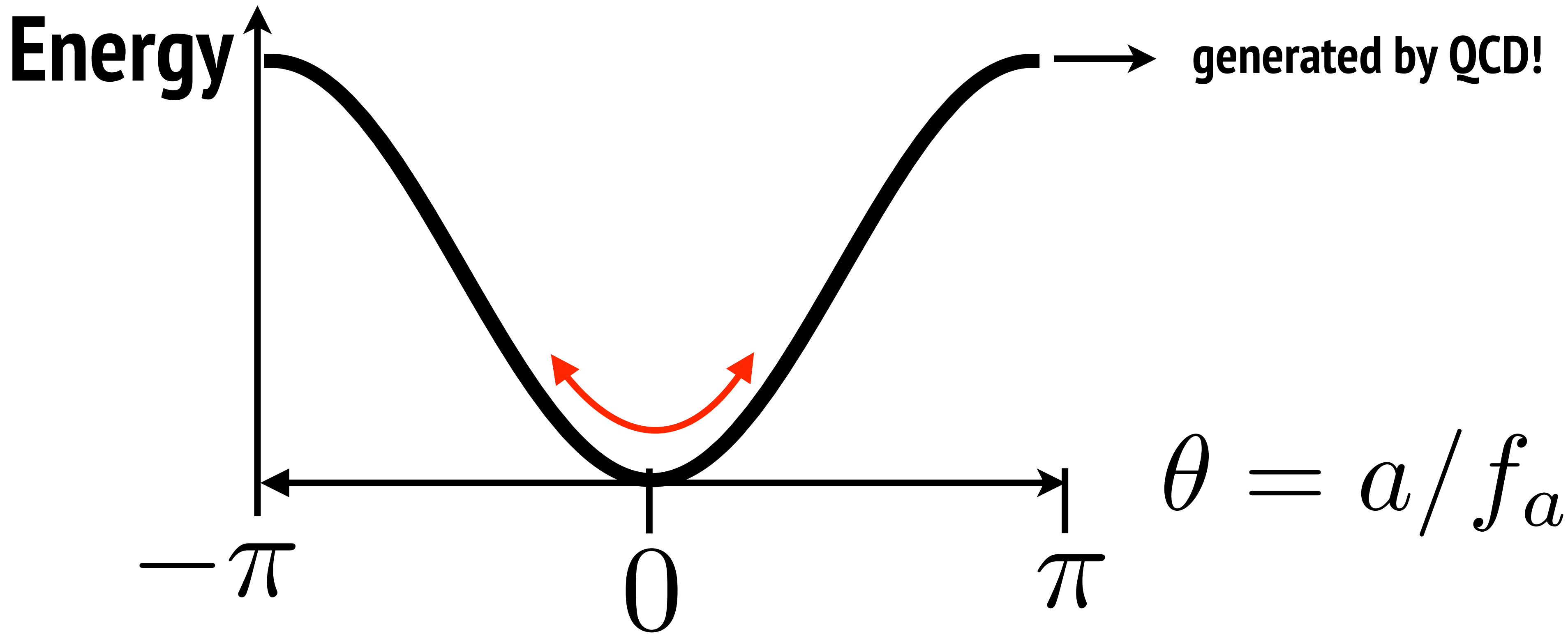
- if $\theta(t, \mathbf{x})$ is dynamical field



how do we search for the axion?

and a new scale sets the game, fa

- kinetic term for θ requires a new scale



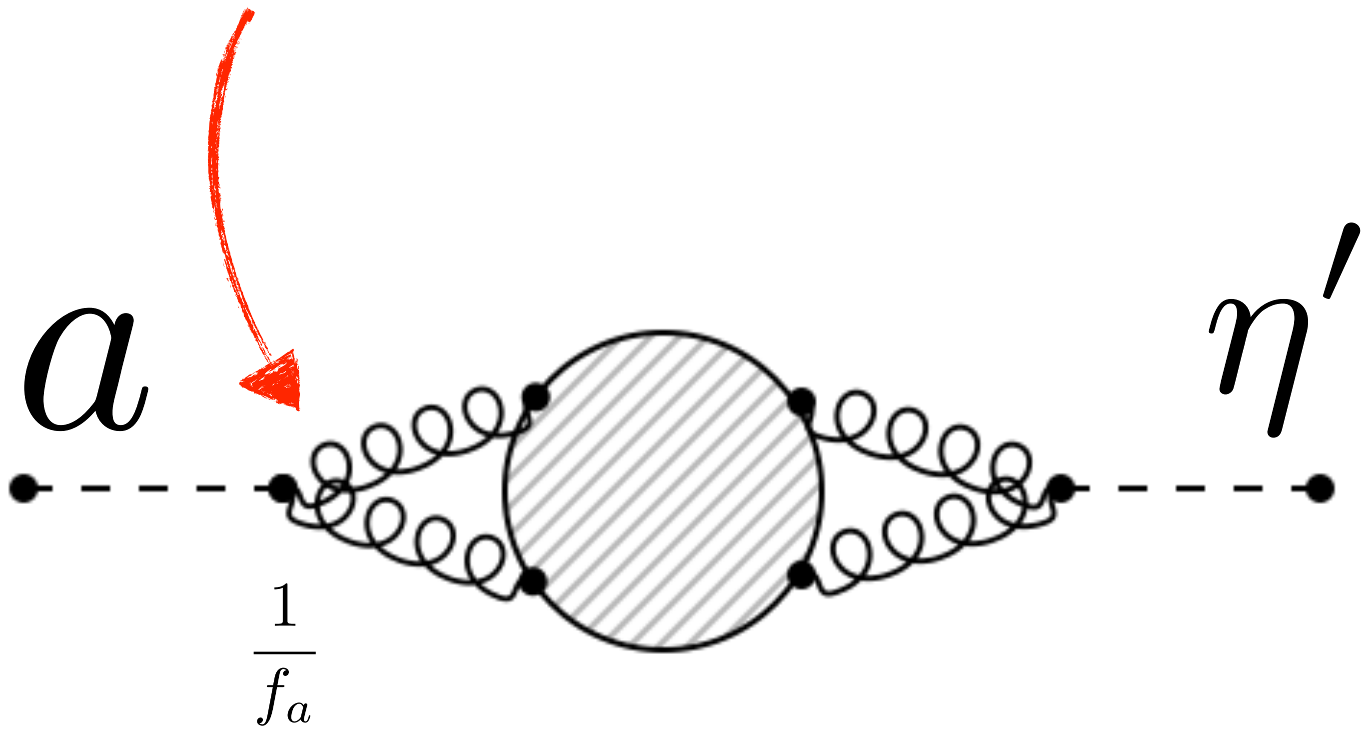
$$\mathcal{L}_\theta = \frac{\alpha_s}{8\pi} G_{\mu\nu a}\widetilde{G}^{\mu\nu}_a \theta + \frac{1}{2}(\partial_\mu\theta)(\partial^\mu\theta) f_a^2$$

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

Axion couplings at low energy

- From θ-term, axion mixes with eta' and the rest of mesons

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

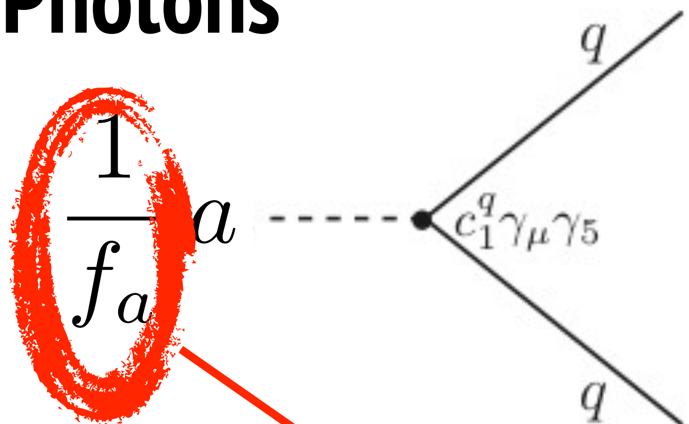


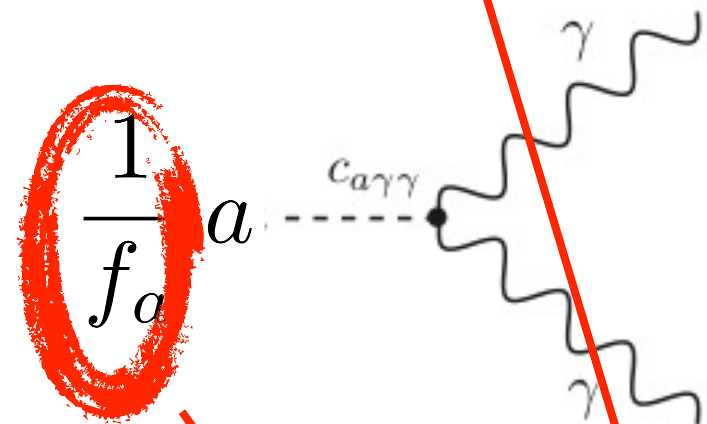
Axion couplings at low energy

Mass

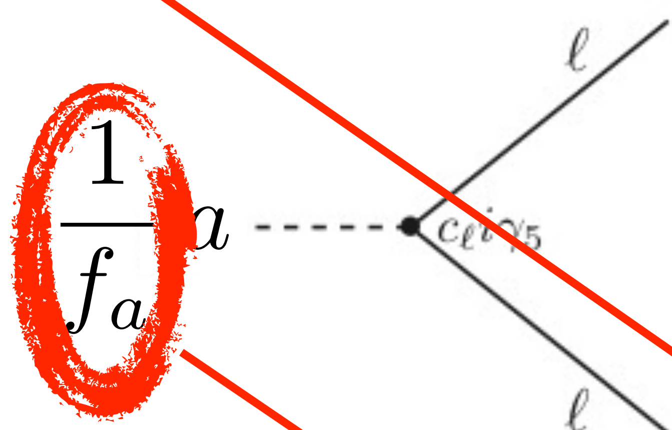
$$m_a \simeq m_\pi \frac{f_\pi}{f_a} \simeq 6 \text{ meV} \frac{10^9 \text{GeV}}{f_a}$$

hadrons, Photons



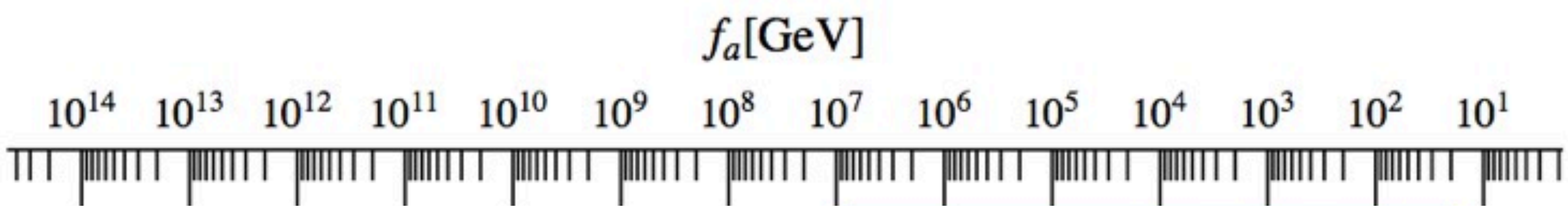


Leptons (in some models)



The lighter the more weakly interacting

Axion Landscape



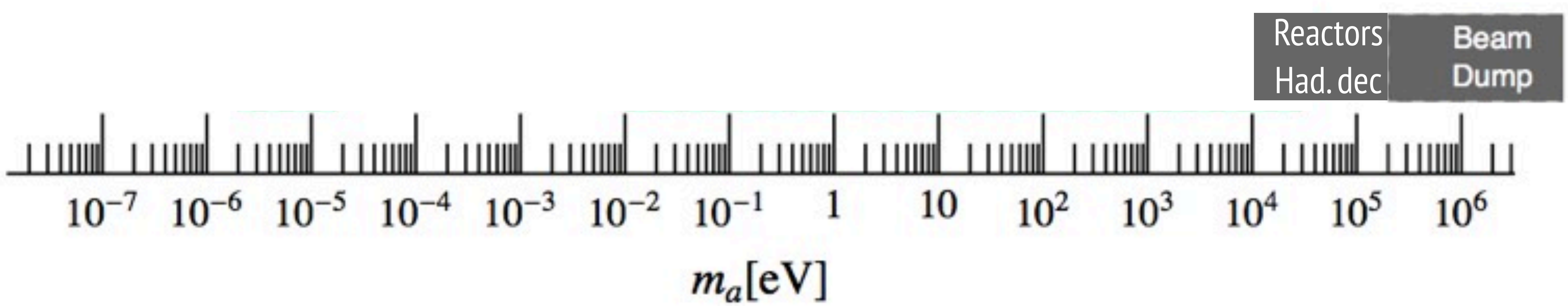
$$f_a \gg v_{\rm EW}$$

Invisible models

$$f_a \sim v_{\rm EW}$$

PQWW models

(soon ruled out)



where does this new scale come from?

- Electroweak scale ruled out
- higher new physics scale, unrelated to others ...
- It can be ~ grand unification scale
- It can be ~ string scale

where does this new scale come from?

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- higher new physics scale, unrelated to others ...
- It can be ~ grand unification scale
- It can be ~ string scale

E. Witten ’06

heterotic string theory has a model independent axion

but others have plenty ... a string axiverse!

S. Dimopoulos ’10

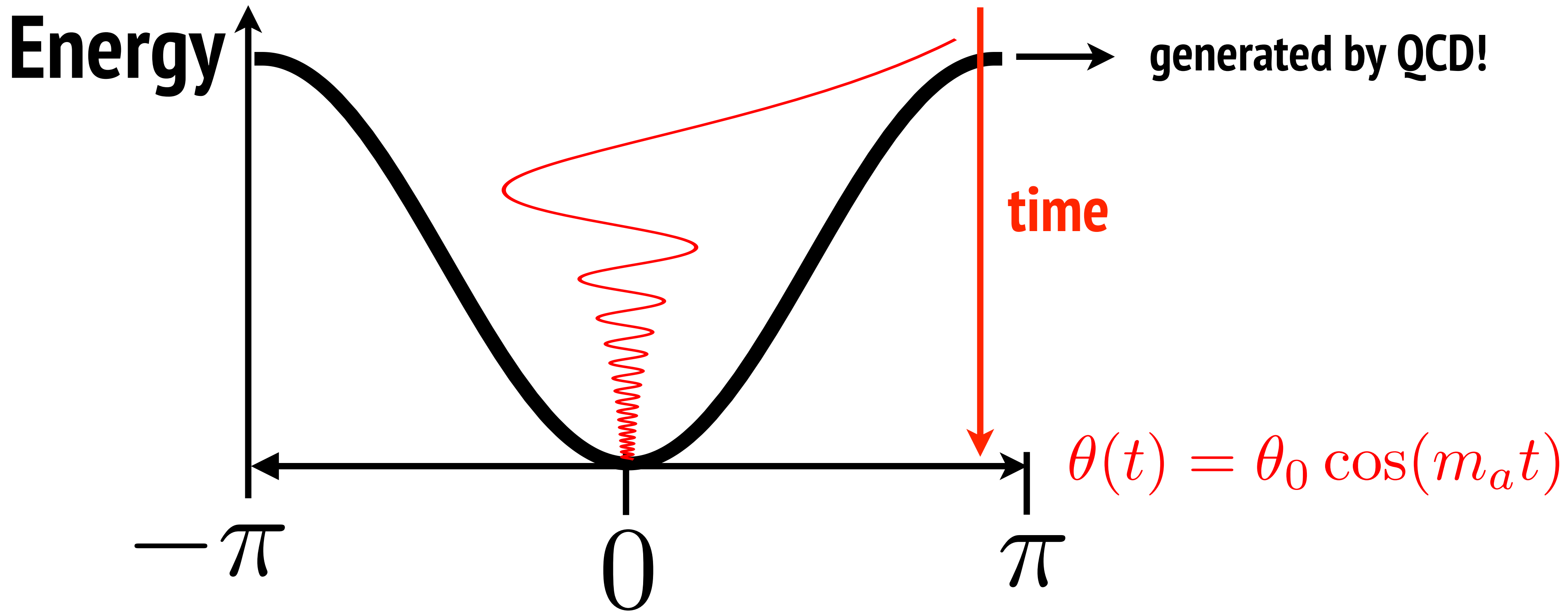
how do we search for such a weakly interacting (low mass) particle that interacts like a meson?

astrophysics and dark matter

Dark Matters

Axions and dark matter

- $\theta(t, \mathrm{x})$ **relaxes to its minimum, overshoots and oscillates**



Axions and dark matter

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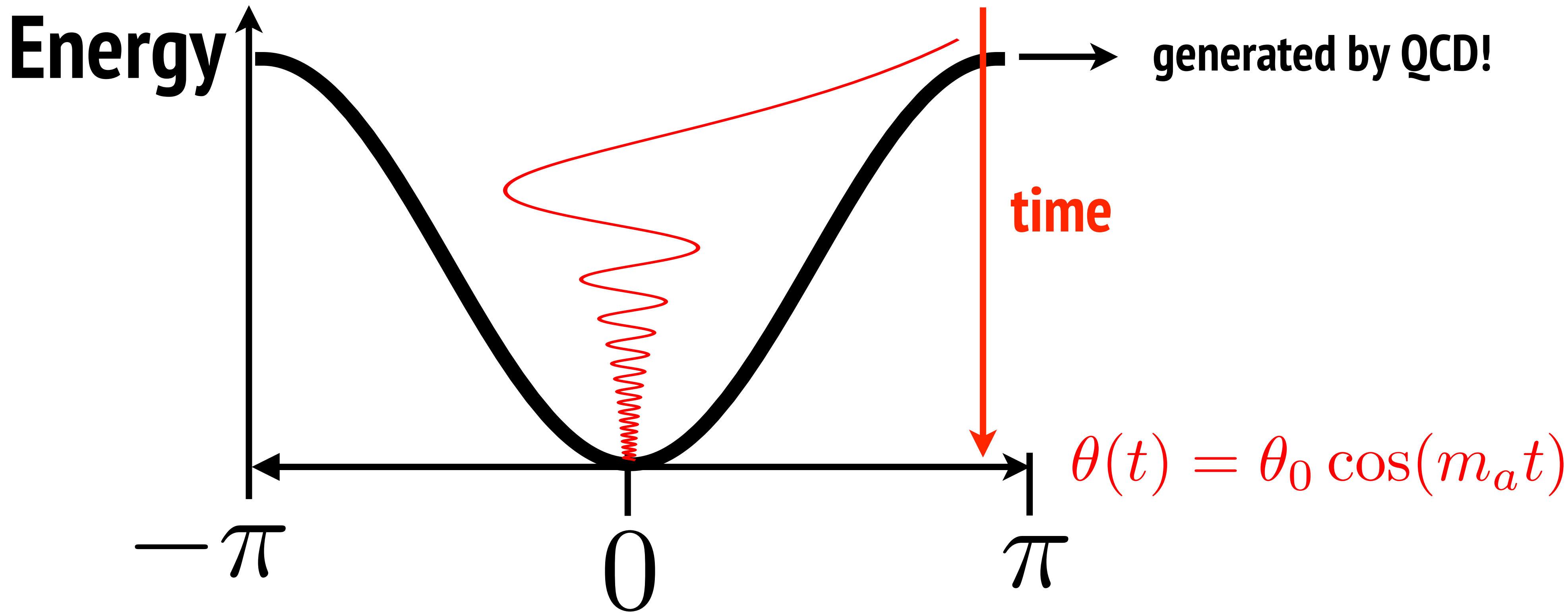
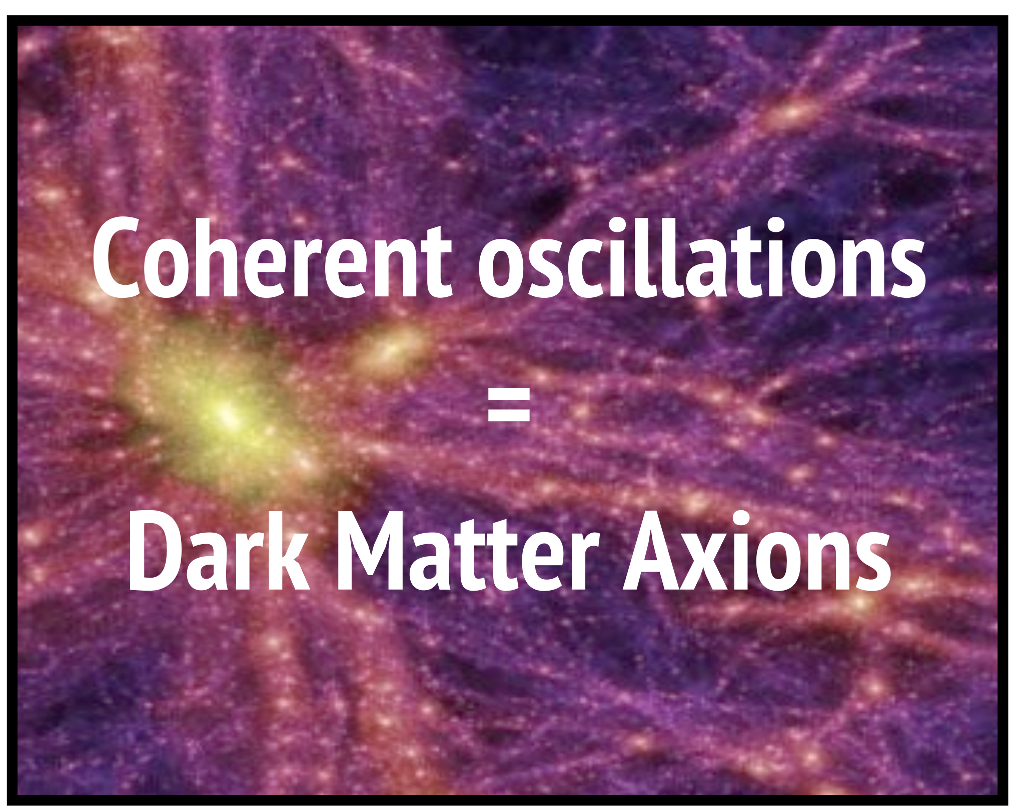
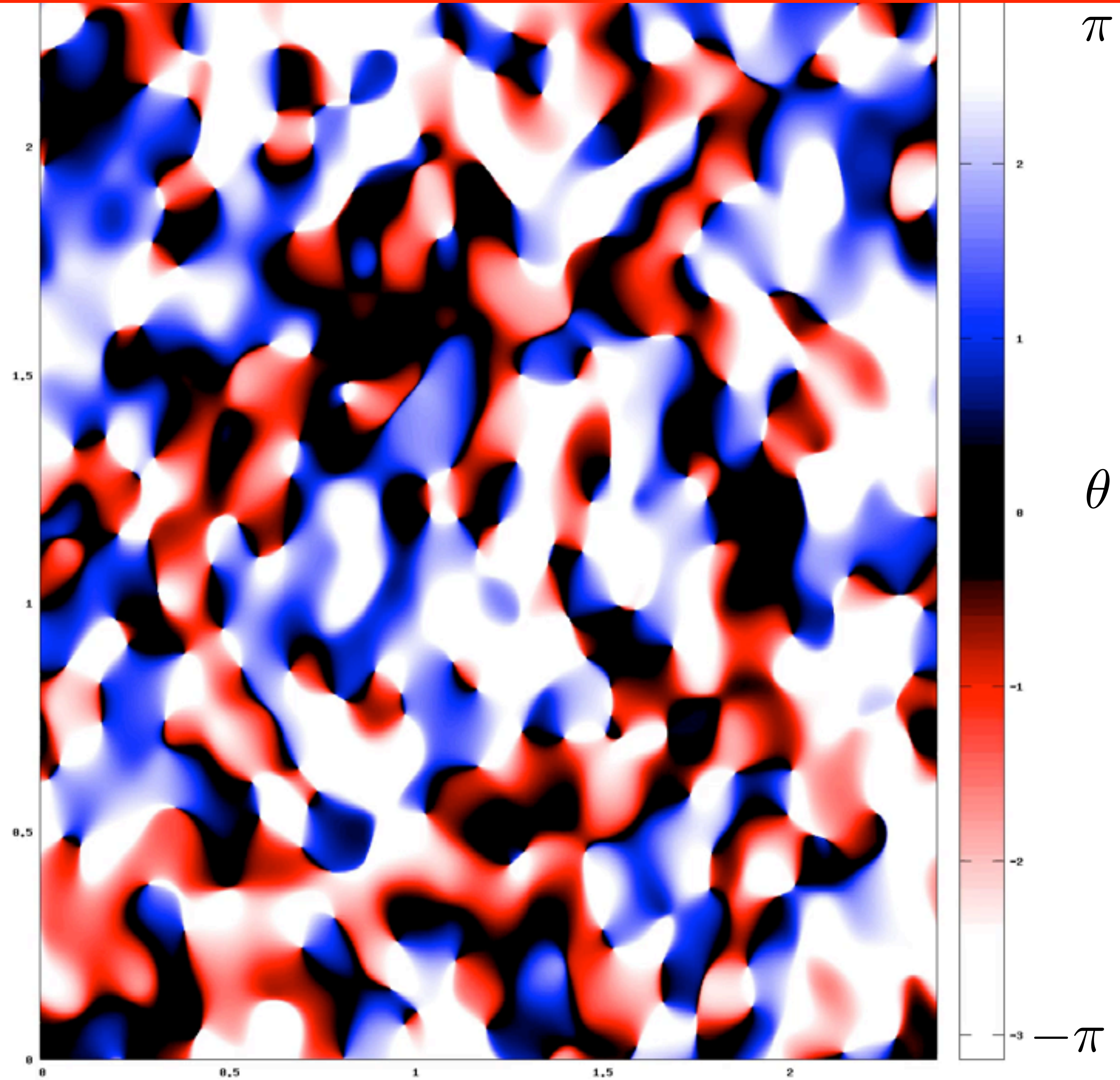
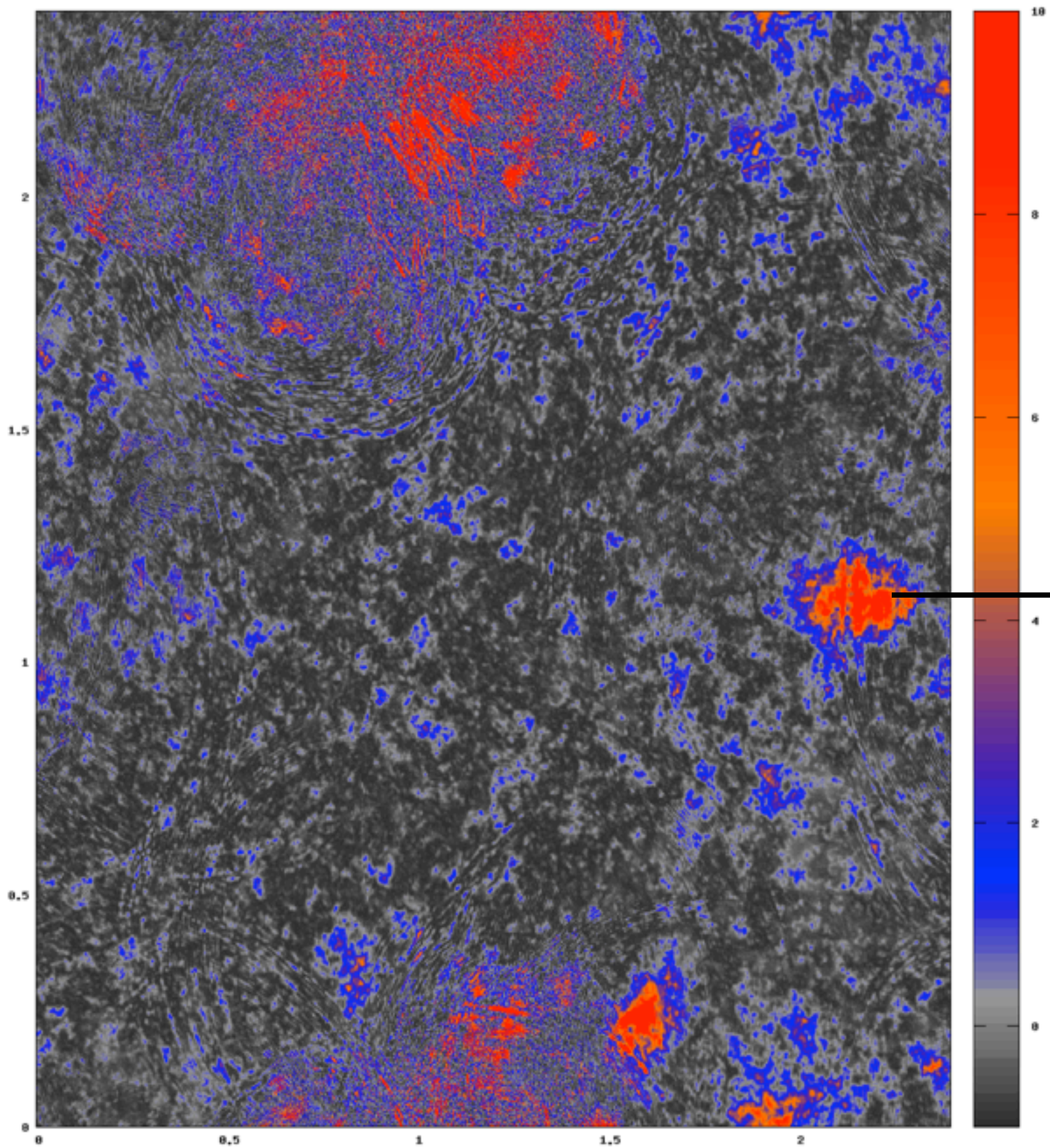




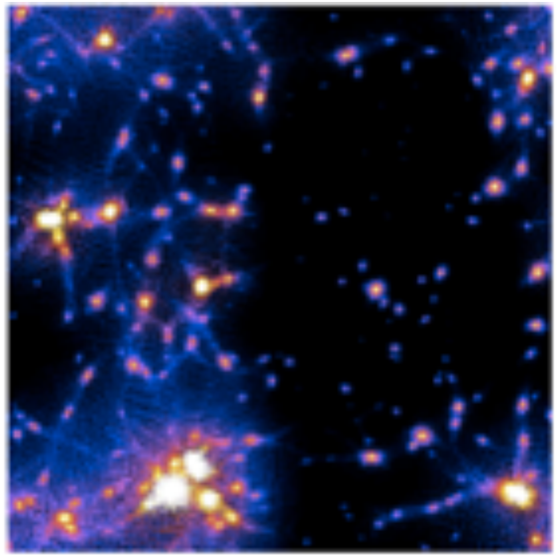
Theta evolution, Averaged SCENARIO I



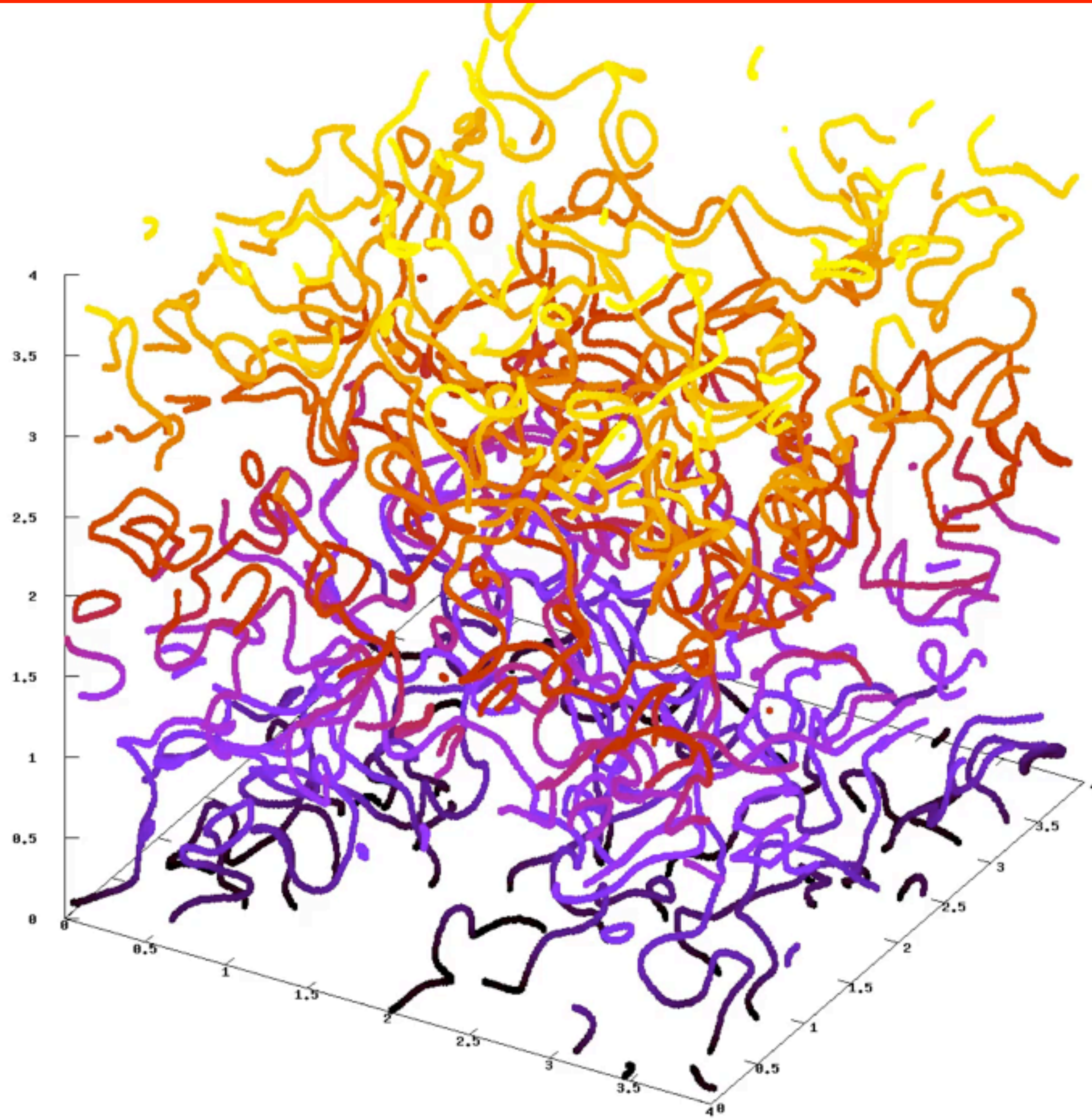
Dark matter density, inhomogeneous at comoving mpc scales



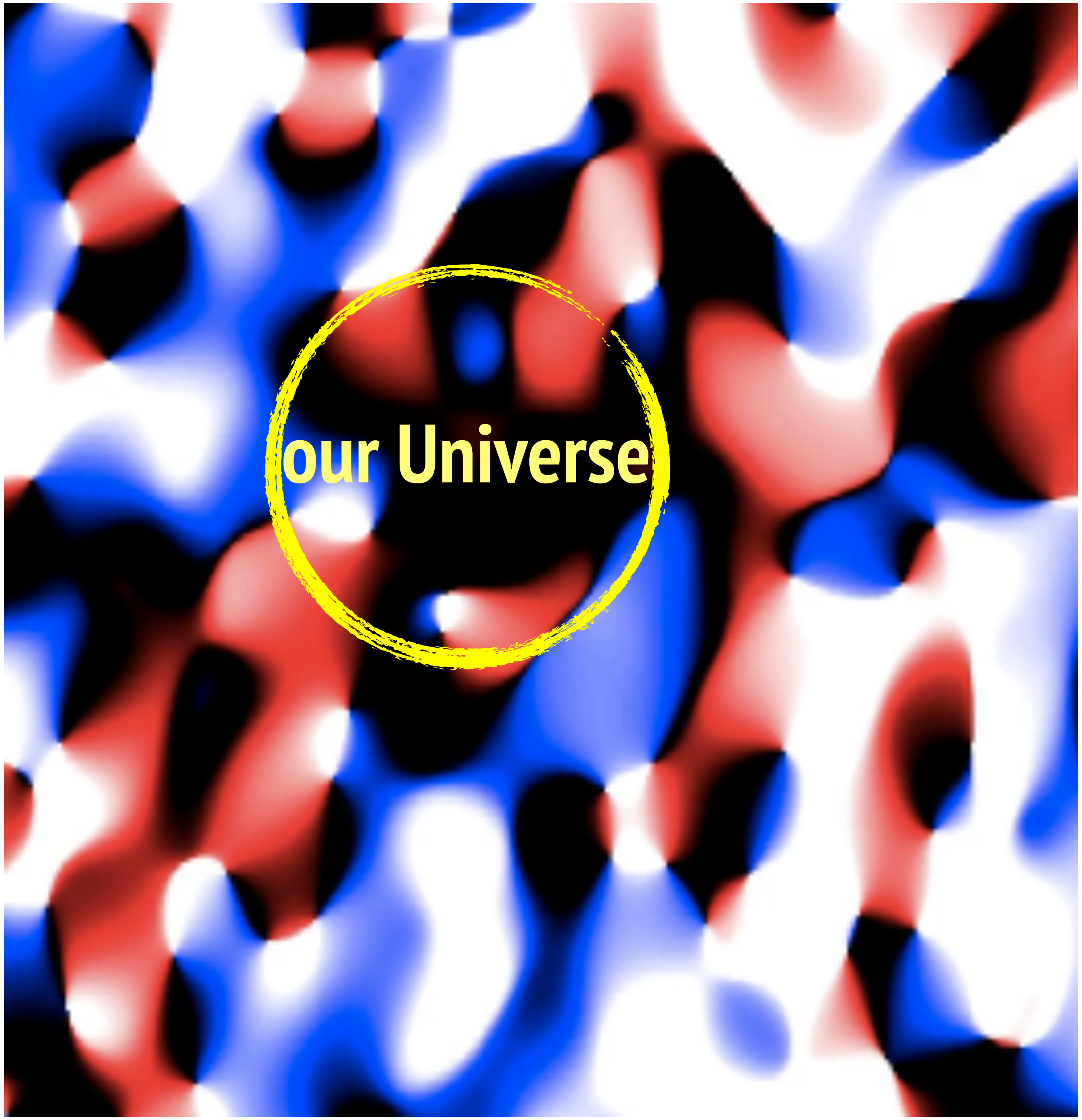
minicluster seed!



Strings



Theta evolution, inflated SCENARIO I



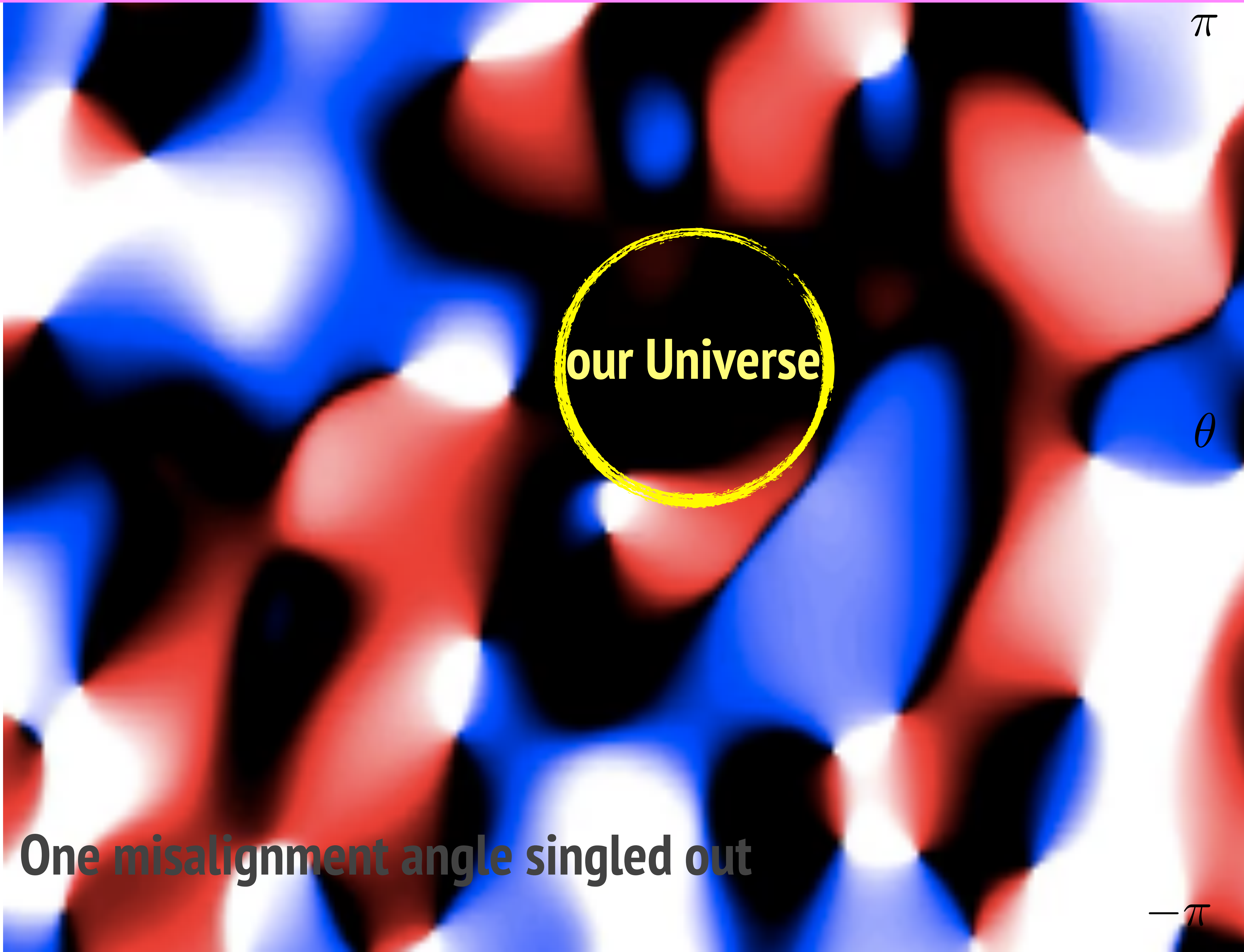
π

θ

$-\pi$

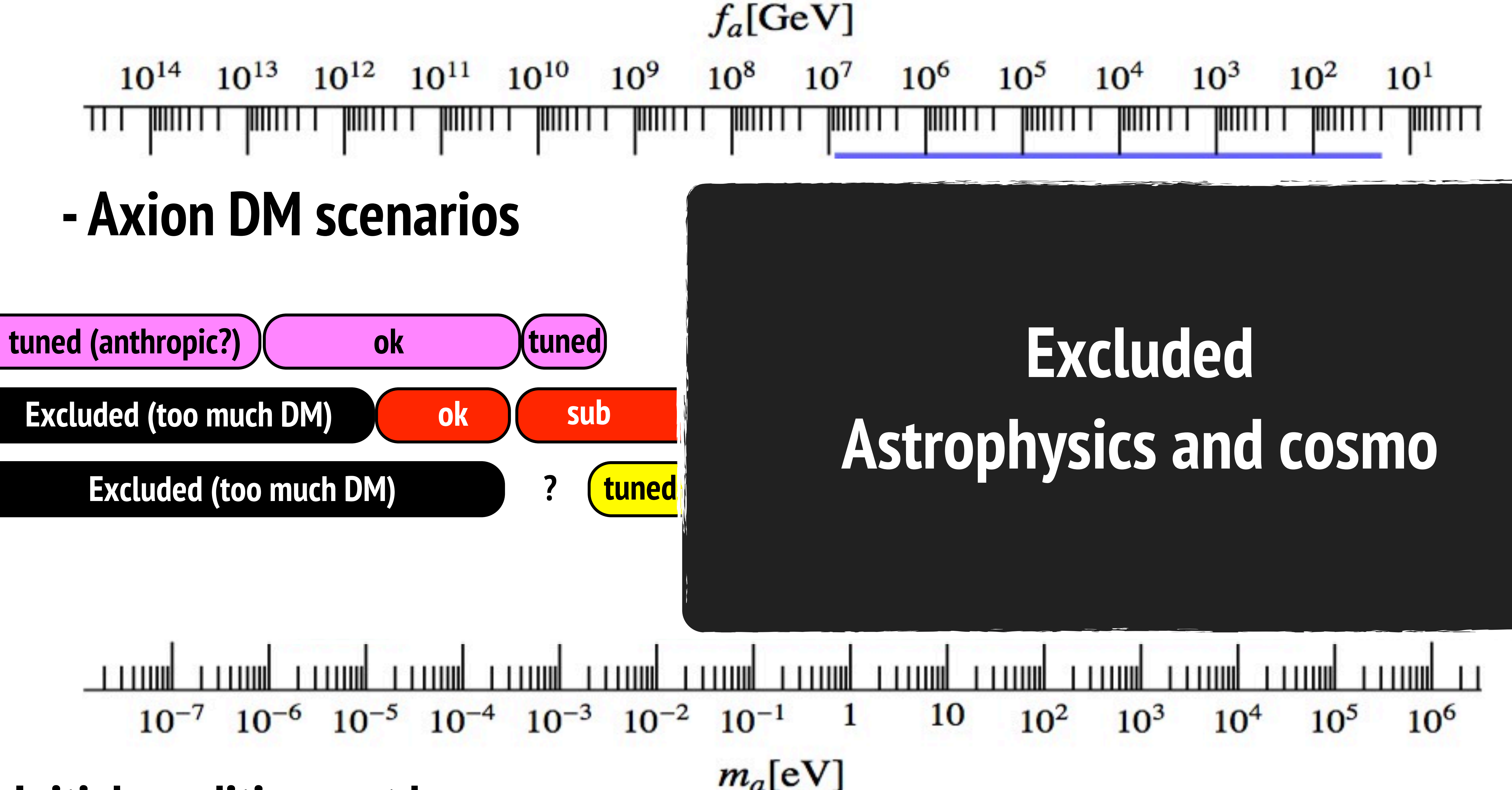
One misalignment angle singled out

Theta evolution, inflated SCENARIO I



Axion dark matter scenarios

- Axion DM scenarios



Initial conditions set by :

Inflation smooth

$$\Omega_{\rm aDM} h^2 \simeq \theta_I^2 \left(\frac{80\,\mu\rm eV}{m_a}\right)^{1.19}$$

Phase transition (N=1)

strings+unstable DW's

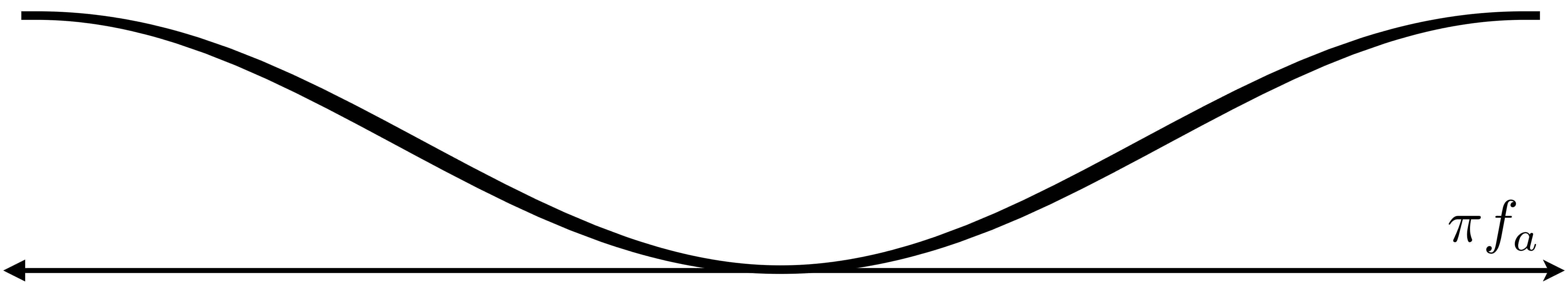
Phase transition (N>1)

strings+long-lived DWs

Axion dark matter

- The amount of axion DM produced depends on fa

- large fa, small curvature, oscillations start later->more DM



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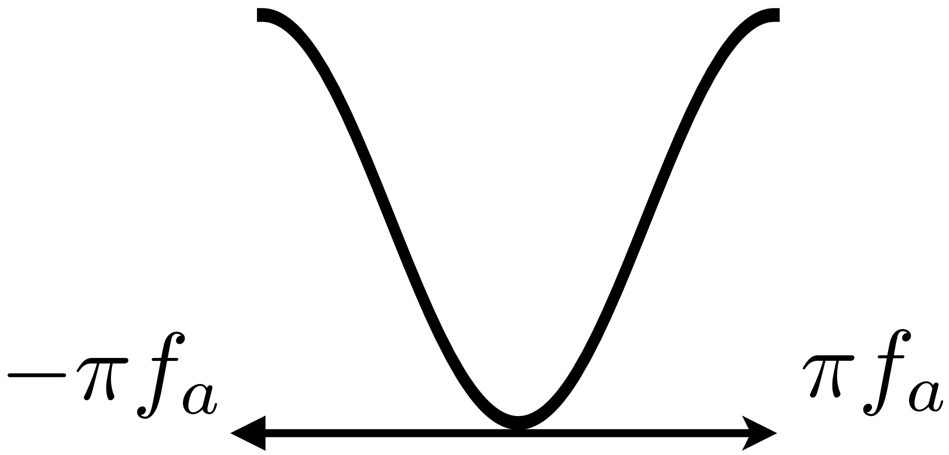

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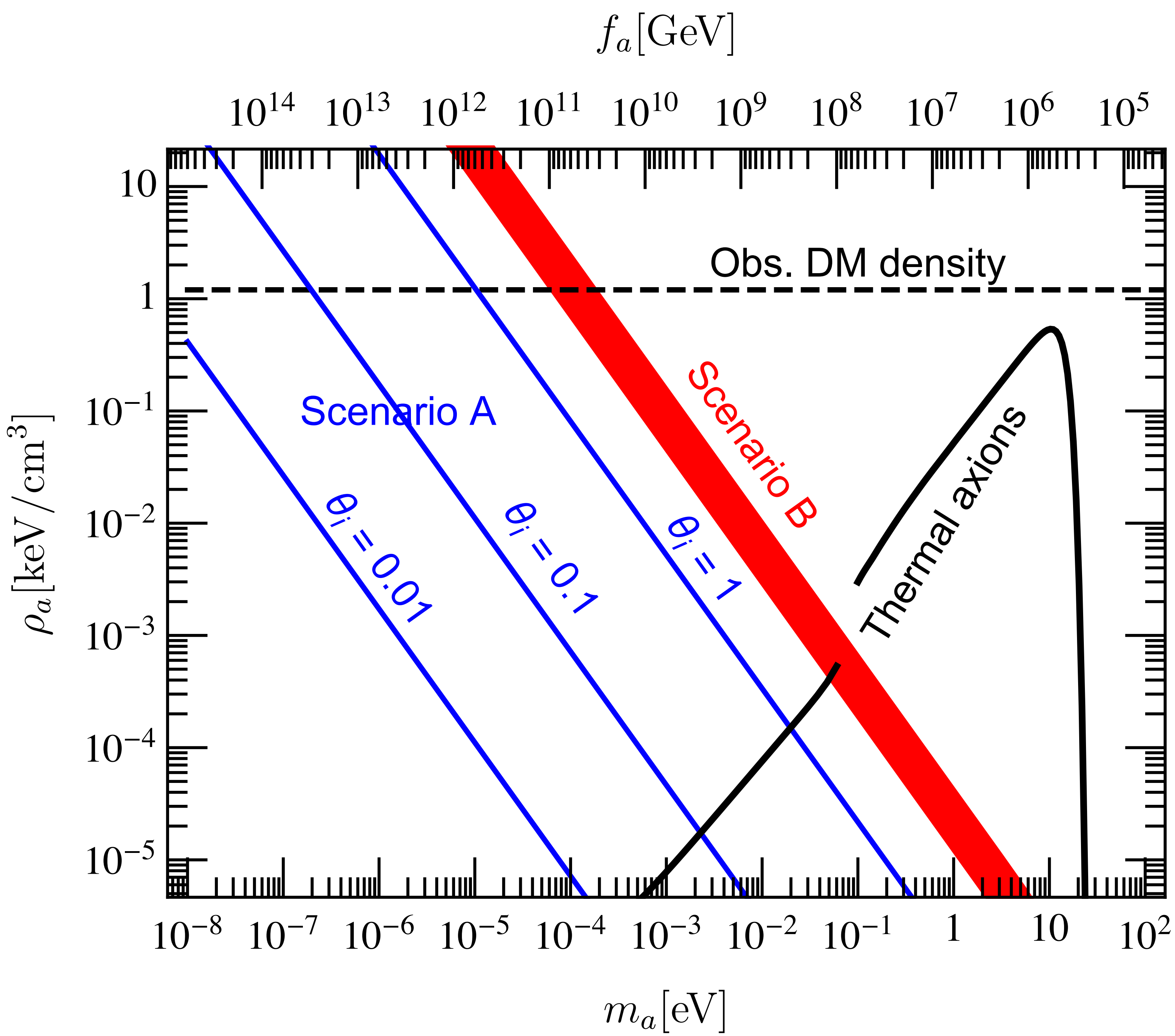
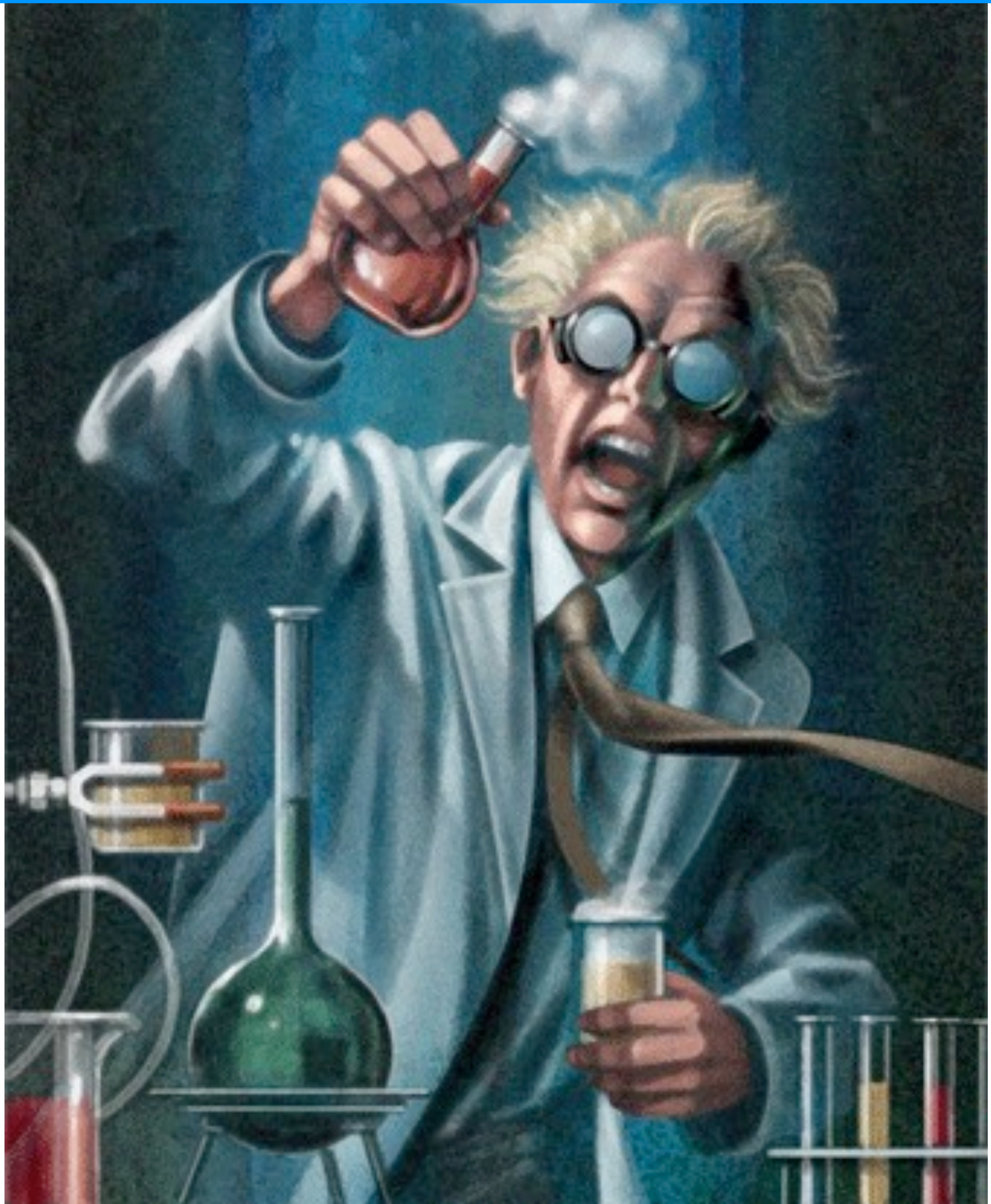
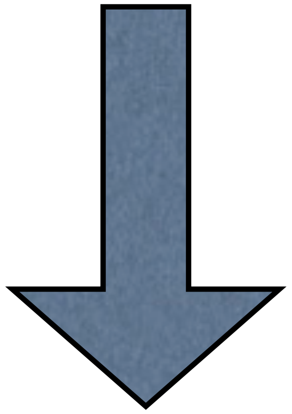


Detecting SCI Axions

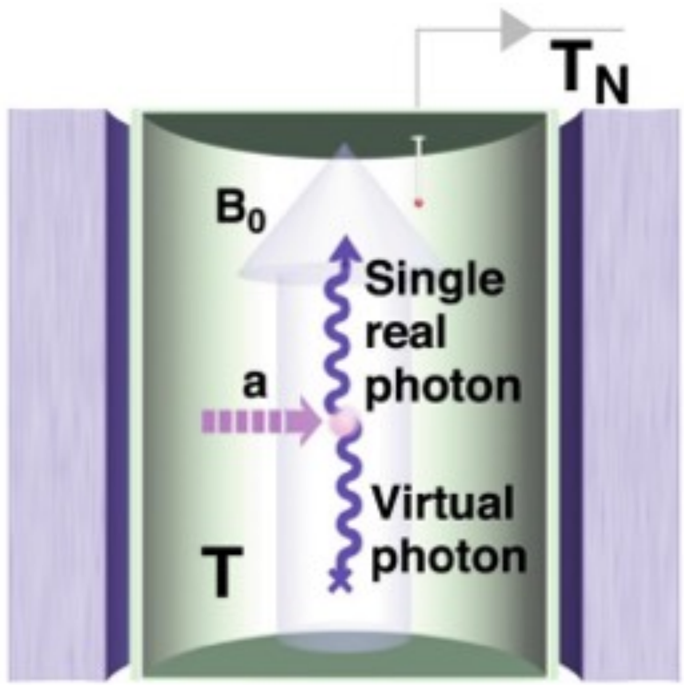


$$\rho_{\mathrm{aDM}} = 0.3 \frac{\mathrm{GeV}}{\mathrm{cm}^3}$$

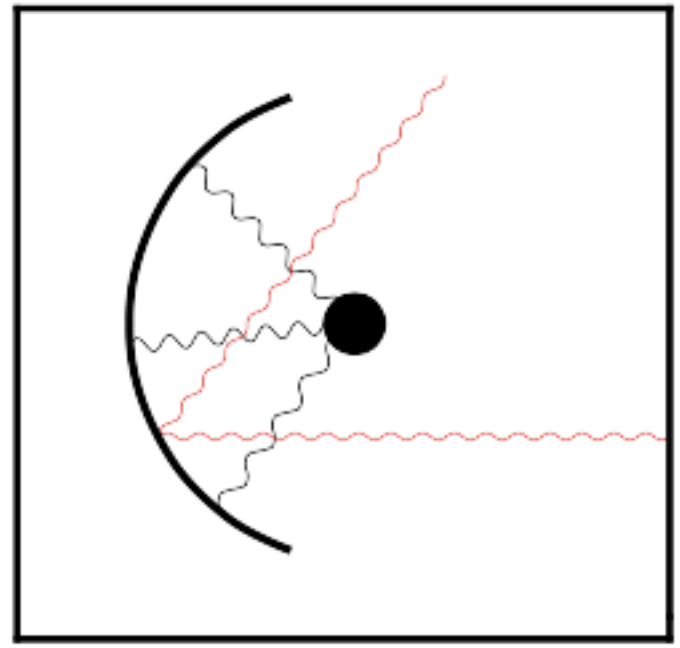


$$\theta_0 = 3.6 \times 10^{-19}$$

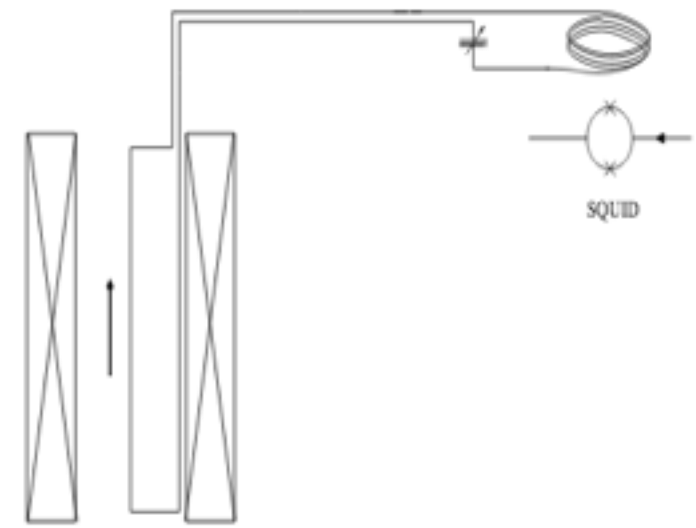
Cavities



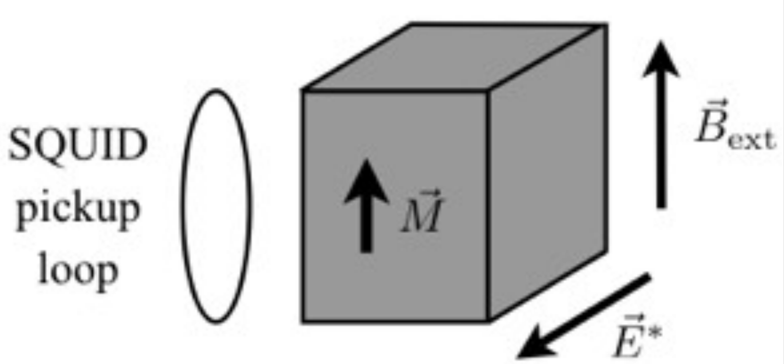
Mirrors



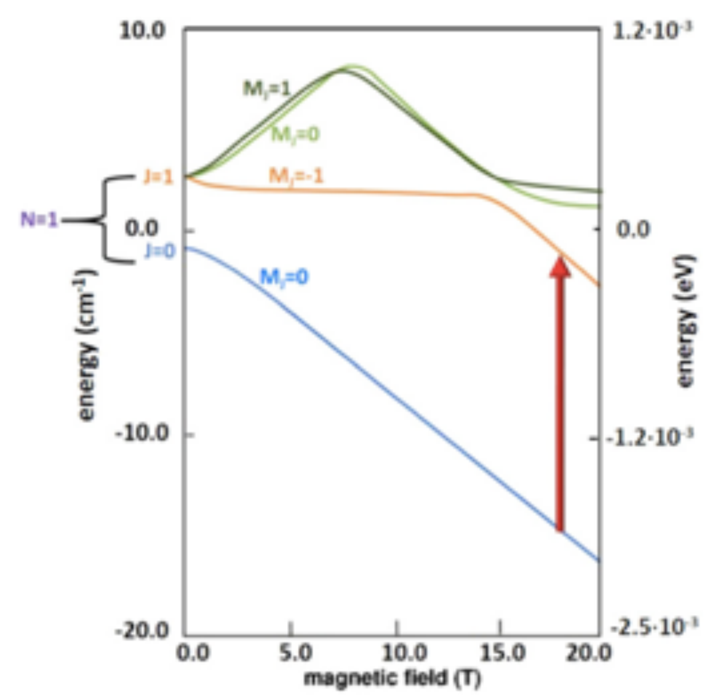
LC-circuit



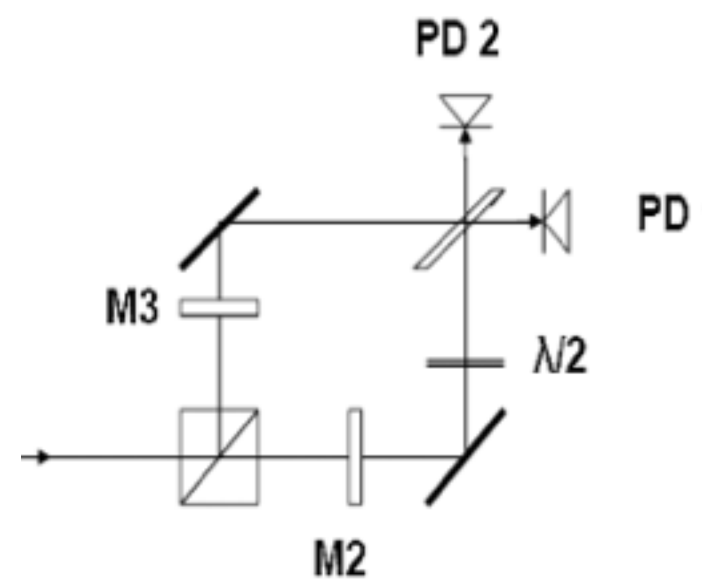
Spin precession



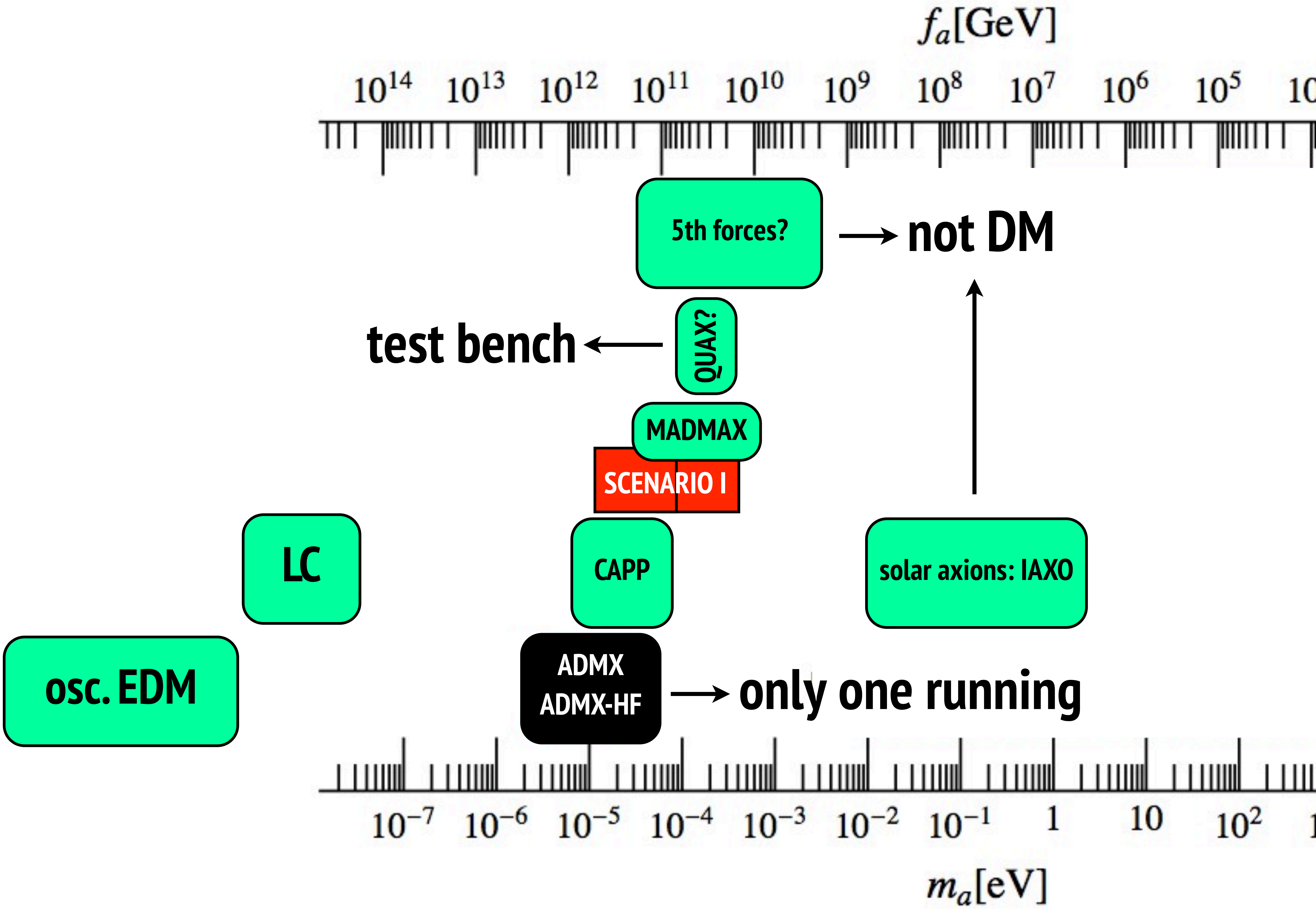
Atomic transitions



Optical

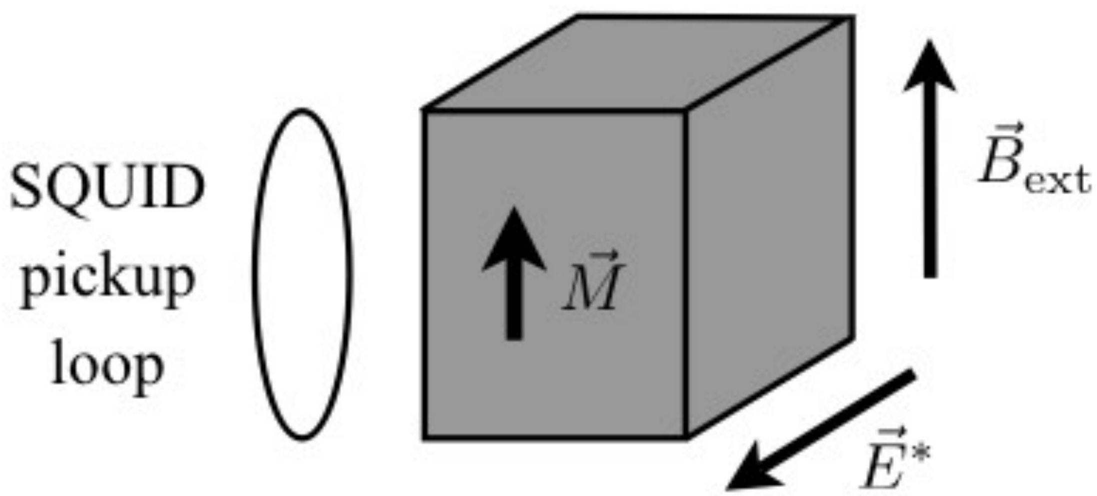


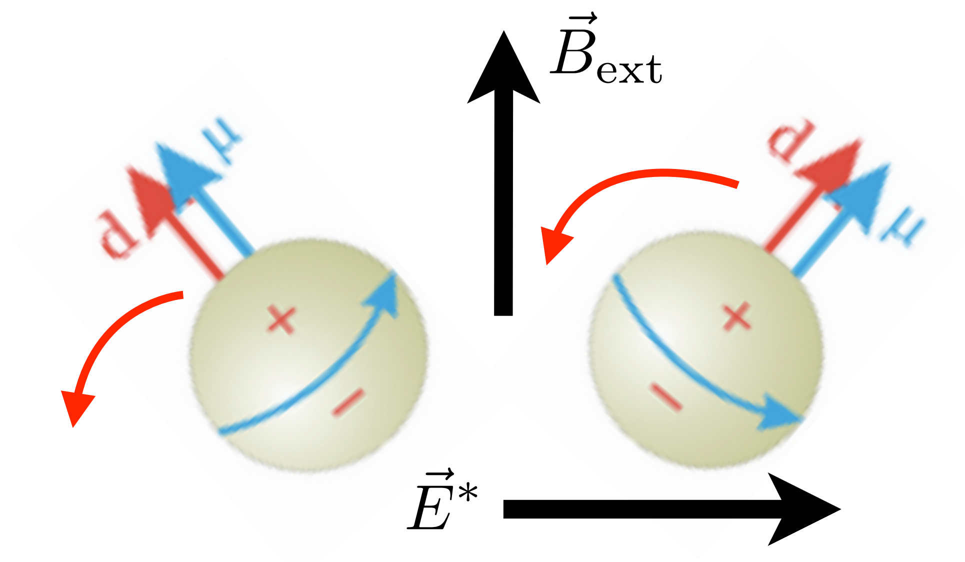
Axion Dark matter experiments (target areas)



Oscillating EDM: CASPER

Mainz, Berkeley



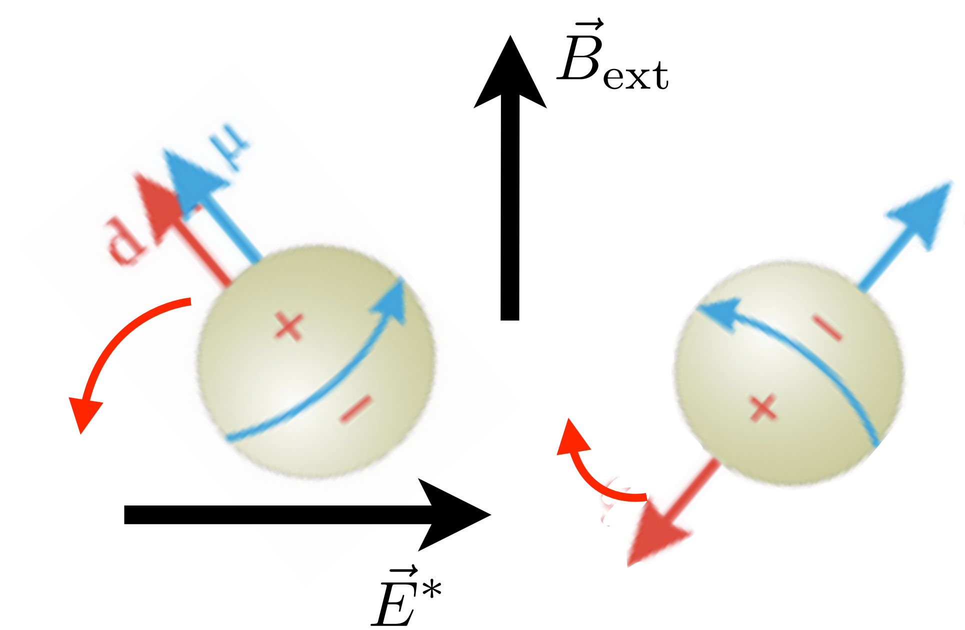


Static EDM, effects cancel in a period

magnetic signal $\propto n p \varepsilon_S d E^* T_2$

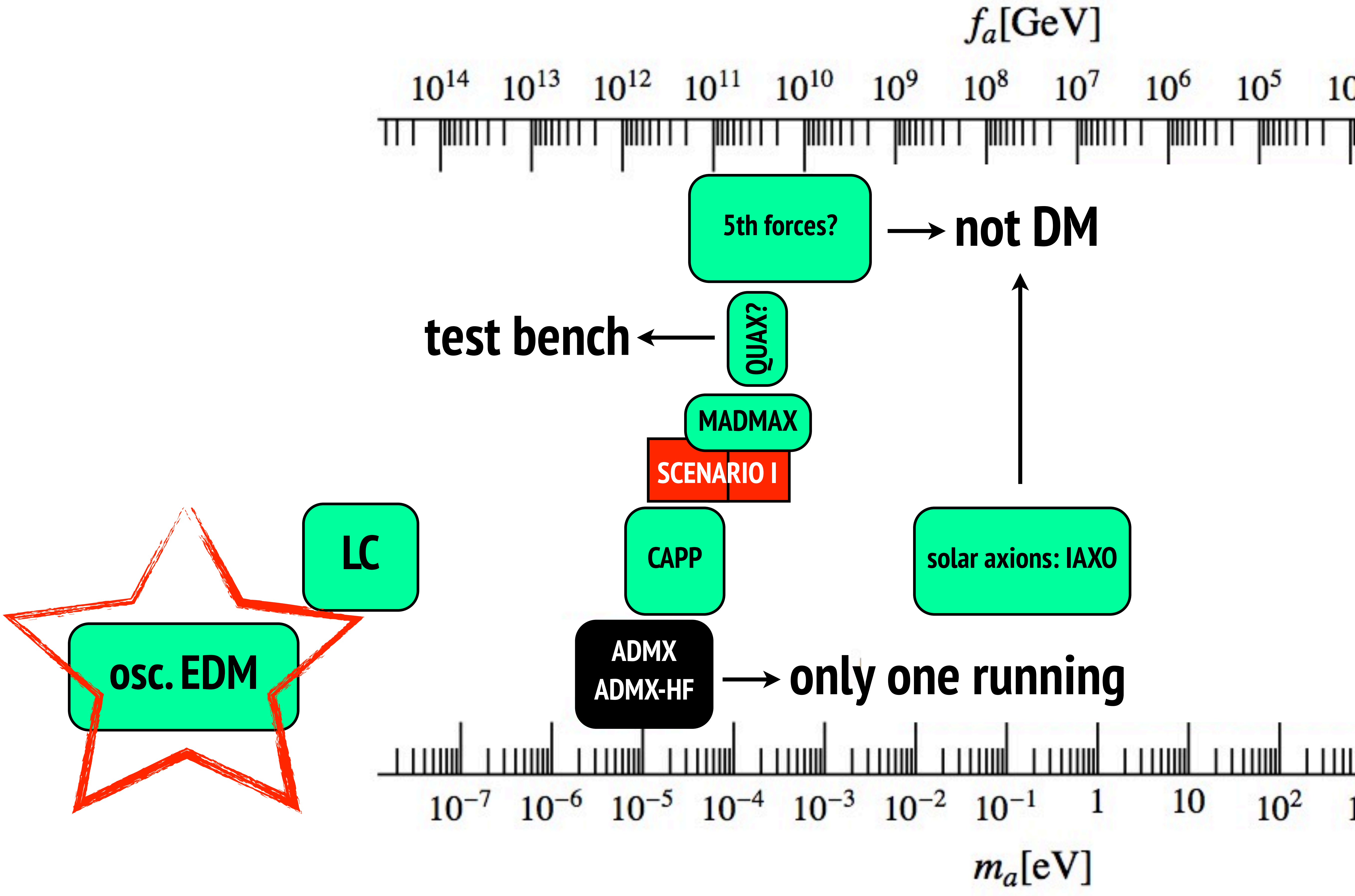
- number density → n
- nuclear spin polarization → p
- Schiff suppression → ε_S
- nuclear spin coherence time → T_2

- EDM + Large E-fields in PbTiO3
- Mainz (D. Budker's group) & Berkeley
- B-field, coherence time, sensitivity to m < neV
- Timescales ... ask your colleagues!
- Mass range limited by B-field strength



Oscillating EDM, effects add up, transverse magnetisation grows if $m_a = \omega = \mu|\vec{B}_{\mathrm{ext}}|$

Axion Dark matter experiments (target areas)



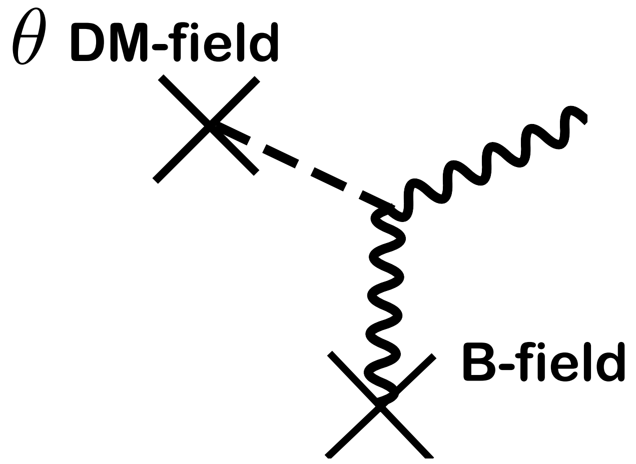
Axion DM in a B-field : two photon coupling

$$\mathcal{L}_I = -C_{a\gamma}\frac{\alpha}{2\pi}\frac{a}{f_a}\mathbf{B}\cdot\mathbf{E}$$

- In a static magnetic field, the oscillating axion field generates EM-fields

$$\mathcal{L}_I = -C_{a\gamma}\frac{\alpha}{2\pi}\theta(t)\,\mathbf{B}_{\rm ext}\cdot\mathbf{E}$$

source



Detecting axion DM

- **Axion DM, $\theta = \theta_0 \cos(m_a t)$, in a B-field is a source in Maxwell's eq.**

$$\begin{aligned} \nabla \cdot \epsilon \mathbf{E} &= \rho_f \\ \nabla \times \mathbf{H} - \frac{\partial \epsilon \mathbf{E}}{\partial t} &= \mathbf{J}_f - C_{a\gamma} \frac{\alpha}{2\pi} \mathbf{B} \frac{\partial \theta}{\partial t} \\ \nabla \cdot \mathbf{B} &= 0 \\ \frac{\partial \mathbf{B}}{\partial t} + \nabla \times \mathbf{E} &= 0 \end{aligned}$$

In a magnetised medium

$$\mathbf{E}(t) = \frac{c_\gamma \alpha \theta_0 \mathbf{B}}{2\pi\epsilon} \cos(m_a t)$$

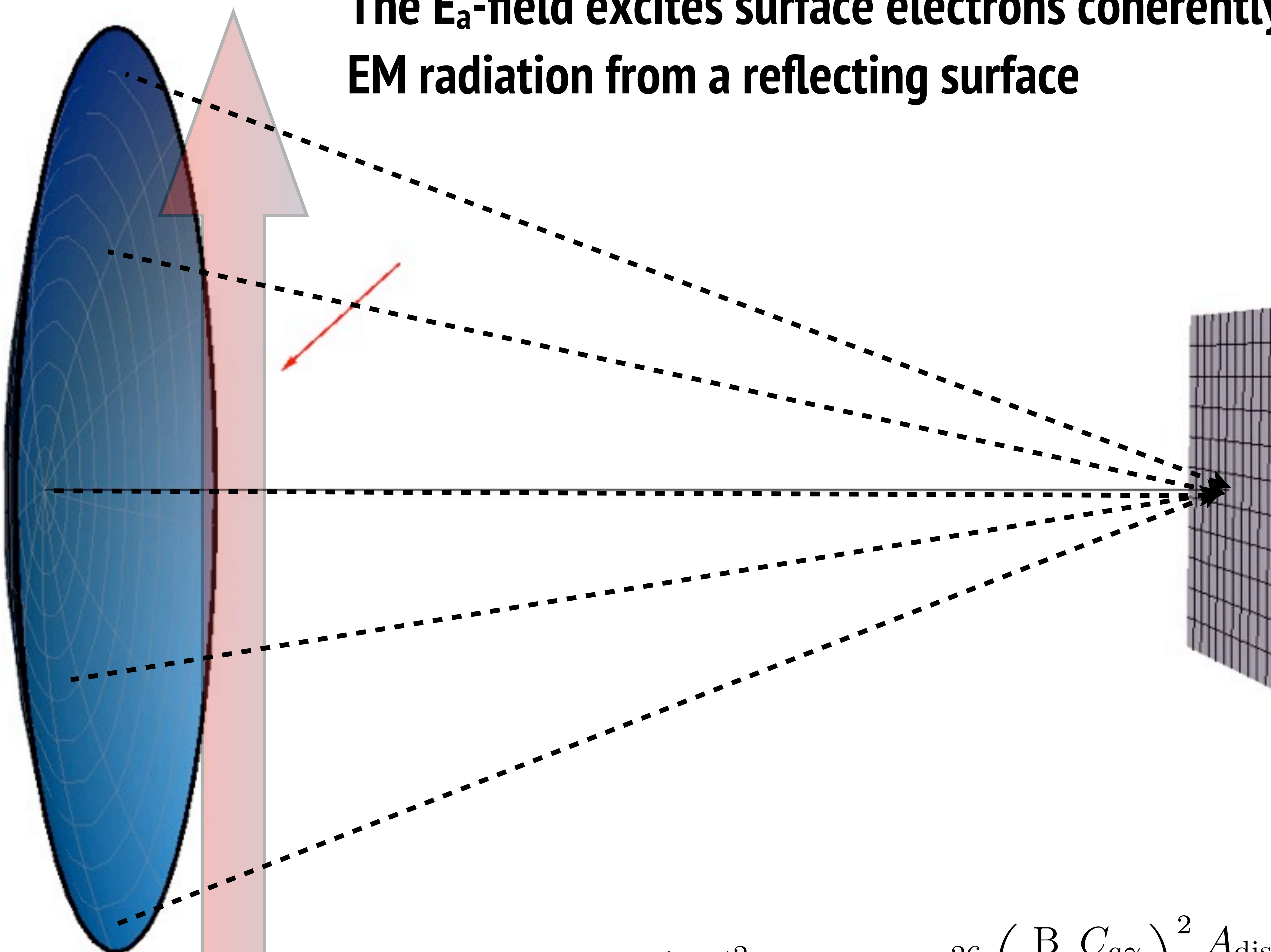
- **Electric fields** $E = 1.3 \times 10^{-12}\ \mathrm{V/m}\ \frac{B_{\mathrm{e}}}{10\ \mathrm{T}} \frac{C_{a\gamma}}{\epsilon}$. **(amp independent of mass!)**

- **Oscillating at a frequency** $\omega \simeq m_a$

Dish antenna experiment?

Horns 2012

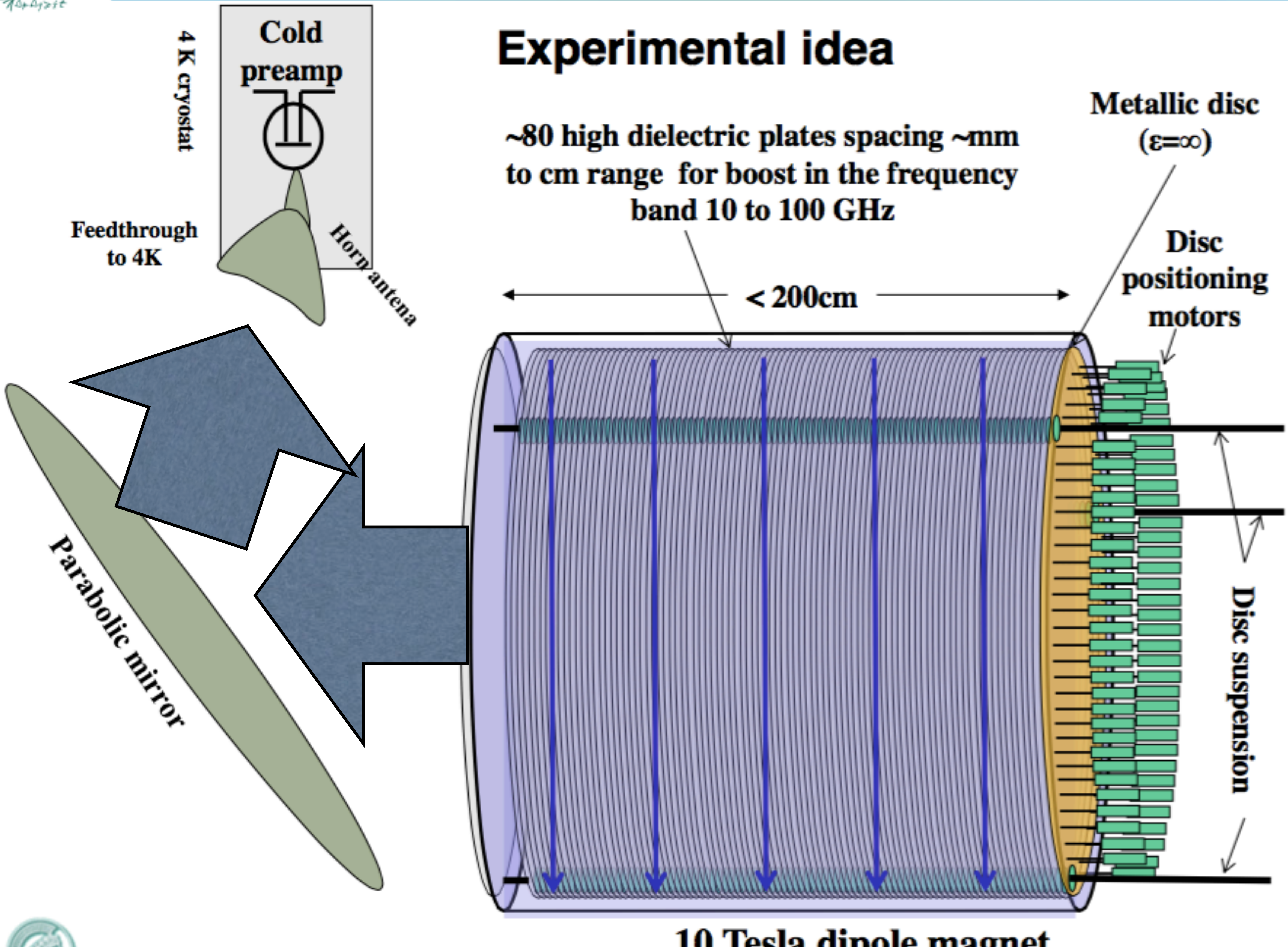
The E_a-field excites surface electrons coherently
EM radiation from a reflecting surface



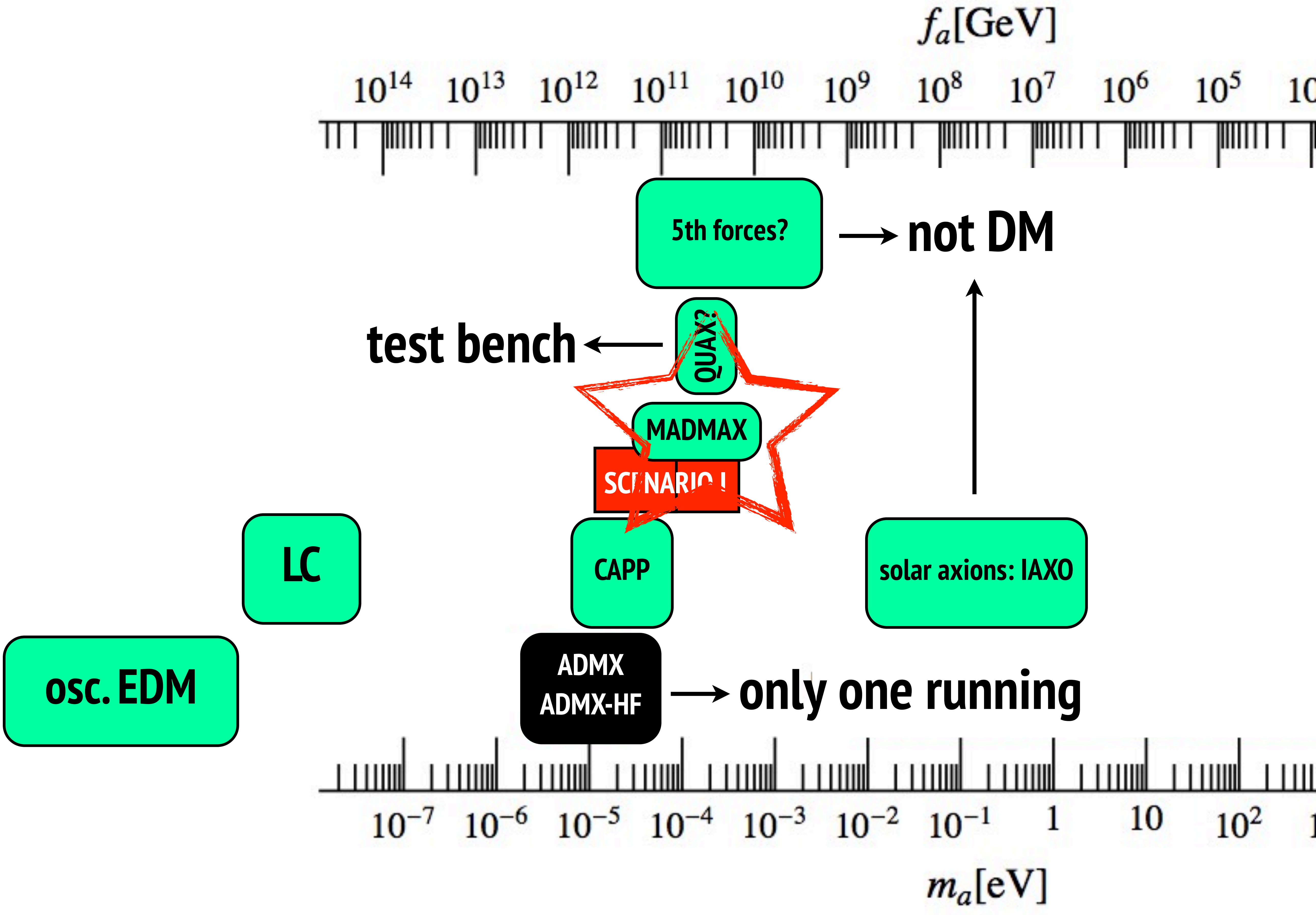
spherical reflecting dish

$$P \sim |\mathbf{E}_a|^2 A_{\rm dish} \sim 10^{-26} \left(\frac{\rm B}{5\rm T}\frac{C_{a\gamma}}{2}\right)^2 \frac{A_{\rm dish}}{1\,{\rm m}^2}{\rm Watt}$$

Layered dielectric haloscope: MADMAX



Axion Dark matter experiments (target areas)



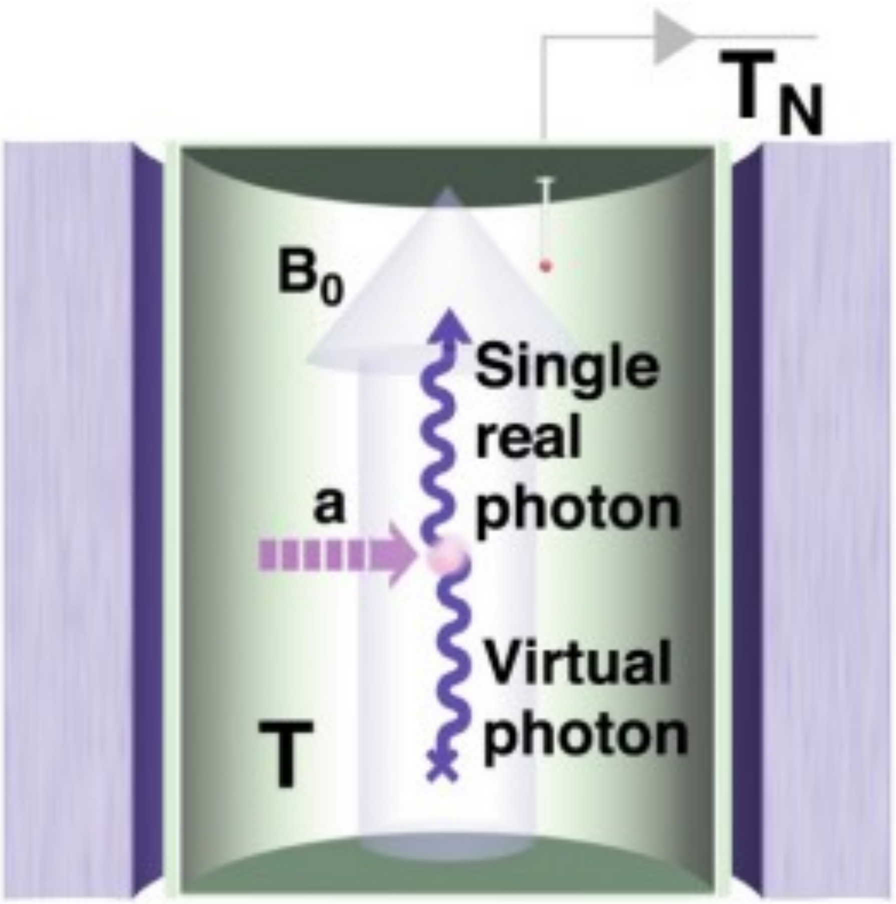
Cavity experiments

Sikivie 2013

- Haloscope (Sikivie 83)
  "Amplify resonantly the EM field in a cavity"

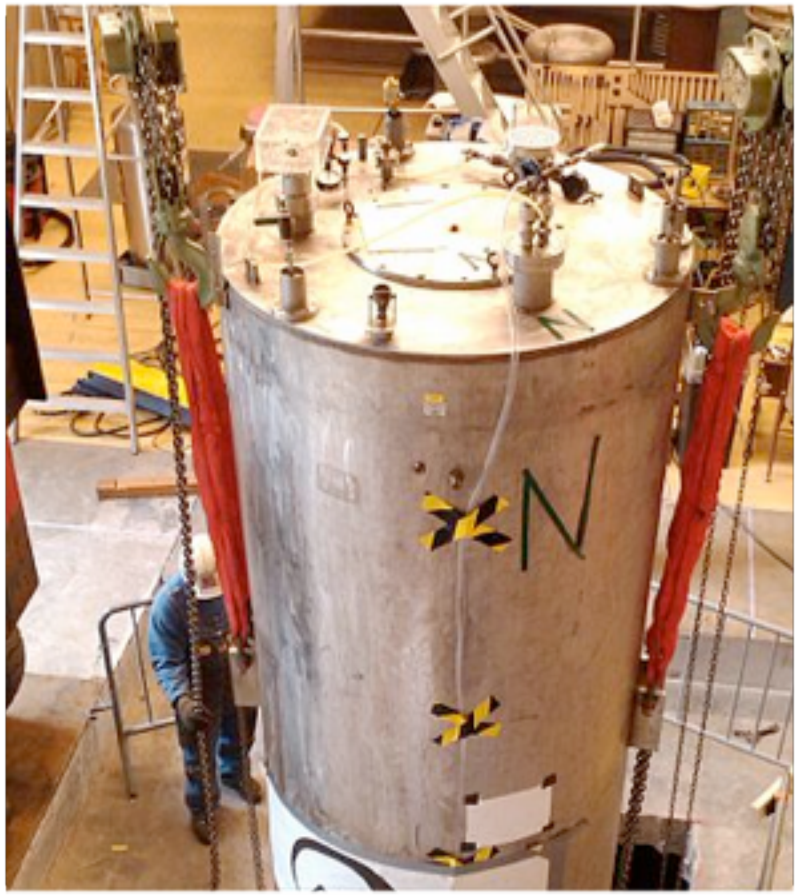
$$P \sim Q|\mathbf{E}_a|^2 (V m_a) \mathcal{G} \kappa$$ (on resonance!)

(integrate the power in a coherent time)



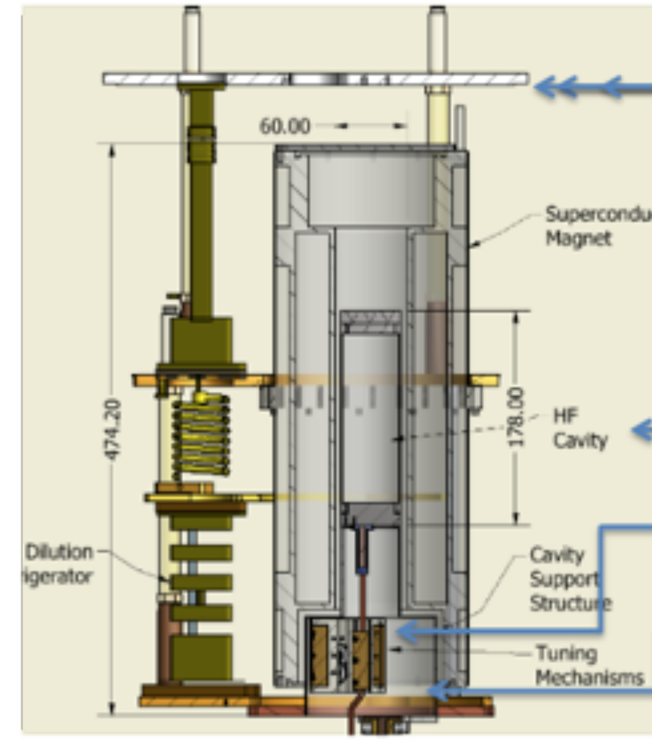
Cavity experiments

ADMX



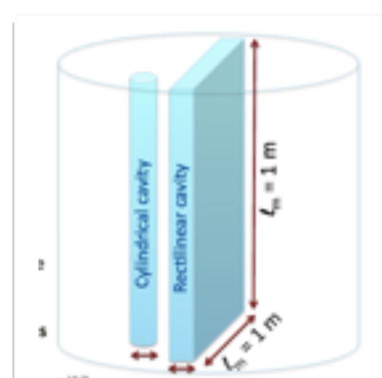
CARRACK (discontinued)

CULTASK - CAPP -Korea

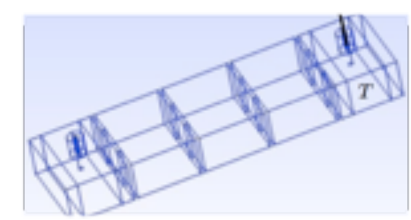


ADMX-HF

ADMX-Fermilab



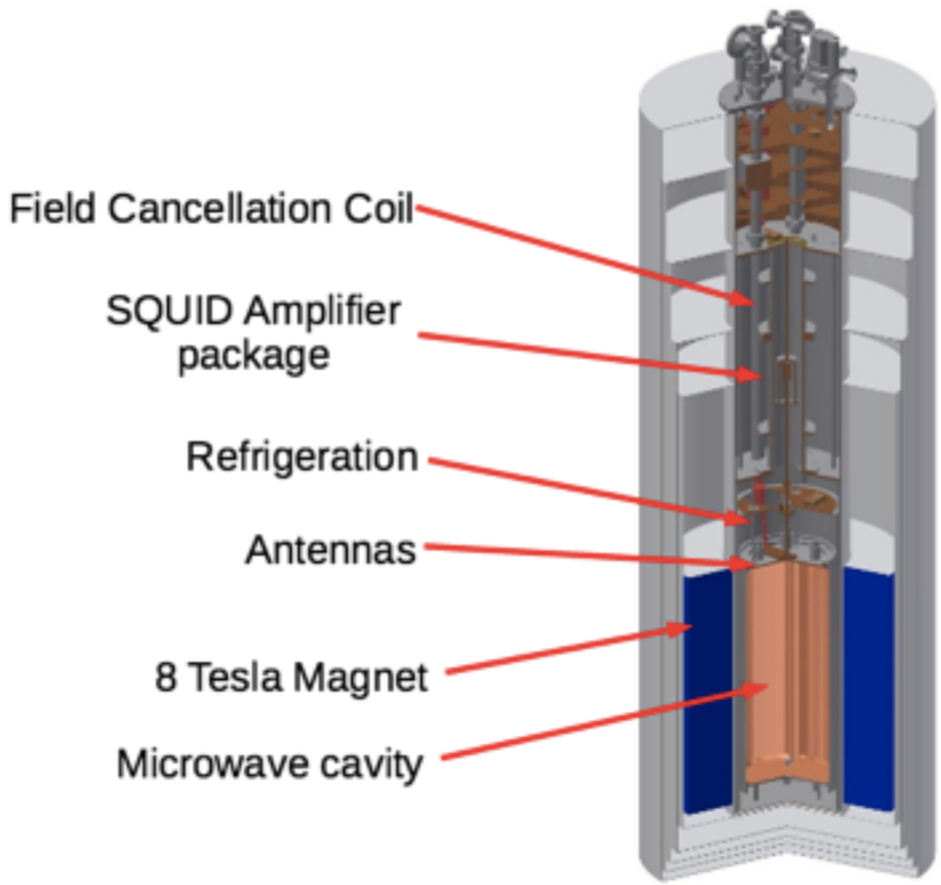
RADES



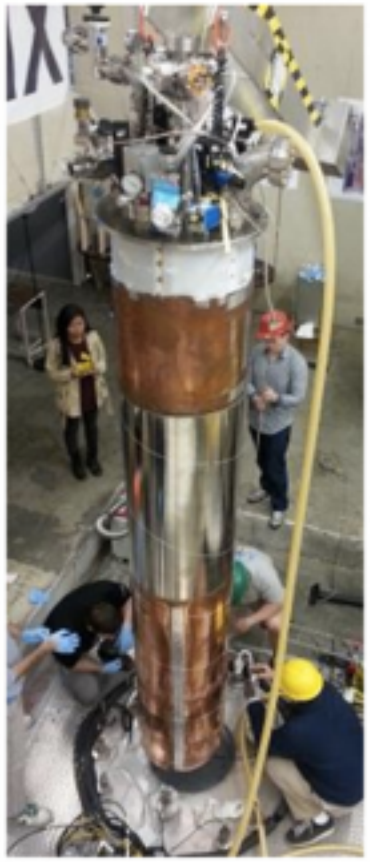
CAST-CAPP

ADMX

Washington University, DOE, NSF

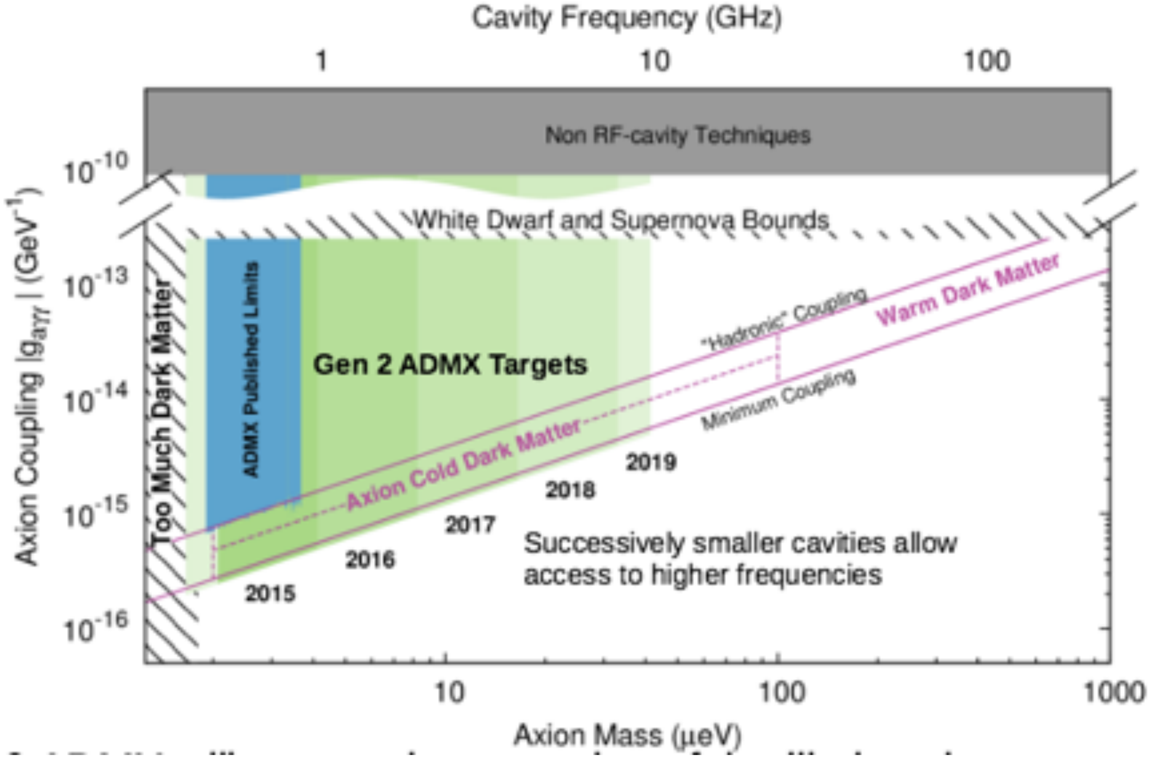


Insert + Magnet Schematic

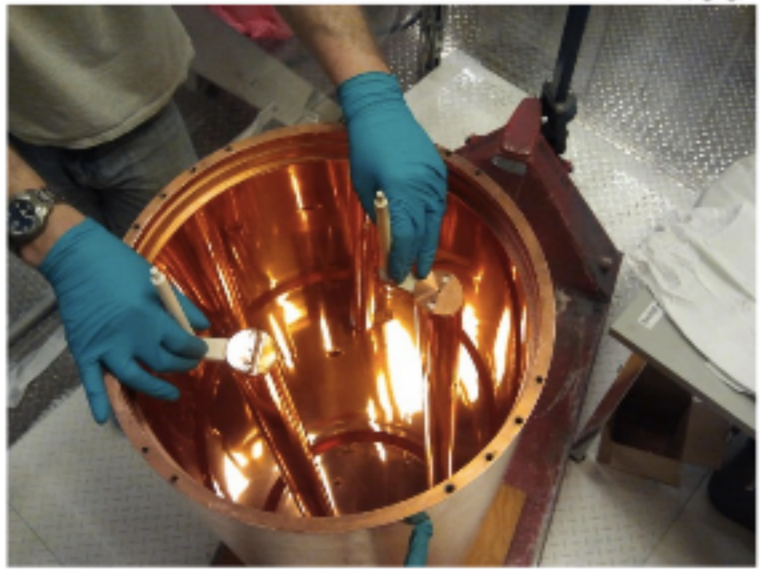


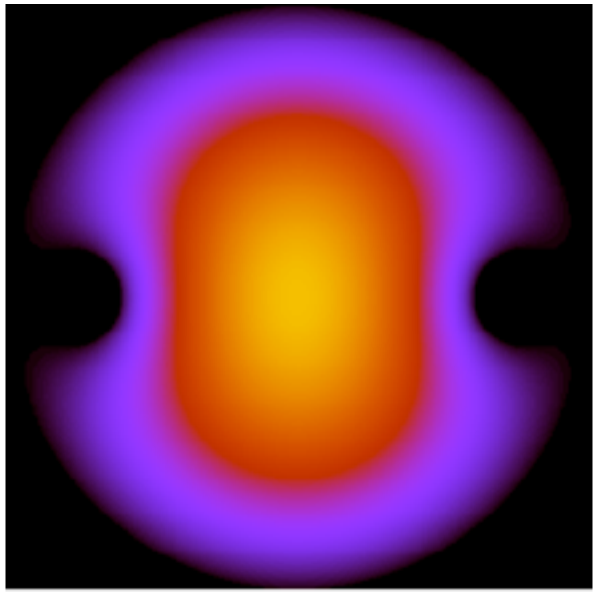
Insert extraction from magnet

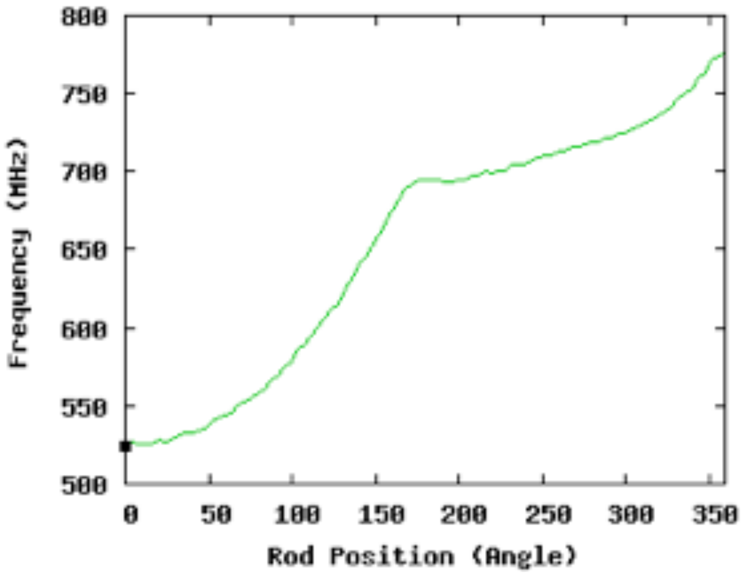
Goals



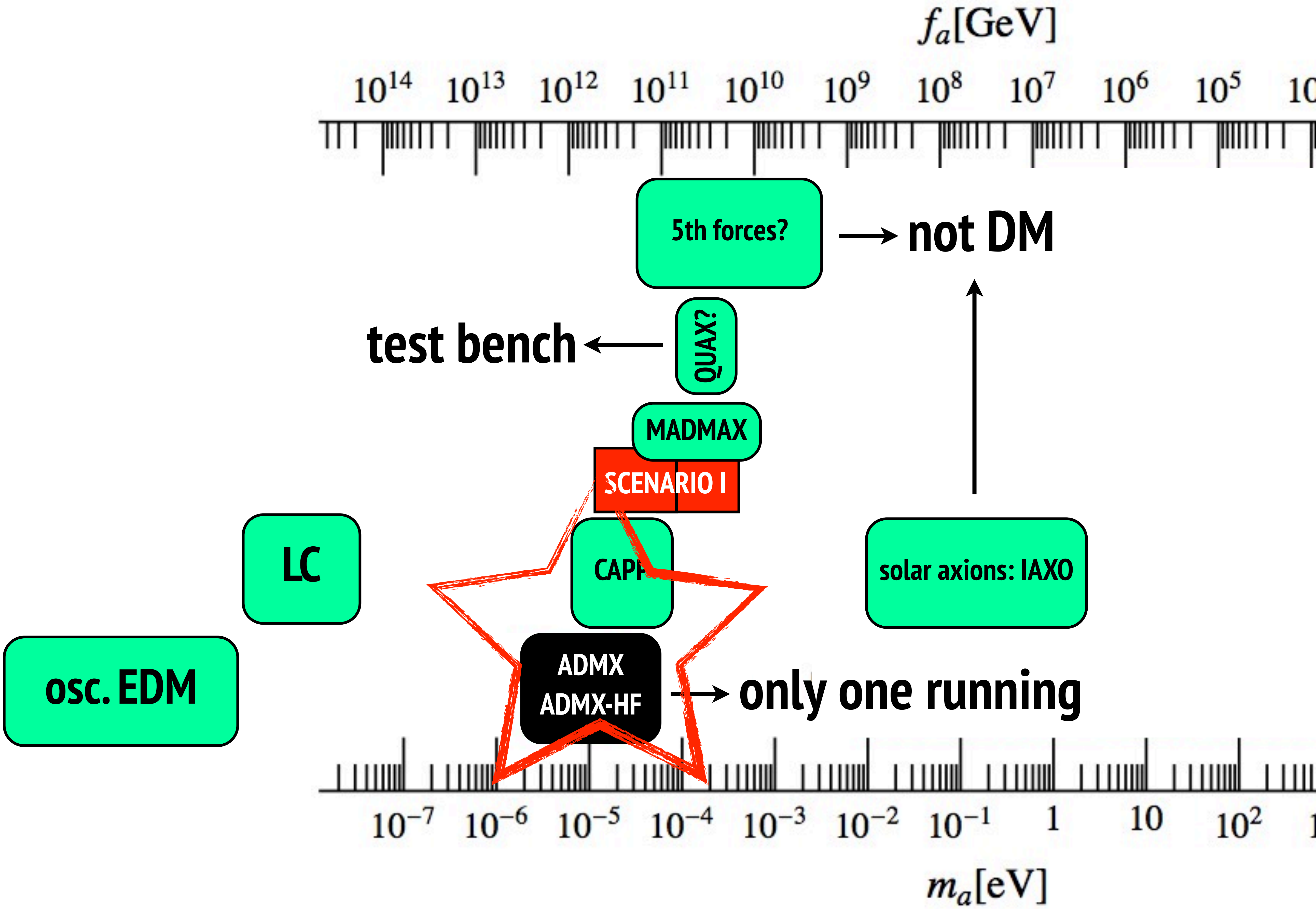
Scanning over frequencies







Axion Dark matter experiments (target areas)



Conclusions

- Strong CP ~~problem~~ "hint" for new physics

- Axion solution, almost embedded in QCD

- Axion Dark matter UNAVOIDABLE

- DM density related to f_a, but initial condition problem

- Axion DM experiments :
    - Oscillating EDM
    - Cavity (ADMX running, more to come)
    - Layered Haloscope (future)
    - other ideas pursued

- Axion non-DM experiments too