Axions

TAE 2018

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Overview

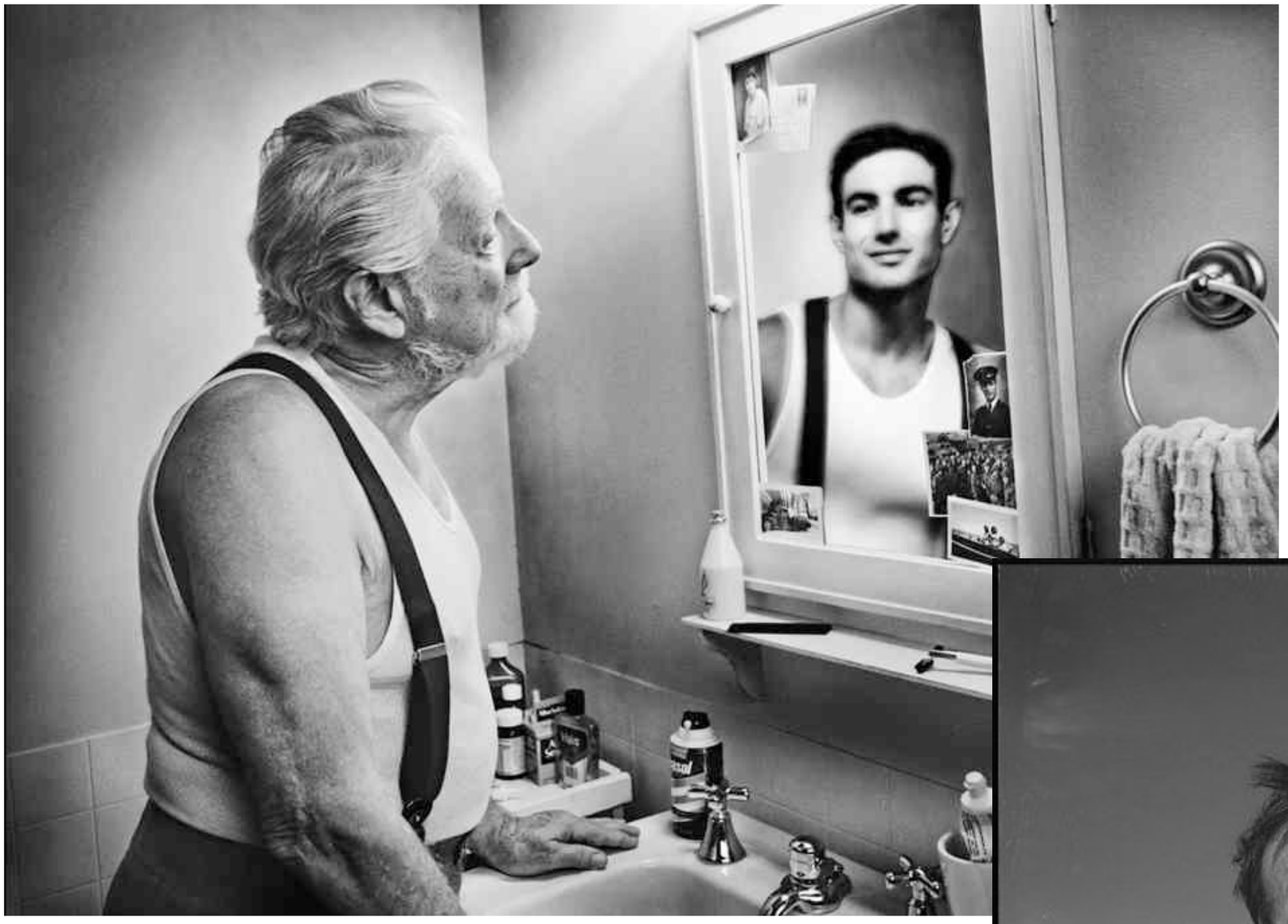
- Strong CP problem

- Axions

- Axion Dark matter

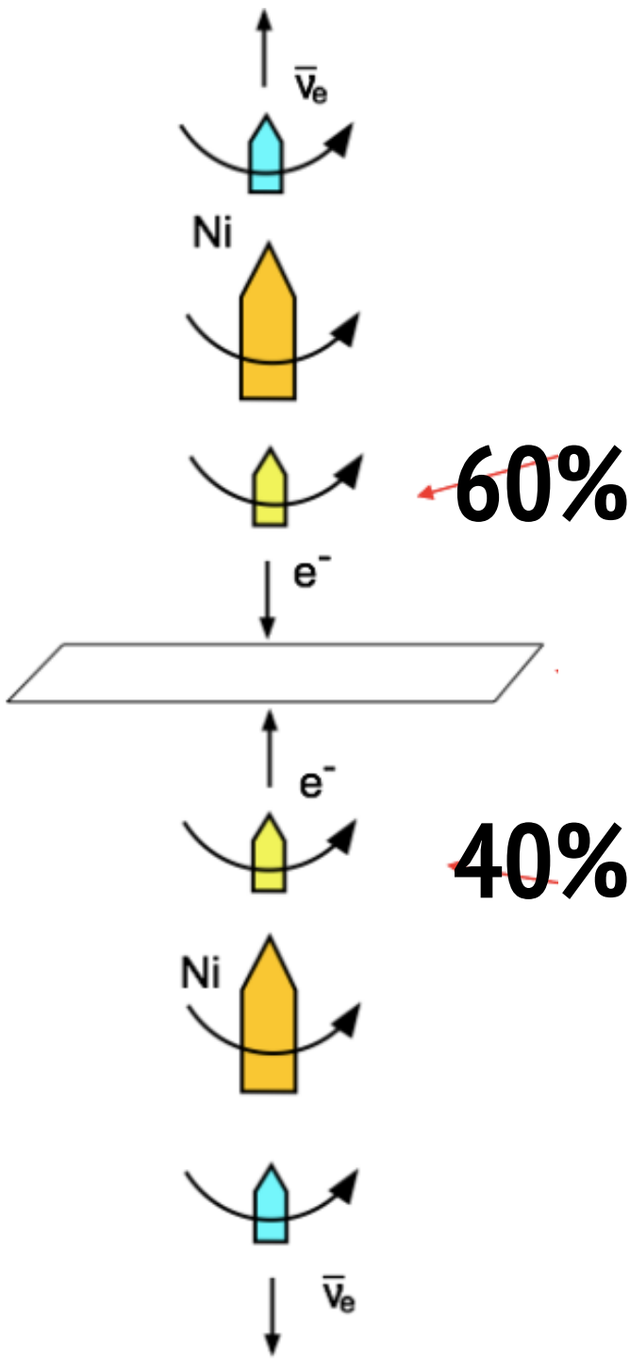
- Searching for axions in the sky in the lab

Parity and Time reversal



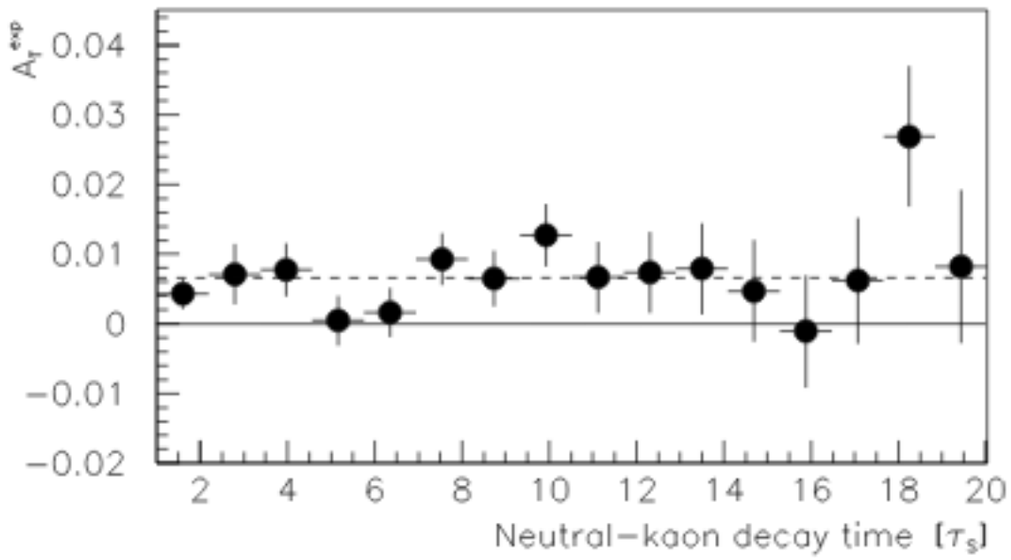
in particle physics (electroweak interactions)

P-violation (Wu 56)



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

many theories based on SU(3)c (QCD)

$$\mathcal{L}_{\rm QCD} = \underbrace{-\frac{1}{4}G_{\mu\nu a}G_a^{\mu\nu} + \sum_q i\bar{q}\gamma^\mu D_\mu q - \bar{q}mq}_{\text{P,T conserving}} + \underbrace{\frac{\alpha_s}{8\pi}\theta G_{\mu\nu a}\widetilde{G}_a^{\mu\nu}}_{\text{P,T violating}}$$

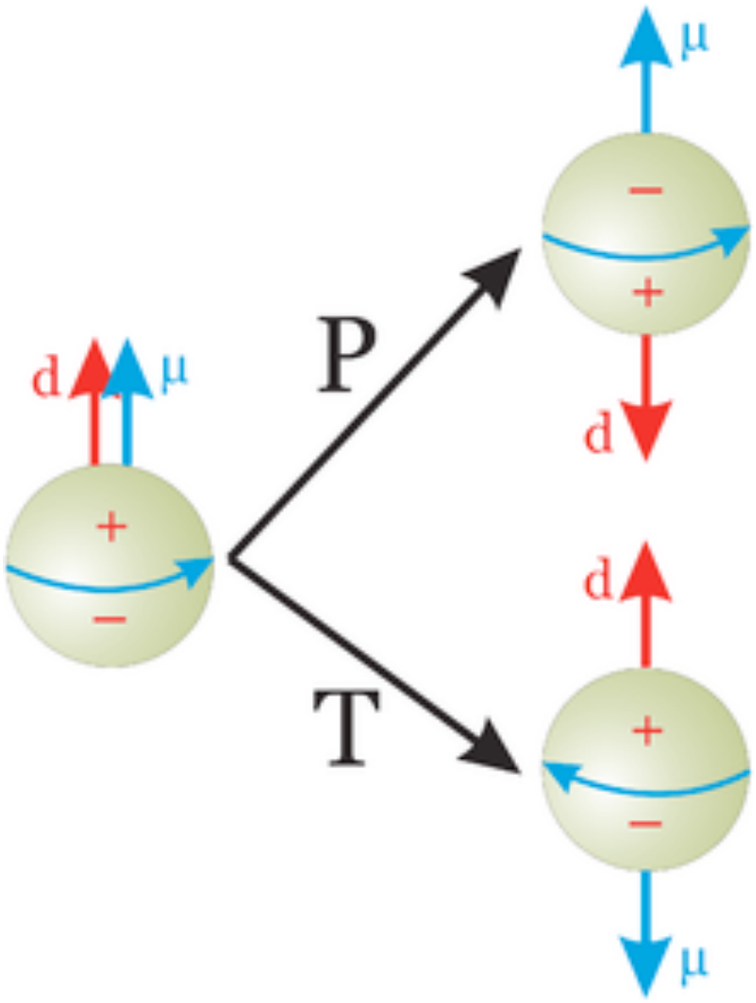
we tend to forget this

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

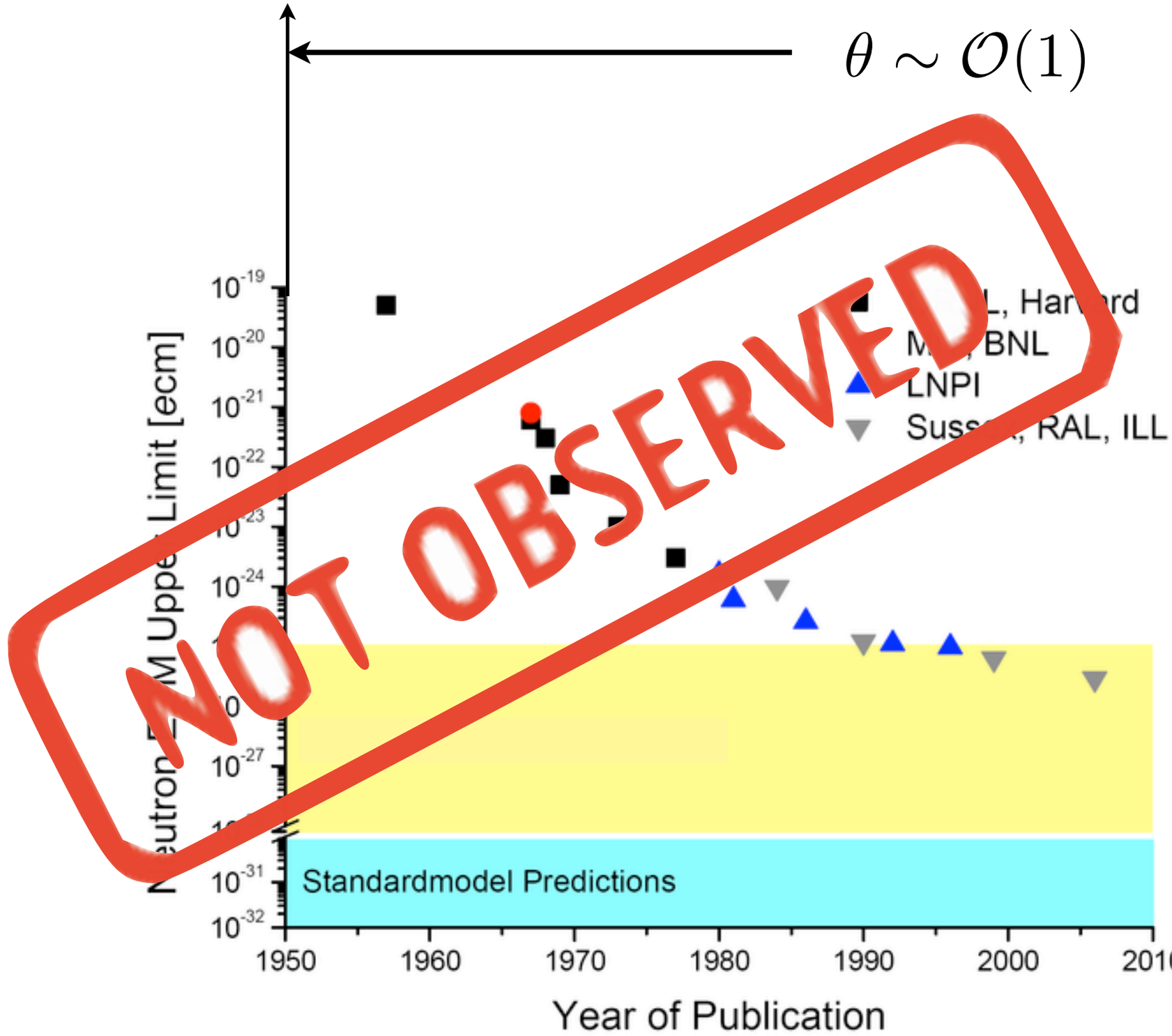
$\theta \in (-\pi, \pi)$ **infinitely versions of QCD... all are P,T violating**

Neutron EDM

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

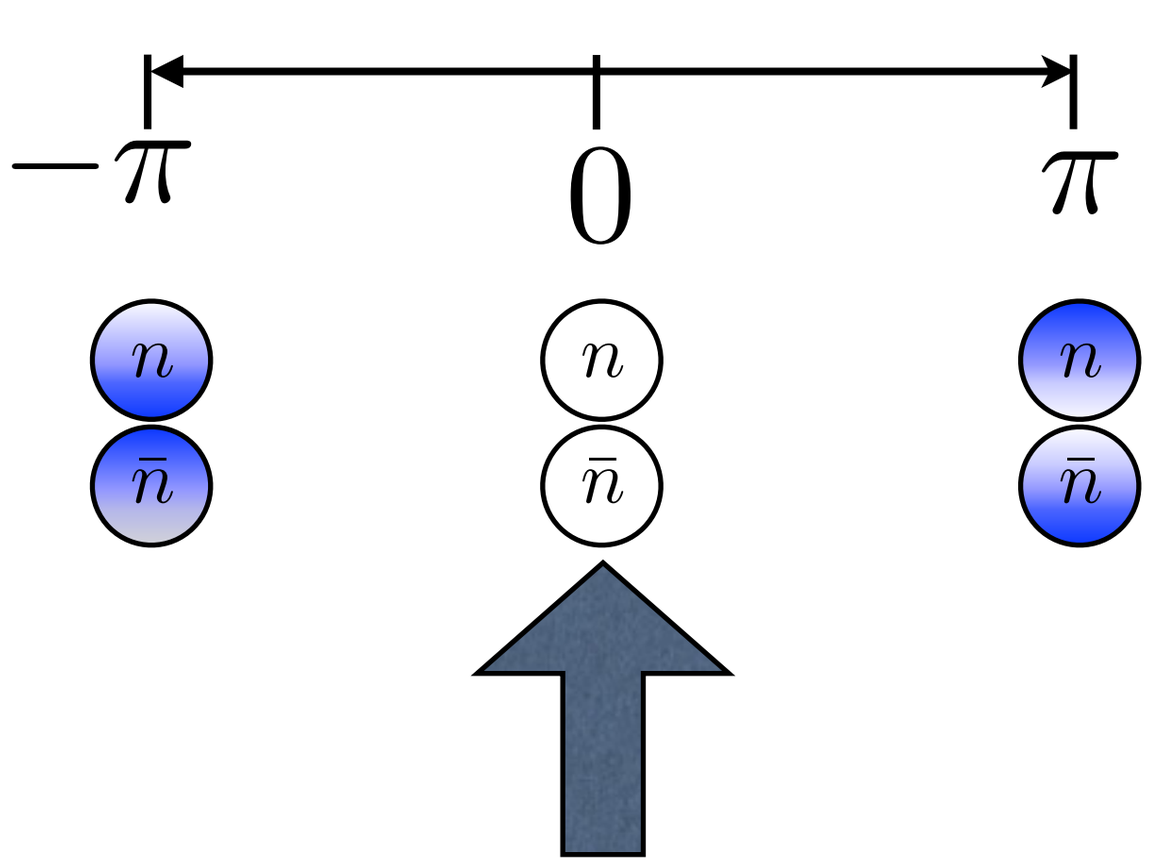


EDM violates P,T



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)**

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.

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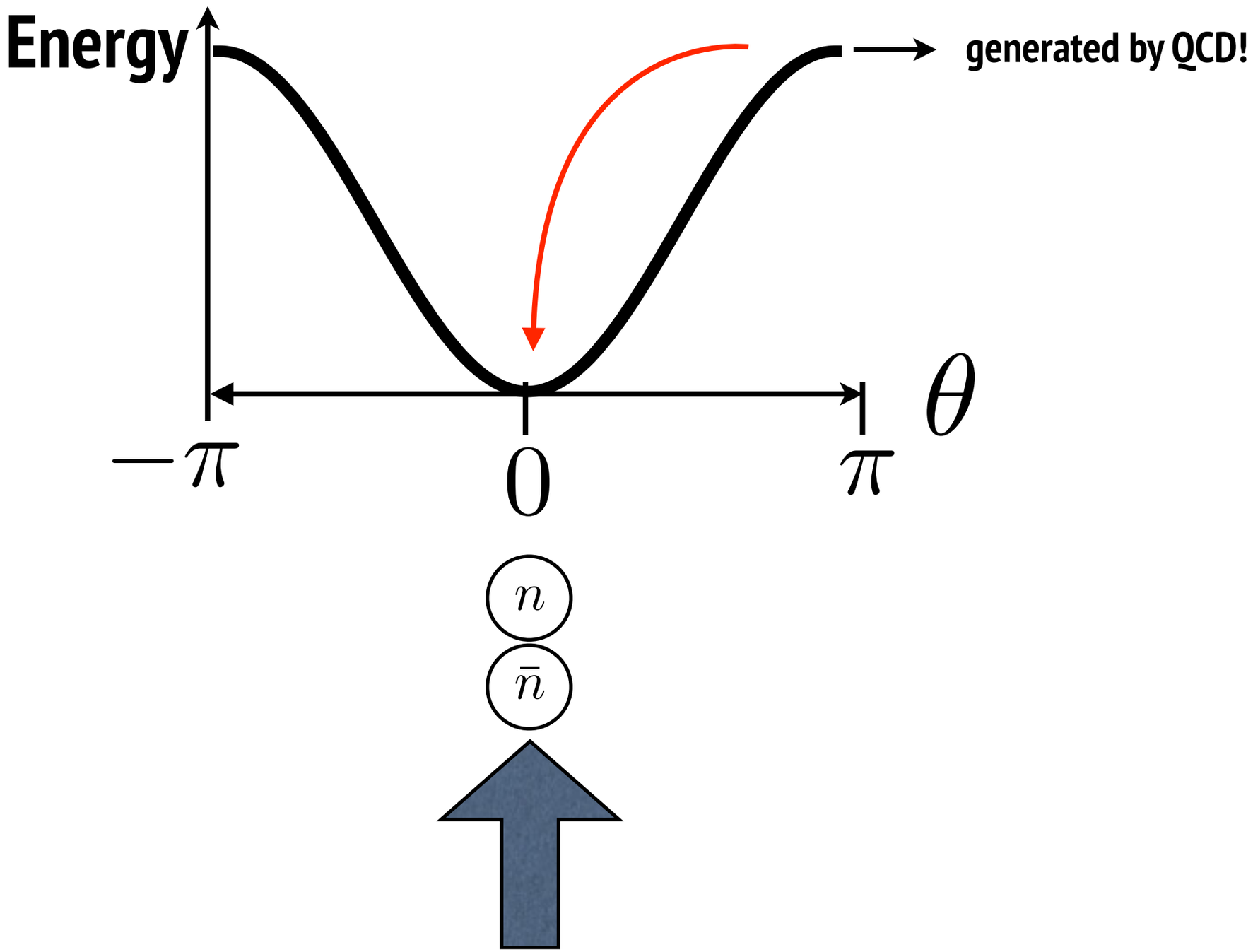
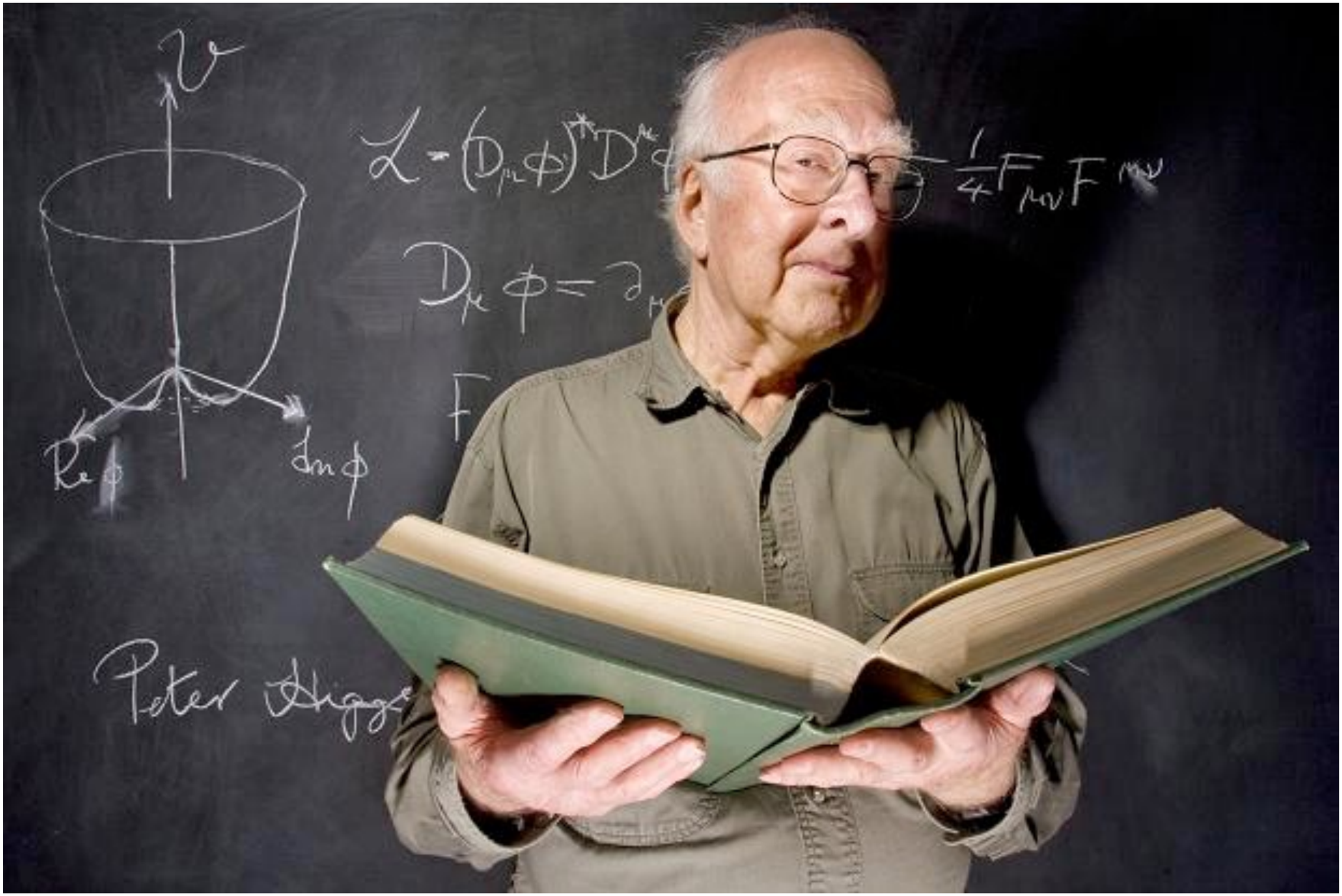
QCD vacuum energy minimised at theta = 0

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



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

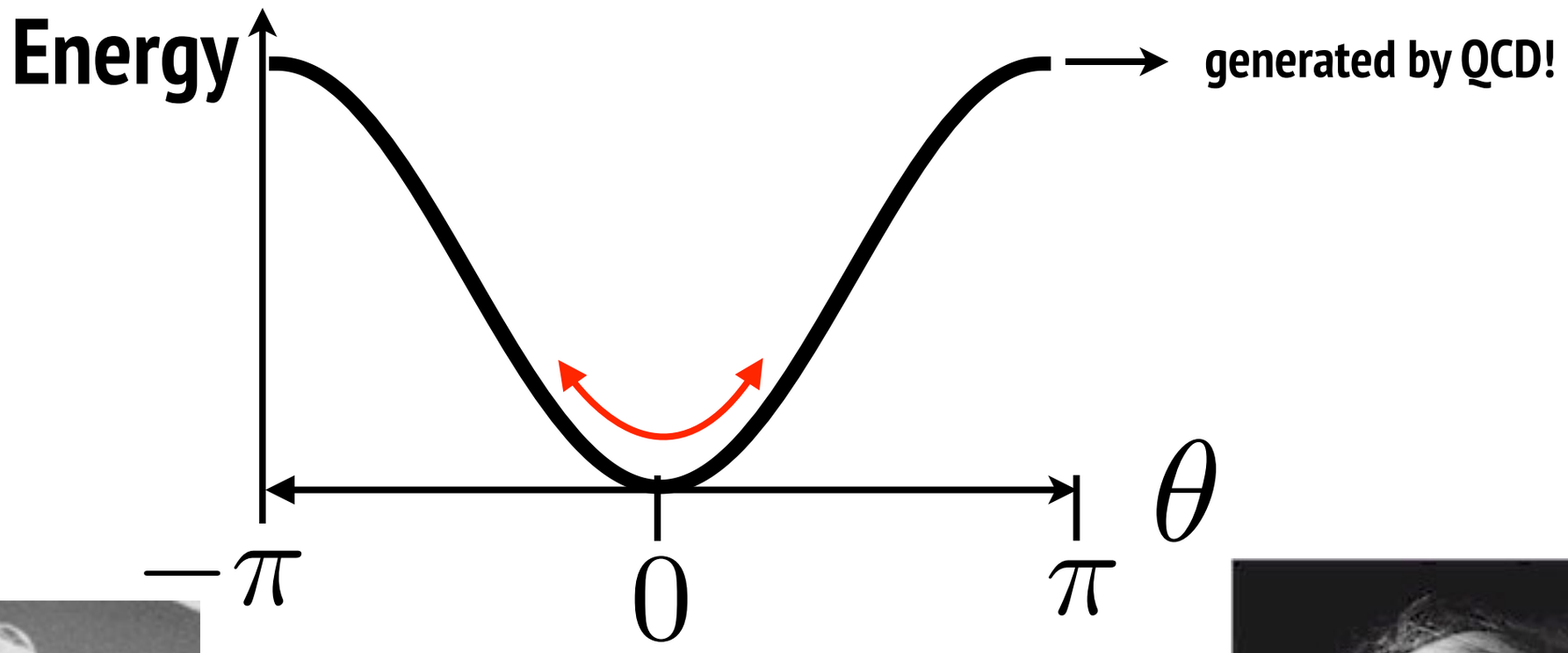
ain’t you forgetting something?



P. Higgs

and a new particle is born ...

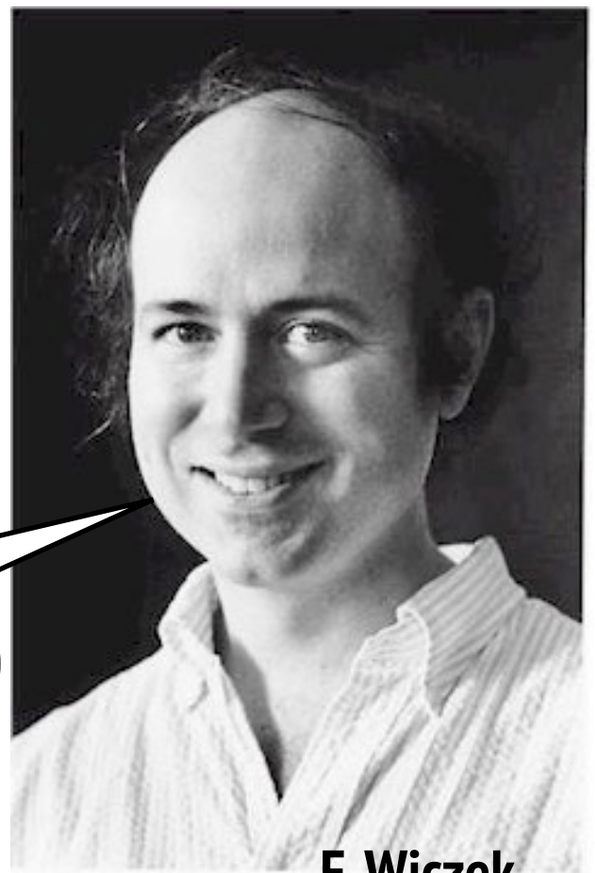
- if $\theta(t, \mathbf{x})$ is dynamical field



Field Excitations around the vacuum are particles

S. Weinberg

clears the strong CP problem like my favorite soap



F. Wiczek

and a new particle is born ... the axion

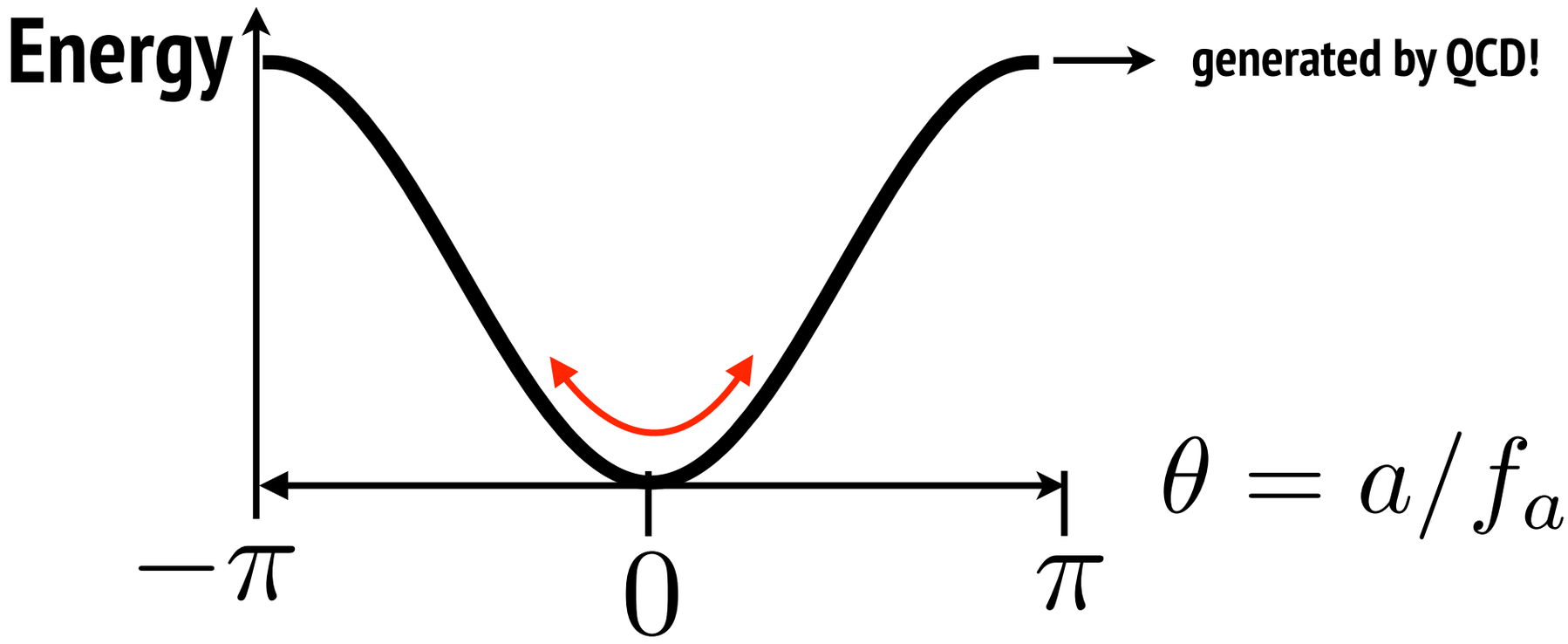
- if $\theta(t, \mathbf{x})$ is dynamical field

it's a higgslet!

clears the
strong CP problem
like my favorite soap

and a new scale sets the game, fa

- kinetic term for θ requires a new scale



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

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

How to get the axion-term?

- **Peccei-Quinn idea: New symmetry, spontaneously broken**

Goldstone theorem: Global continuous symmetry SB -> massless boson

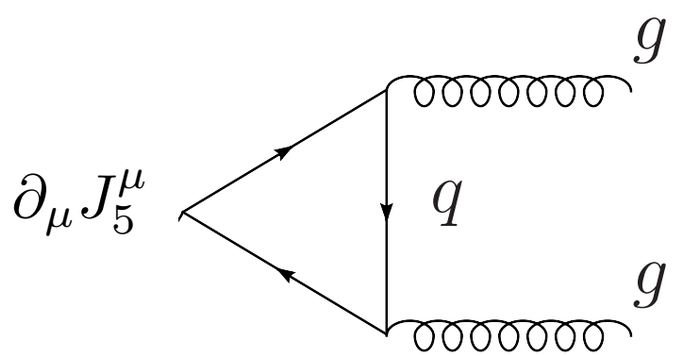
$$\mathcal{L}_? = \frac{f^2}{2}(\partial_\mu\theta)(\partial^\mu\theta) + \dots$$

Other terms that preserve the symmetry $\theta \to \theta + \alpha$

symmetry protects the mass and other non-derivativeinteractions $V(\theta) = 0$

Quantum level ....

If symmetry is color anomalous -> anomalous 2-gluon coupling



$$\mathcal{L}_? + = N\frac{\alpha_s}{8\pi}G\tilde{G}\theta$$

N = number of quarks running in the loop

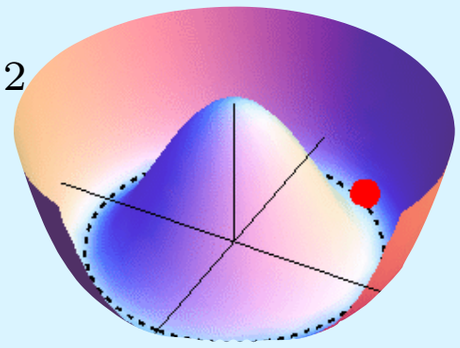
~number of quarks charged under PQ symmetry

$$\theta \equiv \frac{a}{f}, N\theta \equiv \frac{a}{f_a} \to f_a = f/N$$

Simple model KSVZ

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

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



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

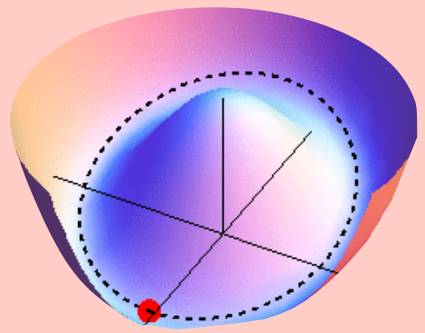
- At energies below f_a**(SSB)**

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

- 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

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

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

ENERGY ~GeV ~f_a

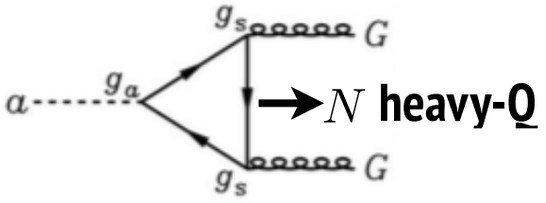
couplings

- Shift symmetry allows some generic types of interactions

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

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

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



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

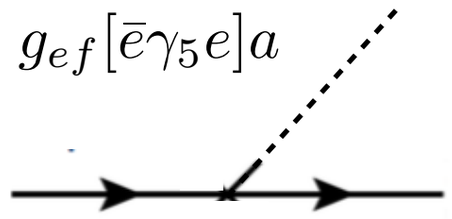
$$V(A) \sim \frac{1}{2}\chi_{\rm QCD}\left(\frac{A}{f_A}\right)^2 = \frac{1}{2}m_A^2A^2$$

photon coupling

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

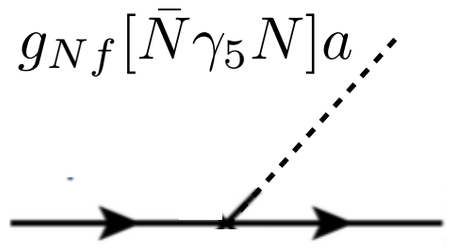
electron coupling

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



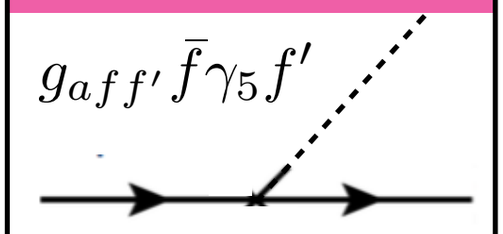
nucleon coupling

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



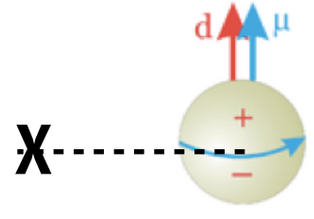
FCNC

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



~~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...

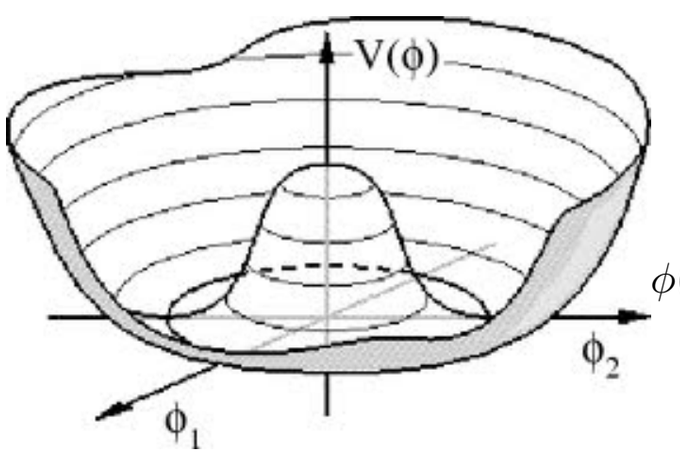
		High-E couplings				Low-E couplings			
Model	$N_{\rm DW}$	E/N	C_{Au}	C_{Ad}	C_{Ae}	$C_{A\gamma}$	C_{Ap}	C_{An}	C_{Ae}
PQWW	3	$^8/_3$	$c_\beta^2/3$	$s_\beta^2/3$	$s_\beta^2/3$	0.75	...	...	...
DFSZ I	6,3	$^8/_3$	$c_\beta^2/3$	$s_\beta^2/3$	$s_\beta^2/3$	0.75	(-0.2,-0.6)	(-0.16,0.26)	(0.024,⅓)
DFSZ II	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	$^1/_6$...$^{44}/_3$	g-loop	g-loop	γ-loop	-0.25 ... 12.7†	-0.47	-0.02(3)	$(0.05\ ...\ 5)\times10^{-3}$
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

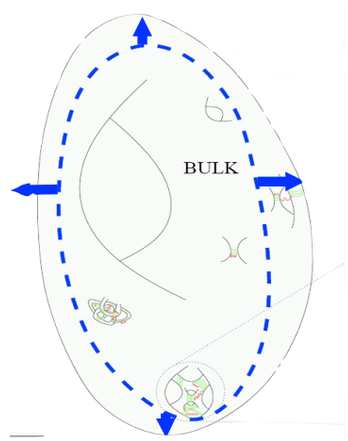
- Global symmetry spontaneously broken

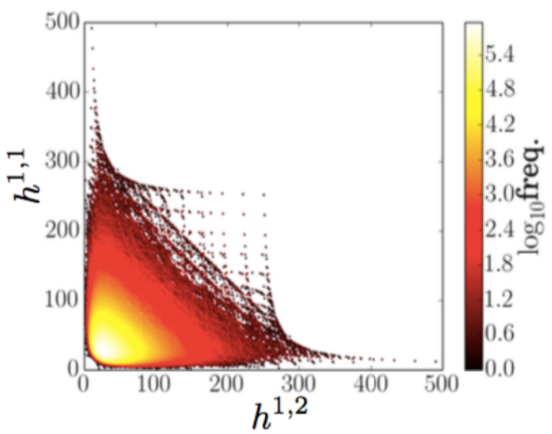


$$\phi(x) = \rho(x)e^{i\theta(x)}$$

stringy axions

- Im parts of moduli fields (control sizes)





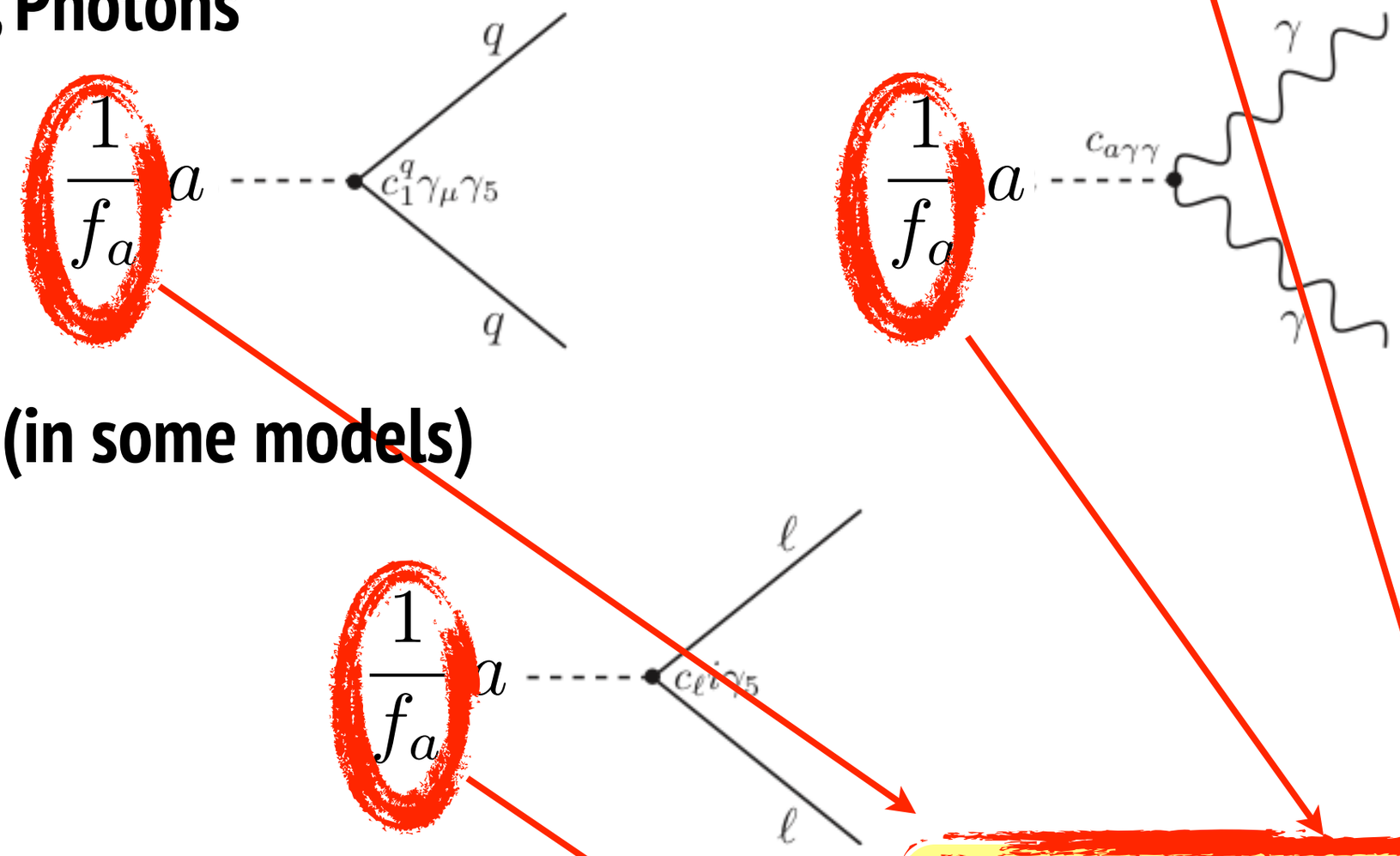
- O(100) candidates in typical compactifications
- masses from non-perturbative effects

Axion couplings at low energy

Mass

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

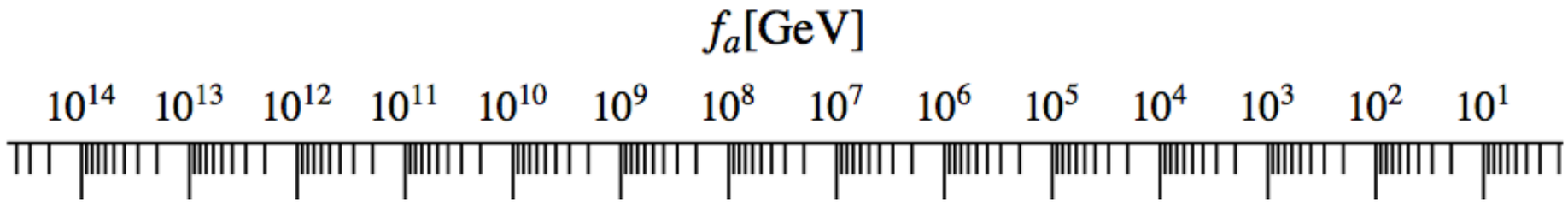
hadrons, Photons



Leptons (in some models)

The lighter the more weakly interacting

Axion Landscape

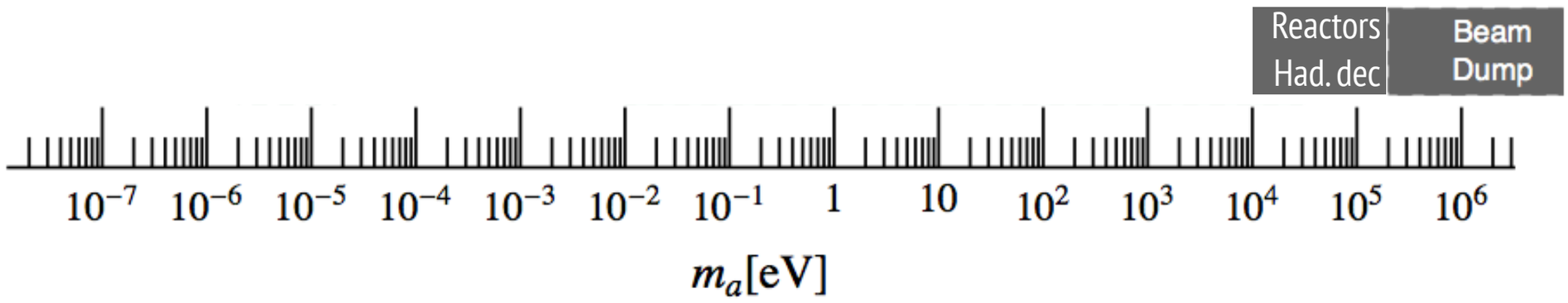


$f_a \gg v_{\rm EW}$

Invisible models

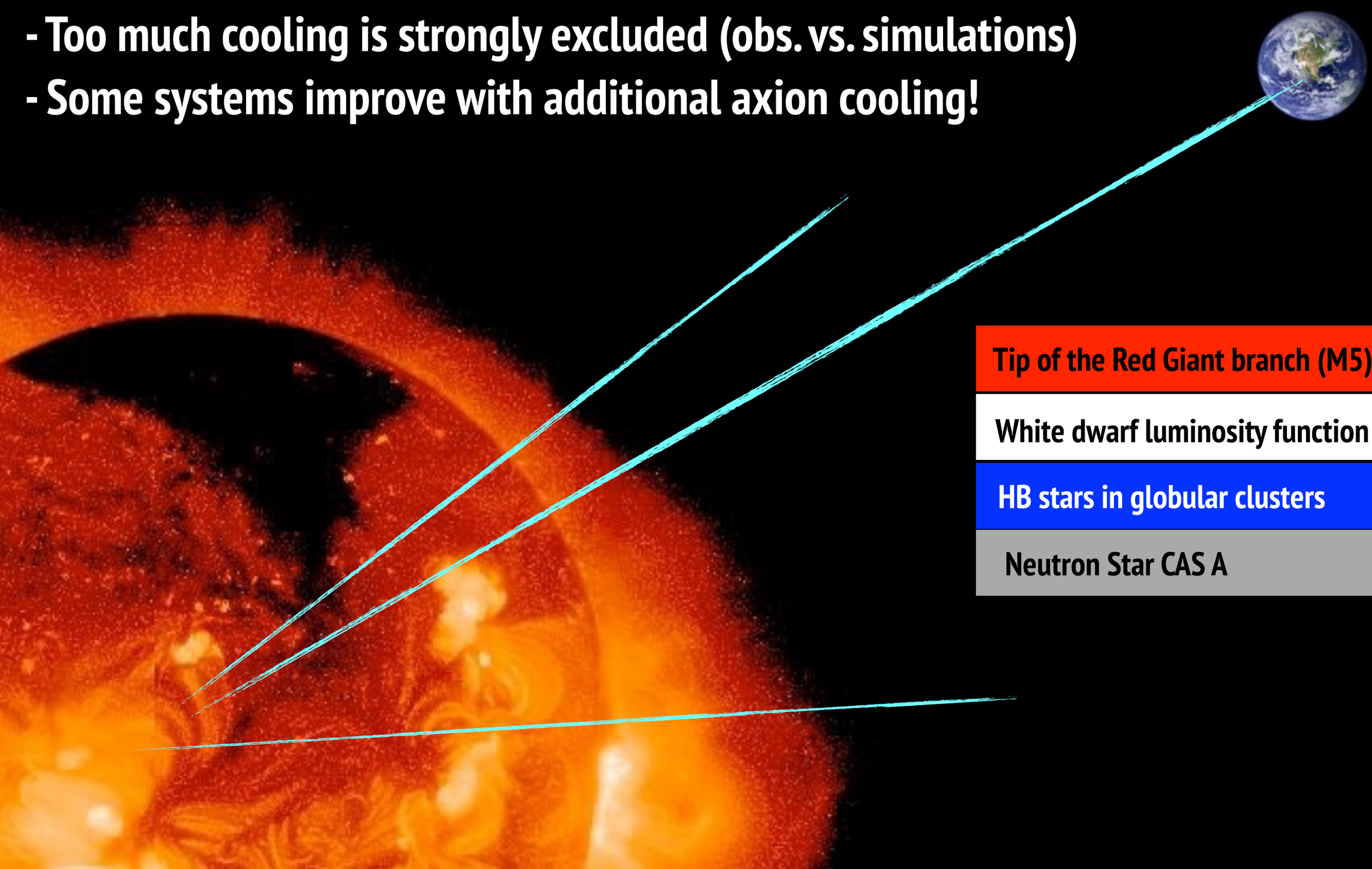
$f_a \sim v_{\rm EW}$

PQWW models



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!



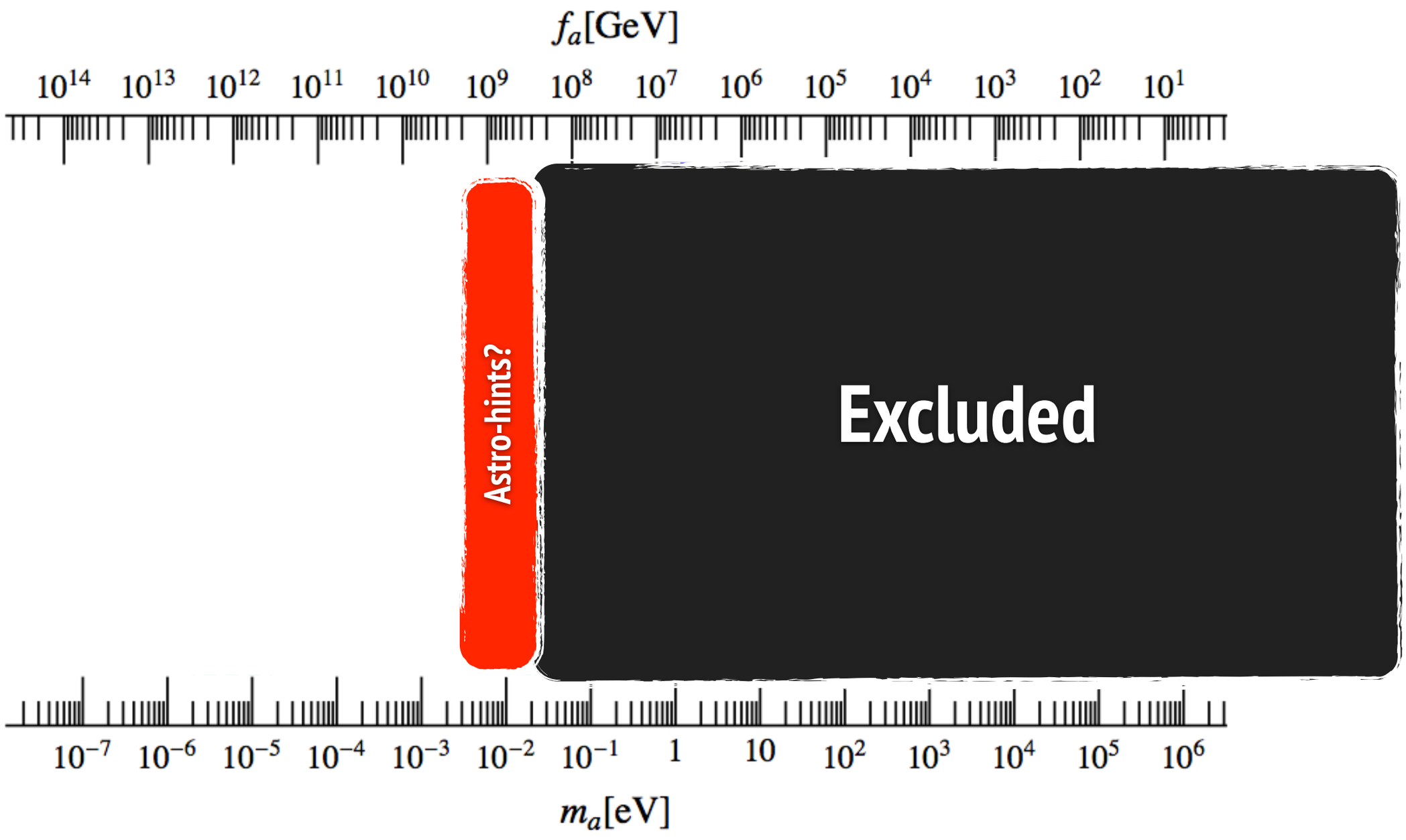
Tip of the Red Giant branch (M5)

White dwarf luminosity function

HB stars in globular clusters

Neutron Star CAS A

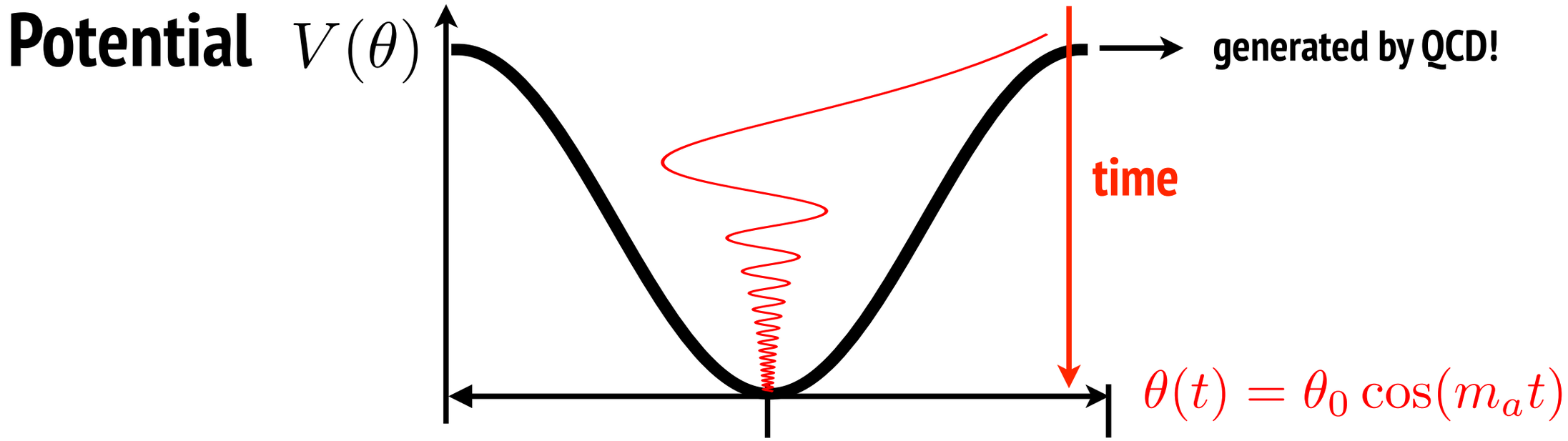
Axion Landscape

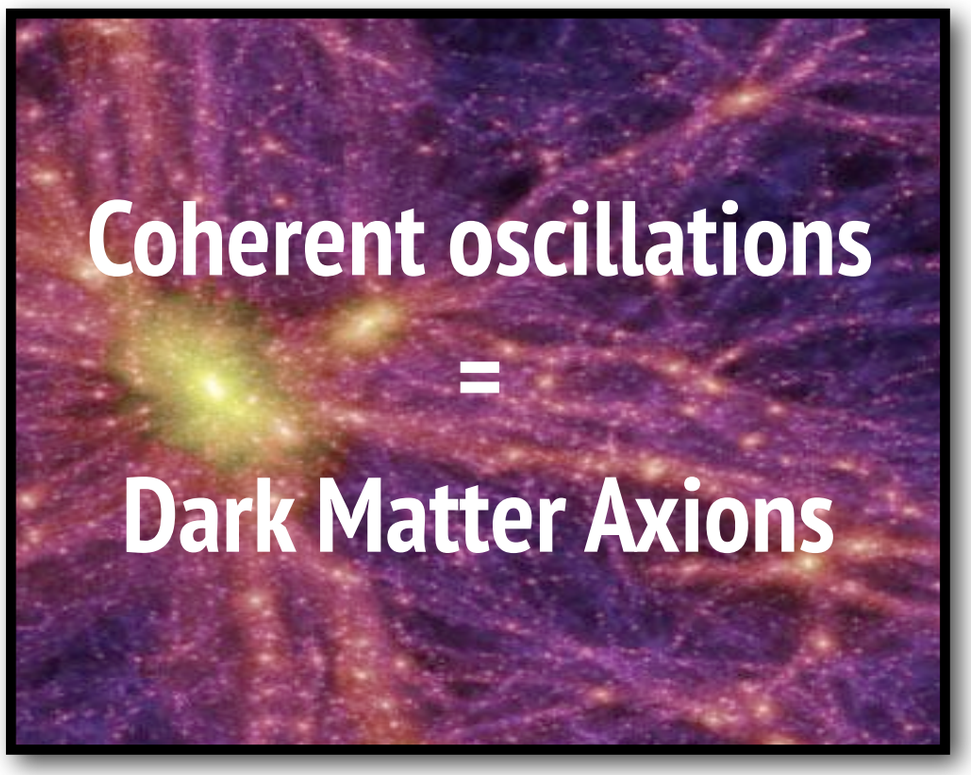


Dark Matters

Axions and dark matter

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





Oscillation frequency

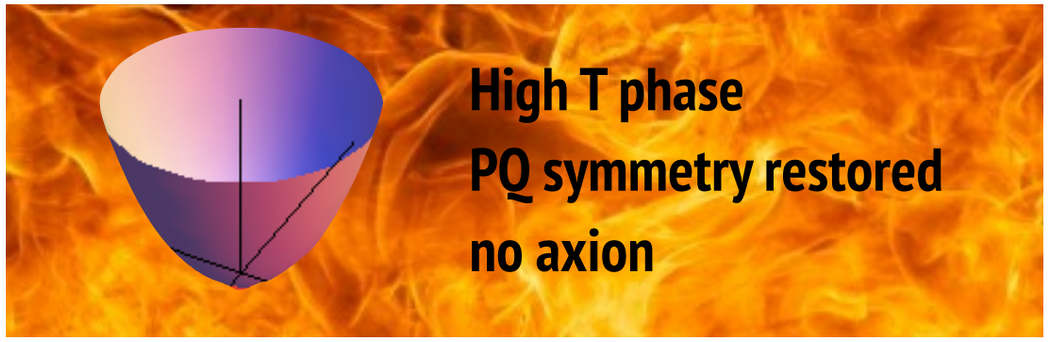
$$\omega = m_a$$

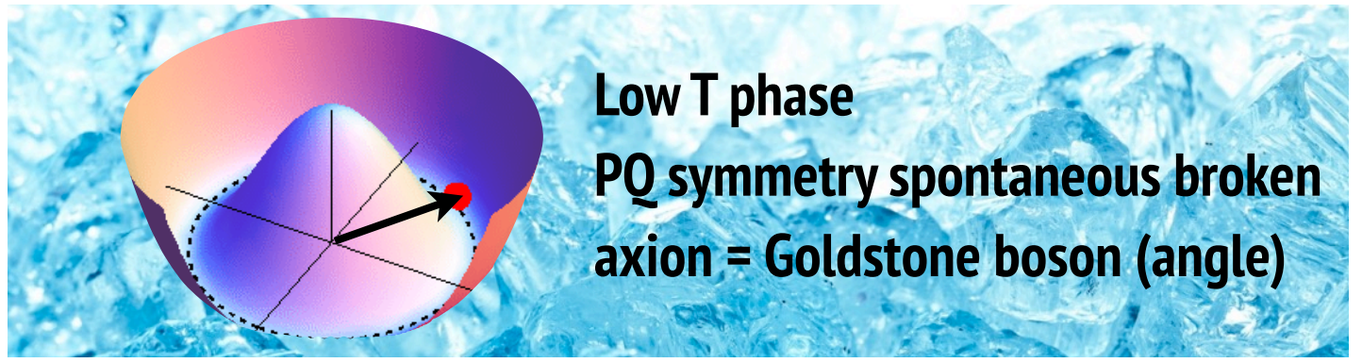
Energy density (harm. oscillator)

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

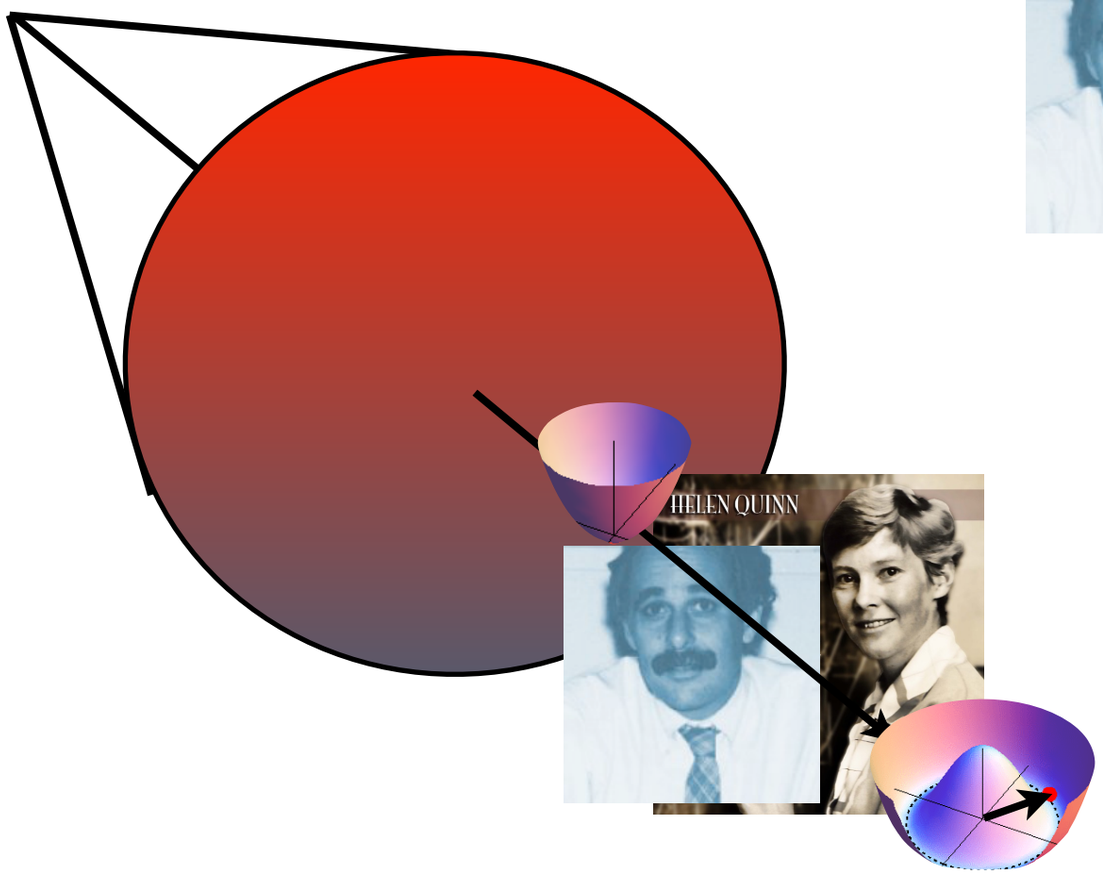
Two scenarios

- Consider axion as a Goldstone boson: exists only below spontaneous symmetry breaking (PQ symmetry)

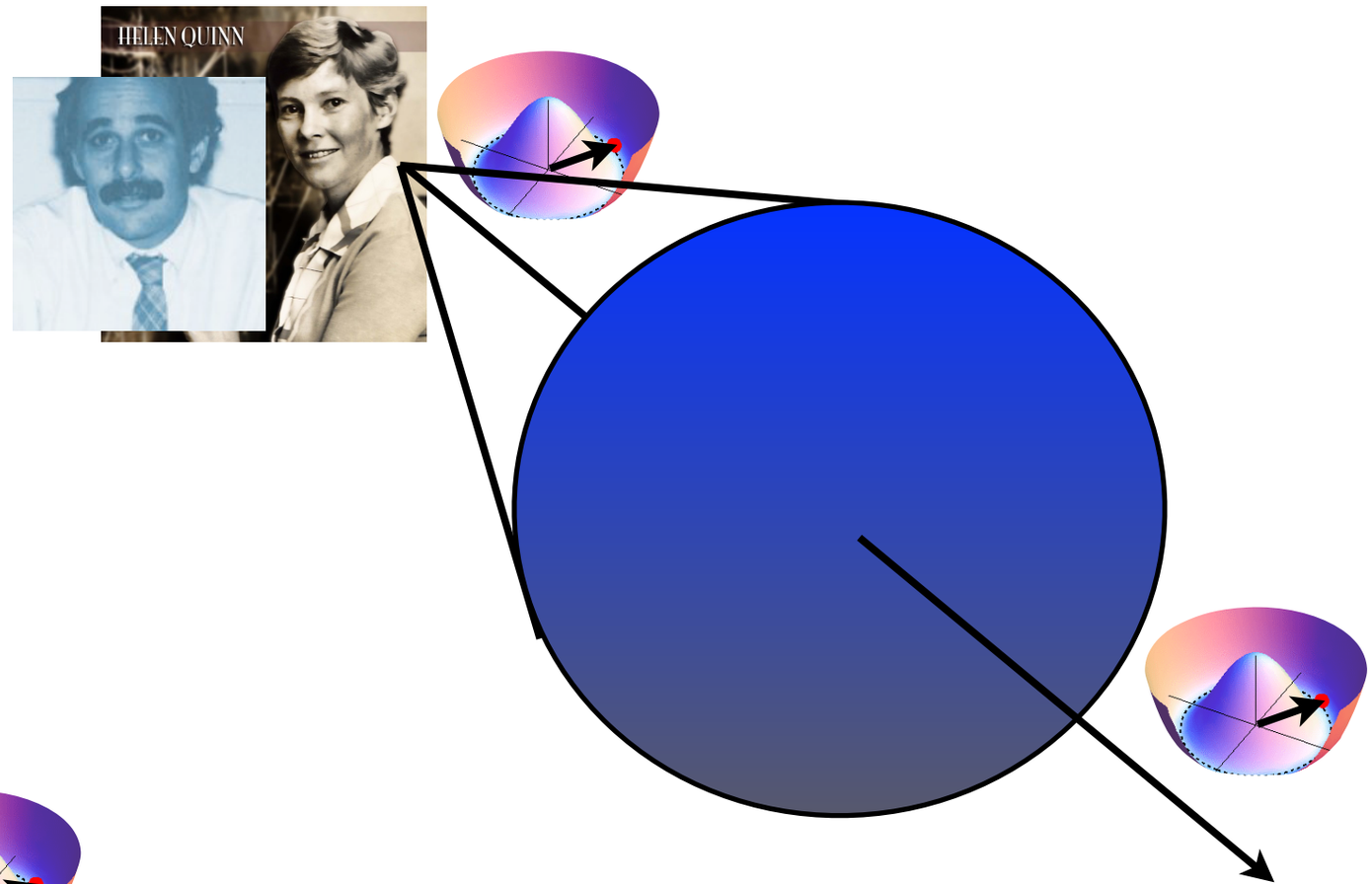




- PQ breaking after inflation



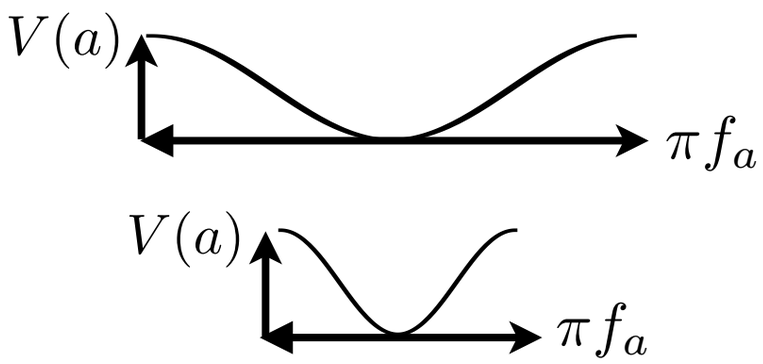
- PQ breaking before inflation



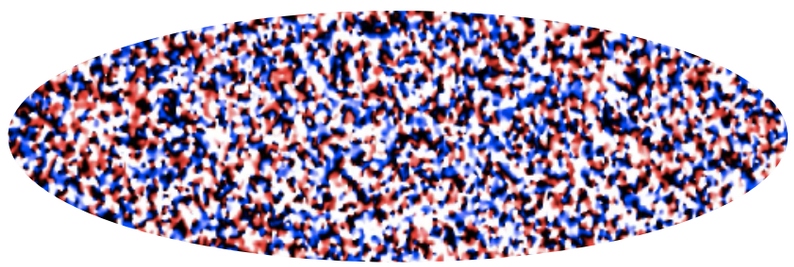
Axion dark matter

- The amount of axion DM produced depends on f_a AND on the initial conditions

large fa, small acceleration, energy stored longer

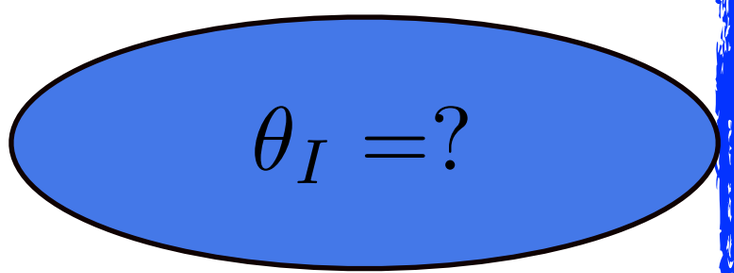


After PQ phase transition, theta IC conditions
no-correlation beyond causal horizon

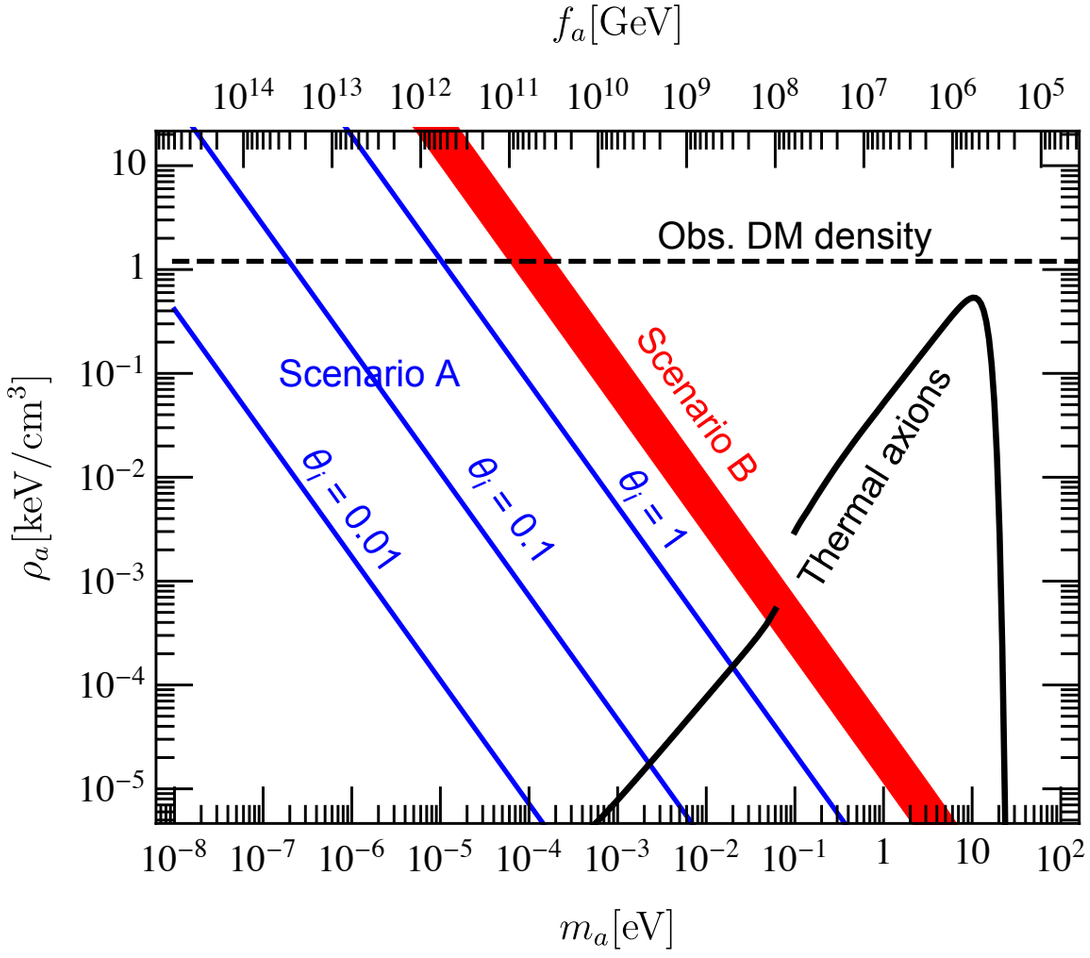


average over initial conditions! -> prediction!

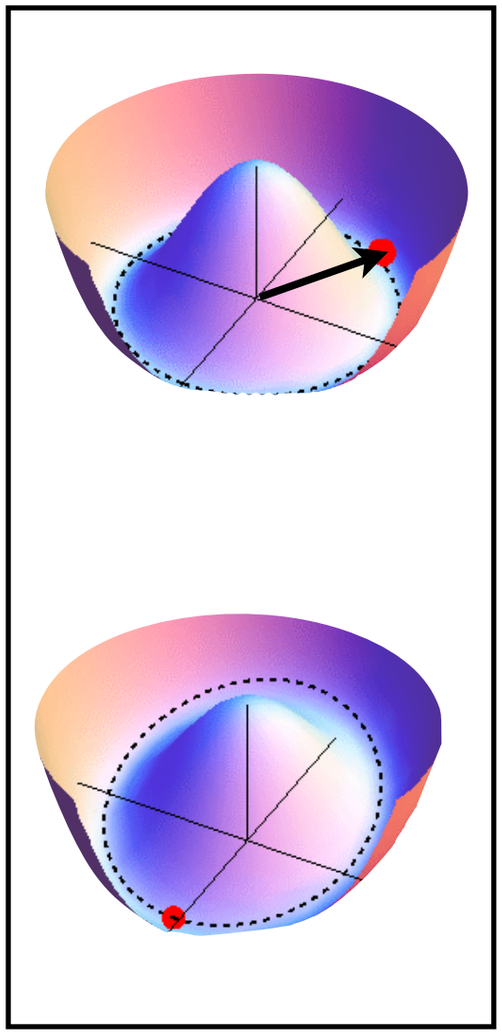
Inflation after PQ phase transition...
one domain stretched beyond our horizon!

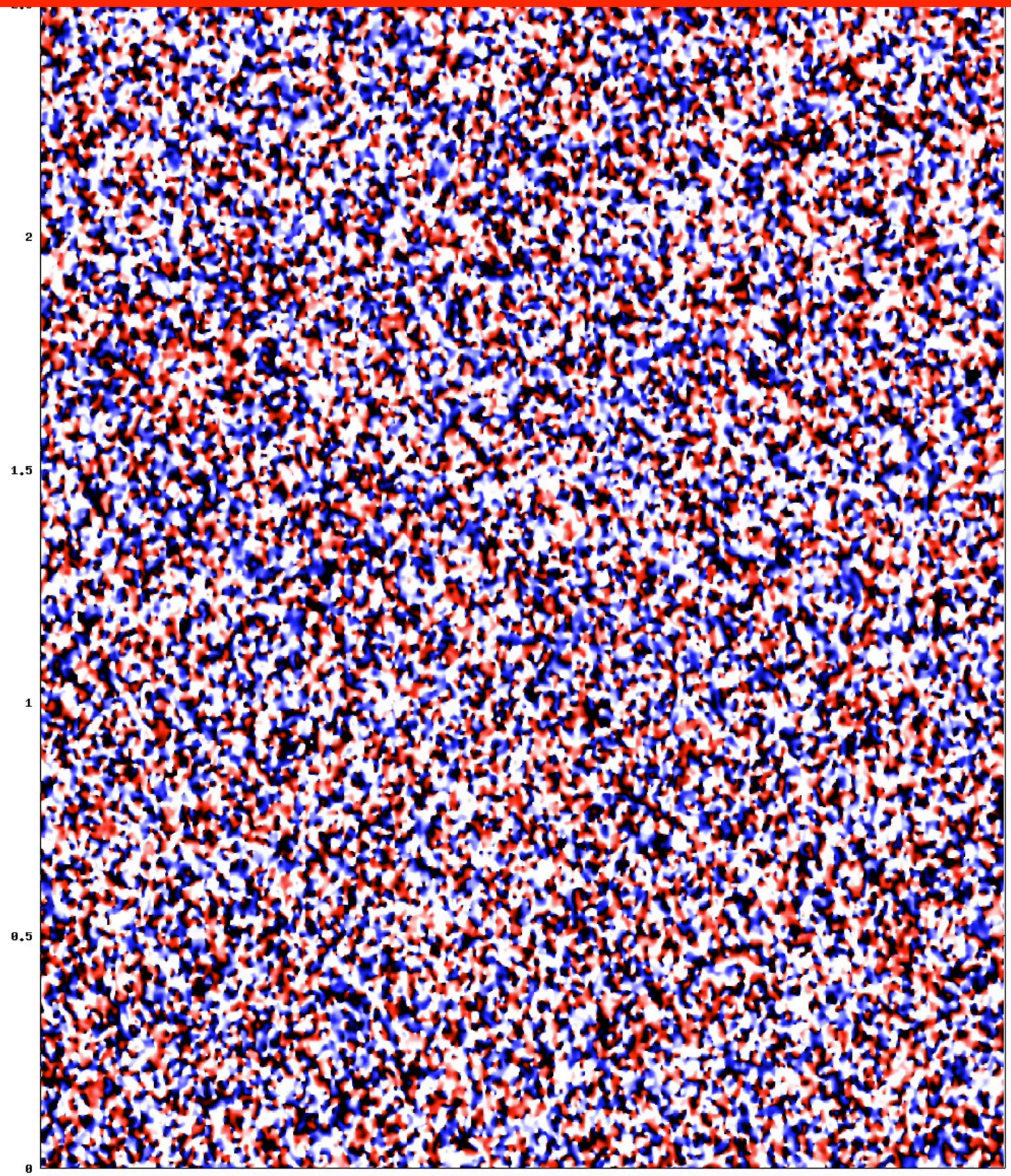


but which one??? no prediction!

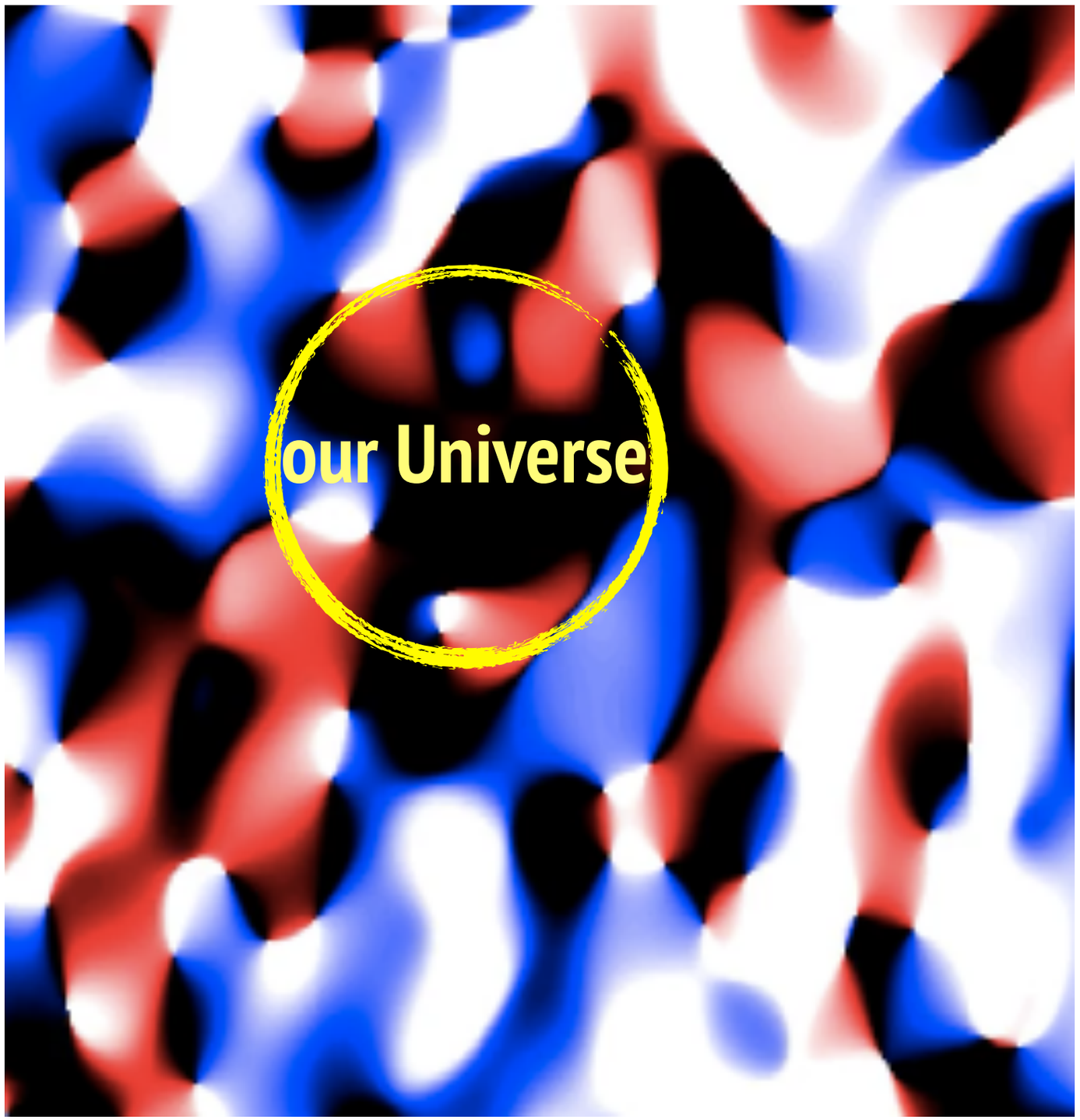


SCENARIO I (N=1): axion evolution around t1





PQ Before inflation, one patch stretched to be our Universe



π

θ

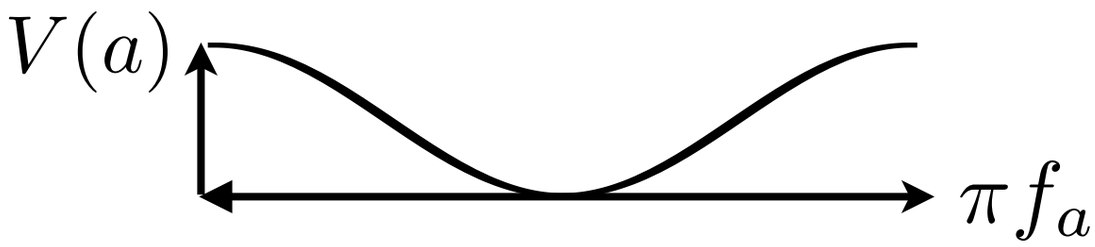
$-\pi$

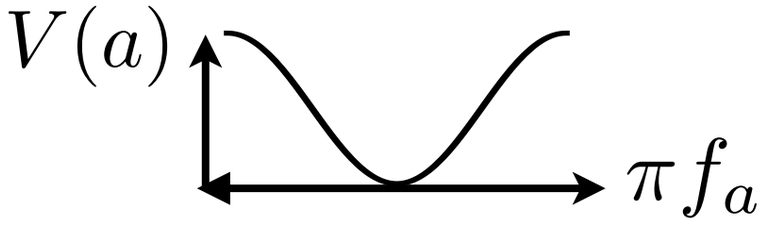
One misalignment angle singled out

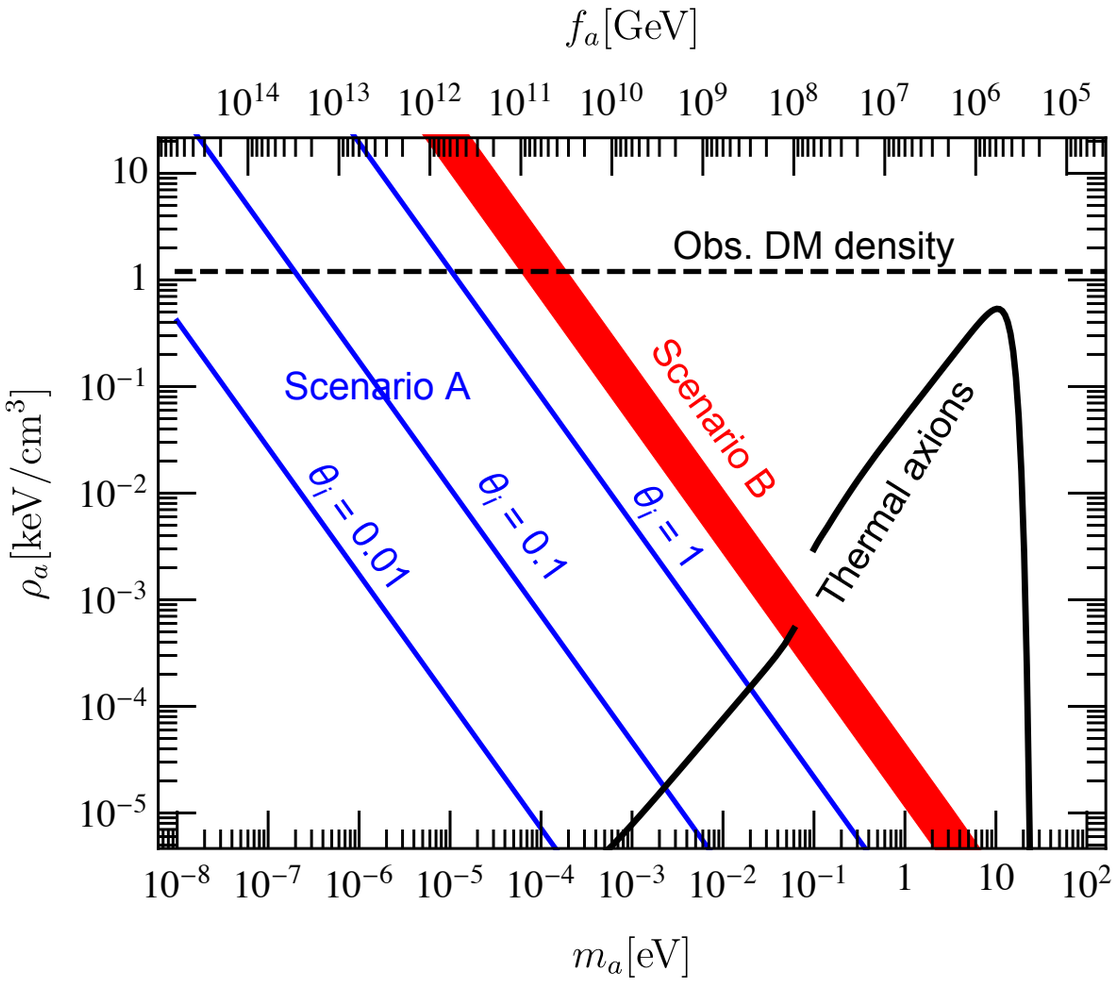
Axion dark matter

- The amount of axion DM produced depends on fa

large fa, small acceleration, energy stored longer

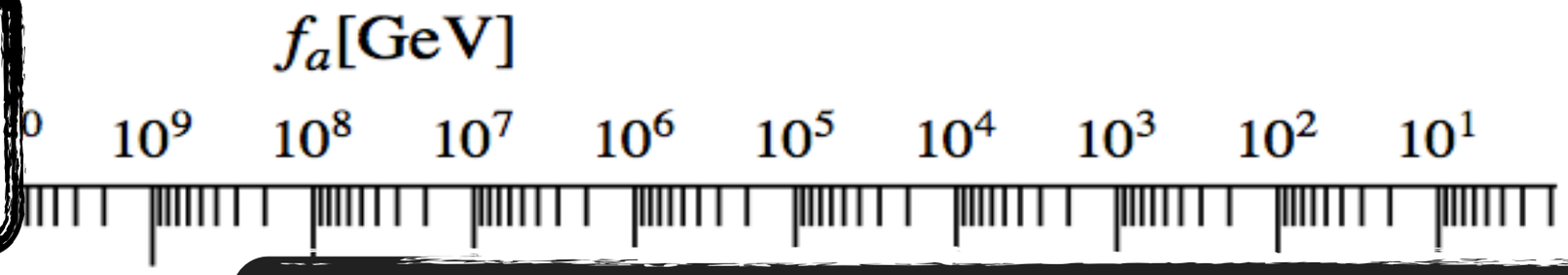






What value of f_a for $\Omega_{cdm}h^2 = 0.12$?

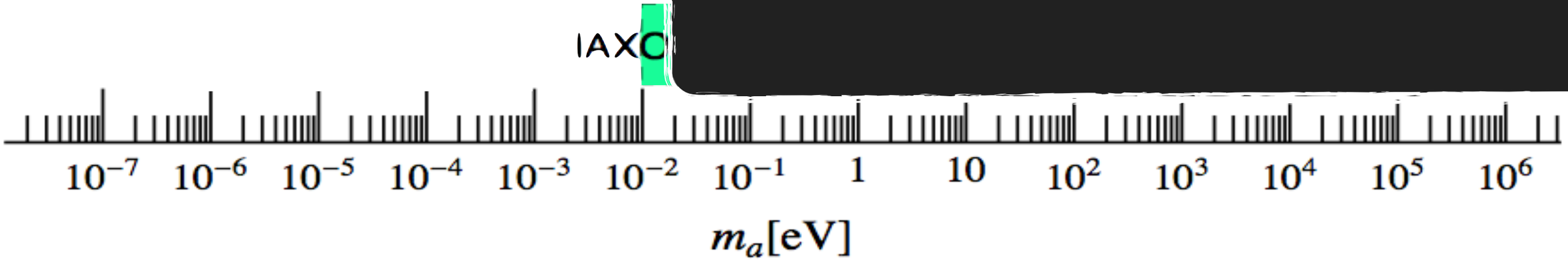
Dark Matter
huge parameter space!



- Axion DM scenarios

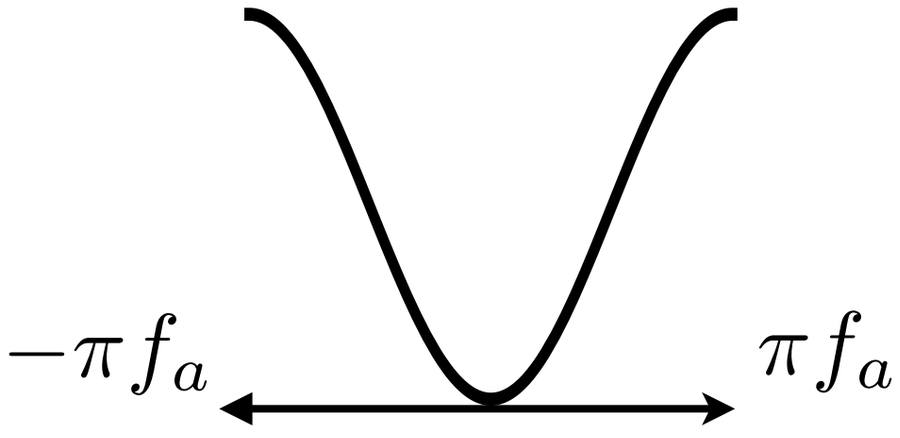
	$\theta_I \sim O(1)$	$\sim \pi$	?
Excluded (too much DM)	ok	sub	?

Excluded by Lab+Astro



- Less minimal axion models have further possibilities ....

SCENARIO I, N=1



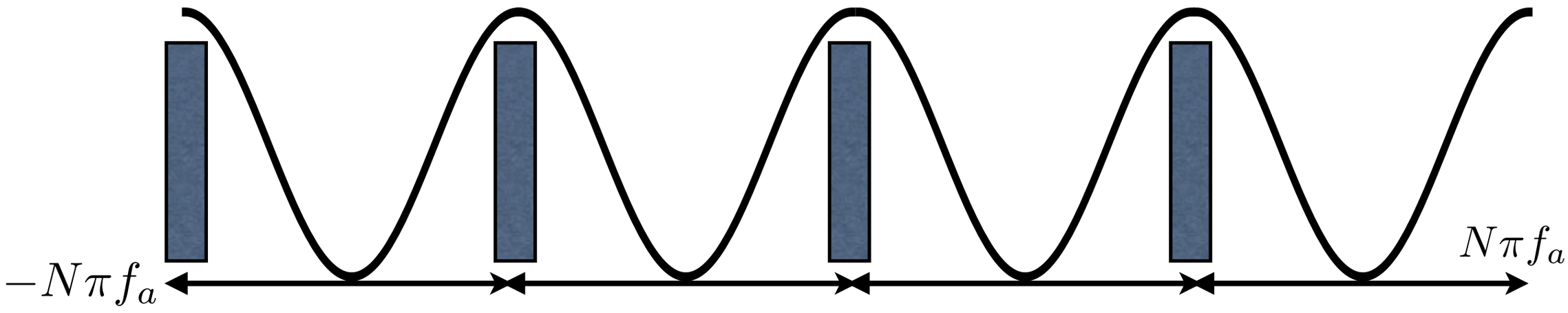
$$\mathcal{L}_\theta = \frac{\alpha_s}{8\pi} G_{\mu\nu a} \widetilde{G}_a^{\mu\nu} \theta$$

$$\theta \in (-\pi, \pi)$$

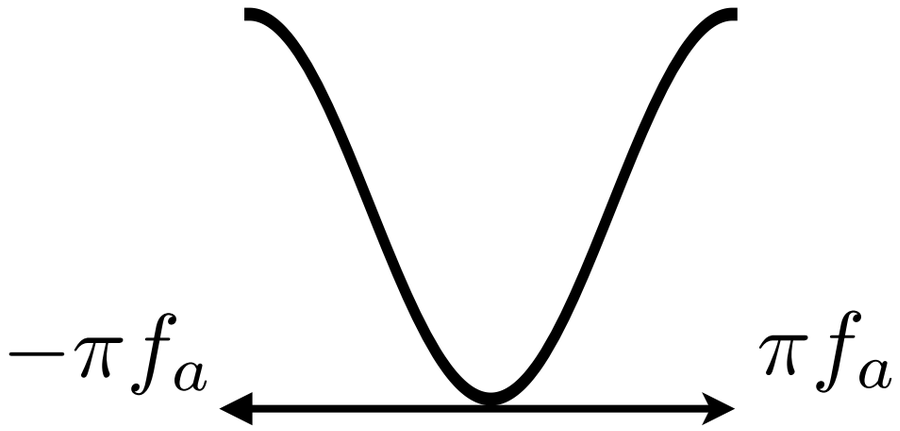
SCENARIO I, N>1, Domain Walls stable-> cosmological disaster

In some axion models, the Goldstone is $\theta_g \in (-\pi, \pi)$ **but the anomaly leads to** $\mathcal{L}_\theta = \frac{\alpha_s}{8\pi} G_{\mu\nu a} \widetilde{G}_a^{\mu\nu} \theta_g N$

-> the axion field is defined $\theta = \theta_g N$ **up to Npi and has thefore N degenerate (CP conserving) minima**

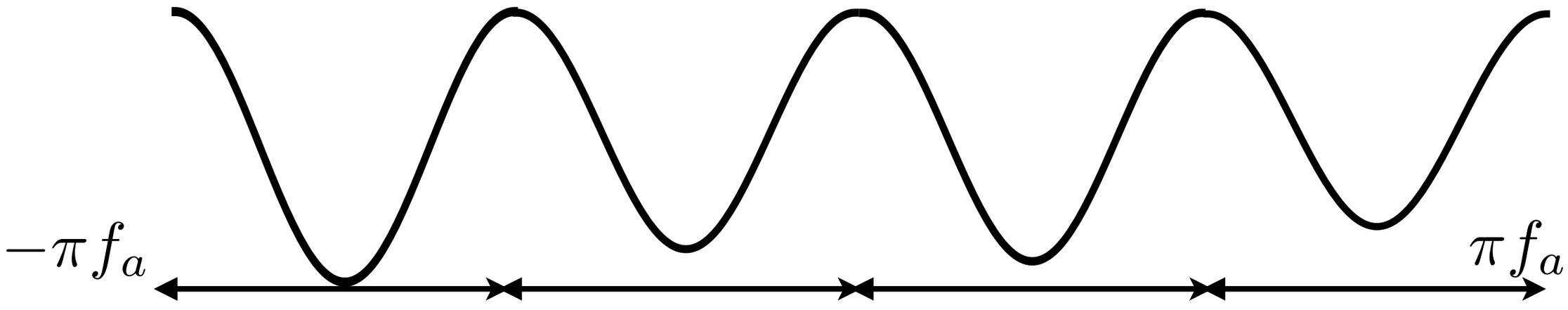


SCENARIO I, N=1



$$\frac{a}{f_a} = N\theta$$

SCENARIO I, N>1, break slightly degeneracy (but tuning...)



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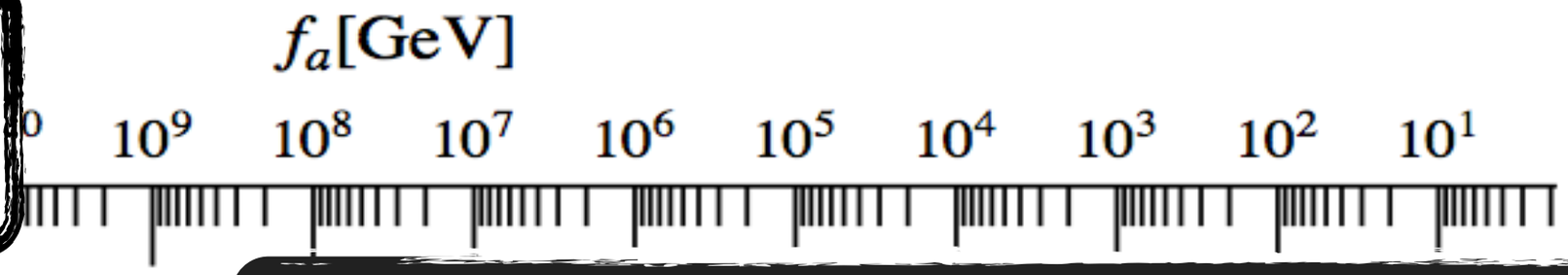

- Axion DM scenarios

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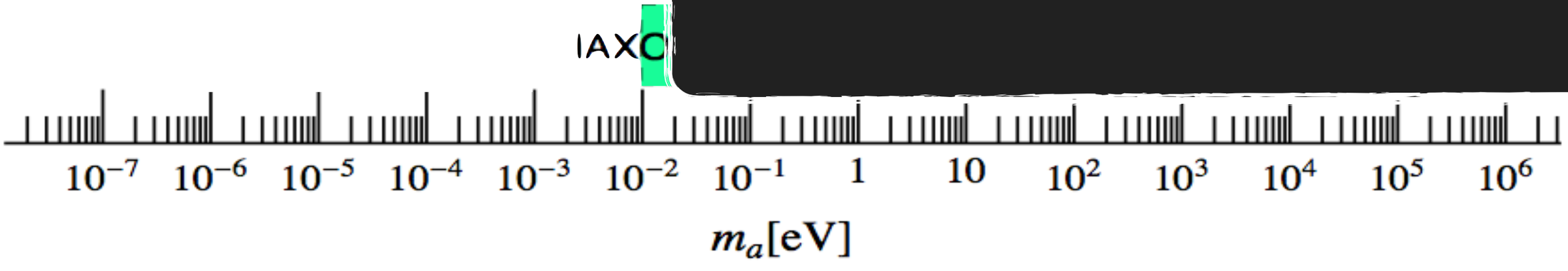
Excluded (too much DM)	?	tuned	

Excluded by Lab+Astro

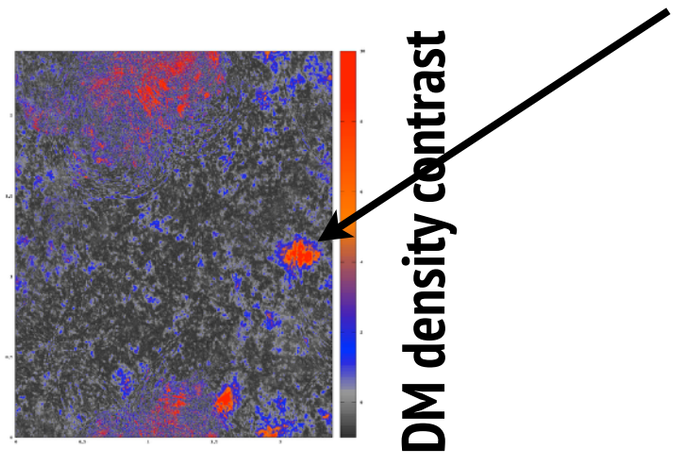


- Less minimal axion models have further possibilities ....

Most important constraints I

- PQ breaking after inflation

-> DM inhomogeneous, Axion miniclusters

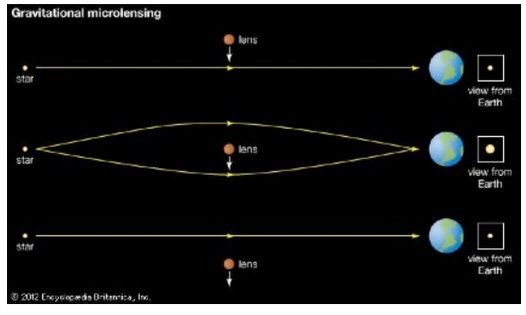


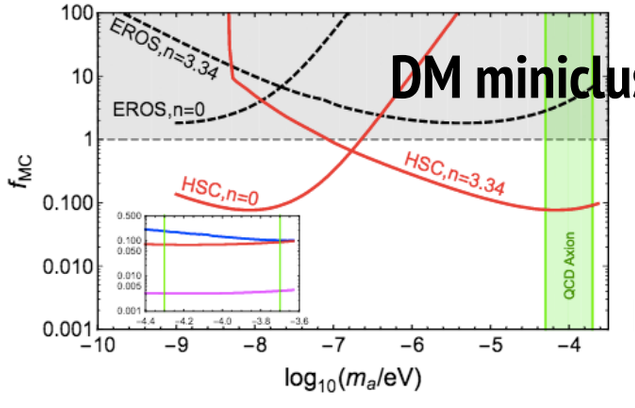
~ 0.1 comoving pc

Mass ~ $M \sim 10^{-12} M_\odot$

Merging to heavier masses? $10^{-7} M_\odot$?

Microlensing





DM minicluster fraction <0.1

Marsh 1701.04787

Scenario I Length scales

- **Time scale**

$$3H(T_1) = m_a(T_1) \qquad t_1 \sim \frac{1}{2H_1}$$

- **Horizon size (shorter wavelengths decay)**

$$L_1 = 2t_1 \sim \frac{1}{H_1}$$

- **Full Axion DM in this model** $f_a \sim 10^{11}\,\mathrm{GeV}$

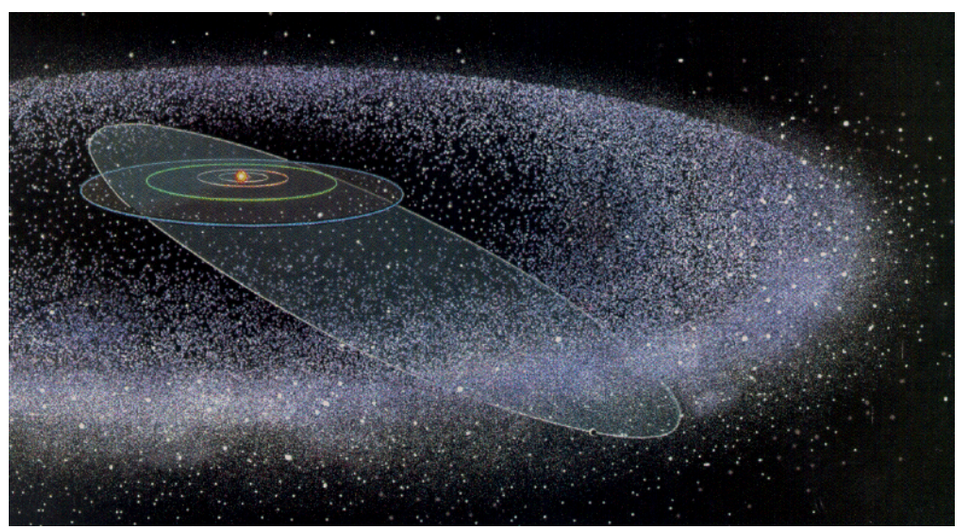
$$T_1 \sim 1.5\,\mathrm{GeV}\left(\frac{10^{11}\,\mathrm{GeV}}{f_a}\right)^{0.16}$$

- **Horizon scale at t1**

$$L \sim 10^4\,\mathrm{AU}$$ **(comoving)**

- **Mass scale in L-cube**

$$M \sim 10^{-12}\,M_\odot$$

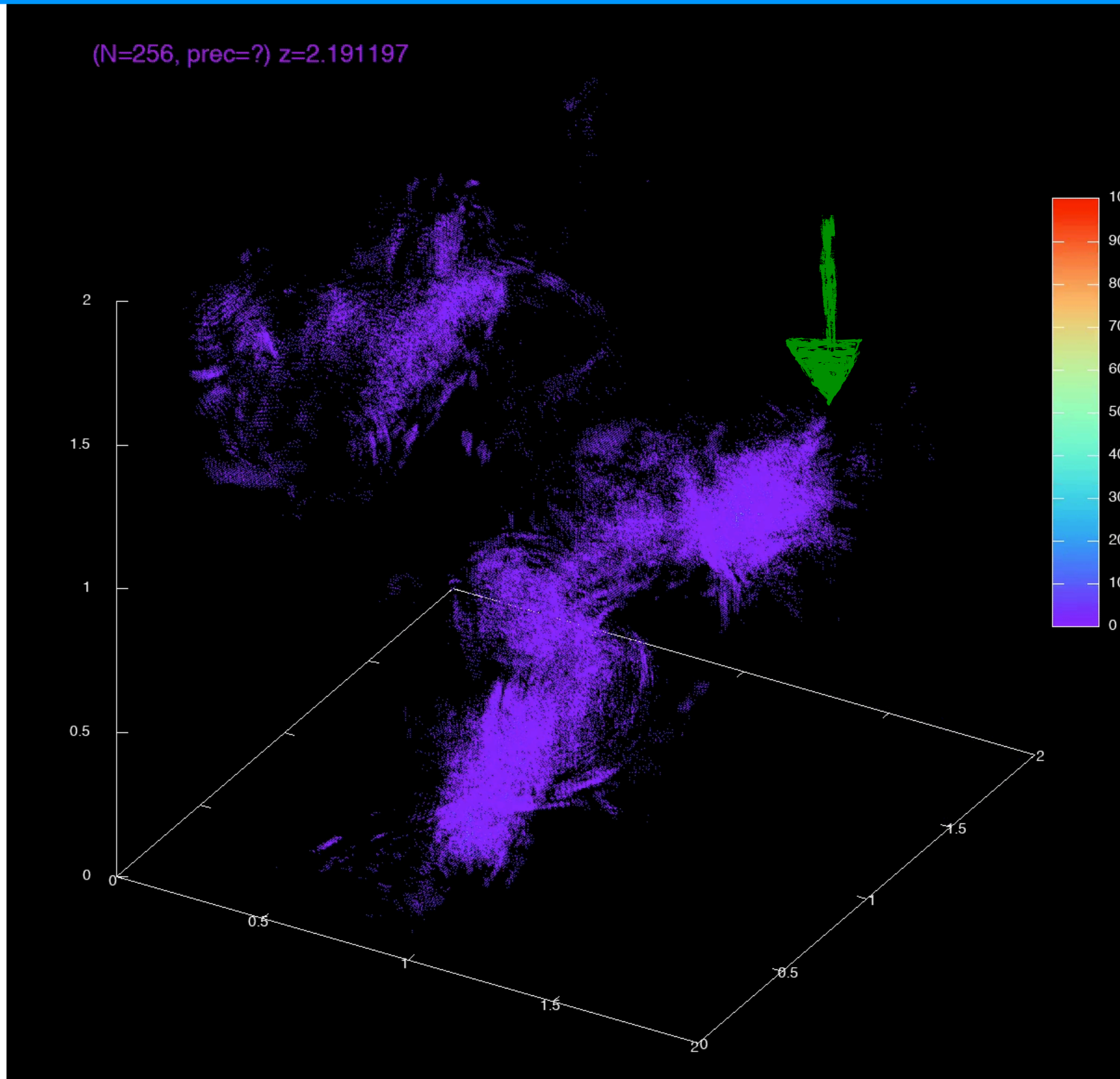


today corresponds to distances ~ Oort cloud

3 D energy density

$$\delta = \frac{\rho - \langle\rho\rangle}{\langle\rho\rangle} > 10$$

- axion miniclusters
- axitons (axion stars in core)



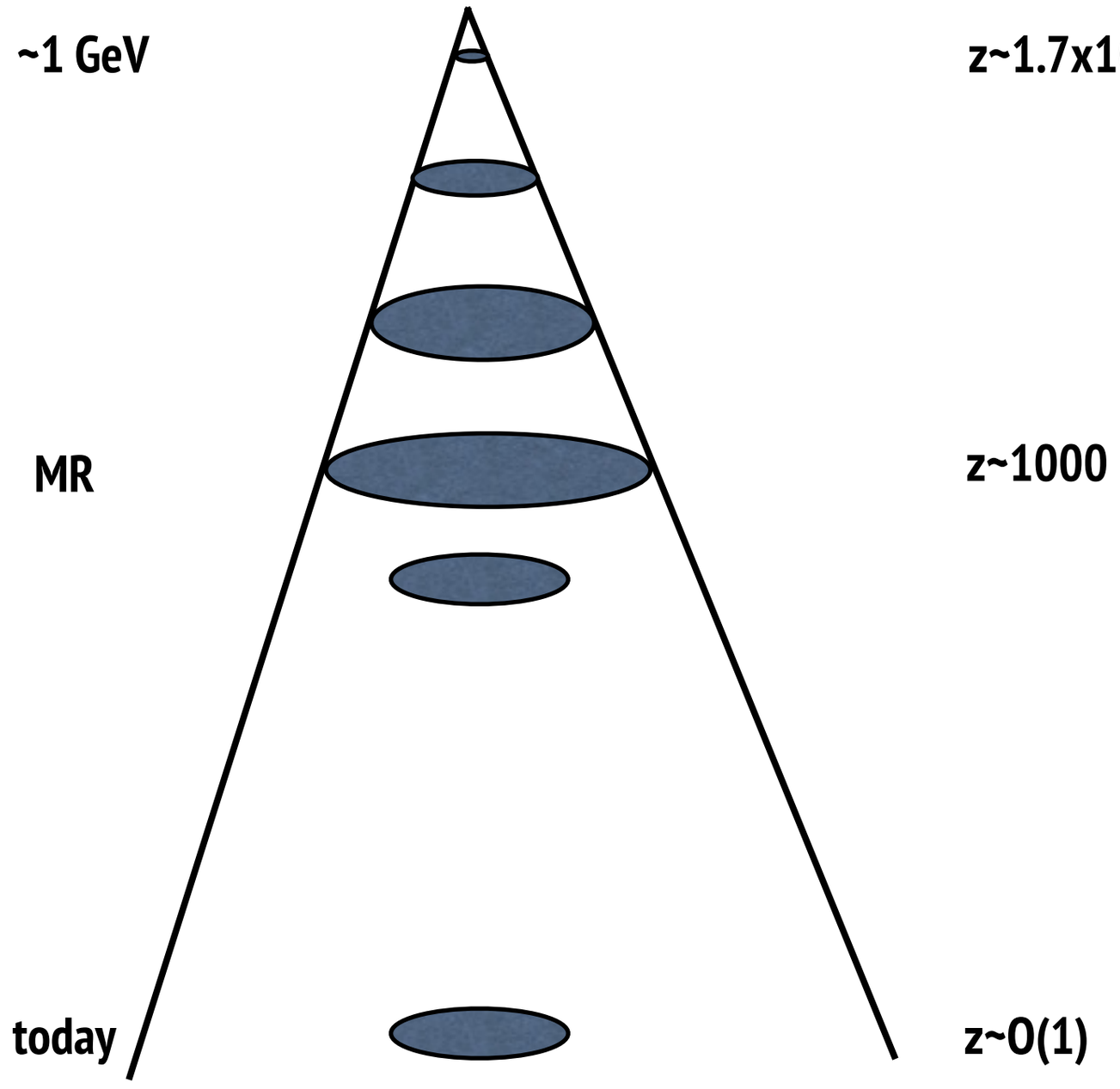
Minicluster size

frozen **~1 GeV** **z~1.7x10^13**

size expands with the Universe

local $\rho_m = \rho_r$ **collapse** $z \sim \delta z_{\rm eq}$

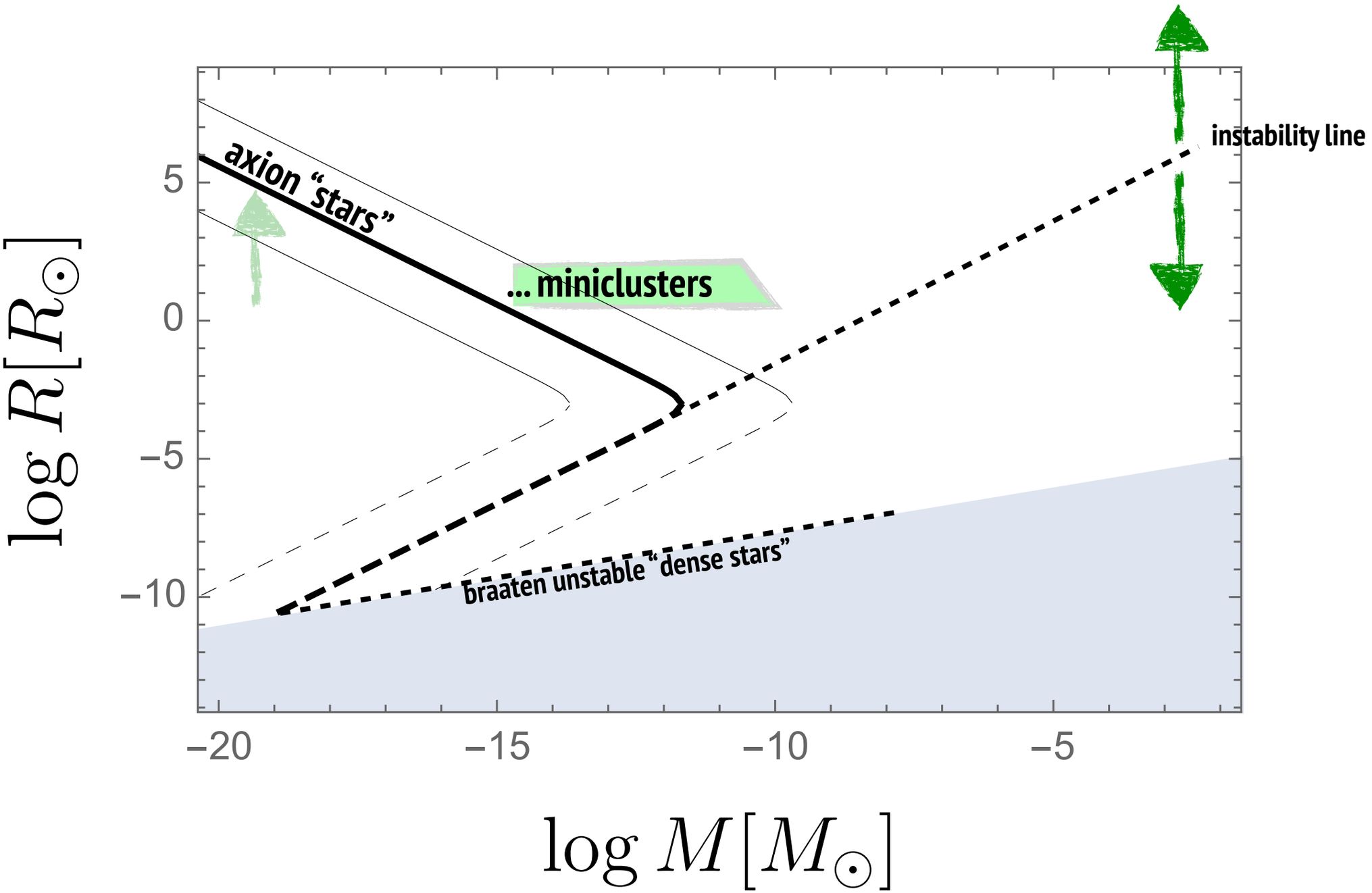
MR **z~1000**



They expand with the Universe until ~ Matter-radiation equality (z~1000)

$L \sim \mathcal{O}(1)\mathrm{A.U.}$

A picture

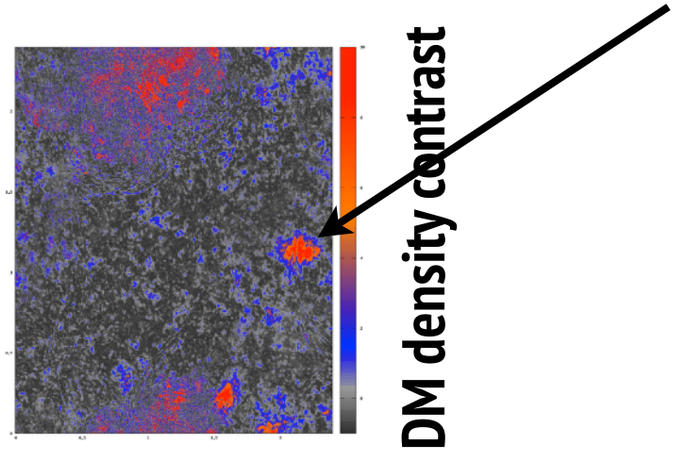


Braaten 2016
Visinelli 2017
JR work in progress ...

Most important constraints II

- PQ breaking after inflation

-> DM inhomogeneous, Axion miniclusters



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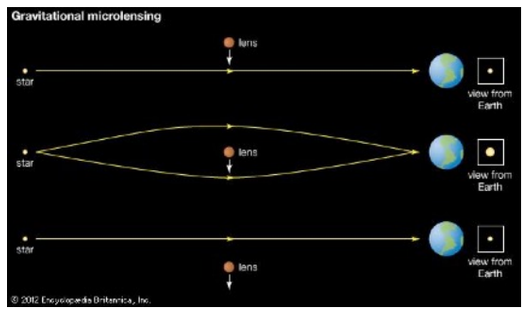
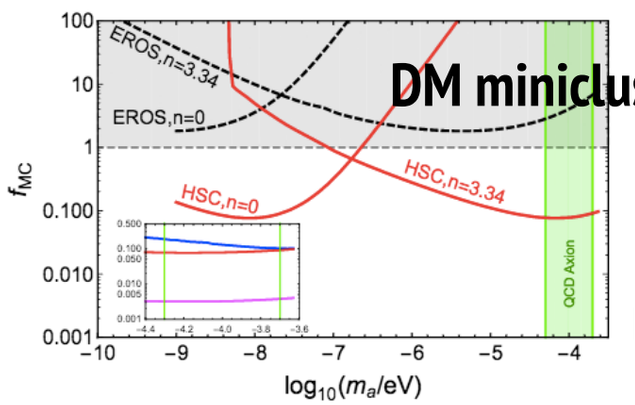


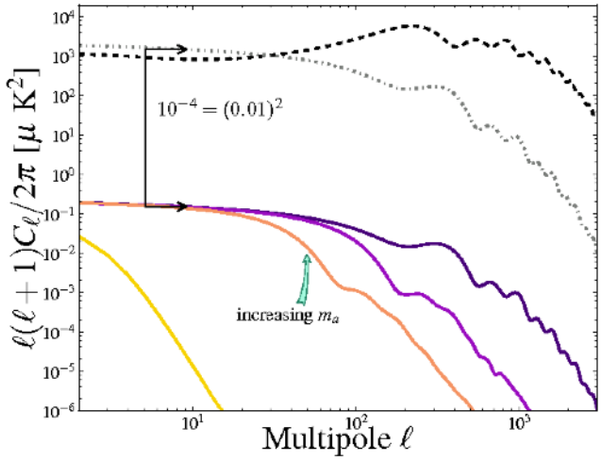


DM minicluster fraction <0.1

Marsh 1701.04787

- PQ breaking before inflation

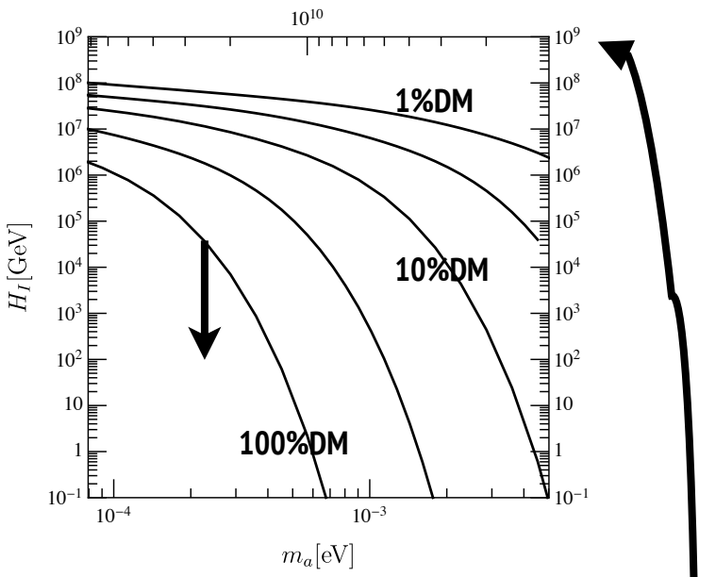
* Axion fluctuations during inflation -> CMB isocurvature



- Planck sees no Isocurvature fluctuations, strong limit!

$$P_{\rm iso} = \frac{d\langle n_a\rangle}{n_a} \sim \frac{d\langle a^2\rangle}{a_I^2} = \frac{H_I^2}{\pi^2 a_I^2} = \frac{H_I^2}{\pi^2 f_a^2 \theta_I^2} < 0.039 P_s = 0.88 \times 10^{-10}$$

Depends on Hubble rate during inflation ... H_I



- If H_I is measured by next generation CMB Polarisation axion DM is excluded (avoided in some models)