Dark matter & Axions!

Javier Redondo (Zaragoza U. & MPP Munich)

Overview

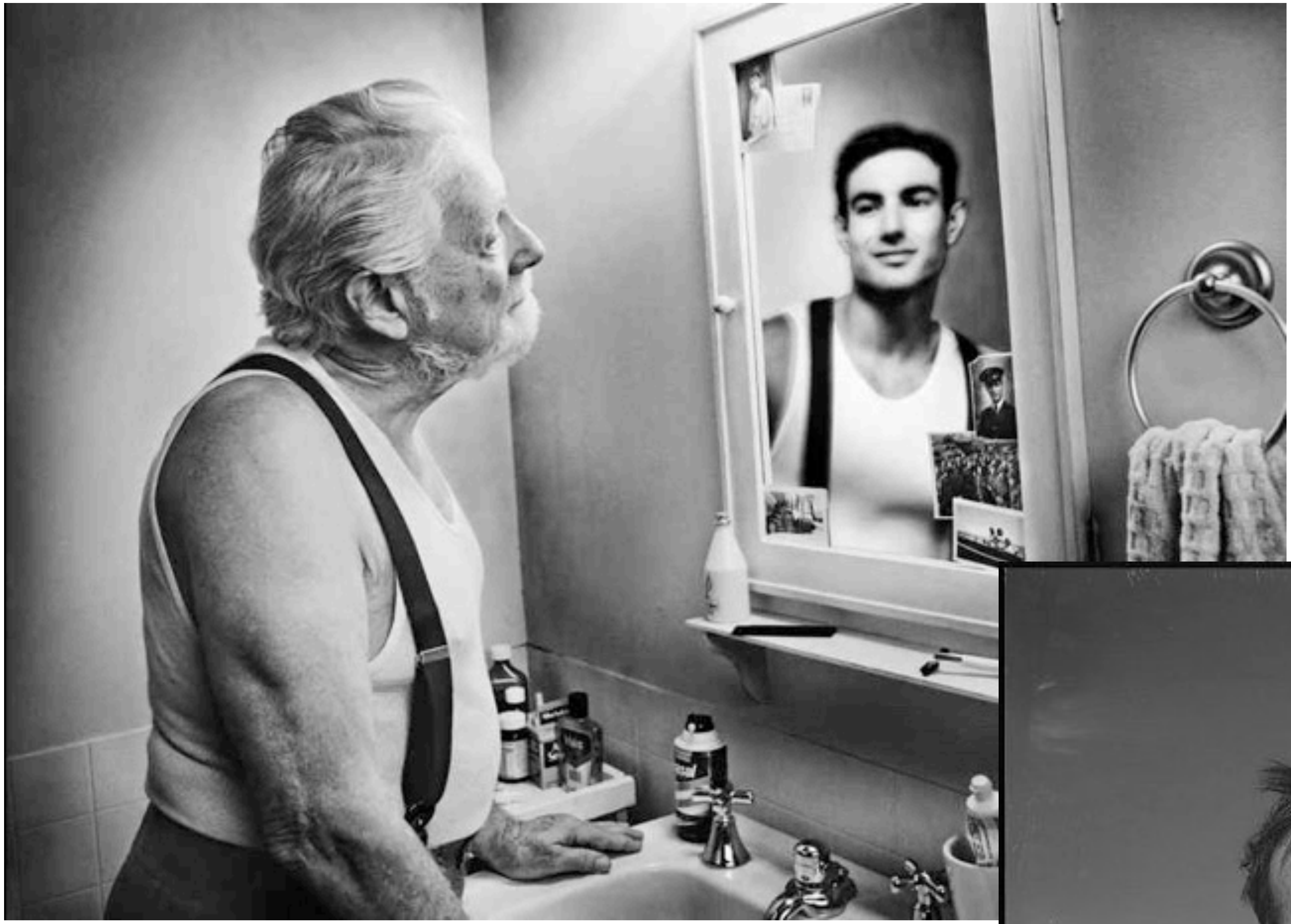
- Strong CP problem

- Axions and ALPs

- Axion Dark matter

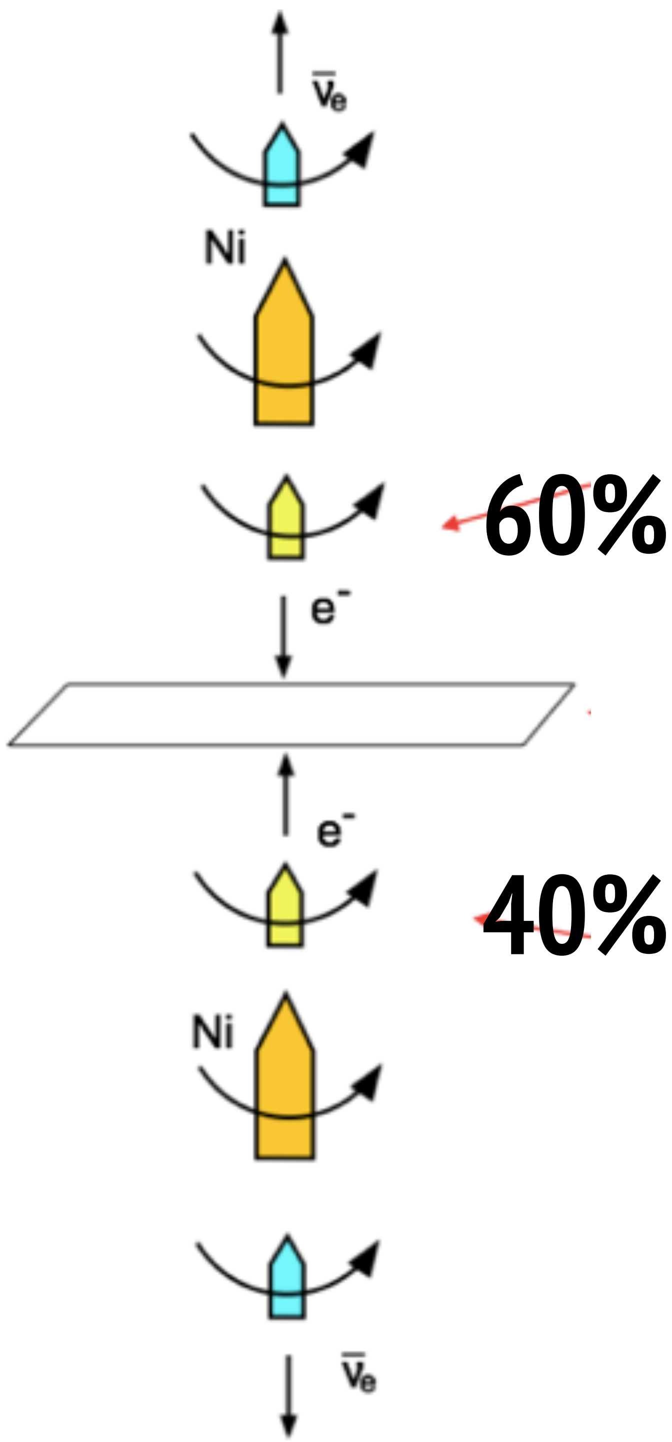
- Dark matter experiments

Parity and Time reversal



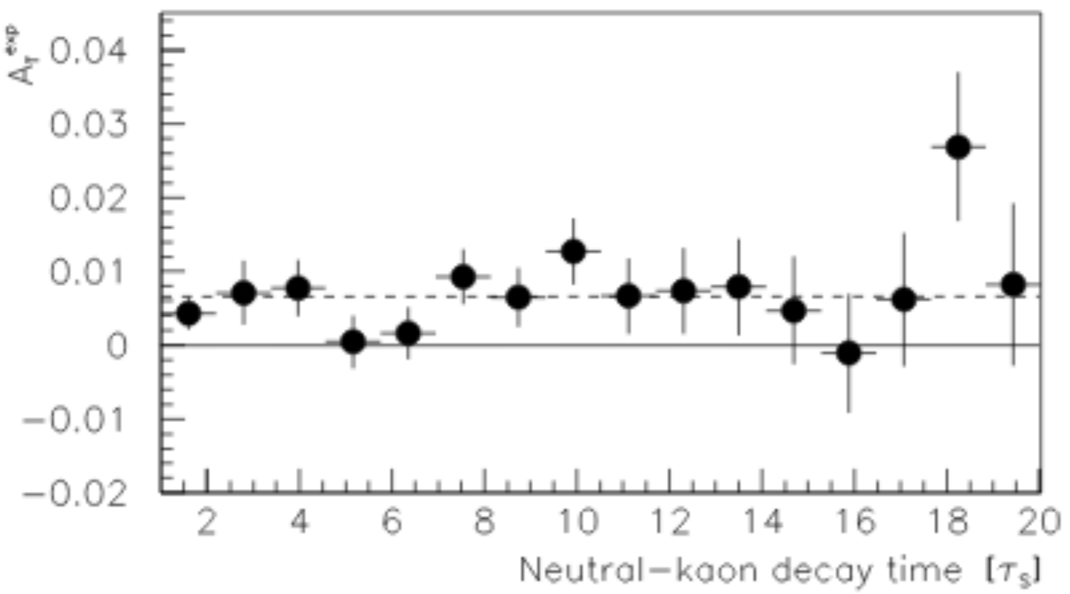
in particle physics (electroweak interactions)

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)

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

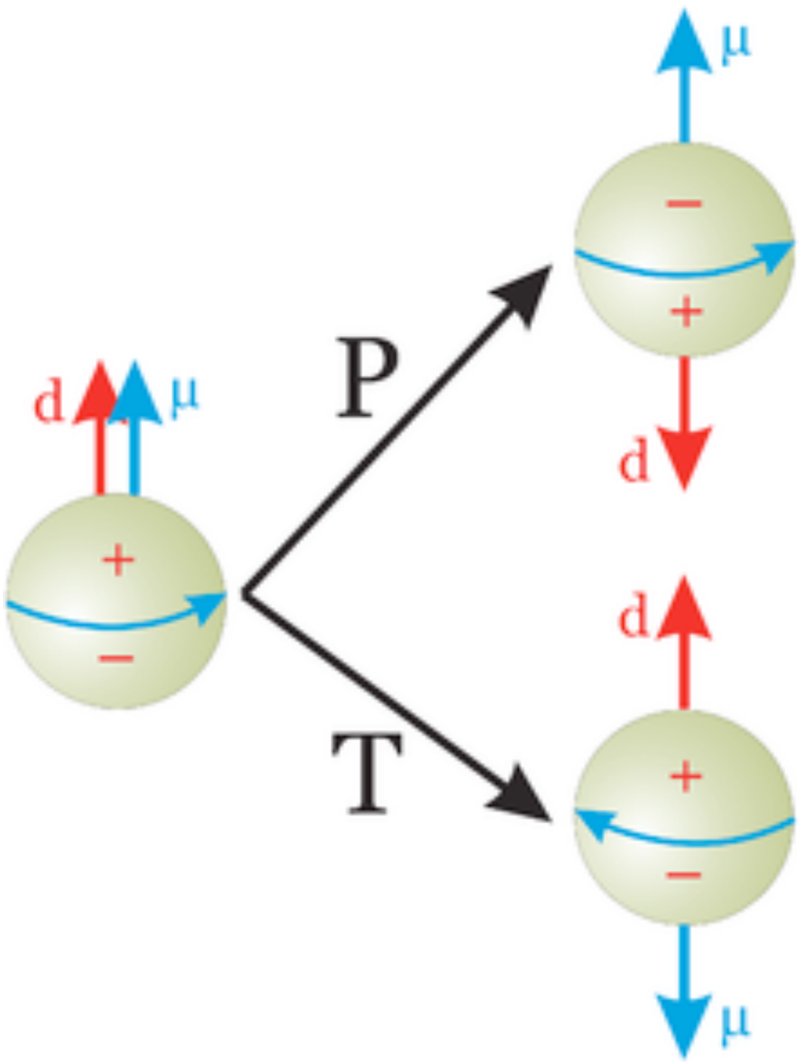
we tend to forget this

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

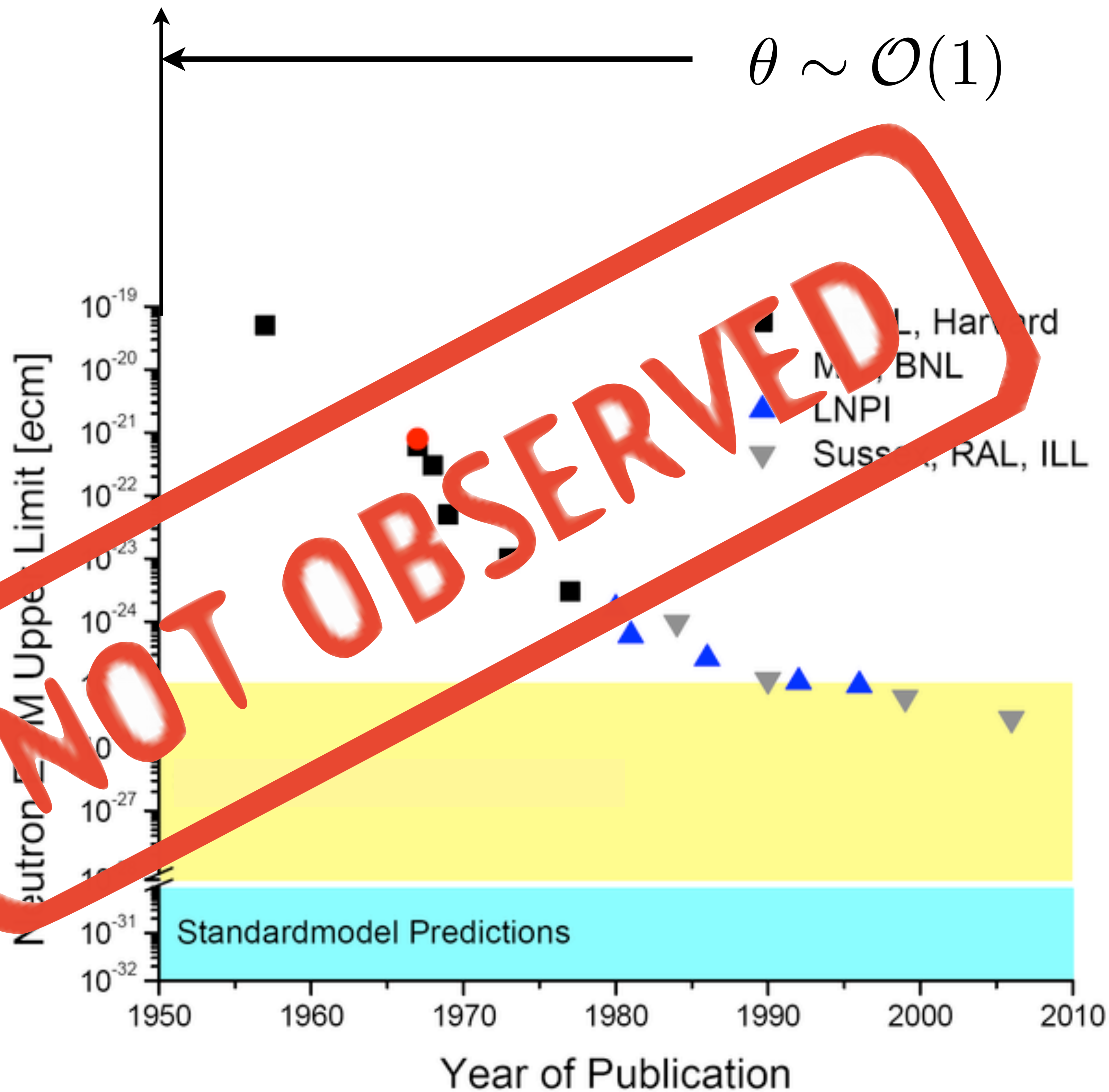
$\theta \in (-\pi, \pi)$ **infinitely versions of QCD... all are P,T violating**

Neutron EDM

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

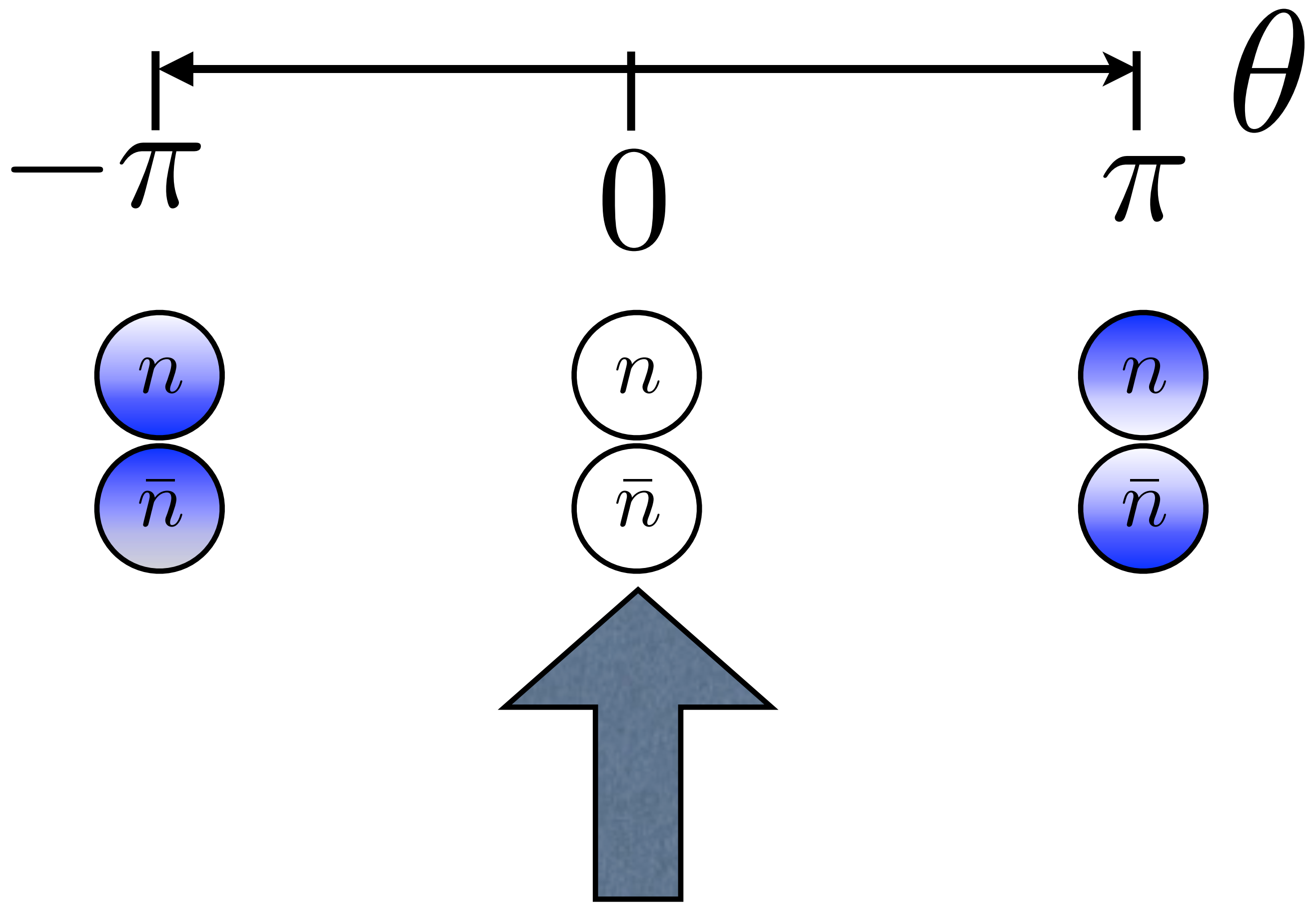


EDM violates P,T



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)**

Roberto Peccei and Helen Quinn 77

CP Conservation in the Presence of Pseudoparticles*

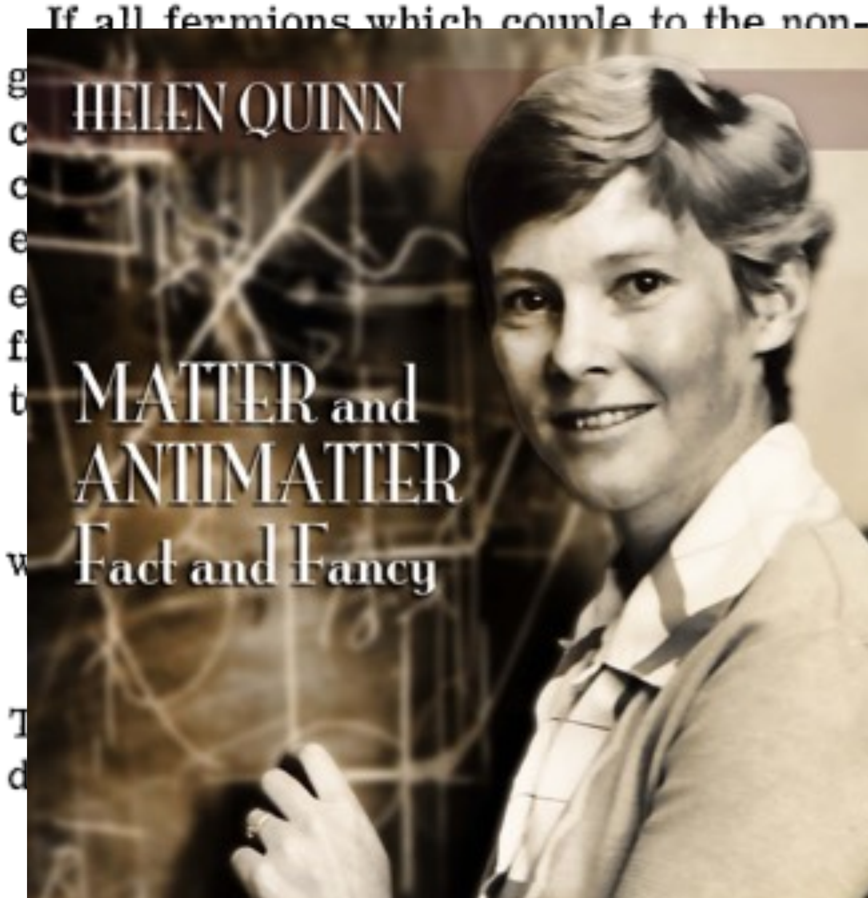
R. D. Peccei and Helen R. Quinn†
Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305
(Received 31 March 1977)

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)

any special value?

- QCD vacuum energy is minimum at $\theta = 0$

Energy density (potential) as a function of θ (Euclidean path integral) $t \to -ix_0$

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

$$\leq \int \mathcal{D}g_\mu^a e^{-S_E[g_\mu^a]} \left| e^{-i\theta \int d^4x_E \frac{\alpha_s}{8\pi} G^a_{\mu\nu}\widetilde{G}^{\mu\nu}_a} \right|$$

$$\leq \int \mathcal{D}g_\mu^a e^{-S_E[g_\mu^a]} = e^{-\int d^4x V[0]}$$

*we have assumed S_E does not contain P, T violation->Real
In the SM, CP-violation in the CKM will propagate (three loops) and shift slightly the minimum of the potential from 0

- Potential is periodic $V(\theta) = V(\theta + 2\pi)$

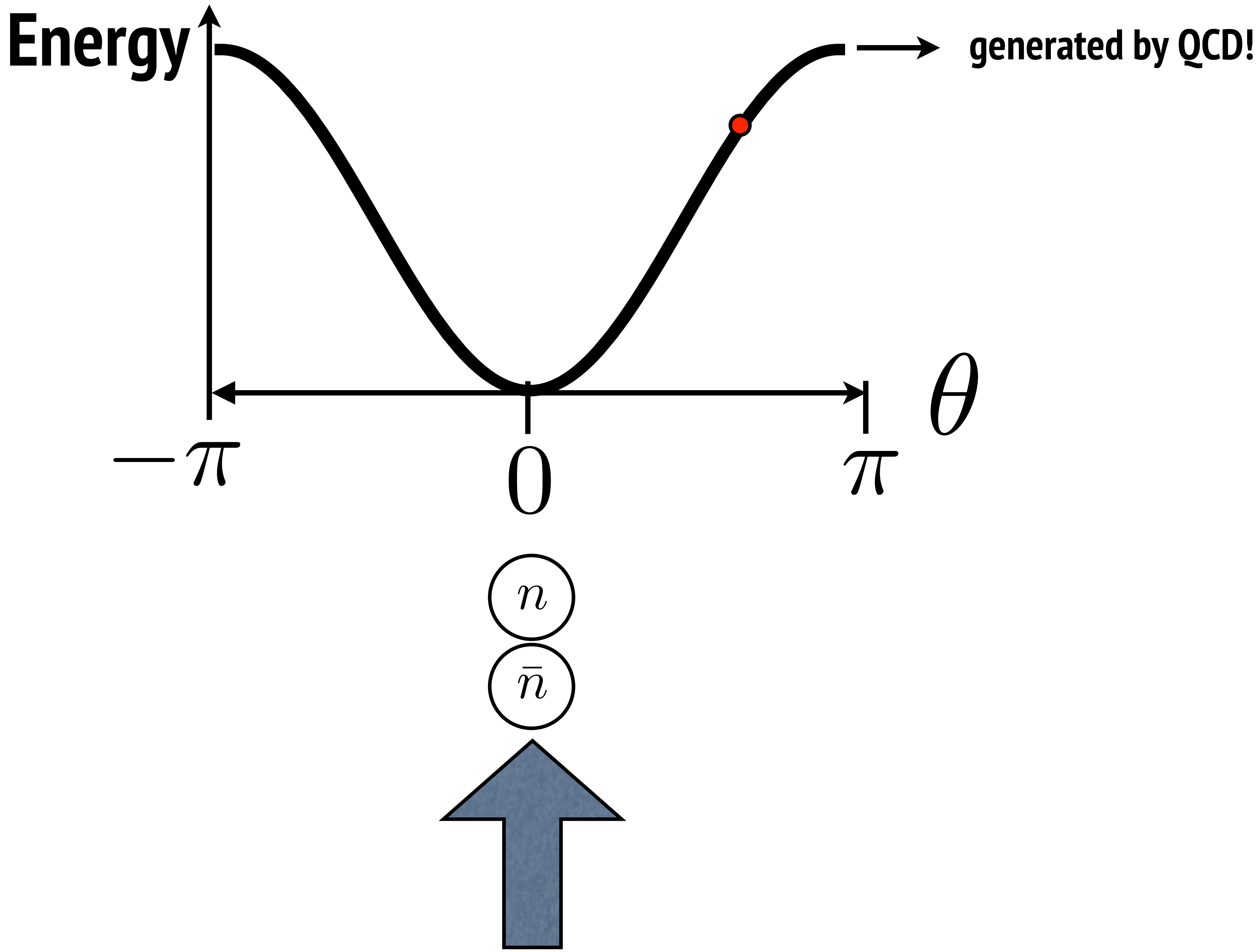
The theta-term is a total derivative and its integral a topological index

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

$$e^{iS} = e^{iS + i2\pi}$$

QCD vacuum energy minimised at CP conservation!!

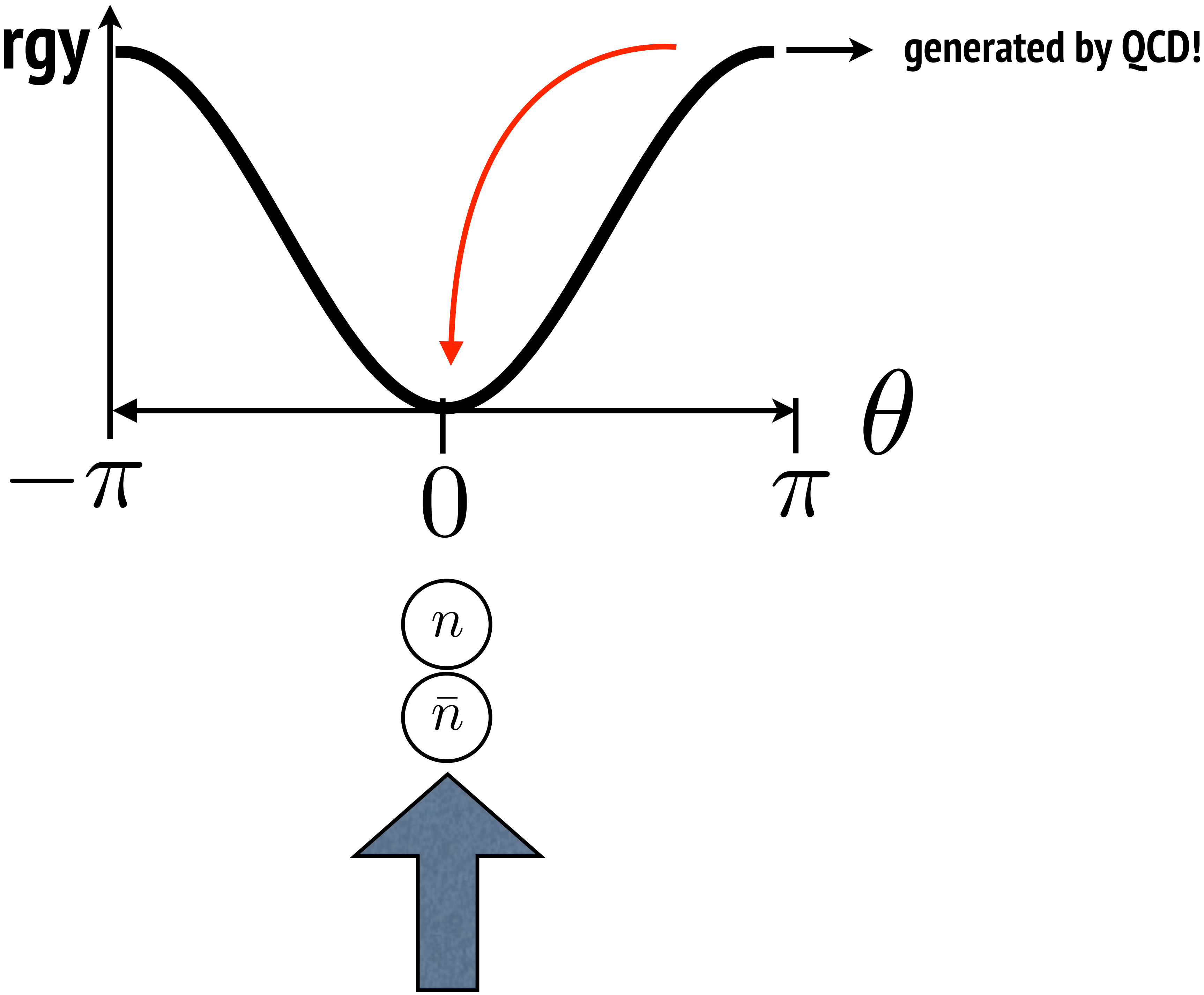
- but ... theta is a constant of the SM



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

beyond the SM ...

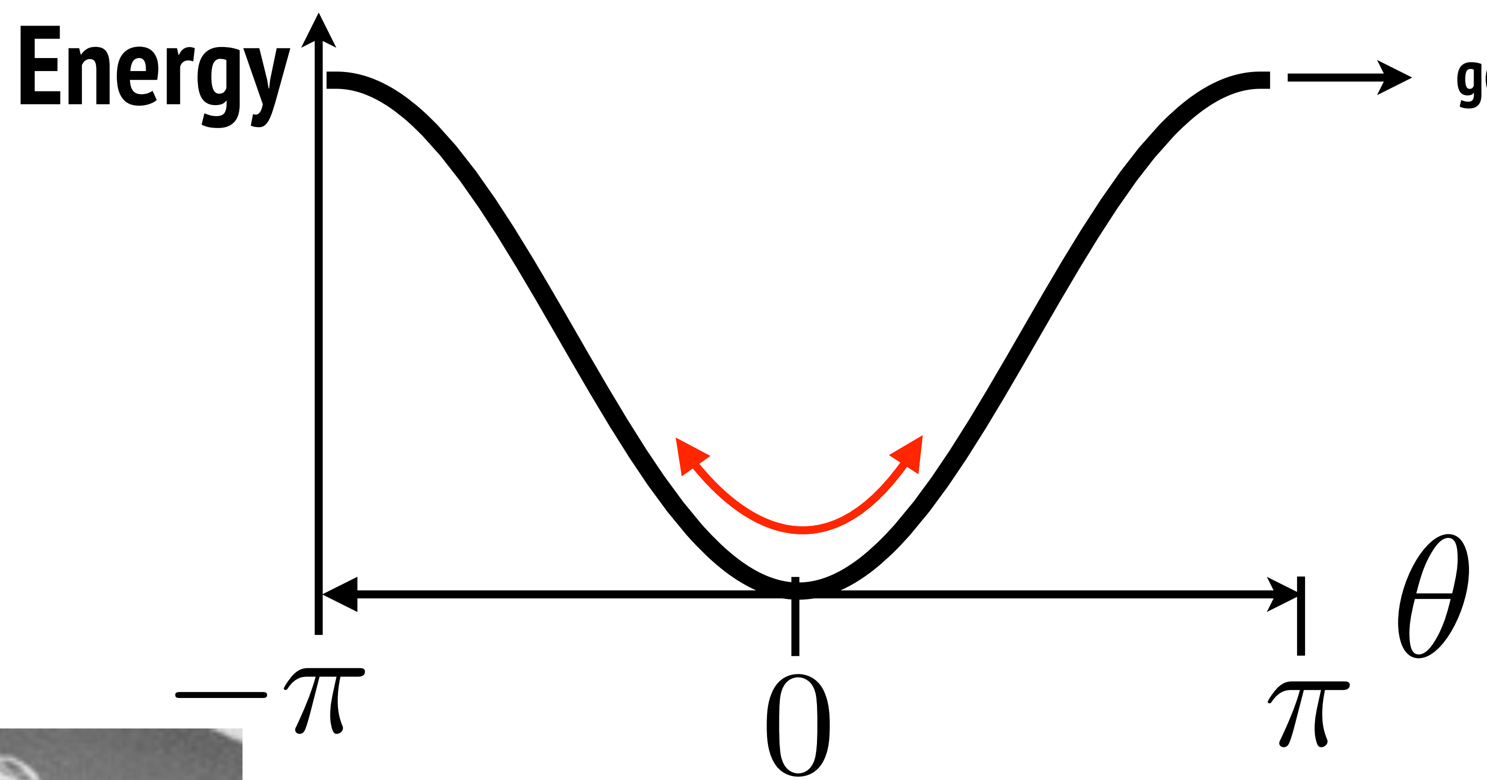
- ... if $\theta(t, \mathbf{x})$ is dynamical field, relaxes to its minimum



Measured today $|\theta| < 10^{-10}$ (strong CP problem will be solved dynamically!)

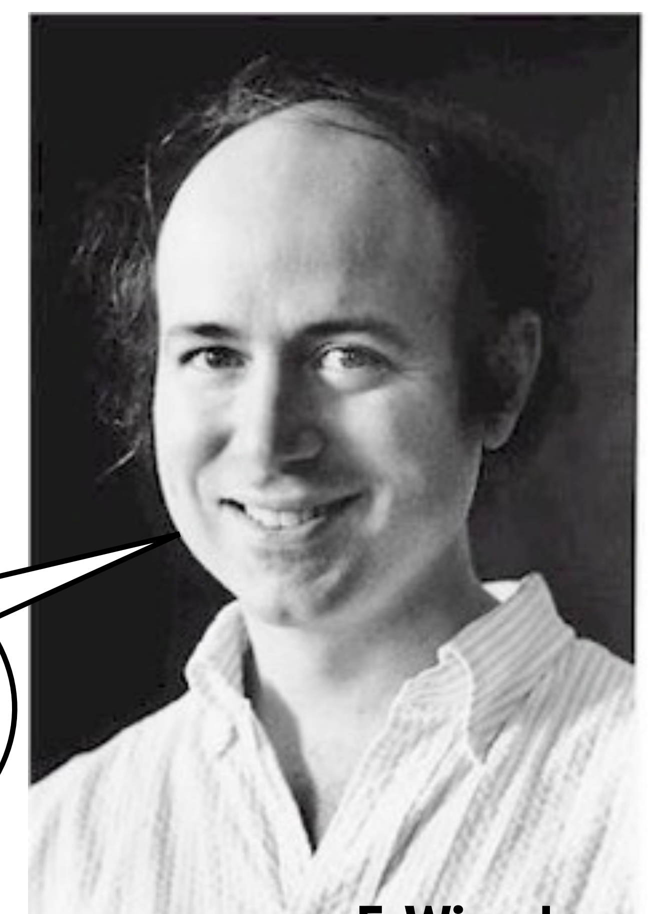
a new particle is born ...

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



Field Excitations around the vacuum are particles

S. Weinberg



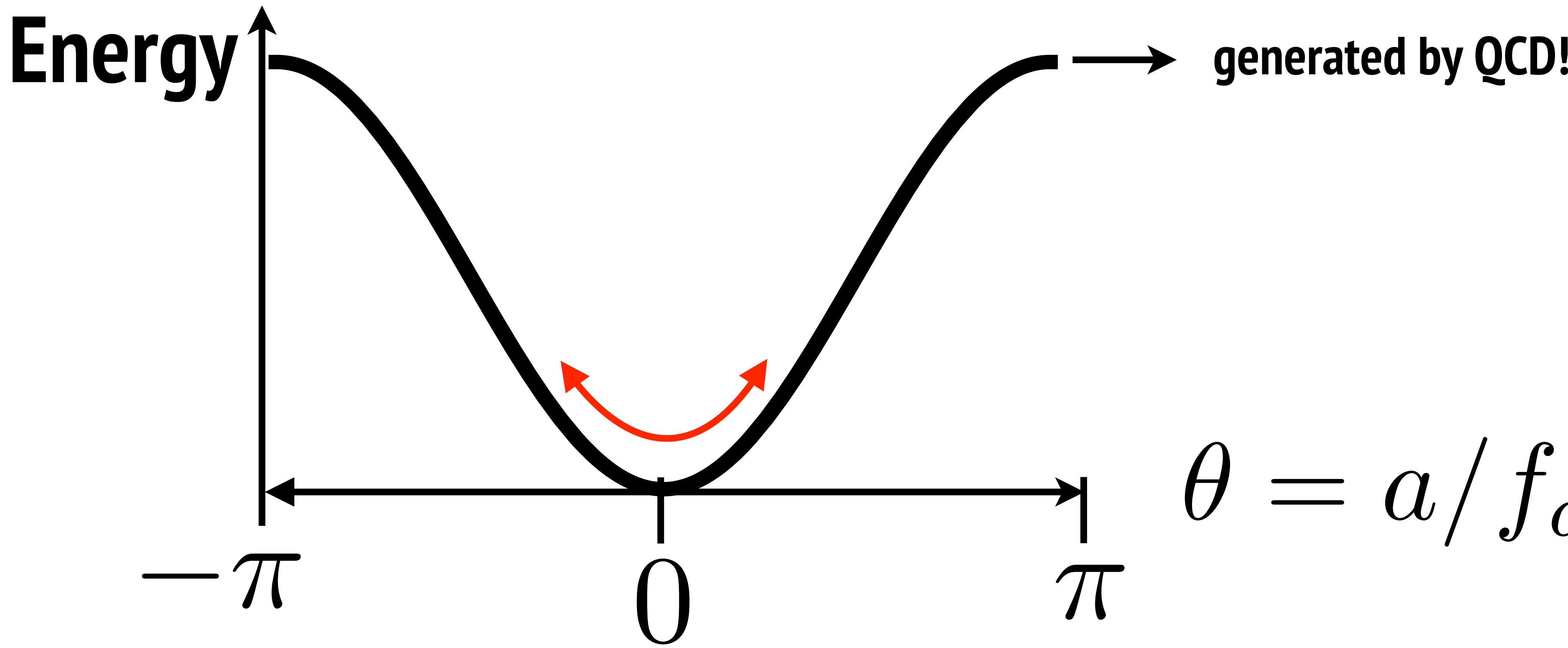
F. Wiczek

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



$$\theta = a/f_a$$

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

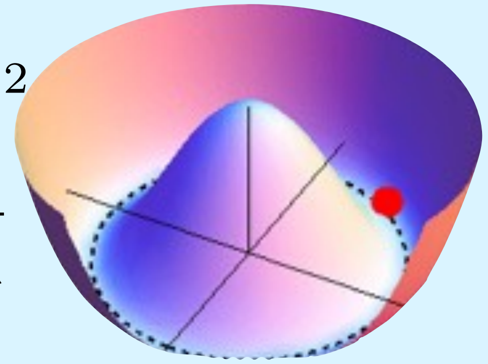
$$\mathcal{L}_\theta = \frac{\alpha_s}{8\pi} G_{\mu\nu a} \widetilde{G}_a^{\mu\nu} \frac{a}{f_a} + \frac{1}{2} (\partial_\mu a)(\partial^\mu a)$$

And we have our simplest axion model (low energy theory ... of course!)

Example: Simple model KSVZ

- Peccei-Quinn global U(1) symmetry, color anomalous + spontaneously broken at f_a

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

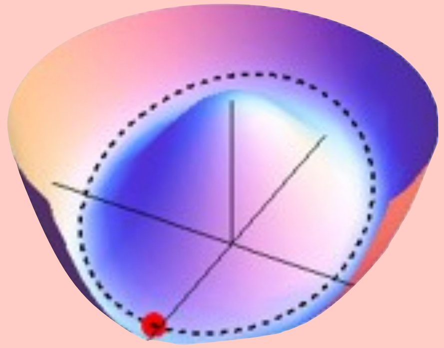


$$\sigma(x) = \rho(x) e^{i\frac{a(x)}{f_a}} \qquad f_a = \sqrt{\mu^2/2\lambda}$$

- At energies below f_a, (also PQ scale)

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

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



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

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

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

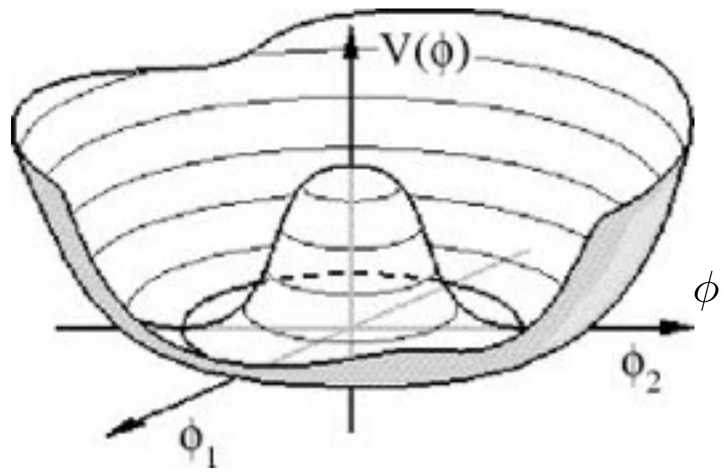
ENERGY ~GeV ~f_a

Axion-like particles (ALPs)

Axions and axion-like particles (ALPs) appear very naturally beyond the SM

pseudo Goldstone Bosons

- Global symmetry spontaneously broken



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

- massless Goldstone Boson @ Low Energy

shift symmetry $\theta(x) \to \theta(x) + \alpha$

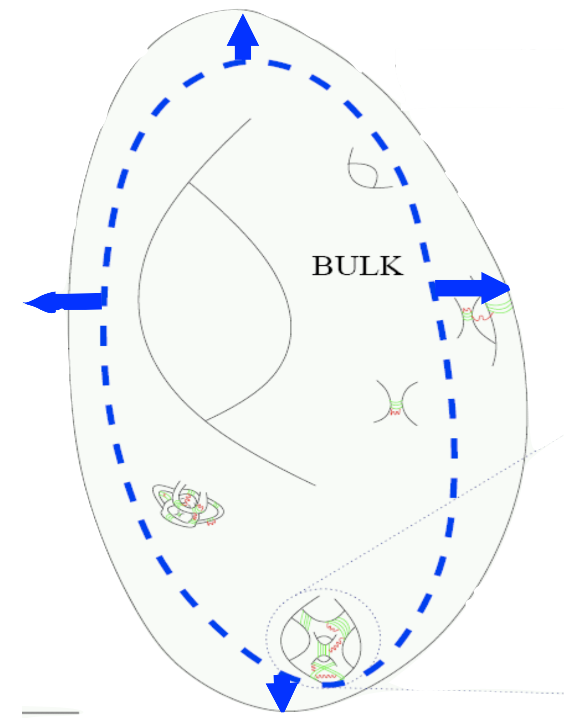
$$\mathcal{L}_{\rm kin} = \frac{1}{2}(\partial_\mu \theta)(\partial^\mu \theta) f^2$$

- HE decay constant, $f = \langle \rho \rangle$

- small symmetry breaking $\longrightarrow$ small mass

stringy axions

- Im parts of moduli fields (control sizes)



- O(100) candidates in compactification

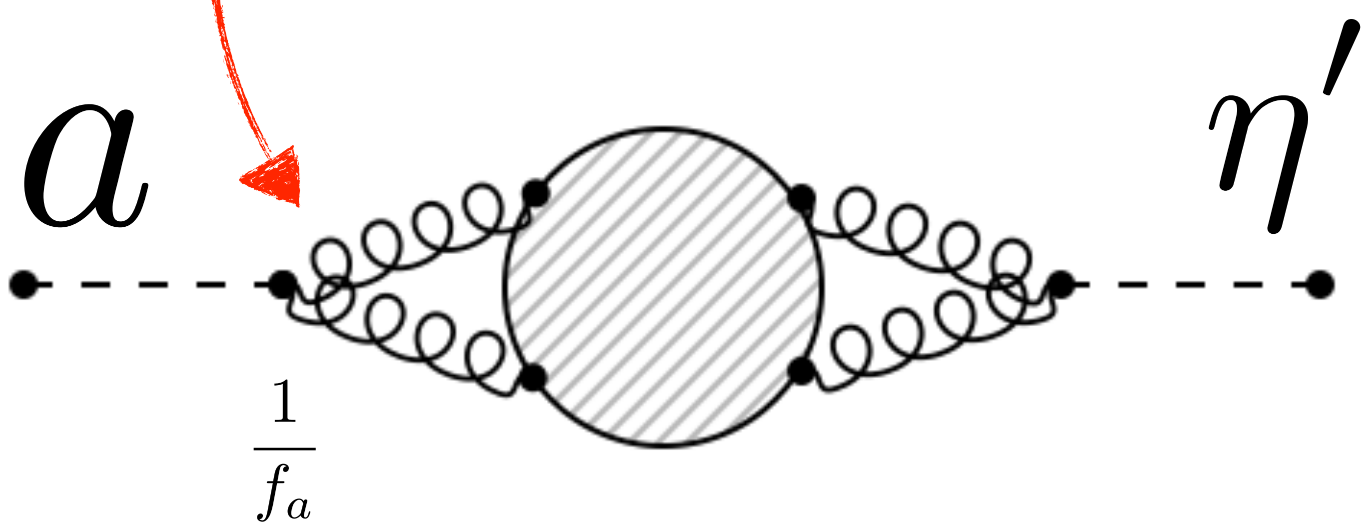
- "decay constant", string scale M_s

- masses from non-perturbative effects

Axion couplings at low energy

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

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



In our simple axion theory, axion interactions are all generated from $\theta \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \widetilde{G}^{\mu\nu}_a$
so the axion field interations will always be suppressed by 1/fa

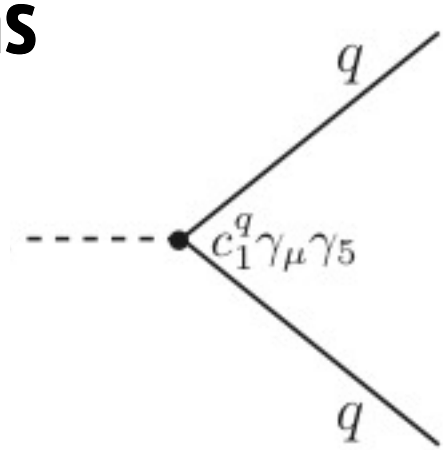
Axion couplings at low energy

Mass

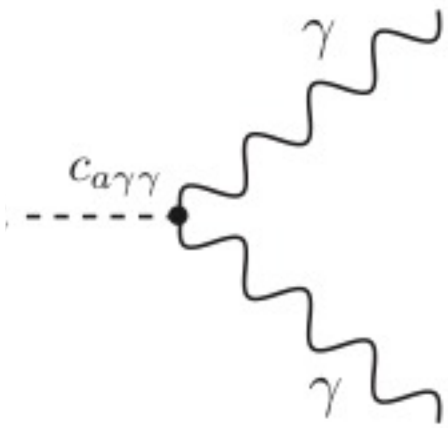
$$m_a = \sqrt{V_{\theta\theta}(\theta)}\frac{1}{f_a} = \sqrt{\chi}\frac{1}{f_a} \simeq 5.7\ \mathrm{meV}\frac{10^9\mathrm{GeV}}{f_a}$$

hadrons, Photons

$\frac{1}{f_a}\, a$

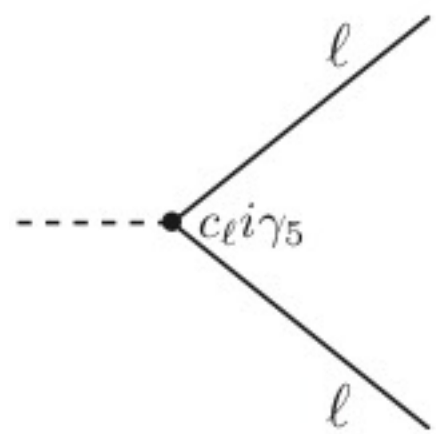


$\frac{1}{f_a}\, a$



Leptons (in some models)

$\frac{1}{f_a}\, a$



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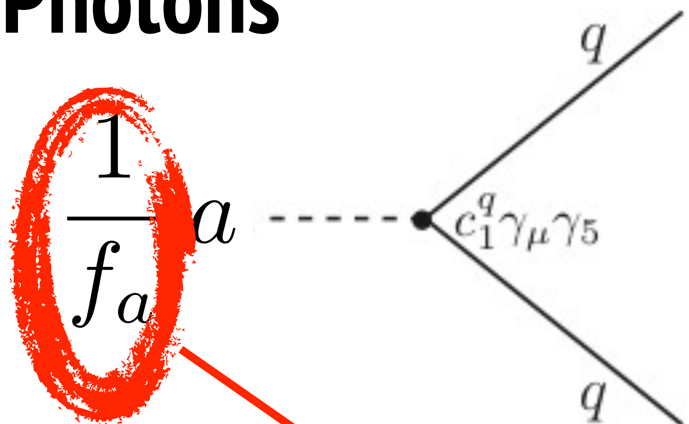
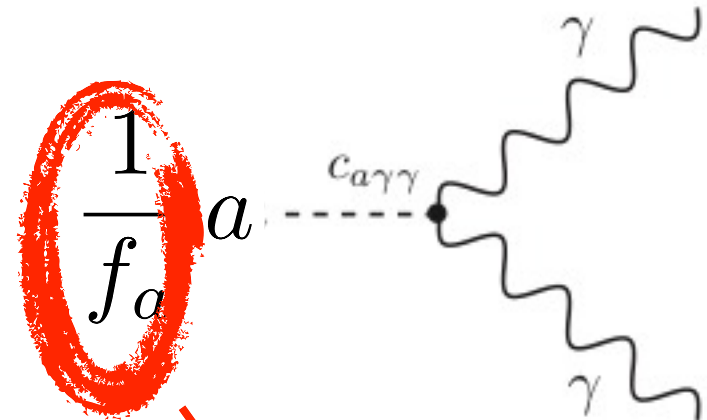
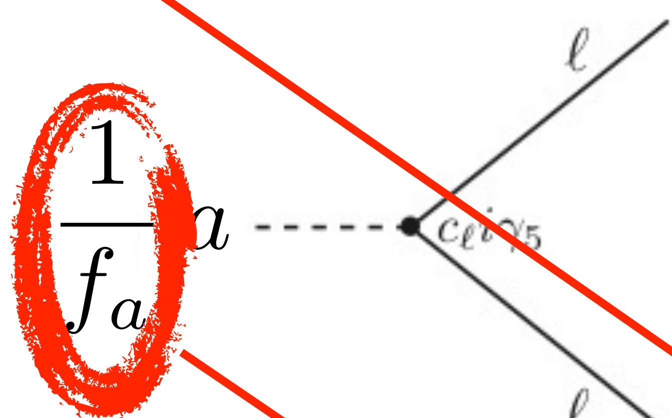
hadrons, Photons



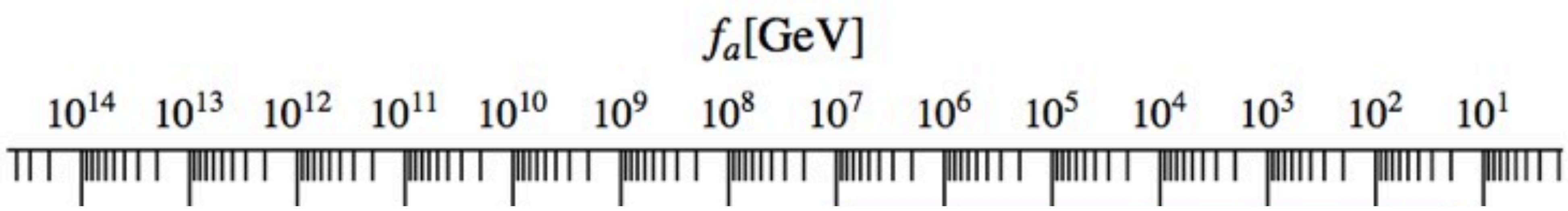


Leptons (in some models)



The lighter the more weakly interacting

Axion Landscape

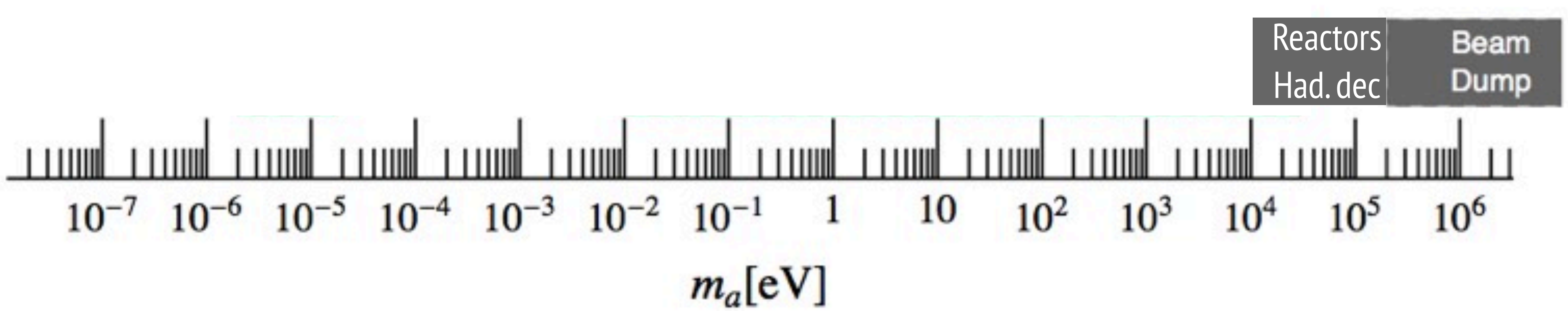


$f_a \gg v_{\mathrm{EW}}$

Invisible models

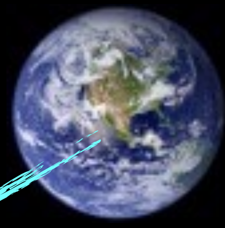
$f_a \sim v_{\mathrm{EW}}$

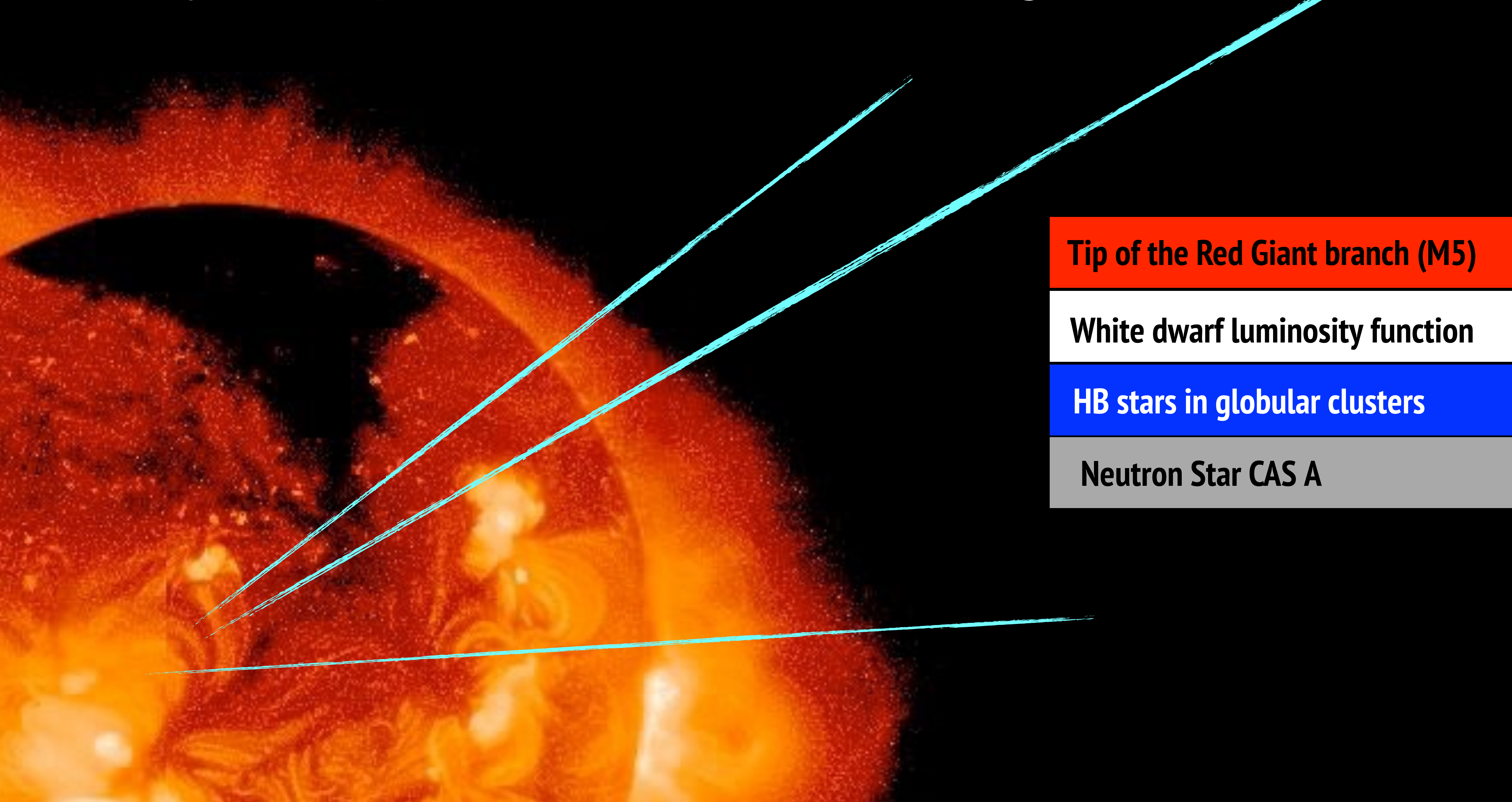
PQWW models



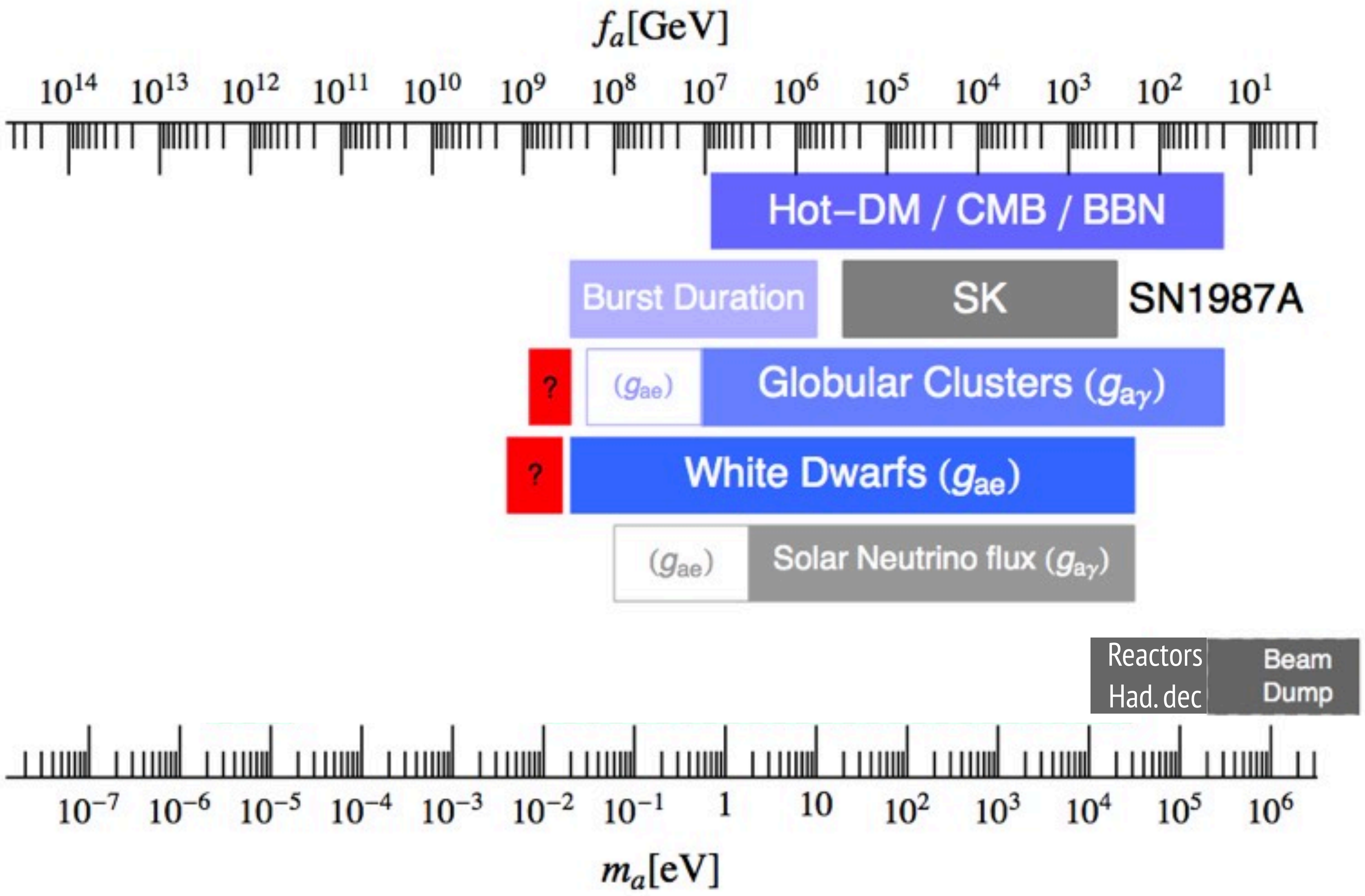
Bounds and hints from astrophysics

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

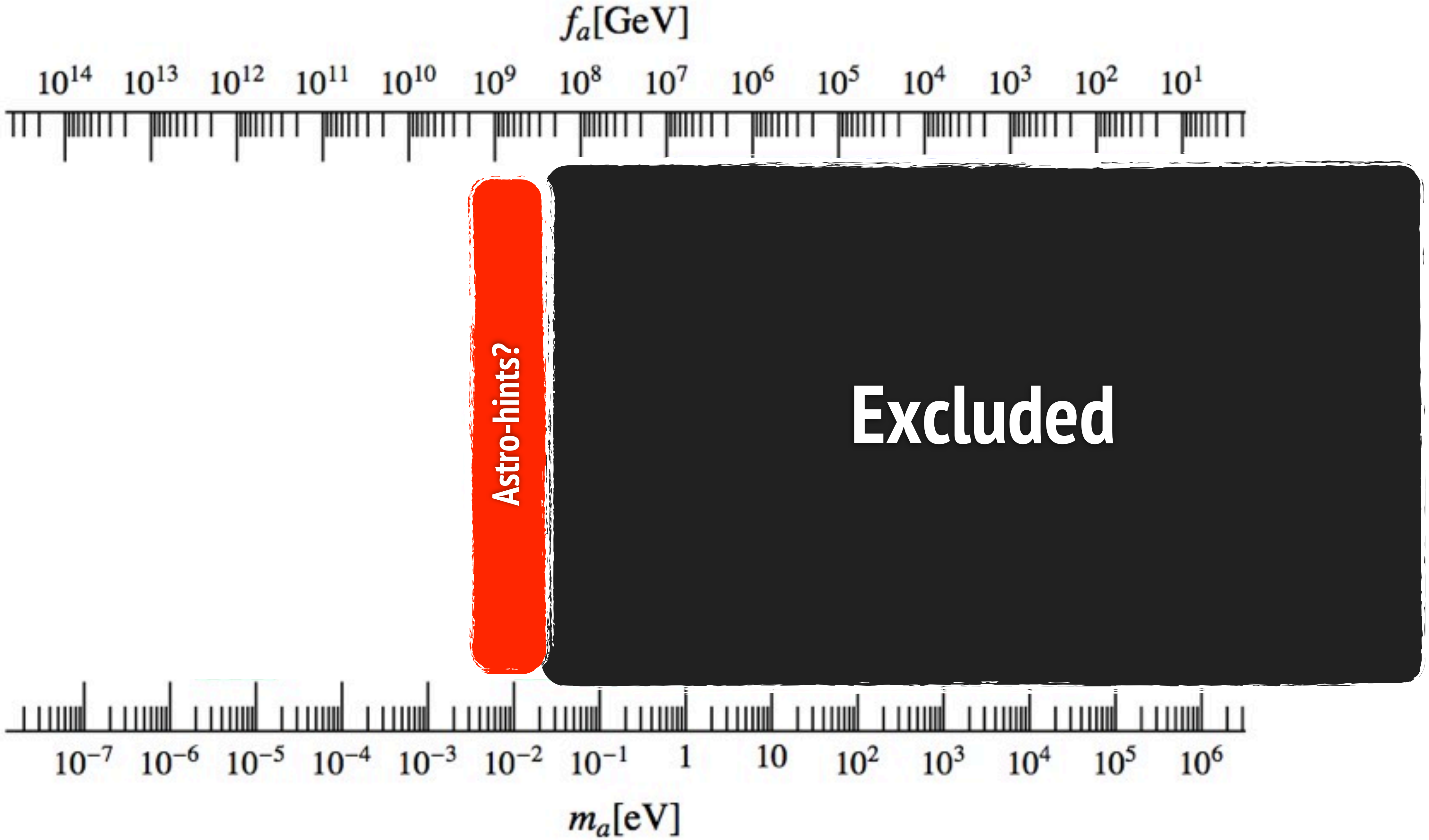




Axion Landscape

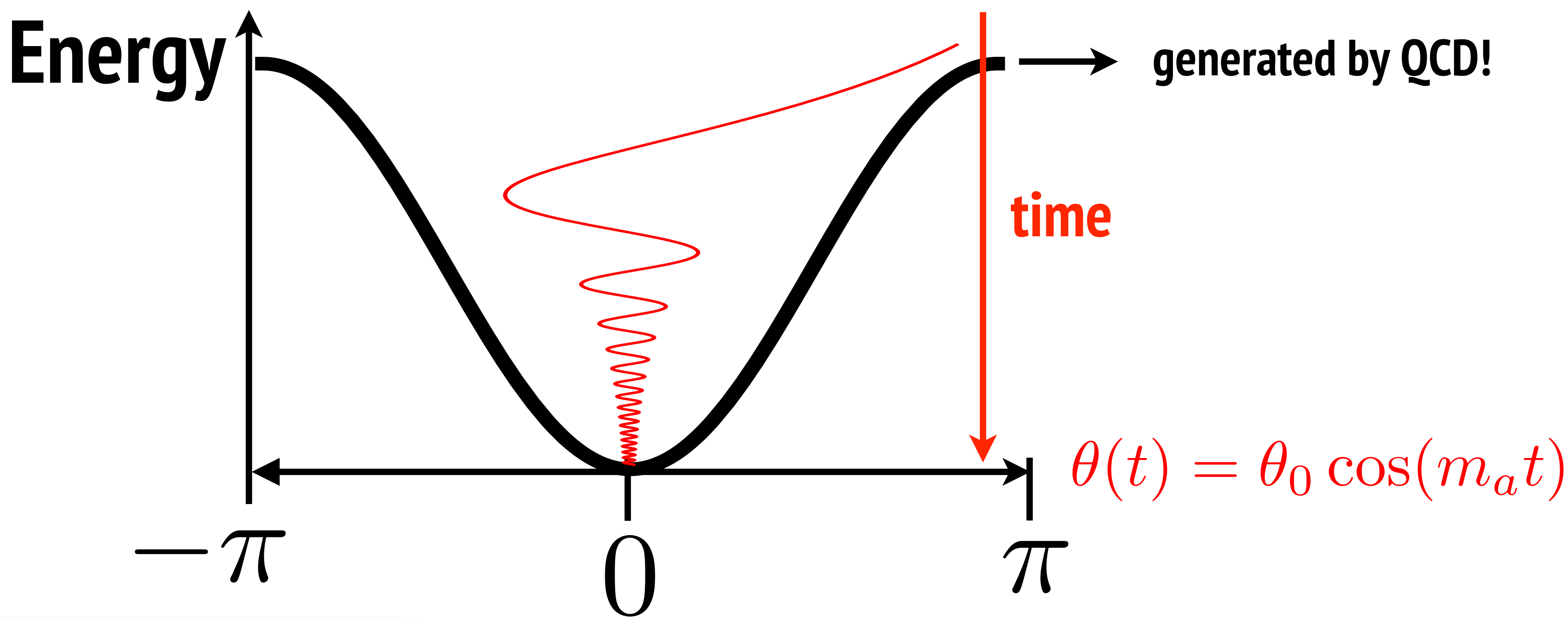


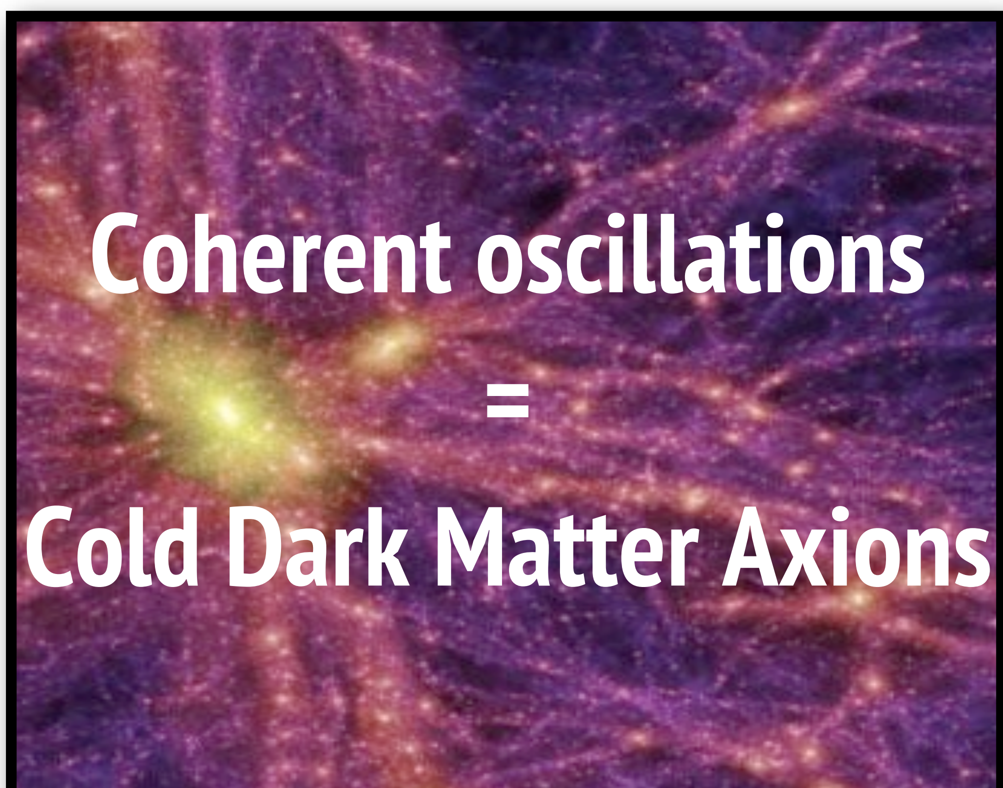
Axion Landscape



Axions and dark matter

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





Oscillation frequency

$$\omega = m_a$$

Energy density (harm. oscillator)

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

Evolution of the axion dark matter field

- We move back to the very early Universe ...

- Assume some random set of initial conditions ...

- Let us see how the field evolves !

- fa is soooooo small, and the relevant momenta sooooo small than we neglect all interactions of the axion

- The evolution of a lonely scalar field

Field evolution

$$S = \int d^4x\sqrt{-g}\mathcal{L} = \int d^4x\sqrt{-g}\left(\frac{f_a}{2}(\partial_\mu\theta)(\partial^\mu\theta) - V(\theta) + \mathcal{L}_{int}\right)$$
$$= \int d^4x\sqrt{-g}\left(\frac{1}{2}(\partial_\mu a)(\partial^\mu a) - V(a/f_a) + \mathcal{L}_{int}\right)$$

Equations of motion $\delta S = 0$

Scale factor is now $R(t)$

$$\left(\frac{\delta\mathcal{L}}{\delta(\partial^\mu a)}\right)_{;\mu} - \frac{\delta\mathcal{L}}{\delta a} = 0$$

$$\ddot{a} + 3H\dot{a} - \frac{1}{R^2}\nabla^2 a + \frac{\partial V}{\partial a} = 0$$

For simplicity I linearised around a=0

$$\frac{\partial V}{\partial a} = \frac{\chi}{f_a}\sin\theta \sim \frac{\chi}{f_a}\theta = m_a^2 a$$

Fourier transform (linear equation) and modes decouple

$$\ddot{a}_k + 3H\dot{a}_k + \frac{k^2}{R^2}a_k + m_a^2 a_k \simeq 0$$

Energy density and pressure

$$T^{\mu}{}_{\nu} = (\partial^{\mu} a)(\partial_{\nu} a) - \mathcal{L}\delta^{\mu}{}_{\nu}$$

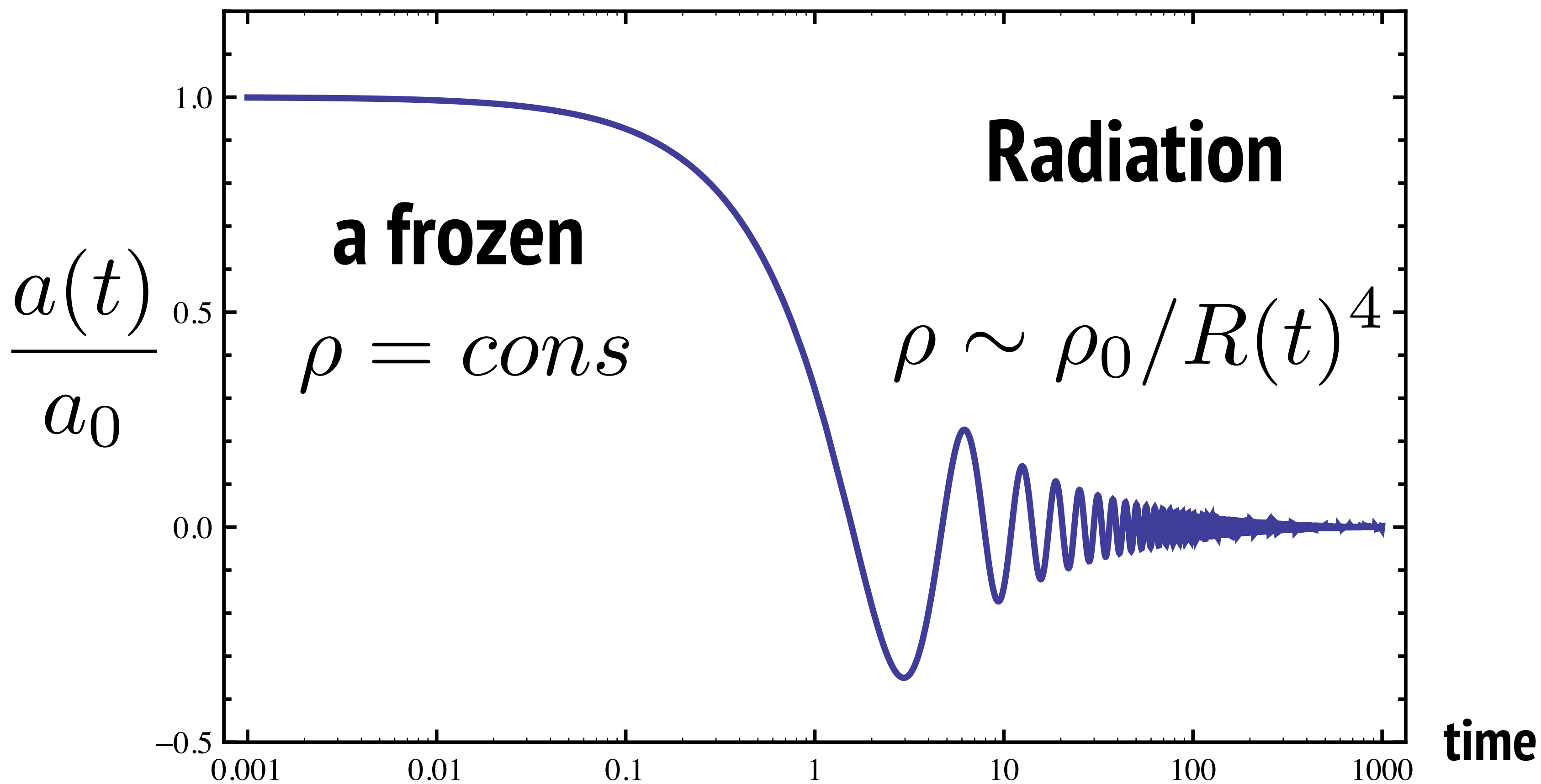
$$\rho = \frac{1}{2}(\dot{a})^2 + \frac{1}{2}(\nabla a)^2 + V(a)$$

$$p = \frac{1}{2}(\dot{a})^2 - \frac{1}{2}(\nabla a)^2 - V(a)$$

Relativistic modes

Again a damped oscillator (time-dependent frequency...)

$$\ddot{a}_k + 3H\dot{a}_k + \frac{k^2}{R^2}a_k = 0 \longrightarrow \ddot{a}_k + 3H\dot{a}_k + \omega^2(t)a_k = 0$$



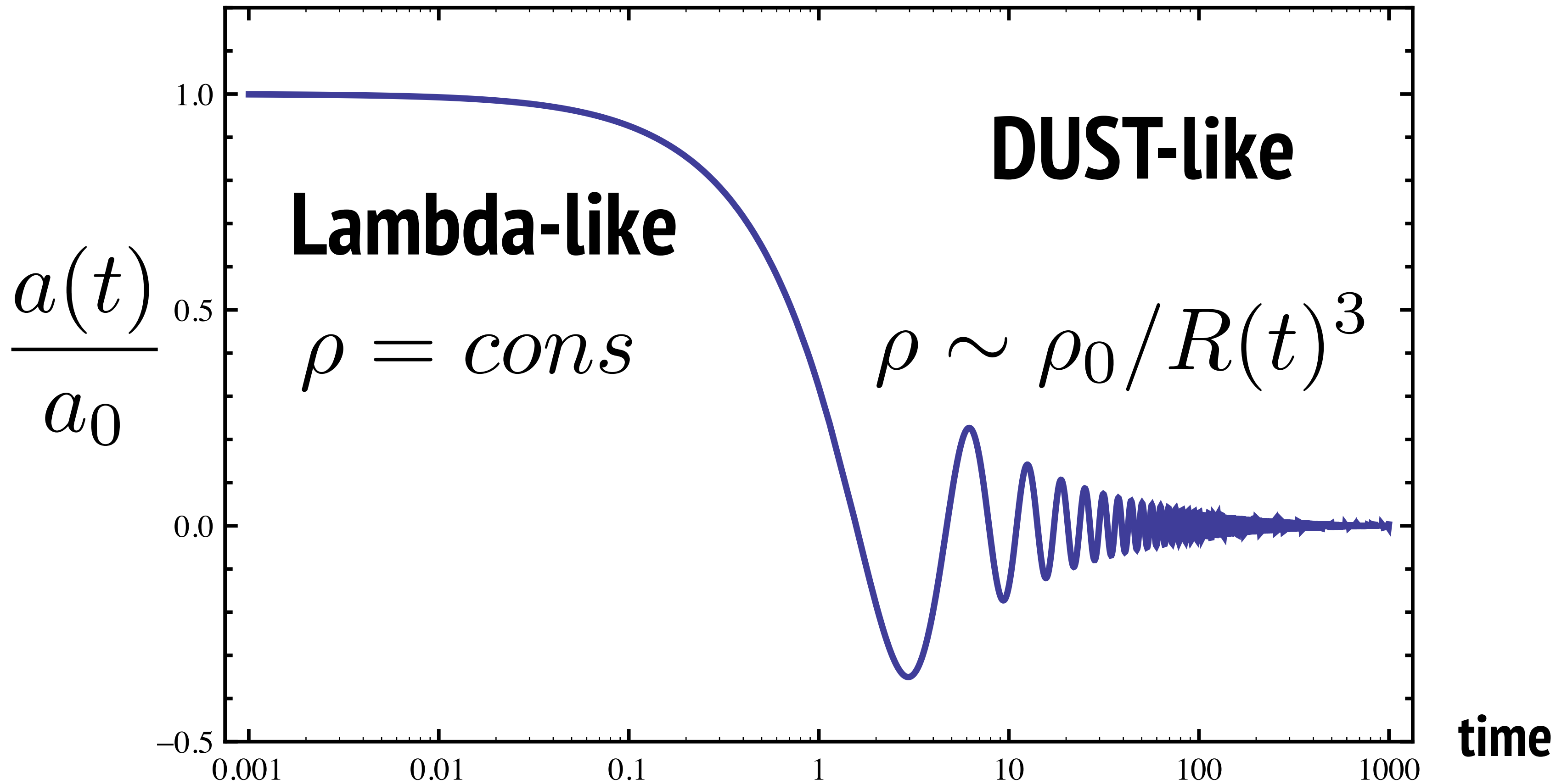
$$t_k \sim \frac{1}{\omega} = \frac{R}{k}$$

(This corresponds to the wavelength entering the horizon) $t = 1/H \rightarrow HR \sim k$

Zero and non-relativistic modes

Again a damped oscillator $\omega = m_a$

$$\ddot{a}_k + 3H\dot{a}_k + m_a^2 a_k \simeq 0$$ **(SIMPLIFIED)**

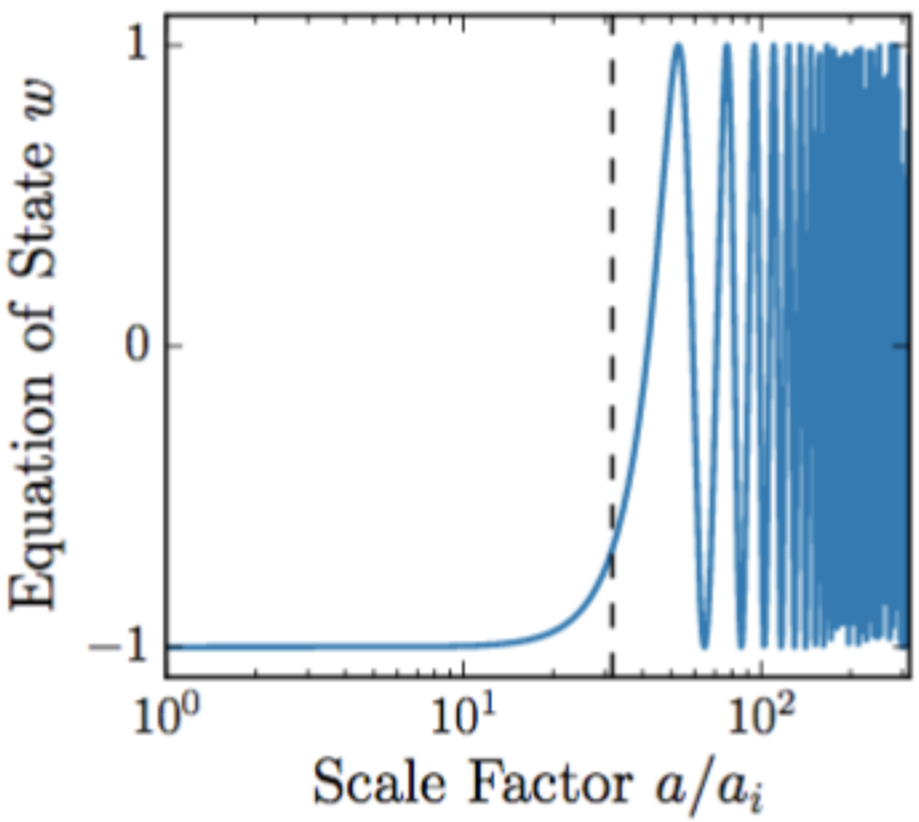


$$t_1 = \frac{1}{2H} \sim \frac{1}{m_a}$$

$$H \sim m_a$$

Equation of state and speed of sound

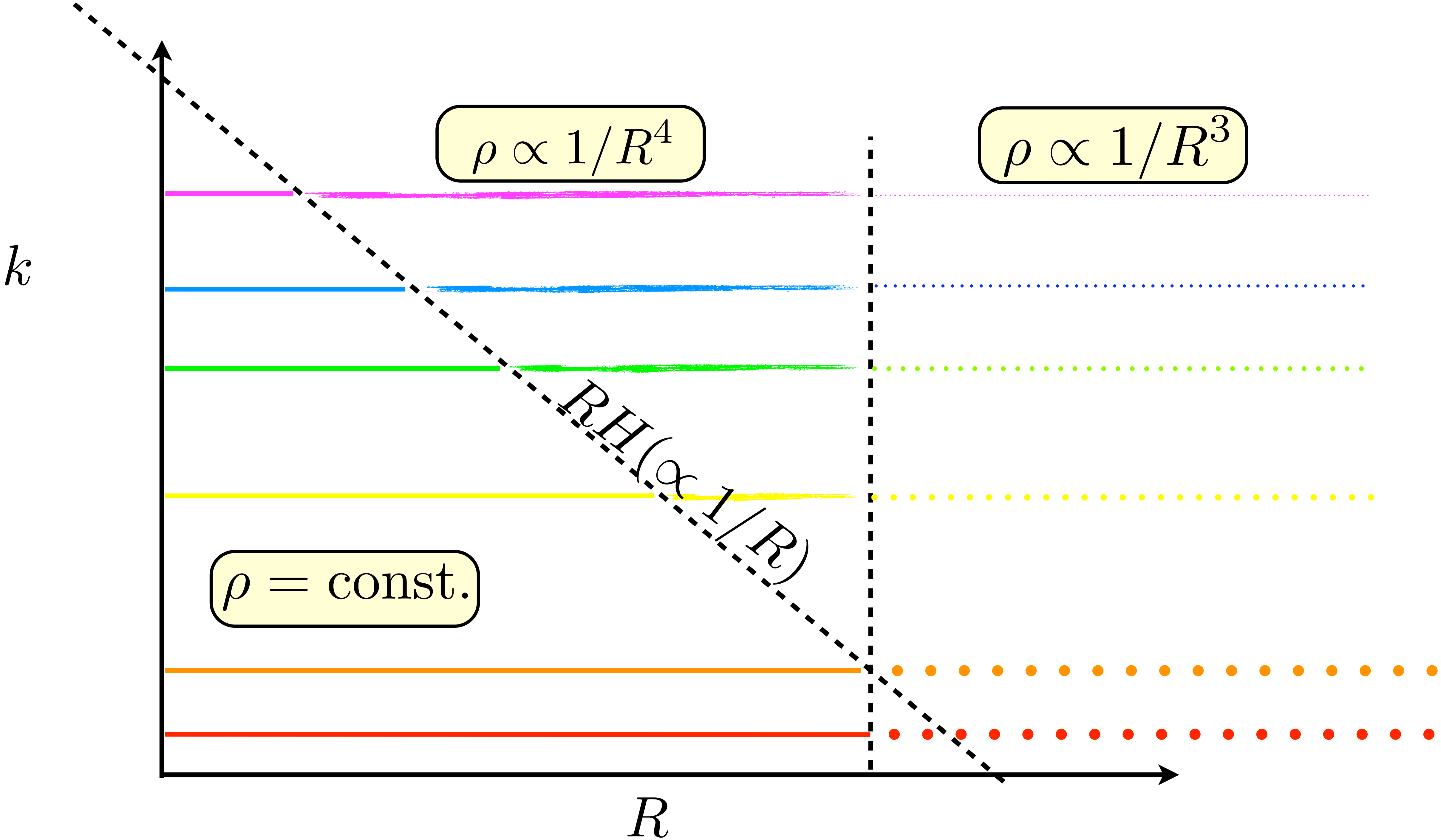
$$\ddot{a}_k + 3H\dot{a}_k + (k^2/R^2 + m_a^2)a_k \simeq 0$$



$$\langle c_s^2 \rangle_t = c_{s,\mathrm{eff}}^2 = \frac{k^2/4m_a^2a^2}{1+k^2/4m_a^2a^2}\,.$$

Even for NR modes, k/R << ma, the fact that axions and ALPs have non-zero momentum can be important -> field gradients oppose to compression because of the uncertainty principle leading to a "uncertainty pressure", (sometimes called "quantum pressure"….)

Why the axion is so COLD ?



Modes above $k \sim m_a R$ **are quite suppressed**

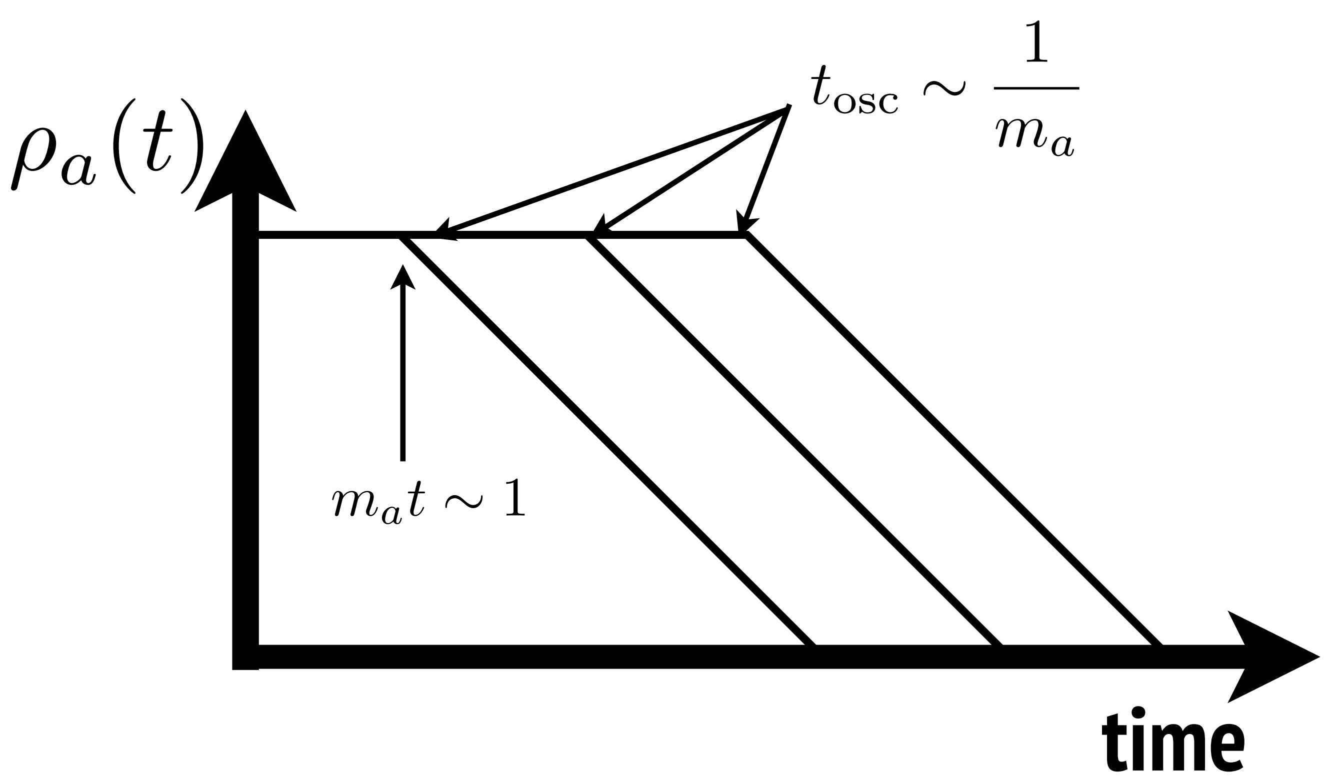
Energy density

- **Energy density redshifts as matter, from the onset of oscillations** $H(t_1) \sim m_a$

$$\rho_a(t) \sim \theta_I^2 \chi \left(\frac{R_1}{R(t)}\right)^3 \propto \theta_I^2 \chi m_a^{-3/2}$$

- **dilution until today** $\left(\frac{R_1}{R_0}\right)^3 \sim \left(\frac{T_0}{T_1}\right)^3 \sim \left(\frac{T_0}{\sqrt{H_1 m_{\rm Pl}}}\right)^3 \sim \left(\frac{T_0}{\sqrt{m_a m_{\rm Pl}}}\right)^3 \propto m_a^{-3/2}$

Smaller mass axions, start oscillating later, and get less diluted ...



- **with** $\chi \propto T^{-n}$

$$\rho_a(t_0) \propto \theta_I^2 m_a^{-\frac{6+n}{4+n}}$$

Effective mass, lattice calculations

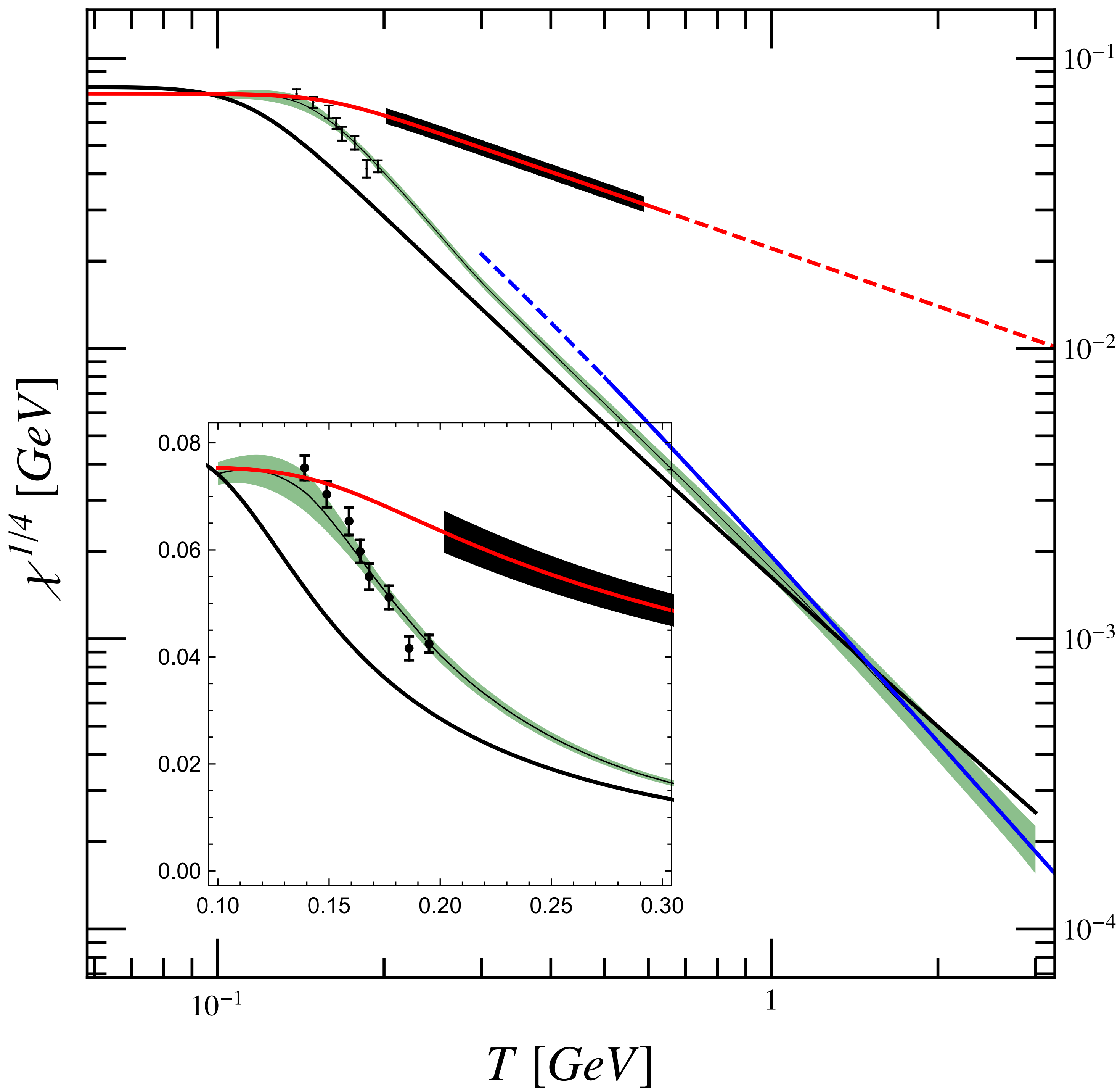
Lattice QCD: we can compute axion mass

$$m_a^2 f_a^2 = \chi(T)$$

At high T (no mesons)

we can analytically compute potential (DIGA)

$$V(\theta) = -\chi(T)\cos\theta$$



Lattice QCD 2+1+1 [Borsanyi]

Lattice QCD 2+1 [Bonati]

Lattice QCD (DWF) 2+1 [Buchoff] (points)

DIGA (T>>Tc) [Borsanyi]

IILM [Wantz]

Axion-like particle and axion dark matter

Everything I've told you applies to any ALP weakly coupled

$$V = \frac{1}{2}m^2\phi^2 \qquad \rho_\phi^0 \sim V_I (R_1/R_0)^2 = m_\phi^2 \phi_I^2 \left(\frac{T_0}{\sqrt{m_\phi m_{\rm Pl}}}\right)^3$$

Many things :

- production is NON-THERMAL
- the relic density depends on initial condition!
- typical momenta k~H(t1)R(t1) related to Hubble, not T

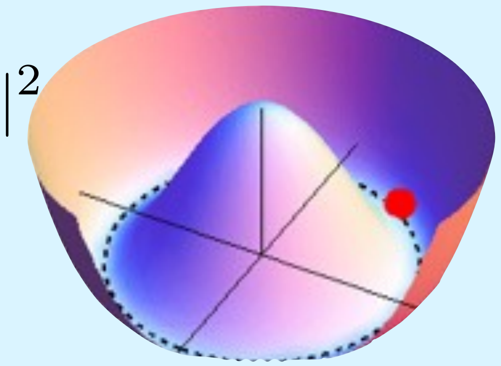
Axions are a bit special because their periodic potential

$$V = \chi(1 - \cos\theta)$$

Simple model KSVZ

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

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

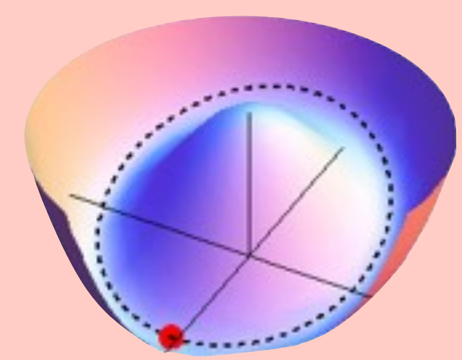


$$\sigma(x) = \rho(x)e^{i\frac{a(x)}{f_a}} \qquad f_a = \sqrt{\mu^2/2\lambda}$$

- At energies below f_a **(SSB)** $\qquad \mathcal{L} \in \frac{1}{2}(\partial a)^2 + \frac{\alpha_s}{8\pi}G\widetilde{G}\frac{a}{f_a}$

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

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



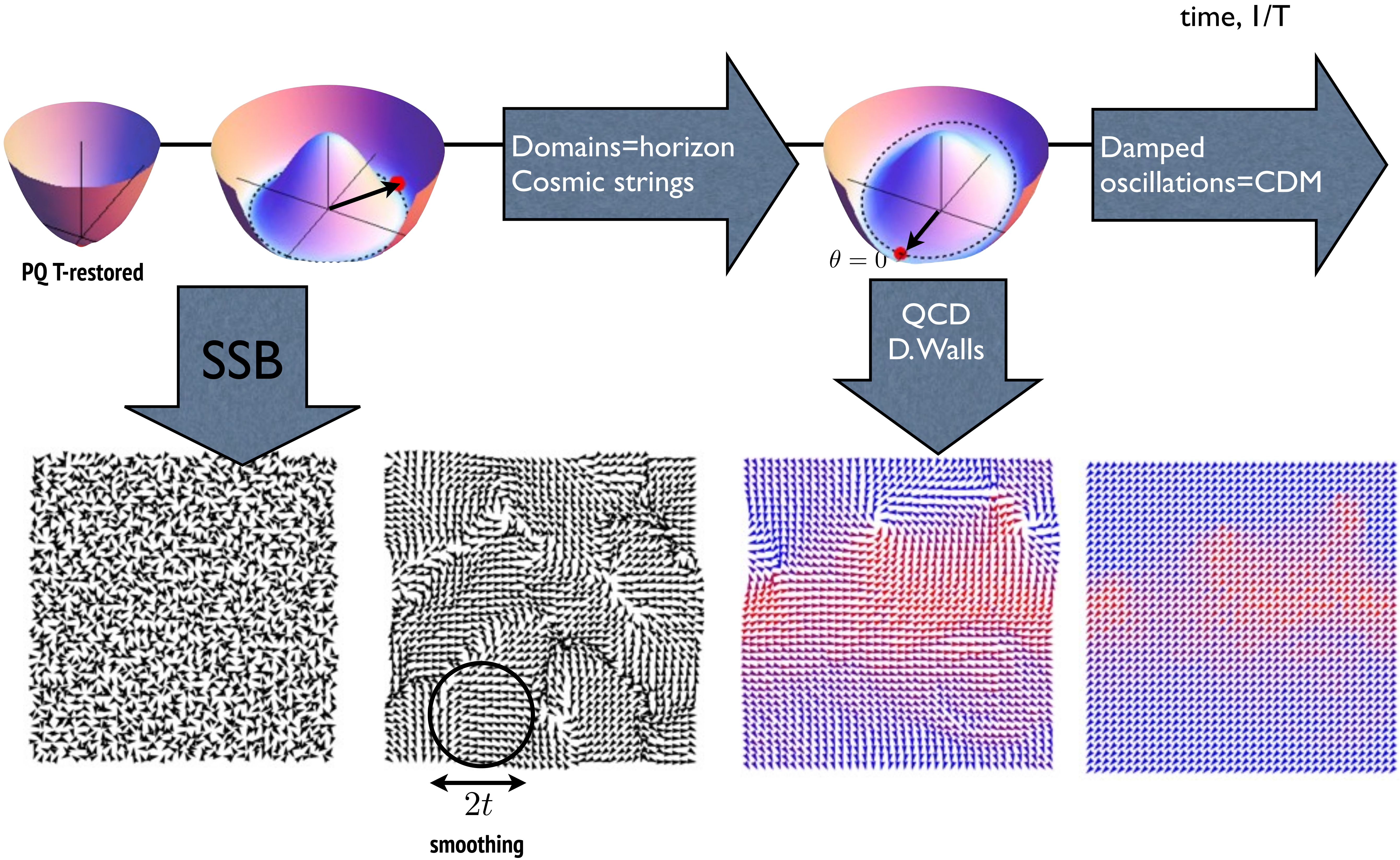
couplings $\quad \mathcal{L}_{a,I} = \sum_N c_{N,a}\bar{N}\gamma^\mu\gamma_5 N\frac{a}{f_a} + c_{a\gamma}\frac{\alpha}{2\pi}F_{\mu\nu}\widetilde{F}^{\mu\nu}\frac{a}{f_a} + \ldots$

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

ENERGY **~GeV** **~f_a**

1st typical scenario: random initial conditions in our Universe

- PQ transition after inflation



1st typical scenario: random initial conditions in our Universe

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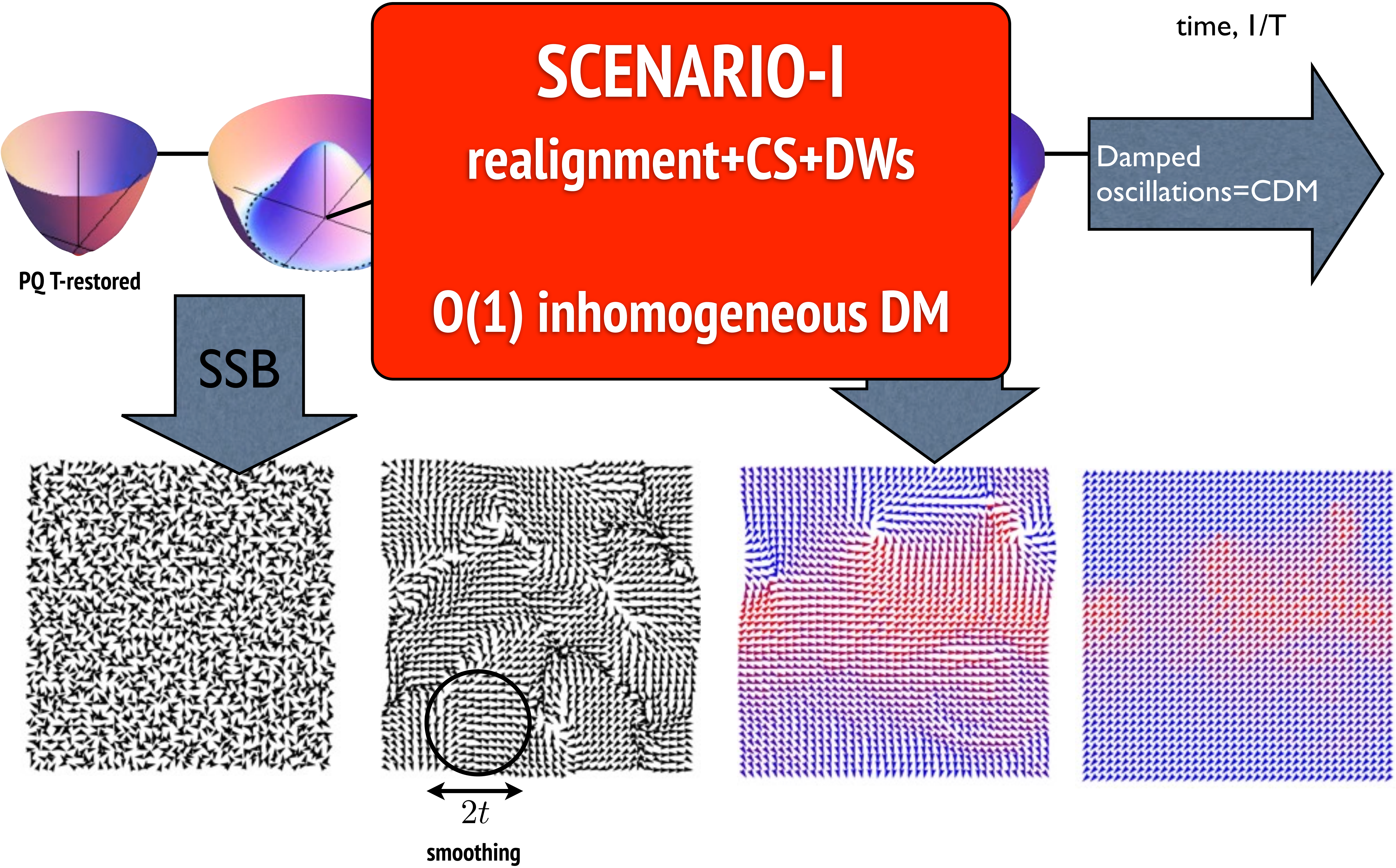
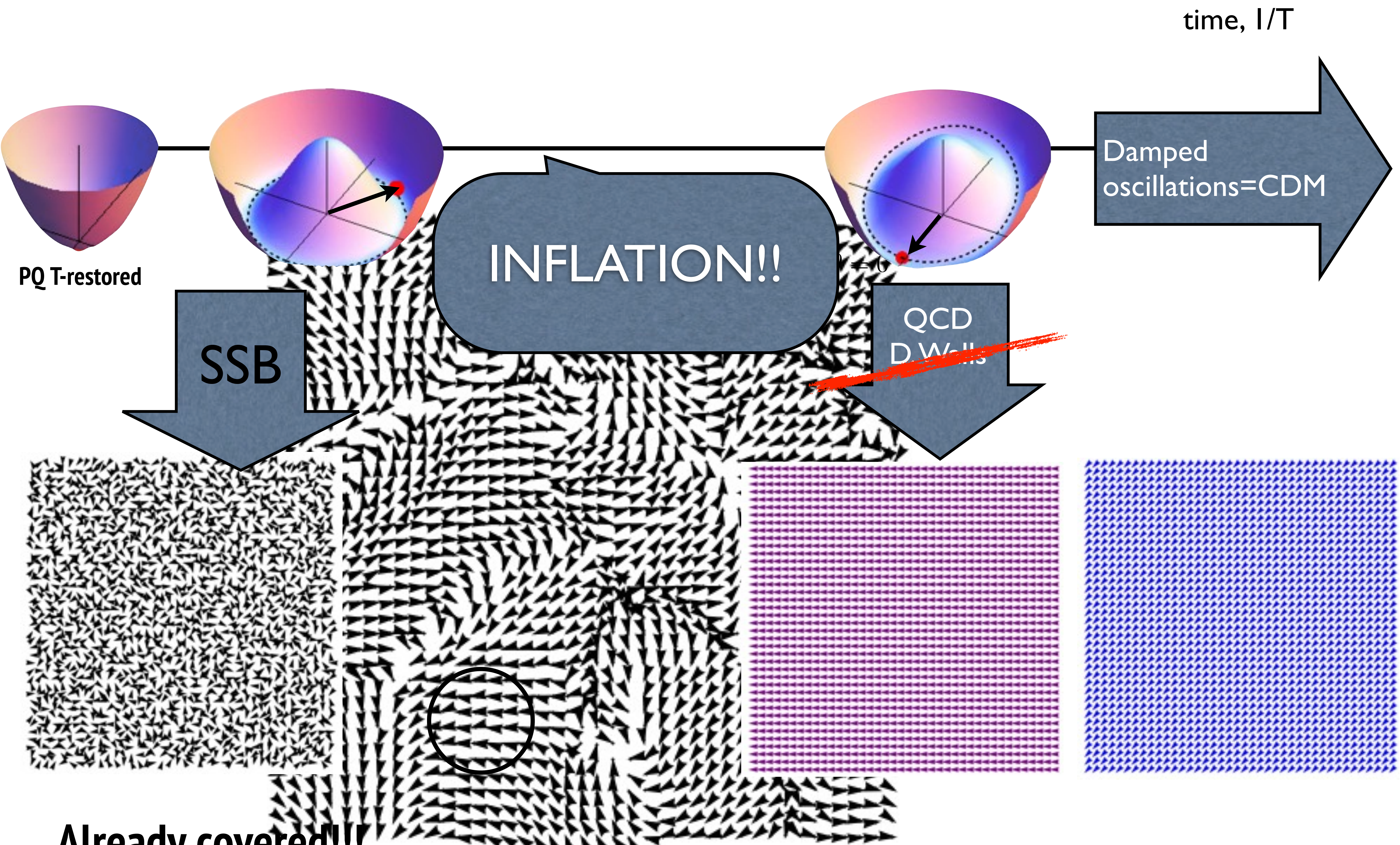


2nd typical scenario: 1 initial condition for our whole Universe

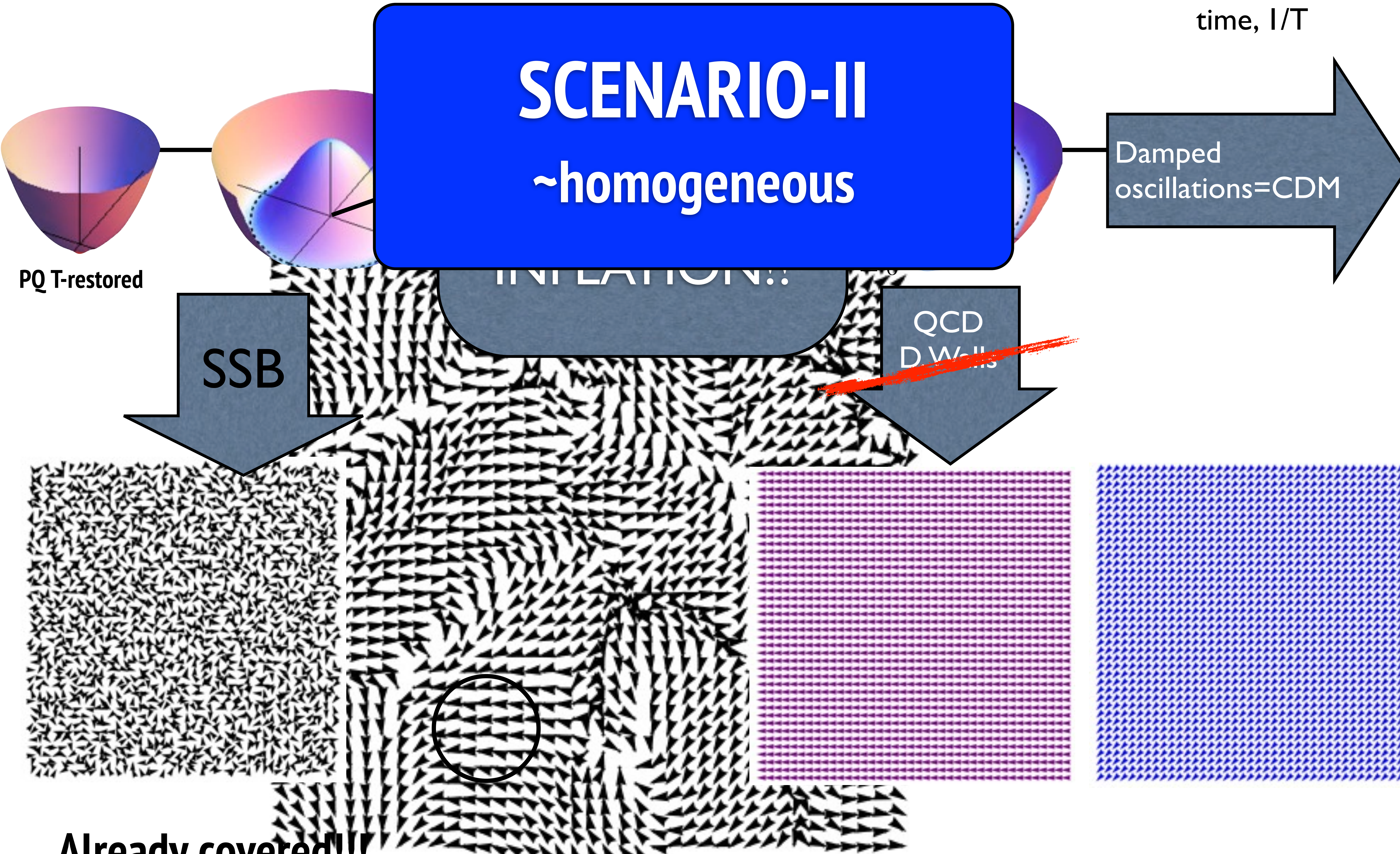
- PQ phase transition before inflation



Already covered!!!

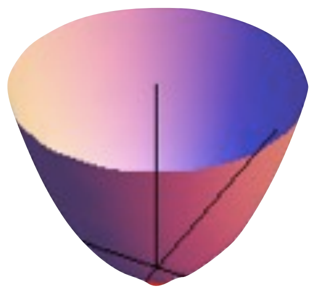
2nd typical scenario: 1 initial condition for our whole Universe

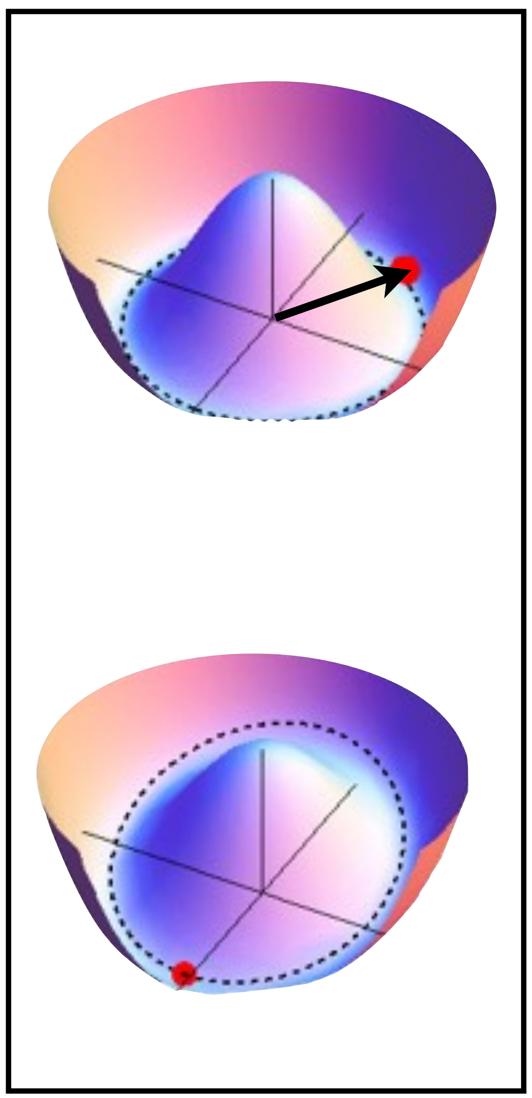
- PQ phase transition before inflation

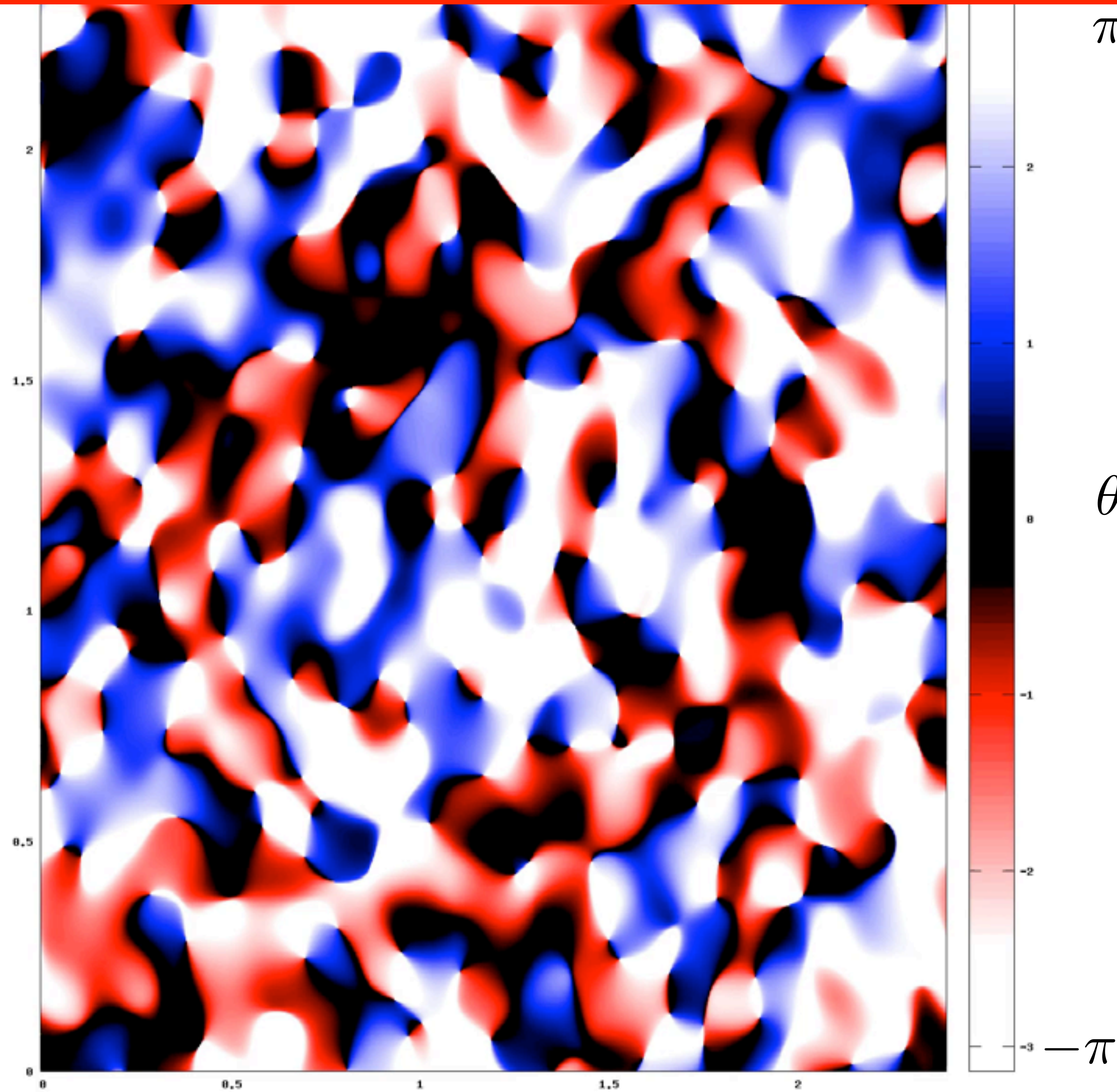


Already covered!!!

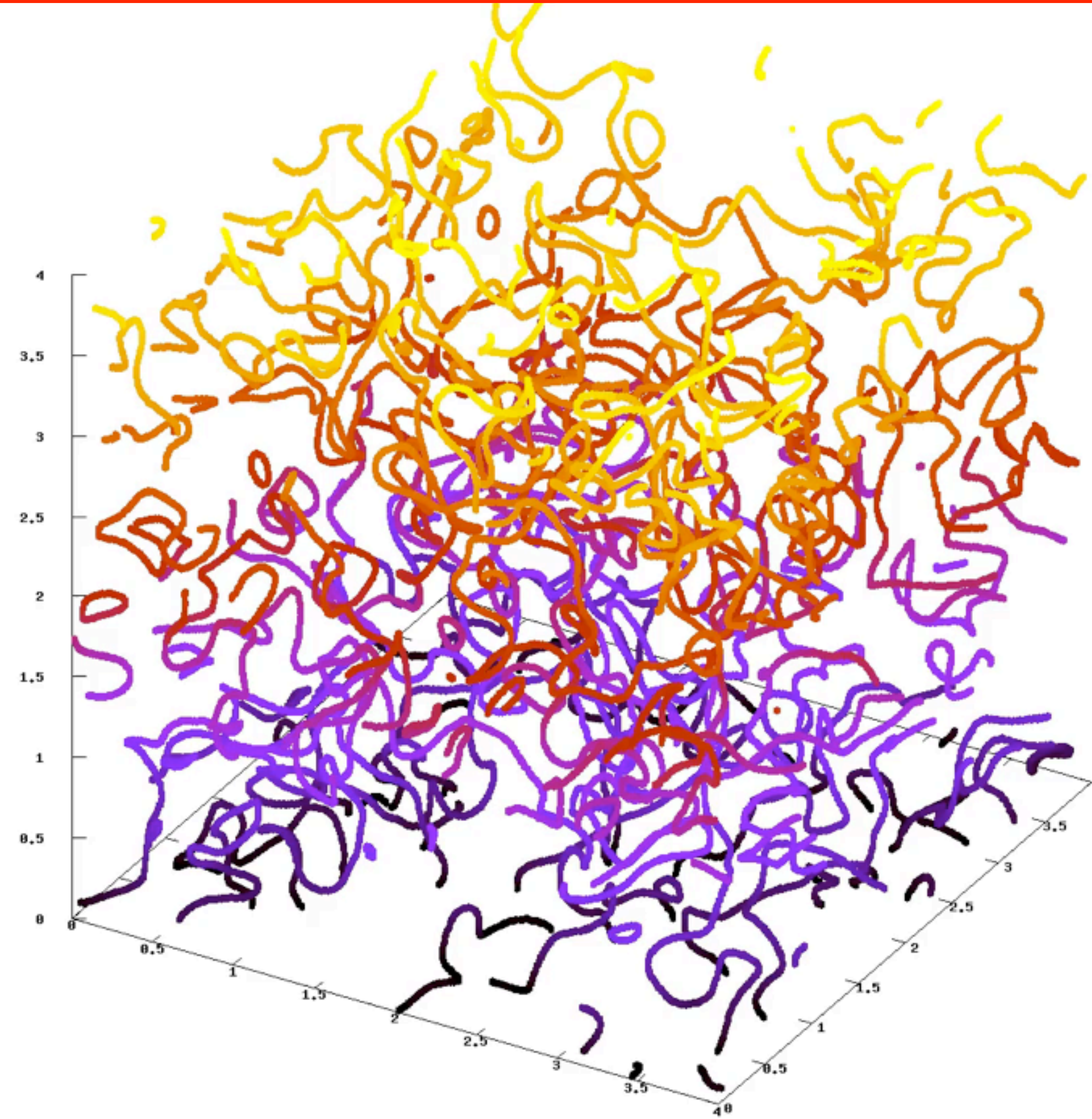
SCENARIO I (N=1): axion evolution around t1



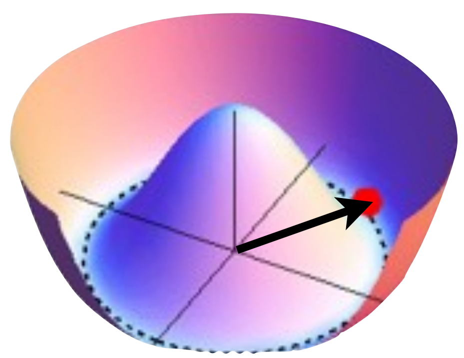




Strings



Axionic strings : cores

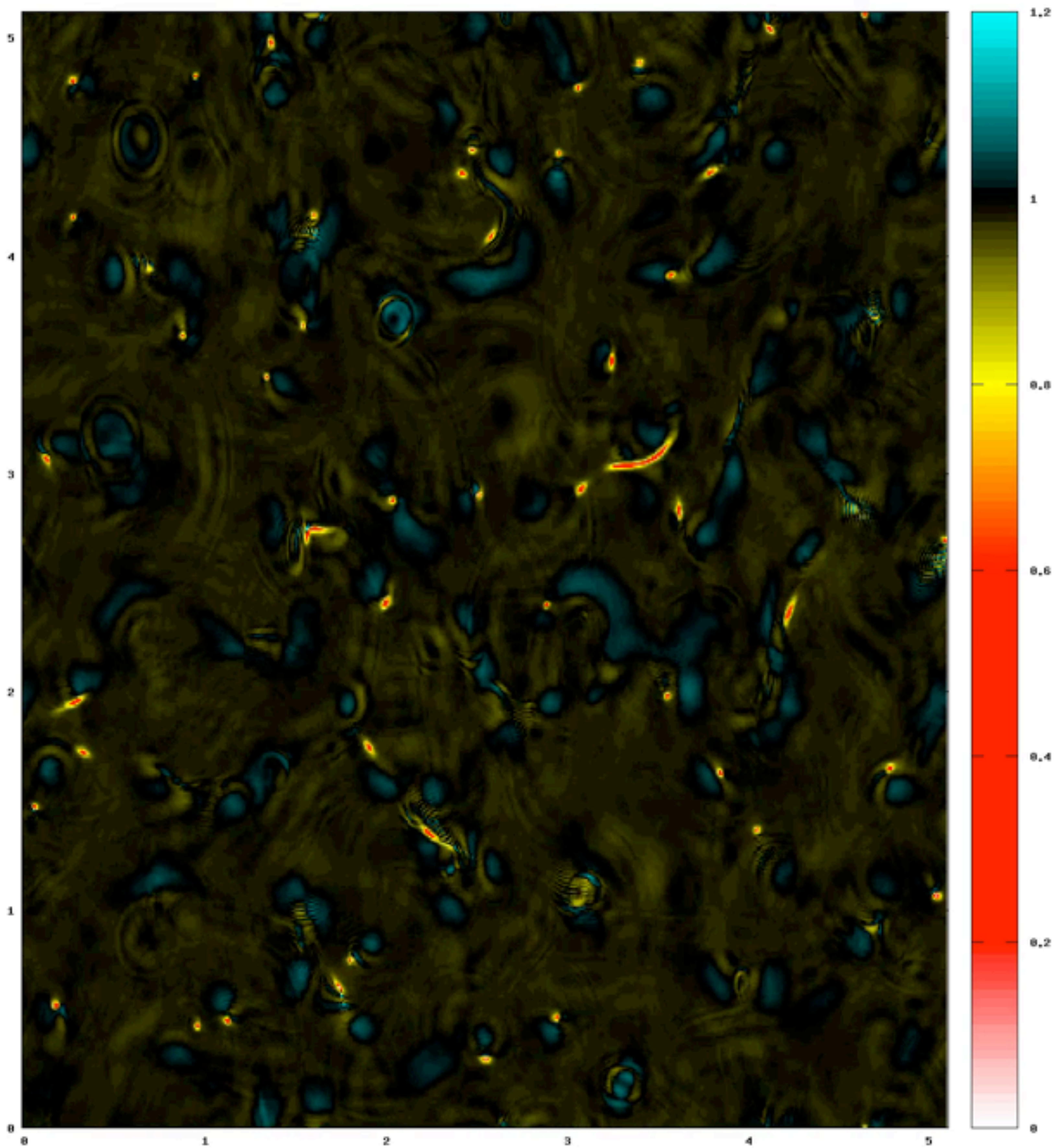


- Huge din. range!
- realistic strings have

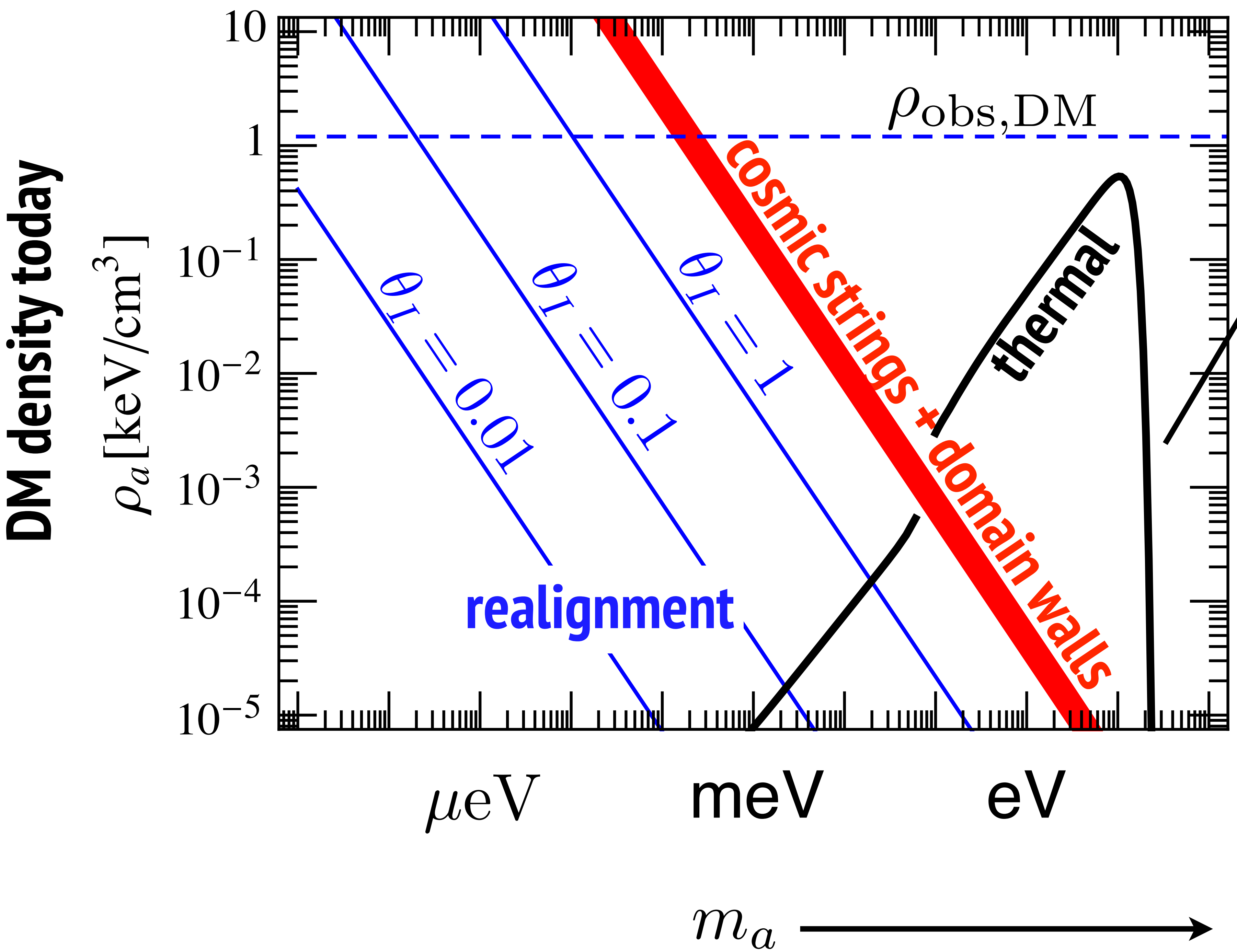
  d ~ 1/f_a

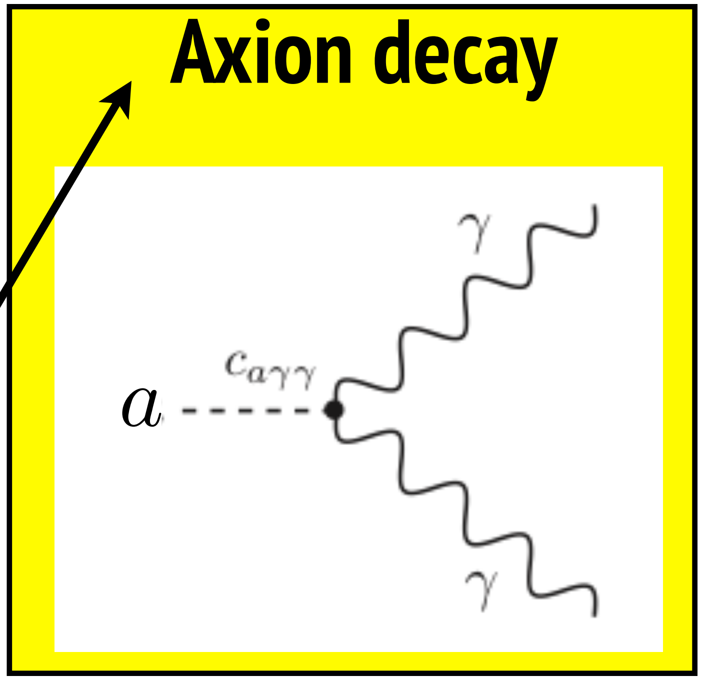
  distances ~ t

$$\frac{d}{t} \sim \frac{H}{f_a} \sim \frac{T^2}{M_p f_a}$$



Axion DM, how much

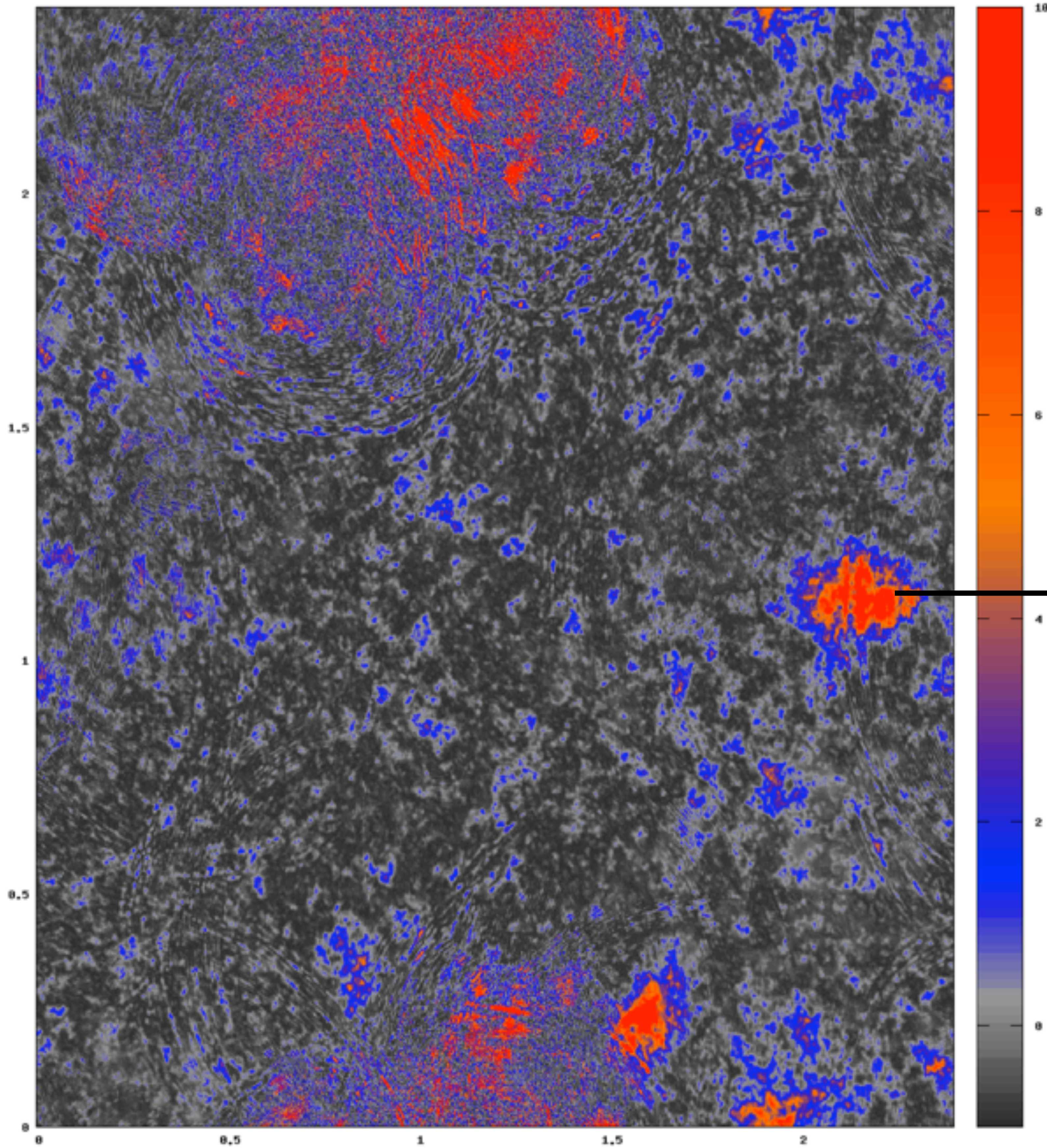




less interacting

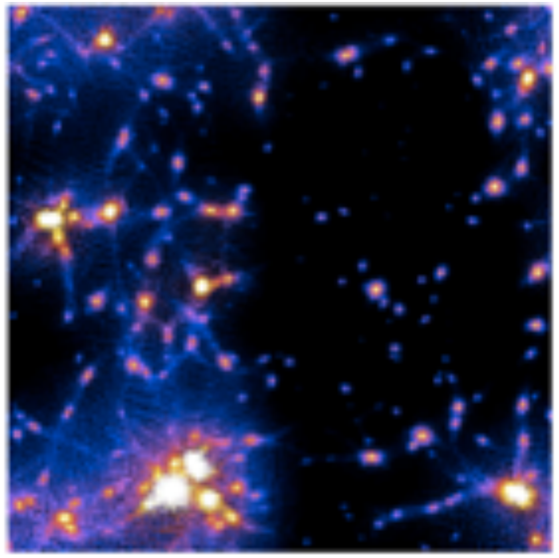
more interacting

Dark matter density, inhomogeneous at comoving mpc scales



final overdensity $\frac{\rho - <\rho>}{<\rho>}$

minicluster seed!



do mc's survive?

Minicluster size $\delta \sim 1$

Region with delta~1 and size ~ 1/H(t1) , axion field freezes out soon after t1, overdense region expands

At Matter-radiation equality

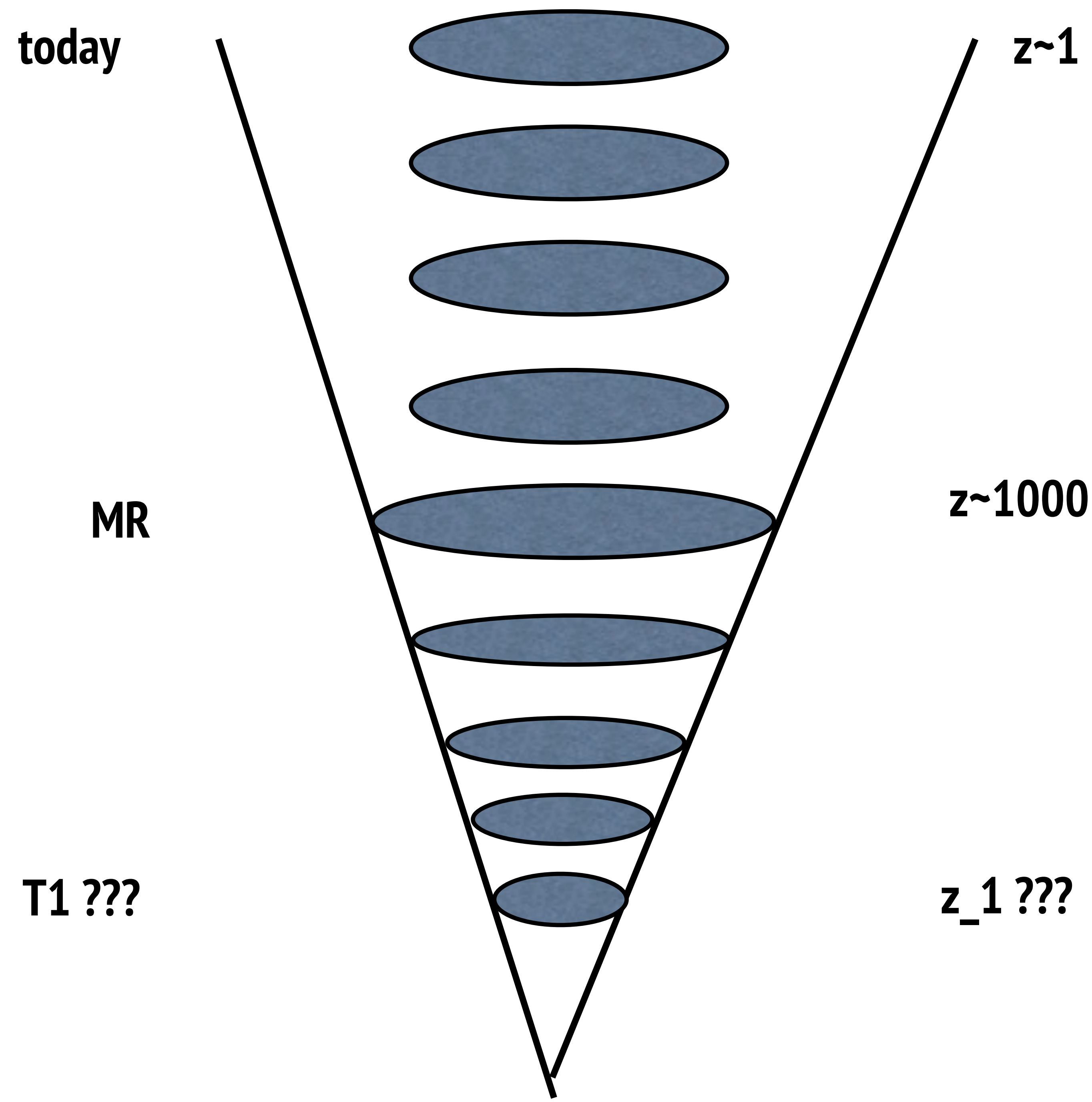
$$m_a \sim 100\mu\text{eV}$$

Q: Horizon size at t1? H(t1)~m(T1)

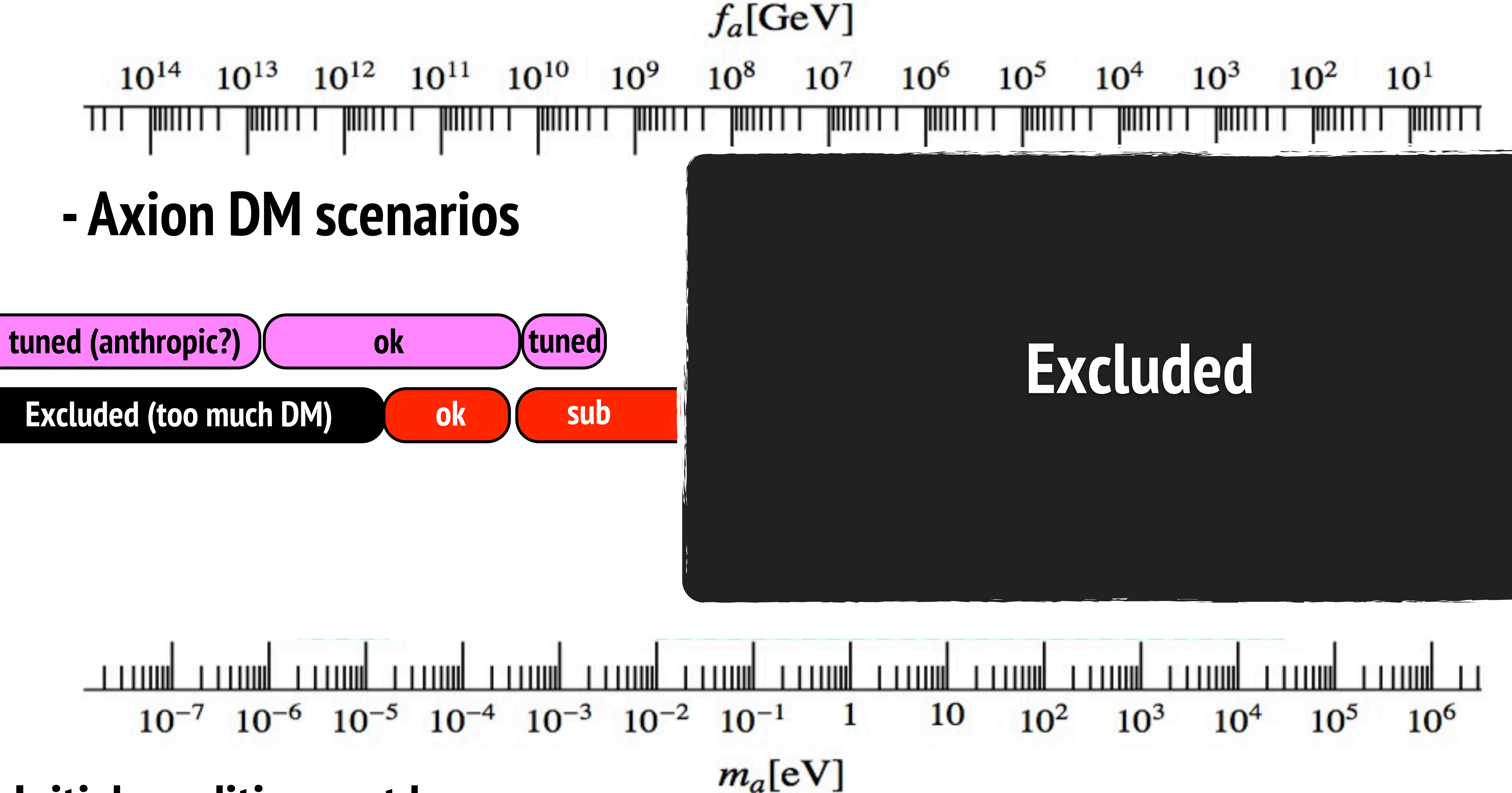
Q: What is the mass inside a Horizon^3 ?

Q: what is the physical size at z~1000

Q: what will be the density in a MC today?



Axion dark matter



Initial conditions set by :

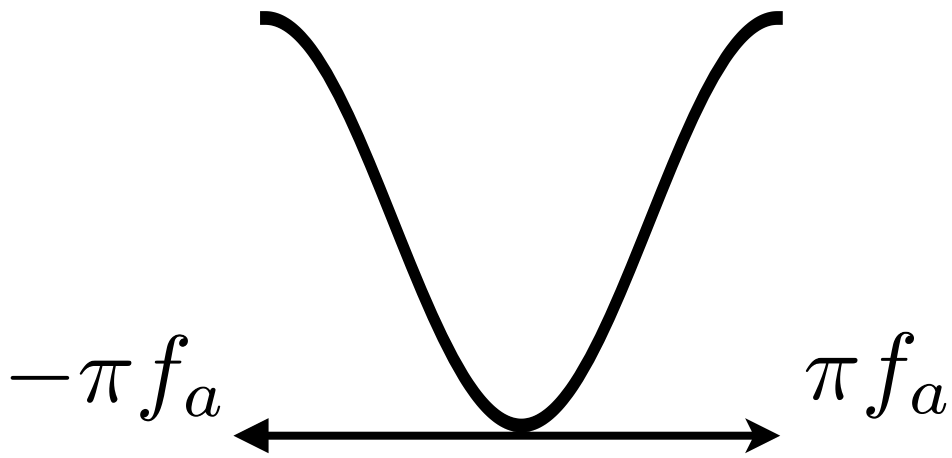
Inflation smooth

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

Phase transition (N=1)

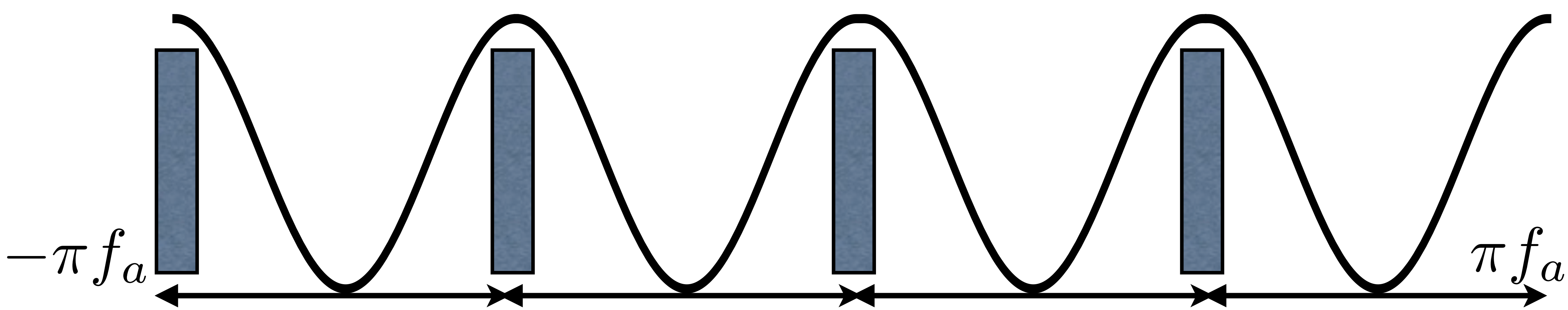
strings+unstable DW's

SCENARIO I, N=1

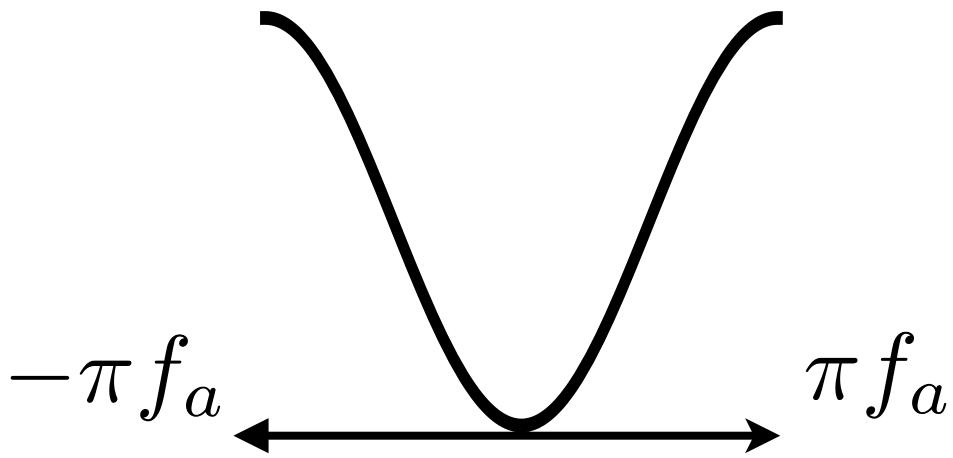


$$\frac{a}{f_a} = N\theta$$

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

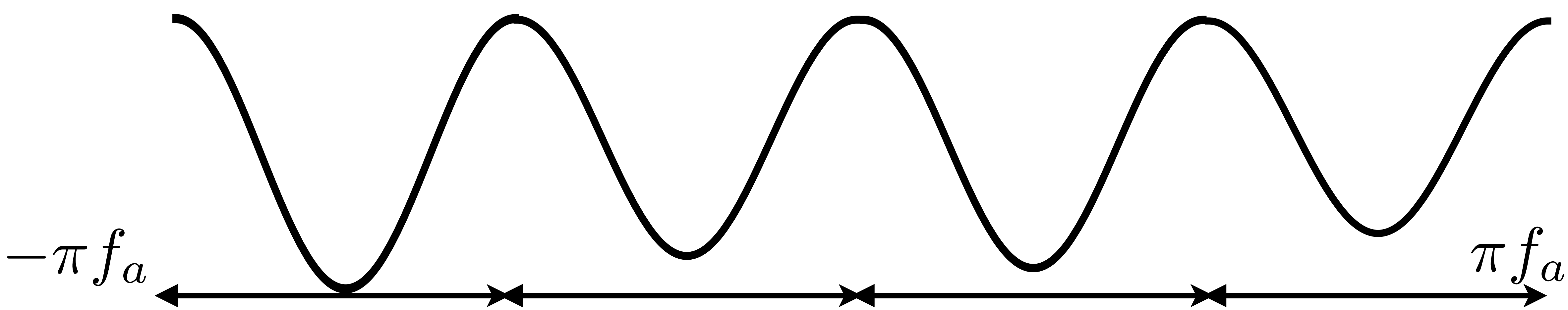


SCENARIO I, N=1



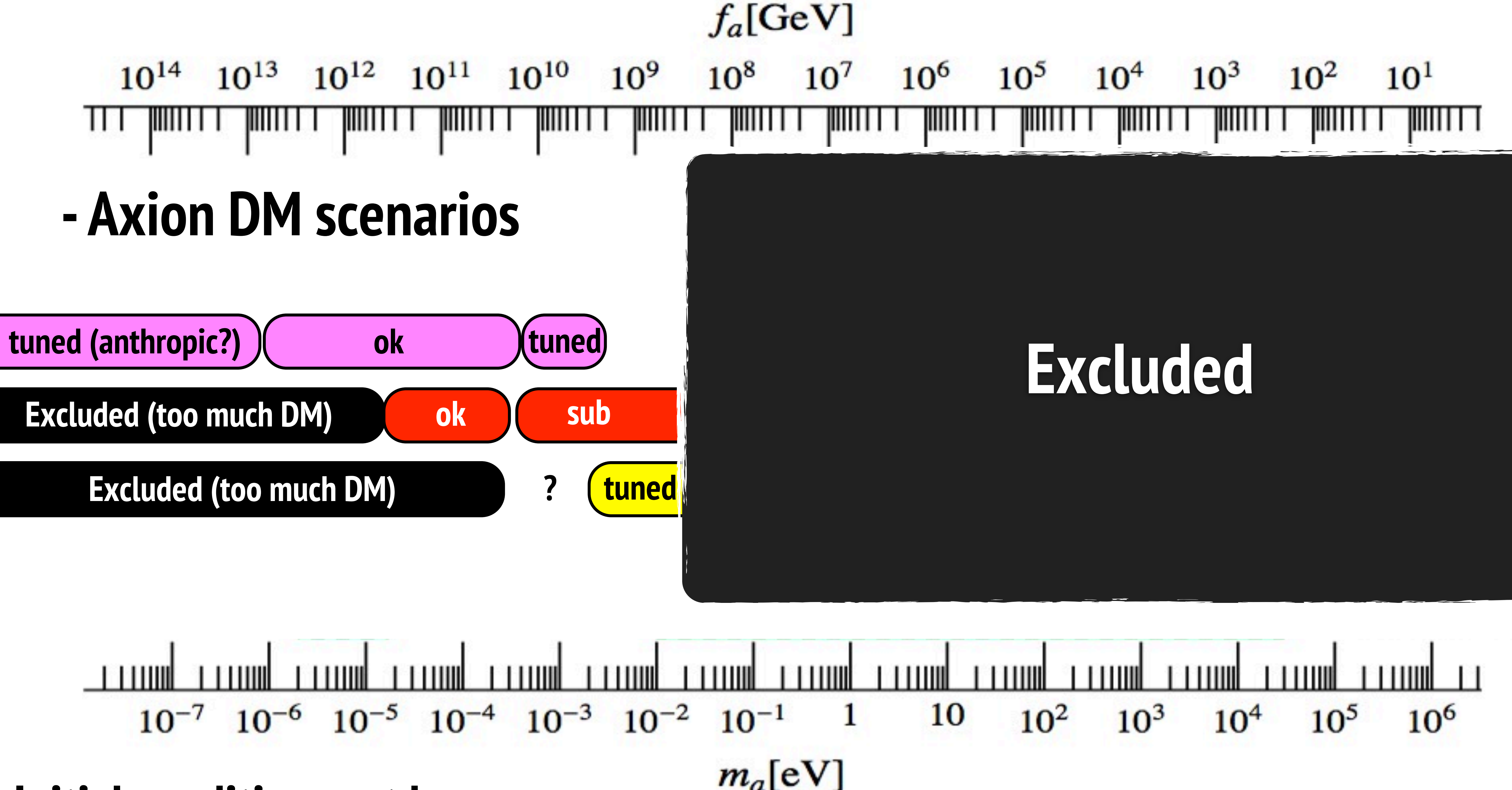
$$\frac{a}{f_a} = N\theta$$

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



Domain walls move by pressure difference, they are long-lived -> large misalignments for longer time -> more DM

What fa gives the correct relic abundance??



Initial conditions set by :

Inflation smooth	Phase transition (N=1)	Phase transition (N>1)
$\Omega_{\rm aDM}h^2 \simeq \theta_I^2 \left(\frac{80\,\mu{\rm eV}}{m_a}\right)^{1.19}$	strings+unstable DW's	strings+long-lived DWs

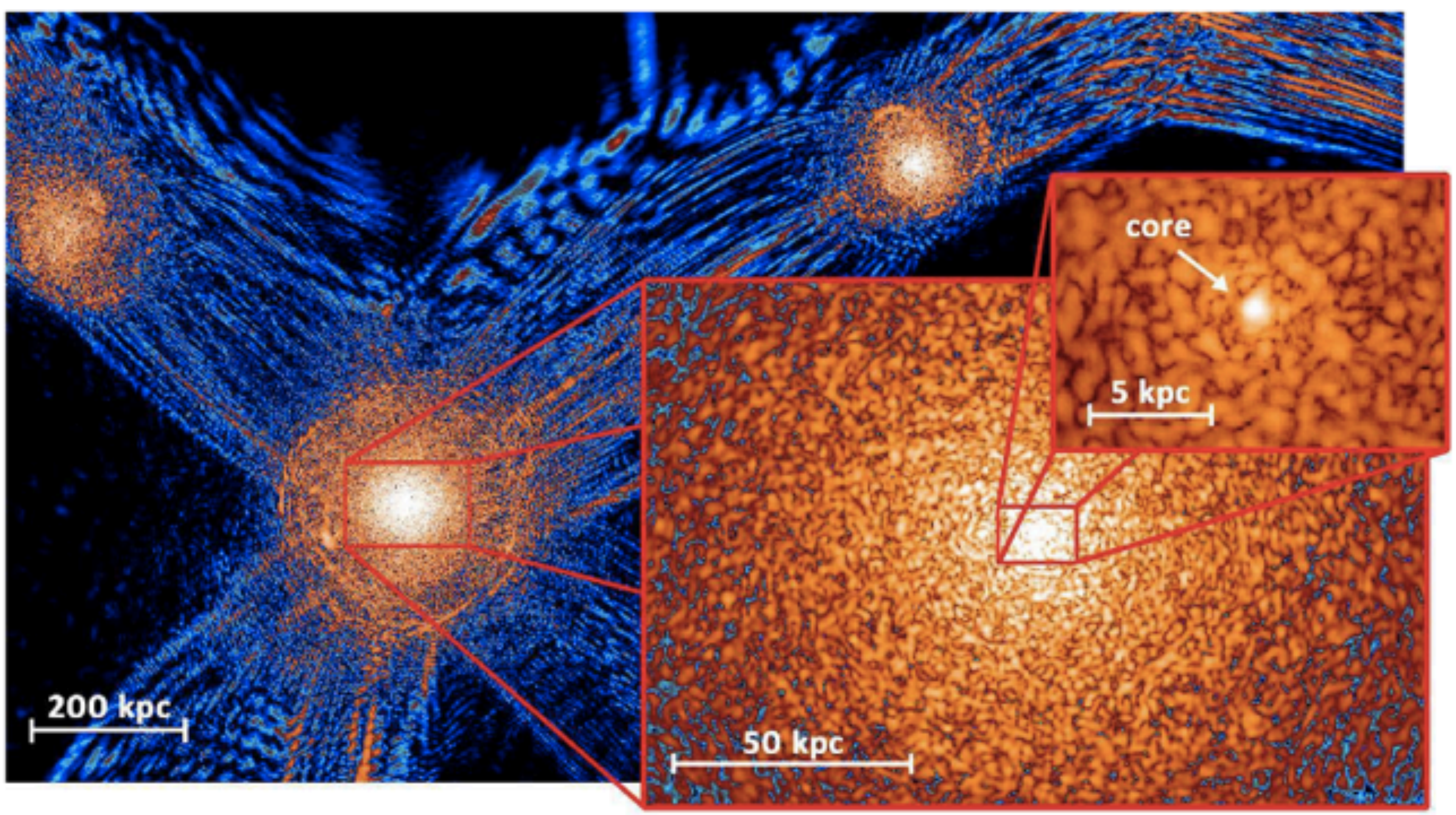
Fuzzy DM and small-scale structure problems

(Hu 2000,…, Hui 2017)

- If ALP DM has small mass,

- Gradient pressure implies a Jeans mass in structure formation, which suppresses small scale features (cusps, # low mass satelites…)

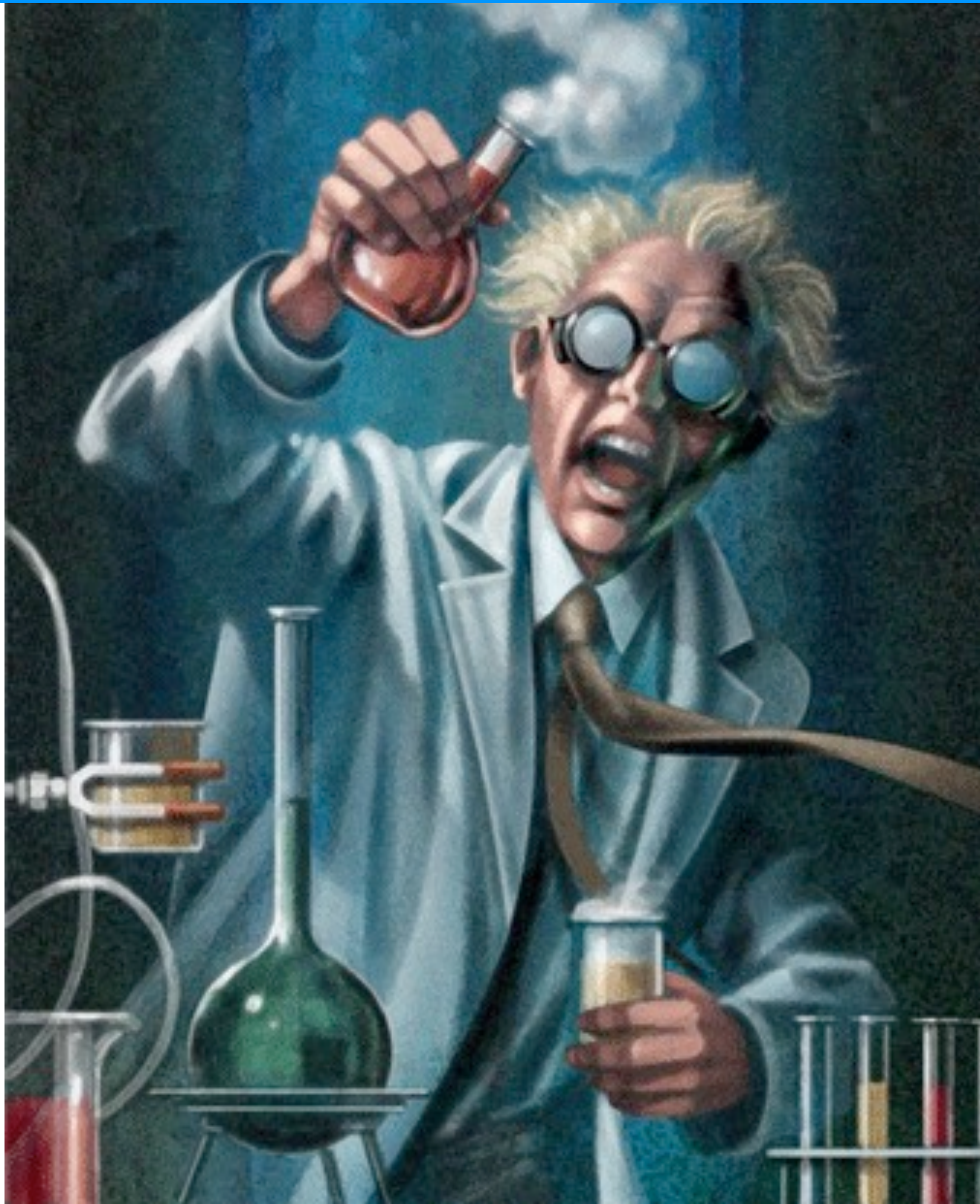
- Typical value $m \sim 10^{-22}\mathrm{eV}$ at odds with Ly-alpha



Halos composed of central cores' (Bose star) + CDM-like halo

Schive 2014

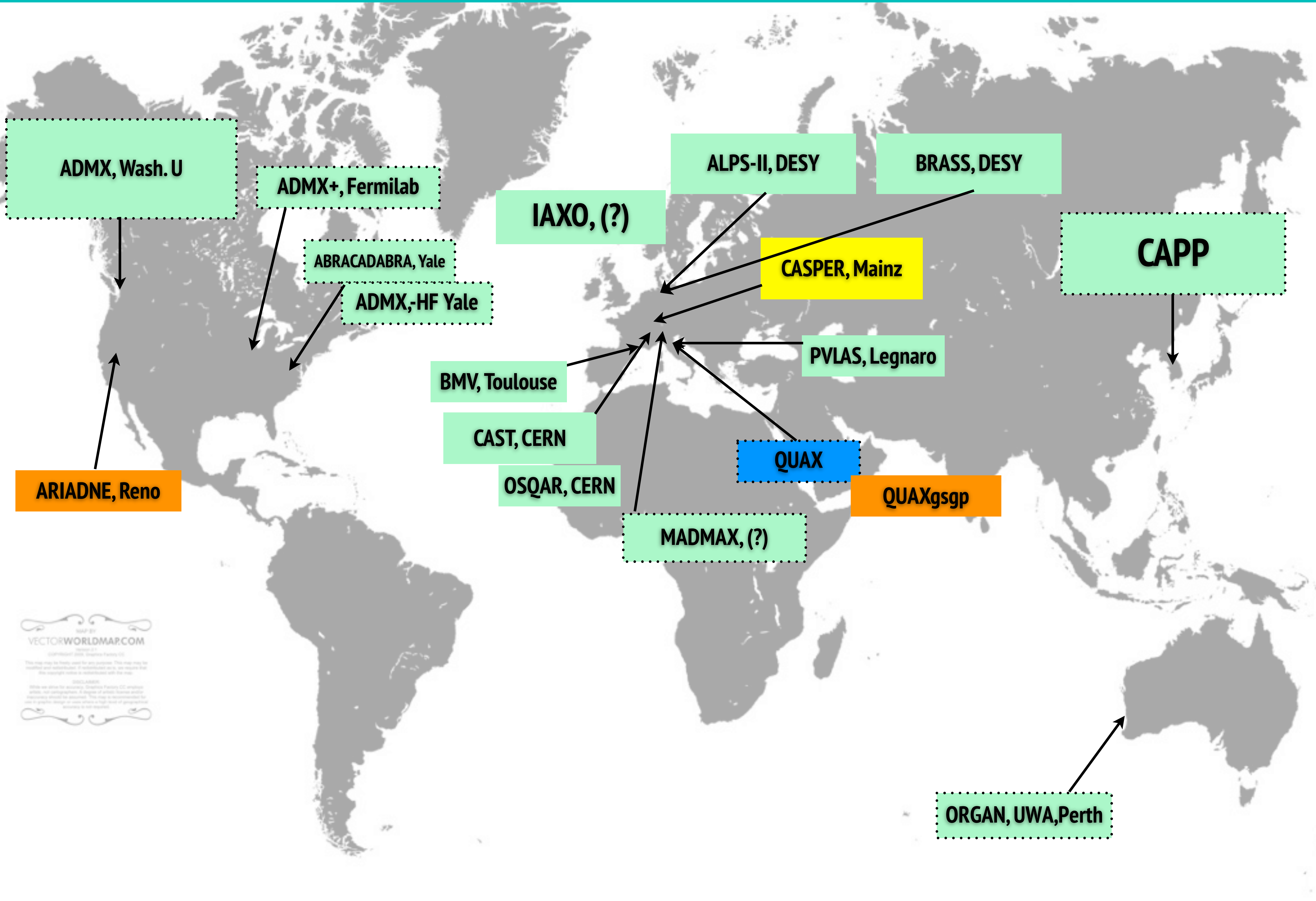
Detecting Axions



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

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

Axion experiments 2017



Detecting Dark Matter

Imperfect Vacuum realignment $\theta(t) = \theta_0 \cos(m_a t)$

$$\rho_{\rm CDM} = 0.3\frac{\rm GeV}{\rm cm^3} \equiv \frac{1}{2}(\dot{a})^2 + \frac{1}{2}m_a^2 a^2 = \frac{1}{2}m_a^2 f_a^2 \theta_0^2$$

$$\xrightarrow[m_A^2 f_A^2 = \chi_{\rm QCD}]{\textbf{QCD axion}} \theta_0 \sim 3.6 \times 10^{-19}$$

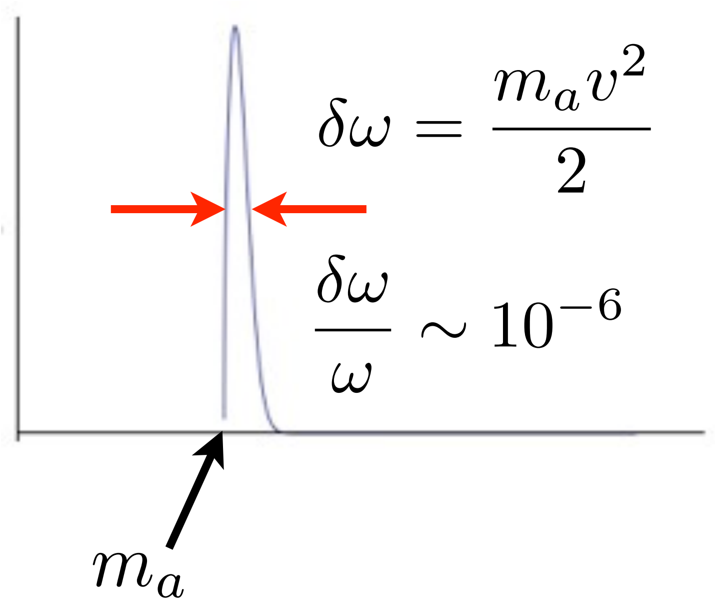
Non-zero velocity in galaxy -> finite width

$$\omega \simeq m_a(1 + v^2/2 + \dots)$$

~ 10^-6

coherence time

$$\boxed{\delta t \sim \frac{1}{\delta\omega} \sim 0.13{\rm ms}\left(\frac{10^{-5}{\rm eV}}{m_a}\right)}$$



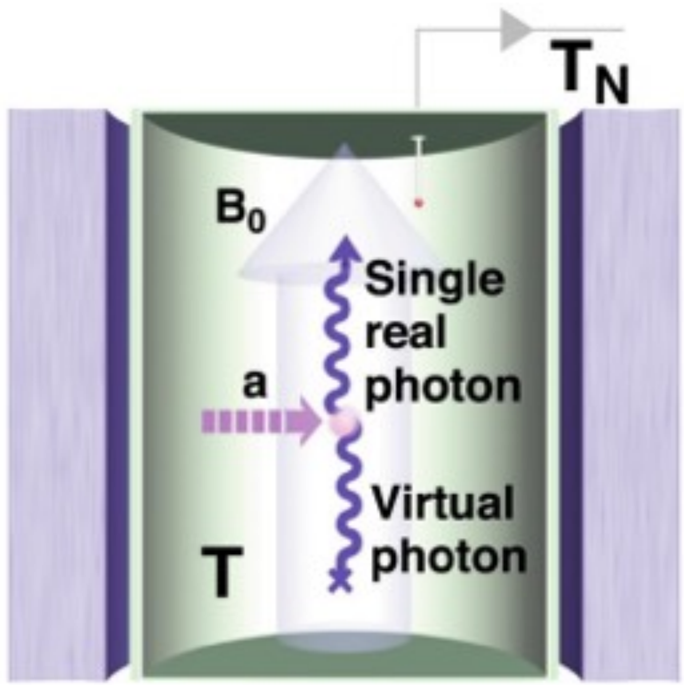
$$\delta\omega = \frac{m_a v^2}{2}$$

$$\frac{\delta\omega}{\omega} \sim 10^{-6}$$

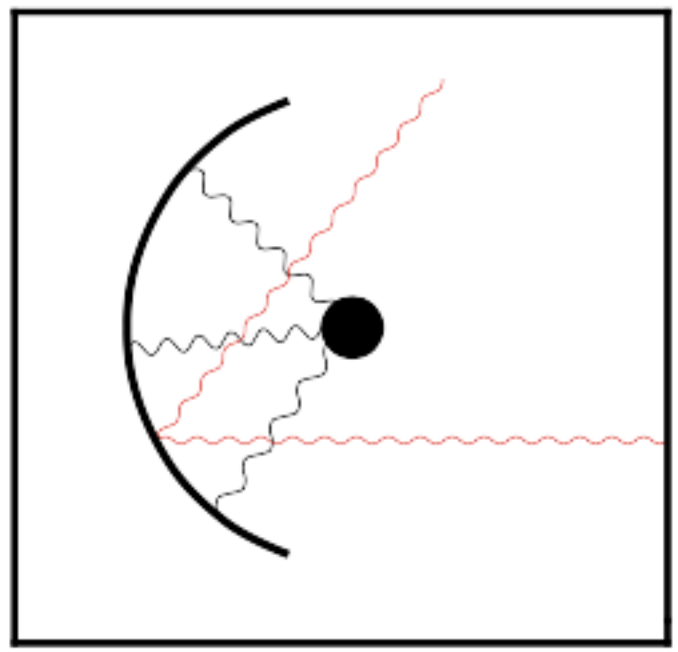
coherence length

$$\boxed{\delta L \sim \frac{1}{\delta p} \sim 20{\rm m}\left(\frac{10^{-5}{\rm eV}}{m_a}\right)}$$

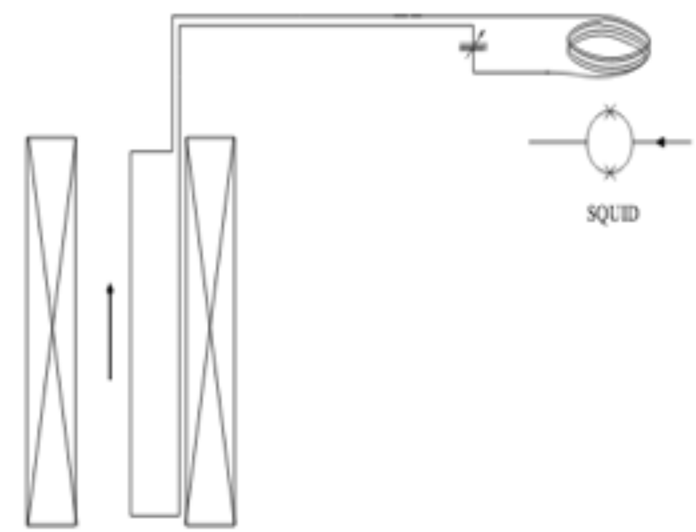
Cavities



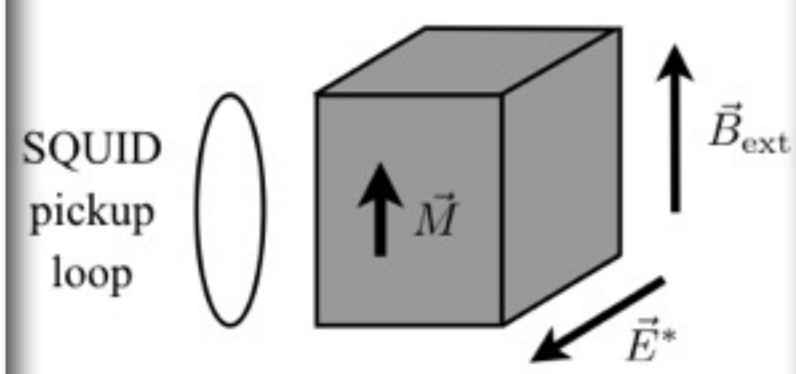
Mirrors



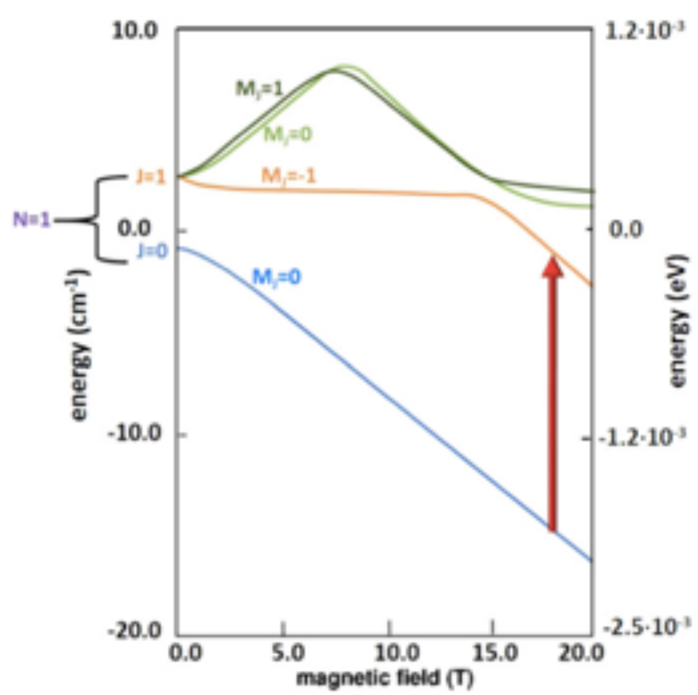
LC-circuit



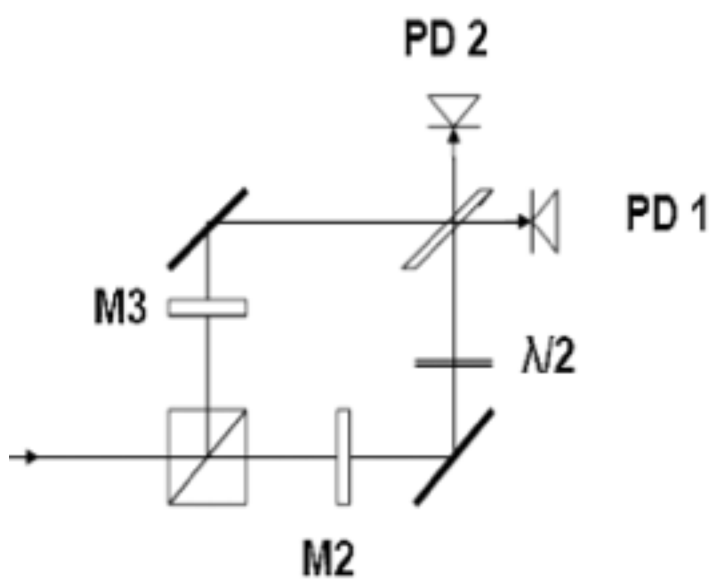
Spin precession



Atomic transitions



Optical



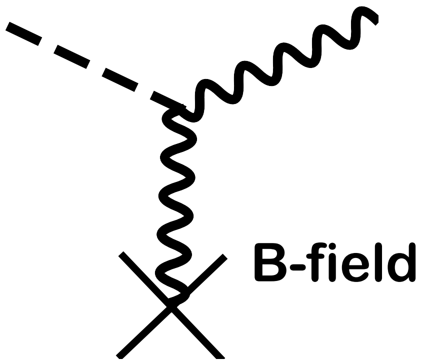
Axion DM in a B-field

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

- 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

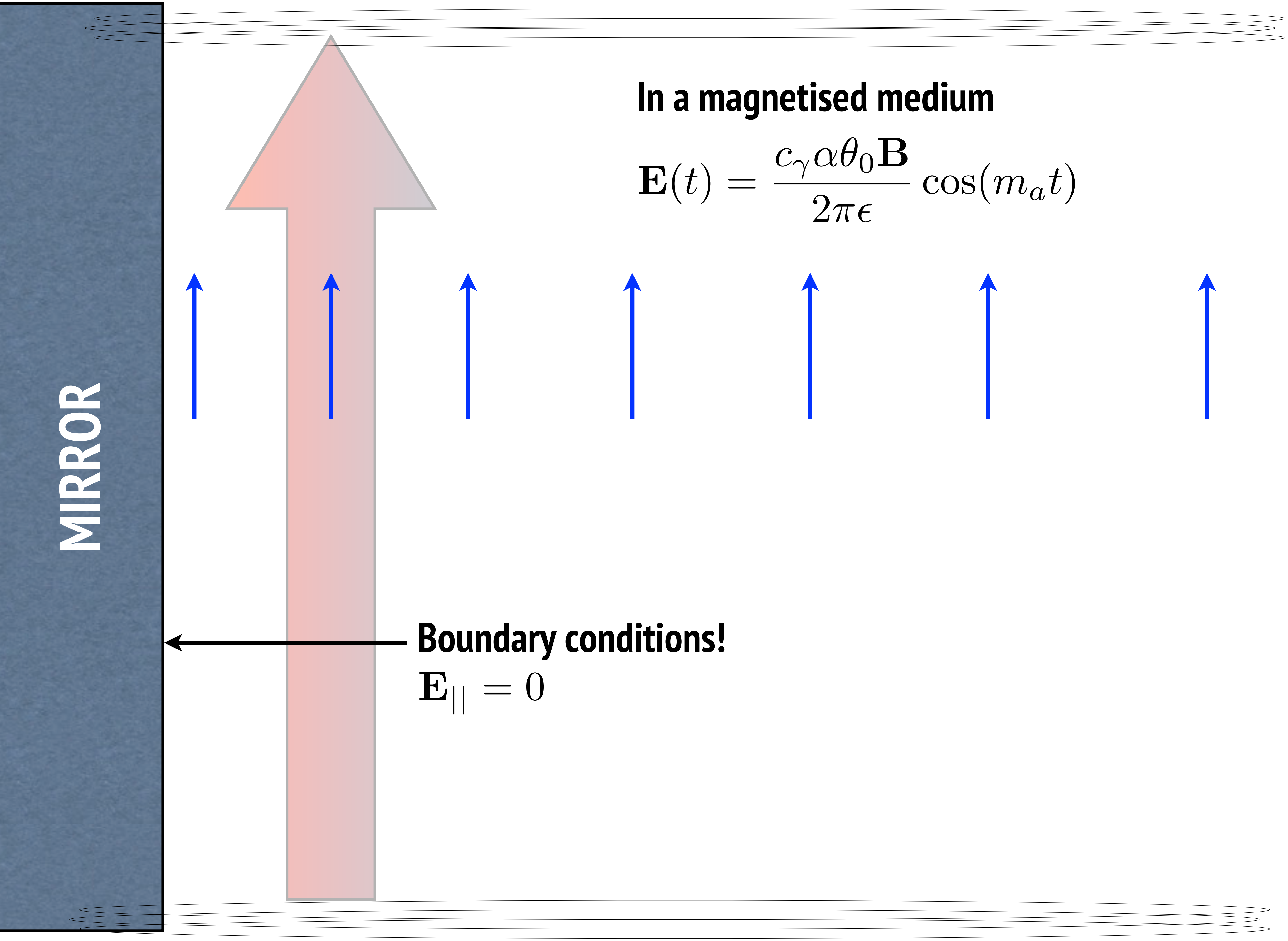


- Electric fields $\mathbf{E}_a = C_{a\gamma}\frac{\alpha\mathbf{B}_{\rm ext}}{2\pi}\theta_0\cos(m_a t)$ **(amp independent of mass!)**

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

- B-fields $\propto \nabla\theta$ $\quad |\mathbf{B}_a| \sim \langle v\rangle|\mathbf{E}_a|$

Radiation from a magnetised mirror



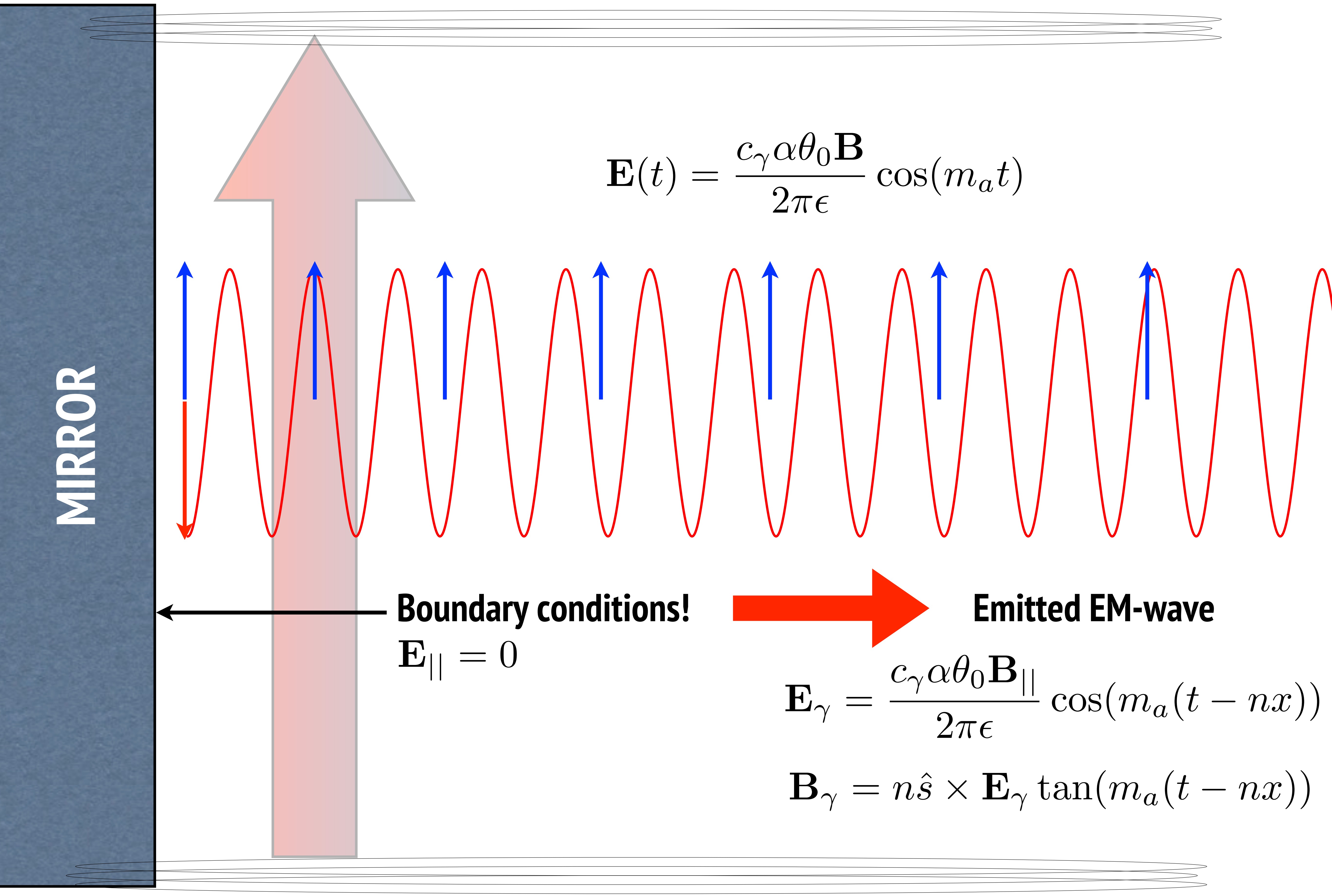
In a magnetised medium

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

Boundary conditions!

$$\mathbf{E}_{||} = 0$$

Radiation from a magnetised mirror



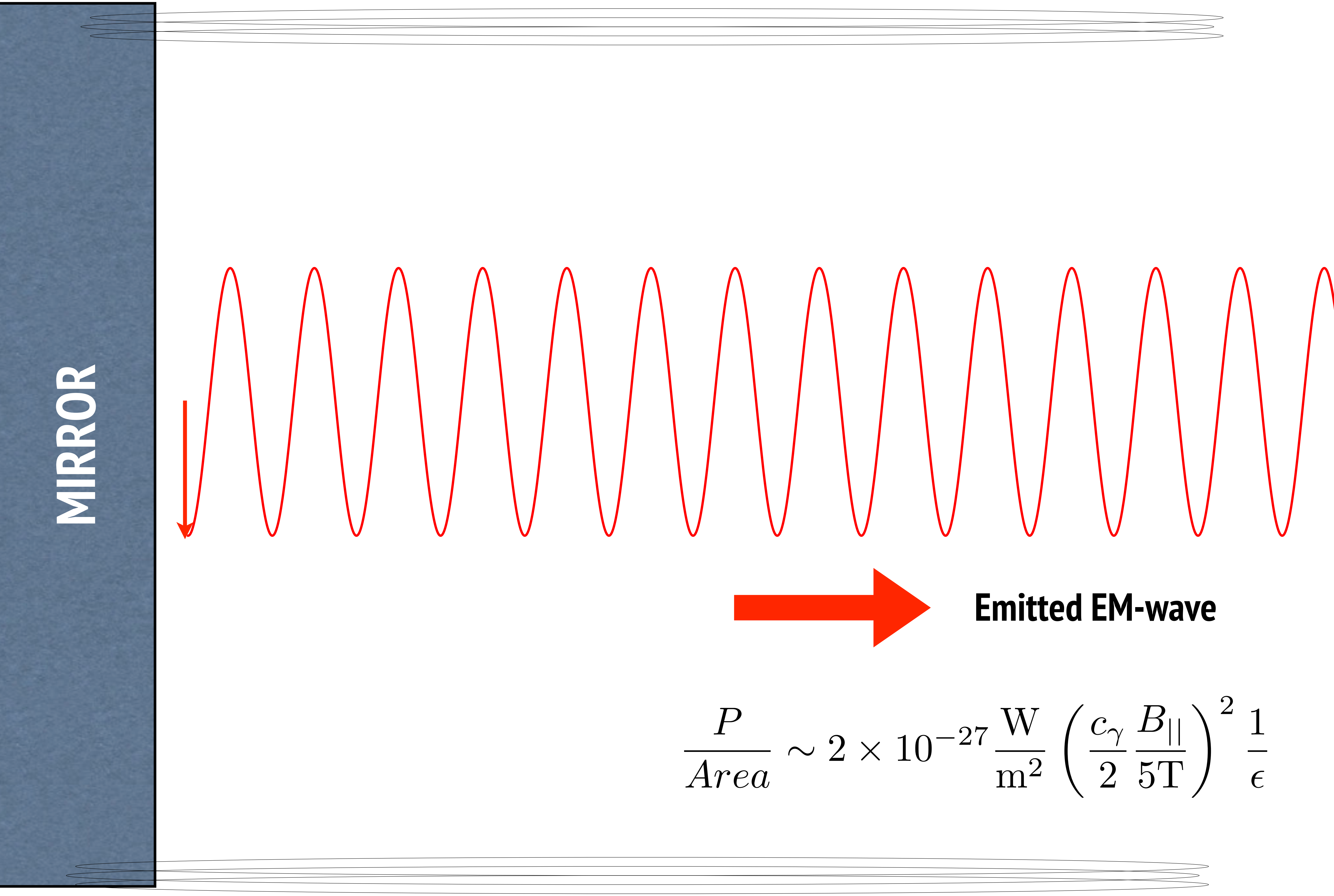
$$\mathbf{E}(t) = \frac{c_\gamma \alpha \theta_0 \mathbf{B}}{2\pi\epsilon} \cos(m_a t)$$

$$\mathbf{E}_{||} = 0$$

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

$$\mathbf{B}_\gamma = n\hat{s} \times \mathbf{E}_\gamma \tan(m_a(t - nx))$$

Radiation from a magnetised mirror : Power



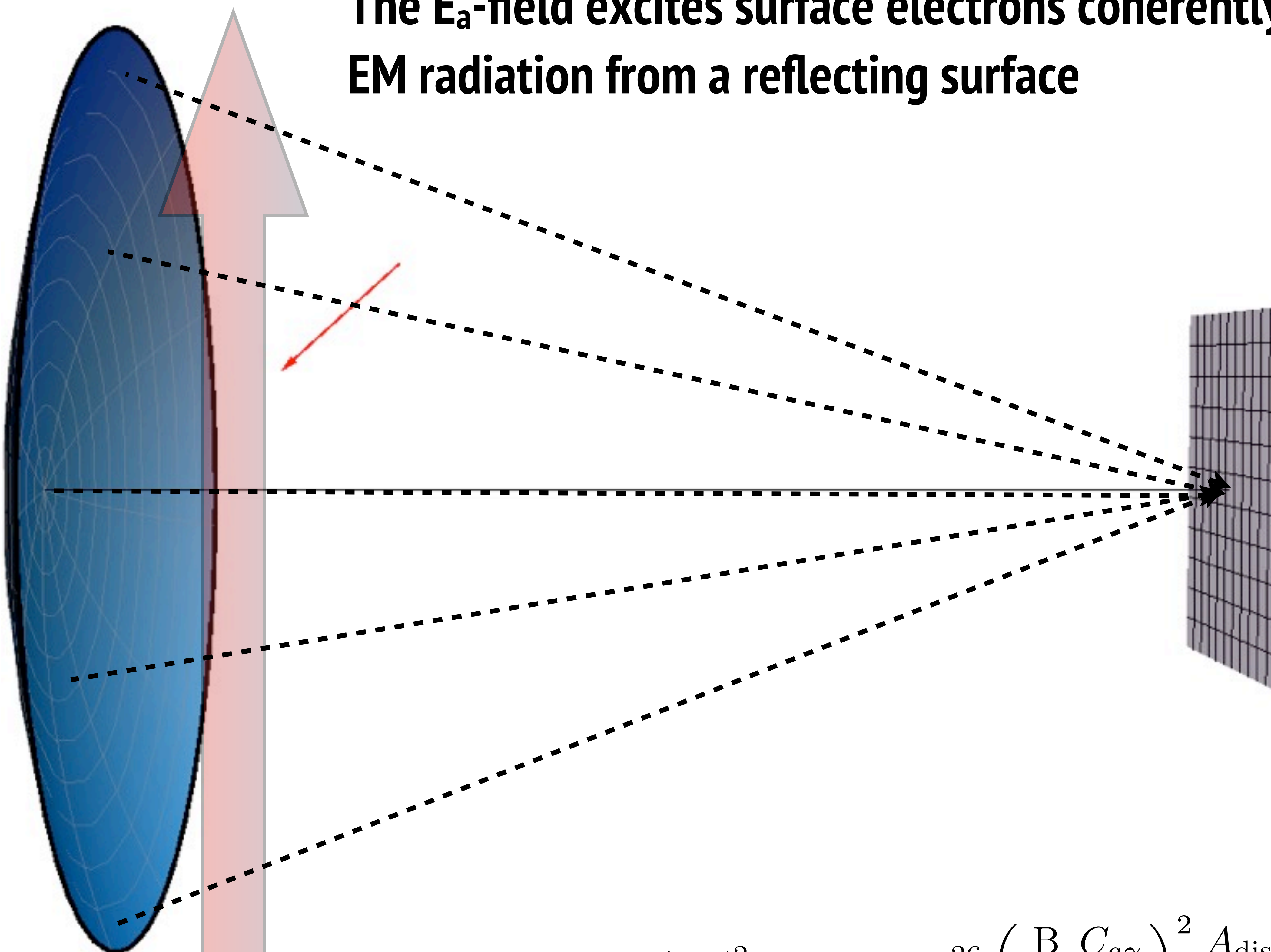
$$\frac{P}{Area} \sim 2 \times 10^{-27}\,\frac{\mathrm{W}}{\mathrm{m}^2}\left(\frac{c_\gamma}{2}\,\frac{B_{||}}{5\mathrm{T}}\right)^2\frac{1}{\epsilon}$$

Dish antenna experiment?

Horns 2012

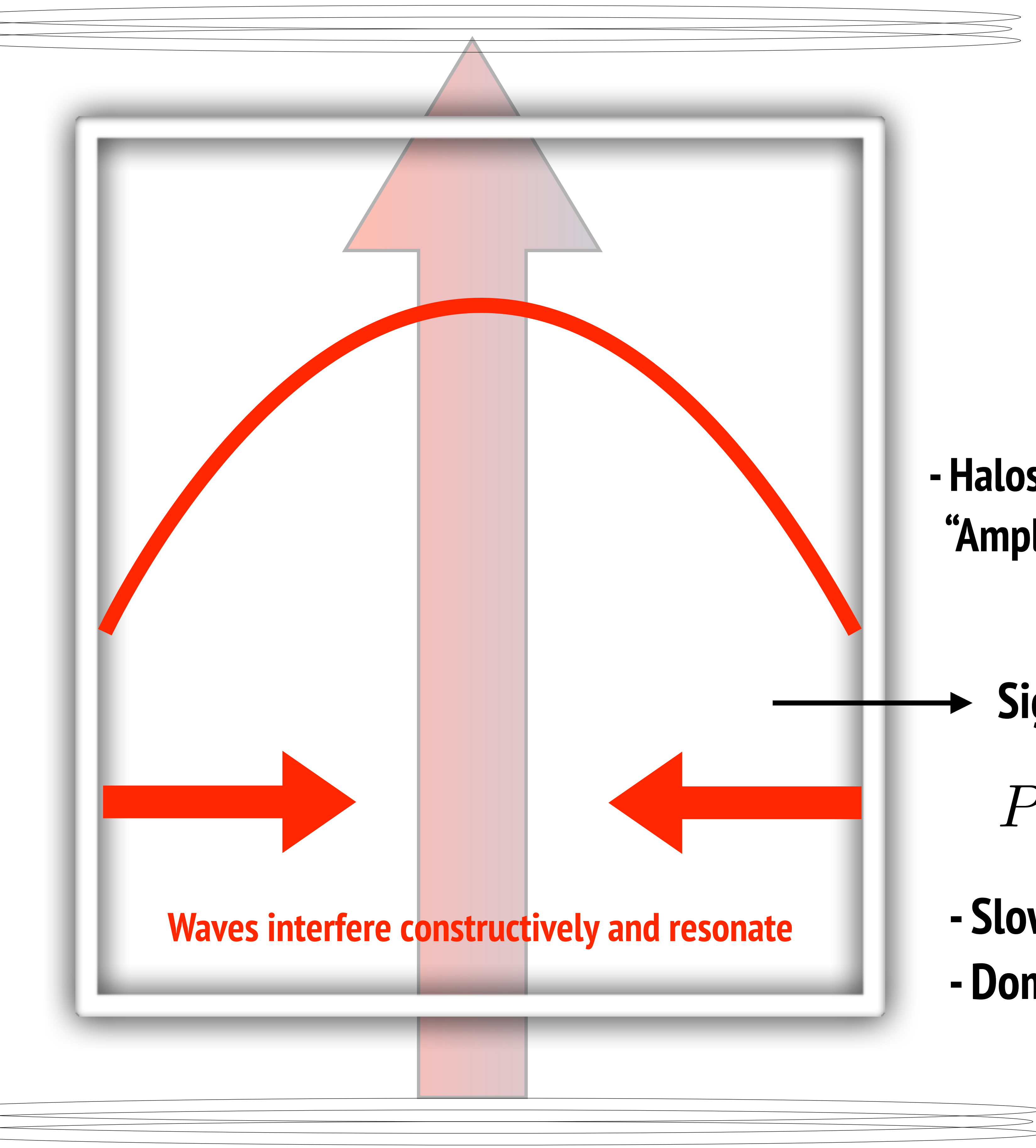
The E_a-field excites surface electrons coherently

EM radiation from a reflecting surface



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

Cavity experiments



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

Signal if tuned

$$P \to P \times Q$$

- Slow scan over frequencies
- Dominated by thermal+preamp noise

Signal power in cavity experiments (haloscopes)

$$c_\alpha = \frac{c_\gamma \alpha}{2\pi}$$

Combine MW equations into an oscillator

$$\ddot{\mathbf{E}} - \nabla^2 \mathbf{E} = -\frac{c_\gamma \alpha}{2\pi} \mathbf{B}_{\rm ext}\, \ddot{\theta}$$

Expand in eigenmodes of the cavity satisfy (with appropriate boundary conditions)

$$\mathbf{E}(t, \mathbf{x}) = \sum_i E_i(t) \mathbf{e}_i . \qquad -\nabla^2 \mathbf{e}_i = \omega_i^2 \mathbf{e}_i .$$

Equation for the amplitude of one mode

geometric factor ...

$$\ddot{E}_i + \omega_i^2 E_i + \Gamma \dot{E}_i = -c_\alpha B C_i \ddot{\theta} . \qquad C_i = \frac{1}{VB} \int dV \mathbf{e}_i \cdot \mathbf{B}_{\rm ext} .$$

damping (energy loss by walls and pick up signal)

damping (energy loss by walls and pick up signal)

Forced oscillator solution

$$E_i = -\frac{c_\alpha B m_a^2 C_i}{(m_a^2 - \omega_i^2)^2 + (m_a \Gamma)^2} \left(\theta(t)(m_a^2 - \omega_i^2) + \dot{\theta}(t)\Gamma \right) ,$$

Signal power in cavity experiments (haloscopes)

Energy stored in a mode

$$U_i = V \frac{1}{2}\left(\frac{\omega^2+\omega_i^2}{2\omega^2}\right) E_i(t_0)^2$$

Energy loss and quality factor

$$\frac{dU_i}{dt} = -\Gamma_i U_i \qquad \Gamma = \Gamma_s + \Gamma_c \qquad Q_i = \frac{\omega_i}{\Gamma_{s,i}+\Gamma_{c,i}}$$

signal I pick from an antenna / intrinsic losses

Extracted power (Signal!)

$$P_{\rm signal} = \Gamma_{s,i} U_i = V\Gamma_{s,i}\frac{1}{2}\left[\frac{m_a^2+\omega_i^2}{2m_a^2}\right]\left(\frac{c_\alpha B m_a^2 \theta_0 C_i}{(m_a^2-\omega_i^2)^2+(m_a\Gamma)^2}\right)^2\left((m_a^2-\omega_i^2)^2+(m_a\Gamma)^2\right),$$

On resonance $\omega_i = m_a$

$$P_{\rm signal} = \frac{\Gamma_s}{\Gamma_s+\Gamma_c}\frac{Q}{\omega_i}\left(g_{a\gamma}BC_i\right)^2\rho_{\rm DM}V.$$

Outside the resonance $\omega_i - m_a \gg \Gamma = \omega_i/Q$

$$P_{\rm signal} \sim 0$$

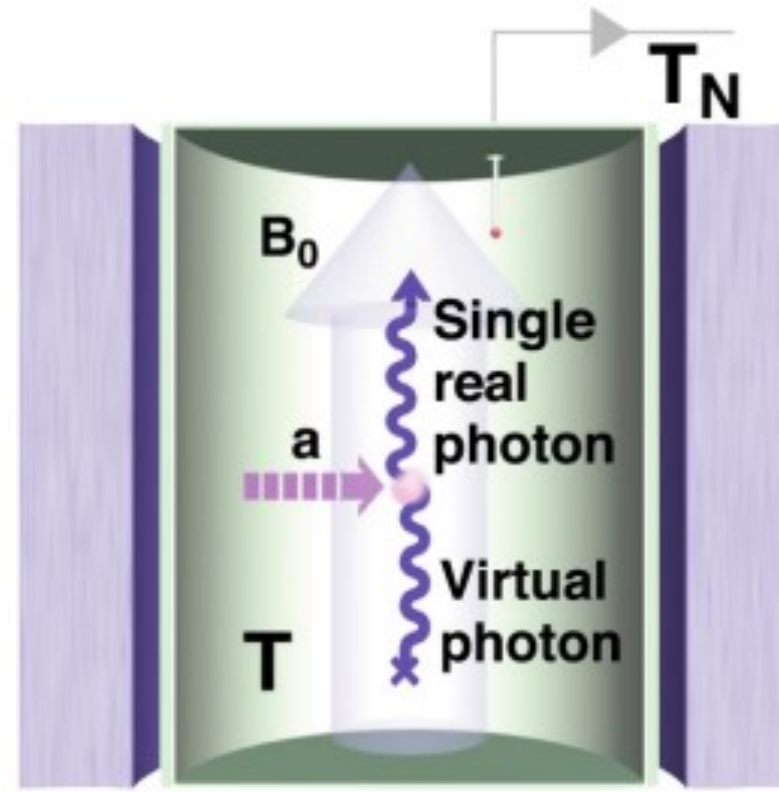
Cavity resonators (Haloscopes)

- Haloscope (Sikivie 83)

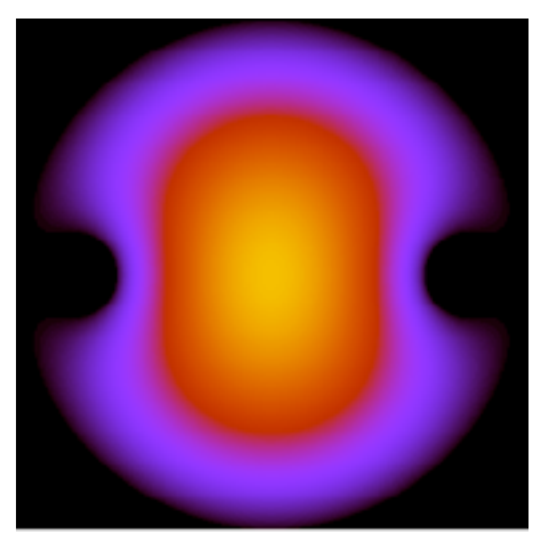
$$P \sim Q|\mathbf{E}_a|^2 (V m_a)\mathcal{G}\kappa$$ (ON RESONANCE)

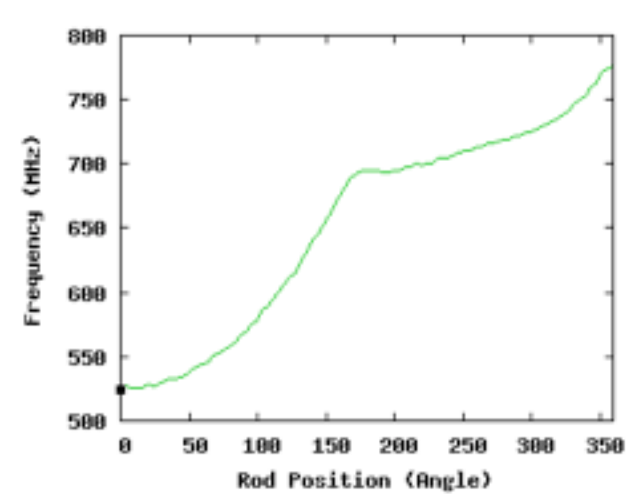
- Naive ADMX scaling (e.g. an ADMX every octave)

- Signal $(V \propto m_a^{-3})$ $\quad P_{\rm out} \propto V m_a \sim \frac{1}{m_a^2}$
- Noise $\quad P_{\rm noise} = T_{\rm sys}\Delta\nu_a \propto m_a^2$
- Signal/noise in $\Delta\nu_a$ of time, t, $\quad \frac{S}{N} = \frac{P_{\rm out}}{P_{\rm noise}}\sqrt{\Delta\nu_a t}$
- Scanning rate $\quad \frac{1}{m_a}\frac{d\Delta m_a}{dt} \propto \frac{C_{A\gamma}^4}{m_a^7}$



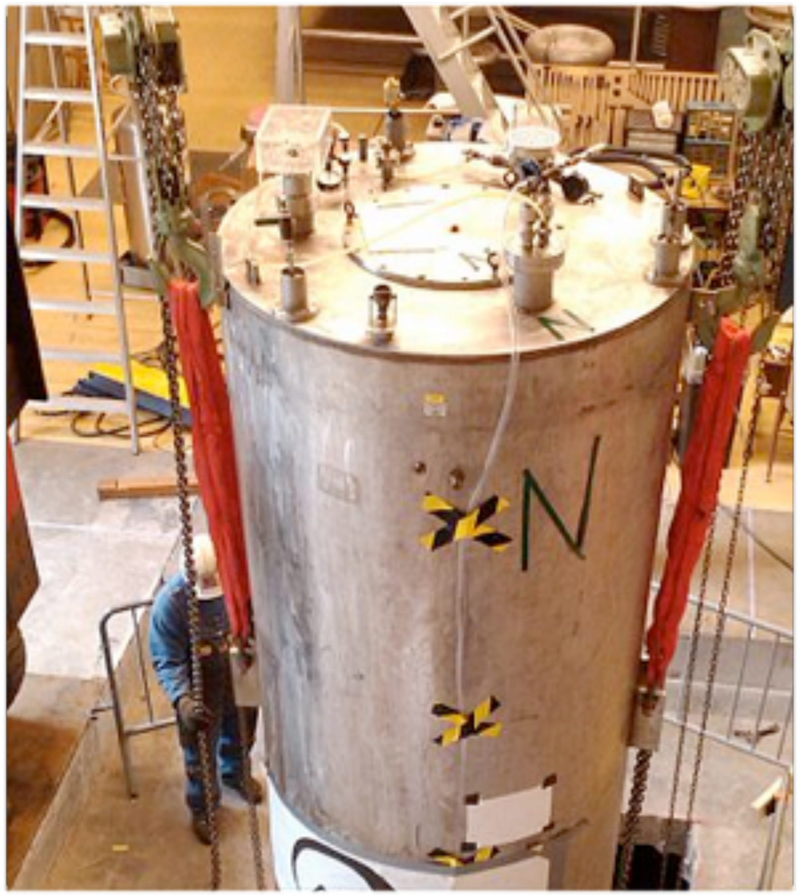
Scanning over frequencies



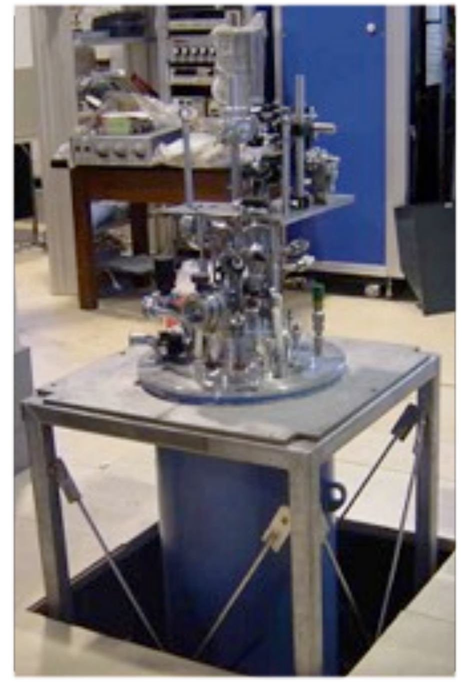


Cavity experiments

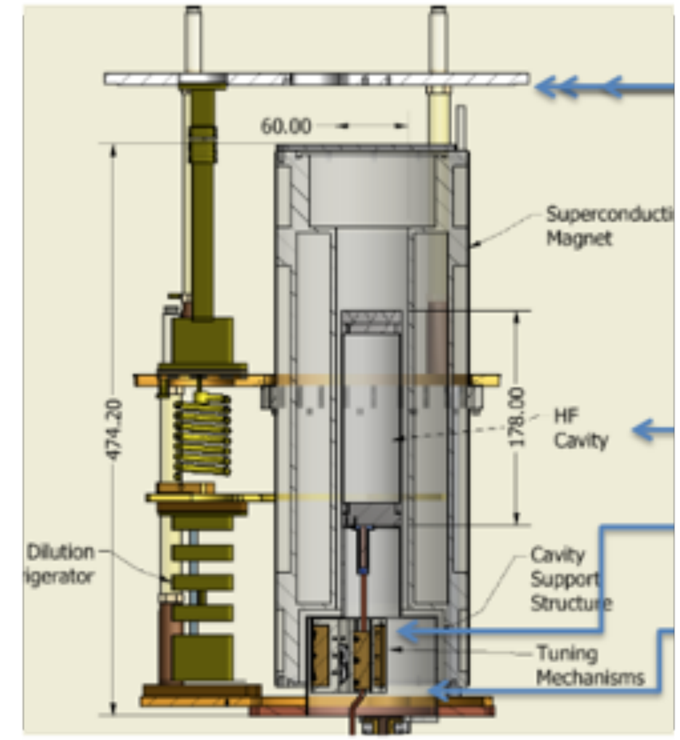
ADMX



CARRACK (discontinued)

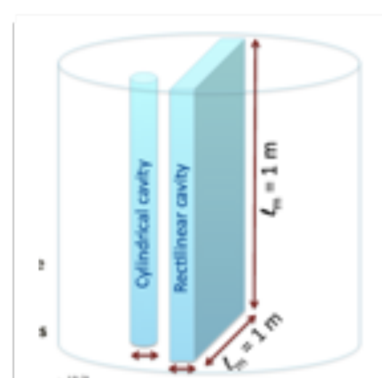


CULTASK - CAPP -Korea

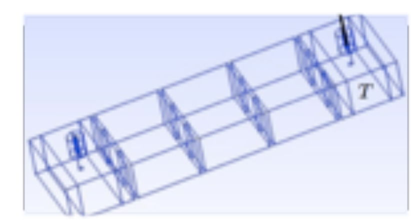


HAYSTAC

ADMX-Fermilab

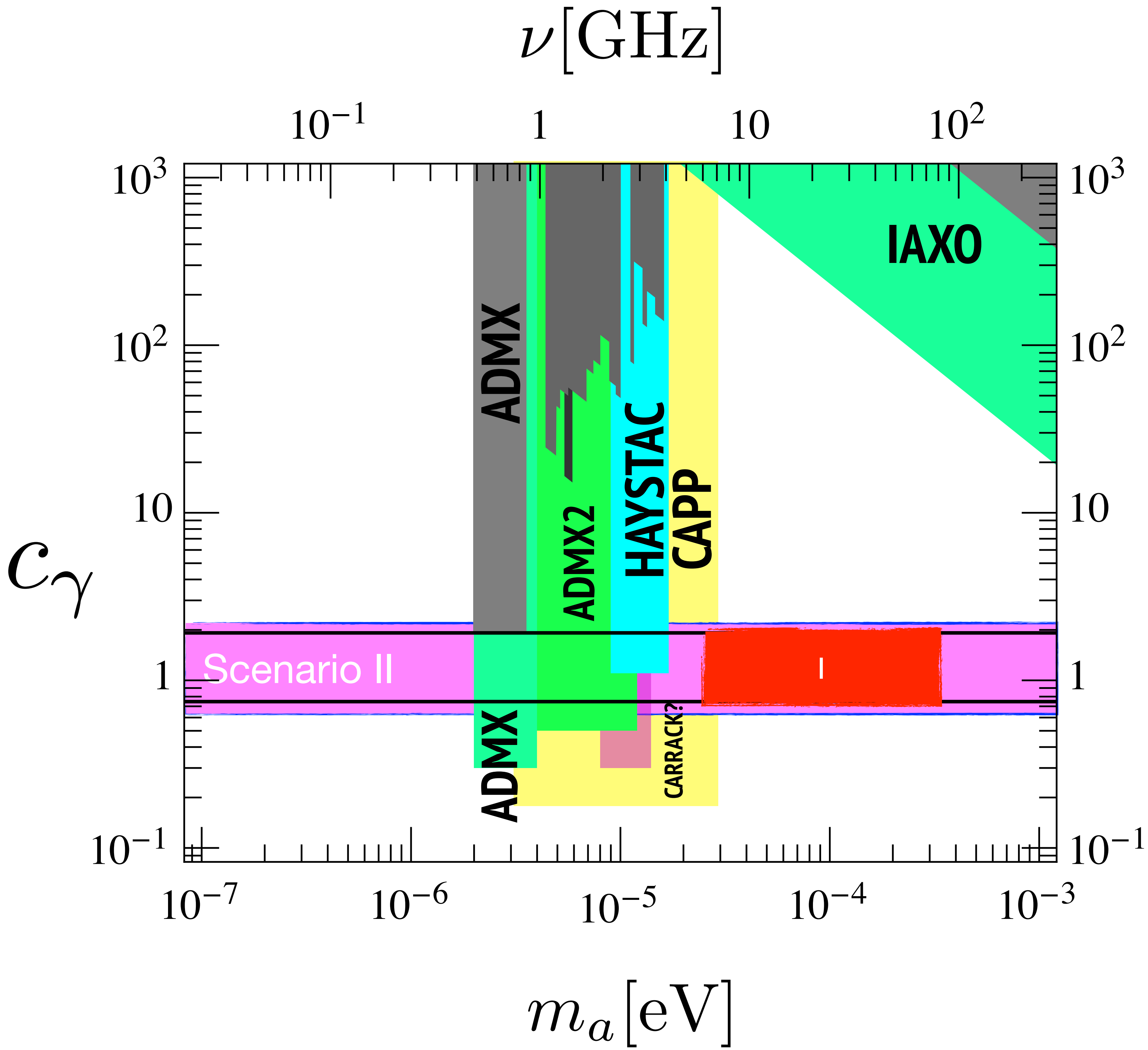


RADES

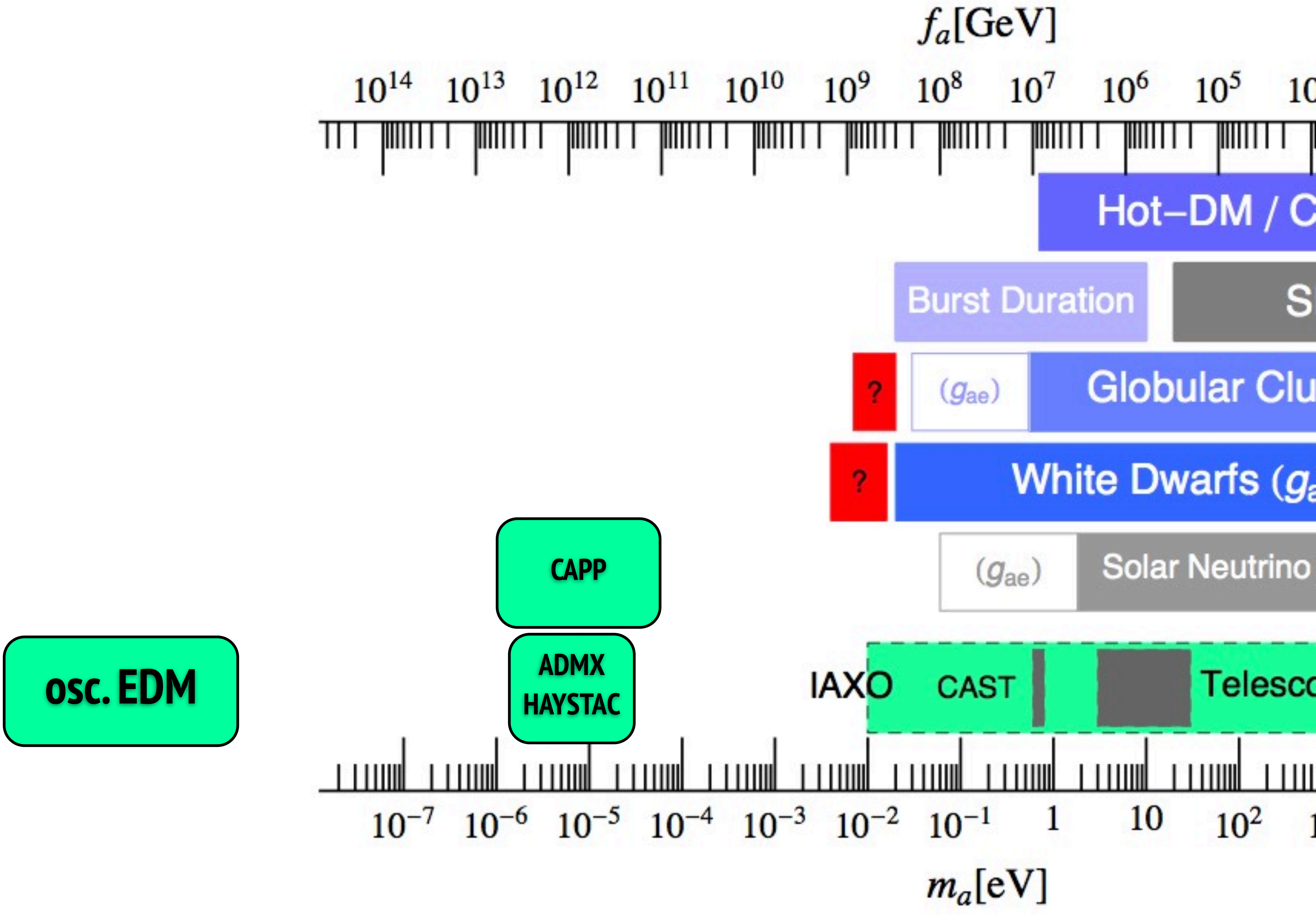


CAST-CAPP

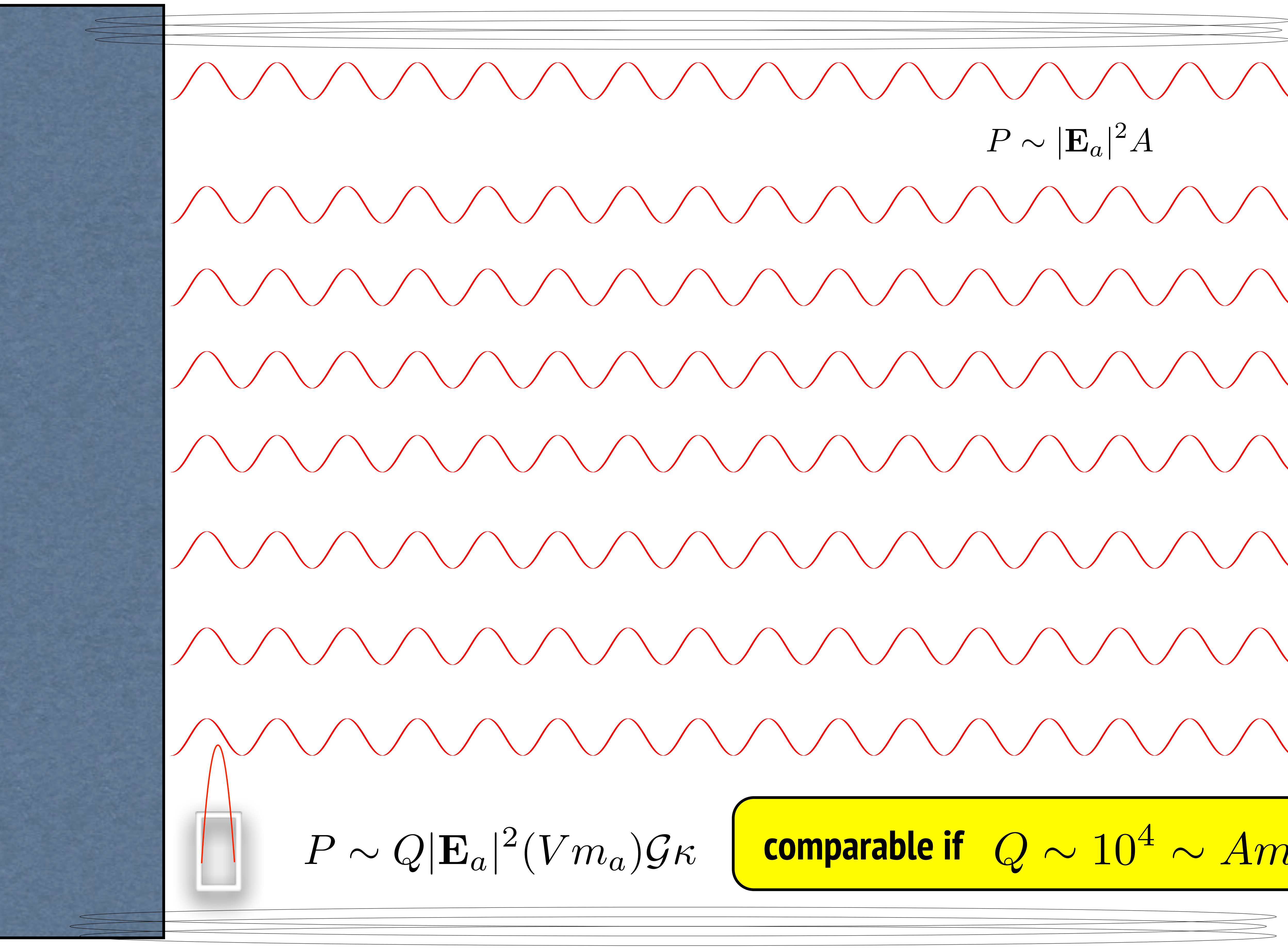
Cavity experiments



Conclusions : a developing picture



Large freq ... Area vs volume

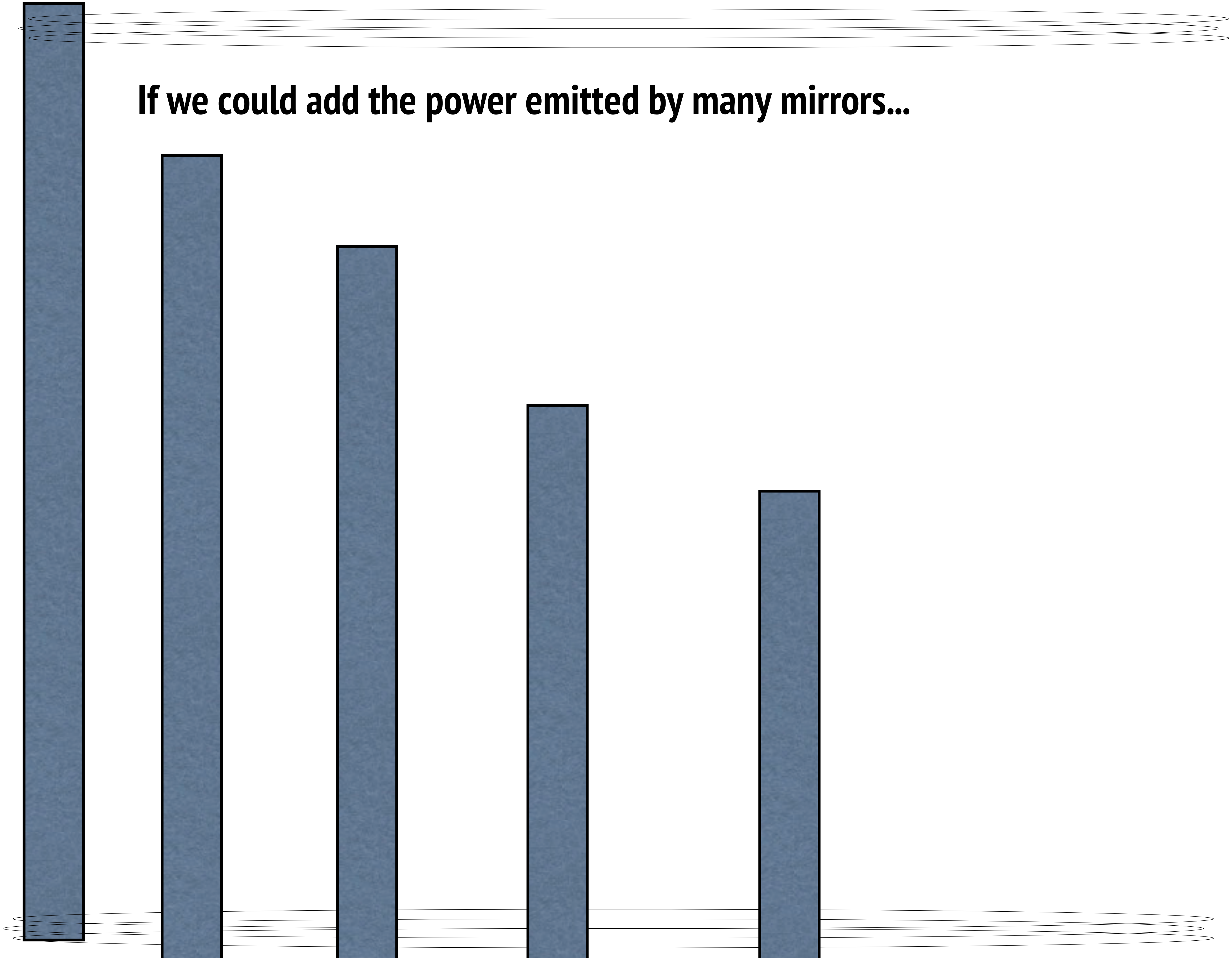


$$P \sim |\mathbf{E}_a|^2 A$$

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

comparable if $Q \sim 10^4 \sim A m_a^2$

Mixed scheme?



If we could add the power emitted by many mirrors...

Radiation from a dielectric interface ...

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

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← Boundary conditions!

$$\mathbf{E}_{||1} = \mathbf{E}_{||2}$$

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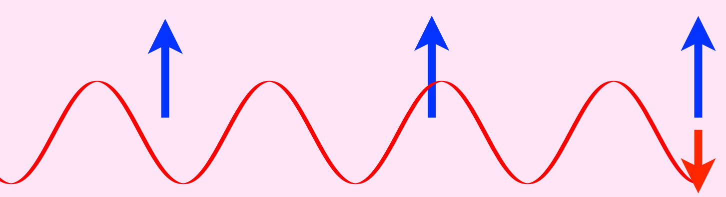
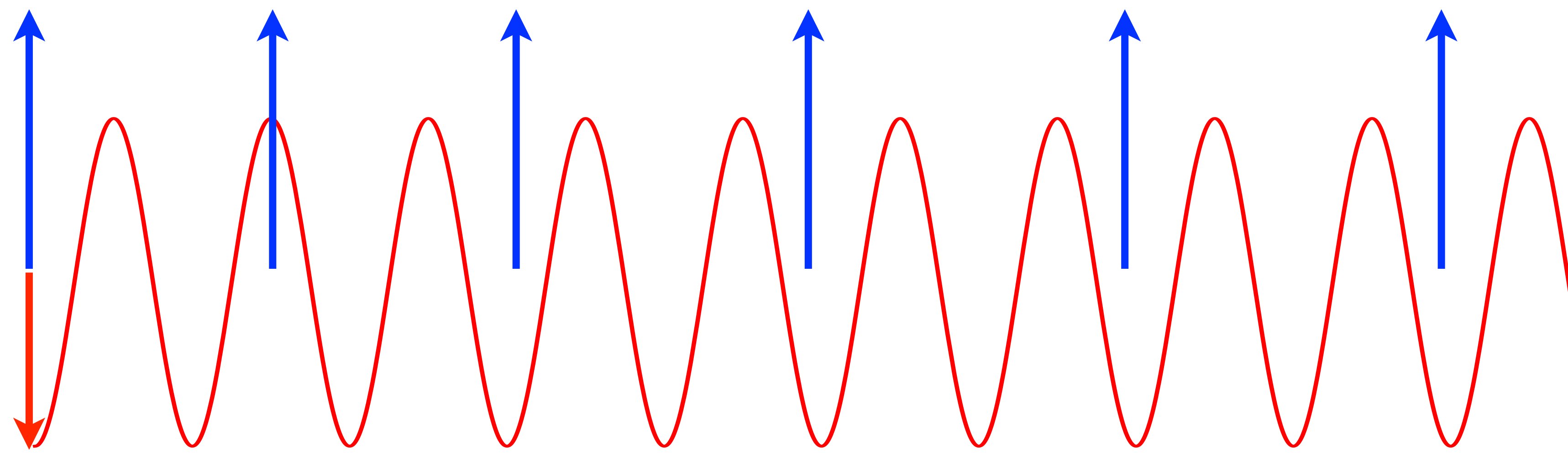




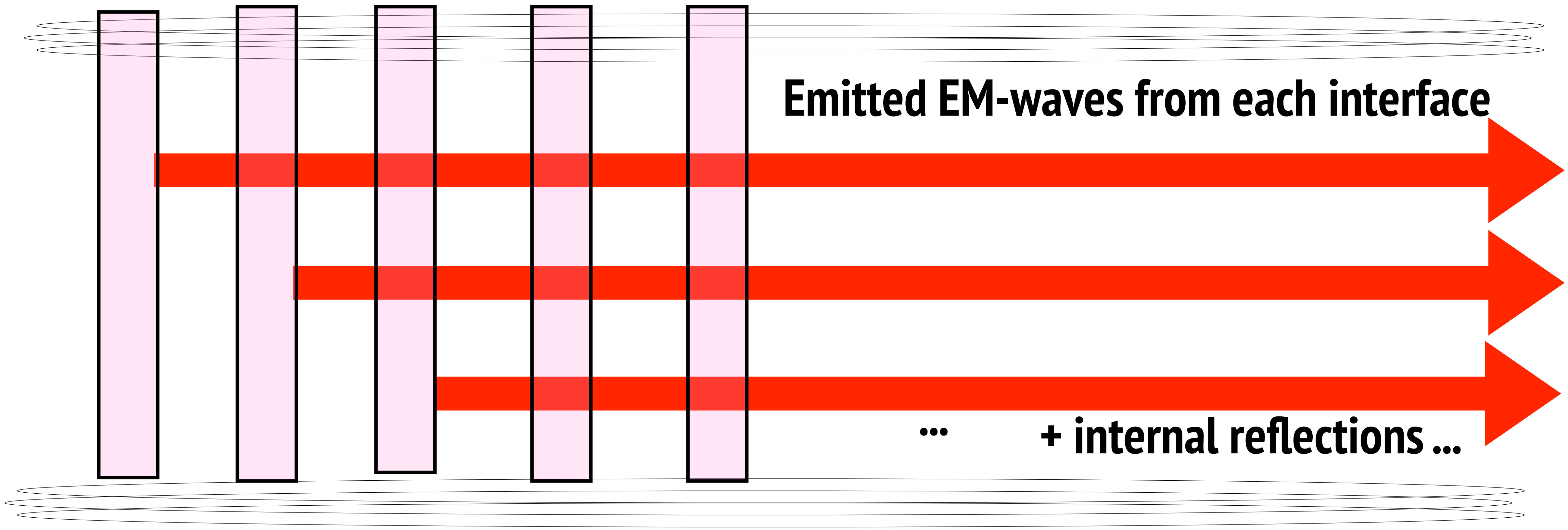
← **Boundary conditions!**

$$\mathbf{E}_{||1} = \mathbf{E}_{||2}$$

Emitted EM-wave

Emitted EM-wave

Many dielectrics : MADMAX at MPP Munich

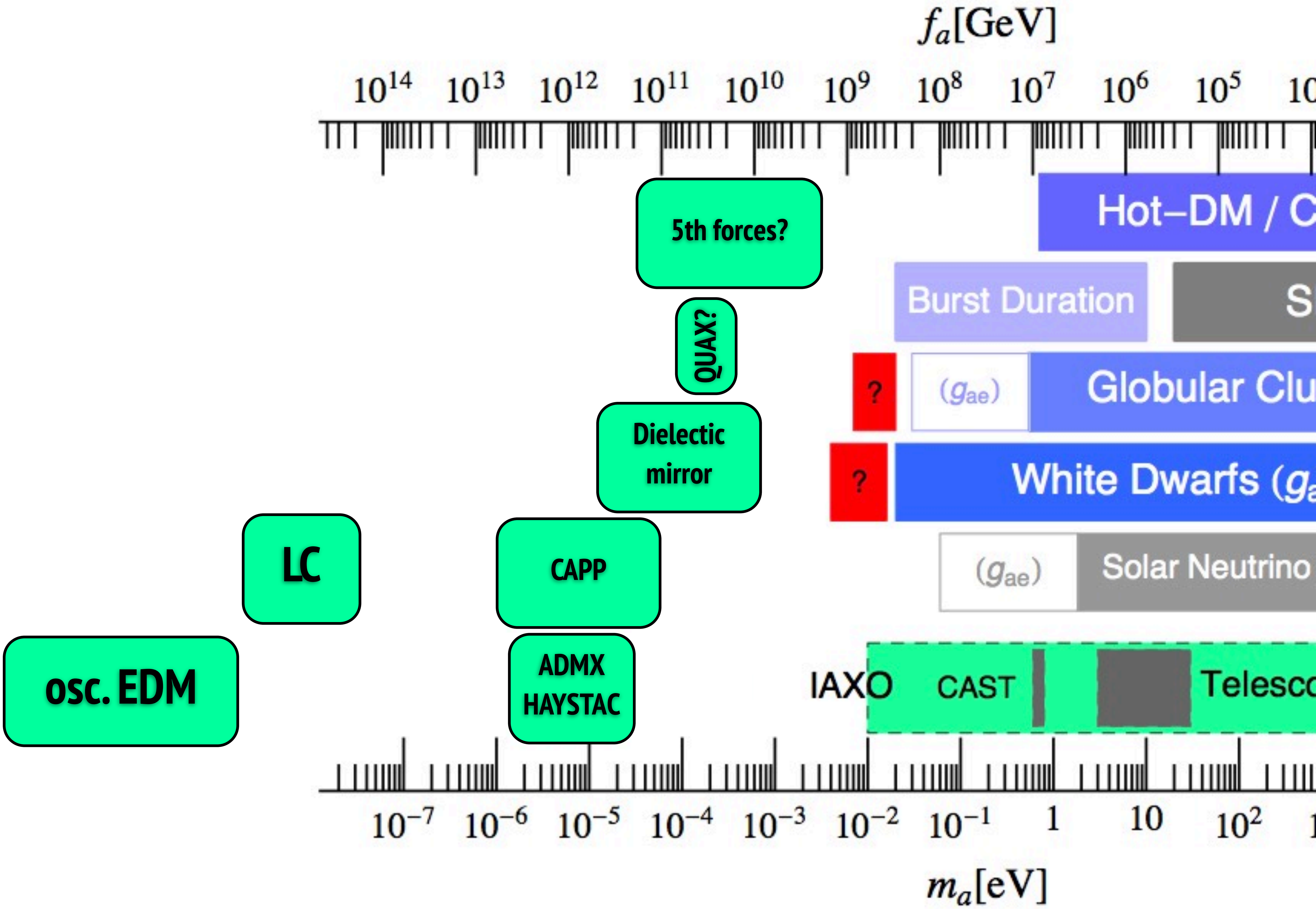


- Emission has large spatial coherence; adjusting plate separation -> coherence

$$\frac{P}{Area} \sim 2 \times 10^{-27} \frac{\mathrm{W}}{\mathrm{m}^2} \left(\frac{c_\gamma}{2} \frac{B_{||}}{5\mathrm{T}} \right)^2 \frac{1}{\epsilon} \boxed{\times \beta(\omega) \quad \text{boost factor}}$$

- Work in progress at Max Planck Institute fur Physik (Conceptual design)

Axion DM : A developing picture



Axion Dark matter experiments (target areas)