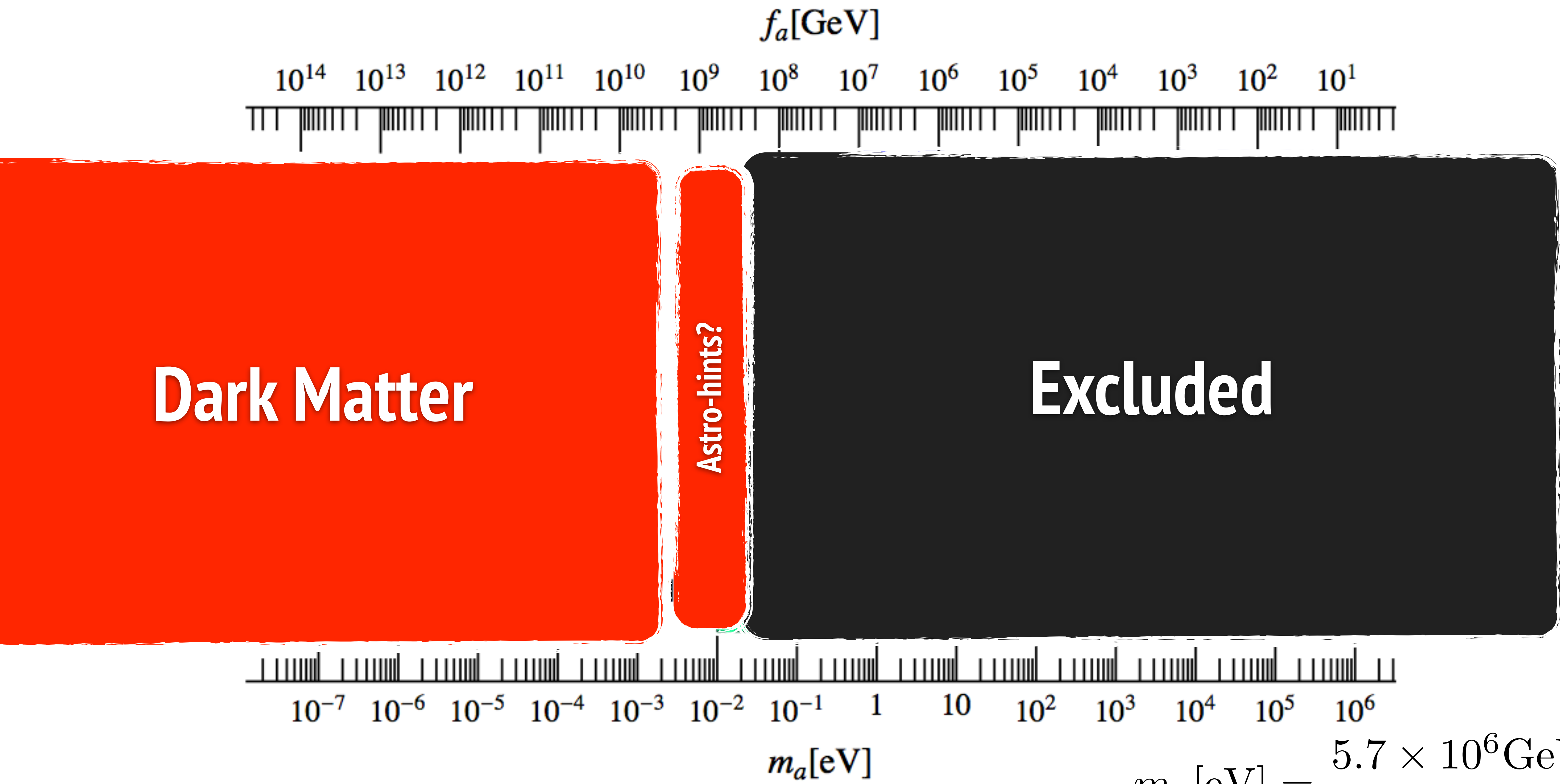
Axion dark matters

Landscape, what do we know?

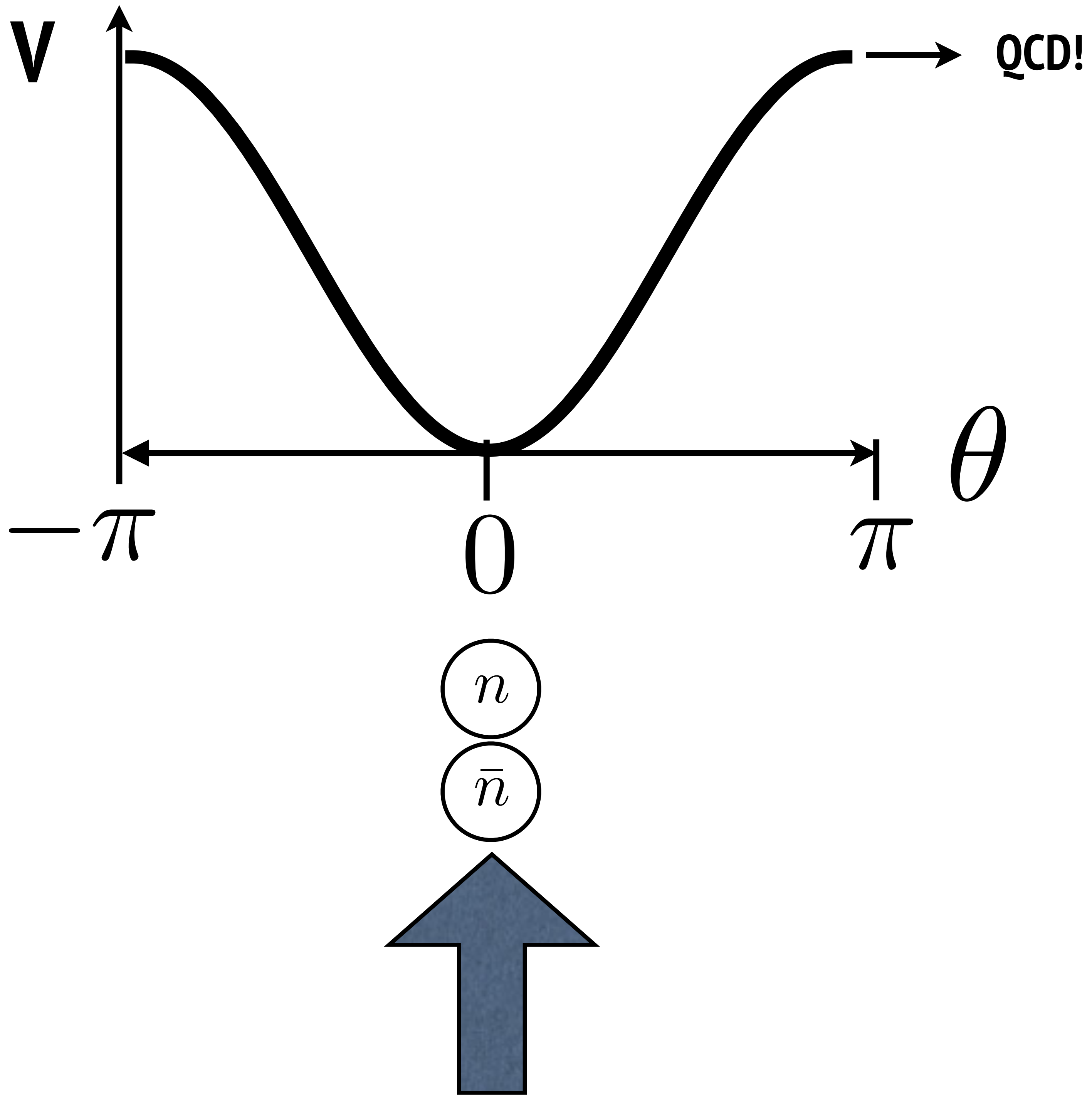


$$m_a[\mathrm{eV}] = \frac{5.7 \times 10^6 \mathrm{GeV}}{f_a}$$

If axions exist, they are very light and VERY weakly interacting!

Axions

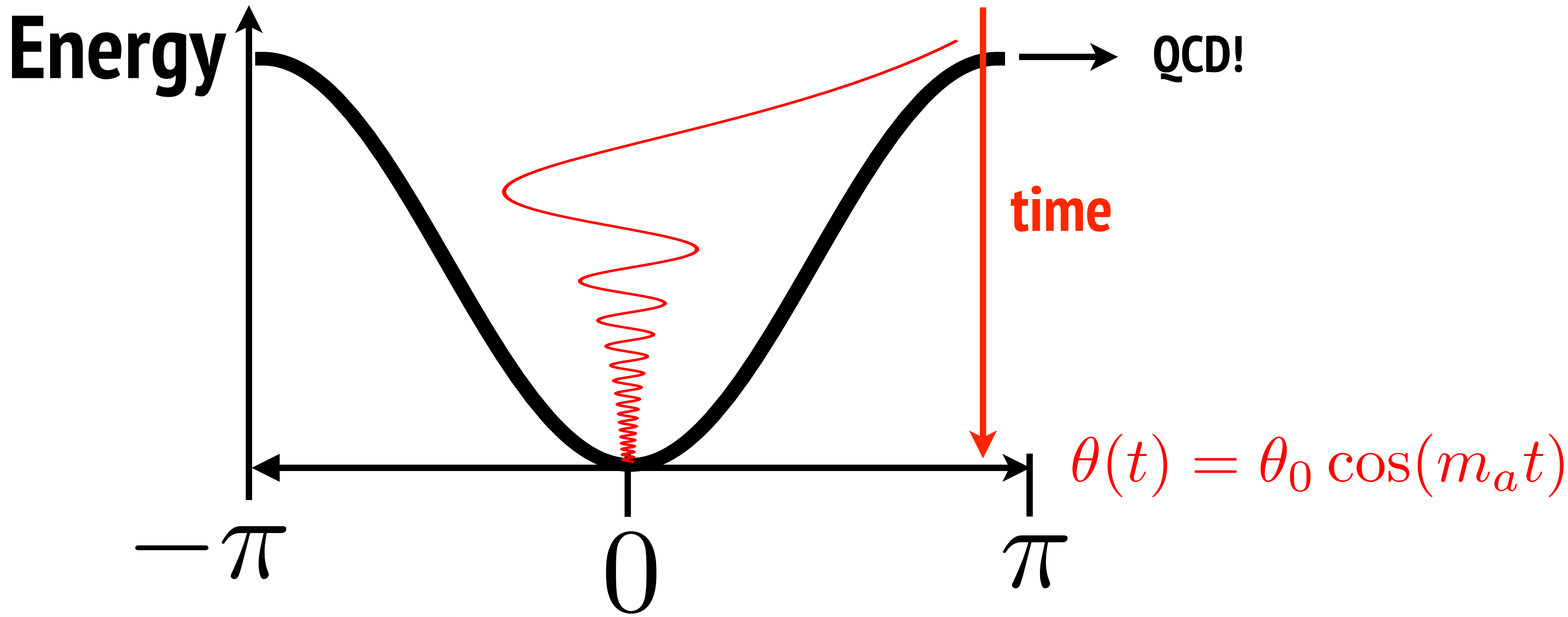
- **theta is dynamical** $\theta(t, \mathbf{x})$

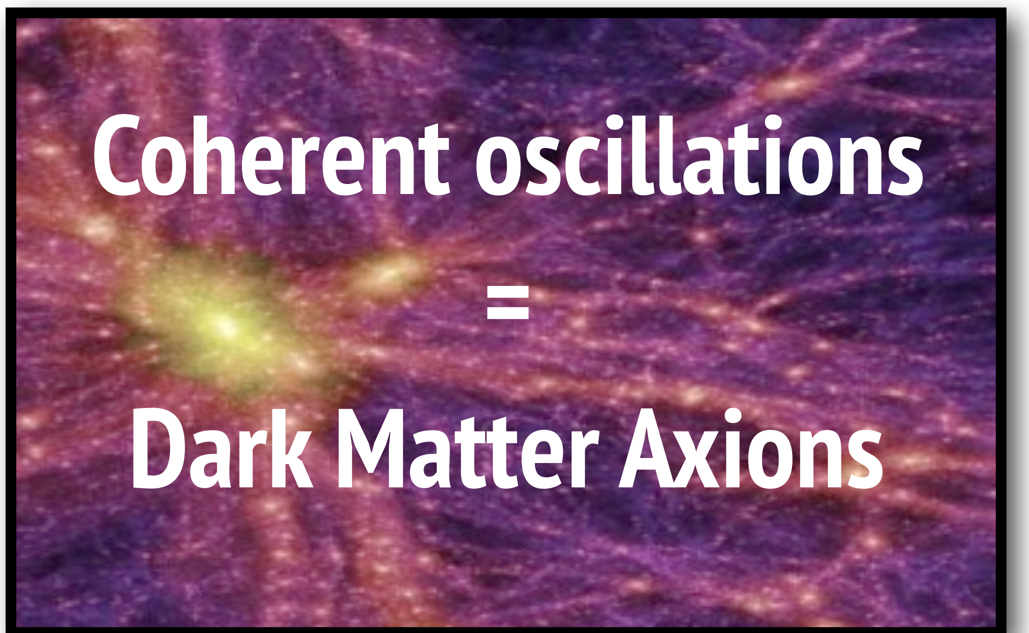


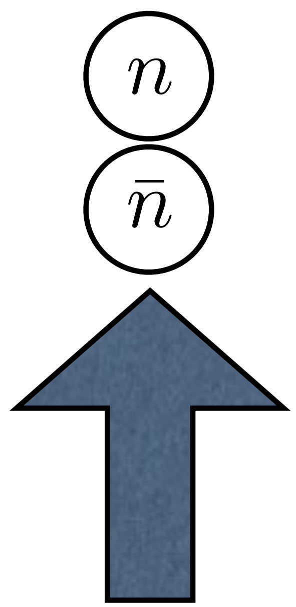
Measured today $|\theta| < 10^{-10}$ **(strong CP problem)**

Axions imply dark matter

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



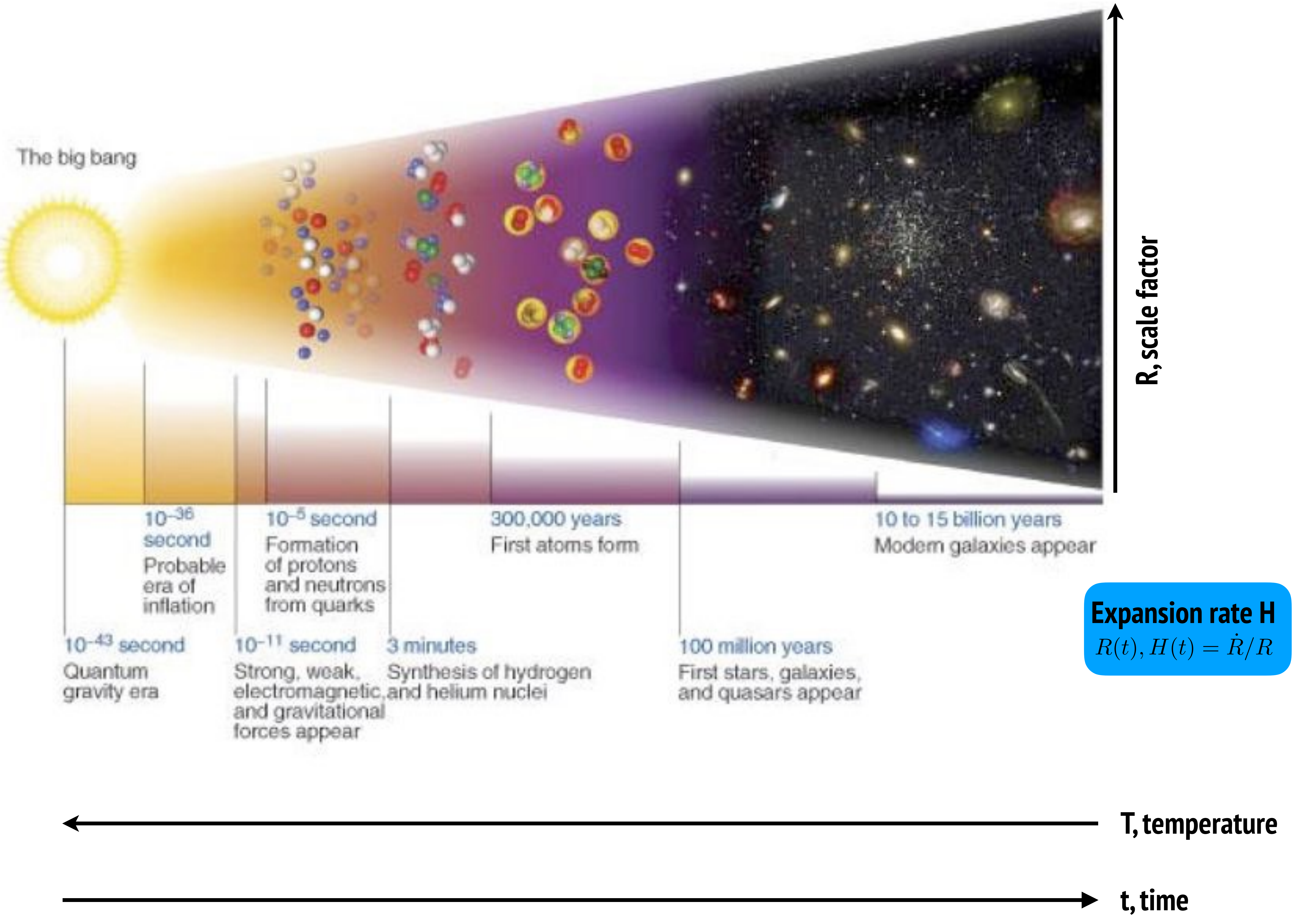




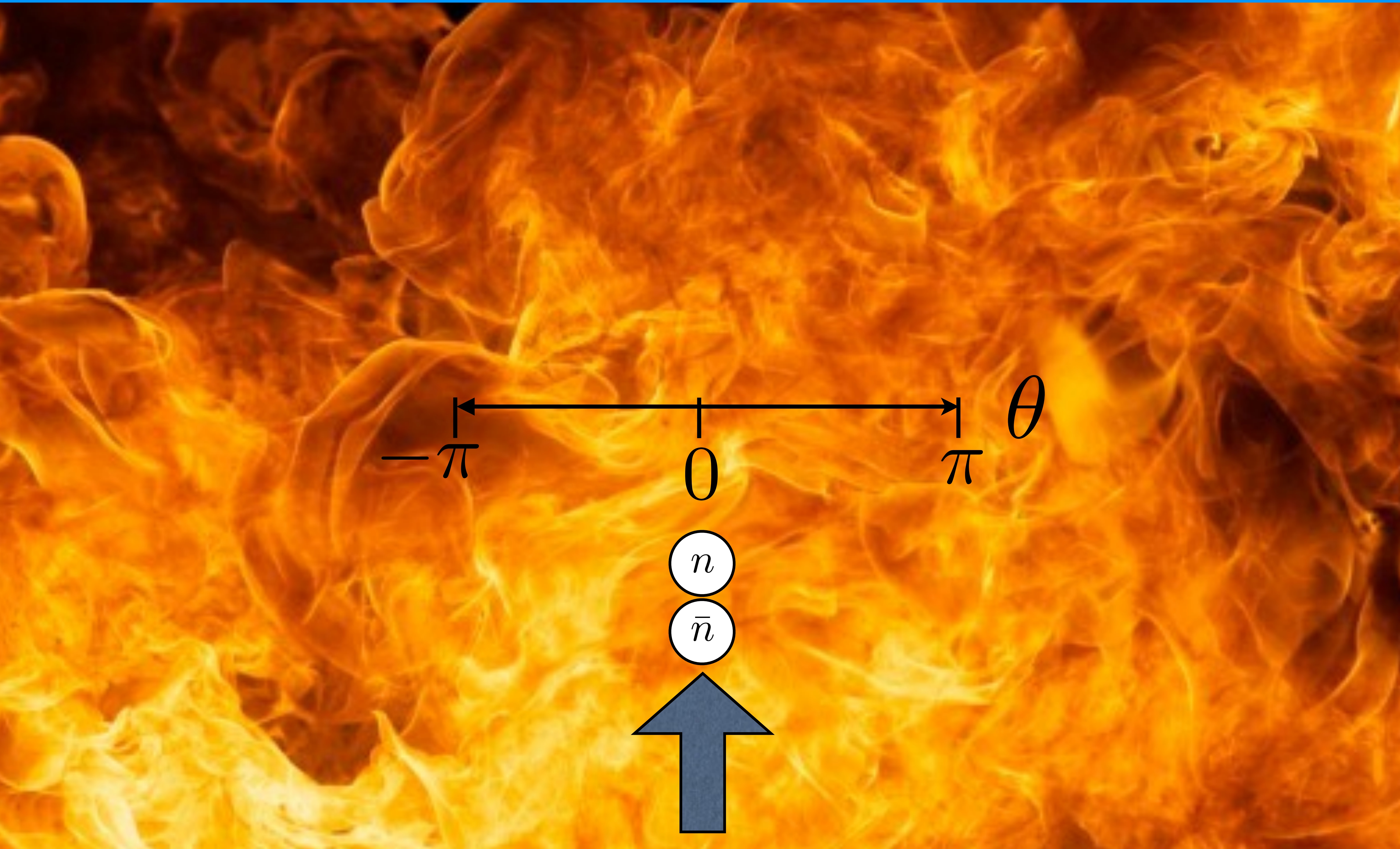
Initial conditions ?

= model-dependency

CP conserving


The big bang
R, scale factor
10^{-43} second
Quantum gravity era
10^{-36} second
Probable era of inflation
10^{-11} second
Strong, weak, electromagnetic, and gravitational forces appear
10^{-5} second
Formation of protons and neutrons from quarks
3 minutes
Synthesis of hydrogen and helium nuclei
300,000 years
First atoms form
100 million years
First stars, galaxies, and quasars appear
10 to 15 billion years
Modern galaxies appear
Expansion rate H
$R(t), H(t) = \dot{R}/R$
T, temperature
t, time

high Temperature ($T \gg \Lambda_{\mathrm{QCD}}$)

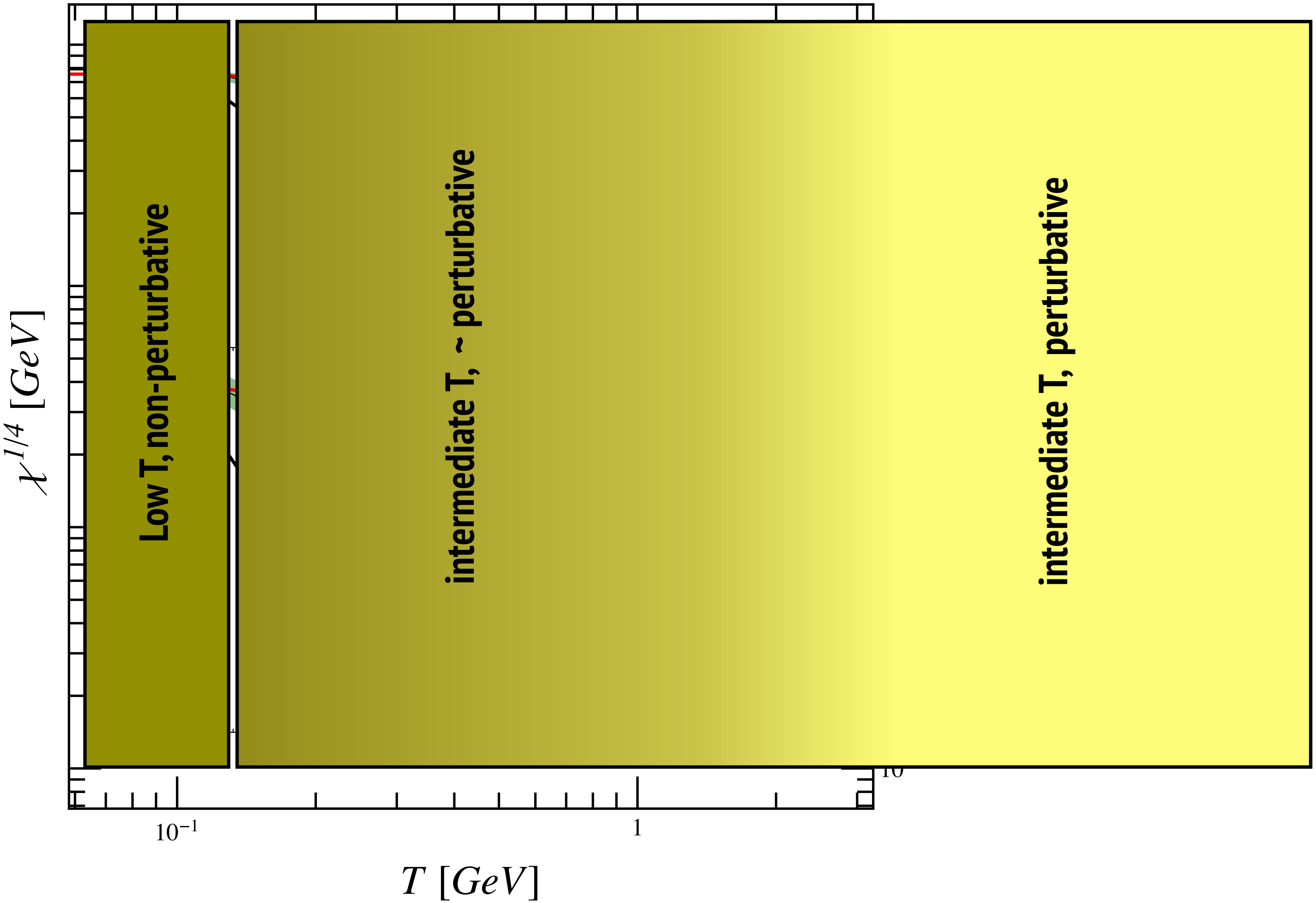


Measured today $|\theta| < 10^{-10}$ **(strong CP problem)**

Effective mass, lattice calculations

Axion mass/potential depend on non-perturbative QCD parameters $\langle \bar{q} q \rangle, \Lambda^4$

T > Tc ~ 160 MeV, running QCD coupling decreases, QCD becomes perturbative
quark condensate quickly disappears, Lambda also decreases



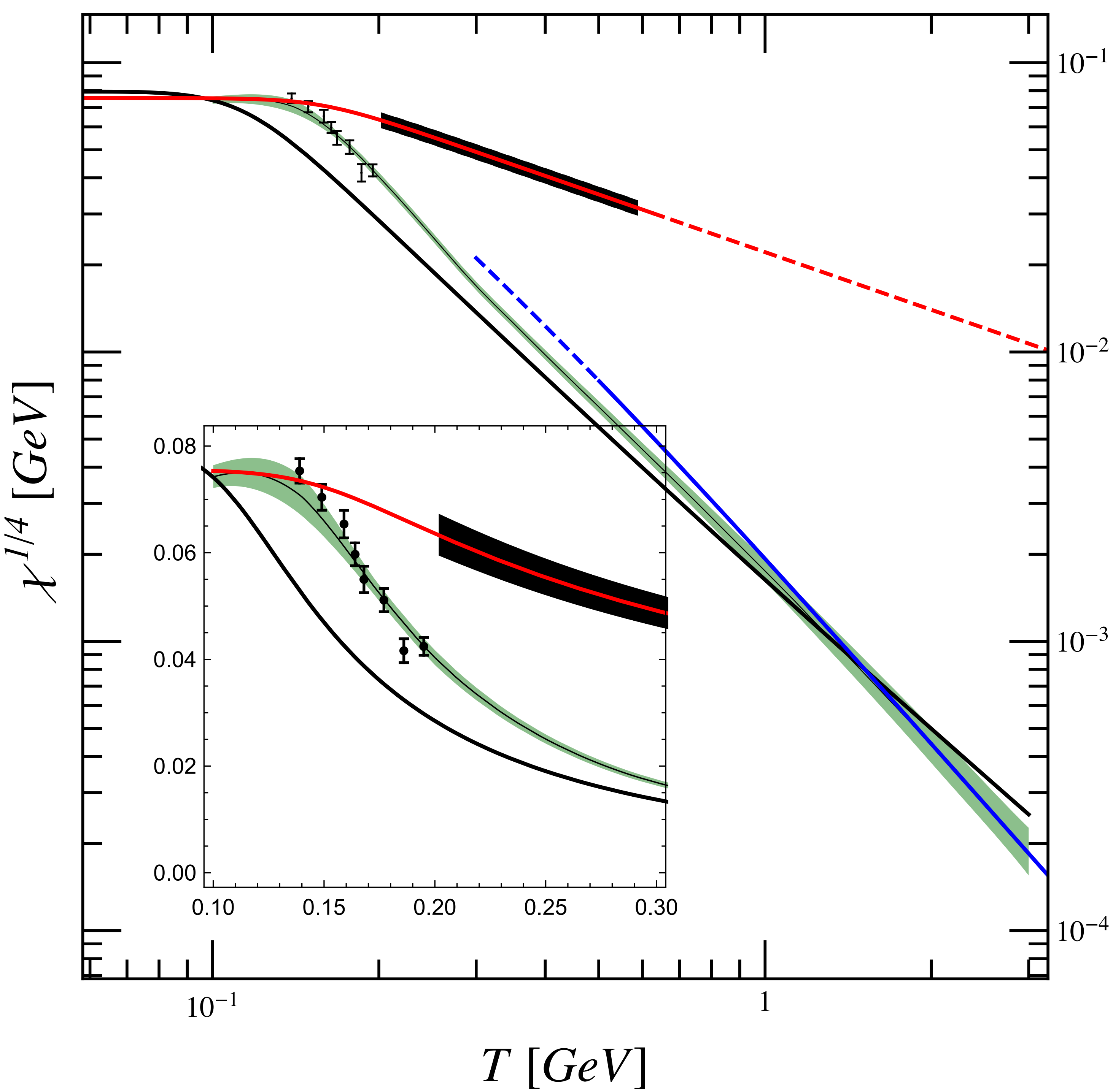
Effective mass, lattice calculations

Lattice QCD: we can compute axion mass

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

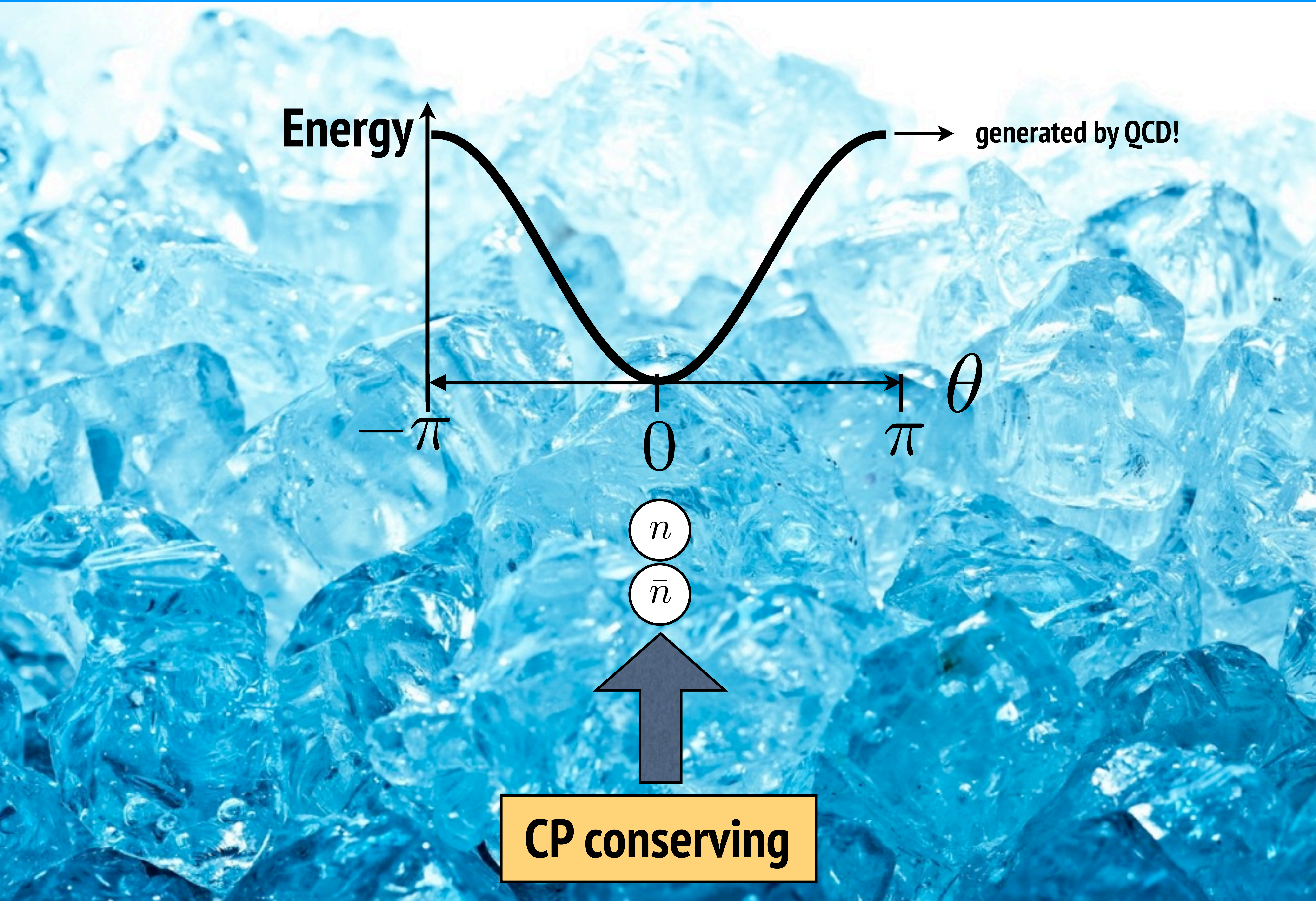
At ultra-high T (no mesons)
we can analytically compute potential (DIGA)

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



Lattice QCD 2+1+1 [Borsanyi]
Lattice QCD 2+1 [Bonati]
Lattice QCD (DWF) 2+1 [Buchoff] (points)
DIGA (T>>Tc) [Borsanyi]
IILM [Wantz]

at low temperatures ...



2 "typical" scenarios for initial conditions

- **Initial conditions are cosmological and axion-model dependent**

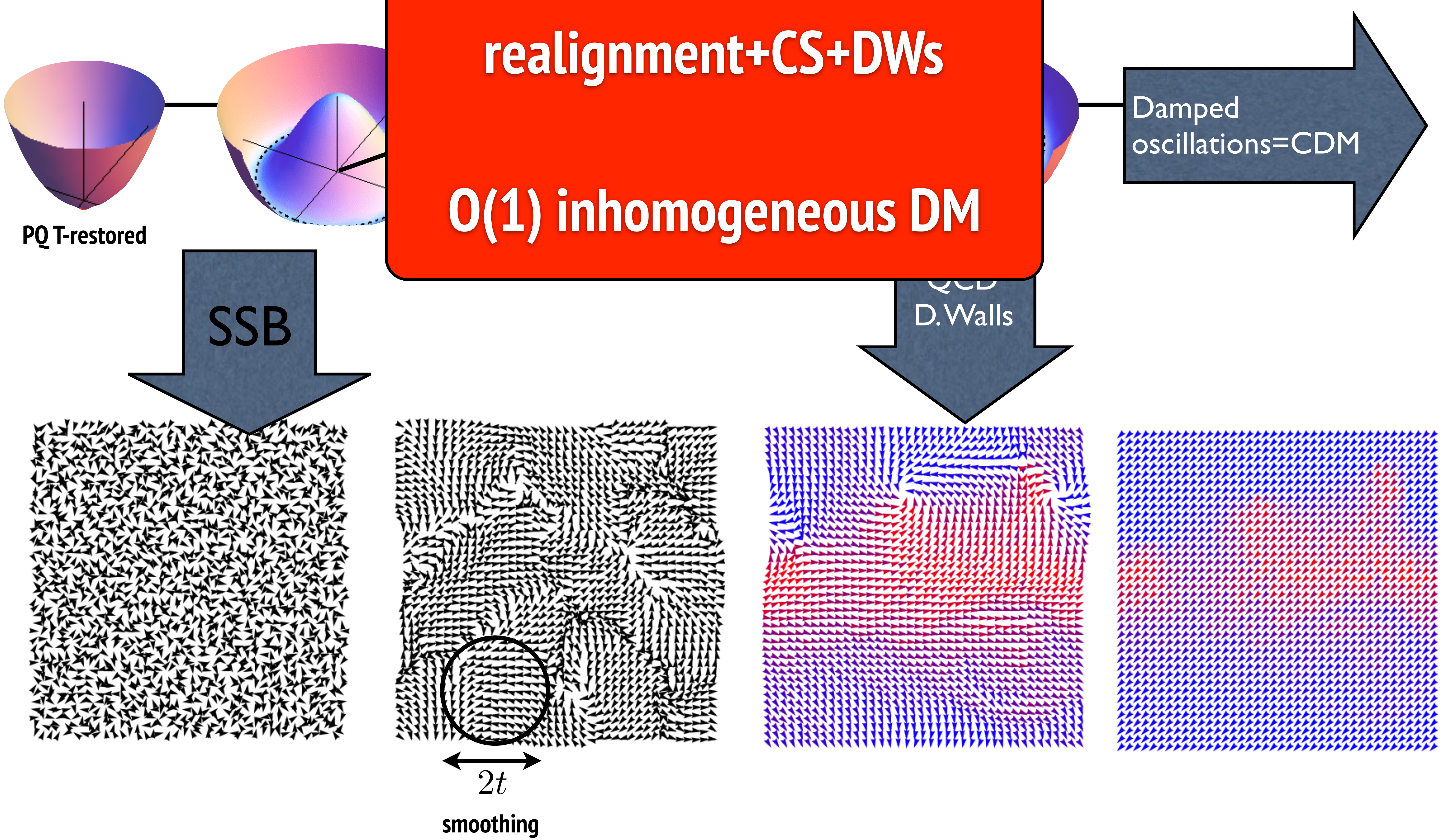
- **Two typical (and extreme) scenarios are:**

- **random initial conditions in patches of our Universe**

- **One common initial condition for the whole Universe**

1st typical scenario: random initial conditions in our Universe

- Example KSVZ



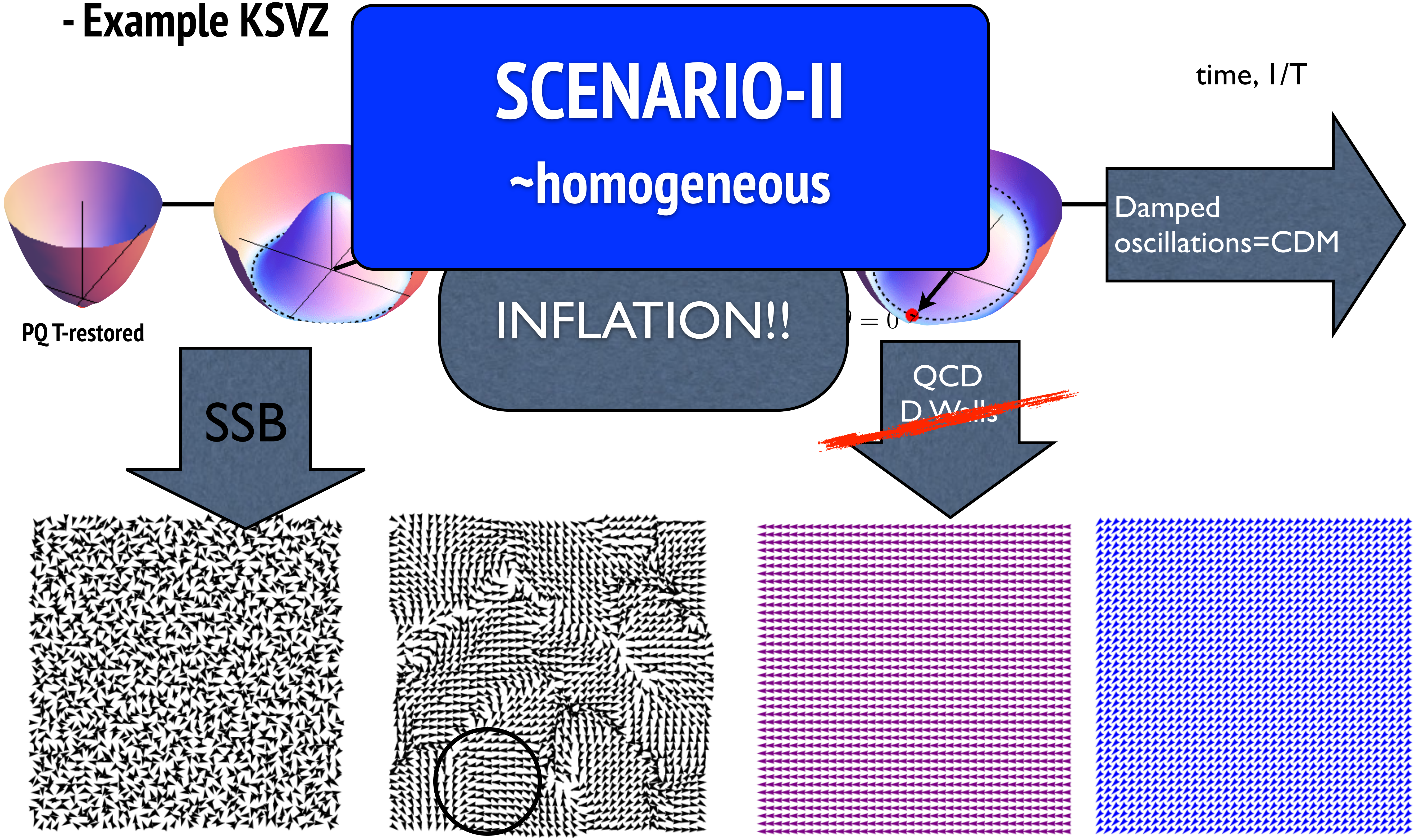
SCENARIO-I

realignment+CS+DWs

O(1) inhomogeneous DM

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

- Example KSVZ

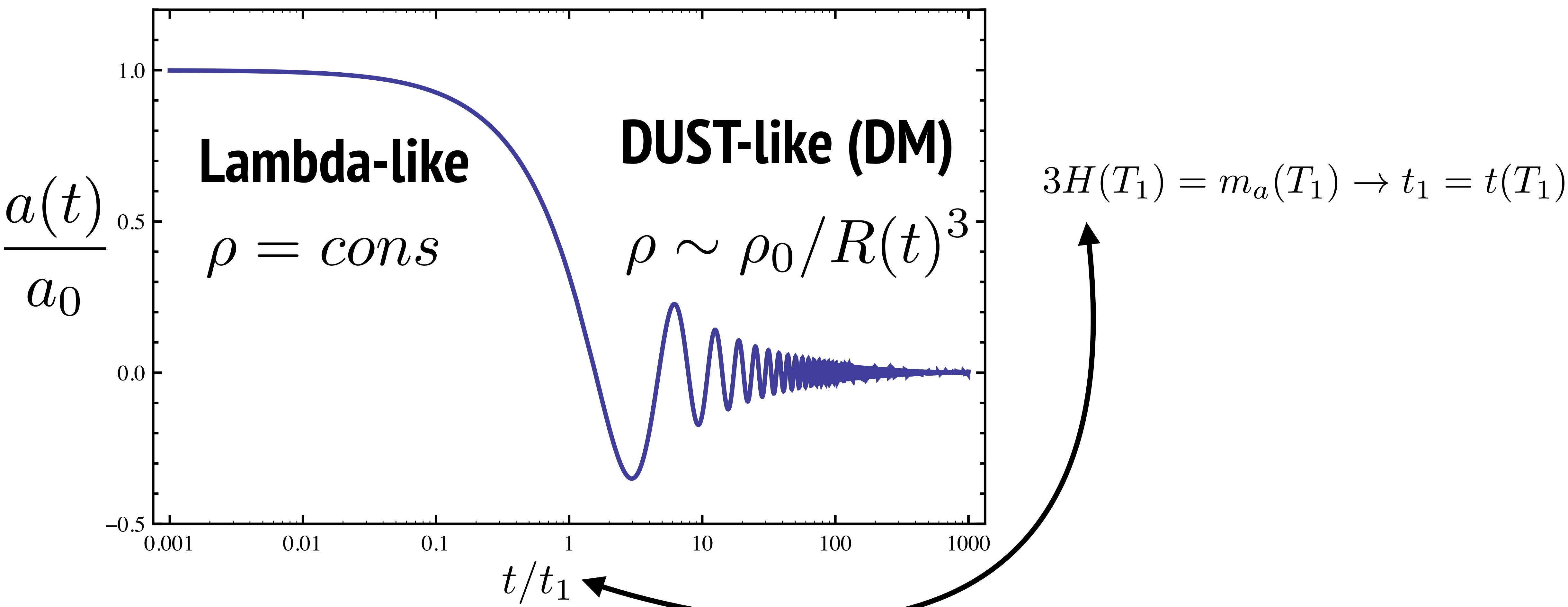


Axion Dark Matter Evolution (scenario 2)

Non-thermal, decoupled = Initial conditions + simple evolution

E.O.M. $$\ddot{a} + 3H\dot{a} + m_a^2 a \simeq 0$$ **(SIMPLIFIED)**

Energy density (harmonic osc) $$\rho = \frac{1}{2}(\dot{a})^2 + \frac{1}{2}(\nabla a)^2 + V(\theta) \sim \frac{1}{2}(\dot{a})^2 + \frac{1}{2}m_a^2 a^2$$

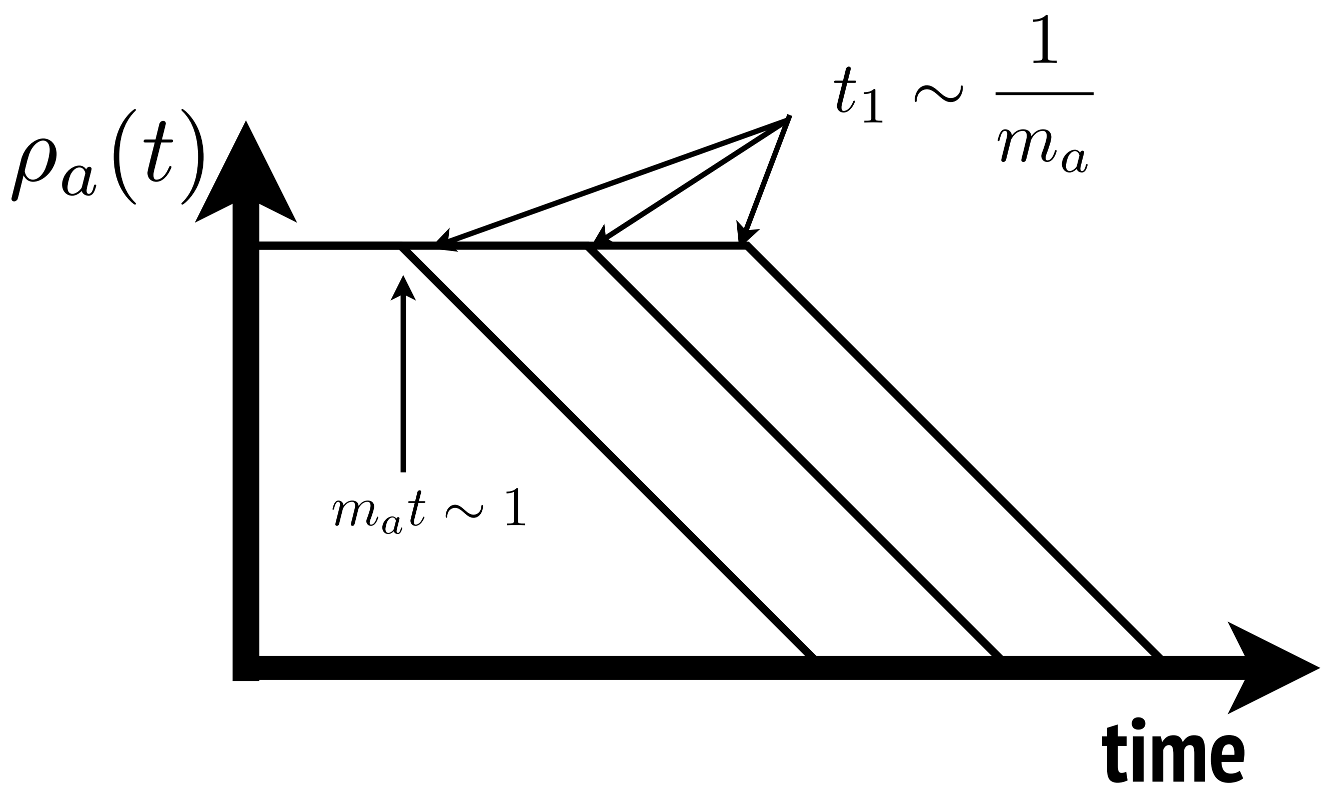


Note: No spatial dependence -> no momentum, no velocity (up to H)= ultracold dark matter

Axion dark matter

- The amount of axion DM produced depends on ma (eq. fa)

$$H = \frac{1}{2t} \to t_1 \sim \frac{1}{m_a(T(t_1))} \propto f_a$$



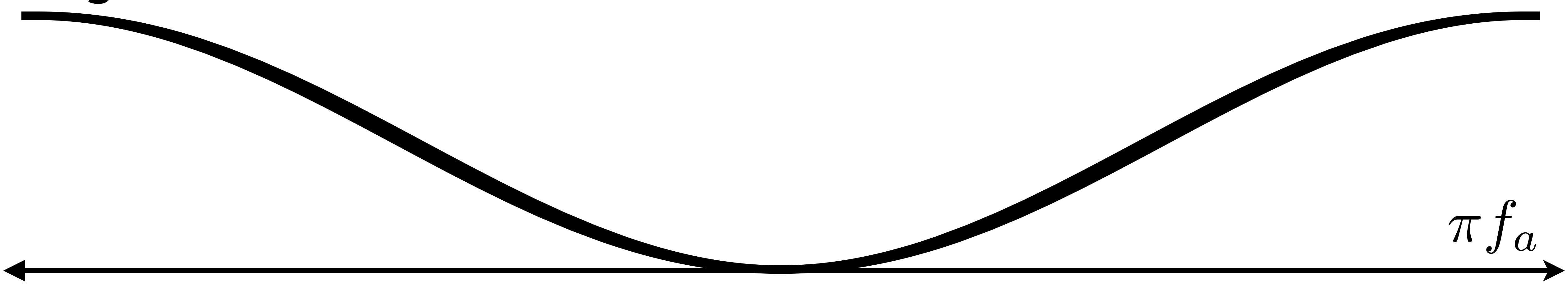
- Axion starts to oscillate later, ~ initial energy -> more DM

Axion dark matter

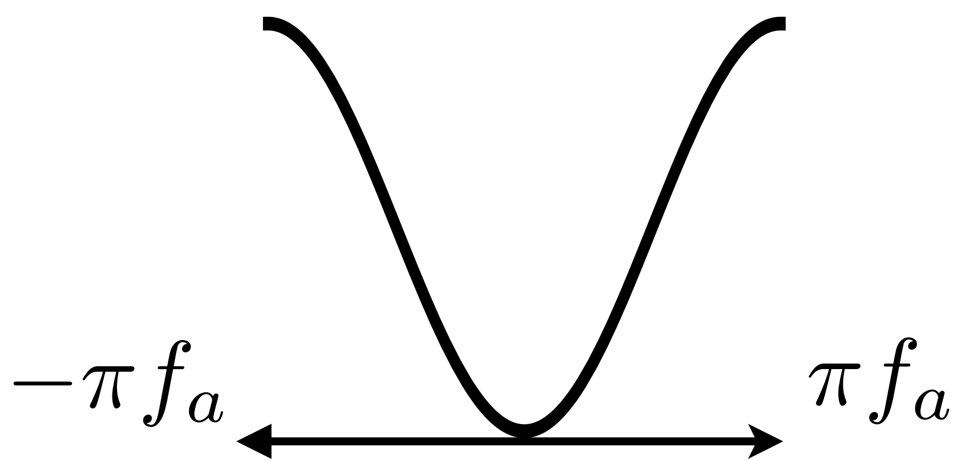
- The amount of axion DM produced depends on fa

$$H = \frac{1}{2t} \to t_1 \sim \frac{1}{m_a(T(t_1))} \propto f_a$$

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



- small fa, large curvature, oscillations start earlier -> less DM



Accounting for the axion mass rapid increase

At late times ... $m_a \gg H$ **(m increases, H decreases ... e.g. in radiation epoch** $H \simeq 1/2t$ **)**

$$\ddot{a} + 3H\dot{a} + m_a^2(t)a \simeq 0$$

can be solved perturbatively in the adiabatic limit $H/m_a \ll 1$ **(weak damping)**

$$\ddot{a} + m_a^2 \simeq 0 \to a = Ae^{i\int^t m_a dt'} + O(\dot{m}_a/m_a \sim H/m_a) + h.c.$$

$$a = A(t)e^{i\int^t m_a dt'} + h.c.$$

O(m^2) $-m_a^2 a + ... + m_a^2 a = 0$

O(m) $2im_a\dot{A} + i\dot{m}_a A + 3\frac{\dot{R}}{R}im_a A + ... = 0$

O(1) ...

$$\frac{d}{dt}\left(m_a A^2 R^3\right) = \frac{d}{dt}\left(\frac{\rho_a}{m_a}R^3\right) = 0$$

adiabatic invariant!

number of axions in a "comoving volume" $V_c = V * R^3$

Prob: Relic abundance calculation

DM density $(m_a \gg 3H)$

$$\rho_a \sim \frac{\rho_1}{m_a(t_1)} m_a(t) \left(\frac{R_1}{R(t)}\right)^3$$

initial number density, mass, dilution due to Universe expansion

$$\rho_1 \sim \frac{1}{2} m_a^2(t_1) f_a^2 \theta_1^2$$

$$H^2 = \frac{8\pi}{M_p^2} \frac{\pi^2}{30} g_* T^4$$

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

$$3H(T_1) = m_a(T_1) \to t_1 = t(T_1) \quad \to T_1$$

Entropy conservation from T1 until now

$$g_S(T)(RT)^3 = cons$$

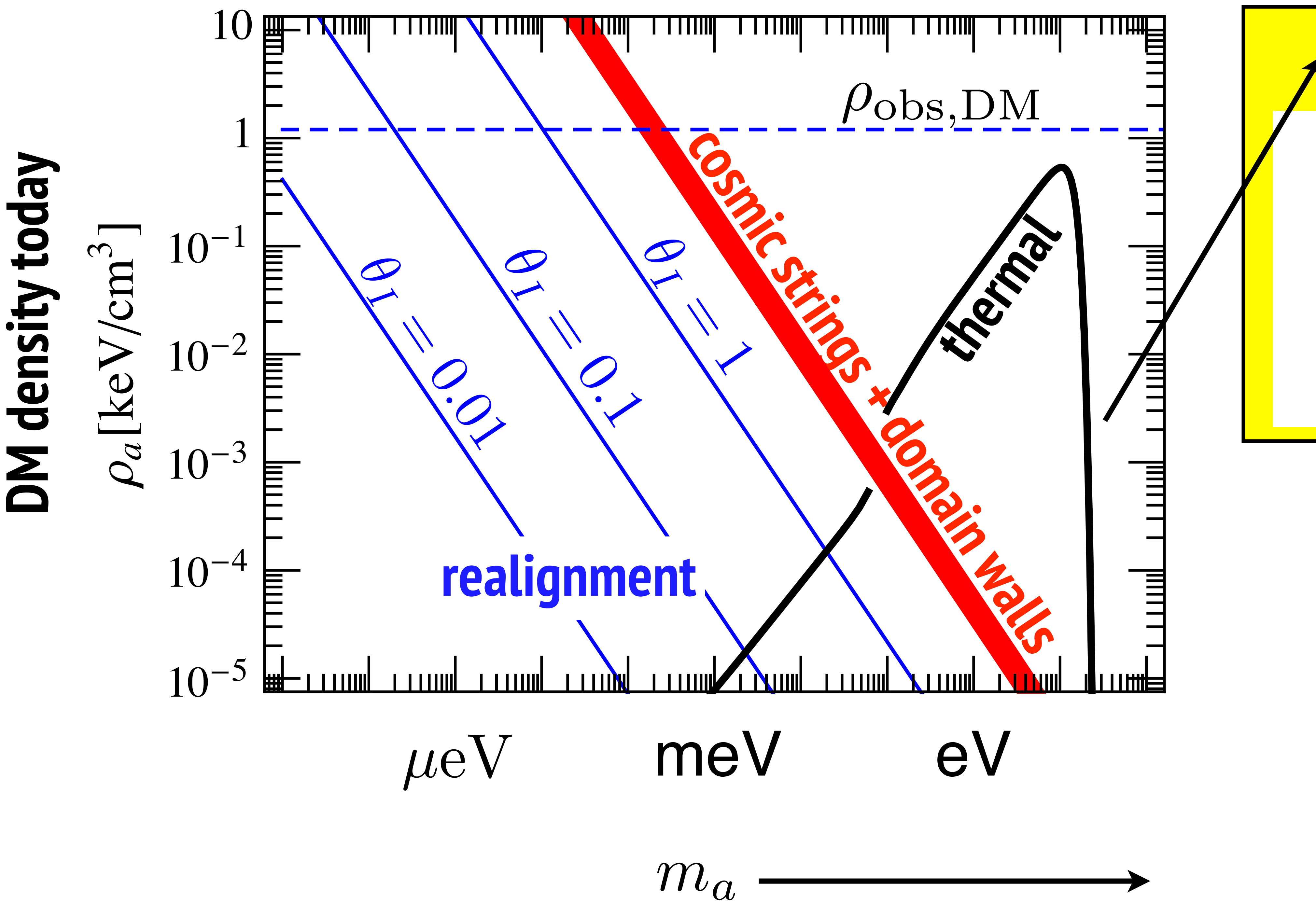
$$g_S(T_1)(R_1 T_1)^3 = g_S(T_0)(R_0 T_0)^3$$

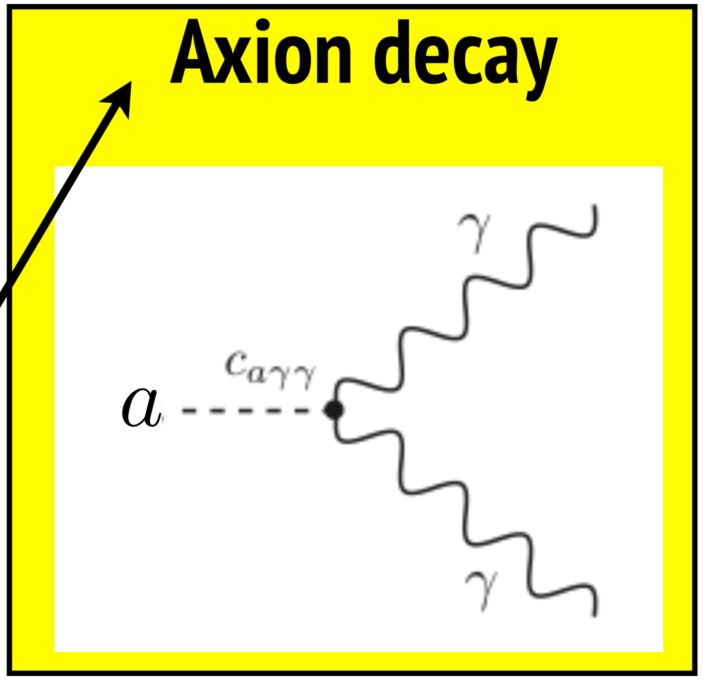
Compute $\rho_a(\text{today}), \Omega_{\text{DM}} h^2 = \dfrac{\rho_a(\text{today})}{\rho_c}$

As a function of θ_1, f_a **and** θ_1, m_a

$$M_p = 1.22 \times 10^{19} \text{GeV}$$

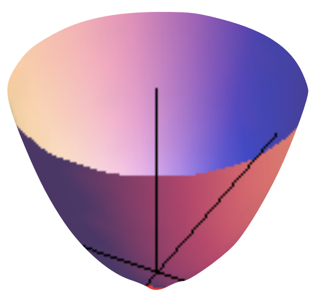
Axion DM, how much

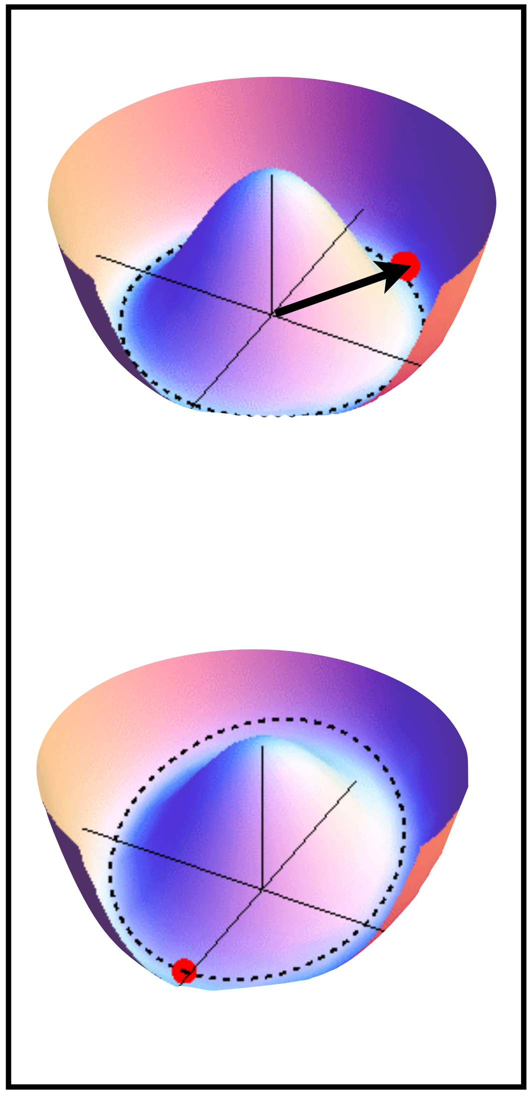


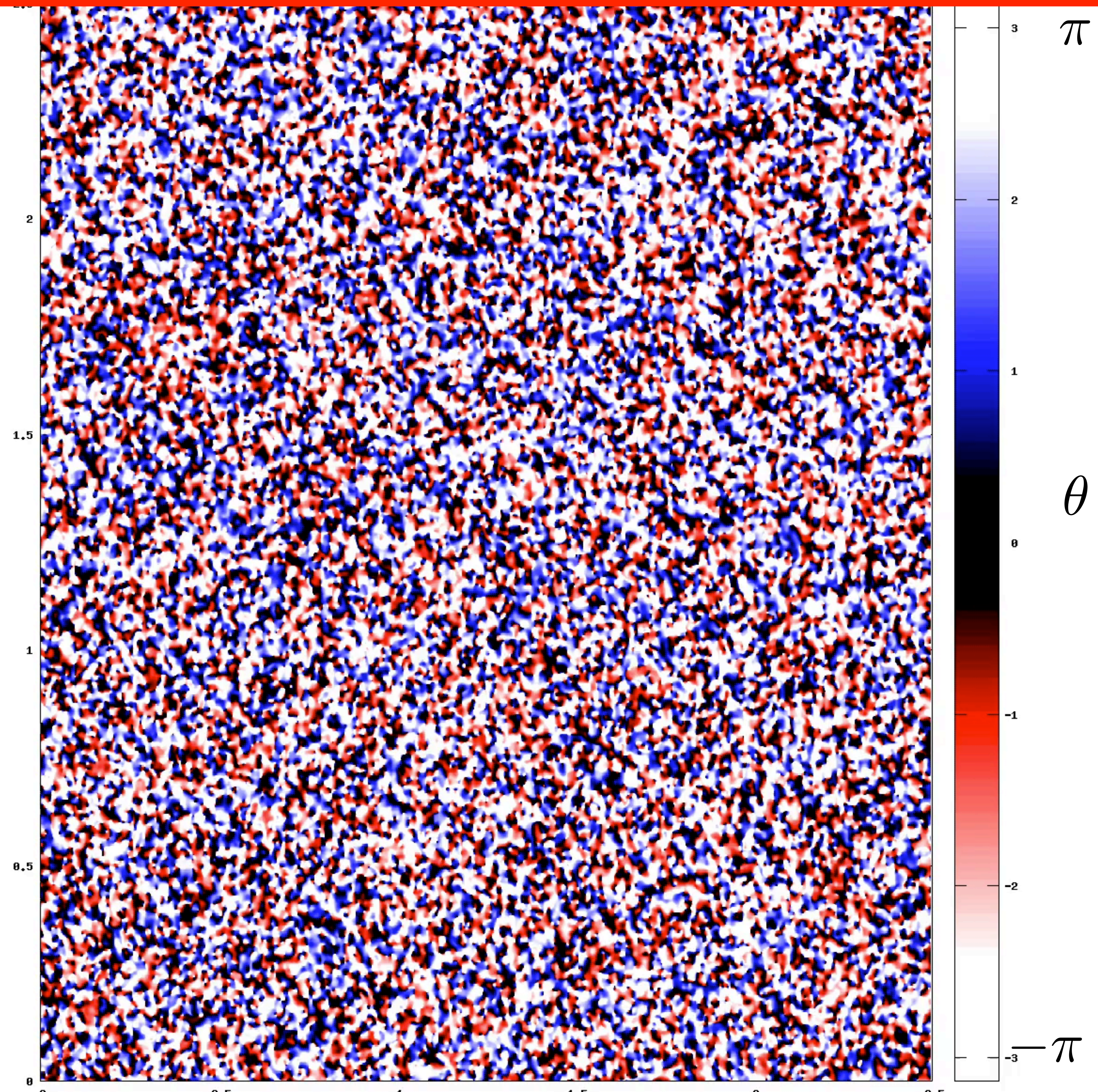


less interacting **more interacting**

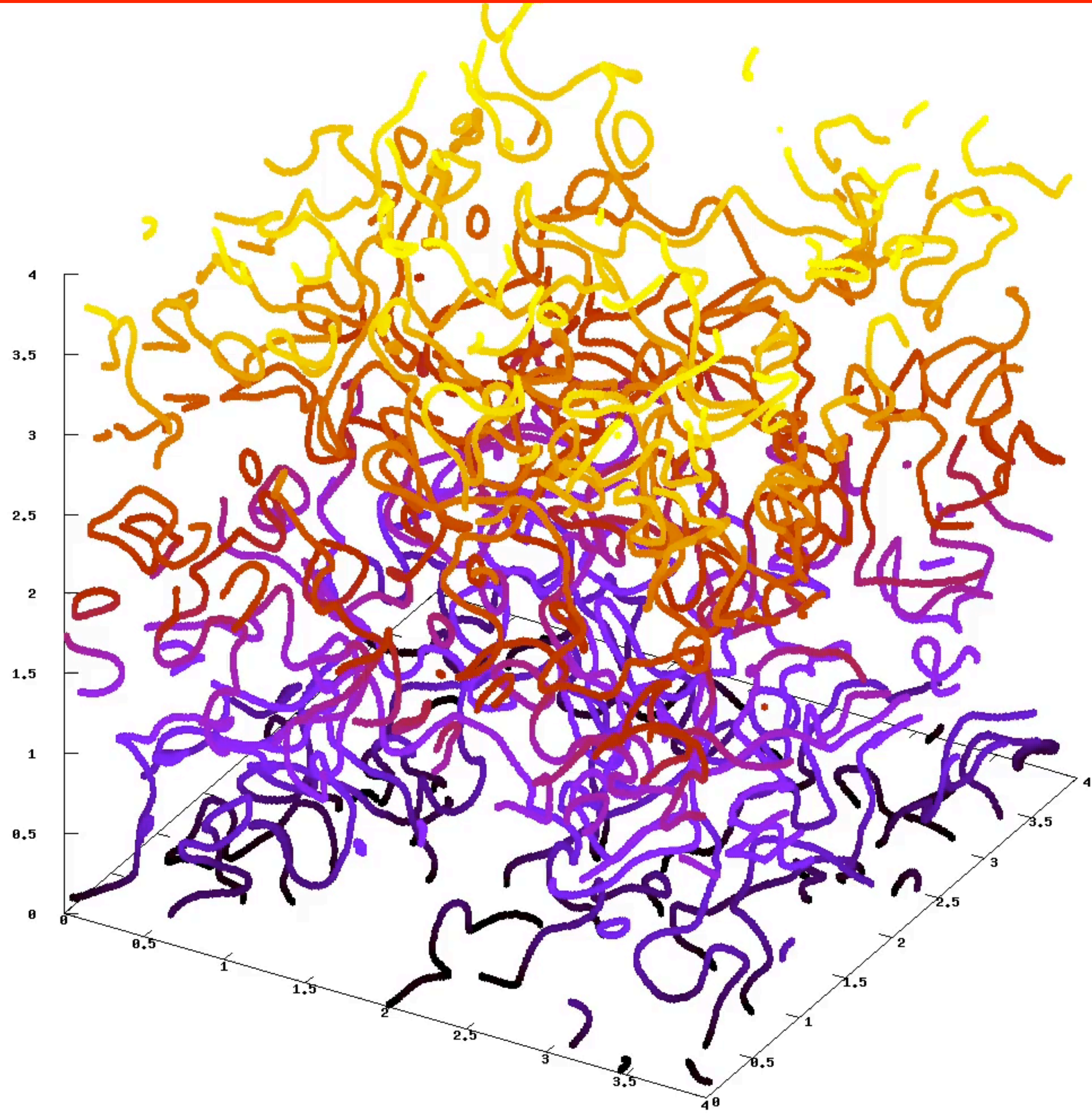
SCENARIO I (N=1): axion evolution around t1







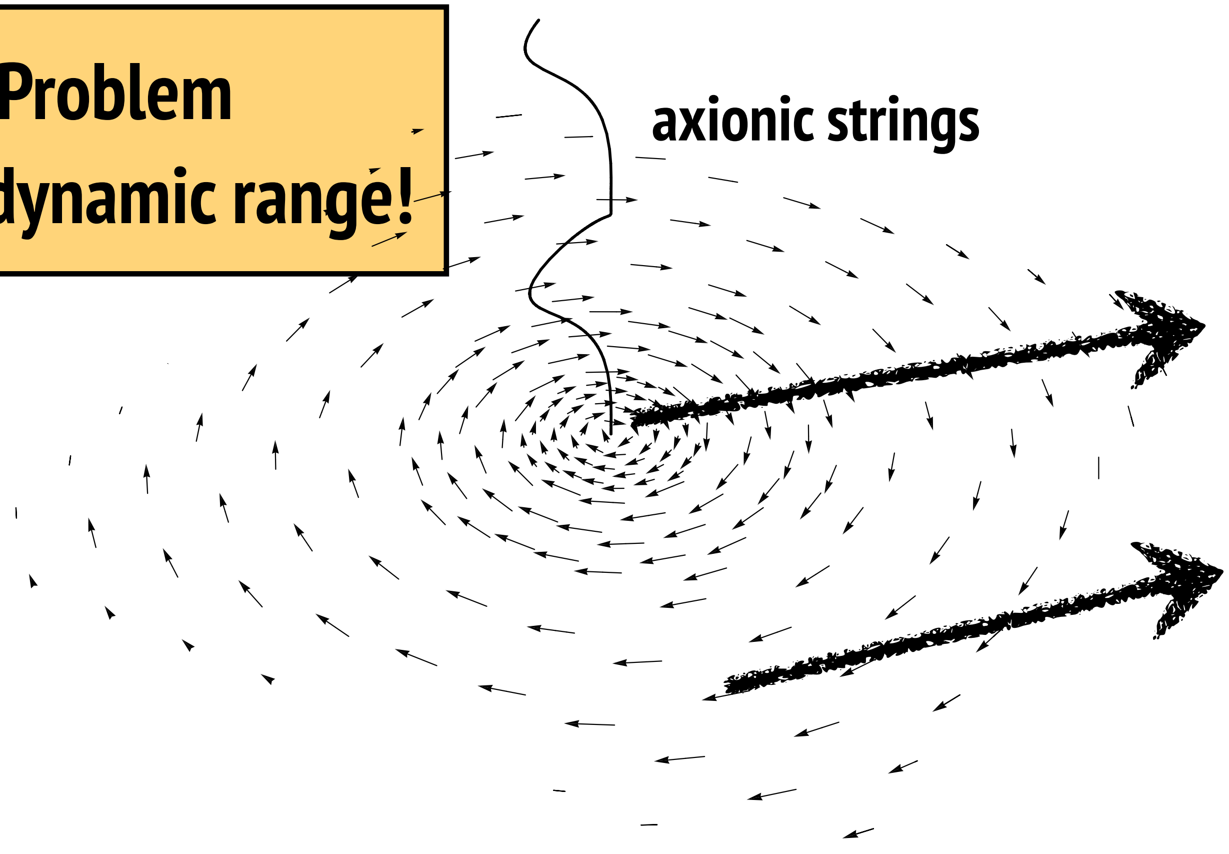
Strings



Prob: Relic abundance calculation

DM density can be obtained from numerical simulations

Problem
Huge dynamic range!



small scale dynamics $\left(l \sim \frac{1}{f_a}\right)$

large scale dynamics $\left(l \sim t \sim \frac{1}{m_a}\right)$

We usually split it into two pieces:

- averaged misalignment $$\langle \rho_a \rangle_{\theta_1} = \int \frac{d\theta_1}{2\pi} \rho_a(\theta_1)$$

- axions radiated from topological defects (extrapolated from simulations) [work in progress]

Length scales

- **Time scale**

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

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

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

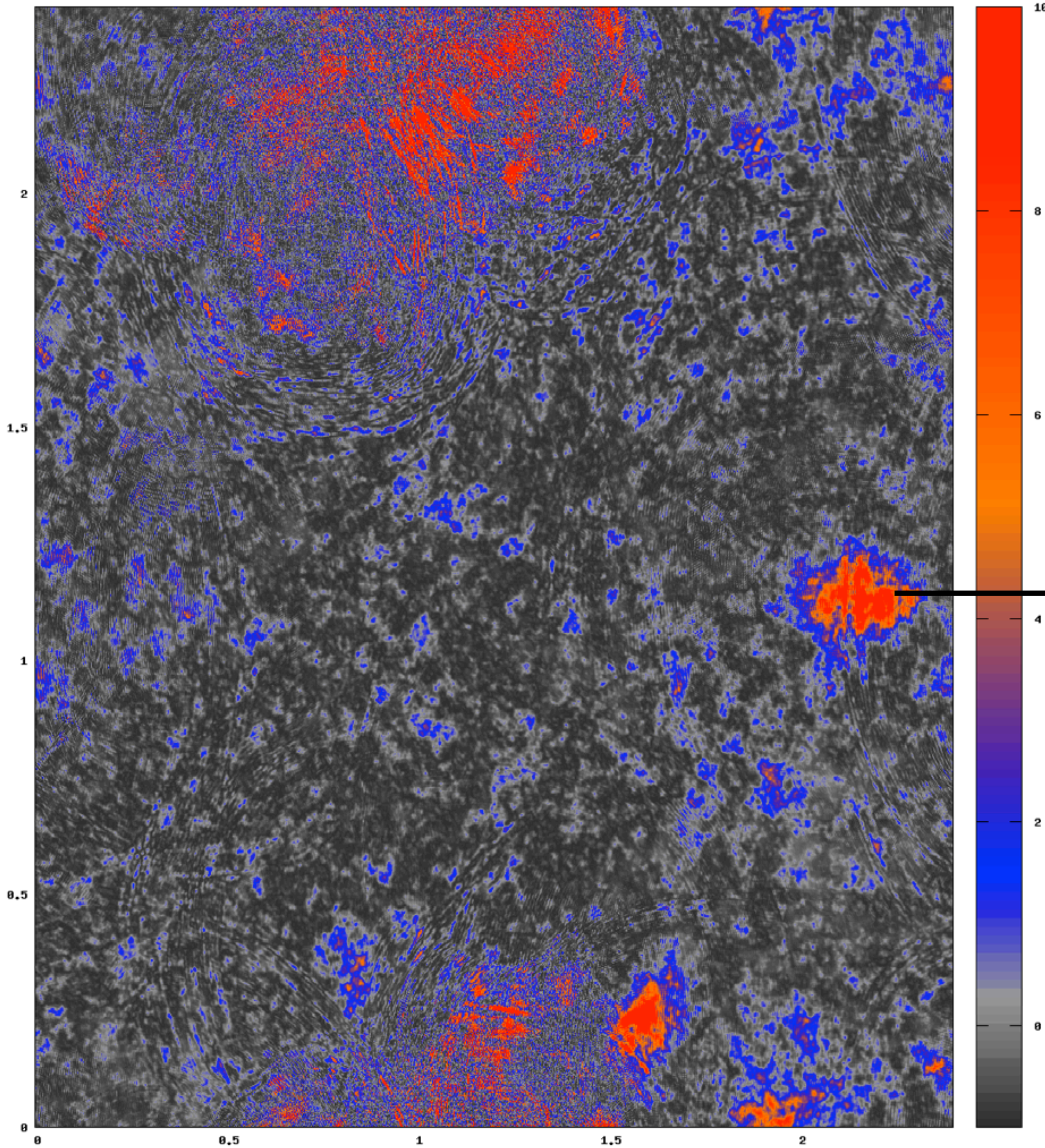
- **Full Axion DM in this model** $f_a \sim 10^{11}\mathrm{GeV}$

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

- **Horizon scale at t1**

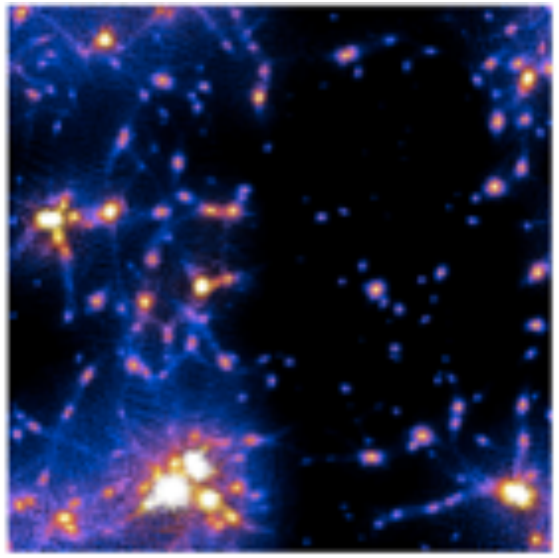
$$L \sim 100\,\mathrm{AU}$$ **(comoving)**

Dark matter density, inhomogeneous at comoving mpc scales



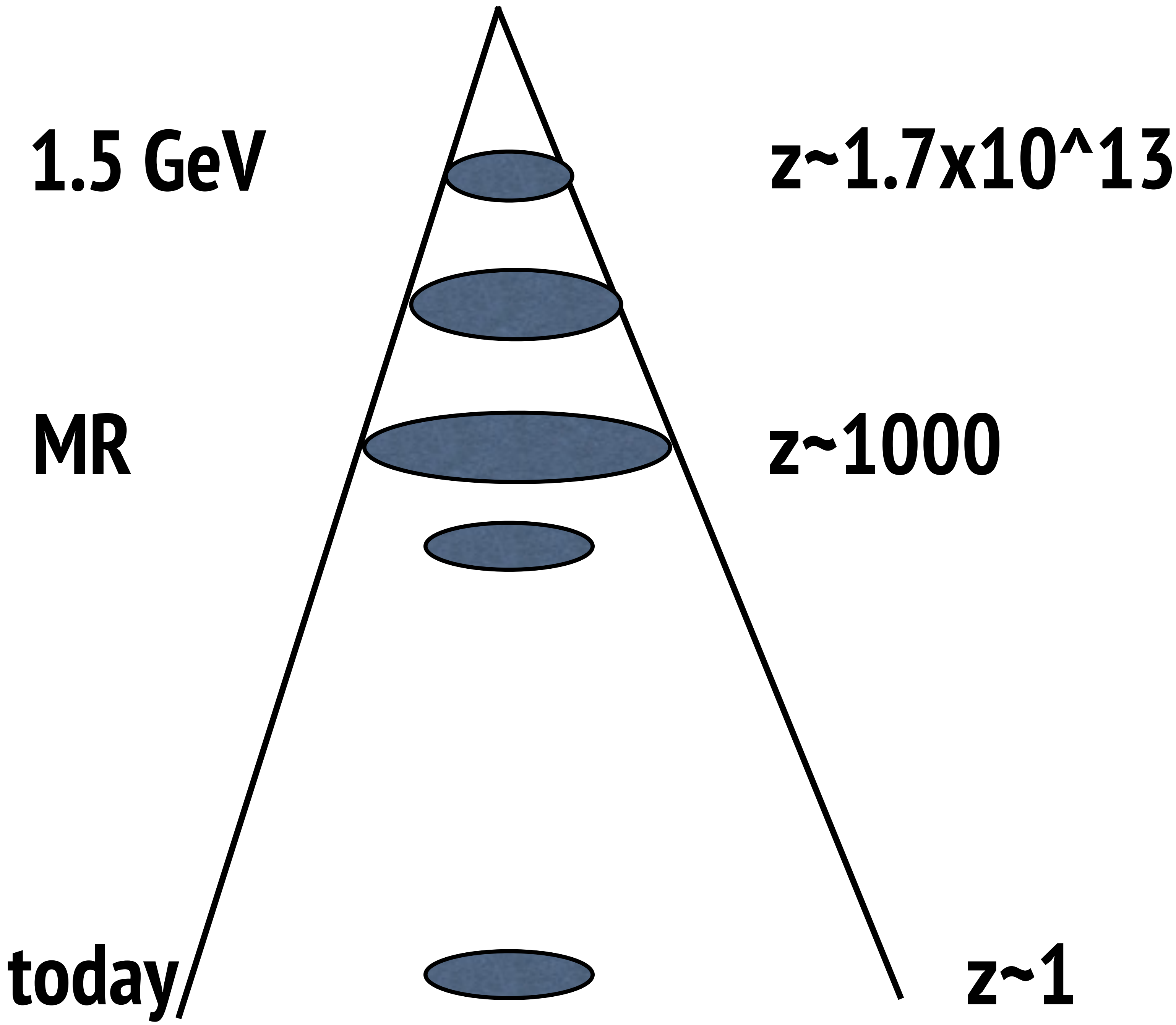
final overdensity $\frac{\rho - <\rho>}{<\rho>}$

minicluster seed!



do mc's survive?

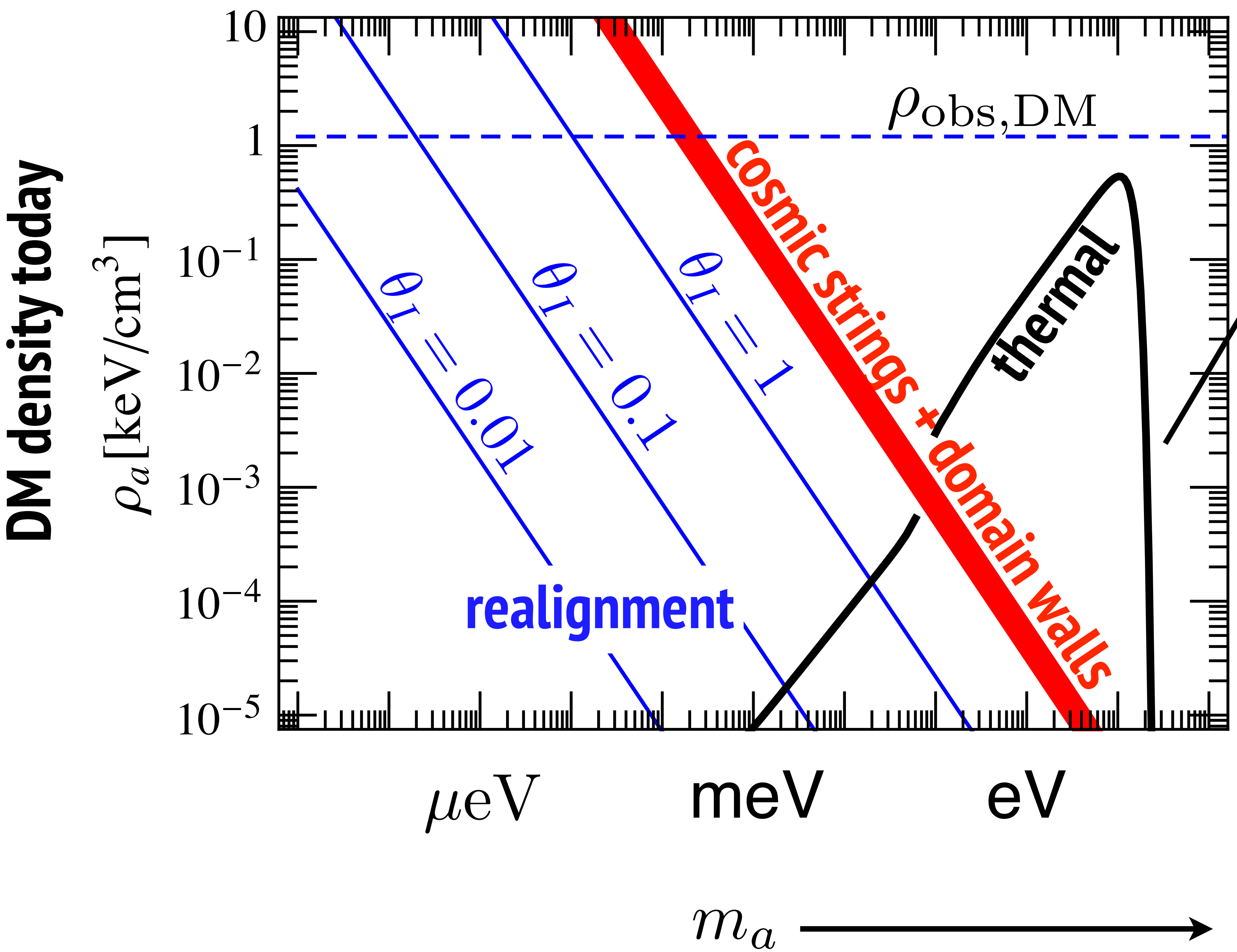
Minicluster size

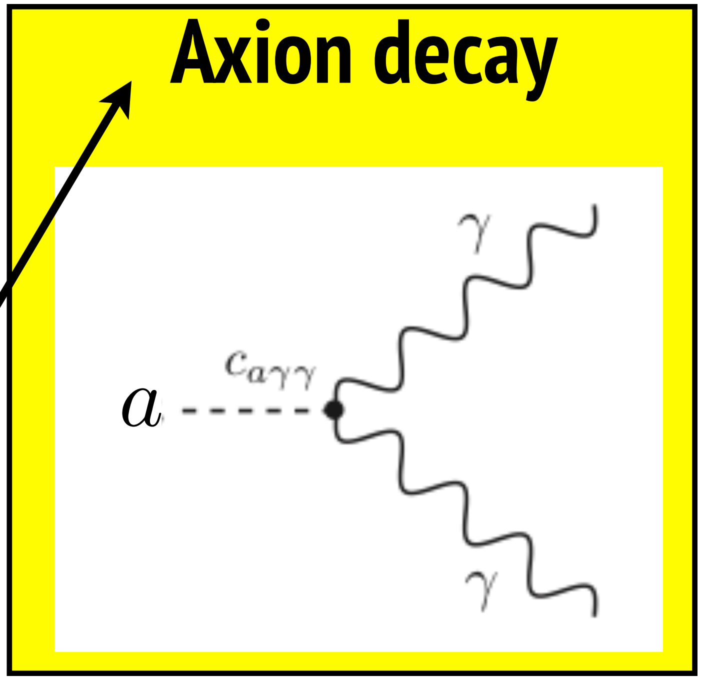


They expand with the Universe until ~ Matter-radiation equality (z~1000)

$L \sim \mathcal{O}(0.1)\mathrm{A.U.}$

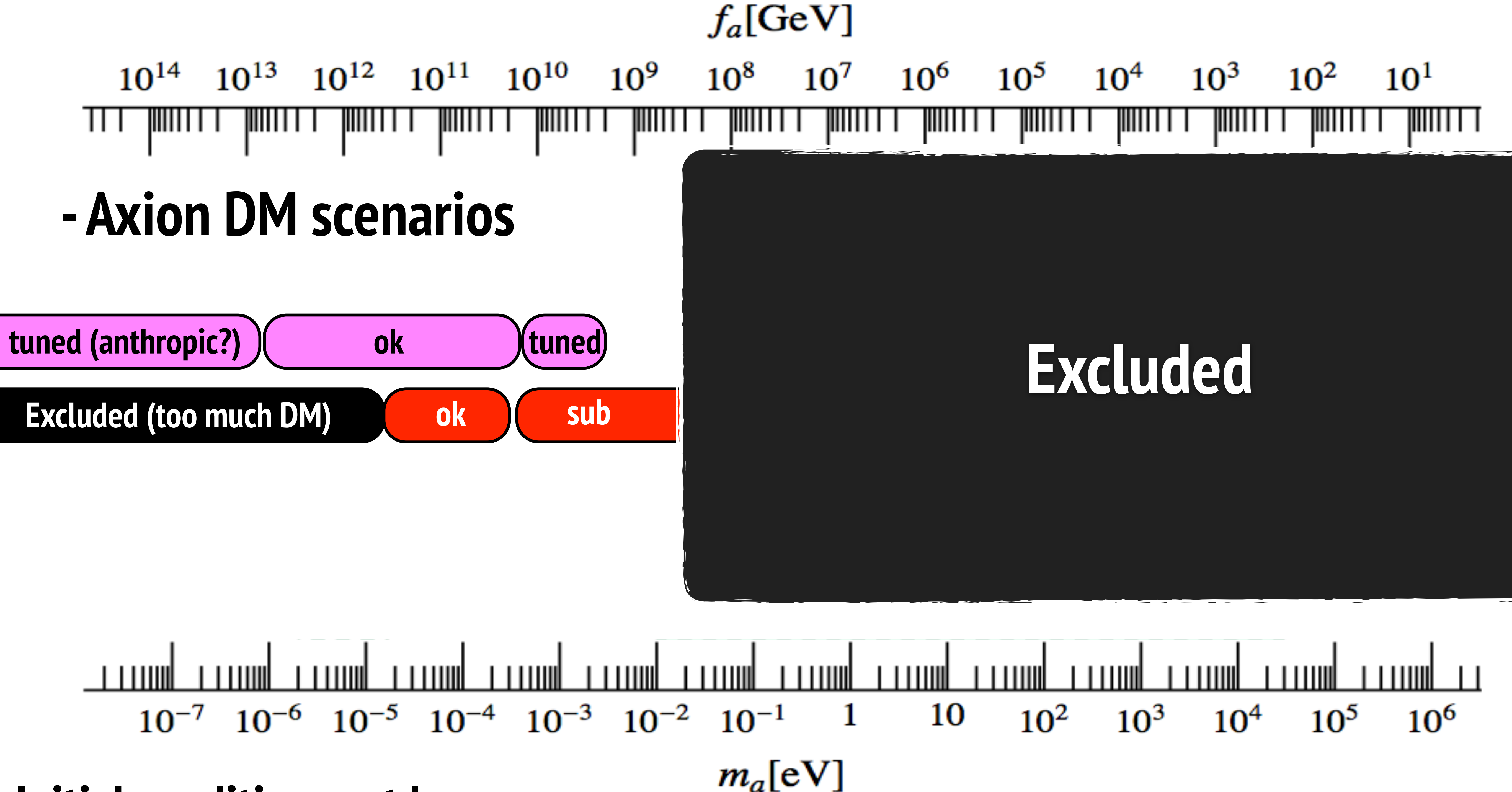
Axion DM, how much





less interacting **more interacting**

Axion dark matter



Initial conditions set by :

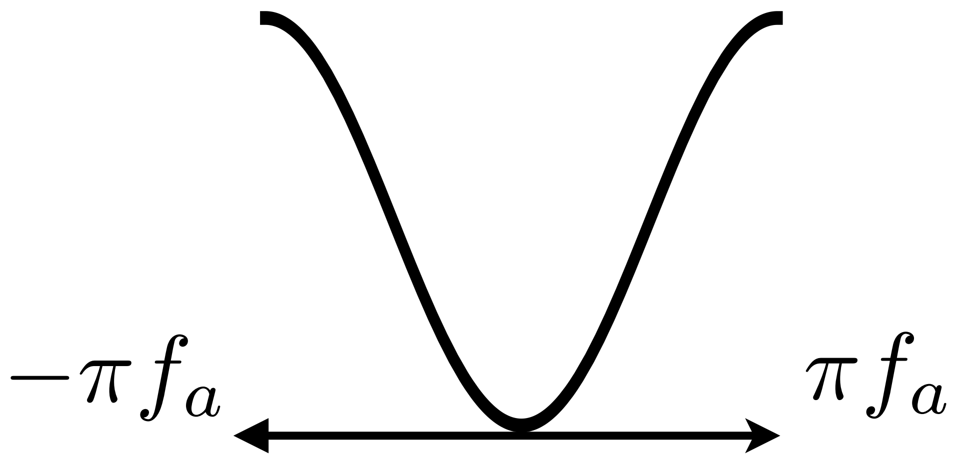
Inflation smooth

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

Phase transition (N=1)

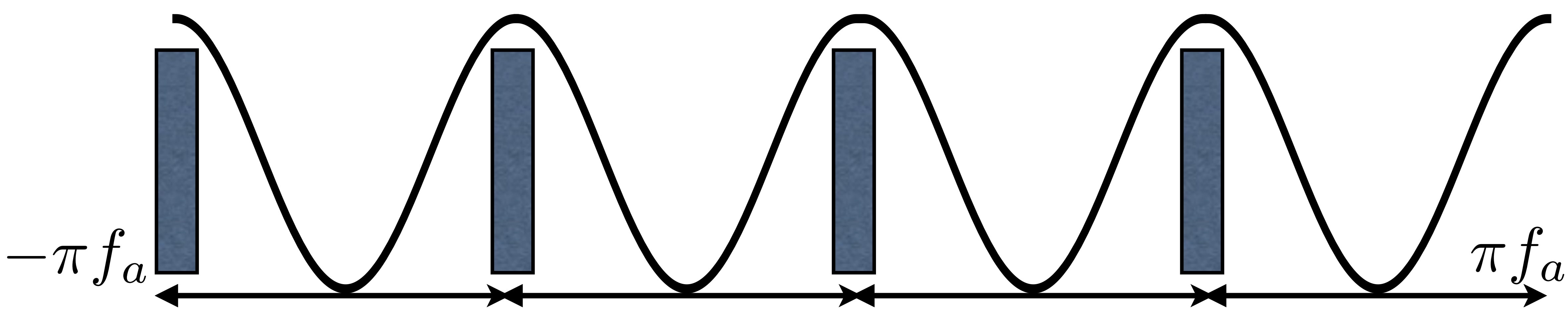
strings+unstable DW's

SCENARIO I, N=1

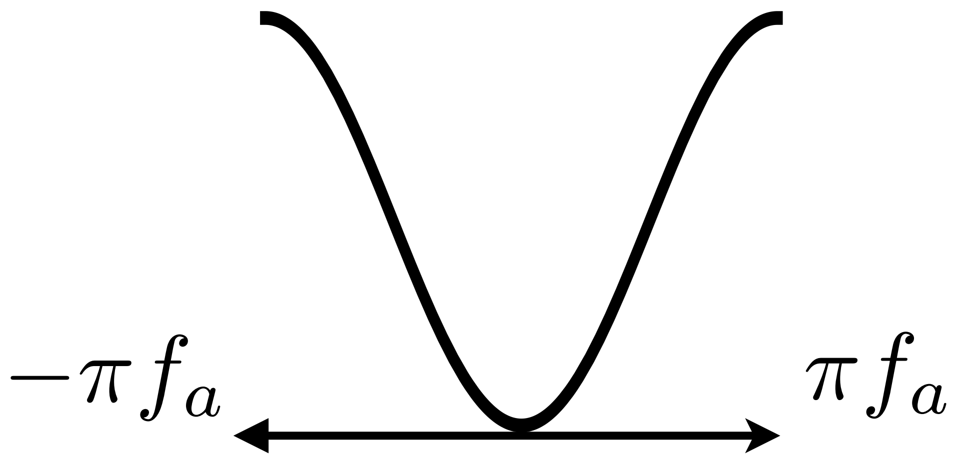


$$\frac{a}{f_a} = N\theta$$

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

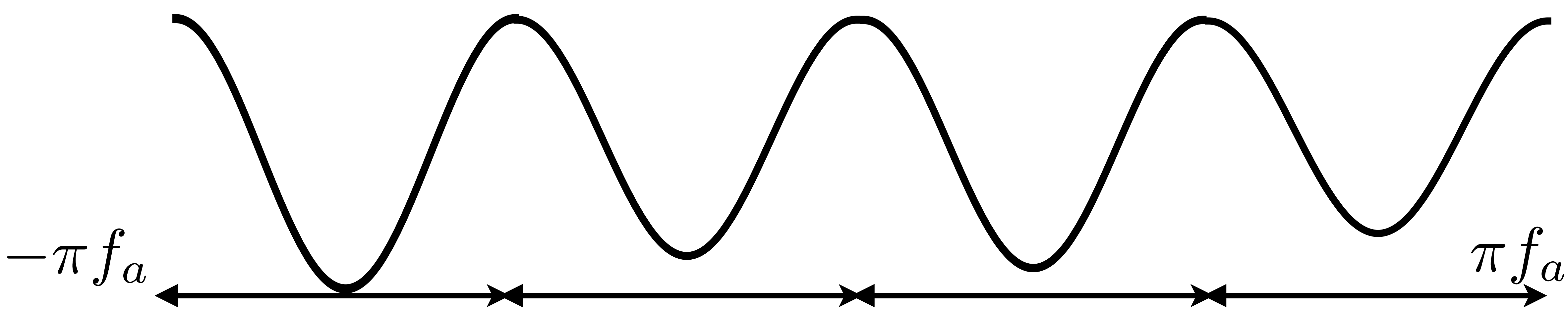


SCENARIO I, N=1



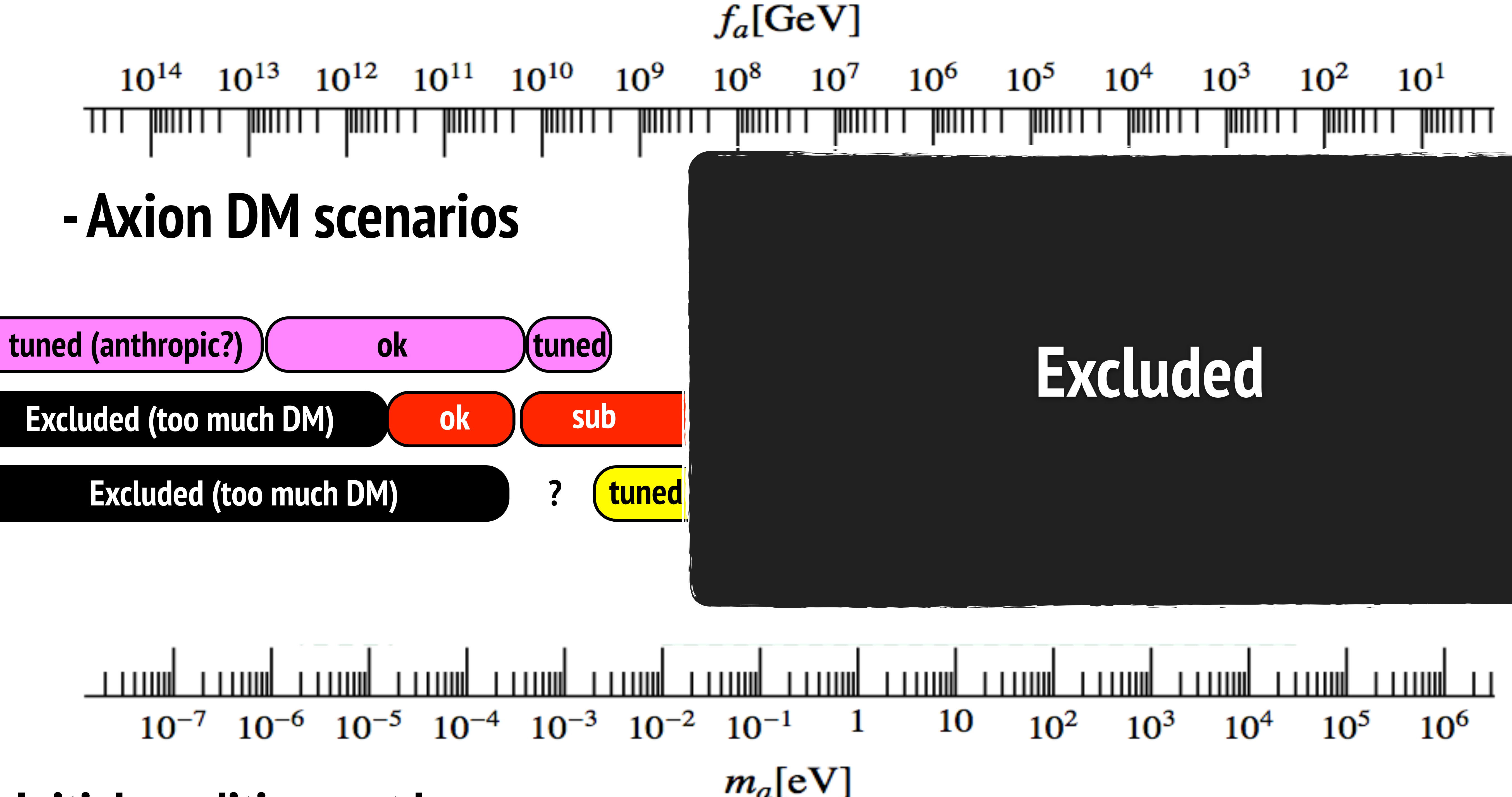
$$\frac{a}{f_a} = N\theta$$

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



Axion dark matter

- Axion DM scenarios



Initial conditions set by :

Inflation smooth

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

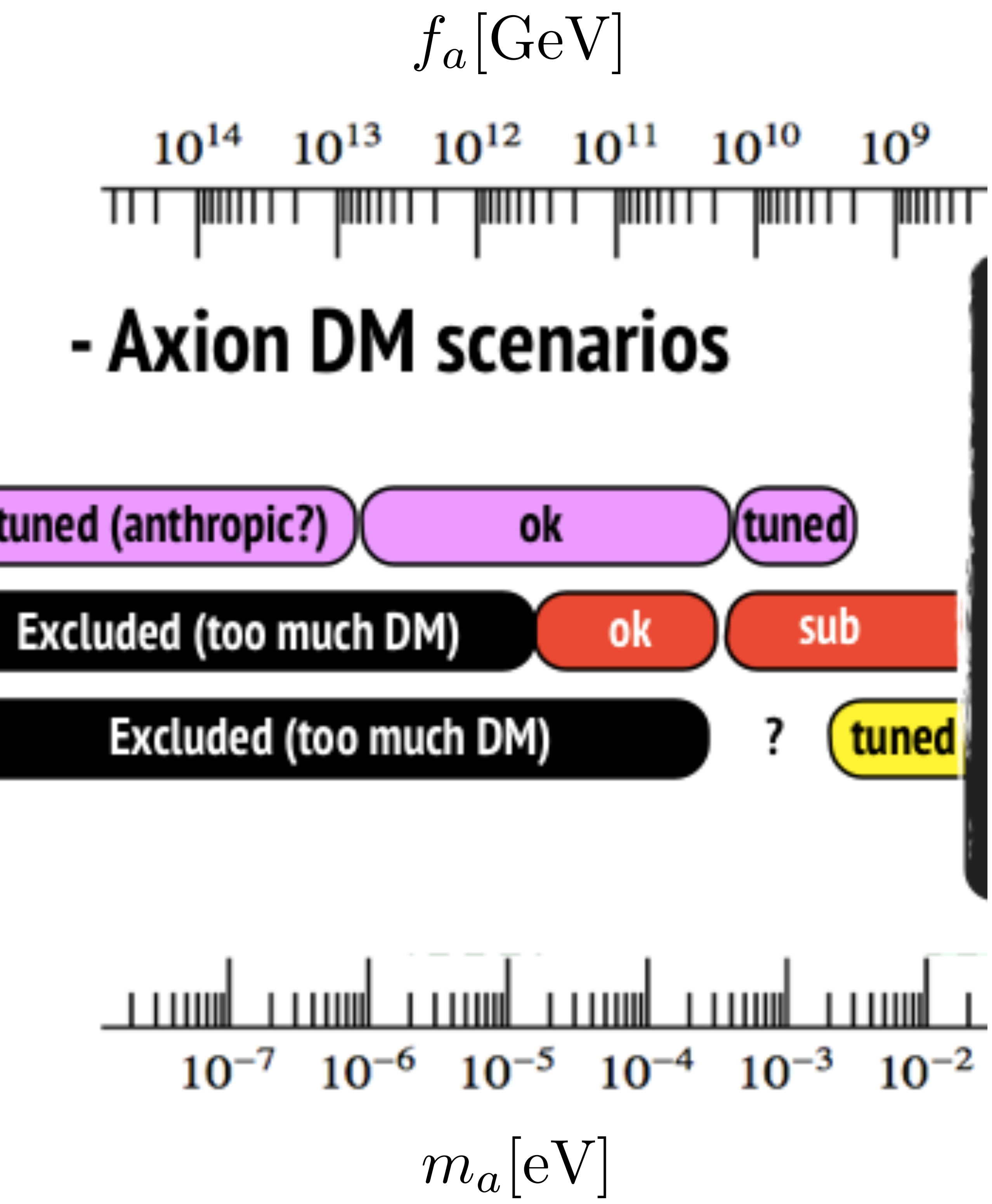
Phase transition (N=1)

strings+unstable DW's

Phase transition (N>1)

strings+long-lived DWs

Conclusions



- Some axion DM is inevitable
- DM ab. depends on i.c. and fa
- Some scenarios "excluded"
  - standard thermal history
  - extrapolations
  - isocurvature constraints
- fa ~ 10^11 GeV favoured (?)
- larger fa possible (anthropic)
- much do to!