IBS-ICTP 7th MultiDark workshop

The meso-inflationary QCD axion

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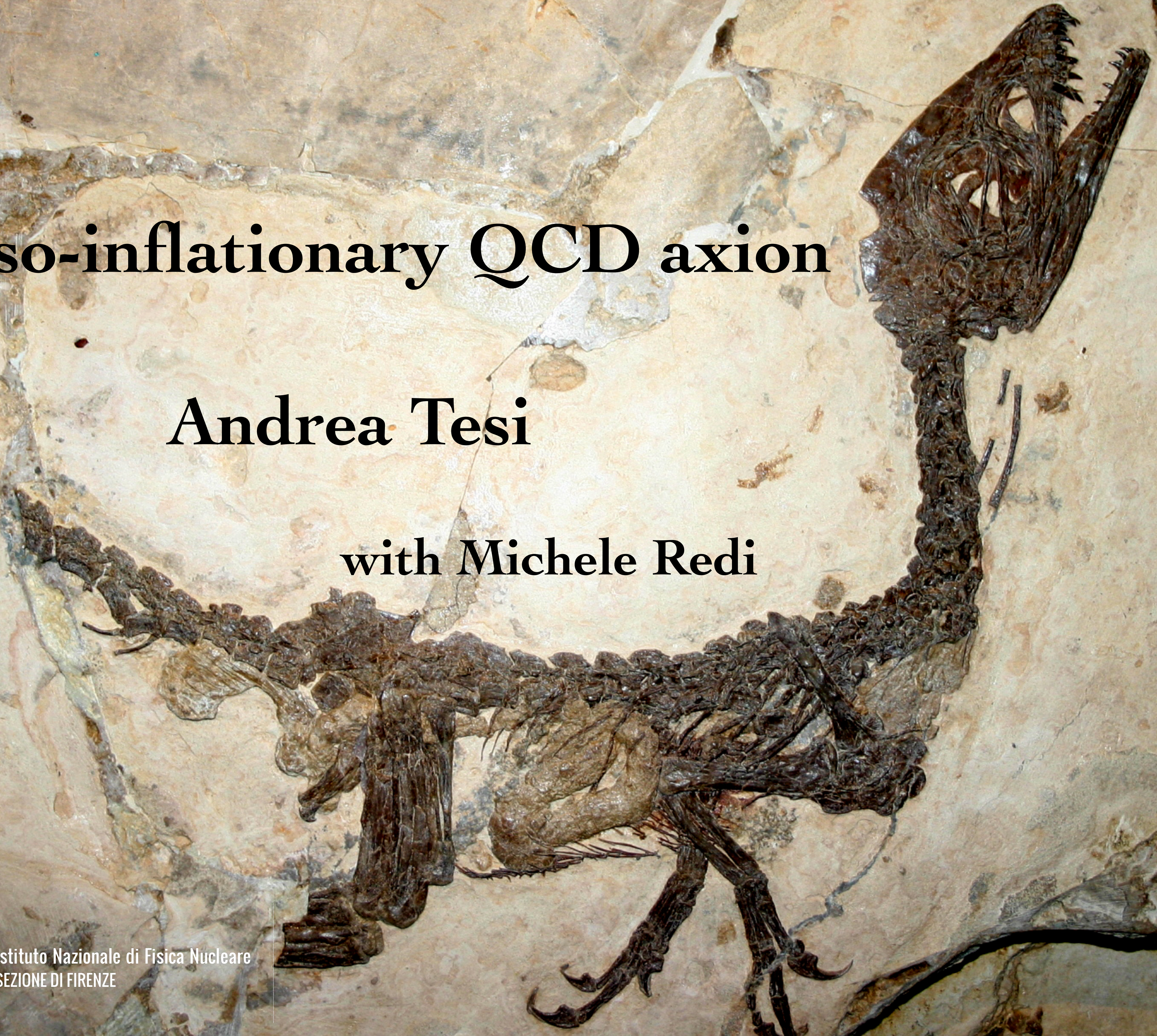
SEZIONE DI FIRENZE



[Peccei-Quinn '77
Weinberg-Wilczek '78]

"the axion solves more problems than it causes" [cit??]

$$(\theta - \frac{a}{f_a})\,\frac{\alpha_s}{8\pi} G\,\tilde{G}$$

- **strong CP conservation**

$$V(a) = \frac{1}{2} m_a^2(T) a^2 + \cdots$$

- **behaves as cold dark matter**

really is that good?

ingredients:

- **Peccei-Quinn potential**
  (must be only broken by QCD anomaly!)

$$V = \lambda \left(|\Phi|^2 - \frac{f_a^2}{2} \right)^2$$

- **Possibly avoid stable domain walls**
  (KSVZ-type with quarks U and D)

$$N_{\rm DW} = 1 \qquad f_a = f_a$$

- **Plagued by isocurvatures for H_I >fa**
  (also, 'anthropic' selection of initial field value?)

- **Relic abundance from the network?**
  (out of experimental - admx - window?)

it's sensitive to the UV. what changes if we twist the UV?

cosmology of the qcd axion

axion relic abundance depends on cosmological history
with **two main scenarios** determined by the size of **fa**

- **pre-inflationary scenario**

relic abundance from **misalignment**

inflation makes the axion field homogeneous

$$f_a > \max[\frac{H_I}{2\pi}, T_{\max}]$$

incalculable initial field value $a_0 = \theta_0 f_a$

large (calculable) quantum fluctuations: isocurvatures

Peccei-Quinn broken when the scale factor: $a_{PQ} \ll a_e \exp(-60)$

cosmology of the qcd axion

axion relic abundance depends on cosmological history
with **two main scenarios** determined by the size of **fa**

- **post-inflationary scenario**

relic abundance uncertain: **string/wall-network**

domain wall problem, only KSVZ-type model

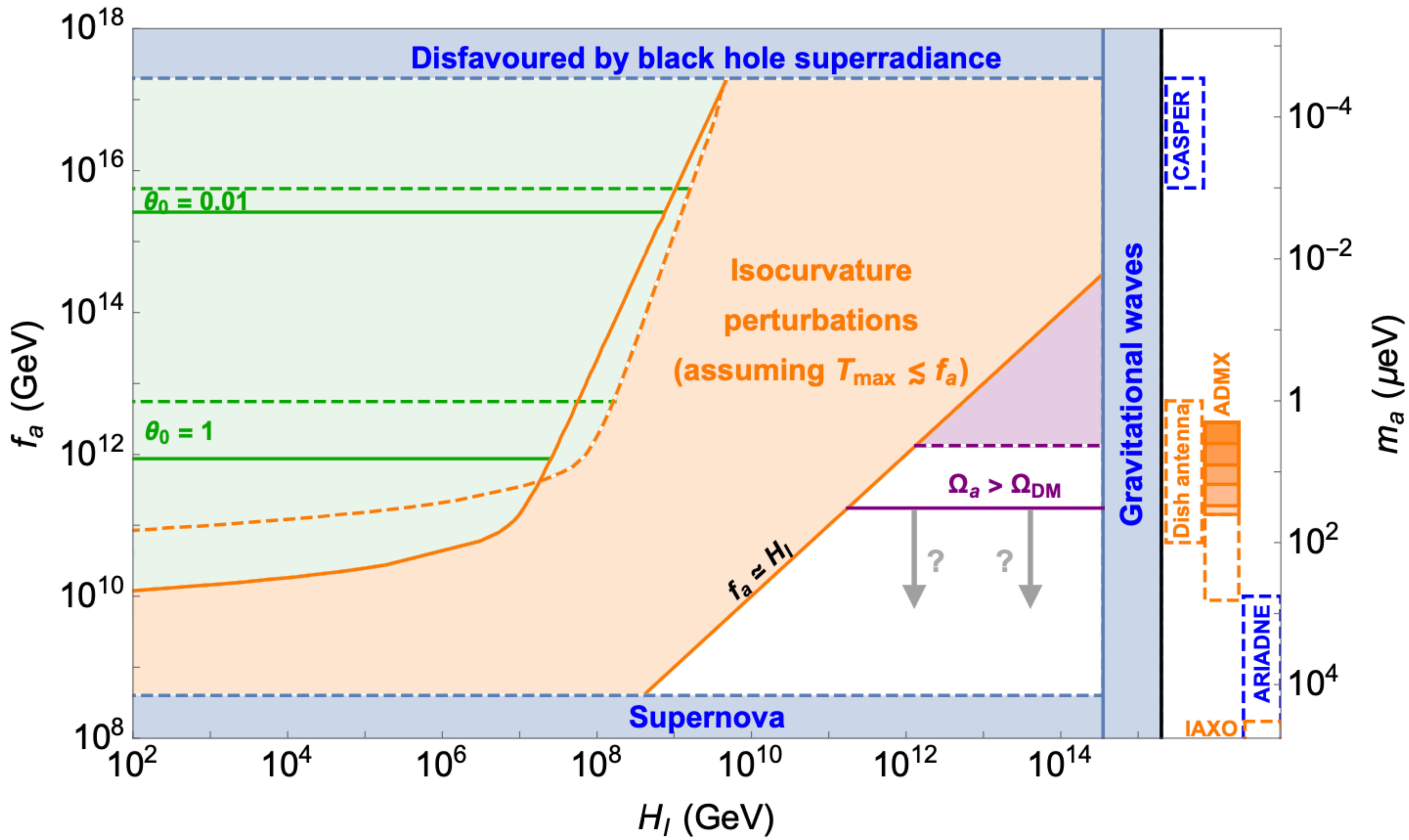
large (?) power at small scales, miniclusters

no isocurvature at cosmological scales

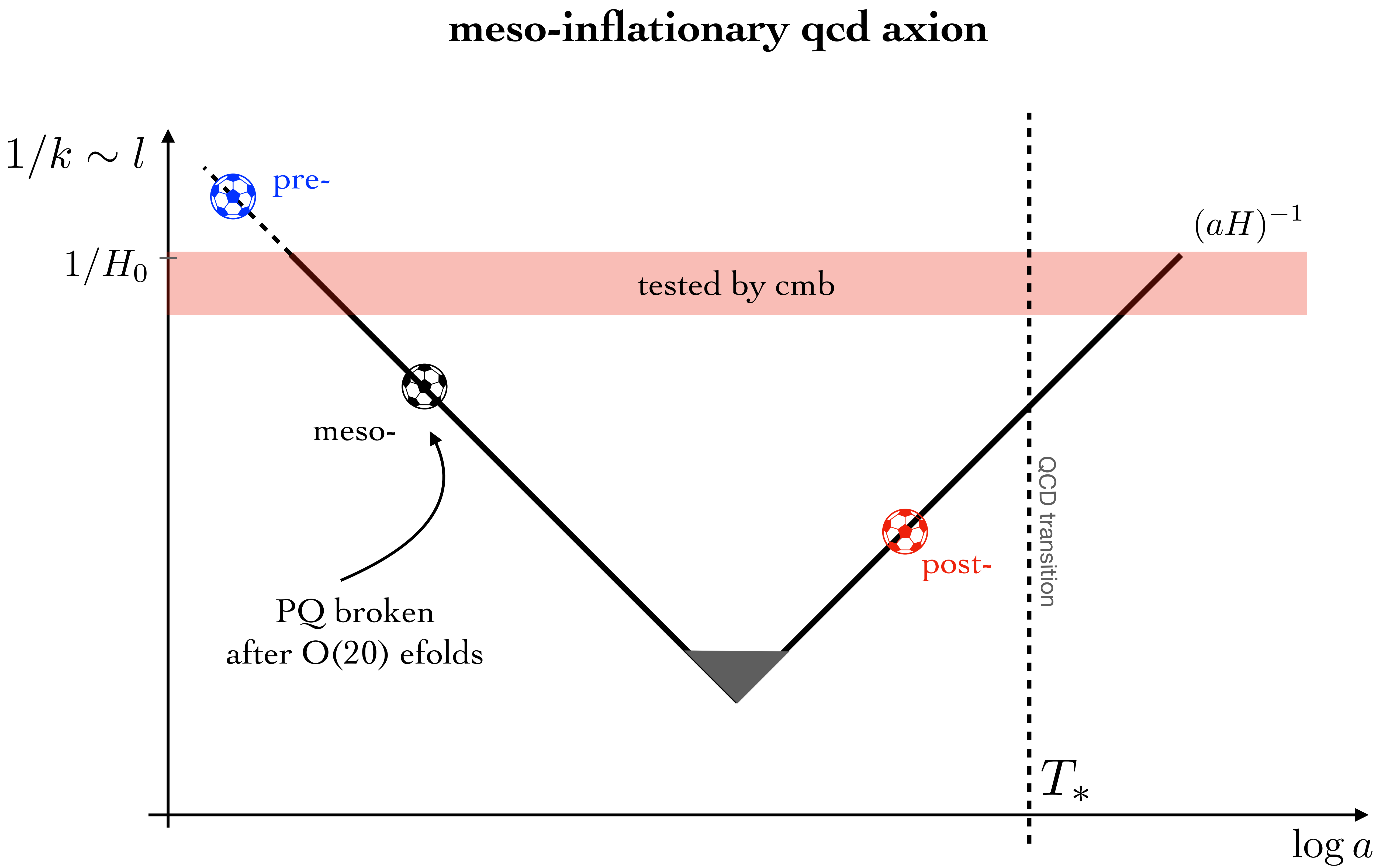
$$f_a < \max[\frac{H_I}{2\pi}, T_{\rm max}]$$

Peccei-Quinn broken when the scale factor: $T(a_{\rm PQ}) \approx f_a$

cosmology of the qcd axion



[Grilli di Cortona, Hardy, Villadoro]



meso-inflationary qcd axion
1/k ~ l
1/H_0
pre-
(aH)^{-1}
tested by cmb
meso-
PQ broken
after O(20) efolds
post-
QCD transition
T_*
log a

meso-inflationary qcd axion

Peccei-Quinn is broken after the start of the last 60 e-folds of inflation

- **meso-inflationary scenario**

no isocurvatures at large scales (no axion initially)

large quantum fluctuations: new contribution to abundance and power spectrum

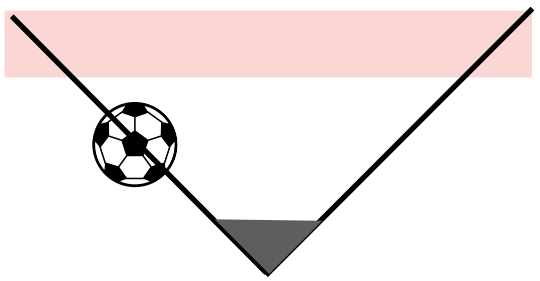
potentially long-lived string/wall network

more difficult to compute

calculable

axion emerges at PQ transition,
homogenous today on scales

$$d \sim \frac{1}{k_{\rm PQ}} \equiv \frac{1}{H_0} \exp[-N_{\rm PQ}]$$



meso-inflationary realizations

Peccei-Quinn mass term modified by coupling to other dynamics

$$V = \lambda \left(|\Phi|^2 - \frac{f_a^2}{2} \right)^2 + \mathcal{O}|\Phi|^2$$

operator ***O*** has a vev during inflation

- **symmetry restoration for** $f_a > H_I/(2\pi)$

$$\langle \mathcal{O} \rangle \approx \lambda f_a^2$$

for example coupling to inflaton

[Linde '91]

field Phi heavy before the transition, no fluctuations
unlikely to justify HI ≈ fa

meso-inflationary realizations

Peccei-Quinn mass term modified by coupling to other dynamics

$$V = \lambda\left(|\Phi|^2 - \frac{f_a^2}{2}\right)^2 + \mathcal{O}|\Phi|^2$$

operator ***O*** has a vev during inflation

- **symmetry breaking starting with** $f_a < H_I/(2\pi)$

  requires drop in Hubble during PQ transition **(non trivial inflationary scenario)**

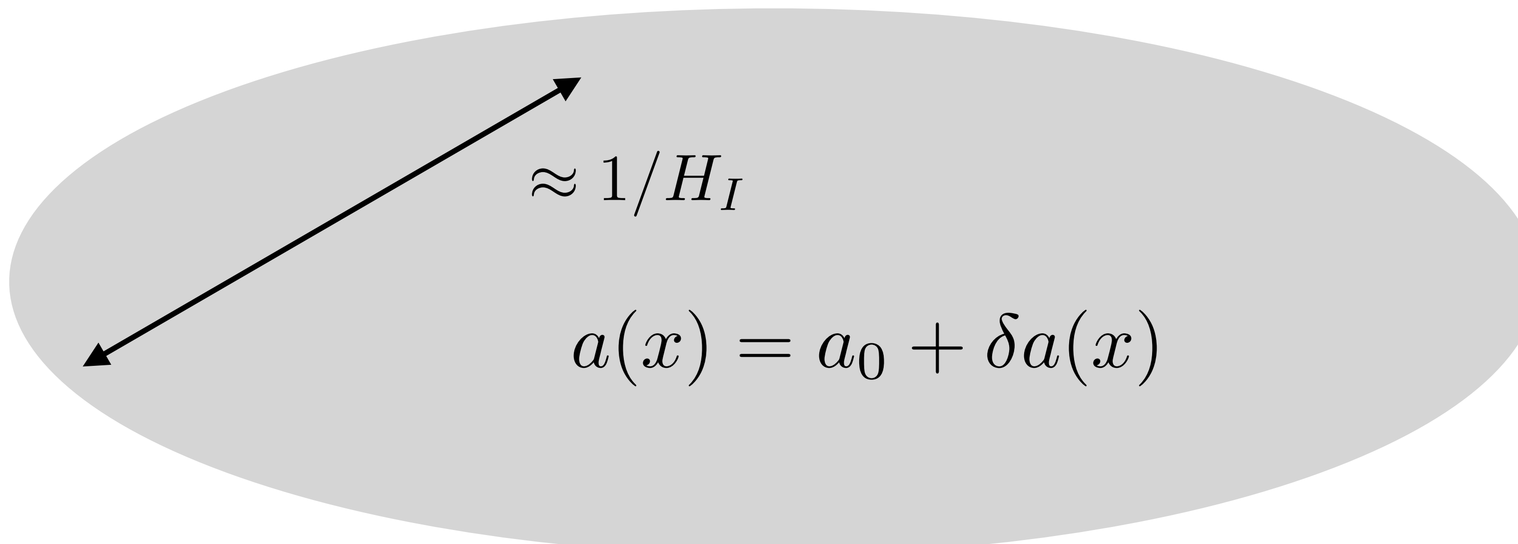
  can explain parameter space HI ≈ fa

  special choice by conformal coupling to Ricci $\mathcal{O} = -\frac{1}{6}R$

[i will not give more details than these, let's see what are the consequences of the scenario]

at the PQ phase transition during inflation

$k_{\rm PQ} \approx a_{\rm PQ} H_I$



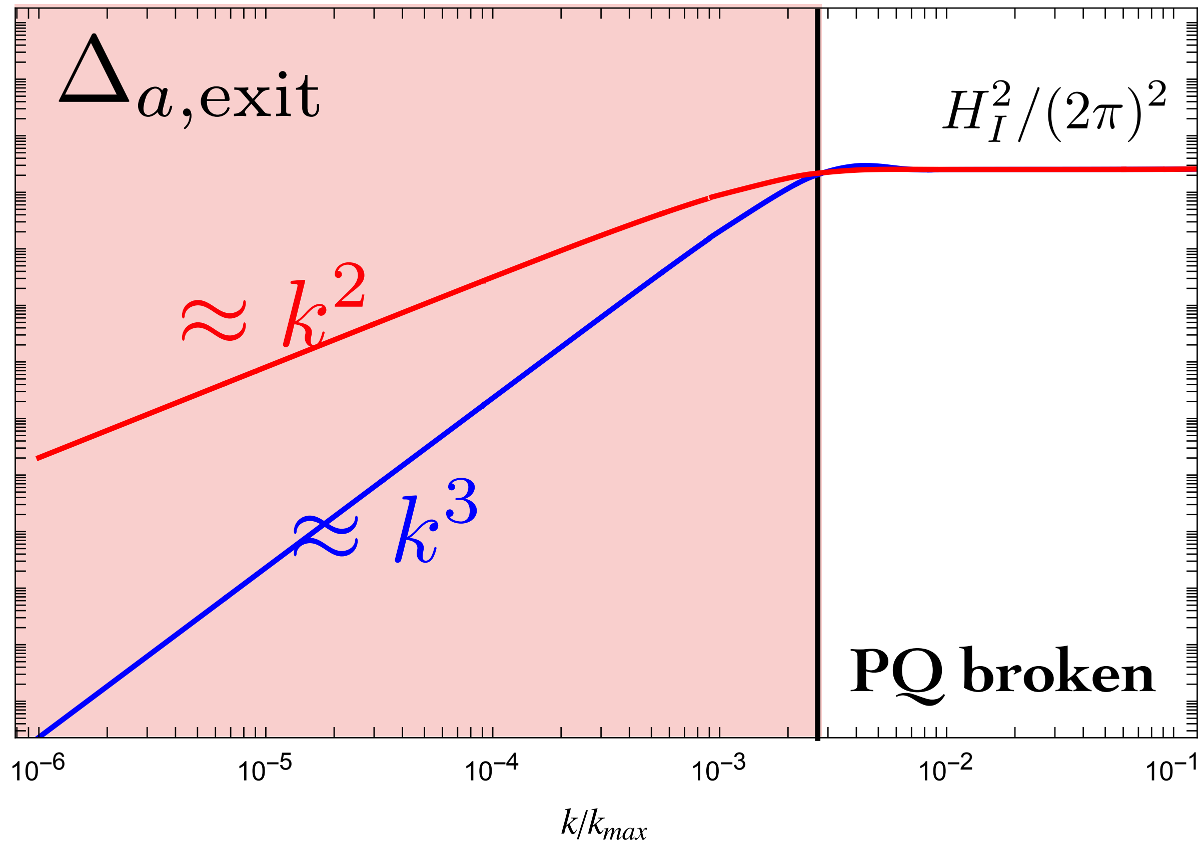
field homogenous on these patches	$\langle a_0^2 \rangle \approx 2.15 f_a^2$		$\Omega_{a,\rm mis.}$
unconstrained quantum fluctuations	$\langle \delta a \, \delta a \rangle \approx \dfrac{H_I^2}{(2\pi)^2}$	for $k \gtrsim k_{\rm PQ}$	$\Omega_{a,\rm inf.}$
one string per patch, that soon leaves the horizon			$\Omega_{a,\rm net.}$

need to estimate how much energy is stored in the axion field in these three contribution

axion abundance from inflationary fluctuations

mechanism of inflationary production of minimally coupled scalars
(scalar/tensor perturbations, production of Stueckelberg vector from inflation...)

$$\Delta_a(\eta_e, k) = \frac{k^3}{2\pi^2} \int d^3x e^{-i\vec{k}\cdot\vec{x}} \langle a(\eta_e, \vec{x}) a(\eta_e, 0) \rangle = \frac{H_I^2}{4\pi^2} \min[1, \frac{k^n}{k_{\rm PQ}^n}] \,.$$

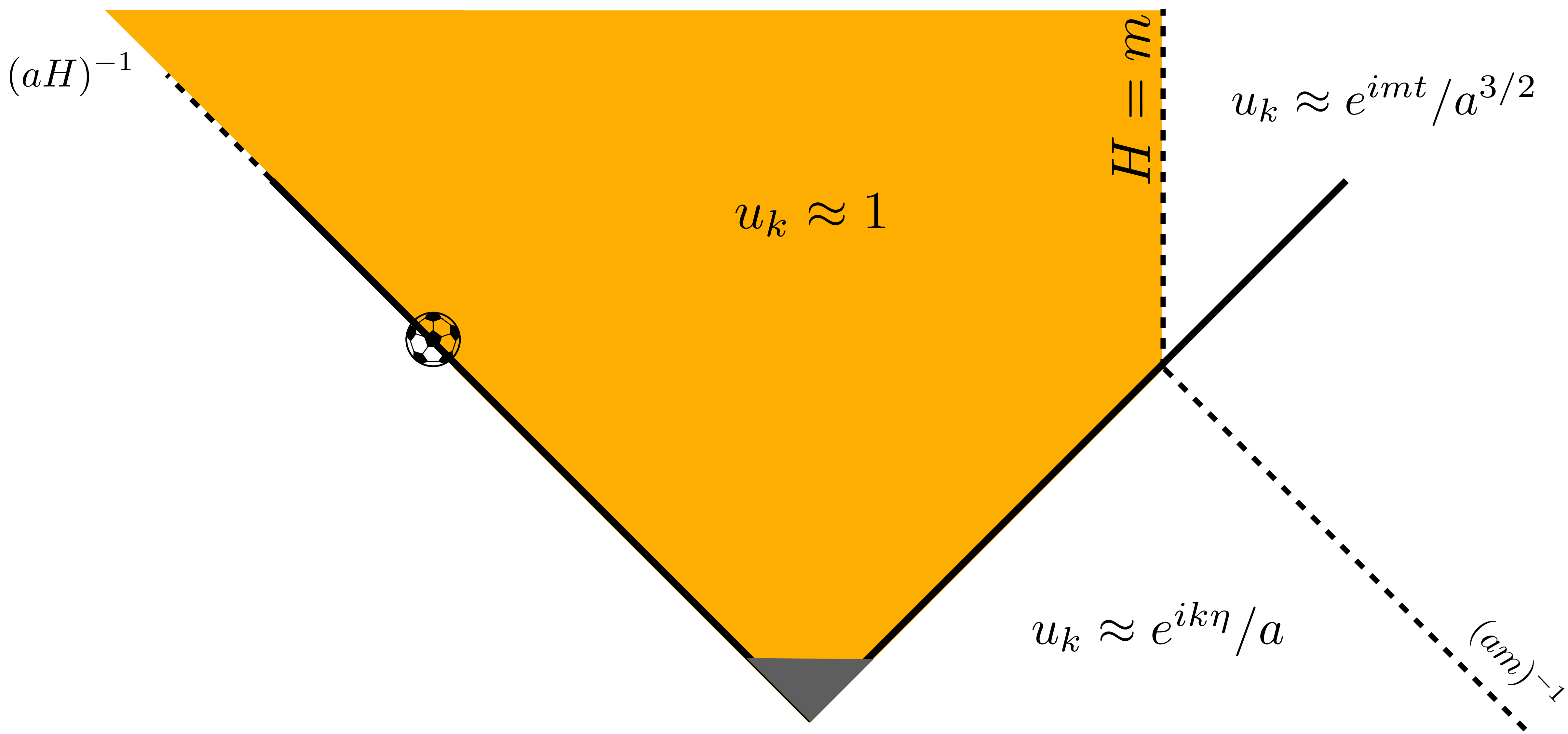


- **classical evolution** after horizon exit

$$\frac{d\rho_a^{\rm inf}}{d\log k} = \frac{\Delta_a(\eta_e, k)}{2} \left[g^{00}|\dot{u}_k|^2 - (g^{ij}k_ik_j - m_a^2)|u_k|^2 \right]$$

$$u_k|_{\rm exit} = 1, \; \dot{u}_k|_{\rm exit} = 0$$

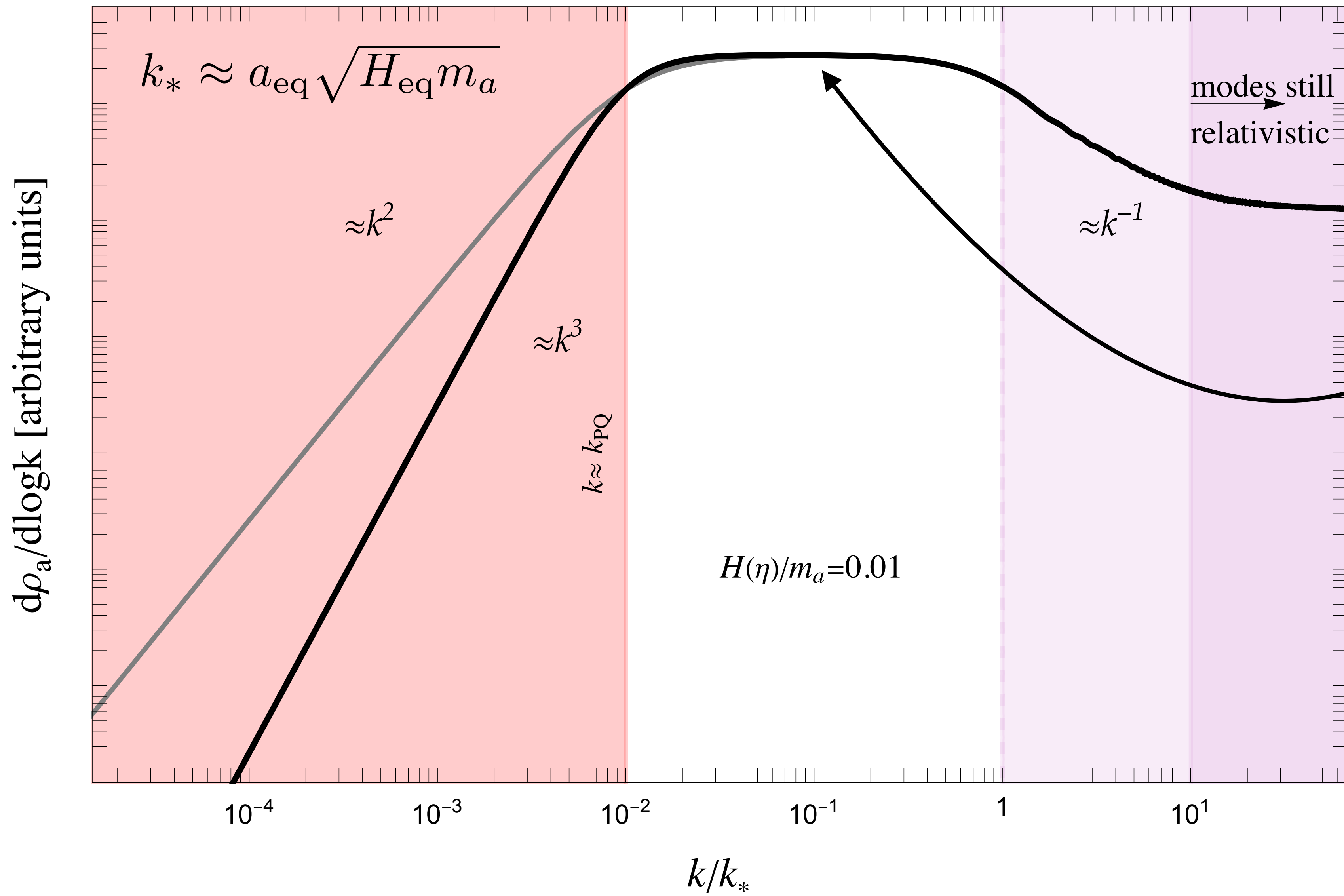
axion abundance from inflationary fluctuations



classical evolution determines the spectral shape of the energy density

[as in Graham, Mardon, Rajendran]

axion abundance from inflationary fluctuations



$$\frac{\rho_{a,\rm inf}}{s} \approx \frac{\log(k_*/k_{\rm PQ})}{\sqrt{g_*(T_*)}}\frac{H_I^2}{(2\pi)^2}\frac{m_a}{M_{\rm pl}T_*}\,.$$

sizeable contribution to relic abundance from quantum fluctuations

$$\frac{\Omega_a^{\rm inf}}{\Omega_a^{\rm mis}} \approx \log\left(\frac{k_*}{k_{\rm PQ}}\right) \times \left(\frac{H_I}{2\pi f_a}\right)^2$$

isocurvature power spectrum

isocurvature power spectrum **calculable** knowing as a function of time
it is confined to short scales

$$\langle \frac{\delta\rho_a}{\bar\rho_a}\frac{\delta\rho_a}{\bar\rho_a}\rangle\Big|_{\rm iso} \approx \frac{\langle a(\eta,x)a(\eta,0)\rangle^2 + 4a_0^2\langle a(\eta,x)a(\eta,0)\rangle}{(a_0^2+\langle a(\eta)^2\rangle)^2}$$

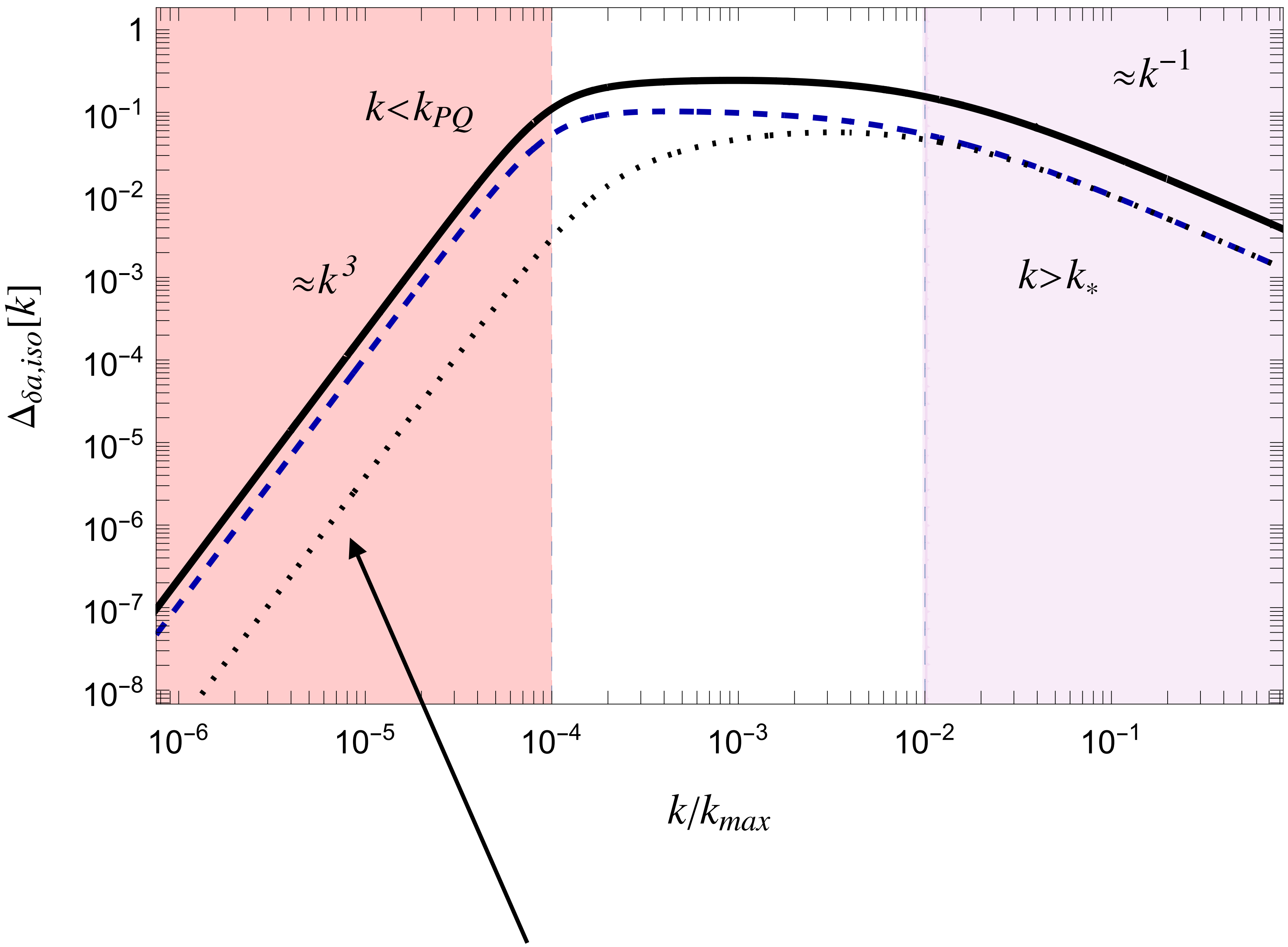
$$\Delta^{\rm iso}_{\delta_a}(\eta,k) = \frac{\Omega^2_{a,\rm inf}}{\Omega_a^2\langle a^2\rangle^2}\frac{k^3}{4\pi}\int d^3q\,\frac{\Delta_a(\eta,q)\Delta_a(\eta,|\vec k-\vec q|)}{q^3|\vec k-\vec q|^3} + 4\frac{\Omega_{a,\rm inf}\Omega_{a,\rm mis}}{\Omega_a^2\langle a^2\rangle}\Delta_a(k)$$

new contribution
(non-gaussian)

usual term for axion DM

[similar to dark photon from inflation]

isocurvature power spectrum

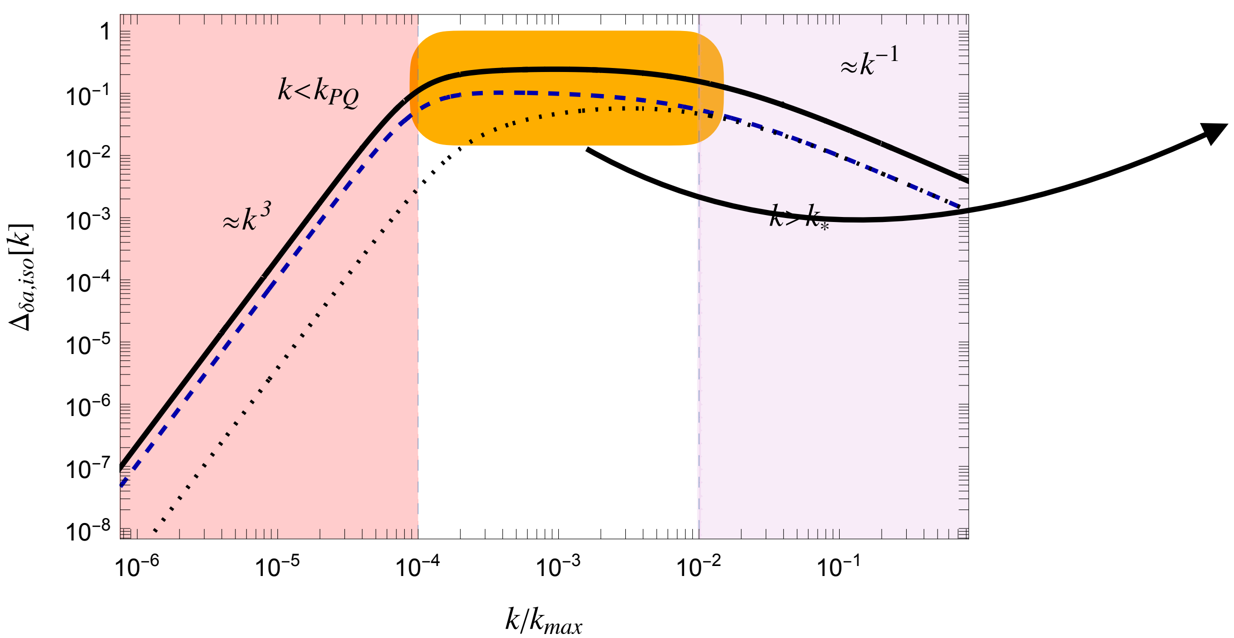


$$\Delta^{\rm iso}_{\delta_a}(\eta, k) \approx \frac{\Omega^2_{a,\rm inf}}{\Omega^2_a} \frac{k^3}{3\log^2(k_*/k_{\rm PQ})k^3_{\rm PQ}}$$

the pure quantum contribution
(present also for no misalignment)
is universal and goes as k^3

isocurvature power spectrum

the O(1) overdensity on the plateau leads to the formation of mini-halos and mini-clusters



$$M_{\rm cluster} \approx 10^{-16} M_\odot (k_*/k)^3$$

[Gorghetto, Hardy et al]

- **also bounds from CMB, spectral distortions and structures**

a generic isocurvature power spectrum $\Delta_{\rm iso} = A_{\rm iso}(k/k_0)^3$ $k_0 = 0.05{\rm Mpc}^{-1}$

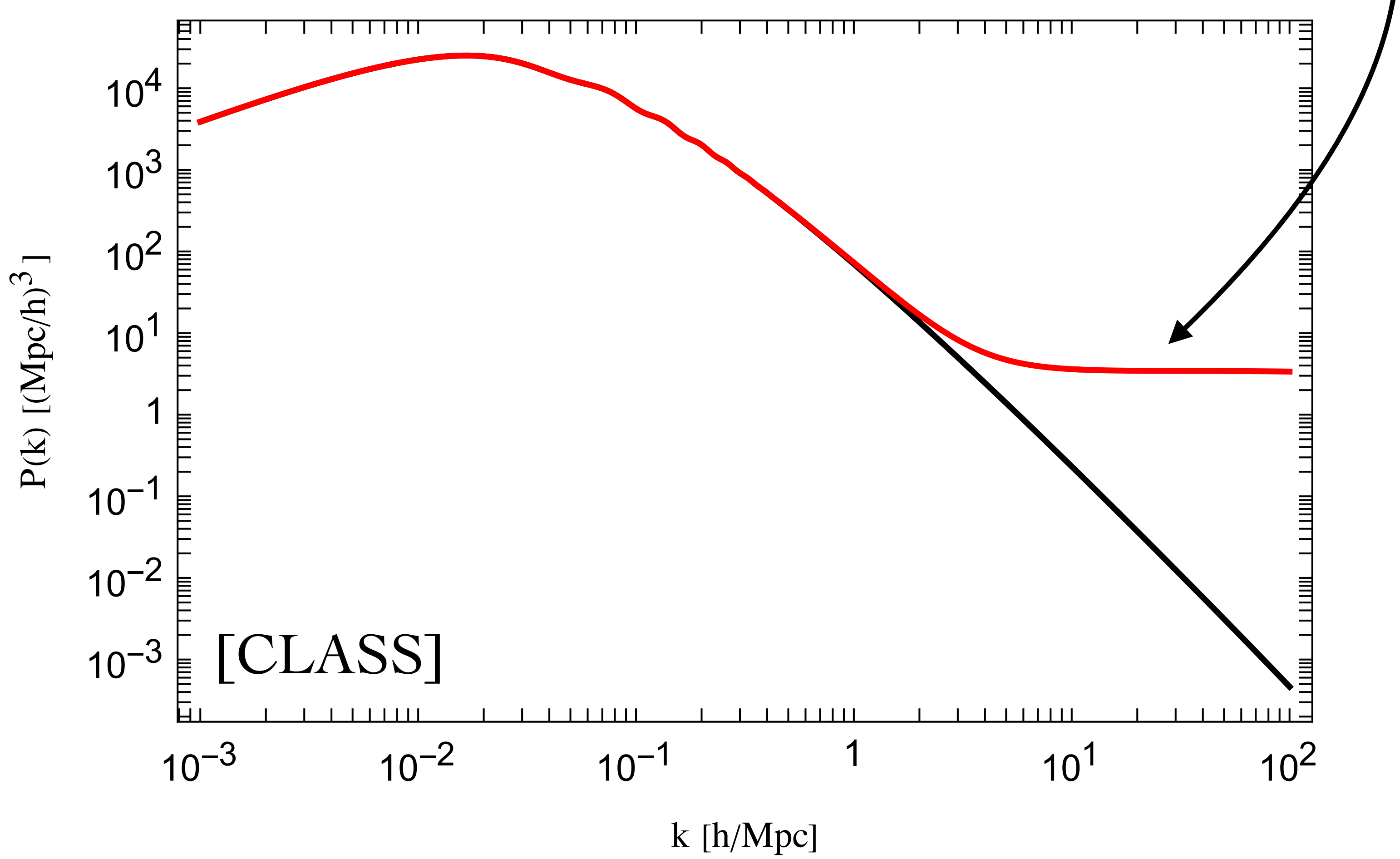
$A_{\rm iso}|_{\rm cmb} \lesssim 0.8\ 10^{-10}$ $A_{\rm iso}|_{\rm lyman-\alpha} \lesssim 10^{-14}$ $A_{\rm iso}|_{\rm pixie} \lesssim 10^{-11}$

[matter power spectrum]

the cdm linear matter power spectrum has a drop 1/k^3
new effects grow with k (like SMEFT at colliders…)

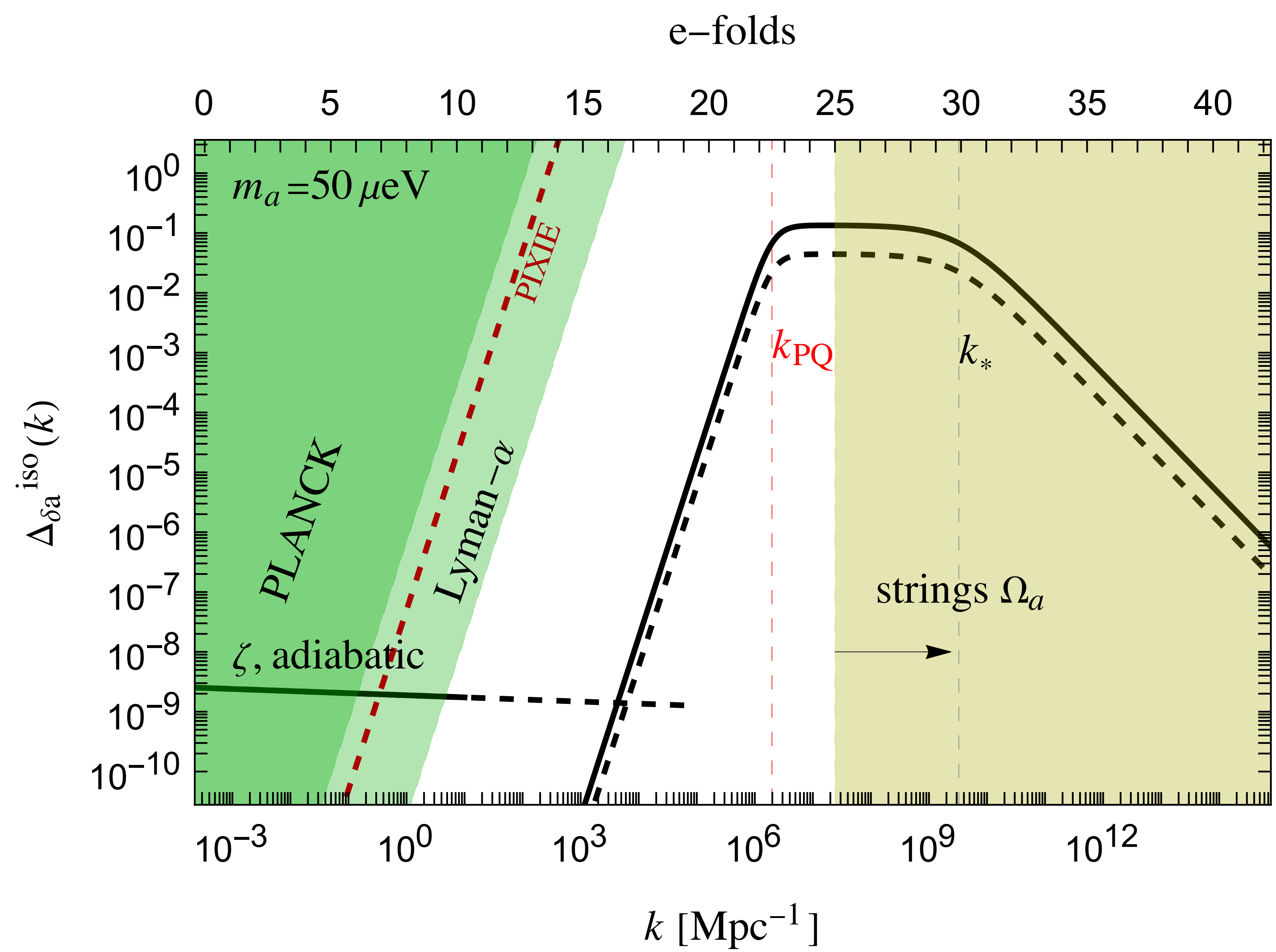
$$P_m(k) \propto \frac{1}{k^3}\big(\Delta_\zeta(k) + \beta\Delta_{\rm iso}(k)\big) \propto \beta\frac{A_{\rm iso}}{k_0^3}$$

(for uncorrelated iso)



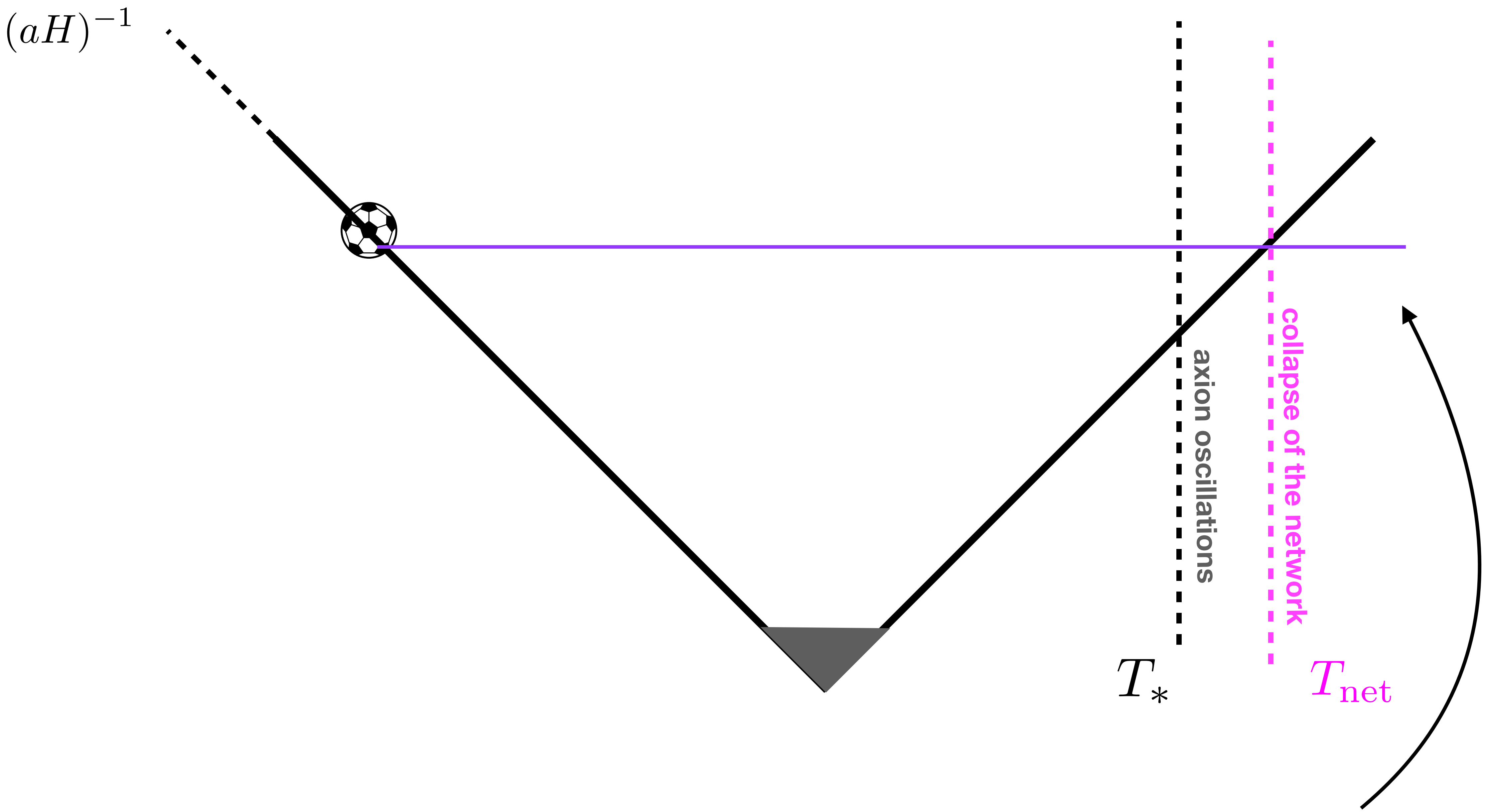
(ongoing work!)

qcd axion without strings and isocurvatures



axion abundance from the string network

inhomogeneities generated at the PQ phase transition leave the horizon immediately



they re-enter the horizon at **Tnet**, before or after the QCD transition
when they start to evolve and annihilate

axion abundance from the string network

if they enter the horizon after the axion starts to oscillate,
they behave like a long lived network

$$T_{\rm net} \lesssim T_*$$

the domain wall energy density can easily become dominant $\rho_{\rm dw} \approx 9 m_a(T) f_a^2 H(T)$

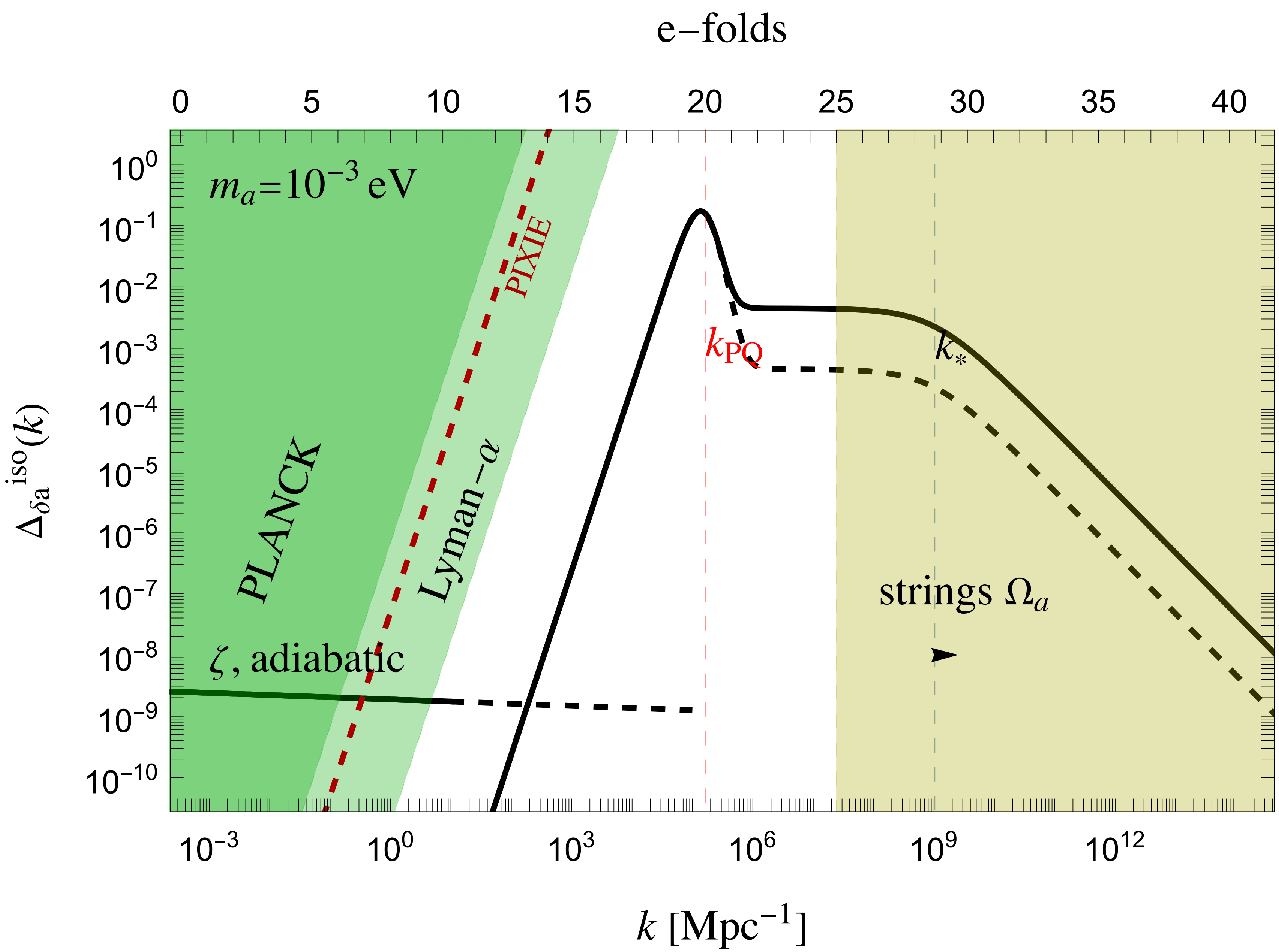
when they enter the horizon, they immediately decay/annihilate to axions

$$\Omega_a^{\rm net.} \lesssim \Omega_a^{\rm mis}\, e^{(23-N_{\rm PQ})}$$

final abundance depends on details, **hard to compute**
lower bound given by astrophysical constraints on the axion decay constant

$$f_a \approx 10^9 {\rm GeV} \leftrightarrow N_{\rm PQ} \approx 18-20$$

axion abundance from the string network



sketch!!!

conclusions

axion + isocurvature

so far less explored scenario for axion dark matter,
with signatures
lyman-alpha + miniclusters/minihalos/stars..

outlook

interesting to explore the cases:
- of ALP dark matter
- of phase transitions during inflation (heavy to light, conformal to minimal,..)

THANK YOU!