

Portorož 2023: Particle Physics from Early Universe to Future Colliders

the meso-inflationary QCD axion

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with Michele Redi + in progress



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“the axion solves more problems than it causes”

[cit. unknown]

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

- **strong CP conservation**

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

- **behaves as cold dark matter**

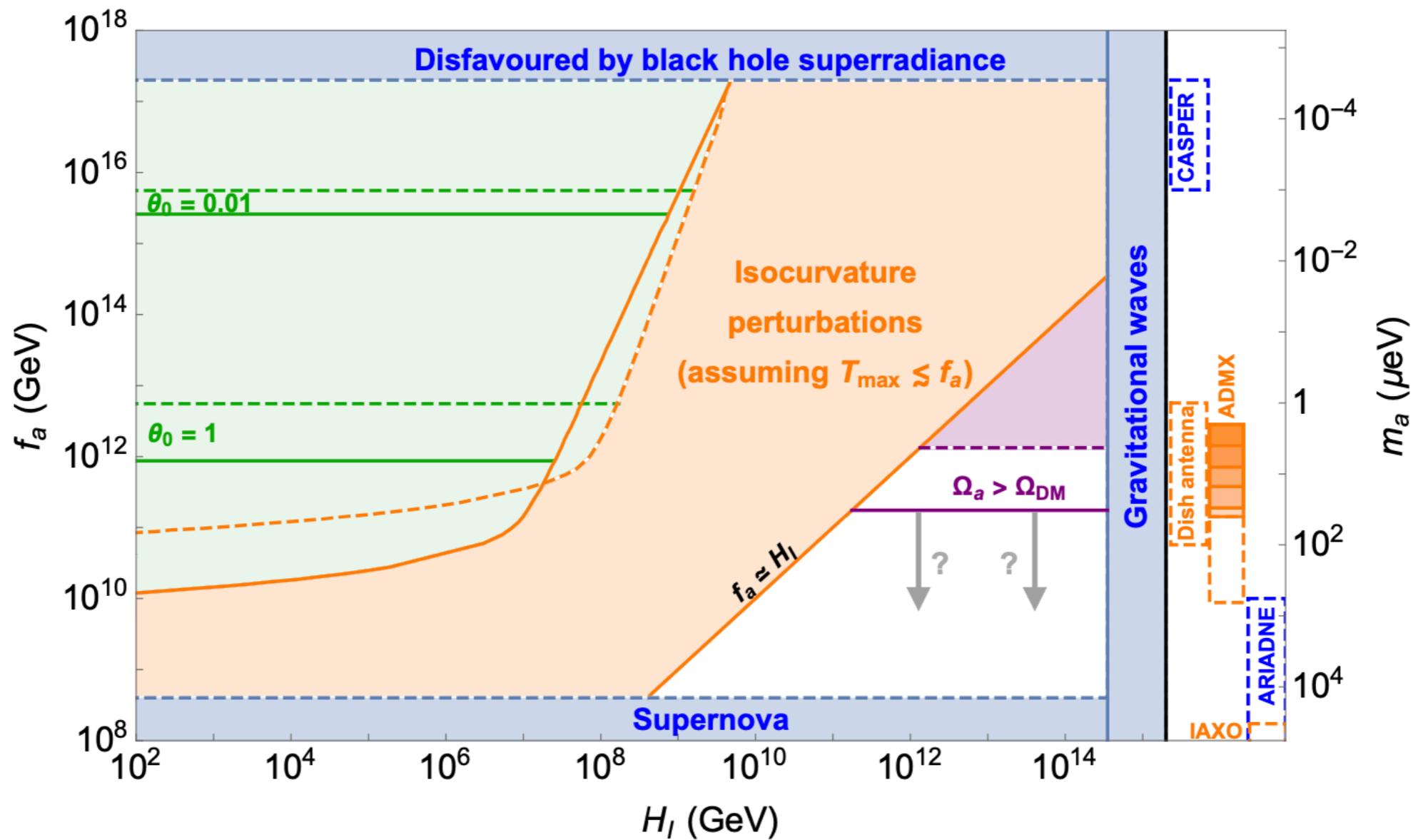
$$V(a) = \frac{1}{2} m_a^2(T) a^2 + \dots$$

really is that good?

a bit too sensitive to the UV physics...

cosmology of the qcd axion

two main scenarios determined by the size of f_a



[Grilli di Cortona, Hardy, Villadoro]

two common scenarios

$$f_a \gtrless \max\left[\frac{H_I}{2\pi}, T_{\max}\right]$$

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- **pre-inflationary scenario**



relic abundance from **misalignment**

incalculable initial field value

large isocurvatures $\Delta_{a,iso} \lesssim 10^{-11}$

PQ broken at $a_{PQ} \ll a_e \exp(-60)$

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relic abundance **uncertain**: **string-network** domain wall **problem**, only KSVZ-type model no isocurvature at cosmological scales

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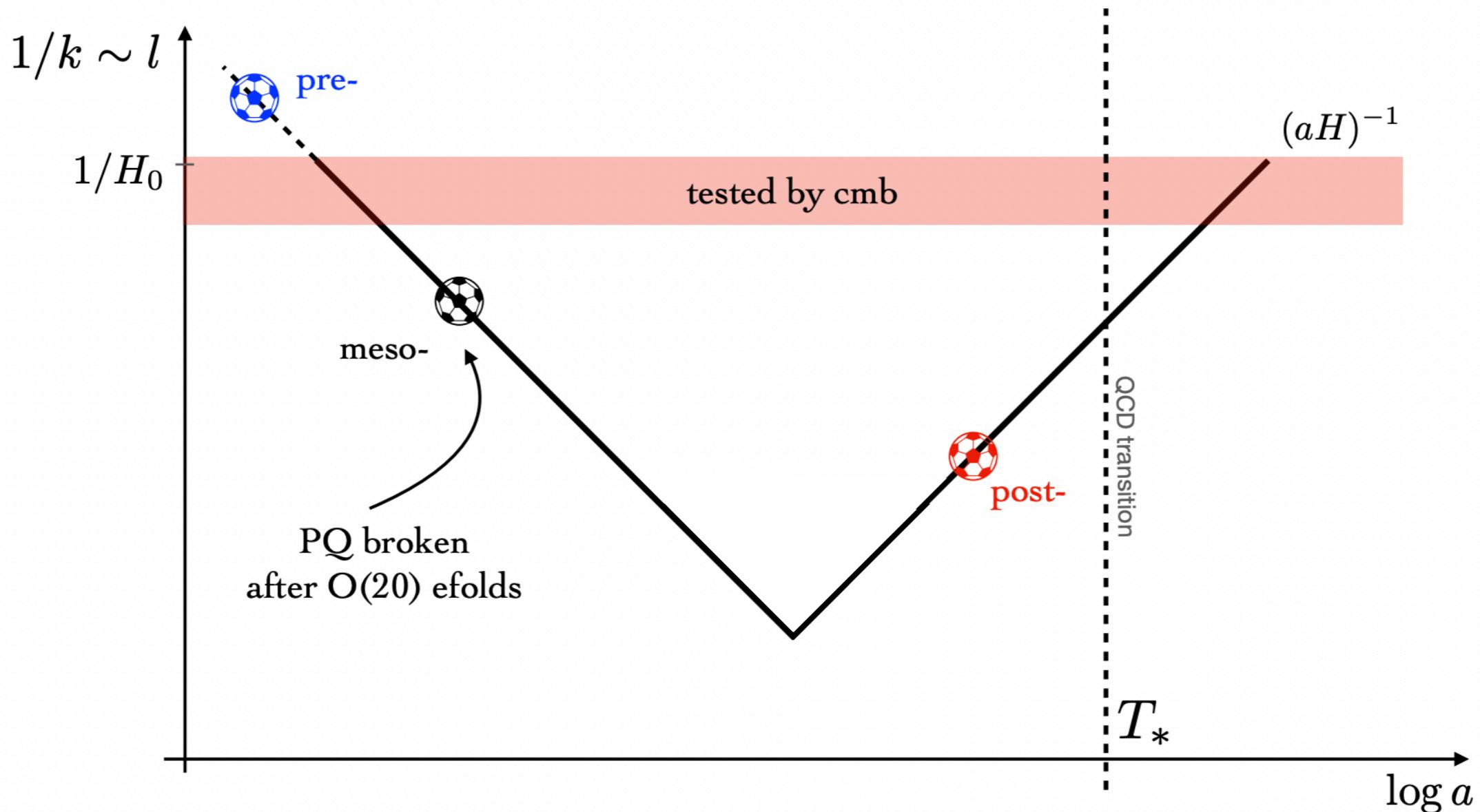


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what happens in the between?

meso-inflationary qcd axion



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 \mathcal{O} has a vev during inflation

[i will not give more details than these, let's look at the cosmology]

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

$$\langle \mathcal{O} \rangle \approx \lambda f_a^2 \quad [\text{Linde '91}]$$

field heavy before the transition

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drop in Hubble during PQ transition
special choice by conformal coupling

[i will not give more details than these, let's look at the cosmology]

at the PQ phase transition during inflation

$$a(x) = a_0 + \delta a(x)$$

axion emerges at PQ transition,
homogenous today on scales

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

field homogenous on these patches $\langle a_0^2 \rangle \approx 2.15 f_a^2$ $\Omega_{a,\text{mis.}}$

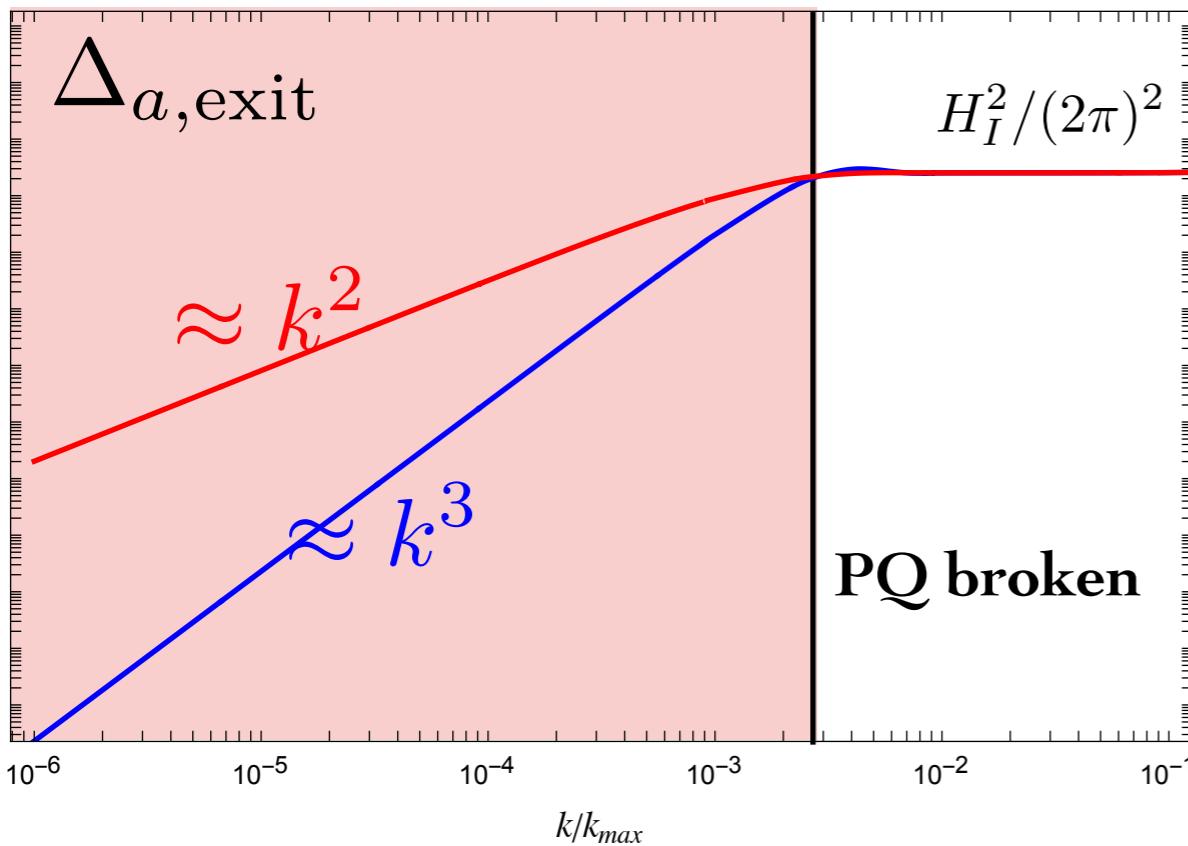
unconstrained quantum fluctuations $\langle \delta a \delta a \rangle \approx \frac{H_I^2}{(2\pi)^2}$ for $k \gtrsim k_{\text{PQ}}$ $\Omega_{a,\text{inf.}}$

one string per patch, that soon leaves the horizon $\Omega_{a,\text{net.}}$

axion abundance from inflationary fluctuations

mechanism of inflationary production of minimally coupled scalars

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



- **classical evolution** after horizon exit

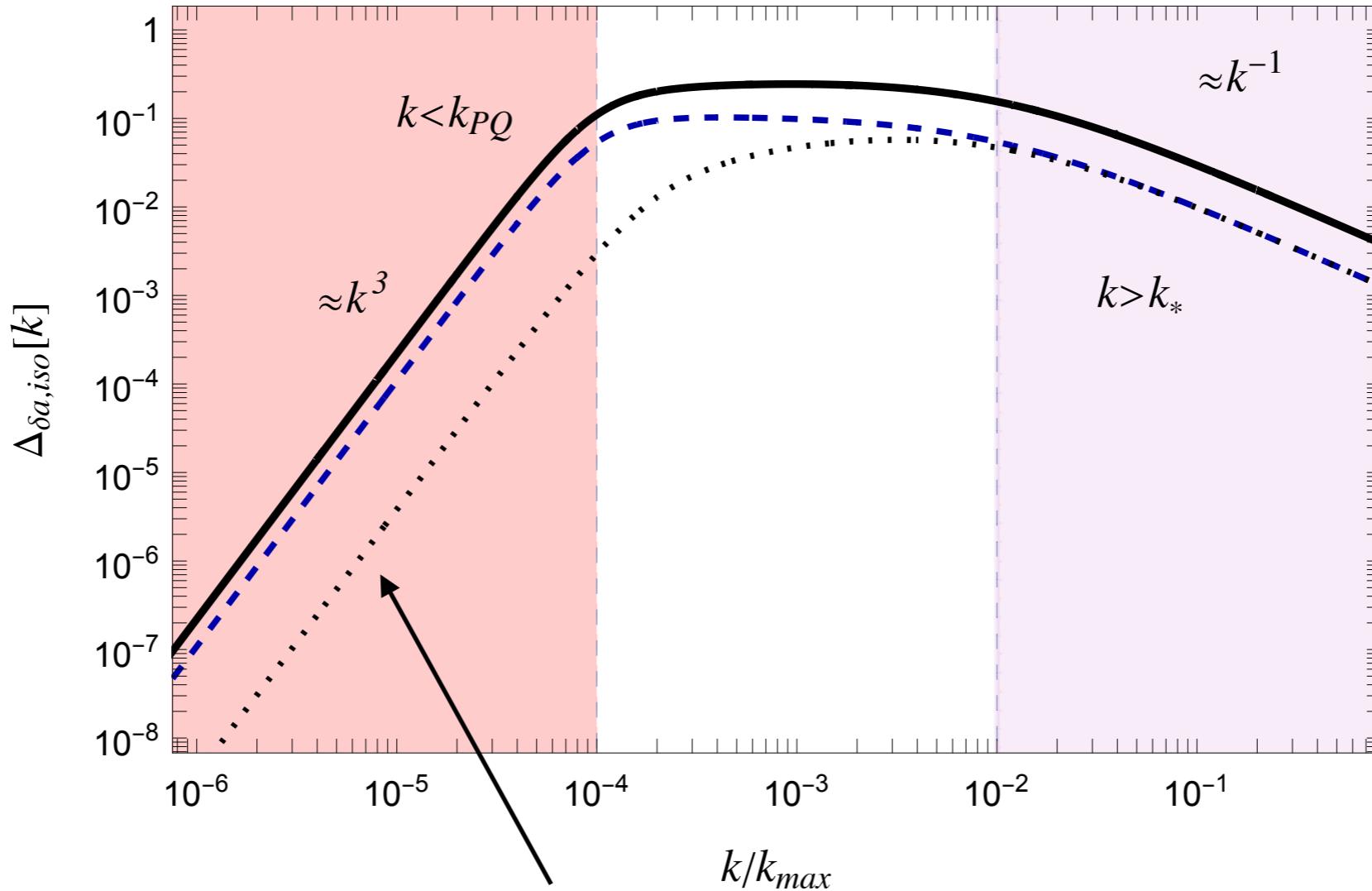
$$\frac{d\rho_a^{\text{inf}}}{d \log k} = \frac{\Delta_a(\eta_e, k)}{2} [g^{00}|\dot{u}_k|^2 - (g^{ij}k_i k_j - m_a^2)|u_k|^2]$$

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

sizeable contribution to relic abundance

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

isocurvature power spectrum



$$\Delta_{\delta_a}^{\text{iso}}(\eta, k) \approx \frac{\Omega_{a,\text{inf}}^2}{\Omega_a^2} \frac{k^3}{3 \log^2(k_*/k_{PQ}) k_{PQ}^3}$$

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

isocurvatures: mini-clusters + cosmological bounds

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

$$M_s \approx 2 \times 10^{-15} M_\odot \times (\mu\text{eV}/m)^{3/2}$$

[Gorghetto et al [2203.10100](#)]

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+ a DM isocurvature power spectrum peaked at small scales parametrized as

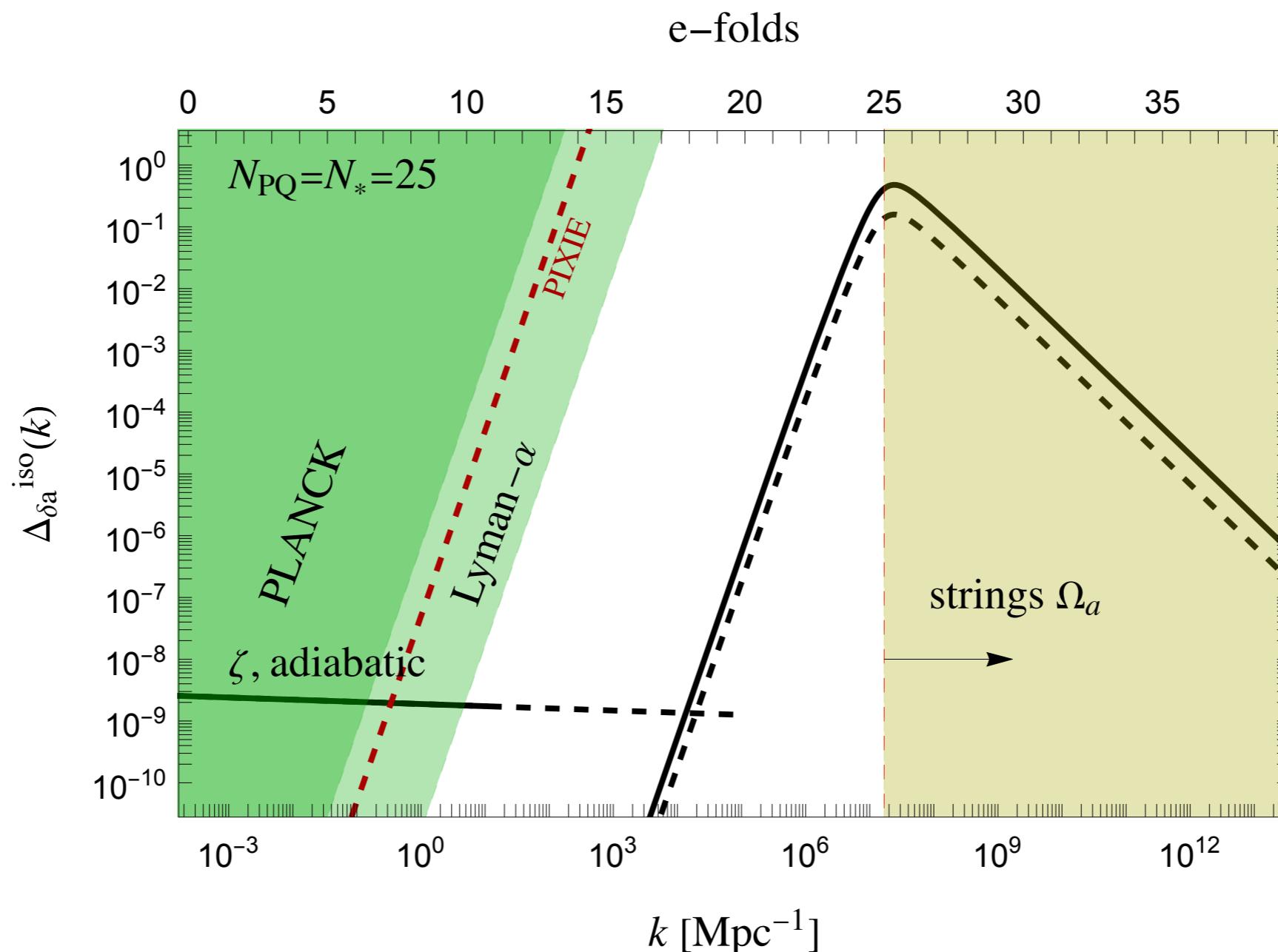
$$\Delta_{\text{iso}} = |f_{\text{iso}}|^2 A_s (k/k_0)^3 \quad \begin{aligned} A_s &= 2 \times 10^{-9} \\ k_0 &= 0.05/\text{Mpc} \end{aligned}$$

[see also Feix et al]

tested with CMB and LSS dataset!

* applies to a broad class of scenarios

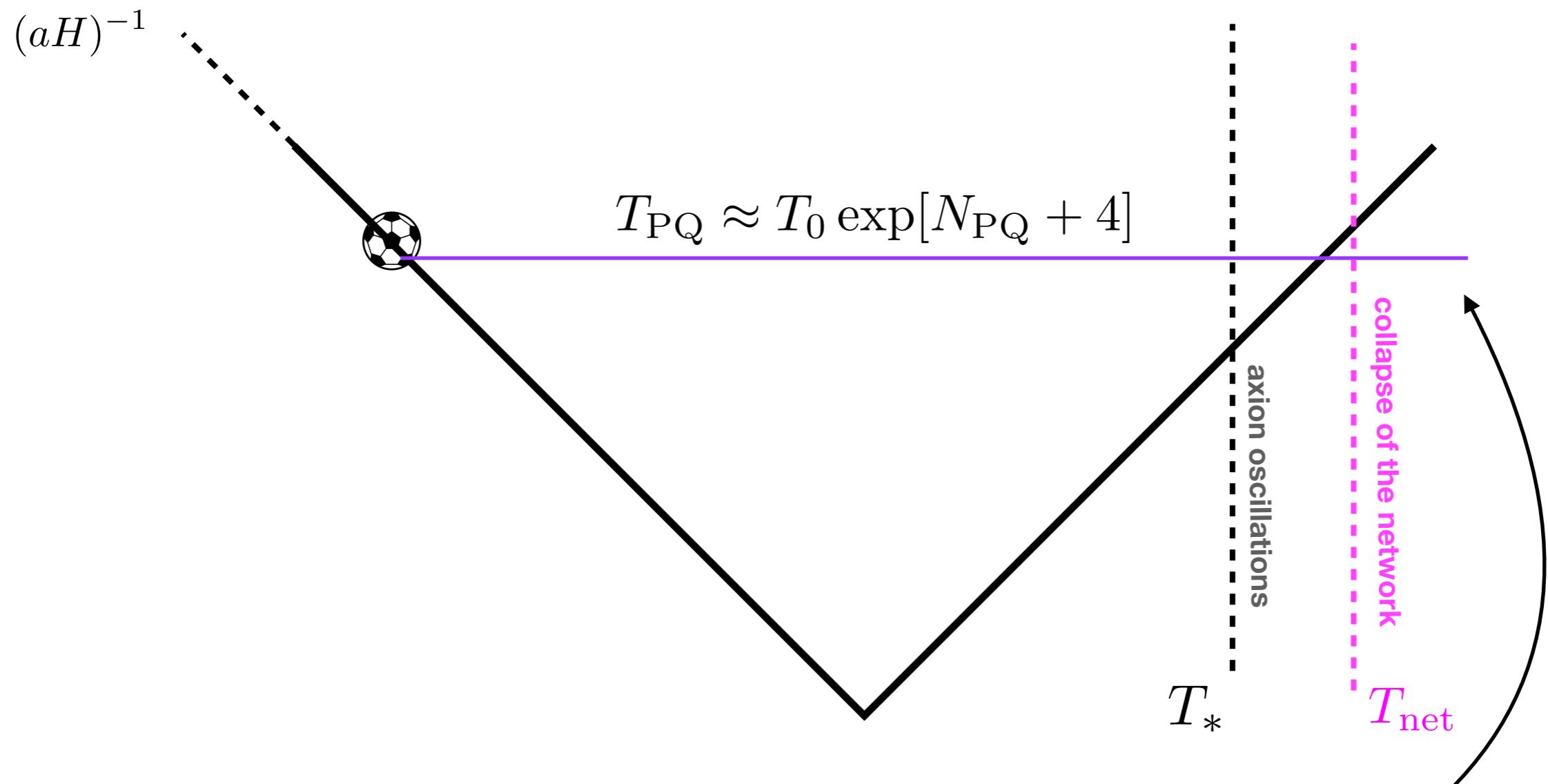
qcd axion without strings and isocurvatures



[cosmological bounds a bit far from interesting region: constraint from strings]

axion abundance from the string network

inhomogeneities generated at the PQ phase transition leave the horizon immediately



they re-enter the horizon at T_{net} , before or after the QCD transition
when they start to evolve and annihilate

strings for the meso-inflationary axion

they behave like a long lived network

$$T_{\text{net}} \lesssim T_* \quad \rho_{\text{dw}} \approx 9m_a(T)f_a^2 H(T)$$

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

[see also Harigaya, Wang;
Baratella, Pomarol, Rompineve]

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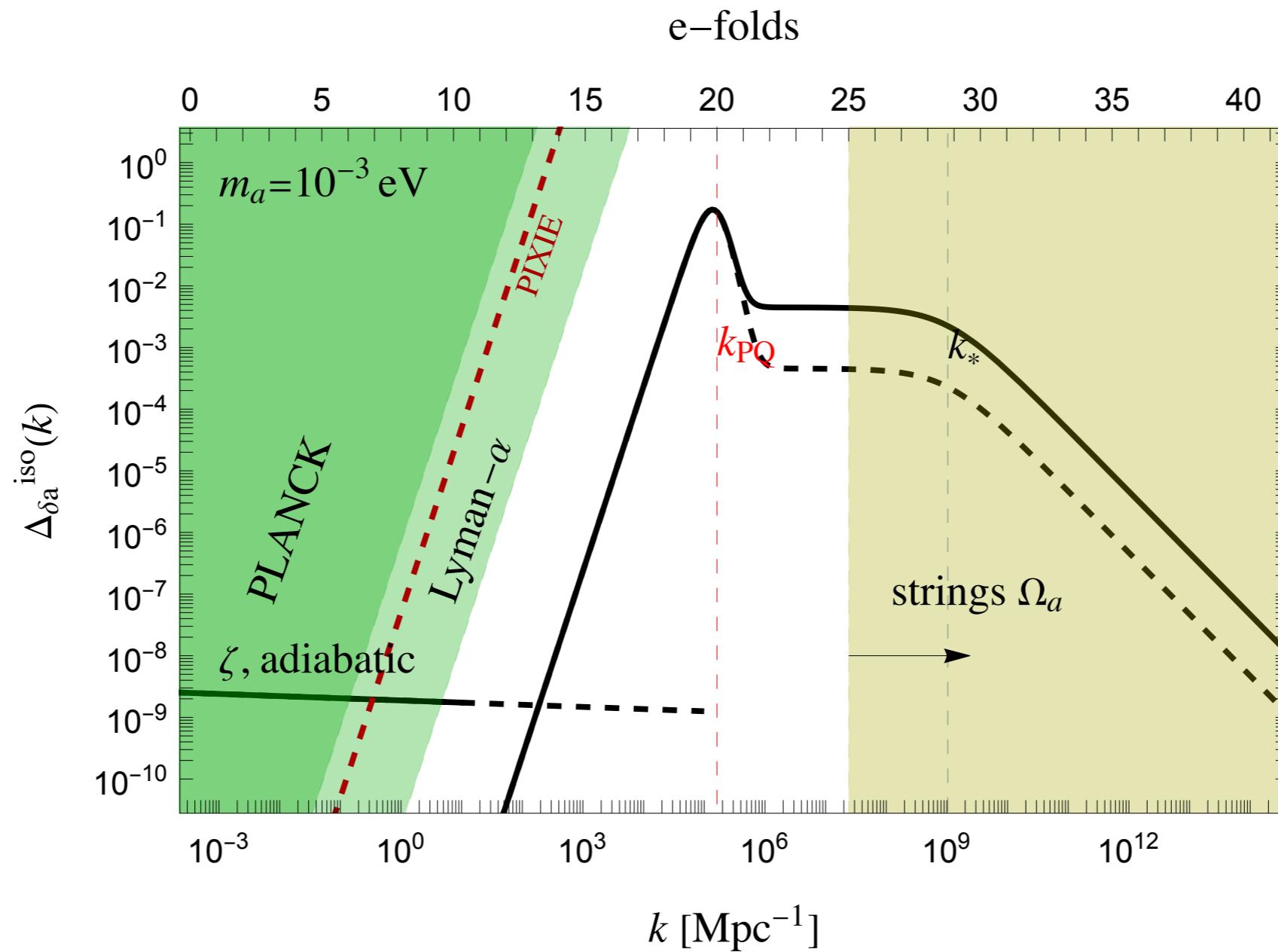
$$\Omega_a^{\text{dw}} \sim \Omega_a^{\text{mis}} \frac{\Lambda_{\text{QCD}}}{T_{\text{net}}}$$

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

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

[a scenario where DM is reproduced at **small fa**]

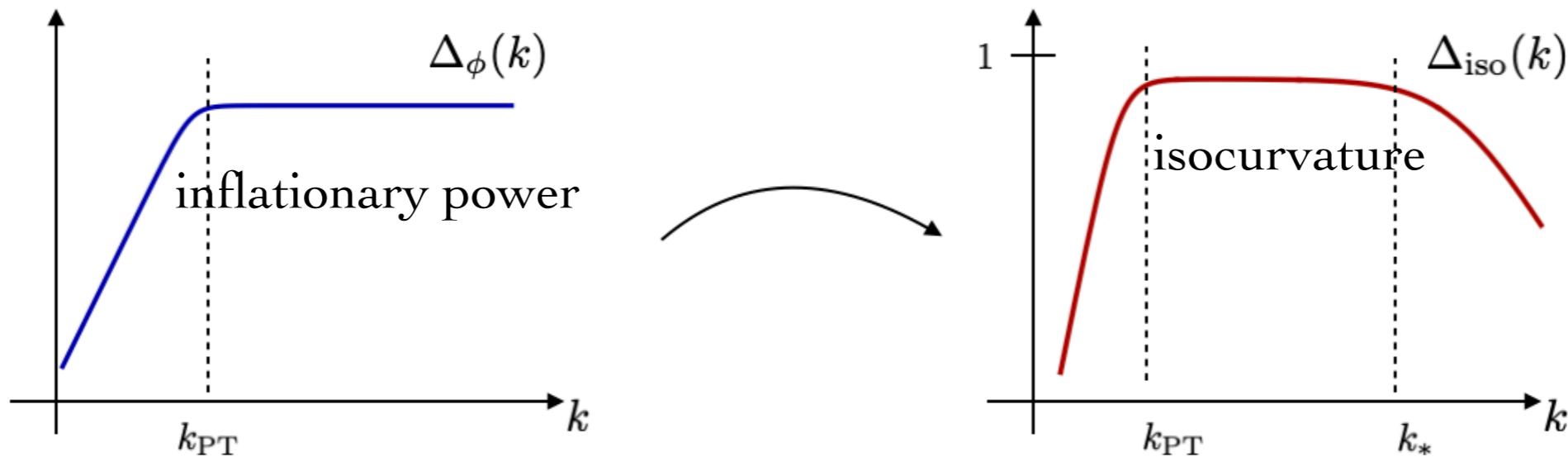
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[still far from cosmological bounds: maybe constraints from miniclusters?]

more generic phase transitions producing DM

if DM is a light scalar that emerges at the end of inflation:

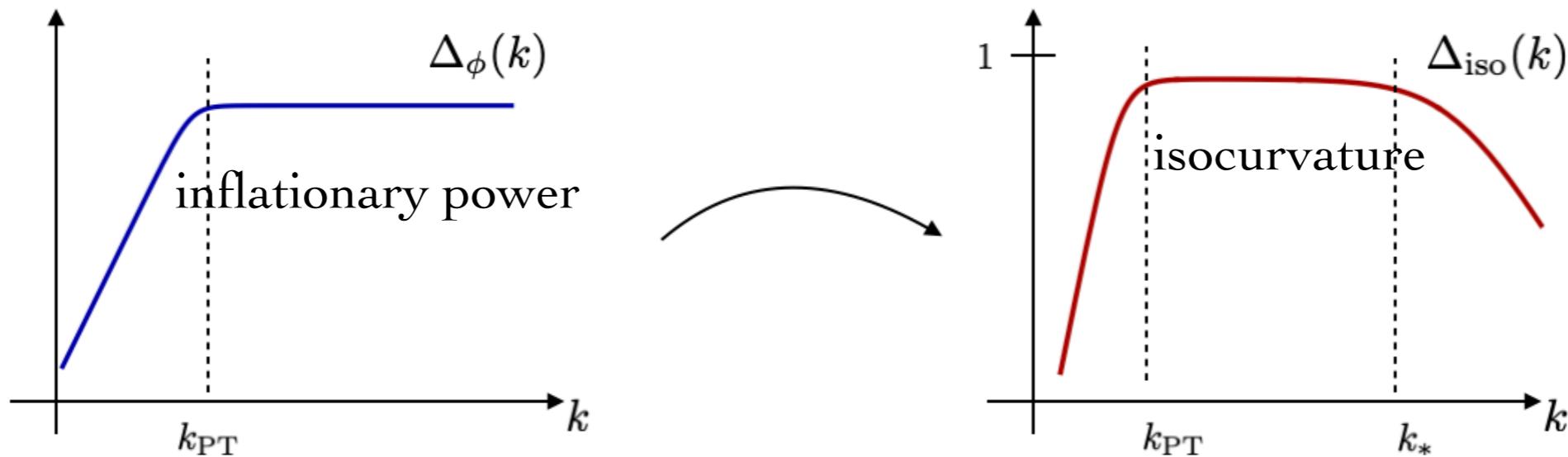


sizeable power spectrum + plateau
phase transition producing DM during inflation
[for example axion-like alps without strings]

$$\left(\frac{n}{s}\right)_{\text{today}} \approx \sqrt{\frac{M_{Pl}}{m}} \left(\frac{H_I}{2\pi M_{Pl}}\right)^2 \gg 1$$

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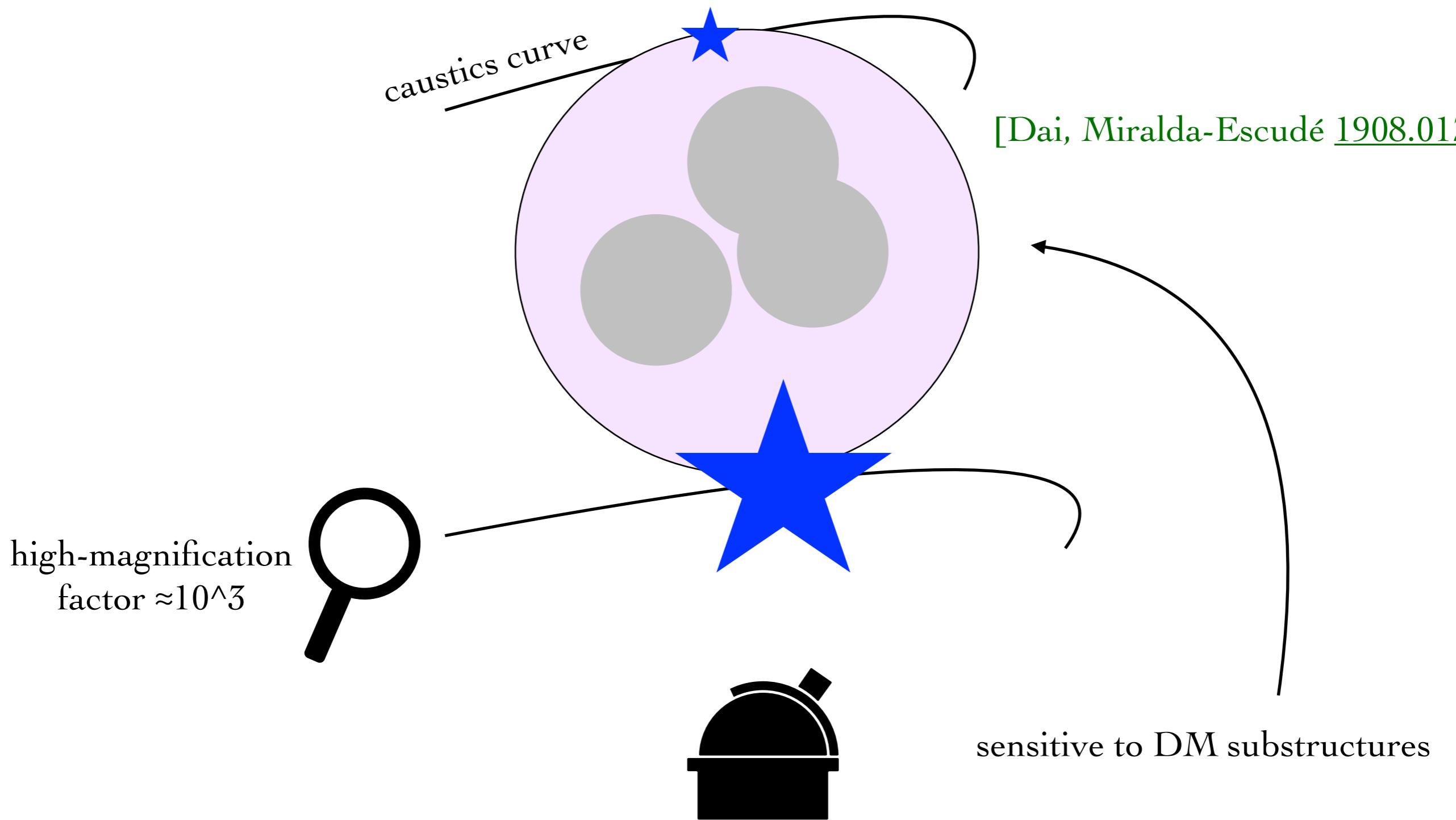
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miniclusters at the scales corresponding to the plateau
can we constrain them?

[in progress with Cabras, Garani, Redi]

photometric lensing for DM miniclusters



convergence depends on mass distribution

claim to be sensitive to $1/10^4$ variation to the lensing convergence $\rho \times r / \Sigma_{\text{crit}}$

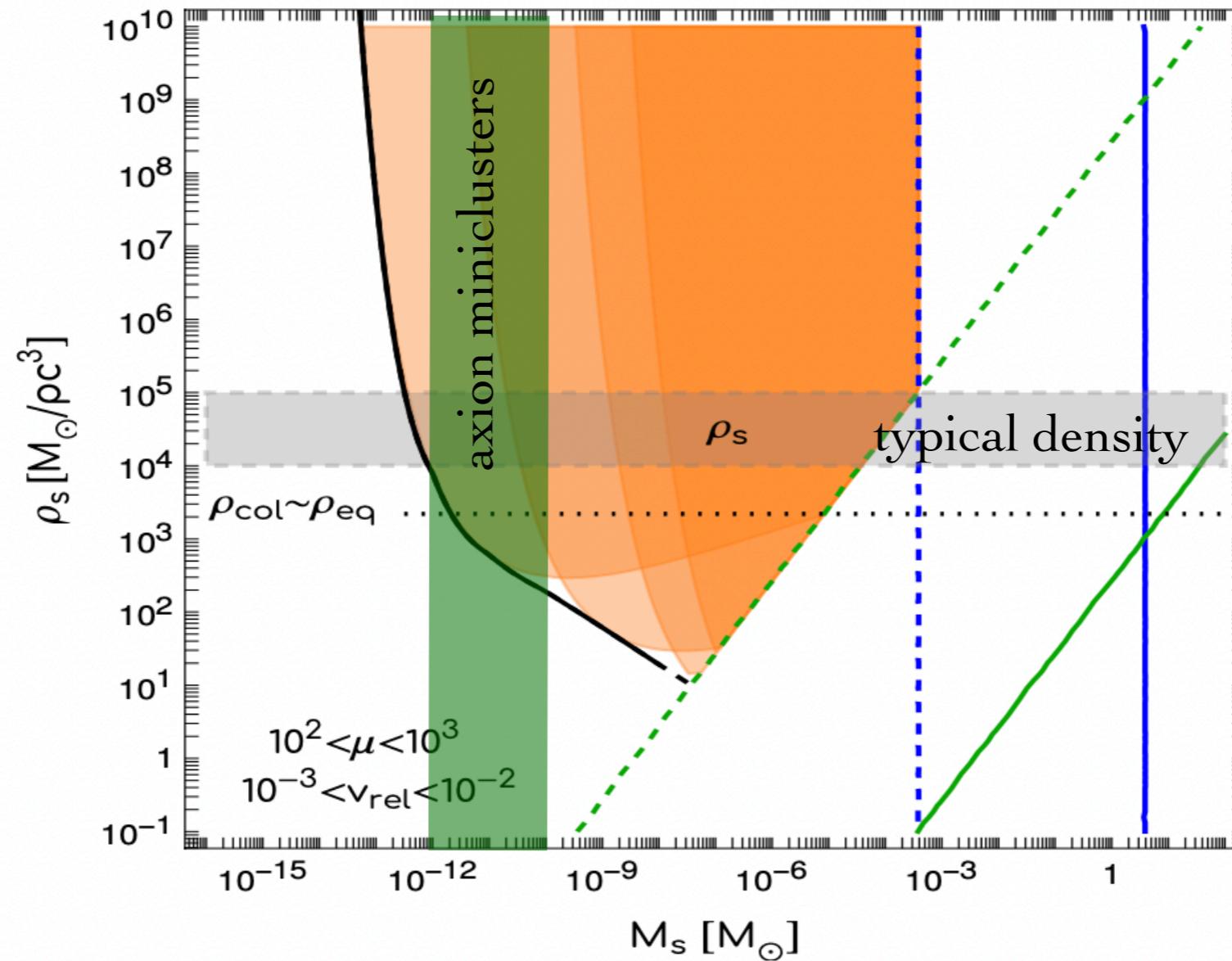
$$\Delta(q)^2 = \frac{q^2}{2\pi} \frac{\Sigma_{cl}}{\Sigma_c^2} \int \frac{dM}{M} \frac{df(M)}{dM} |\rho_{\text{NFW}}(q; M_s)|^2$$

mini-cluster
mass distribution

$$\Delta(q) \gtrsim 10^{-3} \quad L = 2\pi/q \in [10, 10^4] \text{AU}$$

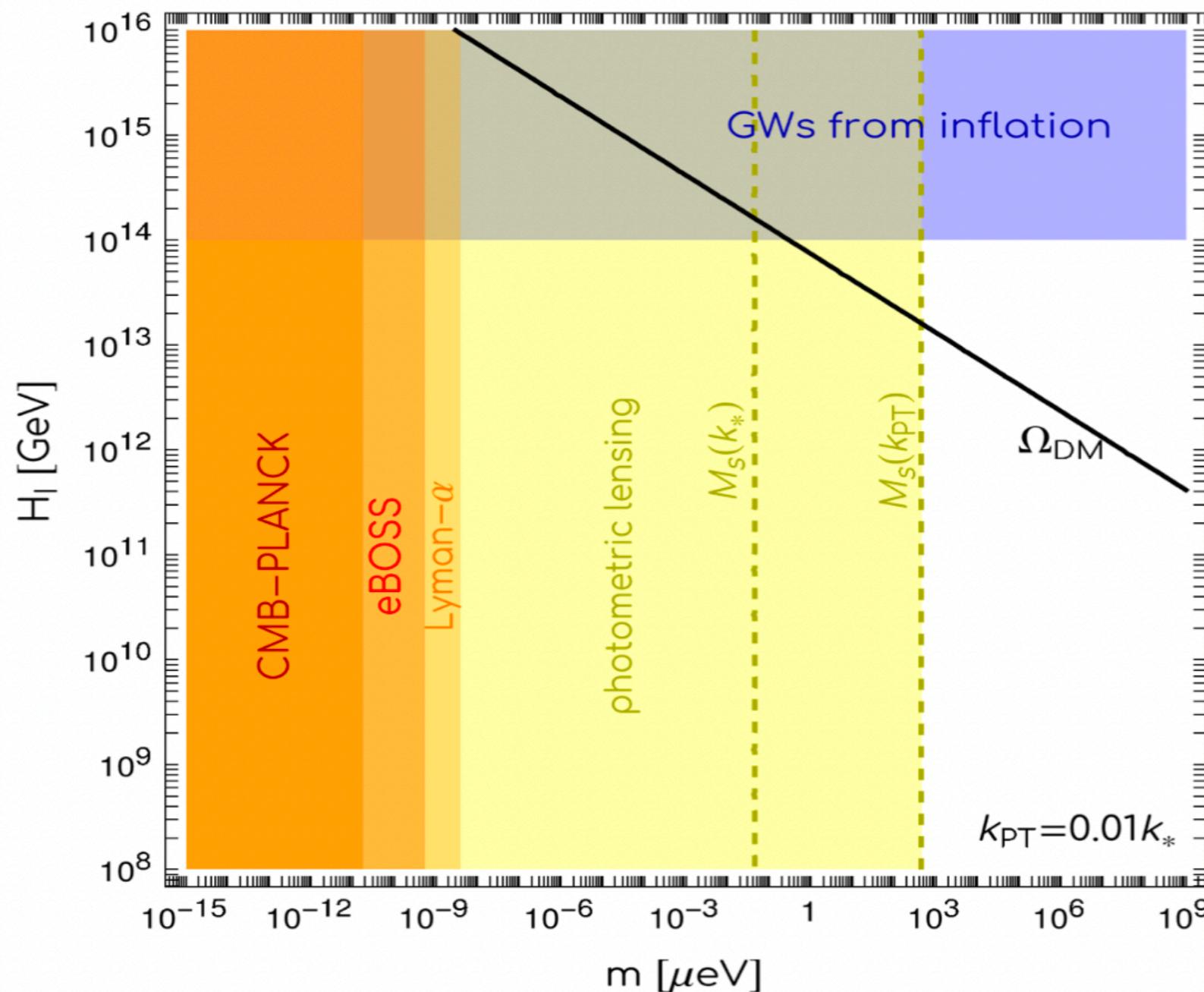
[Dai, Miralda-Escudé [1908.01773](#);
Arvanitaki et al [1909.11665](#)]

photometric lensing constraints



[comparison with Arvanitaki et al [1909.11665](#)]

summary (mass vs hubble) for light scalar DM



[preliminary]

phase transition producing light DM during inflation

conclusions

axion + isocurvature

so far less explored scenario for axion dark matter, with signatures

lyman-alpha + miniclusters/minihalos/stars..

long-lived domain wall network

outlook

interesting to explore the cases:

- of ALP dark matter
- of phase transitions during inflation (heavy to light, conformal to minimal,..)

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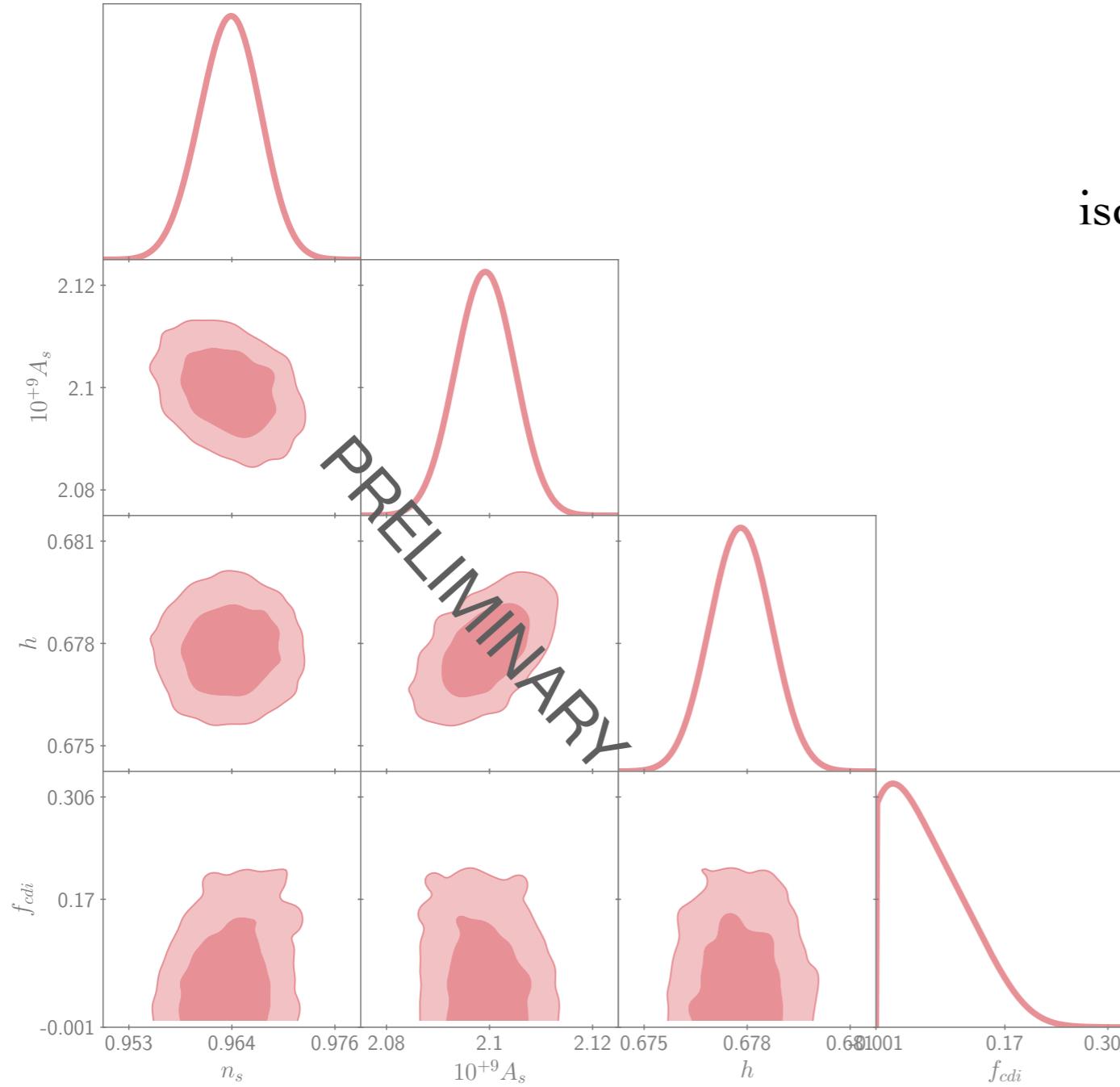
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THANK YOU!

BACKUP

cosmological tests of DM produced inflationary



iso DM affects CMB TT-power spectrum
can be studied in linear theory

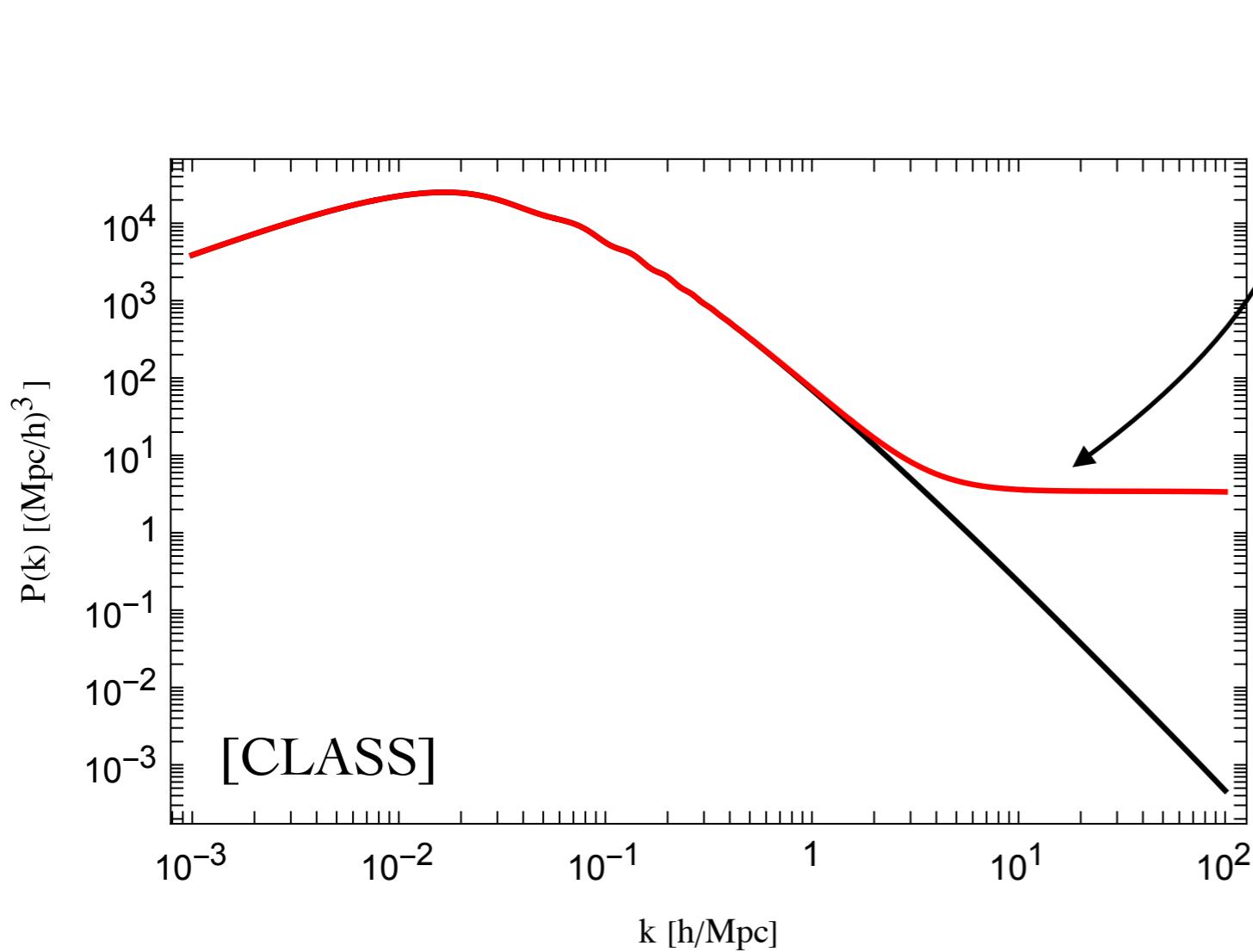
$$\delta C_\ell / C_\ell \propto |f_{\text{iso}}|^2 (\ell / \ell_{\text{eq}})$$

[PLANCK likelihoods]

$$|f_{\text{iso}}| \lesssim 0.2$$

cosmological tests of DM produced inflationary

Matter Power Spectrum



$$P_m(k) \propto \frac{1}{k^3} (\Delta_\zeta(k) + \beta \Delta_{\text{iso}}(k)) \propto \beta \frac{|f_{\text{iso}}|^2}{k_0^3}$$

effects grows with k
(like SMEFT at colliders...)

$$|f_{\text{iso}}| \lesssim 0.003$$

[recast of Murgia et al,
[1903.10509](#)]