Towards a new scenario of QCD clump formation

based on 2111.05785

by NK, K. Kogai (Nagoya U.), Y. Urakawa (KEK)

Naoya Kitajima

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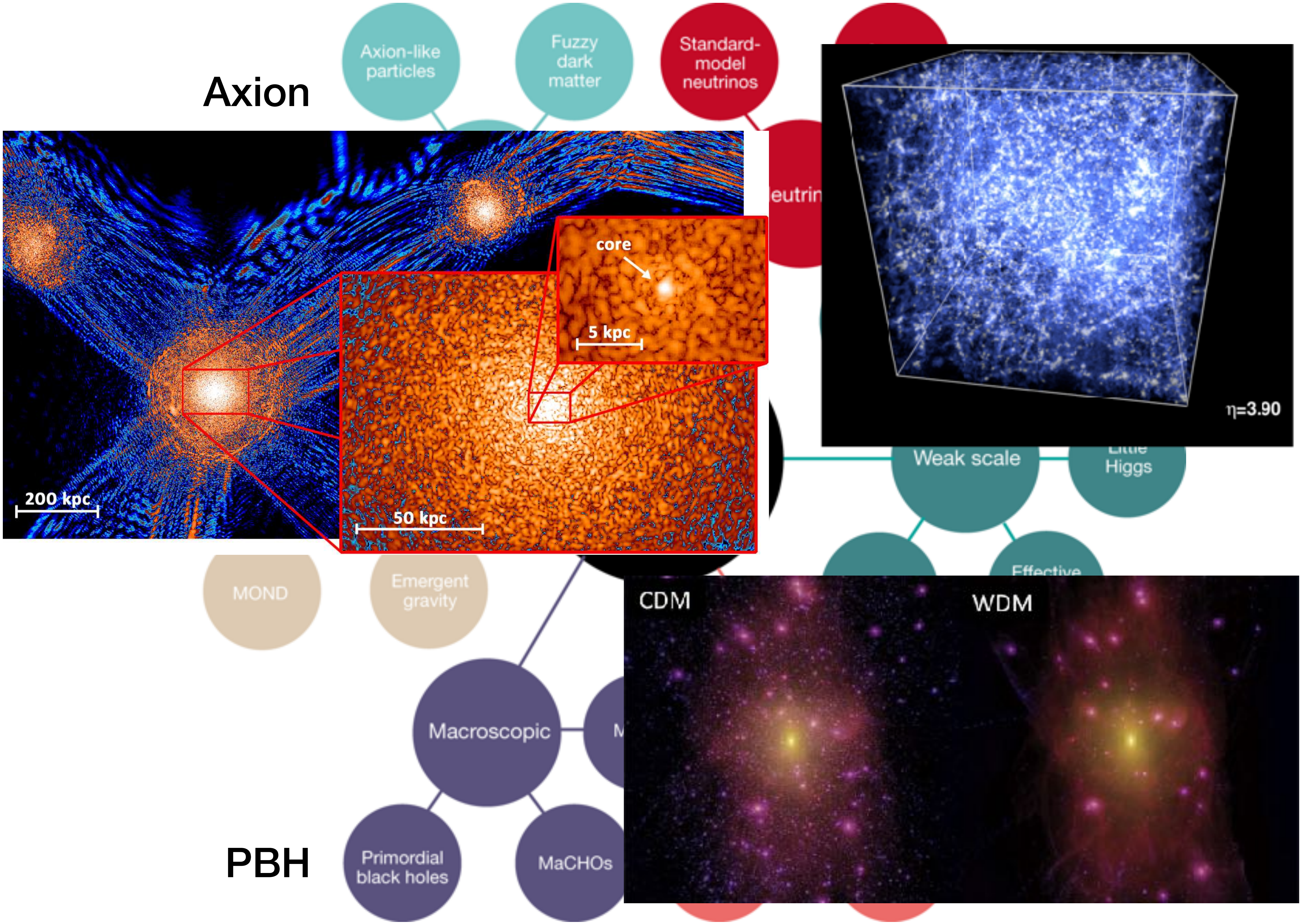
I. Introduction

Bertone & Tait, Nature 562, 51-56(2018)



Bertone & Tait, Nature 562, 51-56(2018)

QCD axion <u>generally</u> predicts characteristic imprints on the structure of the Universe

QCD axion in particle physics

$$\mathcal{L}_{\cancel{CP}} = -\frac{\alpha_s}{8\pi}\theta G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

Measurement of neutron electric dipole moment:

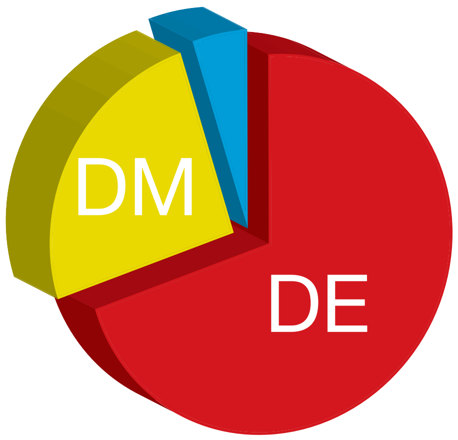
$|\theta| < 1.3 \times 10^{-10}$ (strong CP problem)

$\downarrow$

θ : dynamical field = QCD axion

Peccei, Quinn (1977), Weinberg (1978), Wilczek (1978)

QCD axion in cosmology



= dark matter candidate

Preskill, Wise, Wilczek (1983), Abbott, Sikivie (1983), Dine, Fischler (1983)

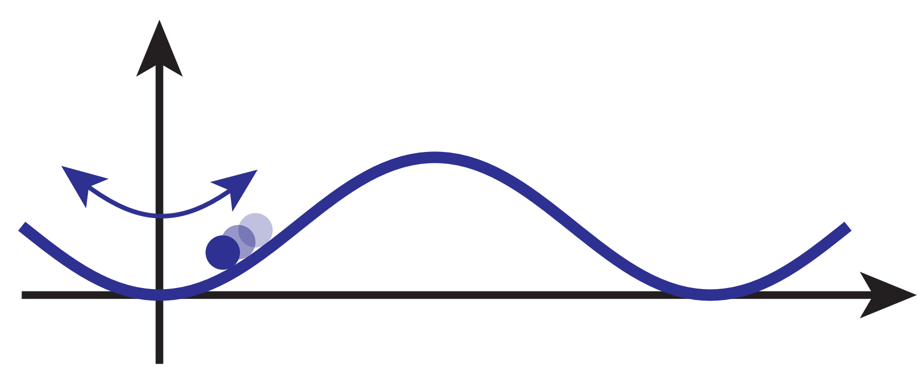
QCD axion potential

- temperature-dependent axion mass: $$\boxed{m_a(T) = \begin{cases} \chi\left(\frac{T_c}{T}\right)^b & T > T_c \\ m_a & T < T_c \end{cases}}$$

$$b \simeq 8.16,\ T_c \simeq 0.15\mathrm{GeV}$$ Borsanyi et al 1606.07494

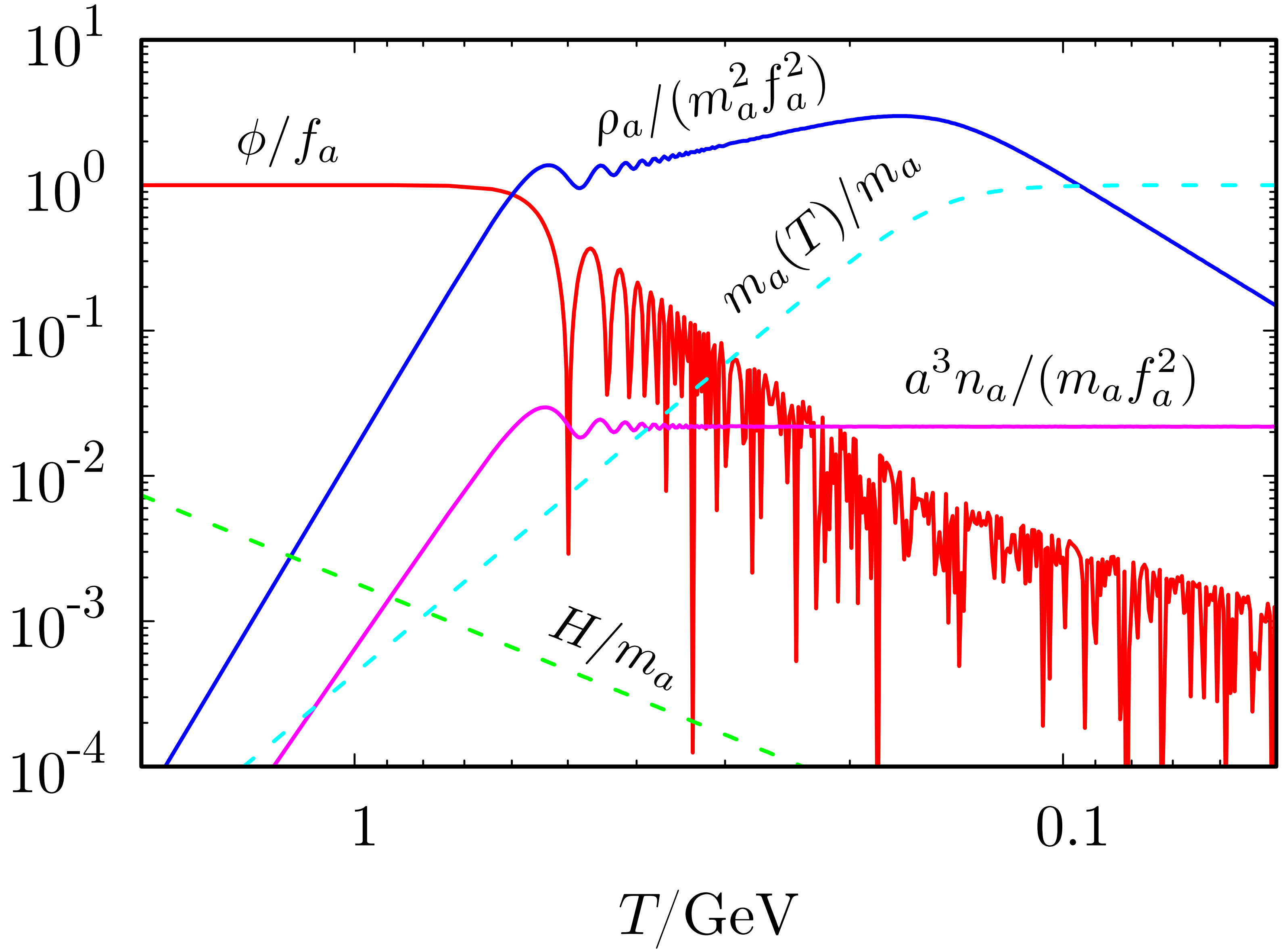
- zero-temperature axion mass: $$m_a \simeq 6\mu\mathrm{eV}\left(\frac{10^{12}\mathrm{GeV}}{f_a}\right)$$

- (typical) axion potential: $$V(\phi) = m_a^2(T) f_a^2\left(1 - \cos\left(\frac{\phi}{f_a}\right)\right)$$



Misalignment production of the QCD axion

$$\ddot{\phi} + 3H\dot{\phi} + V_\phi = 0$$

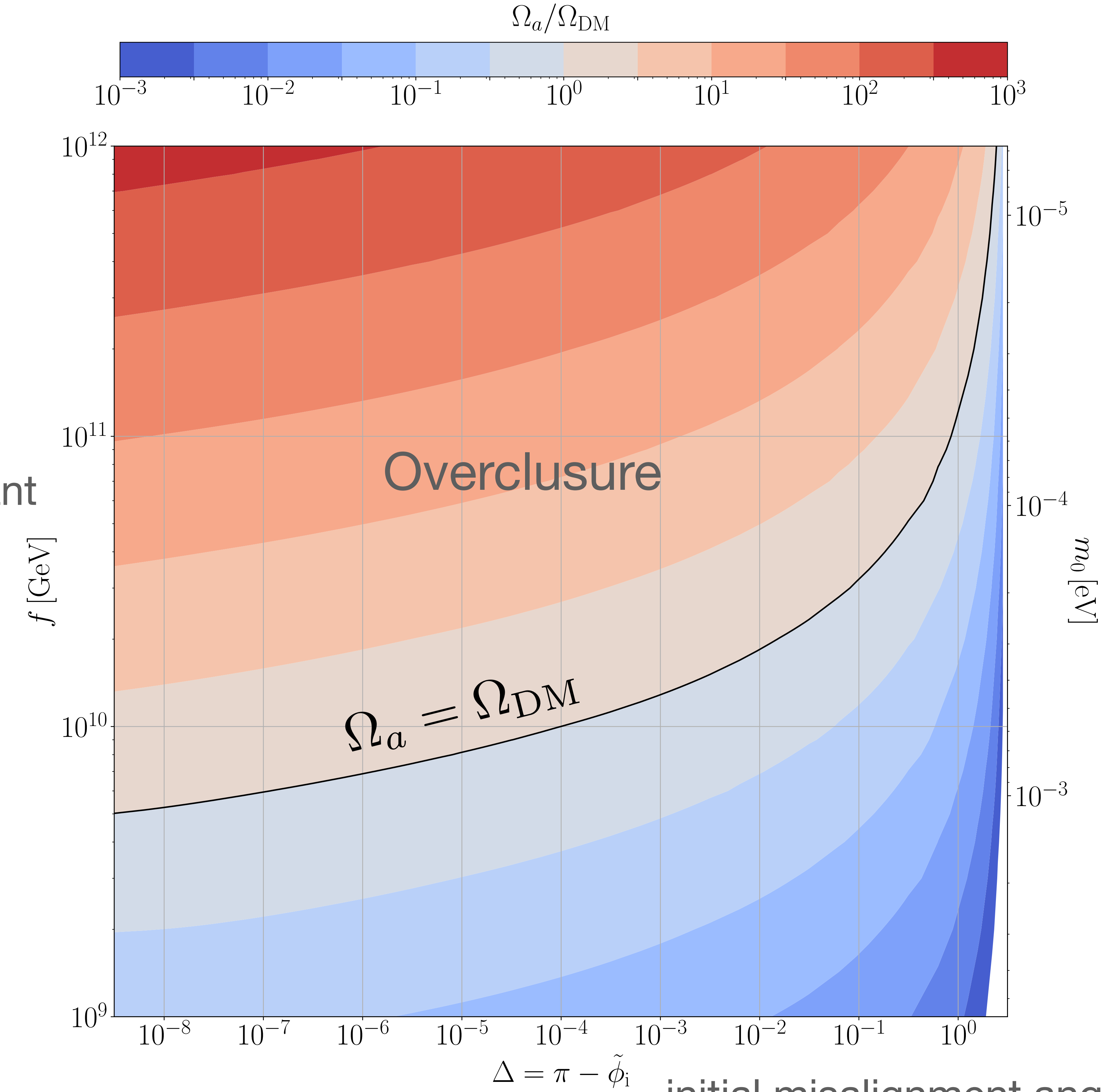


$f_a = 10^{13}\mathrm{GeV}$

$\theta_i = 1$

$$T_{\rm osc} \simeq 1\,\mathrm{GeV}\left(\frac{60}{g_*}\right)^{0.082}\left(\frac{10^{12}\mathrm{GeV}}{f_a}\right)^{0.16},\;\; \Omega_a h^2 \simeq 0.15\,\theta_i^2\left(\frac{60}{g_*}\right)^{0.42}\left(\frac{f_a}{10^{12}\mathrm{GeV}}\right)^{1.16} F_{\rm ah}(\theta_i)$$

Axion DM abundance with hilltop initial condition

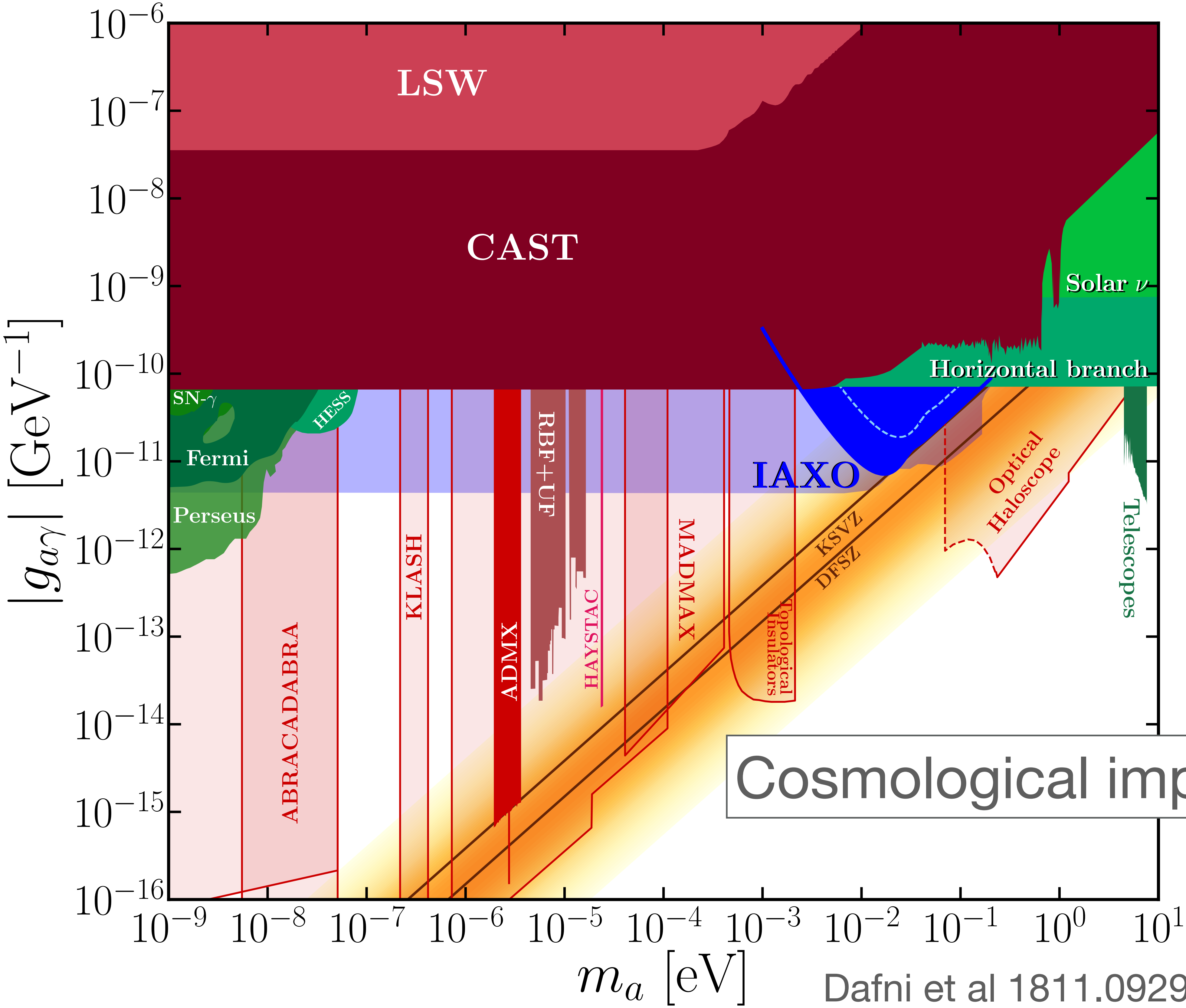


decay constant

axion mass

initial misalignment angle

Current status of QCD axion search



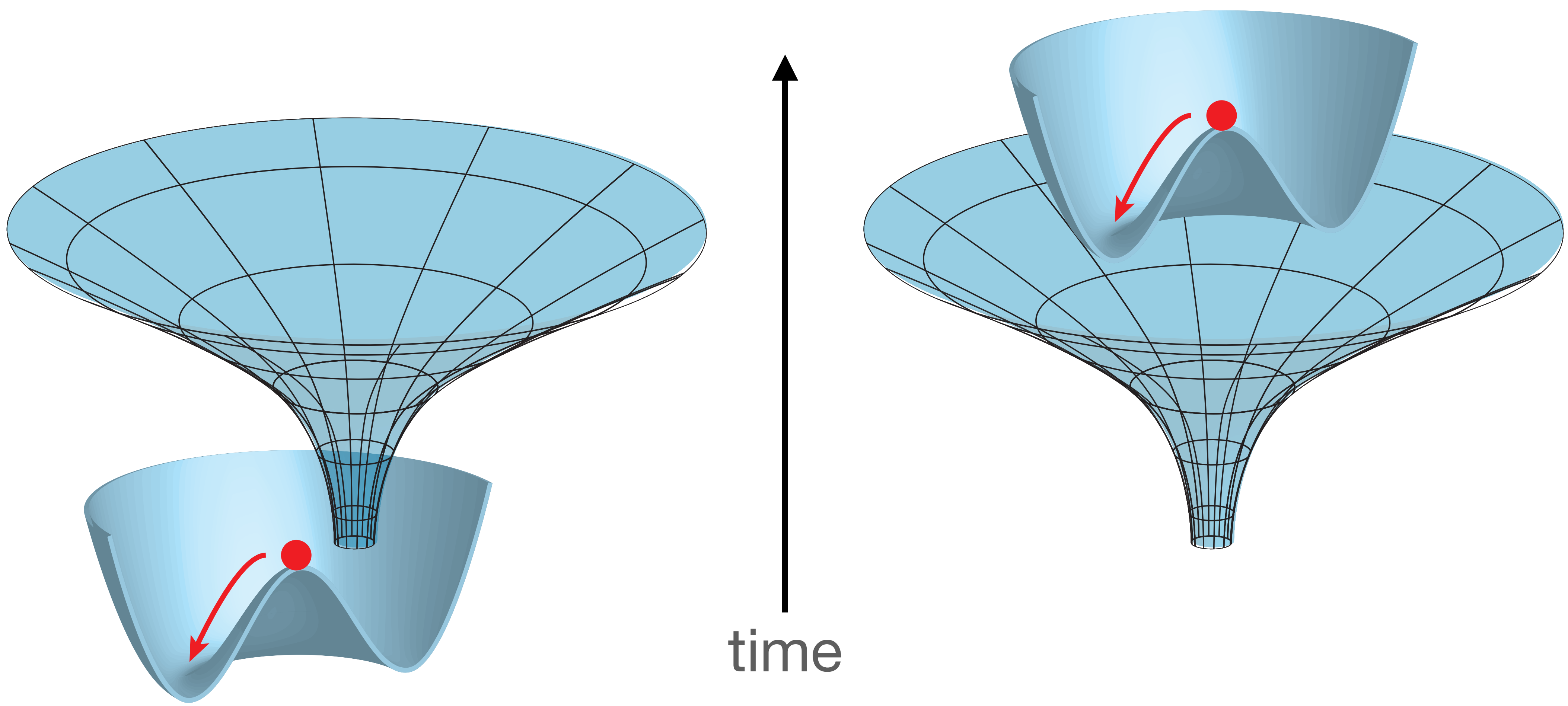
Cosmological imprints?

Dafni et al 1811.09290

Axion cosmology — two scenarios

Pre-inflationary scenario

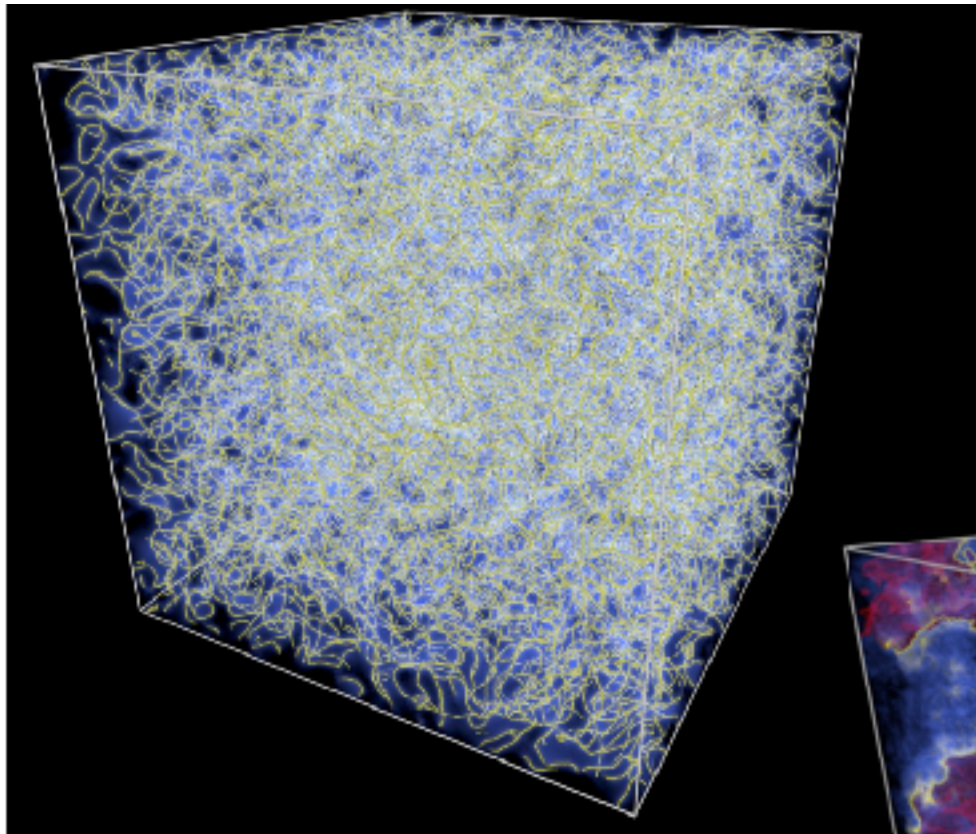
Post-inflationary scenario



- large-scale isocurvature

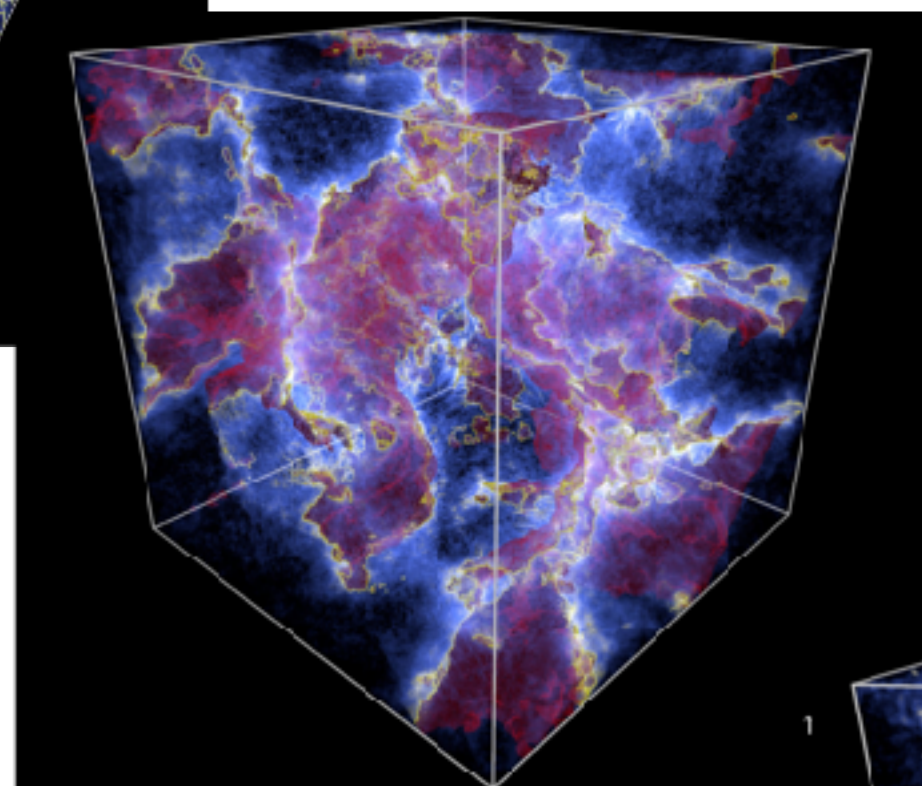
- O(1) isocurvature fluctuation
- Topological defect

Post-inflationary scenario

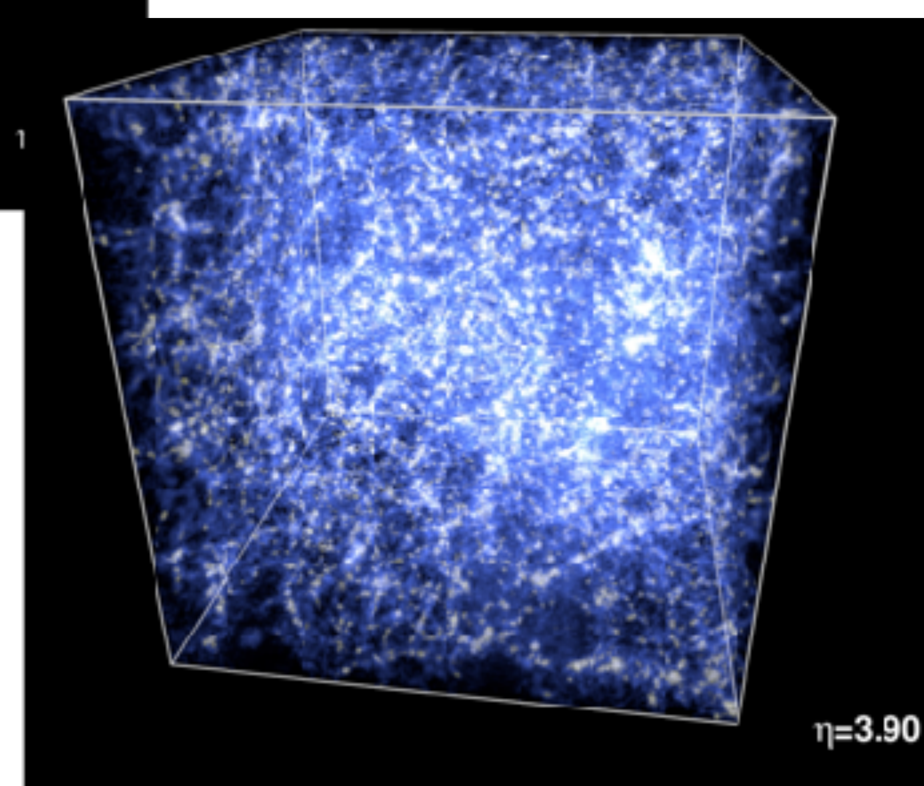


cosmic string

cosmic string & domain wall



axion minicluster



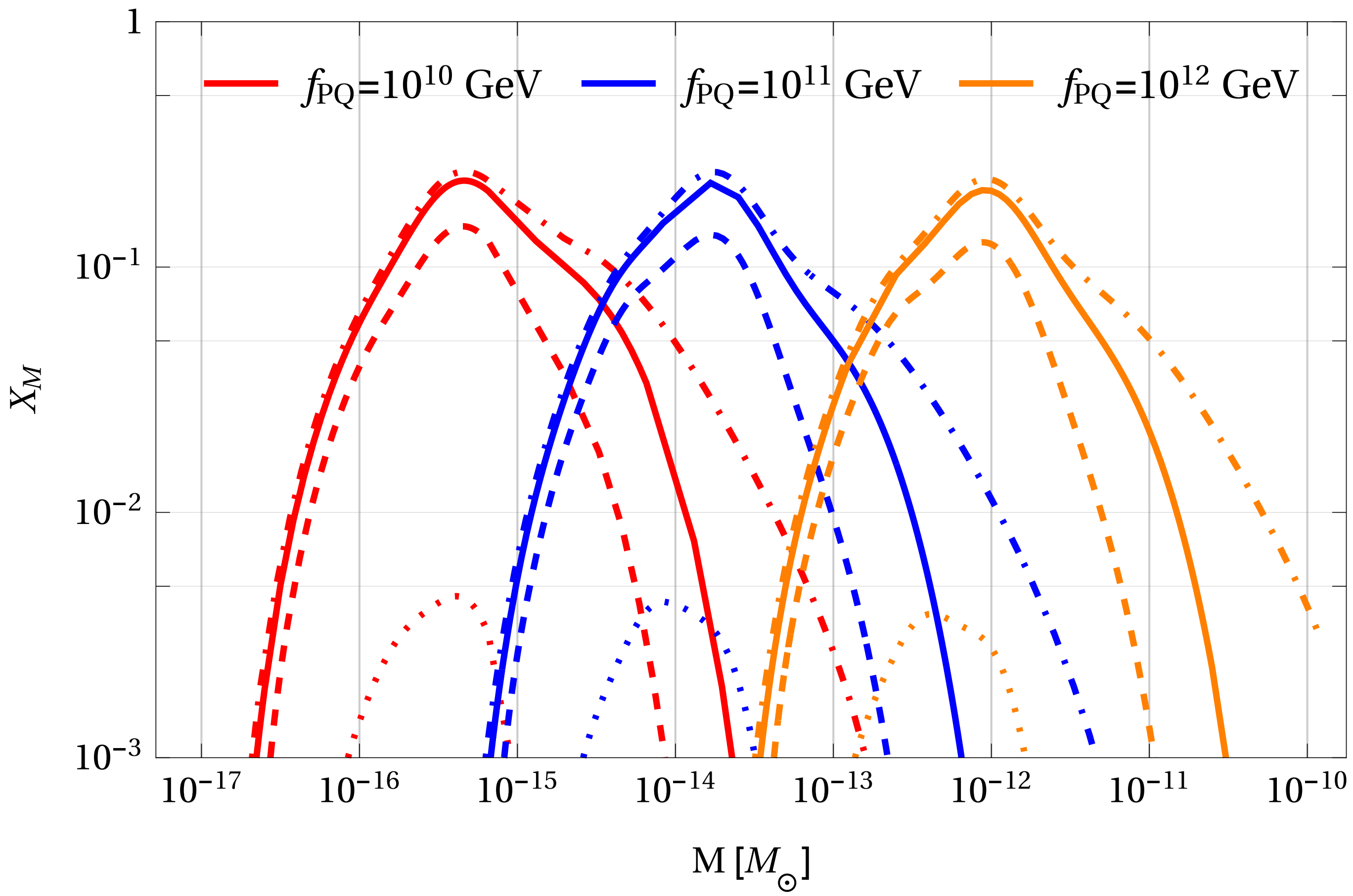
$$\Omega_a = (0.102 \pm 0.02) \times (f_a/10^{11}\mathrm{GeV})^{1.187}$$

$$f_a = (2.27 \pm 0.33) \times 10^{11}\mathrm{GeV}$$

$$(m_a = 25.2 \pm 3.6\mu\mathrm{eV})$$

Buschmann, Foster, Safdi 1906.00967

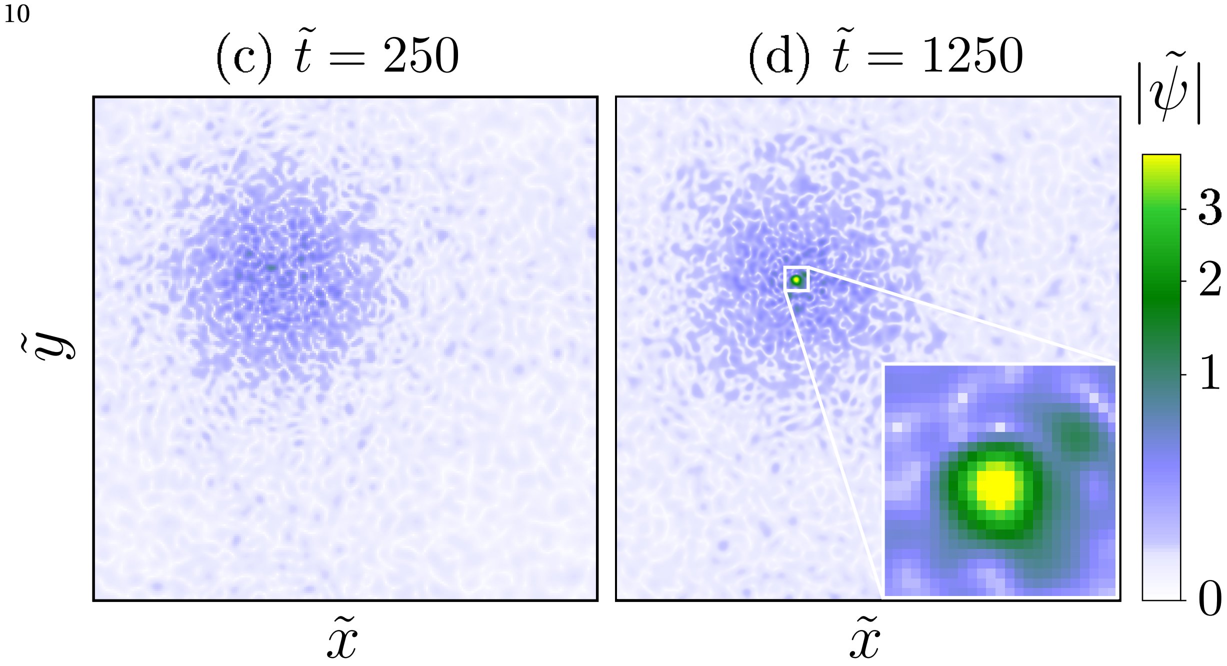
Axion minicluster



Enander, Pargner, Schwetz 1708.04466

Hogan, Rees (1988)
Kolb, Tkachev (1993)
Seidel, Suen (1994)

Axion star

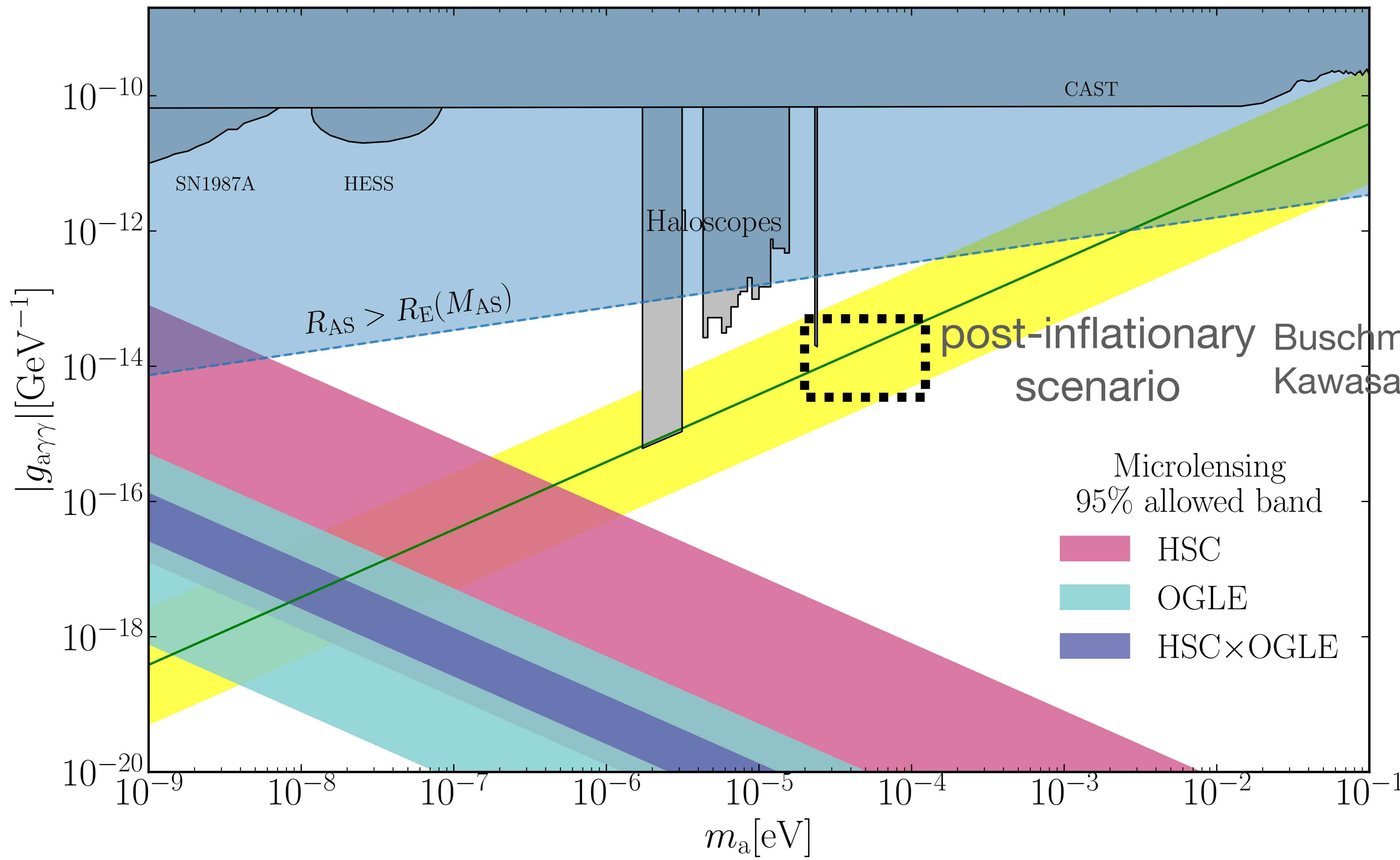


Levkov, Panin, Tkachev 1804.05857

see also Schiappacasse, Hertzberg 1704.04729

HSC & OGLE microlensing events as evidence of QCD axion star

Sugiyama, Takada, Kusenko 2108.03063



see also Fujikura, Hertzberg, Schiappacasse, Yamagichi 2109.04787
(constraints from EROS-2 & HSC)

II. Axion fluctuation & clustering

Possible amplification of QCD axion fluctuation

- O(1) isocurvature fluctuation (post-inflationary)

- cosmic string/domain wall decay (post-inflationary)

- resonant (tachyonic) instability from self-interaction

  Arvanitaki et al 1909.11665; Fukunaga, NK, Urakawa 2004.08929

- resonant (tachyonic) gauge field production

  Agrawal, Marques-Tavares, Xue 1708.05008; NK, Sekiguchi, Takahashi 1711.06590

- adiabatic (curvature & temperature) fluctuation

  Arvanitaki et al 1909.11665; Sikivie, Xue 2110.13157; NK, Kogai, Urakawa 2111.05785

(pre-inflationary scenario)

Strategy

Axion field evolution in curved spacetime:

$$\frac{1}{\sqrt{-g}}\partial_\mu\left(\sqrt{-g}g^{\mu\nu}\partial_\nu\phi\right)+\frac{\partial V(\phi,T)}{\partial\phi}=0$$

$$V(\phi,T)=m_a^2(T)f_a^2\left[1-\cos\left(\frac{\phi}{f_a}\right)\right]$$

Perturbing metric & temperature (energy-momentum tensor):

$$g_{\mu\nu}=\bar{g}_{\mu\nu}+\delta g_{\mu\nu},\quad T\to T+\delta T\ (\rho\to\rho+\delta\rho)$$

* linear perturbation

<u>Evolution of axion fluctuation sourced by adiabatic fluctuations</u>

(metric/temperature fluctuations)

Metric perturbation with Conformal Newtonian gauge:

$$ds^2 = -a^2(1-2\Phi)d\tau^2 + a^2(1+2\Psi)d\boldsymbol{x}^2$$

Perturbed (linearized) Einstein equations:

$$-3\mathcal{H}^2\Phi - 3\mathcal{H}\Psi' + \nabla^2\Psi = -4\pi G a^2 \delta\rho$$

$$\partial_i(\mathcal{H}\Phi + \Psi') = 4\pi G a^2(\rho + p)\partial_i v$$

$$-\mathcal{H}(\Phi' + 2\Psi) + \mathcal{H}^2\Phi - \frac{1}{3}\nabla^2(\Phi - \Psi) - \Psi'' - \frac{2a''}{a} = 4\pi G a^2 \delta p$$

Energy-momentum conservation: $T^{\mu}_{\nu;\mu} = 0$

$$\delta' + (1+w)\nabla^2 v + 3(c_s^2 - w)\mathcal{H}\delta + 3(1+w)\Psi' = 0$$

$$\mathcal{H}(1-3c_s^2)\partial_i v + \partial_i v' + \frac{c_s^2}{1+w}\partial_i\delta - \partial_i\Phi = 0$$

Radiation-dominated Universe & no anisotropic stress

$(c_s^2 = w = 1/3)$ $(\Psi = \Phi)$

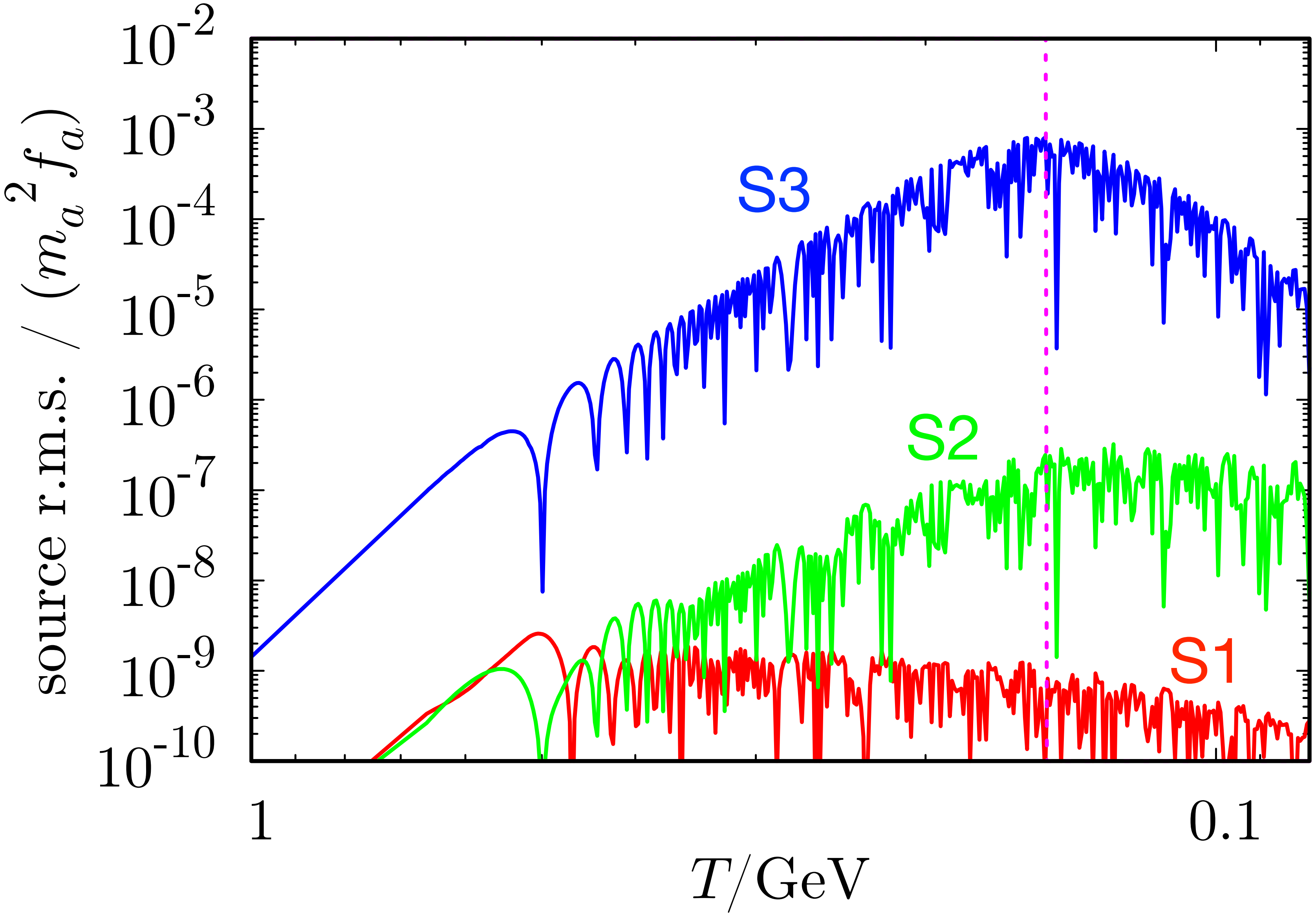
$$\delta_r'' - \frac{1}{3}\nabla^2\delta_r + 4\Phi'' + \frac{4}{3}\nabla^2\Phi = 0$$

$$\Phi'' + 4\mathcal{H}\Phi' - \frac{1}{3}\nabla^2\Phi = 0$$

Axion field evolution:

$$\phi'' + 2\mathcal{H}\phi' - (1-4\Phi)\nabla^2\phi + a^2 V_\phi + \underbrace{4\Phi'\phi' - 2a^2\Phi V_\phi + a^2 V_{\phi T}\delta T}_{\text{source terms}} = 0$$

Source for axion fluctuation

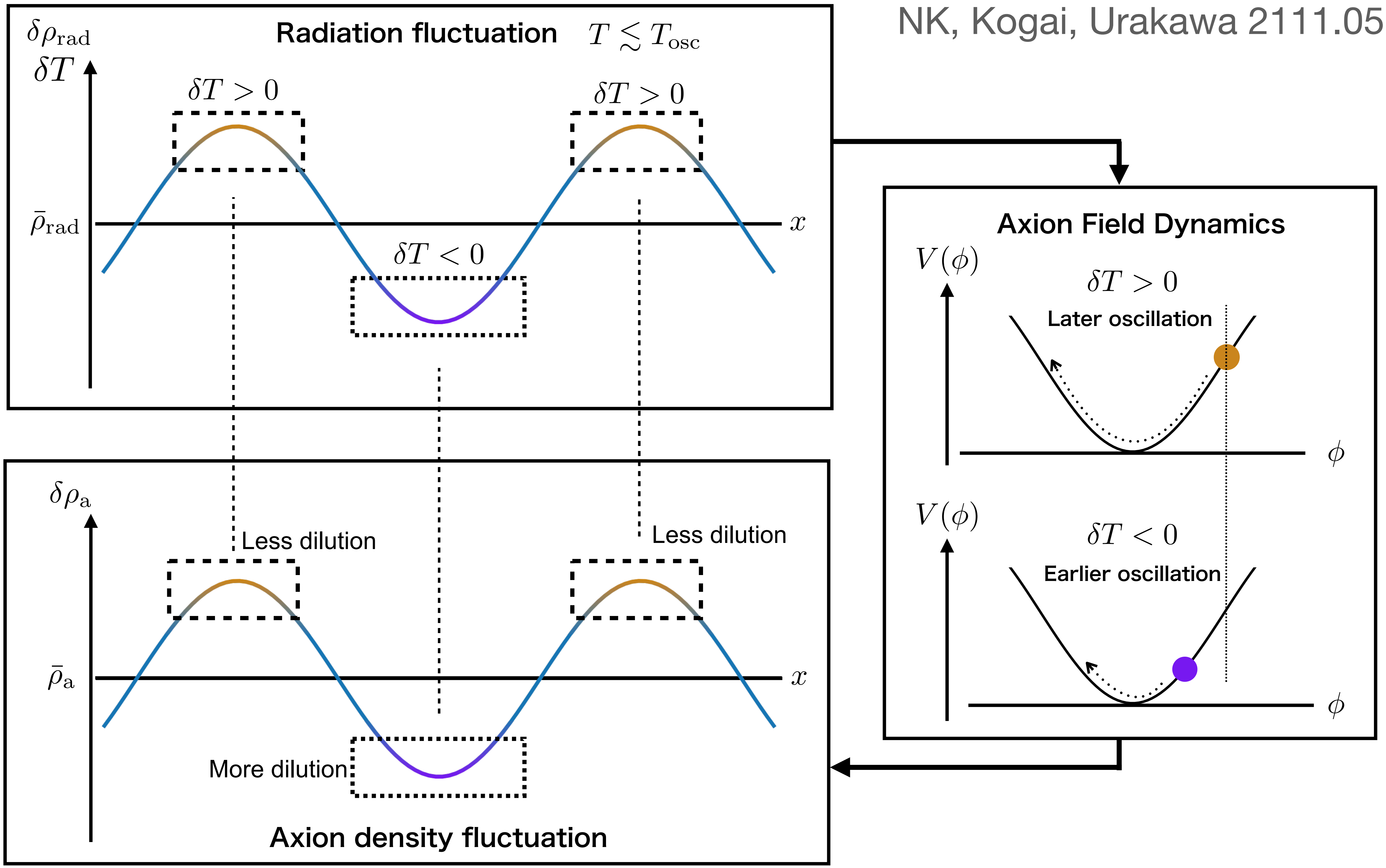


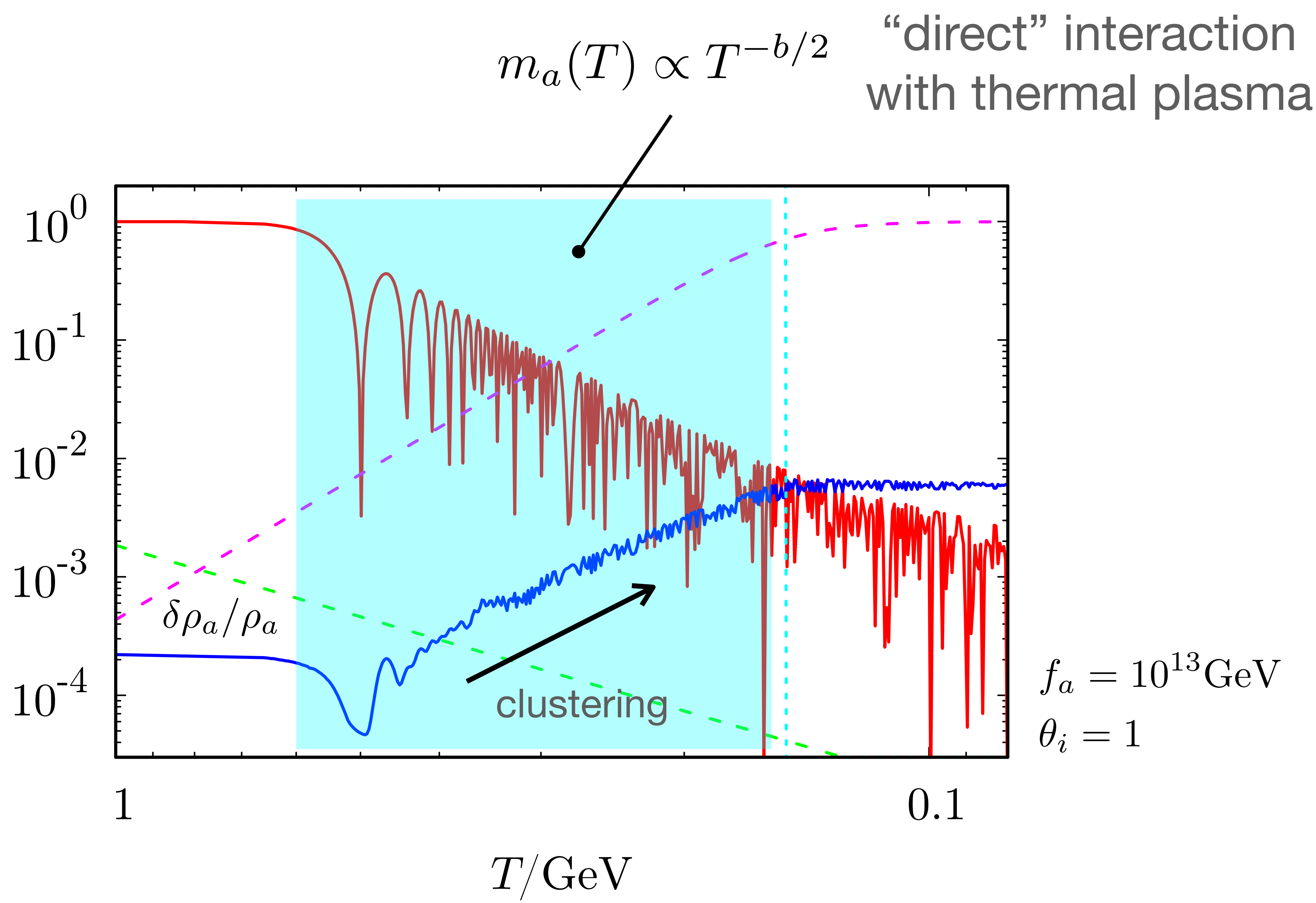
$$\phi'' + 2\mathcal{H}\phi' - (1-4\Phi)\nabla^2\phi + a^2 V_\phi + \underbrace{4\Phi'\phi'}_{\text{S1}} - \underbrace{2a^2\Phi V_\phi}_{\text{S2}} + \underbrace{a^2 V_{\phi T}\delta T}_{\text{S3}} = 0$$

"indirect" "direct"

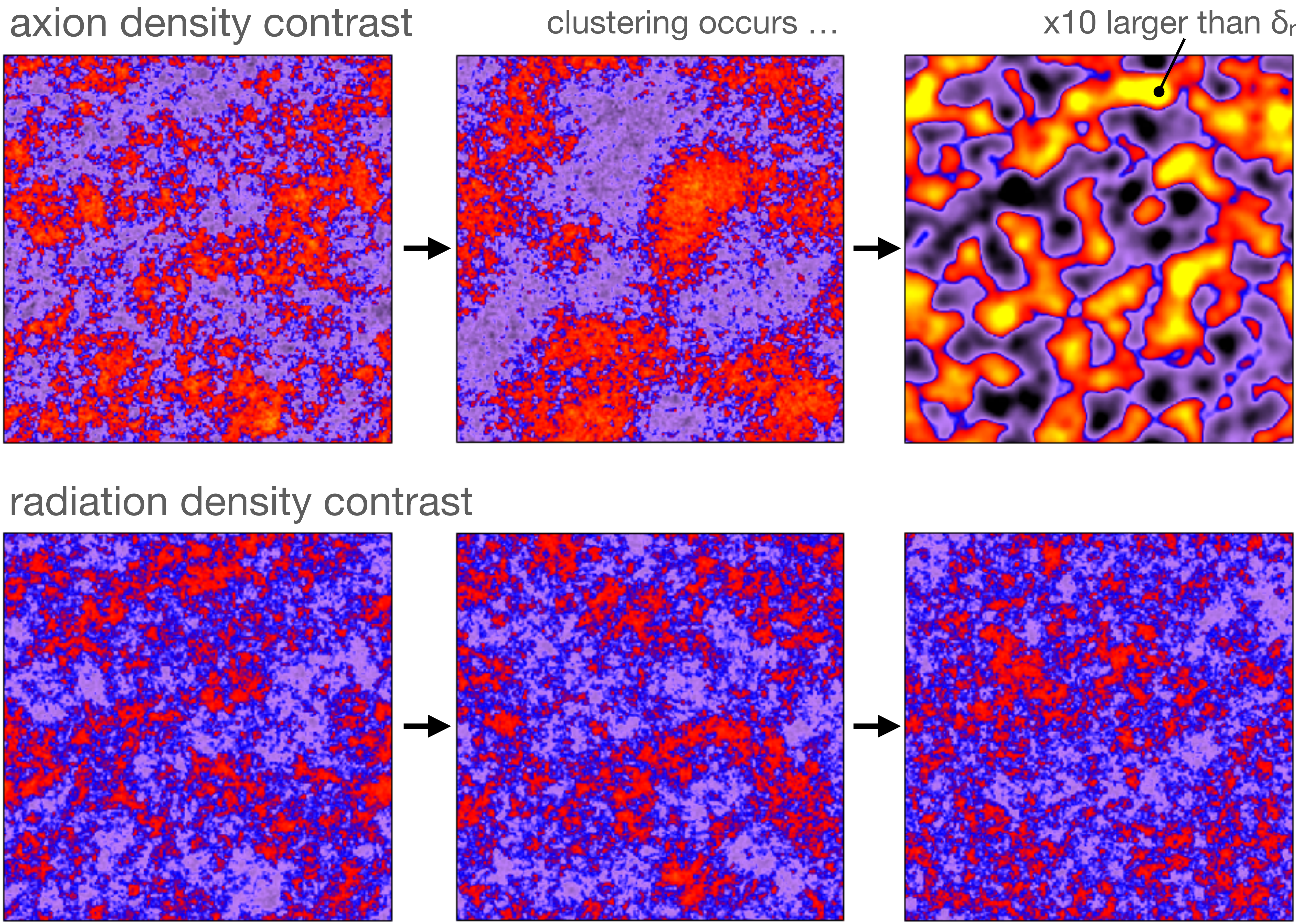
Clustering of axion due to the temperature fluctuation

NK, Kogai, Urakawa 2111.05785





$m_a(T) \propto T^{-b/2}$
"direct" interaction
with thermal plasma
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$\delta\rho_a/\rho_a$
clustering
1
0.1
T/GeV
$f_a = 10^{13}\mathrm{GeV}$
$\theta_i = 1$



axion density contrast
clustering occurs …
x10 larger than δr
radiation density contrast

III. Linear analysis

Evolution of Fourier mode

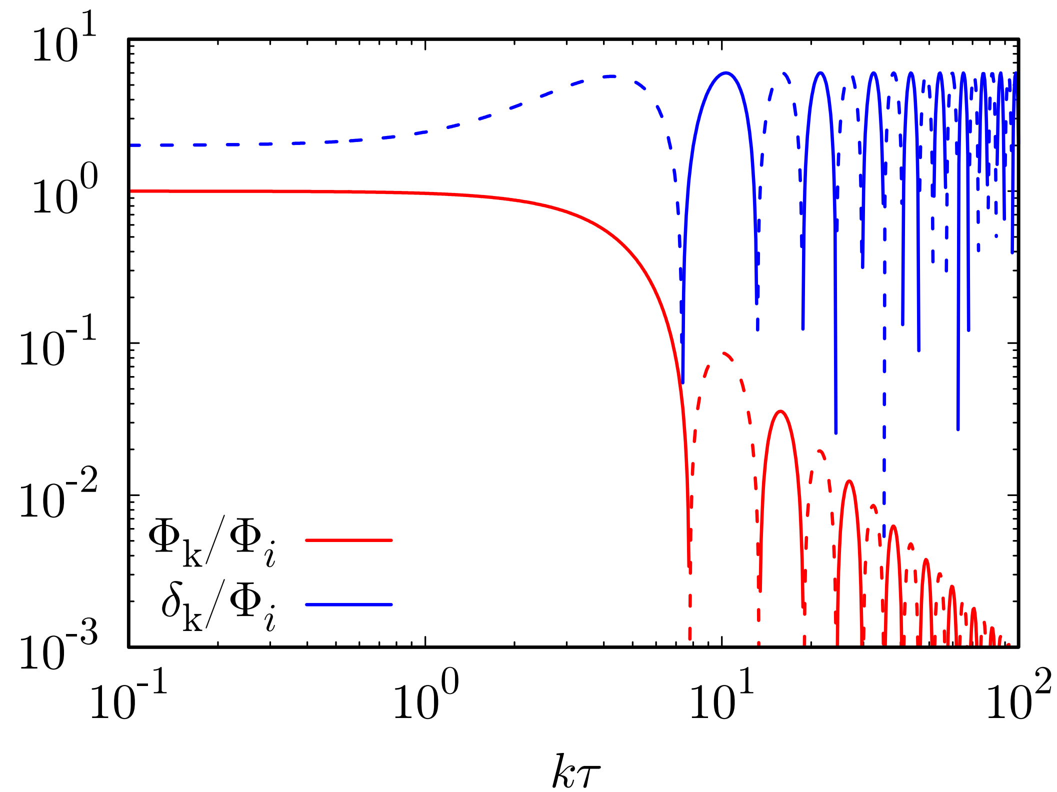
$$\boxed{\delta\phi''_{\mathbf{k}} + 2\mathcal{H}\delta\phi'_{\mathbf{k}} + 4\phi'\Phi'_{\mathbf{k}} + k^2\delta\phi_{\mathbf{k}} + a^2(V_{\phi\phi}\delta\phi_{\mathbf{k}} - 2V_\phi\Phi_{\mathbf{k}} + V_{\phi T}\delta T_{\mathbf{k}}) = 0}$$

- radiation density fluctuation & scalar metric perturbation

$$\delta_{\mathbf{k}} = \frac{36\Phi_i}{(k\tau)^2}\left(\left(1 - \frac{(k\tau)^2}{3}\right)\frac{\sqrt{3}}{k\tau}\sin\left(\frac{k\tau}{\sqrt{3}}\right) - \left(1 - \frac{(k\tau)^2}{6}\right)\cos\left(\frac{k\tau}{\sqrt{3}}\right)\right) \quad \left(\to \delta T_{\mathbf{k}} = \frac{T}{4}\delta_{\mathbf{k}}\right)$$

$$\Phi_{\mathbf{k}} = \frac{9\Phi_i}{(k\tau)^2}\left(\frac{\sqrt{3}}{k\tau}\sin\left(\frac{k\tau}{\sqrt{3}}\right) - \cos\left(\frac{k\tau}{\sqrt{3}}\right)\right)$$

(radiation dominated Universe)



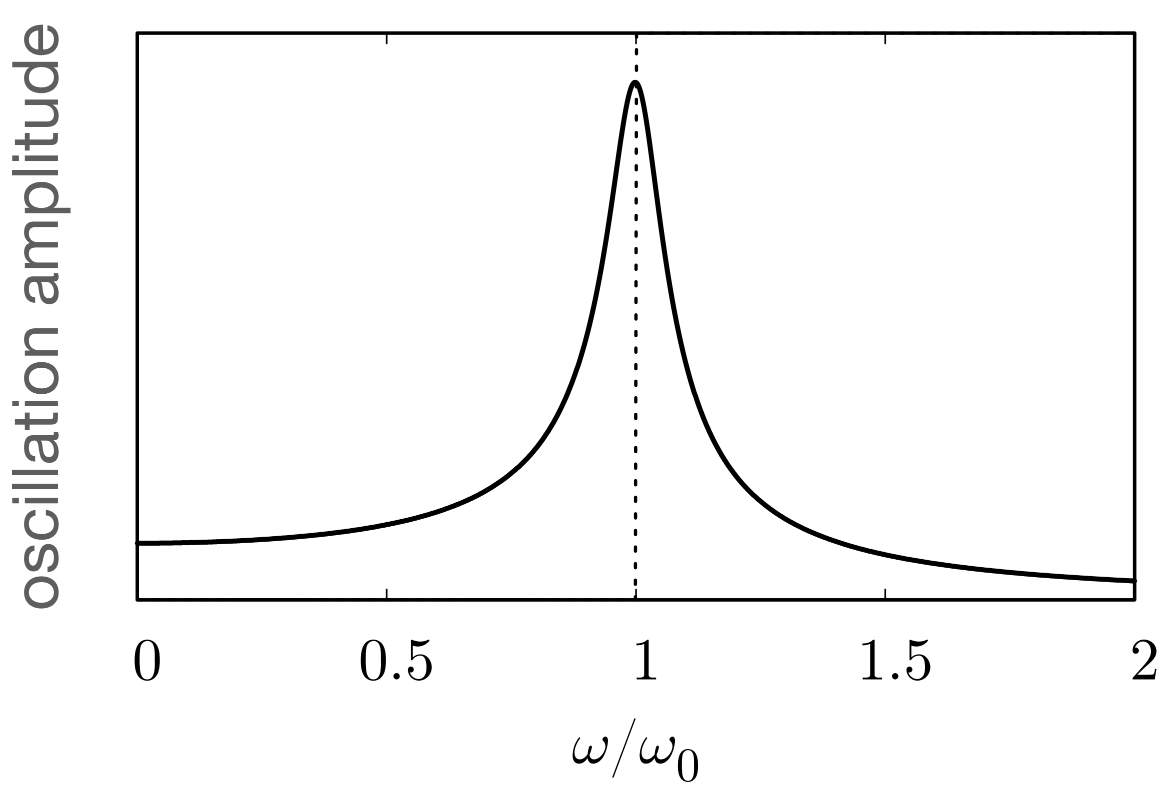
EoM: $\delta\phi''_{\mathbf{k}} + 2\mathcal{H}\delta\phi'_{\mathbf{k}} + (k^2 + a^2 m^2(T))\delta\phi_{\mathbf{k}} = -a^2 V_{\phi T}\delta T_{\mathbf{k}}$

$\updownarrow$ analogy

Forced oscillation model: $\ddot{x} + 2\gamma\dot{x} + \omega_0^2 x = F_0 \sin(\omega t + \delta)$

$$\longrightarrow \quad x(t) = \frac{F_0}{\sqrt{(\omega^2 - \omega_0^2)^2 + (2\gamma\omega)^2}} \sin(\omega t + \delta)$$

(particular solution)



EoM: $\delta\phi''_{\mathbf{k}} + 2\mathcal{H}\delta\phi'_{\mathbf{k}} + (k^2 + a^2 m^2(T))\delta\phi_{\mathbf{k}} = -a^2 V_{\phi T}\delta T_{\mathbf{k}}$

$\downarrow$

analogy with forced-oscillation system

$\delta\phi_{\mathbf{k}} \to x$ (position)

$\mathcal{H} \to \gamma$ (damping term)

$k^2 + a^2 m^2(T) \to \omega_0^2$ (eigen frequency)

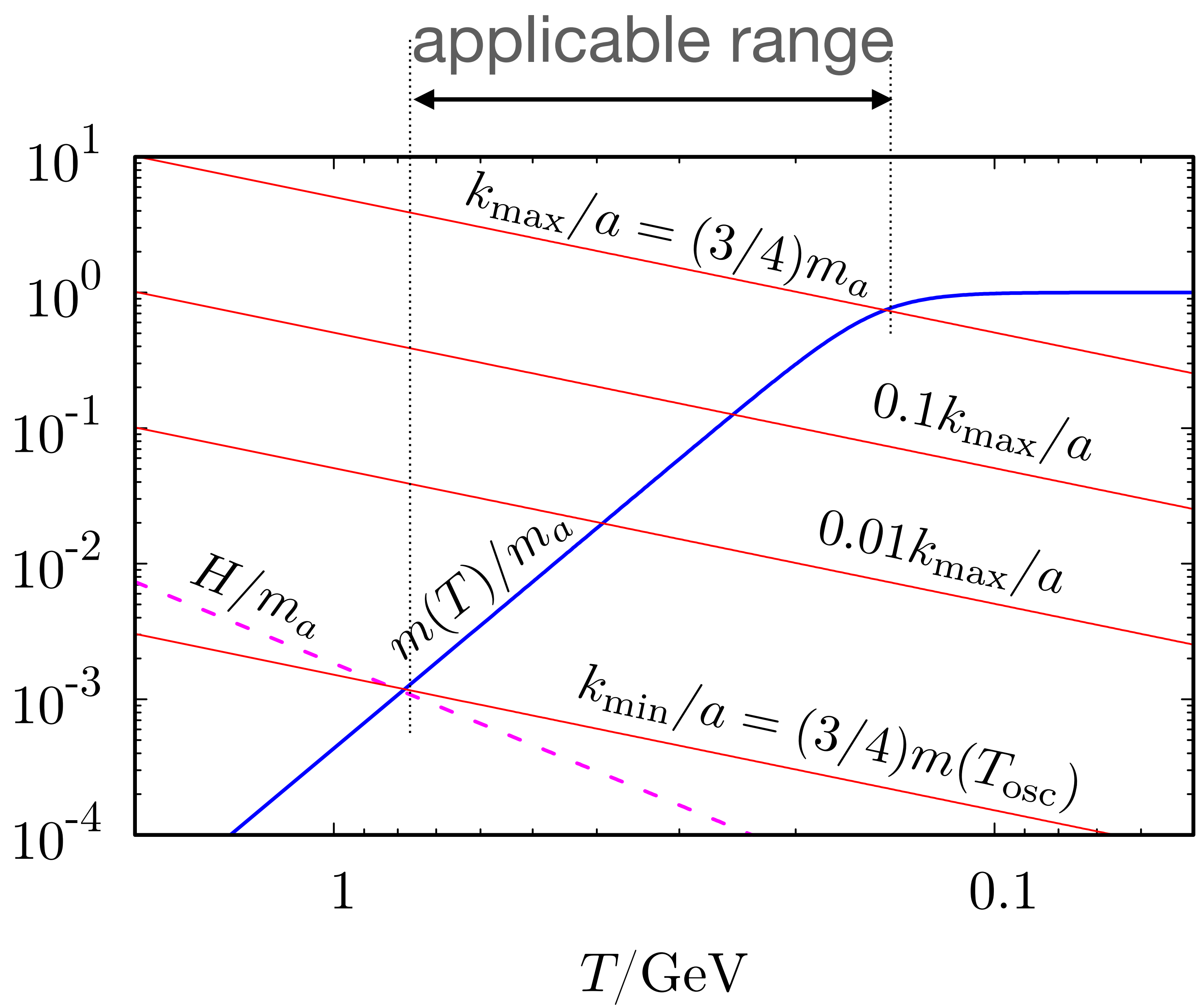
$$\mathrm{r.h.s} = b a^2 m^2(T) \underline{\phi_0 \delta T_{\mathbf{k}}/T} \to F_0 \sin(\omega t - \delta)$$

(driving force)

$$\propto \cos\left[\left(\frac{am(T)}{2} \pm k\right)\tau + \alpha\right]$$

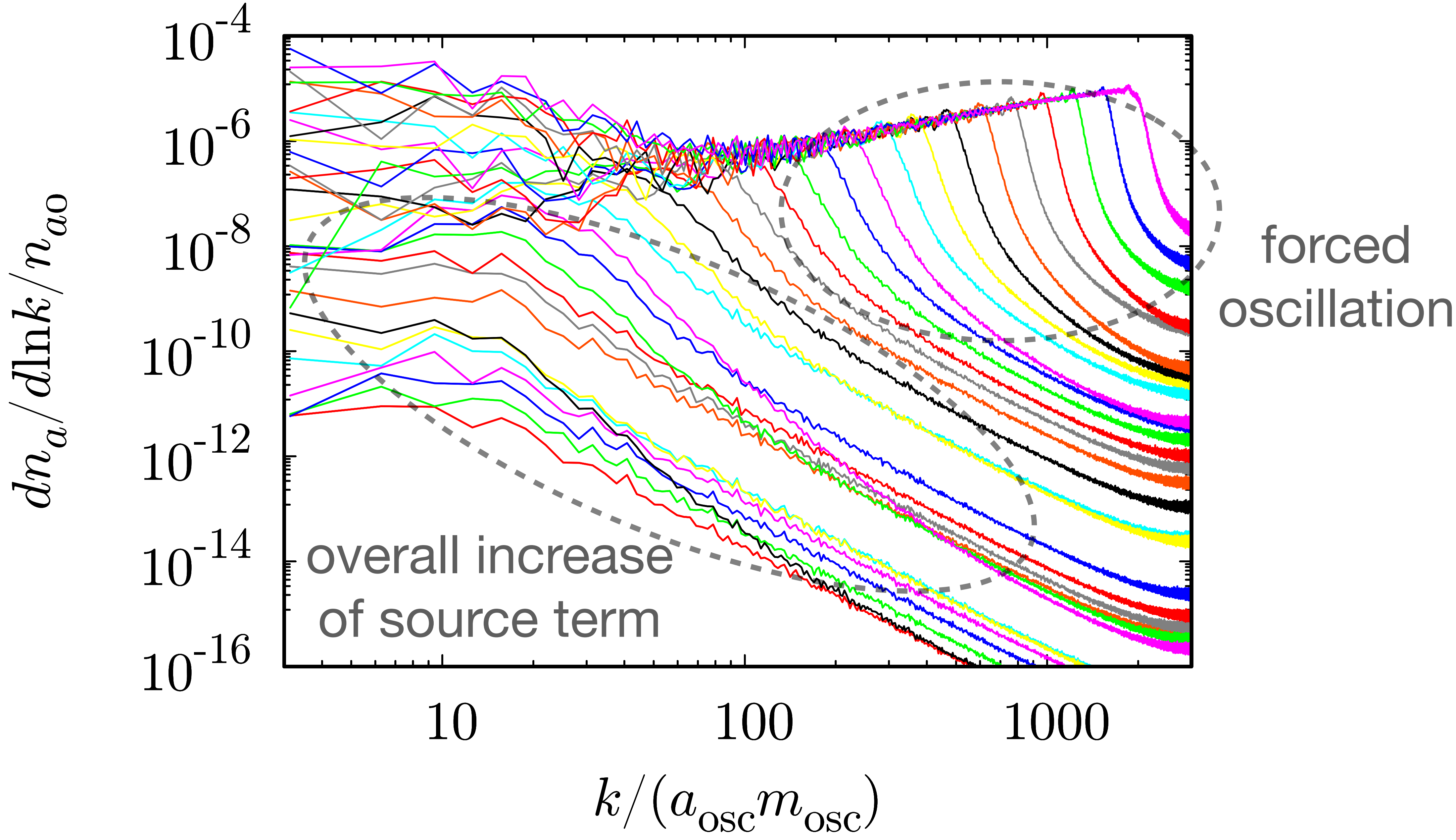
resonance condition : $\omega = \omega_0 \to \dfrac{k}{a} = \dfrac{3}{4} m(T)$

resonance condition : $\frac{k}{a} = \frac{3}{4} m(T)$

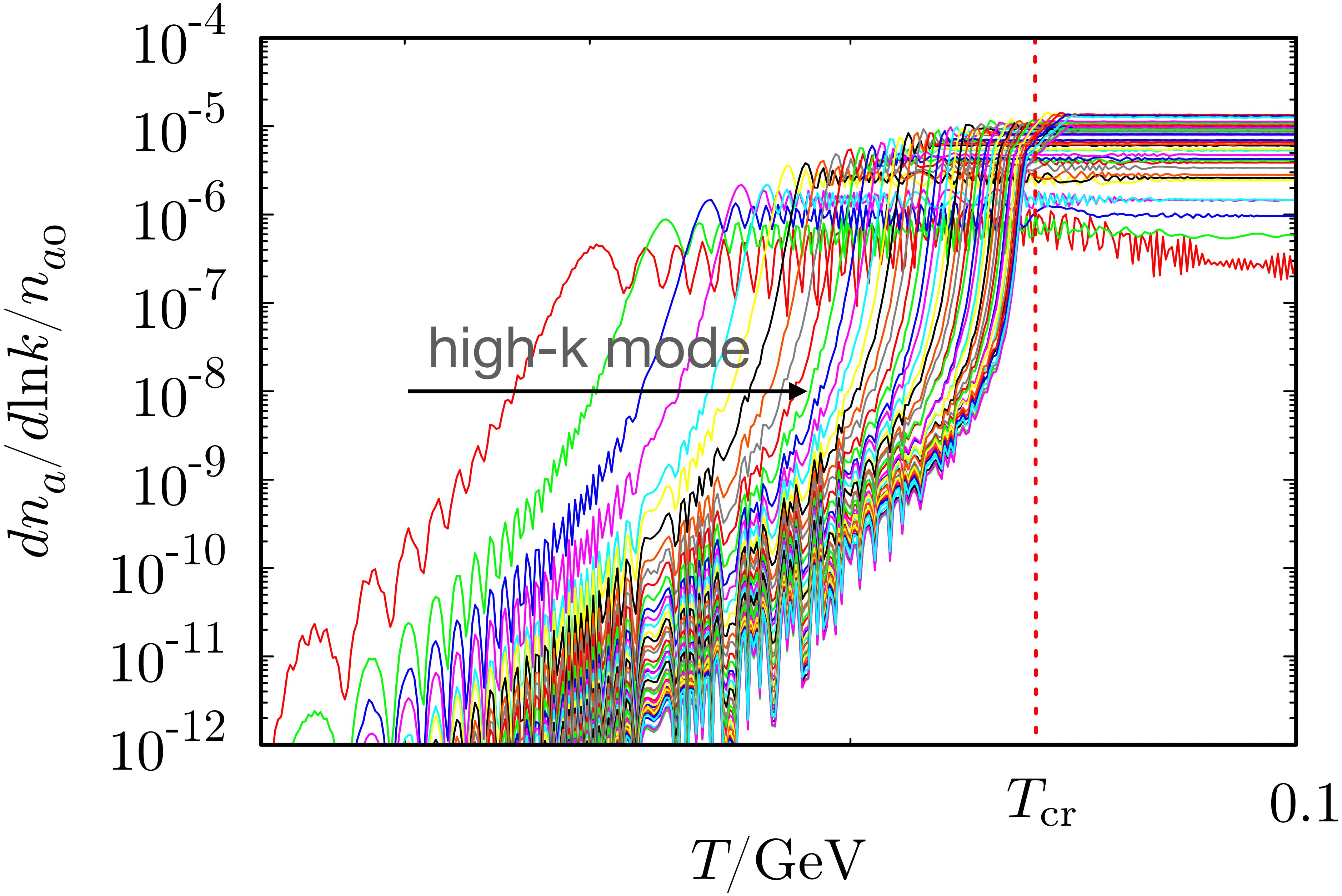


Resonance condition is met **from low-k to high-k modes**

Time evolution of the spectrum (number density)

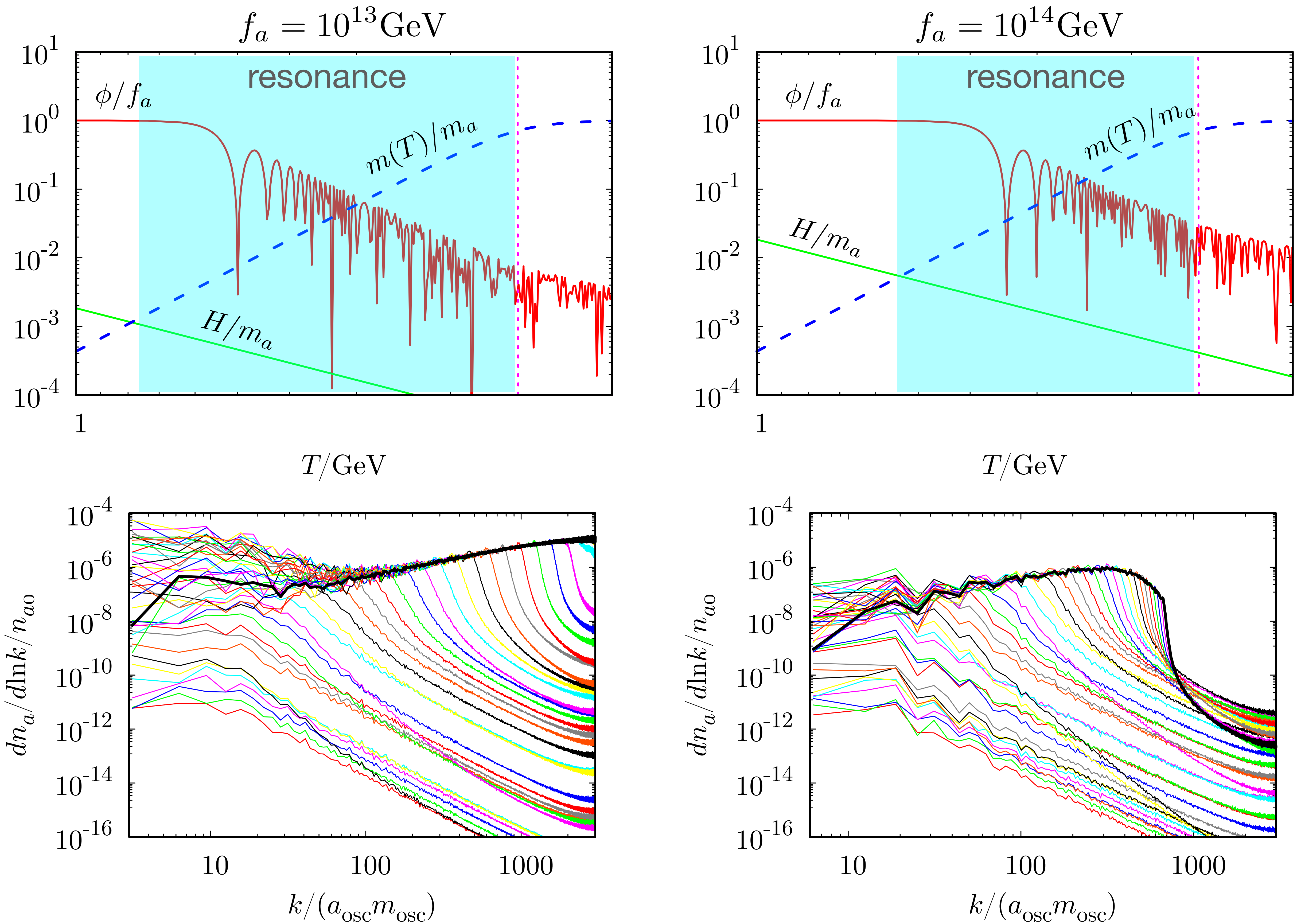


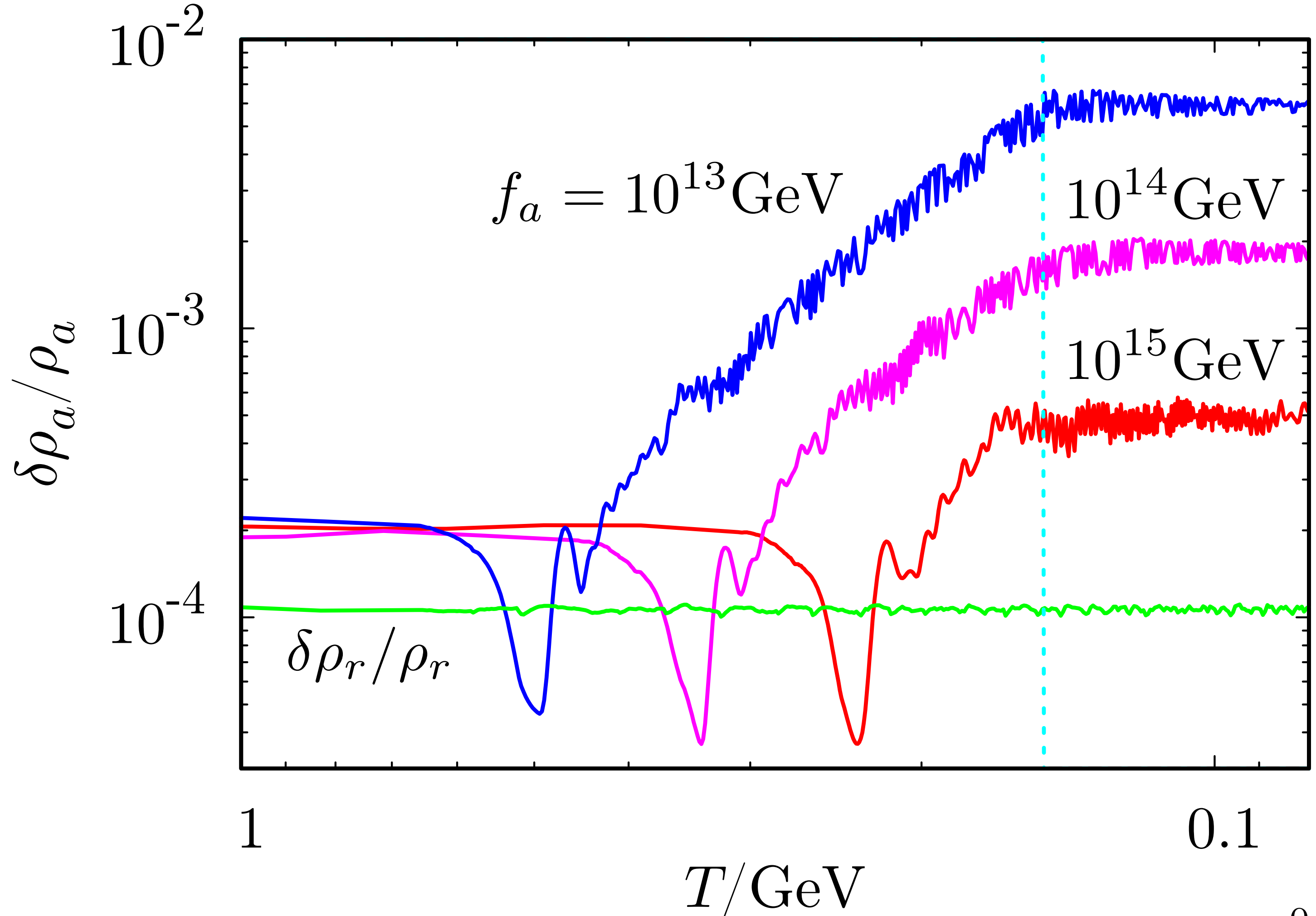
Time evolution of mode functions



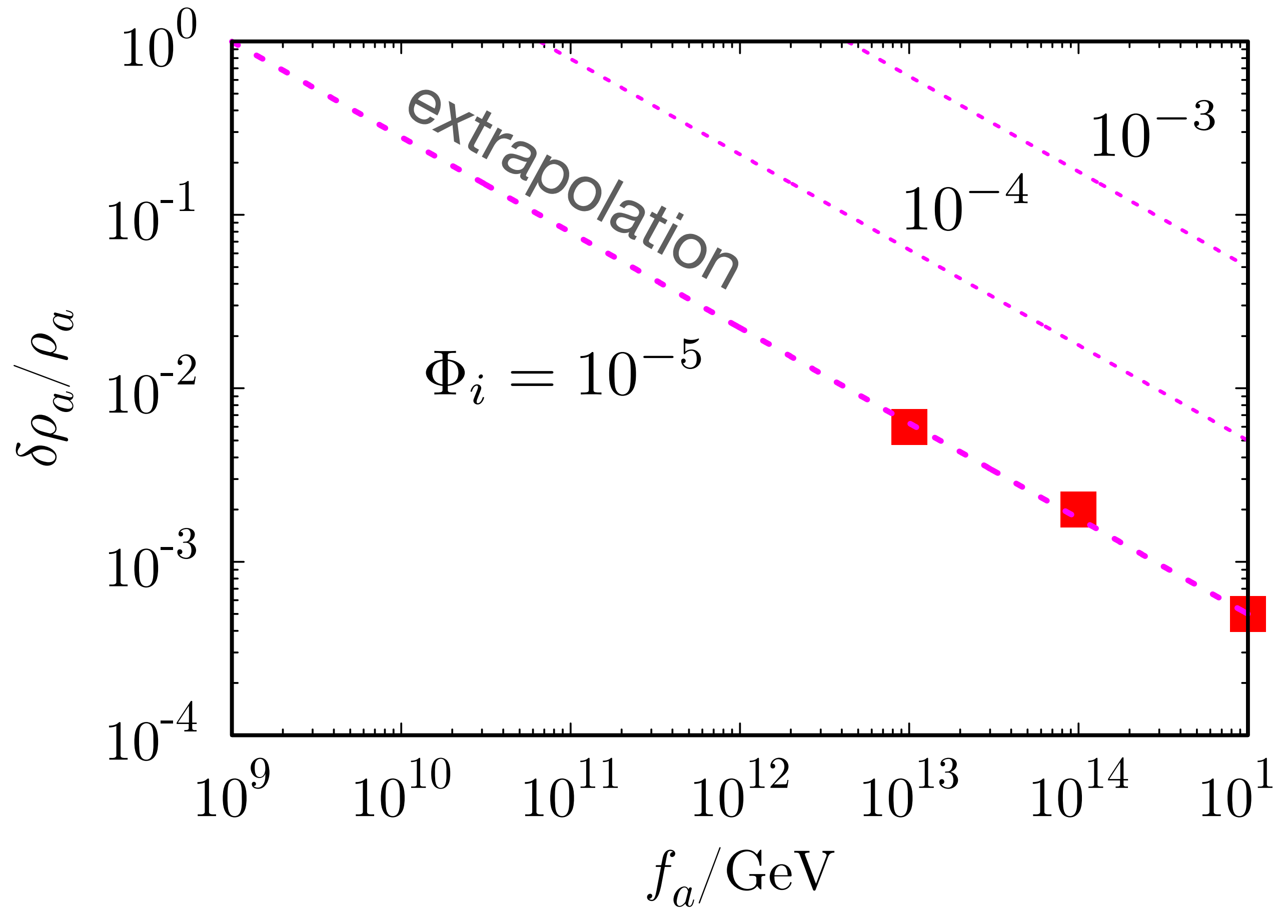
Amplification ends at $T = T_{cr}$

Dependence on the decay constant





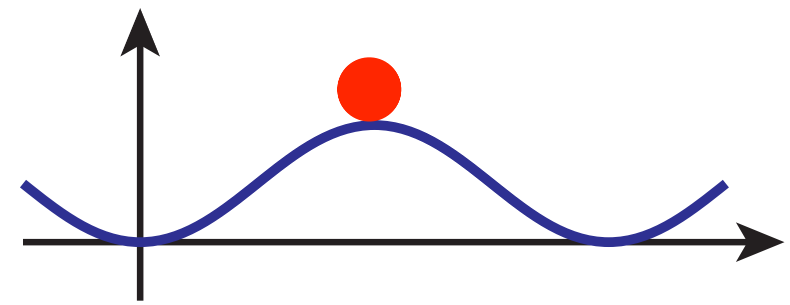
<— enhancement of axion density contrast

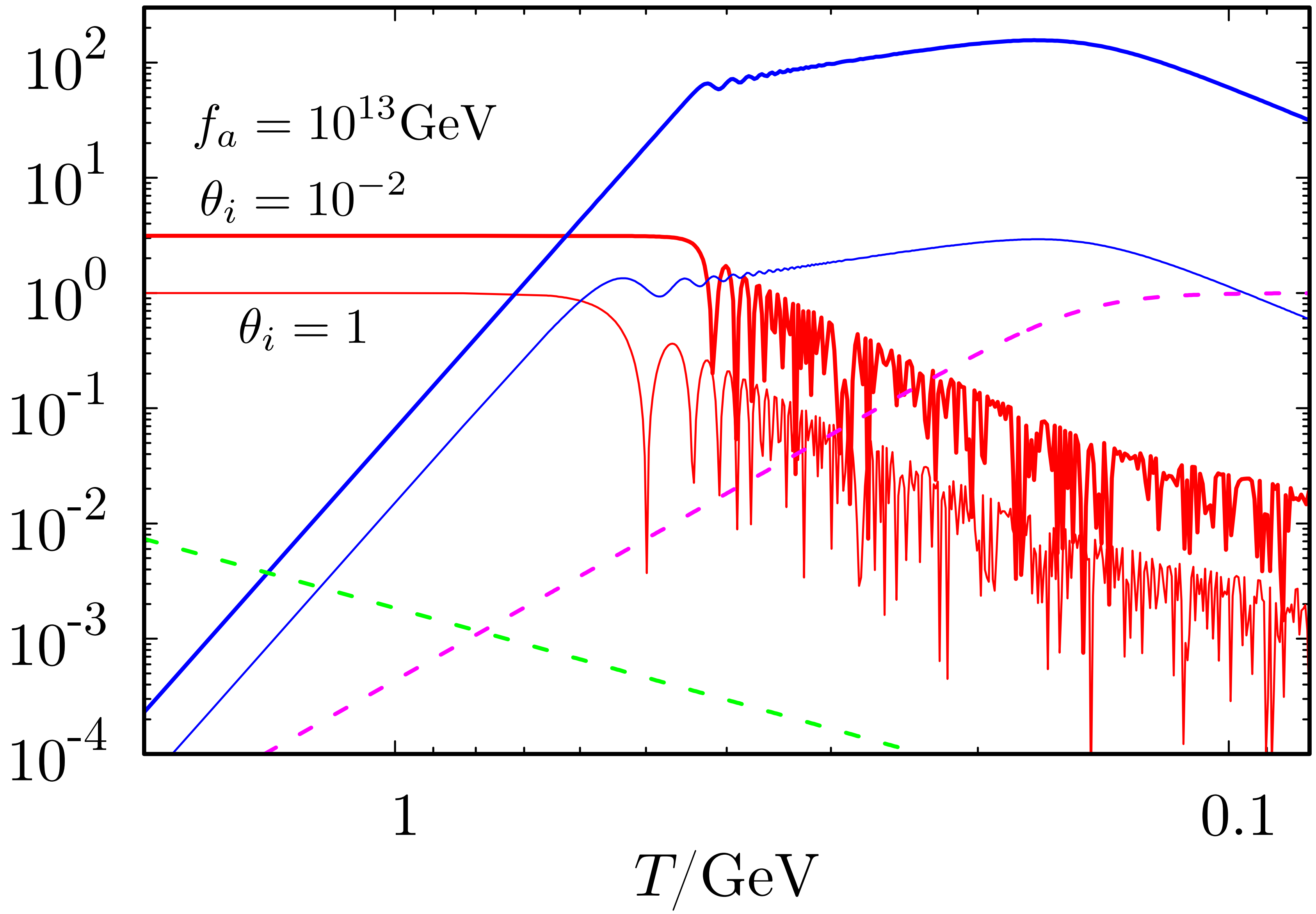


$\Phi_i \sim 10^{-3}$

—> O(1) density fluctuation

Fine-tuned initial misalignment
(hilltop)

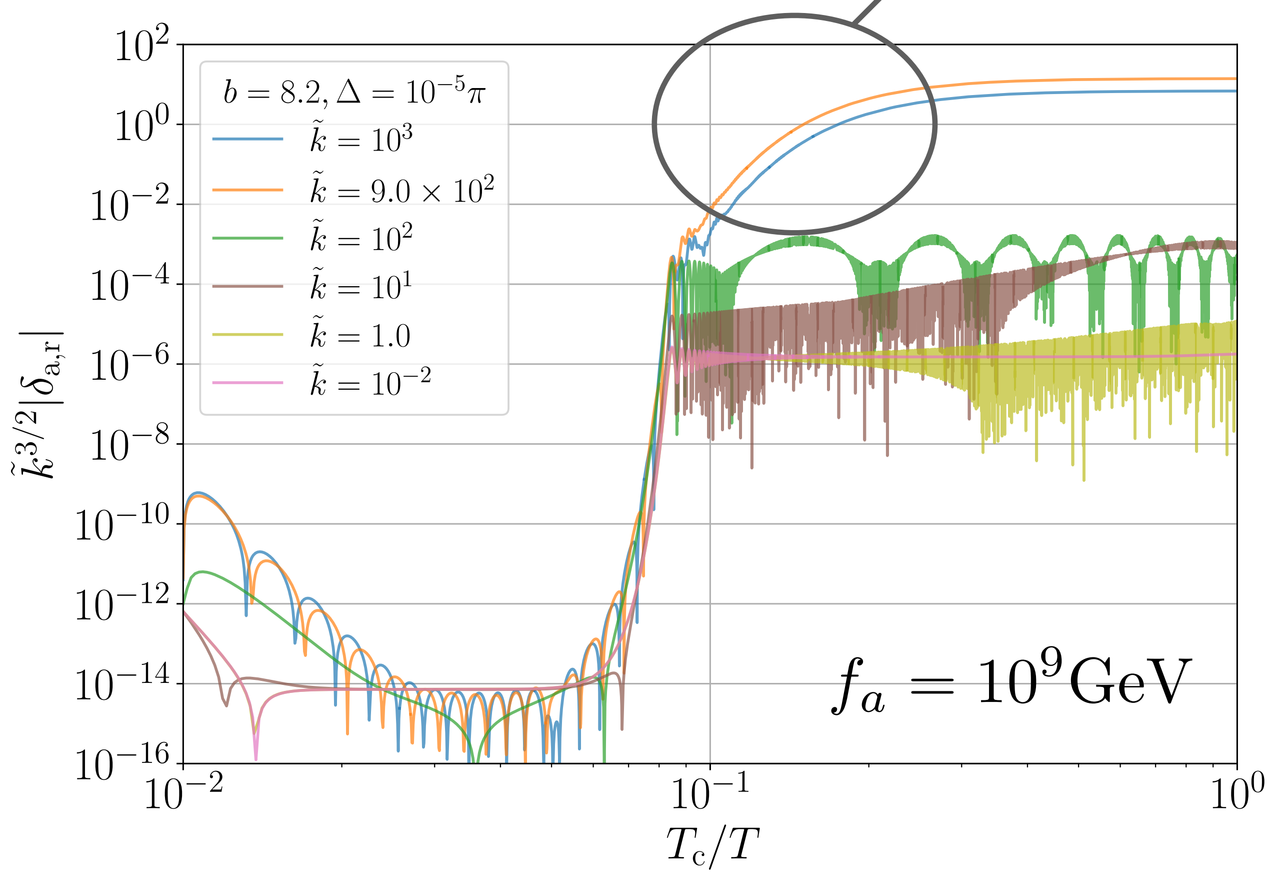


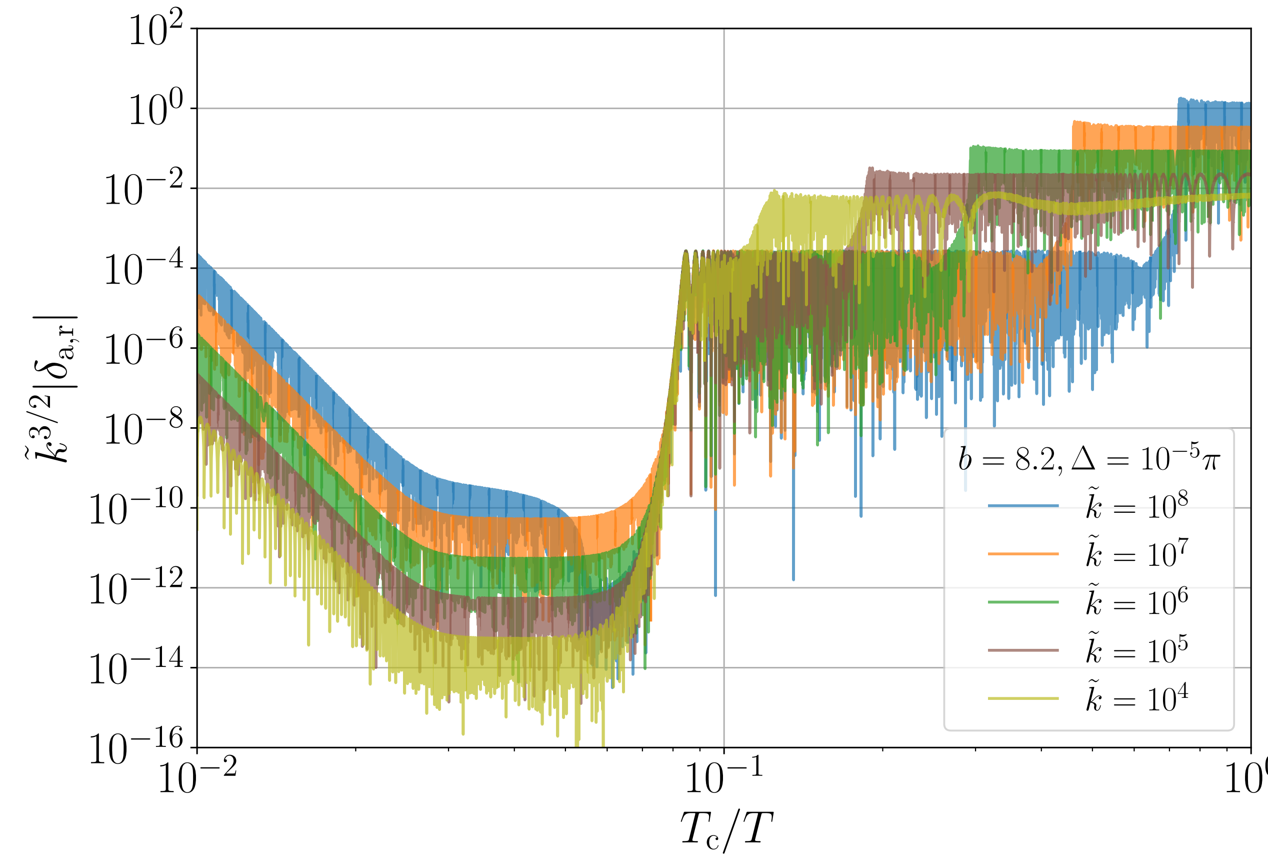


- delayed onset of oscillation —> less Hubble friction

- more efficient self-interaction —> resonance instability resonant instability due to self-interaction

→ O(1) density fluctuation





$$\Delta = \pi - \theta_i, \ \tilde{k} = \frac{k}{a(T_c)H(T_c)}$$

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Resultant spectrum

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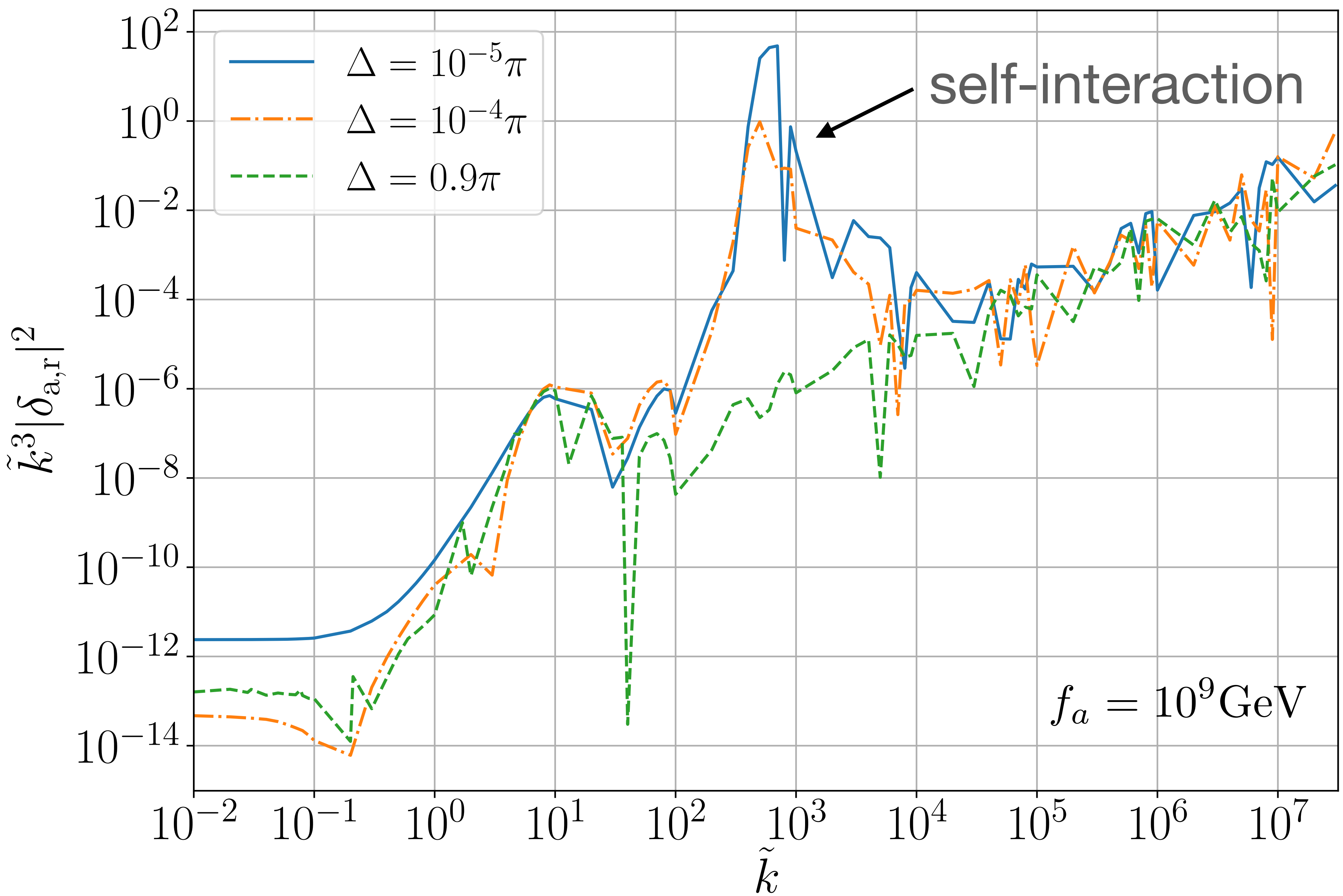
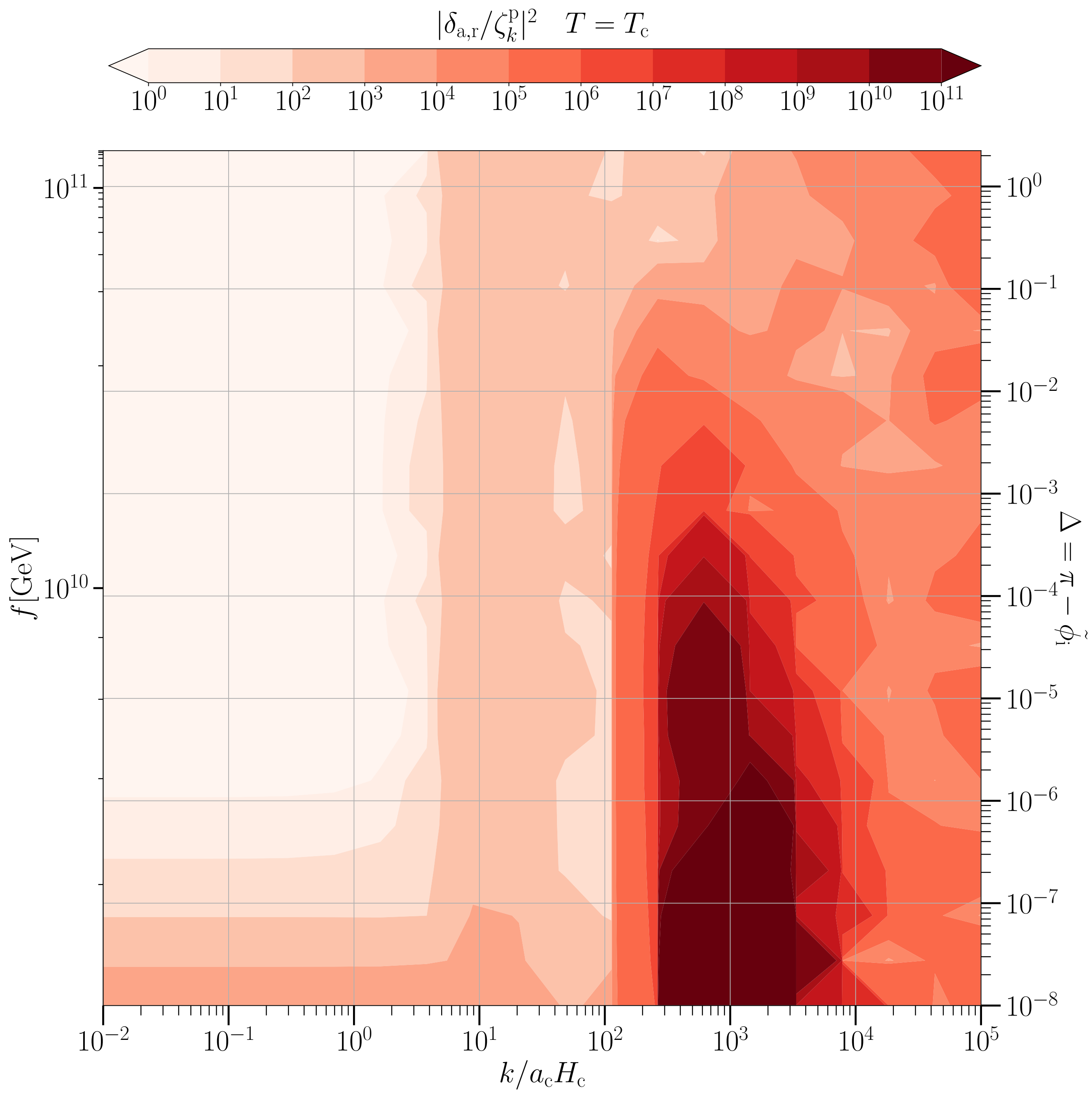
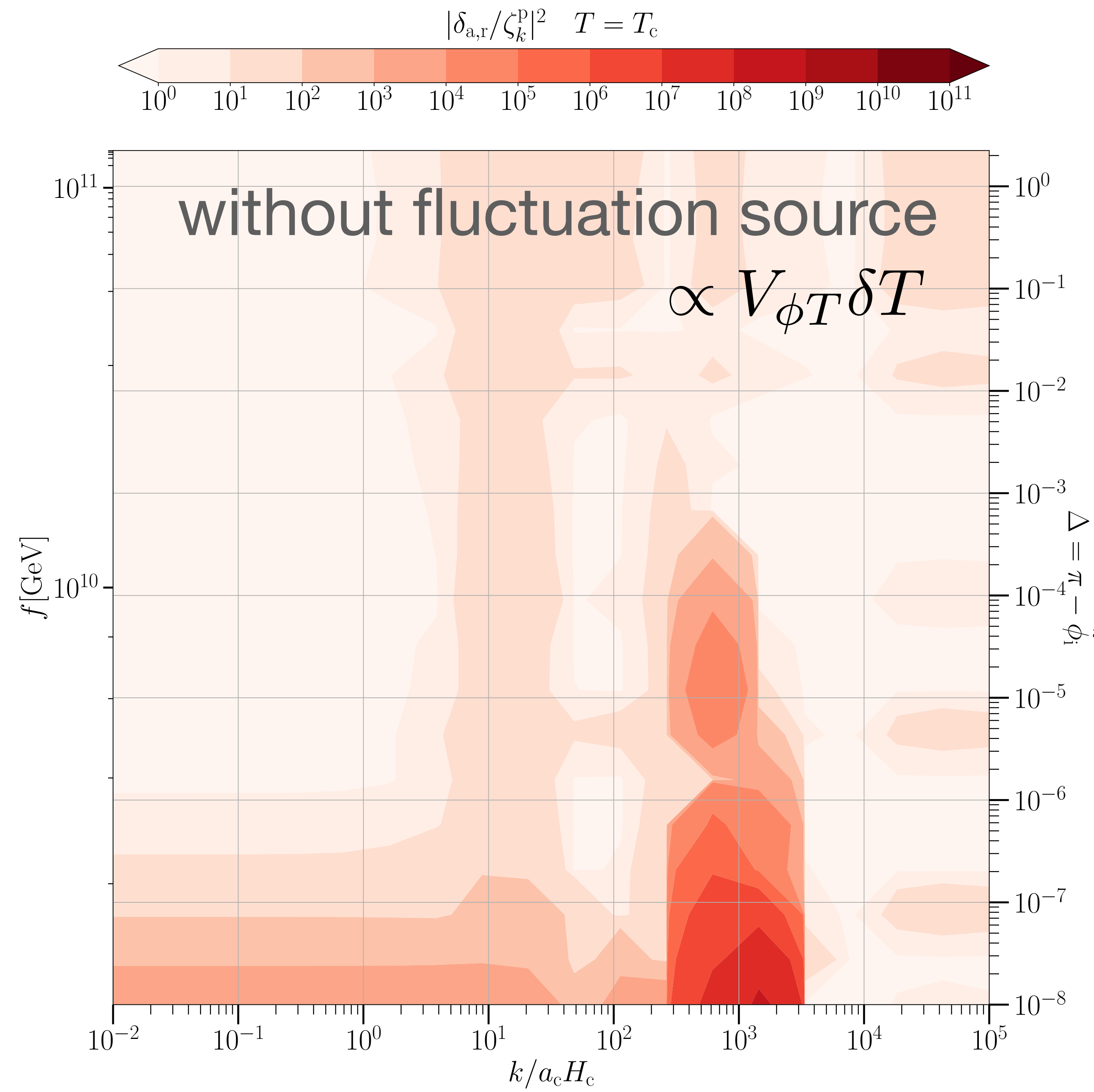


$$\Delta = \pi - \theta_i,\ \tilde{k} = \frac{k}{a(T_c)H(T_c)}$$





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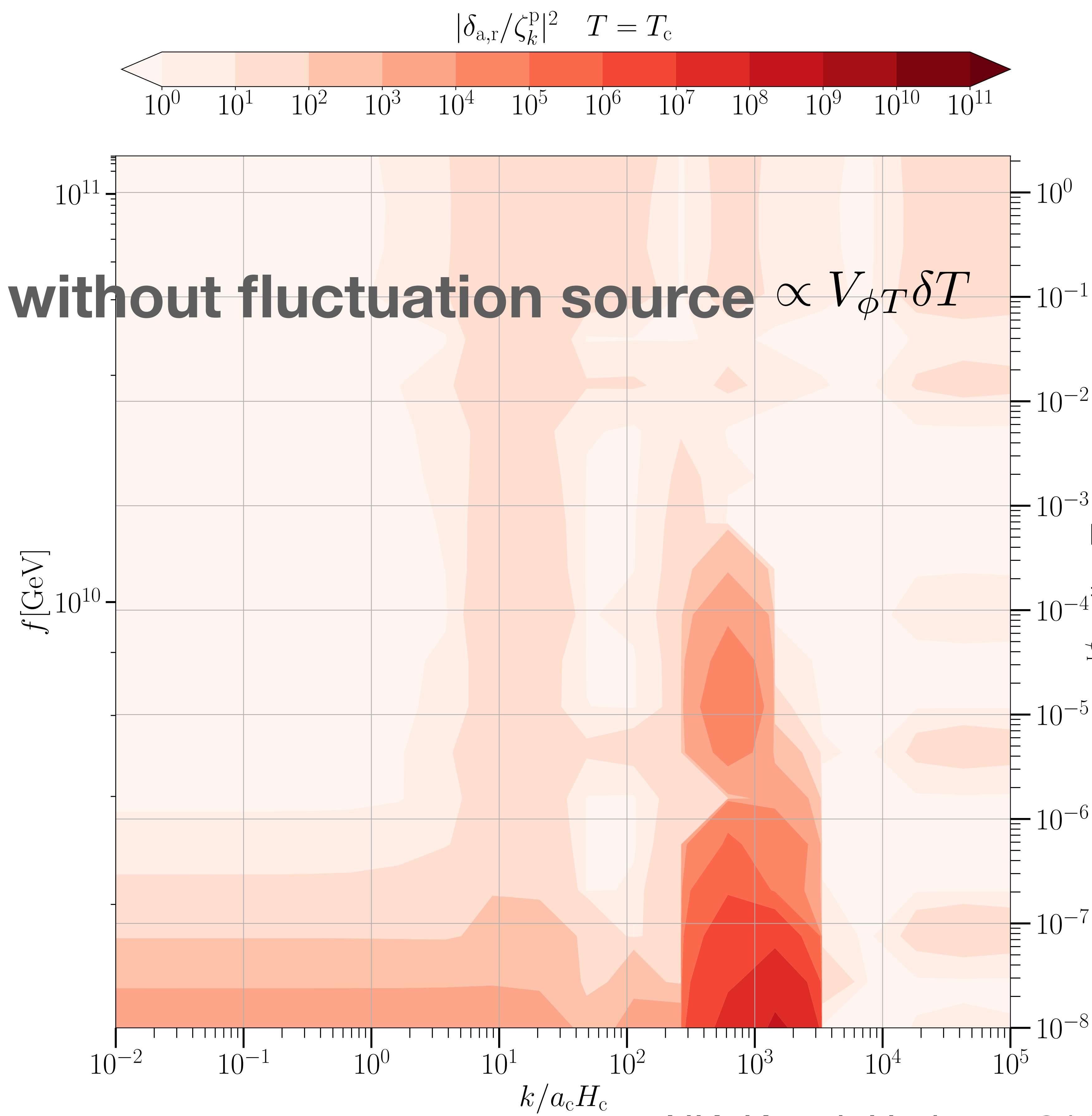

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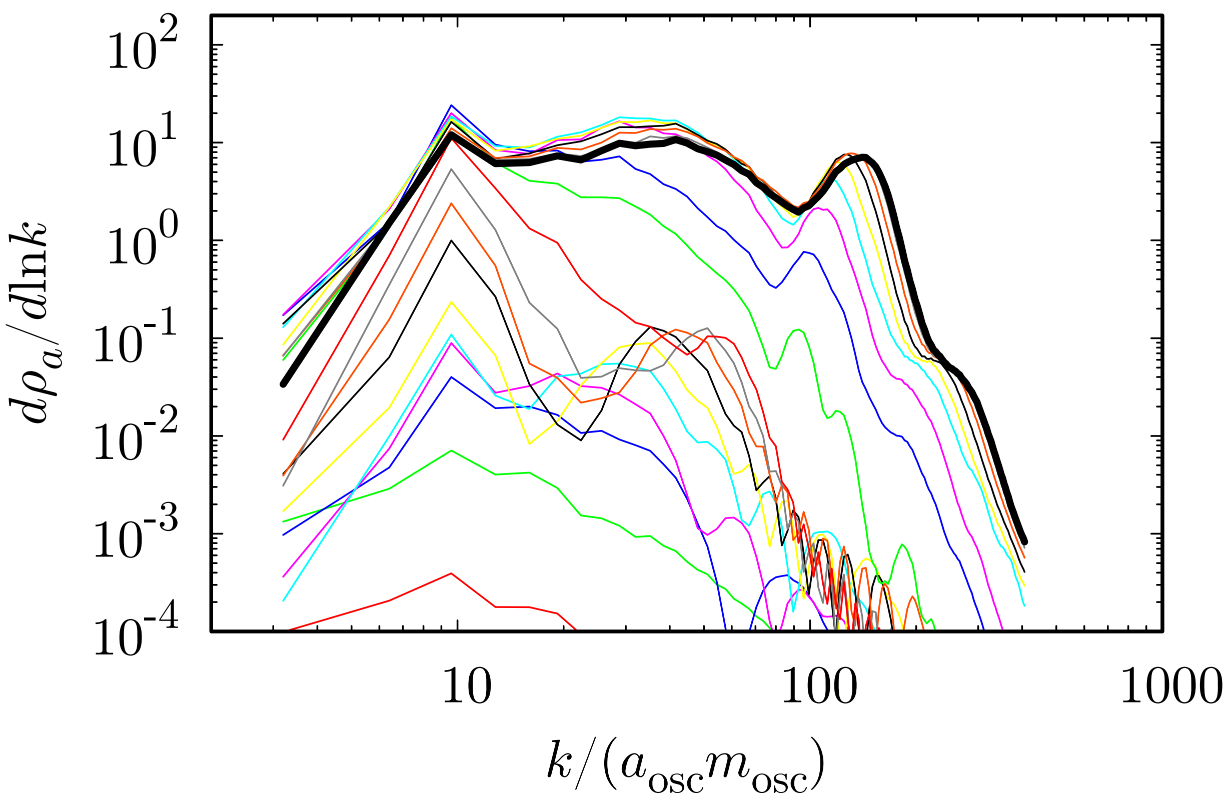
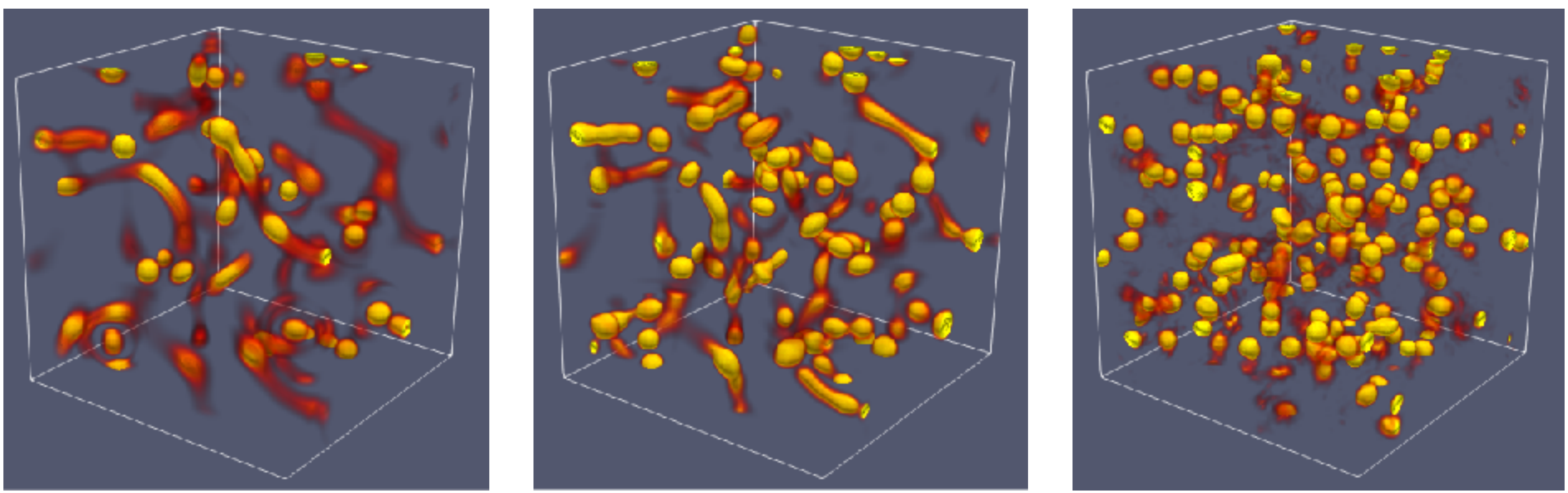
O(1) fluctuation

nonlinear analysis

- nonlinear power spectrum
- oscillon formation / decay

Nonlinear simulation (preliminary)





Summary

- Microlensing can be a powerful tool for QCD axion search

—> possibility to search cosmological imprints of QCD axion

Q. Any path for axion clump formation in pre-inflationary scenario?

- Adiabatic fluctuations can enhance the axion fluctuations in general / model-independent way

(through the direct interaction with thermal plasma)

& it can (probably) modify the mass function of axion minicluster

- nonlinear analysis is necessary (in progress)

Initial fluctuation and gauge issue

gauge-invariant curvature perturbation: $-\zeta = -\Psi + \frac{H}{\dot{\rho}}\delta\rho$

gauge-invariant scalar field fluctuation: $\delta\phi_I = \delta\phi - \frac{\dot{\phi}}{\dot{\rho}}\delta\rho$

(isocurvature fluctuation)

- Newtonian gauge
- superhorizon scale
- radiation dominant
- no anisotropic stress

$\longrightarrow$

$$\zeta \simeq \frac{3}{2}\Phi$$

$$\delta\phi \simeq \delta\phi_I - \frac{\dot{\phi}}{2H}\Phi$$

fluctuation at the onset of the oscillation: $\delta\phi \sim \delta\phi_I - f_a\theta_i\Phi$

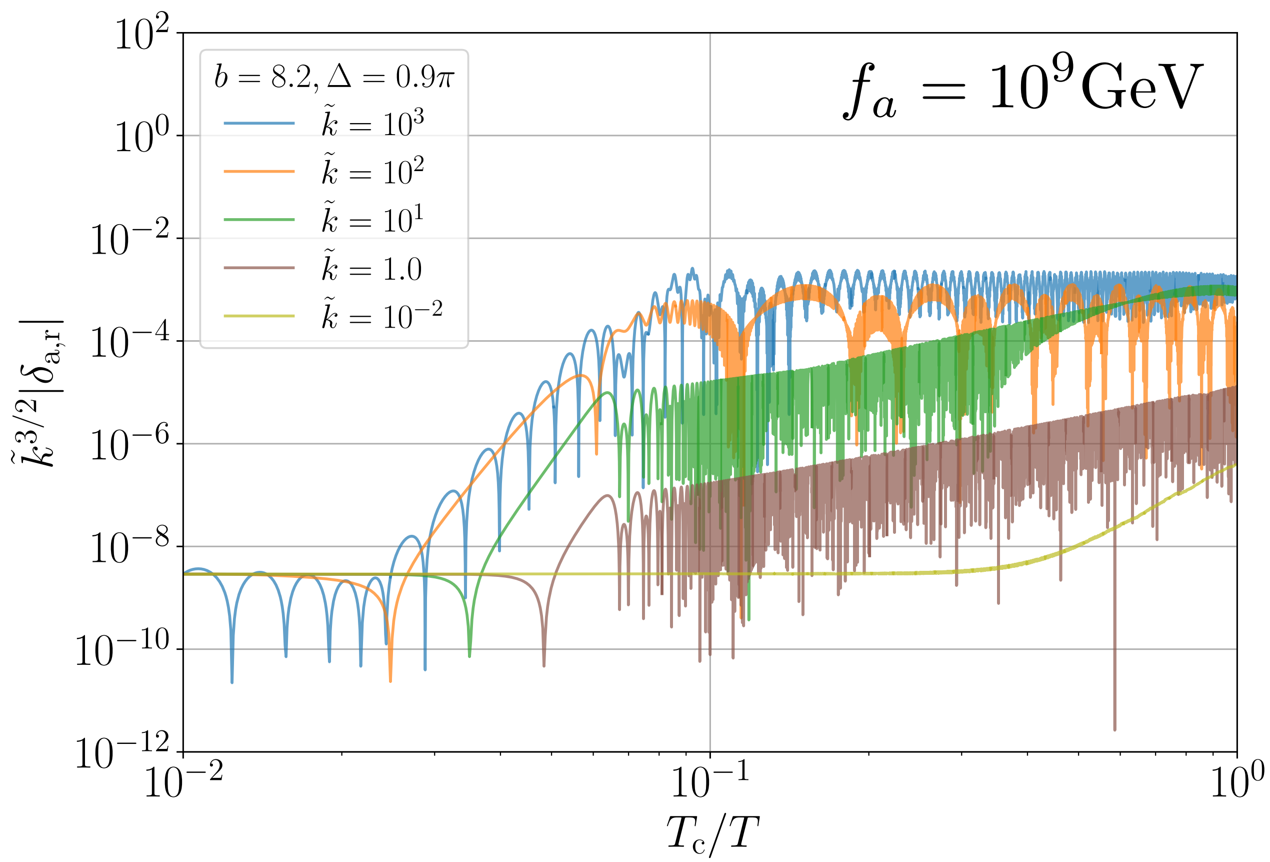
$(\dot{\phi} \sim m_a(T) f_a\theta_i,\ H \sim m_a(T))$

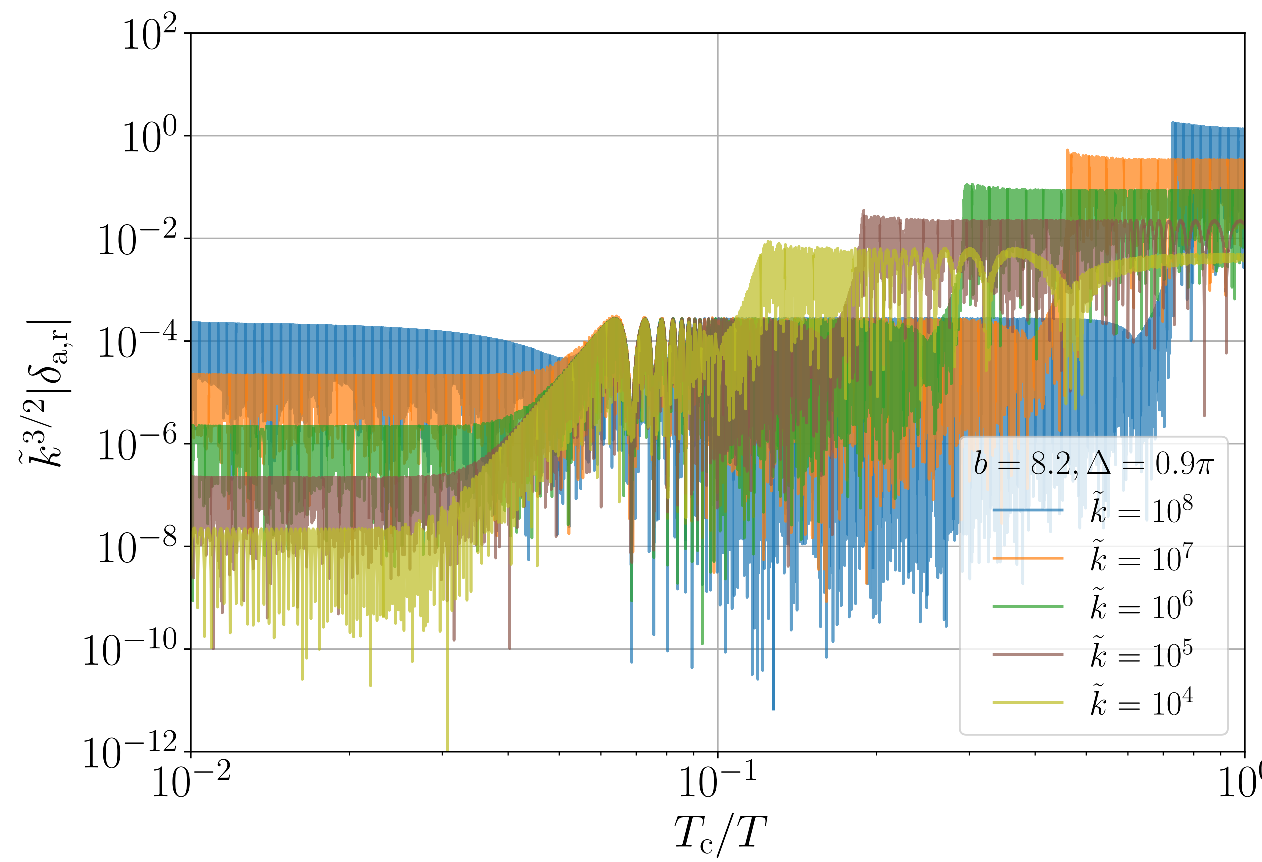
1. clustering due to the temperature fluctuation

(soon after the onset of oscillation)

2. resonant enhancement due to the oscillating source

(radiation density wave)





$$\Delta = \pi - \theta_i, \ \tilde{k} = \frac{k}{a(T_c)H(T_c)}$$

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