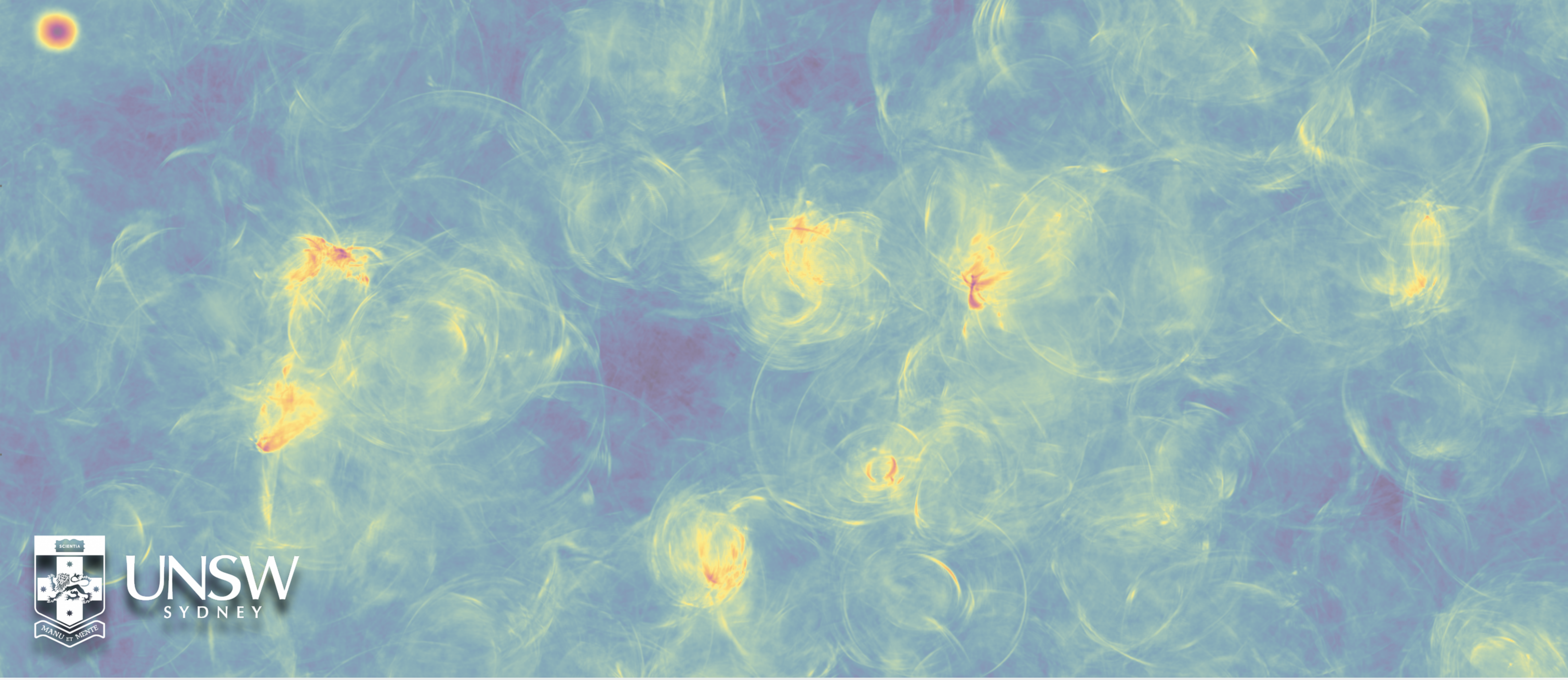

SIMULATIONS OF AXIONS IN THE POST-INFLATIONARY SCENARIO

Giovanni Pierobon

Cosmology from Home 2022

In collab. with C. O'Hare, J. Redondo, Y. Wong
Based on arXiv:2112.05117

Motivations: CP violation in QCD

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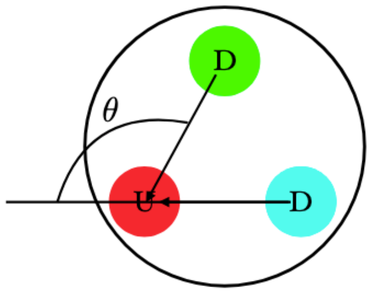
The strong CP problem



Theory

QCD vacuum structure generates a CP violating term

$$\mathcal{L}_\theta = -\frac{\alpha_s}{8\pi}\theta G\tilde{G}$$

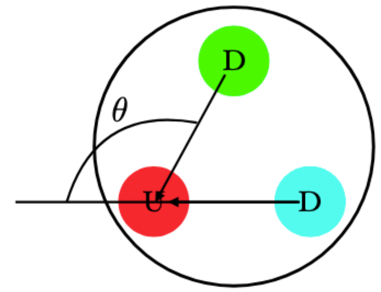
Consider the matter fields (quarks) and find physical CPV source

$$\mathcal{L}_{\mathrm{CPV}} \propto \bar{\theta} G\tilde{G}$$

$$\bar{\theta} = \theta + \theta_q$$

Motivations: CP violation in QCD

The strong CP problem



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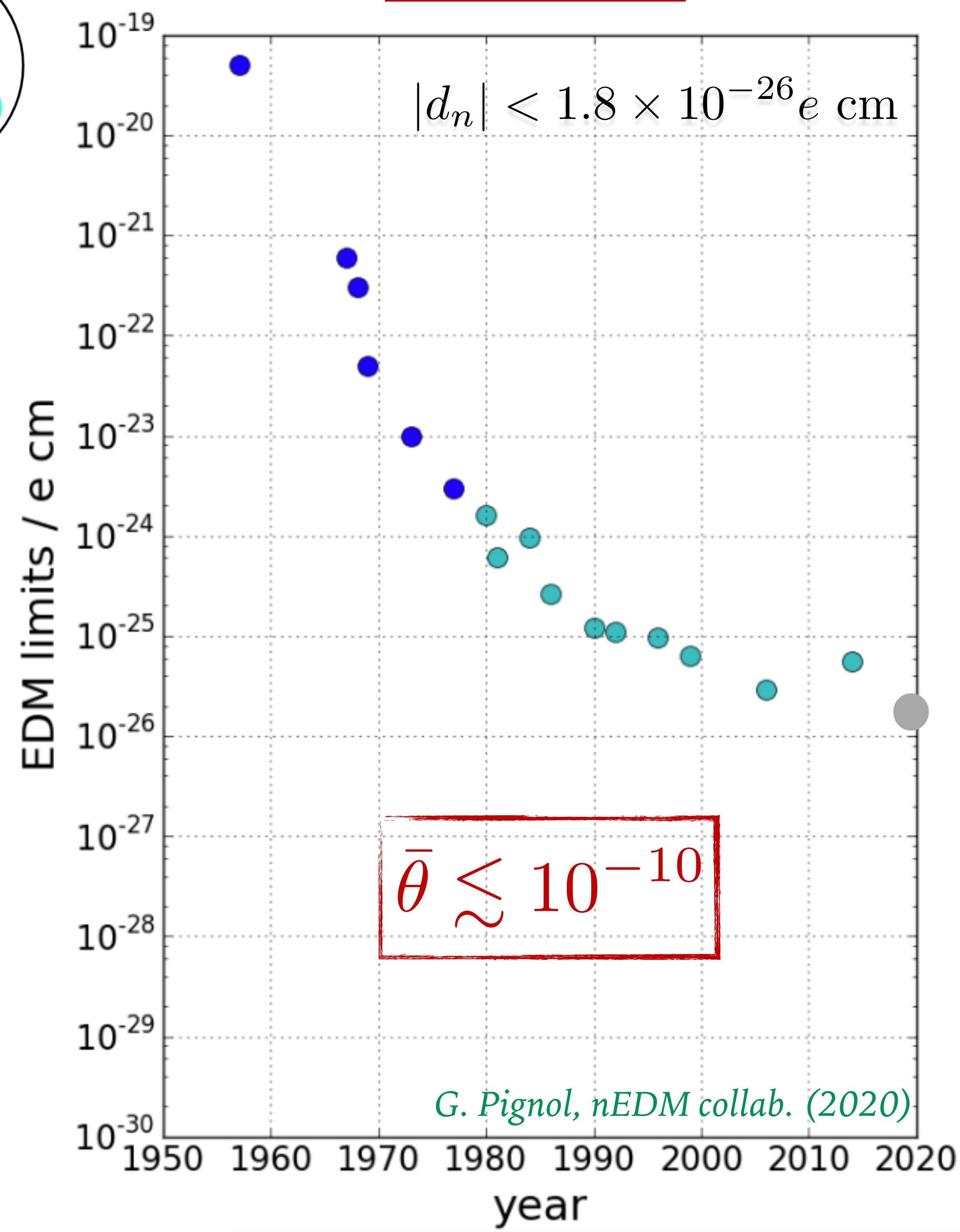
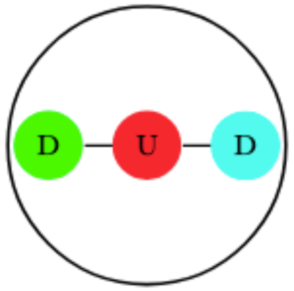
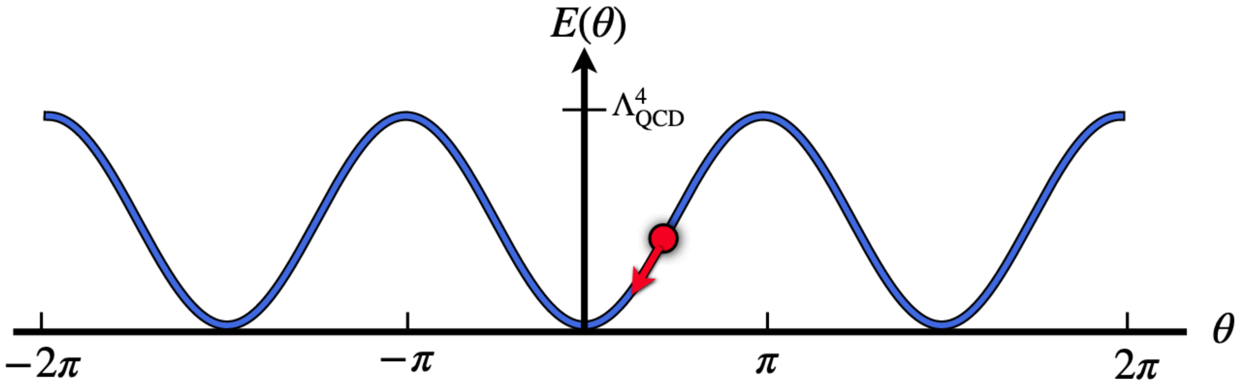
Observations



Motivations: QCD Axion

Peccei-Quinn solution





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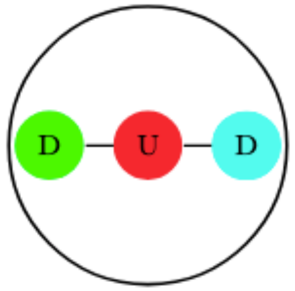
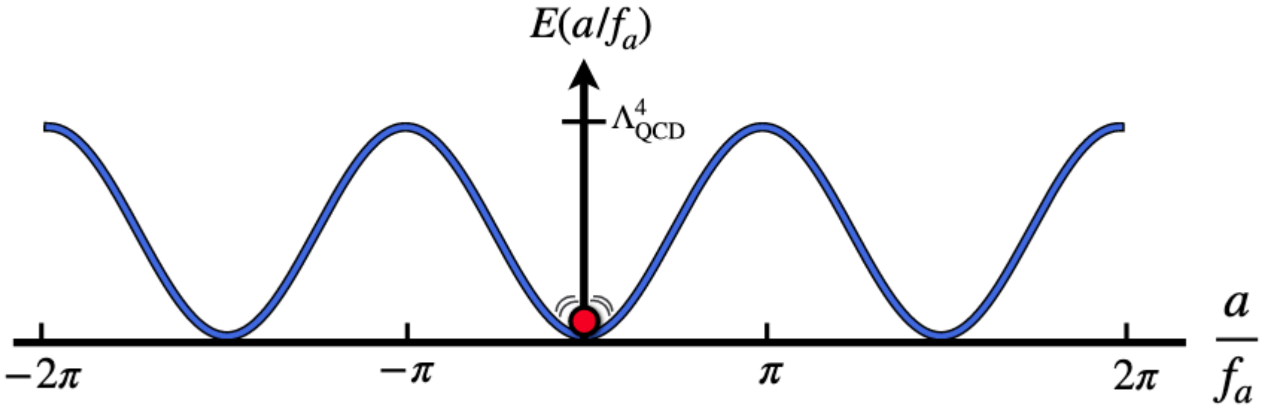


Vafa-Witten theorem + dynamical relaxation



$$\bar{\theta} \to \bar{\theta}(x) = a(x)/f_a$$

$$V_a \simeq -\Lambda^4_{\rm QCD} \cos\left(\frac{a}{f_a}\right) \quad m_a^2 \simeq \Lambda^4_{\rm QCD}/f_a^2$$

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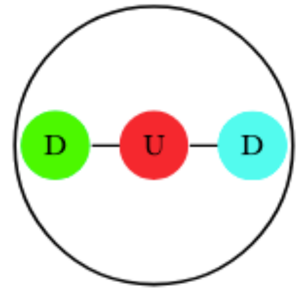

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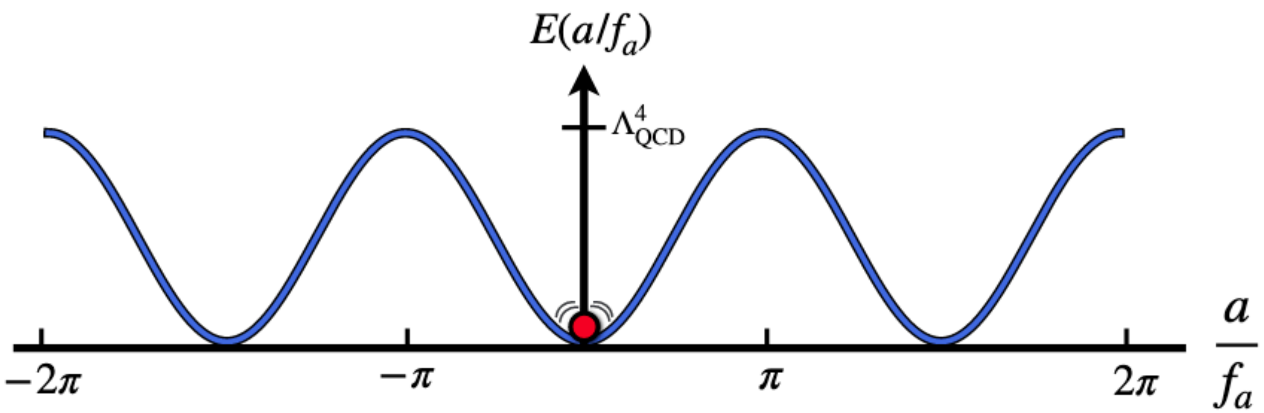

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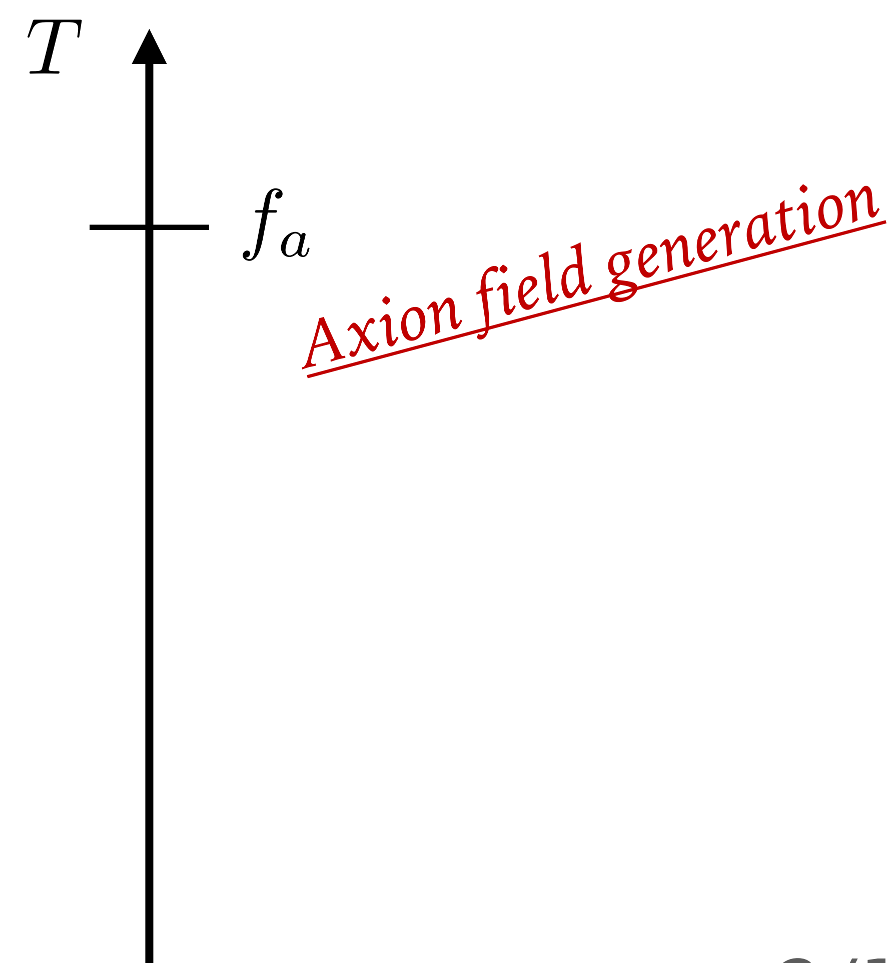
- Assume an abelian global symmetry, <u>spontaneous</u> breaking at large temperature



Motivations: QCD Axion

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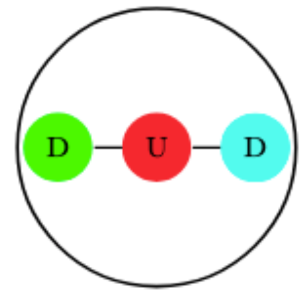

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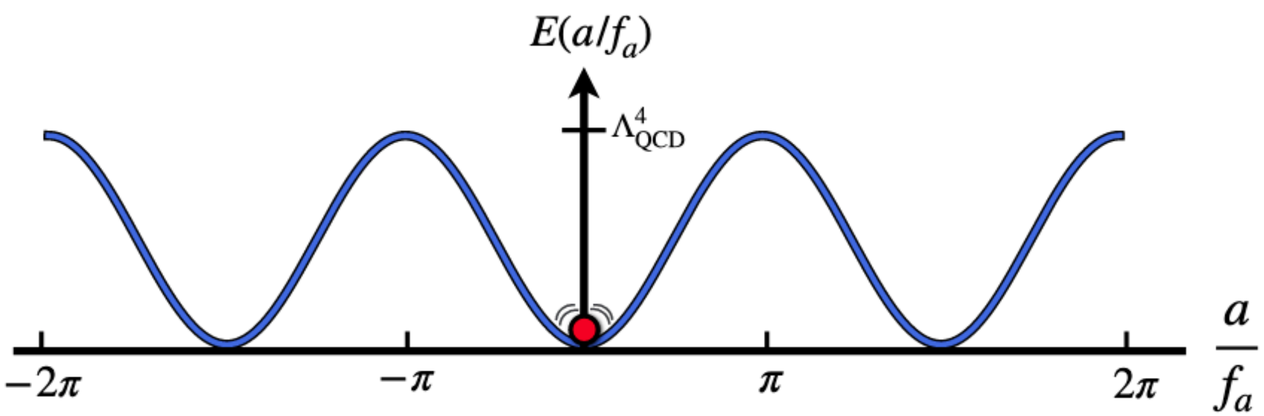

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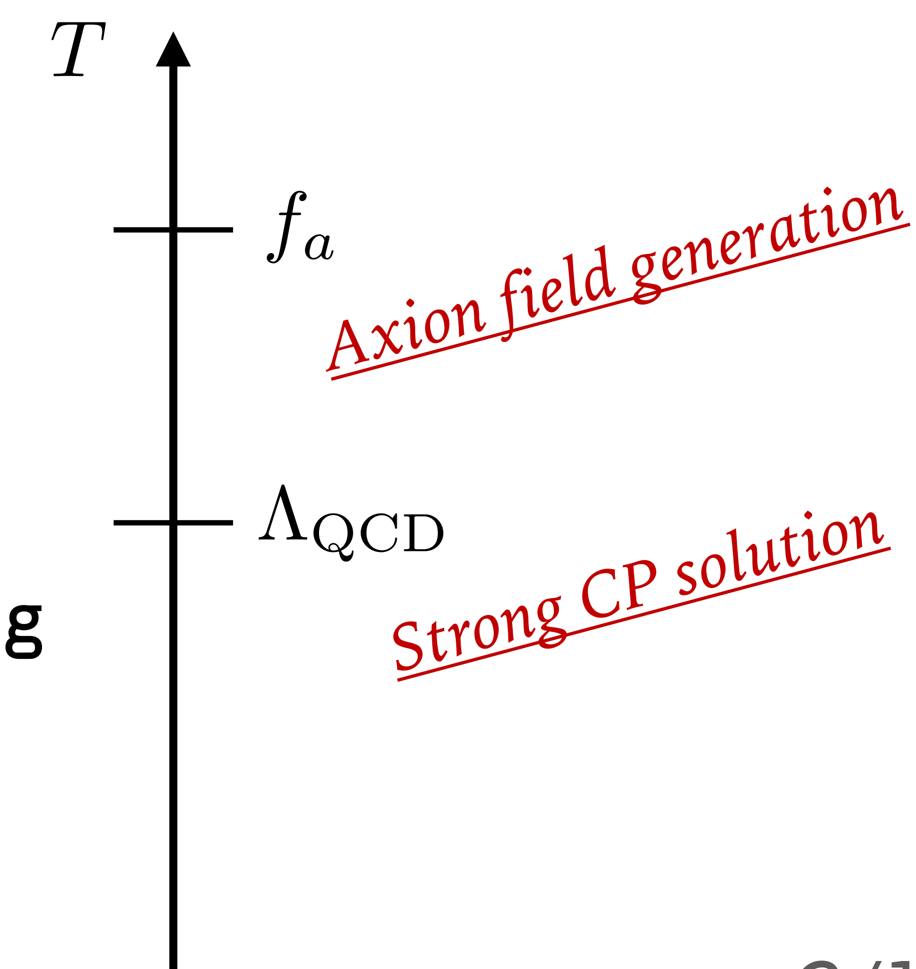
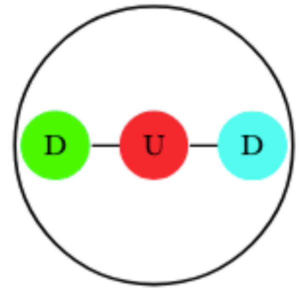
- Axion appears as Goldstone boson, but symmetry is anomalous. Axion potential is generated at QCD era due to explicit breaking



Motivations: QCD Axion

Peccei-Quinn solution



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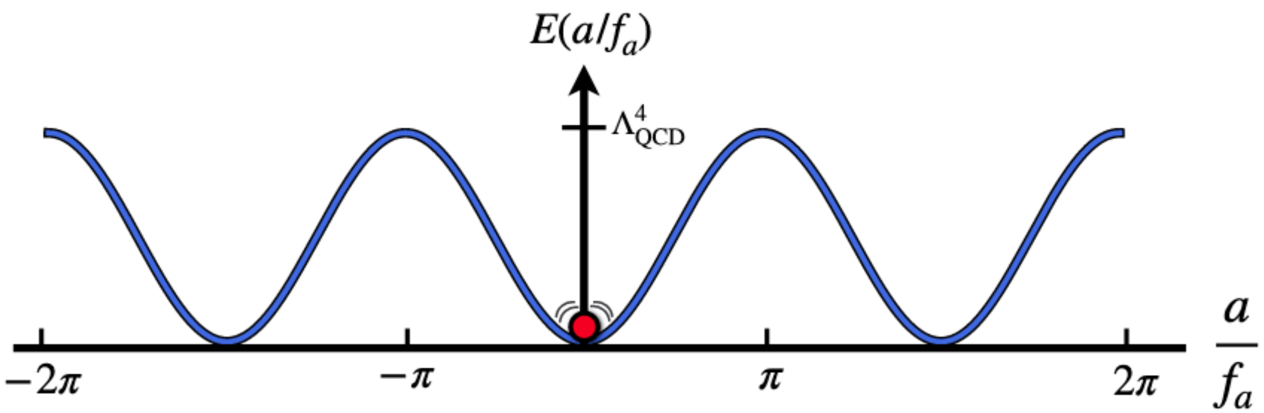

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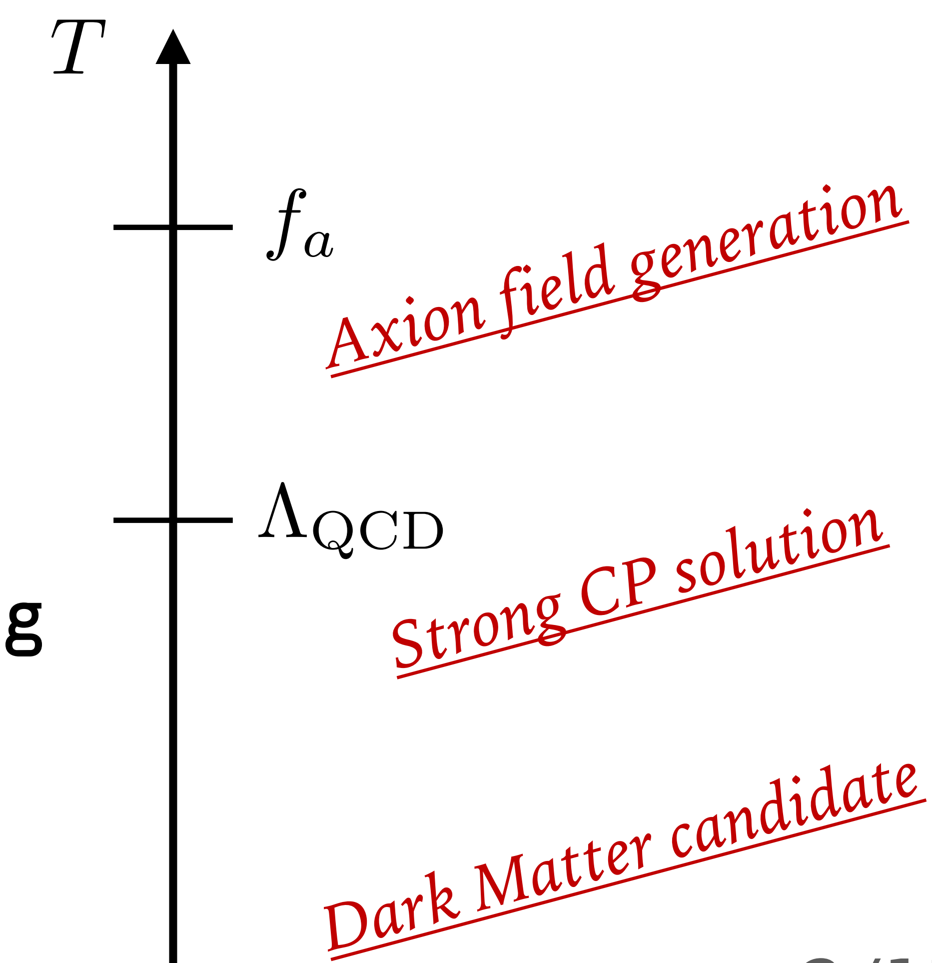
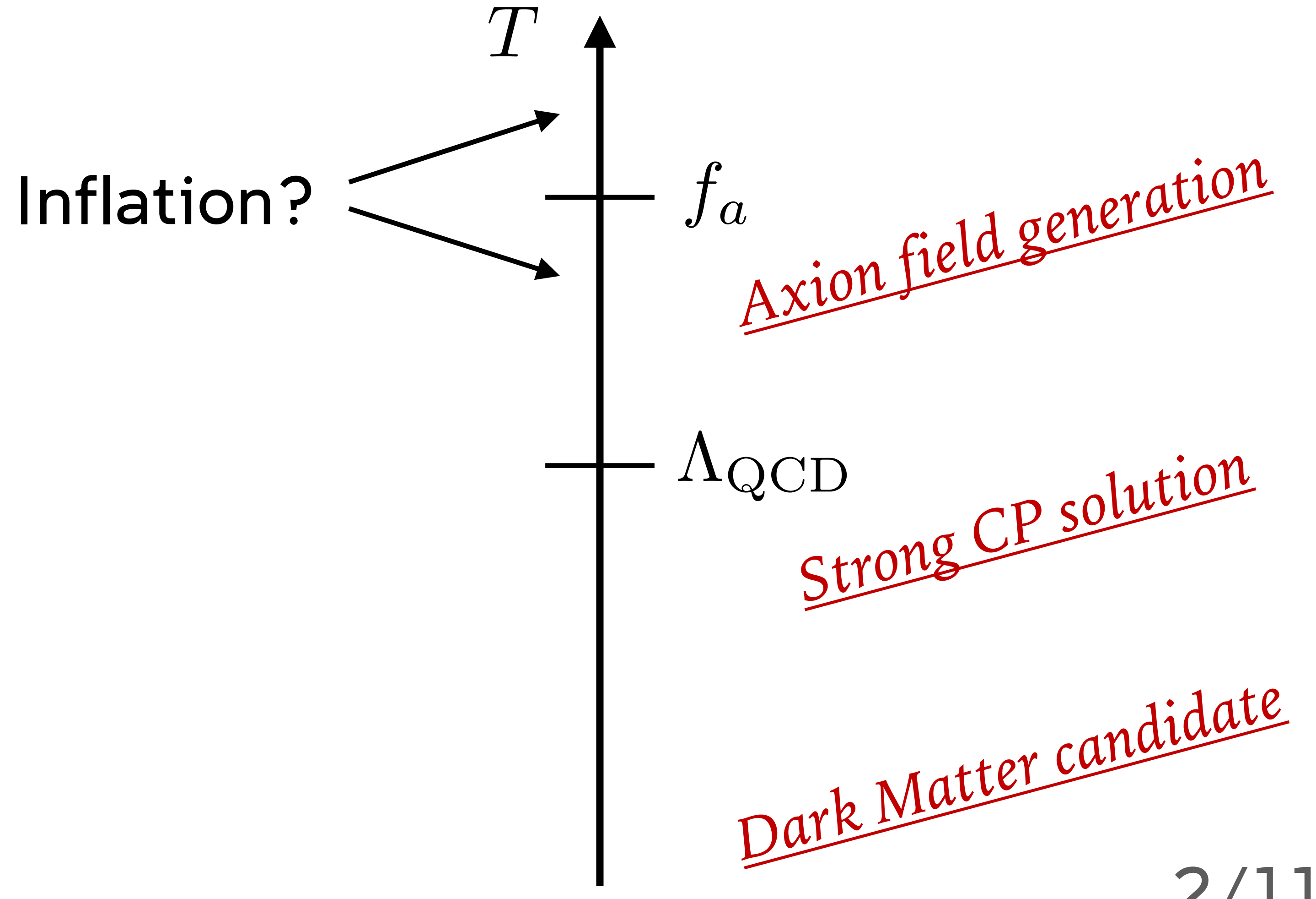
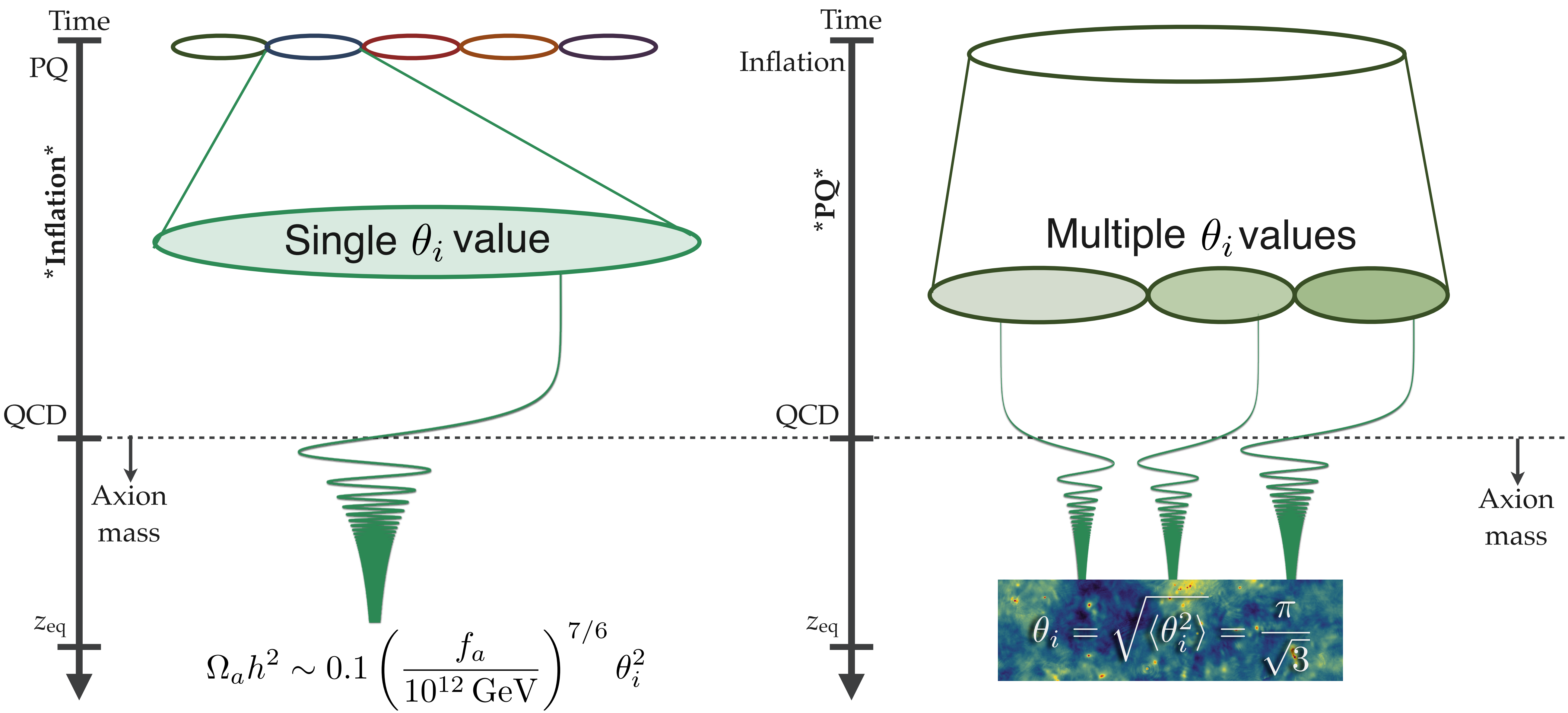
- Axion appears as Goldstone boson, but symmetry is anomalous. Axion potential is generated at QCD era due to explicit breaking
- Oscillations around potential behave as NR condensate



Motivations: QCD Axion



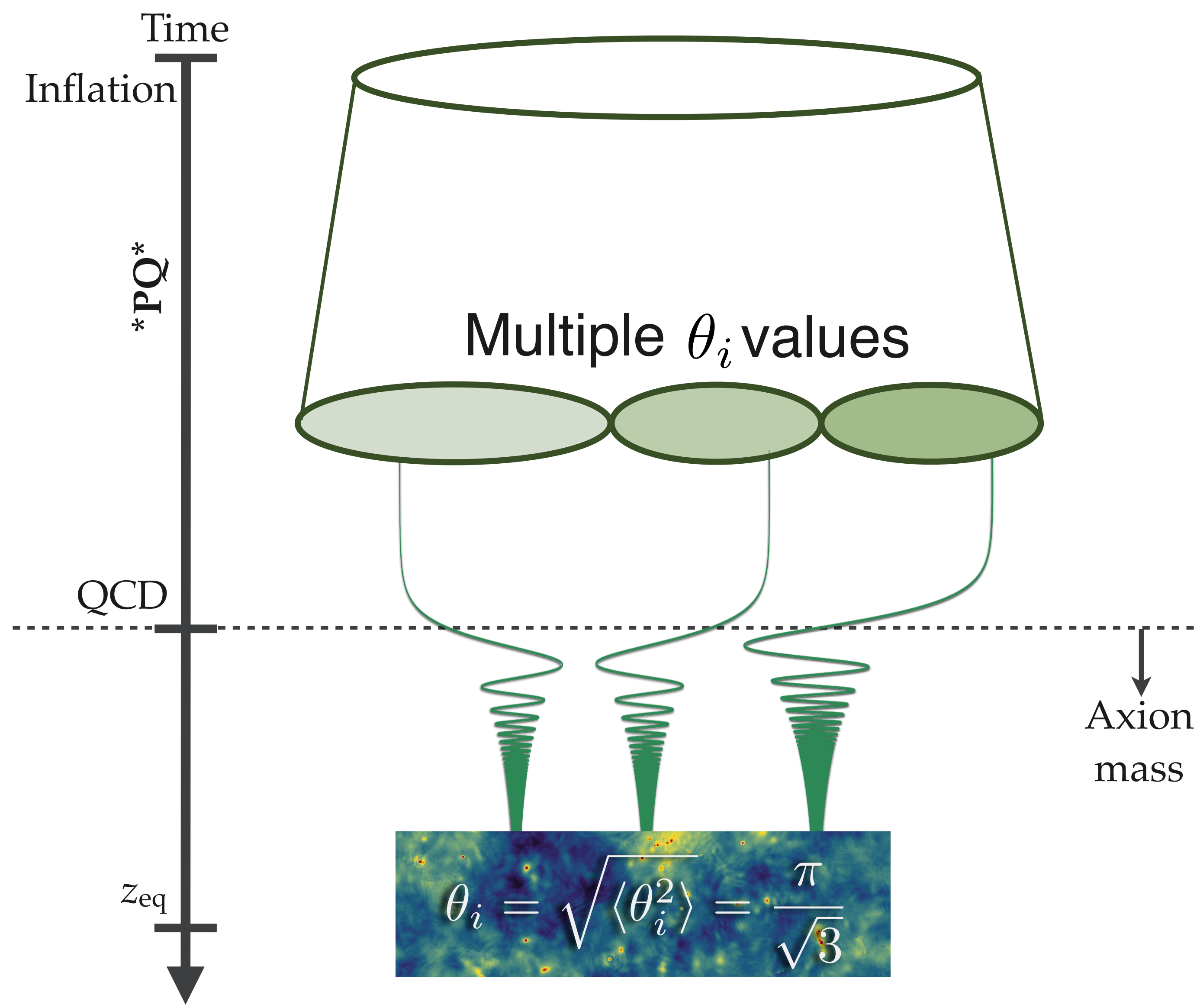
Pre vs.Post-Inflation scenario



Relic density just depends on single initial misalignment angle

Distribution of initial misalignment angles → distribution highly inhomogeneous

Pre vs.Post-Inflation scenario



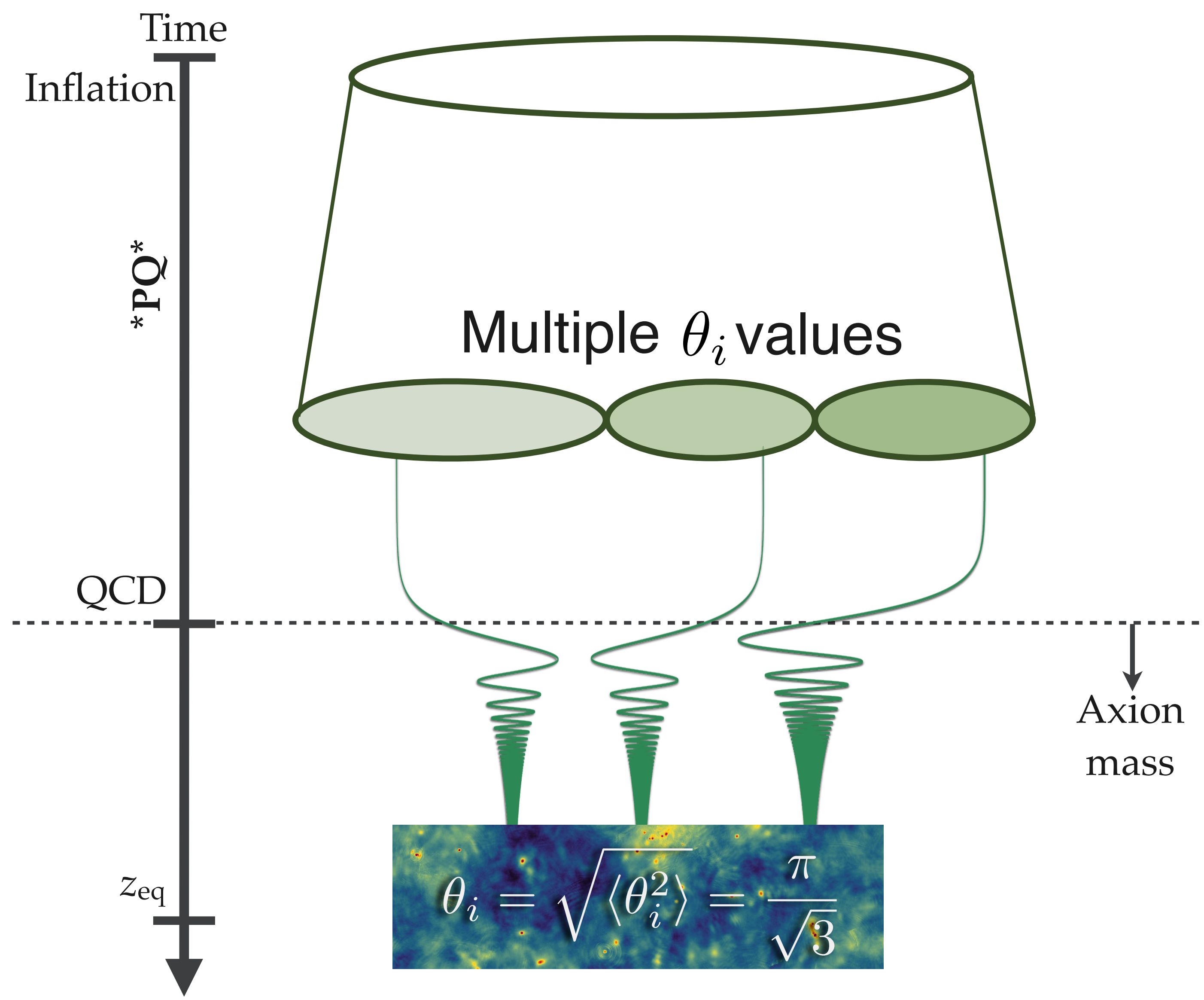
Distribution of initial misalignment angles
→ distribution highly inhomogeneous

Pre vs.Post-Inflation scenario

Topological defects and Axion miniclusters

- Axion strings form due to spontaneous breaking
- Domain walls form due to explicit breaking
- Miniclusters form due $\mathcal{O}(1)$ fluctuations in energy

Hiramatsu et al. [1012.5502] [1012.4558] [1202.5851]
Fleury, Moore [1509.00026]
Klaer, Moore [1707.05566] [1708.07521]
Gorghetto et al. [1806.04677] [2007.04990]
Vaquero et al. [1809.09241]
Buschmann et al. [1906.00967] [2108.05368]
Hindmarsh et al. [1908.03522] [2102.07723]



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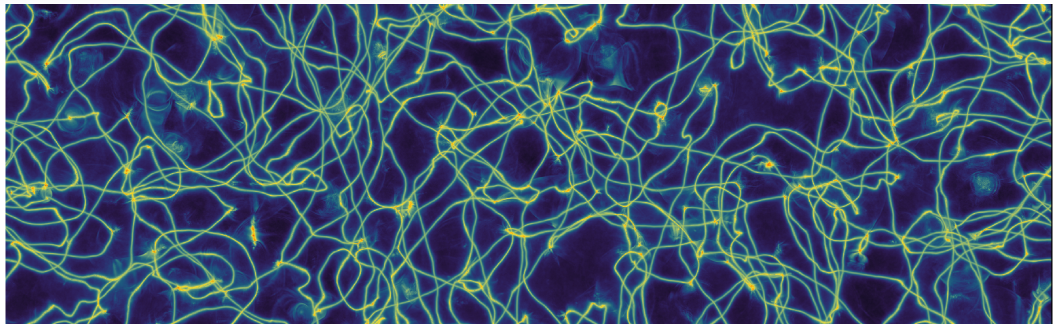

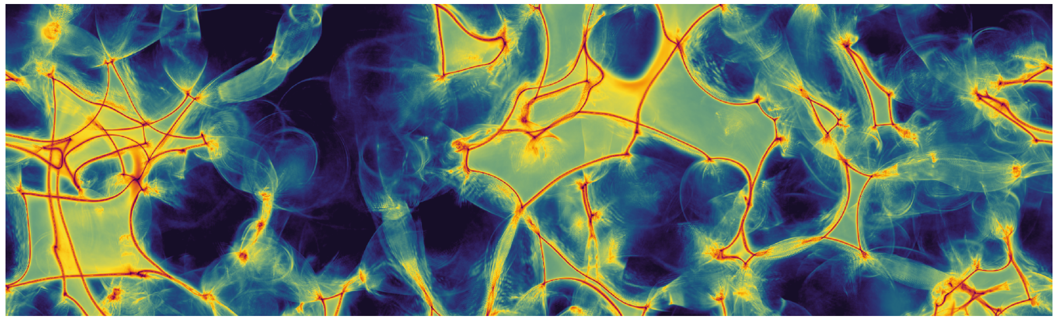

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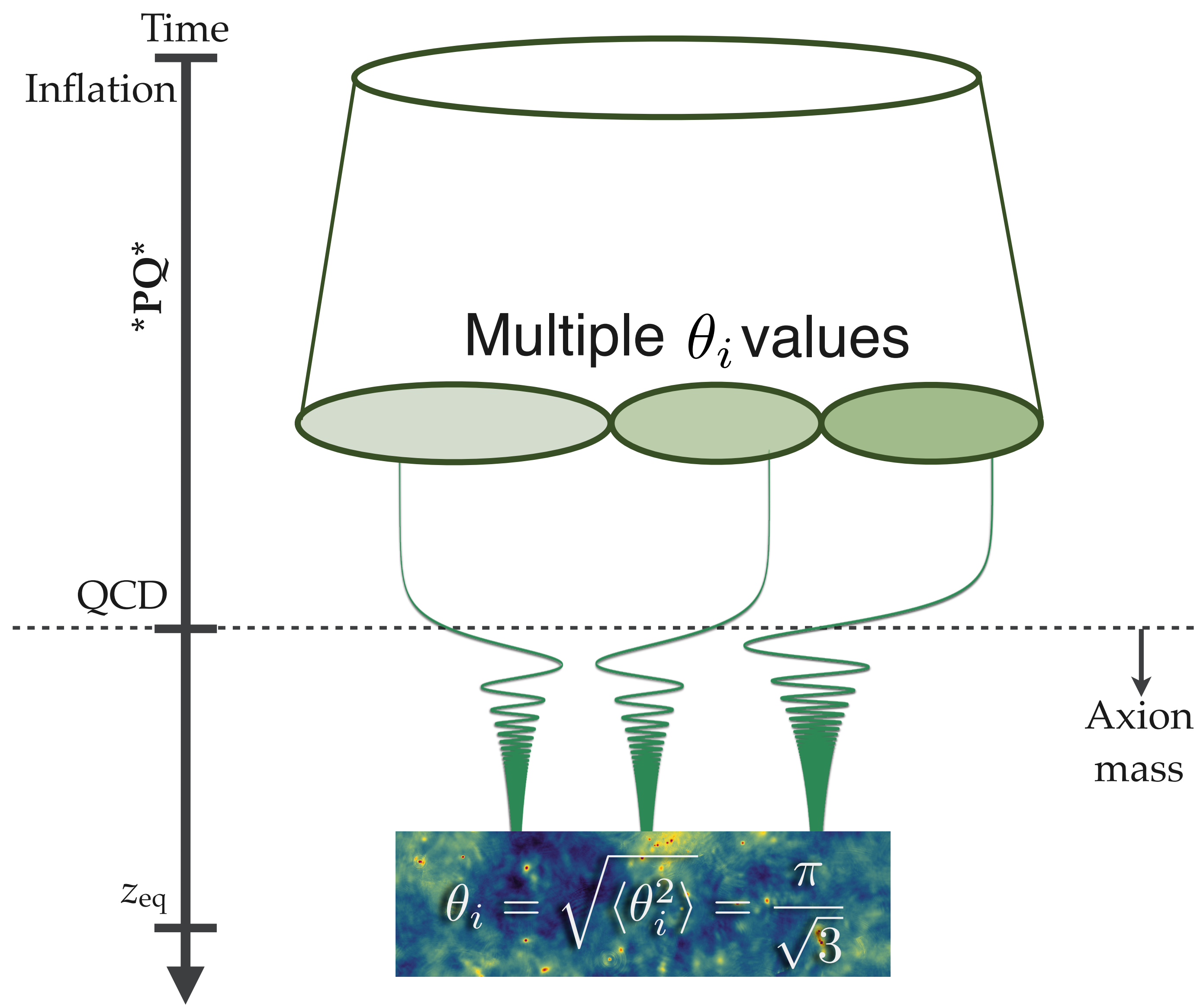
- Miniclusters form due $\mathcal{O}(1)$ fluctuations in energy

Dark matter production starts when the mass becomes comparable to Hubble horizon

$$m_a(t) \sim H(t)$$



Distribution of initial misalignment angles → distribution highly inhomogeneous

How is the system affected by mass parametrisation?

Overview

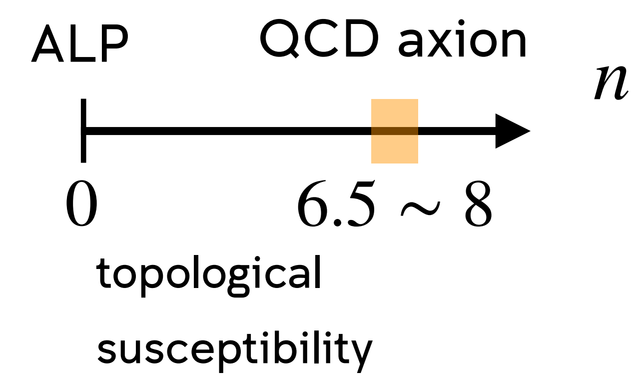
Studied production of axions, energy density substructure as a function of the axion mass parametrisation

Extend to temperature independent mass, model-independent ALP

$$\ddot{\phi} + 3H\dot{\phi} - \frac{\nabla^2}{a^2}\phi + \frac{\partial V}{\partial \phi} = 0 \qquad \phi = |\phi| e^{i\theta}$$

$$V(\phi) = \lambda(|\phi|^2 - f_a^2)^2 + m_a^2(T) f_a^2 (1 - \cos\theta)$$

$$m_a^2(T) = m_a^2 \left(\frac{T_\star}{T}\right)^n$$



Gross et al. Rev. Mod. Phys. 53 (1981)
Wantz, Shellard [0910.1066]
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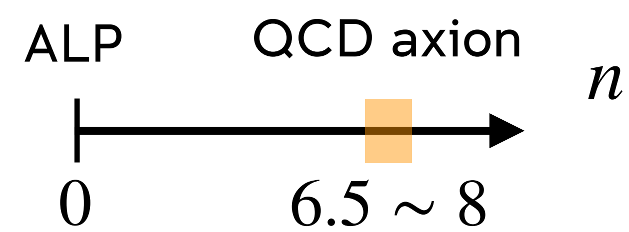

topological susceptibility

Gross et al. Rev. Mod. Phys. 53(1981)
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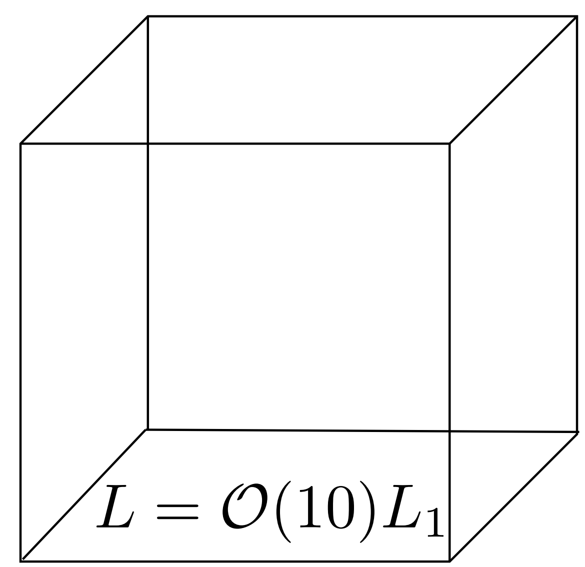
Performed ~100 simulations with large resolution and with $n \in [0{,}6]$



$$m_a(t_1) = H(t_1)$$

$$L_1 = \frac{1}{a(t_1) H(t_1)}$$

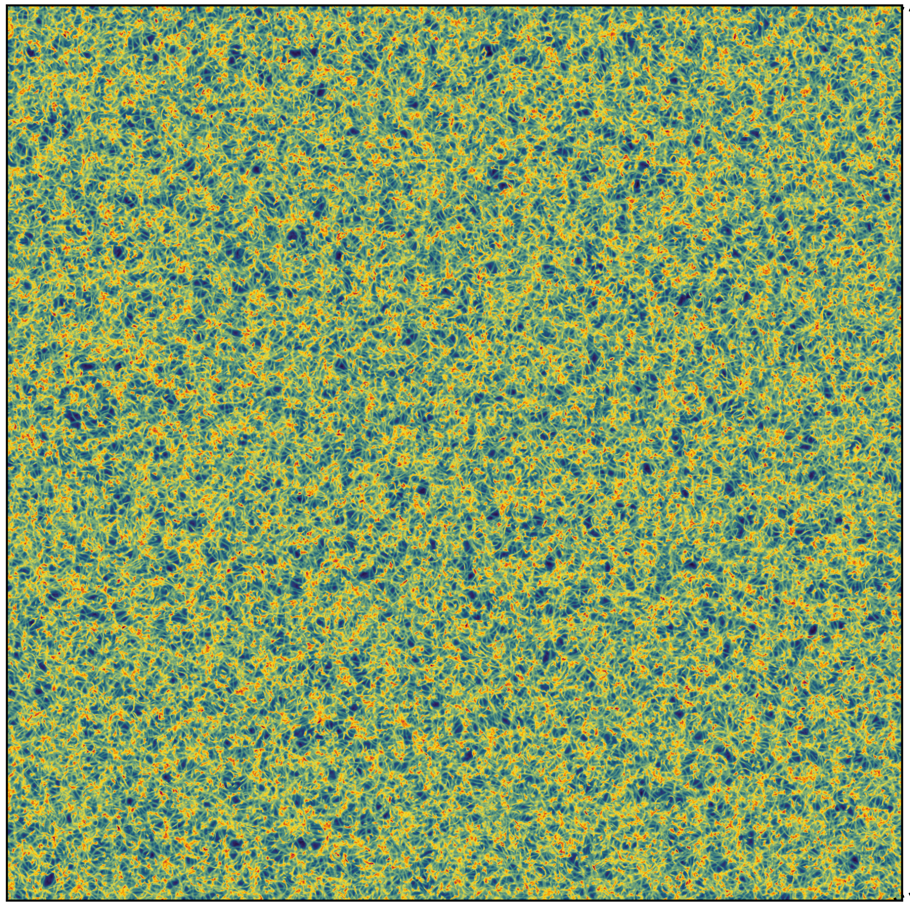
$$\kappa = \log(f_a/H)$$

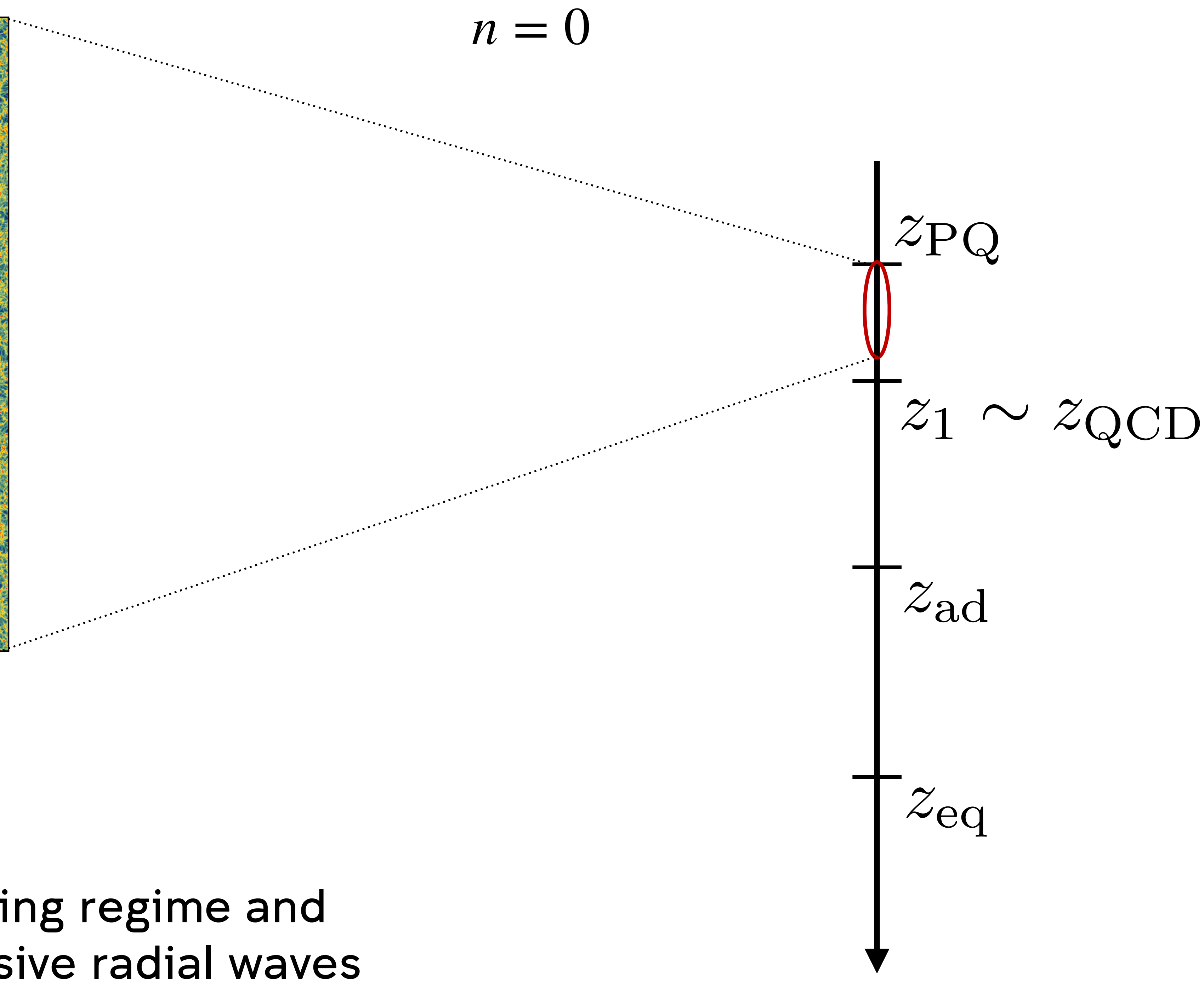
$$\kappa_{\rm QCD} \sim 60$$

Assumptions

- PRS trick to extend dynamical range in the presence of strings
- Cannot achieve physical values of string tension
- Domain wall instability, $N_{\rm DW} = 1$

Time evolution



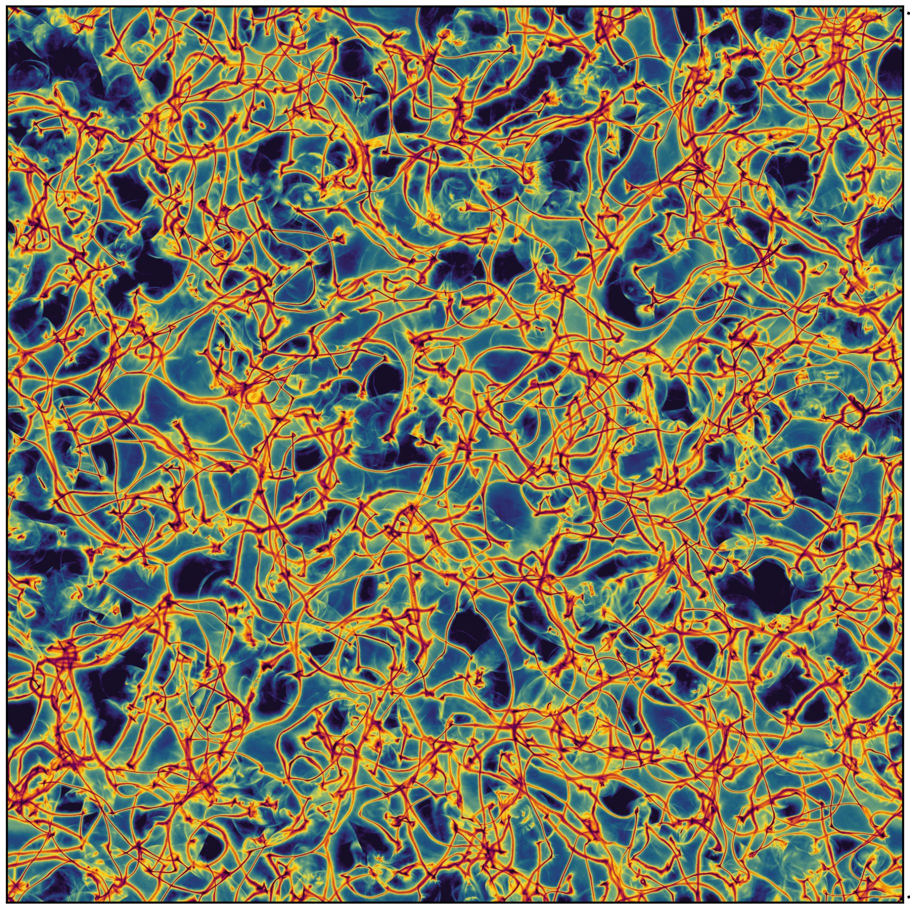


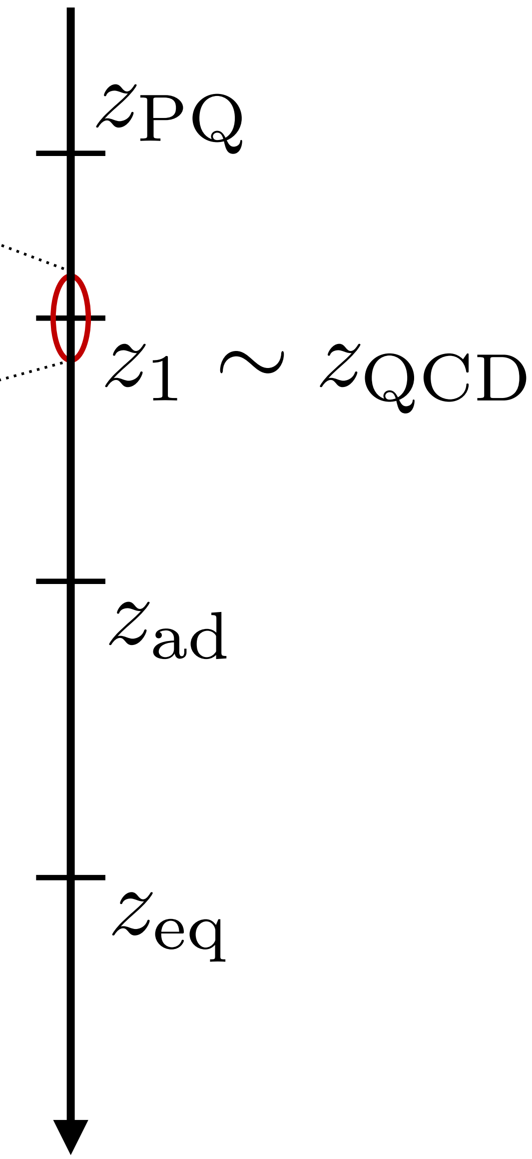
$t \ll t_1$

Axion string dynamics: scaling regime and massless axion waves, massive radial waves

Evolution: The ALP simulation

$n = 0$



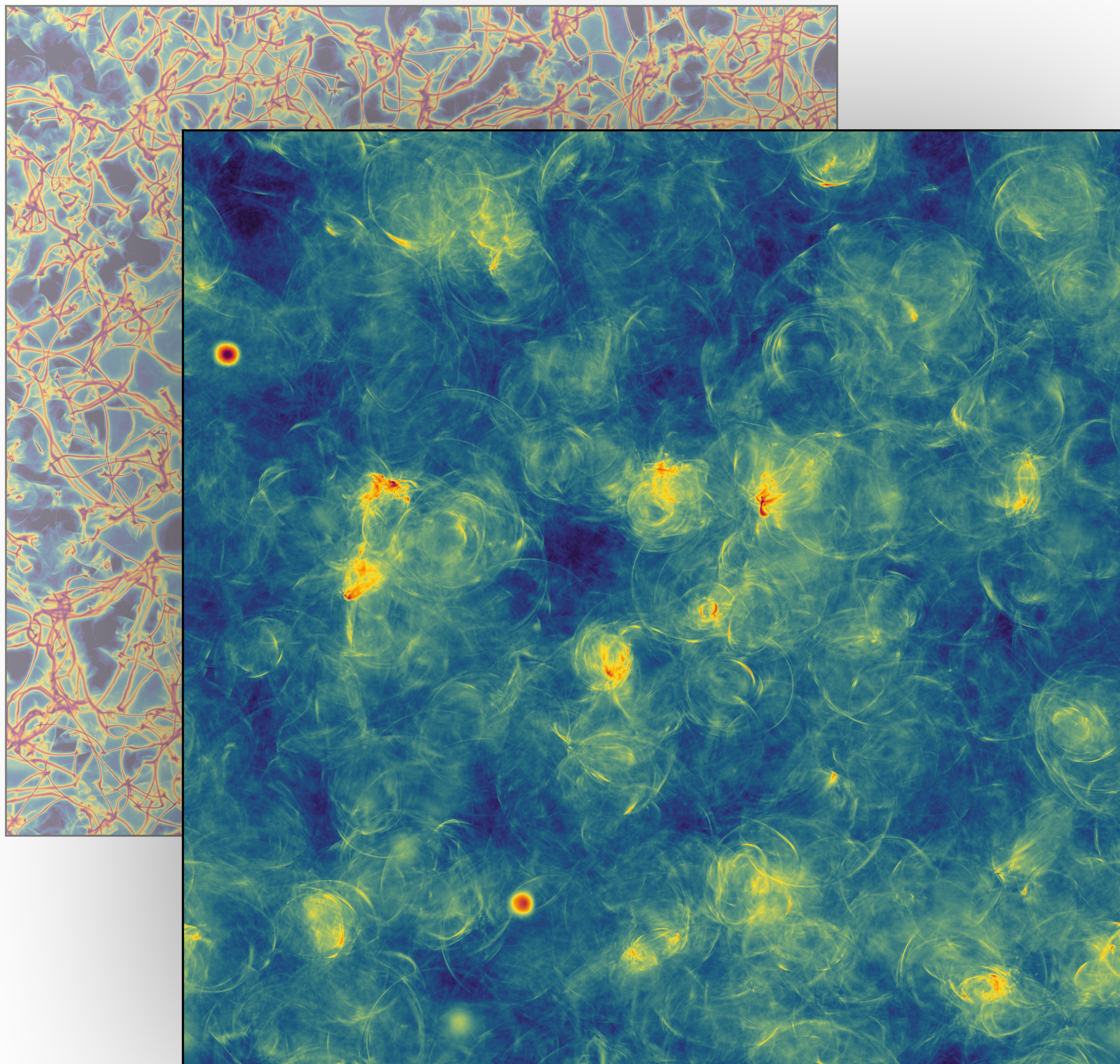


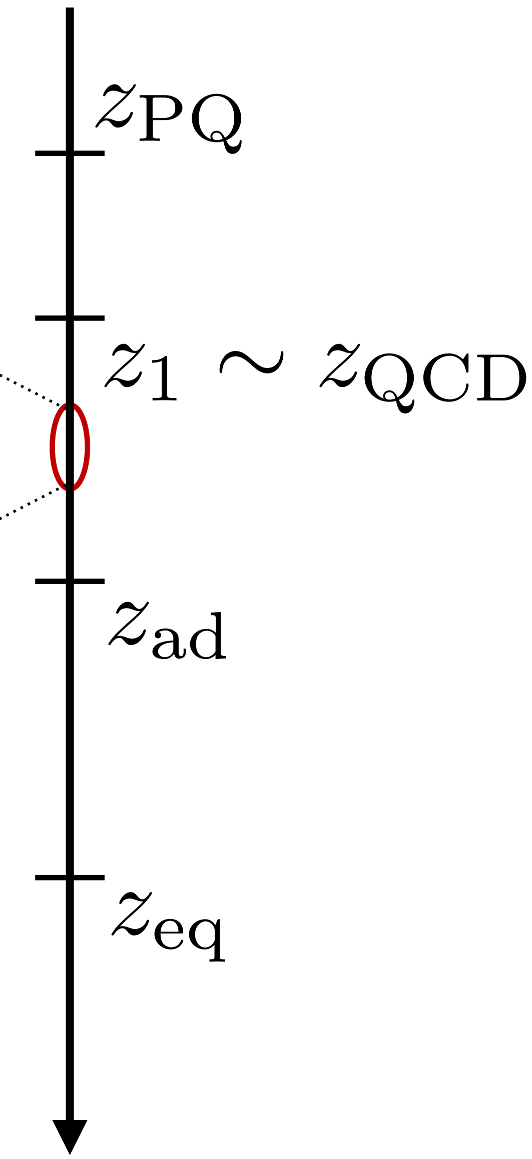
$t \sim t_1$

String-Wall network dynamics: collapse of defects and onset of axion field oscillations

Evolution: The ALP simulation

$n = 0$

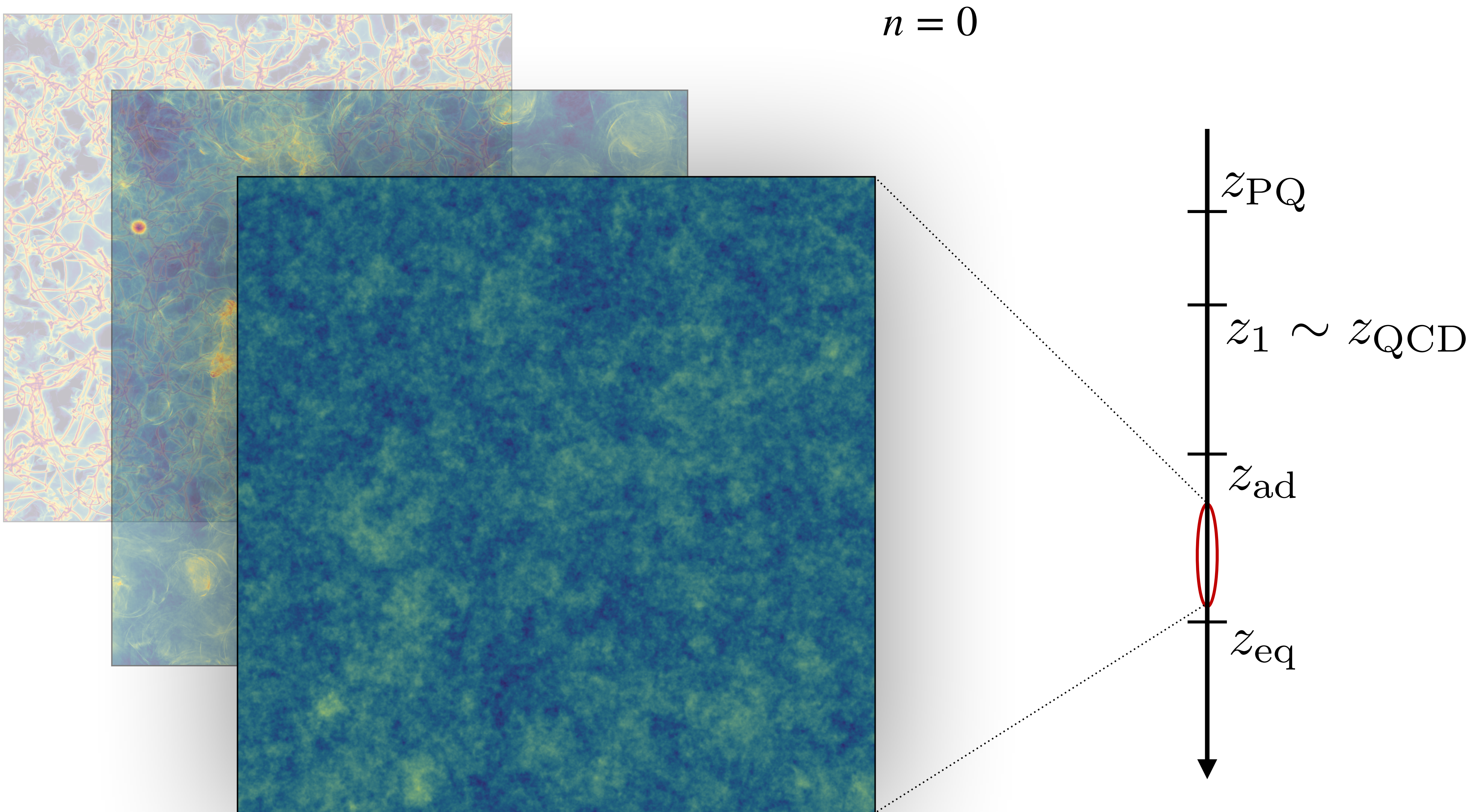




$t \gtrsim t_1$

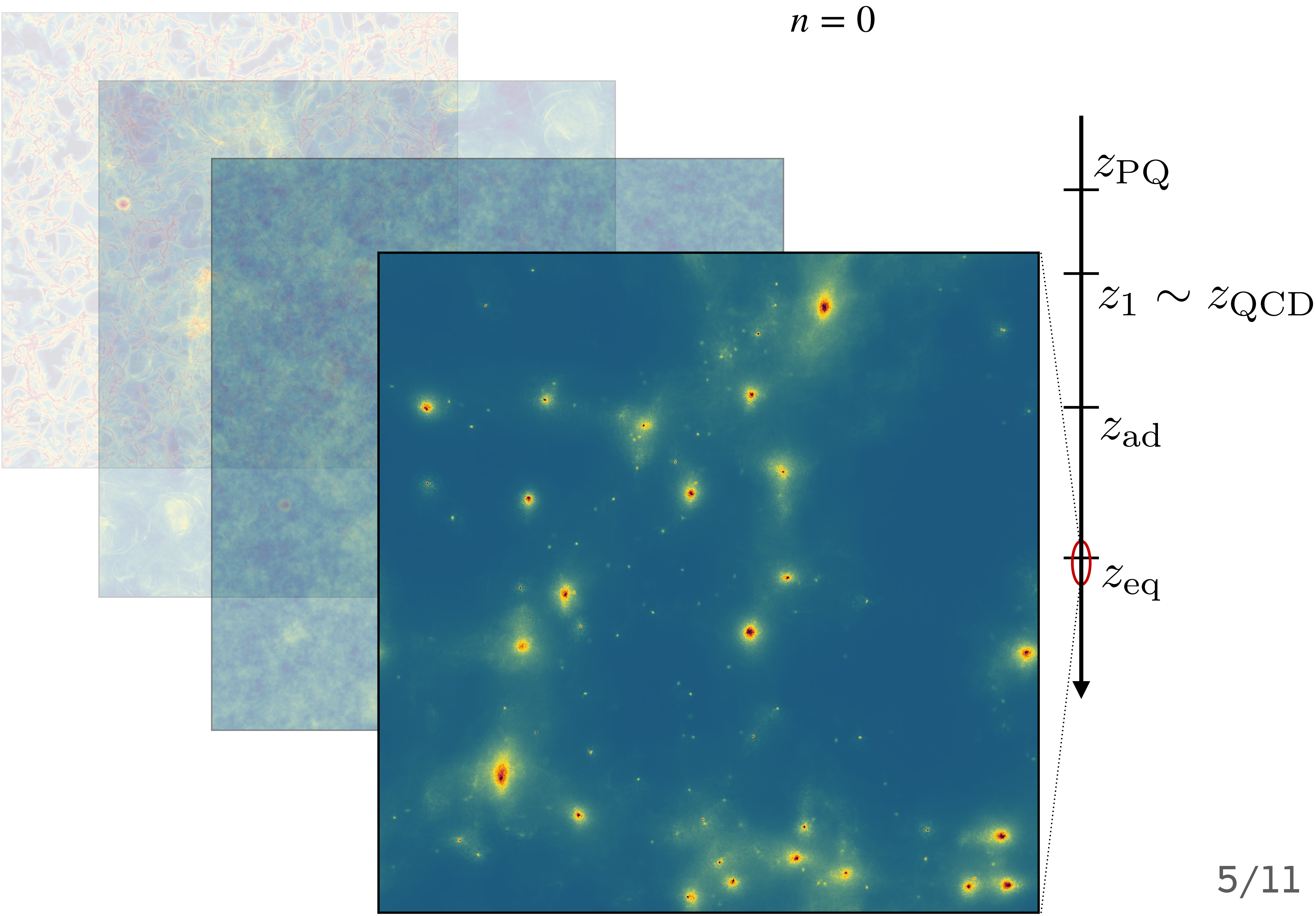
Axion field oscillations and formation of axitons (oscillons) for large n values

Evolution: The ALP simulation



$t \gtrsim t_{\rm ad}$ Axion number density frozen, free streaming of axion waves

Evolution: The ALP simulation



Mass parametrisation impact

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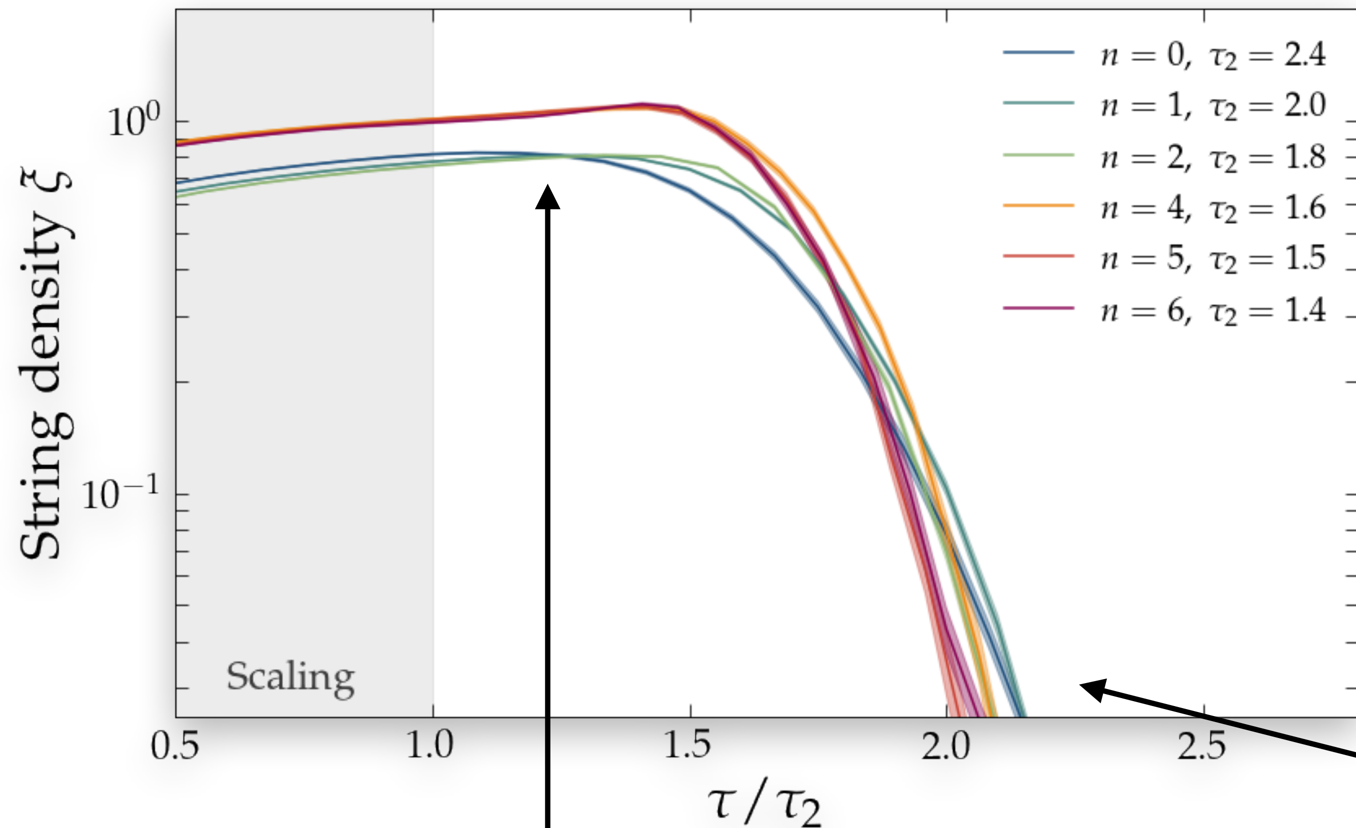


$$\xi = \frac{\ell(t) t^2}{\mathcal{V}}$$

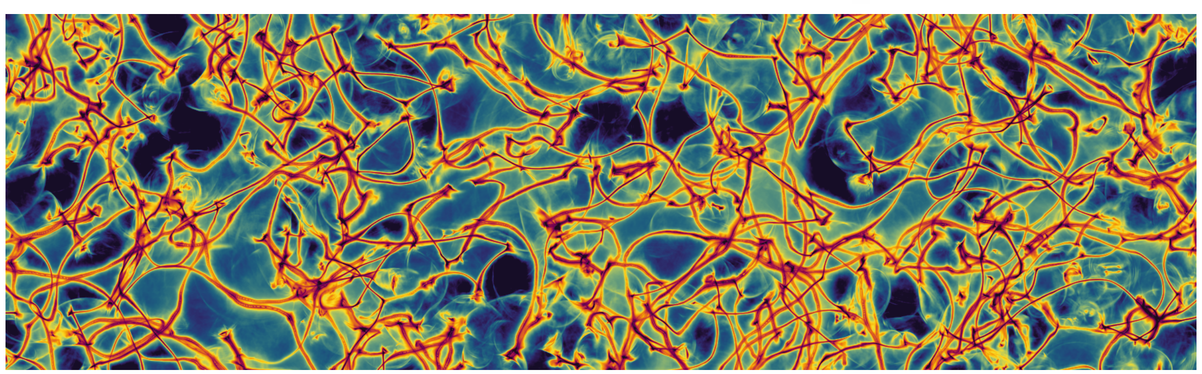
Number of strings per causal volume

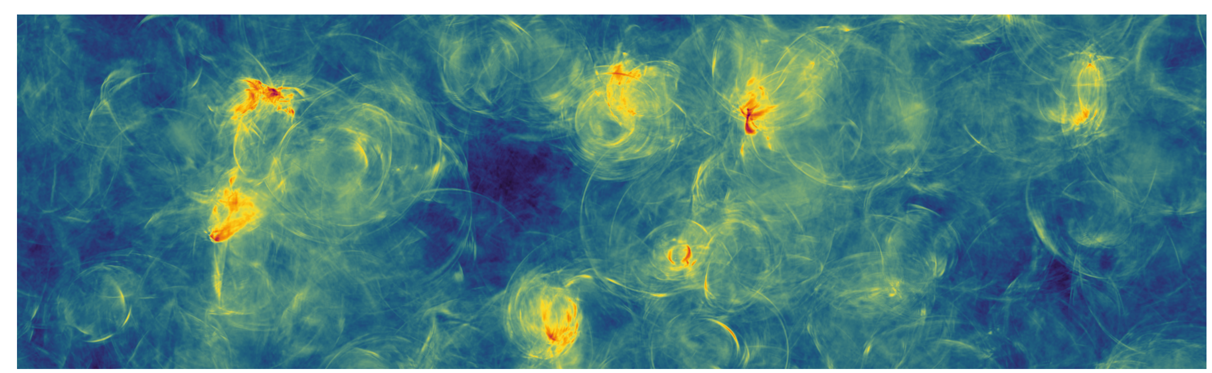
Log-growth before mass turns on and destroys the network

Smooth annihilation for low n

$$\tau_2(n) = (\pi\kappa/4)^{2/(n+4)}$$

$\kappa = \log(f_a/H)$





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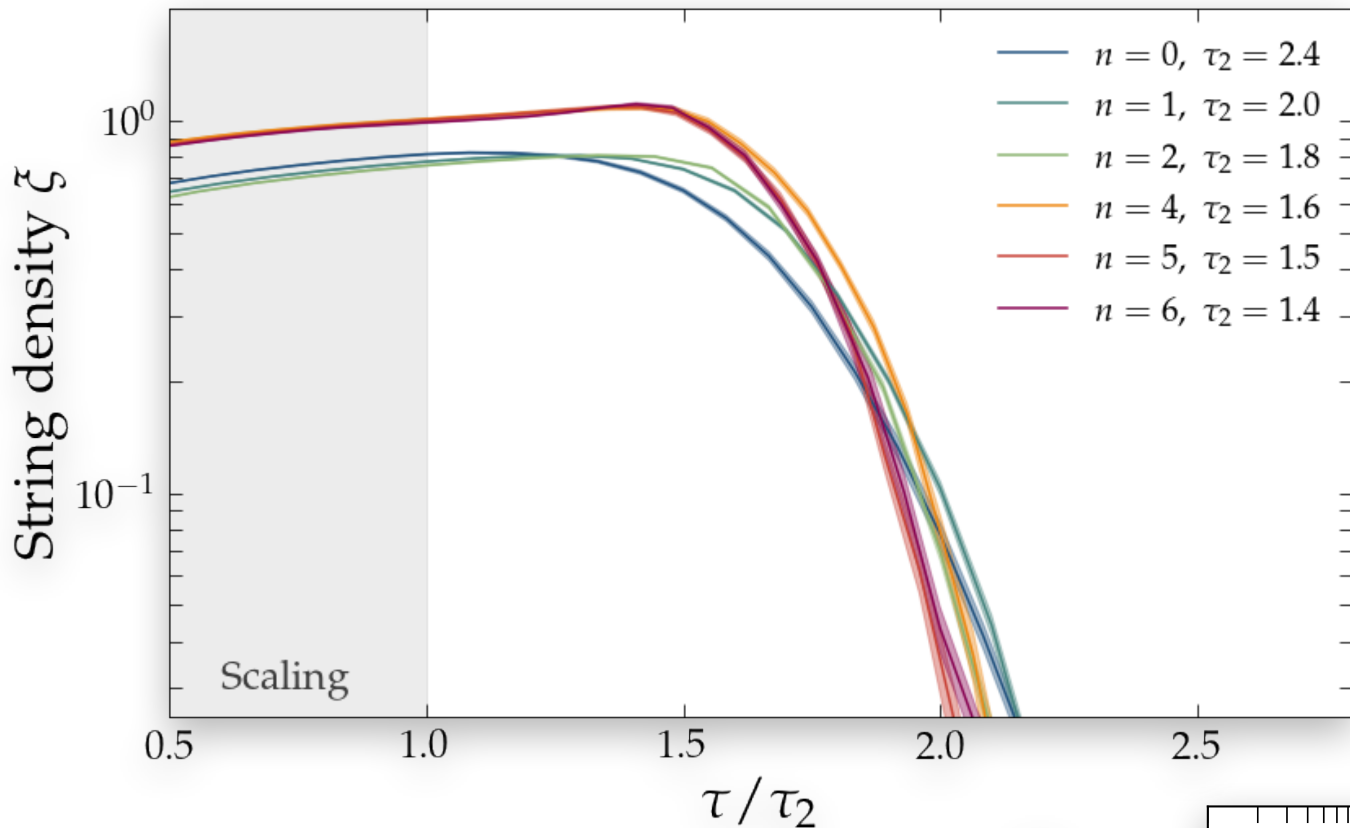

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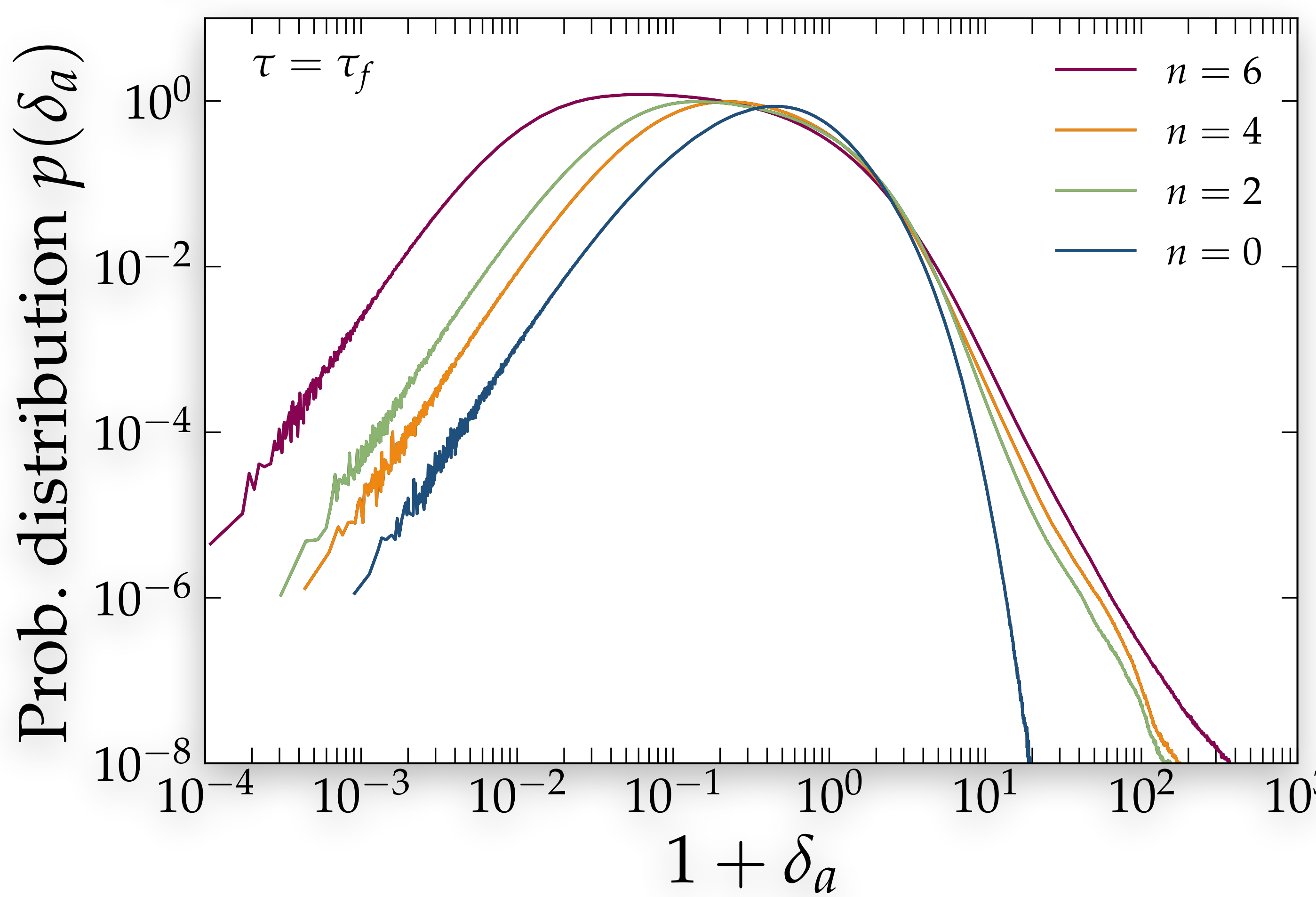
After network has entirely collapsed we can evolve with just the angular d.o.f.

Study density contrast in axion energy field

$$\delta = \frac{\rho_a}{\langle\rho_a\rangle} - 1$$



Substructure: Power spectrum

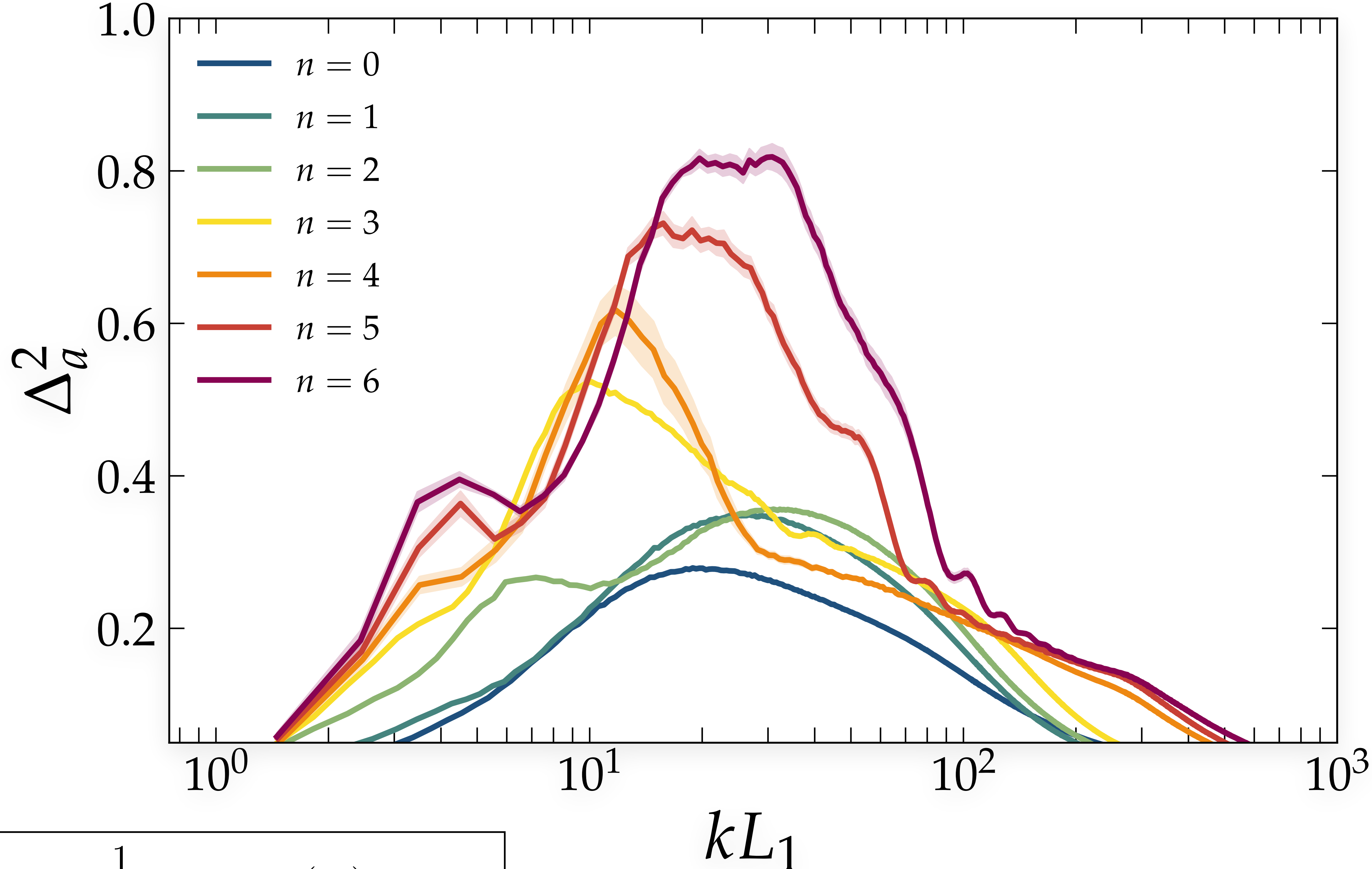
$$\Delta_a^2(k) = \frac{k^3}{2\pi^2}\langle|\widetilde{\delta}(k)|^2\rangle$$

$\tau \gtrsim \tau_f$

$\theta \ll 1$

Linearize equations

$$\ddot{\theta} + 3H\dot{\theta} + m_a^2(T)\theta = 0$$



$$L_1 = \frac{1}{a_1 H_1} \qquad m_a(t_1) = H_1$$

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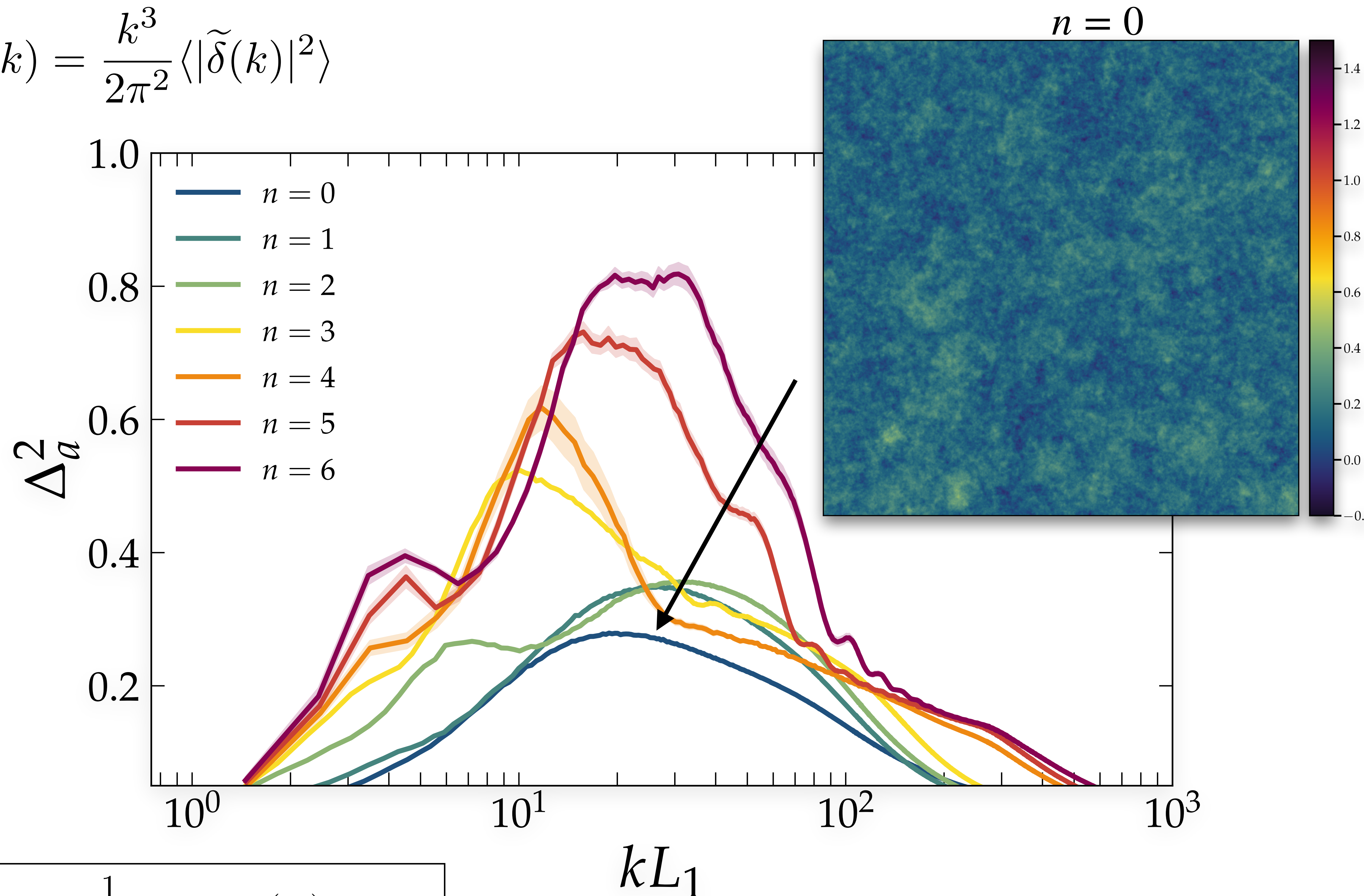

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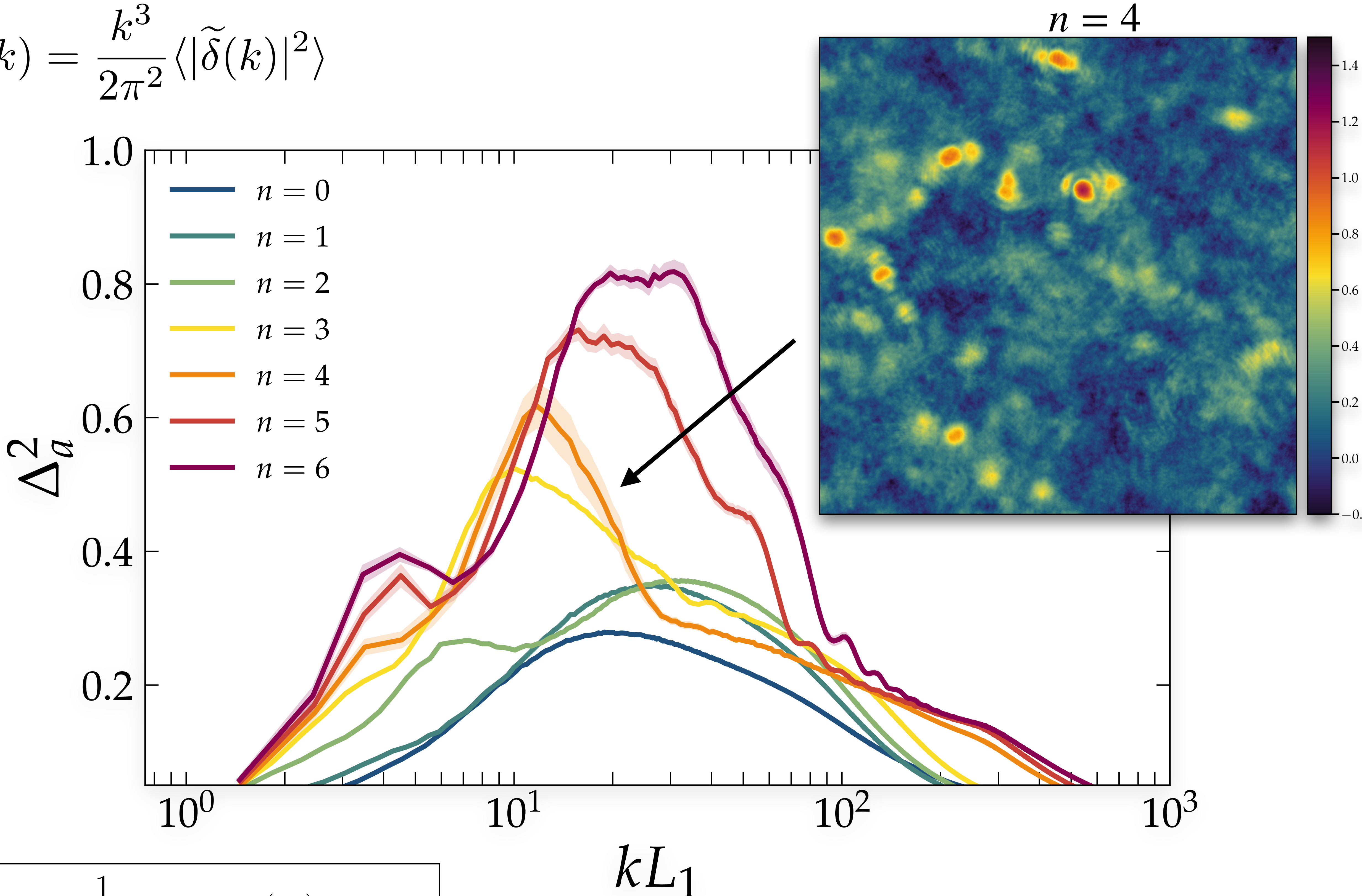

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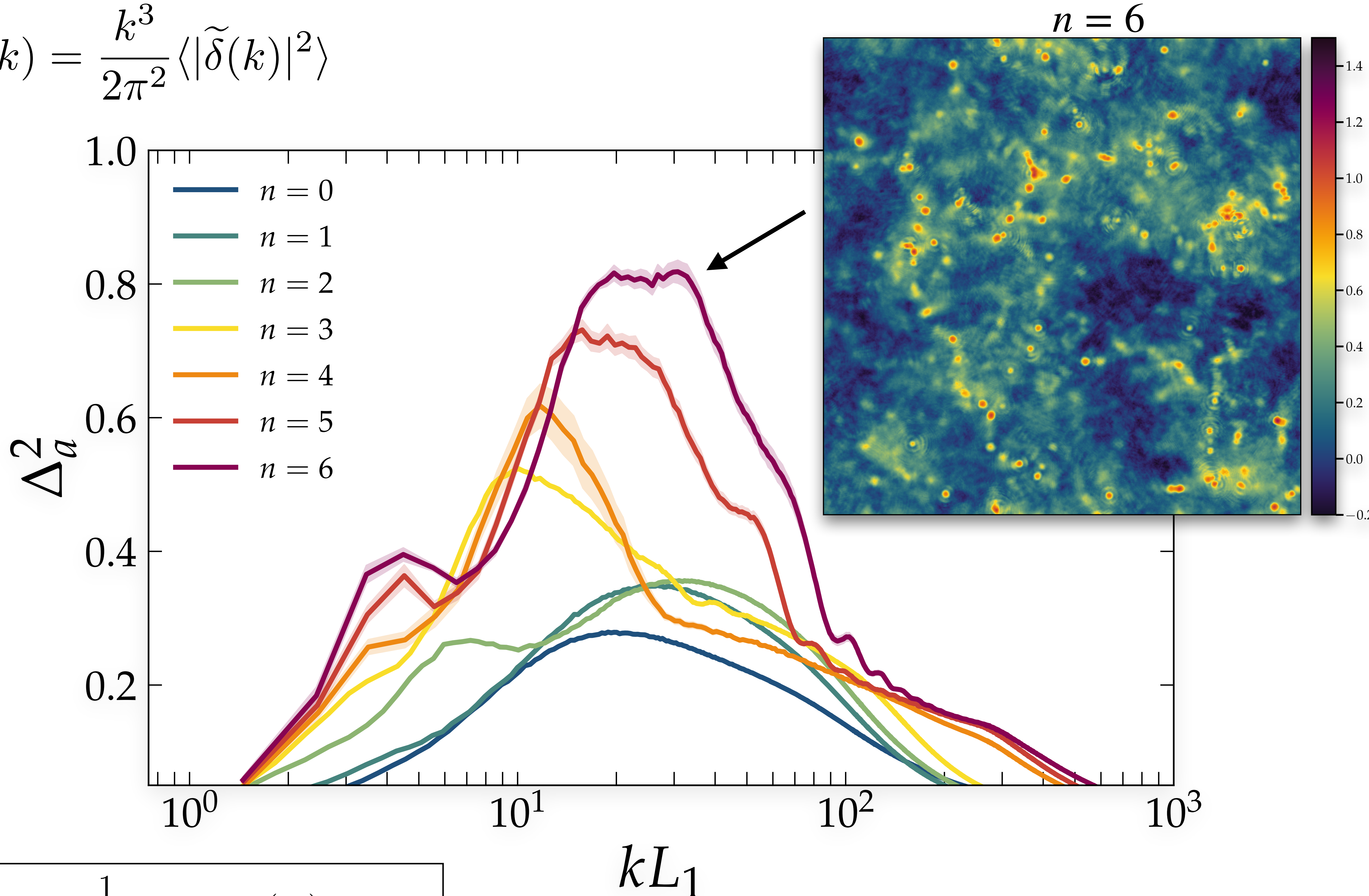

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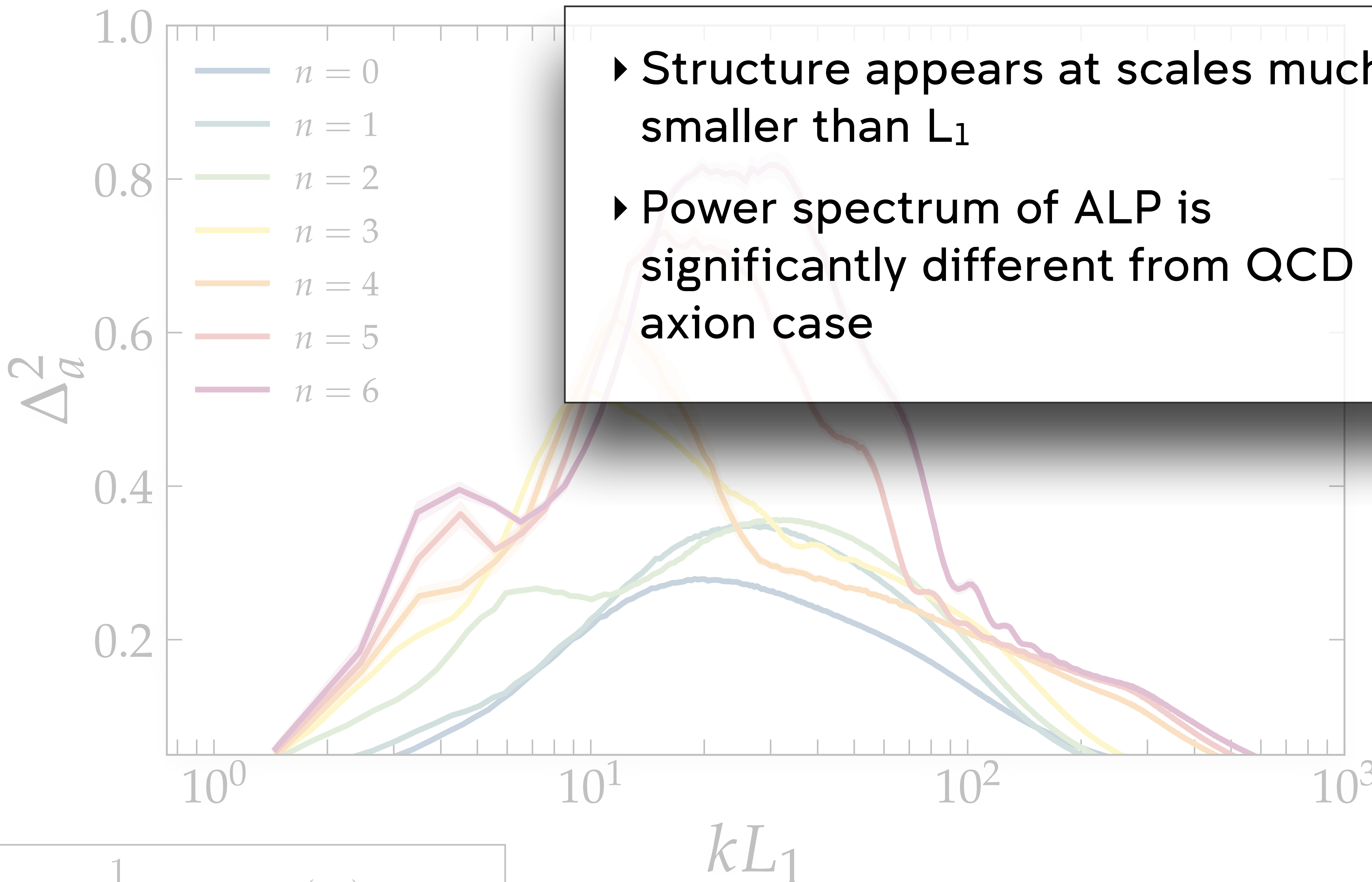
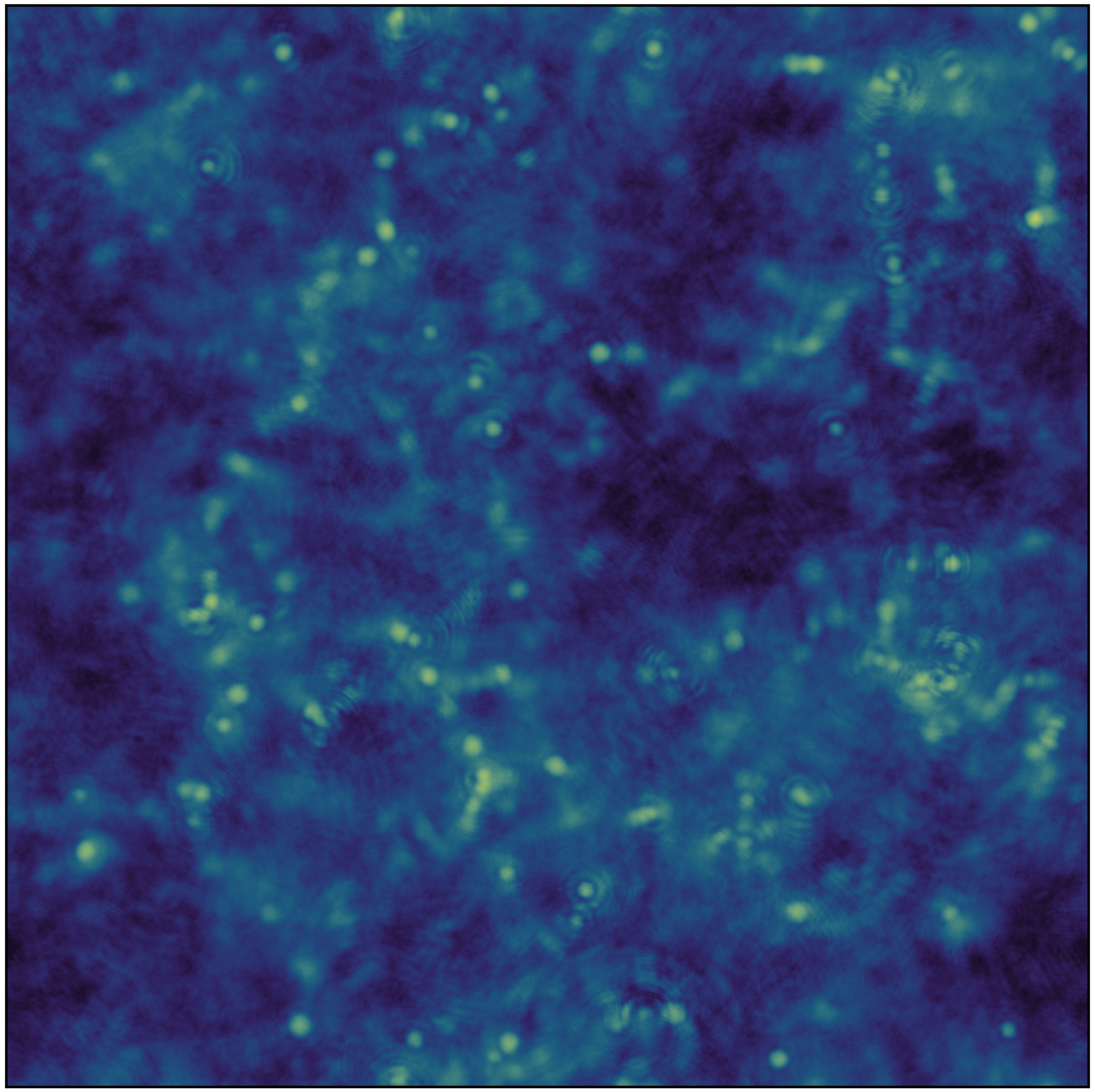


- Structure appears at scales much smaller than L_1
- Power spectrum of ALP is significantly different from QCD axion case

$$L_1 = \frac{1}{a_1 H_1} \qquad m_a(t_1) = H_1$$

Substructure: Minicluster seeds



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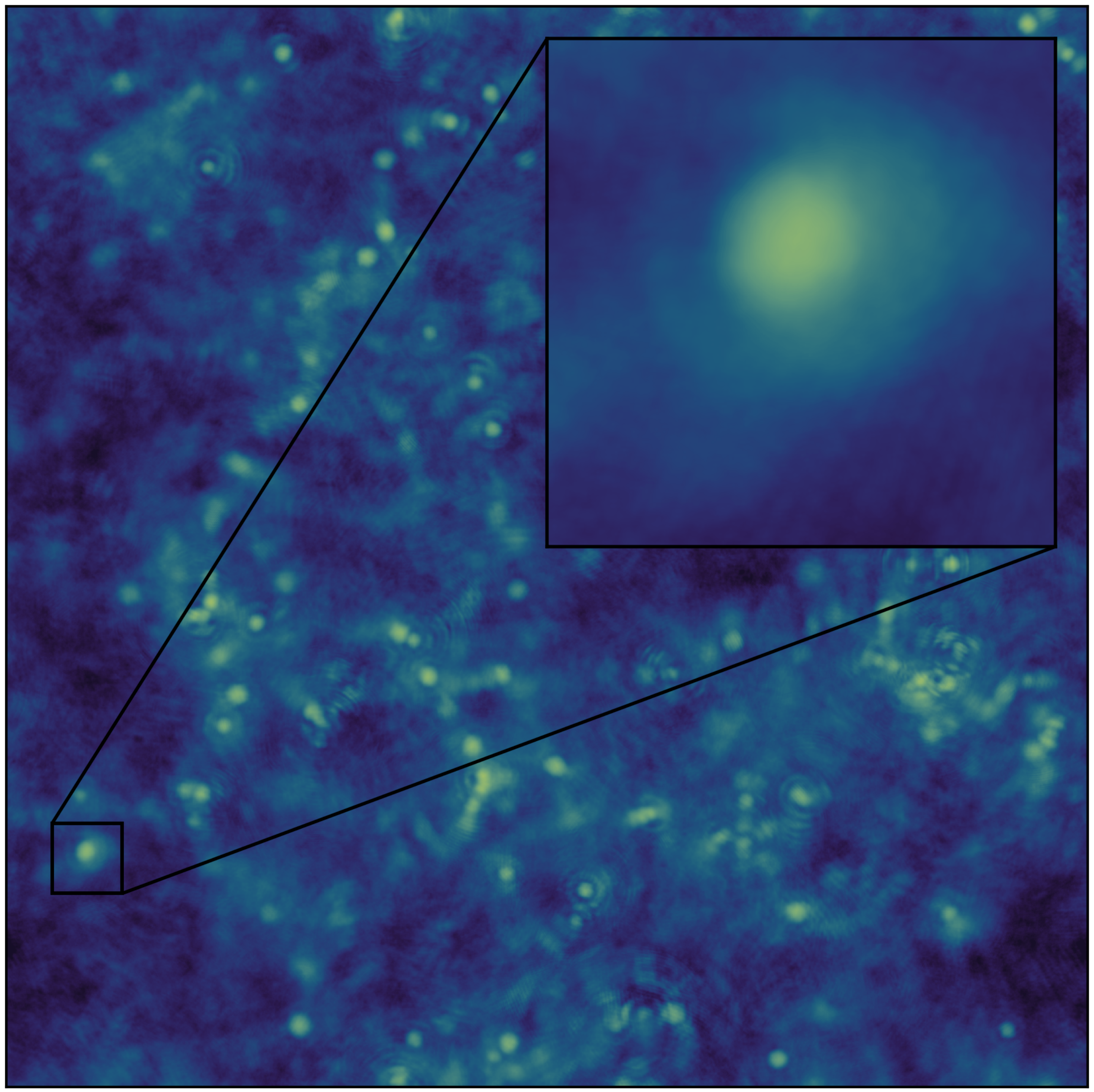
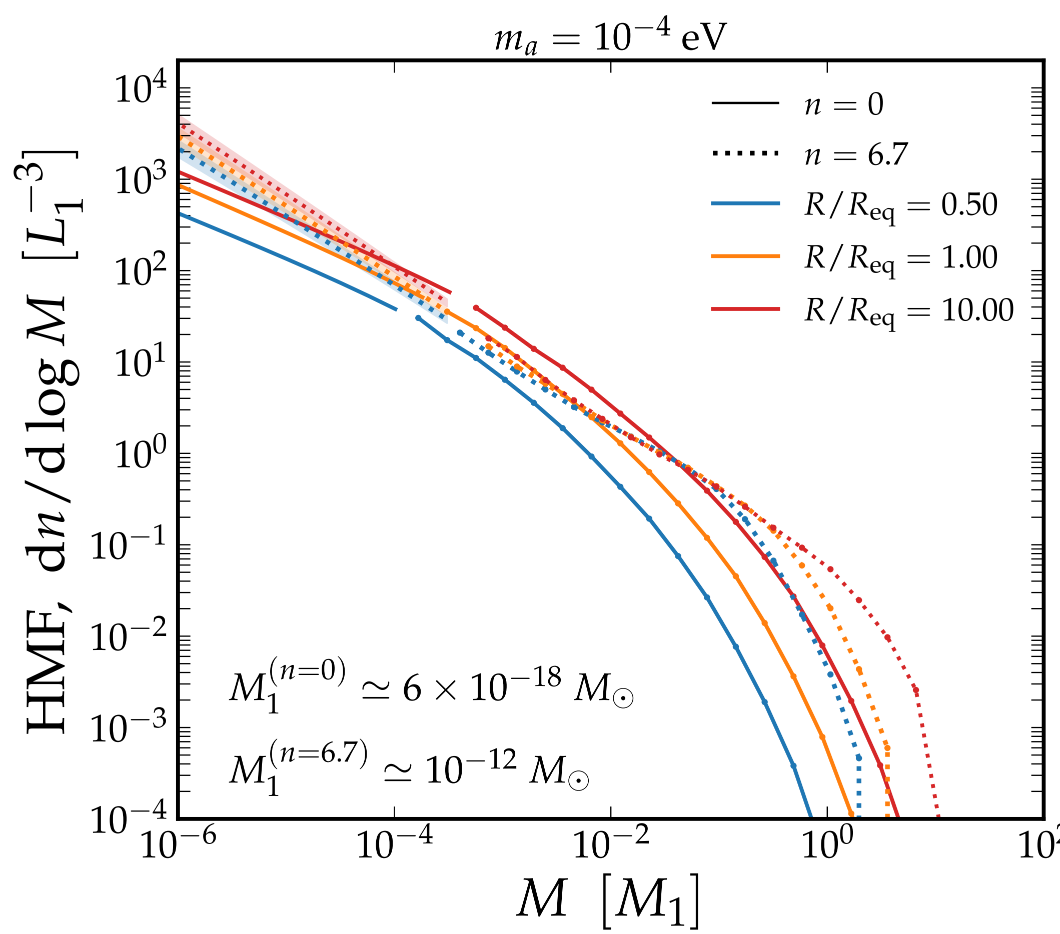


Small-scale power in the axion field can lead to miniclusters around equality

$$M_1 = \frac{4\pi}{3}\langle\rho_a\rangle L_1^3 \sim 10^{-12} M_\odot$$

Implemented a modified PS prescription to estimate halo-mass function

$$\delta_c = \frac{1.686}{3}\frac{2+3a/a_{\rm eq}}{a/a_{\rm eq}}$$



Dark Matter: Axions vs ALPs

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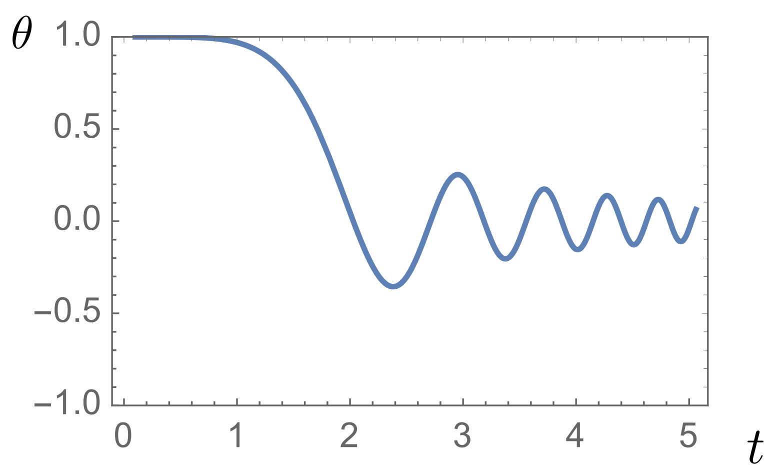
Cold axions produced coherently
after few field oscillations



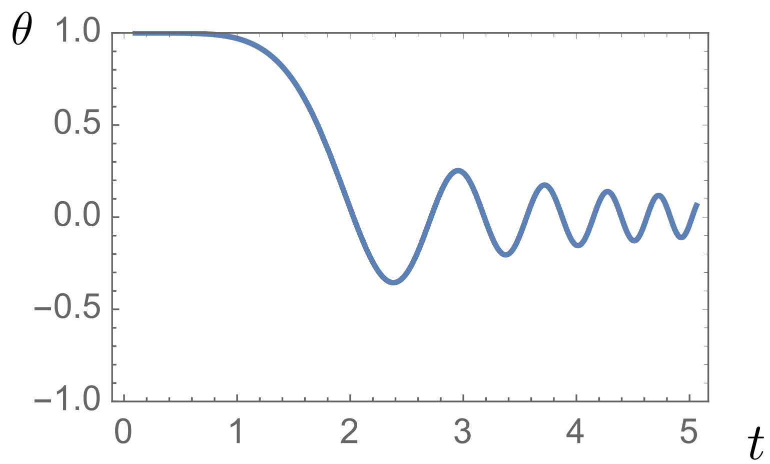
$$\rho(t) = m_a(t_1) m_a f_a^2 \langle \theta_i^2 \rangle \left(\frac{a(t_1)}{a(t)} \right)^3$$

Standard linear $\langle \theta_i^2 \rangle = \pi^2/3$

Measured number of axions
at the end of our simulations

Dark Matter: Axions vs ALPs

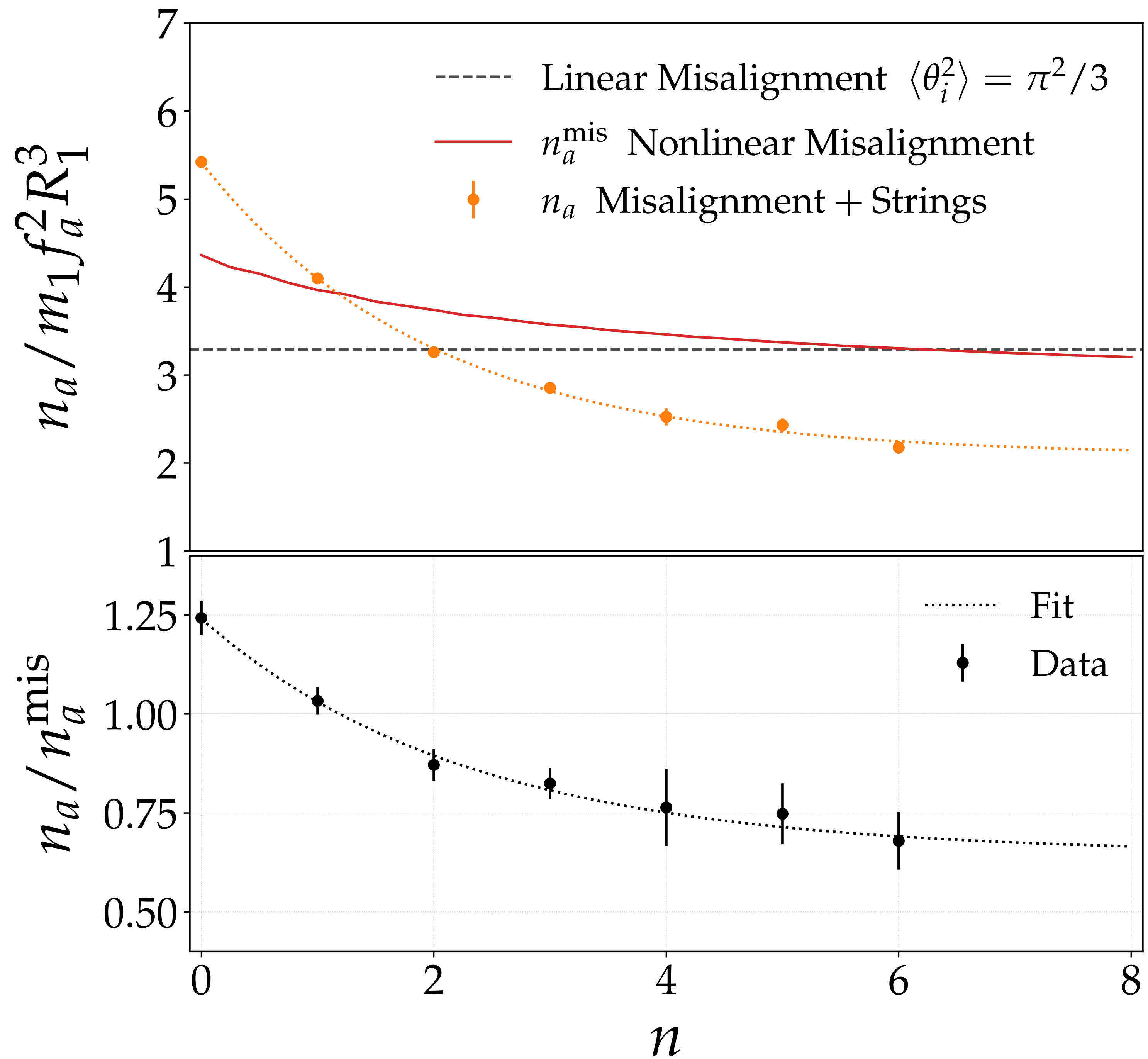
Cold axions produced coherently after few field oscillations



$$\rho(t) = m_a(t_1) m_a f_a^2 \langle \theta_i^2 \rangle \left(\frac{a(t_1)}{a(t)} \right)^3$$

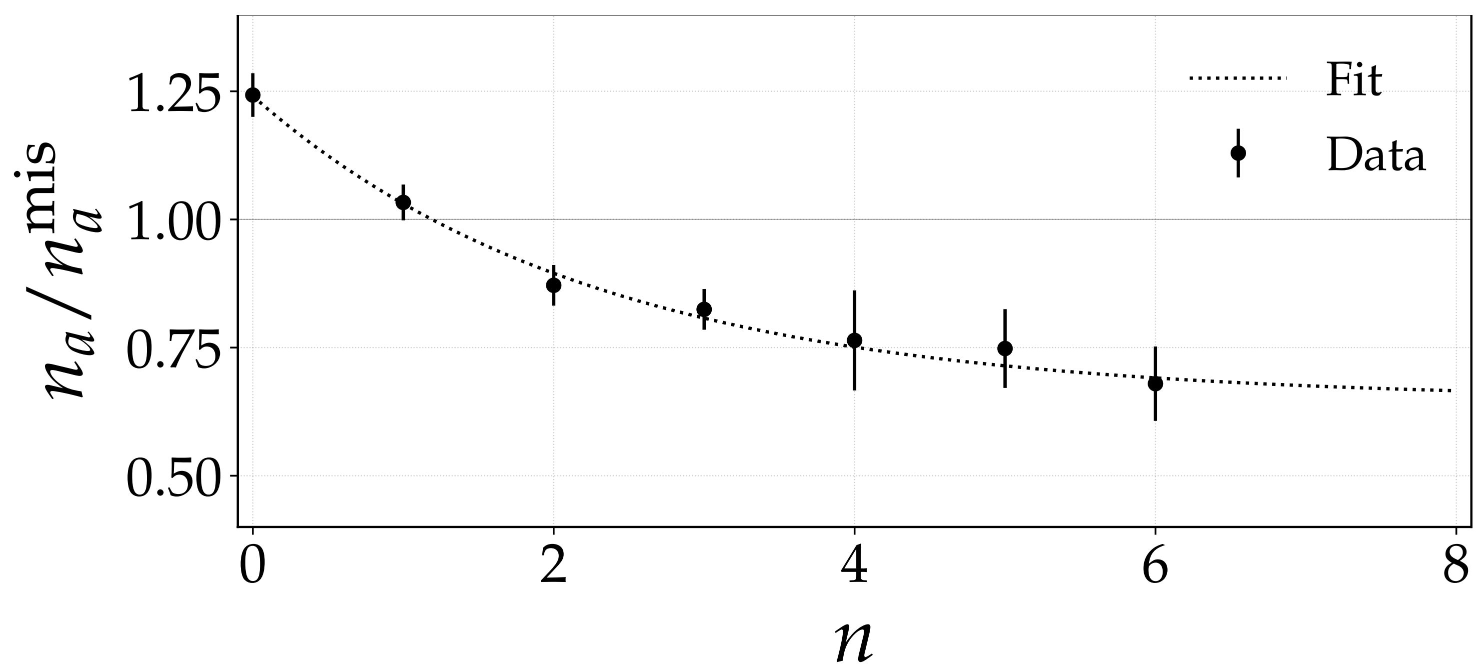
Standard linear $\langle \theta_i^2 \rangle = \pi^2/3$

Measured number of axions at the end of our simulations



Large n values are less efficient than standard misalignment estimation

- Our results assume small string tension when defects collapse
- Extrapolation can lead to substantially different results *Gorghetto et al. [2007.04990]*
- Adding string tension might affect more at small n



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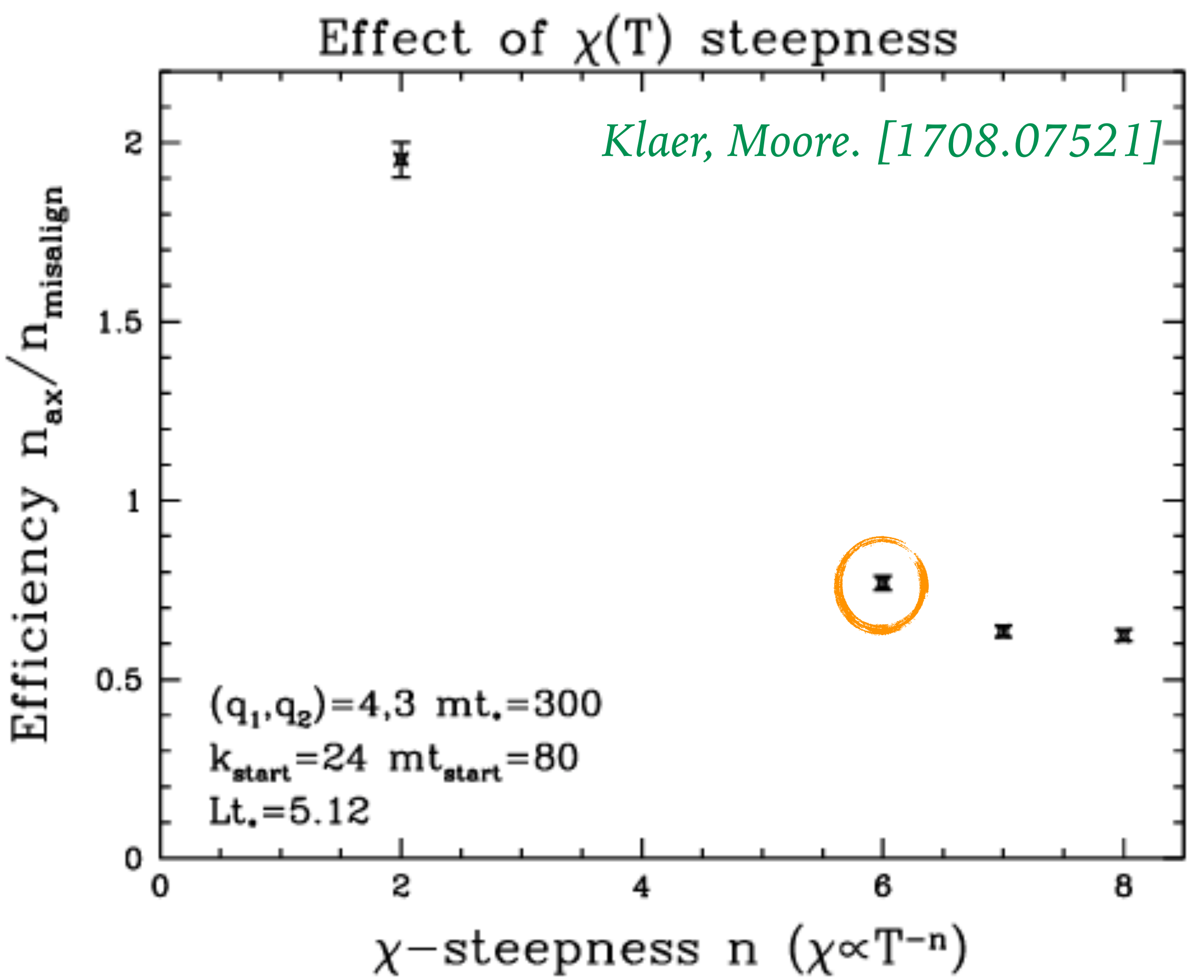

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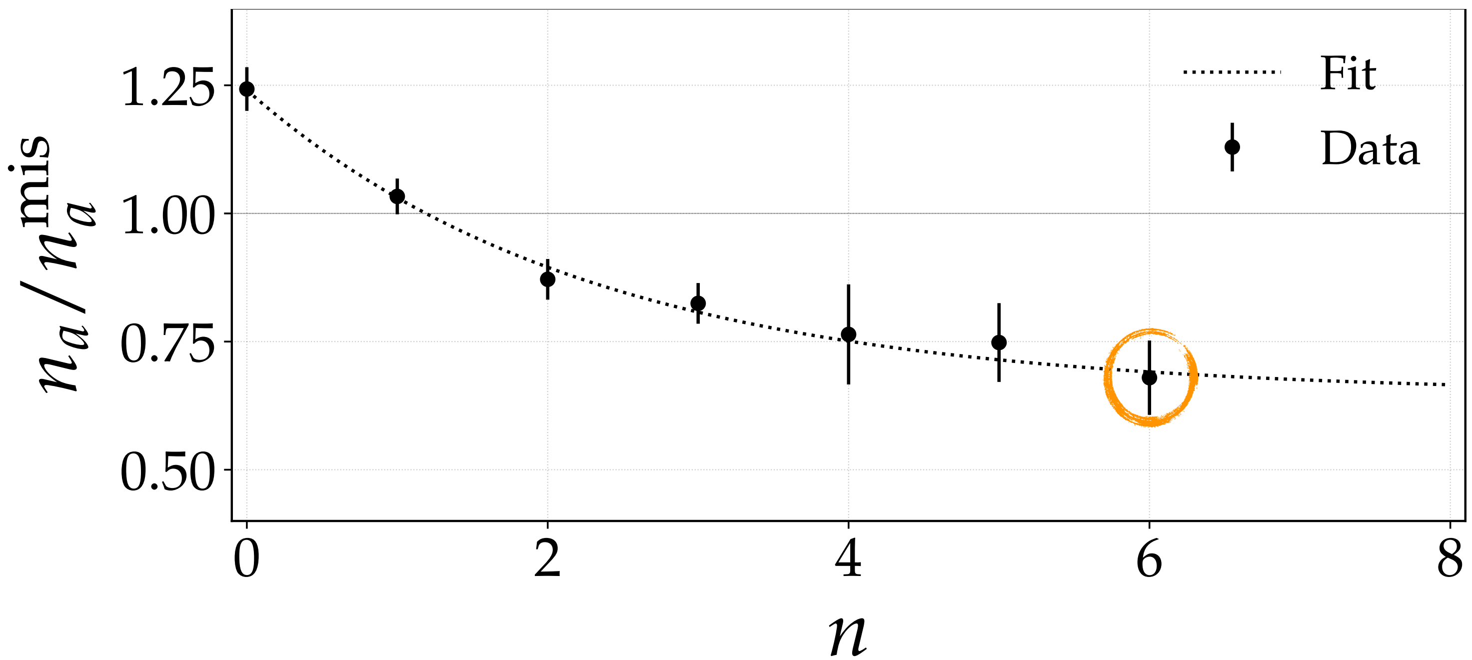
For the QCD axion efficiency seems to be comparable



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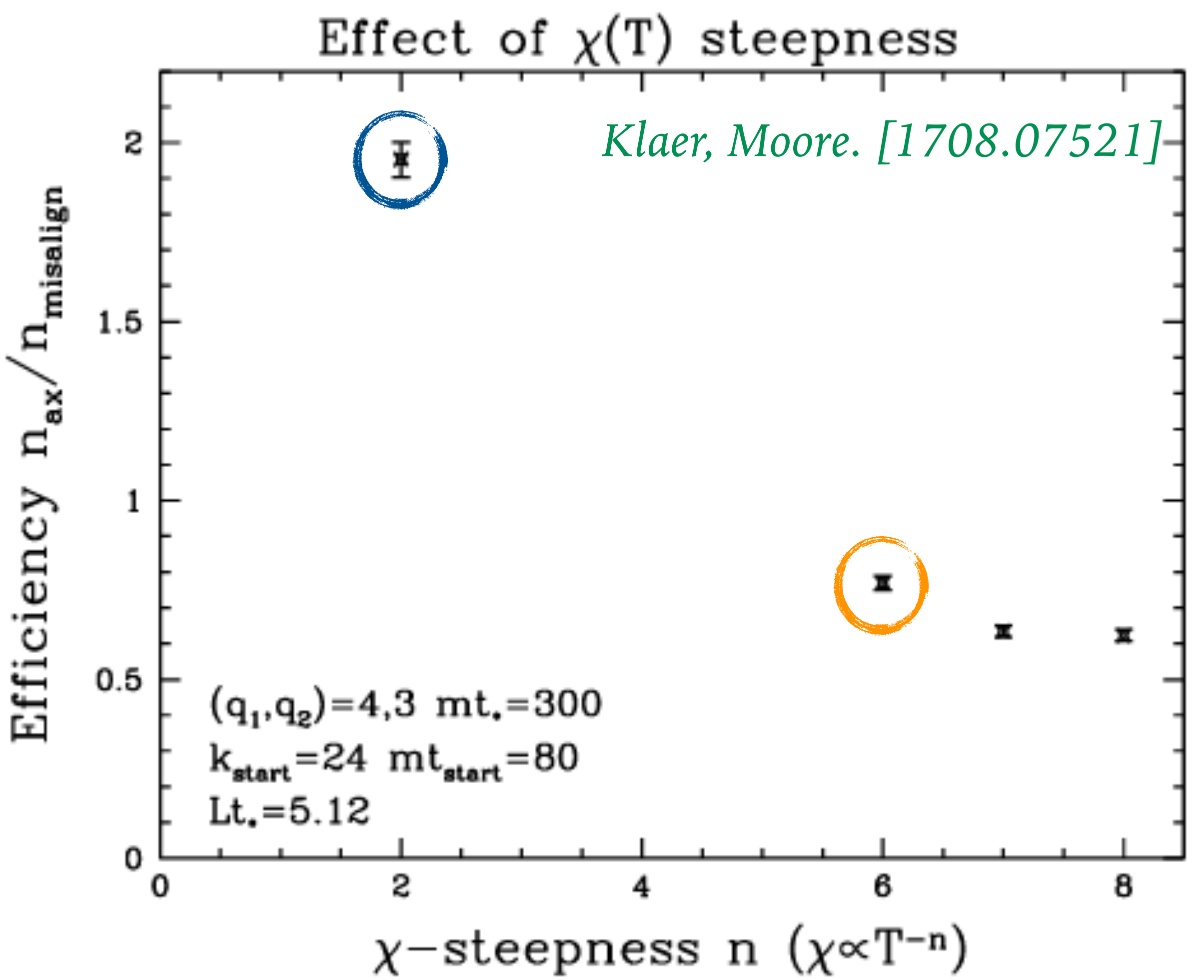

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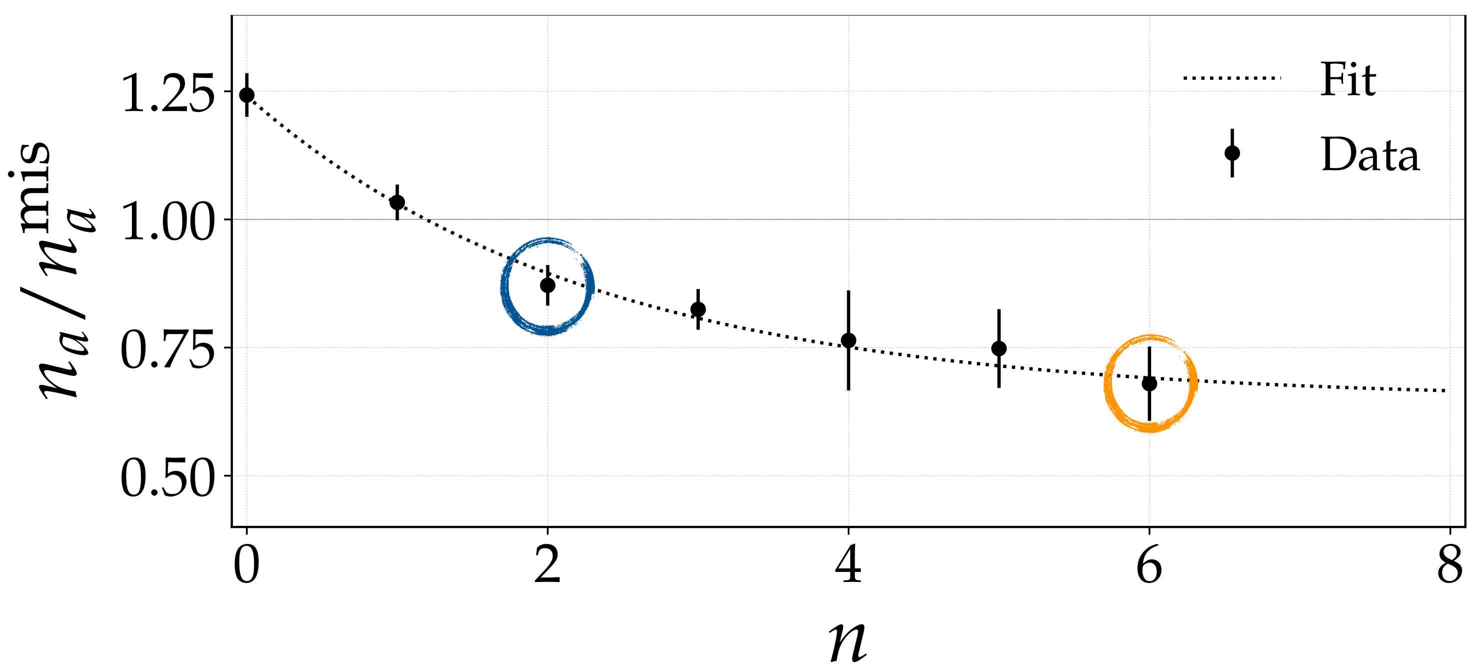
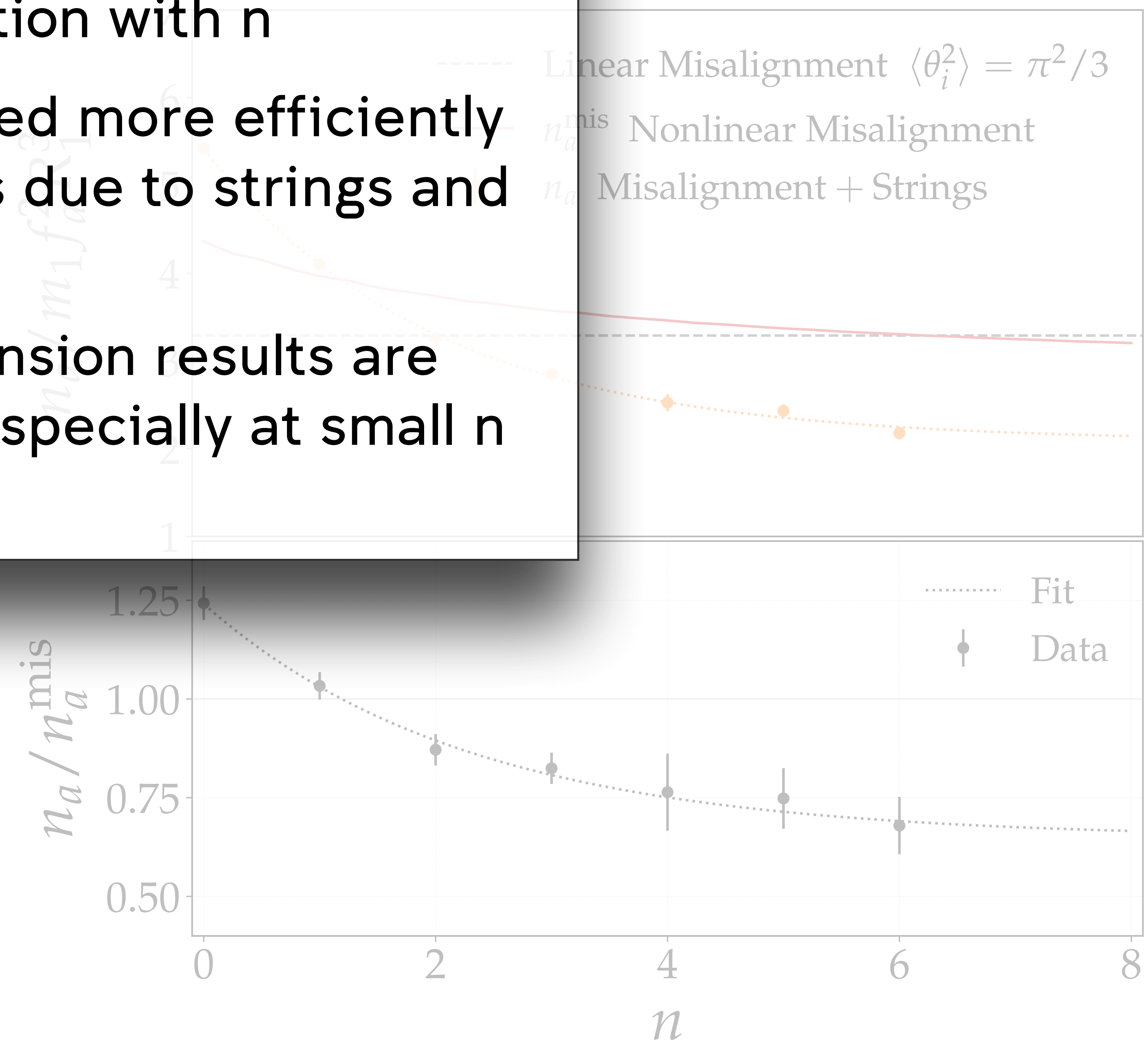
The effect of string tension enhances results for $n = 2$

Might be larger for $n = 0$



Dark Matter: Axions vs ALPs

- Axion production efficiency has a substantial variation with n
- ALPs are produced more efficiently than QCD axions due to strings and walls
- At large string tension results are likely different, especially at small n



Conclusions

- Performed high resolution simulations for class of axion-like particle models

- Simulating ALPs and QCD axions lead to different results in dark matter production and substructure

- QCD axions have more small scale power leading to much large overdensities with respect to ALPs

- ALPs have a more efficient production, we expect this <u>qualitatively</u> to hold even at large (physical) values of string tension

Thank you for watching!