

QCD axion dark matter and cosmology

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Based on

2307.09941 with G. Pierobon, J. Redondo, A. Vaquero, and G. D. Moore

2401.17253 with J. Redondo, A. Vaquero, and M. Kaltschmidt

2608.04139 with K. Chathirathas, C. Eröncel, M. Kaltschmidt, J. Redondo

The QCD axion

*"The axion is a very compelling theoretical idea,
perhaps the most minimal extension of the standard model."*

E. W. Kolb and M. S. Turner, The Early Universe

- Strong CP problem

- Quantum chromodynamics (QCD) allows a CP violating term

$$\mathcal{L}_\theta = \frac{\alpha_s}{8\pi} \theta G_{\mu\nu}^a \tilde{G}^{a\mu\nu}$$

$G_{\mu\nu}^a$: gluon field strength
 α_s : strong coupling constant

- Non-observation of neutron electric dipole moment implies

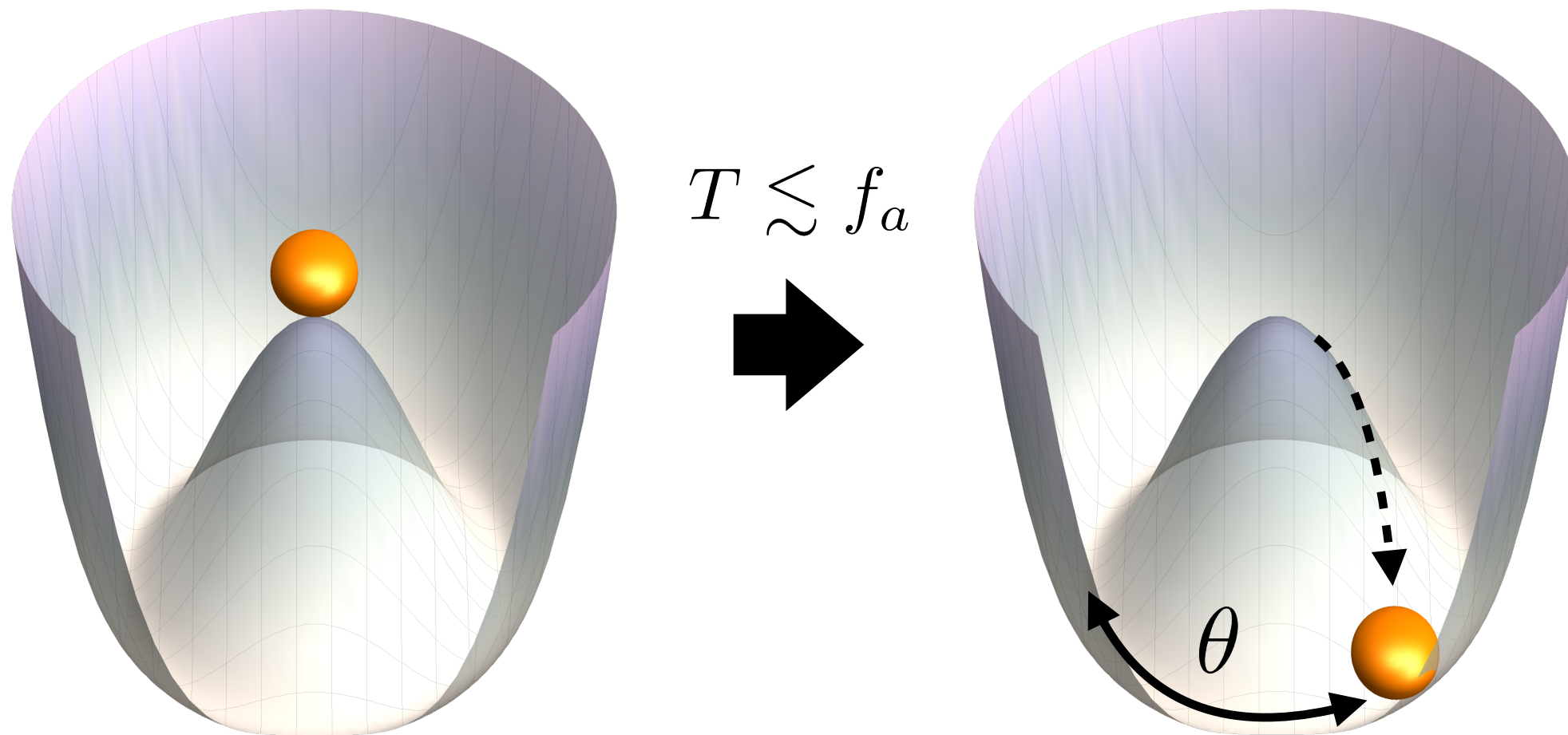
$$|\theta| < 10^{-10}$$

"Why is it so small?"

- Peccei-Quinn (PQ) mechanism [Peccei and Quinn (1977)]

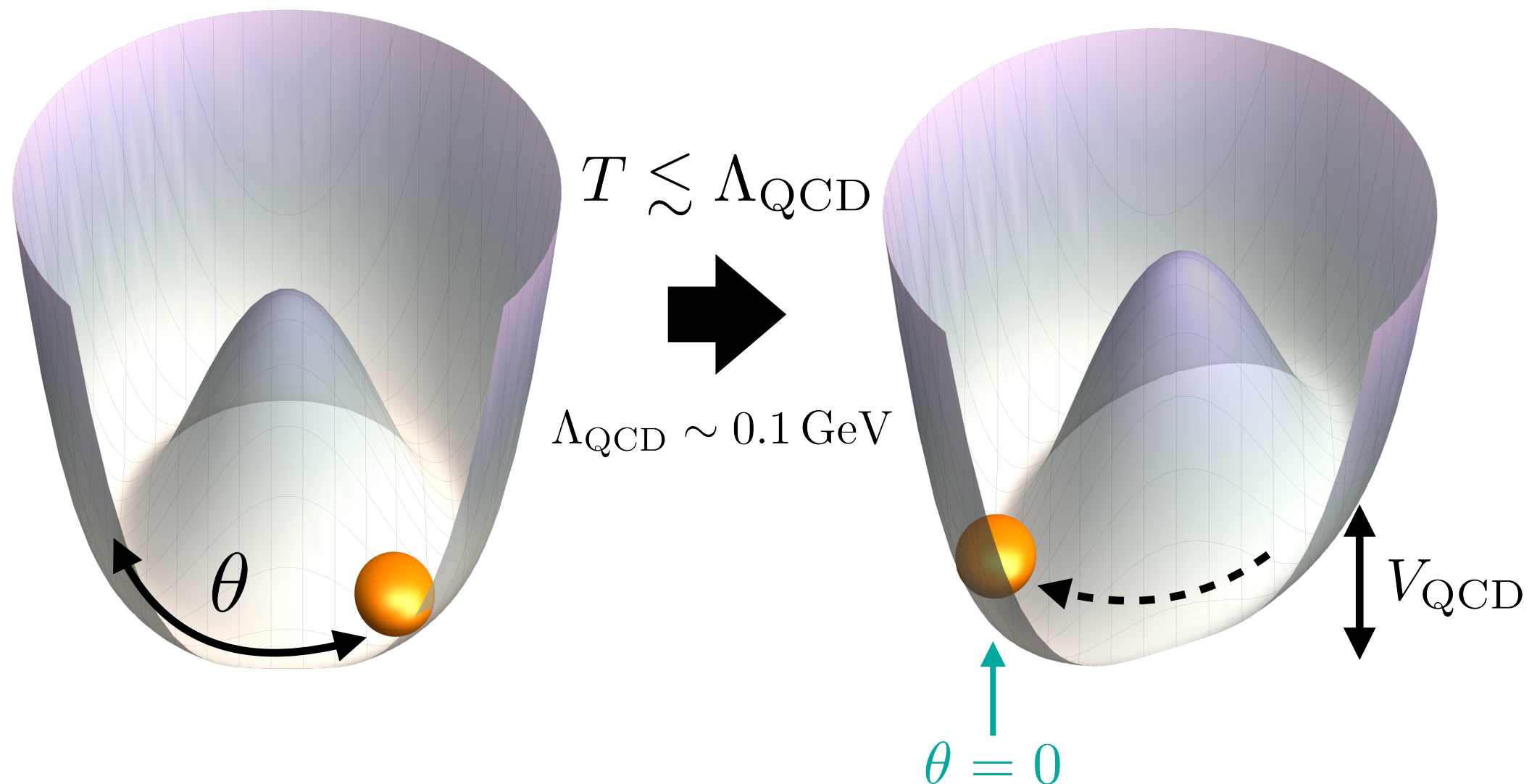
- Take θ as a dynamical variable which explains its smallness.
- Predicts the existence of light particle = axion. [Weinberg (1978), Wilczek (1978)]

Axion as a pseudo Nambu-Goldstone boson



- Spontaneous breaking of global U(1) symmetry ([Peccei-Quinn \(PQ\) symmetry](#)) at the scale f_a ("axion decay constant").
- Massless phase degree of freedom θ is the axion.

Axion as a pseudo Nambu-Goldstone boson



- Tipping the "wine bottle" potential due to the non-perturbative effects of QCD.
- Oscillation of the θ field around the minimum = cold dark matter!

Axion as a cold dark matter candidate

- Unlike WIMPs, the properties of axion dark matter depend sensitively on its cosmological history.
- Key properties:
 - **Mass** required to account for the relic abundance

$$m_a \simeq 57 \mu\text{eV} \left(\frac{10^{11} \text{ GeV}}{f_a} \right)$$

$$\Omega_a(m_a) = \Omega_{\text{CDM}} \quad \Rightarrow \quad m_a = ??? \mu\text{eV}$$

- **Small-scale distribution**

Field could become inhomogeneous at $L = \frac{R_0}{R_{\text{QCD}} H_{\text{QCD}}} = 0.036 \text{ pc} \left(\frac{50 \mu\text{eV}}{m_a} \right)^{0.167}$

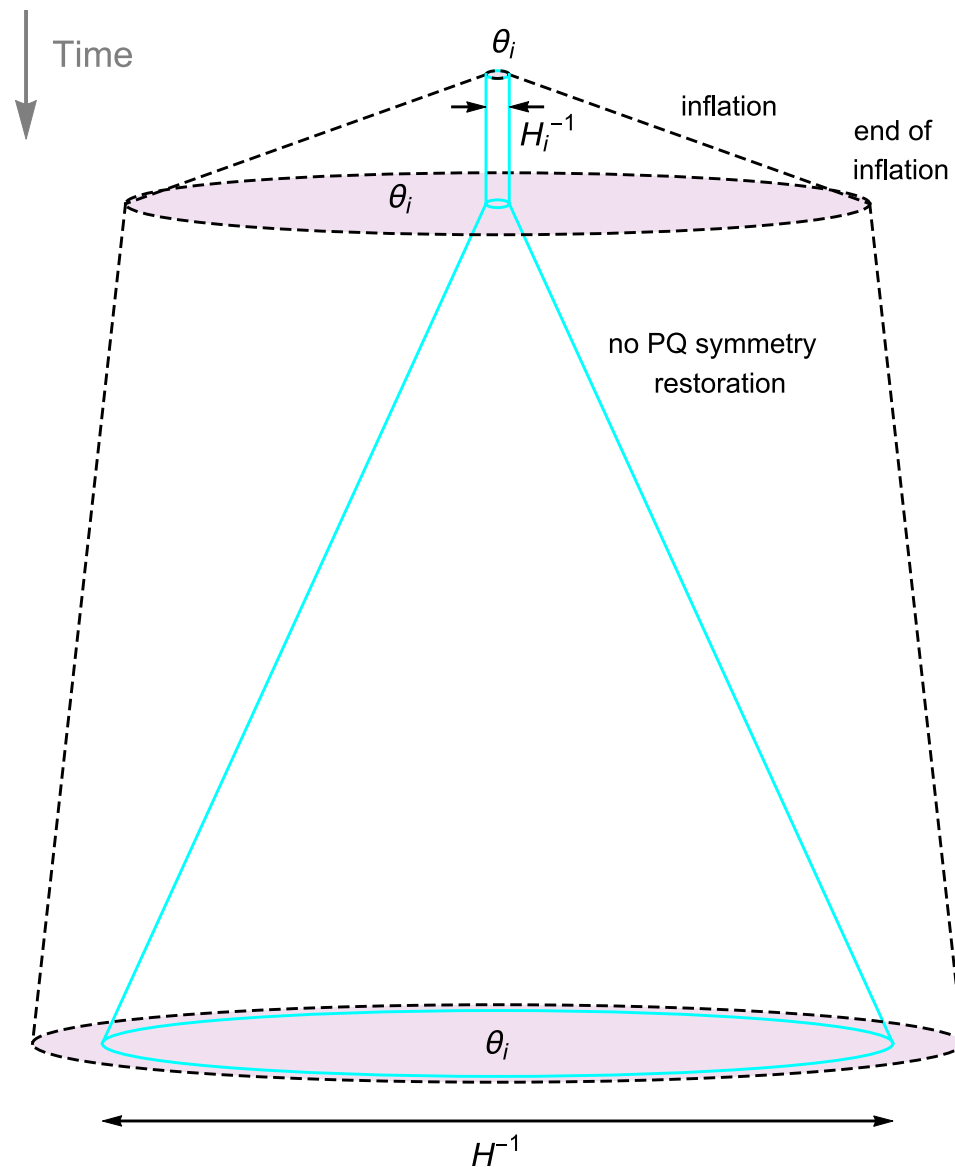
R : scale factor of the universe

$\Rightarrow$ Formation of dark matter "miniclusters".

- Different cosmological scenarios can lead to different consequences.

Initial conditions

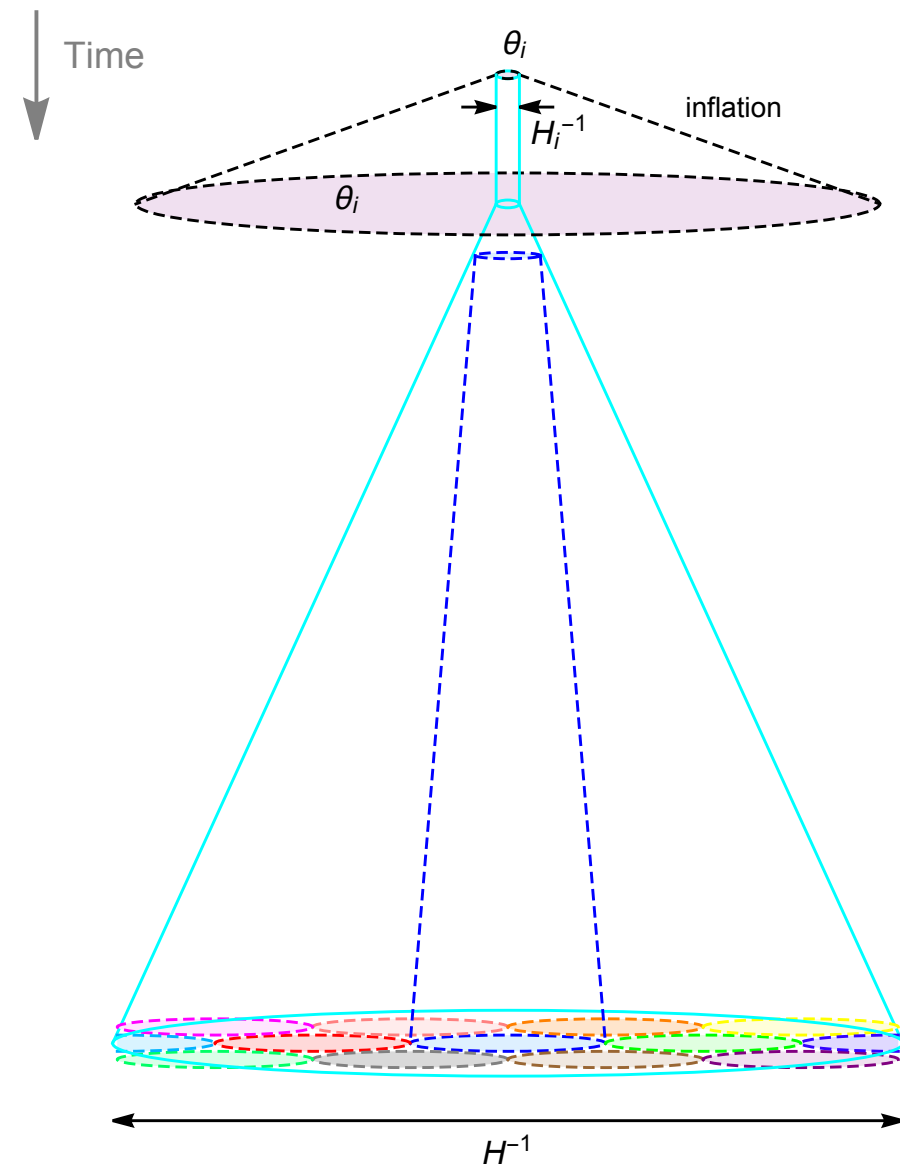
Pre-inflationary PQ symmetry breaking scenario



Pre-inflationary symmetry breaking:

Axion field takes a certain initial value θ_i in the entire observable universe.

Post-inflationary PQ symmetry breaking scenario



Post-inflationary symmetry breaking:

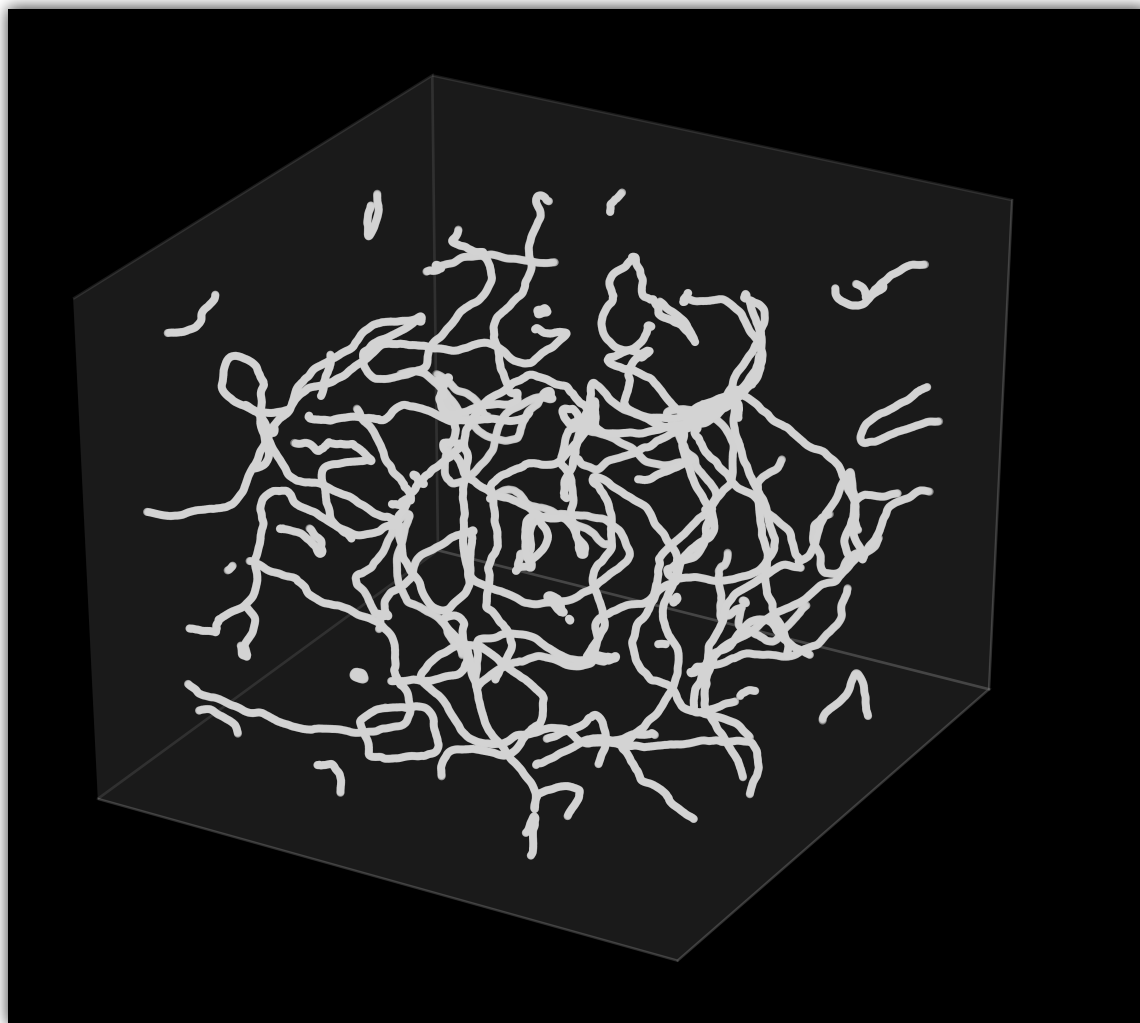
Present observable universe contains many different patches with different values of θ .

Post-inflationary scenario

Post-inflationary scenario

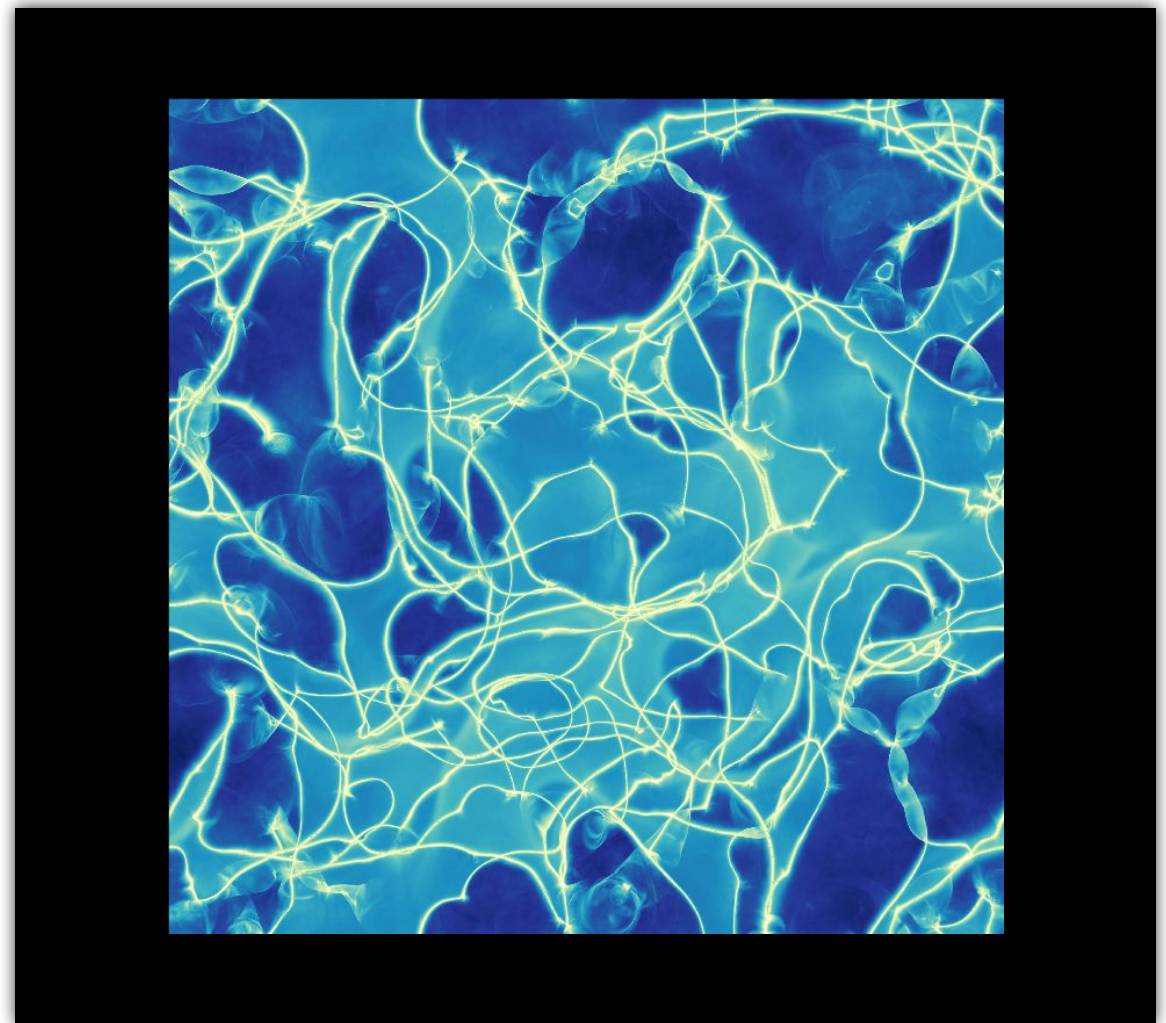
Strings

formed at the PQ phase transition
($T \lesssim f_a$)



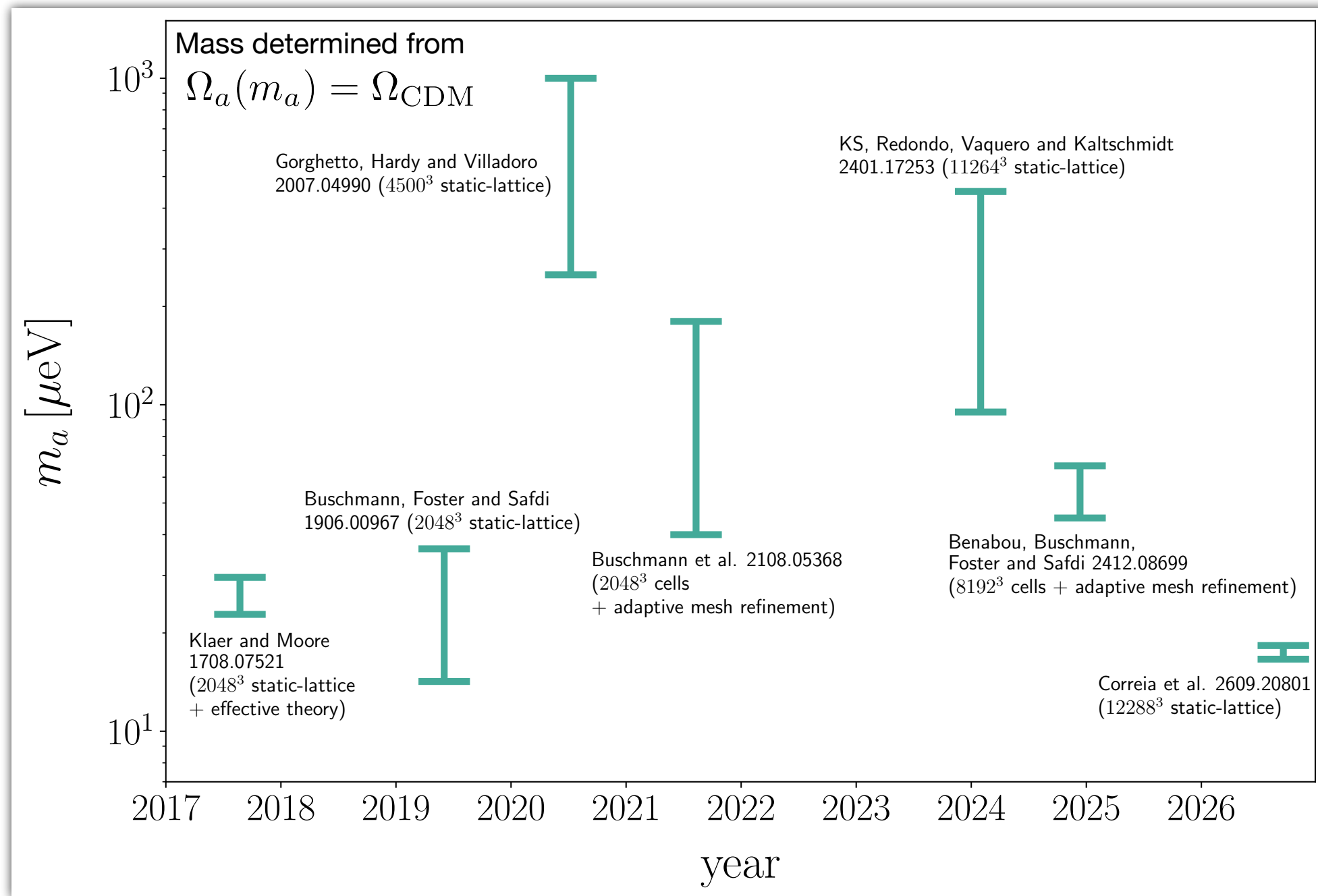
Domain walls

formed at around the QCD phase transition
and collapse afterwards (if $N_{\text{DW}} = 1$)



Axion production from strings and domain walls are relevant
if the PQ symmetry is broken after inflation.

Controversy on the axion abundance estimation



- Simulations performed by several groups.
- Not only the final result for the axion DM mass but also several outcomes (such as the shape of the radiation spectrum) are disparate.

Difficulty in string dynamics

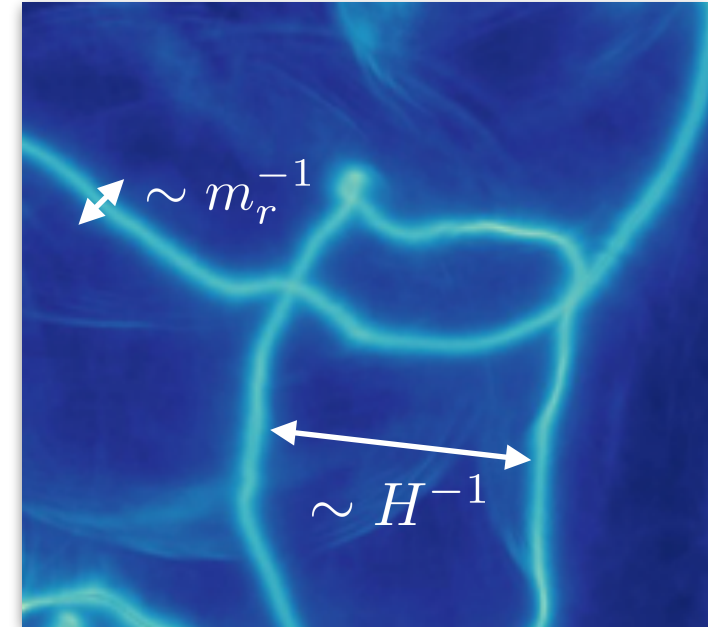
- Existence of two extremely different length scales.
- String tension acquires a **logarithmic correction**.

$$\mu = \frac{\text{energy}}{\text{length}} \simeq \pi f_a^2 \ln \left(\frac{m_r}{H} \right)$$

- Realistic value

$$f_a / H_{\text{QCD}} \sim 10^{30} \quad \Rightarrow \quad \ln(m_r / H) \sim 70$$

- Impossible to reach it in simulations with limited dynamical ranges. One has to perform extrapolation by many orders of magnitude.



H^{-1} : Hubble radius

m_r^{-1} : string core radius

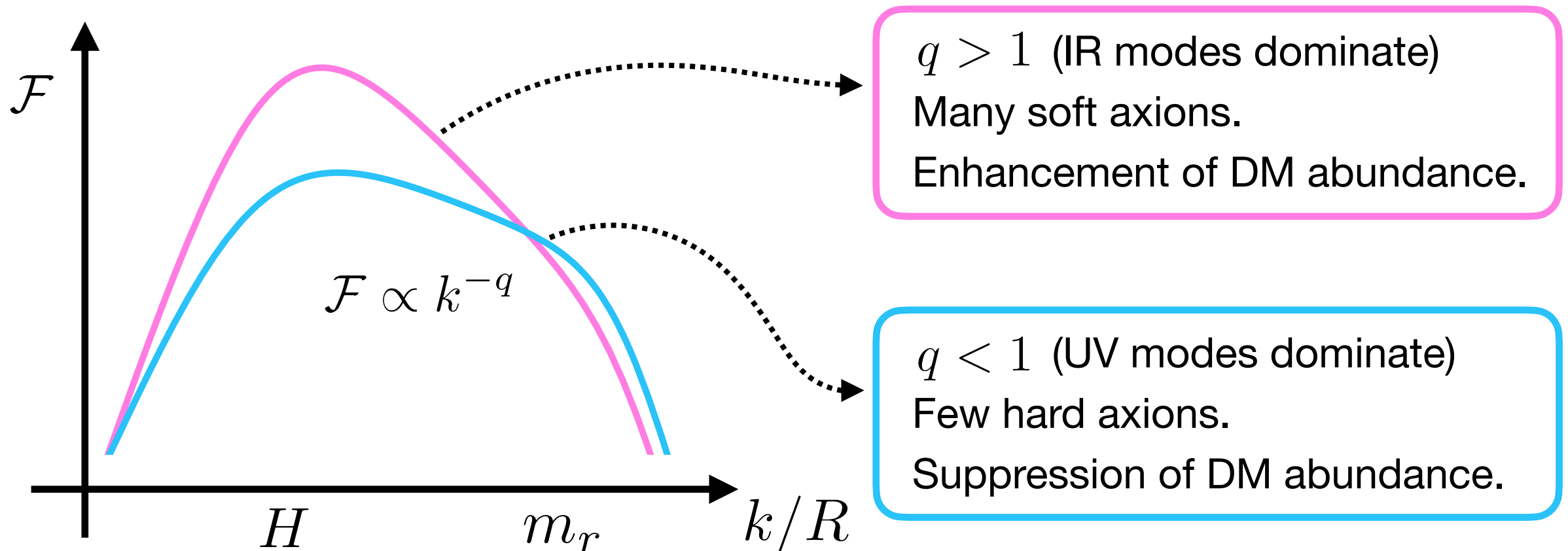
($m_r \sim f_a$: mass of the radial field)

Spectrum of radiated axions

- Instantaneous emission spectrum

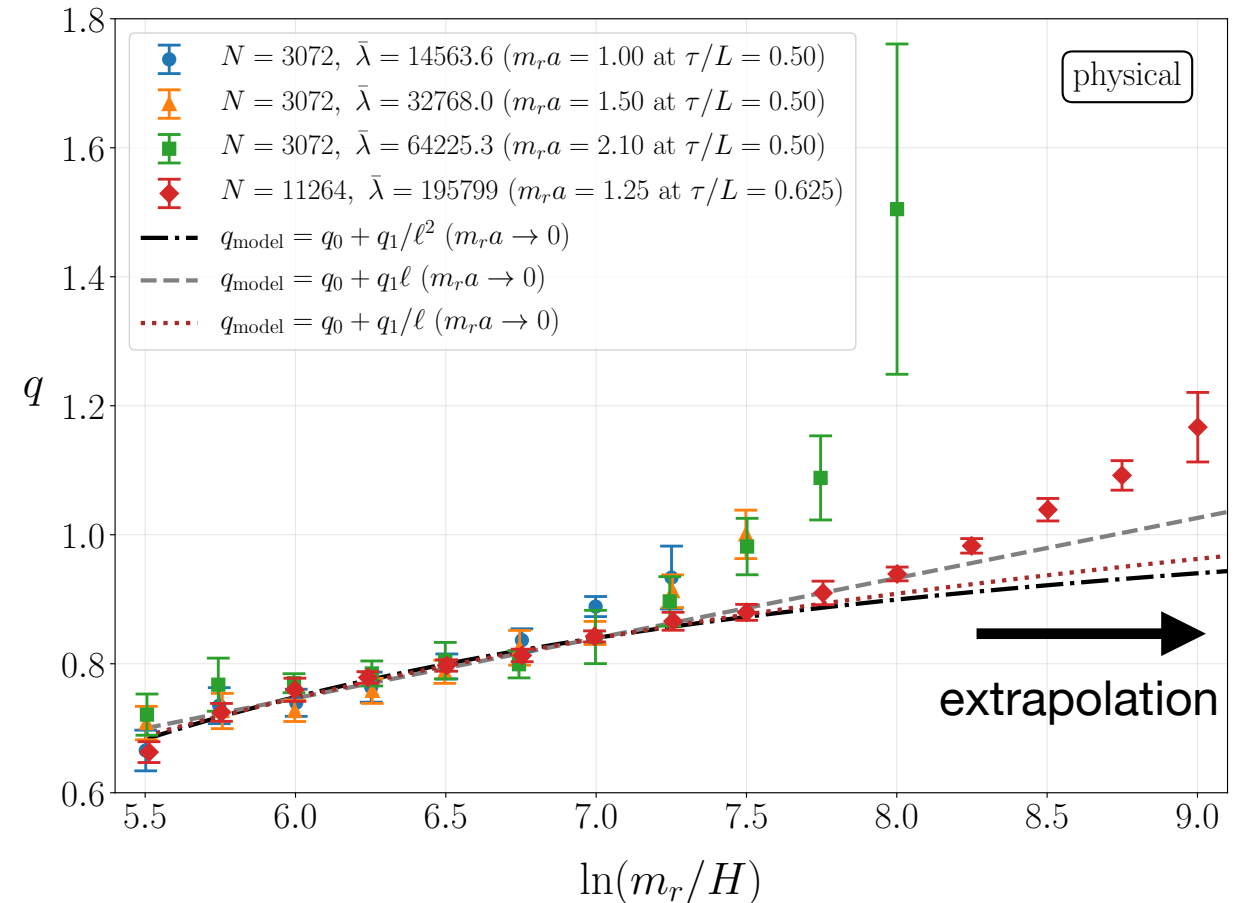
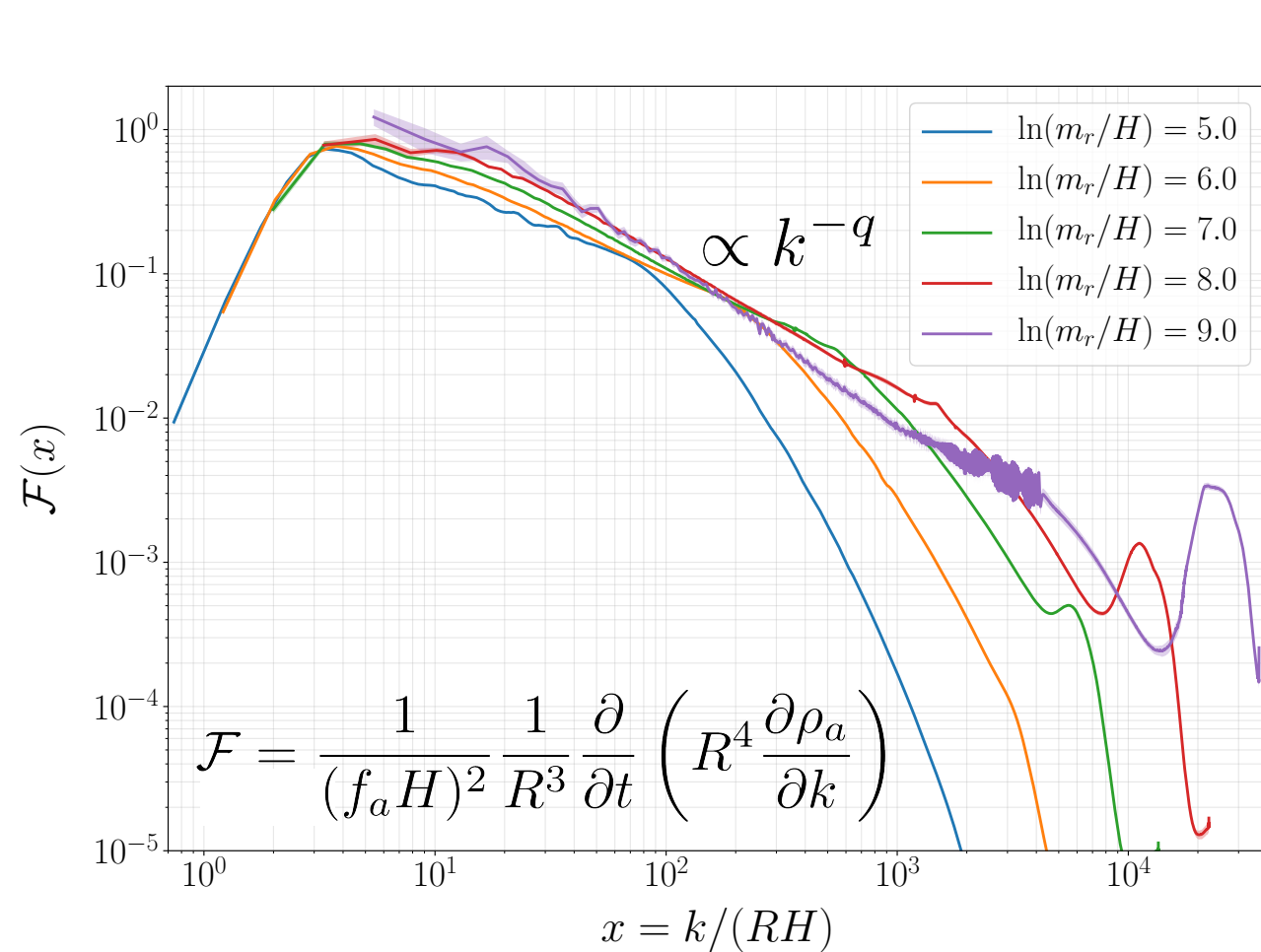
$$\mathcal{F} \left(\frac{k}{RH}, \frac{m_r}{H} \right) \equiv \frac{1}{(f_a H)^2} \frac{1}{R^3} \frac{\partial}{\partial t} \left(R^4 \frac{\partial \rho_a}{\partial k} \right) \quad R : \text{scale factor}$$

- $\mathcal{F}$ seems to be well approximated by a simple power law, whose exponent is important. [Gorghetto, Hardy, Villadoro, 1806.04677]



Uncertainties in simulations

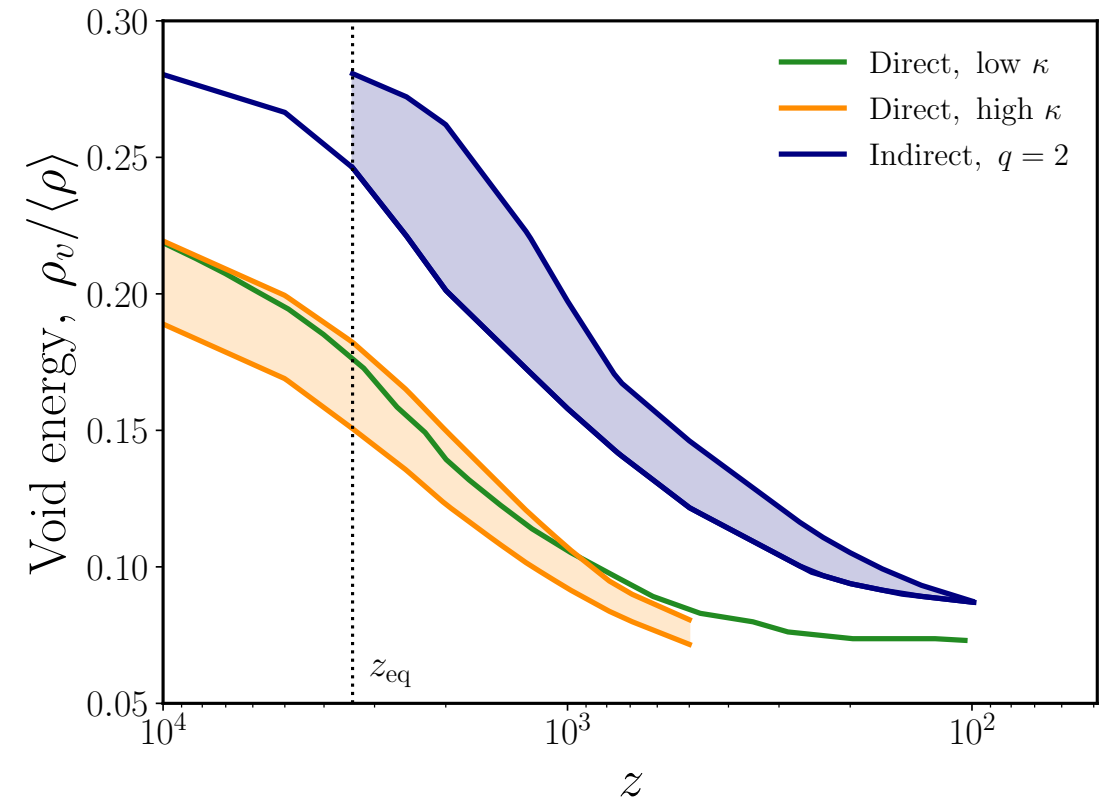
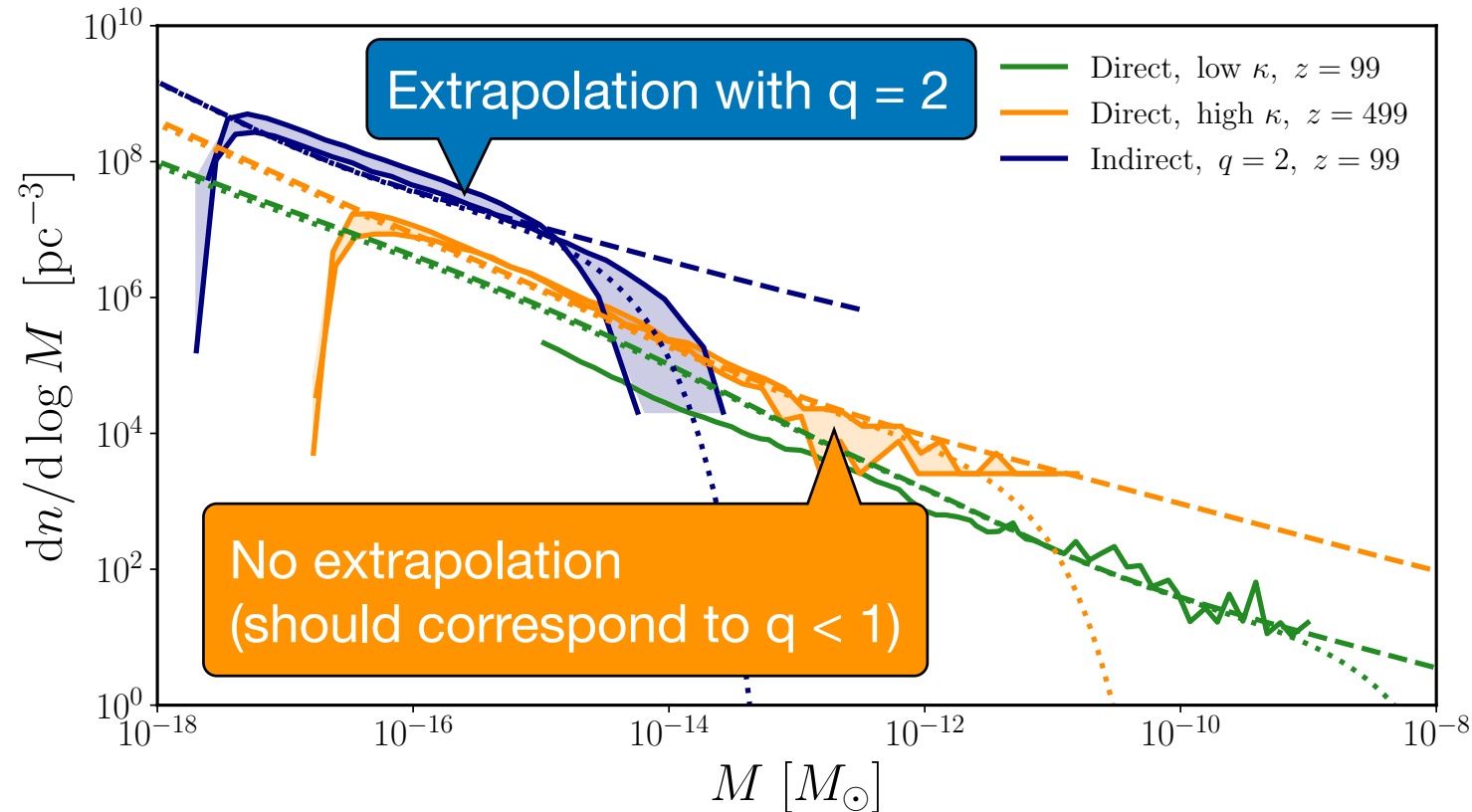
- Compute the axion emission spectrum from strings and fit a power law $\mathcal{F} \propto k^{-q}$.



- The data show a logarithmic increase in q at $\ln(m_r/H) \lesssim 7$, but the behavior at larger $\ln(m_r/H)$ remains uncertain due to the discretization effects.
- Extrapolation with different assumption on q is translated to the uncertainty in the dark matter mass prediction: $95 \mu\text{eV} \lesssim m_a \lesssim 450 \mu\text{eV}$

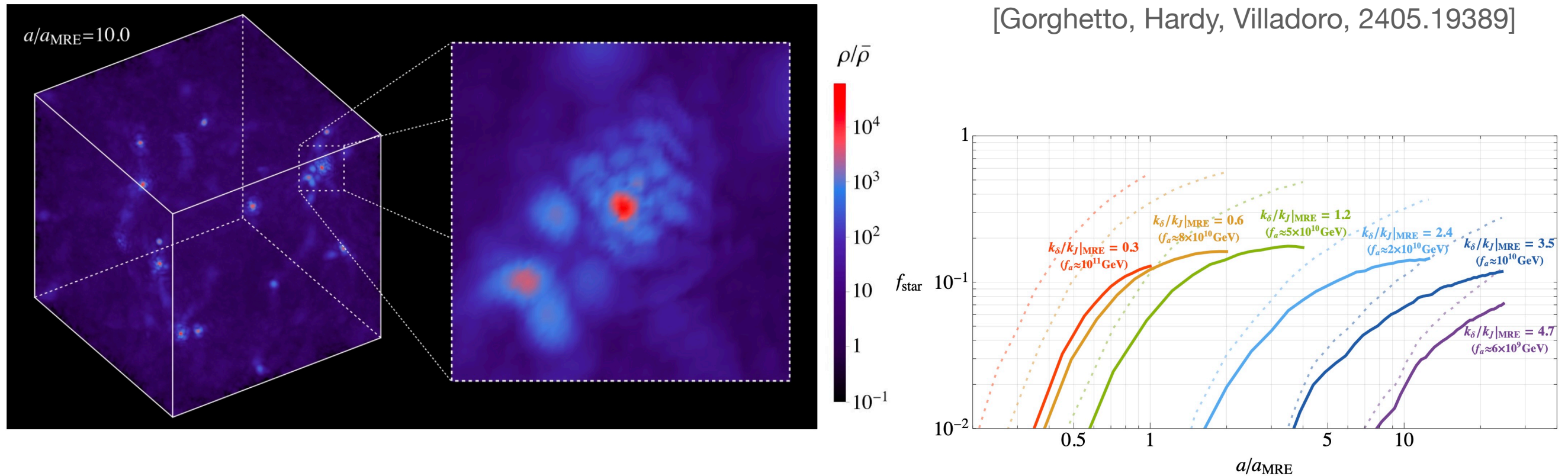
Miniclusters, minivoids, and axion stars

[Pierobon, Redondo, KS, Vaquero, Moore, 2307.09941]



- Inhomogeneity in the axion field at the scale $L_{\text{QCD}} \sim 10^{-2} \text{ pc}$ may lead to the formation of gravitationally bound objects (*miniclusters*), while the direct detection experiments are likely to be probing the space in between miniclusters (*axion minivoids*).
- Substantial differences in the mass distribution according to the initial axion spectrum, but the void density becomes similar (about 8% of the average dark matter density).
- For $f_a \lesssim 5 \times 10^{10} \text{ GeV}$, self-interactions have a substantial effect on the axion spectrum, which might lead to the efficient production of dense solitons (*axion stars*).

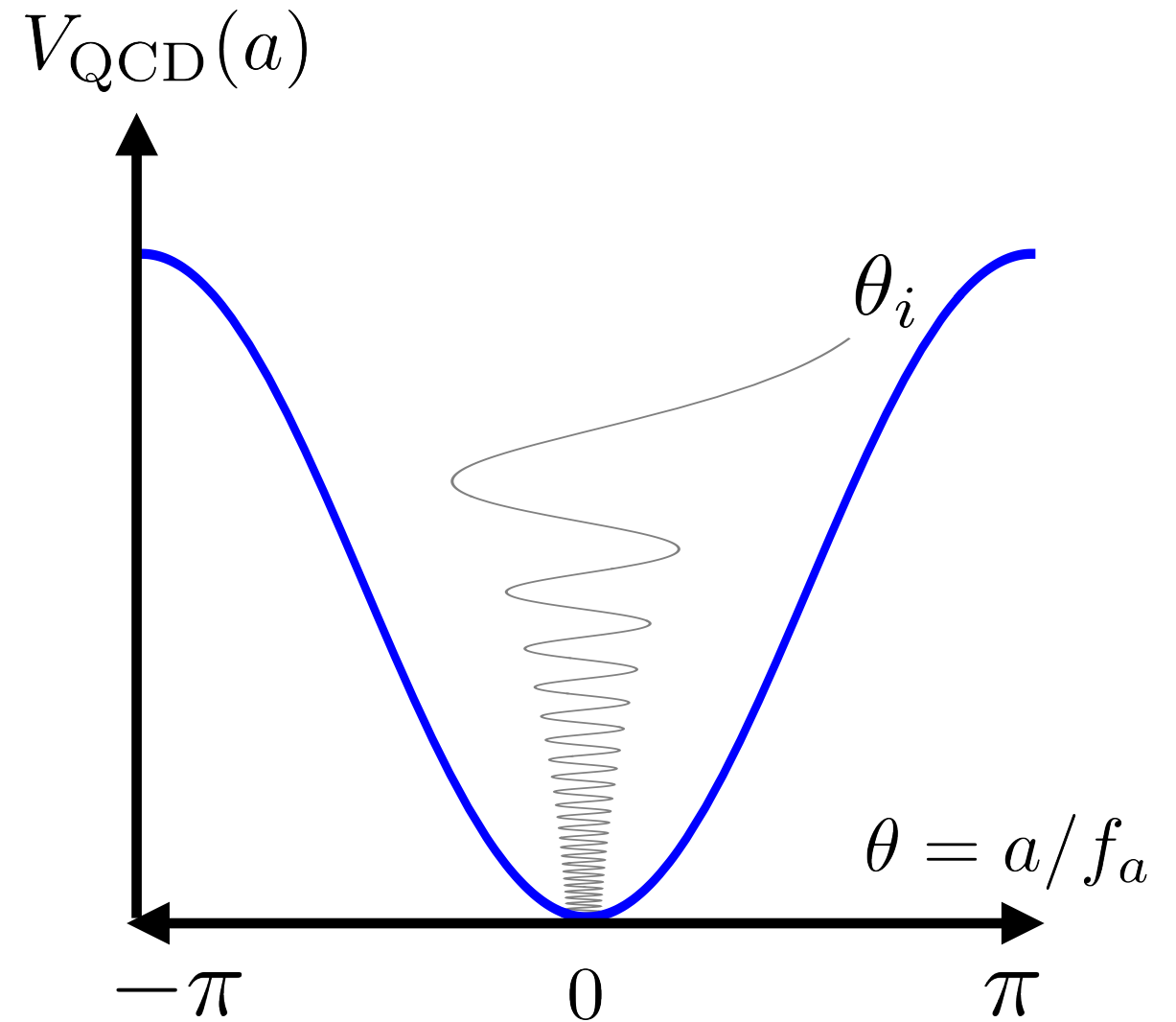
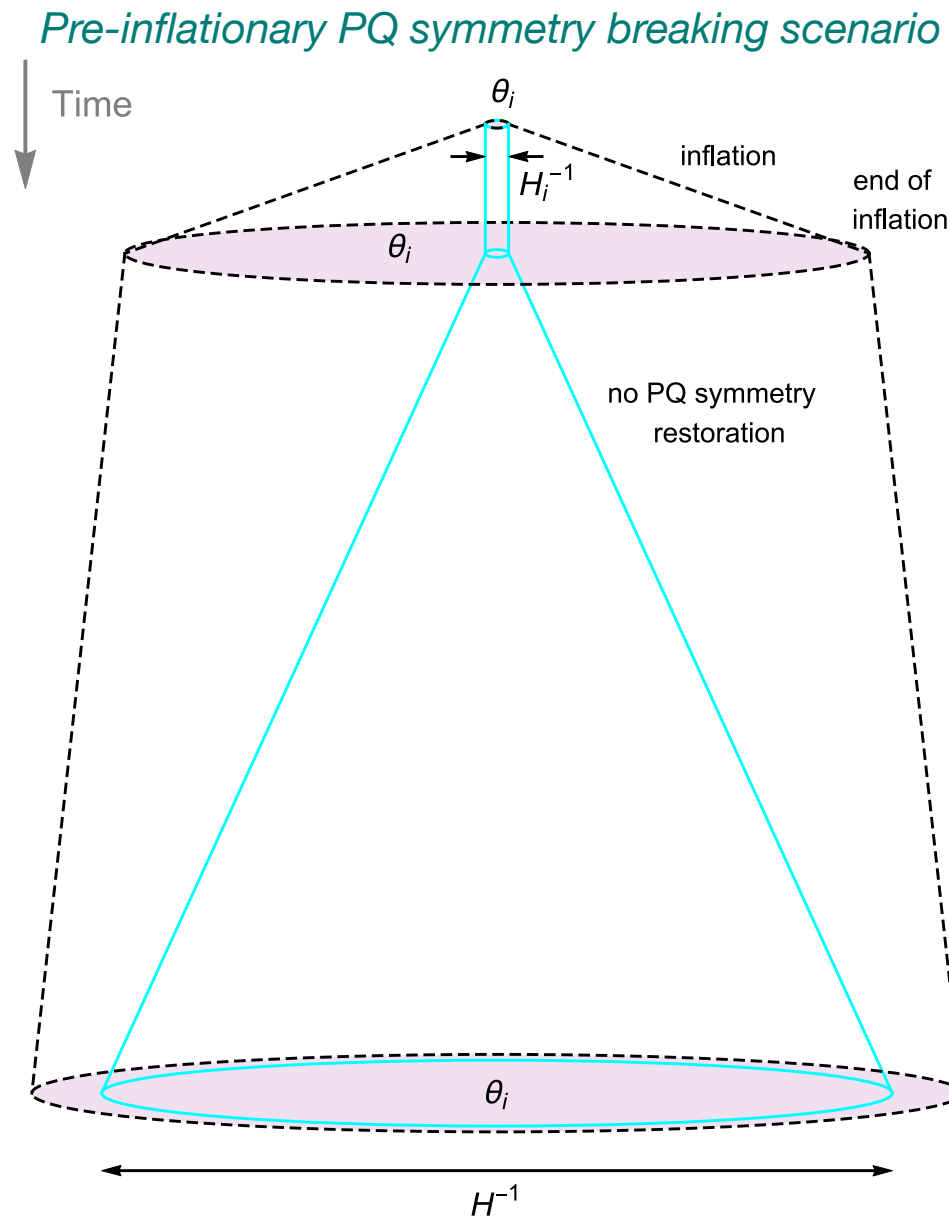
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Pre-inflationary scenario

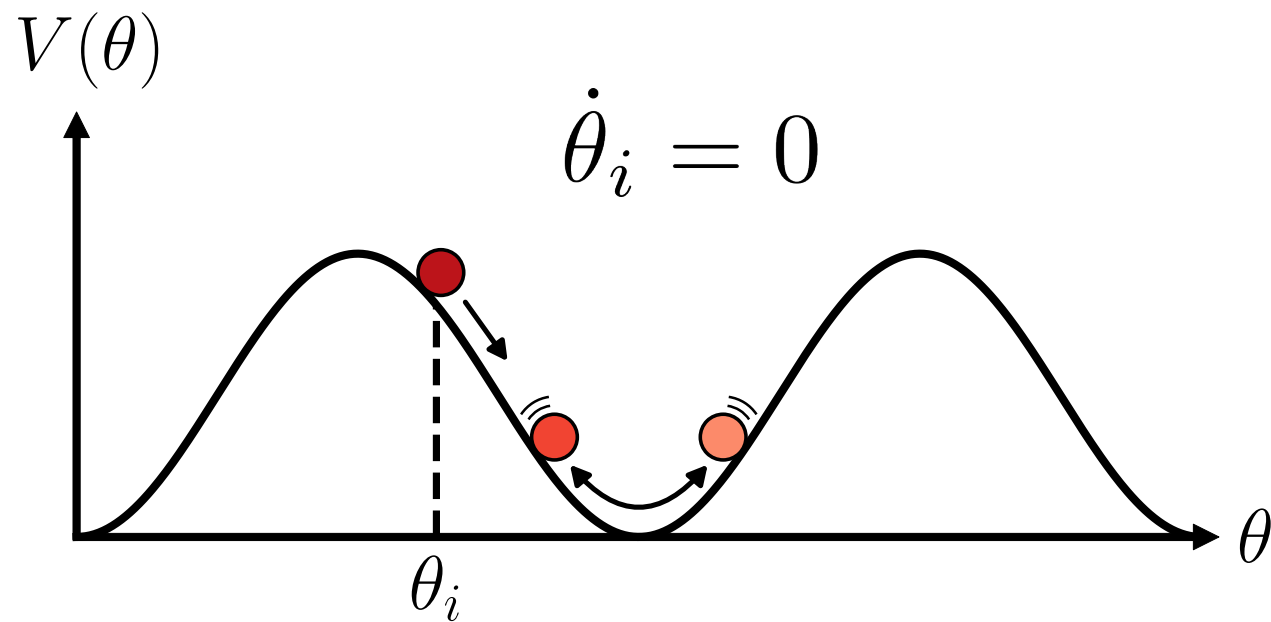
Pre-inflationary scenario



- Axion field is initially almost homogeneous.
- Dark matter produced via the misalignment mechanism.
- No strings and domain walls.

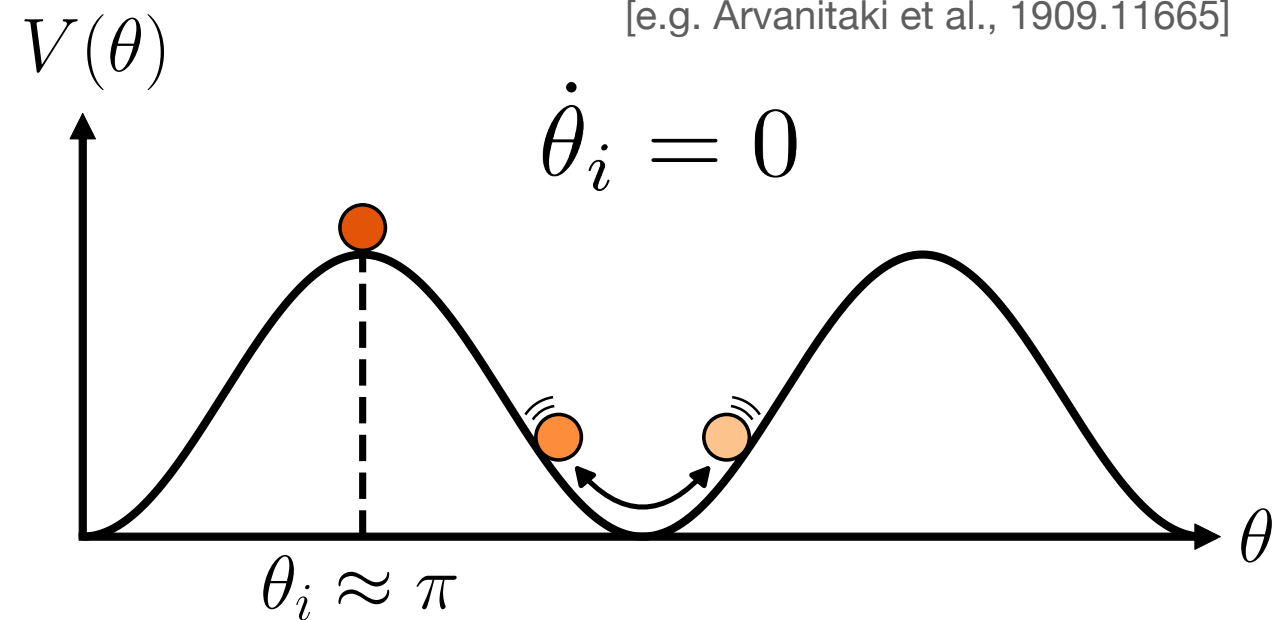
Axion misalignment landscape

Standard misalignment



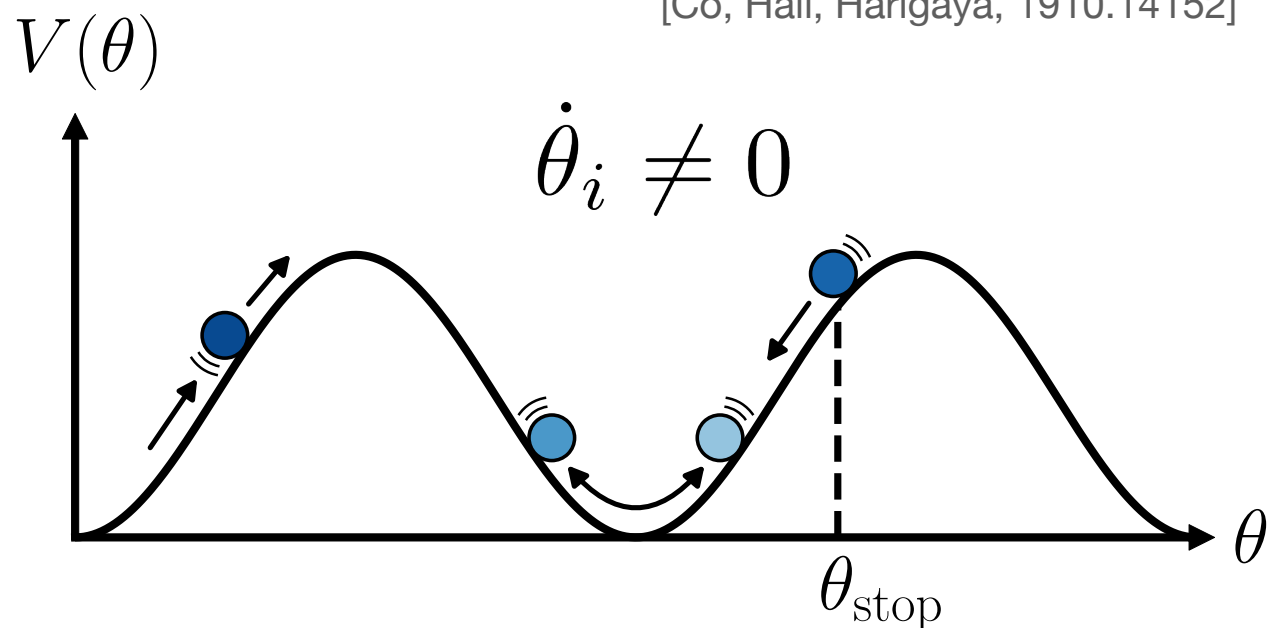
Large misalignment

[e.g. Arvanitaki et al., 1909.11665]



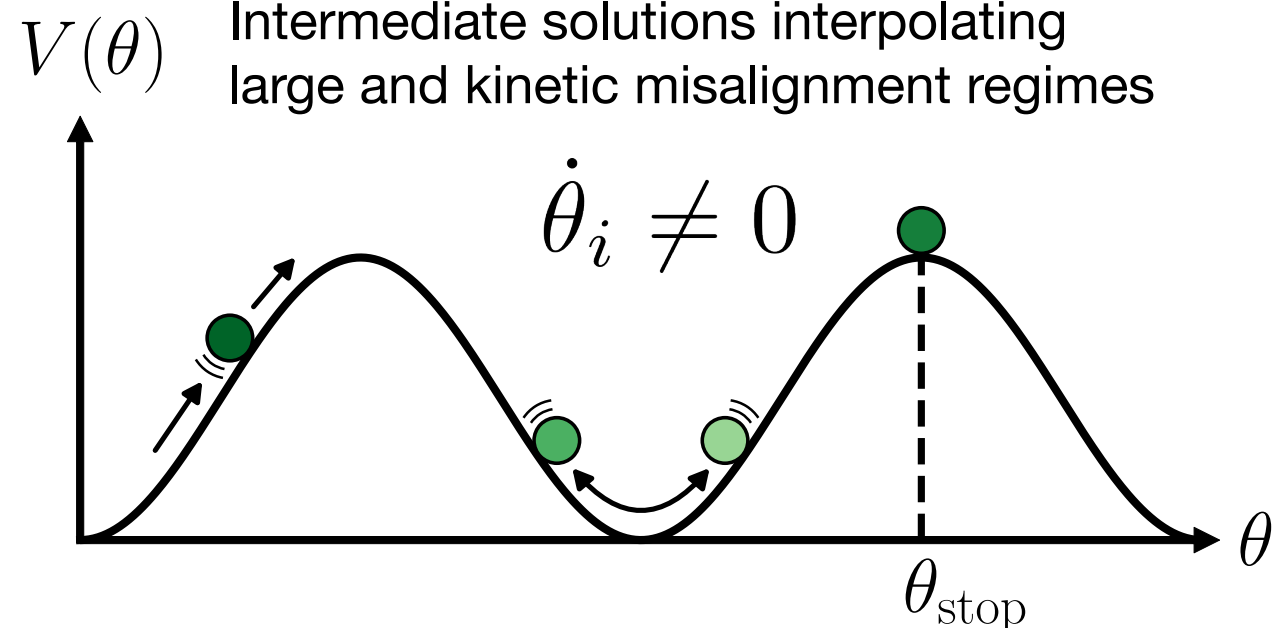
Kinetic misalignment

[Co, Hall, Harigaya, 1910.14152]



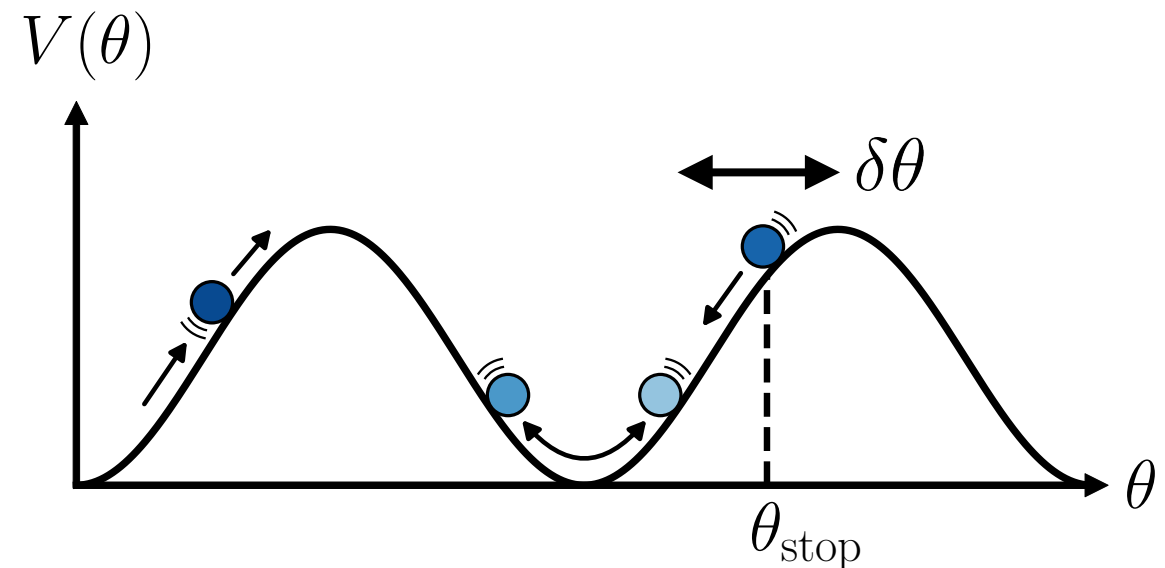
Summit landing

Intermediate solutions interpolating large and kinetic misalignment regimes



Amplification of fluctuations

- Pre-inflationary scenario:
Axions acquire quantum fluctuations generated during inflation.
- Fluctuations are amplified via **tachyonic** and **parametric resonances** when the field is trapped by the QCD potential.



[Eröncel, Sato, Servant, Sørensen, 2206.14259]
[Eröncel, Servant, 2207.10111]

- Nonlinear dynamics plays important roles. [Chathirathas, Eröncel, Kaltschmidt, Redondo, KS, 2608.04139]
- Fragmentation of the zero mode to fluctuations occurs efficiently for sufficiently large initial velocity, changing the abundance estimate for

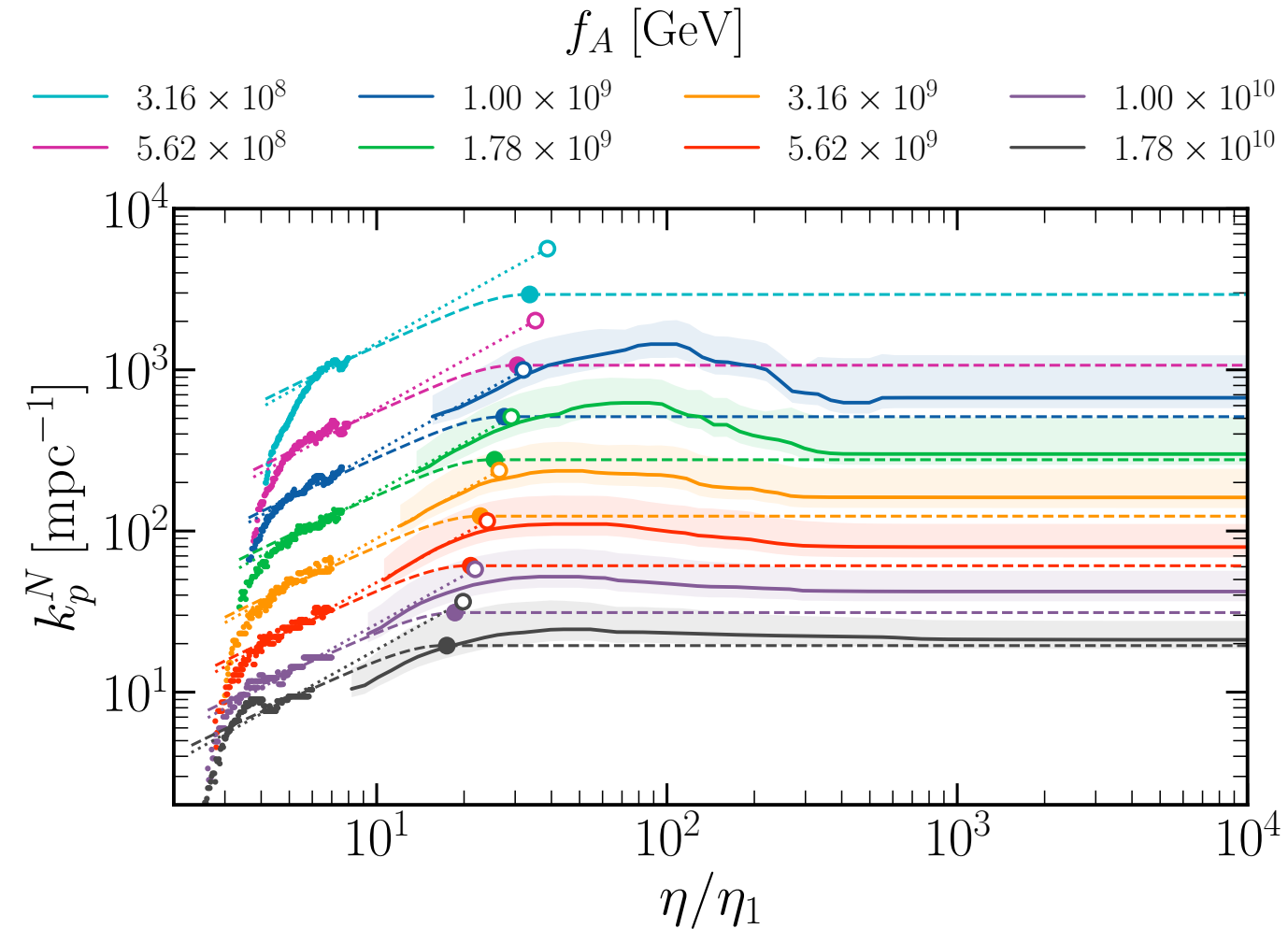
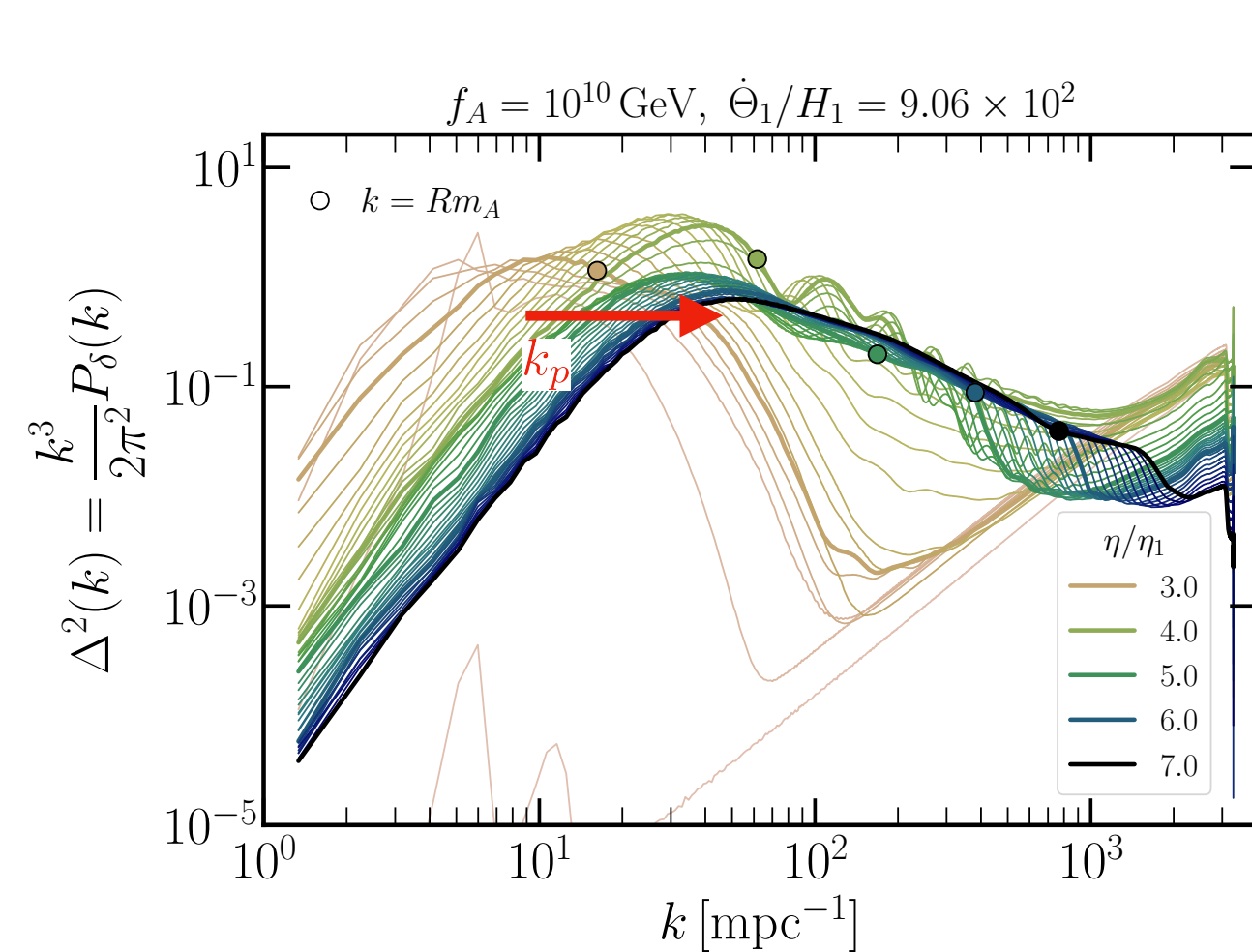
$$\dot{\theta}_1 / H_1 \gtrsim 100$$

(Initial time is defined by $m_a(T_1) = H(T_1)$)

- Large fluctuations can seed miniclusters (next slides).

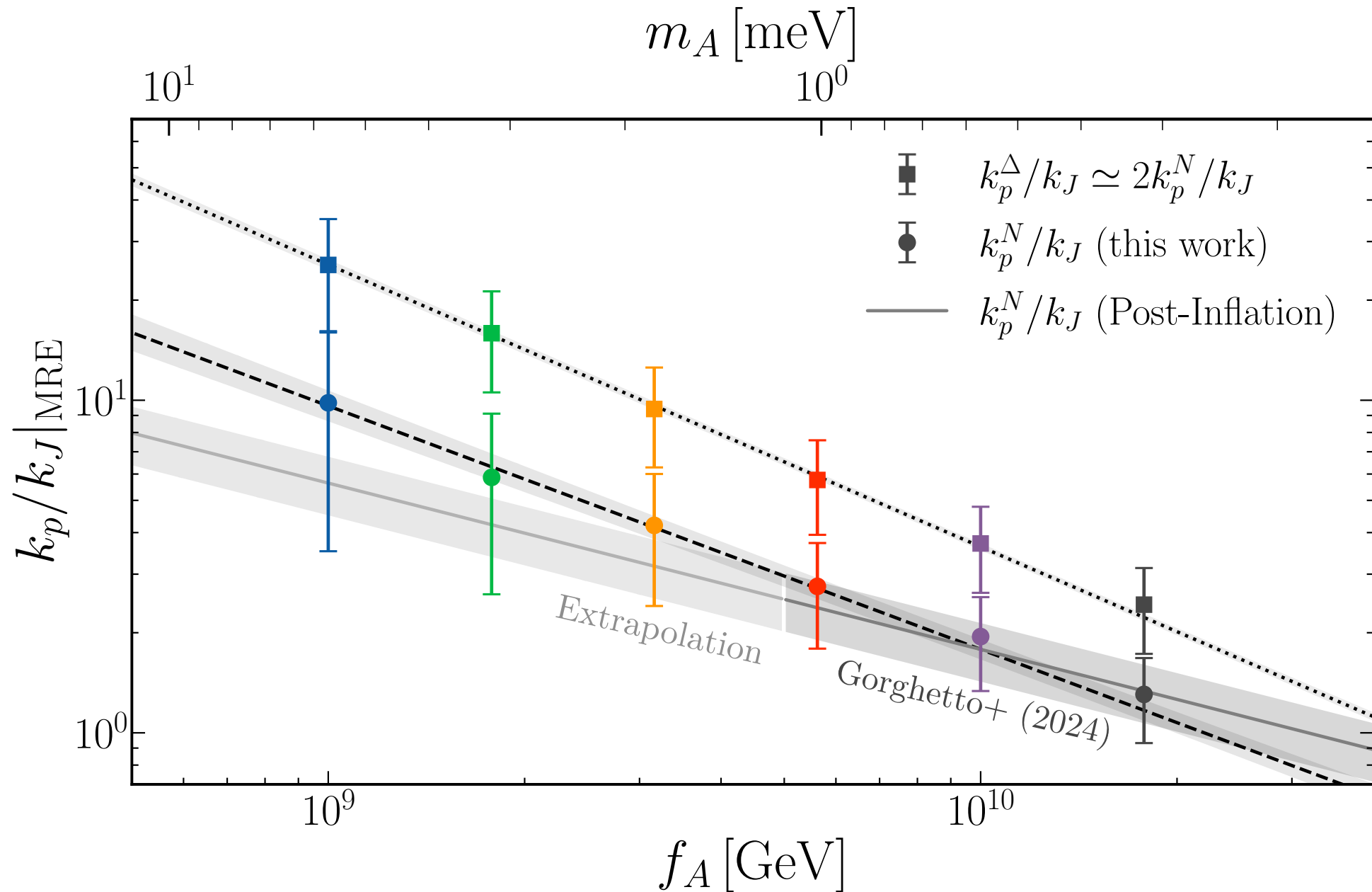
Power spectrum and peak drift

[Chathirathas, Eröncel, Kaltschmidt, Redondo, KS, 2608.04139]



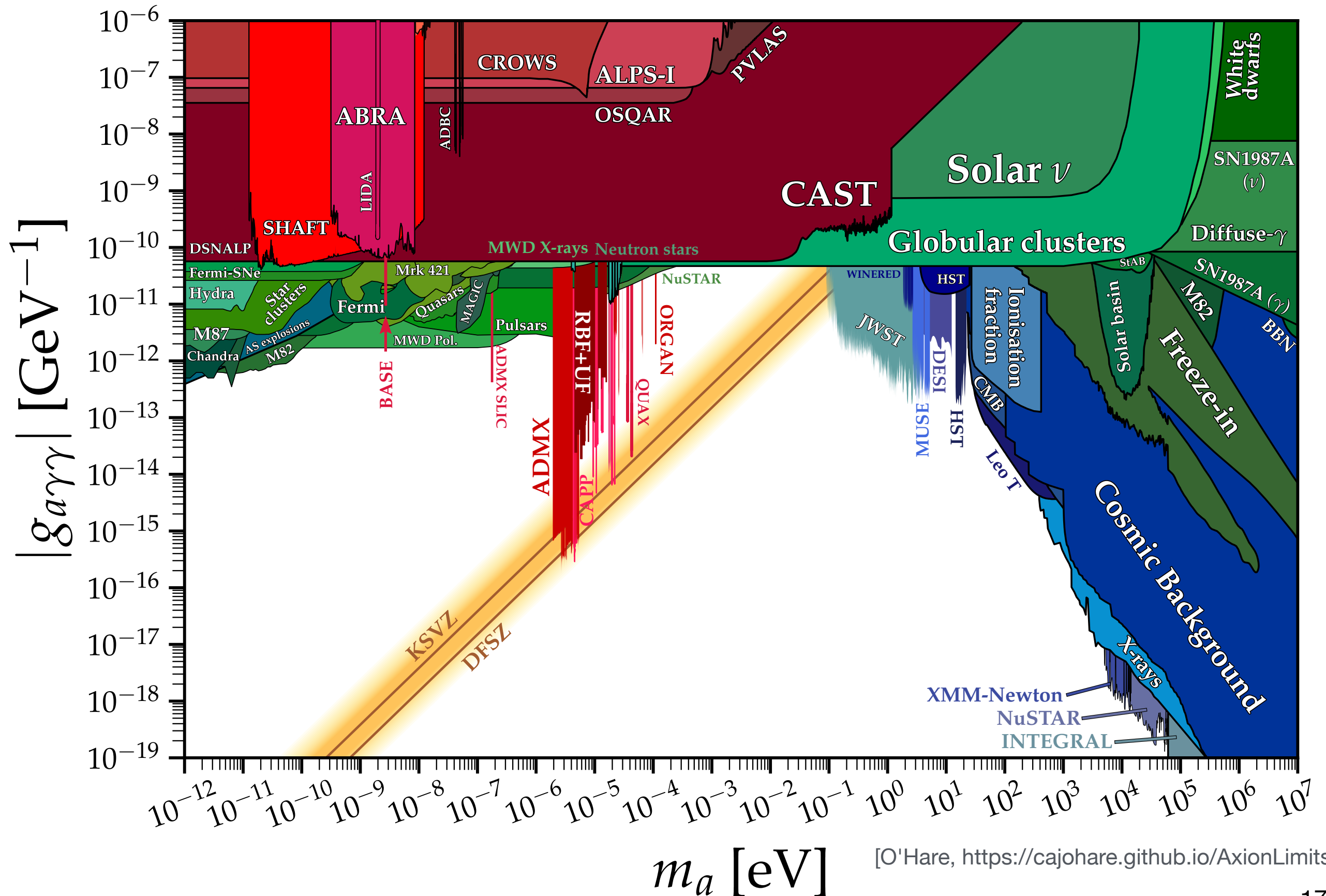
- Main peak $k_p \sim (m_a R)(\eta_s)$ appears due to the amplification at the stopping time η_s .
- Followed by a slow peak drift towards UV due to number-conserving $2a \rightarrow 2a$ self-interactions.
- The peak stops growing after $m_a(T)$ reaches the zero-temperature value.

$$\Gamma_{\text{self}} \simeq \frac{\lambda^2 n_a^2 R^2}{64 m_a^3 k_p^2} \quad \text{with} \quad \lambda = \frac{m_a^2(T)}{f_a^2}$$

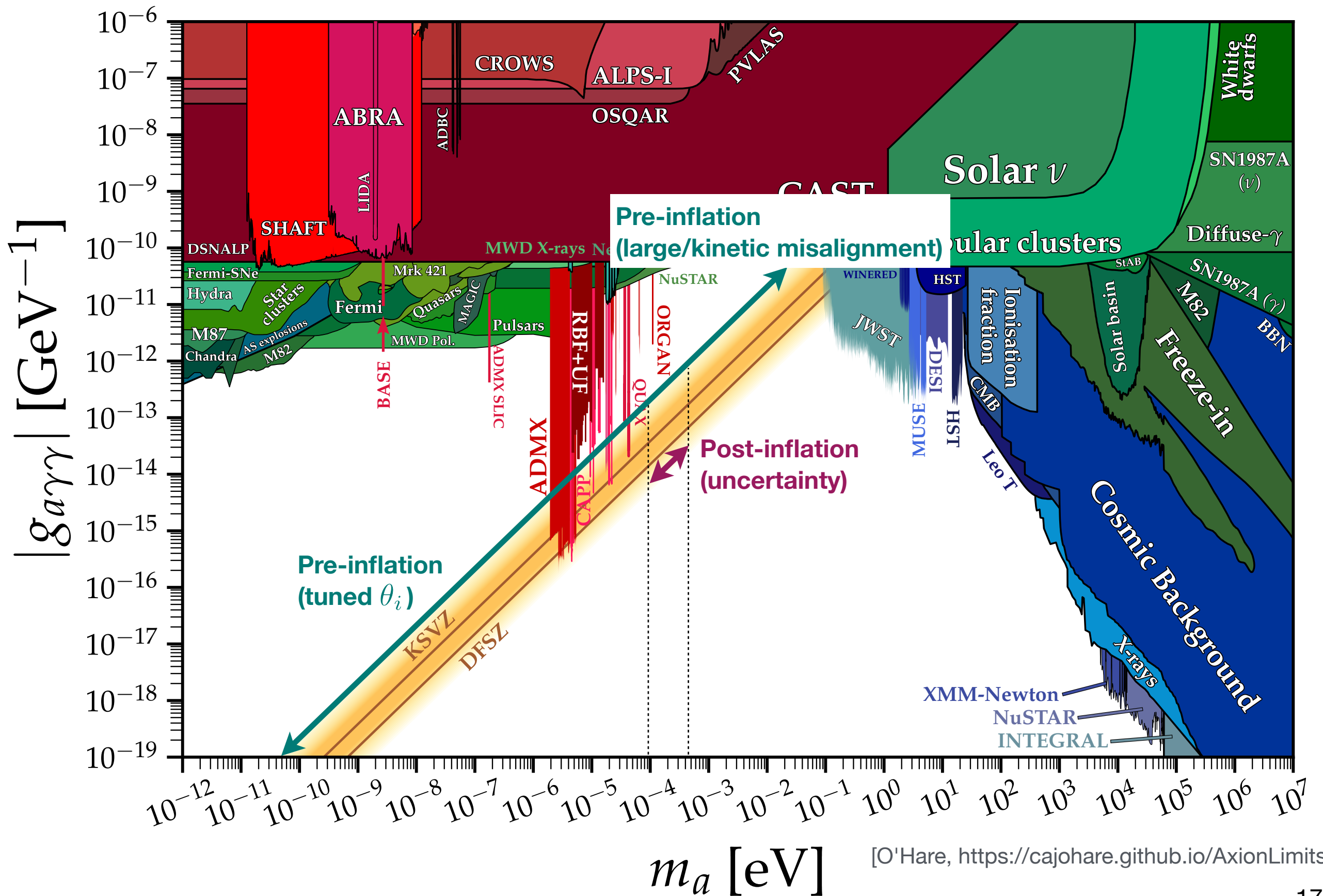


- Peak momentum at matter-radiation equality (MRE) in units of the Jeans scale k_J .
- Results comparable with the post-inflationary prediction found in Gorghetto et al. (2024).
[Gorghetto, Hardy, Villadoro, 2405.19389]
- Similar implications for structure formation (e.g. more axion stars for $k_p/k_J|_{\text{MRE}} \sim \mathcal{O}(1)$).

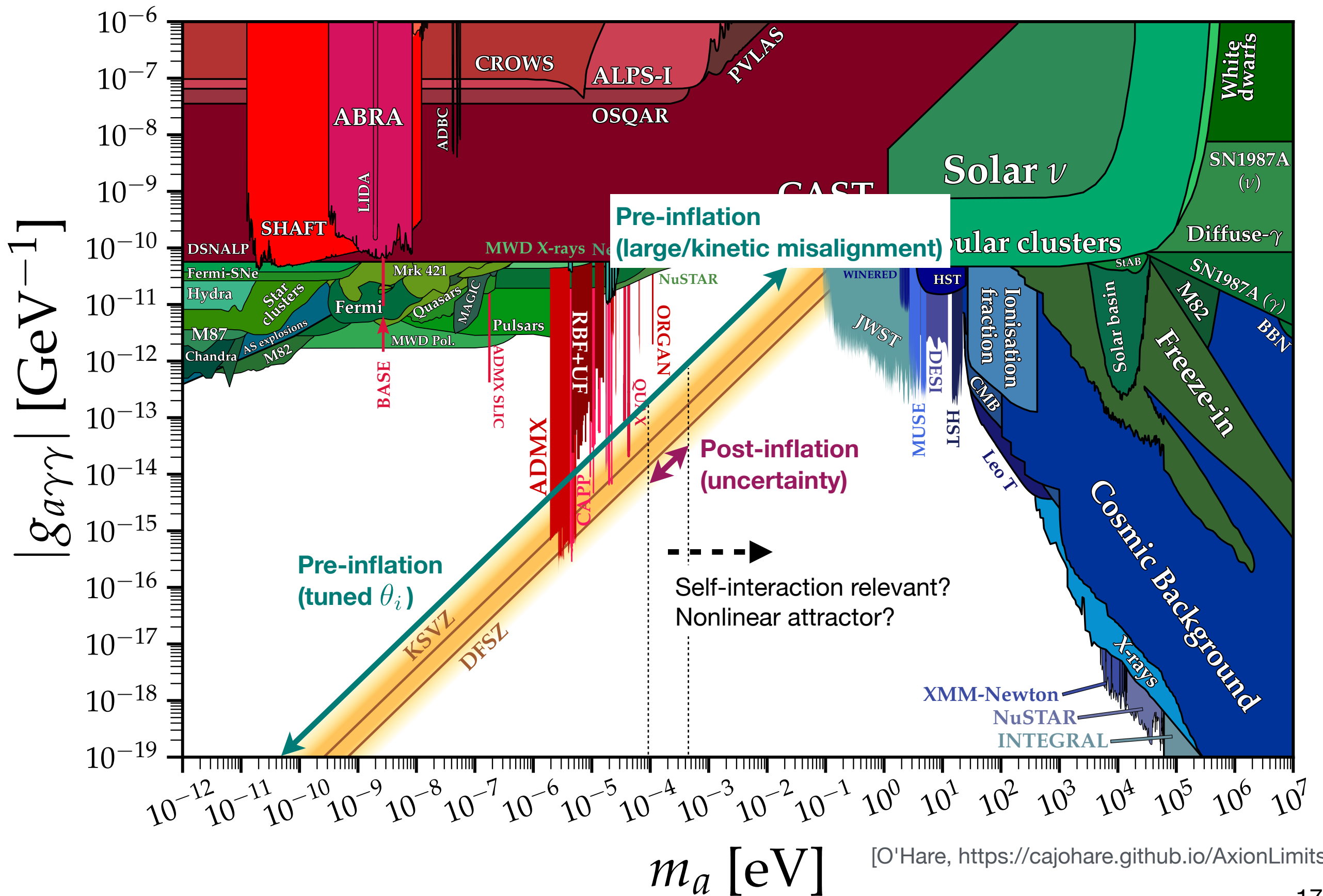
Comparison with current axion searches



Comparison with current axion searches



Comparison with current axion searches



Conclusions

- The axion: a well-motivated hypothetical particle.
 - A solution to the strong CP problem.
 - A promising candidate for cold dark matter.
- Axion dark matter properties are closely tied to the early universe history.
 - Mass, abundance, and small-scale distribution.
- Recent simulations have greatly advanced our understanding of axion physics in the early universe, but further computational advances are crucial for precision predictions.