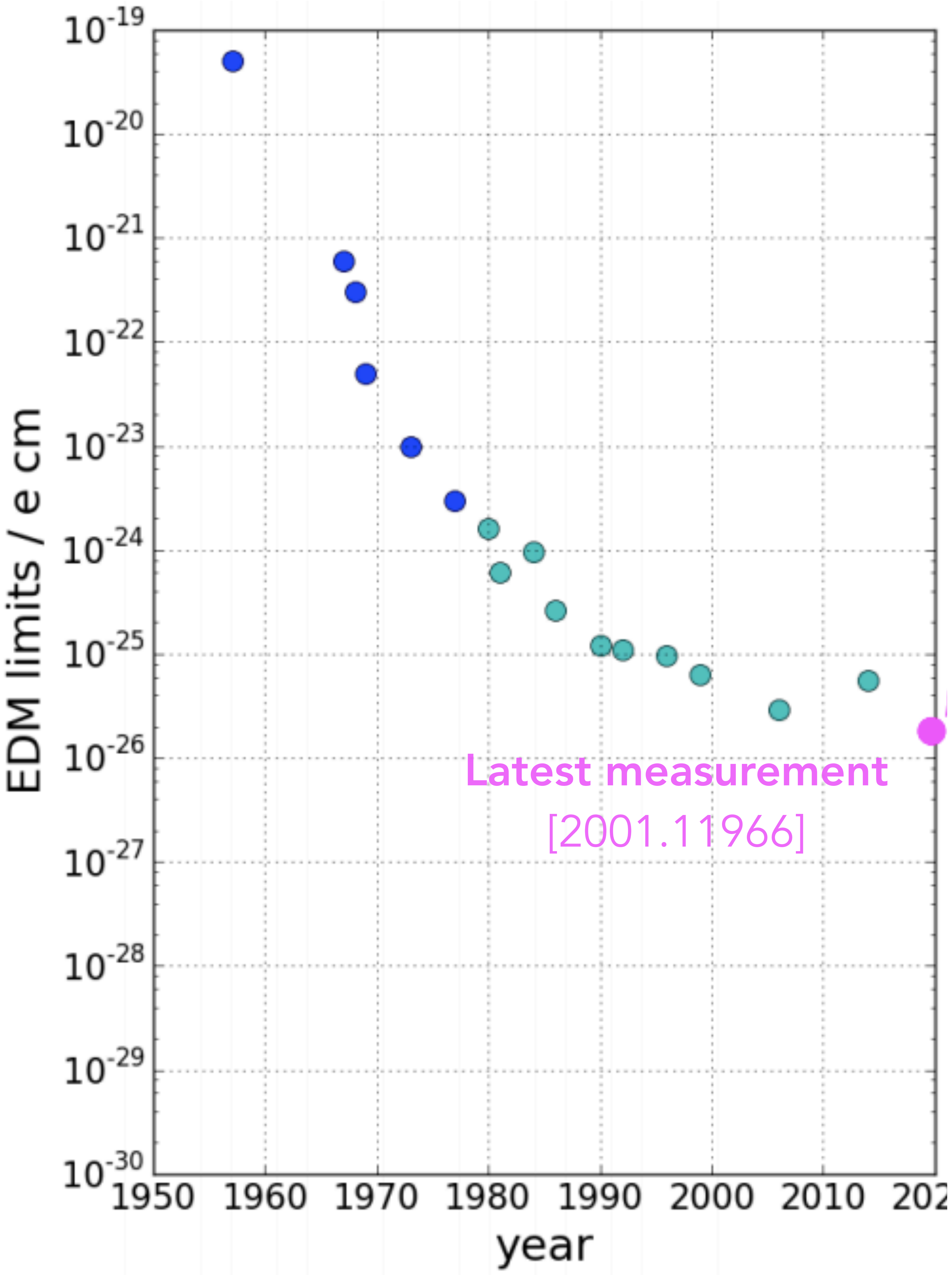
THE UNIVERSITY OF SYDNEY

ARC CENTRE OF EXCELLENCE FOR DARK MATTER

Axions in the solar neighbourhood

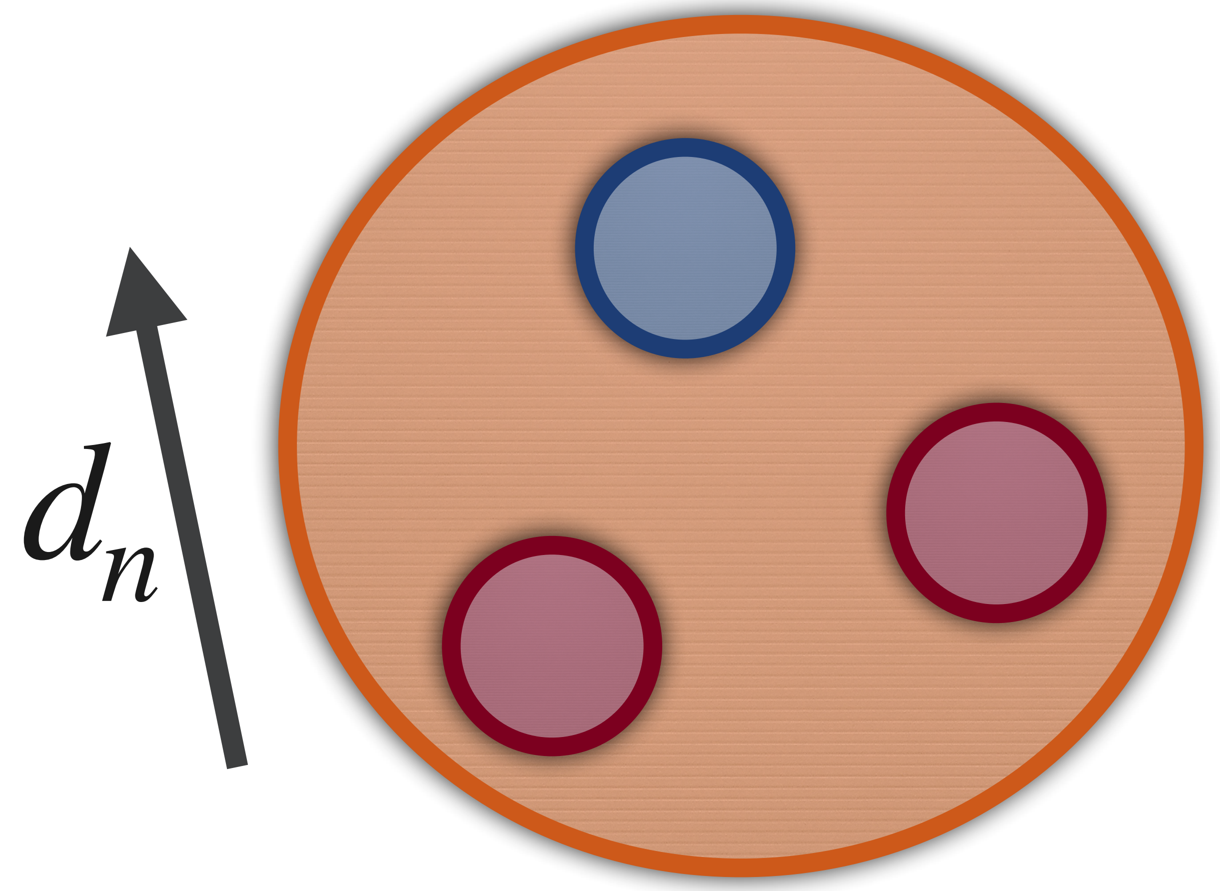
Ciaran O'Hare
University of Sydney



Strong CP problem

Neutron EDM set by fundamental constant of SM (QCD theta)

$$d_n = (2.4 \pm 1.0)\bar{\theta} \times 10^{-3}\, e\,\mathrm{fm}$$

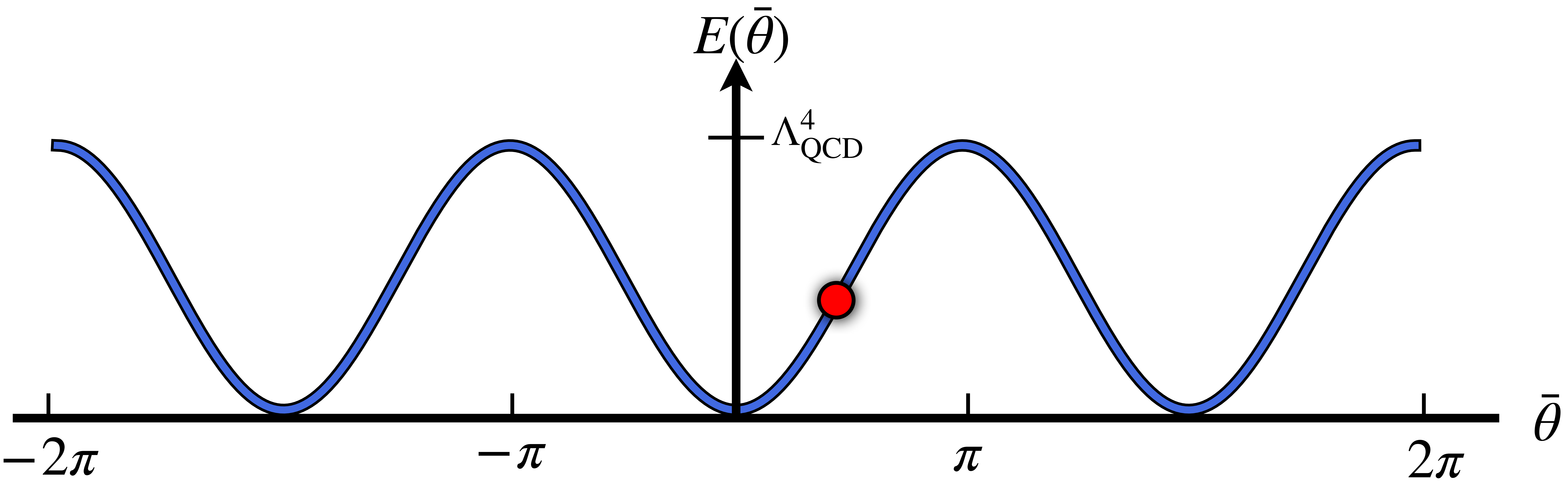


$$\Rightarrow \bar{\theta} \lesssim 10^{-10}$$

The solution, a la Peccei-Quinn

QCD vacuum energy already minimised at $\bar{\theta} = 0$ (Vafa-Witten theorem).

However $\bar{\theta}$ is just a parameter, there is no mechanism to cause it to want to minimise energy



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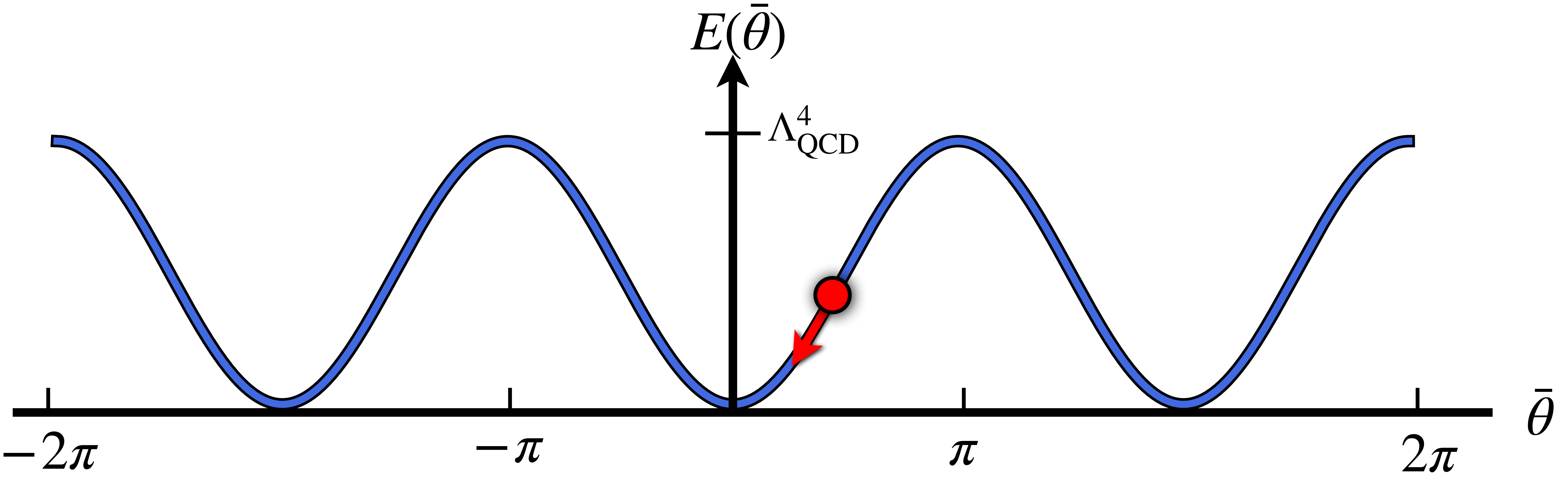
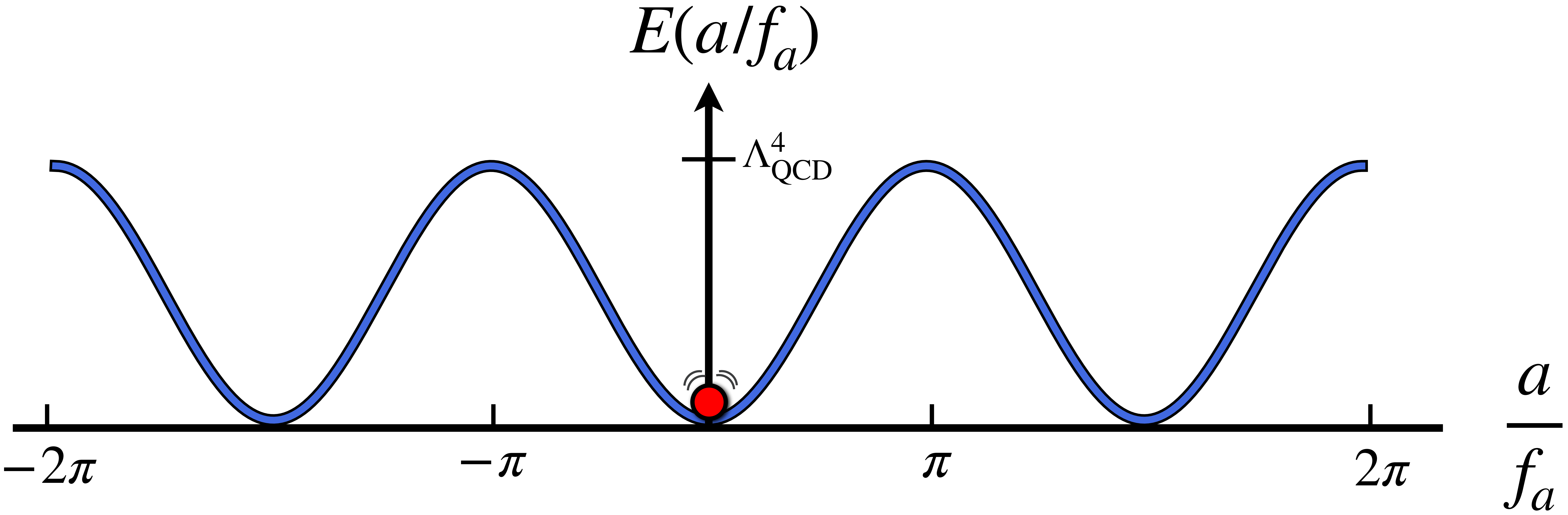


PQ mechanism: what if there was?

The axion



- Introduce Goldstone boson, a, that couples to gluons $\propto (a/f_a)\, G\tilde{G}$. It will have an (approximate) shift symmetry that can be used to cancel off any unwanted CP violation while VW theorem ensures $\langle a \rangle = 0$
- In the process the field acquires a potential and thus a small mass

$$V(a) \approx \Lambda^4_{\rm QCD}\left[1 - \cos\left(\bar{\theta} + \frac{a}{f_a}\right)\right] \longrightarrow m_a \simeq \frac{\Lambda^2_{\rm QCD}}{f_a} \simeq 6\,{\rm meV}\left(\frac{10^9{\rm GeV}}{f_a}\right)$$

The axion effective theory

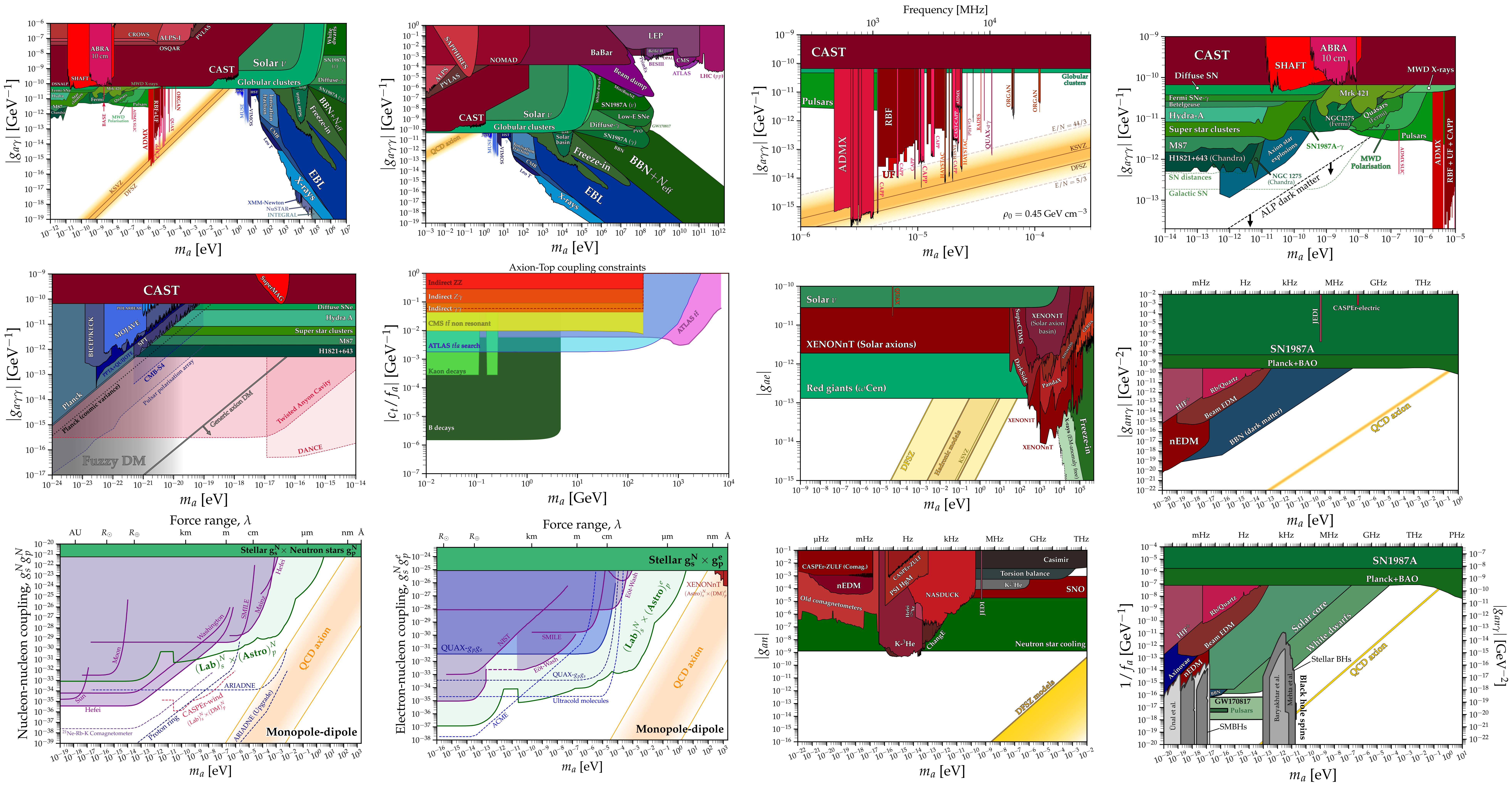
Introduce axion as the pseudo-Goldstone boson of a new global $U(1)$, spontaneously broken at scale f_a. May also couple to the photon and fermions

$$\mathcal{L} = \frac{1}{2}\left(\partial_\mu a\right)\left(\partial^\mu a\right) - \frac{1}{2}m_a^2 a^2 - \frac{g_{a\gamma}}{4} a F_{\mu\nu}\widetilde{F}^{\mu\nu} + \partial_\mu a \sum_\psi \frac{g_{a\psi}}{2m_\psi}\left(\bar{\psi}\gamma^\mu\gamma^5\psi\right)$$

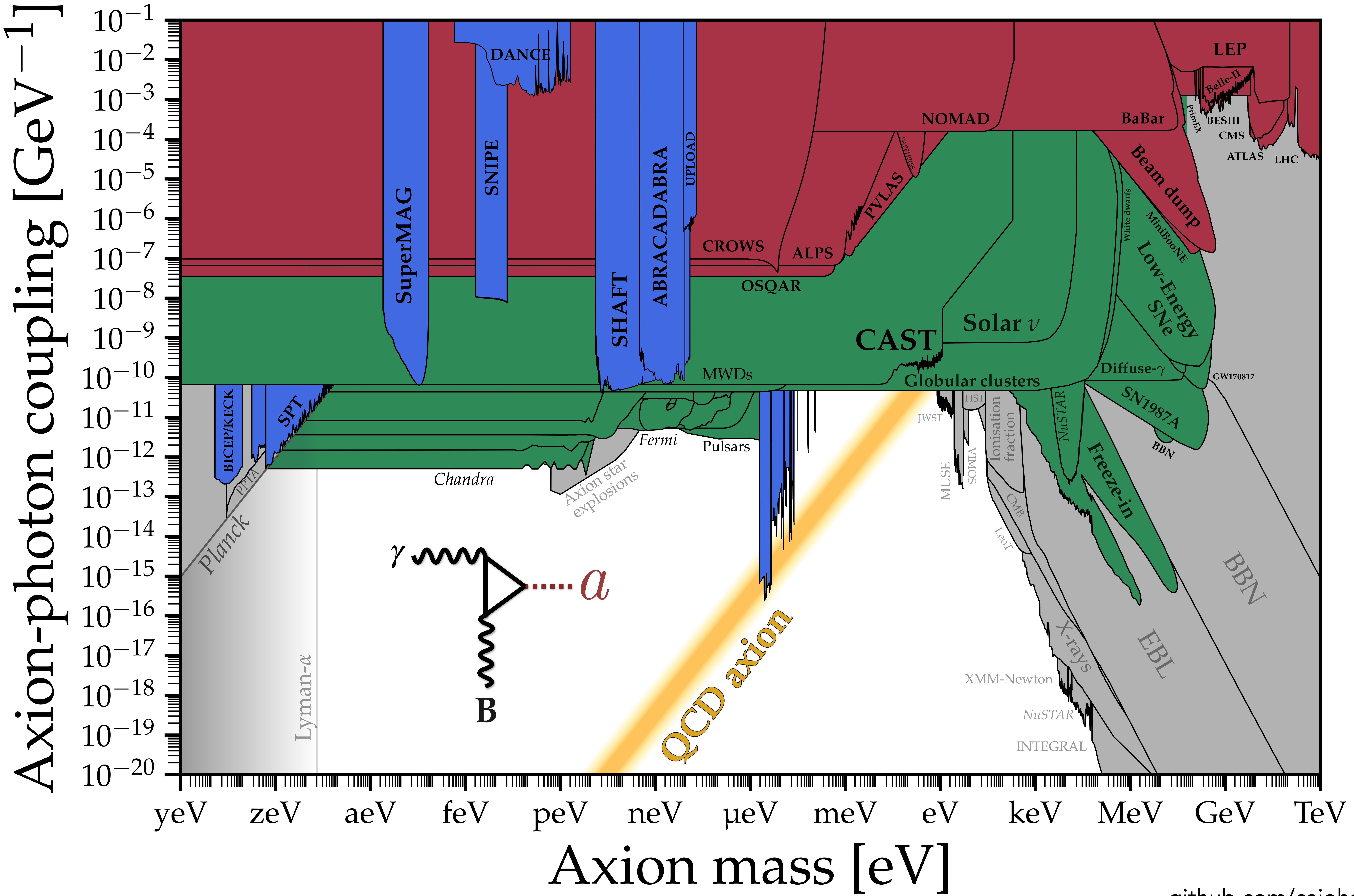
Importantly, all couplings suppressed by $g \sim f_a^{-1}$. So set symmetry breaking scale as high as you like to evade observational constraints

→ ideal candidate for **dark matter**

Lots of activity, but still potentially many years away from a discovery



For more, see cajohare.github.io/AxionLimits/ → Now hosts results from >300 publications!



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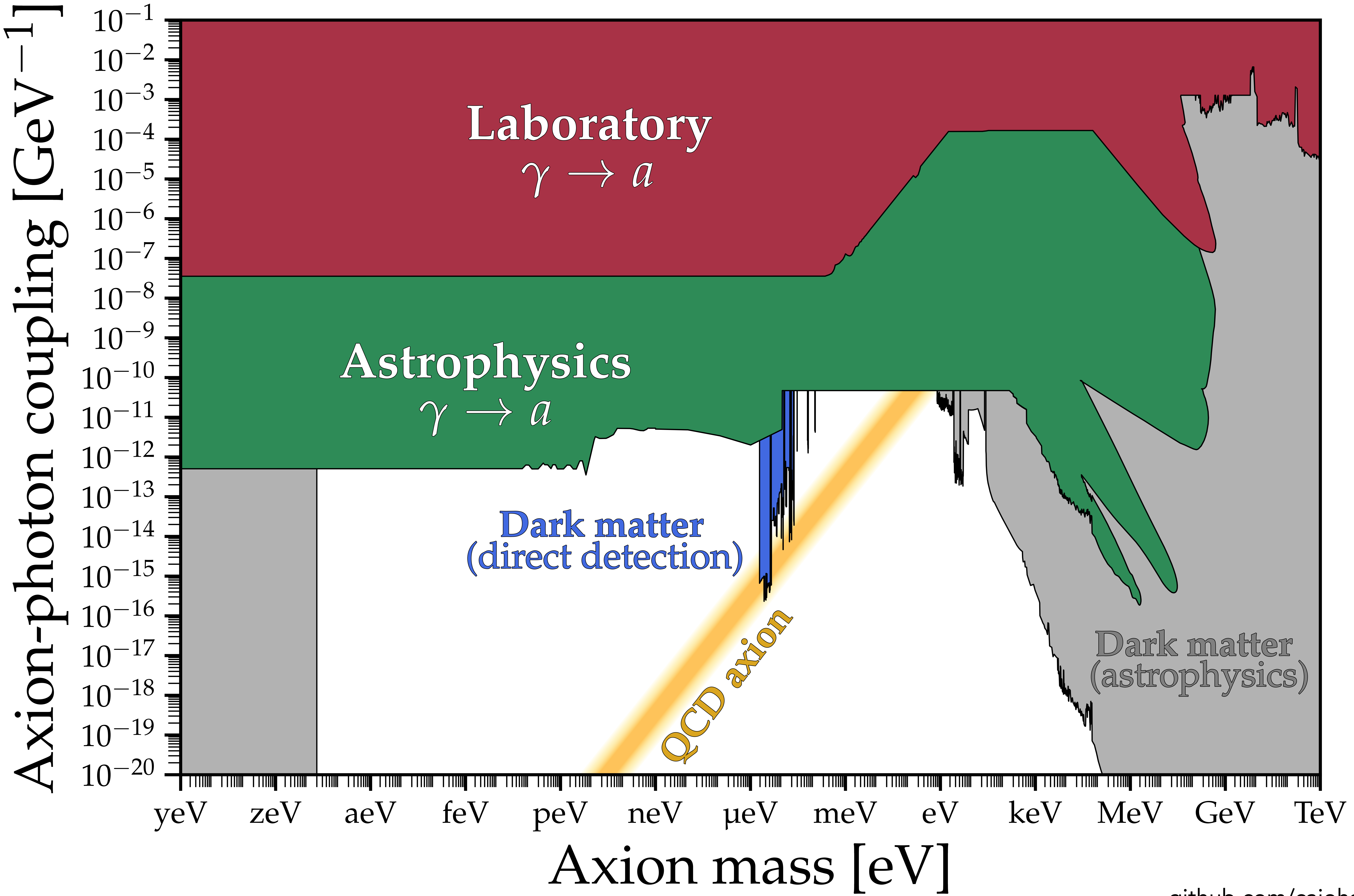

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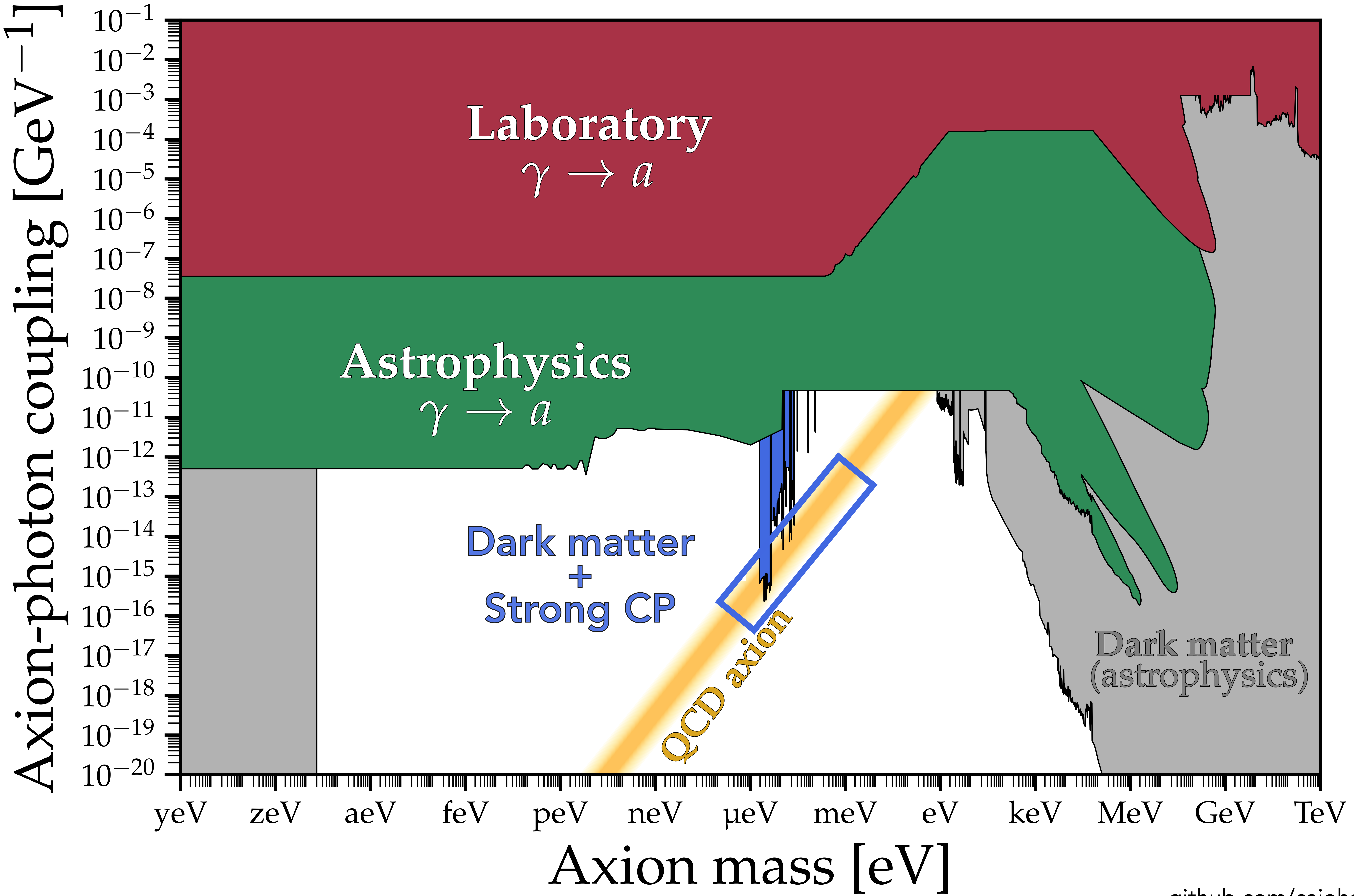

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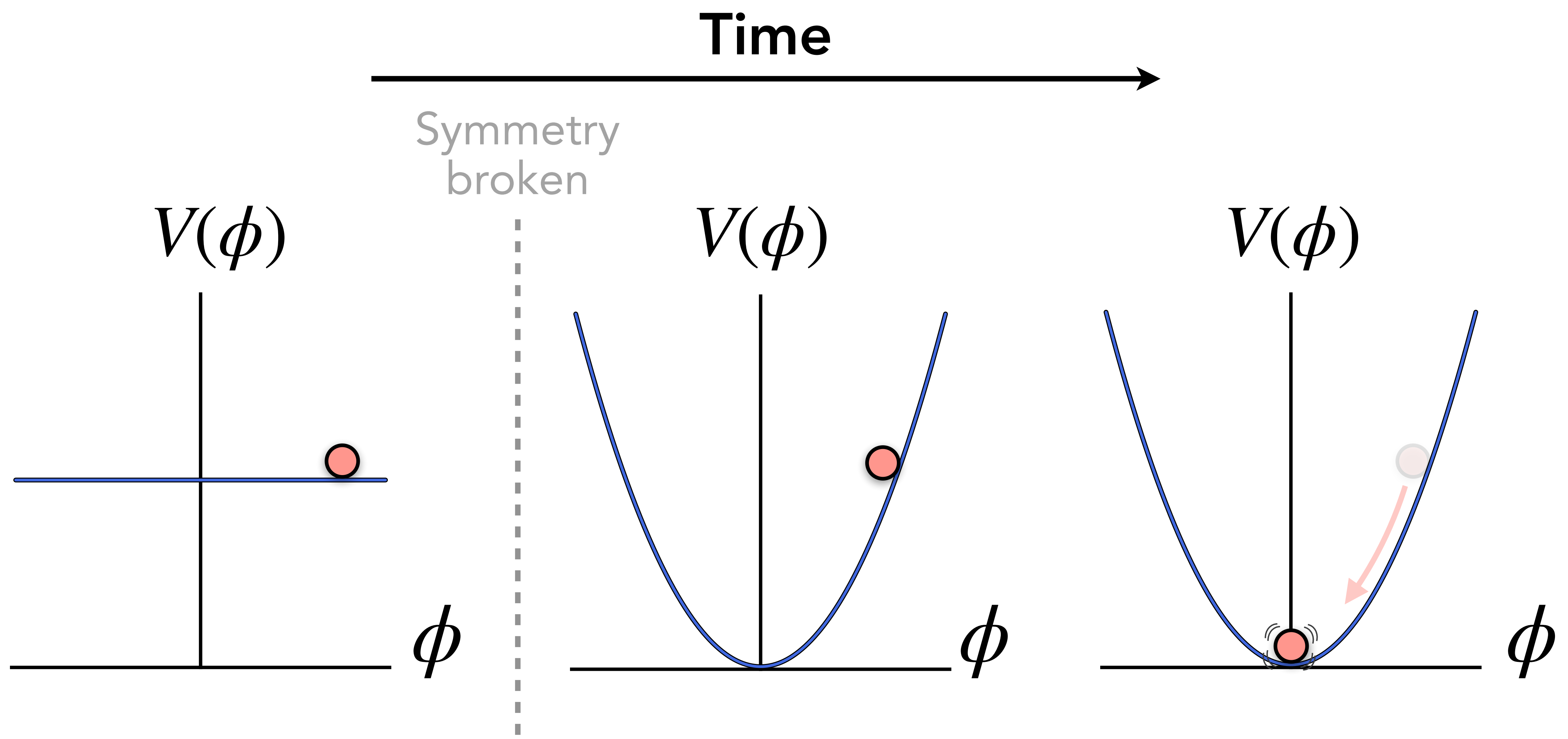
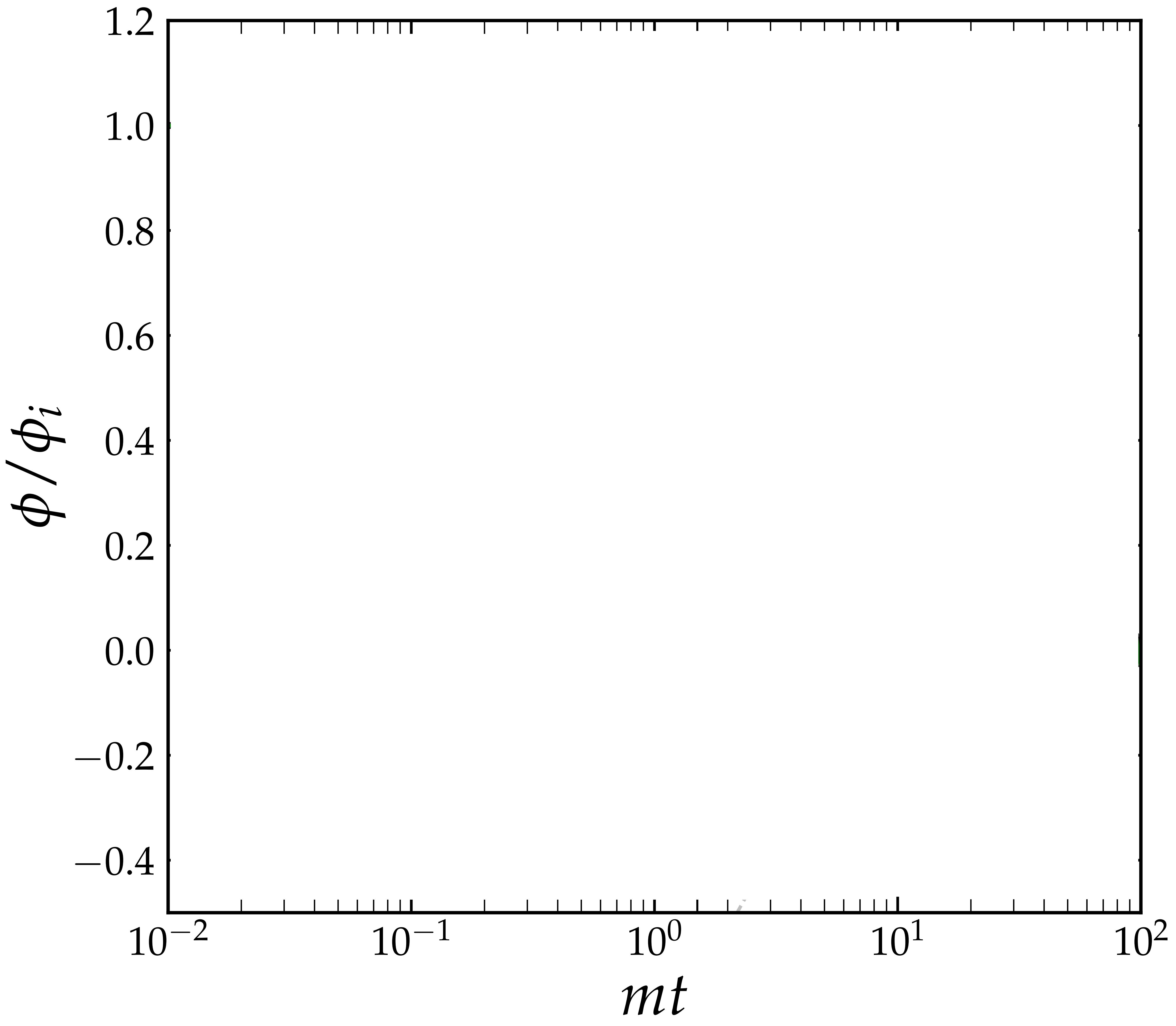
How can a scalar field be the dark matter?

→ the misalignment mechanism

Misalignment mechanism



$$\ddot{\phi} + 3H(t)\dot{\phi} + m^2\phi = 0$$



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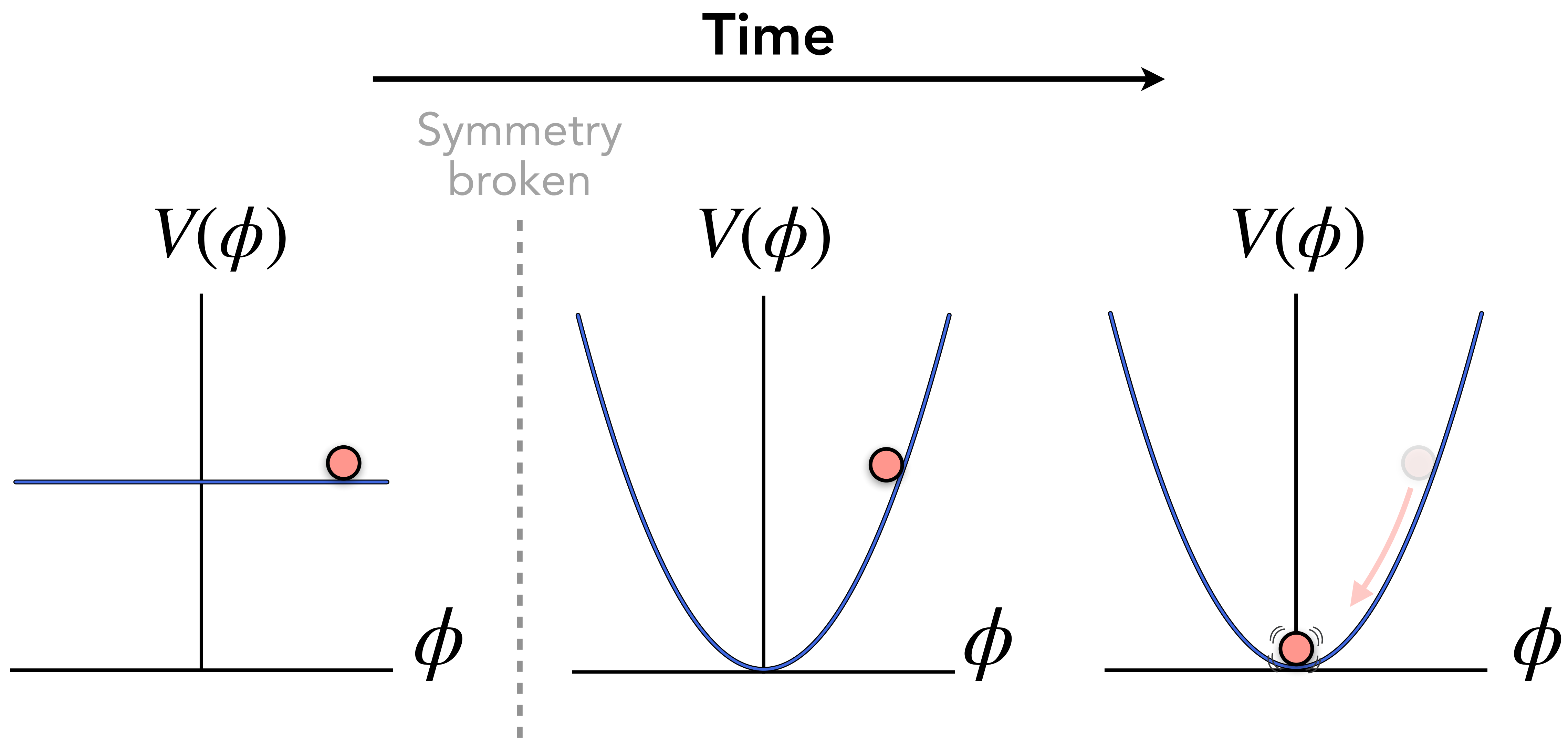

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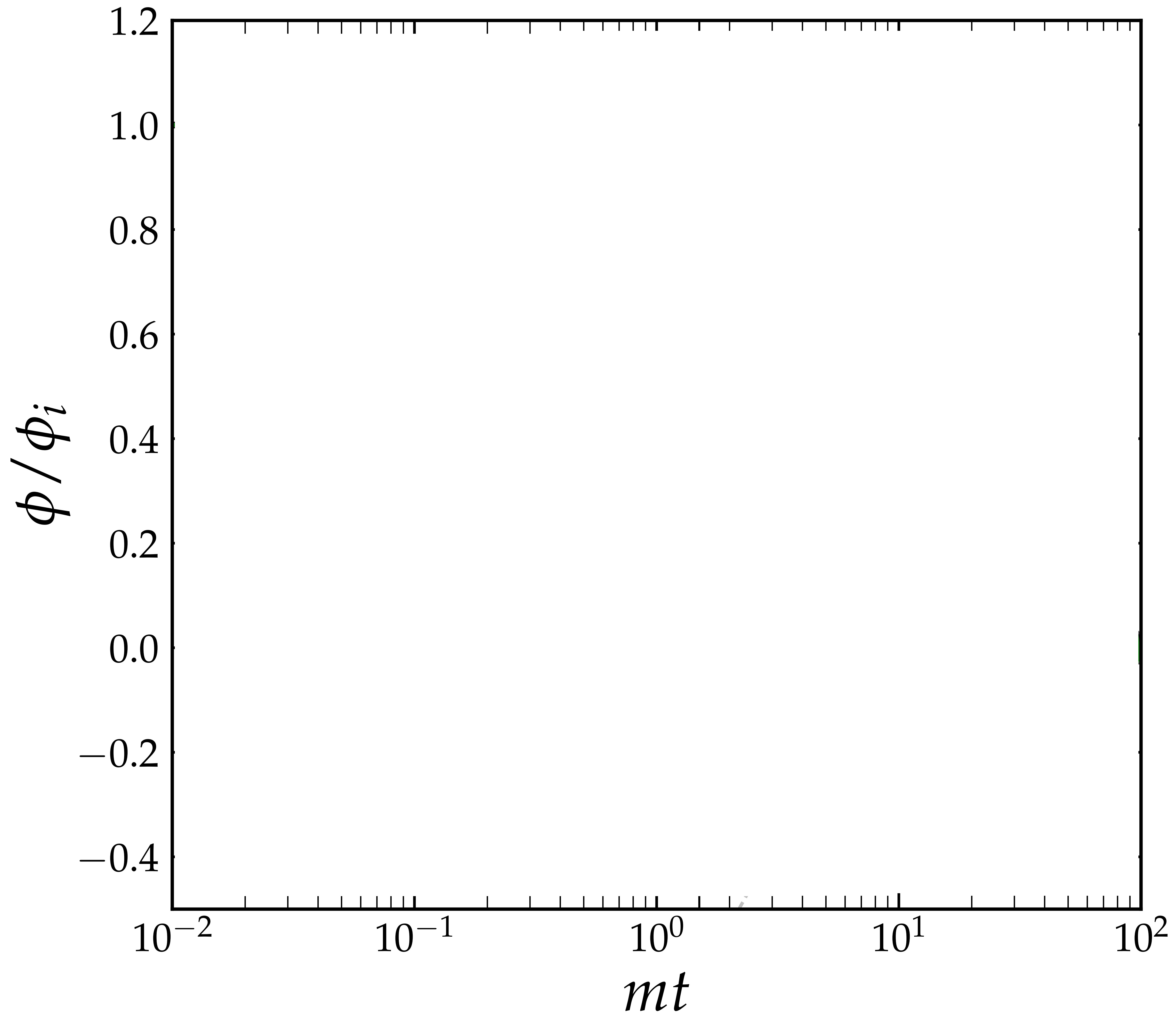
Two regimes:



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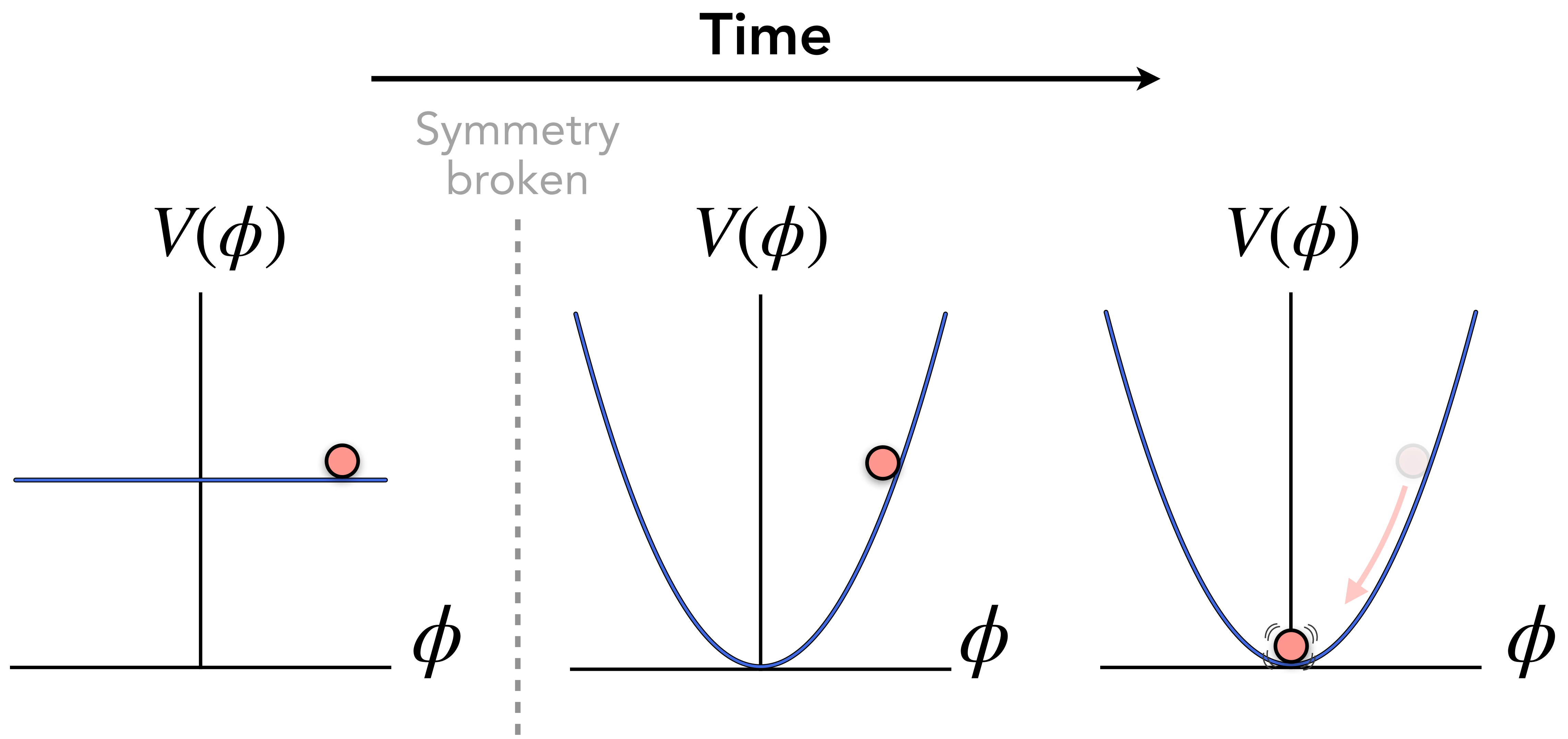

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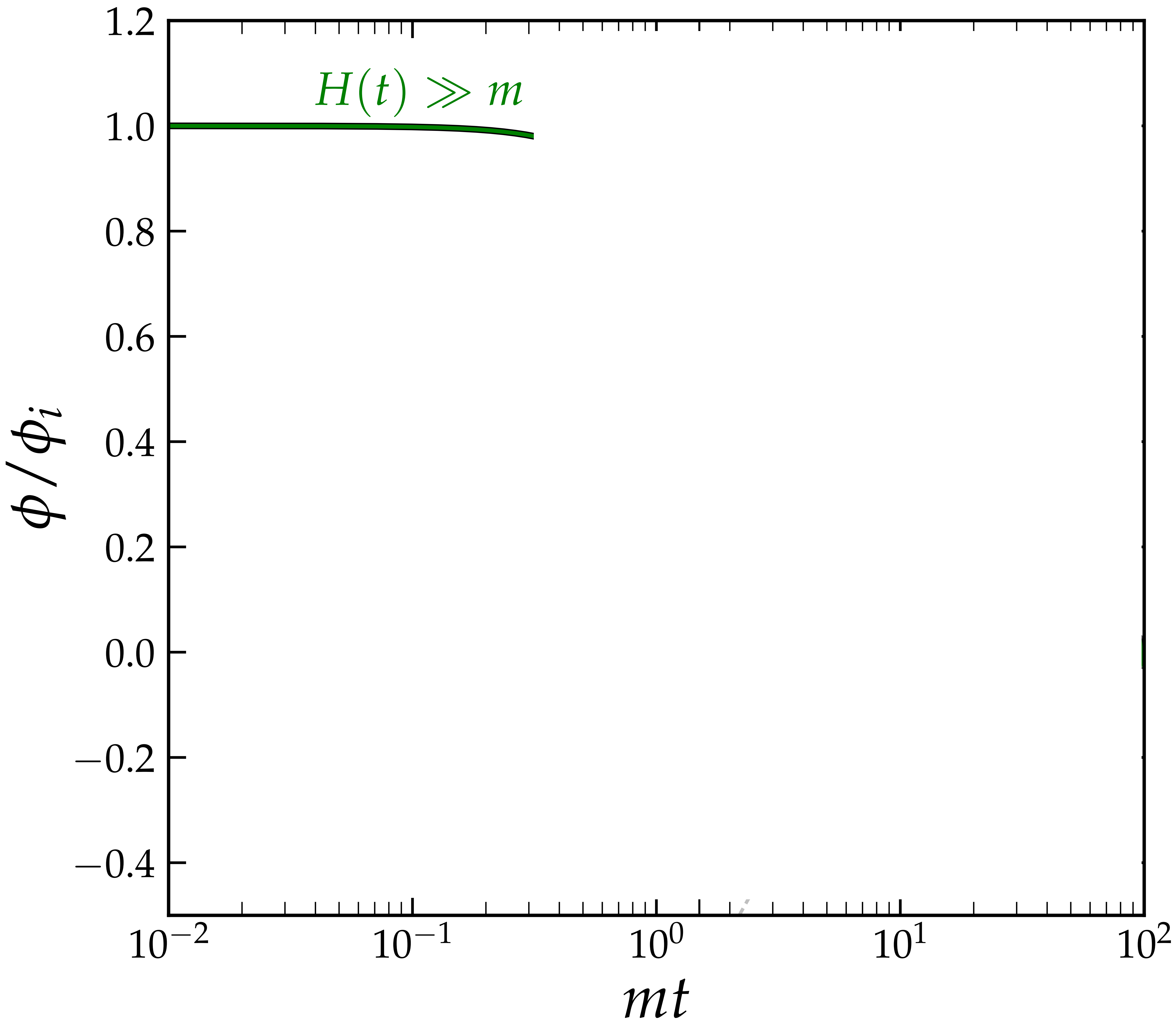

Two regimes:

- $3H(t) \gg m$ → overdamped

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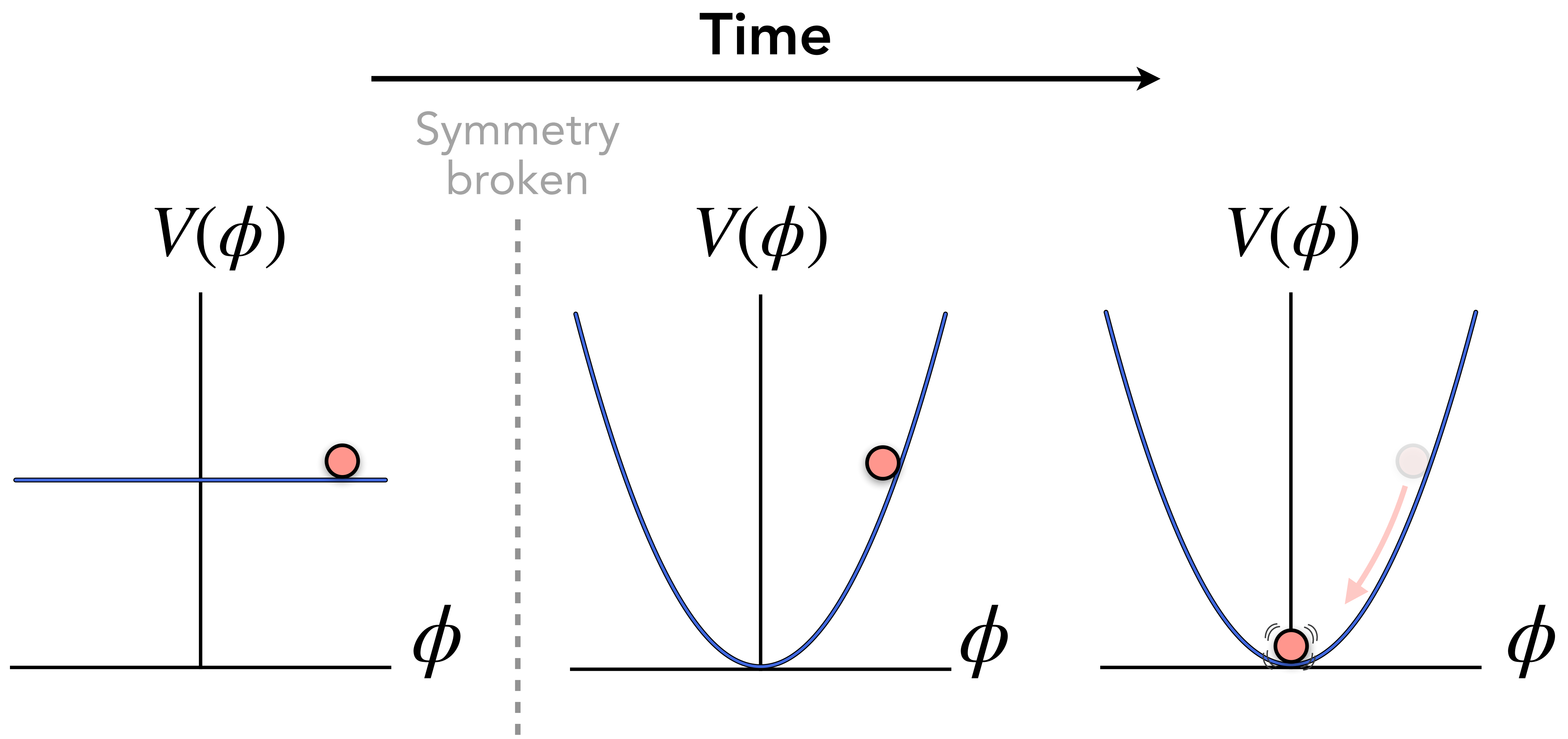

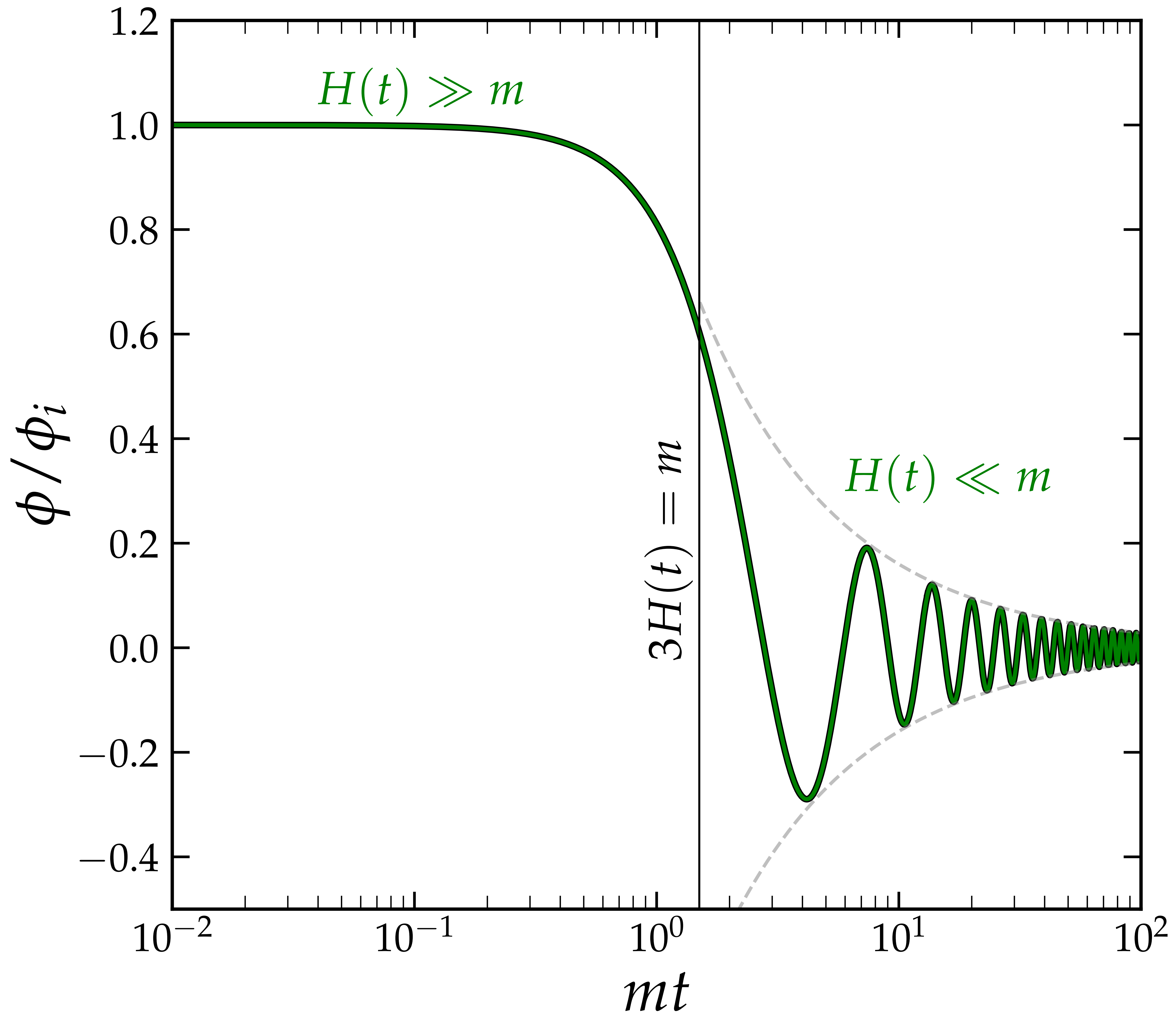

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Two regimes:

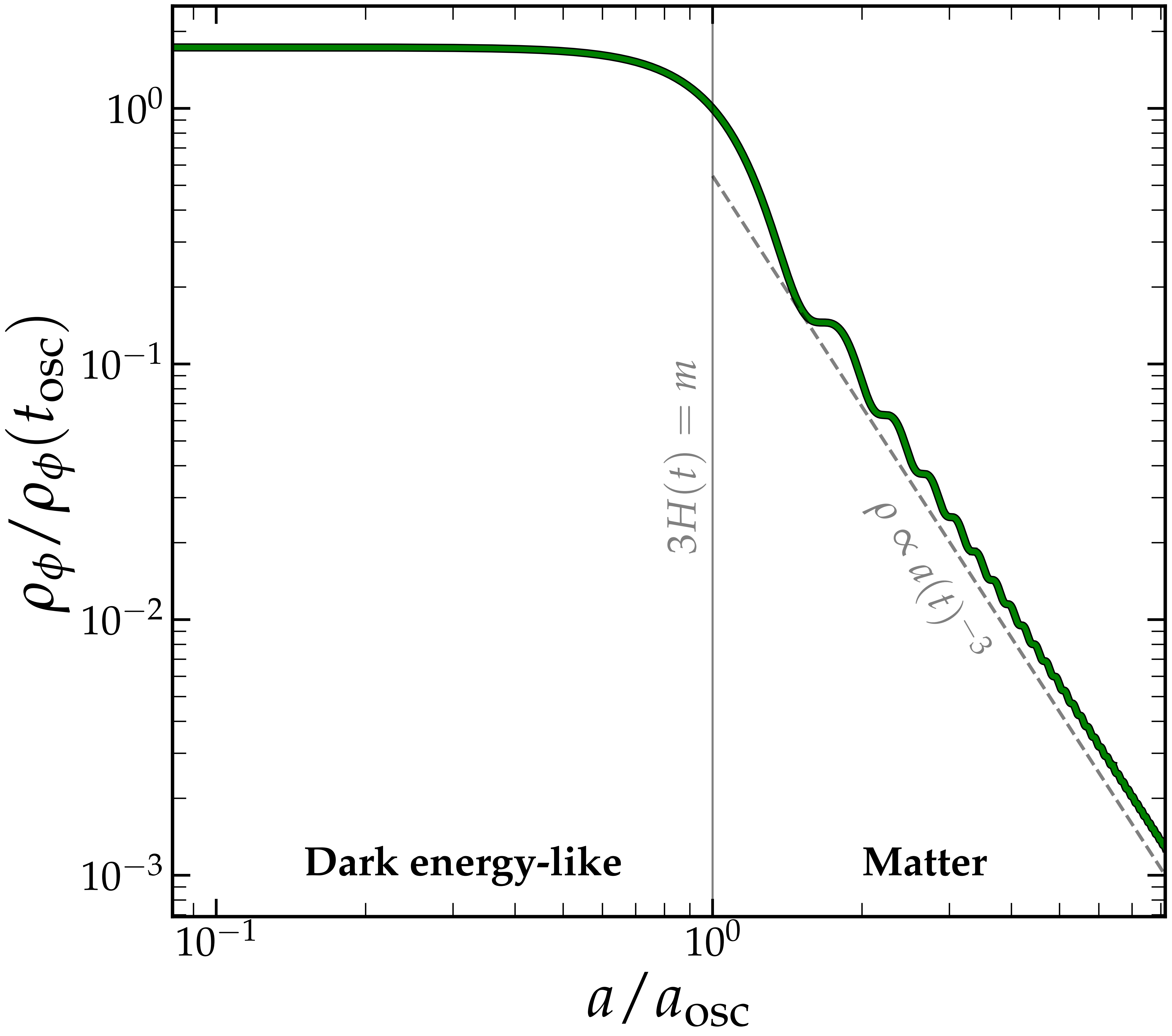
- $3H(t) \gg m$ → overdamped
- $3H(t) \ll m$ → damped harmonic oscillator

Misalignment mechanism for a generic scalar

Consider energy density in the scalar field

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + \frac{1}{2}m^2\phi^2$$

$$\implies \quad \rho_\phi \propto a^{-3}$$



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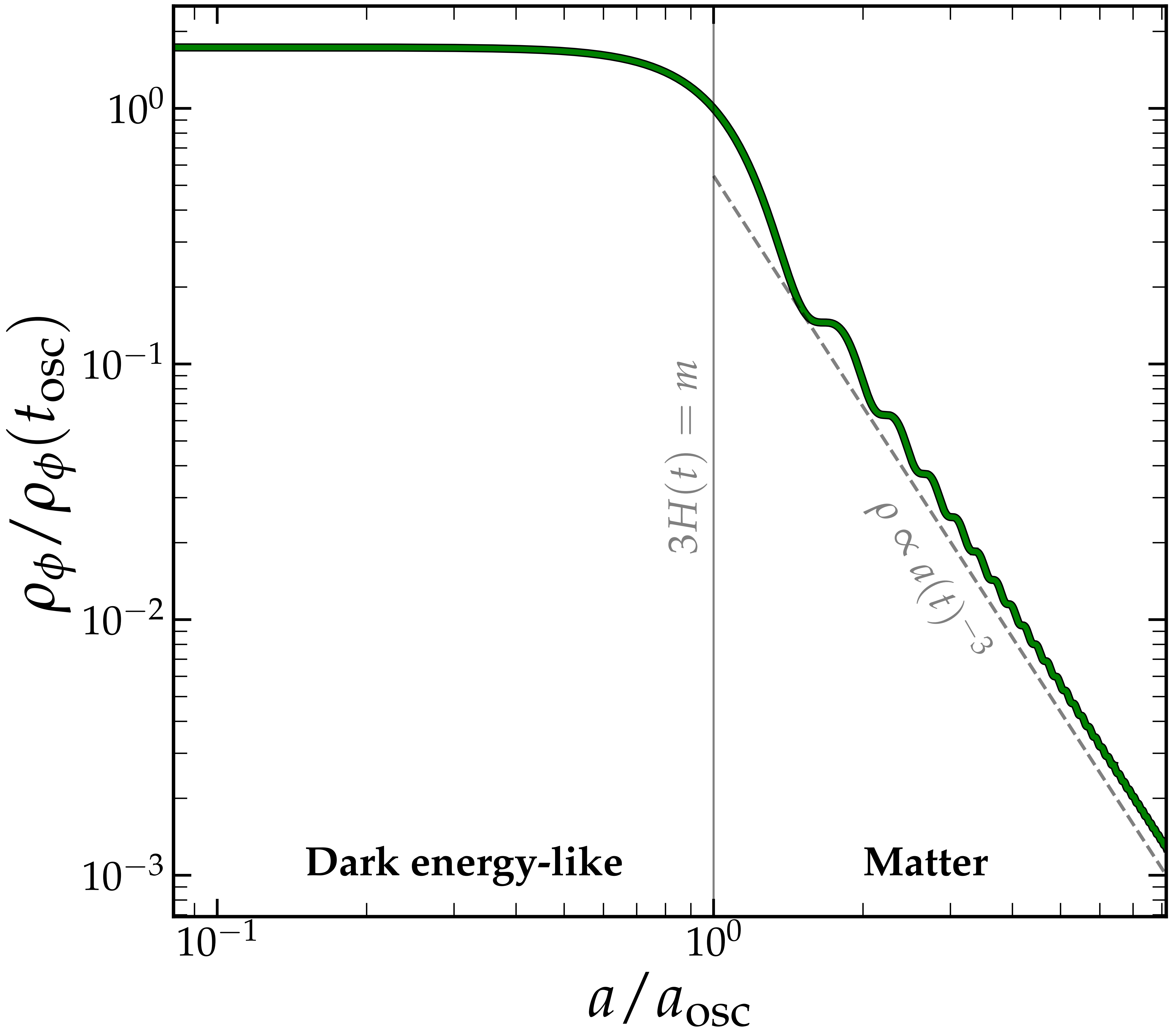
Redshifts like dark matter, with abundance today:

$$\Omega_{\rm DM}h^2 \propto \phi_i^2 m^{1/2}$$

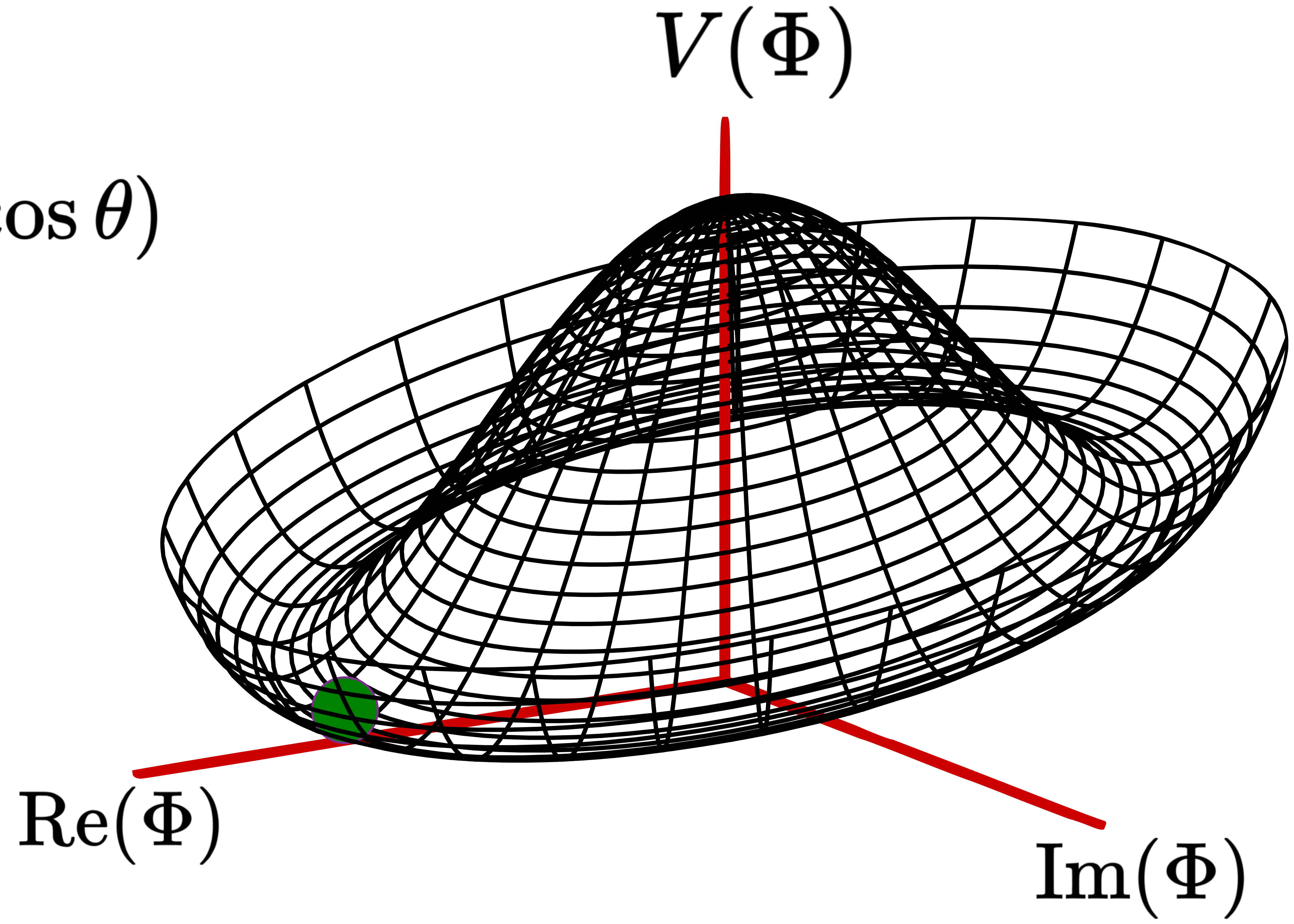


Axion misalignment

Axion is the Goldstone (θ) appearing after the U(1)$_{\rm PQ}$ is broken at scale f_a.

We write it as the phase of a complex scalar field: $\Phi(t) = \rho\, e^{i\theta}$

$$V(\Phi) = V_{\rm PQ}(\rho) + V_{\rm QCD}(\theta)$$
$$= \frac{\lambda}{8}\left(\rho^2 - f_a^2\right)^2 + m_a^2(T) f_a^2 (1 - \cos\theta)$$



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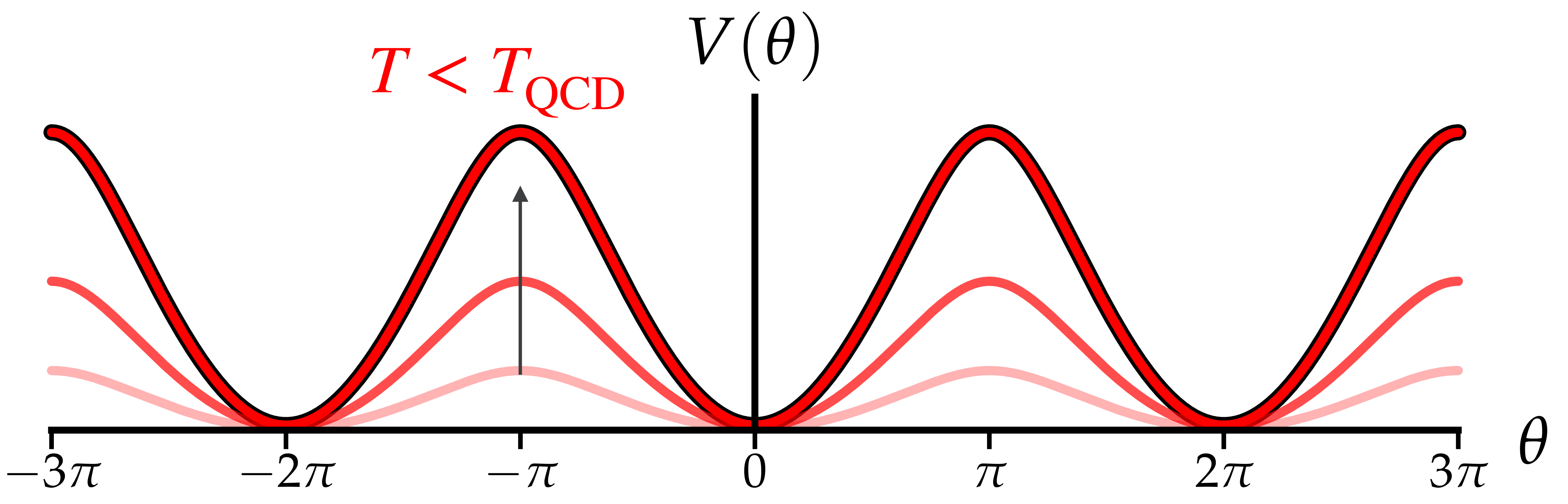
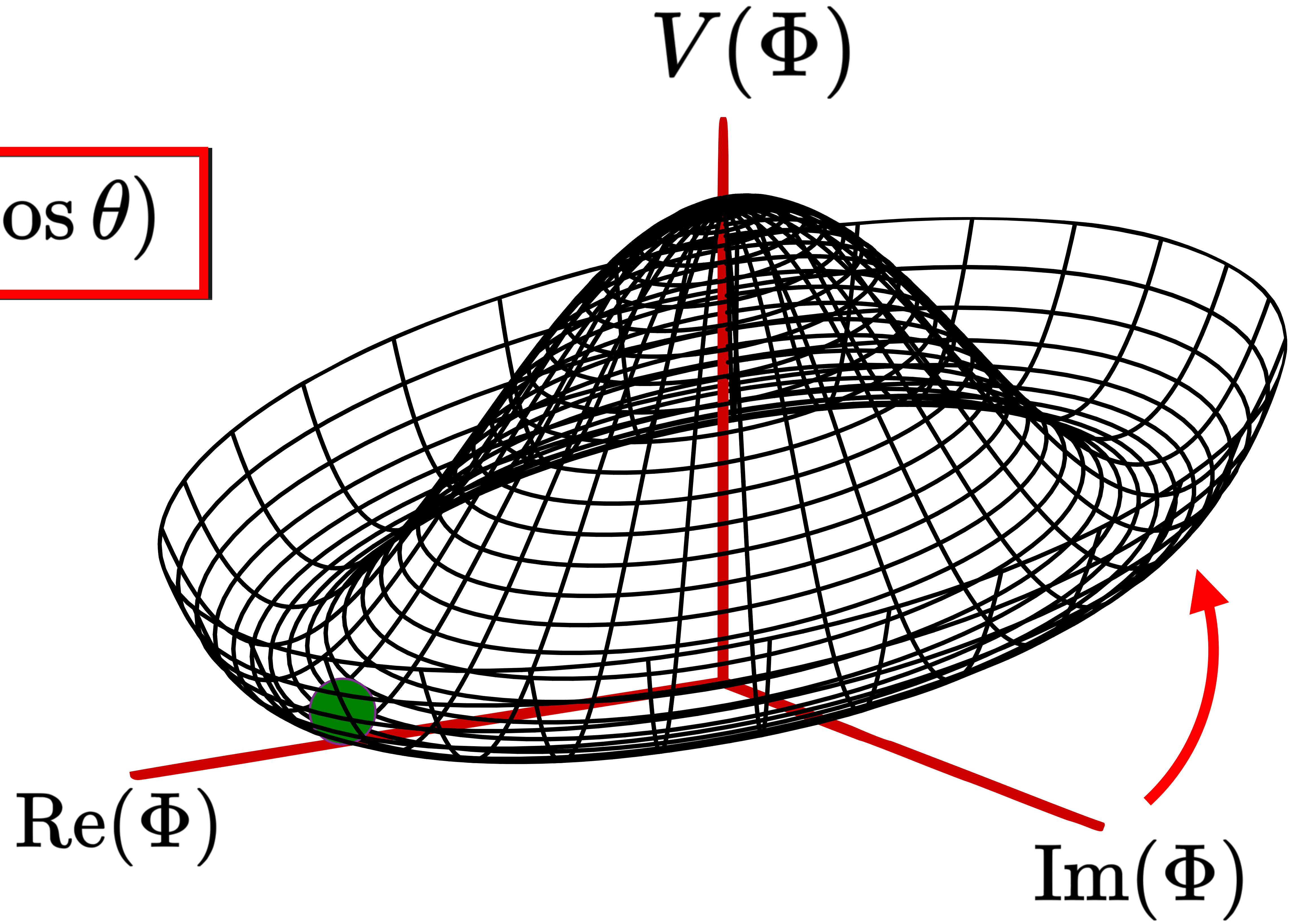
QCD



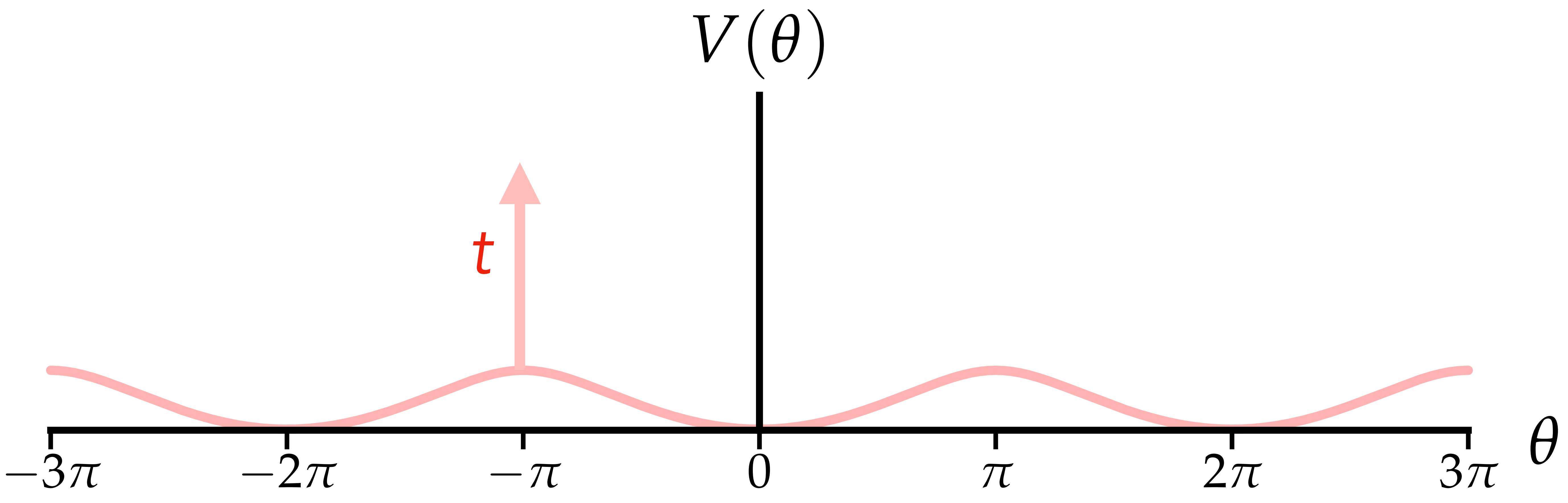


The QCD axion

Mass is generated by instantons whose effects are temperature-dependent
In the literature this dependence is called the "topological susceptibility", $\chi(T)$

$$V(\theta) \approx \chi(T)(1 - \cos\theta) = m_a^2(T) f_a^2 (1 - \cos\theta)$$

Axion mass grows as temperature drops,
reaching a constant when $T < T_{\rm QCD}$



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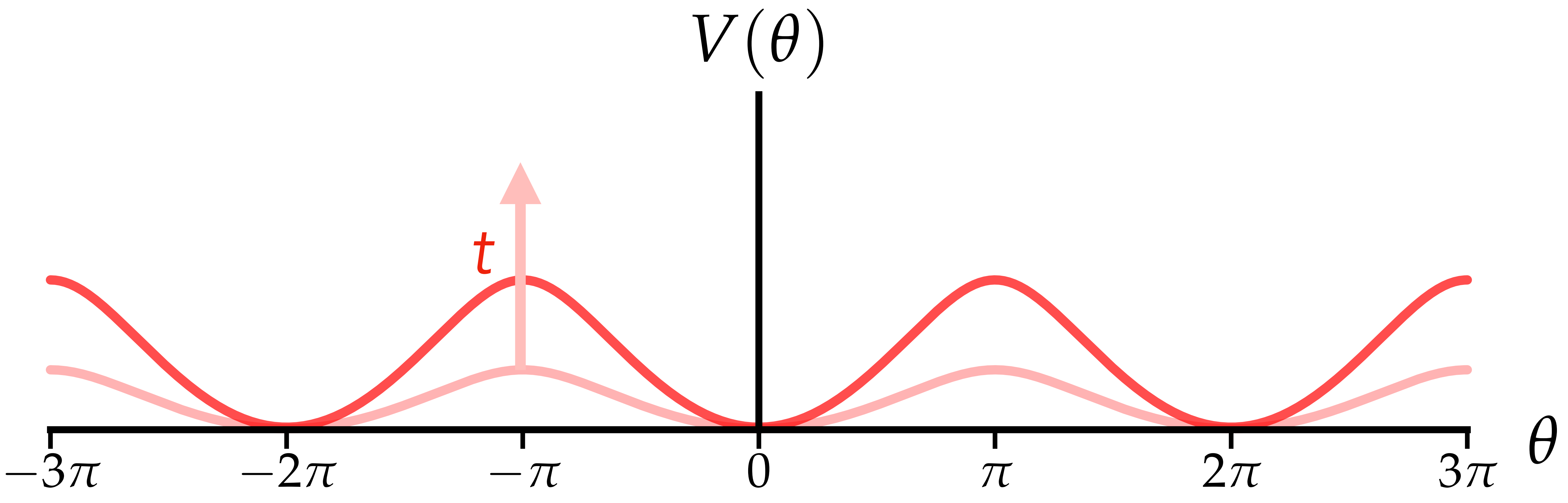

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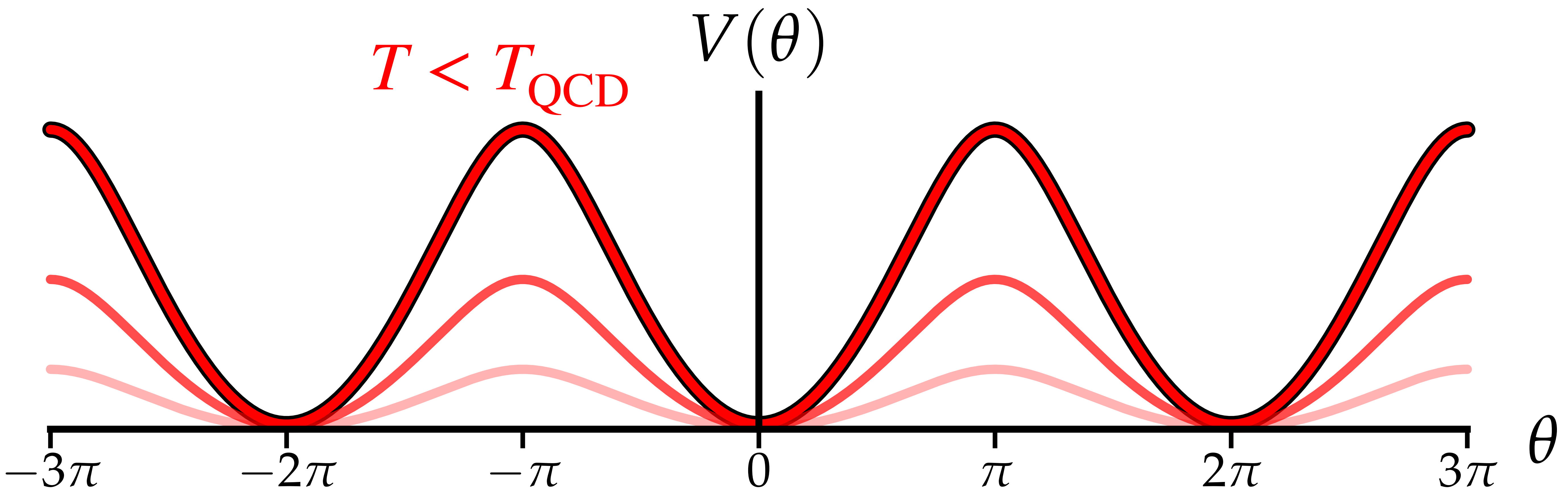

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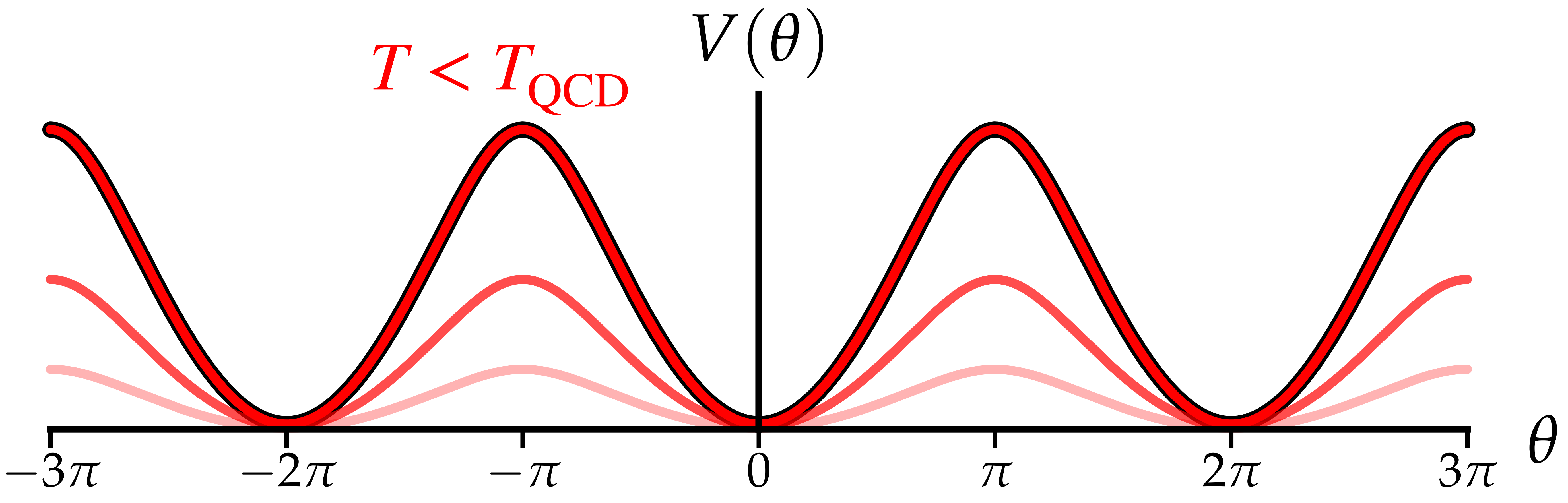
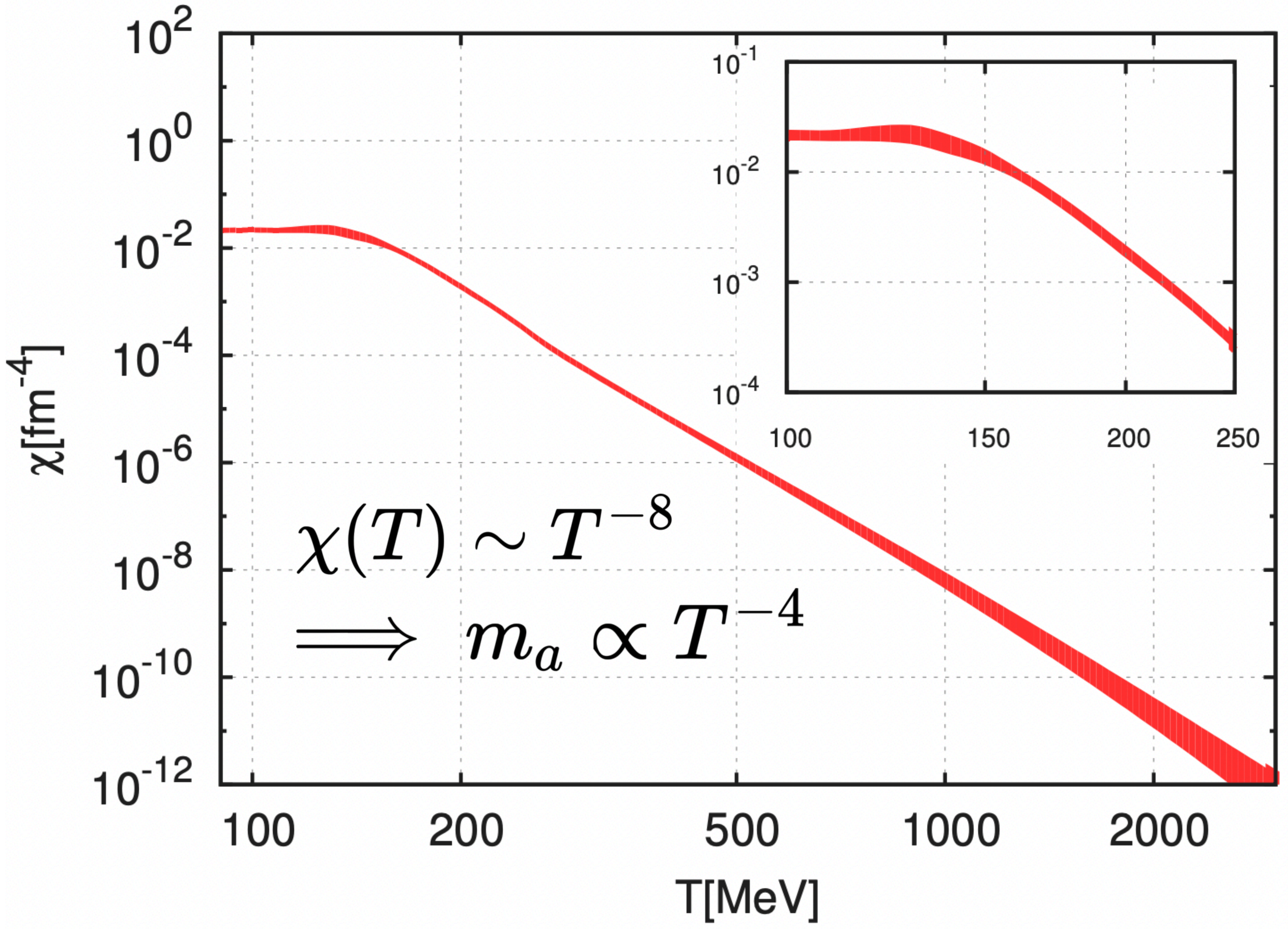


Lattice QCD calculation, Borsanyi+ [1606.07494]



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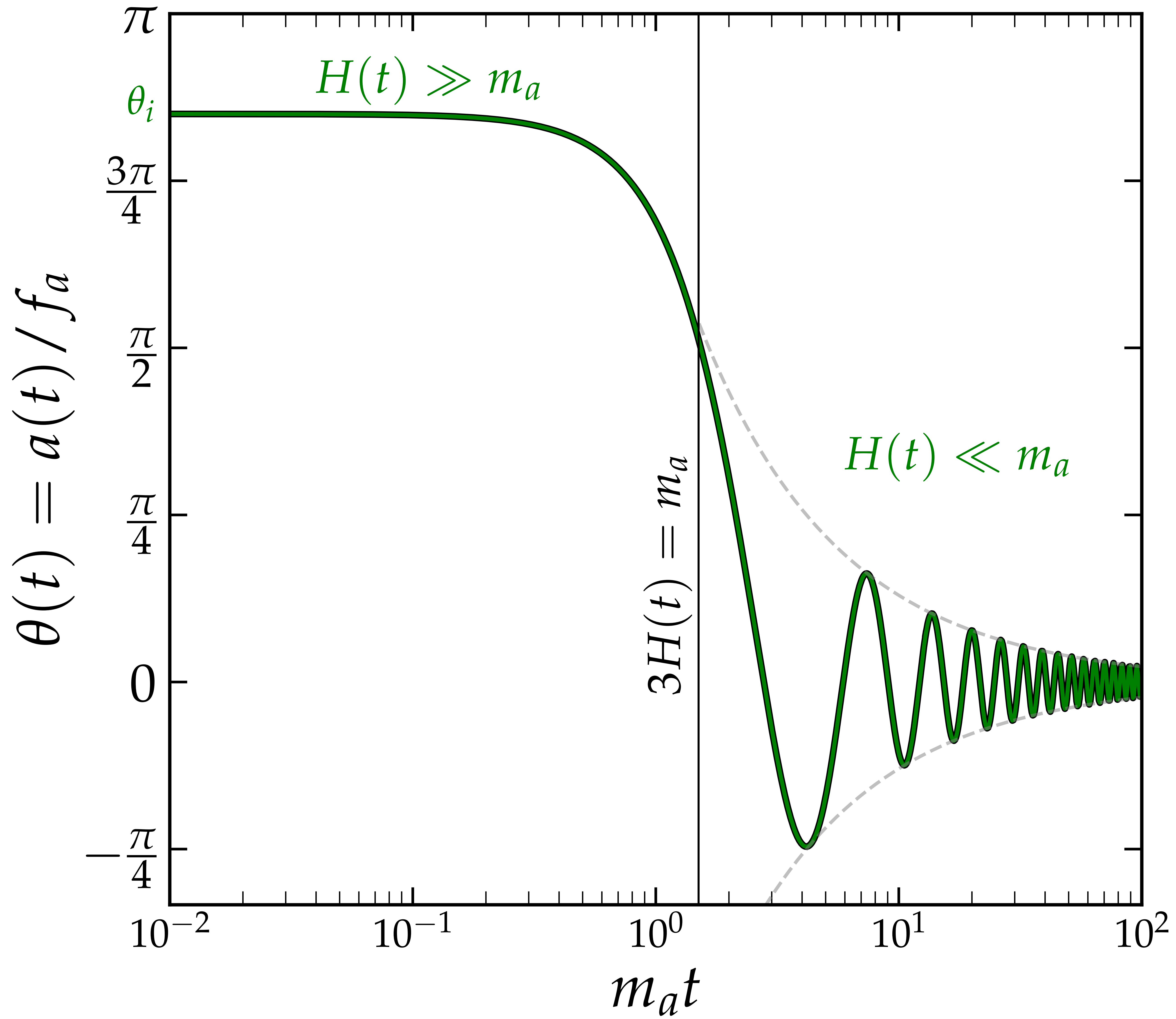
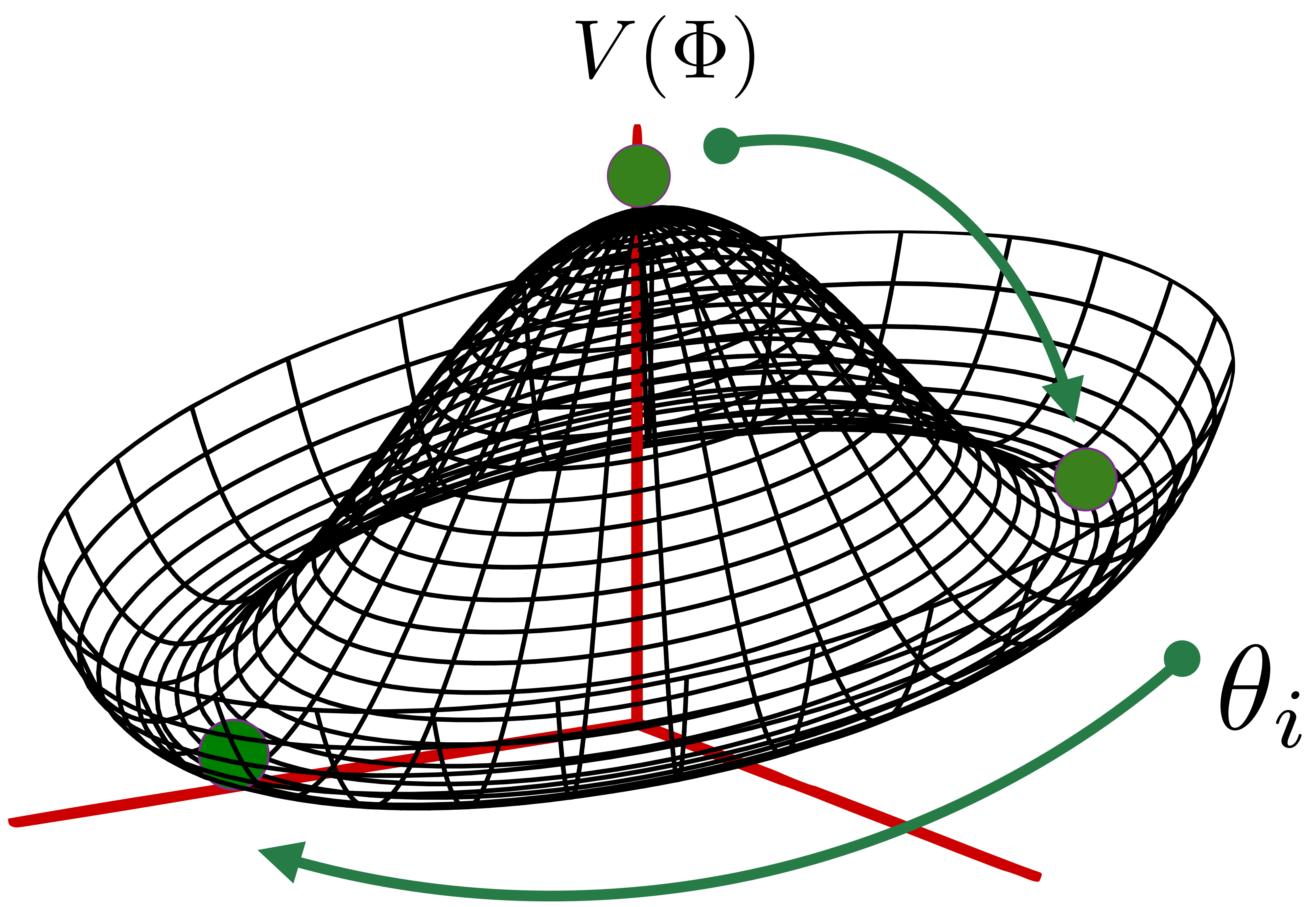


QCD topological susceptibility: The tilt comes on gradually as the temperature drops

$\Longrightarrow m_a \propto T^{-n/2}$



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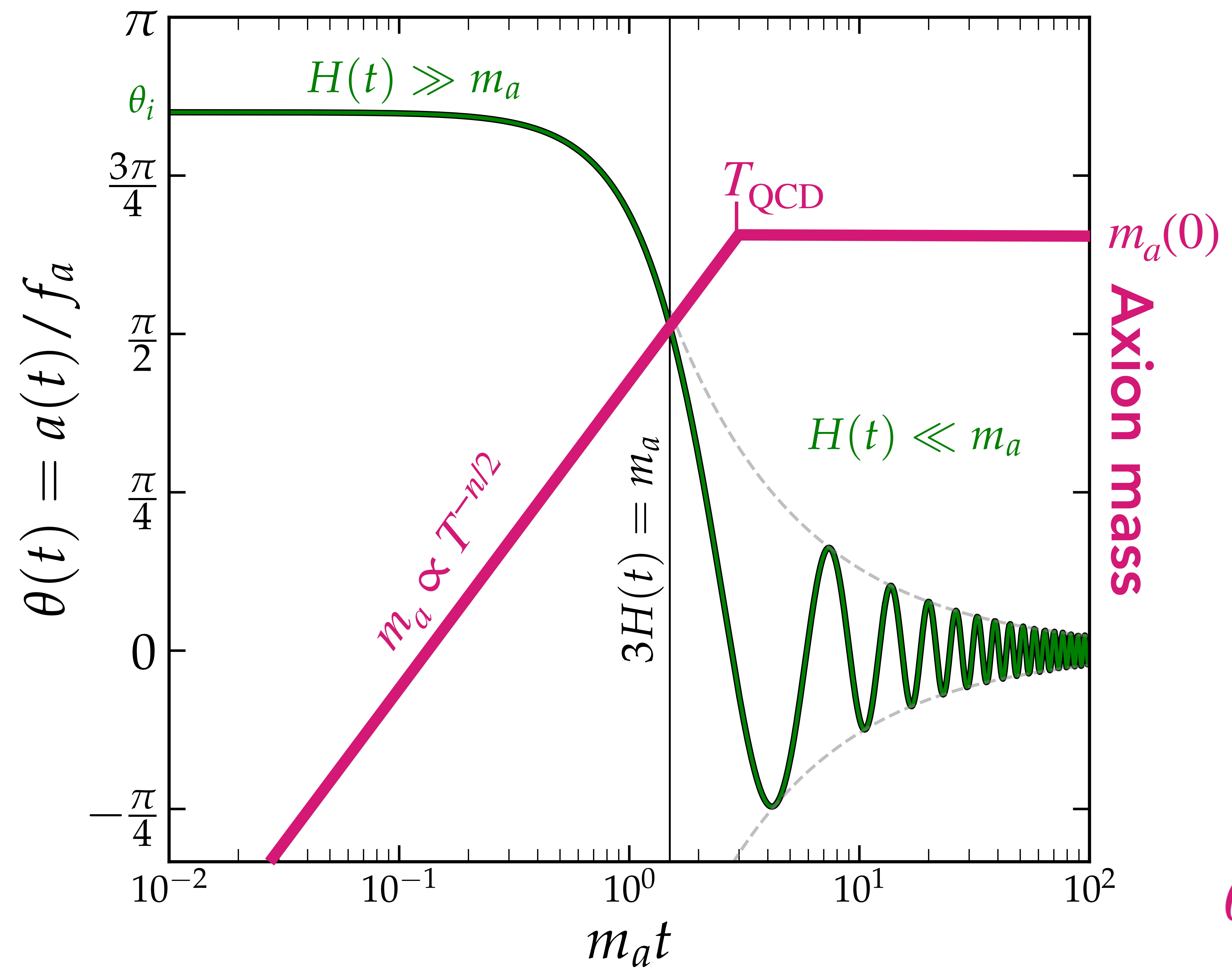

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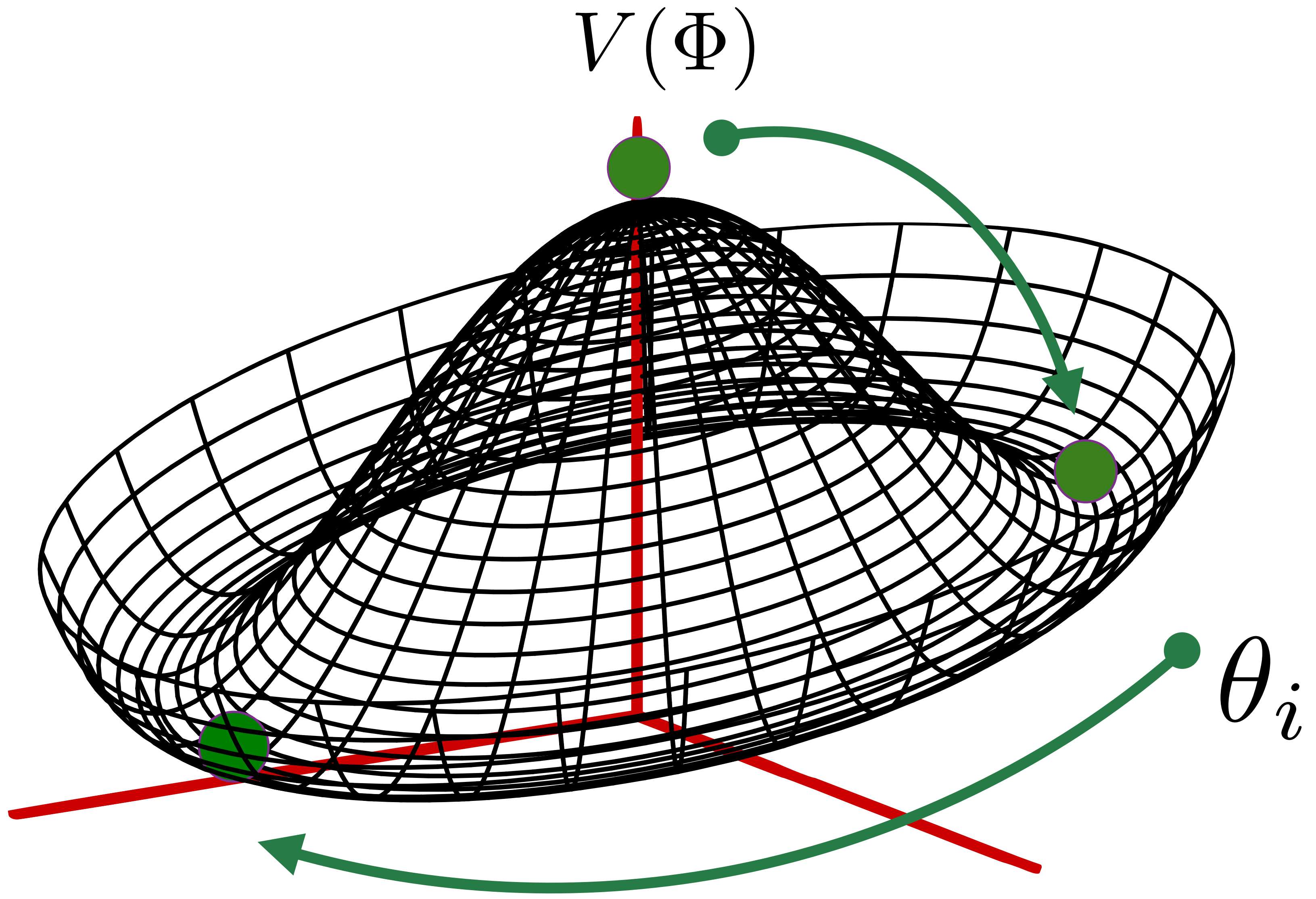


$$\ddot{\theta} + 3H\dot{\theta} + m_a^2\theta = 0$$

$$\downarrow$$

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

QCD axion abundance

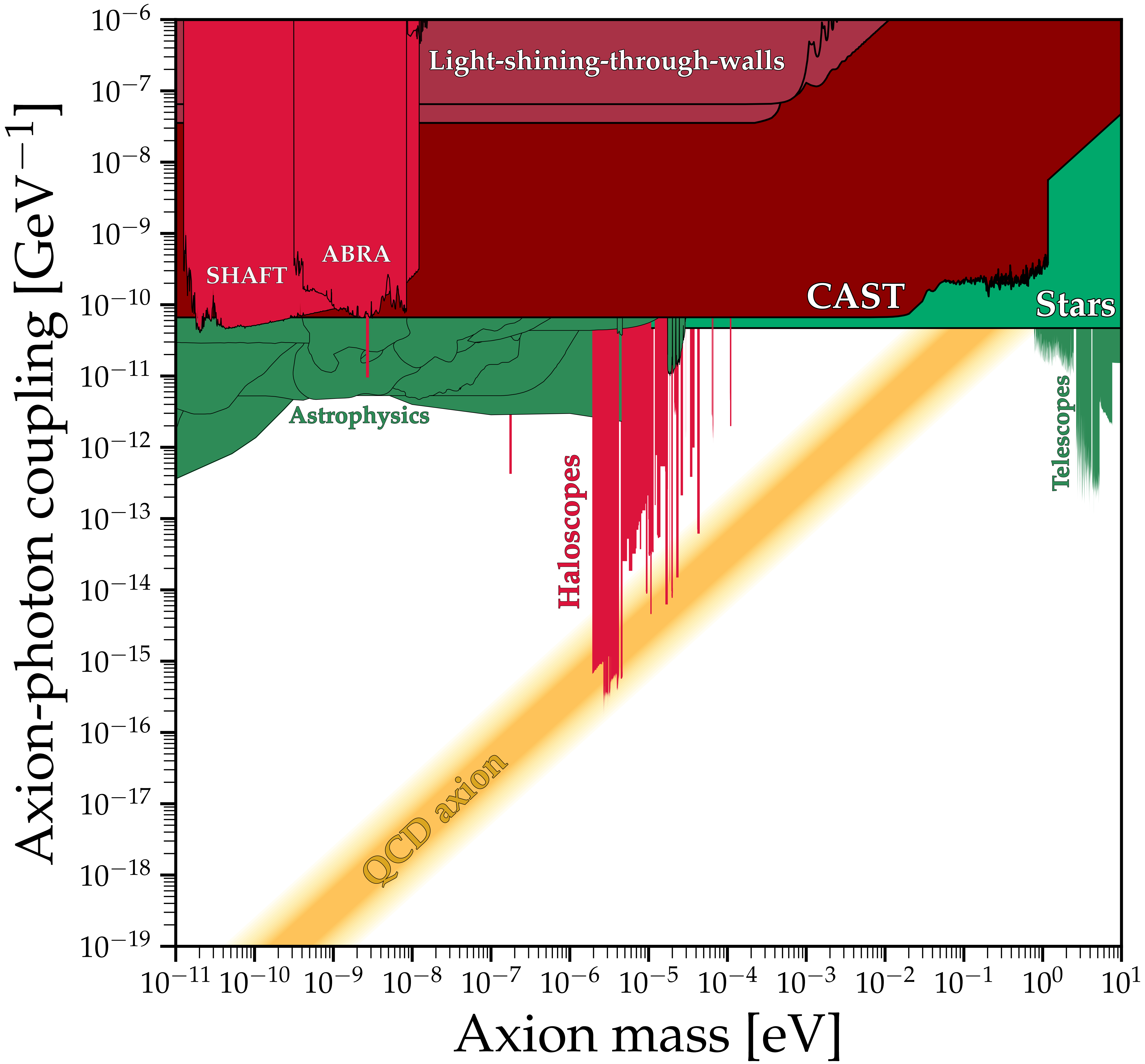
- Generic scalar misalignment:

$$\Omega_\phi h^2 \propto \phi_i^2 m^{1/2}$$

- For QCD axion we get:

$$\Omega_a h^2 \approx 0.12\, \theta_i^2 \left(\frac{7.26\, \mu\text{eV}}{m_a} \right)^{\frac{n+6}{n+4}}$$

where $n \sim 8$ (from Lattice QCD, e.g. 1606.07494)



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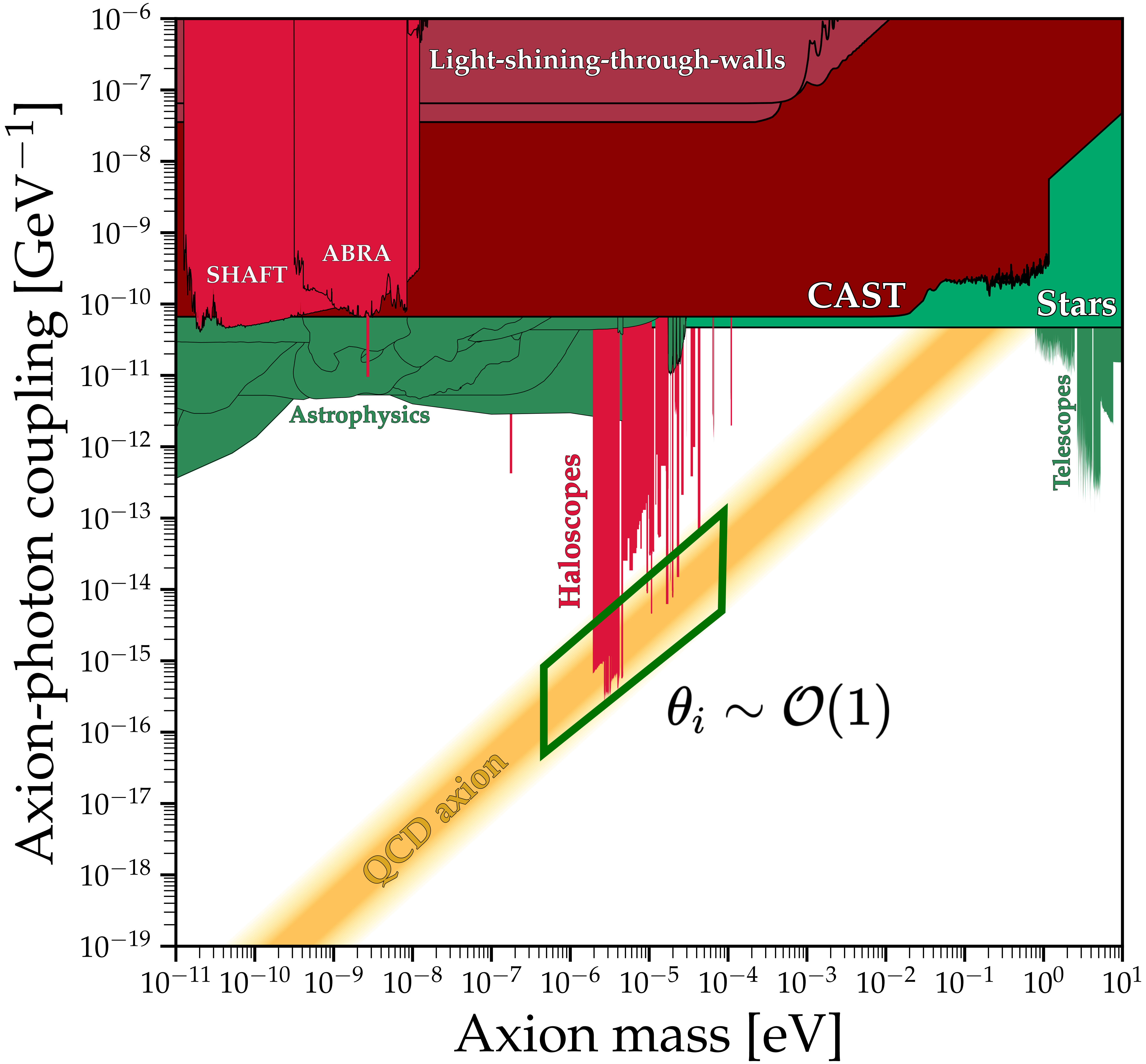
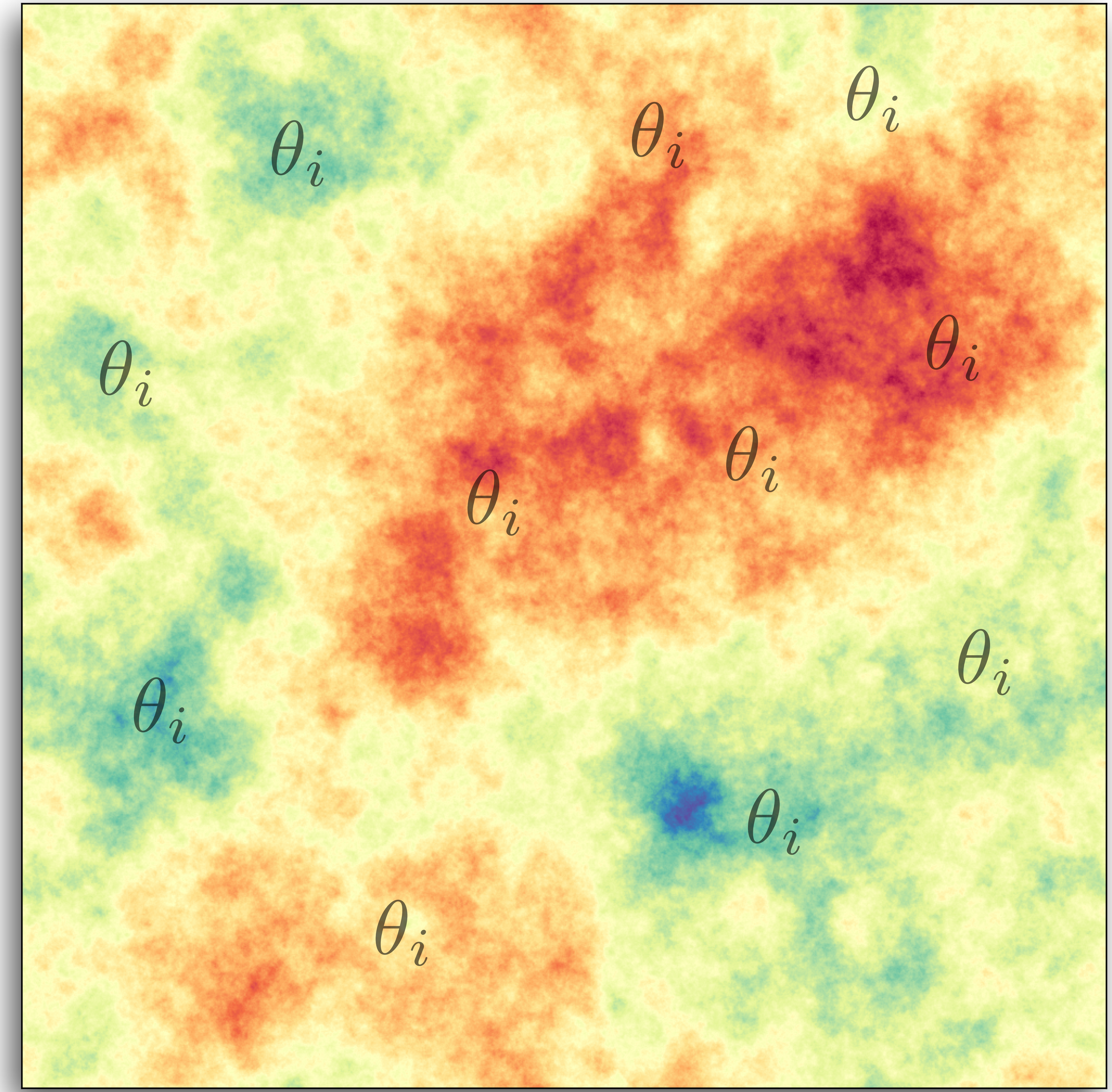
- Leads to "classic QCD axion window": $\mathcal{O}$(1—10) μeV

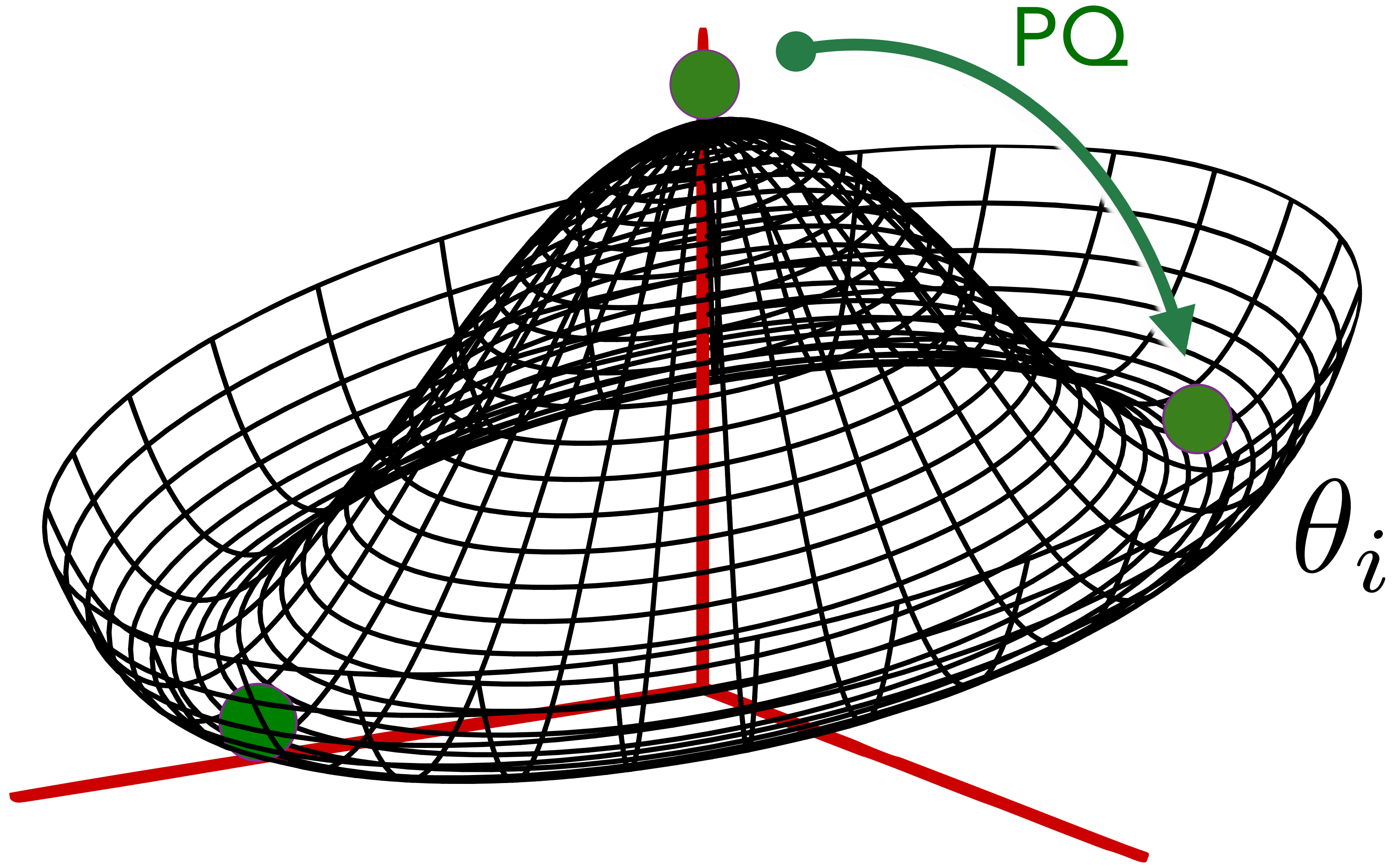
→ **but what should we pick for θ_i ?**





The issue is that $T_{\rm PQ} \gg T_{\rm QCD}$

The Universe should be filled with random θ_i everywhere since the axion was massless when it was born at PQ phase transition, i.e. it didn't know about the preferred angle



When did inflation happen?

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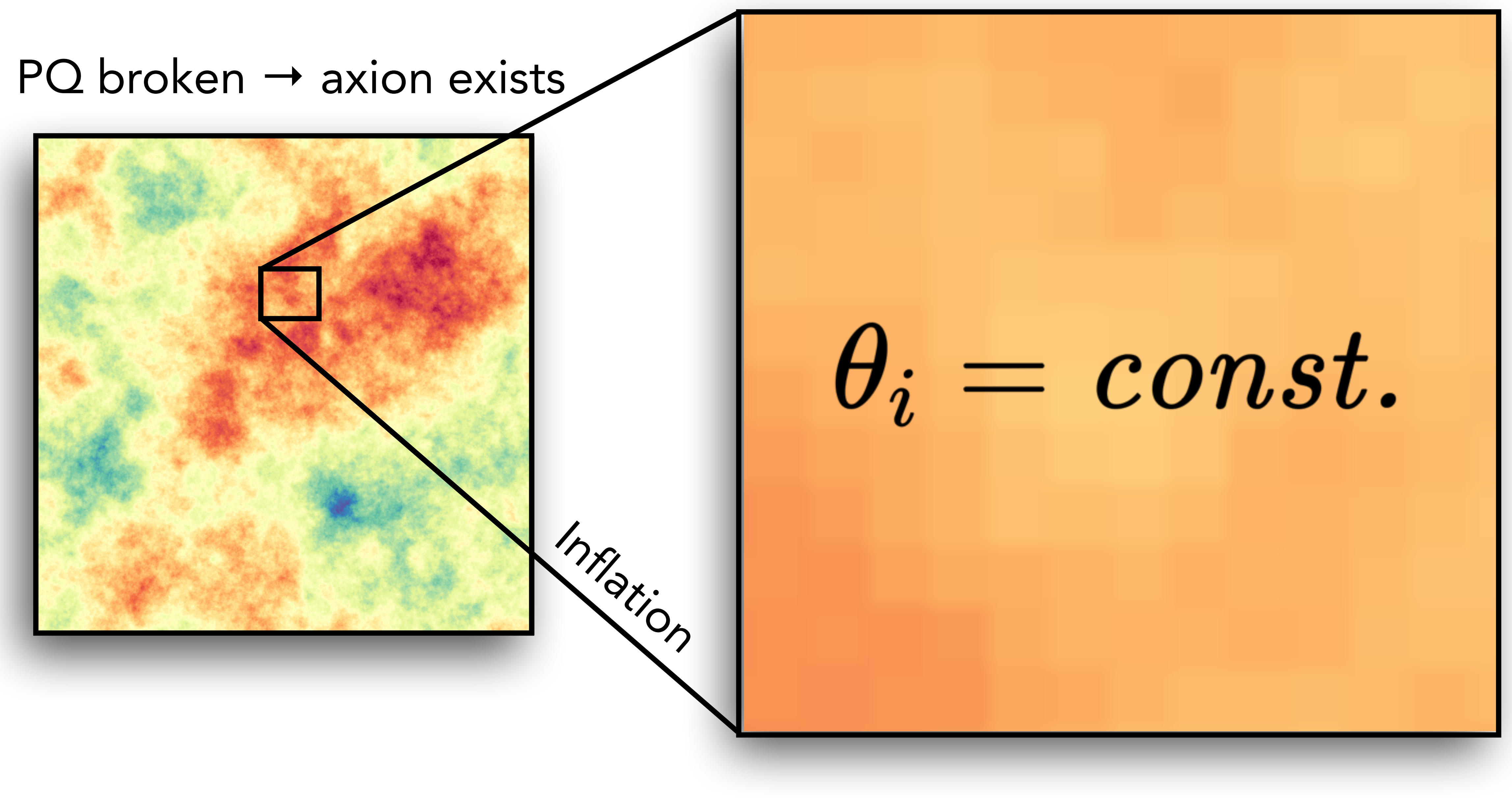
Option 1:

PQ is broken *before and during* inflation



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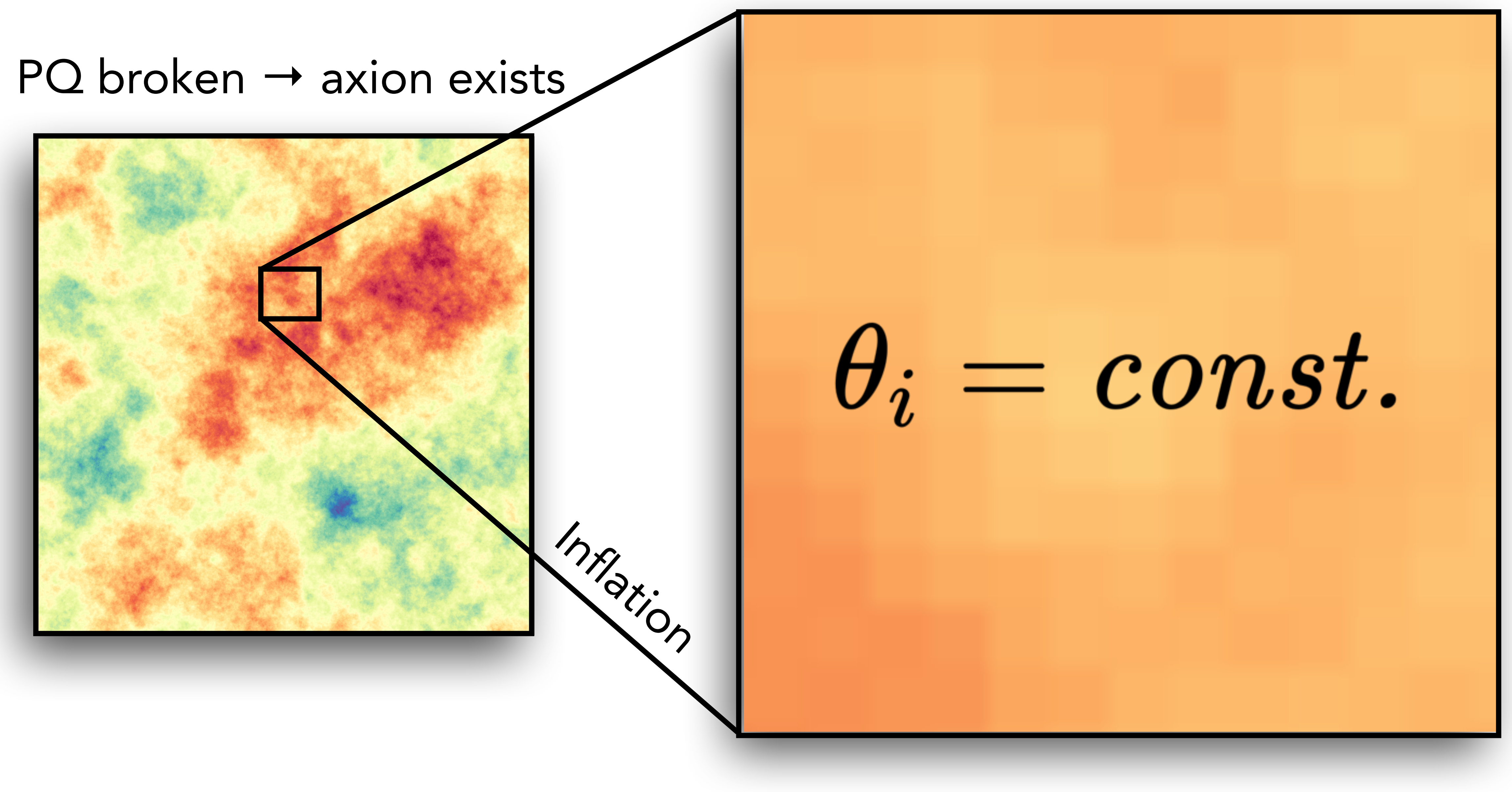
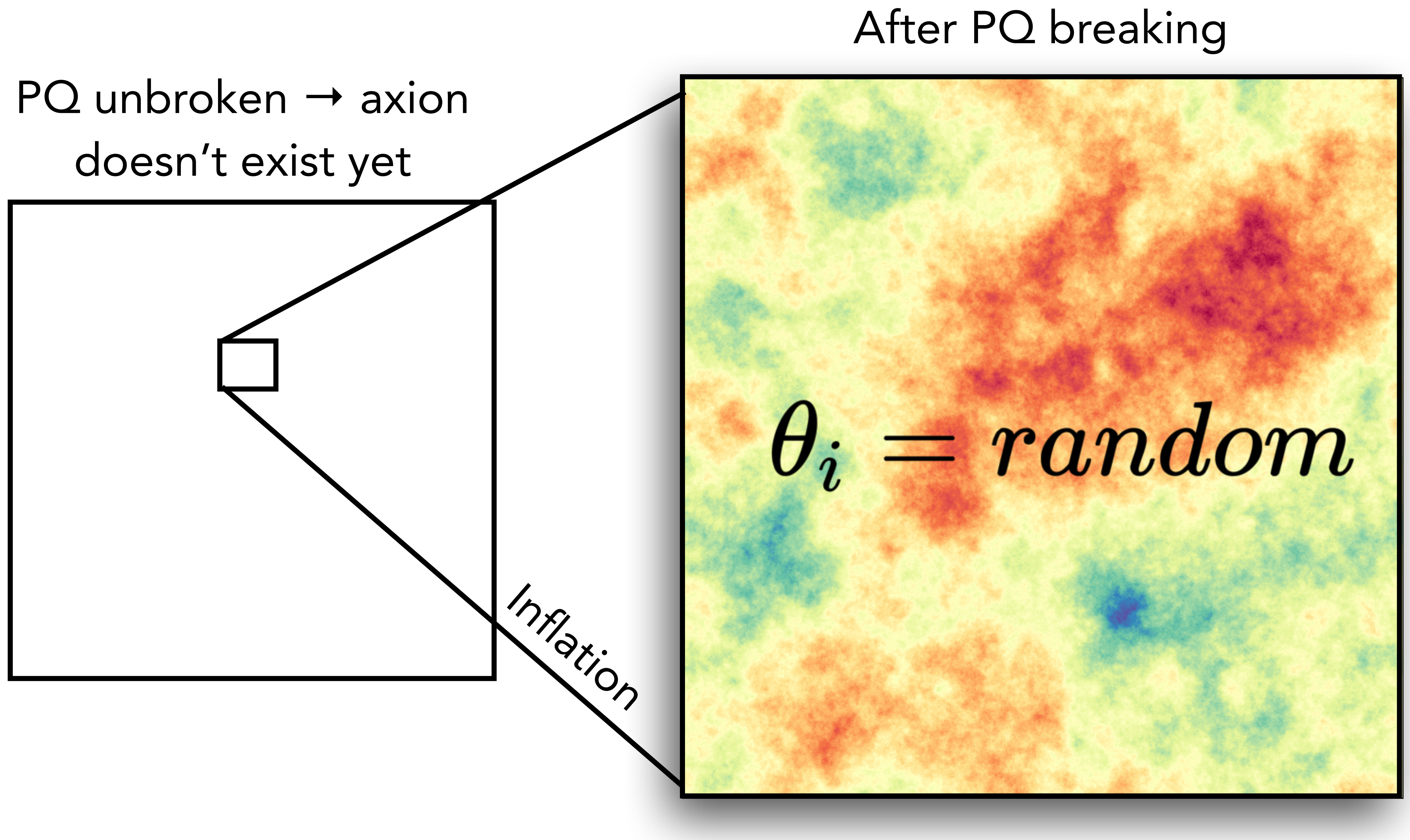


Option 2:

PQ is broken *after* inflation



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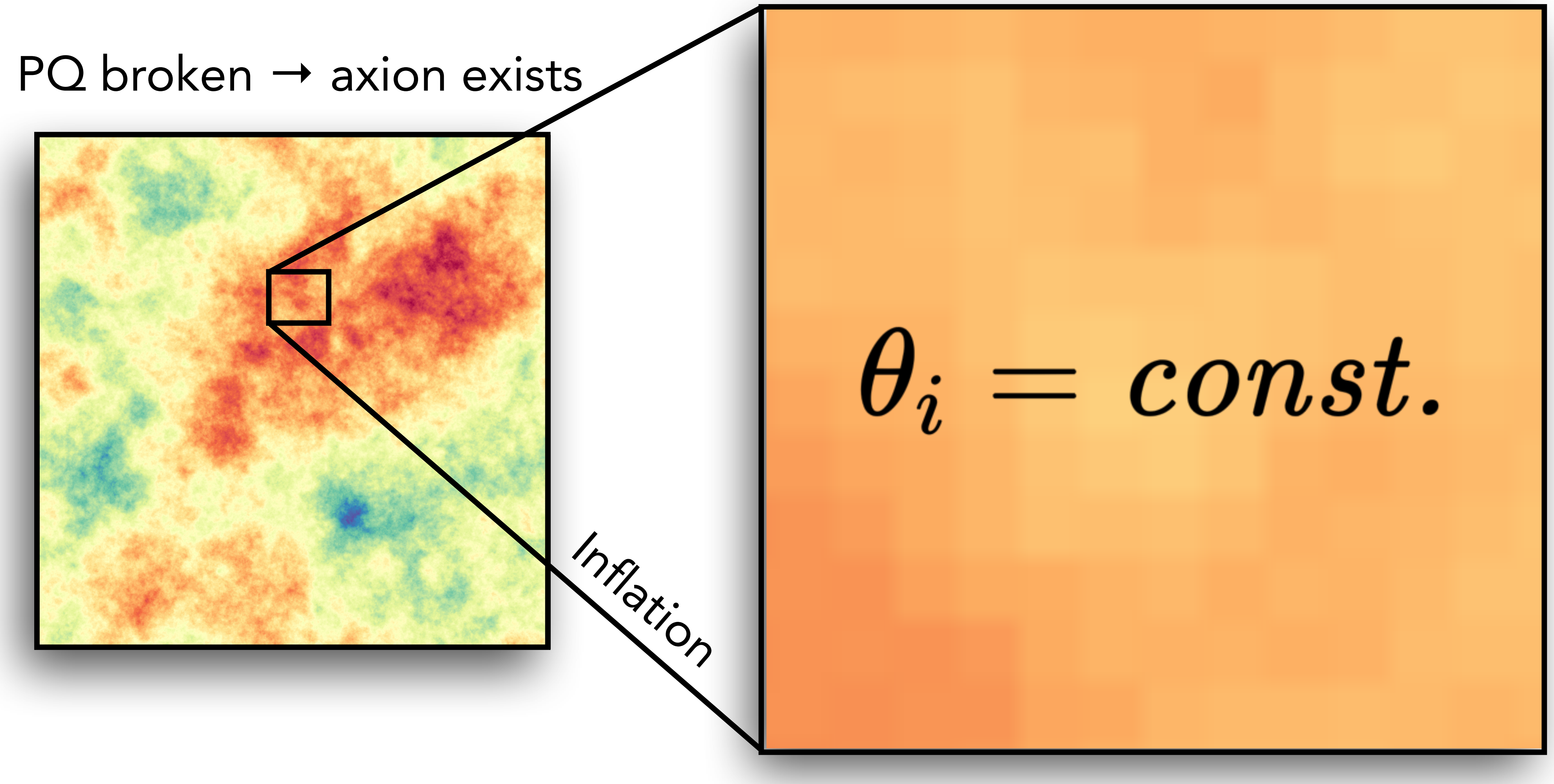

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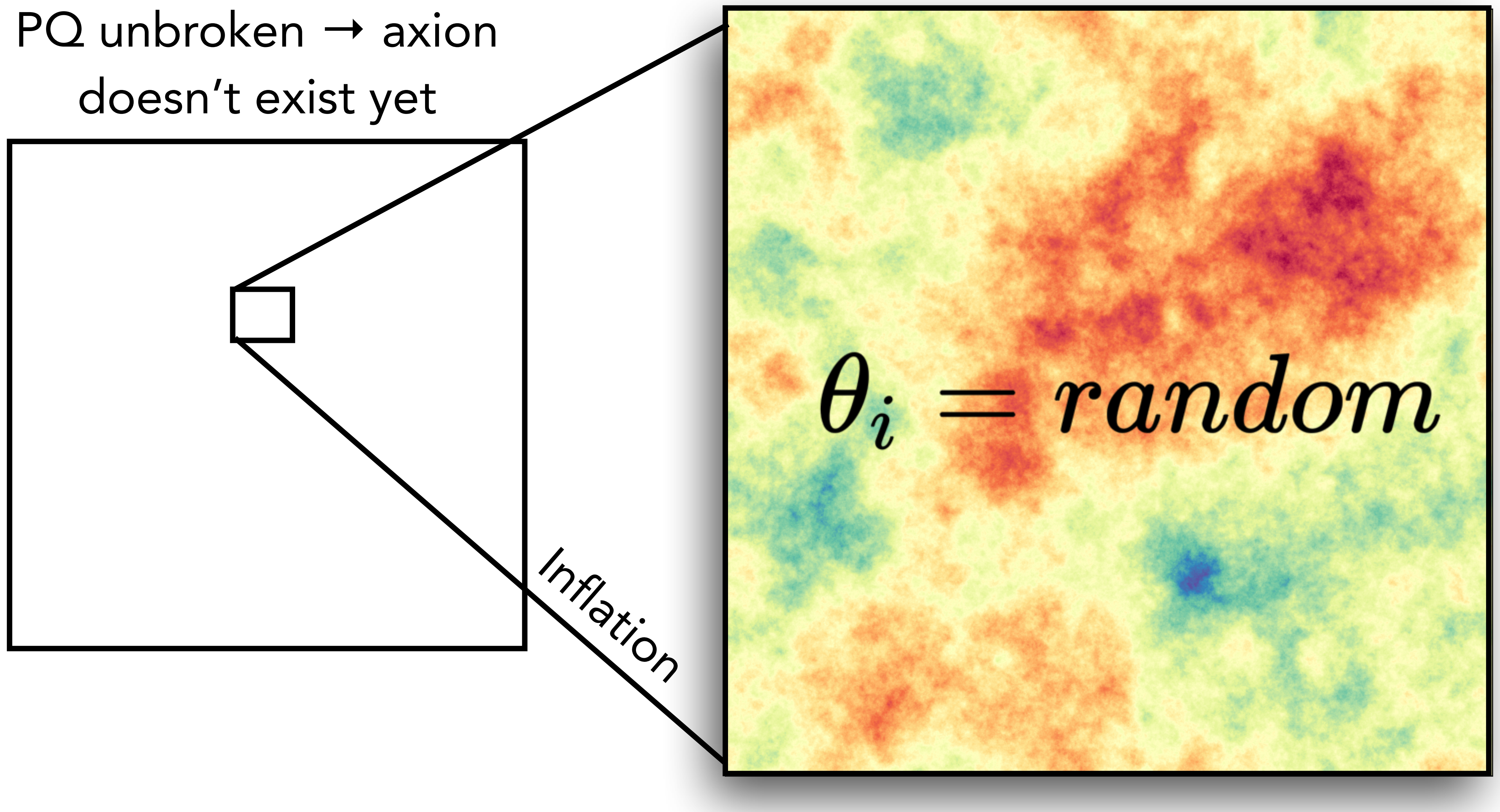

Pre-inflationary scenario

Post-inflationary scenario

When did inflation happen?

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Pre-inflationary scenario

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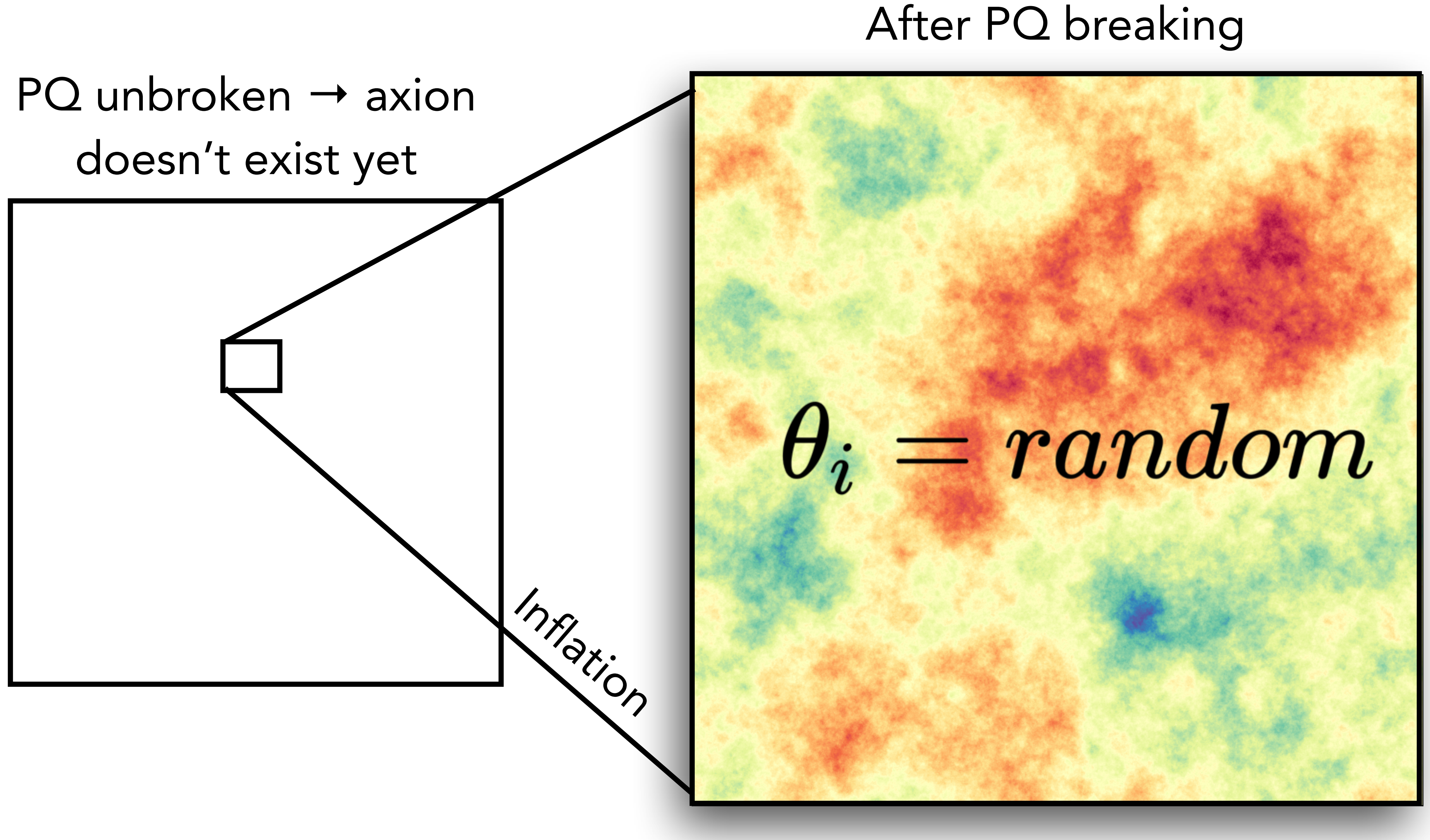

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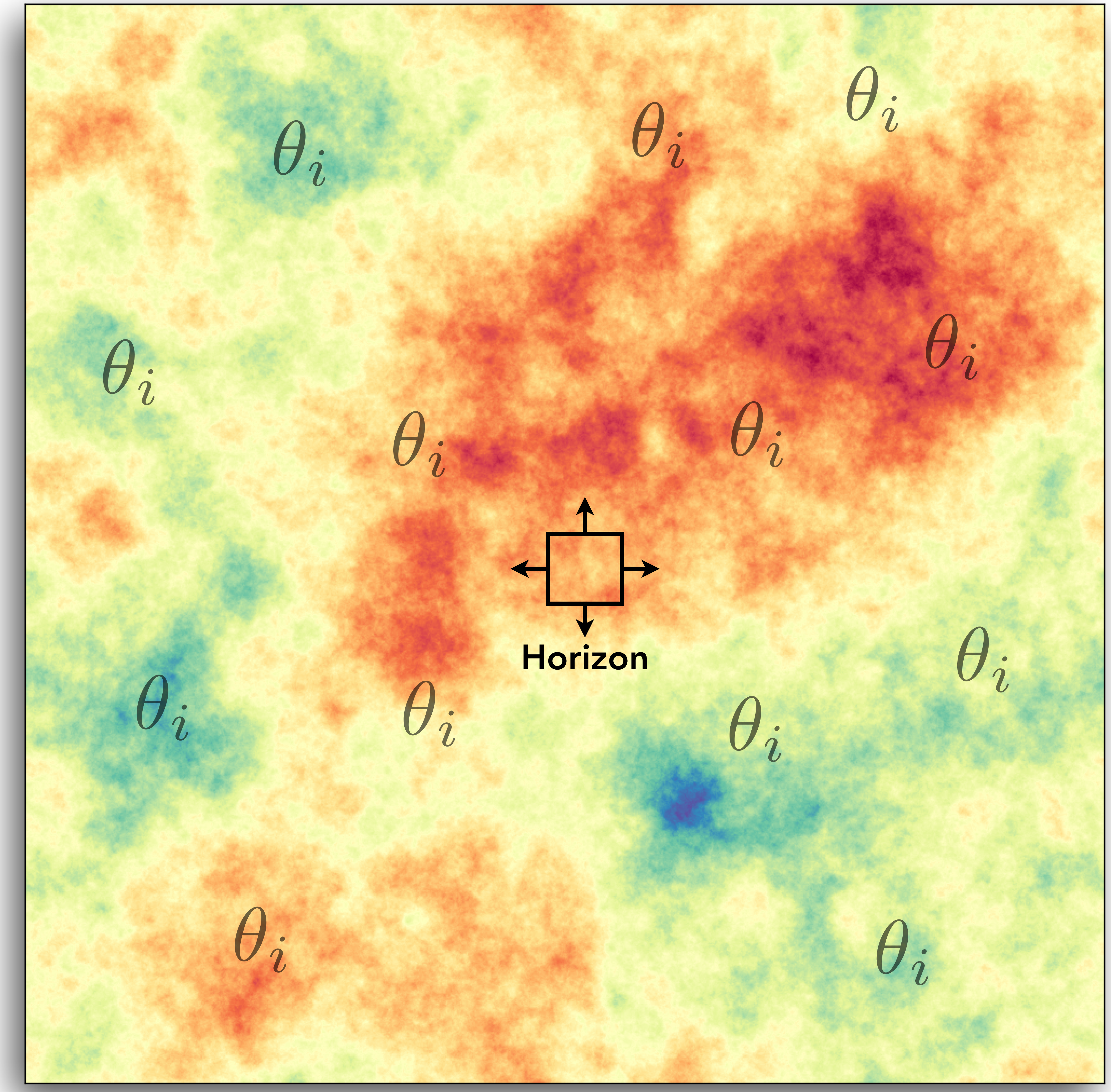
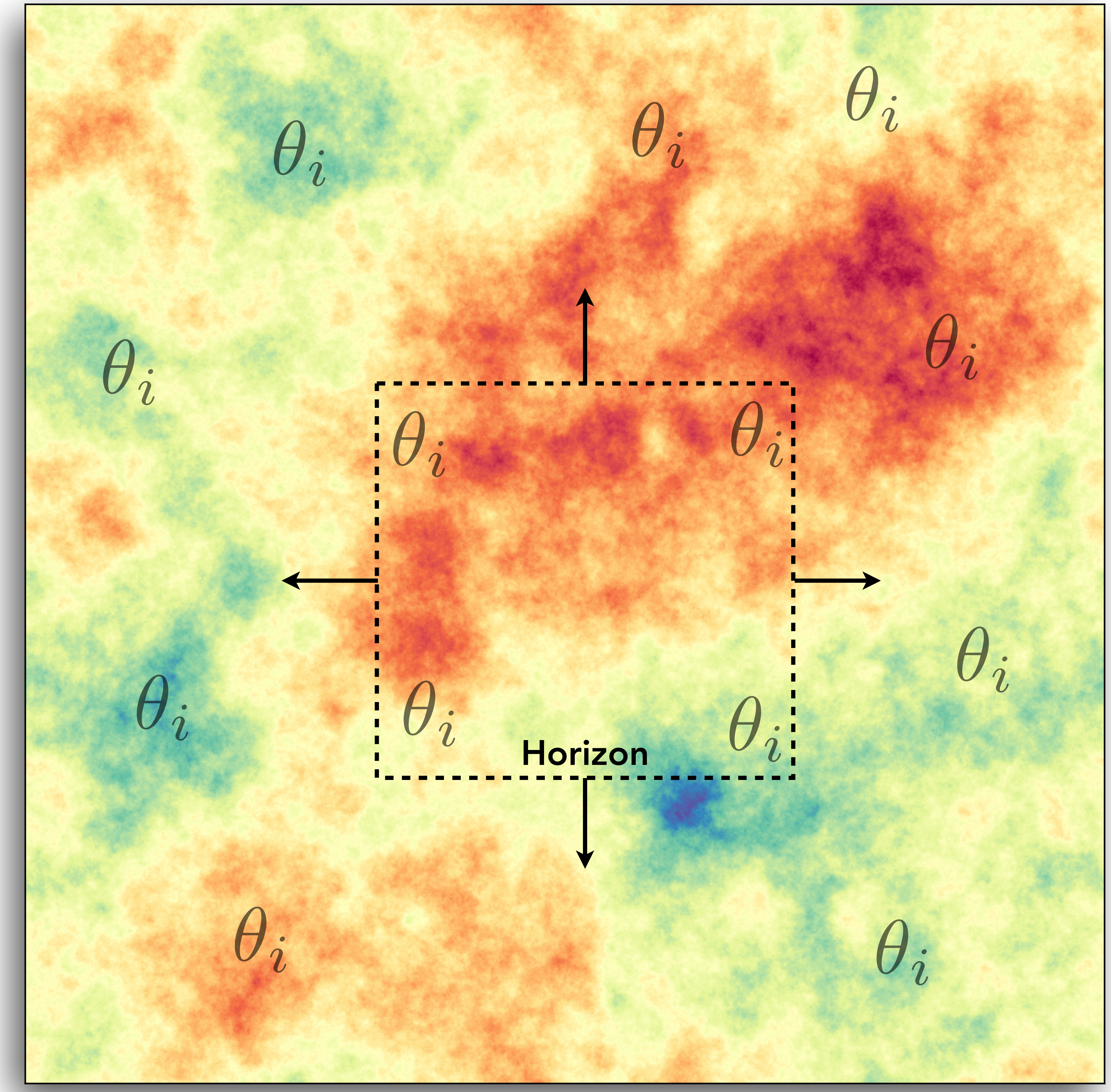


Inflation has already happened *before* axion was born

→ Universe filled with many values of θ_i

→ Different value in every causal patch

Post-inflationary scenario



Inflation has already happened *before* axion was born

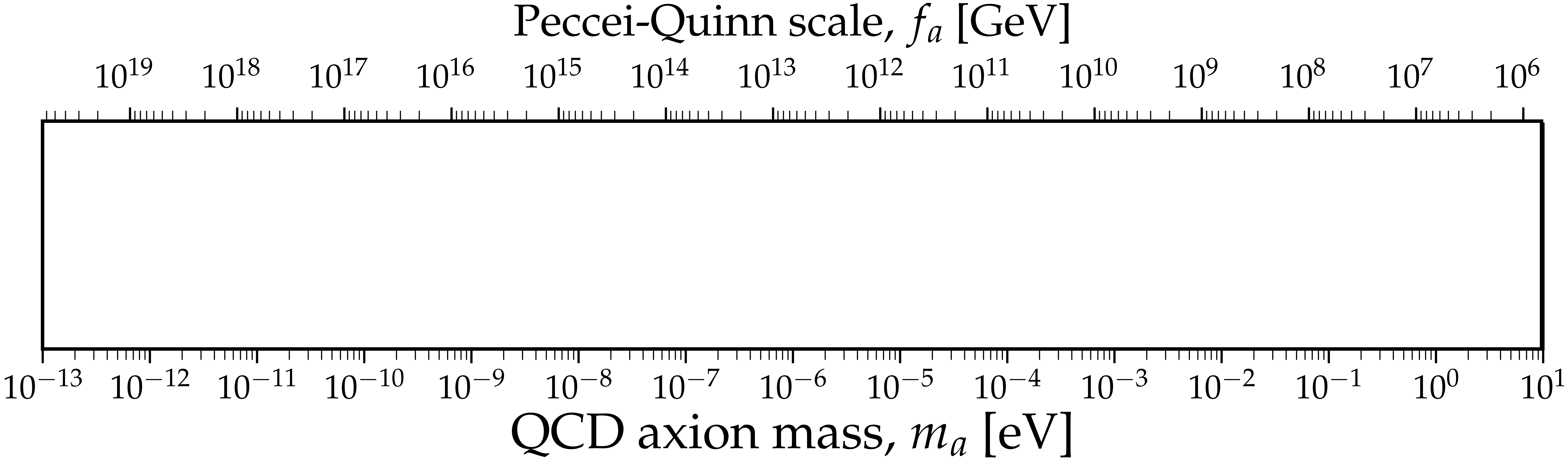
→ Universe filled with many values of θ_i
→ Different value in every causal patch
→ Patches come into contact as horizon grows.

Post-inflationary scenario

- We have an ensemble of every possible θ_i sampled across our Universe.
- Stochastic average:

$$\langle \theta_i^2 \rangle \approx \left(\frac{\pi}{\sqrt{3}} \right)^2 \approx (1.81)^2$$

$$\Omega_a h^2 \approx 0.12 \frac{\langle \theta_i^2 \rangle}{(1.81)^2} \left(\frac{20\mu\text{eV}}{m_a} \right)^{\frac{n+6}{n+4}}$$



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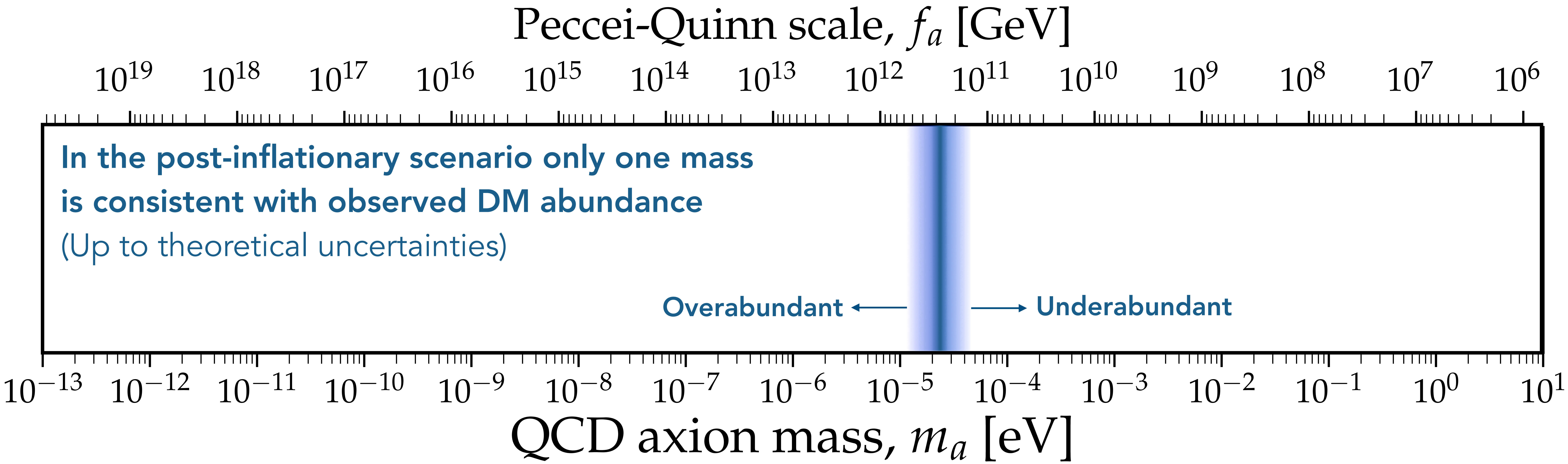
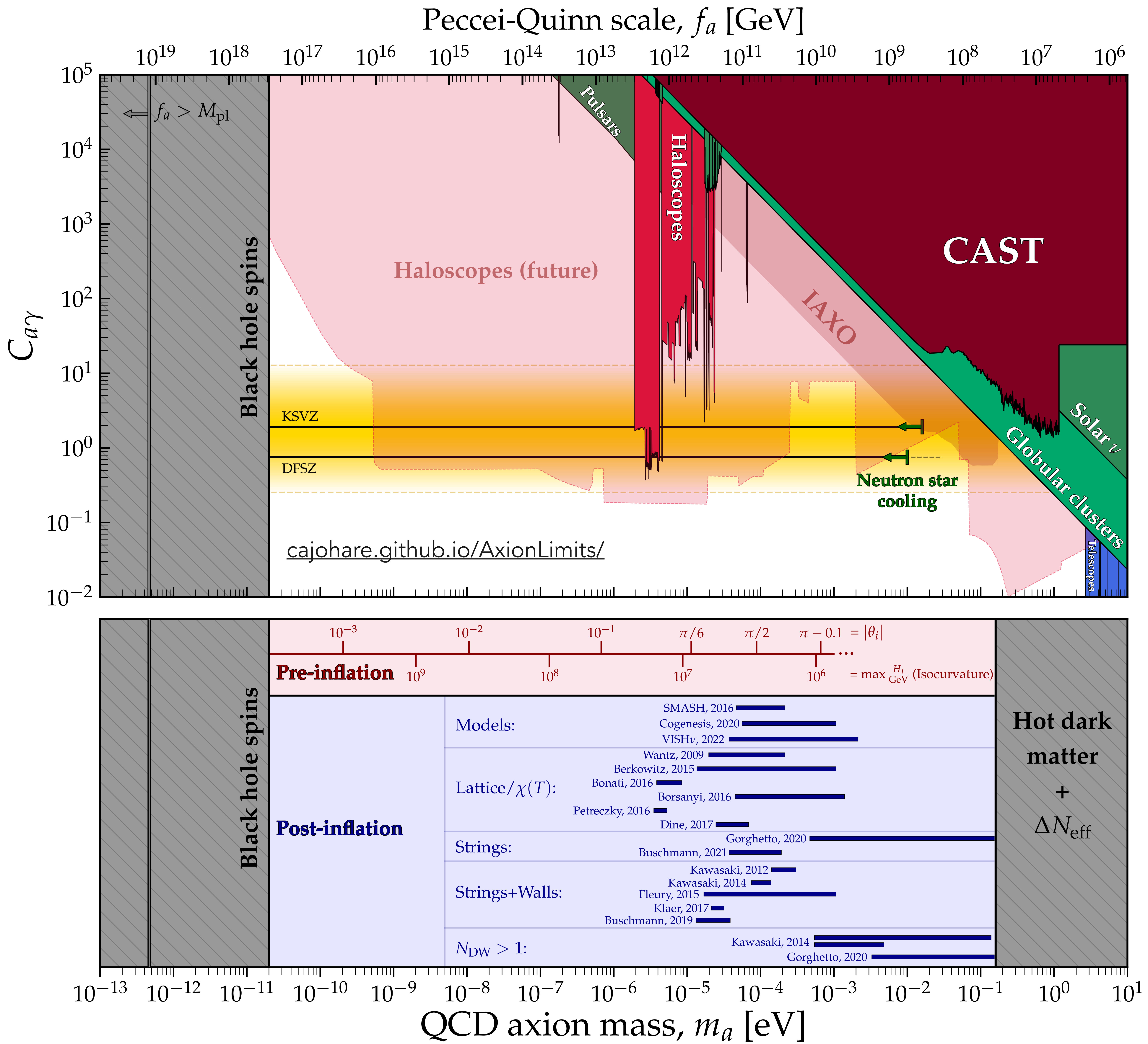




Post-inflationary axion mass range

$\mathcal{O}(10 - 100\,\mu\text{eV})$

Relevant for experiments like:

→QUAX

→ MADMAX

→ ORGAN

→ ALPHA

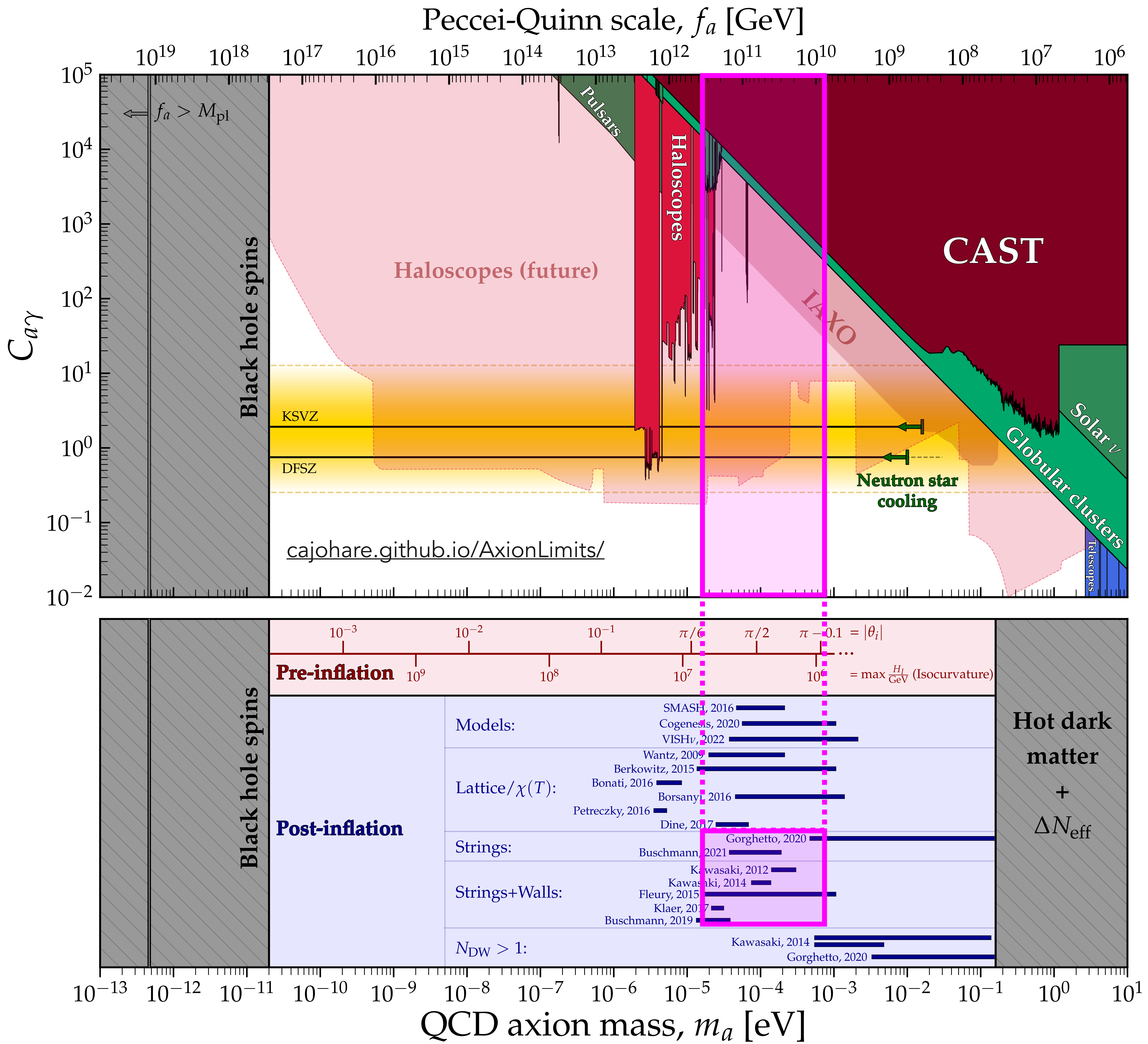
→ DALI

→ CADEx

→ BRASS

→ BREAD

github.com/cajohare/AxionLimits



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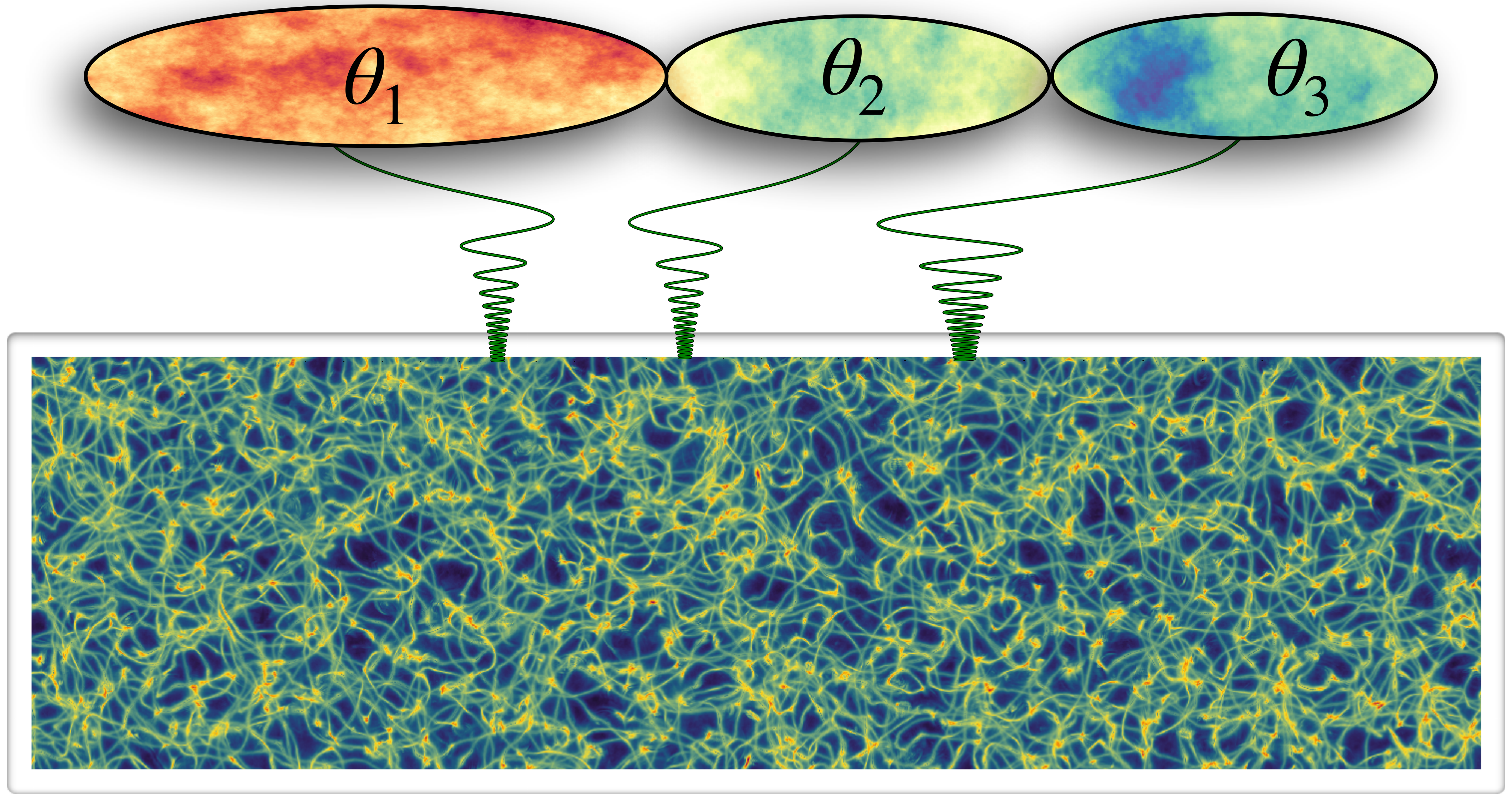
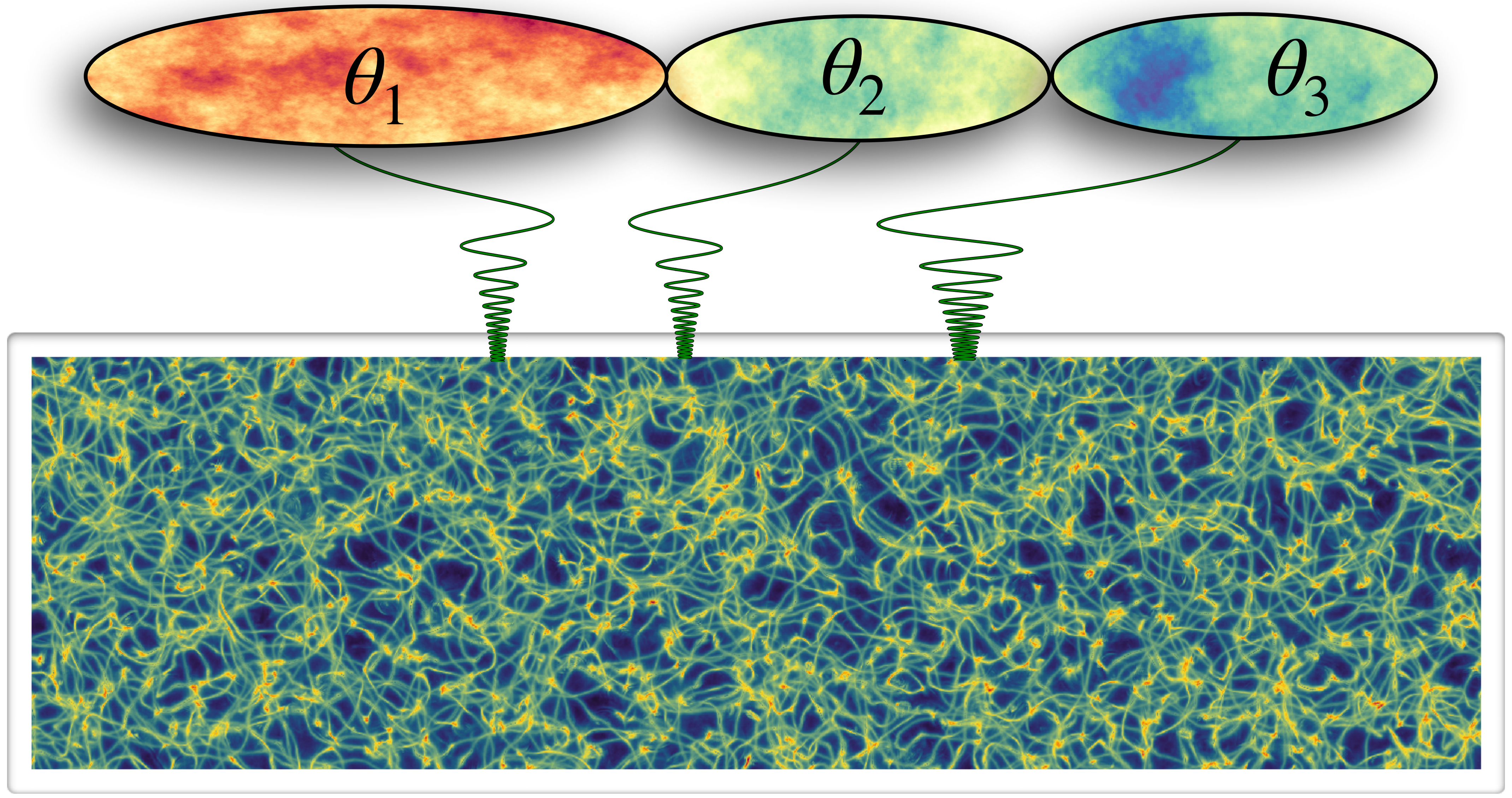
But there's a complication: $\nabla\theta$



Different patches meet up
→ Field gradients!

$$\longleftarrow \quad \ddot{\theta} + 3H\dot{\theta} - \frac{1}{a^2}\nabla^2\theta + m_a^2\theta = 0$$

But there's a complication: $\nabla\theta$



Different patches meet up

→ Field gradients!

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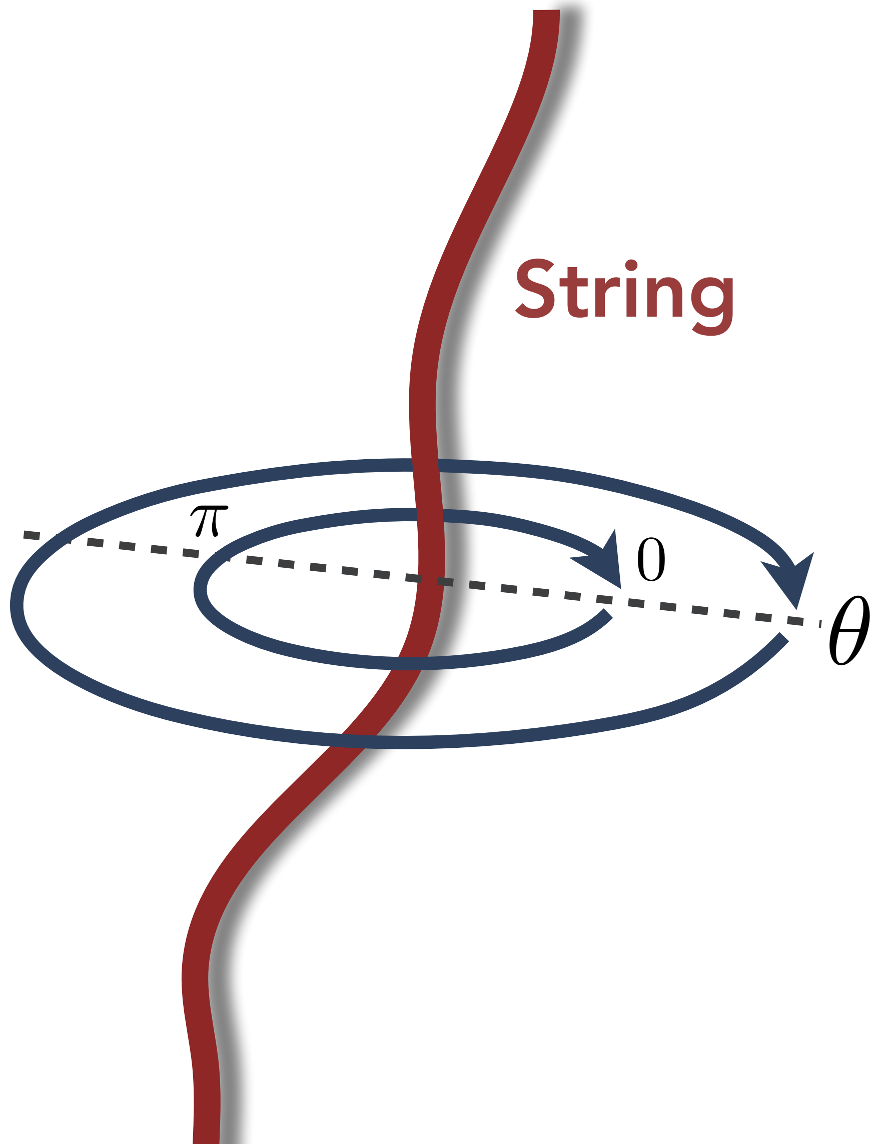
⇒ **Cosmic strings**

from axion field

winding around 2π



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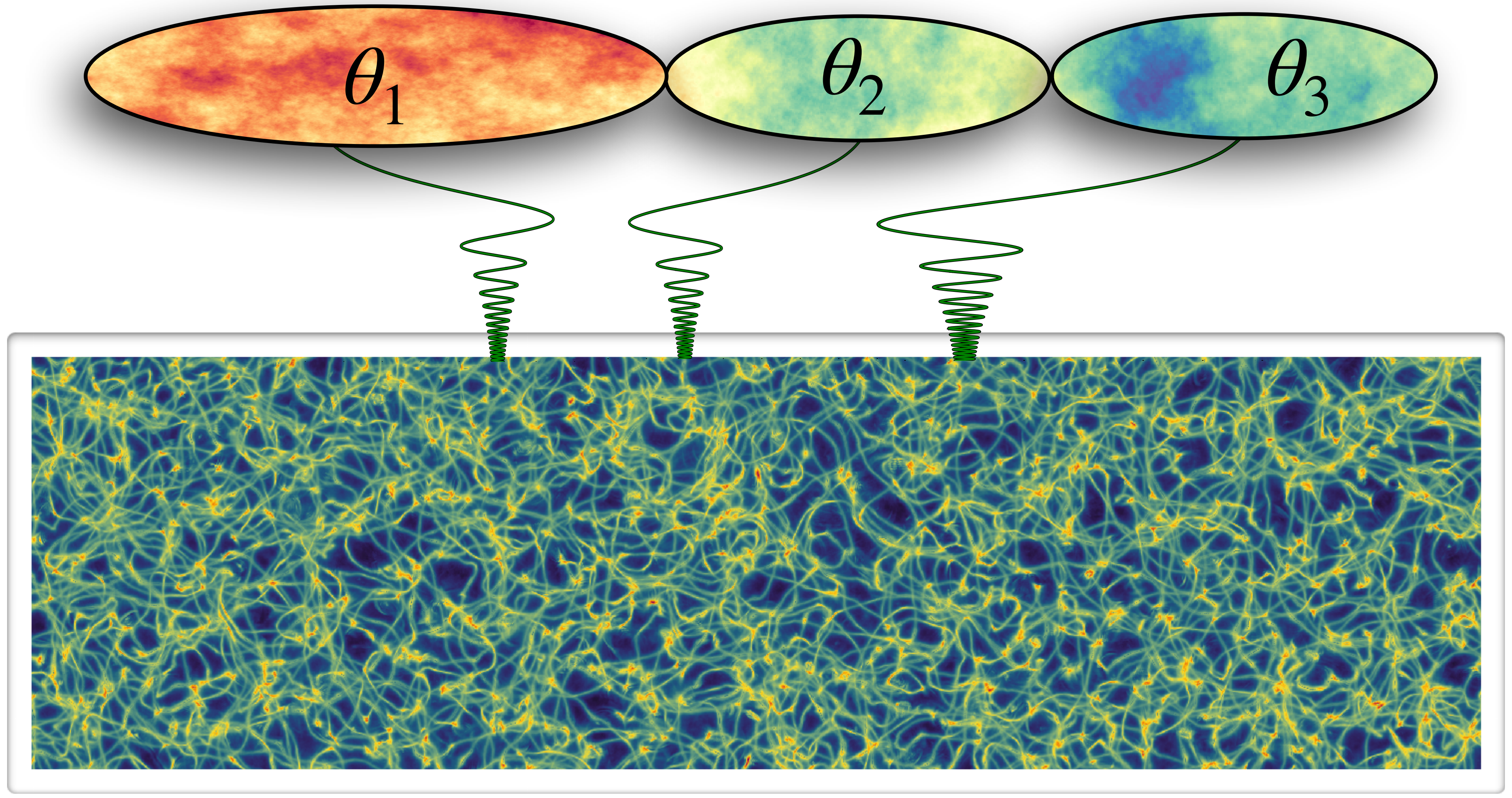

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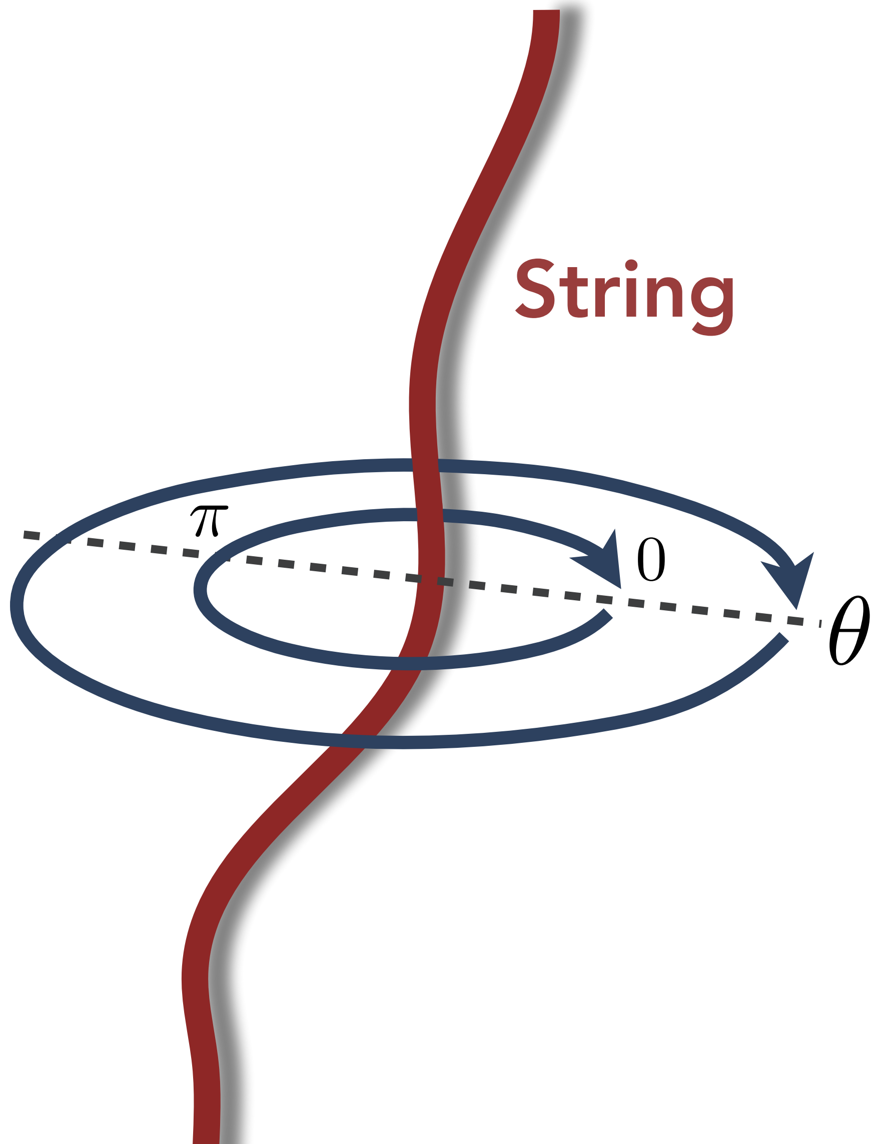
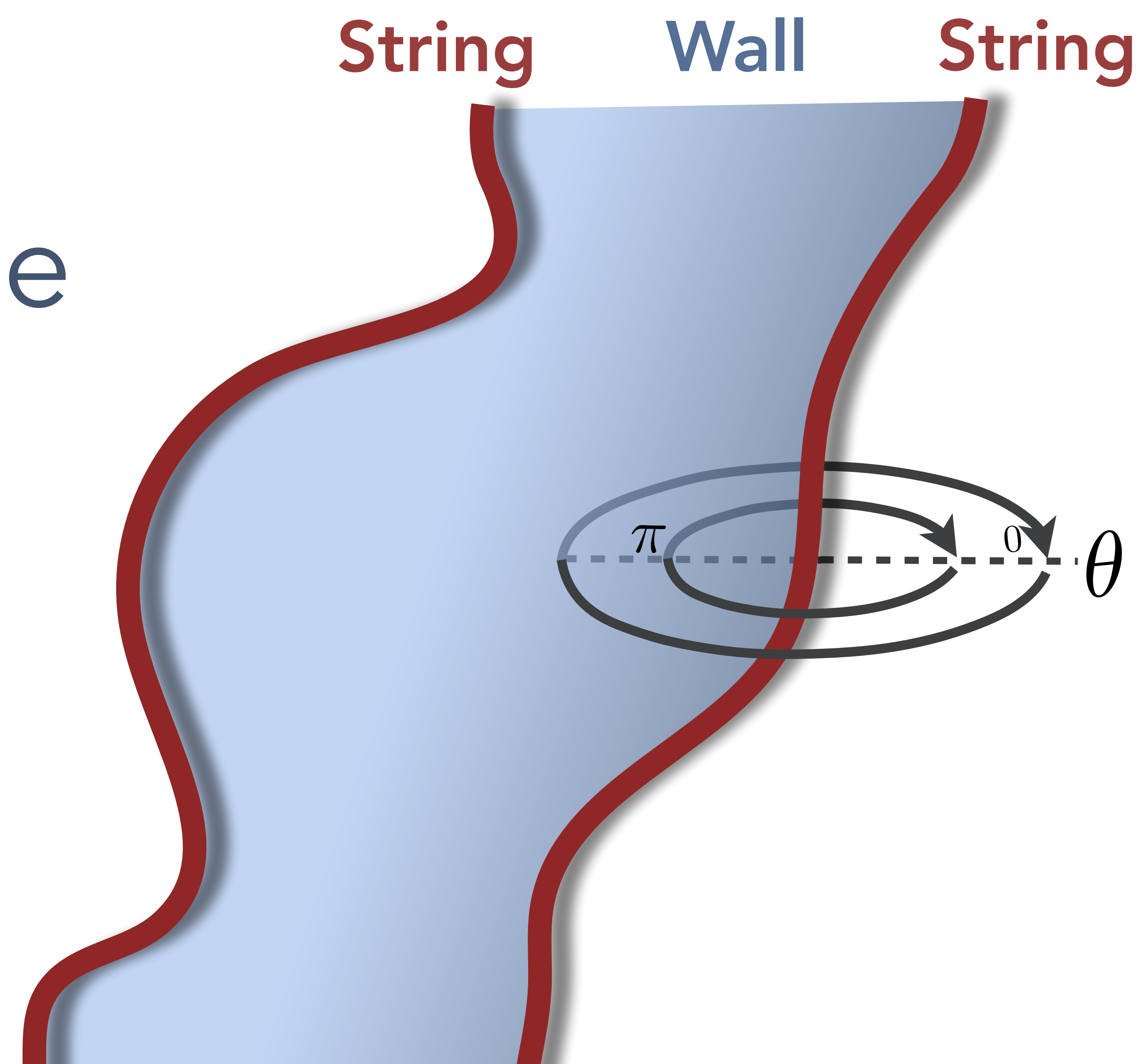
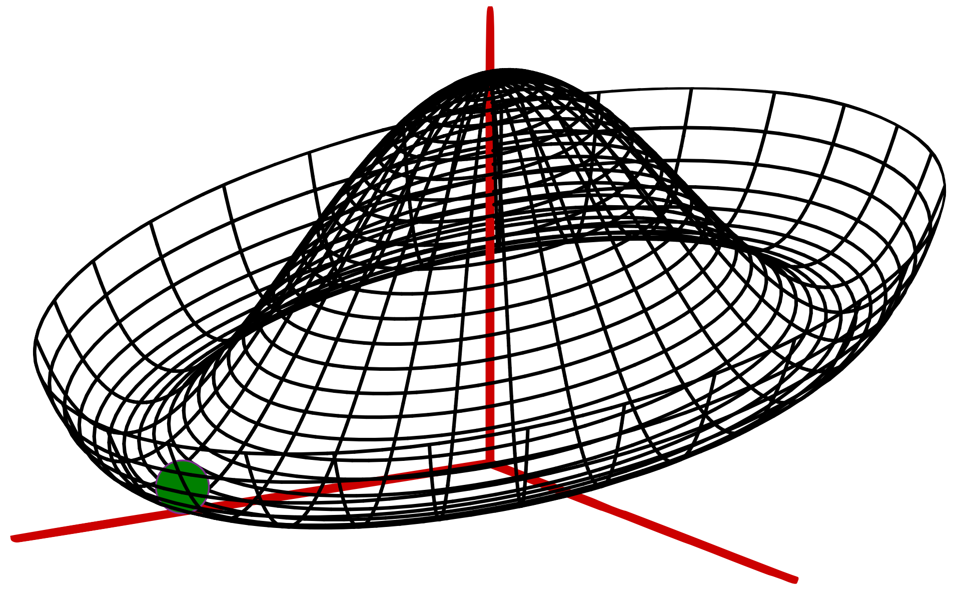


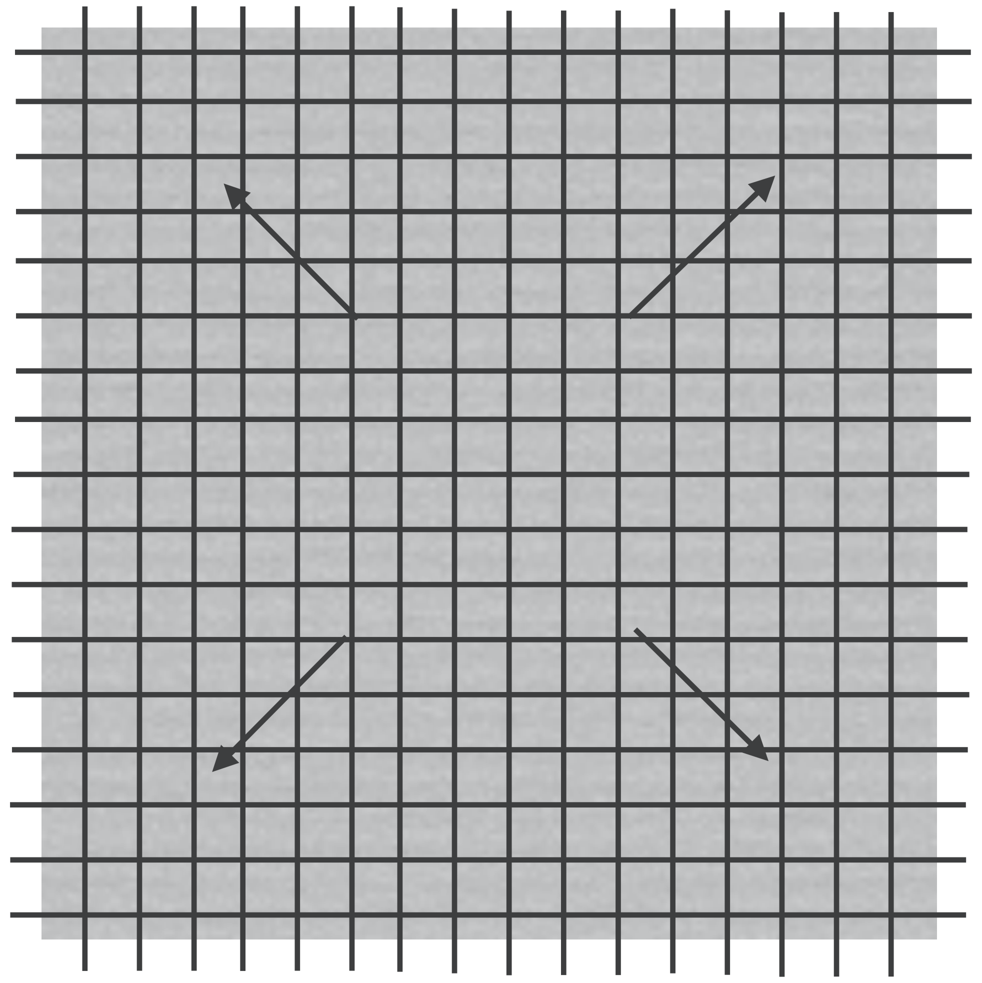
⇒ **Domain walls**

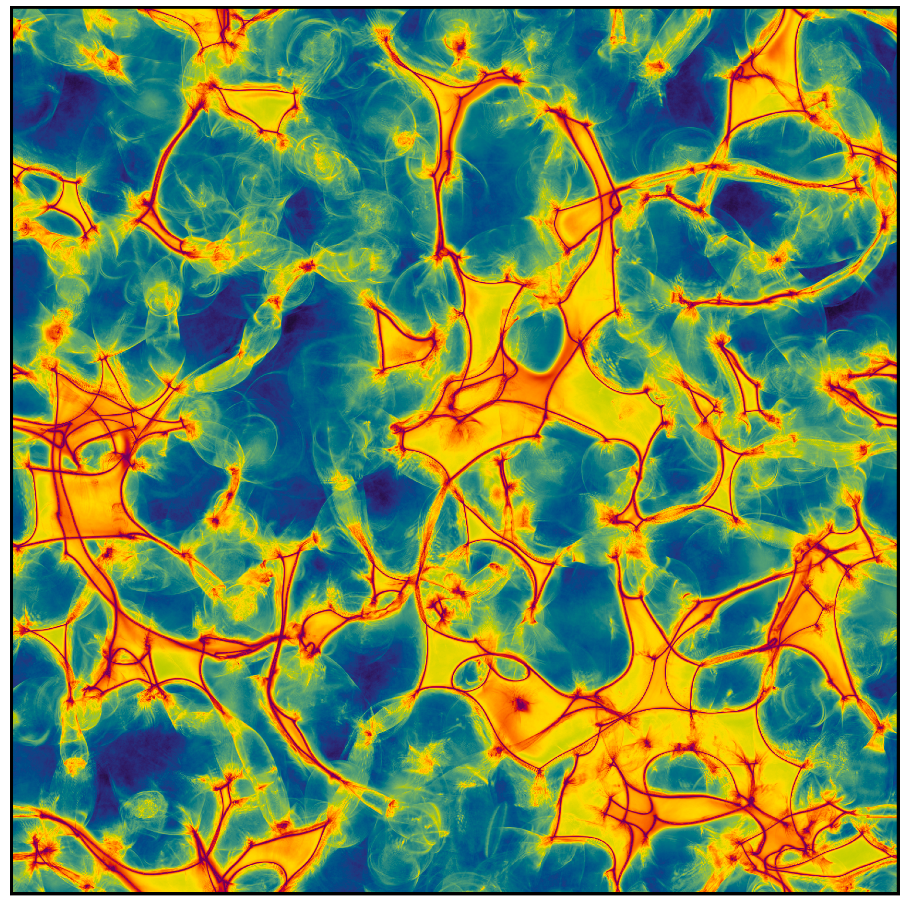
between true/false vacuum (0 and π)

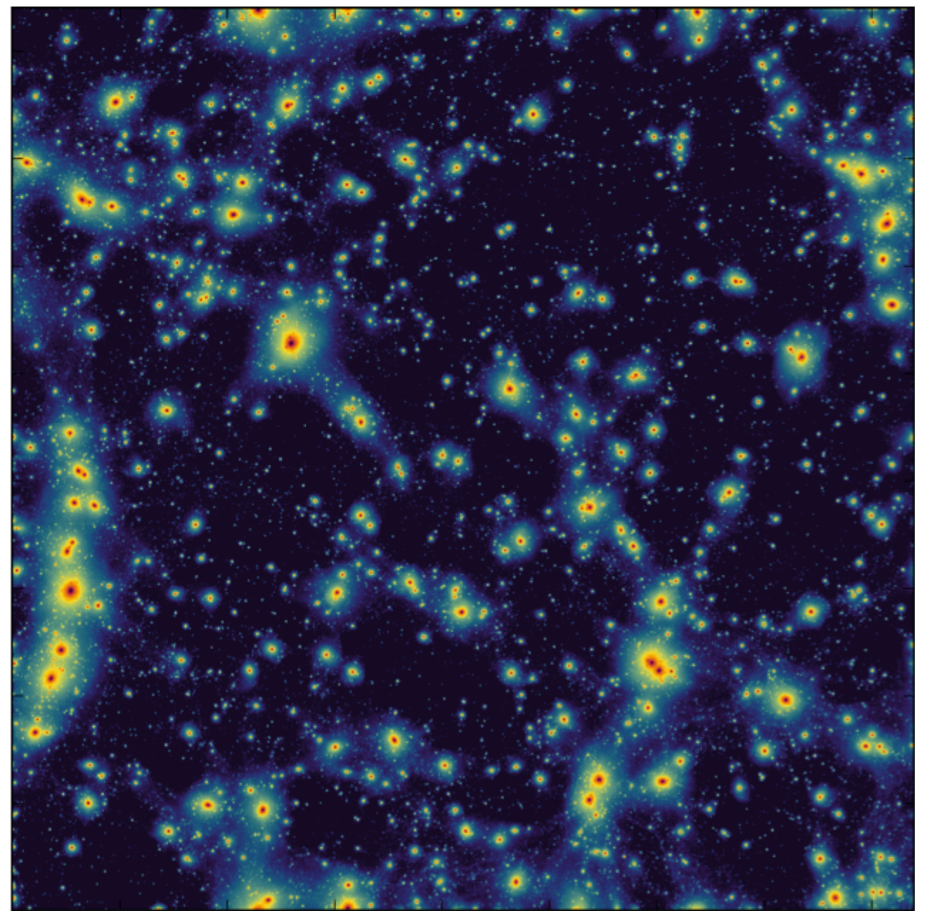


Brute force solution: simulate









Evolve the axion field…

…on an expanding lattice…

…to measure the relic abundance of axions…

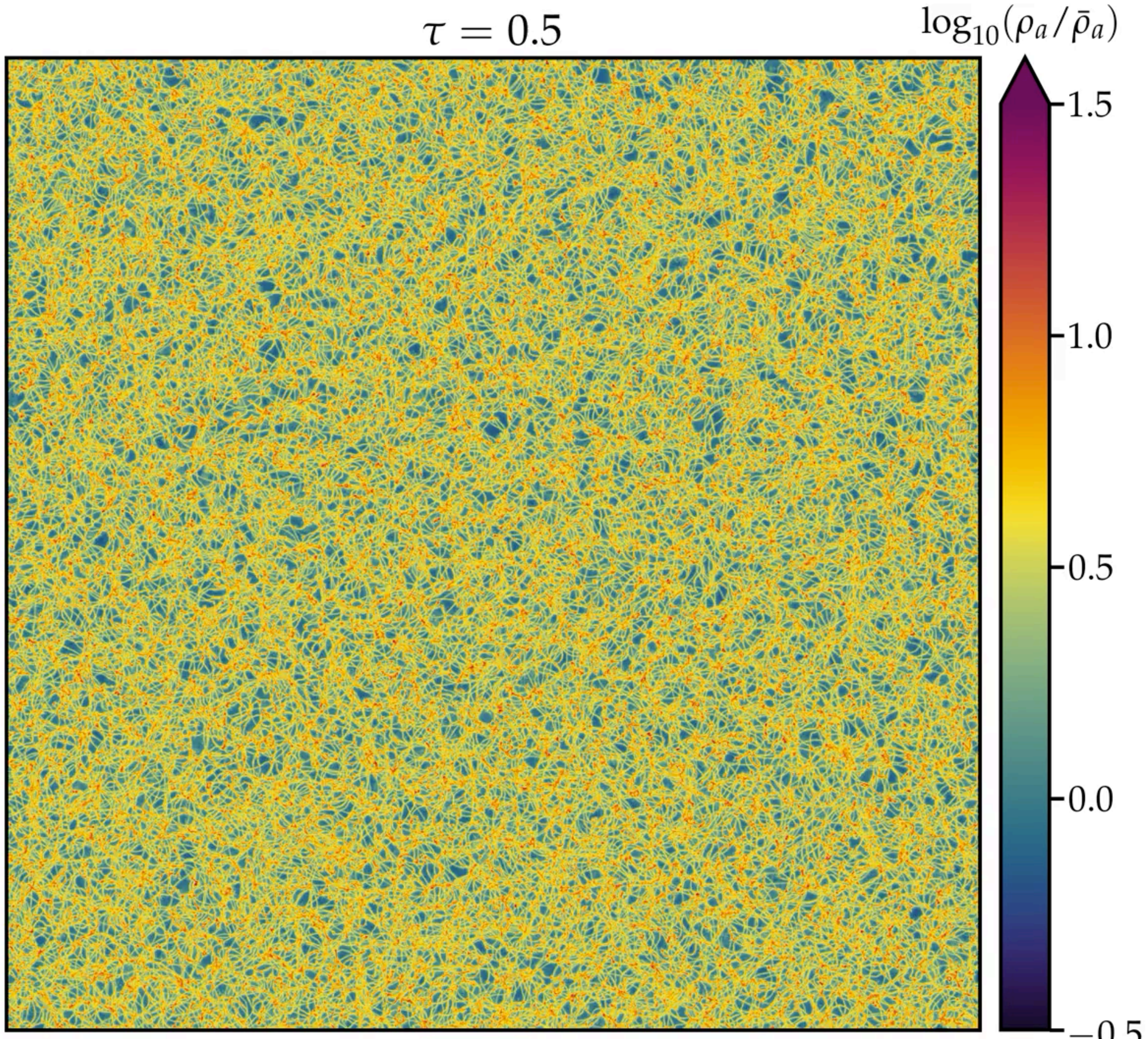
…and predict its present day distribution

For more comprehensive accounts see, e.g.: Gorghetto+[2007.04990], Buschmann+ [2108.05368], Vaquero+ [1809.09241], O'Hare+ [2112.05117]

Evolution of the axion field in the post-inflationary scenario

Projection through 3D co-moving box, coloured by integrated axion energy density:

$$\rho_a = \frac{1}{2}\dot{a}^2 + \frac{1}{2R^2}(\nabla a)^2 + \chi\left(1 - \cos a/f_a\right)$$



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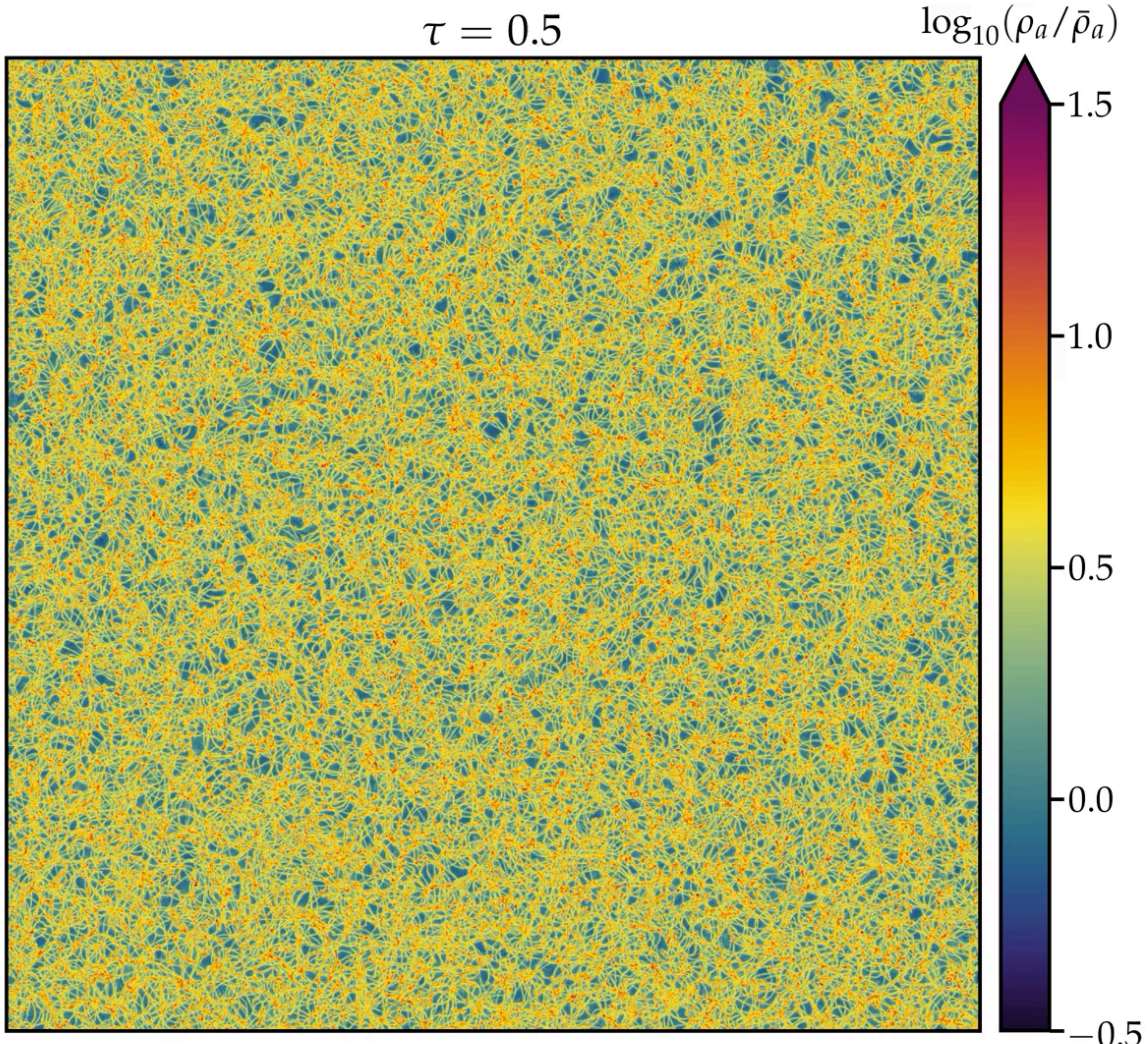

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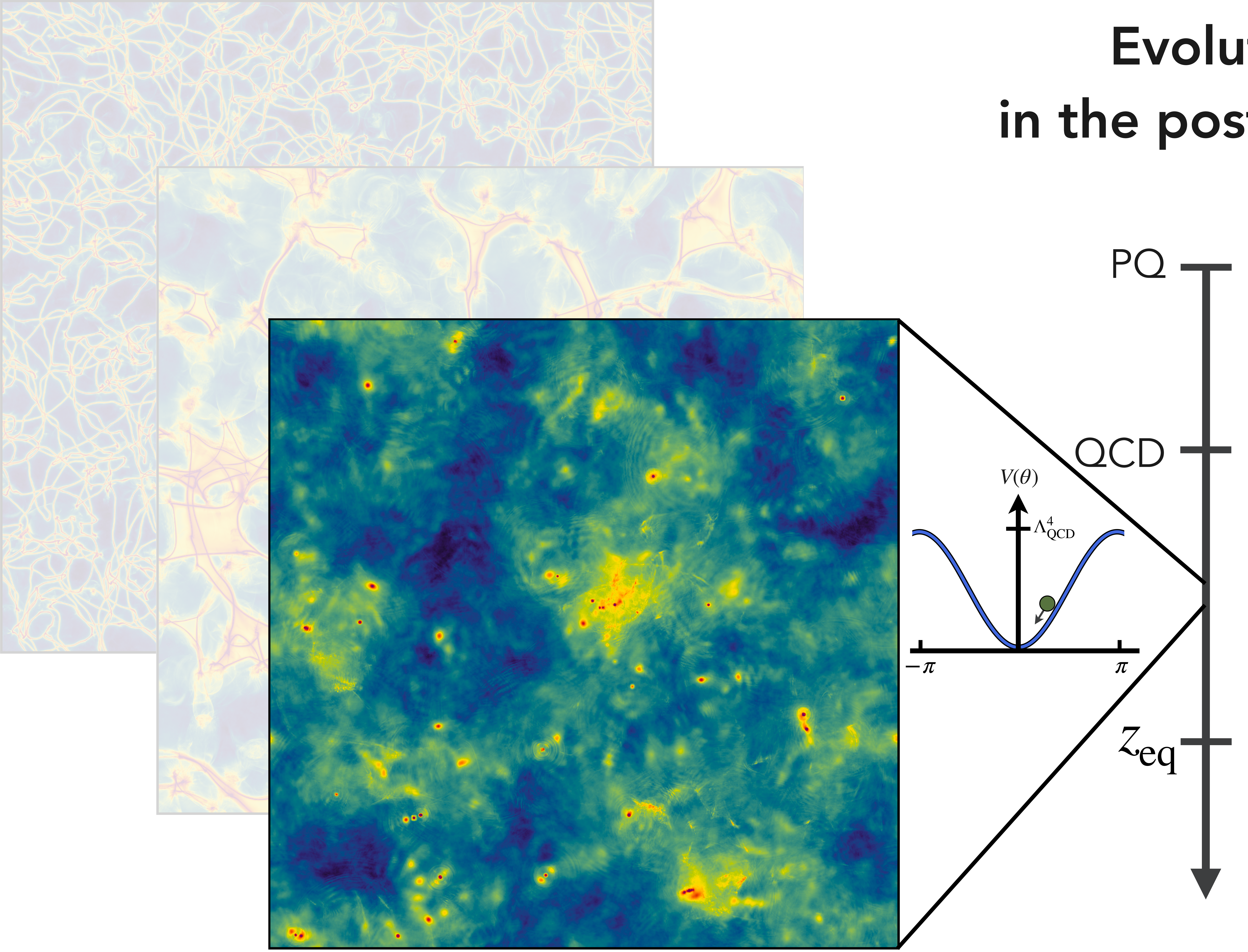

String network scaling

Domain walls attached to strings
→ network collapses

Inhomogeneous distribution of axions free streams until non-relativistic

Seeds of structure gravitationally collapse into miniclusters and halos

What is the ultimate distribution of axions in galaxies?

Will it be like vanilla ΛCDM halos?

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Pre-inflationary axion: probably, yes.

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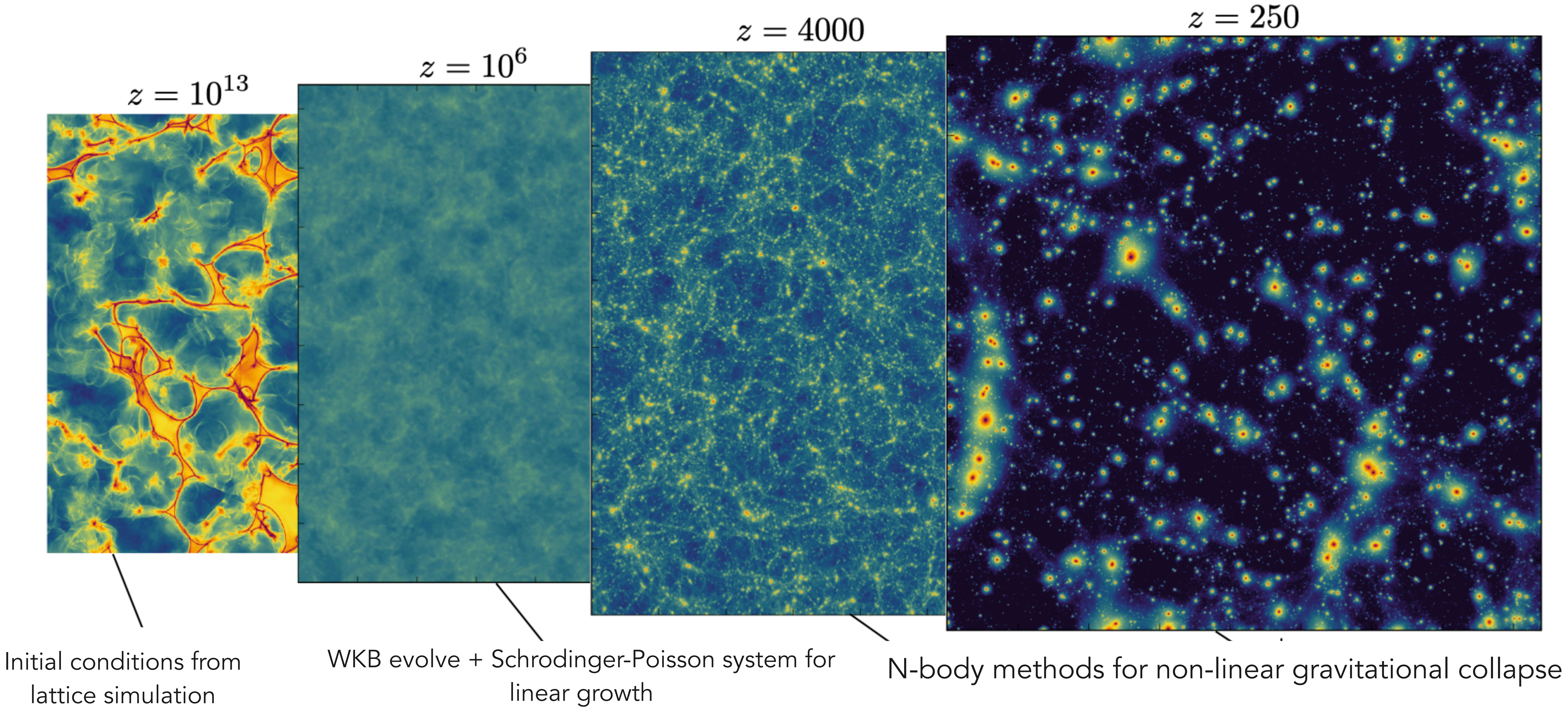
Will it be like vanilla ΛCDM halos?

Pre-inflationary axion: probably, yes.

Post-inflationary axion: NO

Gravitational collapse

Axion distribution is highly *inhomogeneous*. Large density fluctuations from QCD-horizon scale dynamics that can collapse prior to matter-radiation equality → we need to keep simulating!

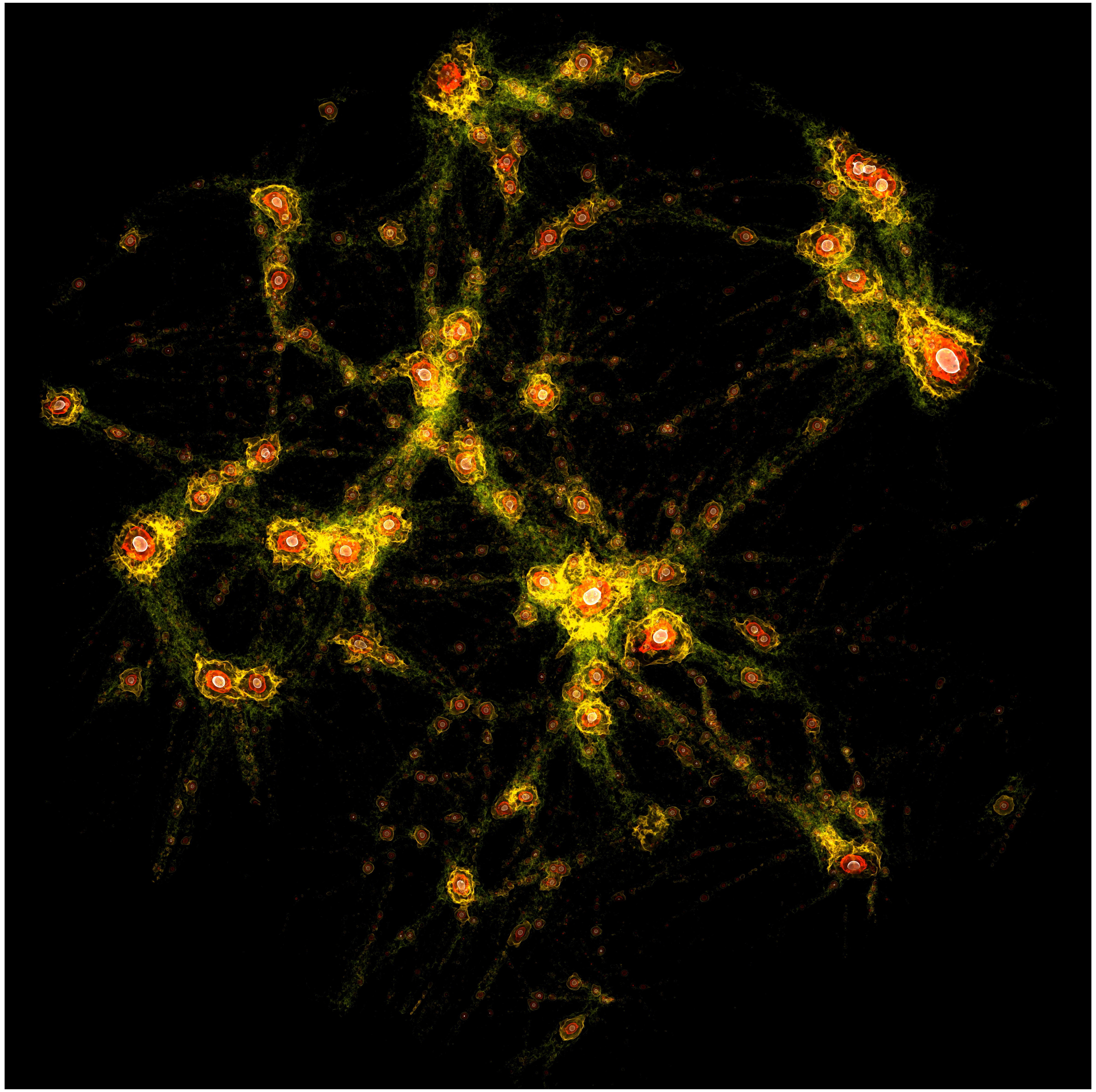


Eggemeier, CAJO+ [2212.00560]

After t_{QCD} axion field forms quasi-stable solitons that lay down small-scale perturbations

These eventually seed AU—mpc gravitationally bound clumps of axions with masses $M \in [10^{-15}, 10^{-9}]\ M_{\odot}$

→ **axion miniclusters**



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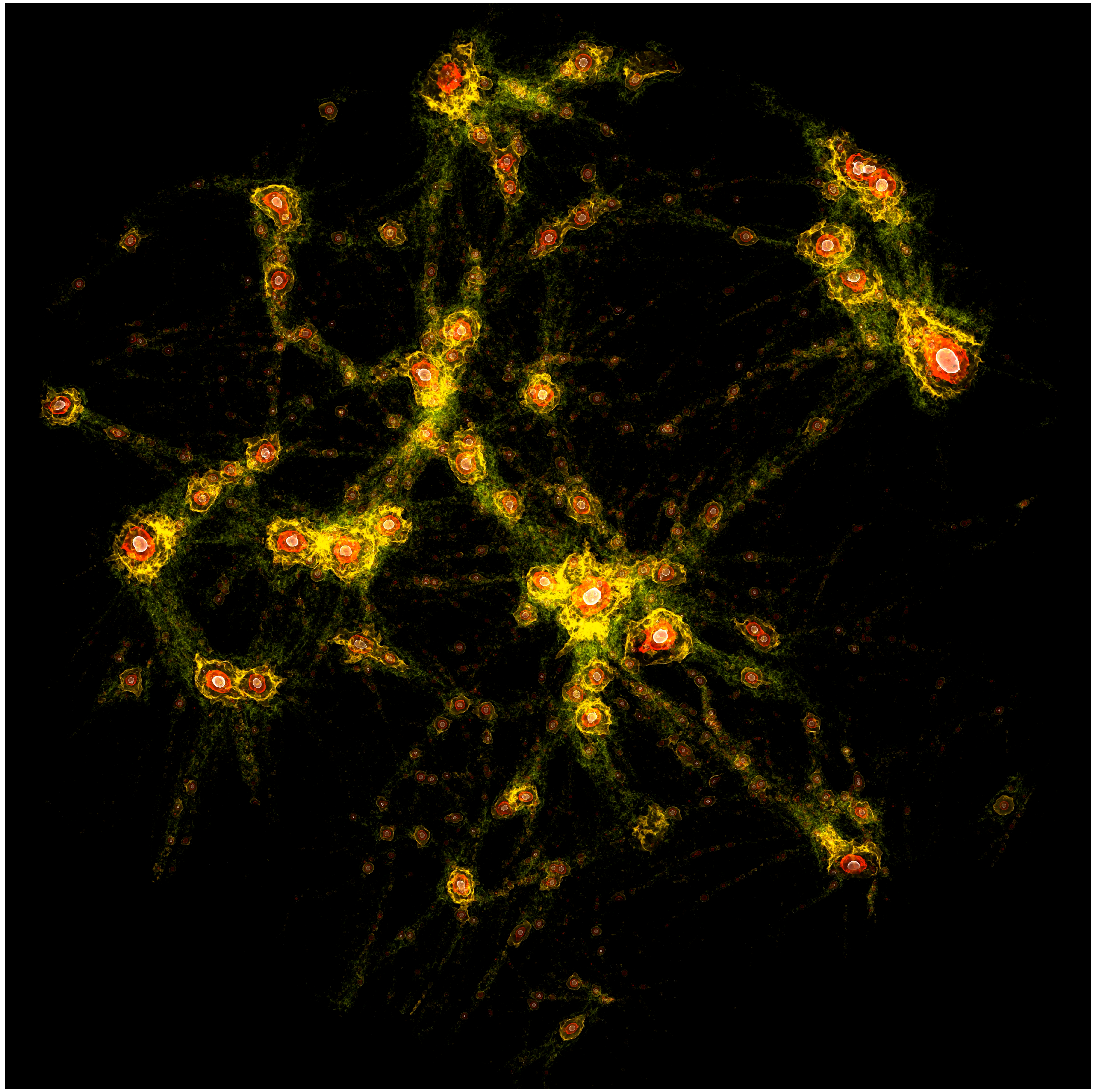

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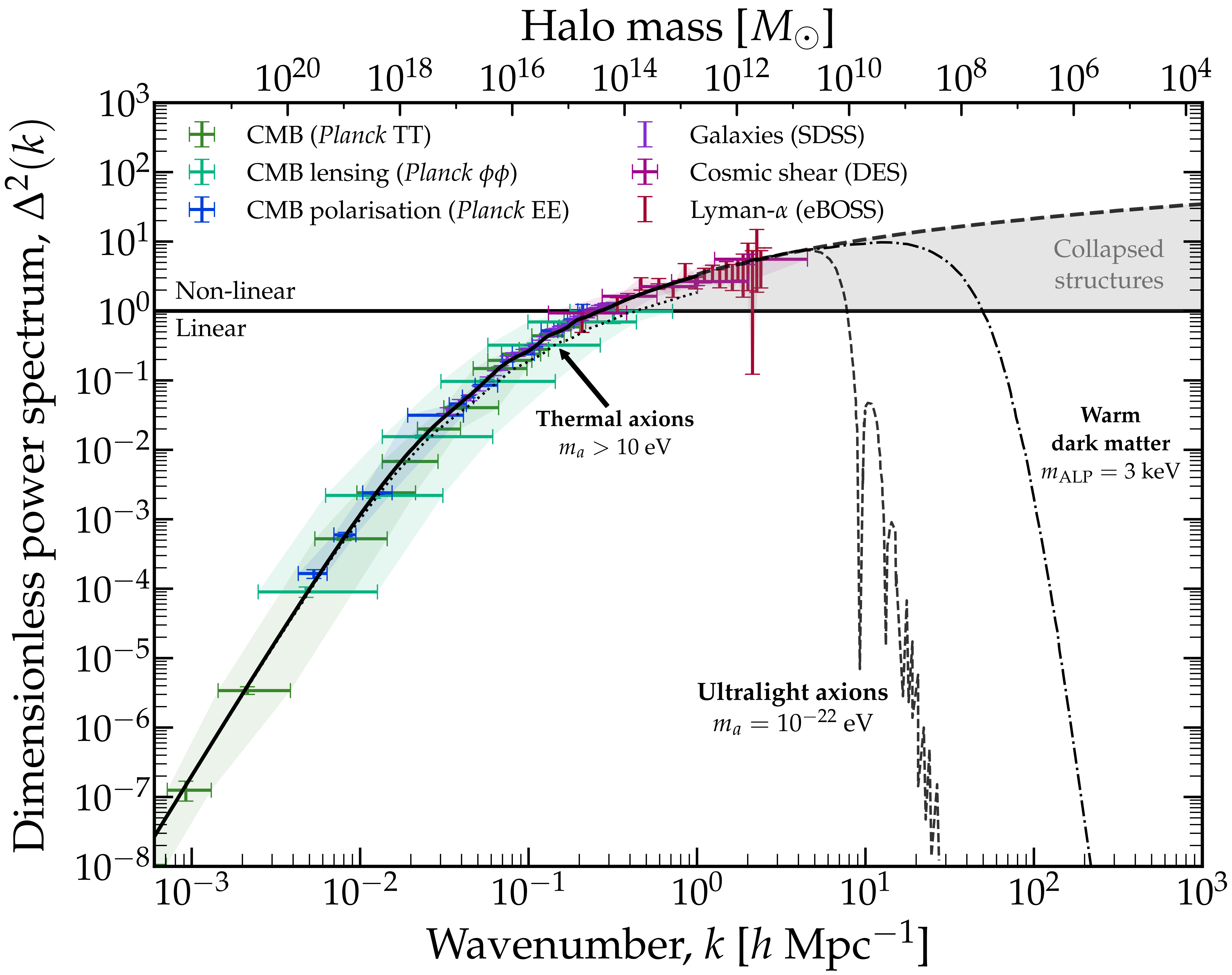

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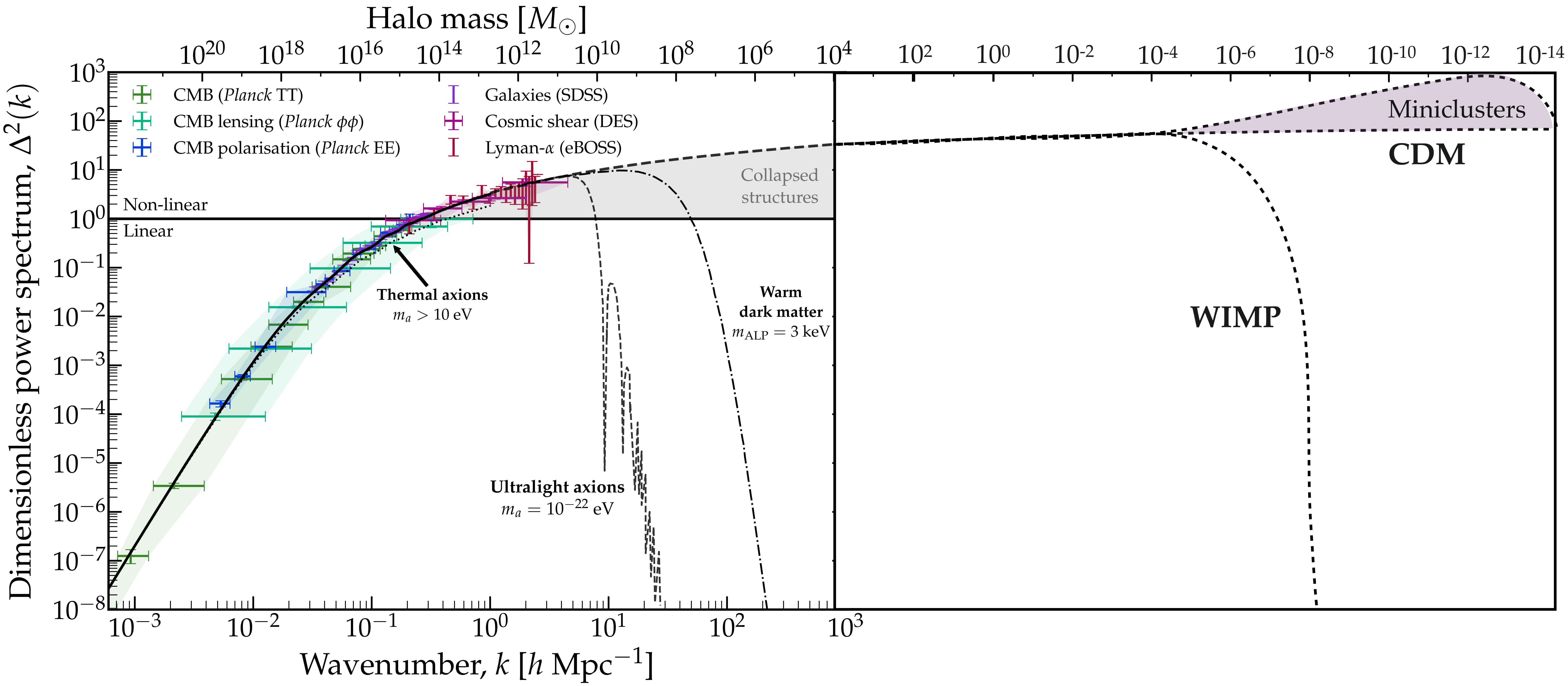

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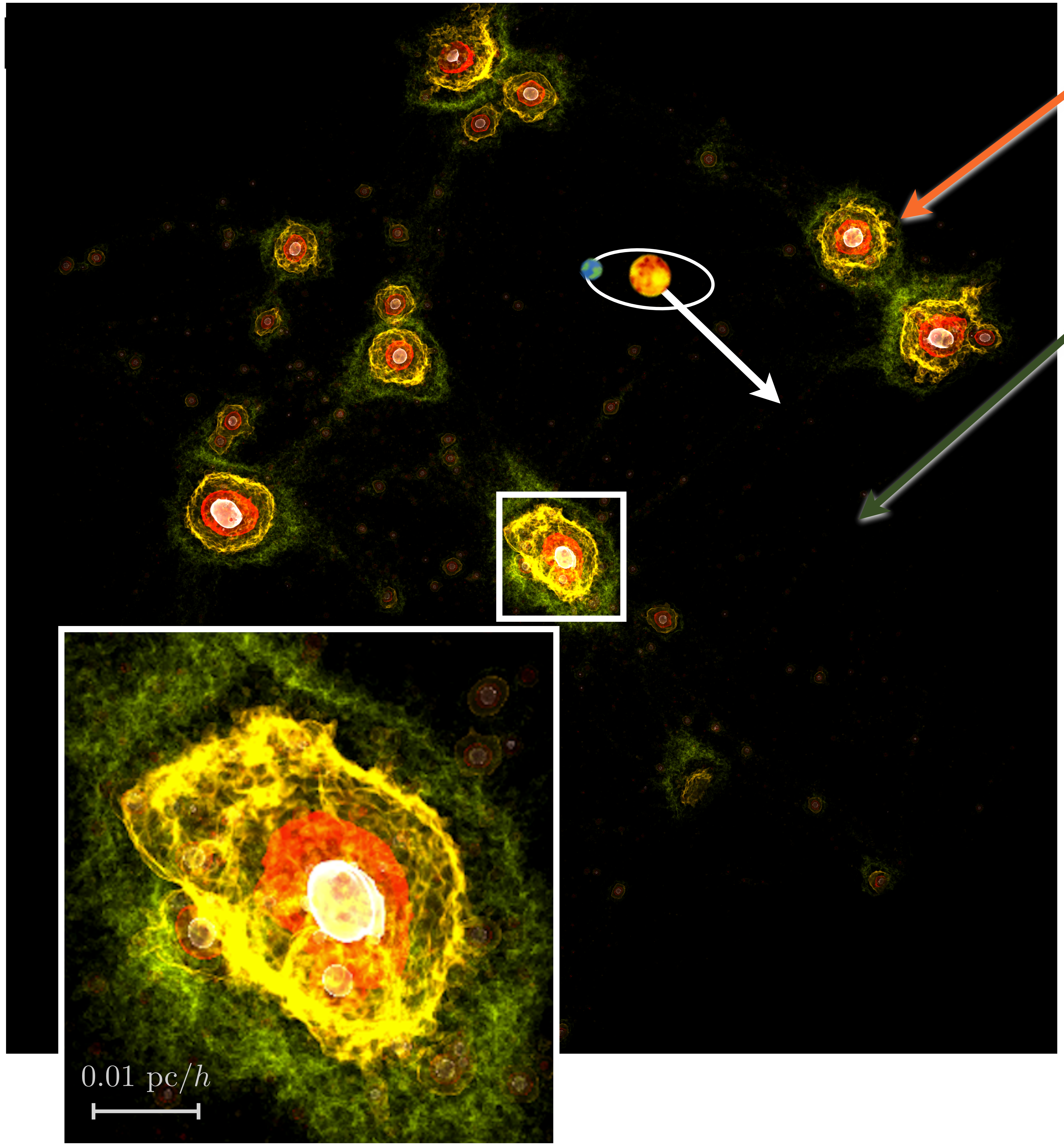


Miniclusters

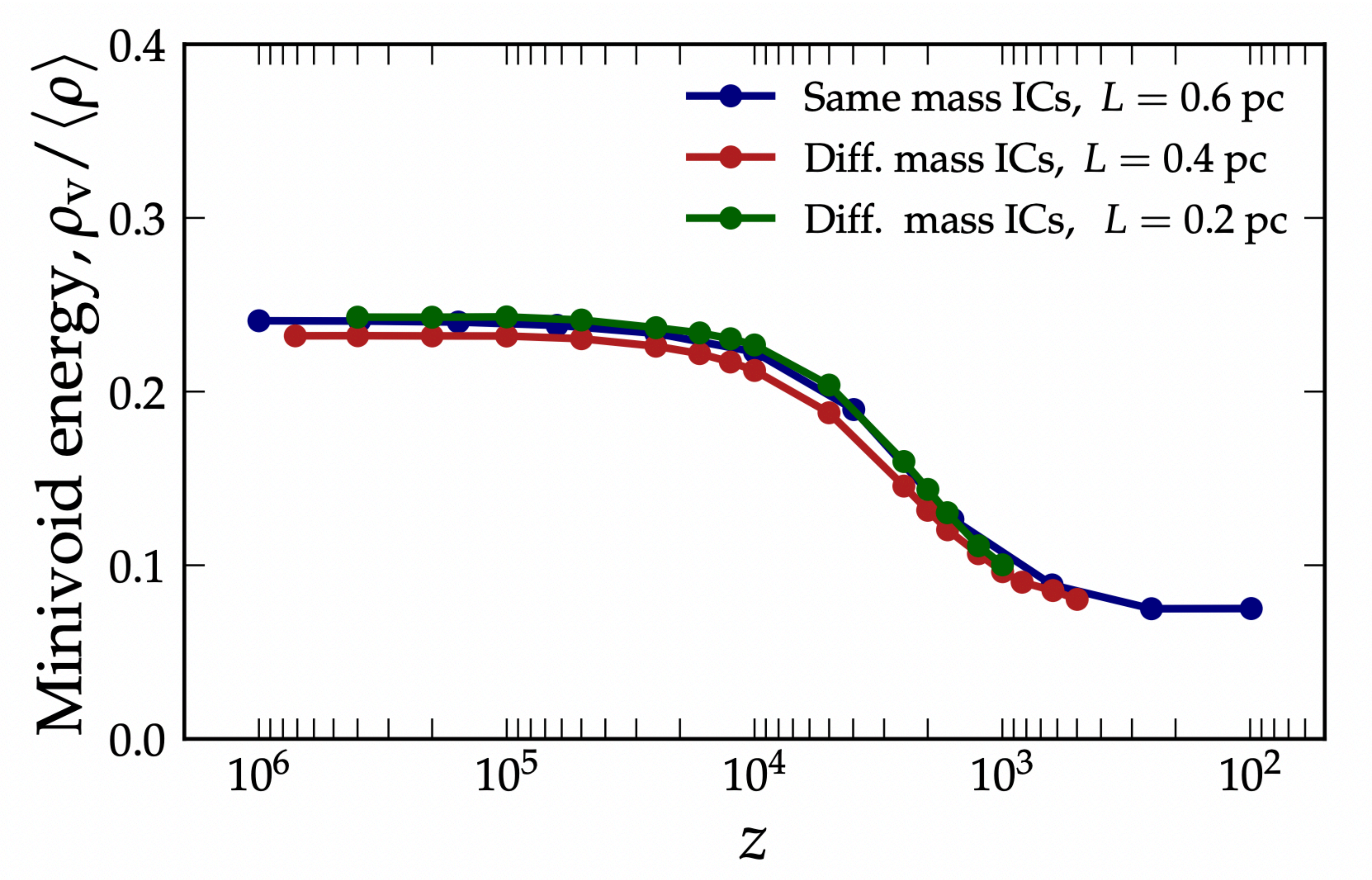
Minivoids

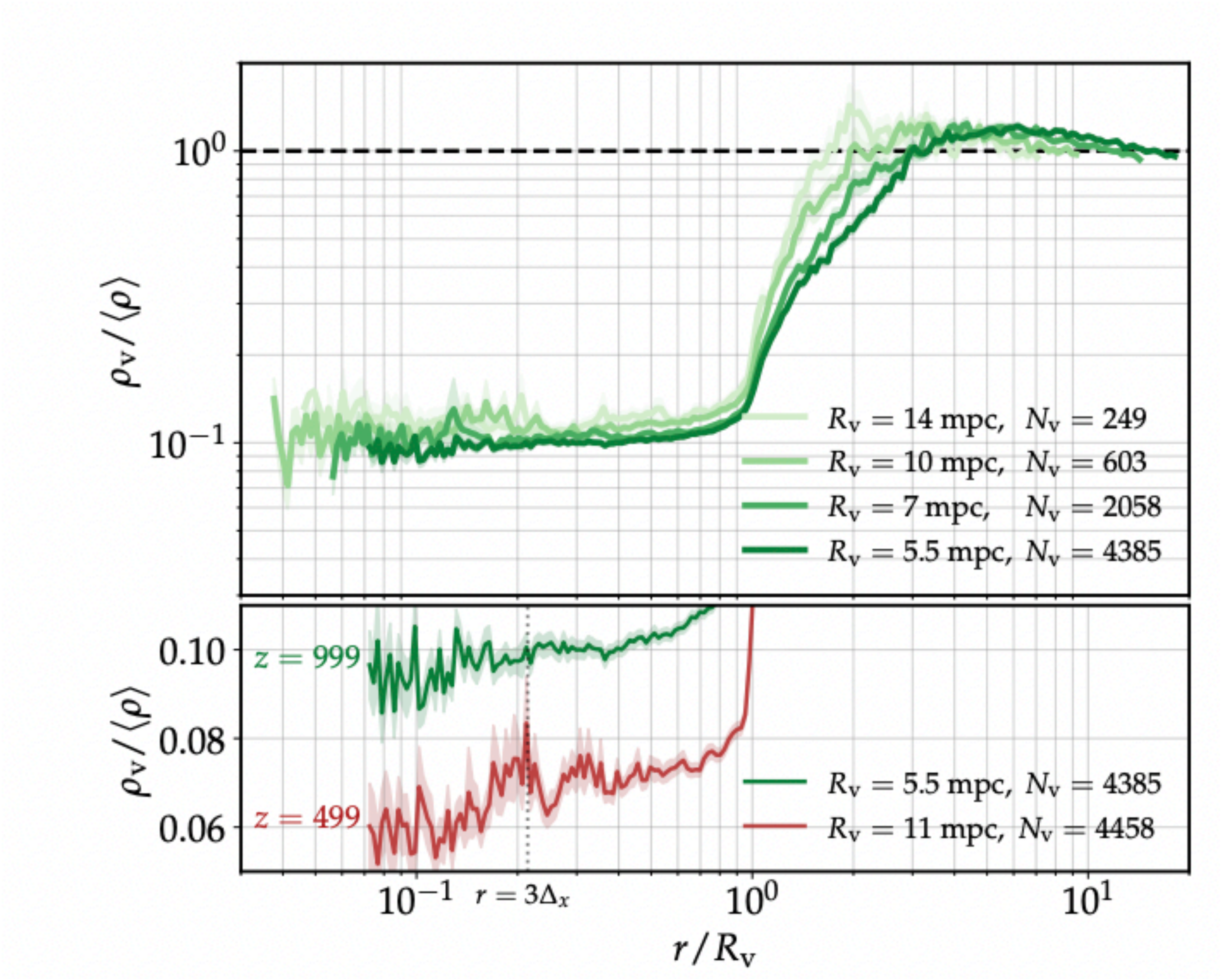
Miniclusters contain >80% of the axions but make up <1% of the volume

Earth travels through galaxy at about 0.2 mpc per year, so experiments are much more likely to sample the mini*voids* than the mini*clusters*

Minivoids are mostly stable by final simulation time (z~100)

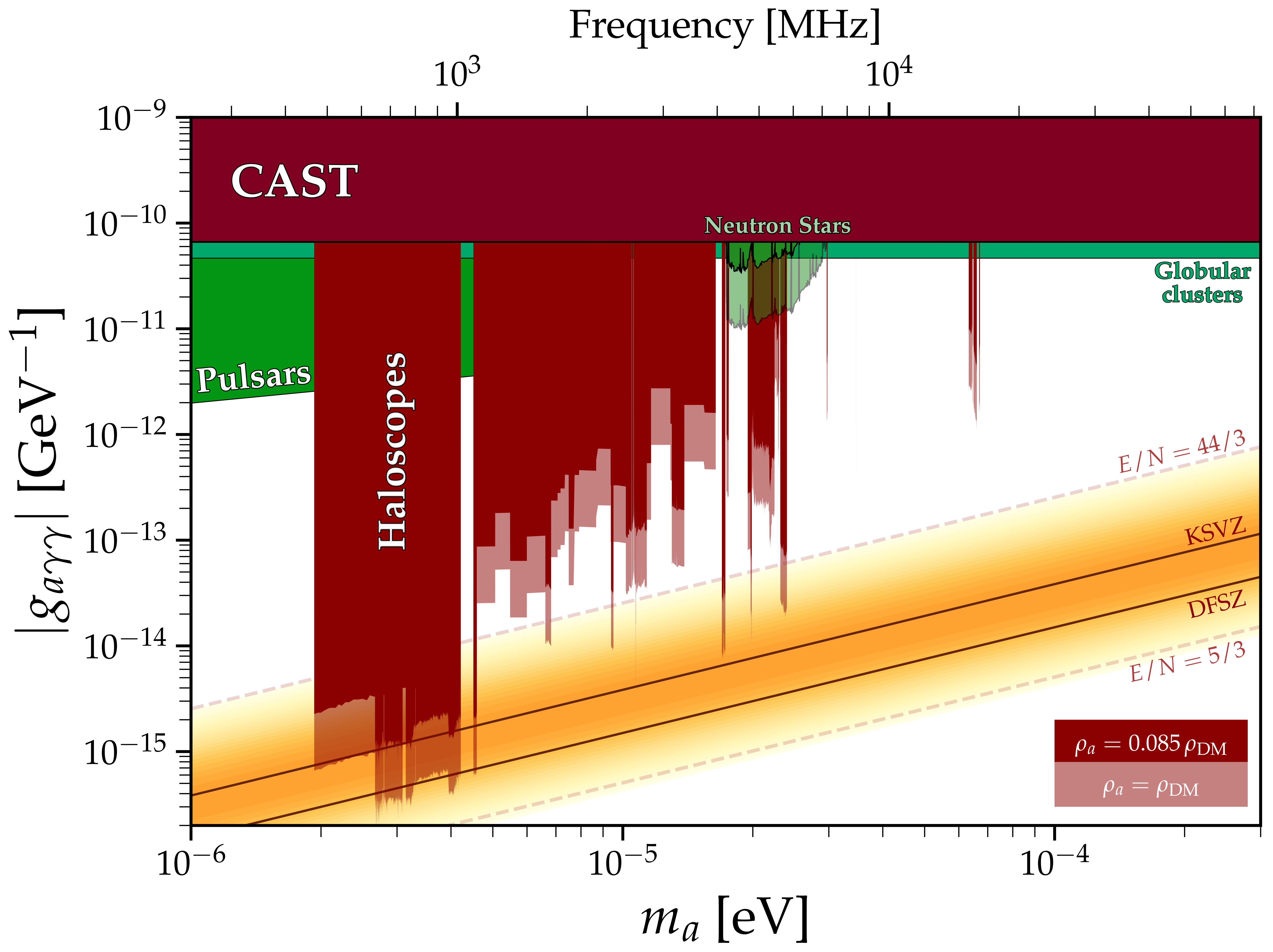
Typical "worst case scenario" density would be inside the minivoids ~10% of large-scale average density





Eggemeier, CAJO+ [2212.00560]

Why is the dark matter density a problem?



Haloscope sensitivity scales *slowly*.

$$\sqrt{\rho_{DM}}\, g_{a\gamma} \propto \frac{1}{\sqrt[4]{T}}$$

Usually assume $\rho_{DM} = 0.45$ GeV/cm^3 inspired by from inferences using Milky Way stars on >100 pc scales

If true (local) value was only ~10% of large-scale average then this is equivalent to a haloscope thinking they've excluded DFSZ when they've only excluded KSVZ

Is this the end of the story?

Not the end of the story...

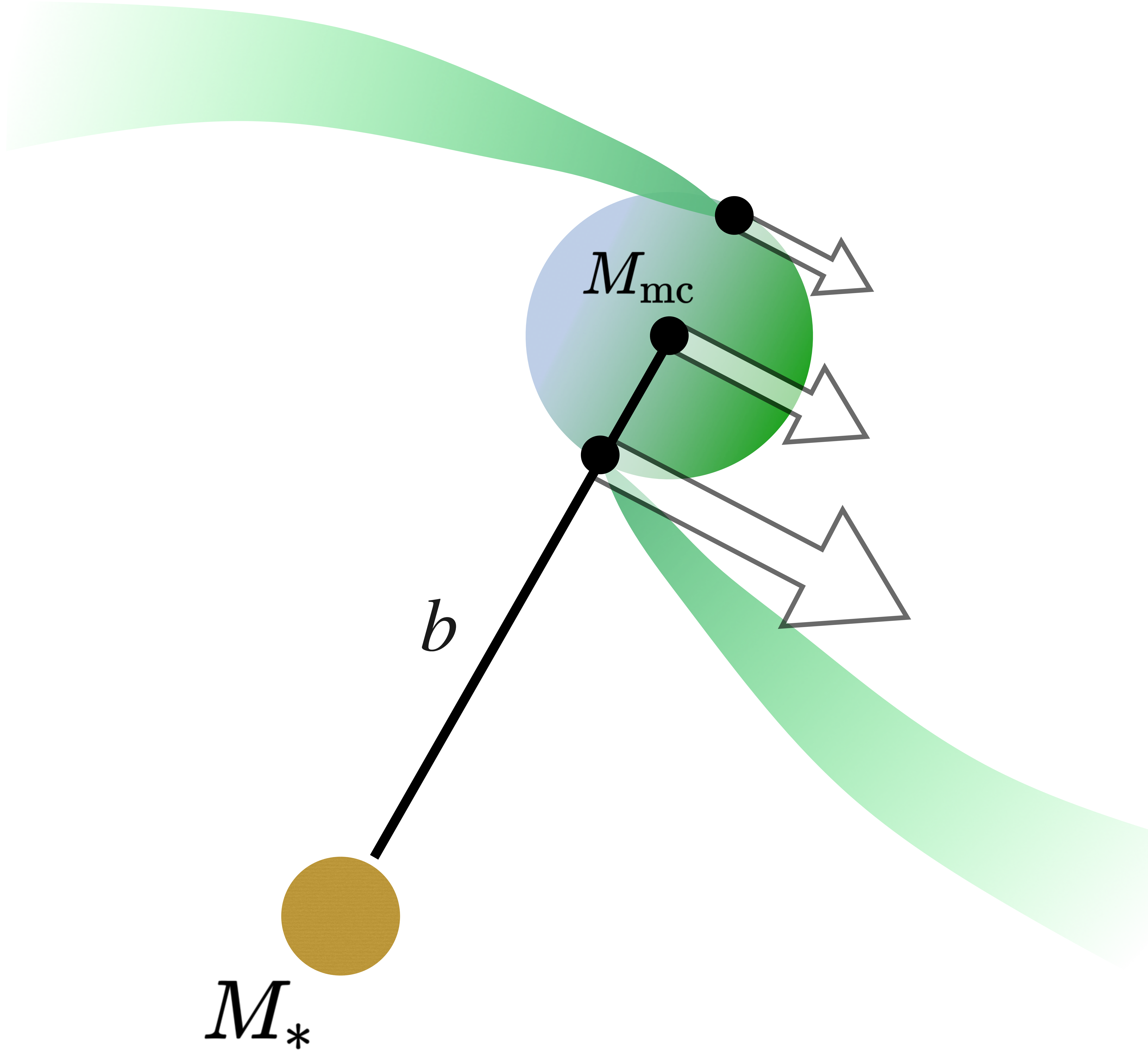
Miniclusters are susceptible to tidal disruption by stars

$$\Delta E \simeq \left(\frac{2GM_*}{bv_{\mathrm{rel}}}\right)^2 \frac{M_{\mathrm{mc}}R_{\mathrm{mc}}^2}{3}$$

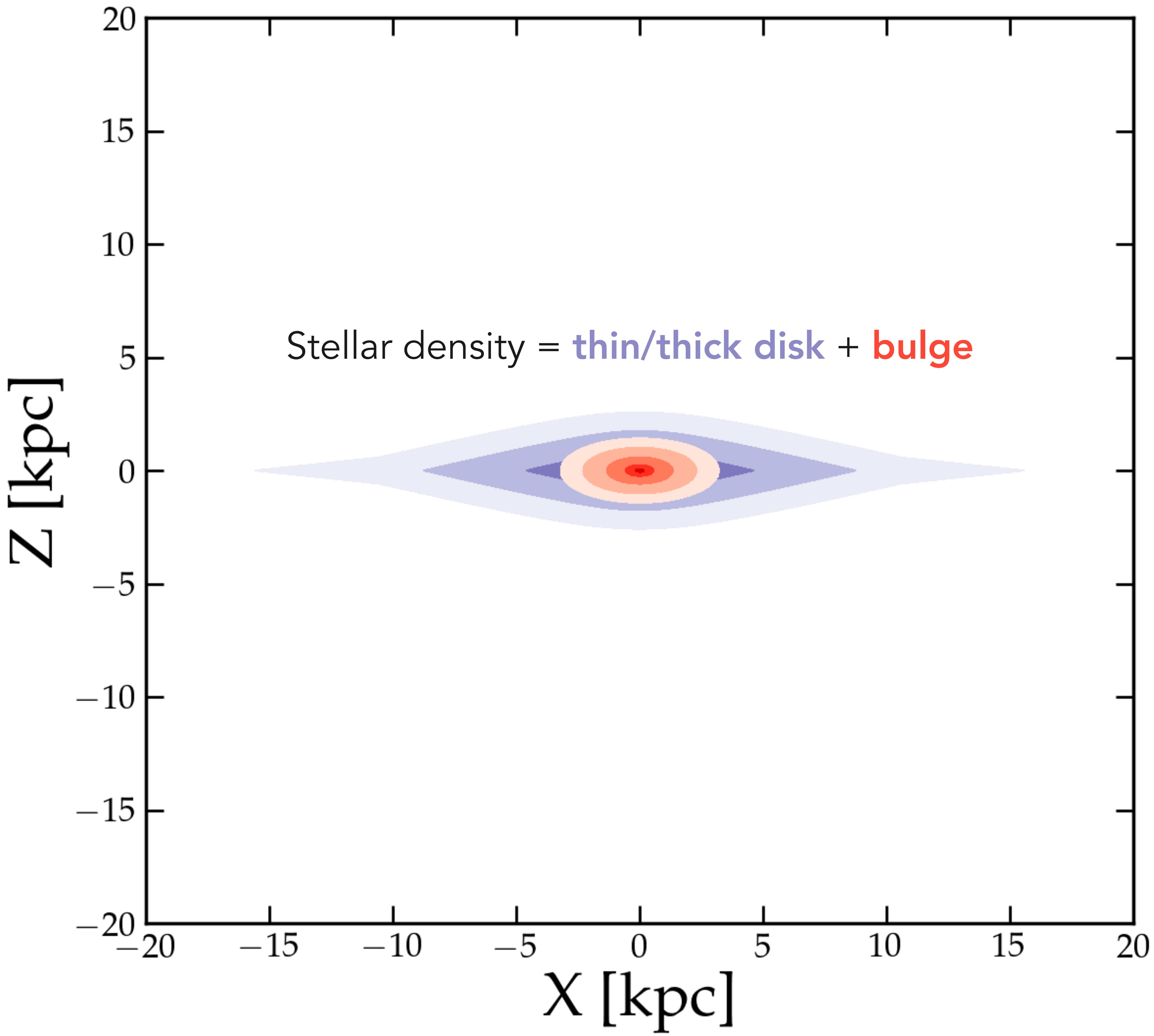
↑

Energy injected into minicluster

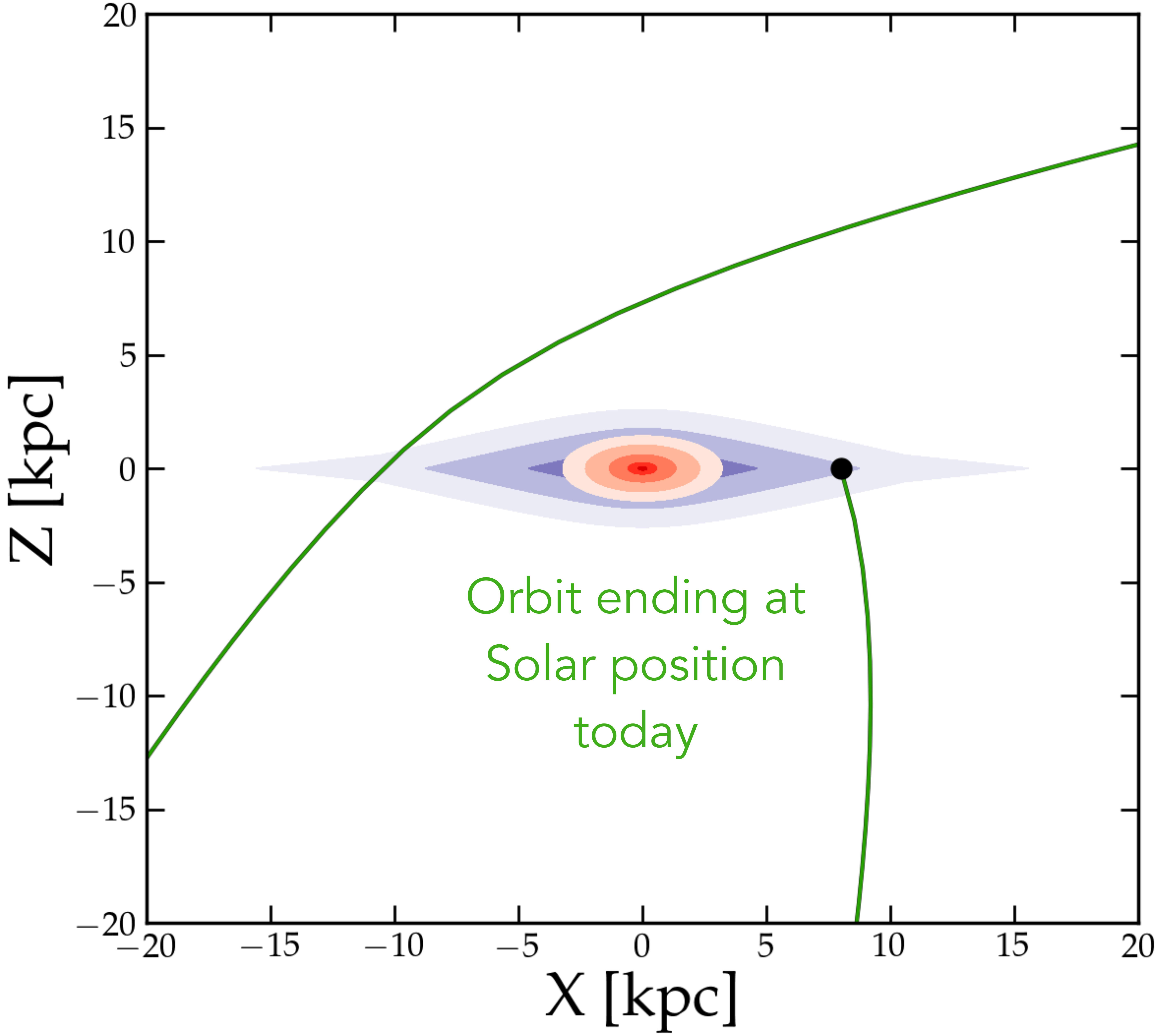
Axions with E>Binding energy will evaporate away → form **tidal stream**



See e.g., Tinyakov+ [1512.02884], Kavanagh+ [2011.05377]



Monte-Carlo miniclusters orbiting the galaxy, undergoing stellar encounters that gradually strip mass away from them



Monte-Carlo miniclusters orbiting the galaxy, undergoing stellar encounters that gradually strip mass away from them

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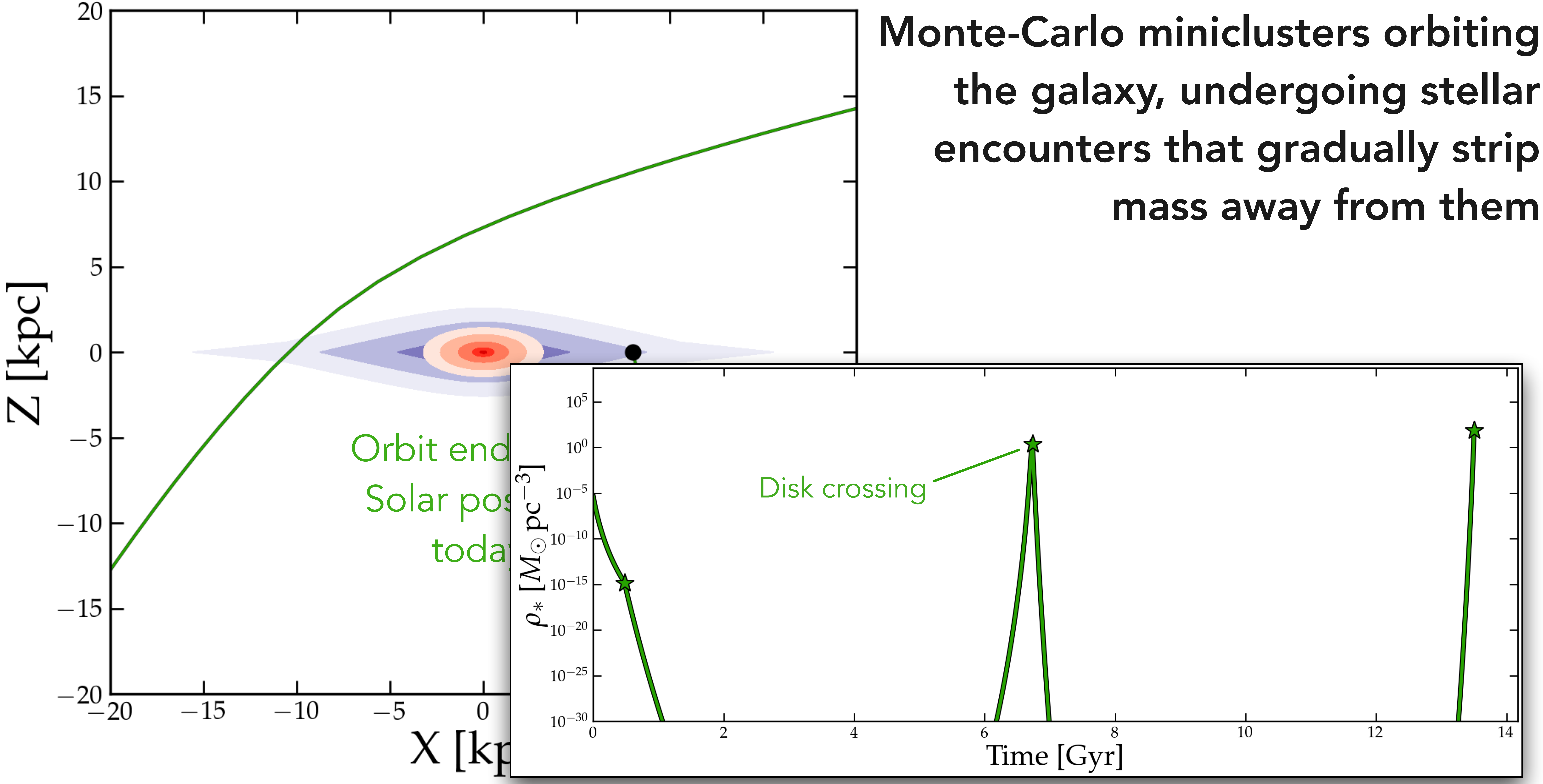

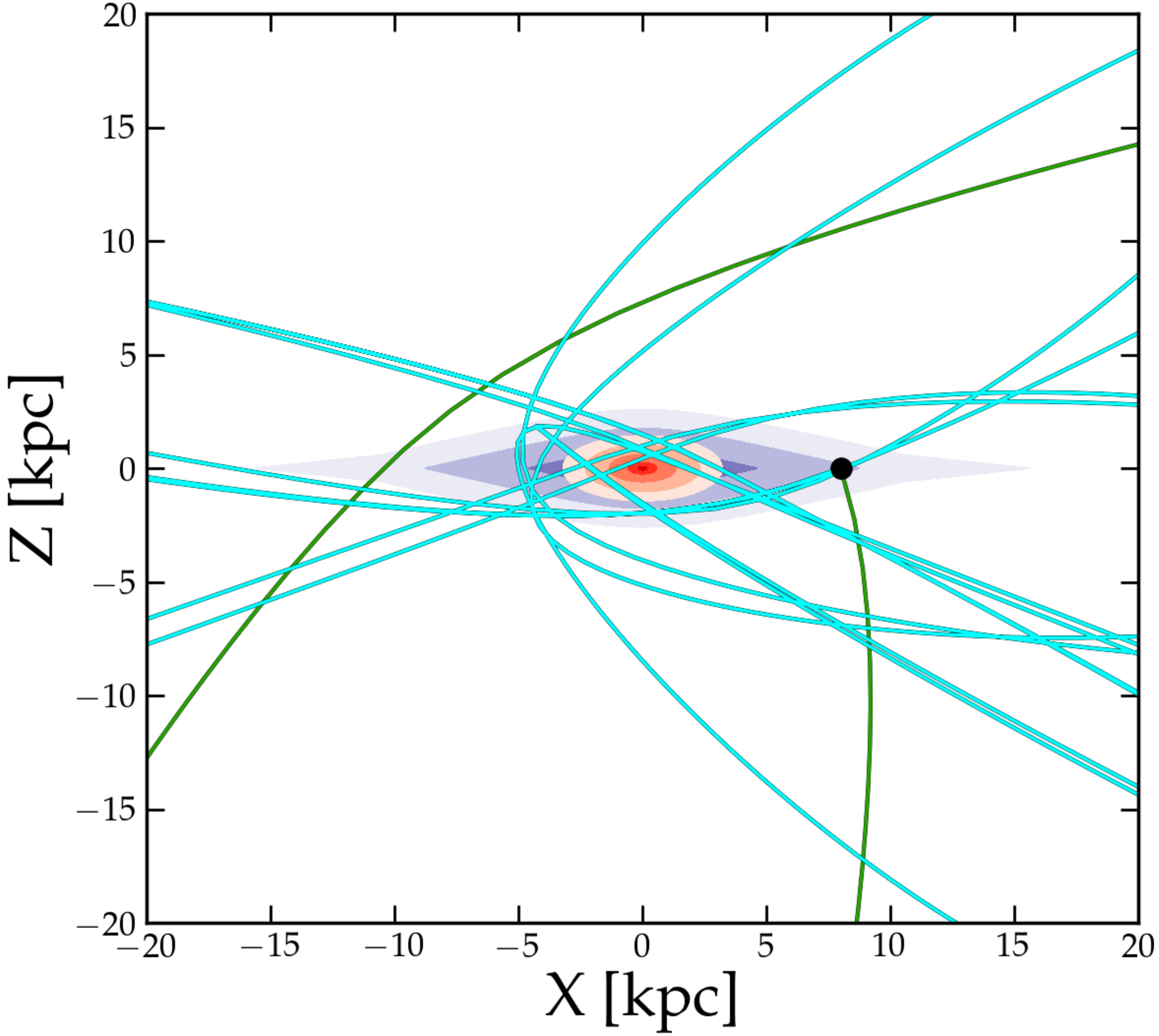

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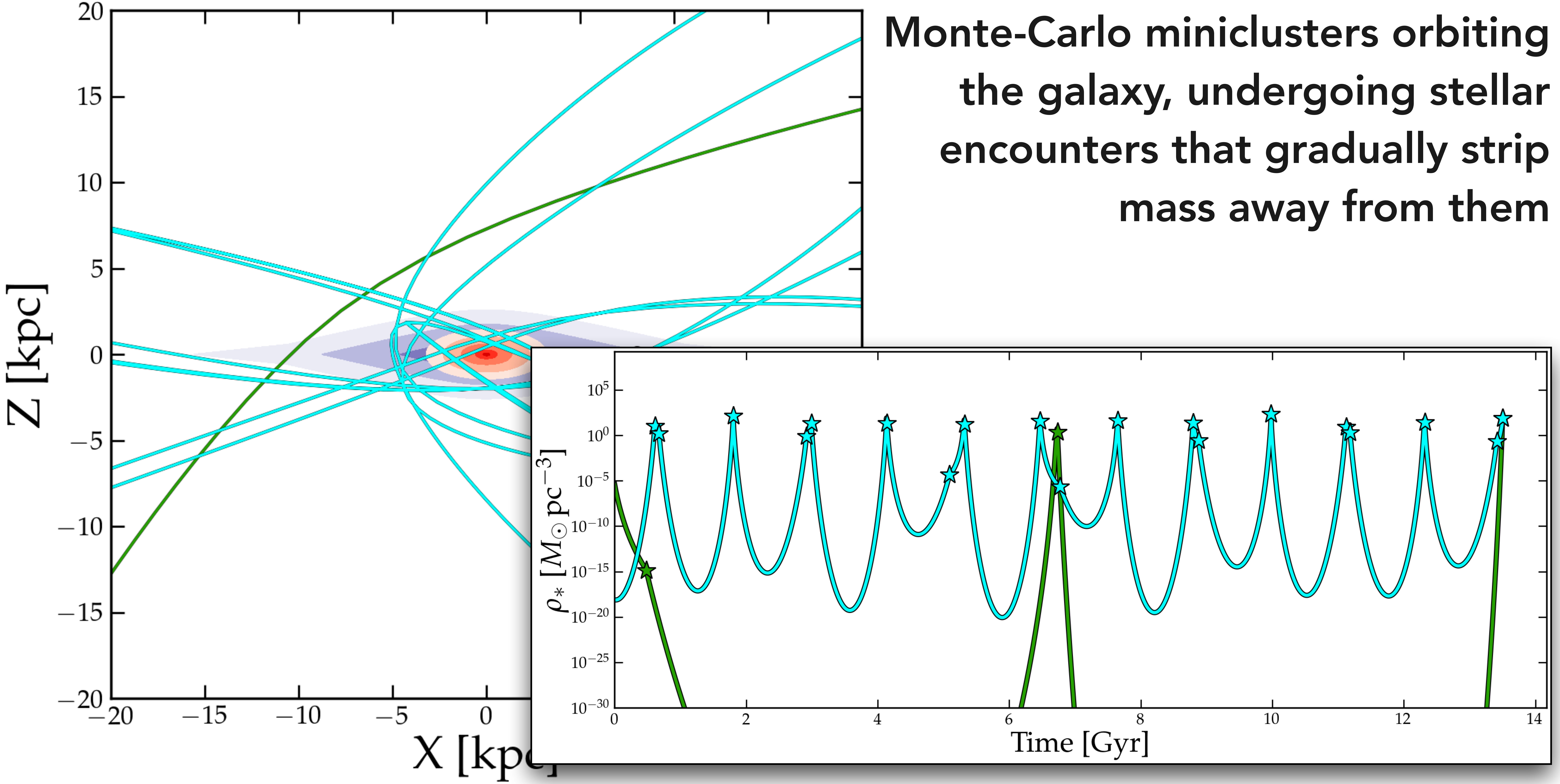

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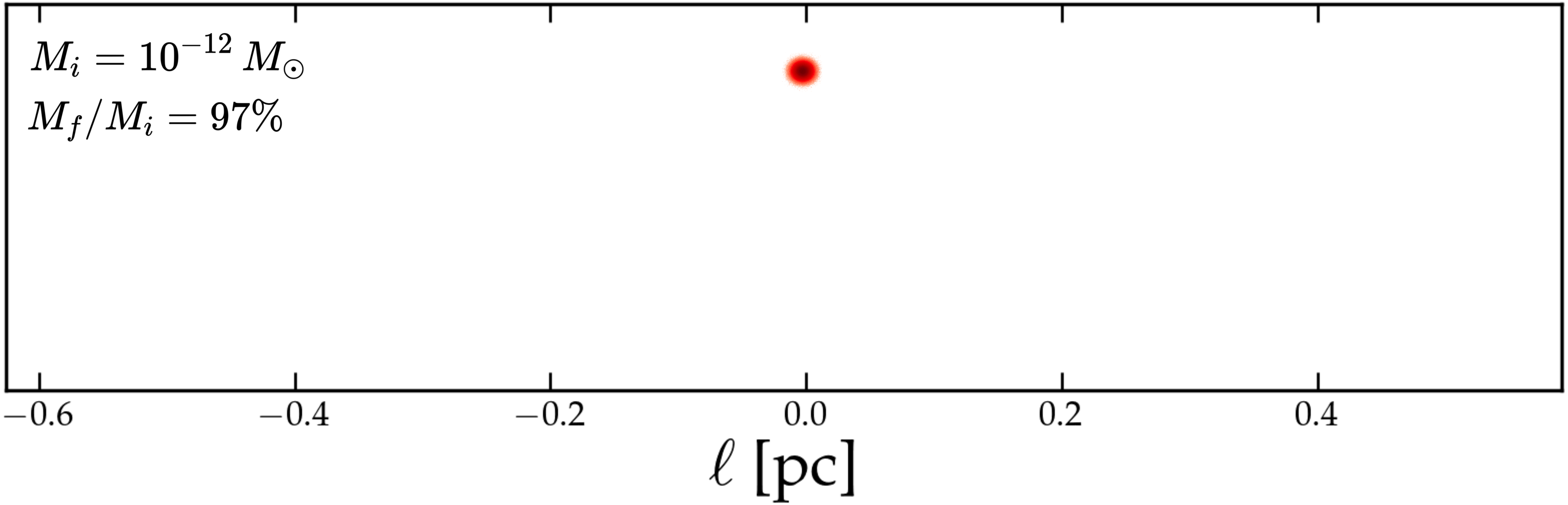
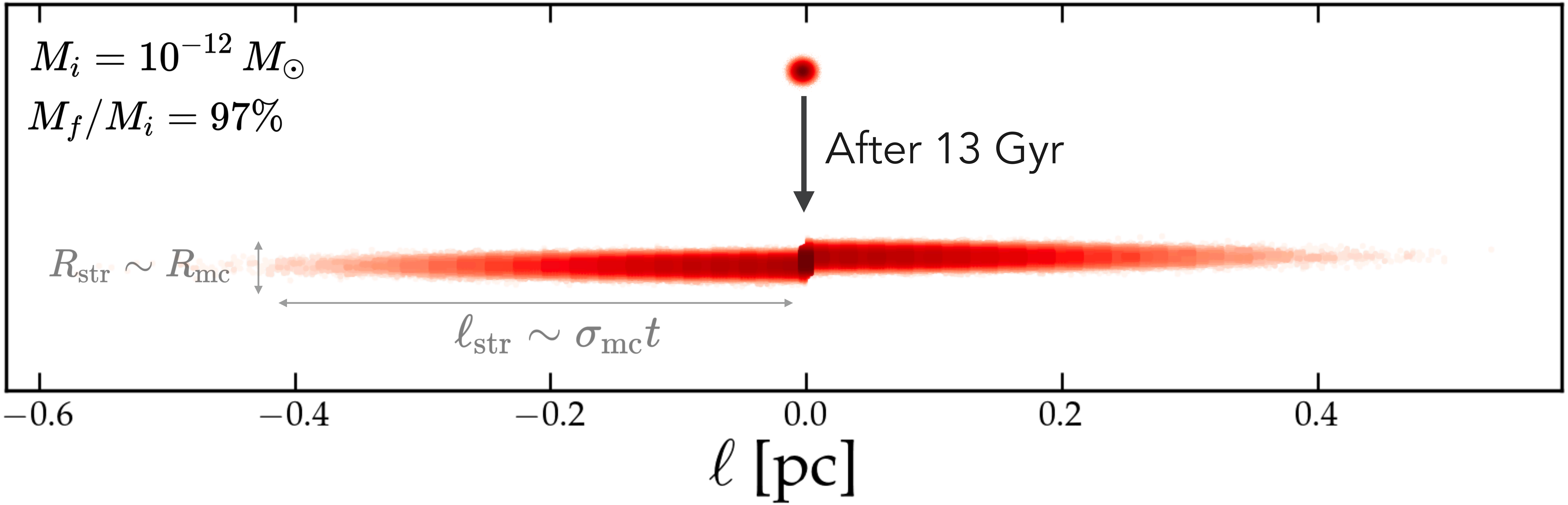
Tidal stream formation



At solar position, most miniclusters are not 100% disrupted.

However, a sizeable amount will form ~pc-long tidal streams

Tidal stream formation



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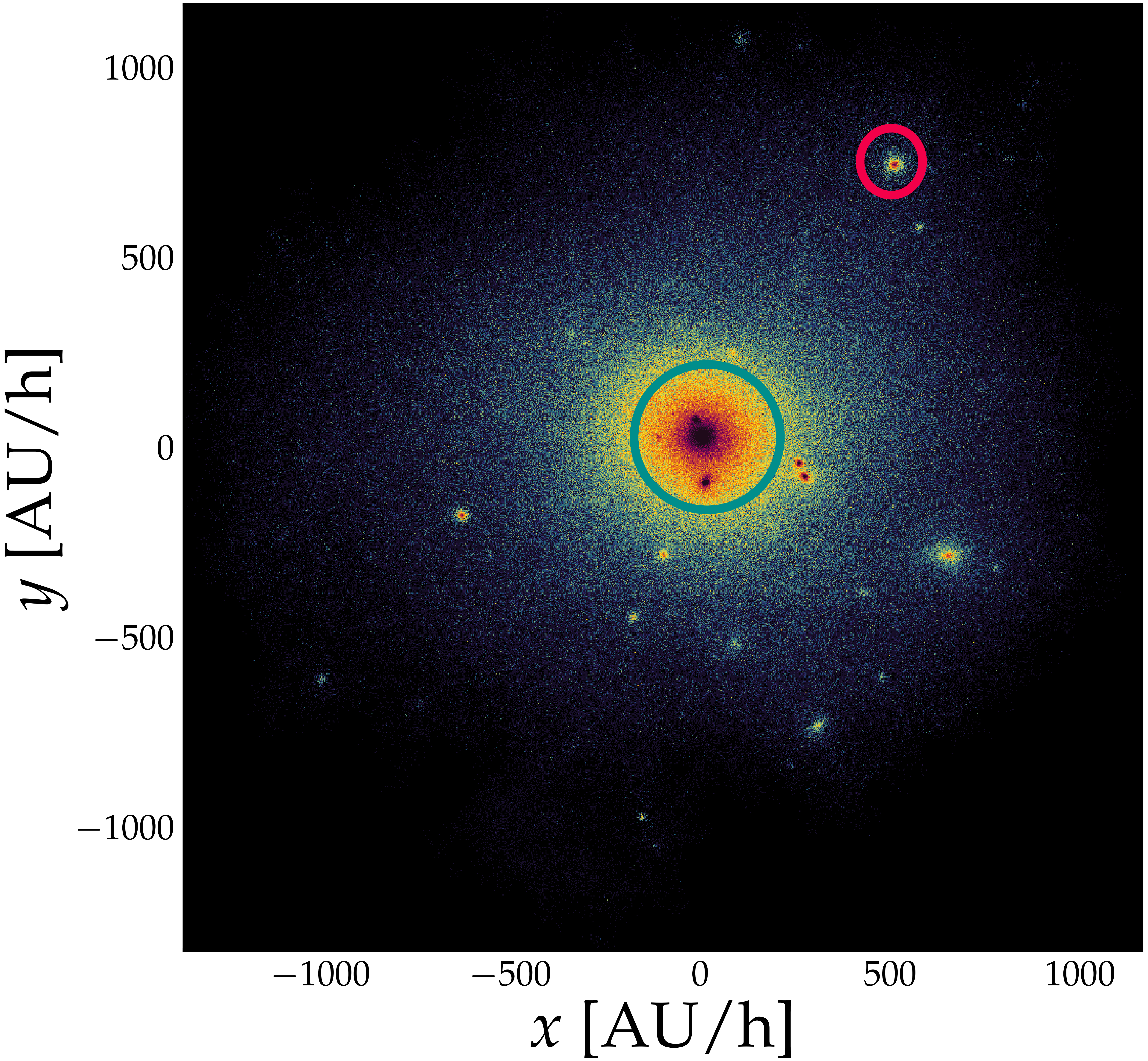
Different populations of miniclusters



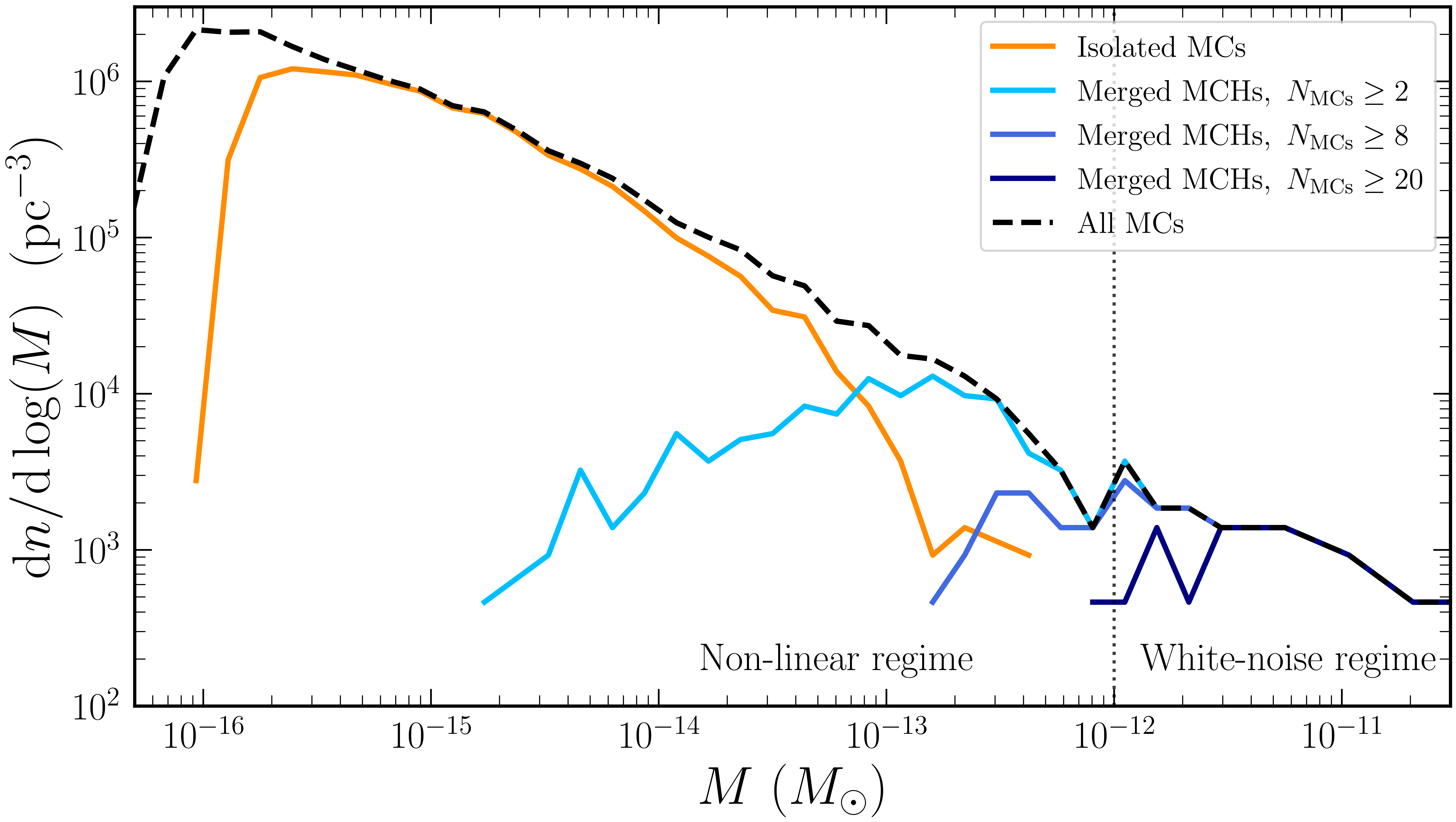
Isolated

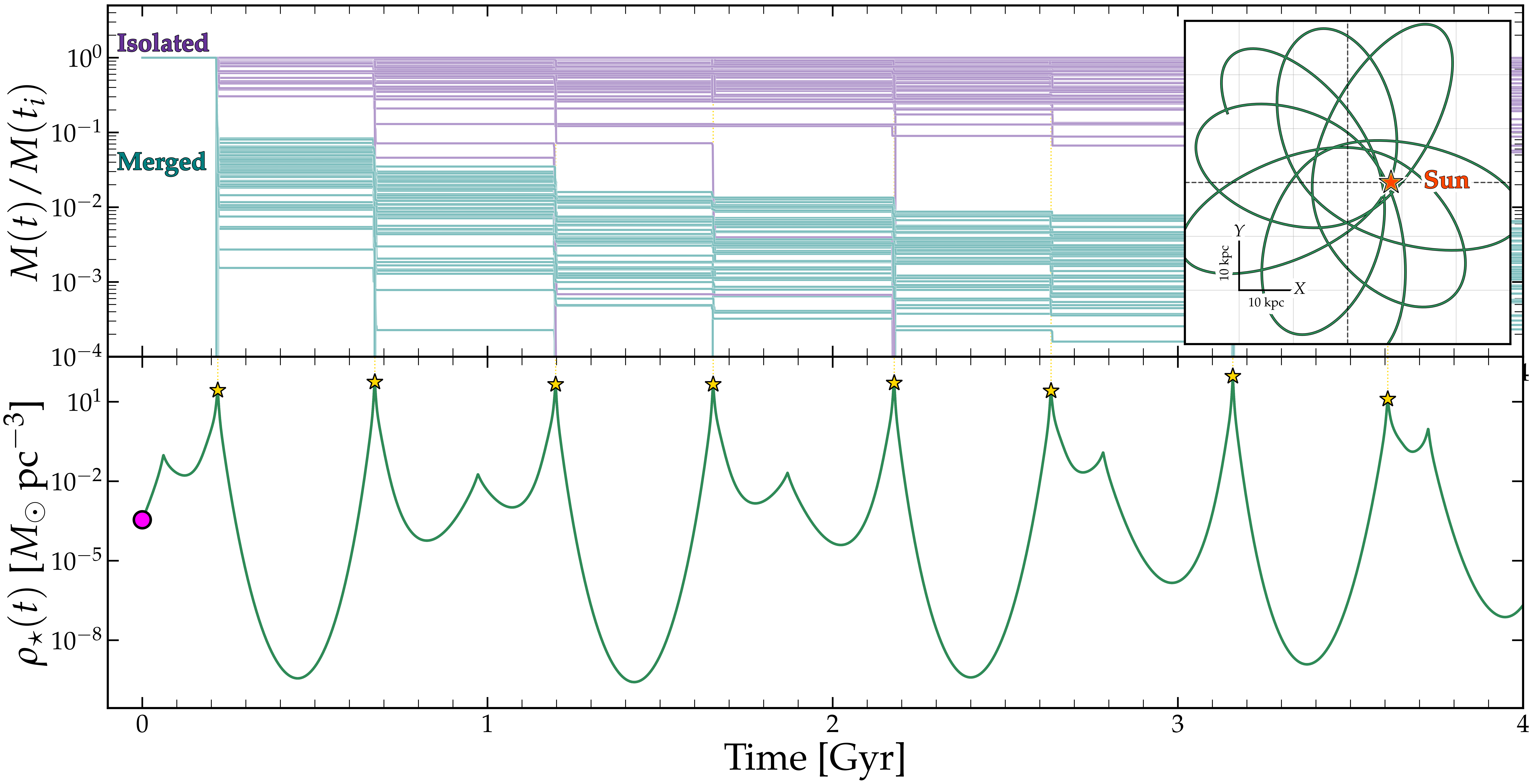
- → About 70% of MCs by number
- → Masses $M \in [10^{-16}, 10^{-12}]\, M_\odot$
- → Form from prompt collapse
- → Power law density profiles $\rho \sim r^{-2.71}$
- → ~0% are *fully* disrupted

Merged

- → About 30% of MCs by number
- → Masses $M \in [10^{-12}, 10^{-7}]\, M_\odot$
- → Form from mergers of MCs
- → NFW density profile
- → 45% are *fully* disrupted

Minicluster mass function



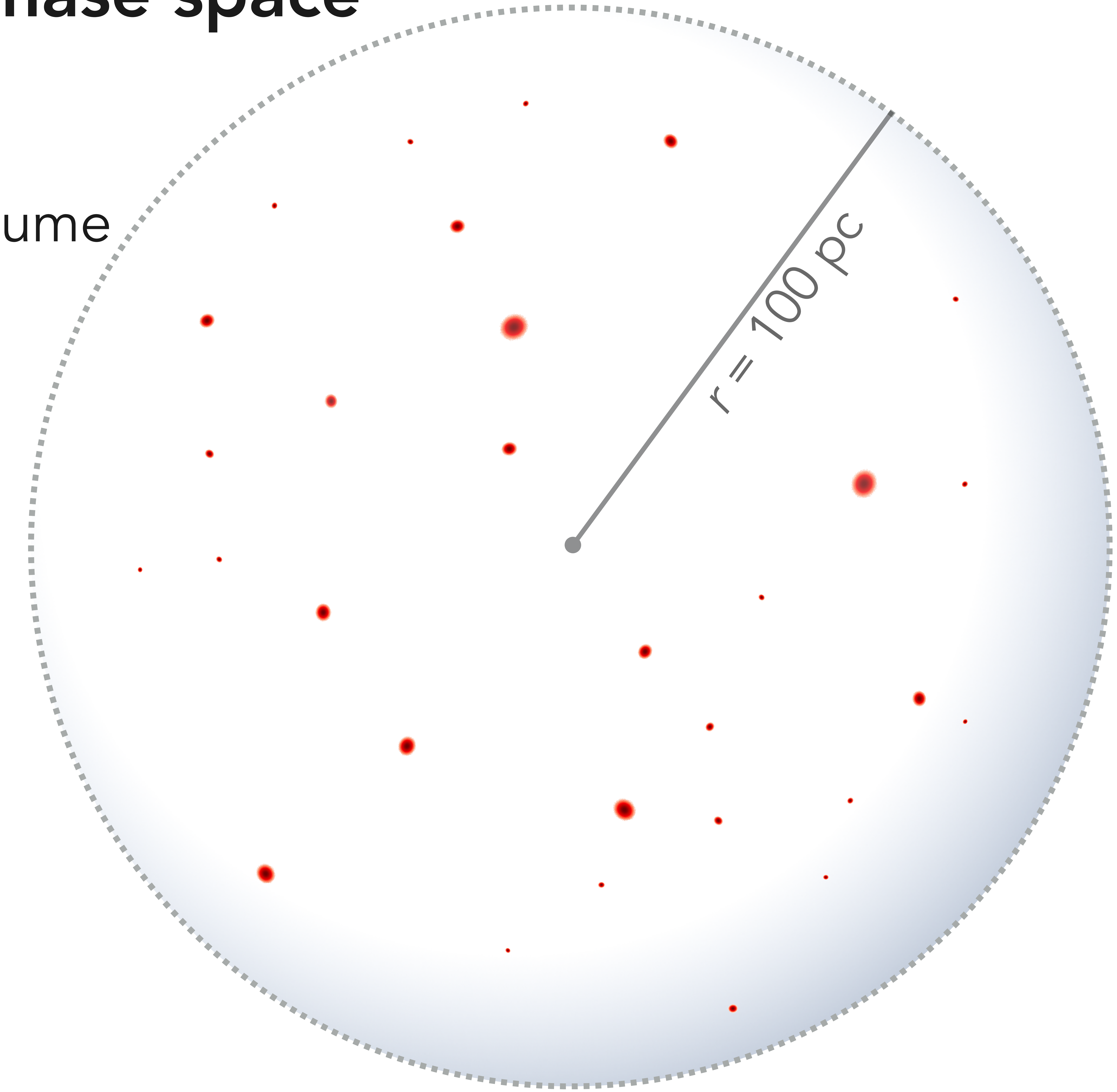


Isolated
Merged
Sun
Y
X
10 kpc
10 kpc
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$M(t)/M(t_i)$
10^1
10^{-2}
10^{-5}
10^{-8}
$\rho_\star(t)$ [$M_\odot$ pc^{-3}]
0
1
2
3
4
Time [Gyr]

Tidally stripped MCs refill the phase space

We measure $\rho_{\rm DM}$ on scales ~100 pc

→ Must be $\sim 10^{14}$ miniclusters in that volume



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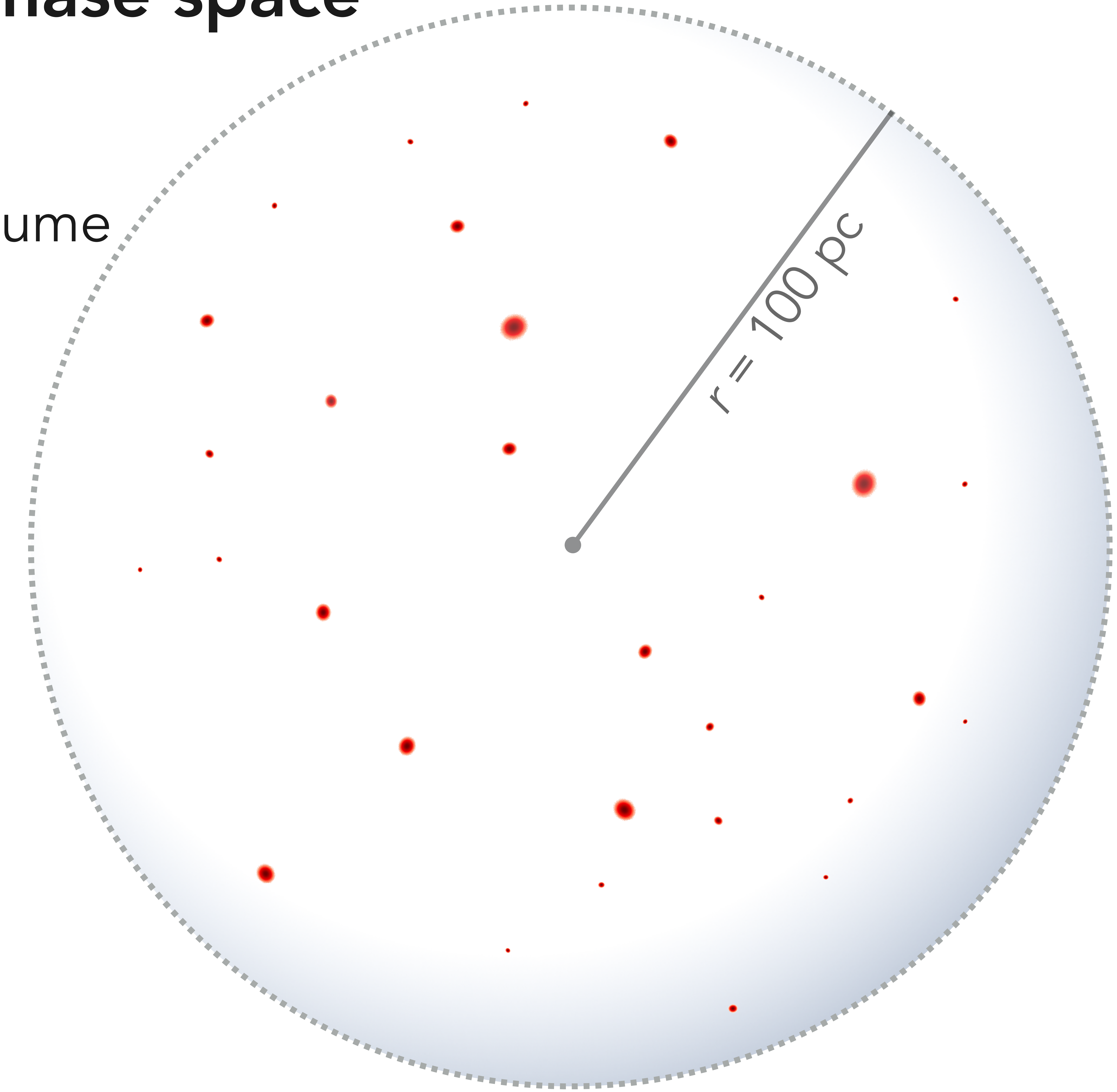

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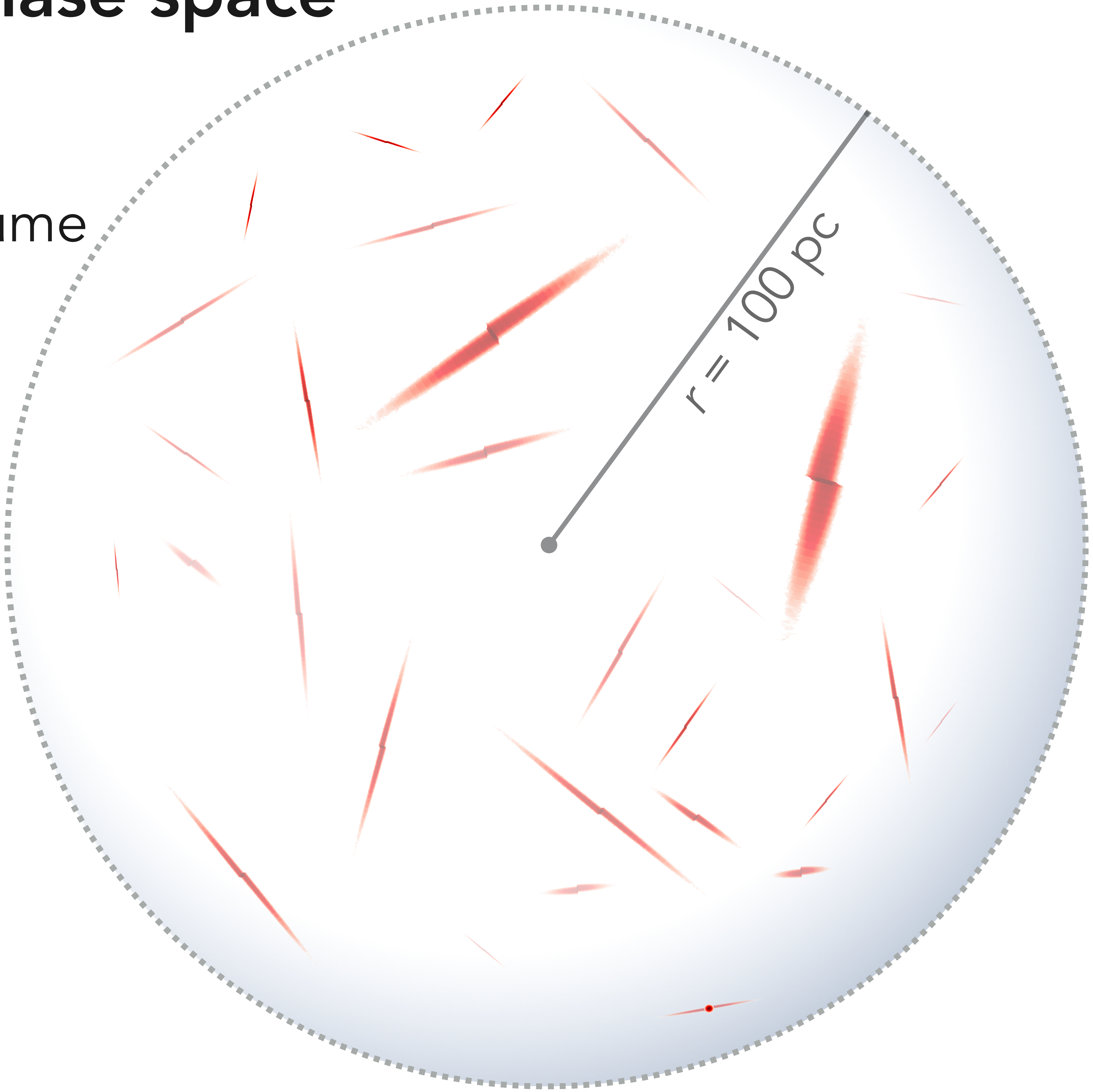
After disruption, MCs turn into extended ~pc-long streams. Volume filled with axions is enhanced by a factor of $\sim 10^4$



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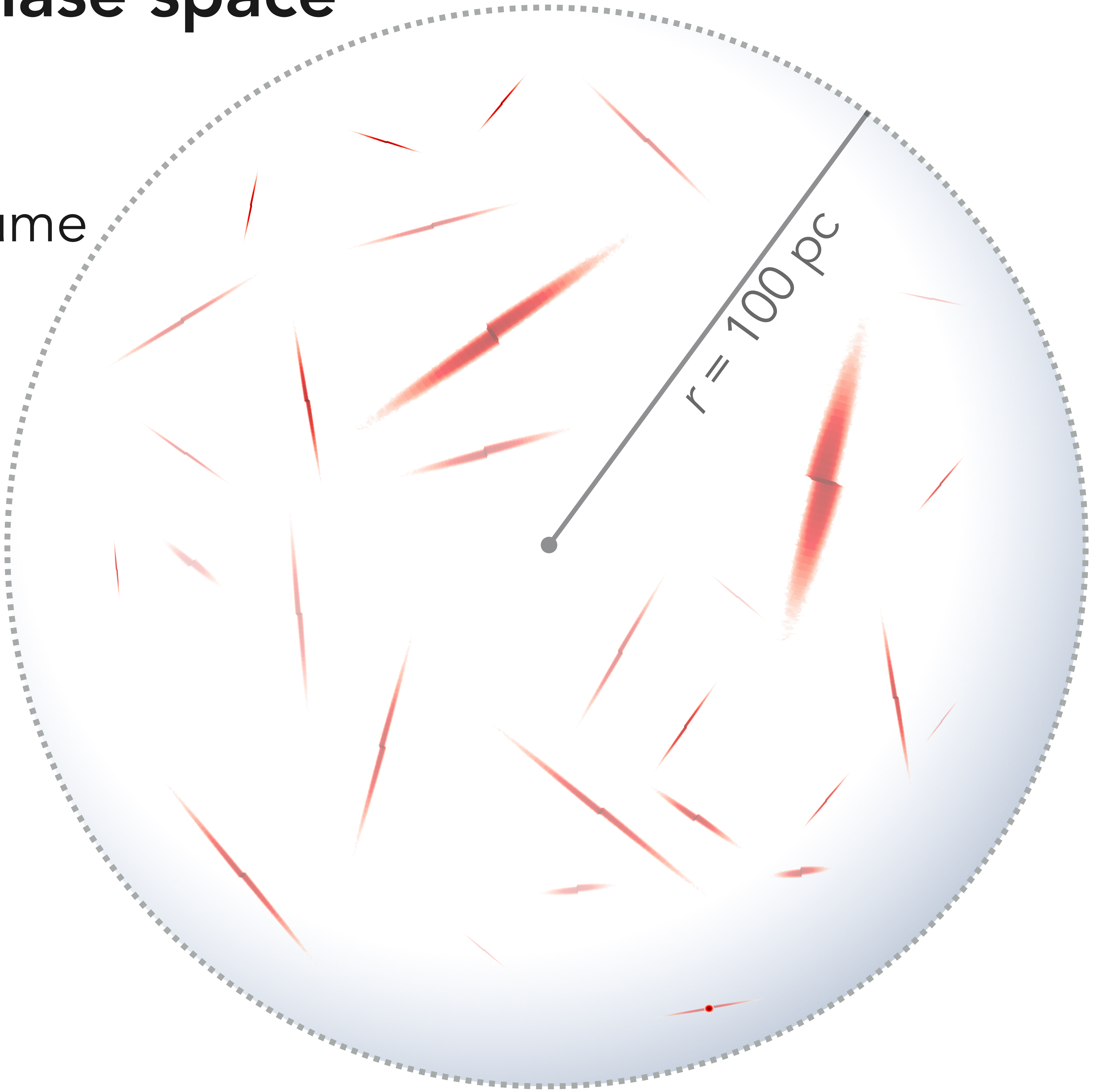
Q: How many streams overlap at a given position in the box?

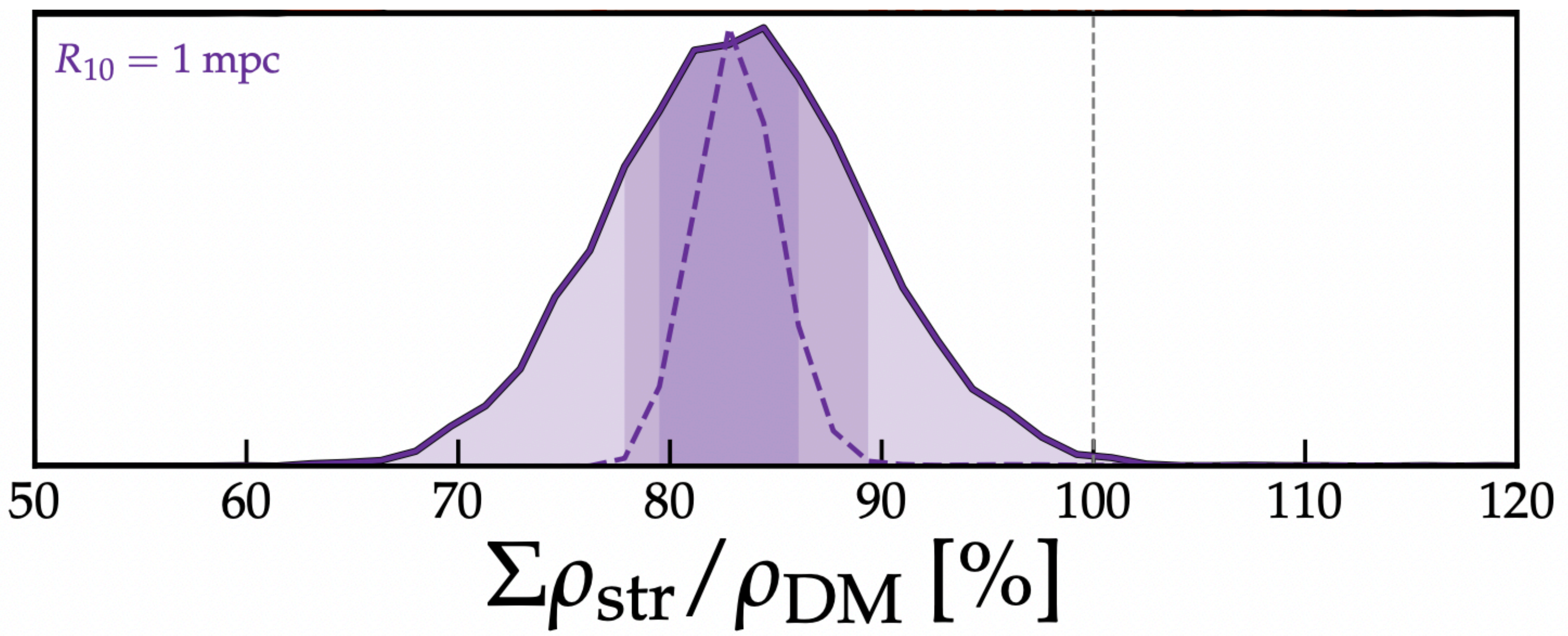
Q: How much is the density enhanced due to the re-filling of phase space

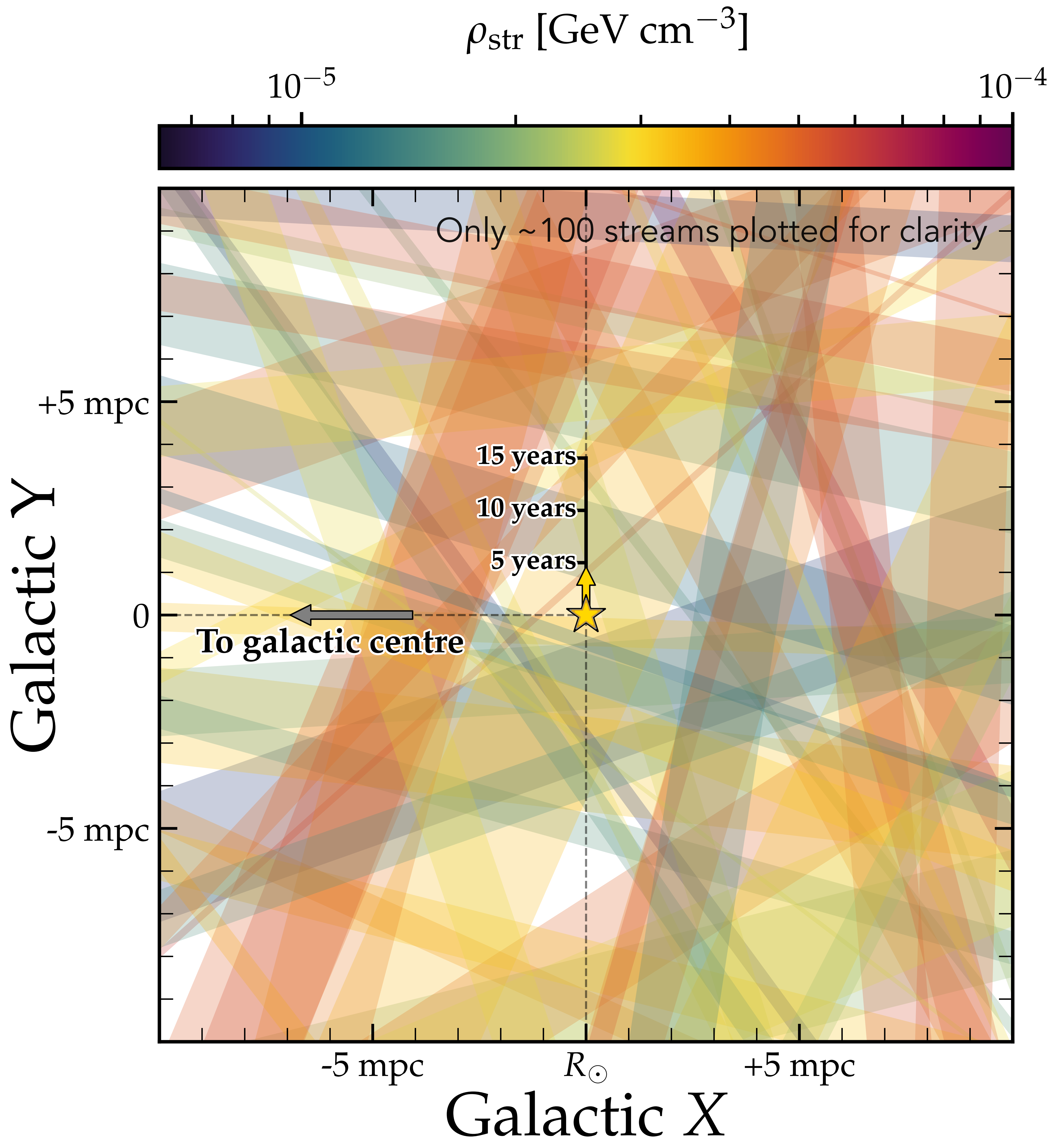


Axion streams at the Solar position

Answer: typically there are O(100-1000) tidal streams overlapping a given position. Vast majority do not contribute substantially to the density

Together they add up to ~70-90% of large-scale measured value of $\rho_{\rm DM}$



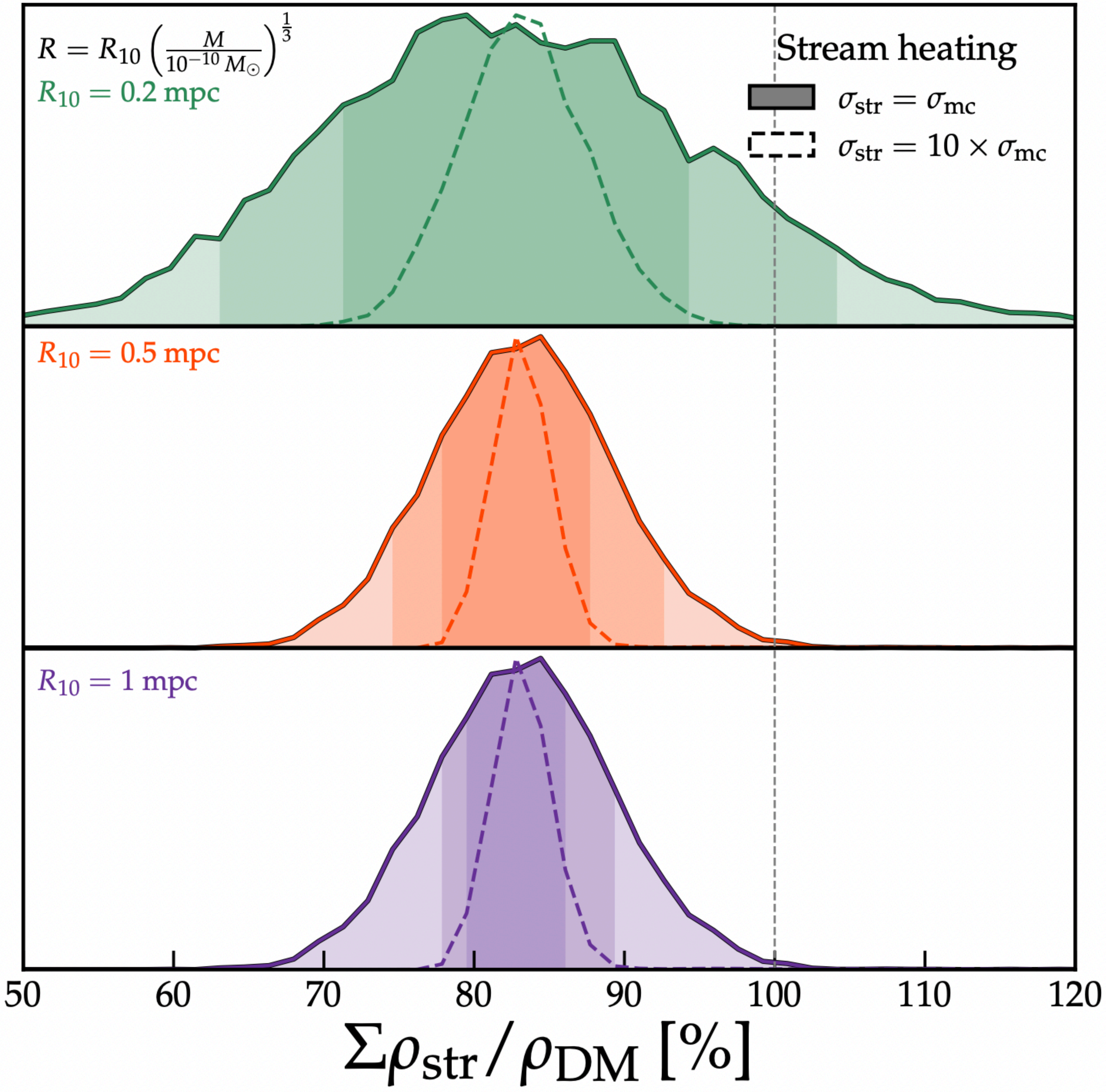


Uncertainties

We find very little dependence on the details of the mass function or the orbit models, which can be supported up with a back-of-the-envelope calculation. The only things that matter are:

→ That the most massive miniclusters are described by smooth NFW halos. If they are “clusters of miniclusters” they are probably more resiliant.

→ The NFW concentration parameter (or Mass-radius relation), which affects the variance in our answer.

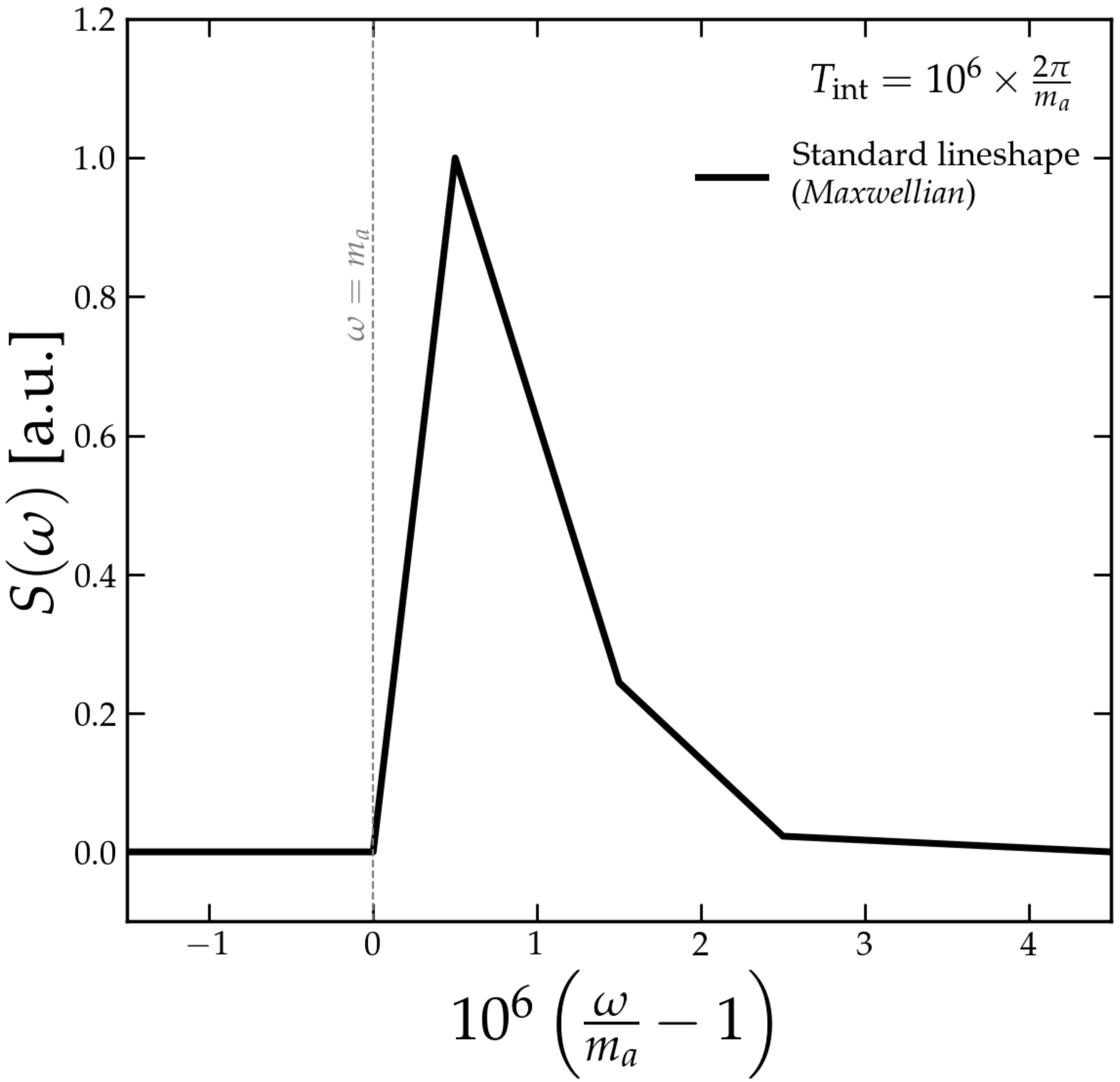


Haloscope signal

Signal $S(\omega) \propto$ discrete FT of timestream
Frequency resolution = $\Delta\omega \sim T_{\rm int}^{-1}$

The power spectrum of the oscillating axion signal in a haloscope have a distinct Maxwellian **lineshape**. Frequency resolution depends on the duration of the timestream samples that are put through a discrete Fourier transform in order to calculate that power spectrum

$$S(\omega) \propto \frac{\rho_{\rm DM}}{m_a^2} g_{a\gamma}^2 f(\omega)$$



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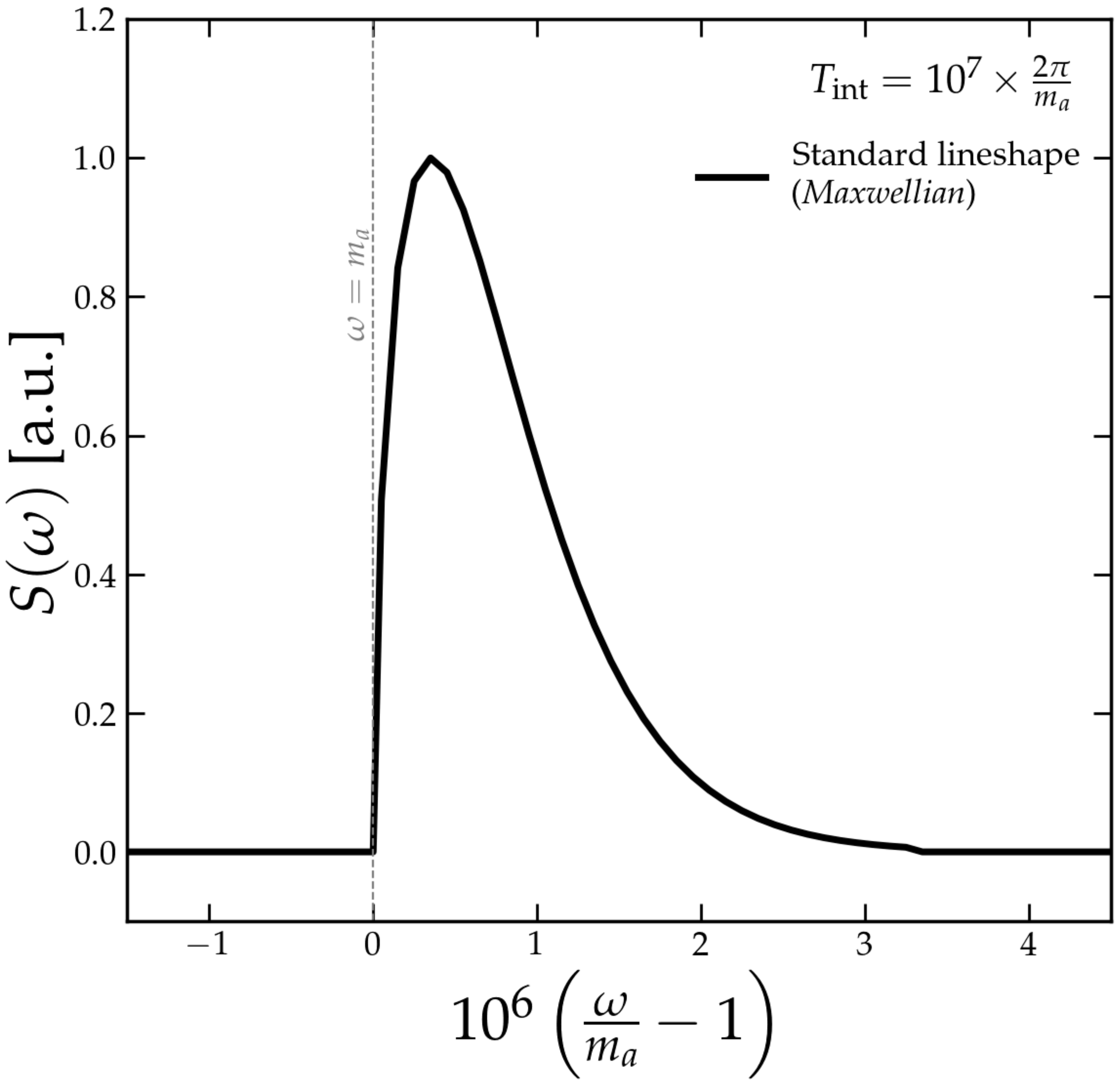

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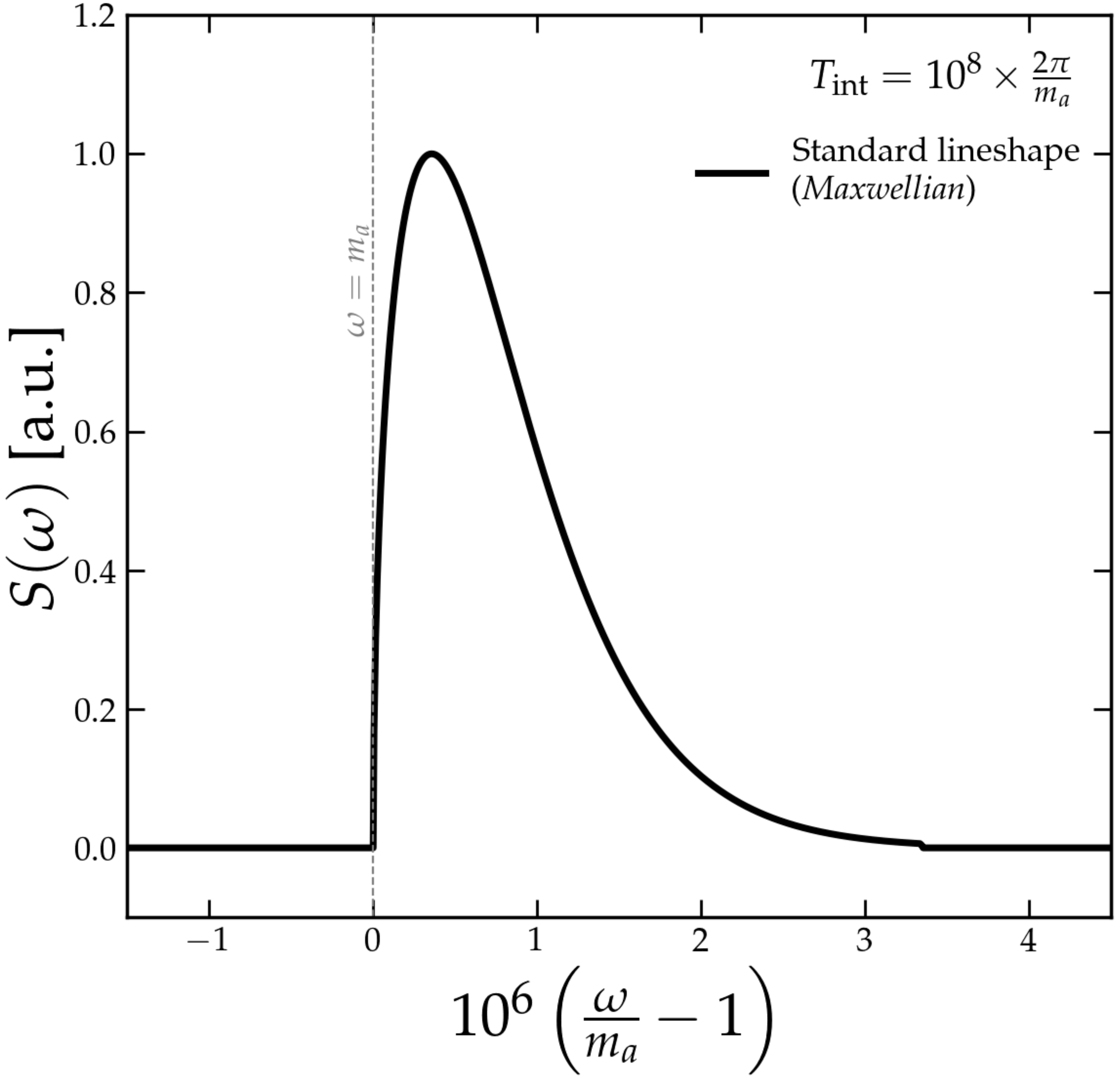

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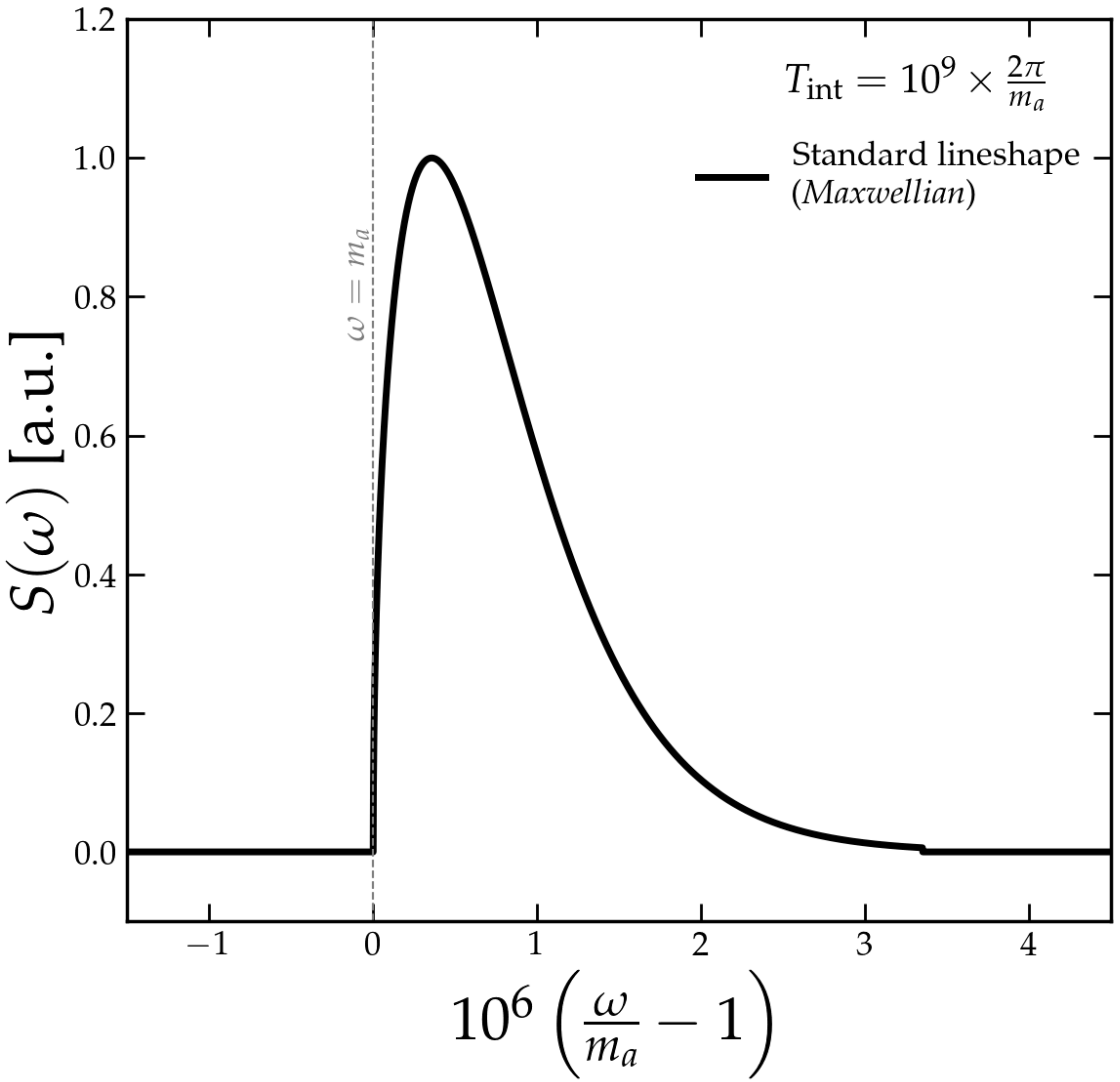

Haloscope signal

Disrupted minicluster **streams** are extremely cold ($\sigma < 1$ km/s) and do not contribute a significant density enhancement. However they become extremely prominent if lineshape is sufficiently well-resolved (long integration times)

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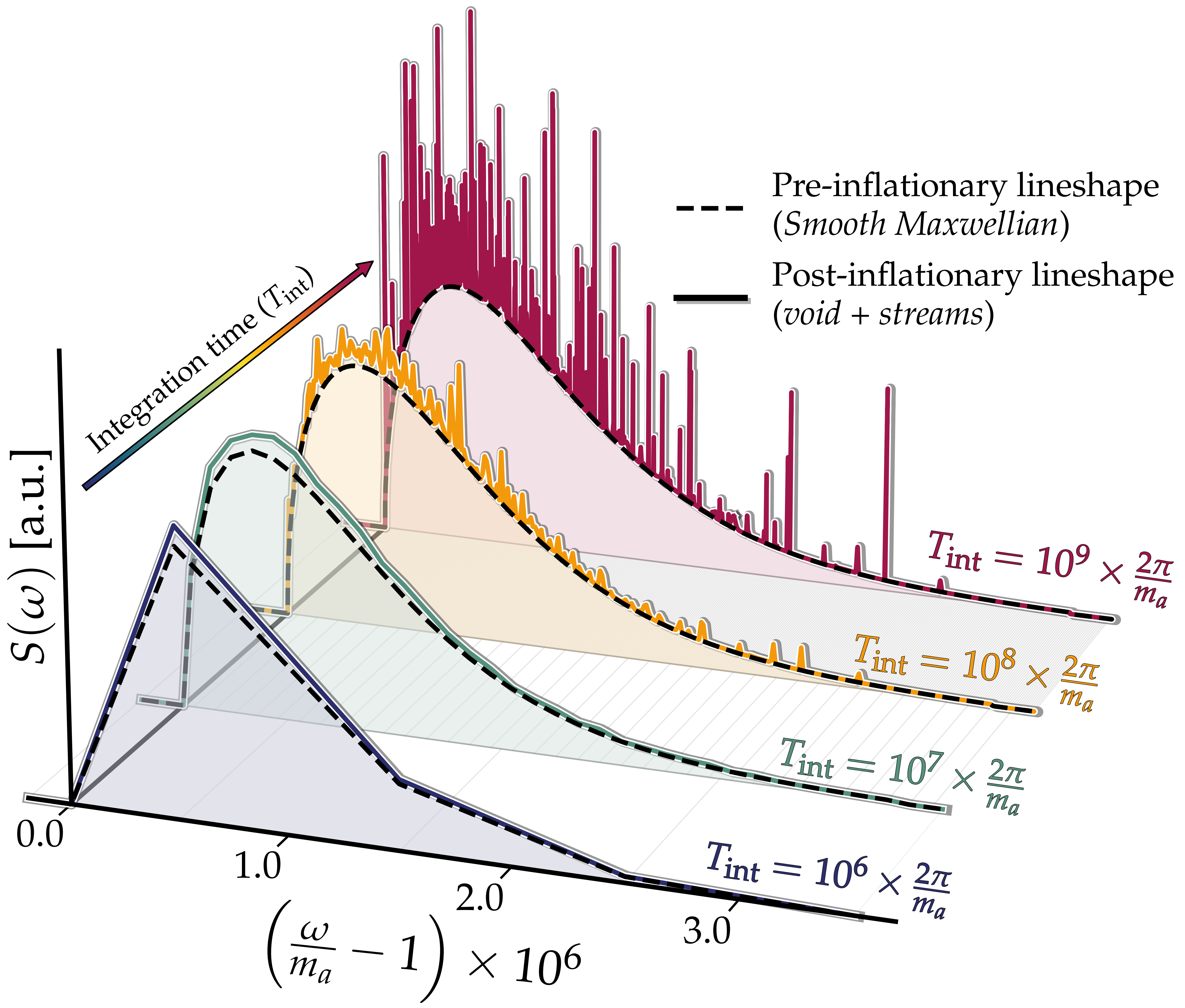

Haloscope signal

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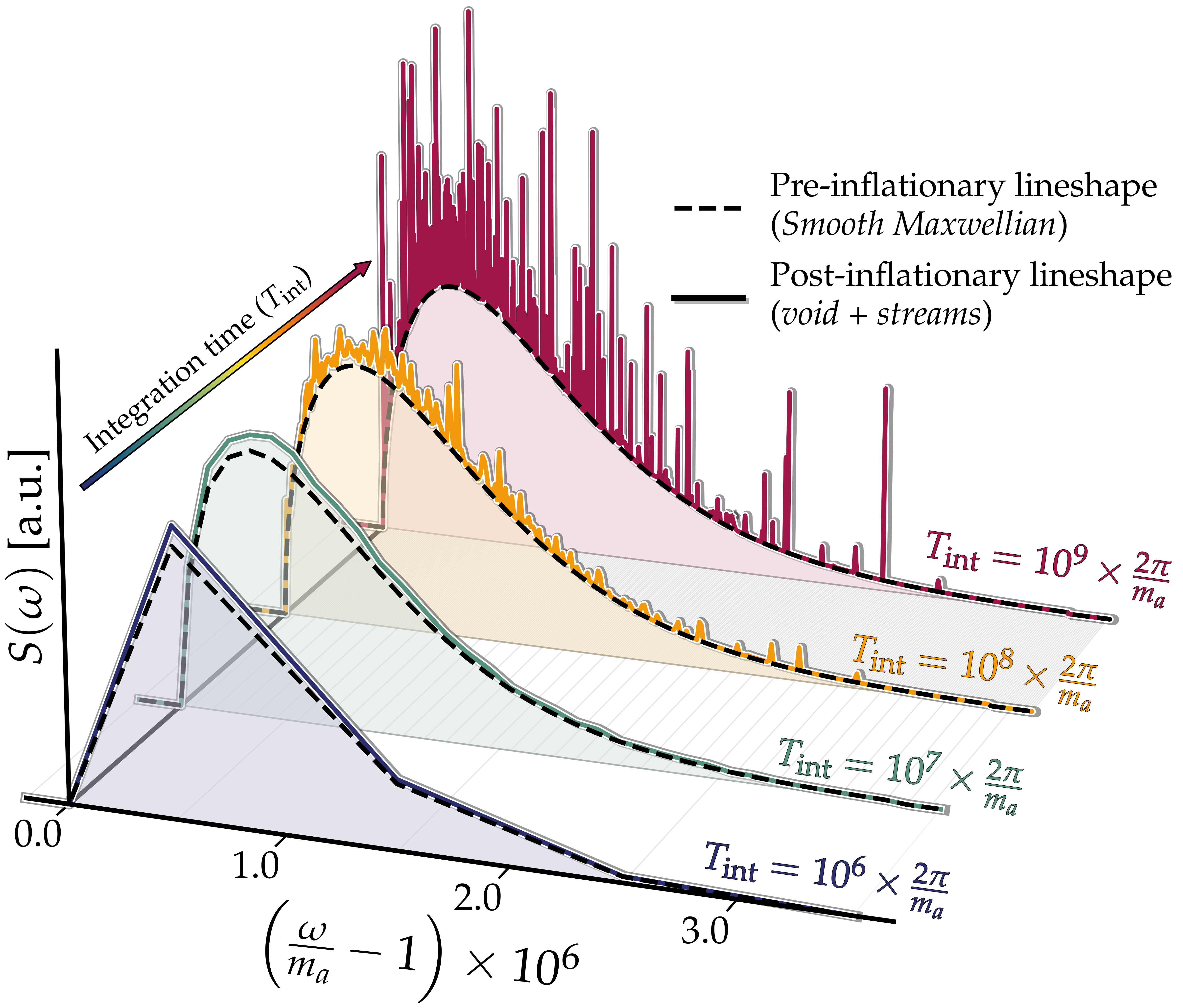
Some important observations:

- Streams only enhance the signal by $\rho_{\rm str}/\rho_{\rm void} \sim 7$, but can enhance it by many orders of magnitude more in the *resolved* lineshape in certain bins
- Many streams are narrower than daily modulation in lab motion $v \sim 0.47$ km/s
- Streams persist in lineshape $\mathcal{O}$(days-years) at a time

Signal $S(\omega) \propto$ discrete FT of timestream

Frequency resolution = $\Delta\omega \sim T_{\rm int}^{-1}$



Summary

- **Miniclusters, voids and streams** are a *consequence* of the post-inflationary axion dark matter scenario so cannot be ignored

- Ignoring tidal disruption, the worst-case scenario is that we are in a minivoid which have only about ~10% of $\rho_{\rm DM}$ (suppression in $g_{a\gamma}$ by a factor of 3)

- Accounting for tidal disruption, phase space at Solar position re-filled by a factor of 6, to about 70% of $\rho_{\rm DM}$ (suppression in $g_{a\gamma}$ by a factor of 1.2)

- $\mathcal{O}$(1000) ultra-cold tidal streams present in axion lineshape at any one time that persist for $\mathcal{O}$(days—years) at a time

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