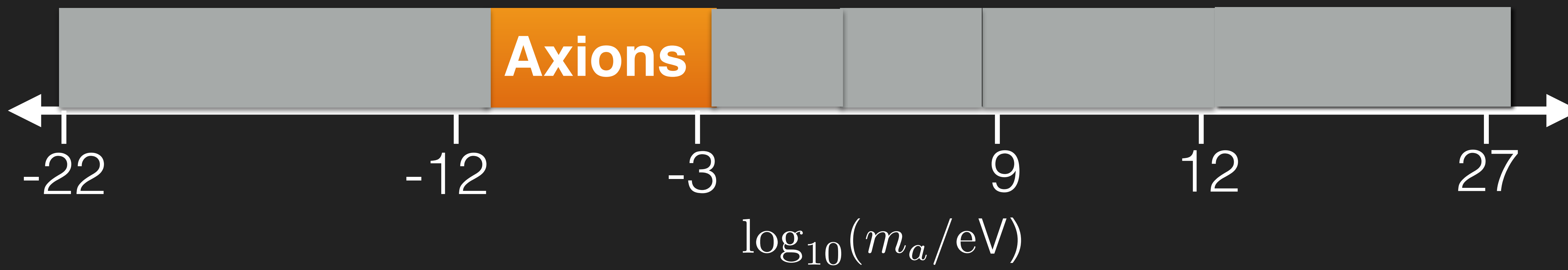
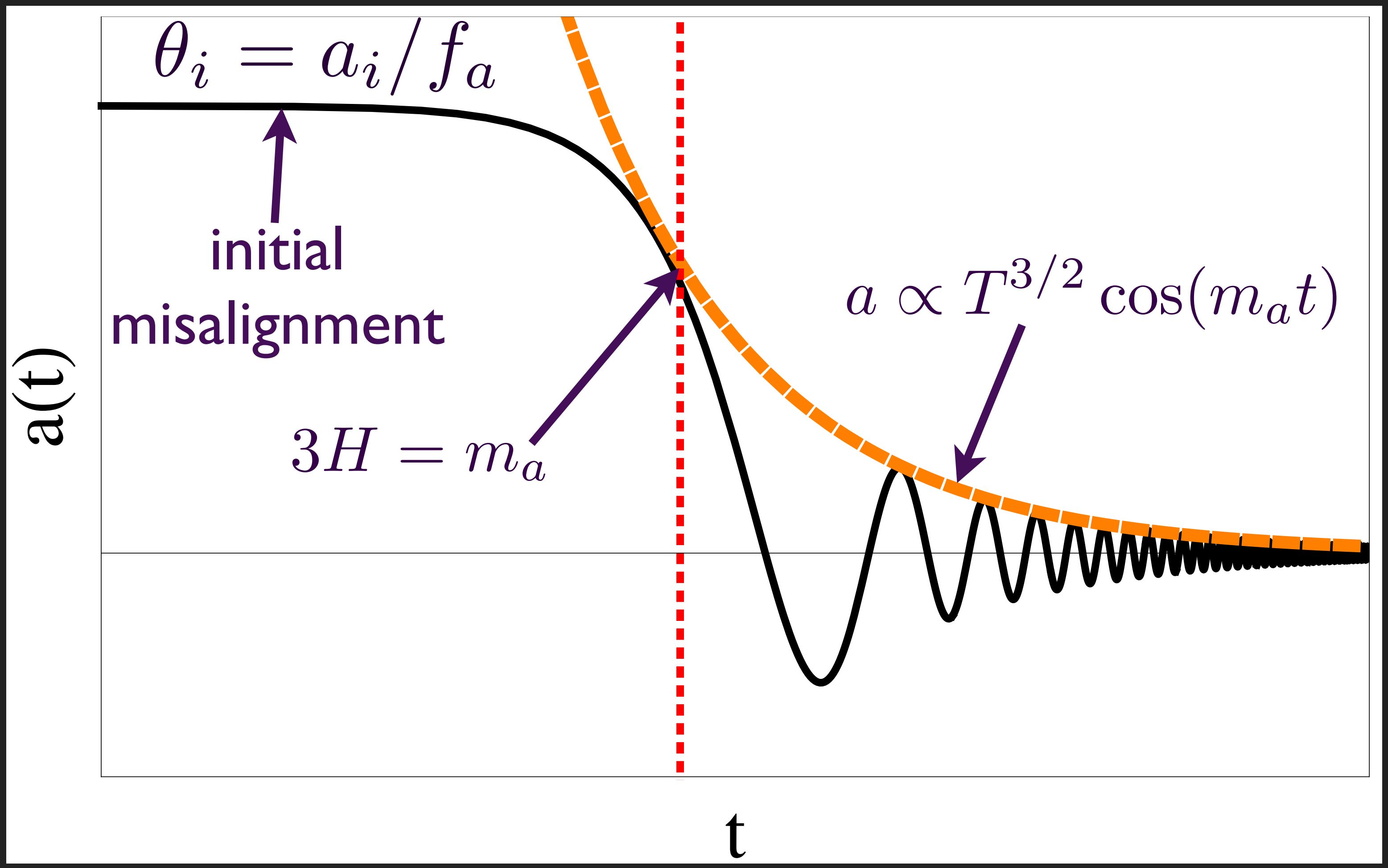
THE QCD AXION MASS

BEN SAFDI

BERKELEY CENTER FOR THEORETICAL PHYSICS
UNIVERSITY OF CALIFORNIA, BERKELEY



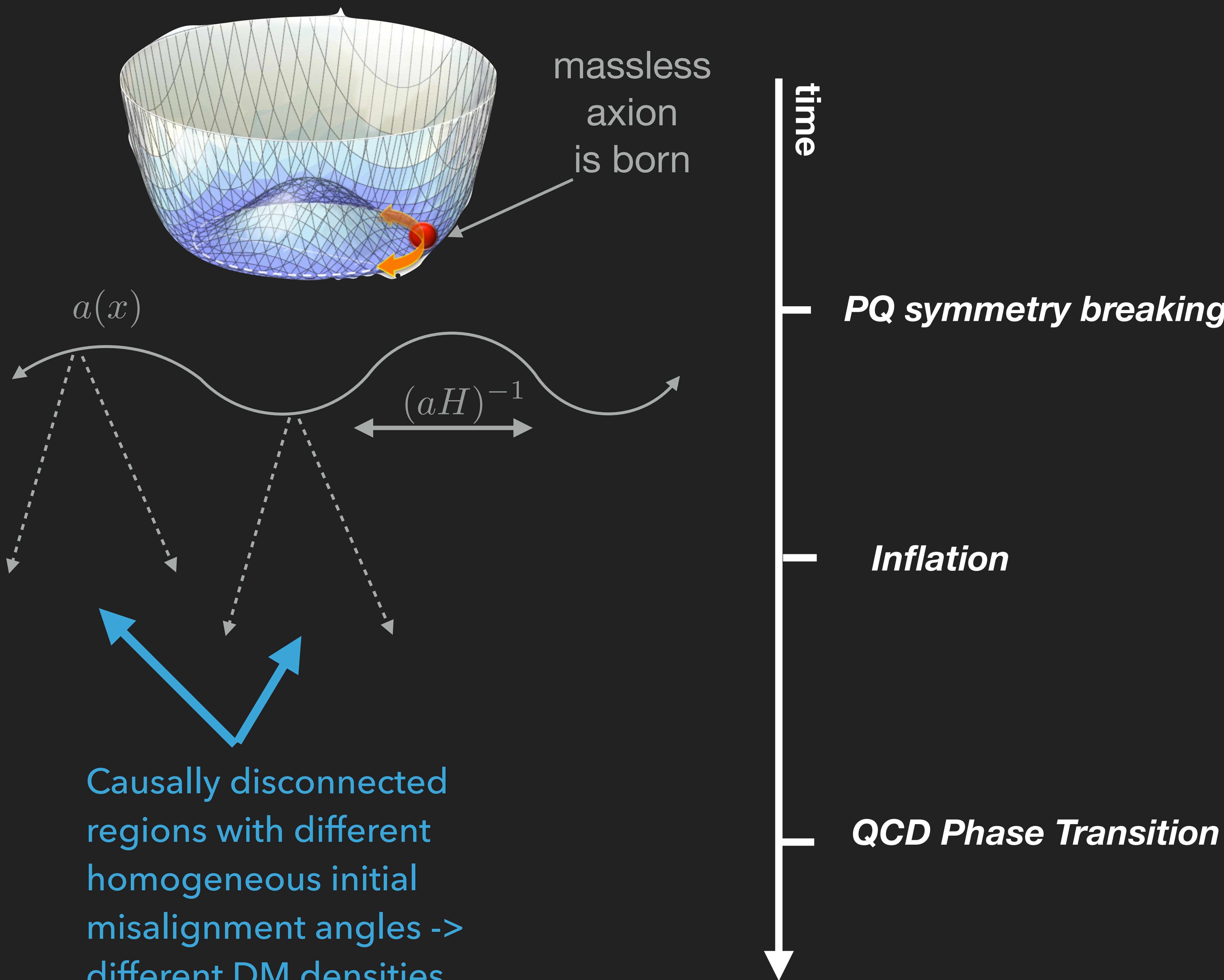
$$\sin a/f_a \sim a/f_a \;:\qquad \ddot{a} + 3H\dot{a} + m_a^2 a = 0$$



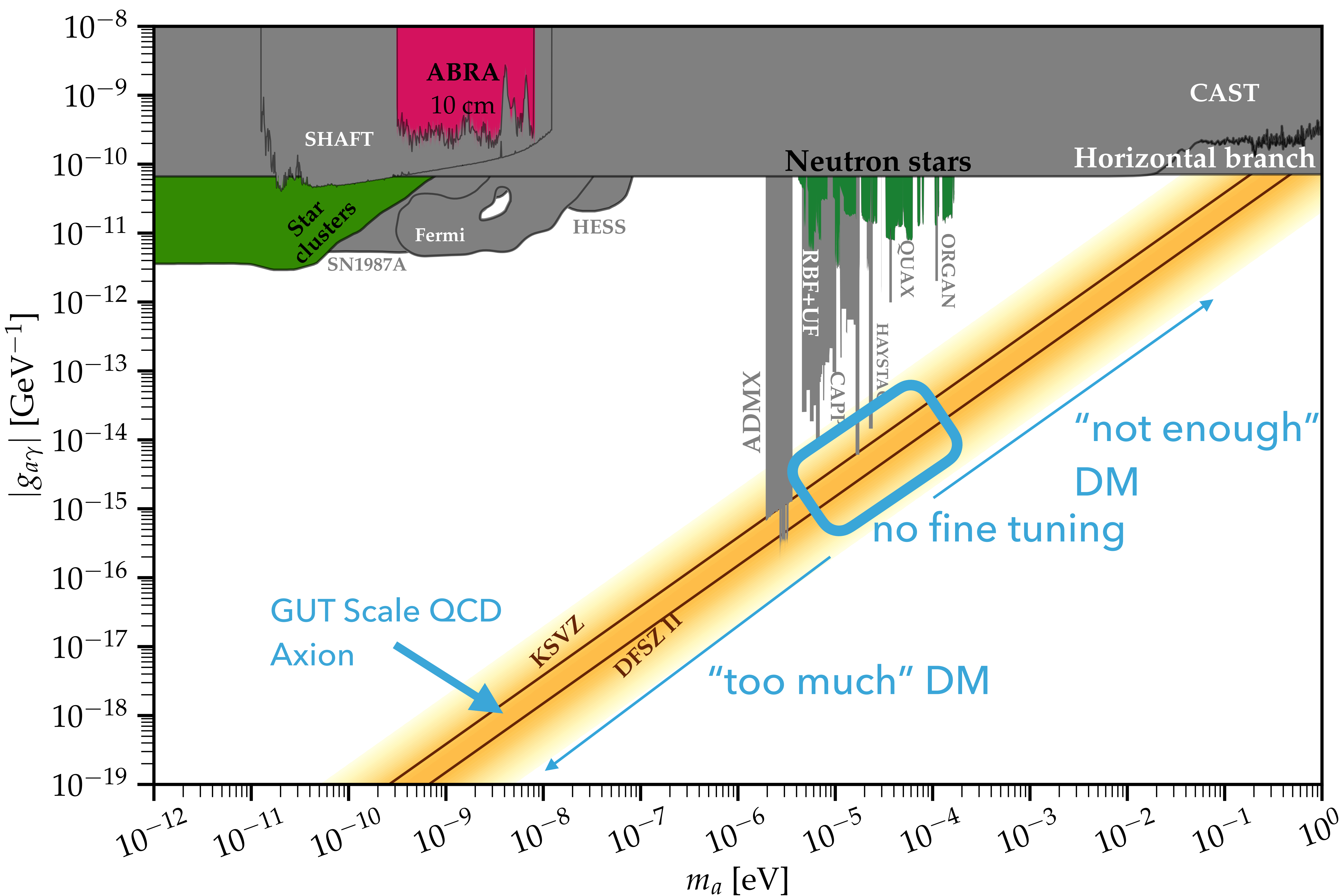
PQ broken
before inflation!

$$\Omega_a h^2 \sim 0.1 \left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{7/6} \theta_i^2$$

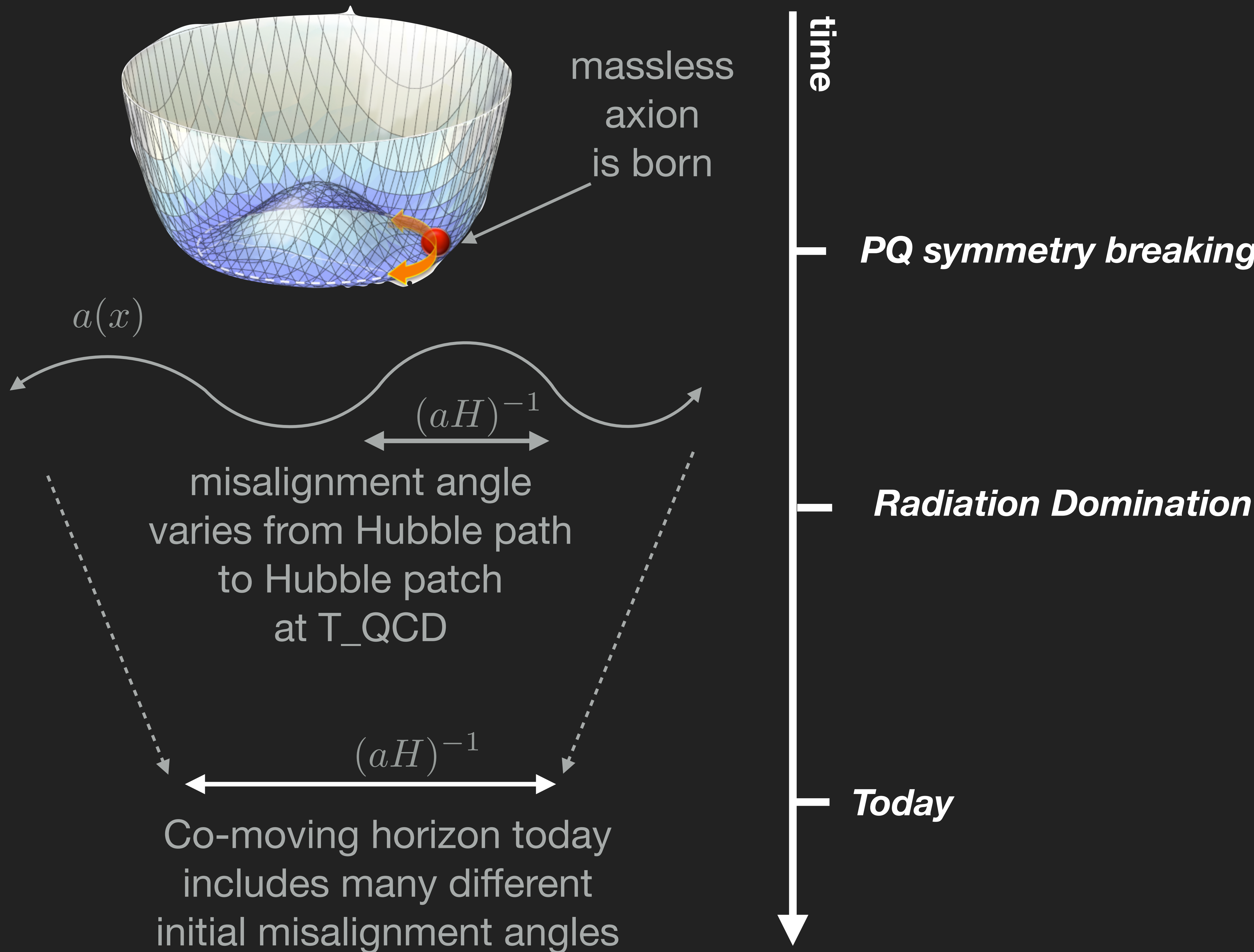
Axion generated before inflation



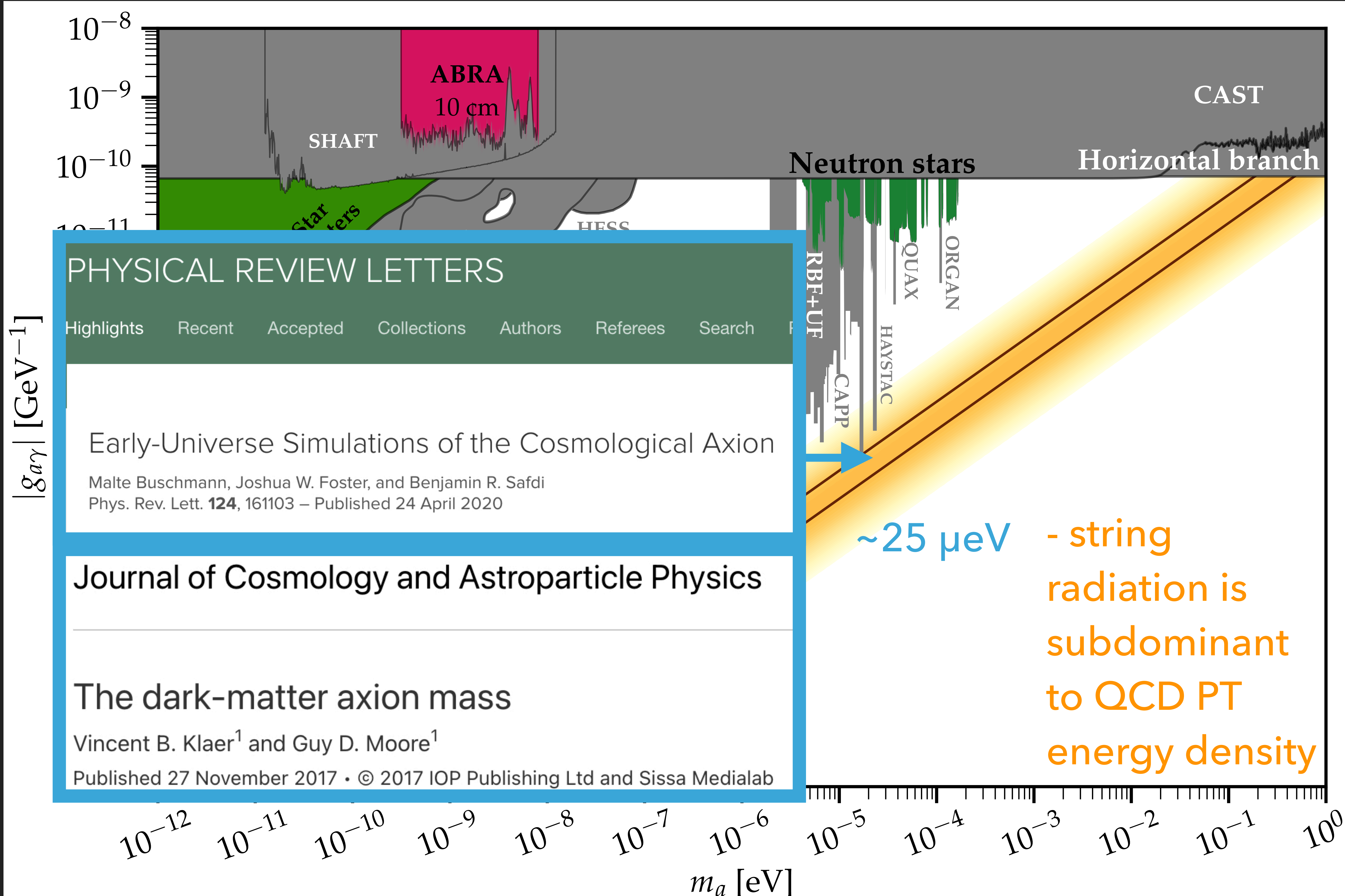
PQ Broken Before Inflation



Axion generated after inflation



What does the literature say?



PHYSICAL REVIEW LETTERS

Highlights Recent Accepted Collections Authors Referees Search

Early-Universe Simulations of the Cosmological Axion

Malte Buschmann, Joshua W. Foster, and Benjamin R. Safdi
Phys. Rev. Lett. **124**, 161103 – Published 24 April 2020

Journal of Cosmology and Astroparticle Physics

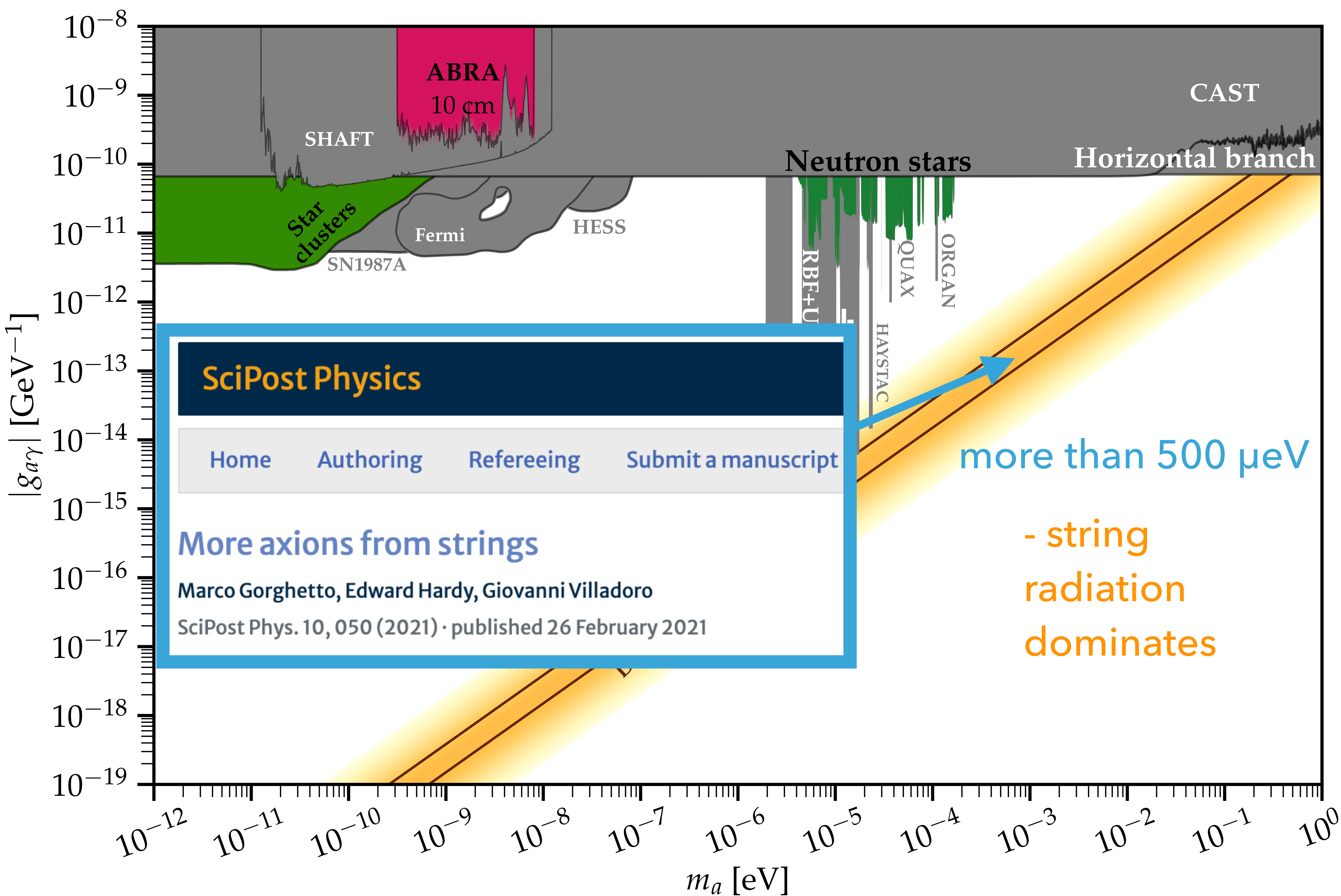
The dark-matter axion mass

Vincent B. Klaer[1] and Guy D. Moore[1]
Published 27 November 2017 • © 2017 IOP Publishing Ltd and Sissa Medialab

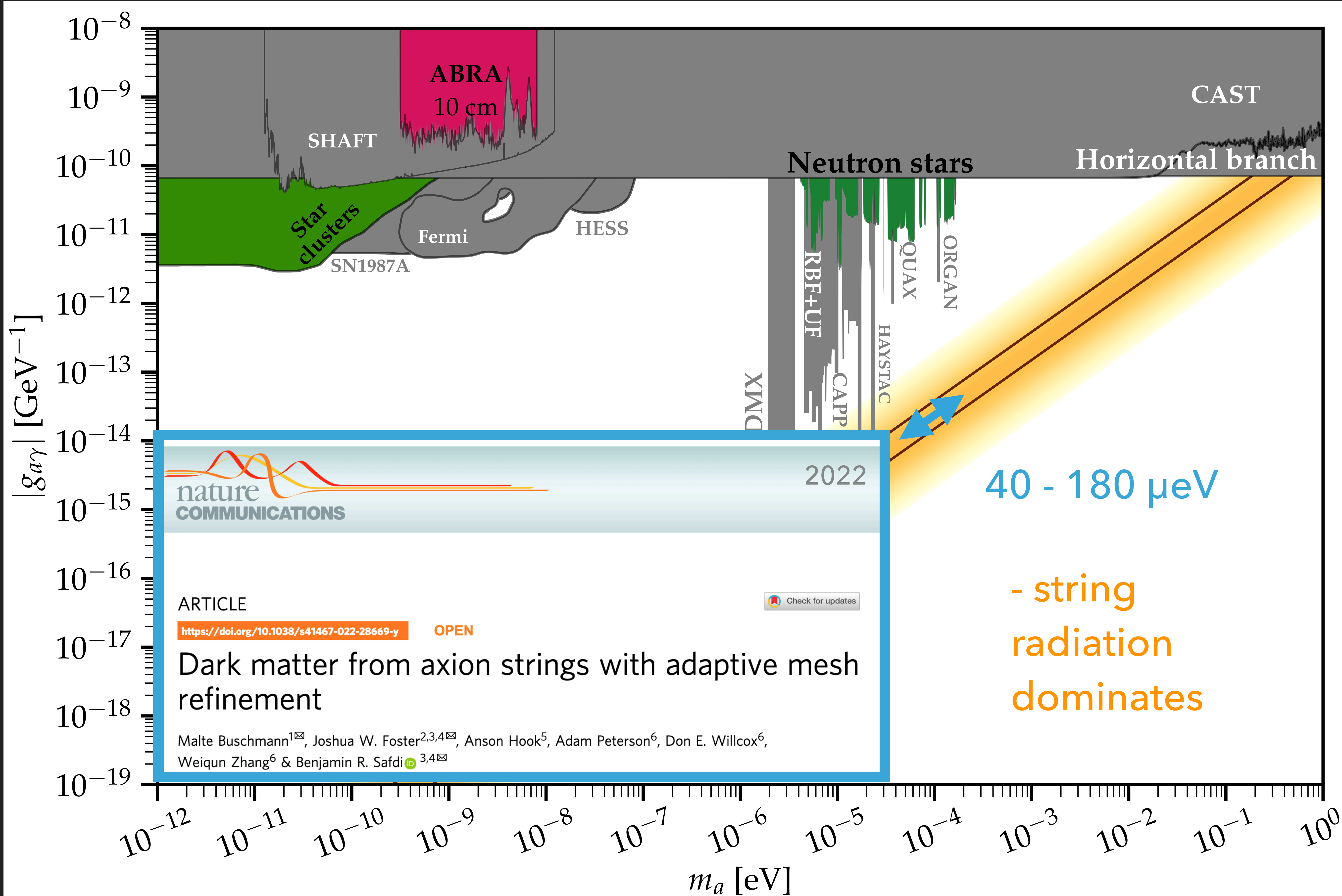
~25 μeV

- string radiation is subdominant to QCD PT energy density

What does the literature say?



What does the literature say?

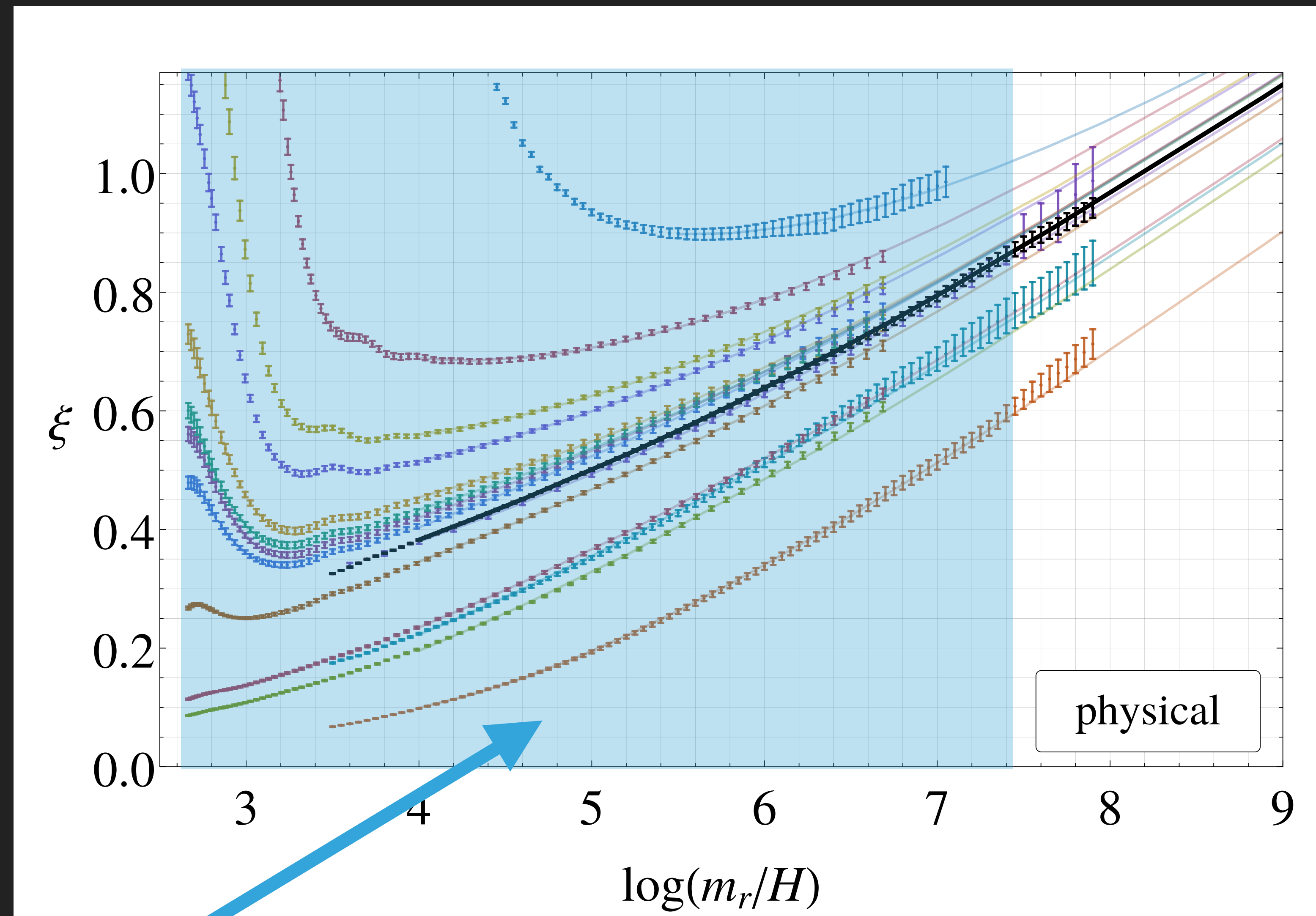


Why? Two reasons

1. strings per Hubble increases logarithmically with time

A good point!

we can only simulate at small log



PHYSICAL REVIEW LETTERS

Highlights Recent Accepted Collections Authors Referees Search

Early-Universe Simulations of the Cosmological Axion

Malte Buschmann, Joshua W. Foster, and Benjamin R. Safdi
Phys. Rev. Lett. **124**, 161103 – Published 24 April 2020

SciPost Physics

Home Authoring Refereeing Submit a manuscript

More axions from strings

Marco Gorghetto, Edward Hardy, Giovanni Villadoro

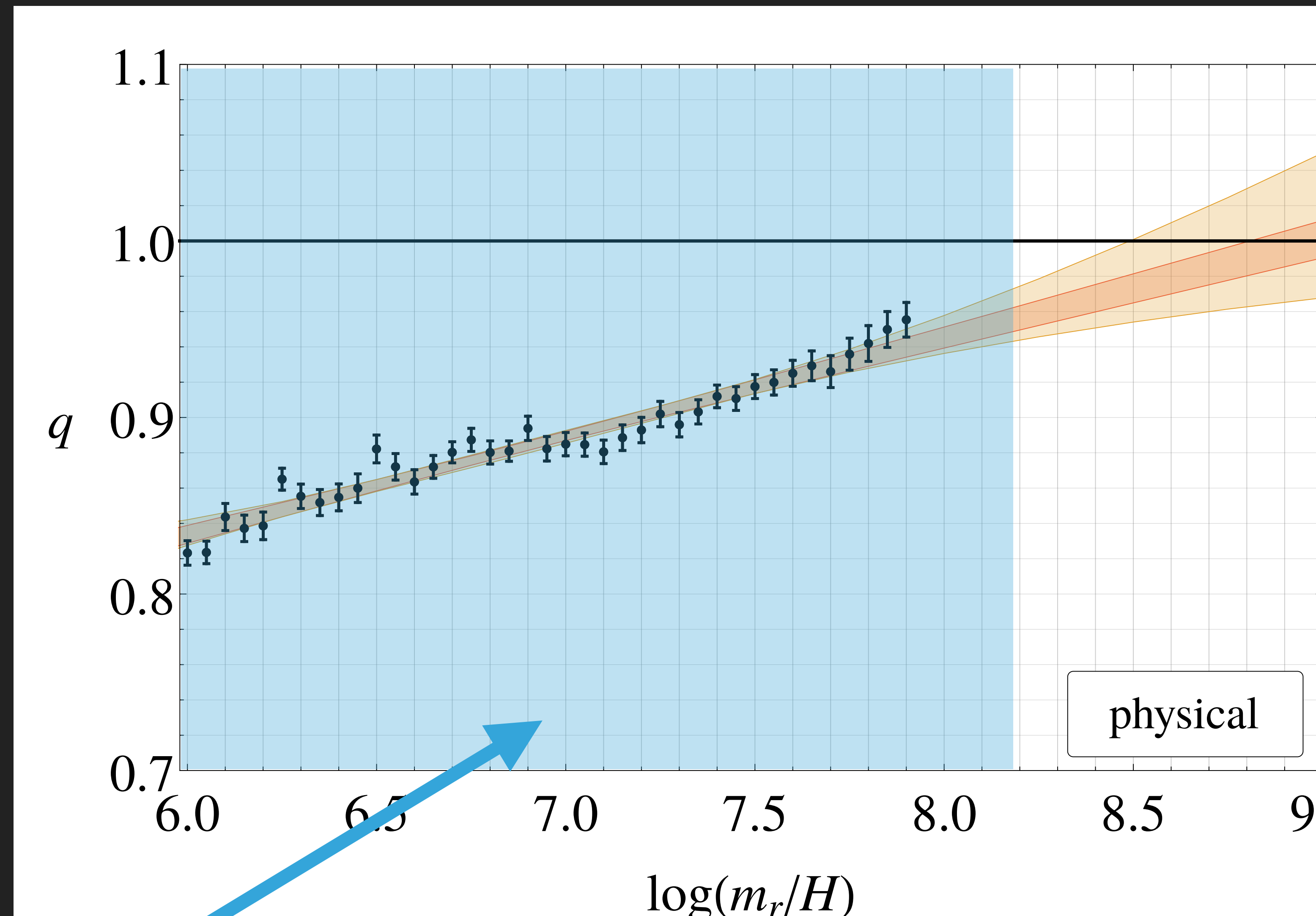
SciPost Phys. 10, 050 (2021) · published 26 February 2021

Why? Two reasons

2. strings radiate more in the IR with time

$$\frac{\partial \rho}{\partial k} \sim \frac{1}{k^q}$$

We do not seem to confirm this! (but also only marginally rule it out)



we can only simulate at small log

PHYSICAL REVIEW LETTERS

Highlights Recent Accepted Collections Authors Referees Search

Early-Universe Simulations of the Cosmological Axion

Malte Buschmann, Joshua W. Foster, and Benjamin R. Safdi
Phys. Rev. Lett. **124**, 161103 – Published 24 April 2020

SciPost Physics

Home Authoring Refereeing Submit a manuscript

More axions from strings

Marco Gorghetto, Edward Hardy, Giovanni Villadoro
SciPost Phys. 10, 050 (2021) · published 26 February 2021

Axion generated after inflation

M. Buschmann, J. Foster, **B.S.** PRL 2020

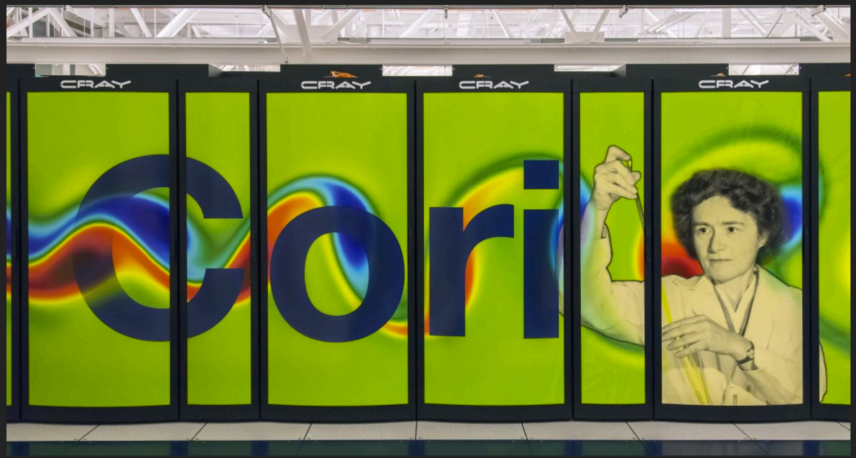
Simulate on static grid with ~10^{10} sites

Simulate from PQ phase transition to matter-radiation equality

M. Buschmann, J. Foster, **B.S.,** A. Hook, AMReX Collaboration, Nature Communications (Feb. 2022)

Simulate on adaptive grid equiv. to static grid with ~10^{15} sites

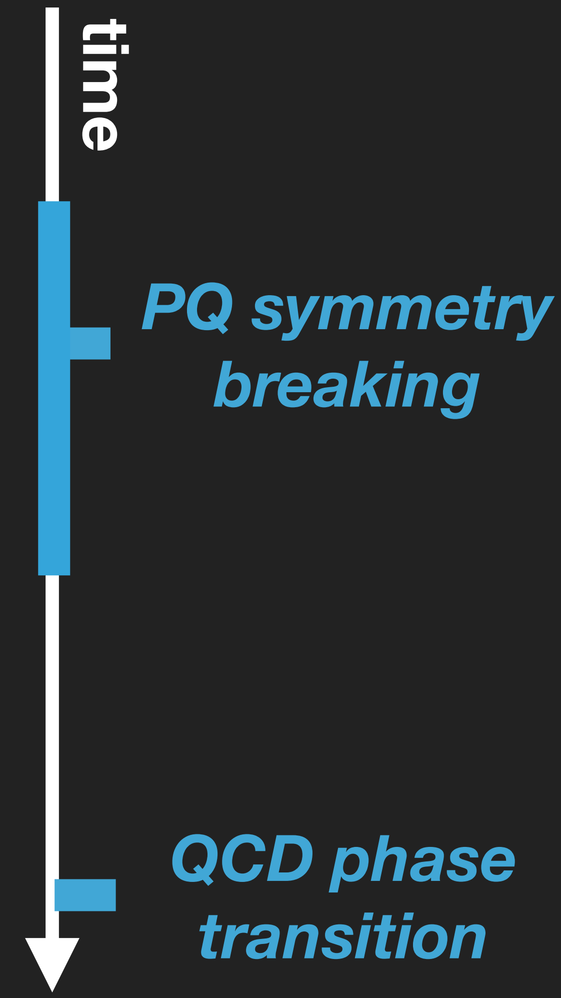
NERSC National Energy Research Scientific Computing Center



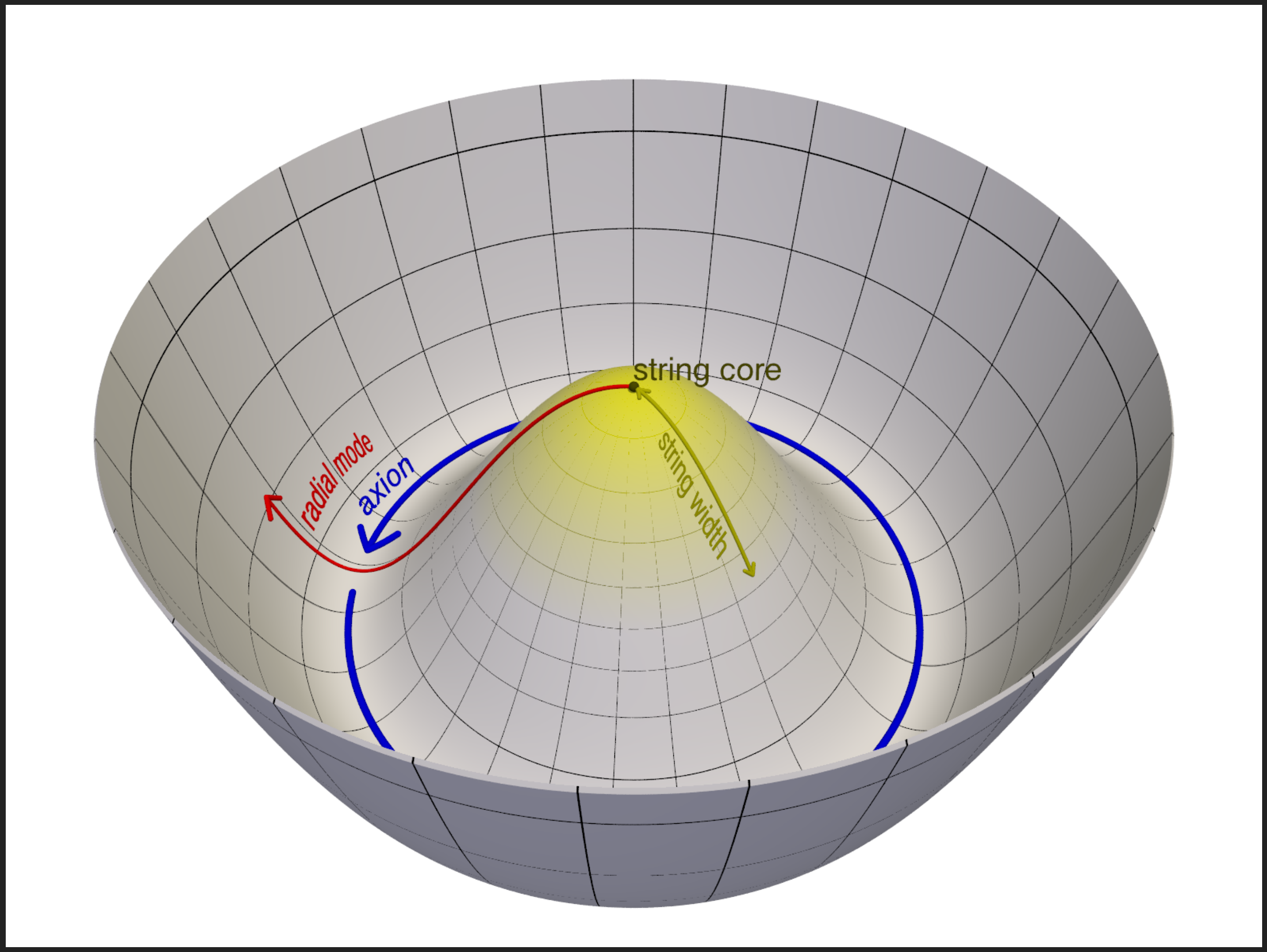
U.S. DEPARTMENT OF ENERGY | Office of Science

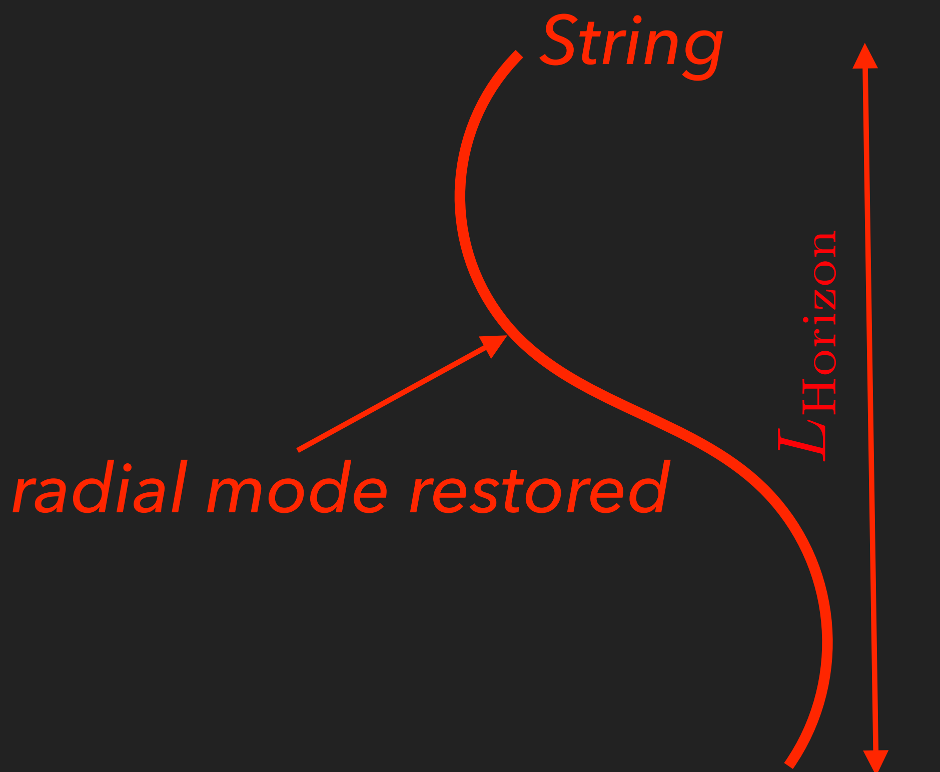
Axion dark matter primarily produced from strings

$$\mathcal{L}_{\rm PQ} = \frac{1}{2}|\partial\Phi|^2 - \frac{\lambda}{4}\left(|\Phi|^2 - f_a^2\right)^2 - \frac{\lambda T^2}{6}|\Phi|^2$$



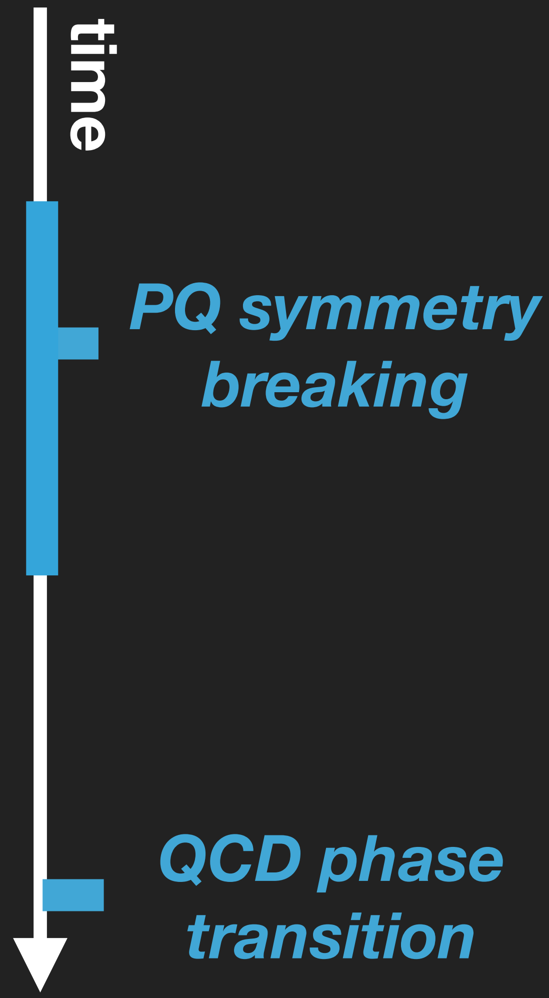
- symmetry broken for $T \lesssim f_a$
- write $\Phi(x) = \frac{r(x) + f_a}{\sqrt{2}} e^{ia(x)/f_a}$
- radial mode acquires mass: $m_r \sim \sqrt{\lambda} f_a$ (take $\lambda \sim 1$)





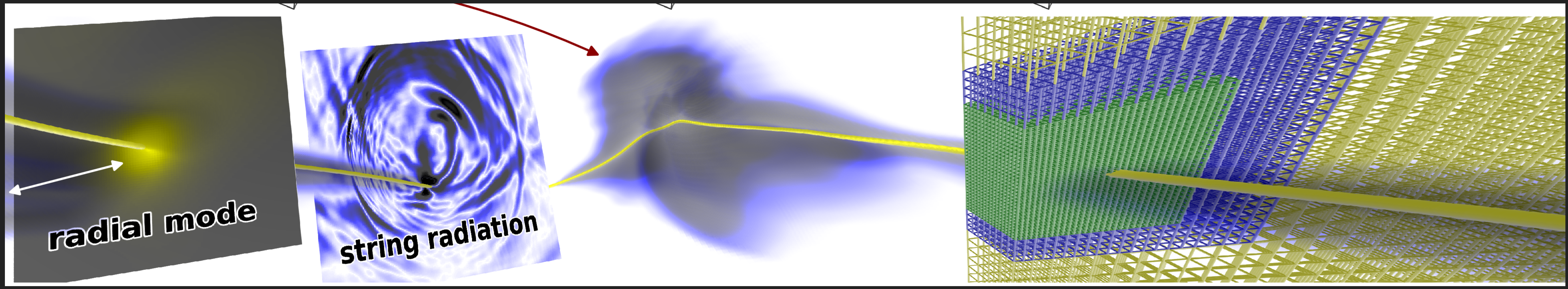
Axion dark matter primarily produced from strings

$$\mathcal{L}_{\rm PQ} = \frac{1}{2}|\partial\Phi|^2 - \frac{\lambda}{4}\left(|\Phi|^2 - f_a^2\right)^2 - \frac{\lambda T^2}{6}|\Phi|^2$$

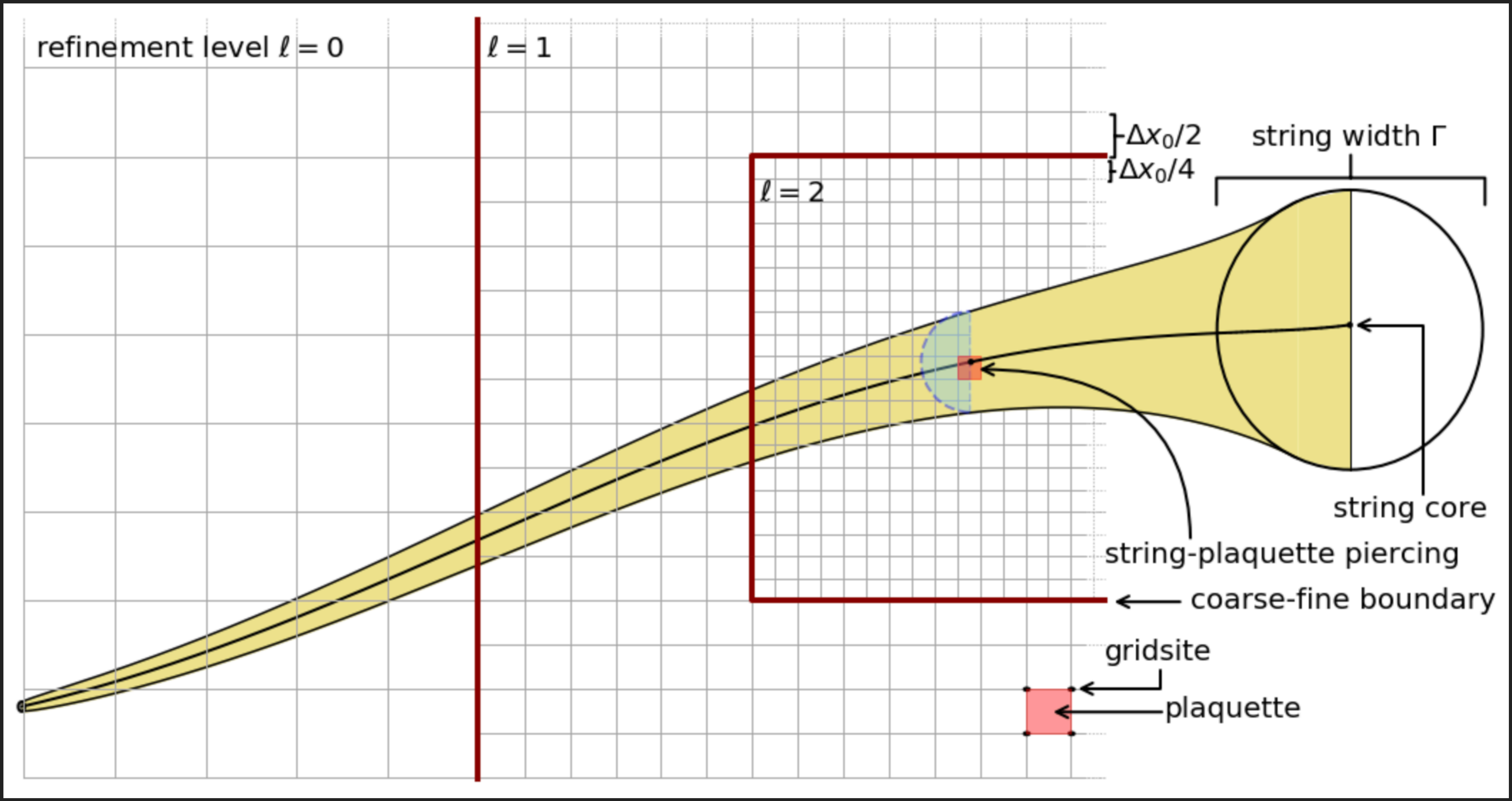


- symmetry broken for $T \lesssim f_a$
- write $\Phi(x) = \frac{r(x) + f_a}{\sqrt{2}} e^{ia(x)/f_a}$
- radial mode acquires mass: $m_r \sim \sqrt{\lambda} f_a$ (take $\lambda \sim 1$)
- Adaptive mesh to maintain high resolution around strings
- 6e6 CPU-hours over ~100,000 CPUs and ~100 TB RAM
- Goal: measure axion radiation from strings to compute DM abundance

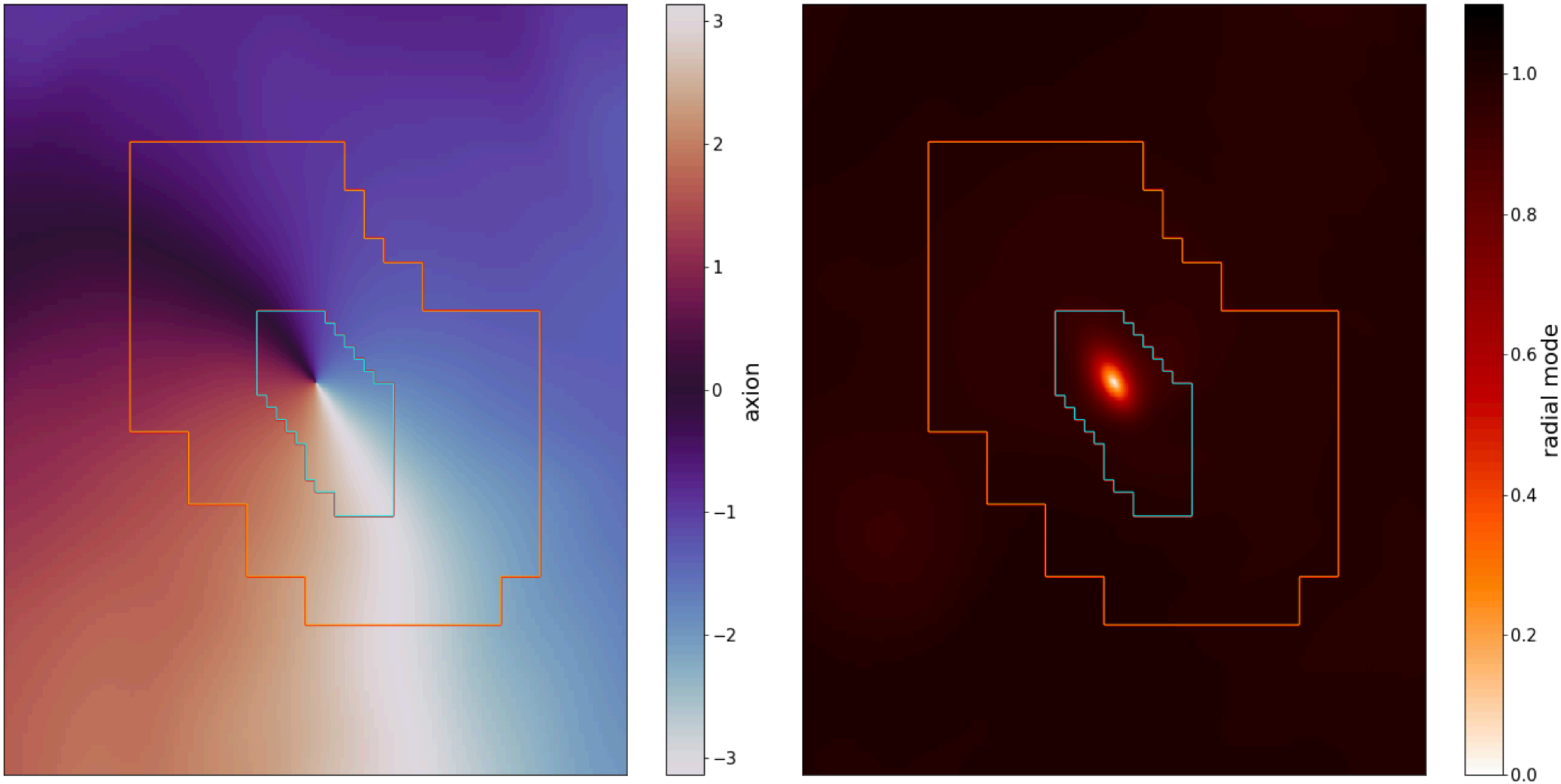
Adaptive mesh



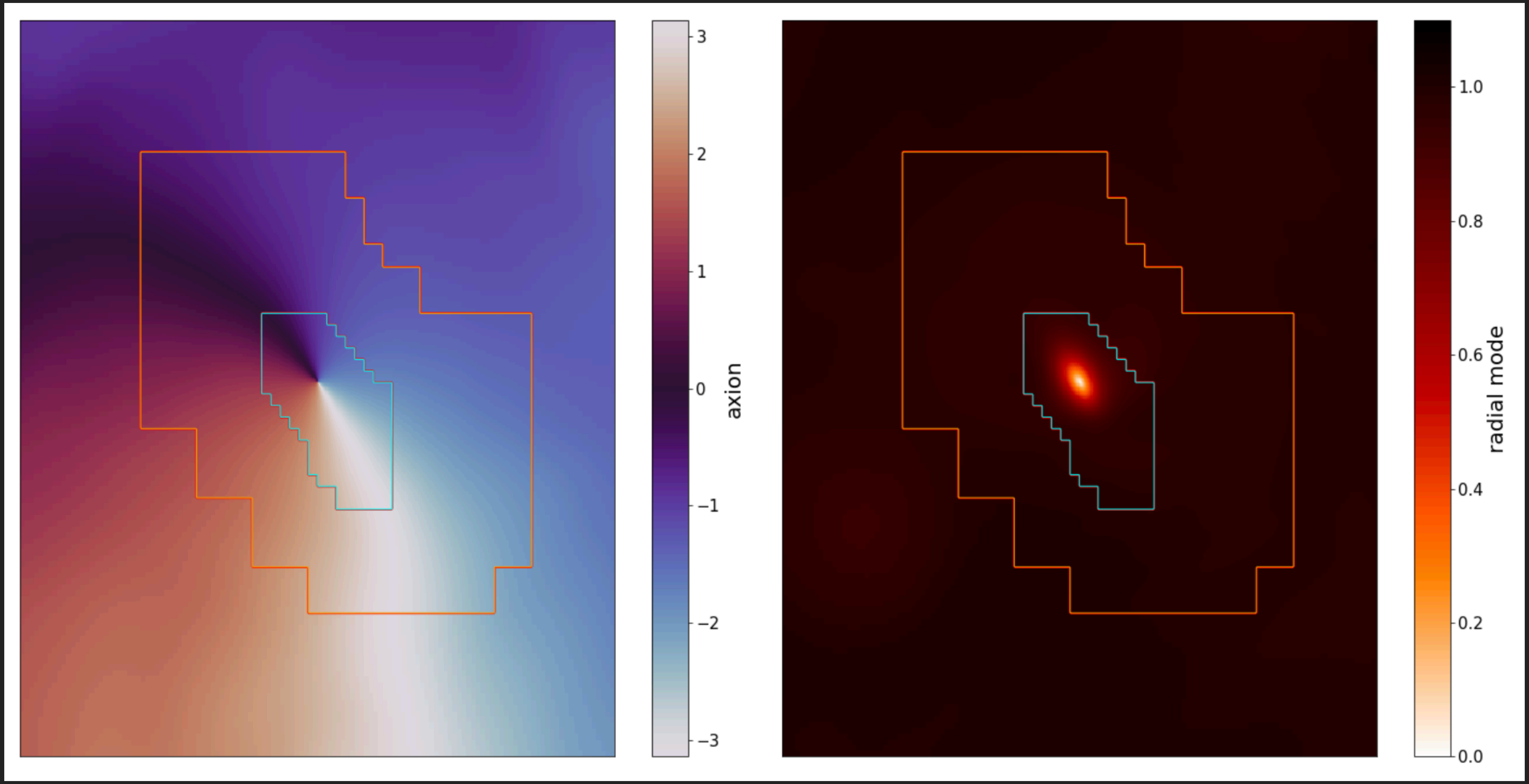
Answer with Adaptive Mesh Refinement Simulations (AMReX)



Answer with Adaptive Mesh Refinement Simulations (AMReX)

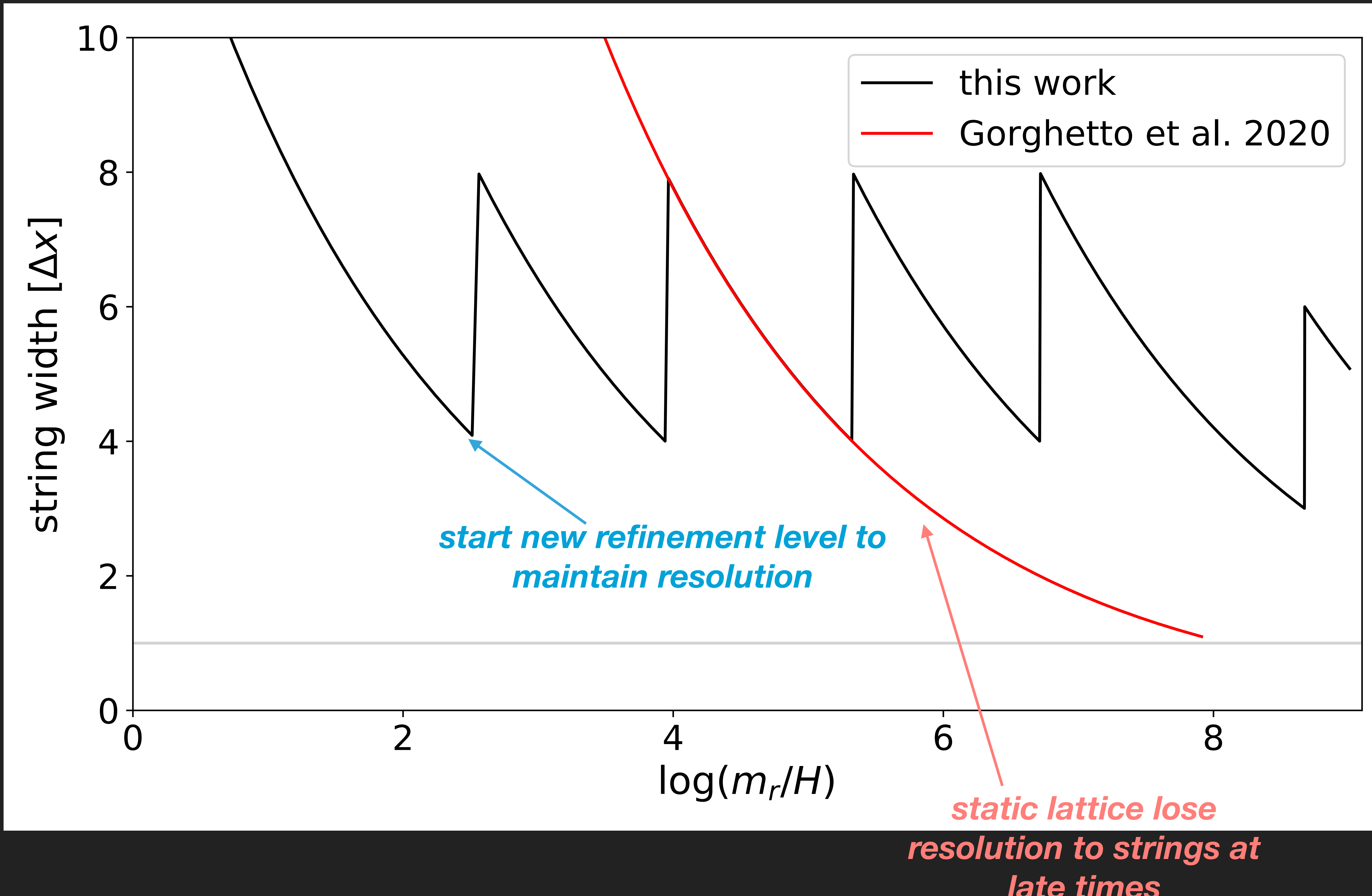


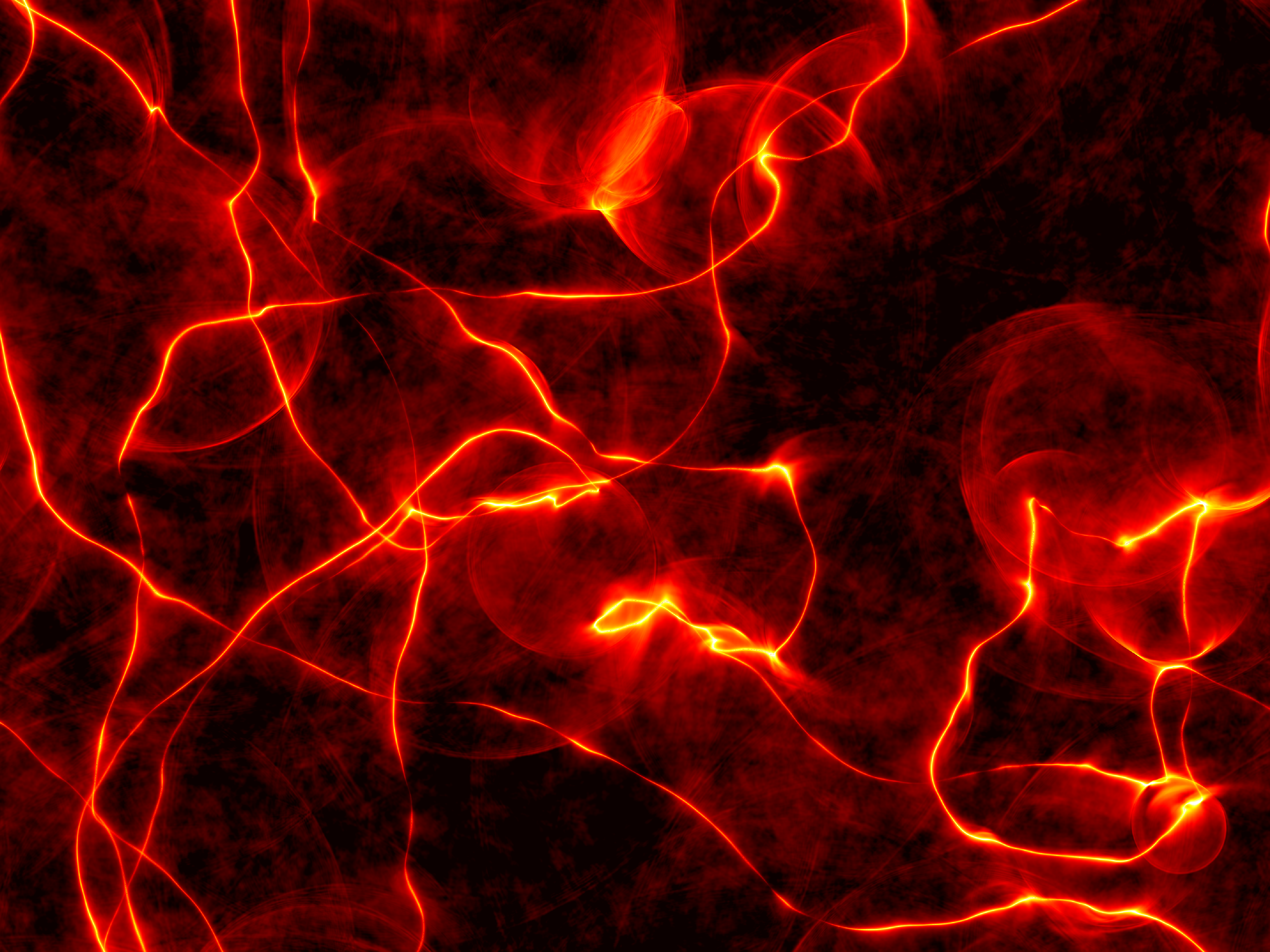
Axions with AMReX

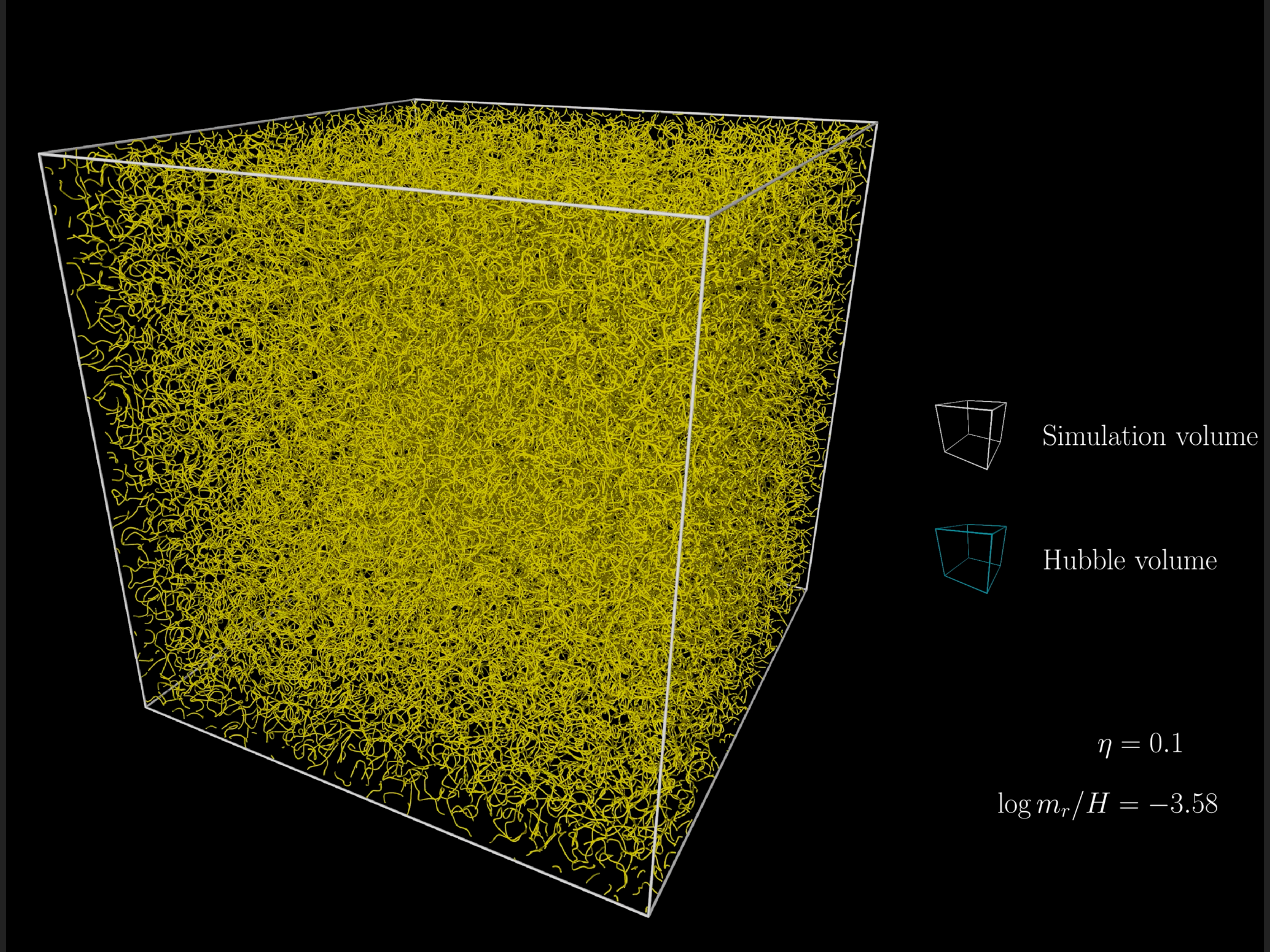


1. We use 6 refinement levels (up to 131,072^3 resolution)
2. 1,024 KNL nodes (~70,000 cores) on Cori (NERSC) – 100 TB memory
3. Refinement criteria: use radial mode to indicate presence of strings
4. Comparison: Buschmann et al. 2020 – ~2,000^3 resolution

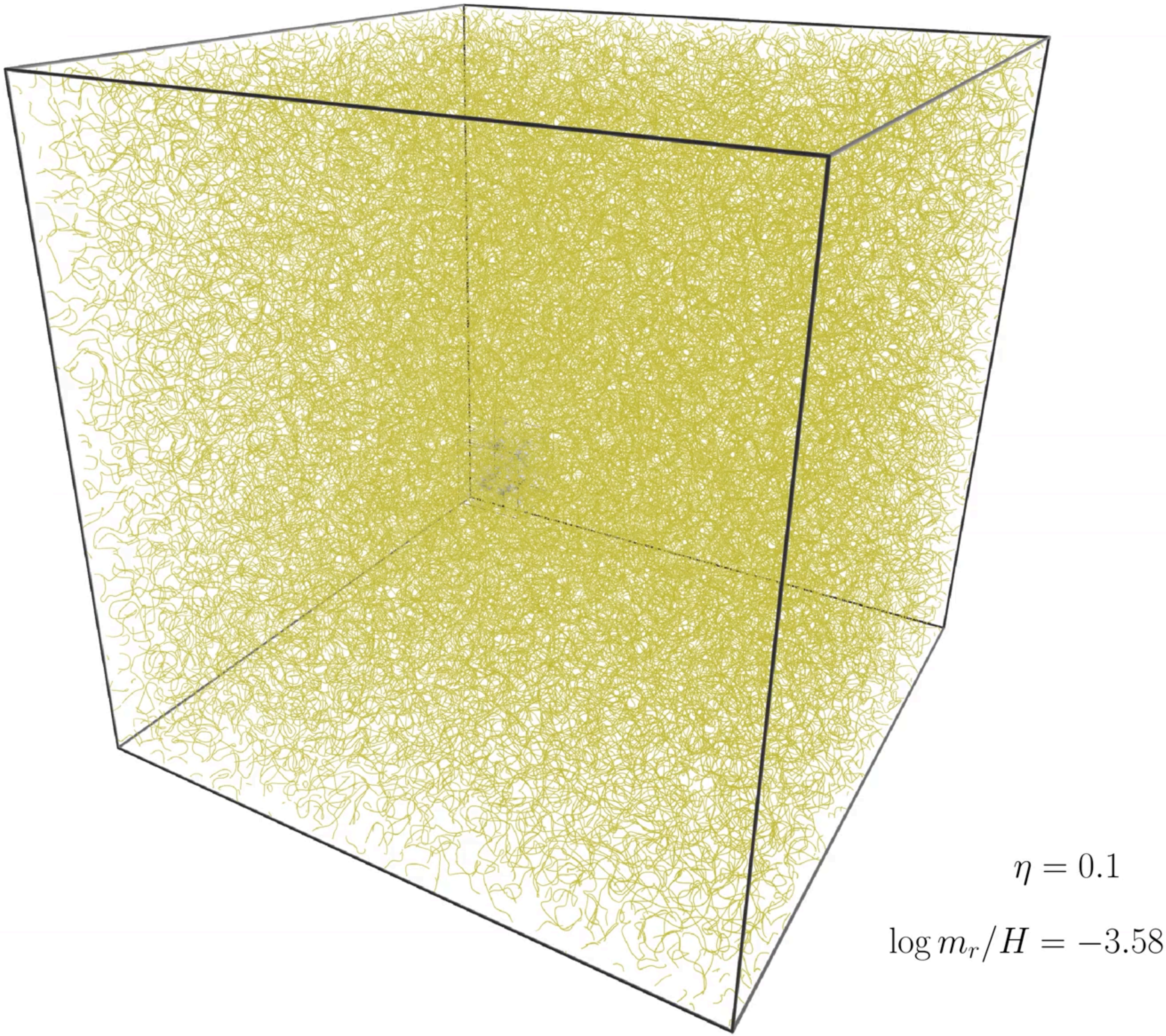
Axions with AMReX







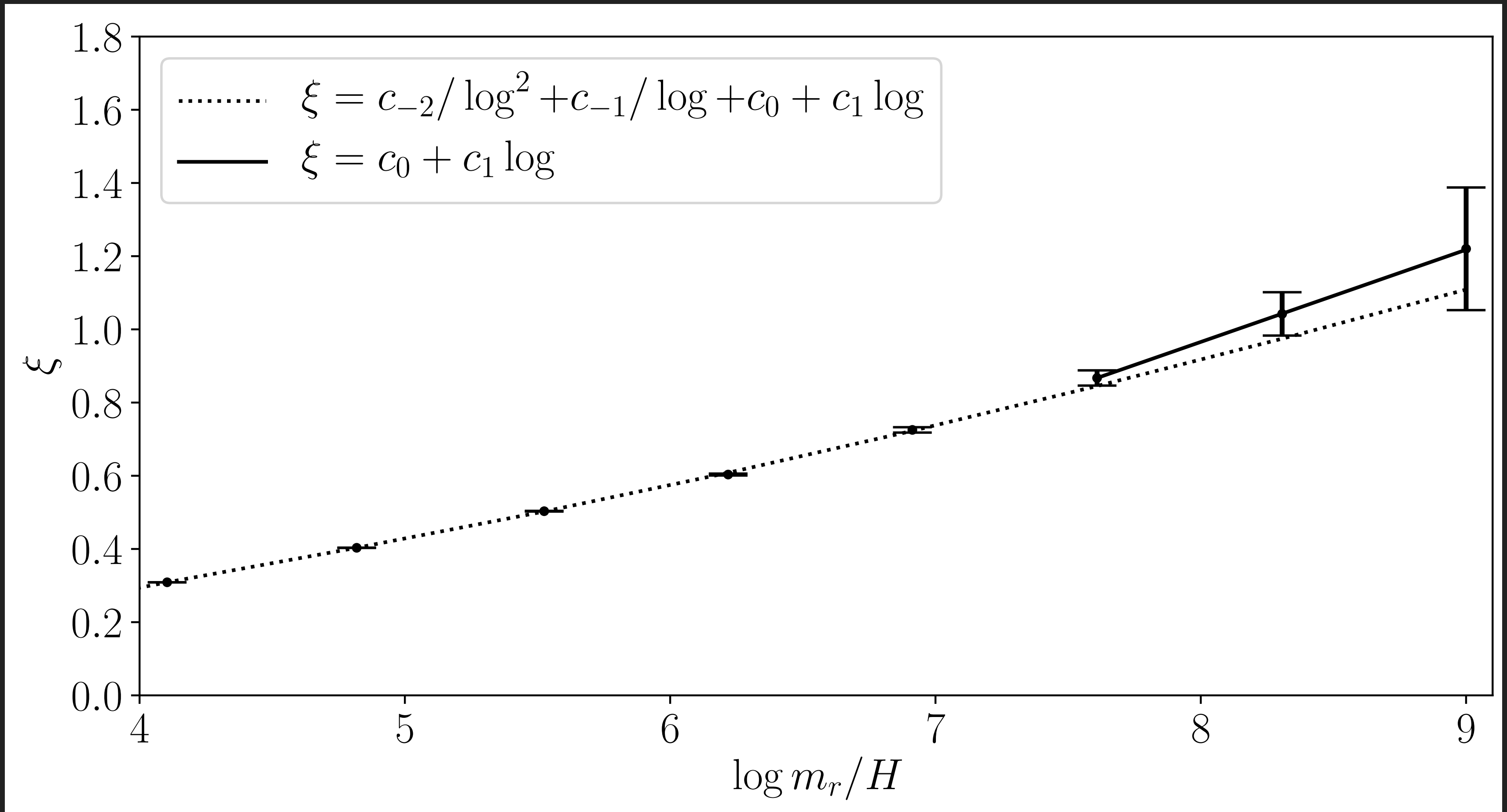
Simulation volume
Hubble volume
$\eta = 0.1$
$\log m_r/H = -3.58$



$\eta = 0.1$
$\log m_r/H = -3.58$

What do we find?

1. strings per Hubble increases logarithmically with time (and understand this analytically)

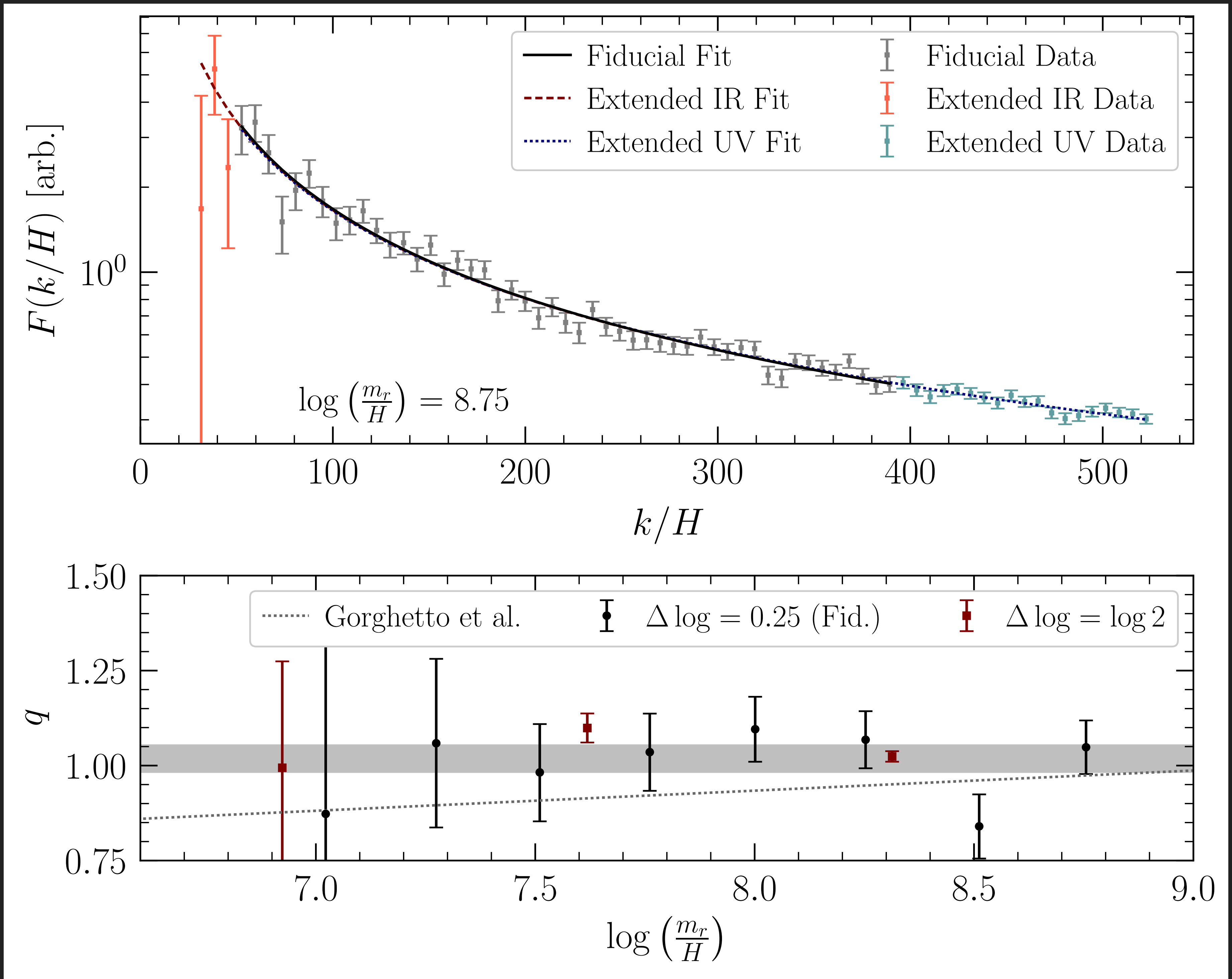


What do we find?

2. radiation does not become IR dominated – conformal to within few %

$$\frac{\partial \rho}{\partial k} \sim \frac{1}{k^q}$$

$$q \in (0.98, 1.04)$$



$$m_a \in (40, 180)\ \mu\text{eV}$$

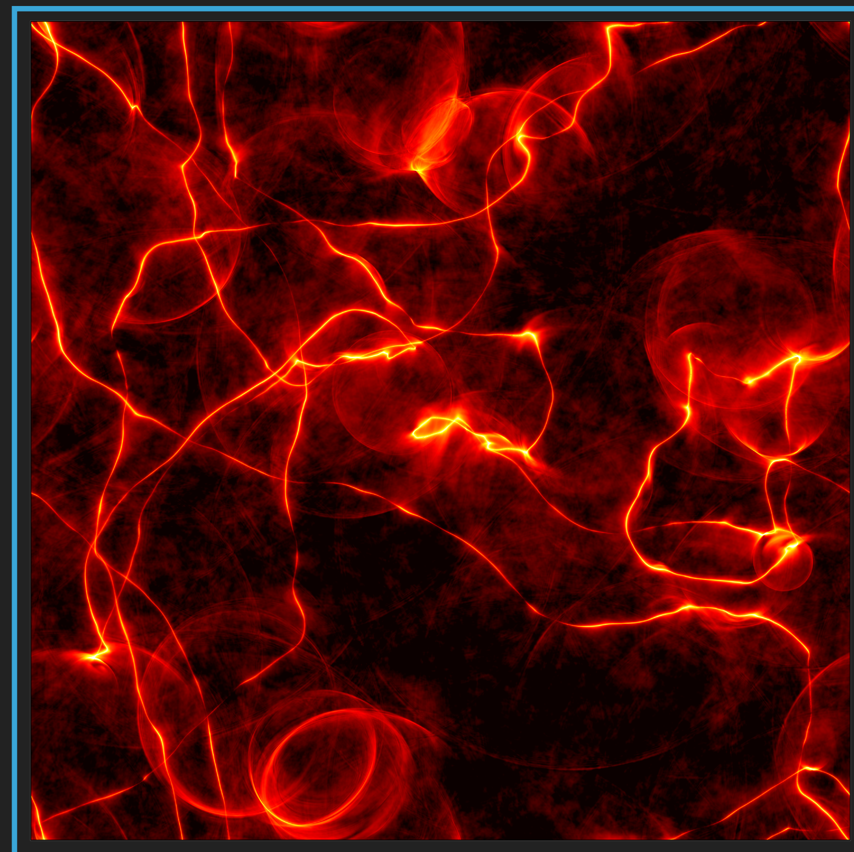
$$m_a = 65 \pm 6\ \mu\text{eV} \longleftarrow q = 1$$

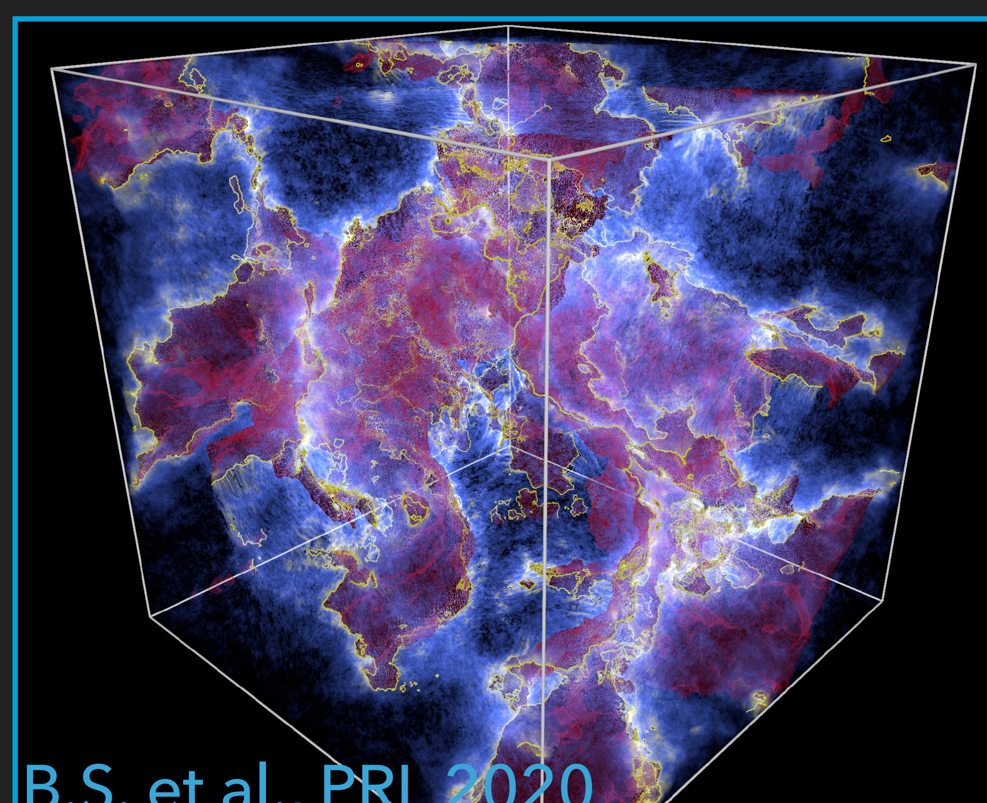
Why does the spectrum matter?

1. Axions from string radiation non-relativistic at QCD phase transition

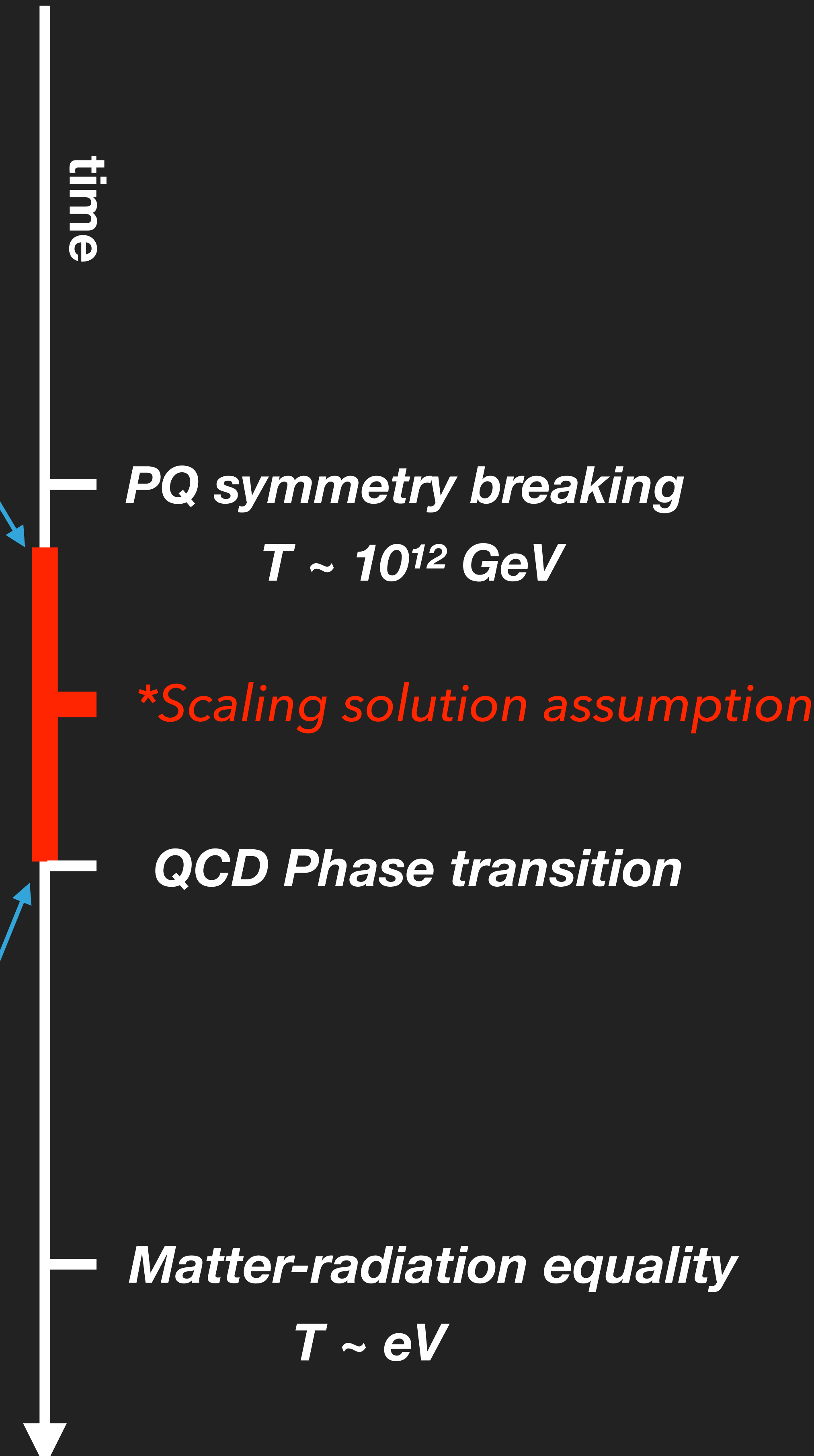
2. DM abundance determined by axion number density

3. For fixed energy density, spectral index determines number density





B.S. et al., PRL 2020



How to calculate the DM relic abundance

$\Omega_a^{\rm str} \propto$ axion number density at QCD phase transition

$$\Omega_a^{\rm str} \propto \xi_* \times \langle \frac{H}{k} \rangle$$

← leaving off dependence on string tension

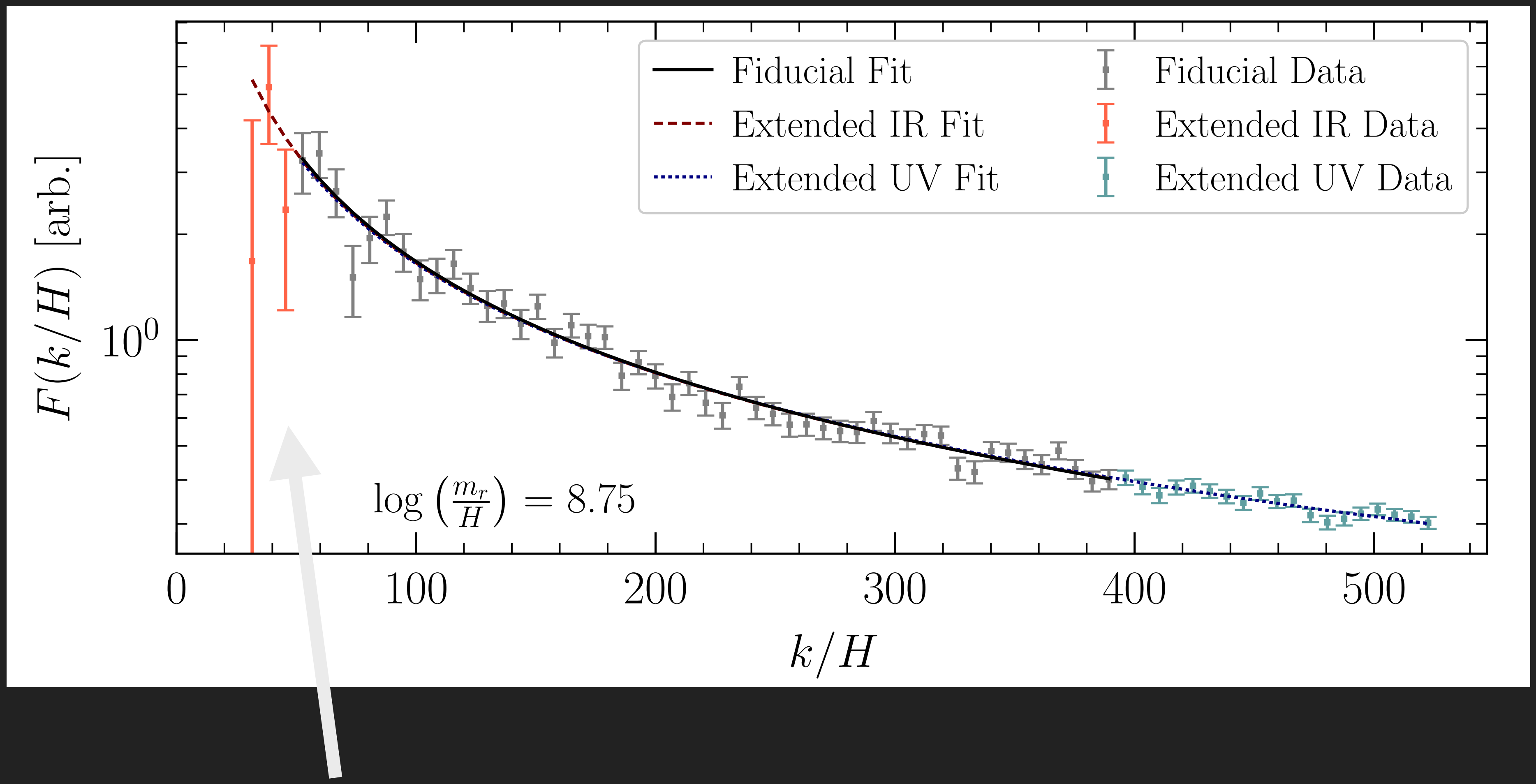
↑ number of strings per Hubble at QCD

↖ inverse axion wavelength from string radiation at QCD

How to calculate the DM relic abundance

$$\Omega_a^{\rm str} \propto \xi_* \times \langle \frac{H}{k} \rangle$$

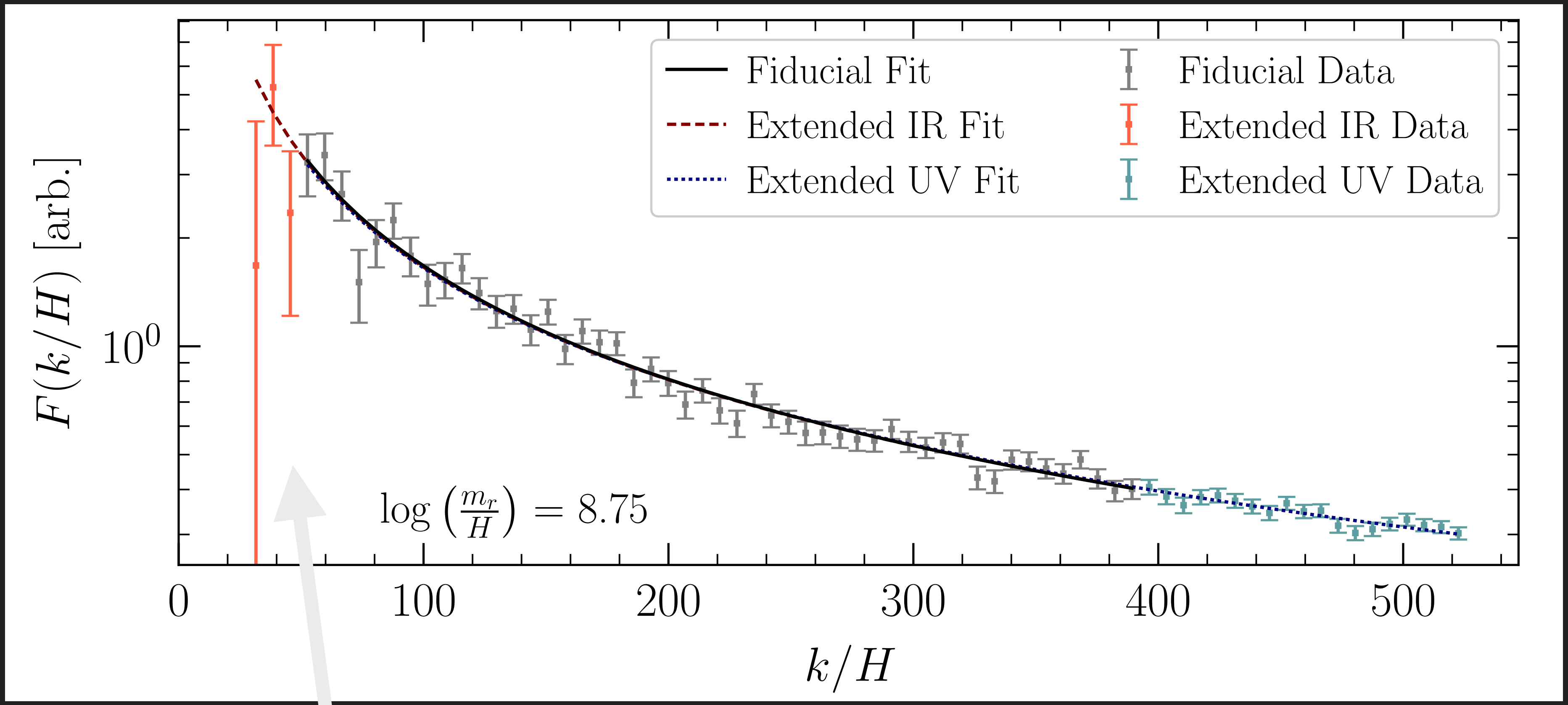
How to compute <H/k>: Numerically integrate spectrum in IR, power-law fit in UV



IR cut-off moves to UV like $\sqrt{\xi}$ **(maximum string curvature scale)**

How to calculate the DM relic abundance

$$\Omega_a^{\rm str} \propto \xi_* \times \langle \frac{H}{k} \rangle$$



IR cut-off moves to UV like $\sqrt{\xi}$ **(maximum string curvature scale)**

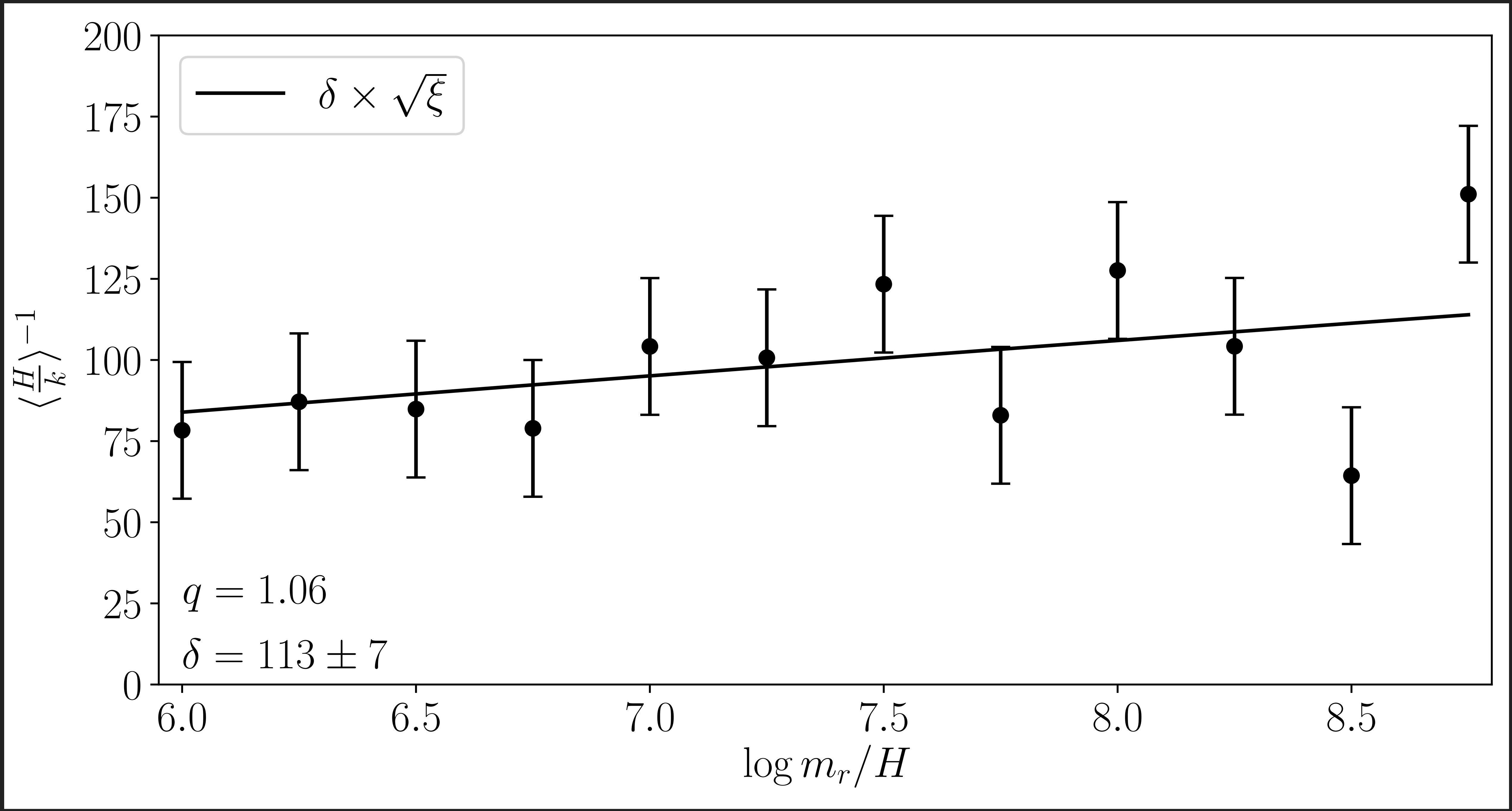
If q > 1 (IR dominated), we expect $\langle \frac{H}{k} \rangle^{-1} = \delta \times \sqrt{\xi}$

$$\Omega_a^{\rm str} \propto \frac{\sqrt{\xi_*}}{\delta}$$

How to calculate the DM relic abundance

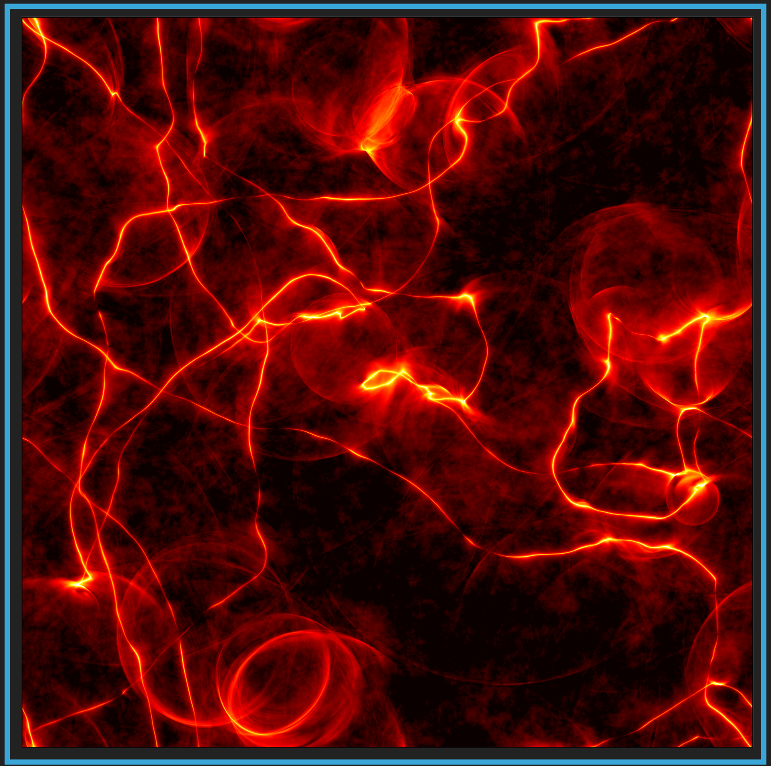
$$\Omega_a^{\rm str} \propto \frac{\sqrt{\xi_*}}{\delta}$$

Numerically integrate spectrum in IR, power-law fit in UV



The DM relic abundance

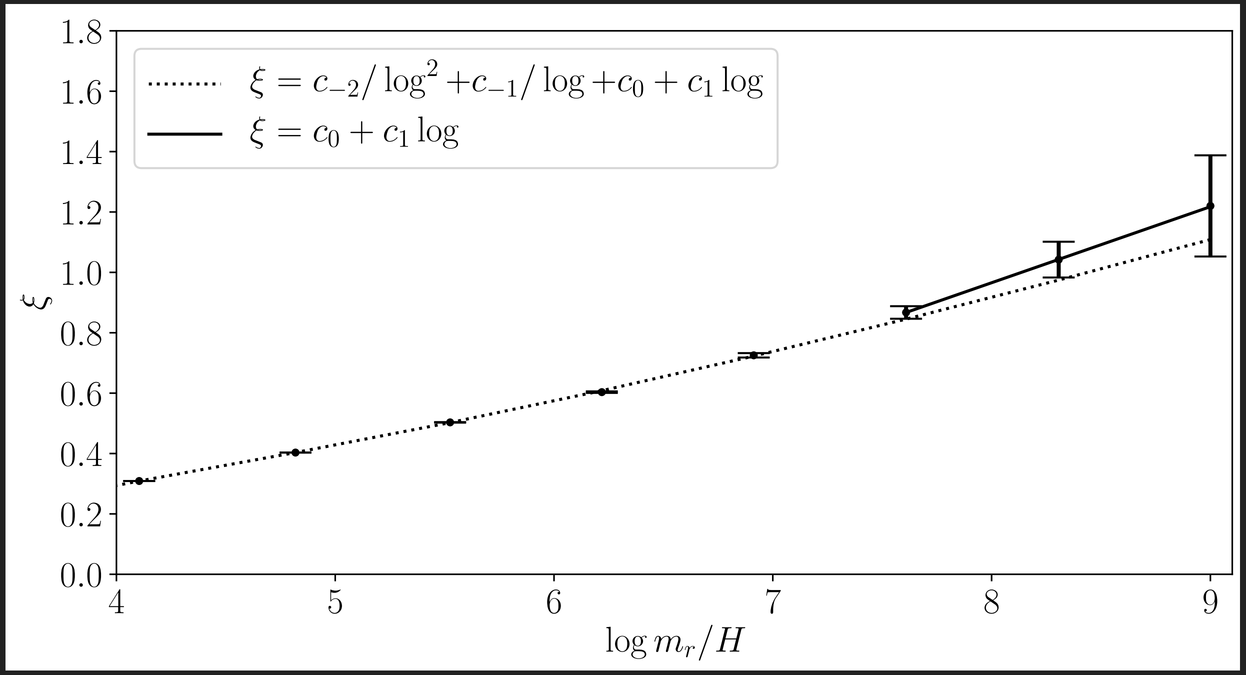
$$\Omega_a^{\rm str} \approx 0.12\, h^{-2} \left(\frac{f_a}{4.3\cdot 10^{10}\mathrm{GeV}}\right)^{1.17} \frac{107}{\delta}\sqrt{\frac{\xi_*}{17}}\,\frac{\log_*}{70}$$



String number density: dominant uncertainty from spectral index

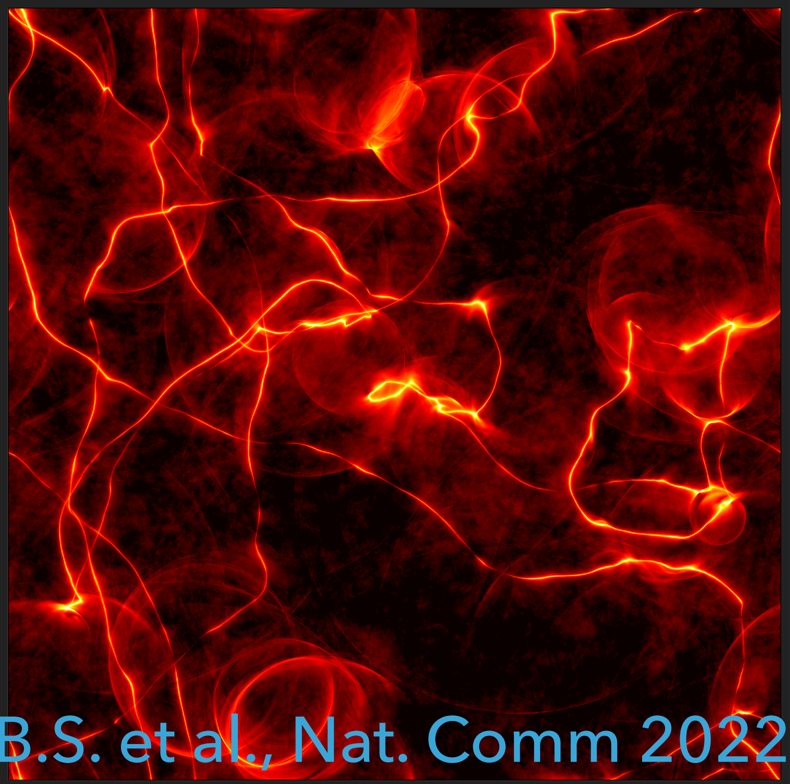
strings per Hubble at QCD phase transition

log of Horizon scale versus PQ scale at QCD phase transition



The DM relic abundance

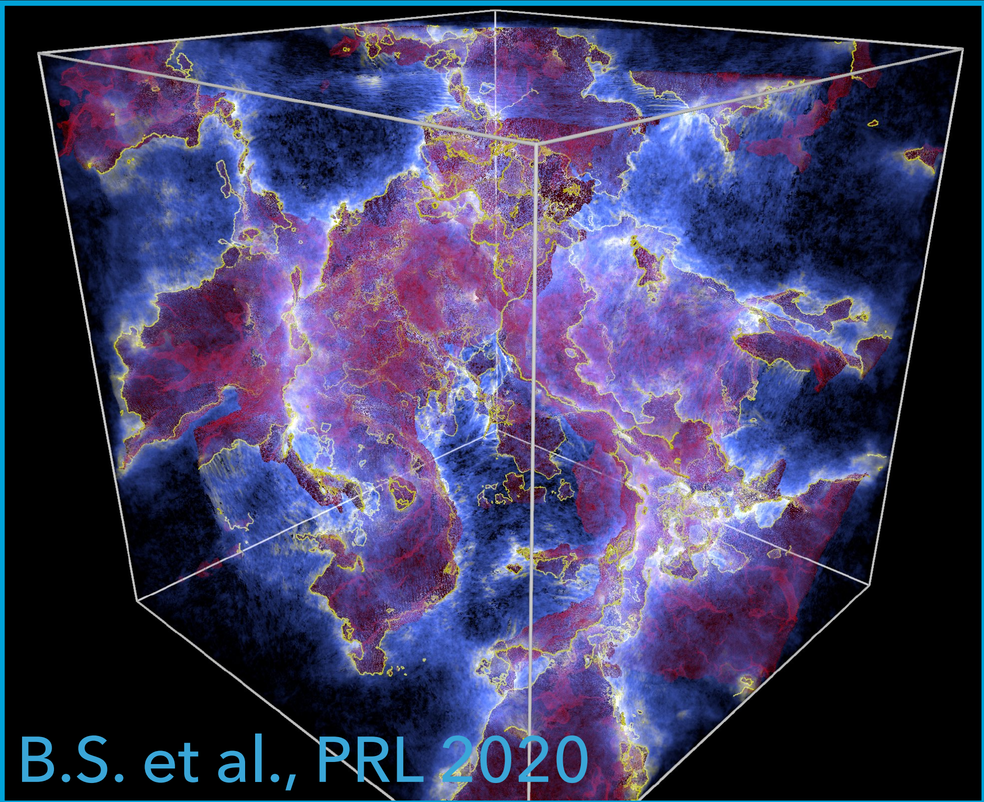
$$\Omega_a^{\rm str} \approx 0.12\, h^{-2} \left(\frac{f_a}{4.3\cdot 10^{10}\,{\rm GeV}}\right)^{1.17} \frac{107}{\delta}\sqrt{\frac{\xi_*}{17}}\,\frac{\log_*}{70}$$



B.S. et al., Nat. Comm 2022

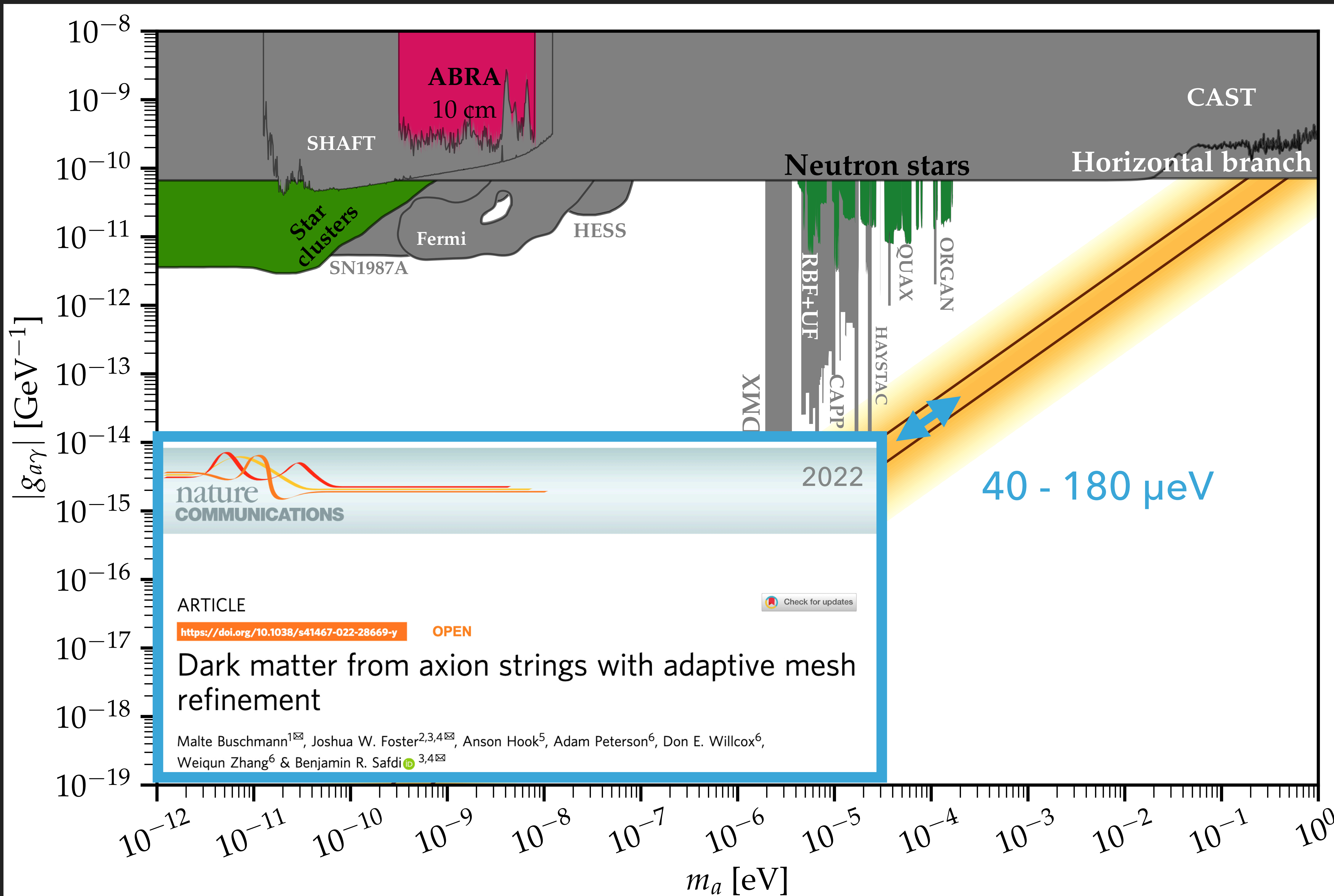
String production prior to QCD phase transition dominates over contribution from QCD phase transition

$$\Omega_a^{\rm QCD} \approx 0.017\, h^{-2} (f_a/4.3\cdot 10^{10}\,{\rm GeV})^{1.17}$$



B.S. et al., PRL 2020

Our preferred mass range



2022

nature COMMUNICATIONS

ARTICLE

Check for updates

https://doi.org/10.1038/s41467-022-28669-y OPEN

Dark matter from axion strings with adaptive mesh refinement

Malte Buschmann[1✉], Joshua W. Foster[2,3,4✉], Anson Hook[5], Adam Peterson[6], Don E. Willcox[6], Weiqun Zhang[6] & Benjamin R. Safdi[3,4✉]

Caveats

1. Maybe we made a mistake (running larger sims now and more systematics, *see next slide)
2. PQ symmetry broken before inflation
3. PQ symmetry broken after inflation by non-standard cosmology (e.g., early matter domination)
4. PQ symmetry broken after inflation but domain wall number great than one, domain walls stable, decay through explicit PQ breaking

Summary: should search over full possible mass range, but our work gives a special place to look

What are we doing now?

Perlmutter + GPU acceleration

1. GPU cluster being commission now. Already 5th most powerful supercomputer in world

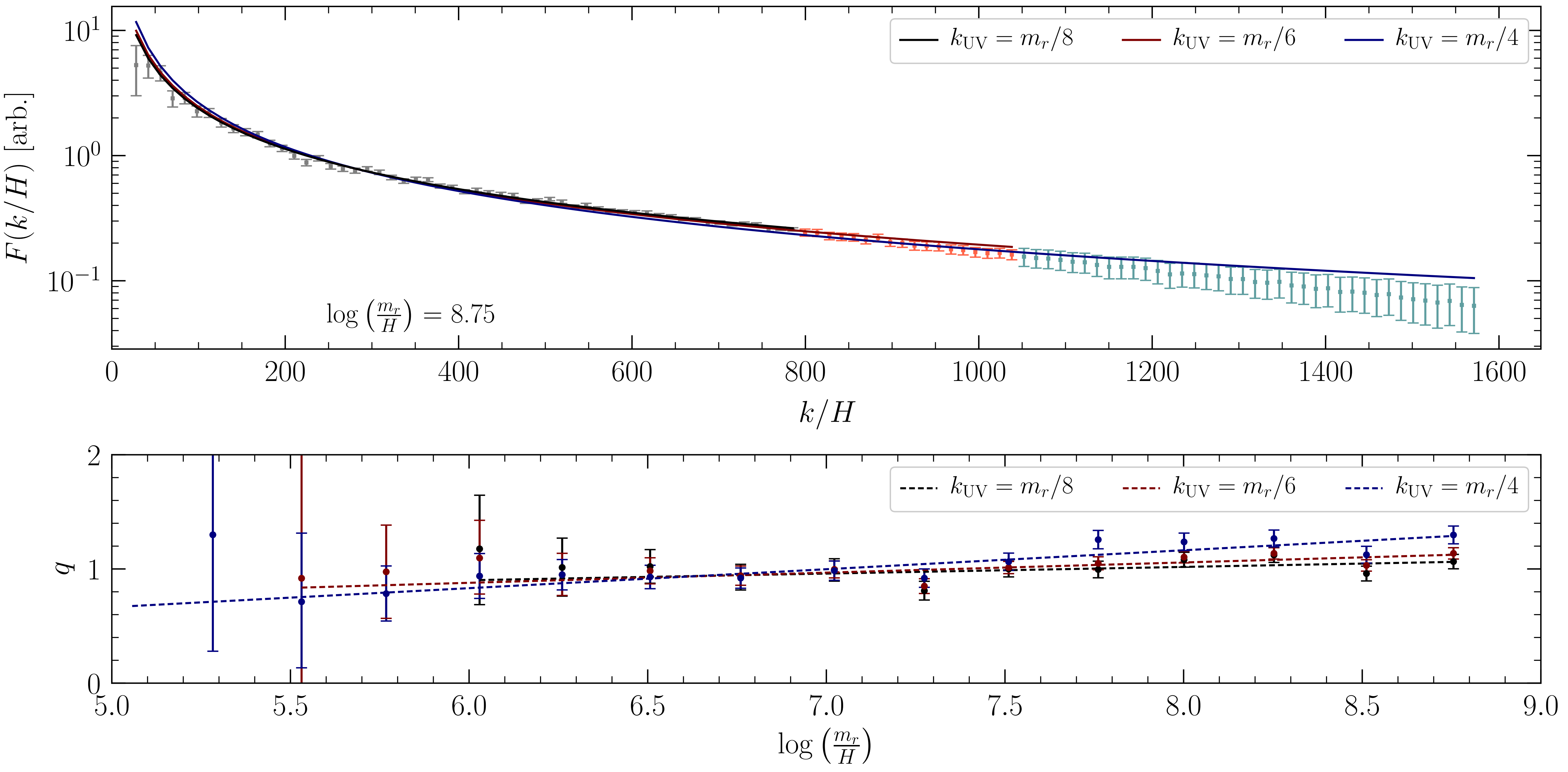
2. our plan: run on few thousand GPUs for increase in dynamic range

QUESTIONS?

*SPECIAL THANKS TO LEAD AUTHORS MALTE BUSCHMANN AND JOSH FOSTER

Systematic Tests: UV cut-off in fitting q

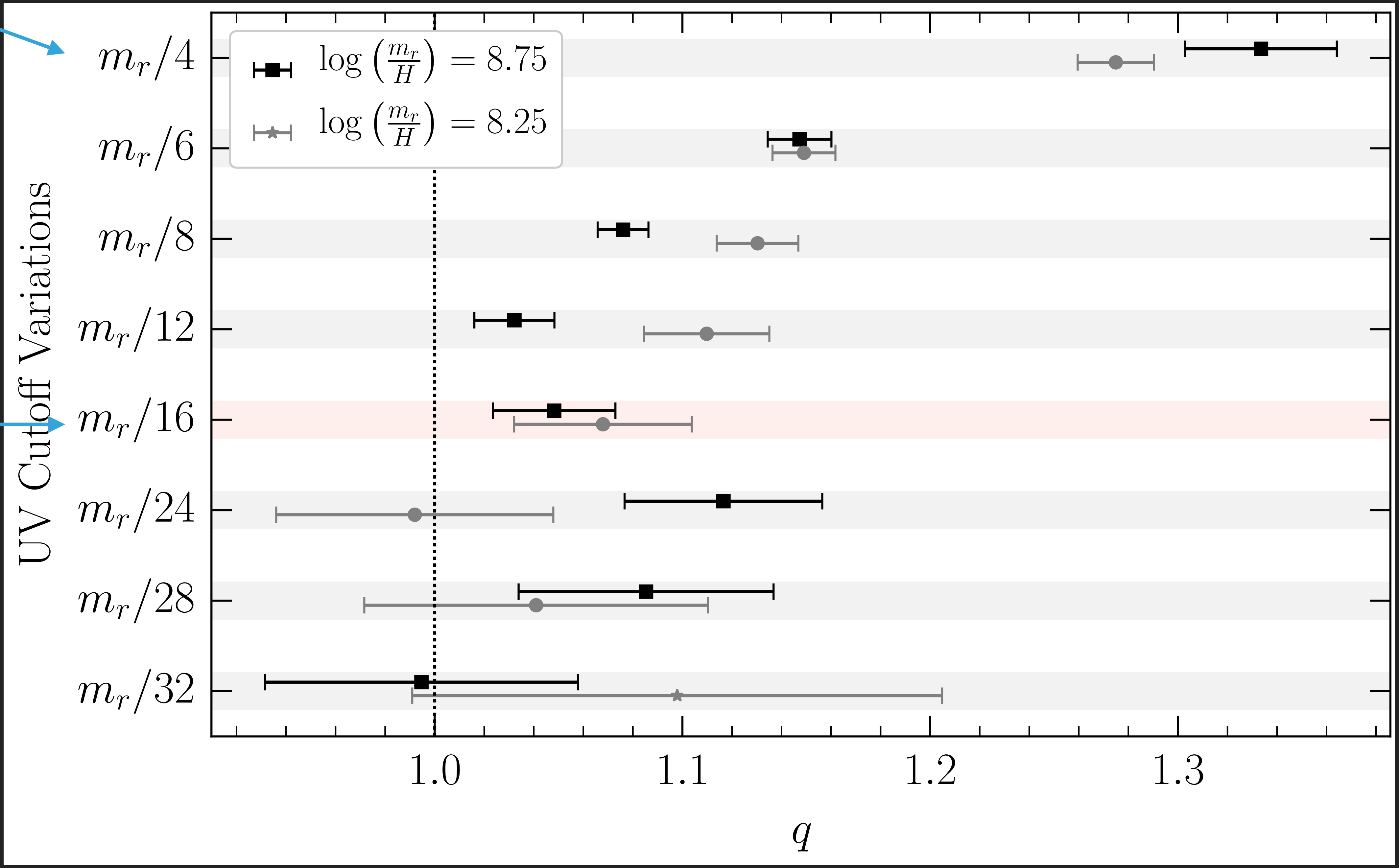
Important to be far away from the UV cut-off when fitting power-law for q



Systematic Tests: UV cut-off in fitting q

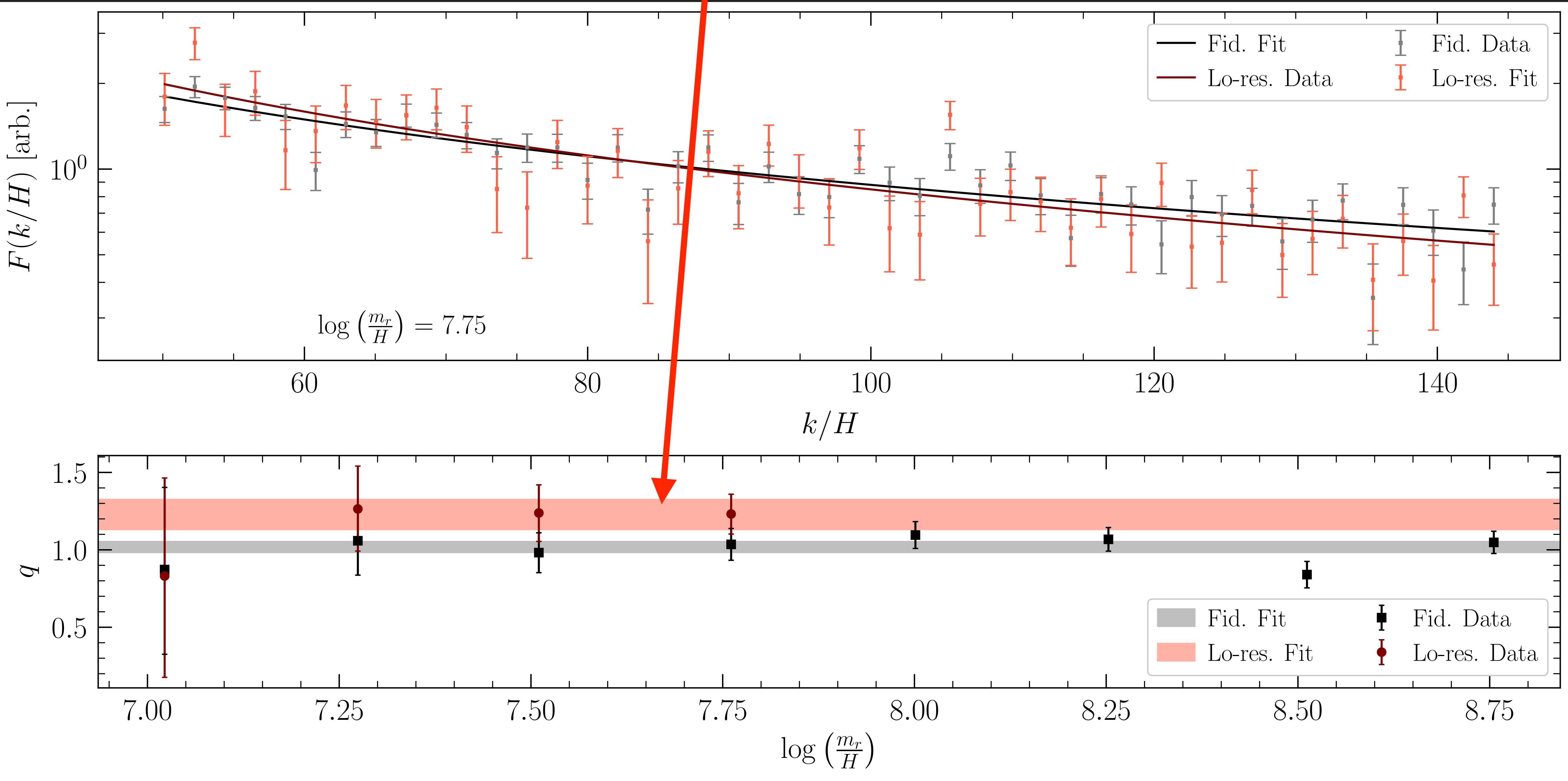
previous simulations

our work



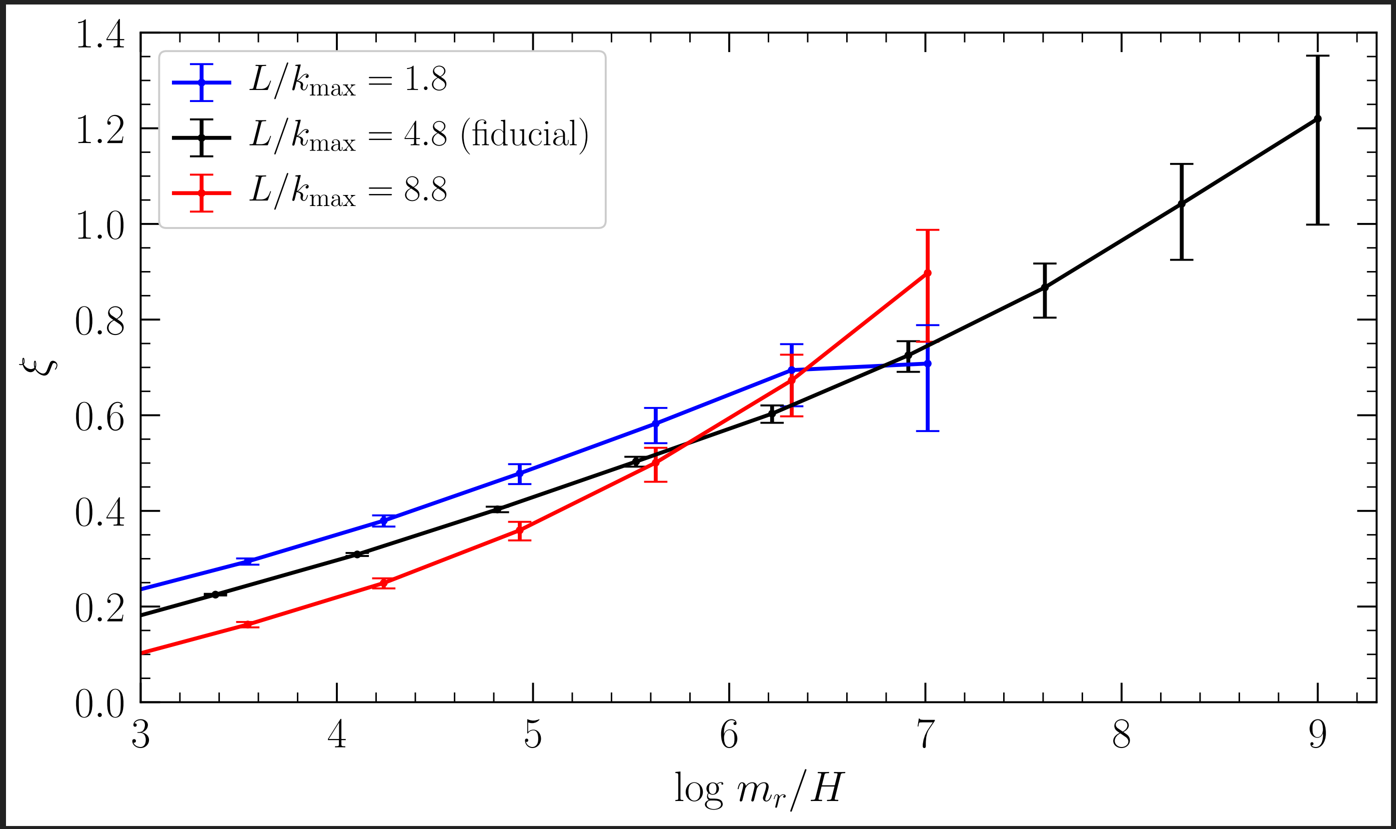
Systematic Tests: resolving string cores

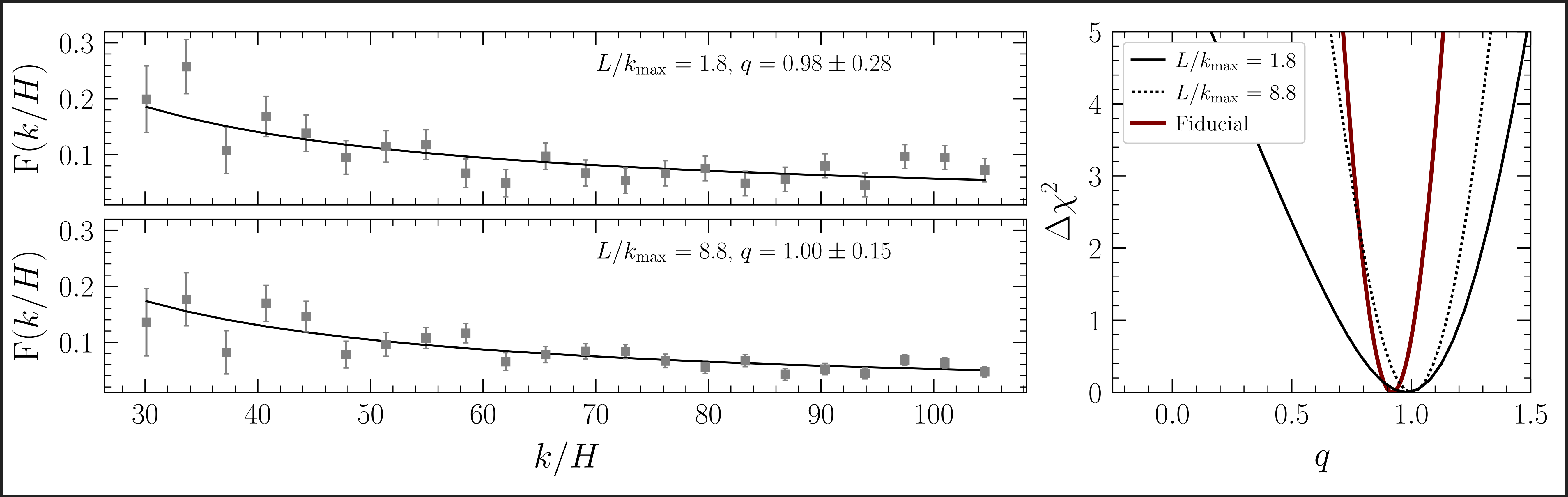
same simulation without refinement levels:
resolve core by 1 grid site at the end



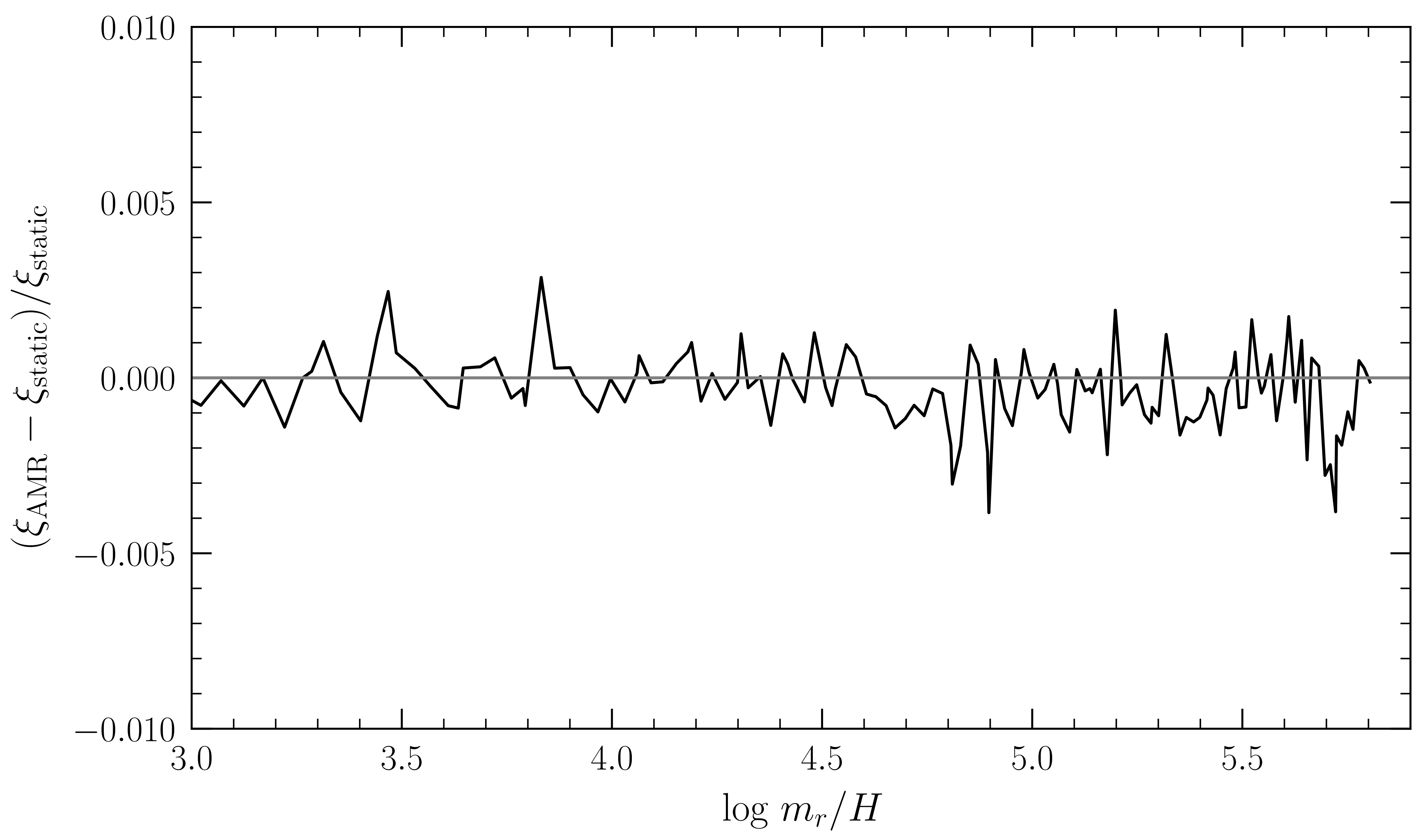
Systematic Tests: results appear robust to initial conditions

*performing more systematic tests now





Systematic Tests: AMR and static lattice simulations give consistent results in range of validity



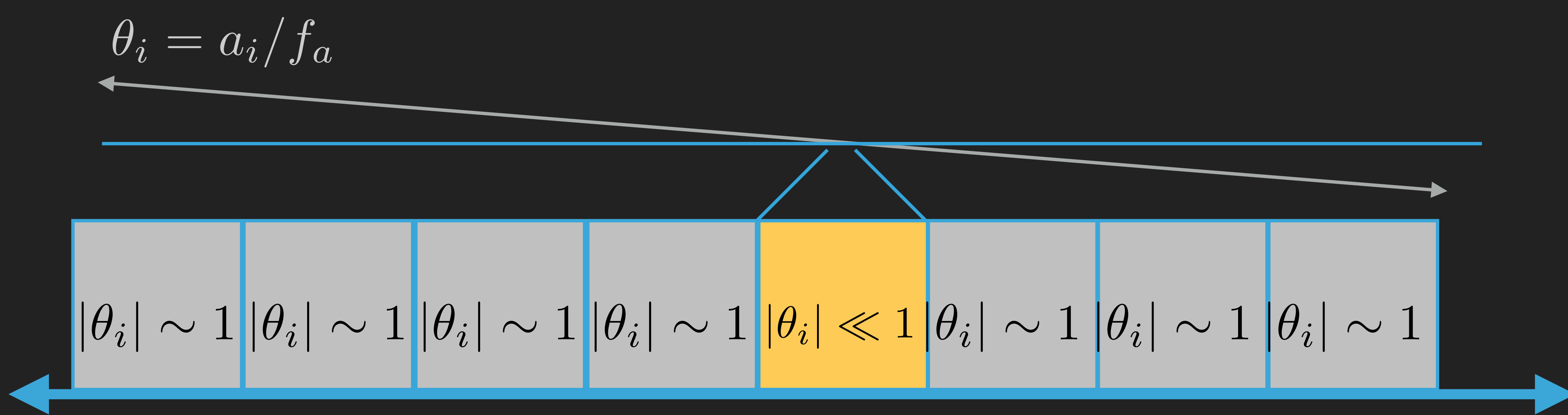
Axion generated before inflation

PHYSICAL REVIEW D **73,** 023505 (2006)

Dimensionless constants, cosmology, and other dark matters

Max Tegmark,[1,2] Anthony Aguirre,[3] Martin J. Rees,[4] and Frank Wilczek[2,1]

$f_a \sim 10^{15} - 10^{16}$ GeV produces too much DM for generic θ_i



Tegmark et al.: too much DM does not allow for life (and us!)

(Other solution high f_a: entropy dilution)