Axion Dark Matter Simulations with Adaptive Mesh Refinement

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1st Cosmic WISPers Training School
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Background: G. Pierobon

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GOBIERNO DE ARAGON

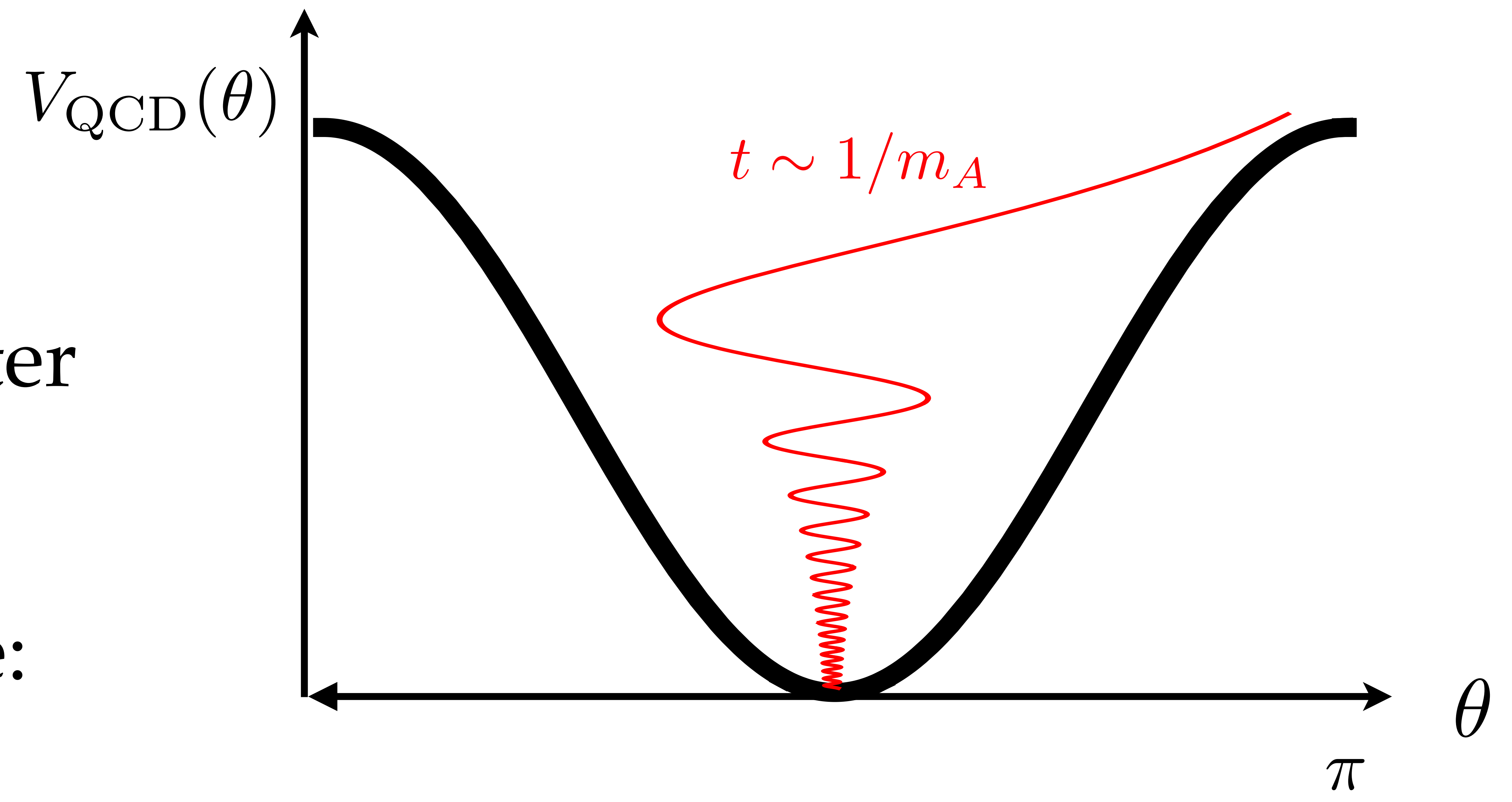
COSMIC WISPERS

COST
EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

QCD Axion

- Pseudo Nambu-Goldstone boson associated with the spontaneous breaking of of the global Peccei-Quinn (PQ) symmetry at the scale f_a
- Solution to the strong-CP problem
- Suitable candidate for cold Dark Matter
- Acquires a mass below the QCD scale:

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

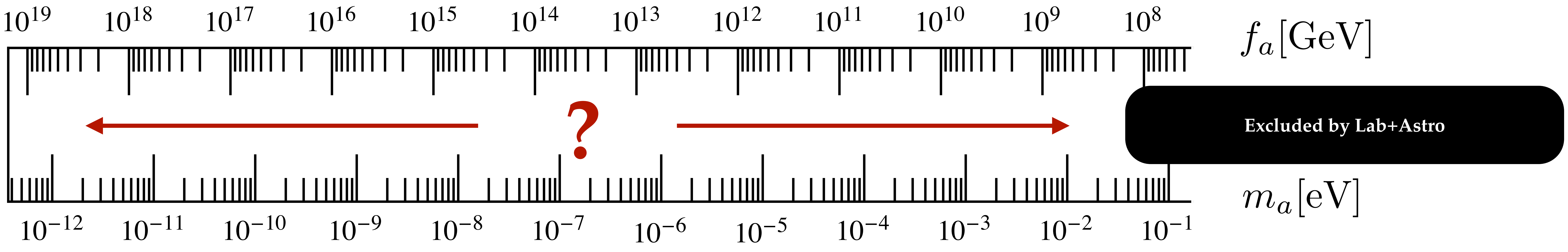


$$m_A|\theta|^2R^3 = \frac{\rho_A}{m_A}R^3 \equiv N_A$$

damped harmonic oscillations around minimum, N_A adiabatically conserved

Axion Dark Matter Mass

- What is the "typical mass" of axion dark matter?



- Relic axion abundance depends on the PQ scale and hence on the axion mass: $\Omega_a = \Omega_a(f_a)$

- Assuming the axion is the (dominant) component of Dark Matter, we can give a precise prediction for its mass in certain scenarios:

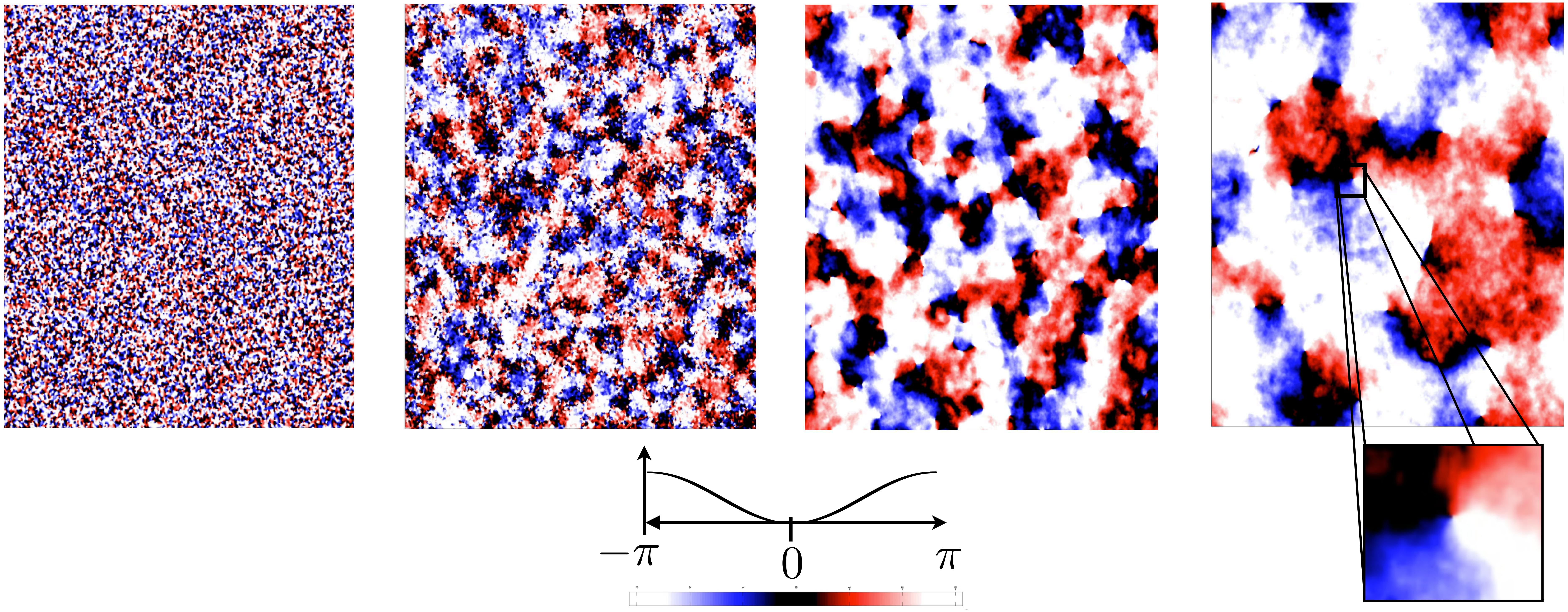
$$\Omega_A \propto m_A N_A \frac{V'}{V}$$

$$(\Omega_a h^2 \simeq 0.12)$$

Post-Inflationary Scenario

- If the PQ symmetry is broken after inflation, topological defects, known as axion strings form immediately after the phase transition via the Kibble mechanism Kibble [1976]

- In addition, domain walls ($N_{\rm DW} = 1$) form at QCD phase transition

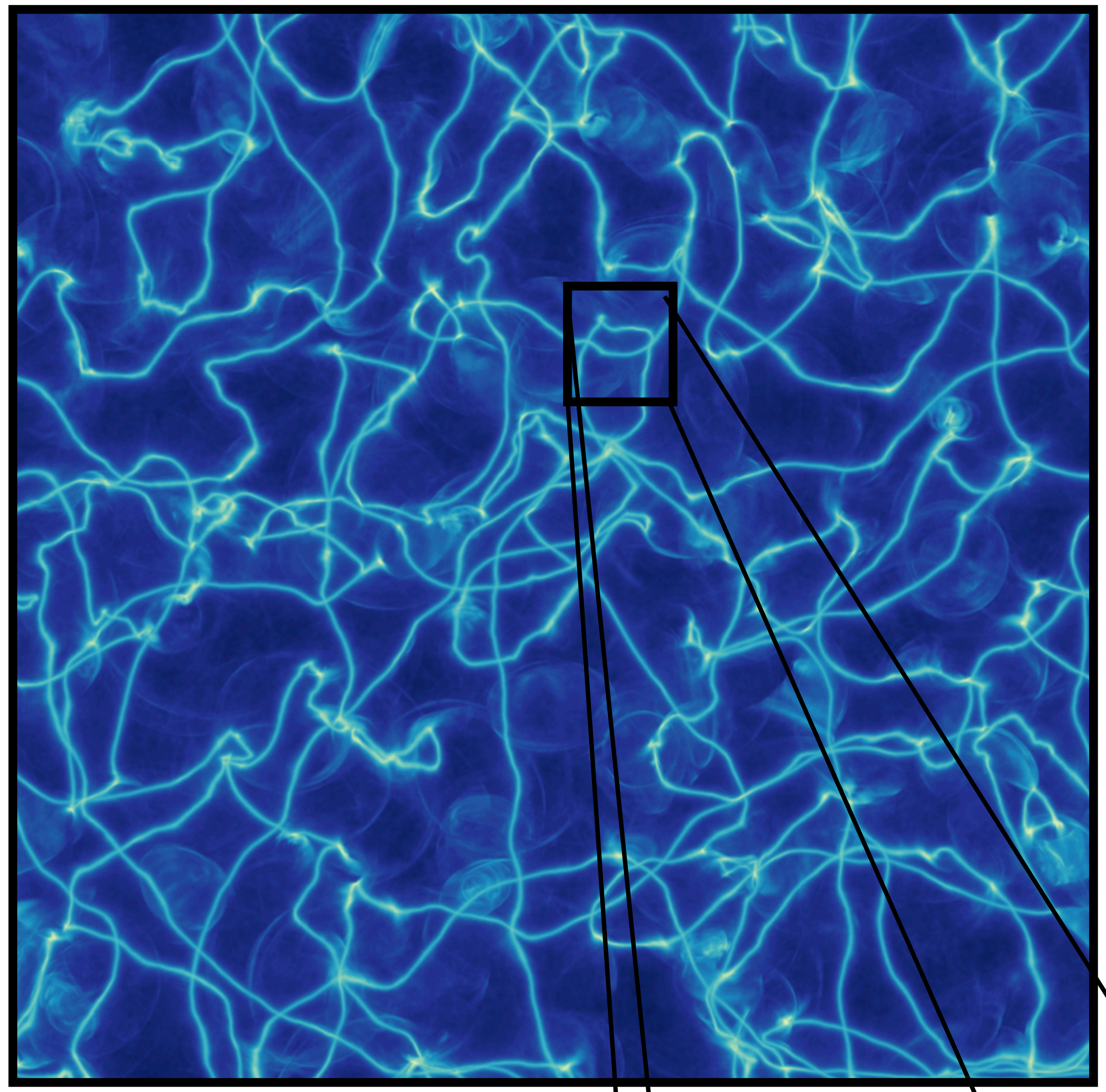


Axions on the Lattice

- Solve the classical EoM for a complex scalar field in comoving coordinates, discretized on (static) lattice:

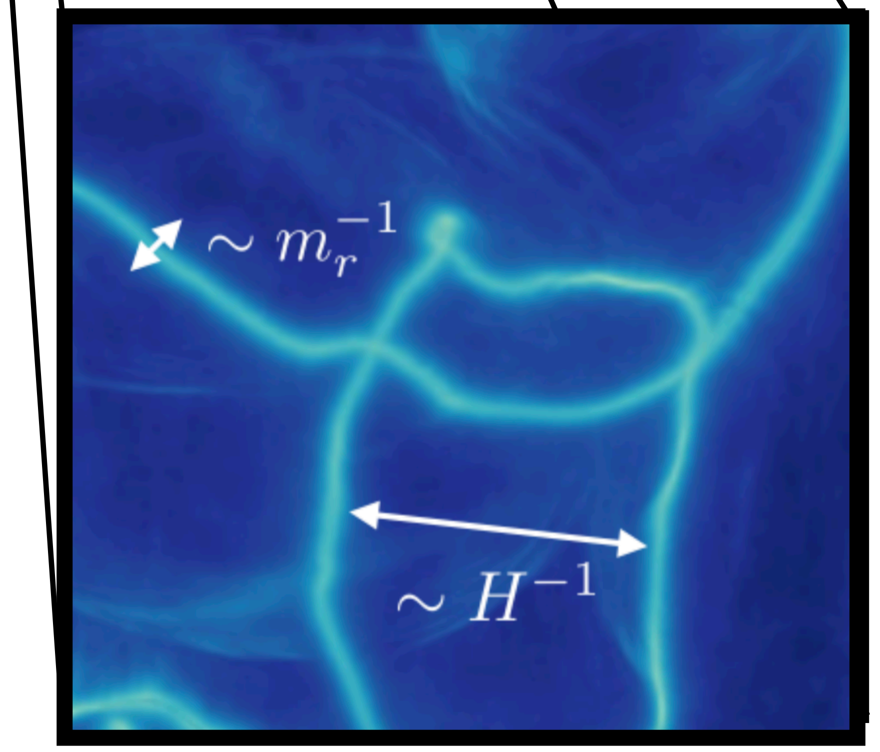
$$\partial_\tau^2 \phi - \nabla^2 \phi + \lambda \phi \left(|\phi|^2 - \tau^2 \right) = 0$$

JAXIONS - Redondo, Saikawa, Vaquero (+ MK & Pierobon)
(https://github.com/veintemillas/jaxions)



Credit: K. Saikawa

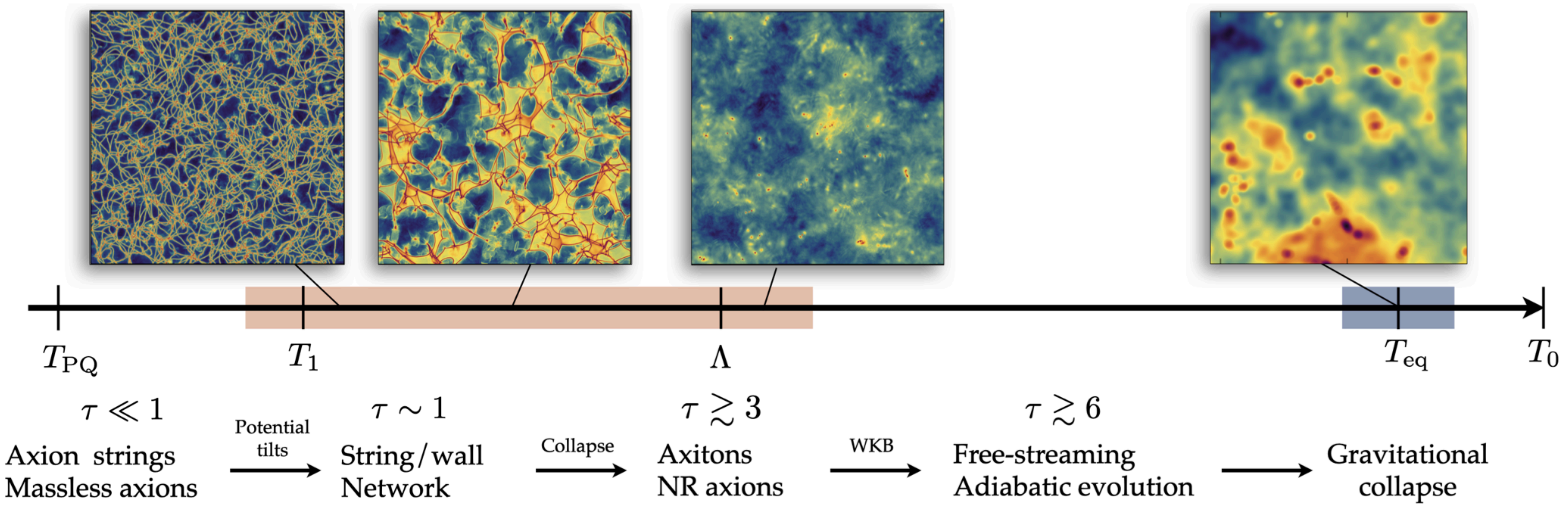
- Need to resolve two very different length scales:
  - String core radius $\sim m_s^{-1} \sim f_a^{-1}$
  - Hubble radius $\sim H^{-1}$



- String tension acquires logarithmic correction:

$$\mu = \frac{\text{Energy}}{\text{Length}} \simeq \pi f_a^2 \log\left(\frac{m_r}{H}\right) \equiv \kappa \sim 70$$

Cosmological Evolution in the Post-Inflationary Scenario

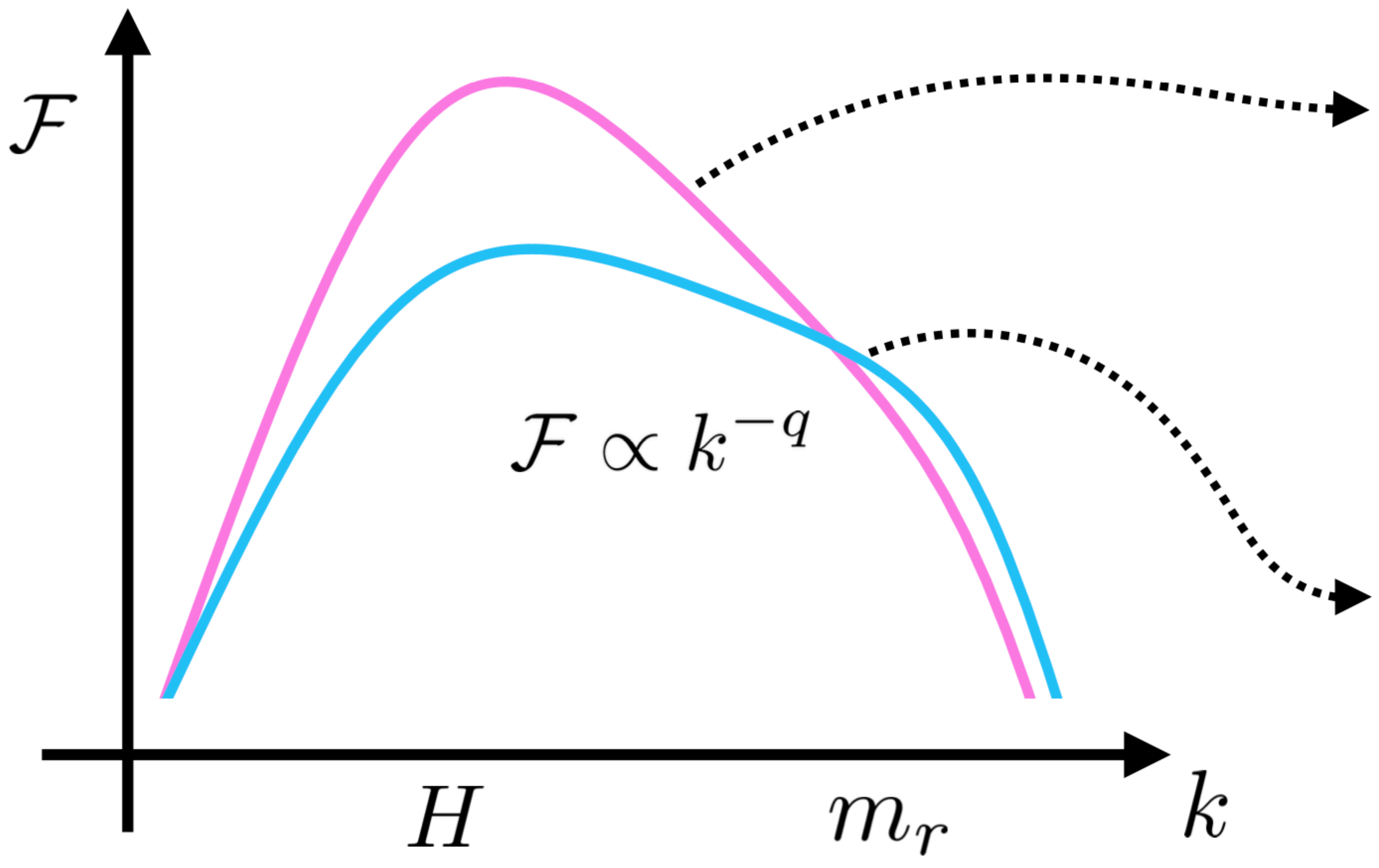


O'Hare, Pierobon, Redondo, Wong [2110.11014]

Axion Radiation from Strings

- Differential Energy Transfer Rate:

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

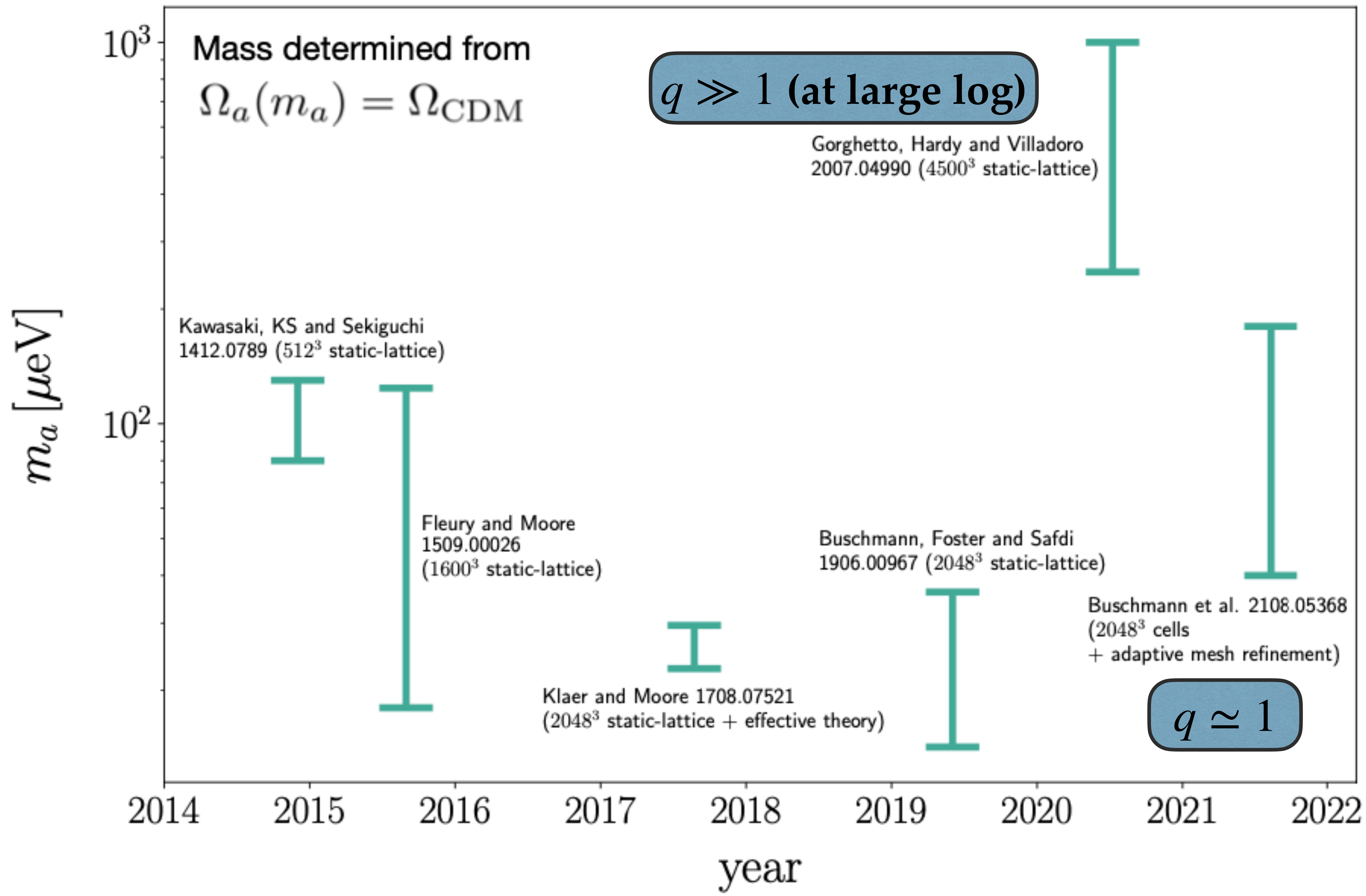


Credit: K. Saikawa

$q > 1$ (IR modes dominate)
Many soft axions.
Enhancement of DM abundance.

$q < 1$ (UV modes dominate)
Few hard axions.
Suppression of DM abundance.

Interpretation of current Simulation Results



Compiled by K. Saikawa

Indirect Method:

1. Simulate
2. Compute Spectrum
3. Extrapolate
4. Derive Axion Number

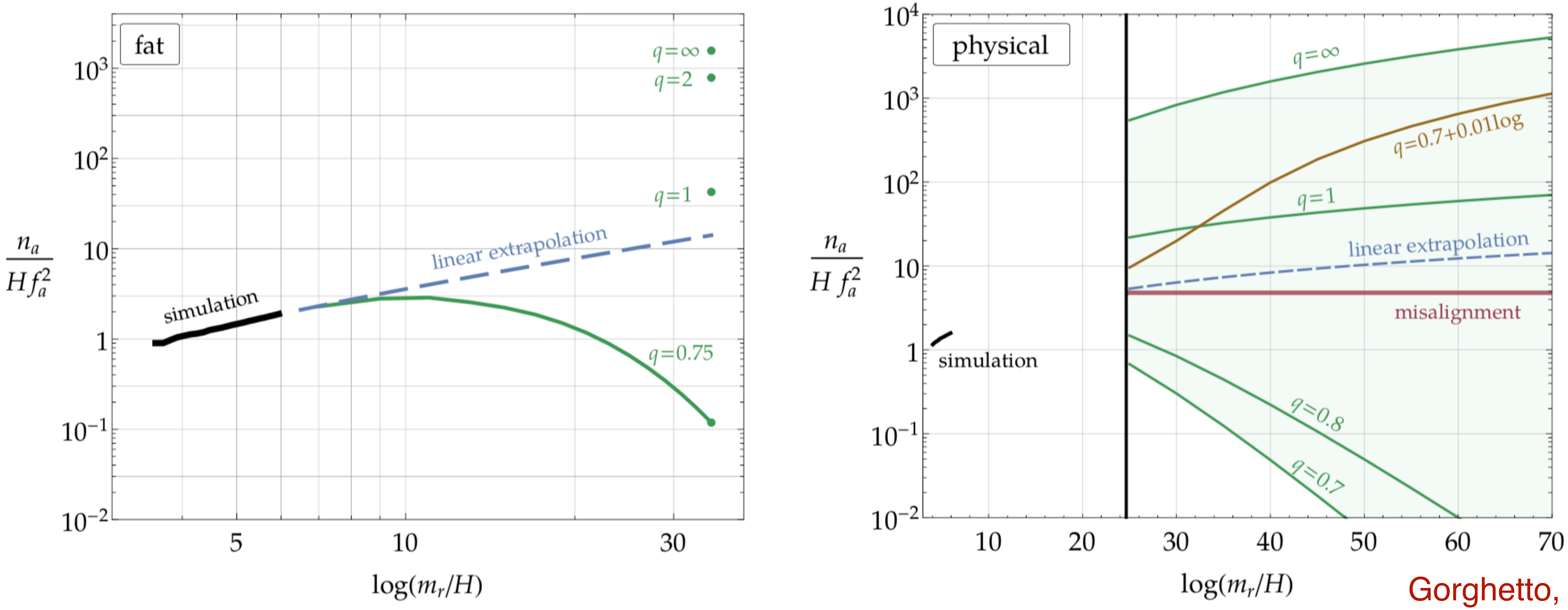
vs.

Direct Method:

1. Simulate
2. Count Axions
3. Extrapolate

Extrapolation to higher String Tensions

- Results for the predicted number of axions strongly depend on value of q !



Gorghetto, Hardy, Villadoro [2007.04990]

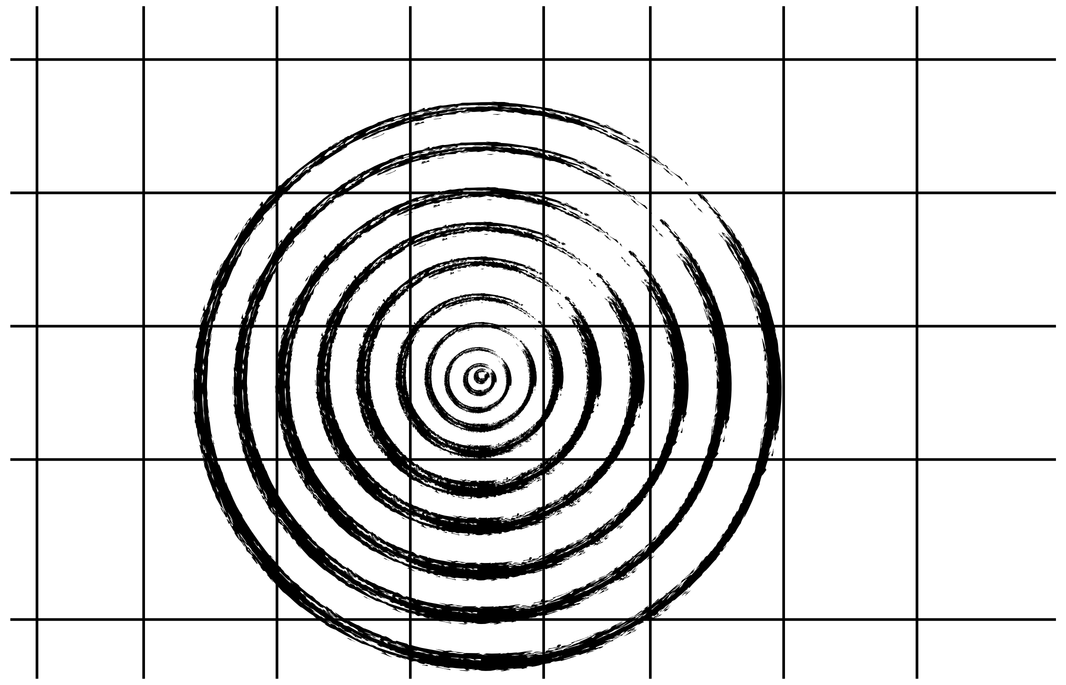
- **Possible error sources:** ICs, discretization effects, missing statistics …

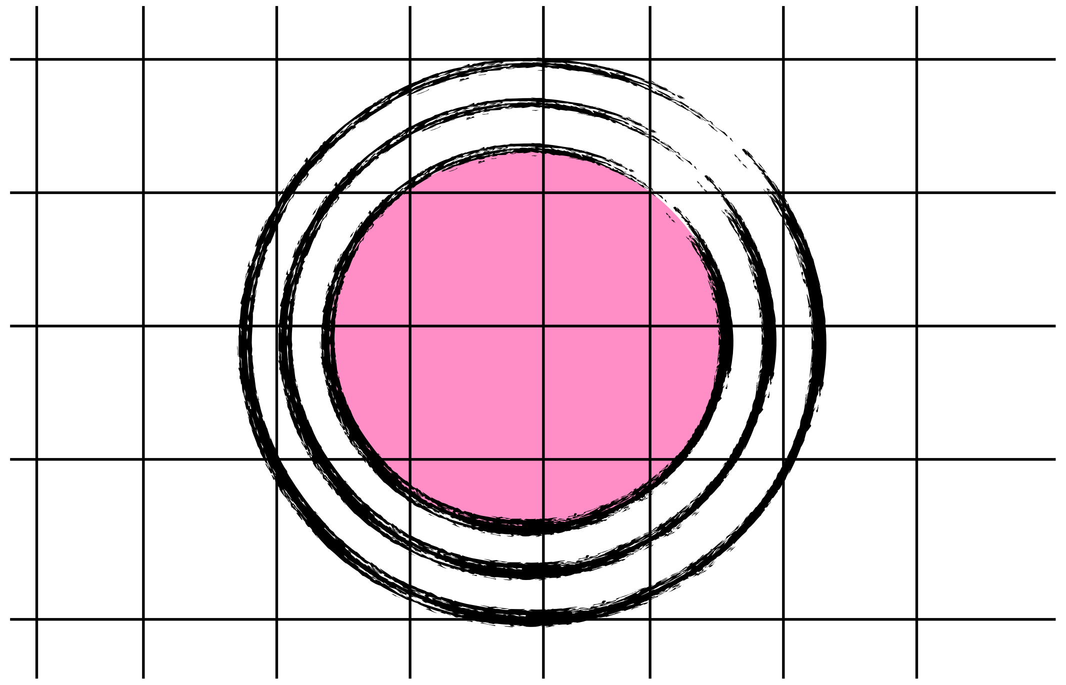

Model Dependence?
Cosmology?
Do the best simulations we can do!
Computational Limitations?

How can we reach a larger dynamical range?

- **Brute Force**: Larger simulations on more powerful supercomputers
- **Better:** Use the given computational power more efficiently: **AMR!**
- **In addition:** Study effective models that allow us to study the network dynamics at high tension, Moore strings, with 2+3 extra degrees of freedom (two additional Higgs + one vector field) Klaer, Moore [1707.05566, 1708.07521, 1912.08058]

Credit: J. Redondo



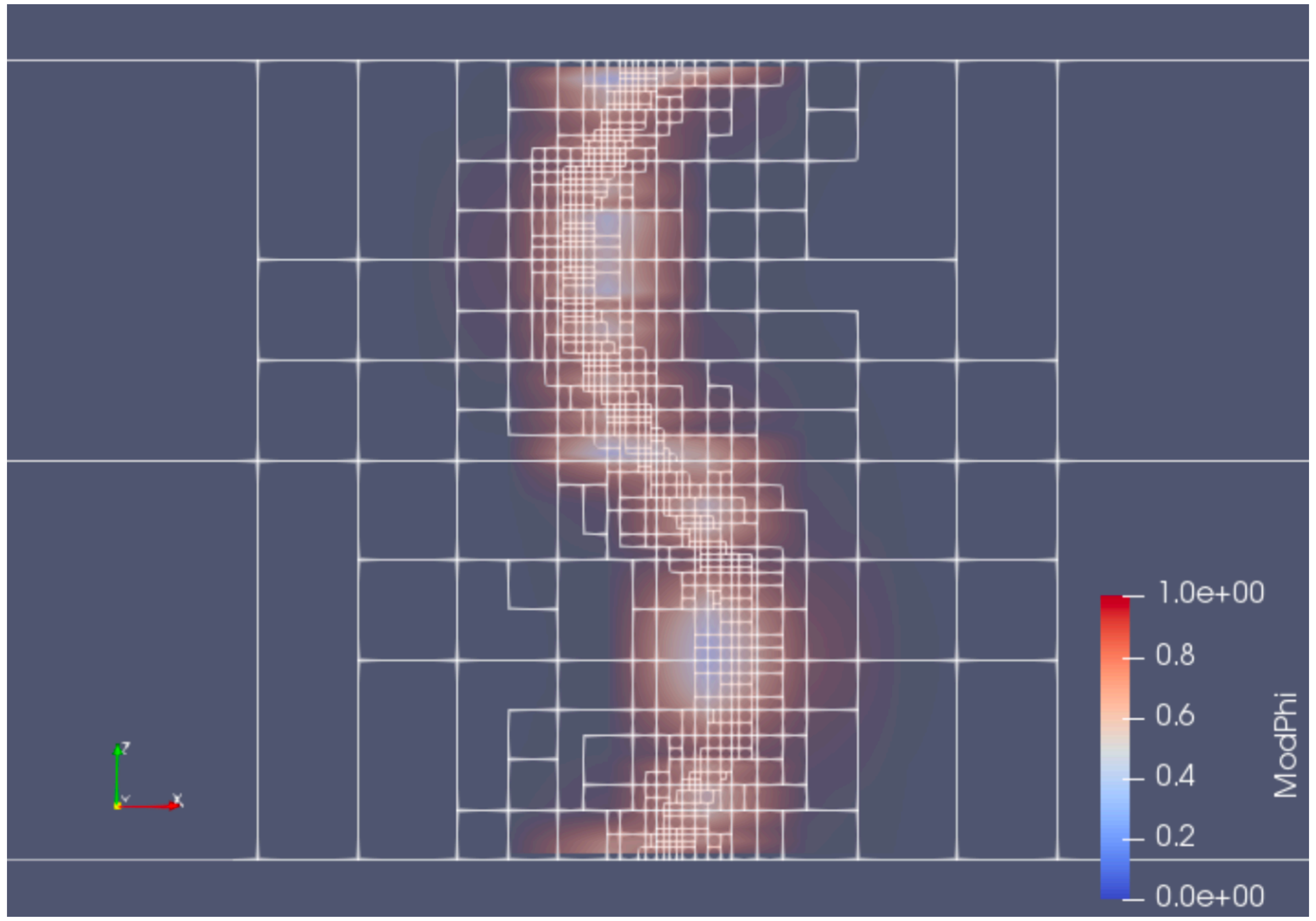


$$\kappa \sim 2(q_1^2 + q_2^2)$$

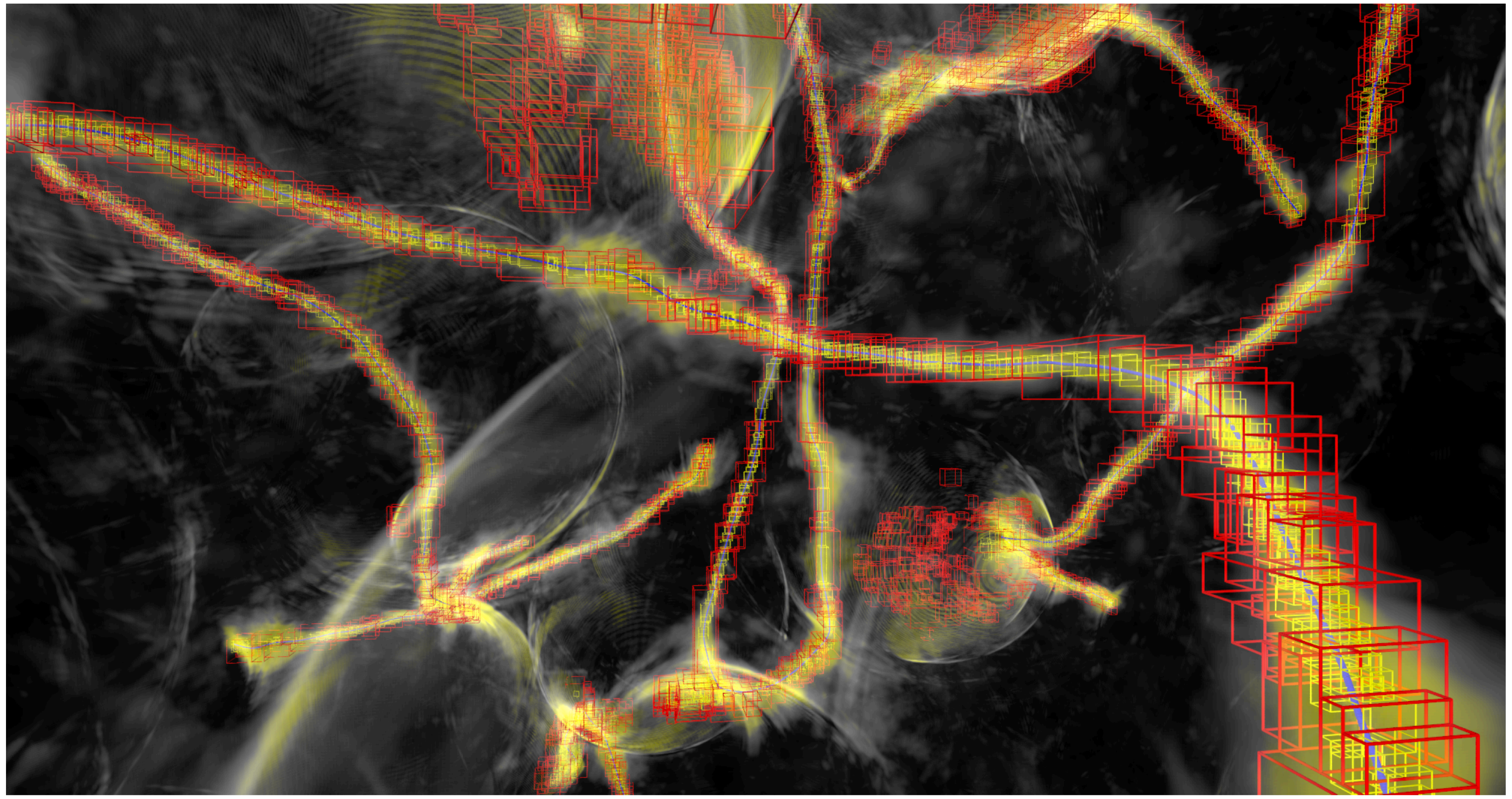
$$\mu = \sim 2v^2 + \pi \frac{v^2}{q_1^2 + q_2^2} \log (v r_{\text{cut}})$$

Adaptive Mesh Refinement I

- Need high resolution around the string cores
- **Idea:** Maintain high resolution only where its needed!
- Current codes mostly based on AMReX (axioNyx, GRchombo)



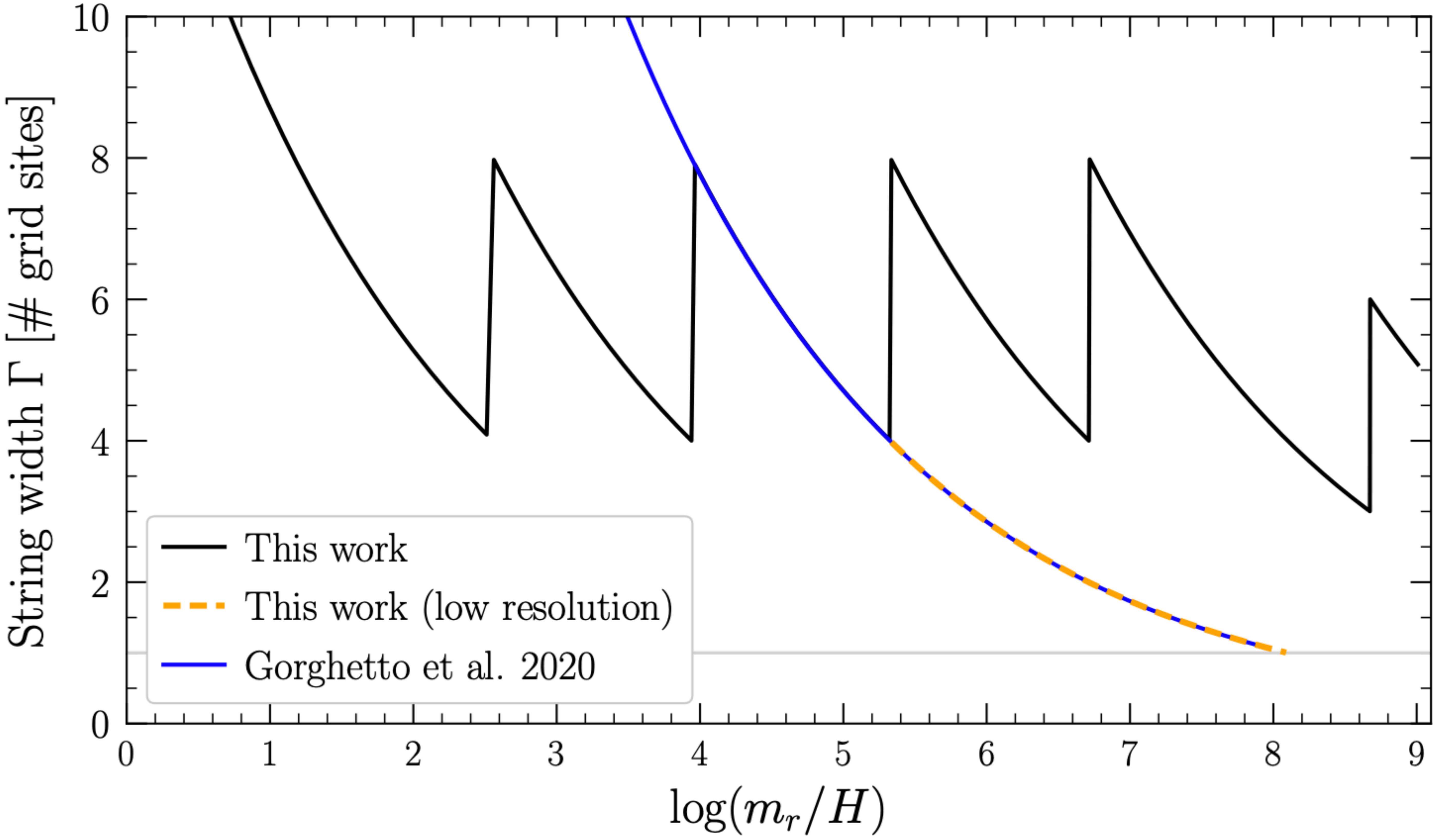
Drew & Shellard [1910.01718]



Benabou *et al.* [2308.01334]

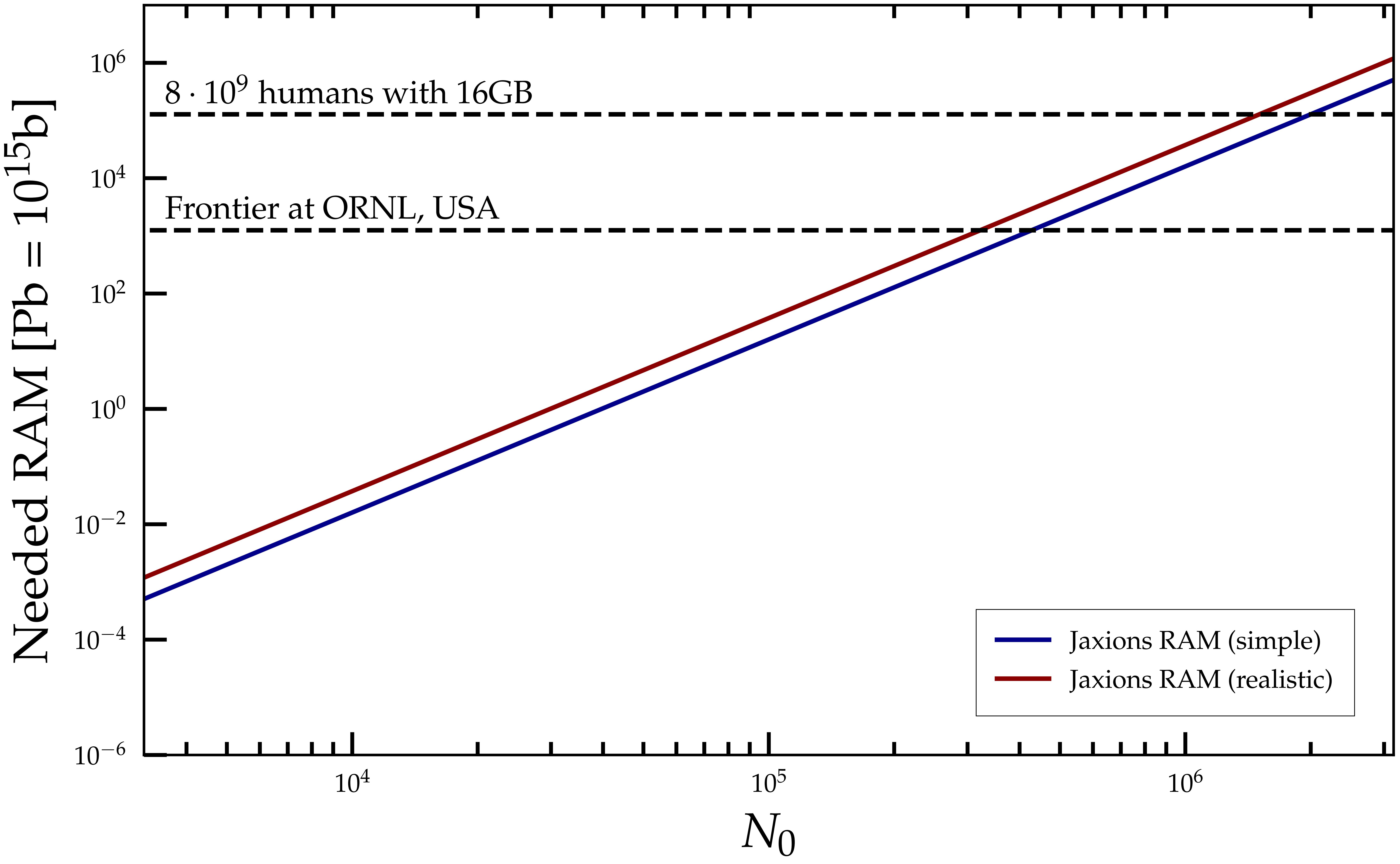
Adaptive Mesh Refinement II

- We can (optimistically) estimate to achieve values of up to log ~ 18!
- Buschmann *et al.* achieved $N_{\text{eff}} = 65.536$ and log ~ 9 in first simulation(s)

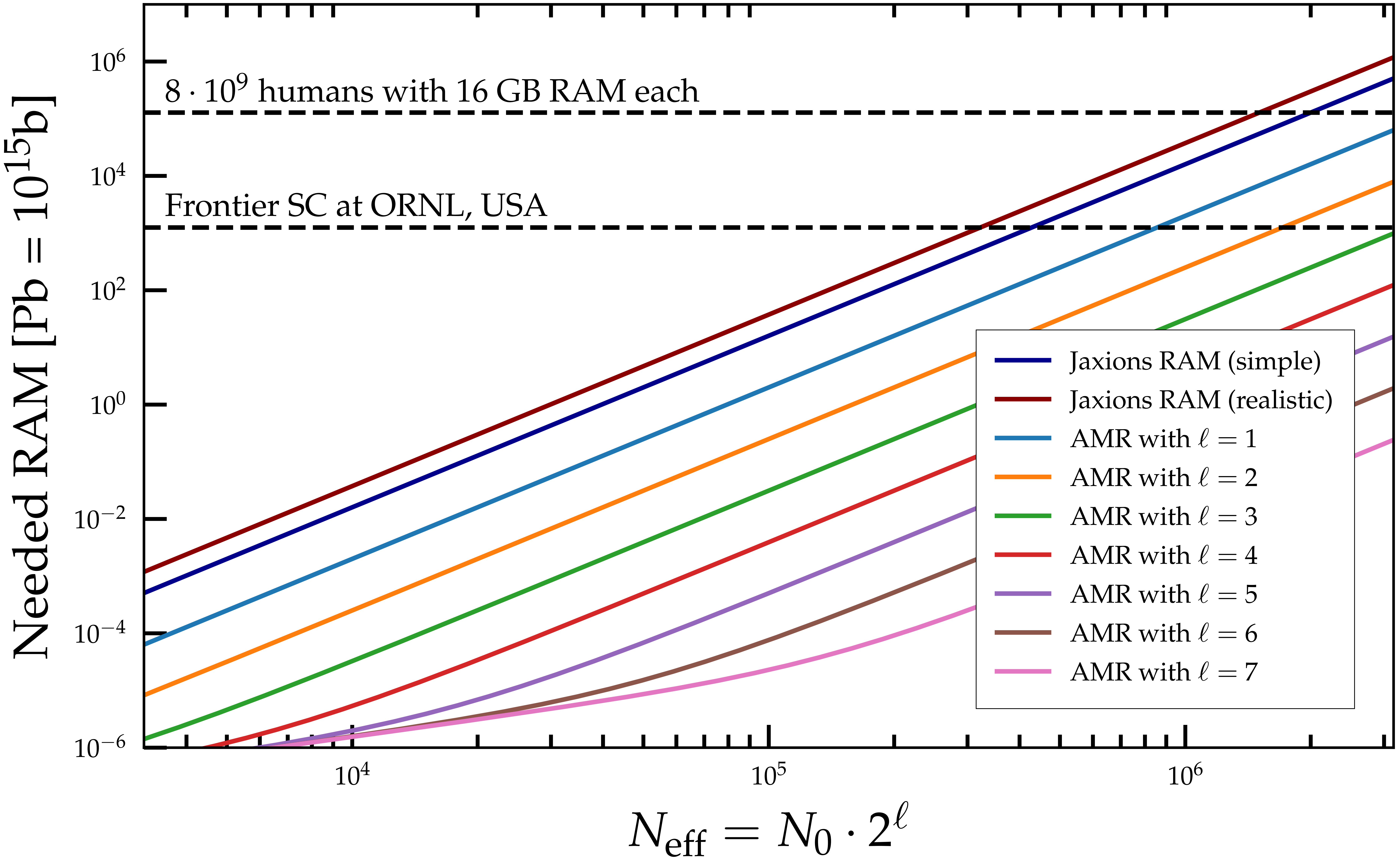


Buschmann *et al.* [2108.05368]

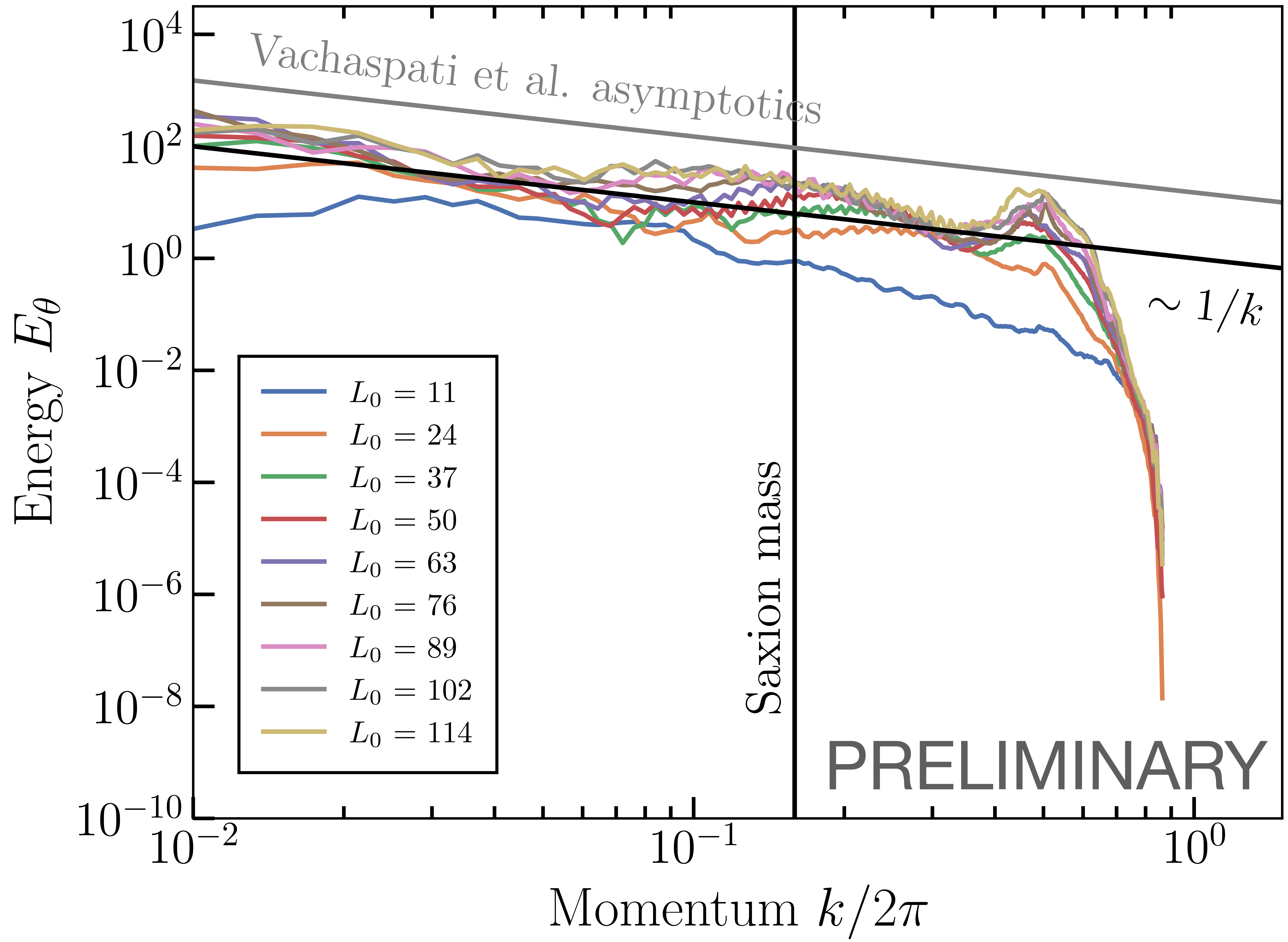
RAM Limitations for Axion String Simulations

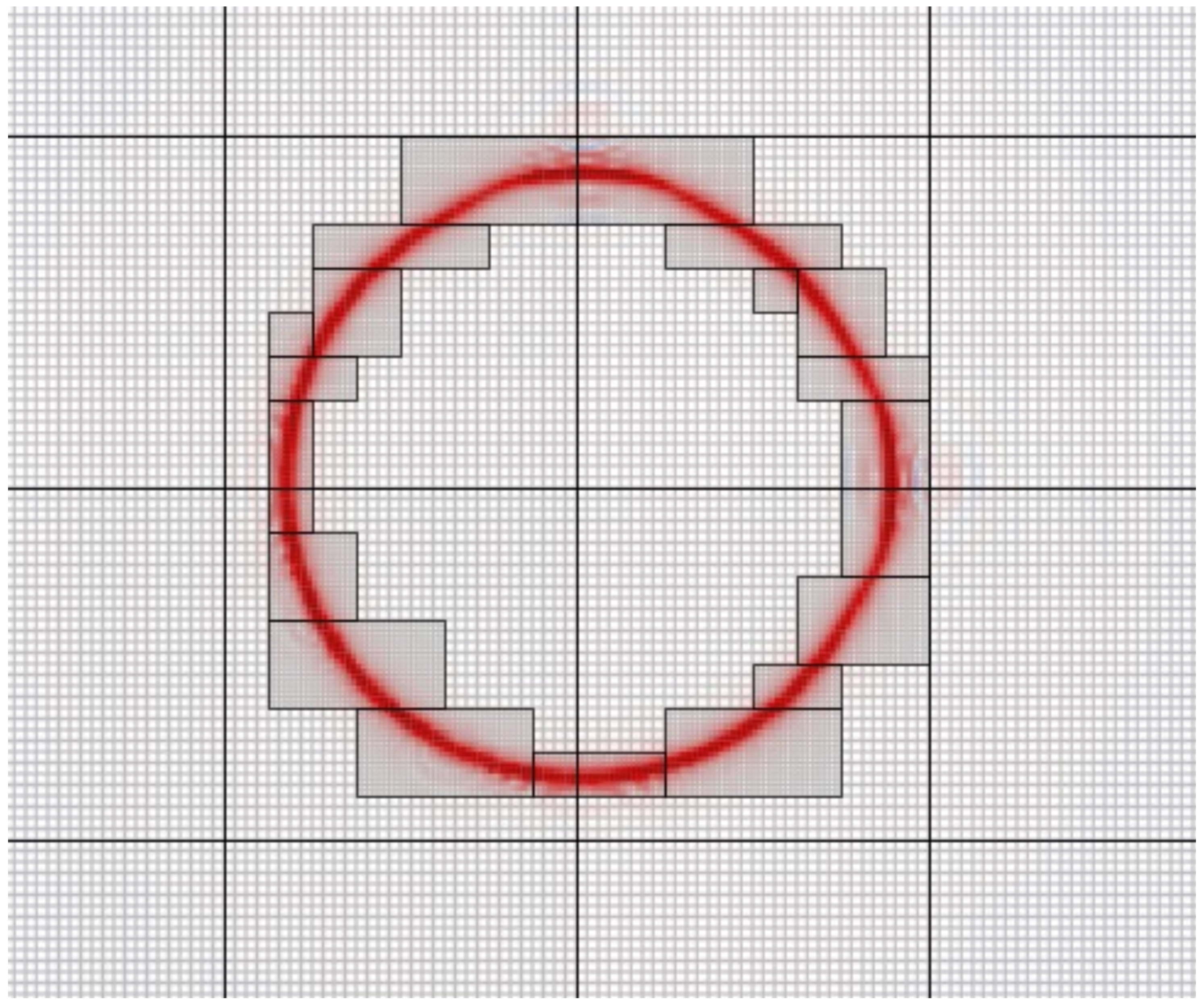


RAM Estimates with AMR



Work in progress: Global String Loop Decays





Screenshot of one of our simulations with axioNyx
Schwabe *et al.* [2007.08256]

Conclusion

- Understanding of the global axion string dynamics is very important for a precise prediction of the axion dark matter mass.
- Different ways of extrapolating/interpreting the results leads to discrepancies in the current literature.
- The use of AMR seems to be the logical next step to increase the dynamical range, although the current setup might not be optimised yet!
- Effective models such as the one introduced by Moore+ allow us to study the behaviour of the network evolution at "realistic" tensions.
- If we manage to provide a very precise prediction for the mass, experimental detection might be accelerated drastically!

Thank you for your attention!