Tales of Axion DM substructure

Javier Redondo

Less Travelled Path of Dark Matter: Axions and Primordial Black Holes

(ONLINE) 5/11/2019

Dep. Theoretical Physics
Universidad de Zaragoza

MPP Munich

Axion DM is different

- Can have very different substructure properties

- Purely "gravitational" tests can be a smoking gun of the nature of DM

- Topic is vast, focus on QCD axion

- Topic is vast, focus on <u>post-inflationary scenario with N=1 for quantitative predictions</u>

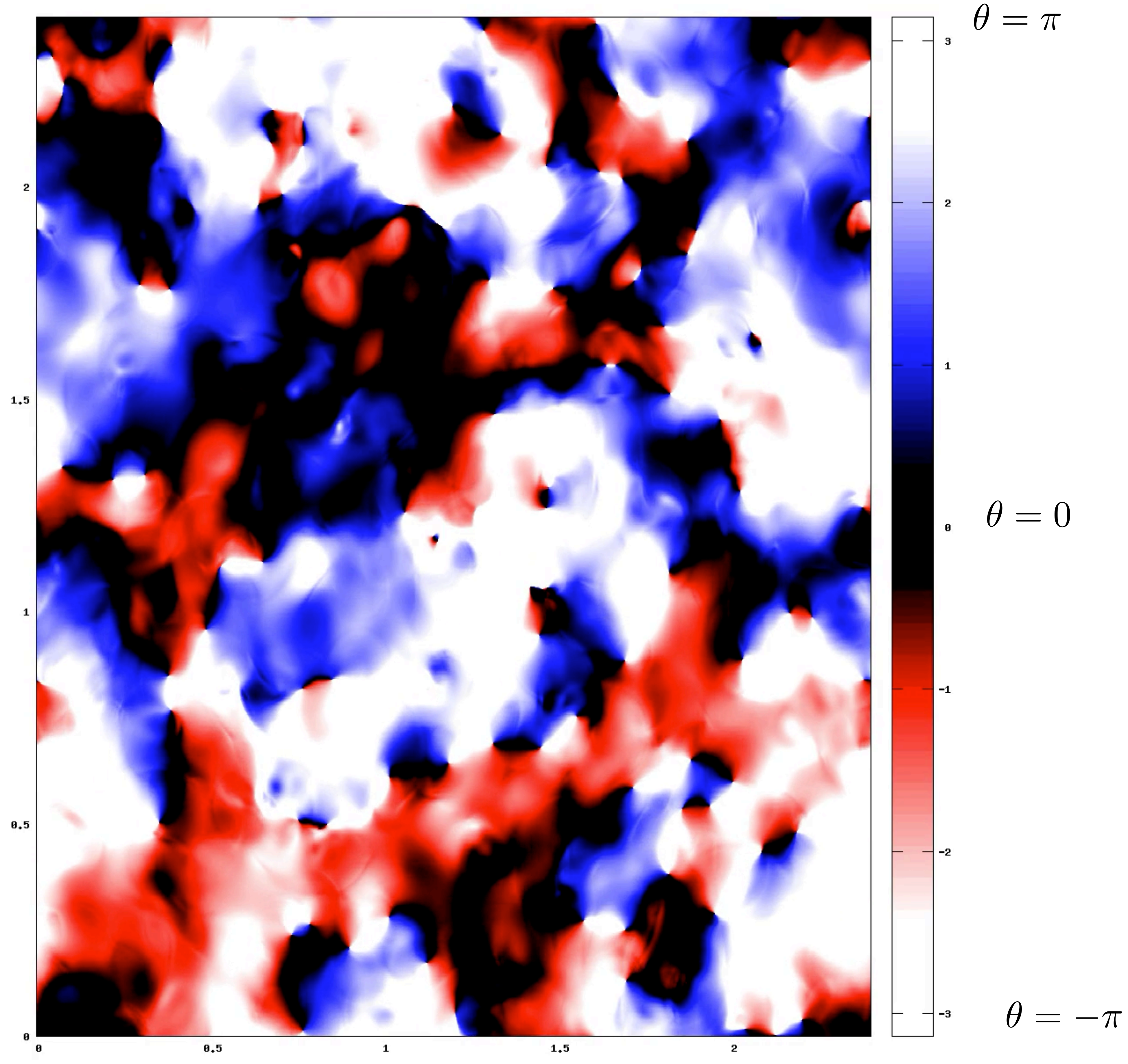
QCD Axion DM mass can be predicted

$$\sim 15\mu\text{eV (Moore,JR)}, \sim 26\mu\text{eV (Moore HT)}, \sim 26\mu\text{eV (Safdi LT)} \gtrsim 500\mu\text{eV (Gorghetto EX)}$$

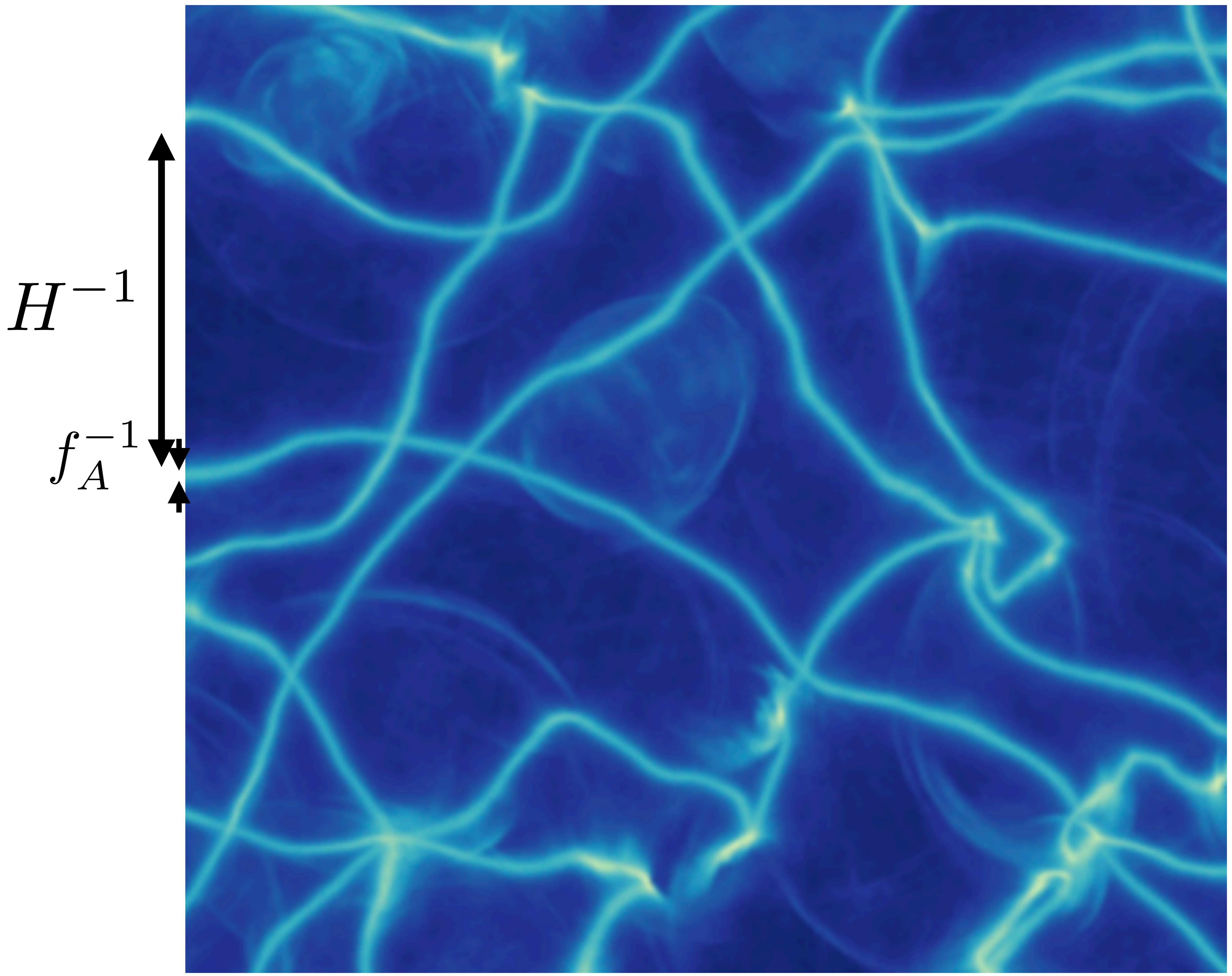
Substructure in Post-inflationary scenario N=1

Cosmic strings

- Produce axions that contribute to DM
- Determine the axion DM spectrum at t1
- Are color superconducting *Fukuda 2020*
- String-leptogenesis ... *Sahu 2006, Jeannerot 2007*

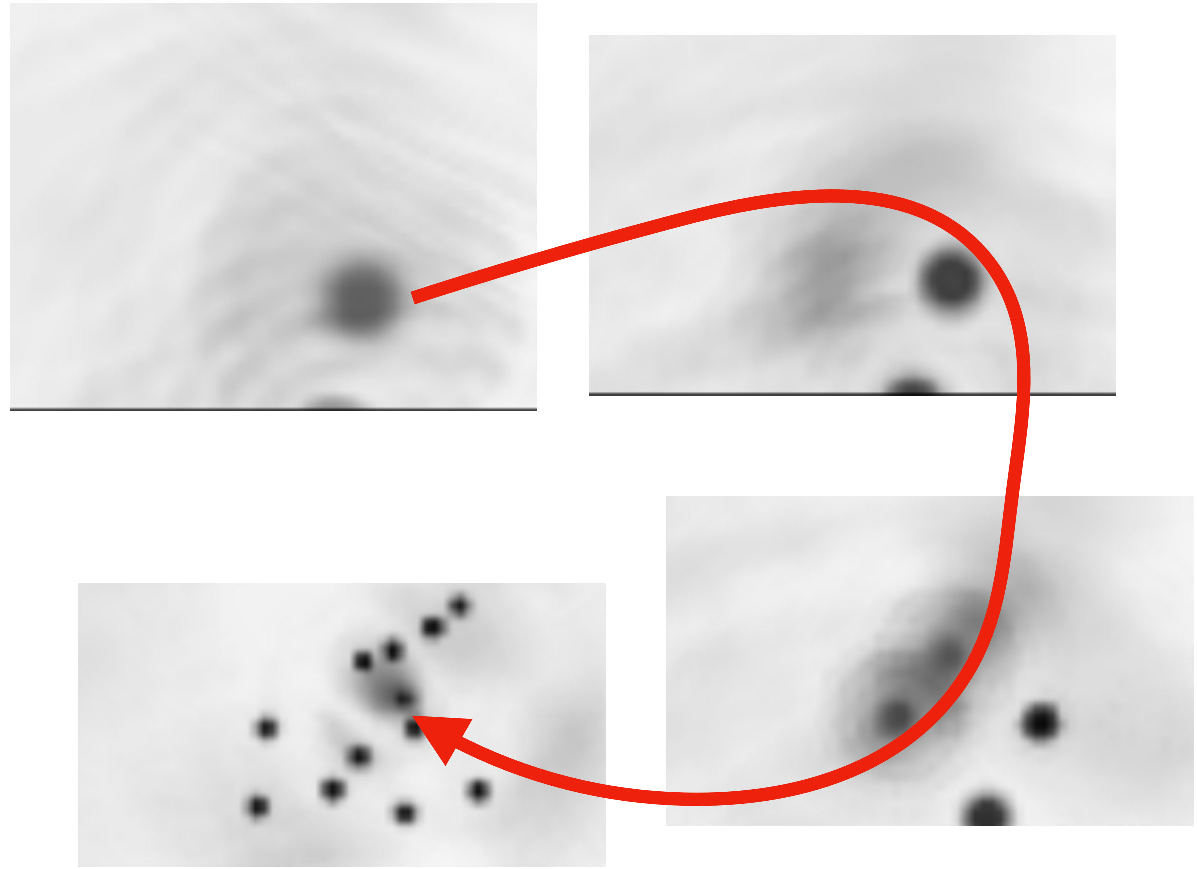


Scaling regime (proyection plot of axion energy density) a.units.



Axitons, Dense axion stars and dilute axion stars

- Axiton (oscillon): Pseudo-breather of axion-field in the early Universe (~UNSTABLE) when mass increases



$R \sim 1/m_A(T)$

- Axitons dominate temporarily the Power-spectrum of fluctuations @ k~m(T)
- Highest density seeds

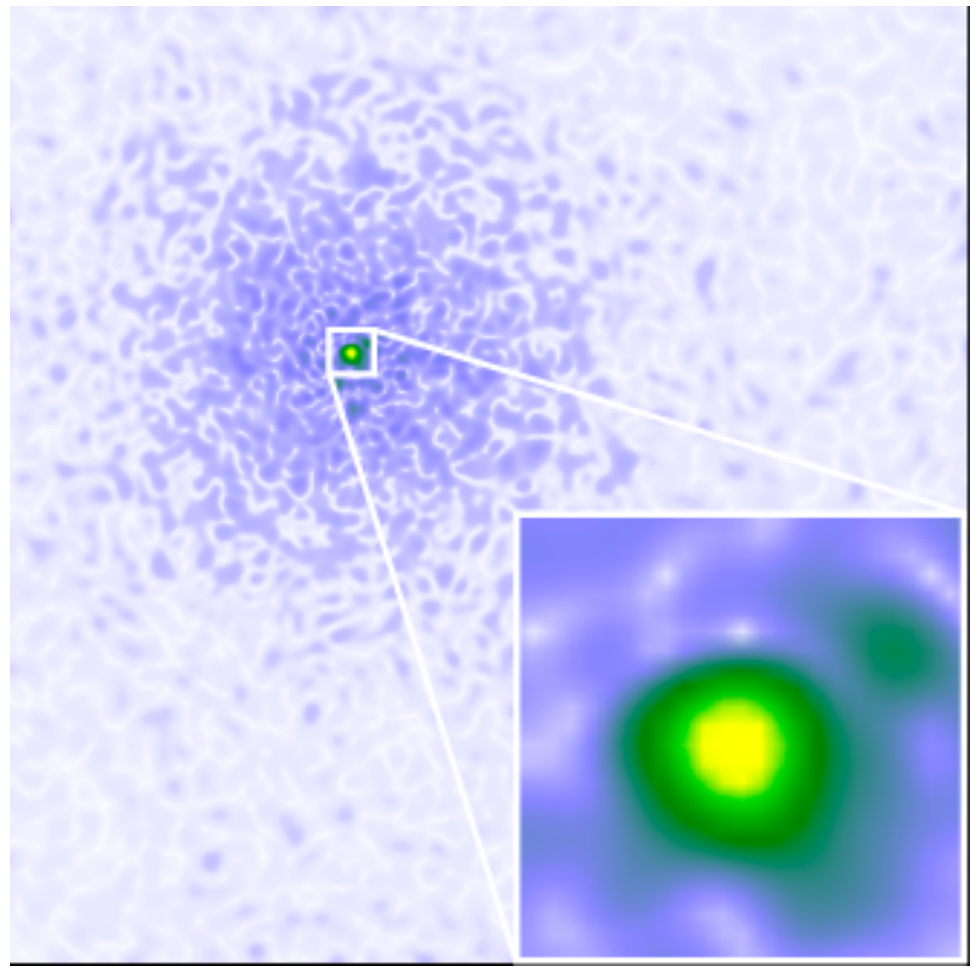
- Dense Axion Star: (Axitons when mass~ constant) UNSTABLE

$$\Gamma \sim m_A$$

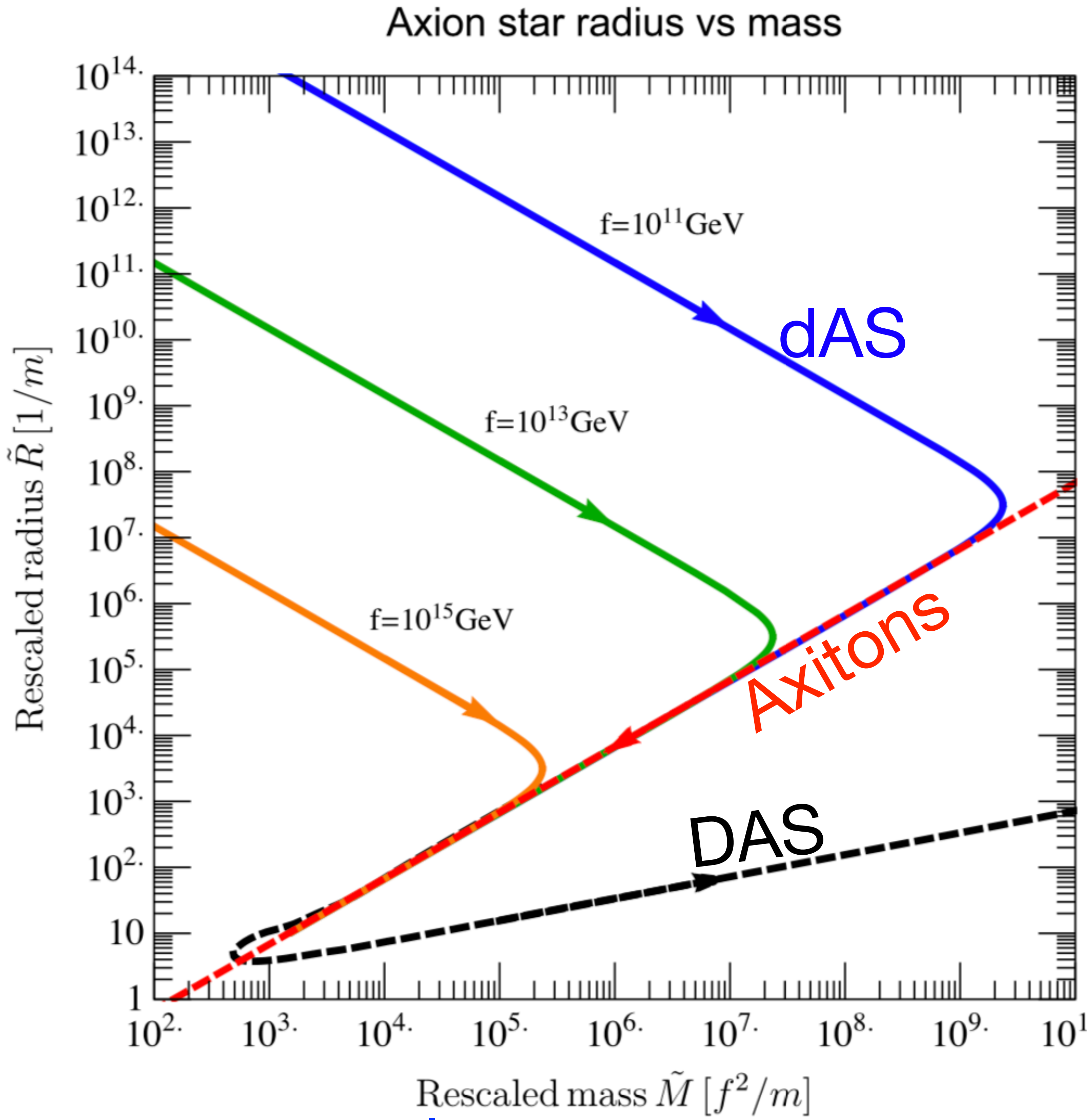
$$R > 1/m_A(\rho \sim \chi_{\rm QCD})$$

- DAS: largely irrelevant, only R~1/mA form (temporarily) in the collapse of dAS.

- Dilute axion star (oscilloton): gravitationally bound coherent lump of non-relativistic axions



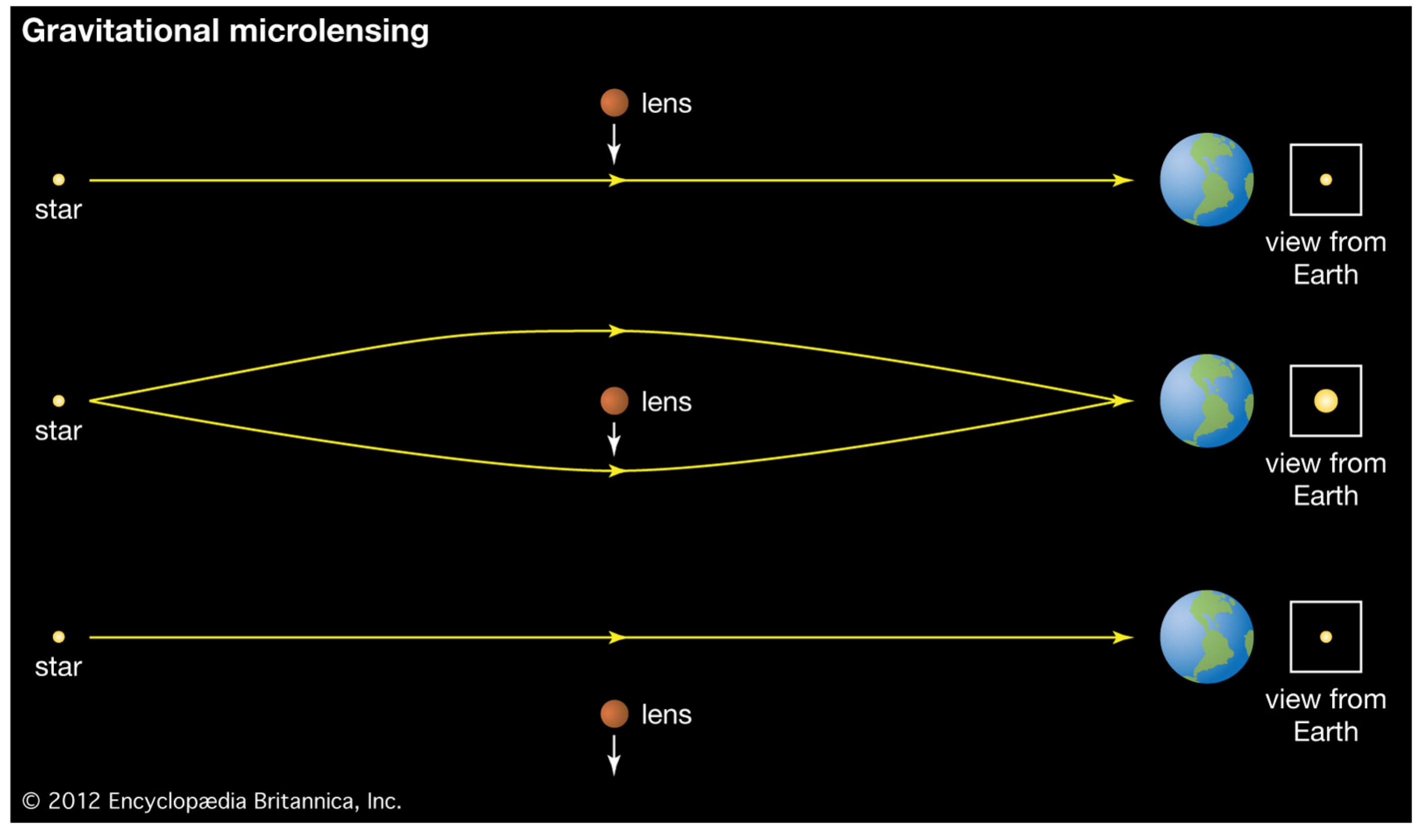
$$R \sim 10/Gf^2M$$

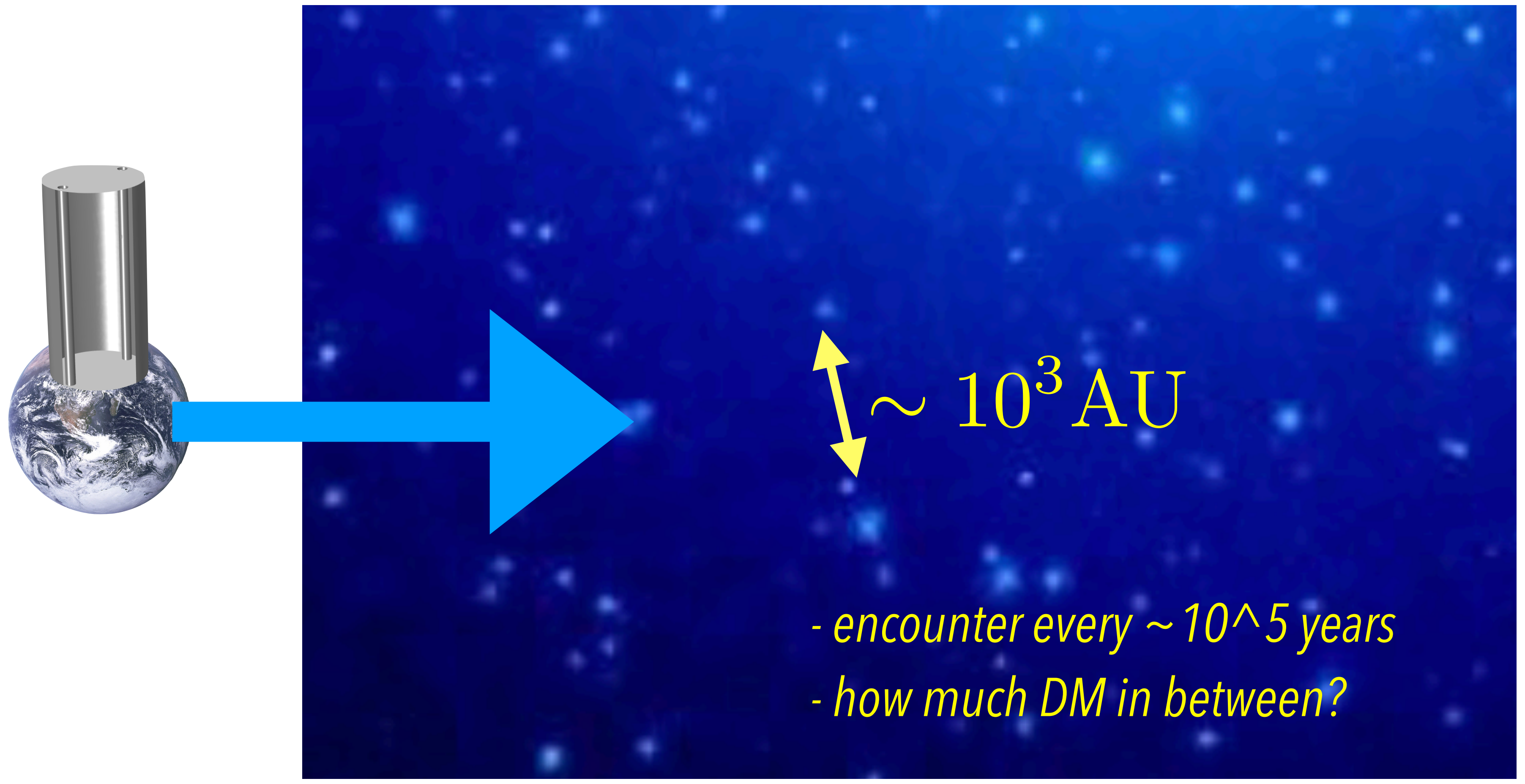


- dAS: fascinating but not very conspicuous;
  - can accrete, become critical, collapse, radiate, relax (Change e.o.s of DM)
  - can coherently decay into radio-waves

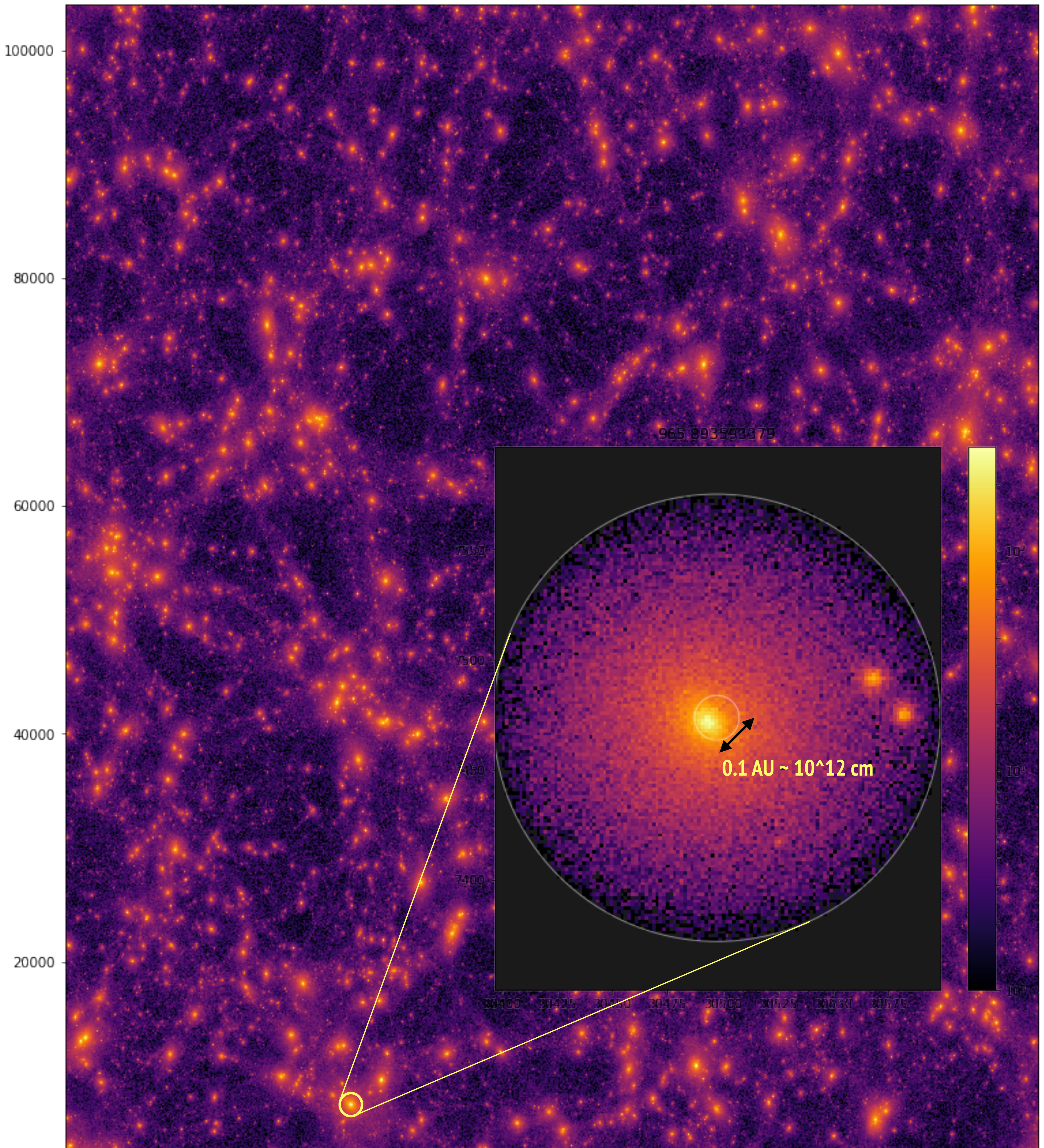
Miniclusters

- Gravitationally bound AxionDM halos
- Small mass, large density $M_{\rm mc} \sim 10^{-12} M_{\odot}, \rho \sim 10^{6} \frac{\rm GeV}{\rm cm^3}$
- Micro, femto-lensing?
- Hide DM to direct-detection experiments?





Dark matter proyection map $z = 1000$



Quantitative issues

Q1 - What is the minicluster mass function?
Q2 - How are the minicluster density profiles?
Q3 - what is the dAS mass function?
Q4 - what is the rate of dAS collapse? (e.o.s, radio signals)

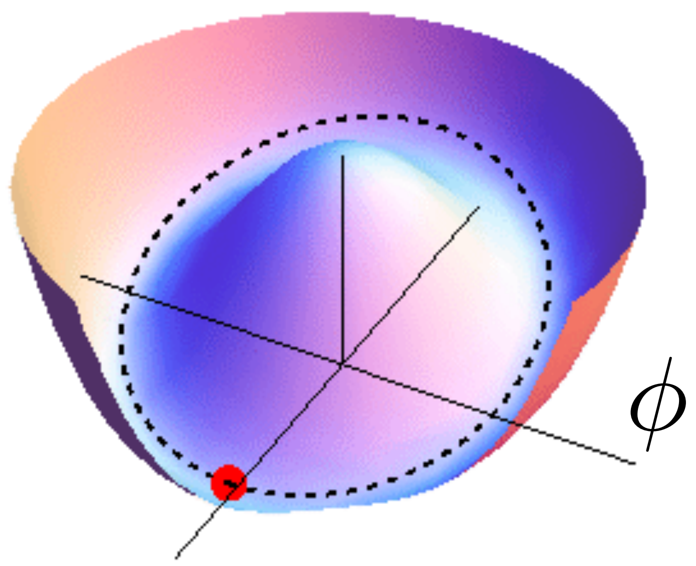
R1 - Need the distribution of axion DM at L1 scales before zeq *Vaquero, JR 2018, Buschmann 2019*
R2 - Need to simulate gravitational collapse of axion DM fluctuations *Eggemeier, JR... 2020*
R3 - Need the above at scales L<<L_1 + FDM simulations *only first steps ... formation of Bose-stars in MCs (Tkachev 18, Eggemeier 19)*
R4 - Need the above, acretion rates, collapse simulations *only first steps ... (Tkachev 20)*

Distribution of axion DM

- Early analytical attempts in vain (initial spectrum put by hand, no string-network) *..., Zurek 2007, Enander 17*
- Numerical Simulations of global cosmic strings *Vaquero, JR 2018, Buschmann 2019*

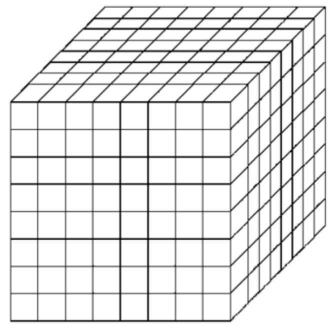
$$\ddot{\phi} - \frac{1}{R^2}\nabla^2\phi + 3H\dot{\phi} + \lambda_\phi \phi(|\phi|^2 - f_a^2) + m_a^2 f_a = 0$$

$V(\phi)$



$\phi = \rho e^{i\theta}$

- Cartesian grids (up to 8192^3 in SCs)
- Public code *https://github.com/veintemillas/jaxions*

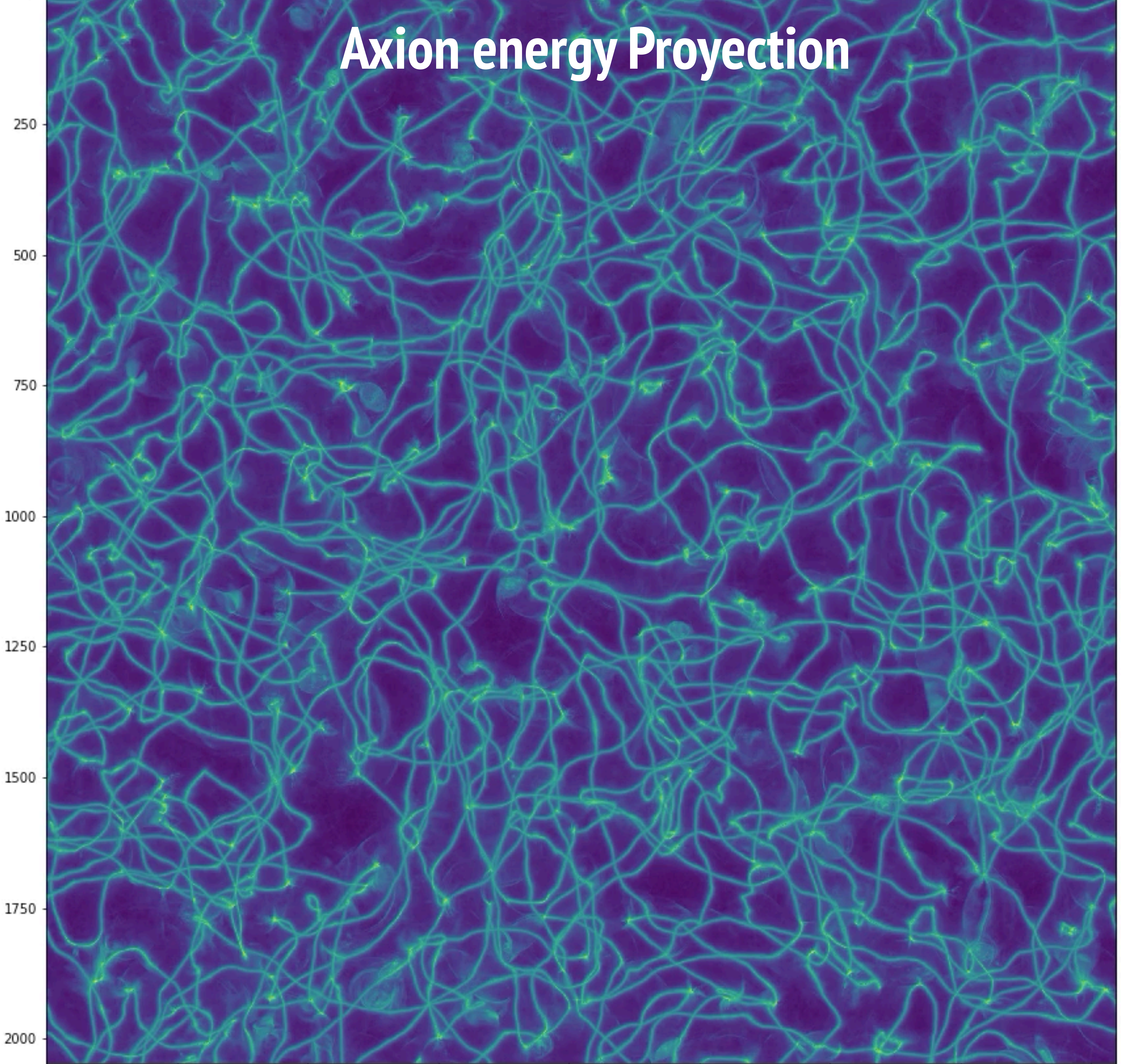


Vaquero, JR 2018

(proyection plots of axion energy density) a.units.

conformal time normalised to t1, $\tau = z_1/z$ axion mass $m_A^2 = \chi_T(T)/f_A^2 \propto \tau^n, n \sim 7$

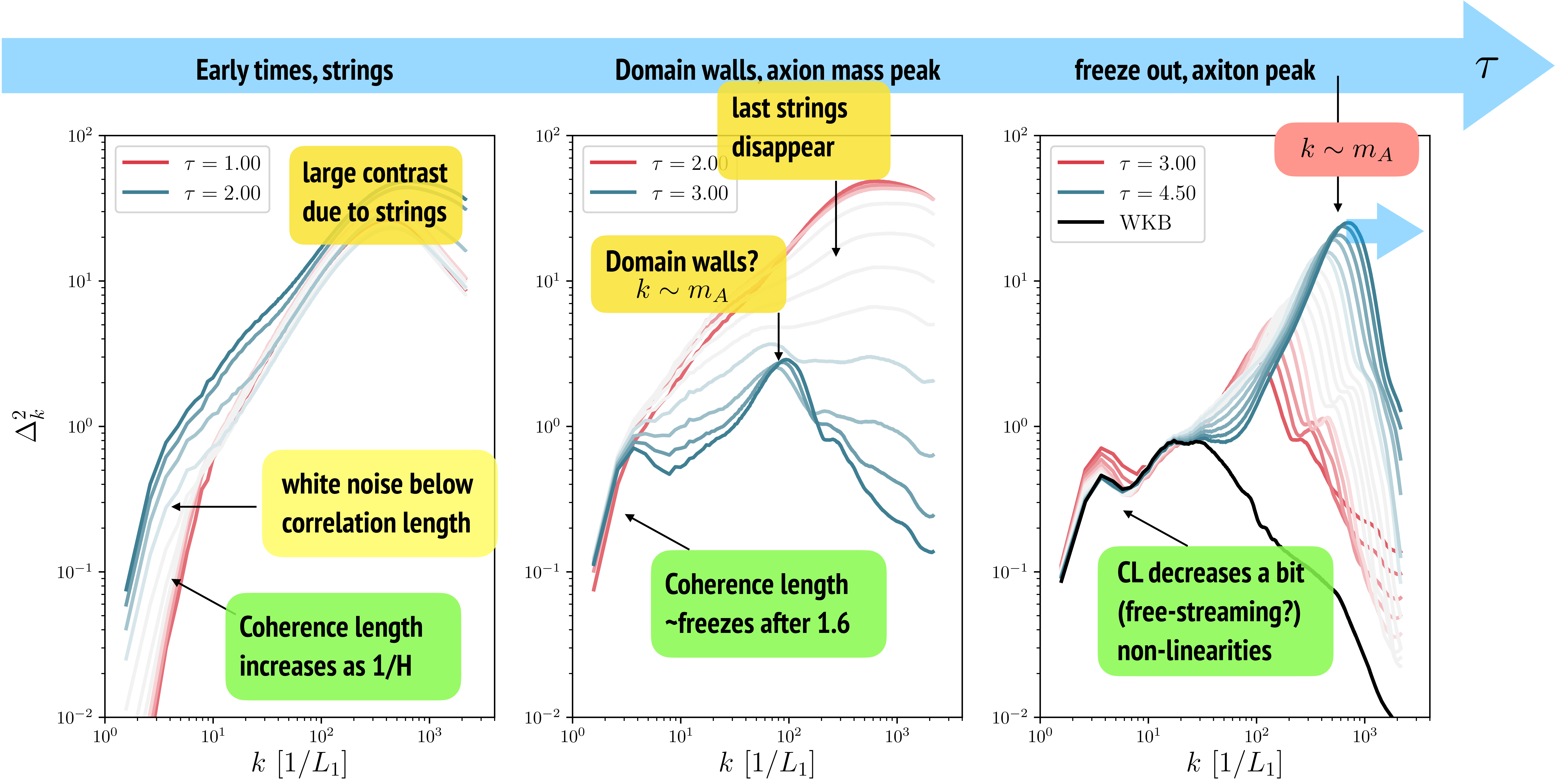
Axion energy Proyection



Axion energy density (contrast) evolution

L=6, N=8192

- Dimensionless variance $\Delta_k^2 = \frac{k^3}{2\pi^2}\frac{1}{V}\langle|\widetilde{\delta}(k)|^2\rangle$

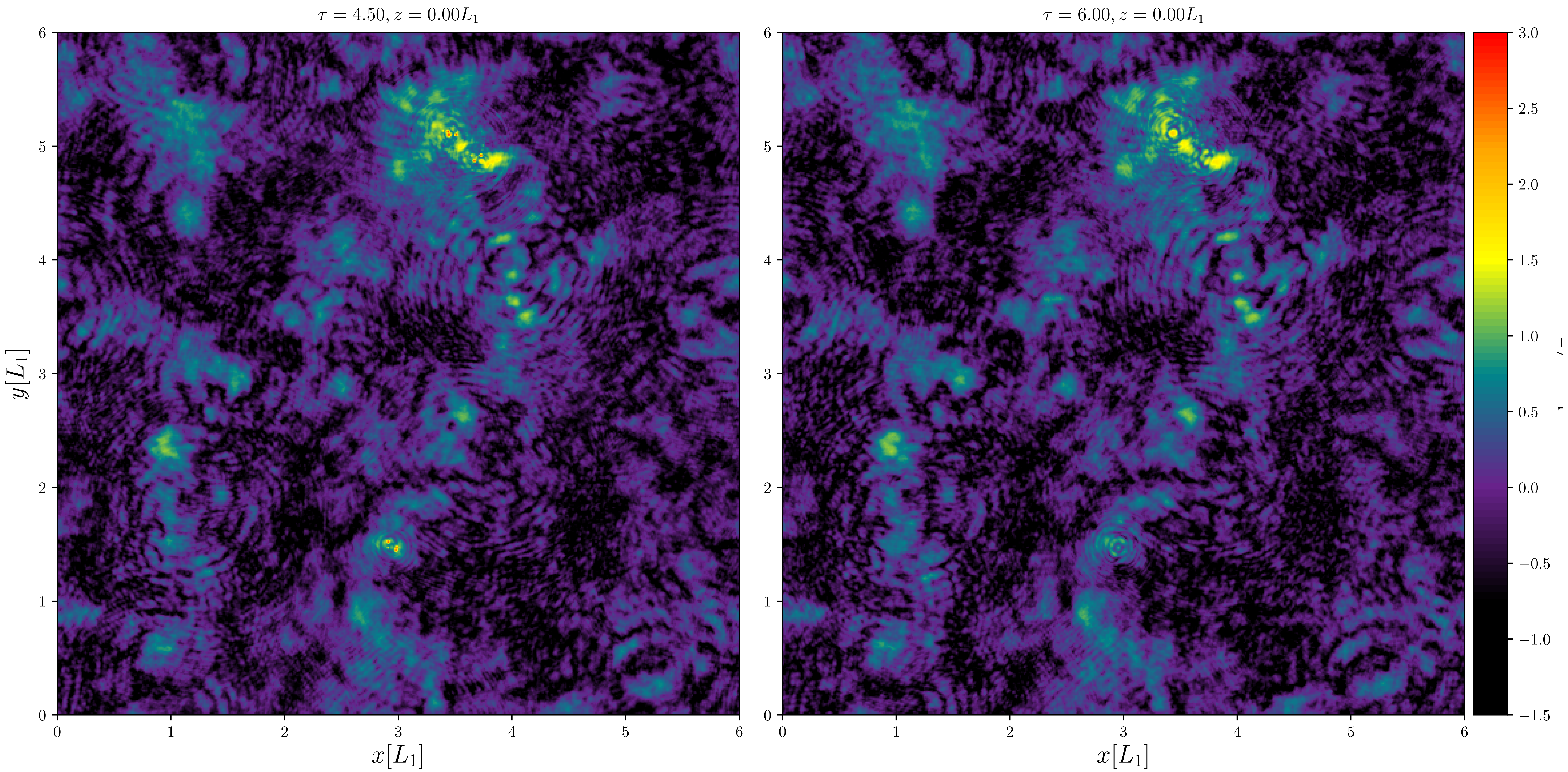


Axiton-free-streaming

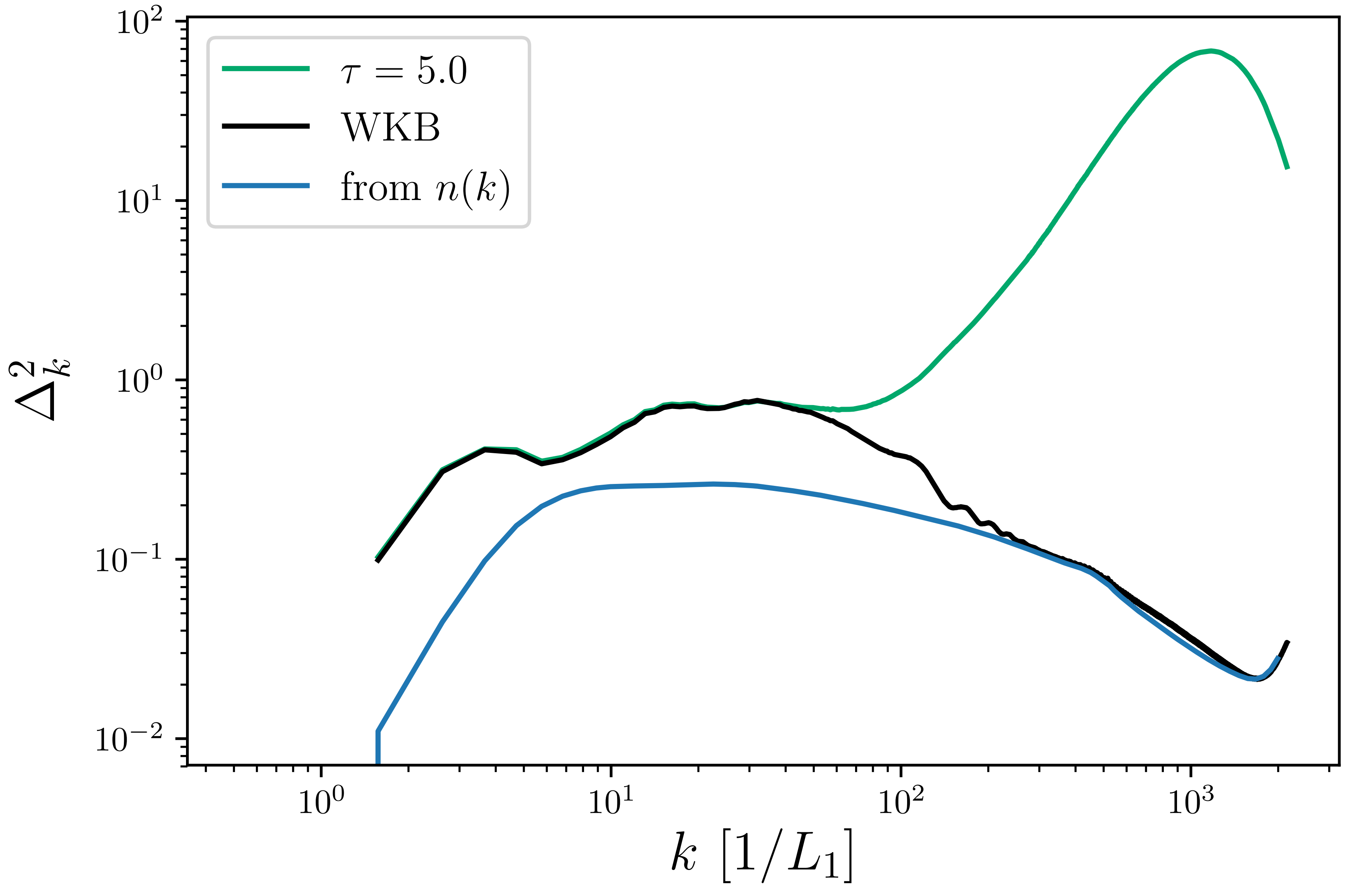
- Axitons pack a few axions into decreasing lumps of volume $\propto 1/m_A^3(\tau)$, part of which are periodically released
- At late times, the radiation free-streams more, becomes less relevant
- We allow axions to free-stream before <u>discretisation problems</u> $m_A \delta x \sim 1$ (remove SI by hand, linearise->WKB)

BEFORE

AFTER

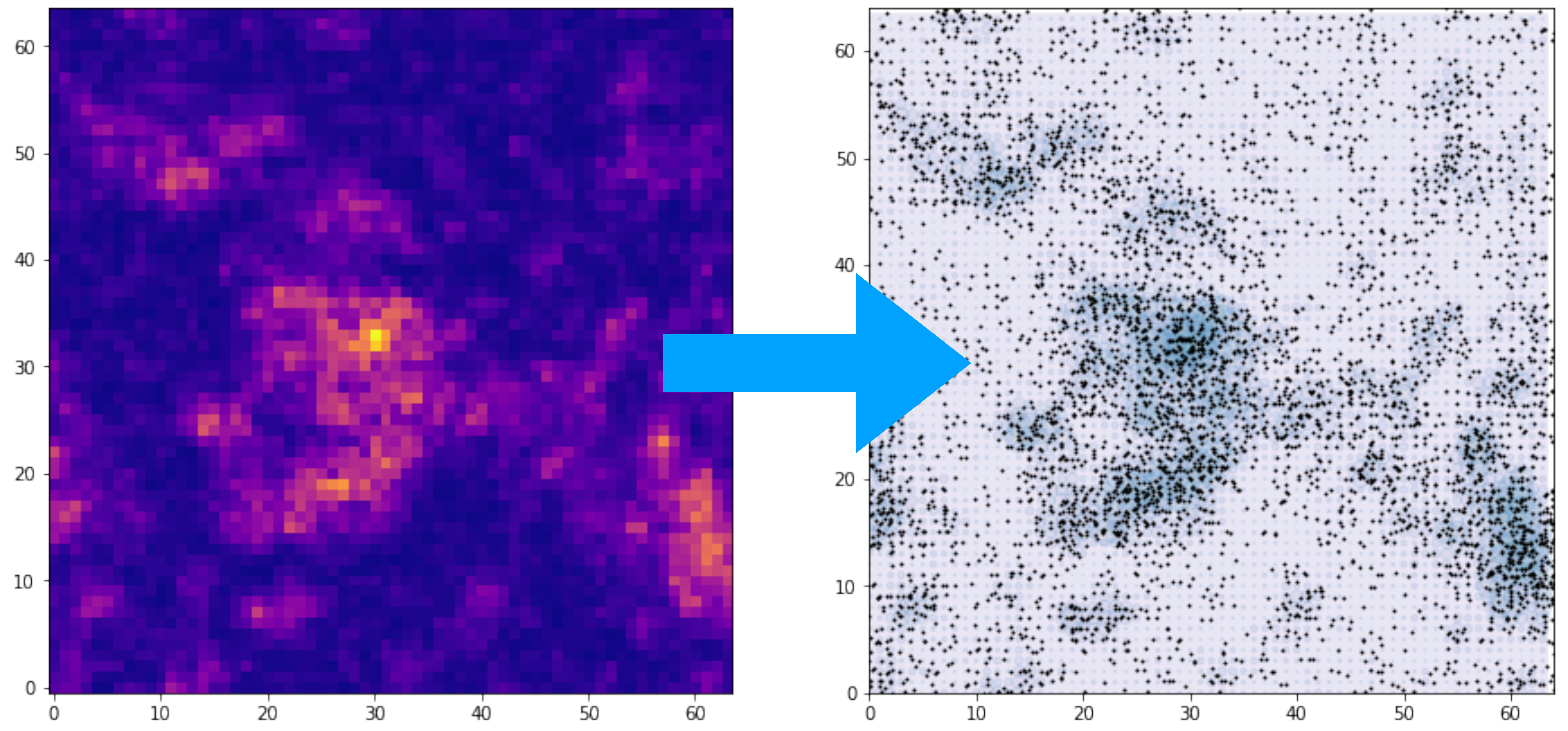


LARGE and MEDIUM scales unaffected

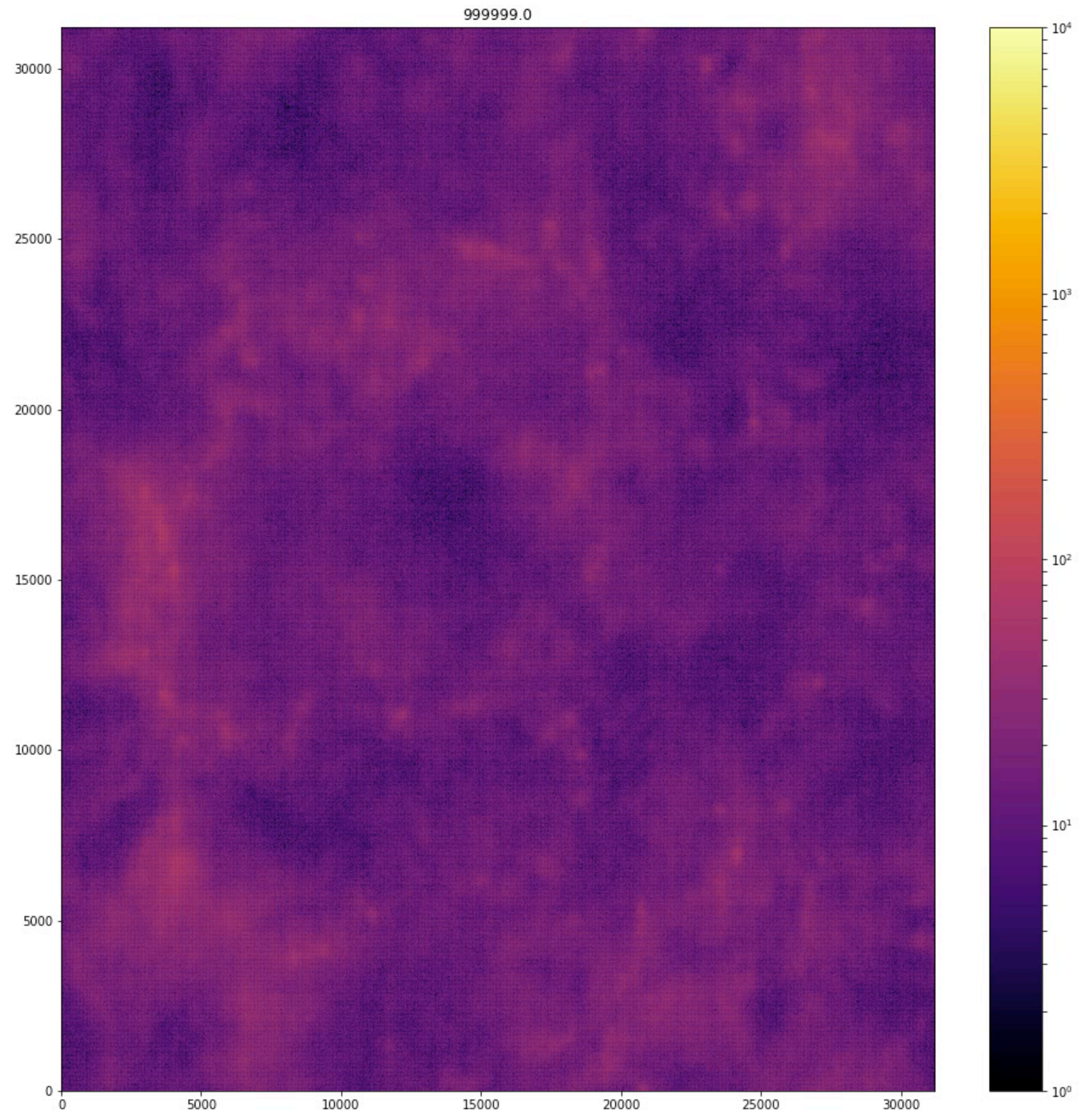


Gravitational Formation of Miniclusters

- At comoving scales of interest (L > 0.01 L1 or so) we can produce density maps
- de Broglie wavelength of axions negligible at these scales (small scales can be checked a posteriori)
- Sample density with "particles" and use N-body codes for gravitational evolution



DM density proyection (JR 2018) with Gadget2 (Springer 2005)

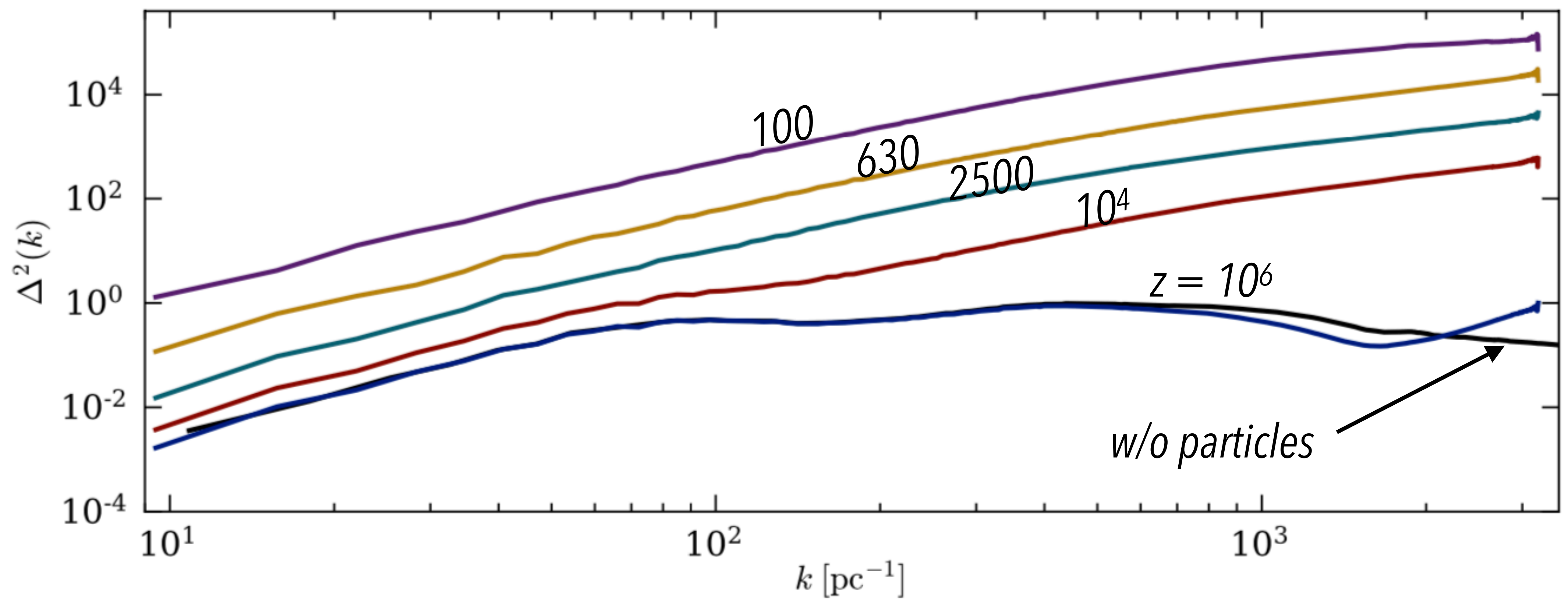


Halo mass function, density profiles, bound fraction!

Eggemeier, JR... 2020

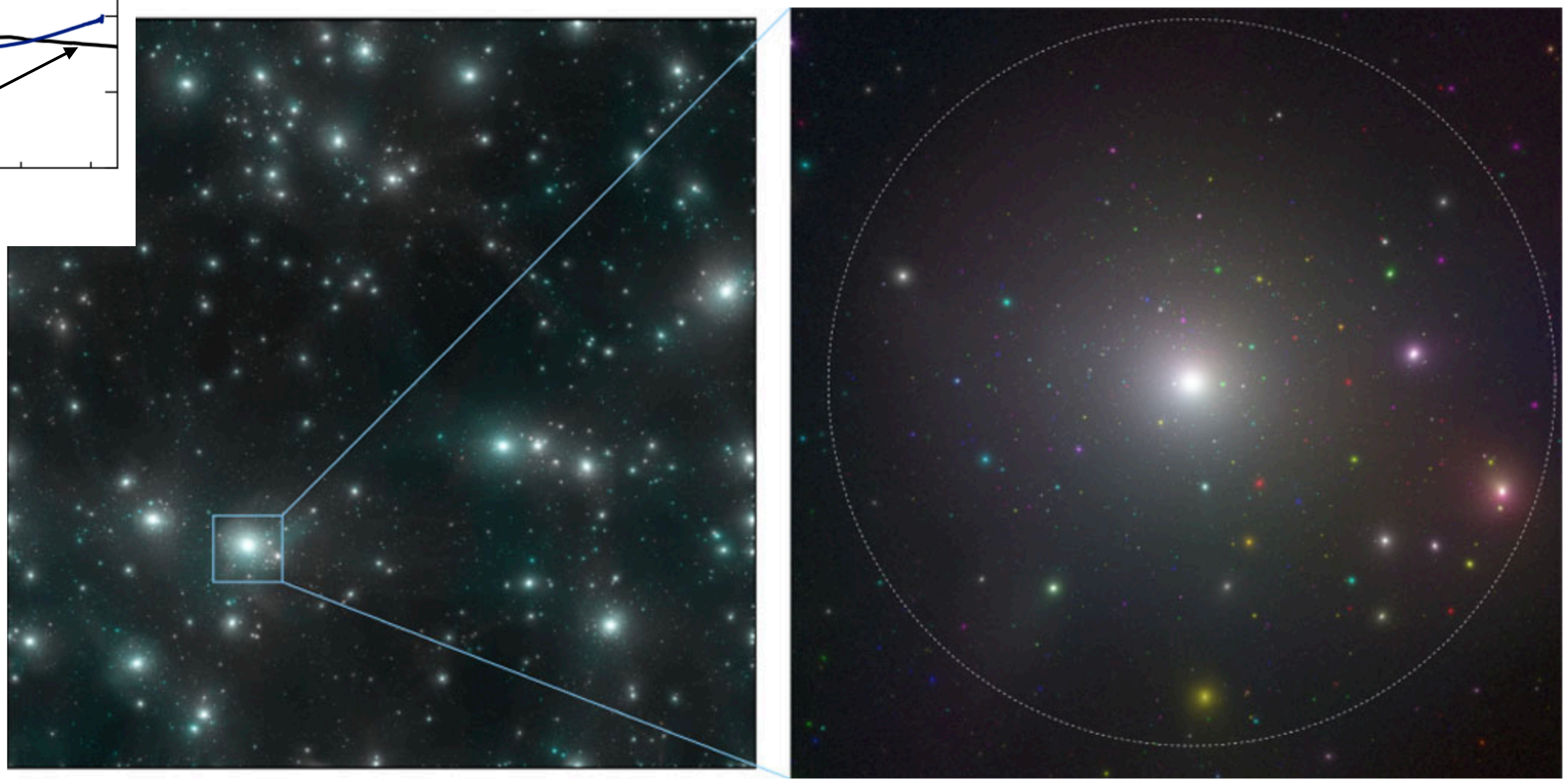
- Large simulation (*N=1024*^{3} particles) in a Large box (*L= 24 L*$_1$) simulated with jaxions in a 8192^3 grid
- Periodic boundaries, volume effects when smallest scale becomes non-linear

Growth of density fluctuations as function of redshift



DM density projection at z=100

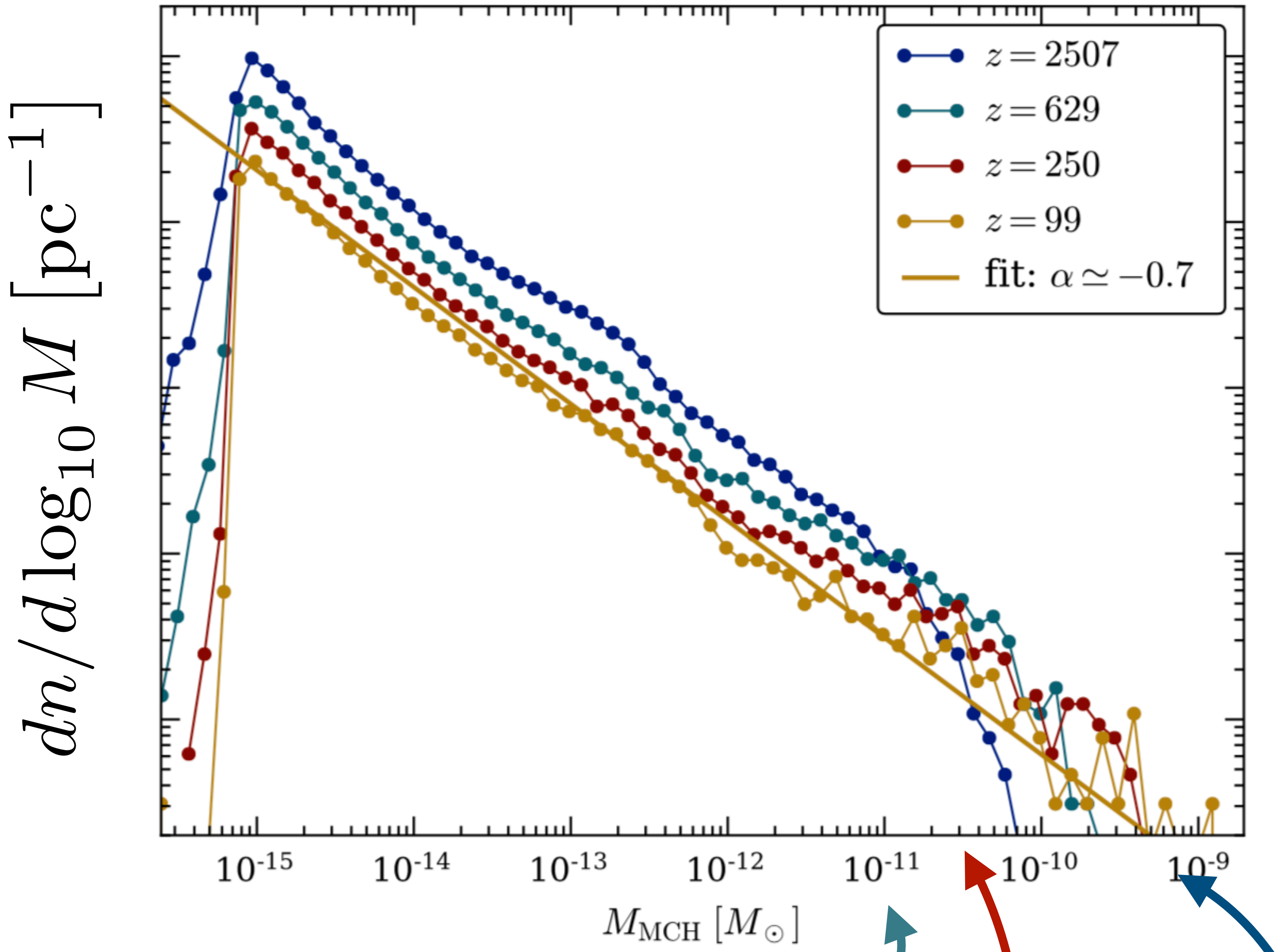
Largest minicluster

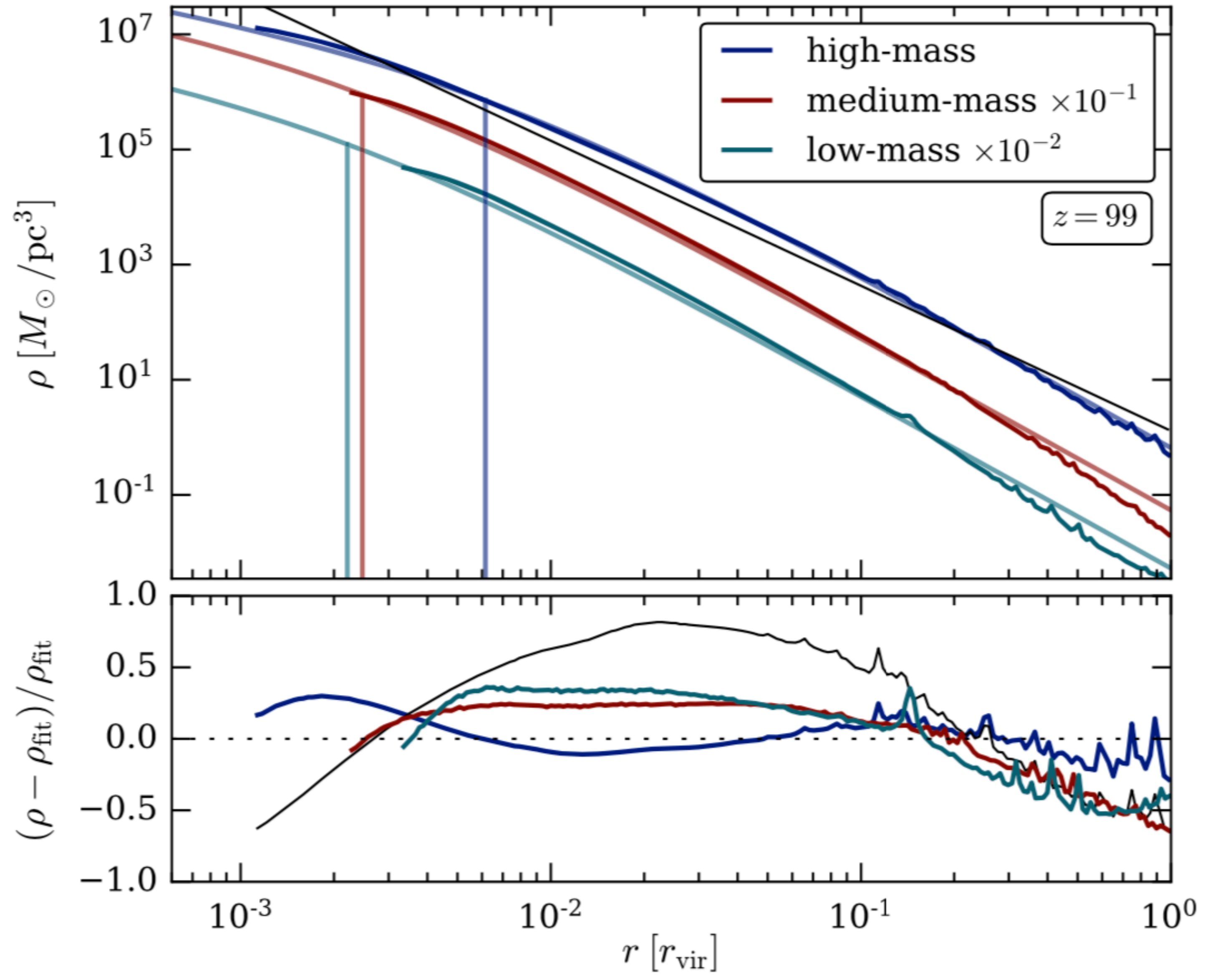


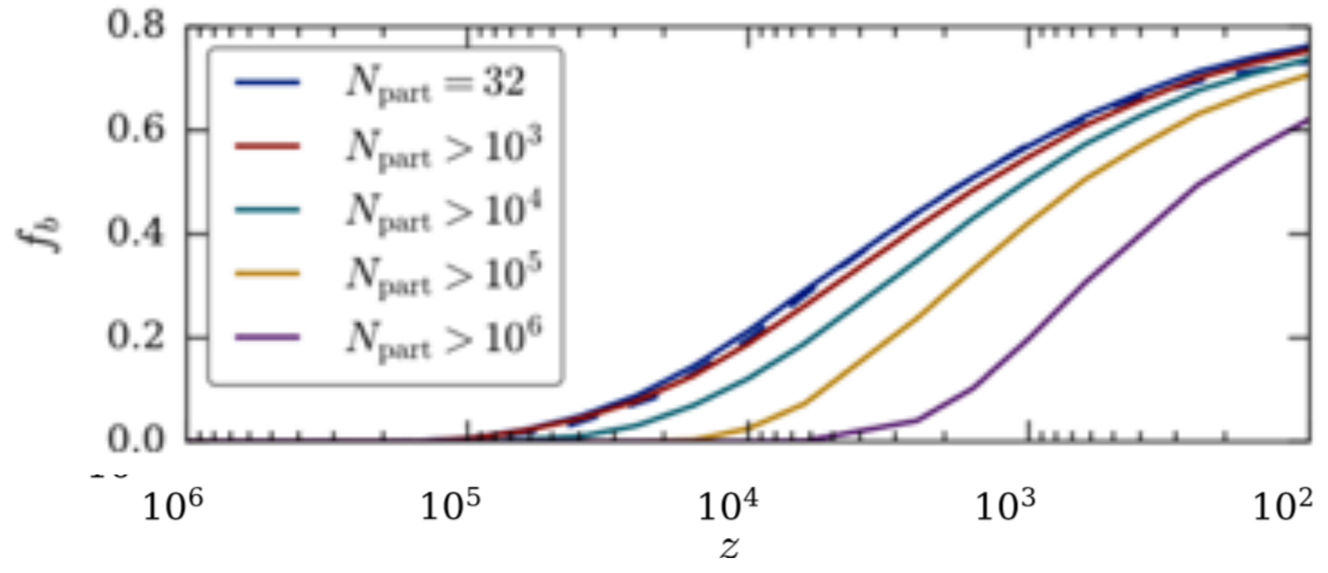
Halo mass function, density profiles, bound fraction!

Eggemeier, JR... 2020

- Large simulation (*N=1024*^{3} particles) in a Large box (*L= 24 L*$_1$) simulated with jaxions in a 8192^3 grid
- Periodic boundaries, volume effects when smallest scale becomes non-linear







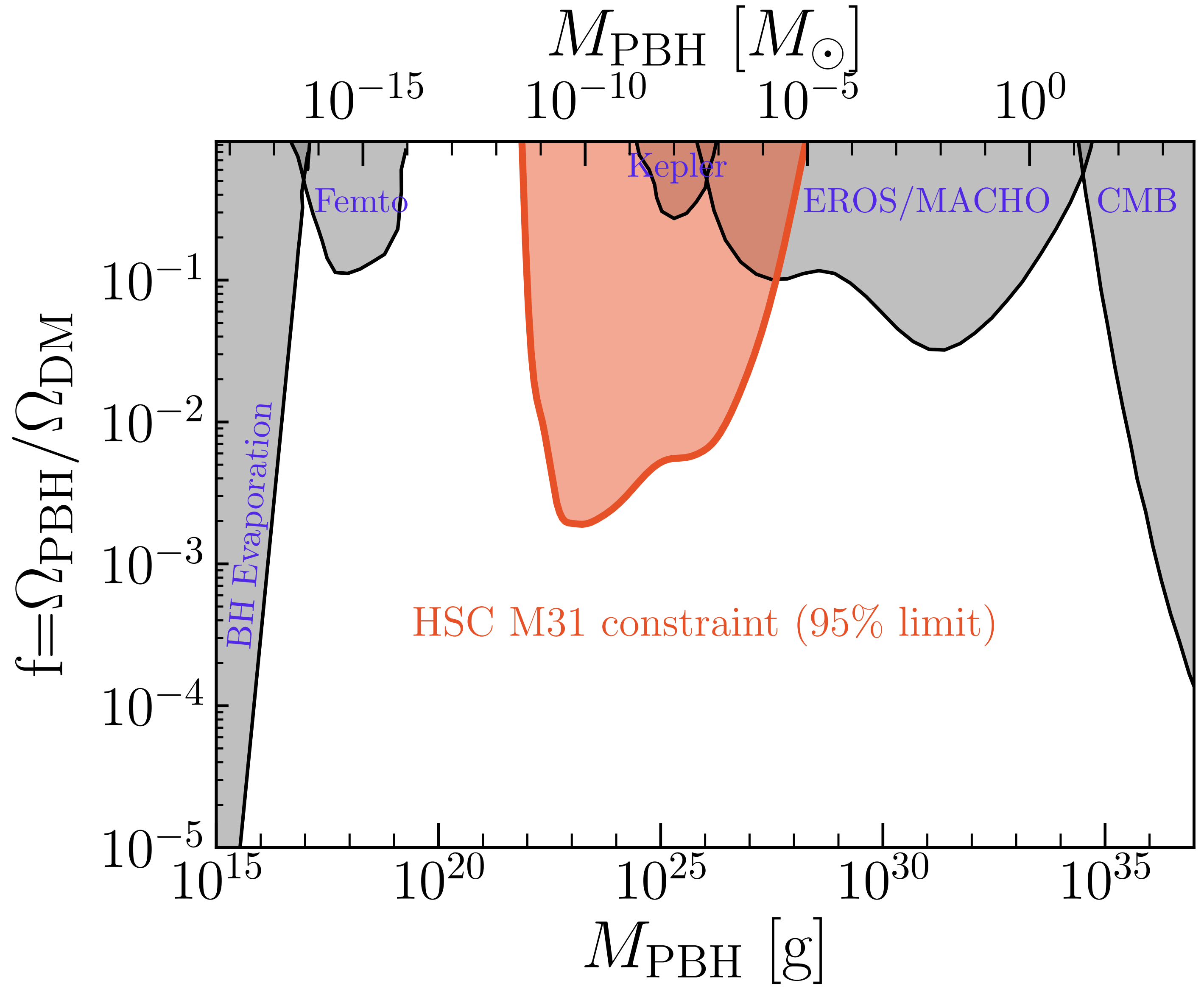
- Loads of low-M MCs
- Spherical collapse with
  $\Phi=\langle\delta\rangle\sim1$ at $z\sim z_{\rm eq}\Phi$
- Typical MC $\Phi\sim1\rightarrow M_0\sim10^{-11}M_\odot$
- Clusters of miniclusters $\Phi<1$

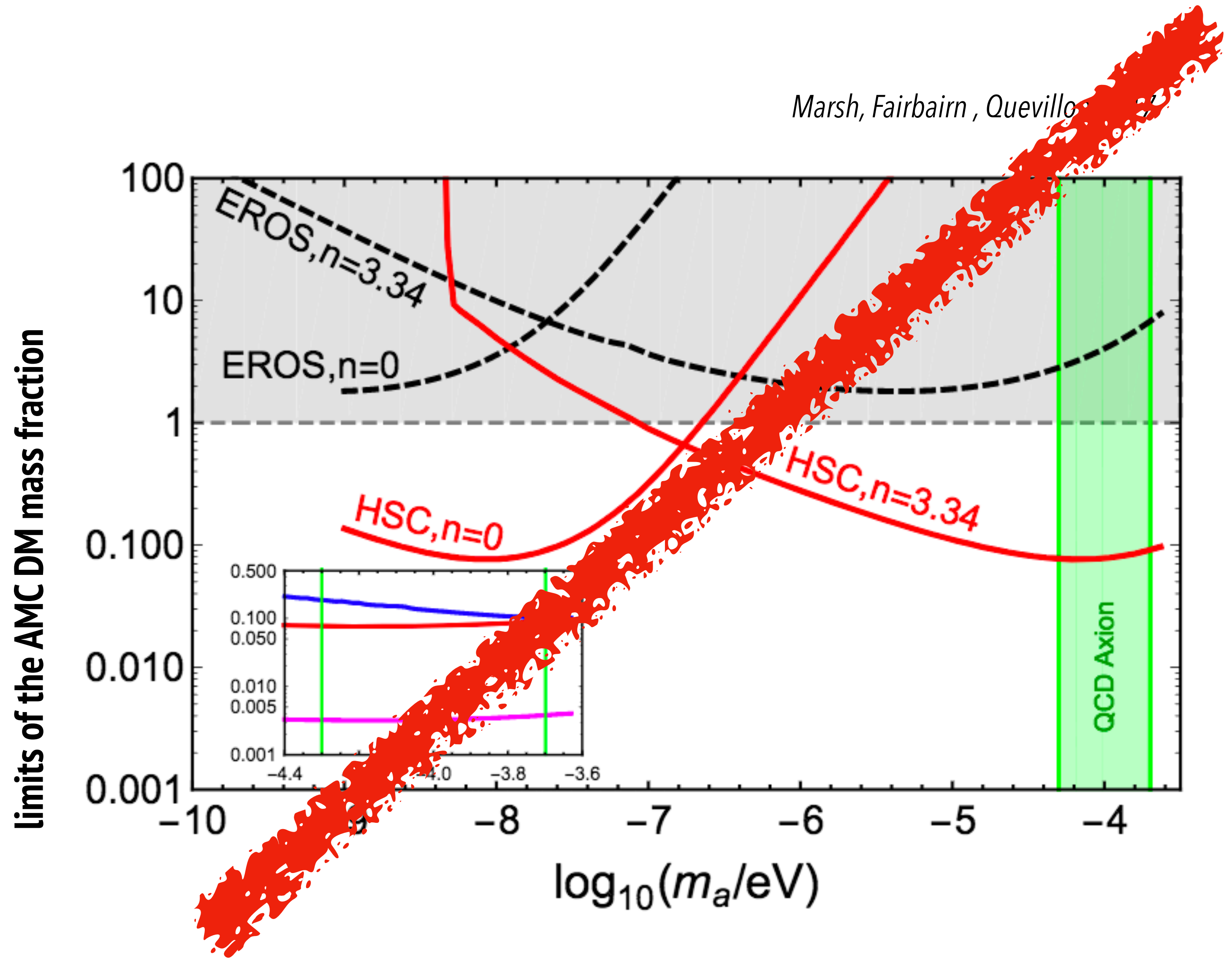
- NFW reasonable fit
- better than $r^{-9/4}$(acretion)
- concentration ~ M
  not well resolved for small M

- Nearly 80% of axions bound in MCs!!
- Tidal disruption with galaxy stars can lower the number
- Most axions in Massive MCs
- Mean MC has low mass

Implications for microlensing, etc ...

- Subaru HSC dedicated search of PHBs along M31
- 10^7, t~2min sampling rate





- Finite source, wave diffraction kill signal below 10^{-11} Msun
- Very few halos with higher masses
- NFW "too fluffy" core distribution kills signal $\quad r_s \gg r_E \quad$ and bounds (assumed $P(\langle\Phi\rangle) = P(\Phi_{\rm point})$)

$$\beta_{E_p} = 6.91 \times 10^{-16} \sqrt{\frac{M_s}{10^{-11} M_\odot} \frac{1\mathrm{Mpc}}{d_A(ES)} \frac{1-d}{d}} \qquad \beta_s = \frac{r_s}{d_A(EL)} = \frac{6.60 \times 10^{-14}}{d} \left(\frac{4.5 \times 10^4}{c}\right) \left(\frac{M_{\rm vir}}{10^{-12} M_\odot}\right)^{1/3} \left(\frac{\rm Mpc}{d_A(ES)}\right)$$

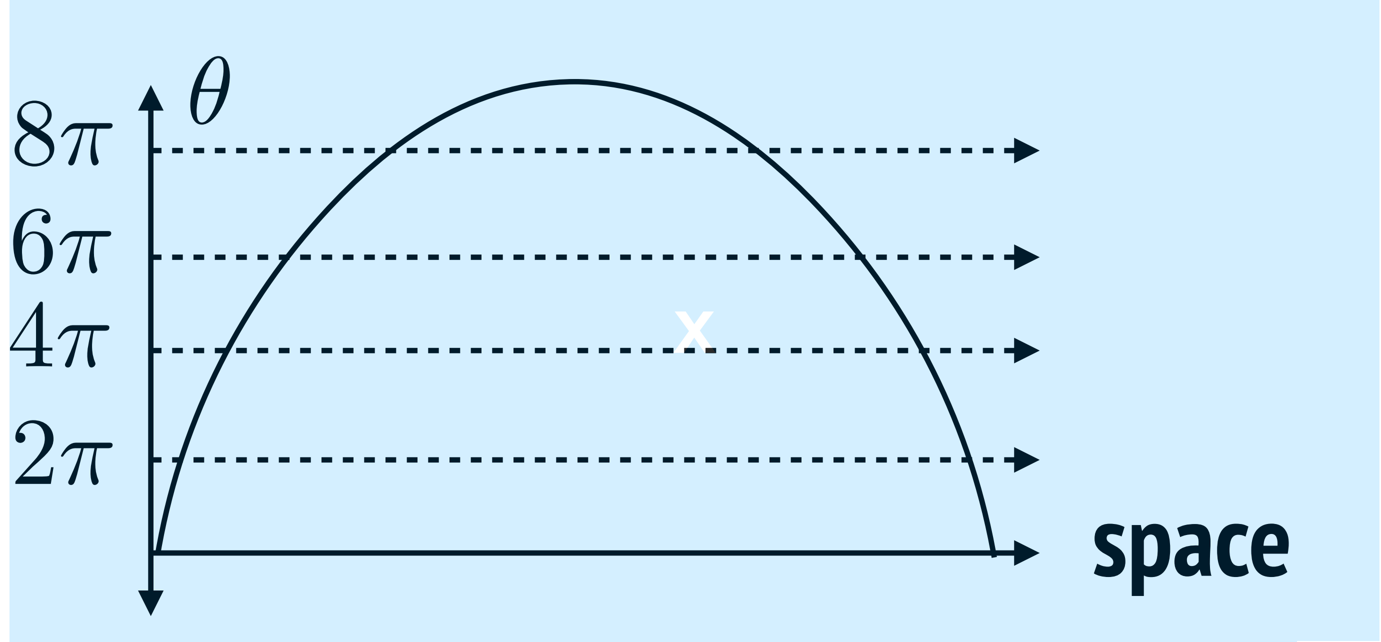
- Need more MC statistics to find the rare ultra-compact MCs (found correspond to $\langle\Phi\rangle \sim 3 \sim 1.5$)

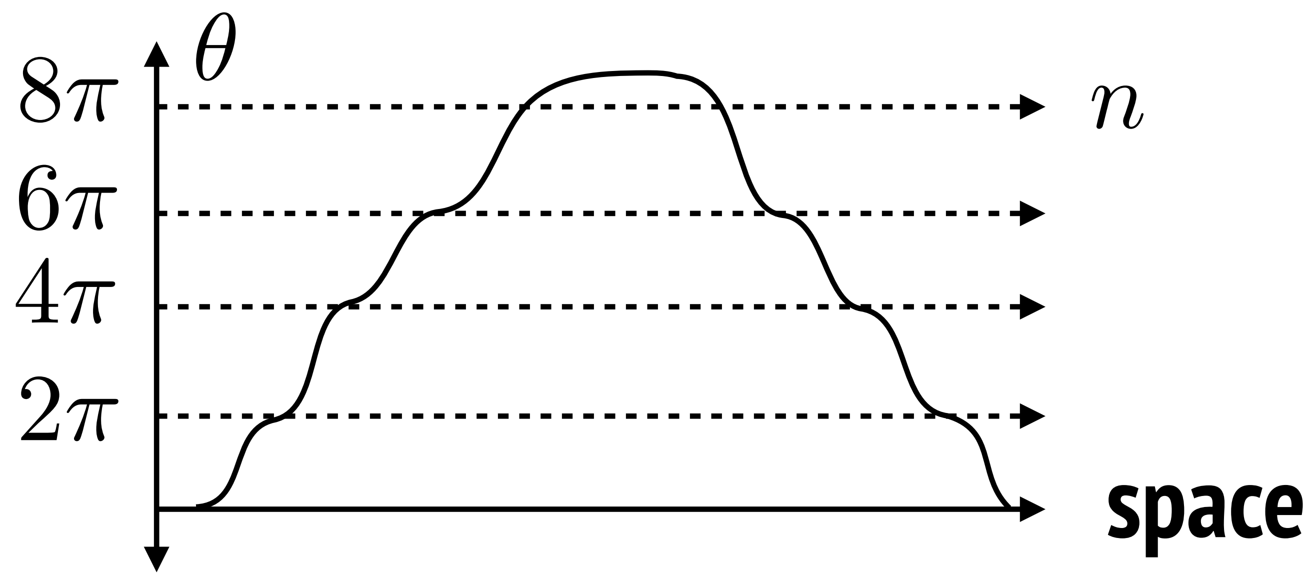
Perhaps we do not need to simulate with N-body (Peak-Path -> Miniclusters made easy... Ellis 2020)

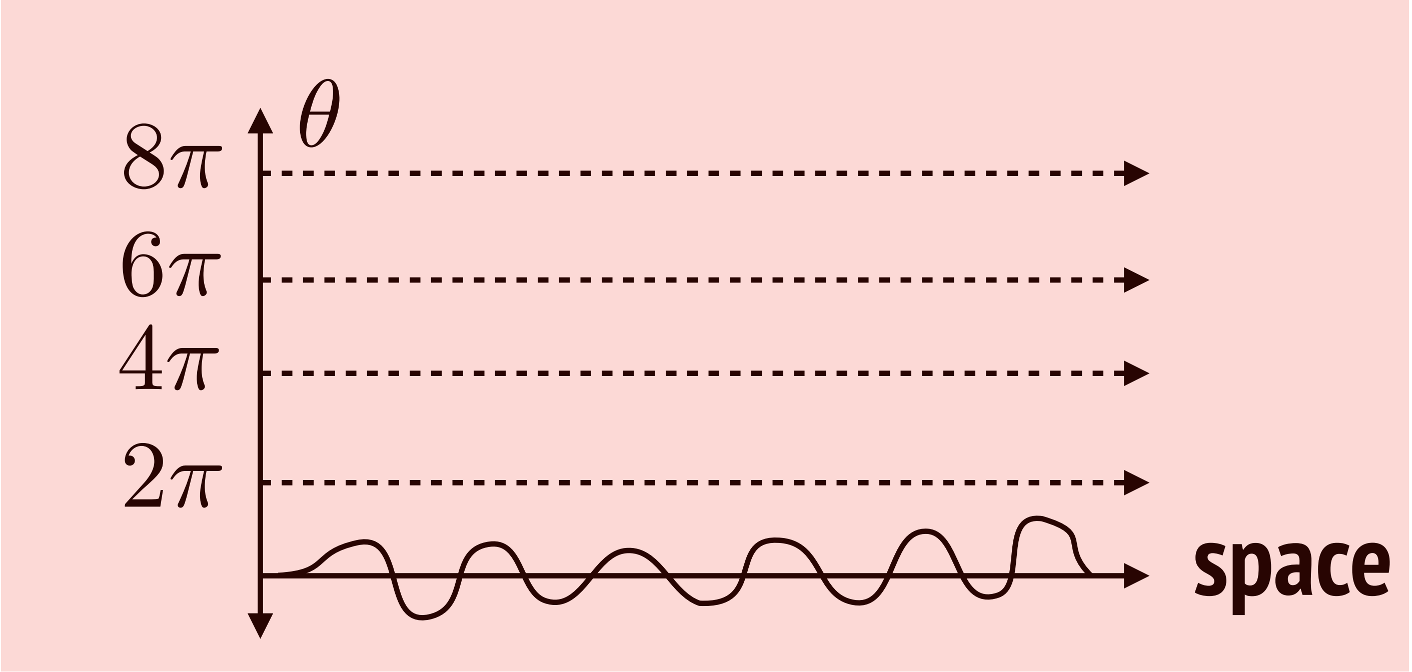
Critical look

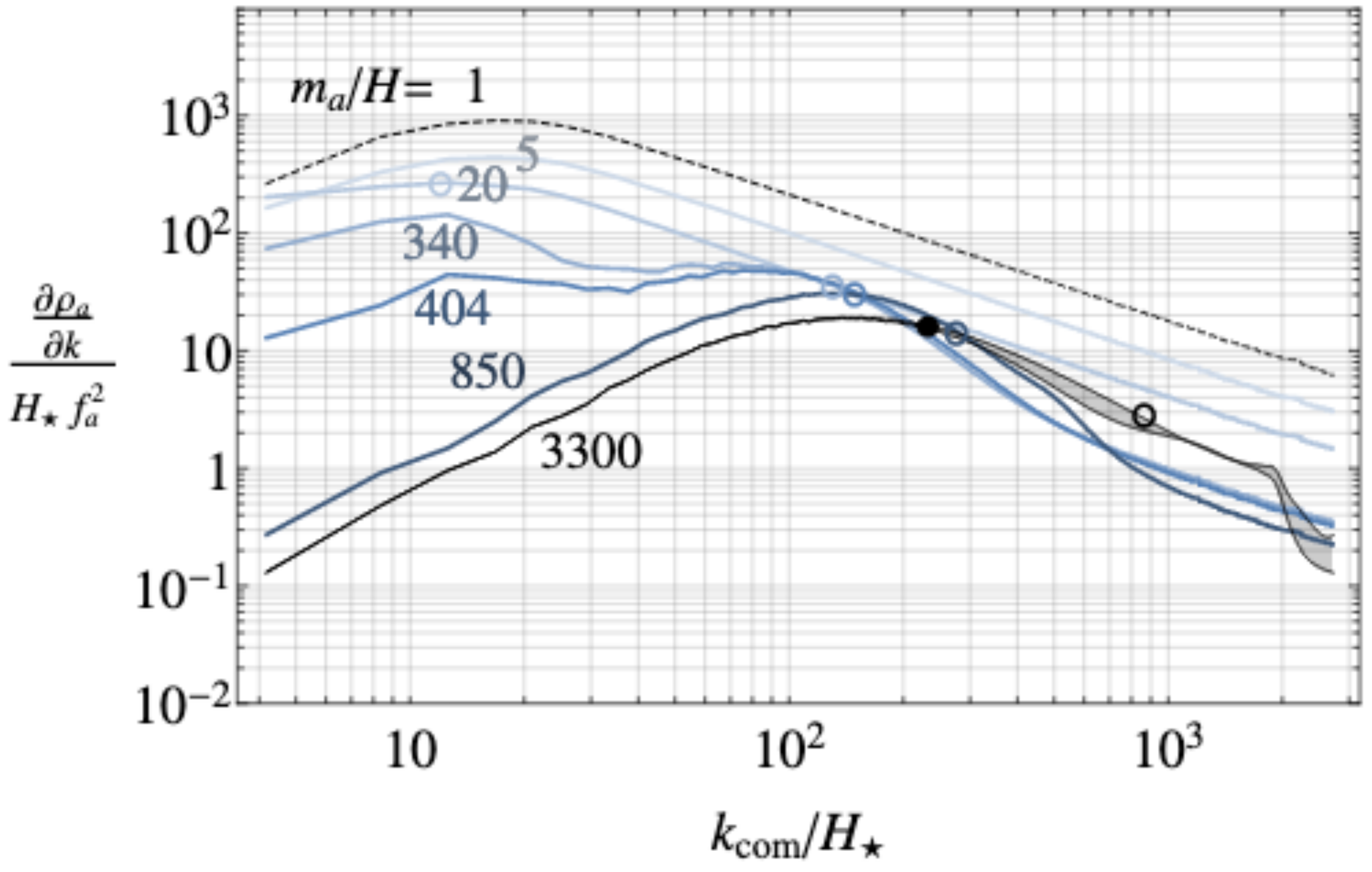
- Our string simulations are not the end of the story (dynamical range)
  Our strings have small tension $\log\left(\frac{m_s}{H}\right) \sim 8$)

- A recent study of the scaling regime (atractor) predicts <u>more axions</u> and spectral index $\frac{\partial \rho}{\partial k} \sim \frac{1}{k}$
  More axions imply $\langle \theta^2 \rangle \gg 1$
  New non-linear effects at QCD times (Onion domain walls) upscatter axions in momentum



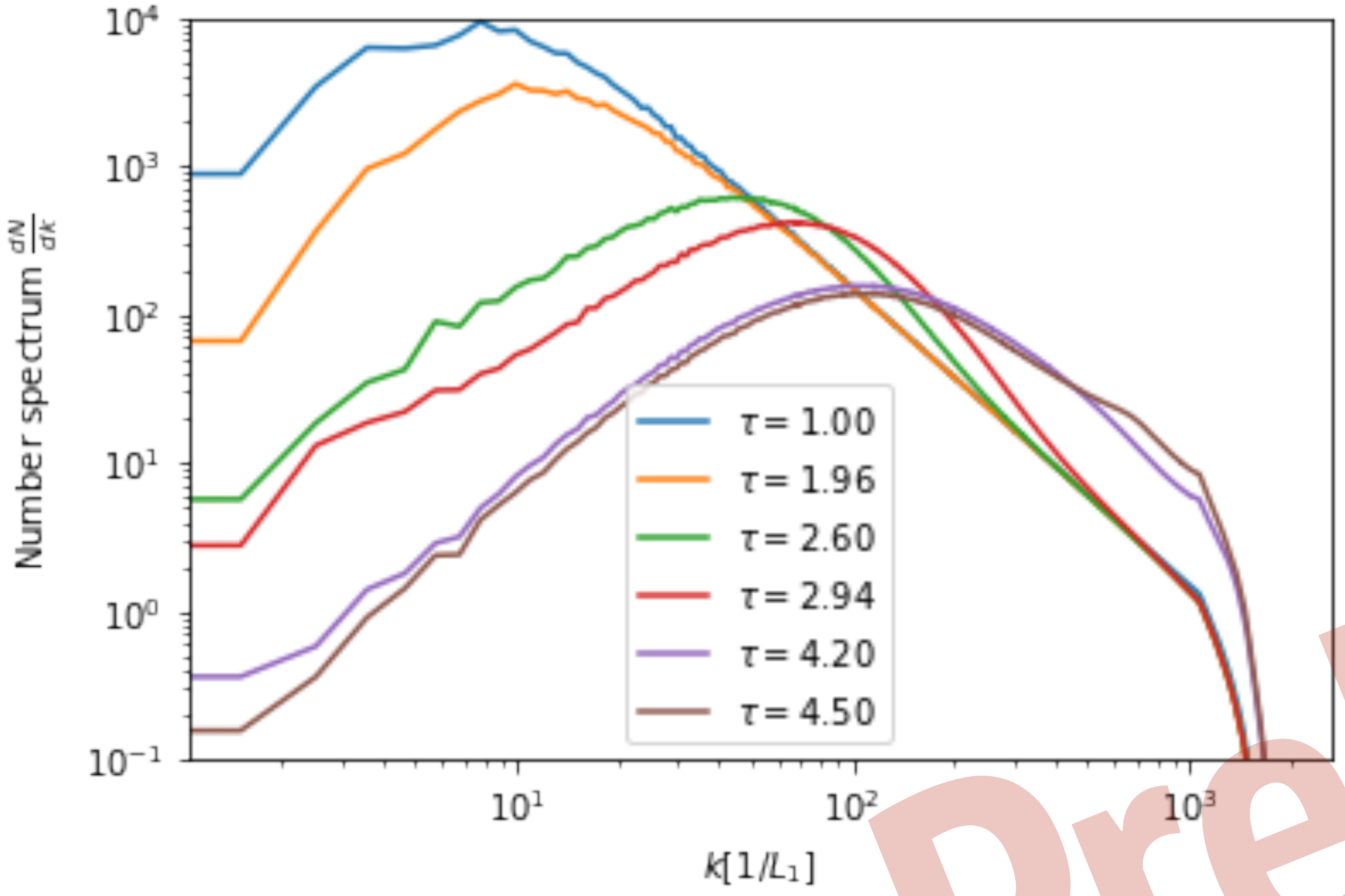


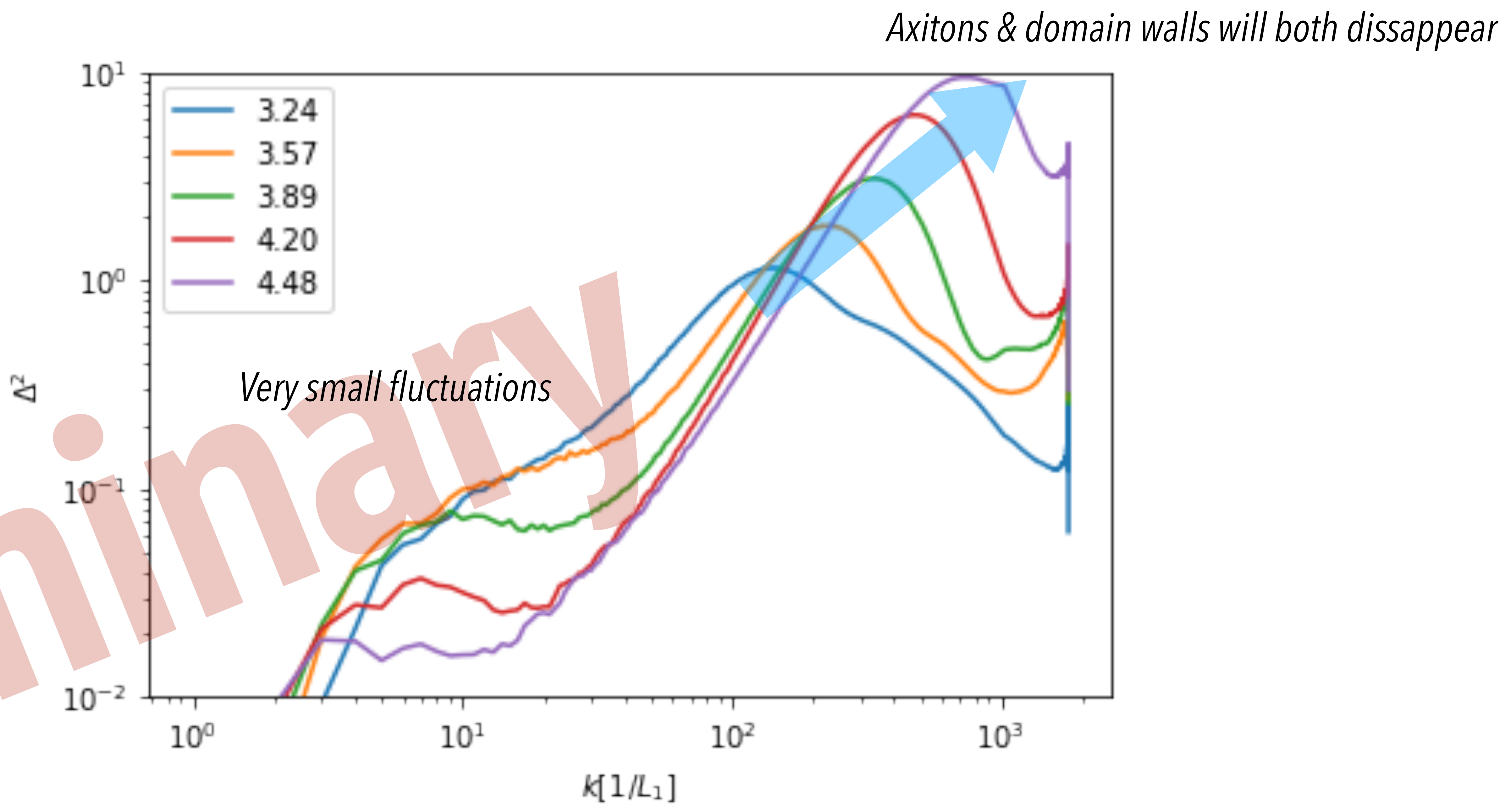




Preliminary

- Simulate the evolution of theta @jaxions as axions go through the non-linear epoch
- Initial spectrum as in VGH20 at $\tau = 1$
- At $m_A \delta x \sim 1$ Axion spectrum converges well
- Density fluctuations do not (many axitons and some domain walls)



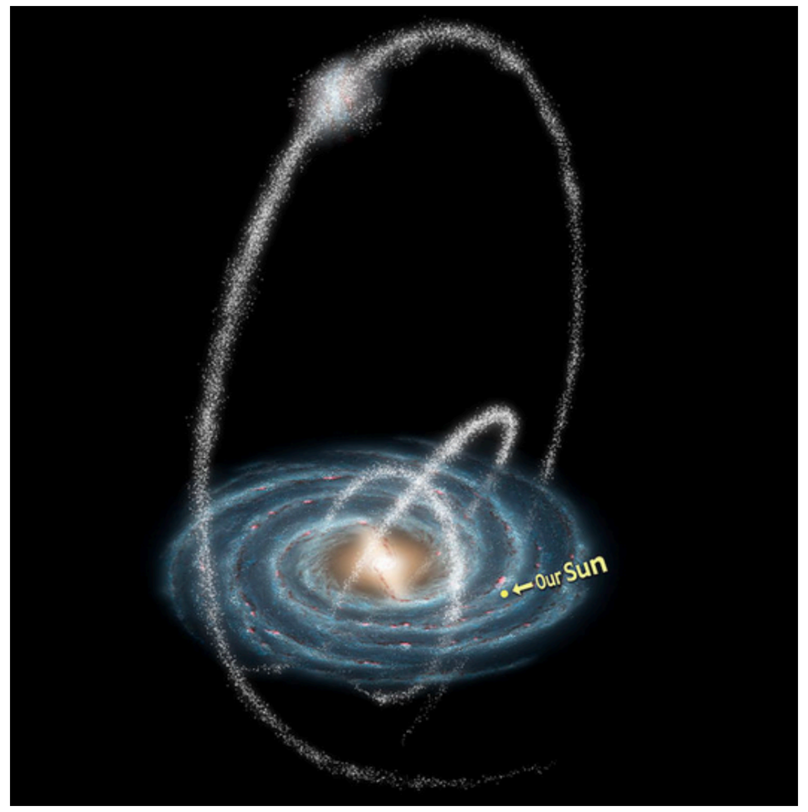


-Spectacular damping of large scale fluctuations,
  free-streaming?
  cut-off effects?
- Much lower mass MCs
- Much less dense ($\Phi \ll 1$)

Implications

- VGH20 suggest axion mass $m_A > 500\mu\mathrm{eV}$ (already makes L_1 smaller)
- "free-streaming" effects push the natural peak of fluctuations to >> $1/L_1$
- "Typical" miniclusters extremely fluffy

much easier to disrupt!



$$P(\Phi) = 0.022 \frac{1}{\Phi^{3/2}\sqrt{1+\Phi}}$$

Tinyakov, Tkachev, Ziouta 2016

- Ultra dense, low mass ones? (bose-stars?)

more frequent encounters ...?

Conclusions

- Axion DM substructure offers some smoking guns to discover axions

- Need to understand <u>QUANTITATIVELY the power spectrum</u>

- Scaling regime of strings quite relevant to set the IC

- First simulations with "fluffy strings"

    - Many low-M MCs,
    - No large-mass and large Φ MCs (or very atypical)
    - No microlensing constraints from HSC/M31
    - Very large Axion MC bound fraction -> direct detection!

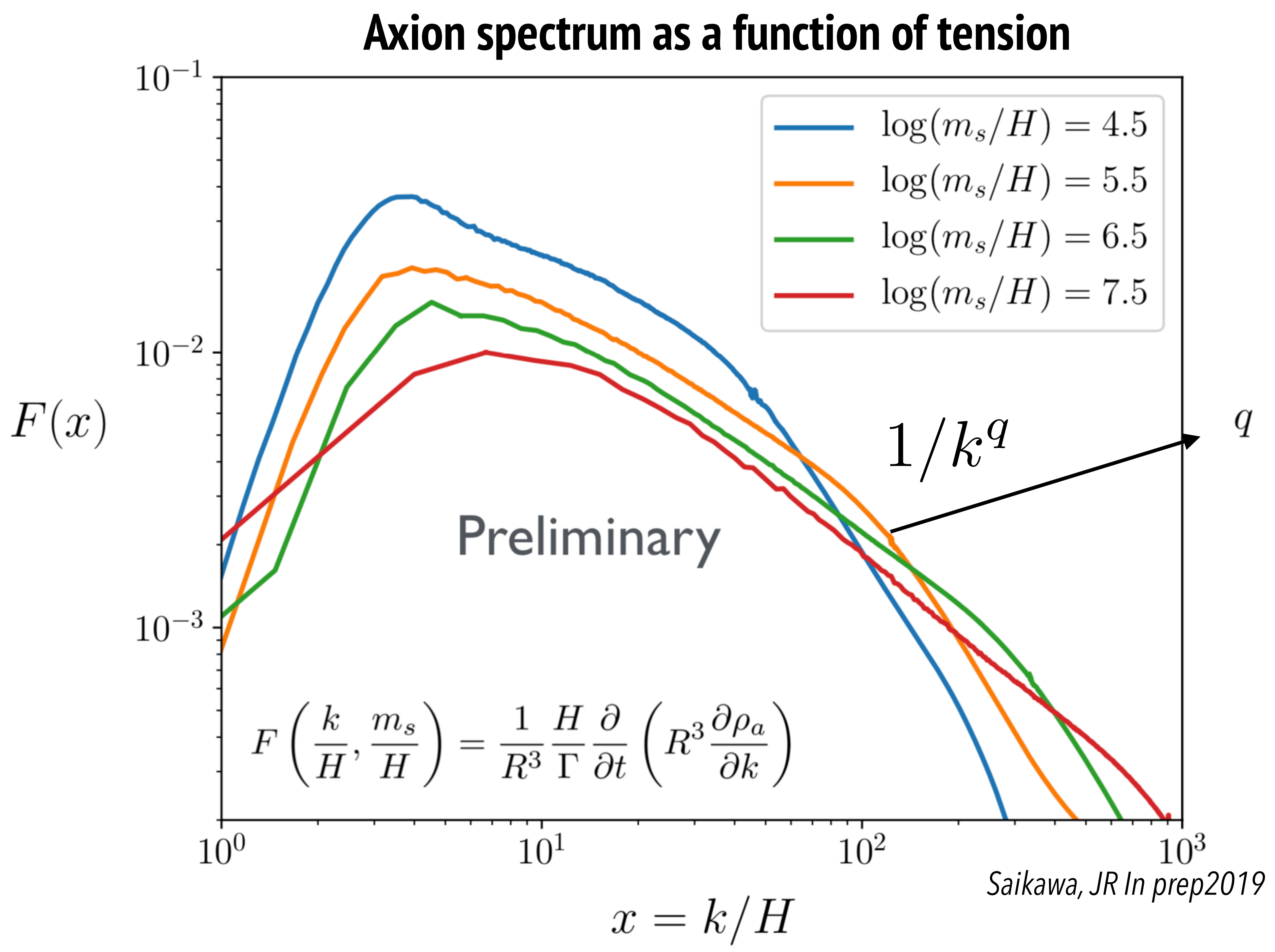
- We are exploring the implications of refinements (atractor ICs, Moore's high tension simulations...)

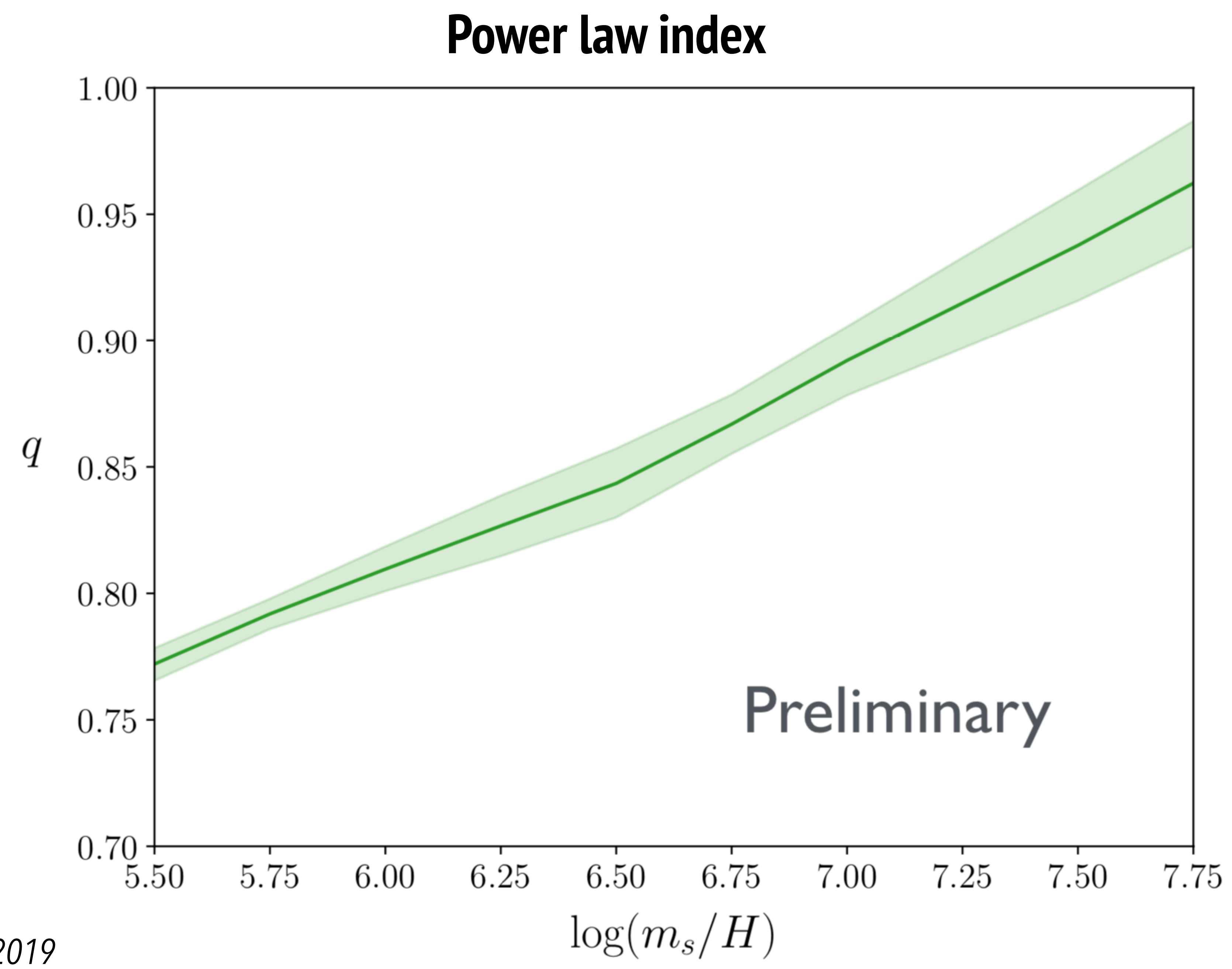
Gorghetto 2020 *Klaer 2017*

    - Differences can be quite dramatic

Axion radiated spectrum

- Method 2, understanding radiation (safer extrapolation)





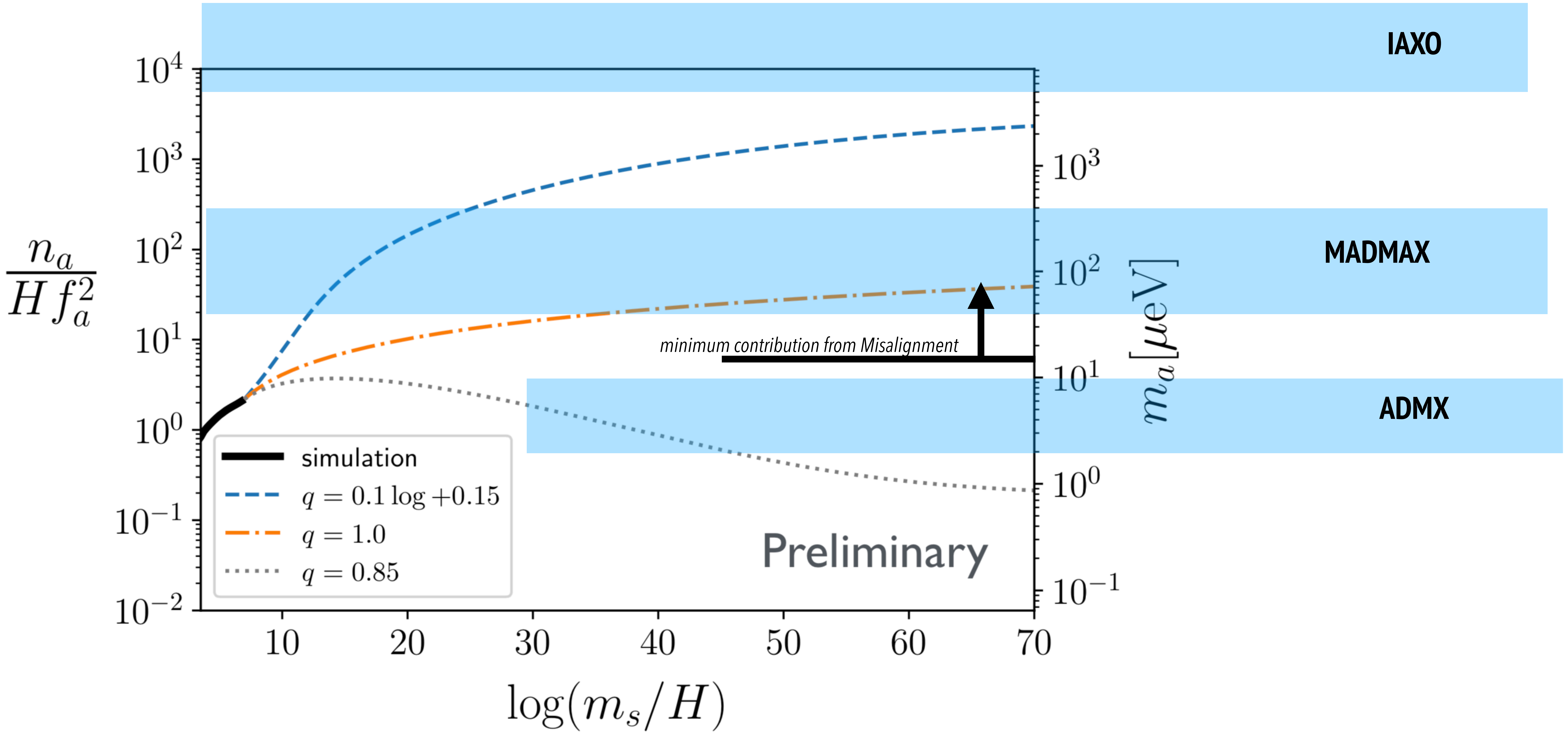
Current simulations are in a tension regime where q<1 (few UV axions take most energy);

Trend towards q>1 is seen -> (many IR axions take most energy -> more DM!)

Extrapolation to physical values

- Extrapolate in q and integrate the axion emission from strings from PQ to QCD epochs

- Very large uncertainties at the moment



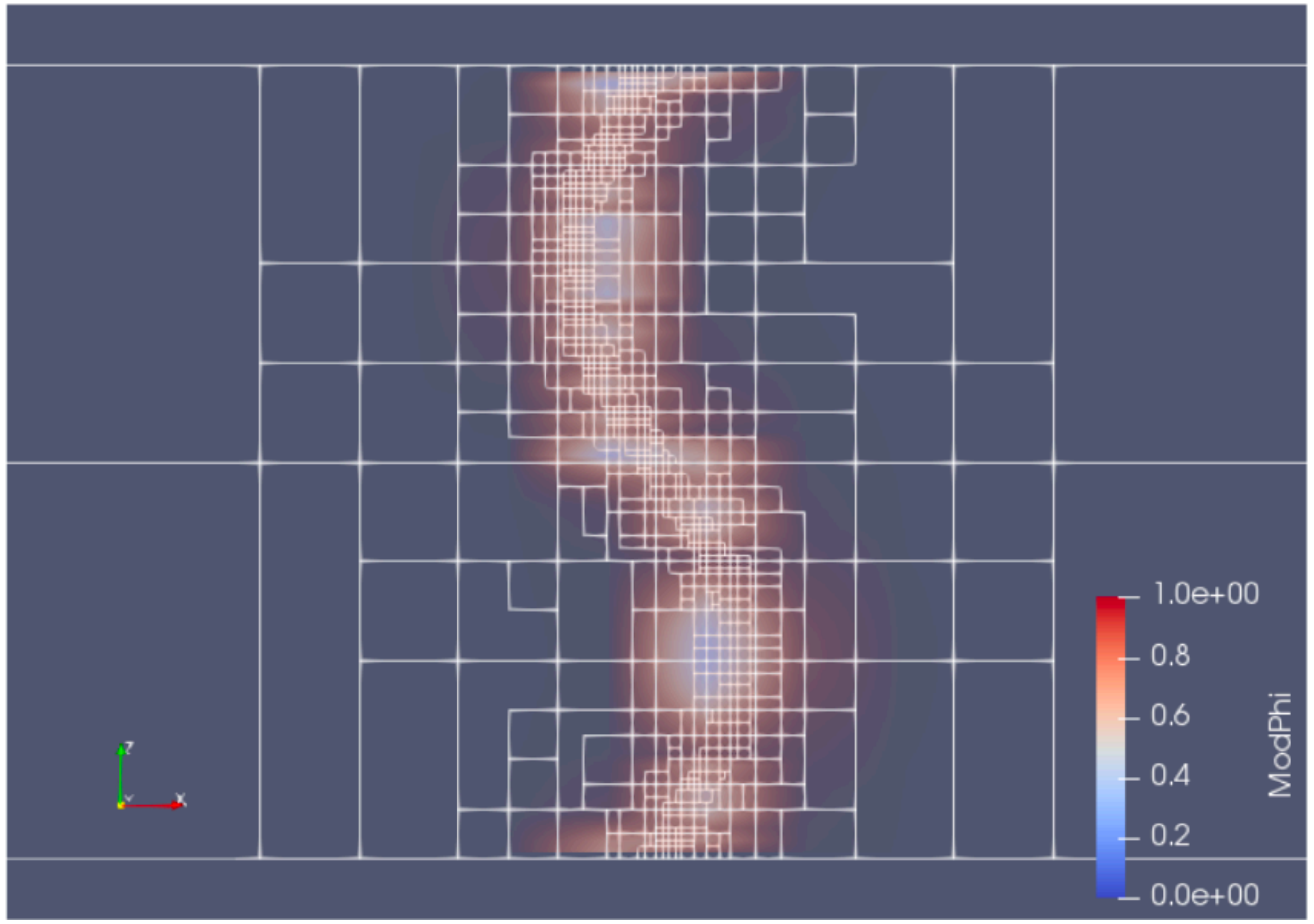
Saikawa, JR In prep2019

The future : AMR?

Perhaps we do not need to be able to extrapolate to log = 70

A factor of 2 in log will be more than sufficient to understand much better dynamics and reduce uncertainty

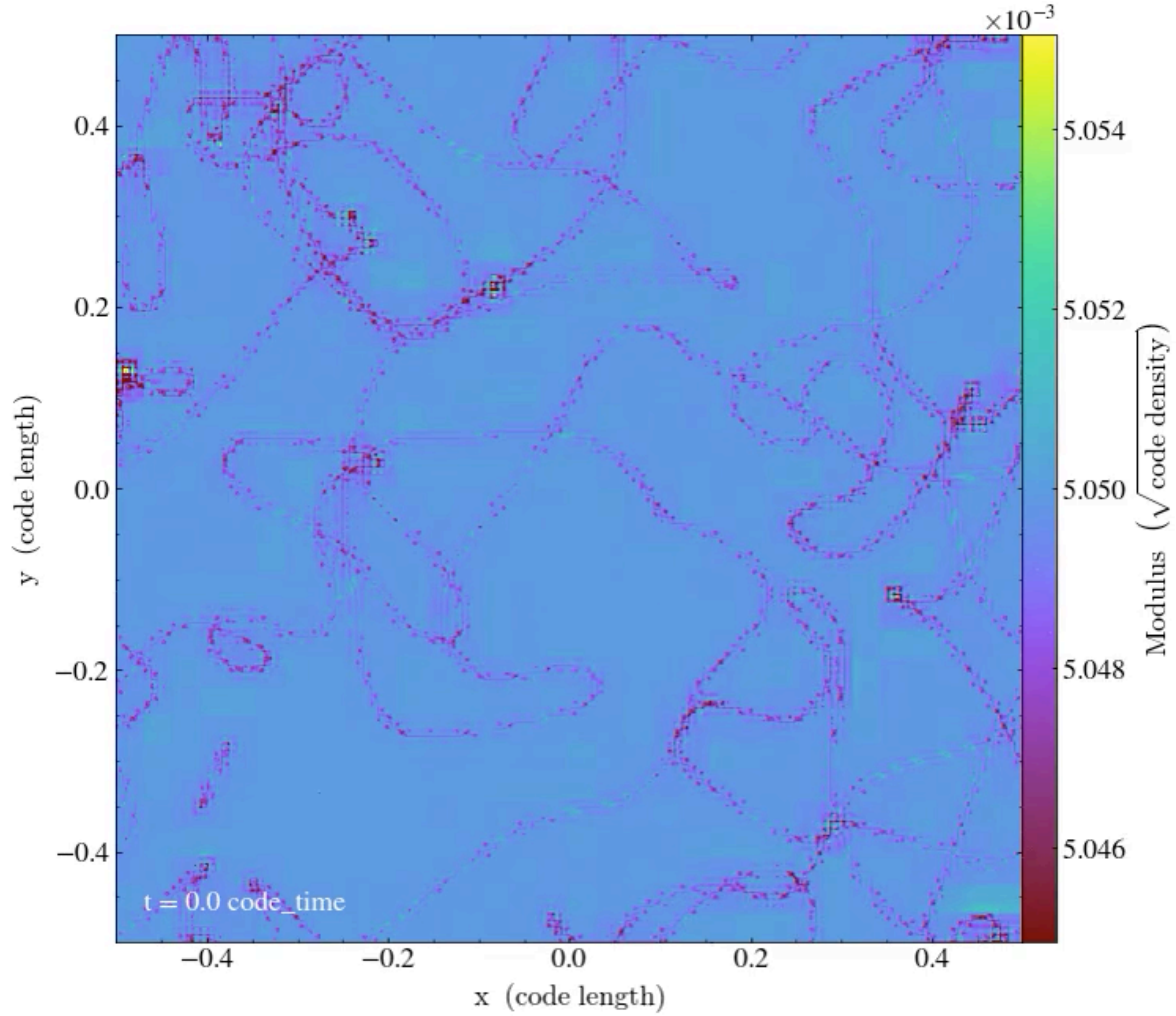
Dedicated Adaptive Mesh Refinement simulations can cover this gap and see if there is a change of behaviour at q = 1

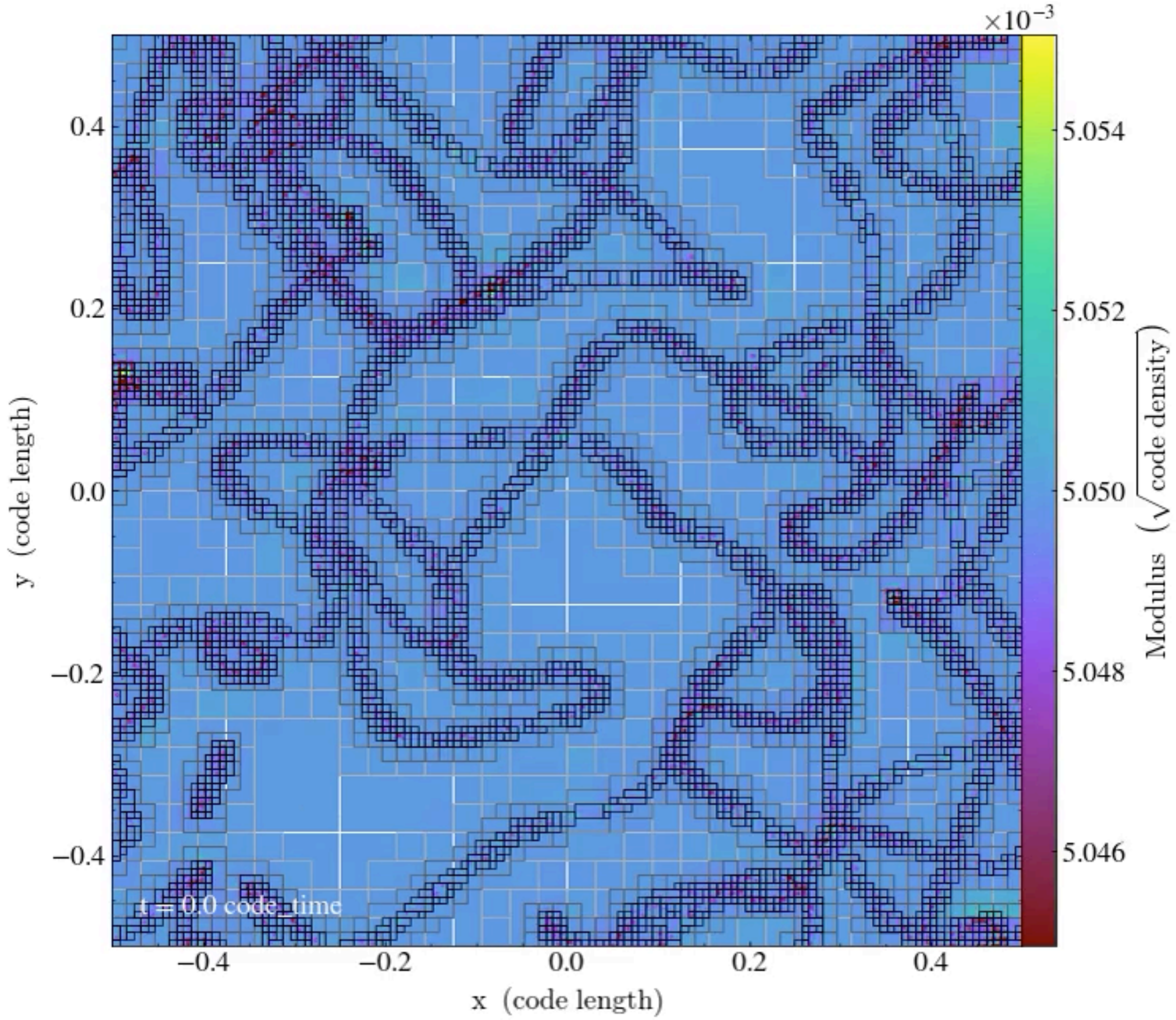


Shellard 2019

Next generation, AMR

Schwabe JR in prep





Aux Slides

Text … 1

Captions.… 2

Reference [citation]