# Seeds of axion miniclusters

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IBS-ICTP on Axion-like particles

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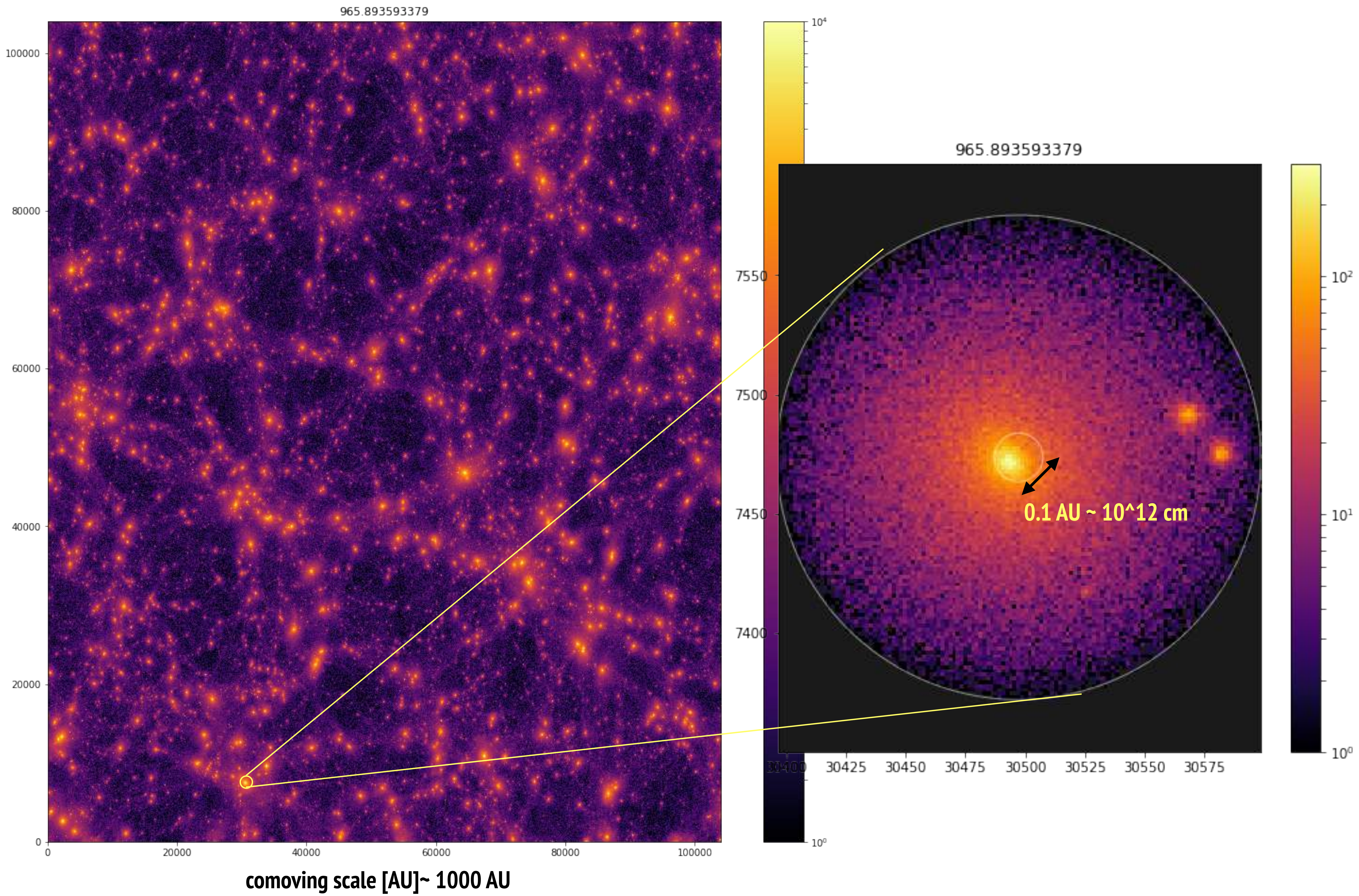


965.893593379
0.1 AU ~ 10^12 cm
comoving scale [AU]~ 1000 AU

# Storyline

- Intro: Axions and ALPs

- (QCD) Axion dark matter in the post-inflationary scenario

- Seeds of axion miniclusters (Sim 1)

- Gravitational evolution (Sim 2)

# Axions

- Motivated by the strong CP problem, $\mathcal{L}_{\rm SM} \in -\frac{\alpha_s}{8\pi} {\rm tr}\{G_{a\mu\nu}\widetilde{G}_a^{\mu\nu}\}\theta$ why are nuclear EDMs sooo small?

- **Why is $\theta < 10^{-10}$?**

- Peccei-Quinn, if theta is a field implies $\theta = 0$ *Peccei, Quinn, Weinberg, Wilczek 1978*

*Axion field = Goldstone boson of a new Global Spontaneously-broken colour-anomalous U(1) symmetry =* $\theta$

- QCD Axion and axion-like particles fit BSM (pseudo Nambu-Goldstone bosons, stringy axions...)

- Low-energy effective action is restricted by U(1) shift symmetry $a \to a + {\rm ct.}$

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) + \sum_f g_{af}[\bar{f}\gamma^\mu\gamma_5 f]\frac{\partial_\mu a}{m_f} - \frac{g_{a\gamma}}{4}F_{\mu\nu}\widetilde{F}^{\mu\nu}a - C_{ag}\frac{\alpha_s}{8\pi}\{G_{i\mu\nu}\widetilde{G}_i^{\mu\nu}\}\frac{a}{f_a}$$

$g_{ai} \propto \frac{C_{ai} \sim O(1)}{f_a}$

- $C_{ai} \sim O(1)$ → O(1) model-dependent parameters
- $f_a$ → new energy scale (decay constant)

If Cag is non-zero, you ALP is the QCD axion $\frac{a(x)}{f_a} \equiv \theta(x)$

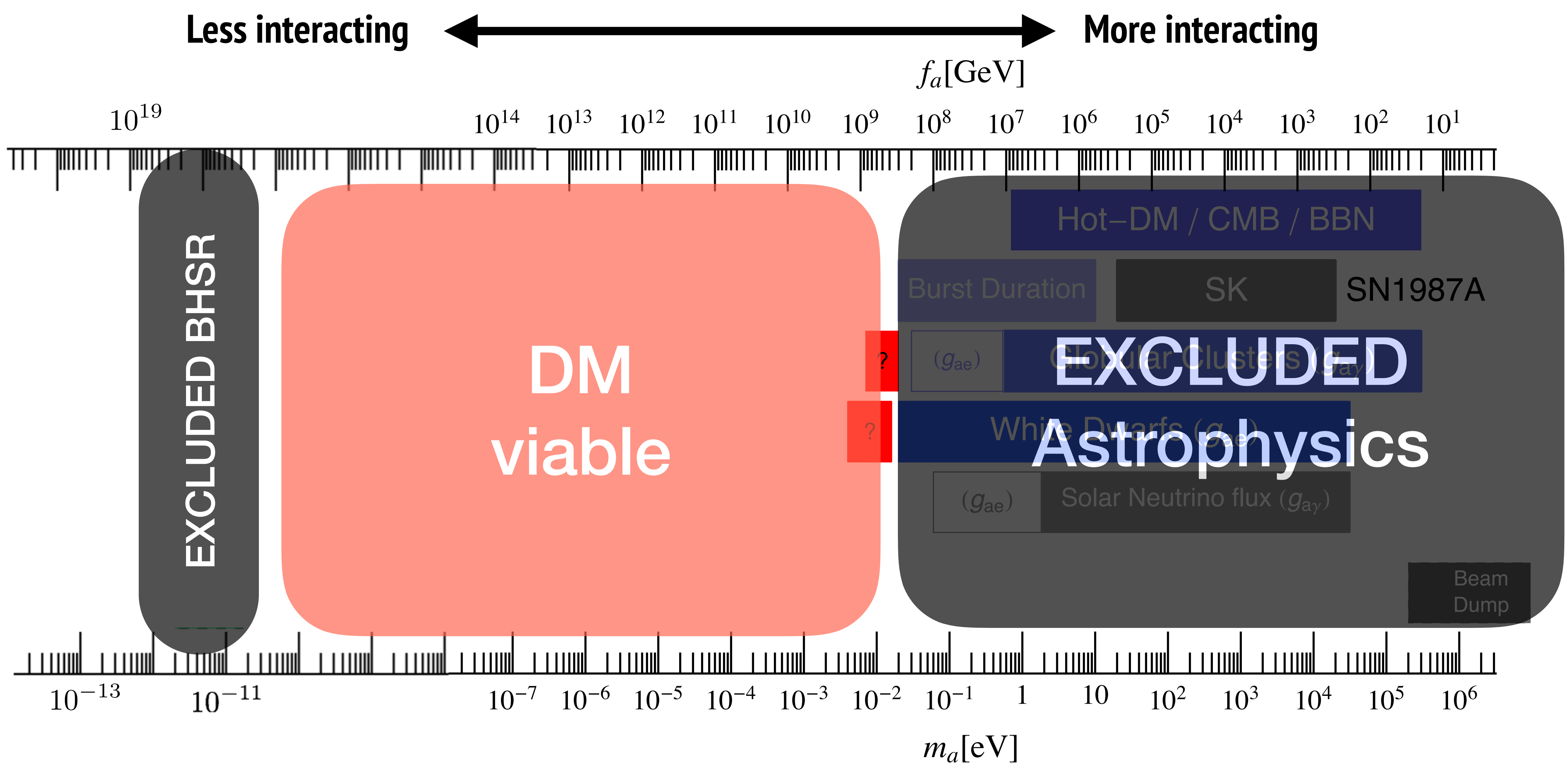
Shift-symmetry breaking corrections can generate a small mass + ...

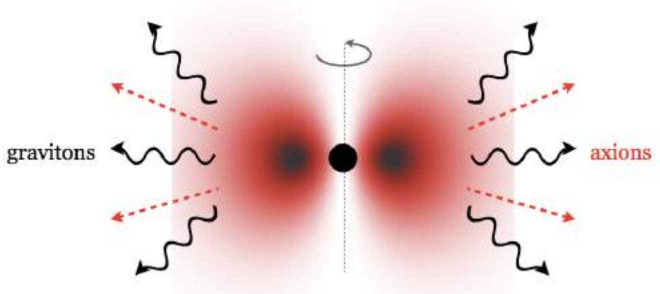
$\mathcal{L}_a \ni -\frac{1}{2}m_a^2 a^2 ...$

At low-energies $V_{\rm QCD}(\theta) \sim \chi(1-\cos\theta)$

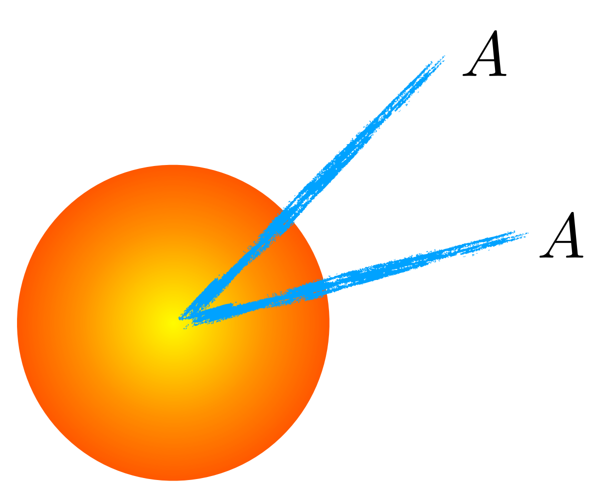
$$m_A = \frac{\sqrt{\chi}}{f_A} \sim 60\,\mu{\rm eV}\frac{10^{12}{\rm GeV}}{f_a}$$

# what do we know about $f_A$ ?



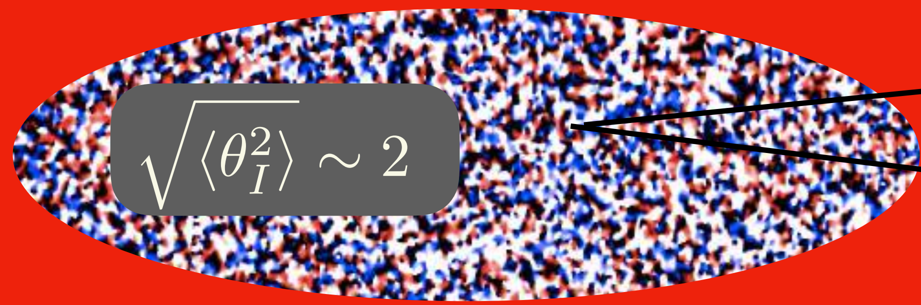

**Black hole spin radiated**




**Stellar evolution accelerated***

# Axion dark matter in a nutshell

5: Scenario B : Initial conditions after inflation




dark matter inhomogeneous at scales below ~ pc

6: Scenario A : Inflation AFTER initial conditions

$\theta_I = ?$

dark matter homogeneous

4: Axion dark matter abundance depends:
- Axion mass
- Initial angle

$$\Omega_c h^2 \sim 0.12 \theta_I^2 \left(\frac{10\mu\text{eV}}{m_A}\right)^{1.17}$$

3: Axions field rolls down potential at

$$t_{\rm osc} \sim 1/m_A$$

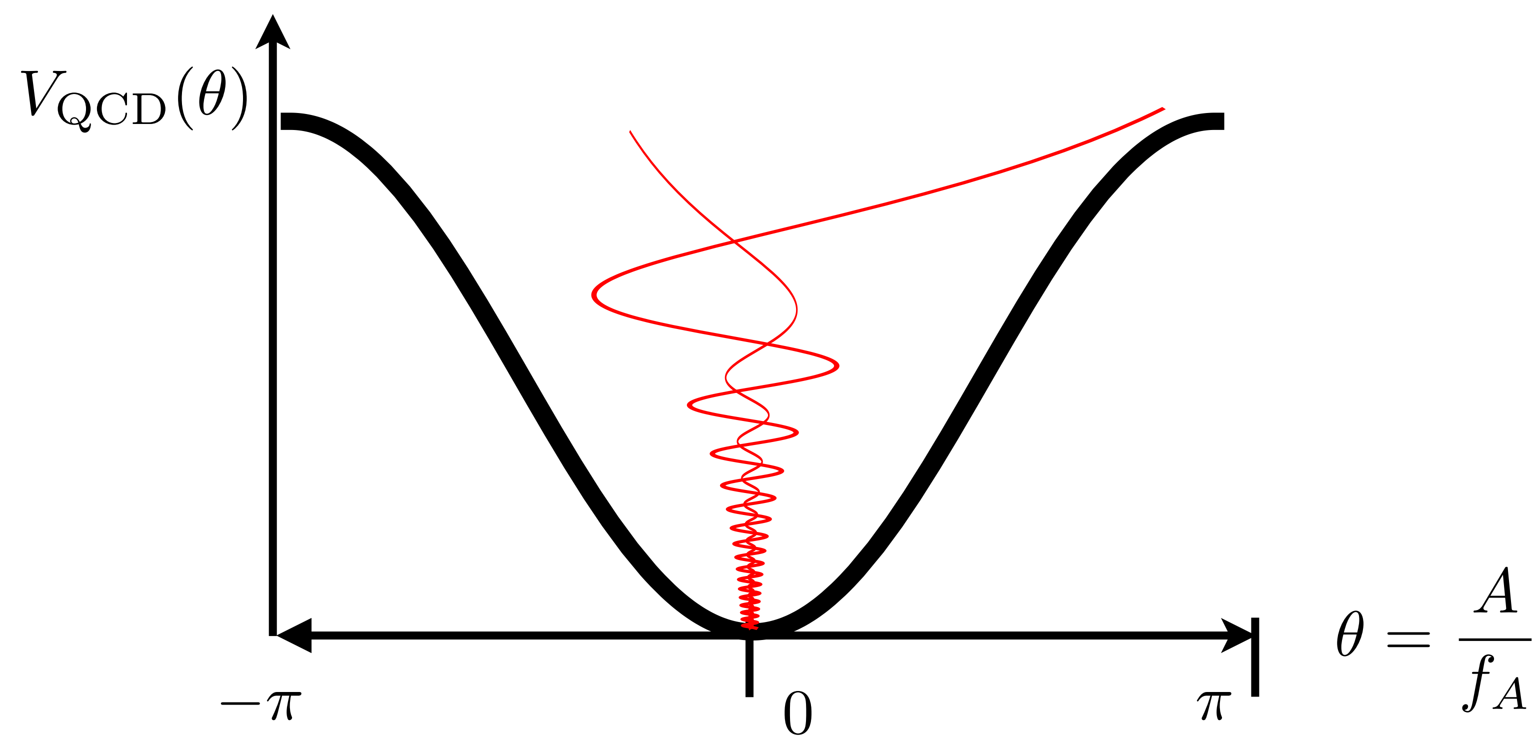
and becomes dark matter (like inflaton)

2: The QCD vacuum energy depends on $\theta$

it has a minimum at $\theta = 0$ !!!!

1: The axion field (A) is the dynamical version of the theta angle of QCD

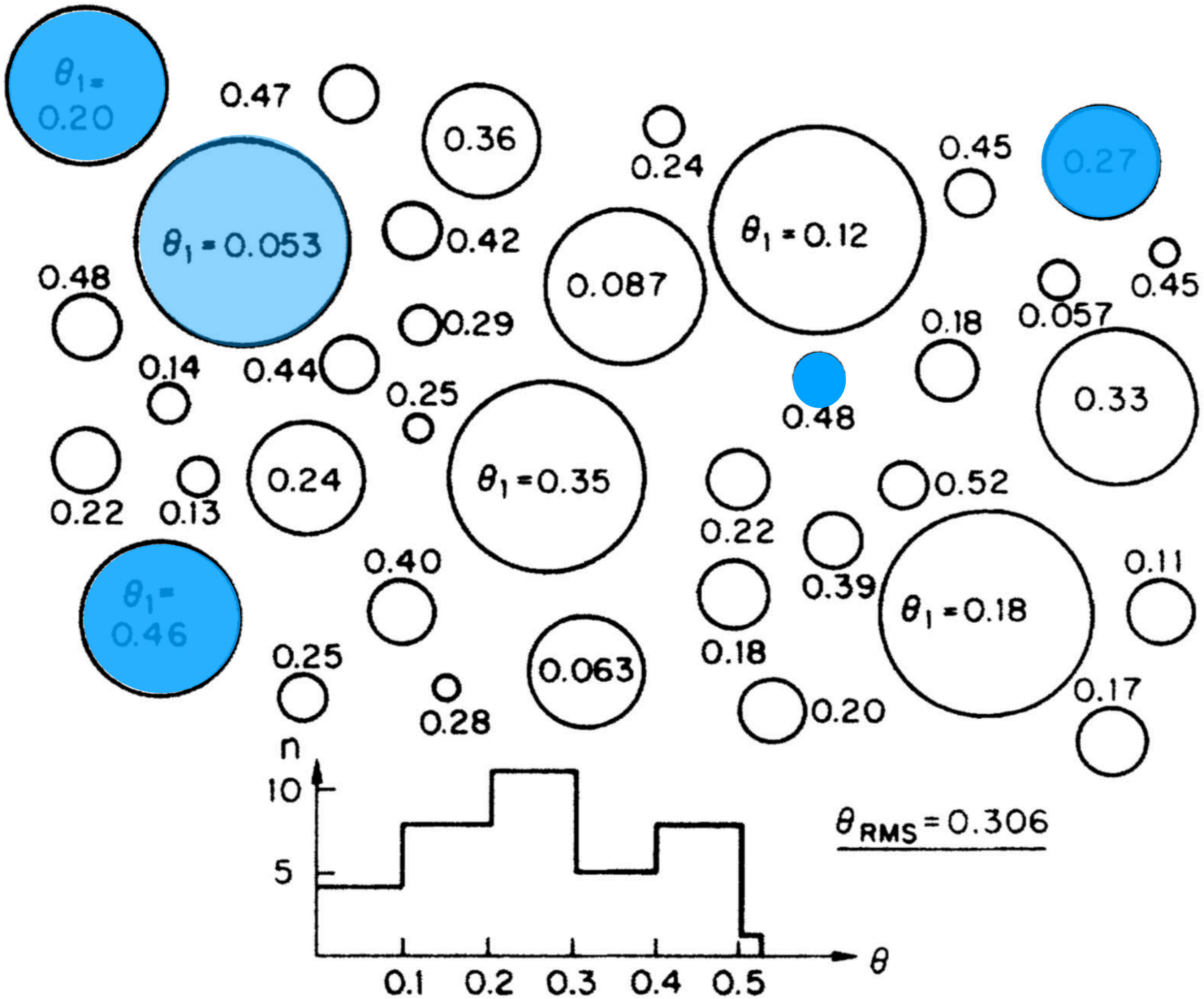
We observe $\theta \simeq 0$



# post-inflationary scenario

**After the Phase transition, initial misalignment angle is different in causally disconnected regions of the Universe**

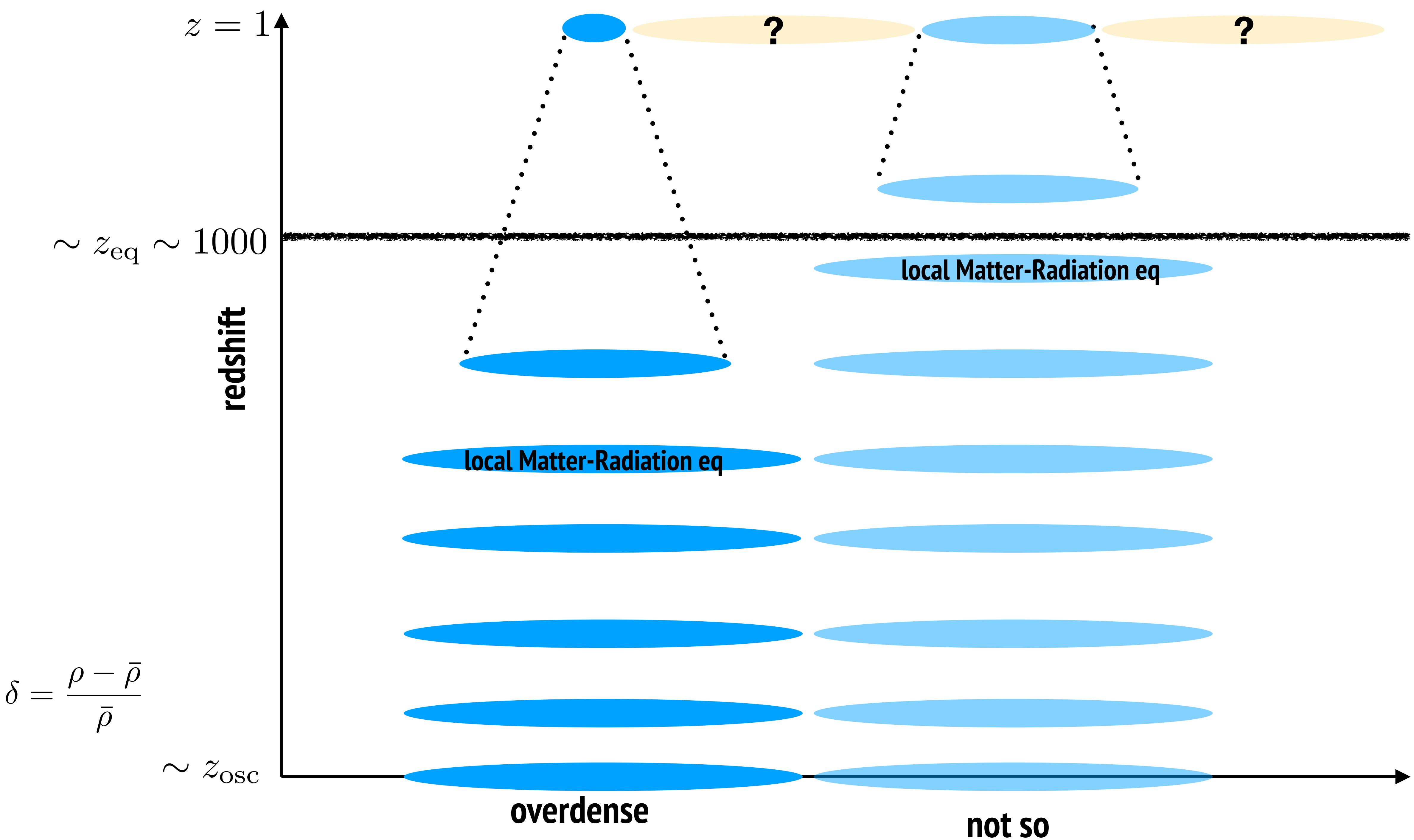
$\rho_{\rm DM} \propto \theta_i^2$



# miniclusters

**DM distribution is frozen shortly after $T_1$ : the density field expands with the Universe**

**Regions with overdensity $\delta$ collapse gravitationally at $z_{\rm col} \sim z_{\rm eq}\delta$ (keep a fixed size)**



# miniclusters

**Kolb-Tkachev, properties determined by** $\delta$

$$R_{mc} \sim L_1/(z_{\rm eq}\delta) \sim 10^{12}\,{\rm cm}$$

$$M \sim (1+\delta)M_0 \qquad \frac{4\pi}{3}R_{mc}^3\rho_{\rm DM} \sim 10^{-12}M_\odot$$

$$\rho \sim \rho_{\rm eq}\delta^3(1+\delta) \sim 10^{-12}{\rm g/cm^3}$$

**Important issues are quantitative:**

- how many MCs?, which mass and radius?
- how void is the space between them? (direct detection?)
- encounter rates with Earth?
- sensitivity to lensing?

$\Phi(=\delta)$ distribution

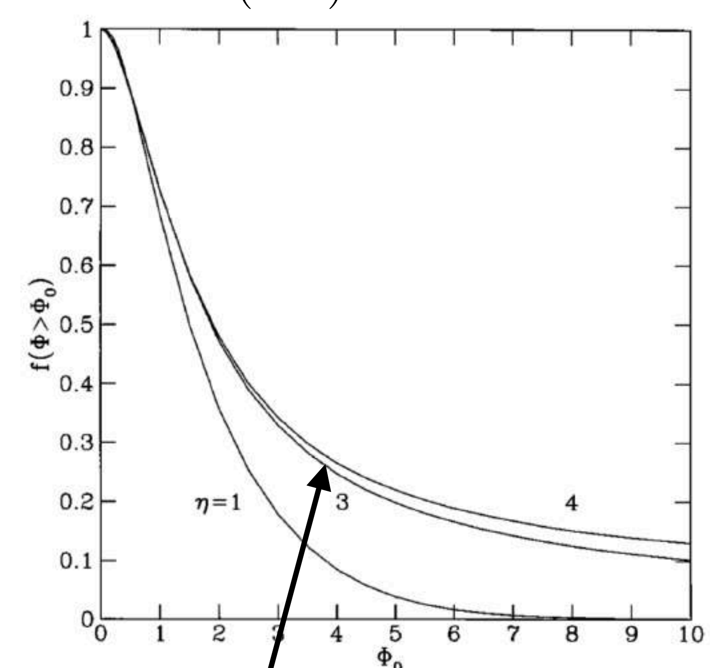



FIG. 2.—Mass fraction of axions in miniclusters with $\Phi > \Phi_0$ as a function of $\Phi_0$. By $\eta = 4$ the evolution has very nearly frozen.

*Kolb -Tkachev 1996*

**this was not a MC probability distribution!**

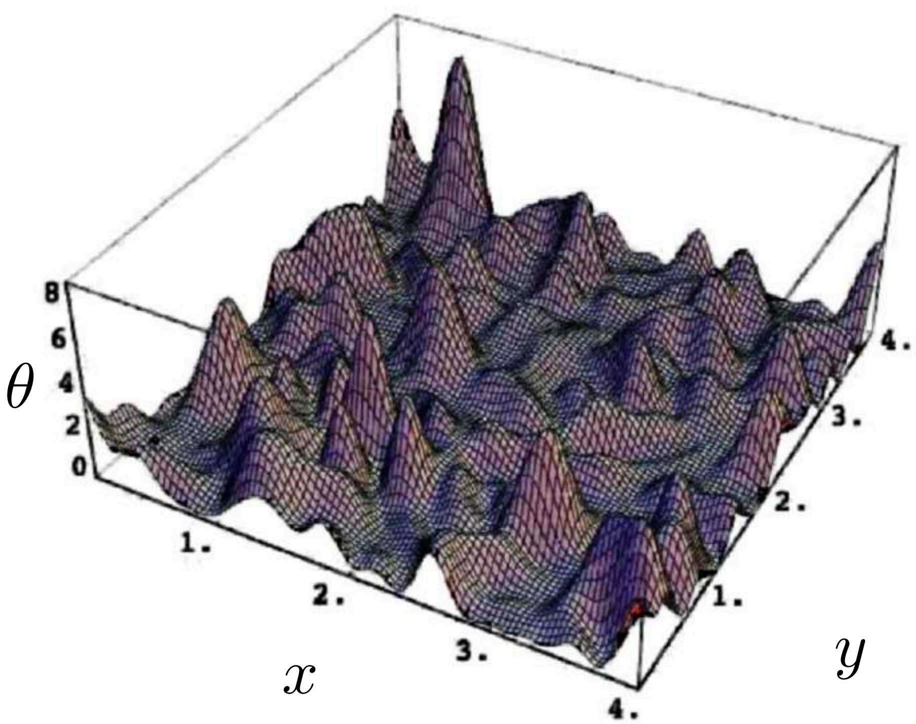
# first simulations (Scalar Miniclusters ScaMs)

*Zurek Hogan Quinn 2007*

- **Simulated axion field** $\ddot{\theta} + 3H\dot{\theta} - \frac{1}{R^2}\nabla^2\theta + m_A^2(T)\sin\theta = 0$
- **Initial conditions ad-hoc (tuned to avoid domain-walls) white noise in field values**

$$\theta = A \sum_{k=1,\ldots,6/L} \sin(k_x x)\sin(k_y y)\sin(k_z z)$$

- **Evolve until density field is frozen -> switch to N-body simulations**
- **Generalisation to ALPs, Femtolensing estimates, no MC distribution function, IC-dependent!**



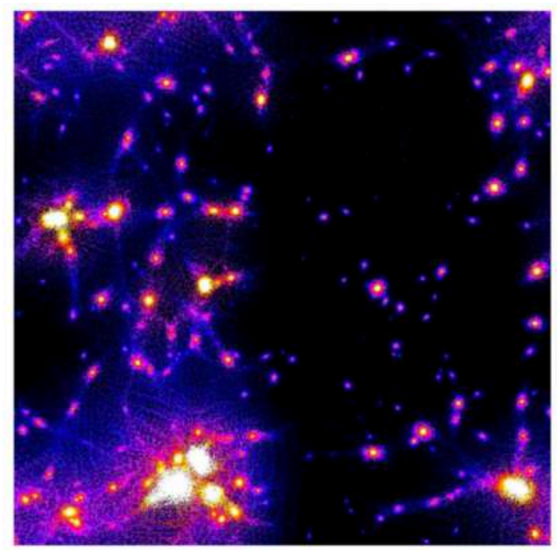



FIG. 5 (color online). Snapshot of structure formation at $z = 3000$ for axion-like ScaMs; the plot is colored according to the logarithm of the density. The scale here is $0.4h^{-1}$ kpc, in physical coordinates, although the result is expected to be invariant for any box size, given that we rescale the smoothing scale accordingly. Note that structure formation has already commenced before matter-radiation equality.

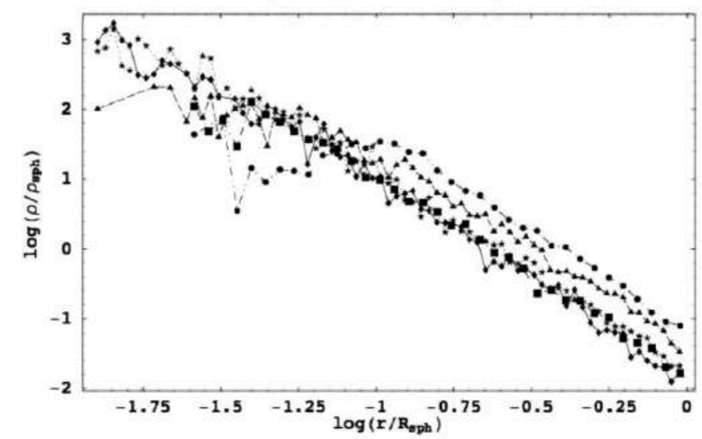
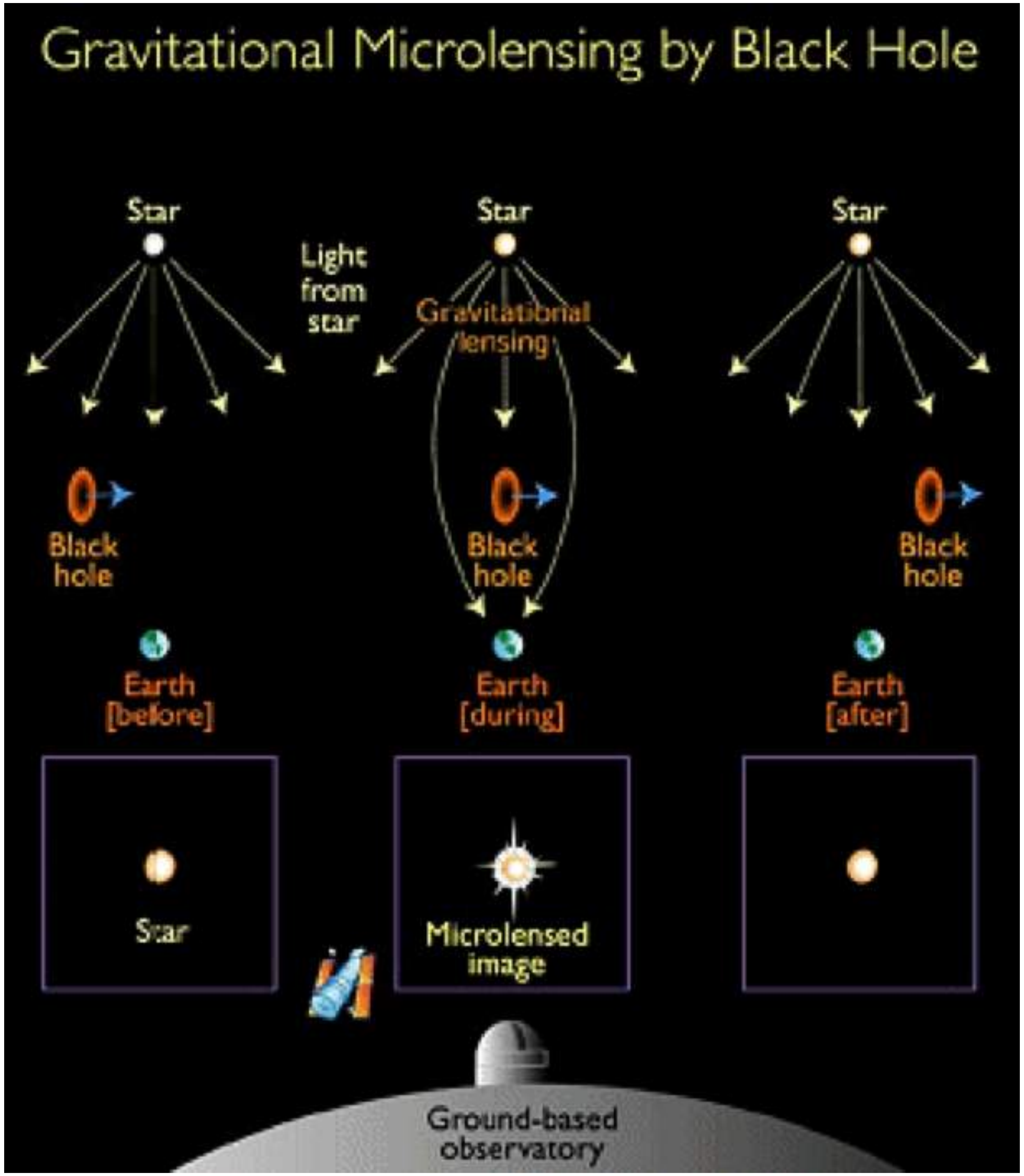



FIG. 7. Axion-like ScaM density profiles for five gravitationally collapsed ScaMs. Vertical axis is $\log(\rho(r)/\rho_{\rm sph})$, where $\rho_{\rm sph}(\delta = 1) = 280\rho_{\rm eq}$; that is, we normalized the density profile against the uniform density prediction of the spherical model, Eq. (14), with $\delta = 1$. Horizontal axis is $\log(r/R_{\rm sph})$, where $R_{\rm sph}$ is the radius computed from $\rho_{\rm sph}$ and the total mass contained within the horizon at the phase transition, $d_H(T_{\rm trans})$.

- **Recent semi-analytical estimates with linear equation have the same IC problem**

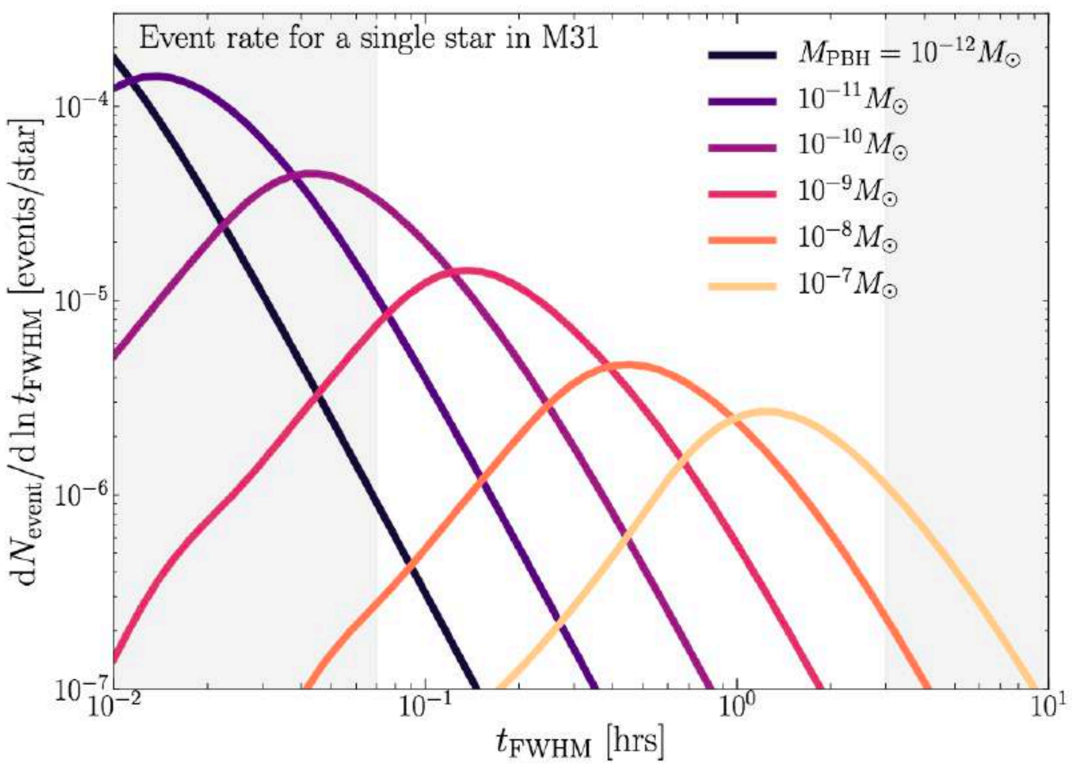
$$\ddot{\theta} + 3H\dot{\theta} + m_A^2(T)\theta = 0$$ *Enander 2017*

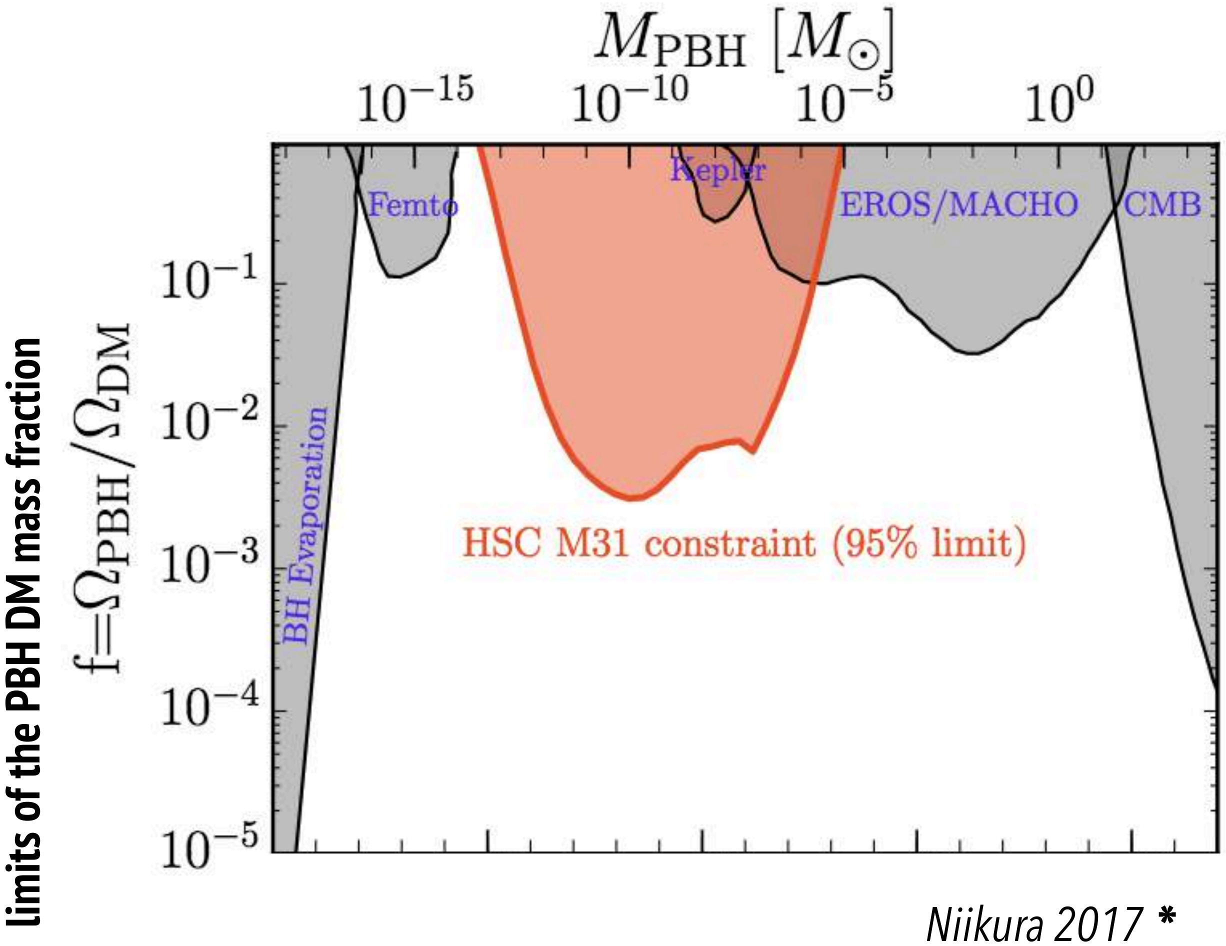
# Microlensing



# Microlensing

- Subaru HSC dedicated search of Primordial Planck hole events along M31
- $10^7$ stars, t~2 min sampling rate



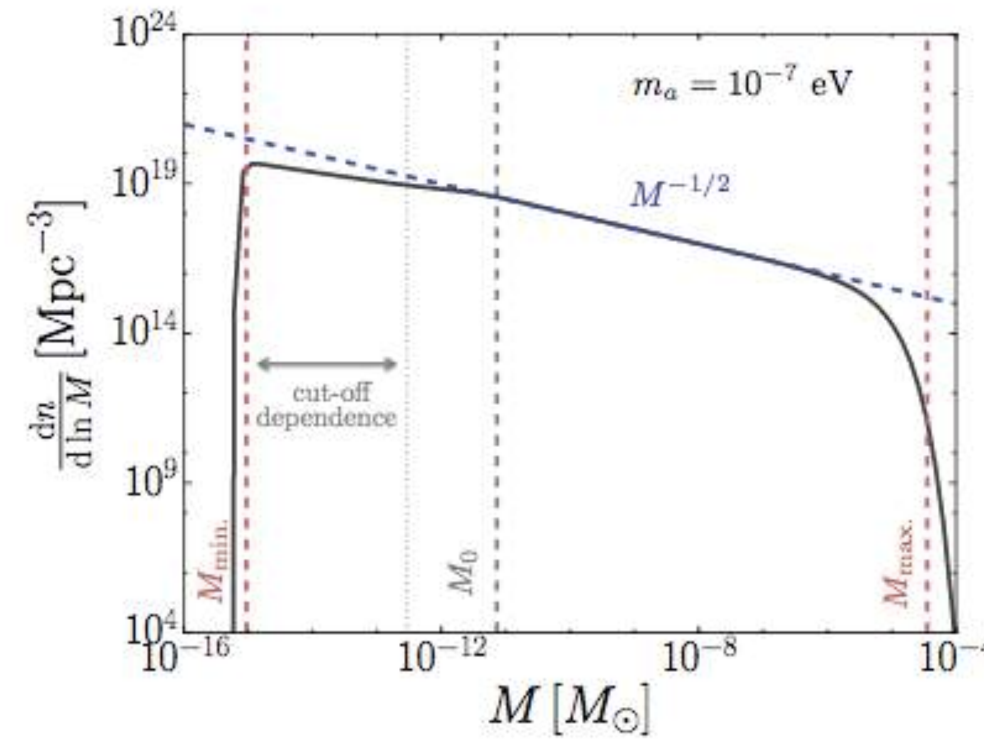

*Niikura 2017* *

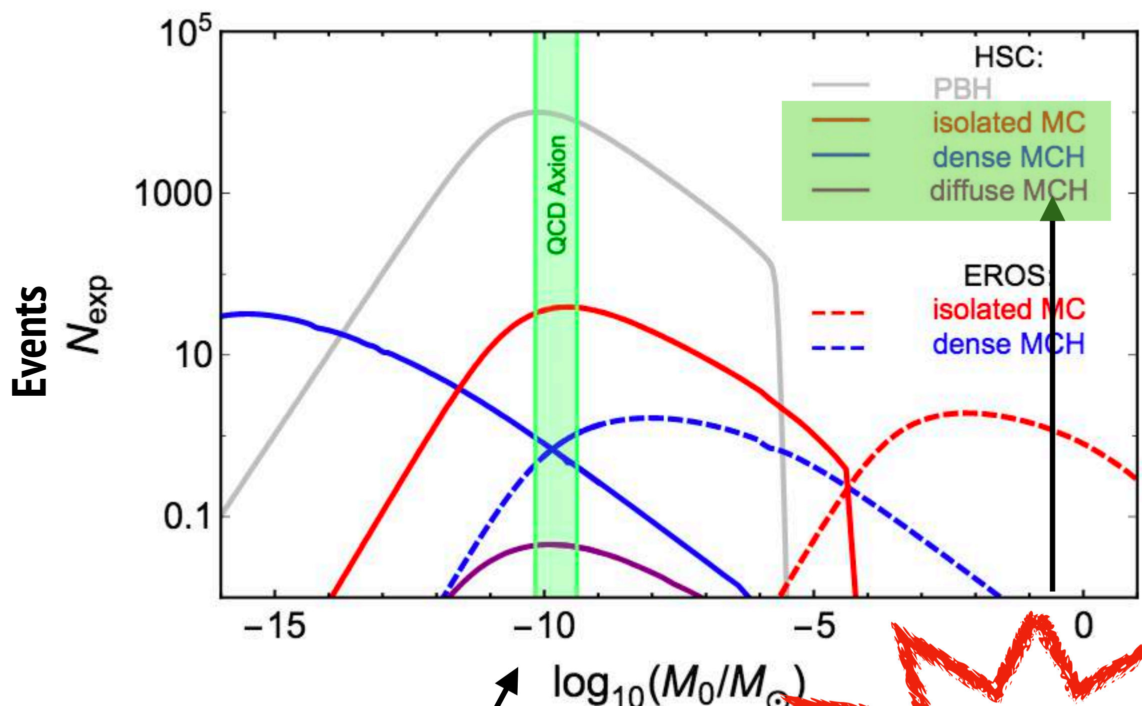
**See however Inomata 2018 (Wave effect decreases constraints below 10^-10 Msun)*

# Microlensing by MCs

- **Axion MCs are fluffy than PBHs (less signal, more duration) but could be detected!** *Marsh, Fairbairn , Quevillon 2017*

  - **model the MC mass function by Press-Schechter**
  - **Used a generous value of** $M_0 \sim (\pi)^3 M_{0,\mathrm{Tkachev}}$

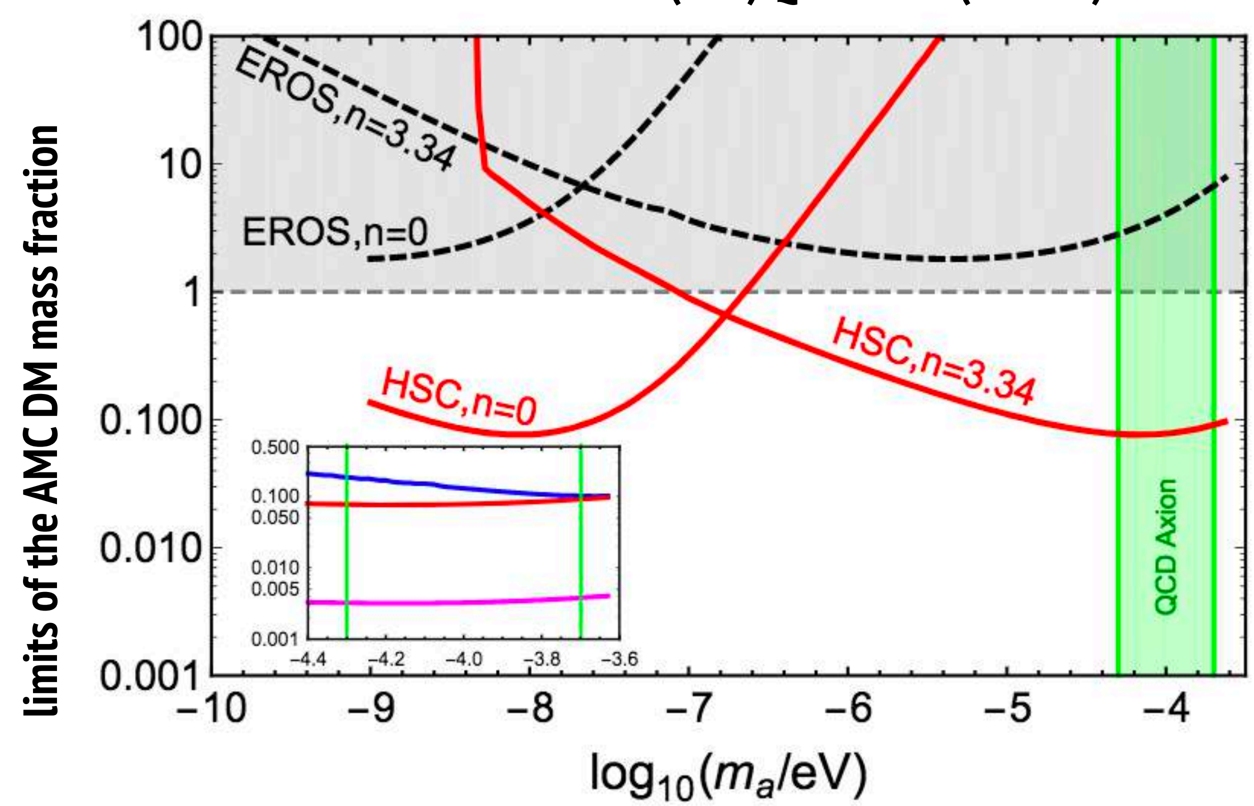



*Uncertainties in the MC mass, profile, mass function dn/dM merging history*

**note the relevance of M0**

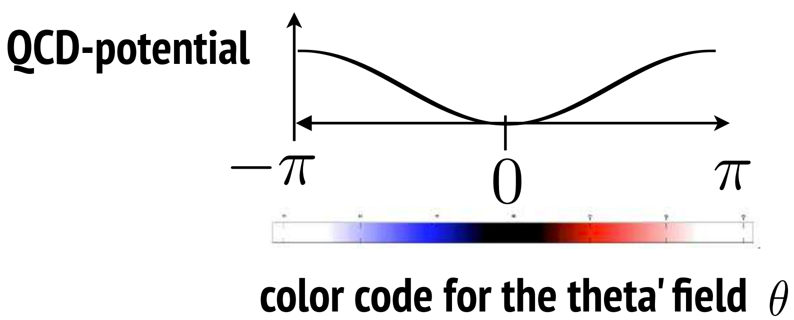
**Constraints ALP (n=0) QCD axion (n=3.34)**

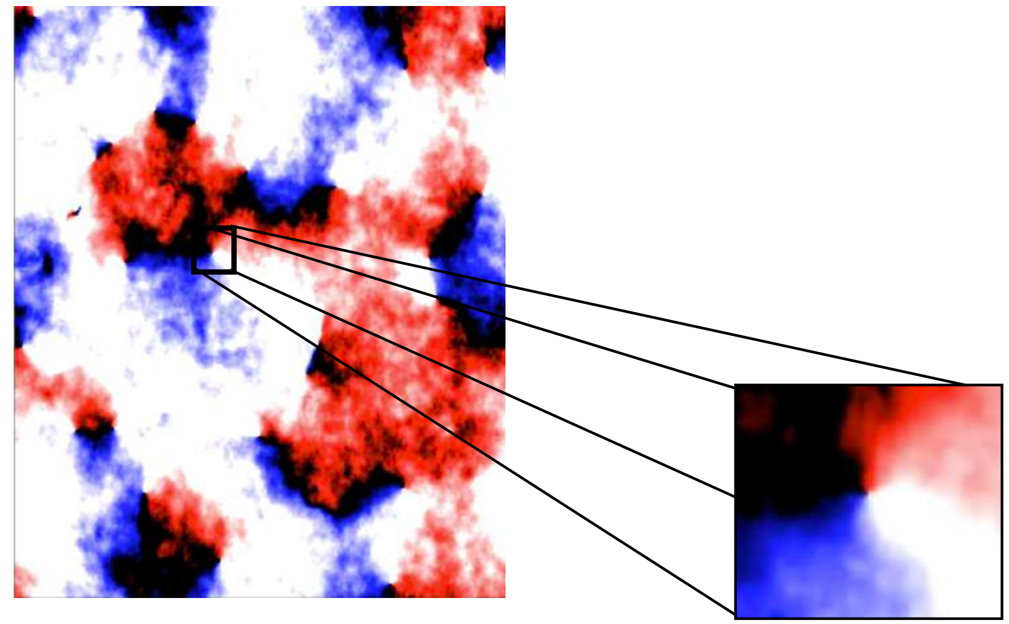


# New simulations of the axion field

*Vaquero, Stadler, JR 2018*

- Previous works used inconsistent ICs
- Random initial conditions in theta imply a network of cosmic (global) strings *Kibble 1980*



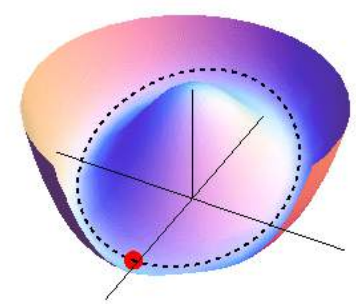
$$\theta \in (0, 2\pi)$$

around one point (2D) one line (3D)

String tension - divergent, needs UV

$$\mu = \pi f_a^2 \log \frac{r_{\rm UV}}{r_{\rm IR}} \sim \pi f_a^2 \log \frac{f_a}{H}$$

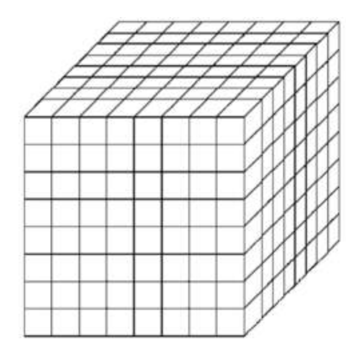
- Simplest UV completion $\Phi = \rho e^{i\theta}$ to regularise string core



$V(\Phi)$

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

- Evolve in large cartesian grids (as much dynamical range as possible)
  Phi simulation -> theta only simulation ->theta frozen... (?)
  Compute final density distribution
  Public MPI/OpenMP code developed ready for HPC *https://github.com/veintemillas/jaxions*

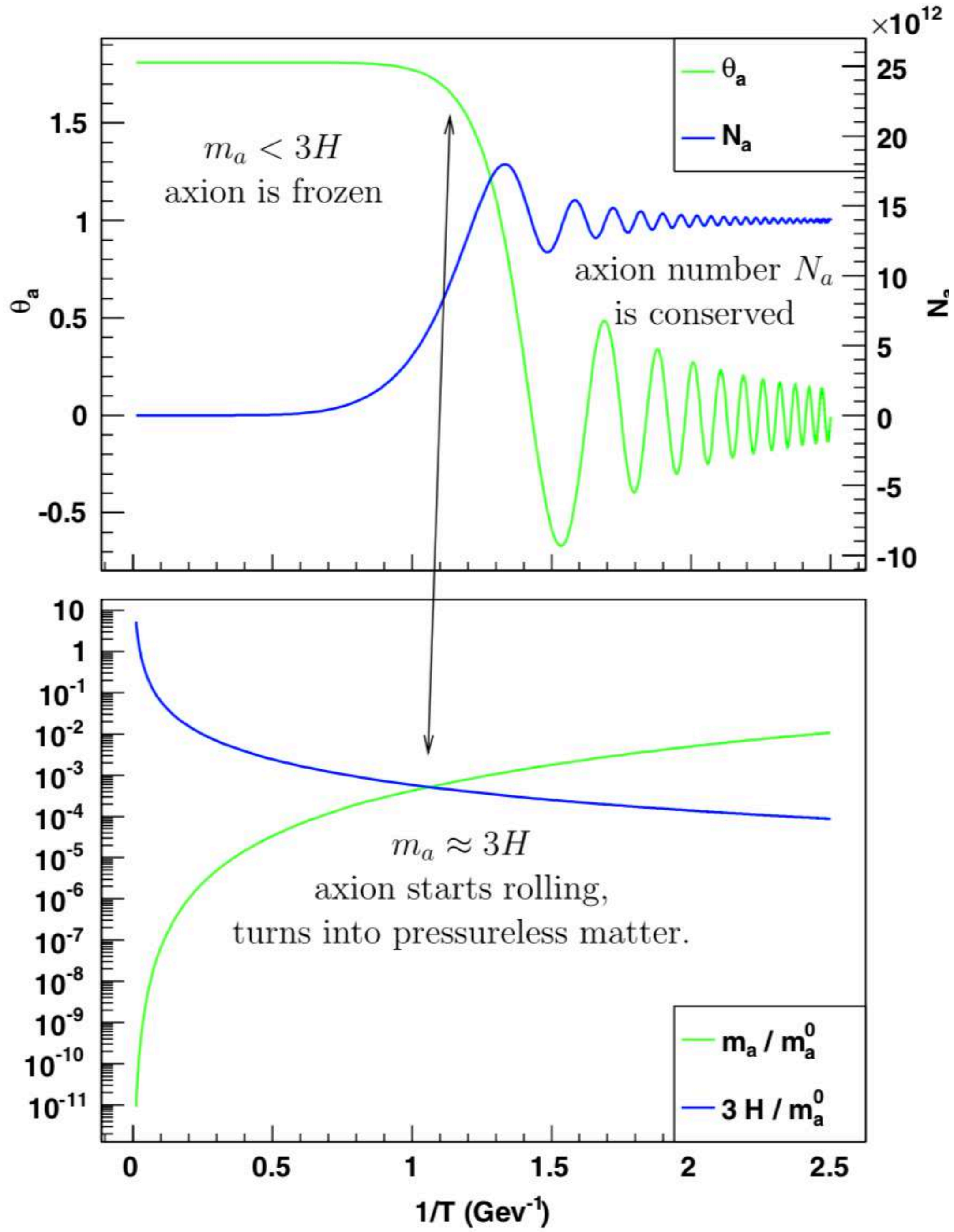


- High-effective tension models available later (work in progress) *Klaer and Moore 2017*

# Evolution, time scales

**<u>Zero mode</u> is "frozen" and starts to oscillate when** $m_a(t_{\rm osc})t_{\rm osc} \sim O(1)$

$$m_A(T_1) = H(T_1) = H_1$$




*Wantz-Shellard 2010*

**Temperature**

$$T_1 \simeq 1.694\,\text{GeV} \left(\frac{m_A}{50\,\mu\text{eV}}\right)^{0.1638} ,$$

**Hubble rate**

$$H_1 \simeq 3.45 \times 10^{-3} \mu\text{eV} \left(\frac{m_A}{50\,\mu\text{eV}}\right)^{0.338}$$

**Redshift**

$$1 + z_1 \simeq R_1^{-1} = 1.956 \times 10^{13} \left(\frac{m_A}{50\,\mu\text{eV}}\right)^{0.1712}$$

**Comoving Horizon size**

$$L_1 \equiv \frac{1}{H_1 R_1} \simeq 1.116 \times 10^{17}\text{cm} \left(\frac{50\,\mu\text{eV}}{m_A}\right)^{0.167} = 0.0362\,\text{pc} \left(\frac{50\,\mu\text{eV}}{m_A}\right)^{0.167}$$

*mA, H from Borsanyi 2016*

**Axion number in comoving volume>adiabatic invariant**

$$N_a \sim \frac{\rho_a}{m_a} R^3$$

# Cosmological model dependence...

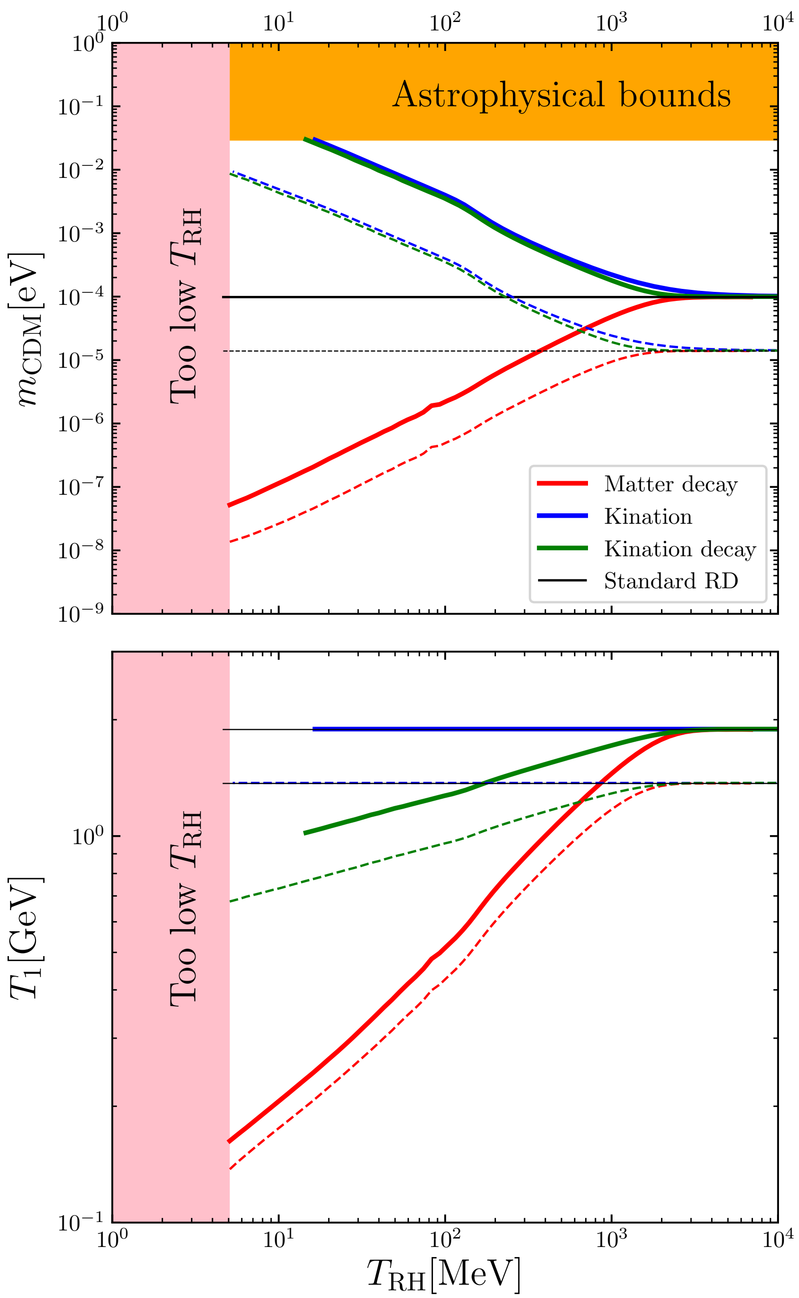
*Visinelli, Redondo 2018*

**Alternative pre-BBN cosmologies change T1 and R1 and so:**

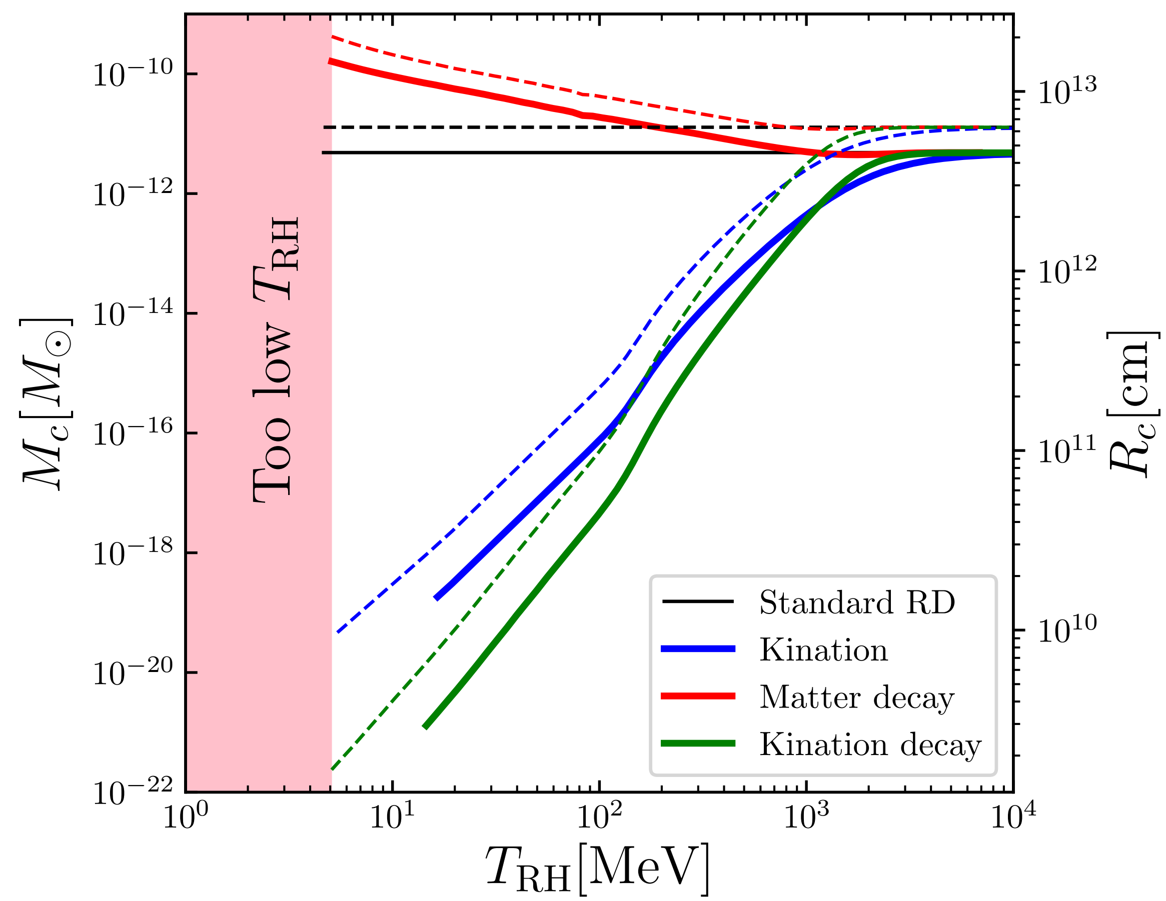
- **the suitable axion mass**
- **The typical Minicluster mass and radius**

**OLD-NEW!**

*Visinelli, Redondo 2019*




**Standard Radiation Domination**
**Decaying matter domination**
**kination**
**kination with decaying field**



# ~Scale-invariant equations

Switching to conformal coordinates and field normalised to natural values, $L_1, H_1, \ldots$

and approximating $m_A^2 \sim m_A^2(T_1)\left(\frac{T_1}{T}\right)^n = H_1^2\tau^n$ ( $\tau$ conformal time)

the dependence on L1 is implicit $\Phi'' - \nabla^2\Phi - \lambda\Phi(|\phi|^2 - \tau^2) - \tau^{n+3} = 0$

**Simulations valid for all consistent values of L1 (function of axion mass today)**

## Parameters

**Volume** $L/L_1 \gtrsim 6$

Around $\tau \sim 2$ strings are strongly pulled by axionic domain walls to collapse in loops

**String tension**

$$\lambda = \lambda_\phi \frac{f_a^2}{H_1^2} = \frac{m_s^2}{H_1^2} \sim 10^{60}$$

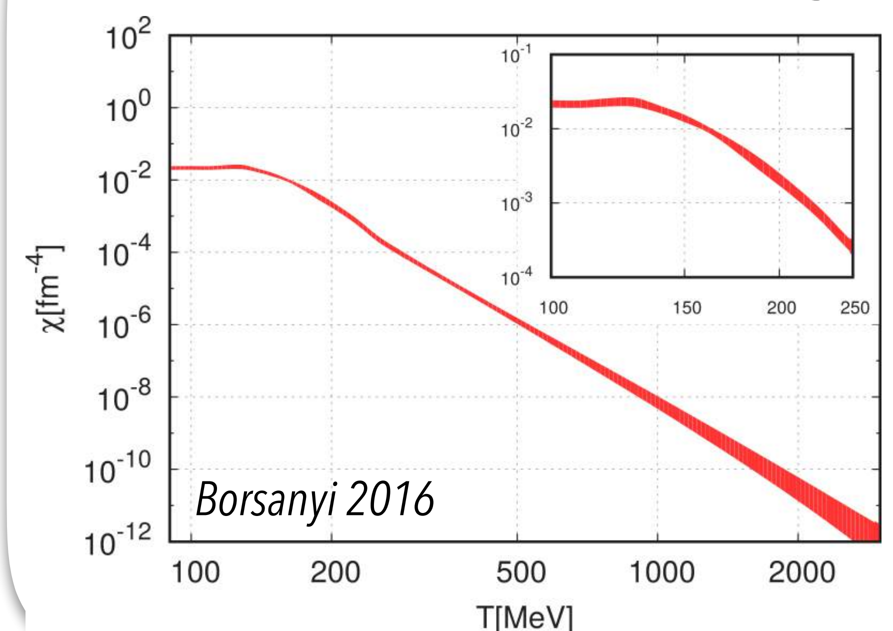
(dynamical range^2)

**Largest simulations + PRS**

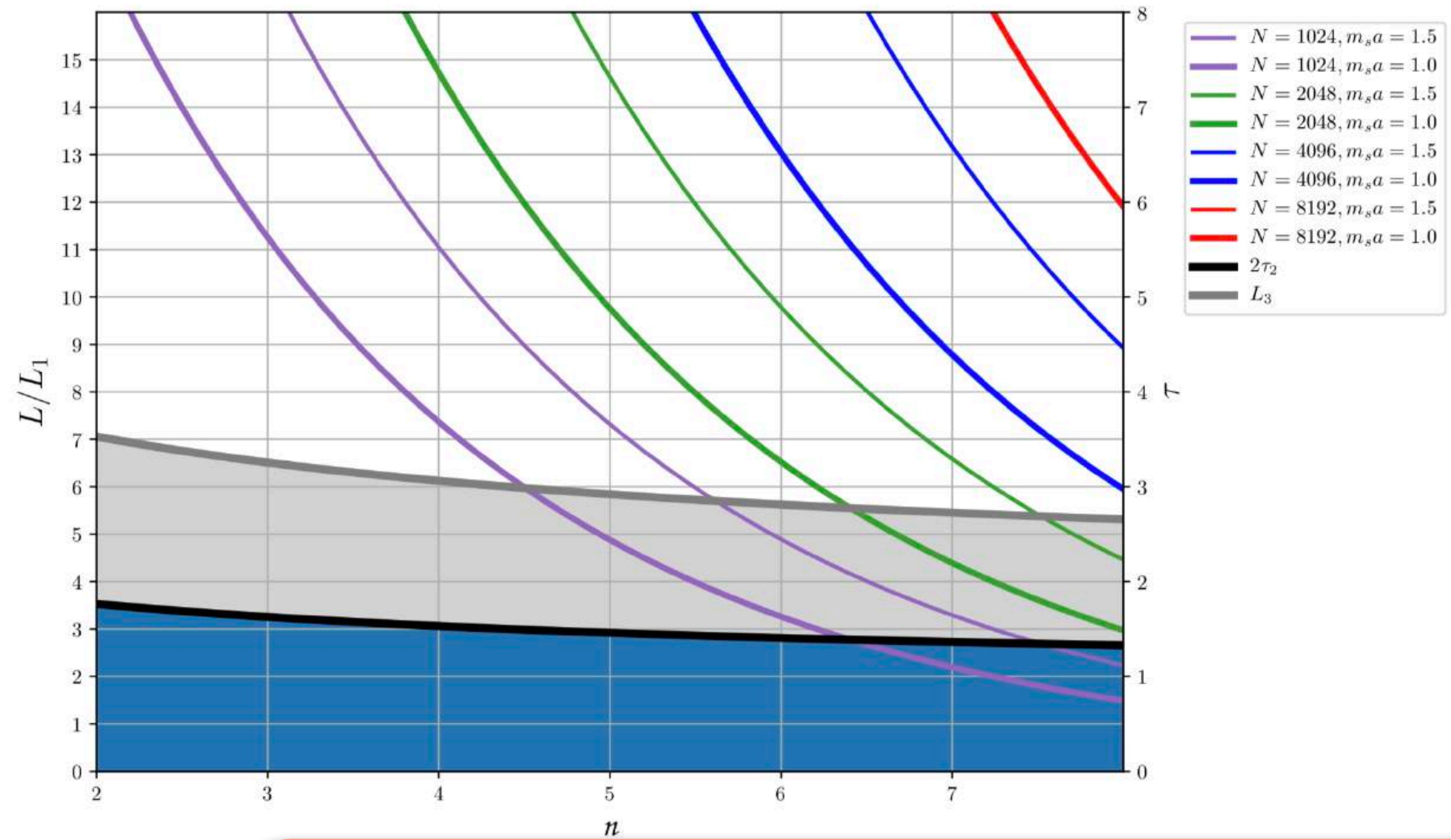
$$\lambda \sim \frac{2\times 10^6}{\tau^2} \qquad \log\frac{m_s}{H} \sim 8$$

(8192^3, L=6)

**n~7-7.5 in the relevant T-range**



# Constraints

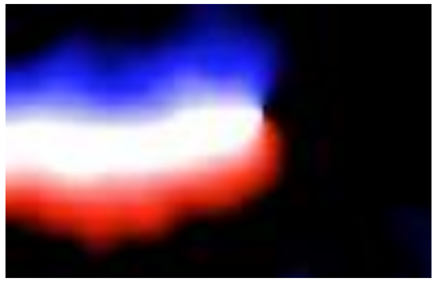


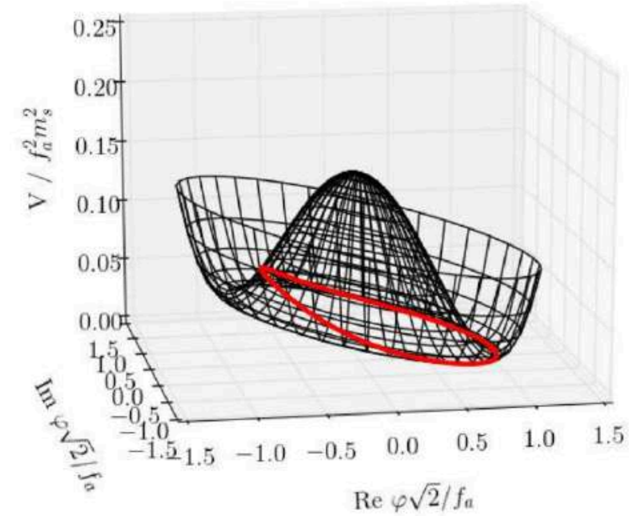

**String tension : unphysical destruction of domain walls**

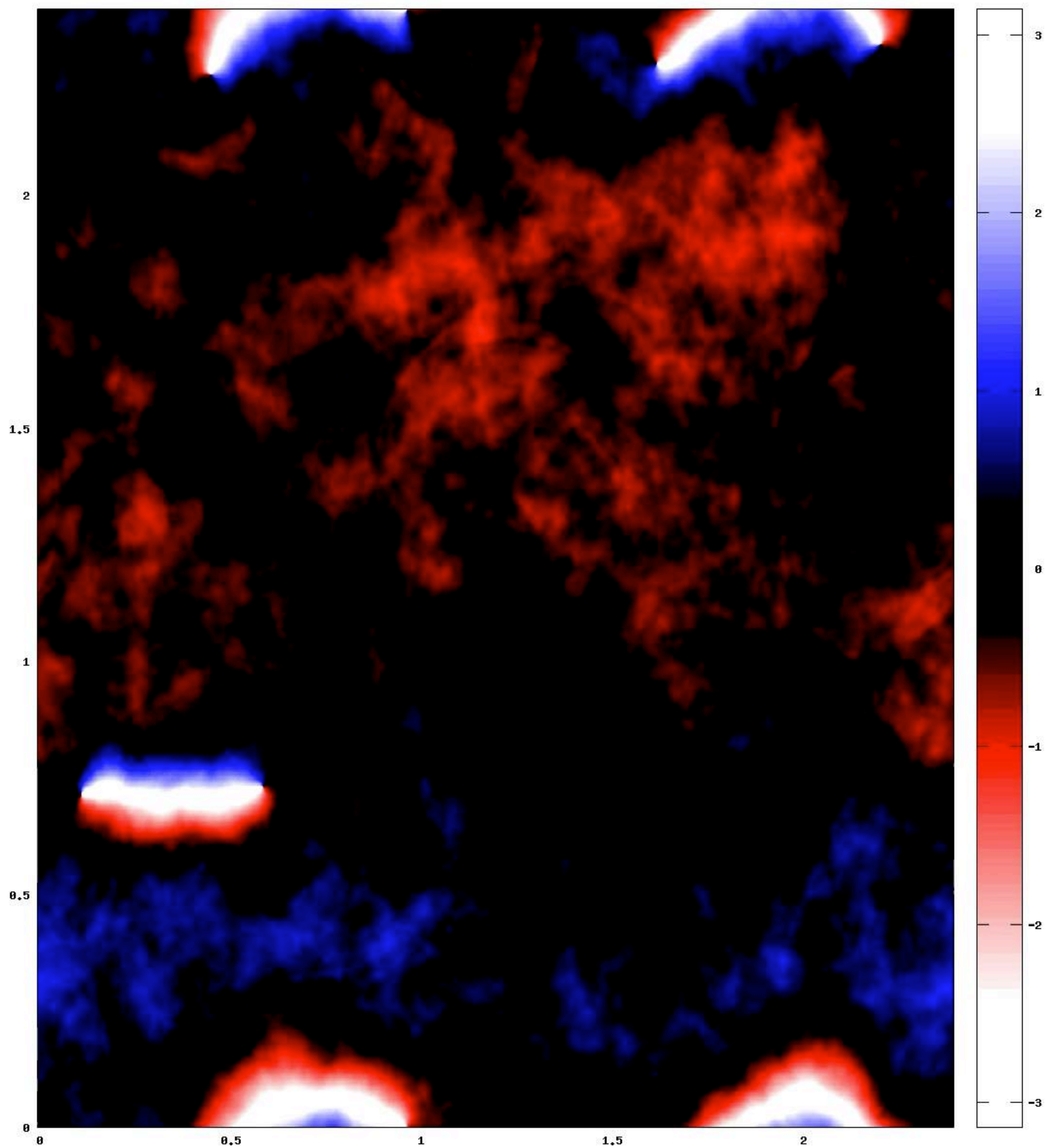
## Parameters

**Volume** $L/L_1 \gtrsim 6$

Around $\tau \sim 2$ strings are strongly pulled by axionic domain walls to collapse in loops





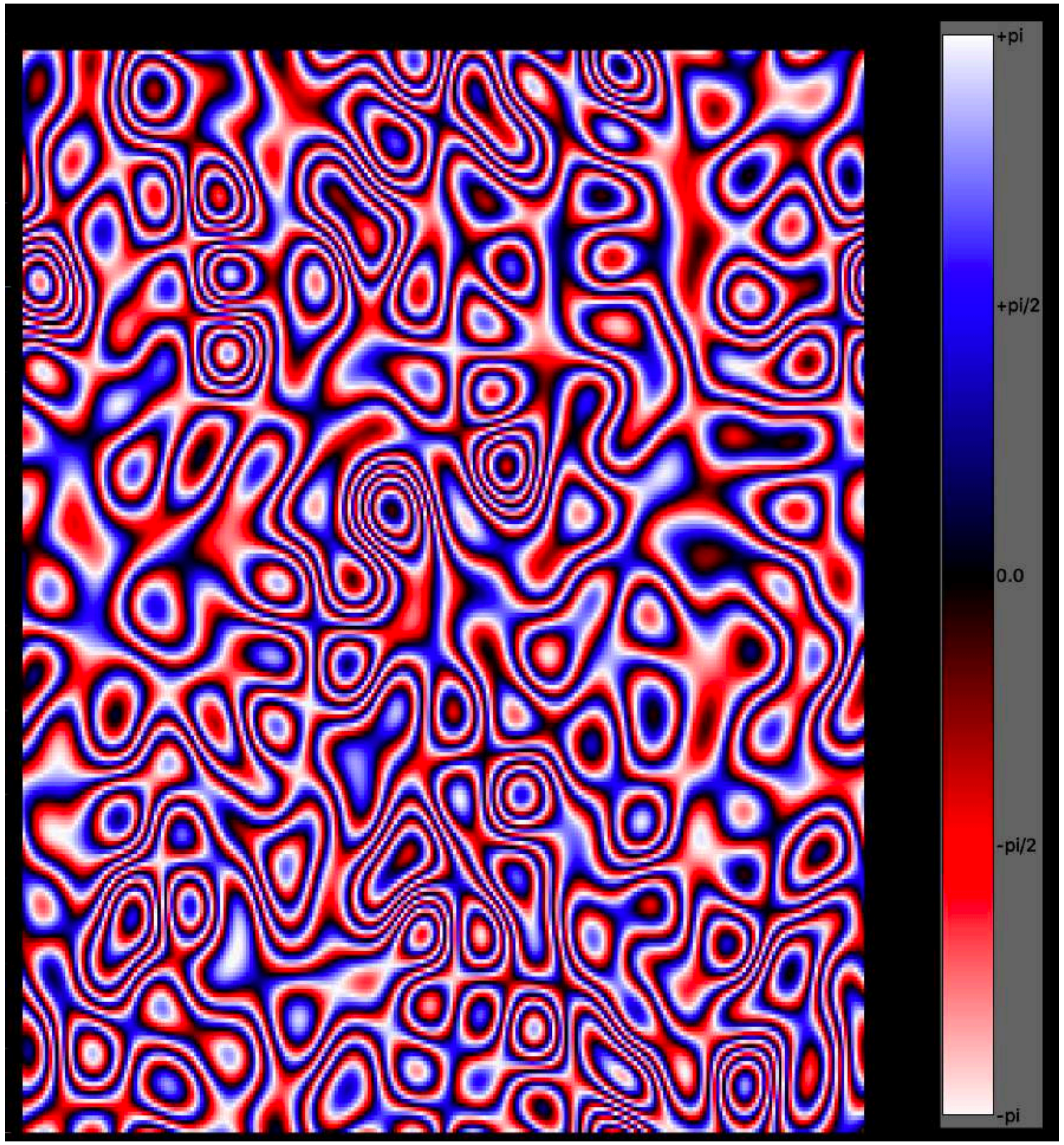


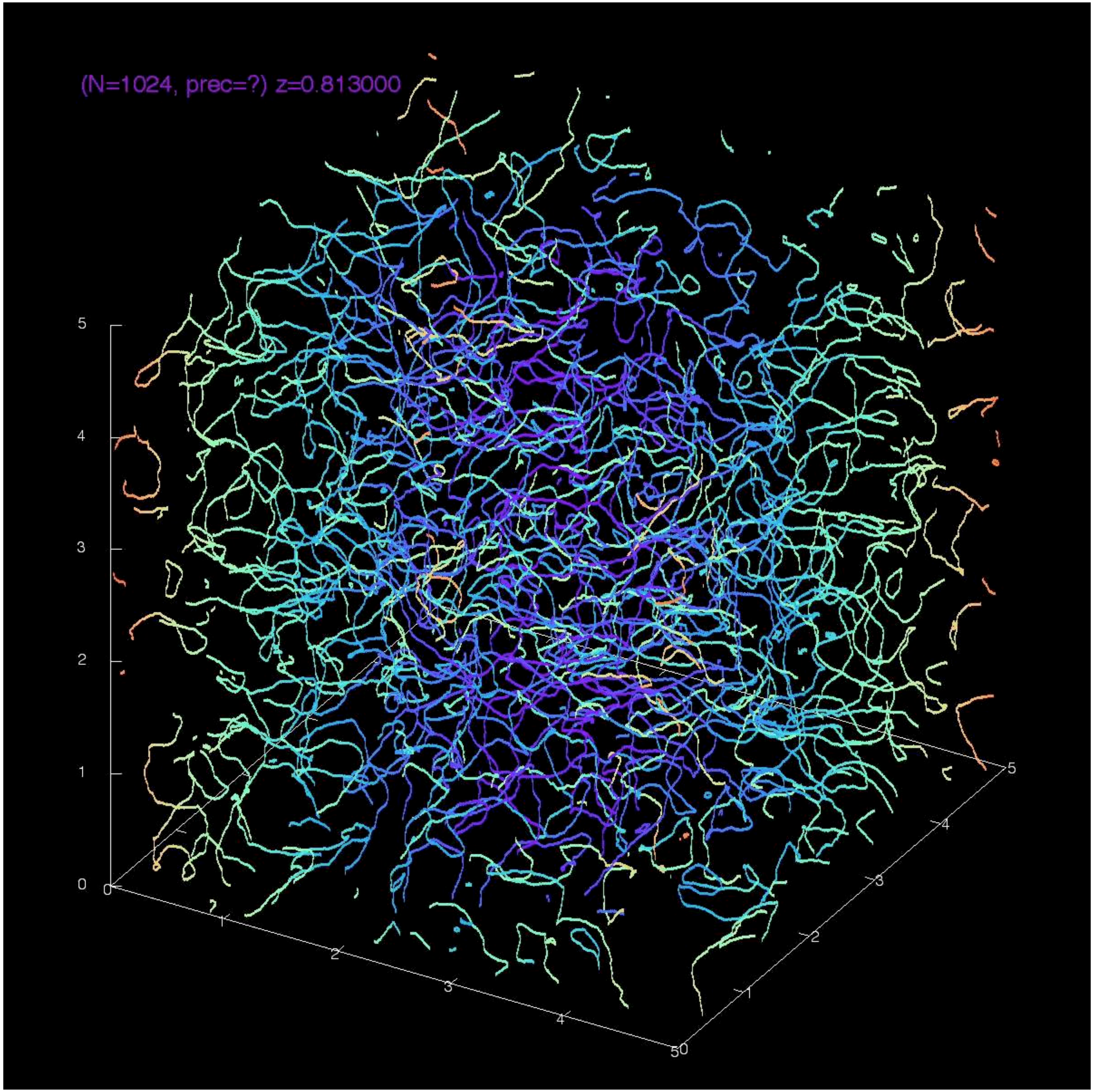

**slice of theta**

# Tkachev Initial conditions

$$\theta = A \sum_{k=1,\ldots,6/L} \sin(k_x x)\sin(k_y y)\sin(k_z z)$$

**White noise in theta angle**






**string evolution**

# Final density is highly inhomogenous

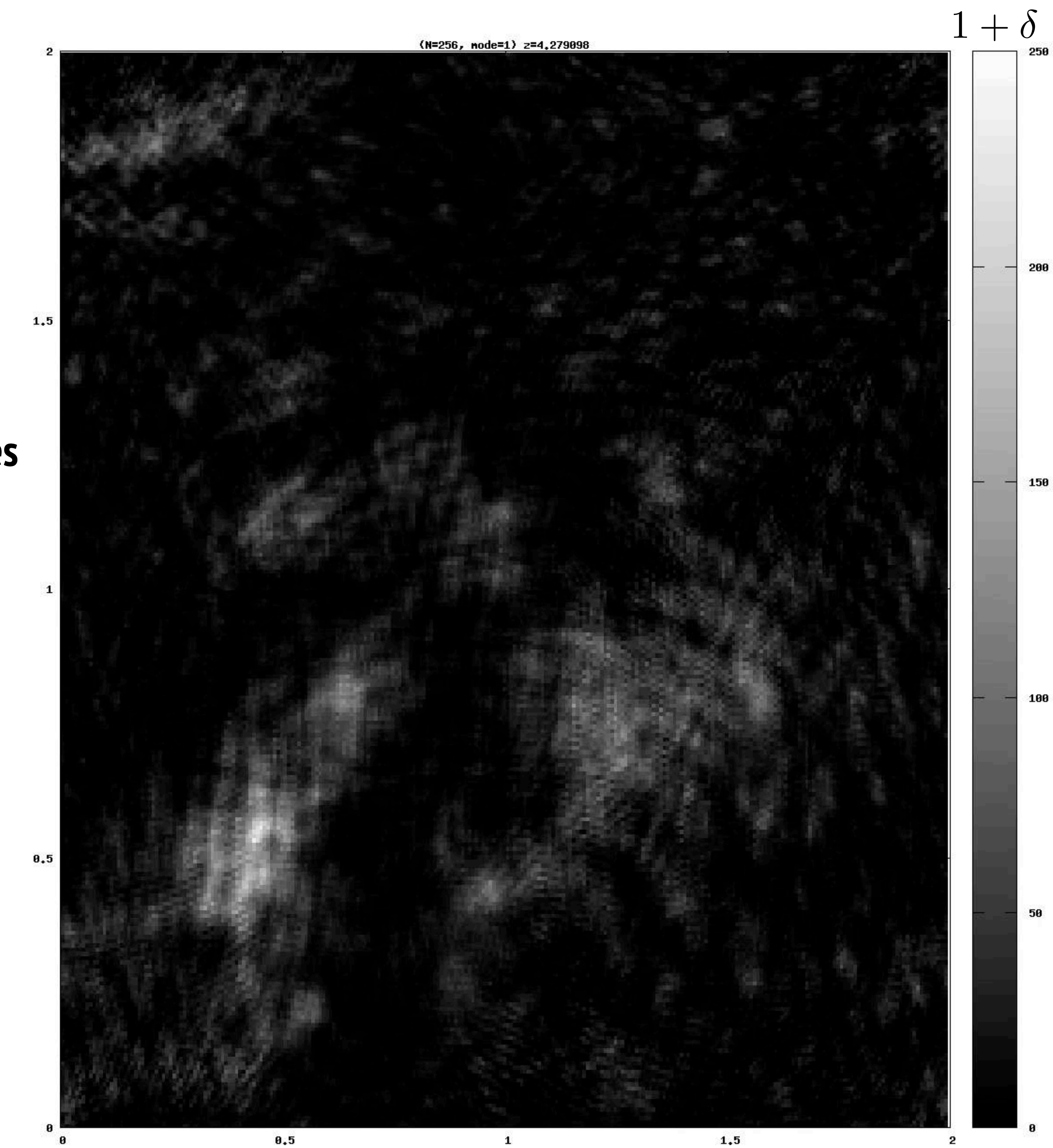
Axion overdensity contrast

$$\delta = \frac{\rho - \bar{\rho}}{\bar{\rho}}$$

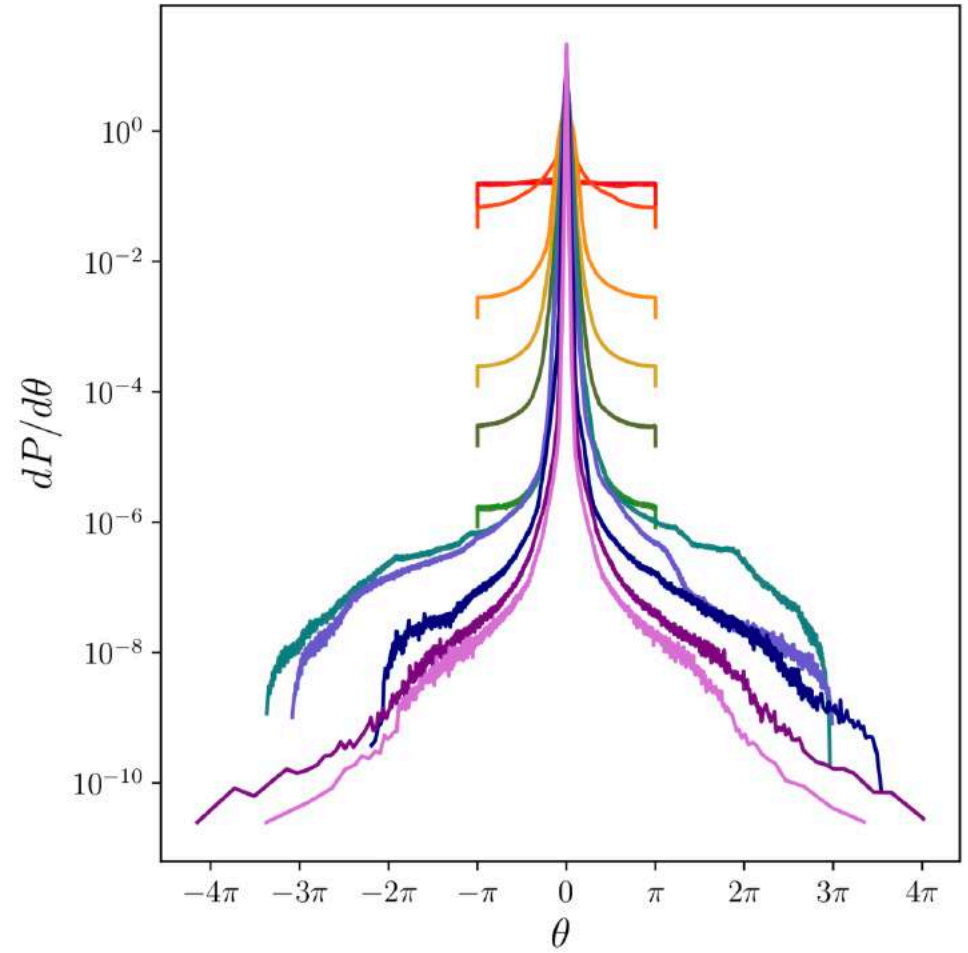
Shown is a 2D slice of $1 + \delta$

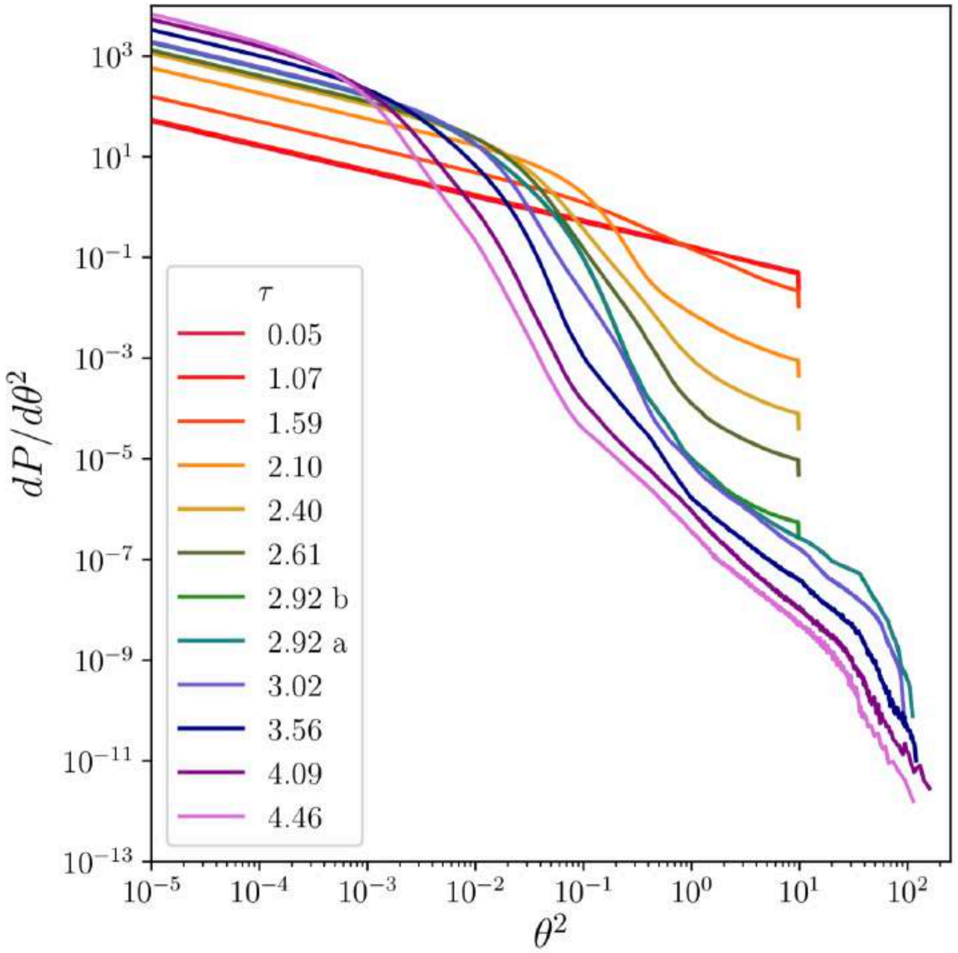
- Starts after last string-domain-wall collapses
- quickly axions become non-relativistic
- long wavelengths become frozen
- small scales very visible
- interference patterns not washed out

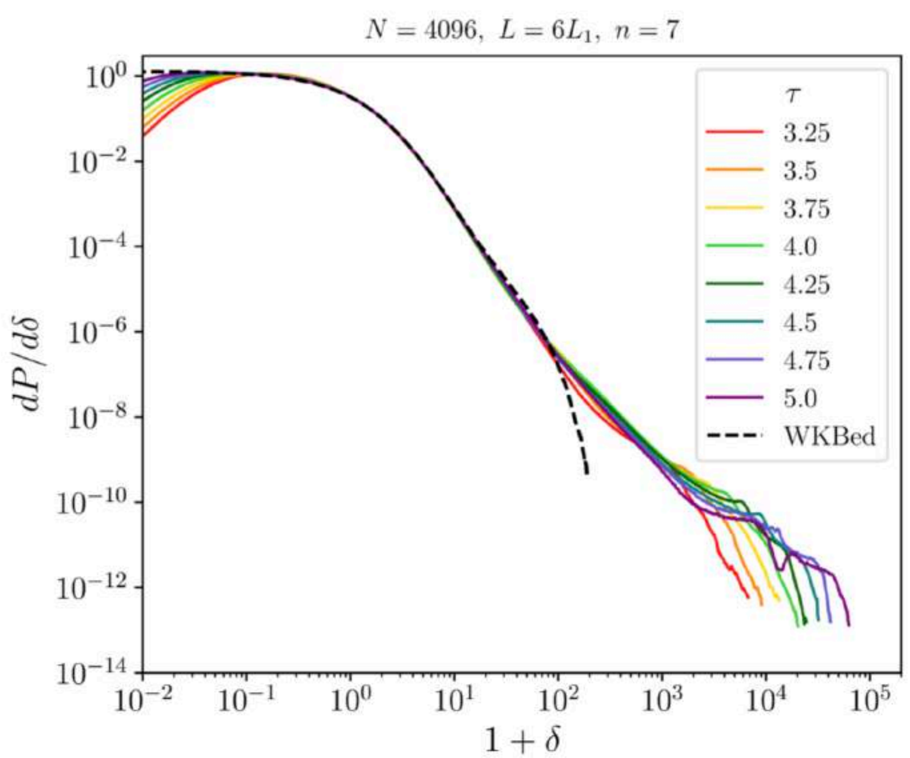
Low resolution example

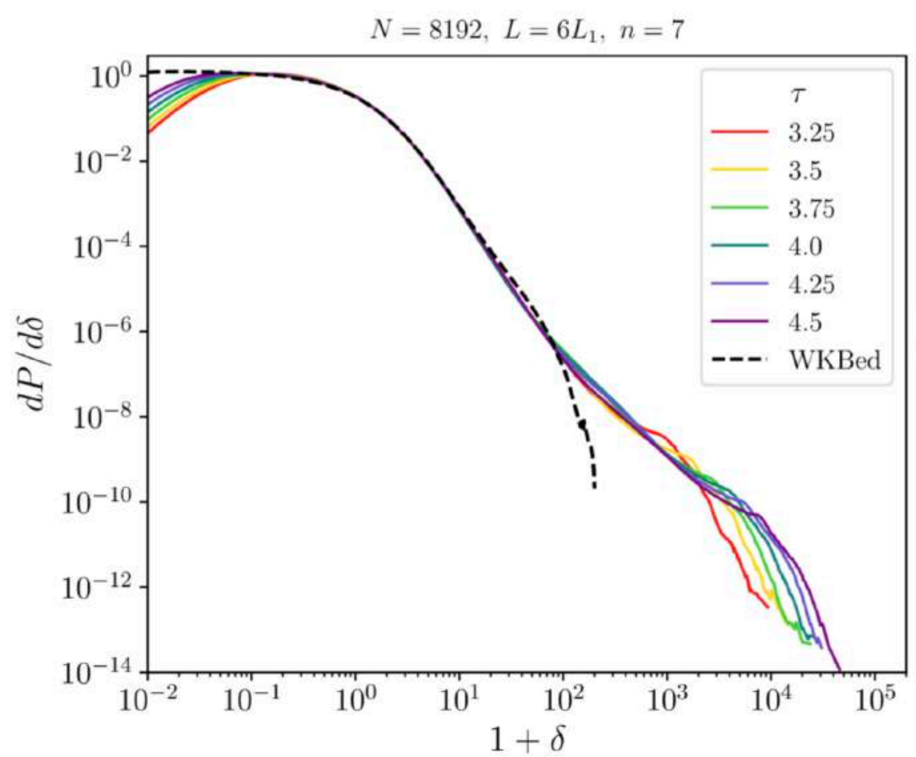


# Distribution of theta, density



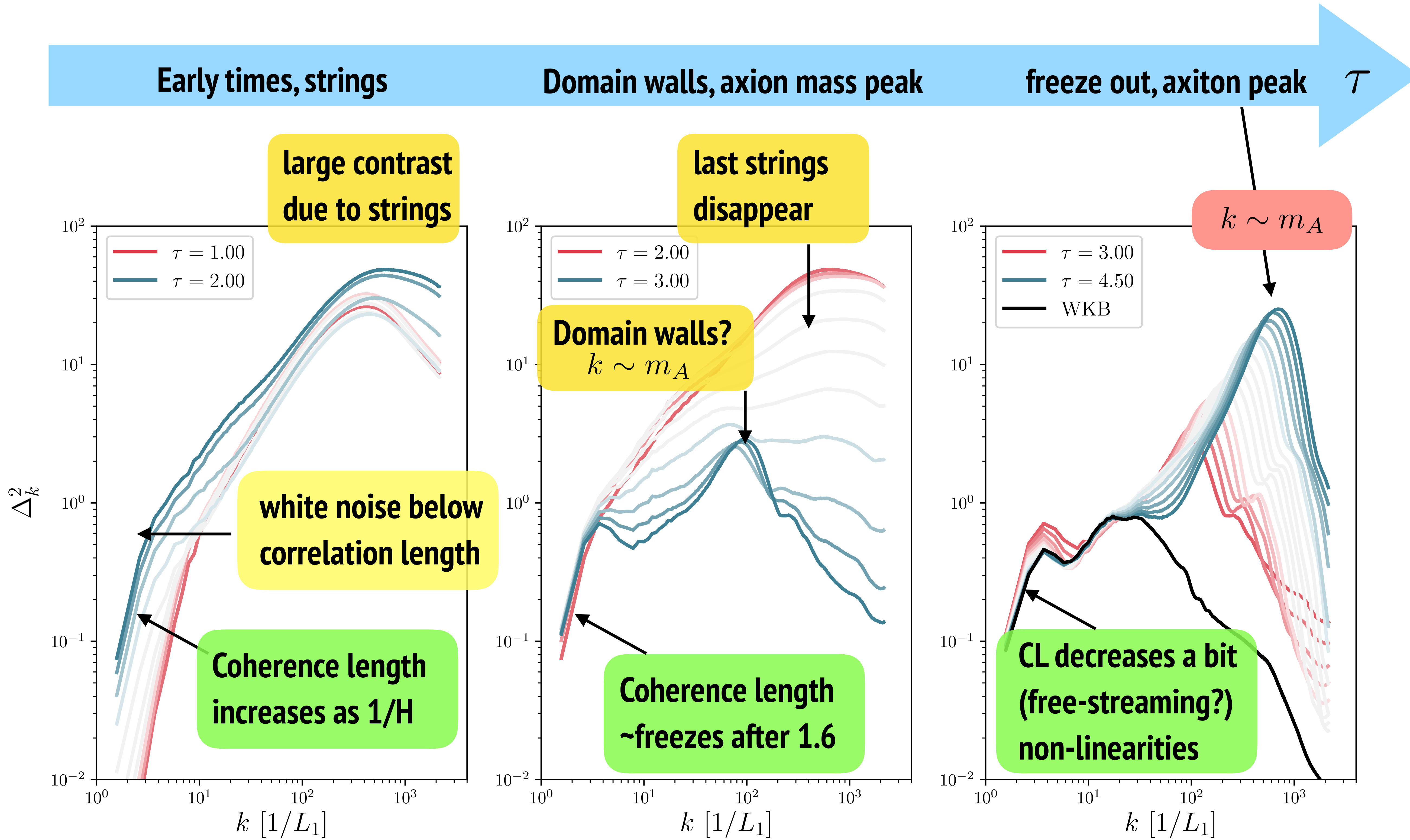



# Density contrast evolution

L=6, N=8192

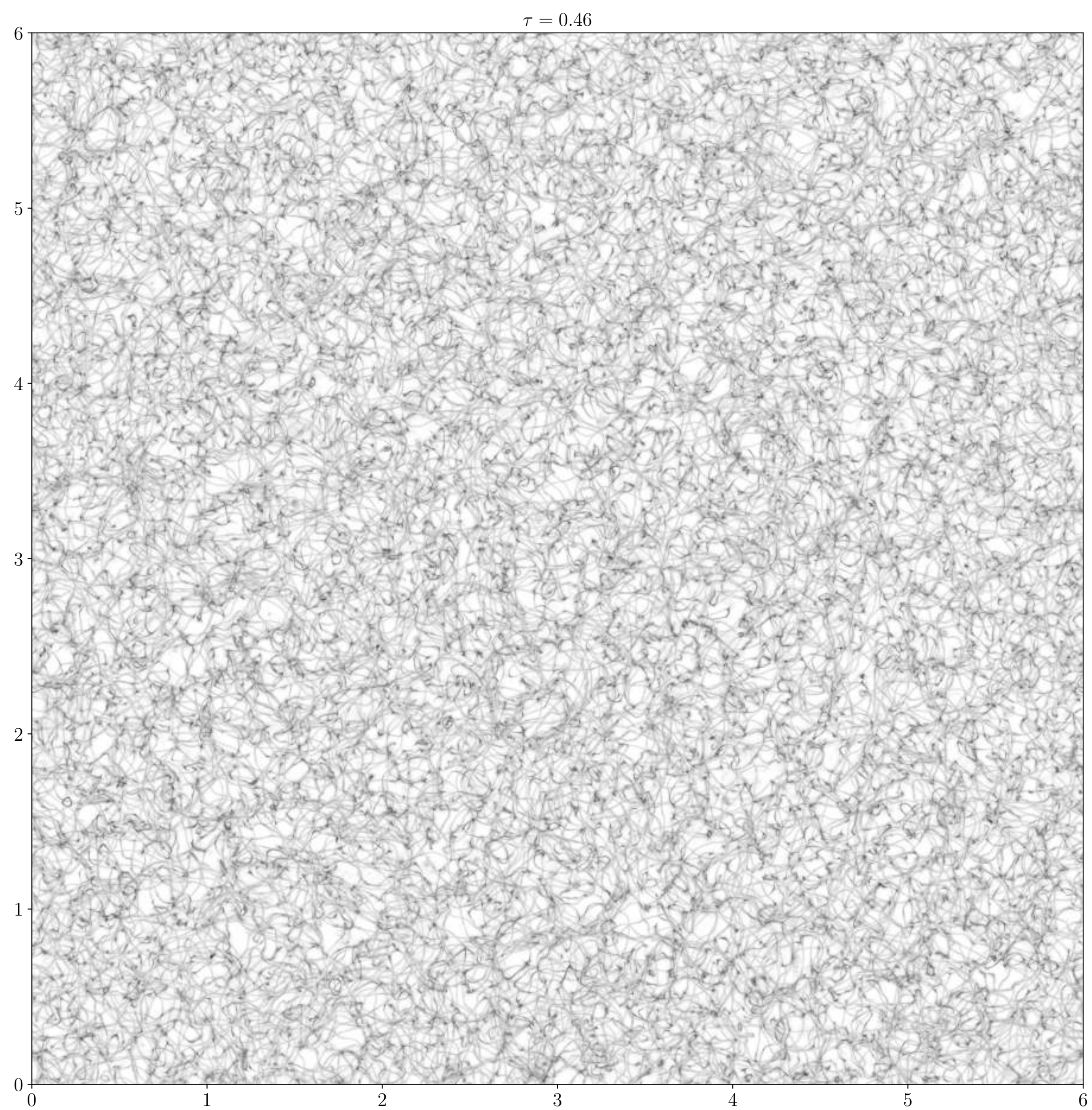
**Dimensionless-variance** $$\Delta_k^2 = \frac{k^3}{2\pi^2}\frac{1}{V}\langle|\widetilde{\delta}(k)|^2\rangle$$

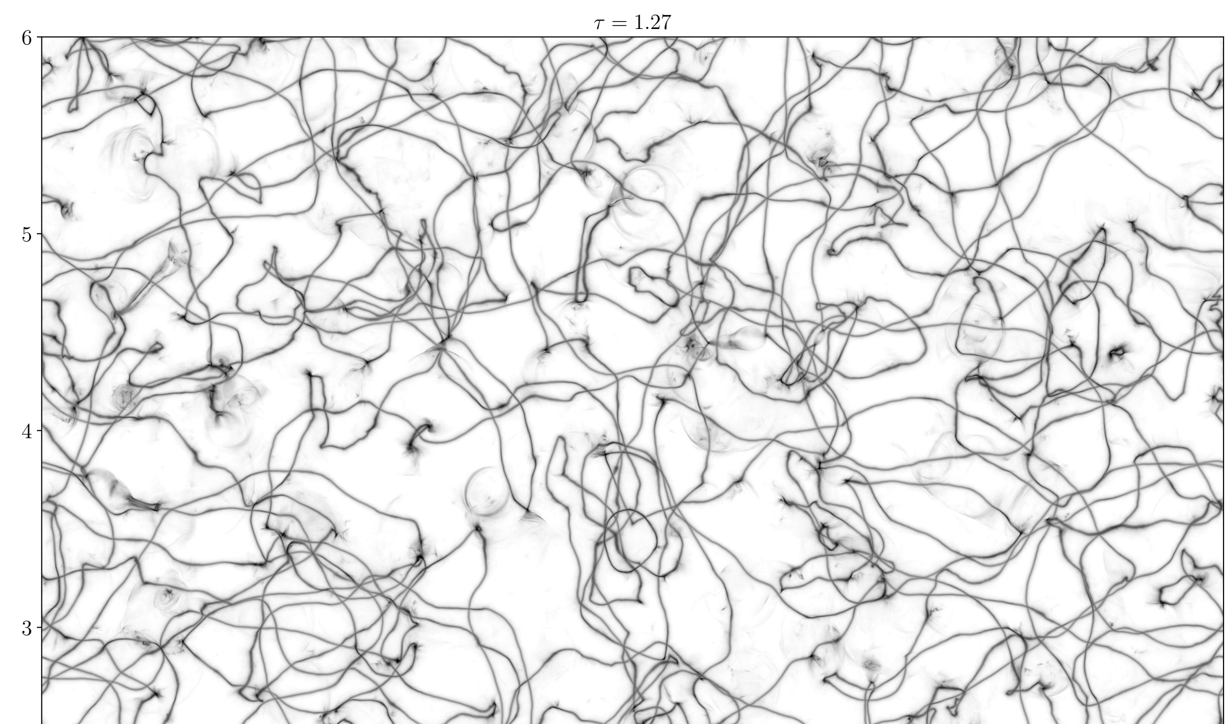


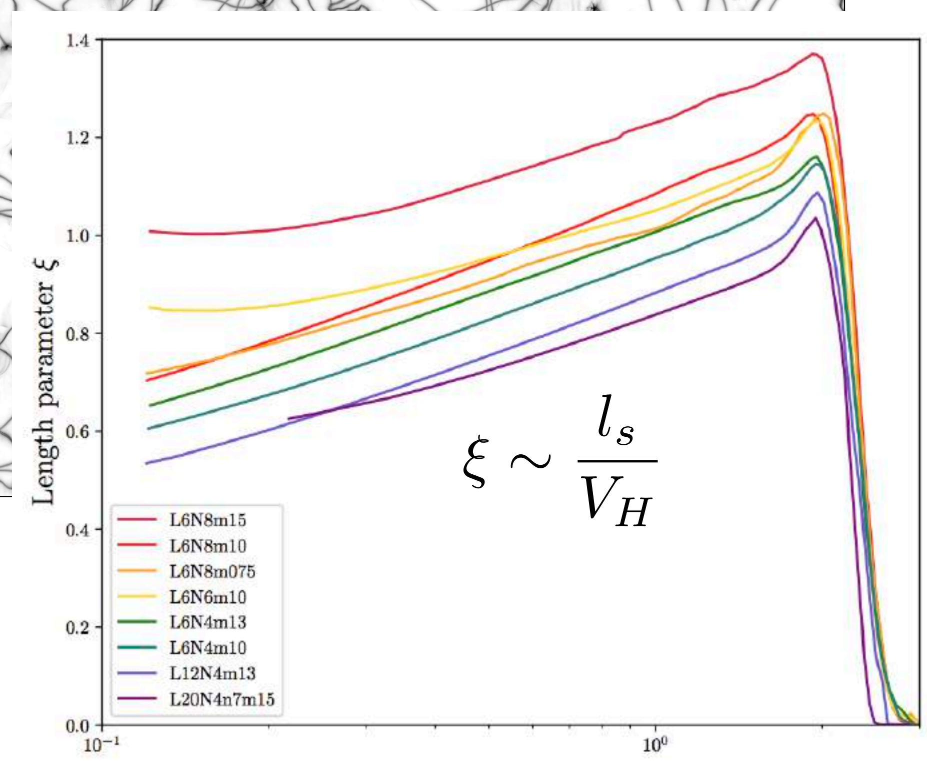
# Density contrast evolution in conf. space

L=6, N=8192

Early times, strings    scaling solution with O(1) string/Hubble volume ... (scaling violations*)



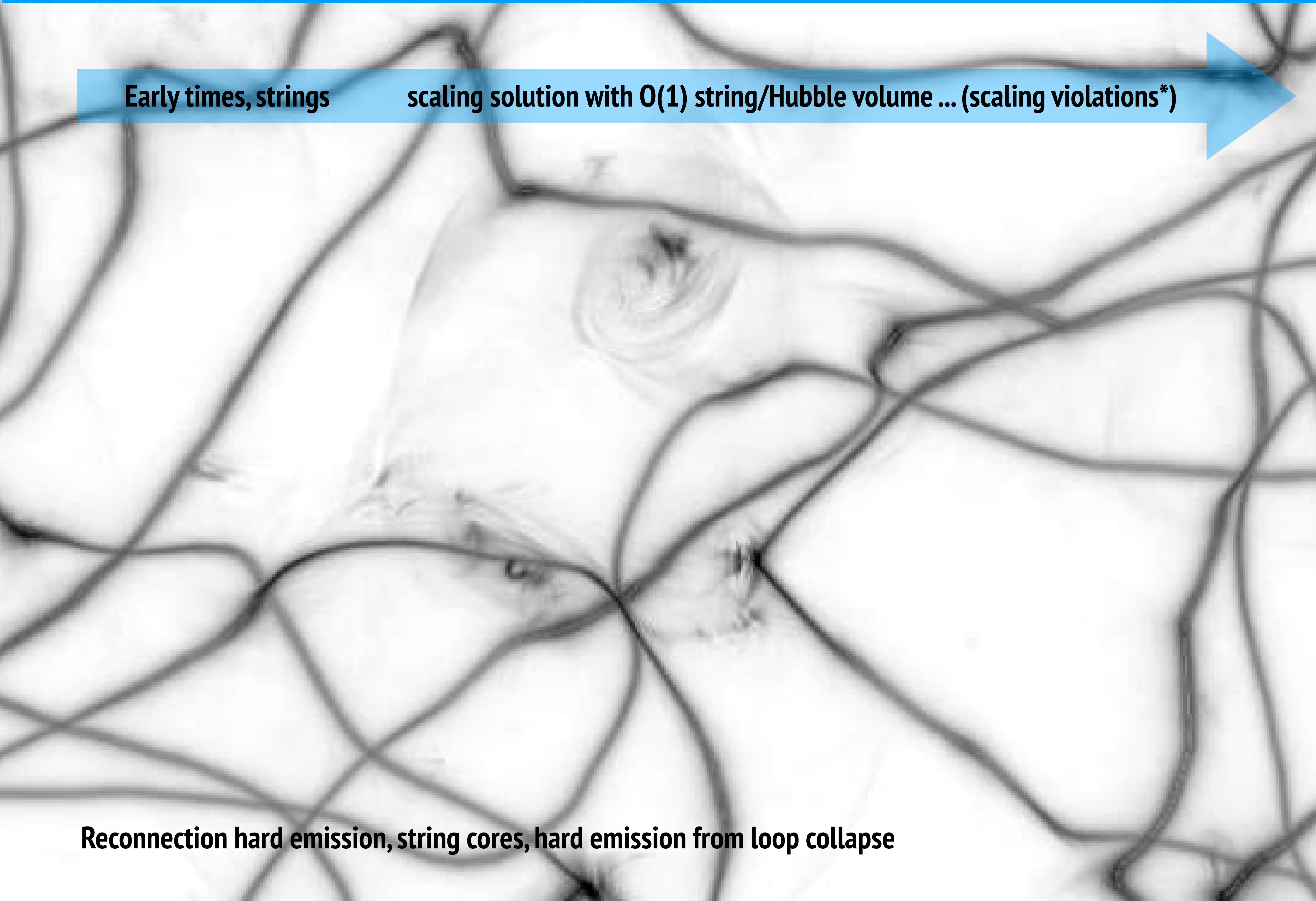




projection plots of density^2 (3D->2D)

# Density contrast evolution in conf. space

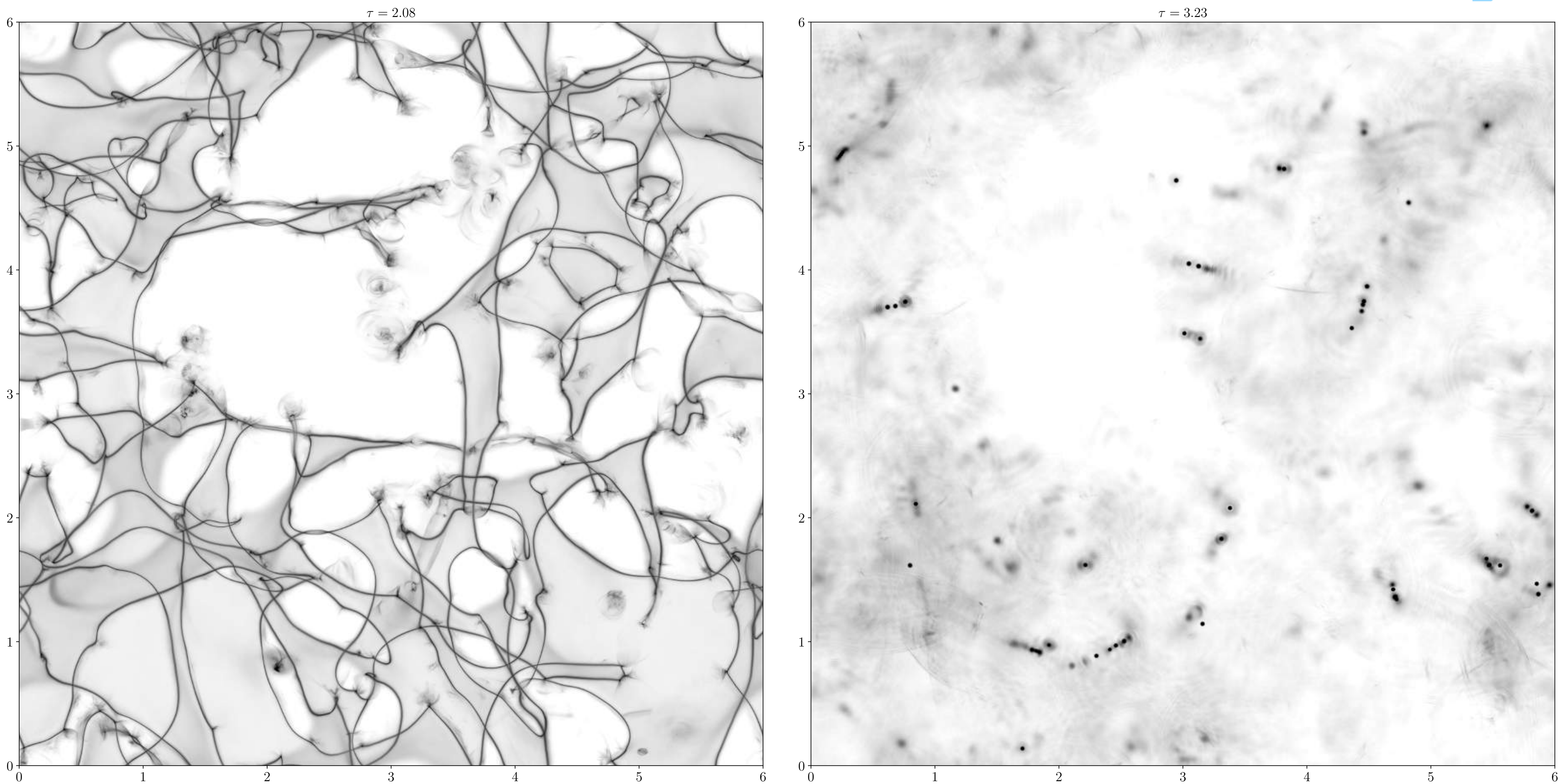
L=6, N=8192



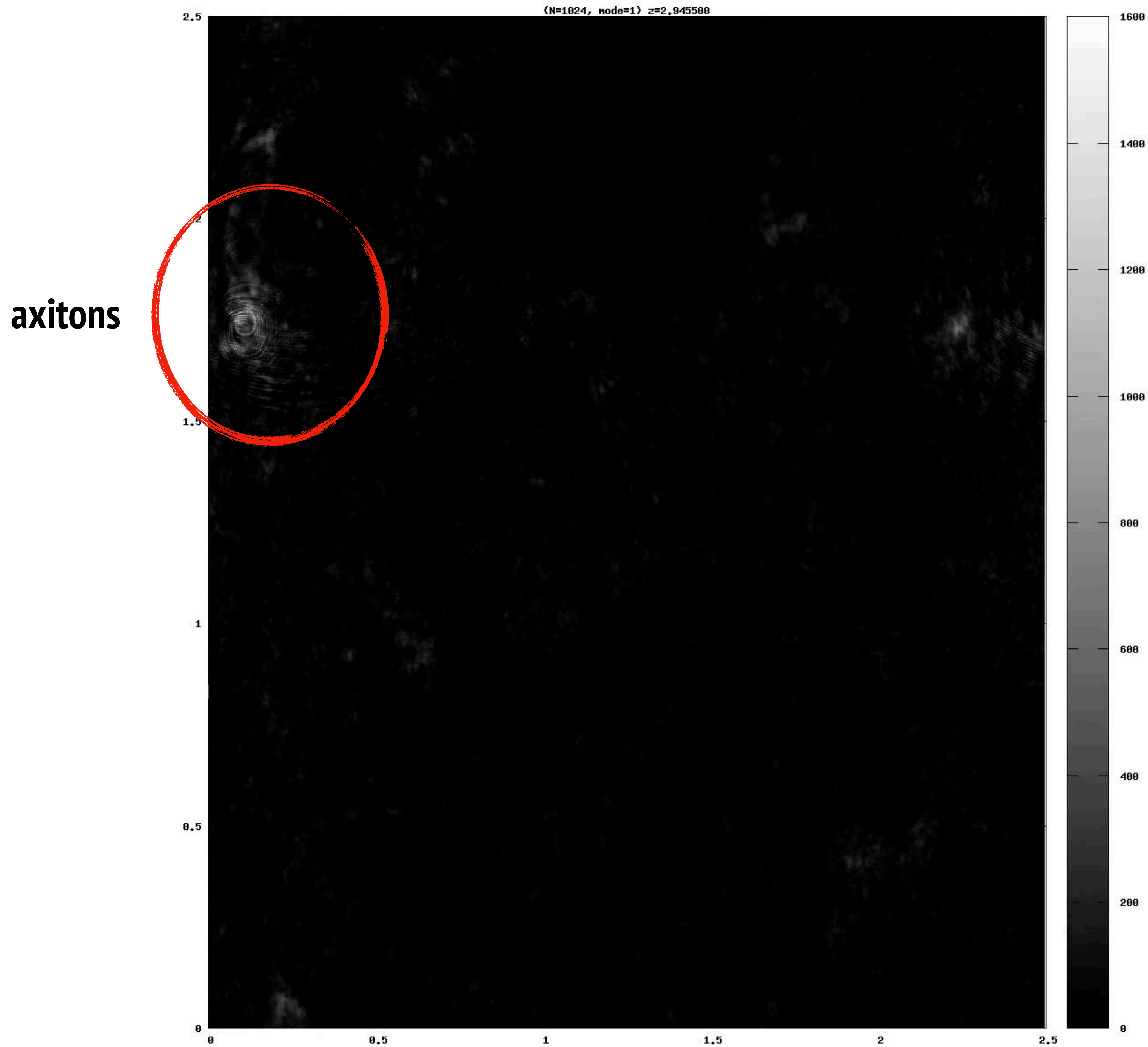
# Density contrast evolution in conf. space

L=6, N=8192

**Domain walls, string network collapse ……………… axitons**




**projection plots of density^2 (3D->2D)**


axitons
(N=1024, mode=1) z=2.945500
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5
2
2.5
1600
1400
1200
1000
800
600
400
200
0

# Axitons

*Kolb, Tkachev 1993*

- The axion equation (Sine-Gordon) has a NR instability (self interactions are attractive)
- Energy of a axion Gaussian lump of size R (fixed axion number)

$$U = \int dV \left(\frac{1}{2}\dot{a}^2 + \frac{1}{2}m^2 a^2 + \frac{1}{2}(\nabla a)^2 - \text{grav} - \lambda a^4 + \ldots\right)$$

$$U \sim M + \frac{M}{m^2 R^2} - \frac{GM^2}{R} - \lambda \frac{M^2}{m^4 R^3}$$

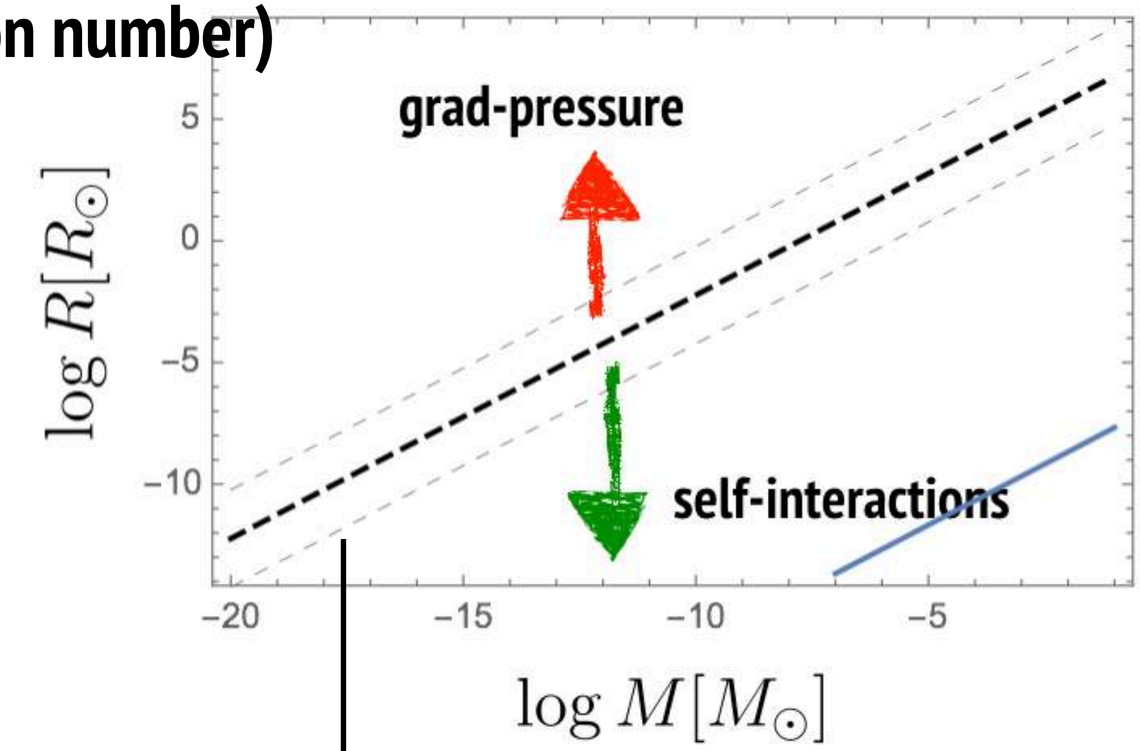
gradient pressure decreases energy expanding

gravity decreases energy contracting

self-interactions decrease energy contracting

FASTER THAN GRAD-PRESSURE

[sometimes called quantum pressure]




- Axitons start as dense lumps below the critical line
- They contract until $R \sim m_A$ and SI saturate
- They become pseudo-breathers
- They breathe emitting relativistic axions and finally relax
- In expanding Universe, they are fuelled by increasing axion masss

  they are resilient until axion mass saturates $R_{\rm end} \sim m_A(\tau \sim 16) \ll H$

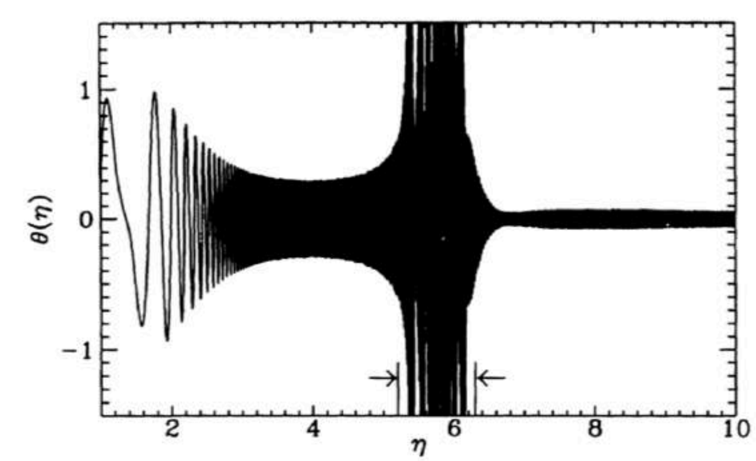


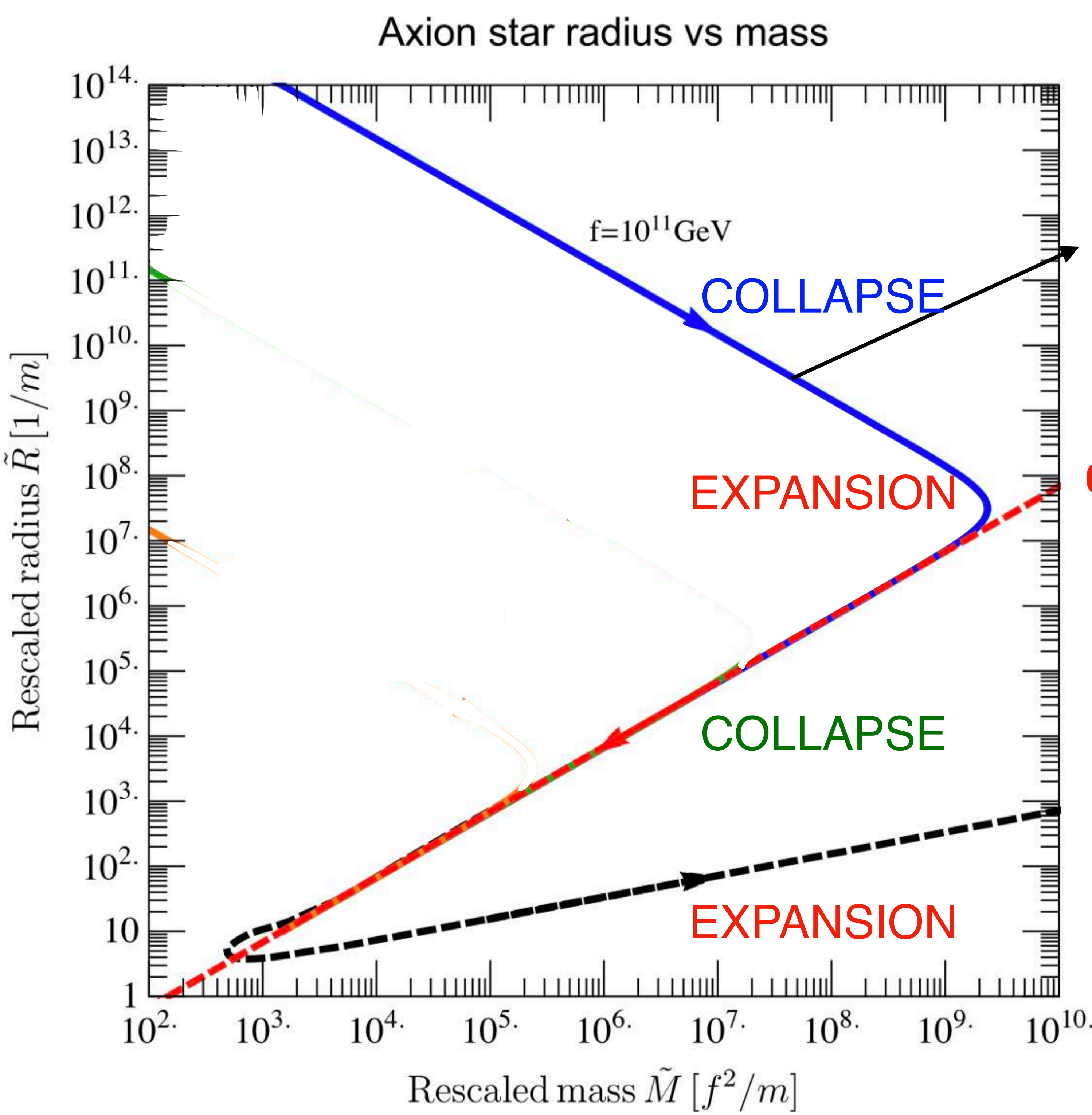

FIG. 8. The time dependence of $\theta$ in the center of an axiton in the (1+1)-dimensional calculation. The axiton was generated by the choice $A = 0.77$.

*Kolb-Tkachev 1993*

# Dilute and dense axion stars

*Visinelli et al 2017*

$$\frac{1}{m} = 3 \times 10^{-11} R_\odot \left(\frac{10^{-5}\,\text{eV}}{m}\right),$$




$$\frac{f^2}{m} = 3 \times 10^{-20} M_\odot \left(\frac{10^{-5}\,\text{eV}}{m}\right)^3,$$

**DILUTE axion-stars**

**Equilibrium between gravity and quantum pressure**

*Kaup 68, Ruffini 69, Tkachev 91*

**Critical line**

**DENSE axion-stars**

**Equilibrium between Si and quantum pressure?**

**nope! lumps decay emitting relativistic axions!**

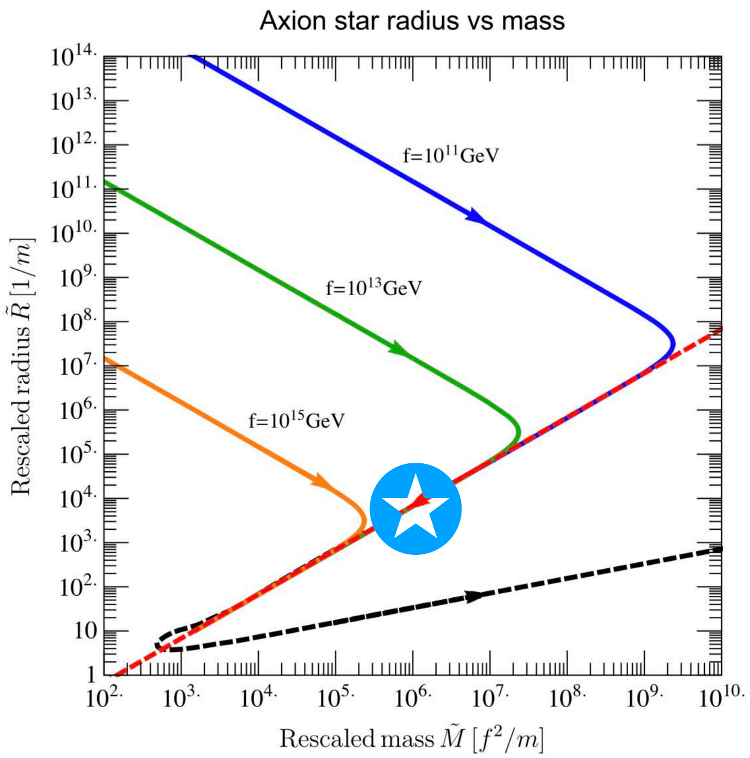
**relativistic + non-perturbative effects required**

**lifetimes ~ 10^3-10^4 1/mass**

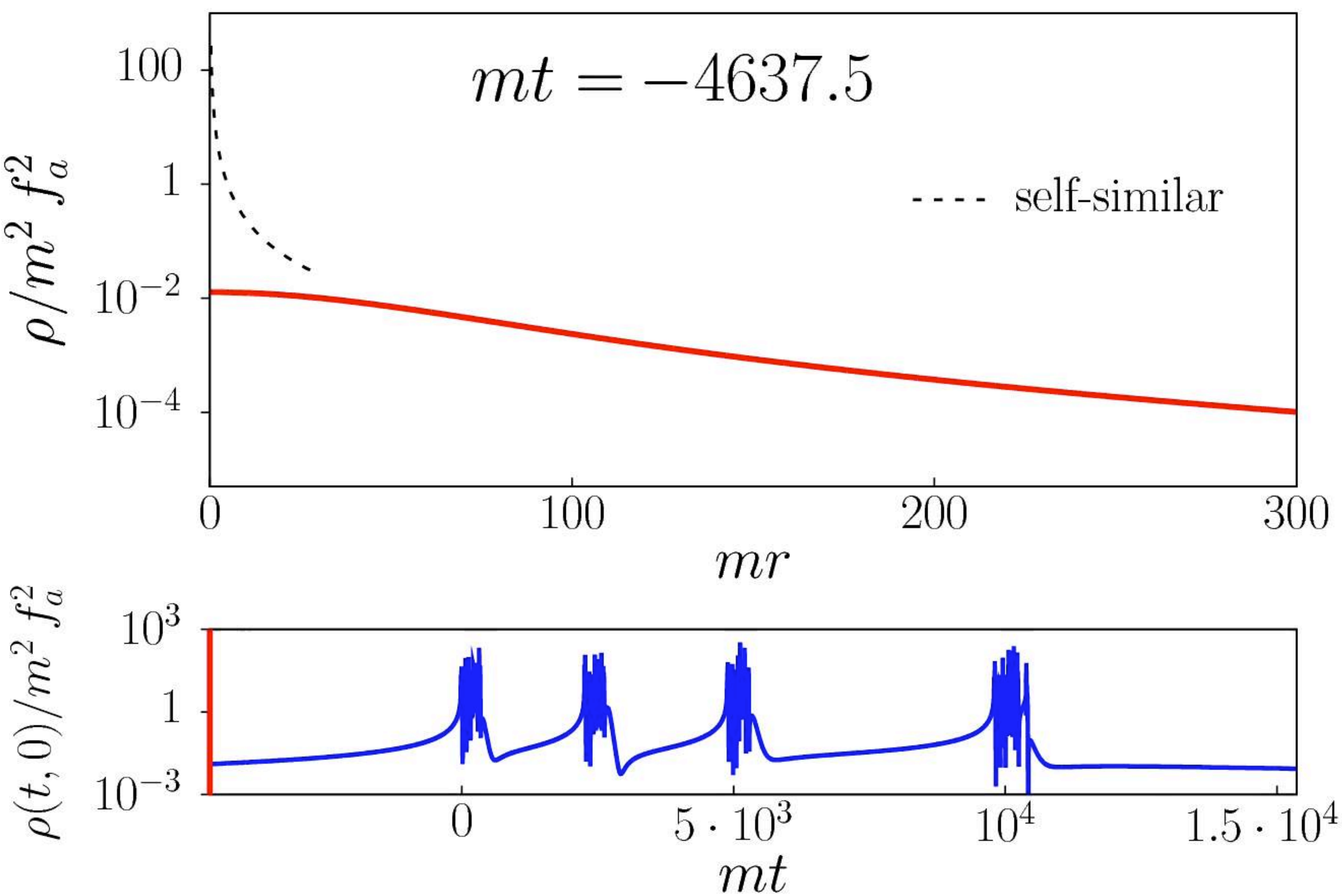
*Braaten 2015 vs Visinelli 2017*

# Collapse of a dilute axion star

*Tkachev et al 2016*

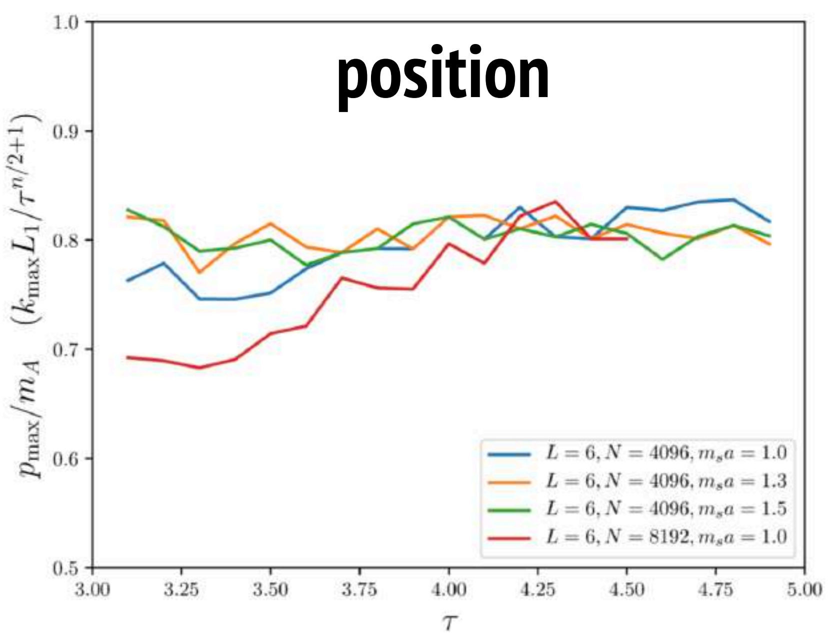


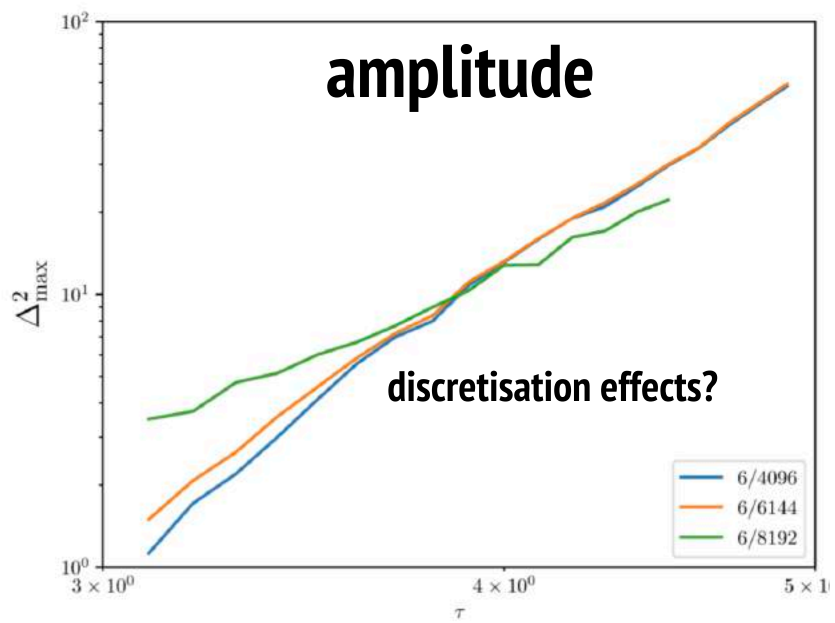

- Initial conditions slightly above critical mass
- Emission of relativistic axions

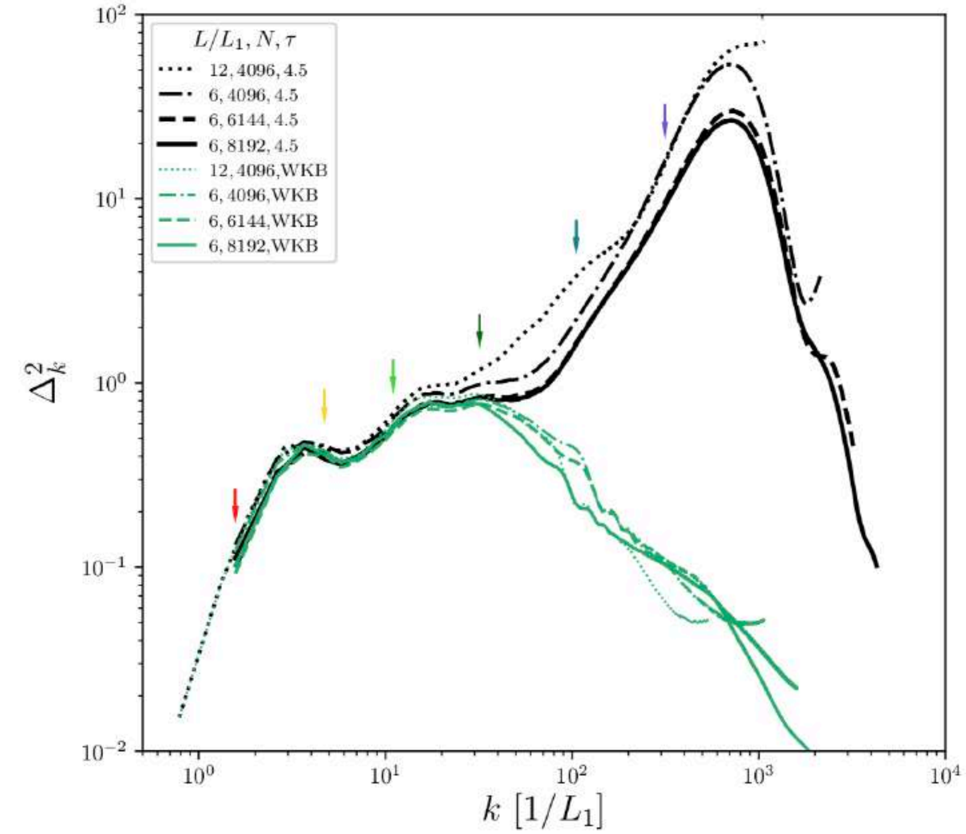


# Axitons in our simulations

## Axiton peak in the power spectrum



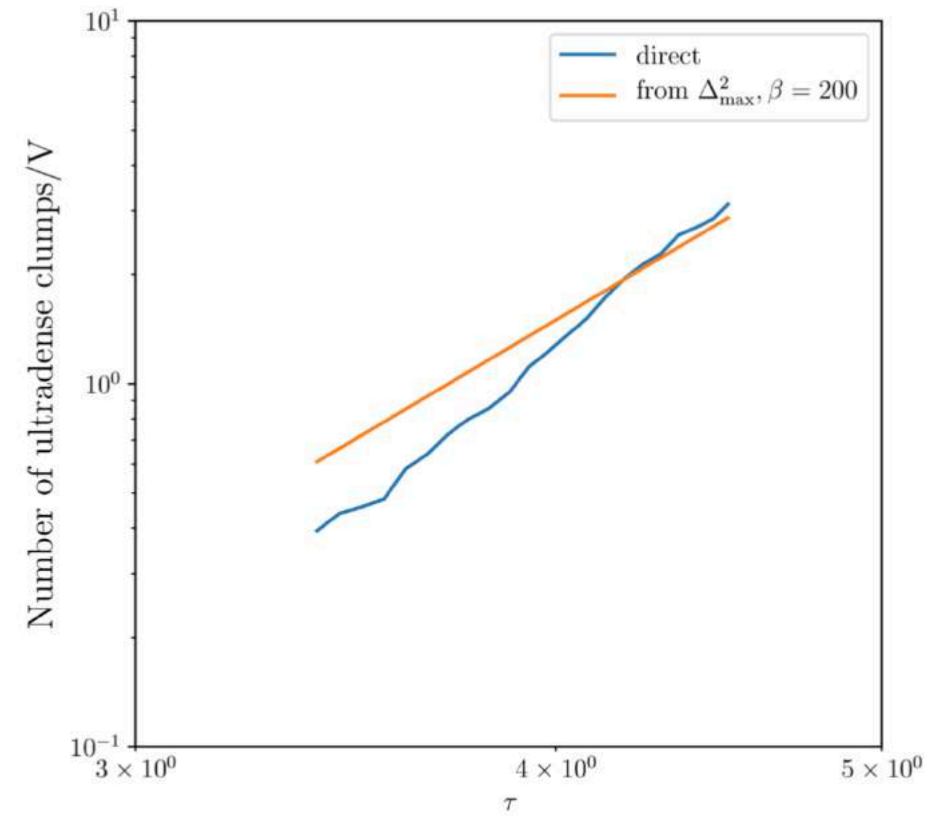




## Number of axitons increases tremendously

- Assuming uncorrelated positions ...

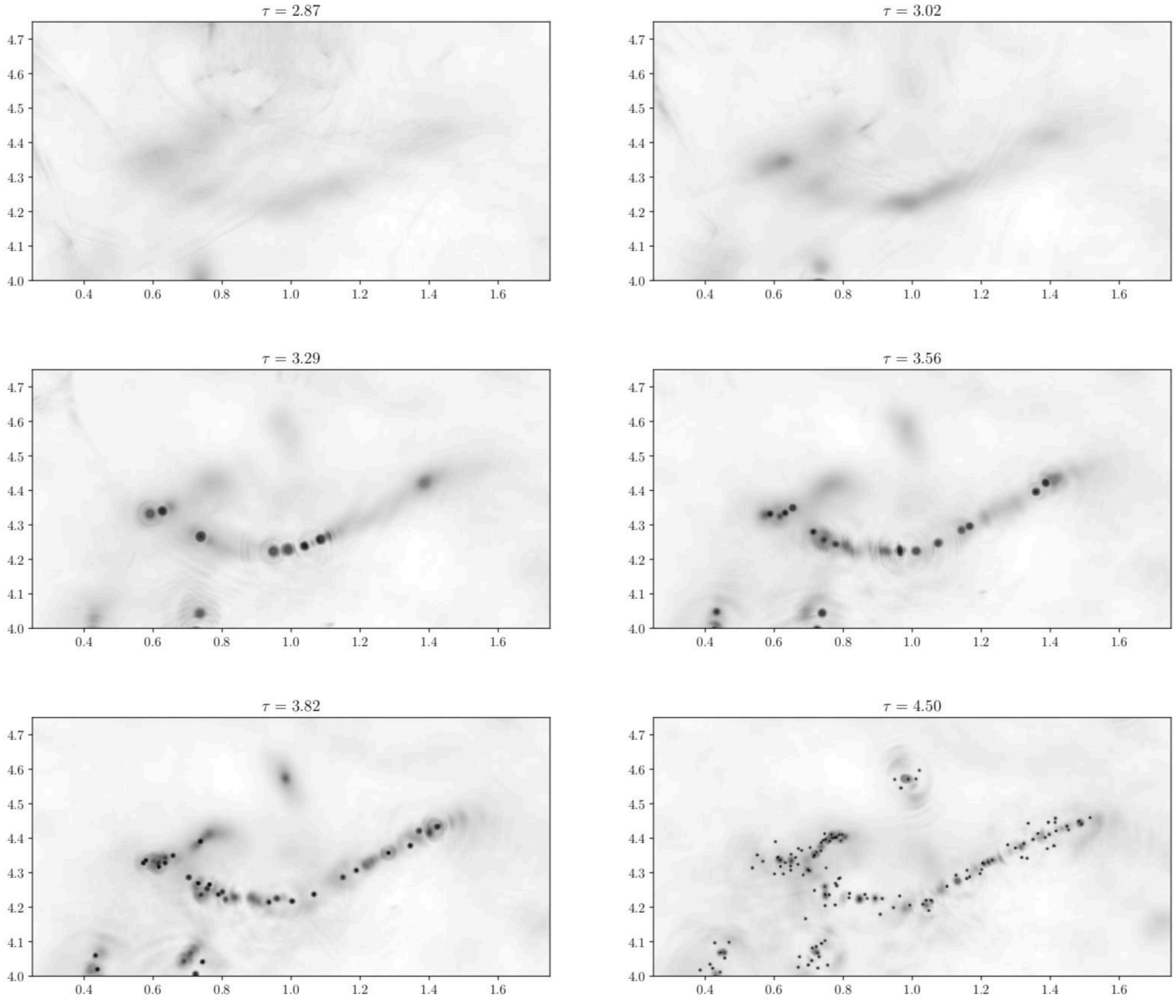
$$\frac{N_\odot}{V} \sim 2\pi^2 \Delta_\odot^2 \frac{125 m_A^4}{k_\odot^3} \frac{1}{H_1 L_1^3} \sim 2.5 \times 10^3 \Delta_\odot^2 \tau^{n/2-3} \frac{1}{L_1^3} .$$

- Direct measurement



# Axitons are family people

**Highly correlated, they appear in regions of large theta ... close to the last domain-walls collapsed?**



# Axitons under control?

**Axitons convert NR axions into relativistic axions >**

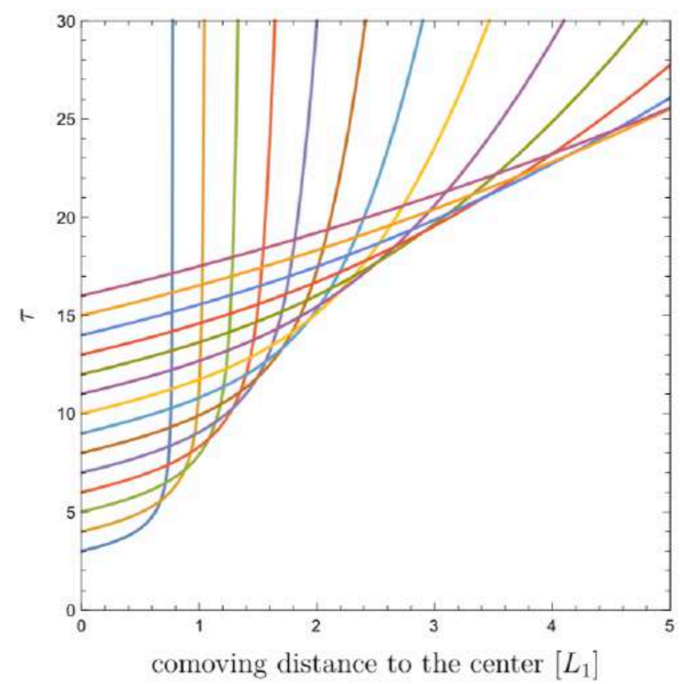
**As time evolves, radius ~ 1/m_A decreases (Volume and power too) and emitted energy >> H**

$$\frac{dN_e}{dt_e} \sim \frac{V_{\circledcirc}\varrho_{\circledcirc}\Gamma_{\circledcirc}}{\omega_k} \sim \frac{m_A^{-3}(m_A^2 f_A^2) m_A \beta}{m_A},$$

$$\frac{dN_e}{d\tau_e} \sim \frac{f_A^2 \beta}{H_1^2} \frac{\tau_e}{\tau_e^{n/2}} \propto \tau_e^{1-n/2},$$

**First emitted axions are most important**

**(are more abundant and free-stream less)**



# More on axion stars and axitons ...

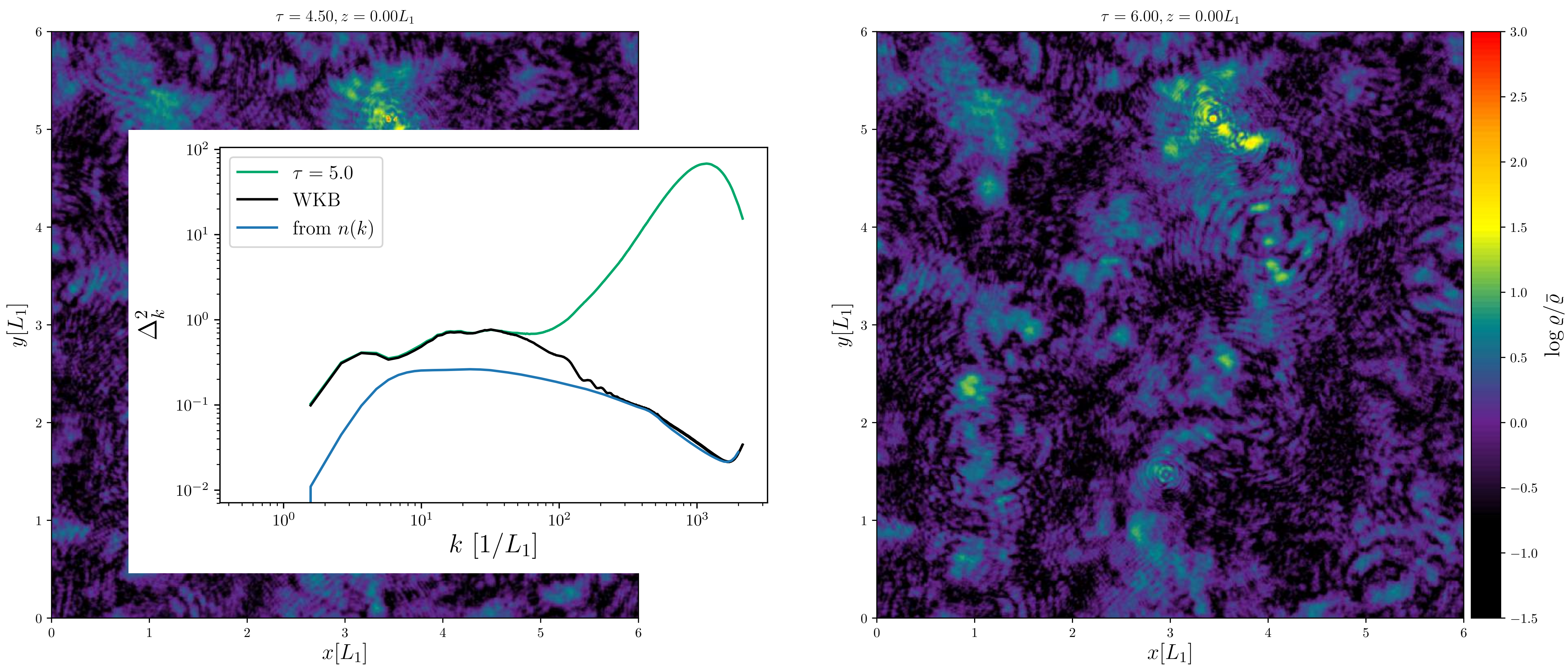
- **Huge overdensities at small scales -> largely diffuse away** *Vaquero, Stadler, JR 2018* **but some remnants...**
- **New studies to come** *Buschman, Safdi 2018?*

- **Relativistic axions from bose-star collapse** *Tkachev 2016*
- **Formation of bose stars in axion/ALP miniclusters** *Tkachev 2018, Niemeyer 2018*
- **Some astrophysical implications ....**
- **Lasing photons** *Hertzberg 2018*
- **Fast radio bursts** *Iwazaki 14, Raby 16*
- **....**

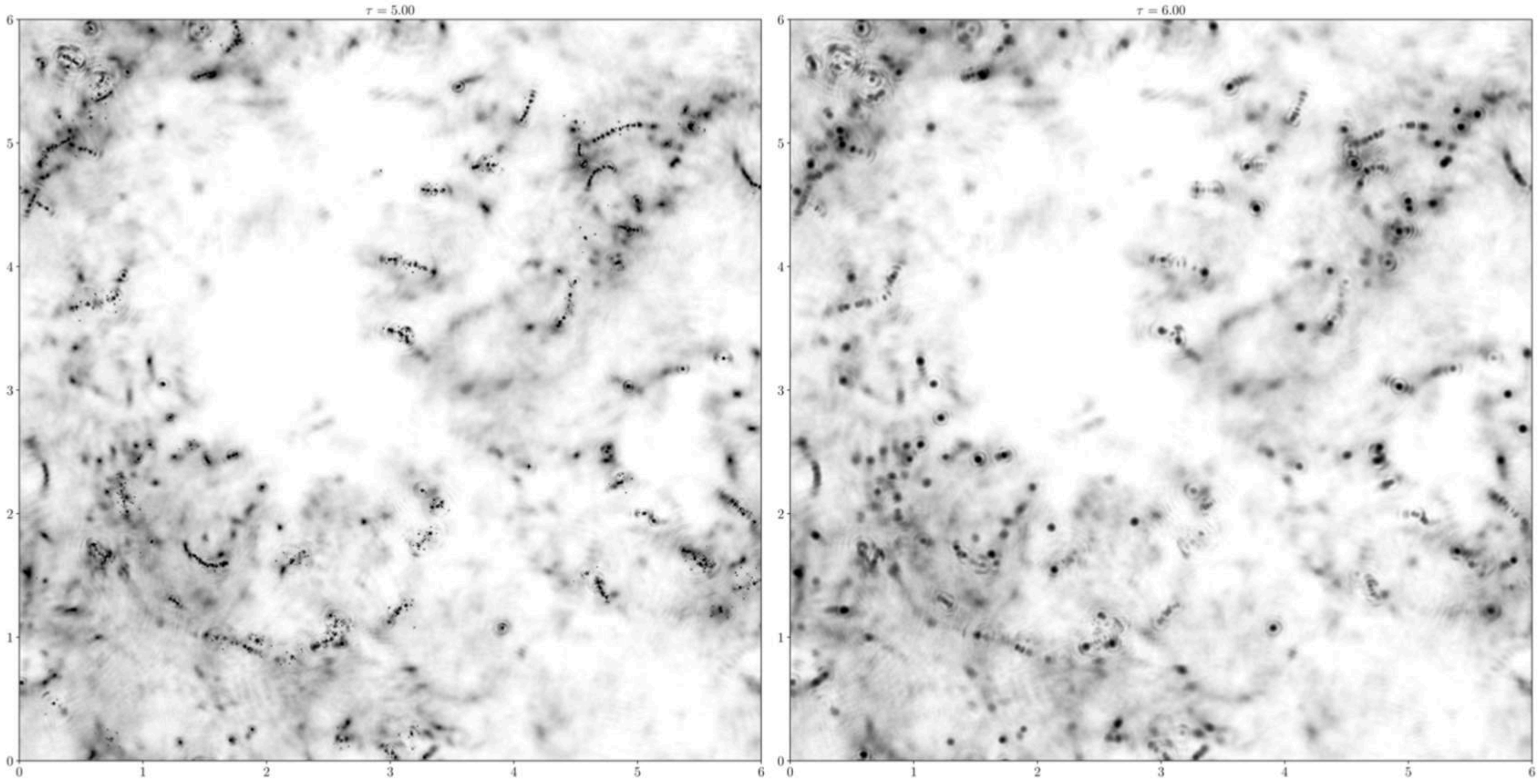
# WKBing the axitons away

- Axitons do not seem to alter large scales much after time ~ 4
- New axitons are small and relatively unimportant (although many could be produced)
- Axiton cores shrink in our simulations and eventually cannot be resolved $R_c \sim 1/m_A$
- Axions in axiton remnants will free-stream a long distance)

>>> we force them to free-stream at the end of our simulations (only impact at very smal scales)

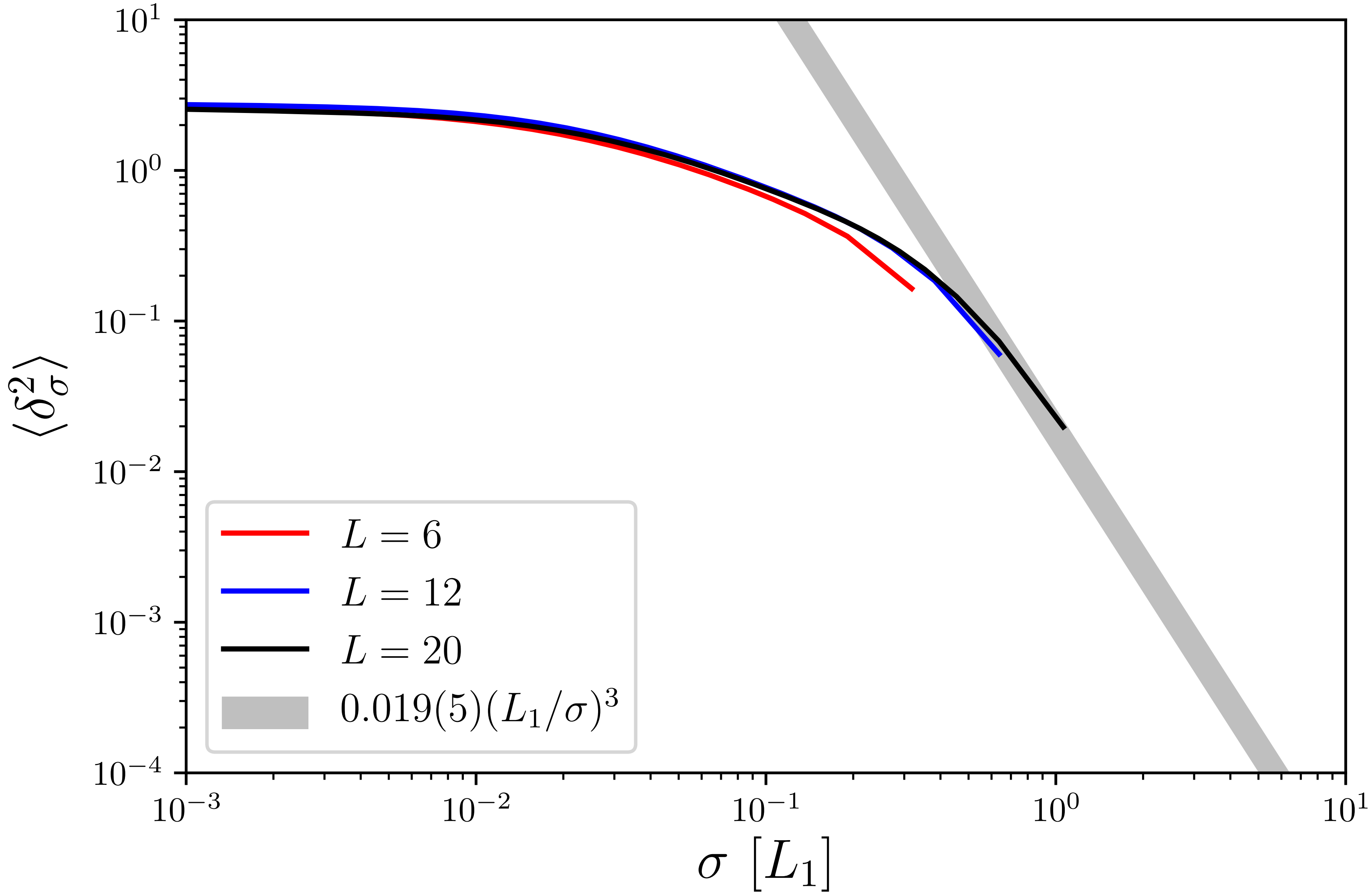


# WKB

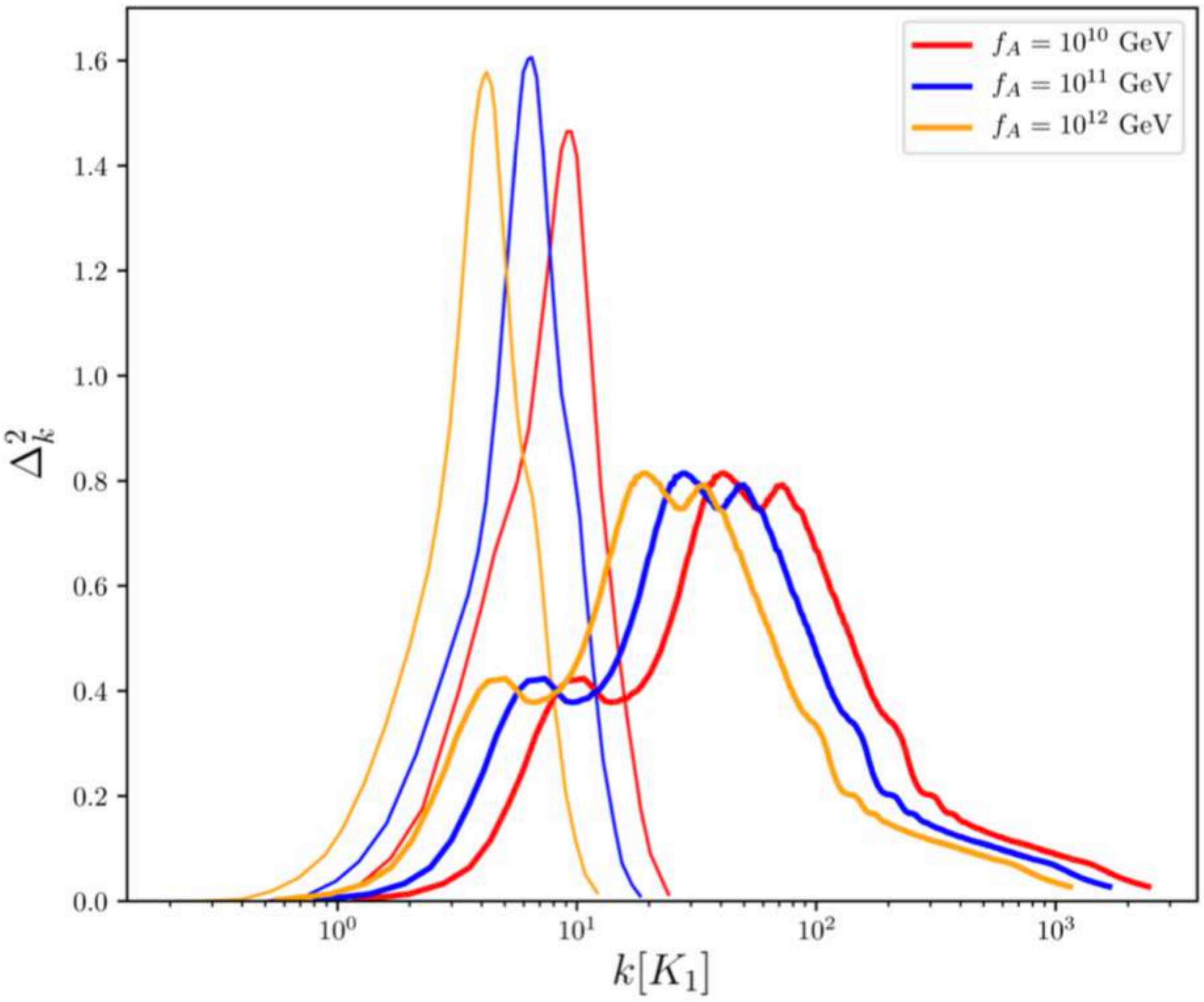


# Typical fluctuation

- Density contrast averaged over a Gaussian window function of a given sigma
- Around sigma~L1, already in the white noise regime, very small "overdensities" at large scales
- Few high-density high-mass miniclusters expected
- Loads of high-density small-radius (small mass) Mcs!



# Comparison to Tkachev-

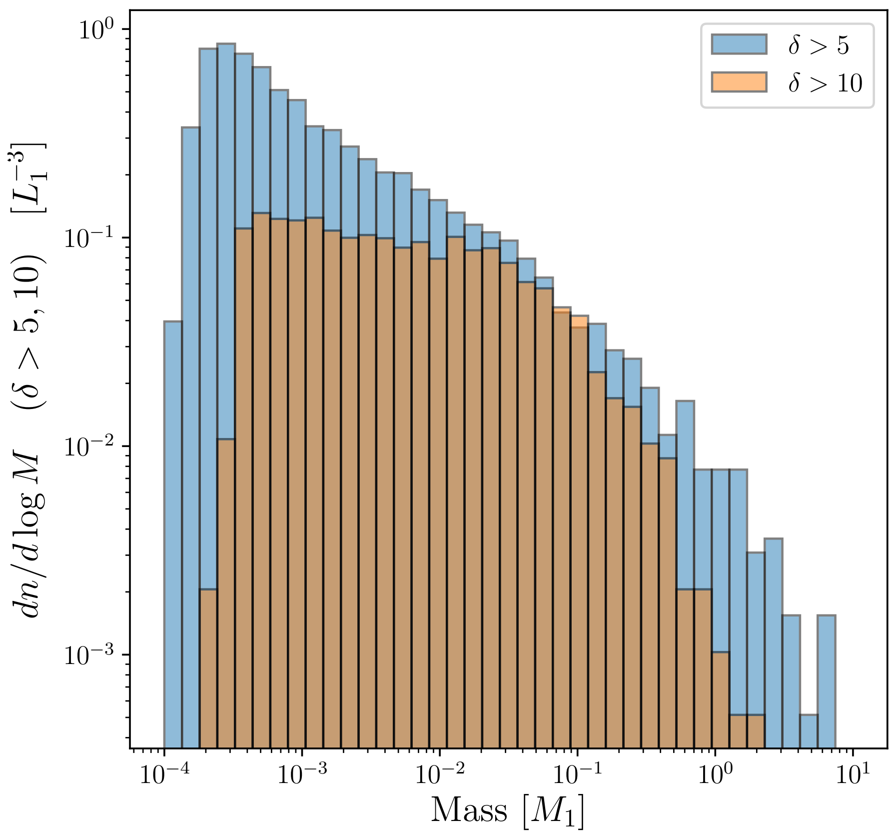


# Distribution of Minicluster seeds

- If we want to talk about mass, we need to specify the amount of DM mass in L1
- It is output by our numerical simulations (function of ma itself)
- Expressed as function of the axion DM fraction, it is

$$M_1 = 2.1 \times 10^{-12} M_\odot \, \frac{\Omega_{Ac} h^2}{0.12} \left( \frac{50\,\mu\mathrm{eV}}{m_a} \right)^{0.49}$$

- Distribution of seeds with all points more dense than 5, or 10



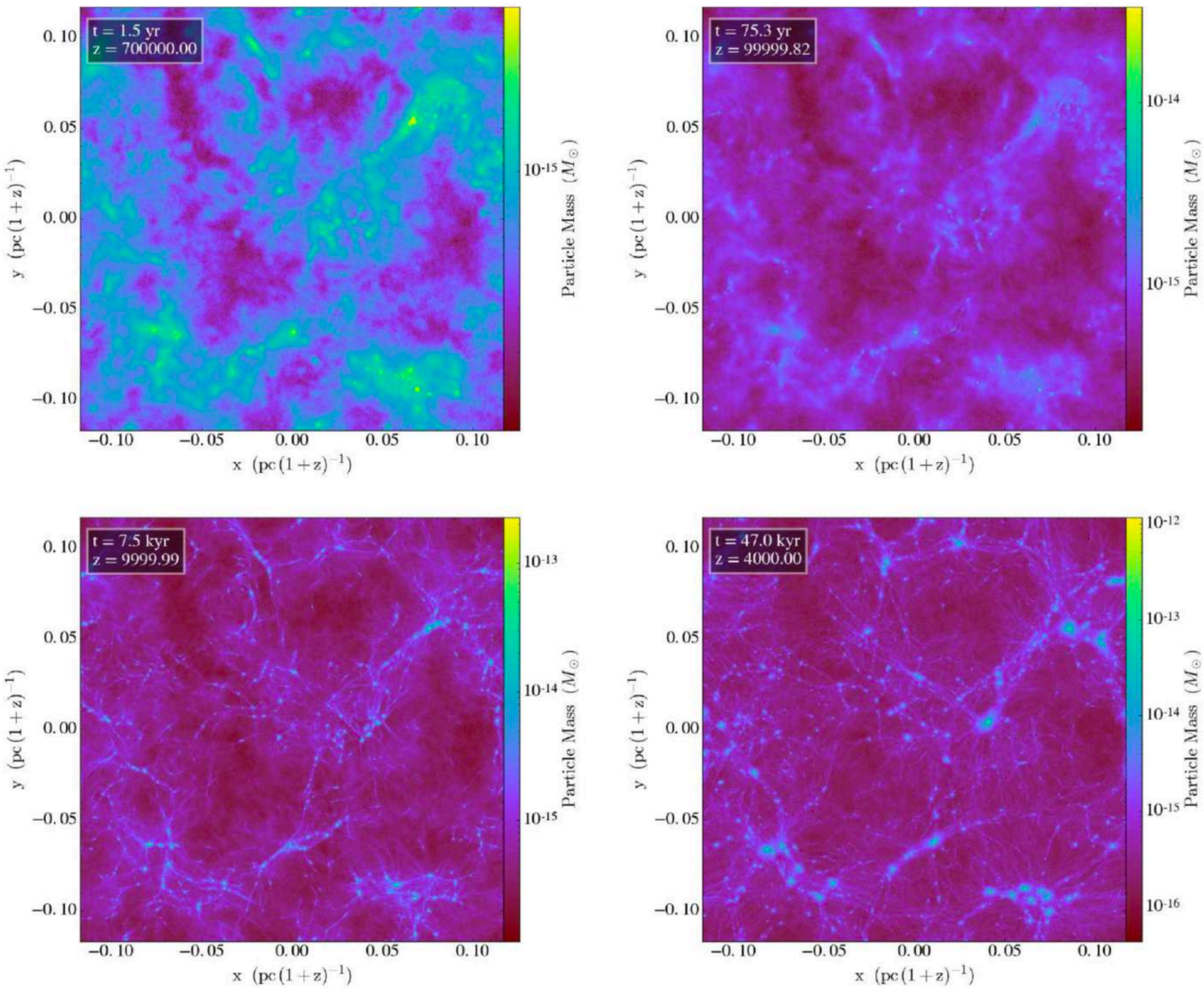

very few dense & large mass seeds

- Halo mass function needs the gravitational evolution

# Minicluster gravitational collapse

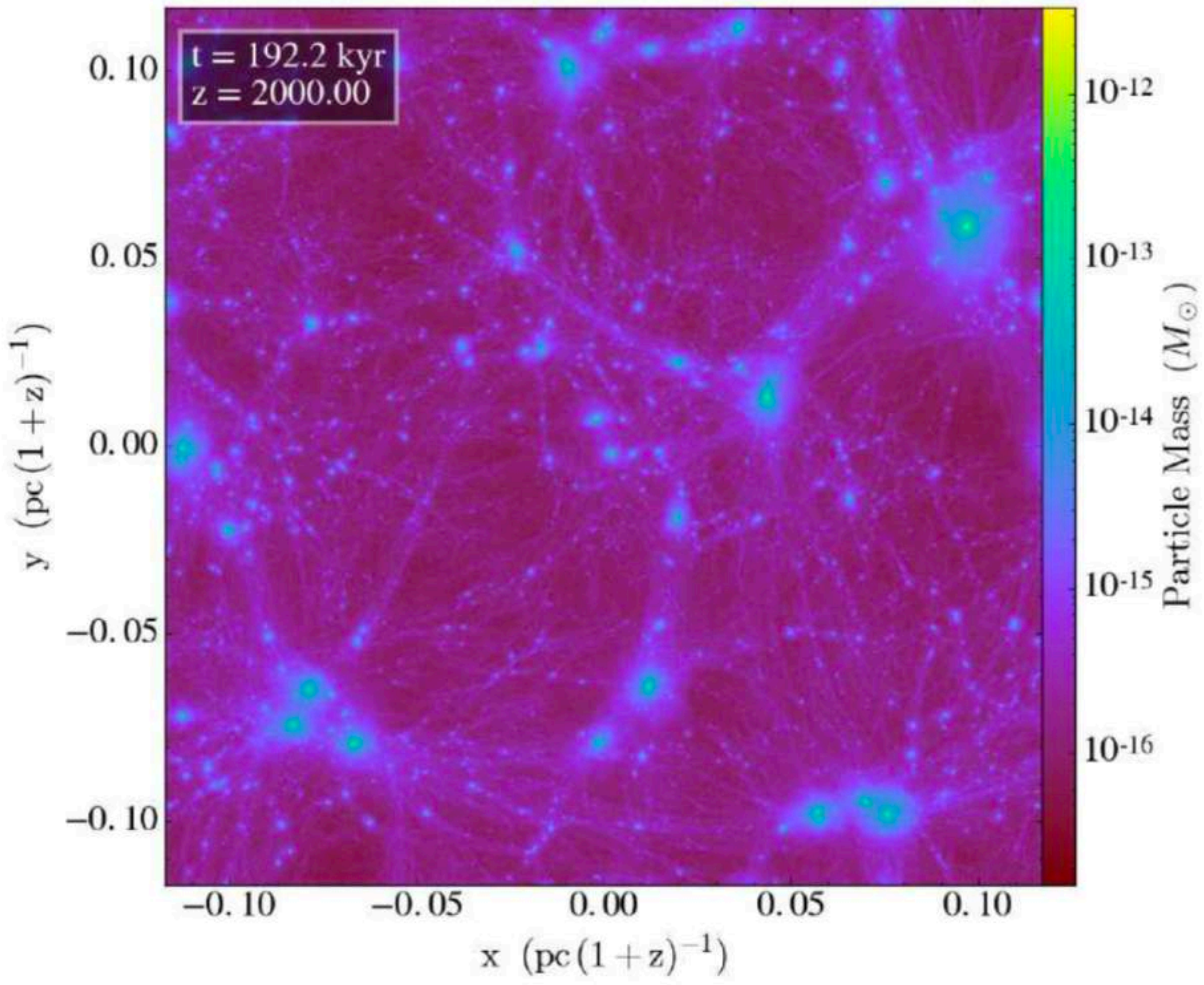
- Gravitational evolution with out final density maps
- deBroglie wavelength so small -> n-Body gravitational solvers (here Enzo)

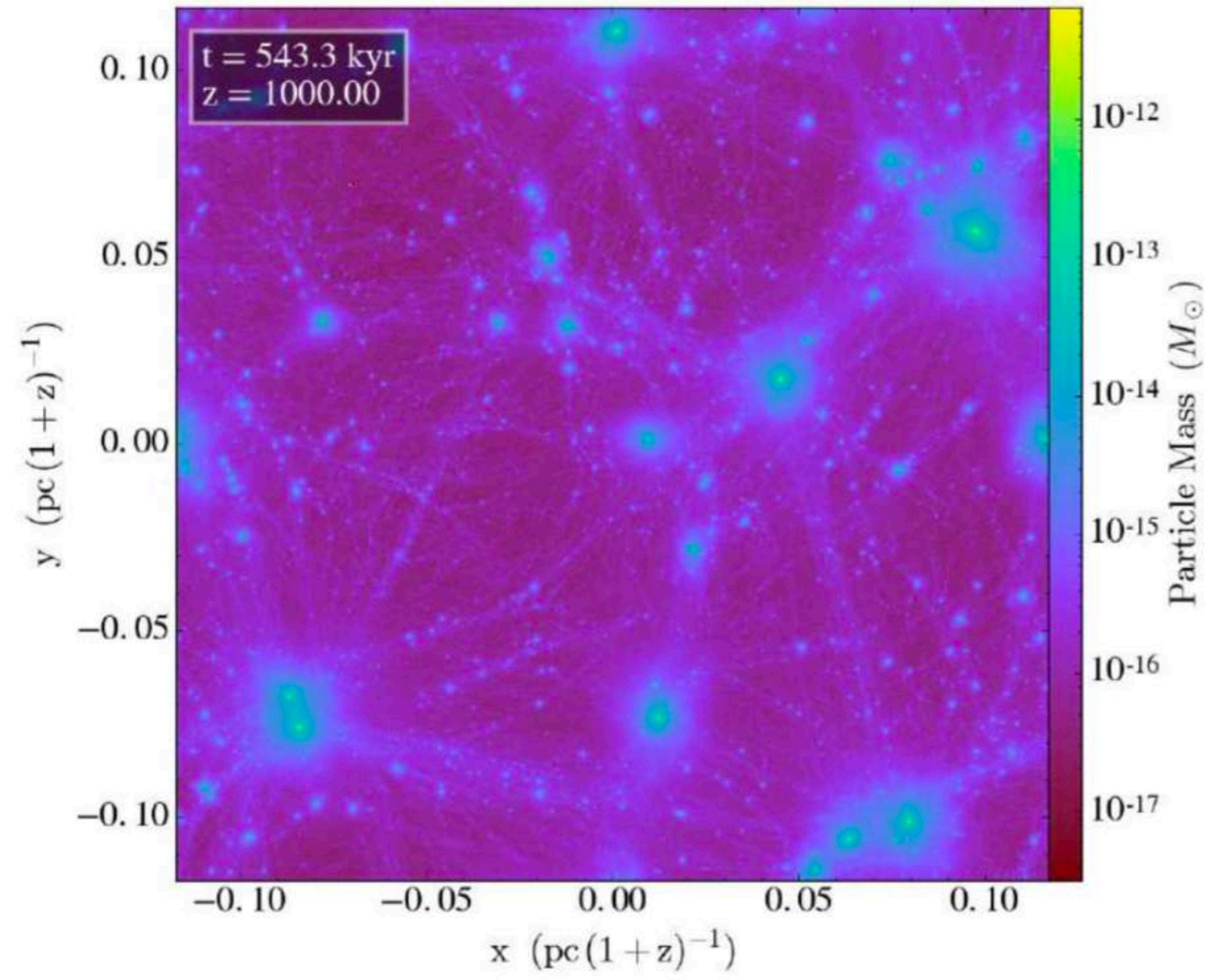
*F. Wiebe, J. Niemeyer, in preparation*



## - Gravitational evolution with out final density maps

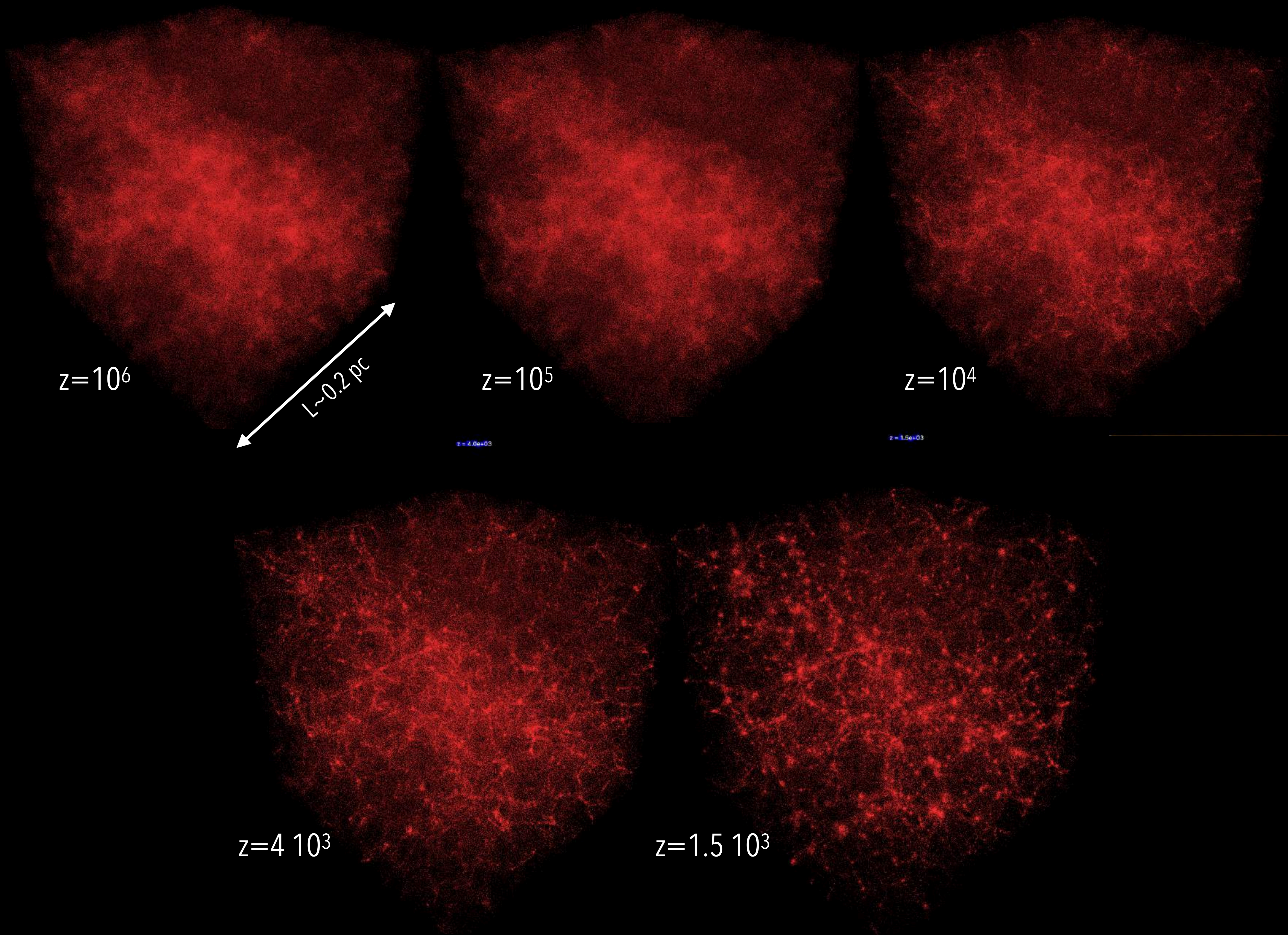
*F. Wiebe, J. Niemeyer, in preparation*



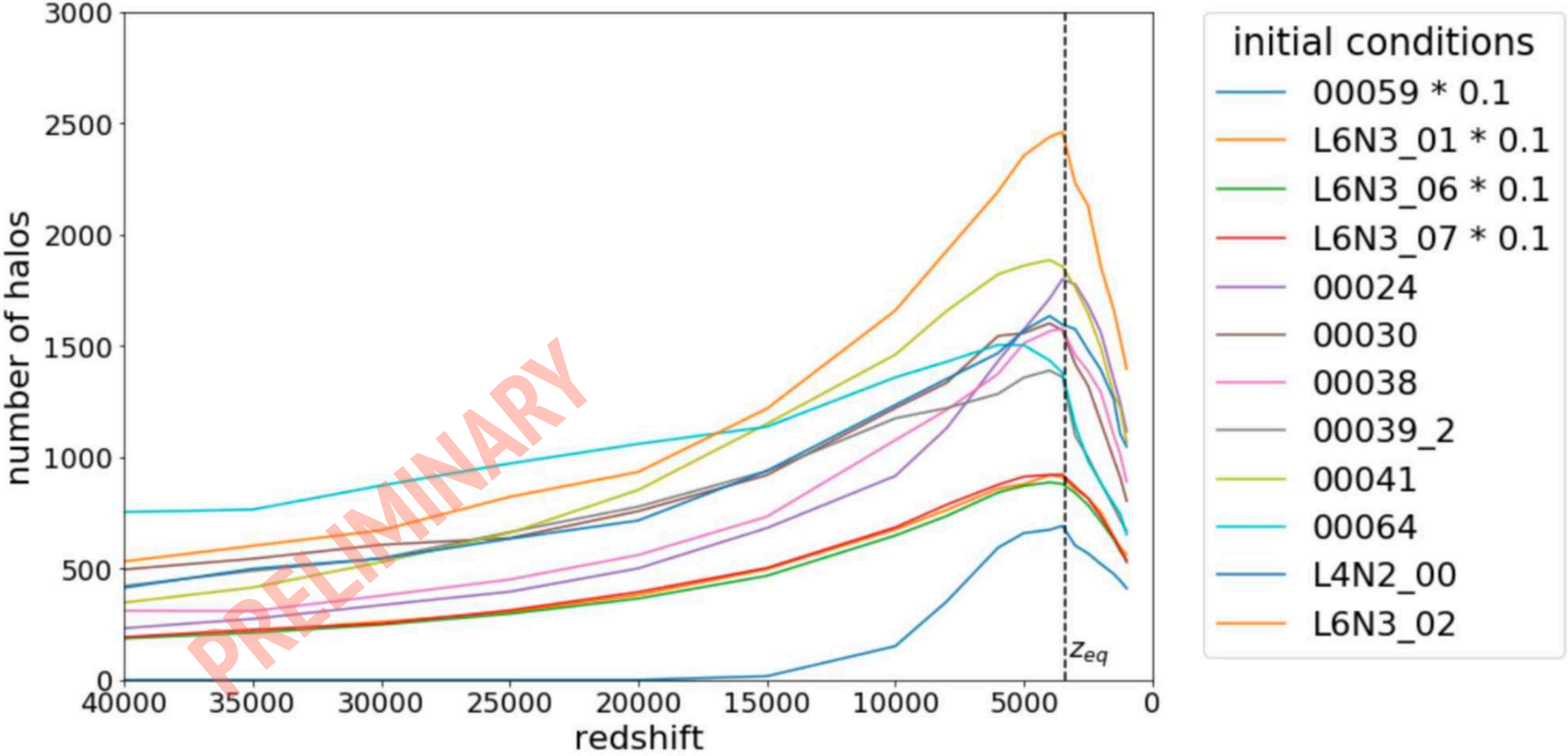



# Using gadget2

- Axion DM inhomogeneous at ~ pc scales -> first structures form at $z \gtrsim z_{\rm eq} \sim 4000$

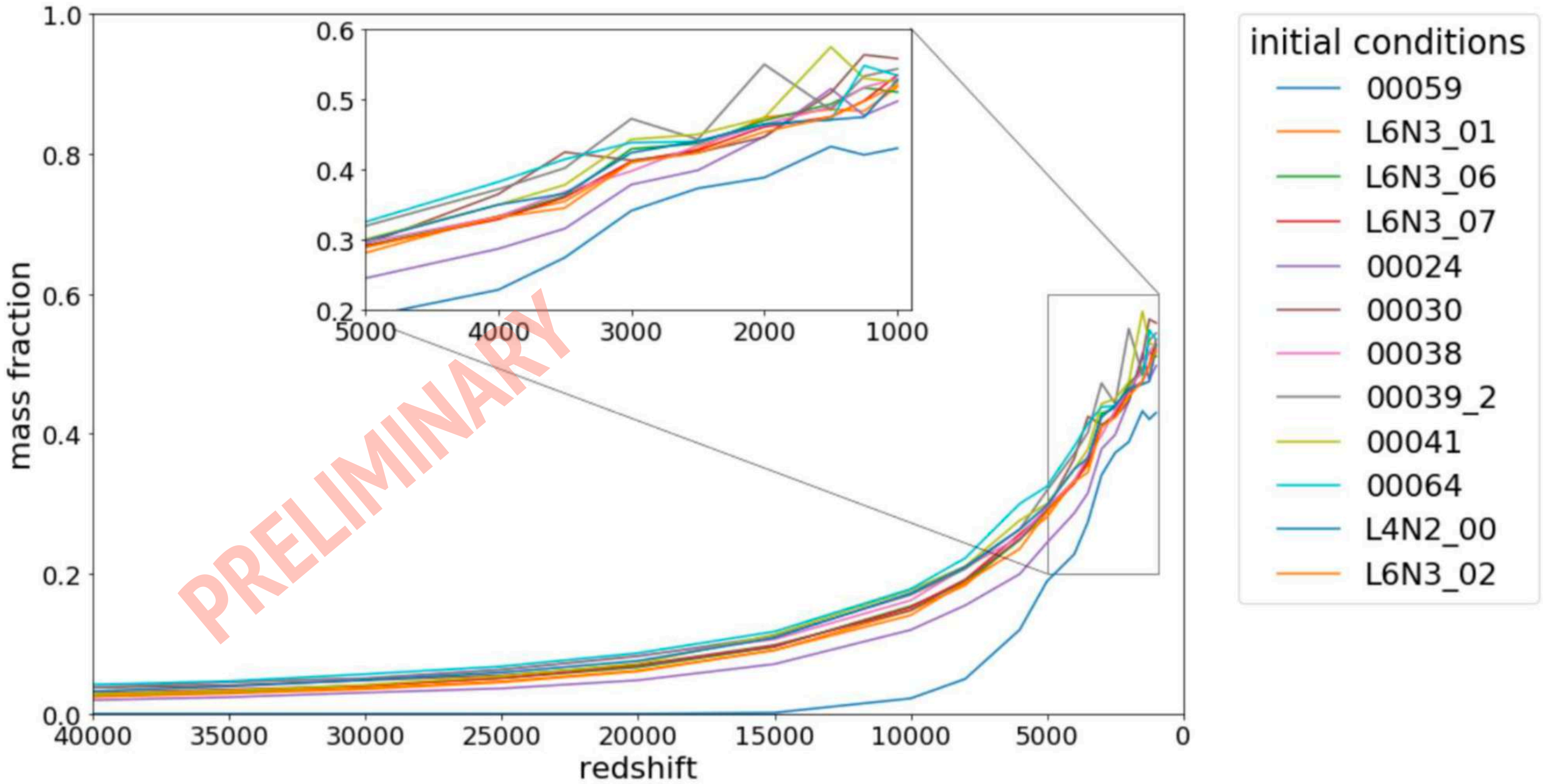


# number of halos

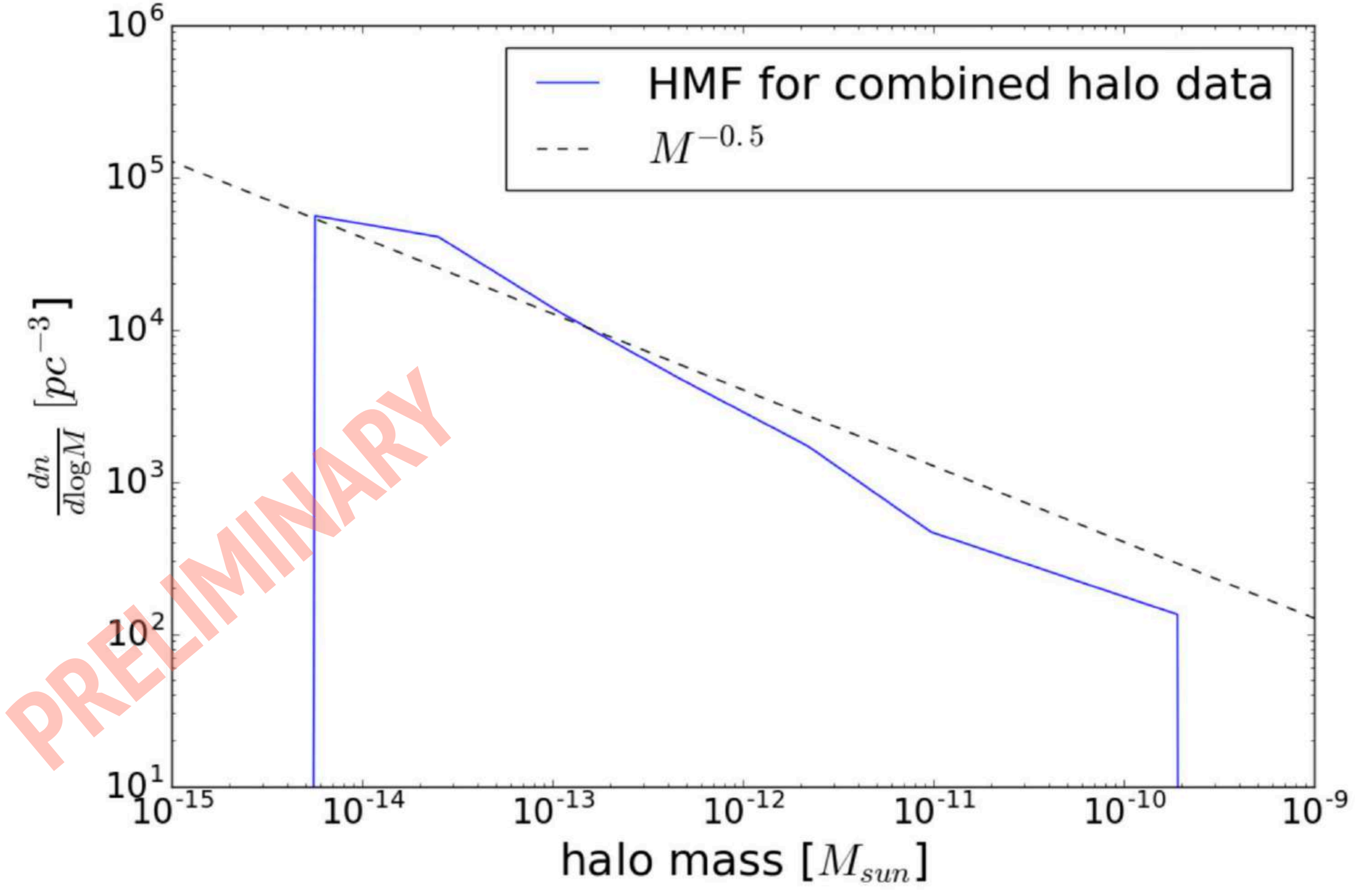


# mass in MC's

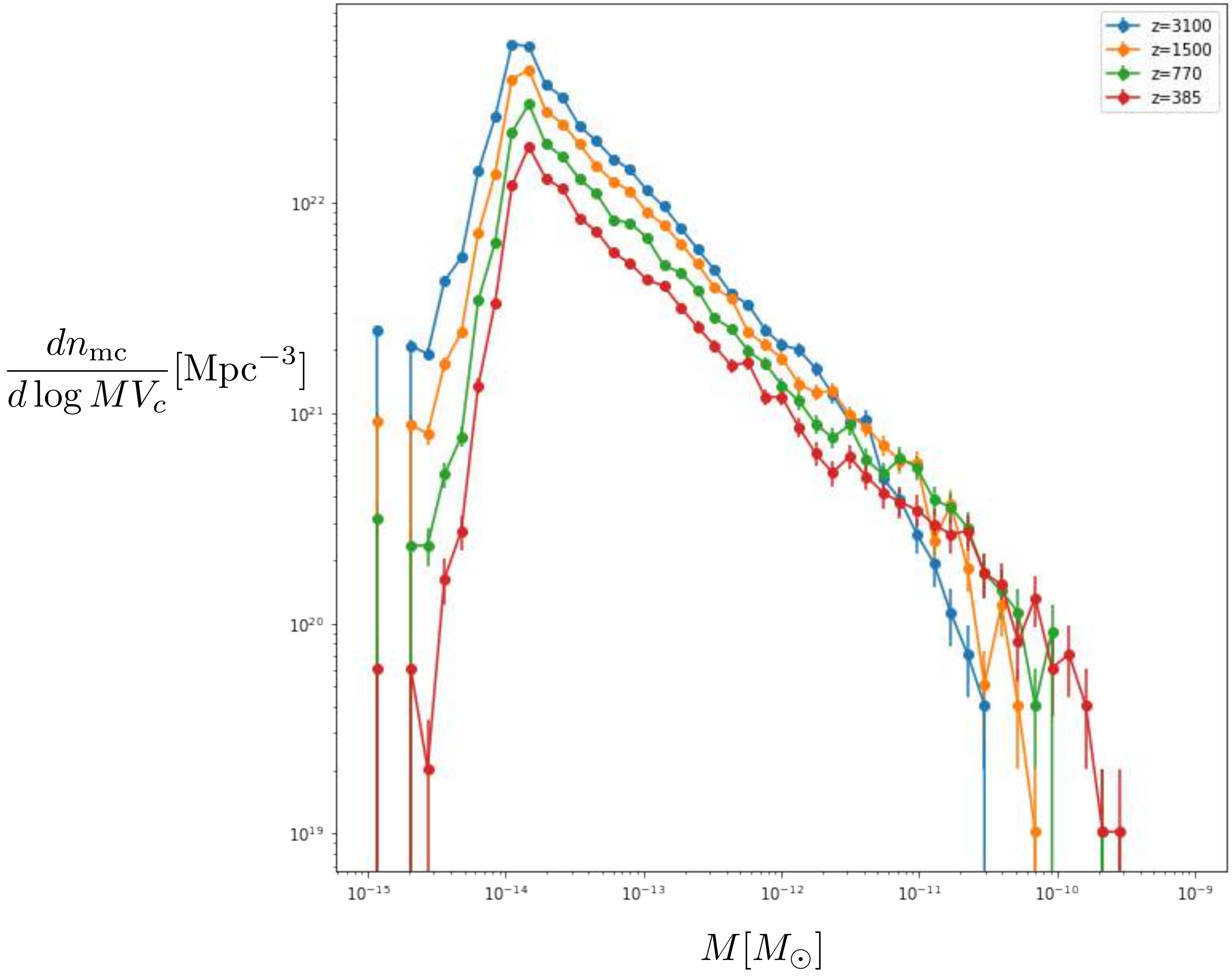
- how much mass lies in DM halos? is there some for us to detect on earth?



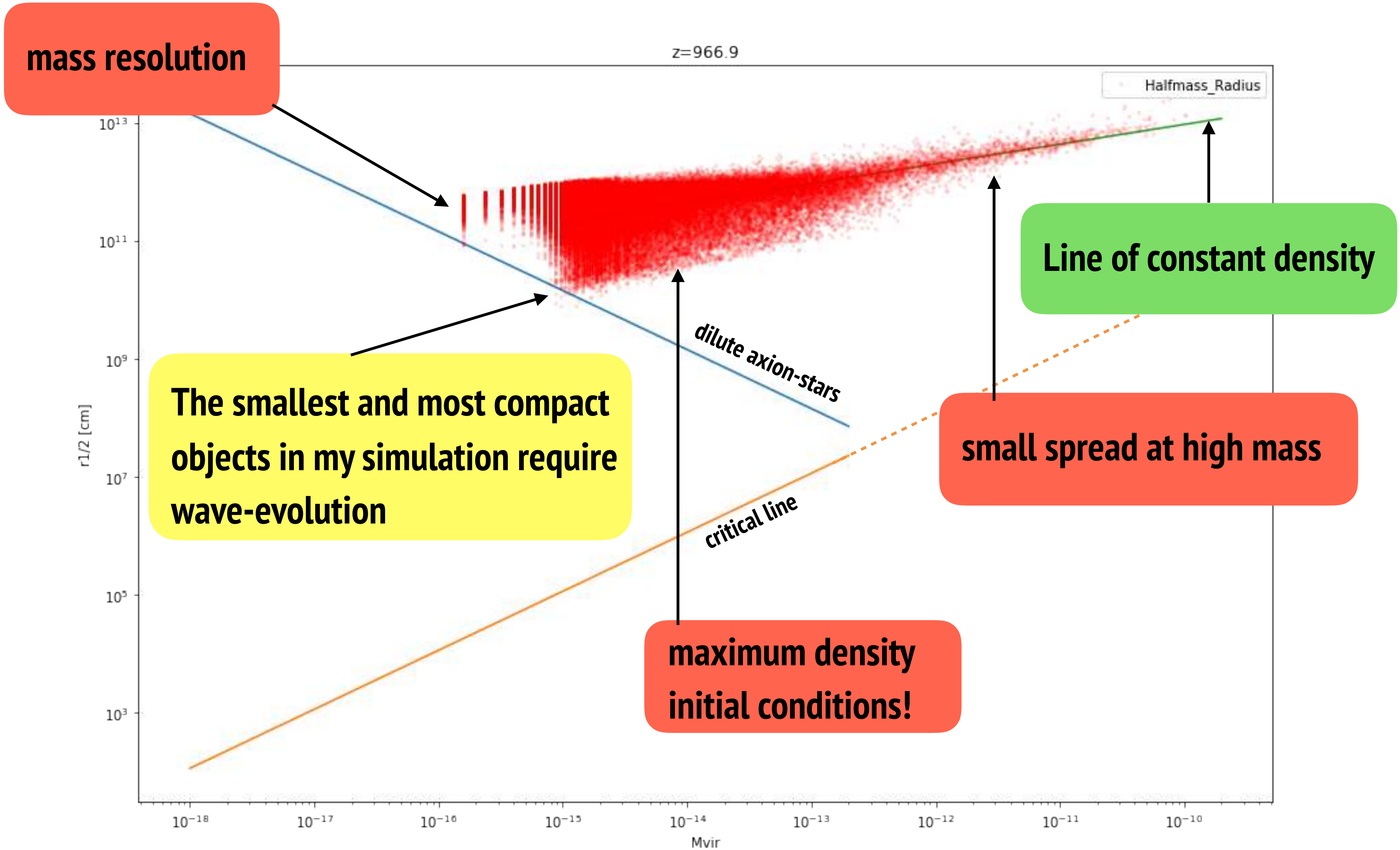
# halo mass function



# halo mass function (Gadget)



# In the context of axion-stars



# Conclusions and more

- New simulations of the axion dark matter field
- Study of the evolution of density perturbations at extremely small scales > non-trivial
- Role of axitons at high-k unhappily avoided > ultradense clumps?*

- Final density at large scales seems little affected by uncertainties (the ones we can simulate!)
- First estimates of minicluster mass and distribution with "correct" initial conditions!

- Study of minicluster seeds > many small seeds, large seeds are not very dense

- Gravitational evolution (N-body) with Enzo and Gadget
- Confirms estimates of typical minicluster mass
- O(1) DM mass unbound
- HMF steeper than $1/M^{0.5}$
- Many low mass miniclusters not previously considered (dominate number, but not mass)
- Smallest and densest clusters (presumably cores of large MCs) require wave-evolution

PRELIMINARY