Simulation of Axion Minihalos

Ongoing project with Matthew McQuinn.

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Axion Miniclusters

In the post-inflationary scenario, large density perturbations are present at the scale of horizon size when the axion became nonrelativistic. Considering **QCD axion**, the comoving horizon size at that time is:

$$L_1 = \frac{1}{a_1 H_1} = 0.0362 \left(\frac{50\mu\mathrm{eV}}{m_a} \right)^{0.167} \mathrm{pc}$$

Axion perturbations lead to the formation of small structures at matter-radiation equality, which are called axion miniclusters.

Natural Questions from Axion Miniclusters

- Are these structures detectable?
- How do they evolve with time?
- Are there still axion particles that remain unbound? (This will be important for the Axion Dark Matter eXperiment)

New Ideas of Detecting Small Structures

- Microlensing (Only sensitive to highly concentrated objects)
- Pulsar timing arrays
- Lensing in Highly Magnified Stars

Now that we have more techniques to detect such small objects, it is crucial to determine the evolution of axion substructures using N-body simulation.

Simulation Setup

QCD axions have different theta values at different horizon patches, resulting white-noise power spectrum:

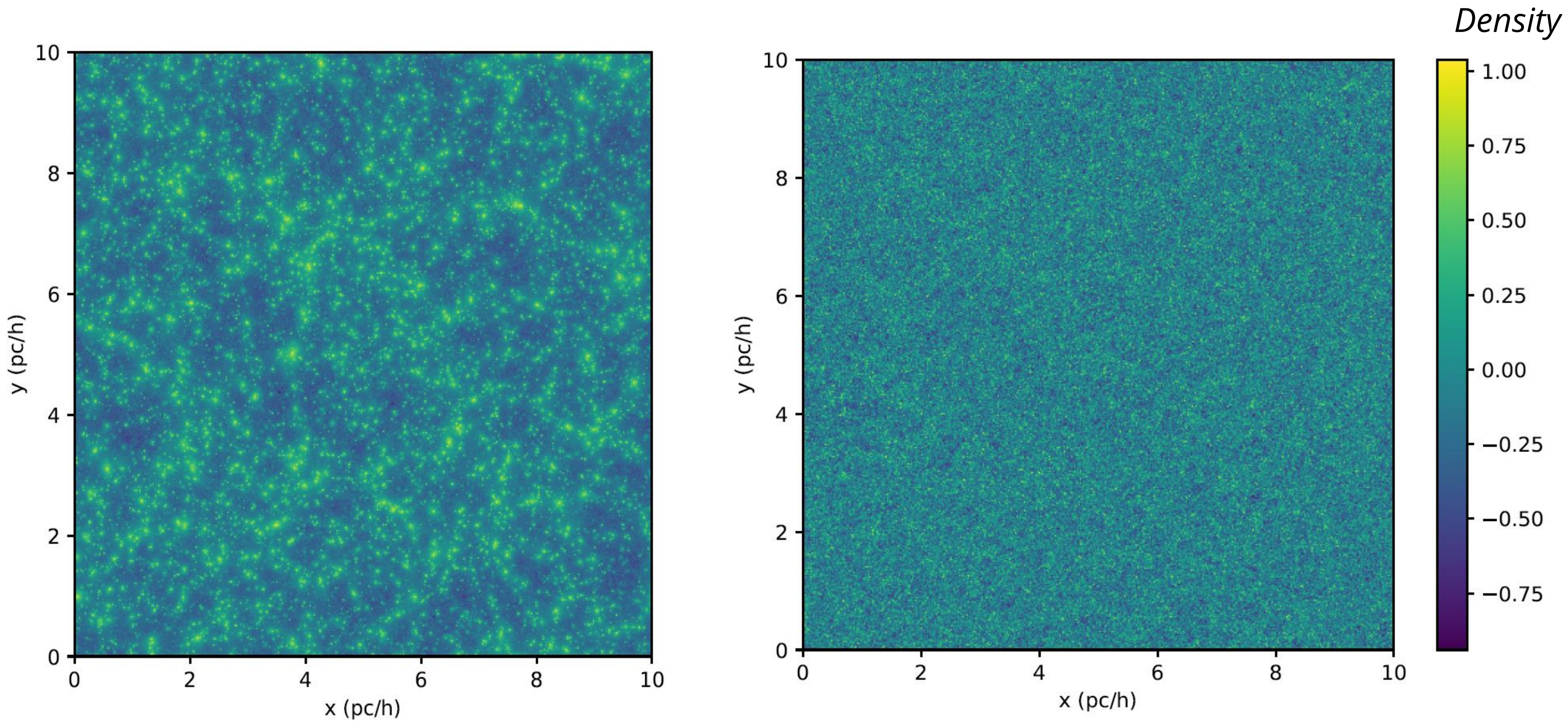
$$\Delta^2_{\mathcal{S}}(k) \equiv \frac{k^3}{2\pi^2} P_{\mathcal{S}}(k) = A_{\rm osc}\left(\frac{k}{k_{\rm osc}}\right)^3 \quad \text{at } k < k_{\rm osc}\,,$$

where $k_{\rm osc} = 1/L_1$ is the momentum cutoff.

$$L_1 = \frac{1}{a_1 H_1} = 0.0362\left(\frac{50\mu\text{eV}}{m_a}\right)^{0.167} \text{pc}$$

simulation box size: 50 pc/h, $A_{\rm osc} = 0.1$, $k_{\rm osc} = 19.83\text{pc}^{-1}$

Particle numbers: 1024^3

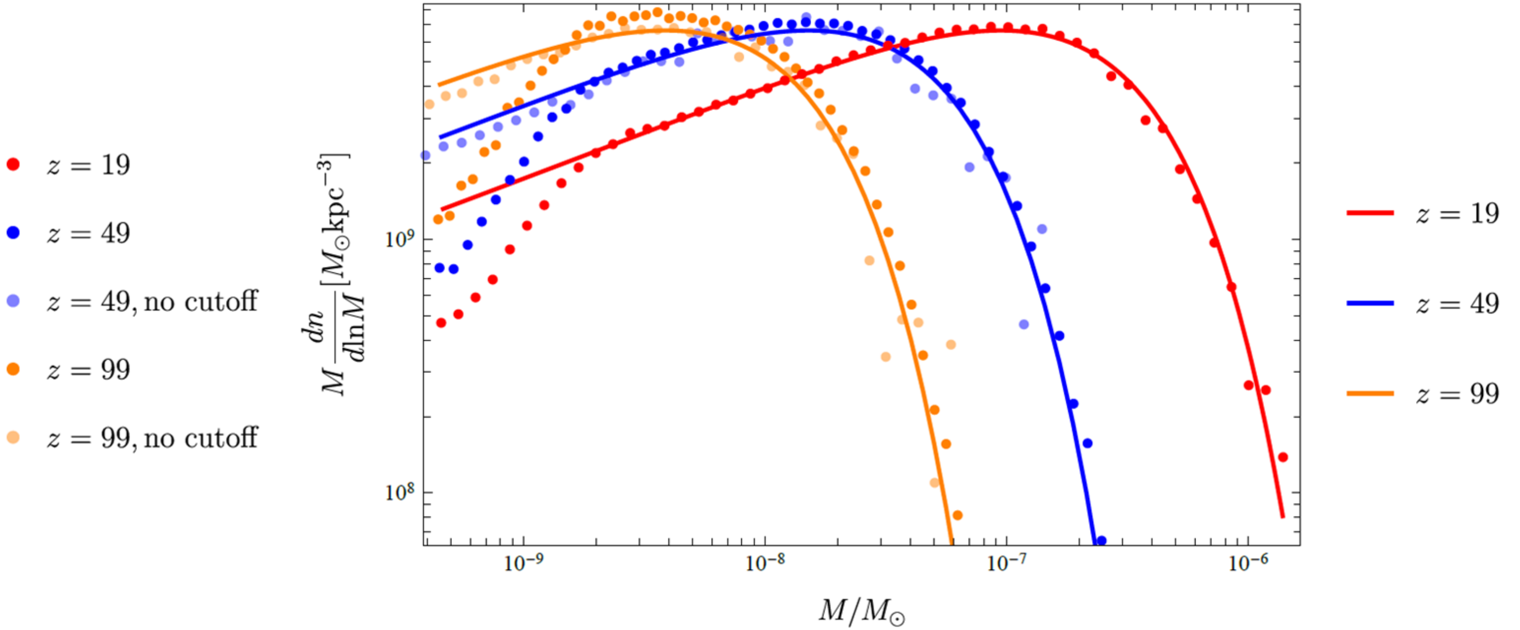


z=24

z=99

Visualization of the structures in our simulation box. This is a selection box with size 10pc/h. As we can see, halos are getting bigger over time.

Mass function of Axion Minihalos



Mass function from our simulation data. We are also using an analytic formula to fit it at different redshifts. Less opacity data points are from simulation without a cutoff in power spectrum.

An Analytic Fit

Sheth-Tormen mass function:

$$\frac{m^2 dn/dm}{\bar{\rho}} \frac{dm}{m} = \nu f(\nu) \frac{d\nu}{\nu}$$

$$\nu f(\nu) = A(p)\left(1 + (q\nu)^{-p}\right)\left(\frac{q\nu}{2\pi}\right)^{1/2} \exp(q\nu/2),$$

$$\nu \equiv \frac{\delta_c^2(z)}{\sigma^2(m)}$$

We can fit the mass function from our simulation by tuning parameters A, q, p.

Testing our Formula

We take the power spectrum from another axion simulation (B.Eggemeier et al. arXiv:1911.09417) and compare our analytic prediction to their results.

They stopped their simulation at z=99 and we would like to have results at lower redshifts.

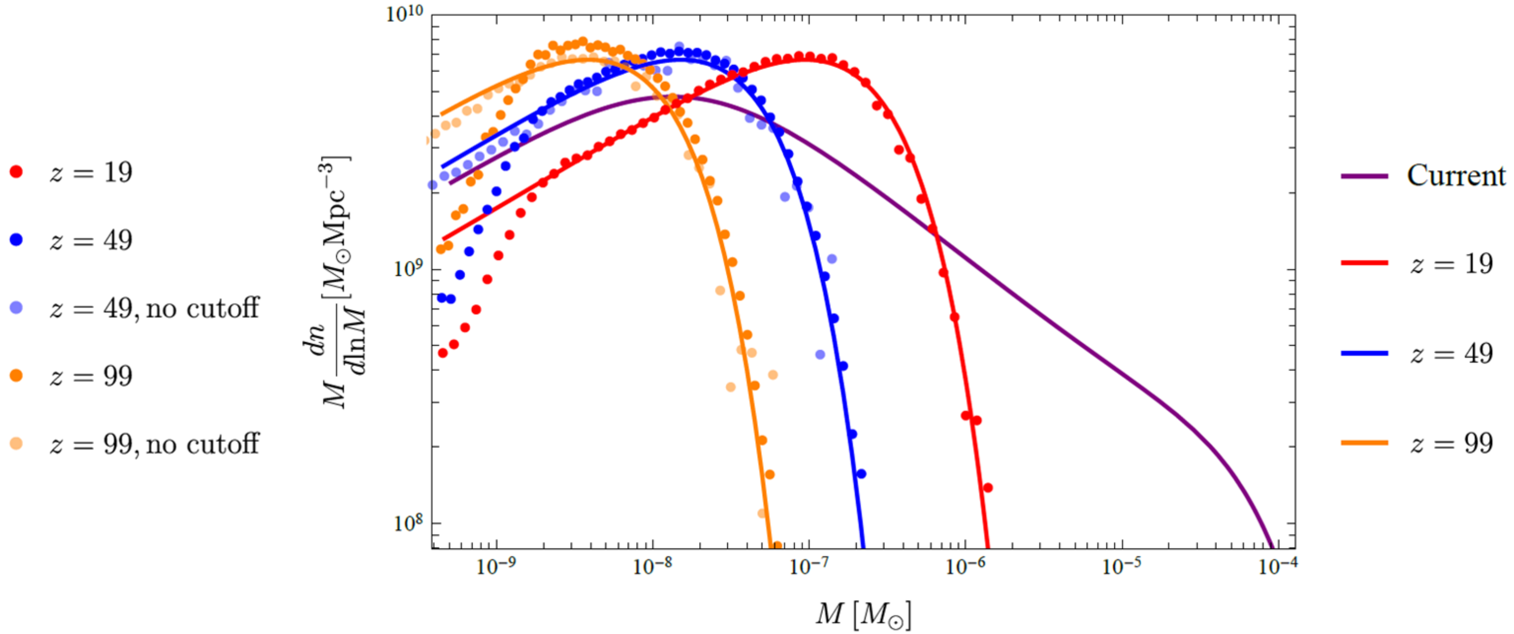
Falling into Large Structures

Our simulation can not tell us about the large scale structure. So the mass function can not be trusted anymore after large structures formed (when z<20). The current mass function can be obtained analytically:

$$\frac{dn_f}{dM} = \int_{z=z_{\rm eq}}^{z=0} dz \frac{df_{\rm col}(z)}{dz} \frac{dn}{dM}(z) + (1 - f_{\rm col}(0)) \frac{dn}{dM}(0)$$

CDM collapse fraction is $f_{\rm col}(z) = {\rm erfc}\left(\frac{\delta_c}{\sqrt{2}\sigma(M_{\rm min})D(z)}\right)$

Mass function of Axion Minihalos



Mass function that can be directly used for observations. We obtained the current mass function of axion minihalos.

Density Profiles of Axion Minihalos

NFW density profile:

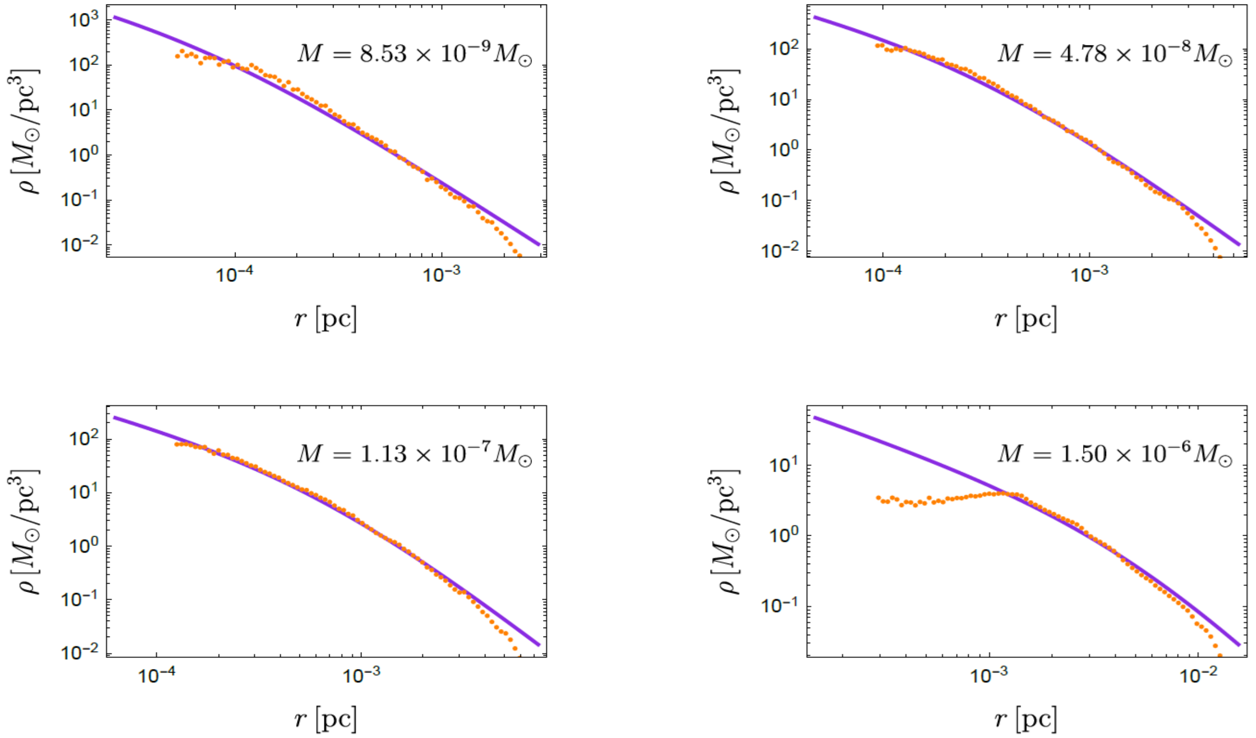
$$\rho(r) = \frac{\rho_s}{r/r_s(1+r/r_s)^2}$$

Concentration number is defined as :

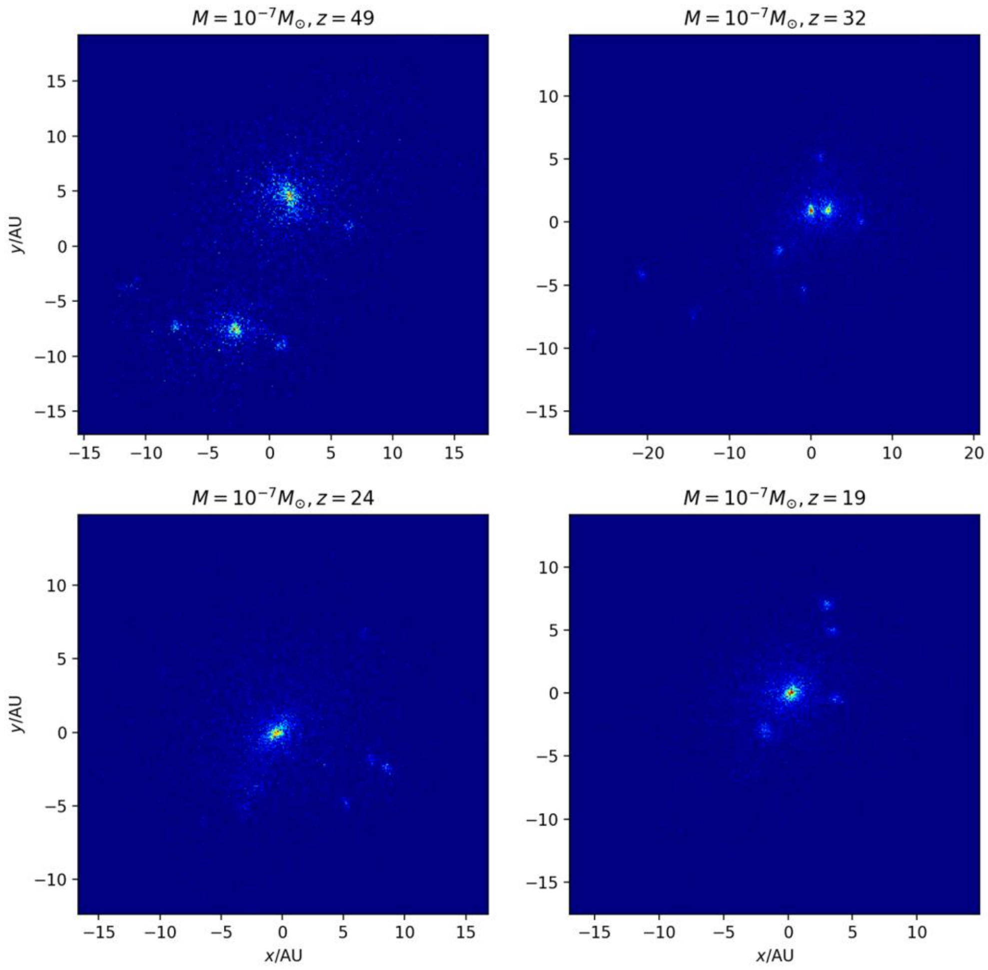
$$c = r_{\rm vir}/r_s$$

The purple curves in plots are the NFW profiles, which tell us the concentration number as a function of halo mass:

$$c = \frac{571}{\sqrt{M/(10^{-8}M_\odot)}}.$$



Visualization of halos at different redshifts. It is more likely to have substructures at higher redshifts for the same mass.



Tentative Results for Observations

Microlensing: In our model, the halos are *not* concentrated enough.

PTA: Future instruments will make axion halos detectable.

Lensing with magnified stars: In the future, it will be detectable.

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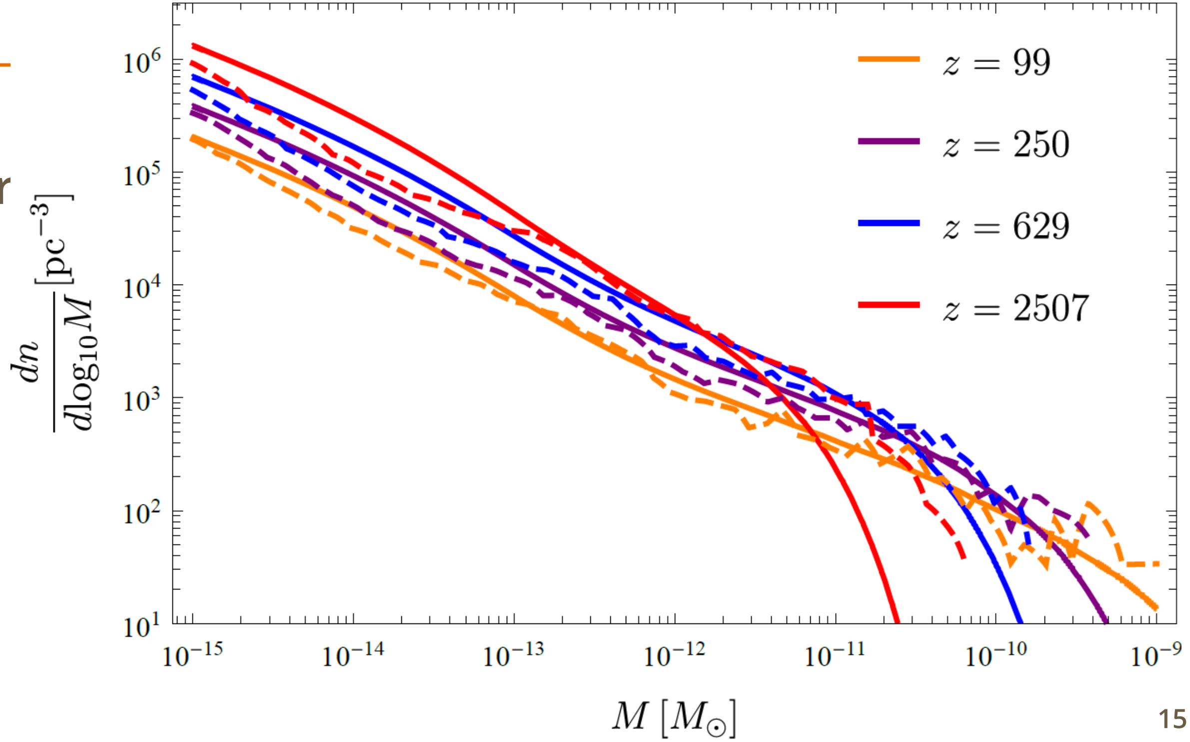

Collapse Fraction of Axion Minihalos

Our simulation is suggesting a collapse fraction of ~75% at z=19.