UNIVERSIDAD DE GUANAJUATO

STRUCTURE FORMATION WITH A SCALAR FIELD DARK MATTER MODEL

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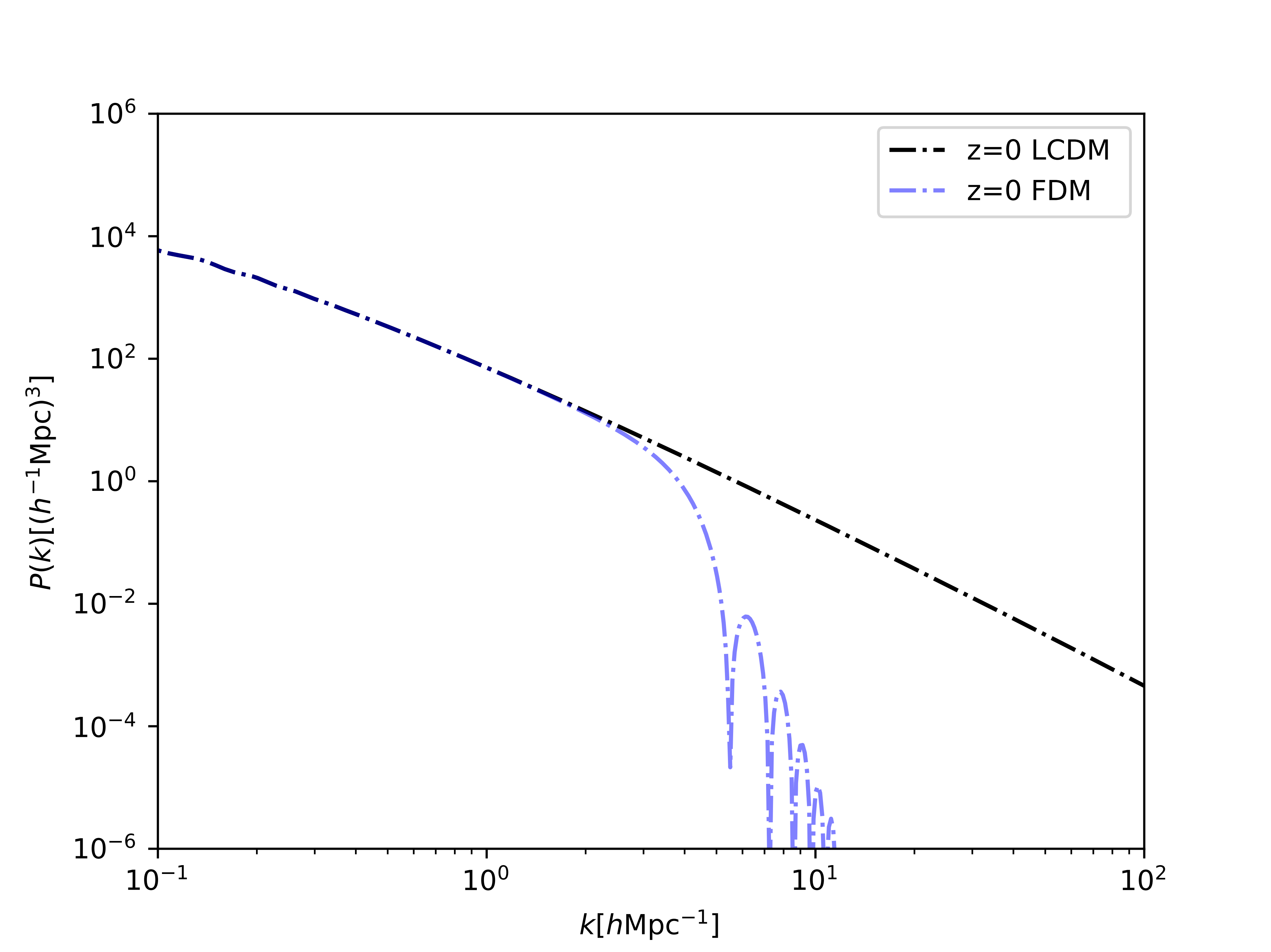
INTRODUCTION

- In this work, we consider the Scalar Field Dark Matter (SFDM) model as an alternative to the standard Λ-CDM model.
- One of its main features is a cut-off in the linear mass power spectrum (MPS). This feature can be reflected in the formation of structure in the Universe and some astrophysical observables.
- We analyze the influence of this proposal on the formation of structure in the Universe using the mass power spectrum (MPS) and the halo mass function (HMF).

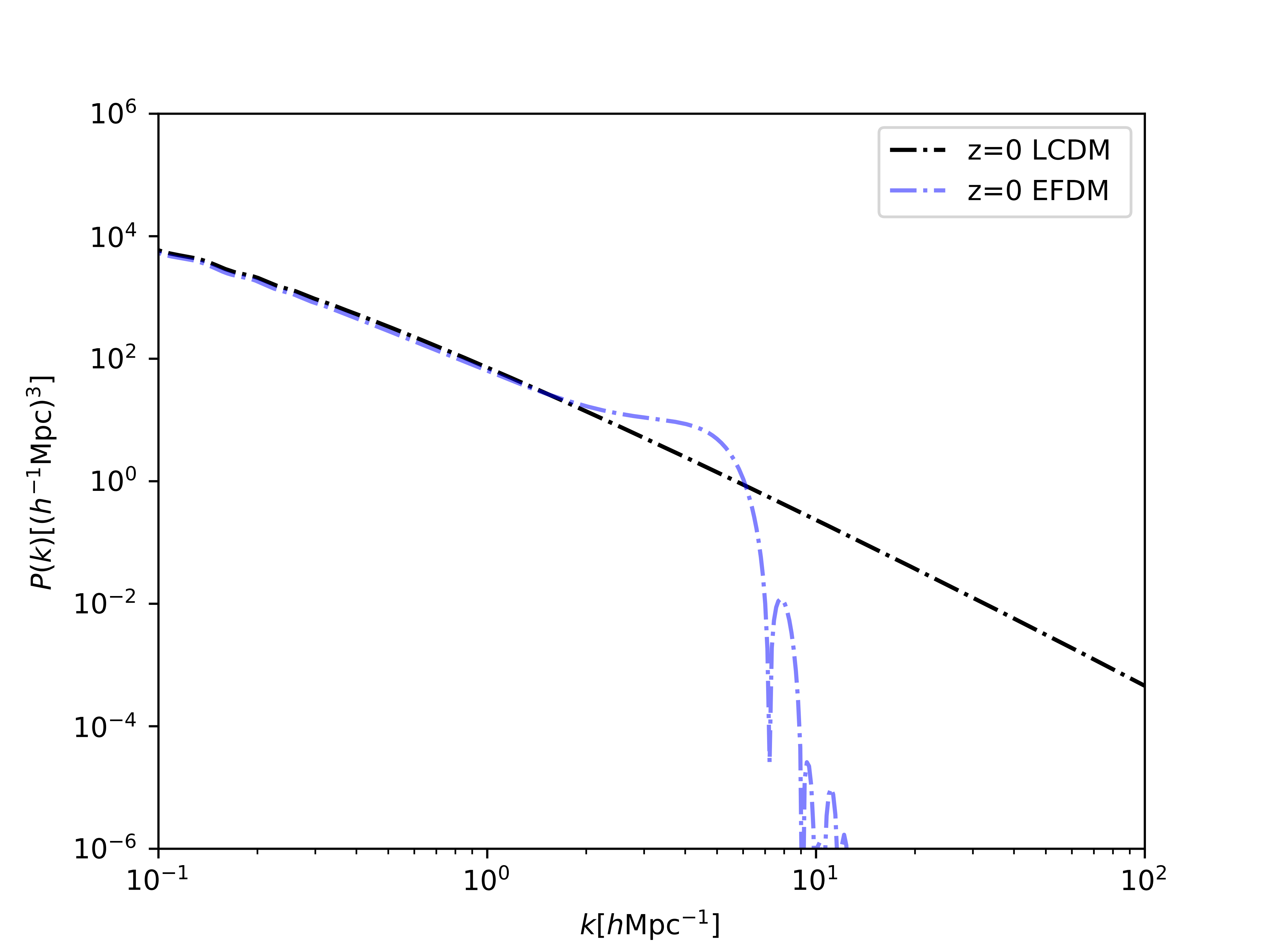
INTRODUCTION

Our main interest are in two cases:

- Non-linear regime for the free case also known as fuzzy dark matter (FDM).



- Non-linear regime for the axion-like potential ('Extreme case').



We make the analysis for the effect of an SFDM in the formation of the structure of the Universe with quick simulations using a modified version of the MG-PICOLA[1] code.

[1]https://github.com/HAWinther/MG-PICOLA-PUBLIC

SFDM MODEL

One of the key steps is the transformation of the axion field equations into their hydrodynamic counterparts.

Taking the non-relativistic limit equations of motion for the SFDM, they can be written in the form of the Gross-Pitaevskii-Poisson (GPP) system.

$$i\hbar\frac{\partial_t(a^{3/2}\psi)}{a^{3/2}} = -\frac{\hbar c}{2\widetilde{m}a^2}\nabla^2\psi + \left(\frac{\Phi}{c^2} + \frac{\widetilde{\lambda}}{2\widetilde{m}^2}|\psi|^2\right)\widetilde{m}\psi\ldots\ldots(1)$$

$$\nabla^2\Phi = \frac{4\pi G}{c^2}a^2\widetilde{m}^2|\psi|^2\left(1 + \frac{\widetilde{\lambda}}{2\widetilde{m}^2}|\psi|^2\right) - \frac{3}{2}a^2H^2\ldots\ldots(2)$$

Using the Madelung transformation $\widetilde{m}\psi = c\sqrt{\rho(t,r)}e^{iS(t,r)/\hbar}$ and the definitions $u = \nabla S/m$ and $\rho = \widetilde{m}^2|\psi|^2/c^2$, the system becomes the quantum barotropic Euler-Poisson (QBEP)

$$\frac{\partial\rho}{\partial t} + 3H\rho + \frac{1}{a^2}\nabla\cdot(\rho\boldsymbol{u}) = 0\ldots\ldots(3)$$

$$\frac{\partial\boldsymbol{u}}{\partial t} + (\boldsymbol{u}\cdot\nabla)\boldsymbol{u} = -\nabla\tilde{\Phi}\ldots\ldots(4)$$

$$\nabla^2\tilde{\Phi} = 4\pi G\rho + \frac{\tilde{\lambda}c^4}{2\tilde{m}^4}\nabla^2\rho - \frac{c^2}{2\tilde{m}^2a^2}\nabla^2\left(\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}\right)\ldots\ldots(5)$$

SFDM MODEL

And in terms of the growth factor

CDM

$$\frac{d^2 D_1}{d\tau^2} - \kappa D_1 = 0$$

$$\frac{d^2 D_2}{d\tau^2} - \kappa D_2 = -\kappa D_1^2$$

Where $\kappa = 4\pi G \rho_0 a^4$

SFDM

$$\frac{d^2 D_1}{d\tau^2} - \kappa\mu D_1 = 0$$

$$\frac{d^2 D_2}{d\tau^2} - \kappa\mu D_2 = -D_1^2 \left(\mu\kappa + 2a^4 H^2 \gamma_2\right)$$

$$\gamma_2 = \gamma_2^E + \frac{3}{2}\Omega_m(a)\left[\left(\mu(k,a) - \mu(k_1,a)\right)\frac{k_1}{k_2} + \left(\mu(k,a) - \mu(k_2,a)\right)\frac{k_2}{k_1}\right]\frac{\mathbf{k}_1 \cdot \mathbf{k}_2}{2k_2^2}$$

Where $\mu(a, k, \tilde{\lambda}) = 1 - k^2/k_{J1}^2 - k^4/k_{J0}^4$.
The γ_2^E is a linear combination between two modes, k_1 and k_2, m, H and a.

- D_1 is the growth factor at first order and D_2 is the growth factor at second order.
- If $\mu = 1$ we recover the CDM case

The second order growth factor in the SFDM model is obtained relying on the expression developed in the MG-PICOLA[2] paper.

[2] H. A. Winther, K. Koyama, M. Manera, B. S. Wright, and G. B. Zhao J. Cosmo. Astropart. Phys. 2017 (2017), arXiv:1703.00879.

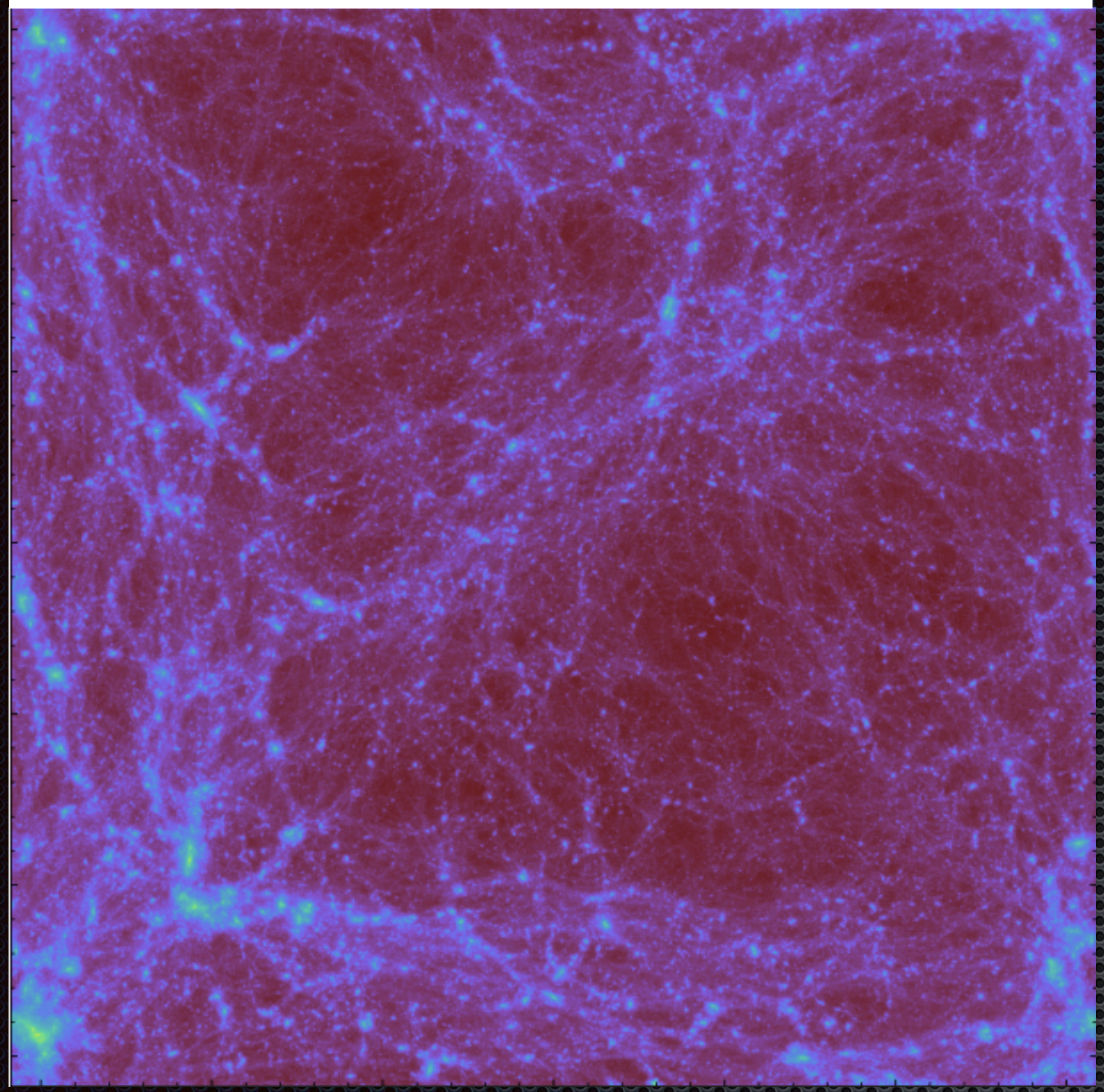
RESULTS

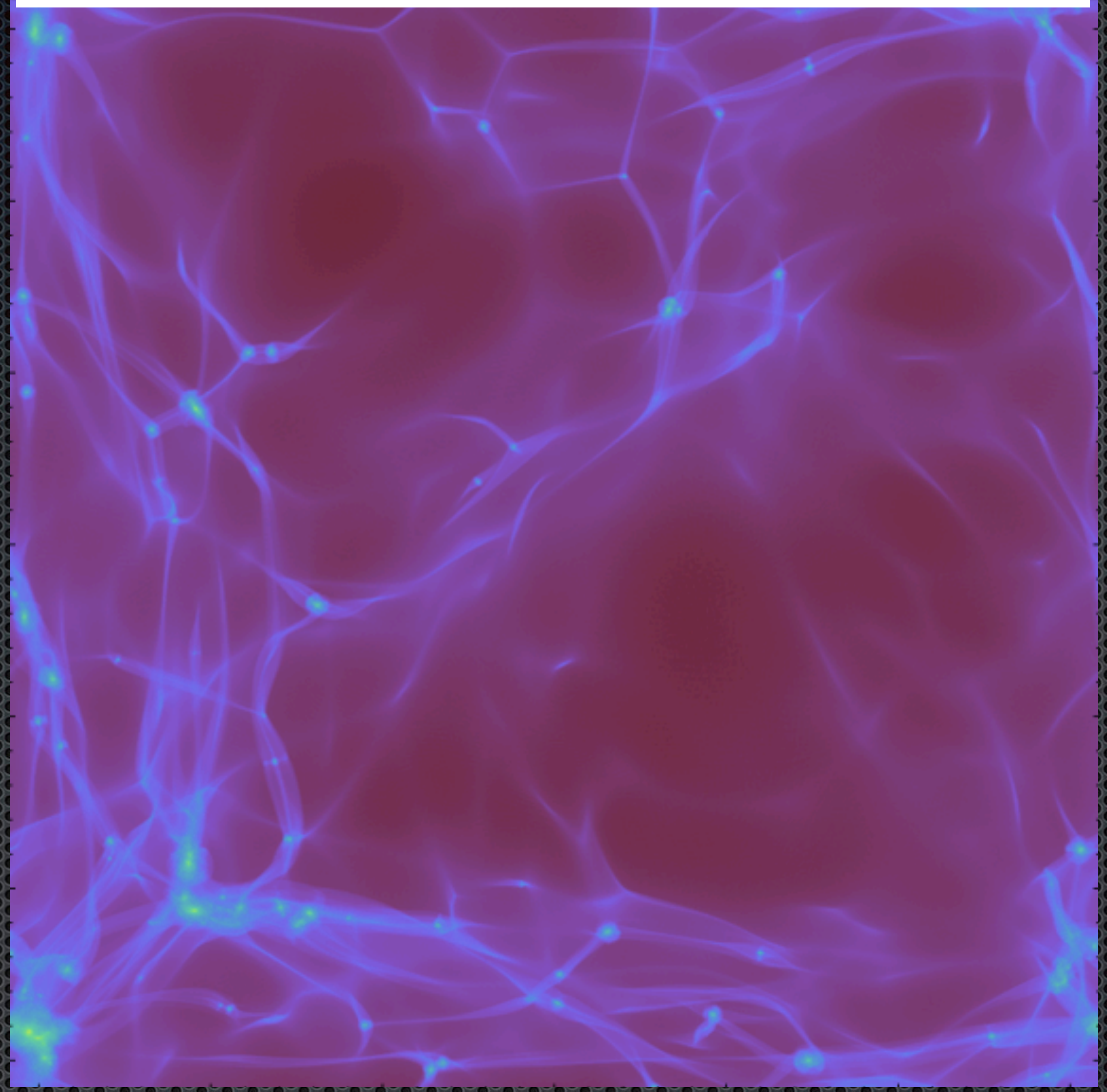
Parameters for the simulations with the models Λ-CDM, SFDM (free case) and SFDM (axion-like potential)

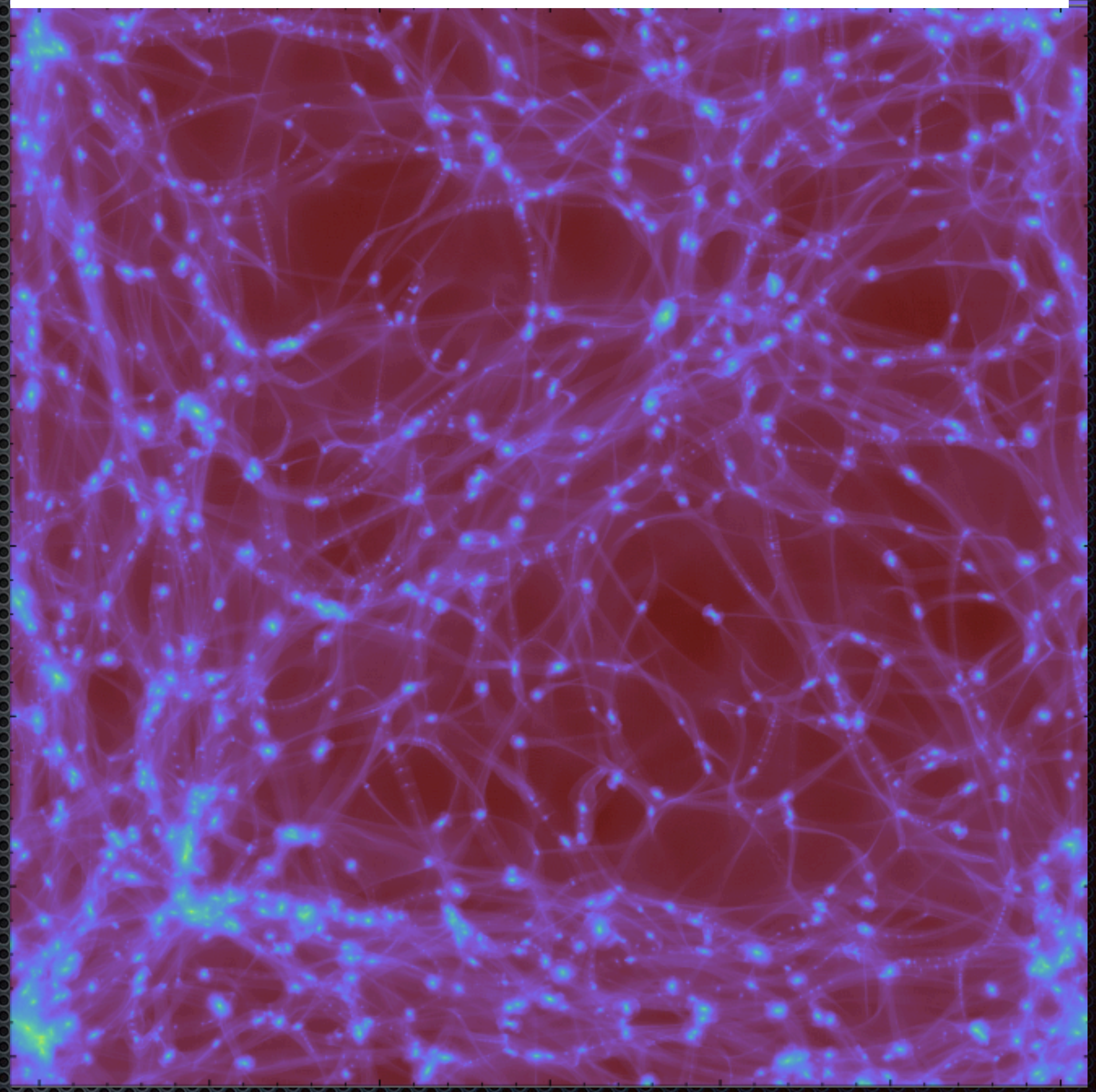
Type	Model	Initial Conditions	m_a (eV/c^2)	N_{part}	Box size (Mpc/h)
CIC	ΛCDM	CDM	-	1024^3	15
FIC	ΛCDM	FDM	3×10^{-23}	1024^3	15
FIC + QP	ΛFDM	FDM	3×10^{-23}	1024^3	15
EIC +QP	ΛFDM	EFDM	3×10^{-23}	1024^3	15

- Cold initial conditions and Λ-CDM model (CIC)
- Fuzzy initial conditions, deactivating the MG functions (FIC)
- Fuzzy initial conditions and activating the MG functions to take into account the quantum potential Q (FIC+QP)
- Extreme initial conditions and activating the MG functions to take into account the quantum potential Q and the axion potential (EIC+QP)

RESULTS


CIC (z=2.5)

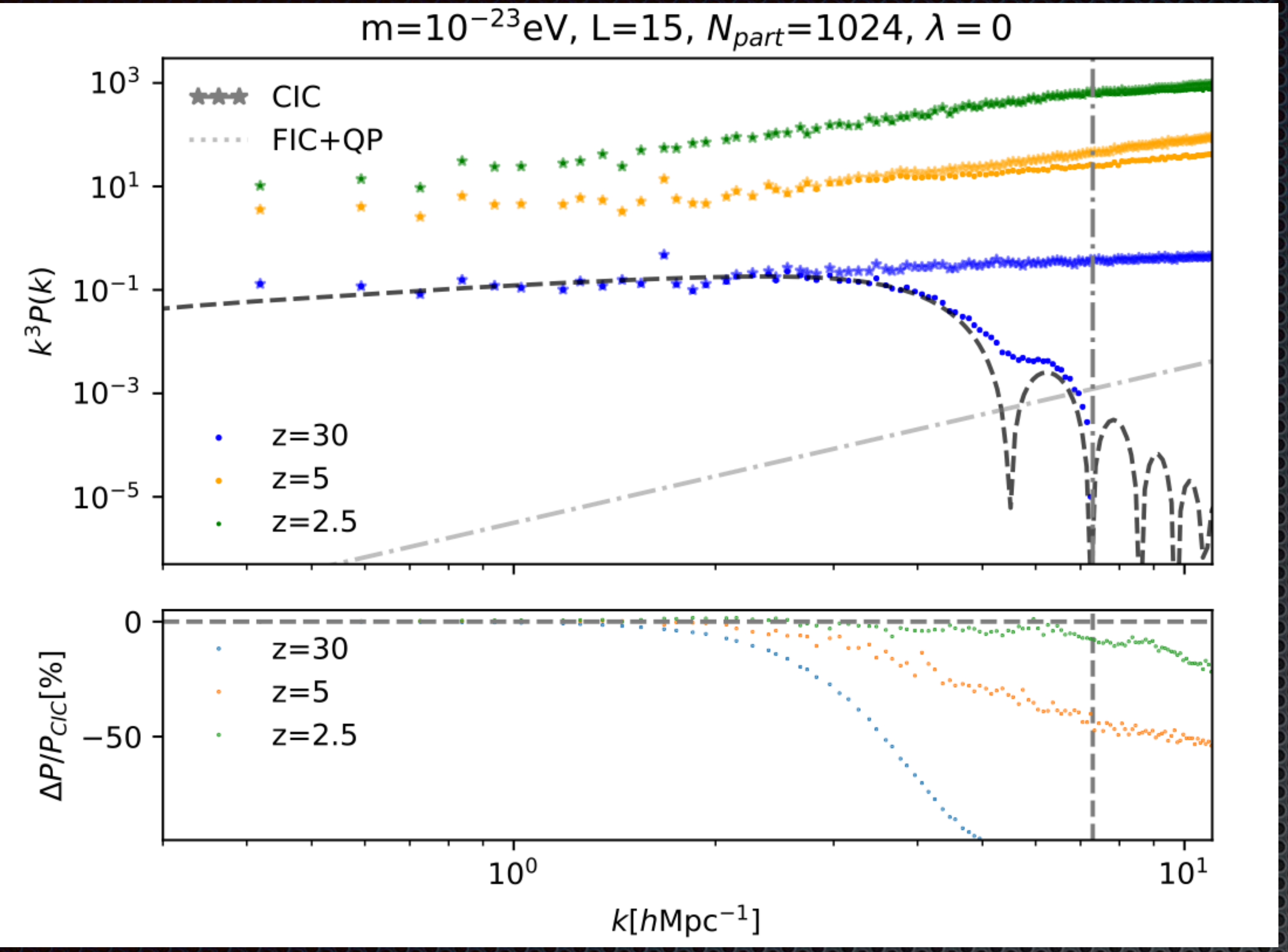

FIC (z=2.5)


EIC+QP (z=2.5, $\lambda = 10^4$)

We show the density projection onto the plane xy for the cases CIC, FIC, FIC+QP and EIC at redshift 2.5. Here we can see by eye that the scalar field has a significant influence on the structure formation in comparison with the cold dark matter

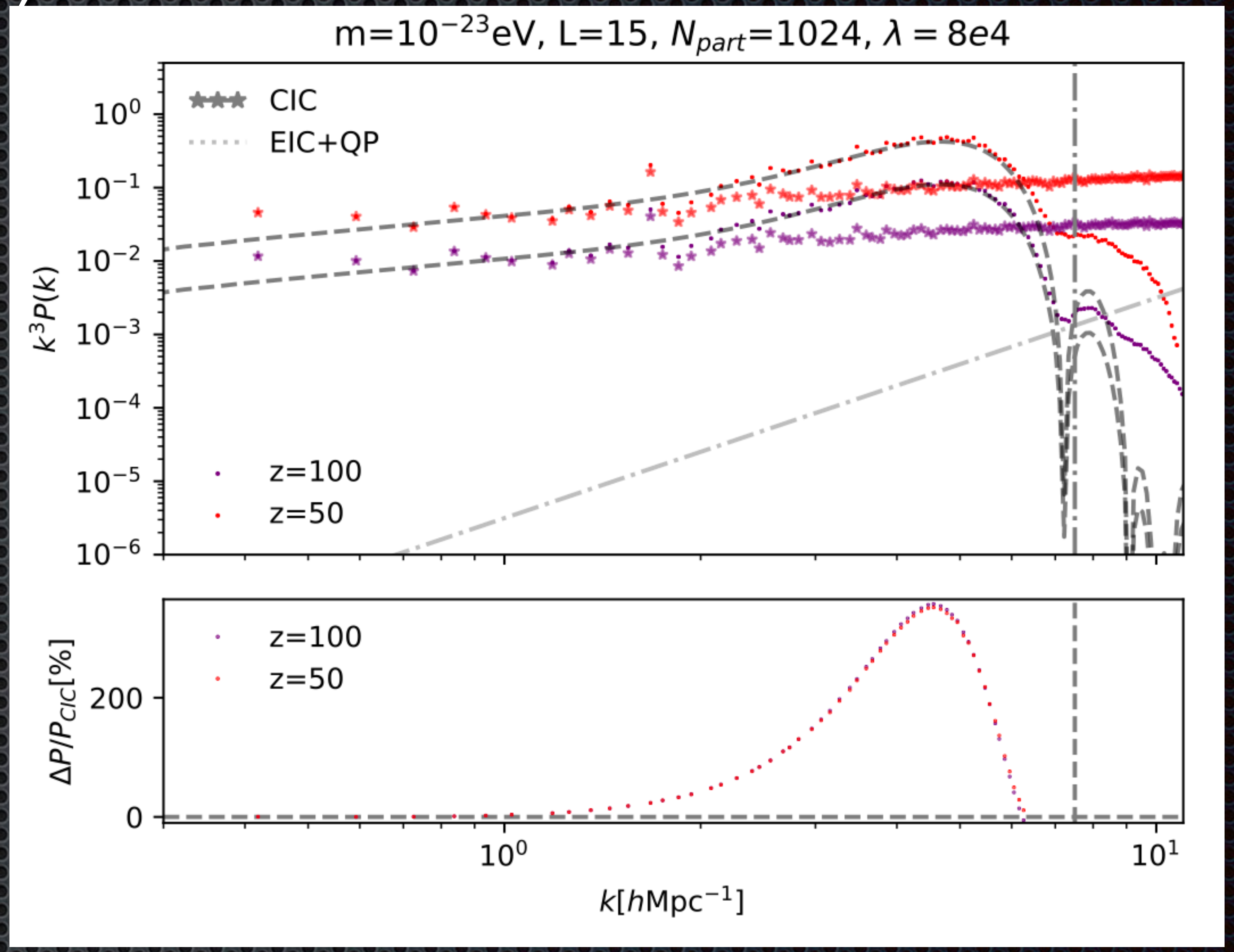
RESULTS

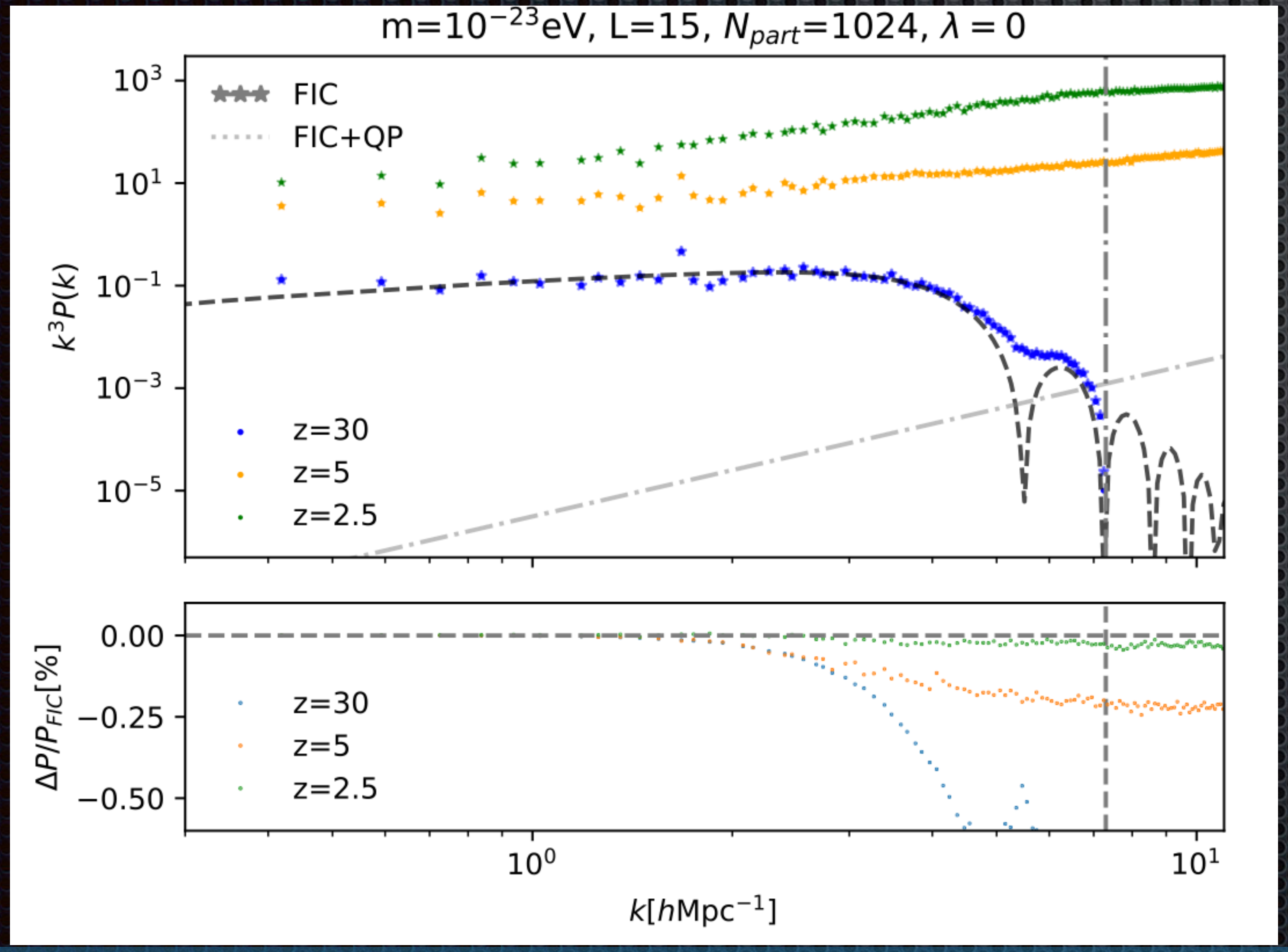
MASS POWER SPECTRUM (MPS).



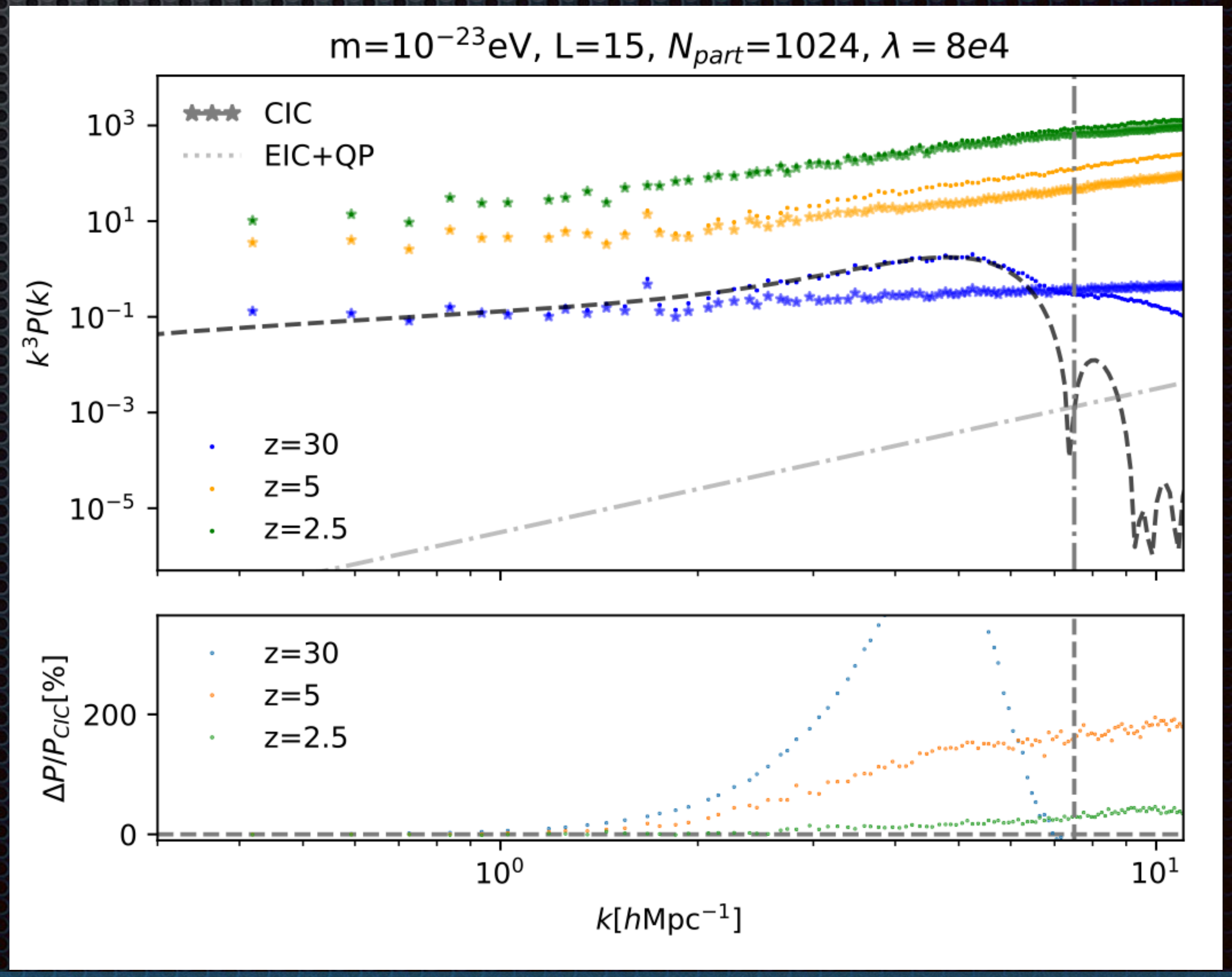
- On the left hand side, in the upper panel, we see a comparison between the standard CDM, and FIC+QP, which considers both the initial conditions and evolution of the FDM type simulations from z=30 to z=2.5.

- On the left hand side, in the bottom panel, we see a comparison between the FIC and FIC+QP simulations from z=30 to z=2.5 simulations.





- On the right had side, we show the comparison between the CDM and EIC+QP simulations from z=100 to z=2.5

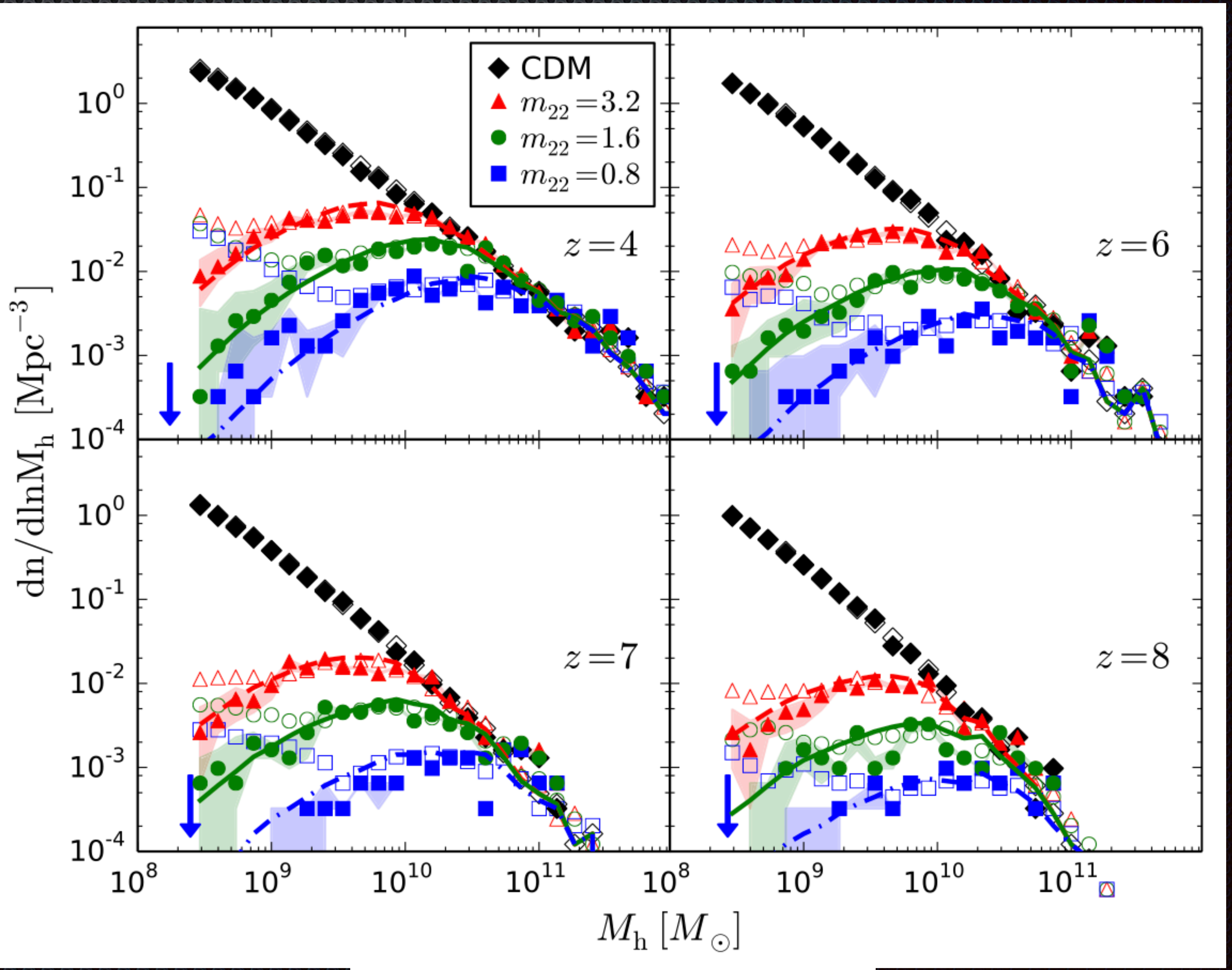


HALO MASS FUNCTION

The halo mass function (HMF) encodes the comoving number density of dark matter halos as a function of the halo mass.

For models with a cut-off in the linear power spectrum, such as the SFDM model, a proliferation of spurious halos has been seen.

This behavior can be seen in the HMF as an step-like upturn in the number of low-mass halos.



Hsi-Yu Schive *et al* (2016)

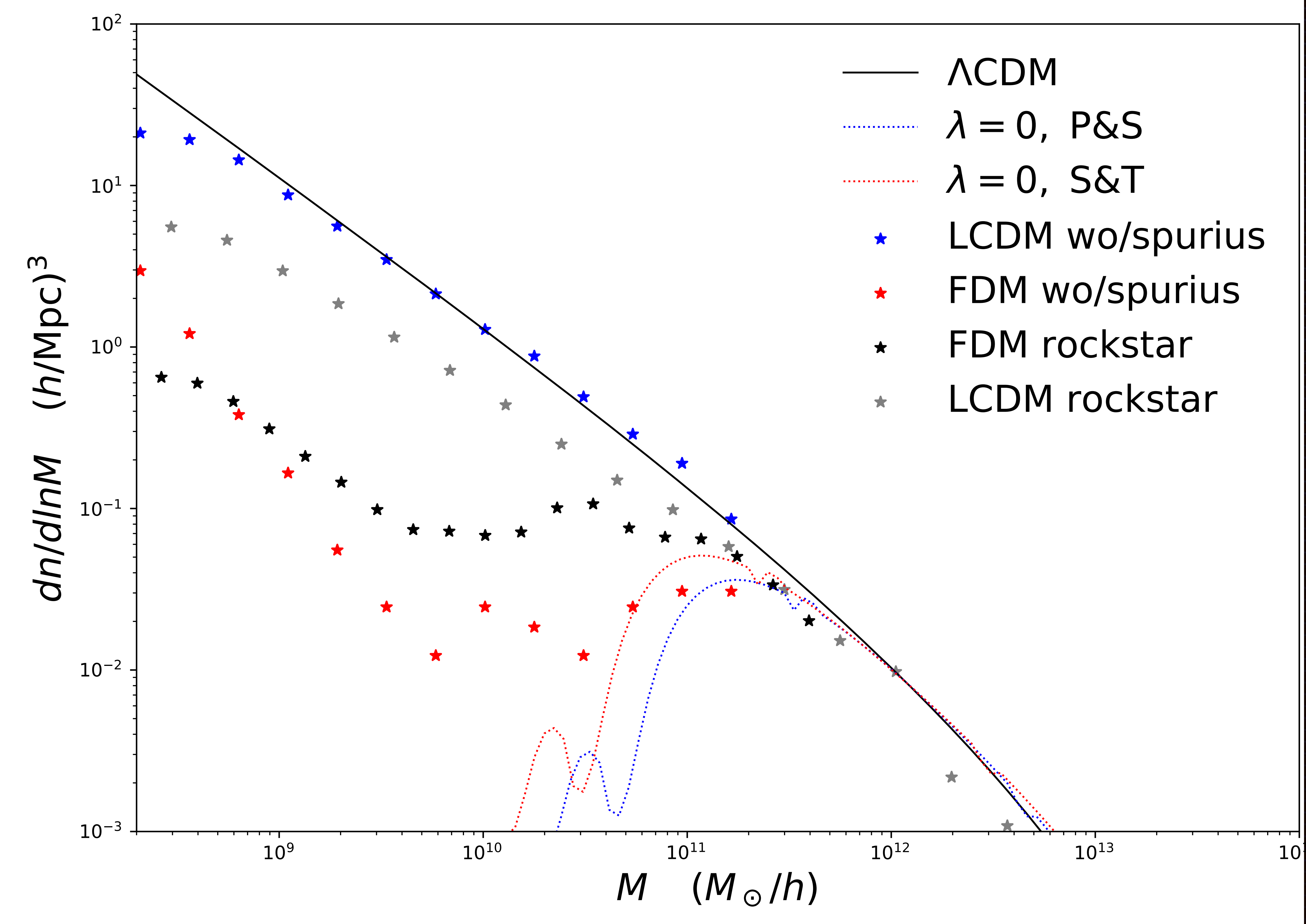
HALO MASS FUNCTION

- We use Rockstar[3] to create a halo catalog using simulations with 512^3 particles.
- To remove these spurious structures, as a first approximation we cut all the masses up to a limit mass

$$M_{lim} = 10.1 \rho d \kappa_{peak}^2$$

- Where ρ is the mean density, κ_{peak} is a characteristic scale often related to the maximum amplitud of the dimensionless power spectrum and d is the interparticle distance

$$d = L_{box}/N^{1/3}$$



[3] https://bitbucket.org/gfcstanford/rockstar/src/main/

HALO MASS FUNCTION

Using the 'protohalo' sphericity

$$s = c/a$$

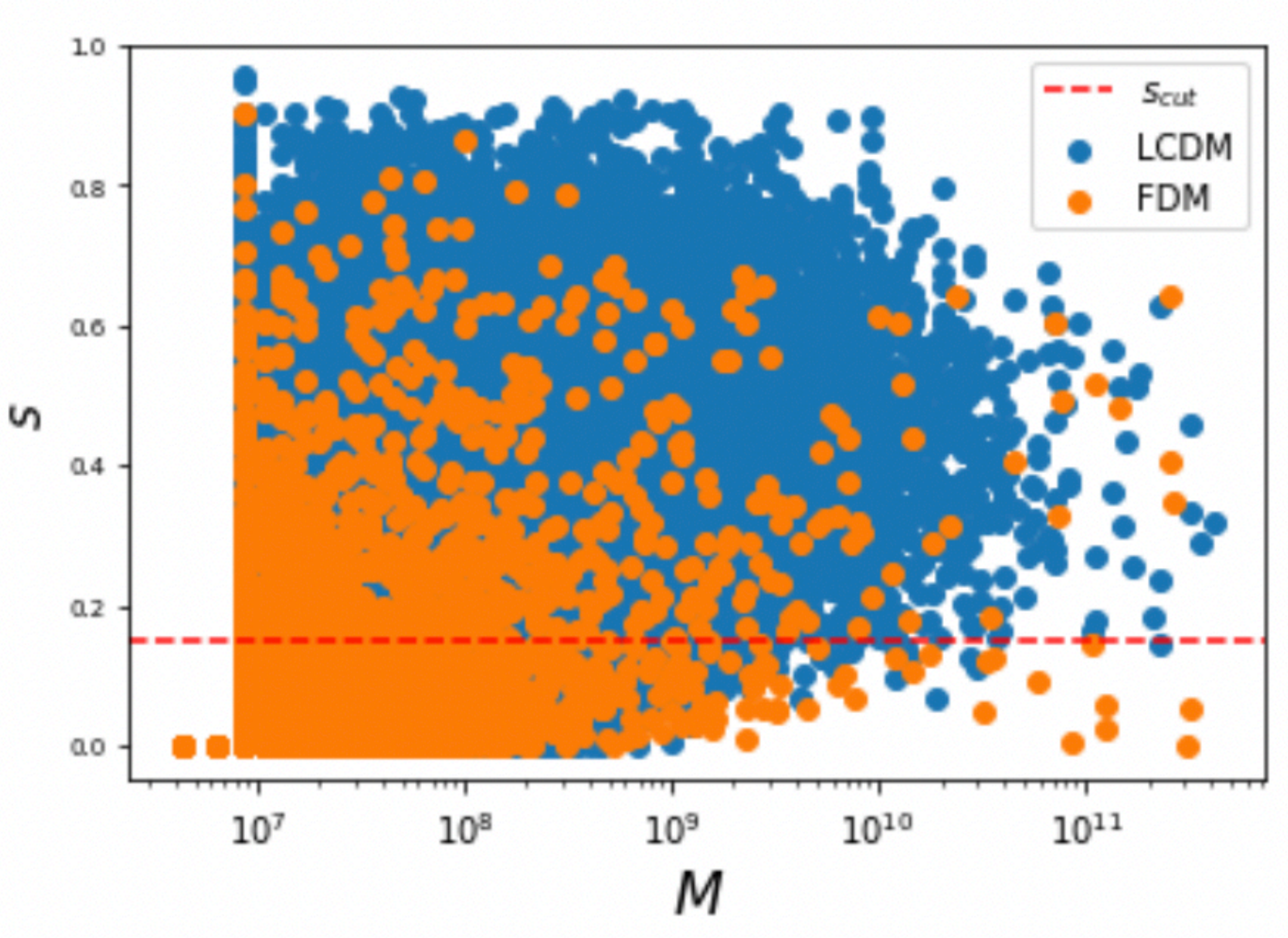
where a and c are the maximum and minimum semi-axis lengths of an ellipsoid of uniform density

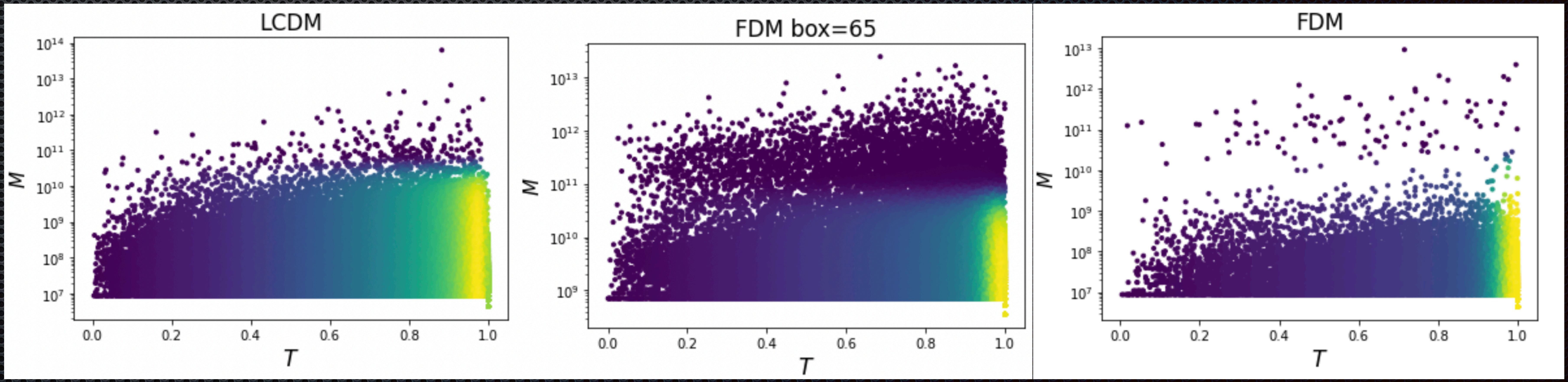
And the triaxiality

$$T = \frac{a_1^2 - a_2^2}{a_1^2 - a_3^2} = \frac{1 - q^2}{1 - s^2},$$

$$q = b/a$$

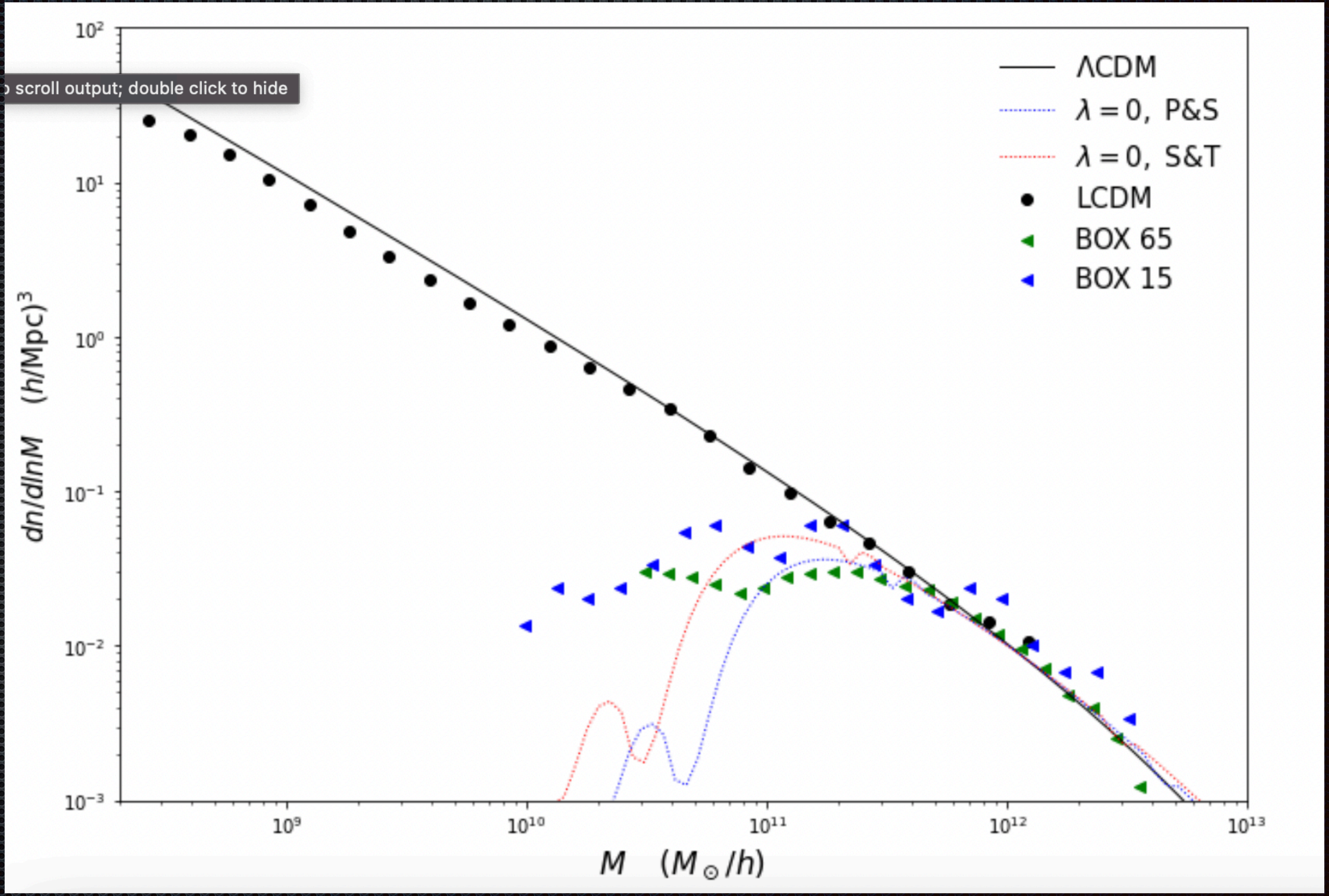
We set limits to remove protohalos with low sphericity.





FIRST RESULTS

- Halo mass function (HMF) without the structures with s < 0.17, T > 0.85 and a mass cutoff on the maximum amplitude scale.



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