QUICK SIMULATIONS FOR A SCALAR FIELD DARK MATTER MODEL

STEFANY GUADALUPE MEDELLÍN GONZÁLEZ

DR. LUIS ARTURO UREÑA LÓPEZ
DRA. ALMA XÓCHITL GONZÁLEZ MORALES

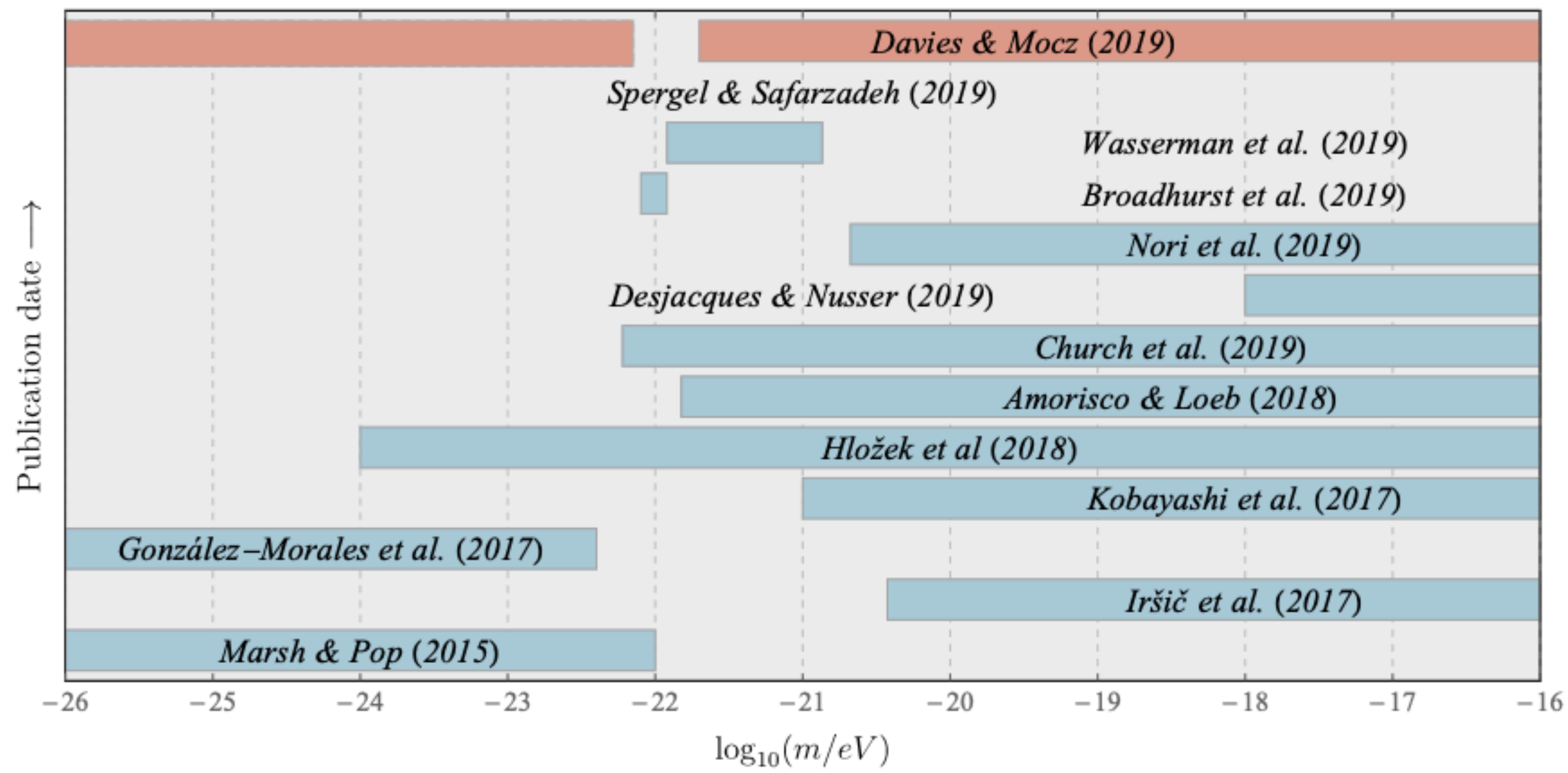
- There are many alternative models to the standard Λ-CDM model, some of them can make modifications to the general relativity (MG) or alternative models of dark energy or dark matter.

- One of the dark matter proposals is the Scalar Field Dark Matter (SFDM) model.

- The Scalar Field Dark Matter (SFDM) model is a model that proposes that dark matter is a very light particle with a mass $m \sim 10^{-22} eV$ that behaves in conjoint as a classic wave.

- We can consider two cases: Free case and Axion-potential case

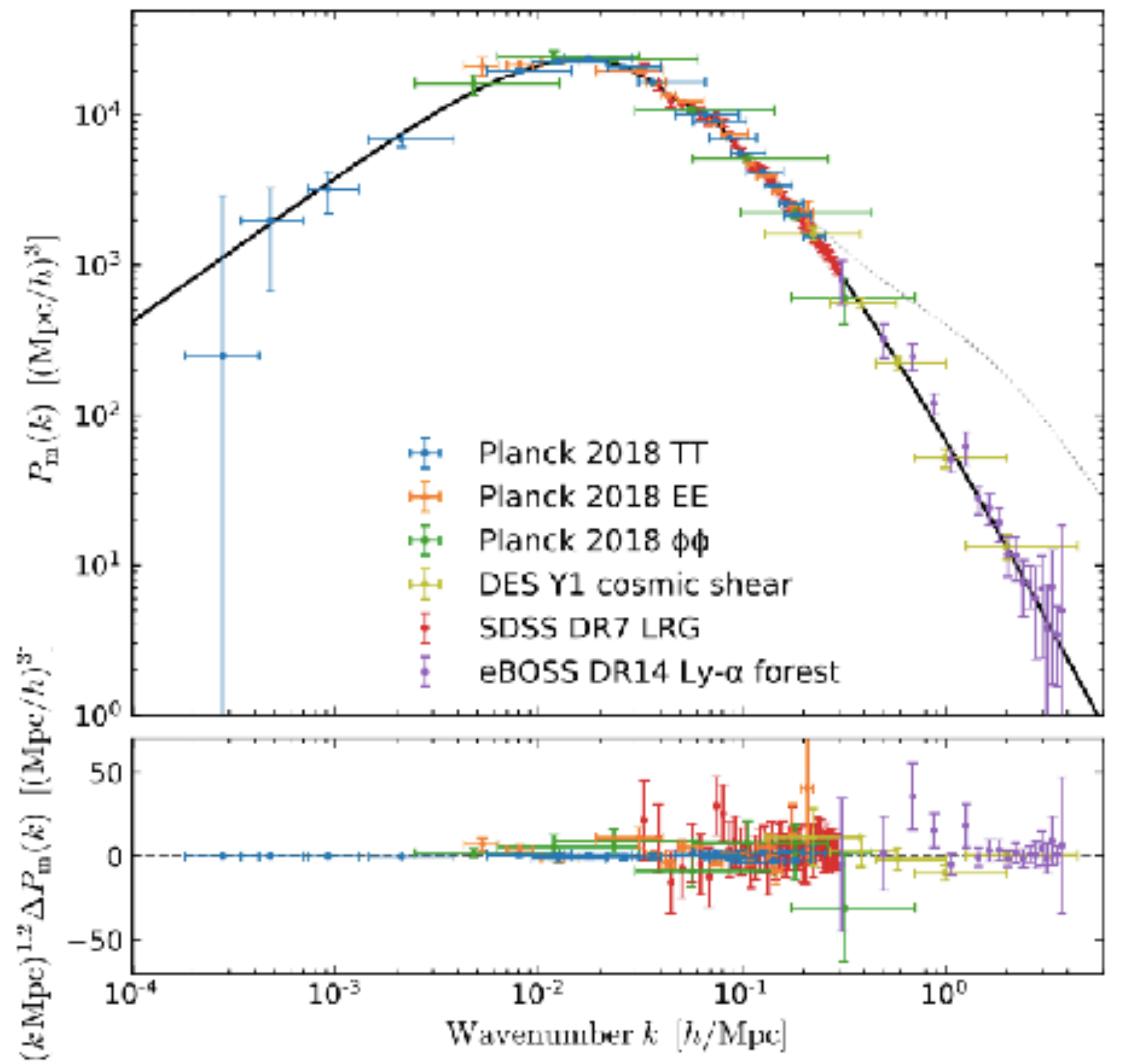
L. Hui, J. P. Ostriker, S. Tremaine, and E. Witten, Physical Review D 95, 043541 (2017), arXiv:1610.08297
L. A. Ureña-López, Front. Astron. Space Sci. 6, 47 (2019).



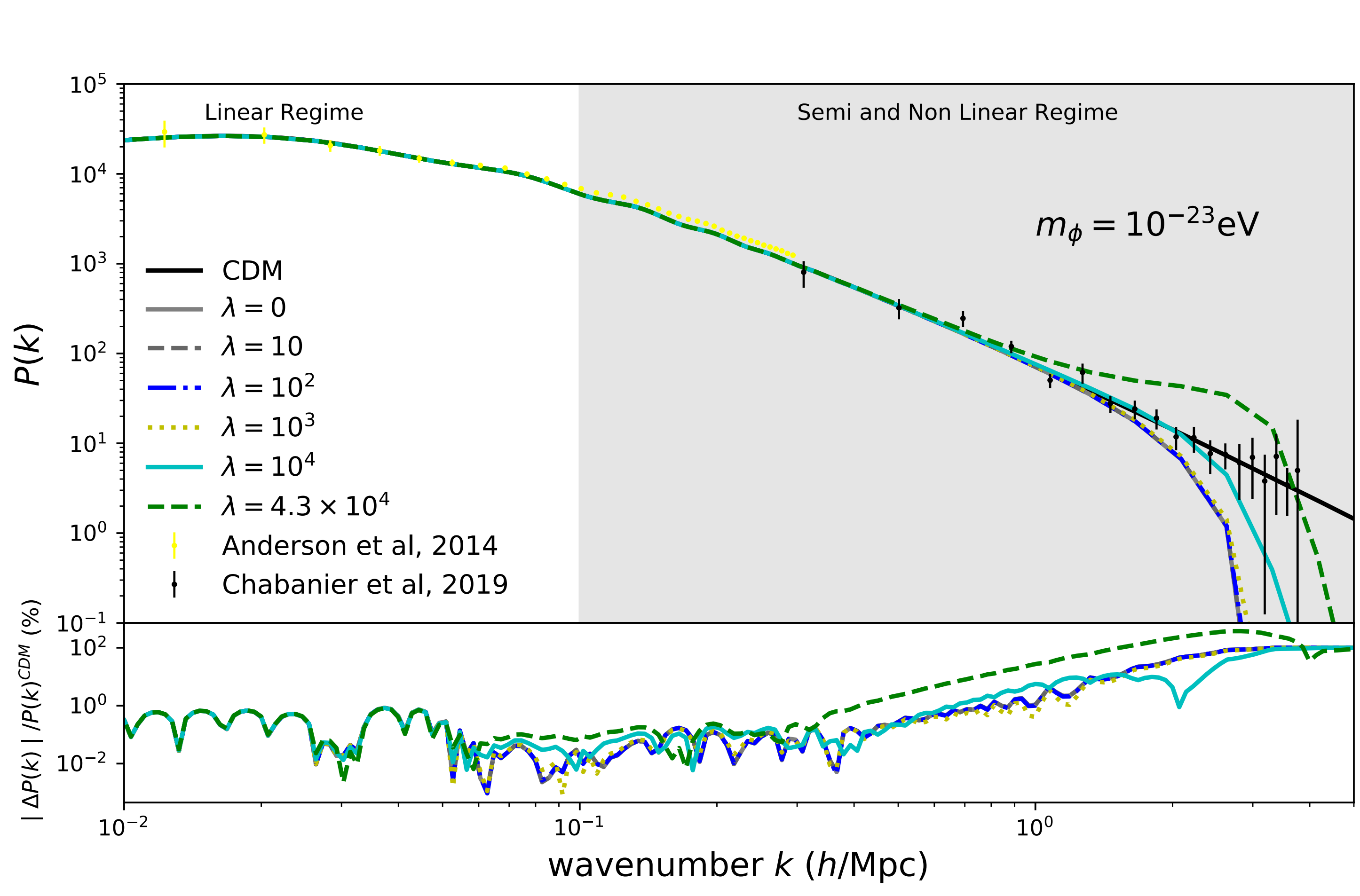
E. Y. Davies et al. (2019)

MOTIVATION

- 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 in some astrophysical observables



Chabanier et al. (2019)



Linares Cedeño et al (2020)

- Stage IV surveys can provide stronger limits to dark matter models.

- Our main interest are the cases
    - Non-linear regime for the free case also know as fuzzy dark matter (FDM) (λ=0)
    - Non-linear regime for the Axion-like potential (λ>0)

- Where $\lambda = 3/(\kappa^2 f_a^2)$, where $\kappa = 8\pi G$ and f_a is the decay constant

- In our work, 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 code.

SFDM MODEL

- The description of the SFDM model in the non-relativistic limit is made through the equations Gross-Pitaevskii-Poisson (GPP)

$$i\hbar\partial_t\psi = -\frac{\hbar^2 c}{2\tilde{m}}\nabla^2\psi + \left(\Phi + \frac{\tilde{\lambda}c^2}{m^2}\mid\psi\mid^2\right)m\psi,$$

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

- Using the Madelung transformation $\widetilde{m}\psi = c\sqrt{\rho(t,r)}e^{iS(t,r)/\hbar}$, the definitions $u = \nabla S/m$ and $\rho = \widetilde{m}^2|\psi|^2/c^2$, the system became a fluid-like system

$$\frac{\partial\rho}{\partial t} + \boldsymbol{\nabla}\cdot(\rho\mathbf{u}) = 0 \qquad \ldots(1)$$

$$\frac{\partial\mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{u} = -\nabla\left[\Phi + Q\right] \ldots(2)$$

$$\nabla^2\Phi = 4\pi G\rho \qquad \ldots(3)$$

$$Q = -\left(c^2/2\widetilde{m}^2\right)\left(\nabla^2\sqrt{\rho}\right)/\sqrt{\rho} \quad \ldots(4)$$

- Using perturbation theory and re-writing the equations in terms of the density contrast $\delta = \dfrac{\rho}{\rho_0} - 1$
- We obtain the equations that describe the evolution of the perturbations and using a Fourier transform we have

$$\frac{d^2\delta_k}{d\tau} = \kappa\mu\delta_k$$

- Where $\kappa = 4\pi G\rho_0 a^4$ and $\tau = a^2 dt$

DARK MATTER AND FORMATION OF STRUCTURE

- If we separate the temporal and spatial terms we obtain the equations that describe the evolution of the structure formation for the model.

Λ-CDM

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

D_1 is the growth factor at first order

$$\mu = 1$$

SFDM

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

Where μ comes from the quantum potential and is defined by

$$\mu(a, k, \widetilde{\lambda}) = 1 - k^2/k_{J1}^2 - k^4/k_{J0}^4$$

MG-PICOLA

- MG-PICOLA is a code that is specialized in the solution of the non-linear structure formation for Modify Gravity models (MG) and Λ-CDM.

- This code perform numerical simulation of structure formation for general theories that exhibit scale-dependent growth using the COLA approach.

- COLA (COmoving Lagrangian Acceleration) method separates the large scales ($> 100 Mpc$) and the small scales of the Universe. For large scales uses the Lagrangian perturbative Theory at 2nd order (2LPT) and a Particle-Mesh code for small scales

- This method is faster than an full N-body, been able to take much larger time steps

NON-LINEAR APROXIMATION

- For the approximation to the non-linear regime the MG-PICOLA code uses 2LPT to obtain
- Λ-CDM case
- $$\frac{d^2 D_2}{d\tau^2} - \kappa D_2 = -\kappa D_1^2$$
- Scale dependent case
- $$\frac{d^2 D_2}{d\tau^2} - \kappa\mu D_2 = -D_1^2 \left(\mu\kappa + 2a^4 H^2 \gamma_2\right)$$
- $$\gamma_2 = \gamma_2^E + \frac{3}{2}\Omega_m(a)\left[\left(\mu(k,a) - \mu(k_1,a)\right)\frac{k_1}{k_2} + \left(\mu(k,a) - \mu(k_2,a)\right)\frac{k_2}{k_1}\right]\frac{\mathbf{k}_1 \cdot \mathbf{k}_2}{2k_2^2}$$
- For SFDM case γ_2^E is a linear combination between two modes k_1 and k_2, m, H and a.

RESULTS

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

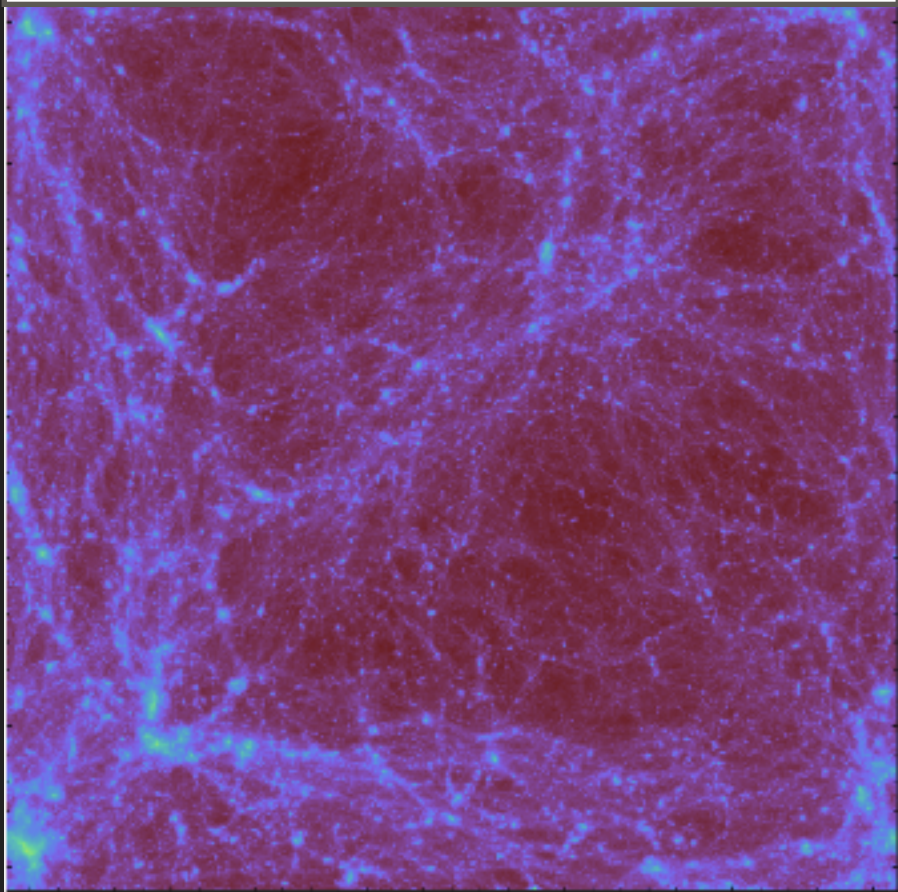
- Cold initial conditions and Λ-CDM model (**CIC**)
- Fuzzy initial conditions and activating the MG functions to take into account the quantum potential Q (**FIC+QP**)
- Extreme initial conditions and activating the MG functions to take into account the quantum potential Q and the axion potential (**EIC+QP**)

	Model	IC	$m_x(eV)$	$\tilde{\lambda}$	L(Mpc/h)	Part	Shotnoise
CIC	Λ-CDM	CDM	-	-	15	1024^3	3.14×10^{-6}
FIC+QP	SFDM	FDM	$1e^{-23}$	0	15	1024^3	3.14×10^{-6}
EIC+QP	SFDM	SFDM	$1e^{-23}$	$8e^4$	15	1024^3	3.14×10^{-6}

- Initial conditions were generated using an MPS from an amended version of the Boltzmann code CLASS (F. X. Cedeño et al. (2017))

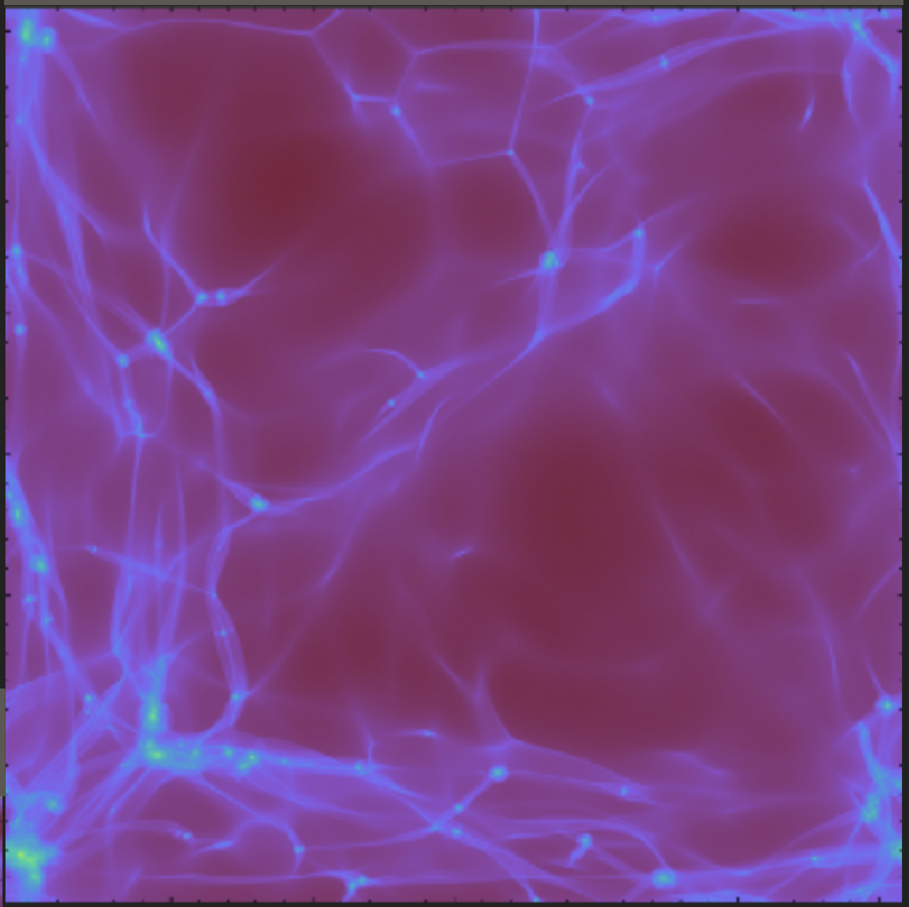
RESULTS

CIC



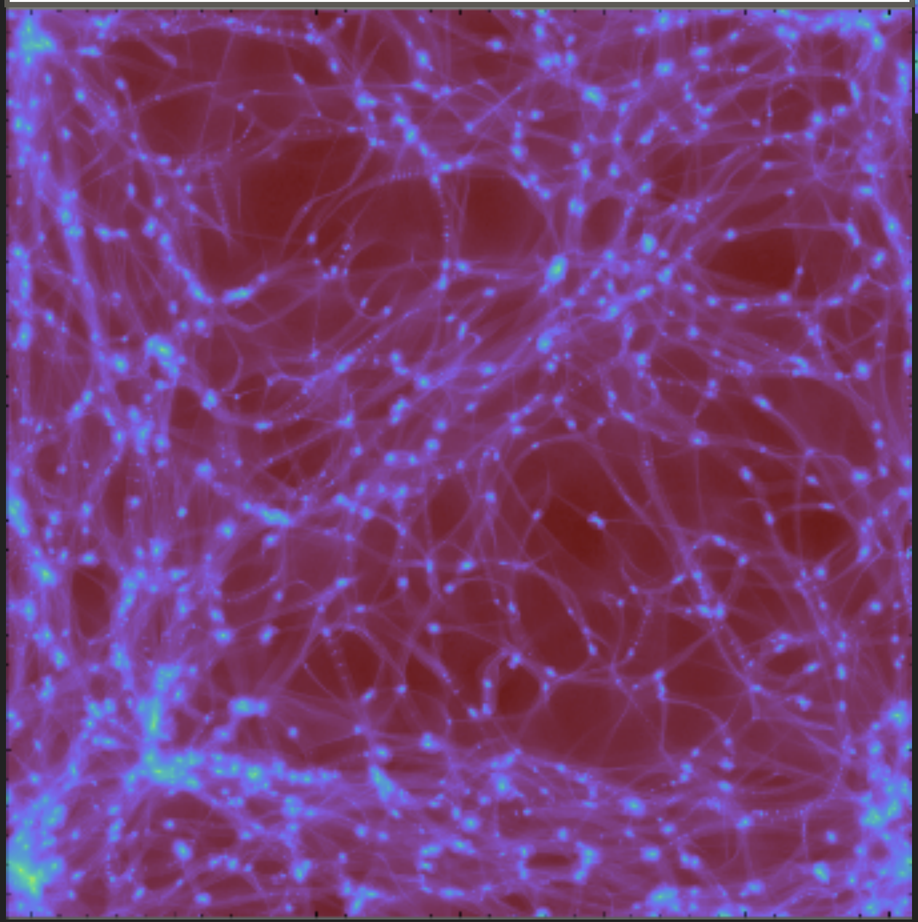
The modification of the code allow to us resolve the formation of structure for SFDM and with this make a comparison with Λ-CDM

FIC+QP



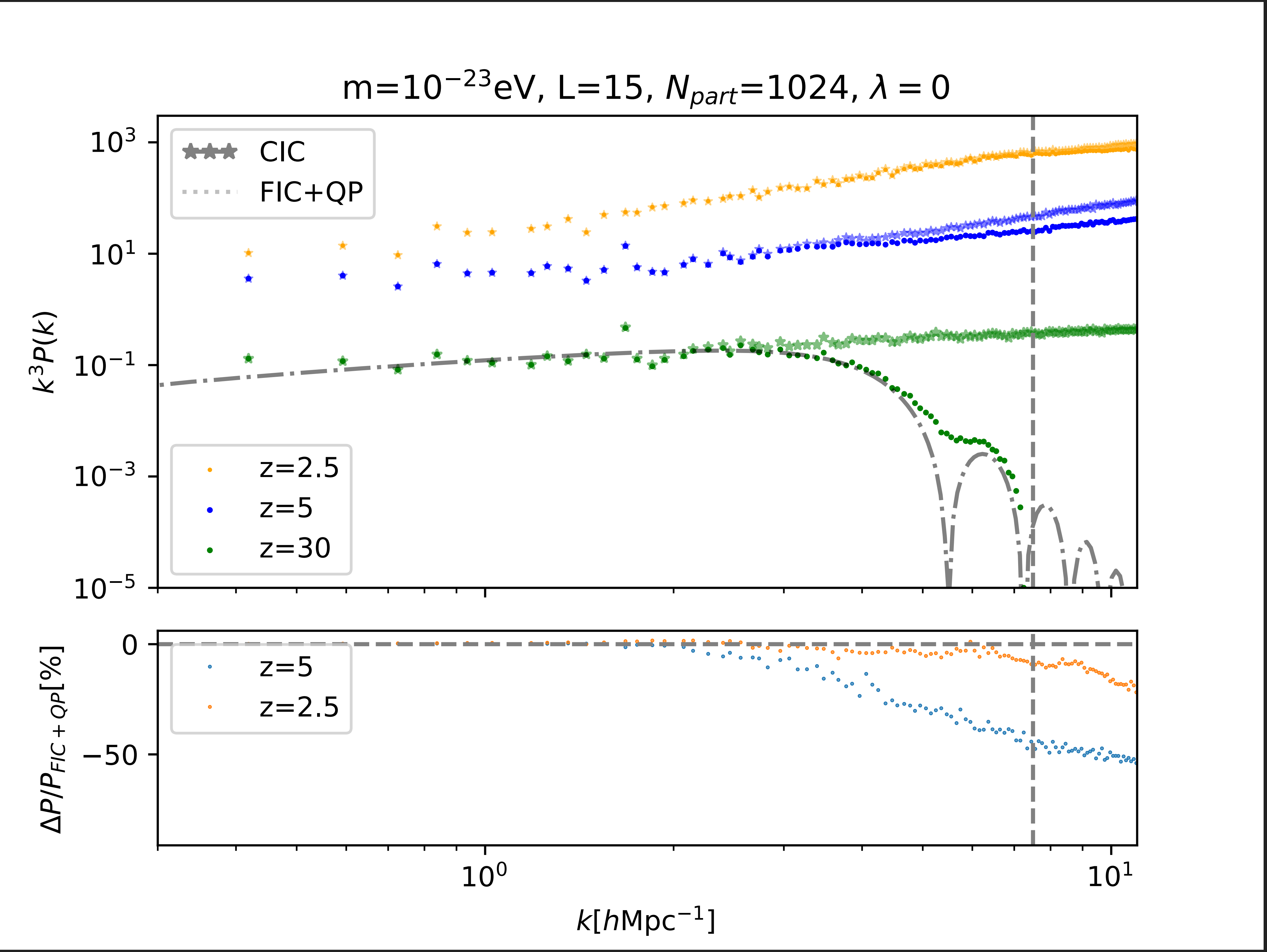
A projection of the density field for each model can show us by eye how different parameters of the model affect the structure formation.

EIC+QP

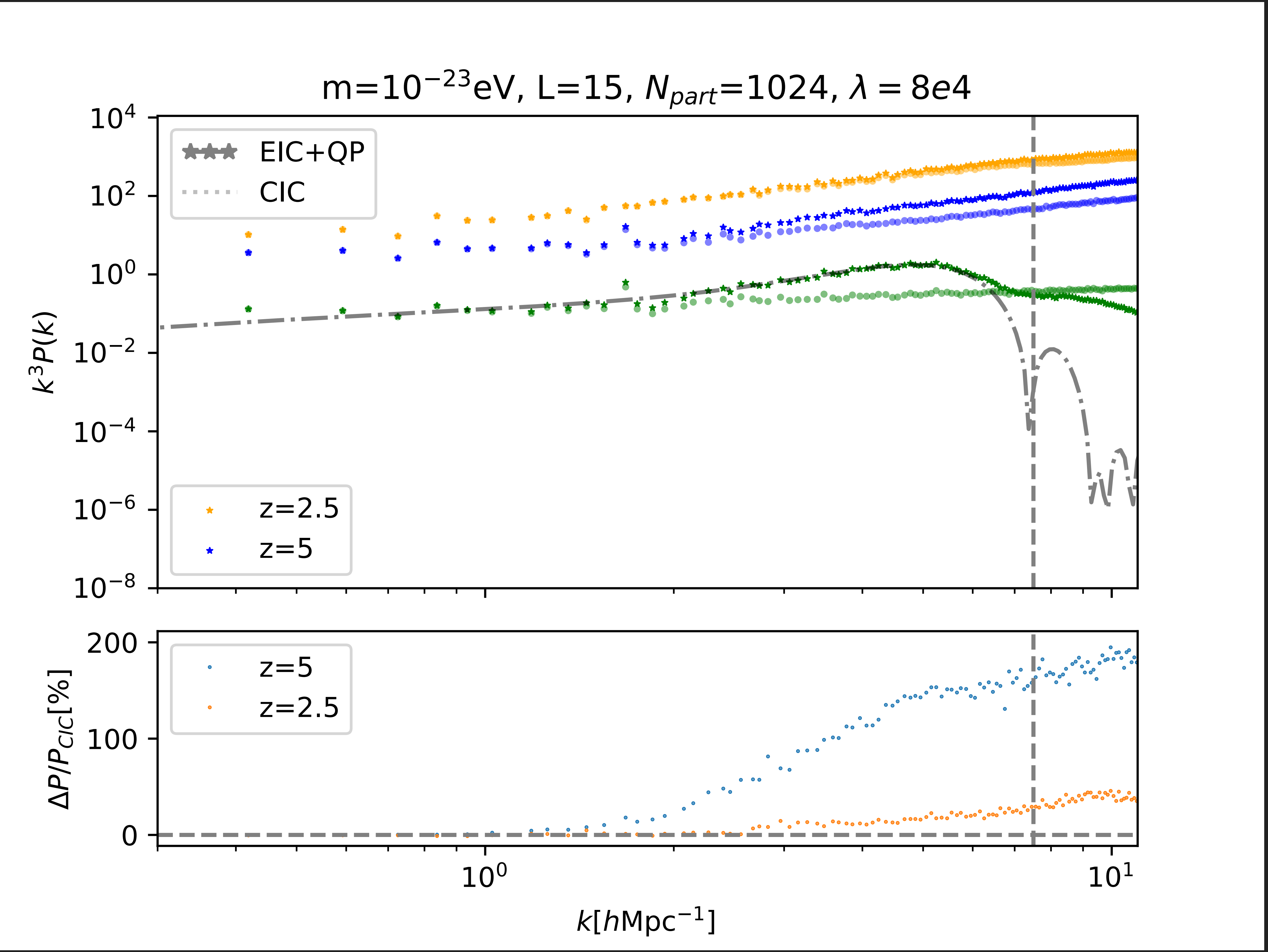


- CIC (Λ-CDM)
- FIC+QP (FDM or Free case)
- EIC+QP (Axion-like potential)

RESULTS


m=10^−23eV, L=15, N_part=1024, λ = 0
CIC
FIC+QP
z=2.5
z=5
z=30
k^3P(k)
10^3
10^1
10^−1
10^−3
10^−5
ΔP/P_FIC+QP[%]
0
−50
z=5
z=2.5
10^0
10^1
k[hMpc^−1]

RESULTS



m=10^{-23}eV, L=15, N_{part}=1024, $\lambda = 8e4$
EIC+QP
CIC
z=2.5
z=5
$k^3P(k)$
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
z=5
z=2.5
$\Delta P/P_{CIC}[\%]$
200
100
0
10^0
10^1
$k[h\mathrm{Mpc}^{-1}]$

CONCLUSIONS

- By making some modifications to the MG-PICOLA code it is posible to obtain a tool that solves the structure formation quicker than an other methods taking into account the non-linear interactions for the SFDM model.
- It was posible to observe a difference between Λ-CDM and SFDM model.
- For the axion-like potential case we observe an increase of the amplitude in the MPS in contrast with Λ-CDM
- We notice that even when the extreme case generate an excess in the amplitud in the MPS this excess it’s been reduced significantly at low redshifts.

THANK YOU