清華大學天文系
Department of Astronomy, Tsinghua University

The Wave Nature of Fuzzy Dark Matter

Xinyu Li 李昕宇
Department of Astronomy, Tsinghua University
with Lam Hui, Greg Bryan, Austin Joyce, Tomer Yavetz, Axel Widmark, Daniel Gilman, Alex Laroche

Fuzzy Dark Matter or Wave Dark Matter/Ultralight Axion etc

- ultralight bosons/axions with macroscopic de Broglie wavelength (~kpc).

$$\lambda_{\rm dB} \equiv \frac{2\pi}{mv} = 0.48\,{\rm kpc}\left(\frac{10^{-22}\ {\rm eV}}{m}\right)\left(\frac{250\,{\rm km\,s^{-1}}}{v}\right) = 1.49\,{\rm km}\left(\frac{10^{-6}\ {\rm eV}}{m}\right)\left(\frac{250\,{\rm km\,s^{-1}}}{v}\right)$$

- just like CDM on scales larger than the de Broglie wavelength
- motivated as a solution to the missing satellite problem
- small scale power spectrum is thought to be suppressed !?

Dynamics of FDM

- Schrodinger-Poisson equation

$$i\hbar\left(\partial_t\psi + \frac{3}{2}H\psi\right) = \left(-\frac{\hbar^2}{2ma^2}\nabla^2 + m\Phi\right)\psi$$

- Madelung (fluid) formalism

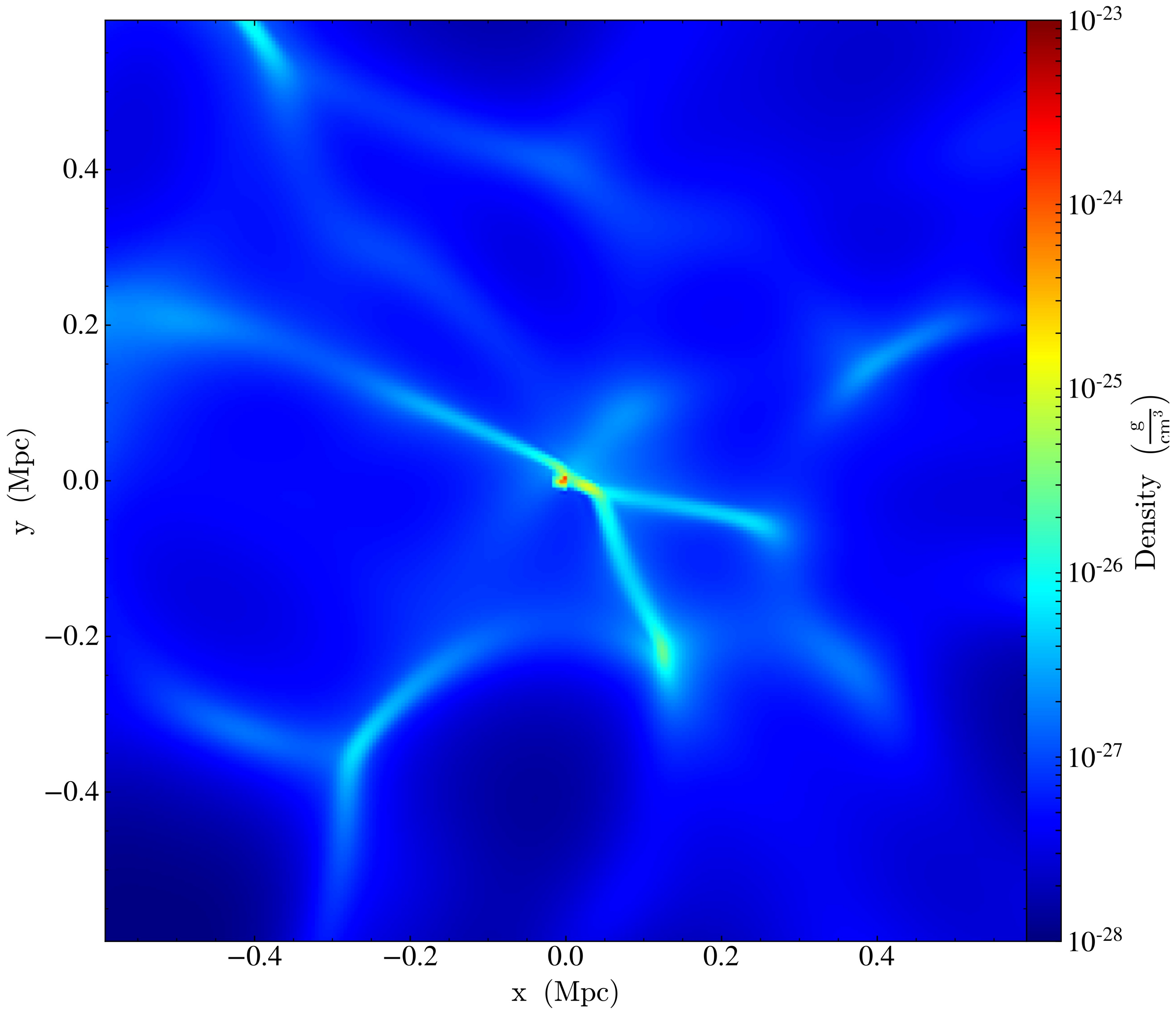
$$\dot{\rho} + 3H\rho + \frac{1}{a}\nabla\cdot(\rho v) = 0\,,$$

$$\dot{v} + Hv + \frac{1}{a}(v\cdot\nabla)v = -\frac{1}{a}\nabla\Phi - \frac{\hbar^2}{2m^2a^3}\nabla p\,,$$

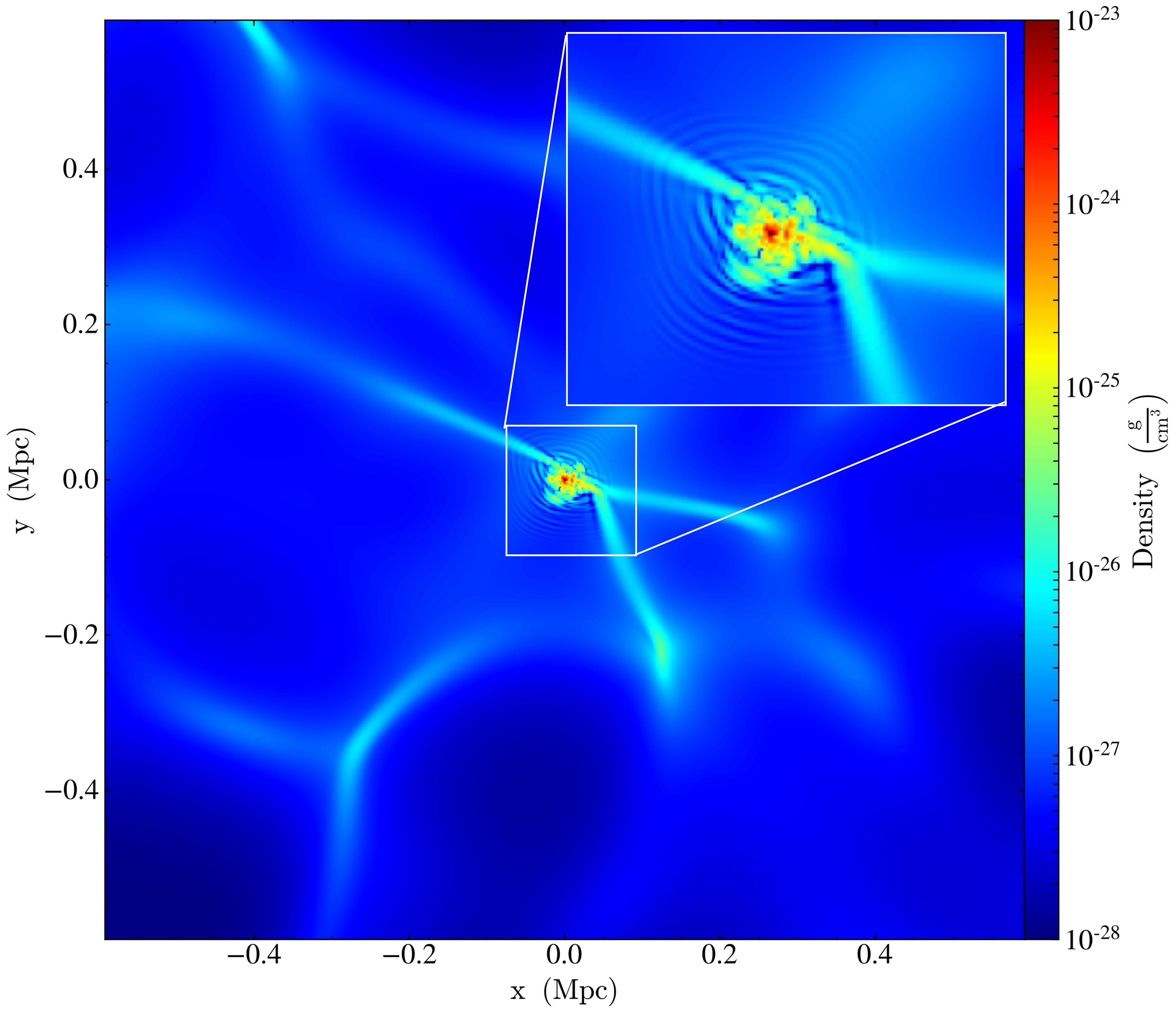
$$\psi \equiv \sqrt{\frac{\rho}{m}}e^{i\theta} \quad , \quad v \equiv \frac{\hbar}{ma}\nabla\theta\,.$$

$$p \equiv -\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}} = -\frac{1}{2}\nabla^2\log\rho - \frac{1}{4}\left(\nabla\log\rho\right)^2\,.$$

Fluid vs Wave Simulations



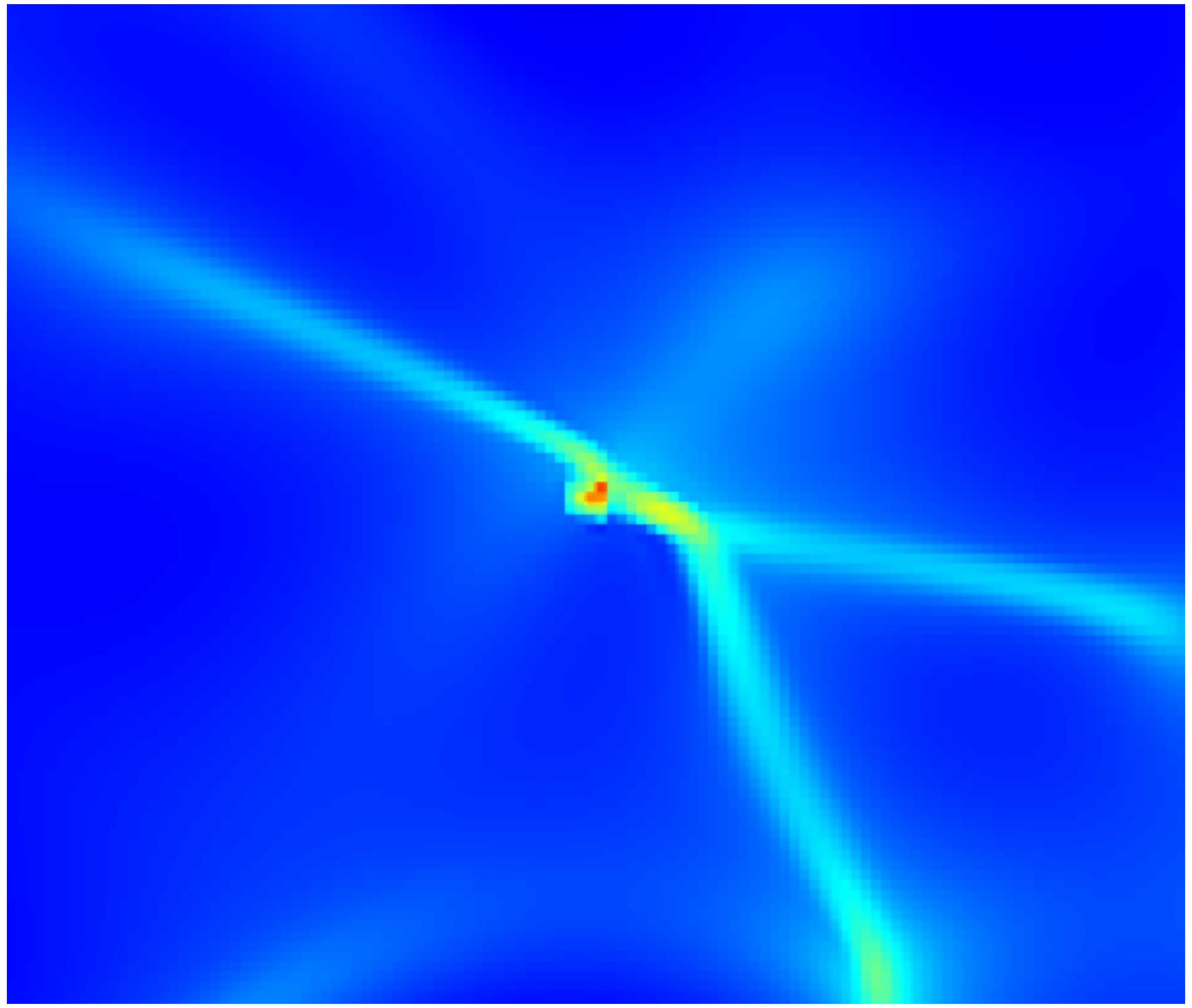
Fluid



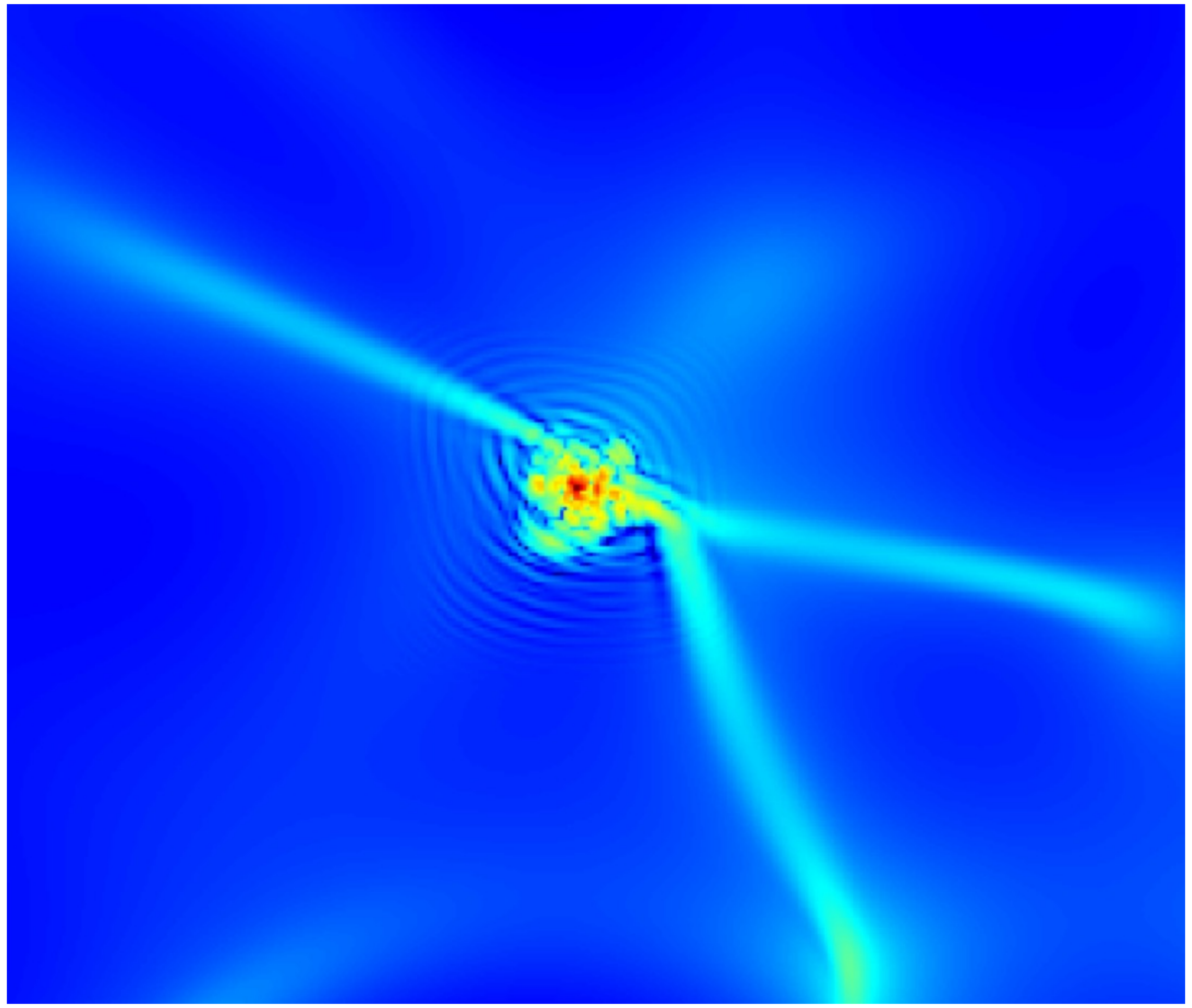
Li et al. 2019

Wave

Fluid vs Wave Simulations



Fluid



Wave

The wave nature of FDM leads to interesting new phenomena!

Method	Constraint	Sources of systematic uncertainties	Refs.
Lyman-alpha forest	$m > 3 \times 10^{-21}$ eV	Ionizing background/temp. fluctuations	1
Density profile	$m > 10^{-21}$ eV	Baryonic feedback/black hole	2
Satellite mass	$m > 6 \times 10^{-22}$ eV	Tidal stripping	3
Satellite abundance	$m > 2.9 \times 10^{-21}$ eV	Subhalo mass function prediction	4

References: 1=Iršič et al. (2017), Kobayashi et al. (2017), Armengaud et al. (2017), 2=Bar et al. (2018), 3=Safarzadeh & Spergel (2019), 4=Nadler et al. (2020). See text on the methodology and systematic uncertainties of each constraint.

Vortex Lines

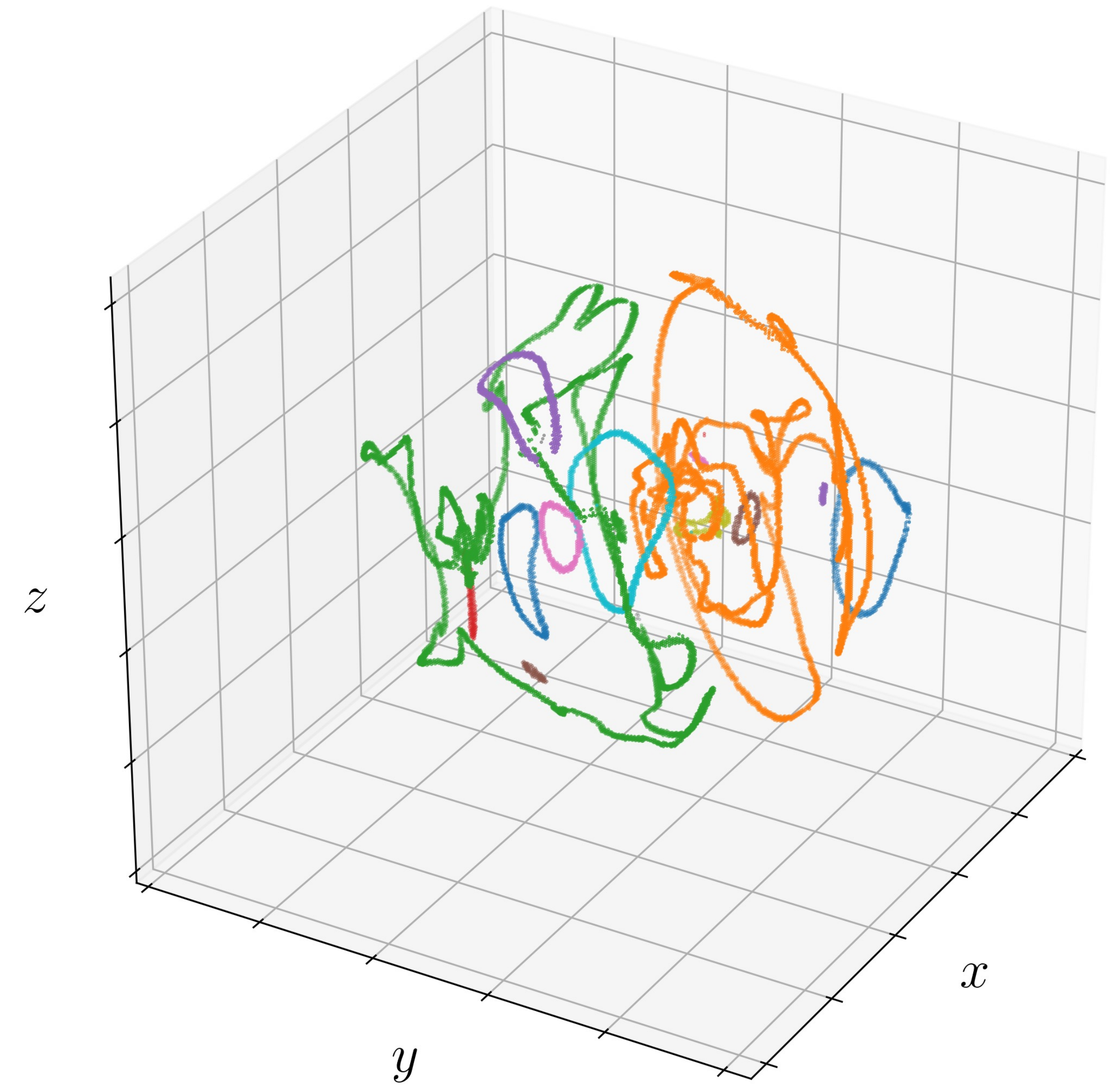
- Let us examine the Madelung representation again

$$\psi \equiv \sqrt{\frac{\rho}{m}} e^{i\theta} \quad , \quad v \equiv \frac{\hbar}{ma} \nabla \theta \, .$$

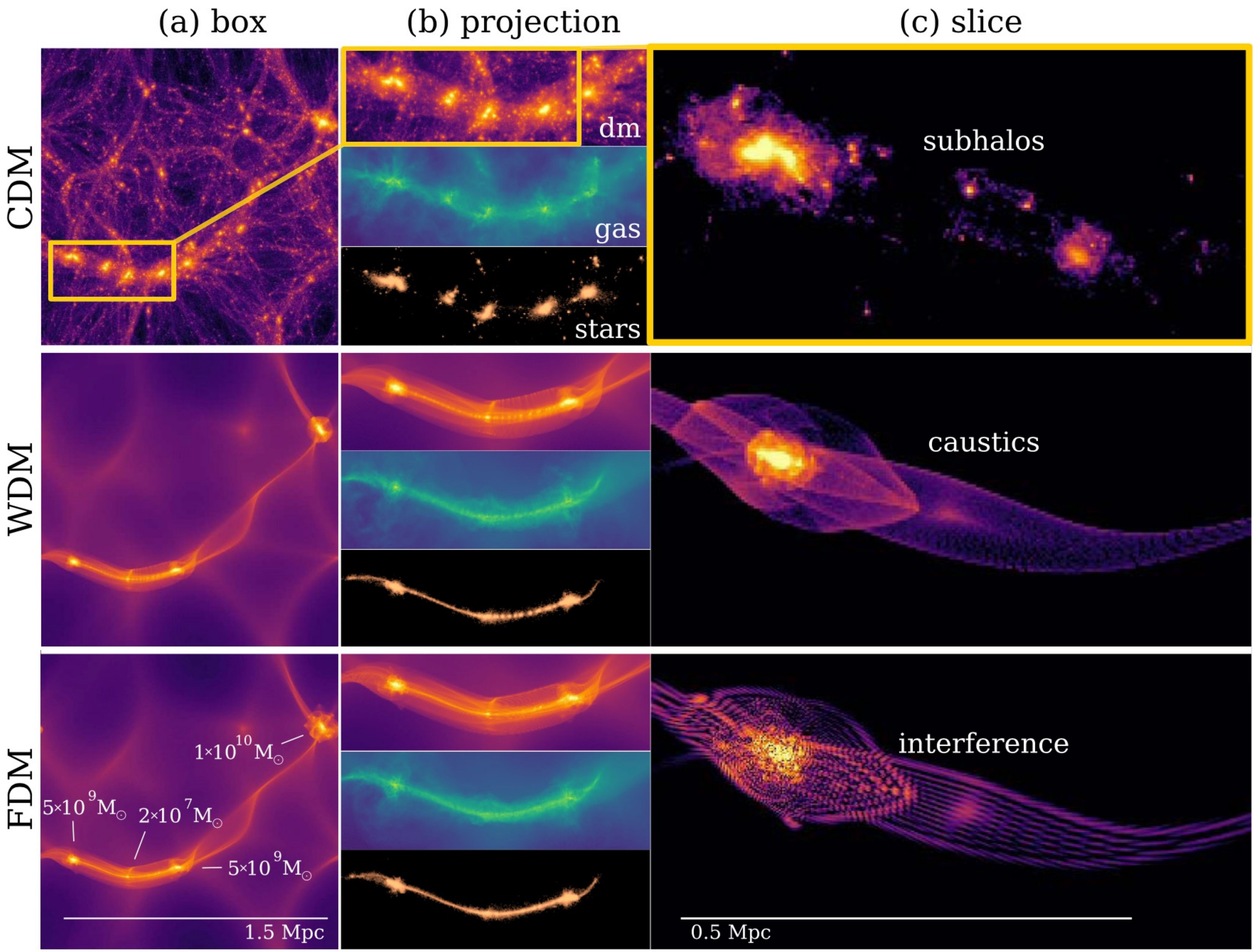
- The phase is not well defined when $\Psi = 0$ => topological defects.

- The typical size of vortices is found to be the de Broglie wavelength.

- Expect to have one vortex line per de Broglie wavelength.



Hui et al. 2021



Mocz et al. 2019

Granules: MORE Small Scale Structure

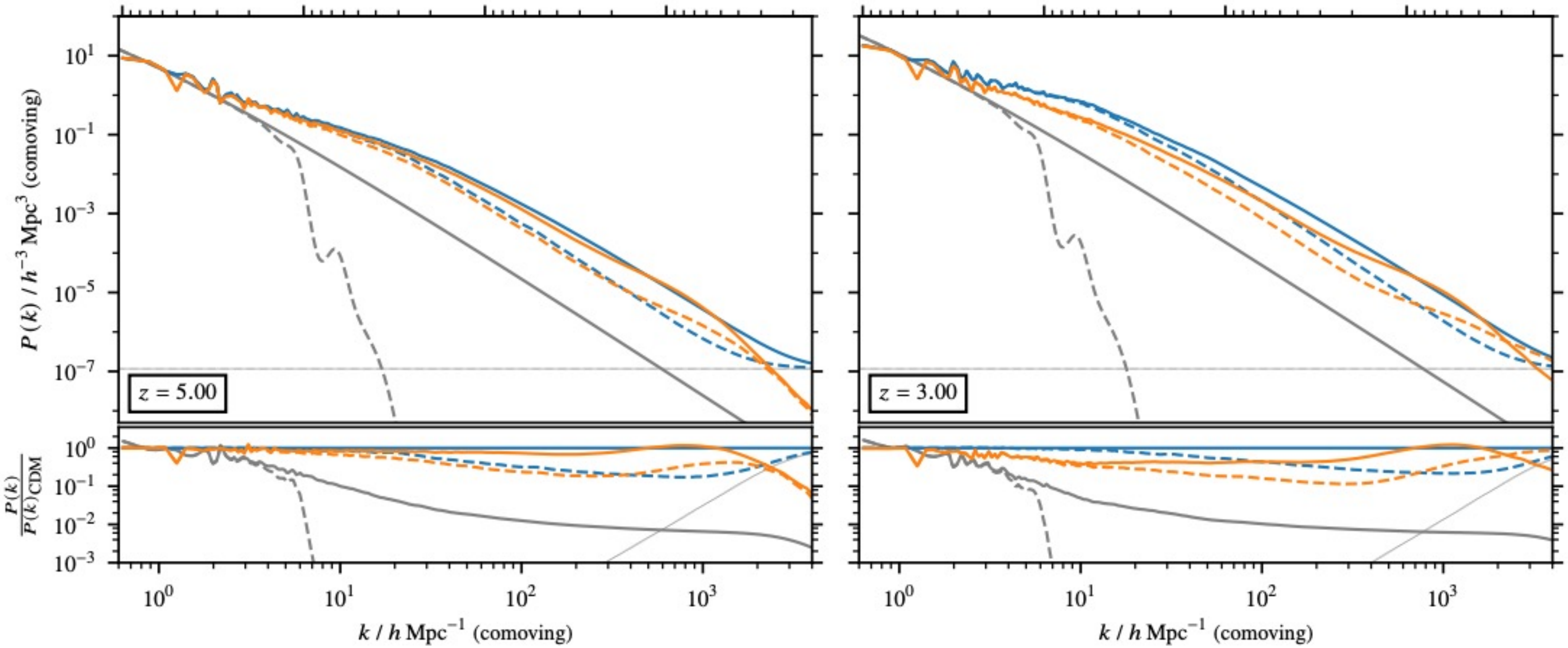
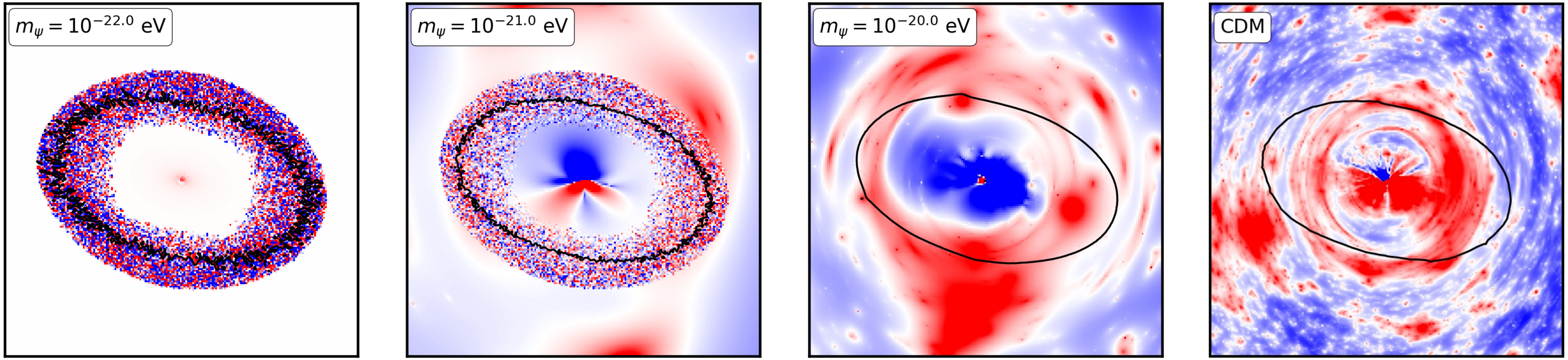


Figure 6. Four-way comparison of dark matter power spectra at different redshifts for cosmological FDM (wave) and CDM (N-body) simulations with FDM and CDM ICs in $L = 10\,h^{-1}$ Mpc boxes. The power spectrum evolved using linear perturbation theory is shown for comparison. The lower panels show the ratio of the power spectra to the CDM result (N-body simulation with CDM ICs). For $z = 63$, the dashed line additionally indicates the FDM Jeans scale (eq. (13)). Faint dotted lines show the shot noise limits of the N-body simulations; the power spectrum cannot be measured accurately once this limit is reached.

May & Springel 2023

Lensing Flux Ratio

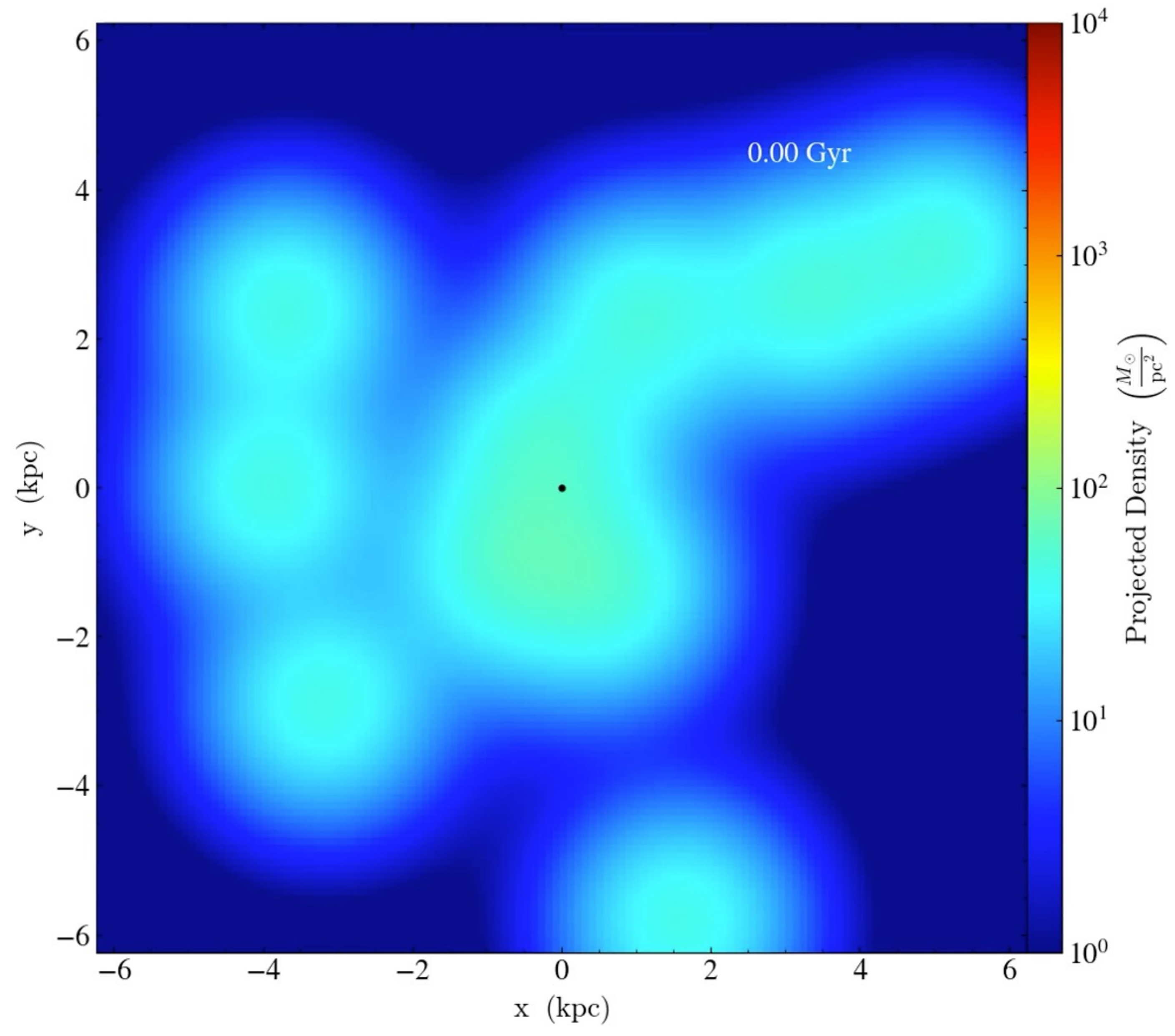
- analyze the flux ratios in a sample of 11 quadruple-image strong gravitational lenses
- $m<10^{-21.5}$eV is disfavoured

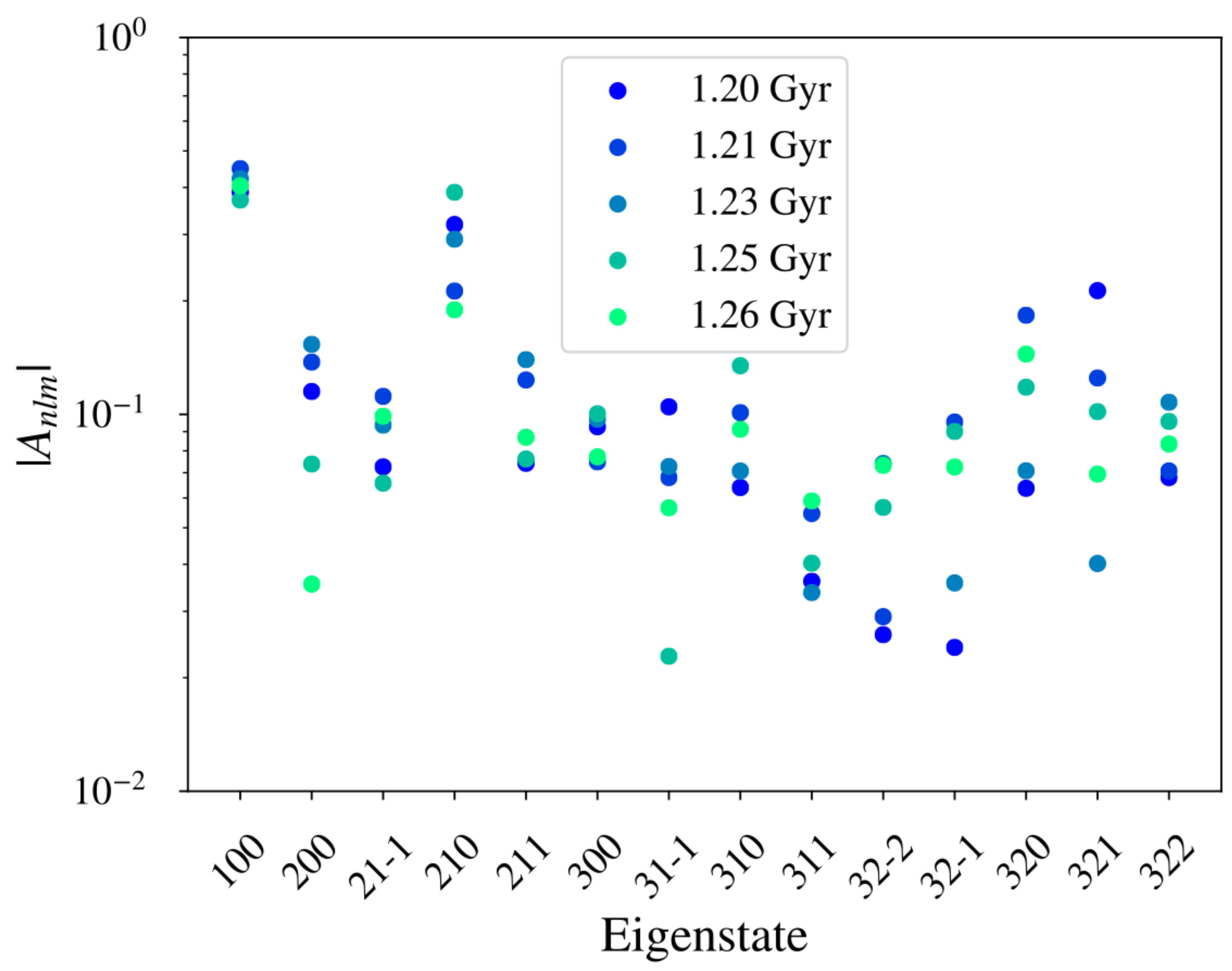


Laroche et al. 2022

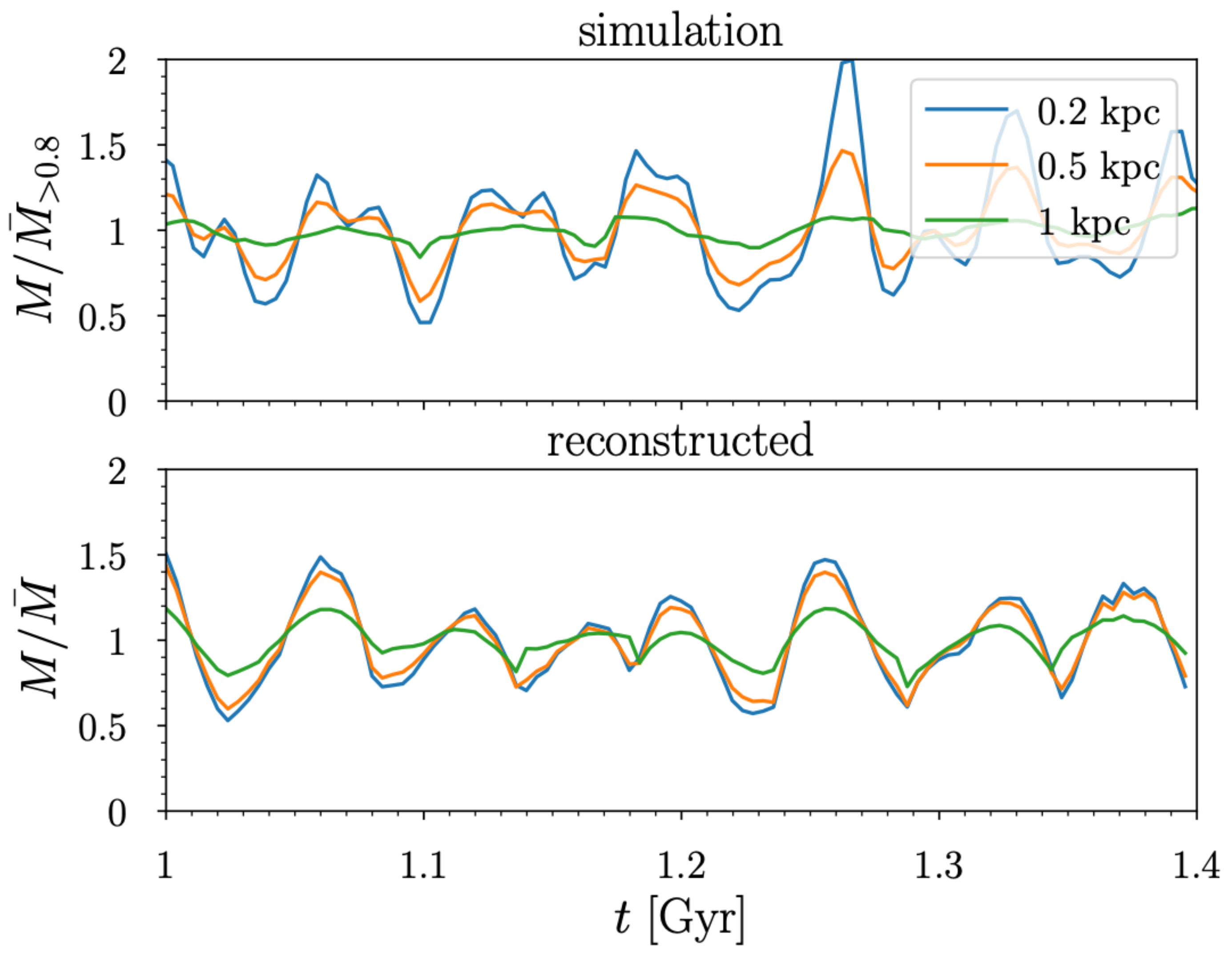
Soliton Oscillation and Random Walk

The soliton is observed to oscillate and random walk around the halo centre due to the interference between eigenstates.





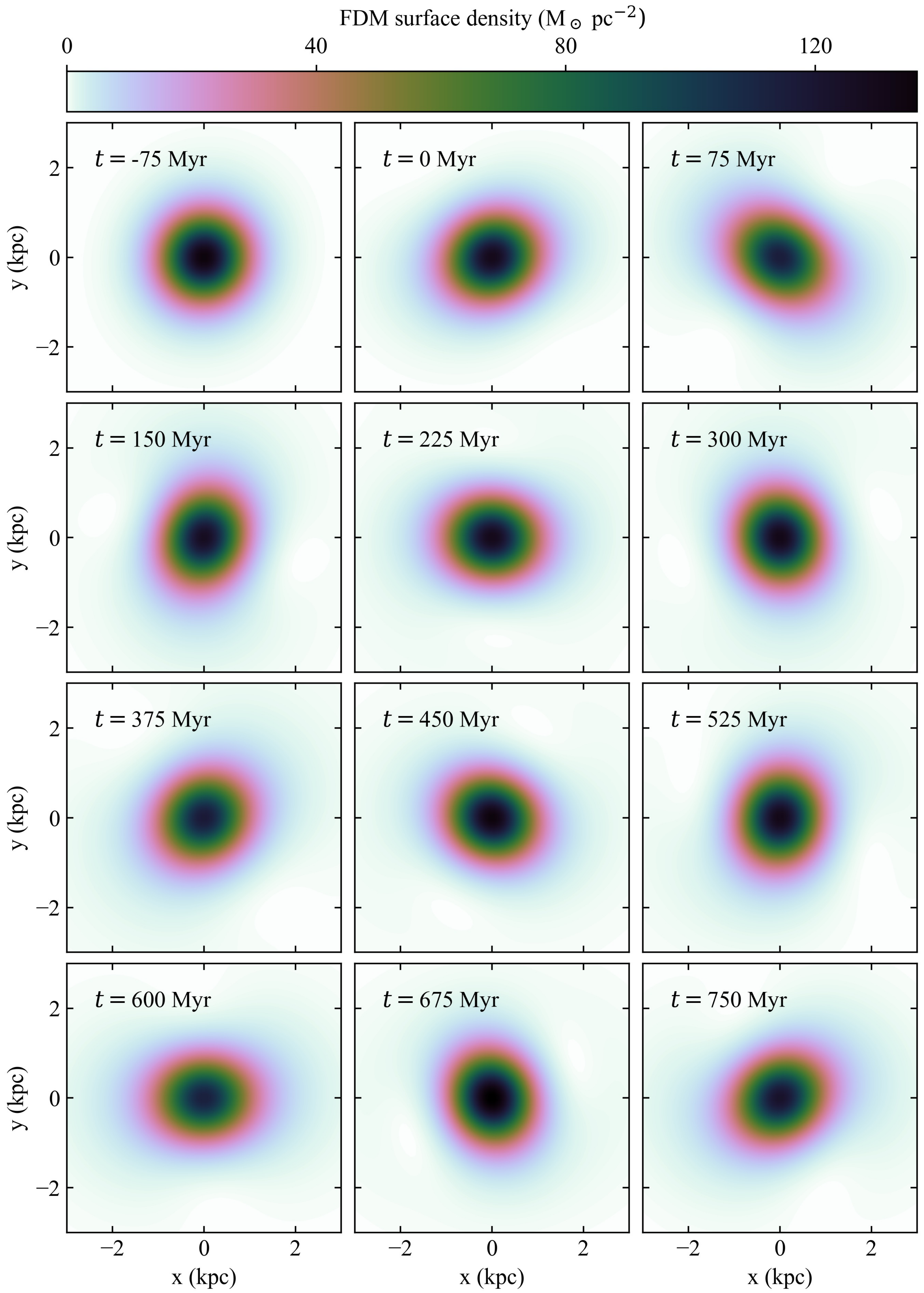
Eigenstates decomposition

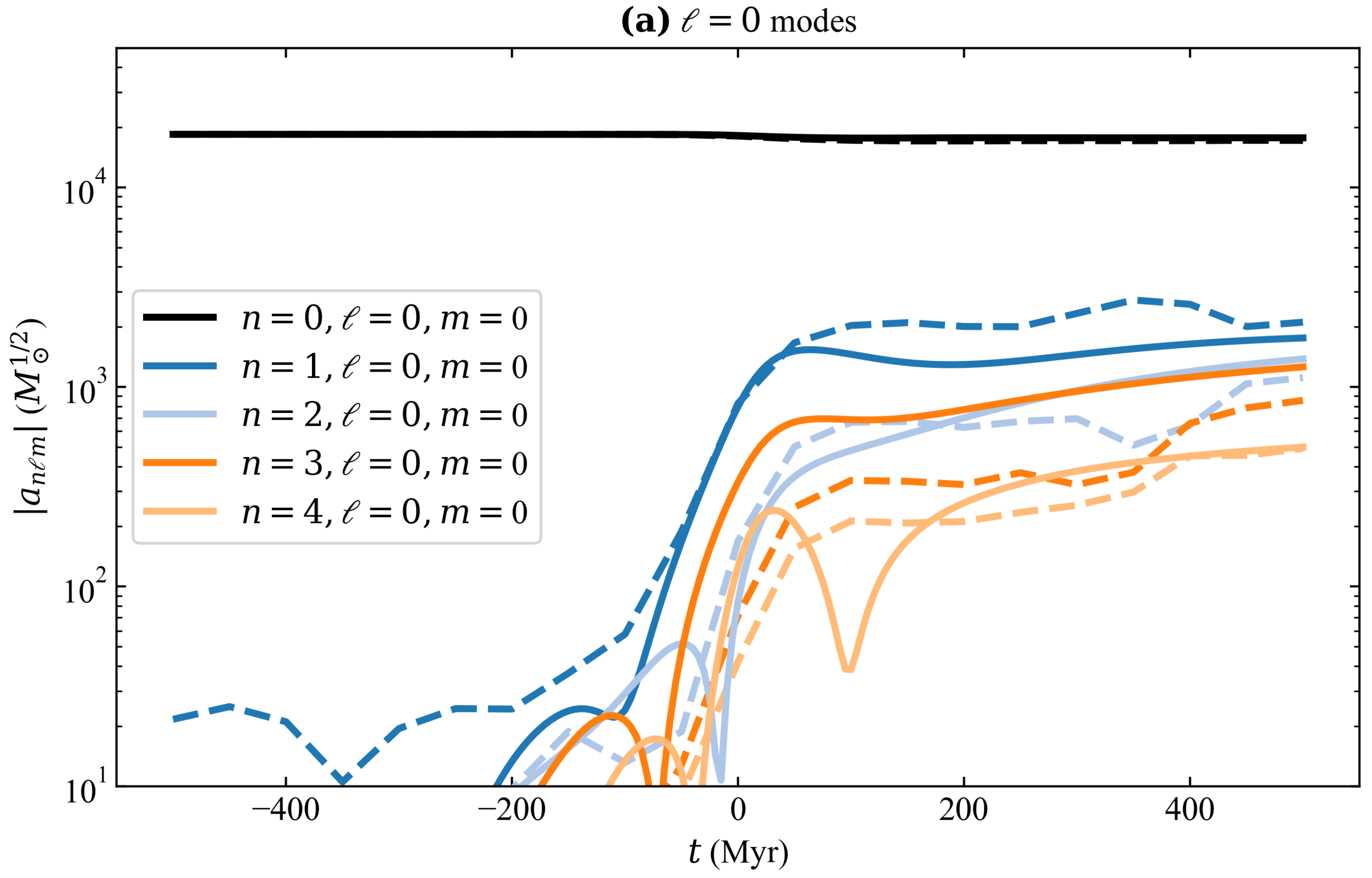


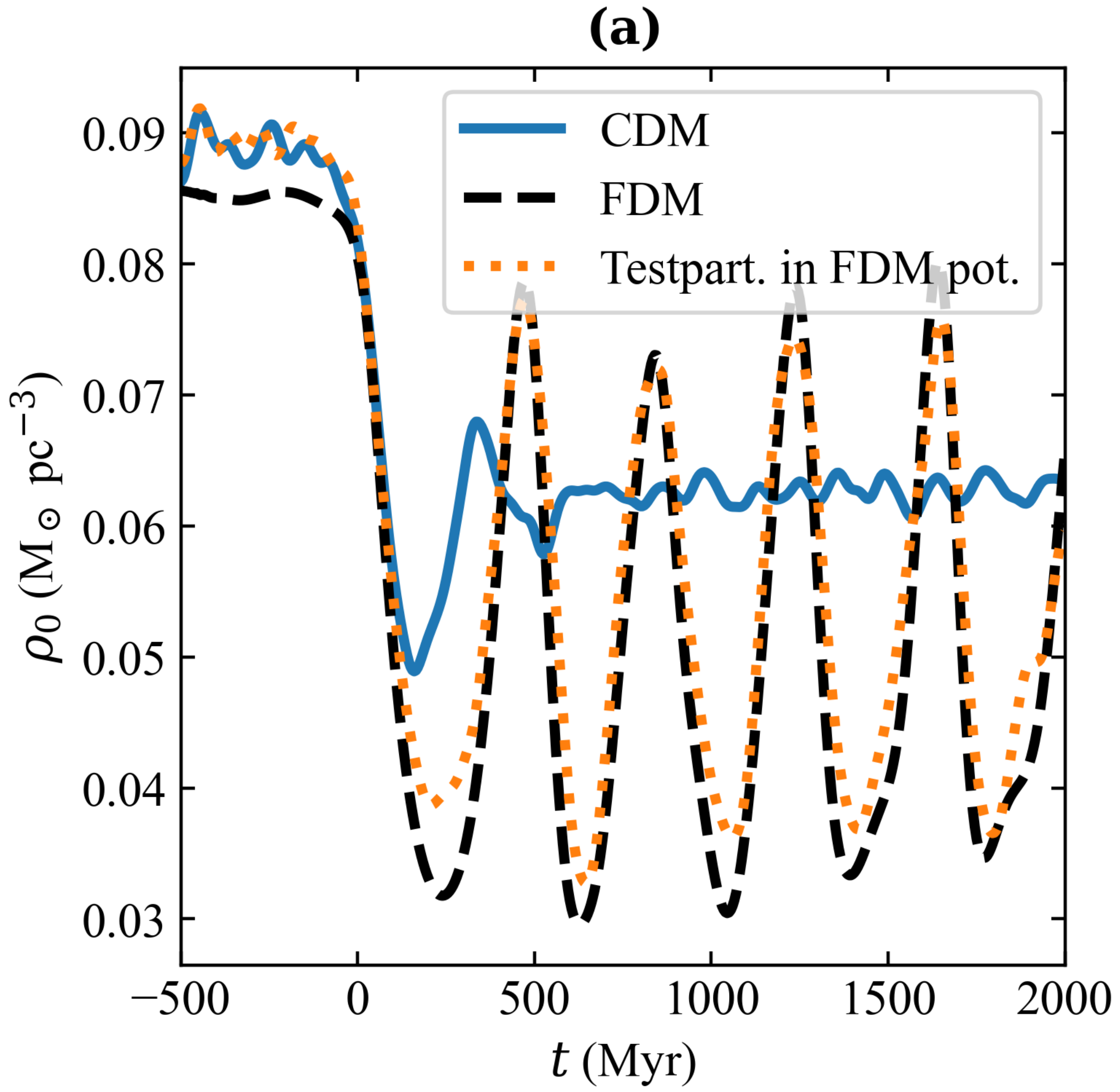
Soliton oscillation

Li et al. 2021

Tidally Perturbed Dwarf Galaxies

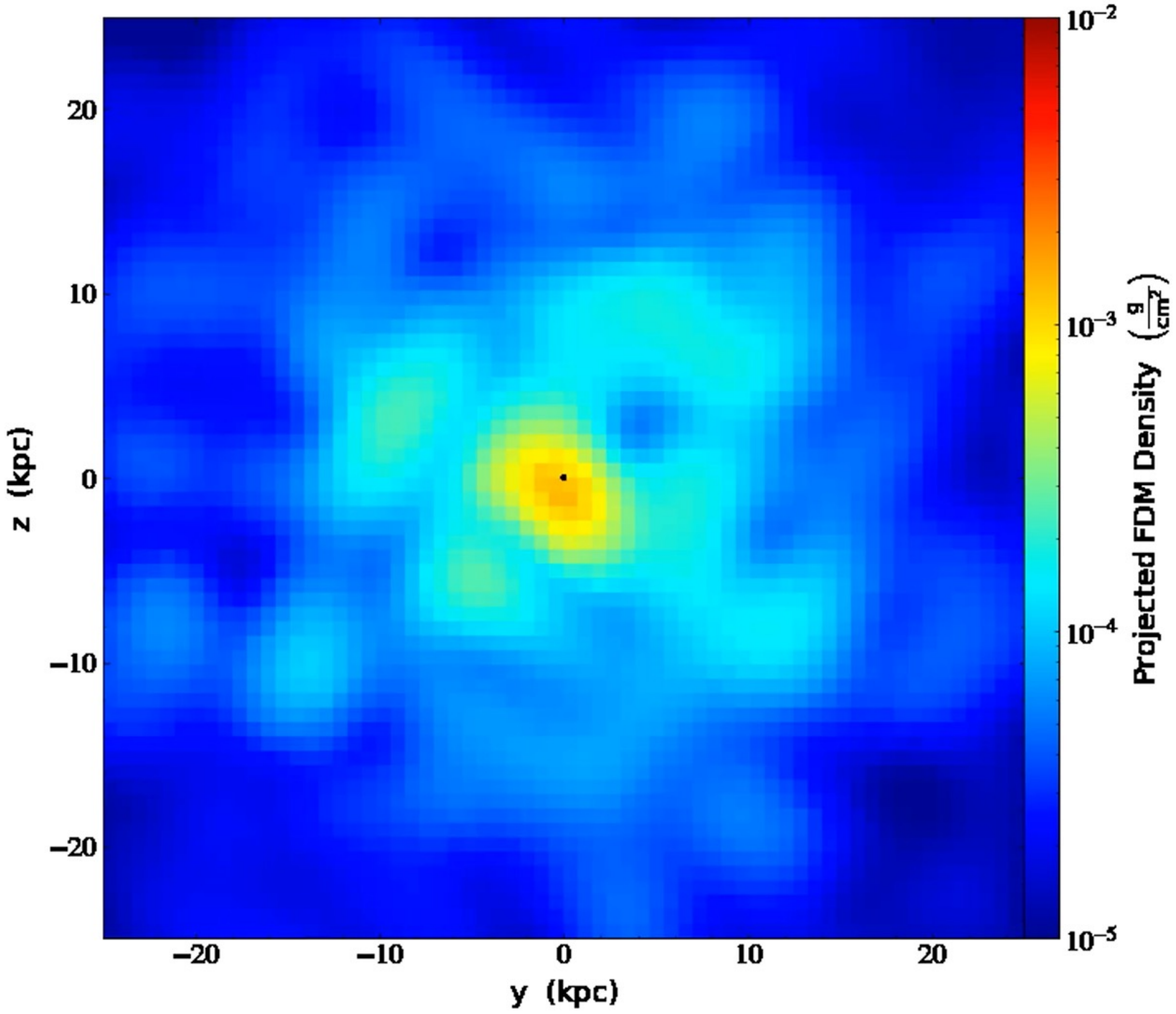






Widmark et al. 2023

Heating of Clusters

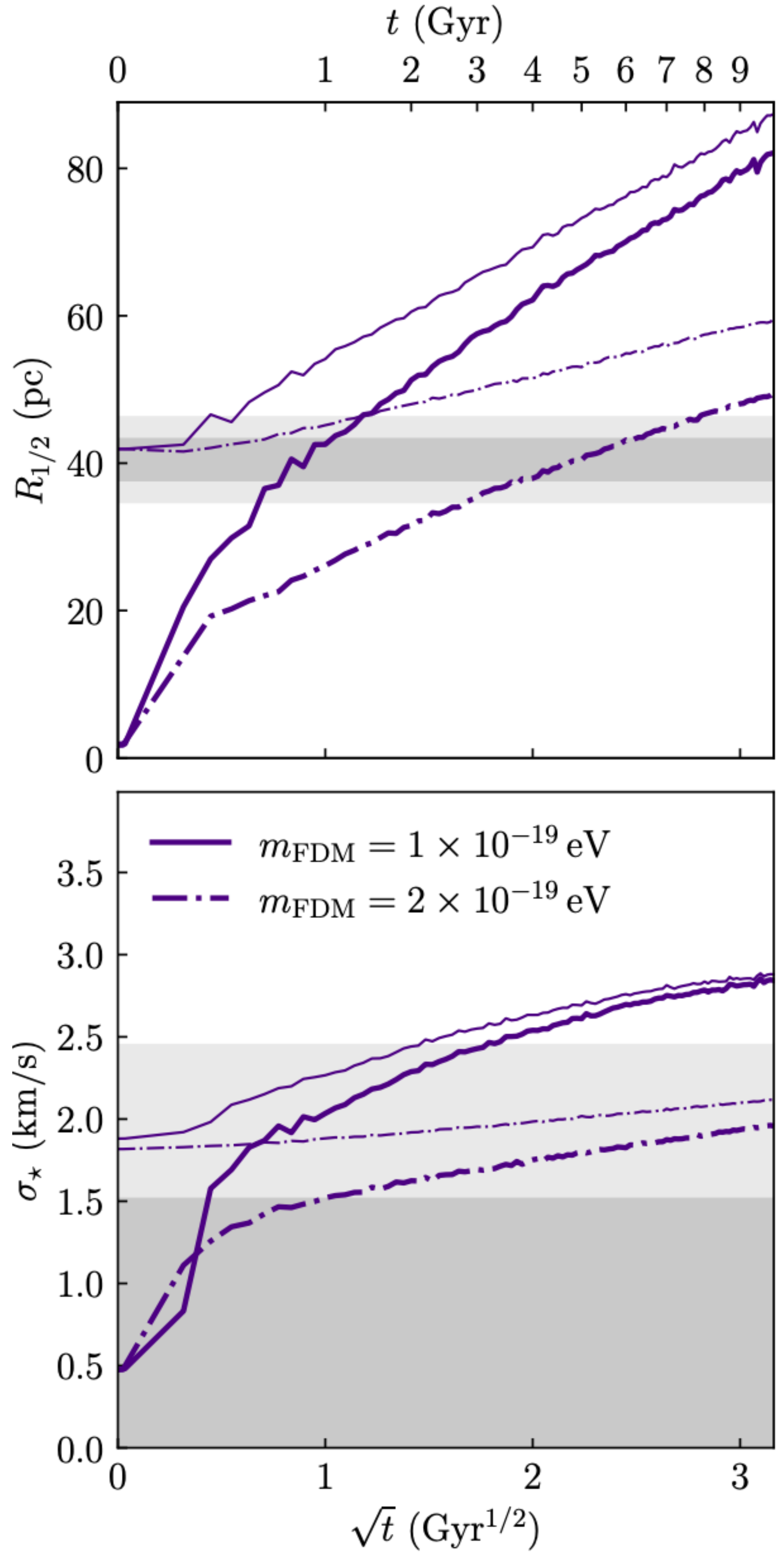


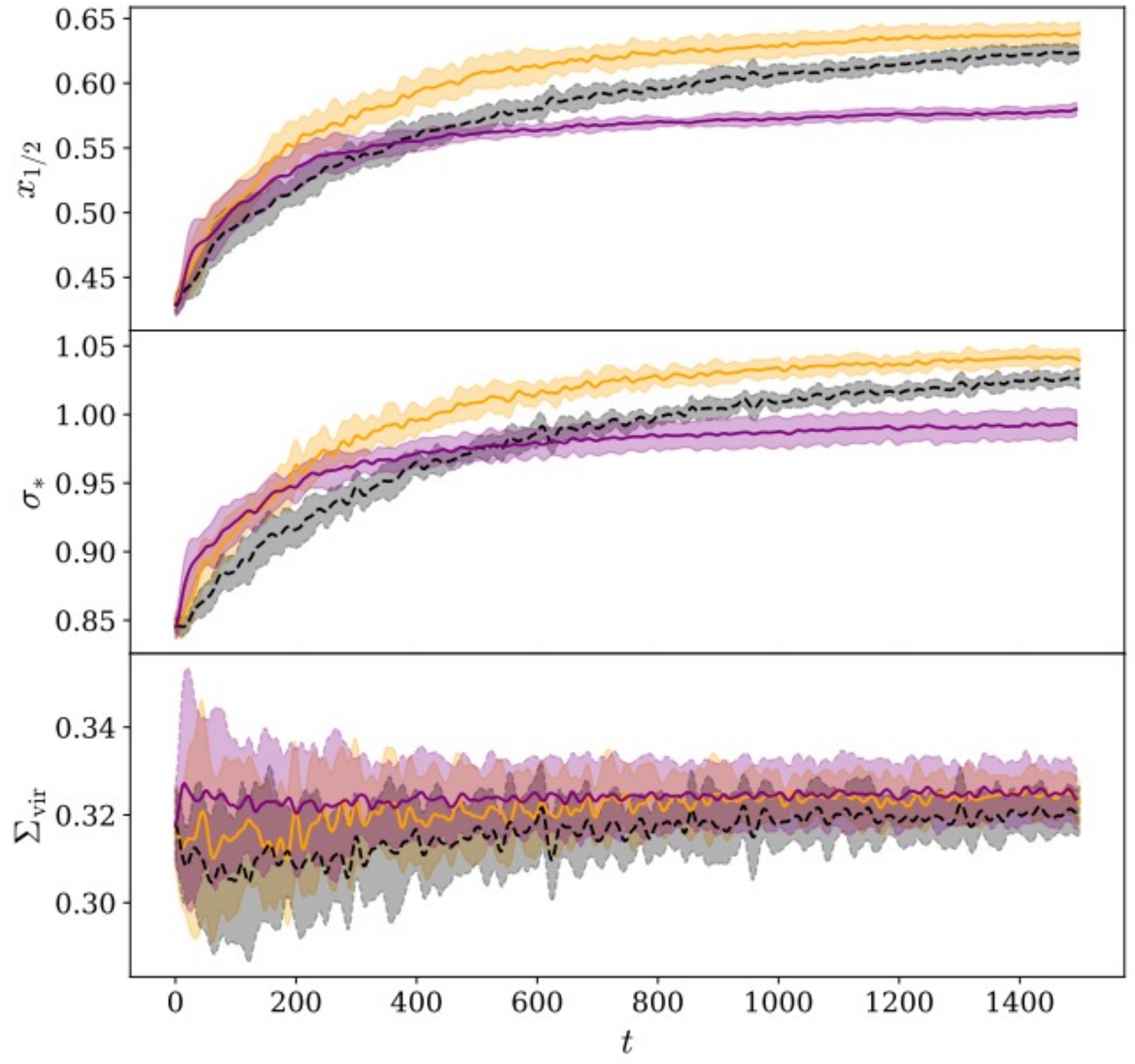
Heating of Clusters

- Dalal & Kravtsov (2022) excluded m<3*10^{-19} eV from Segue 1 and Segue 2
- Treat the heating as random scattering off quasi-particles with de Broglie size

$$\Delta\sigma_\star^2 \simeq 9\left(\frac{\sigma_\star}{\sigma_{\rm dm}}\right)^4\left(\frac{\hbar}{m}\right)^3\frac{t}{r_{1/2}^4}.$$

- applicable when the cluster size >> de Broglie wavelength, what if the cluster size is so small?
- Zupancic & Widrow (2023): treat FDM as quasi-particles overestimate the heating





Conclusion

- The wave nature of FDM has shown many novel phenomena that contradict our simple intuition
- It also opens a new window to test and constrain the FDM model
- More work is needed to understand it before we can obtain robust constraints of the model

Thank you for your attention!