Fuzzy Dark Matter: Dead or Alive?!?

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Cosmology and Lambda Cold Dark Matter

In Cosmology, the standard model is ΛCDM.

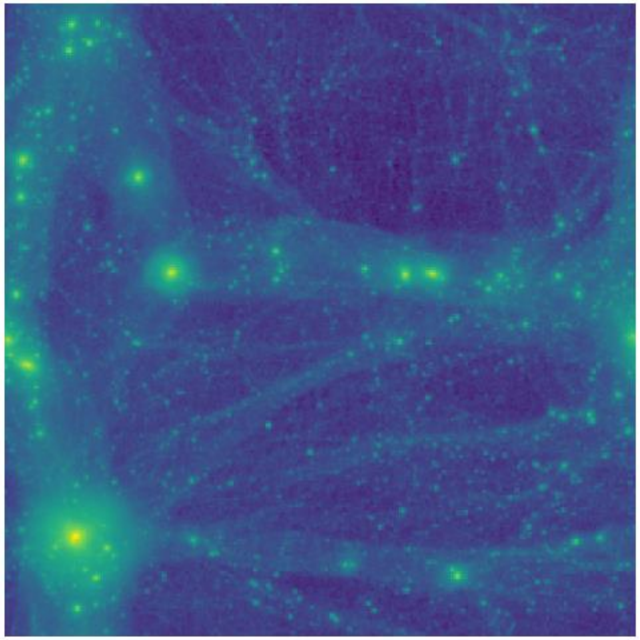

Figure: Simon May and Volker Springel (2021)

Simulations of CDM, both N-Body and fluid, suggest that it's a good theory, on scales (much) bigger than galaxies.

Problems with CDM

Some small-scale structures (in galaxies) characteristic to CDM are not observed (Hui et al. [2017]).

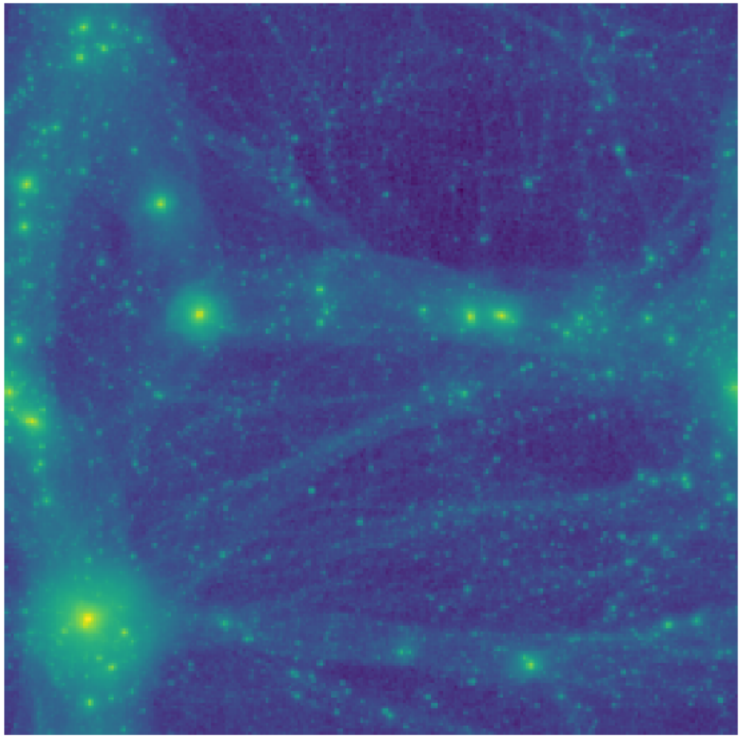

Figure: May and Springel [2021]

"Cusp-core" Problem (Weinberg et al. [2015]):

Predict cuspy galaxies, but observe more core-like density profiles.

Problems with CDM

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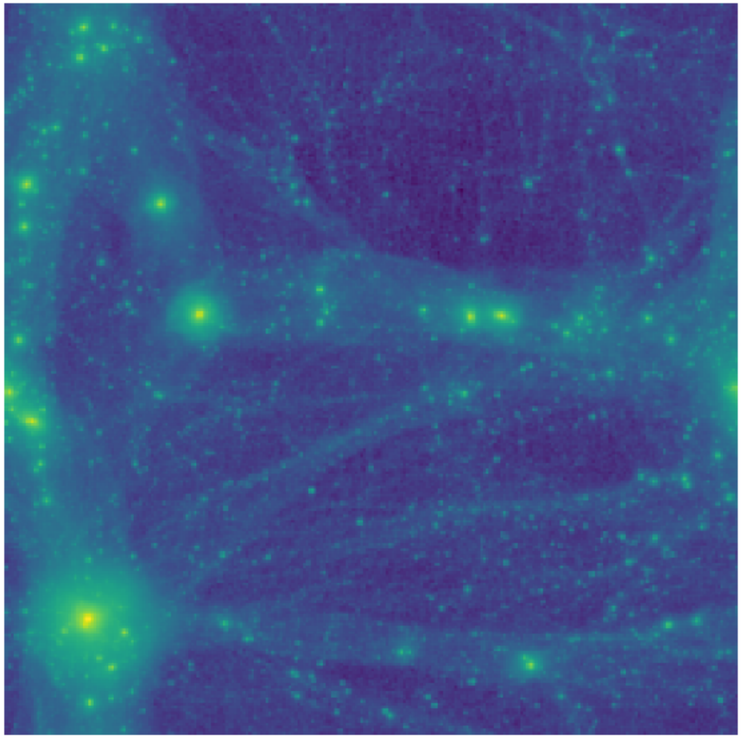


Figure: May and Springel [2021]

"Missing satellites" (Weinberg et al. [2015]):

Predict thousands of sub-halos, but we observe very few.

We Want Something Smoother

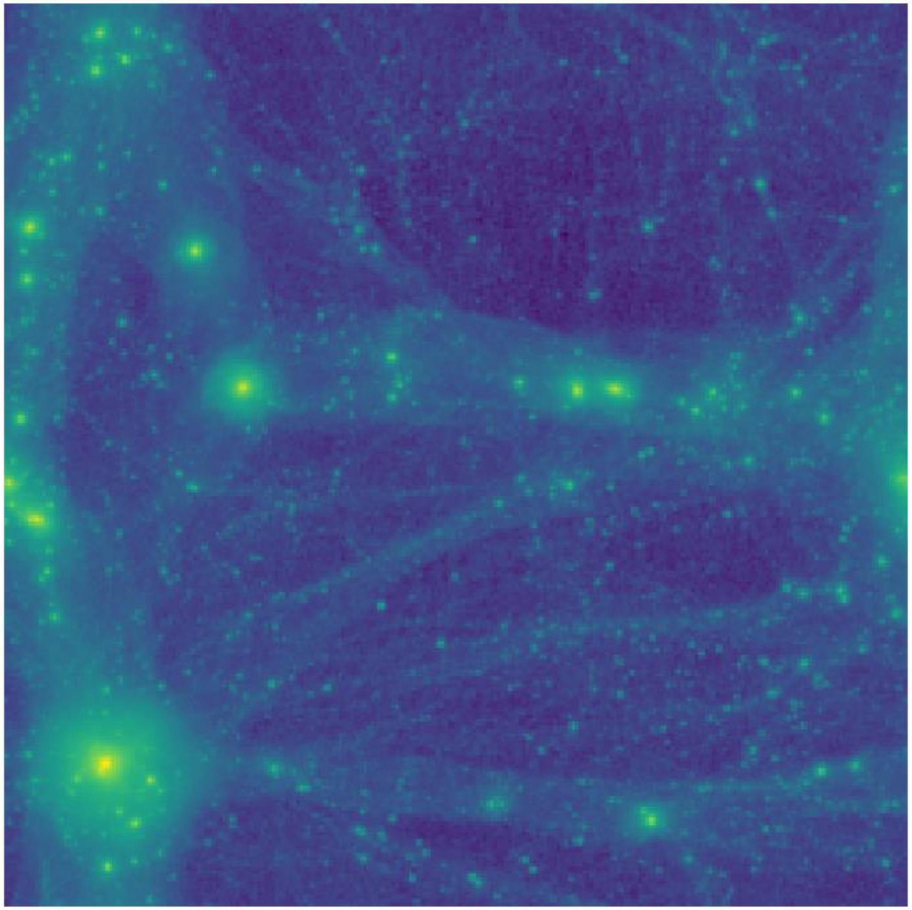


Figure: May and Springel [2021]

We Want Something Smoother

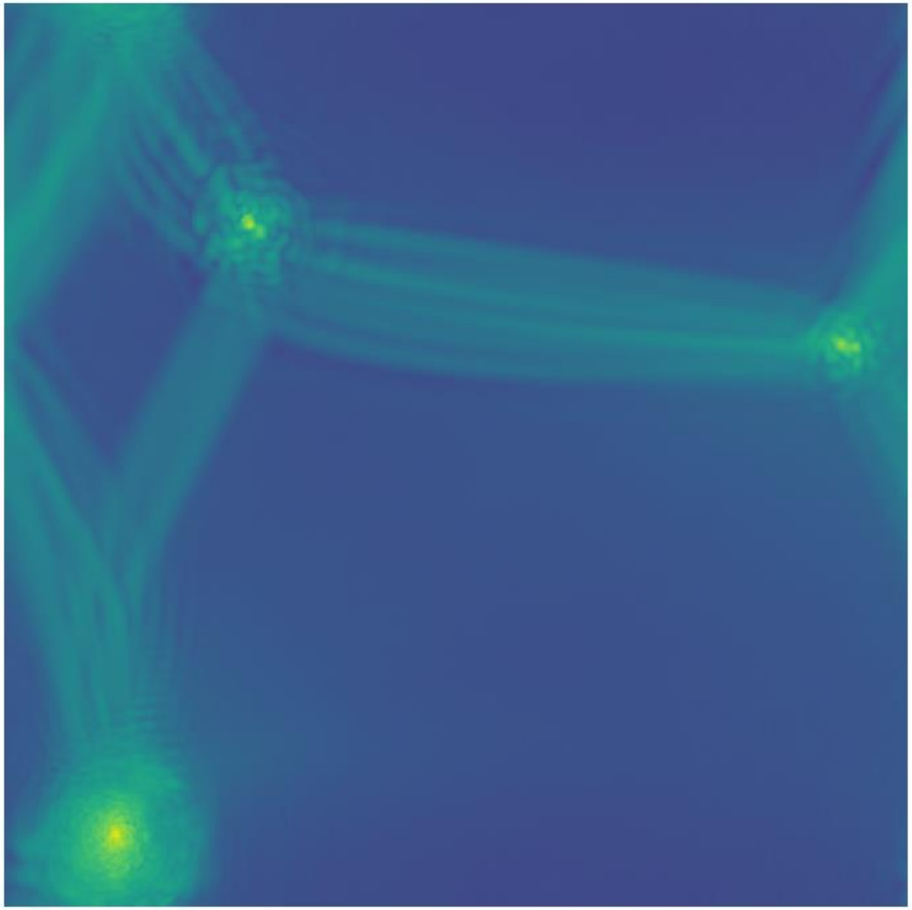


Figure: May and Springel [2021]

Wave Dark Matter

Enter **Wave dark matter**.

Consider a particle so light, it's de Broglie wavelength is on the scale of light years.

$$\lambda_{\mathrm{deB}} = \frac{h}{mv} \tag{1}$$

These **ultra-light** particles are referred to as **"axion-like"** and their theoretical motivations arise from string theory and the QCD axion (Hui [2021]).

Typical masses are considered to be $m \lesssim 30\,\mathrm{eV}$ (Hui [2021]).

What is FDM?

Fuzzy Dark Matter (FDM) is what we call wave dark matter in the mass range (Hui [2021]):

$$m = 10^{-22}\mathrm{eV} - 10^{-20}\mathrm{eV}$$

At this mass, the de Broglie wavelength becomes astrophysical.

The Schrodinger-Poisson System

It turns out ultra-light dark matter behaves like a wave:

Schrodinger-Poisson System (Widrow and Kaiser [1993])

FDM follows two well known equations:

$$\begin{cases} i\hbar\frac{\partial\psi}{\partial t} = \left[\frac{-\hbar^2}{2m}\nabla^2 + \Phi(\vec{r})\right]\psi \\ \nabla^2\Phi = 4\pi G\rho \end{cases} \tag{2}$$

The norm-square of wavefunction is interpreted as the number density, so:

$$\rho = m|\psi|^2$$

Cosmological Simulations

FDM does a good job of erasing small scale structure in cosmological simulations.

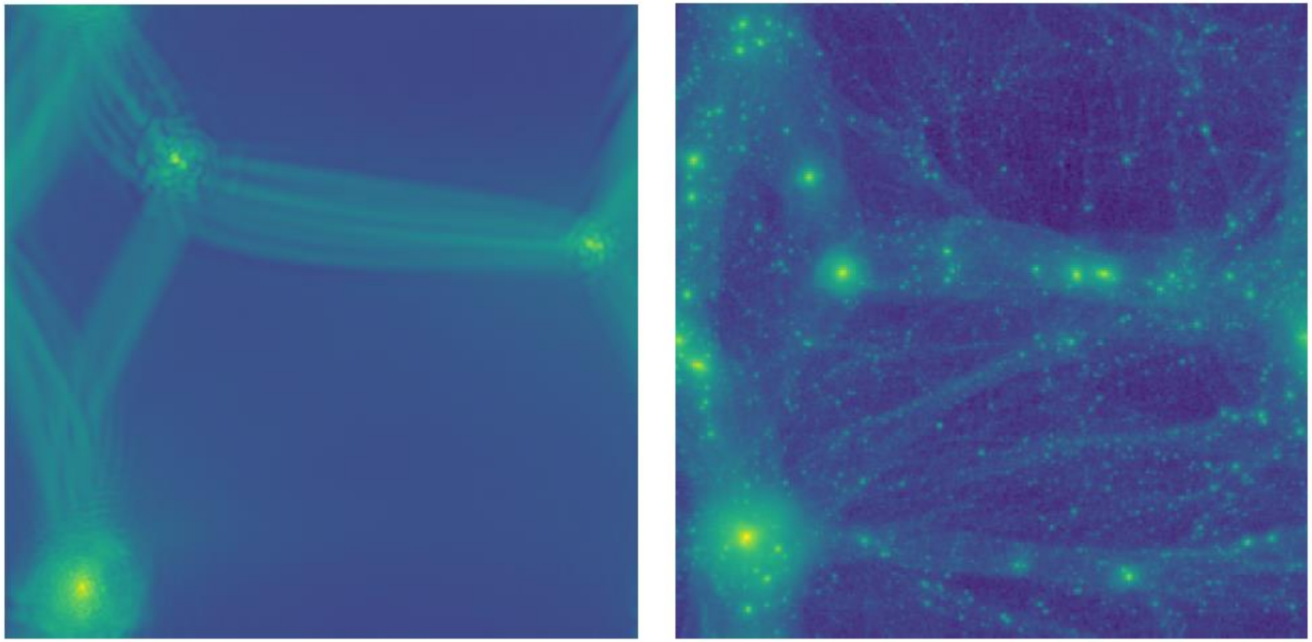


Figure: FDM (left) vs CDM (right). Simon May and Volker Springel (2021)

The Case Against FDM

Recently, Neal Dalal and Andrey Kravtsov released a paper claiming they had excluded FDM as a possible candidate.

Their Claim:

Granules (density fluctuations) in FDM dynamically heat test particles enough to cause galaxies to expand over time, and the necessary mass to suppress this phenomenon is $m \approx 10^{-19}\mathrm{eV}$. This excludes the FDM mass range $m = 10^{-22}\mathrm{eV} - 10^{-20}\mathrm{eV}$. (Dalal and Kravtsov [2022])

The Case Against FDM: Granules?

Granules arise from FDM wave-interference, as seen via **Fourier Expansion**:

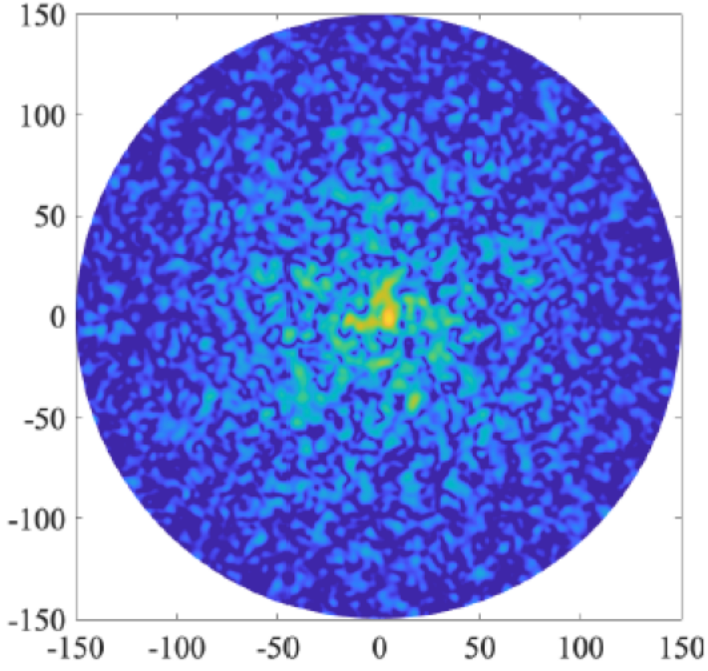


Figure: Dalal and Kravtsov [2022]

(1D and time-independent, for illustration)

$$\psi(x) = \sum_k \hat{\psi}_k e^{ikx}$$

$$\Rightarrow |\psi|^2 = \psi^* \psi$$

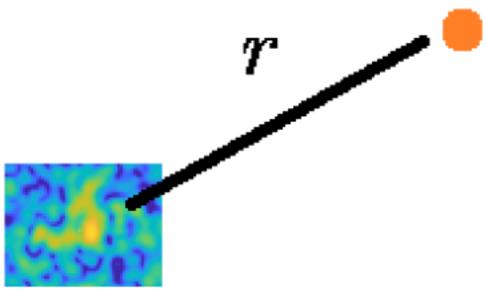
$$= \left(\sum_{k'} \hat{\psi}_{k'} e^{-ik'x} \right) \left(\sum_k \hat{\psi}_k e^{ikx} \right)$$

$$= \sum_k \hat{\psi}_k^2 + \boxed{\sum_{k \neq k'} \hat{\psi}_k \hat{\psi}_{k'} e^{i(k-k')x}}$$

The Case Against FDM: Dynamical Heating?

Granules **"heat"** test particles via gravity (Dalal and Kravtsov [2022]):

$$\delta a = \frac{G \delta M}{r^2}$$



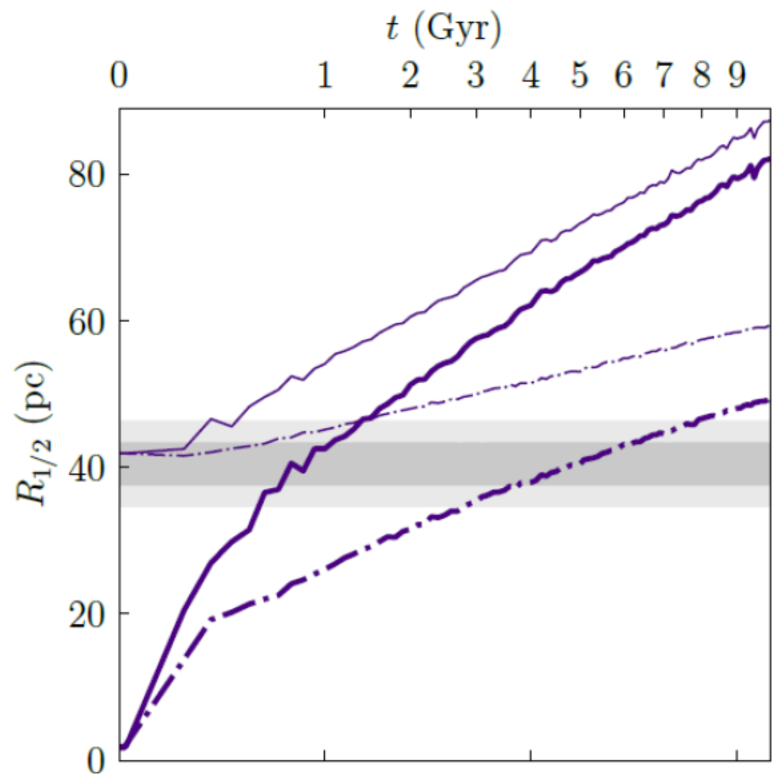


Figure: Dalal and Kravtsov [2022]

A problem?

In Dalal and Kravtsov [2022], the particles (stars) are being treated as **test particles.**

This may pose a problem, in a system with comparable FDM and particle contributions.

Our goal

We wish to create **fully self-consistent** simulations of a FDM and particle system. Meaning:

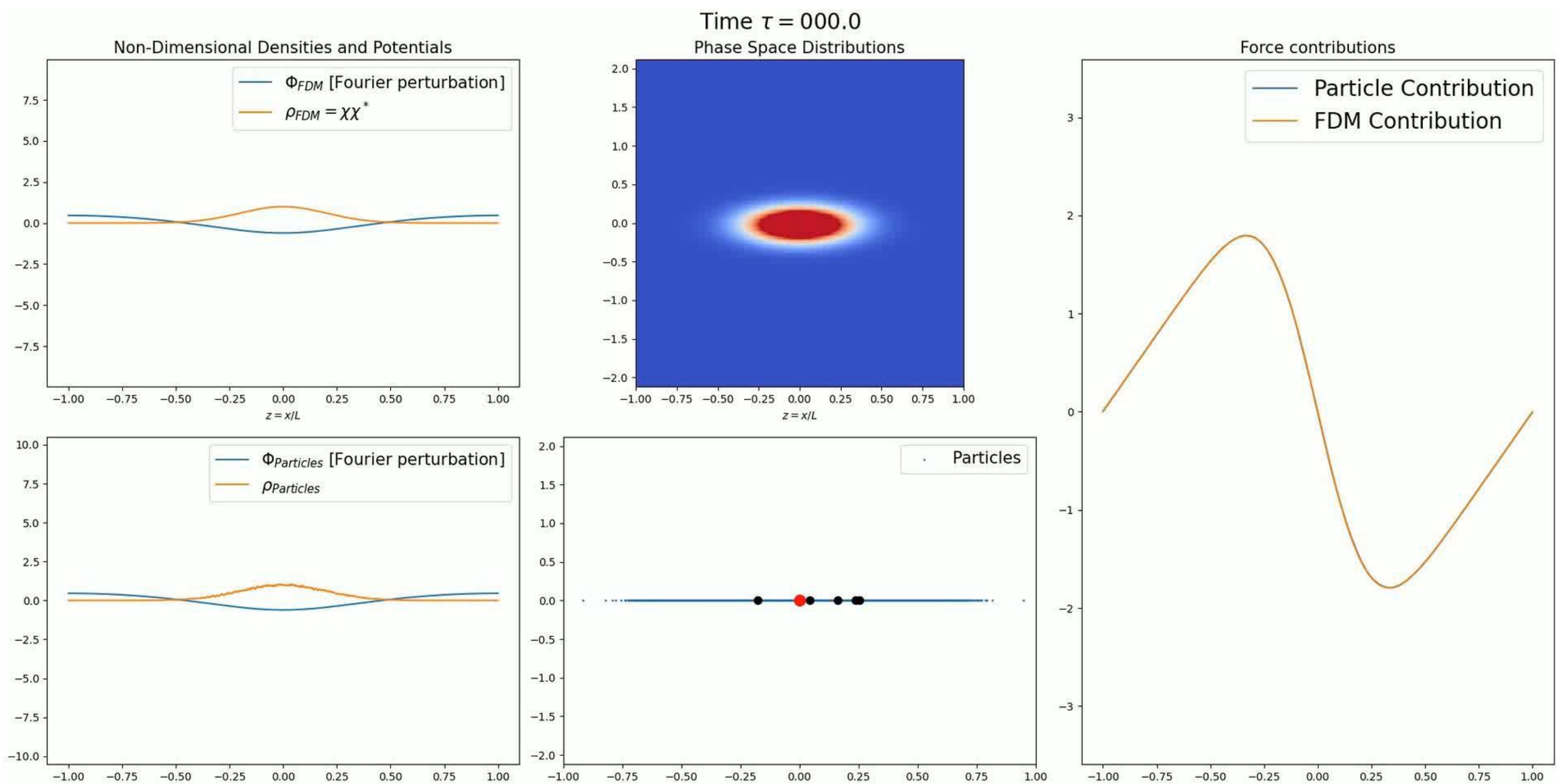
The FDM and particles are both contributing to the potential in the Poisson Equation:

$$\nabla^2\Phi = 4\pi G\rho = 4\pi G\left(\rho_{\mathrm{FDM}} + \rho_{\mathrm{particles}}\right) \tag{3}$$

In a system of comparable FDM and particle (total) masses, one should not be negligible.

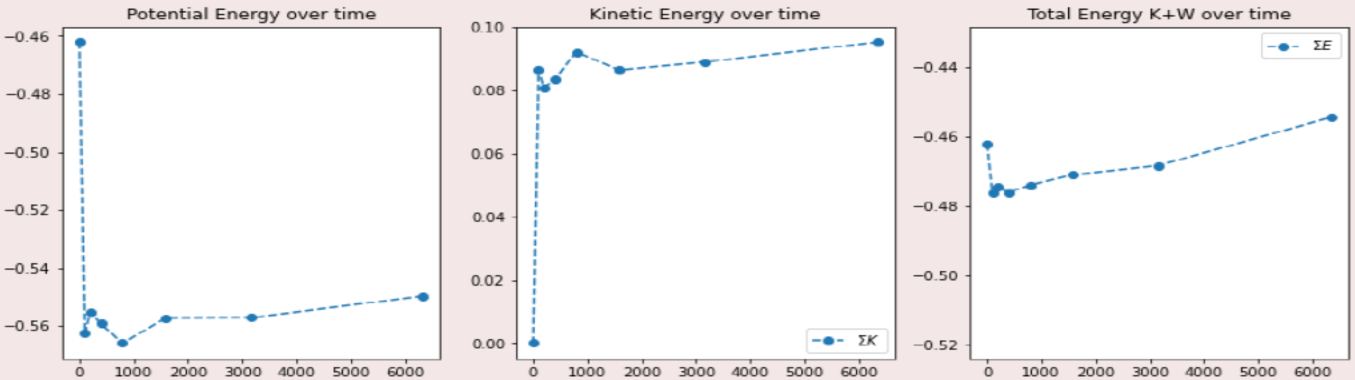
Preliminary Results

Our time evolution mixes a **"Kick-Drift-Kick"** (for Schrodinger) and a **Fast-Fourier-Transform (FFT)** method (for Poisson).

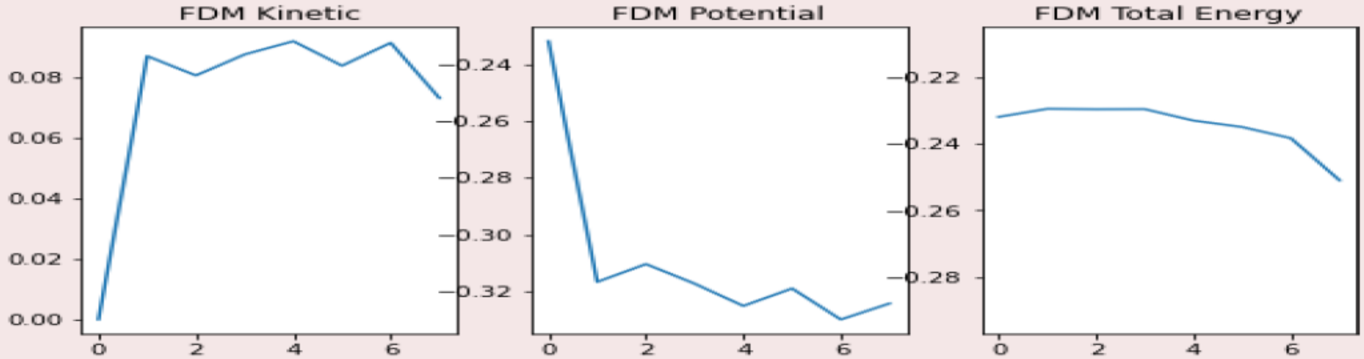


More Results: Dynamical Heating

Energy of Particles



Energy of FDM



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