Probing the quantum mechanics of ultra-light dark matter with strong gravitational lensing

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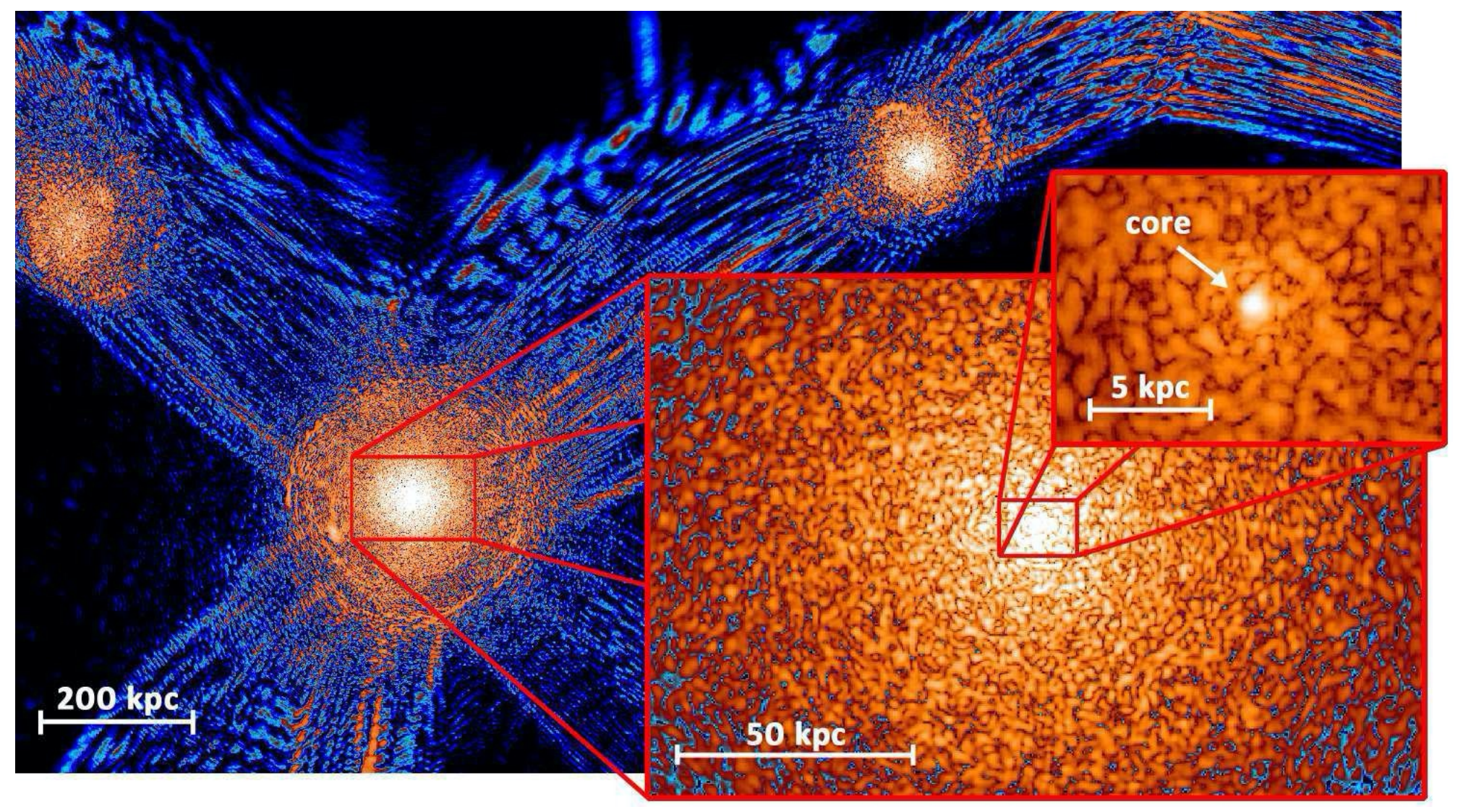
Background

Ultra-light dark matter (ULDM) is a popular dark matter candidate with the potential to resolve the core-cusp and missing satellites problems. ULDM is made up of an ultra-light axion whose mass is around 10^{-22} eV. The corresponding de Broglie wavelength is a few kpc, meaning that quantum fluctuations manifest on small galactic scales. In comparison to cold dark matter (CDM) halos, which have central cusps, ULDM halos have flat inner profiles. This is due to the dense soliton cores which exist in the center of ULDM halos. Within these cores, quantum pressure between axions prevents gravitational collapse. Additionally, clustering is prohibited below a certain mass scale. Thus, ULDM could explain the discrepancy between low observed dwarf galaxy counts relative to ΛCDM simulations.

Strong gravitational lensing is an exciting avenue to investigate ULDM since it probes the low halo mass range within which ULDM is expected to deviate from CDM. Unlike other probes, strong lensing is sensitive to mass along the entire line of sight (LOS). To constrain ULDM, we can analyze the multiple lensed images which we observe when the light from a distant quasar is lensed by a galaxy system. The DM present in the lens plane will affect the relative brightness of the images. Using flux ratios, we can attempt to constrain the ultra-light axion mass.



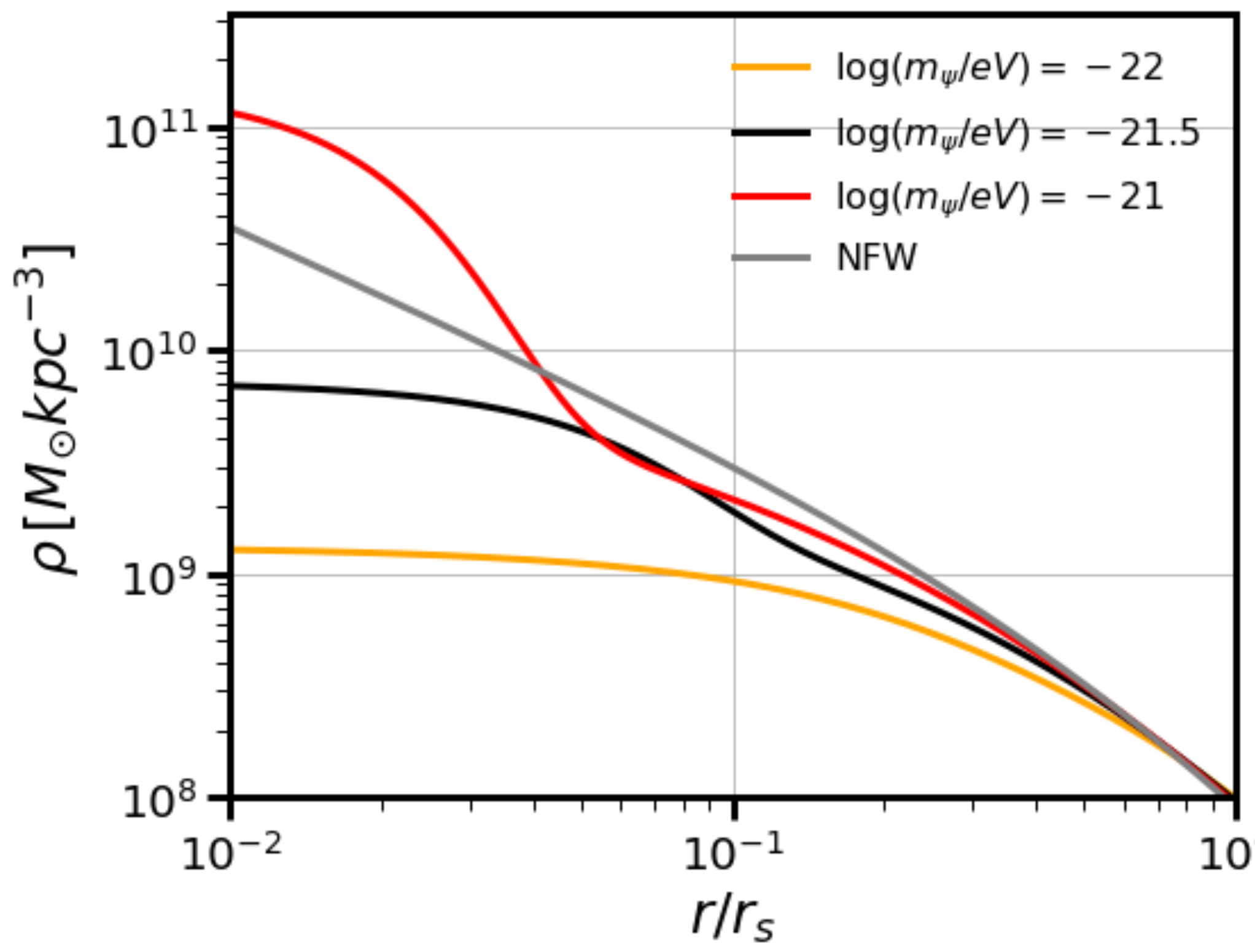
Simulation of ULDM halos. A soliton core with radius ~1 kpc is shown. The granular structure shows the density fluctuations arising from the wave-like nature of ULDM cores *Credit: Schive et al. 2014a*

Simulating ULDM halos

To analyze strong lenses, we created a **ULDM realization model** which accounts for:

1. **The ULDM halo mass function (HMF)**
    - Halo mass cutoff, much like warm dark matter
    - Tends to CDM as the axion mass gets heavier
2. **The ULDM density profile** (see examples on the right)
    - Function of axion and halo mass
    - Superposition of NFW and ULDM density profiles
    - Optimization algorithm used to obtain correct core density/size and halo mass

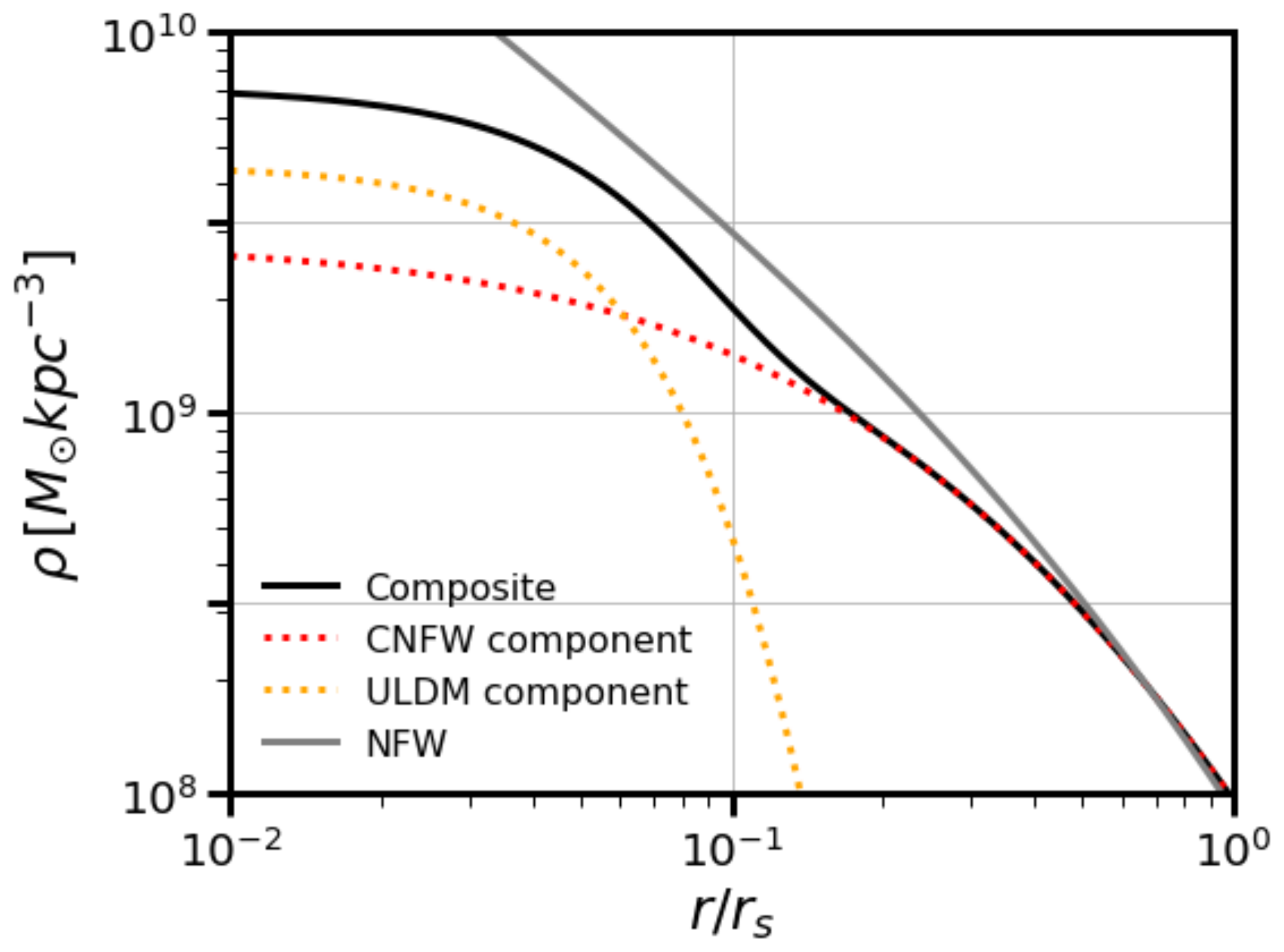
Our model is built into **pyHalo**, a lensing package created by Daniel Gilman which can generate lensing mass distributions.



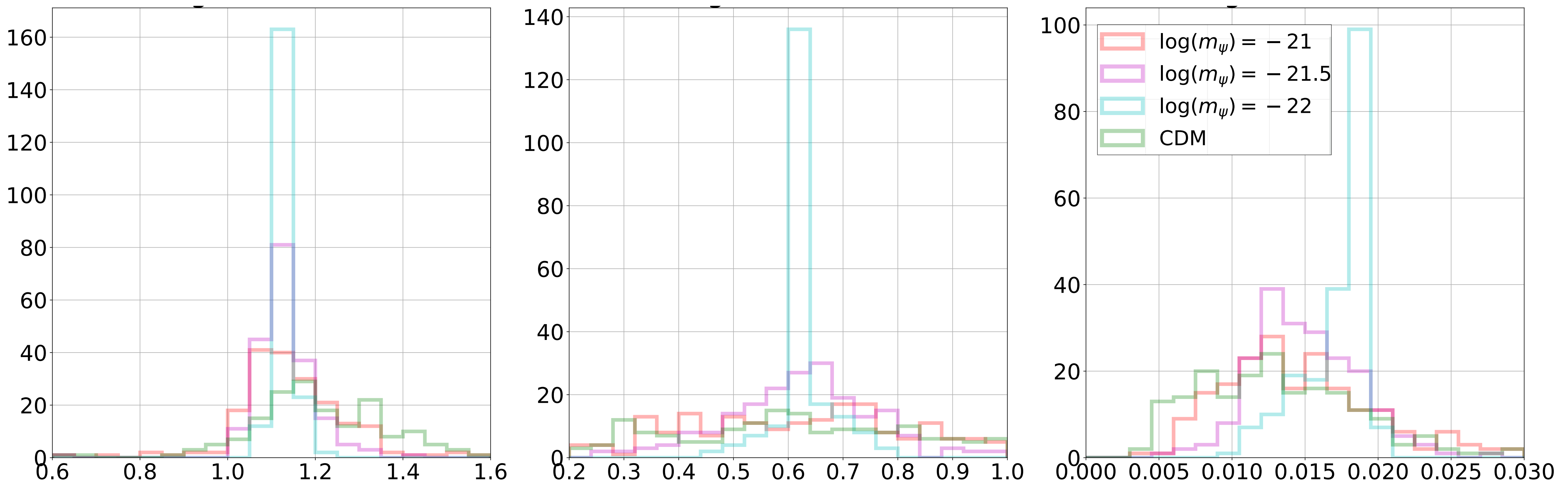
ULDM density profiles for a 10^{10} $M_\odot$ halo. As the axion mass lightens, quantum pressure between the axions increases, leading to larger, less dense cores. In comparison to an NFW profile, ULDM profiles have flat central densities. The brightness of strongly lensed images is sensitive to density variations depending upon axion mass.

Within a background halo, a population of ULDM subhalos are placed in the lens plane. In the relevant mass range of $10^{[6,10]}$ $M_\odot$ for strong lensing, their can exist zero, a few, or hundreds of sub/LOS halos, depending on the axion mass. Variations in structure can be quantified by computing the projected mass distribution (shown on the right).

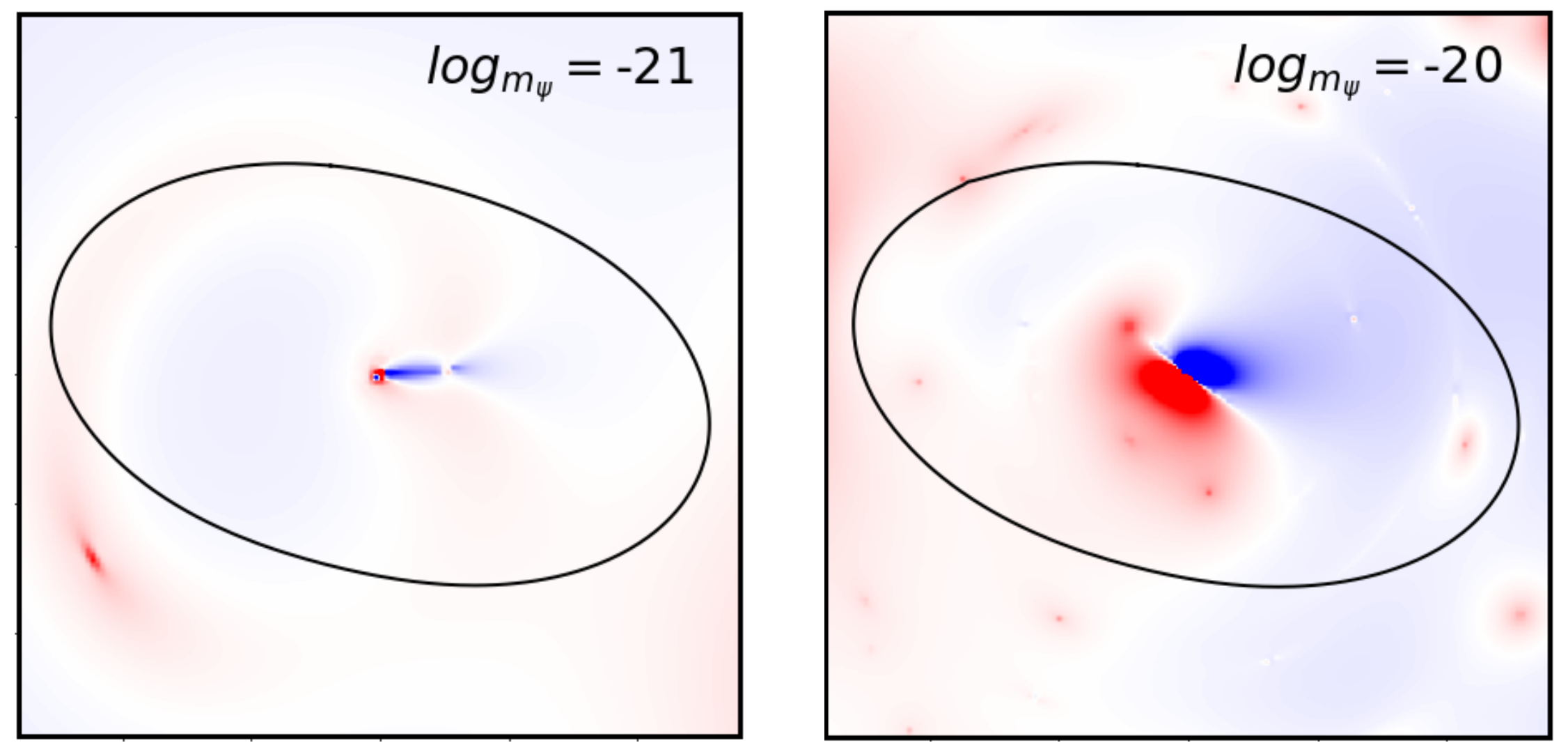
Our model neglects the **density fluctuations** which scale with the axion de Broglie wavelength (see power spectra on the right). We are currently thinking about how to best inject these fluctuations into the density profile of the background halo. Since the amplitude of these fluctuations are thought to be $O(1)$, with respect to the mean density, they may turn out to have a significant impact on image brightness.



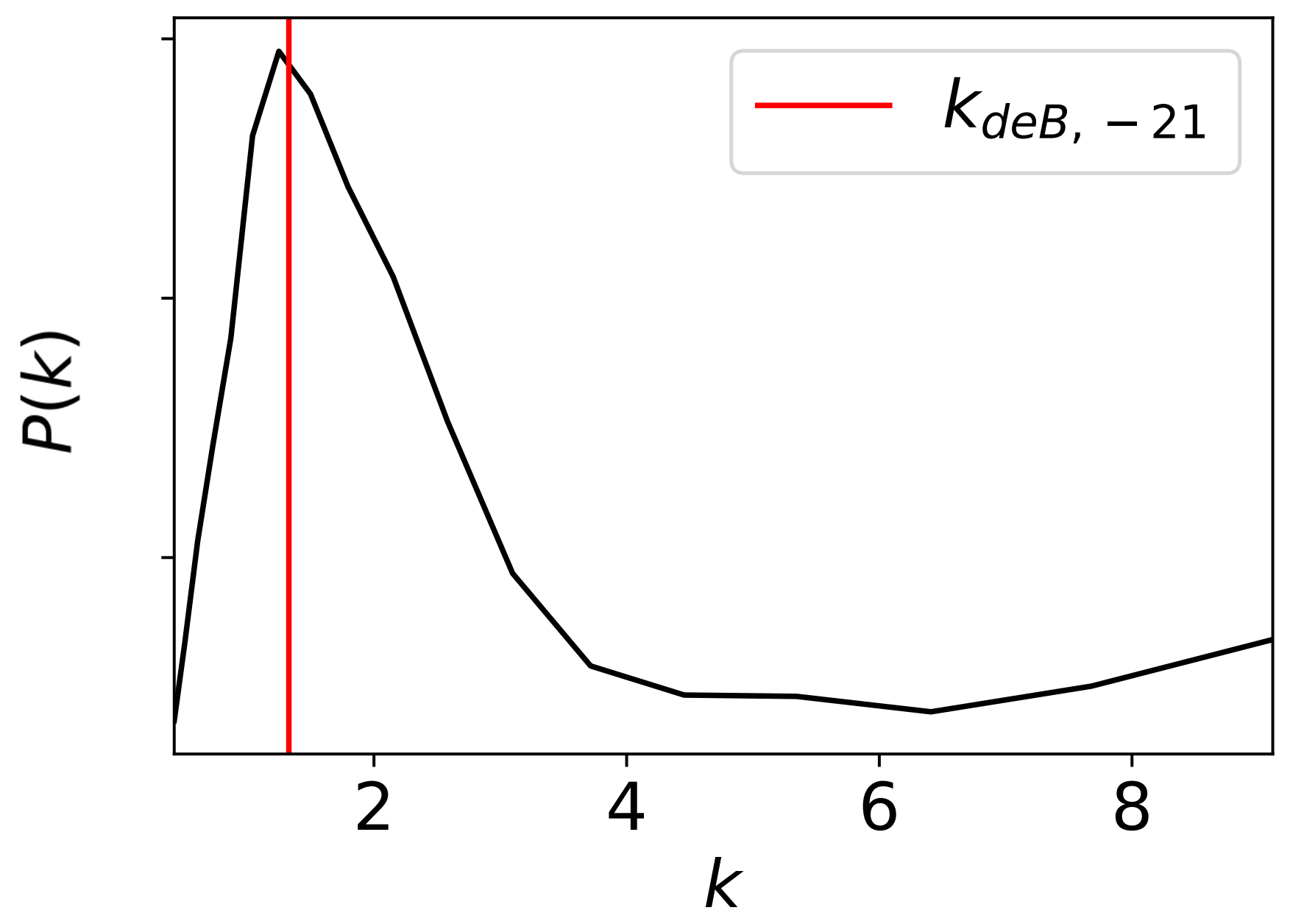
ULDM density profile composition. At large radii, the ULDM profile tends to an NFW profile since ULDM is expected to match CDM on large scales. At small radii, the soliton core of the ULDM halo overtakes the (cored) NFW component, and the profile flattens.



Simulated ULDM flux ratio distributions. Three preliminary flux ratio distributions (FRD) arising from different axion masses are shown in comparison to a cold dark matter distribution. Each FRD is the result of 200 simulations. The lighter the axion mass, the more the FRD approaches a Dirac-delta function since less and less subhalos can form. The FRD tends to the CDM distribution as the axion mass increases. This qualitative change in the probability distributions across a single order of magnitude in the axion mass can potentially yield a meaningful constraint with a relatively small sample.



Projected mass of ULDM halos. A heavier axion realization (right), with almost 100 sub/LOS halos, contributes more structure to a lensing system than a lighter axion realization (left), with only 3 halos.



Power spectra of a simulated ULDM density field. A numerically computed power spectra of a ULDM density field peaks at the de Broglie wave number due to quantum fluctuations manifesting on this specific scale. *Credit: Simulation code written by Xinyu Li.*

Flux ratios of quasar images

Many **strongly lensed quasars** have been experimentally observed, and typically have four highly magnified images. Using our ULDM realization model, we:

- Simulate a lens plane populated with ULDM halos
- Place sub/LOS halos such that observed image positions are recovered and flux ratios are allowed to vary
- Generate many realizations and obtain flux ratio distributions
- Compare these flux ratio distributions to observations

Our eventual goal is to use these distributions to constrain the axion mass. The above figure demonstrates the sensitivity of the distributions to the assumed axion mass. The current observed dataset of lensed quasars will provide us with a large enough sample to derive bounds on ULDM. Observations from Hubble and James Webb space telescopes will soon enlarge the strong lensing dataset and improve these constraints.

Conclusion

The unique physics of ULDM can be constrained using the flux ratio distributions resulting from detailed strong lensing simulations which can access a previously unexplored region of halo masses. The resulting bounds can tightly constrain the ultra-light axion mass.

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