UltraLight Dark Matter in Simulations: A Chapel-Powered Eigenstate Perspective

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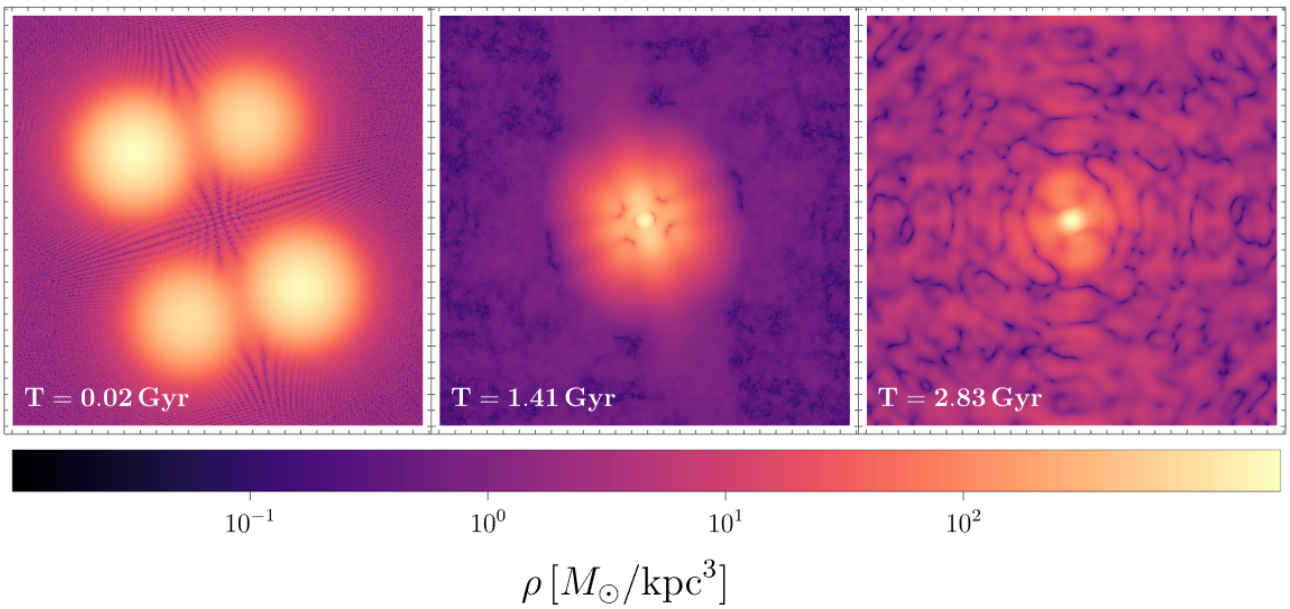

Figure 1: Creation of an UltraLight Dark Matter halo through collisions of solitons in chplUltra.
The density is presented in solar masses per kiloparsec cubed [$M_\odot/kpc^3$], and the snapshot times are given in terms of gigayears (Gyr) from the initial conditions.

ABSTRACT

A large outstanding problem in astrophysics is the nature of dark matter—the mass in the Universe which interacts gravitationally but does not couple to light. One compelling theory of dark matter is called UltraLight Dark Matter (ULDM), describing a particle with a mass $m \sim 10^{-22}$ electron volts which could form so-called 'halos' of dark matter around galaxies. In this talk, we will present (1) the ULDM halos we create and evolve with our Chapel-powered simulator chplUltra, (2) how we use Chapel to calculate the eigenstates of a given ULDM halo, and (3) one application for using these techniques to advance ULDM research. The performance of our solver is particularly boosted by the ease of performing slab and pencil decompositions within Chapel, enabling us to run higher resolution simulations than an equivalent solver in Python.

CCS CONCEPTS

• **Applied computing** → **Astronomy**; **Physics**.

KEYWORDS

dark matter, simulation, distributed computing

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1 EXTENDED ABSTRACT

1.1 The Physical Background

The story of the structures that make up our Universe is primarily told by gravity; gravity, in turn, is driven by mass. Despite its crucial role, about 80% of the mass in the cosmos cannot be observed directly as it does not interact with the light. Currently, most popular explanations for this so-called 'dark matter' rely on new types of particles; of those, one family of particles that has recently been gaining traction are axions and axion-like particles [7]. Axions could be easily created in the early Universe and offer a wide range of behavior depending on the particles' mass. In the case of low-particle masses, it becomes burdensome and inefficient to track individual particles; instead, the wavefunction description used in quantum mechanics is favored. This family of axions with $m \ll 30$ eV (electon volts) is often called wave dark matter, with the very low mass extreme known as fuzzy or ultralight dark matter (ULDM)[3]. The low mass and wavefunction description of ULDM results in intriguing phenomenology of this dark matter candidate and its structures, which is the main topic of this talk.

Numerically simulating ULDM and its behavior requires solving the Schrödinger-Poisson system

$$i\dot{\psi} = -\frac{1}{2}\nabla^2\psi + \Phi\psi \tag{1}$$

$$\nabla^2\Phi = 4\pi|\psi|^2\,, \tag{2}$$

presented here in dimensionless code units. The first line is the Schrödinger equation, which governs the evolution of the dark matter's wavefunction ψ. While ψ is the fundamental building block of ULDM, the related observable quantity is actually the dark matter's density, $\rho = |\psi|^2$. The second line is known as the Poisson equation, and it describes the evolution of the dark matter's gravitational potential, Φ, which depends only on the density $|\psi|^2$. We solve this system of equations using our Chapel-powered pseudo-spectral fixed grid code CHPLULTRA, described in Ref. [6] and based on the algorithm described in Ref. [1].

1.2 Simulating Halos with CHPLULTRA

A ULDM halo itself is not an eigenstate solution to the Schrödinger-Poisson system; instead, the system's ground state is a spherically symmetric mass with a known density distribution, known as a "soliton". One method of forming ULDM halos relies on merging multiple solitons. Their collisions will excite higher-order eigenstates of the system, resulting in a density profile which can be approximated as [4]

$$\rho(r) = \begin{cases} \rho_{\text{sol}}(r), & 0 \le r \le r_\alpha \\ \rho_{\text{NFW}}(r), & r_\alpha \le r \le r_{\text{vir}}\,, \end{cases} \tag{3}$$

where $\rho_{\text{sol}}(r)$ is a soliton profile forming a "core", r_α is a transition radius equal to a few times the full width half maximum (FWHM) of the soliton core, and ρ_{NFW} is the Navarro-Frenk-White[5] profile which falls off as r^{-3} at large radial distances.

A radial cross-section of a CHPLULTRA simulation depicting four merging solitons and the resultant dark matter halo is shown in the teaser figure, Fig. 1. This simulation was run on a Cray system with 44 cores per locale. The ran it in a numerical box of gridsize $N_g^3 = 512^3$ using 16 locales, which took under 4 hours. This is representative of our typical simulation, though sometimes we need to evolve our systems significantly longer; this still takes less than 12 hours. We also occasionally use a finer grid of 768^3 or 1024^3; using 64 locales, these simulations will take about 5 and 13 hours, respectively, which is very tractable for our purposes. See Ref. [6] for more details on CHPLULTRA scaling.

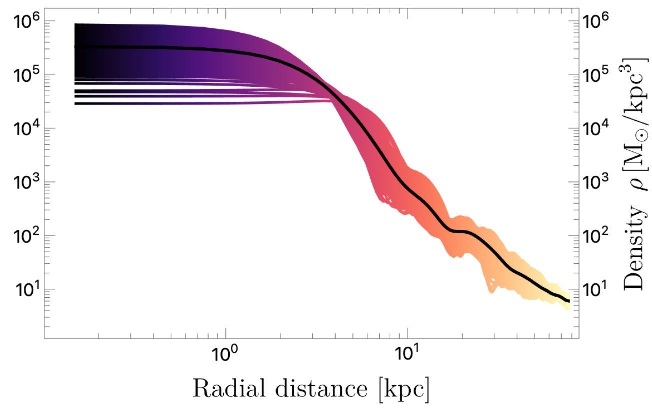

Figure 2: Evolution of the spherically averaged halo profile, $\rho(r)$, in solar masses per kiloparsec cubed [$M_\odot/kpc^3$]. The instantaneous profiles at each saved timestep are shown in color. The time average of those profiles $\langle\rho\rangle$ is shown in black.

The radially averaged density profile $\rho(r)$ at each timestep after the merger shown in that middle panel ($T = 1.41$ Gyr) are shown in color in Fig. 2. Averaging those profiles together (equivalent to averaging over time), we recover the black line in Fig. 2. This type of time- and radially-averaged profile $\langle\rho\rangle$ is crucial for our eigenstate analysis in the following subsections.

1.3 ULDM Halo Eigenstates

Having defined a time-averaged density profile $\langle\rho\rangle$, we can use the Poisson equation to calculate the corresponding gravitational potential $\langle\Phi\rangle$. We can then write the decoupled Schrödinger equation as

$$i\dot{\psi} = -\frac{1}{2}\nabla^2\psi + \langle\Phi\rangle\psi\,. \tag{4}$$

We are now able to calculate the eigenstates of the above formulation of the Schrödinger seeded by a spherically symmetric potential $\langle\Phi\rangle$. We perform this calculation by assuming the eigenstates $\phi_{n\ell m}$ are separable as

$$\phi_{n\ell m} = f_{n\ell}(r)Y_\ell^m(\theta,\phi)\,, \tag{5}$$

as described in Ref. [8]. The radial piece $f_{n\ell}(r)$ varies based on the exact shape of $\langle\Phi\rangle$, and is calculated in Mathematica; the angular piece is represented by well-known spherical harmonics $Y_\ell^m(\theta,\phi)$.

As a post-processing step of our CHPLULTRA simulations, we use Chapel to decompose each saved wavefunction grid of dimension $N_g \times N_g \times N_g$ (stored as an HDF5 array) into spherical components up to $\ell_{\text{max}} = 10, |m_{\text{max}}| \le \ell_{\text{max}}$. It is convenient to perform this step separately from the radial calculation because it is independent of the exact system being evolved, so long as the eigenstates

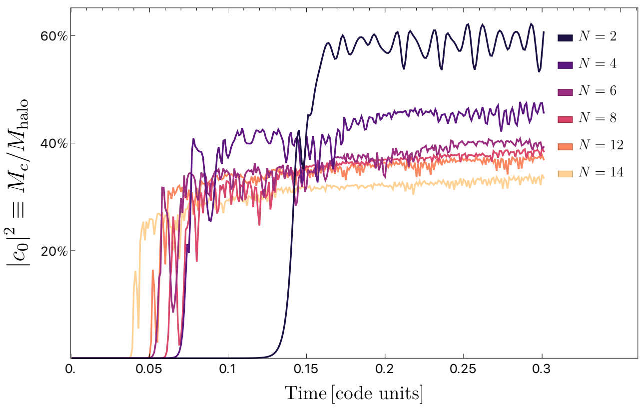

Figure 3: ULDM core formation is evident when observing the contribution of the ground state to the wavefunction of a forming halo. Note that for each collision of N solitons the final value stays approximately constant, providing an estimate of relative mass $M_c/M_{\rm halo}$.

remain separable; thus, there is no need to analyze the profile of the wavefunction before performing the spherical decomposition. Furthermore, we leverage the ability of Chapel to call external libraries such as the GNU Scientific Library (GSL)[2], which includes information on spherical harmonics. Thus, we are able to both process large amounts of data in a fast parallel process, as well as avoiding having to hand-type the forms of the spherical harmonics. For our canonical example of a 512^3 grid with 301 save points, this analysis takes less than 2 hours when using 16 locales.

1.4 Example Application

Precisely isolating eigenstates from high-resolution dark matter simulations has given us a new perspective on existing problems in the ULDM literature. One important application deals with the relative size of a ULDM halo's core and the halo itself, $M_c/M_{\rm halo}$. The core corresponds exactly to the ground eigenstate ϕ_{000}; consequently, the relative contribution of the ground state to the properly normalized wavefunction, $|c_0|$, is directly related to the relative core-halo mass as

$$|c_0|^2 \equiv M_c/M_{\rm halo}\,. \tag{6}$$

We repeated our procedure on halos formed in chplUltra through the simultaneous collisions of $2 < N < 15$ equal mass solitons, as shown in Fig. 3. Studying our results, we were able to directly observe the core formation. Furthermore, this approach enabled us to analyze how $M_c/M_{\rm halo}$ scales with other parameters of the system, like total energy and mass. We also explore the heretofore neglected effects of the order in which solitons merge, which we have found to have a noticeable effect on our results. We expect to submit these results for publication in the late summer of 2022, and we will share our preliminary findings at CHIUW 2022 as a real world example of how the scalability and performance of Chapel powers ongoing scientific reserach.

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