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UltraDark.jl: A Julia package for simulation of cosmological scalar fields

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Software

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Summary

`UltraDark.jl` is a Julia package for the simulation of cosmological scalar fields. Scalar fields are proposed solutions to two of the fundamental questions in cosmology: the nature of dark matter and the universe's initial conditions. Modeling their dynamics requires solving the Gross-Pitaevskii-Poisson equations, which is analytically challenging. This makes simulations essential to understanding the dynamics of cosmological scalar fields. `UltraDark.jl` is an open, performant and user friendly option for solving these equations numerically.

Statement of need

Scalar fields are ubiquitous in physics, as solutions to partial differential equations describing the spatial variation of physical quantities. As dark matter candidates, scalar fields including axion-like particles (ALPs) would explain the nature of the missing 85% of the universe's matter (Adams et al., 2022; Ade & others, 2016; Hu et al., 2000; Matos et al., 2000). As inflaton candidates, scalar fields are proposed to cause a phase of accelerated expansion that sets the stage for big bang nucleosynthesis (Albrecht & Steinhardt, 1982; Amin et al., 2012; Guth, 1981; Linde, 1982). In each case, a scalar field $\psi(t, \mathbf{x})$ represents the density of particles as a function of space and time.

Subject to reasonable conditions, a cosmological scalar field ψ whose particles have mass m obeys the Gross-Pitaevskii equation for the scalar field,

$$i\hbar \frac{\partial \psi}{\partial t} = -\frac{\hbar^2}{2ma(t)^2} \nabla^2 \psi + m \Phi \psi \,, \tag{1}$$

coupled to the Poisson equation for the gravitational potential Φ

$$\nabla^2 \Phi = \frac{4\pi G}{a(t)} m |\psi|^2 \,, \tag{2}$$

where $a(t)$ is the scale factor characterising the expansion of the universe.

These equations are difficult to solve analytically – even static equilibrium solutions do not have a closed form – and necessitate the use of computer simulations. There are codes which solving Equation 1 and Equation 2 with different methods and in different domains, including `PyUltraLight` (Edwards et al., 2018), a code written in Chapel (Padmanabhan et al., 2020), `AxioNyx` (Schwabe et al., 2020), SCALAR (Mina et al., 2020), i-SPin 2 (Jain et al., 2023; Jain & Amin, 2023); see Zhang et al. (2018) for an overview.

`UltraDark.jl` solves Equation 1 and Equation 2 with a pseudo-spectral symmetrized split-step method, in which each time step consists of four sub-steps:

$$\psi \rightarrow \exp\left(-i\frac{h}{2}\Phi\right)\psi \tag{3}$$

$$\psi \rightarrow \mathcal{F}^{-1}\left\{\exp\left(-ih\frac{k^2}{2}\right)\mathcal{F}\left\{\psi\right\}\right\} \tag{4}$$

$$\Phi = \mathcal{F}^{-1}\left\{-\frac{4\pi}{ak^2}\mathcal{F}\left\{|\psi|^2\right\}\right\} \tag{5}$$

$$\psi \rightarrow \exp\left(-i\frac{h}{2}\Phi\right)\psi, \tag{6}$$

where $\mathcal{F}$ is a Fourier transform, k are the corresponding frequencies, and h is the time step. `UltraDark.jl` has adaptive time steps which allow it to accelerate simulations while preserving numerical convergence. This is particularly useful in an expanding universe, where the time step is roughly $h \propto a^2$. Such time steps result in orders of magnitude speedups when simulating collapse of an inflaton field in the early universe (Musoke et al., 2020).

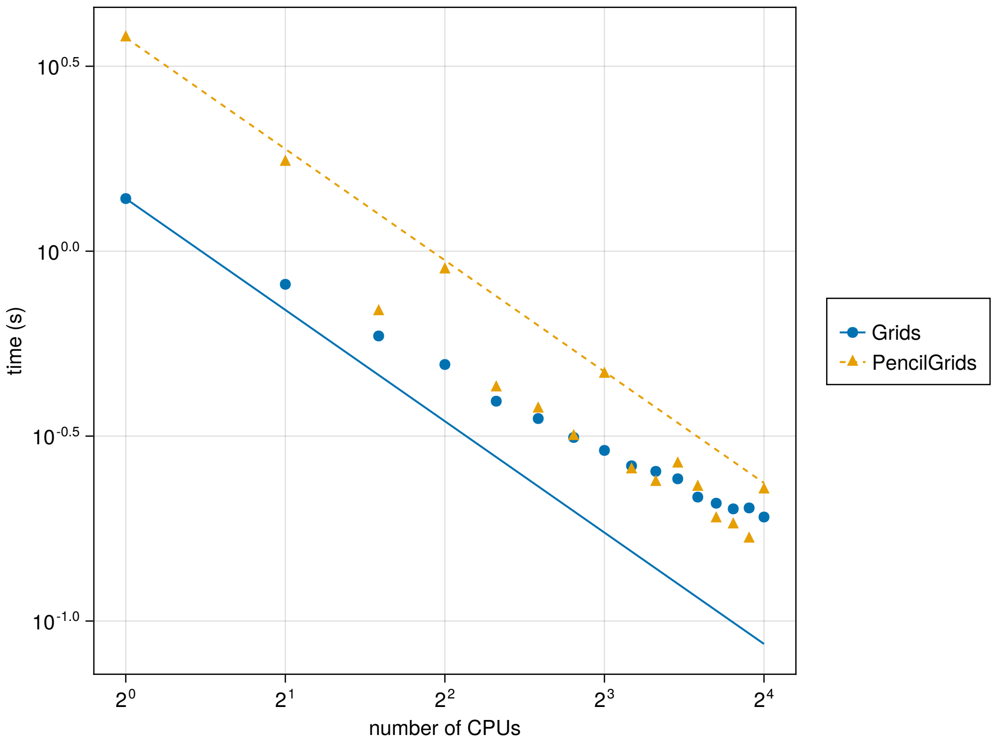

Figure 1: Wall time for a single time step, as a function of number of CPUs. The points represent measured times and the lines represent theoretical $1/\#$CPU scalings. The circles and solid line are for grids constructed from `Arrays` and the triangles and dashed lines are for MPI-distributed `PencilArrays`.

Julia (Bezanson et al., 2017) has seen increasing use in scientific computing; see for example Eschle & others (2023) and Roesch et al. (2021) for overviews of its use in high energy physics and biology. The use of Julia is one of the choices that separates `UltraDark.jl` from similar codes. `UltraDark.jl` uses Julia's has rich parallelism capabilities. The `Threads.@threads` macro provides simple parallelisation of `for` loops. Folds.jl enables simple parallelisation of reduction operations (Arakaki, 2020). In a cluster environment, `PencilArrays.jl` and `PencilFFTs.jl` enable straightforward cross-node parallelism, a capability that is challenging to reproduce in Python (Polanco, 2021a, 2021b). The scaling of this two approaches to parallelism is demonstrated in Figure 1.

The features described above have allowed collaborators and I to produce results presented in 4 publications, each exploring the small scale structure of ultralight dark matter. We have used `UltraDark.jl` to explore tidal disruption in dark matter halos comprised of self-interacting ALPs (Glennon et al., 2022), perform the first simulations of multi-species ALPs with intra- and inter-species interactions (Glennon, Musoke, & Prescod-Weinstein, 2023b) and discover a novel mechanism for vortex stabilisation in scalar dark matter (Glennon, Mirasola, Musoke, et al., 2023a). Work in preparation examines the effect of self-interactions on dynamical friction (Glennon, Musoke, Nadler, et al., 2023). More sample output can be found in Glennon, Mirasola, Musoke, et al. (2023b) and Glennon, Musoke, & Prescod-Weinstein (2023a).

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