Scalar Building Blocks of the Universe

Cosmological Structure Formation with Nonrelativistic Scalar Fields

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In Short

- String theory predicts the existence of axion-like particles whose masses can be so low that their de Broglie wavelength can reach several kiloparsecs. They are a well motivated dark matter candidate. We investigate the impact of ultralight axions as a fraction of dark matter on galaxy formation.
- We employ massively parallel numerical codes for solving the equation of motion in idealized setups as well as in full cosmological simulations of structure formation. We apply these numerical methods to simulate the formation and evolution of inflaton clusters and stars during the matter-dominated era after inflation.

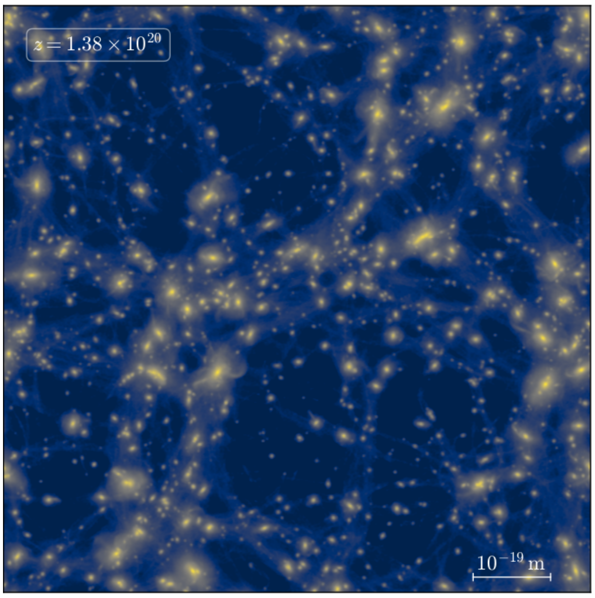

Figure 1: *Projected inflaton density of the full simulation box at the final redshift* $z_f = 1.38 \times 10^{20}$.

In the course of this project we will study the growth of density perturbations and their collapse into gravitationally bound structures in two distinct cosmological scenarios: structure formation with ultralight (fuzzy) dark matter, and the gravitational fragmentation of the inflaton field during the post-inflationary era. Using our experience from previous work (HLRN Großprojekt nip00040) we are in a position to numerically investigate the underlying non-relativistic scalar field dynamics over a wide range of length scales. Recently, we successfully included baryon physics in our simulations [1]. Within the new project, we will be able to refine the implementation of the baryonic physics in our dark matter simulations, generalize them to mixed dark matter scenarios, and to adapt our numerical methods to simulate the formation of bound structures during the so-called primordial dark age preceding the hot big bang.

Cosmological inflation is a period of rapid exponential expansion in the early Universe which was originally introduced to explain the initial flatness and large-scale homogeneity of our Universe. In a broad class of scenarios, the exponential expansion is followed by an epoch of matter-domination in which initially small overdensities grow, eventually forming gravitationally bound structures that are far smaller than the prevailing Hubble horizon. It was recently discovered that this resembles cosmological structure formation with fuzzy dark matter [2]. Correspondingly “inflaton clusters” and “inflaton stars” [3] are expected to form during this early stage of the Universe. Apart from being the first bound structures in the Universe, they can enhance the production of Standard Model particles during reheating significantly and merger events might result in the production of an observable stochastic gravitational wave background.

We have already performed N-body simulations with 512^3 particles to study the gravitational fragmentation of the inflaton field. As can be seen in Figure 1, we find a large amount of inflaton clusters at our final snapshot. In a first step of this project, we will run similar simulations with an increased spatial resolution. This will allow us to study the inner structure of the inflaton clusters over a wide mass range and to investigate the mass distribution of the inflaton clusters over several orders of magnitude. Afterwards, we will use our experience from previous HLRN projects [1,5] to zoom into several inflaton clusters to observe the formation of an inflaton star.

Over the last decades, the ΛCDM model of cosmology has proven extremely successful in explaining observations of the cosmic microwave background and the large-scale structure of the universe. It predicts that our universe is dominated by cold dark matter (CDM) and dark energy in the form of a cosmological constant Λ.

The hypothesis that **dark matter** is composed of an ultralight bosonic field with particle mass $m \geq 10^{-22}$ eV is well-motivated from string theories. In these scenarios, their self-interaction can

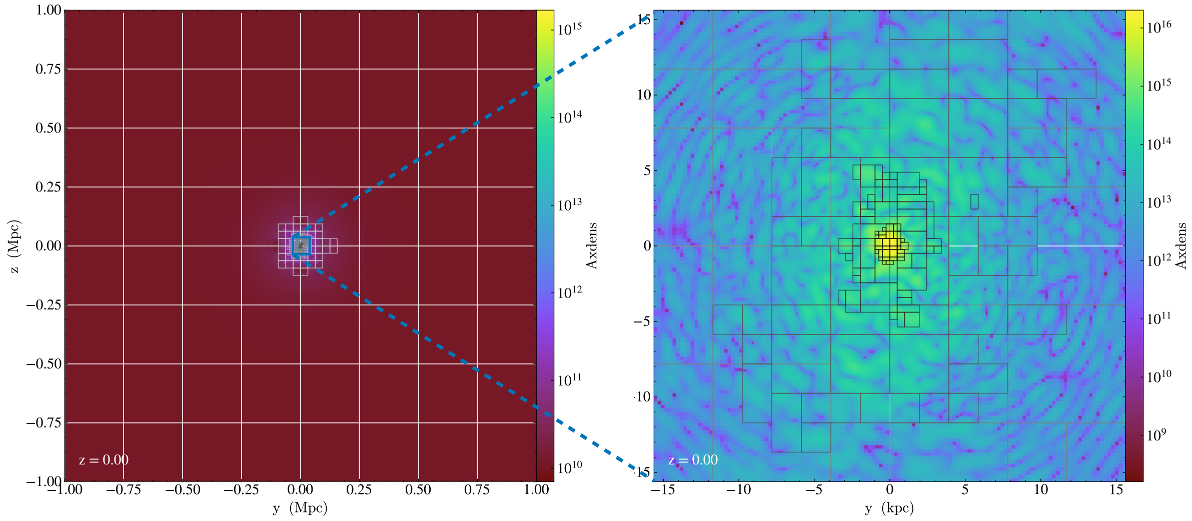

Figure 2: *Adaptively refined mixed dark matter spherical collapse simulation. Shown are slices through the fuzzy dark matter density of the entire volume (left) and the central part (right). We recover the well known interference patterns and central ground state and find that their characteristics depend on the ratio of fuzzy to cold dark matter.*

typically be neglected for questions of structure formation, making them candidates for ultralight scalar, or “fuzzy”, dark matter (FDM). In spite of the simplicity of FDM which is fully specified by its mass, its fundamentally wave-like behavior on scales near the de Broglie wavelength gives rise to interesting new phenomena that can potentially be probed by purely gravitational interactions. Cosmological simulations of FDM structure formation have revealed the formation of coherent, solitonic cores embedded in incoherent, granular halos with CDM-like density profiles. The inner dark matter profile of dwarf galaxies can be probed by stellar kinematics and so far observations favour a cored central density.

In HLRN Großprojekt nip00040 we successfully quantified both the evolution of solitonic cores and of the granular structure. We found a highly dynamical system of merging cores relaxing to new coherent ground states by periodic matter emission [4], excited solitons in FDM halos [5] and their modifications in the presence of an external potential due to baryons [1]. The granular structure building the FDM halo around these cores is equally dynamical. It forms when velocity dispersion results in an interference pattern of plane waves. Mathematically, this is quantified by the Schrödinger-Vlasov correspondence. We found that baryons heat up central halo regions. Higher velocities yield more compact solitons proportional to the de Broglie wavelength corresponding to the local velocity dispersion. Even in centrally baryon dominated halos, we observed the formation of these FDM ground state solutions, though with modified radial density profiles. The core-halo mass relation deduced from pure FDM simulations is then altered by an order one factor.

In the course of this project, we will generalize to a mixed dark matter scenario in which dark matter is comprised of both fuzzy and cold dark matter. Spherical collapse simulations of various ratios already produced valuable insides that will be published soon. Slices through one of the final FDM density configurations are shown in Figure 2. The grid structure of the underlying adaptive mesh refinement code and the granular structure are clearly visible. The solitonic core is the stable central granule. The spherical collapse simulations represent the first step towards full cosmological simulations which is the second objective of this project.

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https://www.uni-goettingen.de/de/201012.html

More Information

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[3] J. C. Niemeyer, R. Easther, *arXiv: 1911.01661*.

[4] B. Schwabe, J. C. Niemeyer, J. F. Engels, *Phys. Rev, D* **94**, 043513 (2016). doi:10.1103/PhysRevD.94.043513

[5] J. Veltmaat, J. C. Niemeyer, B. Schwabe, *Phys. Rev. D* **98**, 043509 (2018). doi:10.1103/PhysRevD.98.043509