Condensate Dynamics of Wave Dark Matter

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Introduction

- Wave Dark Matter (ΨDM) called also "Fuzzy" Dark Matter (FDM) postulates that it is a condensate made of ultra-light particles, $m \sim 10^{-23}$eV, with gravitational (and maybe contact) interactions [1,2].

  → Healing length becomes galaxy-size
  → Condensation at Kelvin or MK temperatures
- On large scales, ΨDM and the standard 'cold dark matter" (CDM) model have very similar properties (left plots below)
- ΨDM density profiles provide an elegant solution to the long-standing "cuspy halo" problem of early CDM and better matches to long standing issues such as Satellite Dwarf Galaxies (Right, below) and recent discoveries such as the almost dark galaxy Nube (below centre).

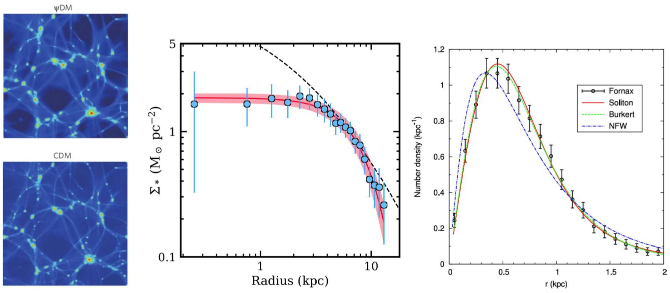

Figure 1: Left [1]: The cosmic structure provided by ΨDM and CDM is equivalent at large scales..
Centre [3]: Surface stellar mass density profile of Nube (blue dots) fitted with a ΨDM soliton whose only free parameter is the core radius $r_c = 6.6 \pm 0.4$ kpc. The black dashed line is a standard Navarro-Frenk-White (NFW) profile.
Right [1]: Stellar number density and the best-fit ΨDM soliton solution (red) with $m = 8.1 \times 10^{23}$ eV. Also show are the best-fit empirical formula of Burkert (green dashed line) and the NFW profile (blue dot-dashed line).

The basic ΨDM dynamics is described by the Schrödinger Poisson equations:

$$i\frac{\partial}{\partial t}\Psi(\mathbf{r},t) = \left[-\frac{\nabla^2}{2} + V_G(\mathbf{r},t)\right]\Psi(\mathbf{r},t); \qquad \nabla^2 V_G(\mathbf{r},t) = 4\pi\varrho\left(|\Psi(\mathbf{r},t)|^2 - 1\right),$$

in dimensionless units, where $\Psi(\mathbf{r},t)$ is the bosonic dark matter wavefunction, $V_G(\mathbf{r},t)$ is the classical gravitational potential and ϱ is the mean astrophysical density.

- Up until now most FDM studies have mostly looked into dark matter profiles of virialized dark matter halos. However, we are attempting to study the non equilibrium dynamics and coherence and what are the metastable states and excitations

Linear 1D model

Perhaps a bit too simplified for most purposes, but can be relevant for structures such as jets or interactions between just two DM haloes.

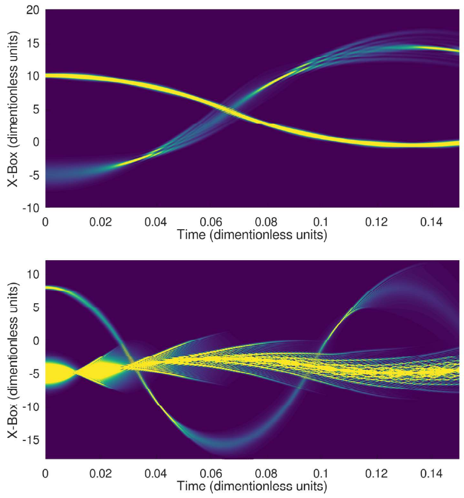

Figure 2: Example: Two DM haloes colliding. The Gaussian initial shapes do not match the ground state profile. When the mismatch is just in shape, gentle pulsation is the result. When there is a strong width mismatch, a violent or very violent (below) collapse occurs and a highly excited cloud is formed, which becomes – perhaps? – thermal.
The clouds collide like superfluids, passing through each other without much effect when the collision is fast as seen here.

Radial model

- Since most galaxies show some kind of radial symmetry it is important to conduct these simulation in radial coordinates for their results to be more directly usable. *Well, at least as a prelude to full 3d simulations.*
- In radial coordinates the Schrödinger Poisson equation looks as follows:

$$i\frac{d\,\phi}{dt} = \left[-\frac{1}{2}\frac{d^2\,\phi}{dr^2} + V_G\phi\right]; \qquad \frac{d^2\mathcal{V}}{dr^2} = 4\pi\,r\,|\psi|^2.$$

Here $\phi = r\psi$ and $V_G = \mathcal{V}/r$ are a scaled wavefunction and gravitational potential.

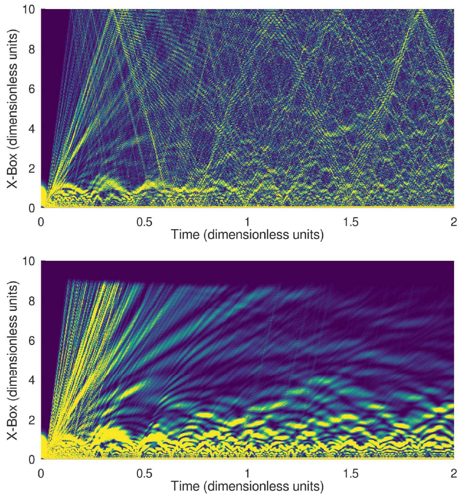

Figure 3: Top: Once again we see a "too-heavy" initial wavefunction (yellow, saturated) which is much broader than the equilibrium state undergoing a violent collapse upon release. Radiation is emitted and excitations excited. However soon we can see unphysical reflections from the boundaries which mask any physics.
Bottom: After implementing a Gaussian absorber near the box edge to mimic the escape of radiation, we can see the formation of an "atmosphere" of (possibly) bound excitations

After such a violent beginning, It was essential to see what happens to the dynamics at large times.

→ *Question: What remains after transients fly off, does something remain bound?*

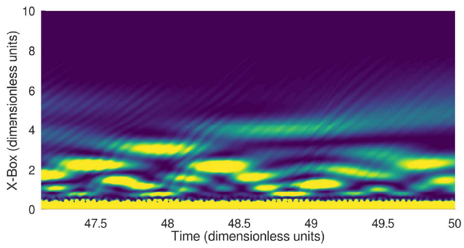

Figure 4: Long time behaviour of the case displayed above. We can see that the atmosphere which seemed to be forming in the Fig 3 has persisted and stabilized. Next step, in progress – to analyze its properties.

Future Objectives

- We are developing simulation tools appropriate for nonzero temperature, studying coherence [5], and conducting exploratory simulations of dynamical scenarios such as binary collisions or long term evolution to produce an excited "atmosphere" and to see on what times they converge to the equilibrium and virialized states.

  → *Question: How will those times compare to real astrophysical times such as free-flight between galaxy collisions?*

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[3] Mireia Montes, Ignacio Trujillo et. al, A&A, **681** A15 (2024)
[4] I. Liu, N. Proukakis, G. Rigopoulos, MNRAS **521**, 3625 (2023); M. Indjin, I-K. Liu, N. Proukakis, G. Rigoupulos, arXiv:2312.14917.

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