Scalar field dark matter scenarios

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Introduction

In the paradigm of the Standard Cosmological Model, **83% of the mass density in the Universe cannot be explained with ordinary baryonic matter** and requires an additional non-baryonic component. The preferred scenario since the 1980s is weakly interacting massive particles scenario (> 1 GeV) (WIMPS). However, despite many experiments, these particles have still not been detected. Moreover, there are discrepancies between the predictions of the standard cold dark matter model (CDM) and observations on galactic and subgalactic scales. This has revived interest in **alternative scenarios, including the possibility that dark matter is associated with a scalar field filling all the space.**

One of the most attractive features of this model is that **scalar fields can form stable equilibrium configurations called solitons (Bose condensates) and then are able to form structure.** These equilibrium configurations lead to smooth density profile at the origin solving one of the CMD tensions at galactic scales, the core- cusp problem.

This PhD aims the development of new numerical studies to analyze the formation of large-scale structures in this scenario. At this first stage, we develop numerical calculations in simple situations such us the relaxation of the scalar cloud in a galactic halo or the collision of two solitons.

1 EQUATIONS OF MOTION

Assuming a classical field with minimal coupling to gravity, scalar field action takes the form:

$$S = \int d^4x\sqrt{-g}\,[g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)]\,. \qquad (1.1)$$

Where ϕ is the scalar field, m is the mass of the scalar field, and $V(\phi)$the potential. We take the non-relativistic limit by decomposing the real field ϕ in terms of a complex field ψ according to :

$$\phi = \frac{1}{\sqrt{2m}}(\psi\, e^{-imt} + \psi^\star\, e^{imt}), \qquad (1.2)$$

Variation of the action then leads to the equations of motion for the complex field ψ, known as the Gross-Pitaevskii-Poisson equations or the Schrödinger-Poisson (SP) system for a self-interacting scalar field [1] :

$$i\dot{\psi} = -\frac{1}{2m}\nabla^2\psi + m\Phi_N\psi + \frac{3\lambda_4}{4m^3}|\psi|^2\psi = -\frac{1}{2m}\nabla^2\psi + m(\Phi_N + \Phi_I)\psi, \qquad (1.3a)$$

$$\nabla^2\Phi_N = 4\pi G m|\psi|^2. \qquad (1.3b)$$

Where Φ_N is the gravitational potential and λ_4 is the is the self-interaction strength due to a quartic self-interaction potential. This parameter can be positive if the interaction is repulsive or negative if the interaction is attractive.

To represent the phase space distribution associated with the dynamics of the field ψ we use Husimi's quasi probability distribution a smoothed version of the Wigner's distribution function:

$$f_W(\vec{x},\vec{p}) = \int \frac{d\vec{x'}}{(2\pi)^3}\psi\left(\vec{x} - \frac{\vec{x'}}{2}\right)\psi^*\left(\vec{x} - \frac{\vec{x'}}{2}\right)e^{i\vec{p}\vec{x'}} \qquad (1.4)$$

$$f_H(\vec{x},\vec{p}) = \int \frac{d\vec{x'}d\vec{p'}}{(2\pi)^3\sigma_x^3\sigma_p^3}\, e^{-\frac{\left(\vec{x}-\vec{x'}\right)^2}{2\sigma_x^2} - \frac{\left(\vec{p}-\vec{p'}\right)^2}{2\sigma_p^2}} f_W(\vec{x'},\vec{p'}) \qquad (1.5)$$

2 NUMERICAL METHODS

To simulate the dark matter scalar field dynamics in 1D we have implemented two Fortran90 codes which solves the SP equations (1.3) in its dimensionless representation.

A. **FINITE DIFFERENCE SCHEME:** The code uses a Crank-Nicholson scheme by discretizing (1.3) and using 2nd-order center-time and center-space algorithm to iterate the value of the field at each grid point in time.

B. **SPECTRAL SCHEME:** The dynamical evolution progresses via a symmetrised split-step Fourier process on a grid with periodic spatial boundary conditions.

INITIAL CONDITIONS: We consider stationary states solving the time-independent Schrodinger equation. For this purpose, we implement a *shooting method* that computes the equilibrium profile with the desired soliton mass.

The conservation of the total energy and the total mass, the momentum of the system guarantees us that the evolution method and the boundary conditions work properly all together.

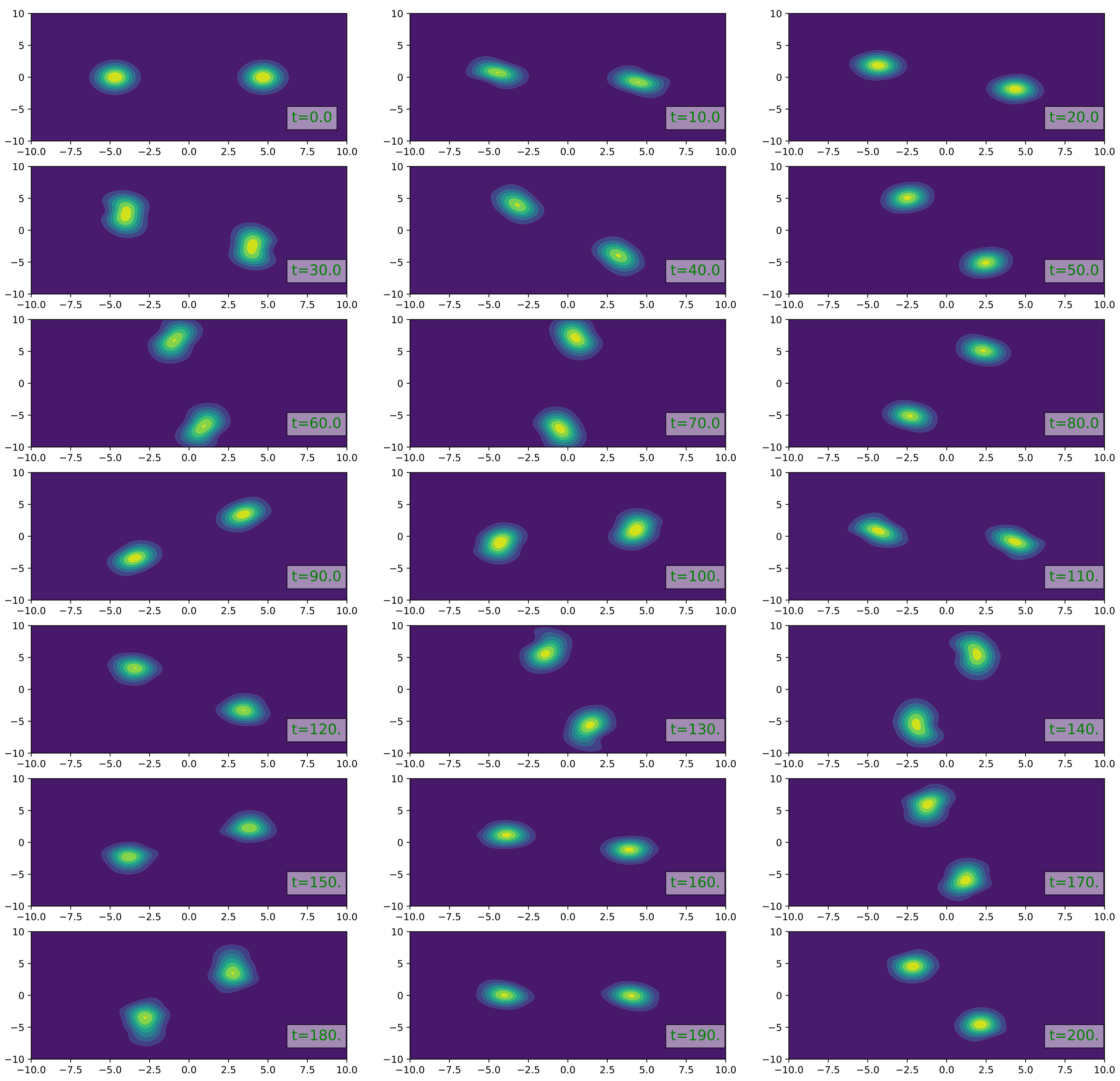

Figure 1. Two colliding solitons with masses M1 = 1 and M2 =1 code units with no self-interaction. Snapshots of the evolution of the Husimi distribution function. These plots show contours of constant values of Husimi distribution function. (x-axis - space, y-axis - velocity). Time progresses from left to right,(top to bottom). The time is 200 code units and the box length is 20 code units. Finite difference scheme.

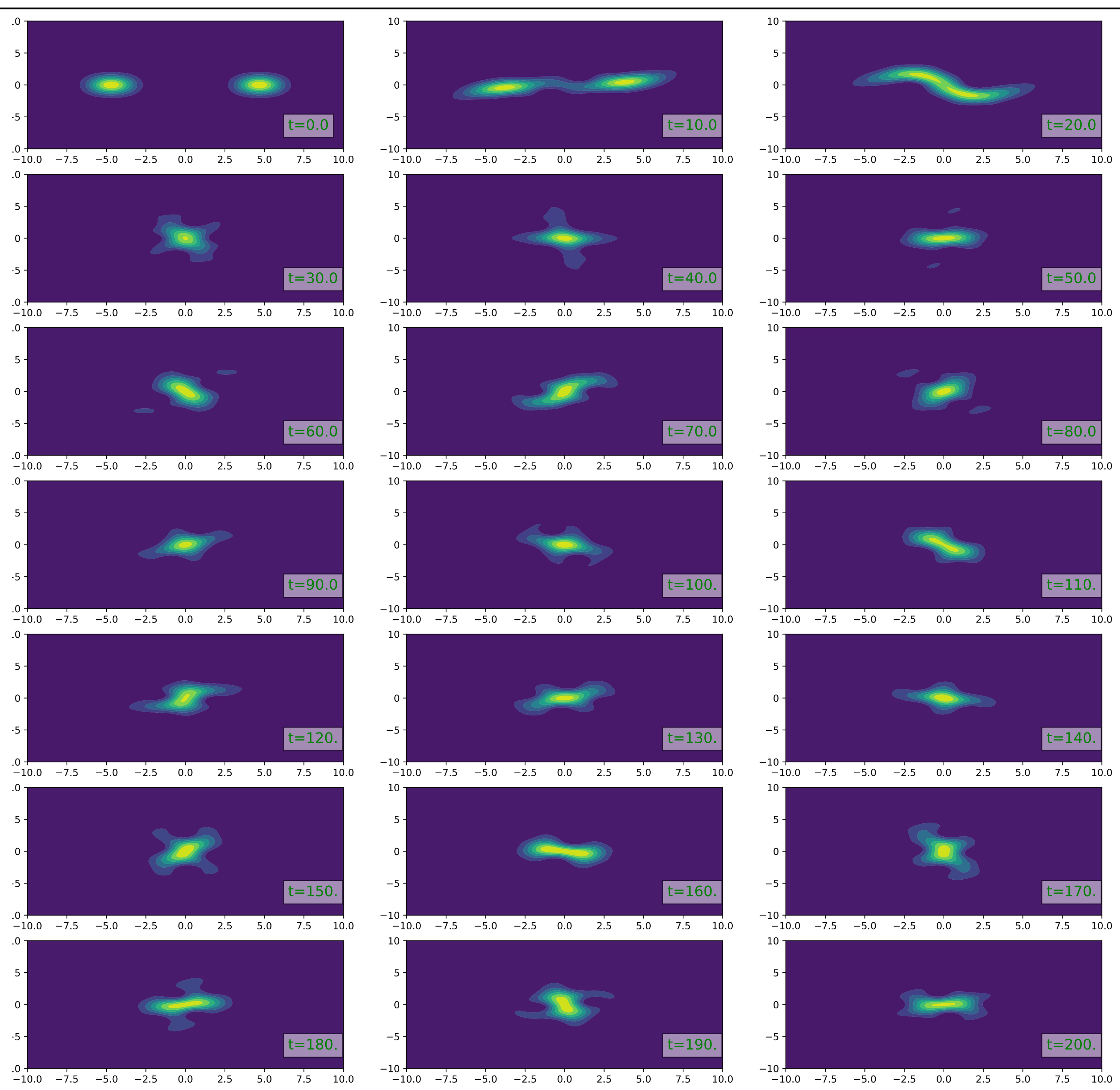

Figure 2. Two colliding solitons with masses M1 = 1 and M2 =1 code units with a repulsive self-interaction. Snapshots of the evolution of the Husimi distribution function. These plots show contours of constant values of Husimi distribution function. (x-axis - space, y-axis - velocity). Time progresses from left to right,(top to bottom). The time is 200 code units and the box length is 20 code units, Spectral method,

FUTURE WORK

- Adapt and test cosmological codes to study these scenarios.
- Conduct large-scale simulations at the Très Grand Centre de Calcul to study how the formation of large-scale structures is modified compared to the CDM scenario, from Lyman-alpha clouds to galaxies.

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References

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