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Based in Karlsruhe



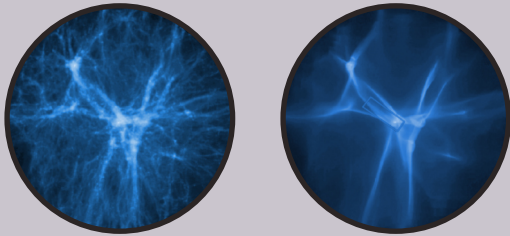
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Monte Carlo simulations for Dark Matter phase space evolution

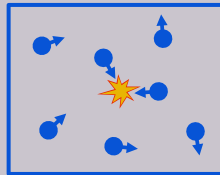
Momentum distribution of Dark Matter affects structure formation



Evolution of the momentum distribution described through Boltzmann equations

$$\frac{\partial f_x(p, t)}{\partial t} - H p \frac{\partial f_x(p, t)}{\partial p} = \frac{\hat{C}[f_x]}{E}$$

We solve Boltzmann equations for Dark Matter using Monte Carlo Simulations



Monte Carlo simulations for Dark Matter phase space evolution

Ann Cathrin Wesener
& Felix Kahlhoefer



1 Motivation

We don't have much information about Dark Matter besides its relic abundance and that it should be non-relativistic early on. The exact distribution of momenta however is unknown. The evolution of the Dark Matter phase space density can be described through Boltzmann equations.

$$\underbrace{\frac{\partial f_x(p, t)}{\partial t}}_{\text{change in the distribution}} - \underbrace{H p \frac{\partial f_x(p, t)}{\partial p}}_{\text{momentum redshift}} = \underbrace{\hat{C}[f_x]}_{\text{collisions}}$$

All interactions of Dark Matter, either with itself or with other particles, influence the phase space distribution. Different phase space distributions could potentially be probed by structure formation.



Cold Dark Matter



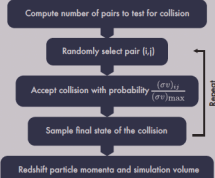
Warm Dark Matter

3 Monte Carlo Approach

General idea: Represent the phase space distribution by N particles and simulate the particle collisions.



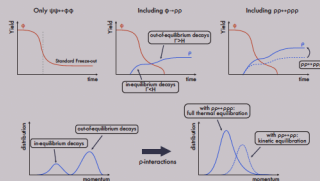
At each time step:



4 Model description

Particle content:

- 1. Massless scalar in thermal equilibrium with the Standard Model bath.
- 2. Heavy scalar, initially in thermal equilibrium, then freezes out.
- 3. Light scalar, produced through decays of ϕ .



2 Standard Approaches

If the phase space distribution is thermal, one can define a temperature and solve the integrated Boltzmann equation, i.e. only solve how number density and temperature change through scattering

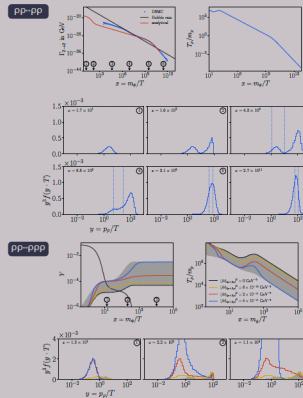
$$\dot{n}_x + 3H n_x = \int \frac{d^3p}{(2\pi)^3} \frac{\hat{C}[f_x]}{E}$$

In case of non-thermal distribution, the full Boltzmann equation needs to be solved.

This is usually done by discretizing the momentum space.

Disadvantage: One needs a lot of grid points for good resolution and also knowledge about the relevant momentum ranges.

5 Results



6 Summary

- Boltzmann equations describe the evolution of dark matter.
- We solve Boltzmann equations on phase space level using Monte Carlo simulations.
- We show that all relevant processes (freeze-in, freeze-out, scattering) can be included in the simulations.
- As a toy-model, we consider a two-step production of dark matter and subsequent kinetic and chemical equilibration.

7 References

- [1] G. Bird, *Molecular gas dynamics and the direct simulation of gas flows*, 1994
- [2] Z. Xu and C. Greene, *Thermalization of gluons in ultrarelativistic heavy ion collisions by including three-body interactions in p-particle cascades*, 2005
- [3] O. Huchler and M. Ondruschka, *Precision calculation of Higgs with neutrino direct simulation Monte Carlo*, 2022
- [4] D. O. R. Lopes, M. A. G. T. S. L. and J. M. T. S., *Building dark matter freeze-in and freeze-out through phase space distribution*, 2022

Poster #17

