How can we simulate dark matter-baryon interactions?

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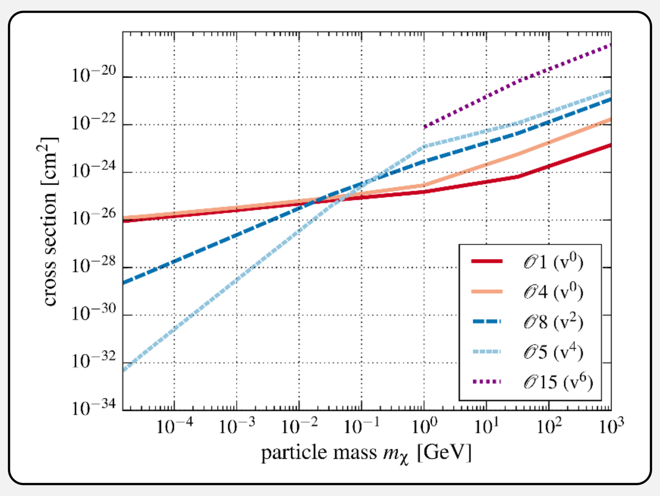
Interacting Dark Matter

Dark matter-proton scattering:

- Interactions can alter the distribution of dark matter (DM) and baryons.
- They may be relevant not only at high redshift but also for the late evolution as well.
- There are constraints from the cosmic microwave background (CMB) on the transfer cross-section, σ_{T} (see figure).
- For a velocity-independent interaction with equal masses, the CMB bounds are $\sigma_{\mathrm{T}}/m_\chi \lesssim 0.1\,\mathrm{cm^2\,g^{-1}}$.

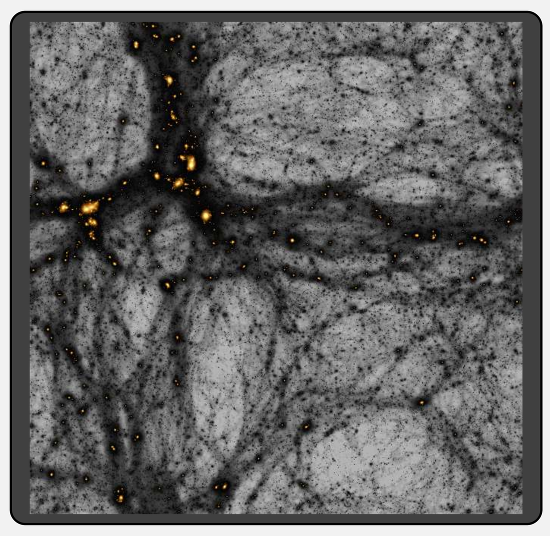


Boddy & Gluscevic 2018

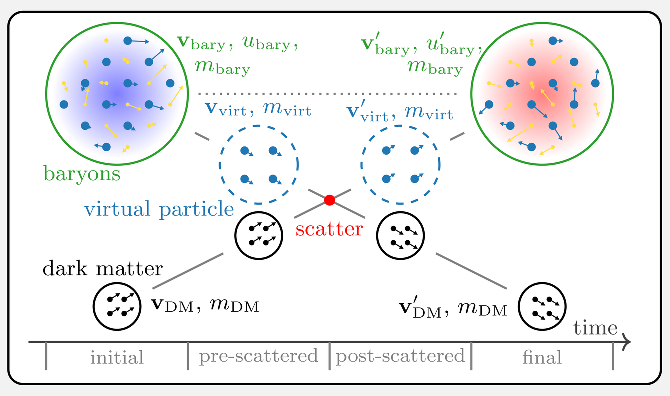
Simulation Code

OpenGadget3:

- Cosmological hydrodynamic simulation code, used for many simulations, e.g. Magneticum.
- Gravity: N-body code with Barnes & Hut tree algorithm and Particle Mesh method.
- Hydrodynamics: Smoothed particle hydrodynamics (SPH, Beck et al., 2016) and meshless finite mass (MFM, Groth et al., 2023).
- Self-interacting dark matter: Small- and large-angle scattering (Fischer et al., 2021).



Numerical Scheme



To facilitate the interaction between a numerical DM particle and an SPH/MFM particle, a "virtual" particle is generated from the SPH/MFM particle. It interacts with the DM particle similar to SIDM. Afterwards, the SPH/MFM and virtual particles are reunited.

For larger-angle scattering a probability whether the DM and virtual particles interact is computed,

$$P_{ij} = \frac{\sigma(v)}{m_\chi} \frac{f_{\mathrm{bary}}}{\mu} m_{\mathrm{DM}}\, v\, \Delta t\, \Lambda_{ij}\,,$$

$\mu = m_{\mathrm{virt}}/m_{\mathrm{bary}}$. In the case of small-angle scattering a drag force is applied,

$$F_{\mathrm{drag}} = \frac{\sigma_{\mathrm{T}}(v)}{m_\chi} \frac{f_{\mathrm{bary}}}{\mu(1+r)} m_{\mathrm{virt}}\, m_{\mathrm{DM}}\, v^2\, \Lambda_{ij}\,,$$

and perpendicular momentum diffusion as done in the scheme for SIDM by Fischer et al. (2021). The interacting mass fraction of baryons is f_{bary}.

Models that can be simulated:

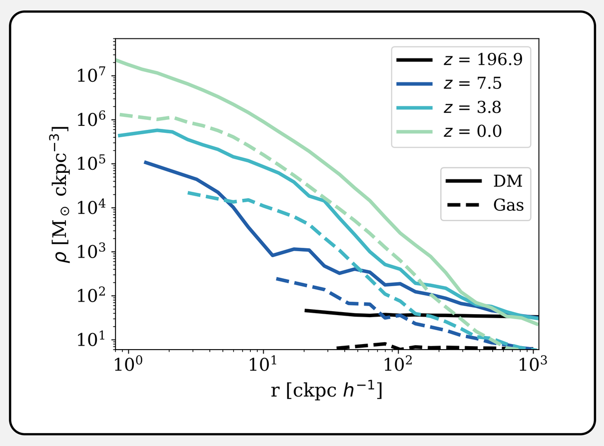
- Various angle- and velocity-dependent cross-sections can be simulated.
- Particle models with unequal masses are possible, e.g. $r = m_{\mathrm{p}}/m_\chi = 1000$ for DM-proton scattering.

Challenges:

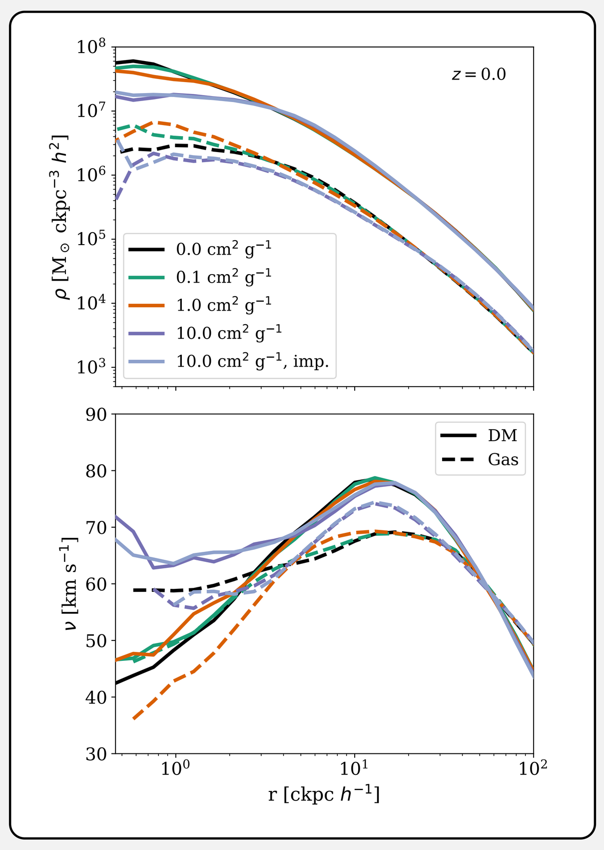
- The numerical particle mass of the SPH/MFM particle should be larger than that of the DM particle.
- Artificial heat conduction and viscosity are needed for many setups.

Halo Formation

Starting from $z = 200$, the collapse of a single spherically symmetric overdensity for a halo of $M \approx 10^{12}\,\mathrm{M_\odot}$ was simulated. The initial density profile follows a slowly rolling power law (Lu et al., 2006). The figure displays the increase of the DM and baryon densities over time for the collisionless case.

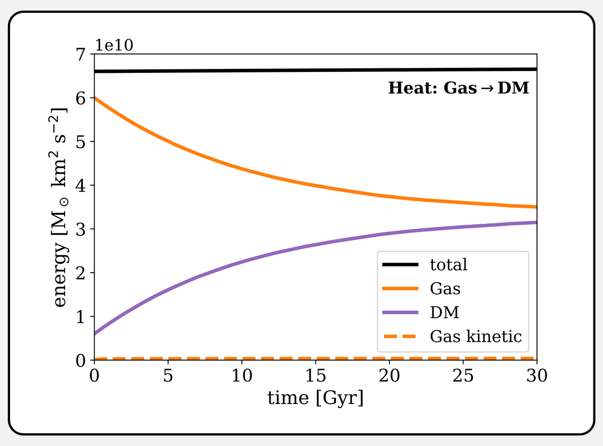


IDM simulations of a collapsing overdensity for several velocity-independent forward-dominated cross-sections with equal-mass scattering, $\sigma_{\mathrm{T}}/m_\chi \in \{0.1, 1.0, 10.0\}$ ($\mathrm{cm^2\,g^{-1}}$). The density profile (upper panel) and the velocity dispersion profile (lower panel) are shown in the figure for $z = 0.0$. In the central region, the interactions can lead to a heat flow from the baryons to the DM, resulting in an increased baryon density and a reduced DM density. The strongest cross-section gives rise to significant heat inflow from large radii, such that even the central baryon density decreases.

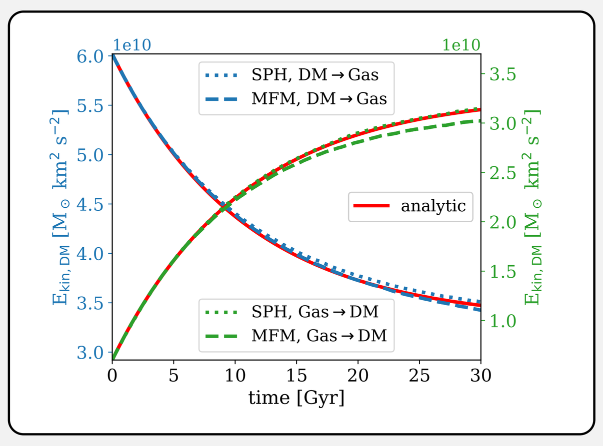


Heat Conduction Test

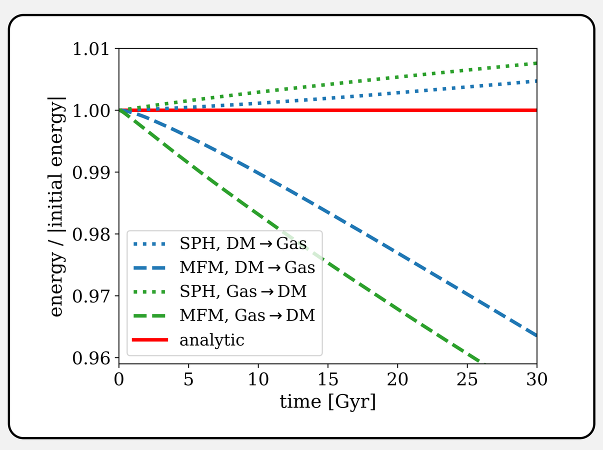
Test where heat flows from the hotter baryons to the cooler DM due to scattering. A periodic box with constant density and uniform velocity dispersion/temperature is used, and no gravity is involved. The simulation was conducted employing SPH for the baryons.



For the same test as above, the kinetic energy of the DM (green) is compared to the analytic expectation from Dvorkin et al. (2014). The results for a simulation with heat flow from DM to baryons (blue) are shown as well. Moreover, the simulations were run with SPH and MFM.



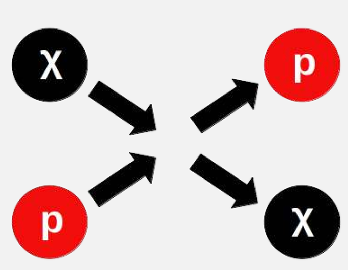
Energy conservation is shown for the simulation of the heat conduction test problem. The red line indicates perfect energy conservation. However, the simulation results deviate, with SPH having a smaller numerical error than MFM.



In Short

Problem:

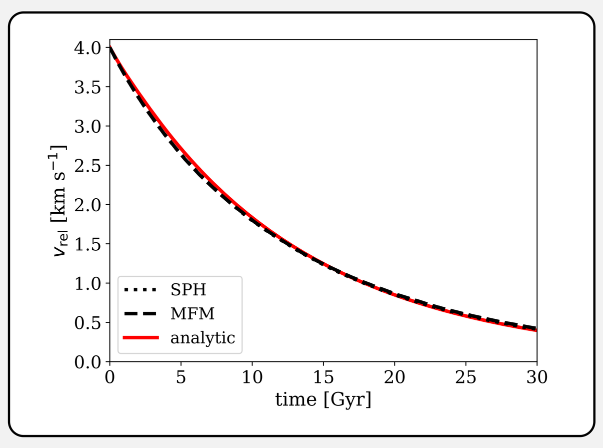
- How to model dark matter-baryon interactions, e.g. DM-proton scattering, and their influence on galaxies in state-of-the-art N-body simulation codes?



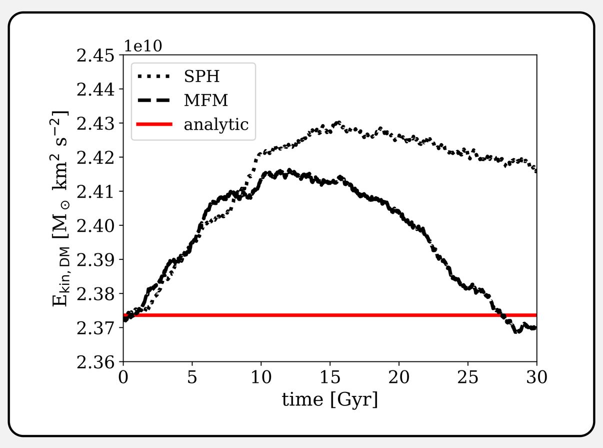
Solution:

- Novel numerical scheme for dark matter-baryon interactions derived from first principles that enables accurate modelling.
- Implementation in the cosmological hydrodynamical simulation code OpenGadget3 (N-body + SPH/MFM + SIDM).

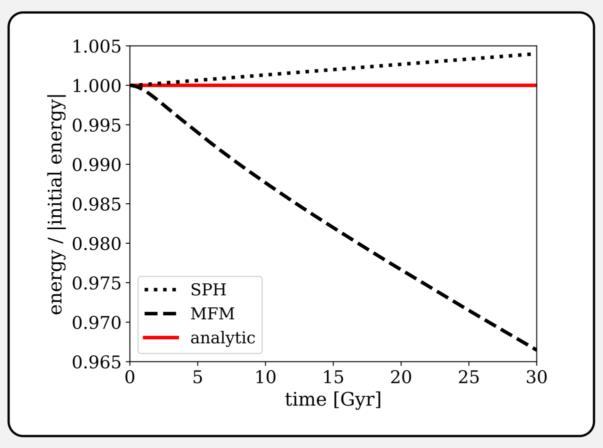
Momentum Transfer Test



A test without gravity where DM and baryons have the same energy but a relative motion was conducted. It is shown how this motion decays as a result of the interactions. The exact solution (red) is from Dvorkin et al. (2014).



The kinetic energy of the DM is shown. No net energy transfer between the DM and the baryons should occur, i.e. the kinetic energy of the DM should stay constant as indicated by the red line.



Energy conservation for the simulations of the momentum transfer test. The total energy (black) is expected to remain constant over time (red). For the SPH simulation, the energy is better conserved than for MFM.

Conclusions

1. It is possible to simulate dark matter interactions, e.g. dark matter-proton scattering. This includes cross-sections with various angular- and velocity-dependencies, as well as unequal mass ratios.
2. IDM simulations are more challenging than SIDM simulations, e.g. in terms of energy conservation or required numerical particle masses.
3. Simulations of halo formation including the effects of DM-baryon interactions such as the formation of a DM density core are possible.

References

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