N-body Modeling and Visualization in the Context of Self-Interacting Dark Matter

International workshop "What comes beyond the standard models"

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Plan

Motivation

Increased positron concentration in cosmic rays

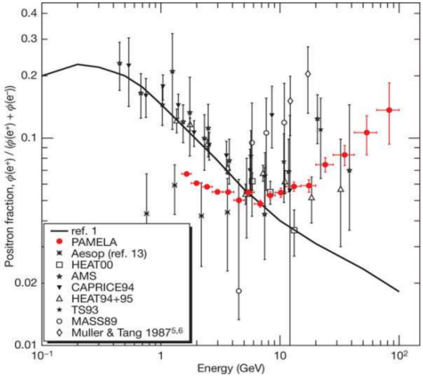


Fig. 1: **[Adriani et al., 2009]**

Increased positron concentration in cosmic rays

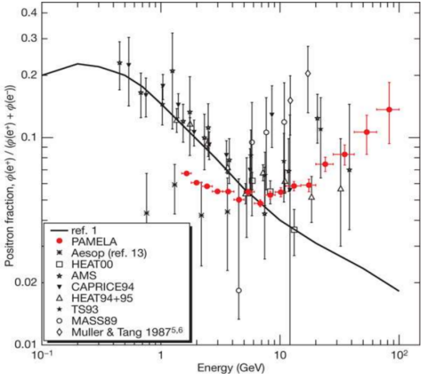
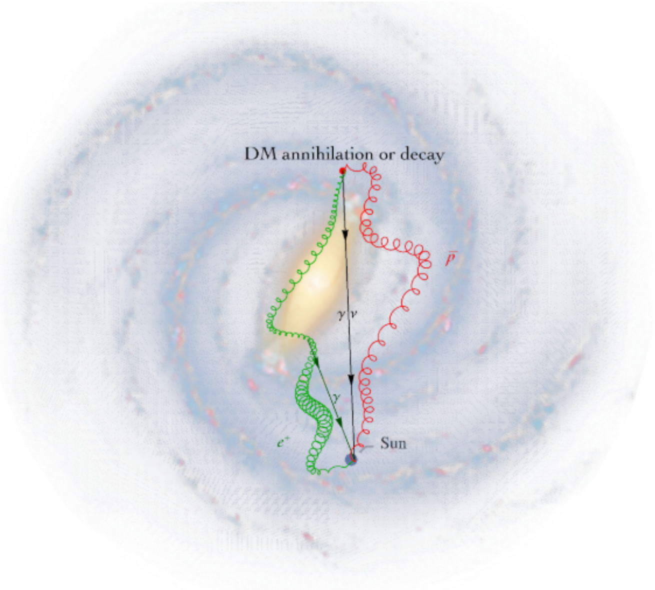


Fig. 2: **[Adriani et al., 2009]**



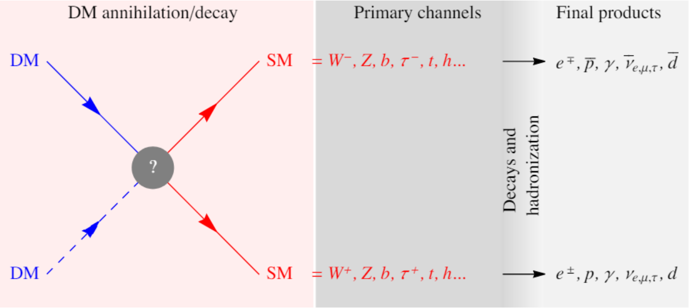
Possible explanations for the positron anomaly

1. **DM-driven mechanisms**
   1.1 *Spatial distribution effects*: distibuted near Earth DM (disks, clusters, ...) — suppress gamma. *(this talk)* [**Alekseev et al., 2016**], [**Belotsky et al., 2017**], [**Belotsky et al., 2018**]
   1.2 *DM interaction physics*: models have decays with gamma suppression (ex. $X^{++} \to e^+e^+$, *in next talk*) [**Barak et al., 2023**]
2. **Astrophysical sources**
   2.1 *Pulsars*.

      [**Hooper et al., 2017**]
   2.2 *Supernova and SNR*.

      [**Malkov et al., 2016**]

$$Q = \begin{cases} \frac{1}{2}\left(\frac{\rho}{M}\right)^2 \langle \sigma v \rangle_{\text{tot}} \frac{dN_{e^\pm}}{dE} & \text{(DM annihilation)}, \\ \frac{\rho}{M}\Gamma_{\text{tot}} \frac{dN_{e^\pm}}{dE} & \text{(DM decay)}, \end{cases}$$



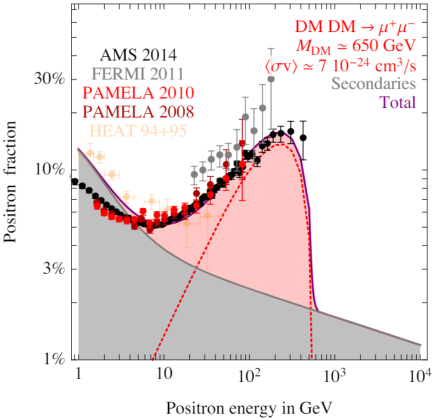
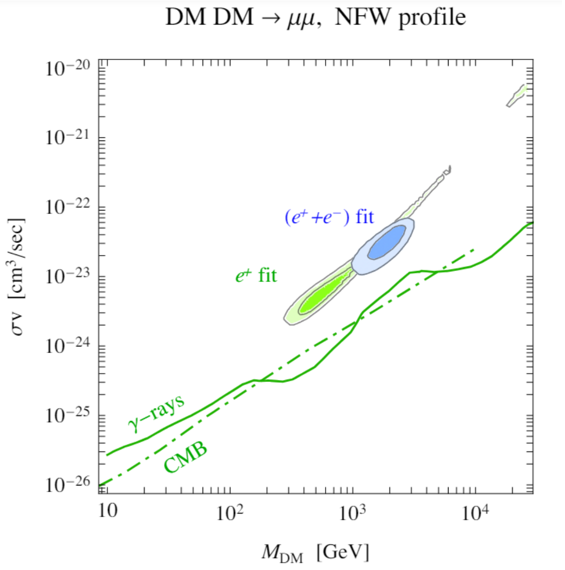
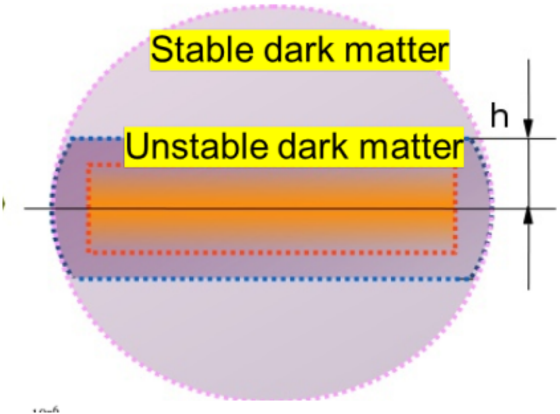


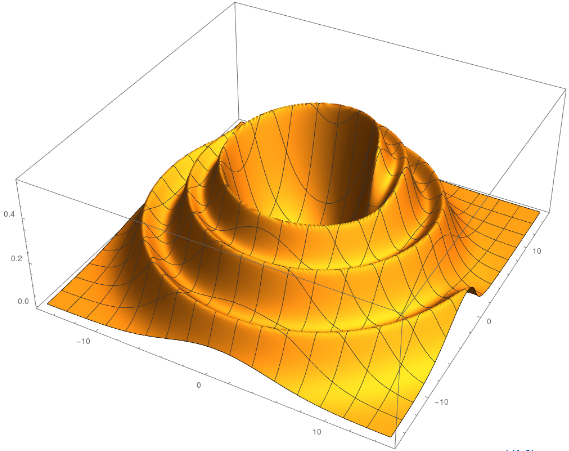
Fig. 3: **[Cirelli et al., 2024]**


DM DM → μμ, NFW profile
σv [cm³/sec]
10−20
10−21
10−22
10−23
10−24
10−25
10−26
10
10²
10³
10⁴
M_DM [GeV]
(e⁺+e⁻) fit
e⁺ fit
γ−rays
CMB

High-energy positrons do not reach us from large distances, unlike gamma rays. Let us distribute their sources around us.

Using different dark matter self interaction cross-sections ⇒ dark matter structures ⇒ DM spatial distribution.





Dark matter interactions ⇒ dark matter structures

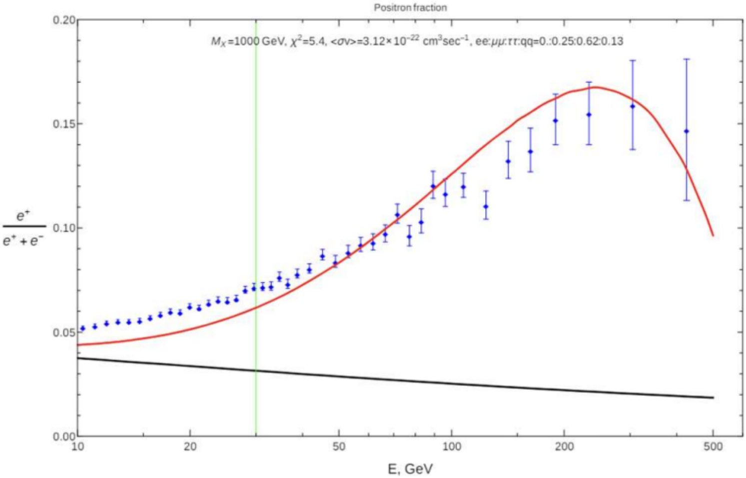
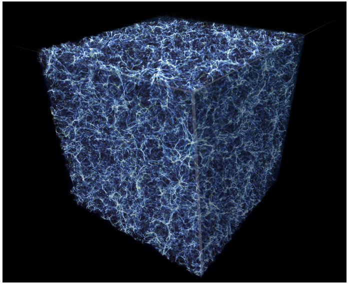


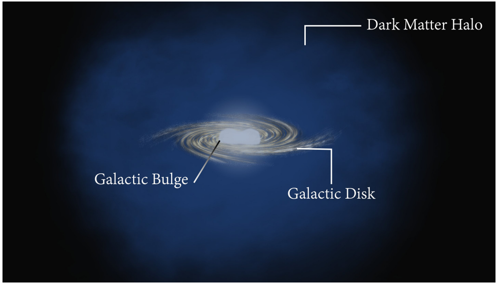
Fig. 4: Positron fraction from DM particles distributed in disk.

[**Belotsky et al., 2018**]

Cold dark matter (CDM)

The simplest assumption about dark matter is that it has **no interactions**.





CDM issues at galactic scales

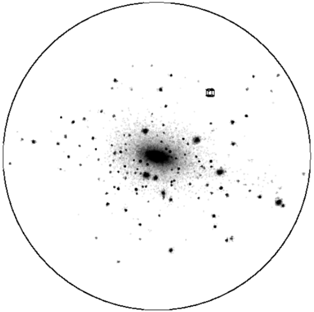


Fig. 5: "Missing satellite" problem,

[Klypin et al., 1999]

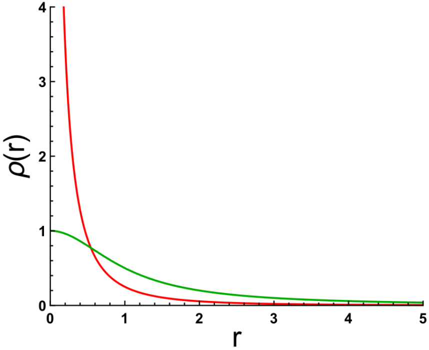


Fig. 6: "Core-cusp" problem,

[Moore, 1994], [Blok, 2010]

Evidences for SIDM

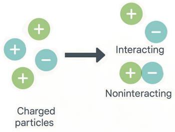
- **Self-Interacting Dark Matter (SIDM)** — additional interaction only between dark matter particles. [Spergel et al., 2000]
- Solves issues of the standard cosmological model at galactic scales.
  [Davé et al., 2001], [Zavala et al., 2013], [Elbert et al., 2015]
- **Mergers of SMBHs:** resolves the final parsec problem [Alonso-Álvarez et al., 2024]
- **Early galaxies excess (JWST):** enhanced early collapse [Kurmus et al., 2022], [Roberts et al., 2025]
- **Non-halo structures:** disks, spirals etc. (this work)
- This work considers a model where SIDM particles make up a small fraction/a subcomponent of CDM.

MEPhI

Idea

A small fraction of interacting dark matter forms non-halo structures (disks, spirals...). The main dark matter component is non-interacting. It forms halo-like structures consistent with ΛCDM on large scales.

Example: charged DM which partly recombines and creates two-component dark matter



Interacting dark matter is unstable and has annihilation/decay channels into Standard Model particles $\Rightarrow$ solves the positron anomaly

- **Goal** — to develop a mechanism for the formation of structures from self-interacting dark matter.
- An important task is to determine the parameters of interacting dark matter that define the shape of the resulting structures.

Example of morphological table

Structure	$\sigma/m = 0.01$, **cm**^{2}/**g**	$\sigma/m = 0.1$, **cm**^{2}/**g**	$\sigma_1(v)/m$, **cm**^{2}/**g**
Halo	✓	✓	✓
Disk	✗	✗	✓
Spirals	✗	✗	✓
Bars	✗	✗	✗
Compact cores	✗	✓	✓

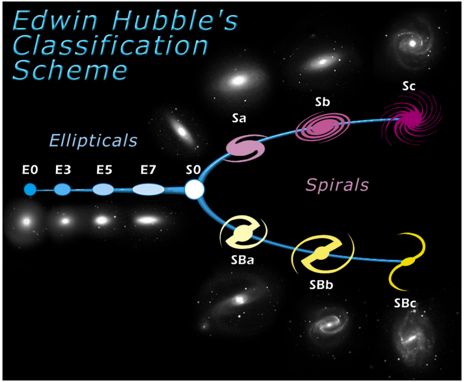
How do galactic structures form with self-interacting DM?

How can we find the answers?

- **Analytically**: using equations developed for structures made of ordinary matter.
- **Numerically**:
  - Using N-body simulations with SIDM models enabled.
  - Modifying existing baryonic N-body simulations as a basis for SIDM.

- There is no general theory of structure formation.
- The primary method is modeling, where initial conditions are essential.
- Inner structure is influenced by competing effects: SIDM collisions, dynamical friction, and adiabatic evolution due to baryonic feedback.
- Complex structures (bars, spirals, etc.) are studied under specific initial conditions.

[**Naab et al., 2017**]



Ref: David Goodstein, Adventures in Cosmology

Simulation codes used for SIDM in the literature

- Main code: **GADGET (2/3/4)** — nearly half of all simulations.

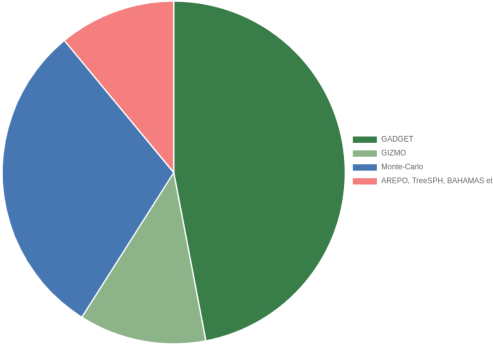
  [**Springel, 2005**] Bhattacharyya, J., et al. (2022); Driskell, T., et al. (2024), Fischer, M., et al. (2024)

- **GIZMO** is used for hydrodynamical simulations (FIRE).

- About 30% of studies use custom-built SIDM codes — often for frequent/anistropic scattering

  . [**Ghigna et al., 2000**], [**Randall et al., 2015**], [**Shen et al., 2021**]

- The rest use AREPO, TreeSPH, BAHAMAS, etc.



Brief history of SIDM simulations: Why historical context matters?

- Historical context helps us to understand how our current ideas and models evolved, and how they became widely accepted in the cosmological community.
- It is important to emphasize that N-body simulations in cosmology have a much longer history, dating back to the pioneering works by Aarseth, White, and Peebles in the 1960s–1970s.
- Here, I specifically focus on the evolution of numerical methods and models for self-interacting dark matter (SIDM).
- Reviewing how the SIDM approach has evolved over the last 25 years allows us to appreciate the current achievements and identify key open questions.

SIDM simulations: early phase (2000–2012)

- **First simulations** using GADGET and custom schemes show the formation of central cores in SIDM halos

  [**Yoshida et al., 2000**] [**Davé et al., 2001**].

- The concept of **gravothermal collapse** in SIDM halos is introduced

  [**Balberg et al., 2002**].

- Development of **velocity-dependent models**: $\sigma(v) \propto 1/v$

  [**Colín et al., 2002**].

- Bullet Cluster is used to constrain σ/m

  [**Randall et al., 2008**].

- Comparison of hydrodynamics and N-body approaches shows good agreement

  [**Koda et al., 2011**].

SIDM simulations: intermediate phase (2012–2020)

- Emergence of **zoom-in simulations** with well-calibrated SIDM modules
  [**Rocha et al., 2013**].
- SIDM provides a solution to the “too big to fail” and “missing satelite” problem
  [**Zavala et al., 2013**], [**Elbert et al., 2015**].
- Inclusion of baryons: GIZMO + FIRE-2 show differences in density profiles between SIDM and CDM
  [**Robles et al., 2017**].
- Development of **frequent scattering models**
  [**Sameie et al., 2018**].
- First **large-scale simulations** with lensing and SIDM — BAHAMAS-SIDM
  [**Robertson et al., 2018**].

SIDM simulations: taking into account more physical effects (2021–2025)

- Shift to **realistic cosmological zoom-in series** with baryons
  [**Vargya et al., 2022**], [**Nadler et al., 2023**].
- Development of drag-force SIDM models
  [**Fischer et al., 2023**].
- Use of GADGET-4 and model comparison in the **Dianoga** project
  [**Ragagnin et al., 2024**].
- SIDM exhibits **new subhalo phenomenology** and asphericity in the presence of frequent scatterings
  [**Ragagnin et al., 2024**].

SIDM numerical simulations: clue conclusions

- SIDM numerical methods significantly evolved: from *simple tests* to **physically realistic simulations**.
- SIDM transitioned from solving basic cosmological issues (core-cusp, missing satellites) to complex models with rich phenomenology (velocity-dependent scattering, baryonic feedback, drag-force).
- Many open questions remain, making SIDM an active and promising research area.

Working with GADGET-2

Containerization and reproducibility

To ensure reproducibility, portability, and ease of installation, a convenient **Docker image** was built, which automatically installs:

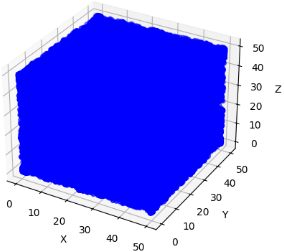
- All necessary libraries: `MPI`, `FFTW`, `GSL`;
- The `GADGET-2` simulator with key make-options: `PERIODIC`, `PMGRID`, `DOUBLEPRECISION`, `TREEPM`;
- The `yt` module and auxiliary Python scripts for analysis and visualization.

The image is published in an open GitHub repository and is accompanied by a **script** that checks:

- successful compilation;
- successful run of a minimal test — growth of perturbations in an expanding universe.

First probe CDM simulations

N-body simulation with only dark matter.
Box size = 50 Mpc.
Number of particles = 128^3.



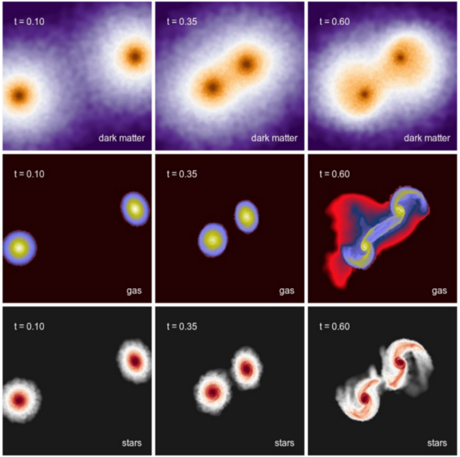
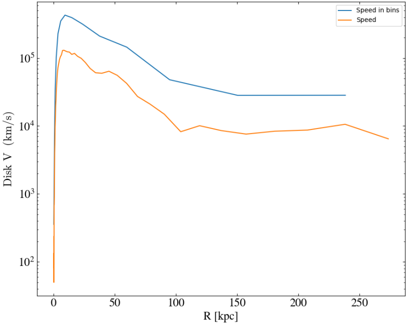
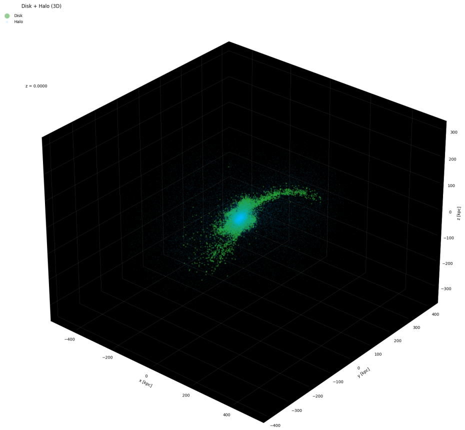


Fig. 7: V. Springel et al. (2021)

Test CDM simulations

N-body simulation of two colliding galaxies (disk + halo).
Box size = 500 kpc.
Number of particles = 10^4.





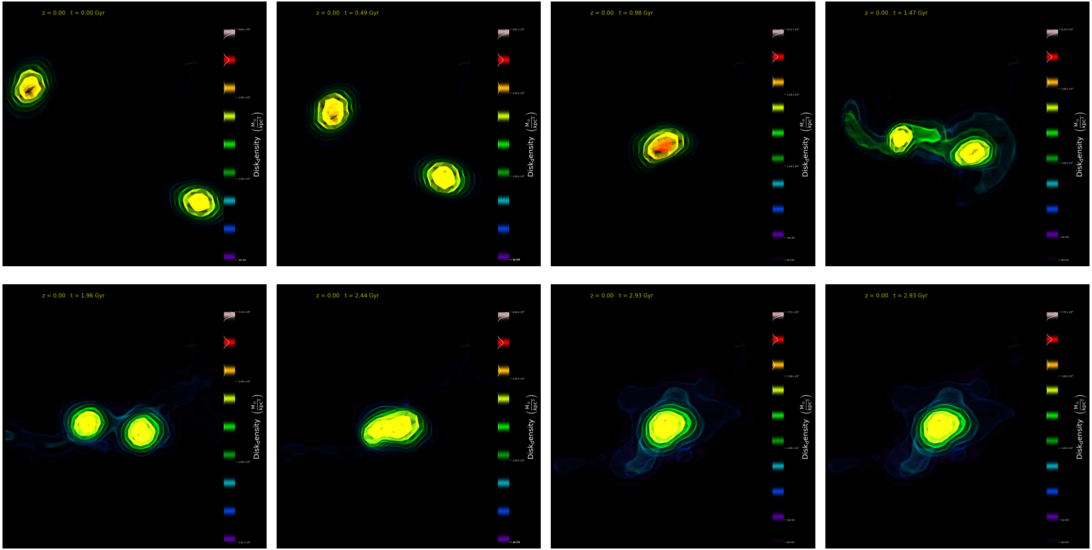


Fig. 8: 3D density distribution of the disk during the galaxy collision (by simulation steps).

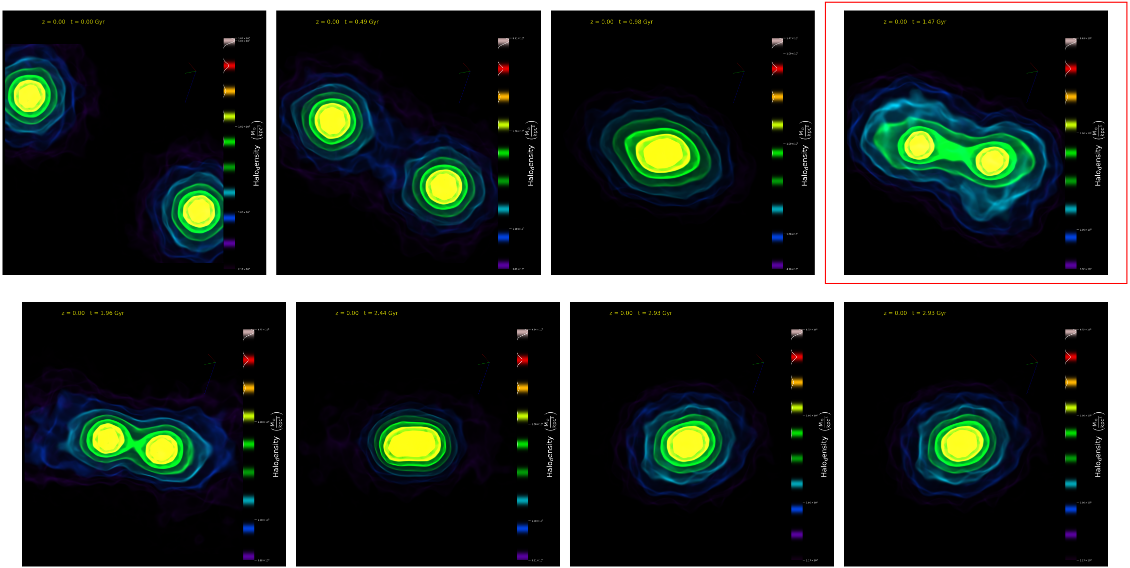
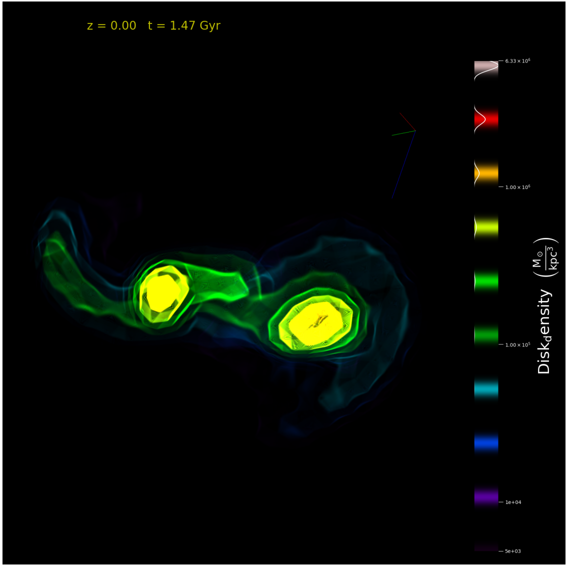
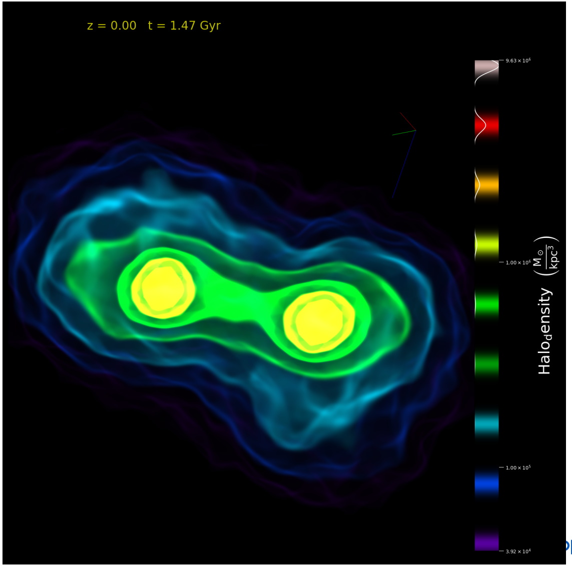


Fig. 9: Evolution of the spatial density distribution of the dark matter halo during the galaxy collision.

Comparison of halo and disk





Conclusion

Conclusion

In this work:

- A convenient Docker build with pre-installed GADGET-2 and support for visualization via `yt` was created;
- Test simulations were conducted and visualization modules were implemented;
- The next step is to implement SIDM interactions based on the existing code;
- A morphological table of possible structures in different SIDM models is planned.

Thank you for attention!

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Kinematics and particle density

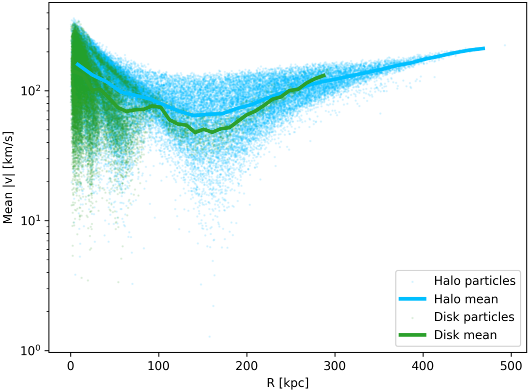

Fig. 10: Rotation curves $v(r)$

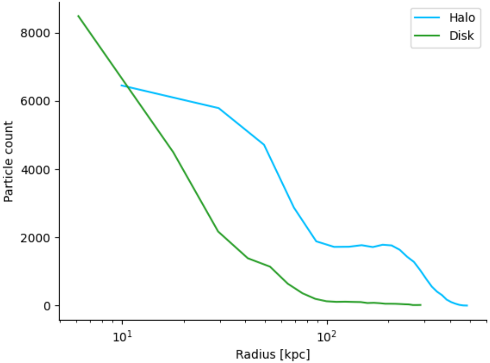

Fig. 11: Density profile $\rho(r)$

Phase diag for Disk and Halo