DREAMS

Release 0.1

DREAMS collaboration

May 03, 2024

DREAMS

DREAMS stands for **D**a**R**k matt**E**r with **AI** and si**M**ulation**S**, and it is a project designed to combine astrophysics with particle physics through machine learning in order to shed light on the nature of dark matter and to learn about the physics that shapes the Universe on small scales. For this purpose, DREAMS will generate thousands of state-of-the-art hydrodynamic simulations with different astrophysics and dark matter models on different environments.

Fig. 1: The above image shows hundreds of Milky-Way like galaxies from DREAMS both face-on and edge-on. Each galaxy was created by running a zoom-in simulation with a different warm dark matter mass and different feedback efficiency from supernovae and super massive black-holes. The simulations are designed to be analyze with machine learning techniques in order to extract the maximum information from the data while marginalizing over uncertain astrophysical effects.

CHAPTER

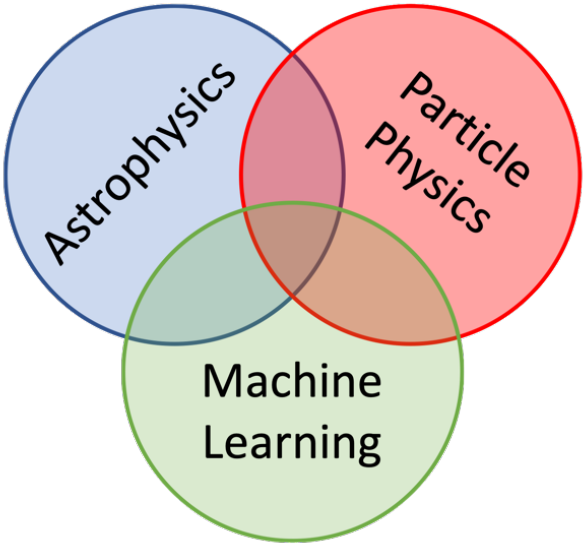
ONE

GOALS

The main goals of the DREAMS projects are:

- To shed light on the nature and properties of dark matter
- To understand the physics that governs the Universe on small scales

To accomplish these goals, DREAMS will run a very large set of state-of-the-art hydrodynamic simulations and explore them with machine learning. The simulations will explore different regimes, from cosmological boxes to dwarf galaxies, and will be run with different dark matter models while varying uncertain astrophysical processes such as the efficiency of supernova feedback.



CHAPTER
TWO

PUBLICATIONS

1. **Introducing the DREAMS Project: DaRk mattEr and Astrophysics with Machine learning and Simulations**

   Jonah C. Rose, Paul Torrey, Francisco Villaescusa-Navarro, Mariangela Lisanti, Tri Nguyen, Sandip Roy, Kassidy E. Kollmann, Mark Vogelsberger, Francis-Yan Cyr-Racine, Mikhail V. Medvedev, Shy Genel, Daniel Anglés-Alcázar, Nitya Kallivayalil, Bonny Y. Wang, Belén Costanza, Stephanie O'Neil, Cian Roche, Soumyodipta Karmakar, Alex M. Garcia, Ryan Low, Shurui Lin, Olivia Mostow, Akaxia Cruz, Andrea Caputo, Arya Farahi, Julian B. Muñoz, Lina Necib, Romain Teyssier, Julianne J. Dalcanton, David Spergel

   2405.00766

2. **Can we constrain warm dark matter masses with individual galaxies?**

   Shurui Lin, Francisco Villaescusa-Navarro, Jonah Rose, Paul Torrey, Arya Farahi, Kassidy E. Kollmann, Alex M. Garcia, Sandip Roy, Nitya Kallivayalil, Mark Vogelsberger, Yi-Fu Cai, Wentao Luo

   2401.17940

3. **Inferring Warm Dark Matter Masses with Deep Learning**

   Jonah C. Rose, Paul Torrey, Francisco Villaescusa-Navarro, Mark Vogelsberger, Stephanie O'Neil, Mikhail V. Medvedev, Ryan Low, Rakshak Adhikari, Daniel Angles-Alcazar

   2304.14432

CHAPTER

THREE

DATA ACCESS

Important: If you are interested in working with data from the DREAMS project please fill out this form.

Data can be accessed via:

- URL
- Globus
- Binder

CHAPTER
FOUR

GENERAL DESCRIPTION

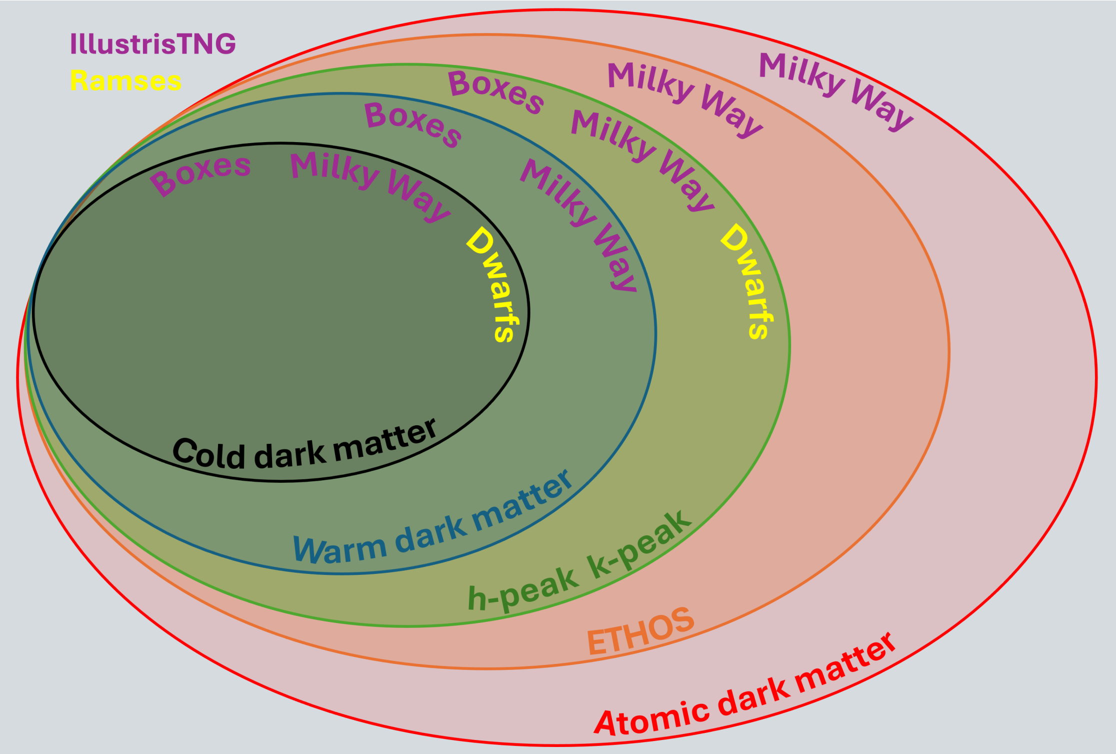
The simulations in the DREAMS project are designed to 1) unveil the nature of dark matter and 2) improve our knowledge on the physics shaping the Universe on small scales.

4.1 Organization

DREAMS contains thousands of N-body and hydrodynamic simulations. The simulations can be organized into:

- *Models*, depending on the dark matter model adopted:
  - Cold dark matter
  - Warm dark matter
  - h-peak k-peak
  - ETHOS
  - Atomic dark matter
- *Types*, depending on the environment simulated:
  - Cosmological boxes
  - Milky-way zooms-ins
  - Dwarfs zoom-ins
- *Suites*, depending on the code used to run them:
  - IllustrisTNG
  - Ramses
  - N-body

The scheme below illustrates the DREAMS data structure. The ellipses represent the different models, and the relation among them. For instance, CDM, WDM, and h-peak k-peak models are a subset of ETHOS. Inside each ellipse, we show the available types. For instance, the CDM model contains cosmological boxes, Milky way zoom-ins, and dwarfs zoom-ins. The color of the types indicates the suite: purple (run with IllustrisTNG), yellow (run with Ramses).



4.2 Characteristics

This table shows the characteristics of the DREAMS simulations:

Model	Type	Suite	Cosmology	Simulations	Status
Cold dark matter (CDM)	Boxes	IllustrisTNG	Varied	1024	Complete
	Milky Way	IllustrisTNG	Varied	1024	Running
	Dwarfs	Ramses	Varied	1024	Planned
Warm dark matter (WDM)	Boxes	N-body	Fixed	600	Complete
	Boxes	N-body	Varied	1000	Complete
	Boxes	IllustrisTNG	Varied	1024	Complete
	Milky Way	IllustrisTNG	Fixed	1024	Complete
Hpeak Kpeak	Boxes	N-body	Fixed	400	Complete
	Boxes	N-body	Varied	1024	Planned
	Boxes	IllustrisTNG	Varied	1024	Planned
	Dwarfs	Ramses	Varied	1024	Planned
ETHOS	Milky way	N-body	Varied	1024	Planned
	Milky Way	IllustrisTNG	Varied	1024	Planned
Atomic dark matter (ADM)	Milky way	N-body	Varied	1024	Planned
	Milky Way	IllustrisTNG	Varied	1024	Planned

4.3 Redshifts

All simulations contain 91 snapshots. This file contains the scale factors of the snapshots. The user can click below to see the redshift, scale factor, and snapshot number for the different snapshots:

Redshift	Scale Factor	snapshot number
14.99	0.063	000
13.34	0.070	001
11.98	0.077	002
11.20	0.082	003
10.48	0.087	004
9.69	0.094	005
9.00	0.100	006
8.49	0.105	007
8.01	0.111	008
7.60	0.116	009
7.24	0.121	010
6.89	0.127	011
6.56	0.132	012
6.28	0.137	013
6.01	0.143	014
5.75	0.148	015
5.50	0.154	016
5.23	0.161	017
5.00	0.167	018
4.80	0.172	019
4.61	0.178	020
4.45	0.183	021
4.30	0.189	022
4.15	0.194	023
4.01	0.200	024
3.87	0.205	025
3.73	0.211	026
3.62	0.216	027
3.49	0.223	028
3.36	0.229	029
3.24	0.236	030
3.12	0.242	031
3.01	0.249	032
2.90	0.257	033
2.80	0.263	034
2.72	0.269	035
2.63	0.276	036
2.54	0.282	037
2.46	0.289	038
2.38	0.296	039
2.30	0.303	040
2.22	0.310	041
2.15	0.318	042
2.07	0.325	043
2.00	0.333	044

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Table 1 – continued from previous page

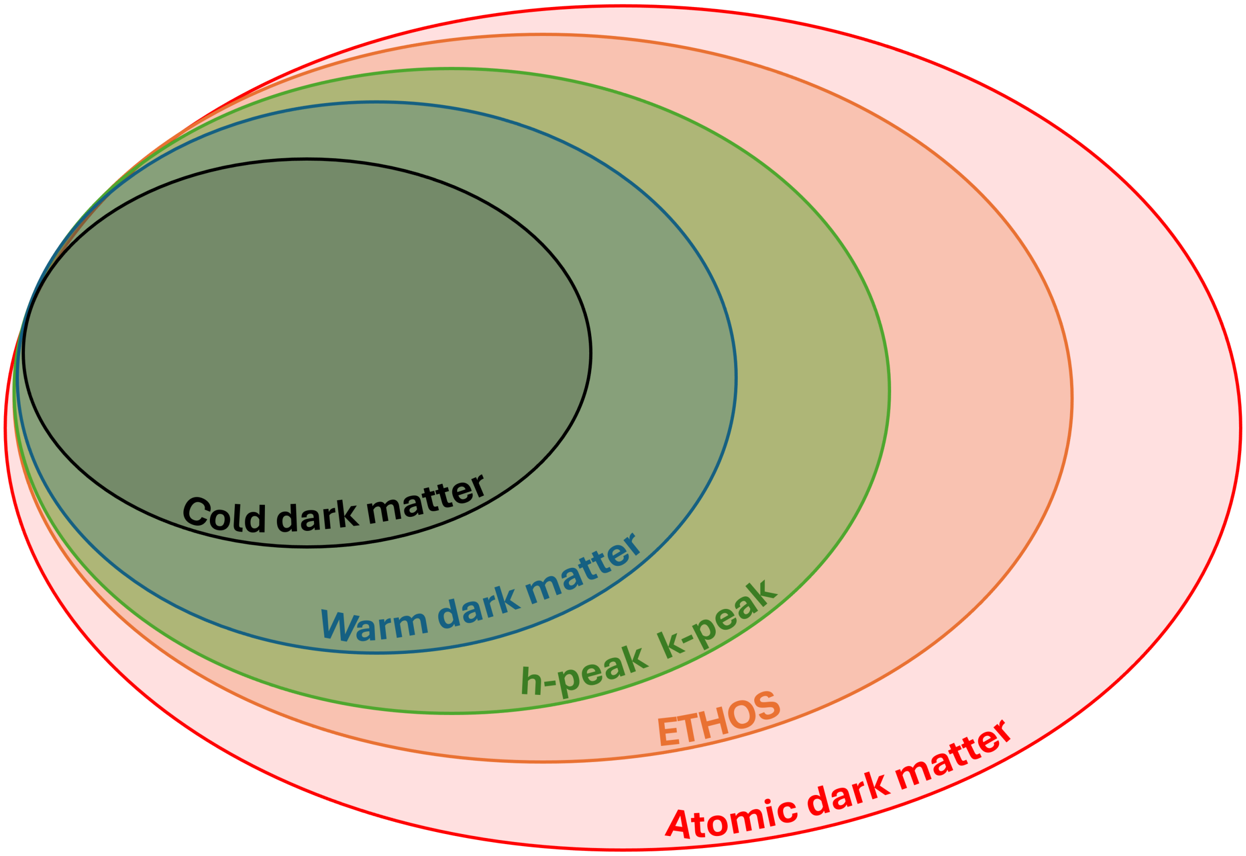
Redshift	Scale Factor	snapshot number
1.93	0.341	045
1.86	0.349	046
1.80	0.358	047
1.73	0.366	048
1.67	0.375	049
1.60	0.384	050
1.54	0.393	051
1.48	0.403	052
1.43	0.412	053
1.37	0.422	054
1.30	0.434	055
1.26	0.443	056
1.20	0.455	057
1.14	0.466	058
1.09	0.478	059
1.05	0.489	060
1.00	0.501	061
0.95	0.513	062
0.90	0.525	063
0.86	0.538	064
0.82	0.550	065
0.77	0.564	066
0.73	0.577	067
0.69	0.591	068
0.65	0.605	069
0.61	0.620	070
0.58	0.635	071
0.54	0.650	072
0.50	0.665	073
0.47	0.681	074
0.43	0.698	075
0.40	0.714	076
0.37	0.731	077
0.34	0.749	078
0.30	0.771	079
0.27	0.789	080
0.24	0.808	081
0.21	0.827	082
0.18	0.847	083
0.15	0.867	084
0.13	0.888	085
0.10	0.910	086
0.07	0.931	087
0.05	0.954	088
0.02	0.977	089
0.00	1.000	090

Note: The exact redshifts of a given snapshot may be slighty different to the above ones. For instance, there are small differences between the exact redshifts of the snapshots in the Astrid and SIMBA suites. In the simulations of the IllustrisTNG suite these numbers can also be slightly different, since AREPO can only write snapshots in the highest time steps in the hierarchy.

Warning: Due to space constraints, we have moved some snapshots to tape. If you need these please reach out.

DARK MATTER MODELS

The simulations of the DREAMS project have been run using five different dark matter models. The scheme belows show the different dark matter models we consider together with their relationship. For instance, the cold dark matter, warm dark matter, and $h_\mathrm{p} - k_\mathrm{p}$ models are subclasses of the ETHOS models, that is more general than all those.



5.1 Cold dark matter

Cold dark matter is the simplest model we consider and it is the model assumed in the standard model of cosmology $\Lambda\mathrm{CDM}$. This model assumes that dark matter only interacts gravitationally with itself and with baryons and have negligible thermal velocities on all scales at all redshifts of interest. In this case, dark matter can be represented as a collisionless and pressureless fluid in the numerical simulations.

Note that this model do not have any free parameters. We will refer to this model as either Cold dark matter or CDM.

5.2 Warm dark matter

Warm dark matter (WDM) is perhaps the simplest extension to CDM. These models consider that dark matter was in thermal equilibrium in the early Universe. Due to the expansion of the Universe, dark matter interactions became inefficient and its thermal distribution was frozen. Candidates for WDM include sterile neutrinos. In the model we use, we only have one free parameter, the WDM mass, $M_{\rm WDM}$. This parameter fully characterizes the distribution of the WDM thermal velocities (which is described by the Fermi-Dirac distribution).

We implement these models in the simulations by assuming that WDM is a collisionless and pressureless fluid (in the same way as CDM). The only difference is that when we generate the initial conditions, we need to account for the impact of WDM mass on the linear power spectrum, that can be described as (Bode et al. 2001)

$$P_{\rm WDM}(k) = \beta(k) P_{\rm CDM}(k) \ ,$$

where

$$\begin{aligned}\beta(k) &= \left[\left(1+(\alpha k)^{2.4}\right)^{-5.0/1.2}\right]^2 \\ \alpha &= 0.048 \left(\frac{M_{\rm WDM}}{1\ \mathrm{keV}}\right)^{-1.15} \left(\frac{\Omega_{\rm m}-\Omega_{\rm b}}{0.4}\right)^{0.15} \left(\frac{h}{0.65}\right)^{1.3} .\end{aligned}$$

Note: In our simulations we do not assign thermal velocities to the WDM particles. See Leo et al. 2017 for a justification.

We emphasize that cold dark matter is contained in these models: cold dark matter can be recovered by taking large WDM masses.

5.3 Hpeak - Kpeak and ETHOS

While WDM is characterized by a single scale below which structure is strongly suppressed, more complex dark matter sectors could lead to matter power spectra with a richer shape characterized by multiple scales (see e.g. Boehm and Schaeffer 2005). In particular, the presence of light (relativistic) degrees of freedom coupling to dark matter in the early Universe can lead to dark sound waves propagating in the dark sector, leading to acoustic oscillations being imprinted on the matter power spectrum. Such “dark acoustic oscillations” (DAOs, Cyr-Racine et al. (2014)) do not generally extend to arbitrarily small scales (large k) since the coupling between dark matter and the relativistic species is finite, leading to dissipation of the sound waves and a net suppression of the matter power spectrum on small scales . Therefore, such dark matter models are typically characterized by at least two parameters: a sound horizon scale and a damping scale (Buckley et al. (2014)).

A convenient and simple parameterization for such a matter power spectrum is the so-called $k_{\rm peak}, h_{\rm peak}$ approach (Bohr et al. 2020). Here, $k_{\rm peak}$ represents the Fourier wavenumber of the first (largest scale) acoustic oscillation in the matter power spectrum, while $h_{\rm peak}$ represents the height of this first acoustic peak relative to what the power spectrum would have been in the CDM case, i.e. $h_{\rm peak} = P_{\rm DAO}(k_{\rm peak})/P_{\rm CDM}(k_{\rm peak})$. With these choices, $k_{\rm peak}$ is closely related to the dark matter sound horizon, while $h_{\rm peak}$ captures the amount of acoustic dissipation in the dark sector. For instance, $h_{\rm peak} = 1$ corresponds to relatively undamped DAOs in the matter power spectrum and $h_{\rm peak} \to 0$ corresponds to strongly damped DAOs. This approach is powerful as it provides a parameterization that can smoothly interpolate between WDM (corresponding to $h_{\rm peak} \to 0$) and CDM ($k_{\rm peak} \to \infty$), allowing one to consider a more diverse range of matter power spectrum shapes than either CDM or WDM. Extended dark sectors typically not only alter the initial matter power spectrum, but also allow for dark matter particles to exchange energy and momentum among themselves. Such self-interacting dark matter (Spergel & Steinhardt 2000) can affect the density profiles of dark matter halos. This can greatly increase the diversity of halo profile types, ranging from those with a constant density core to very dense halos undergoing gravothermal collapse. In their simplest incarnation, self-interactions are elastic and simply redistribute the energy among dark matter particles. Generally speaking, the ability of a given particle model to affect the matter power spectrum and the self-interaction cross section is correlated. To self-consistenly capture this relationship, the Effective THeOry of Structure formation (ETHOS) was created (Cyr-Racine et al. 2016 , Vogelsberger et al. 2016). This allows for a joint and coherent understanding of the impacts of a non-CDM matter power spectrum and dark matter self-interaction on structure formation.

5.4 Atomic dark matter

Atomic dark matter (ADM) covers a broad range of interacting dark matter models. In the simplest minimal model, ADM comprises a dark electron, a dark proton, and dark photon (without dark nuclear physics) and is described by five parameters: m_e', m_p', α', f', and ξ' where the first three parameters are the particle masses and the dark fine structure constant. f' is the dark matter mass fraction of the ADM and ξ' is the ratio of the dark CMB (cosmic microwave background) temperature to the Standard Model CMB temperature. Depending on the choice of particle parameters, the atomic dark matter could comprise all the dark matter ($f' = 100$

In this minimal case, we implement ADM in hydrodynamical simulations as separate dark gas particles which convert into collisionless dark clumps when the dark gas becomes Jeans unstable. The atomic dark gas experiences dark pressure forces and dark cooling physics consistent with the ADM parameters chosen (Roy et al. 2023). The remainder of the dark matter can either be modelled as cold dark matter (CDM) or as self-interacting dark matter (SIDM). Whilst the minimal atomic dark matter model comprises solely of an asymmetric dark sector with dark electromagnetic interactions, atomic dark matter can also encompass more complex dark sectors with dark nuclear physics and dark particle physics as rich as the Standard Model. Such models would have more than the five parameters of the minimal case and potentially as many parameters as the Standard Model (if not more).

Several other models of dark matter can be considered limiting cases of the ADM model. Since the ADM can experience pressure forces as a dark plasma in the early Universe (until dark recombination), the ADM can imprint dark acoustic oscillations (DAOs) and suppress the matter power spectrum, like the ETHOS, h-peak - k-peak and warm dark matter models listed above (see Bansal et al. 2022, Cyr-Racine & Sigurdson 2012). The ADM parameter space which produces DAOs, comprises large mass fractions and results in inefficient galactic cooling will encompass much of the parameter space of these models. However, the ADM model, as currently implemented, will not accurately capture purely elastic collisions between dark matter particles with large mean free paths (compared to simulation softening lengths).

CHAPTER

SIX

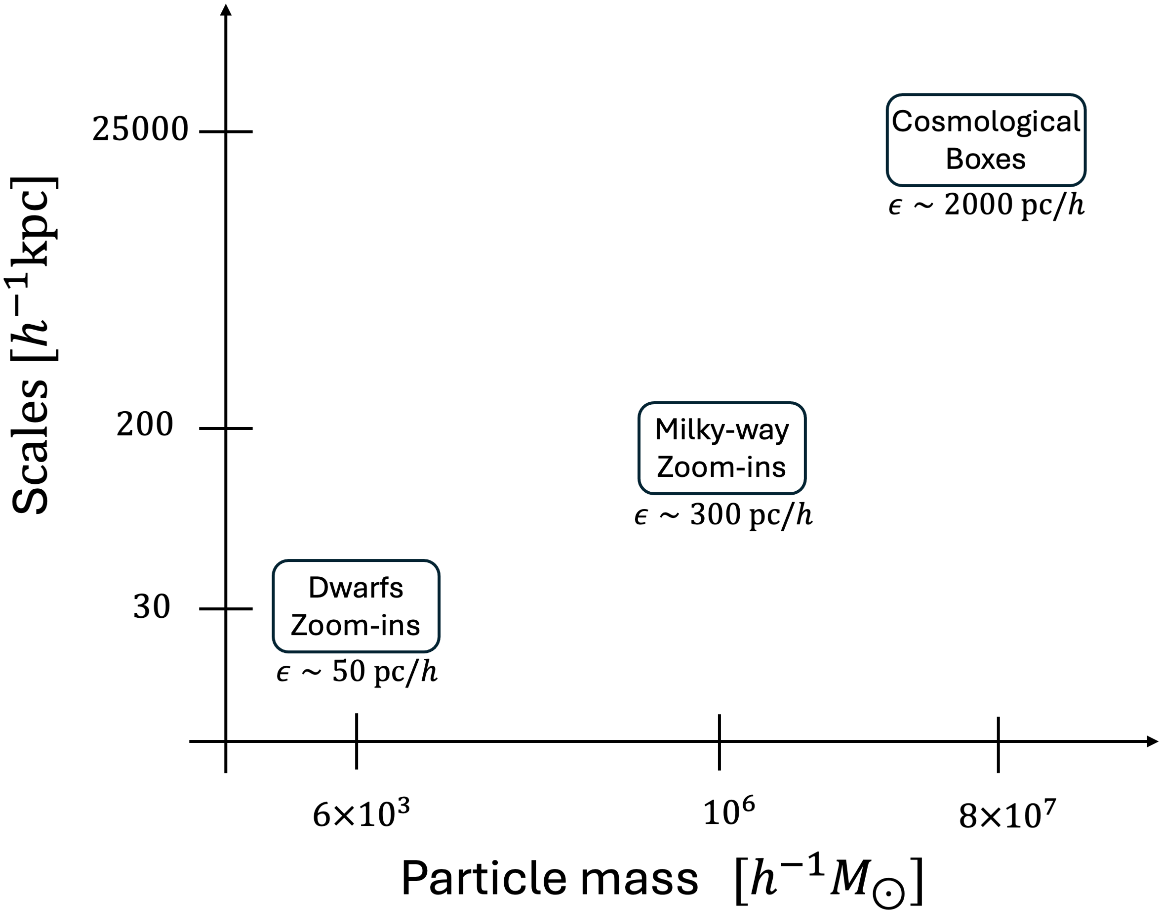
SIMULATION TYPES

Ideally, we would like to have simulations covering a volume as large as possible (to enhance statistics) with the highest possible resolution (to better identify dark matter effects). Unfortunately, at a limited computing time, one needs to make a tradeoff between those. In DREAMS, we balance this by running simulations that cover different physical scales at different resolutions.

Important: In the quest of astrophysical signatures of dark matter properties we also face the challenge of choosing between large statistics at low-resolution versus low statistics at high-resolution.

The DREAMS simulations can then be classified into three categories, depending on the mass resolution, spatial resolution, and the environment they prove:

- Cosmological boxes
- Milky-way zoom-ins
- Dwarfs zoom-ins



6.1 Cosmological boxes

These simulations follow the evolution of 256^3 dark matter particles plus 256^3 initial gas elements in a periodic comoving box of length 25 $h^{-1}\mathrm{Mpc}$ from $z = 127$ down to $z = 0$.

The dark matter particle mass is (assuming fixed $\Omega_\mathrm{b} = 0.049$) $7.81 \times 10^7 \times (\Omega_\mathrm{m}/0.302)\ h^{-1}M_\odot$. The softening length is roughly 2 $h^{-1}\mathrm{kpc}$.

6.2 Milky-way zoom-ins

These simulations target individual dark matter halos with masses similar to the one of the Milky-Way at higher resolution than the cosmological boxes described above. These simulations are carried out as follows. First, we run a cosmological N-body simulation to follow the evolution of 256^3 dark matter particles in a $L = 100\ h^{-1}\mathrm{Mpc}$ periodic box. From this low-resolution simulation, a random isolated dark matter halo with mass similar to the one of the Milky-Way ($\sim 1.6 \times 10^{12}\ M_\odot$) is selected. Next, all particles within 5x the virial radius of this halos are traced back to $z = 127$ and an ellipsoide is used to approximate that region in the initial conditions. That region is then sampled with intermediate resolution particles (500x lower mass) and a new simulation is run. This intermediate resolution simulation allows us to better define the boundary of the considered halo and do not add much to the computational cost. Finally, we take all particles (low resolution and intermediate resolution) within 5x the virial radius of the halo and fit an ellipse to their Lagrangian region. That region is then sampled with high-resolution particles (~8x lower mass than intermediate resolution particles), either dark matter only (for N-body) or dark matter plus gas (for hydrodynamic).

In these simulations, the dark matter particle mass is $1.2 \times 10^6\ h^{-1}M_\odot$ and the gravitational softening length is set to roughly $300\ \mathrm{pc}$.

6.3 Dwarfs zoom-ins

These simulations target individual dark matter halos with masses $\sim 10^{10}\ M_\odot$ that could host individual dwarf galaxies. The procedure we employ to run these simulations is similar to the one described about for the MW-like halos but starting with a uniform box of $35\ h^{-1}M_\odot$ and targetting isolated halos with mass $10^{10}\ M_\odot$.

In these simulations, the dark matter particle mass is $6.53 \times 10^3\ h^{-1}M_\odot$ and the gravitational softening length is set to roughly $50\ \mathrm{pc}$.

CHAPTER

SEVEN

SIMULATION CODES

The simulations of the DREAMS project have been run using three different codes. Below, we provide details about these codes and the physics they model.

7.1 IllustrisTNG

The simulations in the IllustrisTNG suite have been run with the Arepo code using the same subgrid physics as the IllustrisTNG simulation. Arepo uses TreePM to solve for gravity and a moving Voronoi mesh to solve for ideal magnetohydrodynamics (MHD). The IllustrisTNG galaxy formation physics implementation includes sub-grid models for star-formation, stellar evolution and galactic winds, as well as supermassive black hole (SMBH) seeding, merging, accretion and feedback. The latter operates in two modes, selected based on SMBH mass and Eddington ratio, where the high-accretion mode is thermal and the low accretion mode is kinetic and is the more efficient one in ejecting gas and quenching massive galaxies. The galactic winds feedback is kinetic, implemented via briefly hydrodynamically decoupled wind particles, with energy and mass loading factors that are prescribed based on local velocity dispersion and metallicity. Much more detail can be found on the IllustrisTNG project website.

7.2 Ramses

The simulations in the RAMSES suite have been run with the RAMSES code using the same subgrid physics as in Kretschmer & Teyssier (2021) and Teyssier et al. (2011). RAMSES uses Adaptive Particle Mesh to solve for gravity and the Godunov Finite Volume Constrained Transport method to solve for ideal magnetohydrodynamics (MHD). The galaxy formation physics implementation includes a multi-freefall sub-grid model for star-formation and supernovae momentum feedback as in Kretschmer and Teyssier (2021), as well as supermassive black hole (SMBH) seeding, merging, accretion and feedback as in Teyssier et al. (2011) and Pellissier et al. (2023). RAMSES also models metallicity dependent radiative cooling, as well as radiation heating from a self-shielded UV background consistent with standard reionization models.

7.3 N-body

All the N-body simulations hve been run with the AREPO code. The number of voxels in the PM grid is typically set to be 8 times that of the number of particles. The gravitational softening is set to $\sim 1/40$ of the mean inter-particle distance.

CHAPTER

EIGHT

PARAMETERS

CHAPTER
NINE

TEAM

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CHAPTER

TEN

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