CoDECS guide

version 2.0

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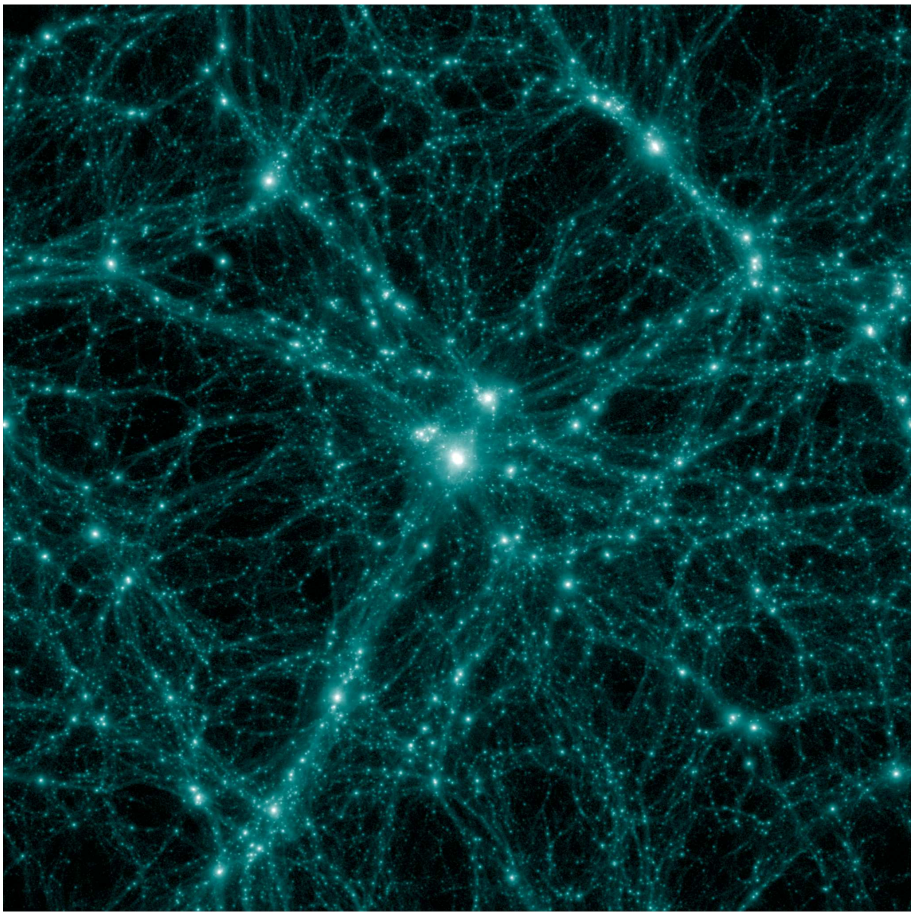
January 14, 2013



Contents

1 The CoDECS project

The COupled Dark Energy Cosmological Simulations (CoDECS) project is a large program of numerical N-body simulations for non-standard cosmological scenarios that feature, instead of the standard cosmological constant Λ, a dynamical field with direct interaction to Cold Dark Matter (CDM) as a source of the cosmic accelerated expansion of the Universe. The simulations follow the evolution of CDM and baryons in the Universe, allowing to study the effects of Dark Energy on the formation of cosmic structures.

At the time of writing, the CoDECS project includes the largest N-body simulations ever performed for this type of cosmological scenarios.

All the CoDECS numerical data are made publicly available under the *Creative Commons Attribution - Share Alike License* [1] either directly through the CoDECS website (www.usm.uni-muenchen.de/people/mbaldi/CoDECS) or indirectly upon request to the author.

By downloading or requesting any of the CoDECS data you implicitly accept the Terms of Use described in the present document in Sec. 4.1.

2 Cosmological models

At the present stage the CoDECS project includes six different cosmological models. Besides the standard ΛCDM scenario, the range of models includes three constant coupling models with an exponential scalar self-interaction potential (**EXP001, EXP002, EXP003**), one model with exponential coupling and exponential scalar self-interaction potential (**EXP008e3**) and one model with constant coupling and a SUGRA scalar self-interaction potential (**SUGRA003**). Please refer to the CoDECS papers [1, 2] for a detailed description of the models. Other interacting Dark Energy models might be added to the CoDECS project in the future, and will be included in the CoDECS website without further notice.

All the models are normalized in order to have cosmological parameters at the present time in agreement with the latest WMAP7 [3] constraints. The linear matter power spectrum for simulations initial conditions is computed using the publicly available software CAMB [4] for the same set of WMAP7 cosmological parameters. The amplitude of perturbations is normalized to be the same at CMB for all cosmologies.

[1] Please see http://creativecommons.org/licenses/by-sa/3.0/ for details on the License terms.

3 N-body simulations

All CoDECS simulations are performed with the modified version by [5] of the parallel Tree-PM N-body code GADGET-2 [6]. Such modification of the GADGET-2 code includes all the effects of interacting Dark Energy cosmologies which are relevant for structure formation on sub-horizon scales. These are:

- A modified background expansion history $H(z)$
- A variable CDM particle mass
- An extra friction term depending on the background evolution of the scalar field
- A fifth-force acting between pairs of CDM particles (but not for any interaction involving baryons)

Please refer to [5] for a detailed description of the the numerical implementation and for accuracy tests.

At the present stage the CoDECS suite consists of two distinct sets of simulations, the L-CoDECS and the H-CoDECS.

The **L-CoDECS** simulations consist of cosmological boxes of 1 comoving Gpc/h aside, filled with 1024^3 CDM and 1024^3 baryon particles. Both types of particles are treated with **collisionless dynamics** only, which means that baryonic particles are not considered as gas particles but just as a different family of collisionless particles distinguished from CDM. This is done in order to account for the effect of the uncoupled baryonic fraction in interacting Dark Energy models which would not be correctly represented by CDM-only simulations. The mass resolution at $z = 0$ for this set of simulations is $m_c = 5.84 \times 10^{10}$ $M_\odot/h$ for CDM and $m_b = 1.17 \times 10^{10}$ $M_\odot/h$ for baryons, while the gravitational softening is set to $\epsilon_s = 20$ comoving kpc/h, corresponding to 0.04 times the mean linear interparticle separation.

The **H-CoDECS** simulations are instead **adiabatic hydrodynamical simulations** on much smaller scales, with a cosmological box of 80 comoving Mpc/h filled with 512^3 CDM and 512^3 gas particles. The mass resolution at $z = 0$ for this set of simulations is $m_c = 2.39 \times 10^8$ $M_\odot/h$ for CDM and $m_b = 4.78 \times 10^7$ $M_\odot/h$ for baryons, while the gravitational softening is set to $\epsilon_s = 3.5$ comoving kpc/h, also corresponding to 0.04 times the mean linear interparticle separation. For these simulations hydrodynamical forces are included in the dynamical evolution of the baryonic particles. These are computed by means of the entropy-conserving formulation of *Smoothed Particle Hydrodynamics* (SPH, [7]) implemented in GADGET. No other non-adiabatic processes such as gas cooling, start formation, and feedback mechanisms from supernovae or Active Galactic Nuclei are included in any of the H-CoDECS runs.

4 Publicly available data

All CoDECS numerical outputs are made publicly available for scientific use either directly through the CoDECS website or indirectly upon request to the author. This Section includes instructions on how to access the data and how to interpret the different file formats.

4.1 Terms of use

The CoDECS outputs are publicly released under the **Creative Commons Attribution - Share Alike License**. Please read the full Licence terms at the URL [8] before downloading the data.

Any scientific use of the CoDECS data has to be notified by email to the author (marco.baldi@universe-cluster.de) and acknowledged with a reference to the following publications describing the CoDECS project and the numerical implementation:

M. Baldi,
“The CoDECS project: a publicly available suite of cosmological N-body simulations for interacting dark energy models"
Mon.Not.Roy.Astron.Soc. submitted (arXiv:1109.5695)

M. Baldi, V. Pettorino, G. Robbers, V. Springel,
“Hydrodynamical N-body simulations of coupled dark energy cosmologies"
Mon.Not.Roy.Astron.Soc.403:1684-1702, 2010 (arXiv:0812.3901)

By downloading or requesting any of the CoDECS data you implicitly accept the Terms of Use described in the License and in the present Section of the CoDECS guide.

4.2 Where to find the data

CoDECS data can be accessed through the CoDECS website at the URL:

www.marcobaldi.it/research/CoDECS

The starting page of the website gives access to a summary page of the whole CoDECS project where all the CoDECS simulations – with a brief description of the corresponding cosmological model and numerical parameters – are listed. Each element of this list is a direct link to a specific web page for the corresponding simulation where all the available data for that individual simulation are stored and can be directly downloaded.

The CoDECS website contains most of the presently available data, namely for each simulation the background and linear perturbations evolution, the extrapolated linear power spectrum at $z = 0$, the nonlinear matter power spectra for CDM, Baryons and total matter at different redshifts, and catalogs of halos and subhalos at different redshifts. Due to the large volume of the raw data (~ 4.5 Tb for each L-CoDECS run) only the snapshot at $z = 0$ is stored on the website for each simulation. Snapshots at different redshifts can be obtained upon request to the author. However, due to the difficulty of transferring large amounts of data over the web, such requests should be appropriately motivated.

The next subsections describe how to interpret the file formats for the different CoDECS data.

4.3 Background and Linear Perturbations

For any given CoDECS run XYZ the section *Background and linear perturbations* of the specific web page on the CoDECS website gives direct access to a series of files describing the background and linear perturbations evolution of that model. These files are named as

- Background → XYZ_CoDECS-background.dat
- Growth Factor CDM → XYZ_CoDECS-growthfactor_CDM.dat
- Growth Factor Baryons → XYZ_CoDECS-growthfactor_baryons.dat
- Growth Factor All → XYZ_CoDECS-growthfactor_all.dat
- Transfer Function → XYZ_CoDECS-linear_power.dat

These are all formatted files whose content is described below.

Background

The background files contain 10 columns and a variable number of lines. The different columns display data for background quantities in the following order:
1) $\ln a$, i.e. the natural logarithm of the cosmological scale factor
2) Ω_{kin}, i.e. the kinetic fractional energy density of the scalar field
3) Ω_{pot}, i.e. the potential fractional energy density of the scalar field, such that $\Omega_\phi = \Omega_{kin} + \Omega_{pot}$
4) Ω_r, i.e. the radiation fractional energy density
5) Ω_b, i.e. the baryon fractional energy density
6) Ω_c, i.e. the CDM fractional energy density, such that $\Omega_M = \Omega_c + \Omega_b$
7) H, i.e. the Hubble function, normalized to 0.1 at the present time
8) β_c, i.e. the coupling between dark energy and CDM
9) ϕ, i.e. the value of the cosmological scalar field
10) w_ϕ, i.e. the equation of state parameter of the dark energy scalar field

Linear Perturbations

The three different linear perturbations files contain 3 columns and a variable number of lines. The different columns display data for the linear growth of density perturbations in the following order:
1) $1+z$, starting from high redshift down to $z = 0$
2) D_+/a, i.e. the linear growth factor divided by the scale factor, normalized to 1.0 today
3) H, i.e. the Hubble function, normalized to 0.1 at the present time

Transfer Function

The file related to the transfer function contains 3 columns and a variable number of lines. The different columns display data for the extrapolated linear power spectrum at $z = 0$ in the following order:
1) k, i.e. the Fourier wave number in units of h/Mpc
2) $\Delta^2_{\rm lin}(k)$, i.e. the dimensionless linear power spectrum at $z = 0$
3) $P_{\rm lin}(k)$, i.e. the linear power spectrum at $z = 0$ in units of h^3/Mpc^3

4.4 The non-linear matter power spectra

For any given CoDECS run XYZ the section *Power Spectra* of the correspondent specific web page provides direct links to files containing the nonlinear matter power spectra for CDM, baryons, and total matter at different redshifts. These files take the names

- All Matter → XYZ_CoDECS_power _all_zzz.dat
- CDM only → XYZ_CoDECS_power _CDM_zzz.dat
- Baryons only → XYZ_CoDECS_power _baryons_zzz.dat

where the tag zzz refers to the snapshot number corresponding to that particular redshift. Each of these files contain 3 columns and a variable number of lines, displaying data for the nonlinear matter power spectrum as computed from the N-body simulations. The different columns have the following meaning:

1) k, i.e. the Fourier wave number in units of h/Mpc
2) $\Delta^2_{\rm nl}(k)$, i.e. the dimensionless nonlinear power spectrum at $z = 0$
3) $P_{\rm nl}(k)$, i.e. the nonlinear power spectrum at $z = 0$ in units of h^3/Mpc^3

Please see [1] for a detailed explanation of the methods used to compute the power spectra.

4.5 Groups and SubGroups Catalogs

Groups catalogs are computed from the CoDECS simulations by means of a Friends-of-Friends (FoF) algorithm with linking length $\lambda = 0.2 \times \bar{d}$, where $\bar{d}$ is the mean interparticle spacing. The FoF algorithm is run over the CDM particles and once FoF groups have been identified with this procedure baryonic particles are attached to their closest CDM group member.

Once the FoF halos have been found, gravitationally bound structures within each FoF halo are identified by means of the SUBFIND algorithm [9] implemented in GADGET.

For any given CoDECS run XYZ the section *Groups and SubGroups Catalogs* of the corresponding specific web page provides direct links to files containing the catalogs at different redshifts. These are archive files (.tar) which take the names:

- FoF Groups → XYZ_CoDECS_Groups _zzz.tar
- Substructures → XYZ_CoDECS_SubGroups _zzz.tar

where the tag zzz refers to the snapshot number corresponding to that particular redshift. Each of these archive files has to be expanded using the tar command, and contains 512 files for the case of L-CoDECS and 128 files for the case of H-CoDECS, corresponding to the number of processors on which the simulations were run. The format of these files is described below.

Groups

Each Group file contains 10 columns and a variable number of lines. The different columns display properties of the FoF halos in the following order:

1) $I_{\rm Gr}$ [long integer], i.e. a FoF Group identifier, unique over the whole catalog of a given snapshot zzz
2) $L_{\rm Gr}$ [long integer], i.e. the total number of particles (CDM and baryons) belonging to the FoF group
3) $M_{\rm Gr}$ [float], i.e. the total mass of the FoF group in units of 1.0×10^{10} $M_{\odot}/h$
4) $N_{\rm sub}$ [integer], i.e. the number of substructures that have been identified within the FoF group by the SUBFIND algorithm
5, 6, 7) $x_{\rm Gr}$, $y_{\rm Gr}$, $z_{\rm Gr}$ [float], i.e. the comoving coordinates of the FoF group in units of kpc/h
8, 9, 10) $vx_{\rm Gr}$, $vy_{\rm Gr}$, $vz_{\rm Gr}$ [float], i.e. the cartesian components of the peculiar velocity of the FoF group in physical units [km/s]

SubGroups

Each SubGroup file contains 18 columns and a variable number of lines. The different columns display properties of the substructures identified by means of the SUBFIND algorithm within each FoF halo, in the following order:

1) $I_{\rm Gr}$ [long integer], i.e. the same FoF Group identifier of the parent halo, unique over the whole catalog of a given snapshot zzz
2) $I_{\rm sub}$ [integer], i.e. the subgroup identifier, unique within a given parent halo $I_{\rm Gr}$
3) $L_{\rm sub}$ [long integer], i.e. the total number of particles (CDM and baryons) belonging to the substructure
4) $M_{\rm sub}$ [float], i.e. the total mass of the substructure in units of 1.0×10^{10} $M_{\odot}/h$
5) M_{200} [float], i.e. the mass within a sphere enclosing a mean overdensity 200 times larger than the critical density around the potential minimum of the substructure, in units of 1.0×10^{10} $M_{\odot}/h$

6) R_{200} [float], i.e. the radius of a sphere enclosing a mean overdensity 200 times larger than the critical density around the potential minimum of the substructure, in units of kpc/h
7, 8, 9) $x_{\rm sub}$, $y_{\rm sub}$, $z_{\rm sub}$ [float], i.e. the comoving coordinates of the most bound particle within the substructure, in units of kpc/h
10, 11, 12) $x^{\rm CM}_{sub}$, $y^{\rm CM}_{sub}$, $z^{\rm CM}_{sub}$ [float], i.e. the comoving coordinates of the center of mass of the substructure, in units of kpc/h
13,14,15) $vx_{\rm sub}$, $vy_{\rm sub}$, $vz_{\rm sub}$ [float], i.e. the cartesian components of the of the peculiar velocity of the substructure in physical units [km/s]
16,17,18) $sx_{\rm sub}$, $sy_{\rm sub}$, $sz_{\rm sub}$ [float], i.e. the cartesian components of the specific angular momentum of the substructure in physical units [kpc/$h\times$ km/s]

Please notice that the columns 4 and 5 have non-zero values only for the main substructure of each parent FoF halo, while they include zero values for all the other substructures.

Please also notice that within a given Group or SubGroup catalog there might be empty files.

4.6 Merger Trees

The growth history of the halos identified through the SUBFIND algorithm has been traced using the merger tree method developed by V. Springel and outlined in [10] and [11]. The merger tree files obtained with this method consist of a single large ($\sim$ 10 Gb) file which includes the whole tree of all the main halos identified at $z = 0$. The format of such files is described as follows:

1) $N_{\rm tr}$ [long integer], i.e. the number of merger trees present in the file;
2) $N_{\rm halos}$ [long integer], i.e. the total number of halos present in the file;
3) $N_{\rm treehalos}(N_{\rm tr})$ [long integer array], i.e. an array containing the total number of halos present in each of the $N_{\rm tr}$ trees;
4) $T(N_{\rm tr}, N_{\rm treehalos})$ [halostruct], i.e. an array of $N_{\rm tr}$ elements each of which consists of $N_{\rm treehalos}$ entries with the format *halostruct* described below.

Each element of *halostruct* type contains the following variables:
a) Descendant [long integer], the number of the descendant of the present halo;
b) First Progenitor [long integer], the number of the main progenitor of the present halo;
c) Next Progenior [long integer], the number of the most massive subhalo that has the same descendant of the present halo;
d) First Halo in FoF Group [long integer], the number of the main halo of the FoF group to which the present halo belongs;
e) NextHalo in FoF Group [long integer], the following halo of the present halo in the mass-ordered list of subhalos of the same FoF group;
f) N [long integer], the number of particles of the present halo;
g) $M_{\rm 200,mean}$ [float], the mass of the present halo computed with respect to the mean cosmic density;
h) $M_{200rm,crit}$ [float], the mass of the present halo computed with respect to the critical cosmic density;
i) $M_{\rm tophat}$ [float], the mass of the present halo computed with a top-hat profile;
j) Position(3) [float], the x, y, and z position of the present halo, in kpc/h;
k) Velocity(3) [float], the v_x, v_y, and v_z components of the velocity of the preset halo, in km/s;
l) VelDisp [float], the velocity dispersion of the present halo;
m) VelMax [float], the maximum rotational velocity of the halo, in km/s;
n) Spin(3) [float], the s_x, s_y, and s_z components of the spin of the present halo in physical units [kpc/$h\times$ km/s];
o) Most bound ID [long long integer], the ID of the particle with the minimum gravitational potential in the present halo;
p) SnapNum [long integer], the number of the snapshot in which the present halo has been identified;

q) $N_{\rm file}$ [long integer], the number of the *subhalo_ tab* file in which the present halo resides;
r) SubHalo Index [long integer], the index of the present subhalo in the file defined by $N_{\rm file}$;
s) SubHalo Half Mass [float], the half-mass radius of the present halo.

4.7 Full Snapshots

Due to the large size of the raw snapshots only the snapshot at $z = 0$ for each simulation is directly accessible from the CoDECS website. Other snapshots can be obtained upon motivated request to the author. The snapshots files are unformatted data and contain the raw particle data according to the standard GADGET format. Please check the GADGET users guide at www.mpa-garching.mpg.de/gadget for details on the GADGET formats.

4.8 Images

A few images extracted from the simulations are available in each specific web page, both in PDF (high-resolution) and JPEG (low-resolution) formats. Any use of these images must acknowledge the source and the CoDECS project.

References

[1] Marco Baldi. The CoDECS project: a publicly available suite of cosmological N-body simulations for interacting dark energy models. *MNRAS*, 422:1028–1044, May 2012.

[2] Marco Baldi. Early massive clusters and the bouncing coupled dark energy. *MNRAS*, 420:430–440, February 2012.

[3] E. Komatsu et al. Seven-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Cosmological Interpretation. *Astrophys. J. Suppl.*, 192:18, 2011.

[4] Antony Lewis, Anthony Challinor, and Anthony Lasenby. Efficient Computation of CMB anisotropies in closed FRW models. *Astrophys. J.*, 538:473–476, 2000.

[5] Marco Baldi, V. Pettorino, G. Robbers, and V. Springel. Hydrodynamical N-body simulations of coupled dark energy cosmologies. *MNRAS*, 403:1684–1702, April 2010.

[6] Volker Springel. The cosmological simulation code GADGET-2. *Mon. Not. Roy. Astron. Soc.*, 364:1105–1134, 2005.

[7] Volker Springel and Lars Hernquist. Cosmological SPH simulations: The entropy equation. *Mon. Not. Roy. Astron. Soc.*, 333:649, 2002.

[8] http://creativecommons.org/licenses/by-sa/3.0/.

[9] V. Springel, S. D. M. White, G. Tormen, and G. Kauffmann. Populating a cluster of galaxies - I. Results at [formmu2]z=0. *MNRAS*, 328:726–750, December 2001.

[10] Volker Springel et al. Simulating the joint evolution of quasars, galaxies and their large-scale distribution. *Nature*, 435:629–636, 2005.

[11] V. Springel, J. Wang, M. Vogelsberger, A. Ludlow, A. Jenkins, A. Helmi, J. F. Navarro, C. S. Frenk, and S. D. M. White. The Aquarius Project: the subhaloes of galactic haloes. *MNRAS*, 391:1685–1711, December 2008.