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THE *AGORA* HIGH-RESOLUTION GALAXY SIMULATIONS COMPARISON PROJECT: COSMORUN PUBLIC DATA RELEASE

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ABSTRACT

The *AGORA* `Cosmorun` (Roca-Fàbrega et al. 2021) is a set of hydrodynamical cosmological "zoom-in" simulations carried out within the *AGORA* High-resolution Galaxy Simulations Comparison Project (Kim et al. 2014, 2016). These simulations show the formation and evolution of a Milky Way-sized galaxy using eight of the most widely used numerical codes in the community (ART-I, ENZO, RAMSES, CHANGA, GADGET-3, GEAR, GIZMO and AREPO.). In this short report, we describe the public release of the raw output data from all of these simulations at $z = 8, 7, 6, 5, 4, 3, 2$ (plus at $z = 1, 0$ when available), and several metadata files containing the halo centers, virial quantities, and merger trees. The data from even thinner timesteps will be released as soon as the upcoming collaboration papers (VII-IX) are submitted and accepted.

Keywords: galaxies: formation – galaxies: evolution – methods: numerical – hydrodynamics

1. THE *AGORA* INITIATIVE: PAST, PRESENT, AND FUTURE

Since its launch in 2012, the *AGORA* High-resolution Galaxy Simulations Comparison Project (*Assembling Galaxies of Resolved Anatomy*) has taken aim at carefully comparing high-resolution galaxy simulations on multiple code platforms widely used in the contemporary galaxy formation research.[1] The main goal of this initiative has been to ensure that physical assumptions are responsible for any success in galaxy formation simulations, rather than manifestations of particular numerical implementations, and by doing so, to collectively raise the predictive power of numerical galaxy formation studies. Over 160 individuals from over 60 different academic institutions worldwide are participating or participated in the collaborative effort of the Project.

The first result by the *AGORA* Collaboration (Kim et al. 2014, hereafter Paper I) was our flagship paper which explained the philosophy behind the initiative and detailed the publicly available Project infrastructure we have assembled. Also described was the proof-of-concept test, in which we field-tested our infrastructure with a dark matter-only cosmological zoom-in simulation using the common initial condition (generated with MUSIC; Hahn & Abel 2011a), finding a

[1] See the Project website at http://www.AGORAsimulations.org/ for more information about the *AGORA* Collaboration.

robust convergence amongst participating codes. In the second paper of the Project (Kim et al. 2016, hereafter Paper II), we focused on the evolution of an isolated Milky Way-mass galaxy. All participating codes shared the common initial condition (generated with MAKEDISK; Springel 2005), common physics models (e.g., radiative cooling and extragalactic ultraviolet background provided by the standardized package GRACKLE; Smith et al. 2017), and common analysis platform (yt toolkit; Turk et al. 2011). Subgrid physics models such as Jeans pressure floor, star formation, supernova feedback energy, and metal production were carefully constrained across code platforms. With a spatial resolution of 80 pc that resolves the scale height of the disk, we find that any intrinsic inter-code difference is small compared to the variations in input physics such as supernovae feedback. In the third paper (Roca-Fàbrega et al. 2021, hereafter Paper III) we presented the Cosmorun project and the calibration process we designed to reduce the number of variables to account for when comparing results from the different code groups. For these simulations, we adopted most of the subgrid physics and simulation strategies developed for Paper II but including the most recent version of the GRACKLE library, leaving only to the decision of each code group the stellar feedback strategy to be used. Following Paper III publication, the Cosmorun data has been used to study many aspects of the formation and evolution of MW-size galaxies focusing on the differences between the participant codes and their stellar feedback strategies. In particular, we presented the analysis of changes in the merger history, the stellar disk properties and the stellar metallicity distribution in Roca-Fàbrega et al. (2024, hereafter Paper IV), the satellites number counts in Jung et al. (2024, hereafter Paper V) and the circumgalactic medium (CGM) in Strawn et al. (2024, hereafter Paper VI). In Table 1 we include a summary of the *AGORA* papers published until August 2024. Currently, many new sub-projects are using the Cosmorun to study the properties and formation of stellar disks, the quenching of satellites, and major merger properties, among many others. After twelve years of workshops and teleconferences, and with common infrastructures built together, the *AGORA* Collaboration has become a successful open forum where users of different simulation codes can talk to and learn from one another, promoting collaborative and reproducible research essential in any scientific community.

2. PUBLIC RELEASE OF COSMORUN DATA

All code groups started their simulations from a common initial condition (IC) generated with MUSIC (Hahn & Abel 2011b),[2] and run by keeping physics prescriptions the same for all codes (e.g., gas cooling and heating, star formation parameters), although some variations were made in each code (see Roca-Fàbrega et al. 2021, for details on these differences). Only the decision concerning the stellar feedback prescription and metal production to be used was left to each code group. Code groups were asked to use a prescription close to the most widely-used practice in each code community. Spatial resolution was ∼80 physical pc at $z = 4$ to resolve the internal structure of a target halo, and to make our physics prescriptions less reliant on platform-specific models.

Here we provide the simulation snapshots used in the analysis of Paper III plus the one at $z = 3, 2$ and $1, 0$ when available (see Appendix A for a detailed description of the released data). We also provide the metadata of the centers, several virial quantities, and the results of applying the rockstar halo finder to each one of the datasets. The cohort of widely-used, state-of-the-art galaxy simulation codes who contributed to this release includes: the Lagrangian smoothed particle hydrodynamics codes CHANGA (e.g., Menon et al. 2015), GADGET-3 (e.g., Choi & Nagamine 2012; Aoyama et al. 2017; Shimizu et al. 2019; Nagamine et al. 2021), and GEAR (e.g., Revaz et al. 2016), the Eulerian adaptive mesh refinement codes ART-I (e.g., Ceverino et al. 2014), ENZO (e.g., Bryan et al. 2014) and RAMSES (e.g., Teyssier 2002), the moving-mesh code AREPO (e.g., Weinberger et al. 2020) and the mesh-free finite-volume Godunov code GIZMO (e.g., Hopkins 2015).

This release is intended to encourage the community to rerun the Cosmorun ICs both after applying the provided calibration procedure or not and using their favourite stellar feedback. Our goal is to enlarge the library of Cosmorun models thus enhancing our insight on how variations in the baryonic physics processes affect the formation of MW size galaxies. The coordination of the Collaboration and its members are at their disposal to help with the calibration process and with running new models.

The simulation data and several of the common analysis scripts in yt are available through the Project website[3]. Additionally, the authors of the published *AGORA* papers (see Table 1) will be happy to provide help to users interested in analyzing the released data. Also available in the same link are isolated and cosmological initial conditions generated by the *AGORA* Collaboration for galaxy simulations, and the links to the key software. We encourage numerical galaxy formation community members to use these resources freely for their research.

[2] The website is https://www-n.oca.eu/ohahn/MUSIC/.

[3] http://www.AGORAsimulations.org/ or http://sites.google.com/site/santacruzcomparisonproject/blogs/quicklinks/

Table 1. Summary of the published *AGORA* papers until August 2024.

Kim et al. (2014)	Paper I	Zoom-in Cosmo.	L_{Box} = 60h^{-1}cMpc	M_{200c}=1.7×10^{11}M$\odot$	Dark Matter Only	9 codes
Kim et al. (2016)	Paper II	Isolated box	L_{Box} = 1.074 Mpc	M_{200c}=1.074×10^{12}M$\odot$	Common stellar feedback	9 codes
Roca-Fàbrega et al. (2021)	Paper III	Zoom-in Cosmo.	L_{Box} = 60h^{-1}cMpc	M_{200c}=1.0×10^{12}M$\odot$	Calibrated feedback	7-8 codes
Roca-Fàbrega et al. (2024)	Paper IV	Study of the merger history and disk morphology down to z=2 and below in the Paper III simulation (`Cosmorun`)				
Jung et al. (2024)	Paper V	Analysis of the satellites population in the `Cosmorun` simulation				
Strawn et al. (2024)	Paper IV	Analysis of the Circumgalactic Medium in the `Cosmorun` simulation				

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APPENDIX

A. DETAILS OF THE RELEASED DATA

In Table 2 we provide the information on the snapshot number at each redshift for each one of the participant codes. We also provide the link to the data for each code, below the table.

In the metadata folder[4] you will find three different kind of files and a subfolder (MERGERTREES_ROCKSTAR) which contains the merger trees generated using `rockstar` (Behroozi et al. 2013a) and `consistent-trees` (Behroozi et al. 2013b). All filenames contain the name of the corresponding code except for CHANGA which is labeled as `CHANGA_6.0e51erg_NSB` for the CHANGA-T and `CHANGA_3.5e51erg_SB` for the fiducial CHANGA. Here we describe the content of each file and of the merger-trees folder:

- `centers_CODE_final_noID.txt`: This file contains the centers of the main halo inside the simulated cosmological box in physical kiloparsecs. The data is structured as follows: redshift, snapnum (see Table 2), [x,y,z].

- `Rvir_cent_CODE.txt`: This file contains similar information to the previous one but in a simpler format, including information on the R_{200c}. The data is structured as follows: redshift, snapnum (see Table 2), x, y, z, R_{200c} (in physical kpc).

- `Rvir_cent_others_CODE.txt`: This file contains information about many general properties of the central halo. The data is structured as follows: redshift, snapnum (see Table 2), R_{200c} [kpc], M_{200c} [$M_\odot$], $M_*(R<R_{200c})$ [$M_\odot$], $M_{*,gal}(R< 0.15R_{200c})$ [$M_\odot$], $R_{1/2}$ [kpc], $M_{tot}(R<R_{1/2})$ [$M_\odot$], Z_* [$Z_\odot$], $R_{1/2*,gal}$ [kpc], $M_{*,gal}(R<R_{1/2*})$ [$M_\odot$], $Z_{*,gal}$ [$Z_\odot$].

- MERGERTREES_ROCKSTAR: In this folder you will find a sub-folder containing the merger for each one of the participant codes except for the fiducial CHANGA. The files can be read and analysed using the `ytree`[5] tool provided by the `yt`[6] community.

[4] https://users.flatironinstitute.org/∼chayward/agora_public_release/PaperIV/Metadata/

[5] https://ytree.readthedocs.io/en/latest/

[6] https://yt-project.org

Table 2. In this table we provide information on the snapshot number at each redshift and for each one of the participating codes. We also provide the links to the data, below.

CODE	Snapshot number as in the metadata files for z=15 to 0															
	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
ART-I[i]	1729	1765	1802	1841	1882	1924	1968	2014	2071	2153	2245	2385	2580	2833	3273	4078
ENZO[ii]	000	009	019	029	039	051	063	077	092	109	129	152	180	213	247	347
RAMSES[iii]	002	011	020	029	041	053	065	079	094	111	131	154	182	220	-	-
CHANGA[iv]	0150	0167	0186	0208	0238	0271	0314	0370	0442	0542	0688	0904	1264	1932	3440	-
CHANGA-T[v]	0142	0159	0177	0199	0224	0258	0298	0352	0422	0516	0654	0860	1202	1838	-	-
GADGET-3[vi]	001	009	017	026	036	046	057	070	084	100	119	141	168	203	252	-
GEAR[vii]	001	022	046	071	098	128	161	196	236	281	333	394	469	566	701	-
AREPO-T[viii]	000	009	017	026	036	046	057	070	085	100	119	142	169	203	152	336
GIZMO[ix]	000	009	019	029	039	051	063	077	092	109	129	152	180	215	-	-

i https://users.flatironinstitute.org/∼chayward/agora_public_release/PaperIV/ART-I/

ii https://users.flatironinstitute.org/∼chayward/agora_public_release/PaperIV/ENZO/

iii https://users.flatironinstitute.org/∼chayward/agora_public_release/PaperIV/RAMSES/

iv https://users.flatironinstitute.org/∼chayward/agora_public_release/PaperIV/CHANGA/SB/output/

v https://users.flatironinstitute.org/∼chayward/agora_public_release/PaperIV/CHANGA/nSB/output/

vi https://users.flatironinstitute.org/∼chayward/agora_public_release/PaperIV/GADGET3/

vii https://users.flatironinstitute.org/∼chayward/agora_public_release/PaperIV/GEAR/

viii https://users.flatironinstitute.org/∼chayward/agora_public_release/PaperIV/AREPO/

ix https://users.flatironinstitute.org/∼chayward/agora_public_release/PaperIV/GIZMO/