AGORA High-resolution Galaxy Simulations Comparison Initiative: 12 Years After Its Conception

The Astrophysical Journal Supplement Series, 210:14 (20pp), 2014 January doi:10.1088/0067-0049/210/1/14
© 2014. The American Astronomical Society. All rights reserved. Printed in the U.S.A.

THE AGORA HIGH-RESOLUTION GALAXY SIMULATIONS COMPARISON PROJECT

Ji-hoon Kim[1], Tom Abel[2], Oscar Agertz[3,4], Greg L. Bryan[5], Daniel Ceverino[6], Charlotte Christensen[7], Charlie Conroy[1], Avishai Dekel[8], Nickolay Y. Gnedin[3,9,10], Nathan J. Goldbaum[1], Javiera Guedes[11], Oliver Hahn[11], Alexander Hobbs[11], Philip F. Hopkins[12,13], Cameron B. Hummels[7], Francesca Iannuzzi[14], Dusan Keres[15], Anatoly Klypin[16], Andrey V. Kravtsov[3,10], Mark R. Krumholz[1], Michael Kuhlen[1,13], Samuel N. Leitner[17], Piero Madau[1], Lucio Mayer[18], Christopher E. Moody[1], Kentaro Nagamine[19,20], Michael L. Norman[15], Jose Onorbe[21], Brian W. O'Shea[22], Annalisa Pillepich[1], Joel R. Primack[23], Thomas Quinn[24], Justin I. Read[4], Brant E. Robertson[7], Miguel Rocha[21], Douglas H. Rudd[10,25], Sijing Shen[1], Britton D. Smith[22], Alexander S. Szalay[26], Romain Teyssier[18], Robert Thompson[7,19], Keita Todoroki[19], Matthew J. Turk[5], James W. Wadsley[27], John H. Wise[28], and Adi Zolotov[8]
for the AGORA Collaboration[29]
[1] Department of Astronomy and Astrophysics, University of California at Santa Cruz, Santa Cruz, CA 95064, USA; me@jihoonkim.org
[2] Department of Physics, Stanford University, Stanford, CA 94305, USA
[3] Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637, USA
[4] Department of Physics, University of Surrey, Guildford, Surrey GU2 7XH, UK
[5] Department of Astronomy and Astrophysics, Columbia University, New York, NY 10027, USA
[6] Department of Theoretical Physics, Universidad Autonoma de Madrid, E-28049 Madrid, Spain
[7] Department of Astronomy, University of Arizona, Tucson, AZ 85721, USA
[8] Center for Astrophysics and Planetary Science, Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel
[9] Particle Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, IL 60510, USA
[10] Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA
[11] Institute for Astronomy, ETH Zurich, Zurich, 8093, Switzerland
[12] Department of Astronomy, California Institute of Technology, Pasadena, CA 91125, USA
[13] Department of Astronomy, University of California at Berkeley, Berkeley, CA 94720, USA
[14] Max-Planck Institut für Astrophysik, D-85741 Garching, Germany
[15] Department of Physics, University of California at San Diego, La Jolla, CA 92093, USA
[16] Department of Astronomy, New Mexico State University, Las Cruces, NM 88001, USA
[17] Department of Astronomy, University of Maryland, College Park, MD 20742, USA
[18] Institute for Theoretical Physics, University of Zurich, Zurich 8057, Switzerland
[19] Department of Physics and Astronomy, University of Nevada, Las Vegas, NV 89154, USA
[20] Department of Earth and Space Science, Graduate School of Science, Osaka University, 1-1 Machikaneyama, Toyonaka, Osaka 560-0043, Japan
[21] Department of Physics and Astronomy, University of California at Irvine, Irvine, CA 92697, USA
[22] Lyman Briggs College and Department of Physics and Astronomy, Michigan State University, Lansing, MI 48825, USA
[23] Department of Physics, University of California at Santa Cruz, Santa Cruz, CA 95064, USA
[24] Department of Astronomy, University of Washington, Seattle, WA 98195, USA
[25] Research Computing Center, University of Chicago, Chicago, IL 60637, USA
[26] Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218, USA
[27] Department of Physics and Astronomy, McMaster University, Hamilton, ON L8S 4M1, Canada
[28] School of Physics, Georgia Institute of Technology, Atlanta, GA 30332, USA
Received 2013 August 12; accepted 2013 November 26; published 2013 December 24

ABSTRACT

We introduce the Assembling Galaxies Of Resolved Anatomy (AGORA) project, a comprehensive numerical study of well-resolved galaxies within the ΛCDM cosmology. Cosmological hydrodynamic simulations with force resolutions of ~100 proper pc or better will be run with a variety of code platforms to follow the hierarchical growth, star formation history, morphological transformation, and the cycle of baryons in and out of eight galaxies with halo masses $M_{\rm vir} \simeq 10^{10}$, 10^{11}, 10^{12}, and $10^{13}\,M_{\odot}$ at $z = 0$ and two different ("violent" and "quiescent") assembly histories. The numerical techniques and implementations used in this project include the smoothed particle hydrodynamics codes Gadget and Gasoline, and the adaptive mesh refinement codes Art, Enzo, and Ramses. The codes share common initial conditions and common astrophysics packages including UV background, metal-dependent radiative cooling, metal and energy yields of supernovae, and stellar initial mass function. These are described in detail in the present paper. Subgrid star formation and feedback prescriptions will be tuned to provide a realistic interstellar and circumgalactic medium using a non-cosmological disk galaxy simulation. Cosmological runs will be systematically compared with each other using a common analysis toolkit and validated against observations to verify that the solutions are robust—i.e., that the astrophysical assumptions are responsible for any success, rather than artifacts of particular implementations. The goals of the AGORA project are, broadly speaking, to raise the realism and predictive power of galaxy simulations and the understanding of the feedback processes that regulate galaxy "metabolism." The initial conditions for the AGORA galaxies as well as simulation outputs

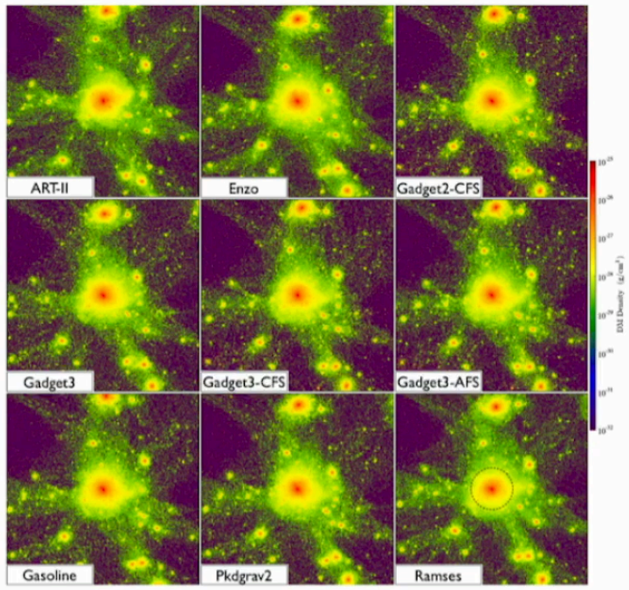


Figure 3. $z = 0$ results of the proof-of-concept dark-matter-only tests on a quiescent $M_{\rm vir} \simeq 1.7 \times 10^{11}\,M_{\odot}$ halo by nine different versions of the participating codes. Density-weighted projection of dark matter density in a $1\,h^{-1}$ Mpc box, produced with the common analysis toolkit yt. We refer the readers to Table 5 and Section 5.2 for descriptions of the participating codes in this test. In particular, see Section 5.2.3 for variations of Gadget. We note that three code groups,—Gadget-2-cfs, Gadget-3-cfs, and Gadget-3-afs—have employed an initial condition in which the resolution outside the Lagrangian volume of the target halo's $2R_{\rm vir}$ sphere is adaptively lowered; see Section 5.1 for more information. Hence, particle distributions only within $\sim R_{\rm vir}$ (marked with a dashed circle in the last panel) can be most reliably compared across all nine codes with the best available resolution. Simulations performed by Samuel Leitner (Art-II), Ji-hoon Kim (Enzo), Oliver Hahn (Gadget-2-cfs), Keita Todoroki (Gadget-3), Alexander Hobbs (Gadget-3-cfs and Gadget-3-afs), Sijing Shen (Gasoline), Michael Kuhlen (Pkdgrav-2), and Romain Teyssier (Ramses).
(A color version of this figure is available in the online journal.)

such variations, substructures within 150 kpc from the center (location of the maximum density) of the target halo are identified by the Hop halo finder included in yt with an overdensity threshold $\delta_{\rm outer}$ of 80 times the critical density of the Universe (Eisenstein & Hut 1998; Skory et al. 2010).[45] The resulting particle group mass functions at $z = 0$ are displayed in Figure 6. Only the groups containing more than 32 particles are drawn. Shown together in a dotted line is a power-law functional

Some of the "subhalos" within $R_{\rm vir}$ might have been linked with the host halo by the Hop algorithm.

The close resemblances of the mass functions among the particle-based codes with tree-based gravity solvers (Gadget-2-cfs, Gadget-3, Gadget-3-cfs, Gasoline, Pkdgrav-2) and among the grid-based codes with adaptive meshes (Art-II, Enzo, Ramses) are noticeable. However, also unmistakable is the mismatch between these two breeds of codes. This

[The Flagship Paper] The AGORA High-resolution Galaxy Simulations Comparison Project

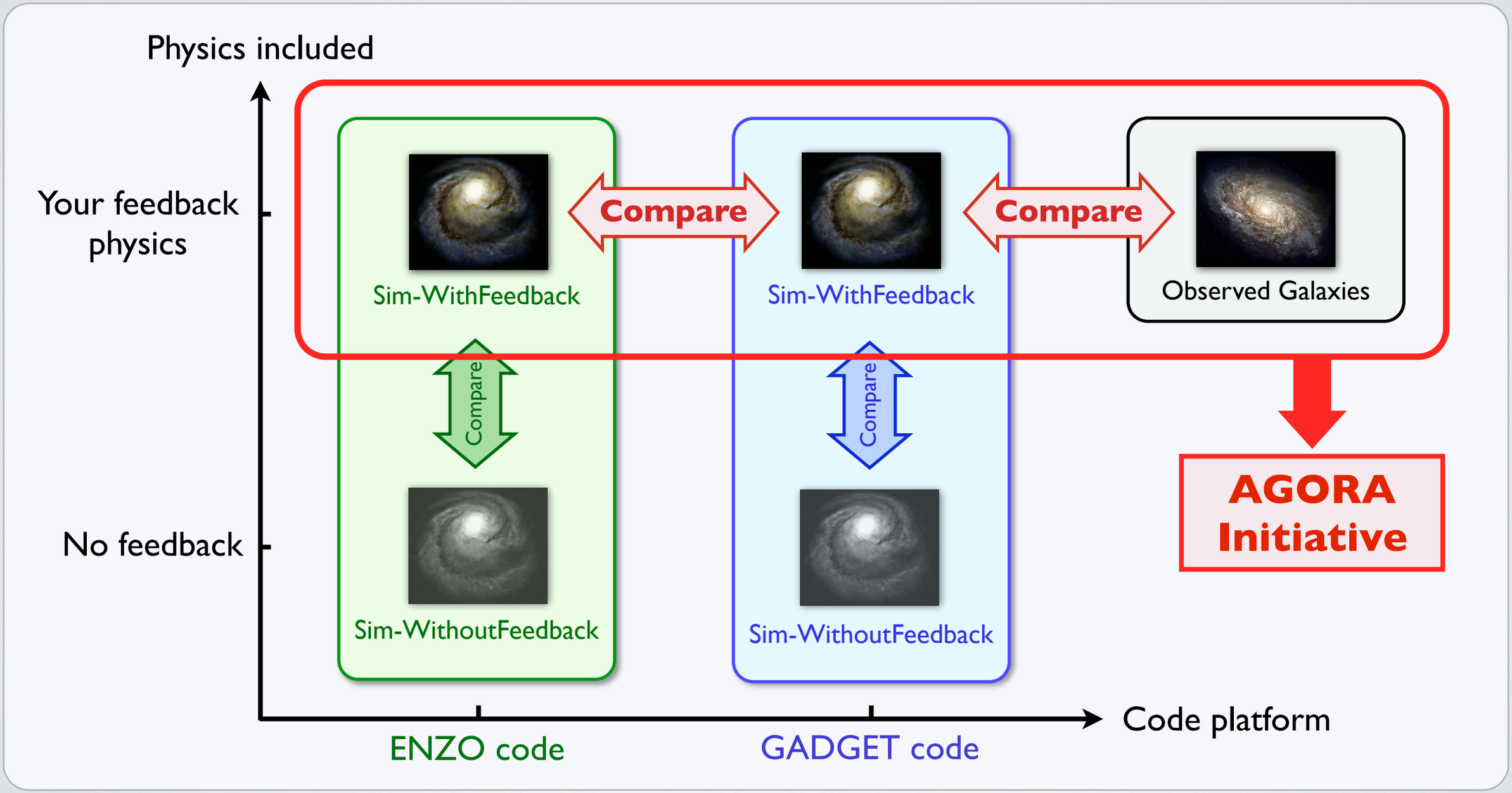
Papers IV to VI to appear on arXiv in Feb. 2024 (Roca-Fabrega et al. 2024; Jung et al. 2024; Strawn et al. 2024).

Ji-hoon Kim (Seoul National University)

Thanks to: O. Agertz (U. Lund), O. Hahn (U.Vienna), M. Jung (SNU), K. Nagamine (Osaka U.), J. Primack (UCSC), Y. Revaz (EPFL), S. Roca-Fabrega (U. Lund), B. Smith (U.Edinburgh), C. Strawn (UCSC), R. Teyssier (Princeton), M. Turk (UIUC), et al.

Reproducible Simulation Raises Realism

- To increase the predictive power of numerical simulations, and the field itself, let us compare simulations across code platforms.



AGORA

A High-resolution Galaxy Simulations Comparison Initiative: www.AGORAsimulations.org

AGORA Project: Goal and Team

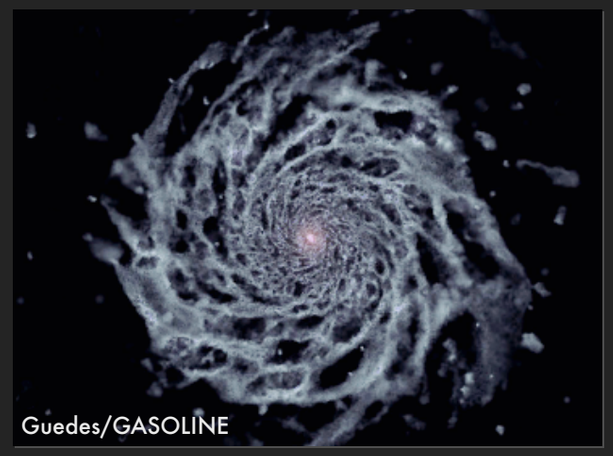
- GOAL: A collaborative, multi-code platform to raise the realism and predictive power of high-res galaxy simulations

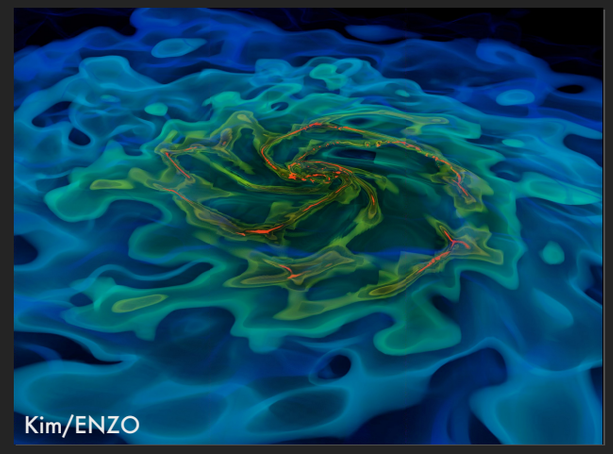
- TEAM - 160+ participants from 60+ institutions, 01/2024
  - 15+ groups each representing 10+ codes
  - 11 workshops & 70+ web conferences organized
  - 6-member Steering Committee
  - Project Coordinator: Ji-hoon Kim

- DATA SHARING: Initial conditions, astrophysics modules, analysis software, and simulation outputs all to be public

- RESULTS - Flagship paper by J. Kim et al. (2014, ApJS)
  - 2nd paper by J. Kim et al. (2016, ApJ)
  - 3rd paper by S. Roca-Fabrega et al. (2021, ApJ)

High-res Galaxy Simulation

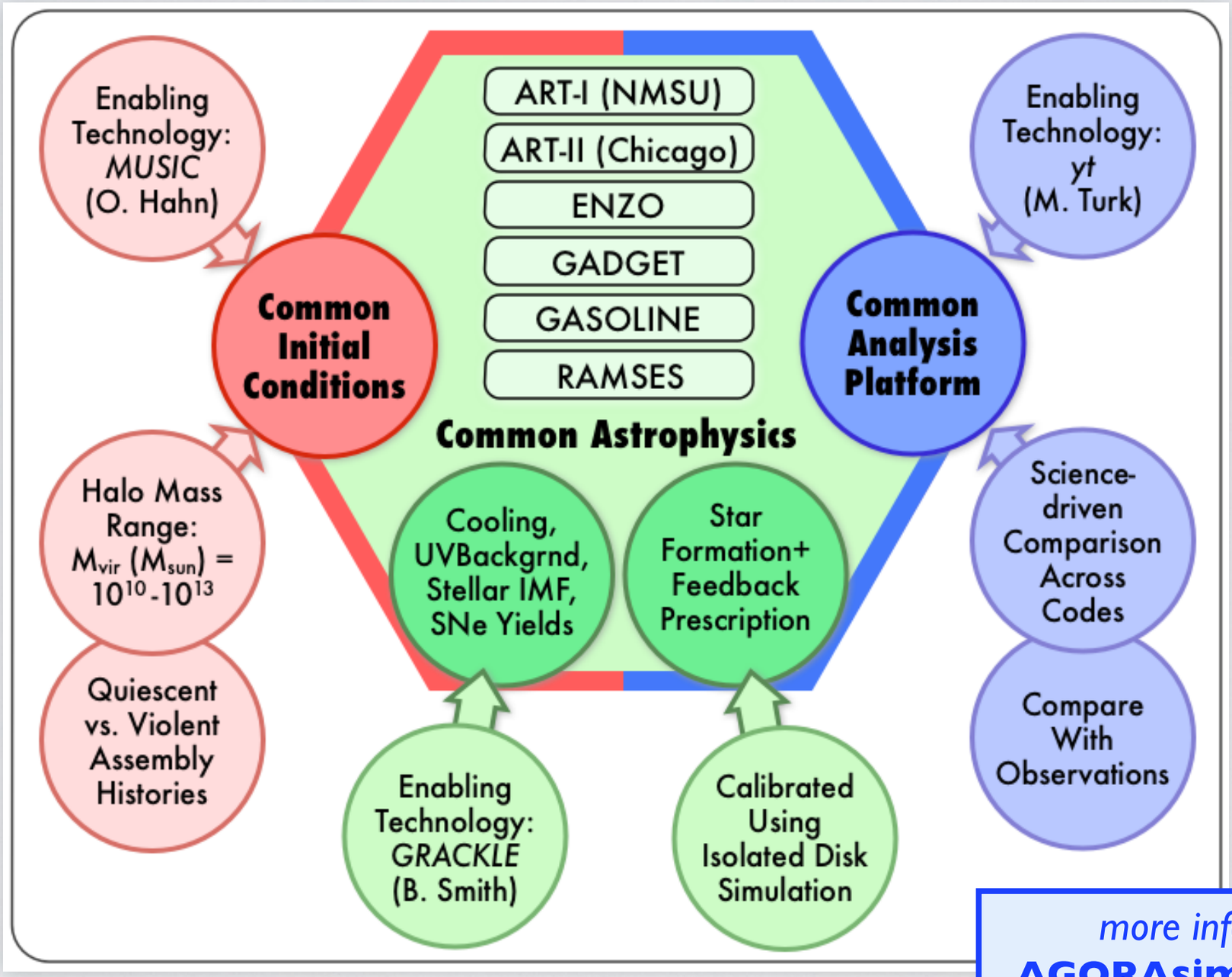

Guedes/GASOLINE


Kim/ENZO

Project supported in part by: NERSC, NSF

AGORA Comparison Infrastructure

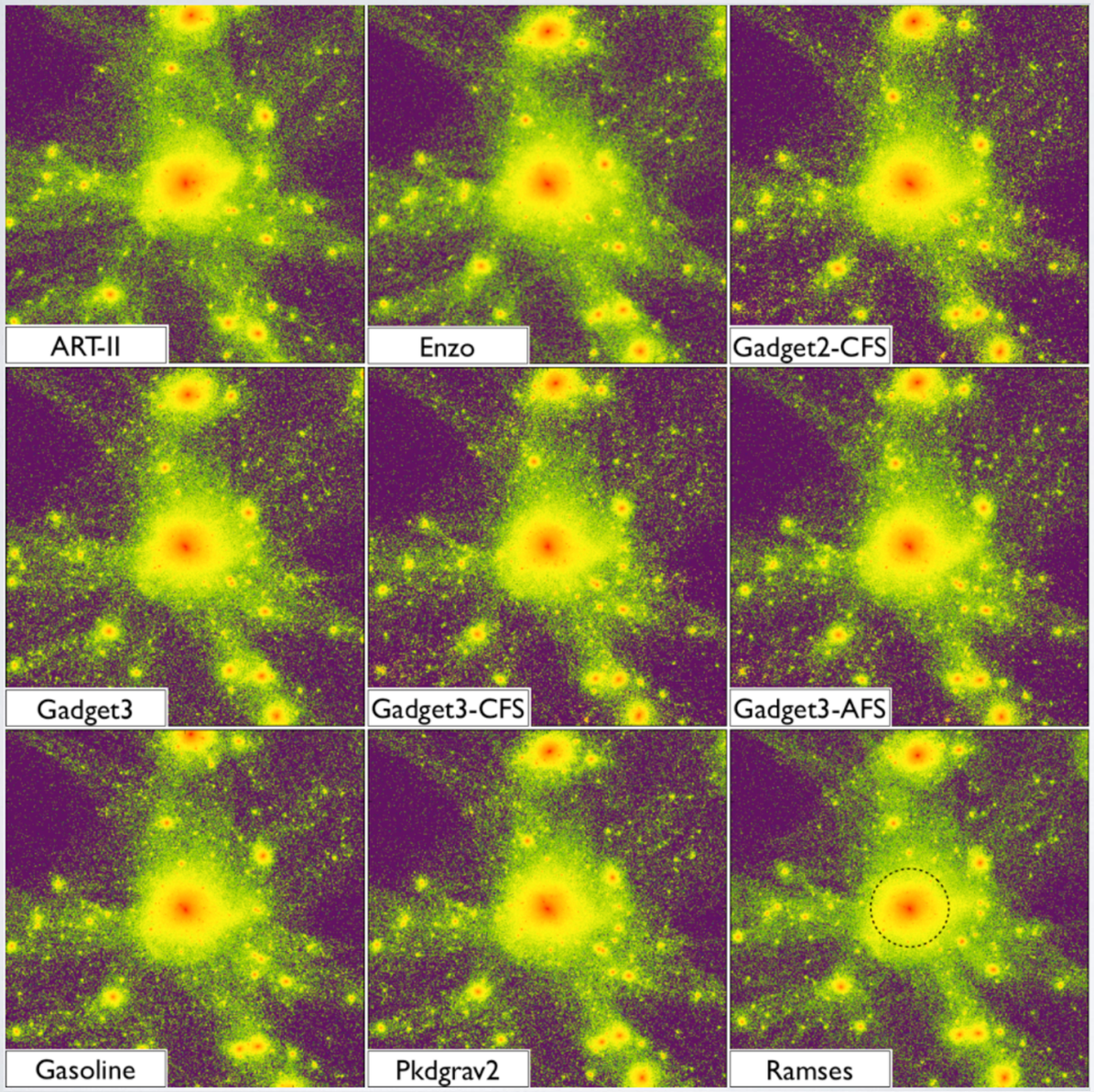
- Includes key components necessary to run galaxy-scale simulations in a reproducible manner: code-independent and publicly available



more information at
AGORAsimulations.org

AGORA Dark Matter-Only Comparison

- Flagship paper with a proof-of-concept test (Kim et al. 2014)

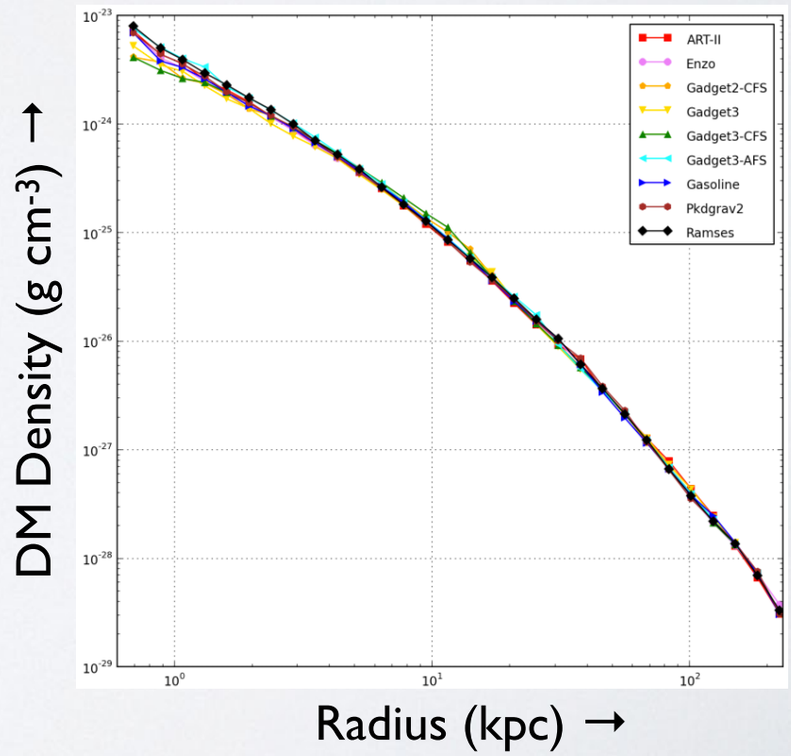


~10^{11} $M_\odot$ halo at z=0, projected DM density, Kim et al. (2014)

- Fully established comparison pipeline

- Runtime parameters identified that make codes compatible with one another

- Publicly available ICs are being used to build a library of AGORA simulations making future comparisons trivial

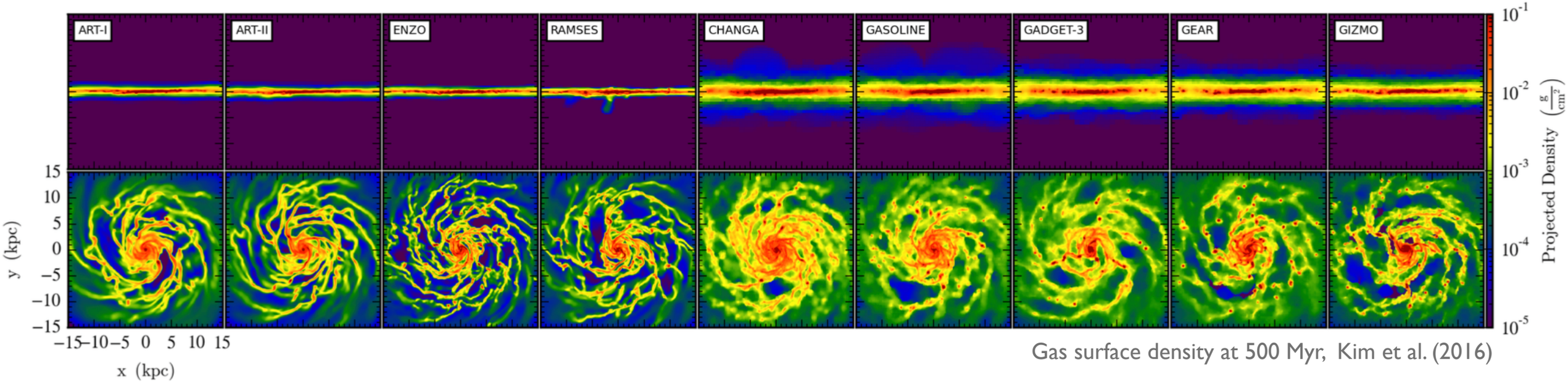


Gravito-Hydrodynamics Comparison

- Second paper with an isolated MW-mass disk test (Kim et al. 2016)

  - Subgrid physics models such as Jeans pressure floor, star formation, supernova feedback energy, and metal production carefully constrained across code platforms

  - High spatial resolution to minimize dependence on a phenomenological model

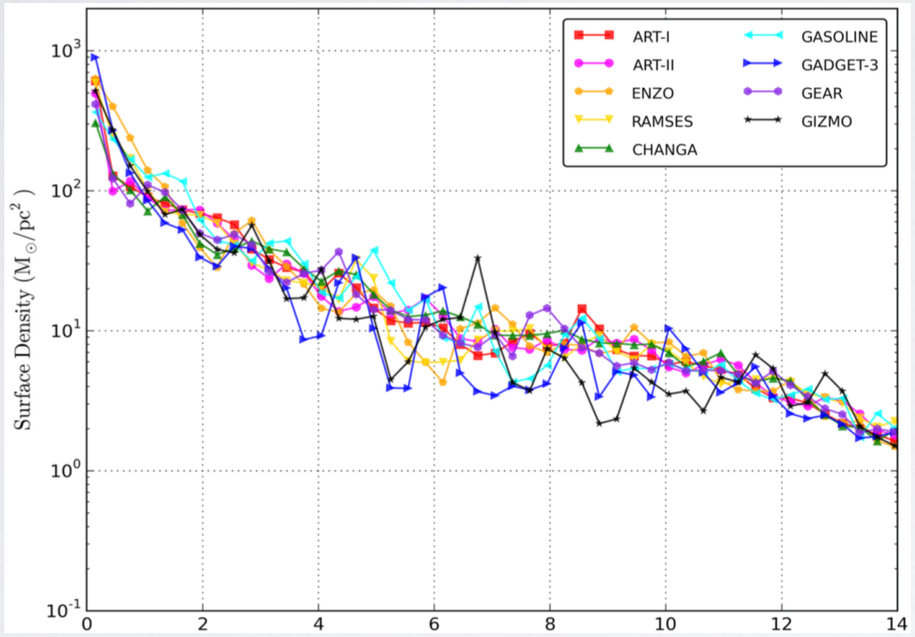


Gas surface density at 500 Myr, Kim et al. (2016)

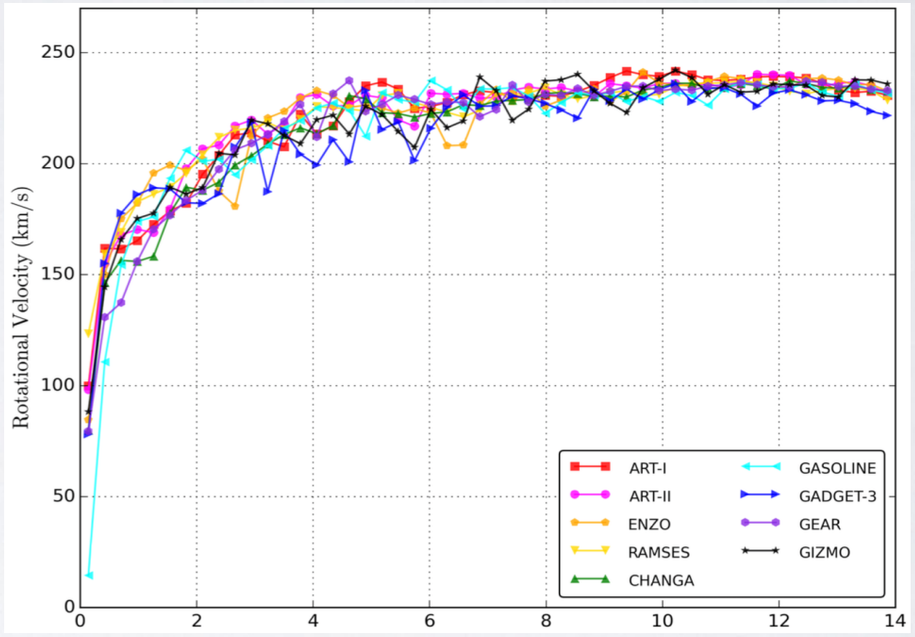
Figure 2. The 500 Myr composite of gas surface densities from *Sim-noSF* with radiative gas cooling but without star formation or supernova feedback. Each frame is centered on the galactic center – location of maximum gas density within 1 kpc from the center of gas mass. For visualizations of the particle-based codes hereafter (Figures 1-3, 14-15, 32, 34, 35) – but not in any other analyses except these figures – `yt` uses an in-memory octree on which gas particles are deposited using smoothing kernels. See Section 5 for descriptions of participating codes in this comparison, and Section 6.1 for a detailed explanation of this figure. Compare with Figure 14. Simulations performed by: Daniel Ceverino (ART-I), Robert Feldmann (ART-II), Mike Butler (ENZO), Romain Teyssier (RAMSES), Spencer Wallace (CHANGA), Ben Keller (GASOLINE), Jun-Hwan Choi (GADGET-3), Yves Revaz (GEAR), and Alessandro Lupi (GIZMO). The full color version of this figure is available in the electronic edition. The high-resolution versions of this figure and article are available at the Project website, http://www.AGORAsimulations.org/.

Convergence Among All 9 Codes

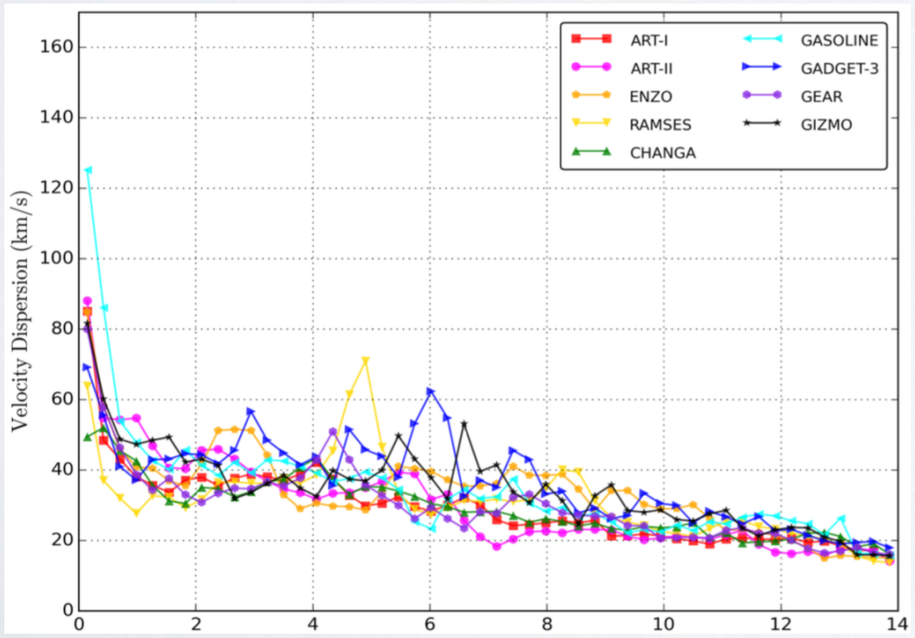
- Modern galaxy simulation codes agree very well with one another in many dimensions (agreement as good as within <10% at all radii).



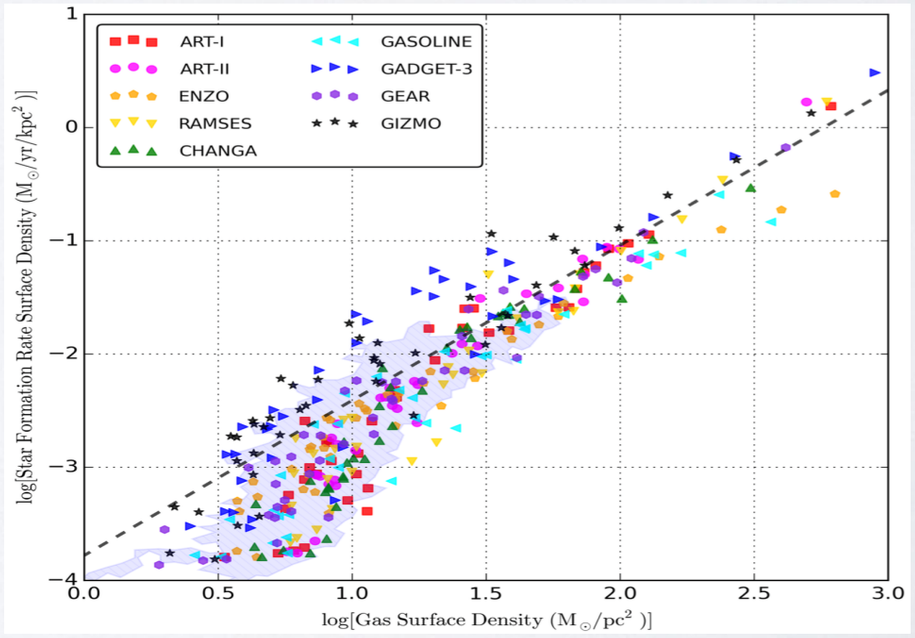
Surface density profile



Rotation velocity profile



Velocity dispersion profile



Kennicutt-Schmidt relation

Great, but how did we get here?

- Inter-code convergence achieved only after a Herculean effort by passionate participants, aided by many workshops and telecons.

7. DISCUSSION AND CONCLUSION

Through workshops and teleconferences, and via common languages and infrastructure built together, Project participants were able to better understand other codes, and improve their own. Participants found an optimal set of simulation parameters that makes their code to be best compatible with others. We came to understand how seemingly identical parameters differ in their meanings in different codes, and how seemingly different parameters have in fact identical meanings. In some comparisons, numerical errors were discovered and fixed in participating codes. The *AGORA* framework, now tested with the common physics and subgrid models, are serving as a launchpad to initiate *astrophysically-motivated* comparisons aimed at raising the predictive power of galaxy simulations, especially as we run the zoom-in cosmological simulations outlined in our flagship paper (Kim et al. 2014). In the coming years, we expect *AGORA* to continue to provide a sustainable and fertile platform on which numerical experiments are readily validated and cross-calibrated, and ambitious multi-platform collaborations are forged.

(1) Human errors fixed

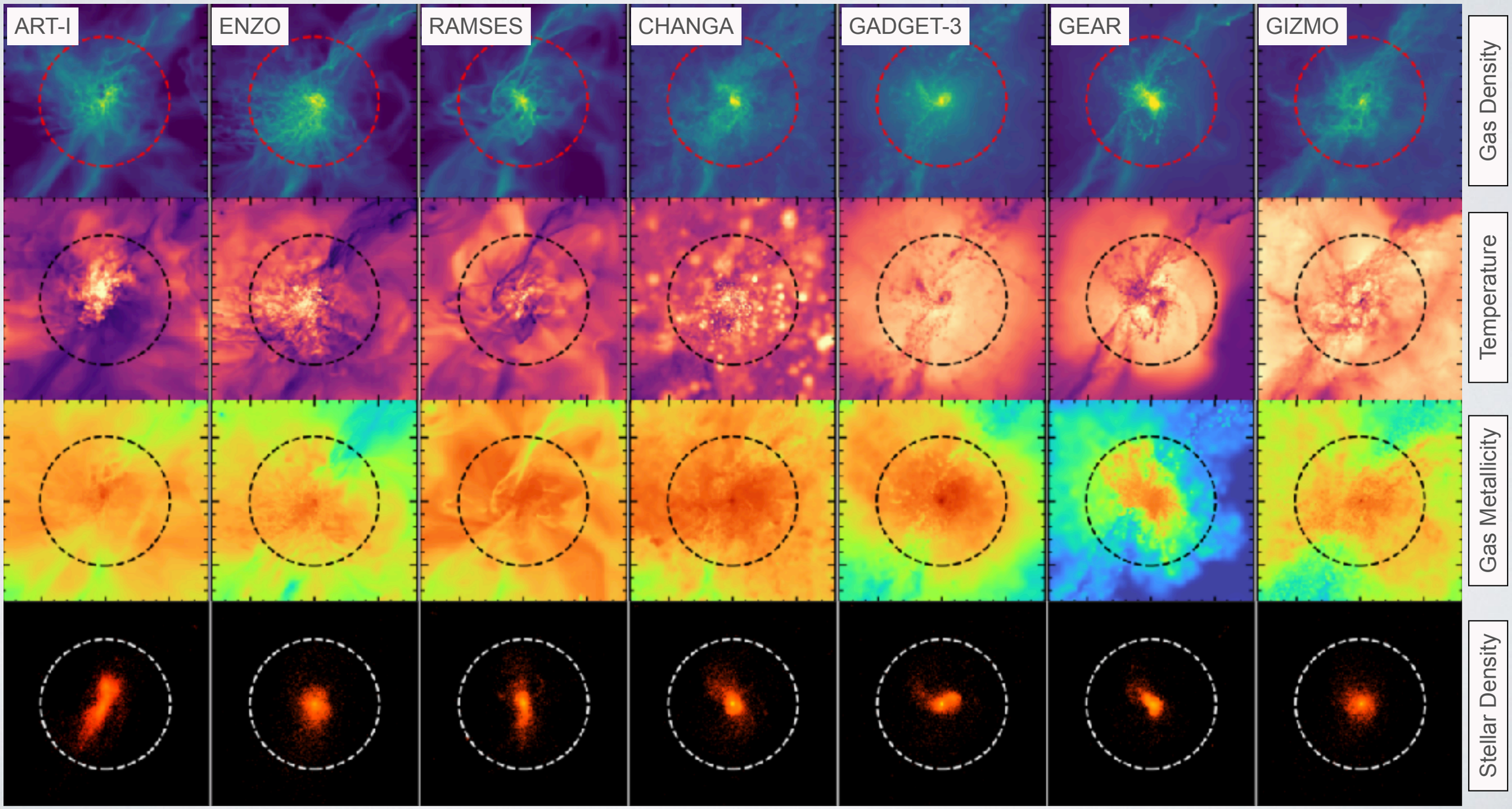
→ (2) Runtime parameters found that make the codes compatible with one another

→ (3) Errors in (some) codes fixed

from Kim et al. (2016)

Cosmological Comparison At Last

- Comparison of a MW-mass halo at after years of infrastructure development and calibration (Roca-Fabrega et al. 2021).



CosmoRun comparison at z=4, Roca-Fabrega, Kim, et al. (2021)

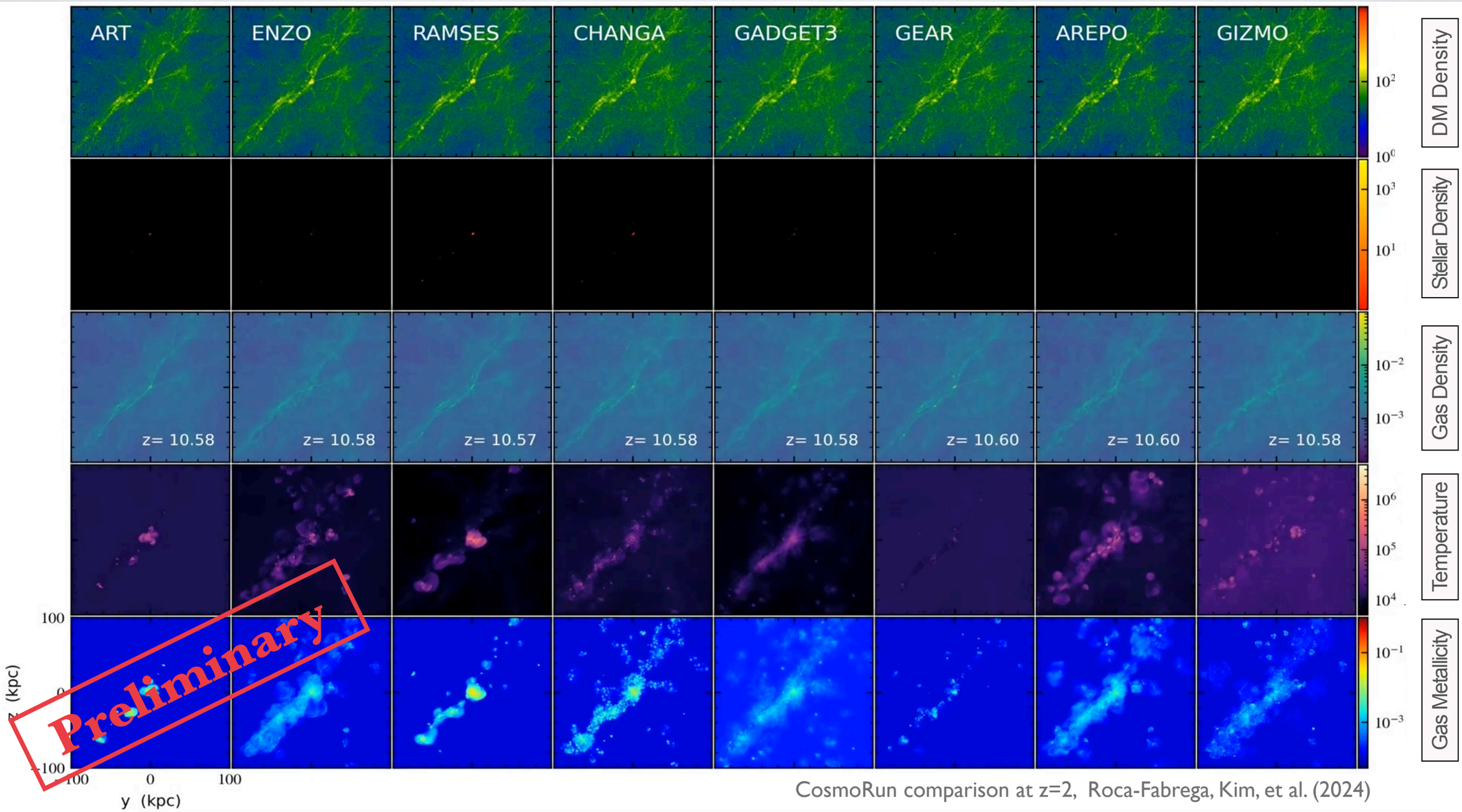
Cosmological Comparison At Last

- Comparison of a MW-mass halo at after years of infrastructure development and calibration (Roca-Fabrega et al. 2024).



Cosmological Comparison At Last

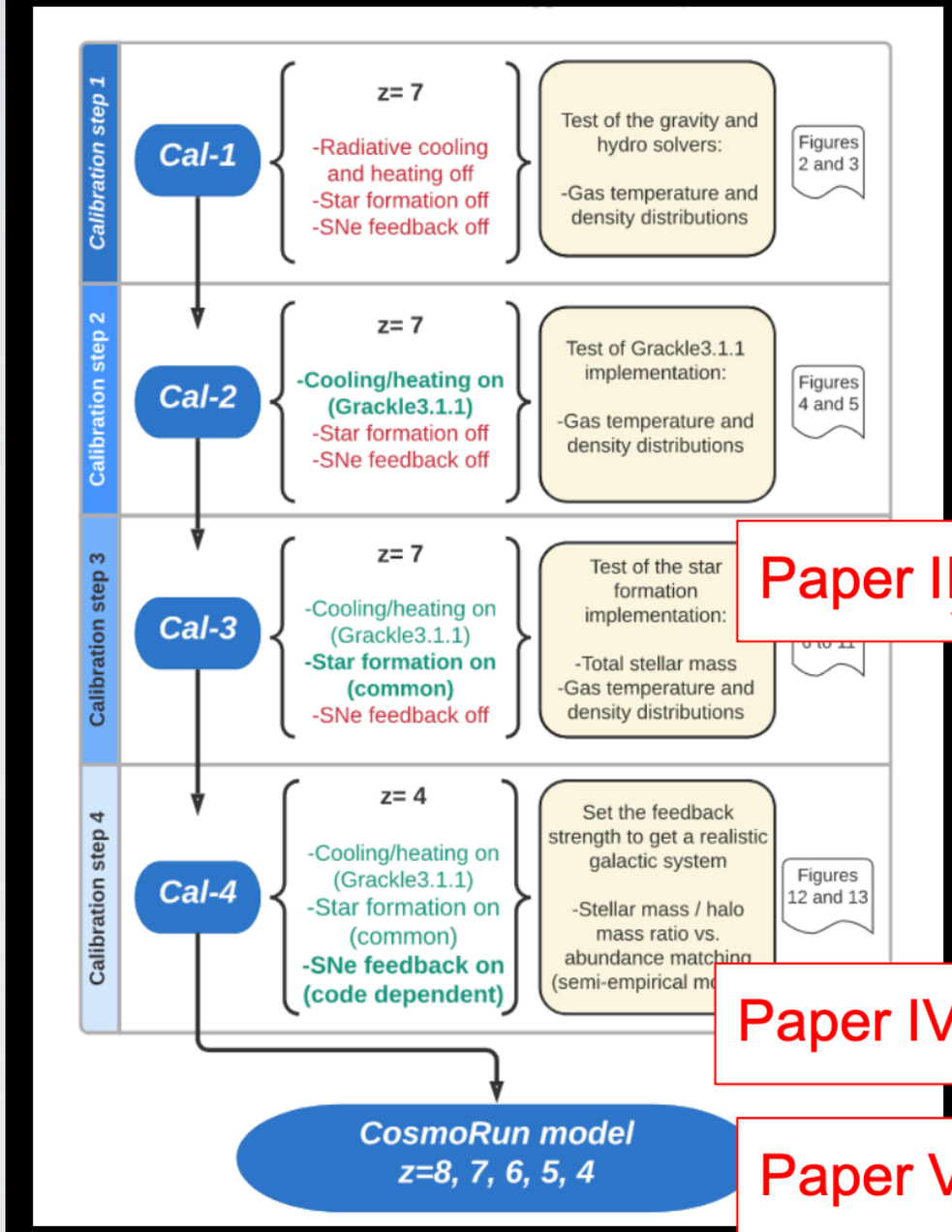
- Comparison of a MW-mass halo at after years of infrastructure development and calibration (Roca-Fabrega et al. 2024).



CosmoRun comparison at z=2, Roca-Fabrega, Kim, et al. (2024)

Three "CosmoRun" Comparison Papers

CosmoRun Papers



- Codes share:
  - Common cosmology
  - Common heating/cooling
  - Common star formation recipe
  - Common initial conditions
  - Each calibrated and checked to make sure results acceptably close
- Codes calibrate:
  - Different SNe feedback recipes (energy-based, kinematic, weighted, etc)
  - Vary parameters until all get same stellar mass at z=4
- Codes do not calibrate:
  - Simulations down to z=2 or below
  - CGM
  - Satellite Galaxies

Paper III

Paper IV

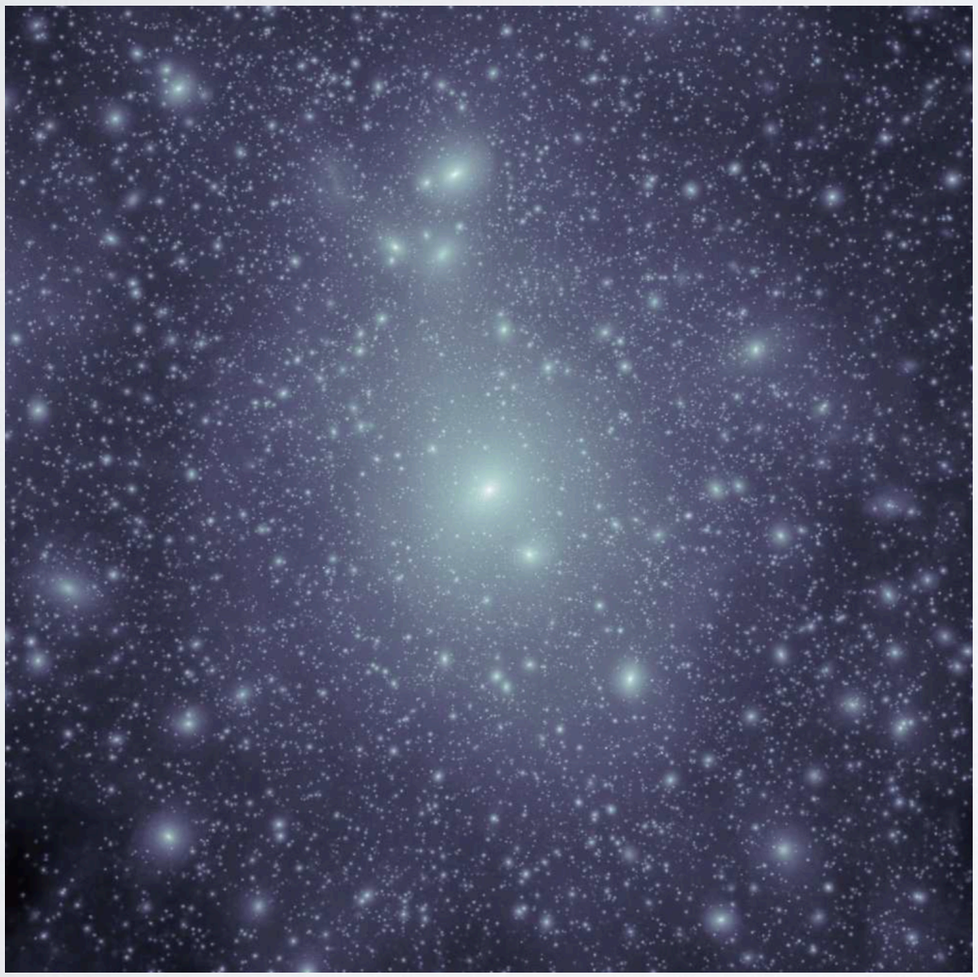
Paper VI

Paper V

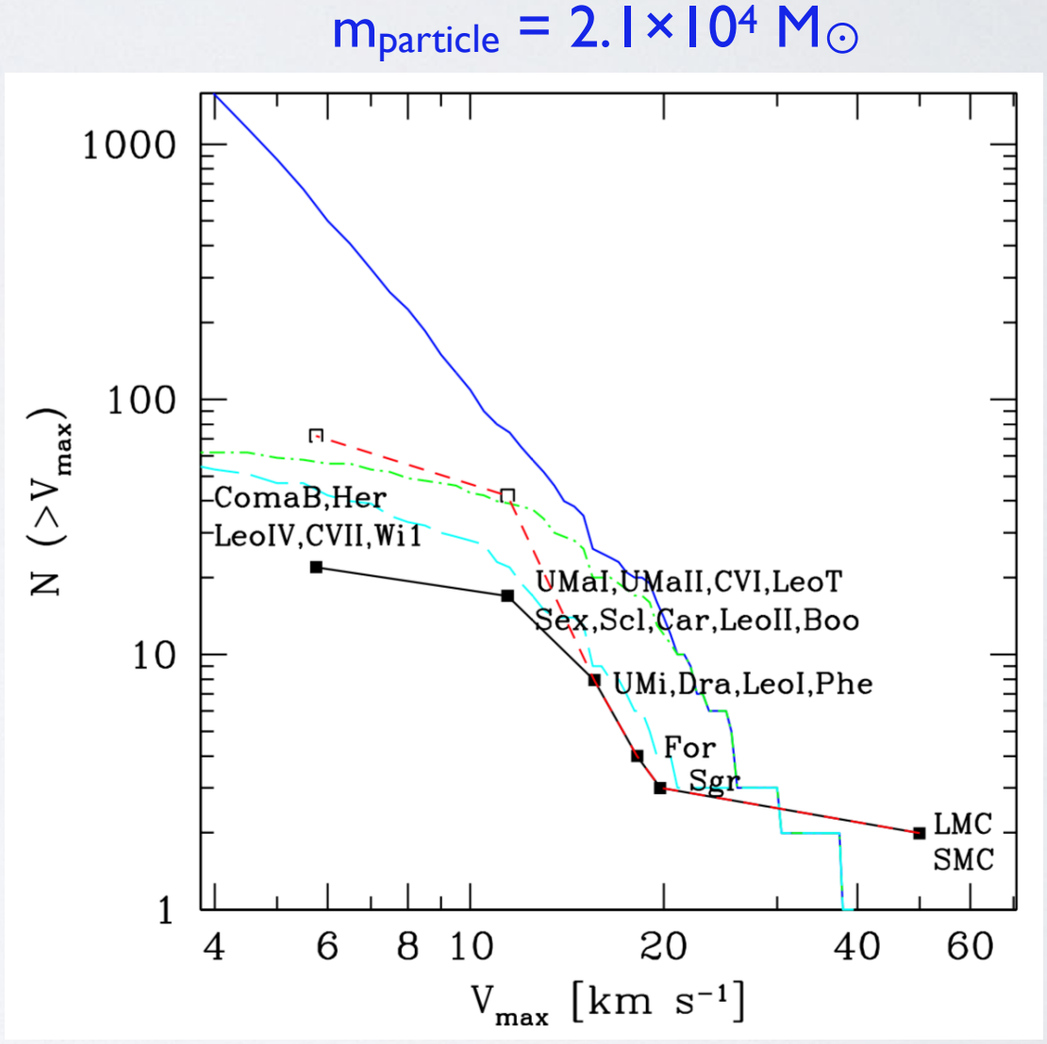
credit: J. Primack

“Missing Satellite Problem”

- Refers to the discrepancy between the predicted number of DM satellites in simulations and observed number of dwarf galaxies around Milky Way (a.k.a. “Dwarf Galaxy Problem”).



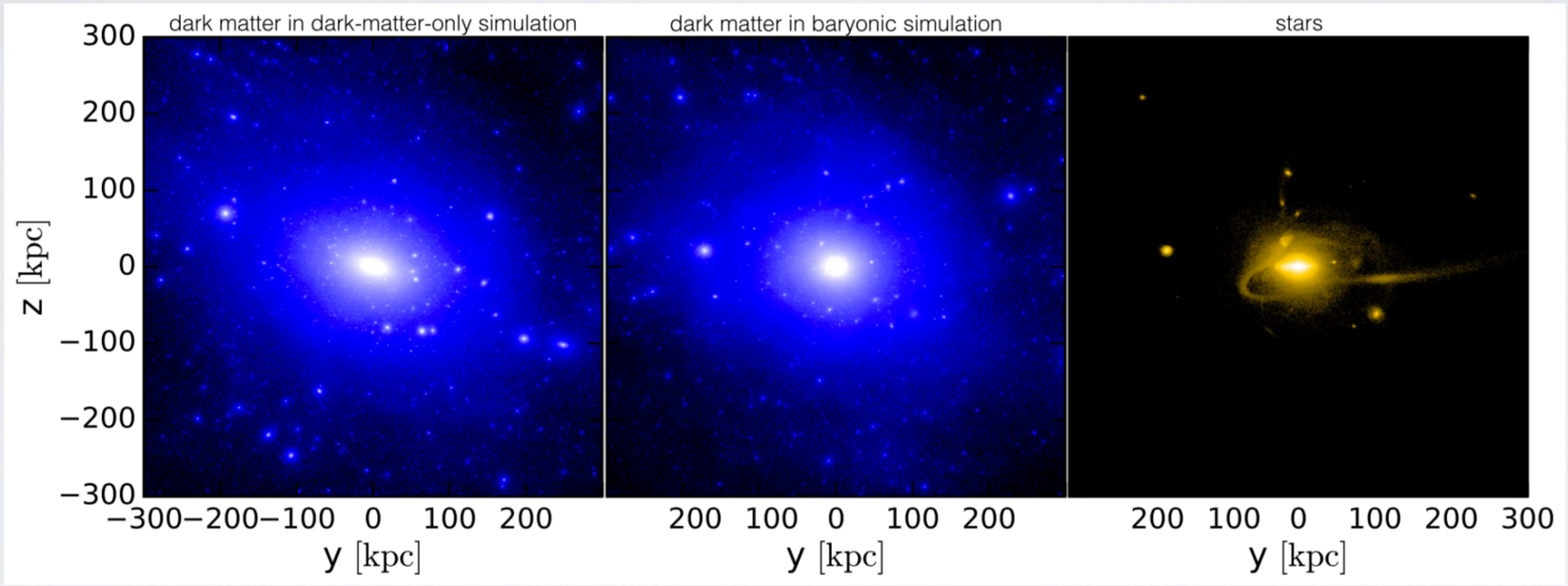
Via Lactea, Madau et al. (2008)



“Missing Satellite Prob” - Suggested Solution 1

- Baryon physics seems to resolve the problem well.

Wetzel et al. (2016)



$m_{particle} = 3.5 \times 10^4\ M_\odot$

$m_{gas} \sim= 7 \times 10^3\ M_\odot$

“No Too Big To Fail problem”

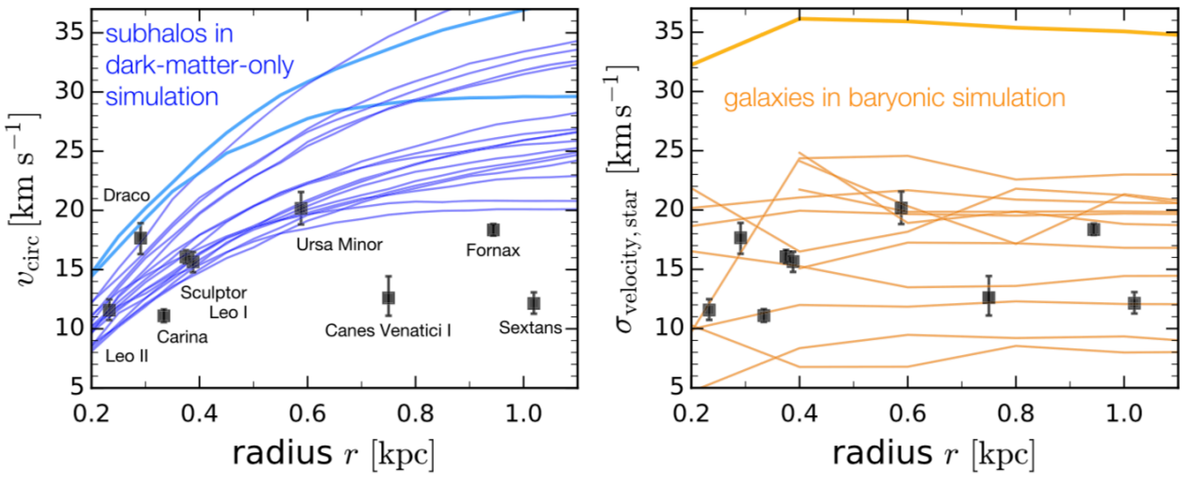


Figure 2. Left: profiles of circular velocity, $v_{\rm circ}(r) = \sqrt{GM_{\rm total}(<r)/r}$ at $z = 0$. Points show observed satellites of the MW with $M_{\rm star} = 2 \times 10^5 - 2 \times 10^7\ M_\odot$ (Wolf et al. 2010). Curves show the 19 subhalos in the dark-matter-only simulation at $d_{\rm host} < 300$ kpc with densities as low as Ursa Minor. Two subhalos (light blue) are denser than all observed satellites. Allowing one to host the SMC and noting that five others are consistent with Ursa Minor, Draco, Sculptor, Leo I, and Leo II leads to 13 that are too dense (the “too big to fail” problem). Right: profiles of stellar 3D velocity dispersion for the 13 satellite galaxies in the baryonic simulation. All profiles are nearly flat with radius. One satellite has high dispersion, closer to the SMC’s 48 km s^{-1}; all others are broadly consistent with the MW.

“No Missing Satellite problem”

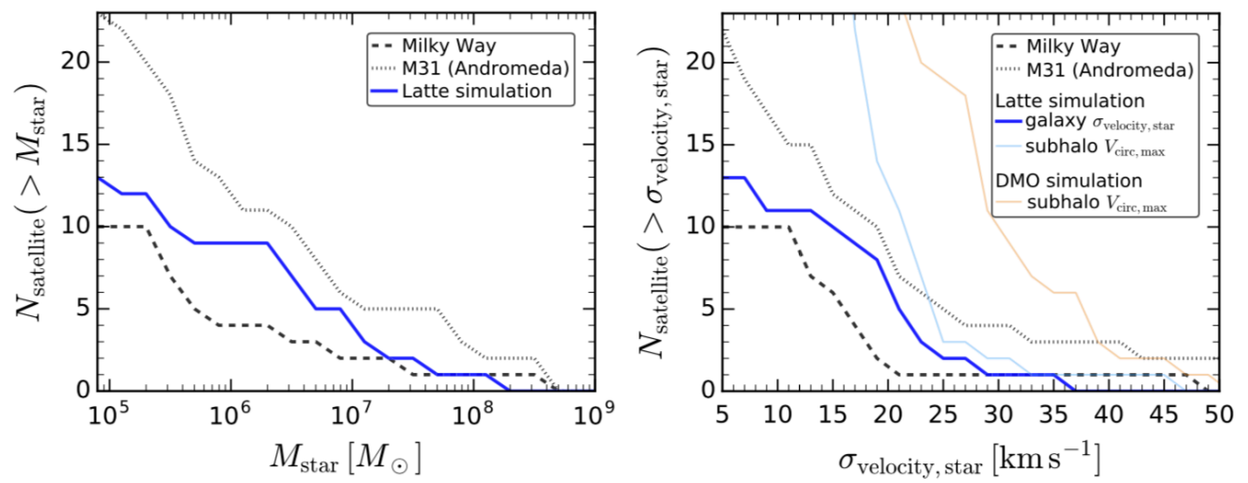
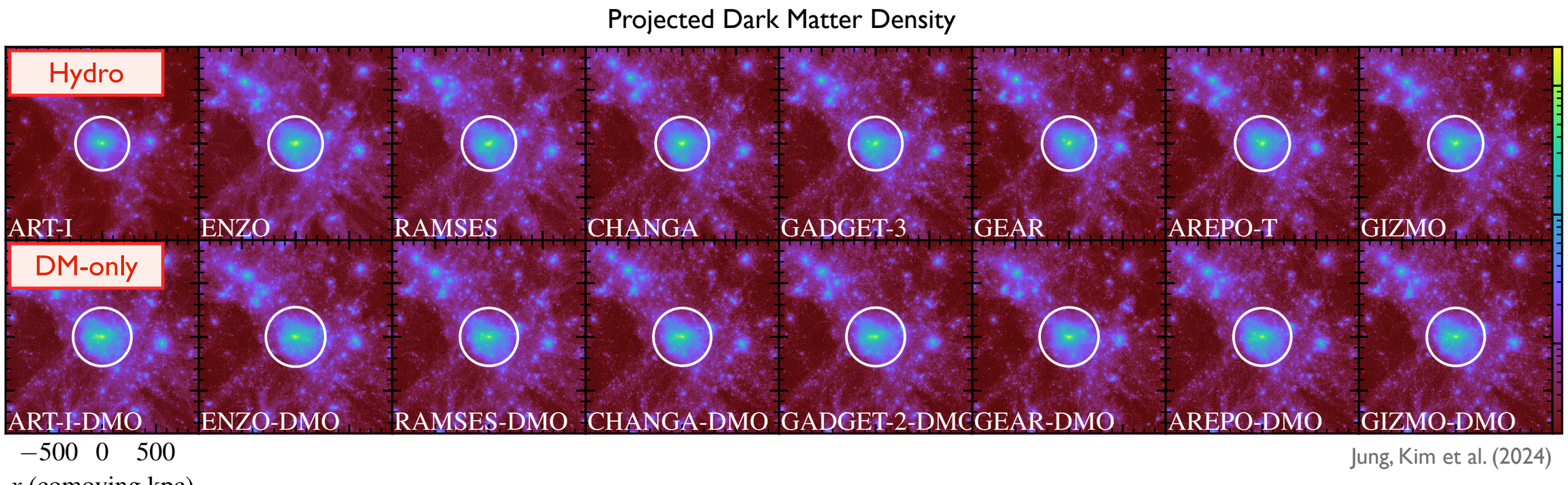


Figure 3. Cumulative number of satellites at $z = 0$ above a given stellar mass (left) and stellar 3D velocity dispersion (right) in the Latte simulation (blue) and observed around the Milky Way (MW; dashed) and Andromeda (M31; dotted), excluding the LMC, M33, and Sagittarius. For both $M_{\rm star}$ and σ, Latte’s satellites lie entirely between the MW and M31, so Latte does not suffer from the “missing satellites” or “too big to fail” problems. Thin curves (right) show $V_{\rm circ,max}$ for *all* dark-matter subhalos in the baryonic (light blue) and dark-matter-only (DMO; orange) simulations, demonstrating the ≈3× reduction from baryonic physics.

No Missing Satellite Problem In AGORA

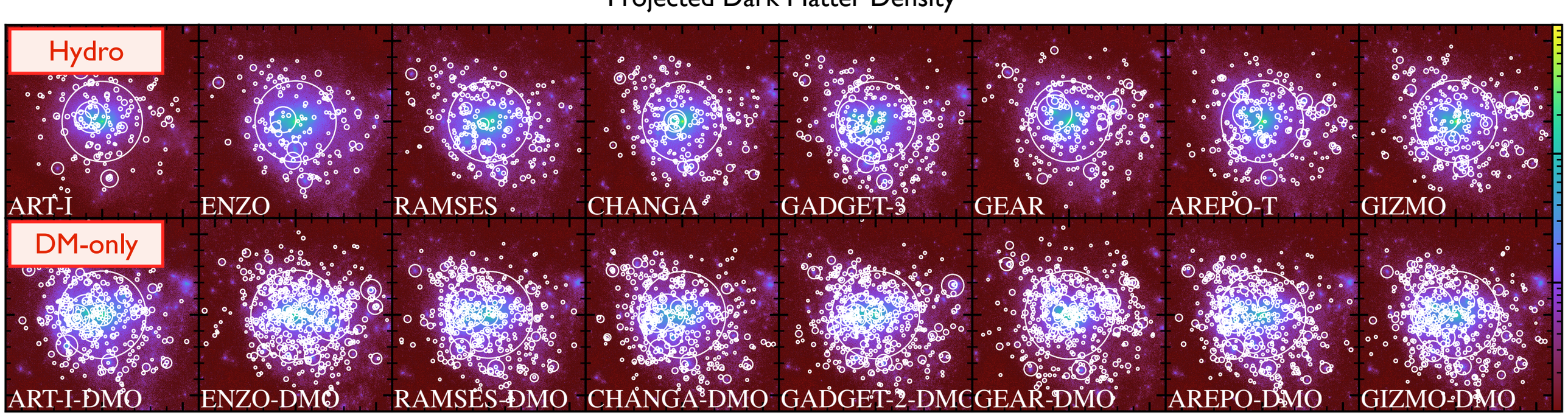
- Across all codes, fewer satellite halos are found in hydrodynamic CosmoRuns than in DM-only runs (Jung et al. 2024).



Jung, Kim et al. (2024)

No Missing Satellite Problem In AGORA

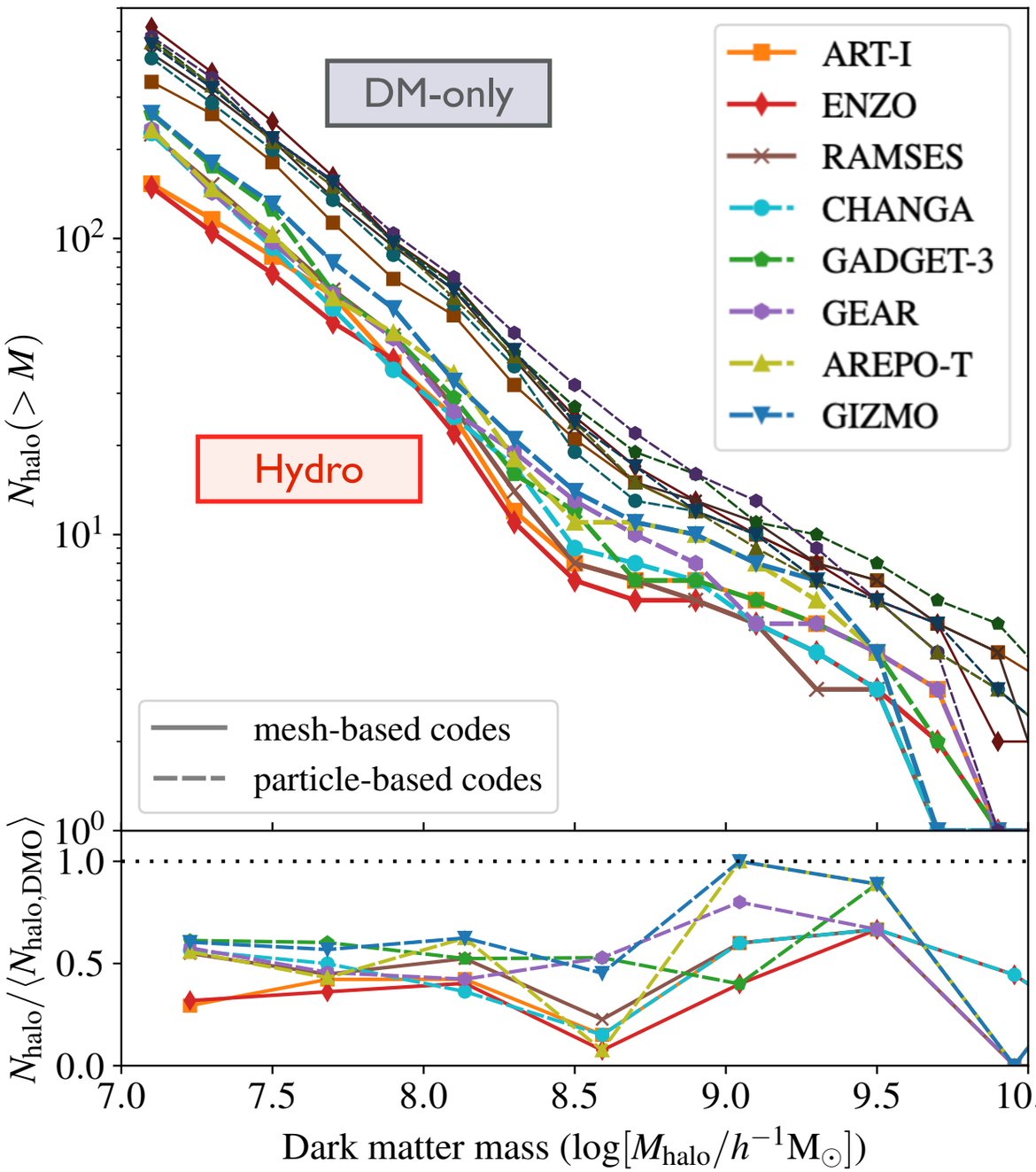
- Across all codes, fewer satellite halos are found in hydrodynamic CosmoRuns than in DM-only runs (Jung et al. 2024).

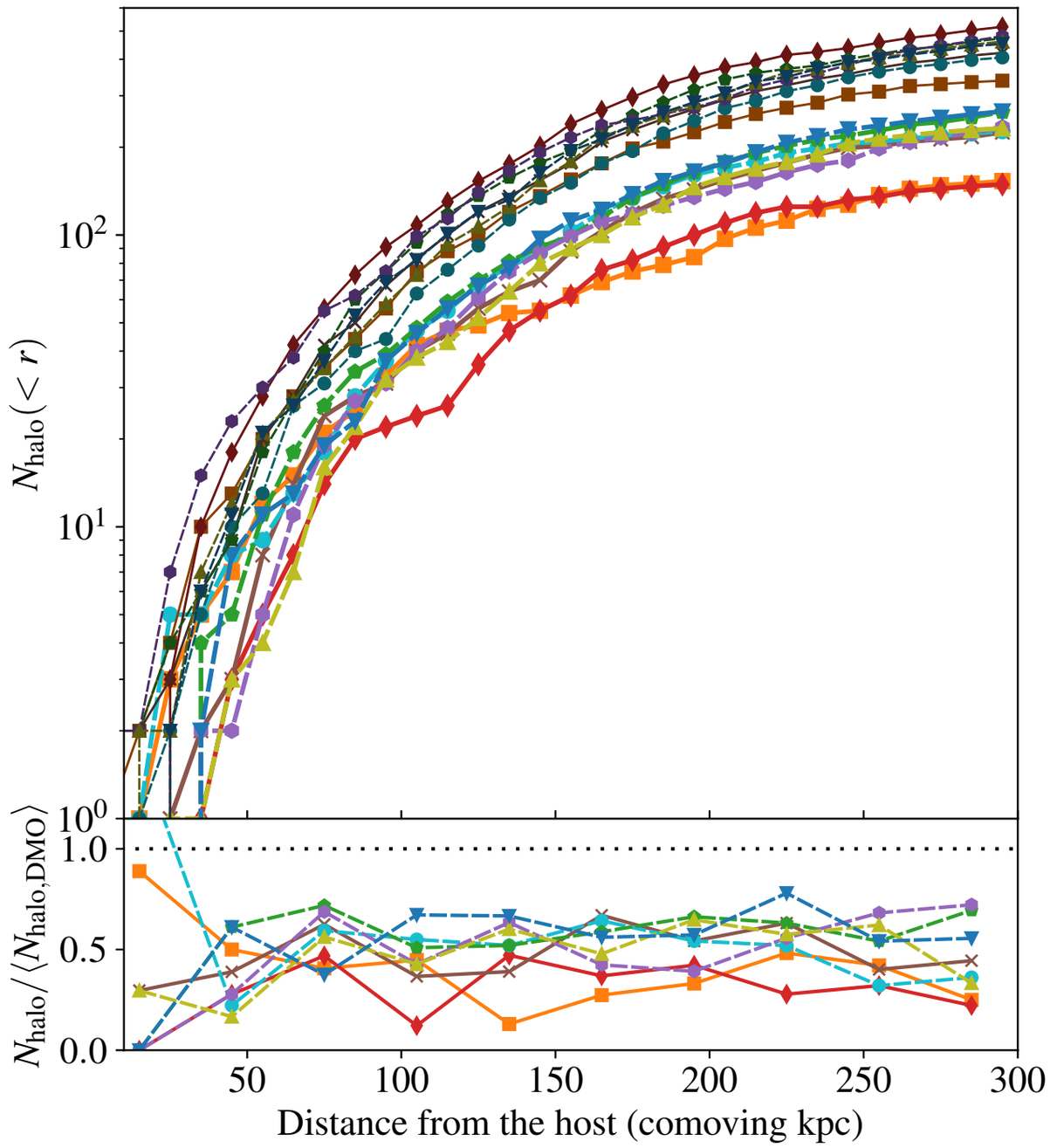


Jung, Kim et al. (2024)

No Missing Satellite Problem In AGORA

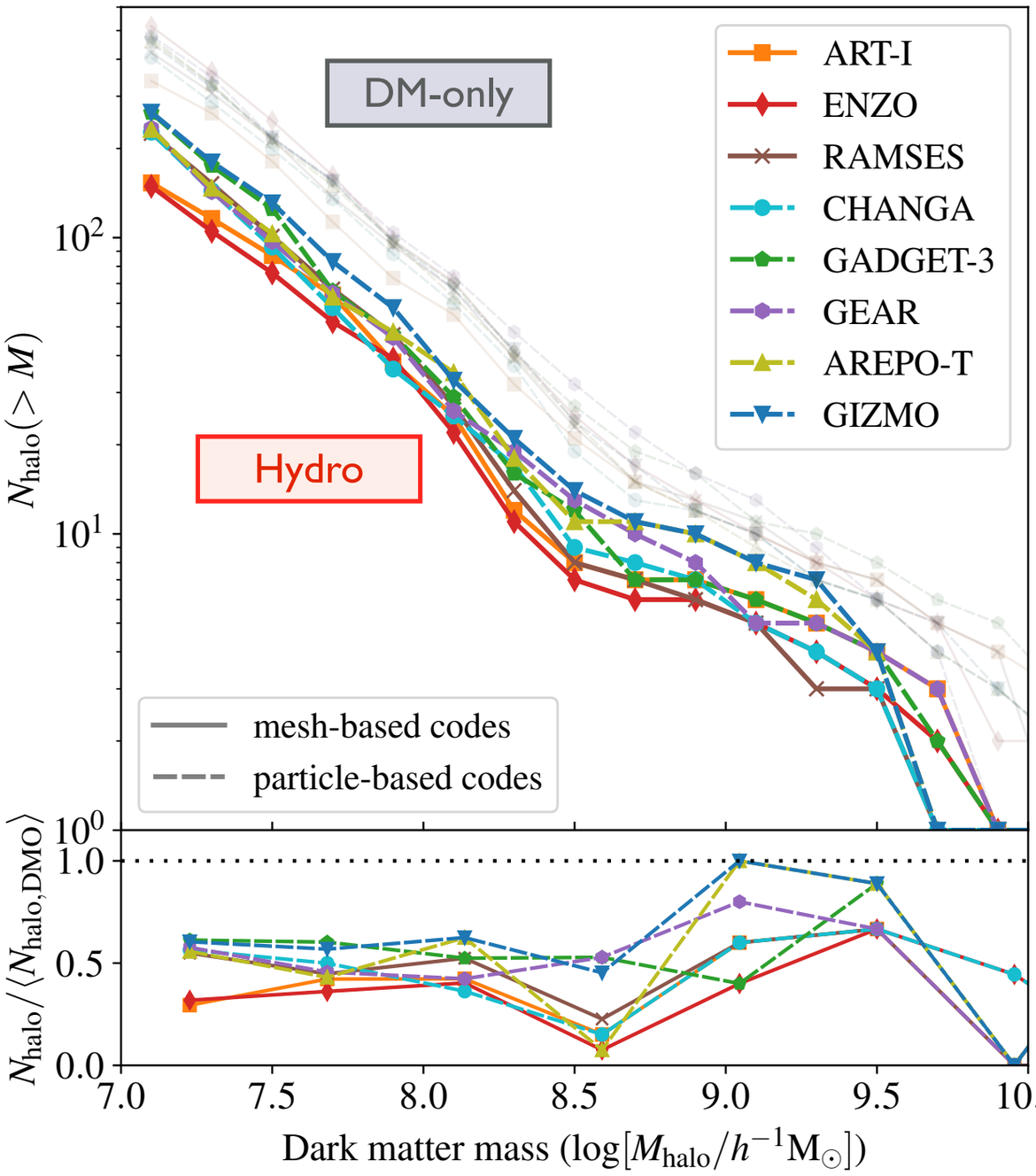
- Across all codes, fewer satellite halos are found in hydrodynamic CosmoRuns than in DM-only runs (Jung et al. 2024).

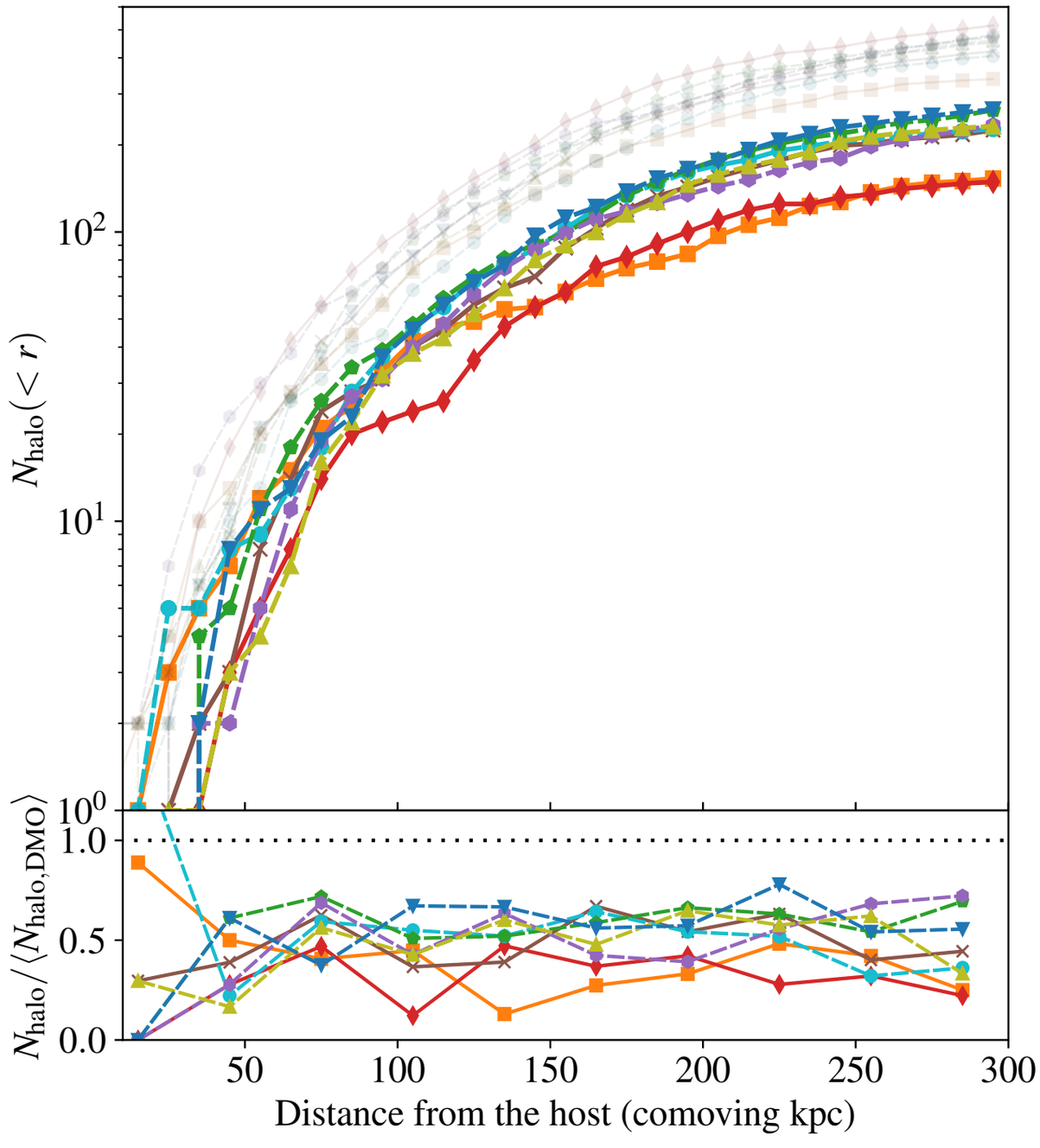




No Missing Satellite Problem In AGORA

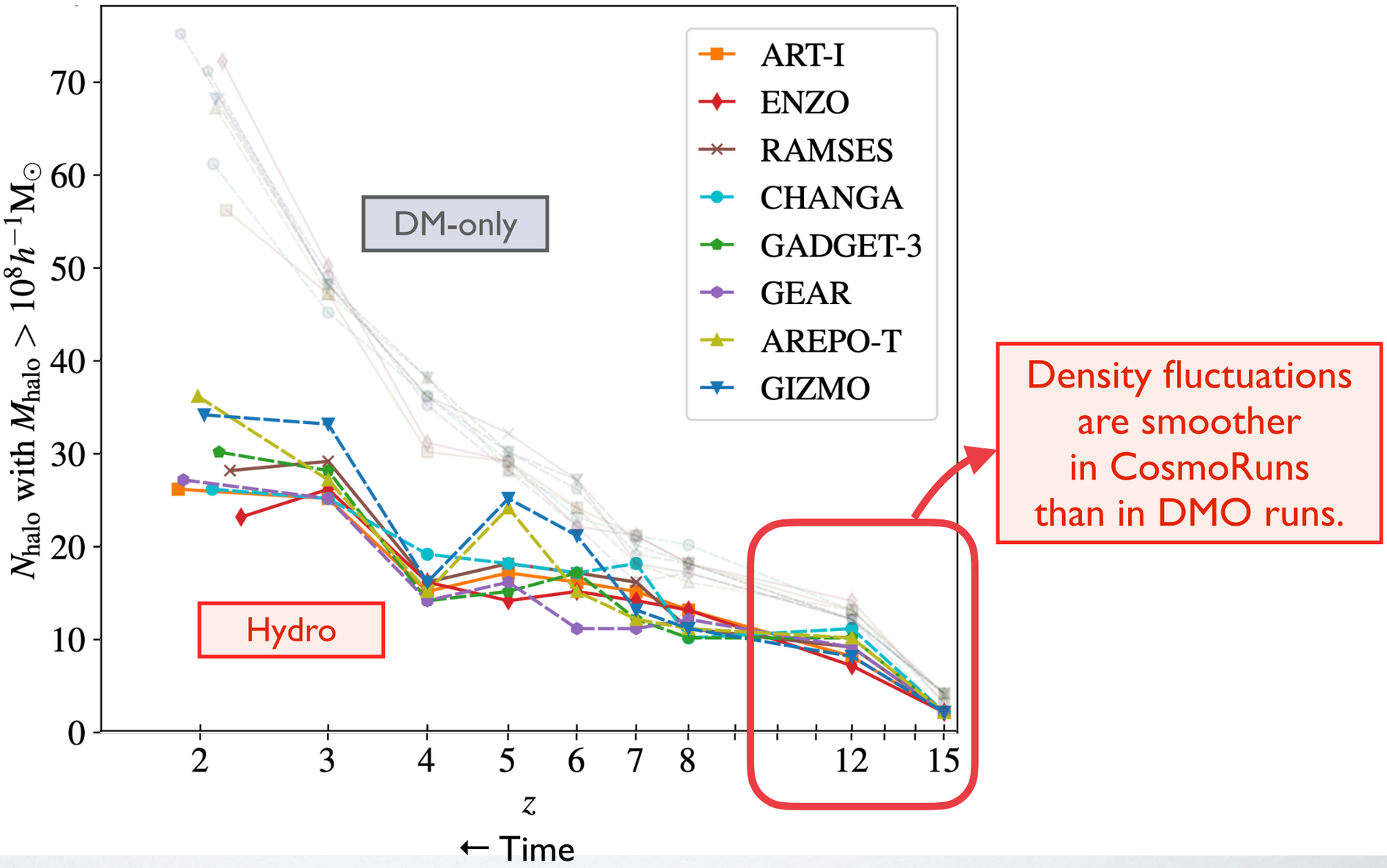
- Across all codes, fewer satellite halos are found in hydrodynamic CosmoRuns than in DM-only runs (Jung et al. 2024).





Evolution of Satellite Halo Numbers In Time

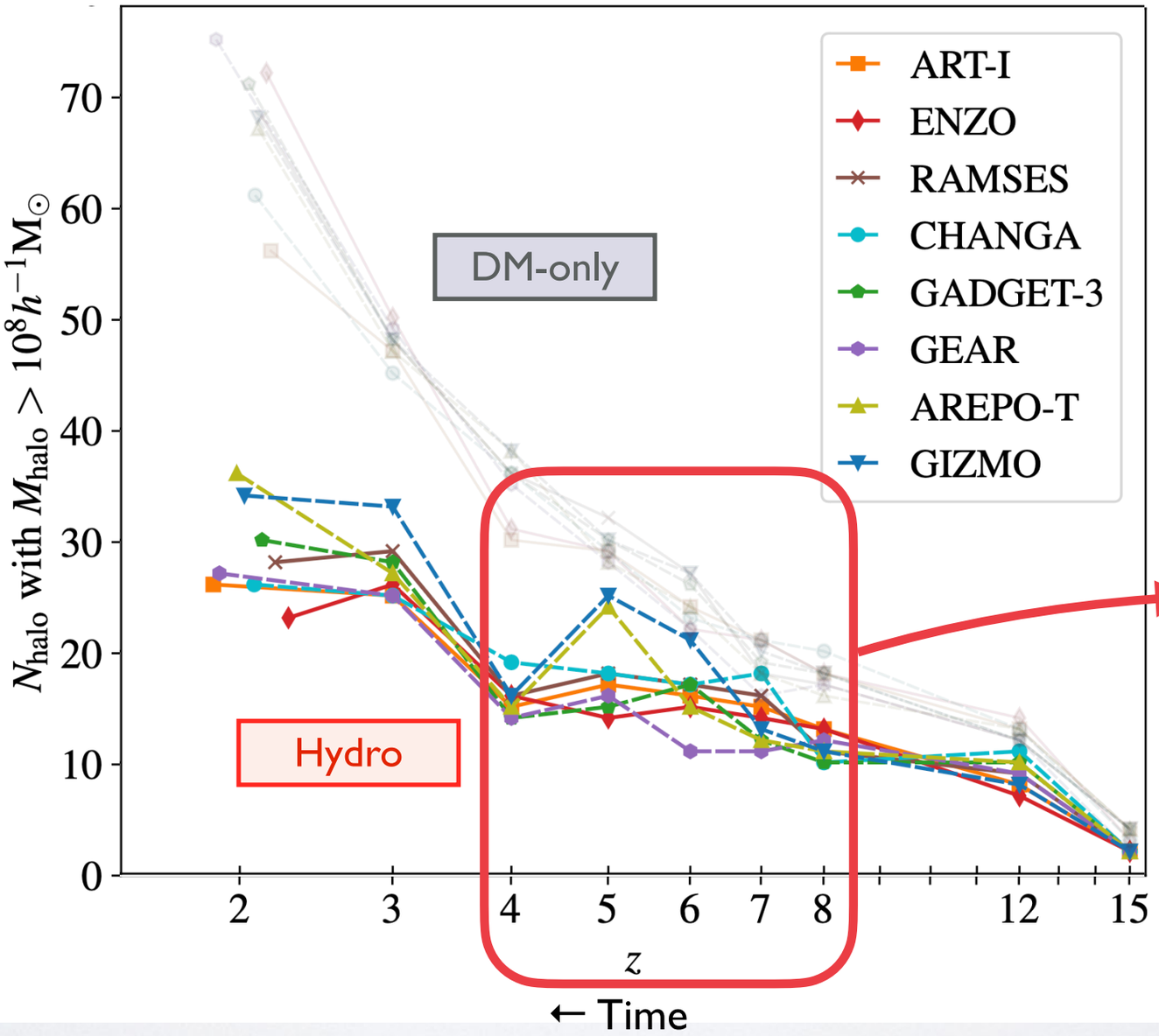
- Various baryonic effects help to reduce the number of satellite halos in hydrodynamic AGORA CosmoRuns.



Jung, Kim et al. (2024)

Evolution of Satellite Halo Numbers In Time

- Various baryonic effects help to reduce the number of satellite halos in hydrodynamic AGORA CosmoRuns.

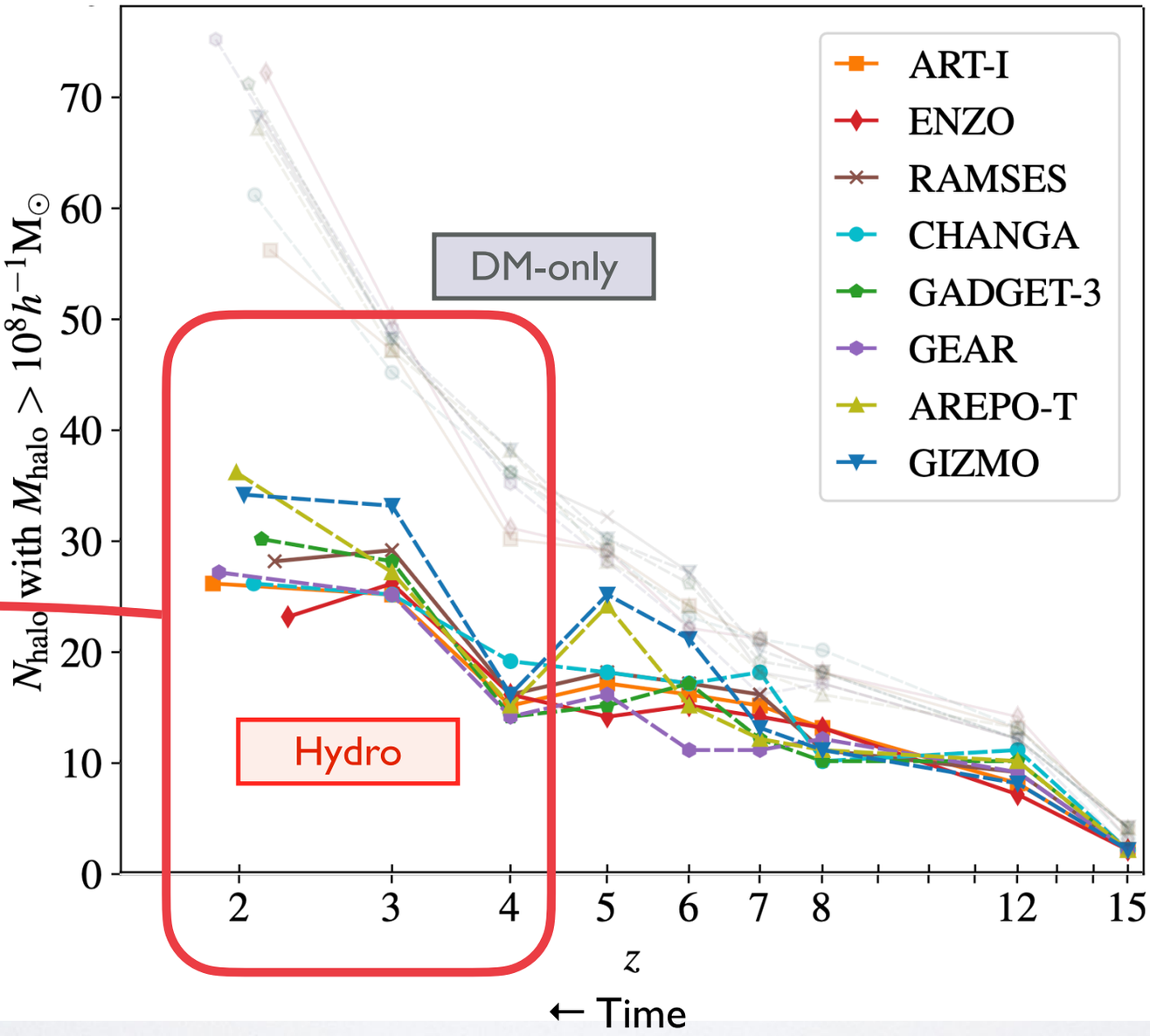


Cosmic reionization slows down the satellite halos' growth by heating up the extragalactic gas.

Jung, Kim et al. (2024)

Evolution of Satellite Halo Numbers In Time

- Various baryonic effects help to reduce the number of satellite halos in hydrodynamic AGORA CosmoRuns.

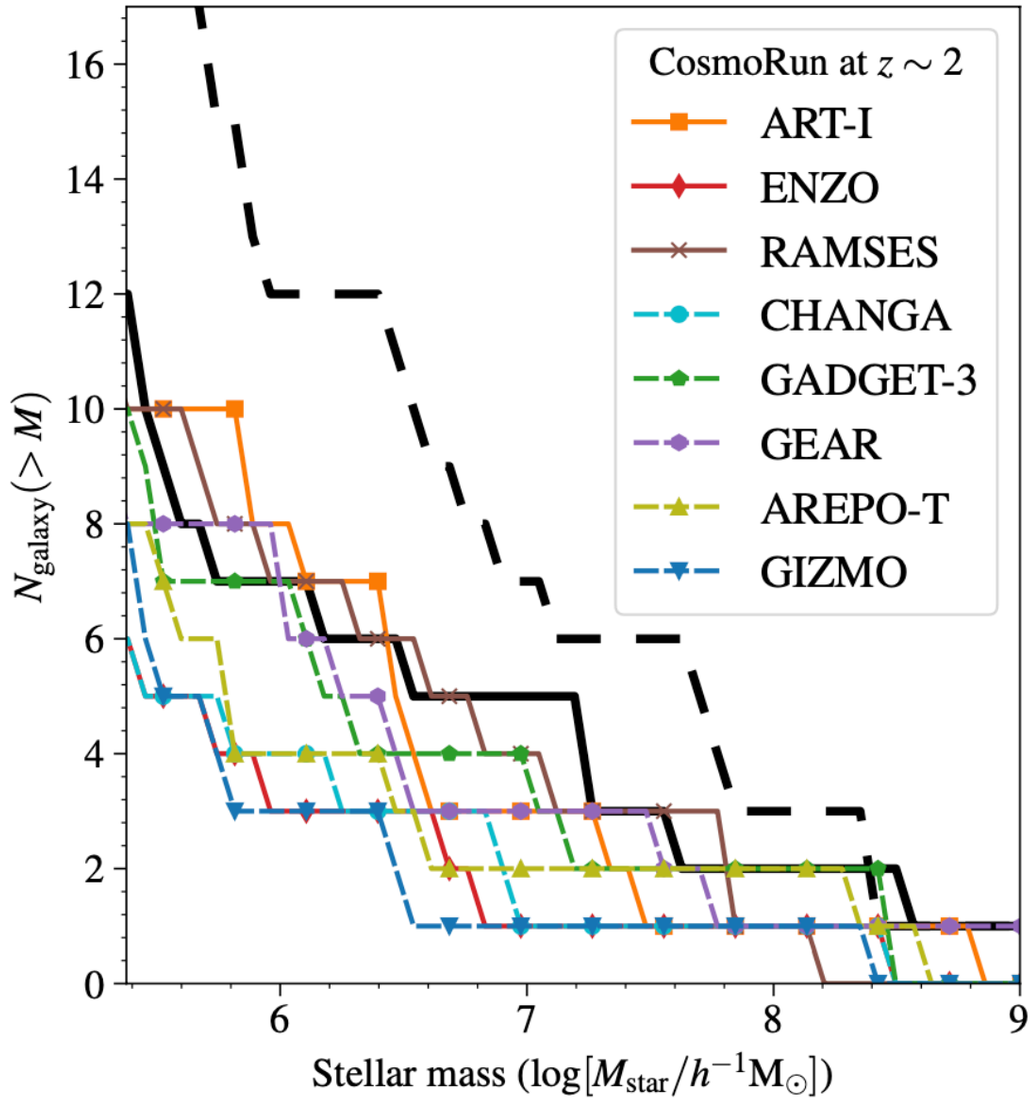


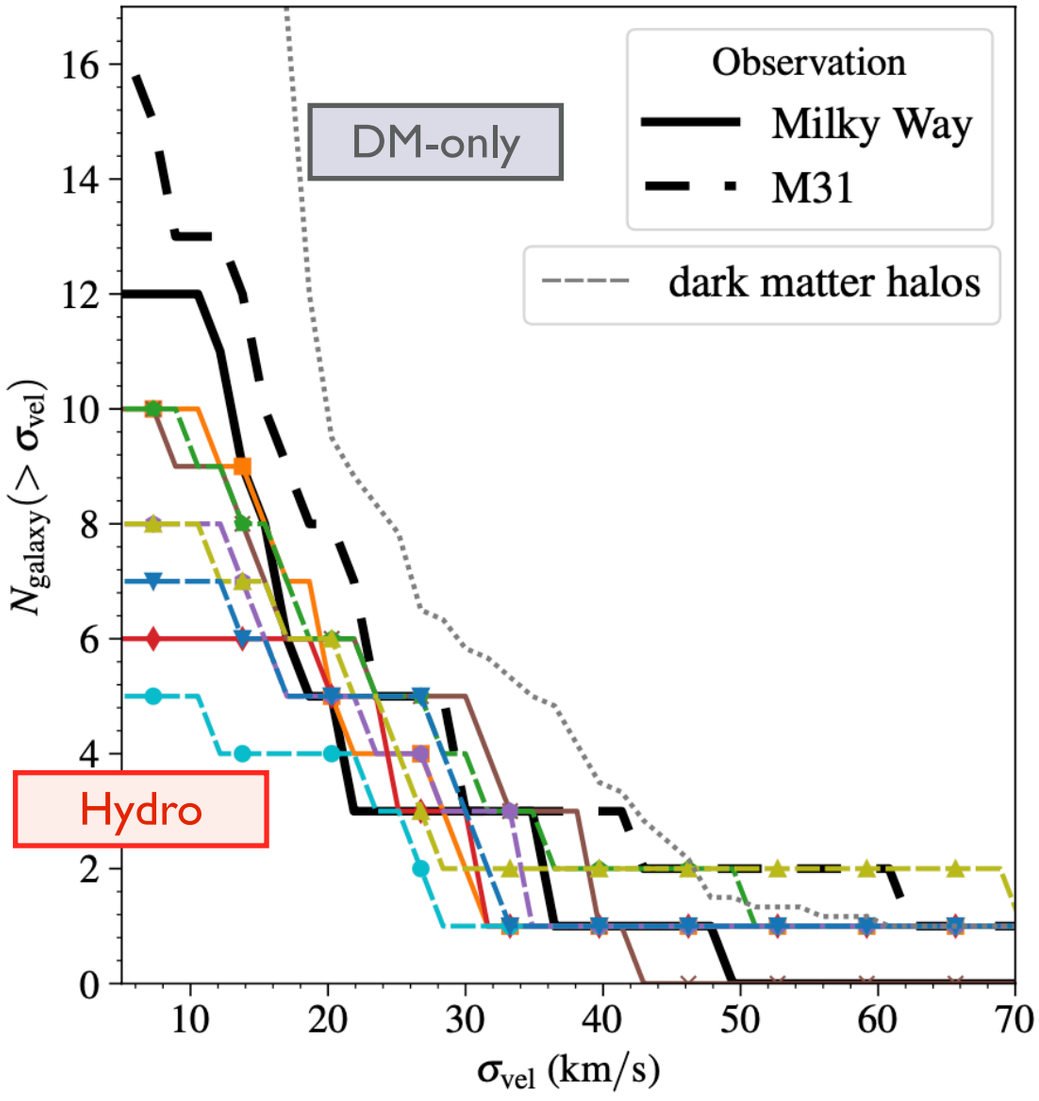
Supernovae feedback and ram pressure stripping slow down or halt the satellite halos' growth.

Jung, Kim et al. (2024)

Consistent With Local Observations

- Across all codes, the number of satellite galaxies — halos that contain star particles — is consistent with MW/M31 observations.

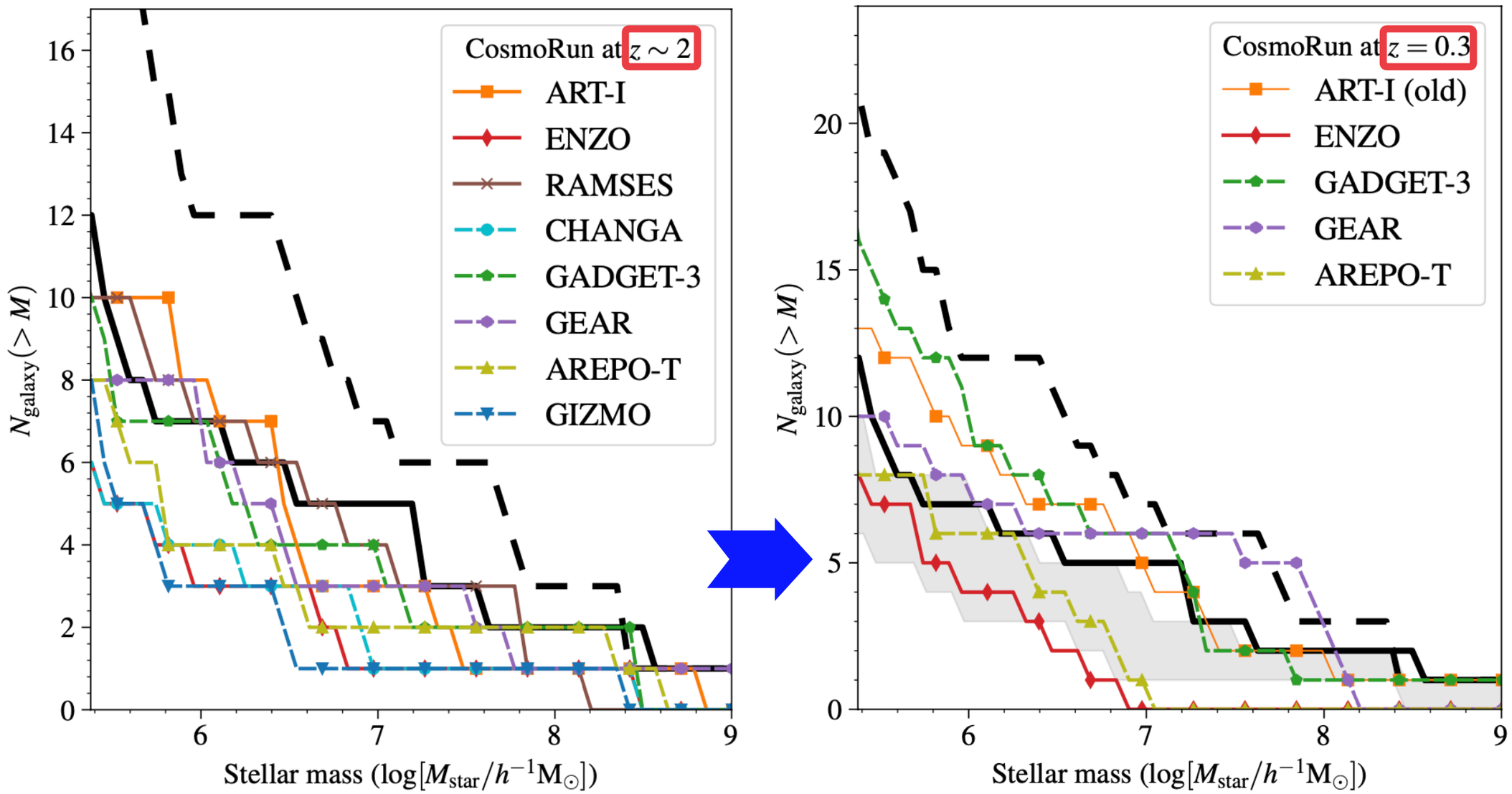




Jung, Kim et al. (2024)

Consistent With Local Observations

- Across all codes, the number of satellite galaxies — halos that contain star particles — is consistent with MW/M31 observations.

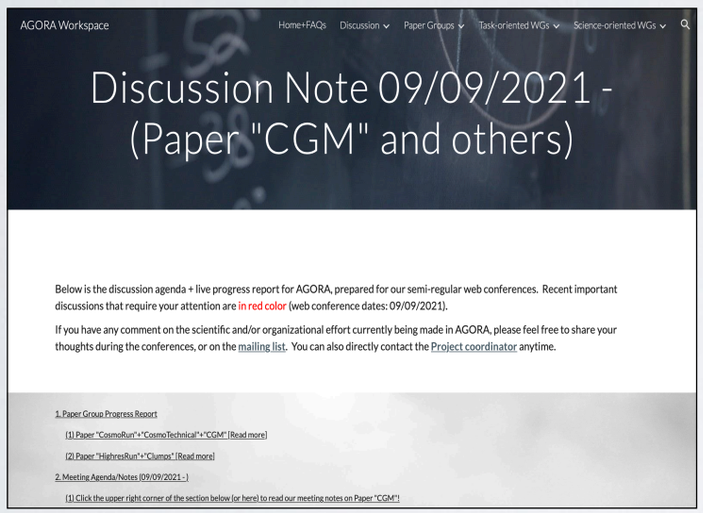


Jung, Kim et al. (2024)

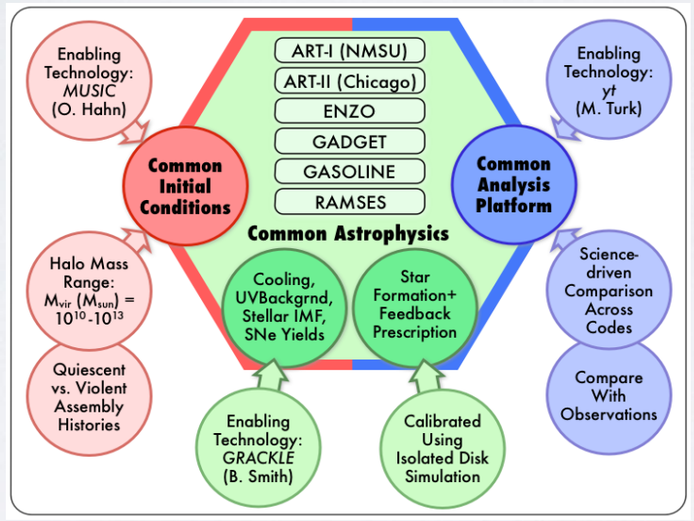
AGORA: A 12-Year Human Experiment

- We have founded an one-of-a-kind, open forum where numerical astrophysicists can talk to and learn from one another.

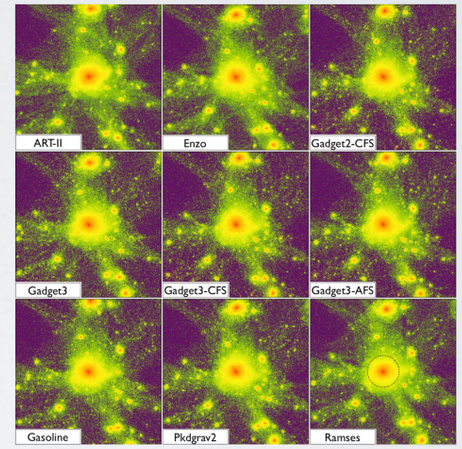
Workspace



Public Infrastructure



Journal Articles



The Astrophysical Journal Supplement Series, 210:14 (20pp), 2014 January doi:10.1088/0067-0049/210/1/14
© 2014. The American Astronomical Society. All rights reserved. Printed in the U.S.A.

THE AGORA HIGH-RESOLUTION GALAXY SIMULATIONS COMPARISON PROJECT

Ji-hoon Kim[1], Tom Abel[2], Oscar Agertz[3,4], Greg L. Bryan[5], Daniel Ceverino[6], Charlotte Christensen[7], Charlie Conroy[1], Avishai Dekel[8], Nickolay Y. Gnedin[3,9,10], Nathan J. Goldbaum[1], Javiera Guedes[11], Oliver Hahn[11], Alexander Hobbs[11], Philip F. Hopkins[12,13], Cameron B. Hummels[7], Francesca Iannuzzi[14], Dusan Keres[15], Anatoly Klypin[16], Andrey V. Kravtsov[3,10], Mark R. Krumholz[1], Michael Kuhlen[1,13], Samuel N. Leitner[17], Piero Madau[1], Lucio Mayer[18], Christopher E. Moody[1], Kentaro Nagamine[19,20], Michael L. Norman[15], Jose Onorbe[21], Brian W. O'Shea[22], Annalisa Pillepich[1], Joel R. Primack[23], Thomas Quinn[24], Justin I. Read[4], Brant E. Robertson[7], Miguel Rocha[21], Douglas H. Rudd[10,25], Sijing Shen[1], Britton D. Smith[22], Alexander S. Szalay[26], Romain Teyssier[18], Robert Thompson[7,19], Keita Todoroki[19], Matthew J. Turk[5], James W. Wadsley[27], John H. Wise[28], and Adi Zolotov[8] for the AGORA Collaboration[29]

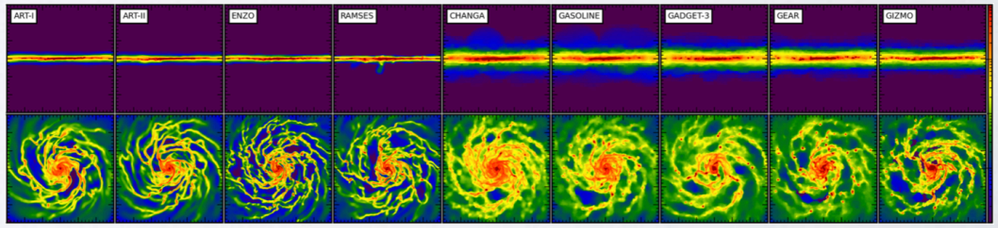
46 authors

Workshops



Telecons





The Astrophysical Journal, 833:202 (34pp), 2016 December 20 doi:10.3847/1538-4357/833/2/202
© 2016. The American Astronomical Society. All rights reserved.

THE *AGORA* HIGH-RESOLUTION GALAXY SIMULATIONS COMPARISON PROJECT. II. ISOLATED DISK TEST

Ji-hoon Kim[1,2,3,36], Oscar Agertz[4,5], Romain Teyssier[6], Michael J. Butler[7,37,38], Daniel Ceverino[8,37,38], Jun-Hwan Choi[9,37,38], Robert Feldmann[6,10,37], Ben W. Keller[11,37,38], Alessandro Lupi[12,37,38], Thomas Quinn[13,37,38], Yves Revaz[14,37,38], Spencer Wallace[13,37], Nickolay Y. Gnedin[15,16,17,38], Samuel N. Leitner[18,38], Sijing Shen[19,38], Britton D. Smith[20,38], Robert Thompson[21,38], Matthew J. Turk[22,38], Tom Abel[1,2], Kenza S. Arraki[23], Samantha M. Benincasa[11], Sukanya Chakrabarti[24], Colin DeGraf[19], Avishai Dekel[25], Nathan J. Goldbaum[21], Philip F. Hopkins[3], Cameron B. Hummels[3], Anatoly Klypin[23], Hui Li[26], Piero Madau[12,27], Nir Mandelker[25,28], Lucio Mayer[6], Kentaro Nagamine[29,30], Sarah Nickerson[6], Brian W. O'Shea[31], Joel R. Primack[32], Santi Roca-Fàbrega[25], Vadim Semenov[16], Ikkoh Shimizu[29], Christine M. Simpson[33], Keita Todoroki[34], James W. Wadsley[11], and John H. Wise[35] (for the AGORA Collaboration)[39]

43 authors

Mini-Workshop in Seoul (May 2023; tentative)

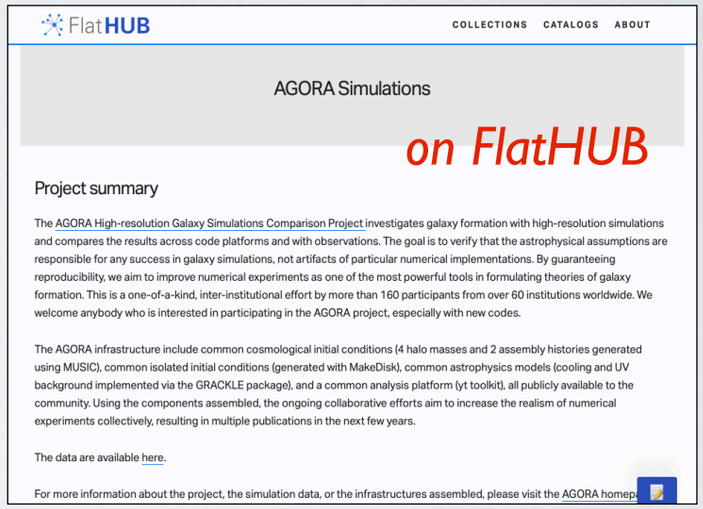
- We aim to speed up the 3+ papers that uses the CosmoRun suite — topics include (but are not limited to) mergers, morphology, etc.



Rationale & Registration

We are pleased to announce that "The 2nd CTP Bosan Workshop[1]: **AGORA in Asia + 5th Numerical Galaxy Formation Meeting in Korea**" will be held at Seoul National University (SNU), Seoul, Korea, from May 7 to 10, 2024. This workshop aims to bring together researchers from around the world for open and active discussions on numerical galaxy formation. It will also facilitate discussions about ongoing and future efforts within the AGORA High-resolution Galaxy Simulations Comparison Project. This workshop is supported in part by the Center for Theoretical Physics (CTP) at SNU, and the SNU Astronomy Research Center (SNUARC). It is also supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government through the DARWIN Project.

Public Data Access



+ More Projects!

- Paper “Mergers-I/II”
- Paper “Satellite-Quenching”
- Paper “AGN-Isolated”

AGORA High-resolution Galaxy Simulations Comparison Initiative: 12 Years After Its Conception

- Realistic, unabridged, high-resolution numerical experiments will help us to better describe the Universe.

I. AGORA Simulation Comparison Initiative
To Guarantee the Reproducibility and
the Predictive Power of Numerical Simulations

II. How Baryonic Physics Helps
To Produce Realistic Satellite Galaxy Populations
In Simulations Across All Codes