



UNIVERSITY OF CALIFORNIA
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WORLDWIDE COLLABORATION ANNOUNCES PROJECT AGORA:
AMBITIOUS COMPARISON OF HIGH-RESOLUTION COMPUTER SIMULATIONS
OF GALAXY FORMATION AND EVOLUTION

More than 90 Astrophysicists from Over 40 Institutions Worldwide

Flagship Paper Accepted for Publication in *Astrophysical Journal Supplement*

A long-standing difficulty with supercomputer simulations of the formation and evolution of galaxies has been getting consistent results among different codes (programs) and with actual observations, so that computationally simulated galaxies look like real galaxies. While such conflicts could be evidence of complex physics in invisible dark matter, emerging evidence suggests that inconsistencies may originate from a poor understanding of processes involving ordinary matter as well as limitations in computational capability and differences in computer codes.

Now, an ambitious new multiyear project—named AGORA, an ancient Greek word meaning meeting place, and an acronym for Assembling Galaxies of Resolved Anatomy—to understand and resolve such inconsistencies is described in a flagship paper by Ji-hoon Kim and 45 co-authors accepted for publication in *The Astrophysical Journal Supplement*.

“Reproducibility is one of the most elementary principles in scientific methods,” write the 46 authors. “A result from an experiment can be established as scientific knowledge only after the result in its entirety can be reproduced by others within the scientific community according to the same procedure in distinct and independent experimental trials.”

“What we are trying to achieve in the AGORA project is to apply the same fundamental rule of reproducibility to computational experiments,” explains the lead author Ji-hoon Kim, a post-doctoral researcher at the University of California, Santa Cruz, who recently joined the California Institute of Technology, and who has been coordinating the AGORA project. “We will make sure that the galaxies one of us simulated is reproduced by our colleagues. If they are not reproduced, we will figure out why. This project will tell us the key physics ingredients that produce realistic galaxies regardless of the numerical codes. It will also challenge the community to put more effort in cross-checking their results against others’.”

Fundamental challenges

Most of the gravitating mass in the Universe is cold dark matter: an abundant, as-yet undetected, slowly moving, weakly interacting elementary particle that emits no light. Cold dark matter holds together individual galaxies such as our own Milky Way and also entire clusters of galaxies. Because we cannot directly see it out in space or construct laboratory experiments to work with it, one of the fundamental problems of astrophysics, particle physics, and cosmology is revealing its nature solely by observing its effects on ordinary matter. A key tool used to test ideas about the nature of cold dark matter is supercomputer models to simulate how it might interact with regular matter to form galaxies.

One big challenge, however, has been numerically modeling astrophysical processes over the vast range of size scales in the Universe. Supercomputer simulations are designed with three different size scales relevant to three different phenomena: star formation, galaxy formation, and the large scale structure of the universe. Computational models of stars forming within galaxies commonly zoom in on giant molecular clouds in a volume of interstellar space tens of light years across with a resolution (ability to distinguish details) smaller than the size of our solar system. At that scale, the computational models can take into account such details as the chemical composition of gas and dust, supernova explosions of nearby stars, and shock waves and turbulence in interstellar gas. In contrast, cosmological simulations that trace the evolution of the cosmic web of from the Big Bang to the present day model volumes hundreds of millions of light years across. At such a gigantic scale, even the biggest supercomputers in the world have been limited to handling primarily simple gravitational interactions of dark matter, if the calculations are to be completed within reasonable time (months) and at affordable cost.

But there is a big scientific issue with viewing either just the small scale process of star formation in isolation from the large-scale process of galaxy evolution: in the real Universe, both scales interact. For example, local star formation within individual galaxies is activated or quenched by the way galaxies “breathe” in and out the gaseous intergalactic medium. And often neither type of simulation creates realistic-looking galaxies with the right proportion of stars in the central bulge compared with the flat disk. Nor, until recently could they show the giant clumps seen in forming galaxies observed in the distant Universe. Now, galaxy simulations covering large regions (a few million light years across) can resolve regions where stars form, and they have begun to succeed in creating realistic-looking galaxies.

The AGORA authors have set up methodology to compare and contrast the results with different versions of participating codes (programs for computer simulations), which numerically handle the physics and the computation in significantly different ways. Comparing a variety of simulation platforms is essential, the authors note, “*to verify that the solutions are robust*—i.e., that the astrophysical assumptions are responsible for any success, rather than artifacts of particular implementations.” Thus, for all the codes, the project’s working groups will input common initial conditions (which determine the masses and formation histories of the galaxies simulated), use common astrophysical assumptions (e.g., the intensity of ultraviolet background radiation, the rate at which gas cools, the distribution of the masses of stars that form, etc.), and compare the computational results with a common analysis and visualization tool (a code called *yt*). “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 authors write, “and by doing so to solve long-standing problems in galaxy formation.”

Getting real

The first major task will be to model a realistic isolated disk galaxy using various codes and their feedback recipes, varying both the feedback parameters and the resolution. The second task will be to compare the codes in cosmological simulations. Specifically, all the participating codes will model the evolution of eight individual galaxies from the Big Bang to the present, resulting in final masses of 10^{10} , 10^{11} , 10^{12} , and 10^{13} times the mass of the sun (a range from a dwarf galaxy to a galaxy more massive than the Milky Way). For each mass, one set of simulations would model a galaxy having a quiescent merger history (having few mergers with another galaxy its own size) and another would model a galaxy having a violent merger history (having many such major mergers especially later in its life). The final task will be to compare the results, including such observable characteristics as the shape, internal structure and

velocities, and spectral energy distribution (distribution of light at different wavelengths) between simulations and with observations of real galaxies.

AGORA is not the first such comparison of supercomputer simulations of galaxy evolution, but it is the most comprehensive and the highest-resolution (finest detail). Previous astronomical simulation comparison studies were the Santa Barbara Cluster comparison project (1999) and the Aquila comparison project (2012). The AGORA project is an open collaboration, which welcomes new participants. AGORA is making all of its initial conditions and common assumptions public, both to make it easy for astrophysicists to join the collaboration and also to raise the level of galaxy simulations worldwide.

The AGORA project was initiated in a kick-off workshop at the University of California, Santa Cruz, in August 2012, under the sponsorship of the University of California High-Performance AstroComputing Center (UC-HiPACC). A second workshop was held at UCSC a year later. The project, involving more than 90 astrophysicists from more than 40 institutions in eight nations, is coordinated by Ji-hoon Kim (formerly a postdoctoral researcher at UCSC and now at the California Institute of Technology) and a steering committee led by Piero Madau and Joel R. Primack of UCSC. Other members of the AGORA steering committee are Tom Abel (Stanford), Nick Gnedin (Fermilab and University of Chicago), Lucio Mayer and Romain Teyssier (University of Zurich), and James Wadsley (McMaster University, Canada). The AGORA project is expected to be completed in 2015 and result in many papers.

For more information:

Details about the AGORA approach, the participating codes, and the analysis methods are in “The AGORA High-Resolution Galaxy Simulations Comparison Project,” which is accepted for publication in *Astrophysical Journal Supplement*. A preprint is available at <http://arxiv.org/abs/1308.2669/> .

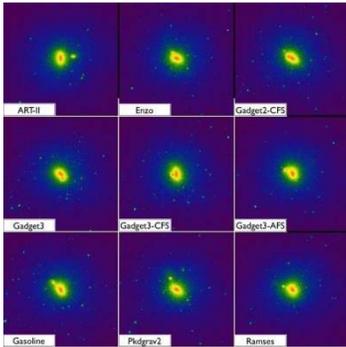
The official AGORA website, with more information about the project and its 13 working groups, is at <http://www.agorasimulations.org/> .

The UCSC press release “Astrophysicists launch ambitious assessment of galaxy formation simulations” is at <http://news.ucsc.edu/2013/12/agora-project.html>. An AstroShort “AGORA: Seeing the Invisible Elephant,” intended for astronomy clubs and other popular outlets, is at <http://hipacc.ucsc.edu/AstroShorts/December2013.html>. (More information about UC-HiPACC’s AstroShorts public service is at <http://hipacc.ucsc.edu/AstroShorts.html>.)

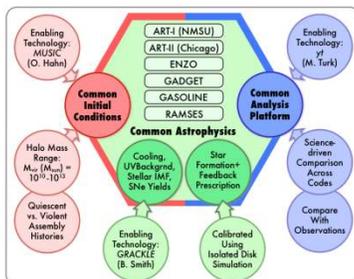
The University of California High-Performance AstroComputing Center (UC-HiPACC), based at the University of California, Santa Cruz, is a consortium of nine University of California campuses and three affiliated Department of Energy laboratories (Lawrence Berkeley Laboratory, Lawrence Livermore Laboratory, and Los Alamos National Laboratory). UC-HiPACC fosters collaborations among researchers at the various sites by offering travel and other grants, co-sponsoring conferences, and drawing attention to

the world-class resources for computational astronomy within the University of California system. More information appears at <http://hipacc.ucsc.edu>.

Illustrations and captions:



Differences in supercomputer simulations to be compared in the AGORA project are clearly evident in this test galaxy produced by each of the nine different codes using the same astrophysics and starting with the same initial conditions. The goal of AGORA is to analyze such differences in order to improve the realism and predictive power of supercomputer simulations, and thus astronomers' understanding of astrophysical processes. *Credit: 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 high-resolution version of this figure is at http://www.slac.stanford.edu/~mornkr/agora/collage_200kpc.png]



The general structure and procedures of the AGORA project is shown in this organizational diagram. *Credit: Ji-hoon Kim, California Institute of Technology.* [This figure is available at http://www.slac.stanford.edu/~mornkr/agora/AGORA_diagram.png]

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