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COSMIC REIONIZATION ON COMPUTERS

Allocation: NSF PRAC/5,850 Knh
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EXECUTIVE SUMMARY

Cosmic reionization—the process of ionization of the bulk of cosmic gas by ultraviolet radiation from the first galaxies and quasars—is the last frontier of modern cosmology. The Cosmic Reionization on Computers (CROC) project aims to, over the course of several years, produce numerical simulations of reionization. These will self-consistently model all relevant physics from radiative transfer to gas dynamics and star formation in simulation volumes of over 100 comoving megaparsecs (Mpc), necessary to model a representative sample of high-mass galaxies, and with spatial resolution approaching 100 parsecs (pc) in physical units, necessary to reliably model star formation in galaxies. CROC simulations, therefore, cover the full range of spatial, temporal, and mass scales important for studying reionization. The largest CROC simulations can only be completed on Blue Waters-class machines.

RESEARCH CHALLENGE

Study of cosmic reionization has been highlighted by the last Decadal Survey as one of the most promising areas of astrophysical research. Because of the observational constraints on reionization, theoretical modeling, including numerical simulations, plays a relatively larger part in reionization studies than in many other fields of modern astrophysics. While the first simulations of reionization were attempted nearly 20 years ago, major breakthroughs in this field are only possible with modern petascale supercomputing platforms.

Taking advantage of this technological progress, we have initiated a CROC project. This aims, over the course of several years, to produce numerical simulations of reionization that model self-consistently all relevant physics, ranging from radiative transfer to gas dynamics and star formation, in simulation volumes of over 100 comoving Mpc, which is necessary to model a representative sample of high-mass galaxies, and with spatial resolution approaching 100 pc in physical units, which is necessary to reliably model star formation in galaxies. Our simulations, therefore, cover the full range of spatial, temporal, and mass scales important for studying reionization.

The primary motivation for focusing on reionization now is the expected major advance in observational capabilities: The James Webb Space Telescope (the next flagship NASA mission) is expected to be launched in mid-2020, and studying galaxies responsible for cosmic reionization is one of its primary goals. Studies of the intergalactic gas will be propelled forward by the deployment of 30-meter telescopes, several of which will become operational in the first half of the next decade. Other novel observational tools will follow in the second half of the next decade.

METHODS & CODES

In order to reach the required dynamic range, we rely on the Adaptive Mesh Refinement (AMR) technique. Our simulations are run with the Adaptive Refinement Tree (ART) code, a publicly available cosmological simulation code developed and supported by our group. The code includes all necessary physical modules for simulationg cosmic reionization (dynamics of dark matter and gas, atomic processes, interstellar chemistry, star formation and stellar feedback, radiative transfer of ionizing and UV radiation). ART is MPI+OpenMP parallel and scales perfectly (on this type of simulation) to about 50,000 cores, with parallel scaling remaining acceptable to about 100,000 cores.

RESULTS & IMPACT

CROC simulations are defining the state of the art in this field. By virtue of including all the relevant physics and extending to volumes that are required to properly capture the process of reionization, they are creating a physically plausible model of cosmic reionization that can be matched against any existing observational data. Such comparisons have been made by our group in the last several years in a series of papers. However, the most constraining observational data set that exists today is the distribution of optical depth in the spectra of distant quasars. Over 100 quasars during the reionization epoch have been discovered so far, and for almost 70 of them, high-resolution and high-quality spectra exist. These data probe the largest spatial scales relevant for reionization of about 70 comoving Mpc.

Our previous simulations in computational volumes of 60 Mpc were just a bit too small to make a fair comparison with the data. Simulations on Blue Waters reach scales of 120 Mpc and are the only existing numerical simulations of reionization suitable for the comparison with the optical depth data. Such comparison is one of the main science goals for our computational program, to be achieved by the end of the proposal period (summer of 2019).

However, comparison of theory (as realized by numerical simulations) with observational data is not the end in itself. A more important and far-reaching goal of our project is to refine and calibrate theoretical tools for the upcoming observations with JWST, 30-meter class telescopes, and other, more distant, observational advances. The success of the CROC project in matching all of the existing observations demonstrates that such a goal is close to being achieved.

WHY BLUE WATERS

Blue Waters is the only existing U.S. supercomputer where the CROC project can be efficiently completed. ART code does not support GPUs, so Titan is not suitable for our purposes. Prior to the Blue Waters allocation, the CROC project was supported by the U.S. Department of Energy's INCITE program with a more modest allocation on Mira at the Argonne Leadership Computing Facility. However, Mira is significantly slower than Blue Waters, is much less stable, and is being poorly administered, so using Blue Waters is more than 10 times more efficient for our purposes.

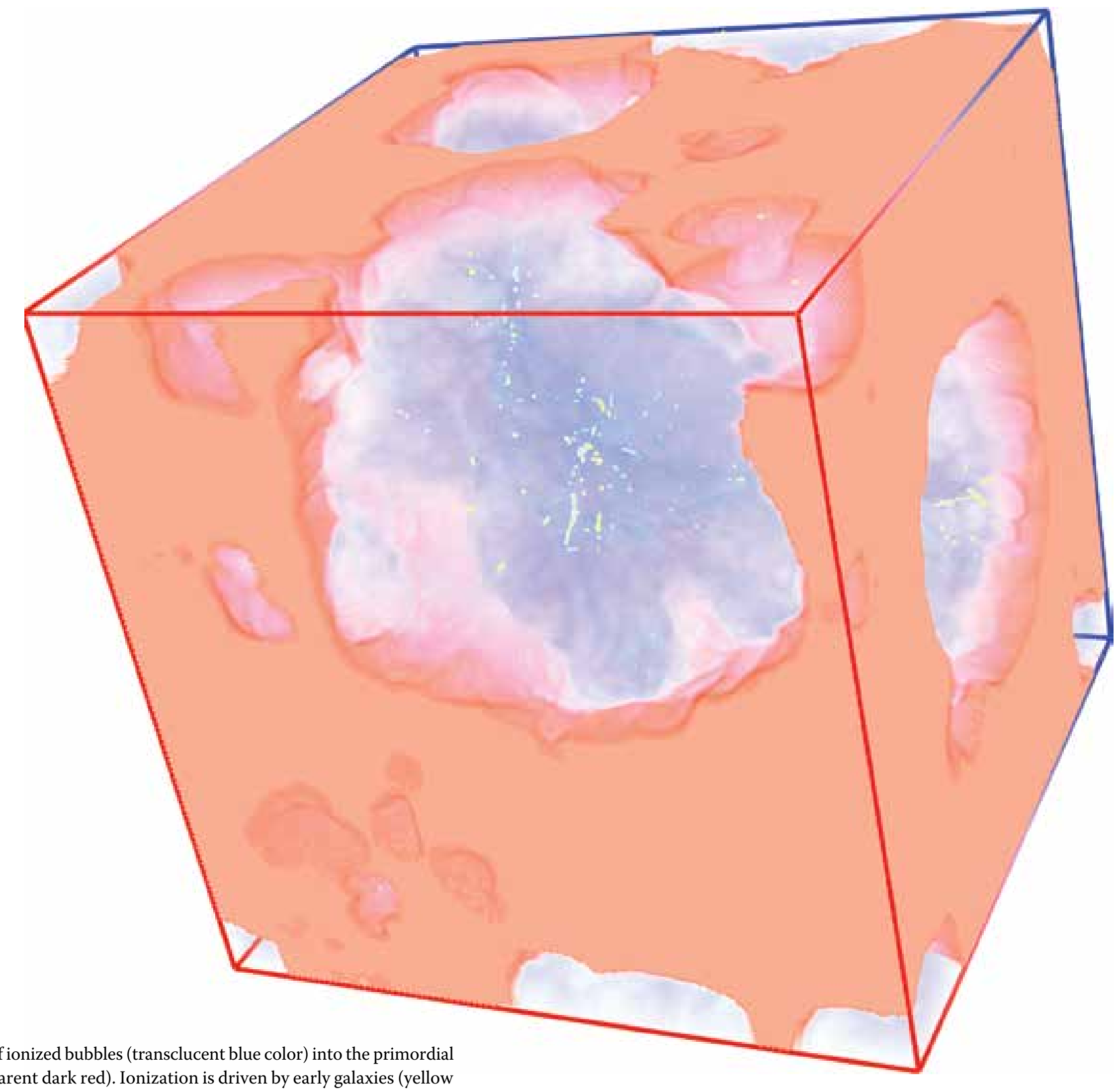

Figure 1: Propagation of ionized bubbles (transclucent blue color) into the primordial neutral gas (nontransparent dark red). Ionization is driven by early galaxies (yellow dots). The cube is a small region of the whole computational volume, which is 20 times larger in each direction.

PUBLICATIONS & DATA SETS

Villanueva–Domingo, P., N.Y. Gnedin, and O. Mena, Warm Dark Matter and Cosmic Reionization. *The Astrophysical Journal*, 852:2 (2018), p. 139.