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When volume meets precision: Zooming into cosmic extremes with the HyperMillennium Simulation

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In the pursuit of understanding large-scale structure, cosmologists face a persistent trade-off: the need for massive volumes to capture cosmic statistics versus the high resolution required to model galaxy physics. The work by Wang et al.,[1] "Reproducing Abell 2744 with the HyperMillennium Simulation," addresses this challenge with a unified solution that delivers both breadth and precision.

TECHNICAL INNOVATION AT SCALE

The HyperMillennium (HM) simulation follows 4.2 trillion dark matter particles within a 2.5 h^{-1} Gpc box, producing a data footprint exceeding 12 petabytes. To manage this extraordinary scale, the team utilized the PhotoNs-3.7 code on heterogeneous CPU+GPU architectures. The project's efficiency is rooted in its algorithmic choices: the Fast Multipole Method (FMM)

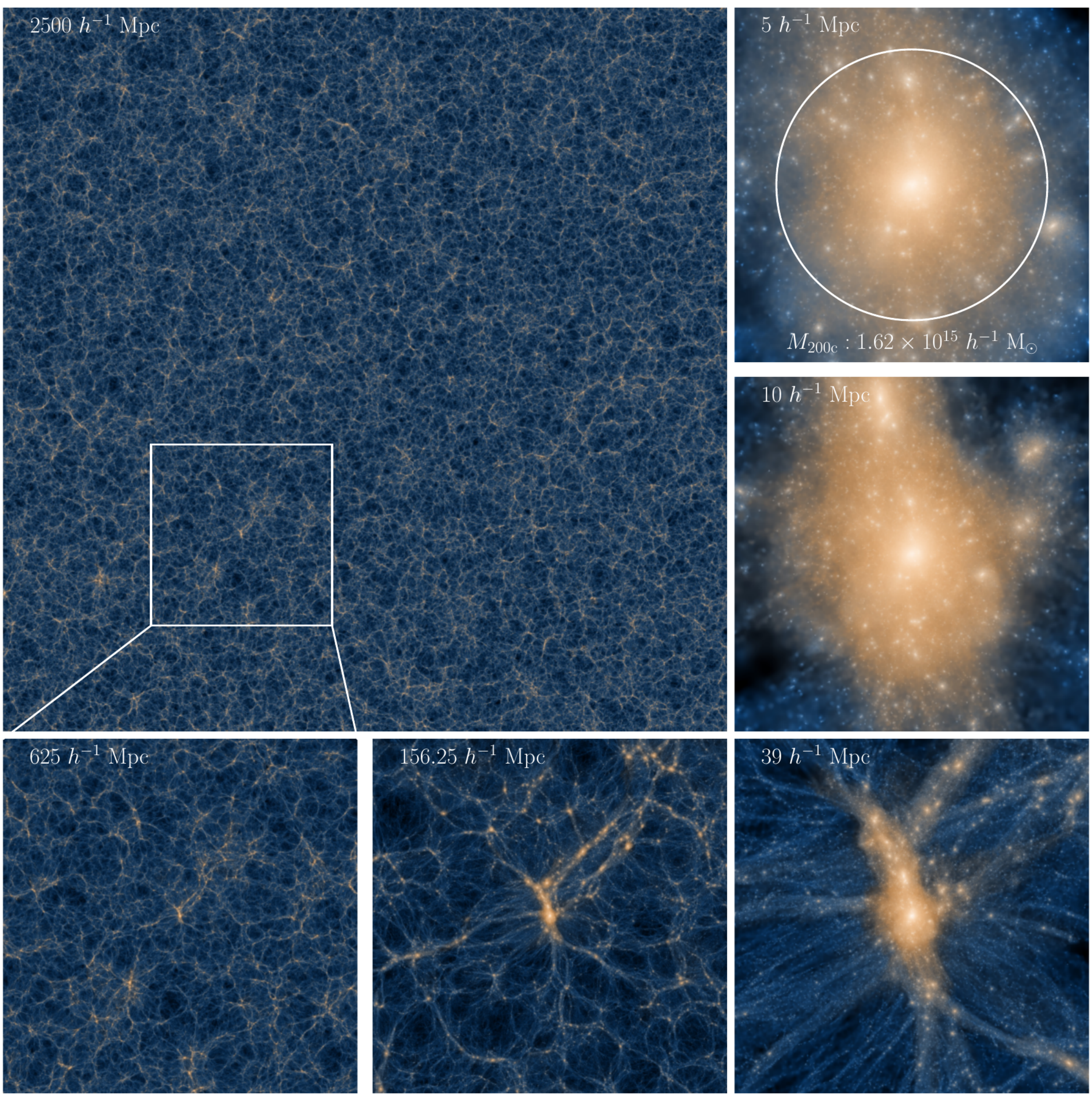

Figure 1. Dark matter density slice from the HM simulation at the present epoch (z = 0.0) The image highlights the simulation's dynamic range, from the full 2500 h^{-1} Mpc box to the internal structure of a massive galaxy cluster. Reproduced from Figure 1 of Wang et al.[1].

provides the O(N) scaling necessary to handle such high particle counts more efficiently than traditional tree-based solvers. Additionally, the authors addressed memory constraints by employing a fixed-point integer format for particle positions, allowing high-precision spatial tracking without the prohibitive memory costs of standard floating-point formats, delivering a mass resolution of $3.2 \times 10^8\ h^{-1}\ M_\odot$ and a force resolution of $3.0\ h^{-1}$ kpc.

A LABORATORY FOR RARE STATISTICS

HM serves as an ideal laboratory for tail statistics, the rare, massive objects that inhabit the extremes of cosmic distribution. A primary highlight of the paper is the identification of analogues for Abell 2744 (Pandora's Cluster). Because of its complex, irregular substructures and intense merging activity, Abell 2744 has previously been cited as a potential challenge to the standard ΛCDM paradigm. By identifying multiple candidates that closely match the observed galaxy density, luminosity, and mass distribution of this cluster, the authors demonstrate that such peculiar systems are naturally occurring within the standard model when the simulation volume is large enough to sample the full diversity of the universe.

As flagship missions like Euclid,[2] the Nancy Grace Roman Space Telescope,[3] and the China Space Station Telescope (CSST)[4] begin producing unprecedented wide-field data, the demand for high-fidelity mock catalogues has never been more urgent. The HyperMillennium project meets this juncture by coupling massive volume with high resolution and a sophisticated semi-analytic galaxy formation pipeline. It proves that even the most extreme cosmic environments are well covered by current theory, providing a critical resource for the next decade of observational cosmology.

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AUTHOR CONTRIBUTIONS

Jiaxin Han drafted and revised the manuscript, contributed to it, and approved the final version.

DECLARATION OF INTERESTS

The author declares no competing interests.