Field-preserving Gaussian Splatting for Interactive Visualization of Large-Scale Cosmological Simulations

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***Abstract*—Large-scale cosmological simulations generate hundreds of millions of particles, making interactive visualization computationally expensive. Gaussian Mixture Models (GMMs) provide an efficient compressed representation of particle datasets, but existing GMM-based renderer incur additional computational overhead from depth-plane sampling and alpha compositing, while Gaussian splatting methods are designed for photorealistic rendering rather than scientific visualization. We present a field-preserving Gaussian splatting framework that combines GMM compression with orthographic projection and GPU tile-based rasterization to reconstruct additive particle density and continuous scalar attributes directly from compressed Gaussian representations. Built on the gsplat framework, the proposed renderer executes entirely on the GPU for interactive visualization. Experiments on the Illustris-3 (94,196,375 particles) and HACC cosmological simulations (331,644,184 particles) achieve density PSNRs of 43.27 dB and 46.07 dB, respectively, while sustaining up to 92 FPS on an NVIDIA RTX A6000 GPU.**

***Index Terms*—Gaussian splatting, Gaussian mixture models, Cosmological simulations, Particle-based visualization, Field-preserving rendering.**

I. Introduction

Large-scale cosmological simulations such as Illustris and HACC generate hundreds of millions to billions of particles together with multiple physical attributes, making interactive visualization computationally demanding. Gaussian Mixture Models (GMMs) provide an efficient compressed representation by approximating particle distributions with a compact set of Gaussian primitives. However, existing GMM-based renderers rely on depth-plane sampling and alpha compositing [1], introducing additional rendering overhead, while existing Gaussian Splatting (GS) methods are optimized for photorealistic rendering rather than preserving physically meaningful scientific fields [2].

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We present a field-preserving Gaussian splatting framework for interactive visualization of compressed cosmological particle datasets. Our contributions are:

- A GPU-accelerated field-preserving Gaussian splatting framework for compressed cosmological particle visualization.
- A conditional Gaussian rasterization formulation that reconstructs additive particle density and continuous scalar attributes directly from Gaussian representations.
- A customized tile-based gsplat renderer that eliminates depth-plane compositing and enables interactive visualization of datasets containing hundreds of millions of particles.

II. Method

Our framework consists of three stages: (1) Gaussian mixture compression, (2) orthographic projection, and (3) GPU-based field-preserving Gaussian splatting. The Gaussian mixture construction follows the GMM fitting method of [1]. Starting from particle positions $\mathbf{x}_i$ and scalar attributes a_i, the dataset is recursively partitioned using a k-d tree, and each leaf is independently fitted with a small Gaussian Mixture Model (GMM). Each Gaussian stores the joint statistics of spatial position and scalar attributes, providing a compact representation of the original particle distribution.

During rendering, Gaussian primitives are projected onto the image plane using an orthographic camera and organized into screen-space tiles for efficient GPU rasterization. Unlike conventional Gaussian splatting, which performs alpha compositing, our method reconstructs additive particle density through

$$D(\mathbf{u}) = \sum_{k=1}^{K} M_k G_k(\mathbf{u}), \tag{1}$$

TABLE I
RECONSTRUCTION QUALITY AT 1024^2 AND RENDERING PERFORMANCE ACROSS RESOLUTIONS. PERFORMANCE IS REPORTED AS RENDERING TIME (MS)/FPS. BOTH MODELS USE A 1% TARGET RATIO.

Dataset	D-P	D-S	A-P	A-S	1K	2K	4K
Illustris-3	43.27	0.9862	44.21	0.9906	4.30/92.29	10.36/50.25	33.18/18.00
HACC	46.07	0.9884	32.79	0.9588	7.73/49.03	19.51/25.62	61.98/8.92

D-P/D-S: density PSNR/SSIM; A-P/A-S: attribute PSNR/SSIM.

where M_k denotes the particle mass represented by the k-th Gaussian and $G_k(\mathbf{u})$ is its projected Gaussian kernel.

Scalar attributes are reconstructed using the conditional Gaussian prediction,

$$A(\mathbf{u}) = \frac{\sum_{k=1}^{K} M_k G_k(\mathbf{u}) m_k(\mathbf{u})}{\sum_{k=1}^{K} M_k G_k(\mathbf{u})}, \tag{2}$$

where $m_k(\mathbf{u})$ is the conditional expectation of the scalar attribute. We build upon the CUDA-based rasterization pipeline provided by `gsplat`, extending its rendering kernels to support additive particle density accumulation and conditional scalar attribute reconstruction.

III. EXPERIMENTAL RESULTS

We evaluate the proposed renderer on the **Illustris-3** and **HACC** cosmological particle datasets using an NVIDIA RTX A6000 GPU. Rendering quality is measured against particle-based ground truth using Peak Signal-to-Noise Ratio (PSNR) and Structural Similarity Index (SSIM). Performance is averaged over 50 frames following five GPU warm-up frames. Rendering time reports the conditional rasterization stage, whereas FPS is computed from the complete end-to-end frame time.

A. Illustris-3 Reconstruction

Illustris-3 contains approximately 9.4×10^7 dark matter particles with the *SubfindVelDisp* attribute. At a 1% target ratio, the dataset is represented by 524,288 Gaussian primitives. As shown in Fig. 1, the proposed renderer preserves filamentary density structures and the corresponding velocity-dispersion field. It achieves density and attribute PSNRs of 43.27 dB and 44.21 dB, respectively, while sustaining 92.29 FPS at 1024^2.

B. HACC Scalability

HACC *m000* contains approximately 3.3×10^8 particles and is represented by 1,048,576 Gaussians at a 1% target ratio. Figure 2 shows that the compressed representation preserves large-scale cosmic-web density structures and particle velocity magnitude. The renderer achieves density and attribute PSNRs of 46.07 dB and 32.79 dB, respectively, while sustaining 49.03 FPS at 1024^2.

Overall, the results demonstrate high-fidelity reconstruction of scientific fields together with interactive visualization of cosmological simulations containing hundreds of millions of particles.

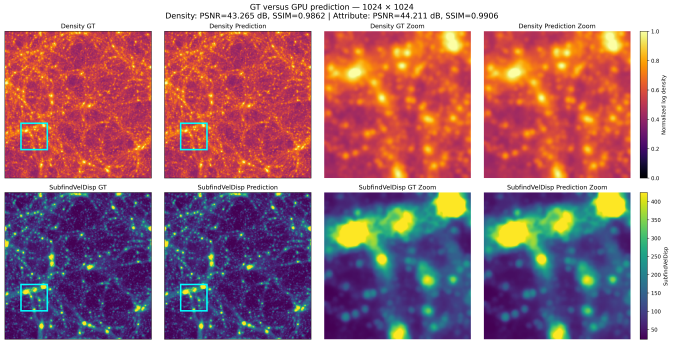


Fig. 1. Illustris-3 density (top) and *SubfindVelDisp* (bottom) reconstruction at 1024^2. From left to right: particle ground truth, Gaussian reconstruction, and enlarged comparison.

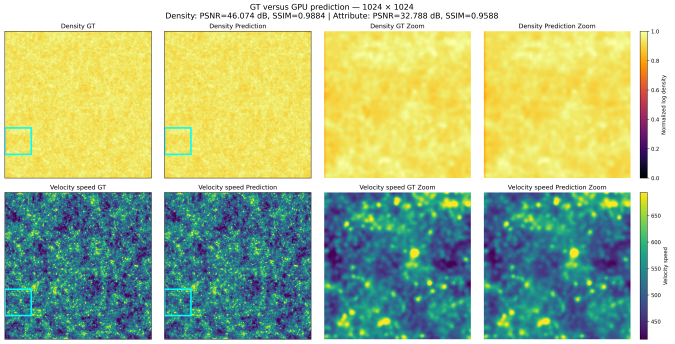


Fig. 2. HACC density (top) and velocity-magnitude (bottom) reconstruction at 1024^2. From left to right: particle ground truth, Gaussian reconstruction, and enlarged comparison.

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IV. CONCLUSION

We presented a field-preserving Gaussian splatting framework for compressed cosmological particle visualization. Our customized `gsplat`-based renderer enables accurate density and scalar attribute reconstruction with interactive performance. Future work will investigate time-varying datasets and multi-GPU rendering.

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