VSB TECHNICAL UNIVERSITY OF OSTRAVA | IT4INNOVATIONS NATIONAL SUPERCOMPUTING CENTER

BRIDGING COSMOLOGICAL SIMULATIONS AND HIGH-QUALITY VISUALIZATIONS USING HPC RESOURCES

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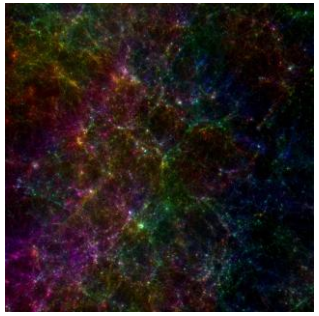
THE SPACE CENTRE OF EXCELLENCE

Scalable Parallel Astrophysical Codes for Exascale (SPACE)

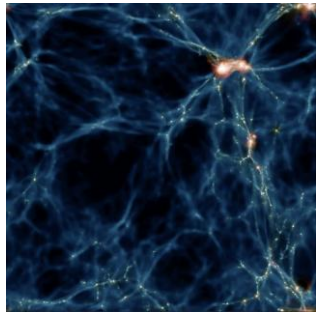
- EU **Centre of Excellence** focused on **Astrophysical and Cosmological (A&C)** applications
- Extensively **re-engineer** A&C codes for the efficient and effective exploitation of exascale computing capabilities
- High-performance **data analysis** of the data torrent produced by exascale A&C simulation applications with **machine-learning** and **visualization** tools.

OpenGADGET



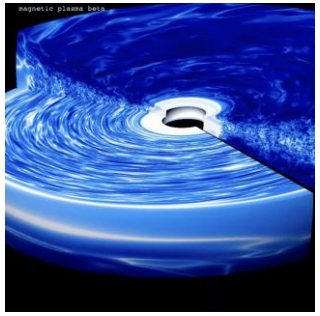
cosmological simulations

CHANGA



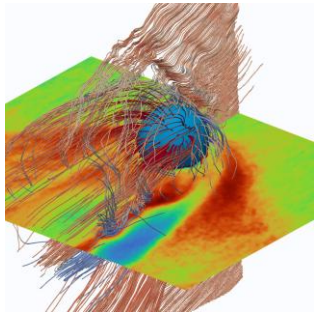
magneto hydro dynamics code

PLUTO



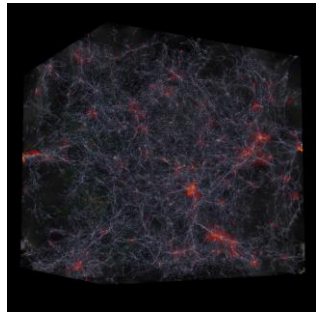
astrophysical plasma simulations

iPic3D



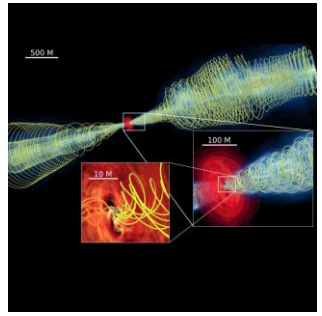
plasma physics

RAMSES



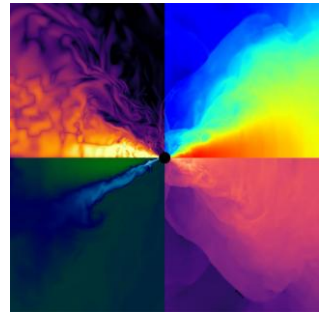
AMR cosmological simulations

BHAC



Black Hole accretion

FIL



general-relativistic MHD

Source: Nicola Tuccari et.al., High Performance Visualization for Astrophysics and Cosmology, PDP 2025

OPEN-30-28 - OVERVIEW

Scalable Parallel Astrophysical Codes for Exascale (SPACE)

- Multiyear - Karolina GPU (9 000NH), Karolina CPU (50 000NH), LUMI-G (7 000NH), LUMI-C (40 000NH), …

Energy Efficiency

- Analyze and optimize A&C applications on Karolina and Barbora supercomputers
- Use MERIC runtime system (developed under H2020 READEX) for energy efficiency assessment and tuning

Performance Optimization

- Assess astrophysics codes with Extrae, Paraver, and POP methodology
- Provide optimization feedback to code owners and re-evaluate performance
- GPU porting: feasibility study, design, and performance analysis using BSC, NVIDIA, and AMD tools

Visualization

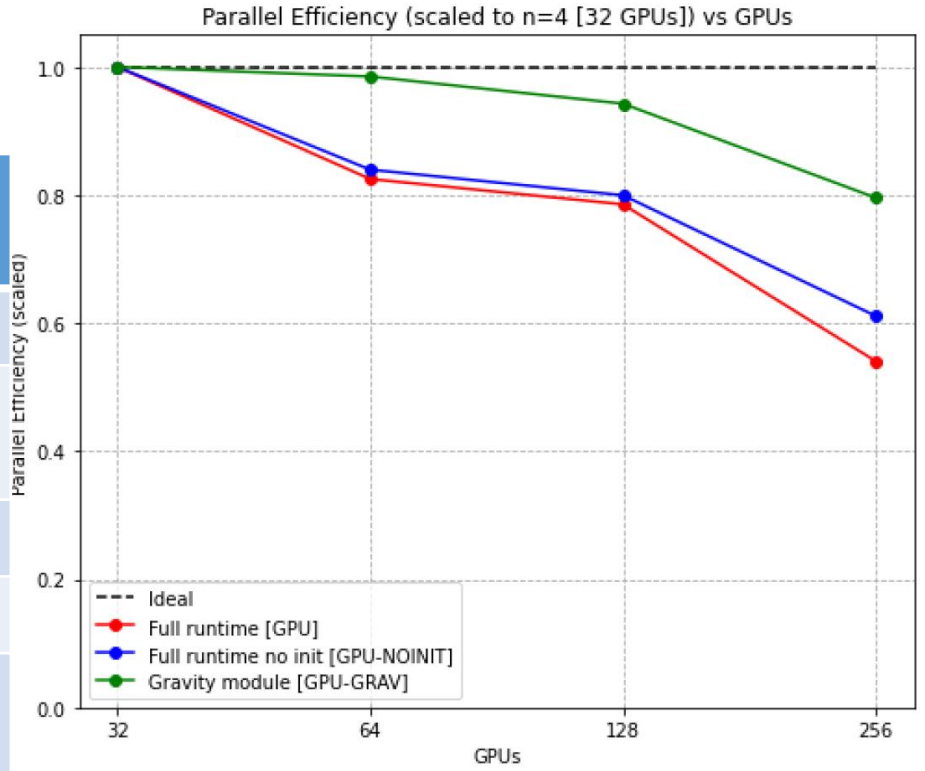
- Handle large-scale simulation outputs (TB–PB range)
- Develop interactive visualization workflow using:
  - Sparse volumetric formats
  - Blender for interaction
  - Path-tracing via CyclesPhi HPC renderer

OPEN-30-28 - RESULTS

Performance & Optimization Highlights

- **Goal**: assess performance and energy efficiency of selected astrophysics codes
- **The example of the achieved speedups**:

Code	Max Speedup (GPU vs CPU)	Key Region / Note
Pluto	2.5 – 5x	Boundary region
RAMSES	1.55x	Whole code, Poisson solver
ChaNGa	3.4x	Gravity-Hydro region
iPic3D	4x	Field solver
BHAC	3.3x	Riemann solver (early GPU port)
OpenGadget3	4x	Domain decomposition



ChaNGa: GPU scaling tests for the cosmological box case performed on the Karolina supercomputer

OPEN-30-28 - RESULTS

The example of the evaluation of Energy Efficiency

- ChaNGa: The results of energy consumption and static frequency tuning measurements in the **Grace CPU system.**

Set CPU frequency [GHz]	Runtime [s]	Runtime extension	Average power consumption of the node [W]	Node energy consumption [kJ]	Compute node energy savings	MFLOPS/W	
0,00	369,0	100,0%	614,5	226,8	0,0%	1239,8	
3,30	374,0	101,4%	597,7	223,6	1,4%	1257,6	
3,10	378,0	102,4%	502,9	190,1	16,2%	1478,9	16.2% energy savings; 2.4% runtime extension
2,90	405,0	109,8%	440,9	178,6	21,3%	1574,5	
2,70	429,0	116,3%	391,7	168,1	25,9%	1673,0	
2,50	493,0	133,6%	343,6	169,4	25,3%	1659,7	
2,30	499,0	135,2%	317,5	158,4	30,1%	1774,7	30.1% energy savings; 35.2% runtime extension
2,10	545,0	147,7%	290,6	158,4	30,1%	1774,9	
1,90	620,0	168,0%	267,1	165,6	27,0%	1697,5	
1,70	687,0	186,2%	257,5	176,9	22,0%	1589,4	
1,50	743,0	201,4%	251,2	186,6	17,7%	1506,5	
1,30	832,0	225,5%	244,5	203,4	10,3%	1382,2	
1,10	984,0	266,7%	235,9	232,2	-2,4%	1211,1	
0,90	1201,0	325,5%	227,2	272,9	-20,3%	1030,2	

DATA VISUALIZATION

- Over the years, the A&C domain has developed a set of ad-hoc tools and software modules to tackle **data processing**.
- Some of these components become candidates to be replaced by either **faster**, **more accurate**, or **more efficient** data-driven technologies based on **high-performance visualization**.
- Collected **requirements** in SPACE CoE include:
  - load directly from **simulations' computing infrastructure** to reduce data-movement overheads
  - load **directly** from the **simulation** to avoid data duplication (in-situ)
  - **interactive** multi-dimensional visualization
  - handling of different specific **data formats**
  - **cinematic visualizations**

Source: Nicola Tuccari et.al., High Performance Visualization for Astrophysics and Cosmology, PDP 2025

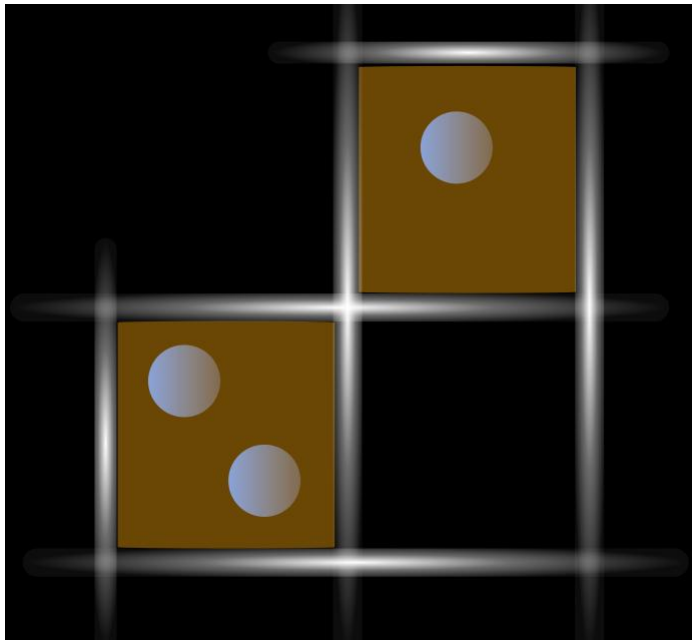
VISUALIZATION CHALLENGE

Challenge:

- Astrophysical and cosmological simulations generate **massive datasets** (terabytes–petabytes), making it difficult to efficiently **visualize and extract insights**

Solution:

- Volume rendering
- Cinematic visualization style
- High-performance, scalable pipeline with Blender and Cycles
- Use of standardized VDB format
- Custom Blender add-on using HPC resources



Voxelization: Particles → Voxels

Source: Nicola Tuccari et.al., High Performance Visualization for Astrophysics and Cosmology, PDP 2025

CURRENT DEVELOPMENT OF TOOLS

Blender (BSpace addon)

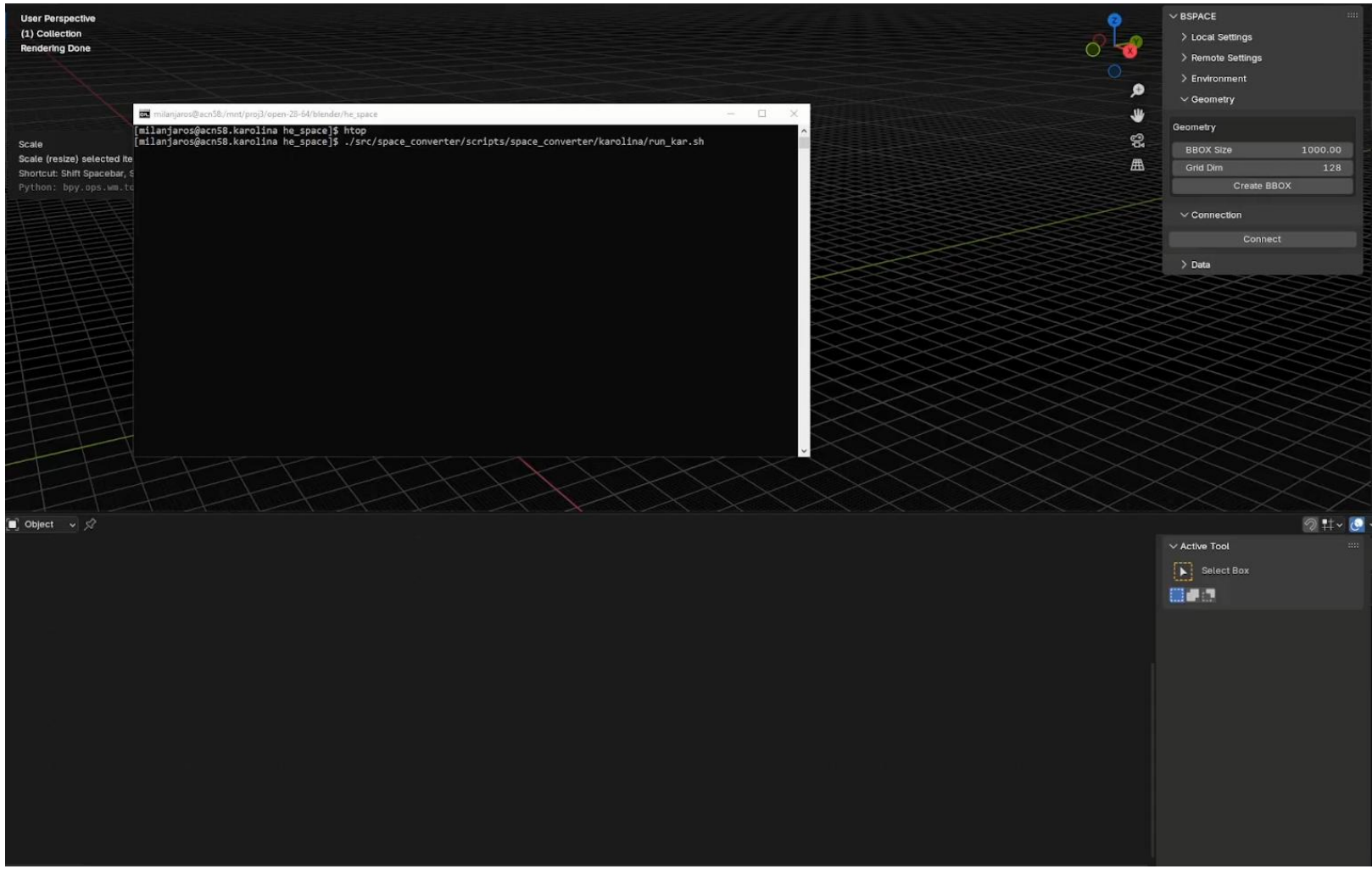
- GUI
- Interacts with converter
- https://github.com/It4innovations/space-converter

Converter (Space Converter):

- Loads data from disk to CPU memory
- Reduces data - voxelization to VDB (volume)
- Sends VDB from server to renderer
- https://github.com/It4innovations/space-converter

Renderer (Blender Cycles/CyclesPhi)

- Modes: part of Blender/remote on cluster
- Imports VDB
- Renders VDB using path-tracer method
- Sends rendered image to Blender
- https://github.com/it4innovations/cyclesphi



Source: Nicola Tuccari et.al., High Performance Visualization for Astrophysics and Cosmology, PDP 2025

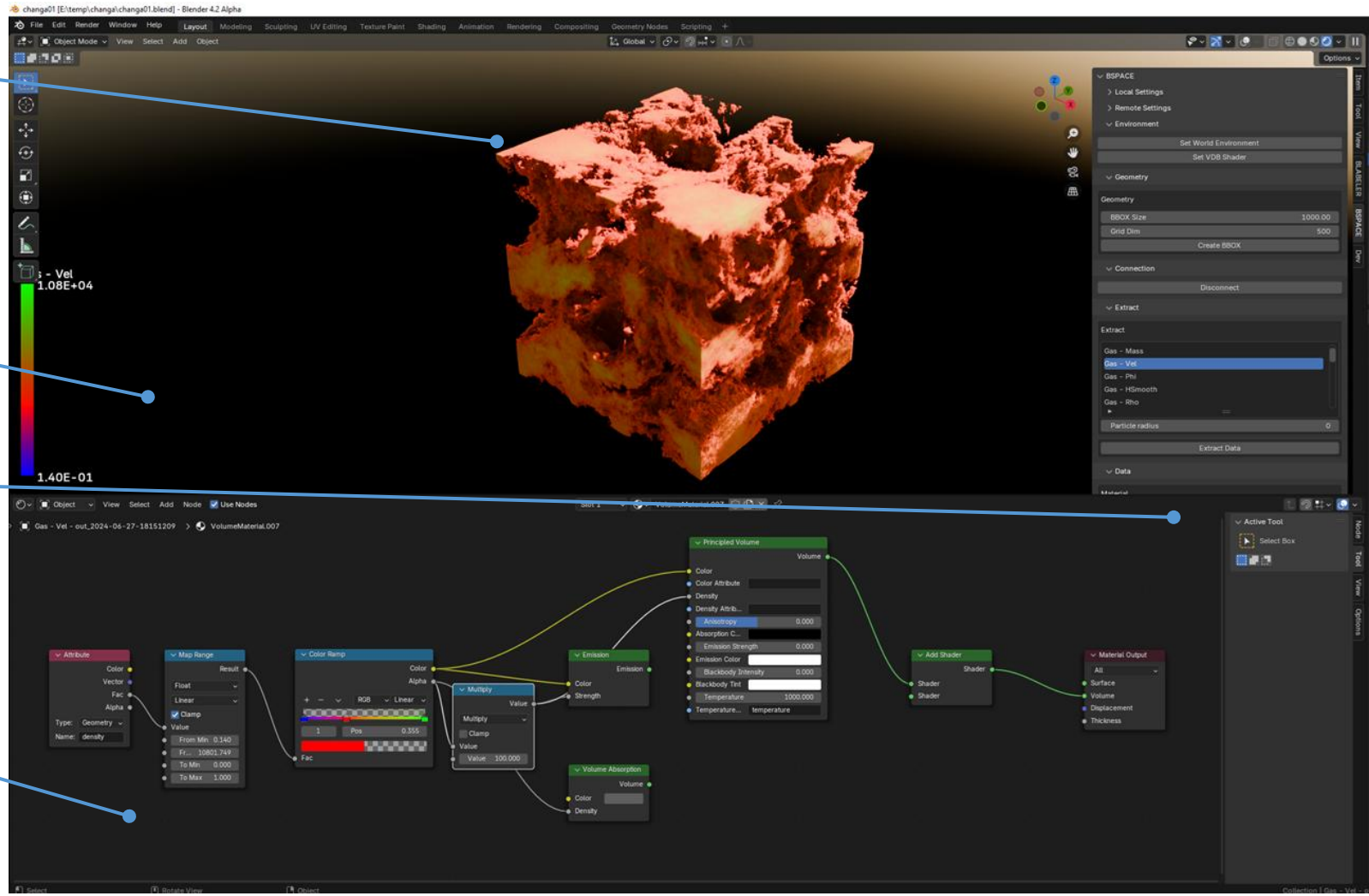
TOOLS: BSPACE

Cosmological box
- ChaNGa (NChilada format, velocity)
- Particles: 12B → Voxels: 15M

Blender Cycles
- Path-tracer renderer

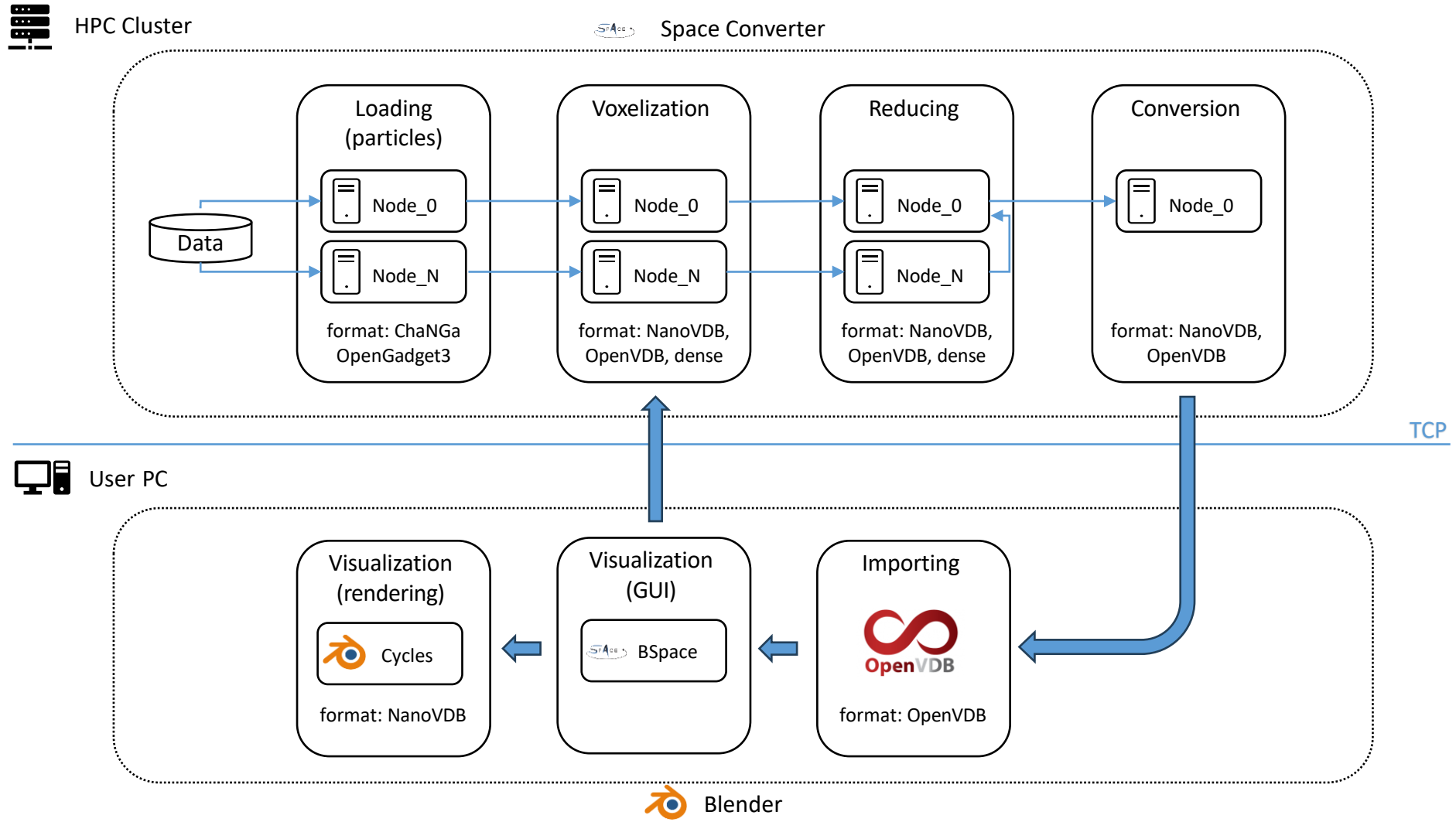
BSPACE addon
- Interact with Space Converter

Advanced shaders
- Shader editor

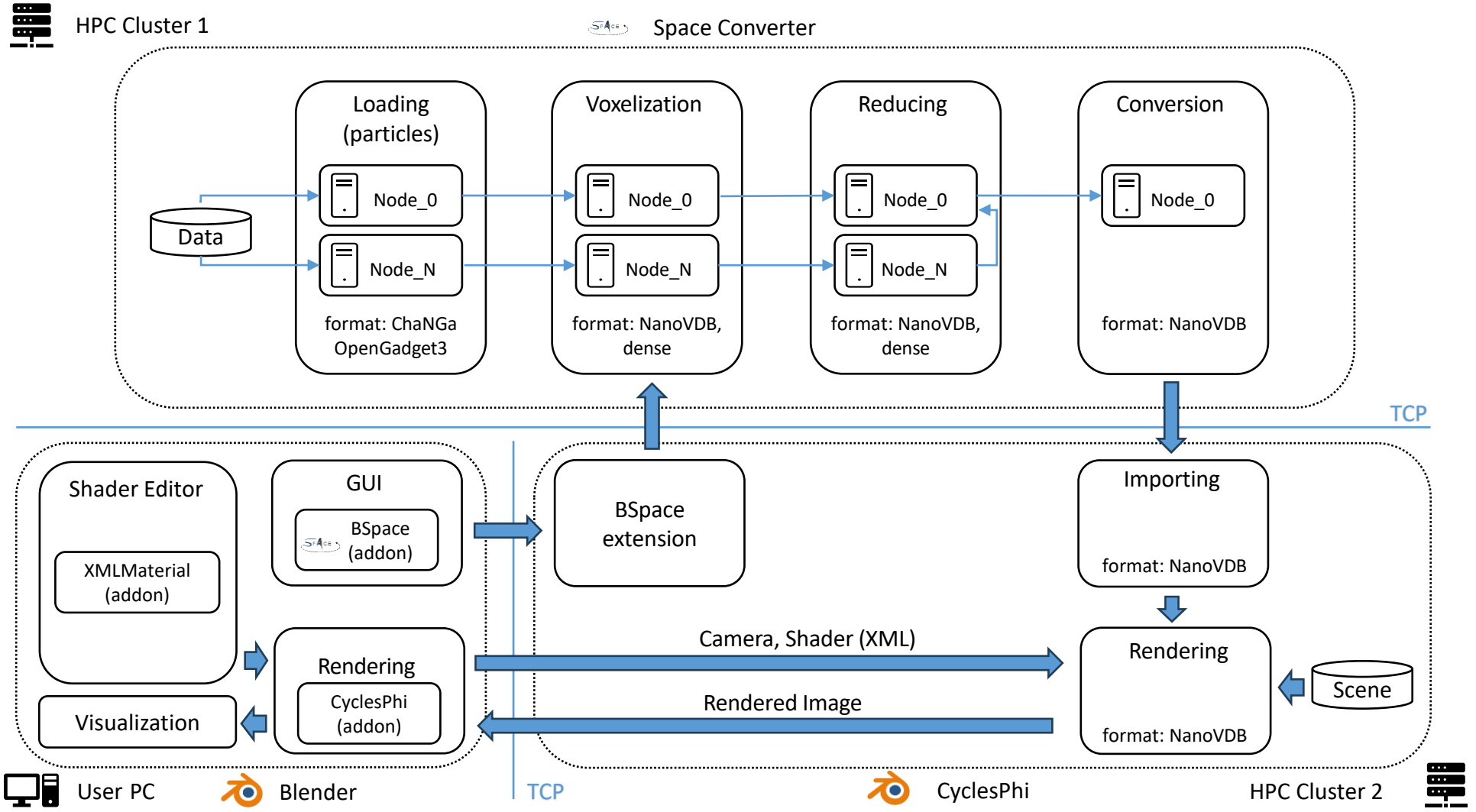


Source: Nicola Tuccari et.al., High Performance Visualization for Astrophysics and Cosmology, PDP 2025

PIPELINE: LOCAL RENDERING



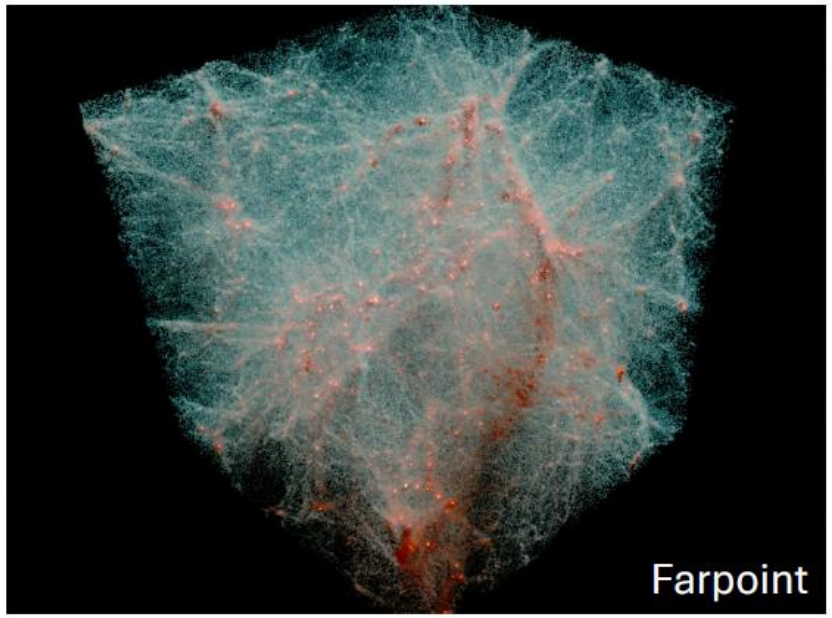
PIPELINE: REMOTE RENDERING

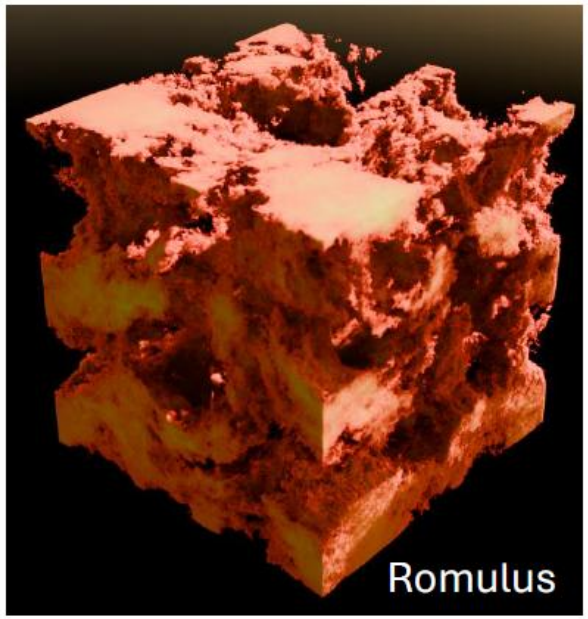


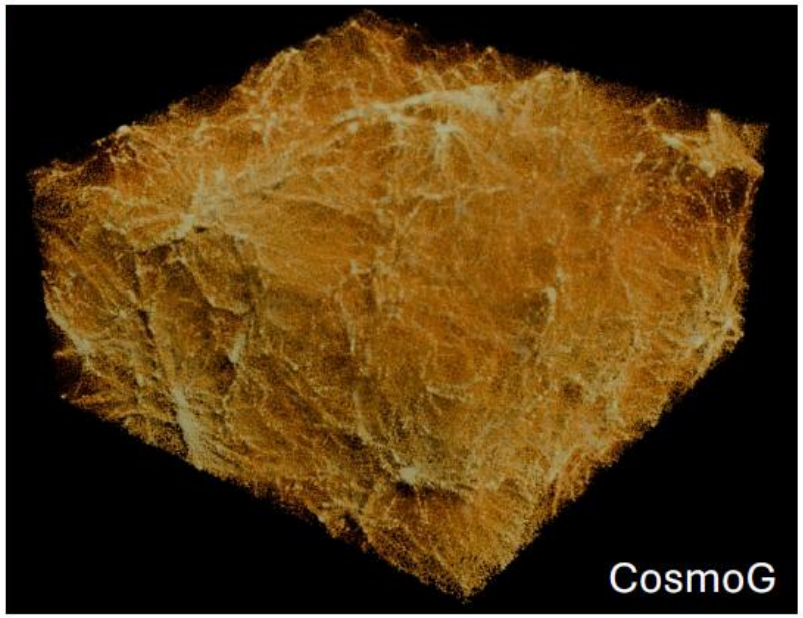
PERFORMANCE TESTS

Datasets

Dataset	#Particles	Format	#Files	Size on disk
Farpoint (HACC)	18 billion	GENERICIO	64	439 GB
Romulus (ChaNGa)	12+12 billion	NChilada	4	547 GB
CosmoG (OpenGADGET)	67 billion	FORMAT2	256	2 TB

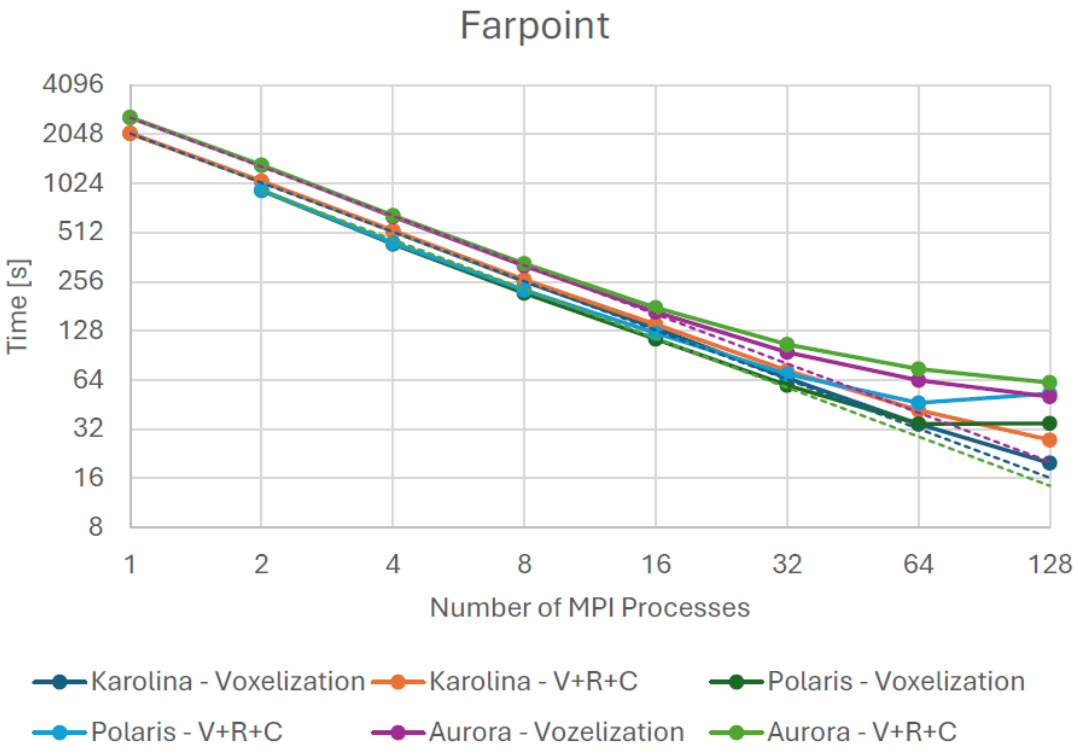


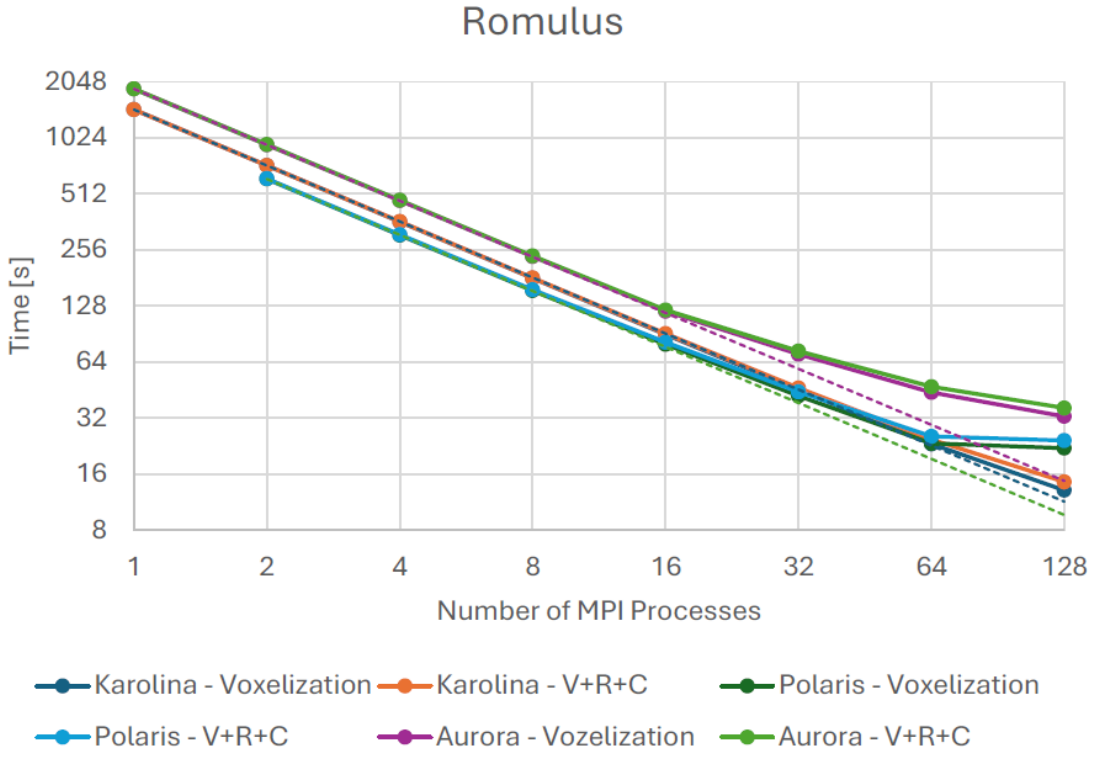




PERFORMANCE TESTS

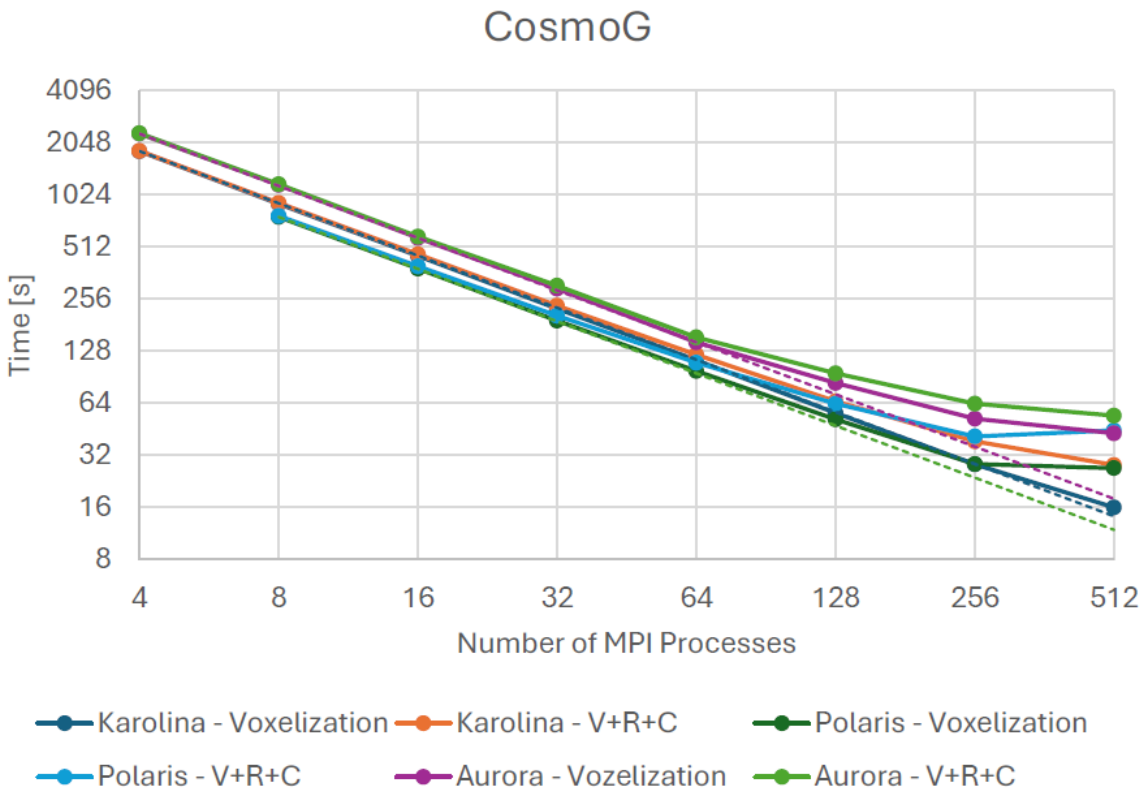
- The scalability performance of voxelization (V), reduction (R), and conversion (C) into a volumetric format.
- One node was used on Karolina and Aurora, while two nodes were used on Polaris.





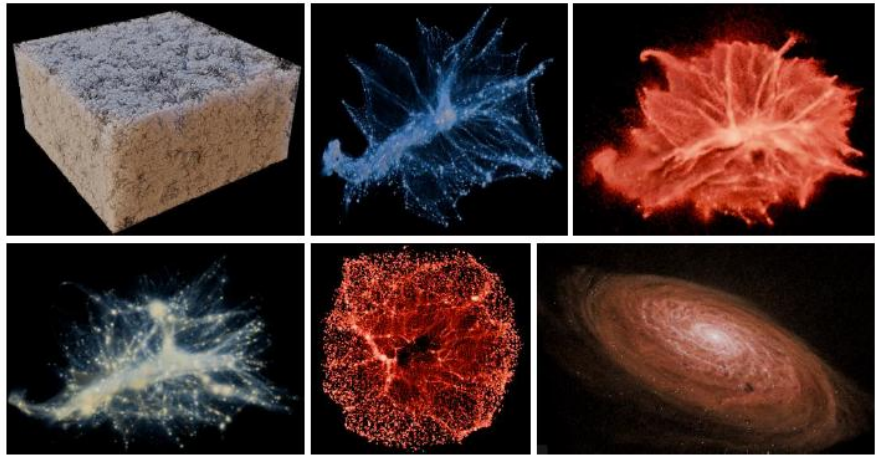
PERFORMANCE TESTS

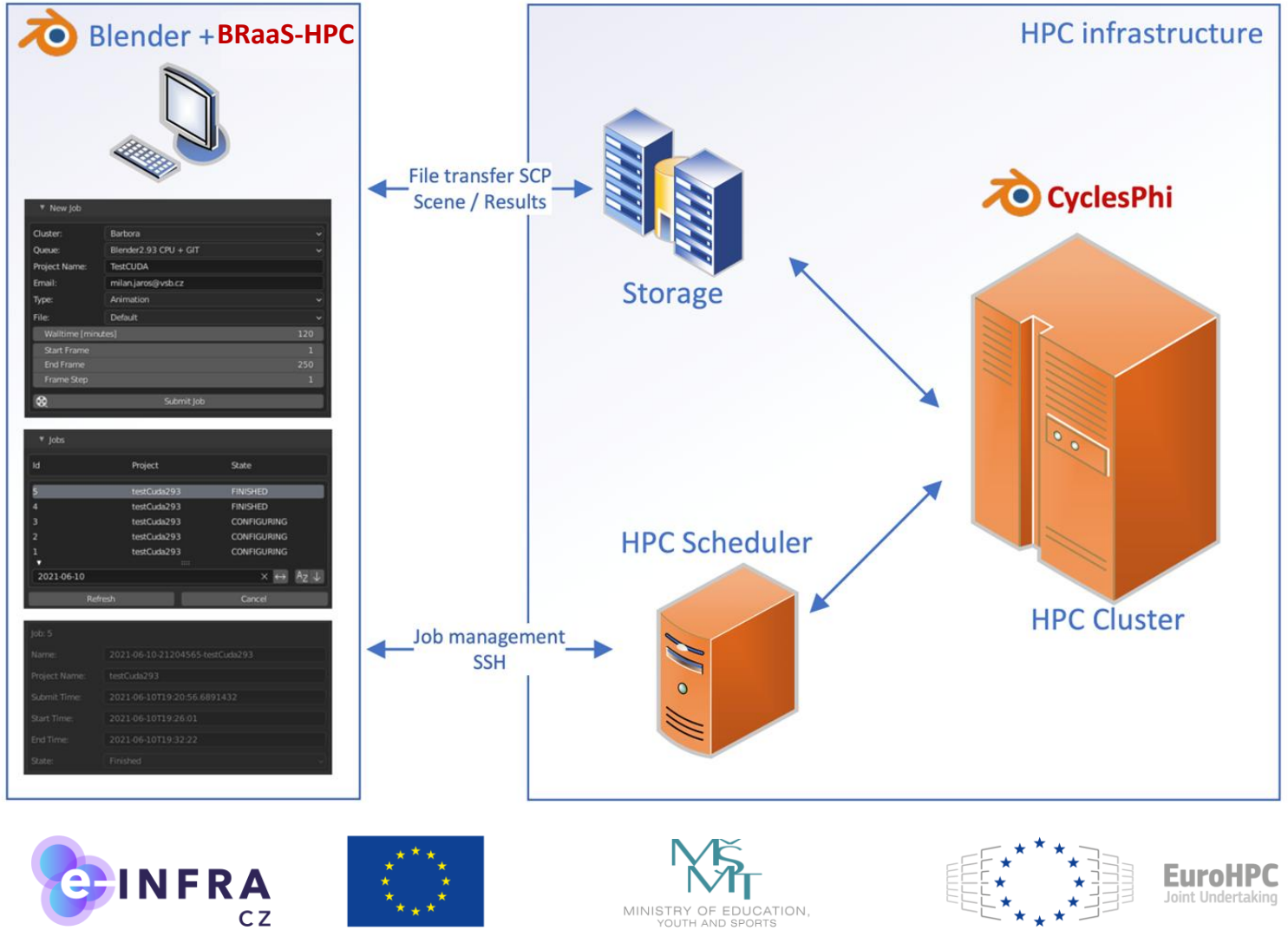
- The scalability performance of voxelization (V), reduction (R), and conversion (C) into a volumetric format.
- Four nodes were used on Karolina and Aurora, while eight nodes were used on Polaris.



RENDERING-AS-A-SERVICE

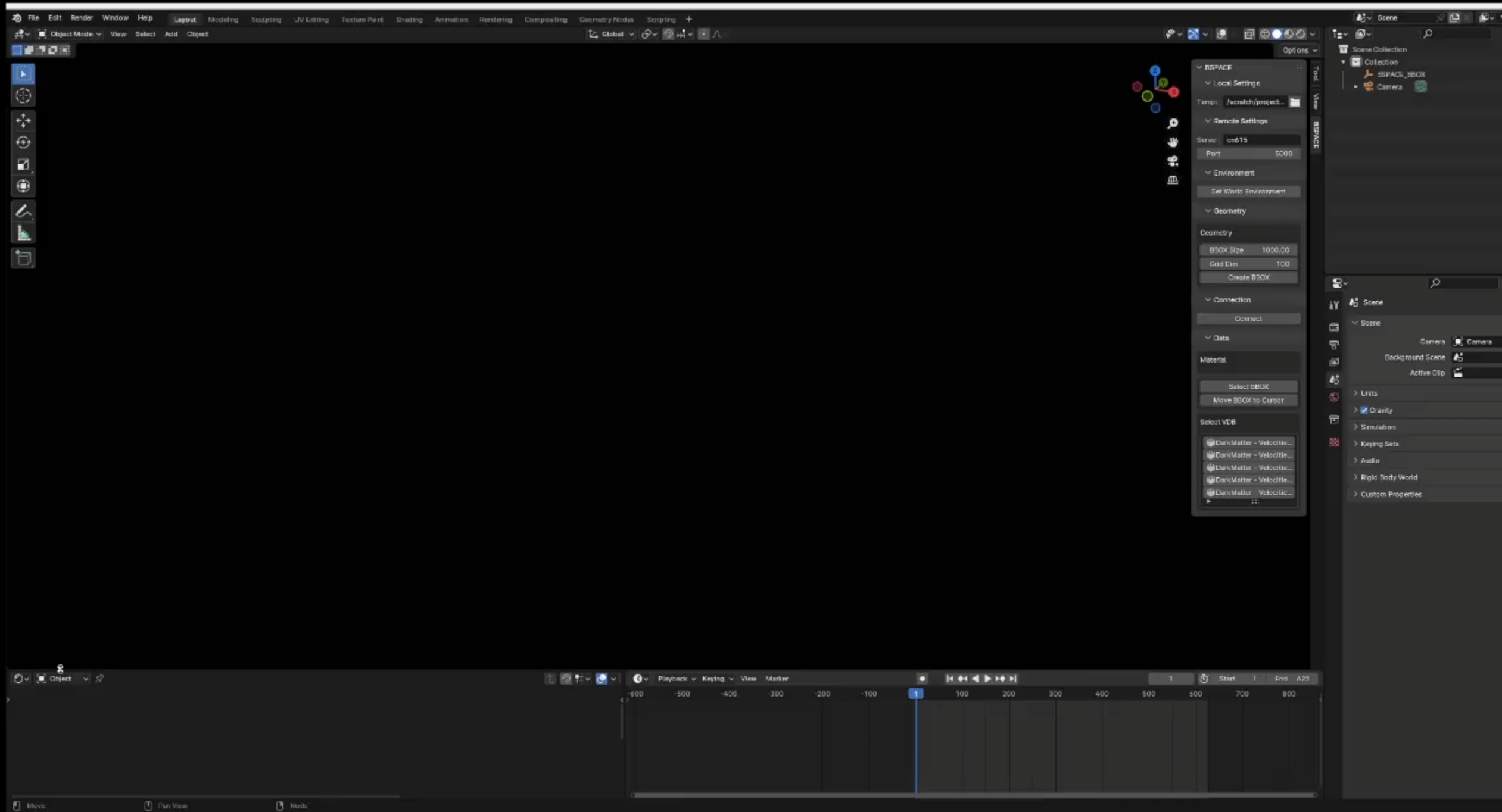
- Photorealistic rendering of 3D scenes
- Rendering on remote computing resources
- Use of HPC resources for rendering
- Support for educational visualization tools

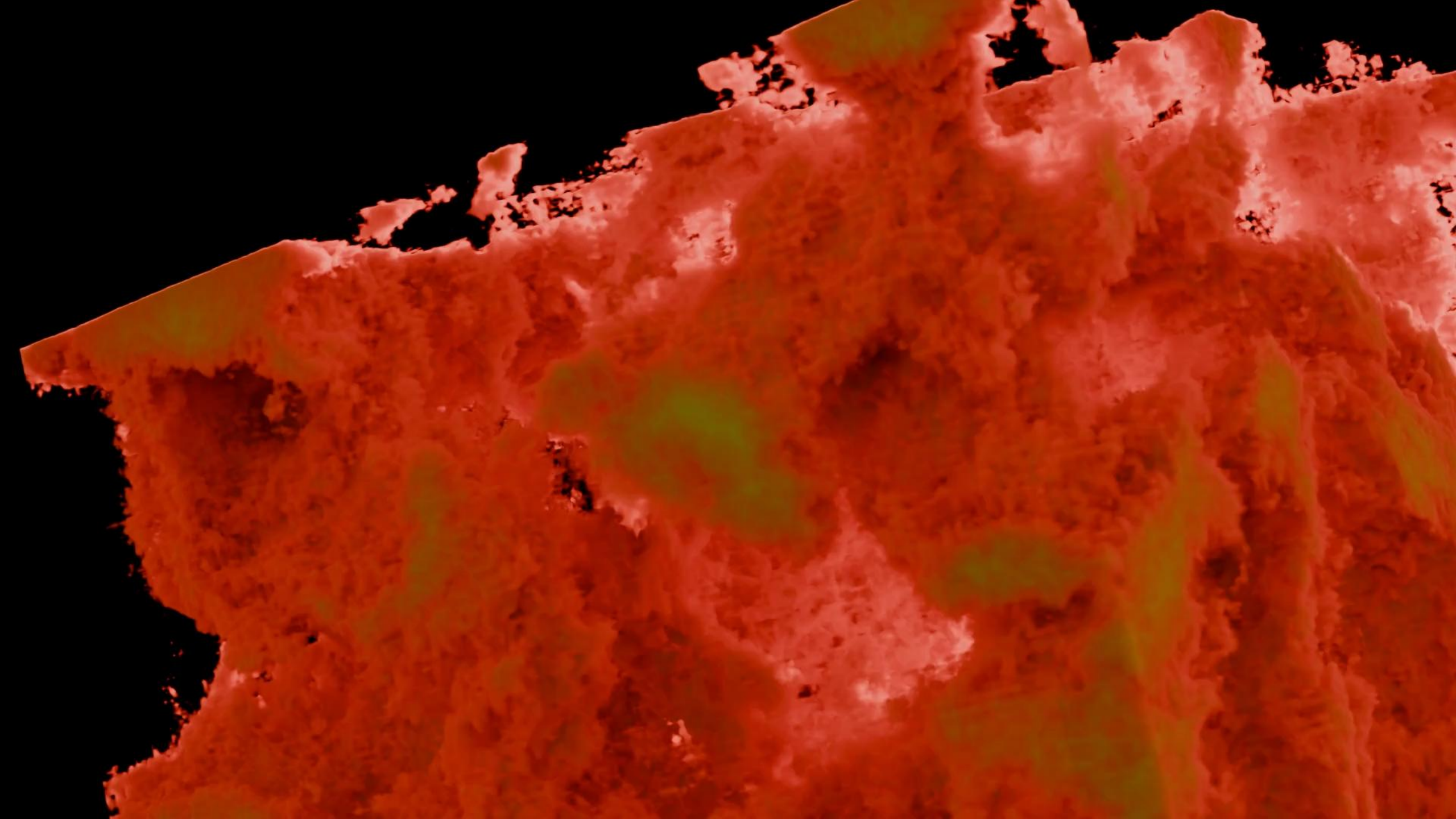


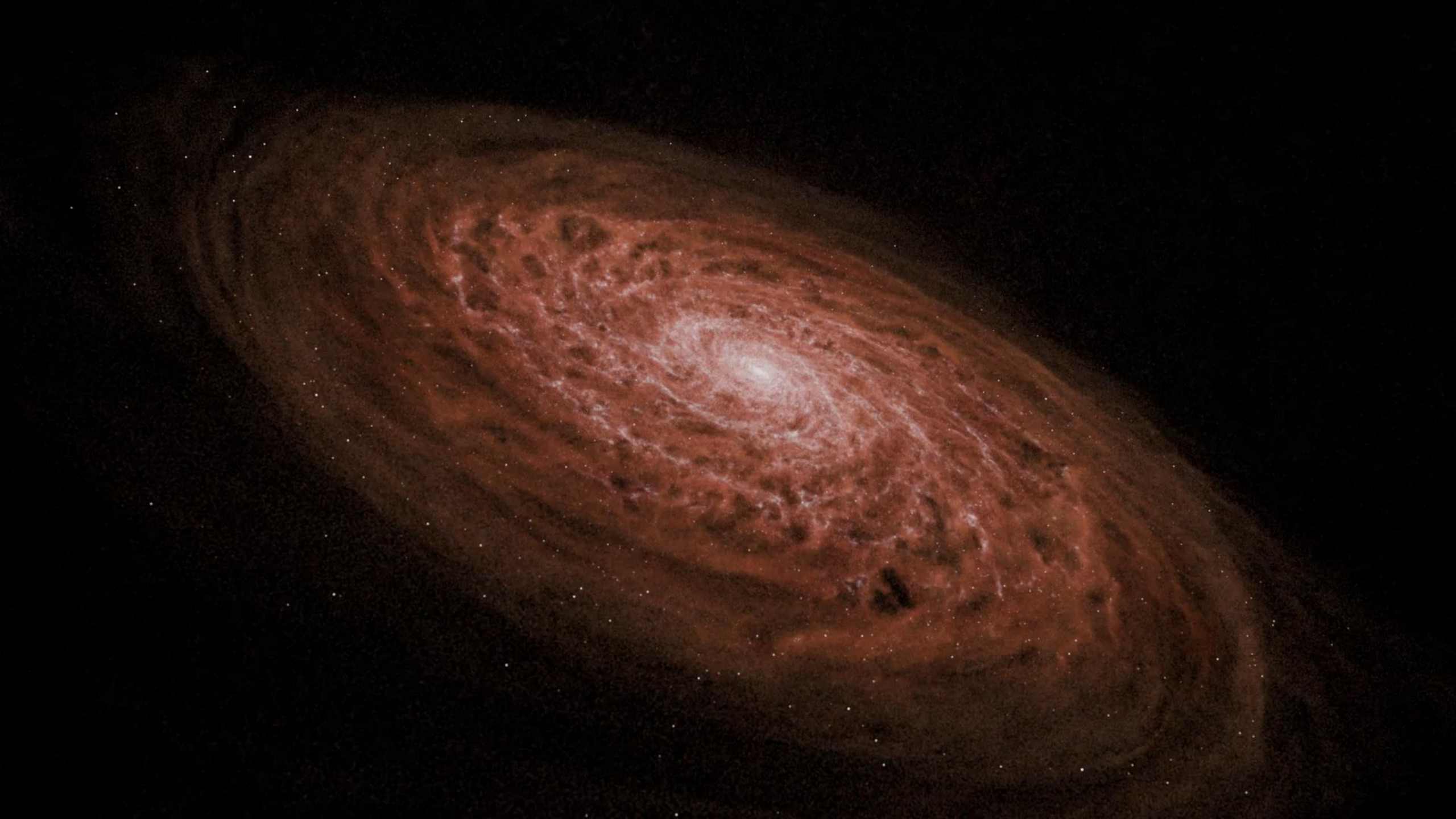


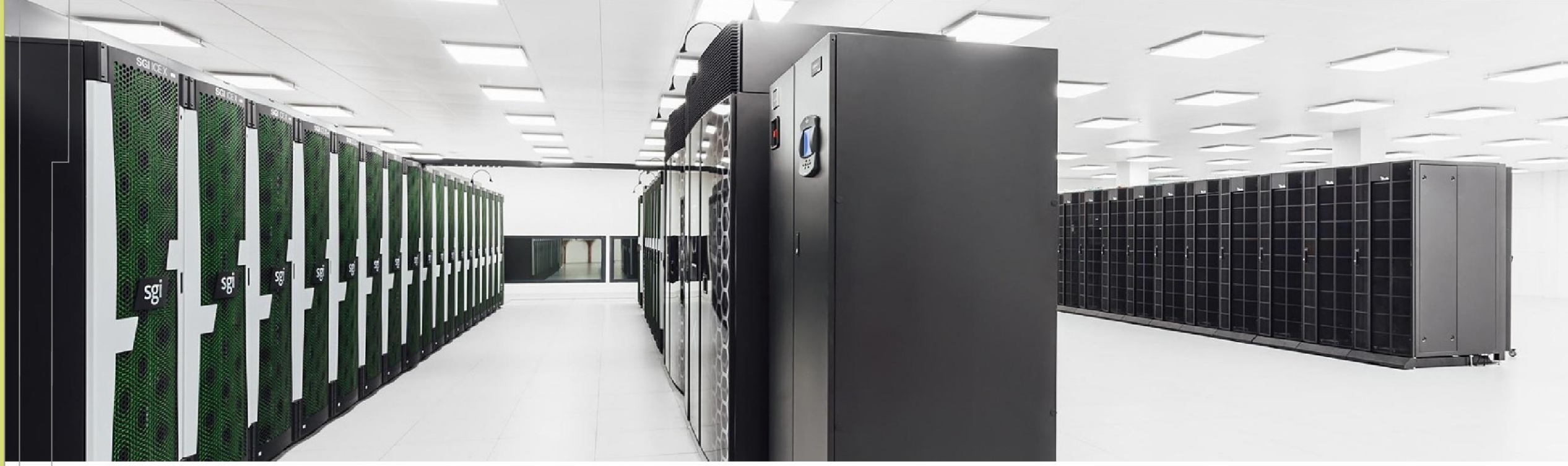
BRaaS-HPC: https://github.com/It4innovations/braas-hpc/

Multiple Timesteps









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