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Visualization of numerical simulations of astrophysical and fusion plasmas with the SDvision code

B. Thooris, D. Pomarède

On behalf of the COAST project team

IRFU, Institut de recherche sur les lois fondamentales de l'Univers

CEA Saclay, 91191 Gif-sur-Yvette CEDEX France

Abstract

The new generation of massively parallel mainframes enabled computational physics to make a quantum leap in complexity and size of numerical simulations, especially in the domain of astrophysics. The COAST project at CEA/IRFU at Saclay, started in 2005, involves astrophysicists and software engineers developing simulation codes in magneto-hydrodynamics and generic tools for data structuration and visualization. A dedicated software for visualizing the massive amounts of data produced by these simulation codes has been developed, the SDvision code, deployed in the framework of IDL Object Graphics. This code is suitable for interactive and immersive navigation for the analysis of 3D results and also for videos and stereoscopic movies productions for people at large.

In this paper, we present the capabilities of the code SDvision and some applications in the domain of astrophysics simulations but also in the domain of fusion plasmas studies. In particular, two challenging simulations have been performed in the framework of the 'Grands Defis GENCI/CINES' on recent supercomputer Jade in CINES in 2010 and we present the visualization studies for such huge computation results.

KEYWORDS: Astrophysics, plasma physics, visualization

1. Introduction

The COAST (for COmputational ASTrophysics) project [1][2][3][4] is a program of massively parallel numerical simulations in astrophysics, mixing astrophysicists and software engineers of CEA/IRFU institute. Computational astrophysics is clearly now a major activity in astrophysics and with the increasing computing power offered by massively parallel mainframes, simulation has become a major tool in the investigation of complex physical phenomena. The COAST team is developing 3D magneto-hydrodynamics codes suitable for studying different scales of the Universe. The scientific objective is the understanding of the formation of structures in the Universe, including the study of large-scale cosmological structures and galaxy formation, turbulence in interstellar medium, stellar magneto-hydrodynamics and proto-planetary systems.

* Corresponding author. Tel.: +33 169083386; fax: +33 169083147.
E-mail address: thooris@cea.fr.

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Due to the complexity, the geometry or the size of the simulations, the codes are using different numerical techniques, regular Cartesian meshes or structures such as Adaptive Mesh Refinement, spherical coordinates or multi-meshes embedded in the geometry. The post-treatment software, and in particular the visualizing software tool, must fulfil all these requirements, so a visualization code has been developed inside the COAST team: the SDvision code [5] , which will be described below. The capabilities of this code allowed us to visualize results of numerical simulation coming from other domains of physics, and the example of fusion plasmas simulations post-treatment is shown also in this paper.

2. The SDvision visualization tool

The visualization plays a very important role in the development of simulations codes. Fundamental aspects including domain decomposition, initial conditions, message passing and parallelization, treatment of boundary limits, can be controlled and evaluated qualitatively through visualization. Once in production phase, visualization is also used for the validation, the analysis and the interpretation of the results. A complete graphical interface named SD*vision* has been developed in order to participate in the development of the simulation codes and visualize the large astrophysical simulation datasets produced in the context of the COAST program.

2.1. SDvision functionalities

The SDvision graphical interface is implemented as an interactive widget as displayed in Fig. 1in its running state. It benefits from hardware acceleration through its interface to the OpenGL libraries, including GLSL shaders. SDvision has been developed in the framework of IDL Object Graphics [6][7]. IDL, the *Interactive Data Language*, is a firmly-established software for data analysis, visualization and cross platform application development. IDL provides a set of tools for developing object-oriented applications. A class library of graphics objects allows to create applications that provide equivalent graphics functionality regardless of the computer platforms.Fig.2. is giving an example of programming in IDL, an object-oriented based language.

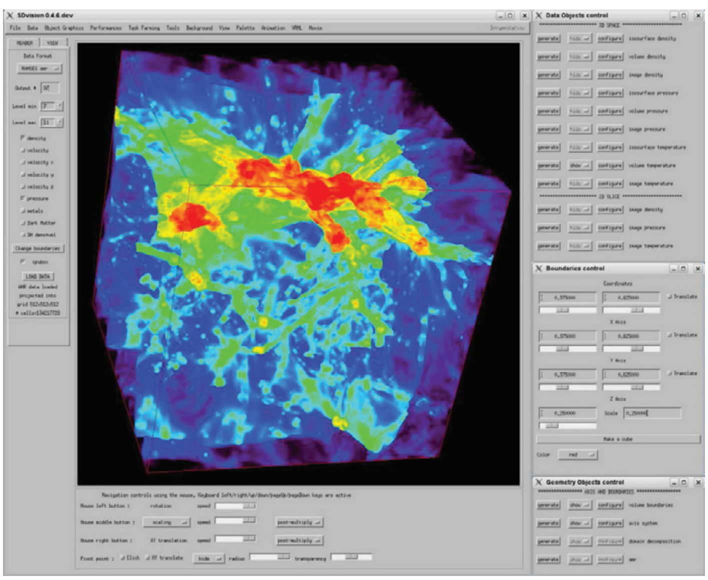


Fig. 1 Layout of the SDvision widget interface.

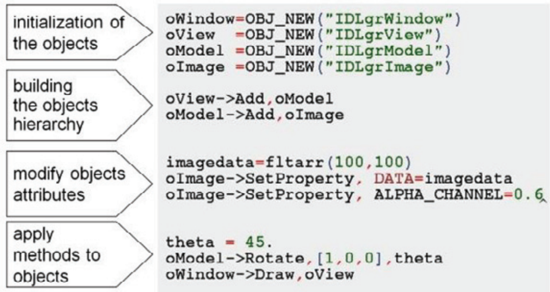


Fig. 2: An example of IDL programming in the 50000lines code SDvision.

Other powerful visualization codes exist and are widely used in the astrophysics community, for instance VISIT [8], VAPOR [9] and PARAVIEW [10]. We developed our own tool from scratch using IDL framework mainly for historical reasons: IDL is the dominant platform for analysis and visualization in the astrophysics community, and as a consequence, many home format reading and data handling modules were readily available; also, IDL provides mathematical and scientific libraries which help both simulations visualization and analysis. And even if using IDL needs licenses, it exits also a virtual machine mechanism for non-licensees users. About data formats, a migration to a unique HDF5 format is in progress, but specific readers for binary data are still needed.
Three-dimensional scalar and vector fields distributed over regular mesh grids or more complex structures such as adaptive mesh refinement data or multiple embedded grids, as well as N-body systems, can be visualized in a number of different, complementary ways. Various implementations of the visualization of the data are simultaneously proposed, such as 3D iso-surfaces, volume projections, hedgehog and streamline displays, surface and image of 2D subsets, profile plots, particle clouds. The difficulty inherent to the hybrid nature of the data and the complexity of the mesh structures used to describe both scalar and vector fields is enhanced by the fact that simulations are parallelized. Large-scale simulations are conducted on high-performance mainframes with potentially thousands of processors associated with a non-trivial domain decomposition.

On Fig. 3, we show an example of multi-objects visualization display: scalar fields (baryonic matter density), vector fields (baryonic velocity field) and particles (Dark Matter particle cloud).

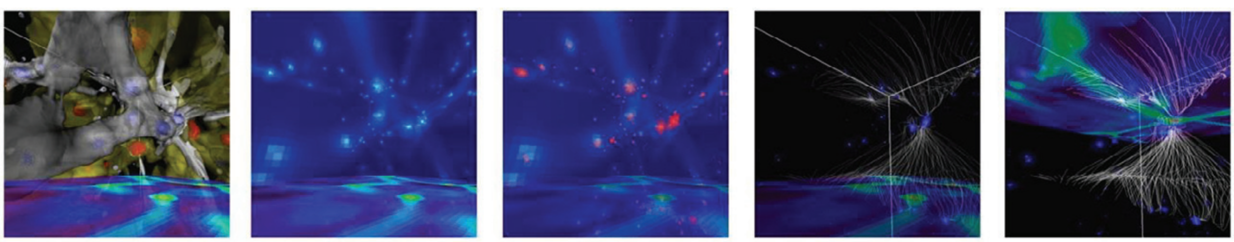


Fig. 3: simultaneous visualization of different cosmological data coming from a RAMSES simulation.

Parallelism is needed for the processing and the visualization of large data sets; some elements of parallelism are provided in IDL, for example we benefit from a multiple-CPU implementation of the IDLgrVolume class to render volume by ray-casting. Fig. 4 shows the performance on local machines for producing frames using different number of nodes; the test was done for this ray-casting algorithm on a 512^3 grid, producing 1024^2 images.

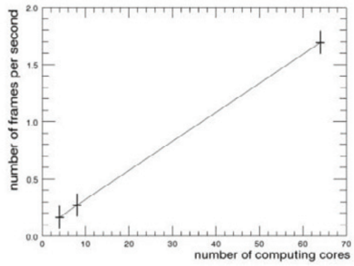


Fig. 4: comparison of frames per second computing performance using different multi-cores local machines.

In order to assess the performances and limitations of the ray-casting algorithms versus the size of the data, a benchmark test is conducted using a powerful graphics cluster with 512 GB shared memory and four octocore processors, amounting to 64 logical computing cores. In this benchmark test, a datacube of bytes with size n^3 is rotated and produce 1024^2 images. The average fps (frames per second) and the RAM used in this process is presented in Fig. 5. The algorithm stands up to the highest available memory, enabling visualization of grid up to nearly 8000^3. The frame rate decreases roughly as the inverse of the cube size.

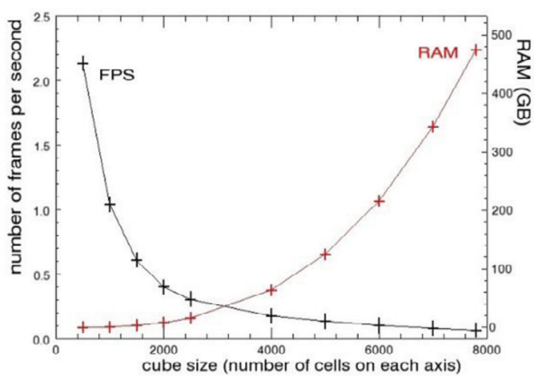


Fig. 5: Performances of the ray-casting algorithm versus the size of the visualized datacube

2.2. *AMR processing*

The analysis of results from complex MHD and N-body AMR-Octree code for cosmological simulations (See part 3.1) implies two steps of processing as we need Cartesian grids as input for multithreading processing. The management of the memory is shown on Fig. 6 and an example of data extraction can be found in Fig. 7. The highest levels of the AMR resolution are reached by successive and synchronous spatial and resolution zooms, using an interactive definition of the sub-volume in which the AMR extraction is performed. New algorithms are studied for direct reconstruction of images from the AMR-Octree structures, to avoid using intermediate Cartesian grids.

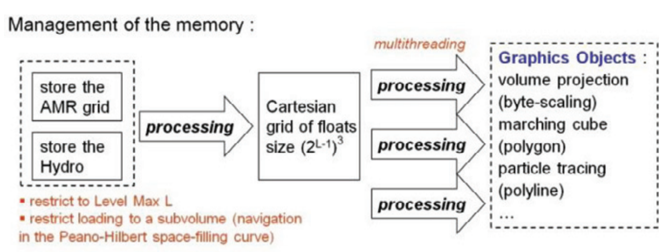


Fig. 6: Management of the memory in the case of AMR octree code data extraction

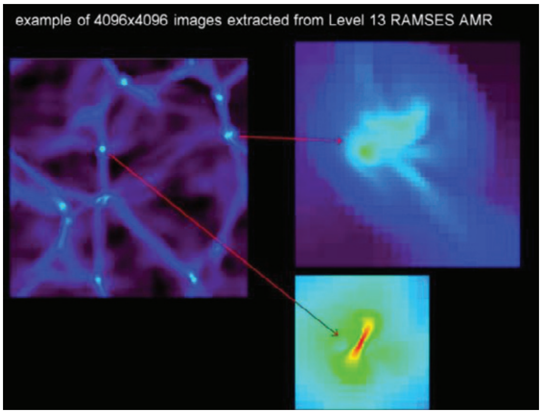


Fig. 7: example of images extracted from high level AMR structure

2.3. *Multi-grid processing*

In order to visualize data resulting from multi-grids codes, such as the Jupiter code[11], a special module has been developed in SDvision, an example of such image is shown on Fig. 8.

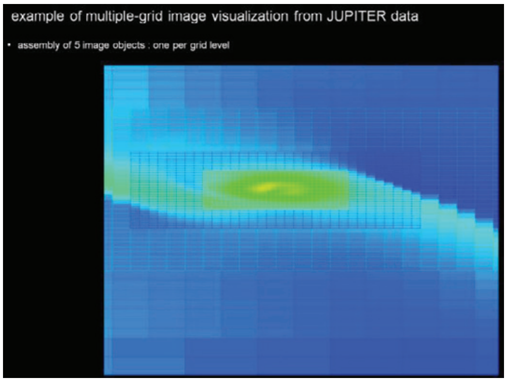
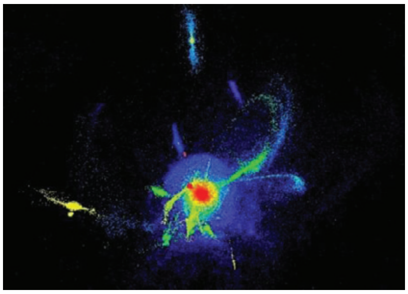


Fig. 8: example of images extracted from a multi-grids code

2.4. *Particle clouds processing*

The development of SDvision was particularly focused on the visualization of grid data produced by finite volumes hydrodynamics codes; the particles clouds are treated as mere 3D scatter plots (See Fig. 9 a representation of stars, simulation performed by M. Martig) typically in astrophysics for dark matter and stars. Other codes exist such as TIPSY [12] and SPLOTCH[13] which are based on more refined algorithms using a computation of the local particle density.

Fig. 9: example of visualization of particle clouds in SDvision showing stars color-coded against their age.

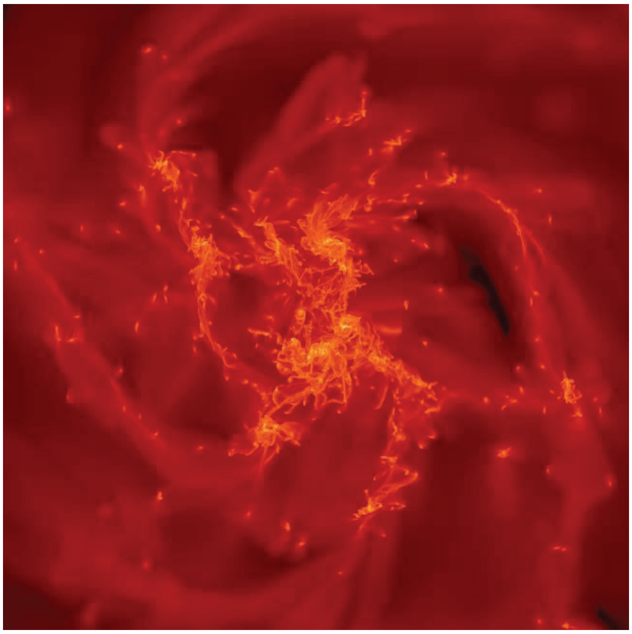


3. Astrophysical simulations visualizations

3.1. Cosmological structures studies

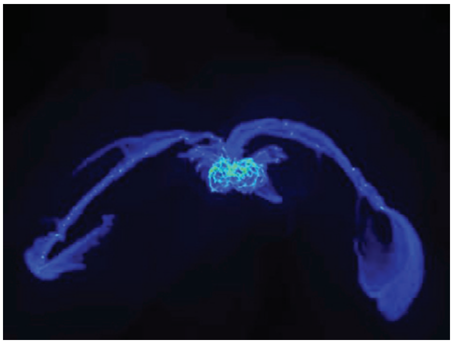
The RAMSES code [14][15][16] is designed as a N-body and hydrodynamical code based on the Adaptive Mesh Refinement (AMR) technique. Hybrid simulations are performed using the RAMSES code to study cosmological large scale structures and galaxy formations. RAMSES has been used in the context of the HORIZON [17] Grand Challenge Simulation at CEA/CCRT on Platine in September 2007, which was the largest ever N-body cosmological simulation performed. For the first time, have been performed a simulation of half the observable universe, with enough resolution to describe a Milky Way-like galaxy with more than 100 dark matter particles. The RAMSES code has been run on 6144 cores, 18 Tb RAM used for 2 months to simulate 70 billion particles. Another challenge in computing in astrophysics with RAMSES was the HORIZON "galaxy formation" simulation at MareNostrum [18]. The characteristics of the run are the following: 1024^3 dark matter particles, 4 billions AMR cells. 2048 processors were needed for computing, 64 processors dedicated to I/O, 3 weeks of computations, 20 Tb of data generated and stored. The run performed simulations from large scale filaments to galactic discs. The visualization of such challenging simulations has been described in previous papers.
RAMSES was used more recently in the studies of galaxies formations [19]. A first example of high-resolution simulation of a galaxy disk is shown in Fig. 10. The image represents the density of the baryon gas in a galaxy disk. The simulation was performed on 700 processors at CEA/CCRT on Titane by F. Bournaud.

Fig. 10: Visualization of the AMR density field in a simulation of a galactic disk. The AMR structure up to level 14 is projected in a 4096x4096x328 grid



Another example of high resolution visualization from RAMSES results is the simulation of the Antennae galaxies formation [20], starting from the collisions of two spiral galaxies. The movement of the galaxies baryonic gas has been simulated during 500 million years in a region of 600000 light-years on each side. Fig. 11 represents the galaxies at the second collision time after 450 million years. The 1000 stored time-steps allowed us to perform a high-resolution video of the simulation using the SDvision capabilities.

Fig. 11: Visualization of Antennae galaxies simulation by D. Chapon, R. Teyssier and F. Bournaud.



3.2. Interstellar Medium Simulations

As another example of astrophysical numerical analysis code, the HERACLES [21][22][23] 3D code is mixing hydrodynamics and radiative transfer studies on Cartesian grids, using the finite volumes method. The HERACLES biggest simulation has been performed in the framework of the Grands Défis CINES 2010 on 2500 processors of the Jade machine in CINES Computing Center in Montpellier, France. The run simulated the Interstellar Medium turbulences in a 2000x2000x2000 cube, using 8 billion cells. The simulations generated 15To of data, and allowed high resolution images and videos for stereoscopic visualization systems, thanks to SDvision. Fig. 12 shows the turbulence of ISM gas in a 2-phases simulation. Fig 13 shows an immersive view of the turbulence of the gas in ISM in a isothermal simulation

Fig. 12: Visualization of the HERACLES simulation on a 2000x2000x2000 grid.

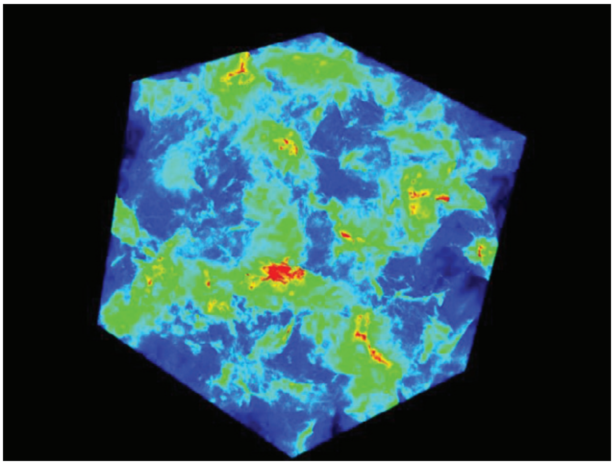
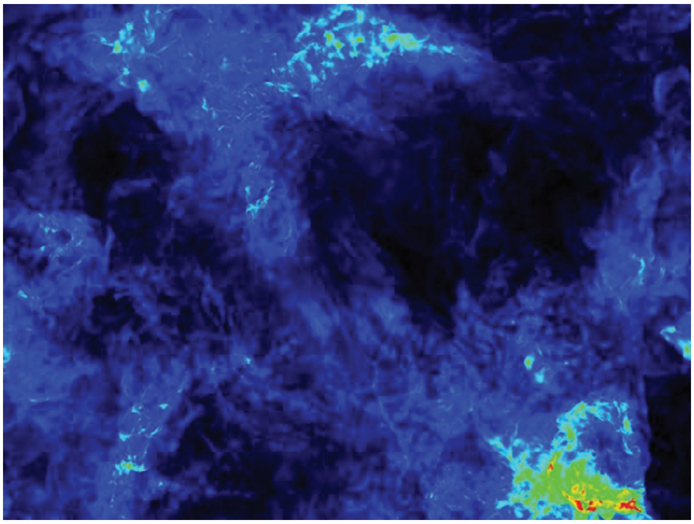


Fig. 13: Visualization of the HERACLES simulation on a 2000x2000x2000 grid, immersive view.



4. Fusion plasma simulations visualizations

To understand the behavior of the plasmas in the next generation of tokomaks, like ITER, simulations are performed with the GYSELA code [24][25], developed at CEA/IRFM Cadarache, with the goal to reduce the turbulences for improving performances in these machines. The GYSELA simulation performed in the framework of the Grands Défis CINES 2010 was the largest simulation ever realized on the ITER model. The simulation used 272 billion cells in the 5-dimentional mesh and had run one month on 8192 processors of the Jade machine in CINES. The code used 27Go by node and generated more than 6To of data. Fig. 14 represents in 3D the temperature fluctuations during the turbulence inside the plasma on a poloïdal cut of the torus. Fig. 15 represents in 3D the electrostatic potential fluctuations inside the torus.

Fig. 14: visualization of the poloidal cross section of the simulated ITER plasma

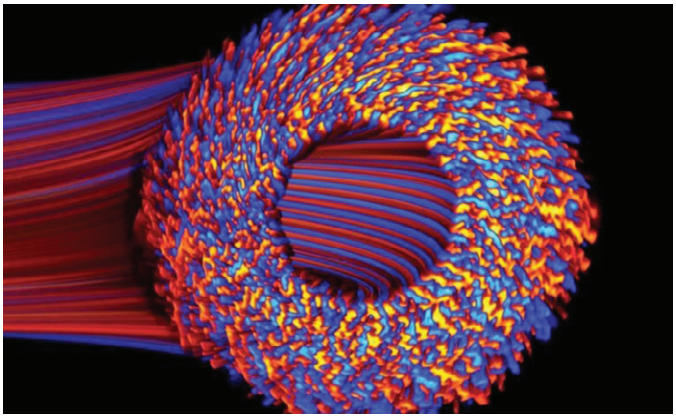
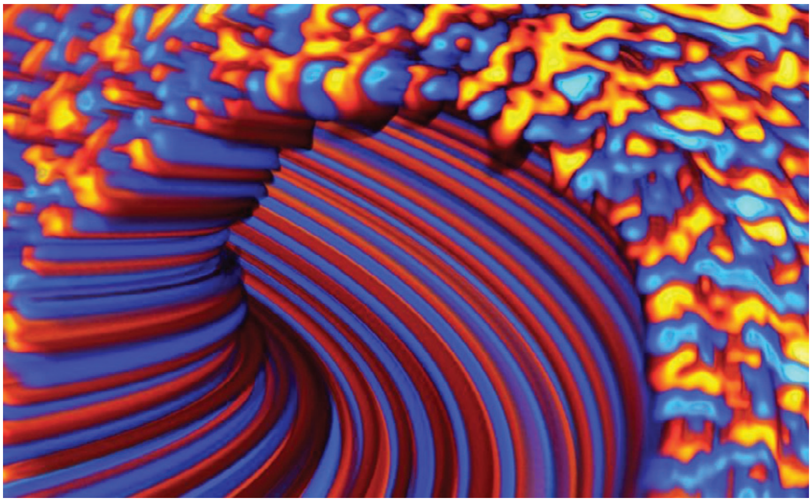


Fig. 15: Immersive view of the simulated ITER plasma inside the torus



5. Perspectives

The SDvision software package, intended primarily for the visualization of massive cosmological simulations, has been extended to provide an interactive visual representation of different classes of redshift surveys [26]. A first study has been carried out with the objective to enable direct comparisons between the low statistics X-ray clusters samples of the XMM-LSS Survey and the high-statistics photometric redshift catalogues of the CFHTLS [27]. The various possibilities offered by the tool in terms of filtering of the data, reconstruction of density fields, interactivity and visual rendering, are opening a new domain of collaborations with astrophysics involved in experiments collecting actual data.

6. Conclusion

If the development of the SDvision visualization code was basically motivated by the need of analyzing the results (and sometimes detecting computing bugs) from huge amounts of data with complex structures, the production, thanks to SDvision , of images, videos and stereoscopic movies in the domain of astrophysics simulation have caused a lot of requests for communication with the general public. Several movies generated by SDvision have been screened in exhibitions, museums and in our 3D room for visitors at Saclay. A new dedicated room with 100 seats has been equipped in our laboratory for the projection of astrophysical stereoscopic movies generated by SDvision. Projects are also in progress with planetariums and museums to present on very high resolution screens the simulations of different scales of the Universe, from cosmology to planet formation.

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F. Masset, S. Fromang, F. Bournaud, D. Chapon, L. Delaye, L. Powell, M. Martig, A. Strugarek and al. for providing their data to the software engineers.
The visualizations presented were obtained using either our local computing resources at CEA/IRFU or the Cesium graphics cluster supported by the CEA/CCRT.

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