PRACE: A Fundamental Resource in Plasma-Astrophysics

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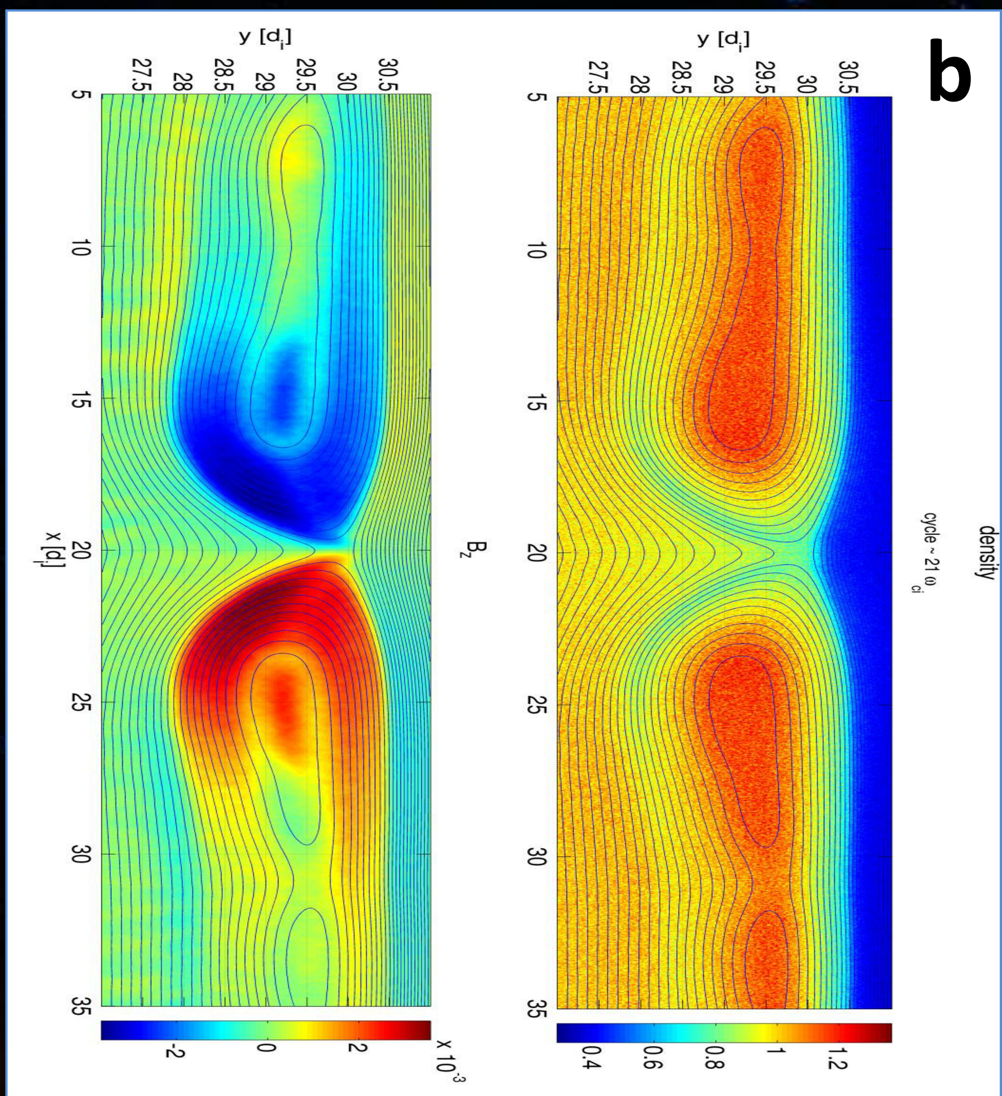
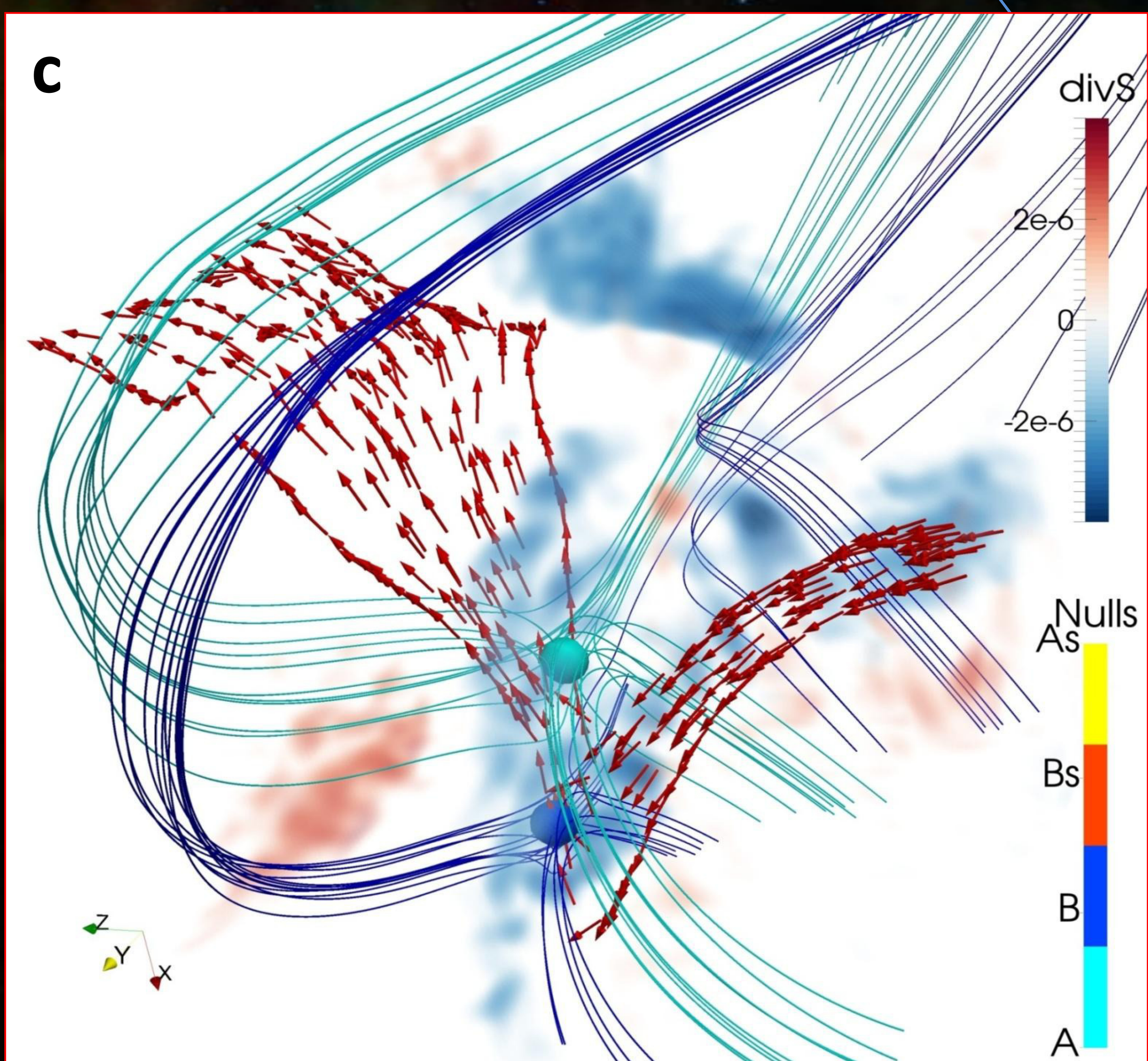
Simulating astrophysical plasmas is a grand challenge due to the extremely wide range of spatial and temporal scales of the systems. We present here HPC models of the evolution of the Earth space environment during geomagnetic storms. The phenomena span from tens of Earth radii in size down to scales as tiny as the motion of single particles. This challenge pushes our community at the cutting edge of HPC. Thanks to the computational resources provided by PRACE Tier-0 we were able to overcome these challenges and obtain some key new discoveries. All the simulations are performed with the fully kinetic implicit Particle-in-Cell code iPIC3D (Markidis et at. 2010), whose implicitness allows us to describe the particles behavior within an acceptable computational time. This code presents a great scalability up to tens of thousand cores and beyond, as well as a minimal use of so-called "bottleneck operations", such as collective communications (panel e).

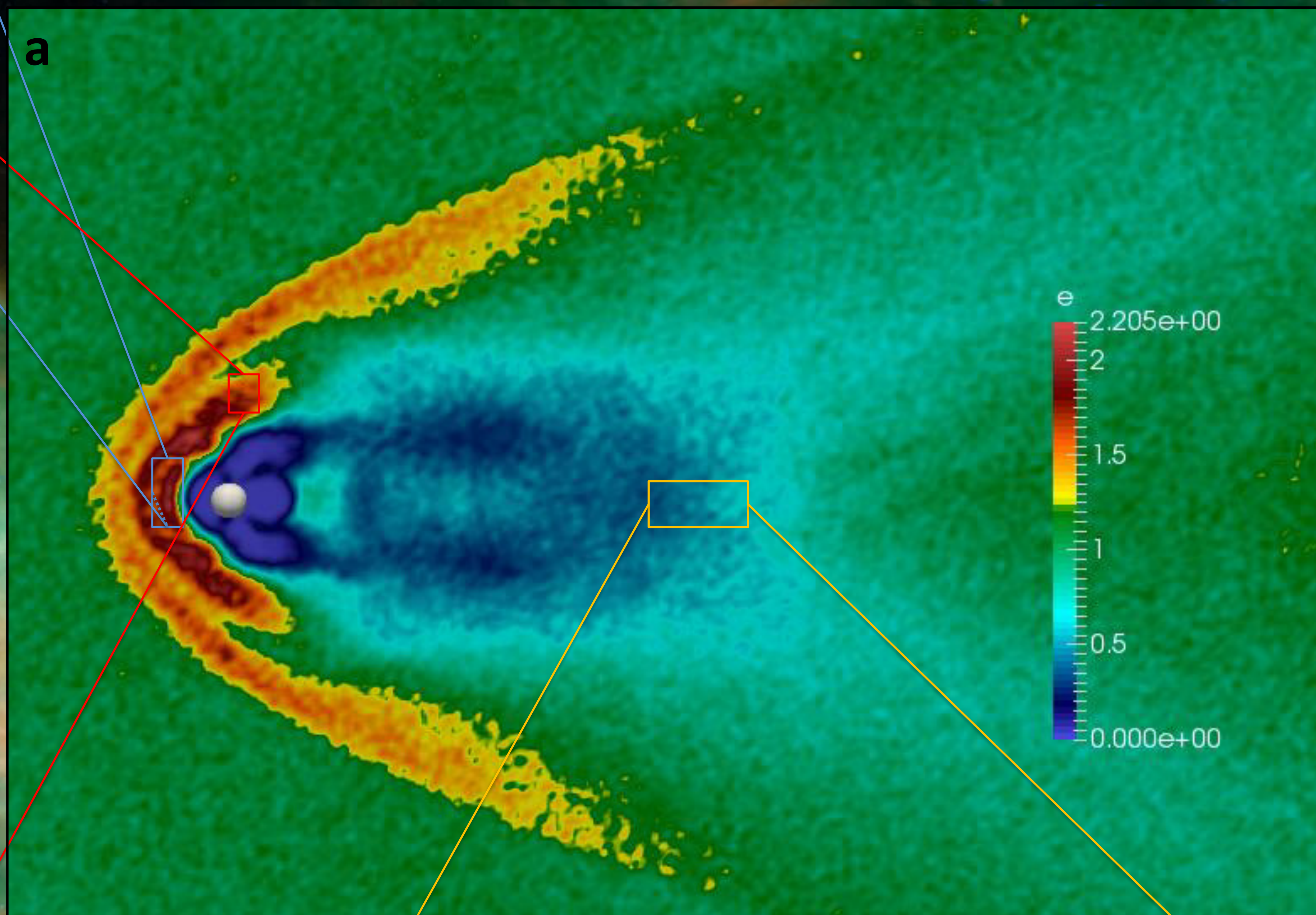
Some of the most relevant accomplishment are shown below. In panel a, we present one of the first fully kinetic descriptions of the global solar wind-magnetosphere interaction, which highlights in particular one of the most interesting kinetic event, i.e. the bow-shock at the dayside. Once the solar wind is violently decelerated and heated in this region, its hot-dense plasma soon comes in contact with the cold rarefied magnetospheric plasma ultimately leading to the asymmetric reconnection shown in panel b and panel c. The 2.5D simulation summarized in panel b aims at describing the still unrevealed local reconnection physics, while the simulation panel c shows the three-dimensional investigation of the real seeds of reconnection: the null points (regions where the magnetic field locally becomes zero).



Asymmetric magnetic reconnection at the magnetopause. This 2.5D simulation required 2048x2048 cells, 4096 processes and around 98000 computational hours. B_z represents the out-of-plane magnetic field in the local frame of reference.



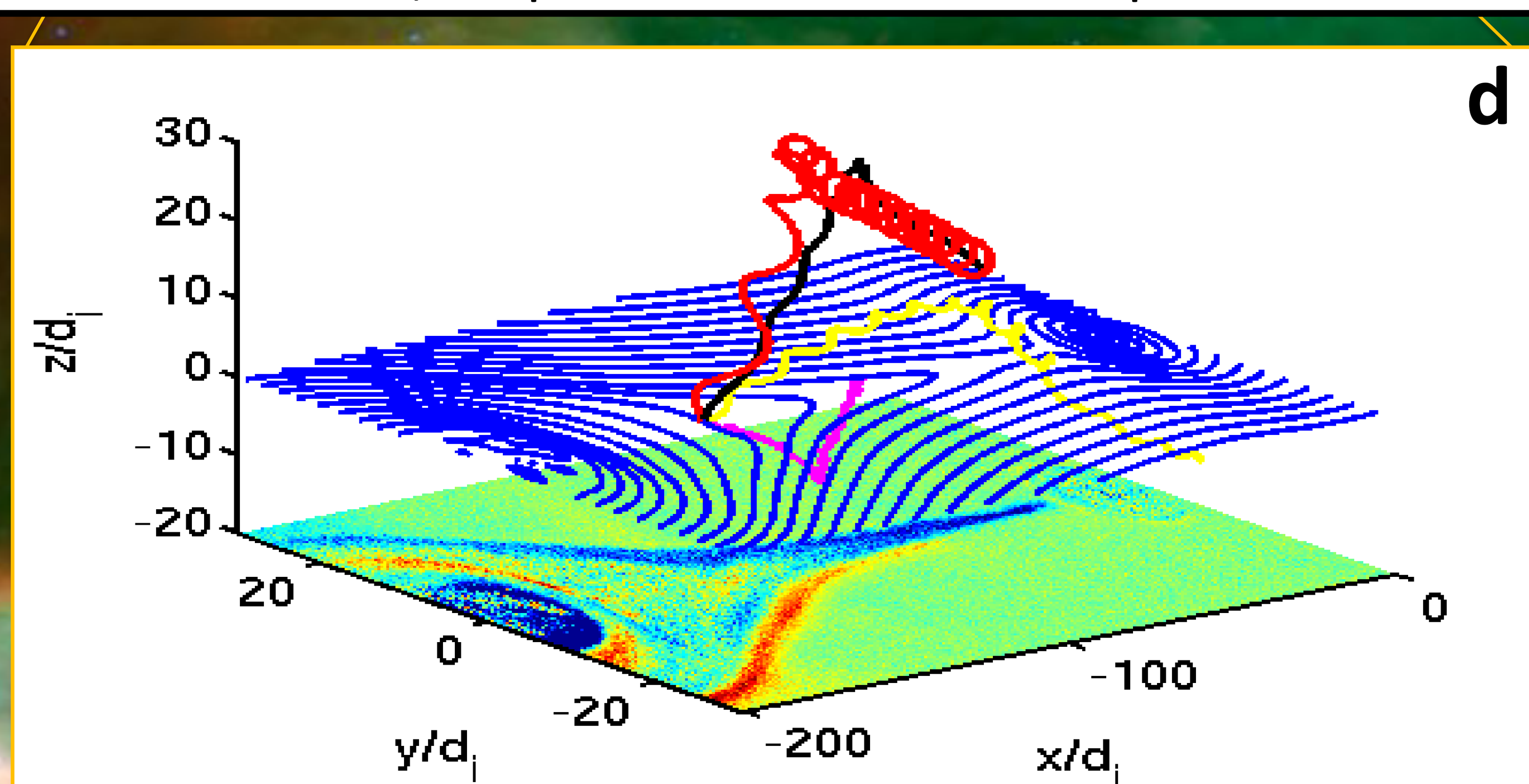
3D plot of, respectively, of the Poynting vector divergence and the type of null points. Simulation of 400x400x400 cells, which required 8000 processes and around 20000 computationl hours (Olshevsky et al. 2013).



Noon-midnight meridian cut of the fully kinetic 3D simulation concerning the whole solar wind-magnetosphere interaction. The solar wind is flowing flow left to right. The color scale represents the normalized electron charge density. This simulation required 416x416x416 cells, 2048 processes and around 131000 computational hours.

Additionally, given the extremely localized loci of the reconnection, a new innovative method has been introduced, namely the Multi-Level-Multi-Domain (MLMD) (Innocenti et al. 2015). In order to further save computational resources without losing any physical meaning, the MLMD permits to use a considerable refined grid only around those sub-domain where an higher resolution is required, leaving the rest physically unnecessary domain with the initial coarse grid.

Finally, panel d shows the first observation of magnetic field switch off in a fully kinetic magnetic reconnection simulation. In our simulations, switch off is achieved by means of compound slow shock-rotational discontinuity structures (Innocenti et al. – paper submitted). The switch-off of the magnetic field by means of back-to-back slow shocks is a cornerstone of Petschek's theory of fast reconnection, developed in 1964. One of the main reasons why switch-off was never observed up to now in kinetic simulations is the necessity to simulate domains of dimensions and for durations which were unattainable up to very recently. Even now, these kind of simulations can be performed only on Tier-0 machines.



A sample of ion trajectories superimposed to the ion current and, in blue, to the magnetic field lines in a portion of a magnetic reconnection simulation in the terrestrial magnetosphere (paper submitted). This simulation required 8192x4096 cells, 8192 processes and more than 390000 computational hours.

ACKNOWLEDGMENT

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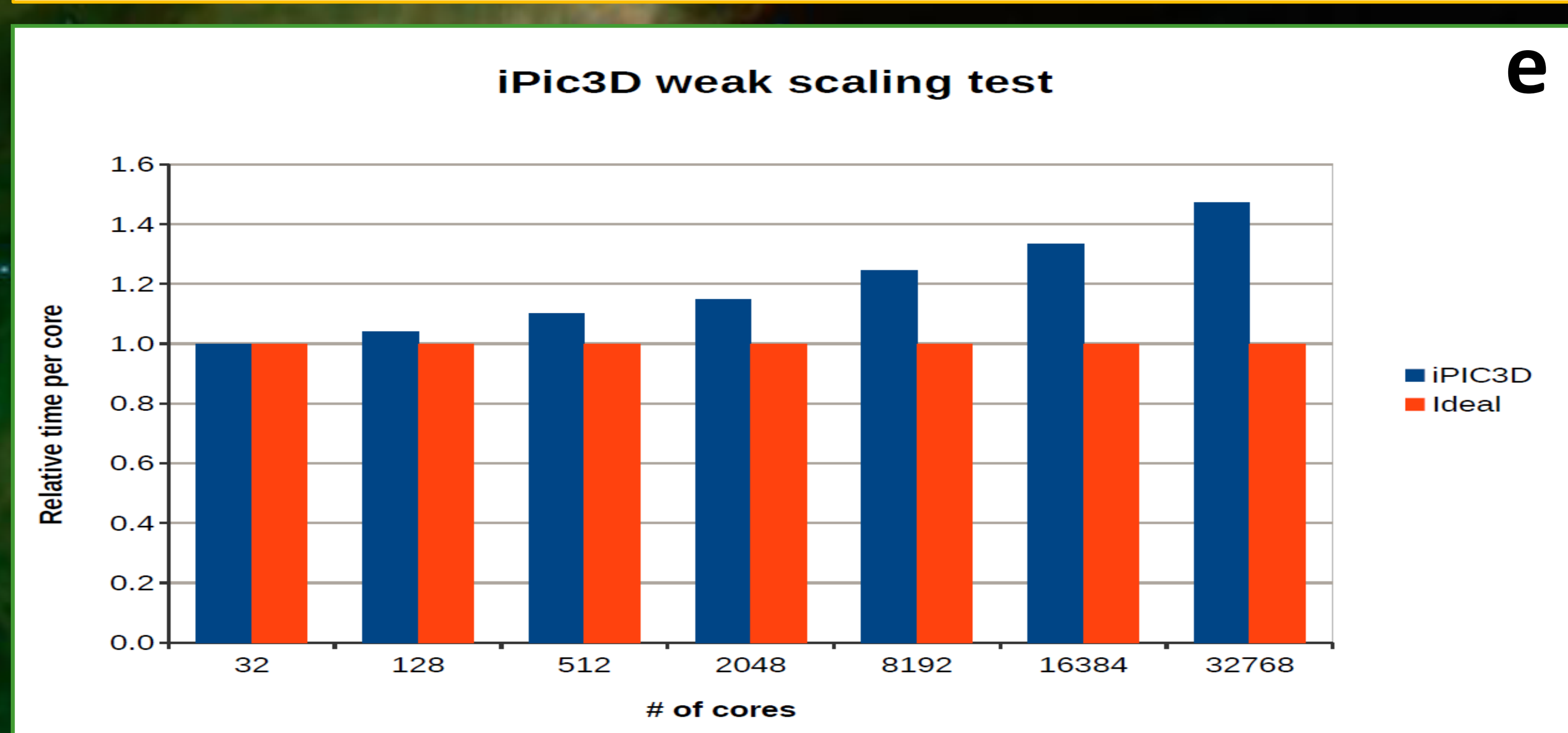

Weak scaling test of iPIC3D remarking the great scalability of this code. The test was performed on SuperMUC.

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Background picture from the Spitzer Space Telescope, www.nasa.gov