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# VLASIATOR: HYBRID-VLASOV SIMULATION CODE FOR THE EARTH'S MAGNETOSPHERE

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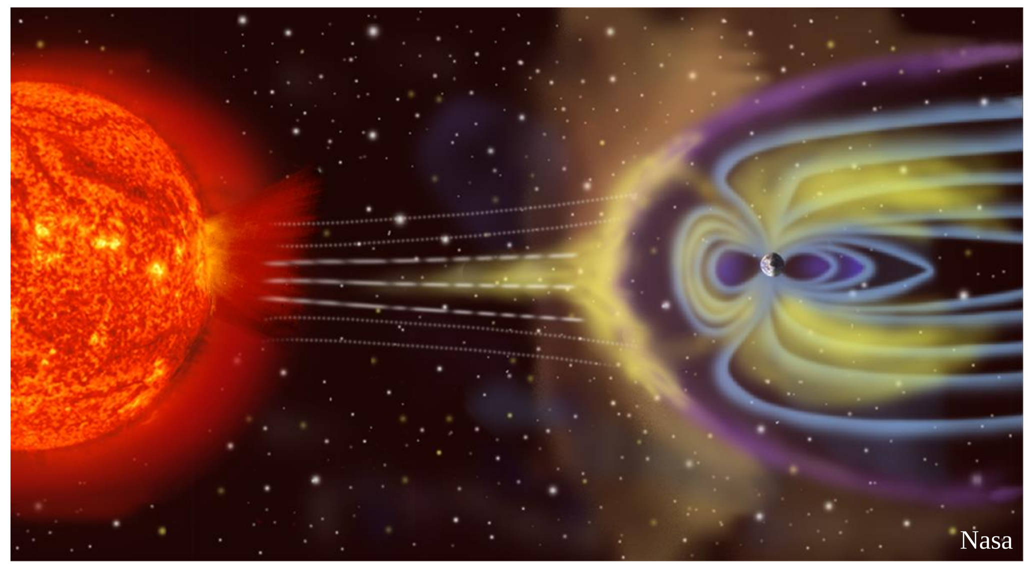
## Vlasiator

- **Vlasiator [1,2] – new hybrid-Vlasov simulation code**
  - **First of its kind –** simulates Earth's magnetosphere on a global scale based on a hybrid-Vlasov description of plasma
  - **Novel sparse representation** of proton distribution function
- **Earth's Magnetosphere**
  - Region of space formed by the interaction between the solar wind and Earth's dipole
  - Solar wind – stream of protons and electrons (plasma)
  - Solar eruptions may cause harmful effects on satellites and electric grids – great interest in better physical understanding
  - Large scale plasma "laboratory" with rich physics but can be experimentally be measured only in few places visited by probes, high quality simulations needed to fill in the gaps




- **Hybrid-Vlasov**
  - Protons modeled by a six-dimensional distribution function *f*(**r**,**v**,t) in ordinary space (r-space) and velocity space (v-space)
  - Electrons fluid, hence *hybrid*-Vlasov
  - Proton distribution function propagated in six dimensions following Vlasov's equation
  - Field solver propagates the magnetic and electric fields and includes the effects of the electrons through Ohm's law

### Ions (protons)

$$\frac{\partial}{\partial t}f(\mathbf{r},\mathbf{v},t)+\mathbf{v}\cdot\nabla_r f(\mathbf{r},\mathbf{v},t)+\mathbf{a}\cdot\nabla_v f(\mathbf{r},\mathbf{v},t)=0$$

$$\mathbf{a}=\frac{q}{m}(\mathbf{v}\times\mathbf{B}-\mathbf{V}_\mathrm{i}\times\mathbf{B}+\frac{1}{\rho_\mathrm{q}}\mathbf{j}\times\mathbf{B})$$

$$\rho_q(\mathbf{r})=q\int f(\mathbf{r},\mathbf{v},t)d^3v$$

$$\mathbf{j}_\mathrm{i}(\mathbf{r})=q\int \mathbf{v}f(\mathbf{r},\mathbf{v},t)d^3v$$

$$\boldsymbol{V}_i=\frac{\boldsymbol{j}_i}{\rho_q}$$

### Fields

$$\nabla\times\mathbf{E}=-\frac{\partial}{\partial t}\mathbf{B}$$

$$\nabla\cdot\mathbf{B}=0$$

$$\nabla\times\mathbf{B}=\mu_0\mathbf{j}$$

$$\mathbf{E}=-\mathbf{V}_i\times\mathbf{B}$$

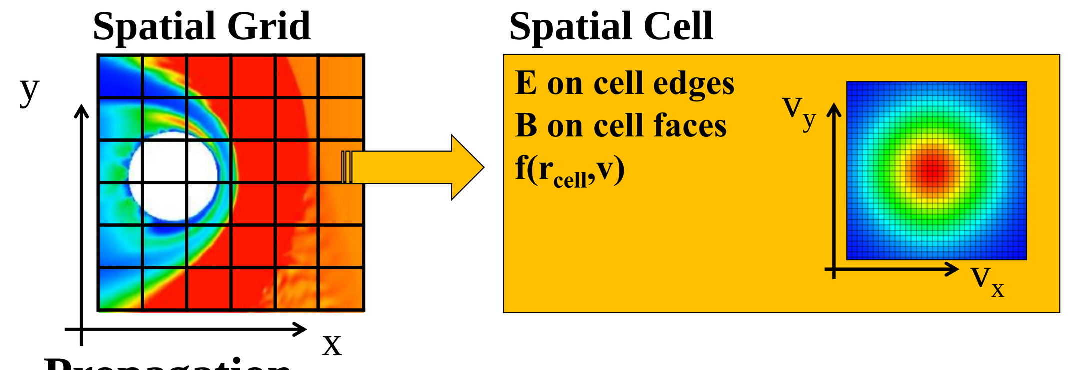
$$+\frac{1}{\rho_{qe}}\mathbf{j}\times\mathbf{B}-\frac{1}{\rho_{qe}}\nabla\cdot\mathcal{P}_e$$

Further terms to Ohm's law

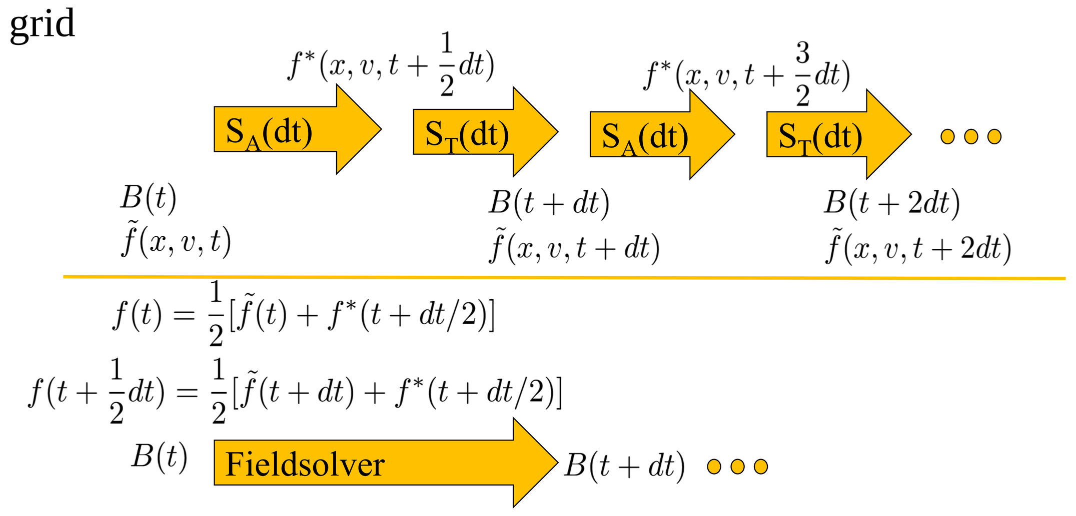
- Hybrid-Vlasov gives noise-free representation of proton distribution function (cf. hybrid particle-in-cell) with good representation of even tenuous regions – new science enabled

## Numerical Implementation

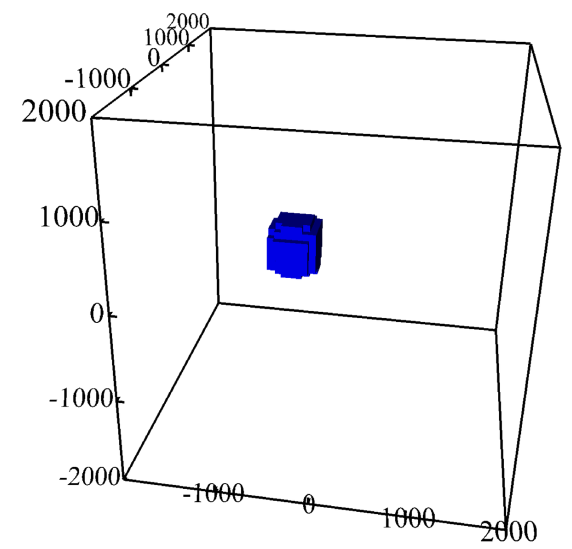
- **6D distribution function discretization**
  - 3D spatial grid [3] in ordinary space
  - Sparse 3D velocity space grid in each spatial cell
  - Stores volume averages in each phase space cell

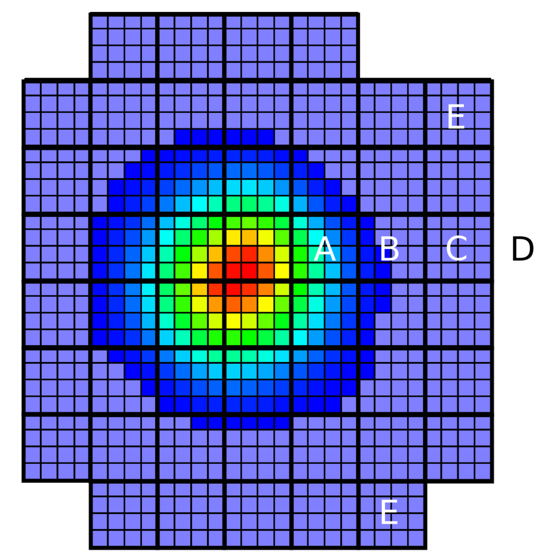



- **Propagation**
  - Protons: **Finite volume** method, second-order wave propagation method [4,5] split into 3D propagations in r-space propagation ($S_T$) and v-space ($S_A$)
  - Fields: Upwind constrained transport method [6] on staggered grid



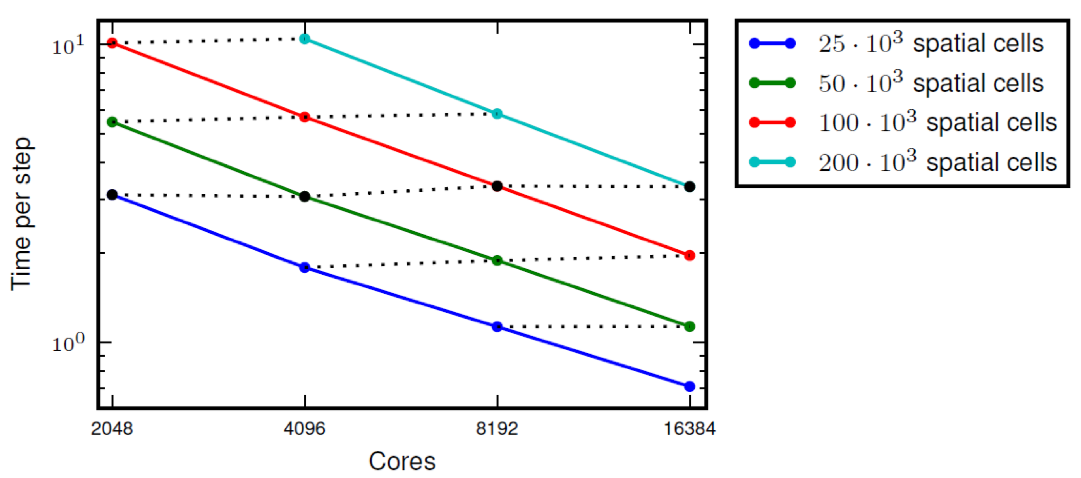

- **Sparse proton distribution function**
  - Reduced problem size, only non-zero velocity block exist
  - In typical simulations 1% fill ratio and overhead less than 10%
  - Increases performance, and also decreases memory, communication and IO proportionally
  - Distribution function is divided in blocks of 4x4x4 velocity cells
  - A block exists if it, or any neighbor in the six dimensions have content
  - A block has content if the value in any of its phase space cells is above a user defined threshold
  - In figure A,B have content; E,C have neighbors with content; D does not exist

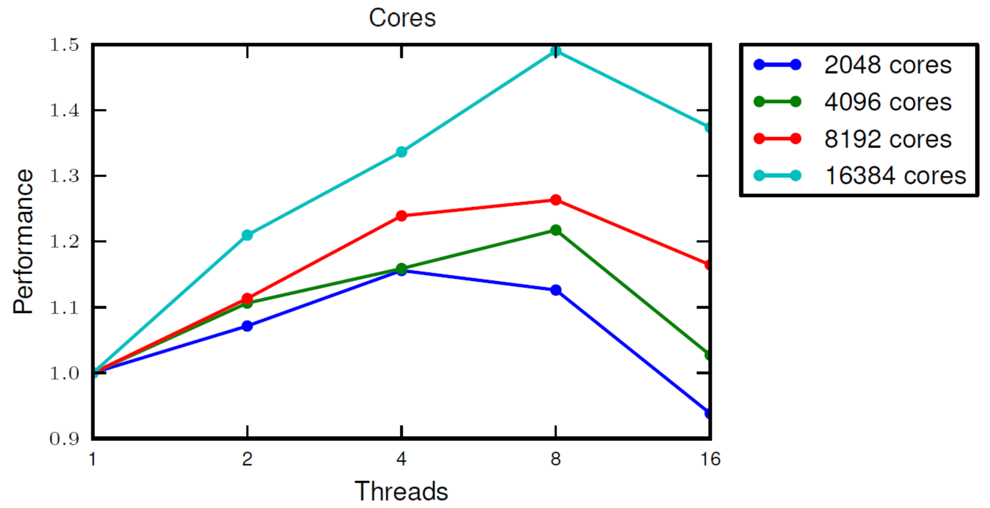


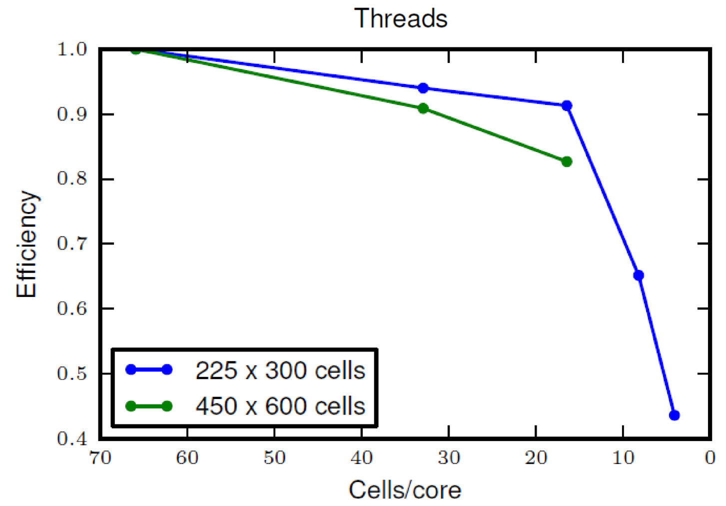




## Scalability & Throughput

- **Computational challenges**
  - Typical global 5D (2 in **r**-space and 3 in **v**-space) has $10^{11}$ phase space cells simulated over $10^5$ steps
- **Parallelization**
  - Target is to scale to tens of thousands of cores
  - Hybrid MPI+OpenMP parallelization
    - r-space over MPI, v-space over OpenMP
    - Reduced overhead from boundary cells and better load balancing
  - Local 5D tests on Cray XE6 with homogeneous plasma
    - Close to perfect strong & weak scalability (upper figure)
    - Improved scalability with threading (middle figure)
  - Global 5D tests on Cray XE6
    - Good efficiency up to 20 spatial cells per core at 16k cores (lower figure)
    - Scalability limited by strong computational imbalance; substepped acceleration and sparse velocity space
- **Vectorization**
  - Core-solvers operate on vectors with 4 floating point values [7]
  - Efficient utilization of SSE2 and AVX instructions
  - 52% better performance on Intel Sandy Bridge
  - 31% better performance on AMD Istanbul

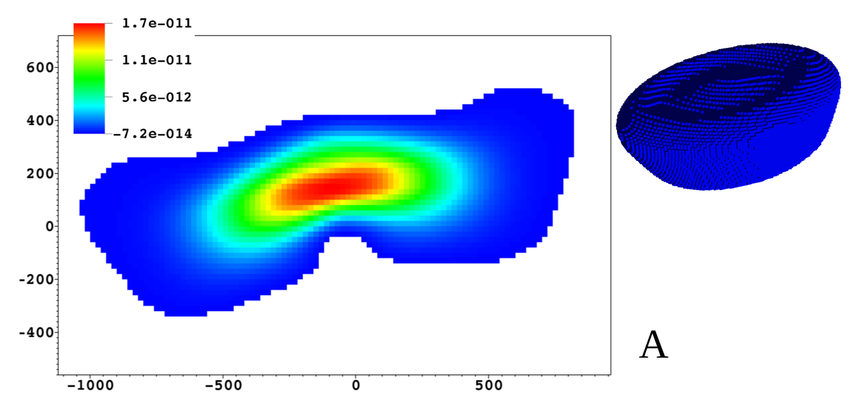



## Science

- **Simulation setup**
  - 5D simulation of ecliptic plane , 450x900 cells in r-space, and up to 50x50x50 in v-space
  - Typical solar wind conditions (velocity 500 km/s, number density 1e6, magnetic field 1 nT at 45 degrees with respect to Earth-Sun axis)
- **Results**
  - Is able to reproduce key features of solar wind-magnetosphere interaction
  - Ion foreshock: Backstreaming ion population and associated EM-waves in agreement with observations
  - Magnetosheath: Subject to mirror instability.
  - Detailed and noiseless description of v-space, breakthrough for understanding kinetic processes



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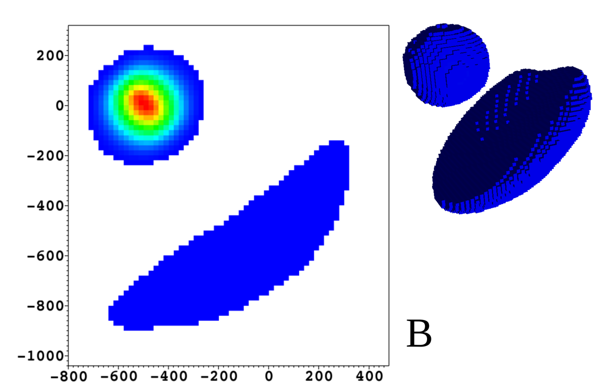

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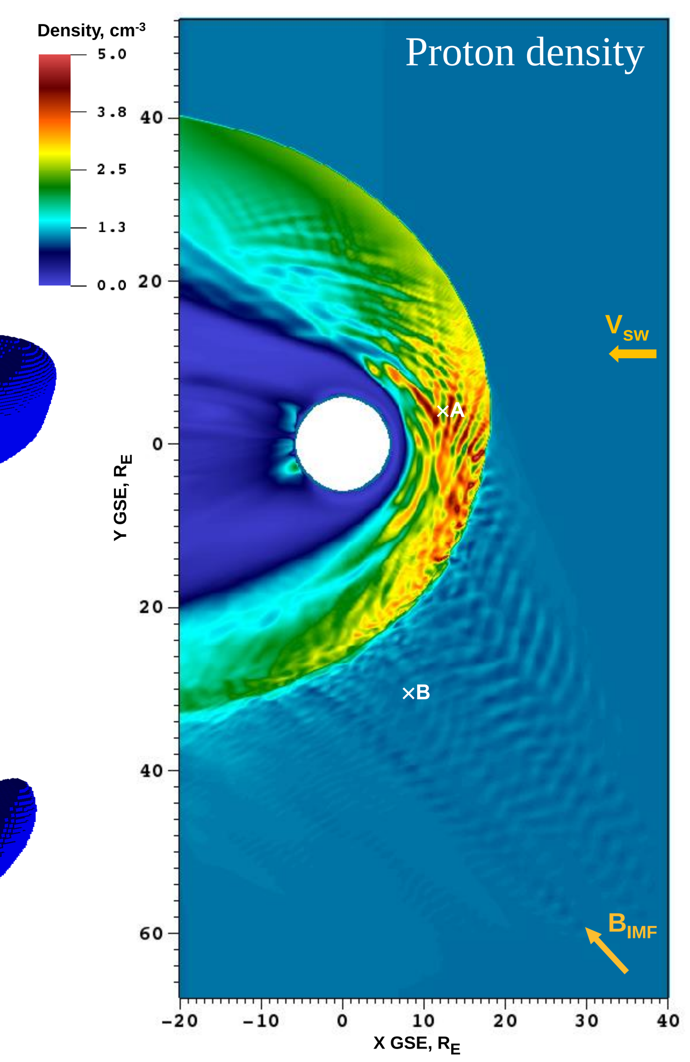


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