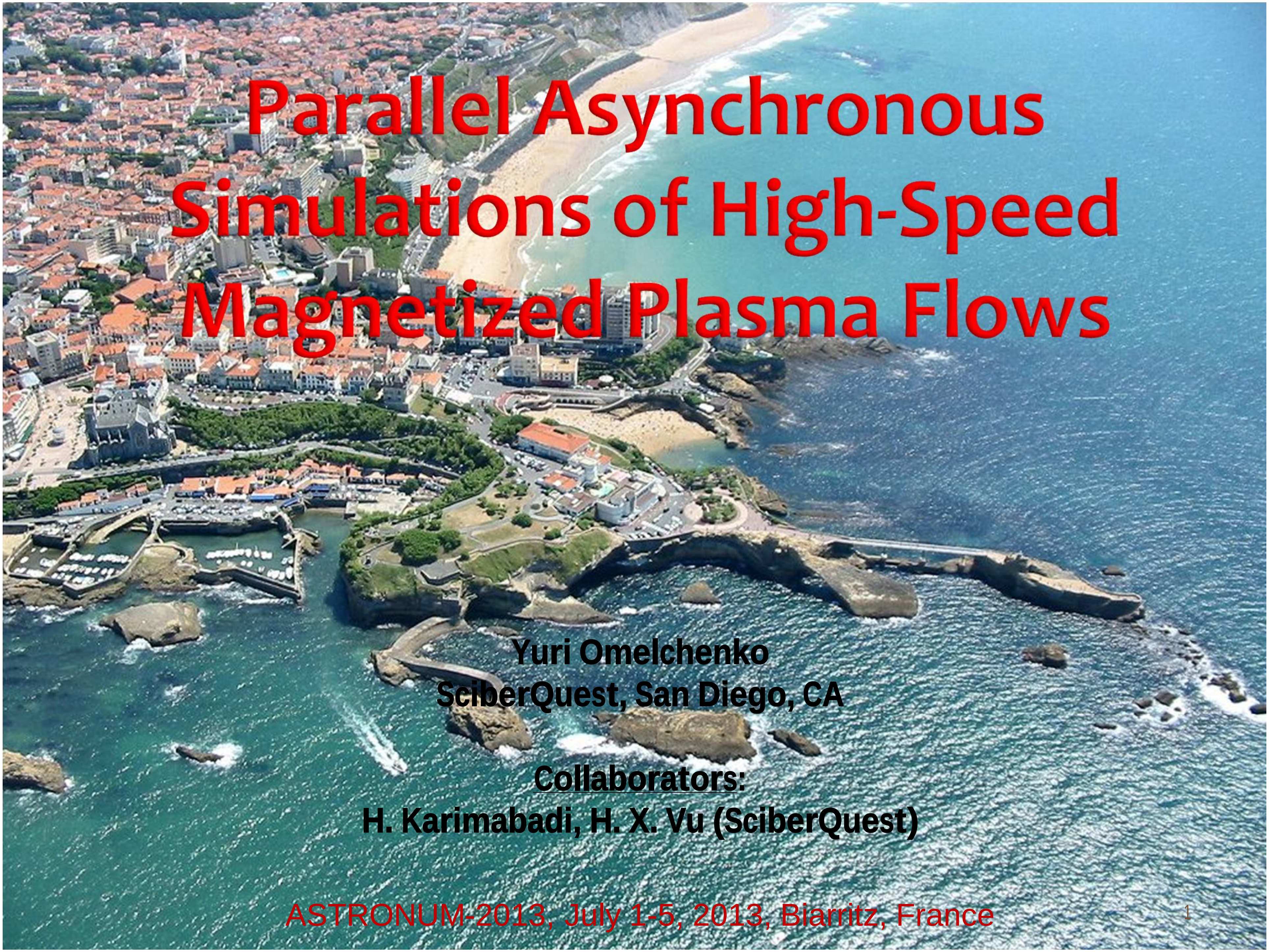

Parallel Asynchronous Simulations of High-Speed Magnetized Plasma Flows

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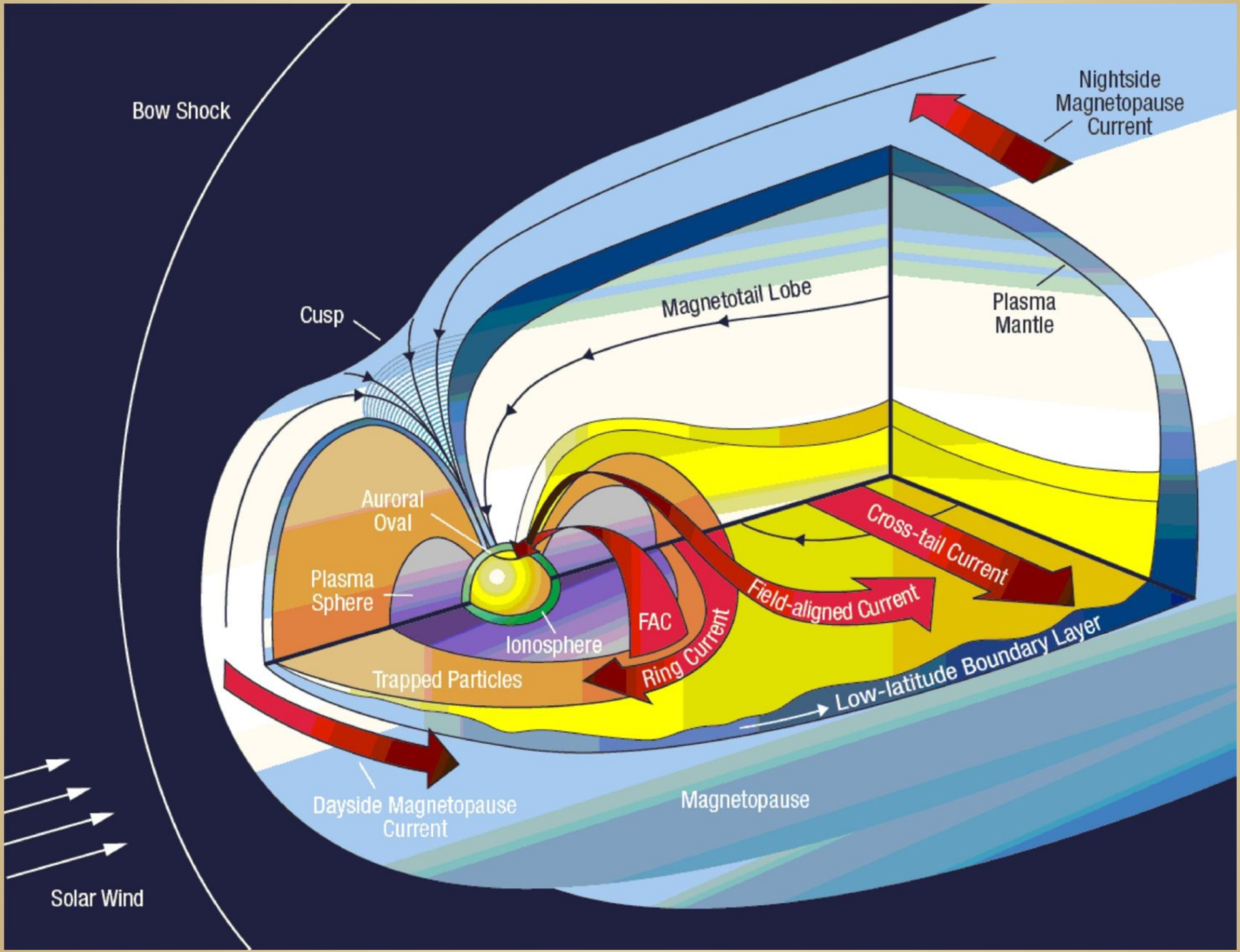
Collaborators:
H. Karimabadi, H. X. Vu (SciberQuest)

ASTRONUM-2013, July 1-5, 2013, Biarritz, France

Motivation

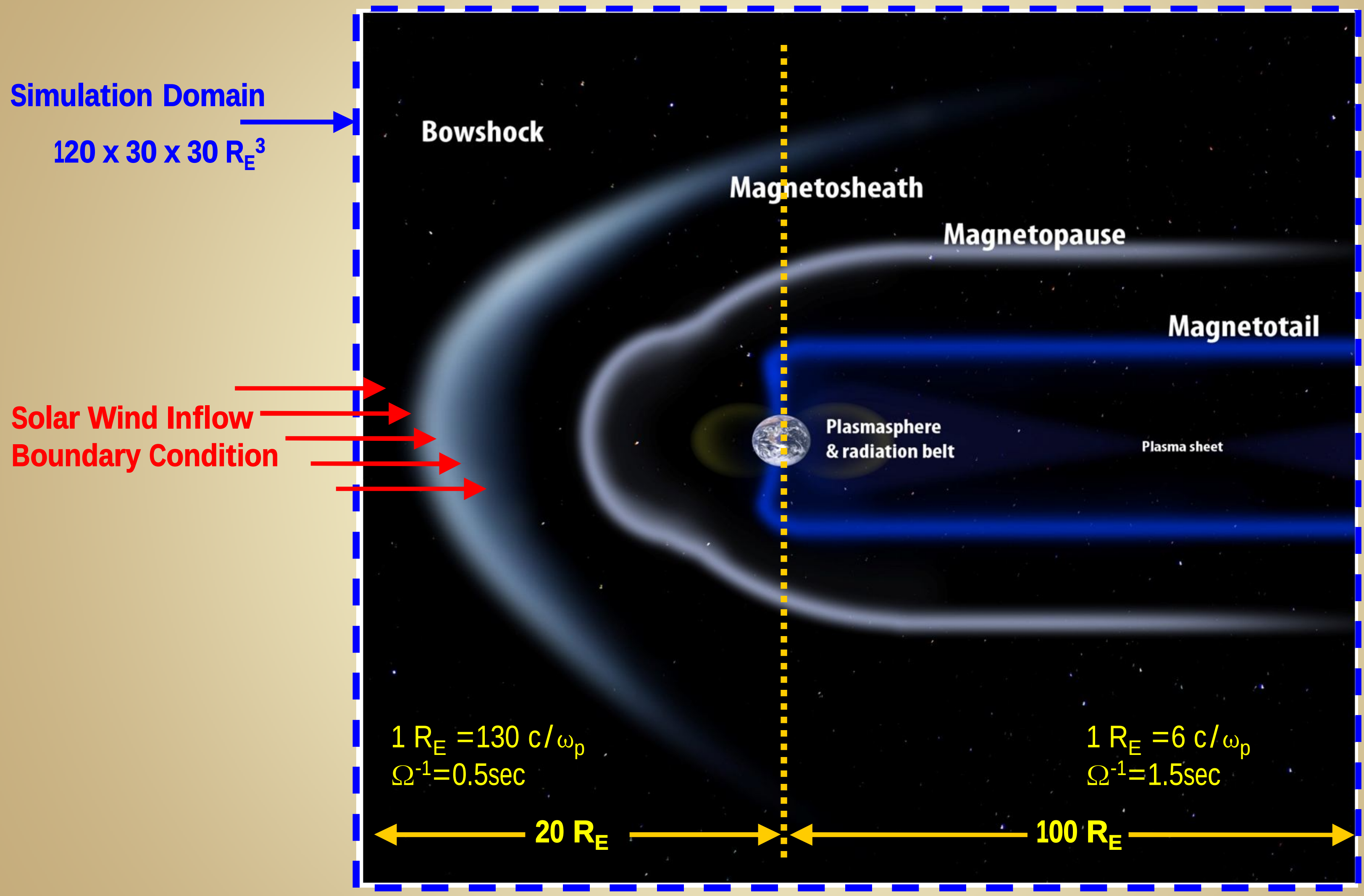
Global Magnetospheric Simulations



Importance of Ion Kinetic Effects

- Bowshock/foreshock physics
- Magnetosheath turbulence
- Ionospheric outflow
- Effect of O+ in magnetotail
- Ring currents
- Turbulence in the magnetotail
- Transport /formation of boundaries

Numerology & the Computational Challenge



Challenges in Kinetic Simulations

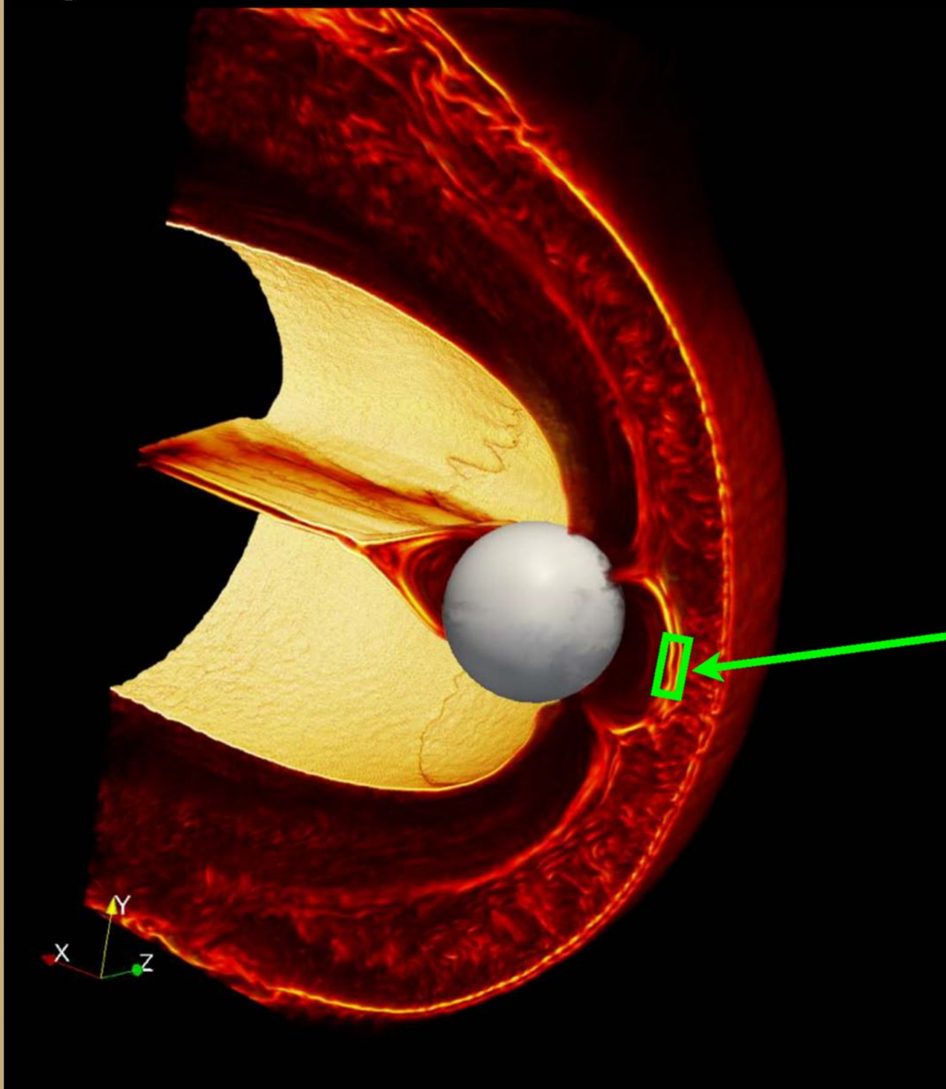
Magnetosphere is a Multiscale Coupled System:

- Spatial scales vary from centimeters to 200 R_E (span of 10^{11} spatial scales!)
- Temporal scales vary from less than milliseconds to days (span of 10^8 temporal scales!)
- Electron physics: e.g., controls reconnection rate
- Ion physics: e.g., accounts for formation of boundaries, transport, energization
- Dynamic M-I coupling: still **missing** in kinetic simulations

➢Requires **yottaflops** (10^{24}) and beyond

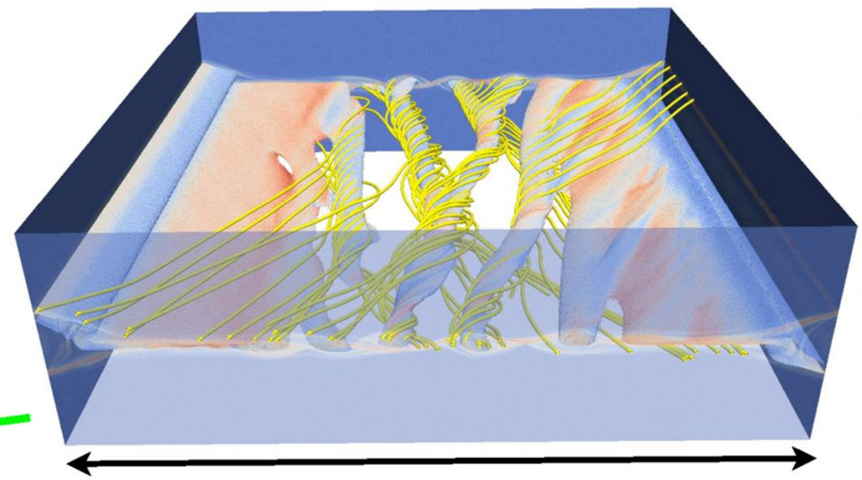
What simulations are feasible at the petascale?

Hybrid ~10^{10} cells ~ 10^{12} ions



Fully Kinetic

$\sim 10^{10}$cells $\sim 10^{12}$ particles



$\sim 100 d_i \sim R_E$

$3D \rightarrow m_i/m_e = 100 - 400$

$2D \rightarrow m_i/m_e = 400 - 1836$

Breakthrough Technology:
Discrete-Event Simulation (DES)

Time-Accurate Simulation

Q: Can we advance solution in time asynchronously in accordance with locally varying time scales?

- **Time-Driven (Stepped) Simulation (TDS)**
  - ✓ stability issues (for dt > CFL)
  - ✓ diffusion/dispersion issues (for dt << CFL)
  - ✓ inactive regions are still time-stepped
  - ✓ local time stepping has synchronization issues

- **Discrete-Event Simulation (DES)**
  - ✓ updates are driven by physical changes (=> speedup)
  - ✓ changes are always limited (=> accuracy/stability)
  - ✓ arbitrary grids may be considered
  - ✓ adaptive synchronization via event preemption

Change-Event (Δf) vs Time-Step (Δt)

Generalized equation:

$$\frac{\partial f}{\partial t} = R(t, f)$$

Cells have different "trajectories"

Event scheduling:

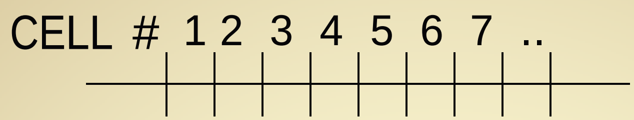
$$\Delta t = \frac{\Delta f}{\left|\frac{\partial f}{\partial t}\right|}$$

Cells have different Δt's

Events are desynchronized by Δf!

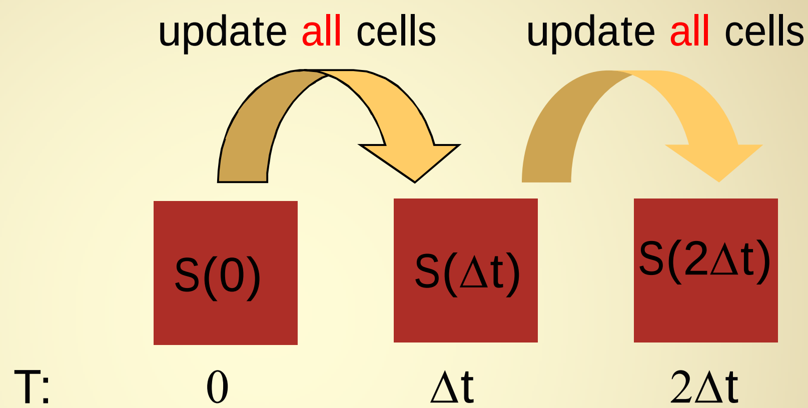
DES vs Time Stepping

S(T) =



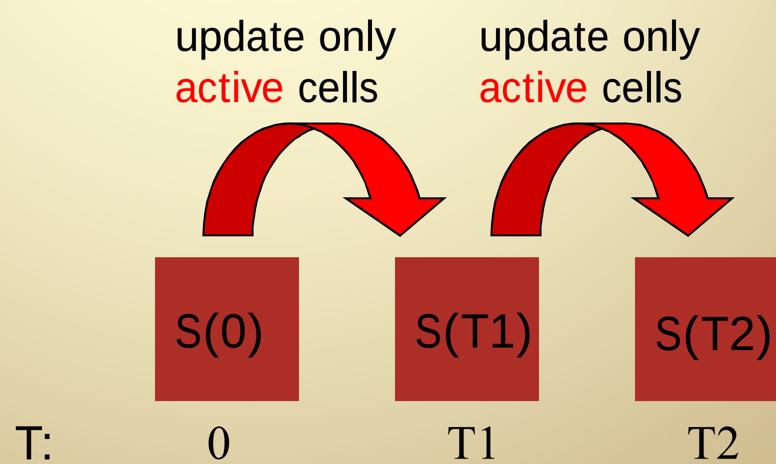
Time-driven simulation

updates the entire system

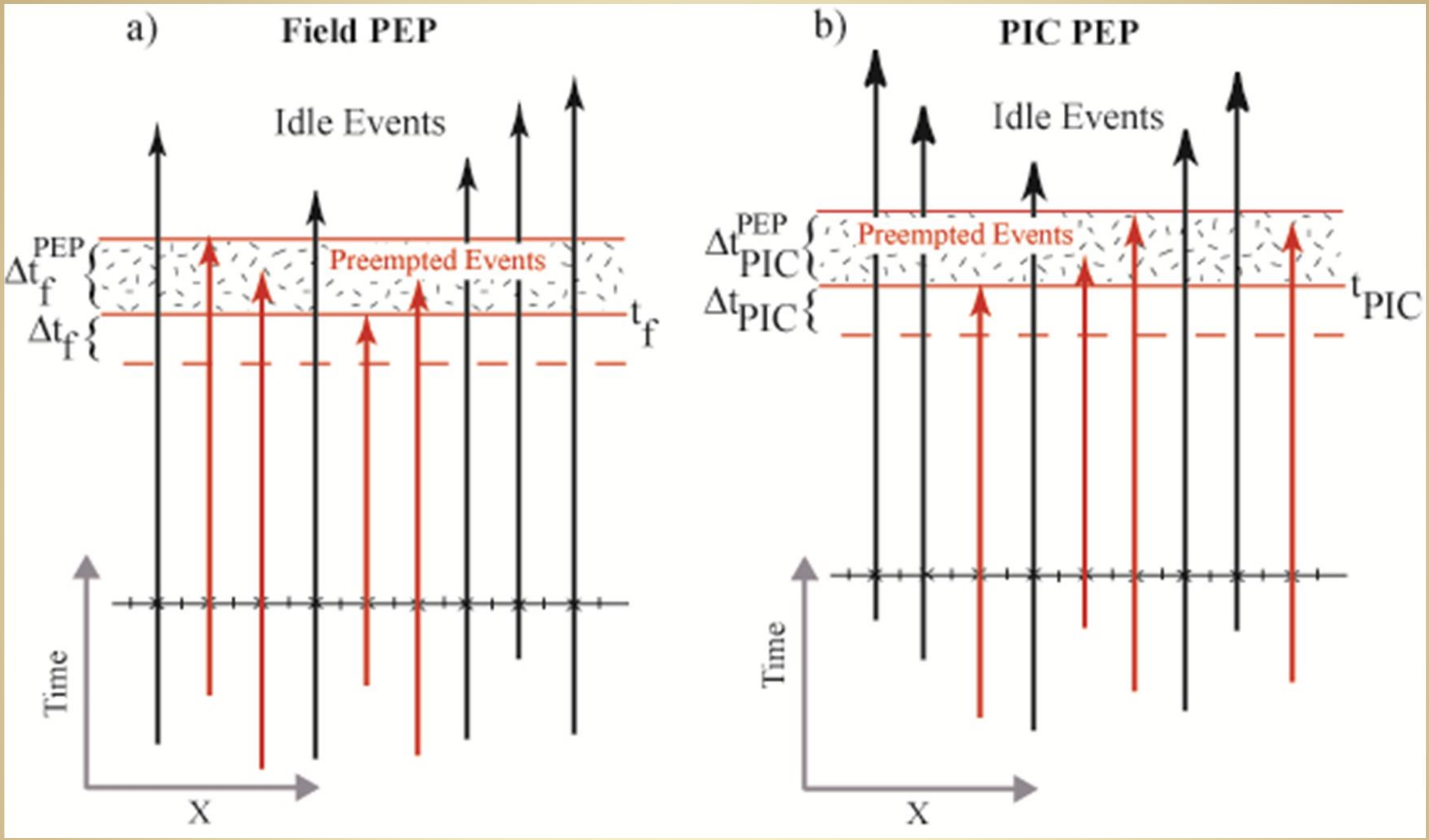


Event-driven simulation

updates active cells only



DES via Preemptive Event Processing (PEP)



1. For **df/dt = R** schedule events: for each “state” predict Δt based on its trajectory, f(t) and accuracy threshold, Δf.
2. Update → synchronize→[preempt?]→reschedule events.

Hybrid DES Code HYPERS (JCP, 2012)

$$0 = \frac{4\pi}{c}\left(\mathbf{j}_i + \mathbf{j}_e\right) - \nabla \times \mathbf{B}$$

$$0 = en_e\left[\mathbf{E} - \eta\left(\mathbf{j}_i + \mathbf{j}_e\right)\right] - \frac{\mathbf{j}_e \times \mathbf{B}}{c} + \nabla p_e$$

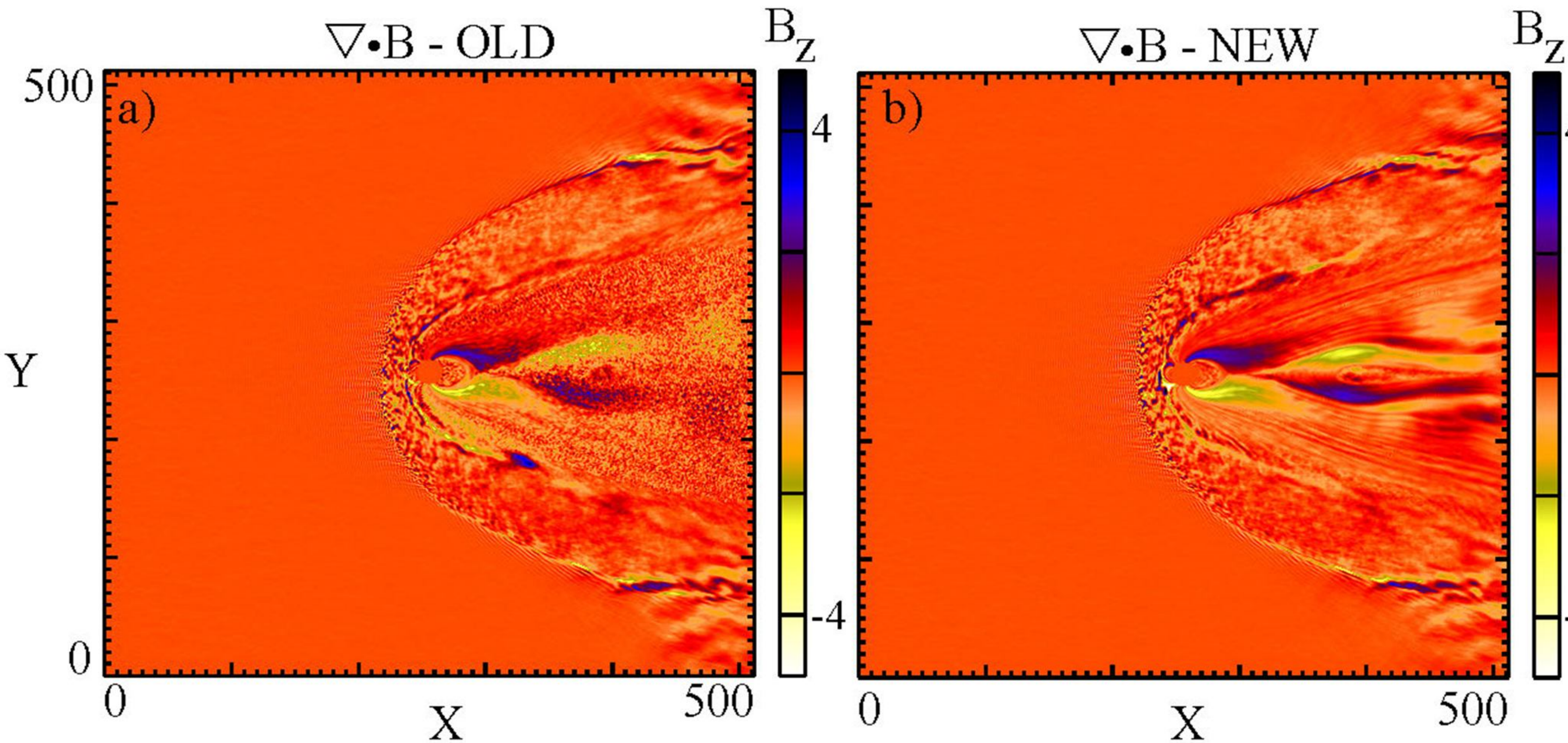
$$\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$$

$$en_e = q_i n_i \, , \mathbf{j}_e = -en_e \mathbf{v}_e$$

$$p_e = n_e T_e \sim n_e^{\gamma}$$

divB=0 is asynchronously preserved (2013)

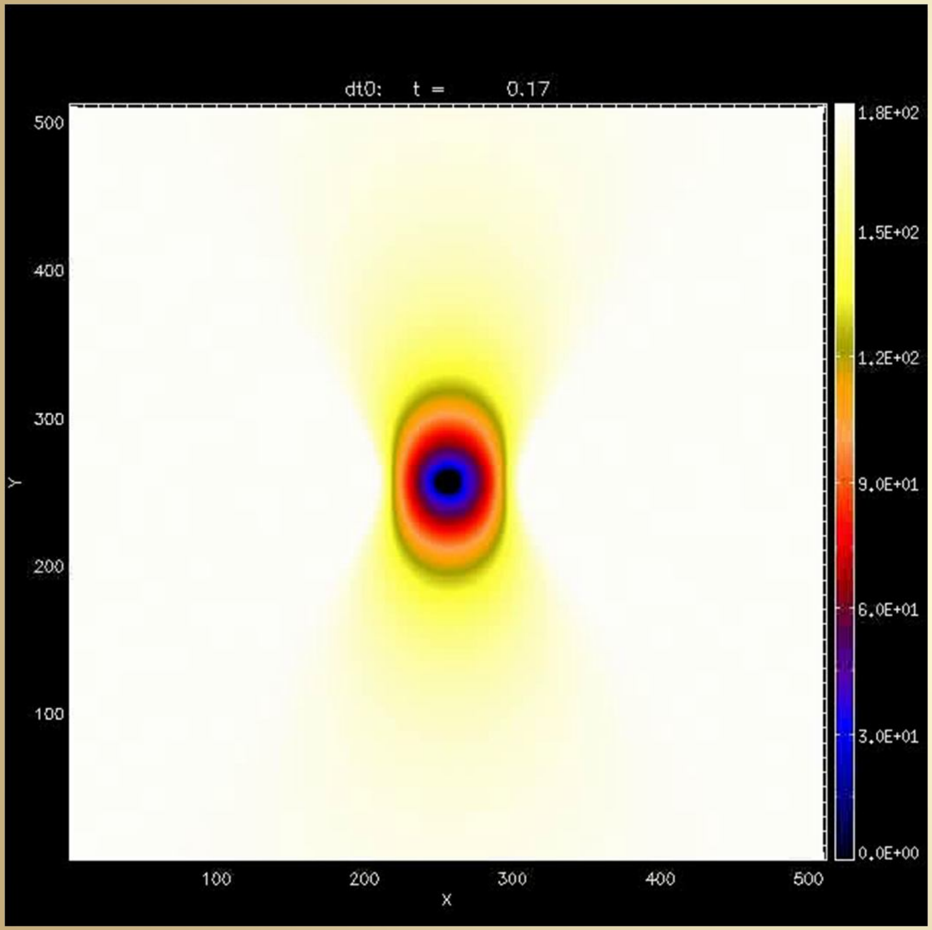
Algorithm improvement (2013)

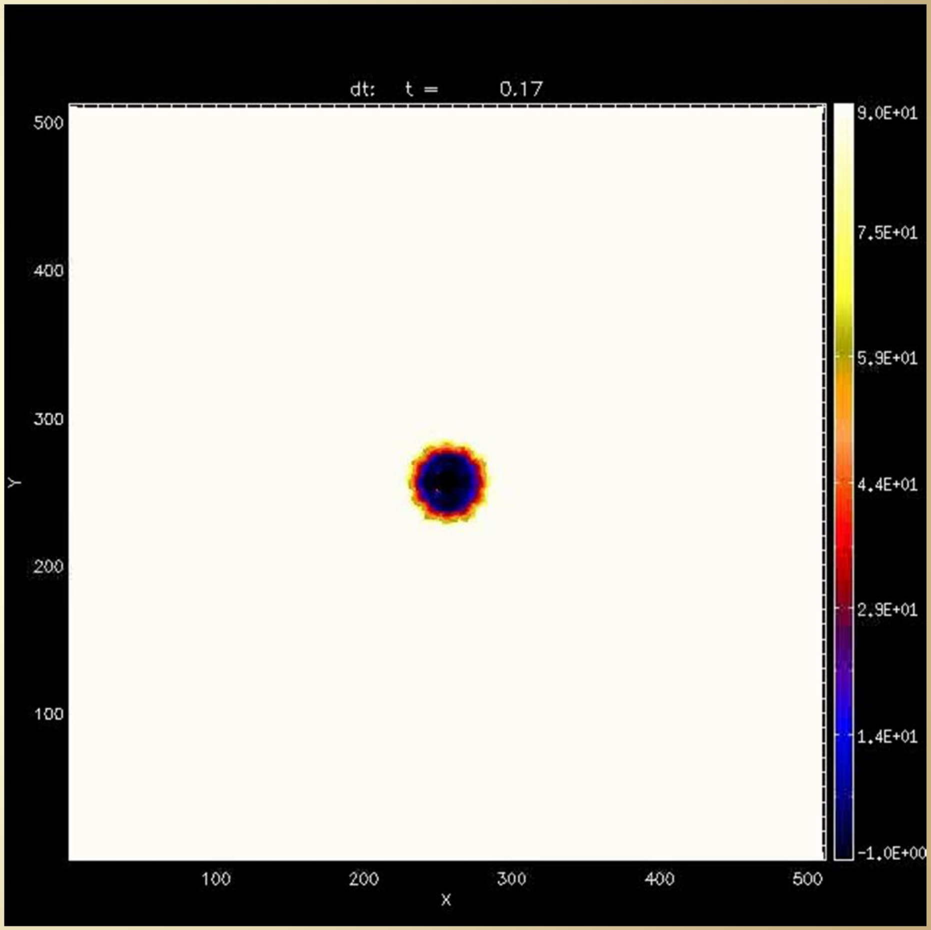


Very large threshold: ΔB=0.5

Self-Adaptive Dynamics in DES

PIC Δt **Field Δt**

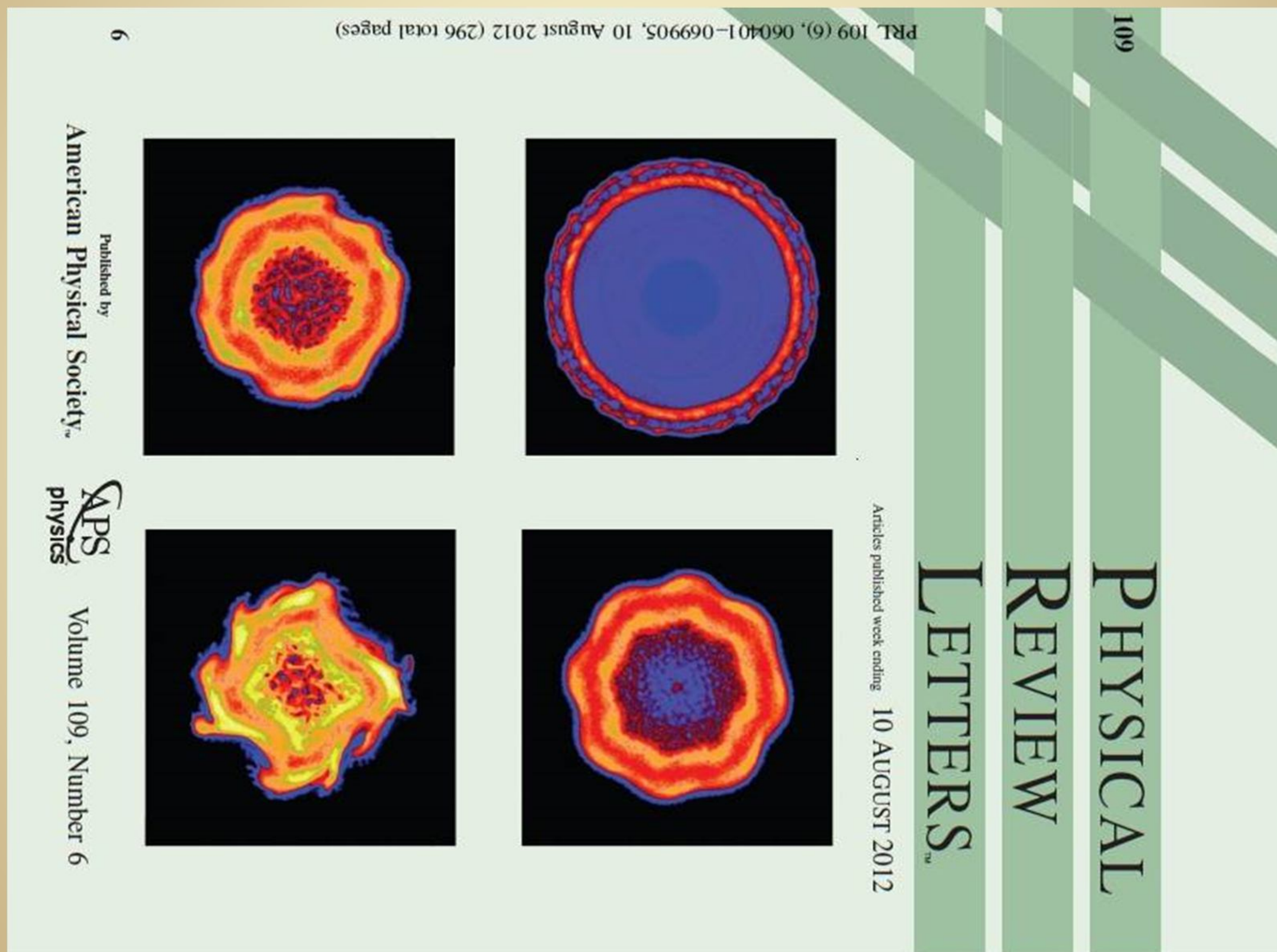




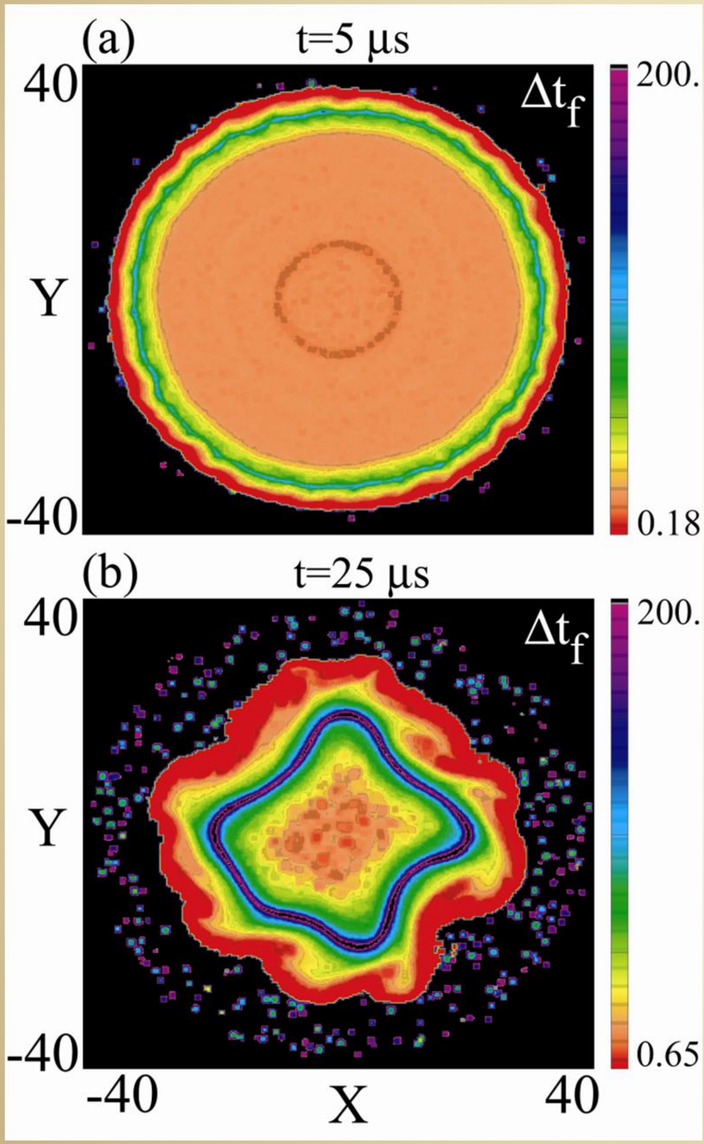
The only code in the world that can do it!

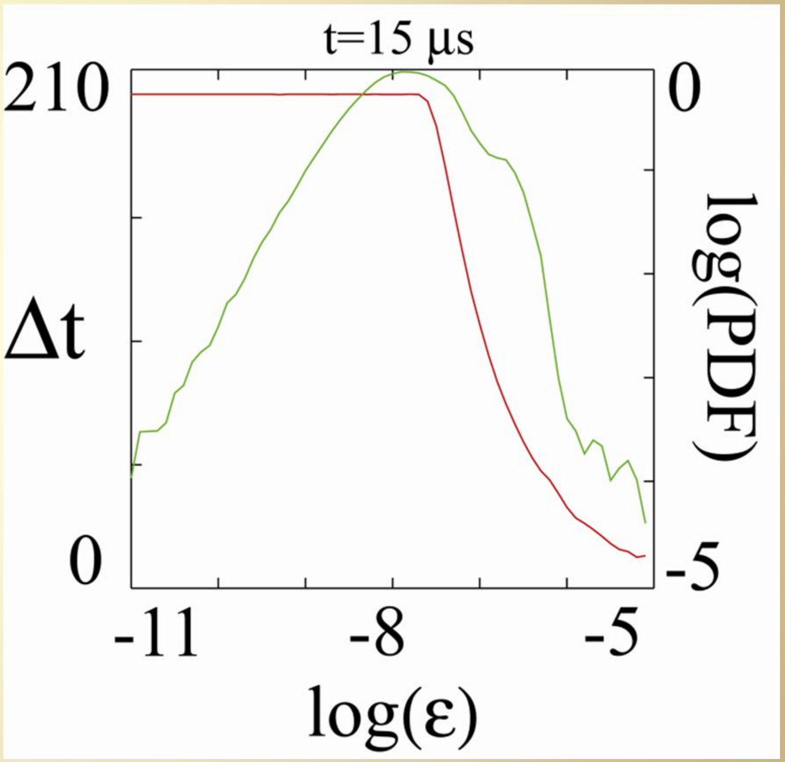
Laboratory Plasmas

Reverse θ-Pinch Discharge

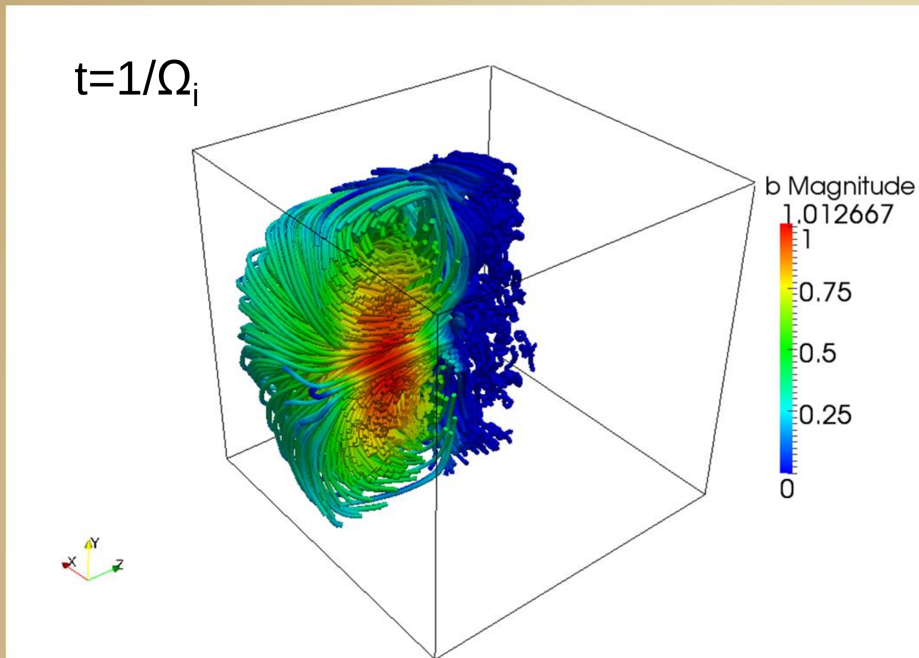


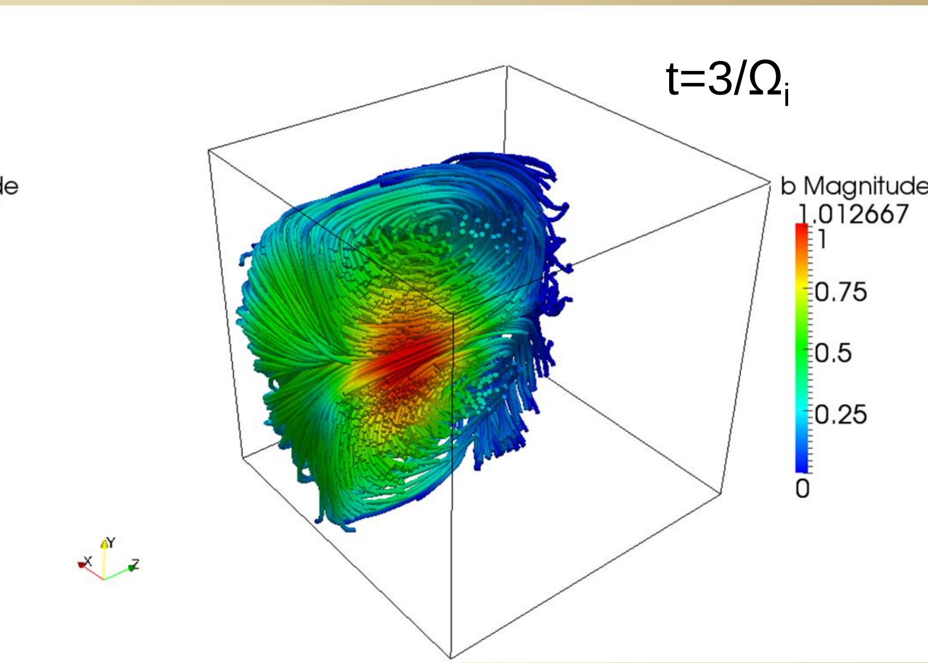
Field-Reversed θ-Pinch (PRL 2012)

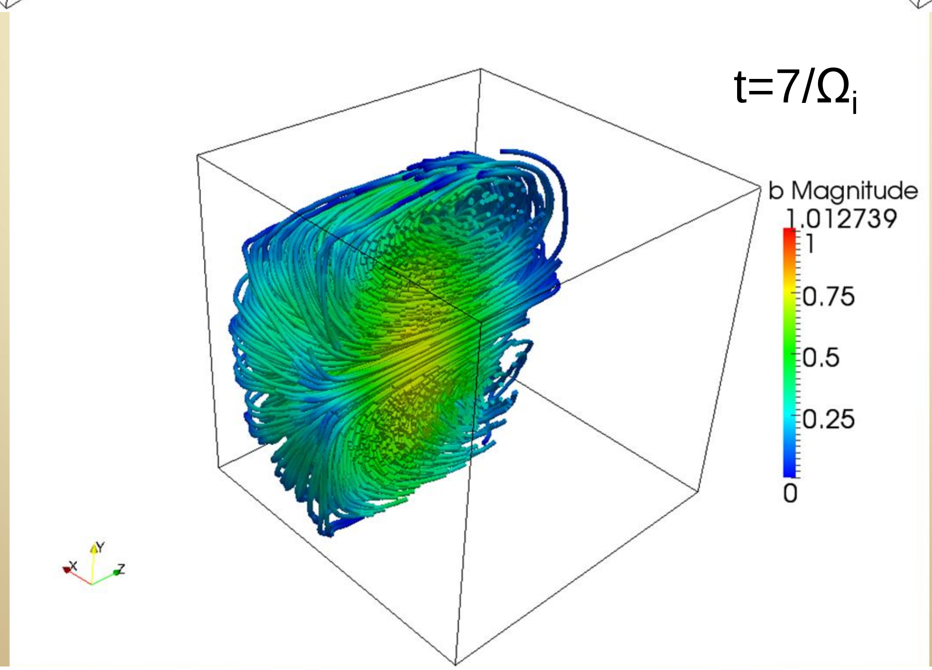




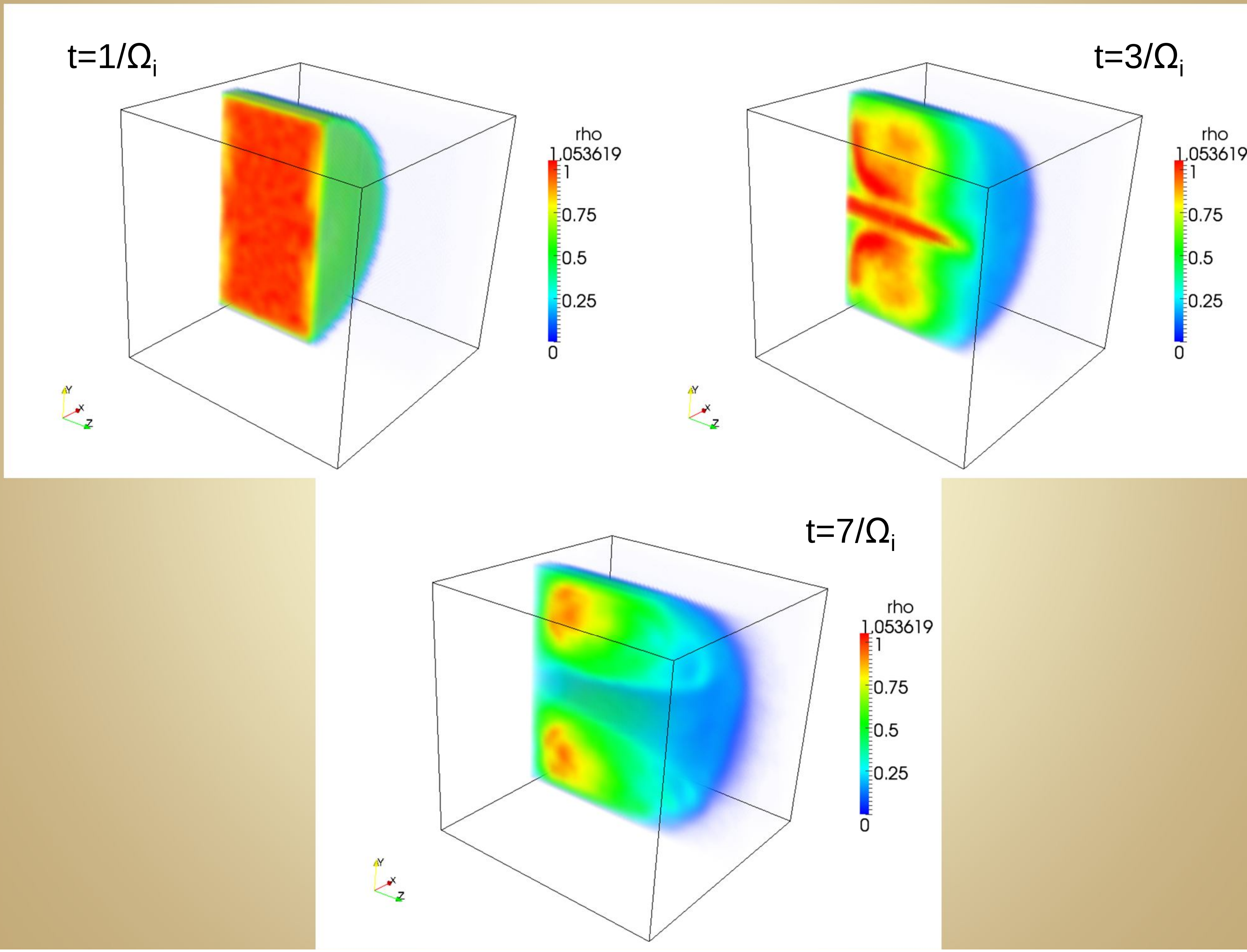
Spheromak Expansion: B-field





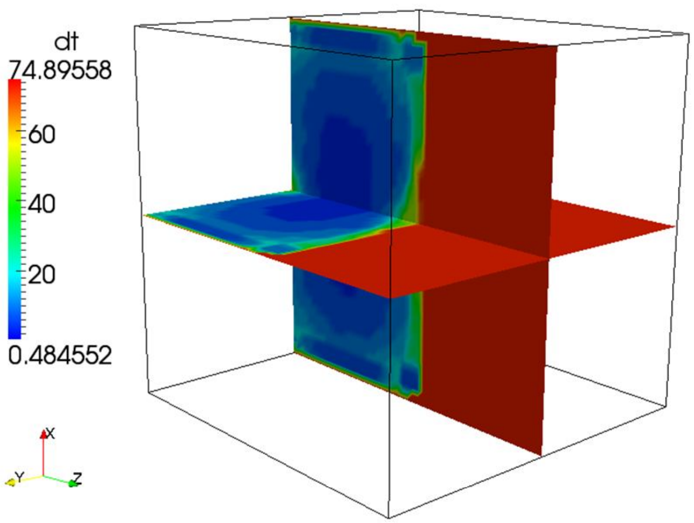


Spheromak Expansion: Density

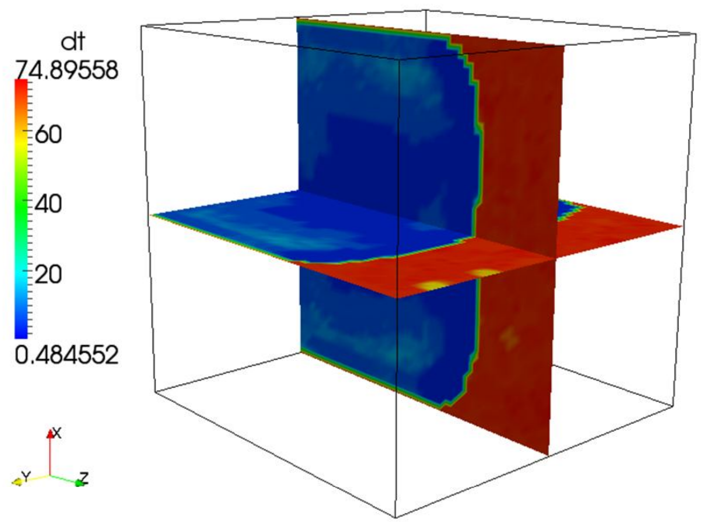


Spheromak Expansion: Field-dt

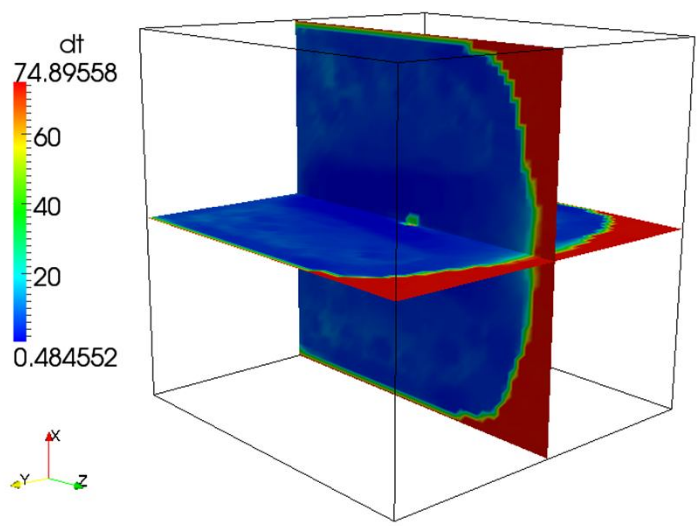
$t=1/\Omega_i$



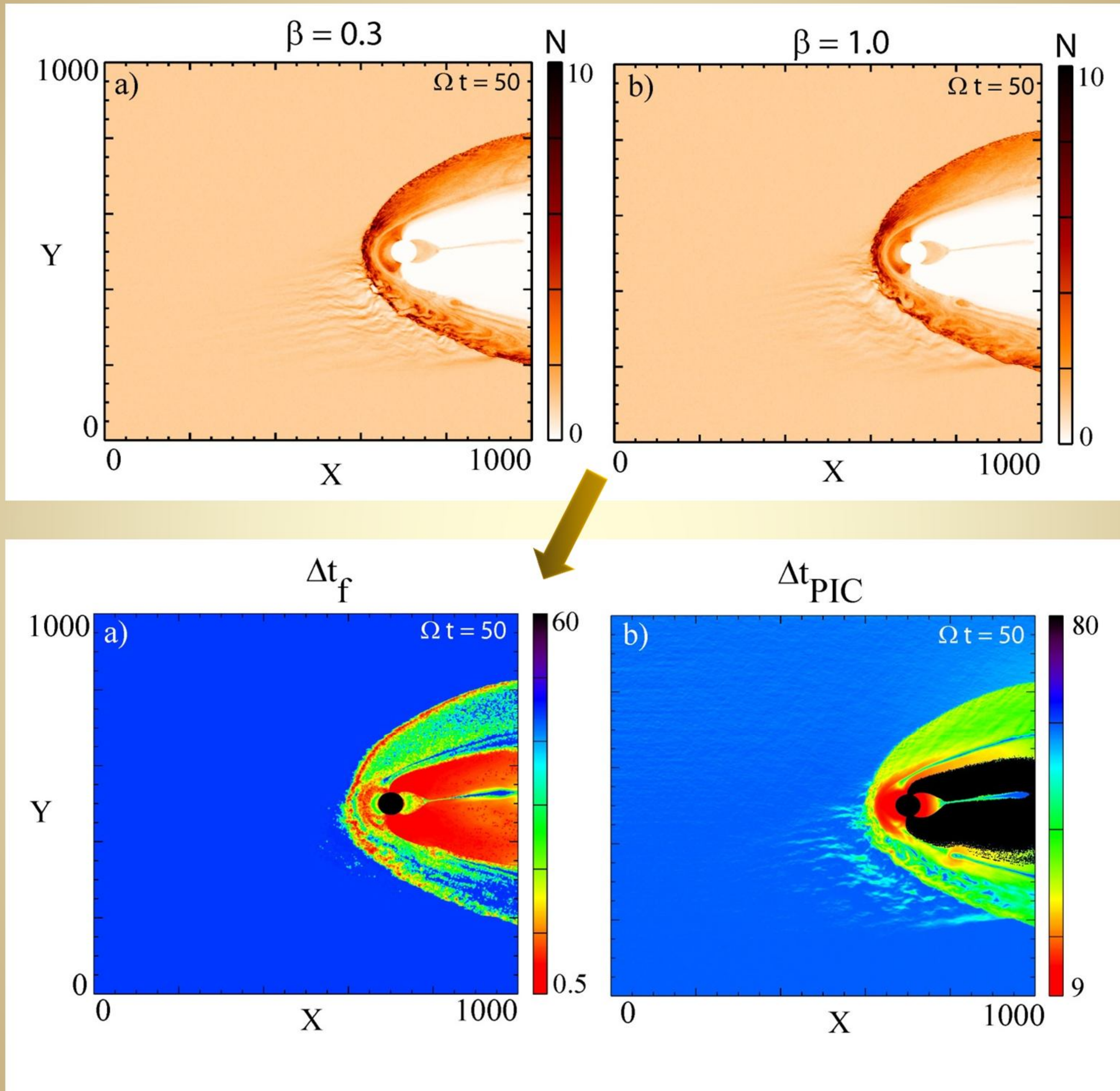
$t=3/\Omega_i$



$t=7/\Omega_i$



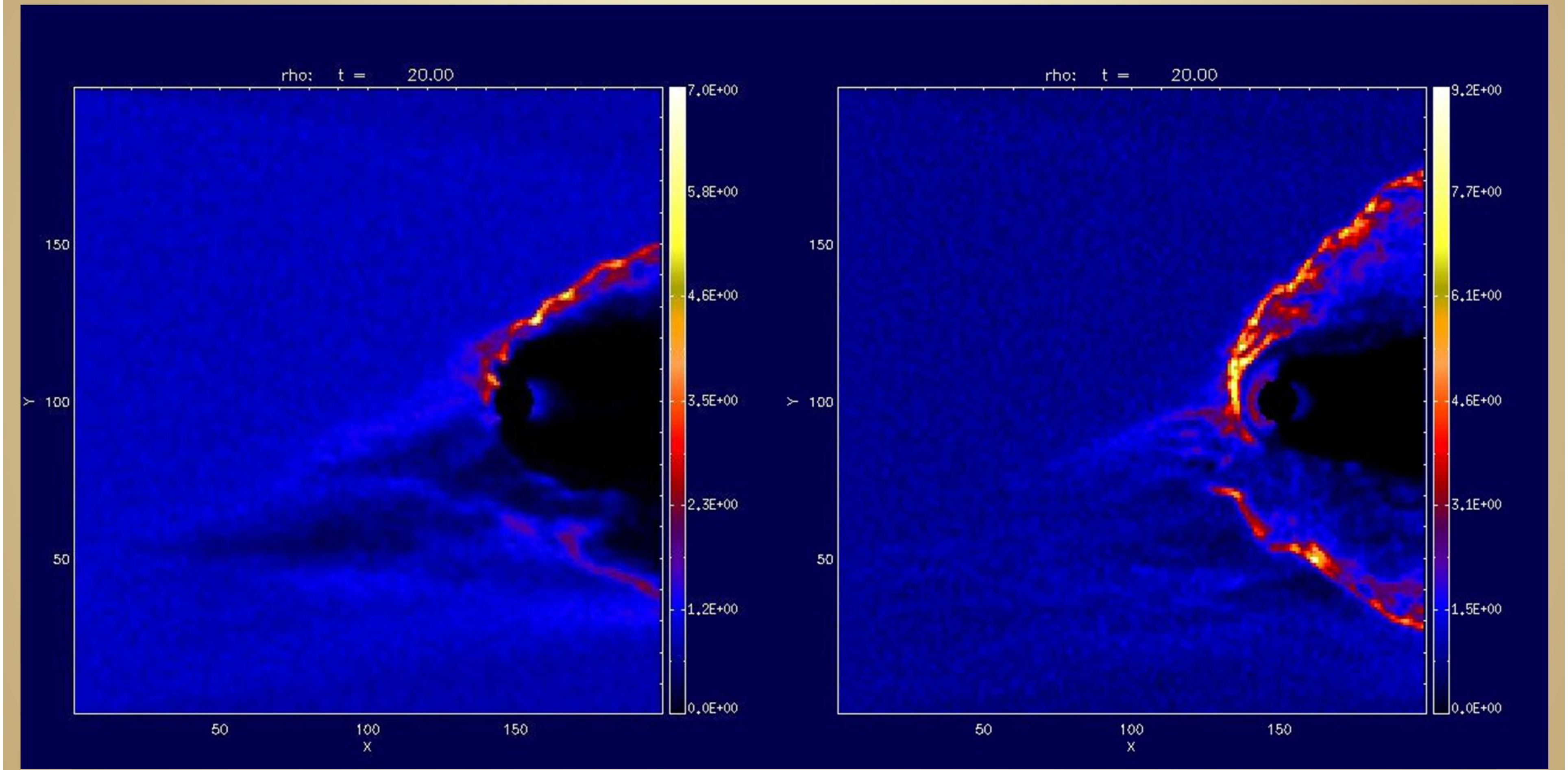
Quasi-Parallel Shocks (2D)



β = 0.3
β = 1.0
N
10
0
a)
b)
Ω t = 50
1000
0
Y
X
Δt_f
Δt_PIC
60
0.5
80
9

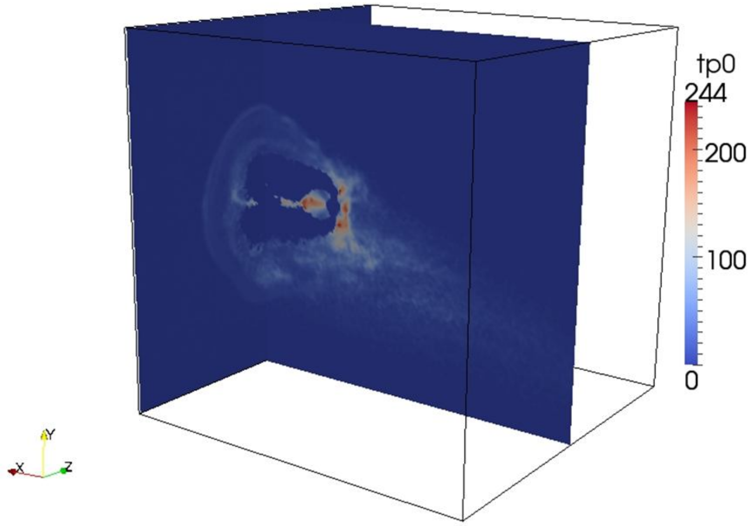
Quasi-Parallel Shocks
(3D – just a few days ago!)

3D   2D

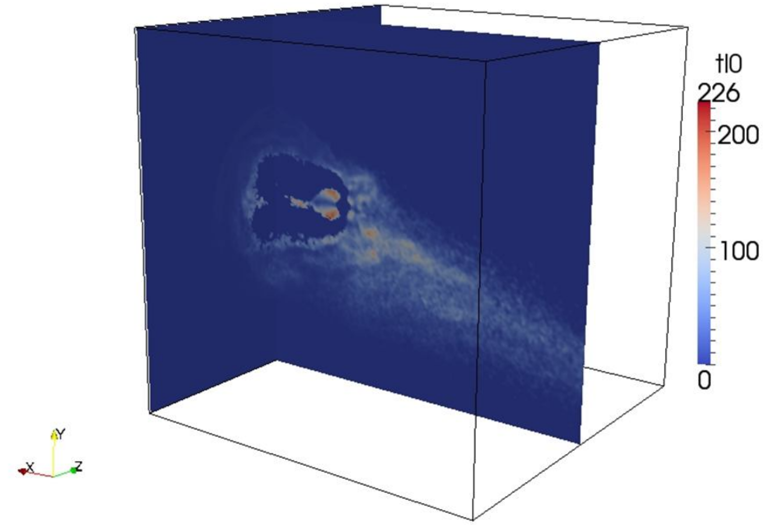


rho: t = 20.00
7.0E+00
5.8E+00
4.6E+00
3.5E+00
2.3E+00
1.2E+00
0.0E+00
150
Y 100
50
50
100
150
X
rho: t = 20.00
9.2E+00
7.7E+00
6.1E+00
4.6E+00
3.1E+00
1.5E+00
0.0E+00
150
Y 100
50
50
100
150
X

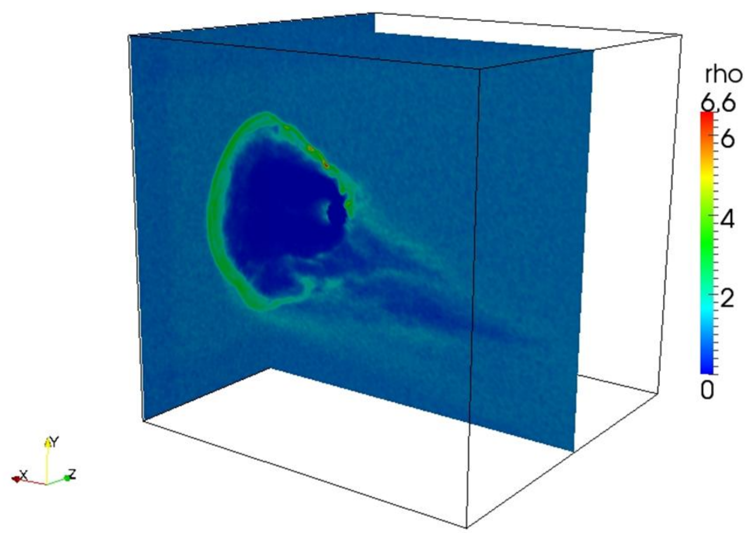
T_{perp}



T_{par}

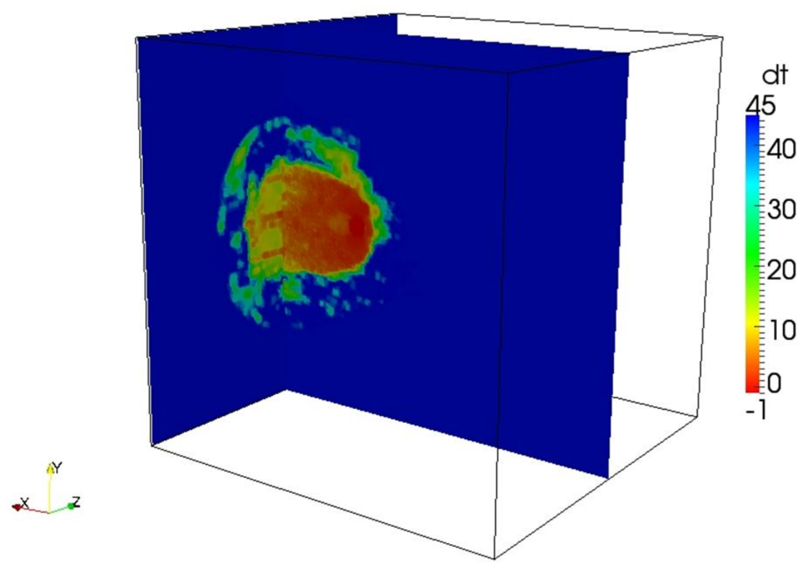


Density

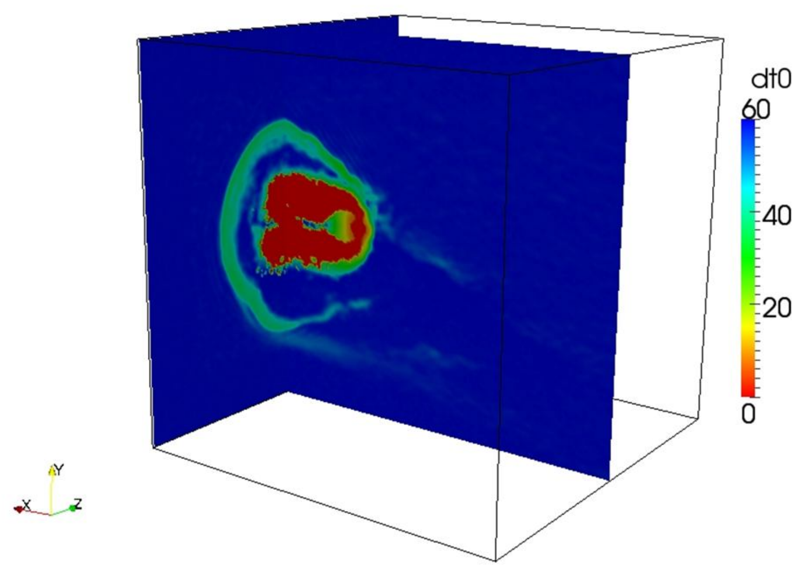


Dynamic load balancing is coming soon

Field Δt

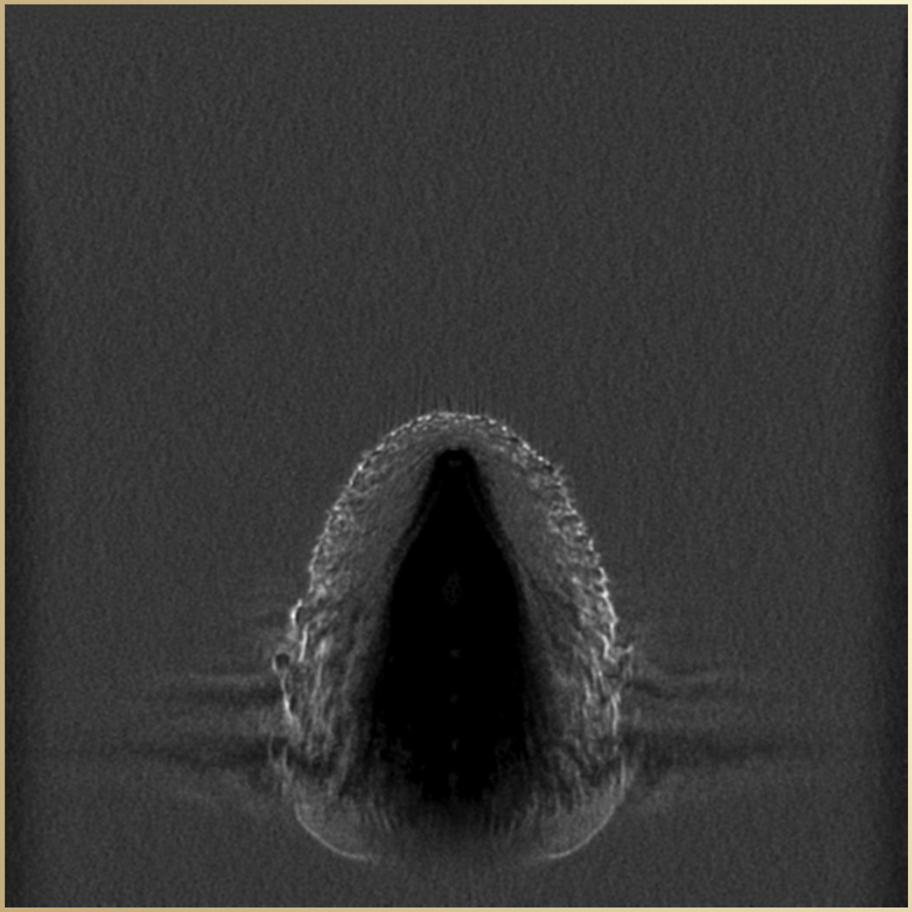


PIC Δt

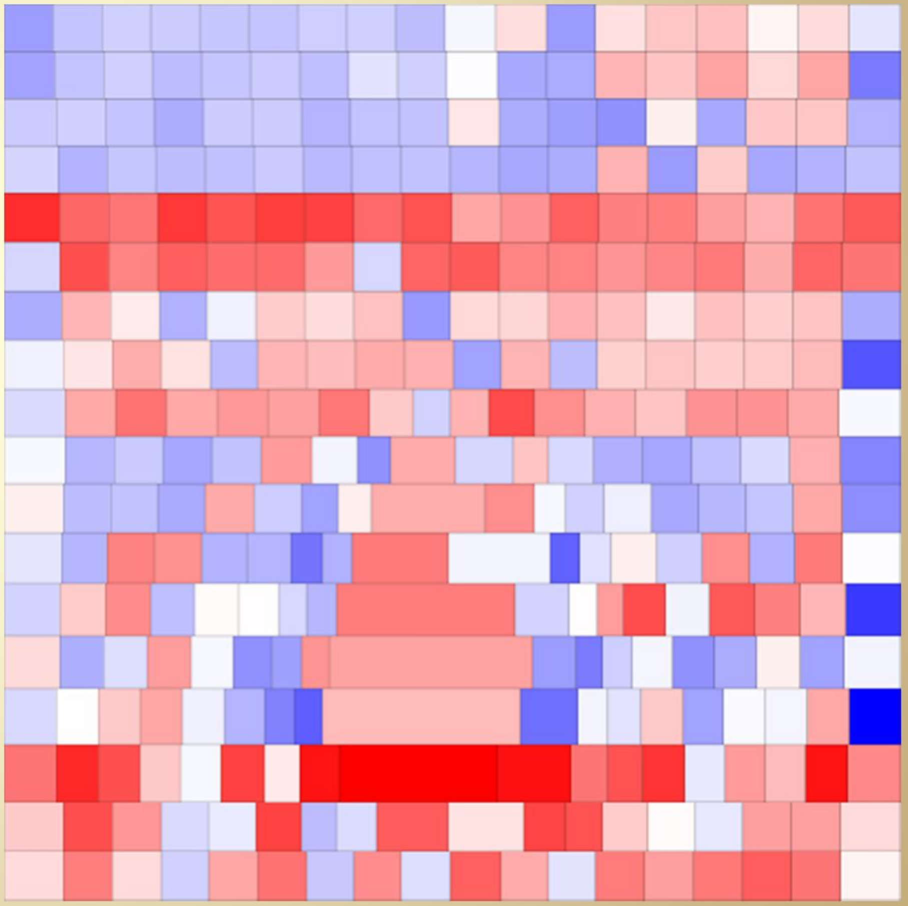


Load balancing Example (18x18 CPUs)

Load



Load imbalance



Summary

►**Hybrid simulations** are revealing new features of the solar wind interaction with the magnetosphere and laboratory plasmas.

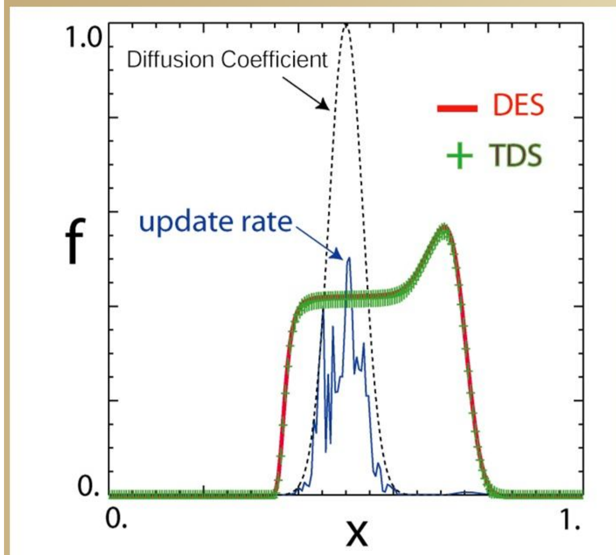
►**Disparate time scales** in global 3D simulations can be addressed with DES. First parallel 3D DES runs have just been performed on 200 cpus.

►**DES** makes possible new advances in global hybrid simulations by enabling: (i) model coupling (e.g., I-M), (ii) new electron physics (e.g., X-Hybrid).

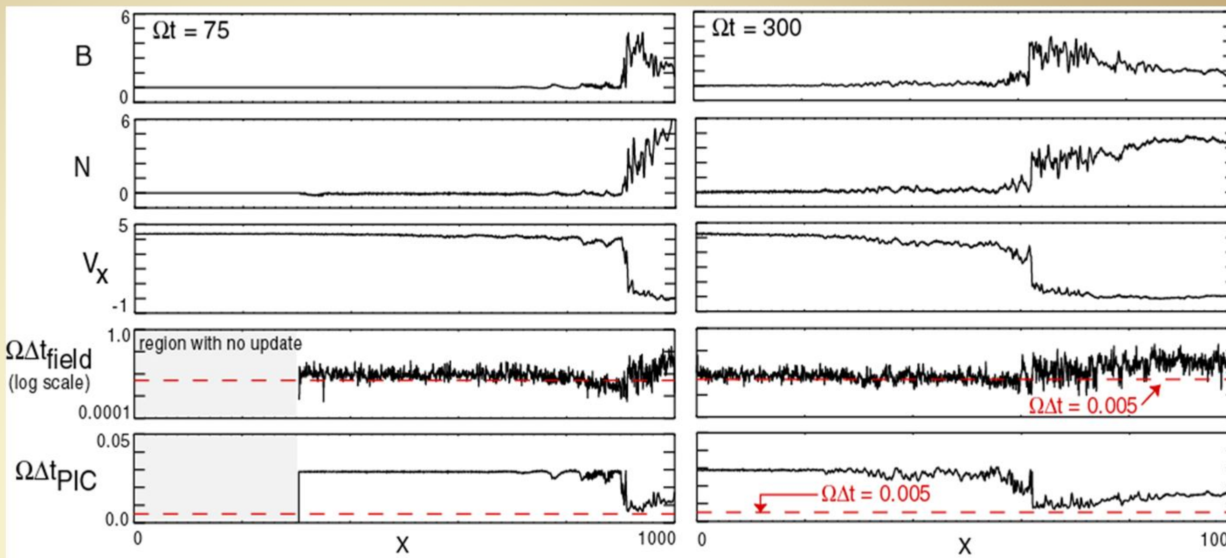
► DES can be applied to **MHD**, **CFD**, **PIC** (turbulence, unstructured grids, higher-order methods, etc).

ASTRONUM 2006-2013

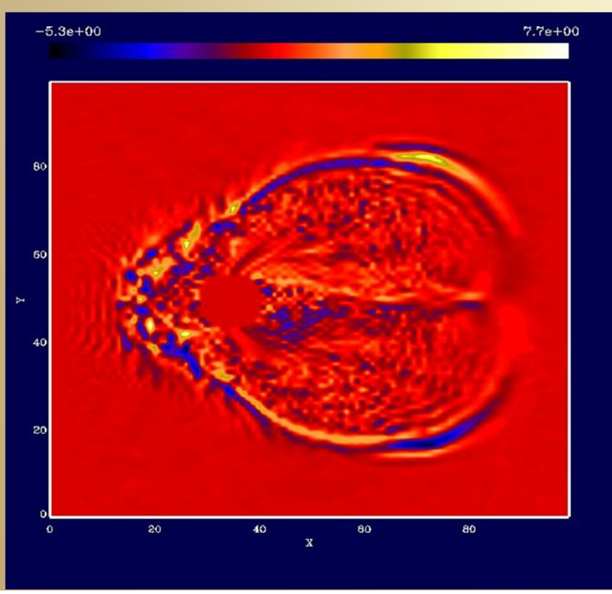
2006: 1D PDEs



2008: 1D Hybrid



2010: 2D Hybrid (serial)



2013: 2D/3D HYPERS (parallel)