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iPic3D

iPIC3D: global planetary simulations

CCMC 2022 Workshop
(College Park, remotely), Wed, 8 June, 2022

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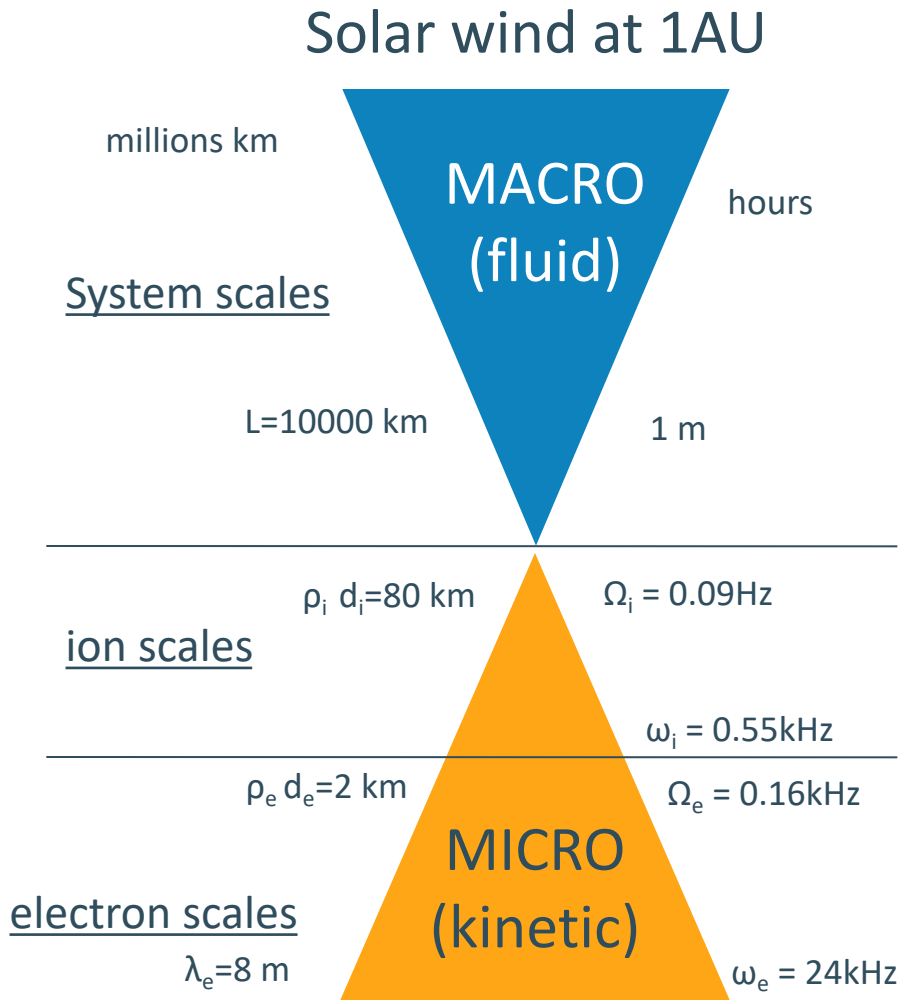
The challenge in modeling space plasmas: multiple scales

- Macroscopic scales are best treated by fluid models
- Microscopic ion scales are best treated by hybrid methods (particle ions and fluid electrons)
- Microscopic electron scales are best treated by fully kinetic methods (electrons and ions are particles)



Explicit and Implicit PIC

EXPLICIT

Operations:

1. Solve Newton equations in previous electromagnetic fields
2. Solve Maxwell equations with previous particle positions

IMPLICIT

Operations:

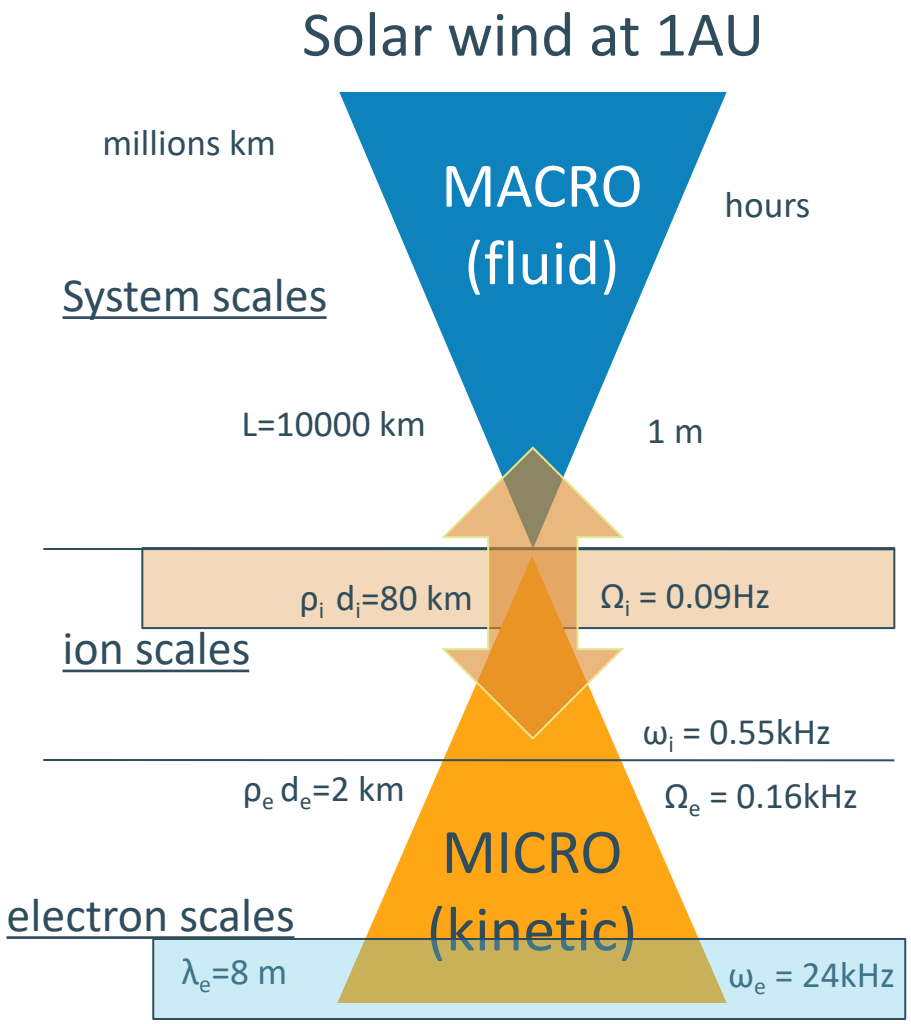
Over each time step,

iteratively solve the two coupled equations until convergence

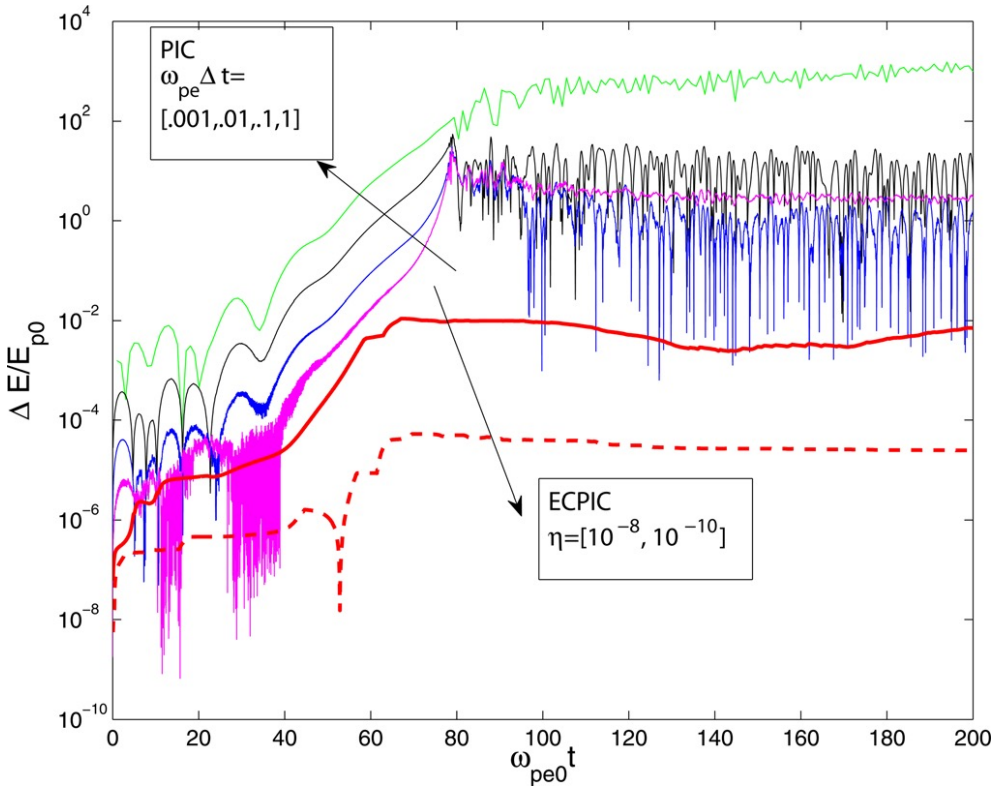
The challenge in modeling space plasmas: multiple scales

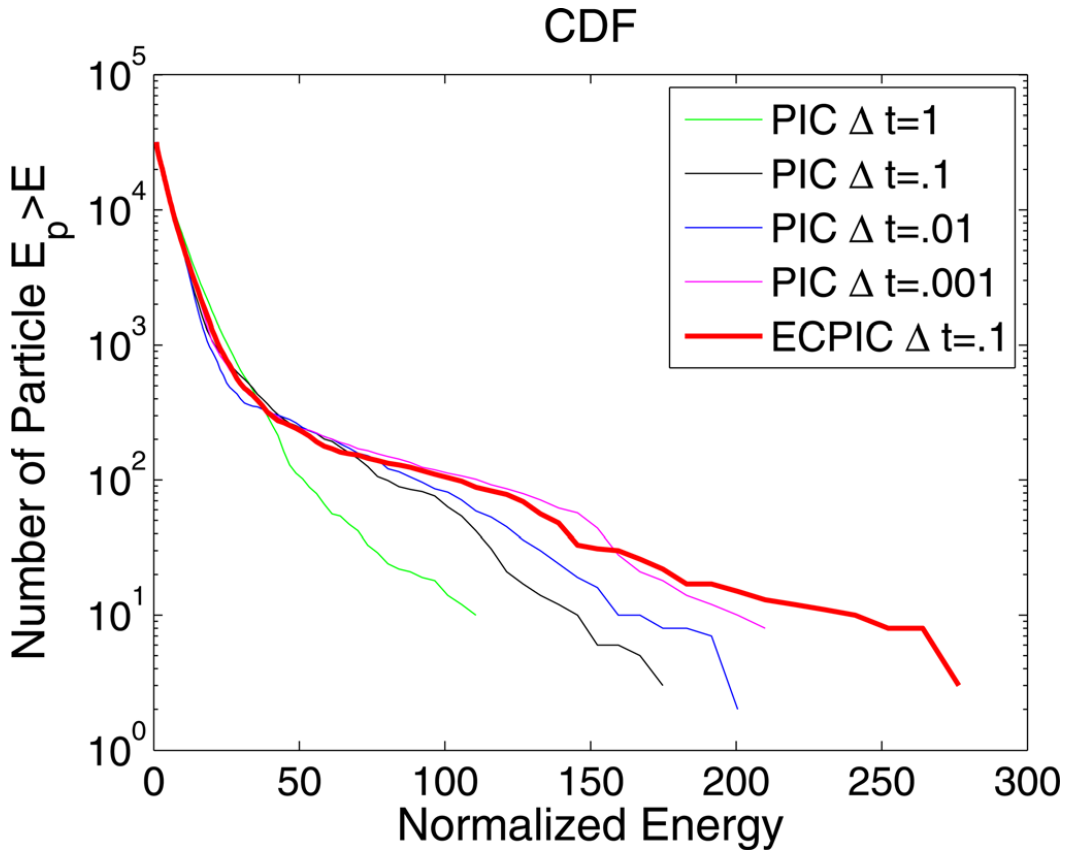
- Explicit methods need to resolve all temporal and spatial scales:
  a) Explicit Maxwell solver: $c\,\Delta t < \Delta x$
  b) Explicit mover : $\omega_{pe}\,\Delta t < 2$
  c) Explicit Particle- Grid coupling: $\Delta x < \xi\lambda_{De}$

- Implicit methods can resolve any range of scales



Critical innovation of implicit PIC: Exact Energy conservation





Implicit PIC development

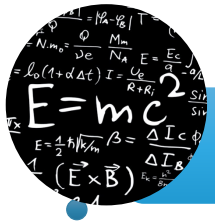
Heterogeneous Computing
Space Weather

heterogeneous computing

CPU-GPU

New direction

Energy conservation



ECsim

ECSIM

Lapenta, JCP, 2017

Energy Conserving Semi-implicit

Heliospheric Grand Challenge

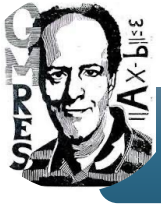
Distributed computing

iPic3D

iPic

Markidis, Lapenta, MCS, 2010

GMRES method



Celeste3D

Celeste

Lapenta, Ricci, Brackbill, PoP, 2005

Numerical Tokamak Project

Vector computers

Venus

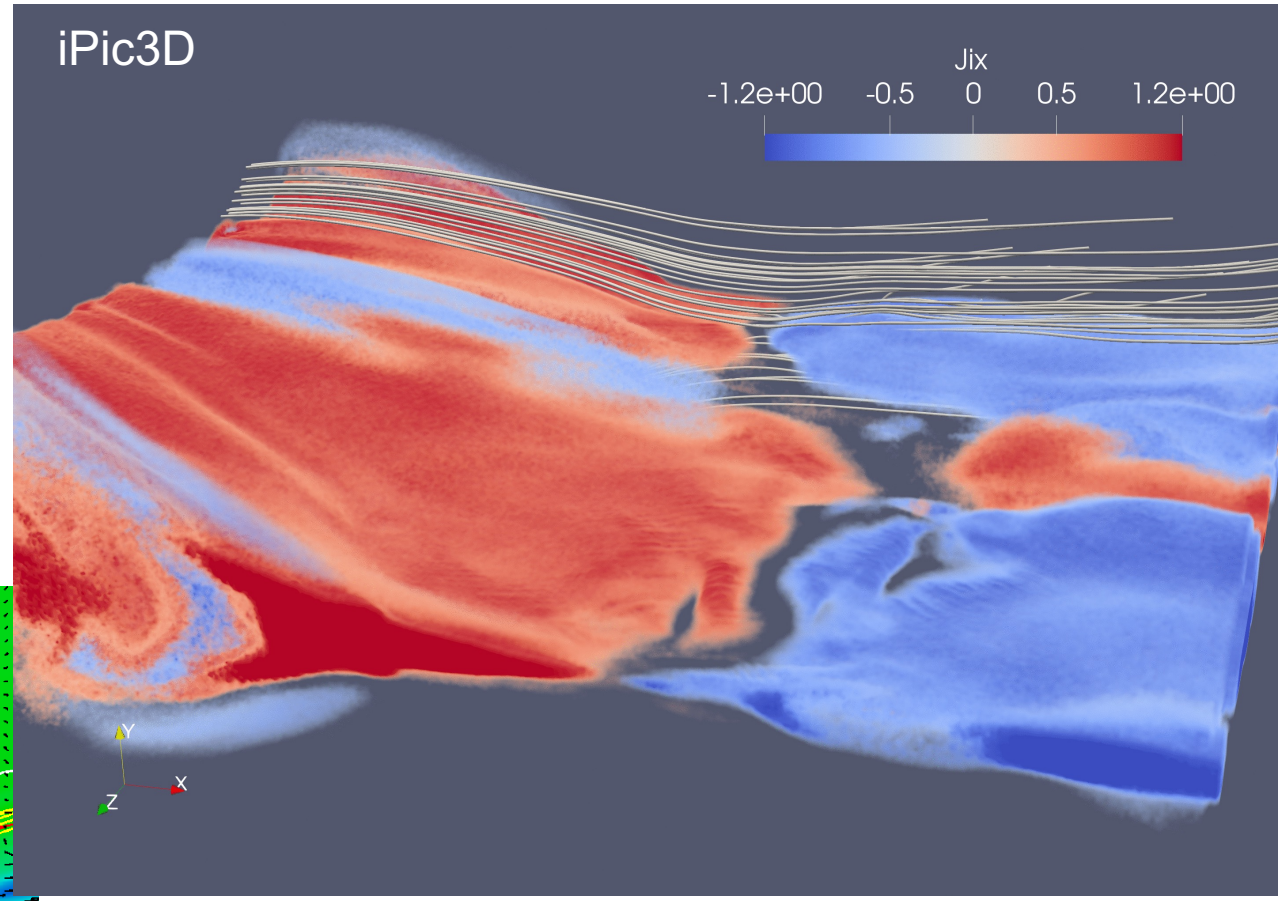
Brackbill, Forslund, JCP, 1985

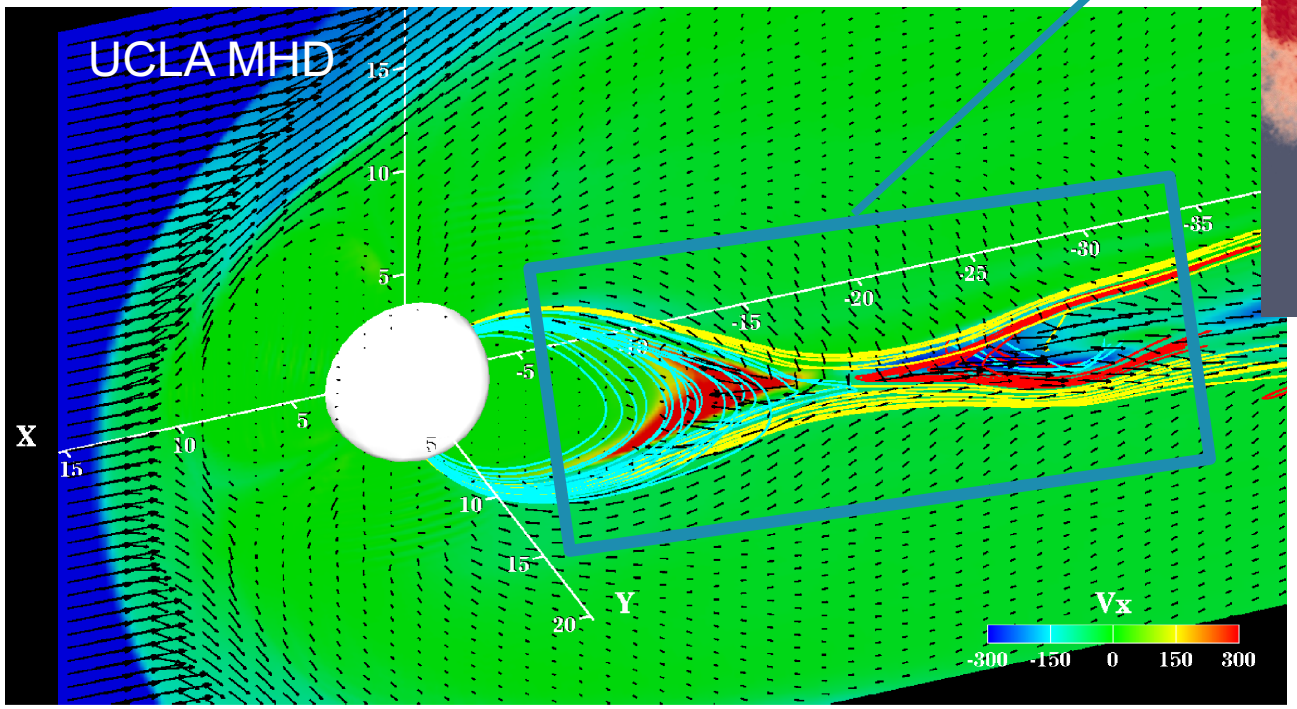
Implicit Moment Method

Los Alamos NATIONAL LABORATORY EST. 1943

iPic3D Global Models

3D PIC simulation spawned from a global MHD model





Details of the approach: Walker, R. J., Lapenta, G., Berchem, J., El-Alaoui, M., & Schriver, D. (2019). Embedding particle-in-cell simulations in global magnetohydrodynamic simulations of the magnetosphere. *Journal of Plasma Physics*, *85*(1).

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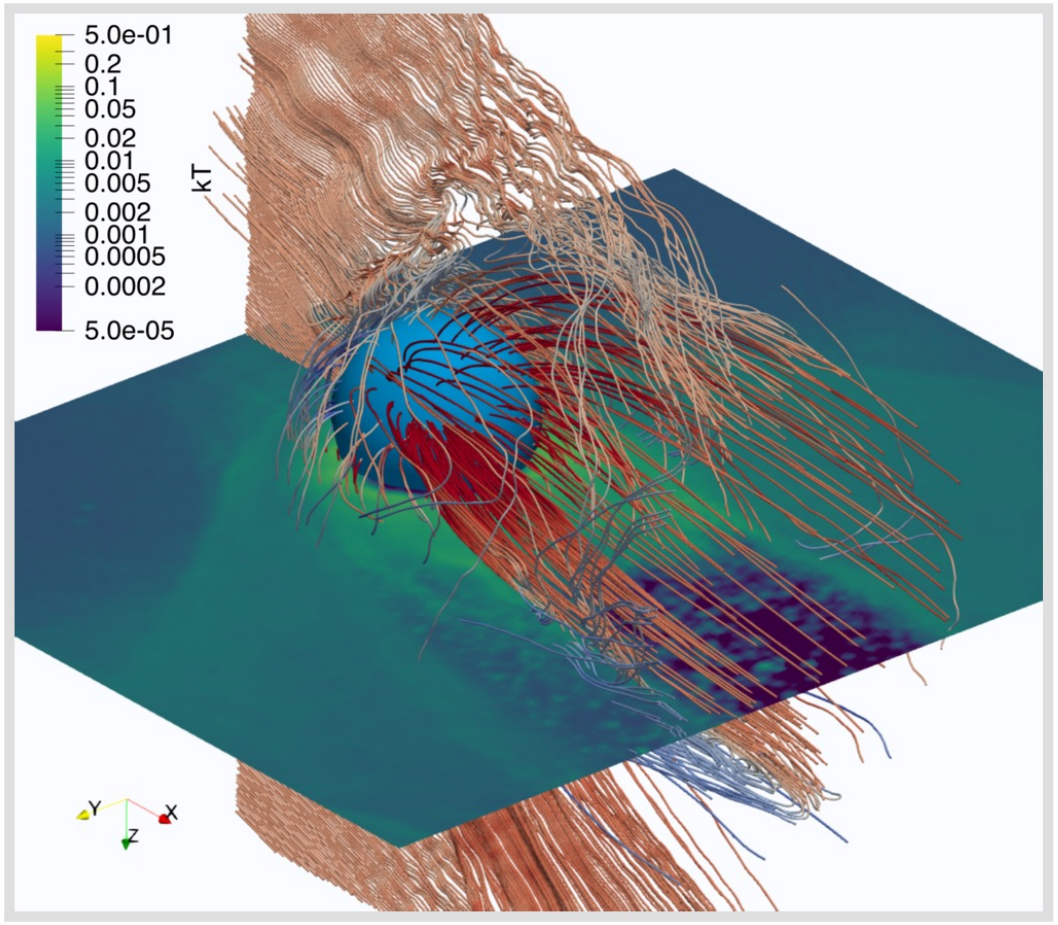
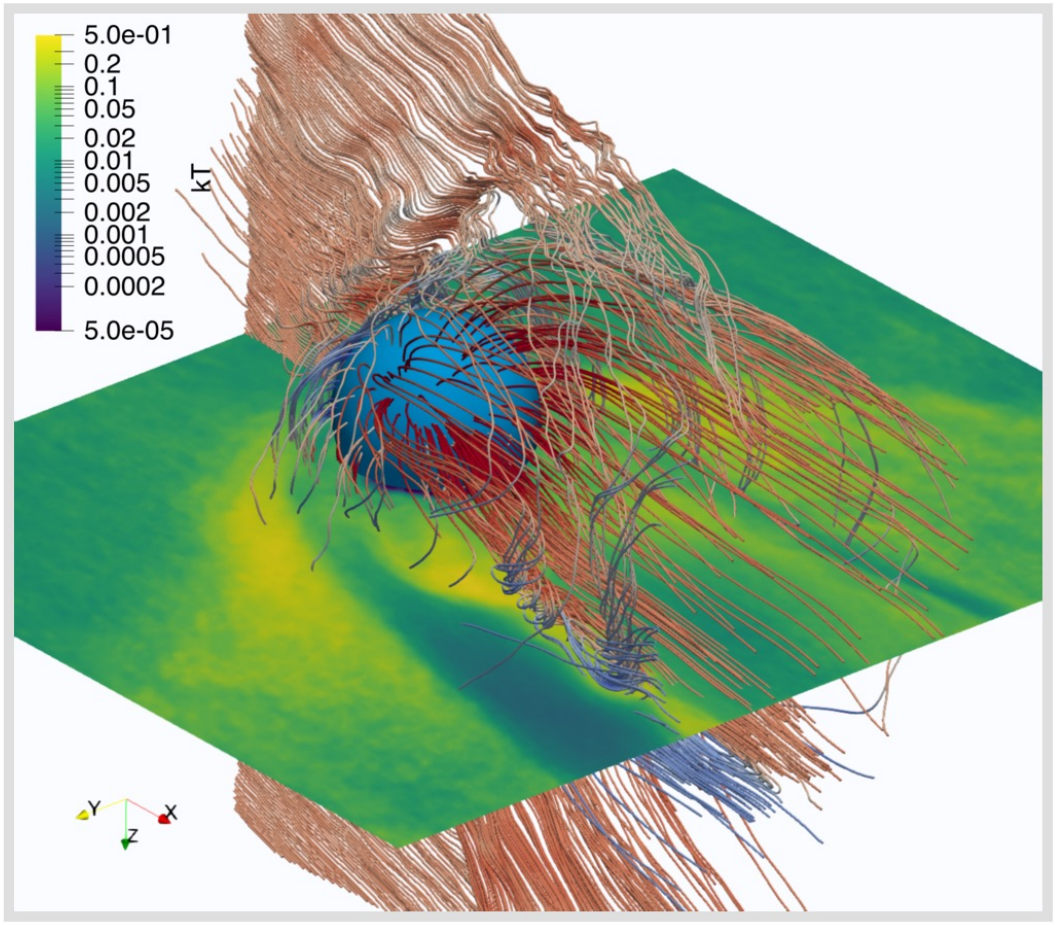
Mercury Global PIC model – Ion Temperature

Hybrid model



Full PIC



Lapenta, et al., J*GR 127, e2021JA030241* (2022).

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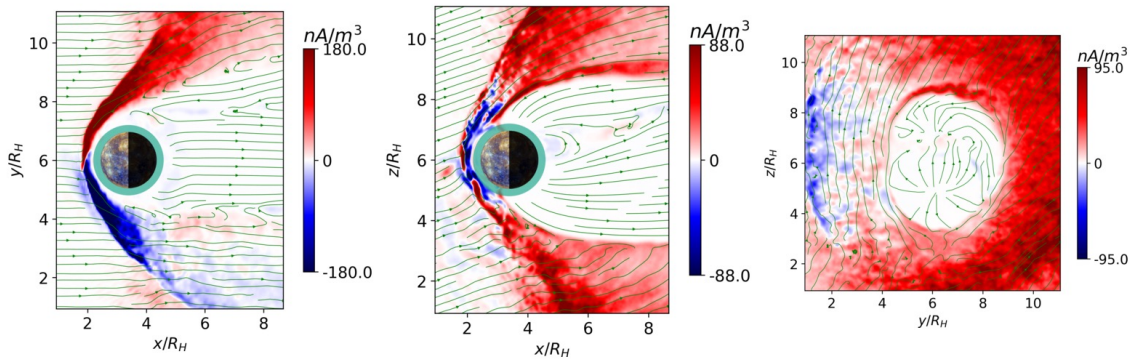
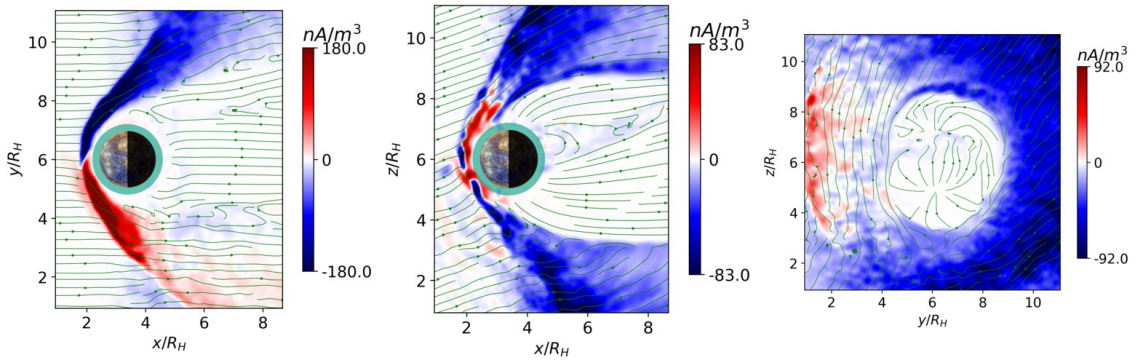
Current interfaces

Current along y: ions



Current along y: electrons



What would have been the cost with other methods

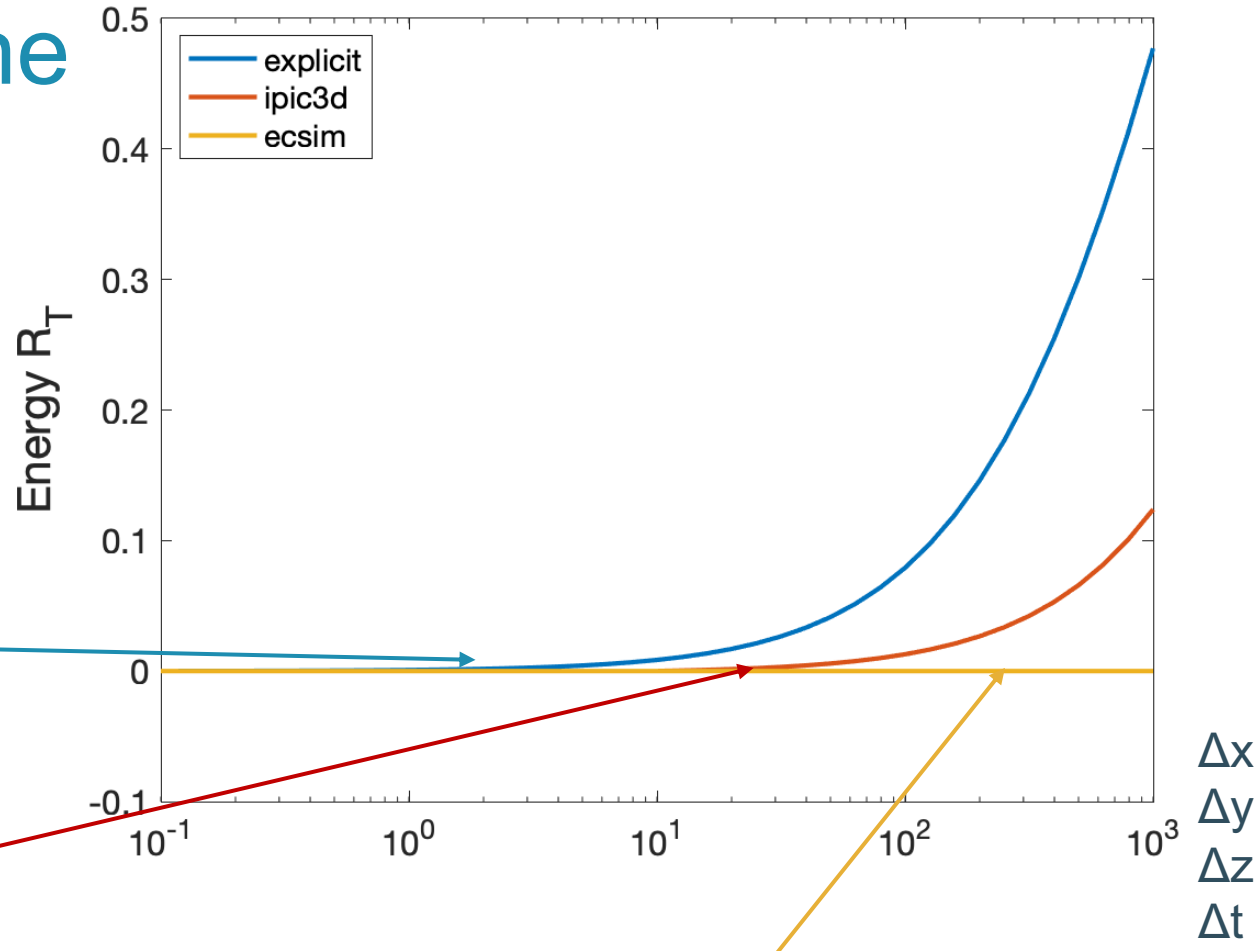
Processors scale like (Δx * Δy * Δz)

CPU Time scales like (Δx * Δy * Δz * Δt)

Explicit: 30 billion procs
Wallclock: 48hrs
CPU time: 150 trillion hours

iPic3D: 30 million processors
Wallclock: 48hrs
CPU time: 15 billion hours

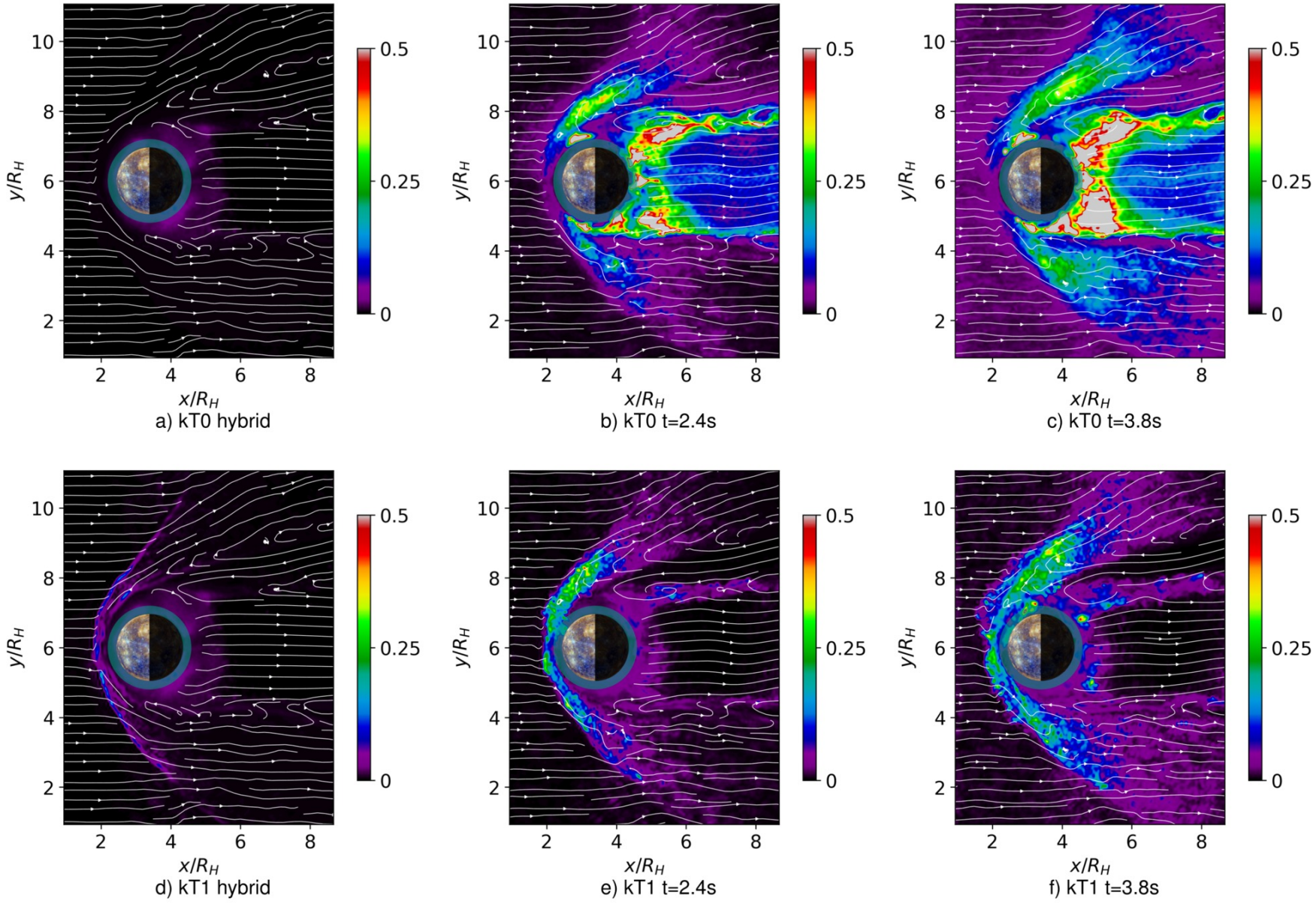
Ecsim: 30,000 processors
Wallclock: 48hrs
CPU time: 1.5 million hours



Energization

Electrons

Ions



Lapenta, et al., JGR 127, e2021JA030241 (2022).

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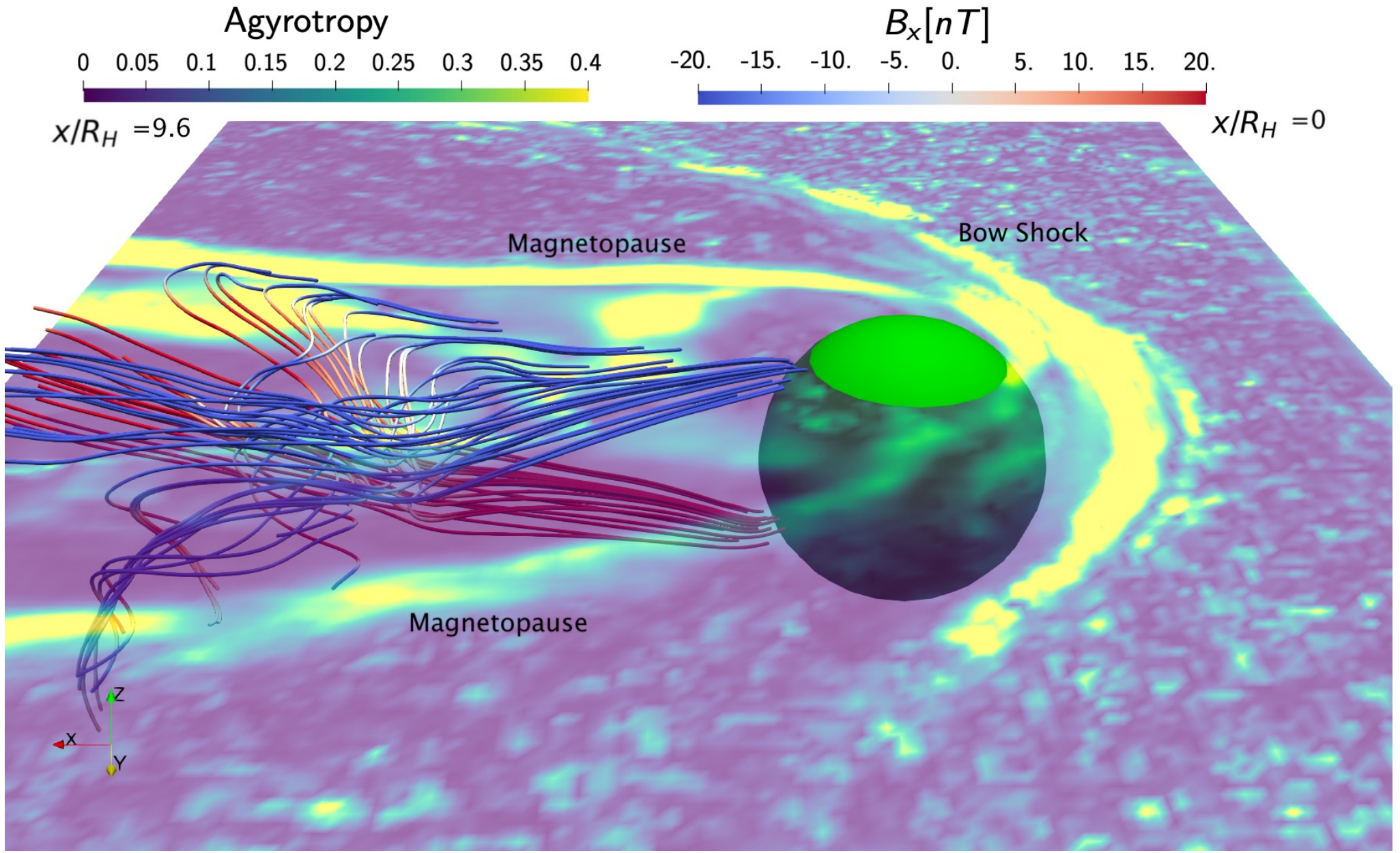
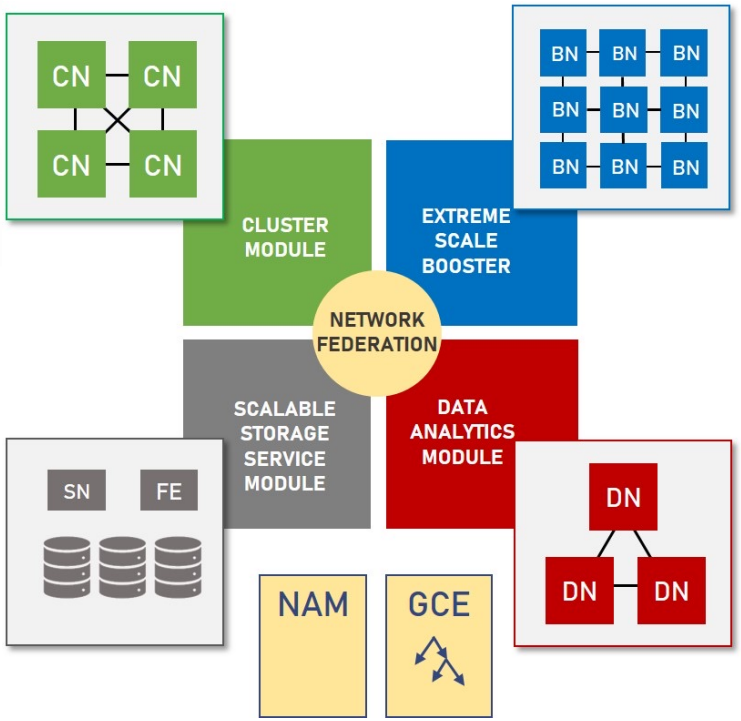
Reconnection regions

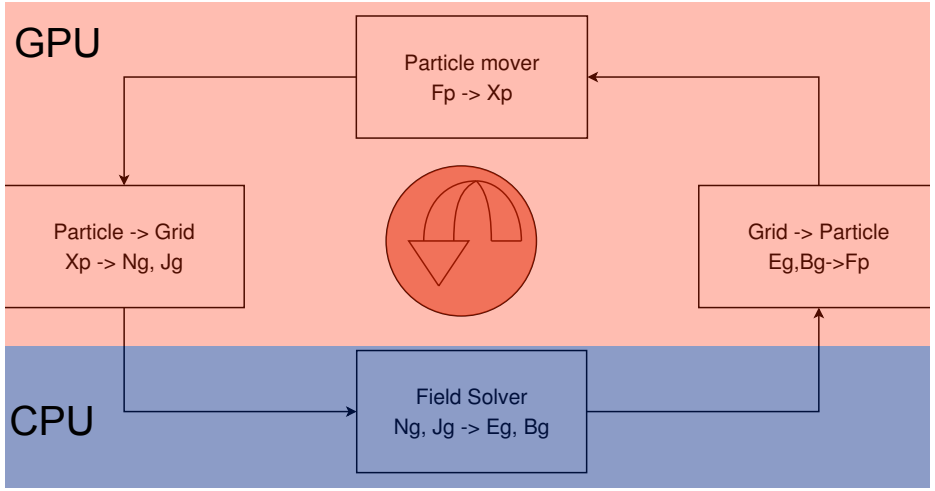


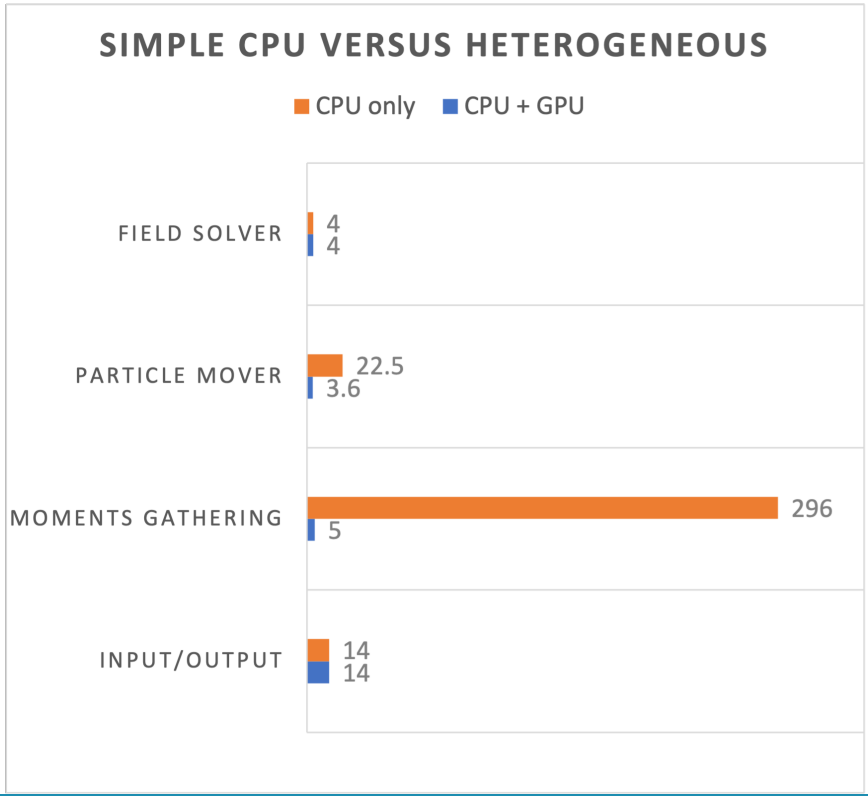
Lapenta, et al., JGR 127, e2021JA030241 (2022).

From Mercury to Earth

DEEP







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Acknowledgments

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The End

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