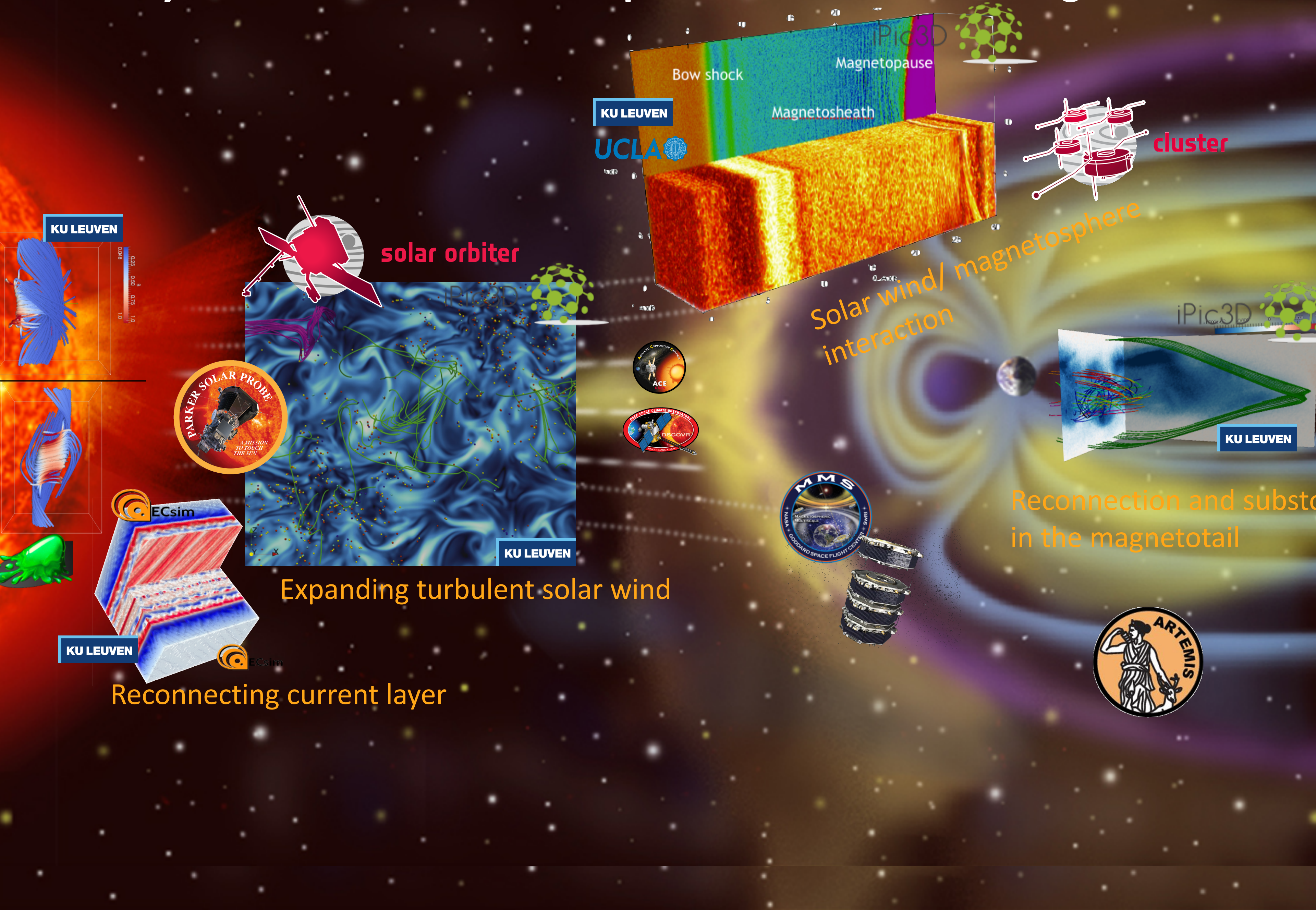
Coupling Fluid and Kinetic Scales for Space Weather Applications

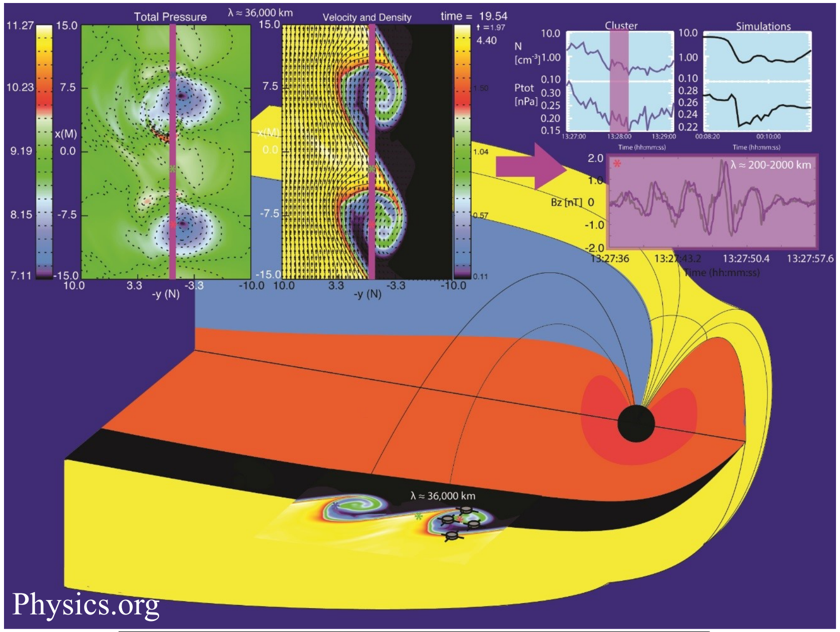
G. Lapenta, S. Poedts, R. Keppens, M.E. Innocenti, V. Olshevsky, D. González-Herrero, E. Boella, F. Pucci, J. Amaya, F. Bacchini, K. Makwana

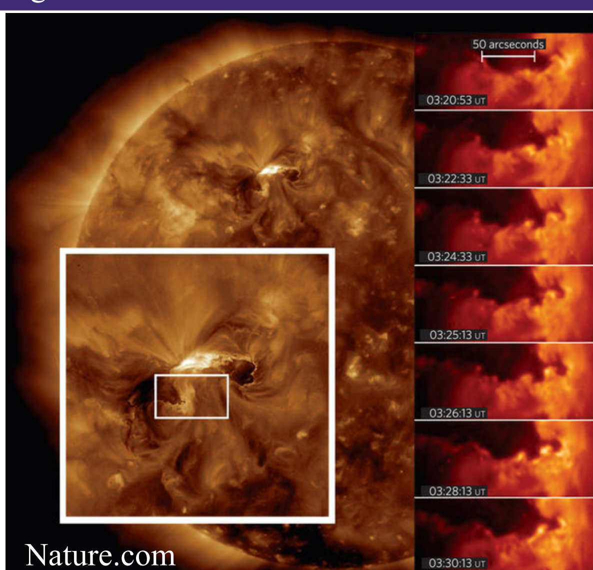
J. Berchem, R. Walker, M. El Alaoui, M. Zhou

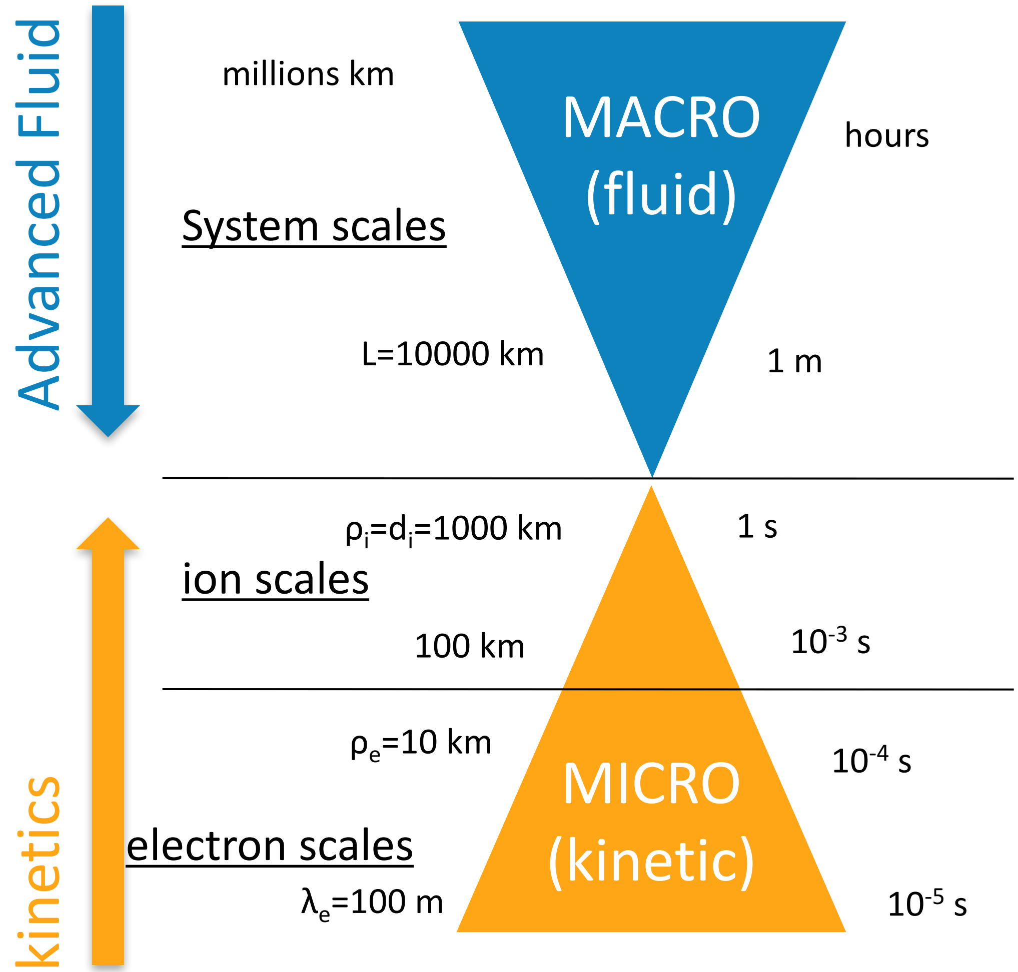
Why do we need kinetics in space weather forecasting?



The challenge in modeling space plasmas: multiple scales







Kinetic Models

xPic — Lapenta et al, CPC, 2017.

Hybridcomputing – Towards Exascale (support from EC)

Exactly energy Conserving PIC (support form AFSOR)

ECSIM — Lapenta, JCP, 2017;

Distributed computing

iPic3D — Markidis, Lapenta, MCS, 2010

Workstations

GMRES Solver for non-symmetric matrices

Vector Computing

Celeste — Lapenta, Ricci, Brackbill, PoP, 2005

Venus — Brackbill, Forslund, JCP, 1985

Evolving geometric tensor from particles (support form AFSOR)

SLURM — Bacchini, Olshevsky, Poedts, Lapenta, CPC, 2017

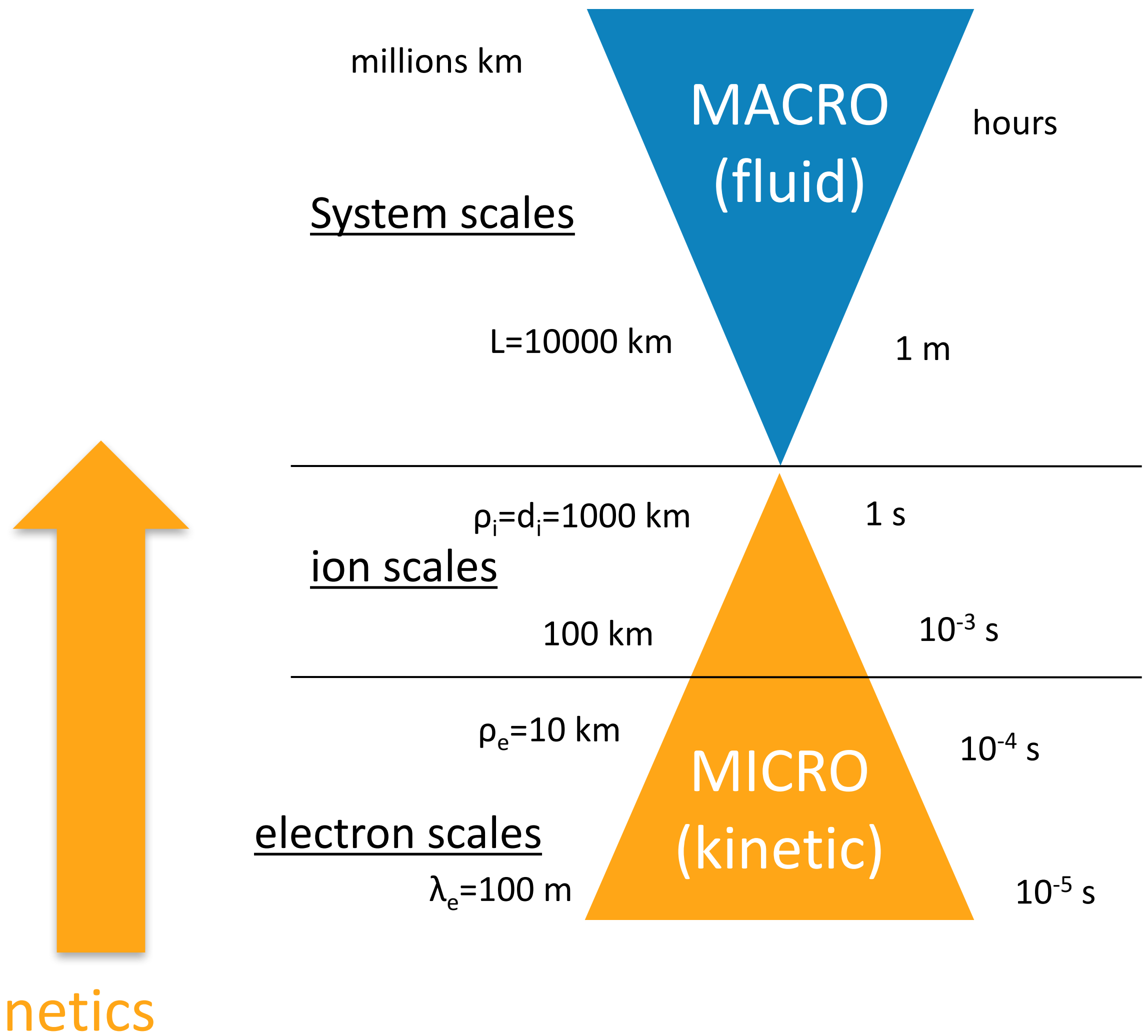
Fluid (MHD) Models

Flip3DMHD — Brackbill, JCP, 1991

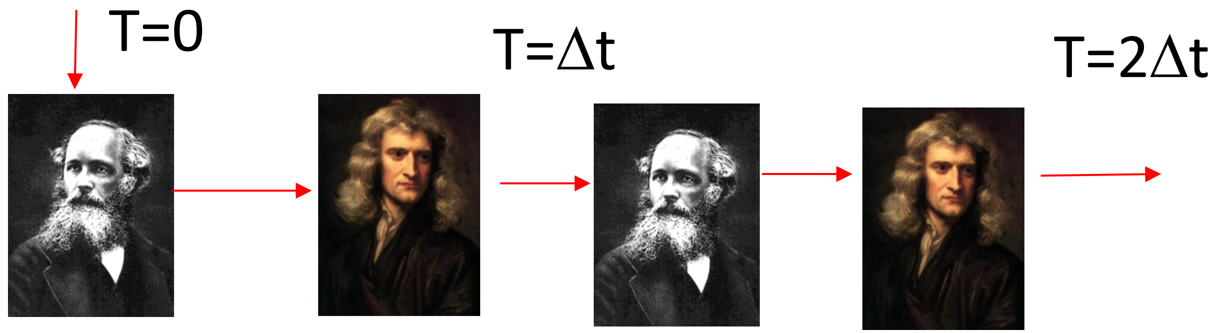
The challenge in modeling space plasmas: multiple scales

Bottom up:

- Making kinetic codes capable of handling larger scales
- Development of methods capable of working at all scales
- Need to remove stability constraints



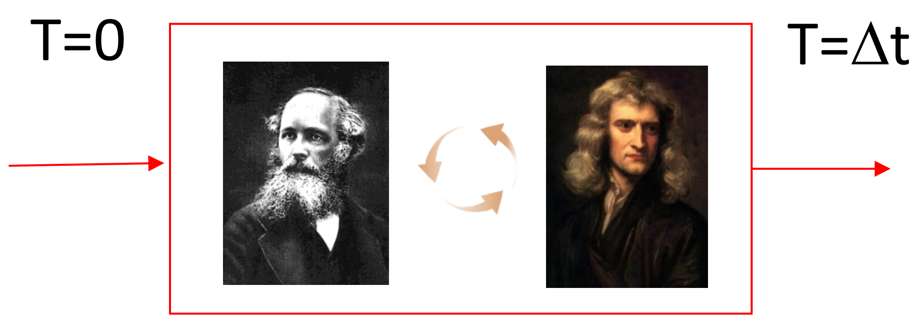
Explicit and implicit Computational approaches



EXPLICIT

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

Implicit Particle in cell



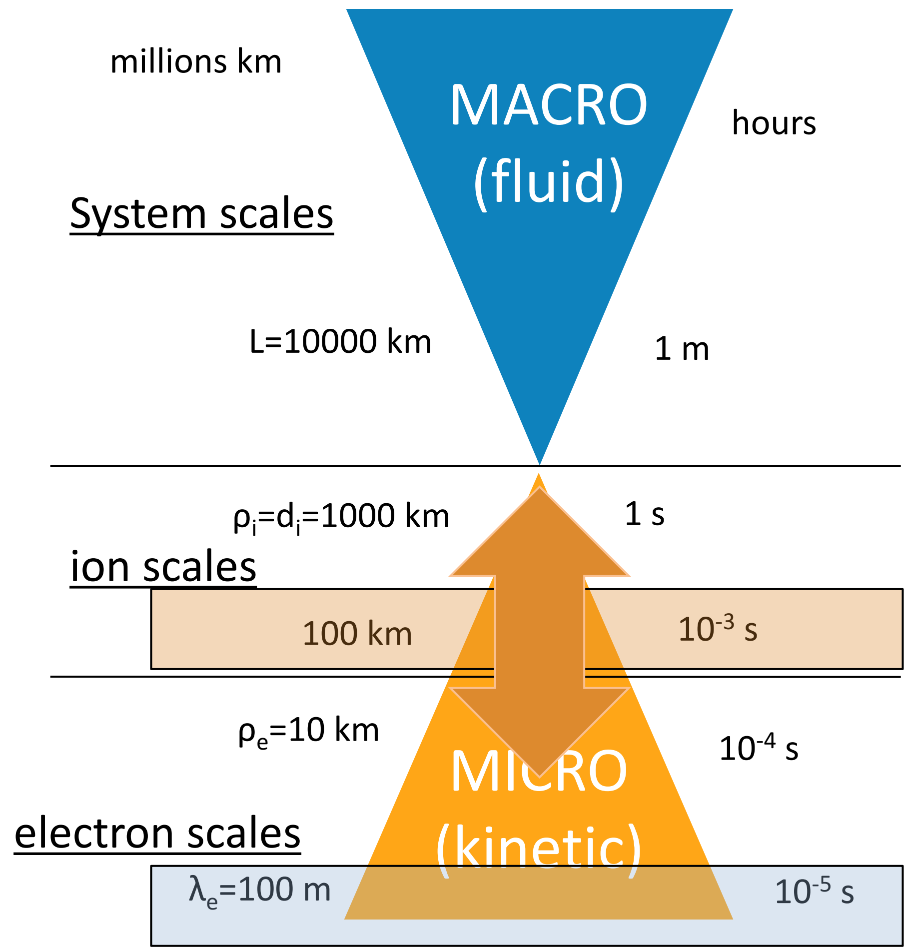
IMPLICIT

Over each time step, iteratively solve the two coupled equations until convergence

The challenge in modeling space plasmas: multiple scales

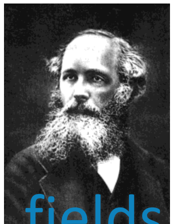
- Explicit methods need to resolve all temporal and spatial scales:
  a) Explicit Maxwell solver: $c\,\Delta t < \Delta x$
  b) Explicit mover : $\omega_{pe}\,\Delta t < 2$
  c) Explicit Particle- Grid coupling: $\Delta x < \xi\lambda_{De}$

- Implicit methods can resolve any range of scales



Semi implicit energy conserving

T=0



fields

particles

T=Δt

Non-linear Newton- Krylov iteration

IMPLICIT

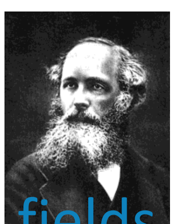
Preconditioners

Formulate the plasma response using the mass matrix **mass matrix**

Enforcing **energy conservation**

Lapenta, JCP, 334, 2017; Lapenta, Gonzalez-Herrero, Boella, JPP, 83.2, 2017.

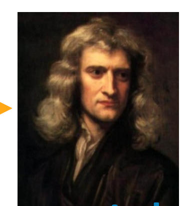
T=0



fields

matrix

T=Δt

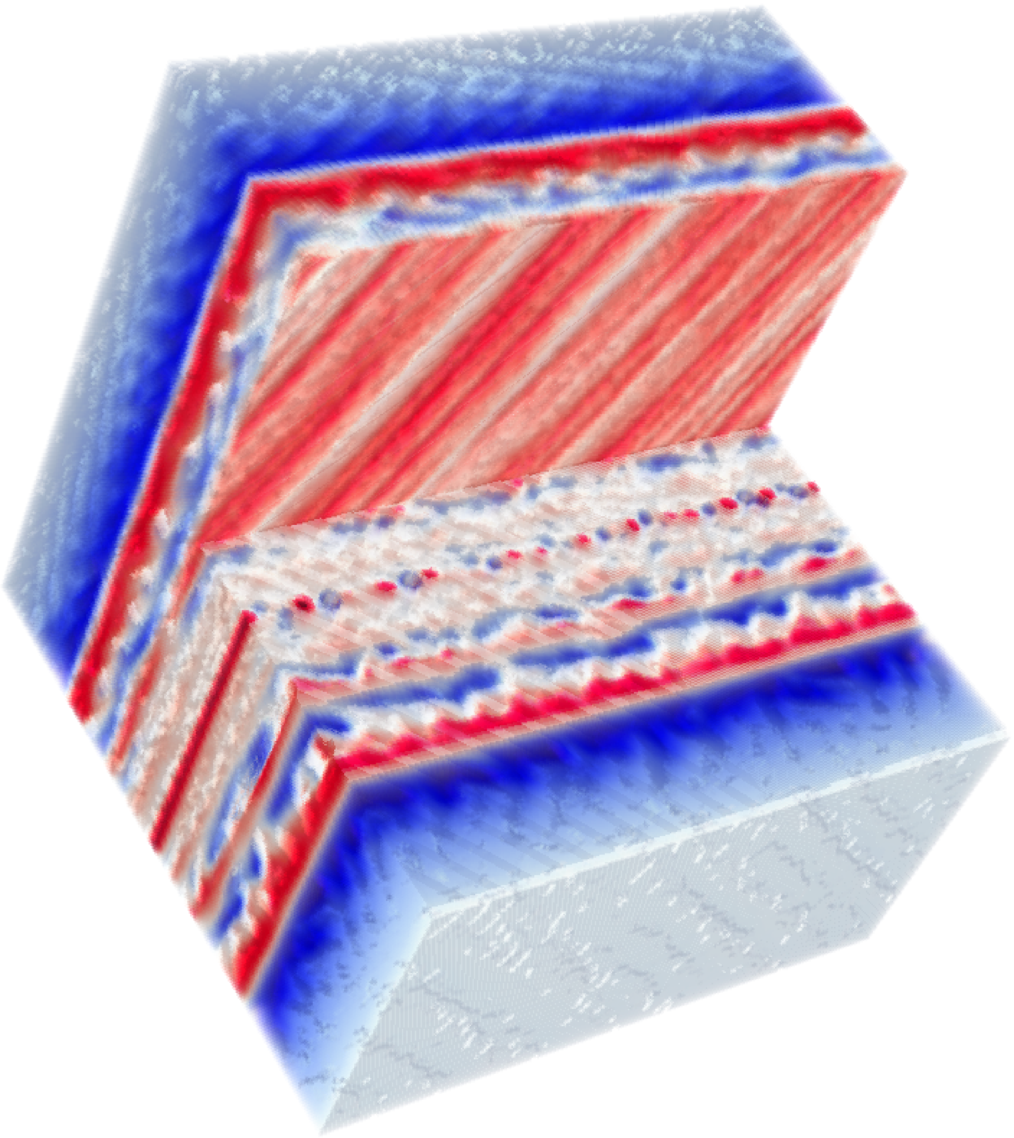


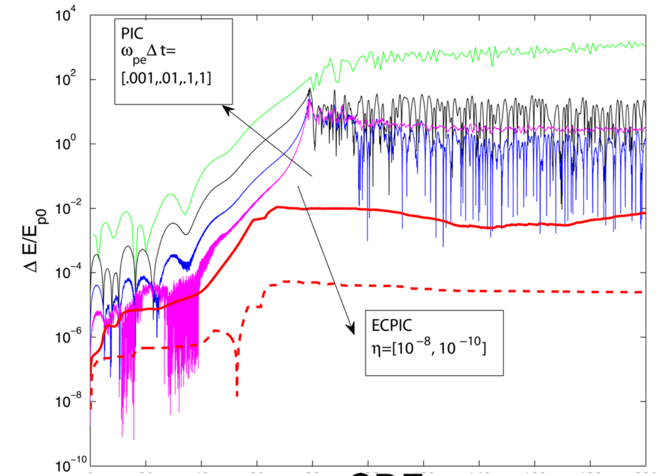
particles

ECsim

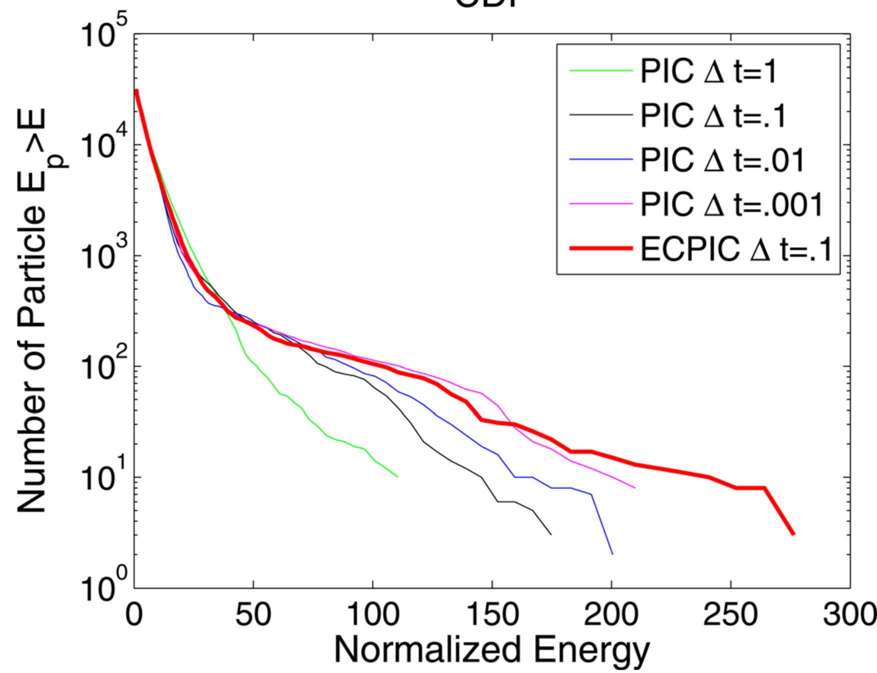
Mass Matrix Formulation

Applications of the ECsim approach



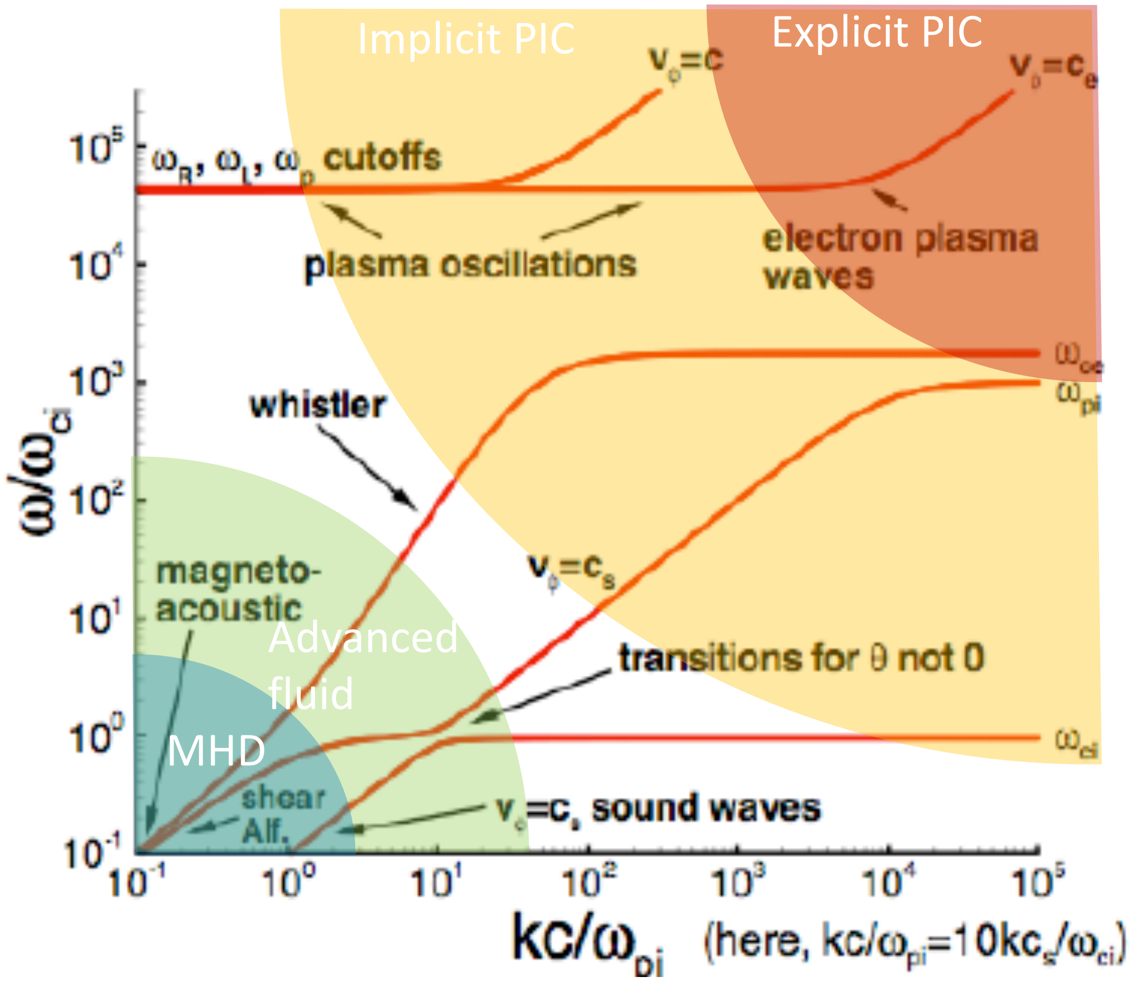


CDF



The crucible of complexity

Parallel propagation



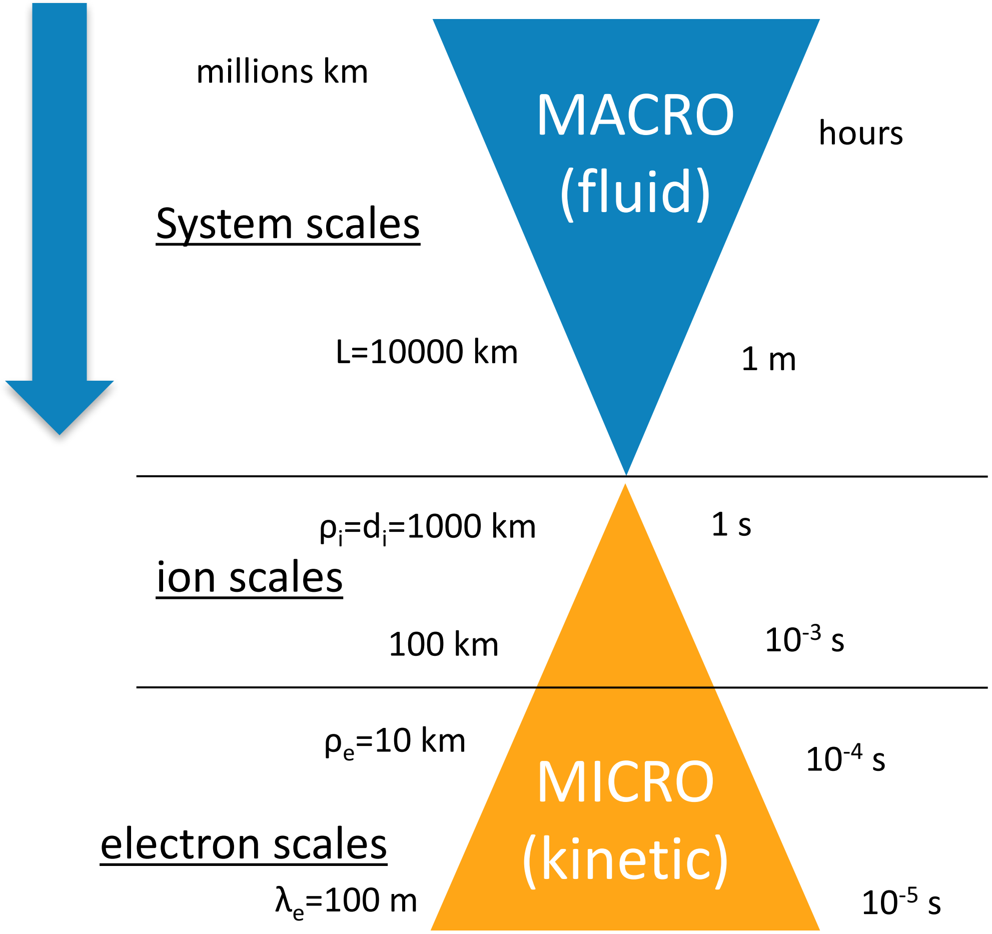
Wave spectra courtesy of Carl Sovinec

The challenge in modeling space plasmas: multiple scales

Advanced Fluid

Connect fluid with kinetic

- Make fluid codes compatible
- Lagrangian fluid PIC method



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Fluid (MHD) Models

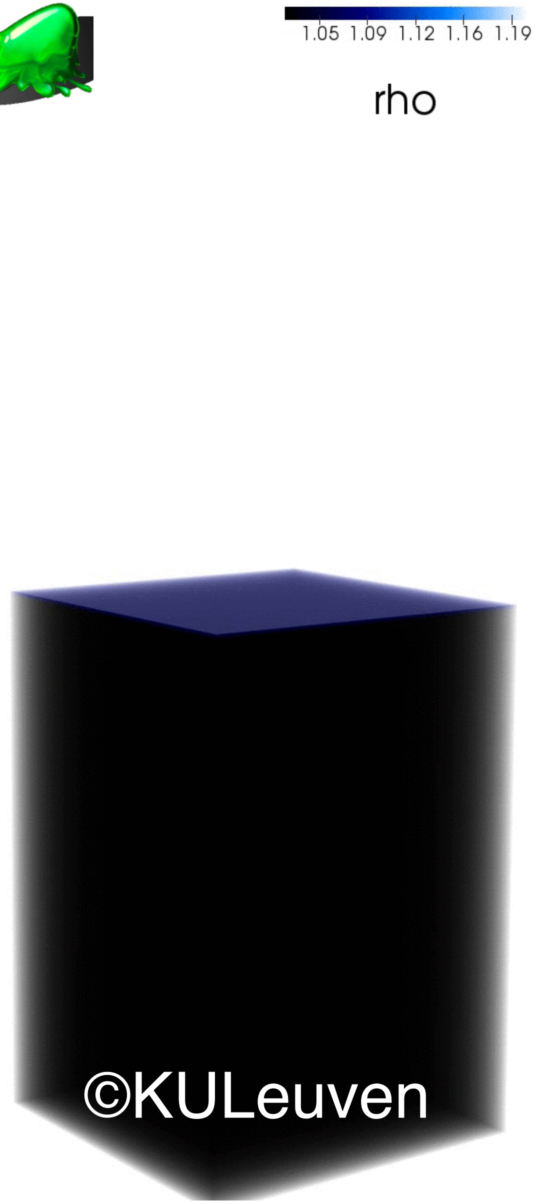
Flip3DMHD — Brackbill, JCP, 1991

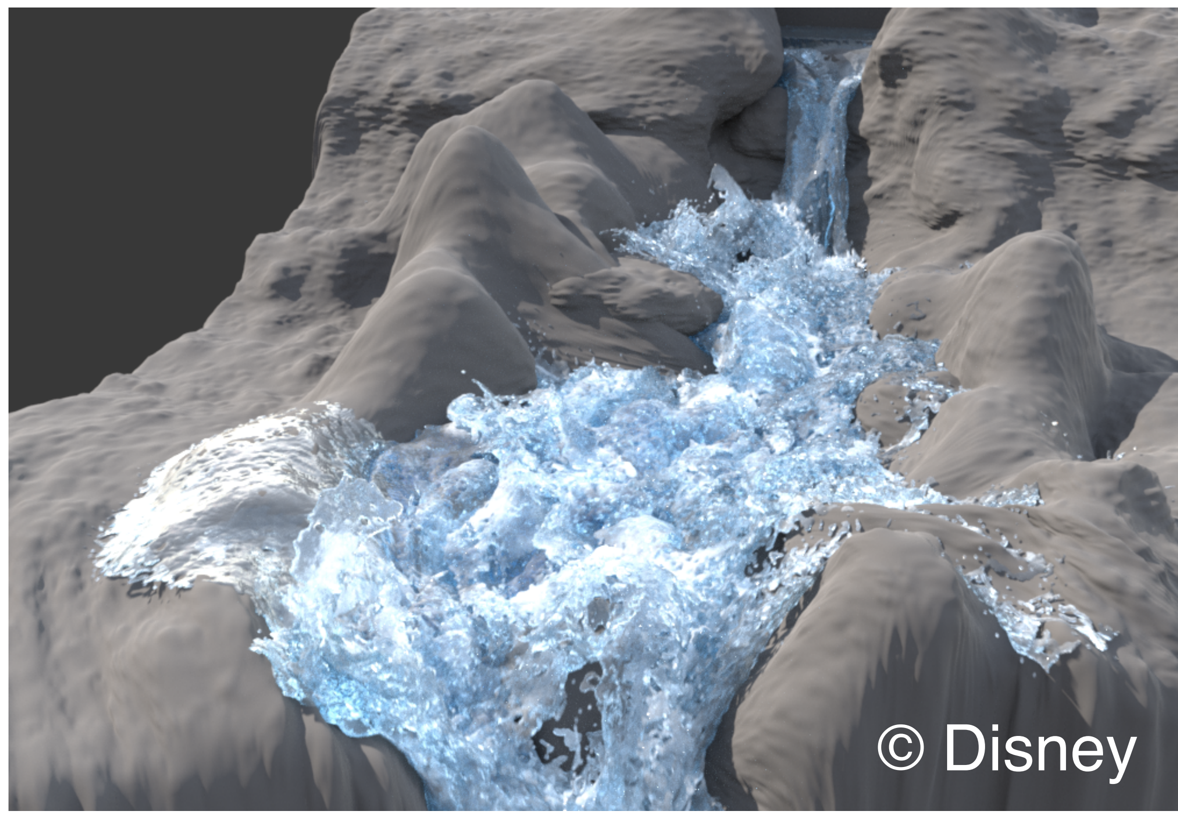
Is NOT a kinetic PIC code!

SLURM

- **Fluid Particle-in-cell** (*PIC or FLIP*) method for compressible fluids was invented by F. Harlow (1963), at LANL. It combines particles to follow material motion with a grid to solve the equations of motion. *Each particle is a blob of fluid.*
- **Kinetic Cloud-in-cell** (*CIC or PIC*) is a reinvention of PIC for plasma simulation, combines Vlasov + Maxwell (Brackbill, 2005, Lapenta 2012 for a review). *Each computational particle is a cloud in phase-space.*
- **Molecular Dynamics** *(MD or PP)* uses particles as real particles and computes forces by pairs

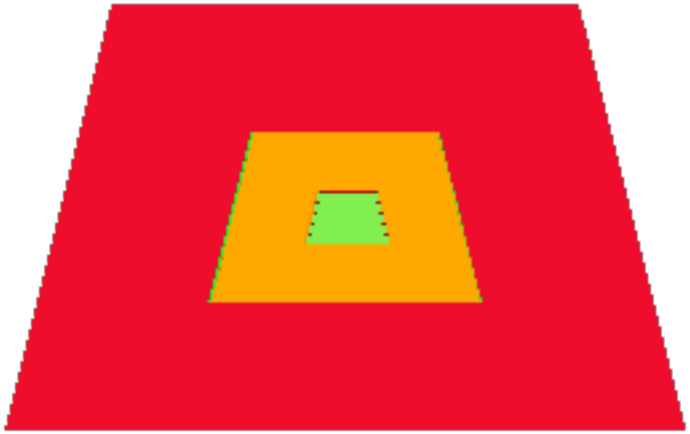
PIC Fluid methods chosen by Disney for the effects in the movie Frozen





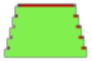
Coupling scales: MLMD Adaptive Approach

Full domain: d_i

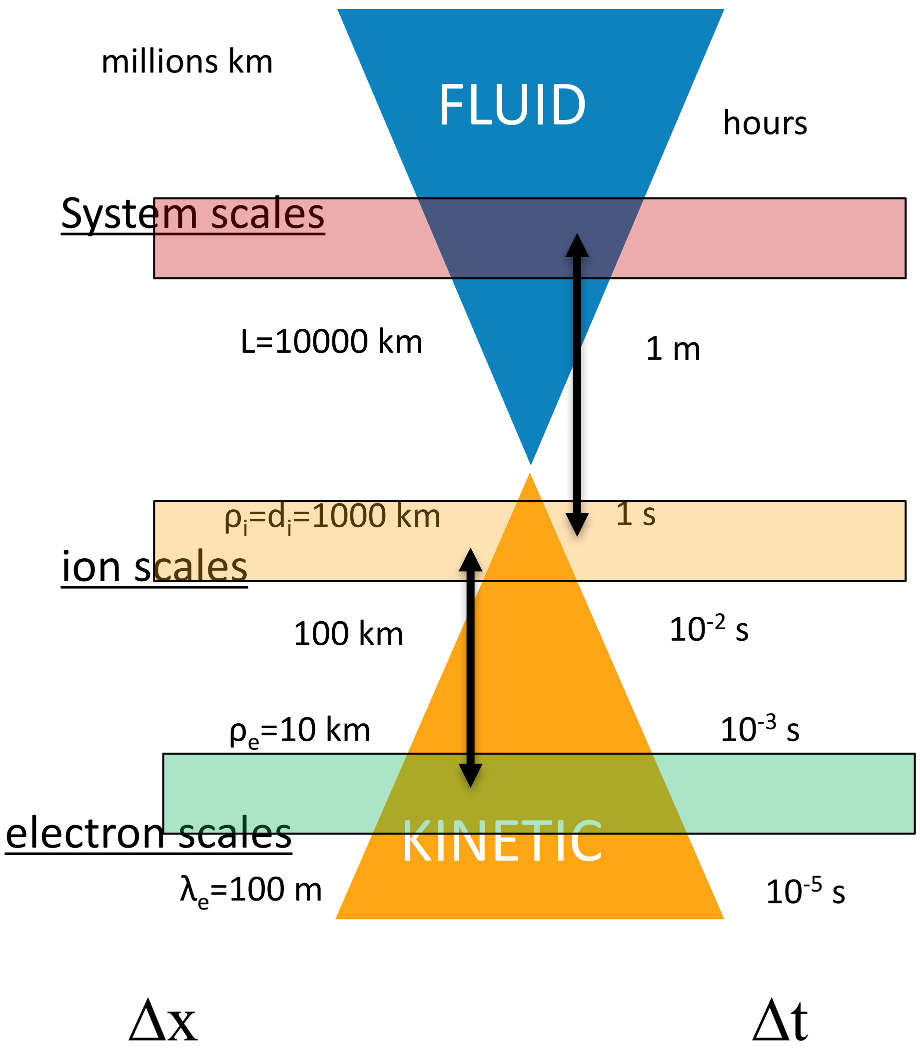


Local: d_e

Local: λ_e

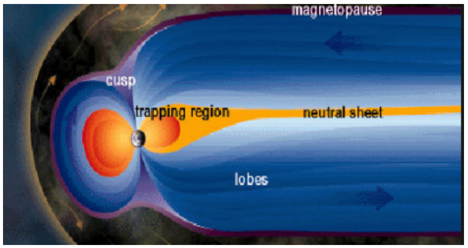


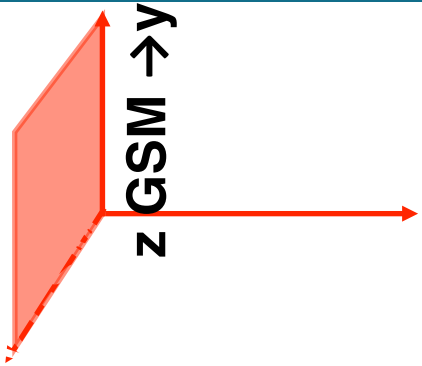
Innocenti, et al. JCP 238 (2013)

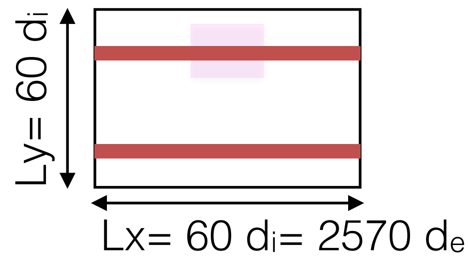


Example of application of the MLMD

Innocenti, et al. PoP, 23 (2016).

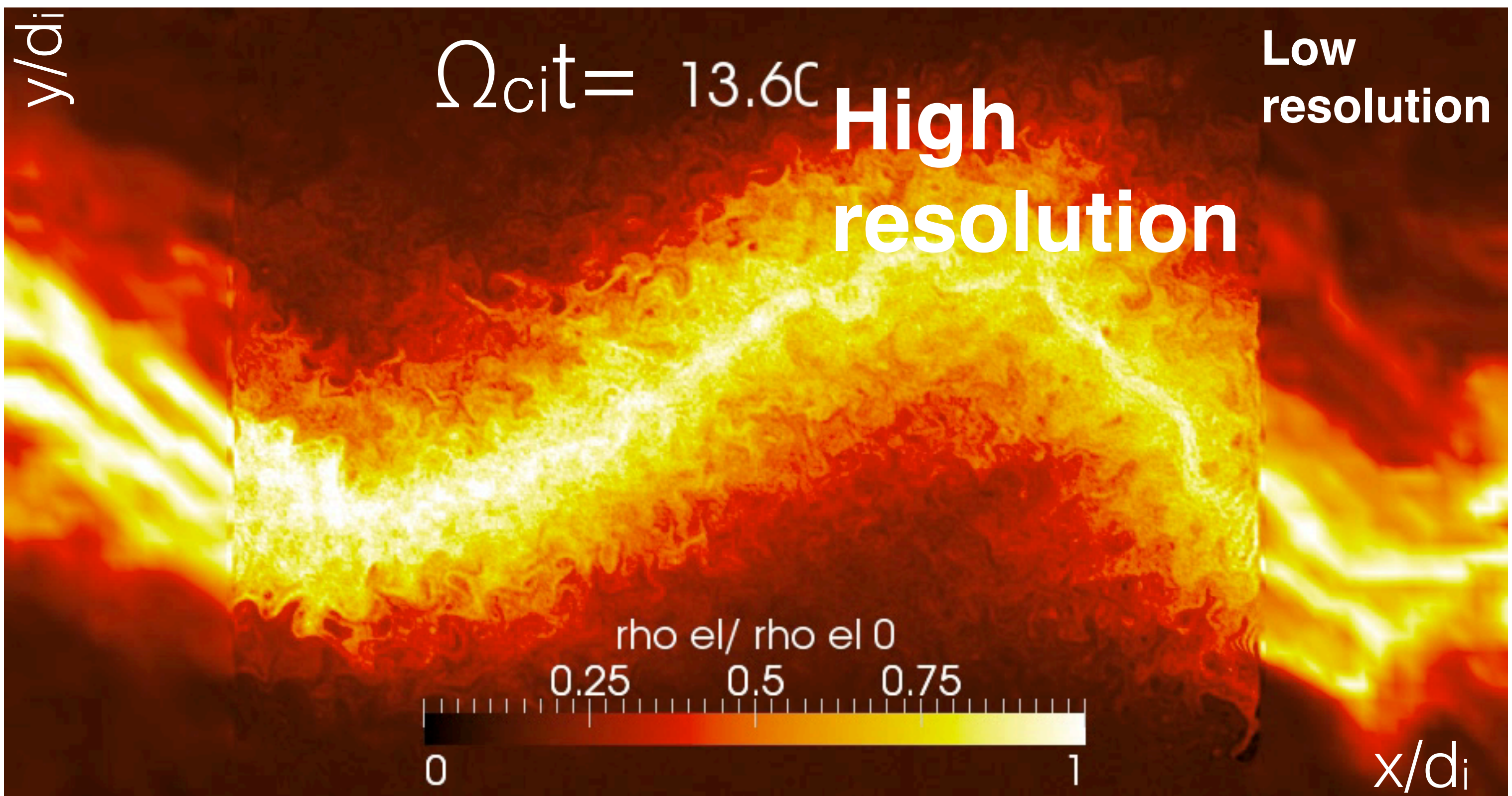




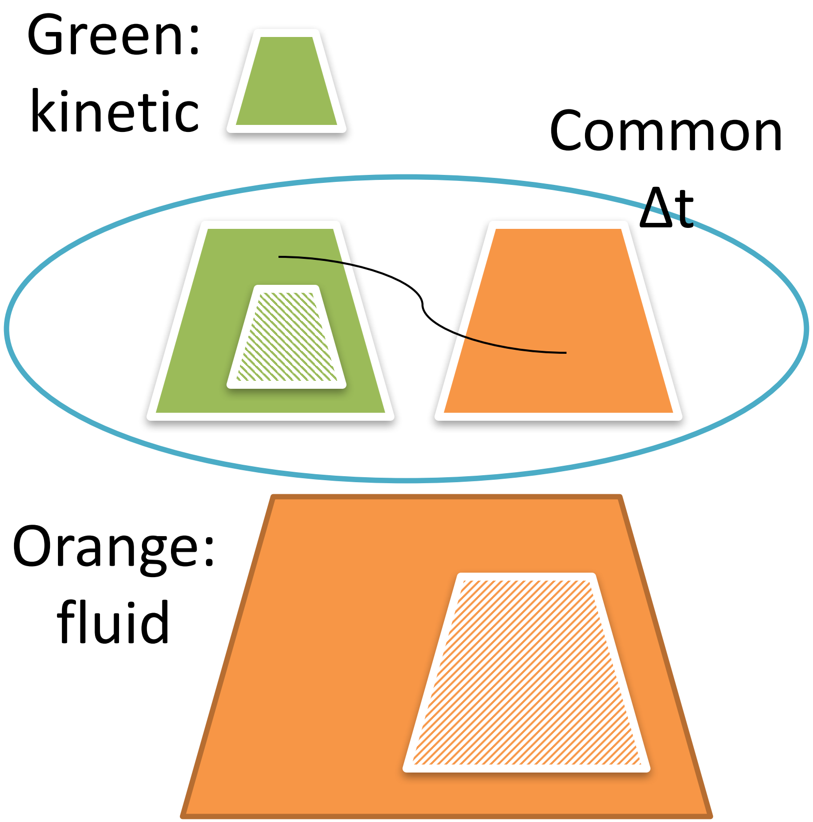


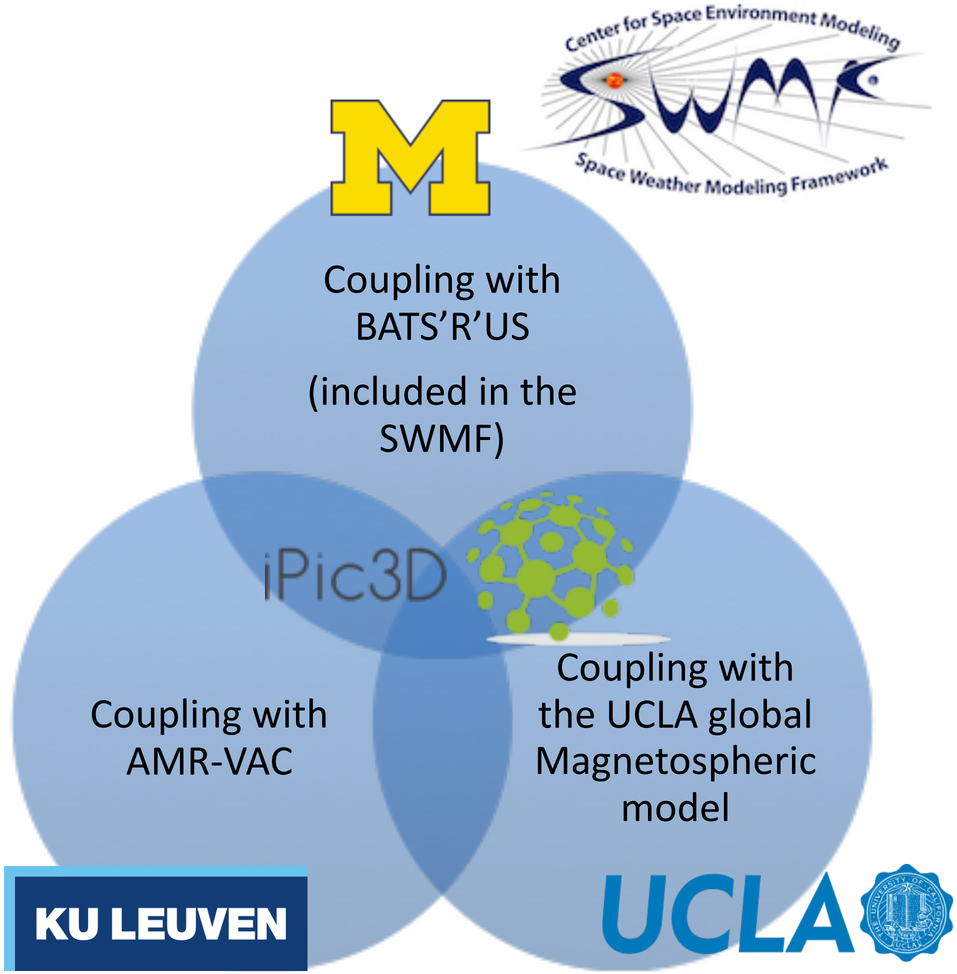
m_i/m_e=1836
dx_{CG}= 0.078 d_i
dx_{RF}= 0.42 d_e
dt_{CG}=0.1 ω_{pi}^{-1}
dx_{CG}/dx_{RF}=8
dt_{CG}/dt_{RF}=2

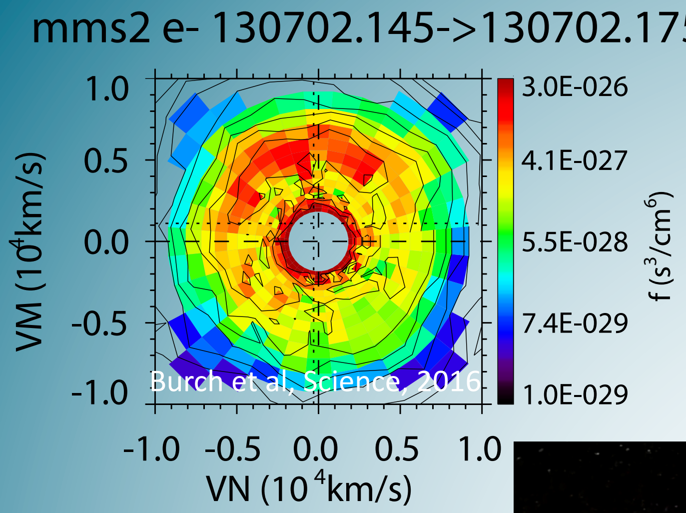
RF=8

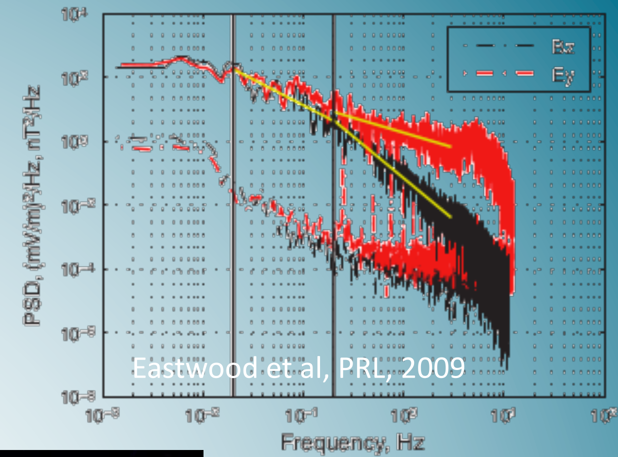


iPic3D coupled with different MHD codes



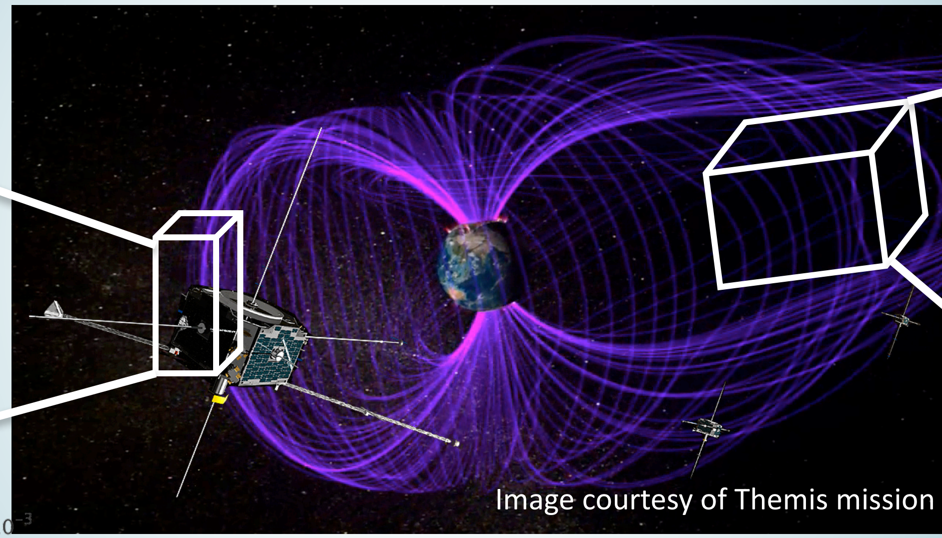






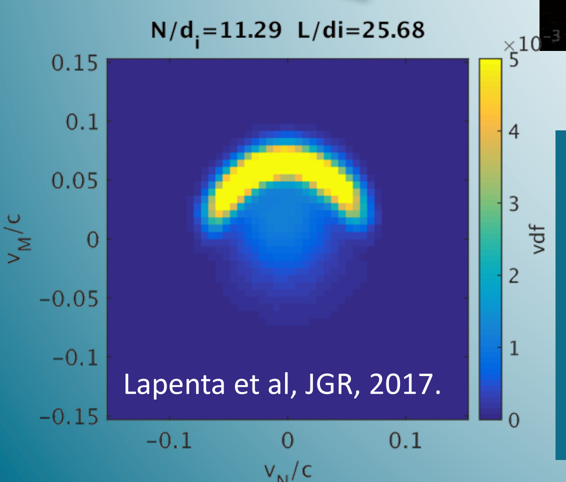
MMS

Cluster



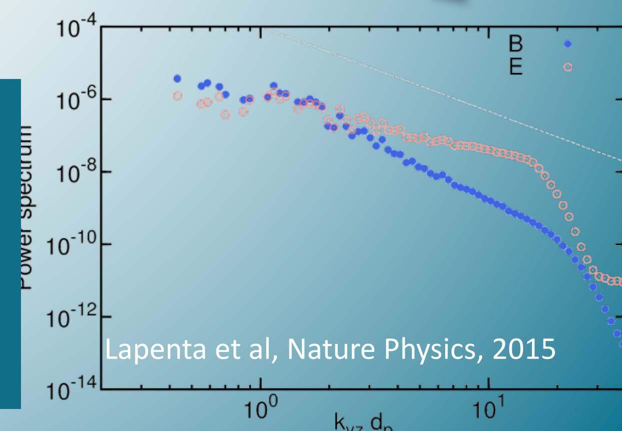
iPic3D

iPic3D



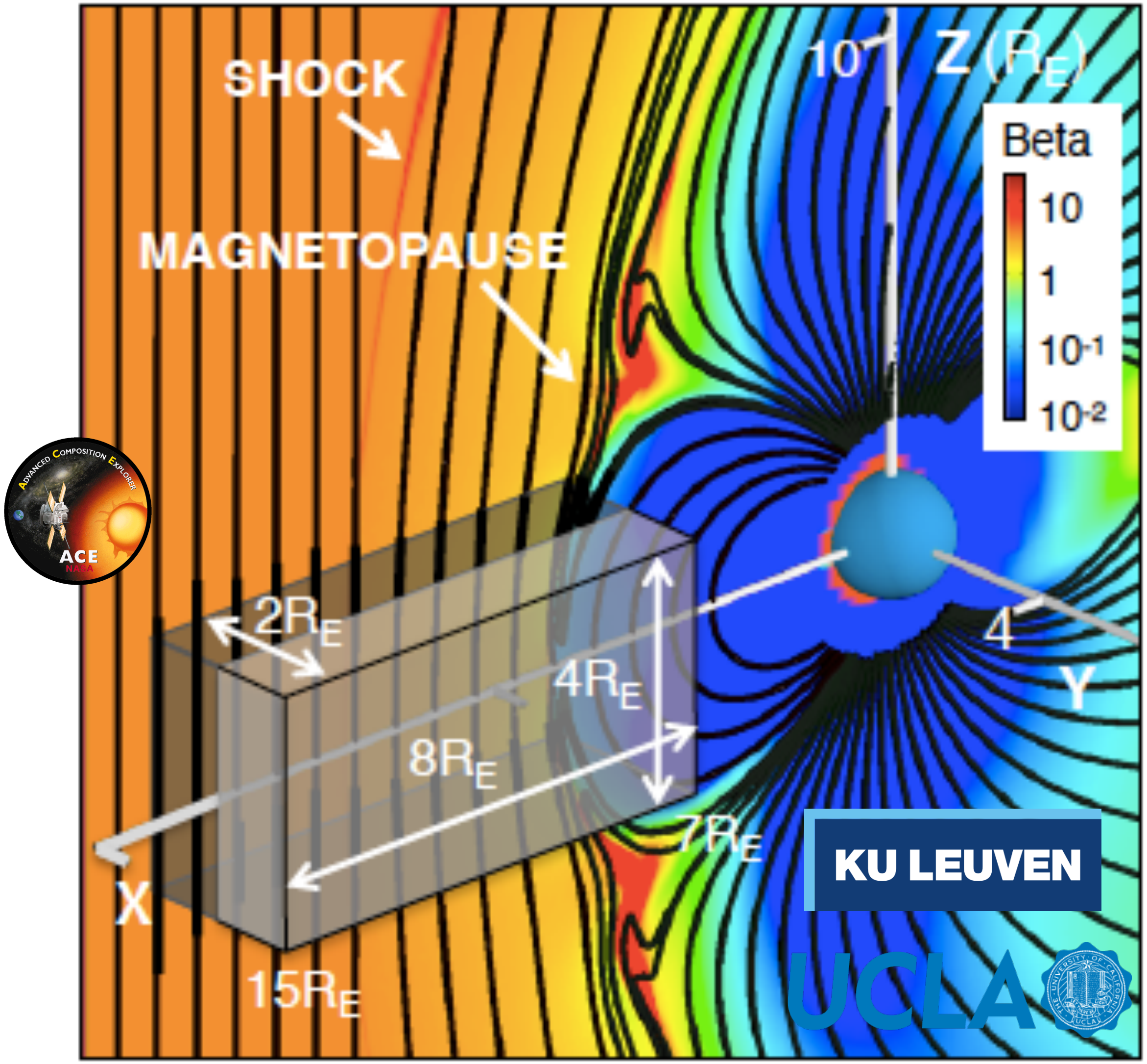
Kinetic model needs context from MHD:

1. Initial state
2. Boundary conditions



Multiscale Global MHD -> PIC Simulation

Collaboration: J. Berchem, R. Walker, M. El Alaoui, M. Zhou (UCLA)



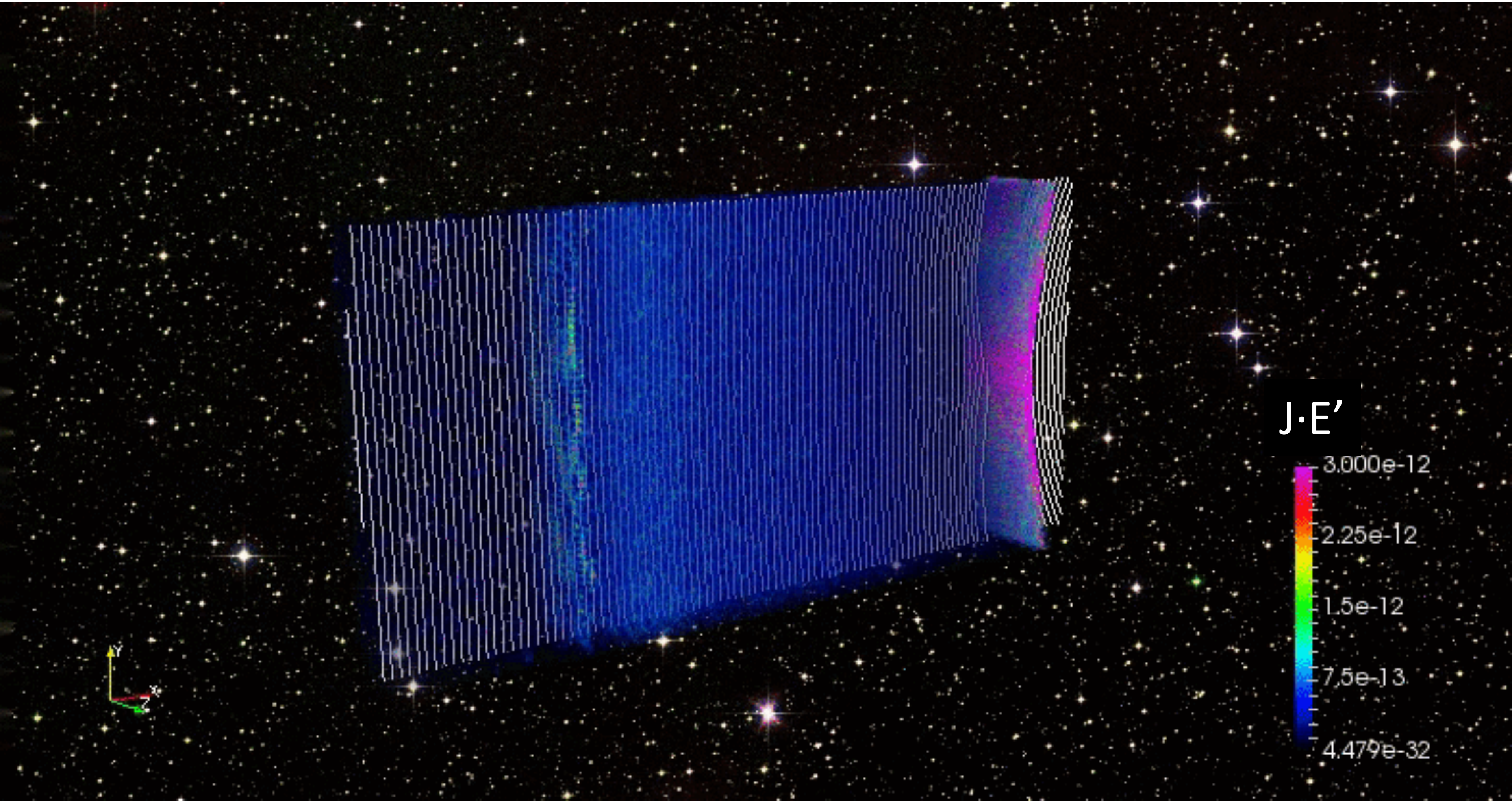
UCLA-MHD: Solar wind input from ACE:

- southward IMF: $B_X = B_Y = 0$; B_Z = -8 nT
- V_{Xc}= -650 km/s
- $V_Y = V_Z = 0$
- n = 4 cm^{-3}
- P_{th} = 360 pPa

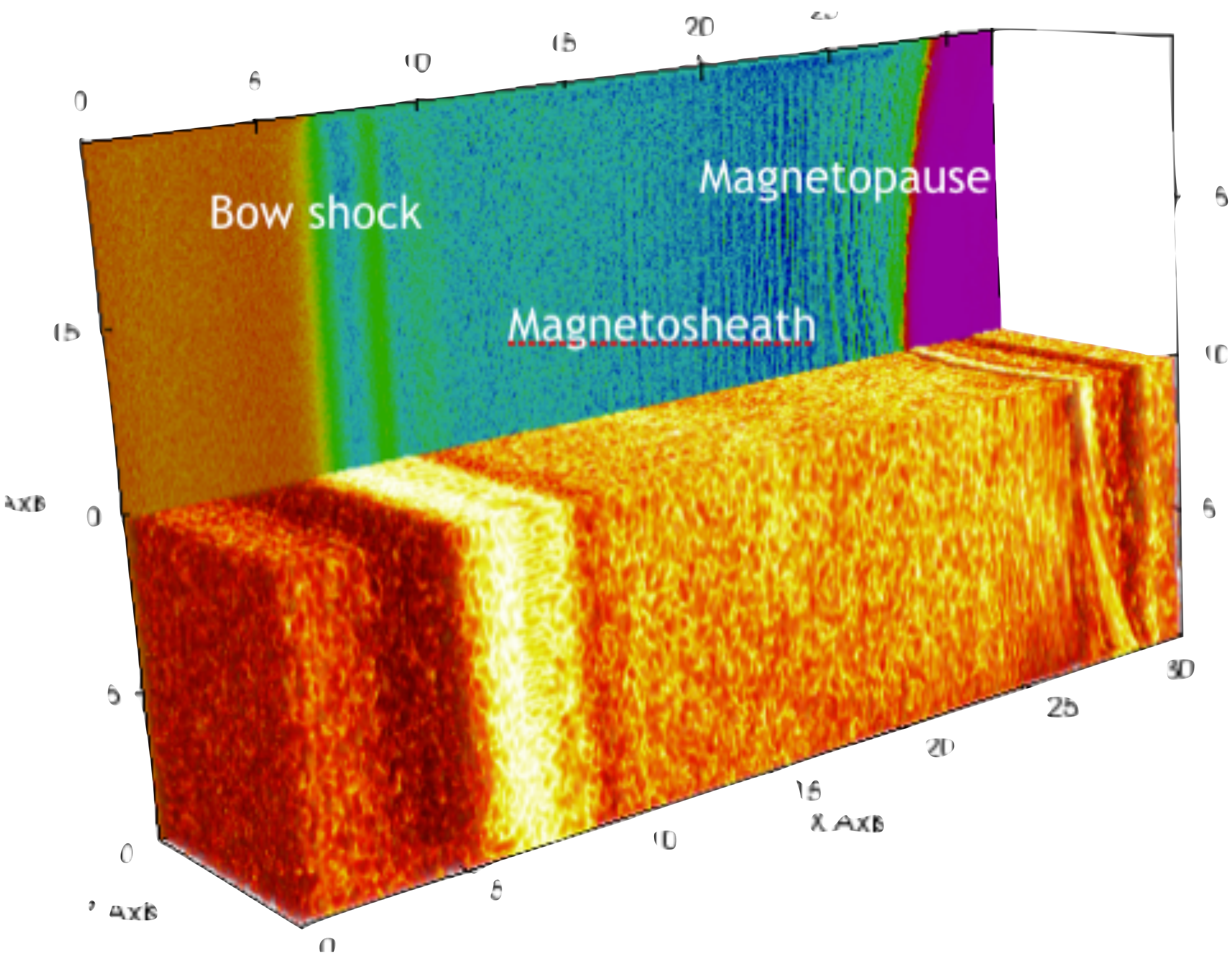
- **iPic3D** initial and boundary conditions are determined from the MHD simulation. Top/Bottom are open BC.

- **Electrons are well resolved**:
  - $\Delta x=\Delta y=0.02\ d_e$
  - $\omega_{ce}\ \Delta t = 0.02$

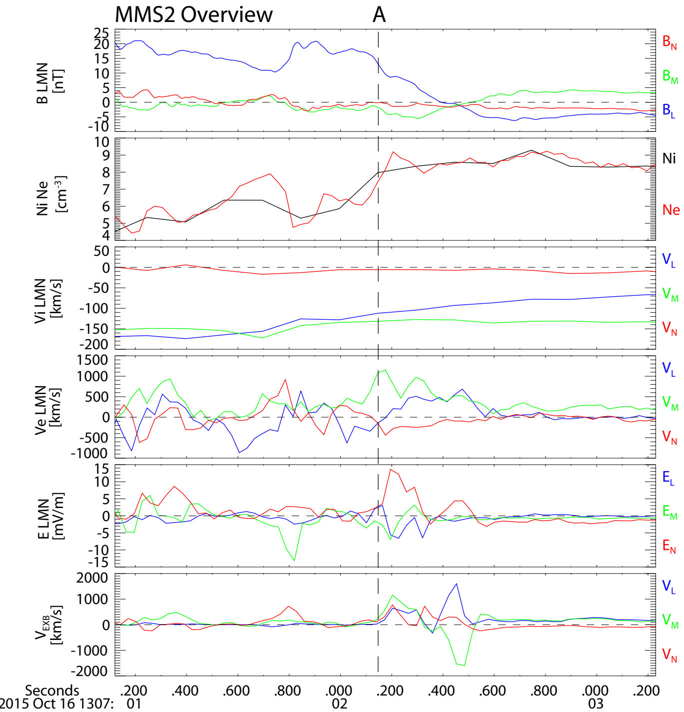
Reconnection and turbulence in the Earth Dayside



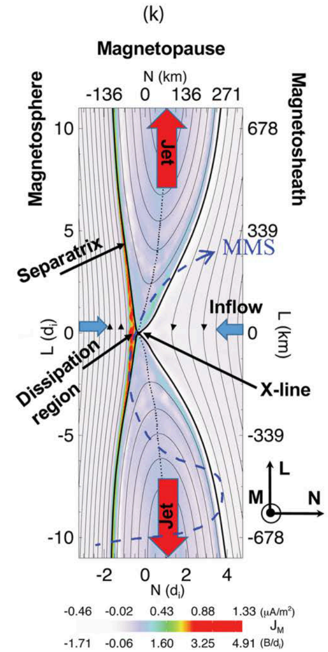
Regions simulated at the kinetic level

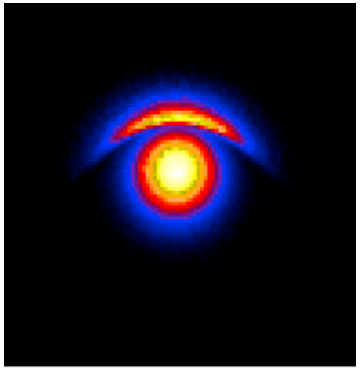


MMS Crescents in LMN Coordinates



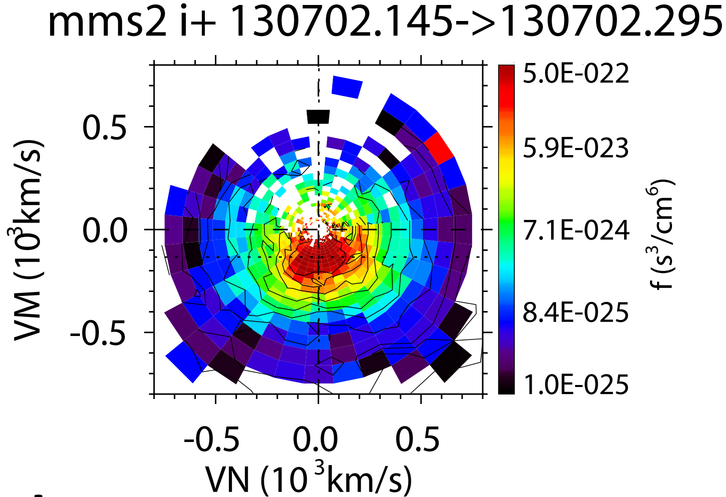
Event reported in Burch et al, Science, 2016



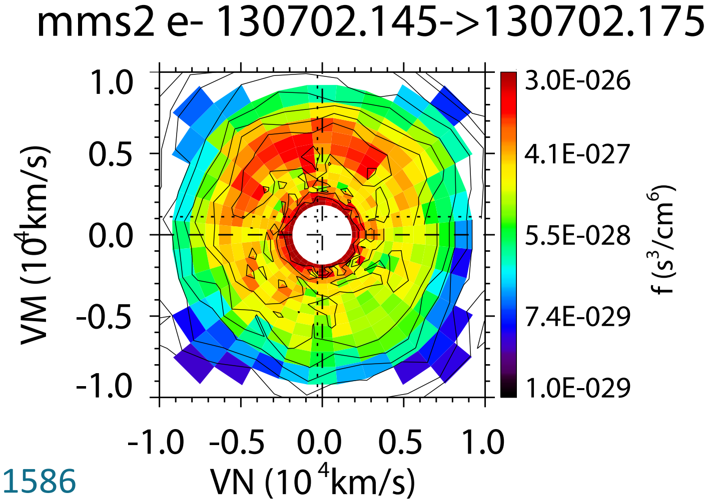


Hesse et al, GRL, 10.1002/2014GL061586

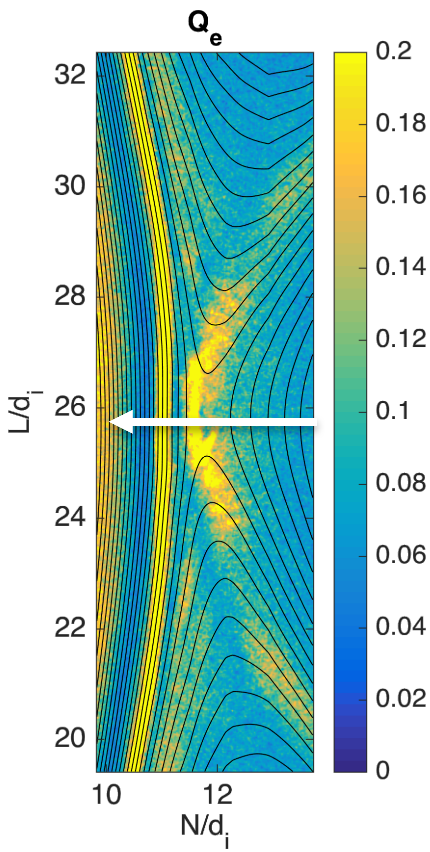
ions

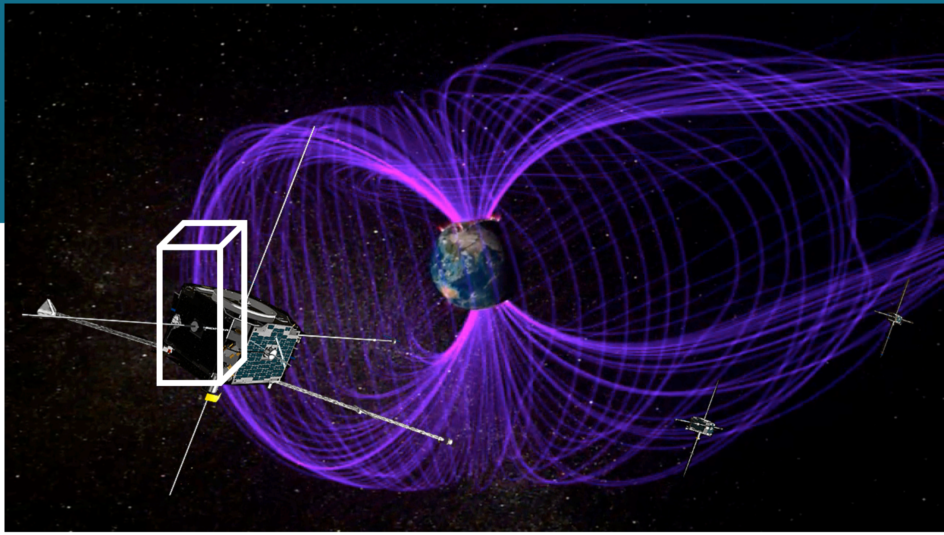


electrons

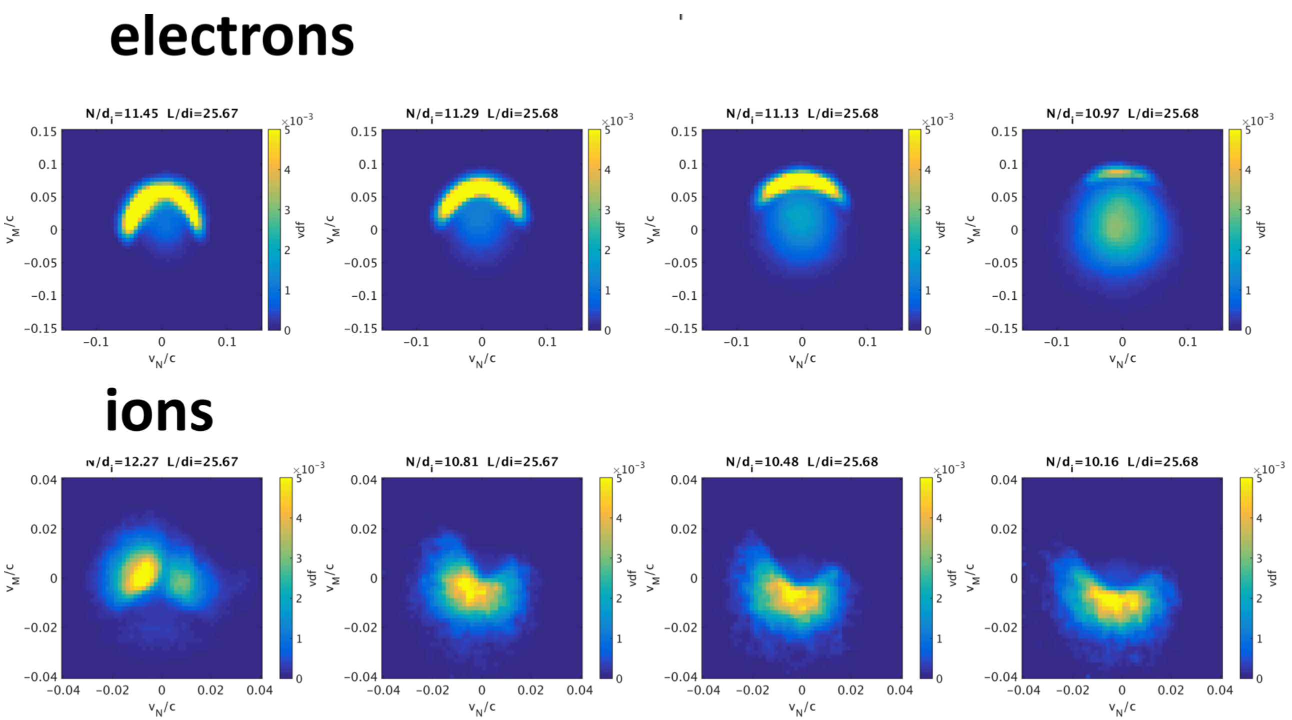


Crescents at the EDR

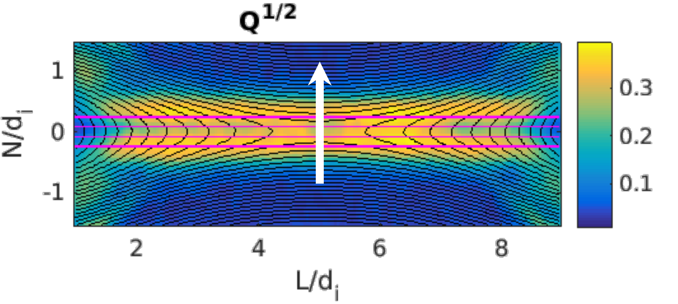


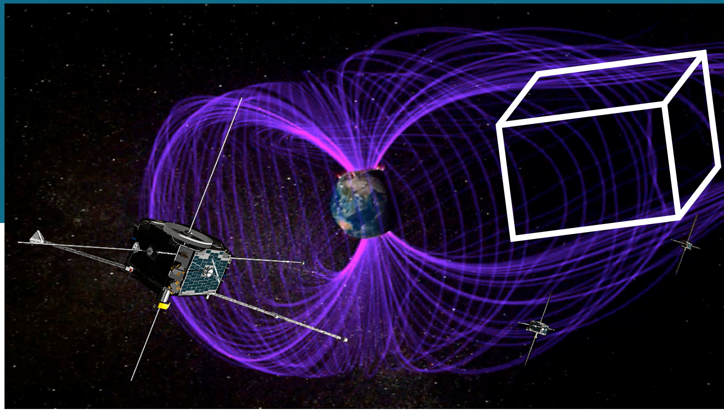


Lapenta et al, JGR, 10.1002/2016JA023290 (2017)

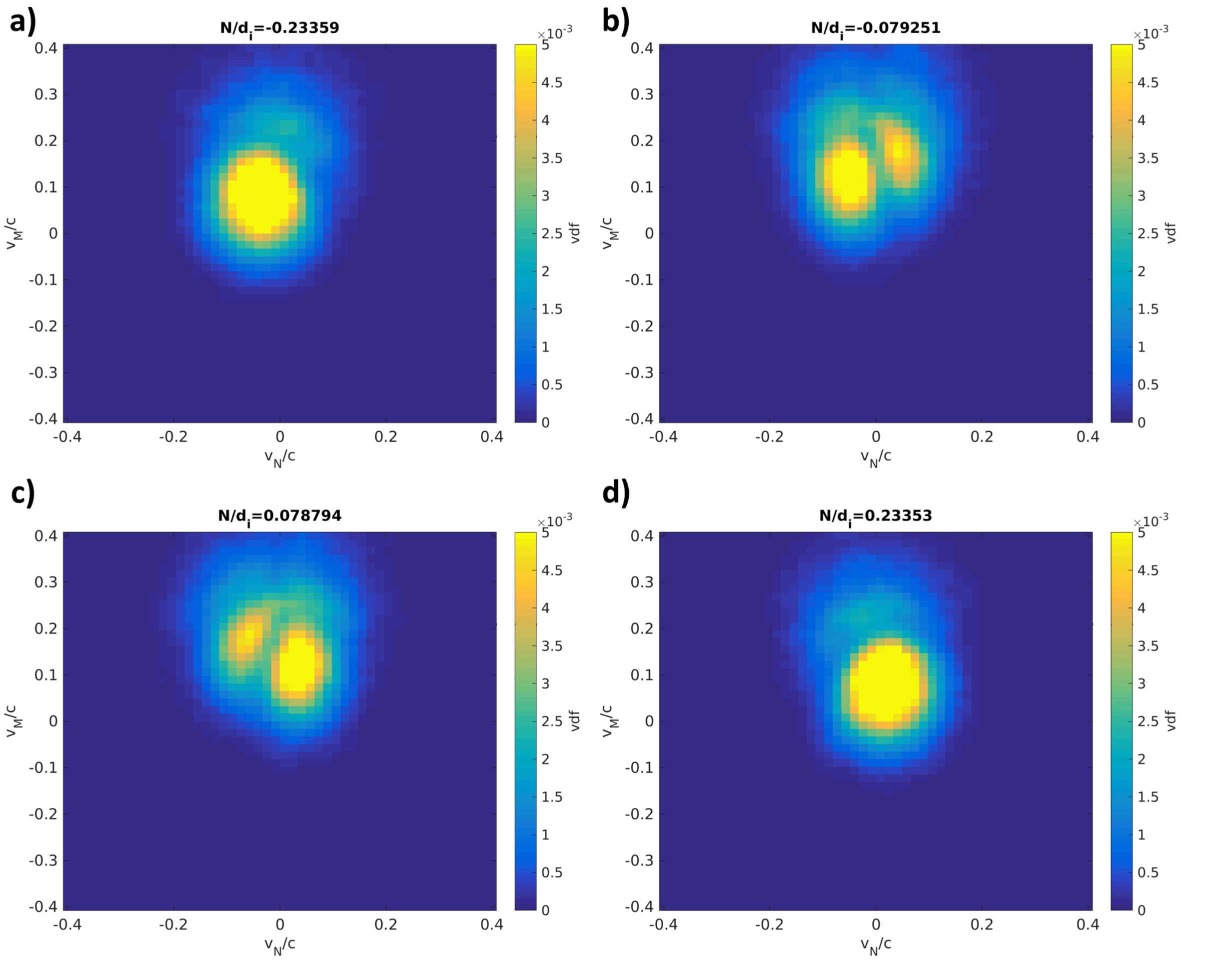


Crescents in the tail

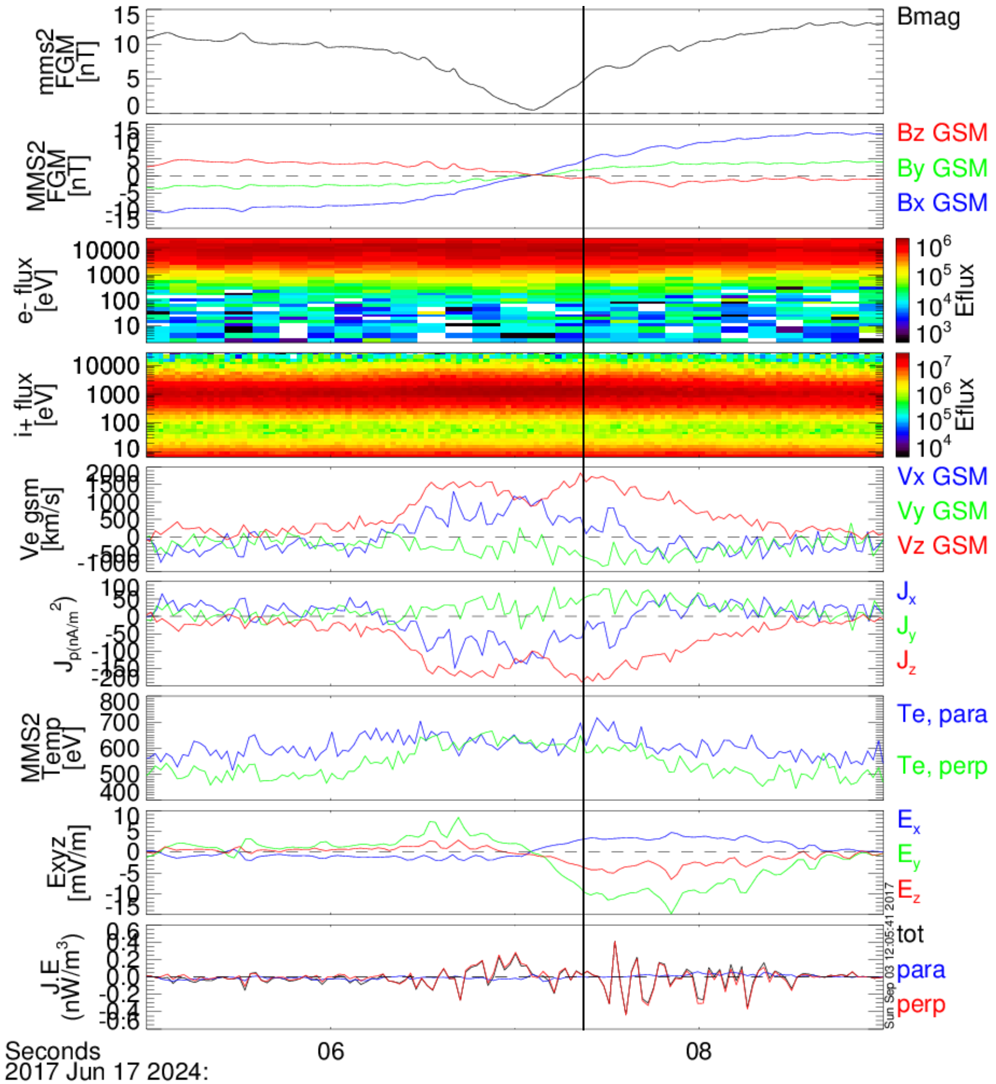


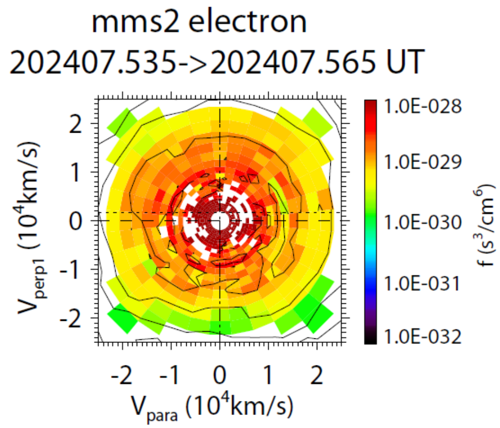


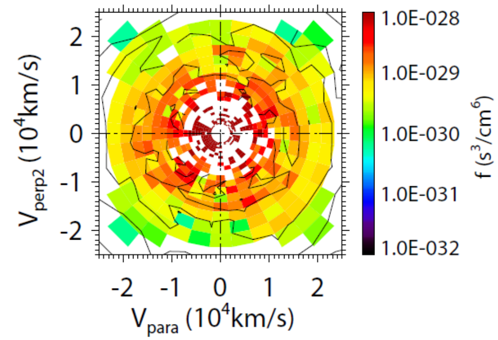
Lapenta et al, JGR,
10.1002/2016JA023290
(2017)

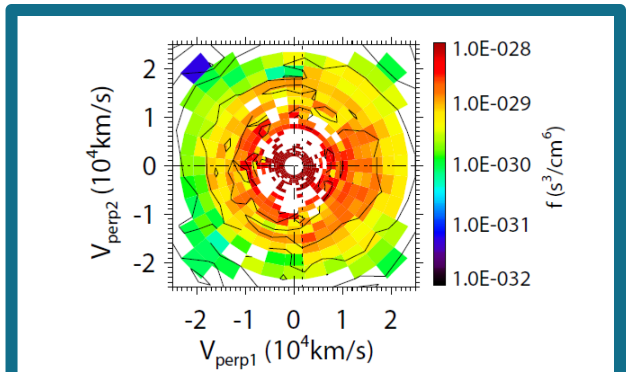


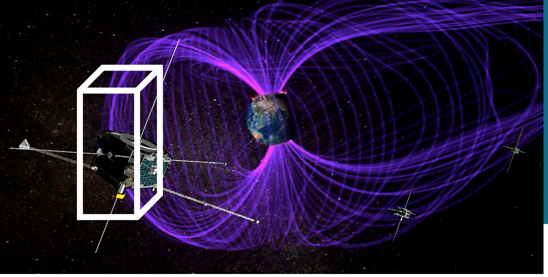
MMS detects crescents also in the tail – June 17, 2017.



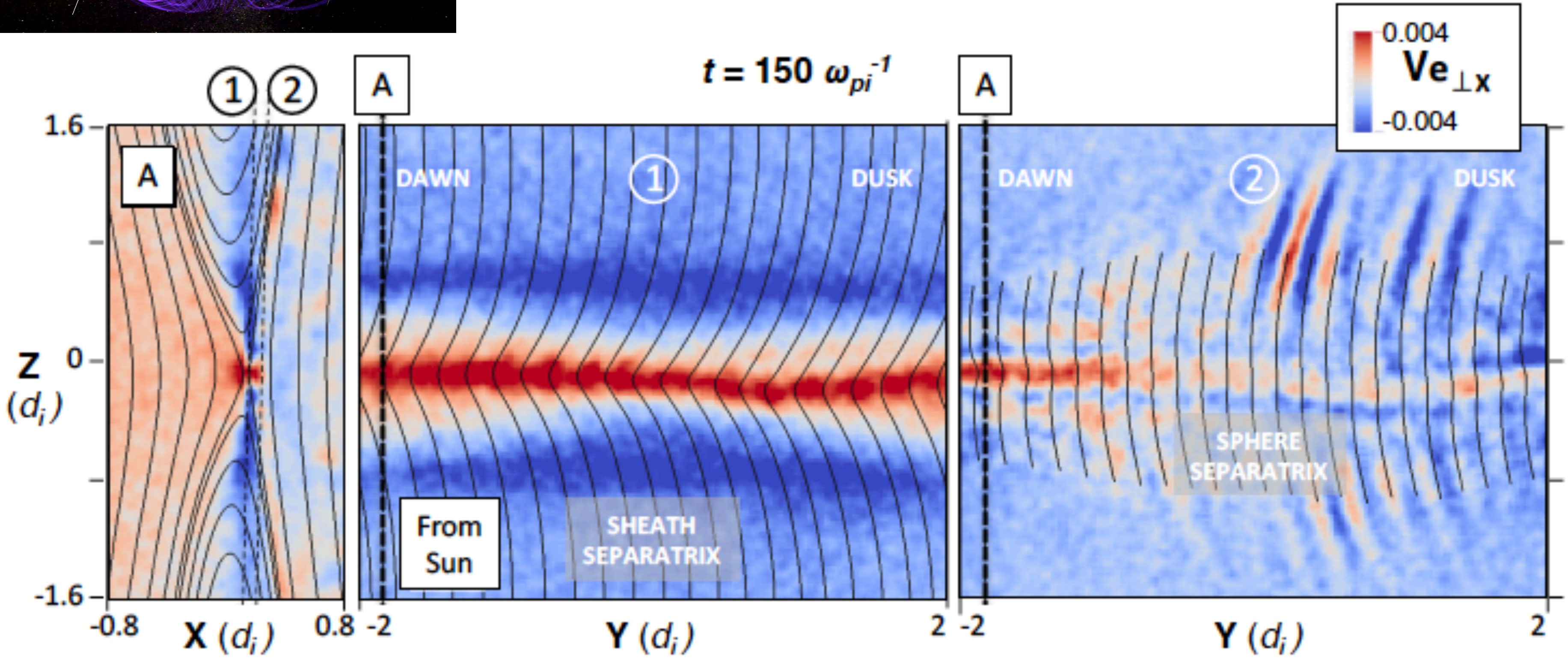


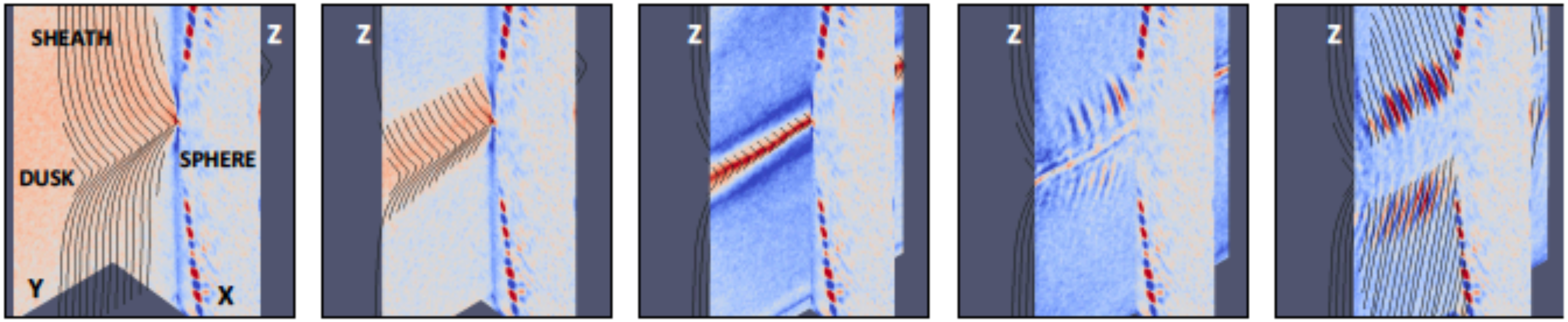




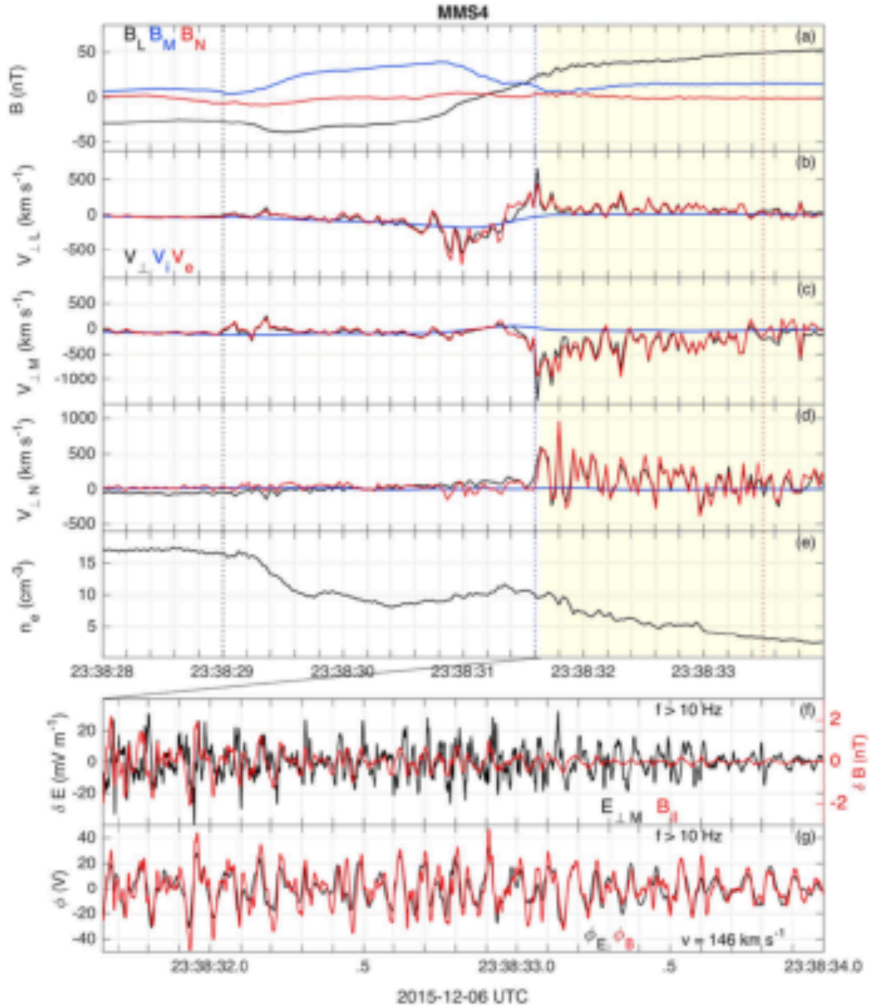


Structure in the dawn-dusk direction

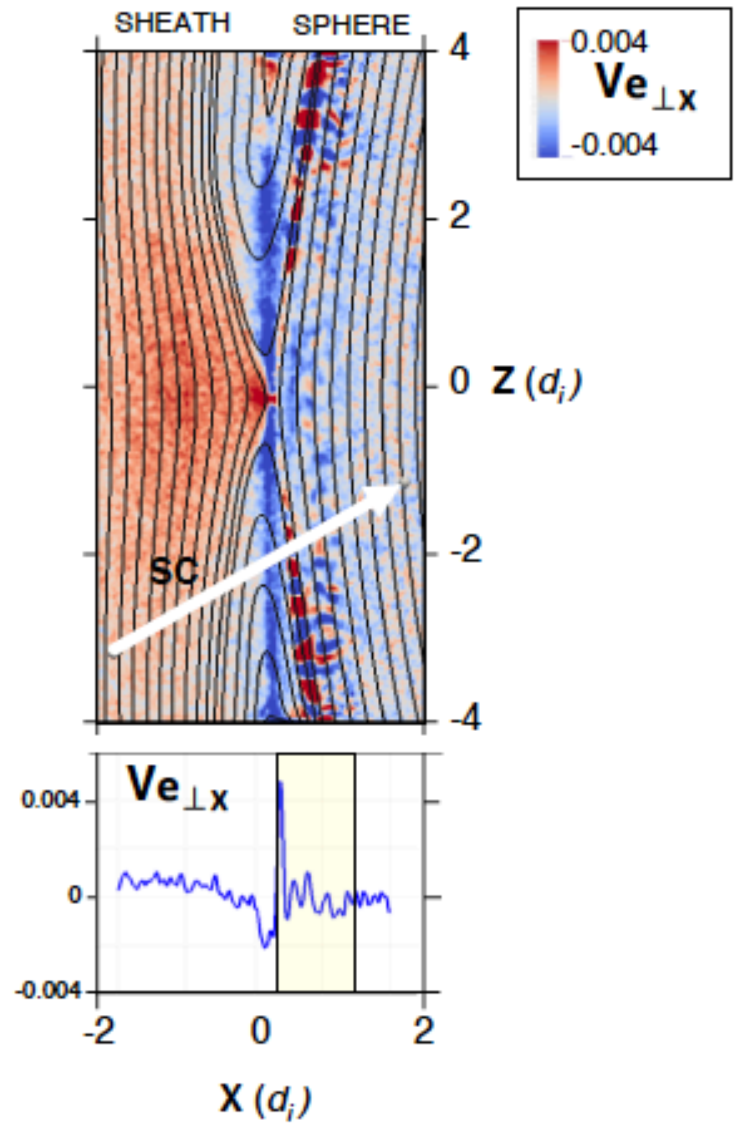




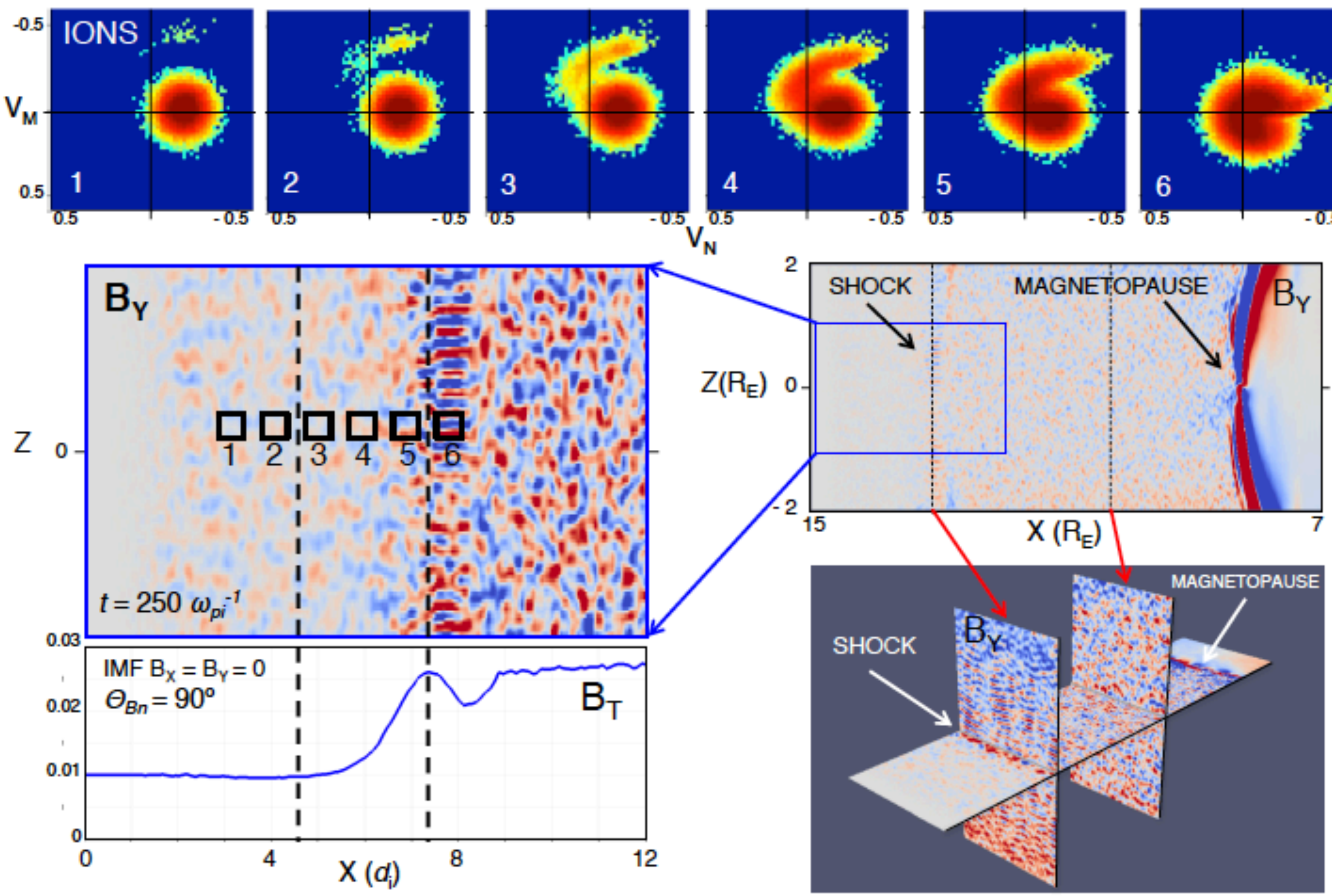
Lower-hybrid drift modes



From *Yu. V. Khotyaintsev et al.* (2016)

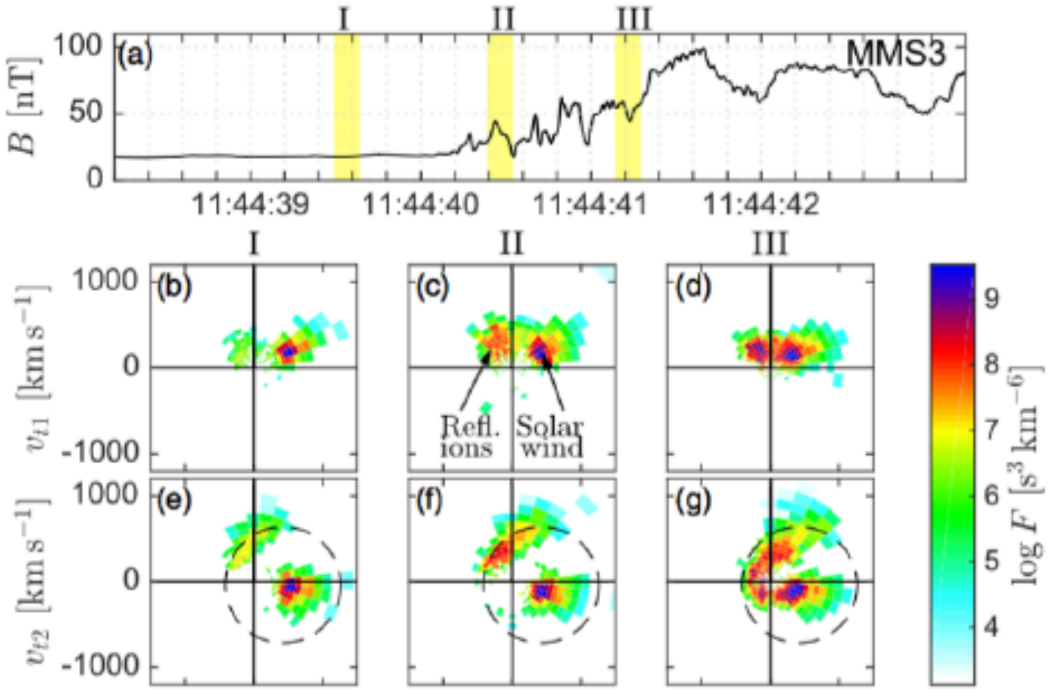


Bow Shock

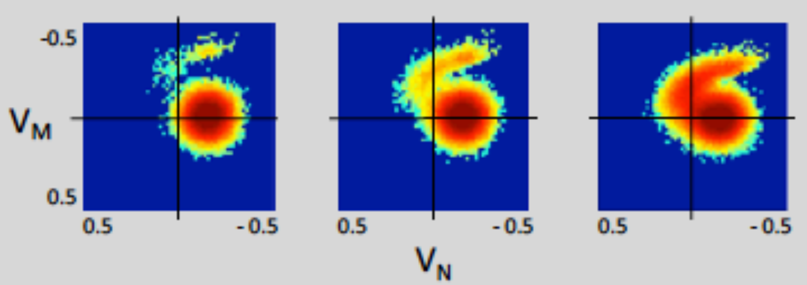


IONS
V_M
V_N
-0.5
0.5
1
2
3
4
5
6
B_Y
Z
0
$t = 250\ \omega_{pi}^{-1}$
1 2 3 4 5 6
IMF $B_X = B_Y = 0$
$\Theta_{Bn} = 90^o$
B_T
0.03
0.02
0.01
0
0 4 8 12
X (d_i)
SHOCK
MAGNETOPAUSE
$Z(R_E)$
2
-2
15
7
X (R_E)
SHOCK
MAGNETOPAUSE
B_Y

Quasi-perpendicular shock

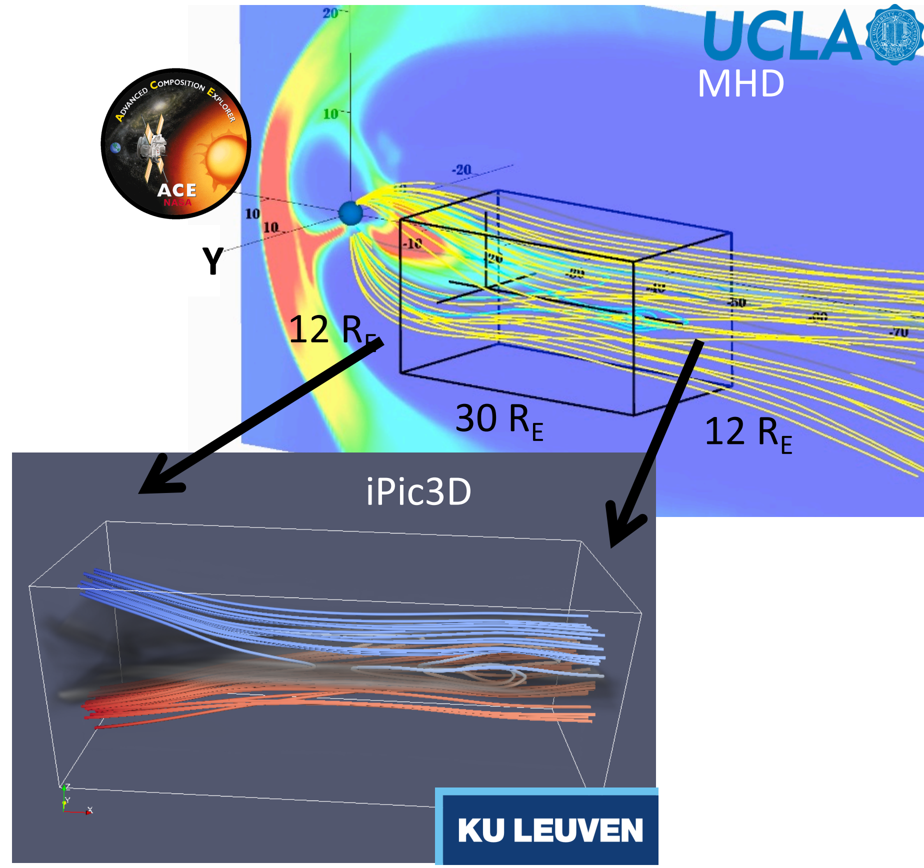


Rippled Quasiperpendicular Shock Observed by the MMS
[Johlander, A. , S. J. Schwartz, A. Vaivads, Y. V. Khotyaintsev, et al., *Phys. Rev. Lett.*, 2016]



Simulation

Magnetotail: Simulation Approach



Multiscale approach:

Combine global MHD with implicit PIC model (iPic3D) using a large-scale simulation system (30 R_E x 12 R_E x 12 R_E)

Method:

Run MHD simulation with upstream solar wind parameters from ACE

At onset of tail reconnection place 3D iPic3D box :

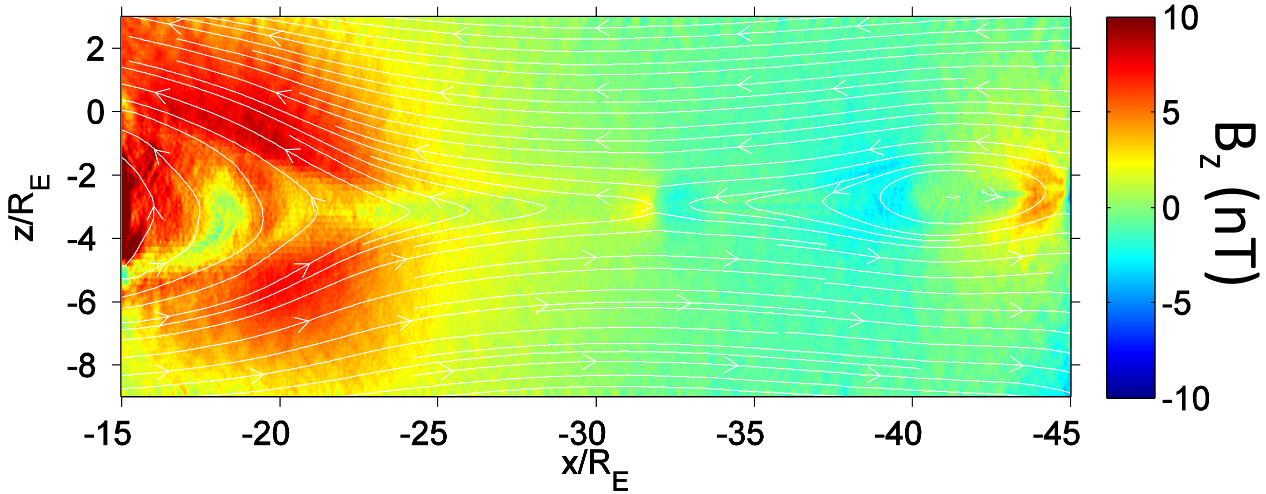
(-45 < x < -15, -3 < y < 9, -9 < z < 3)

$\Delta_{PIC}/d_i = 0.06$
$\Delta_{PIC}/d_e = 1.0$
$m_i/m_e = 256$

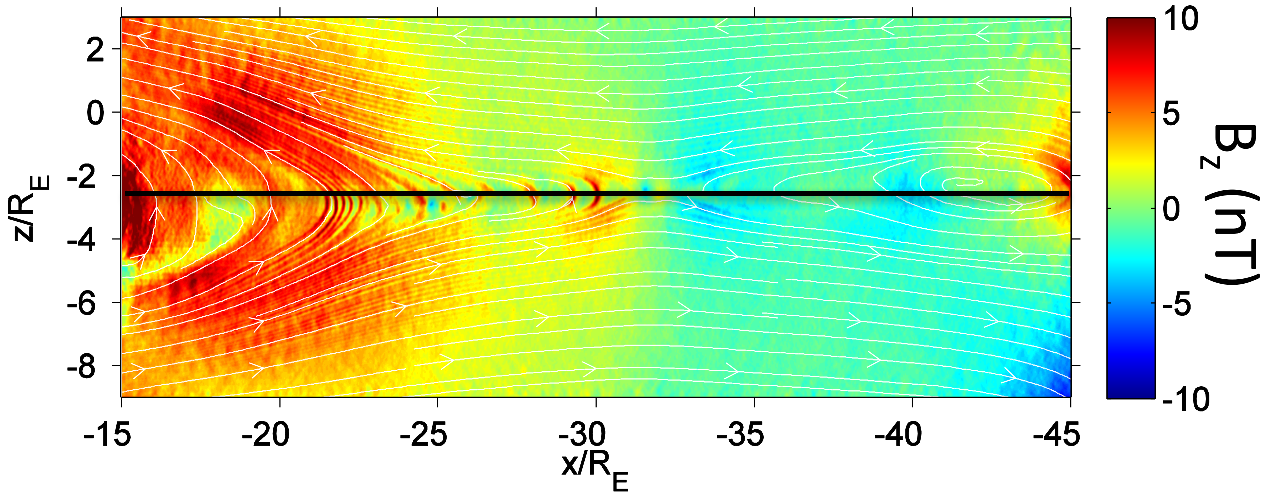
- Use initial and boundary conditions from iPic3D code taken from MHD simulation
- Inject particles with a drifting Maxwellian based on MHD values.

North South (B_z) Component of the Magnetic Field

T= 14.4 s

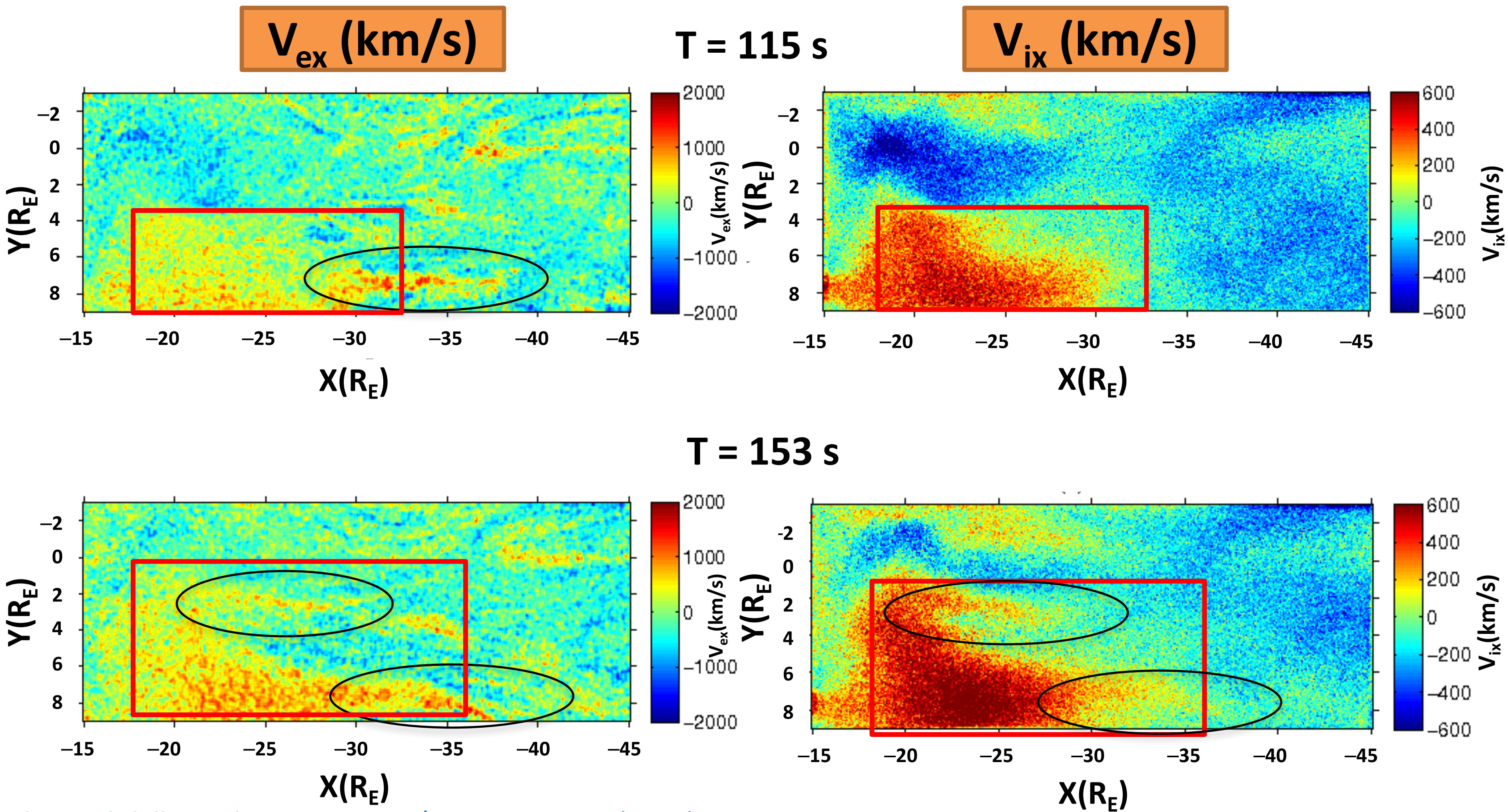


T= 57 s



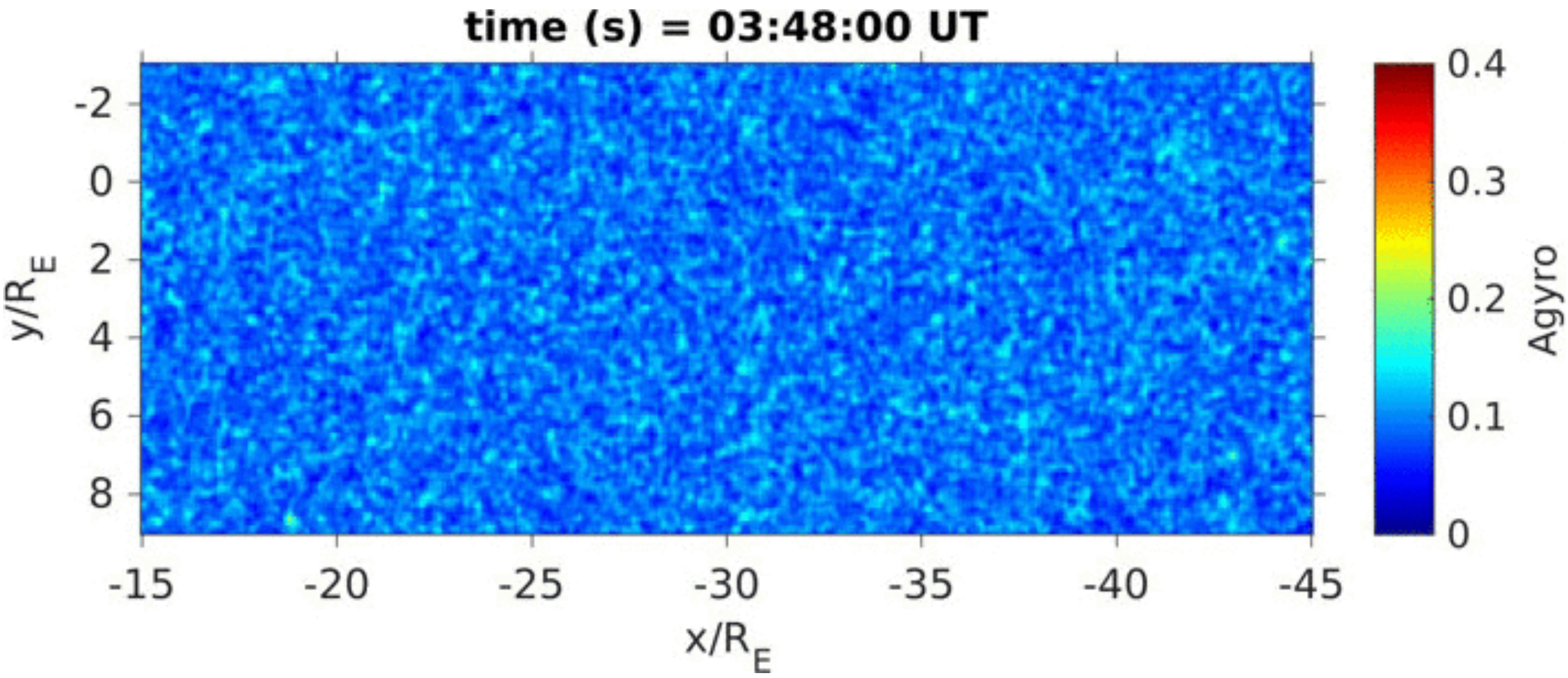
Ashour-Abdalla et al, JGR, 10.1002/2014JA020316 (2015)

Time Development of V_{ex} and V_{ix} on the Maximum Pressure Surface

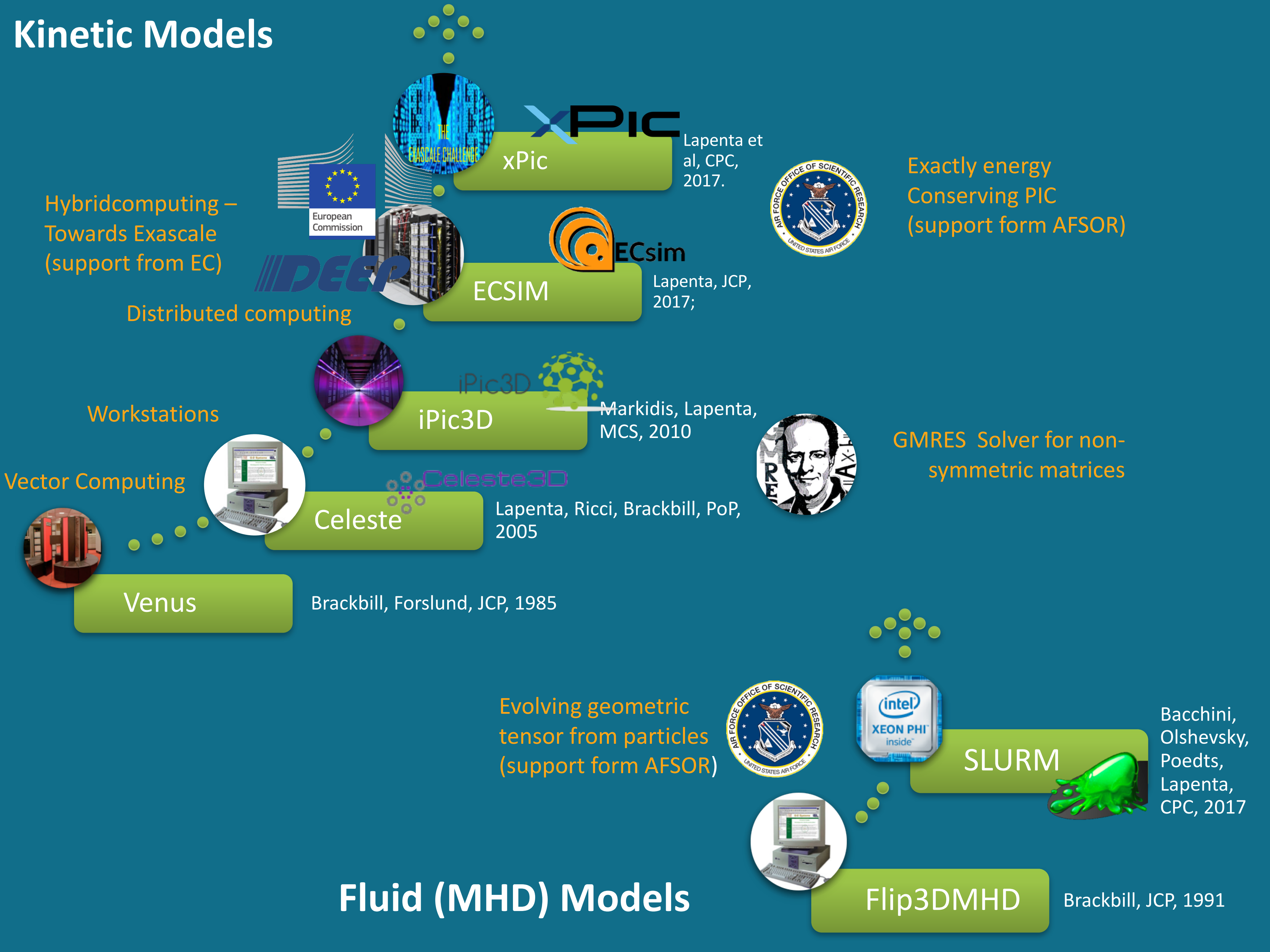


Ashour-Abdalla et al, GRL, 10.1002/2016GL069355 (2016)

Agyrotropy



Walker et al, JGR, submitted (2017)


Kinetic Models
xPic
Lapenta et al, CPC, 2017.
Exactly energy Conserving PIC (support form AFSOR)
Hybridcomputing – Towards Exascale (support from EC)
European Commission
DEEP
ECsim
ECSIM
Lapenta, JCP, 2017;
Distributed computing
iPic3D
iPic3D
Markidis, Lapenta, MCS, 2010
Workstations
GMRES Solver for non-symmetric matrices
Vector Computing
Celeste3D
Celeste
Lapenta, Ricci, Brackbill, PoP, 2005
Venus
Brackbill, Forslund, JCP, 1985
Evolving geometric tensor from particles (support form AFSOR)
intel XEON PHI inside
SLURM
Bacchini, Olshevsky, Poedts, Lapenta, CPC, 2017
Fluid (MHD) Models
Flip3DMHD
Brackbill, JCP, 1991