Advanced Space Weather Modeling

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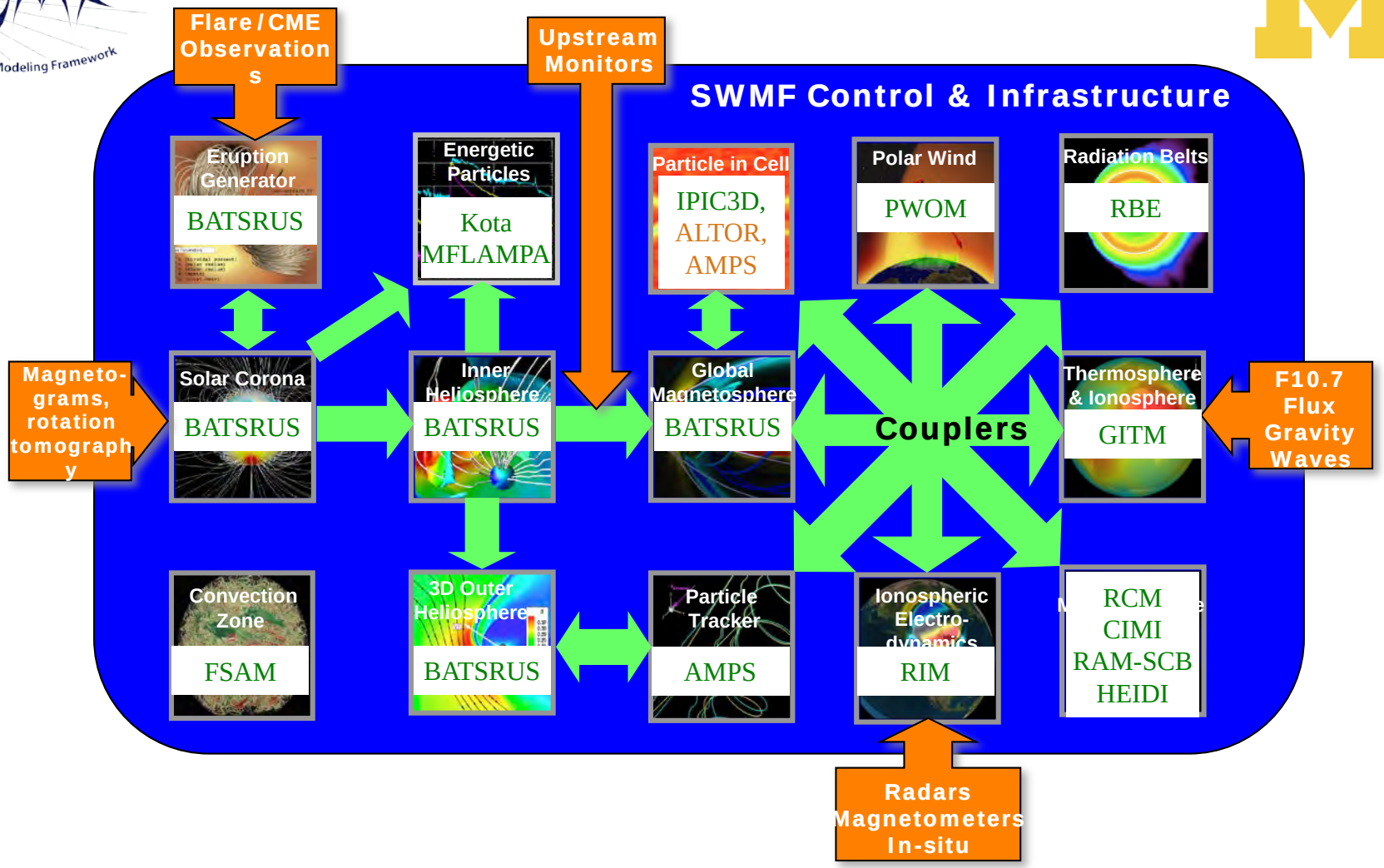


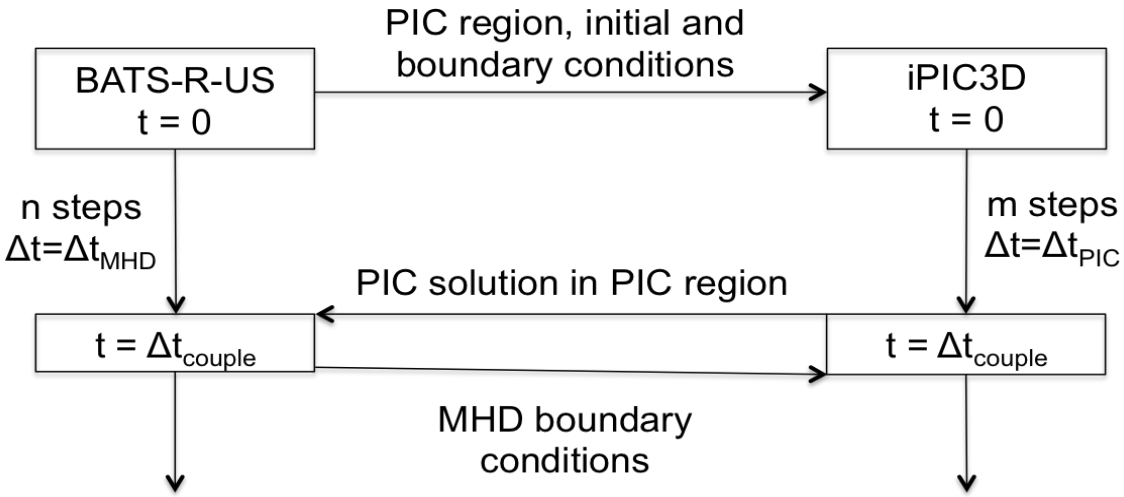
14 domains represented by 18 different models

594K lines of Fortran, 177K lines of C++ with MPI & OpenMP

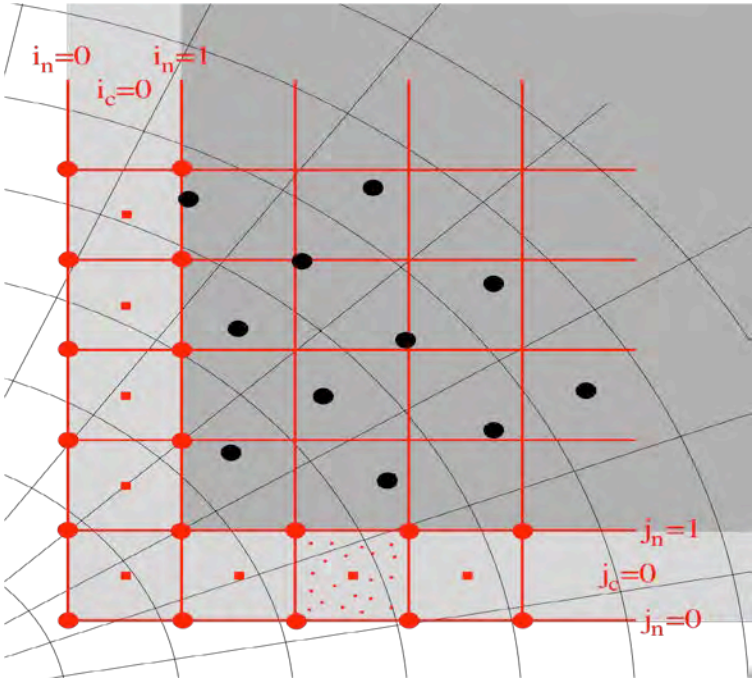
Scripts, Makefiles, visualization macros, documentation, nightly tests.

SWMF is freely available at http://csem.engin.umich.edu/tools/swmf and via CCMC

Couple MHD and PIC



- **MHD with embedded PIC model (MHD-EPIC): combine the efficiency of the global fluid code with the physics capabilities of the local PIC code**
  - PIC covers part of the simulation domain
  - MHD provides the initial state and boundary conditions for PIC
  - PIC overwrites the overlapped MHD cells



PIC Initialization

Ideal MHD equations:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot \left[\rho \mathbf{u}\mathbf{u} + I\left(p + \frac{1}{2\mu_0}B^2\right) - \frac{1}{\mu_0}\mathbf{B}\mathbf{B}\right] = 0$$

$$\frac{\partial e}{\partial t} + \nabla \cdot \left[\mathbf{u}\left(e + p + \frac{1}{2\mu_0}B^2\right) - \frac{1}{\mu_0}\mathbf{u}\cdot\mathbf{B}\mathbf{B}\right] = 0$$

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \cdot (\mathbf{u}\mathbf{B} - \mathbf{B}\mathbf{u}) = 0$$

$$e = \frac{p}{\gamma - 1} + \frac{\rho u^2}{2} + \frac{B^2}{2\mu_0}$$

Particle-in-Cell:

$$\nabla \cdot \mathbf{E} = \frac{\rho_q}{\epsilon_0},$$

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

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

$$\frac{1}{c^2}\frac{\partial \mathbf{E}}{\partial t} = \nabla \times \mathbf{B} - \mu_0 \mathbf{j},$$

$$\frac{d\mathbf{x}_p}{dt} = \mathbf{v}_p,$$

$$\frac{d\mathbf{v}_p}{dt} = \frac{q_s}{m_s}\left(\mathbf{E}_p + \mathbf{v}_p \times \mathbf{B}_p\right),$$

Initialize PIC from MHD

- Calculate Electric field from Ohm's law: $\mathbf{E} = -\mathbf{u} \times \mathbf{B} + \frac{\mathbf{J} \times \mathbf{B}}{q_e n_e}$
- Assume charge neutral: $n_i = n_e$
- Ion and electron velocities can be obtained from the fluid momentum and current: $n(m_i \mathbf{u}_i + m_e \mathbf{u}_e) = \rho \mathbf{u}_{\mathrm{MHD}}$ $\quad n(q_i \mathbf{u}_i + q_e \mathbf{u}_e) = \mathbf{J}_{\mathrm{MHD}}$
- Pressure
  1) Assume a fixed p_i/p_e ratio: $p_i = (1-\alpha)p_{\mathrm{MHD}}$ $\quad p_e = \alpha p_{\mathrm{MHD}}$
  2) Solve the electron pressure equation: $\frac{\partial p_e}{\partial t} + \nabla \cdot (p_e \mathbf{u}_e) = (\gamma - 1)(-p_e \nabla \cdot \mathbf{u}_e)$
- Generate macro-particles from Maxwellian distribution

3D MHD-EPIC Simulation Setup

- **Physical parameters**
  - Artificially increase ion inertial length by a factor of 16, so $d_i \sim 1/6\ R_E$.
  - $m_i/m_e = 100$
  - Typical solar wind conditions:
    $\rho = 5\ amu/cm^3$, $U_X = -400km/s$, $B = [0,0,-5]\ nT$
- **Hall MHD with separate electron pressure equation**
  - MHD domain: $-224 < x < 32$, $-128 < y, z < 128R_E$
  - At the magnetopause $\Delta x = 1/16R_E$ (~400km)
  - MHD uses ~20% CPU time
- **PIC**
  - PIC domain: $8 < x < 12$, $-6 < y < 6$, $-6 < z < 6R_E$
  - $\Delta x = 1/32R_E$: 5 cells per d_i (for f = 16)
  - 216 particles per cell per species: 8B total
  - Consuming ~80% simulation time
- **~18000 core hours modeling 1min**

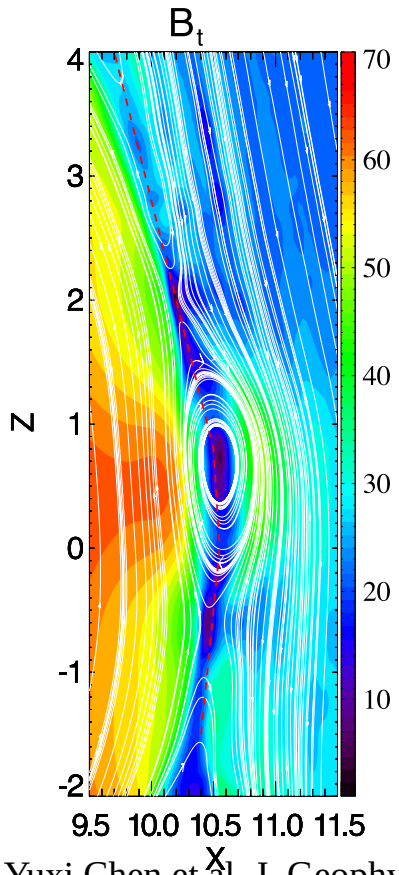
p [nPa]

Yuxi Chen et al. Journal of Geophysical Res. 2017

Simulated Flux Transfer Event (FTE)

FTE simulation: Magnetic Reconnection and Flux Rope Formation

- B_x jumps from the negative peak (z=0) to the positive peak (z=1R_E)
- Bounded by the depressed magnetic field 'trenches' at z=-0.2R_E and z =2R_E
- B_t reaches local minimum at the center



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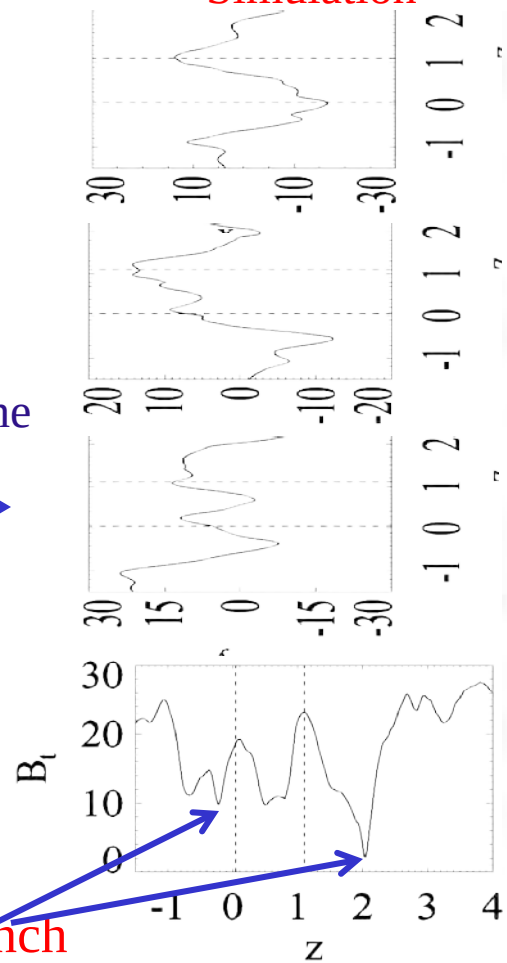
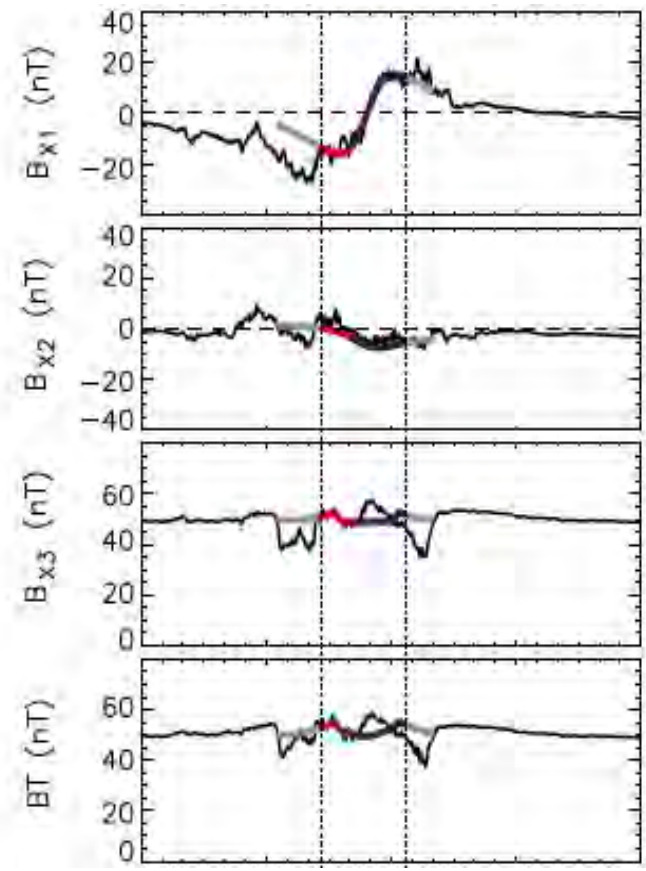
B field along the red dashed line

Simulation



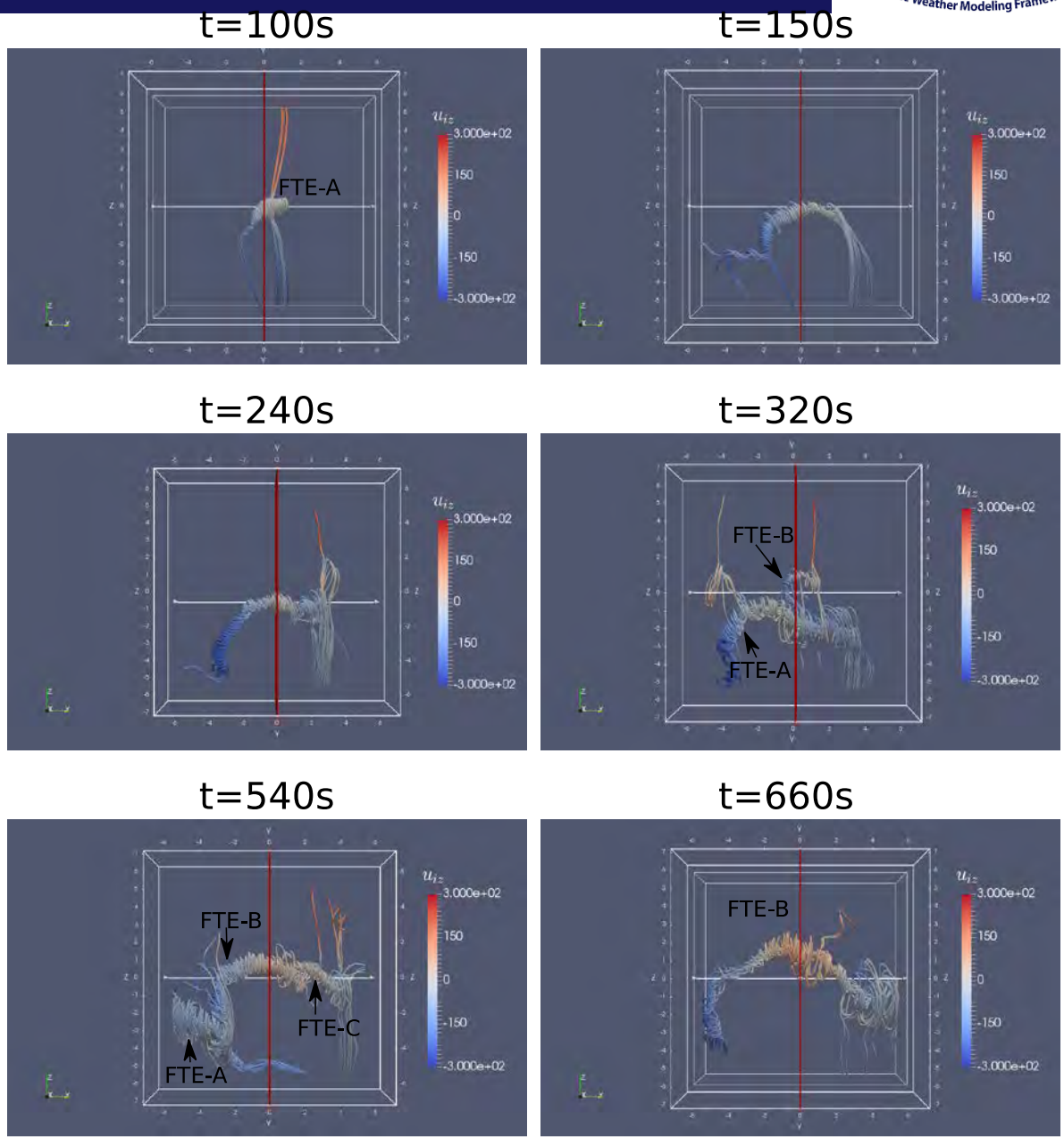
THEMIS data



From *Zhang et al. (2010)*

Evolution of Flux Transfer Events (FTEs)

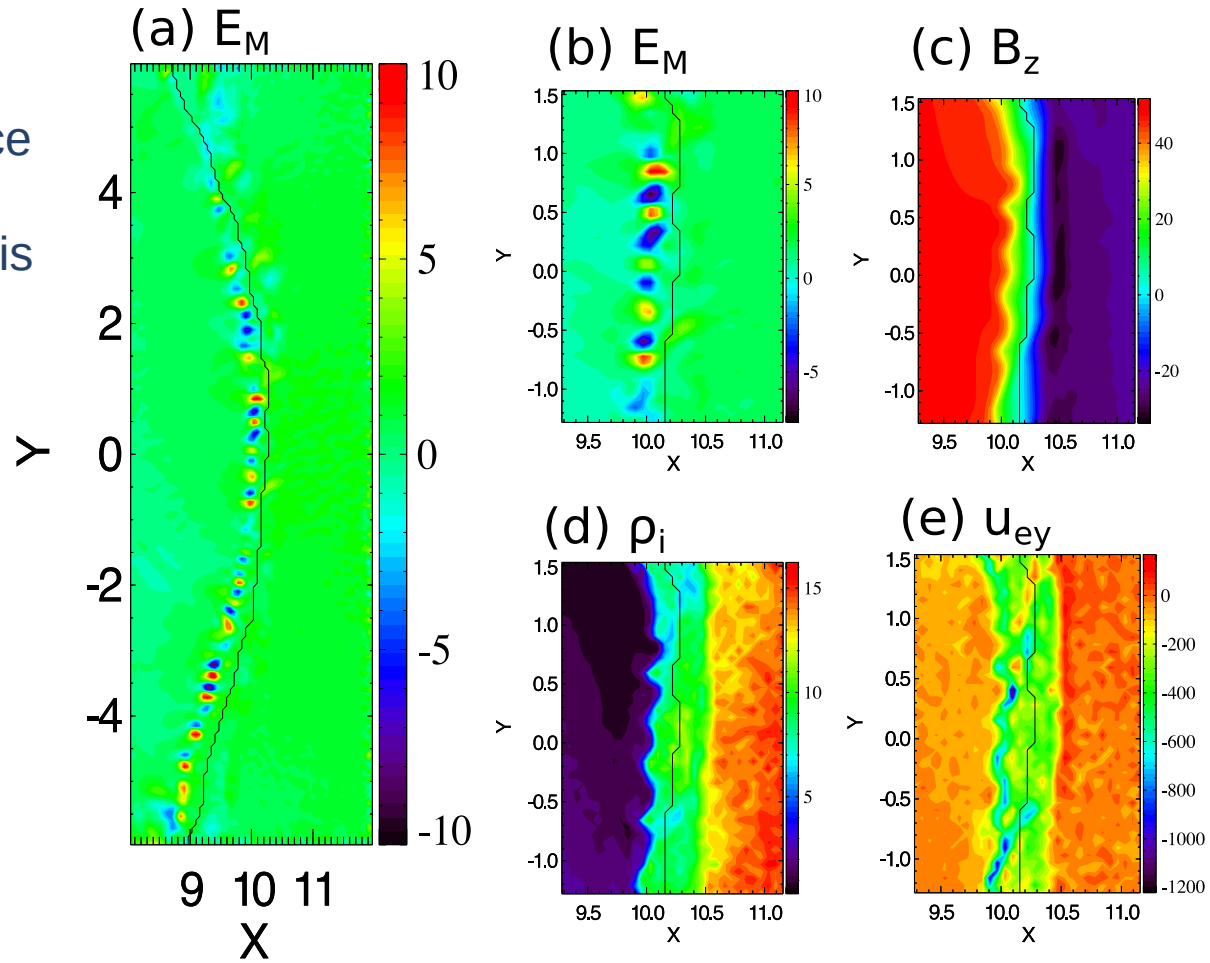
- **FTEs colored by u_{iz}**
  - IMF is purely southward
  - FTEs grow in the dawn-dusk direction
  - The FTEs become tilted
  - Two FTEs can merge into one



Yuxi Chen et al. J. Geophys. Res. 2018

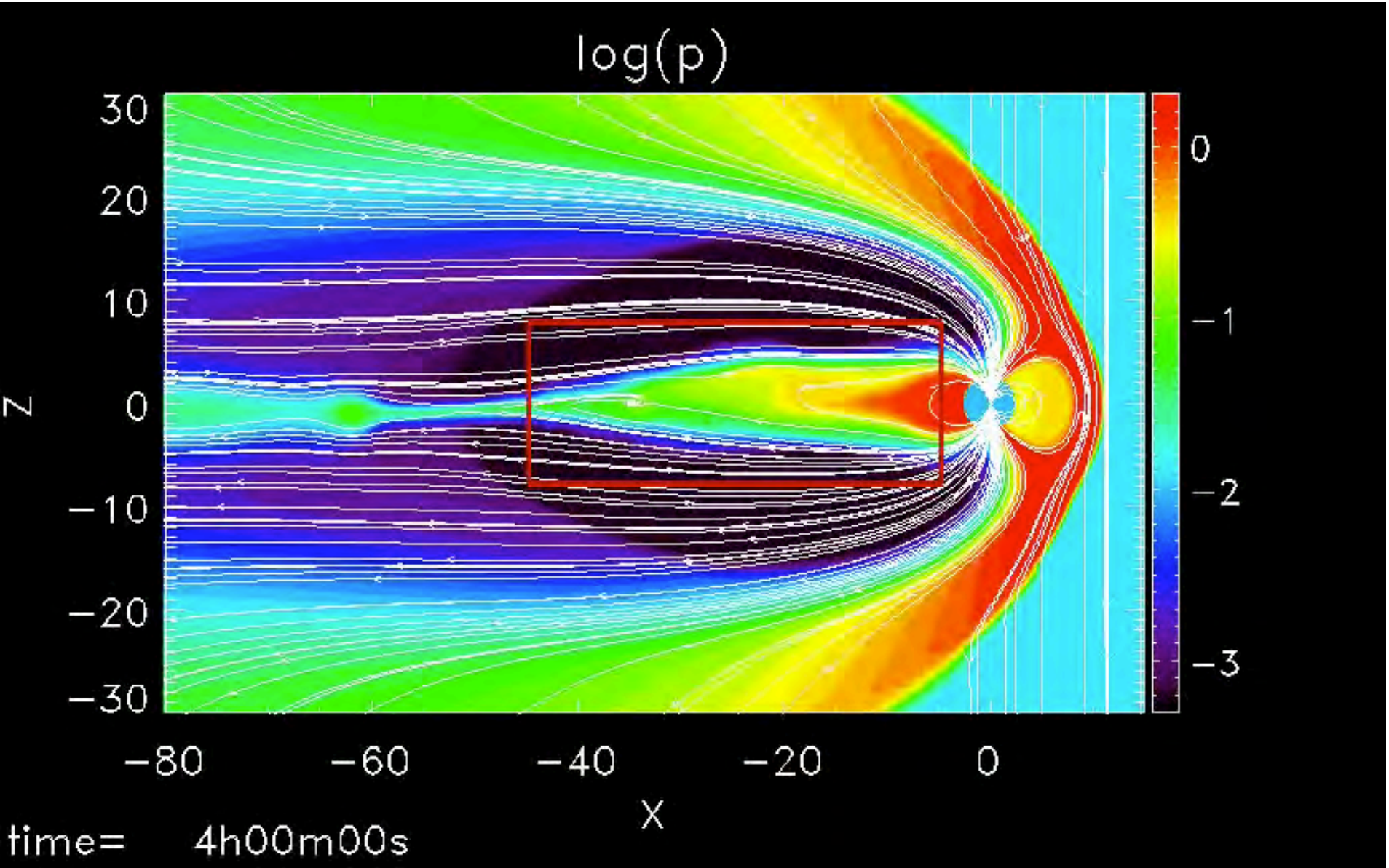
Lower Hybrid Drift Instability (LHDI)

- LHDI arises near the interface of magnetosheath and magnetosphere, where there is a sharp density gradient
- Simulation agrees with MMS observation
  - $E_M \sim 8$ mV/m
  - $kr_e \sim 0.4$, $\lambda \sim 16\ r_e$



MHD-EPIC simulation of the magnetotail

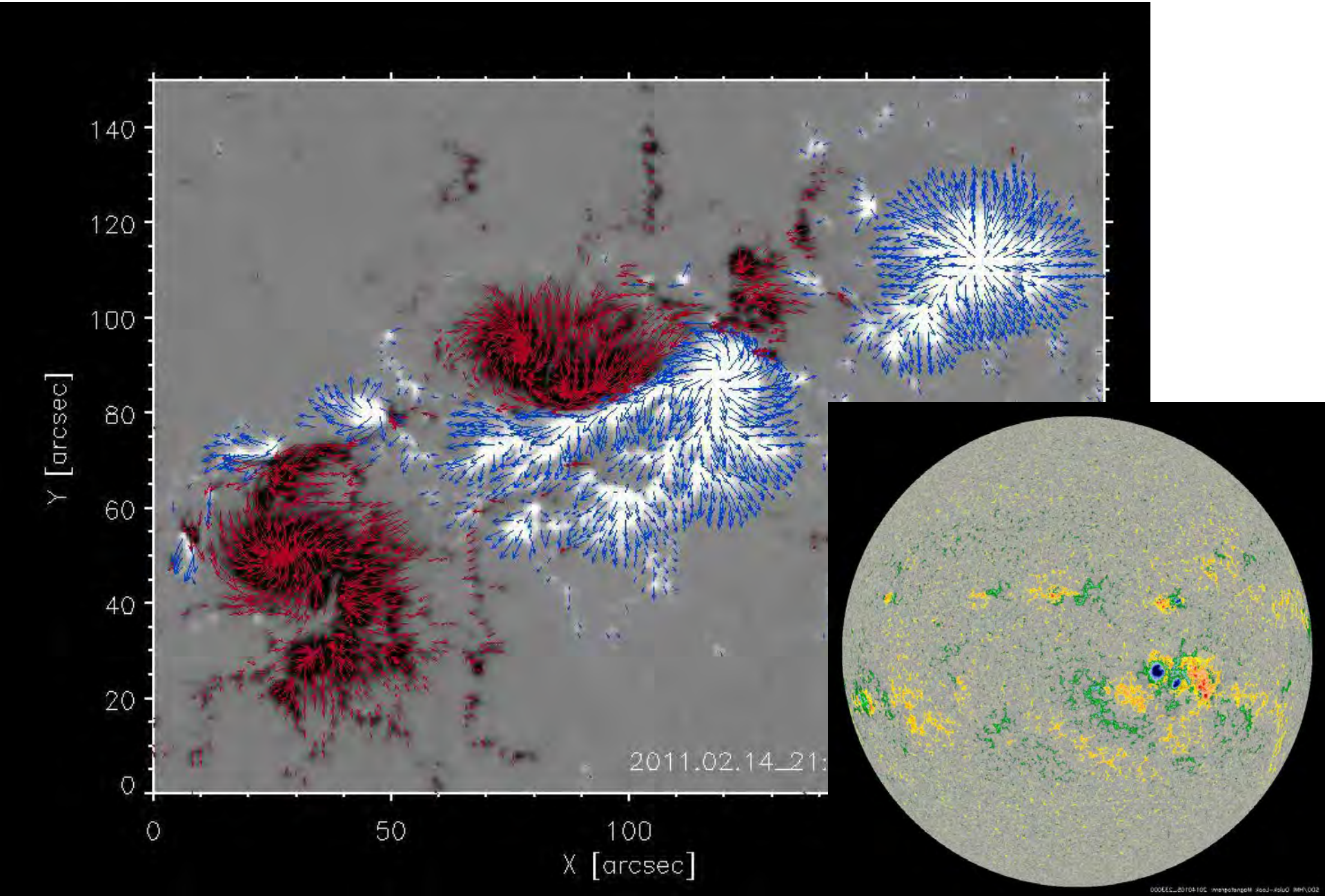
Solar wind: 10 amu/cc, 500 km/s, B_Z=-5nT changing to -15nT at t~6 hours.



Summary

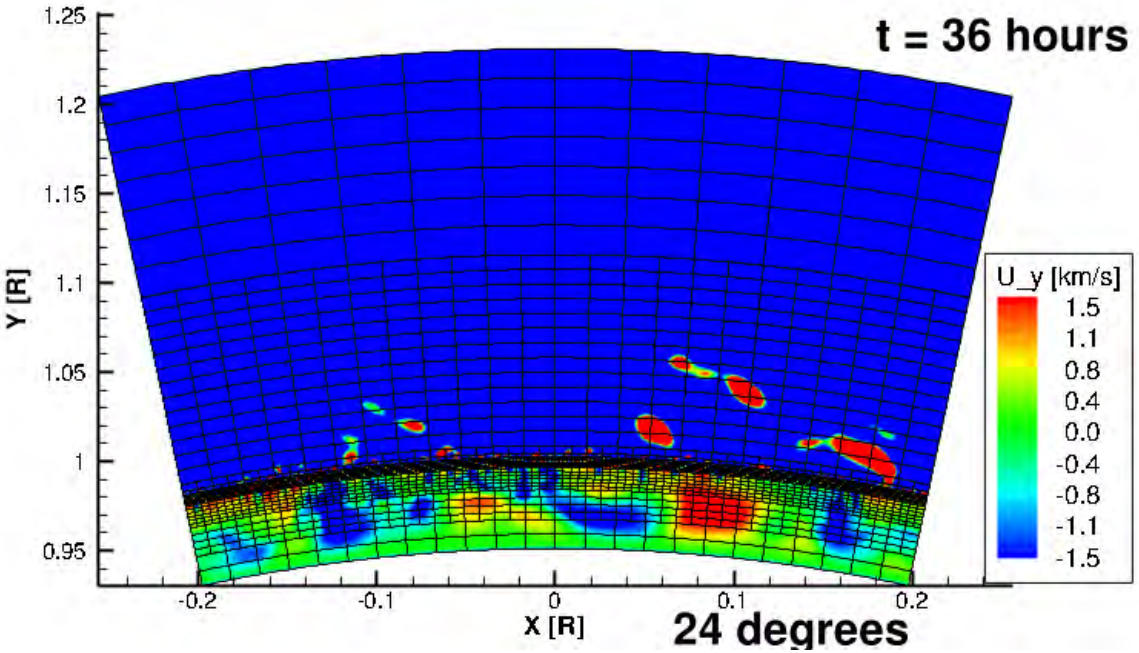
- **The generation and evolution of Flux Transfer Events**
  - FTE grows in dawn-dusk direction
  - Core field gradually increases
  - The core field strength is anticorrelated with plasma pressure
- **Confirms that the magnetic field signature of a FTE can be found at the early stage of formation**
- **Kinetic features**
  - lower hybrid drift instability (LHDI)

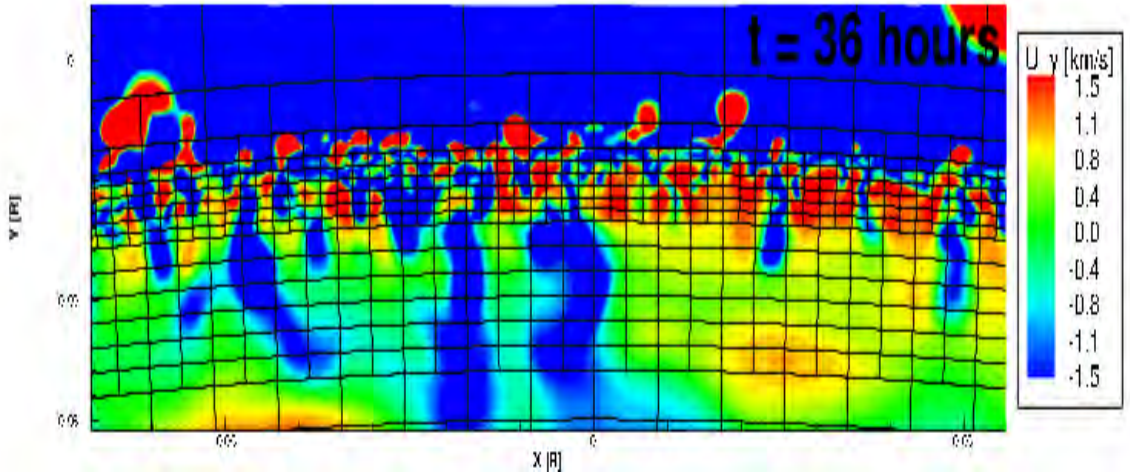
Vector Magnetic Field



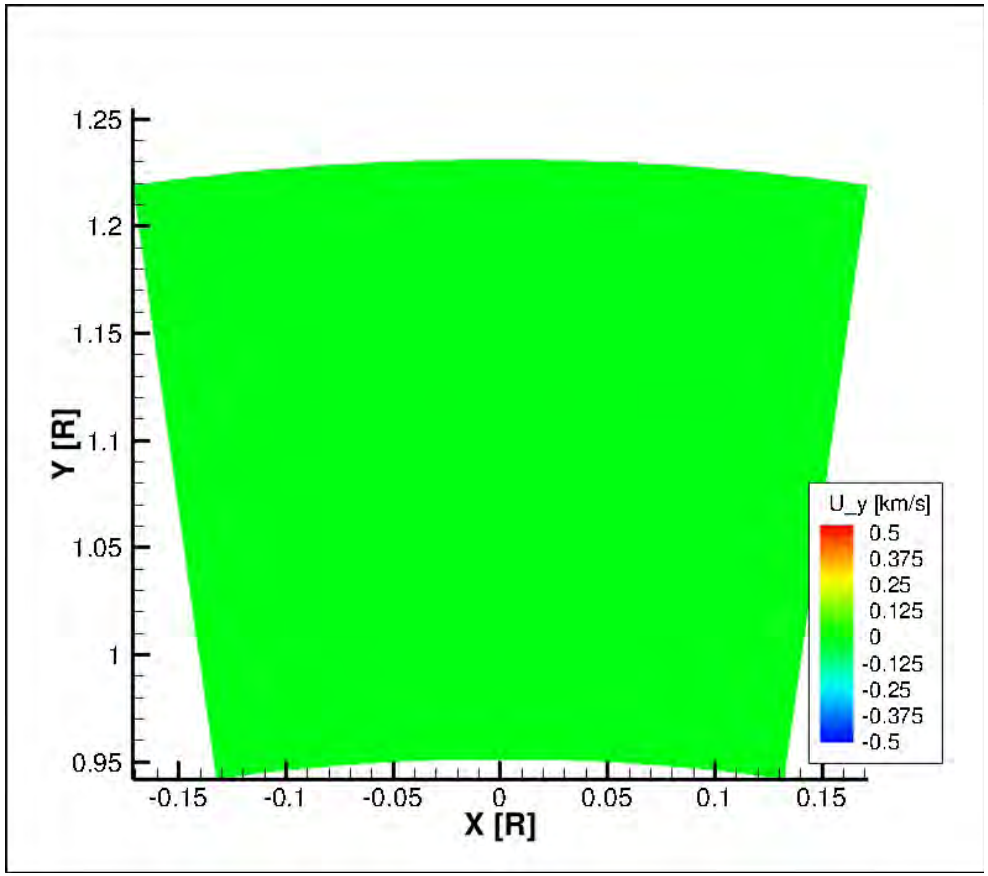
Spherical Wedge Active Region Model (SWARM) on Blue Waters

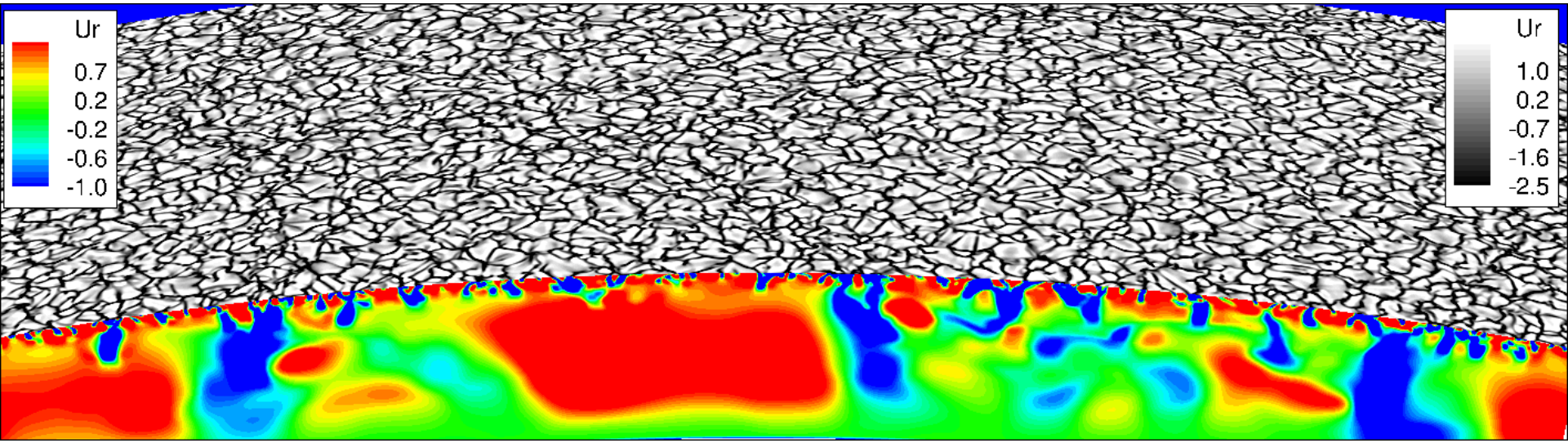
- Spherical wedge grid
- Gravity: $1/r^2$
- Tabular EOS ionization
- Radiative cooling
- 35 Mm deep (0.95 Rs)
- 5 levels of refinement
- 10x10x10 cell blocks
- 160 million grid cells
- 3 million time steps
- 288 hours on 16,384 cores: ~5 million CPU hours

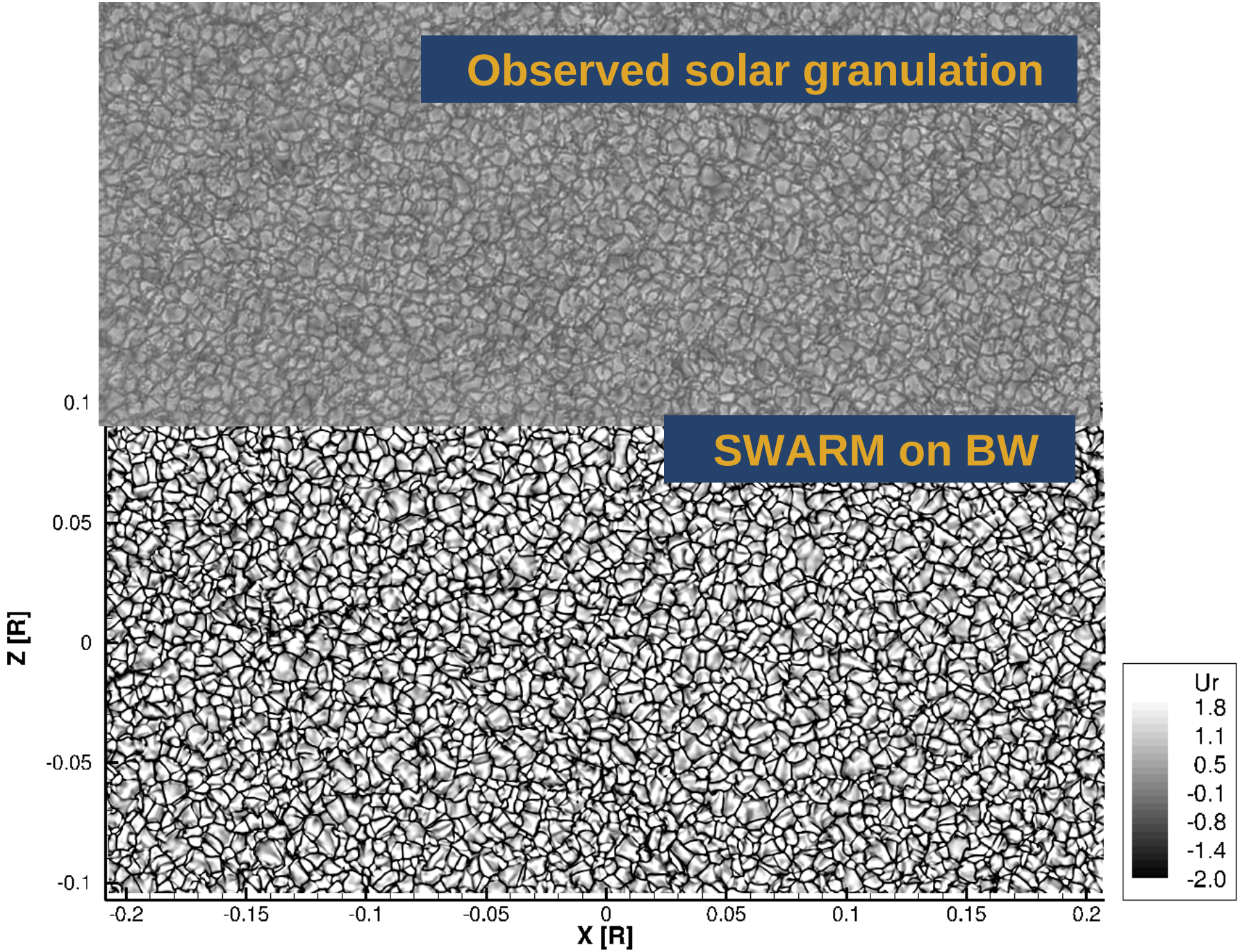




Convection and Granulation

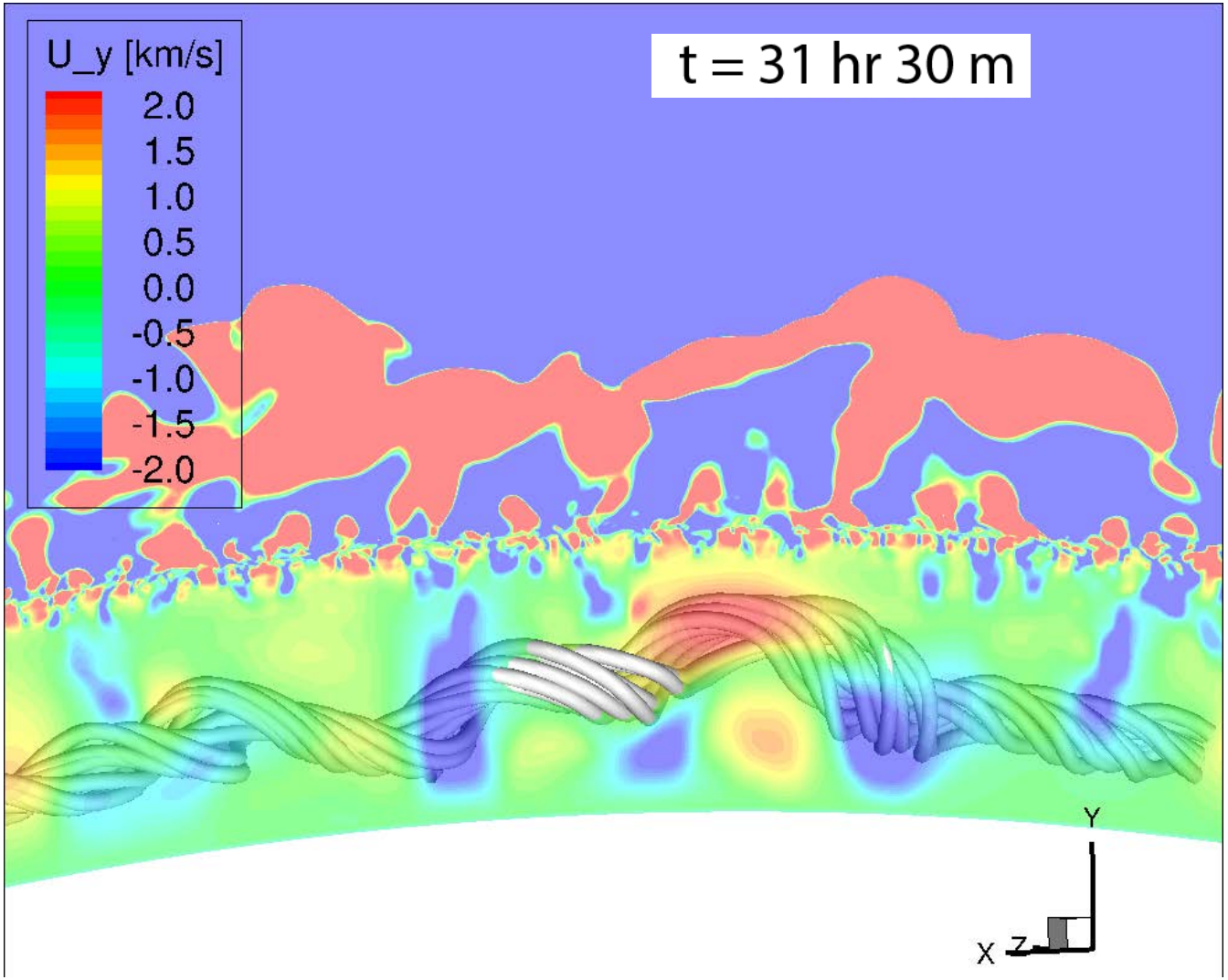





Observed solar granulation
SWARM on BW
0.1
0.05
0
-0.05
-0.1
Z [R]
-0.2
-0.15
-0.1
-0.05
0
0.05
0.1
0.15
0.2
X [R]
Ur
1.8
1.1
0.5
-0.1
-0.8
-1.4
-2.0

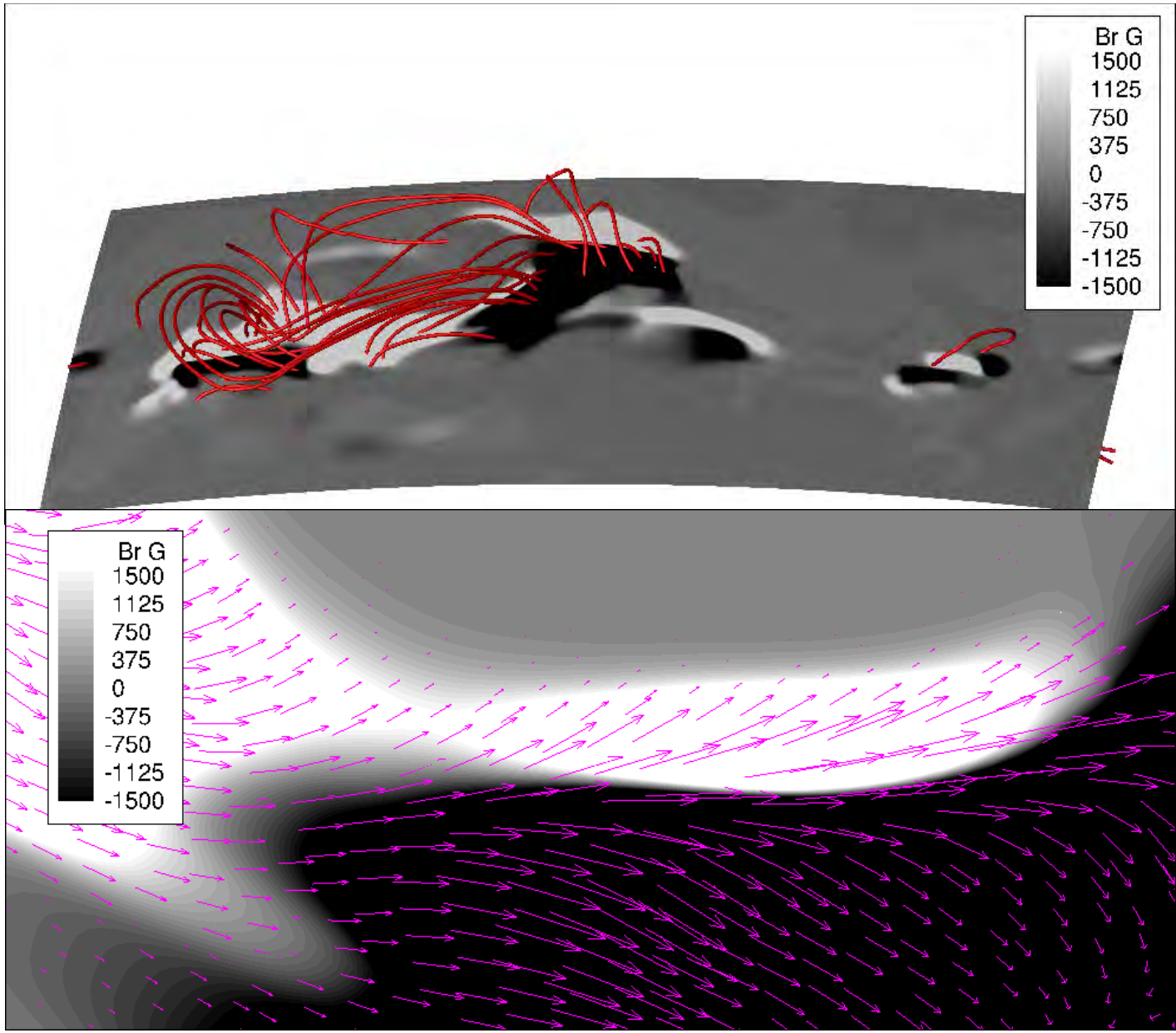
Active Region Scale Flux Emergence Simulation

- Add toroidal magnetic flux rope
- Twist factor =1
- 10^{23} Mx flux
- 20 Mm deep (0.9714 Rs)



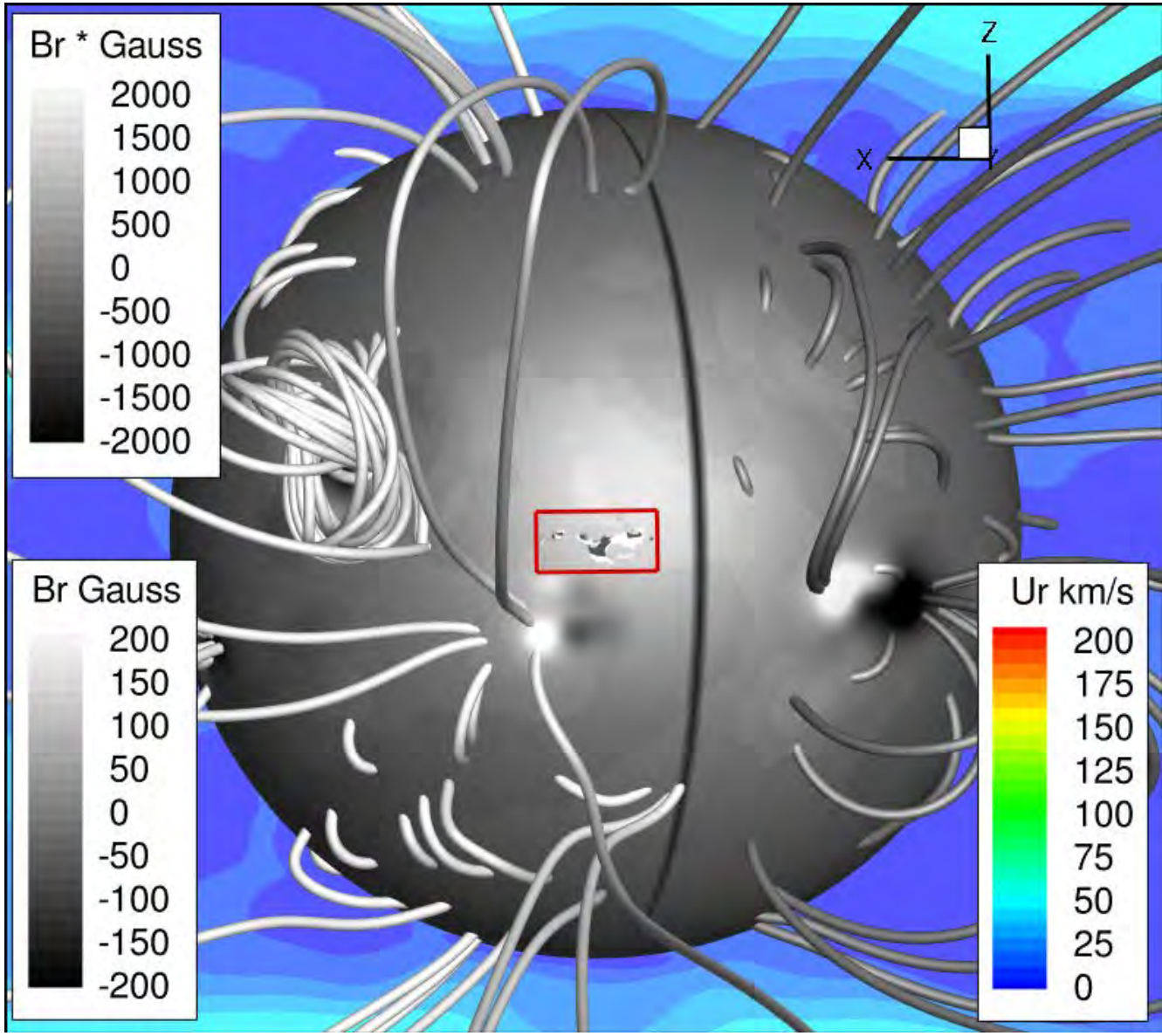
Magnetic Flux Emergence near the Photosphere

- R = 1 Rs
- Magnetic field distribution dominated by convection
- Flux concentrated in downdrafts
- Magnetic field evolves parallel to polarity inversion line
- Shear flows driven by the Lorentz force



Next Step: SWARM + AWSoM Simulations

- Realistic size active region model (SWARM)
- Global solar corona model (AWSoM)
- 2-way coupling at every time step
- Allow erupting flux to expand into corona
- Self-consistent CME initiation



Summary

- **Spherical Wedge Active Region Model (SWARM)**
  - Largest simulation of an active region 150x300Mm
  - Convection zone physics captured
  - Flux emergence simulation and active region formation
  - Manchester et al .AGU 2017

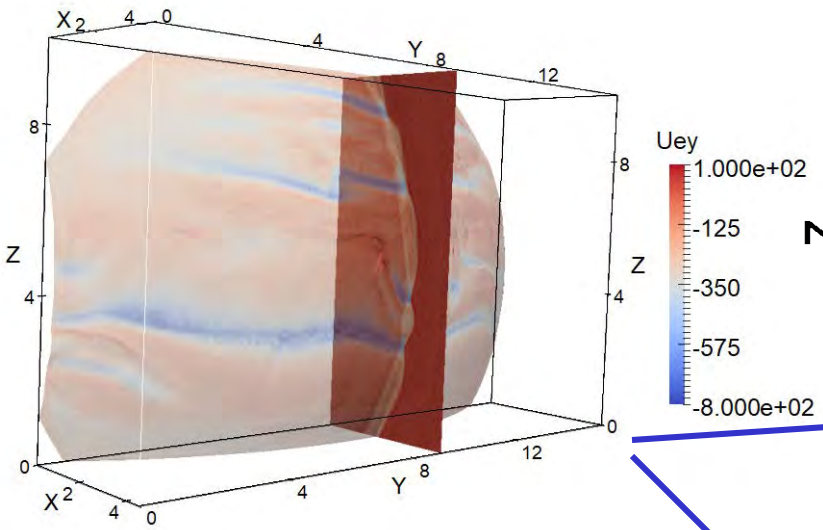
- **MHD-EPIC simulation of Earth's magnetosphere**
  - Day side and tail reconnection are modeled
  - First two-way coupled MHD-kinetic simulation of Earth's magnetosphere
  - Simulation of Flux Transfer Events formed by reconnection
  - Kinetic features: lower hybrid drift instability (LHDI). Agrees with MMS observations.
  - Chen et al. JGR 2017

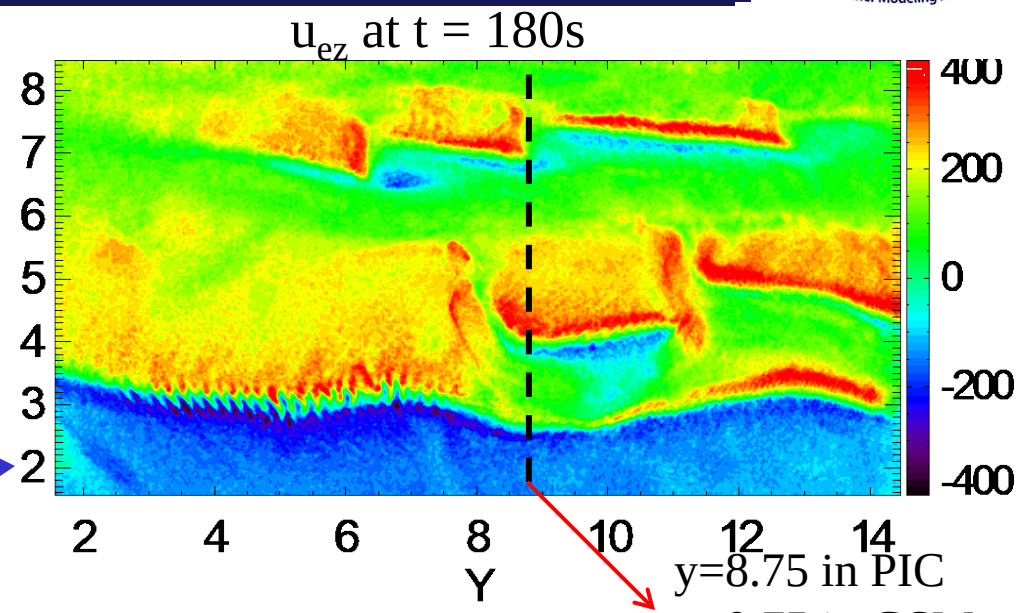
Why Blue Waters & Future Work

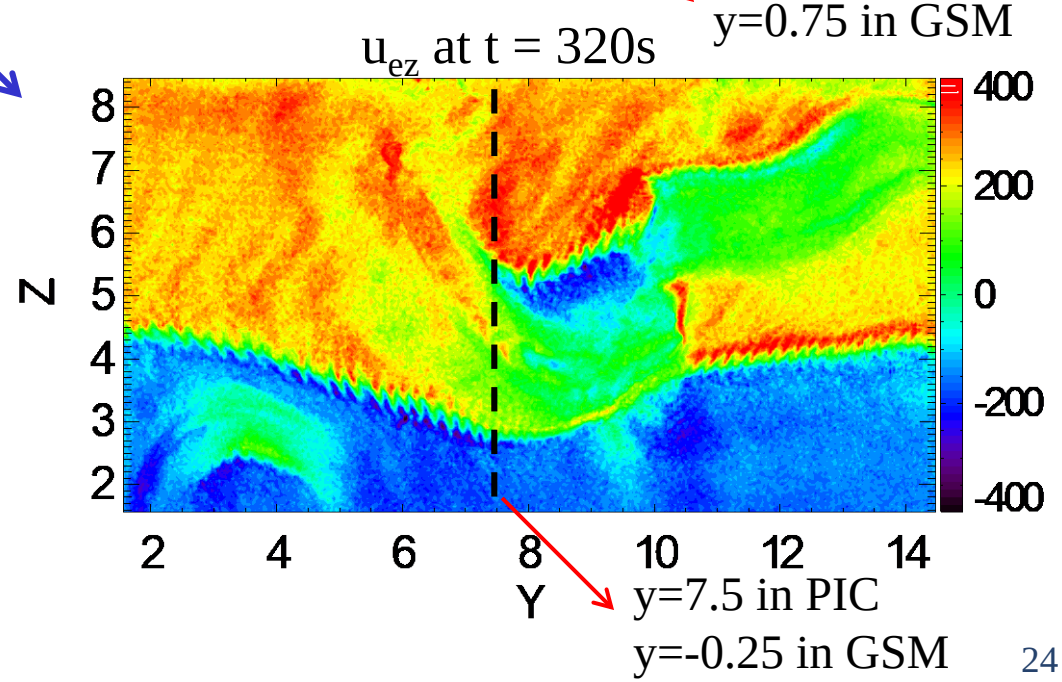
- **Future work**
  - SWARM + AWSoM simulations:
    - Continue flux emergence simulations
    - Continue simulation coupled to global corona model
  - MHD-EPIC simulations of Earth's magnetosphere:
    - Do actual events and compare with MMS observations
    - Cover both magnetopause and magnetotail with PIC boxes to study magnetic storms and sub-storms

- **Why Blue Waters?**
  - Simple and easy access
    - Large-scale file transfer made easy
    - Large-scale data storage & with rapid retrieval
    - Support staff is knowledgable and helpful
  - Order of magnitude more allocation than on other systems
  - Short turn-around times for large runs
  - Good software environment, stable hardware

Azimuthal Evolution of the reconnection site







- SuperDARN radar suggests the reconnection site propagates ~30km/s dawnward (*Nishimura,* GEM talk, 2017)
- The edge of the reconnection site moves from y=0.75R_E (t=180s) to y=-0.25R_E (t=320s). The corresponding speed is ~60km/s