MHD turbulence modeling of the solar wind

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ATMOSPHERIC, OCEANIC AND SPACE SCIENCES
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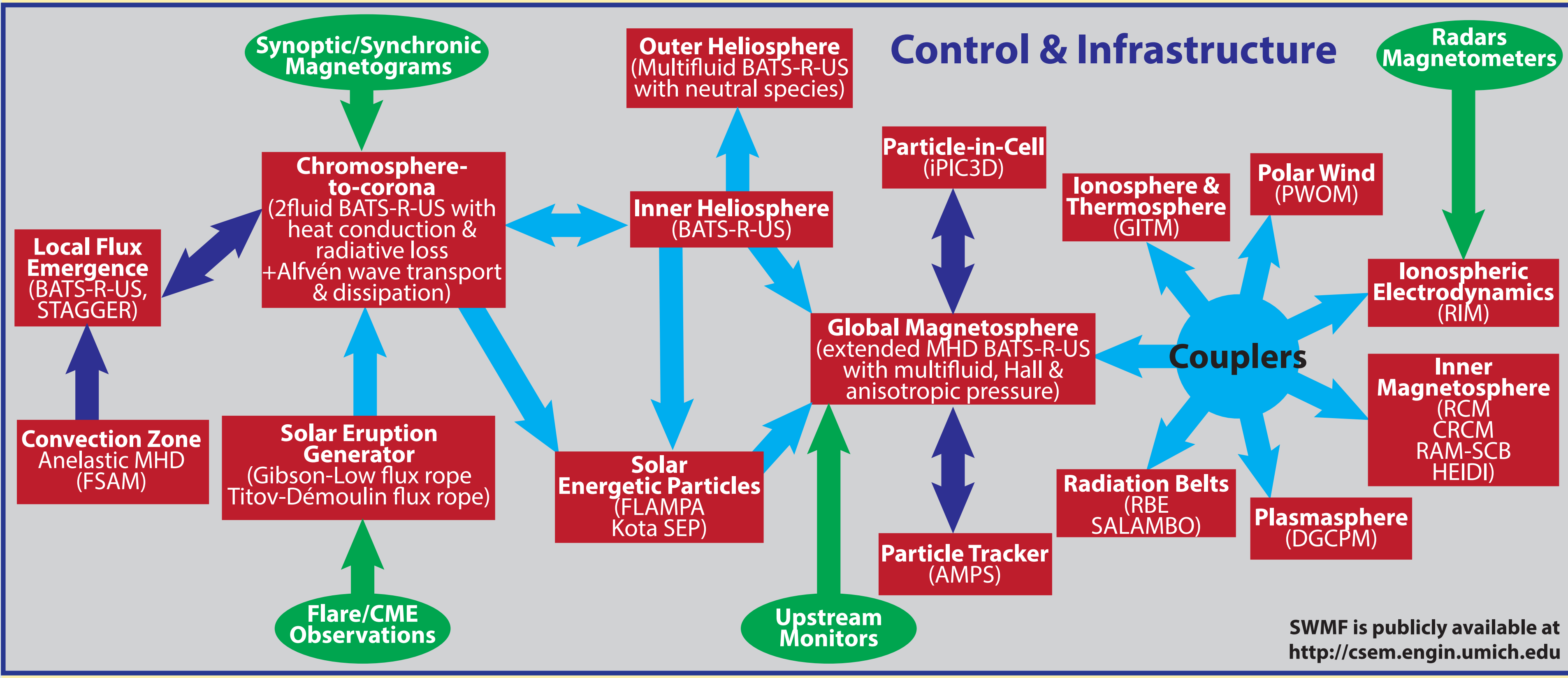
Outline

- **Space Weather Modeling Framework (SWMF)**
- **Solar corona and inner heliosphere model with low-frequency Alfvén wave turbulence**
- **Validation: EUV images**
- **Validation: 1AU in-situ**
  - Turbulence at corotating interaction regions
- **Generalization of solar wind turbulence model to protons and alpha particles**

Space Weather Modeling Framework (SWMF)

Block Diagram of the Space Weather Modeling Framework



The BATS-R-US multi-physics code

Time-stepping
Local explicit (CFL control) for steady state
Global explicit
Part steady explicit
Explicit/implicit
Point-implicit
Semi-implicit
Fully implicit

Conservation laws
Hydrodynamics, MHD
Ideal & non-ideal
Hall
Anisotropic pressure
Semi-relativistic
Multi-species
Multi-fluid
Ideal & non-ideal EOS

Numerics
Conservative finite-volume discretization
2nd (TVD), 4th (PPM) & 5th (MP) spatial order schemes
Rusanov/HLLE/AW/Roe/HLLD
Splitting the magnetic field into $B_0 + B_1$
Divergence B control
CT, 8-wave, projection, parabolic-hyperbolic cleaning

Block **A**daptive-**T**ree **S**olar-wind **R**oe-type **U**pwind **S**cheme

AMR Library (BATL)
Self-similar blocks
Cartesian grid
Curvilinear grid (can be stretched)
Supports 1, 2 and 3D block-adaptive grids
Allows AMR in a subset of the dimensions

Source terms
Gravity
Heat conduction
Ion-neutral friction
Ionization
Recombination
Charge exchange
Wave energy dissipation
Radiative heating/cooling

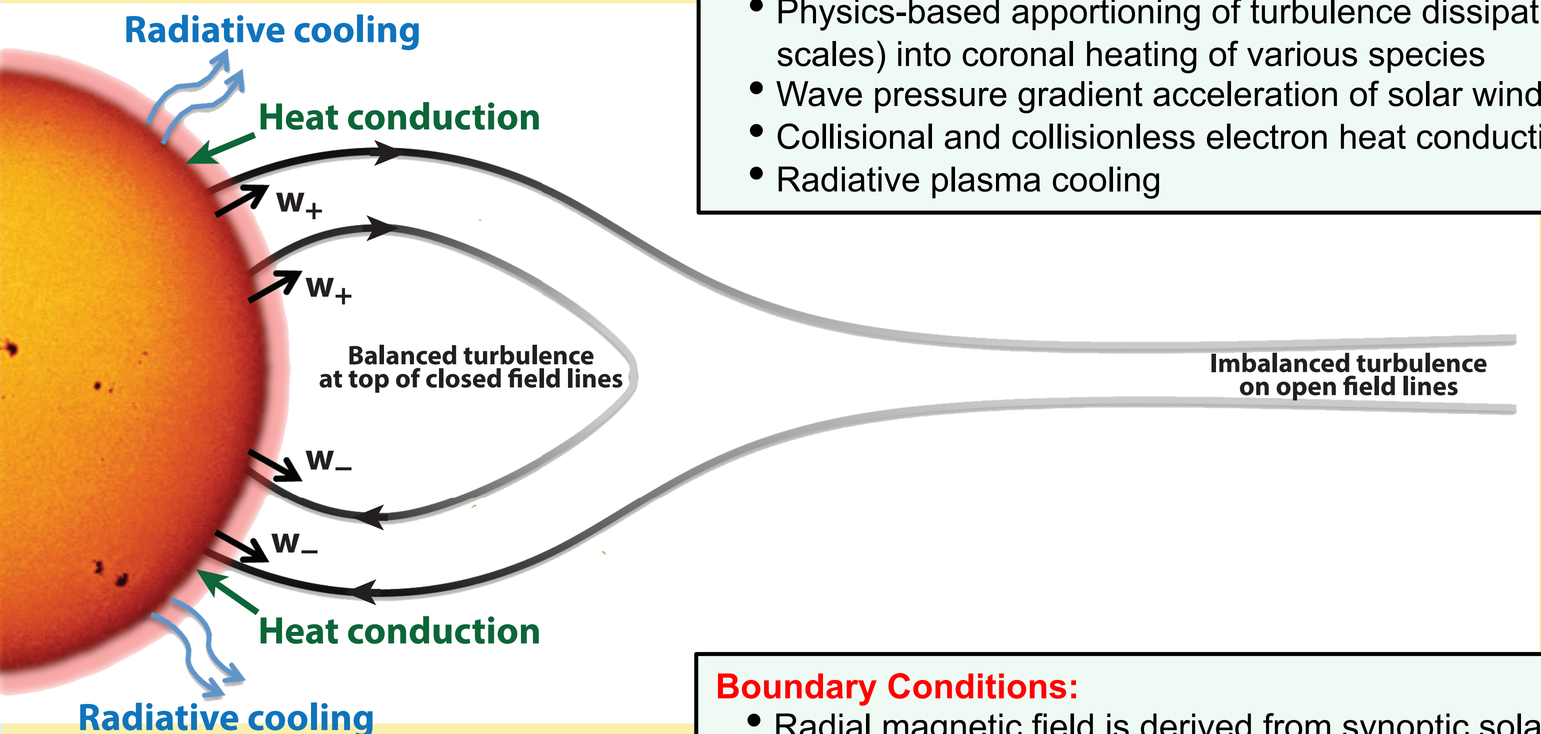
Auxiliary equations
Wave energy transport
Radiation transfer (multigroup diffusion)
Material interface (level set)
Parallel ray-tracing
Tabular equation of state

Alfvén Wave Solar Model (AWSoM)

B. van der Holst et al. ApJ **782**, 81 (2014).

Extended MHD physics:

- Separate $T_{p||}$, $T_{p\perp}$ and T_e
- WKB equations for parallel and antiparallel propagating turbulence ($w_\pm$)
- Non-WKB physics-based reflection of $w_\pm$ results in turbulent cascade
- Correction for presumed uncorrelated waves $w_\pm$ in the balanced turbulence near apex of closed field lines
- Physics-based apportioning of turbulence dissipation (at the gyro-radius scales) into coronal heating of various species
- Wave pressure gradient acceleration of solar wind plasma
- Collisional and collisionless electron heat conduction
- Radiative plasma cooling



Boundary Conditions:

- Radial magnetic field is derived from synoptic solar magnetograms
- Poynting flux of outward propagating turbulence:

$$(S_A / B) = 1.1 \times 10^6 \,\mathrm{W m^{-2} T^{-1}}$$

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SWMF
Space Weather Modeling Framework

Alfvén Wave Turbulence

- **Wave energy densities of counter-propagating transverse Alfvén waves parallel (+) and anti-parallel (-) to magnetic field:**

$$\frac{\partial w_\pm}{\partial t} + \nabla \cdot \left[\left(\mathbf{u} \pm \mathbf{V}_A \right) w_\pm \right] + \frac{w_\pm}{2} (\nabla \cdot \mathbf{u}) = \mp \mathcal{R} \sqrt{w_- w_+} - \Gamma_\pm w_\pm$$

energy reduction in expanding flow

wave dissipation

Alfvén wave advection

wave reflection (field-aligned Alfven speed gradient and field-aligned vorticity)

- **Phenomenological cascade rate (Dmitruk et al., 2002):** $\Gamma_\pm = \frac{2}{L_\perp} \sqrt{\frac{w_\mp}{\rho}}$

- **Similar to Hollweg (1986), we use a simple scaling law for the transverse correlation length** $L_\perp \sqrt{B} = 150\mathrm{km}\sqrt{\mathrm{T}}$

Heat Partitioning

- **Counter-propagating Alfvén waves due to partial reflection of the waves**
- **Non-linear interaction of these waves results in transverse energy cascade**
- **Wave dissipation at the gyro-kinetic scales**

- **We use the coronal heating formulation of Chandran et al. (2011):**
  - Linear damping of kinetic Alfvén waves (KAW), resulting in electron and parallel proton heating
  - Electric field fluctuations due to transverse turbulent cascade can disturb the proton gyro motion enough to give rise to perpendicular stochastic heating
  - Electron heating at scales much smaller than proton gyro-radius

Limiting the Anisotropic Pressure

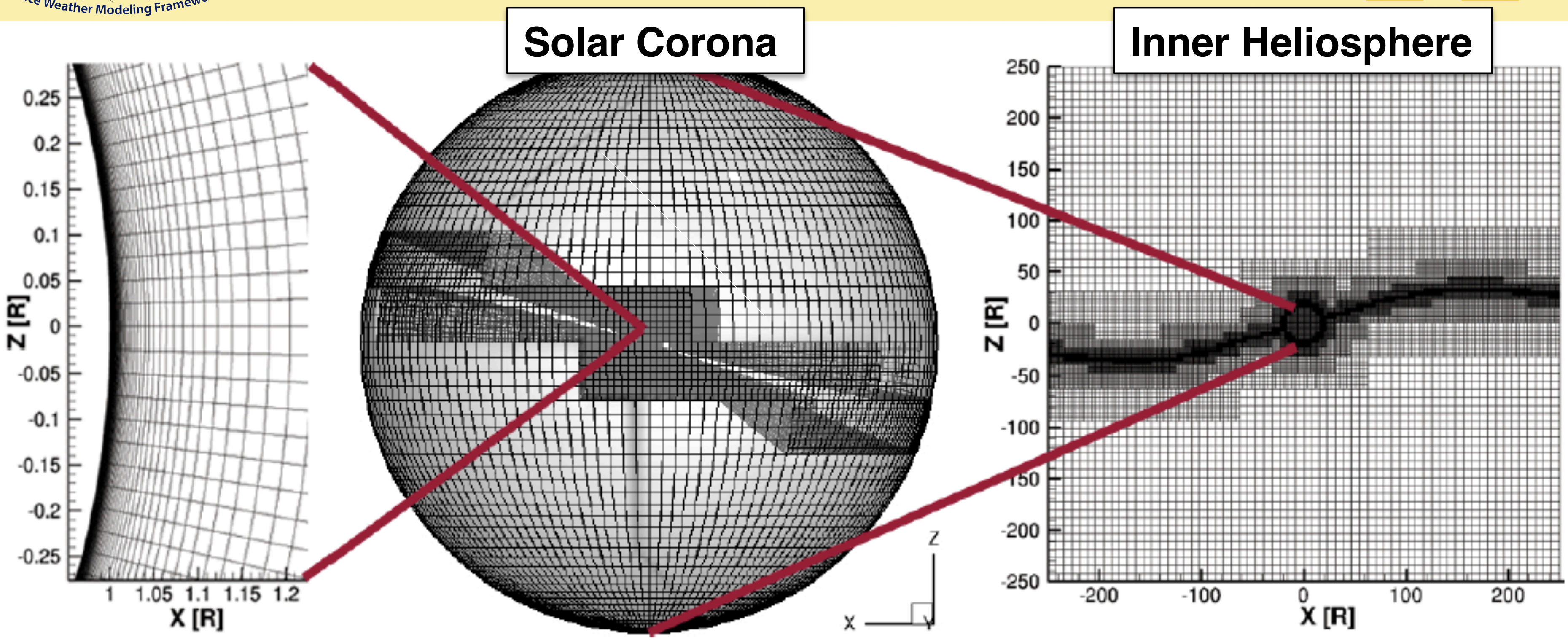
X. Meng et al. 2012 JCP, JGR

The instability-based anisotropic pressure relaxation towards the marginal stable pressure $\bar{p}_\parallel$ while keeping averaged pressure p unmodified: $\frac{\delta p_\parallel}{\delta t} = \frac{\bar{p}_\parallel - p_\parallel}{\tau}$

applied in firehose, mirror and proton cyclotron unstable regions. τ is taken to be the inverse of the growth rates of the instabilities (Hall 1979, 1980, 1981 and Southwood & Kivelson 1993):

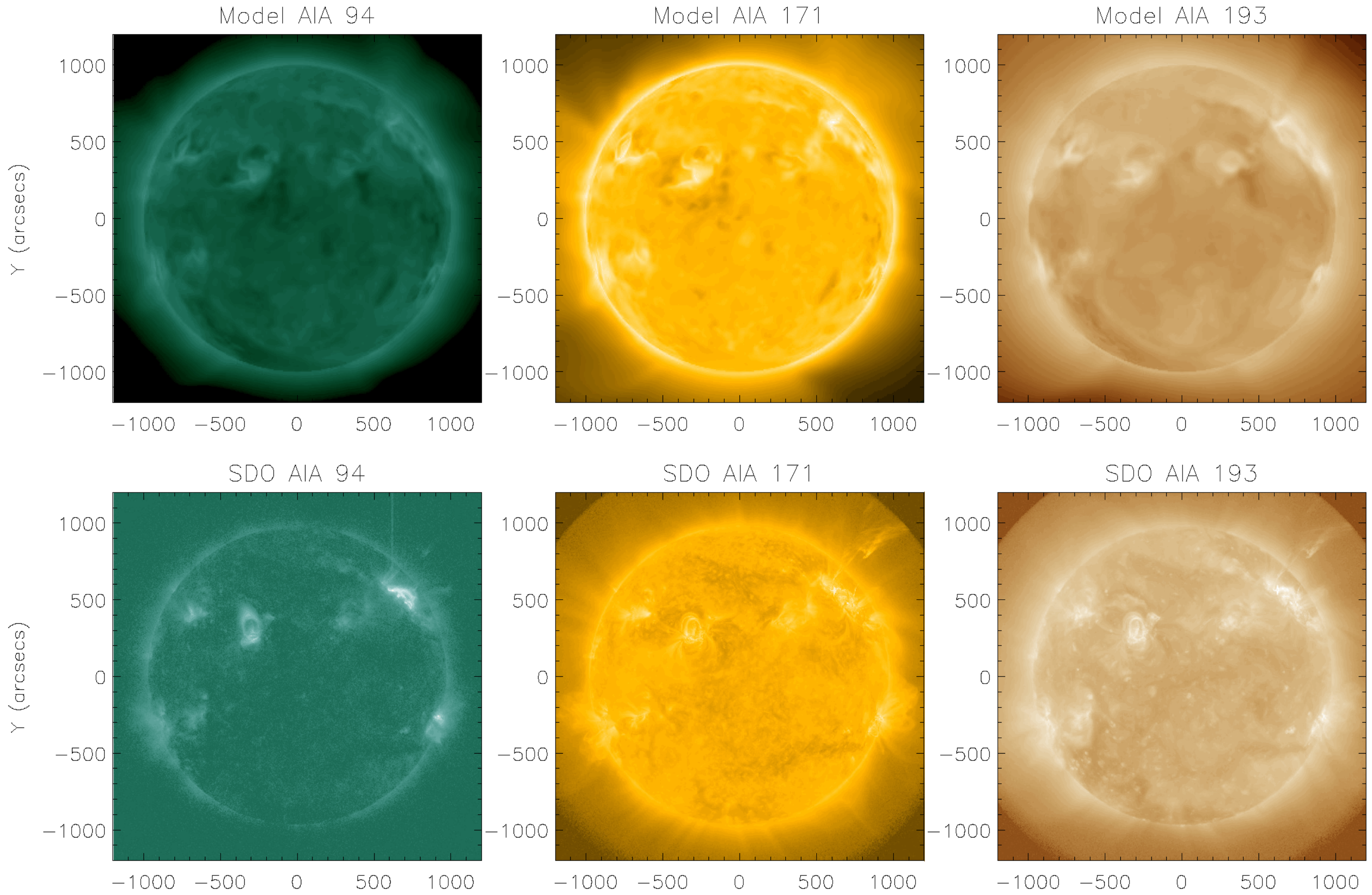
	instability criteria	relaxation time τ
firehose	$\frac{p_\parallel}{p_\perp} > 1 + \frac{\mathbf{B}^2}{\mu_0 p_\perp}$	$\tau_f = \frac{1}{\gamma_{f_{FLR}}(\lambda_f)} = \frac{2}{\Omega_i}\frac{\sqrt{p_\parallel(p_\perp - p_\parallel/4)}}{\Delta p_f}$
mirror	$\frac{p_\perp}{p_\parallel} > 1 + \frac{\mathbf{B}^2}{2\mu_0 p_\perp}$	$\tau_m = \frac{1}{\gamma_m(\lambda_m)} = \frac{3\sqrt{5}}{4\Omega_i}\sqrt{\frac{p_\parallel}{2\Delta p_m}}$
proton cyclotron	$\frac{p_\perp}{p_\parallel} > 1 + 0.3\sqrt{\frac{\mathbf{B}^2}{2p_\parallel}}$	$\tau_{ic} = \frac{10^2}{\Omega_i}$

Computational Grids

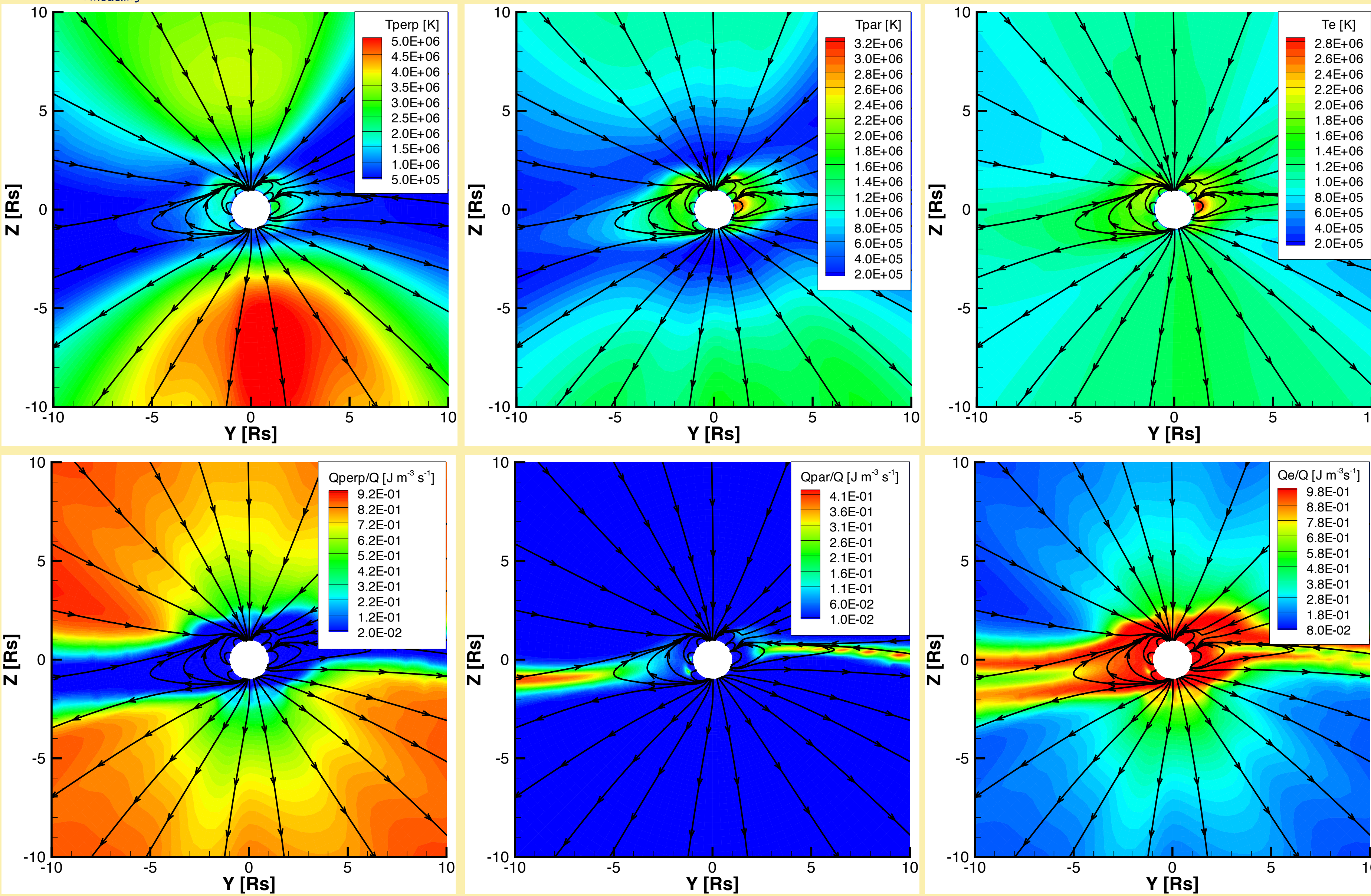


- AWSoM is split in two coupled framework components: stretched spherical grid for solar corona, cartesian grid for inner heliosphere
- Significant grid stretching to grid resolve the upper chromosphere and transition region in addition to artificial transition region broadening
- AMR to resolve the heliospheric currentsheet

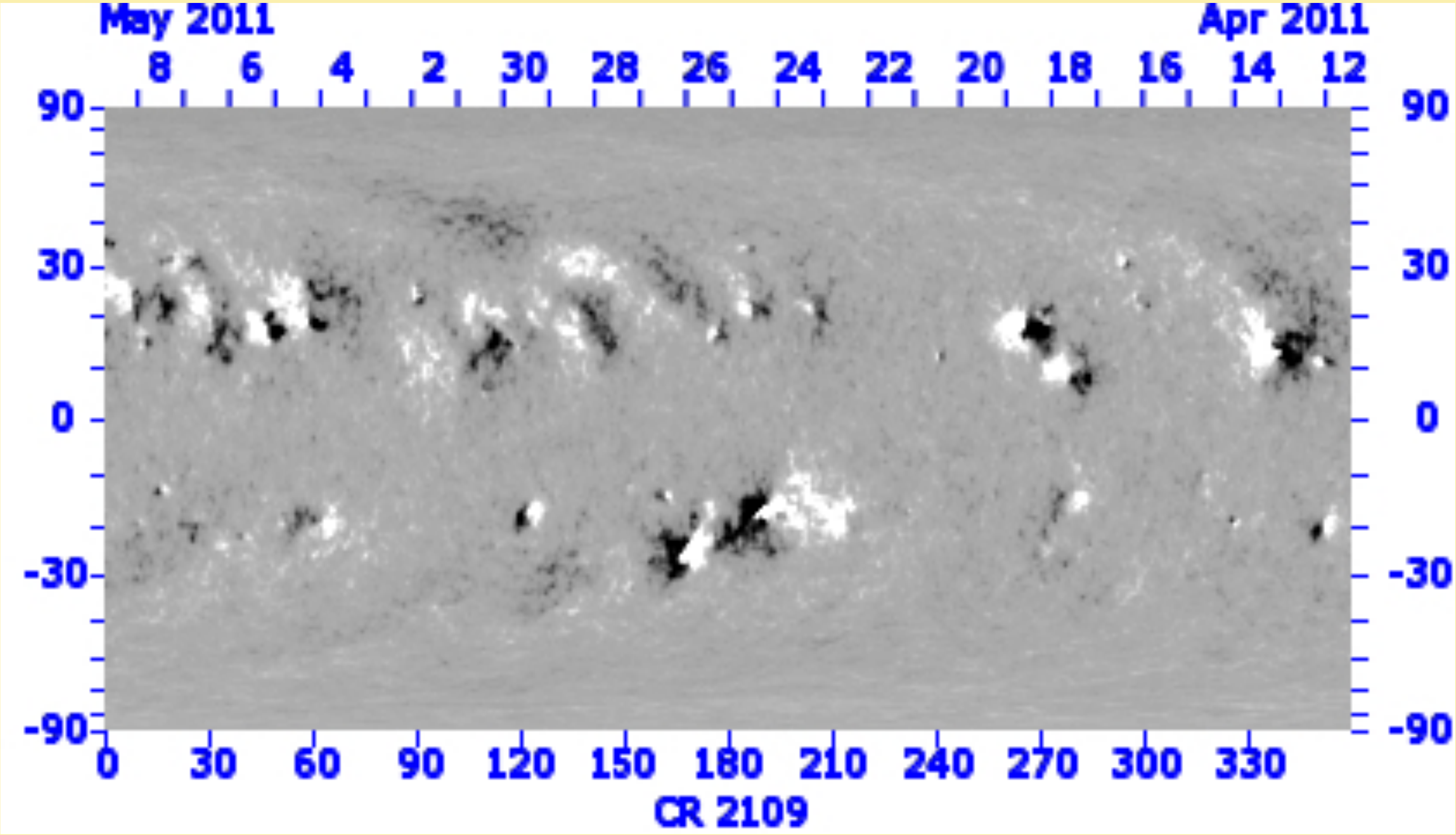
Validation: EUV Images for CR2107



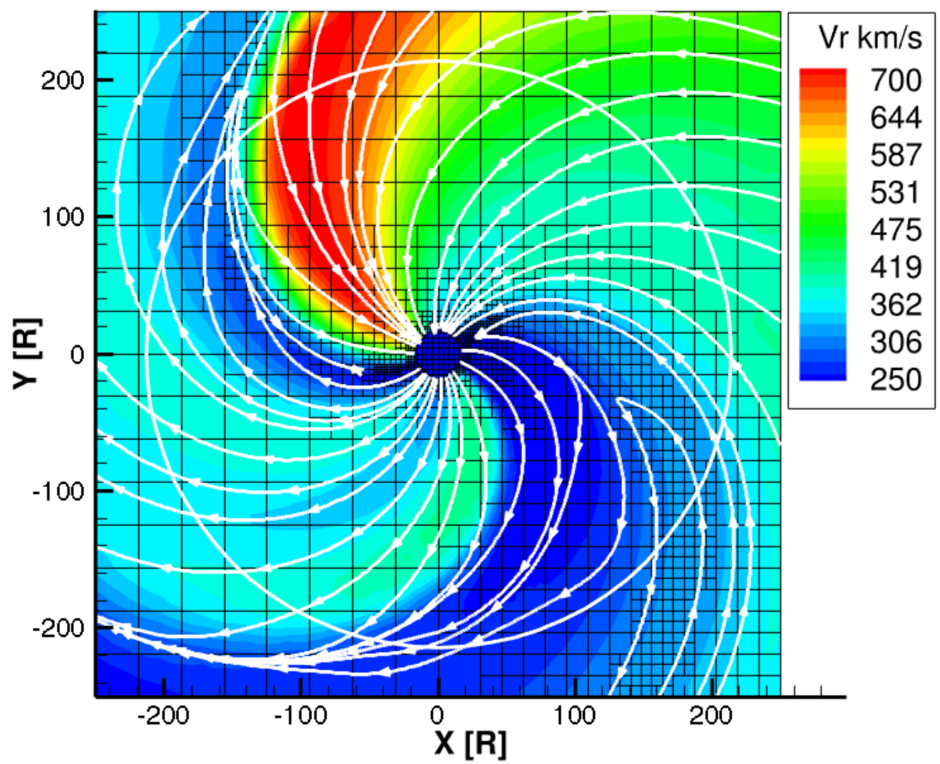
Heat Partitioning for the Electron and Anisotropic Proton Temperatures

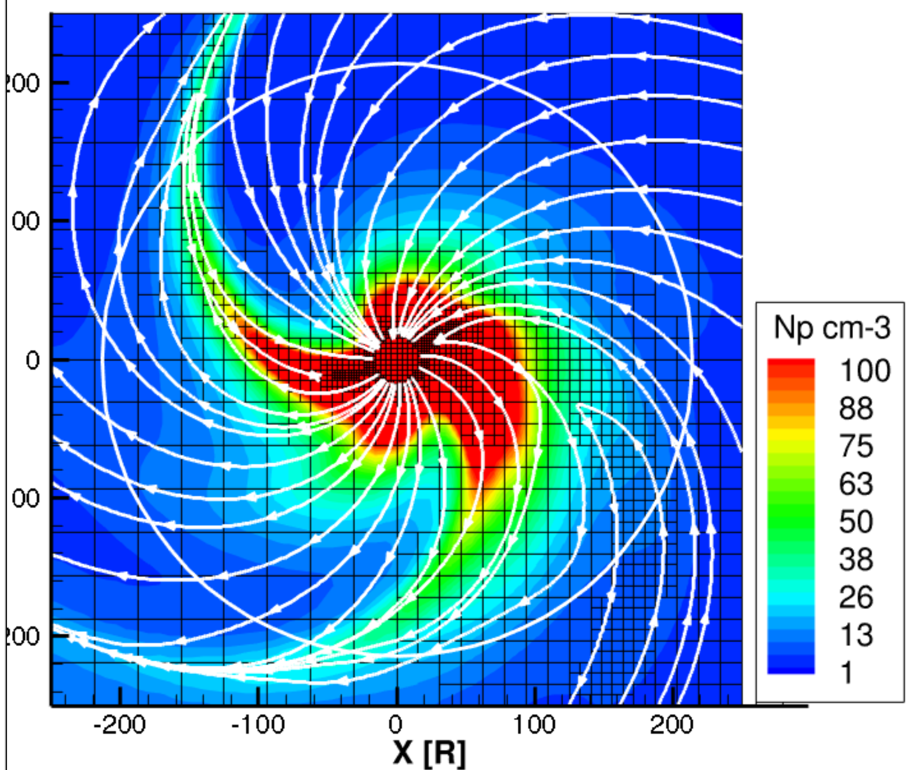


GONG Synoptic Magnetogram for CR2109



CR2109: Corotating Interaction Regions





CR2109: Prediction of MHD Quantities at Earth

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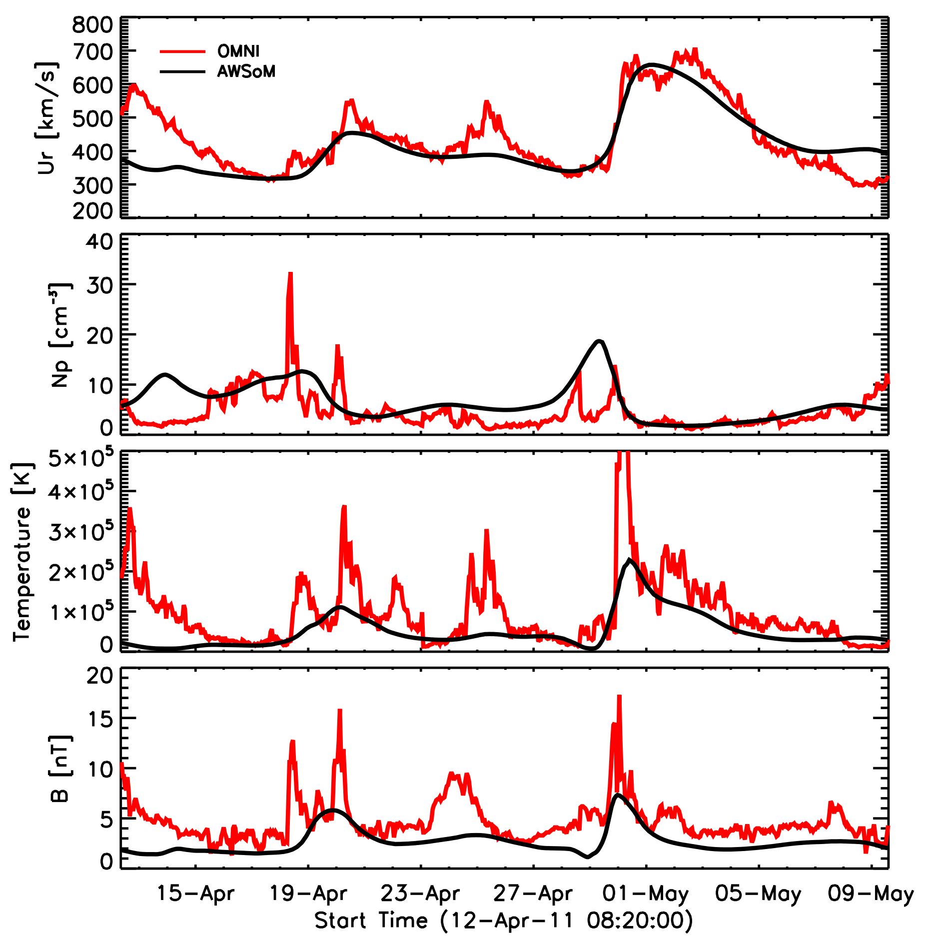
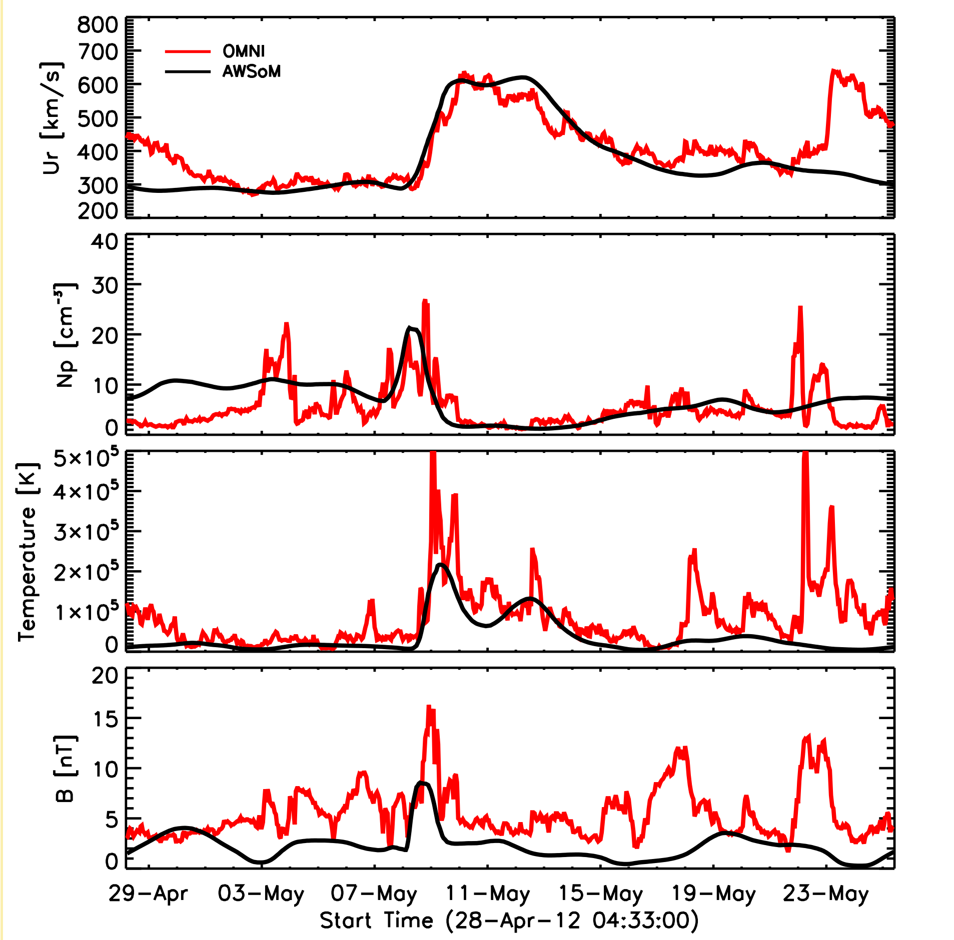
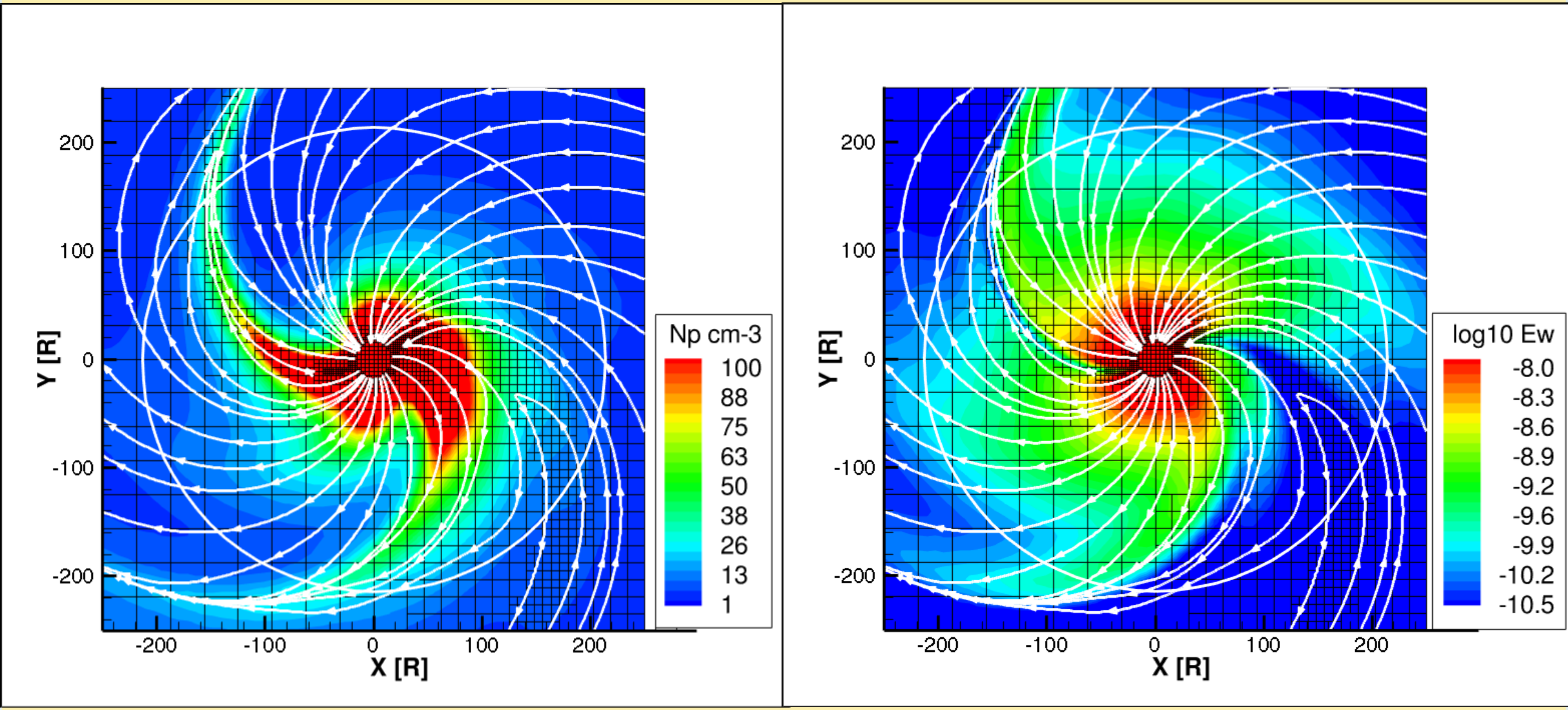
CR2109



Similarly for CR2123

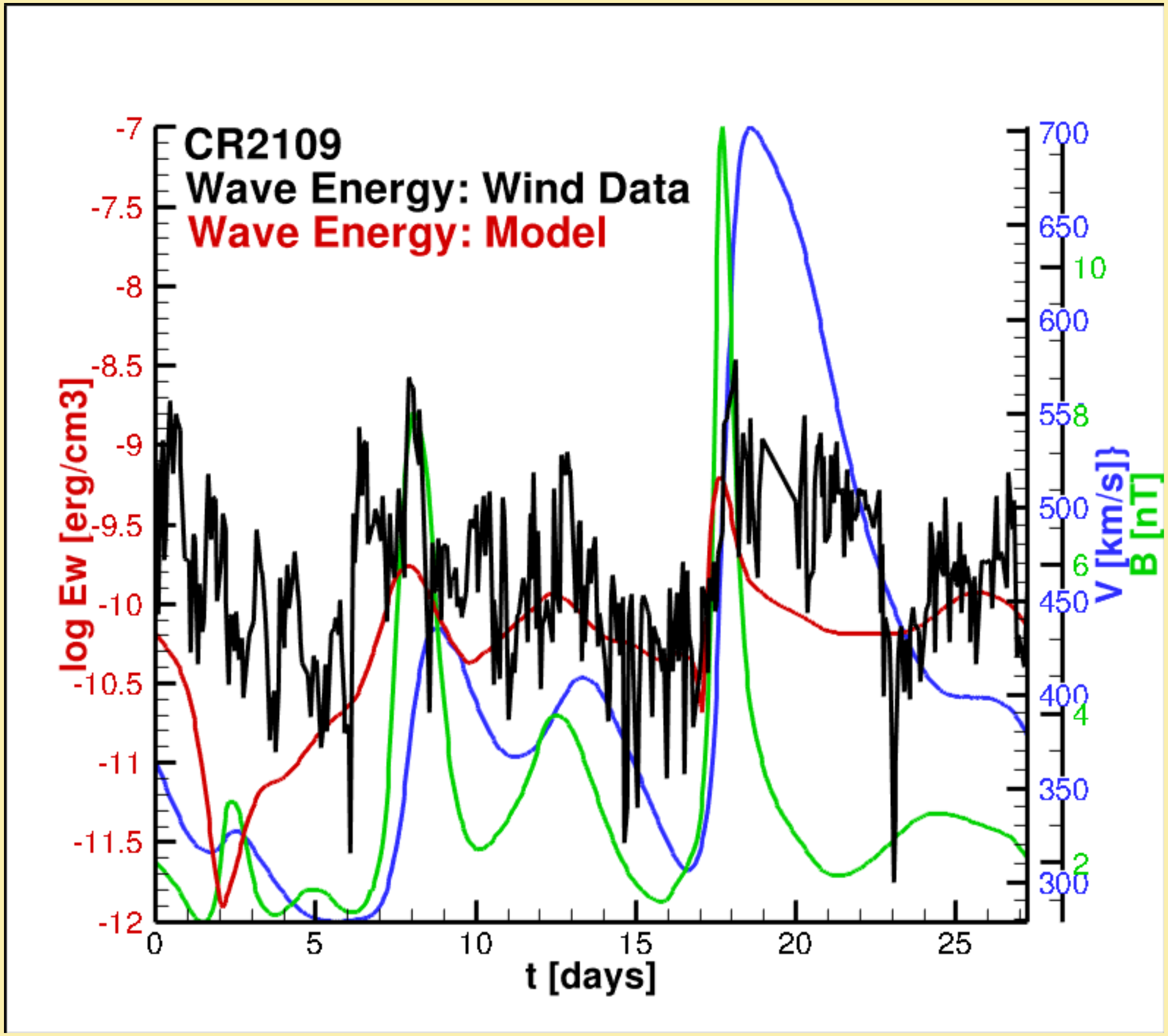


CR2109: Corotating Interaction Regions



Prediction of Turbulent Wave Energy at CIR

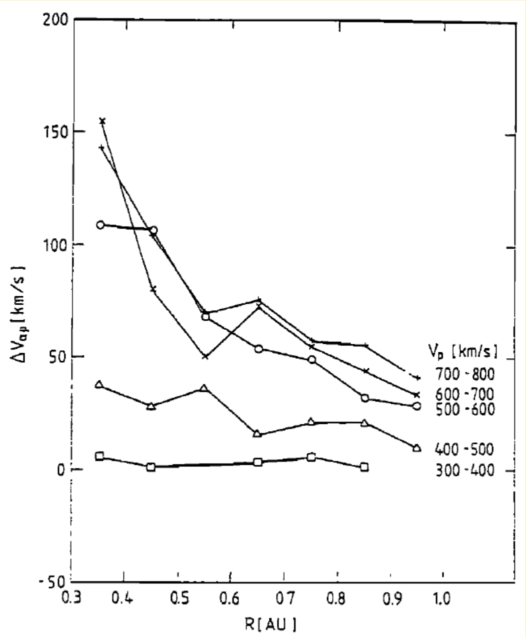
- The AWSoM model does reasonable in capturing the wave energy through most of the Carrington Rotation but falls short at the CIR



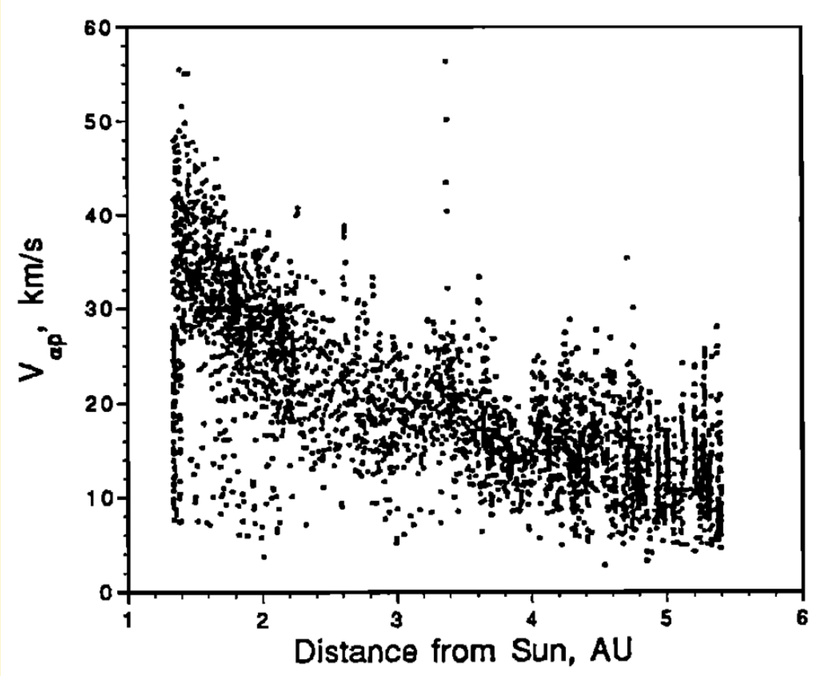
Multifluid AWSoM

- Multifluid generalization of the AWSoM solar wind model
- Different fluid equations for protons and alpha particles (and electron pressure equation)
- Low-frequency Alfven wave turbulence provides coronal heating and solar wind acceleration

Helios, Marsch et al. (1982)

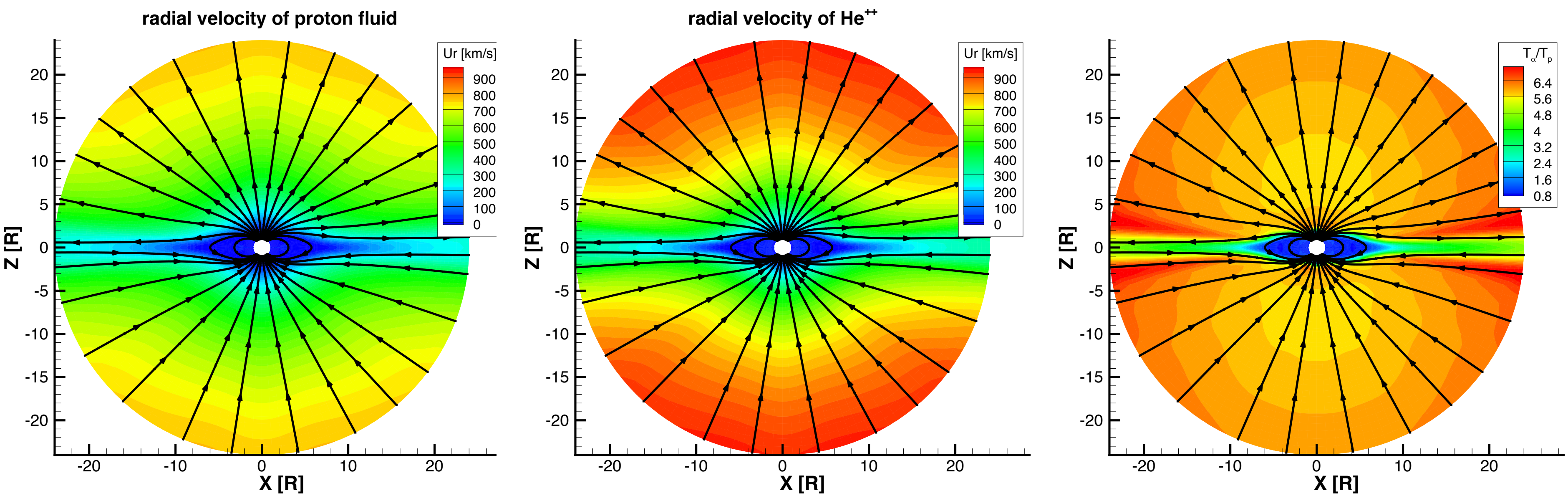


Ulysses, Neugebauer et al. (1996)



Multifluid AWSoM

- A dipole test with 5.6 Gauss field strength at the pole. The He^{++} concentration in the upper chromosphere is set uniform and is 7% of the proton concentration.



- **The alpha/proton temperature ratio is higher than 4 (typically 6-7)**
- **The alpha particle speed in the fast wind is 150 km/s faster than the proton speed**

Summary

- **AWSoM model for the solar corona and inner heliosphere:**
  - Alfvén wave turbulence with wave reflection
  - Three-temperature (with proton temperature anisotropy)
  - Validation studies with EUV images, ACE, STEREO A&B show that this model can capture many features of the solar corona and heliosphere
- **Modeling Steady State Wind and Corotating Interaction Regions**
  - Model MHD quantities at 1 AU & capture CIRs
  - Wave energy increases significantly at the CIR, but is less than observed.
- **Development of new multifluid model**
  - Future SO and SPP will carry critical instrumentation to measure the properties of Helium in the solar wind at distances between within 10 solar radii up to 1 AU.
  - These measurements can be compared with this new model