AWSoM

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PROGRESS

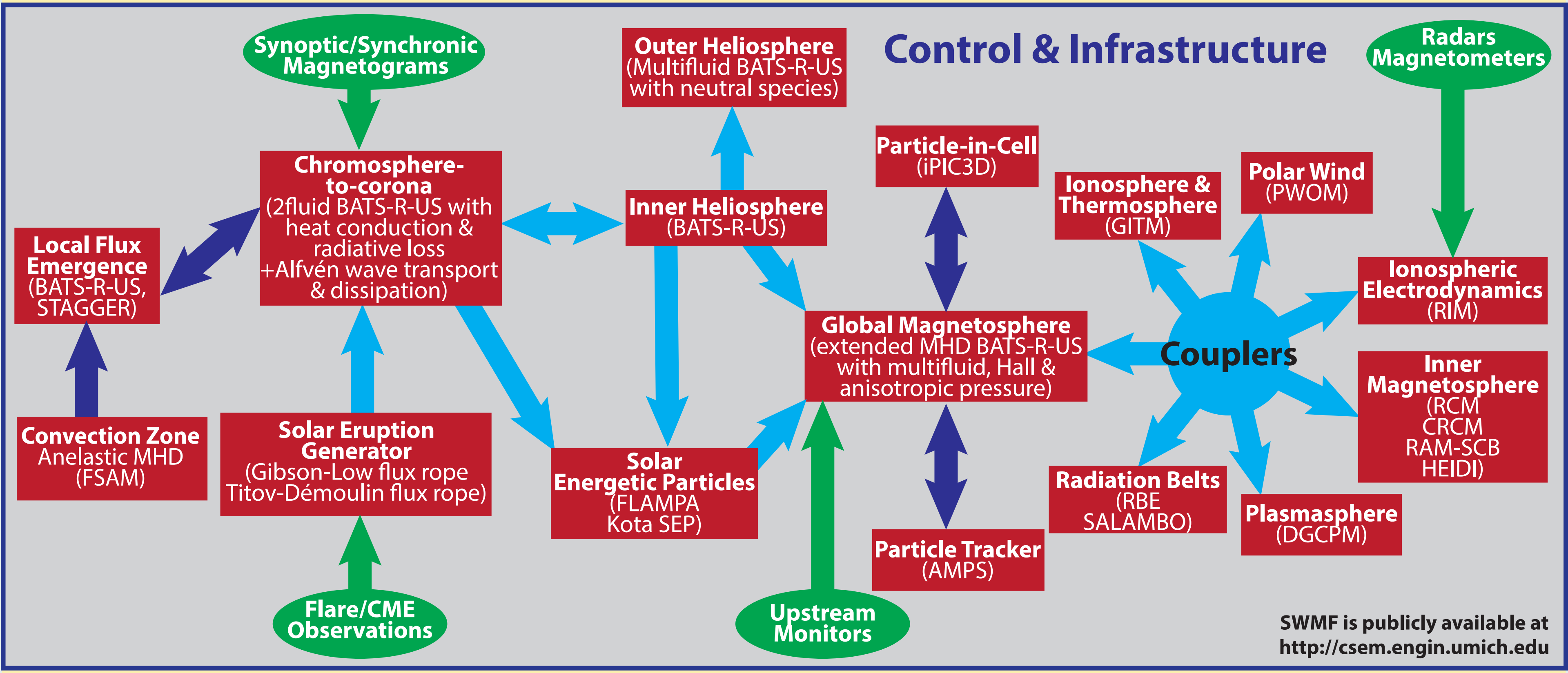
THE FRAMEWORK PROGRAMME FOR RESEARCH AND INNOVATION
HORIZON 2020

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
- Generalization of solar wind turbulence model to proton and alpha particles

Space Weather Modeling Framework (SWMF)

Block Diagram of the Space Weather Modeling Framework



The BATS-R-US multi-physics code

Center for Space Environment Modeling
SWMF
Space Weather Modeling Framework

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

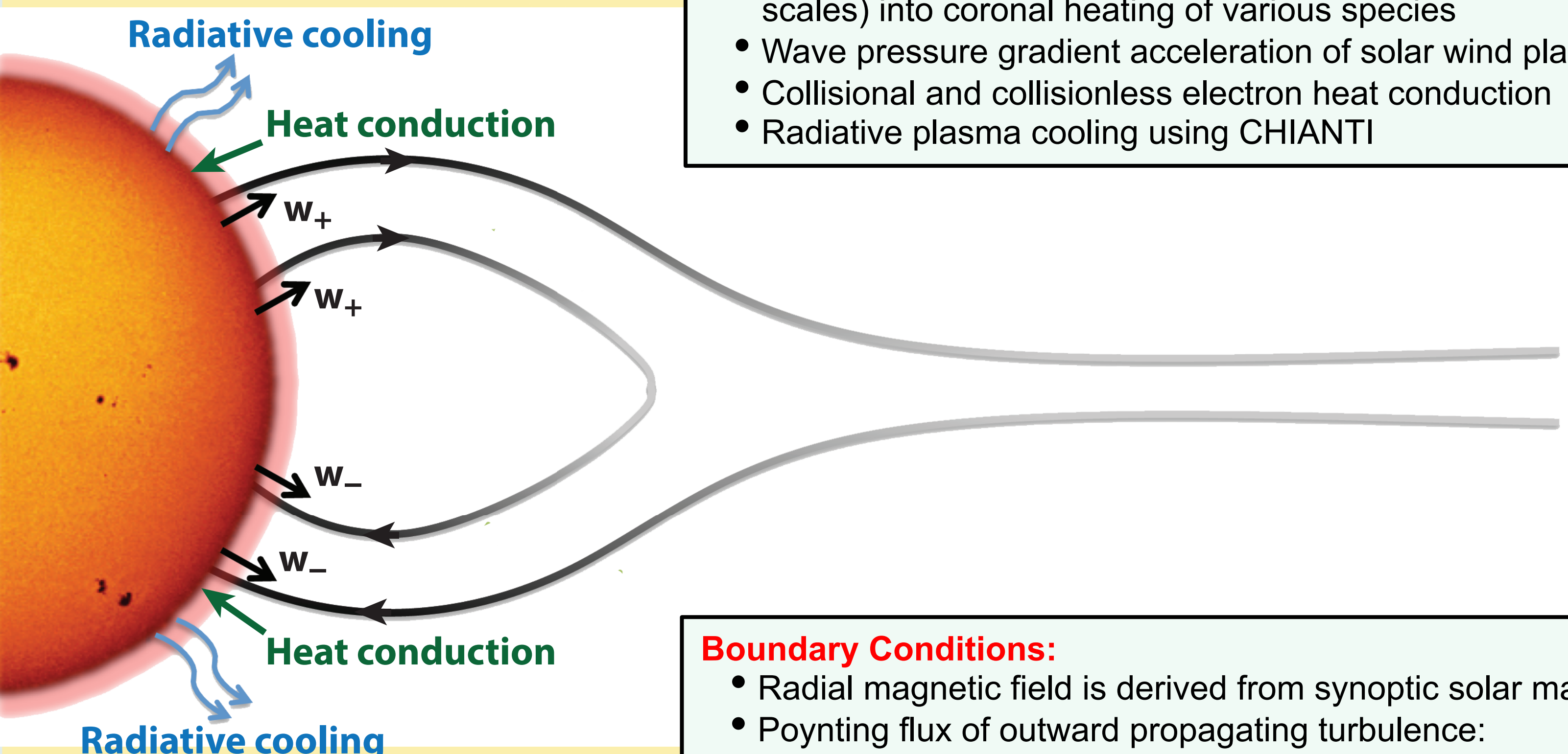
Auxiliary equations
Wave energy transport
Radiation transfer (multigroup diffusion)
Material interface (level set)
Parallel ray-tracing
Tabular equation of state

Alfvén Wave Solar Model (AWSoM)

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

Extended MHD physics:

- Two (T_i, T_e) or three ($T_{i||}$, $T_{i\perp}$, T_e) temperatures
- Equations for parallel and antiparallel propagating turbulence ($w_\pm$)
- Physics-based reflection of $w_\pm$ results in turbulent cascade
- 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 using CHIANTI



Boundary Conditions:

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

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

Center for Space Environment Modeling
SWMF
Space Weather Modeling Framework

Alfvén Wave Turbulence

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

energy reduction in expanding flow → $\frac{w_\pm}{2}(\nabla\cdot\mathbf{u})$; wave dissipation → $\Gamma_\pm w_\pm$

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

Alfvén wave advection → $\mathbf{u}\pm\mathbf{V}_A$; wave reflection (field-aligned Alfven speed gradient and field-aligned vorticity) → $\mathcal{R}\sqrt{w_-w_+}$

$$\mathcal{R}=\min\left[\sqrt{[(\mathbf{V}_A\cdot\nabla)\log V_A]^2+(\mathbf{b}\cdot[\nabla\times\mathbf{u}])^2},\max(\Gamma_\pm)\right]\begin{cases}\left(1-2\sqrt{\frac{w_-}{w_+}}\right) & \text{if} \quad 4w_-\le w_+\\ 0 & \text{if} \quad \frac{1}{4}w_-\le w_+\le 4w_-\\ \left(2\sqrt{\frac{w_+}{w_-}}-1\right) & \text{if} \quad 4w_+\le w_-\end{cases}$$

- Phenomenological dissipation 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 counter-propagating 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

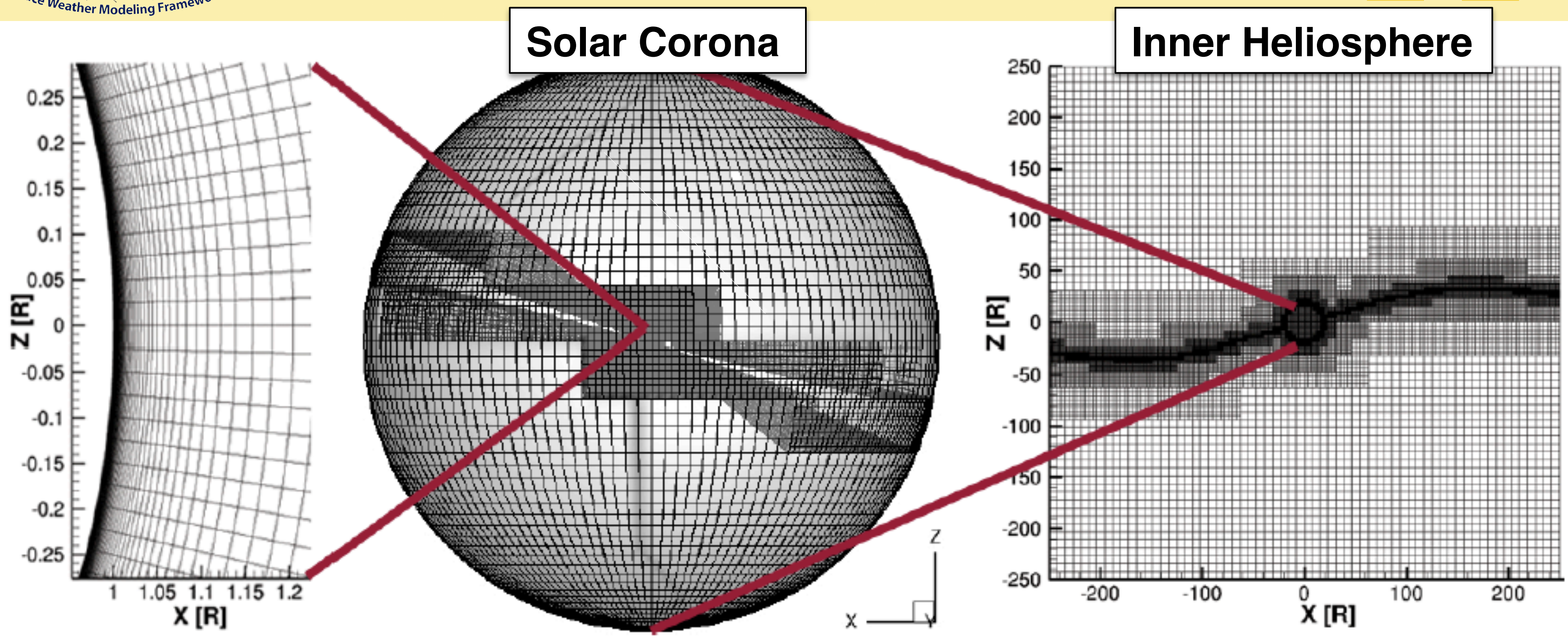
X. Meng et al. 2012 JCP, JGR

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):

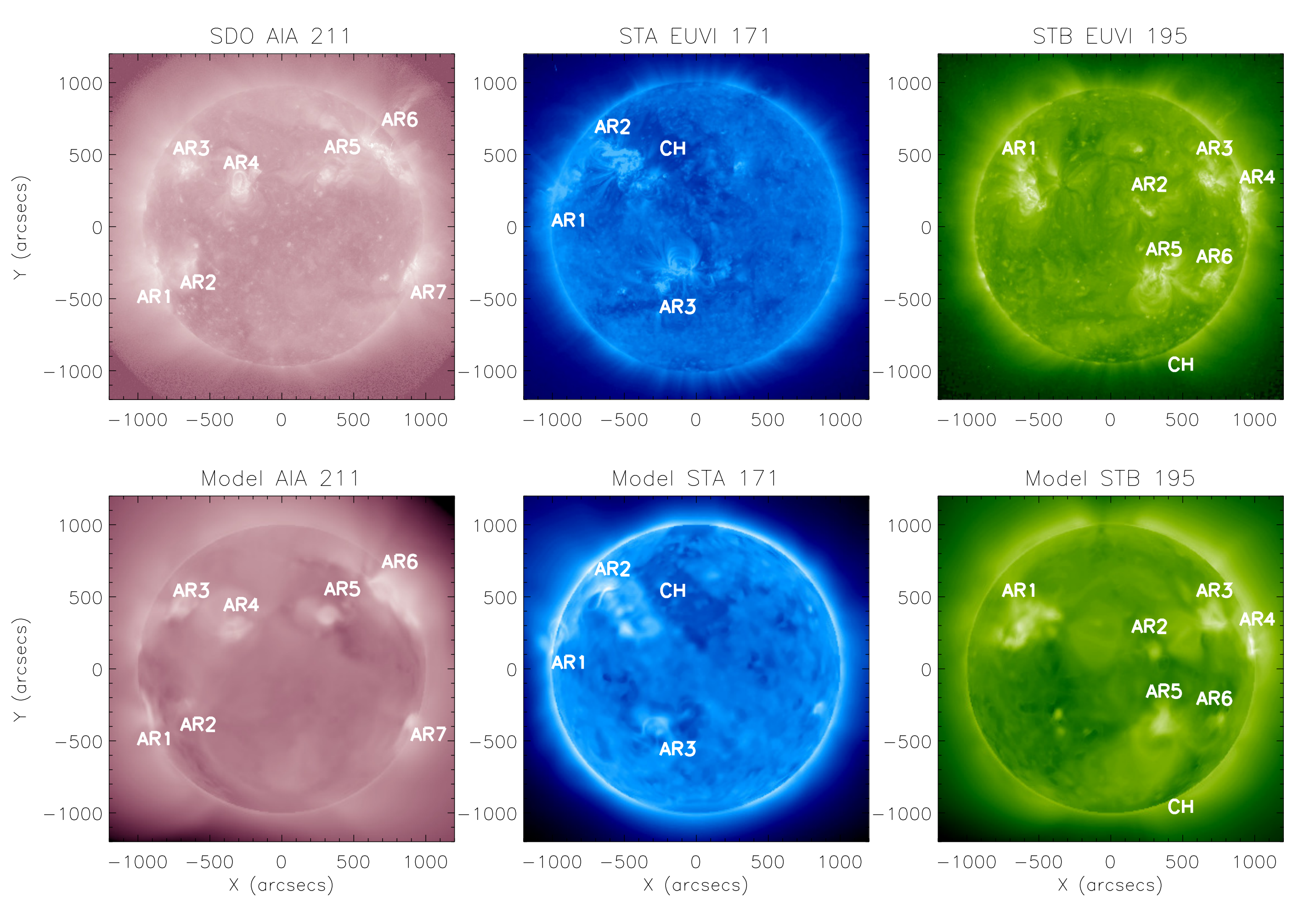
	instability criteria	relaxation time τ
firehose	$\frac{p_\parallel}{p_\perp} > 1 + \frac{\mathbf{B}^2}{\mu_0 p_\perp}$	$\tau_f = \frac{1}{\gamma_{f_{FLR}}(\lambda_f)} = \frac{2}{\Omega_i}\frac{\sqrt{p_\parallel(p_\perp - p_\parallel/4)}}{\Delta p_f}$
mirror	$\frac{p_\perp}{p_\parallel} > 1 + \frac{\mathbf{B}^2}{2\mu_0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



- AWS☼M 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 (Lionello et al. 2009)
- AMR to resolve the heliospheric currentsheet

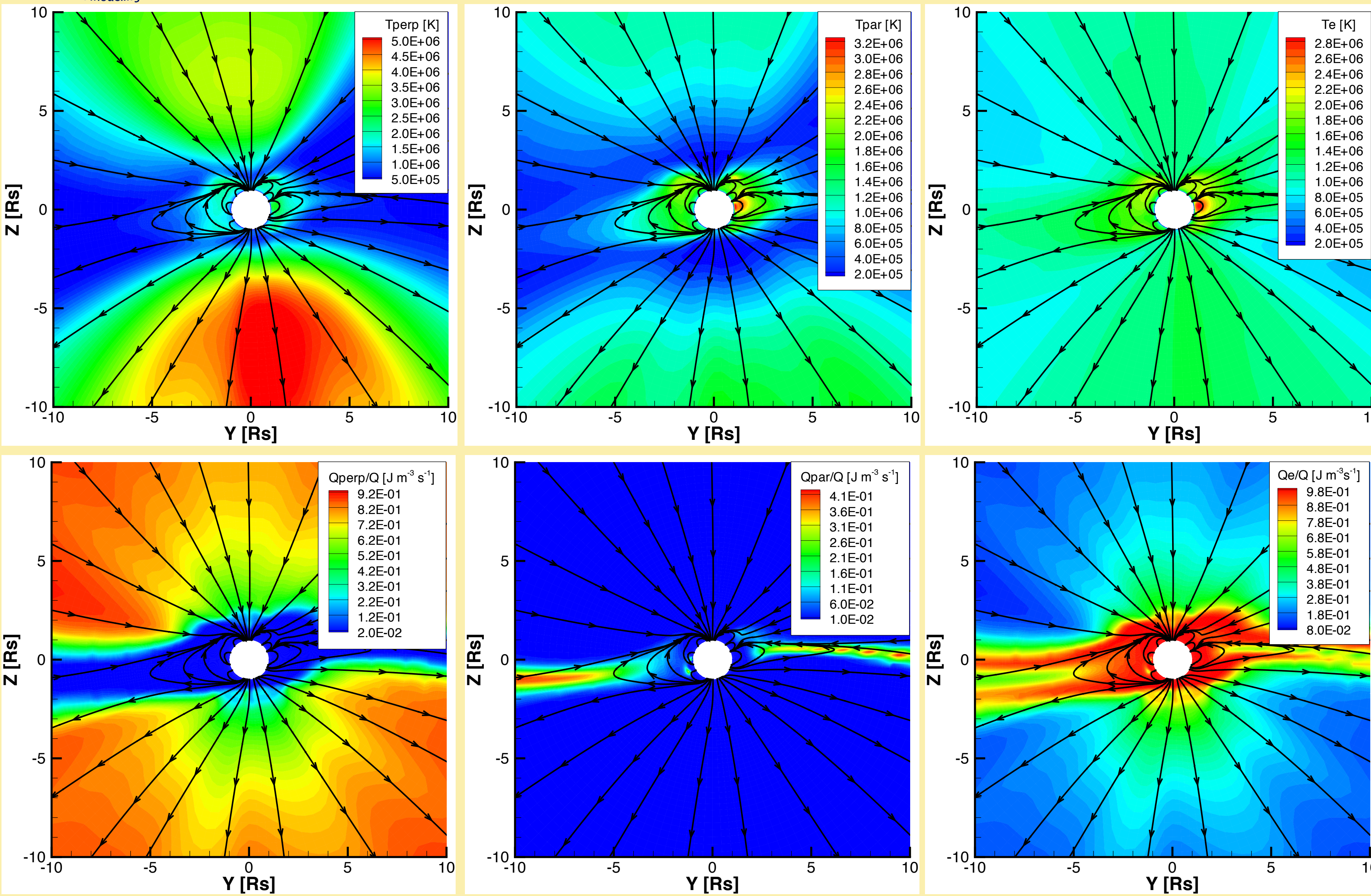
Validation: EUV Images for CR2107



Enhanced emission at AR: - Wave Poynting flux proportional to field strength

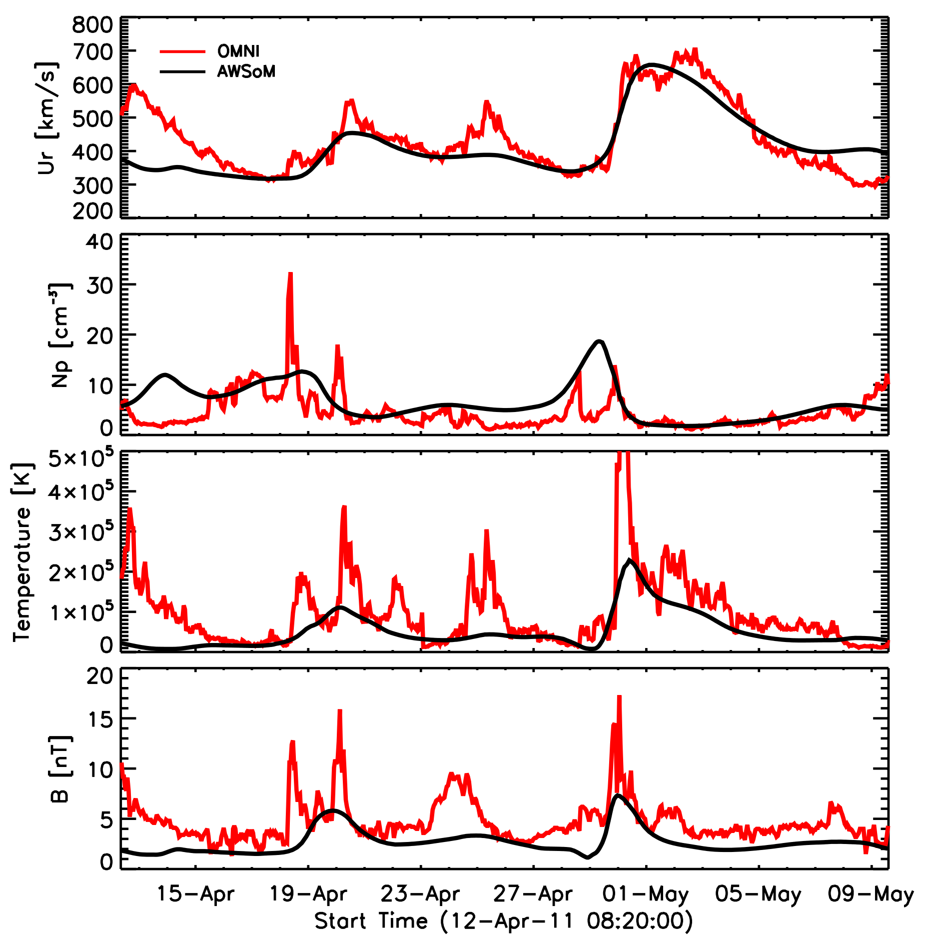
- Enhanced reflection due to Alfven speed gradients -> enhanced dissipation

Heat Partitioning for the Electron and Anisotropic Proton Temperatures

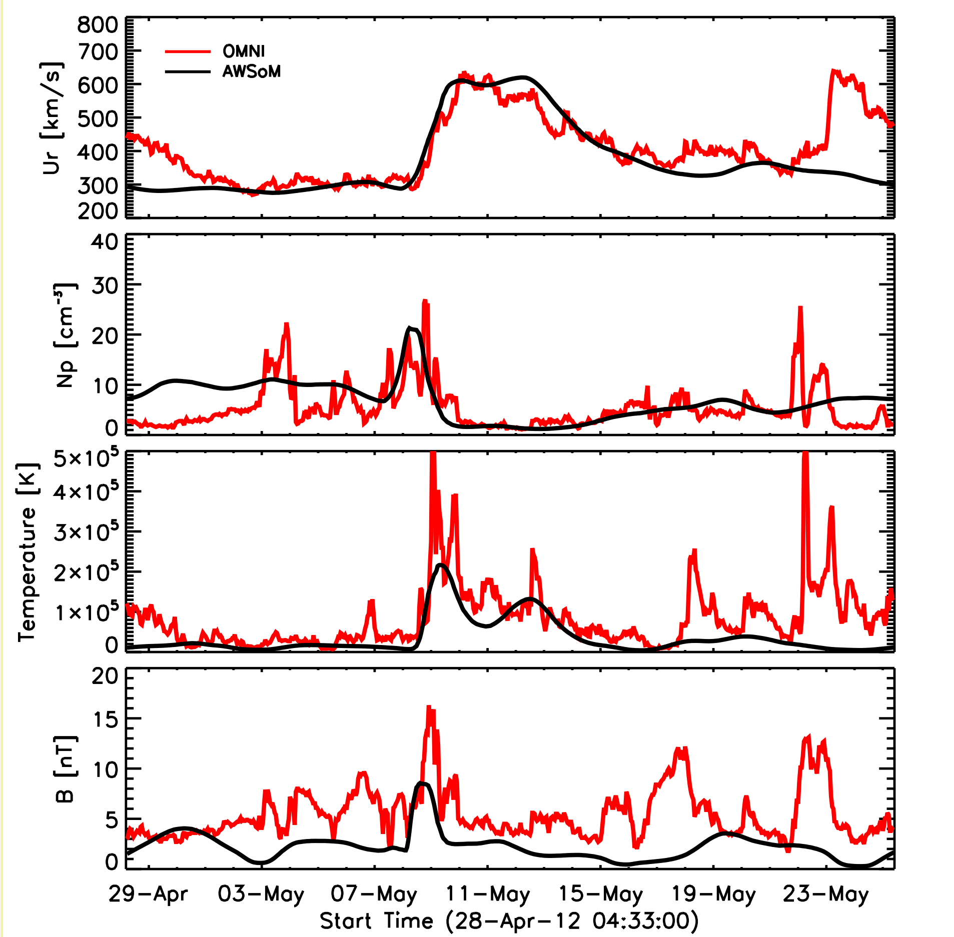


Validation: MHD Quantities at 1AU

CR2109

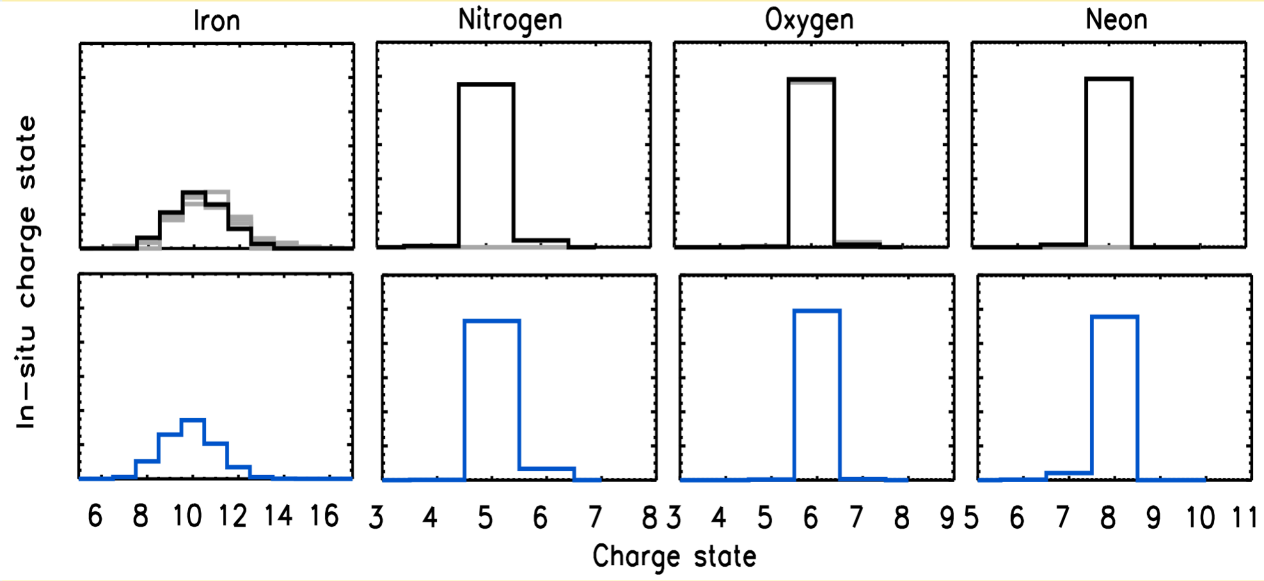


CR2123



Validation: Charge State

E. Landi et al., ApJ (2014)

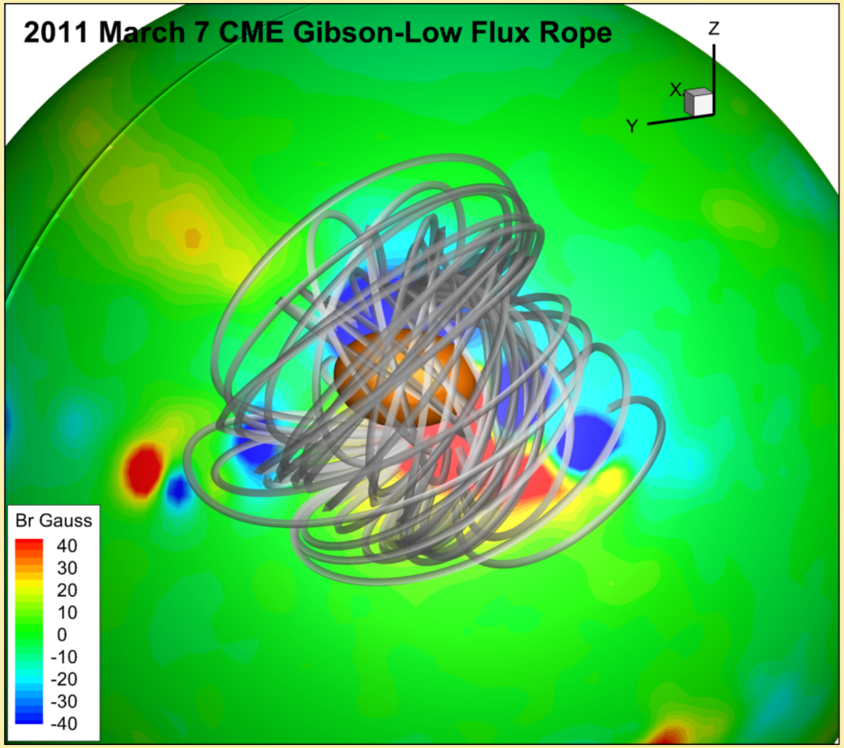


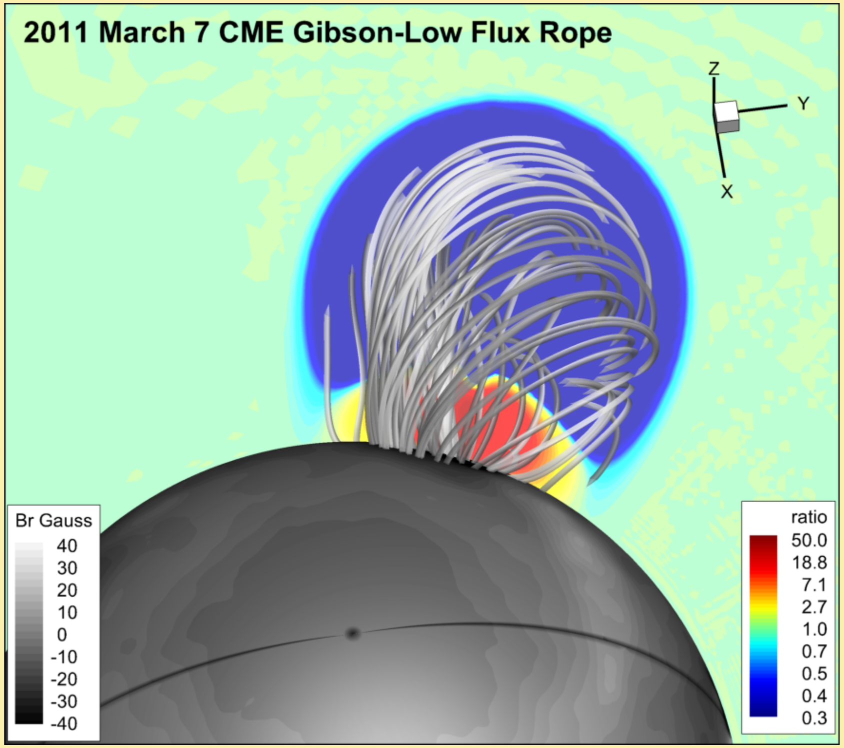
Ulysses/SWICS
Gloeckler & Geis, 2007

AWS☼M with Michigan Ionization Code

- **In-situ Ulysses/SWICS (polar pass) charge state during minimum of solar cycle 23 (1994-1996)**
- **The close match in frozen-in charge states indicates that the model's coronal electron temperature, density and bulk speed are close to that of the solar corona**

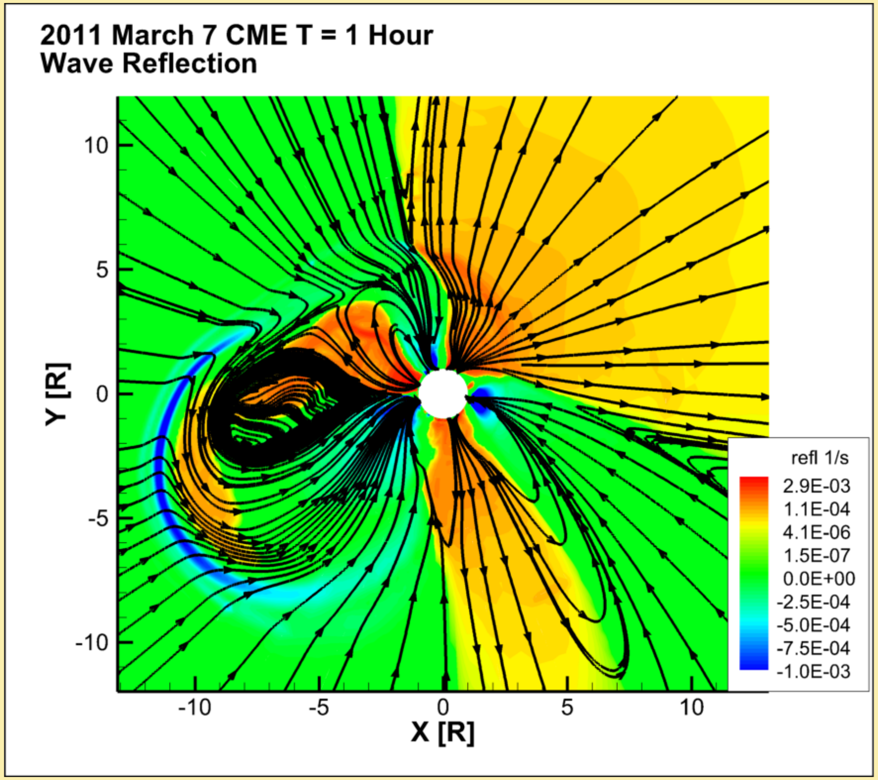
Alfvén wave – CME Shock interaction

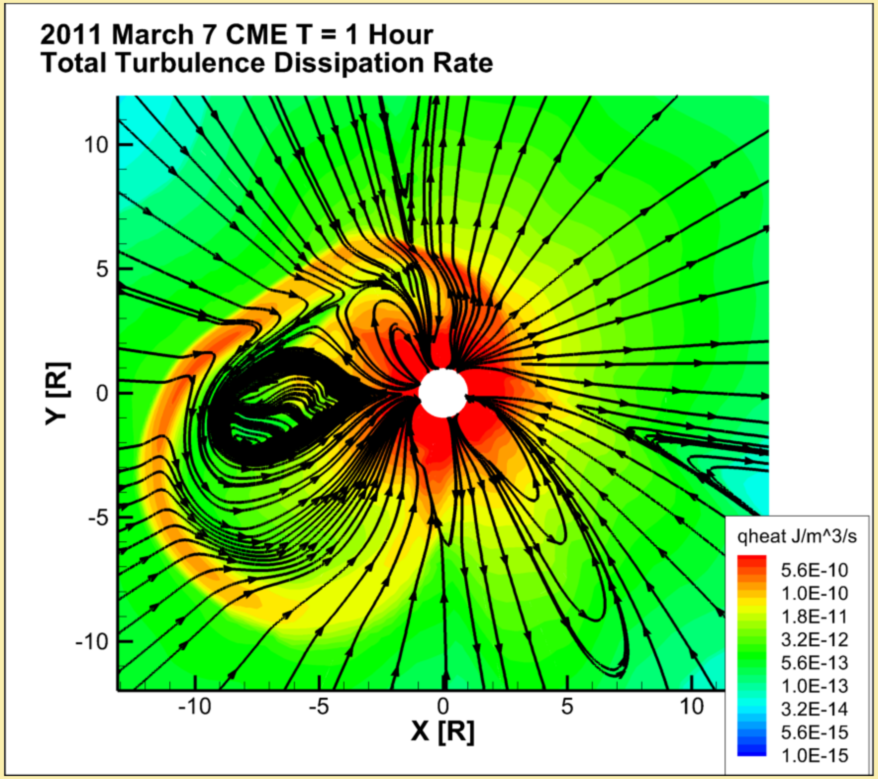




- Analytical flux rope model developed by Gibson & Low (1998)
- Model produces 3 part density of CME progenitors: dense streamer with low-density cavity containing a dense core
- CME initialization by superimposing a Gibson-Low CME

Alfvén wave – CME Shock interaction



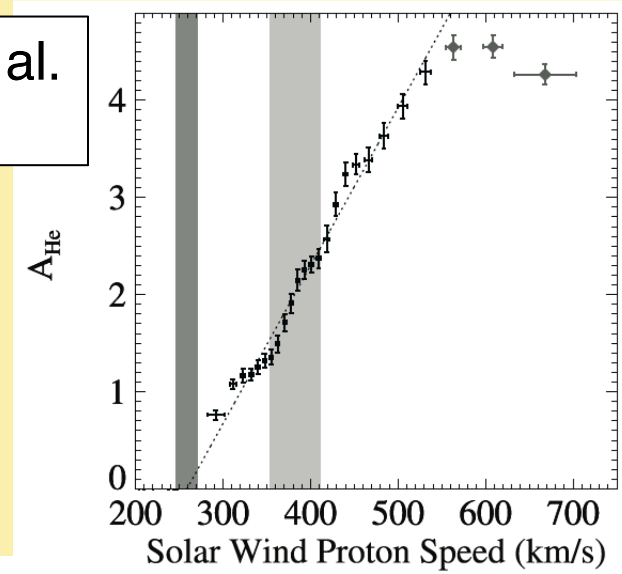


- Enhanced wave reflection and dissipation due to steep density gradients at the CME shock (M. Jin et al. 2015)

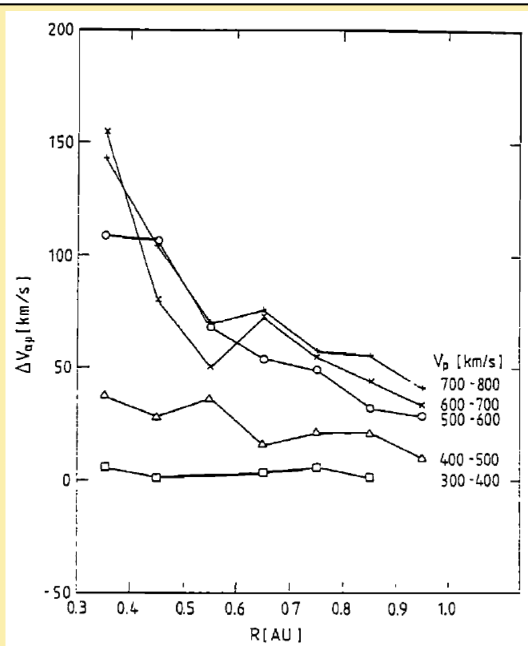
Multifluid AWSoM

- Past measurements of Helium abundance and properties in the solar wind
- Future Solar Probe Plus and Solar Orbiter missions will provide observations between within 10 R_{Sun} and 1 AU

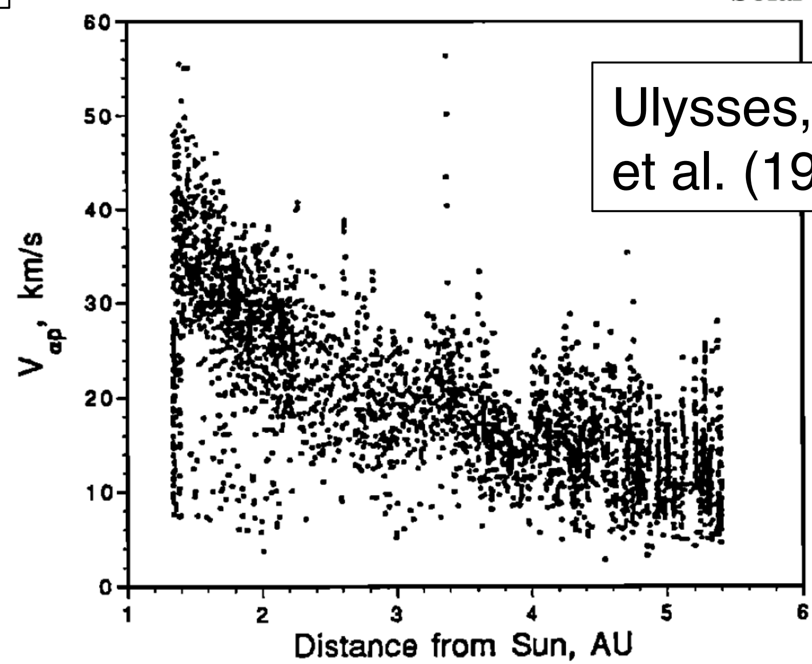
Wind, Kasper et al. (2007)



Helios, Marsch et al. (1982)



Ulysses, Neugebauer et al. (1996)



Multifluid AWSoM

- For each ion fluid *s* (proton or alpha particles):

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

$$\frac{\partial \rho_s \mathbf{u}_s}{\partial t} + \nabla \cdot (\rho_s \mathbf{u}_s \mathbf{u}_s) + \nabla p_s + \frac{q_s n_s}{e n_e}\left[\nabla(p_e + p_A) - \mathbf{J} \times \mathbf{B}\right] = q_s n_s (\mathbf{u}_s - \mathbf{u}_+) \times \mathbf{B} - \rho_s \frac{G M_\odot}{r^3}\mathbf{r} + \frac{\delta \mathbf{M}_s}{\delta t}$$

$$\frac{\partial}{\partial t}\left(\frac{p_s}{\gamma - 1}\right) + \nabla \cdot \left(\frac{p_s}{\gamma - 1}\mathbf{u}_s\right) + p_s (\nabla \cdot \mathbf{u}_s) = \frac{\delta E_s}{\delta t} + Q_s$$

where the charge-averaged ion-velocity is $\mathbf{u}_+ = \frac{1}{e n_e}\sum_s q_s n_s \mathbf{u}_s$

- For electrons:

$$\frac{\partial}{\partial t}\left(\frac{p_e}{\gamma - 1}\right) + \nabla \cdot \left(\frac{p_e}{\gamma - 1}\mathbf{u}_e\right) + p_e \nabla \cdot \mathbf{u}_e = -\nabla \cdot \mathbf{q}_e - Q_{\text{rad}} + \frac{\delta E_e}{\delta t} + Q_e$$

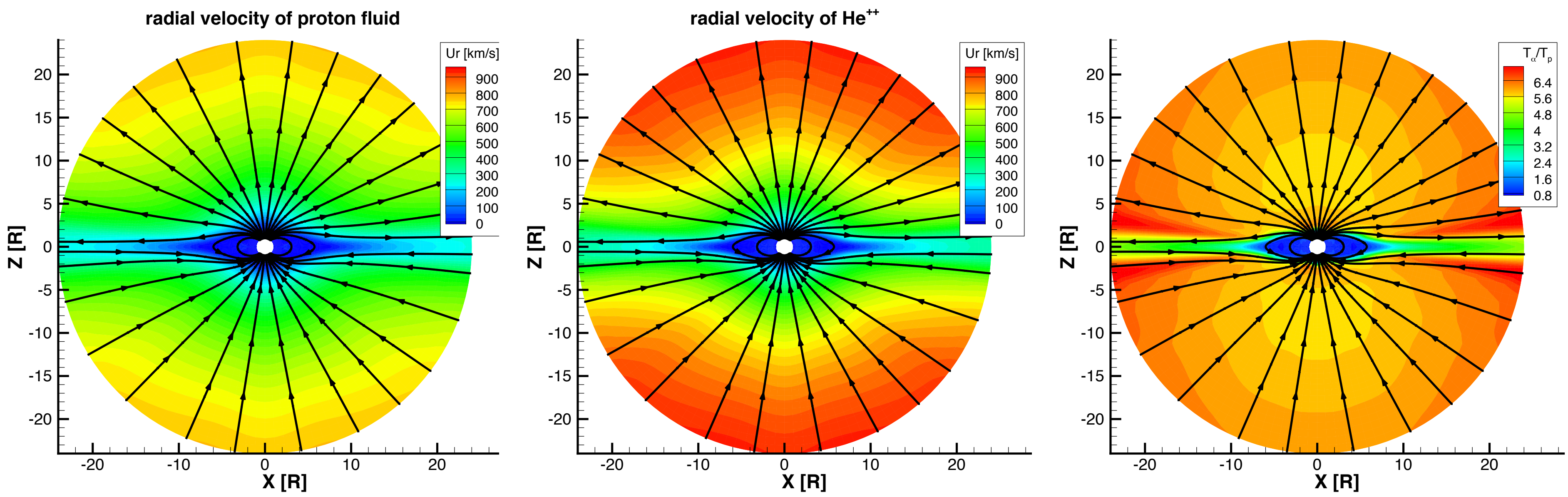
- Induction equation:

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

- We assume the He^{++} abundance to be small enough so that the Alfvén wave turbulence can be assumed to be carried by protons only. Hence, wave turbulence equations are the same as in single fluid.

Multifluid AWSoM: preliminary results

- A dipole test with 5.6 Gauss field strength at the pole. The He^{++} concentration in the upper chromosphere is set uniform and is 5% of the proton concentration.



- **Alpha/proton temperature ratio is more than mass proportional (6-7)**
- **The alpha particle speed in the fast wind is 150 km/s faster than the proton speed**

Summary

- **AWS☼M 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

- **Development of new multifluid model**
  - Future SO and SPP missions will carry critical instrumentation to measure the properties of proton and He^{++} the solar wind at distances between within 10 solar radii up to 1 AU.
  - These measurements can be compared with this new model
  - Future development: two-stream instability restricting the velocity differences parallel to **B**