PROGRESS Review Meeting, Potsdam
9-11 January 2017

WP2 Status

Propagation of the Solar Wind from the Sun to L1

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Full timeline for WP2

GONG observations
\> AWSoM coronal model
\> SWIFT spherical MHD Inner Heliosphere model
Forecast of MHD variables at L1

Deliverables
M12 Swift conversion to spherical geometry report - Approved
M20 Coupling codes report - **Submitted 31 August 2016**
M36 Documentation

Project Milestones
MS5 Availability of ASWoM/SWIFT for testing (Month 20)

Work-package Milestones (Tasks)
M6 Lare3d in spherical and renamed SWIFT
M9 2T SWIFT & Time accurate AWSoM
M15 Improved thermal conduction
M21 Couple AWSoM to SWIFT
M19-27 Validate coupled model against L1 data
M25-36 Real time test of L1 predictions
M36 Manuals

Multi-layered coupled modelling

GONG data used to get potential B-field out to $2.5R_\odot$

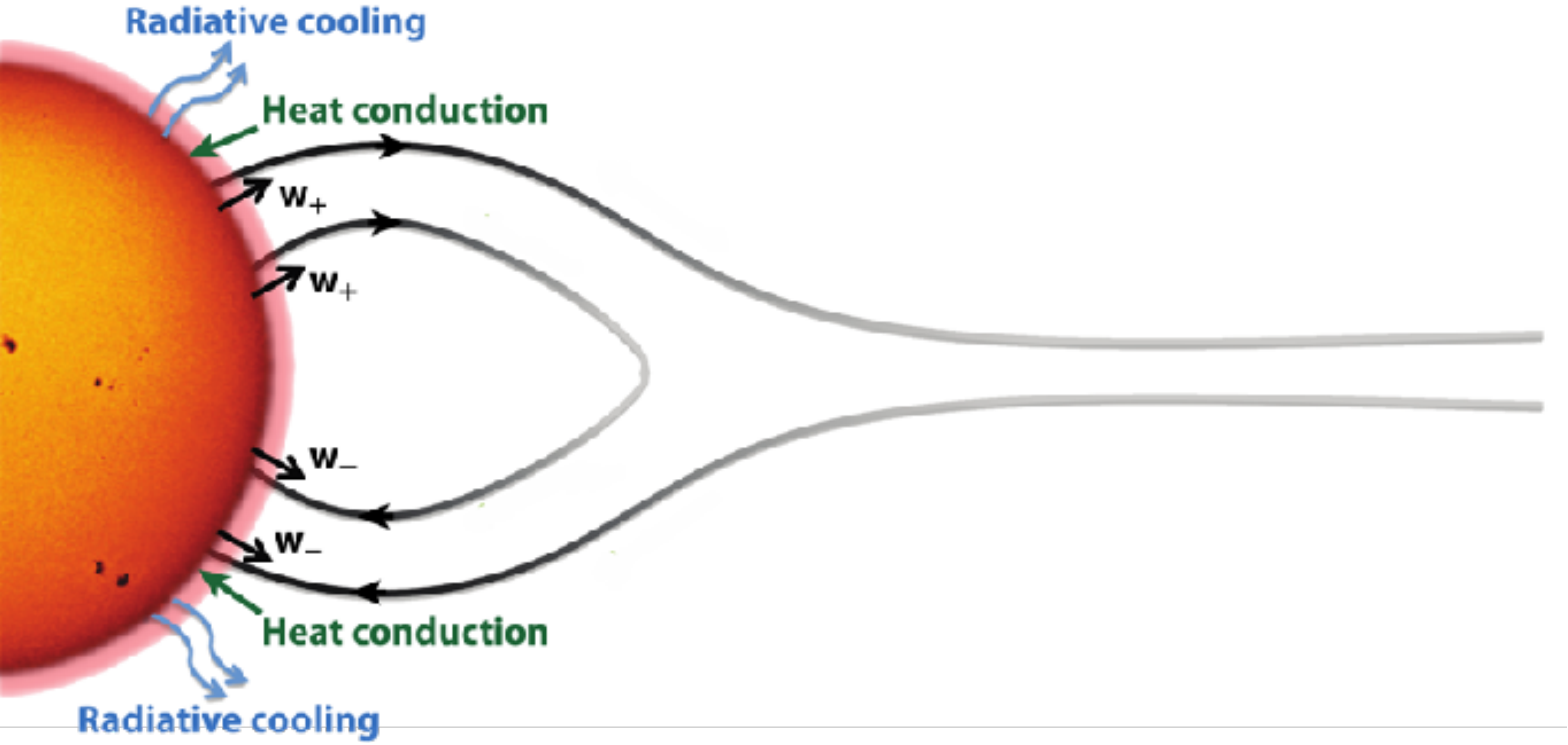
This PFSS field is then held constant between GONG updates ~ 8 hours

AWSoM co-rotating spherical grid overlaid on this PFSS from $1.15 - 20R_\odot$

Ghost/boundary cell information to drive time-dependent AWSoM by following 1D solution along field-lines to solar surface.

1D field-line solutions update with each AWSoM step although magnetic field stationary

At 20 Solar radii data interpolated from AWSoM onto inertial SWIFT grid and solution propagated to 1 AU



Mathematical Models

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

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

$$\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot \left(\rho \mathbf{uu} - \frac{\mathbf{BB}}{\mu_0} \right) + \nabla \left(P_i + P_e + \frac{B^2}{2\mu_0} + P_A \right) = -\frac{G M_\odot \rho \mathbf{R}}{R^3},$$

AWSoM
SWIFT ignores Alfven wave pressure

$R = R_\odot \rightarrow L1$

Mathematical Models

Basic MHD

AWSoM
SWIFT ignores Alfven wave pressure

$R = R_\odot \to L1$

$$\frac{\partial}{\partial t}\left(\frac{P}{\gamma-1}+\frac{\rho u^2}{2}+\frac{\mathbf{B}^2}{2\mu_0}\right)+\nabla\cdot\left\{\left(\frac{\rho u^2}{2}+\frac{\gamma P}{\gamma-1}+\frac{B^2}{\mu_0}\right)\mathbf{u}-\frac{\mathbf{B}(\mathbf{u}\cdot\mathbf{B})}{\mu_0}\right\}=$$
$$=-(\mathbf{u}\cdot\nabla)P_A+\nabla\cdot(\kappa\cdot\nabla T)-Q_{\mathrm{rad}}+\Gamma_- w_- +\Gamma_+ w_+ -\frac{GM_\odot\rho\mathbf{r}\cdot\mathbf{u}}{r^3},$$

AWSoM
SWIFT ignores turbulent drive

$R = R_\odot \to L1$

Mathematical Models

Basic MHD

AWSoM
SWIFT ignores Alfven wave pressure
$R = R_\odot \to L1$

Energy equation including turbulence model

AWSoM
SWIFT ignores turbulent drive
$R = R_\odot \to L1$

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

$$\Gamma_\pm = \frac{2}{L_\perp}\sqrt{\frac{w_\mp}{\rho}}$$

$$\mathcal{R} = \min\left\{\sqrt{(\mathbf{b}\cdot[\nabla \times \mathbf{u}])^2 + [(\mathbf{V}_A \cdot \nabla)\log V_A]^2}, \max(\Gamma_\pm)\right\} \times$$
$$\times \left[\max\left(1 - \frac{I_{\max}}{\sqrt{w_+/w_-}}, 0\right) - \max\left(1 - \frac{I_{\max}}{\sqrt{w_-/w_+}}, 0\right)\right],$$

AWSoM only
$R = R_\odot \to \ 20 R_\odot$

Mathematical Models

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

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AWSoM
SWIFT ignores Alfven wave pressure
$R = R_\odot \to L1$

$$\frac{\partial}{\partial t} \left(\frac{P}{\gamma - 1} + \frac{\rho u^2}{2} + \frac{\mathbf{B}^2}{2\mu_0} \right) + \nabla \cdot \left\{ \left(\frac{\rho u^2}{2} + \frac{\gamma P}{\gamma - 1} + \frac{B^2}{\mu_0} \right) \mathbf{u} - \frac{\mathbf{B}(\mathbf{u} \cdot \mathbf{B})}{\mu_0} \right\} =$$

$$= -(\mathbf{u} \cdot \nabla) P_A + \nabla \cdot (\kappa \cdot \nabla T) - Q_{\text{rad}} + \Gamma_- w_- + \Gamma_+ w_+ - \frac{G M_\odot \rho \mathbf{r} \cdot \mathbf{u}}{r^3},$$

AWSoM
SWIFT ignores turbulent drive
$R = R_\odot \to L1$

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

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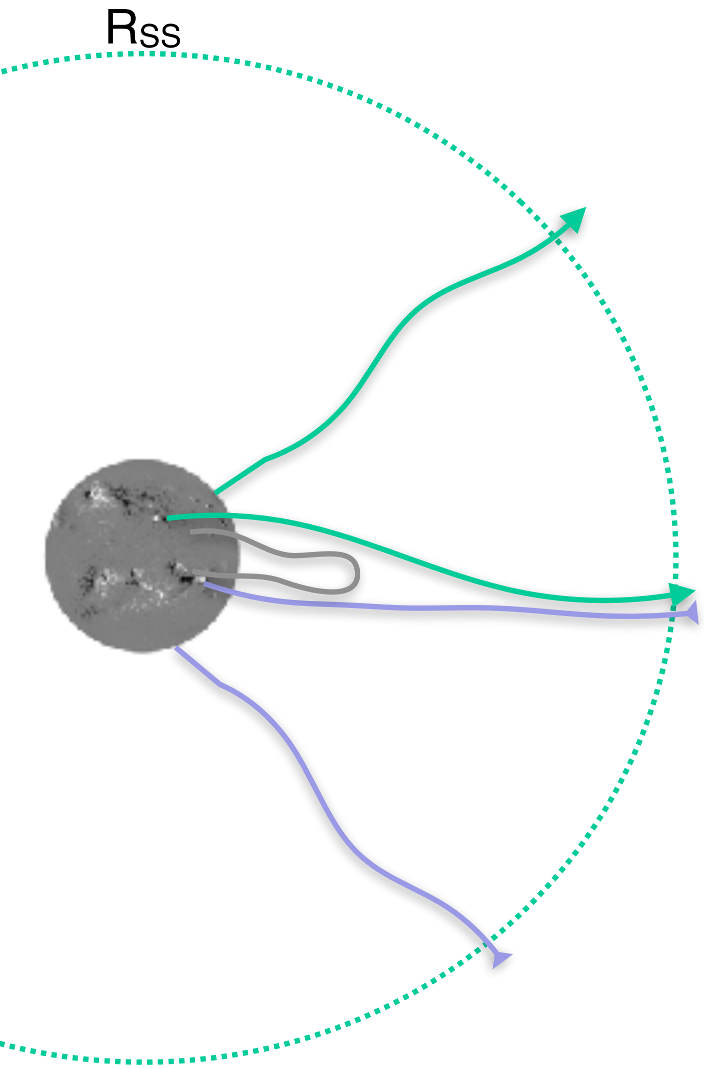
$$\times \left[\max \left(1 - \frac{I_{\max}}{\sqrt{w_+ / w_-}}, 0 \right) - \max \left(1 - \frac{I_{\max}}{\sqrt{w_- / w_+}}, 0 \right) \right],$$

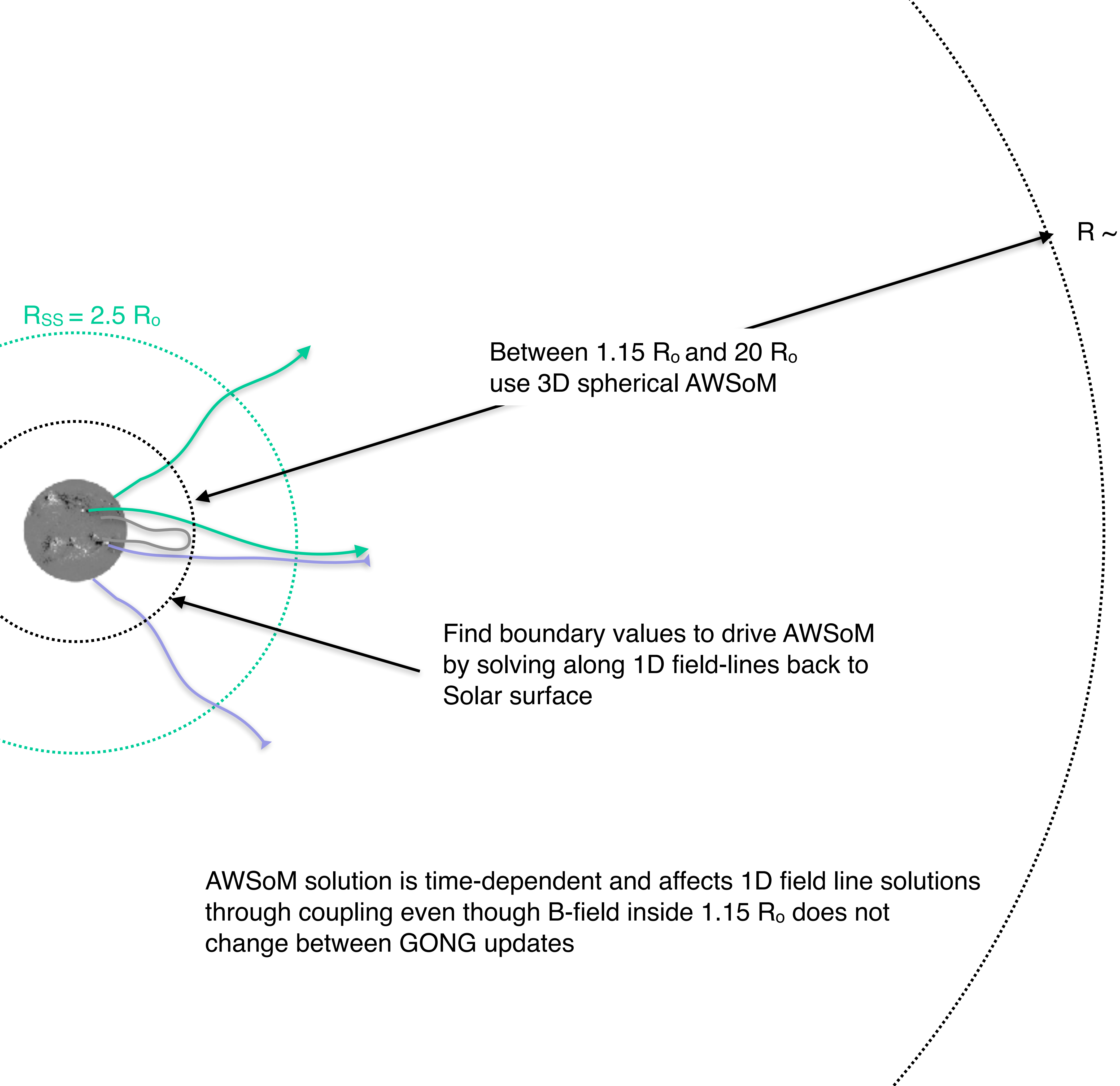
AWSoM only
$R = R_\odot \to \ 20 R_\odot$

Start with GONG magnetogram

Construct potential field up to R_{ss} = 2.5 R solar using PFSS method

These field-lines only update once every 8 hours with GONG updates

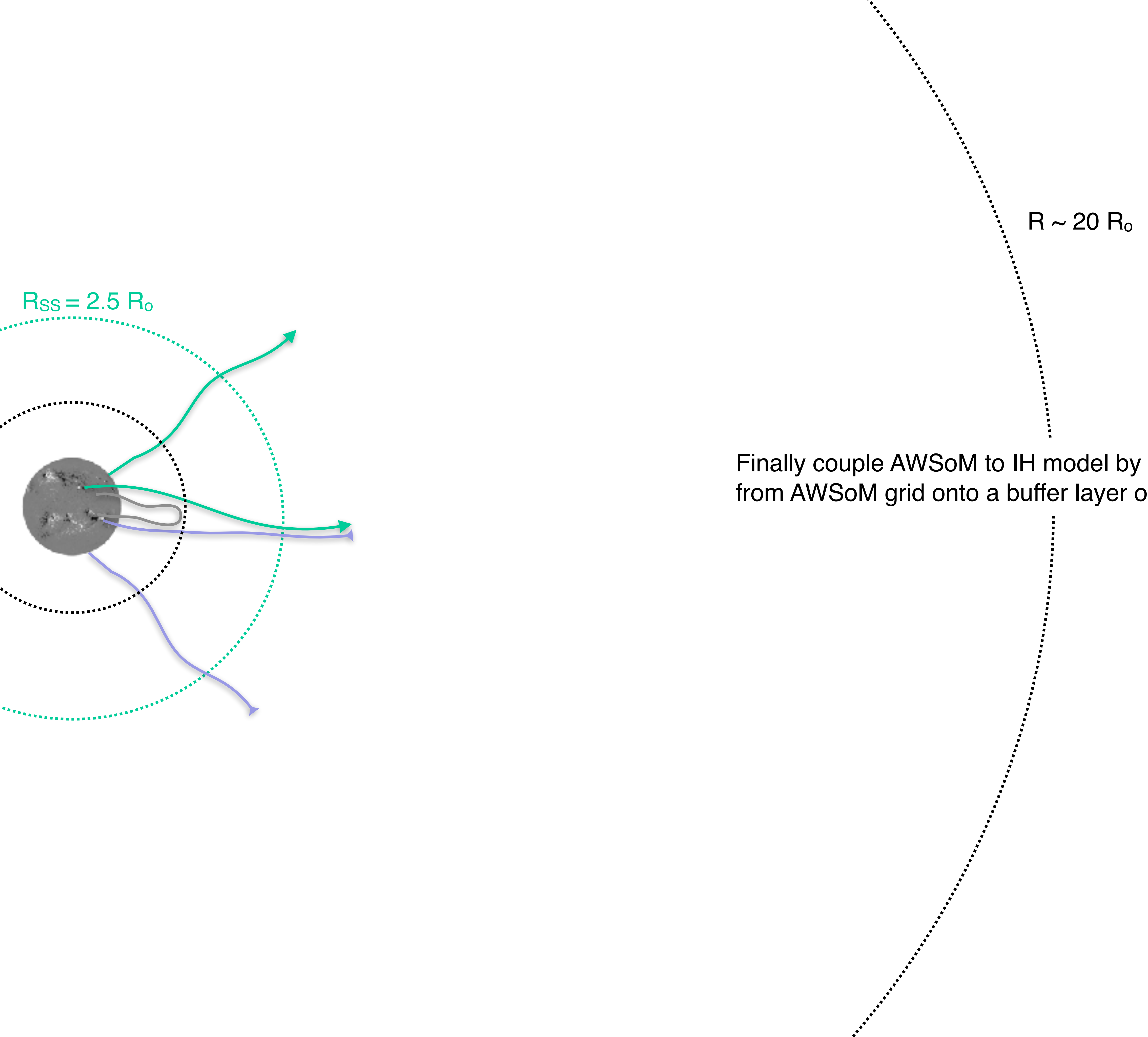




Between $1.15\ R_o$ and $20\ R_o$
use 3D spherical AWSoM

Find boundary values to drive AWSoM
by solving along 1D field-lines back to
Solar surface

AWSoM solution is time-dependent and affects 1D field line solutions
through coupling even though B-field inside $1.15\ R_o$ does not
change between GONG updates



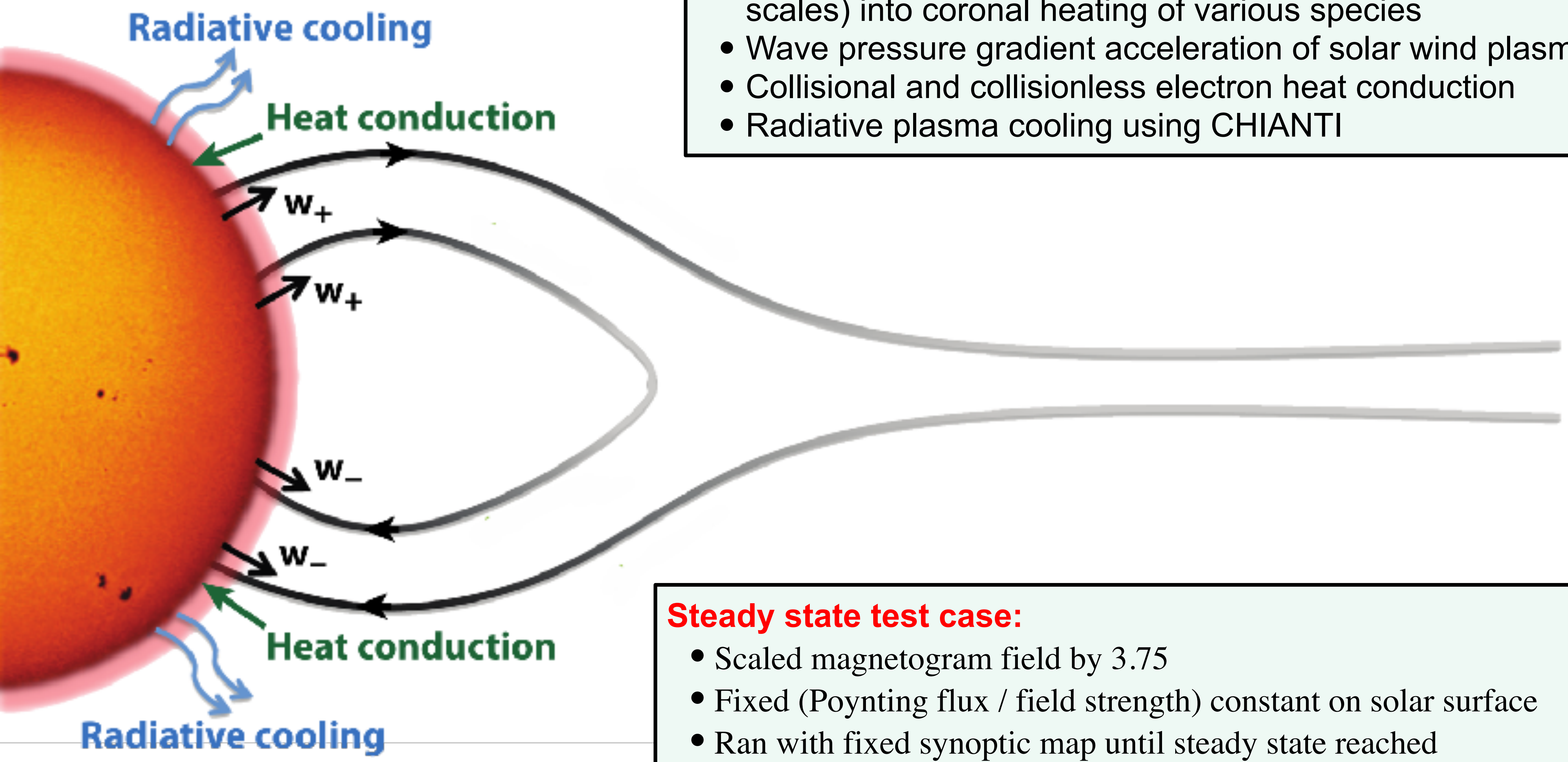
Finally couple AWSoM to IH model by interpolating from AWSoM grid onto a buffer layer of SWIFT cells

Alfvén Wave Solar Model (AWSoM)

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

Extended MHD physics:

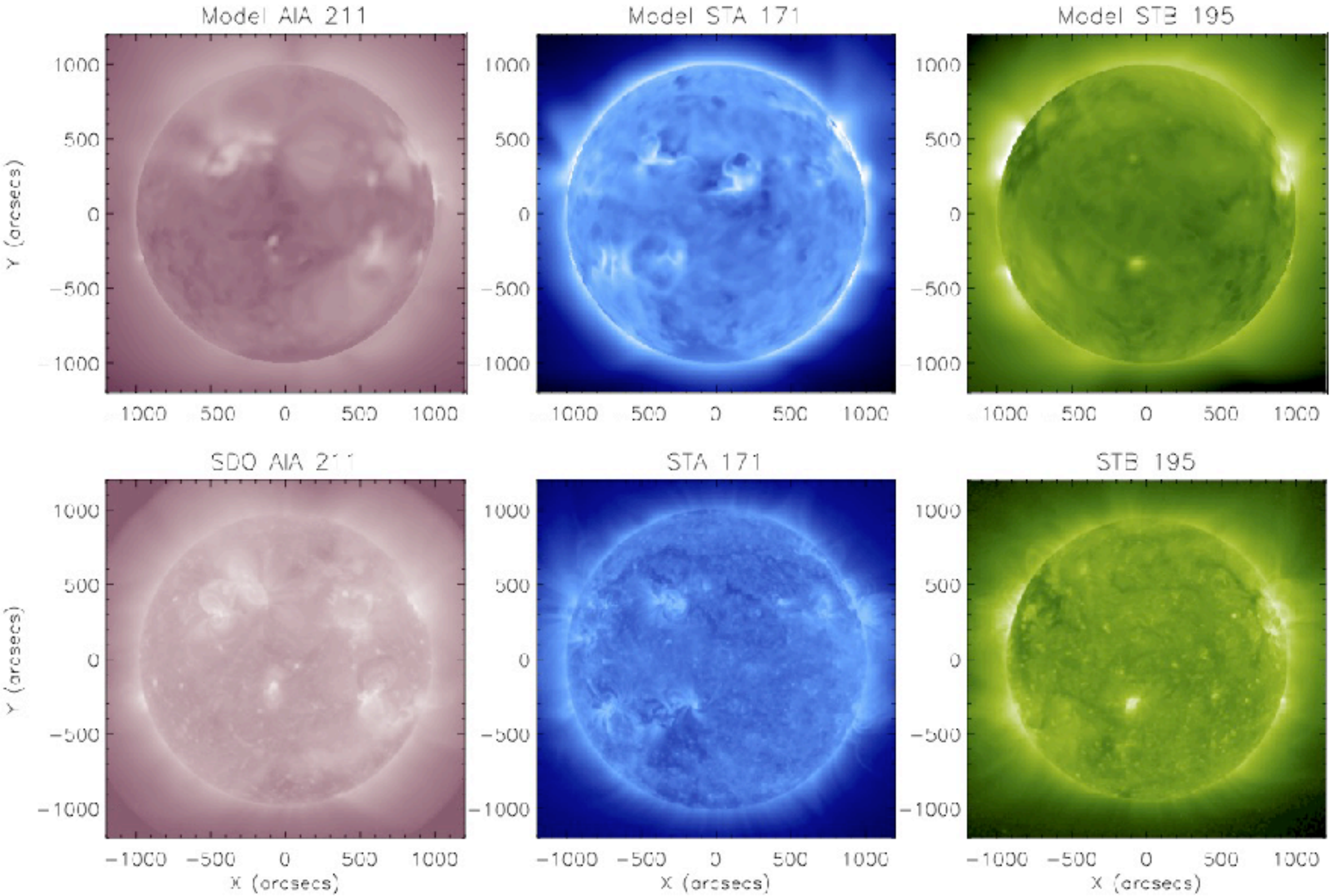
- Two (T_i, T_e) or three ($T_{i\|}$, $T_{i\perp}$, T_e) temperatures
- Equations for parallel and antiparallel propagating turbulence ($w_\pm$)
- Physics-based reflection of $w_\pm$ results in turbulent cascade
- Physics-based apportioning of turbulence dissipation (at the gyro-radius scales) into coronal heating of various species
- Wave pressure gradient acceleration of solar wind plasma
- Collisional and collisionless electron heat conduction
- Radiative plasma cooling using CHIANTI



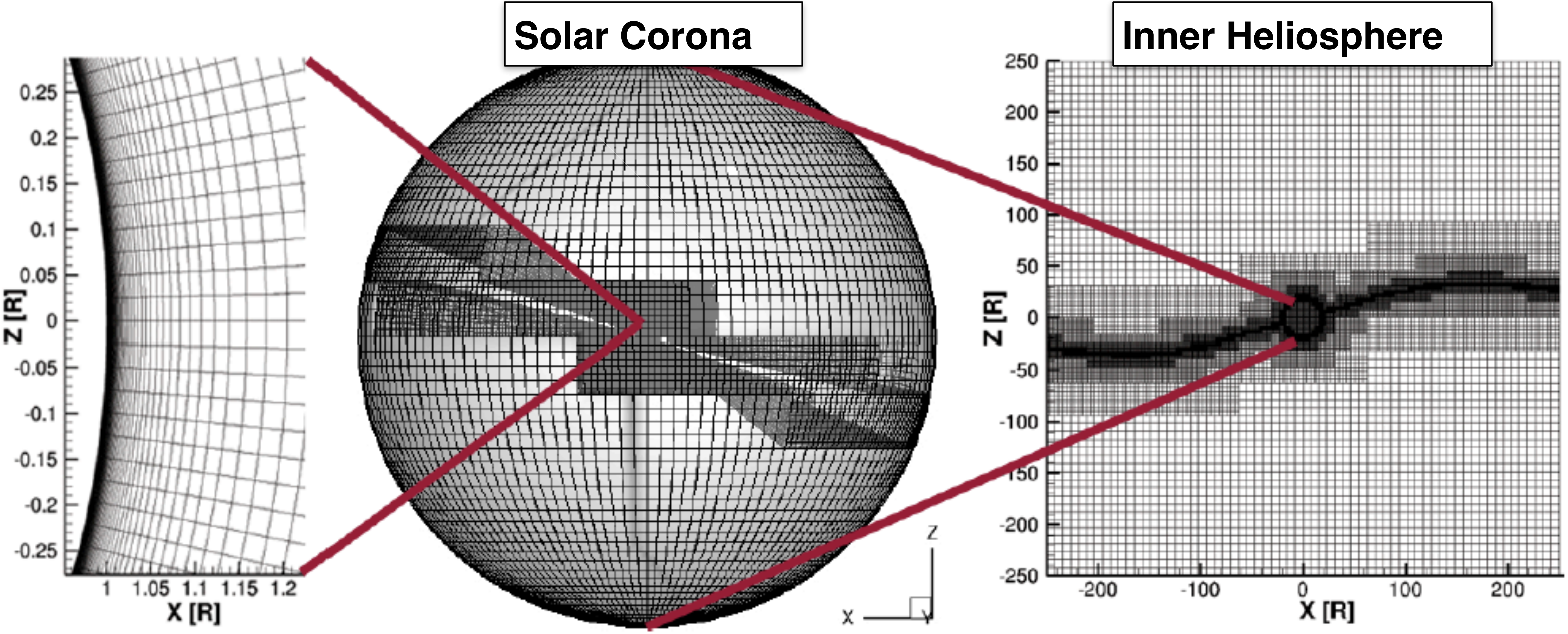
Steady state test case:

- Scaled magnetogram field by 3.75
- Fixed (Poynting flux / field strength) constant on solar surface
- Ran with fixed synoptic map until steady state reached
- Time series from rotating steady state solution

Validation: EUV Images for CR2107

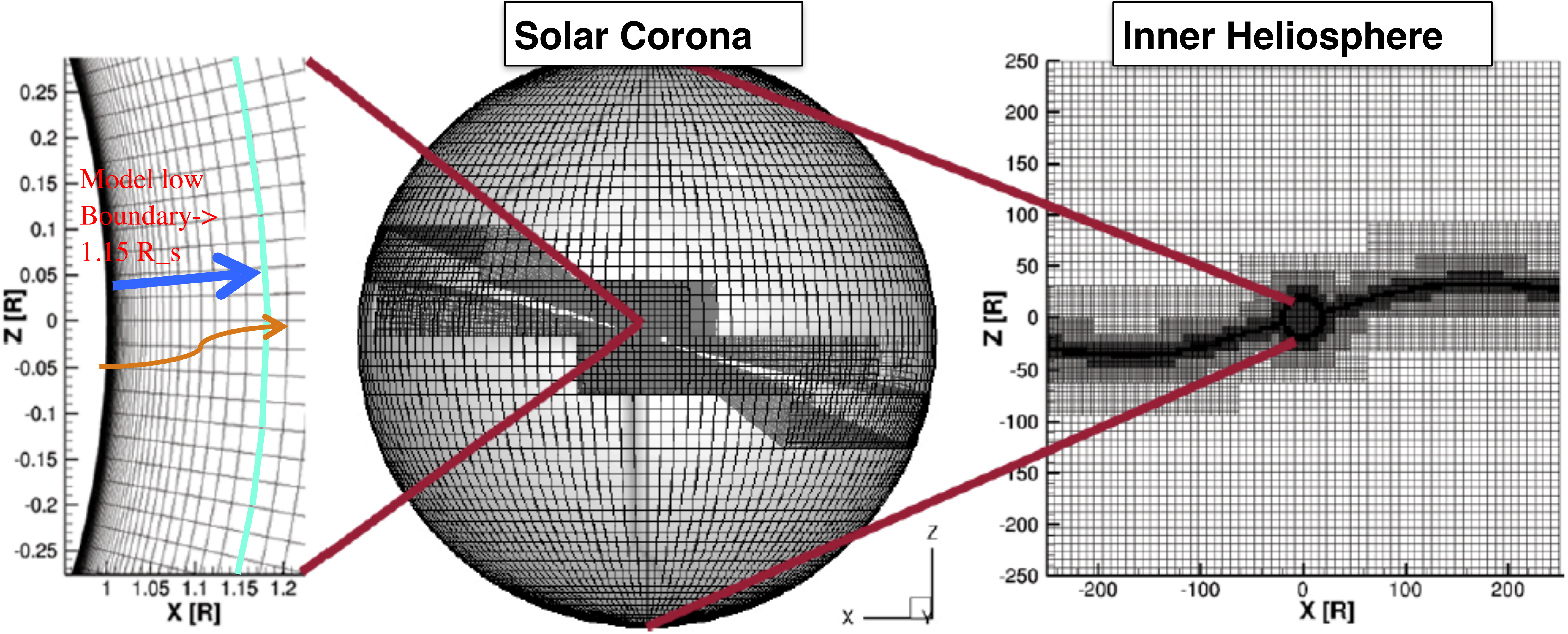


Computational Grid: AWSoM



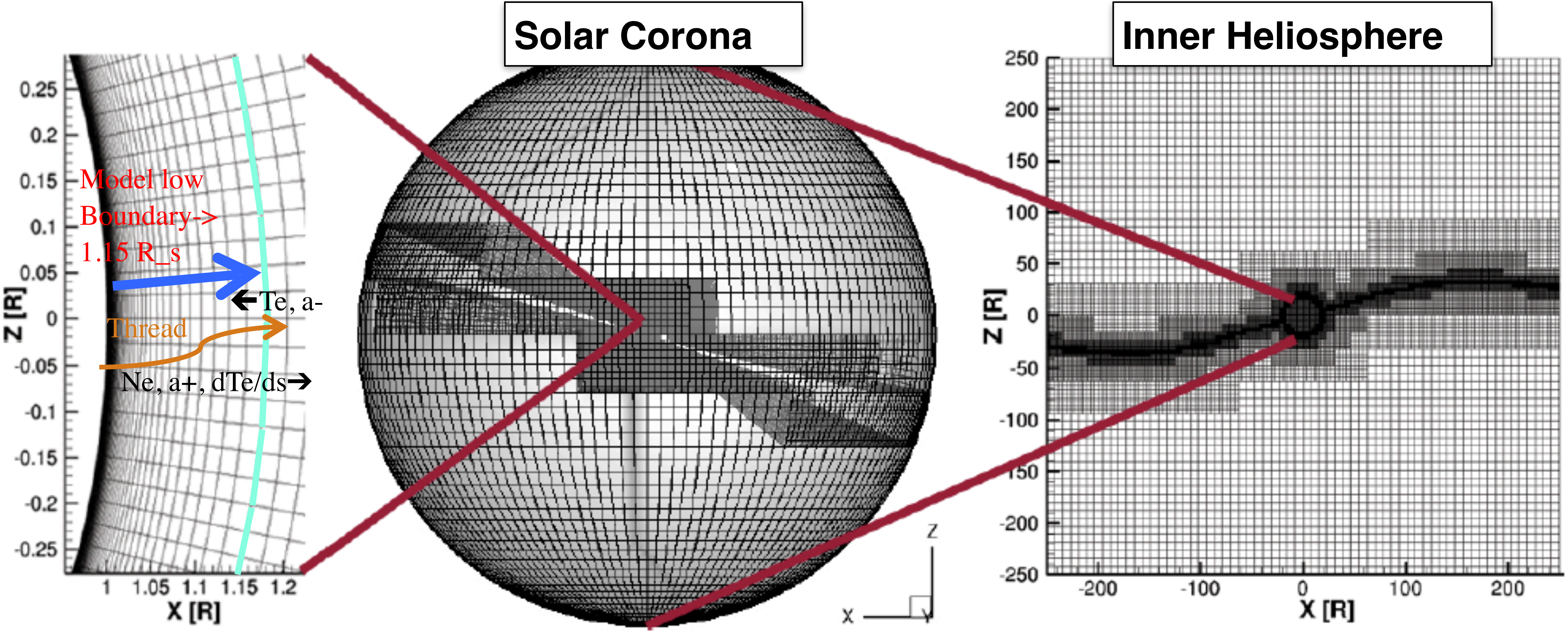
- AWSoM is split in two coupled framework components: stretched spherical grid for solar corona, cartesian grid for inner heliosphere
- Significant grid stretching to grid resolve the upper chromosphere and transition region in addition to artificial transition region broadening
- Due to the very high resolution below 1.15R_{sun} AWSoM is too slow to achieve faster than real-time.

AWSoM-R: Upshift the Inner Boundary



- **We use the lower boundary of the AWSoM-R model at $R = 1.15R_s$**
- **We apply 1D thread solutions along PFSS model field lines to bridge the AWSoM-R model to the chromosphere through the transition region.**

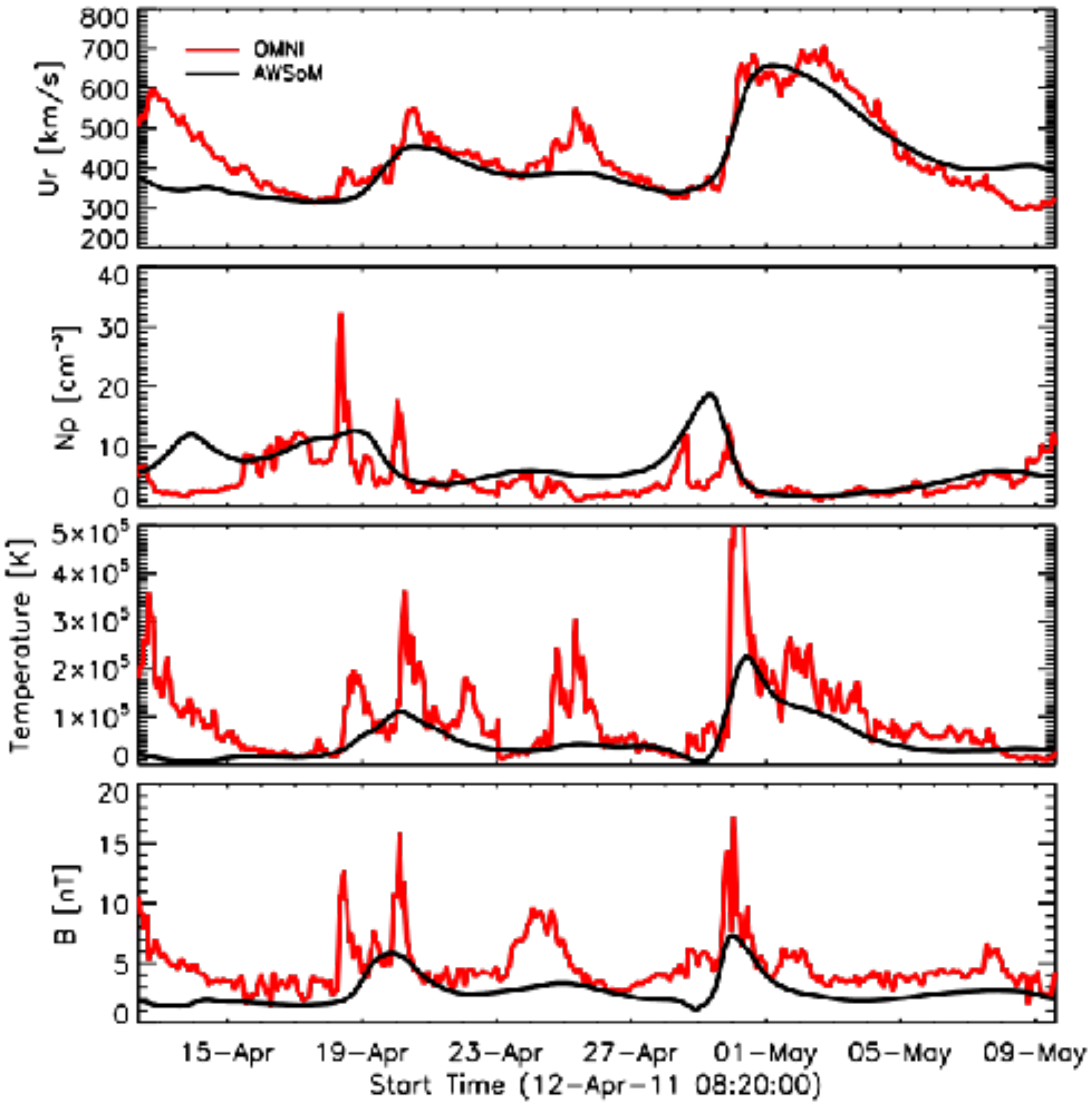
Apply 1D Thread Solution



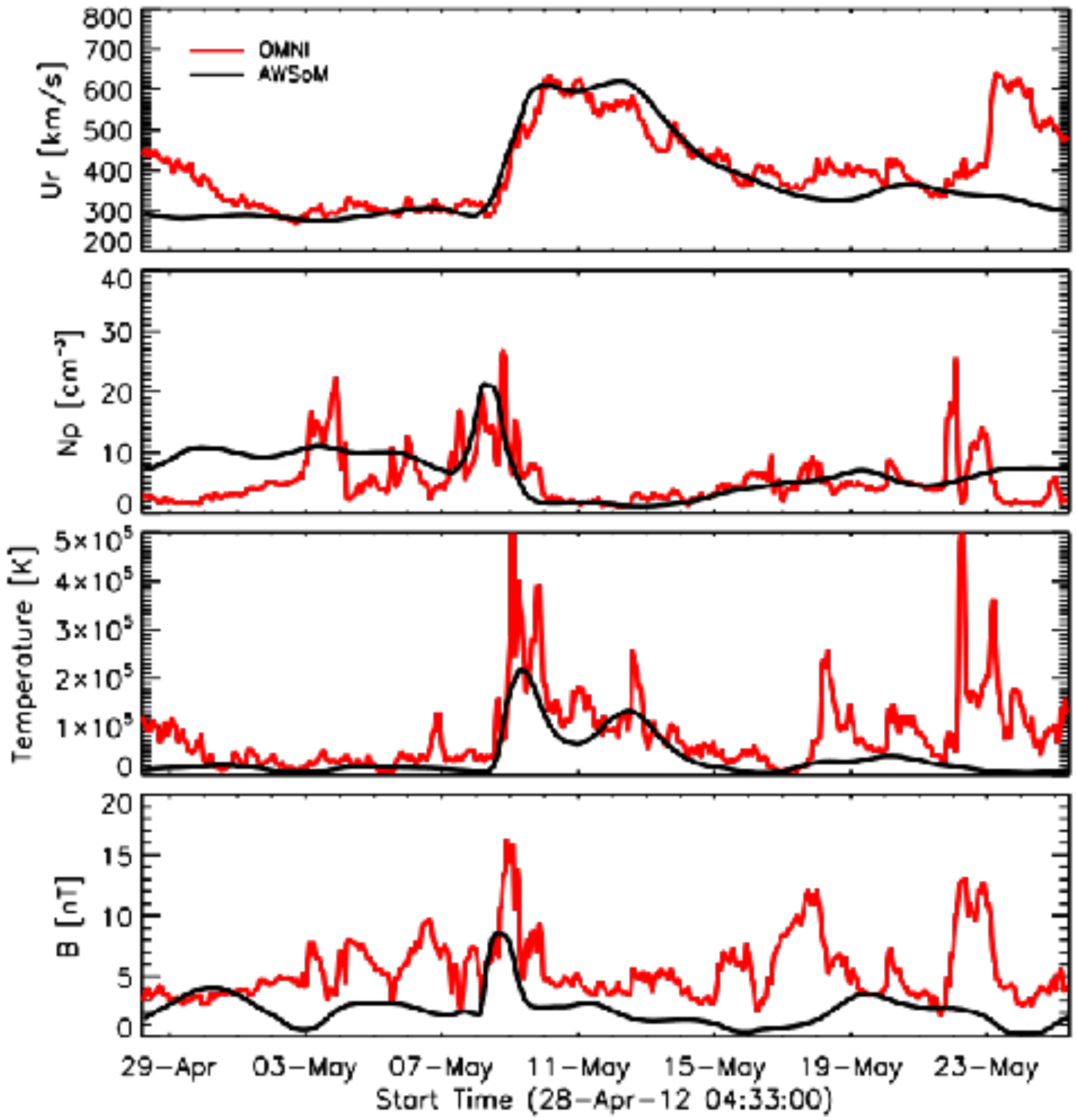
- Recognise that between $1R_s$ and $1.15R_s$ $u \parallel B$ and $u \ll V_{slow}, V_A, V_{fast}$
- Quasi-steady-state mass, momentum, energy transport and wave turbulence transport is solved along the connecting field line implicitly (1D equations!)
- The speed-up of AWSoM-R is about a factor 200 compared to AWSoM

Validation: MHD Quantities at 1AU

CR2109



CR2123



Alfvén Wave Solar Model (AWSoM)

Boundary Conditions:

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

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

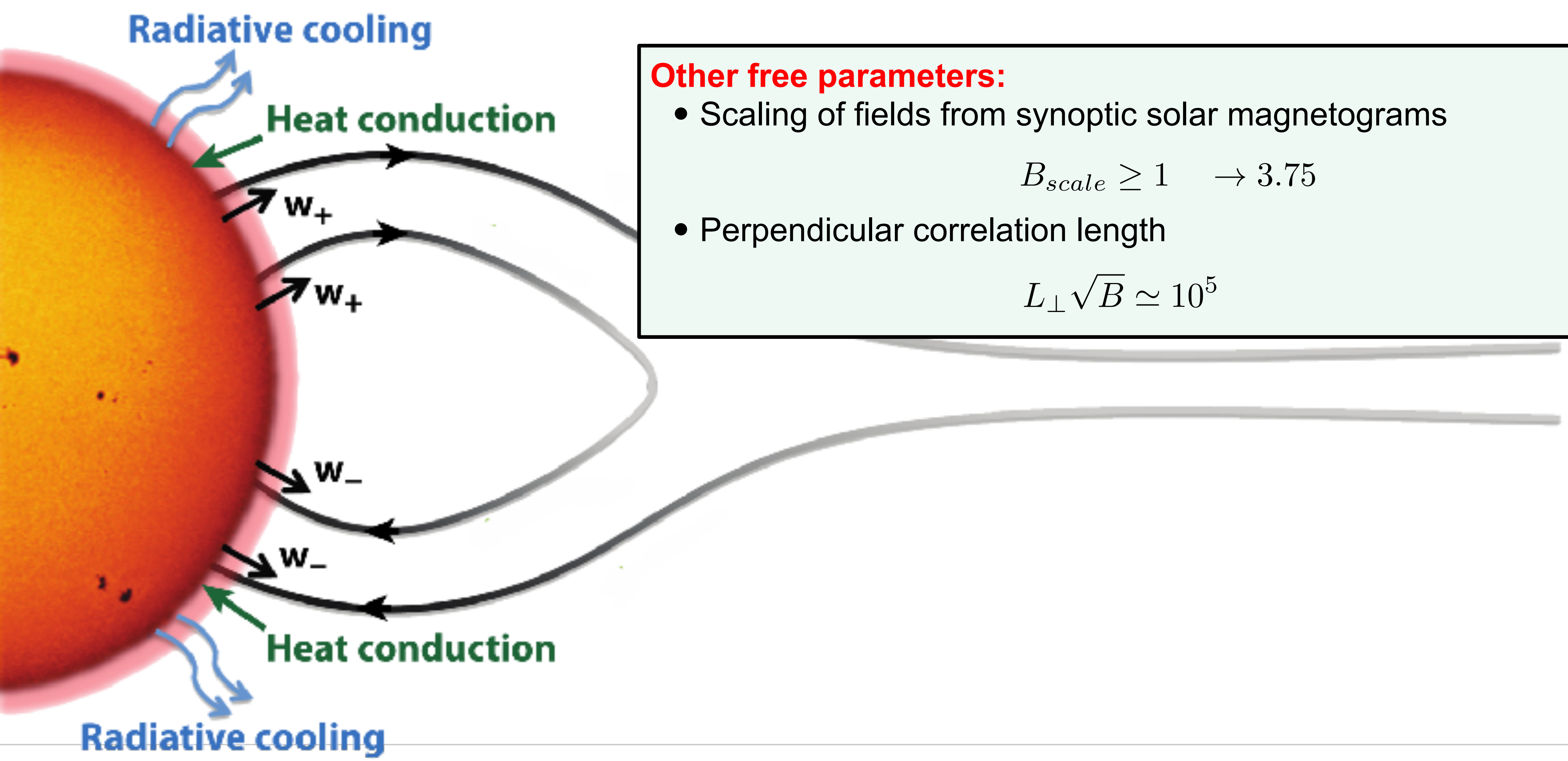
Other free parameters:

- Scaling of fields from synoptic solar magnetograms

$$B_{scale} \geq 1 \qquad \rightarrow 3.75$$

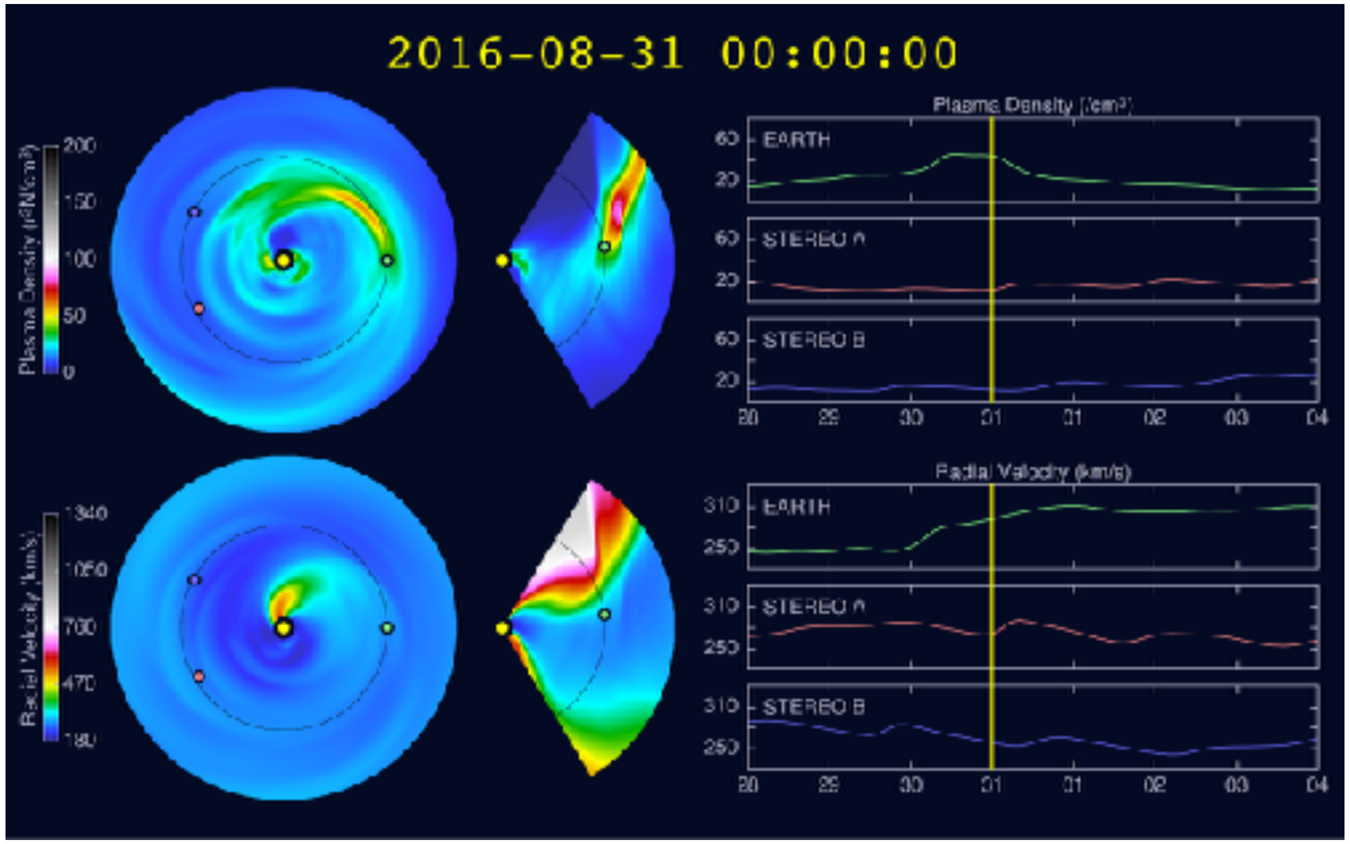
- Perpendicular correlation length

$$L_\perp \sqrt{B} \simeq 10^5$$



First time-dependent AWSoM - SWIFT

AWSoM-SWIFT

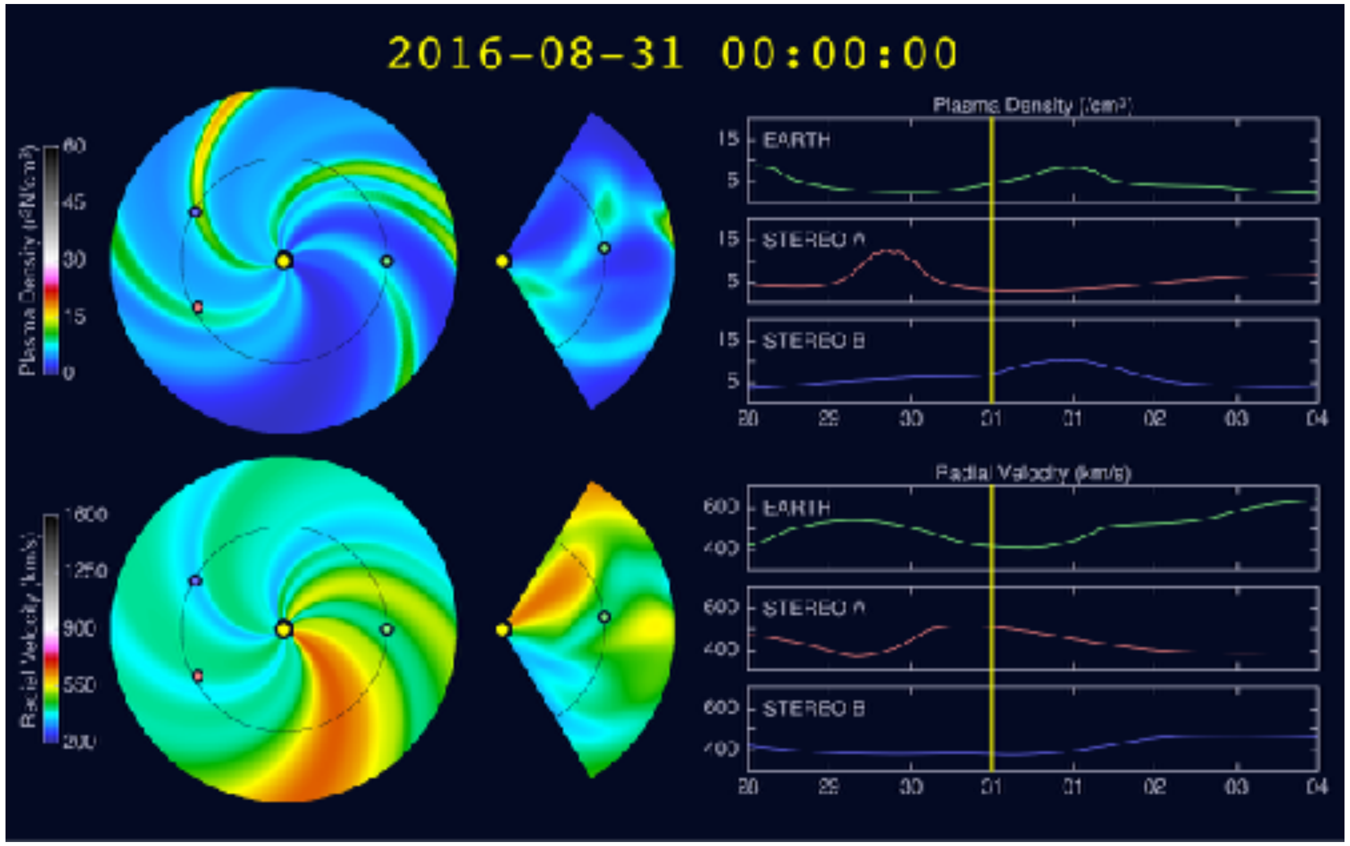


AWSoM-SWIFT simulation with unscaled magneto gram field strength.

No attempt to account for hot electron or Alfven turbulent compost of ASWoM pressures In SWIFT driving.

On ~60 cores this runs in real time

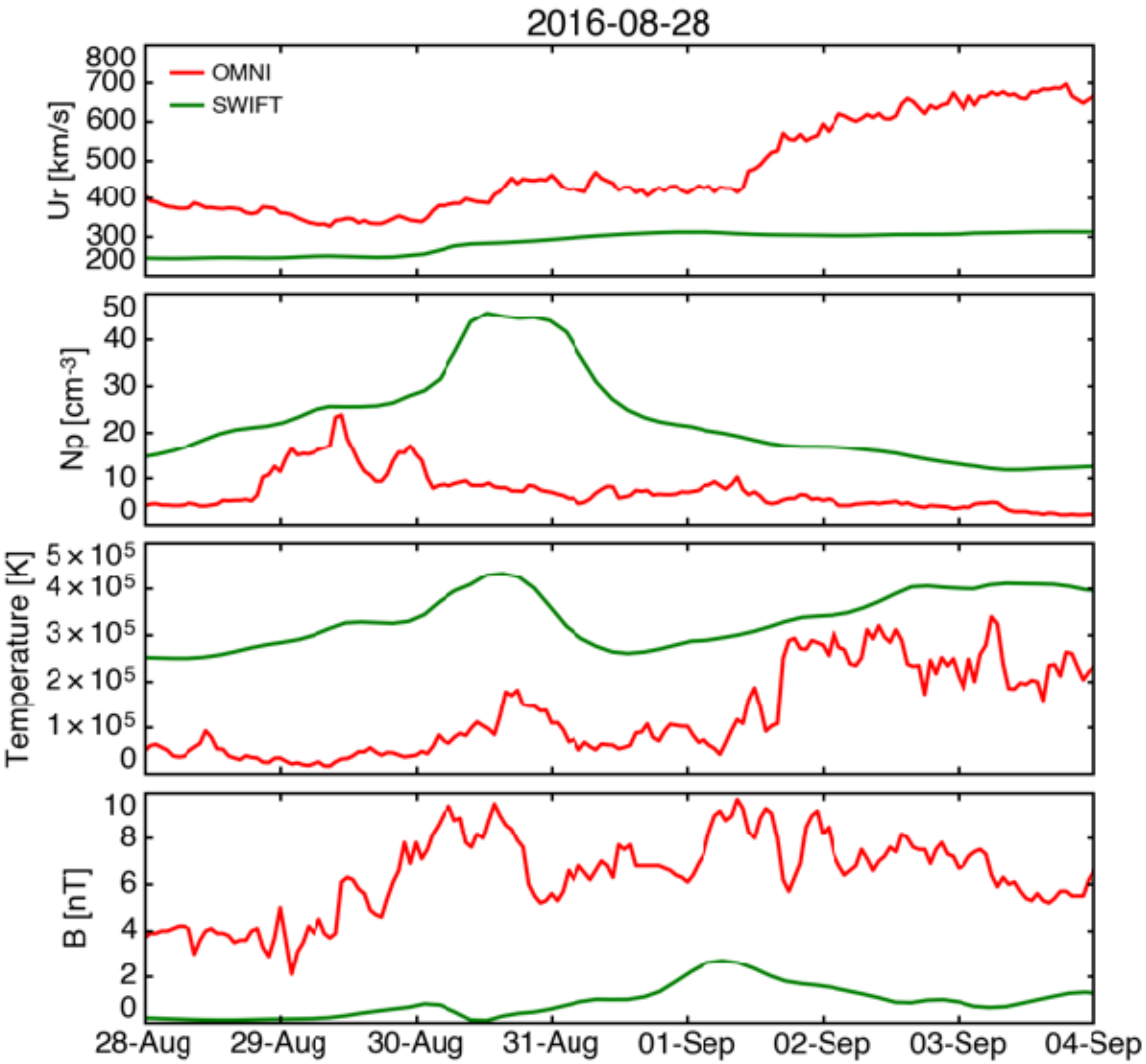
WSA-ENLIL



No similarity to WSA-ENLIL for the same period.

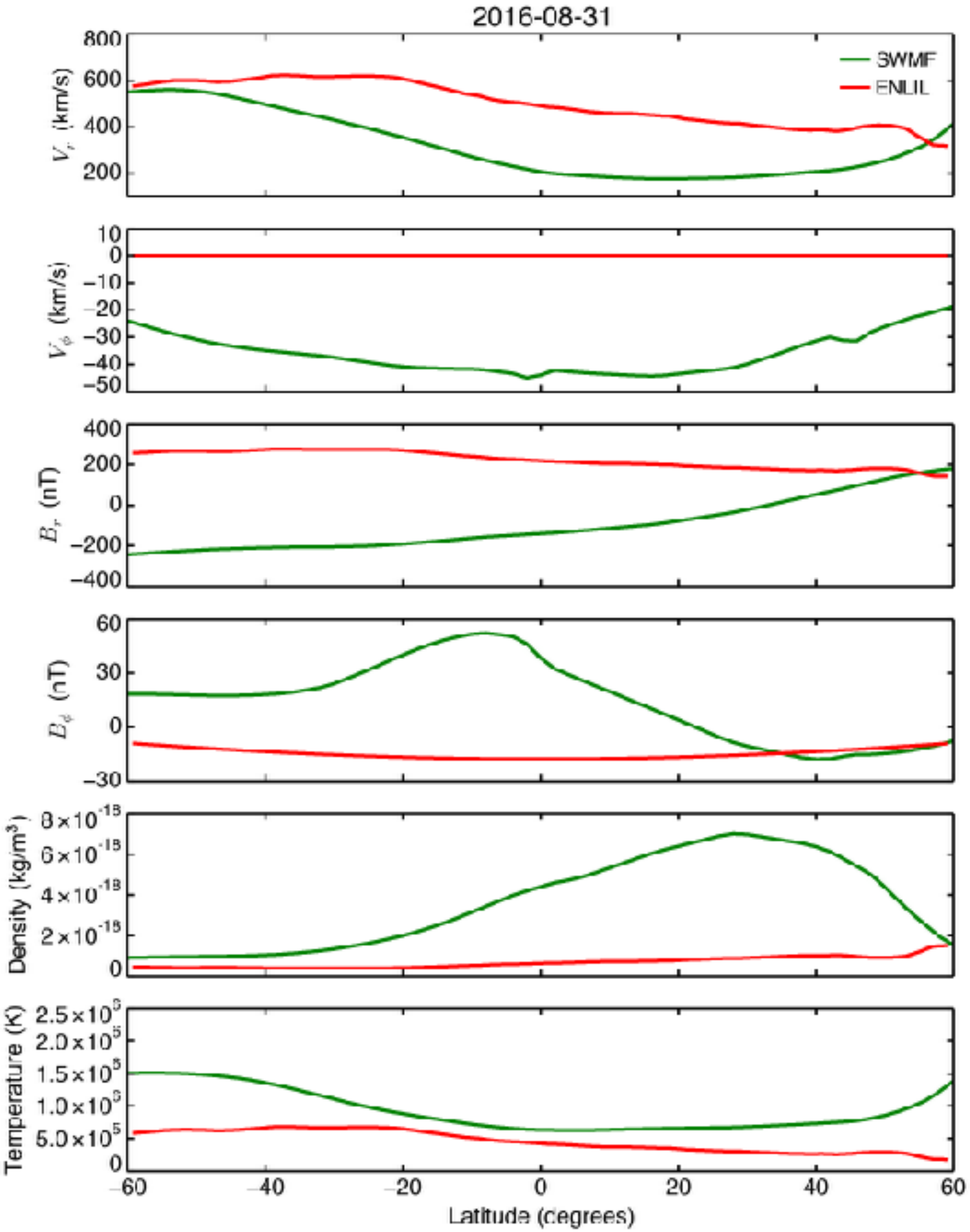
ASWoM-SWIFT densities too high and velocities too low.

AWSoM - SWIFT compared to OMNI data



These runs clearly show that AWSoM-SWIFT in this form simple fails to give any valuable predictions

AWSoM vs. ENLIL boundary values at 20 R_o



AWSoM - SWIFT plans & Conclusion

Current ASWoM-SWIFT solutions are undeniably useless.

However these are the first attempt at a coupled solution and the coupling is known to work for full AWSoM steady steady from solar surface to 1 AU.

- Include hot electron component from AWSoM in electron driving pressure in SWIFT
- Add Alfven wave pressure to SWIFT driving pressure
- Test with range of B_{scale} up to 3.75
- Increase SWIFT resolution
- Reproduce the steady state AWSoM solution
- Introduce scheme to prevent heliospheric current sheet reconnection
- Co-rotating frame

All of these ought to be completed by 31 March to keep on schedule.

We are currently assuming that these will fix the problem!