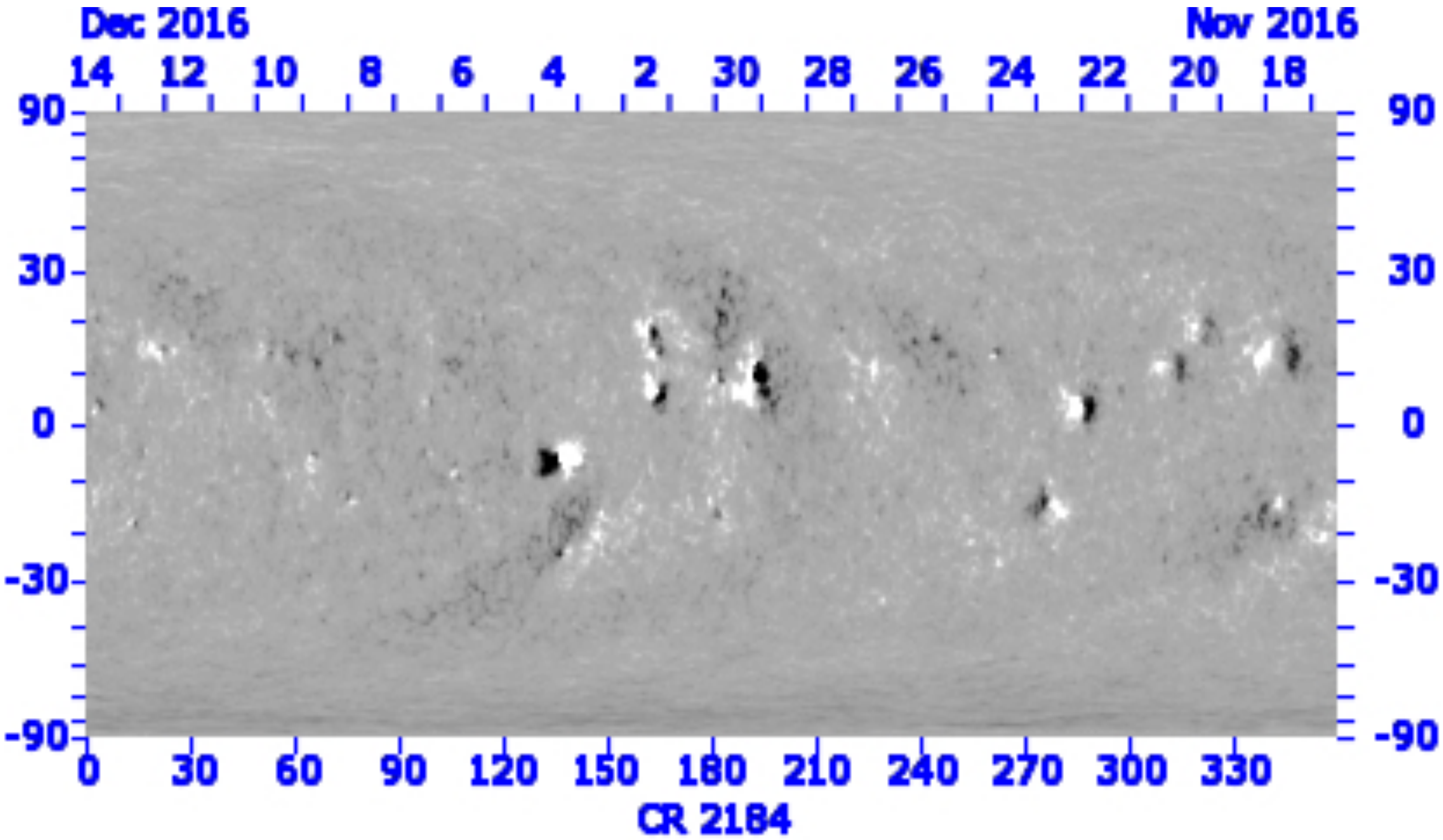
PROGRESS Final Review Meeting
2-3 August 2018
Sheffield

WP 2 - Propagation of the solar wind from the Sun to L1

Tony Arber, Warwick
Keith Bennett, Warwick
Bart van der Holst, Michigan
Mike Liemohn, Michigan

Objective

From solar surface predict the MHD variables at L1 and 1 A.U. using **first principles physics** models

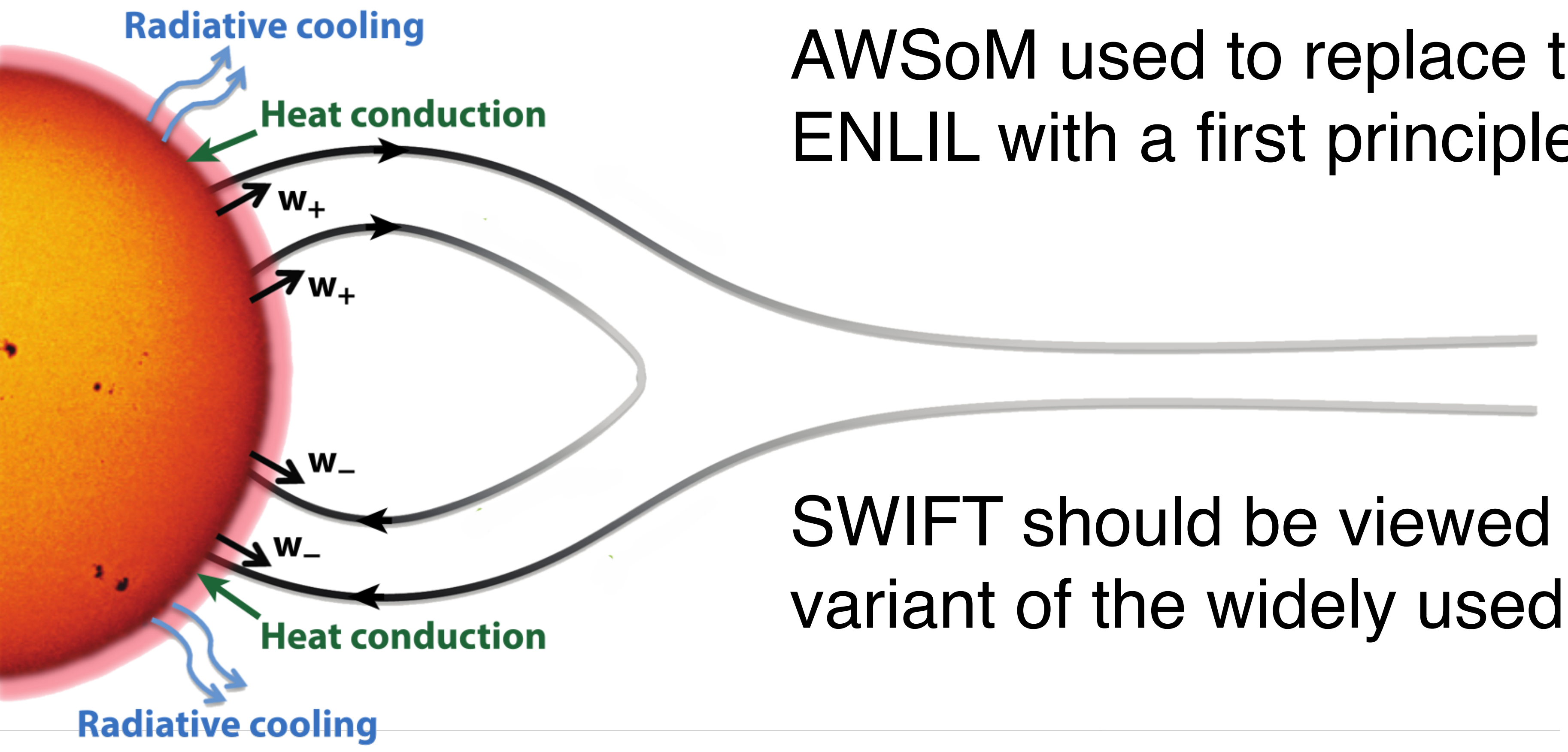


Multi-layered coupled modelling

GONG data used to get potential B-field

Use potential field as starting point for AWSoM simulation

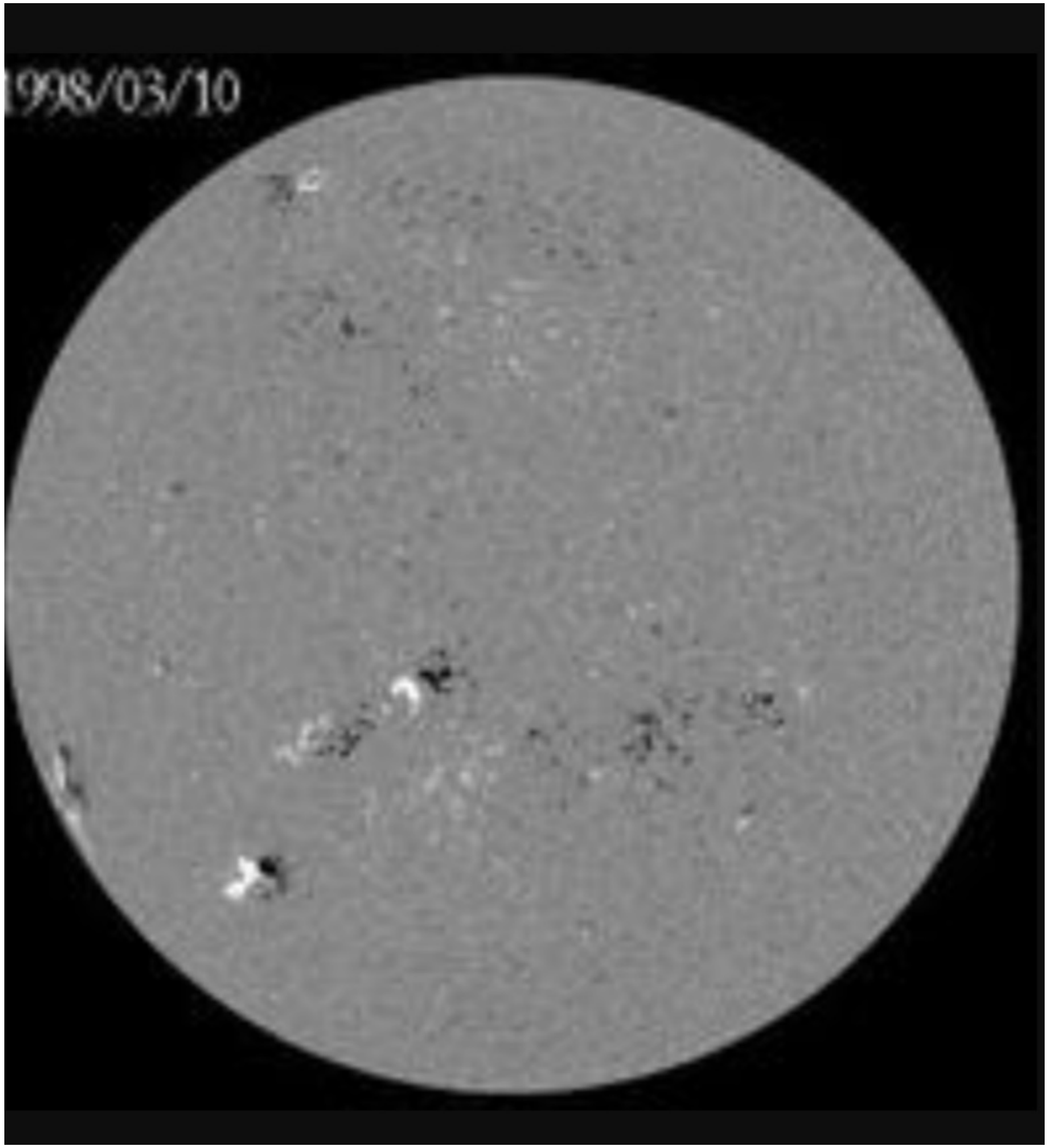
At 20 Solar radii data interpolated from AWSoM onto SWIFT grid and solution propagated to 1 AU



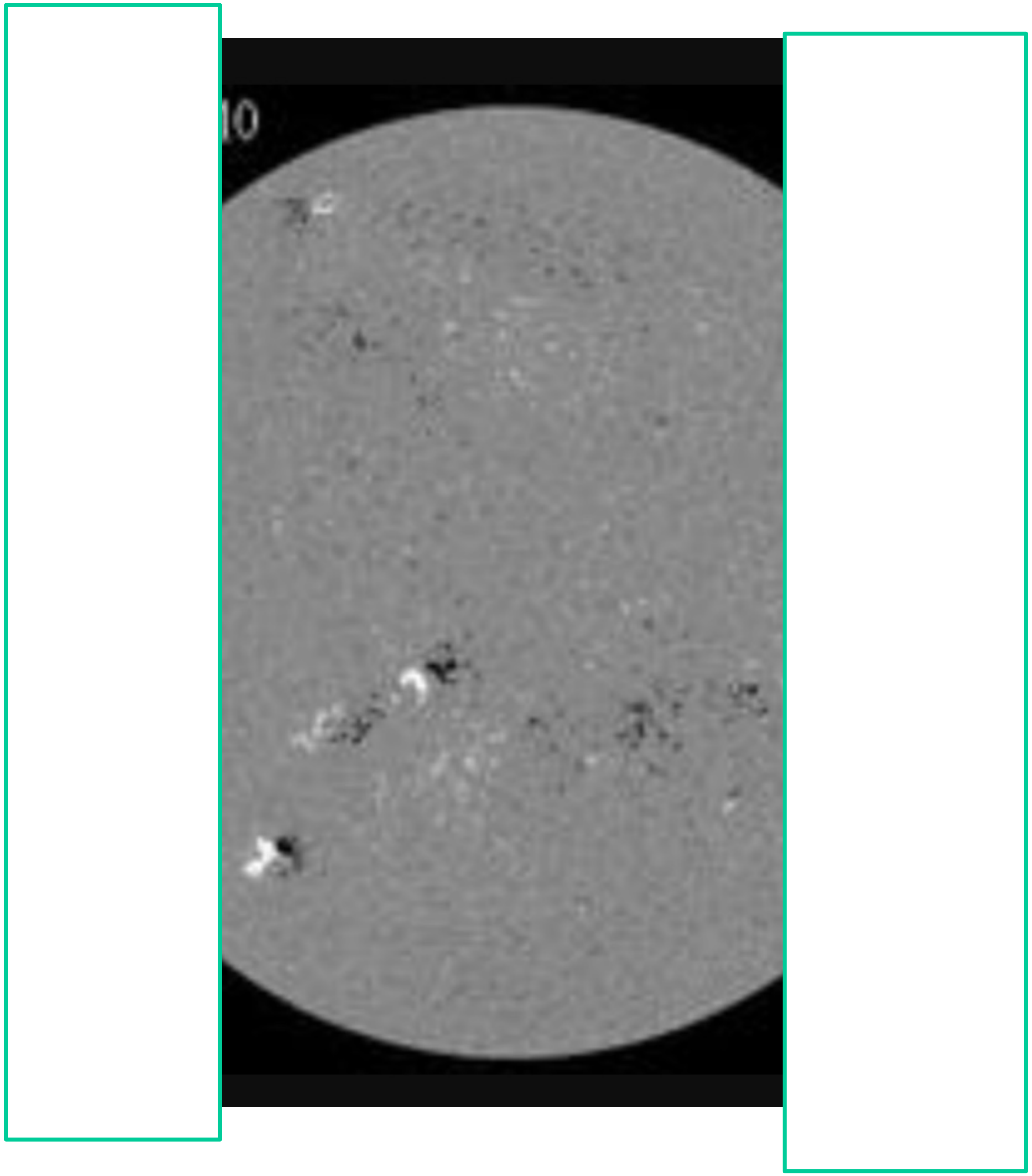
AWSoM used to replace the WSA in WSA-ENLIL with a first principles physics package

SWIFT should be viewed as essential an EU variant of the widely used ENLIL code

GONG data disk image

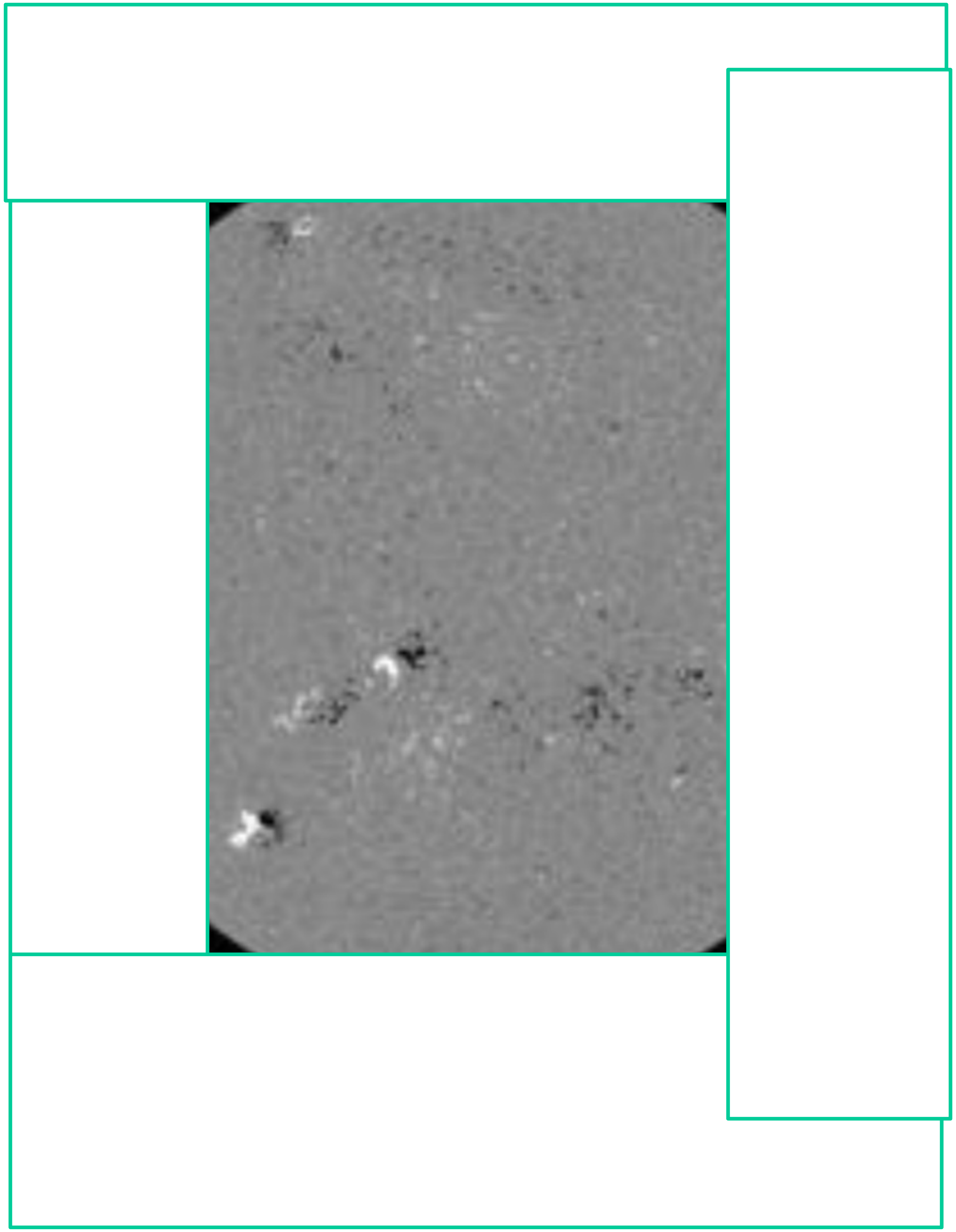


GONG data disk image



Line-of-sight so only
120 degrees used

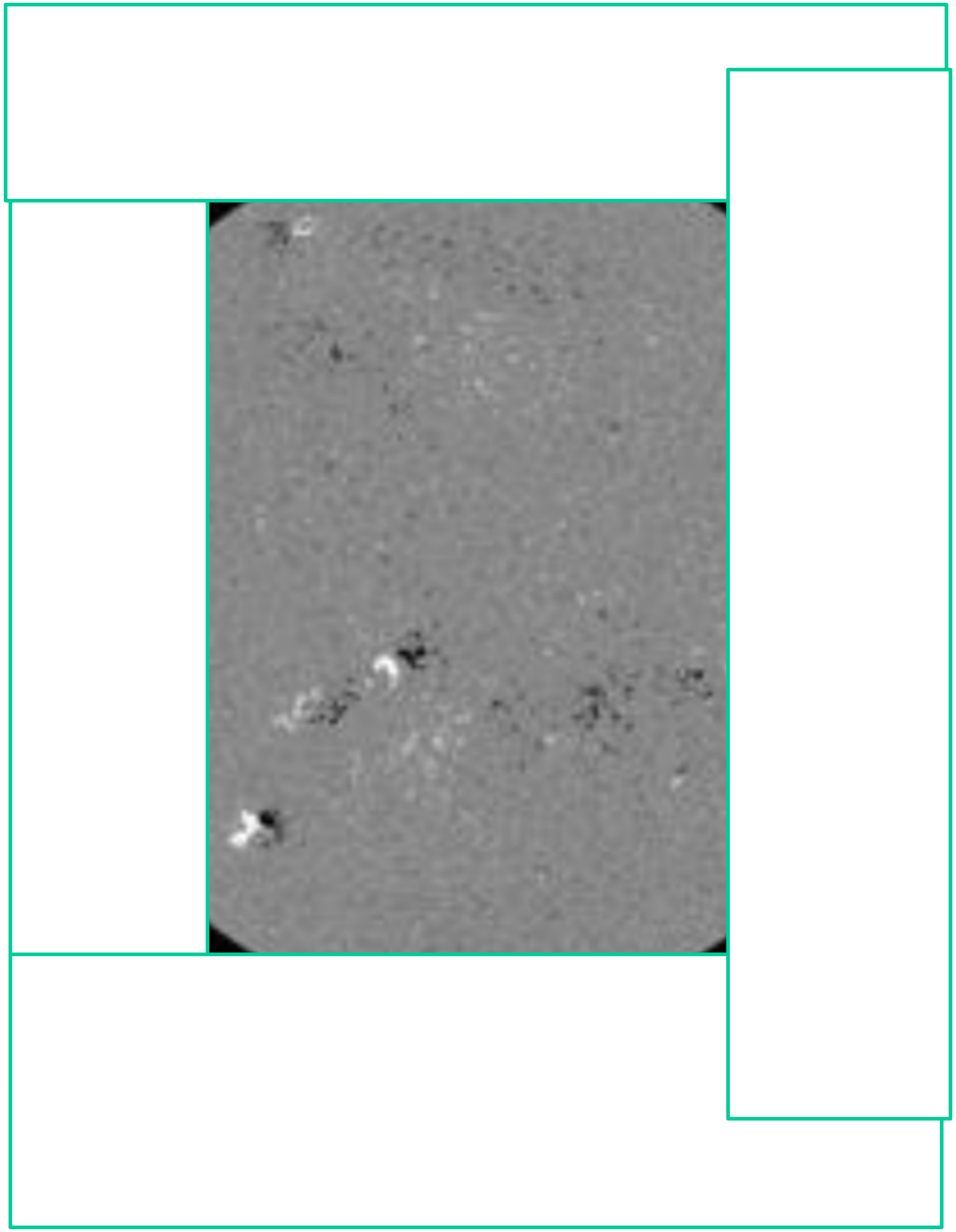
GONG data disk image



Line-of-sight so only
120 degrees used

Poor resolution at poles so
fitting schemes needed

GONG data disk image



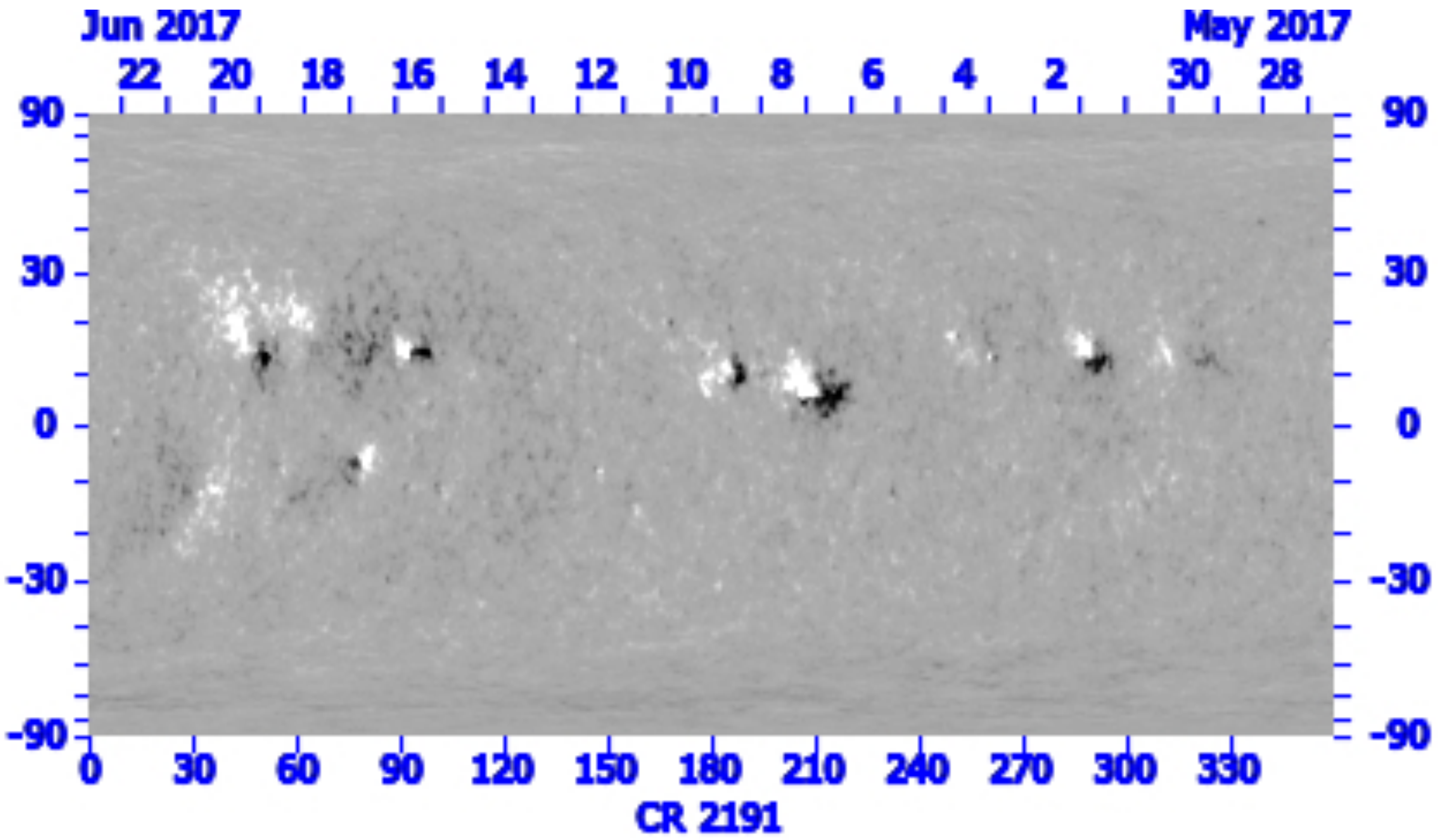
Line-of-sight so only
120 degrees used

Poor resolution at poles so
fitting schemes needed

Project onto
longitude-latitude

GONG Data

6 GONG sites take full-disk images every ~minute



These are averaged into 10 minute images

Image covers 120 degrees

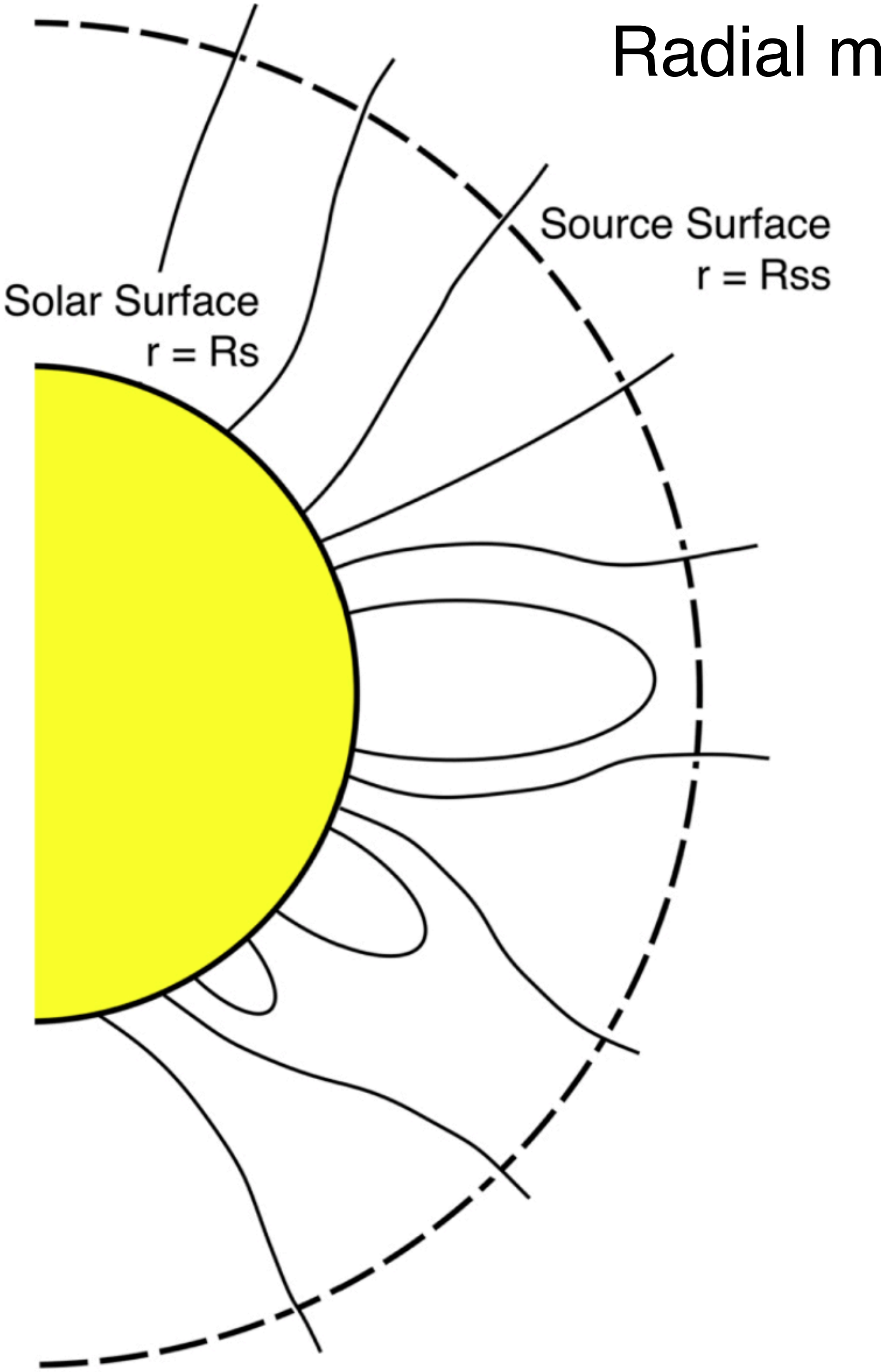
Overlapping images averaged with a weight based on $cos^4(\phi)$

A full rotation image can be updated every ~8hrs

Hourly updates need special treatment of western edge weighting

Poles are poorly resolved and need extrapolation…

Potential Field Source Surface (PFSS)

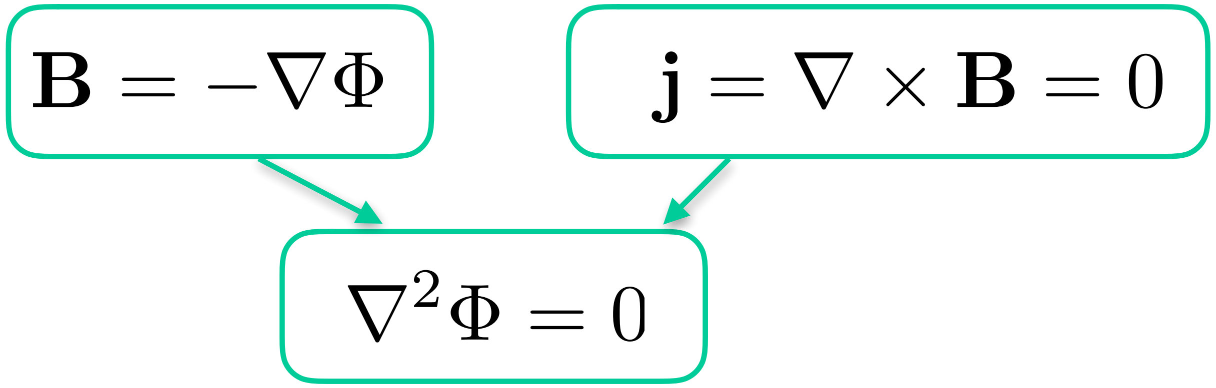


Radial magnetic field at the solar surface from GONG

Chose a surface R_{ss}, usually at 2.5 R_{sun}

On R_{ss} fix the field to be radial to match field structure expected due to solar wind

Potential field between R_{sun} and R_{ss}

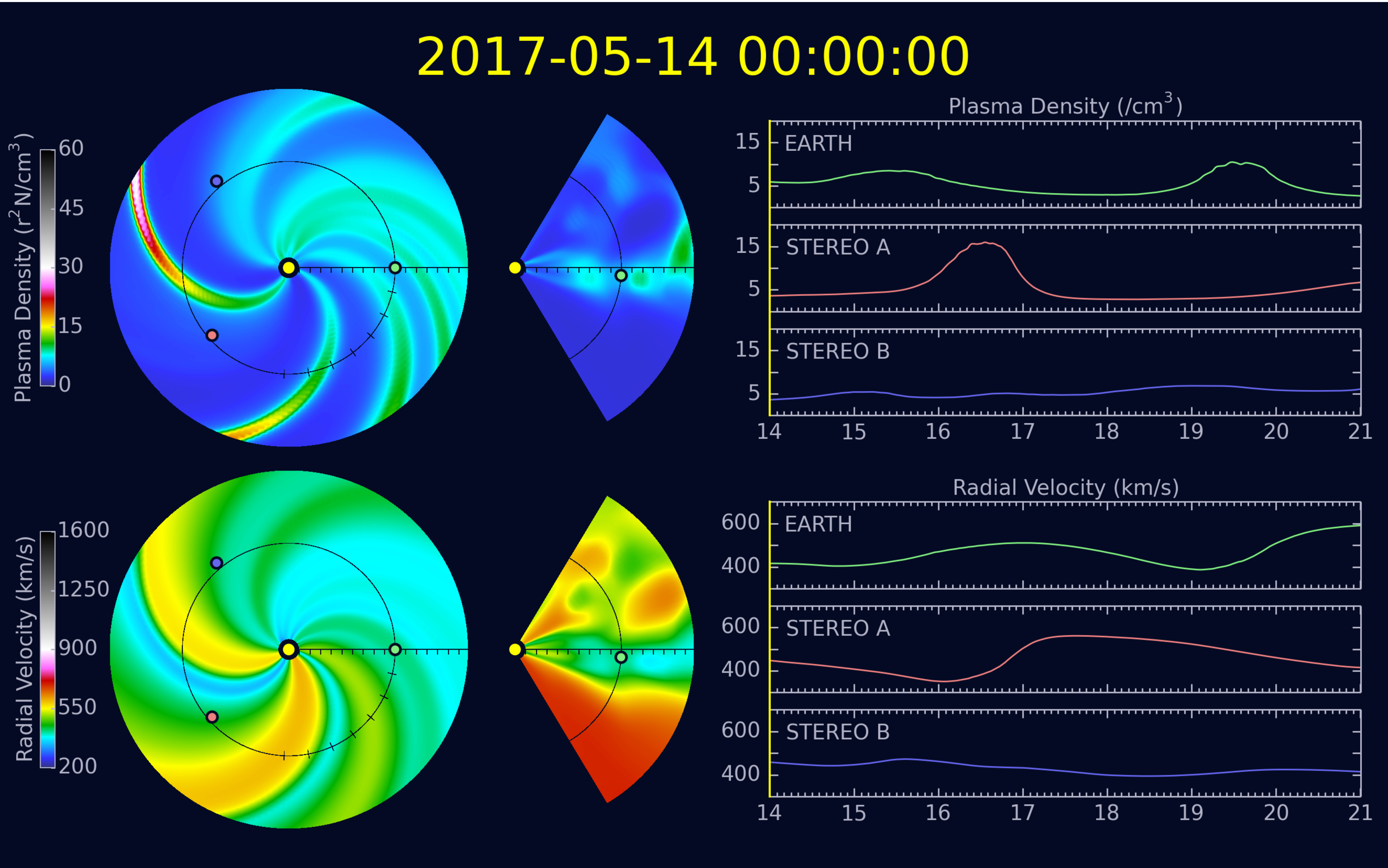


$$\mathbf{B} = -\nabla\Phi$$

$$\mathbf{j} = \nabla \times \mathbf{B} = 0$$

$$\nabla^2\Phi = 0$$

WSA-ENLIL typical results



PROGRESS Project

Aim to predict MHD variables at 1 A.U. from GONG data

Replace empirical models of WSA with first principles model

Allow full vector B-field

Use 2 temperature MHD

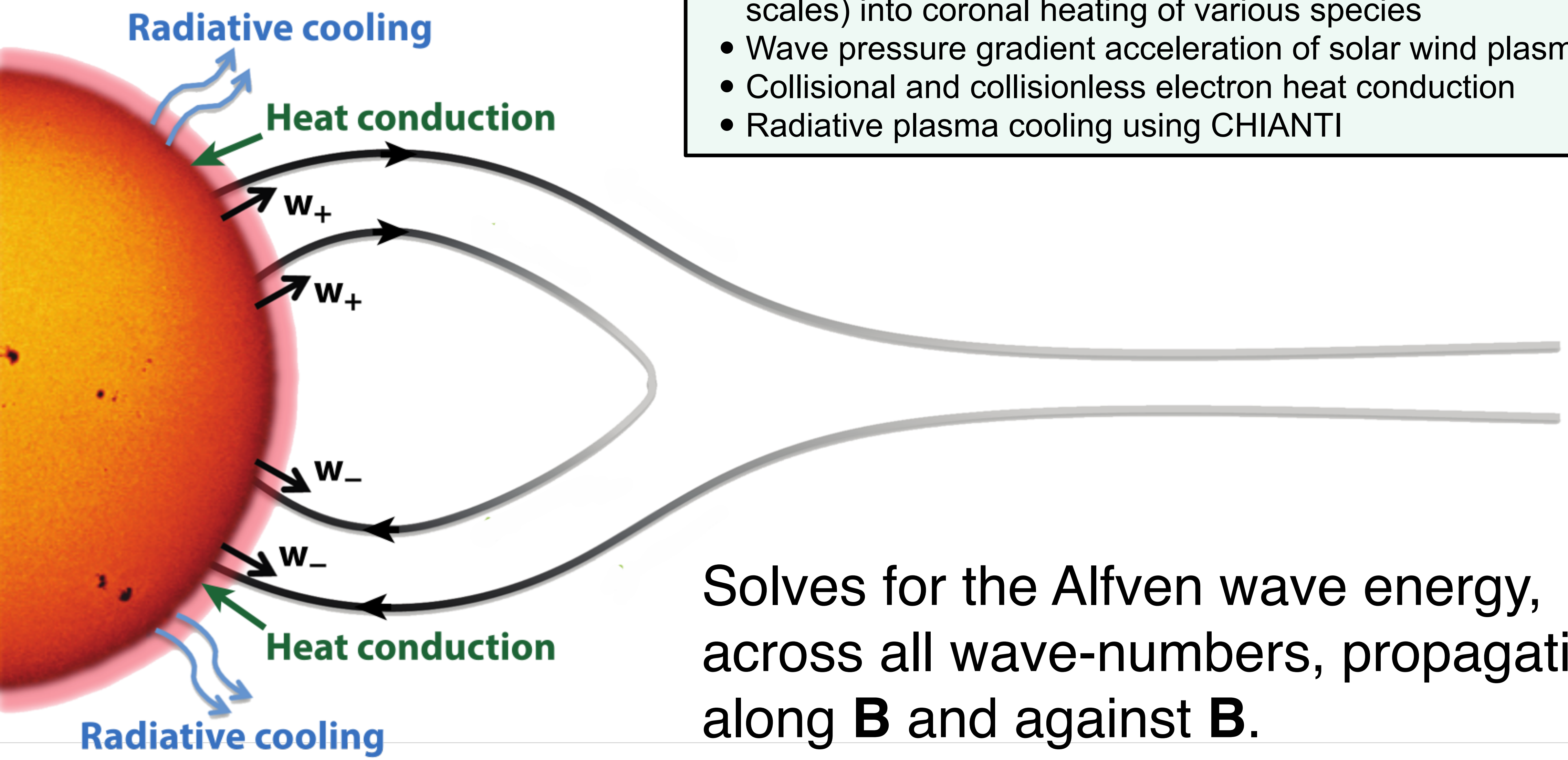
Shock heating of ions, thermal conduction in electrons

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



Solves for the Alfven wave energy, across all wave-numbers, propagating along **B** and against **B**.

Mathematical Models

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

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

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

Normal MHD + 2T and Alfven pressure

$$P_A = \frac{1}{2}(w_+ + w_-)$$

Mathematical Models

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

Heating from Alfven wave turbulence

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

Mathematical Models

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

Turbulence energy advection and reflection

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

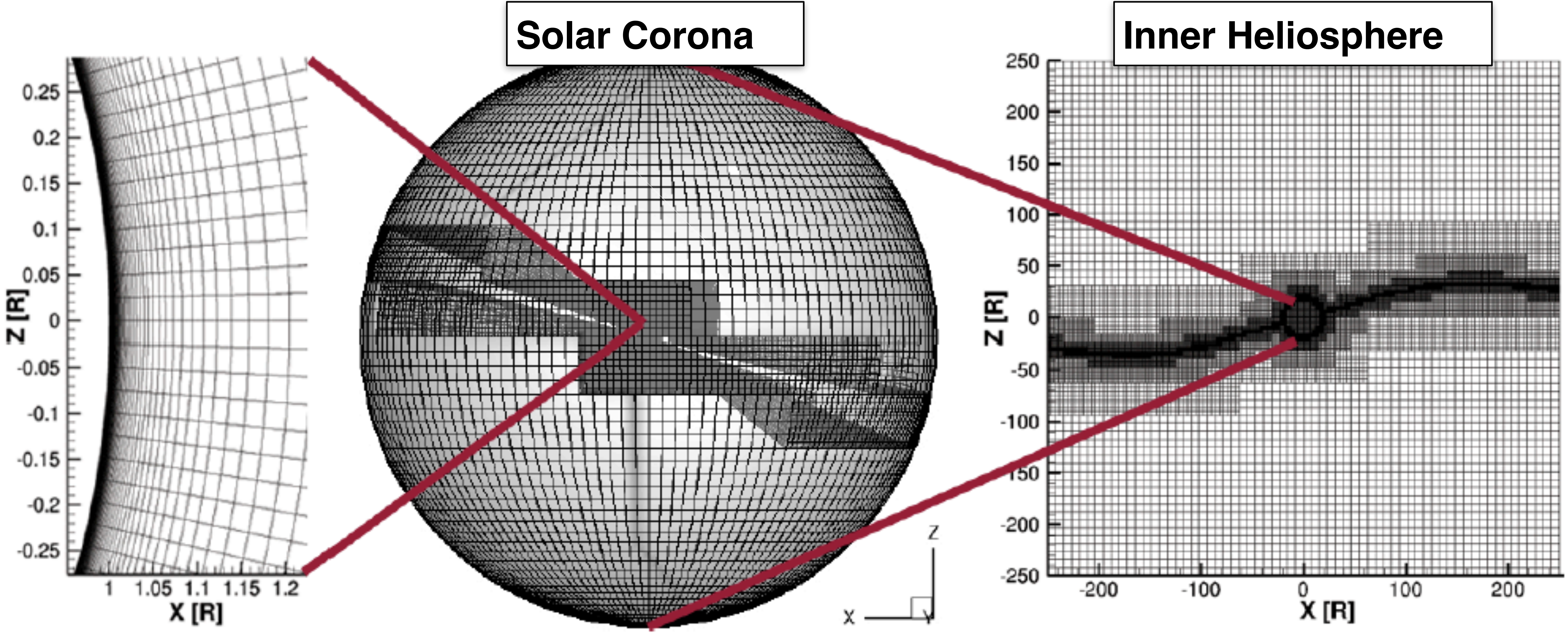
Alfvén Wave Turbulence

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

$$\frac{\partial w_\pm}{\partial t} + \underbrace{\nabla \cdot [(\mathbf{u} \pm \mathbf{V}_A) w_\pm]}_{\text{Alfvén wave advection}} + \overbrace{\frac{w_\pm}{2}(\nabla \cdot \mathbf{u})}^{\text{energy reduction in expanding flow}} = \underbrace{\mp \mathcal{R}\sqrt{w_- w_+}}_{\text{wave reflection}} \overbrace{- \Gamma_\pm w_\pm}^{\text{wave dissipation}}$$

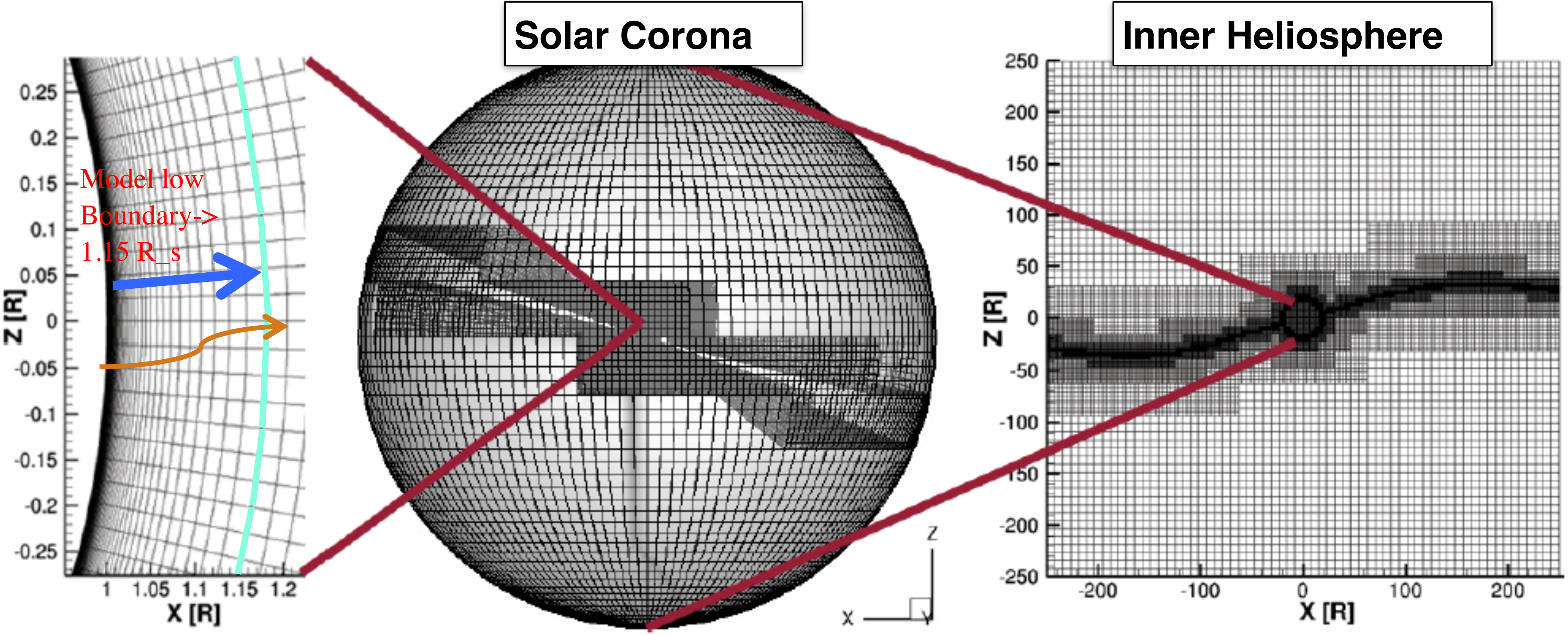
- The wave reflection is due to field-aligned component of the Alfvén speed gradient and vorticity.
- Phenomenological wave dissipation (Dmitruk et al., 2002): $\Gamma_\pm = \frac{2}{L_\perp}\sqrt{\frac{w_\mp}{\rho}}$
- Similar to Hollweg (1986), we use a simple scaling law for the transverse correlation length $L_\perp \sqrt{B} = 150 \text{ km} \sqrt{\text{T}}$
- Poynting flux of outward propagating turbulence: $(S_A/B)_\odot = 1.1 \times 10^6 \text{ W m}^{-2} \text{ T}^{-1}$

Computational Grid: AWSoM



- AWSoM uses stretched spherical grid for solar corona
- 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

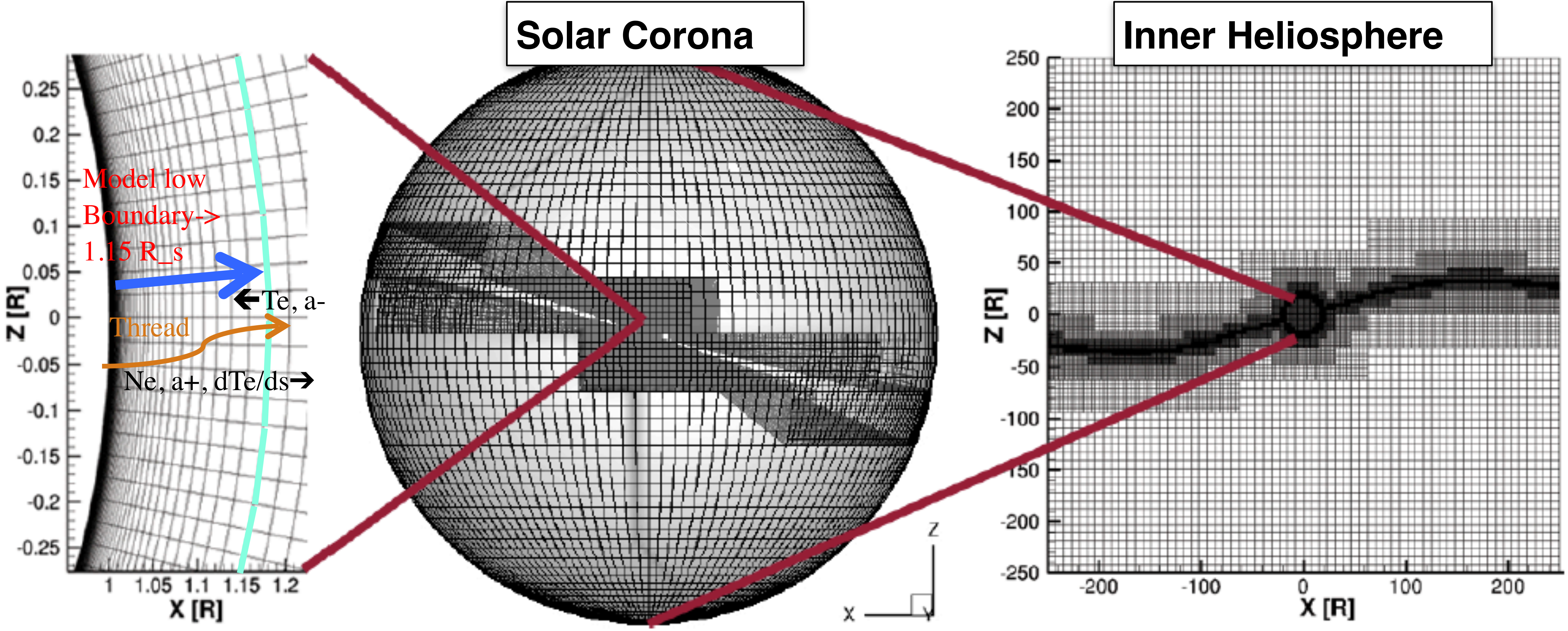


Solar Corona

Inner Heliosphere

- 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 ll B** and **u≪v_MHD**
- 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

Still takes 14 hrs on 128 cores to run from one GONG map

AWSoM - SWIFT Coupling

AWSoM provides MHD variable at 21.5 R_{sun}

AWSoM is in co-rotating frame but output to buffer in inertial

SWIFT uses the inertial frame buffer MHD values as driver for 2T MHD solution of

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

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

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

Energy equations for each species

$$\frac{\partial}{\partial t}\left(\frac{P}{\gamma - 1}\right) + \nabla . \left(\frac{P}{\gamma - 1}\mathbf{u}\right) + P\nabla . \mathbf{u} = -\nabla . \mathbf{q_e} + H_{shock}$$

Shock heating of ions, thermal conduction for electrons

SWIFT Thermal Conduction

Electron mean-free-path in SW is roughly 1 A.U.

Classical Spitzer-Harm conduction not valid

Instead adopt approach of Hollweg

Maximum heat carried by electrons $\mathbf{q_e} = \alpha P_e \mathbf{u_e}$

$$\frac{\partial}{\partial t}\left(\frac{P_e}{\gamma - 1}\right) + \nabla.\left(\frac{P_e}{\gamma_c - 1}\mathbf{u}\right) + P_e \nabla.\mathbf{u} = 0$$

With $\gamma_c = \dfrac{\gamma + (\gamma - 1)\alpha}{1 + (\gamma - 1)\alpha}$

No satisfactory solution to parallel conduction fast enough for a prediction code

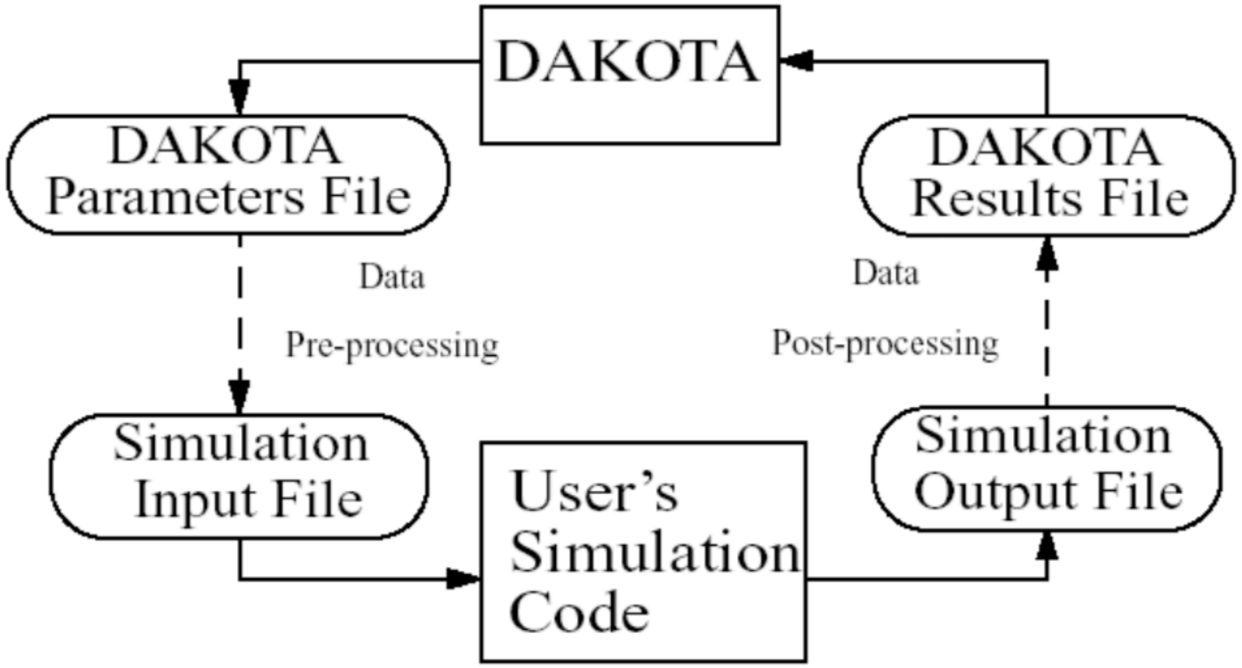
DAKOTA

Explore and predict with confidence.

The Dakota toolkit provides an interface between simulation codes and iterative analysis methods.[2]

Contains algorithms for optimization, uncertainty quantification (UQ), parameter studies, calibration, and sensitivity/variance analysis.

We perform a Sensitivity Analysis (SA) of AWSoM/SWIFT on the three free parameters, quantifying accuracy of solar wind predictions using the L_1-*norm* compared to OMNI data.



DAKOTA

DAKOTA Parameters File

Data Pre-processing

Simulation Input File

User's Simulation Code

Simulation Output File

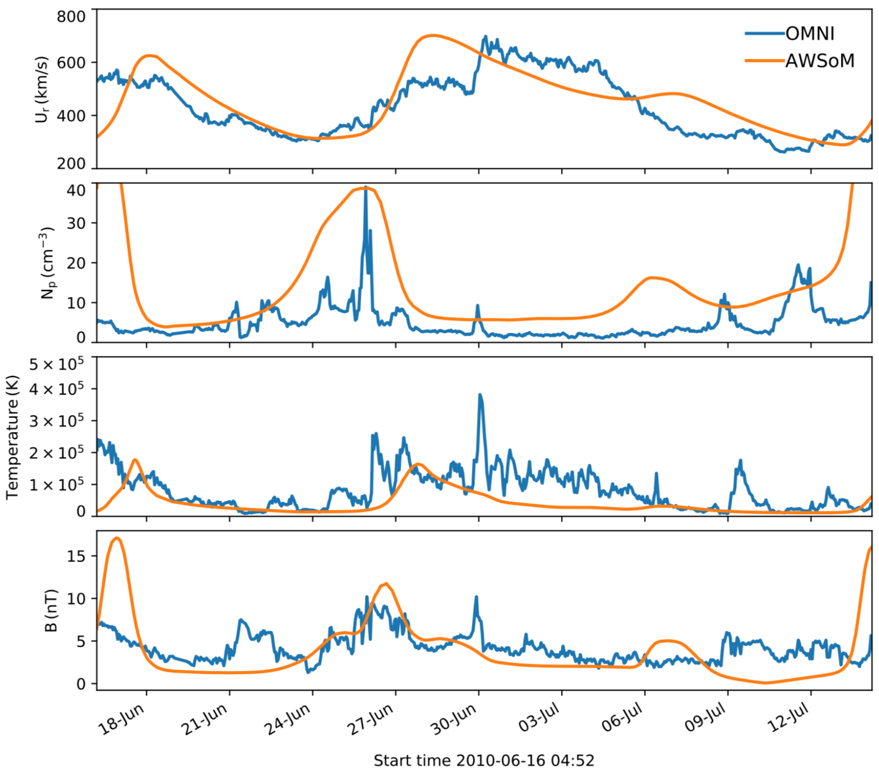
Data Post-processing

DAKOTA Results File

$$||L_i|| = \left\{ \frac{1}{n} \sum^{n} \left[\boldsymbol{u}_{sim} - \boldsymbol{u}_{OMNI} \right]^{i} \right\}^{\frac{1}{i}}$$

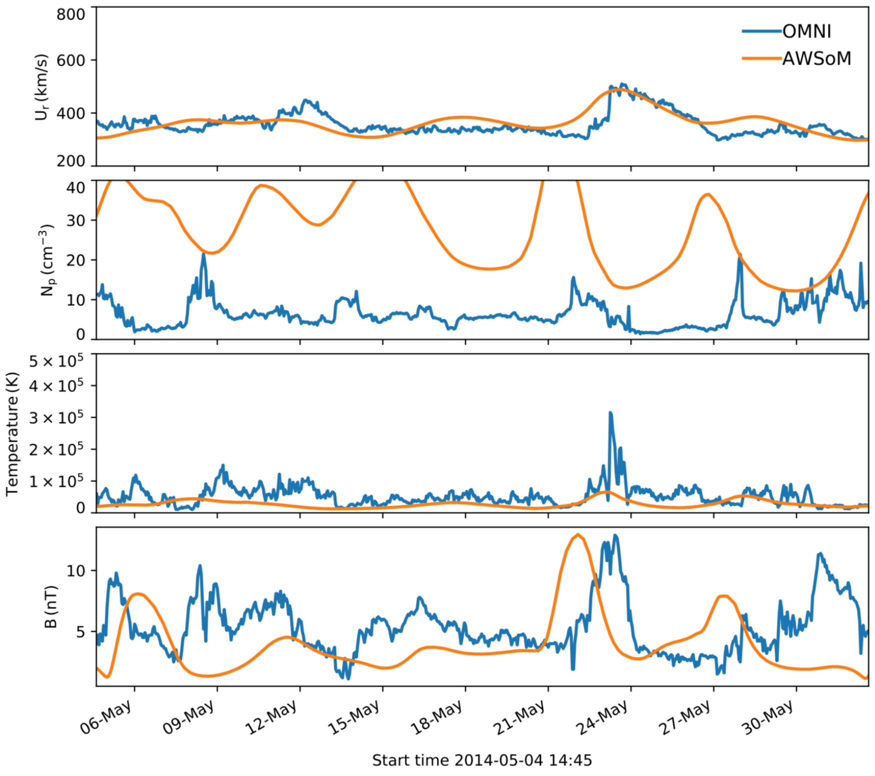
Best fit *L1* results for three Carrington rotations

June 2010



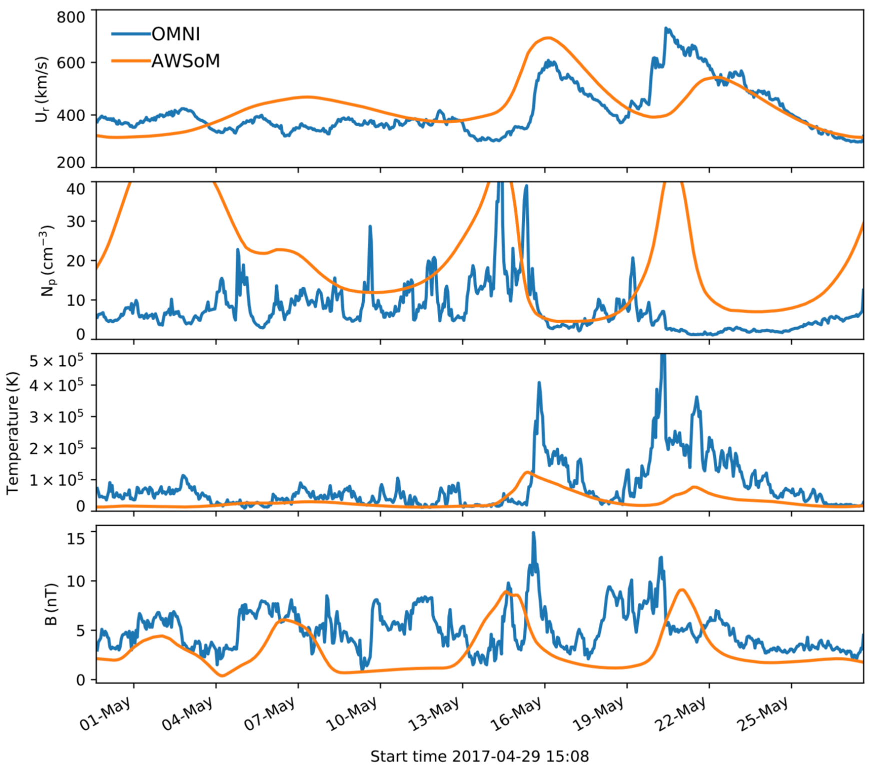
$$(S_A/B)_{.} = 0.9 \times 10^6 \mathrm{W m^{-2} T^{-1}}$$

May 2014



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

May 2017



$$(S_A/B)_{.} = 1.5 \times 10^6 \mathrm{W m^{-2} T^{-1}}$$

The best reliable fit was selected as:

Poynting flux per unit B = 1.1e6 $\mathrm{Wm^{-2}\ T^{-1}}$

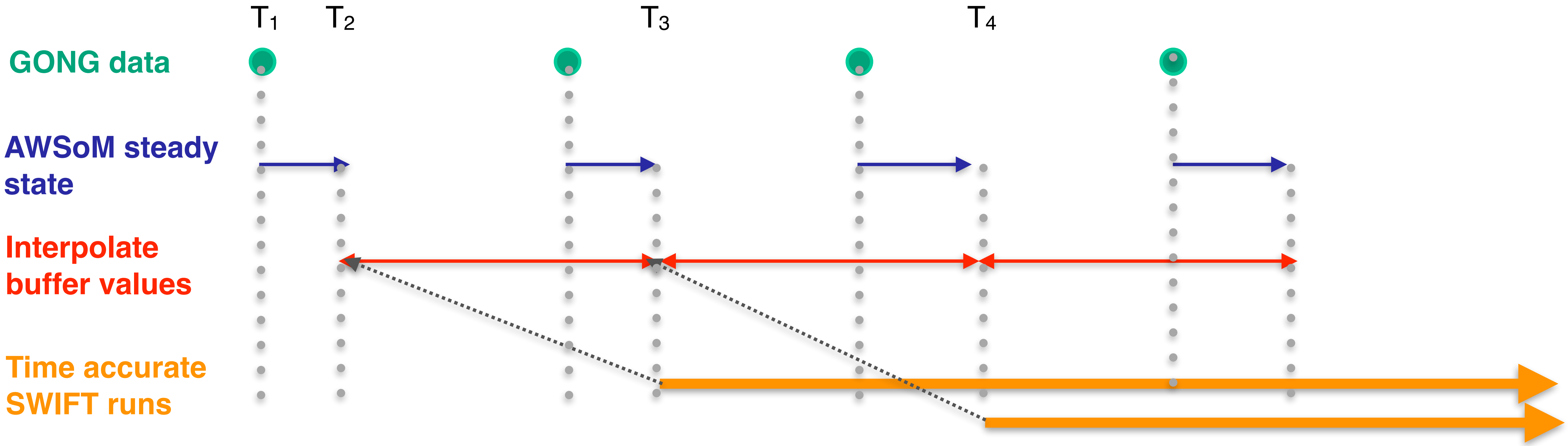
Stochastic exponent (controls Alfven wave heating) = 0.34

While scaling GONG can improve fit this was not chosen as no physics reason to justify

Allowed us to reduce runtime to 14 hours on 32 cores so fits on a workstation

AWSoM-SWIFT Time Dependent

Time accurate for comparison with OMNI and WSA-ENLIL



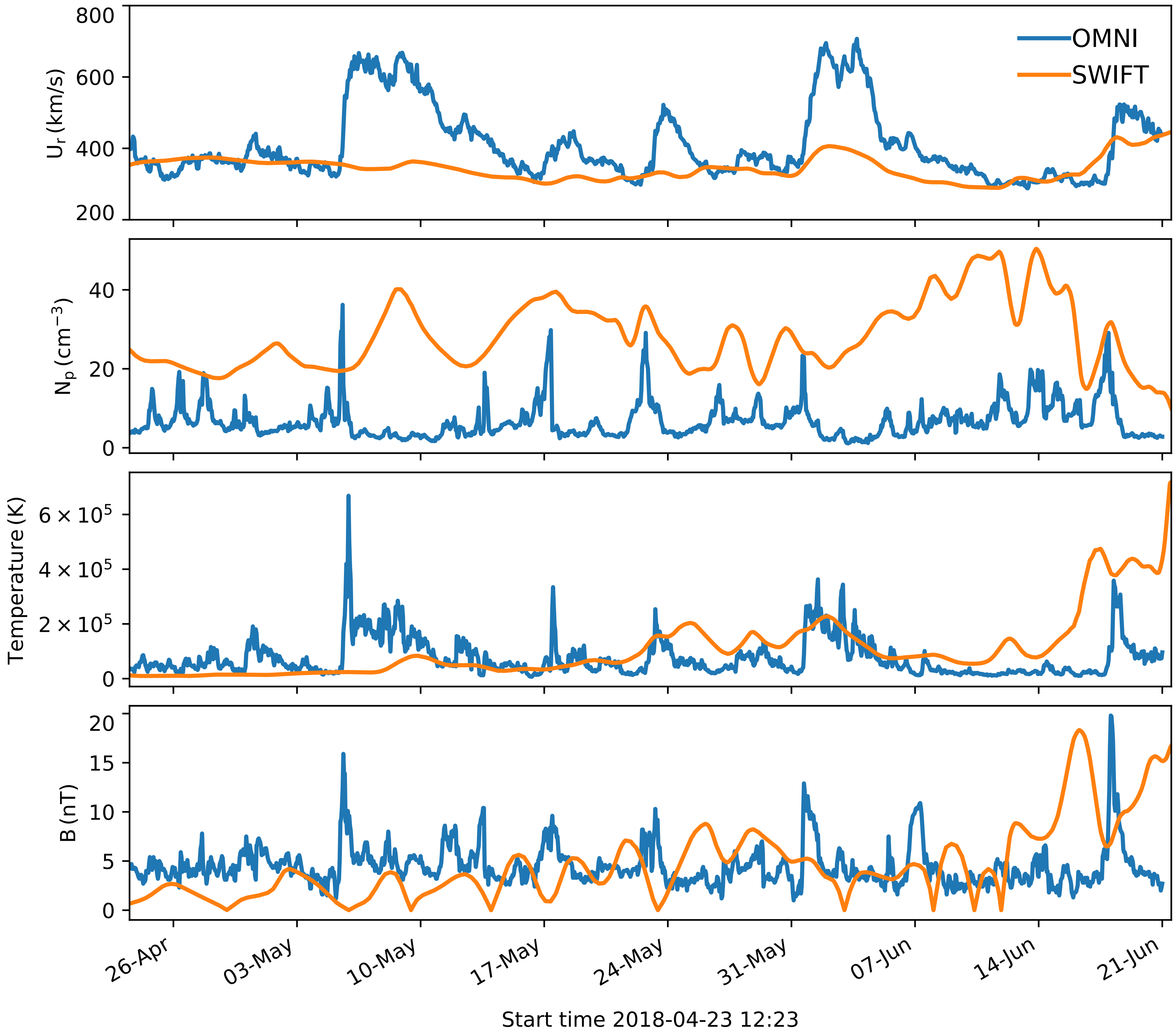
Only at real T_3 can SWIFT time accurate simulations start

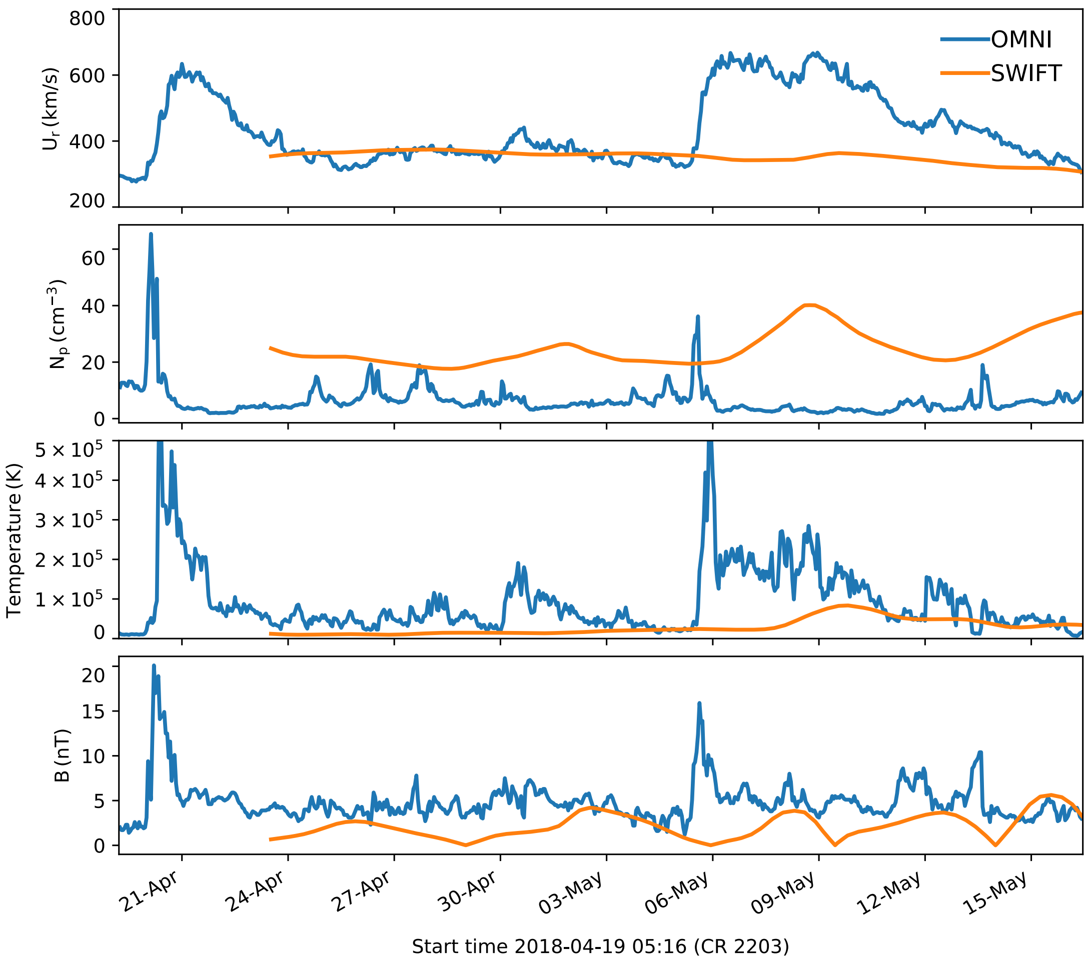
These give time accurate answers from simulation time T_2

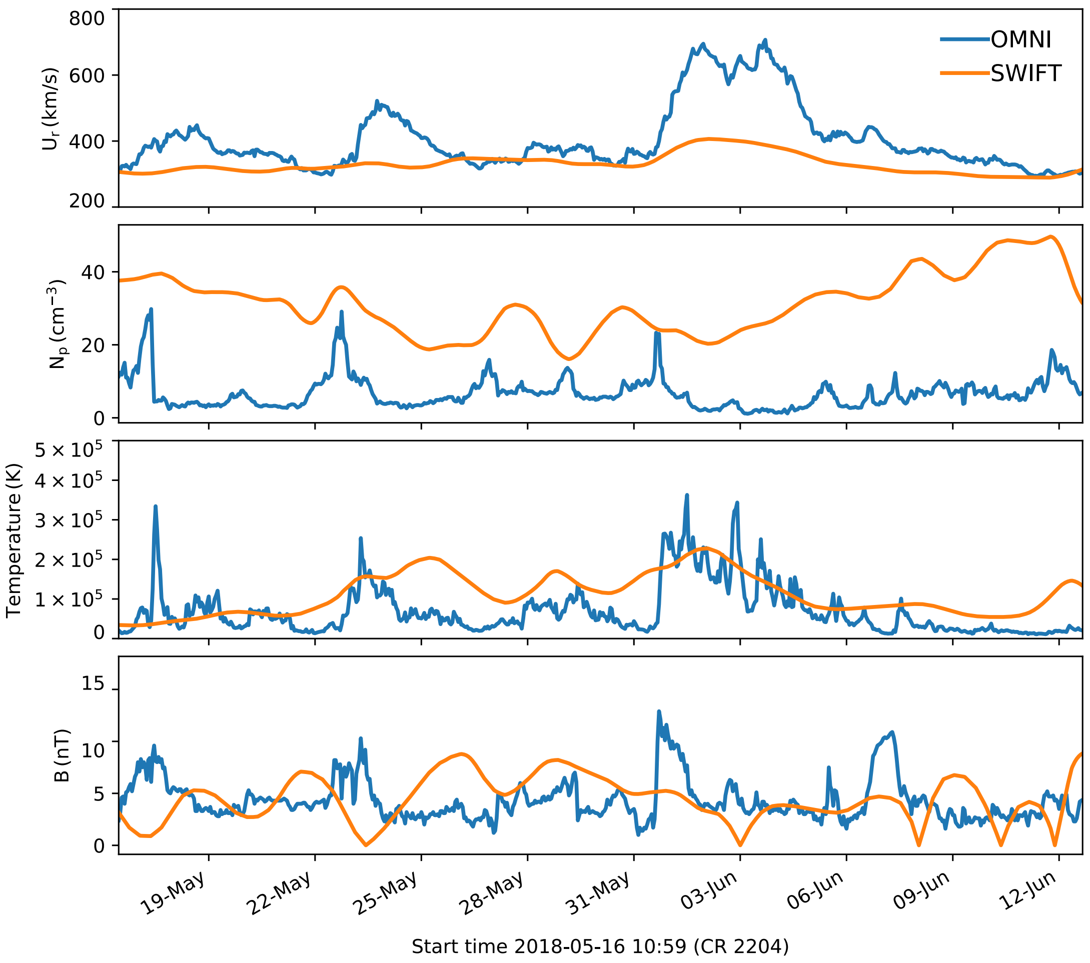
SWIFT simulations fast and continued after T_3 with buffer fixed

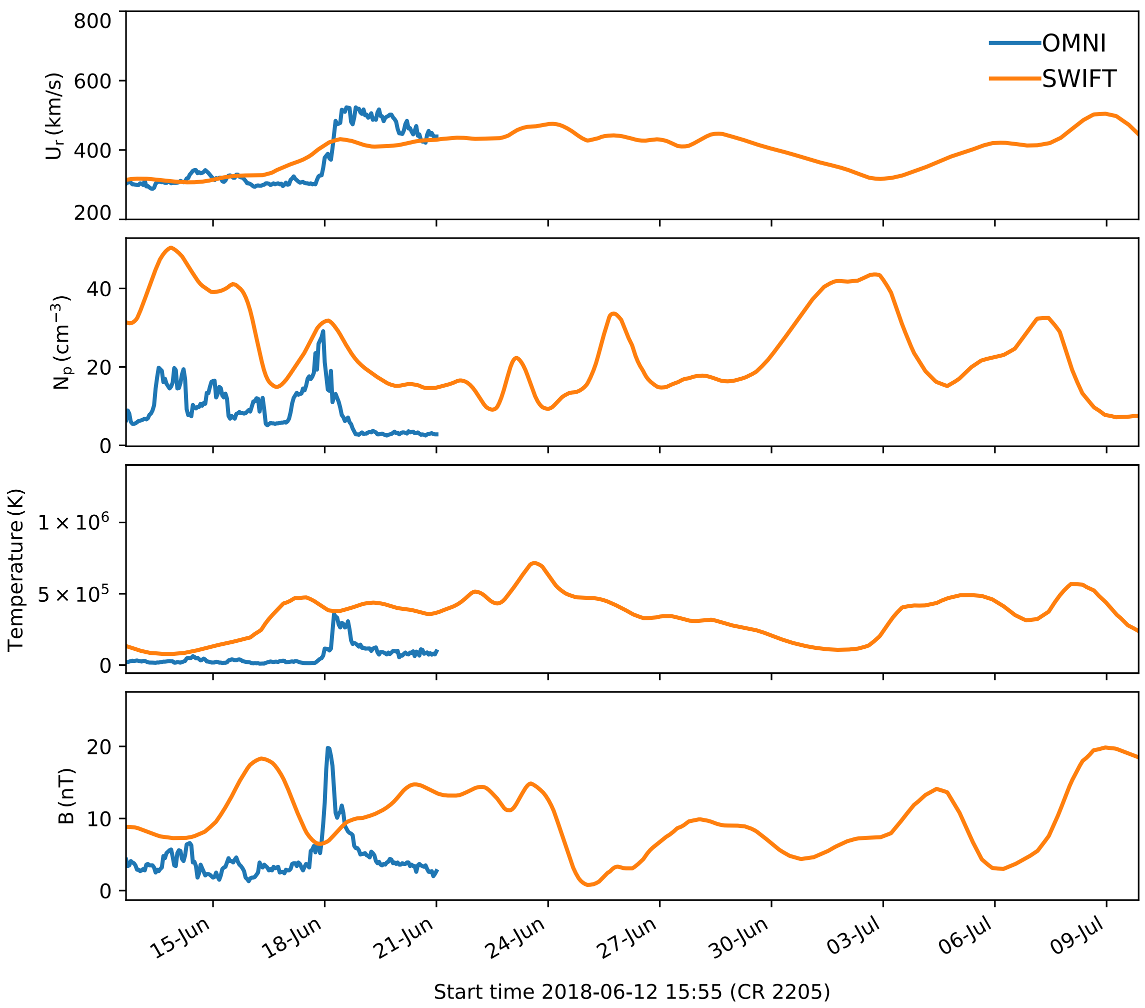
Start a new SWIFT run at T_4 etc.

AWSoM-SWIFT predictions

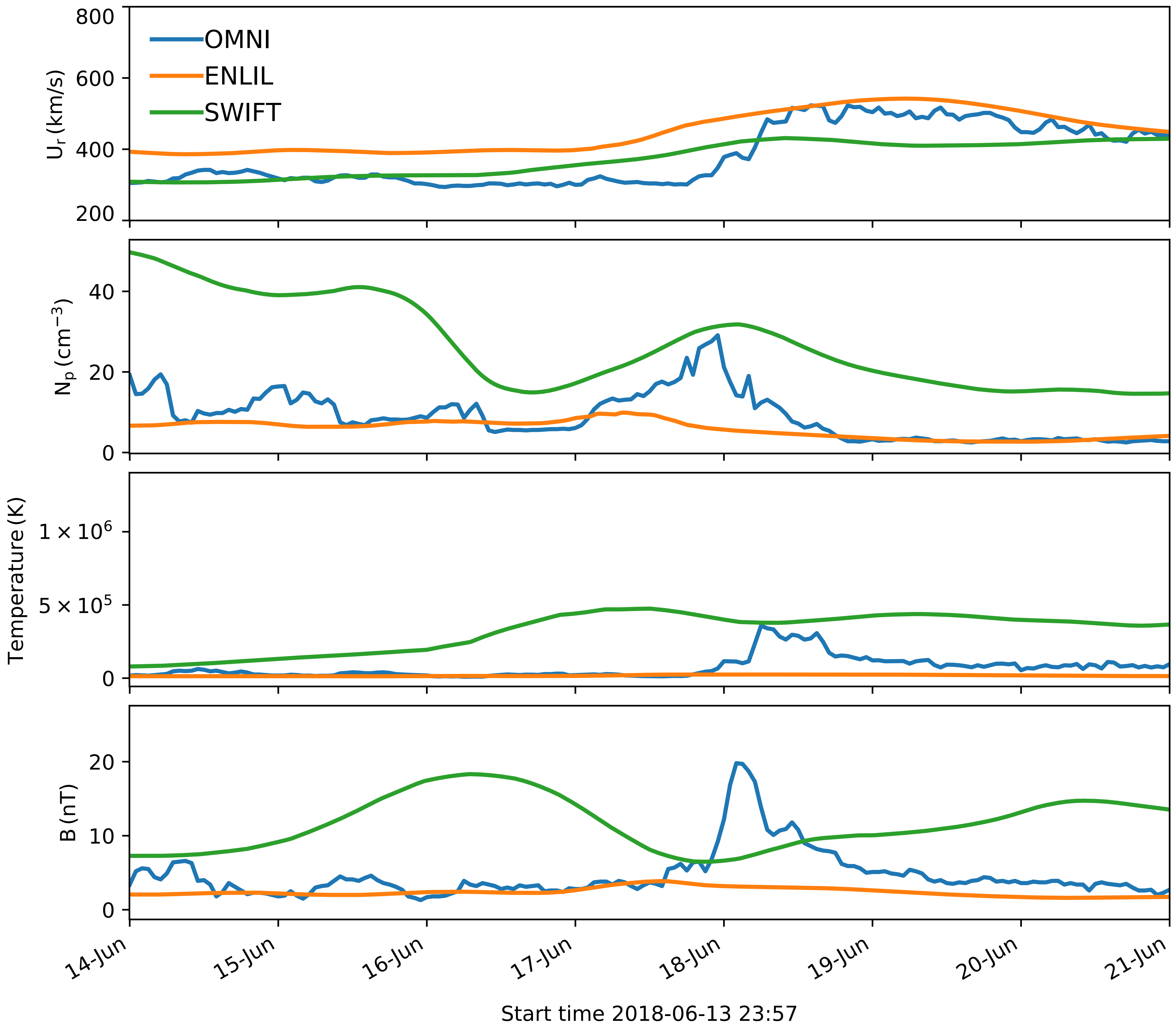



OMNI
SWIFT
U_r (km/s)
200
400
600
800
N_p (cm^{-3})
0
20
40
60
Temperature (K)
0
1×10^5
2×10^5
3×10^5
4×10^5
5×10^5
B (nT)
0
5
10
15
20
21-Apr
24-Apr
27-Apr
30-Apr
03-May
06-May
09-May
12-May
15-May
Start time 2018-04-19 05:16 (CR 2203)

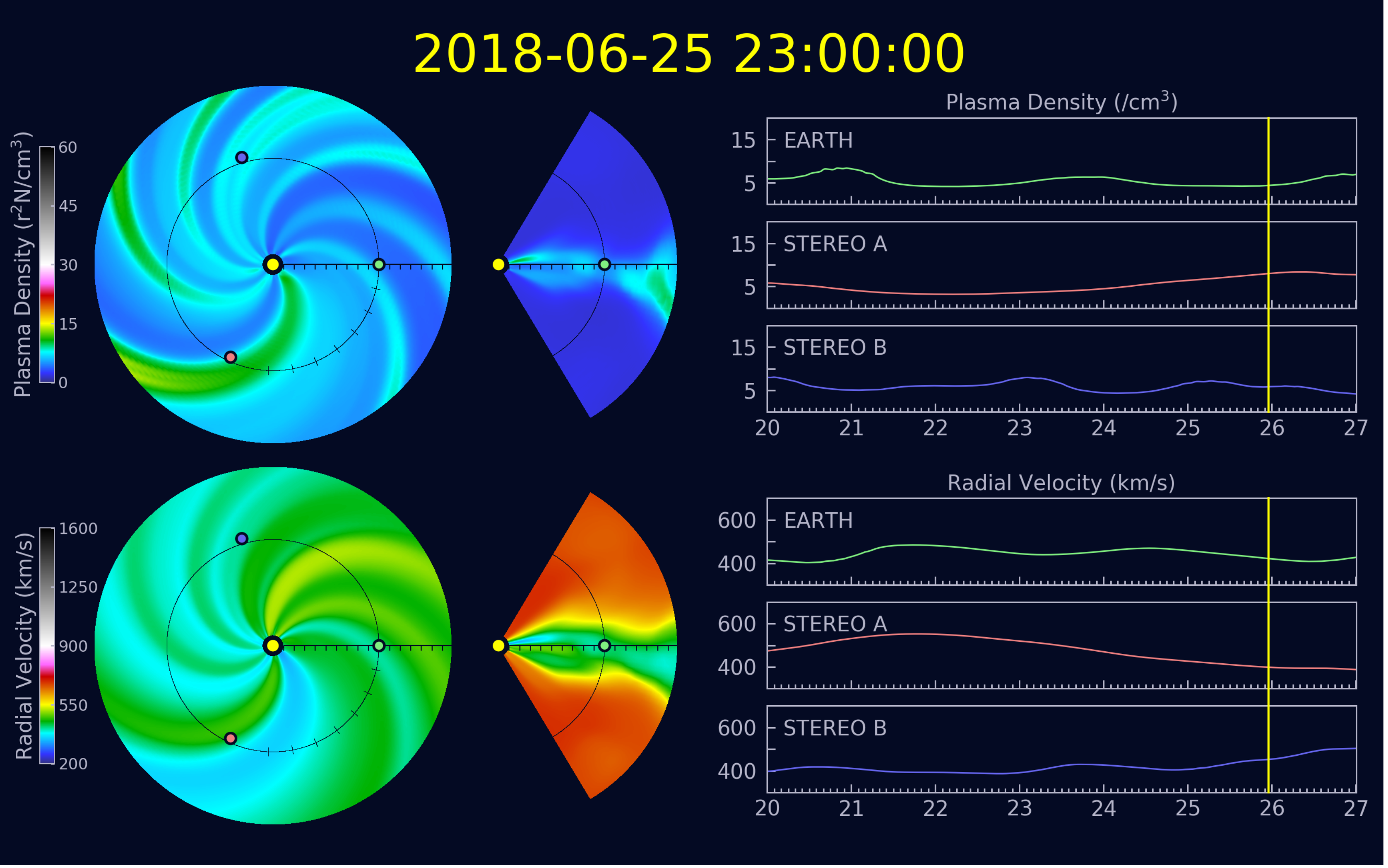

OMNI
SWIFT
U_r (km/s)
200
400
600
800
N_p (cm^{-3})
0
20
40
Temperature (K)
0
1×10^5
2×10^5
3×10^5
4×10^5
5×10^5
B (nT)
0
5
10
15
19-May
22-May
25-May
28-May
31-May
03-Jun
06-Jun
09-Jun
12-Jun
Start time 2018-05-16 10:59 (CR 2204)

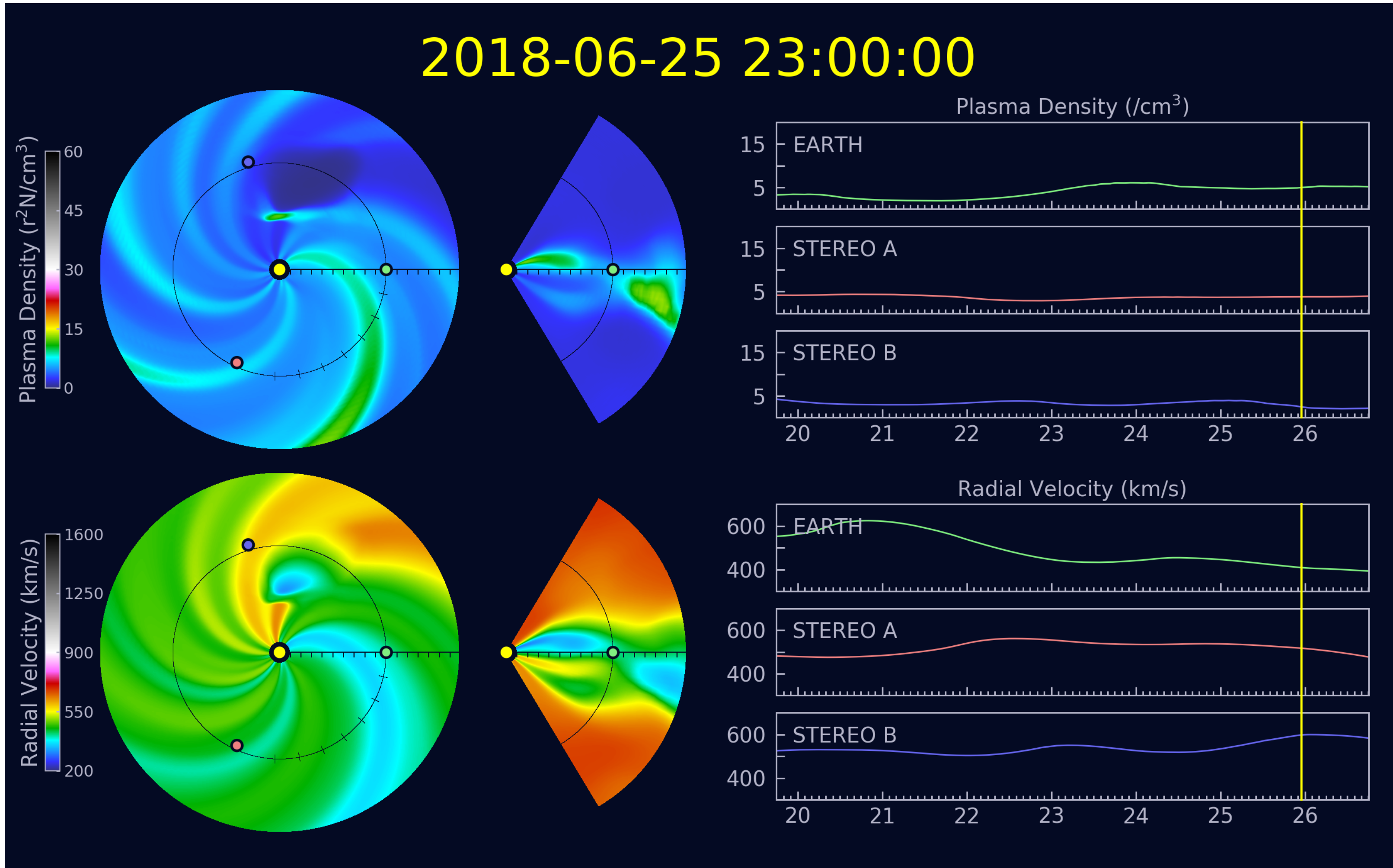

OMNI
SWIFT
U_r (km/s)
200
400
600
800
N_p (cm^{-3})
0
20
40
Temperature (K)
0
5×10^5
1×10^6
B (nT)
0
10
20
15-Jun
18-Jun
21-Jun
24-Jun
27-Jun
30-Jun
03-Jul
06-Jul
09-Jul
Start time 2018-06-12 15:55 (CR 2205)

AWSoM-SWIFT compared to ENLIL



WSA-ENLIL vs WSA_ENLIL Cone





Summary

- AWSoM-SWIFT optimised for full Carrington rotation synoptic GONG magnetograms
- AWSoM speed improved by a factor ~100
- Optimised codes now run on 32 cores in ~12 hours
- Parallel conduction no traceable within fluid model, *ad hoc* limiter chosen over SNB
- Carrington fit ‘good’ but predictions from daily synoptic maps ‘poor’
- Need long time base to test accuracy of predictions cf. WSA-ENLIL but initial visual inspection show neither approach ‘good’ cf. Carrington rotation fits