Applying data assimilation to the solar wind.

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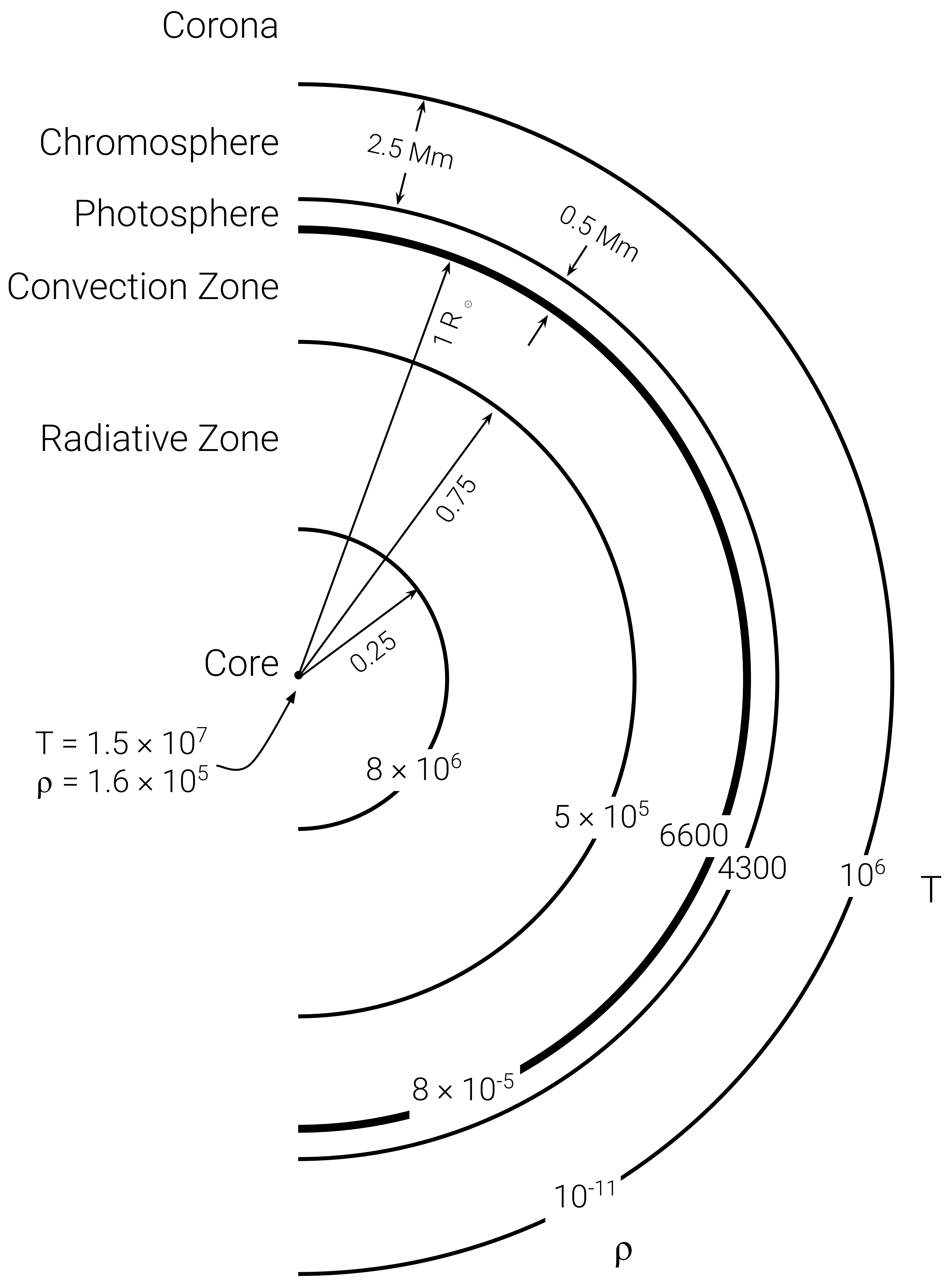
DA training course | 10/06/2025

Introduction and background

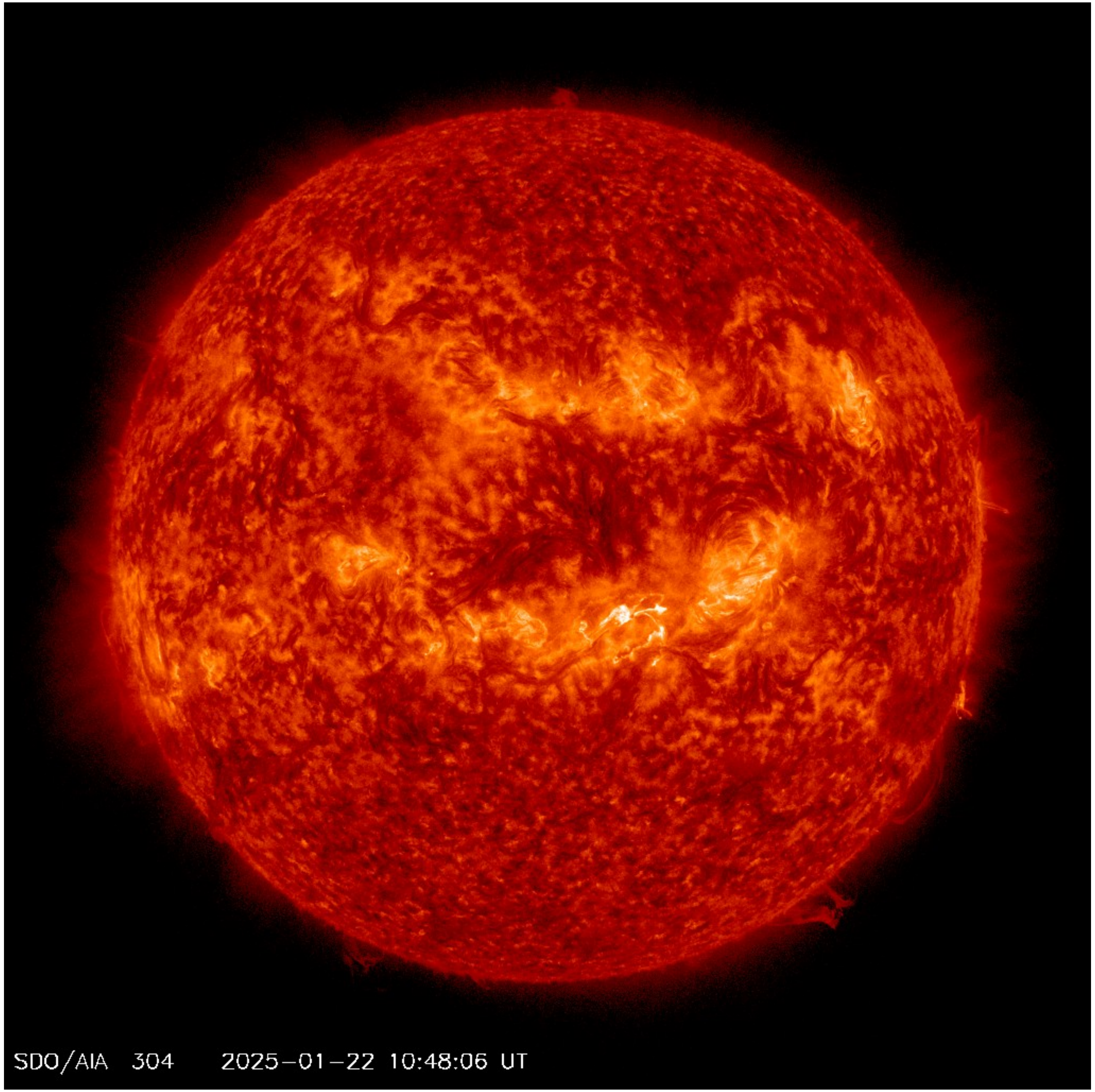
Structure of the Sun

- The Sun is an ordinary star of mass 2.0 x 10^{30} kg and radius 7.0 x 10^{8} m.
- Constructed of plasma.
- Constructed into several layers
  - Solar interior — core, radiative zone, convection zone, photosphere.
  - Solar atmosphere — chromosphere, corona.



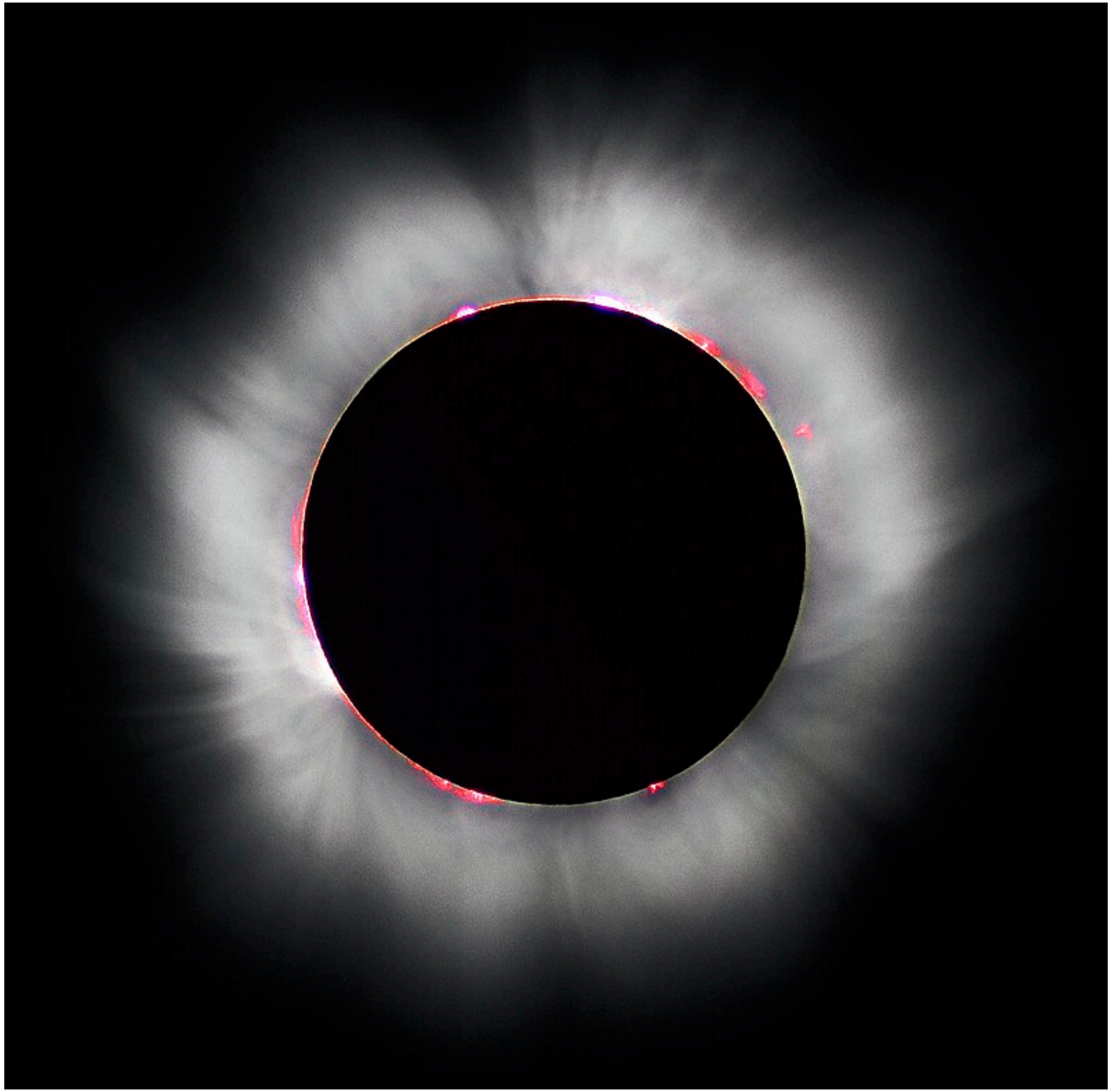
Solar interior

- The solar magnetic field is generated by the motion of plasma in the convection zone.
- The photosphere represents the visible surface of the Sun.
- Almost all the light we receive comes from the photosphere.
- Granular pattern from underlying convection.



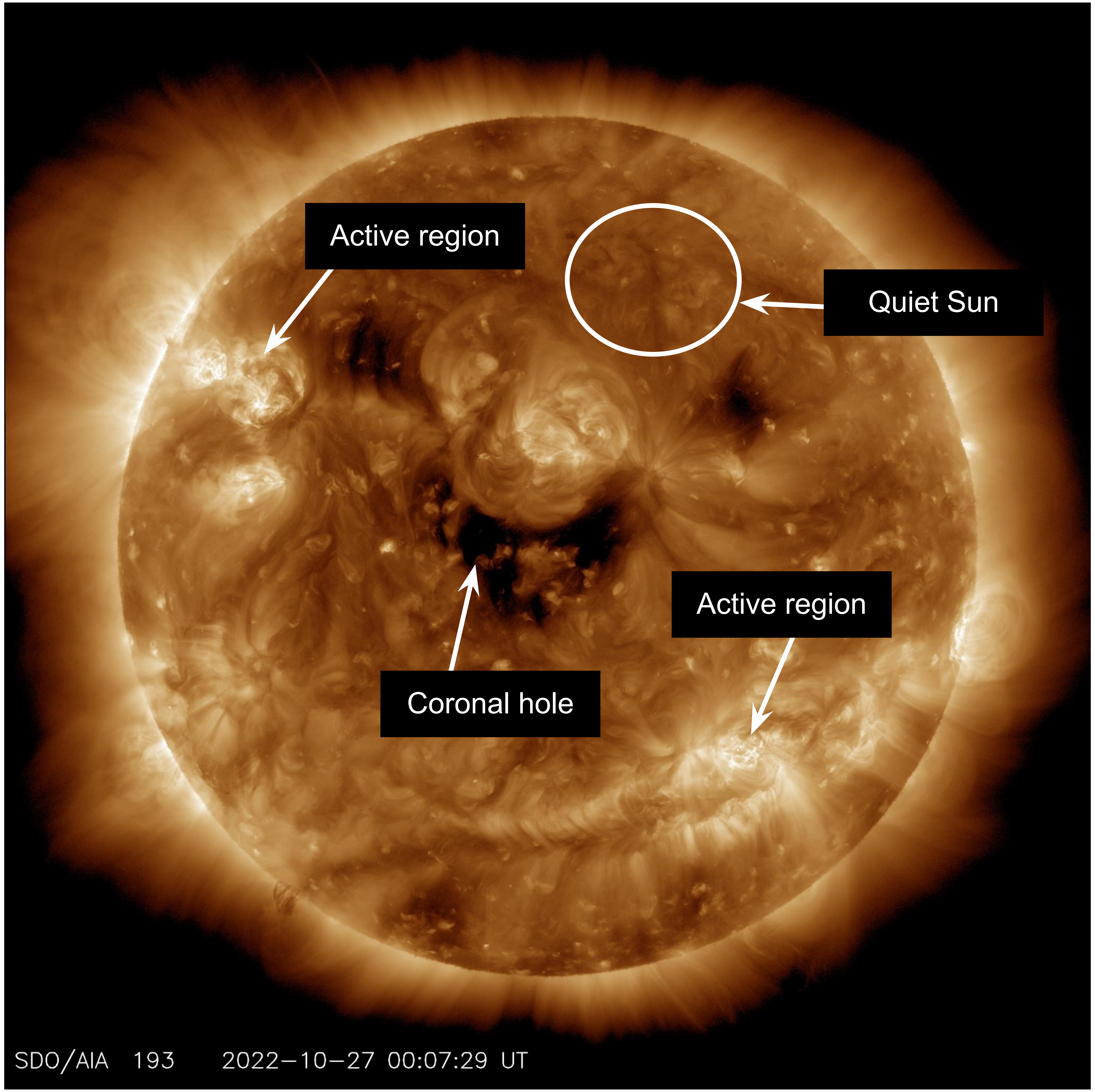
Solar atmosphere

- Temperature *increases* with radius.
- Physical processes behind temperature increase in debated.
- Corona only visible when the light from the photosphere is blocked out, e.g. eclipse or coronagraph.
- Source of the solar wind.



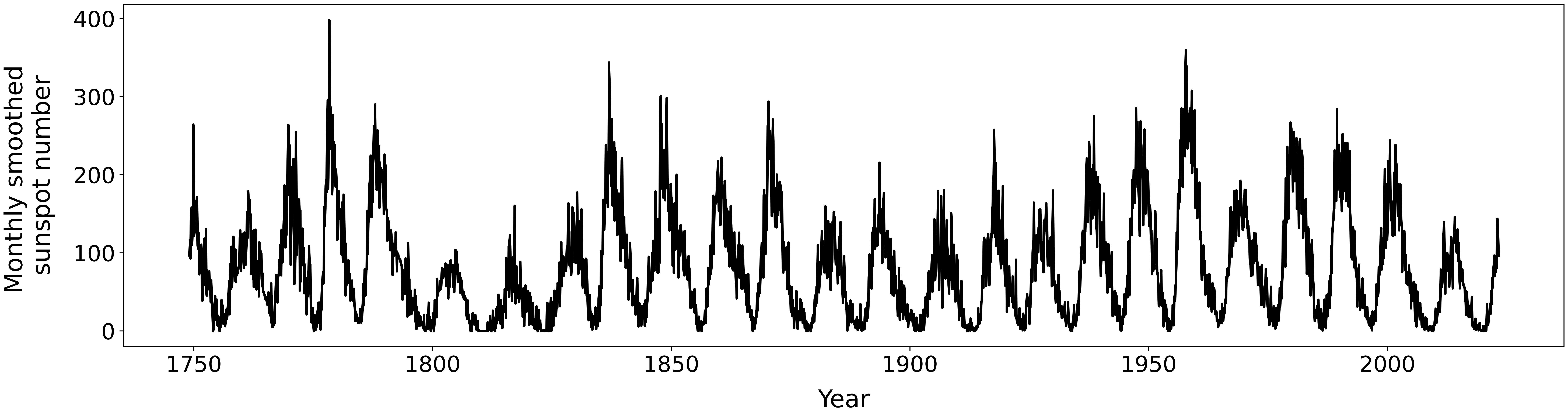
Corona

- Processes dominated by the coronal magnetic field.
- Comprised of open and closed magnetic field.
- Features include active regions and coronal holes.
  - Sunspots underly active regions.
- Structure varies throughout the solar cycle.



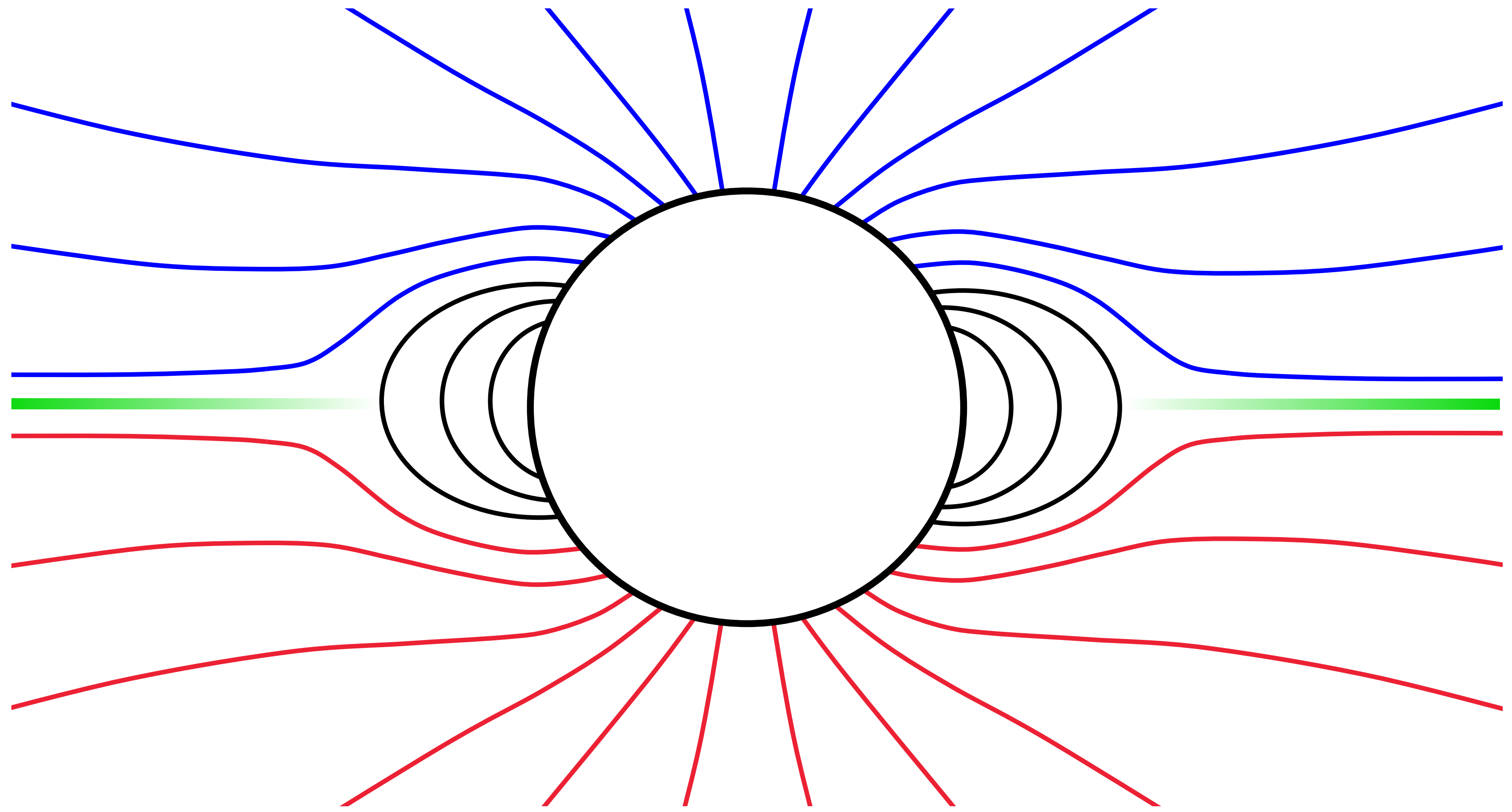
The solar cycle

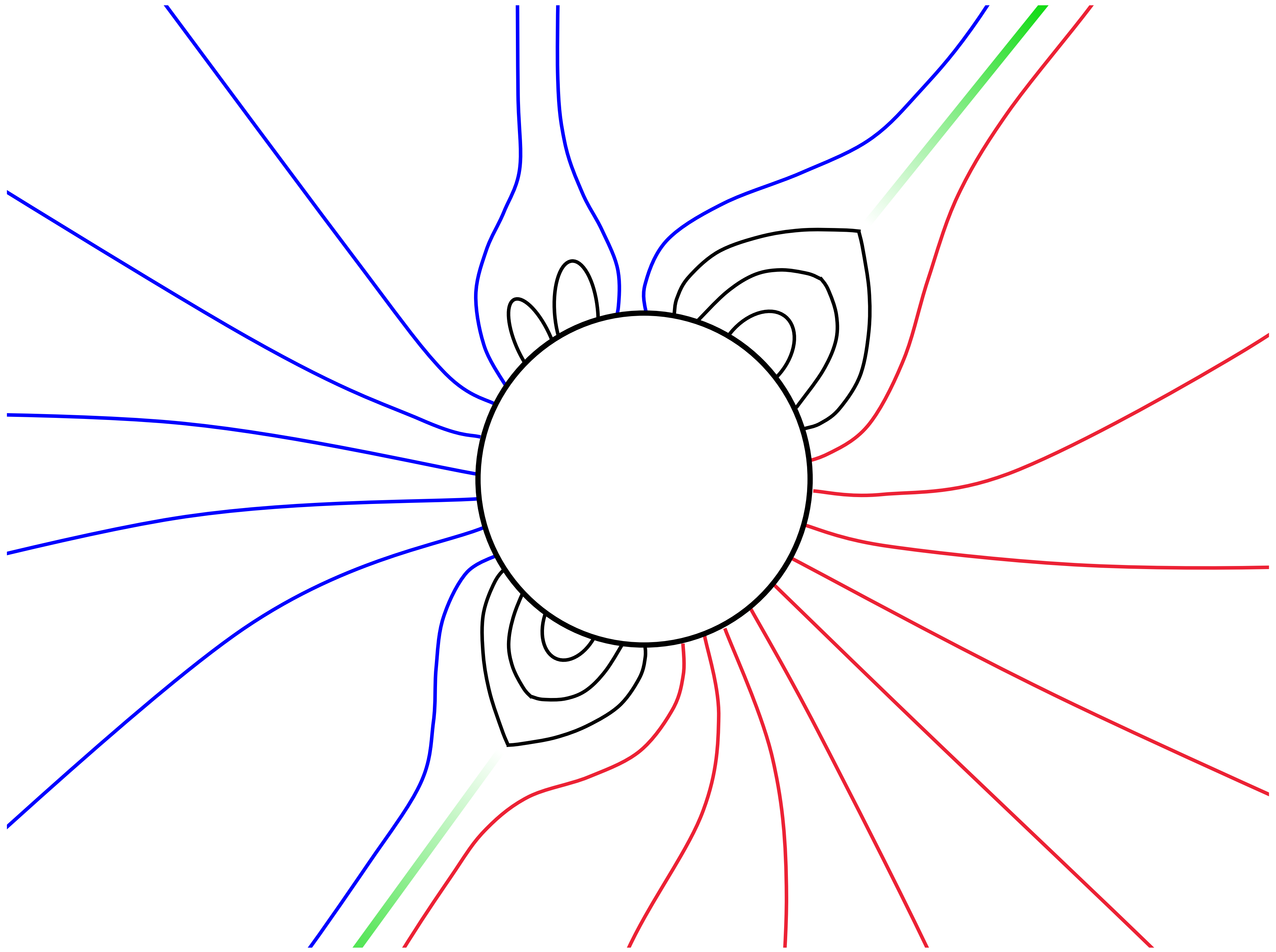
- Approximately 11-year activity cycle.
- Cycle can be monitored through the number of sunspots.
- The magnetic field changes structure throughout the cycle.



Solar magnetic field

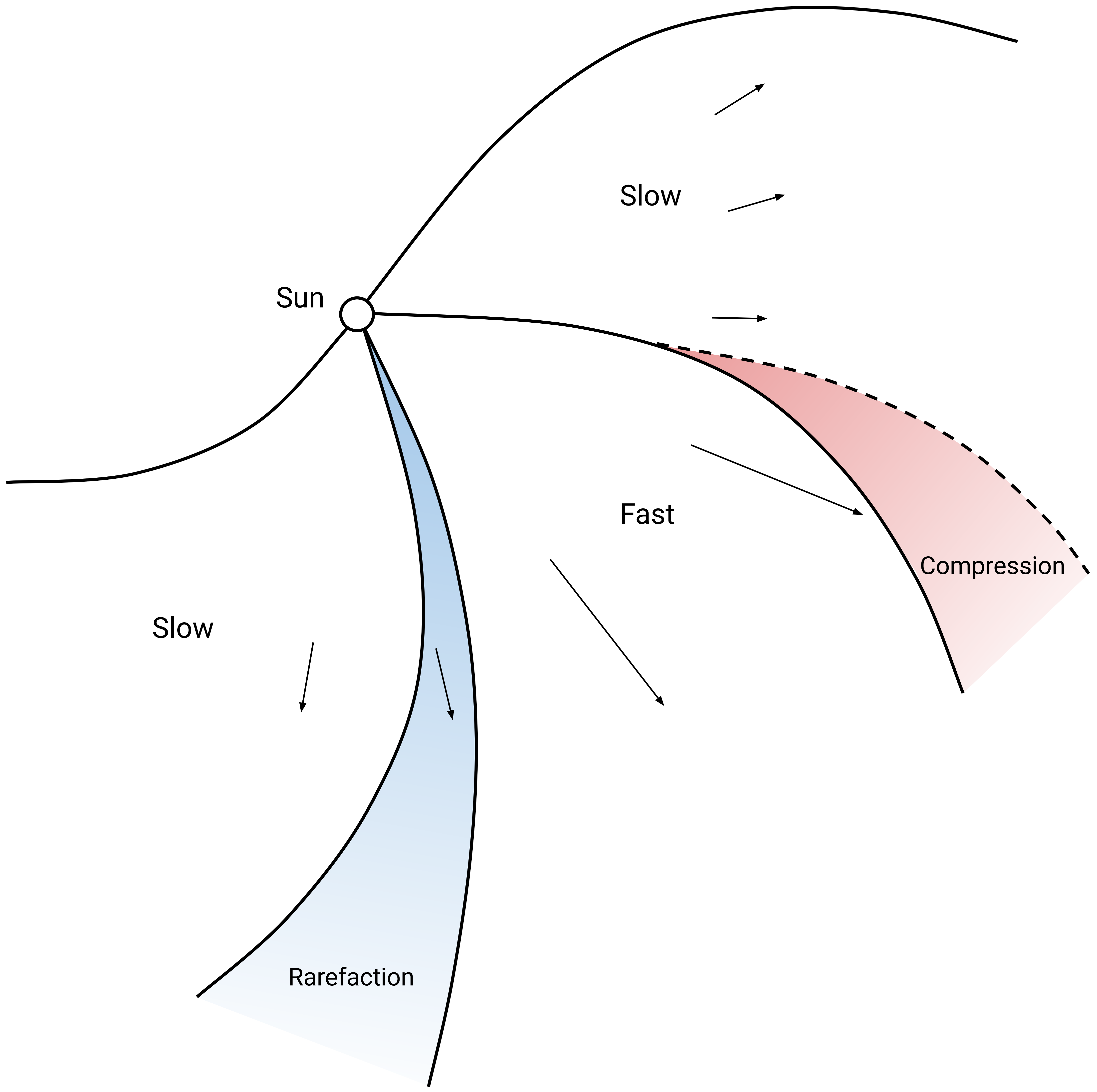
- Solar minimum is approximately dipolar, whereas solar maximum is more dynamic.
- The heliospheric current sheet forms between regions of opposite magnetic polarity.





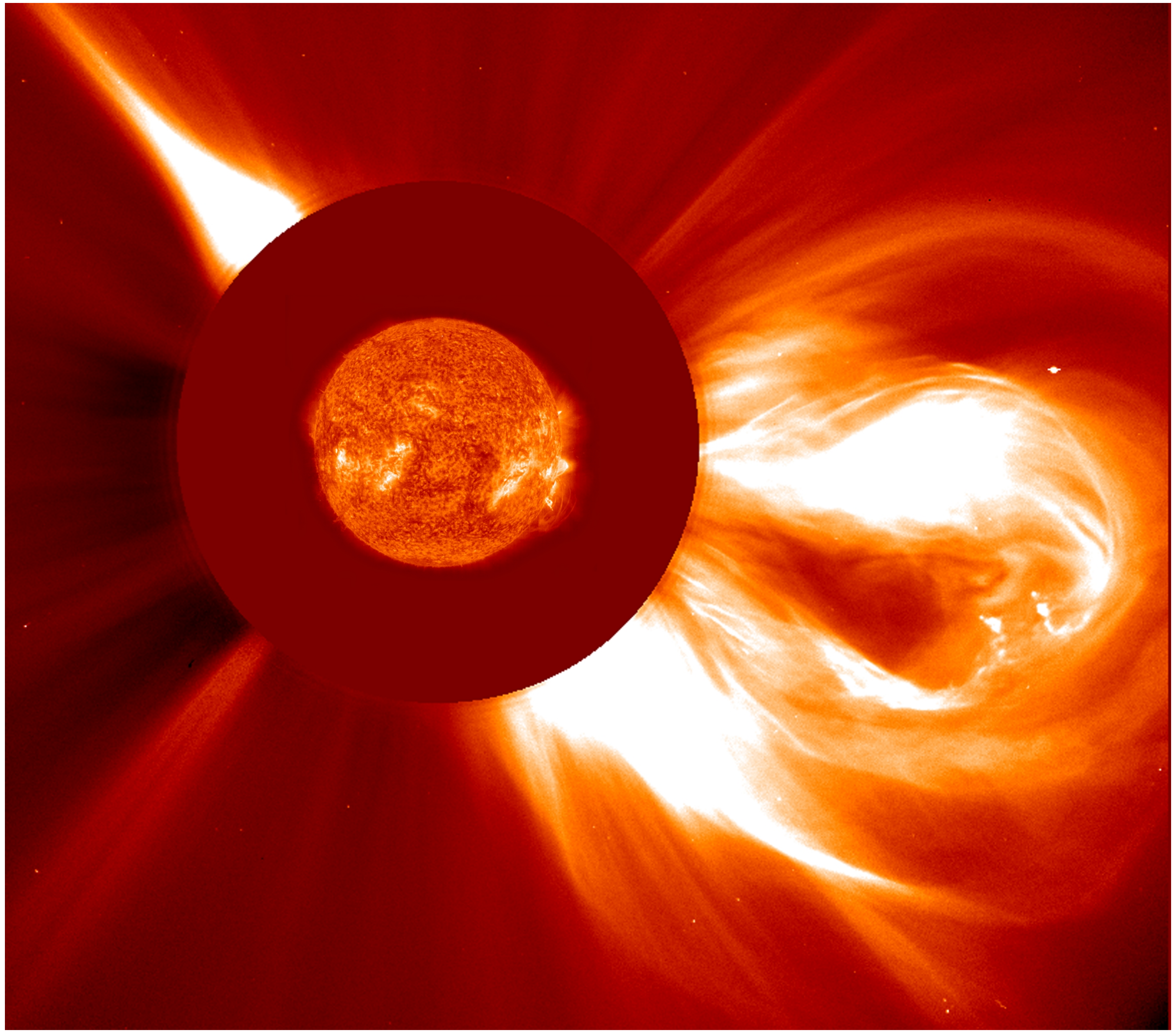
The solar wind

- Constant stream of charged particles that flows into the heliosphere, dragging with it the Sun's magnetic field.
- Fast solar wind emanates from regions of open magnetic field, whereas slow solar wind comes from closed regions.
- Due to the rotation of the Sun, the solar wind forms into a spiral shape, known as the Parker Spiral.



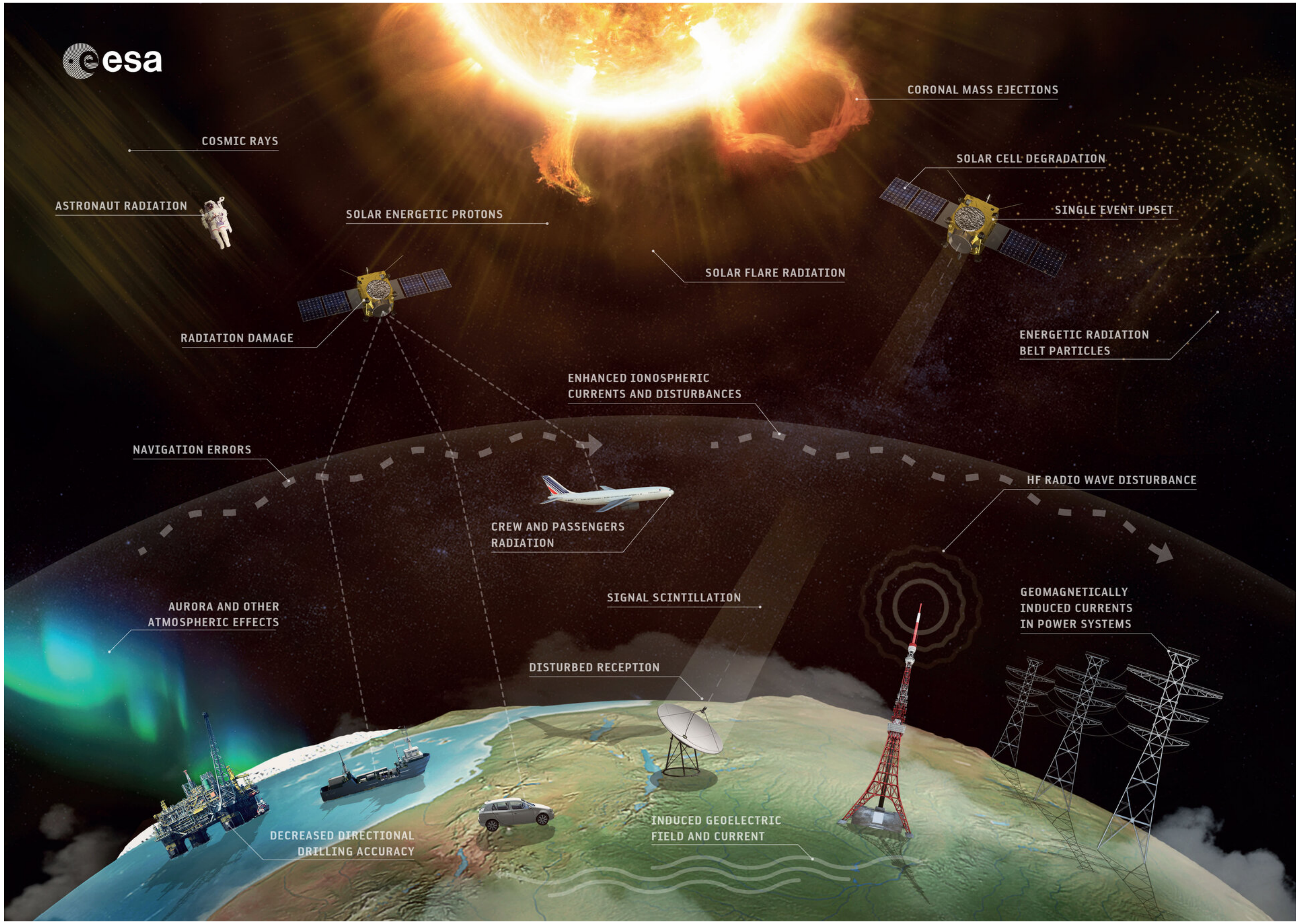
Coronal mass ejections

- Coronal mass ejections (CMEs) are transient eruptions of plasma and magnetic field.
- They propagate through the solar wind, with the background conditions affecting their travel through space.
- Occurrence rate varies with the solar cycle.



Space weather impacts

- Space weather refers to the changing plasma conditions in near-Earth space.
- CMEs are a cause of severe space weather.



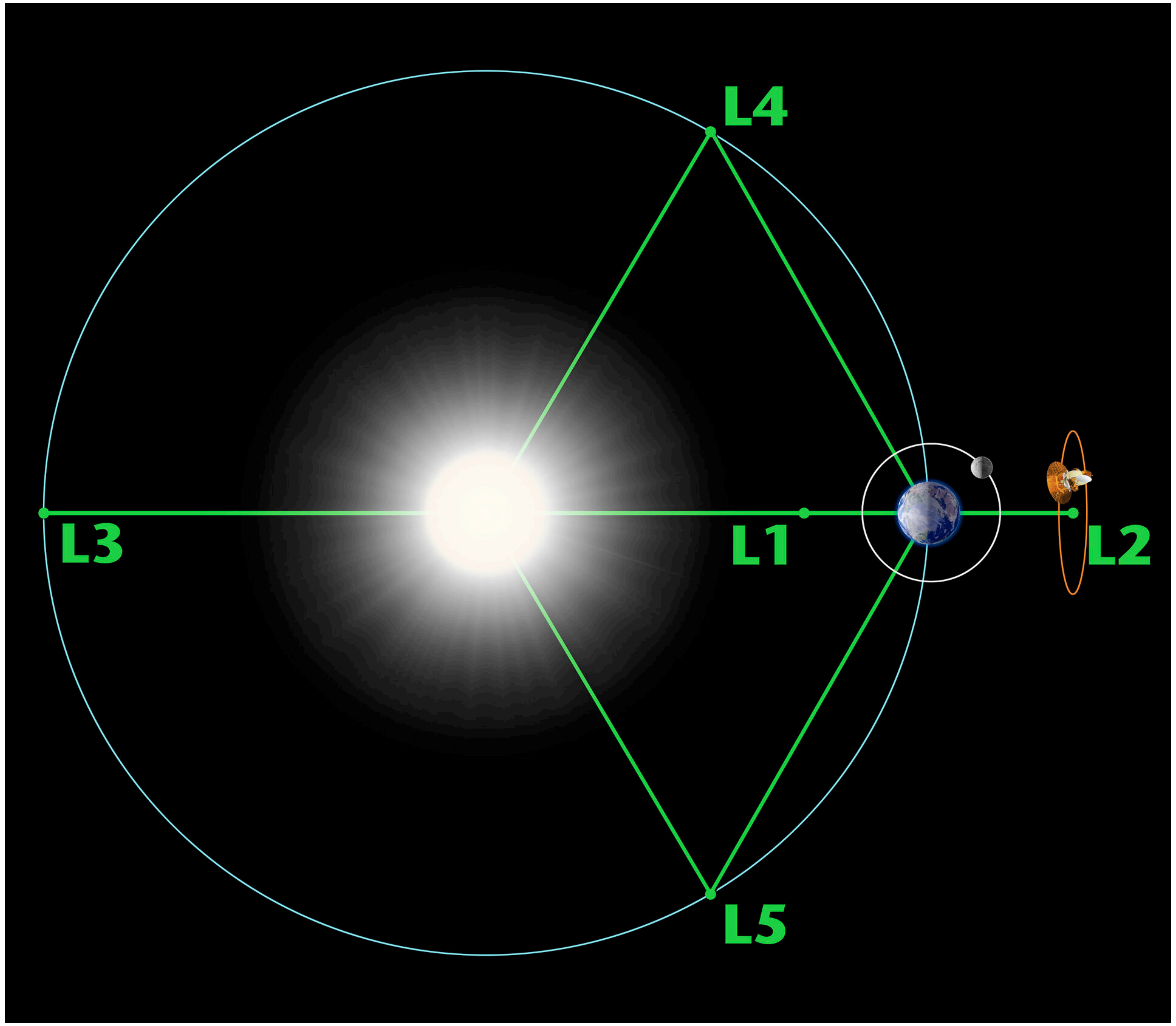
11^{th} May 2024

Hound Tor, Dartmoor

Methodology

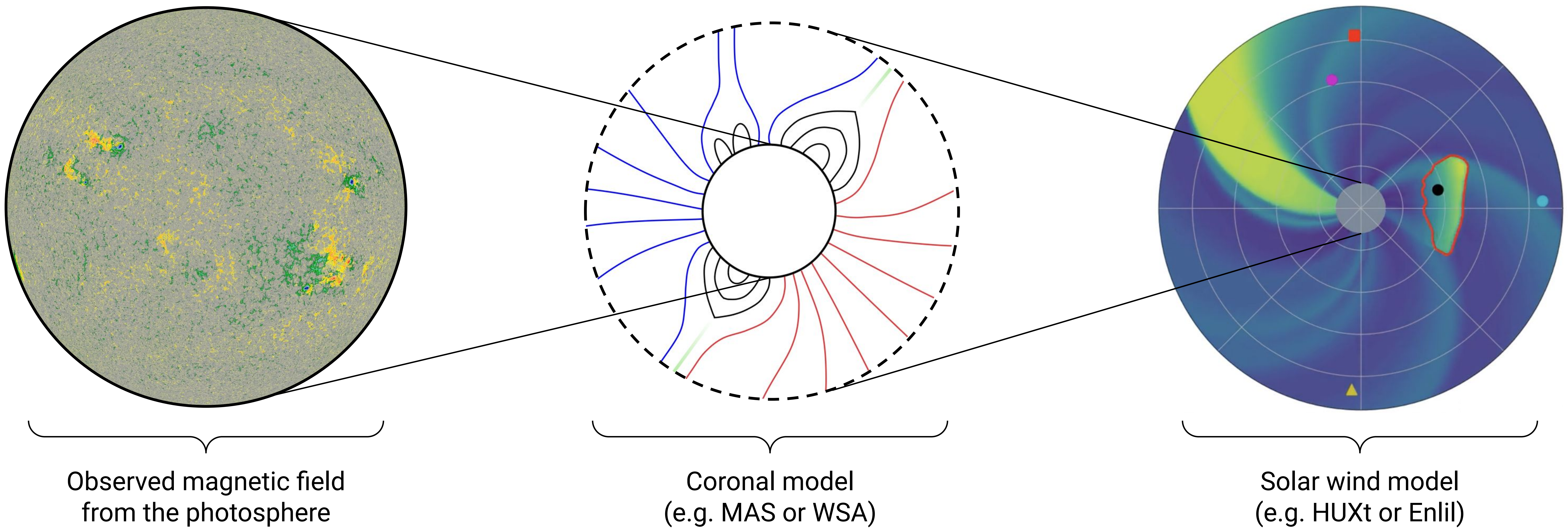
Spacecraft missions

- STEREO — twin spacecraft mission, orbiting at ~Earth's radial distance.
- ACE & DSCOVR — in the L1 position.



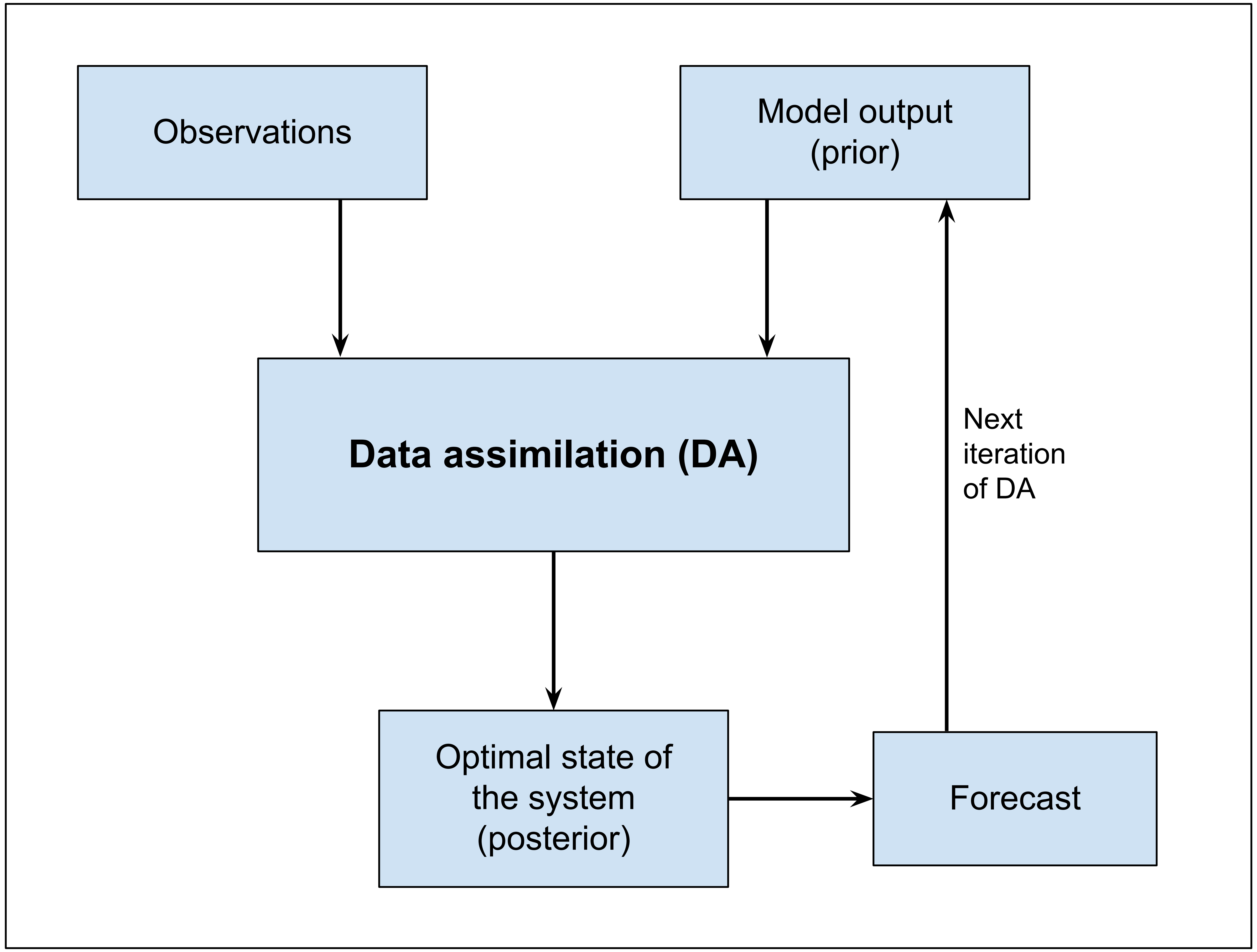
Current solar wind forecasting

- Coupled coronal model and solar wind model, initiated with observations of the photospheric magnetic field.
- The solar wind model can be a full physics-based model (e.g. Enlil) or a reduced-physics model such as HUX/ HUXt.



Data assimilation

- DA is a technique that has led to large forecast improvements in terrestrial weather forecasting.
- It combines observations and model output to form an optimum estimation of reality.
- It has been underused in space weather forecasting.

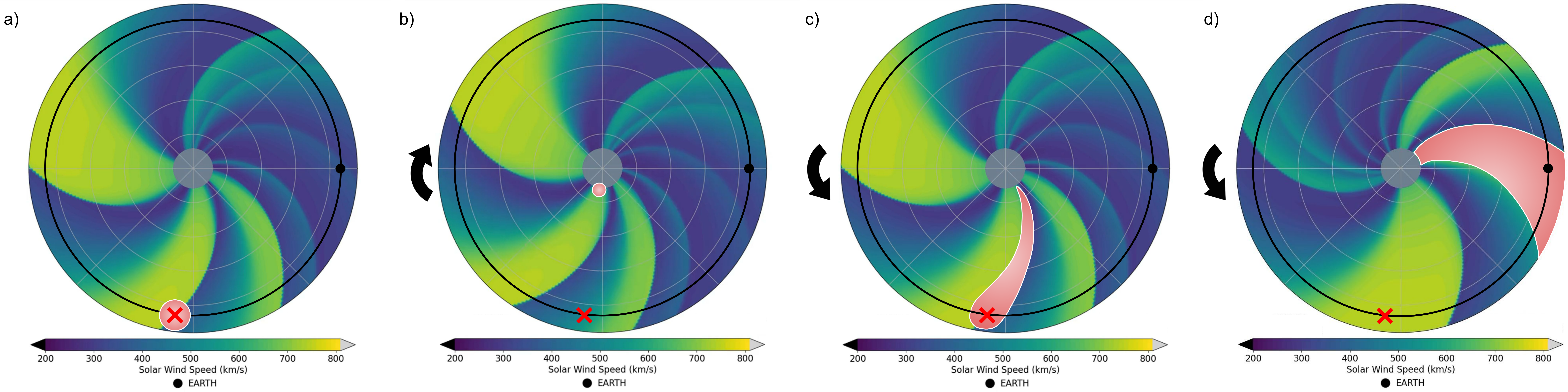


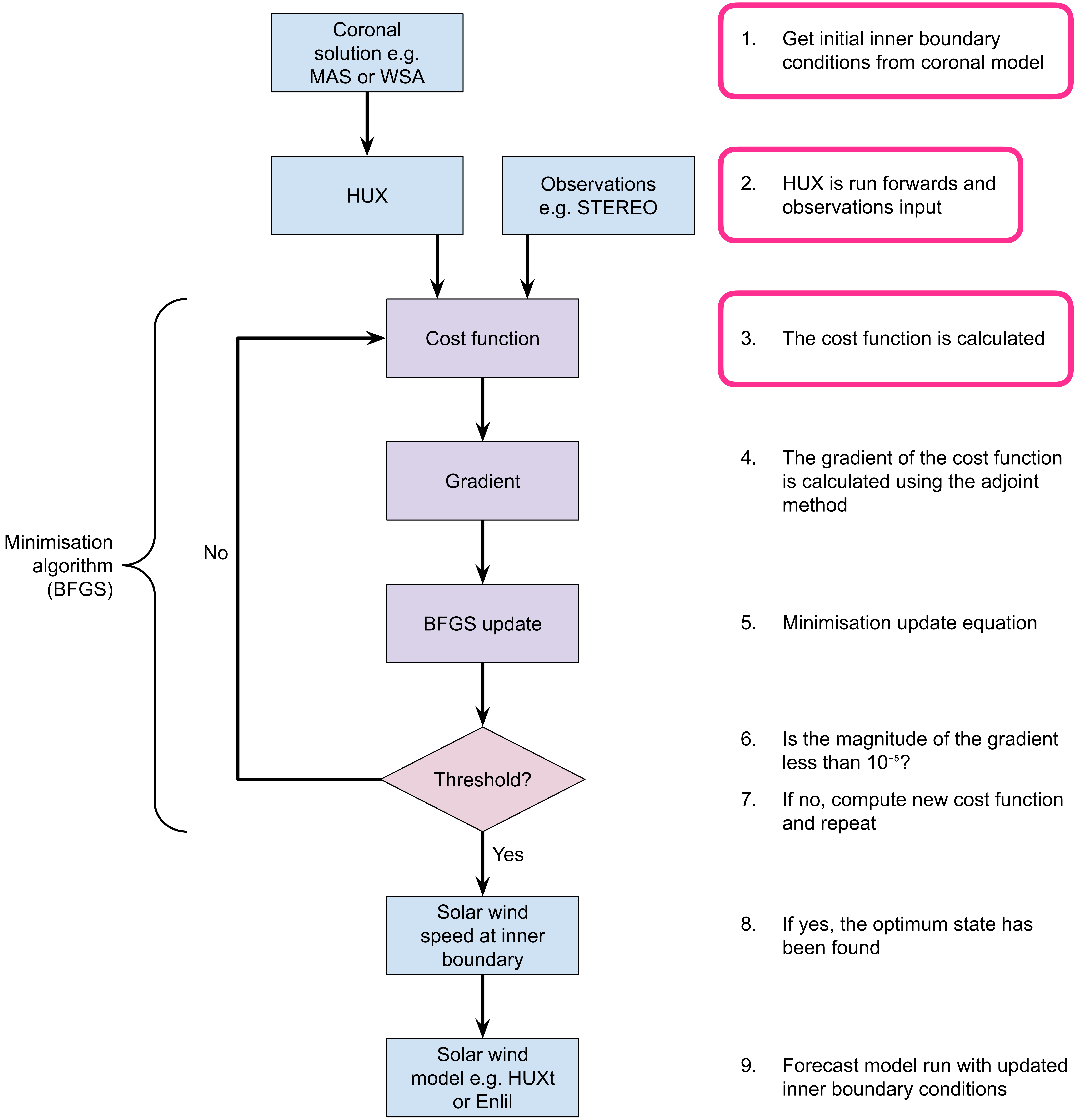
BRaVDA scheme

Burger Radius Variational Data Assimilation

- 4D-Var data assimilation scheme, using the adjoint method to assimilate observations from close to Earth's latitude with the HUX model.

- Information from the observations is used to update the initial conditions of the solar wind model.



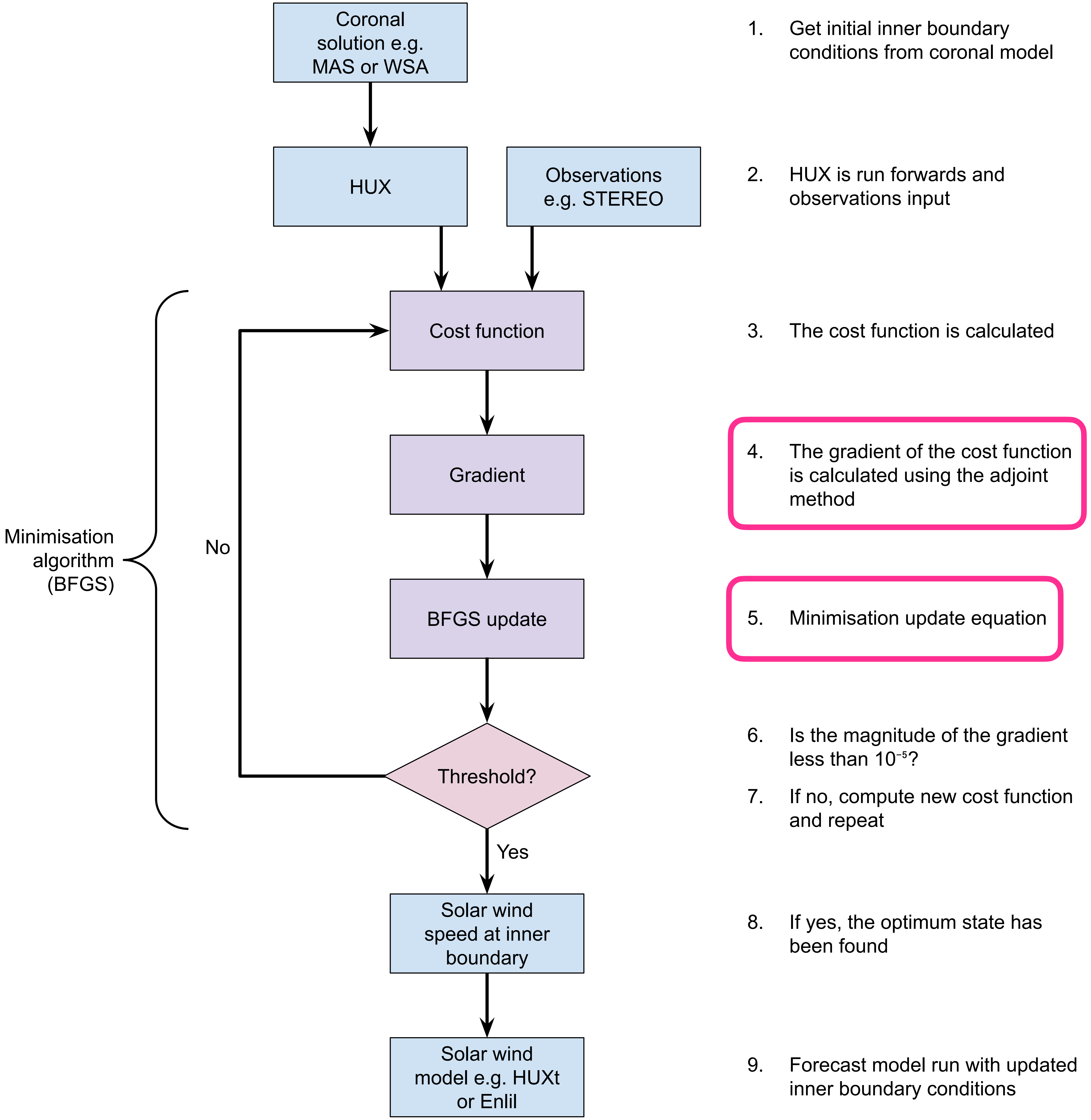

Coronal solution e.g. MAS or WSA
HUX
Observations e.g. STEREO
Cost function
Gradient
BFGS update
Threshold?
No
Yes
Minimisation algorithm (BFGS)
Solar wind speed at inner boundary
Solar wind model e.g. HUXt or Enlil
1. Get initial inner boundary conditions from coronal model
2. HUX is run forwards and observations input
3. The cost function is calculated
4. The gradient of the cost function is calculated using the adjoint method
5. Minimisation update equation
6. Is the magnitude of the gradient less than 10^{-5}?
7. If no, compute new cost function and repeat
8. If yes, the optimum state has been found
9. Forecast model run with updated inner boundary conditions

$$\mathcal{J}(\mathbf{x}) = \boxed{\frac{1}{2}\left(\mathbf{x_0} - \mathbf{x_0^b}\right)^T \mathbf{B_0^{-1}} \left(\mathbf{x_0} - \mathbf{x_0^b}\right)} + \boxed{\frac{1}{2}\sum_{i=1}^{N}\left(\mathbf{y_i} - \mathcal{H}_i(\mathbf{x_i})\right)^T \mathbf{R_i}^{-1}\left(\mathbf{y_i} - \mathcal{H}_i(\mathbf{x_i})\right)}$$

Minimise!

Error contribution from the prior state

Error contribution from the observations



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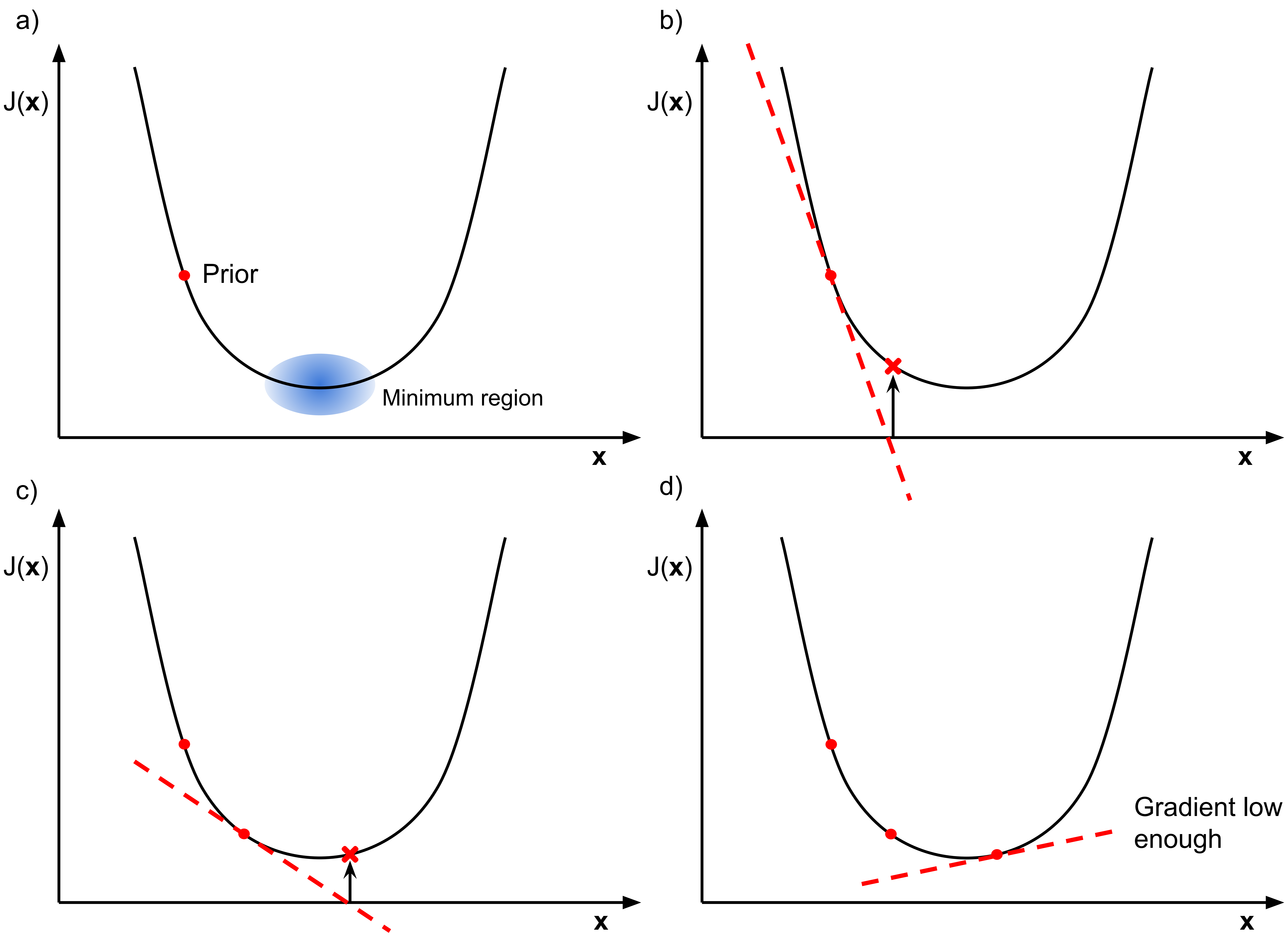
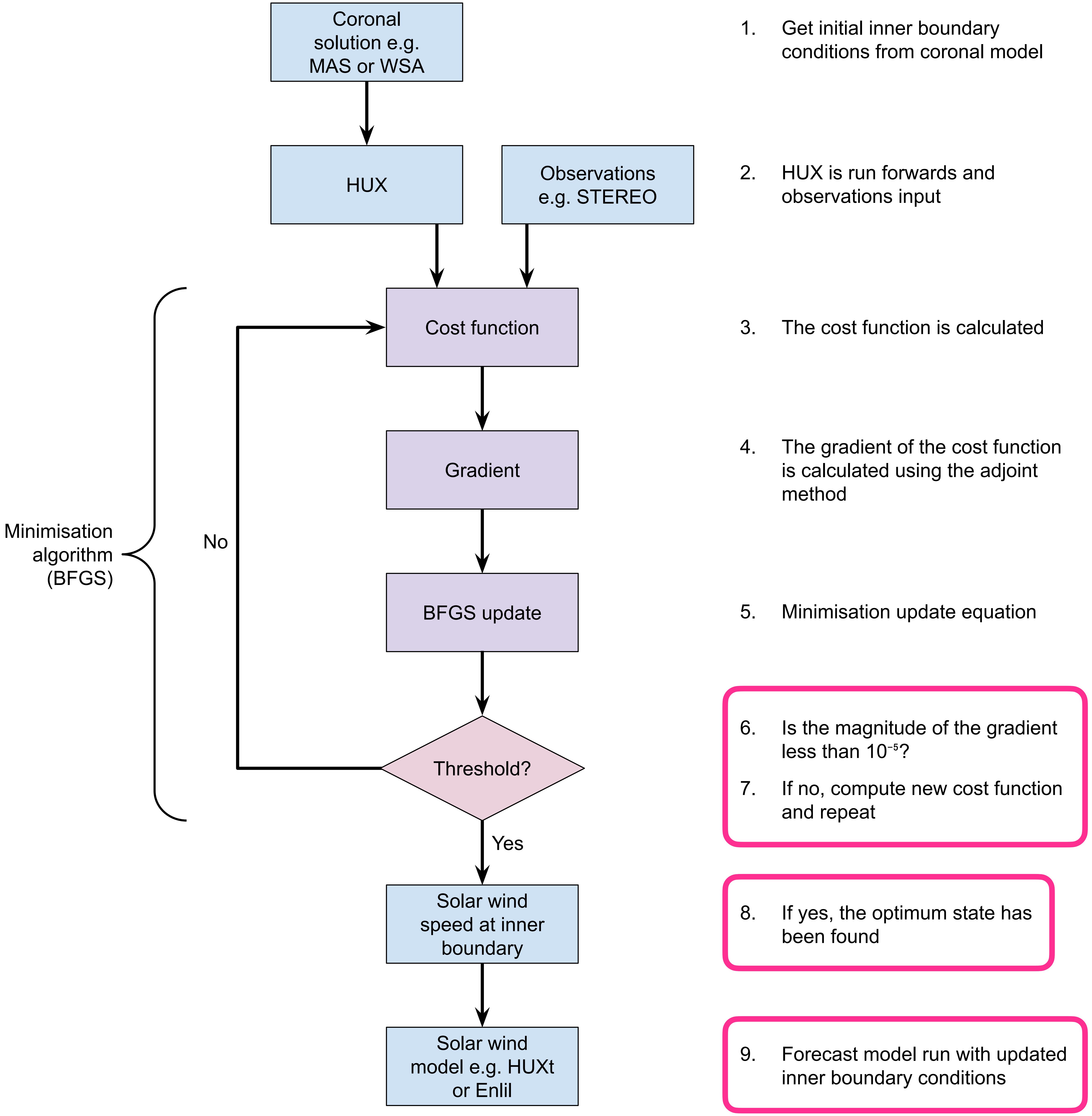
Minimisation algorithm

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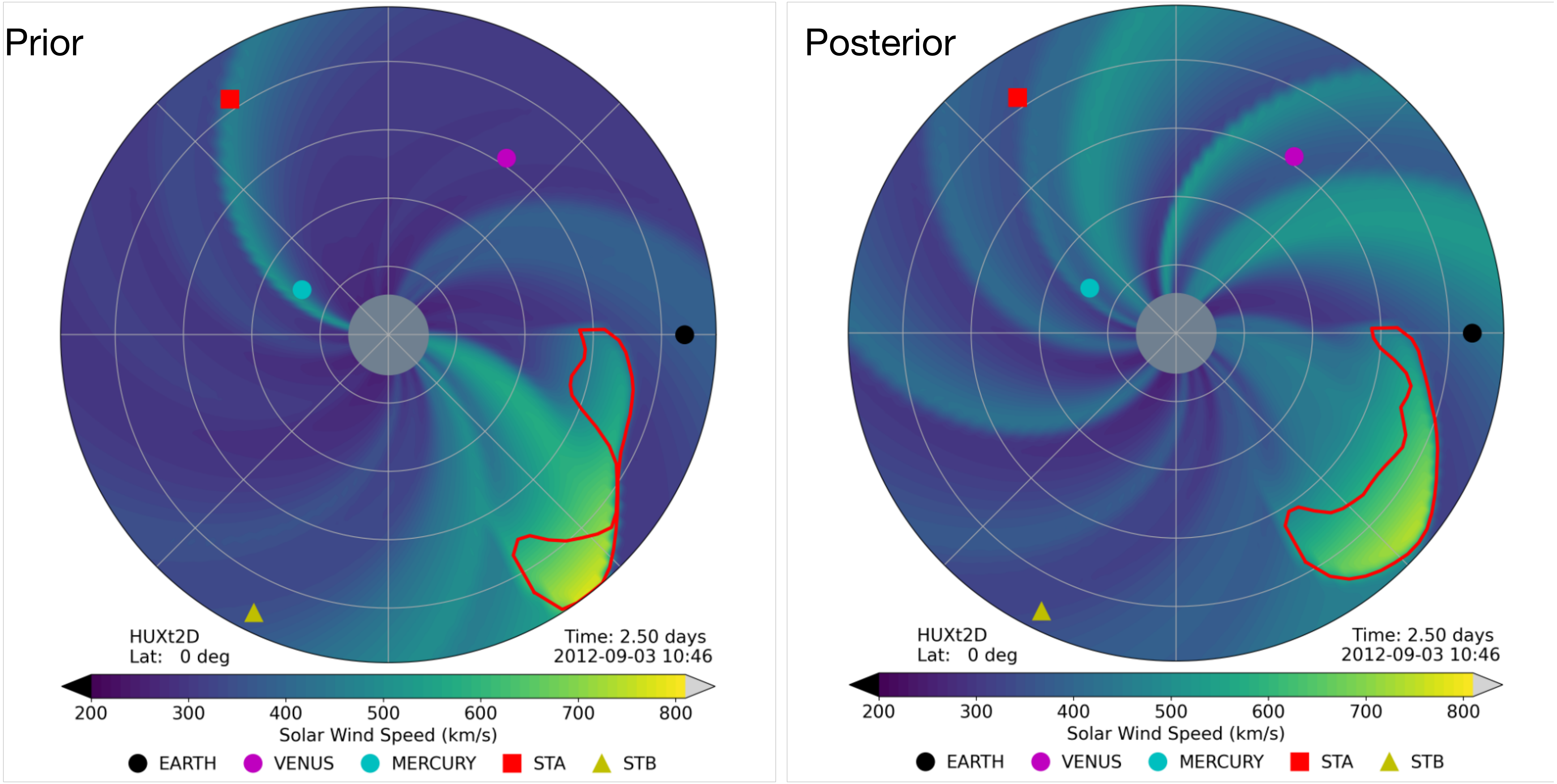
The ultimate aim is to improve CME forecasts.

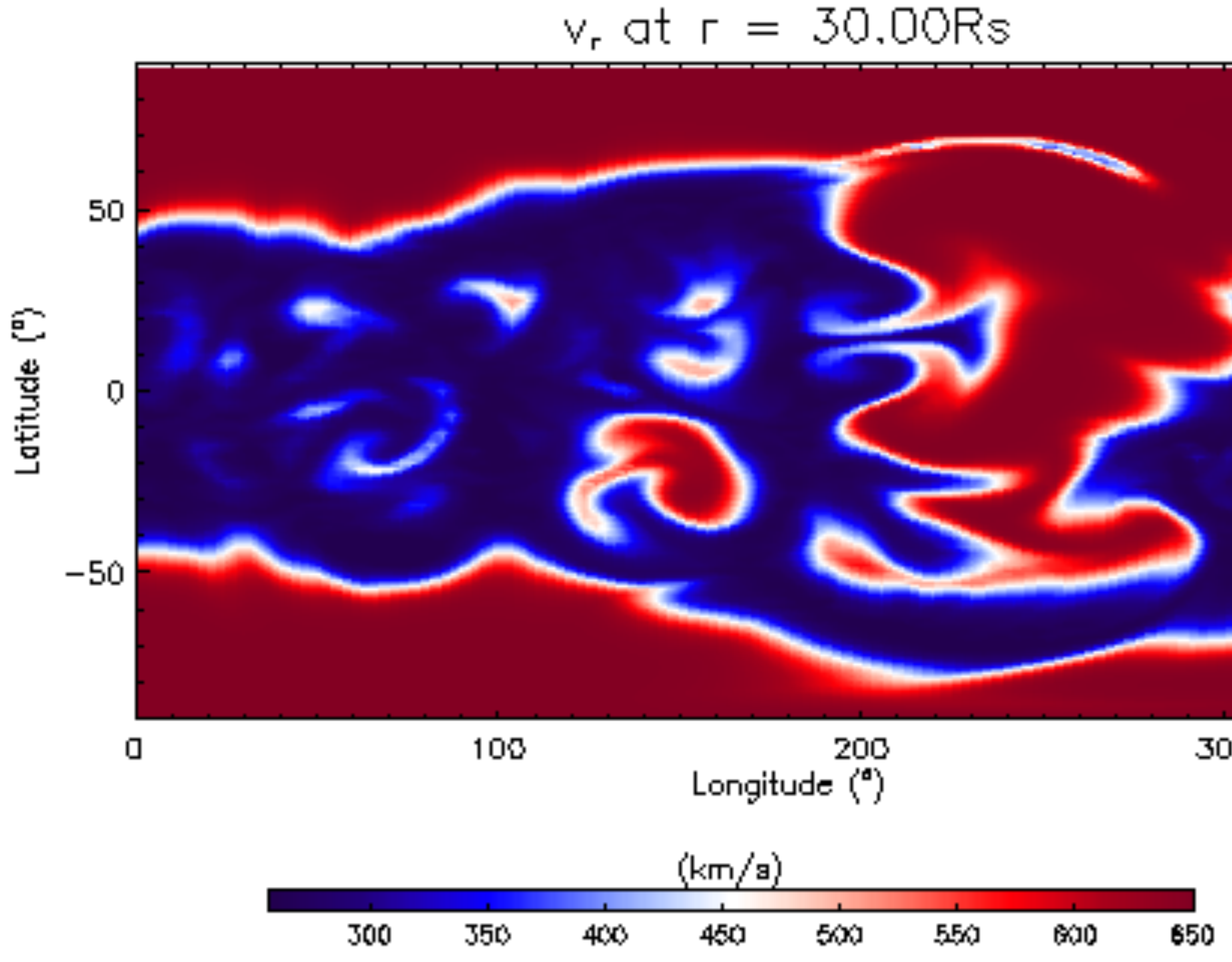


Prior
HUXt2D
Lat: 0 deg
Time: 2.50 days
2012-09-03 10:46
200
300
400
500
600
700
800
Solar Wind Speed (km/s)
EARTH
VENUS
MERCURY
STA
STB
Posterior
HUXt2D
Lat: 0 deg
Time: 2.50 days
2012-09-03 10:46
200
300
400
500
600
700
800
Solar Wind Speed (km/s)
EARTH
VENUS
MERCURY
STA
STB

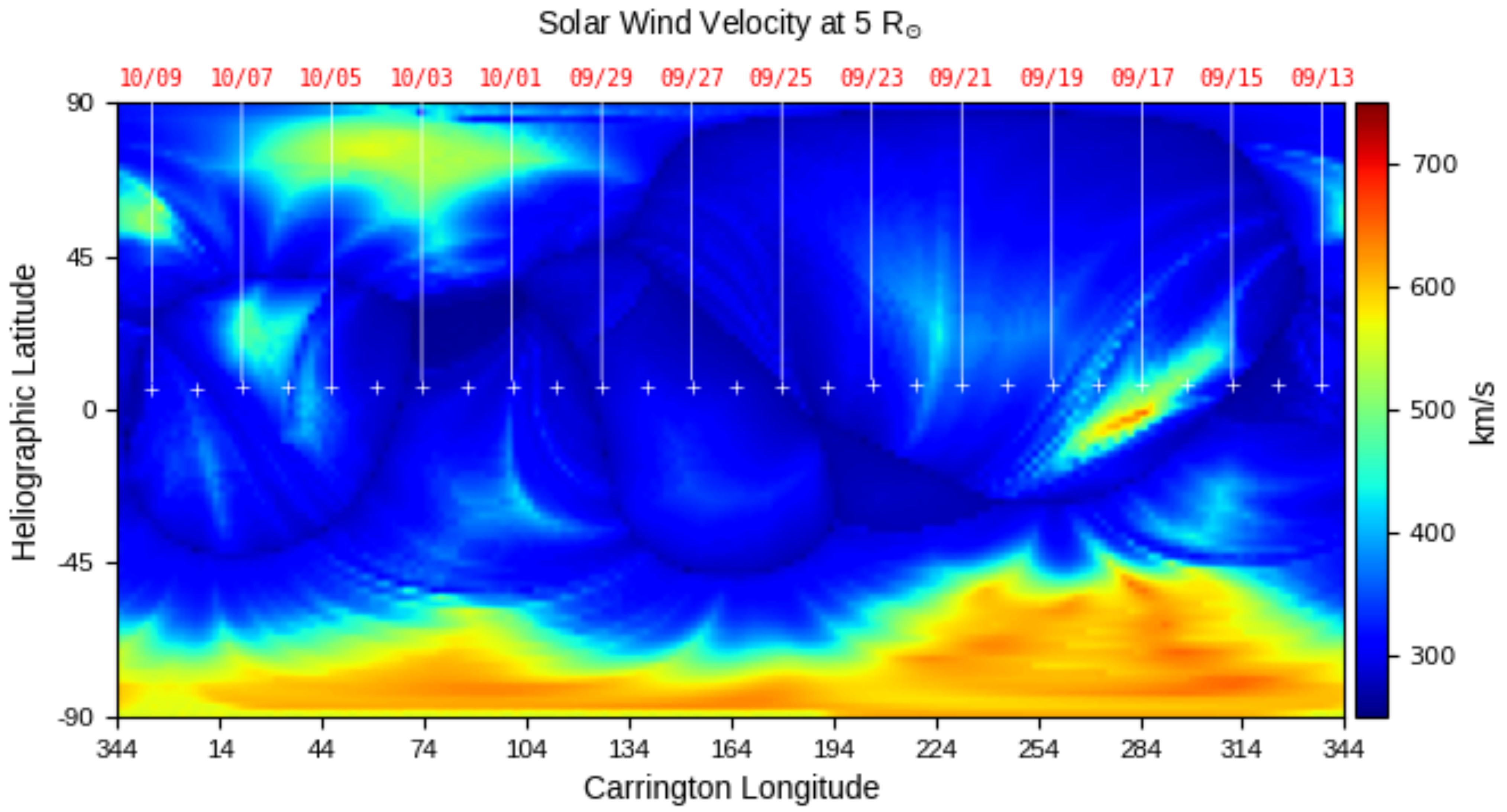
Previous work

- All previous experiments have been done with the Magnetohydrodynamics Around a Sphere (MAS) coronal mode.
- The Wang-Sheeley-Arge model is more widely used and is operational.

MAS



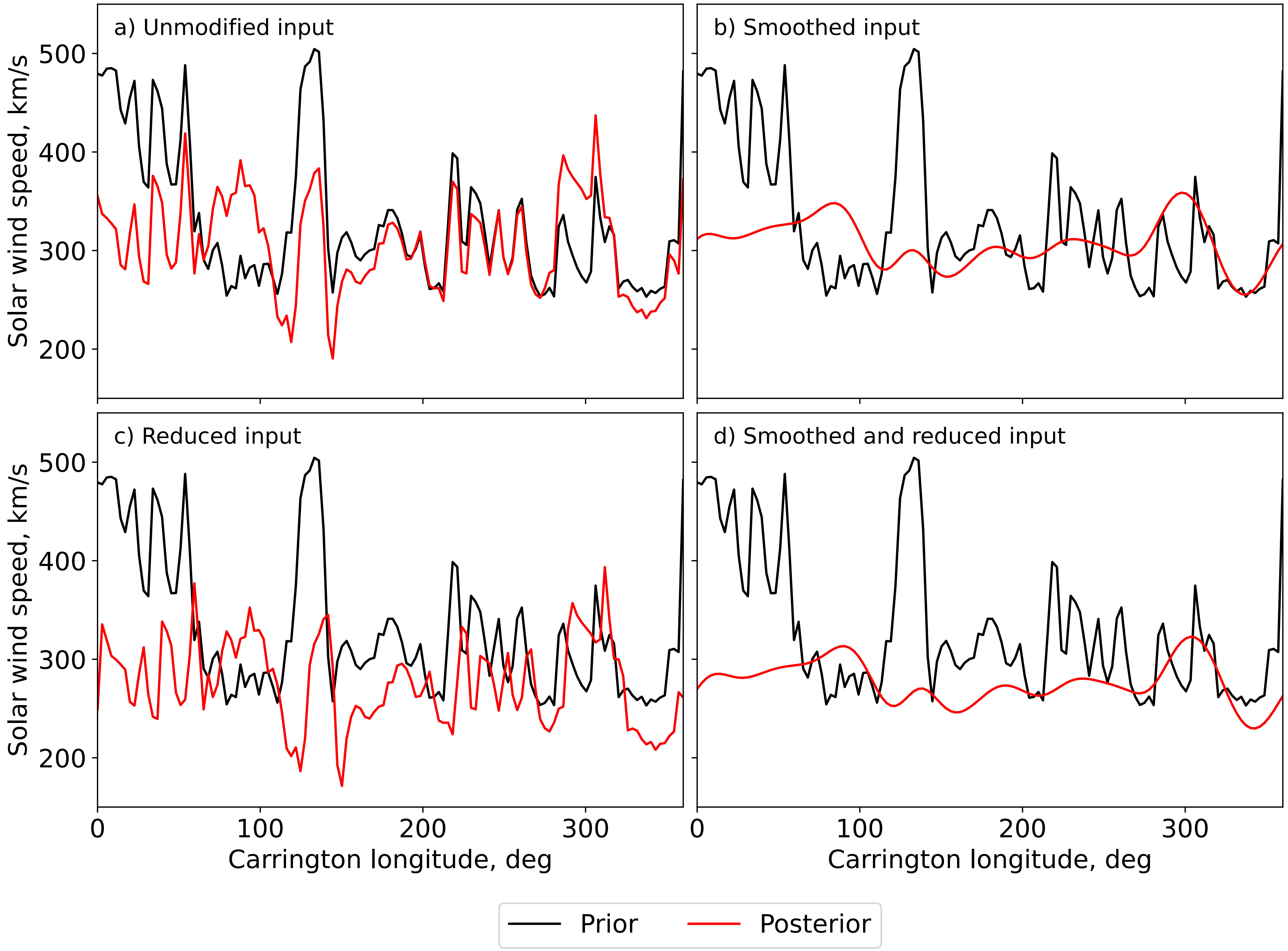
WSA



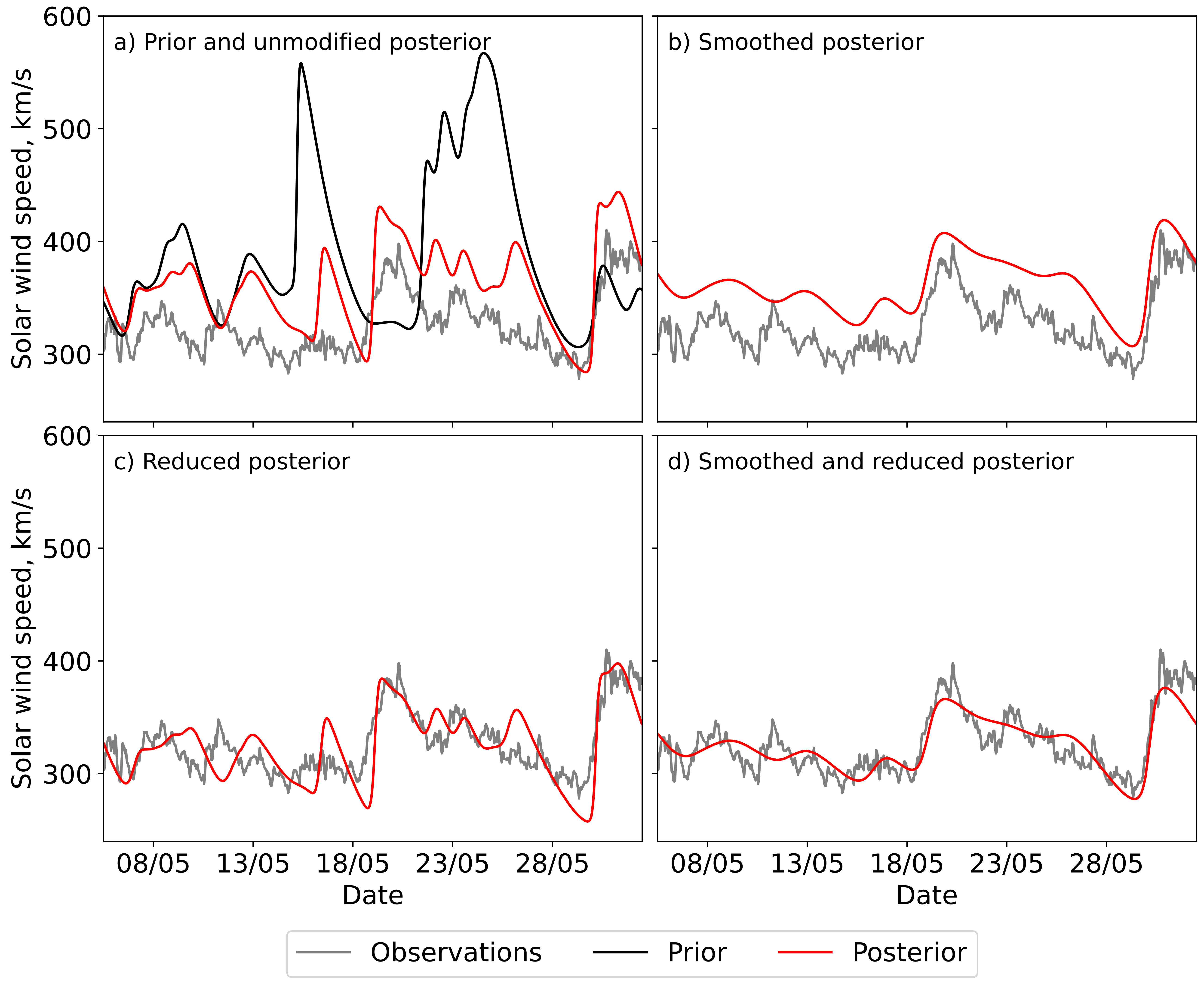
Processing BRaVDA output

- For use in any heliospheric model, the BRaVDA output would need to be processed.
- Setting the standard by processing the output to work well as the inner boundary for HUXt.
- Combination of smoothing the inner boundary to remove small scale structure and reducing the speed to remove over-prediction.

Inner boundary processing



Time series at Earth



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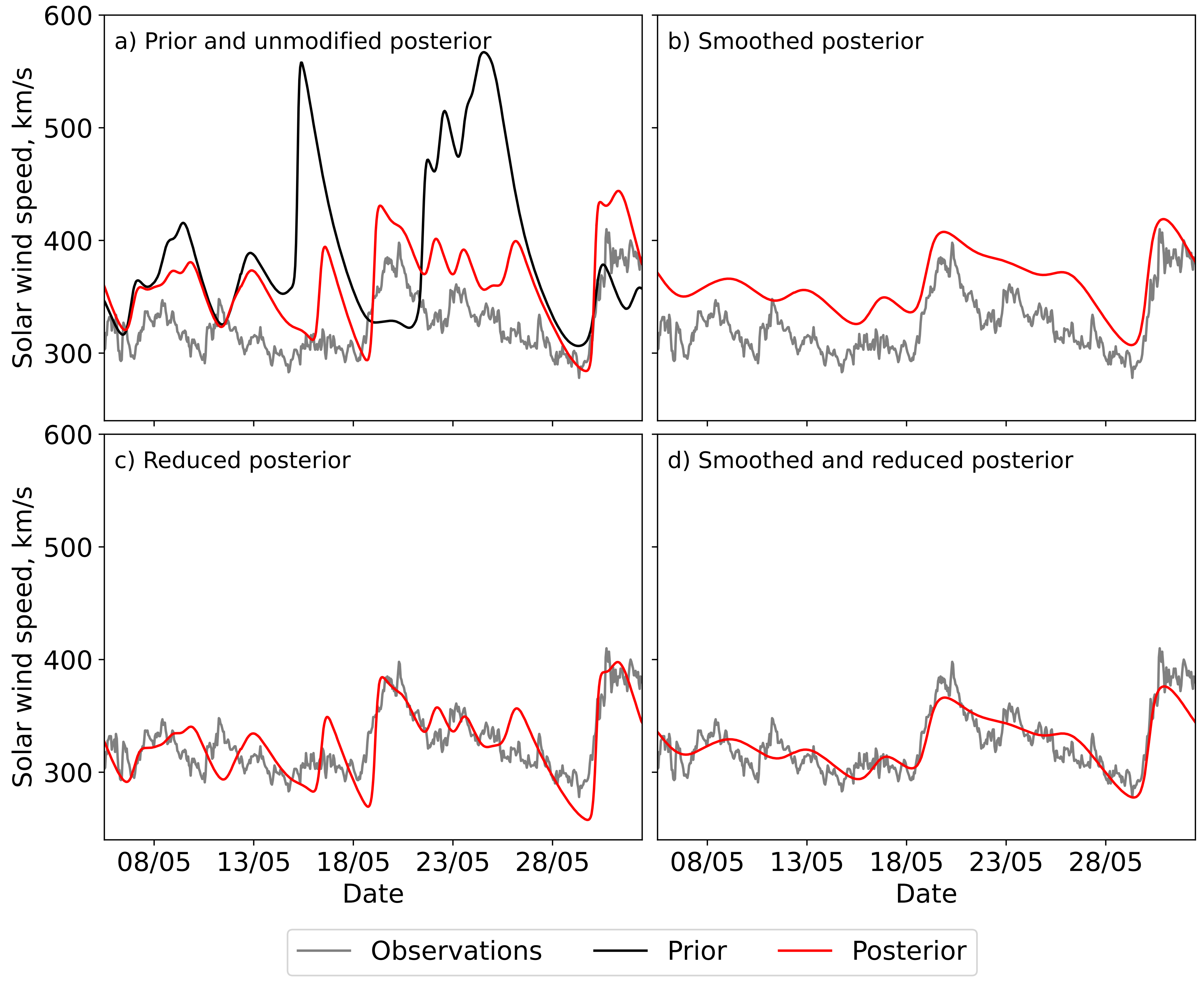
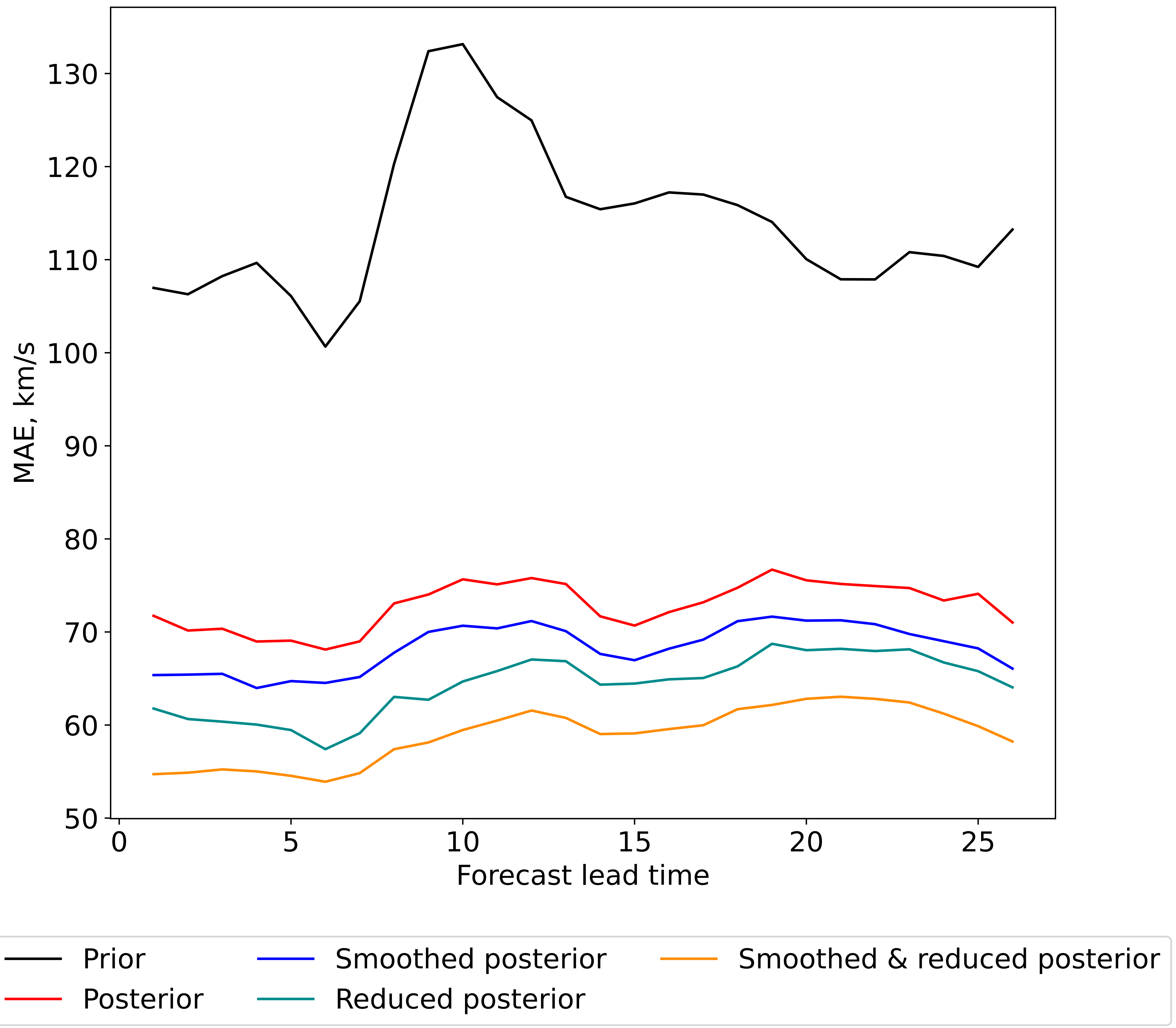
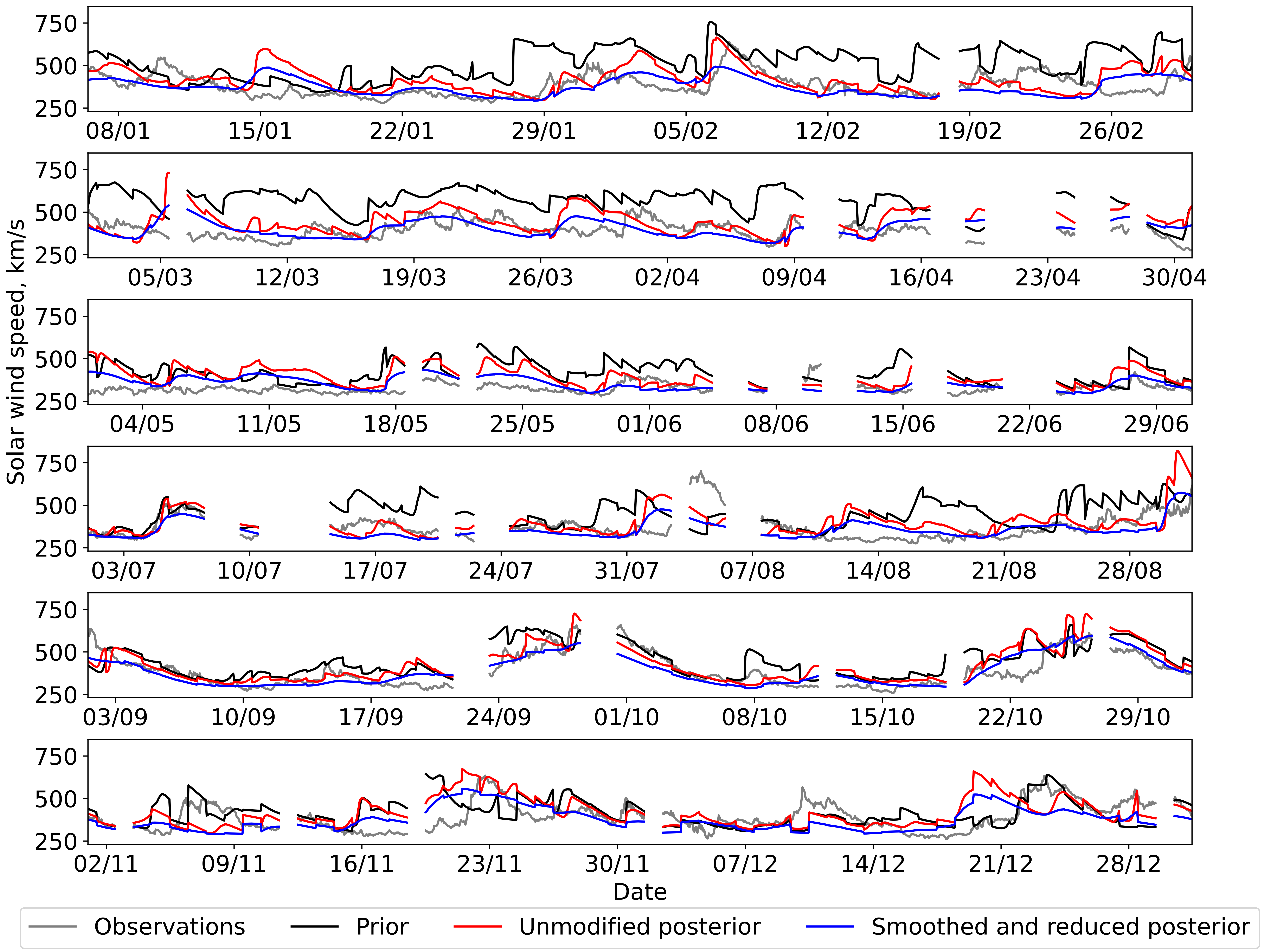


Timeseries	MAE, km/s
Prior	76.0
Unmodified	37.3
Smoothed	35.5
Reduced	17.5
Smoothed & reduced	11.6

Variation of MAE with forecast lead time



5-day forecast lead time at Earth



Conclusions

Tldr; it works!

- Knowing the conditions of the ambient solar wind is important for space weather forecasting.
- Data assimilation can be used to improve our knowledge of the ambient solar wind conditions.
- Has been shown to improve forecasts.
- Needs more testing before it can be fully operational.

“All models are wrong, DA should be less wrong.”

A ~~wise~~ jaded supervisor, 2024