Solar wind data assimilation in an operational context

Use of near-real-time data and the forecast value of an L5 monitor

Harriet Turner

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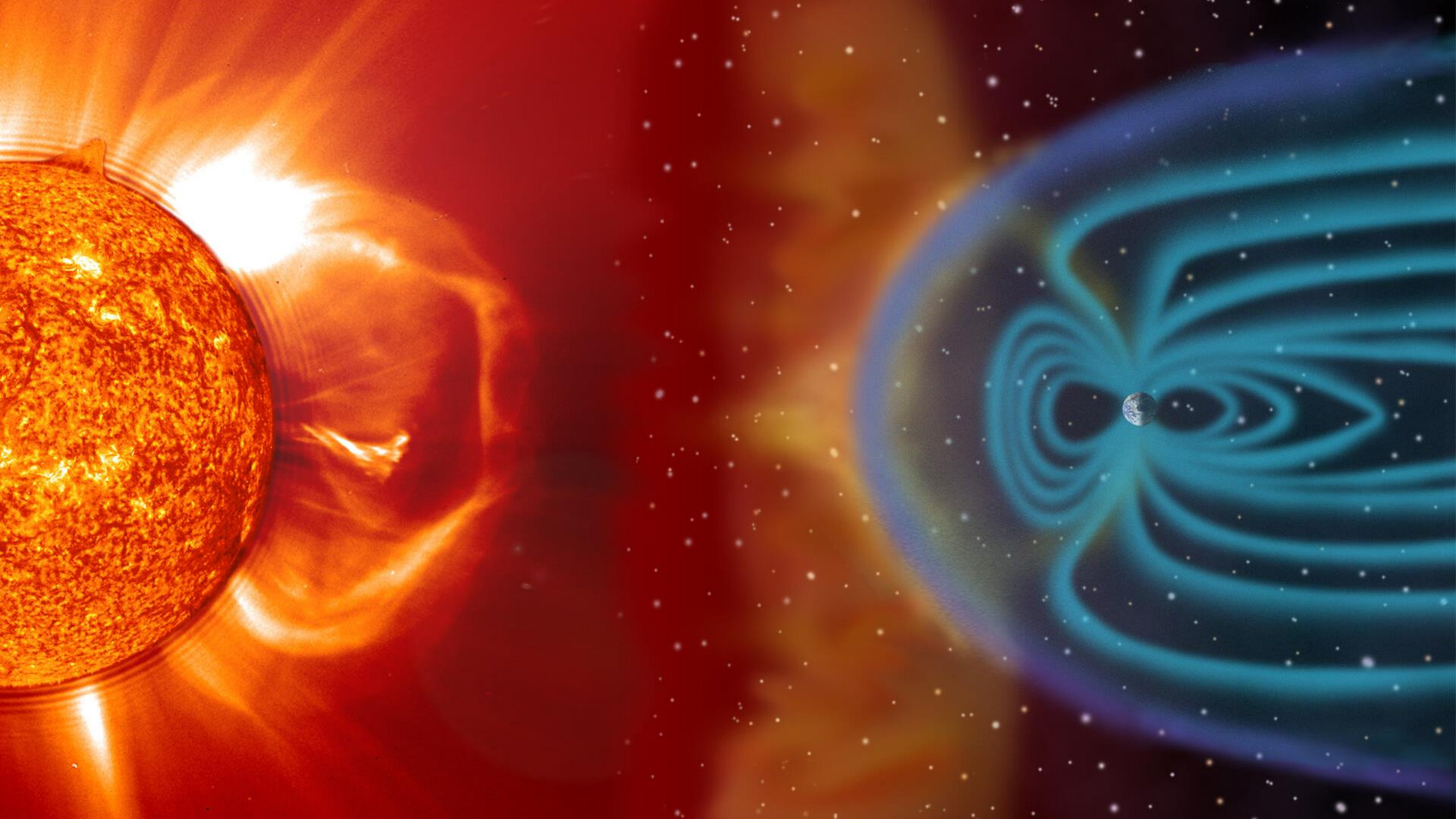
THE SOLAR WIND

Constant stream of charged particles that flows off the Sun and fills the heliosphere (solar system)

Comprised mostly of electrons, protons and ions

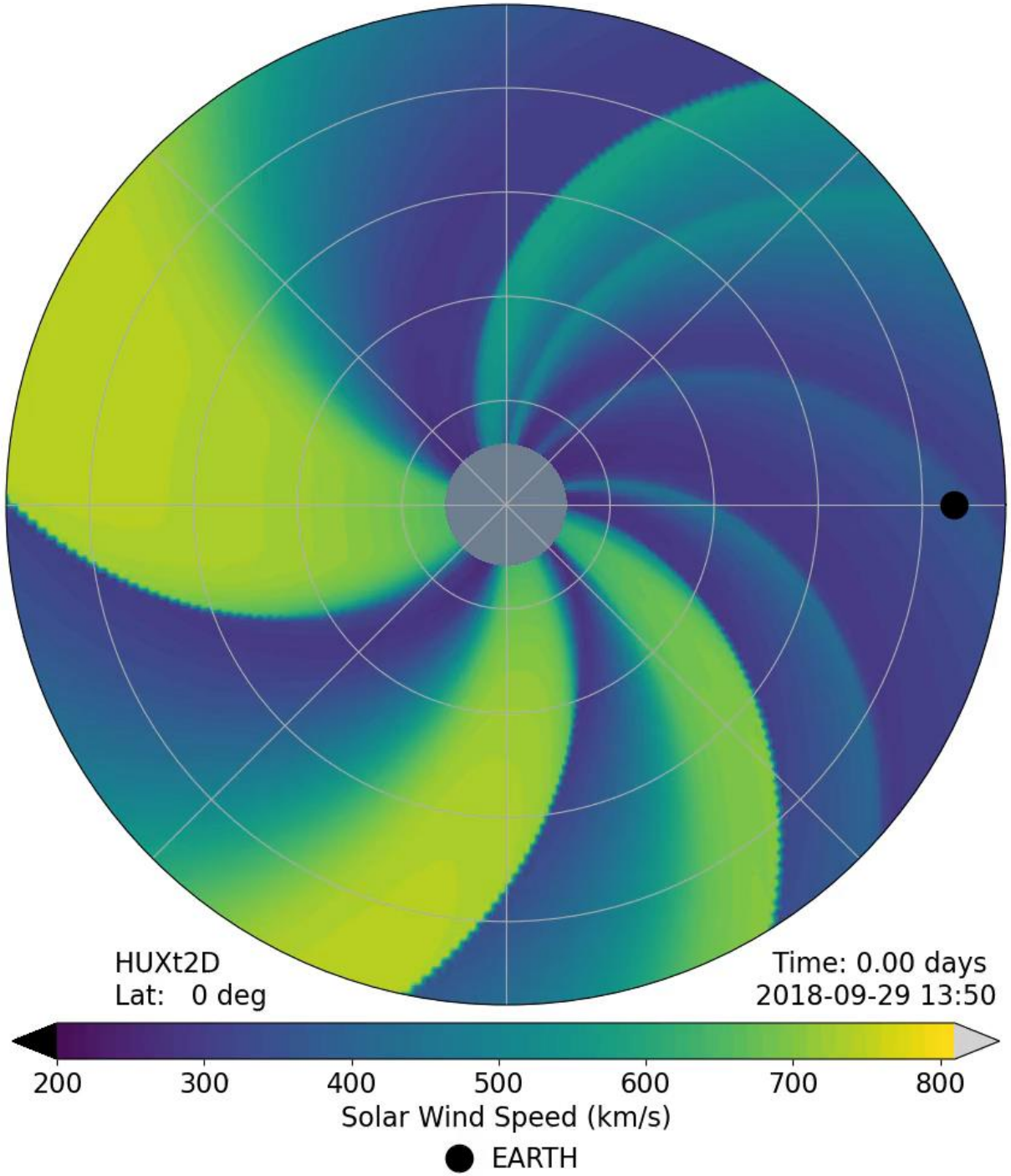


SOLAR WIND STRUCTURE

Solar wind drags out the Sun's magnetic field

Pulled into an Archimedean spiral due to the Sun's rotation

Solar wind flow is **mostly radial**


HUXt2D
Lat: 0 deg
Time: 0.00 days
2018-09-29 13:50
200
300
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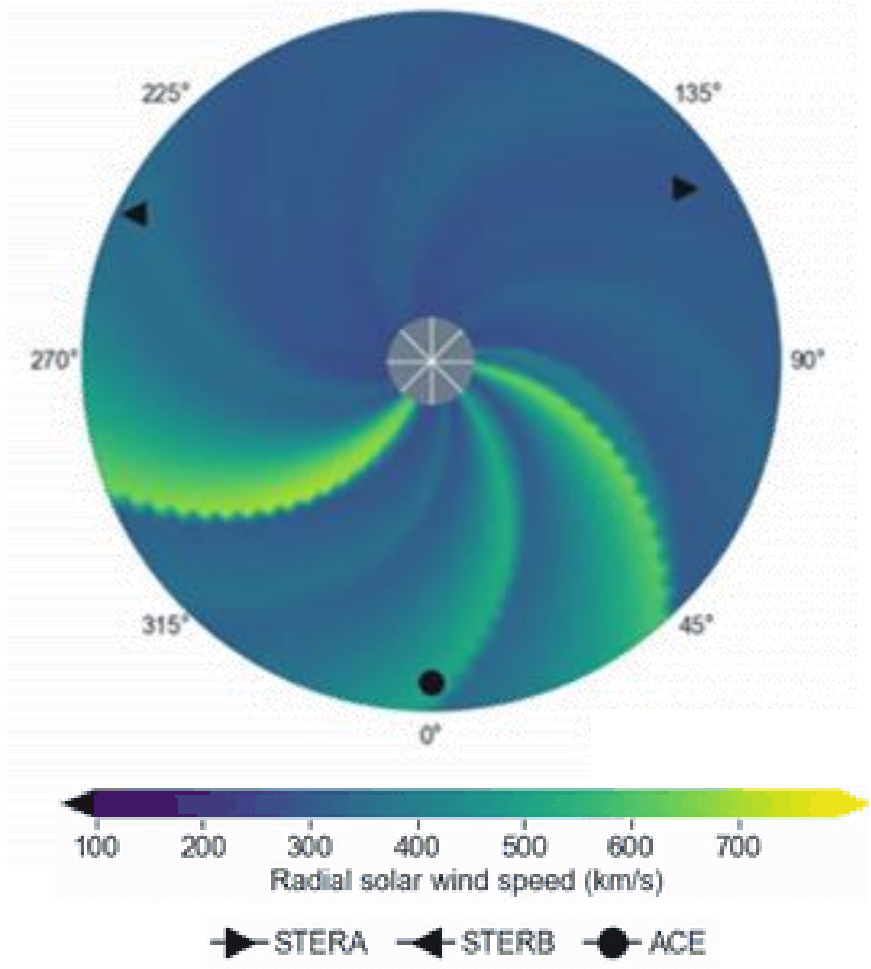
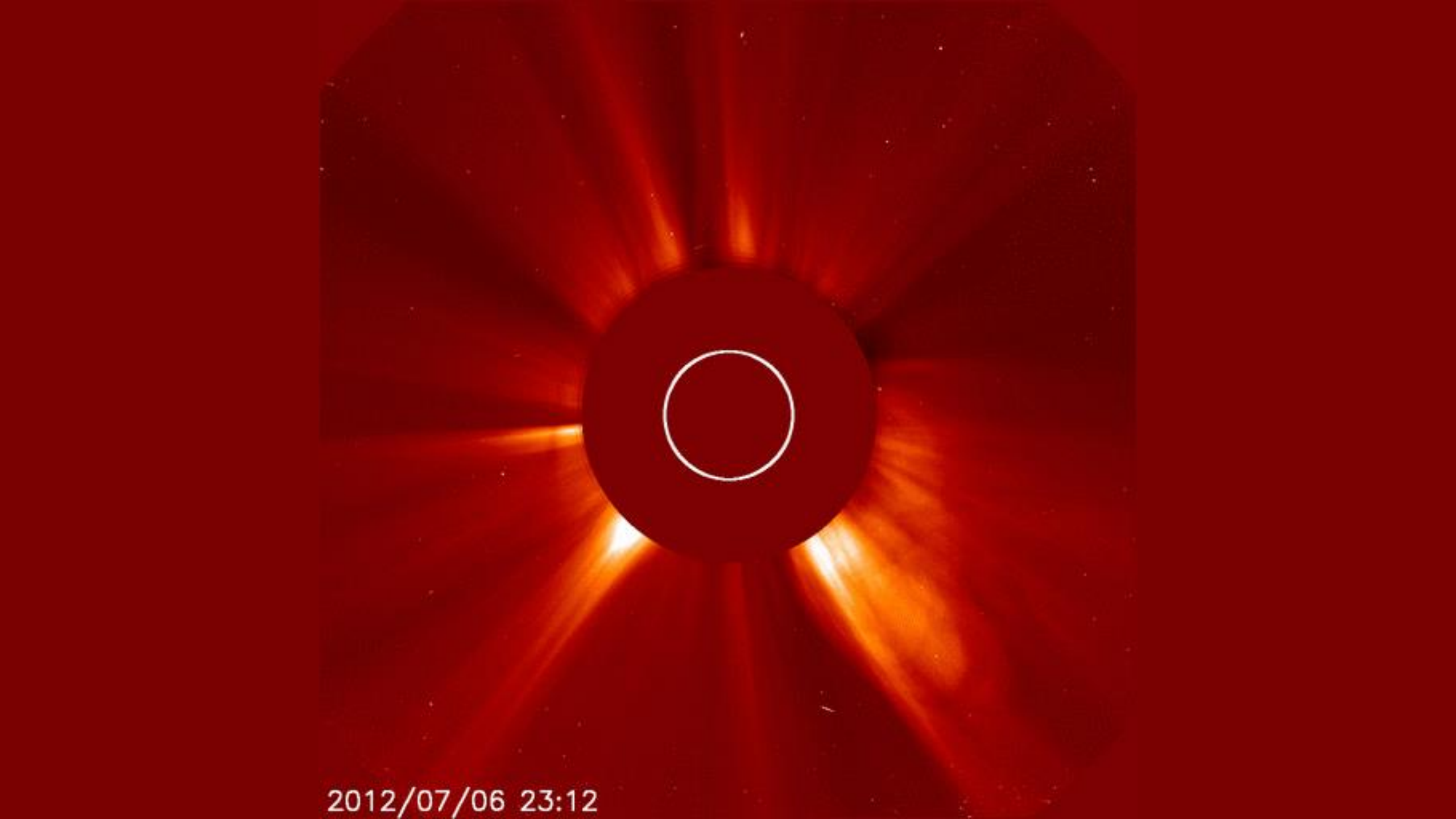
600
700
800
Solar Wind Speed (km/s)
EARTH

CORONAL MASS EJECTIONS

Coronal mass ejections (CMEs) are huge eruptions of solar material and are the main driver of severe space weather

They propagate through the solar wind, so the background conditions affect their speed and arrival time

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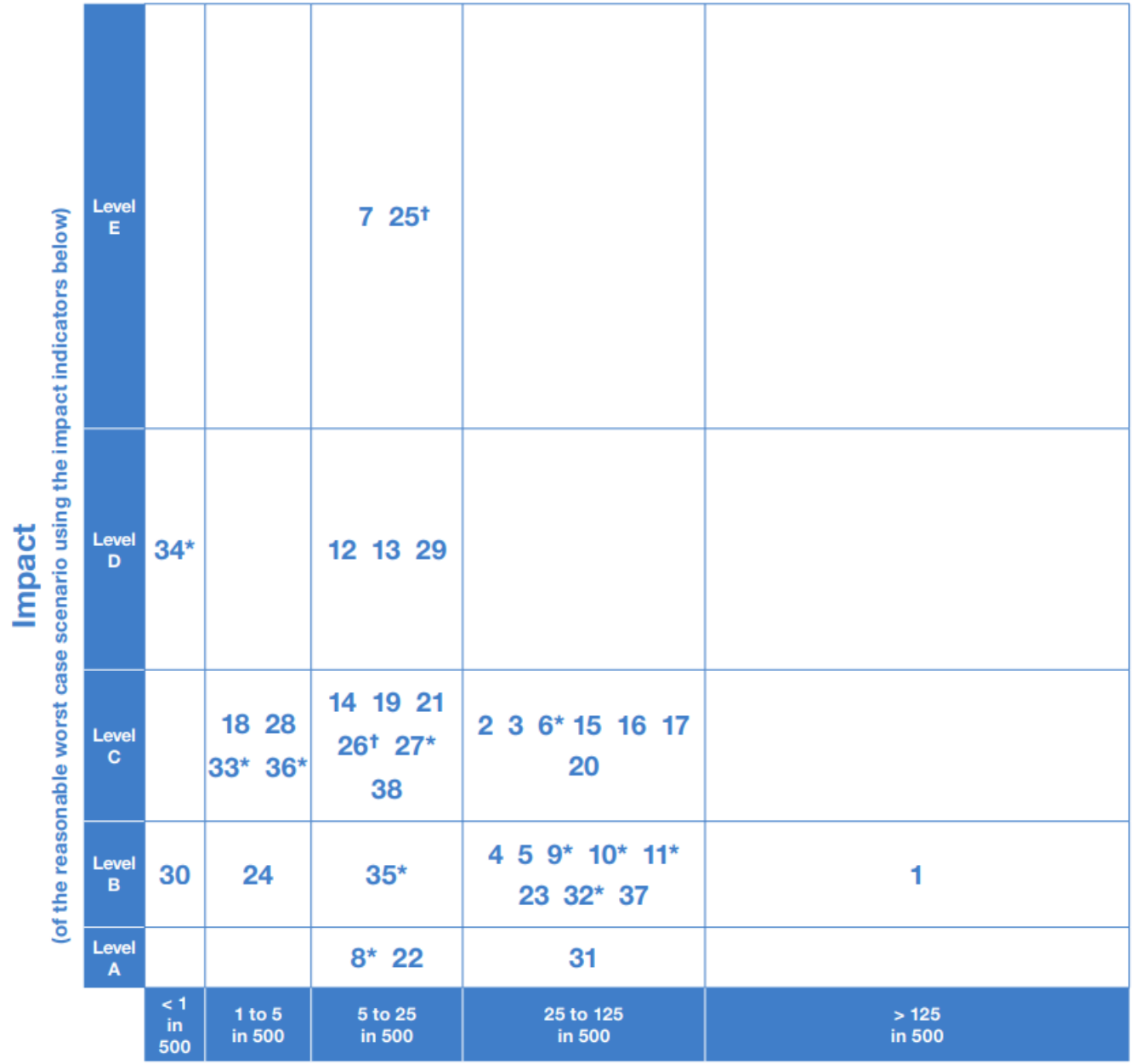
WHY SHOULD WE CARE?

Space weather (the changing plasma conditions in near-Earth space) poses a significant threat to modern technology

Extreme space weather is in the UK's National Risk Register



*Risk not plotted in the 2017 NRR | †COVID-19 is not included in the risk matrix and is therefore not included in these risks

Malicious Attacks

1. Attacks on publicly accessible locations
2. Attacks on infrastructure
3. Attacks on transport
4. Cyber attacks
5. Smaller scale CBRN attacks
6. Medium scale CBRN attacks
7. Larger scale CBRN attacks
8. Undermining the democratic process*

Serious and Organised Crime

9. Serious and organised crime – vulnerabilities*
10. Serious and organised crime – prosperity*
11. Serious and organised crime – commodities*

Environmental Hazards

12. Coastal flooding
13. River flooding
14. Surface water flooding
15. Storms
16. Low temperatures
17. Heatwaves
18. Droughts
19. Severe space weather
20. Volcanic eruptions
21. Poor air quality
22. Earthquakes
23. Environmental disasters overseas
24. Wildfires

Human and Animal Health

25. Pandemics†
26. High consequence infectious disease outbreaks†
27. Antimicrobial resistance*
28. Animal diseases

Major Accidents

29. Widespread electricity failures
30. Major transport accidents
31. System failures
32. Commercial failures*
33. Systematic financial crisis*
34. Industrial accidents – nuclear*
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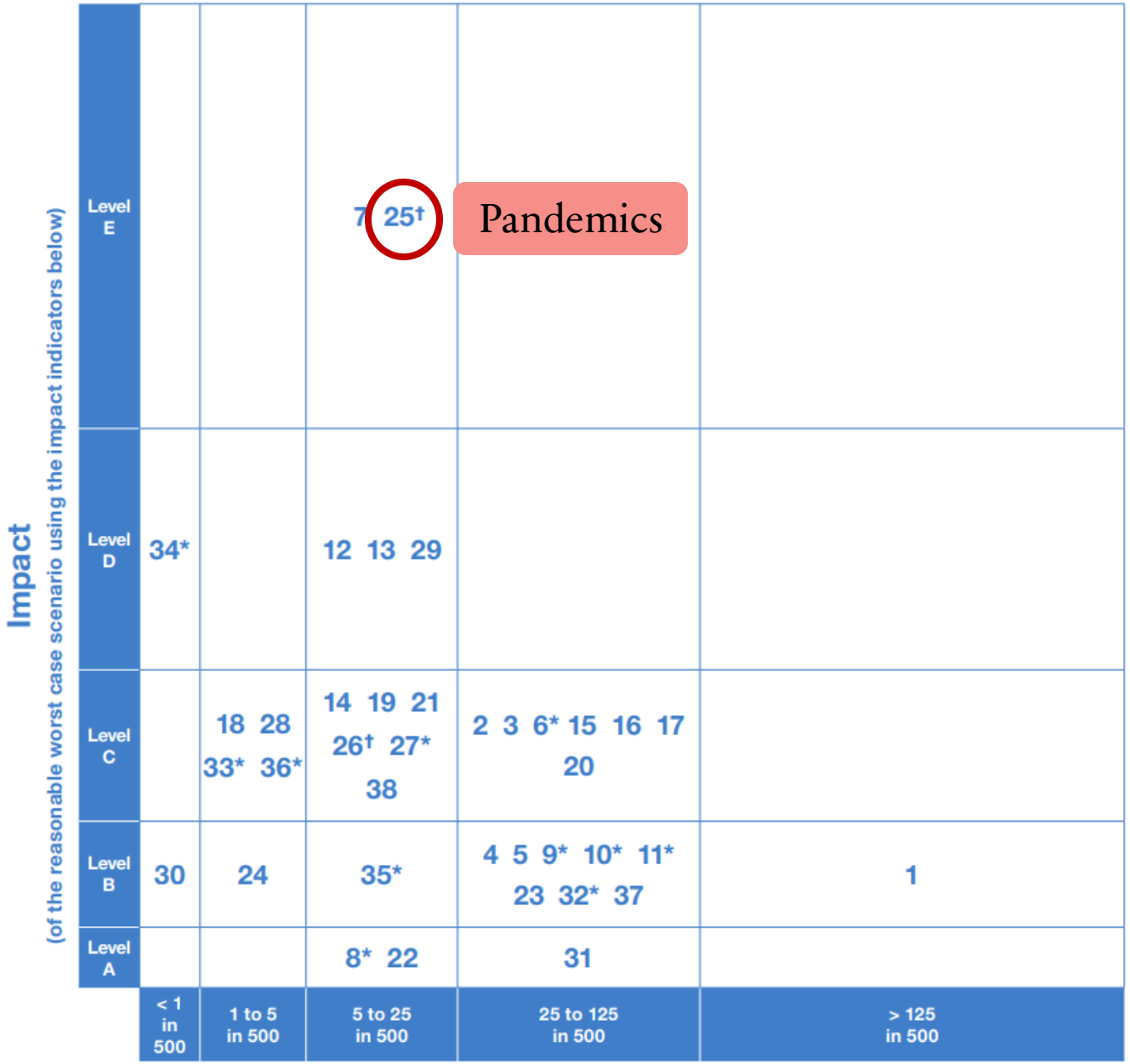
Societal Risks

37. Industrial action
38. Widespread public disorder



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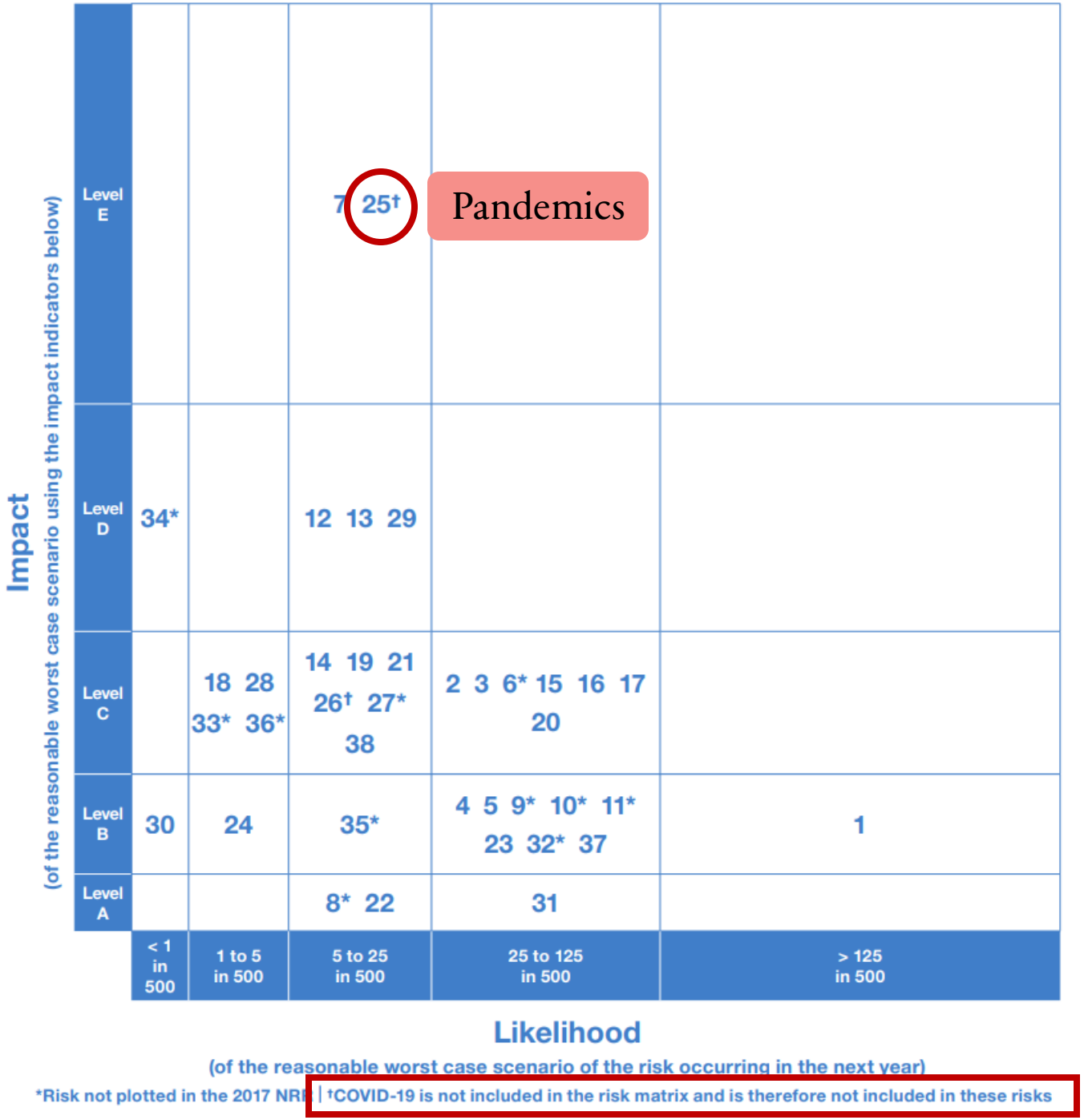

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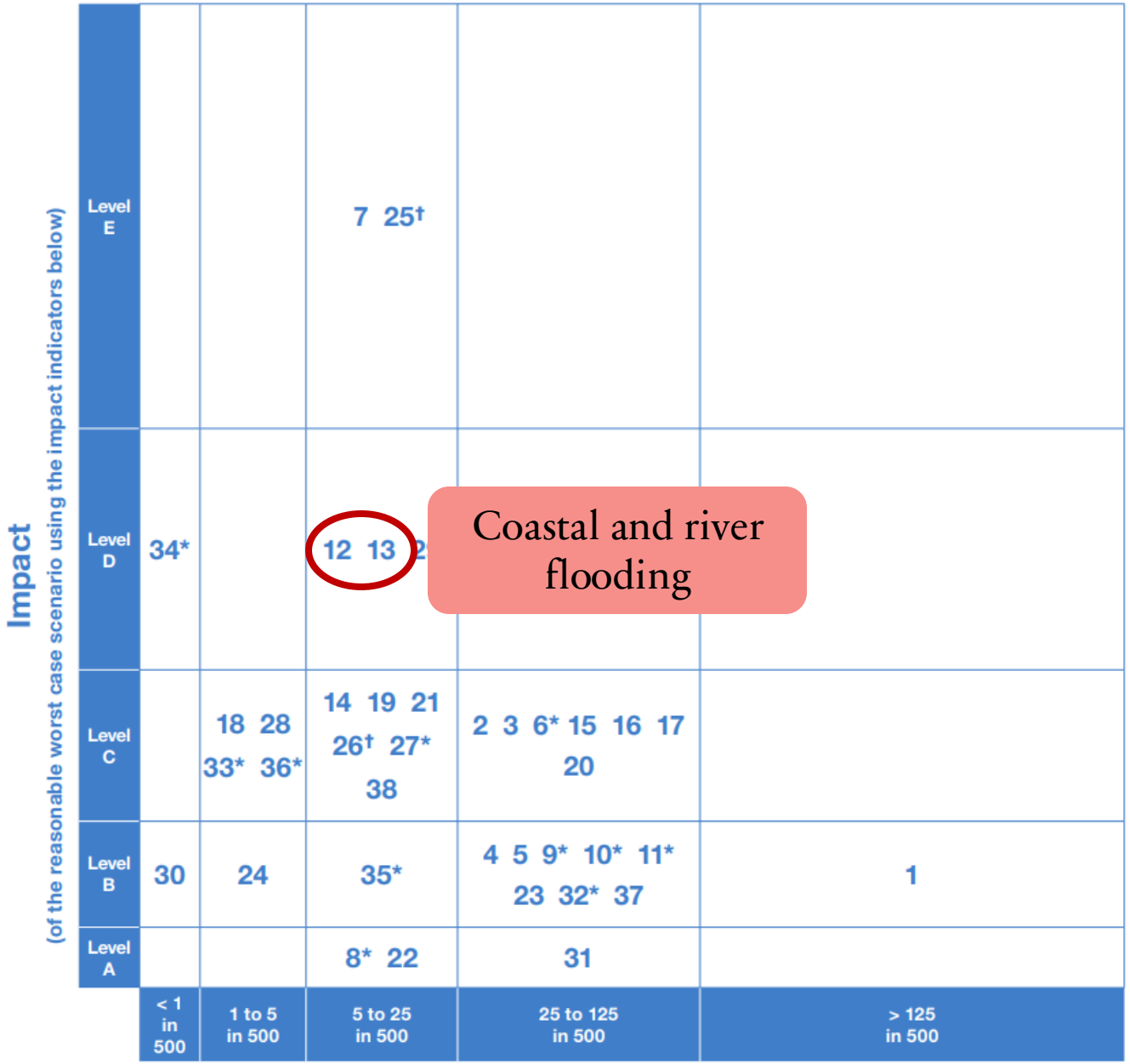

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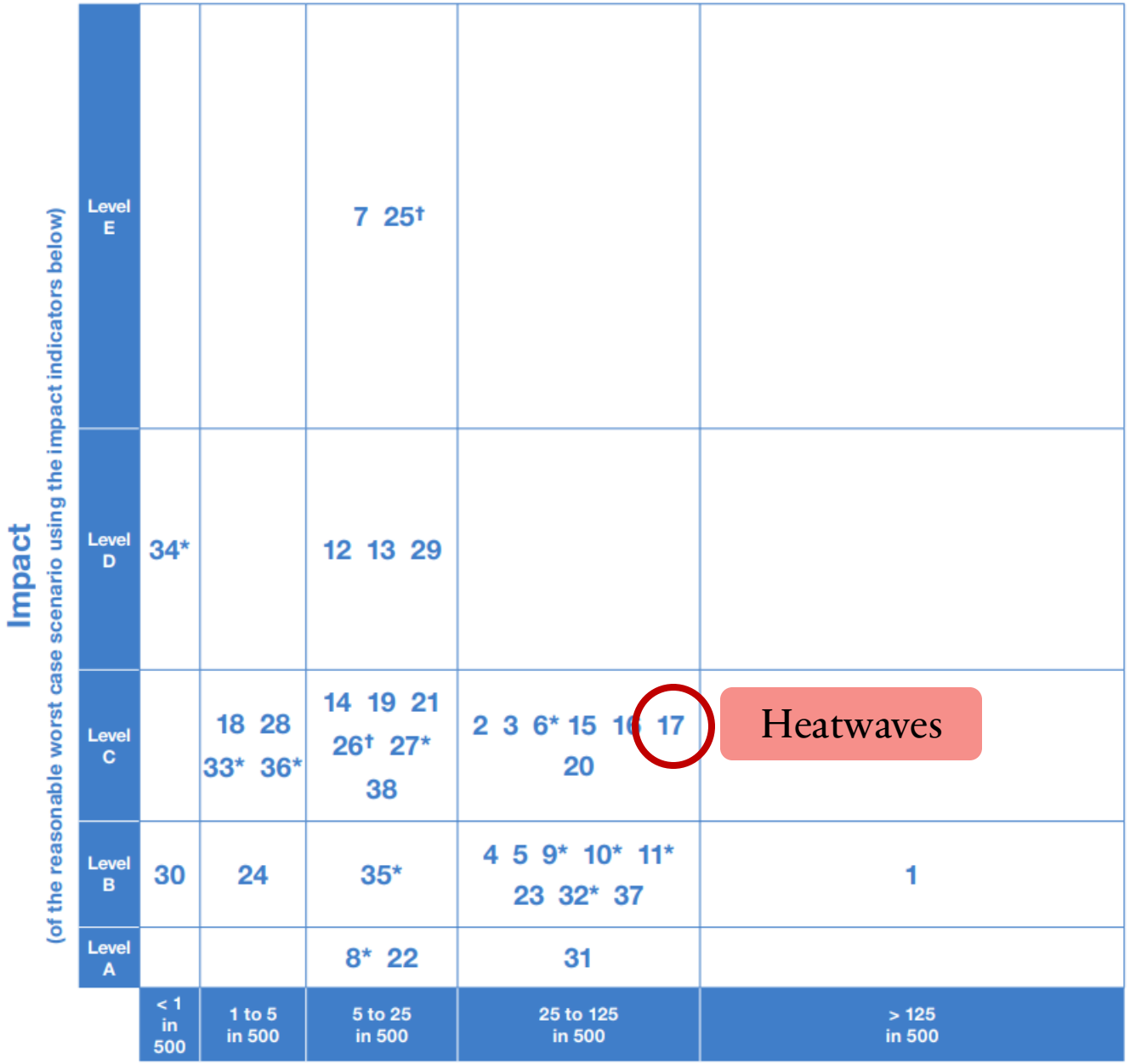

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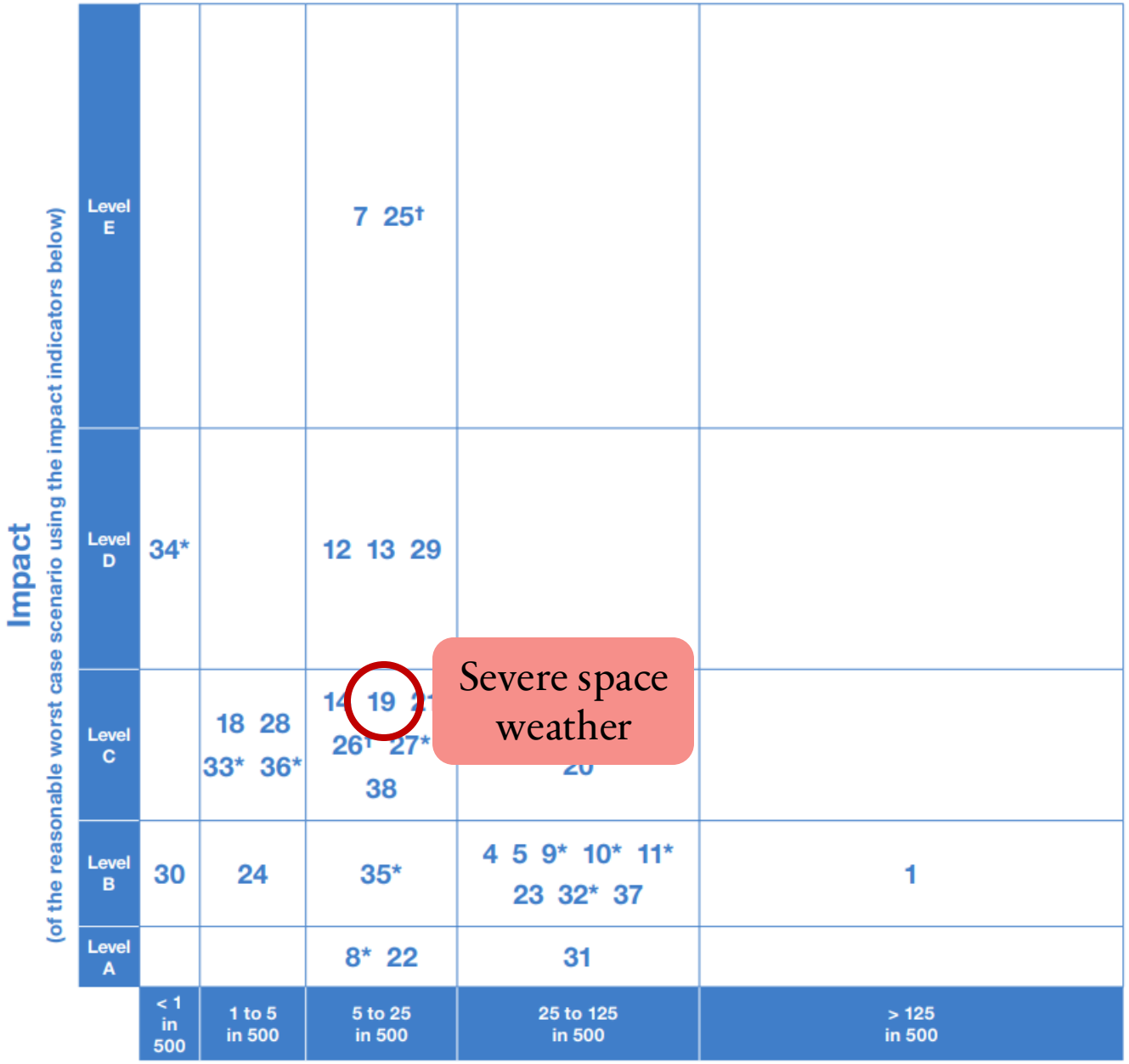

Severe space weather

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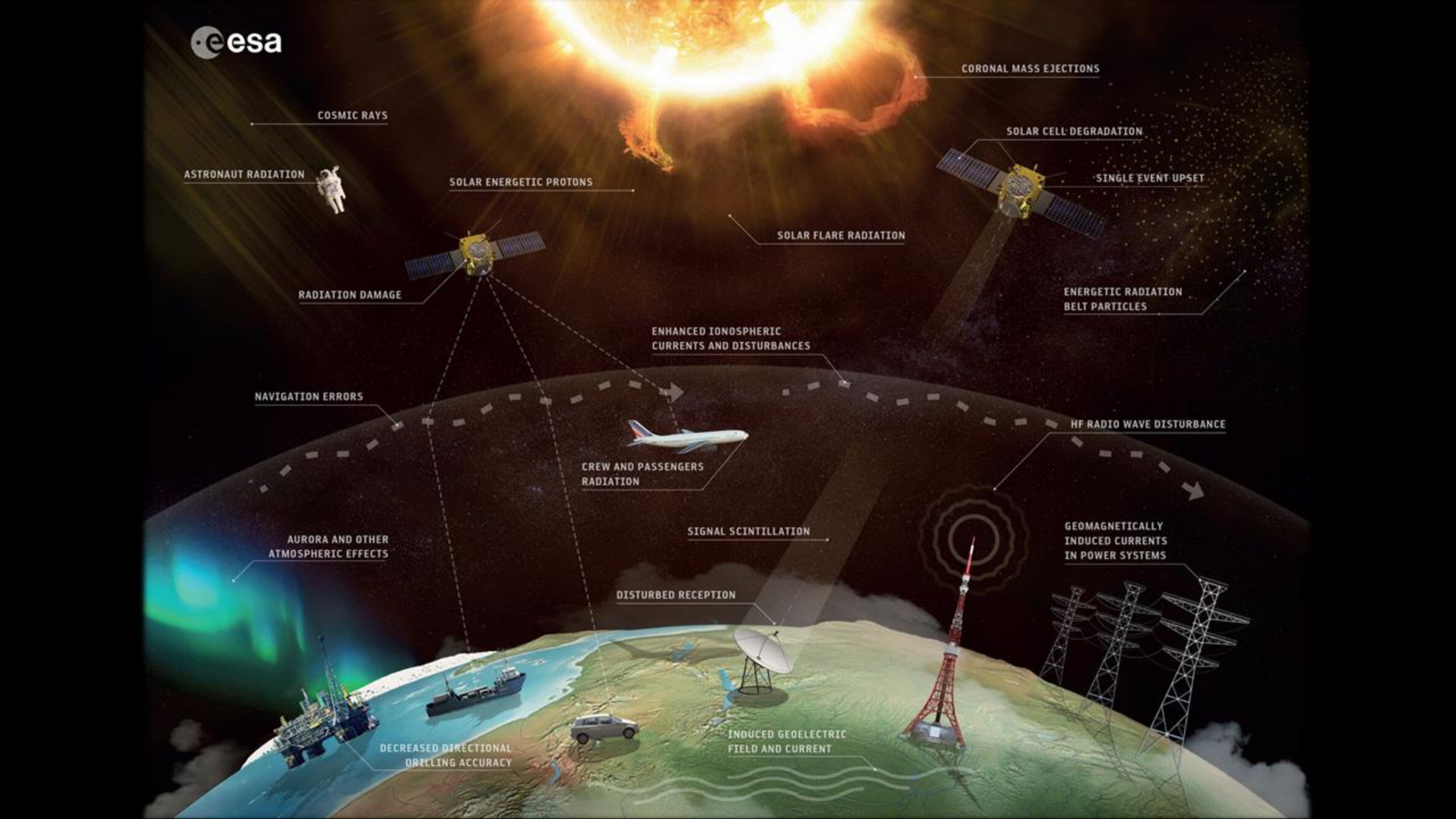
esa
CORONAL MASS EJECTIONS
COSMIC RAYS
SOLAR CELL DEGRADATION
ASTRONAUT RADIATION
SOLAR ENERGETIC PROTONS
SINGLE EVENT UPSET
SOLAR FLARE RADIATION
RADIATION DAMAGE
ENERGETIC RADIATION
BELT PARTICLES
ENHANCED IONOSPHERIC
CURRENTS AND DISTURBANCES
NAVIGATION ERRORS
HF RADIO WAVE DISTURBANCE
CREW AND PASSENGERS
RADIATION
SIGNAL SCINTILLATION
GEOMAGNETICALLY
INDUCED CURRENTS
IN POWER SYSTEMS
AURORA AND OTHER
ATMOSPHERIC EFFECTS
DISTURBED RECEPTION
DECREASED DIRECTIONAL
DRILLING ACCURACY
INDUCED GEOELECTRIC
FIELD AND CURRENT

CURRENT FORECASTING

Typically a **coronal model** coupled to a **heliospheric model**

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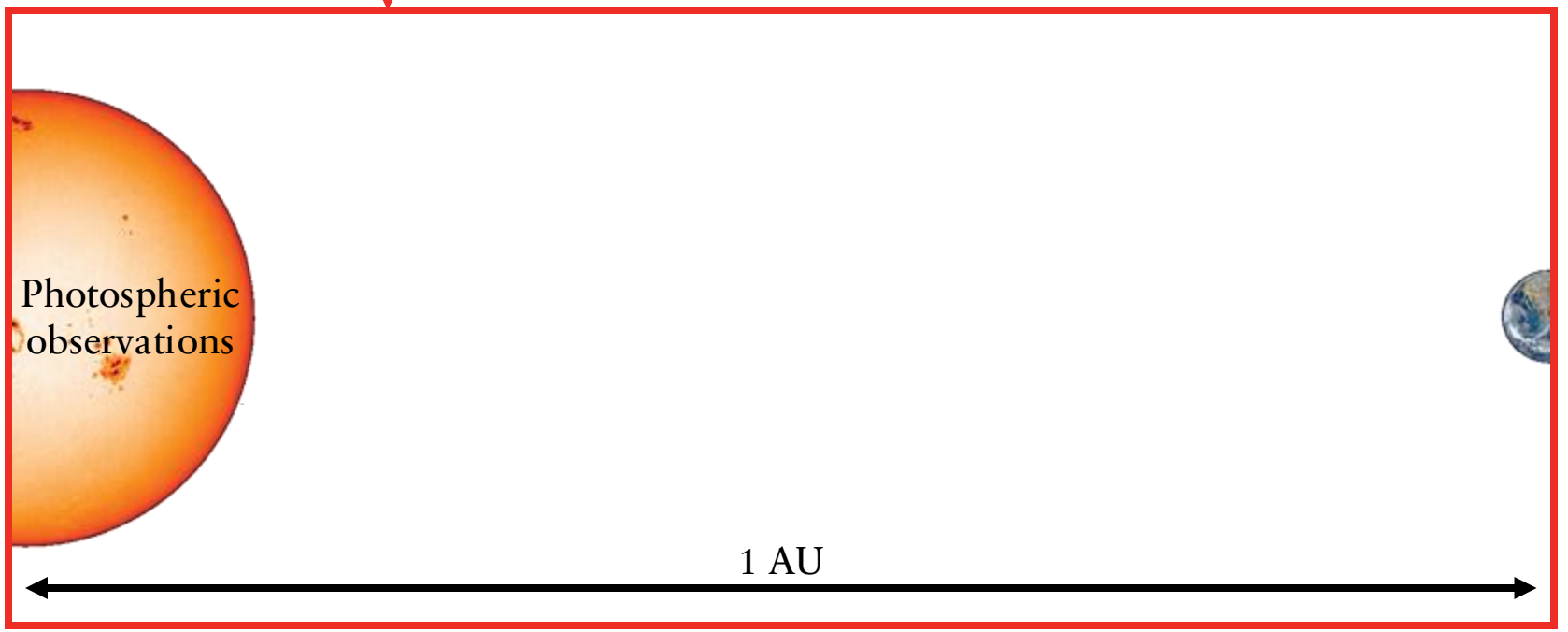

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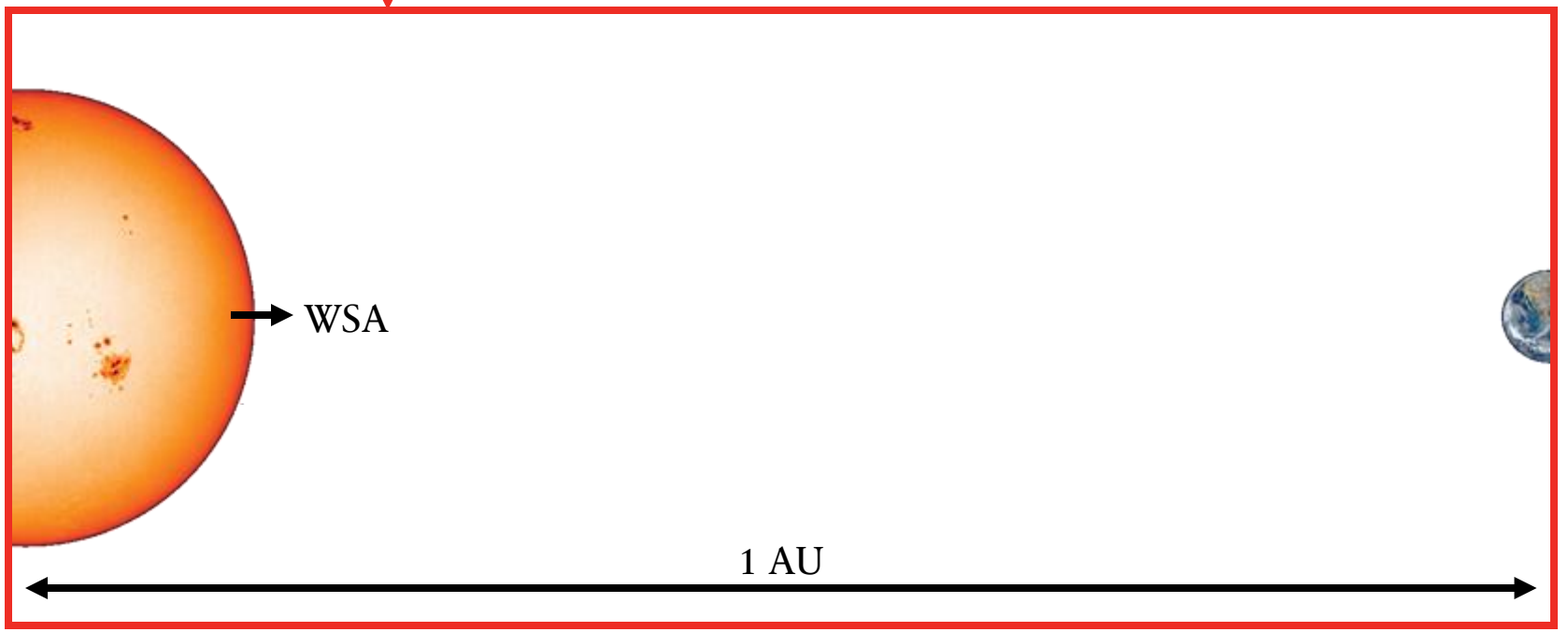

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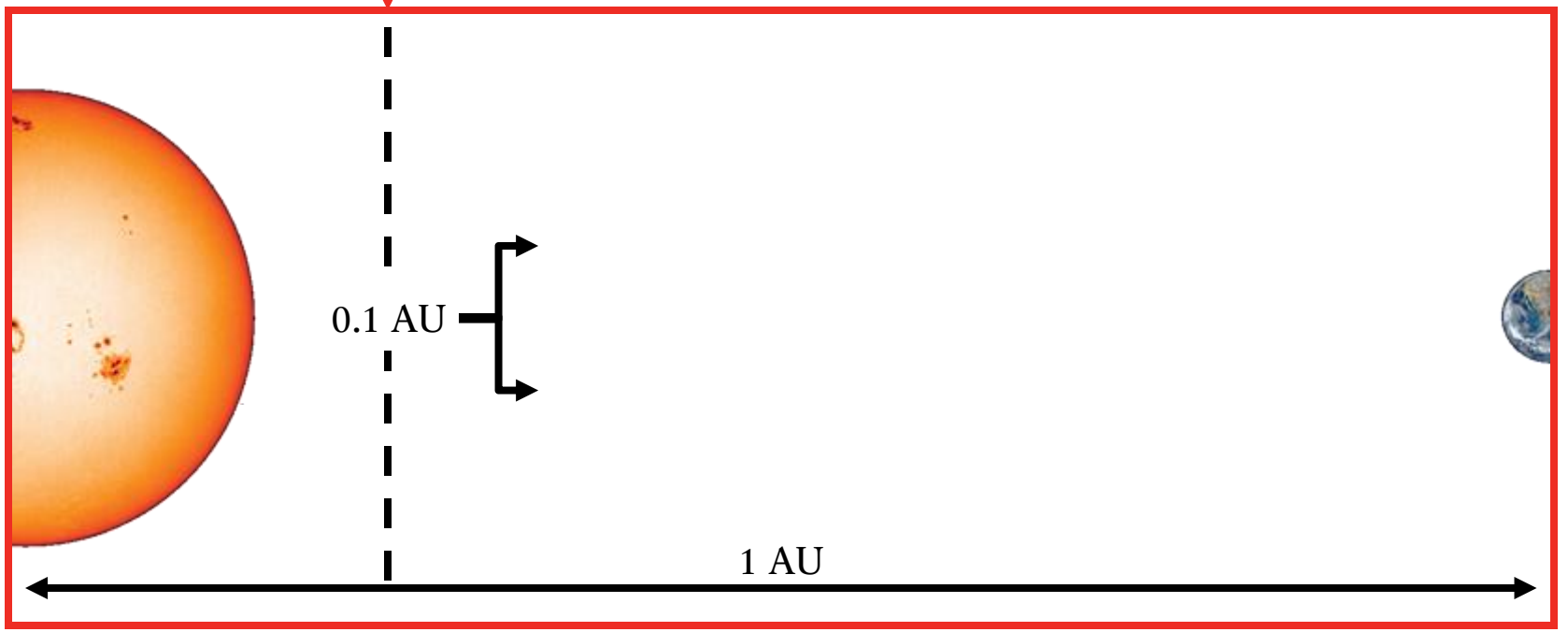

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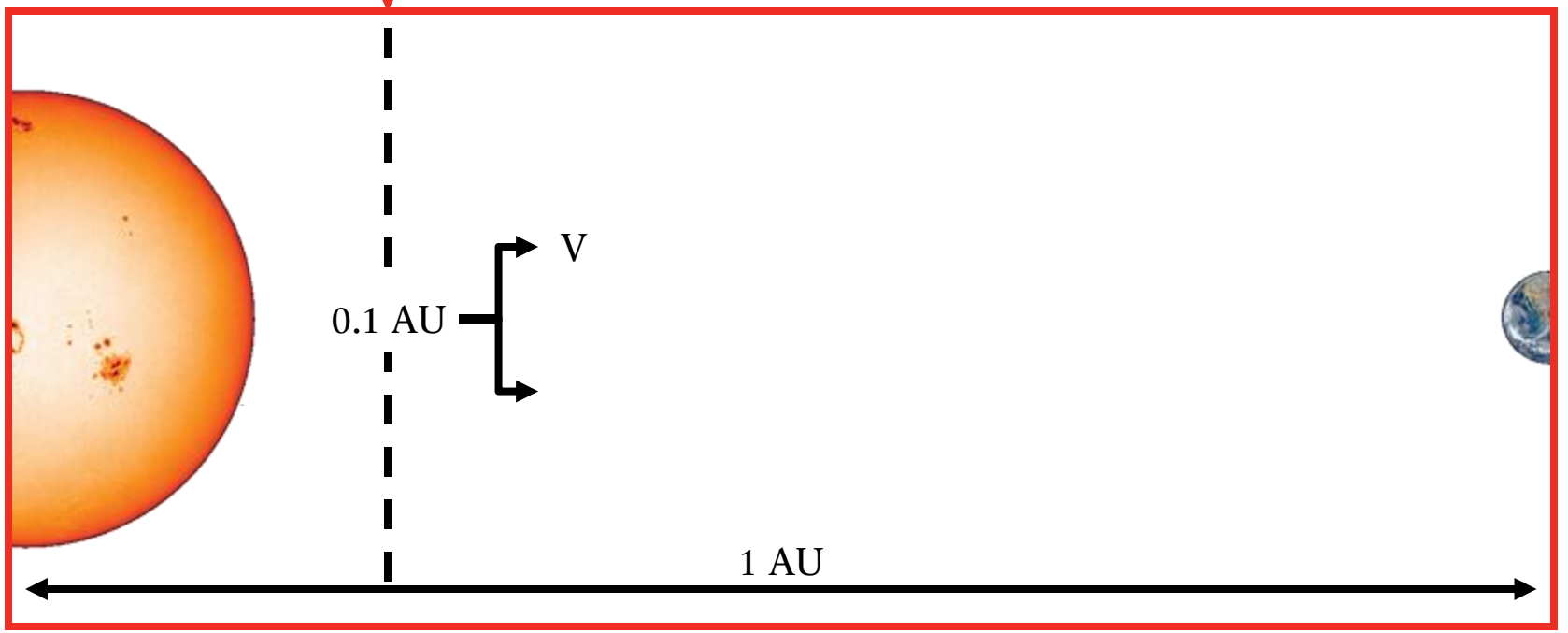

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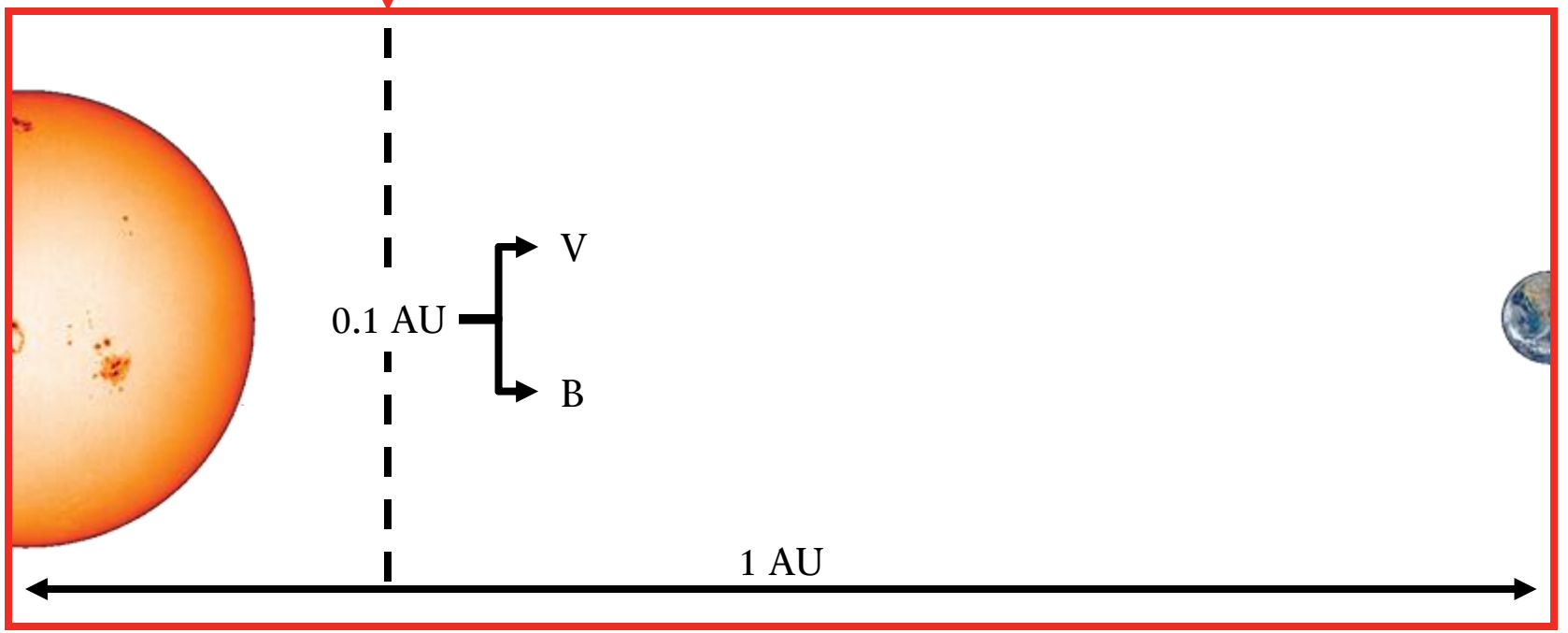

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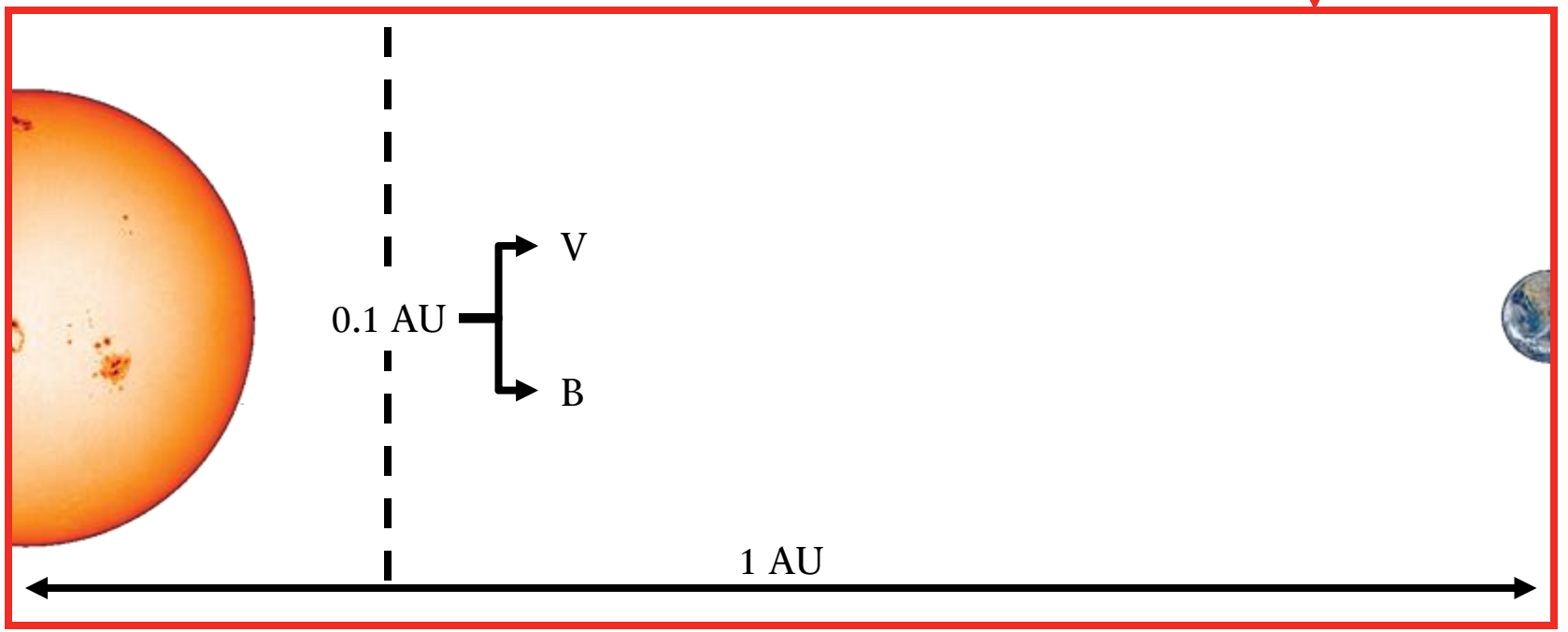

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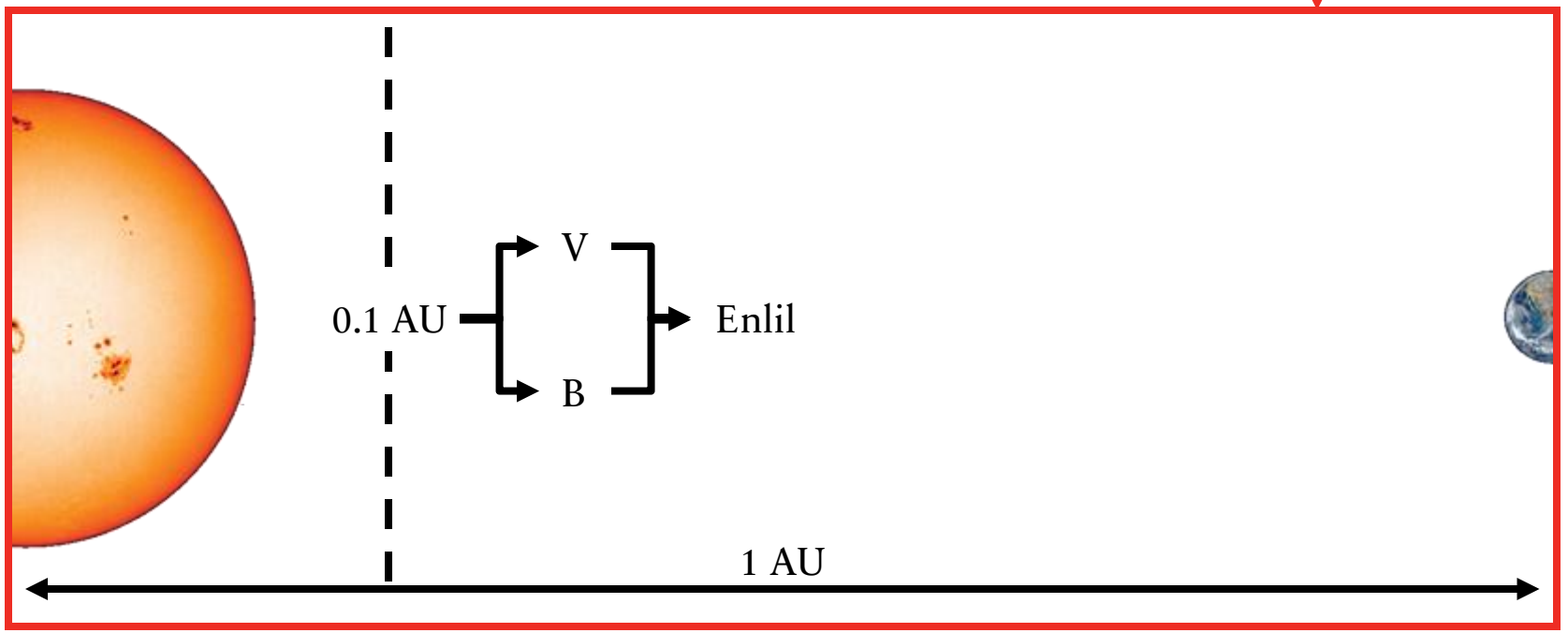

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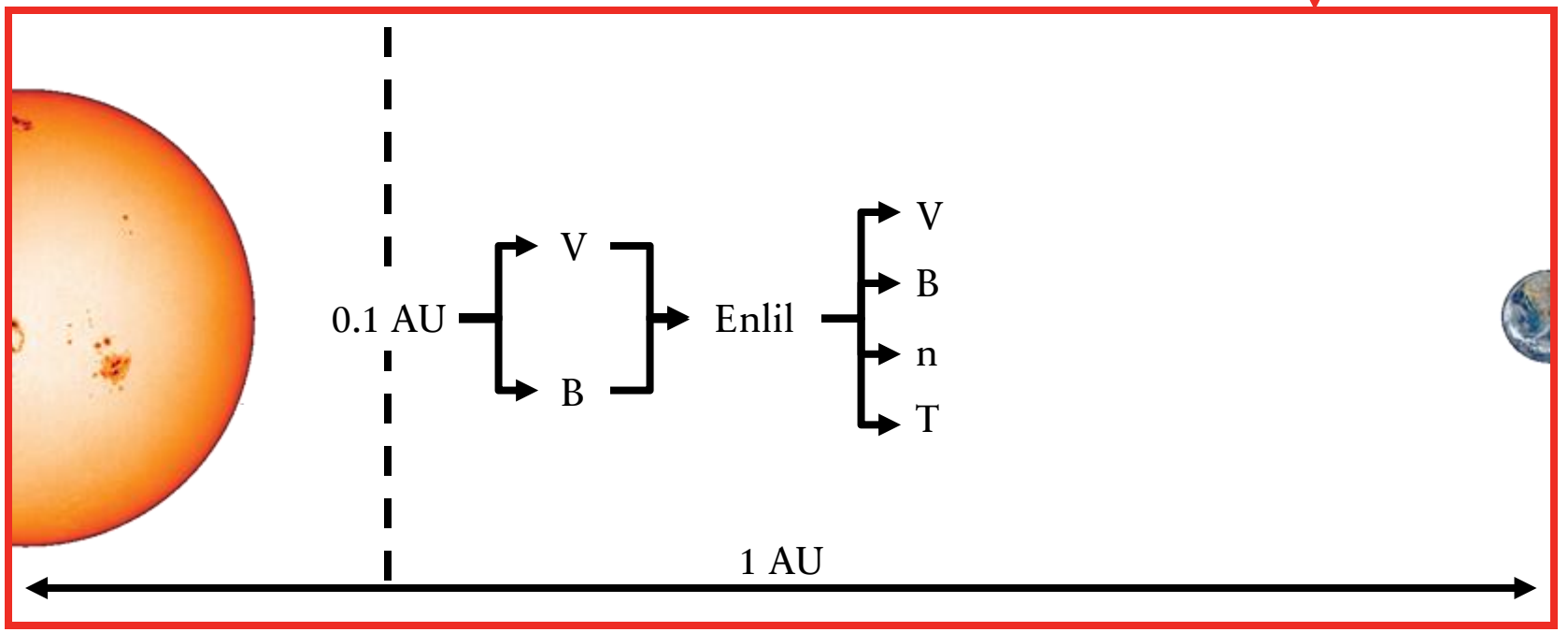

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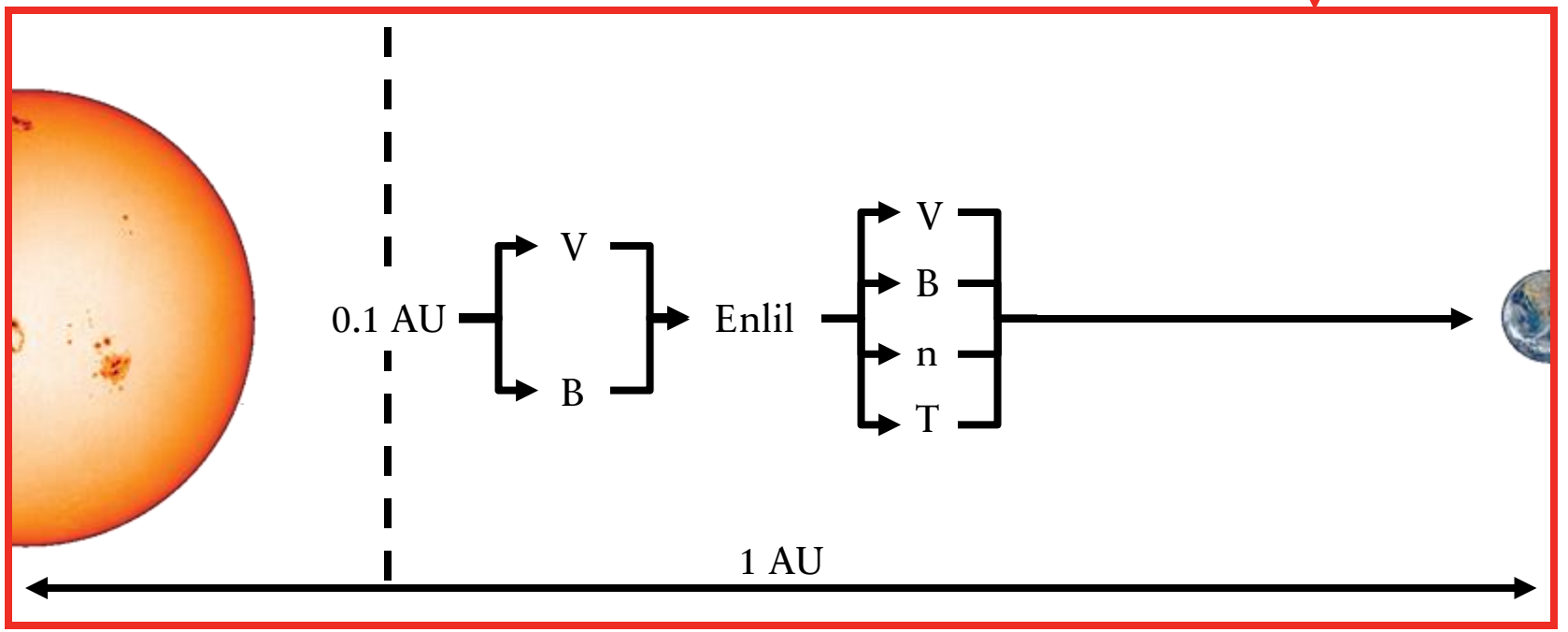


DATA ASSIMILATION (DA)

Data assimilation combines prior information, usually from a model, with observations to find an optimum estimation of reality

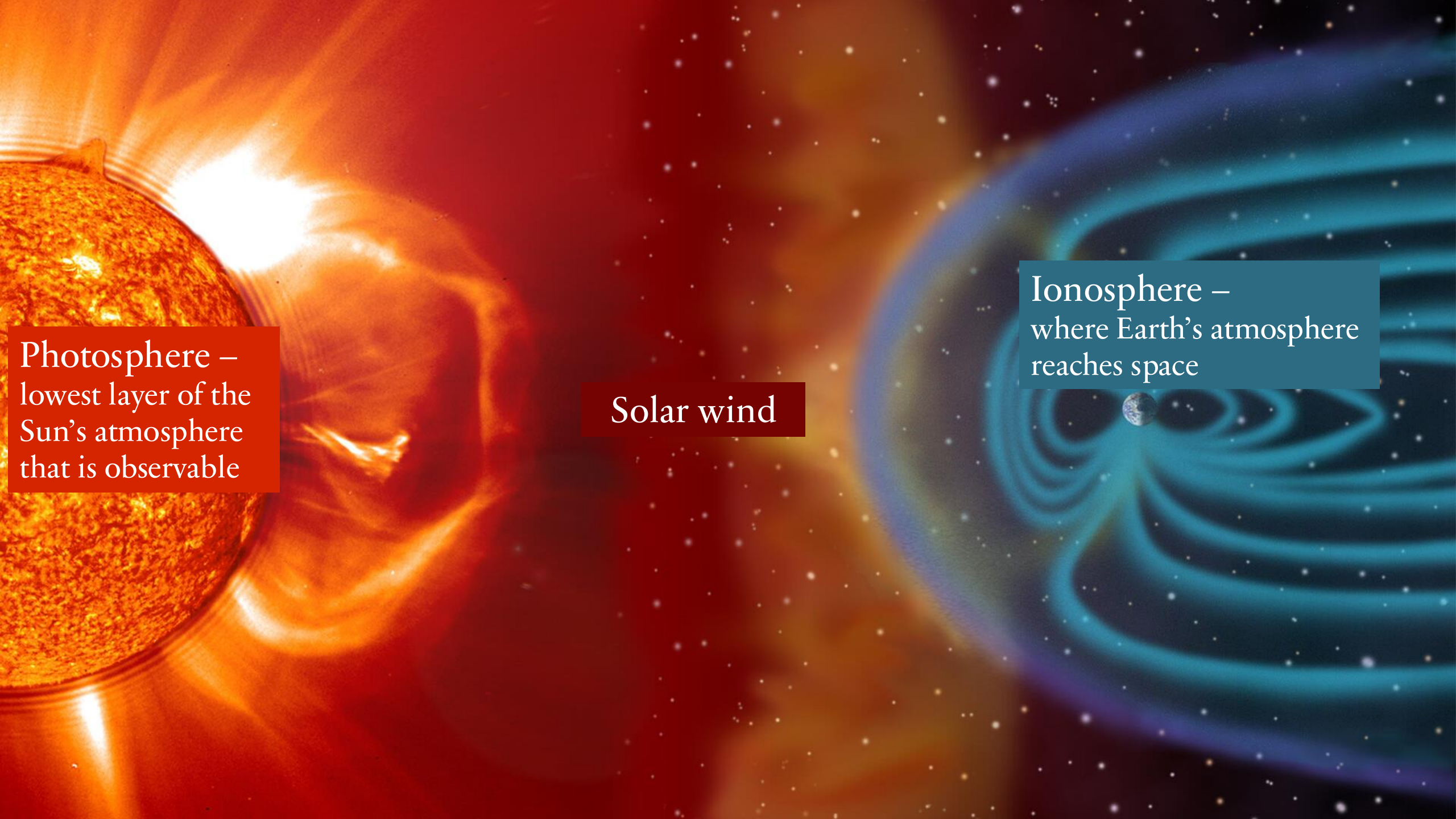
Used in numerical weather prediction and has led to large forecast improvements

Underused in space weather

DA IN SPACE WEATHER

DA is in its infancy in space weather forecasting

Has been used in 3 main areas – the photosphere, solar wind and ionosphere

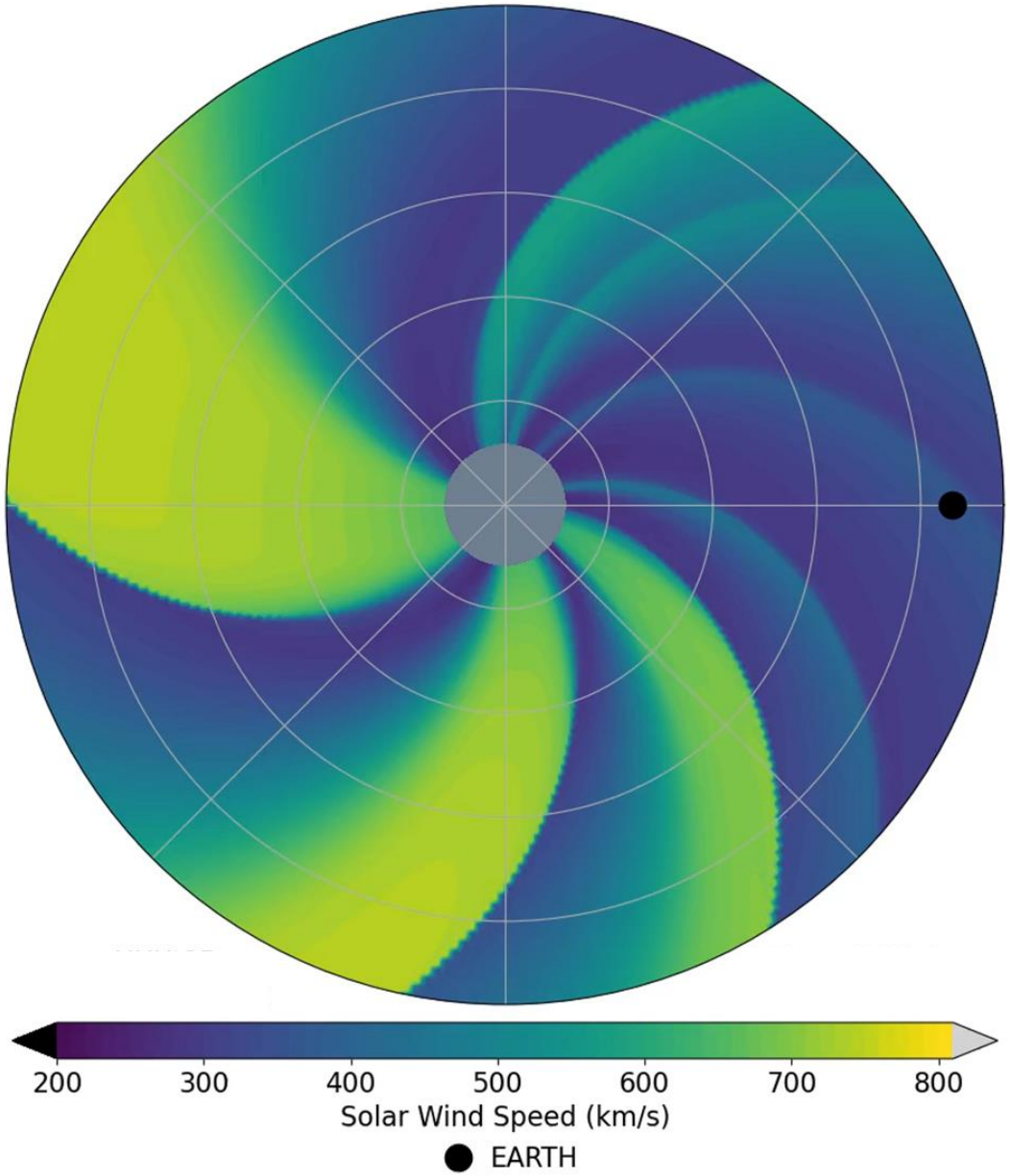

Photosphere –
lowest layer of the
Sun's atmosphere
that is observable
Solar wind
Ionosphere –
where Earth's atmosphere
reaches space

DA IN THE SOLAR WIND

I have been using the Burger Radius Variational Data Assimilation (BRaVDA) scheme developed at the University of Reading (Lang et al., 2019)

Combines observations with a steady-state solar wind model

Prior inner boundary condition from a coronal model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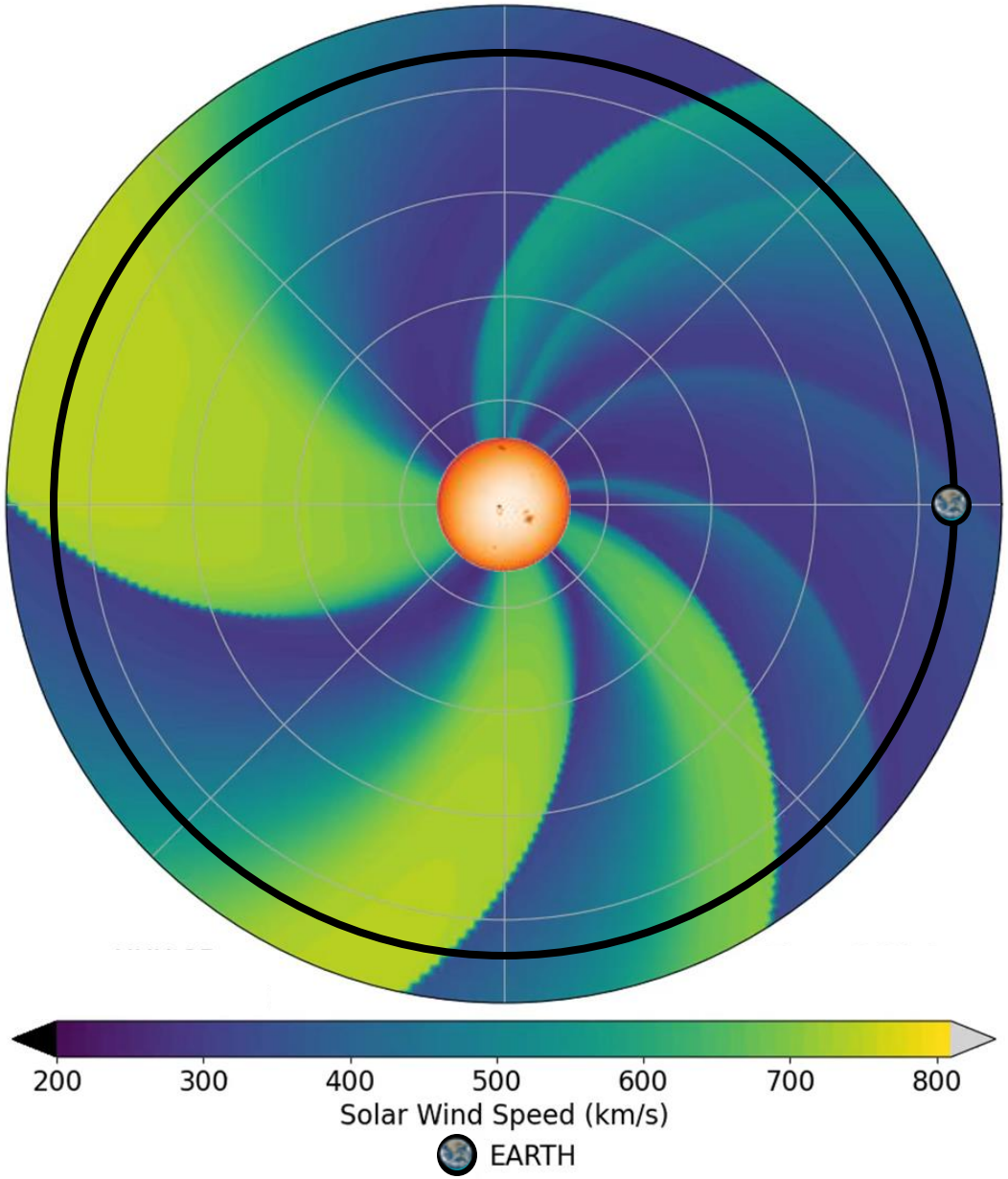
Solar Wind Speed (km/s)
EARTH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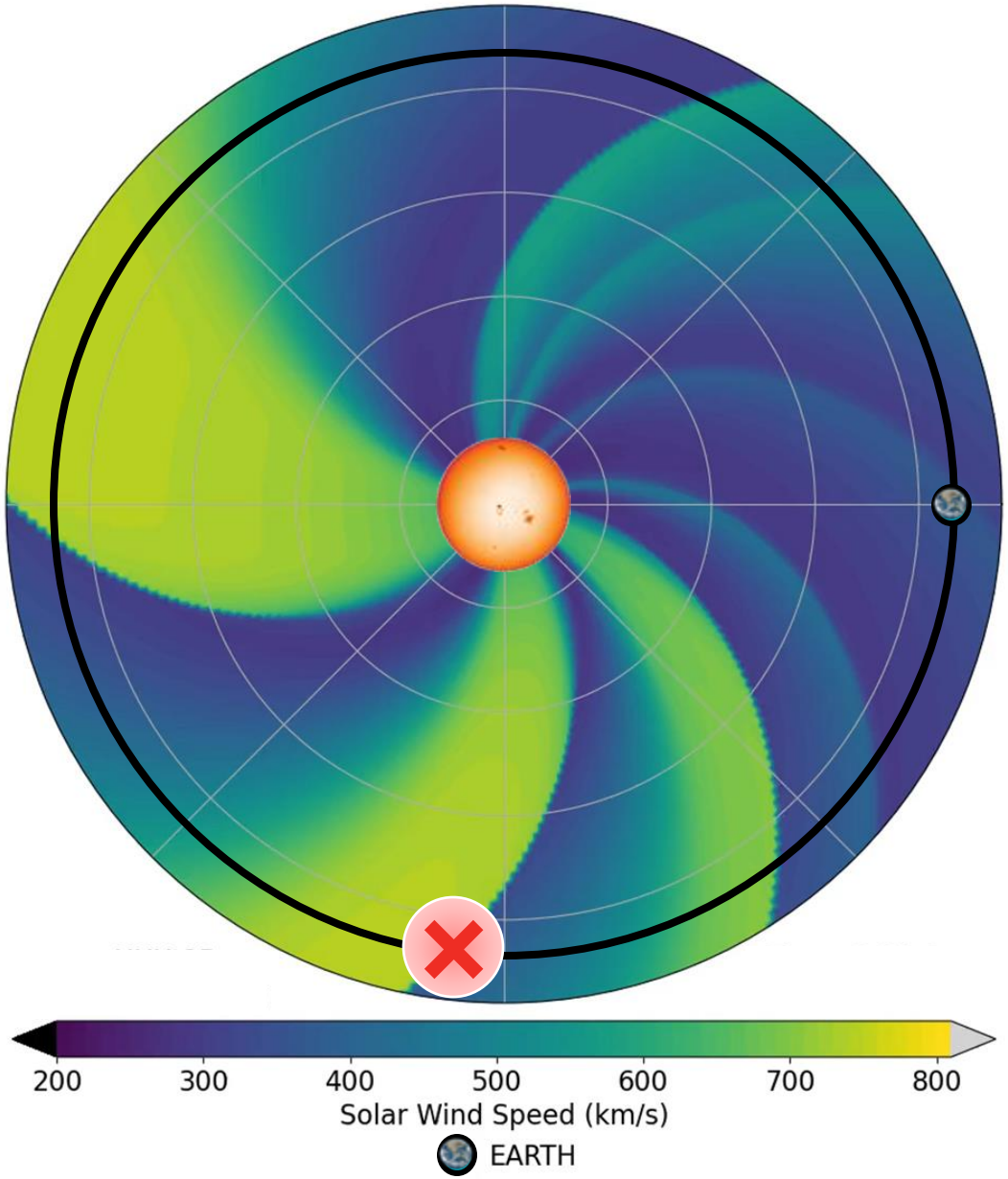
Solar Wind Speed (km/s)
EARTH

Time = t_0

✕ = observation



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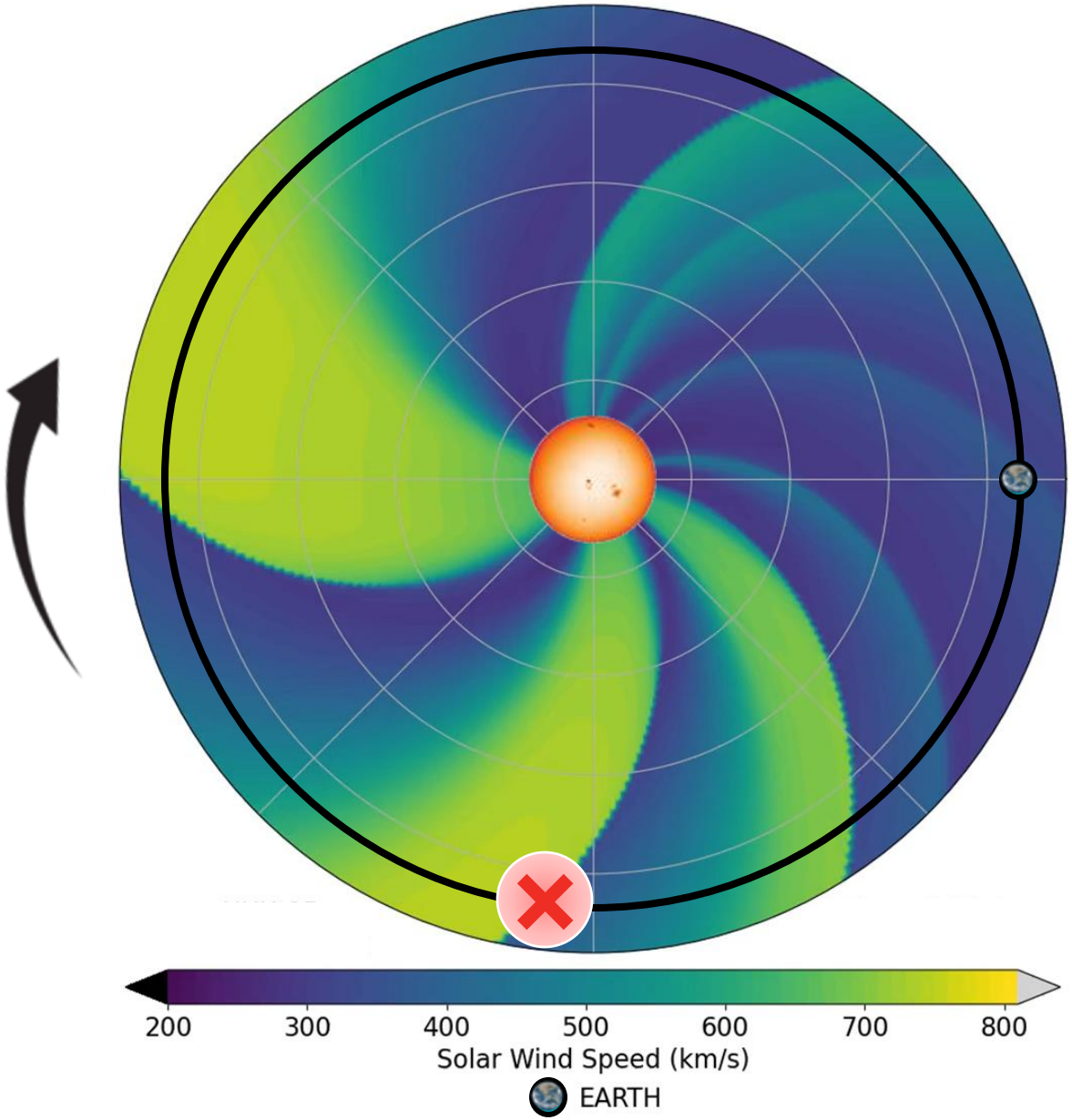

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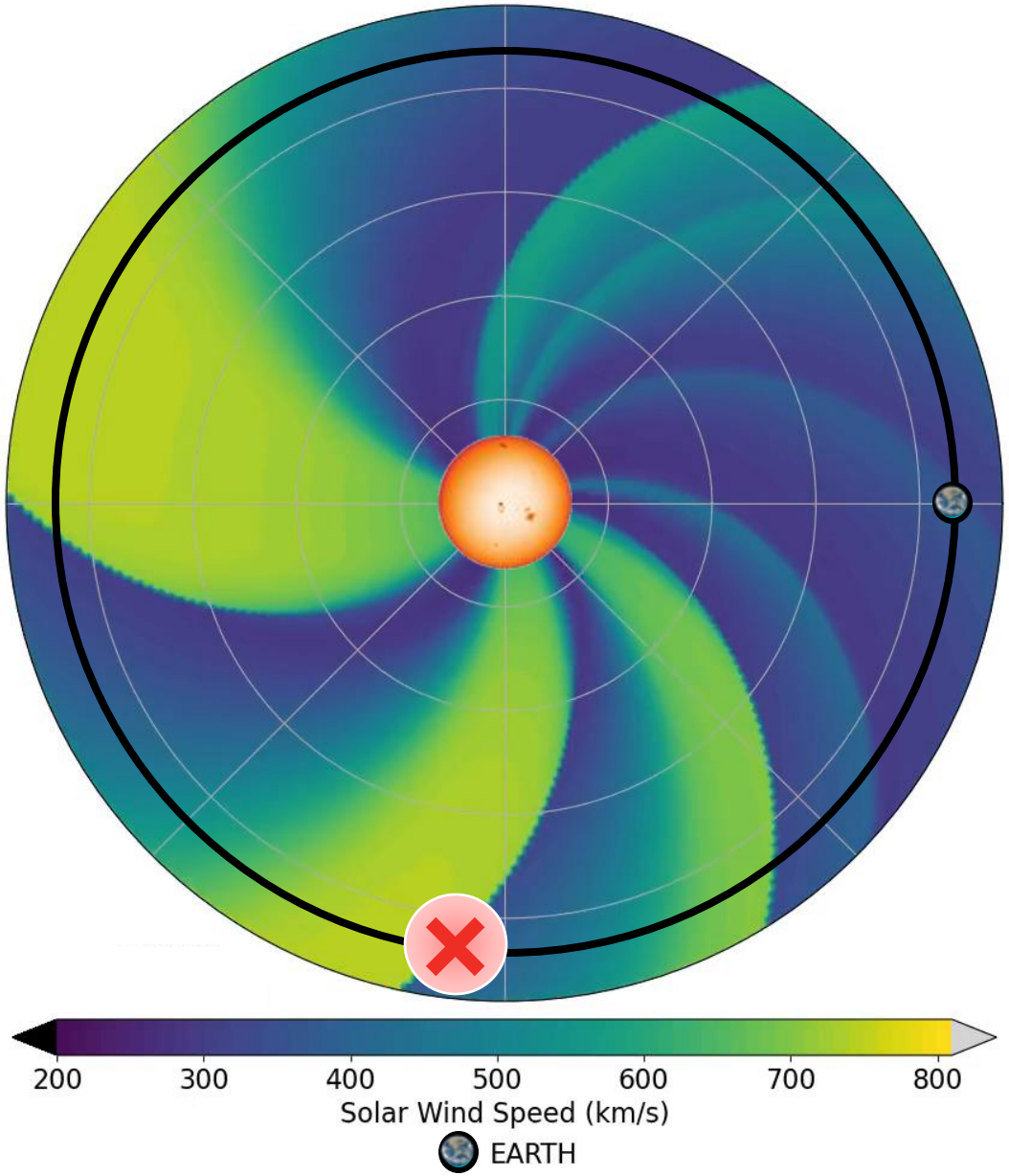
✕ = observation



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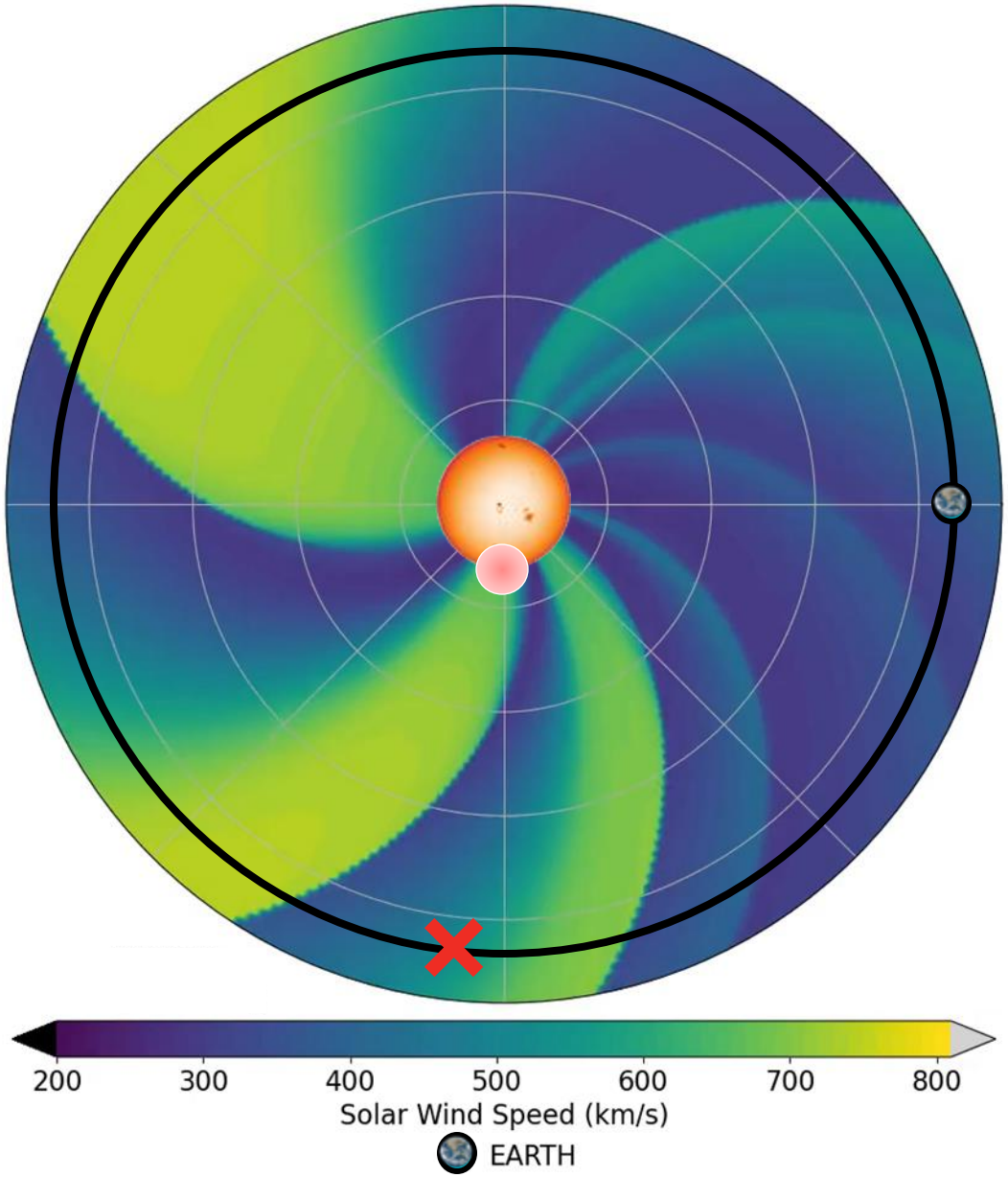

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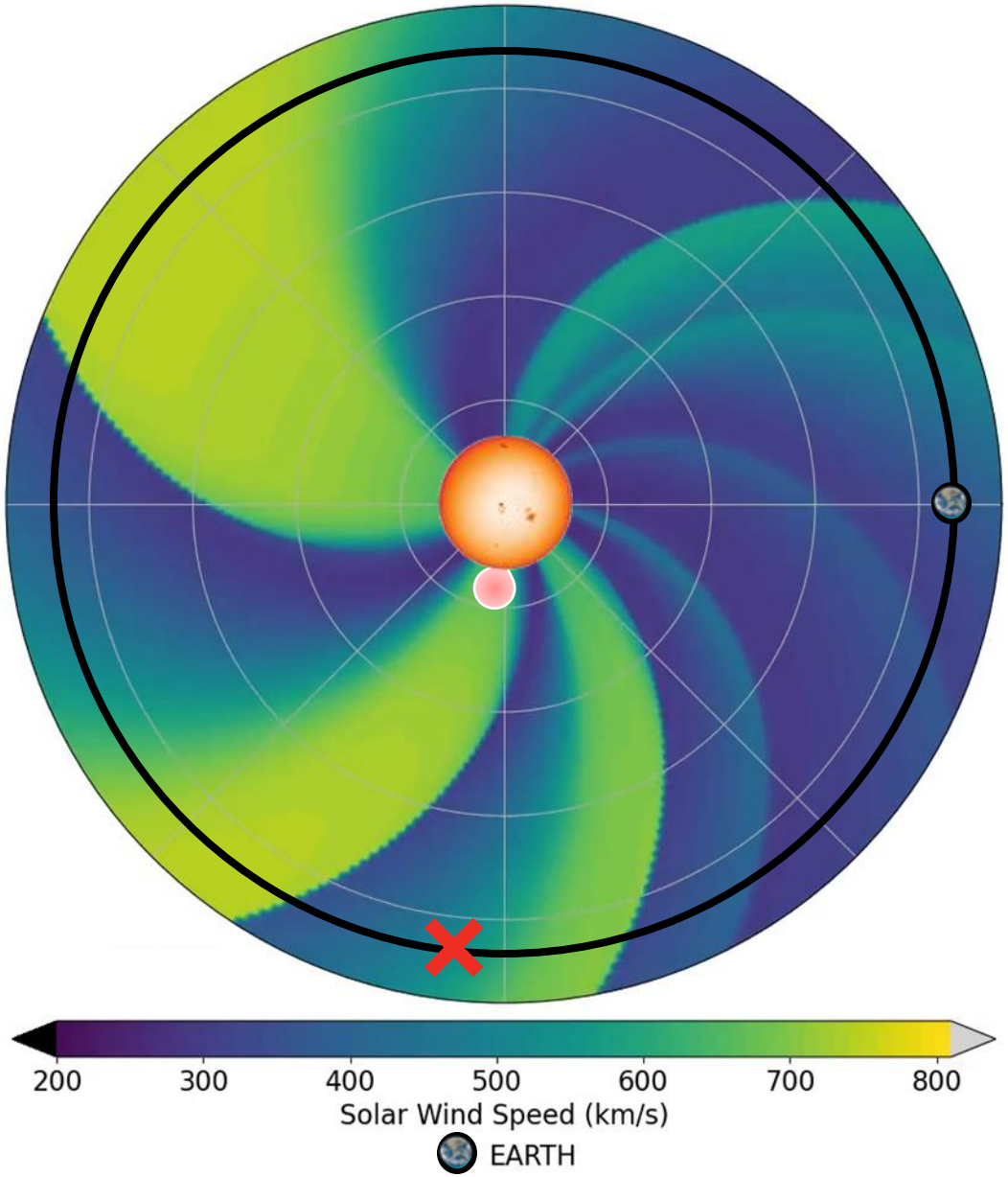

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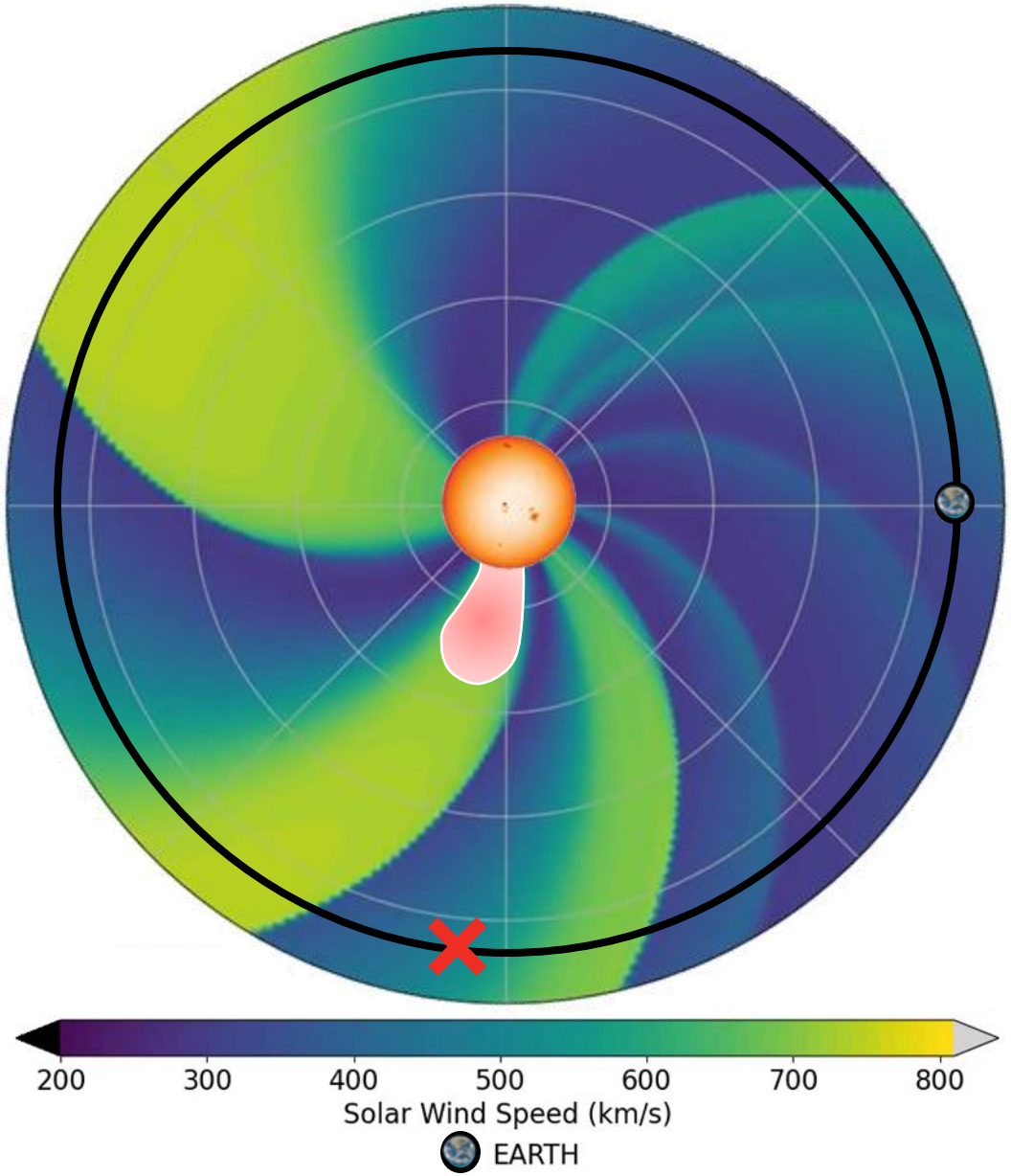

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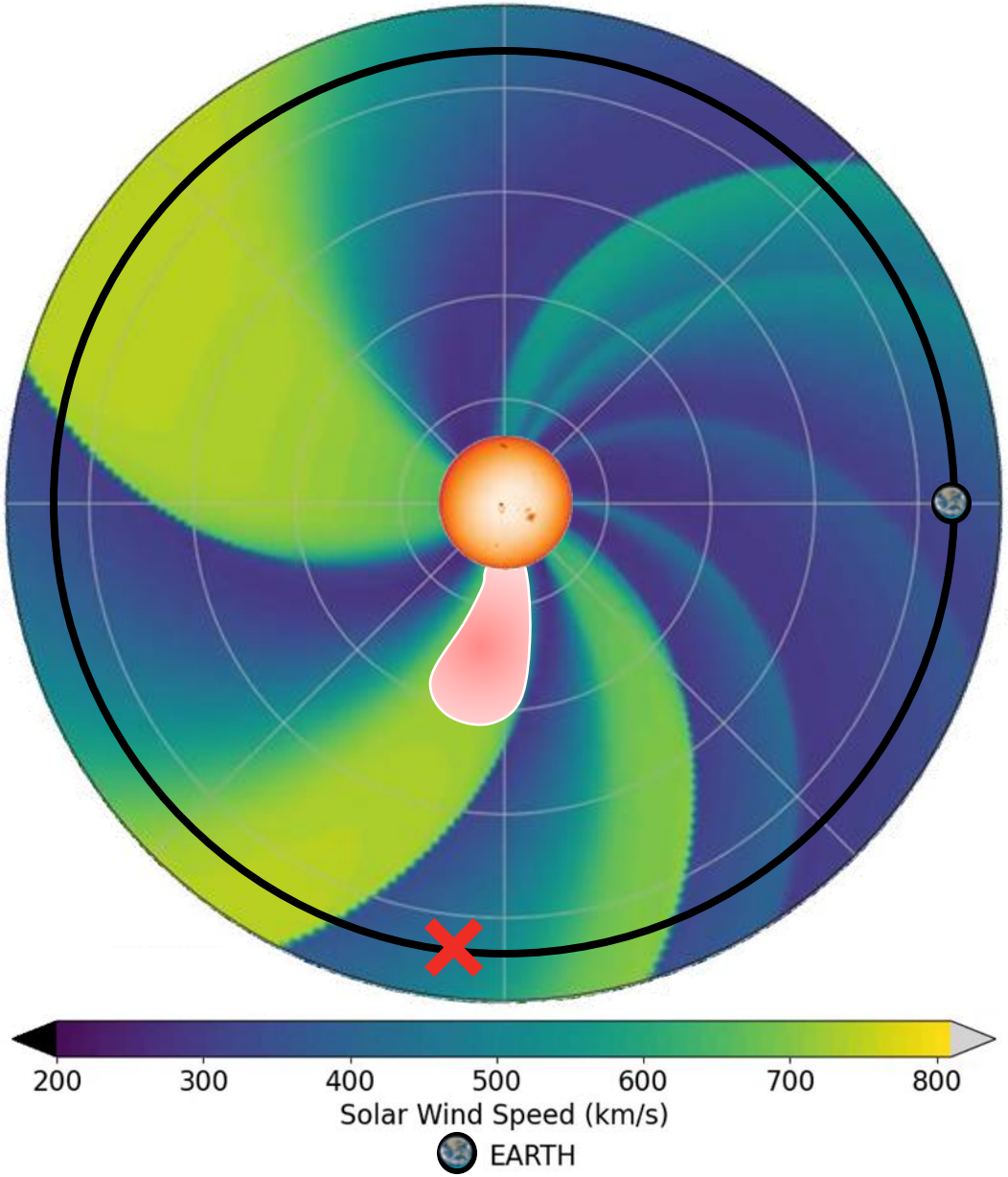

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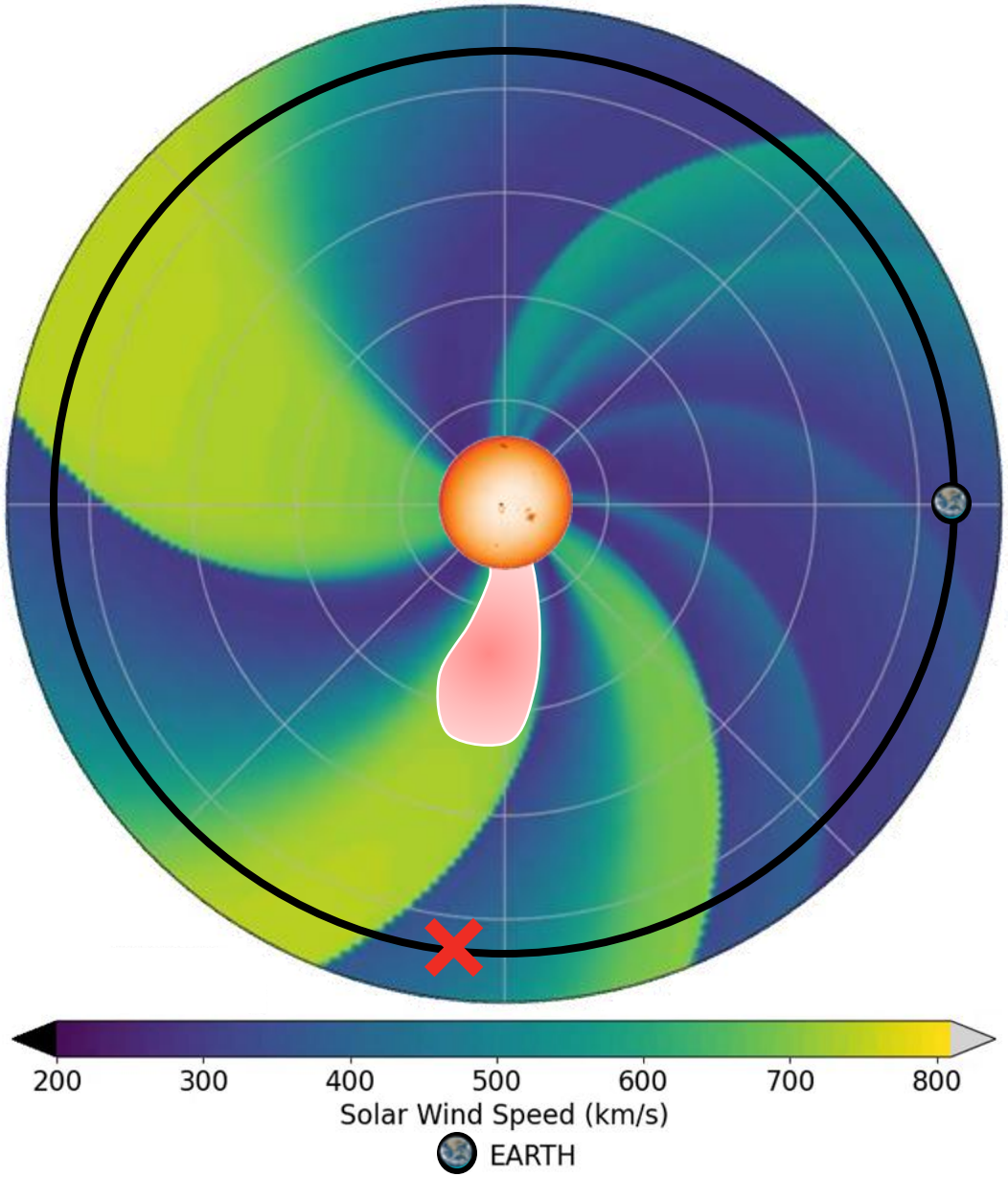

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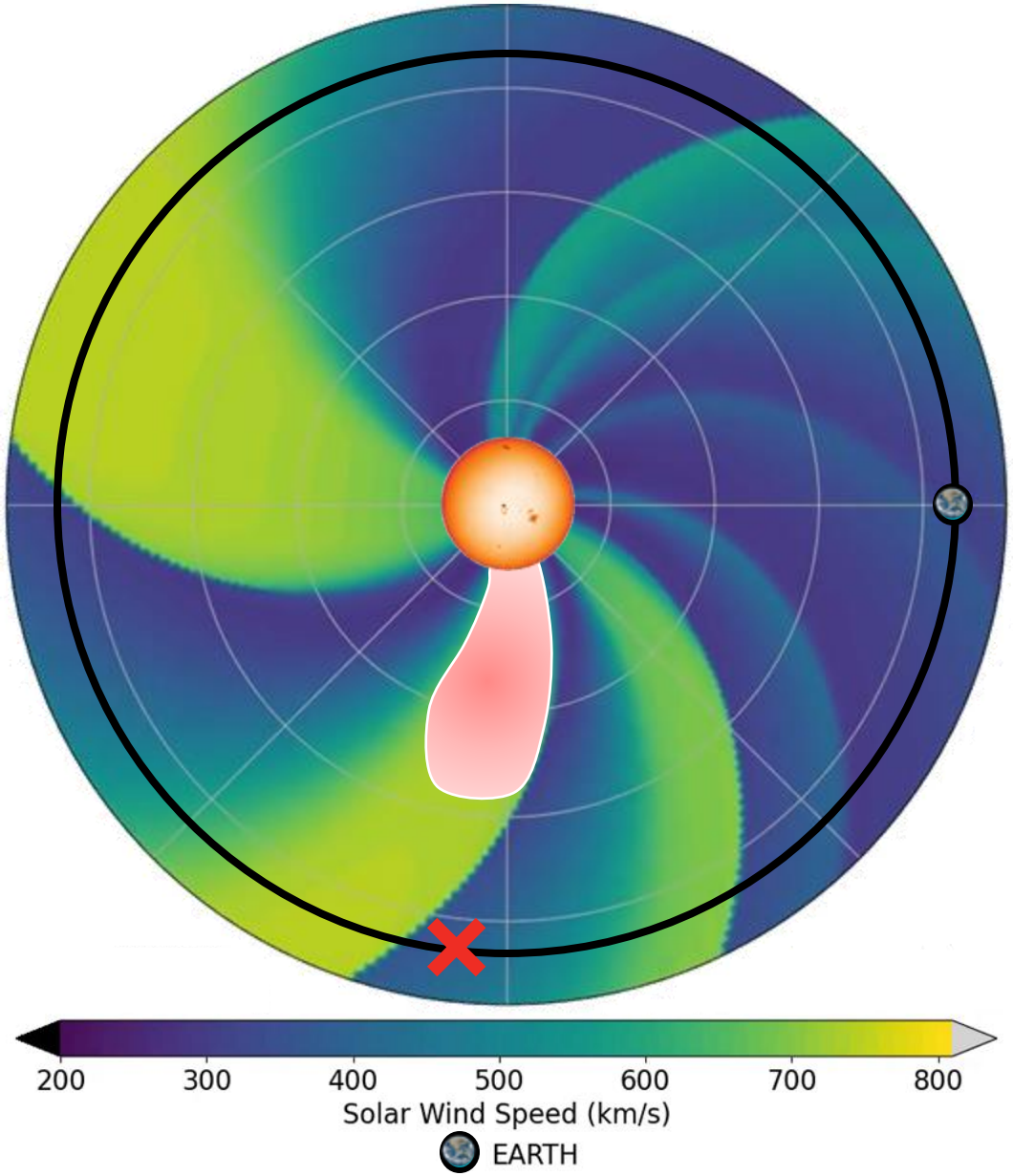

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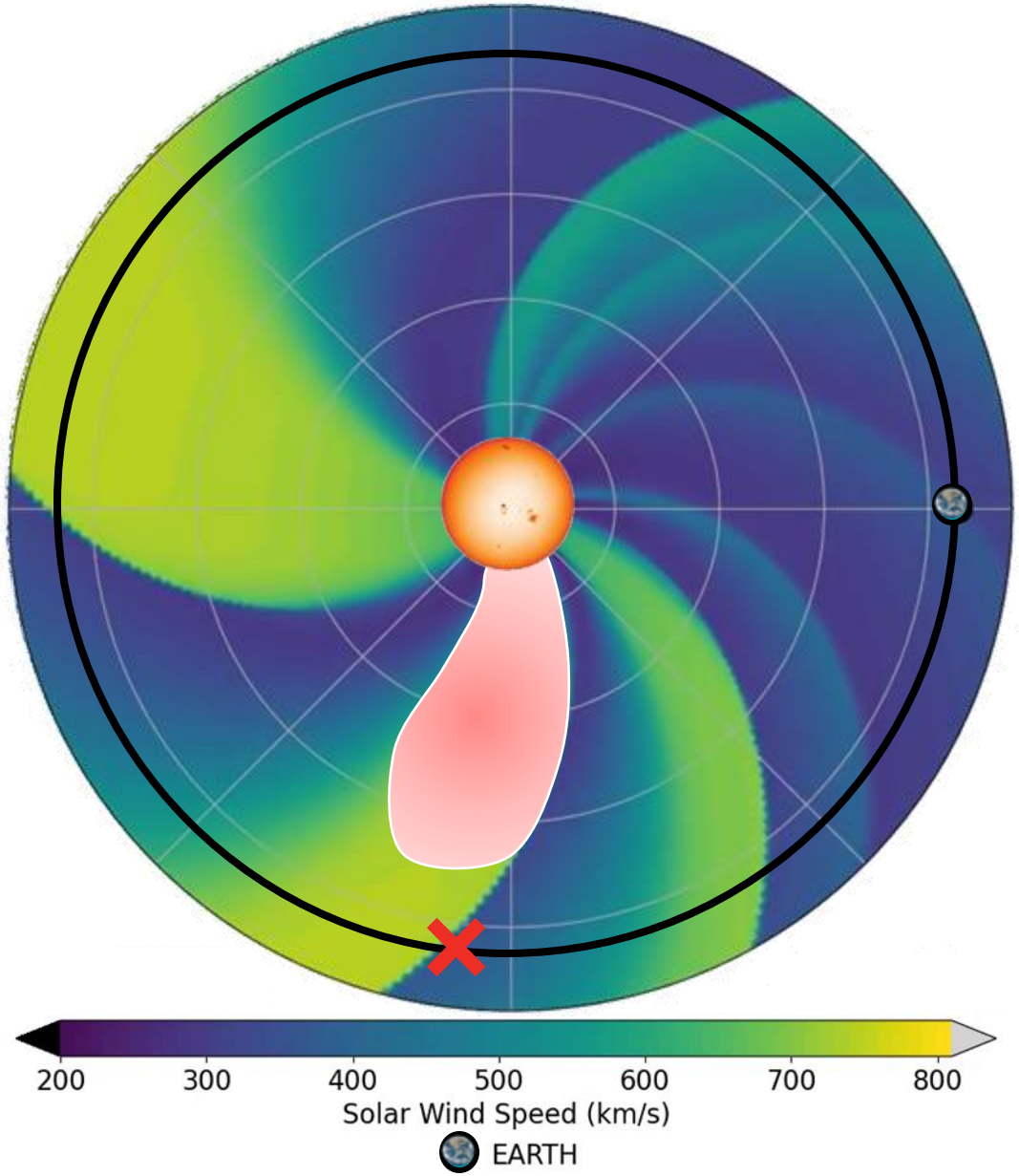

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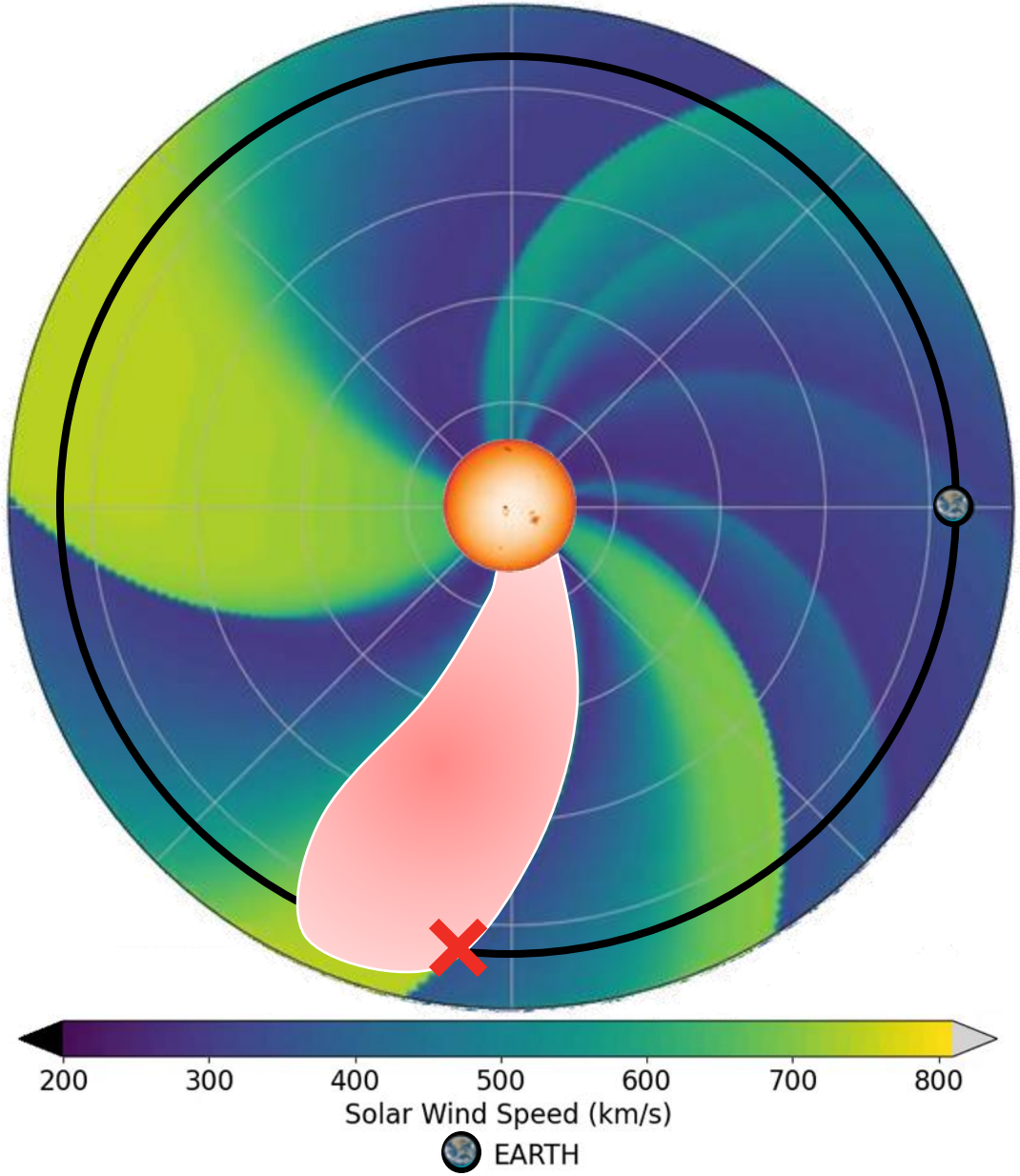

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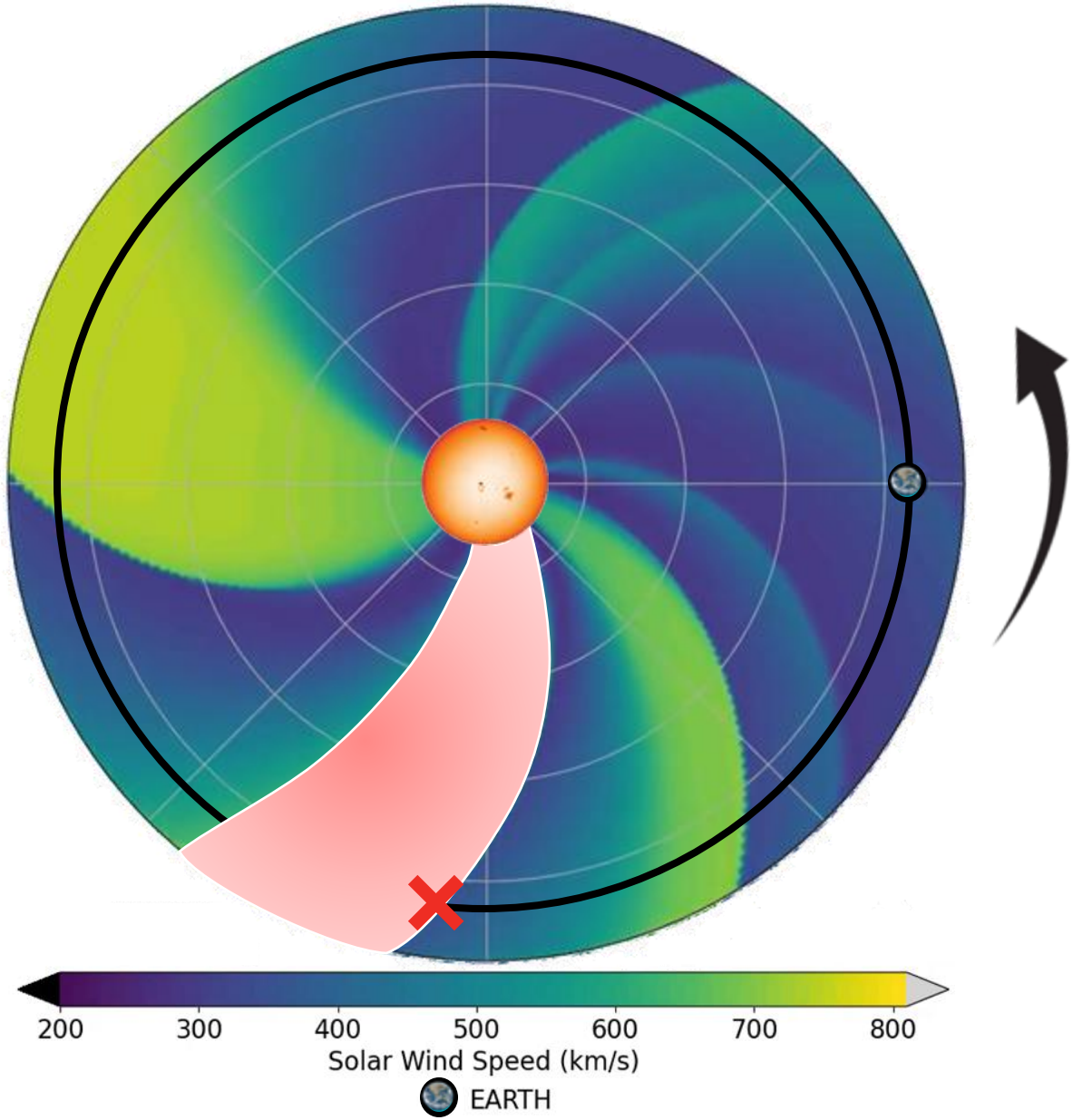

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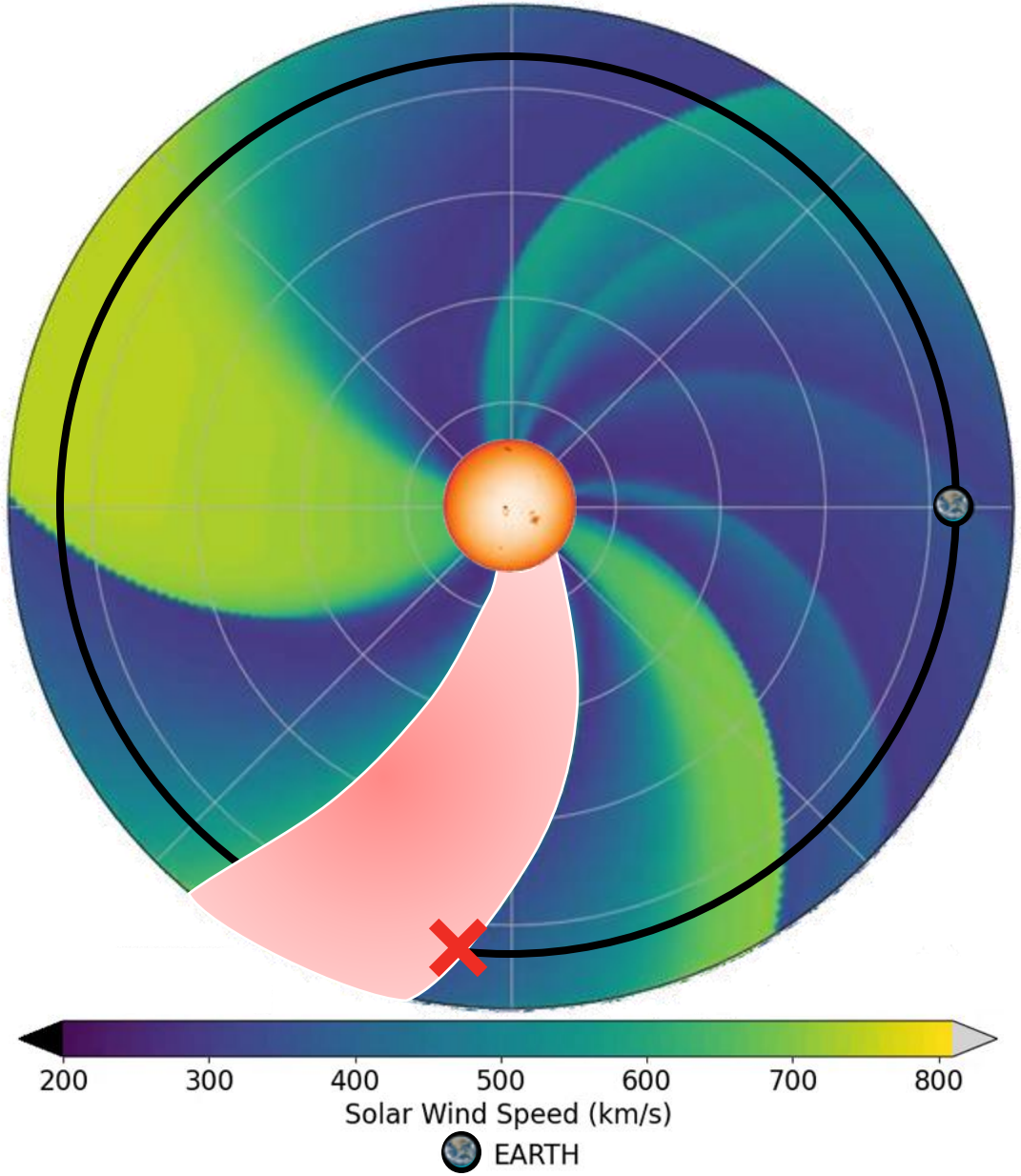
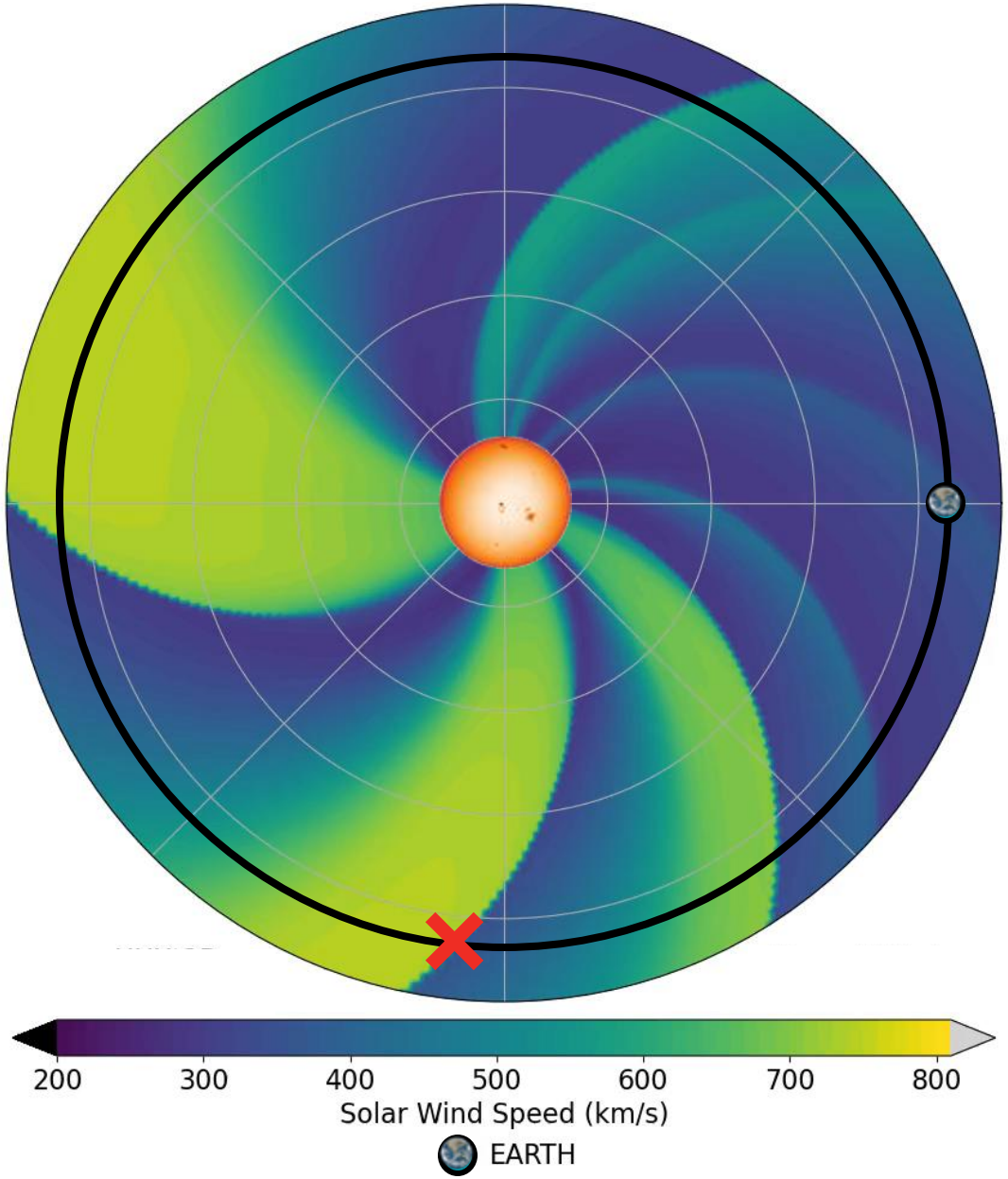


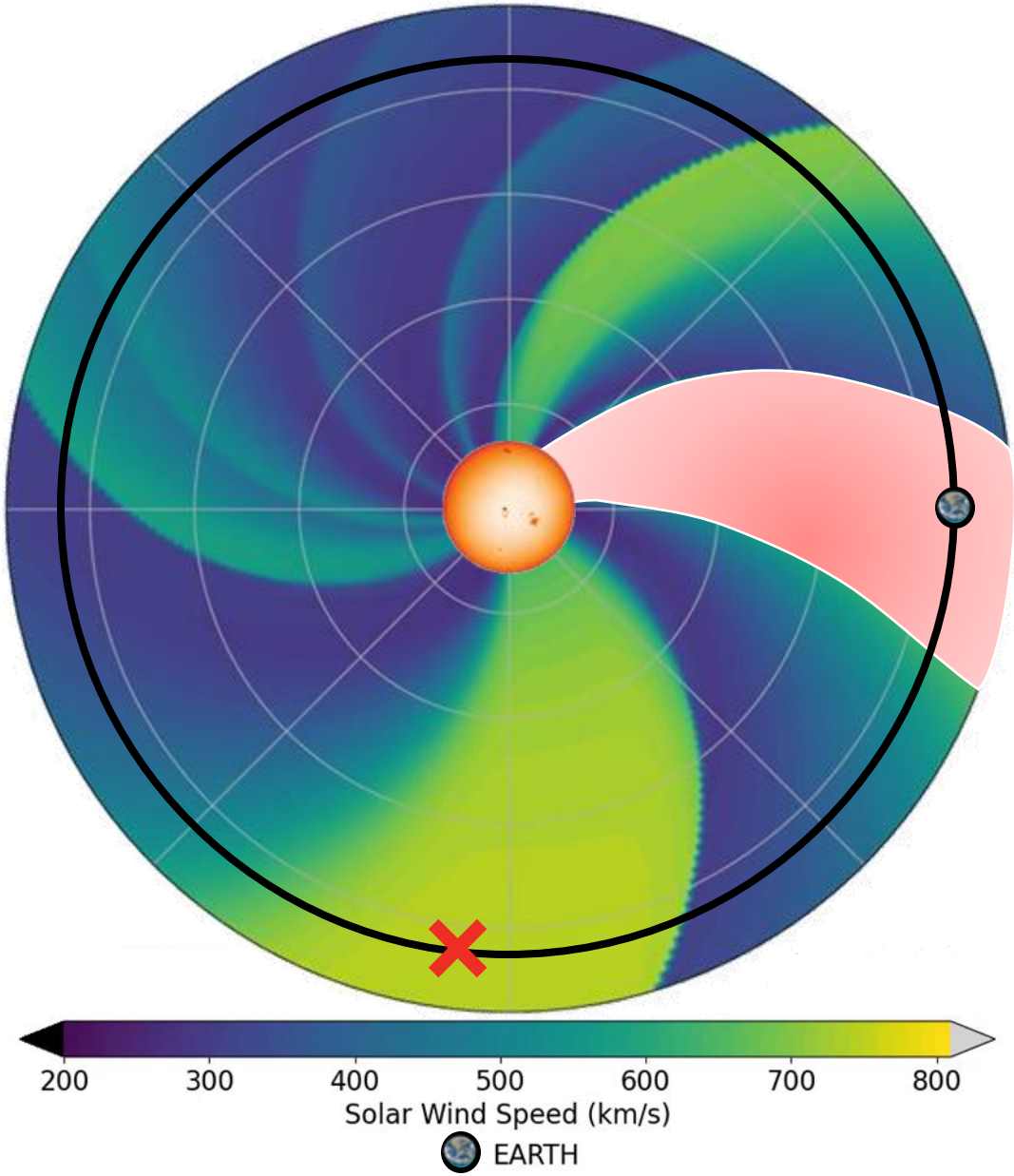
Time = t_0

✕ = observation



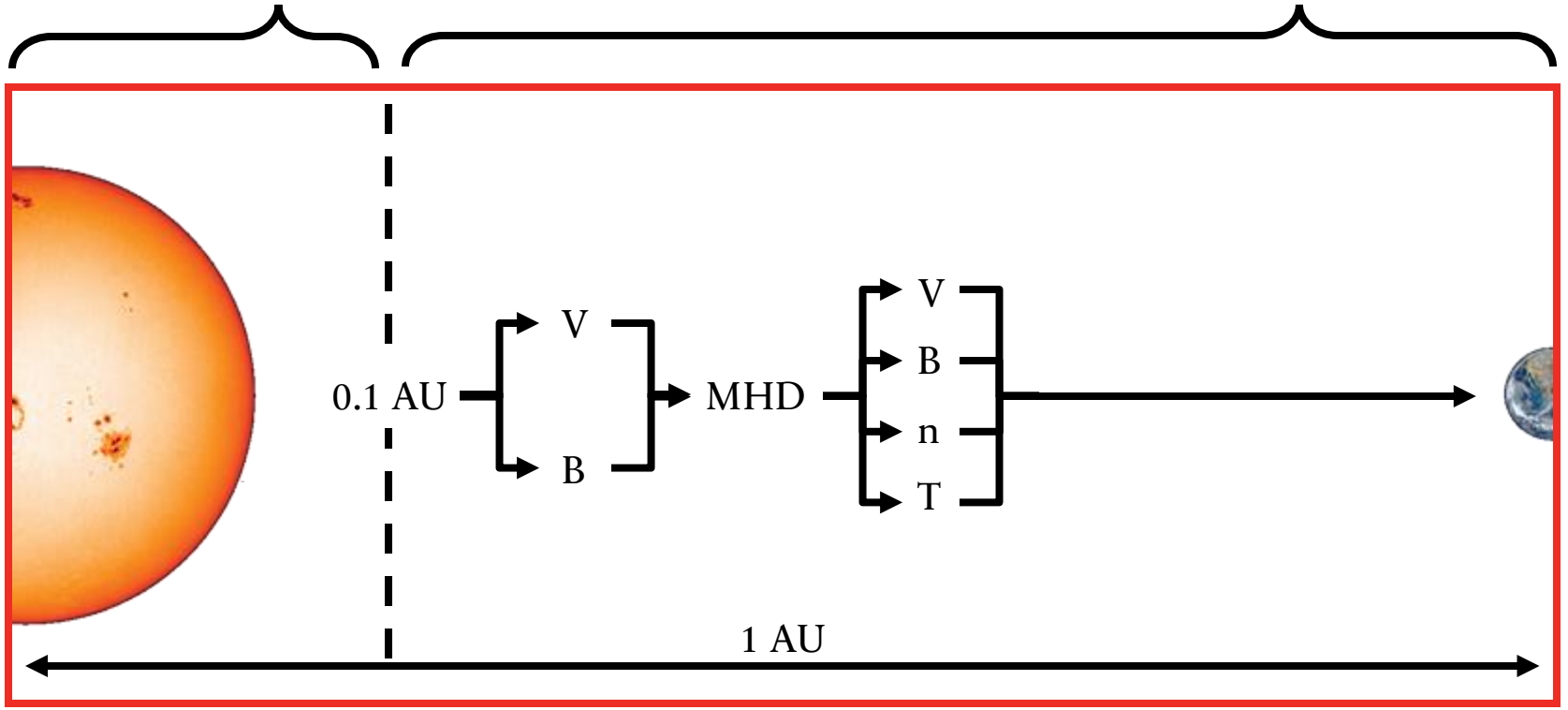
Time = $t_0 + \Delta t$

✕ = observation



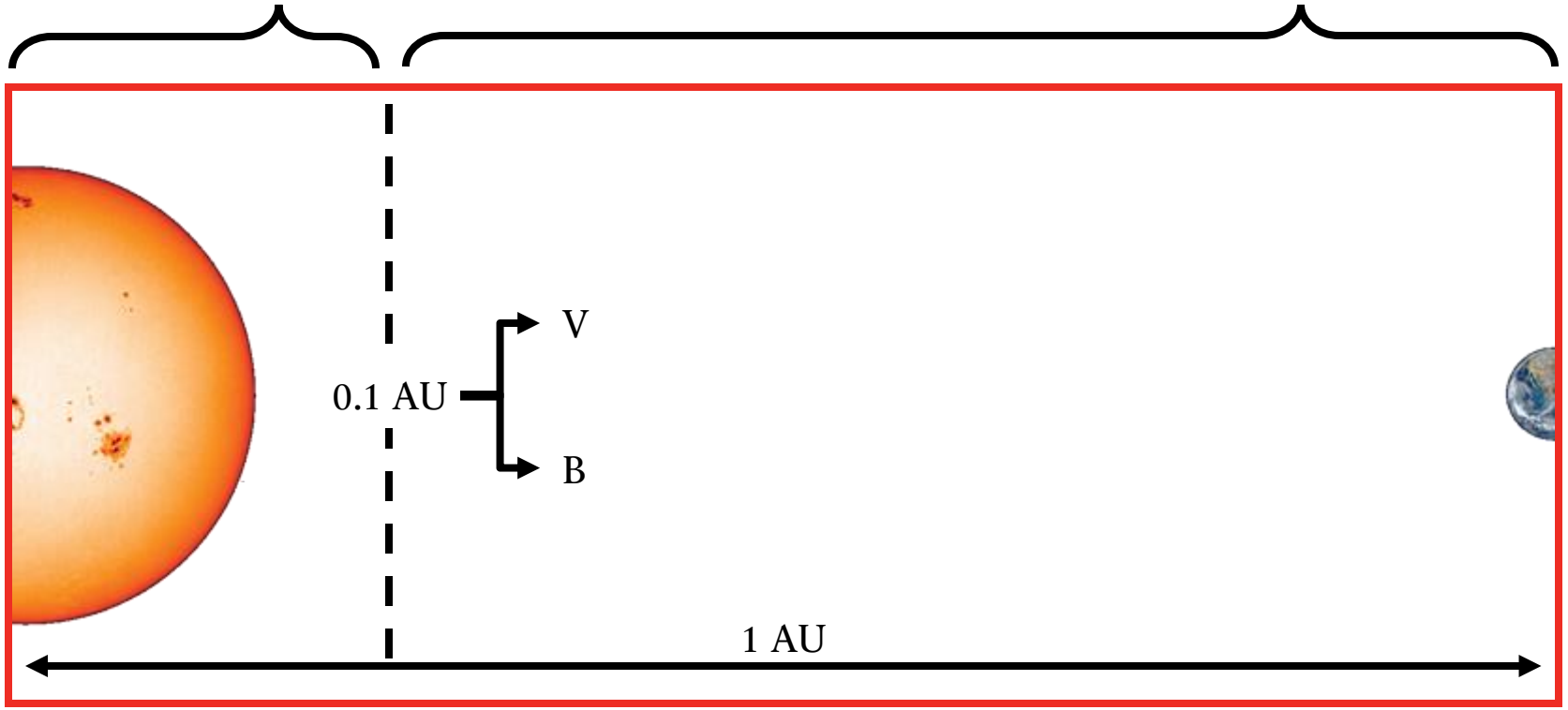
CURRENT FORECASTING

Typically a **coronal model** coupled to a **heliospheric model**



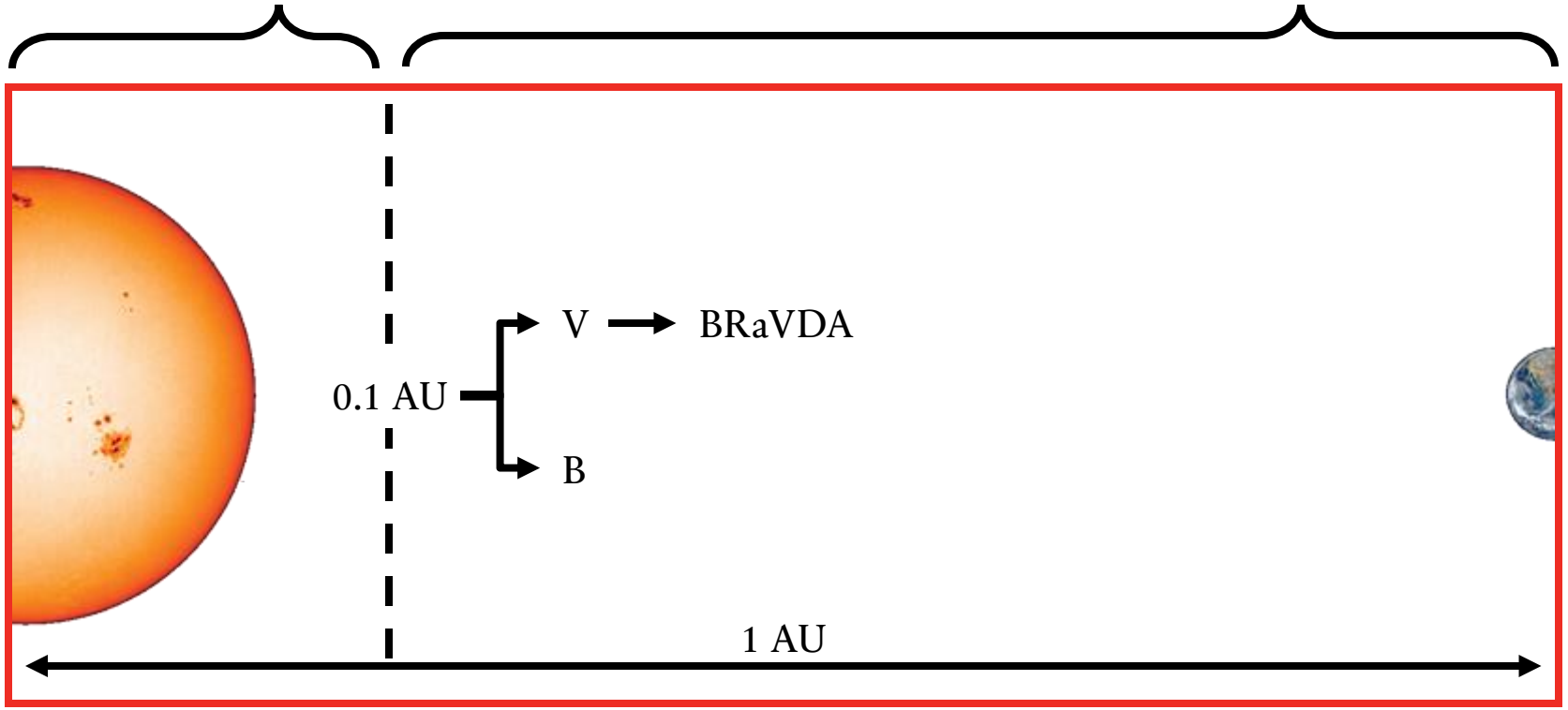
COROTATION USING DA

Typically a **coronal model** coupled to a **heliospheric model**



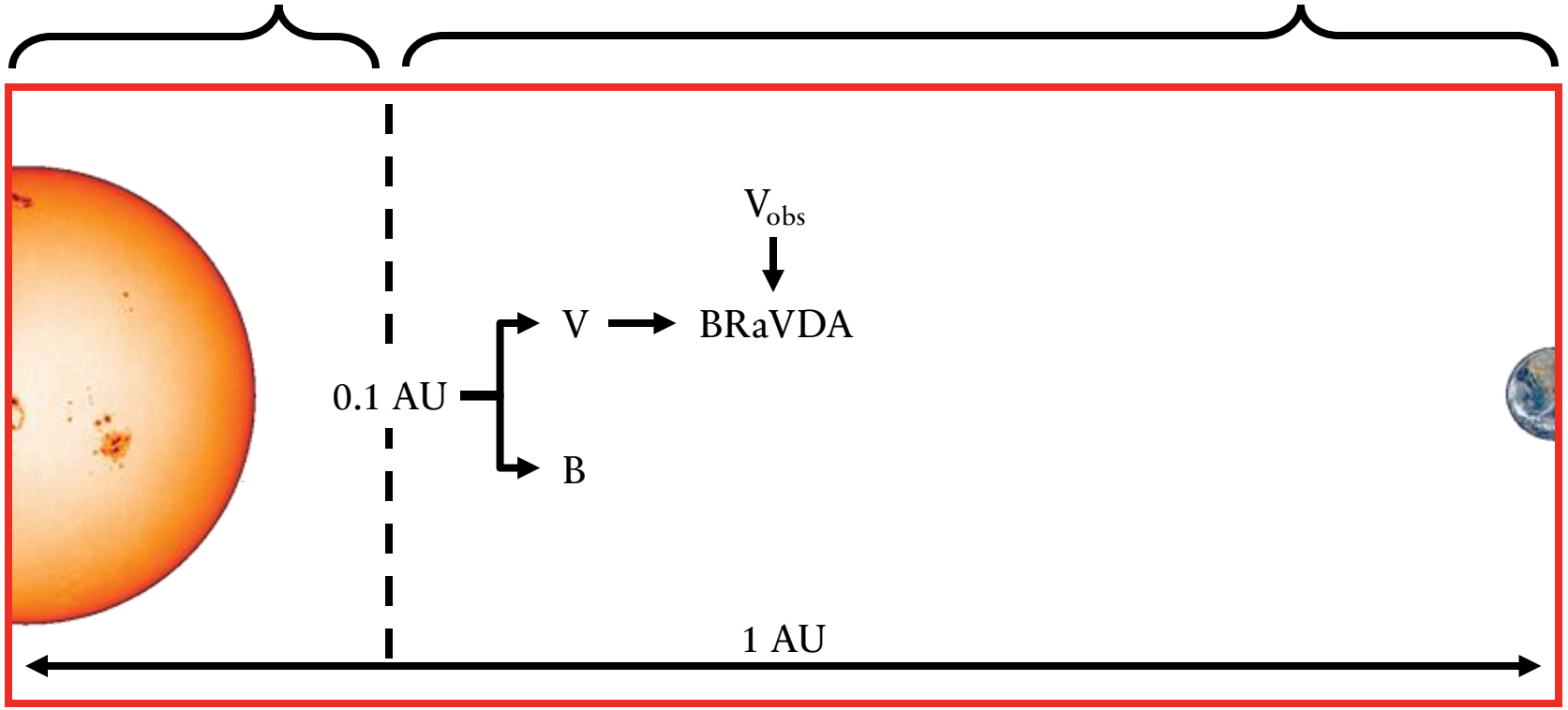
COROTATION USING DA

Typically a **coronal model** coupled to a **heliospheric model**



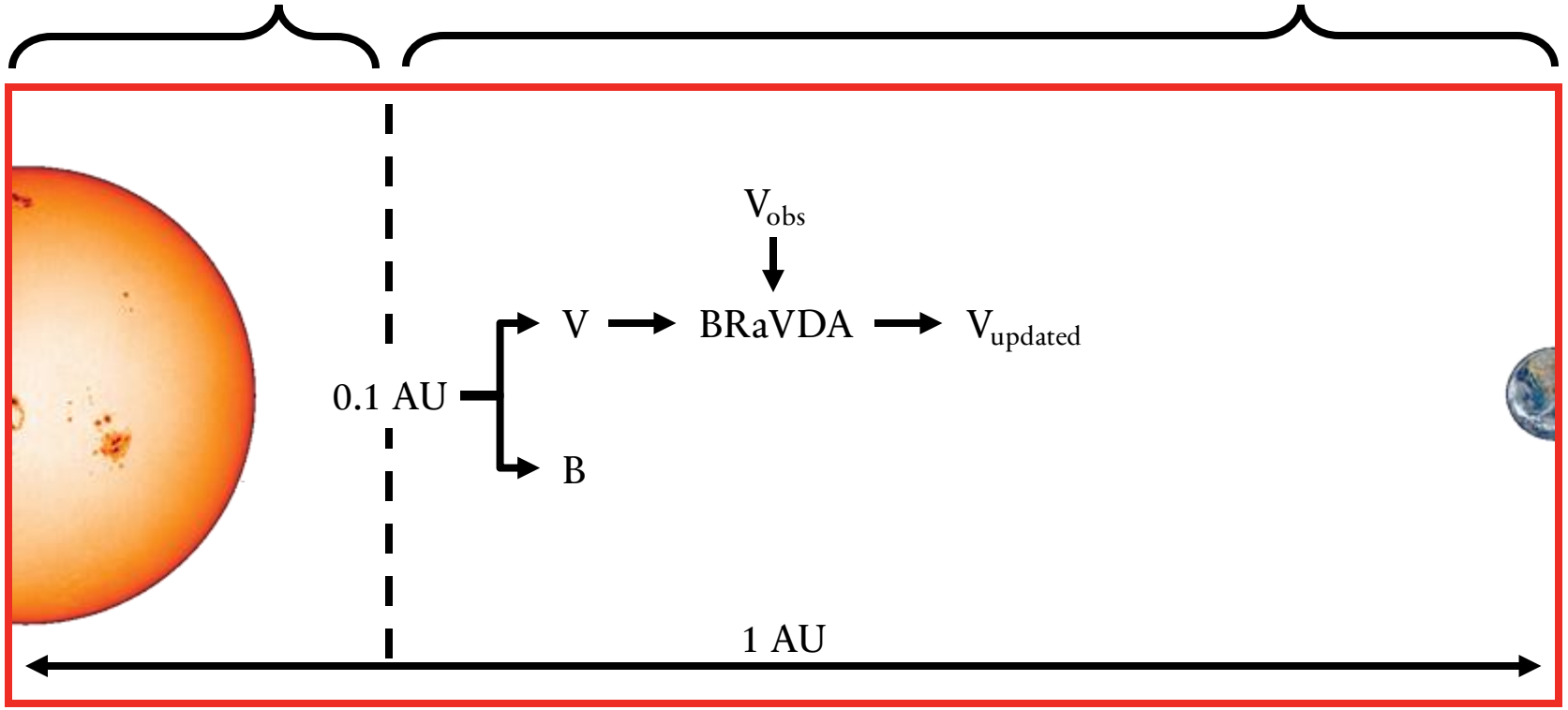
COROTATION USING DA

Typically a **coronal model** coupled to a **heliospheric model**



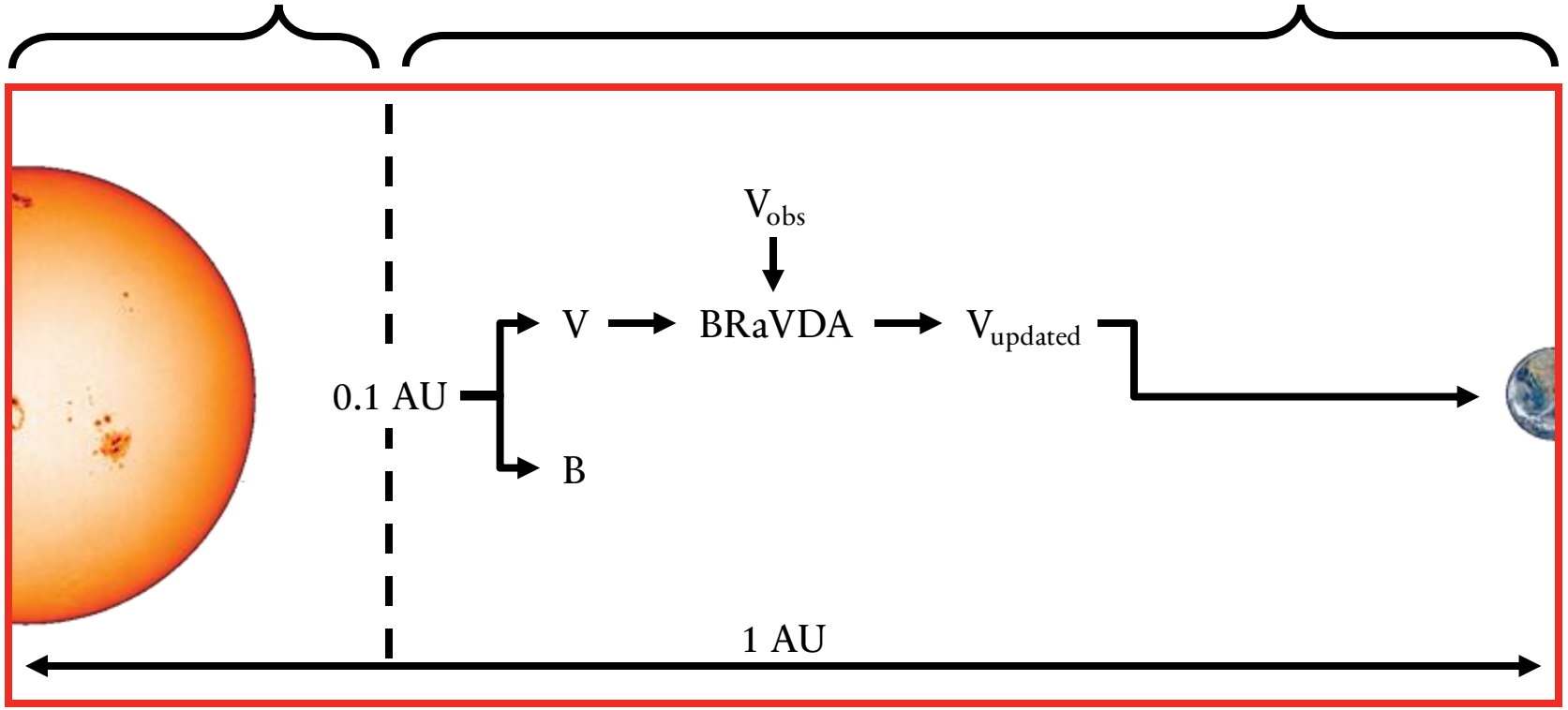
COROTATION USING DA

Typically a **coronal model** coupled to a **heliospheric model**



COROTATION USING DA

Typically a **coronal model** coupled to a **heliospheric model**



OBSERVATIONS – STEREO

Solar Terrestrial Relations Observatory Ahead and Behind – STEREO-A and B

Earth-like orbits, but separating in longitude

Launched in 2007

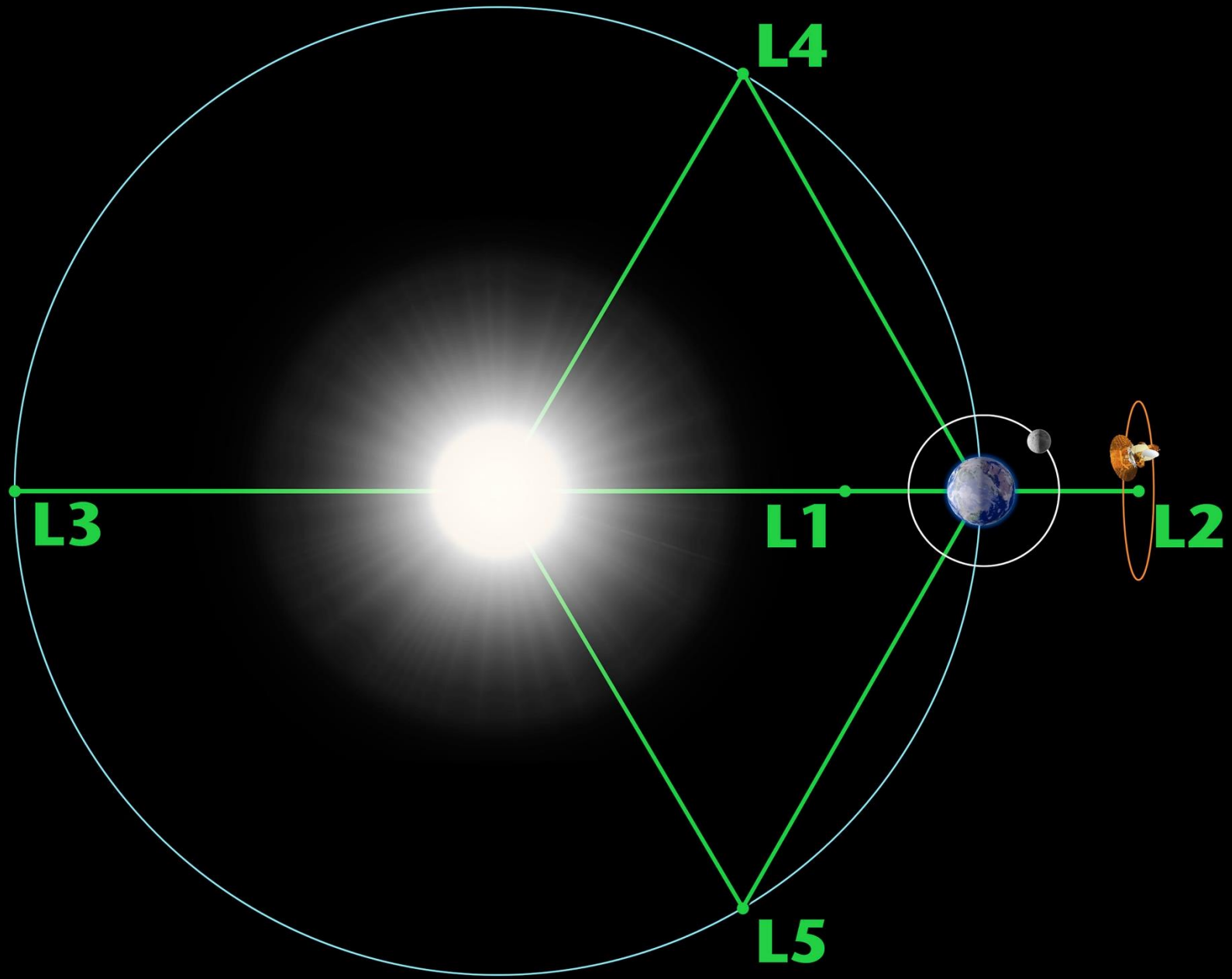
Communication with STEREO-B lost in 2014

OBSERVATIONS – ACE & DSCOVR

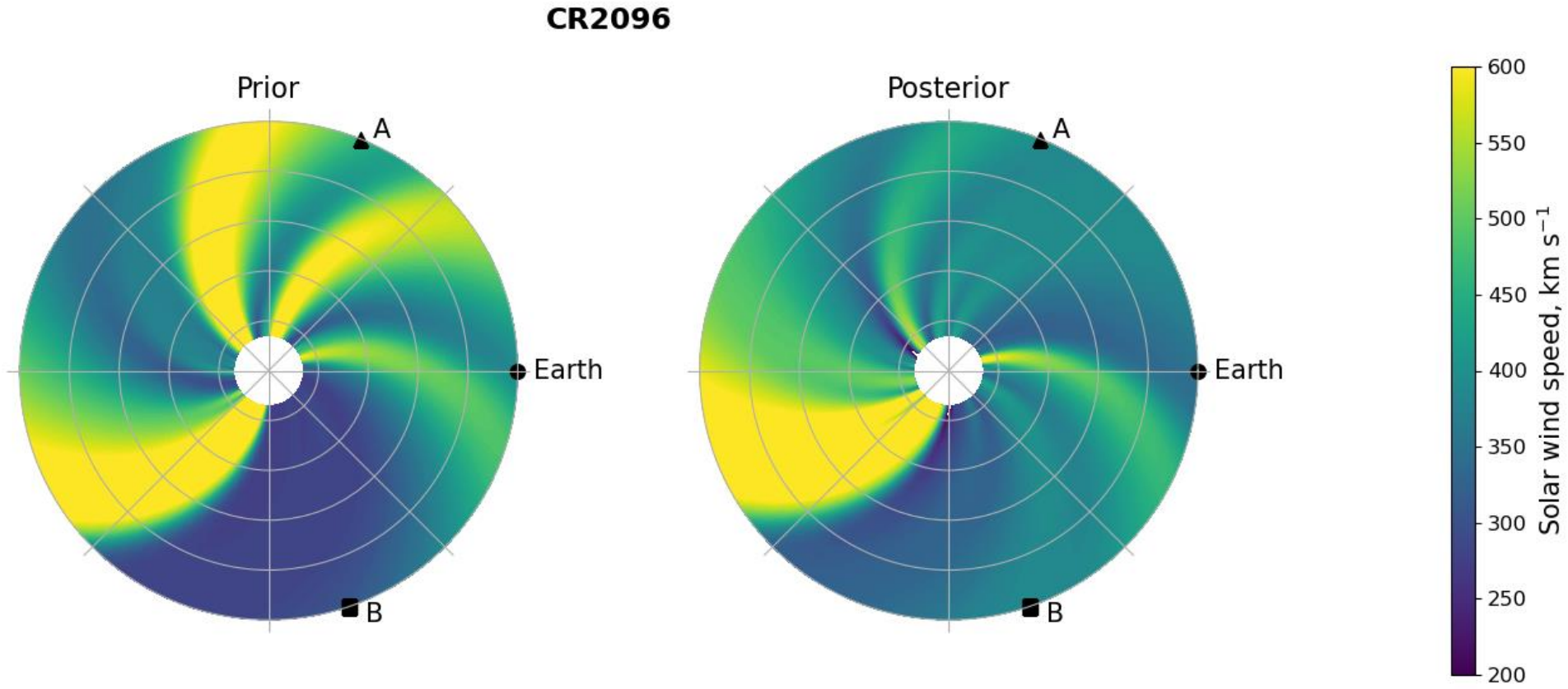
Advanced Composition Explorer – ACE (launched 1997)

Deep Space Climate Observatory – DSCOVR (launched 2015)

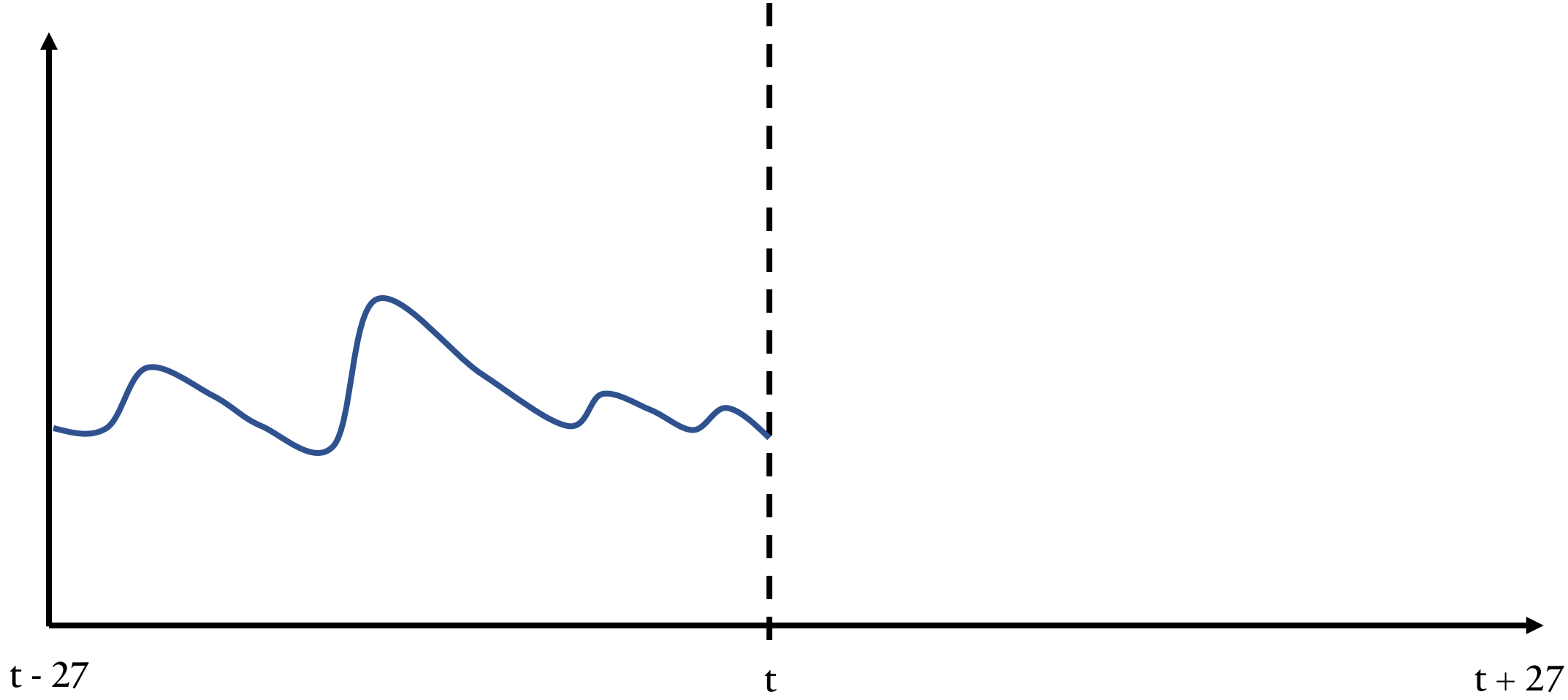
Both give near-Earth observations from L1


L4
L3
L1
L2
L5

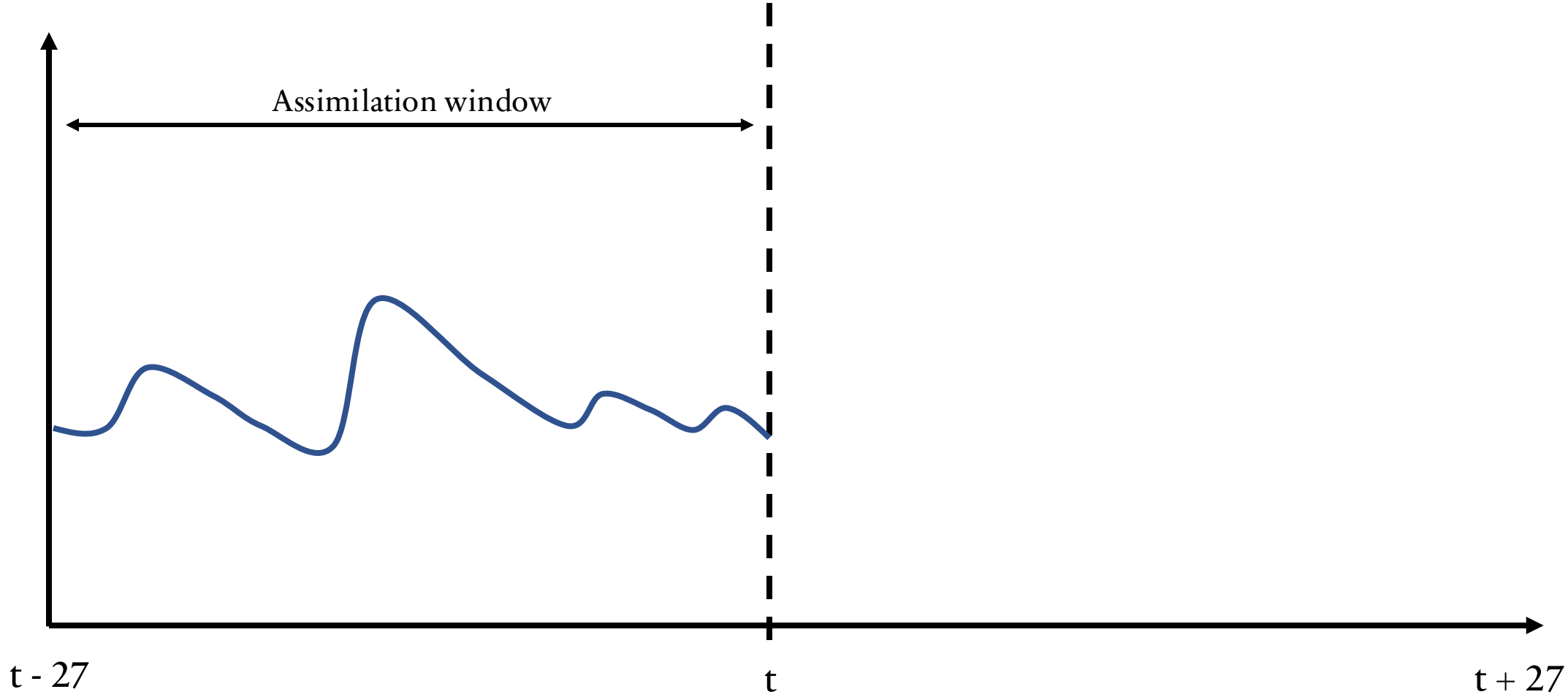
DA OUTPUT – POLAR



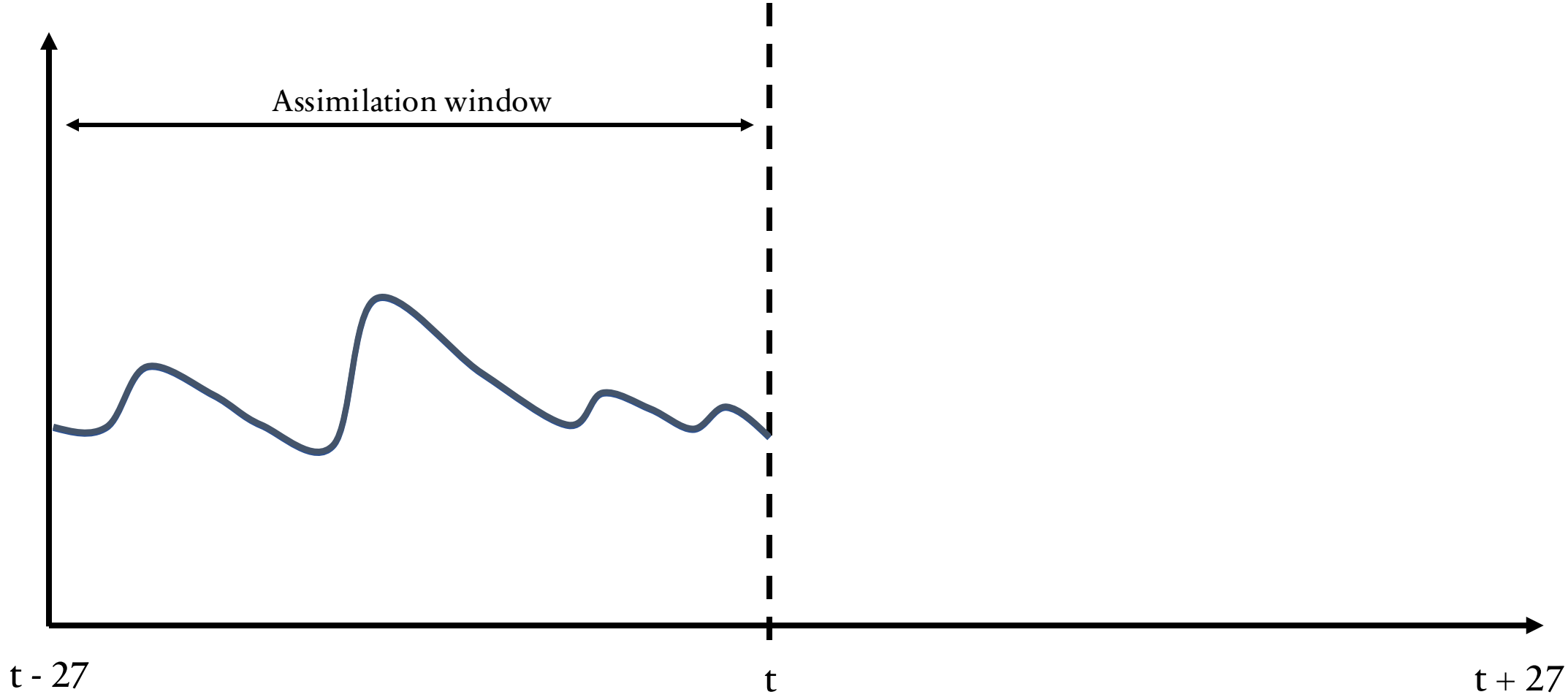
FORECASTING USING OUTPUT



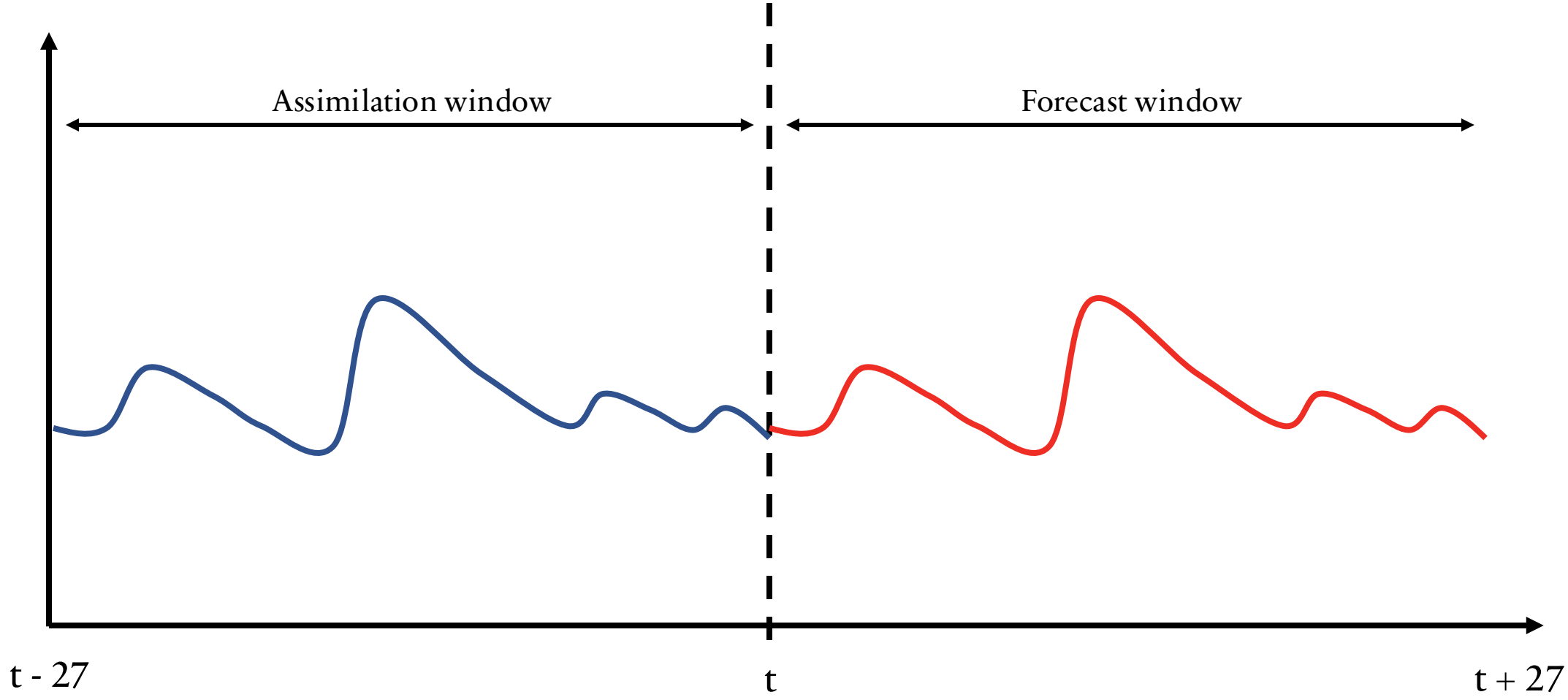
FORECASTING USING OUTPUT



FORECASTING USING OUTPUT



FORECASTING USING OUTPUT



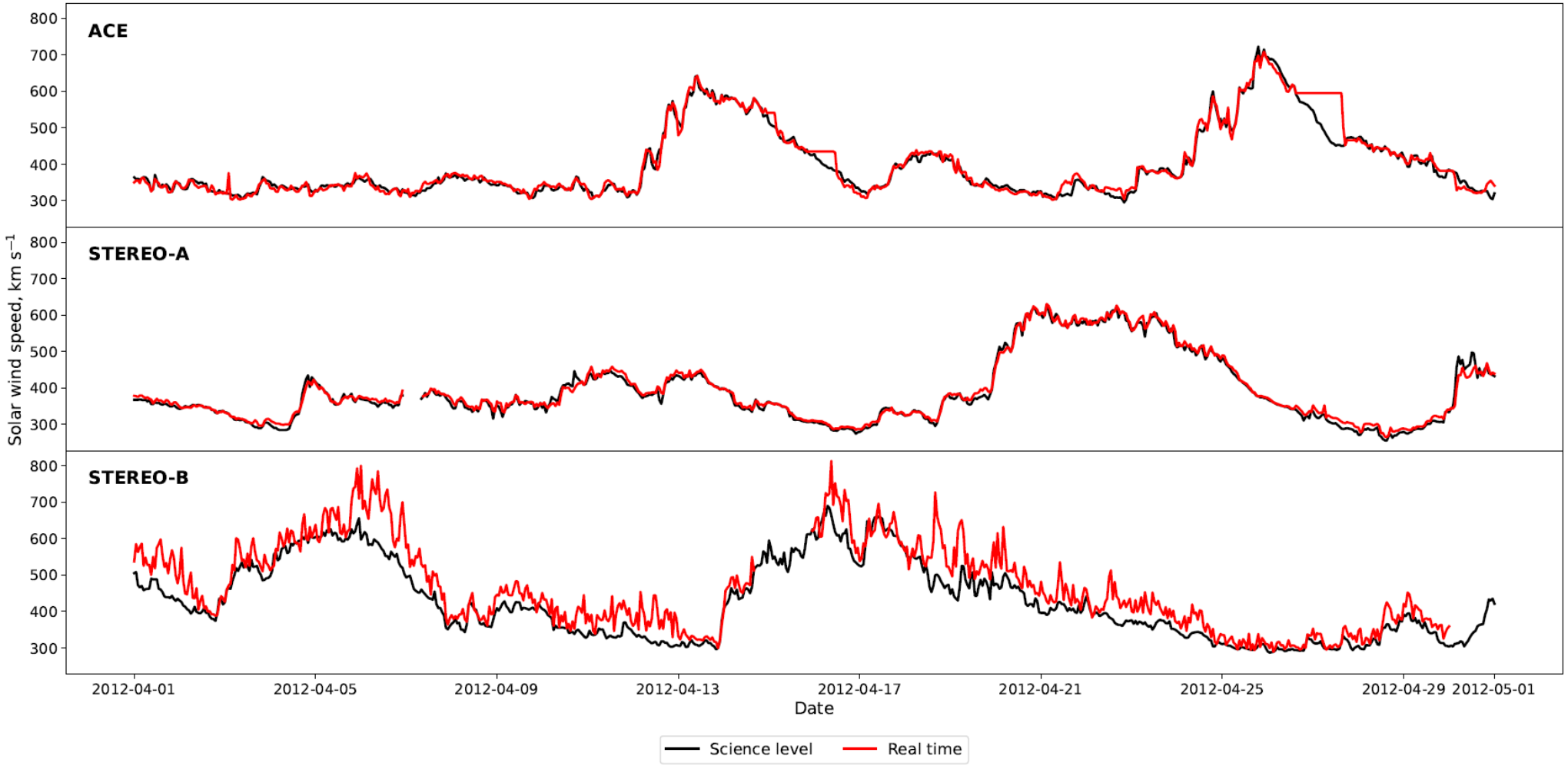
OPERATIONAL SOLAR WIND DA

For BRaVDA to be operational, it needs to work with real time data

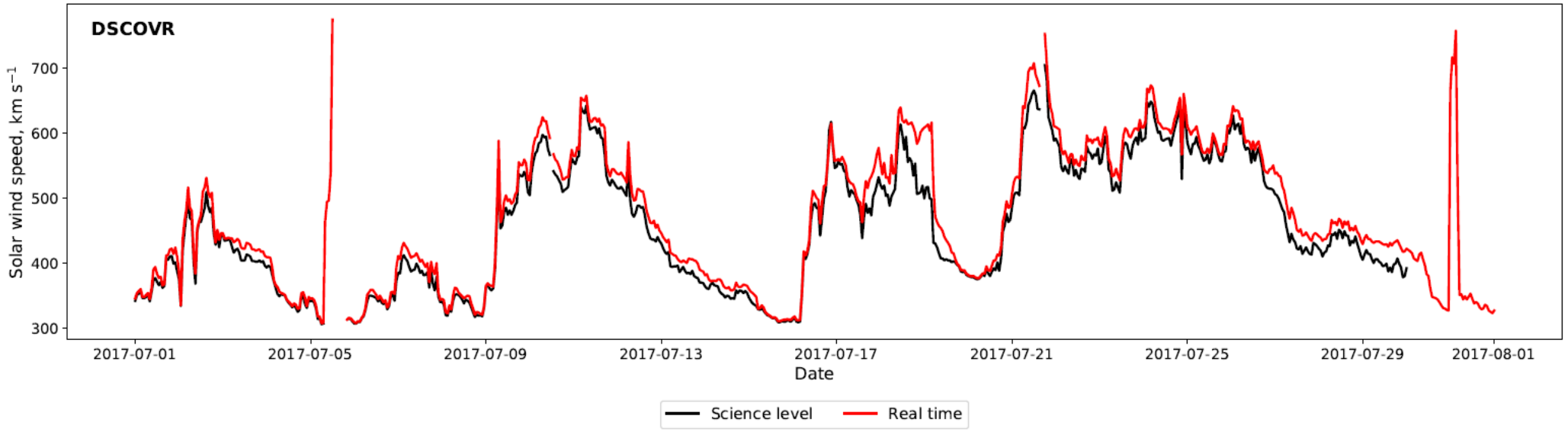
Previous experiments have used science level data, which has been pre-processed to provide a “cleaner” dataset (e.g. Lang et al., 2021 and Turner et al., 2022)

- Removing data gaps, erroneous observations and biases

REAL TIME ISSUES



REAL TIME ISSUES



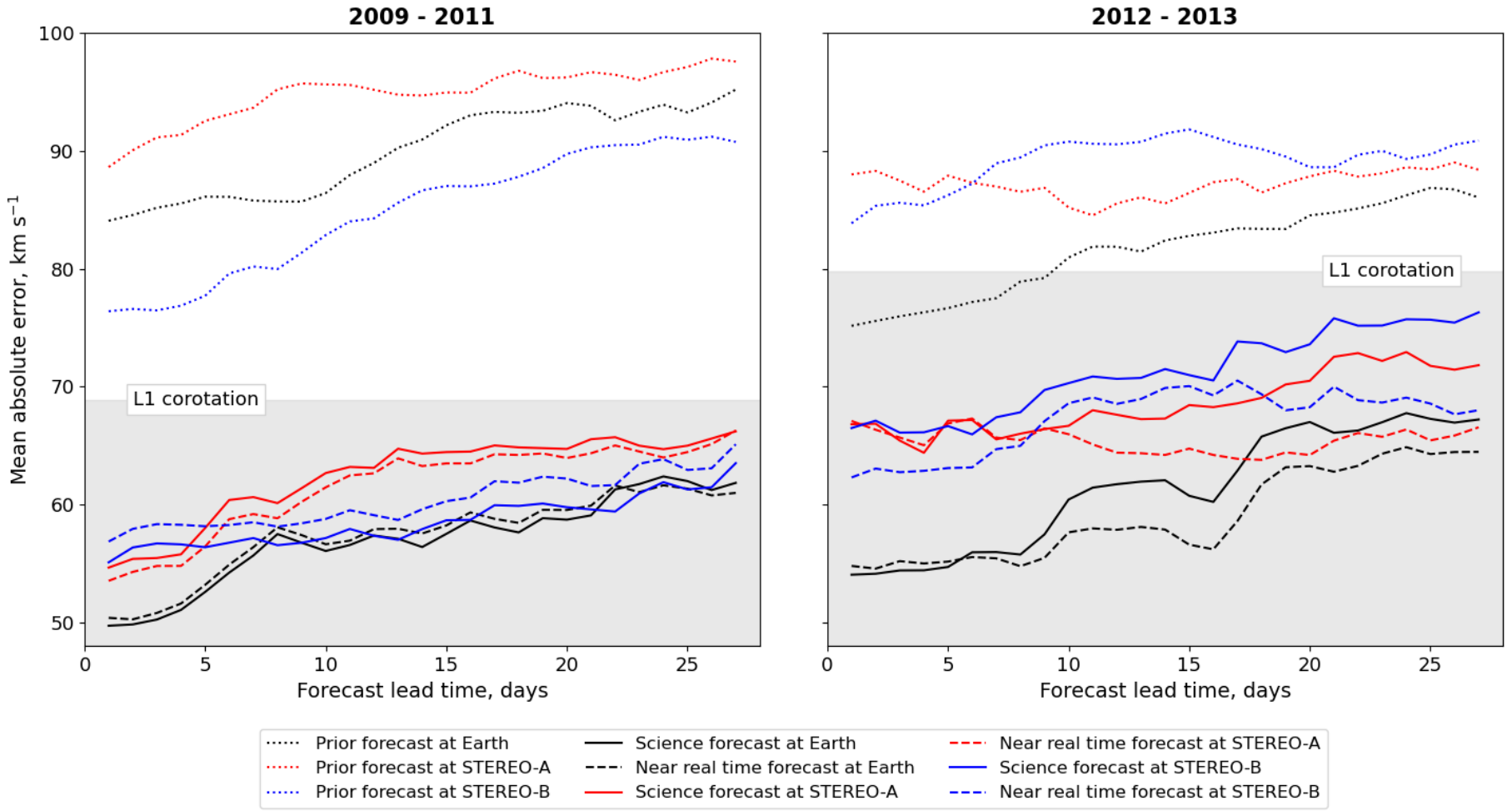
BRaVDA EXPERIMENTS

Assimilating all sources of observations – STEREO-A, B and ACE

Evaluate the forecast accuracy at the three observation locations – verification time series is the science data

Comparing the prior, real time and science forecasts

BRaVDA EXPERIMENTS



FUTURE SOLAR WIND DA

The ESA Vigil mission is (hopefully) going to be launched in 2027 (ish) to the L5 point

> *"The mission will give us advanced warning of oncoming solar storms and therefore more time to protect spacecraft in orbit, infrastructure on the ground and explorers now and in the future, unshielded by Earth's magnetic field and vulnerable to our star's violent outbursts."* – ESA, 2023

Could be useful for future operational solar wind DA

L5 & L1 SIMULATION

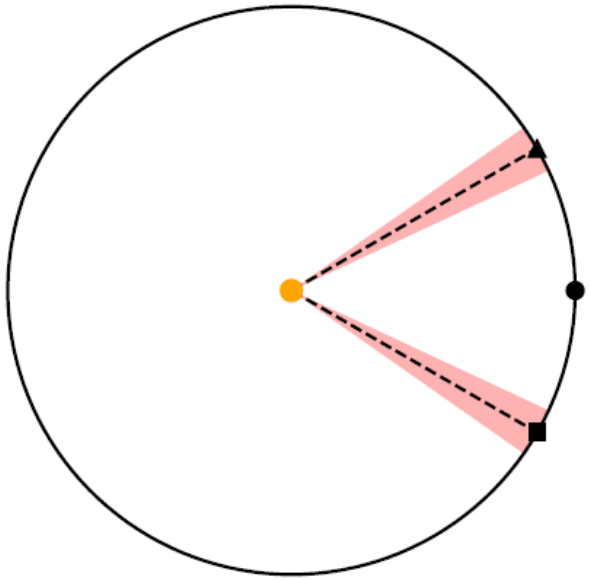
Combinations of spacecraft separated by approximately 60° in longitude

Historic data to see how well a potential L5 and L1 pairing could work for solar wind DA

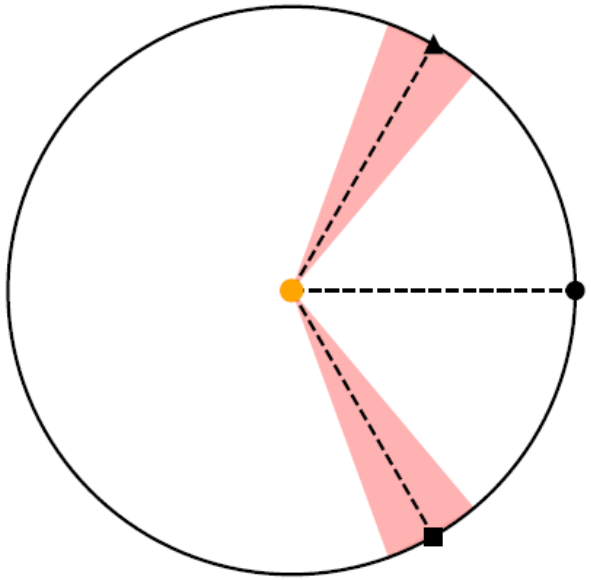
4 time periods

L5 & L1 SIMULATION

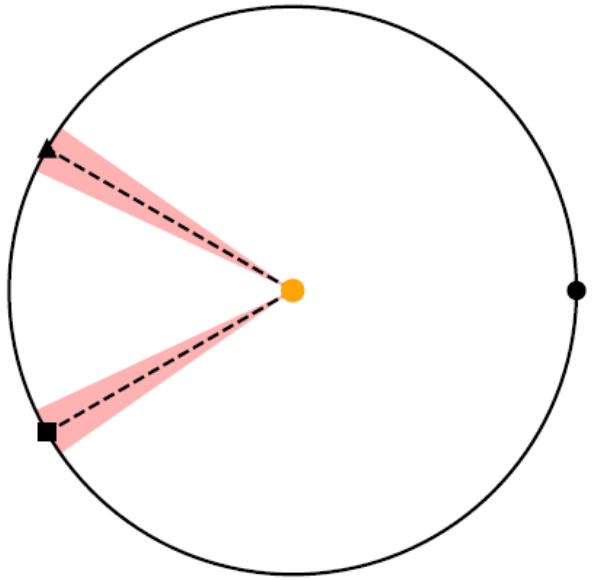
02/05/2008 - 30/08/2008

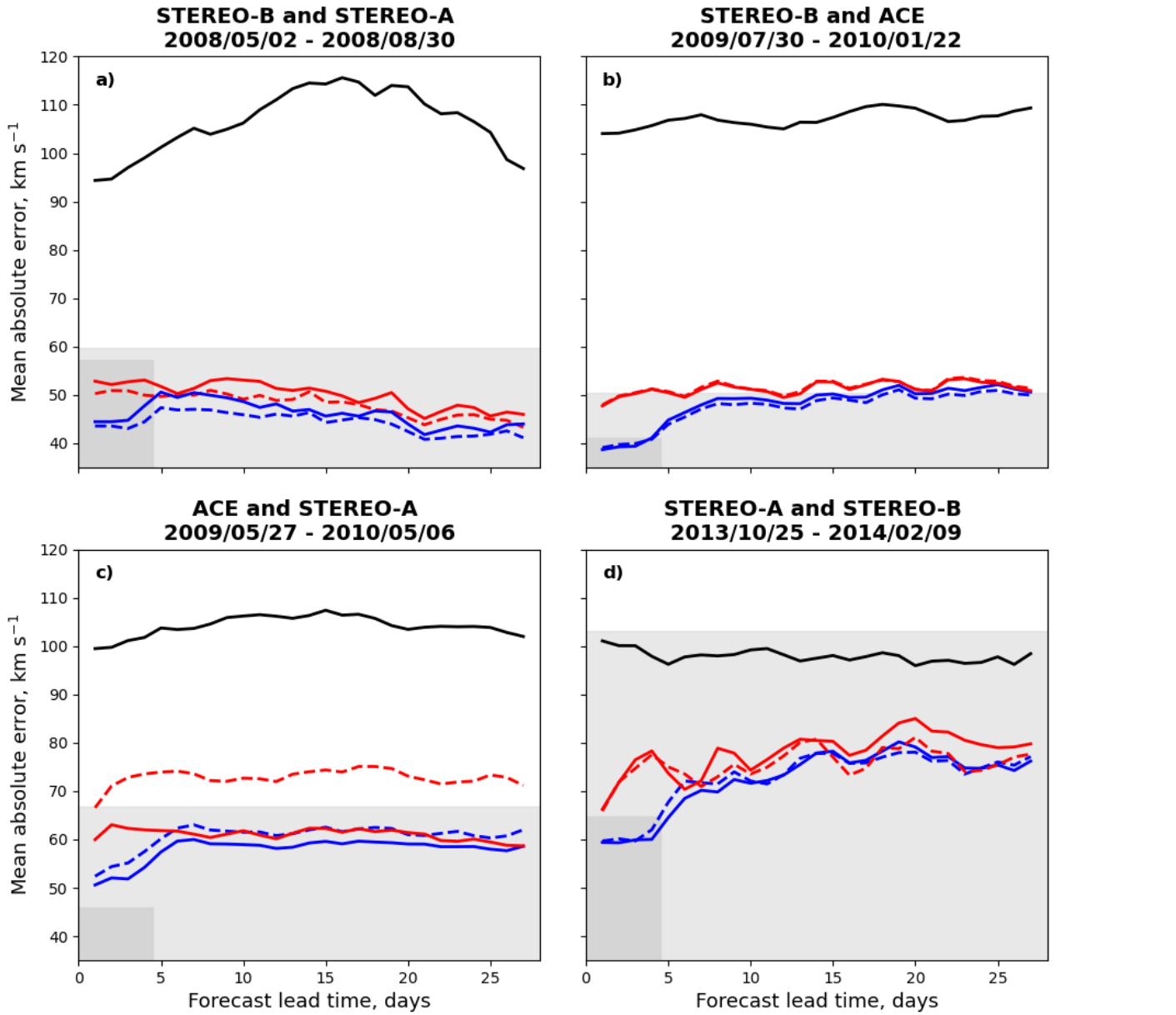


STEREO-A: 27/05/2009 - 06/05/2010
STEREO-B: 30/07/2009 - 22/01/2010

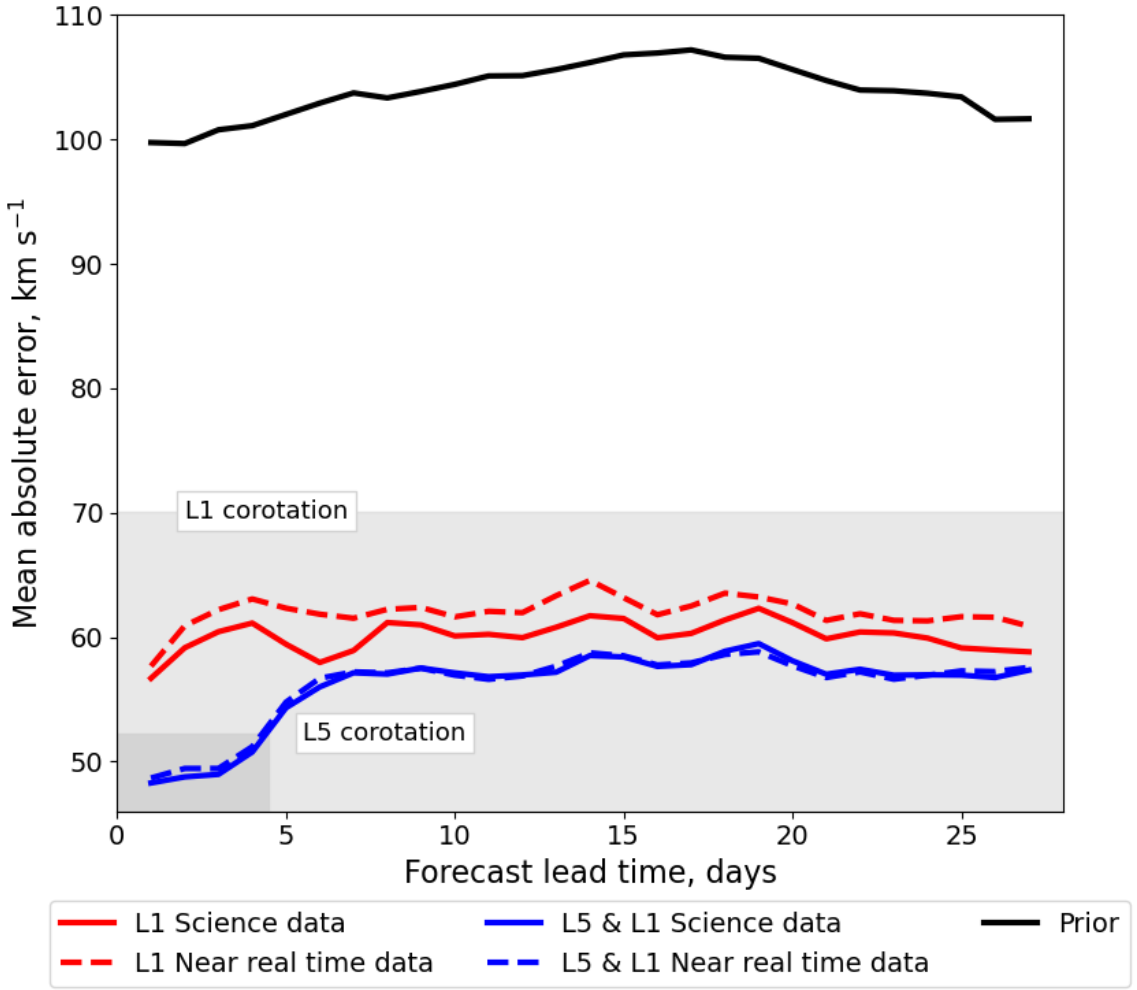


25/10/2013 - 09/02/2014




STEREO-B and STEREO-A
2008/05/02 - 2008/08/30
a)
STEREO-B and ACE
2009/07/30 - 2010/01/22
b)
ACE and STEREO-A
2009/05/27 - 2010/05/06
c)
STEREO-A and STEREO-B
2013/10/25 - 2014/02/09
d)
Mean absolute error, km s^{-1}
Forecast lead time, days
Prior (no DA)
L1 only (science DA)
L1 only (NRT DA)
L1 & L5 (science DA)
L1 & L5 (NRT DA)

L5 & L1 AVERAGE



FUTURE WORK

I am currently working on a semi-operational version of BRaVDA

All the pieces are there but need pulling together

Hoping for a daily updated forecast – a world's first using solar wind DA

Something about a thesis?

CONCLUSIONS

Knowledge of the solar wind is important for timely and accurate space weather forecasting

The BRaVDA scheme reconstructs a full solar rotation using available observations

Leads to improved solar wind forecasts

A future L5 & L1 spacecraft pairing could be useful for operational solar wind DA

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Lang, M., Witherington, J., Owens, M. J., & Turner, H. (2021) Improving solar wind forecasting using data assimilation. *Space Weather*, 1 – 23.

National Risk Register. URL: https://www.gov.uk/government/publications/national-risk-register-2020

Owens, M. J., et al. A Computationally Efficient, Time-Dependent Model of the Solar Wind for use as a Surrogate to Three-Dimensional Numerical Magnetohydrodynamic Simulations. *Solar Physics, 295:43.* DOI: 10.1007/s11207-020-01605-3.

Turner, H., Owens, M. J., Lang, M., Gonzi, S., & Riley, P. (2022). Quantifying the effect of ICME removal and observation age for in situ solar wind data assimilation. *Space Weather, 20.* DOI: 10.1029/2022SW003109.

Paper

Turner, H., Lang, M., Owens, M., Smith, A., Riley, P., Marsh, M., & Gonzi, S. (2023). Solar wind data assimilation in an operational context: use of near-real-time data and the forecast value of an L5 monitor. *Space Weather, 21*, e2023SW003457. https://doi.org/10.1029/2023SW003457