Solar wind data assimilation in an operational context

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

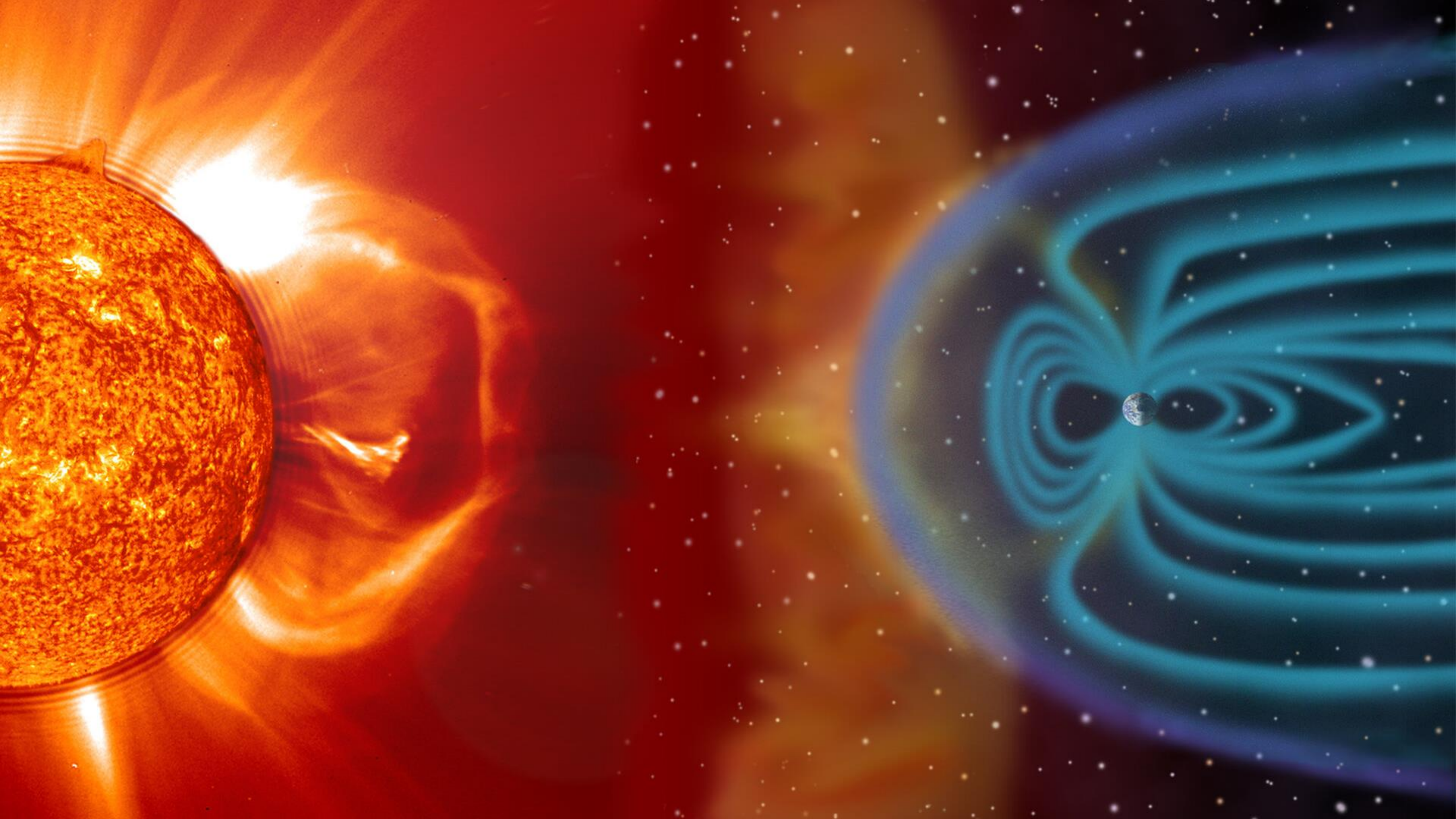
Harriet Turner

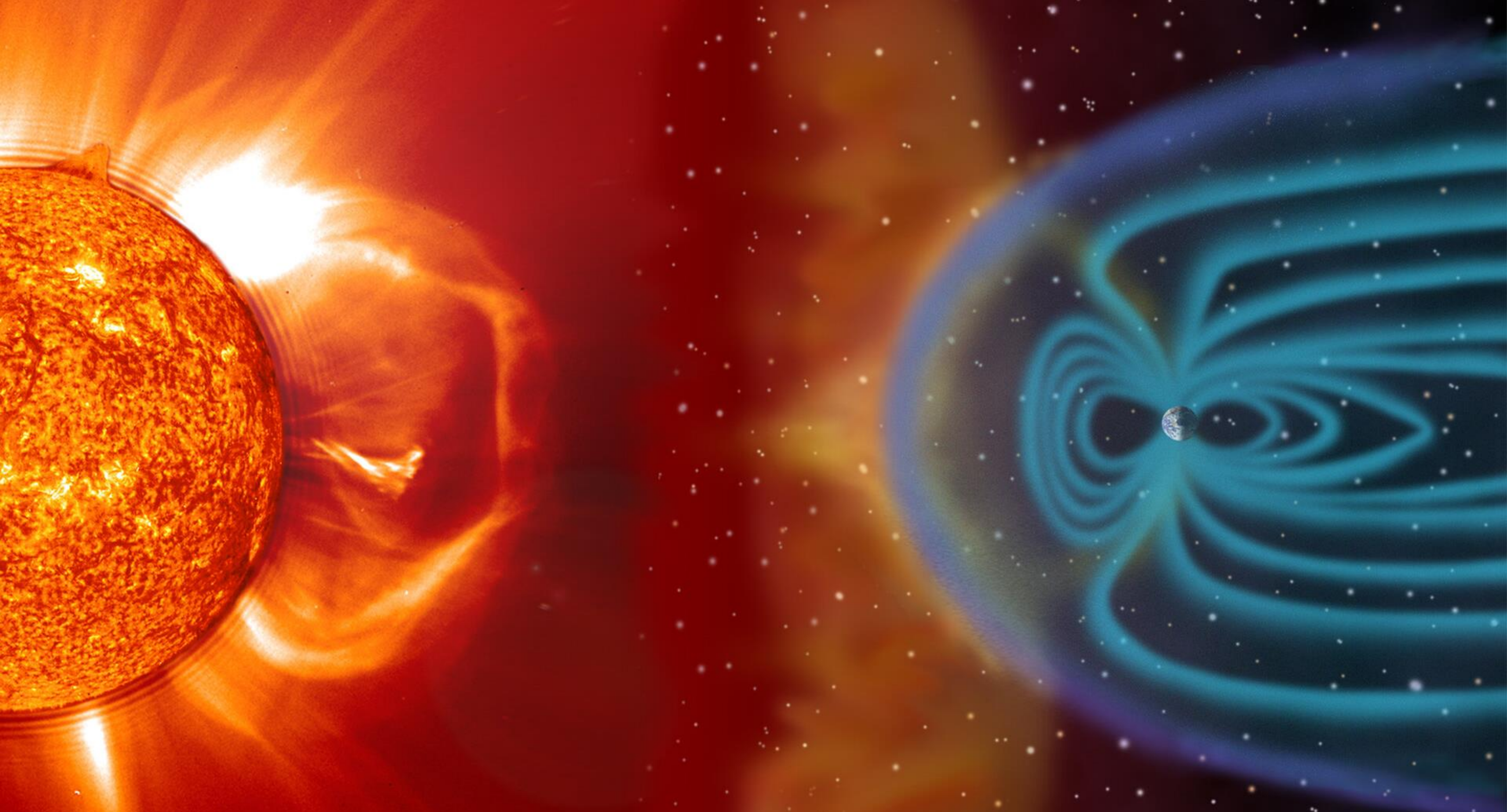
Supervisors: Mathew Owens, Matthew Lang, Mike Marsh and Siegfried Gonzi

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





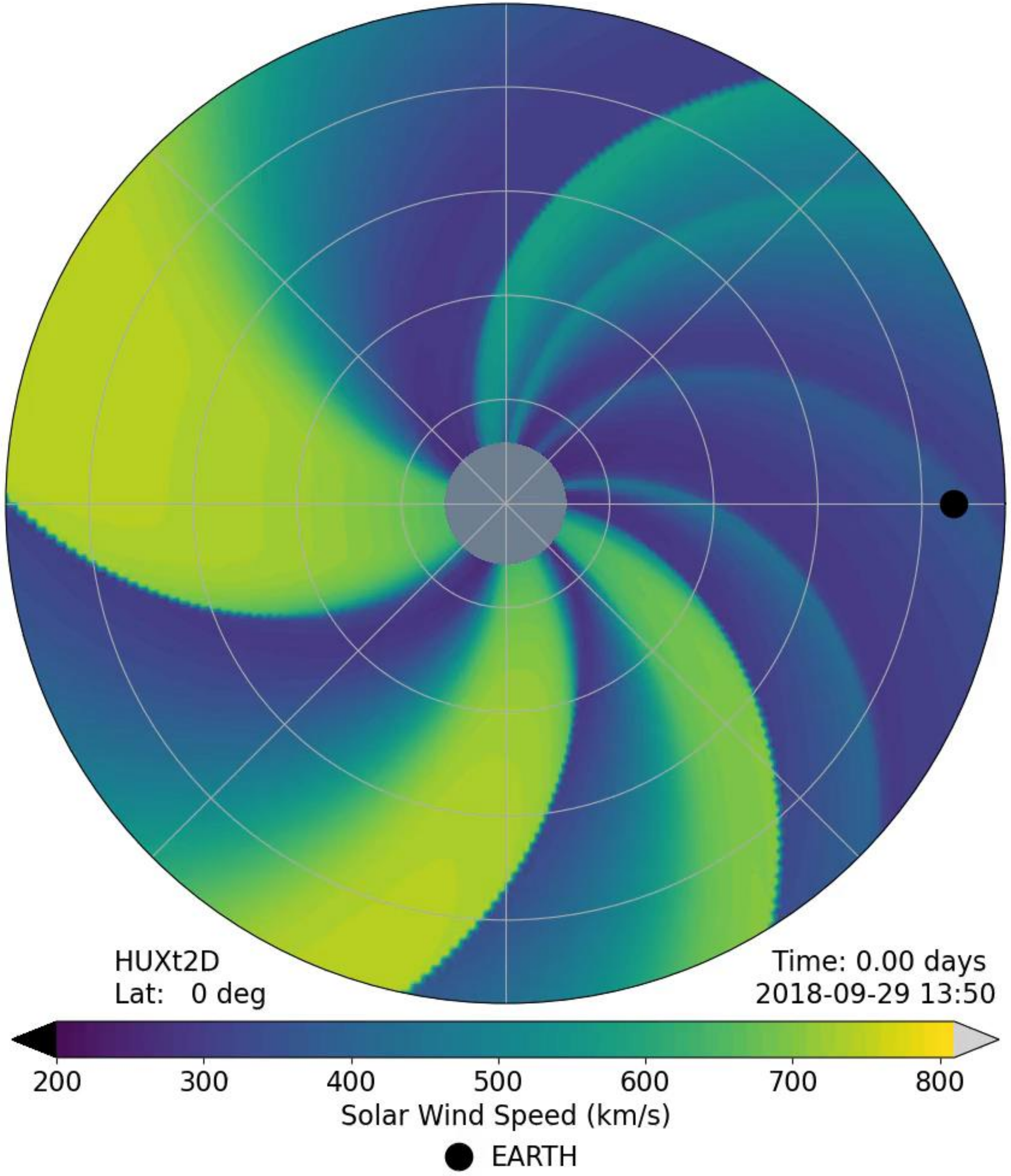
*Not to scale

SOLAR WIND STRUCTURE

Solar wind drags out the Sun's magnetic field

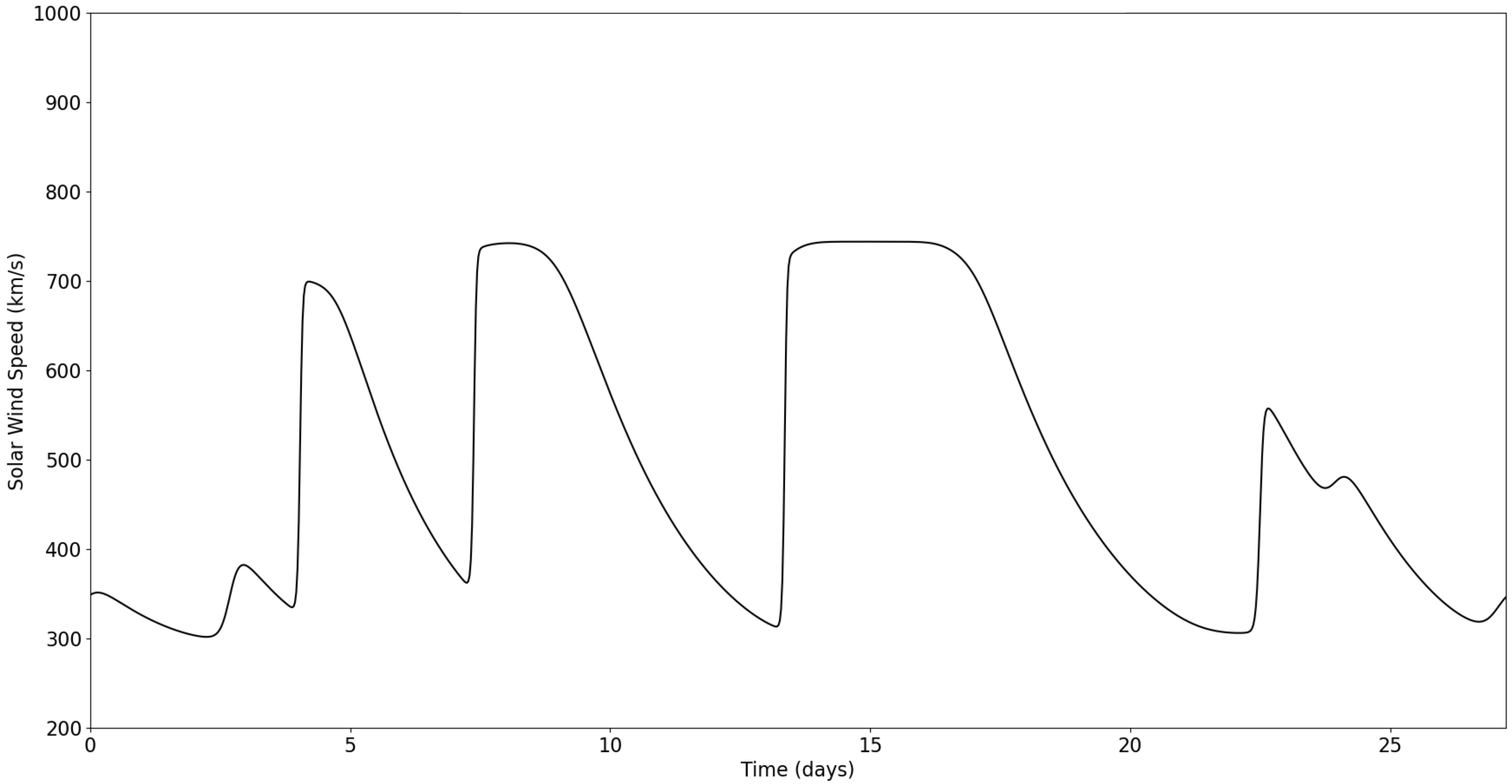
Pulled into an Archimedean spiral due to the Sun's rotation

Solar wind flow is **mostly radial**



HUXt2D
Lat: 0 deg
Time: 0.00 days
2018-09-29 13:50
200
300
400
500
600
700
800
Solar Wind Speed (km/s)
EARTH

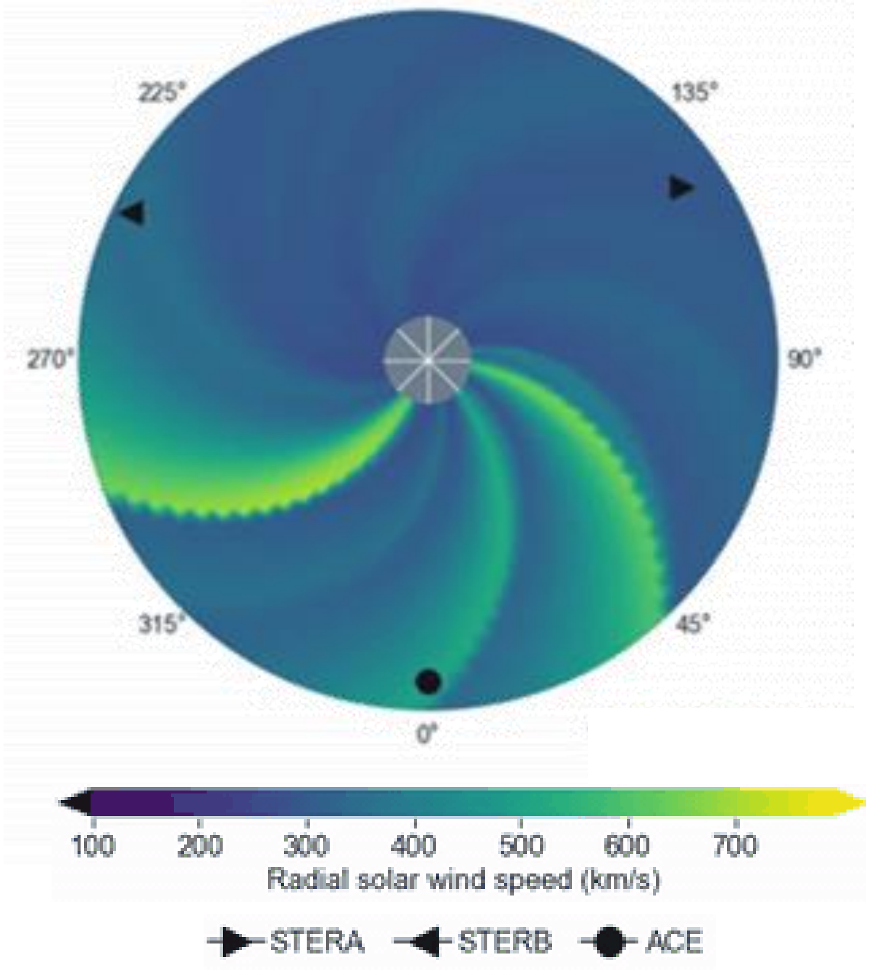
AS A TIME SERIES

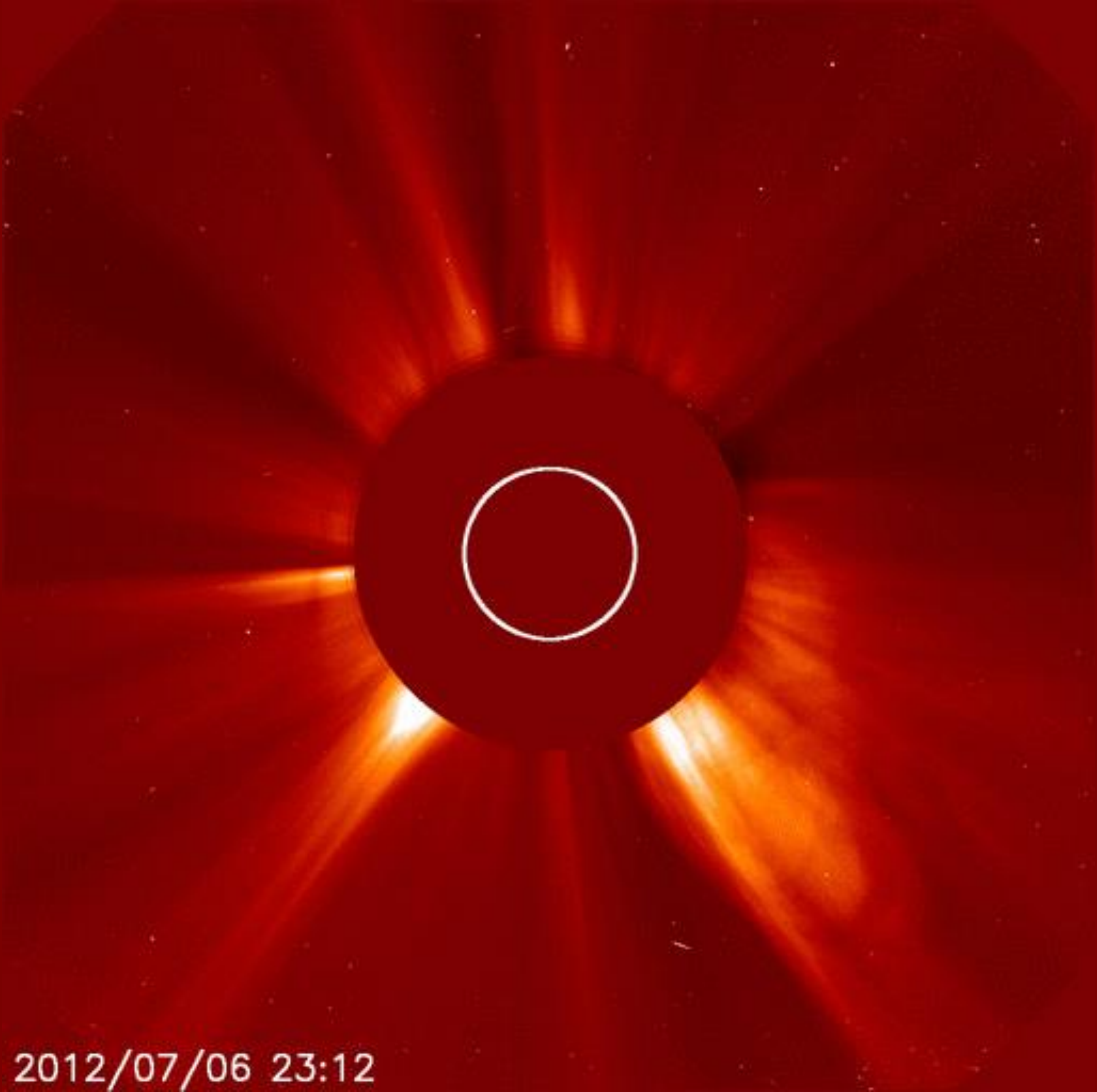


CORONAL MASS EJECTIONS

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




2012/07/06 23:12

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

IMPACT	1 <0.2%	2 0.2-1%	3 1-5%	4 5-25%	5 >25%
Catastrophic 5	28, 29		9, 26a	54	
Significant 4	21	24, 38, 56a	27, 49, 51a, 51b, 51c, 61	10, 47, 50, 55, 63	
Moderate 3	17, 32, 33, 34, 35, 36, 56c	12, 22, 23, 52	25, 26b, 31a, 45, 53, 56b	4, 8, 11, 40, 43, 48, 60	3, 31b, 46, 62
Limited 2	18, 19, 30, 37	5, 16, 41, 42	14, 20, 56d, 58, 59	7, 13, 57b	2, 6
Minor 1	44	39		15	1, 57a

LIKELIHOOD

IMPACT \ LIKELIHOOD	1 <0.2%	2 0.2-1%	3 1-5%	4 5-25%	5 >25%
5 Catastrophic	28, 29		9, 26a	54 (Pandemics)	
4 Significant	21	24, 38, 56a	27, 49, 51a, 51b, 51c, 61	10, 47, 50, 55, 63	
3 Moderate	17, 32, 33, 34, 35, 36, 56c	12, 22, 23, 52	25, 26b, 31a, 45, 53, 56b	4, 8, 11, 40, 43, 48, 60	3, 31b, 46, 62
2 Limited	18, 19, 30, 37	5, 16, 41, 42	14, 20, 56d, 58, 59	7, 13, 57b	2, 6
1 Minor	44	39		15	1, 57a

LIKELIHOOD

IMPACT	1 <0.2%	2 0.2-1%	3 1-5%	4 5-25%	5 >25%
5 Catastrophic	28, 29		9, 26a	54	
4 Significant	21	24, 38, 56a	27, 4[illegible], 51a, 51b, 5[illegible] 61		
3 Moderate	17, 32, 33, 34, 35, 36, 56c	12, 22, 23, 52	25, 26b, 31a, 45, 53, 56b	4, 8, 11, 40, 43, 48, 60	3, 31b, 46, 62
2 Limited	18, 19, 30, 37	5, 16, 41, 42	14, 20, 56d, 58, 59	7, 13, 57b	2, 6
1 Minor	44	39		15	1, 57a

LIKELIHOOD

Coastal and river flooding

IMPACT	1 <0.2%	2 0.2-1%	3 1-5%	4 5-25%	5 >25%
5 Catastrophic	28, 29		9, 26a	54	
4 Significant	21	24, 38, 56a	27, 49, 51a, 6[illegible]	[illegible]0, 55, 63	
3 Moderate	17, 32, 33, 34, 35, 36, 56c	12, 22, 23, 52	25, 26b, 31a, 45, 53, 56b	4, 8, 11, 40, 43, 48, 60	3, 31b, 46, 62
2 Limited	18, 19, 30, 37	5, 16, 41, 42	14, 20, 56d, 58, 59	7, 13, 57b	2, 6
1 Minor	44	39		15	1, 57a

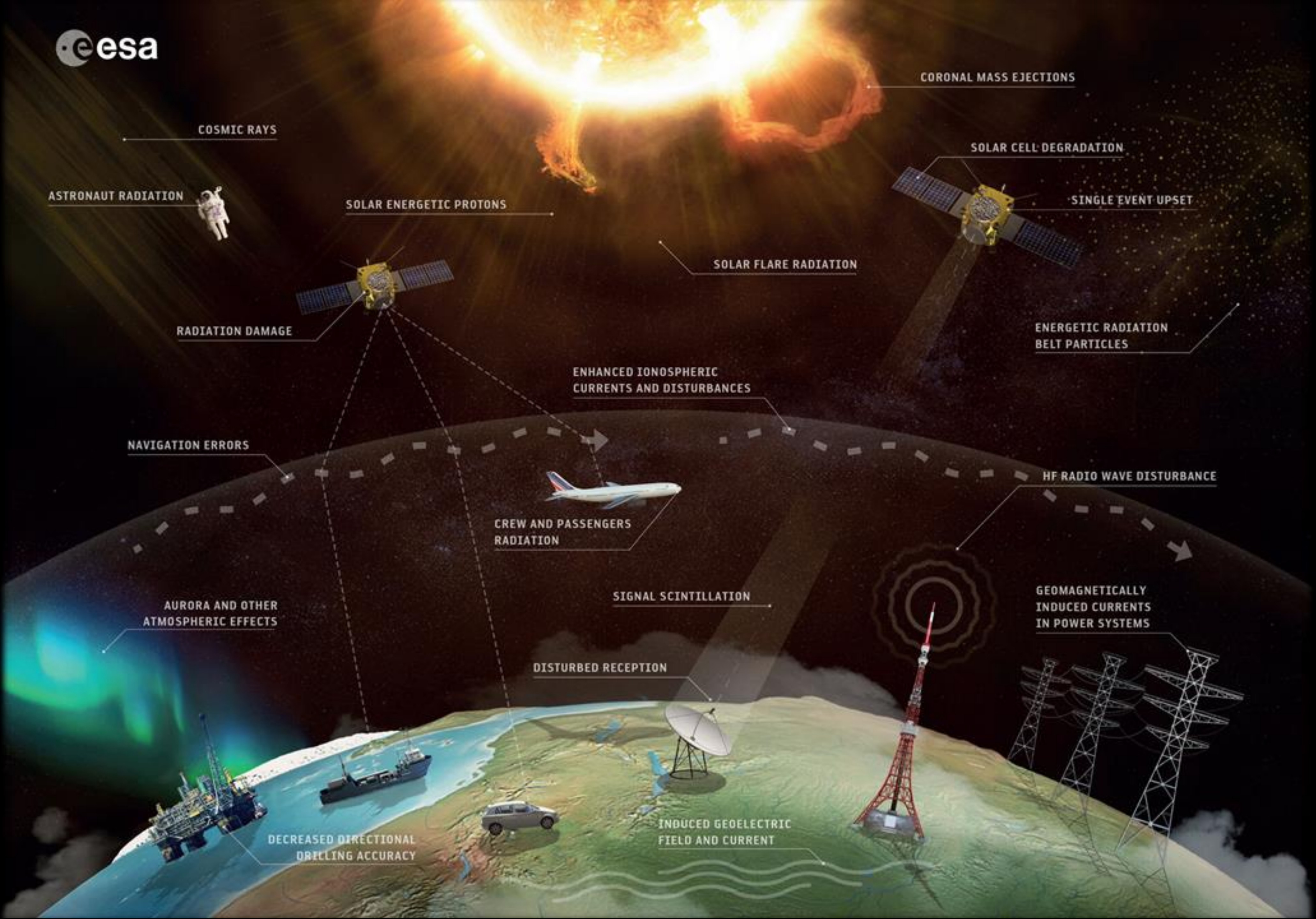
LIKELIHOOD

Heatwaves

IMPACT	1 <0.2%	2 0.2-1%	3 1-5%	4 5-25%	5 >25%
Catastrophic 5	28, 29		9, 26a	54	
Significant 4	21	24, 38, 56a	27, 49, 51a, 51b, 51c, 61	10, 47, 50,	
Moderate 3	17, 32, 33, 34, 35, 36, 56c	12, 22, 23, 52	25, 26b, 31a, 45, 53, 56b	4, 8, 11, 40, 43, 48, 60	3, 31b, 46, 62
Limited 2	18, 19, 30, 37	5, 16, 41, 42	14, 20, 56d, 58, 59	7, 13, 57b	2, 6
Minor 1	44	39		15	1, 57a

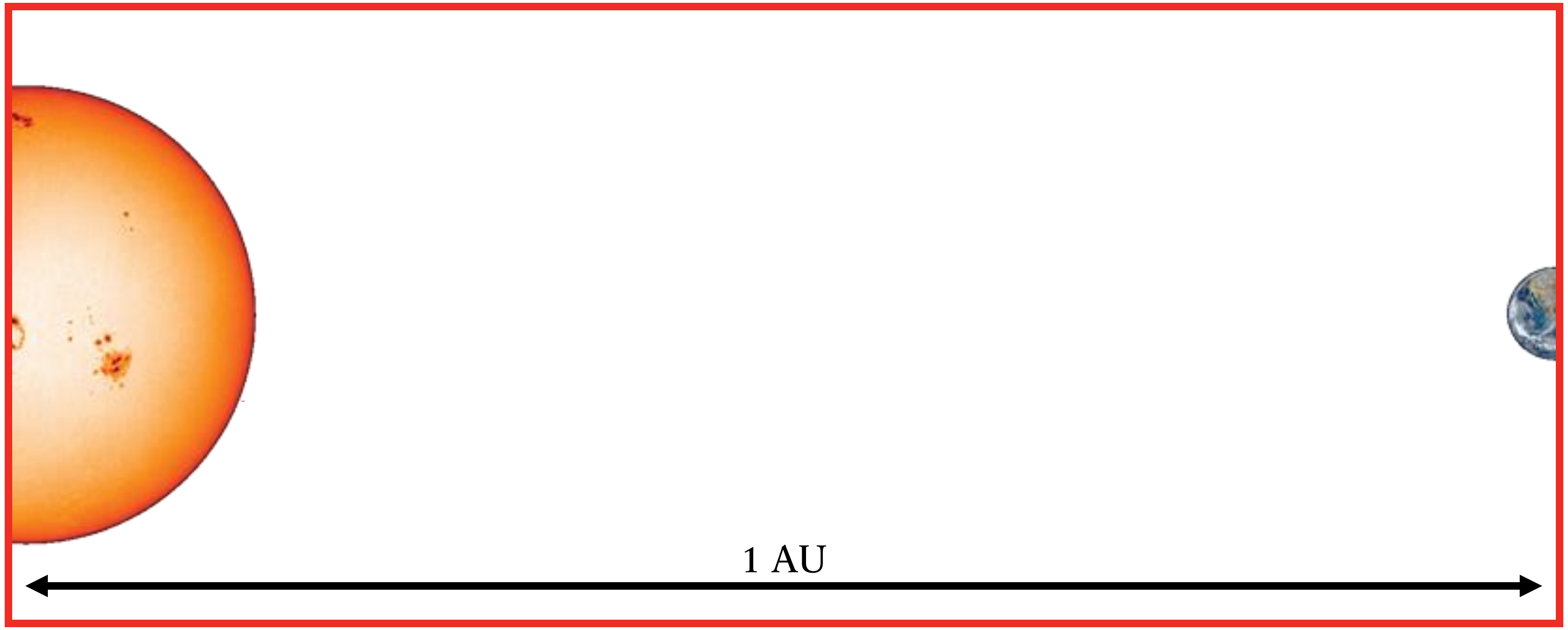
LIKELIHOOD

Severe space weather


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
GEOMAGNETICALLY INDUCED CURRENTS IN POWER SYSTEMS
SIGNAL SCINTILLATION
AURORA AND OTHER ATMOSPHERIC EFFECTS
DISTURBED RECEPTION
INDUCED GEOELECTRIC FIELD AND CURRENT
DECREASED DIRECTIONAL DRILLING ACCURACY

CURRENT FORECASTING

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

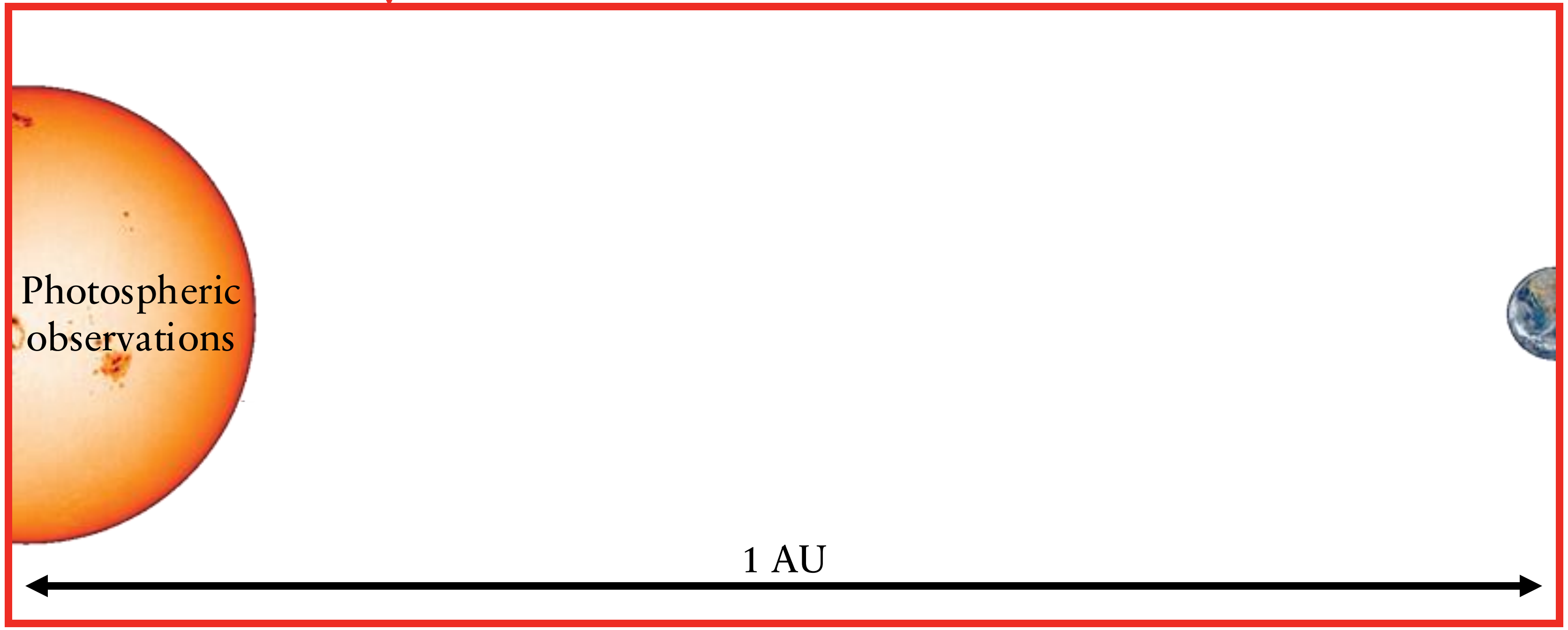


CURRENT FORECASTING

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

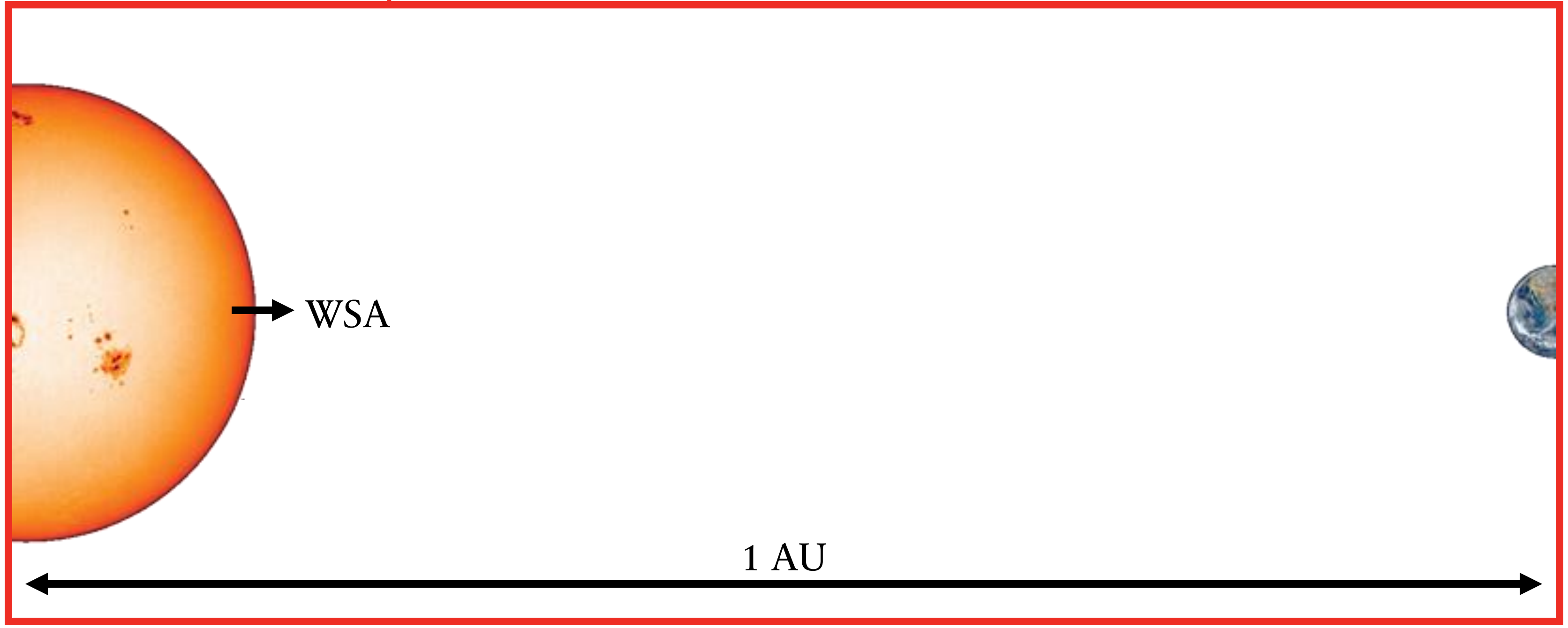
CURRENT FORECASTING

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



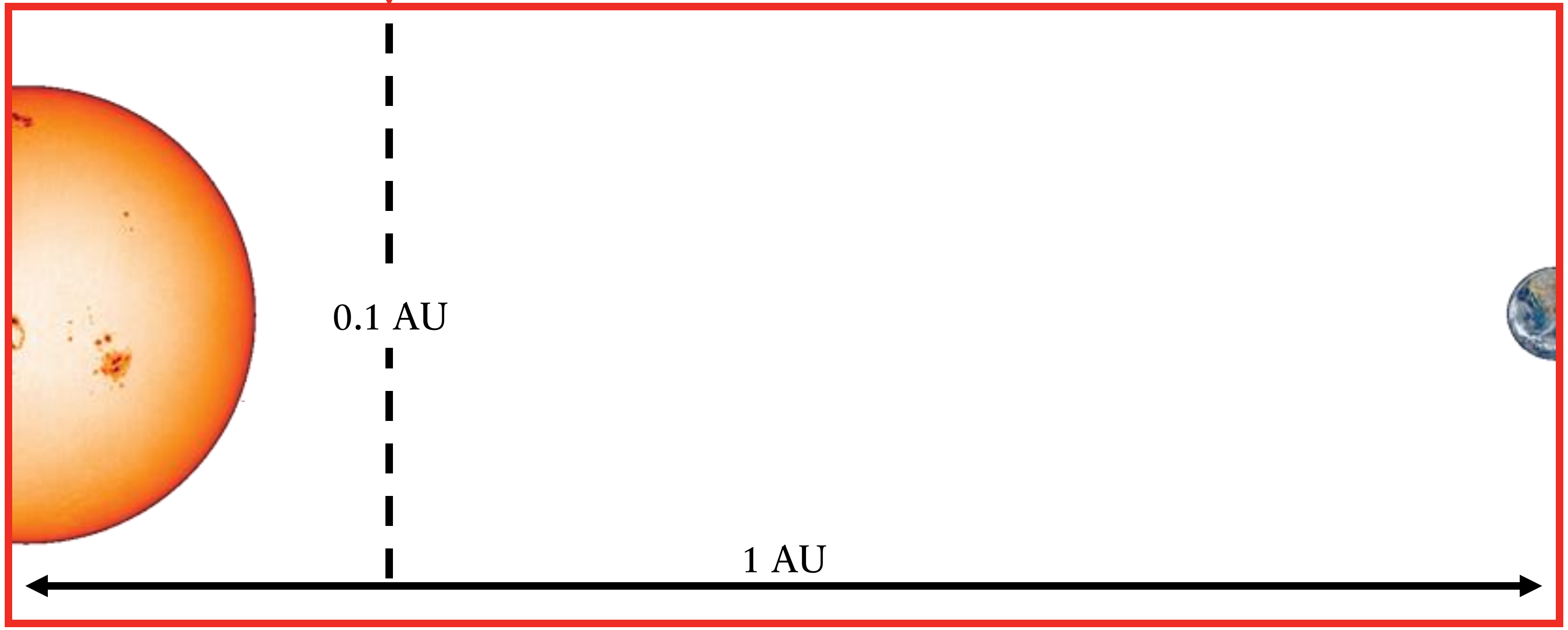
CURRENT FORECASTING

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



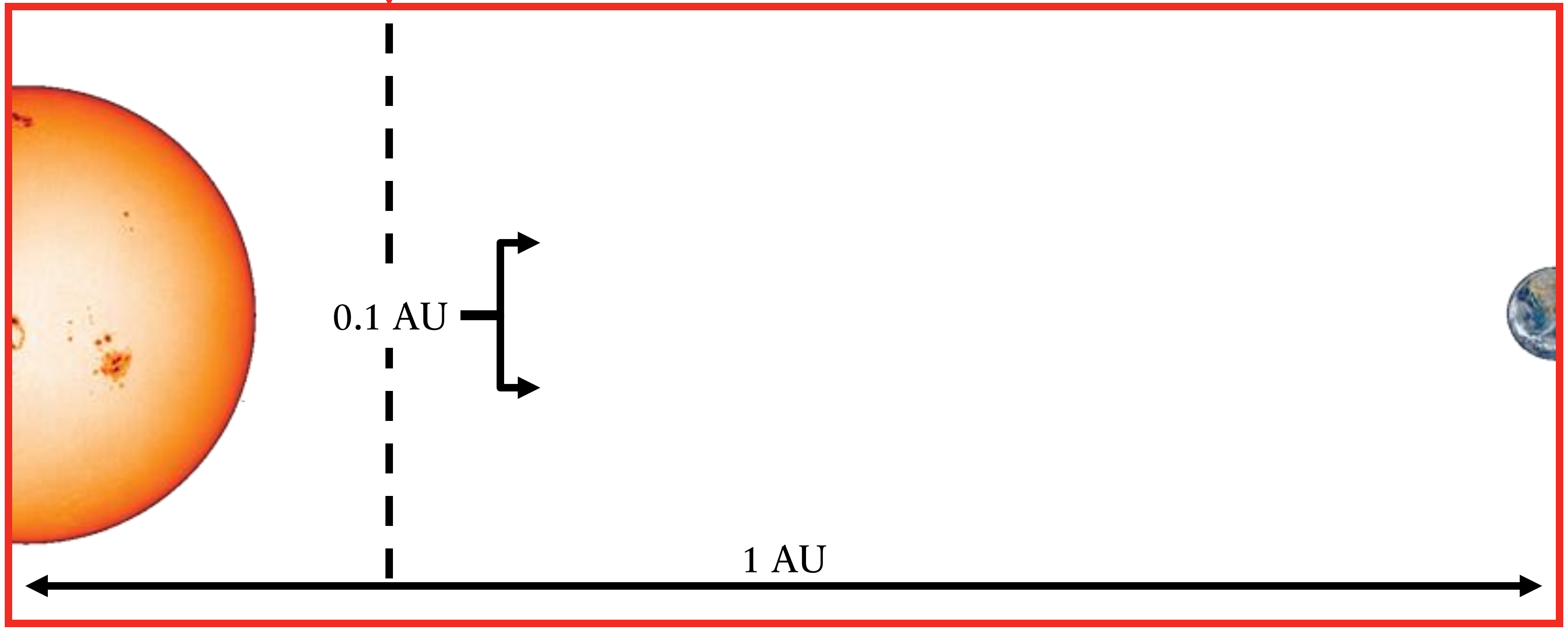
CURRENT FORECASTING

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



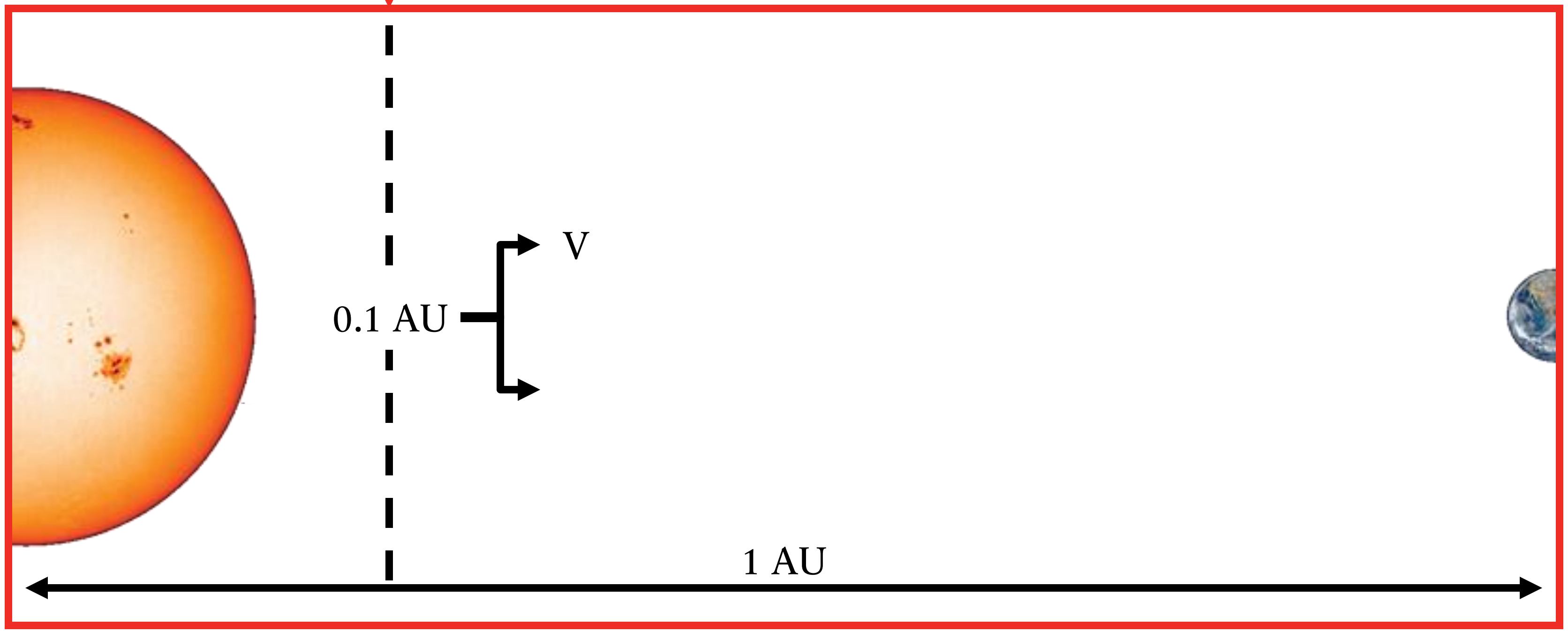
CURRENT FORECASTING

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



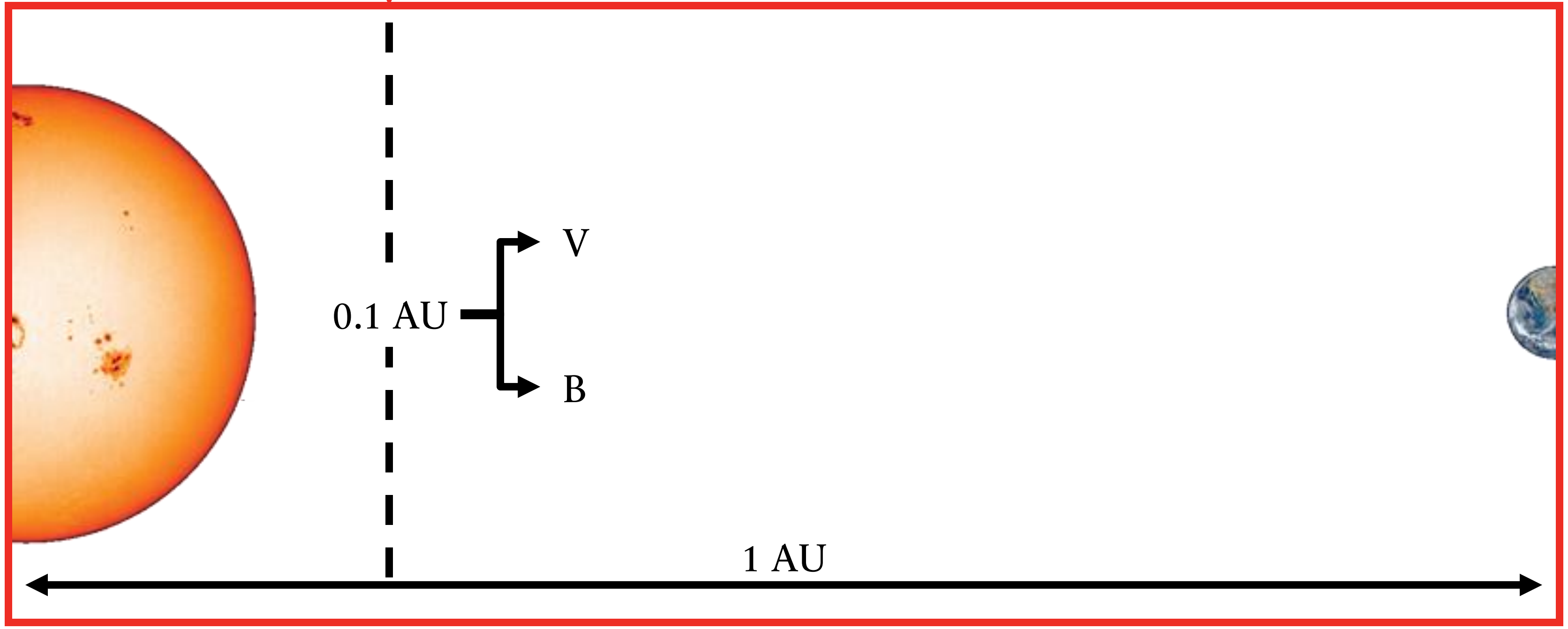
CURRENT FORECASTING

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



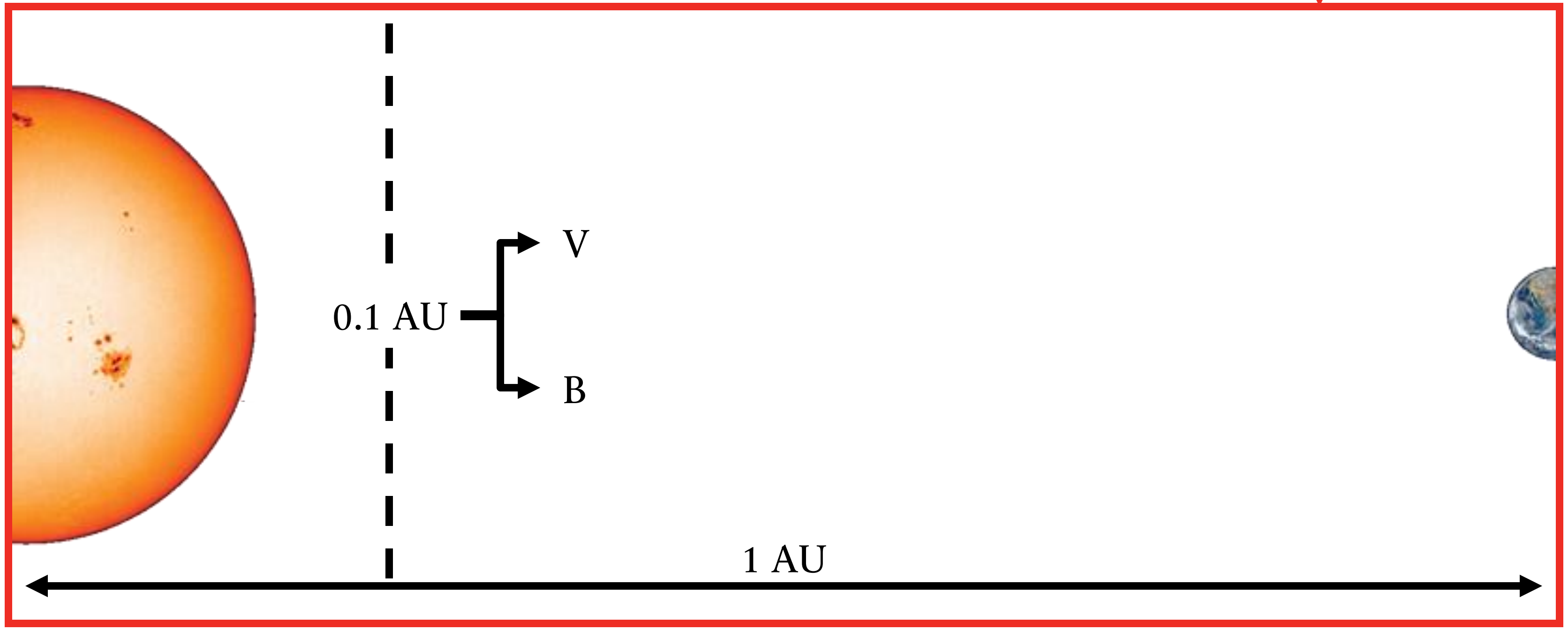
CURRENT FORECASTING

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



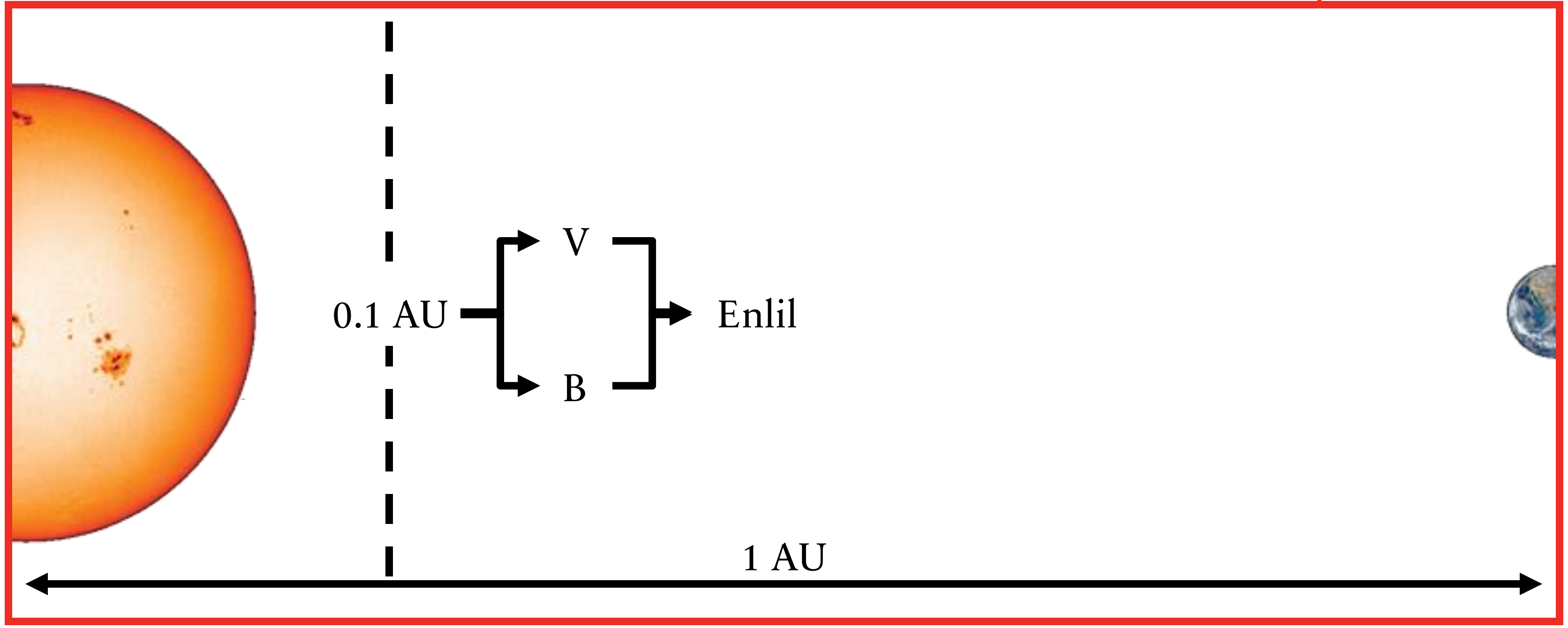
CURRENT FORECASTING

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



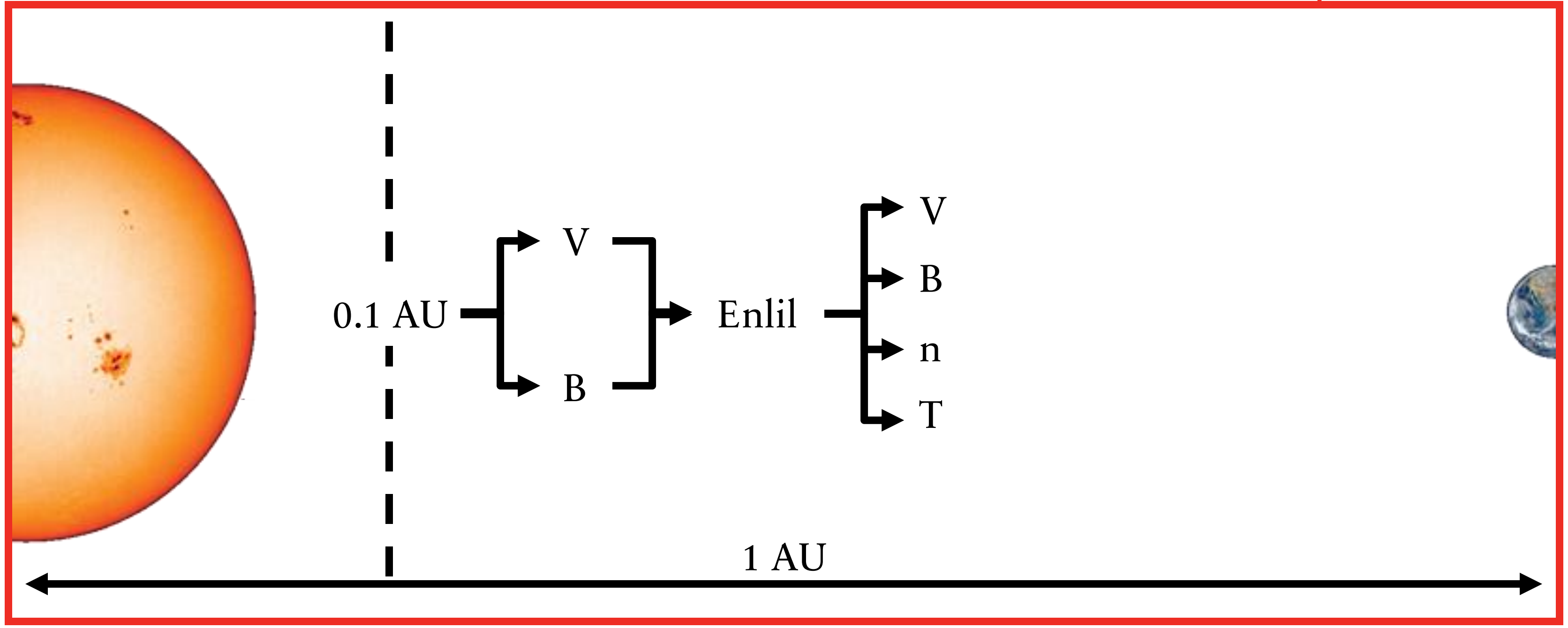
CURRENT FORECASTING

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



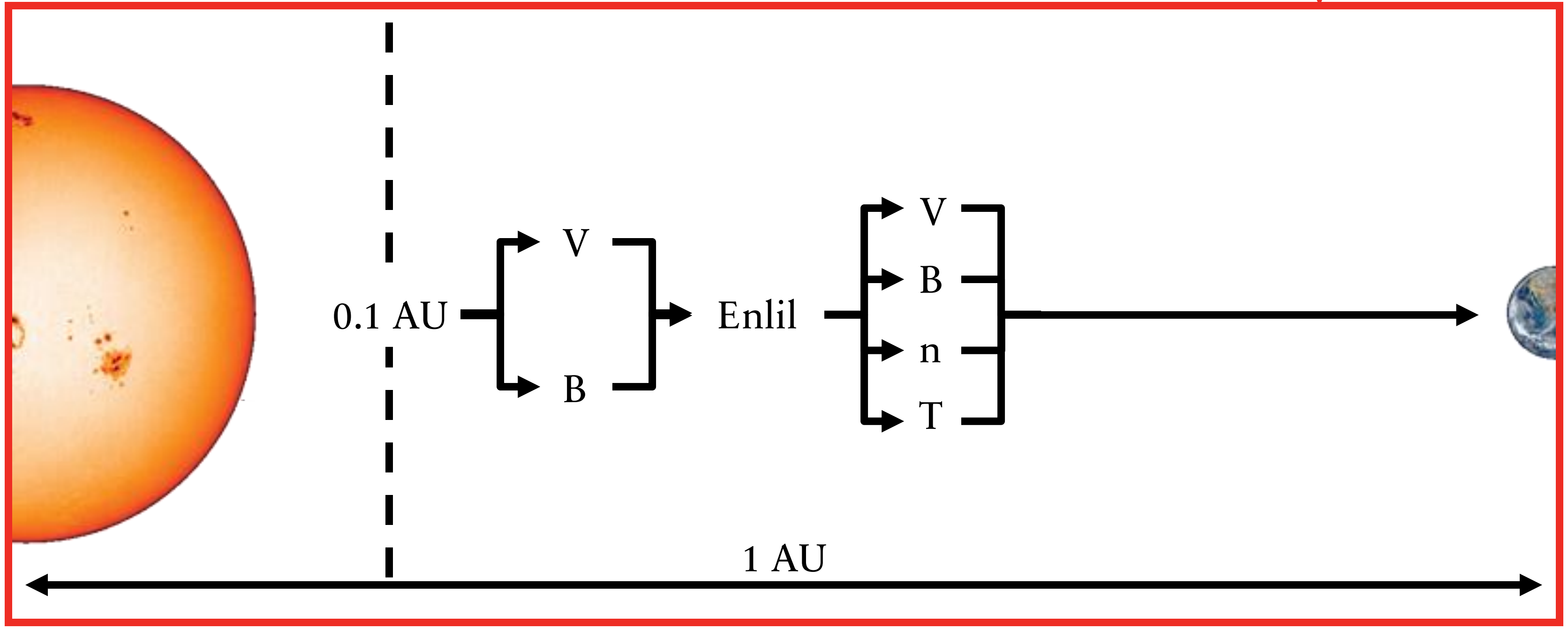
CURRENT FORECASTING

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



CURRENT FORECASTING

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



DATA ASSIMILATION (DA)

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

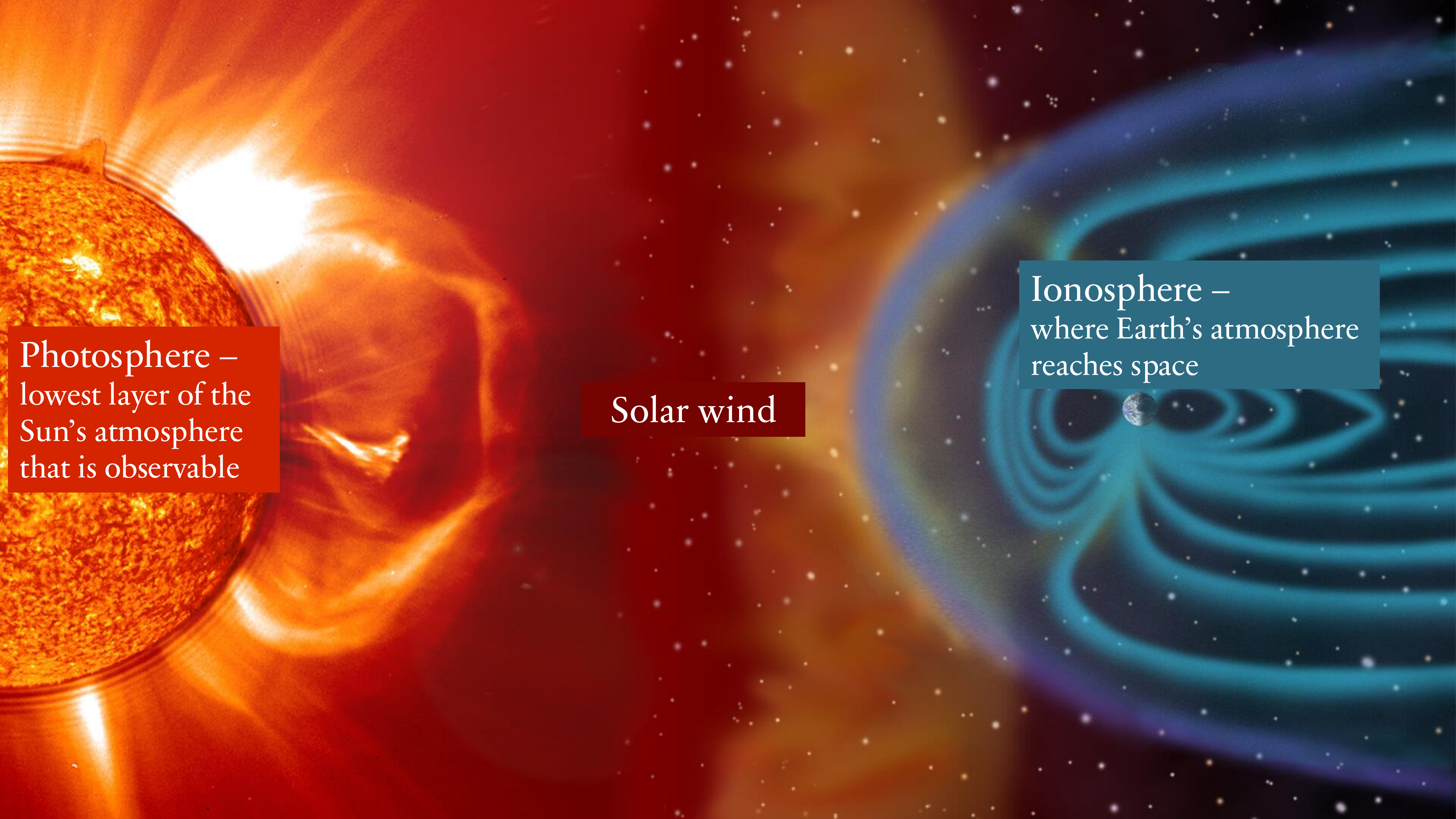
Used in numerical weather prediction and has led to large forecast improvements

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

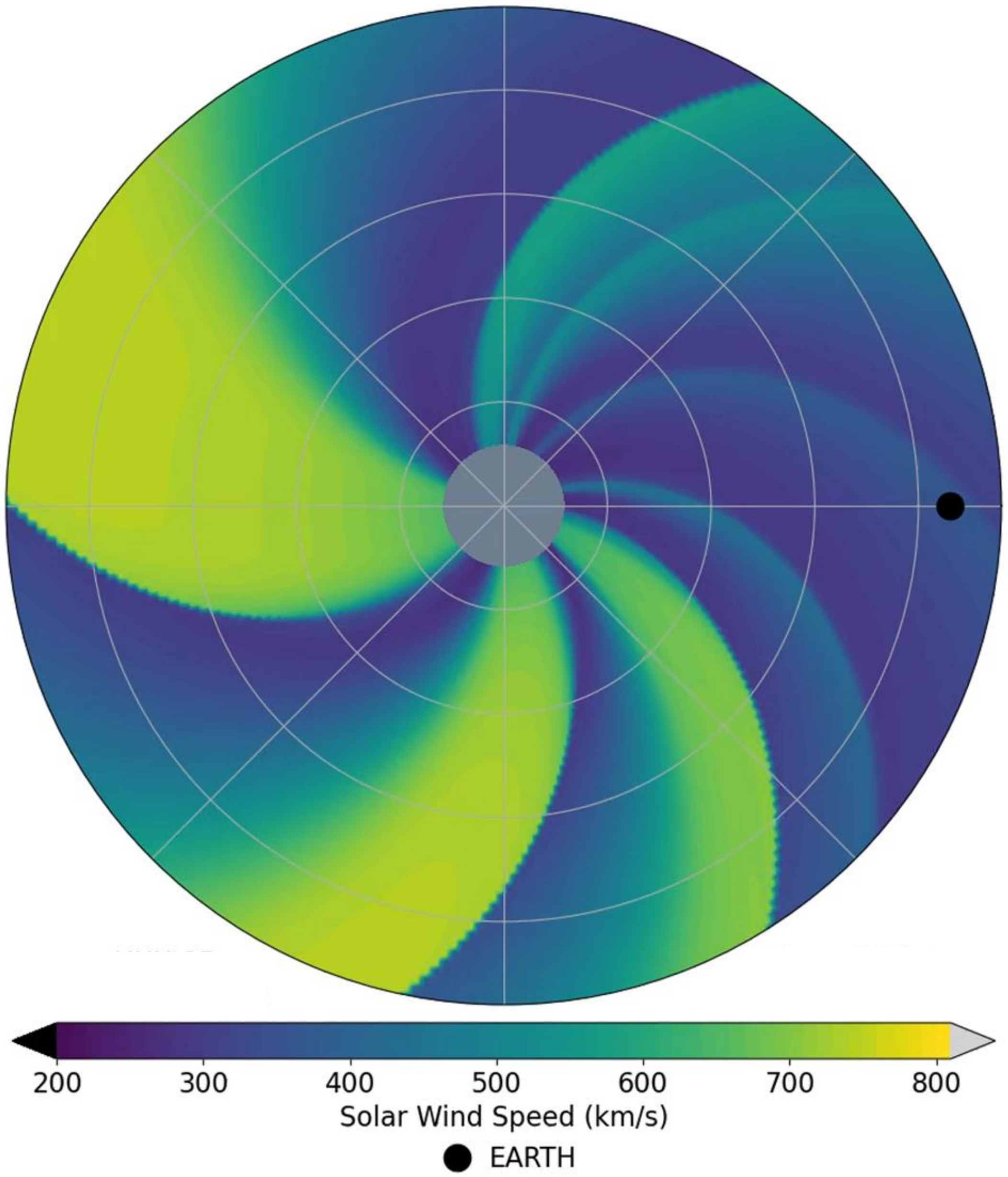

Photosphere –
lowest layer of the Sun's atmosphere that is observable
Solar wind
Ionosphere –
where Earth's atmosphere reaches space

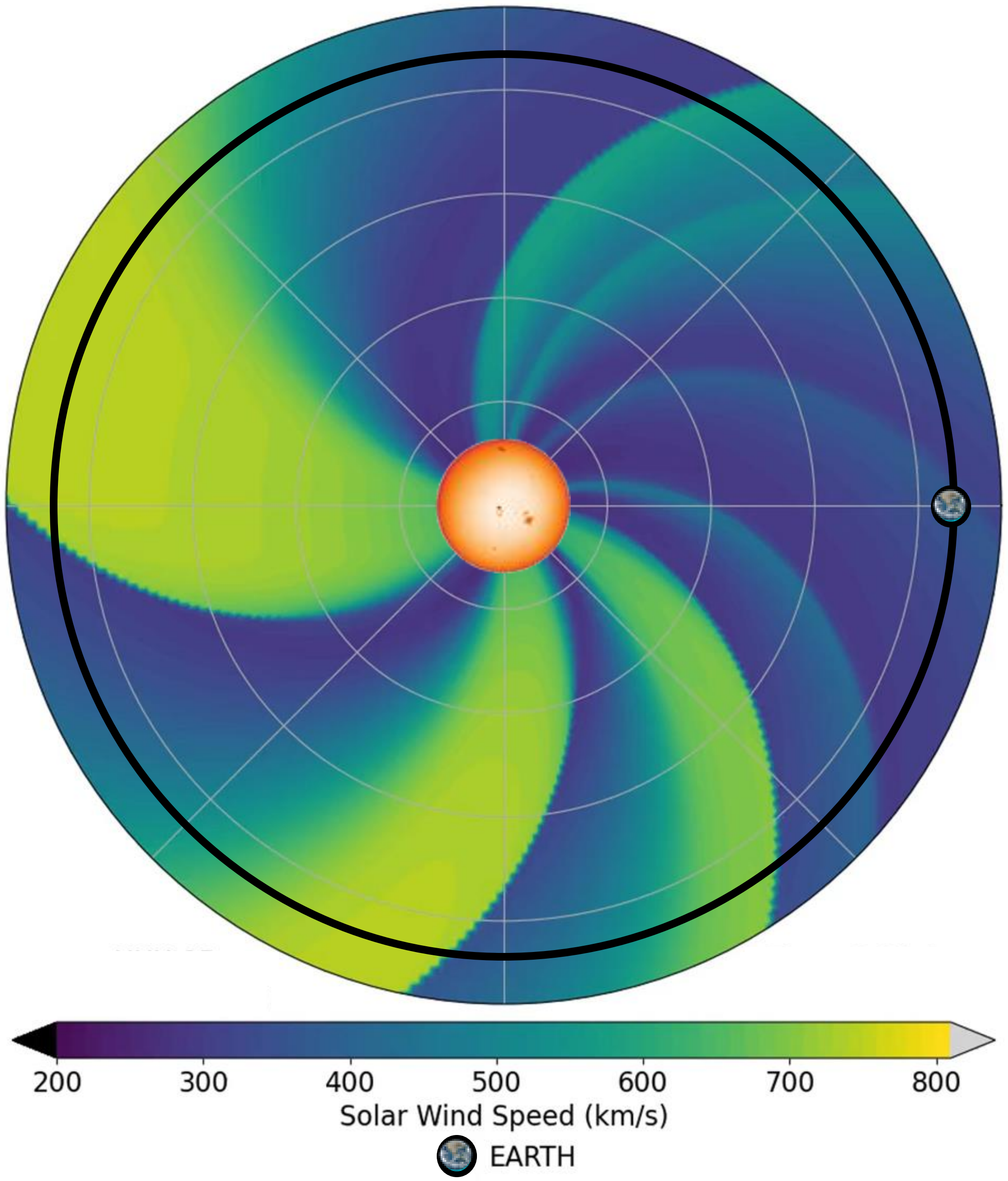
DA IN THE SOLAR WIND

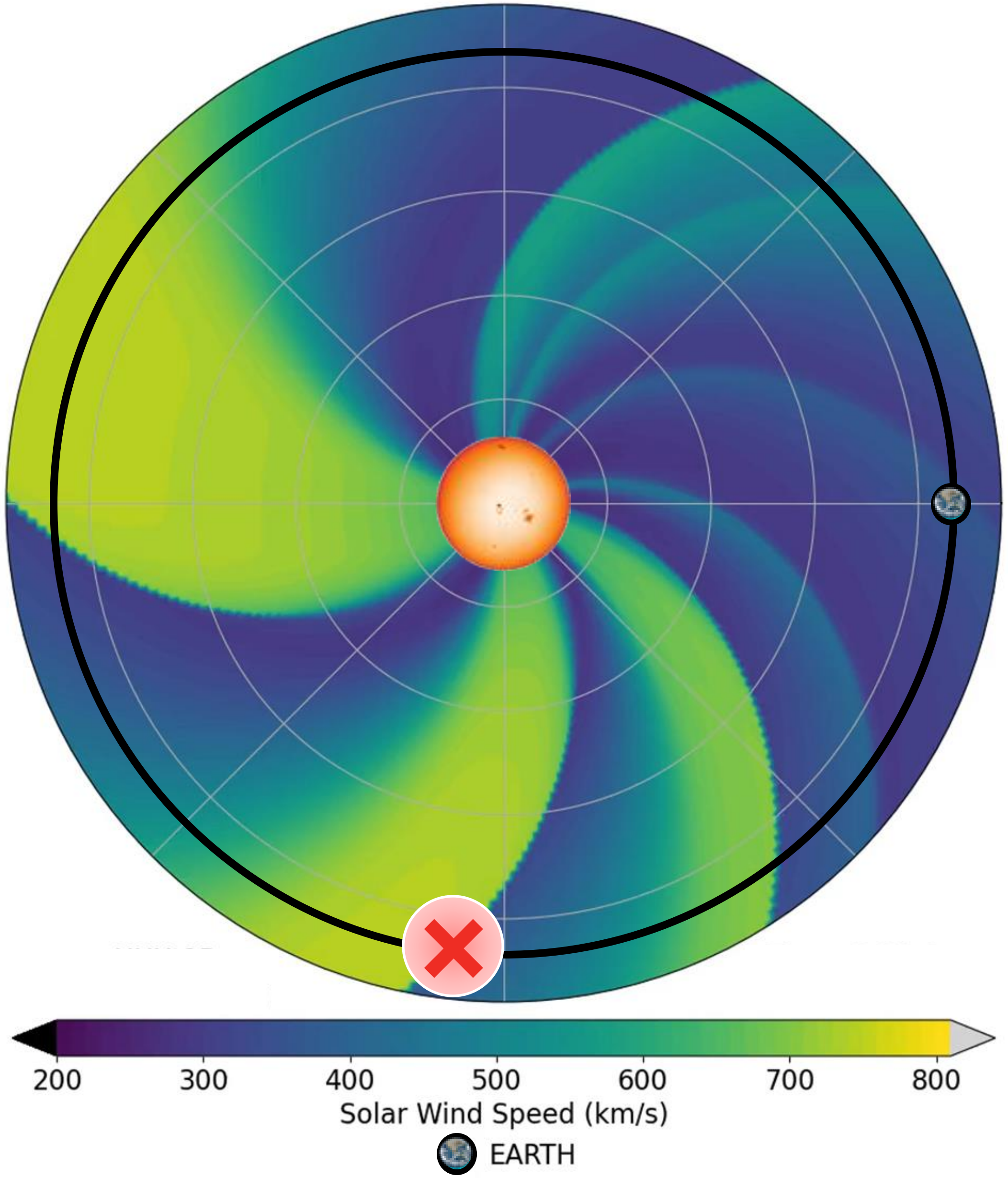
I have been using the Burger Radius Variational Data Assimilation (BRaVDA) scheme developed at the University of Reading (Lang et al., 2019)

Combines observations with a steady-state solar wind model

Prior inner boundary condition from a coronal model

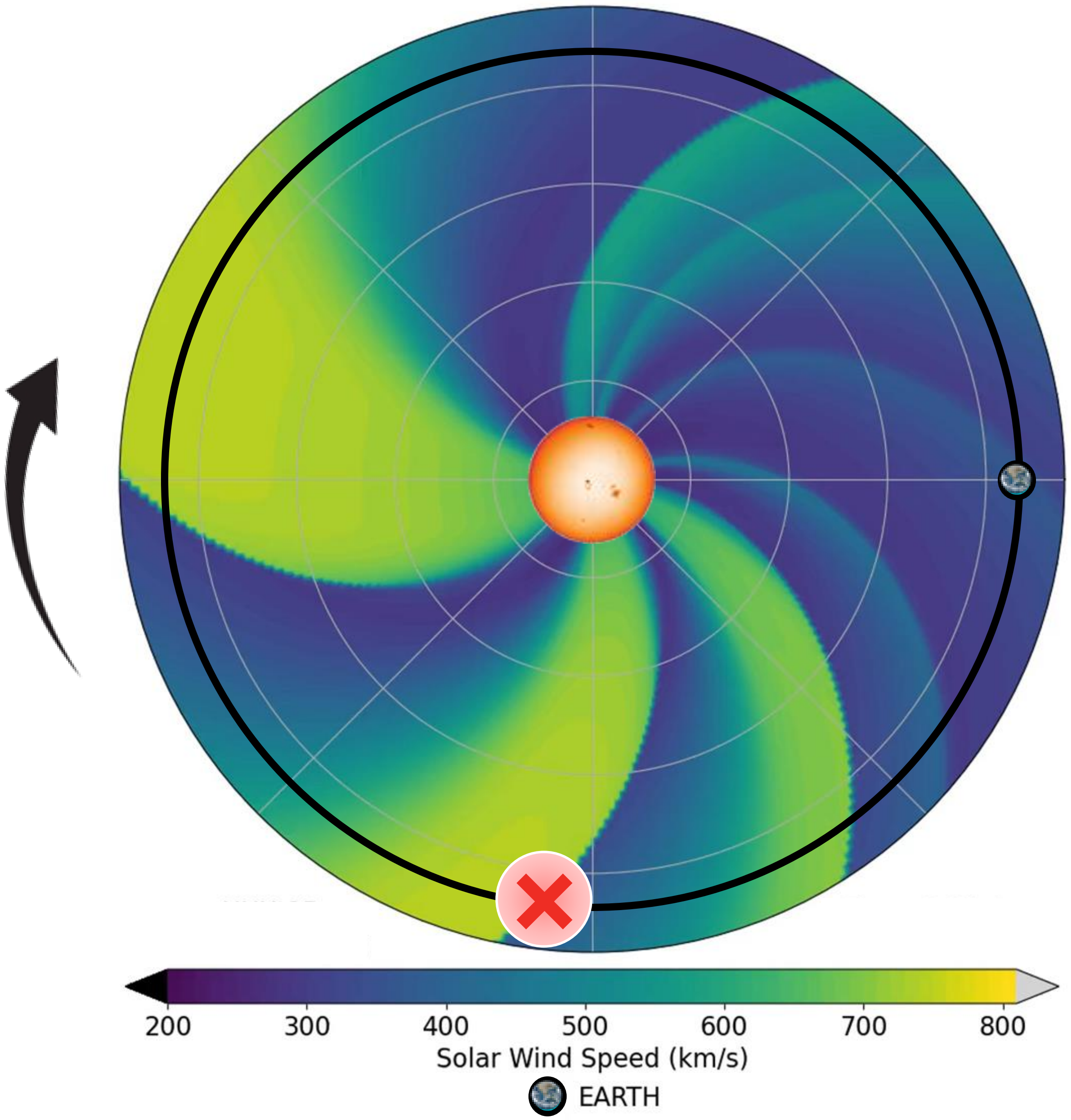

200
300
400
500
600
700
800
Solar Wind Speed (km/s)
EARTH


200
300
400
500
600
700
800
Solar Wind Speed (km/s)
EARTH



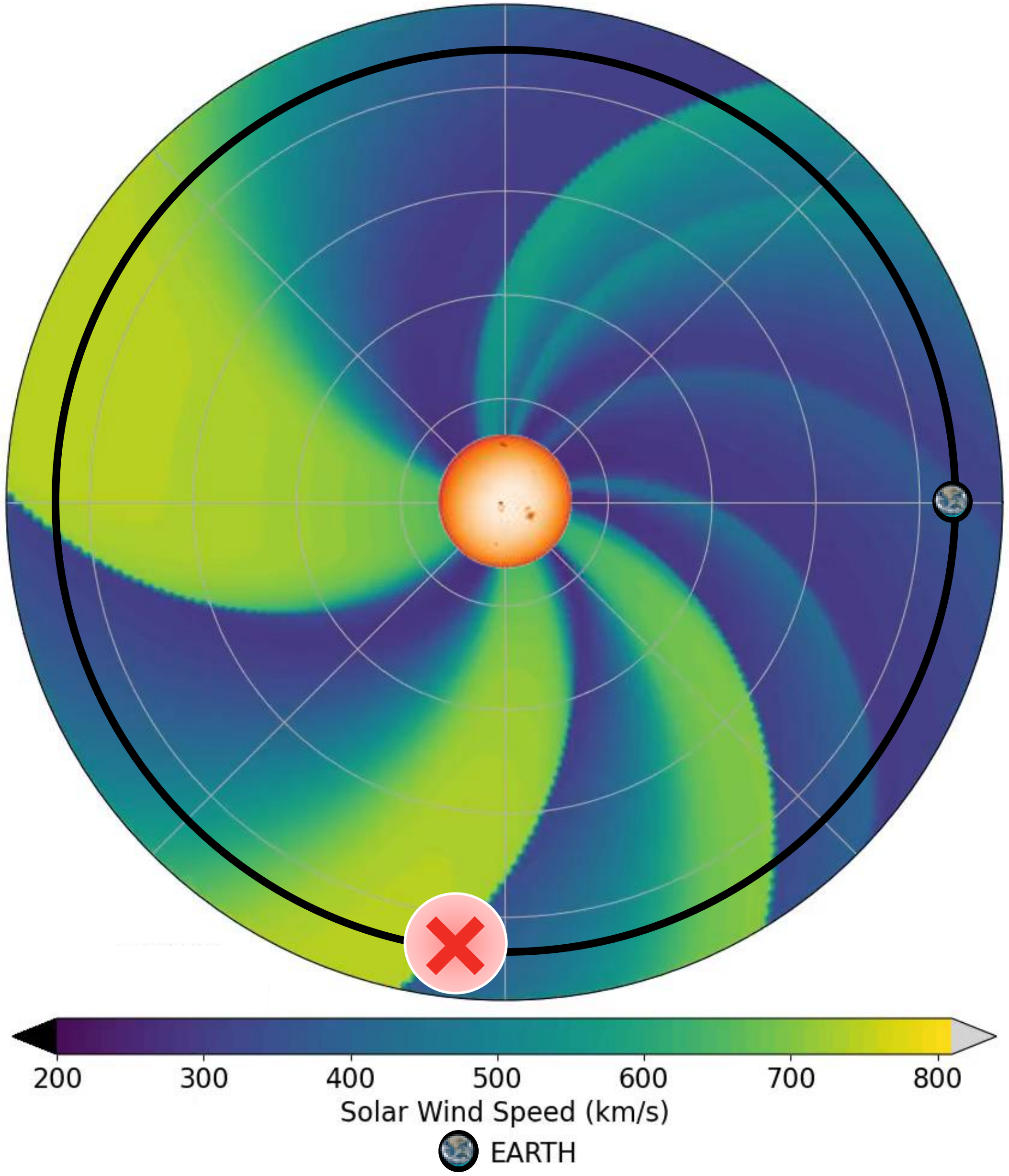
Time = t_0

❌ = observation



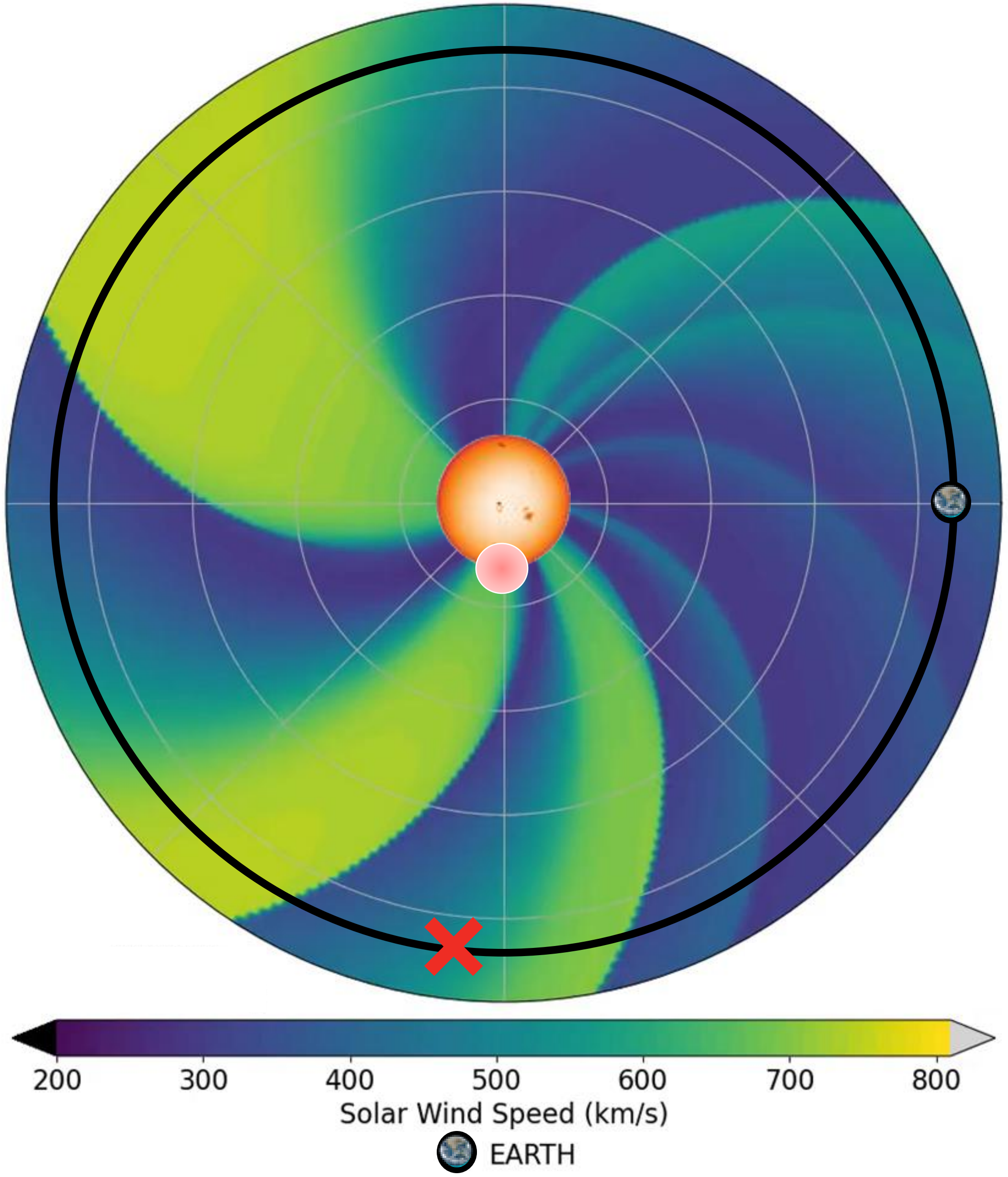
Time = t_0

❌ = observation



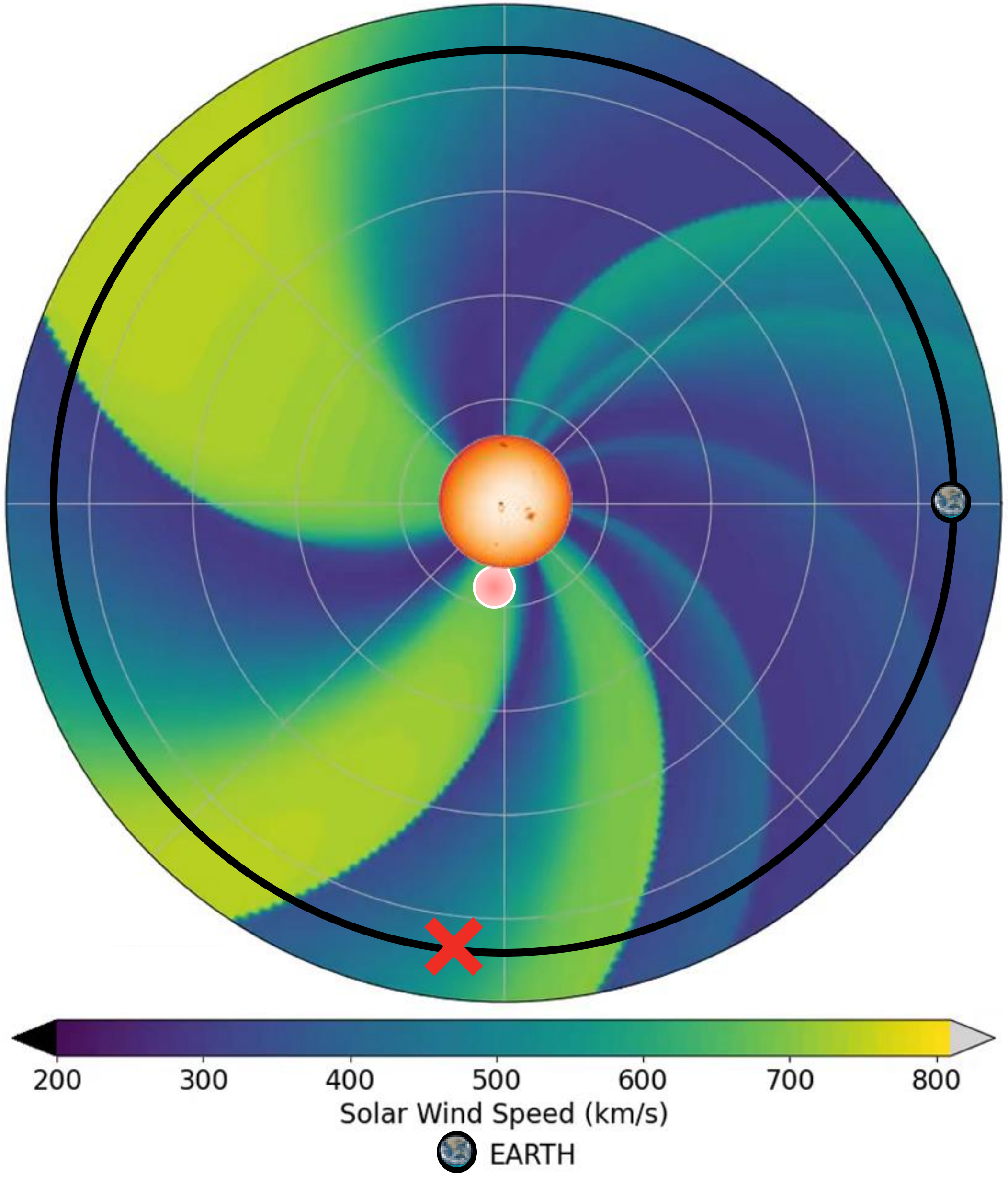
Time = $t_0 - \Delta t$

✕ = observation



Time = $t_0 - \Delta t$

✕ = observation

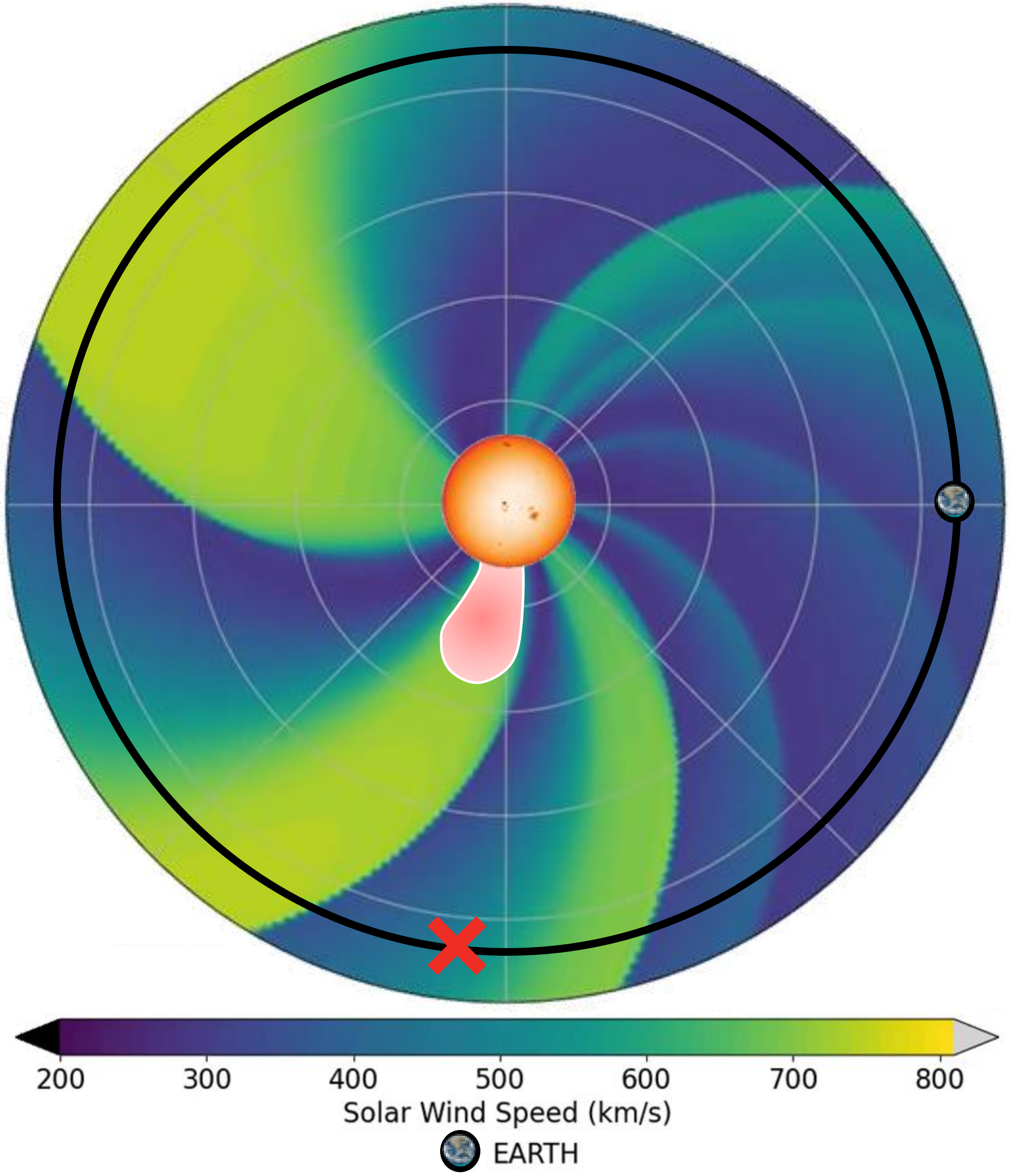


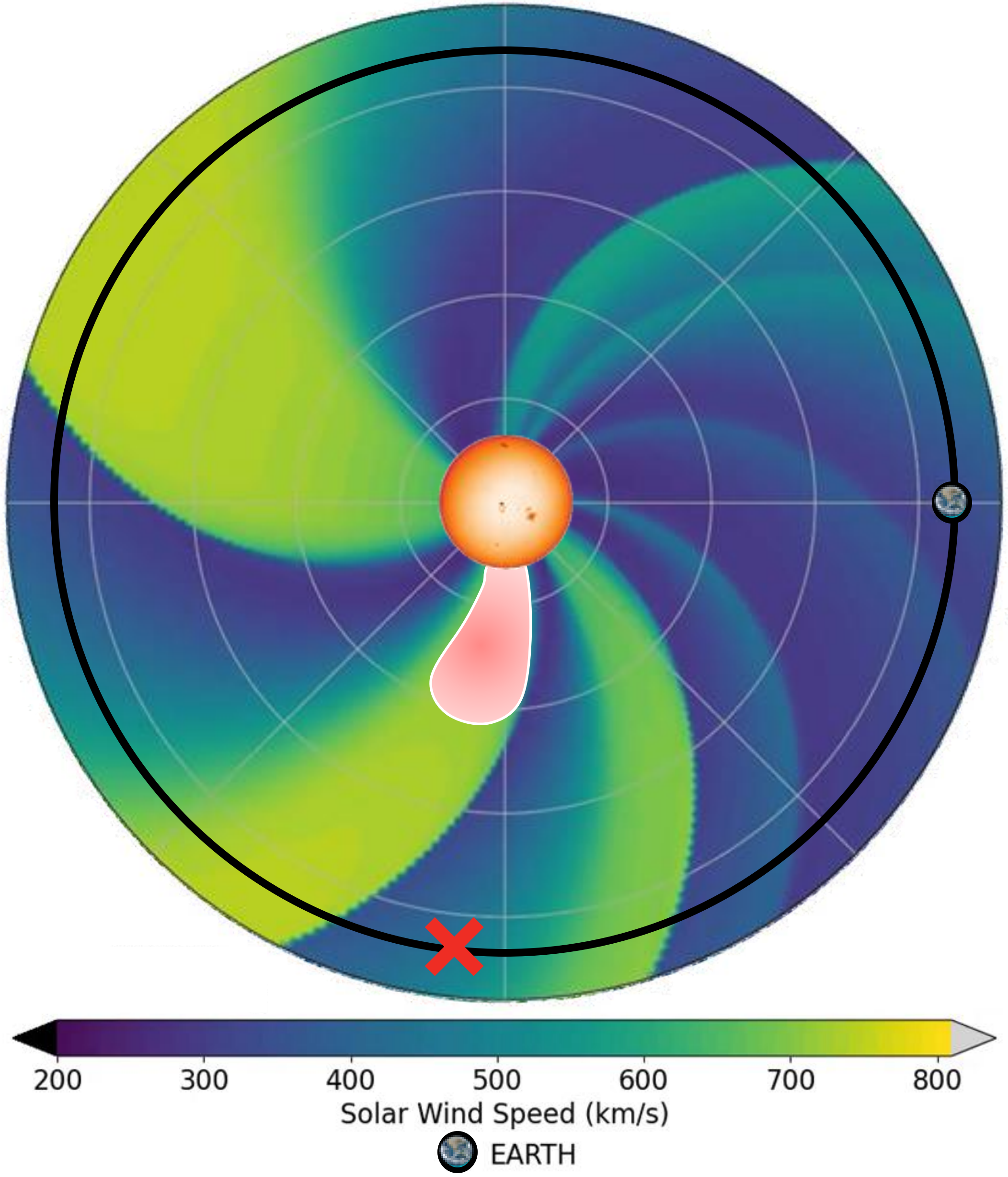
Time = $t_0 - \Delta t$

✕ = observation

Time = $t_0 - \Delta t$

✕ = observation



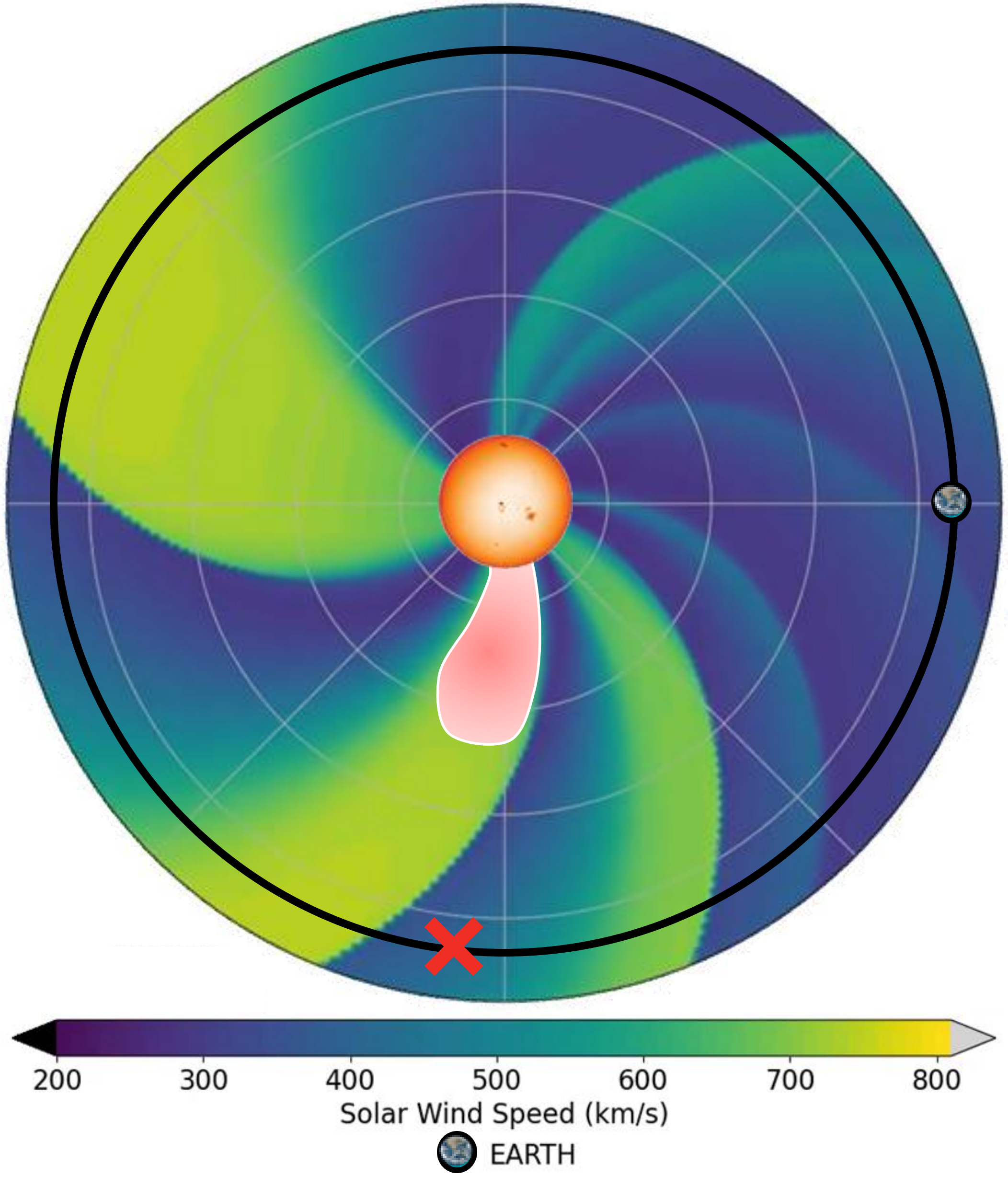


Time = $t_0 - \Delta t$

✕ = observation

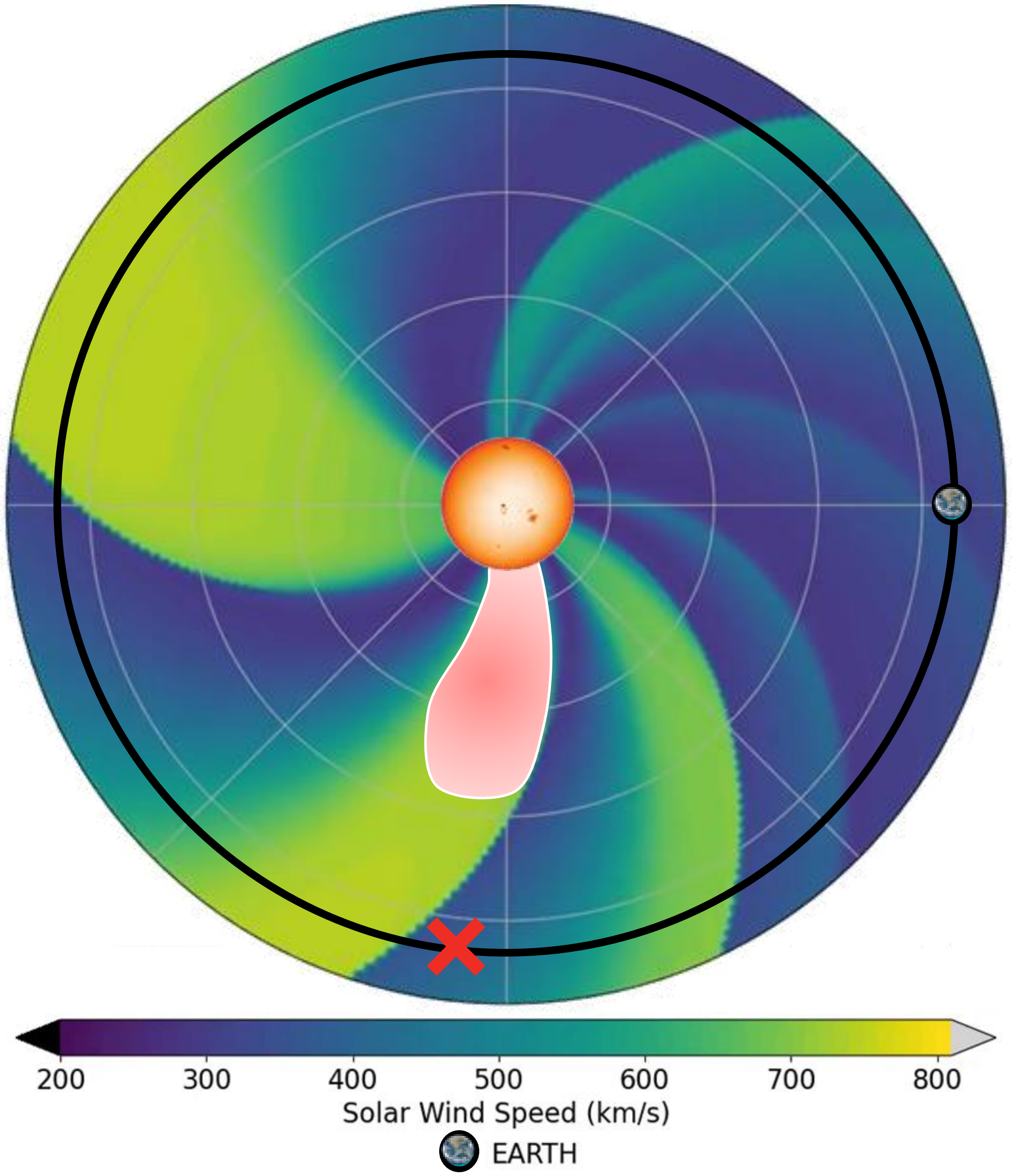
Time = $t_0 - \Delta t$

✕ = observation

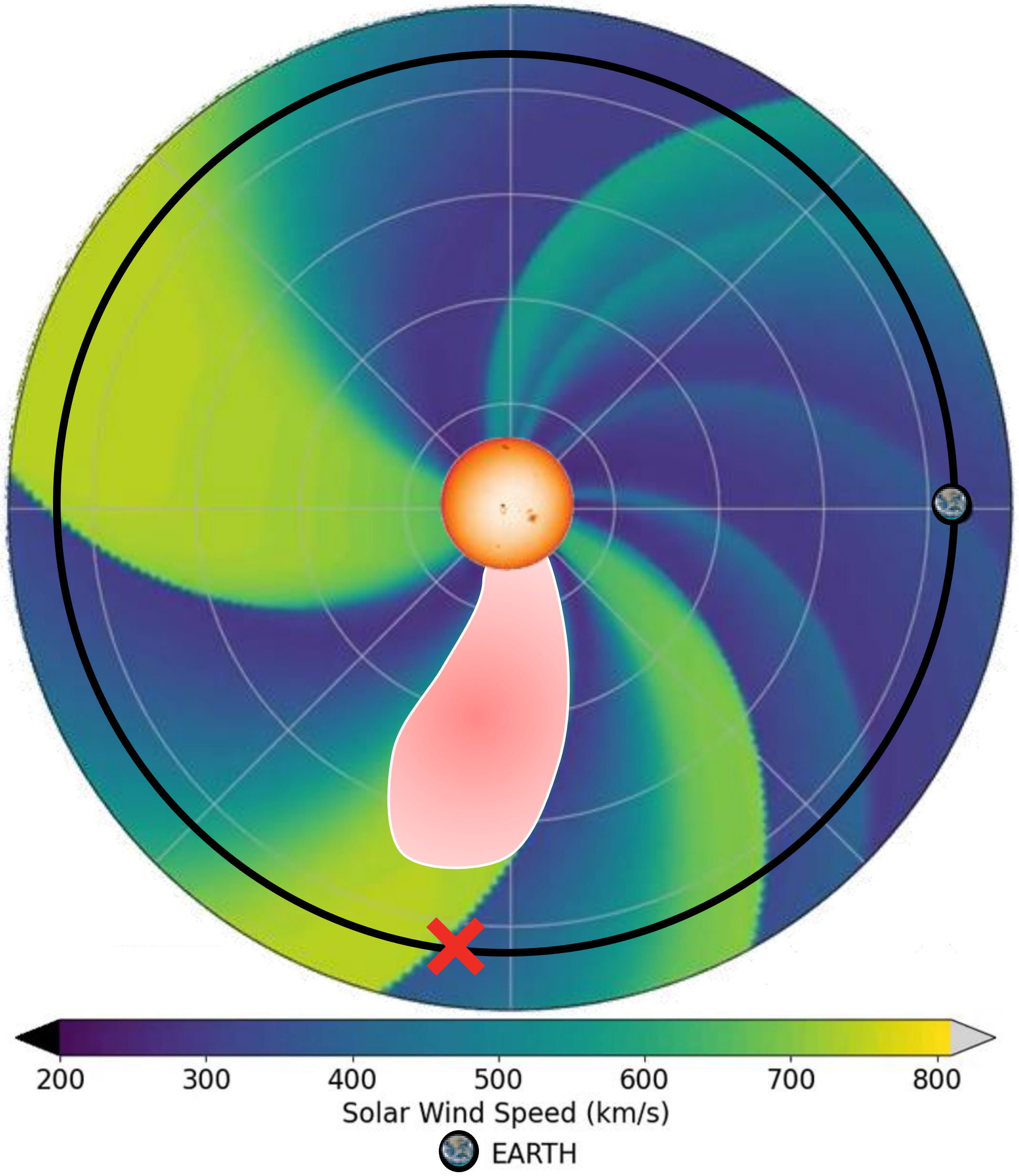


Time = $t_0 - \Delta t$

✖ = observation

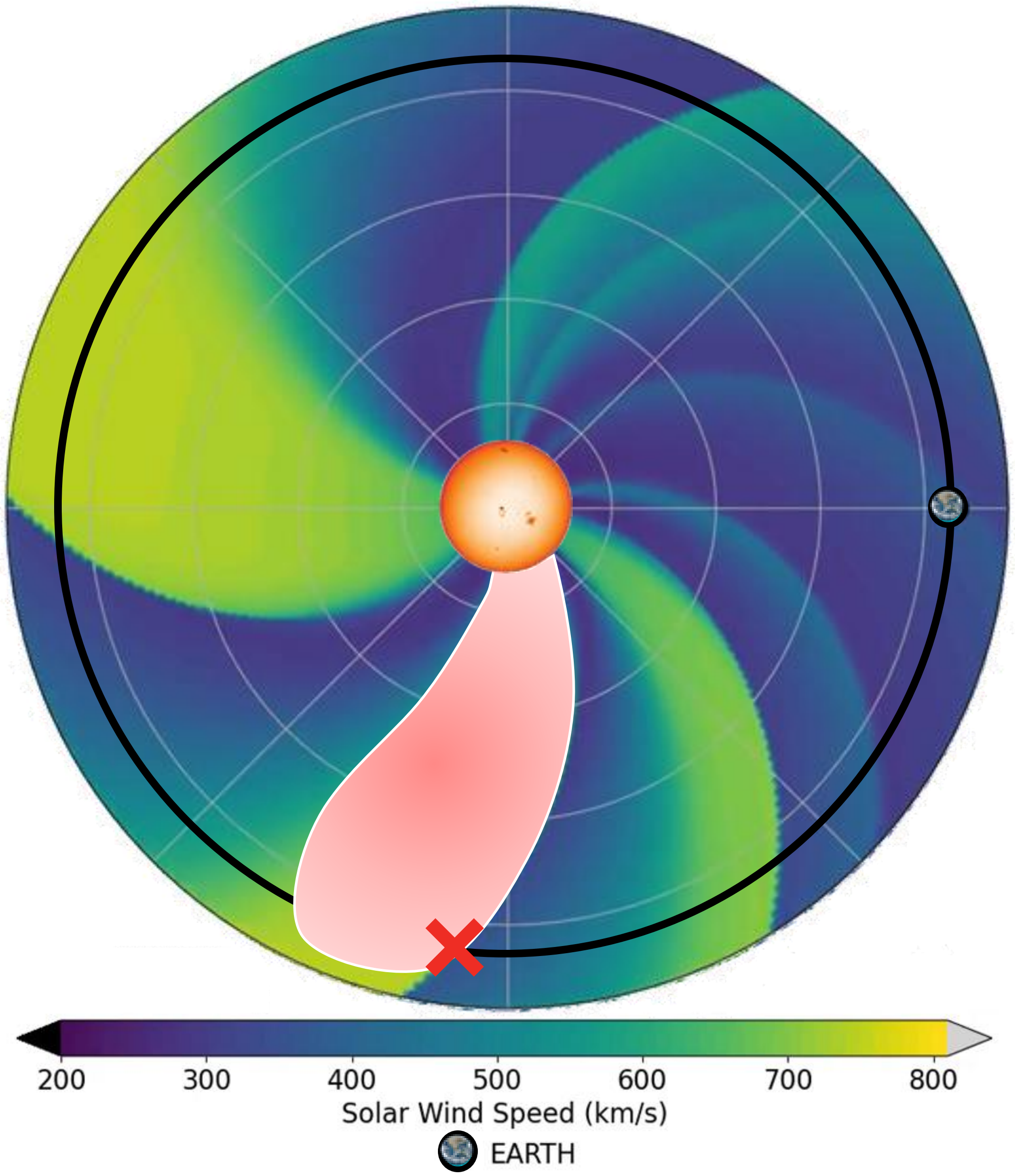


Time = $t_0 - \Delta t$



✕ = observation

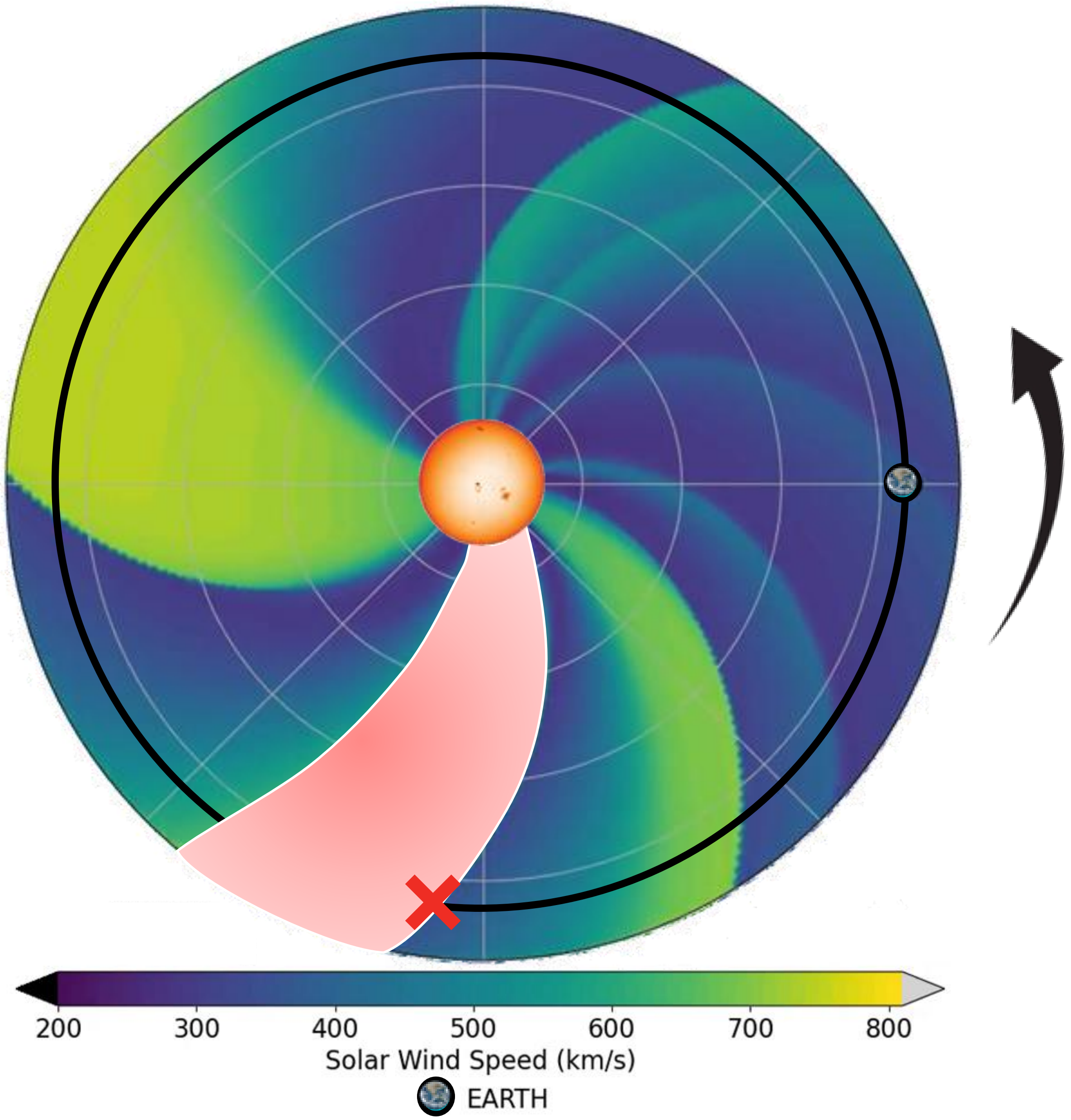
Time = t_0



✕ = observation

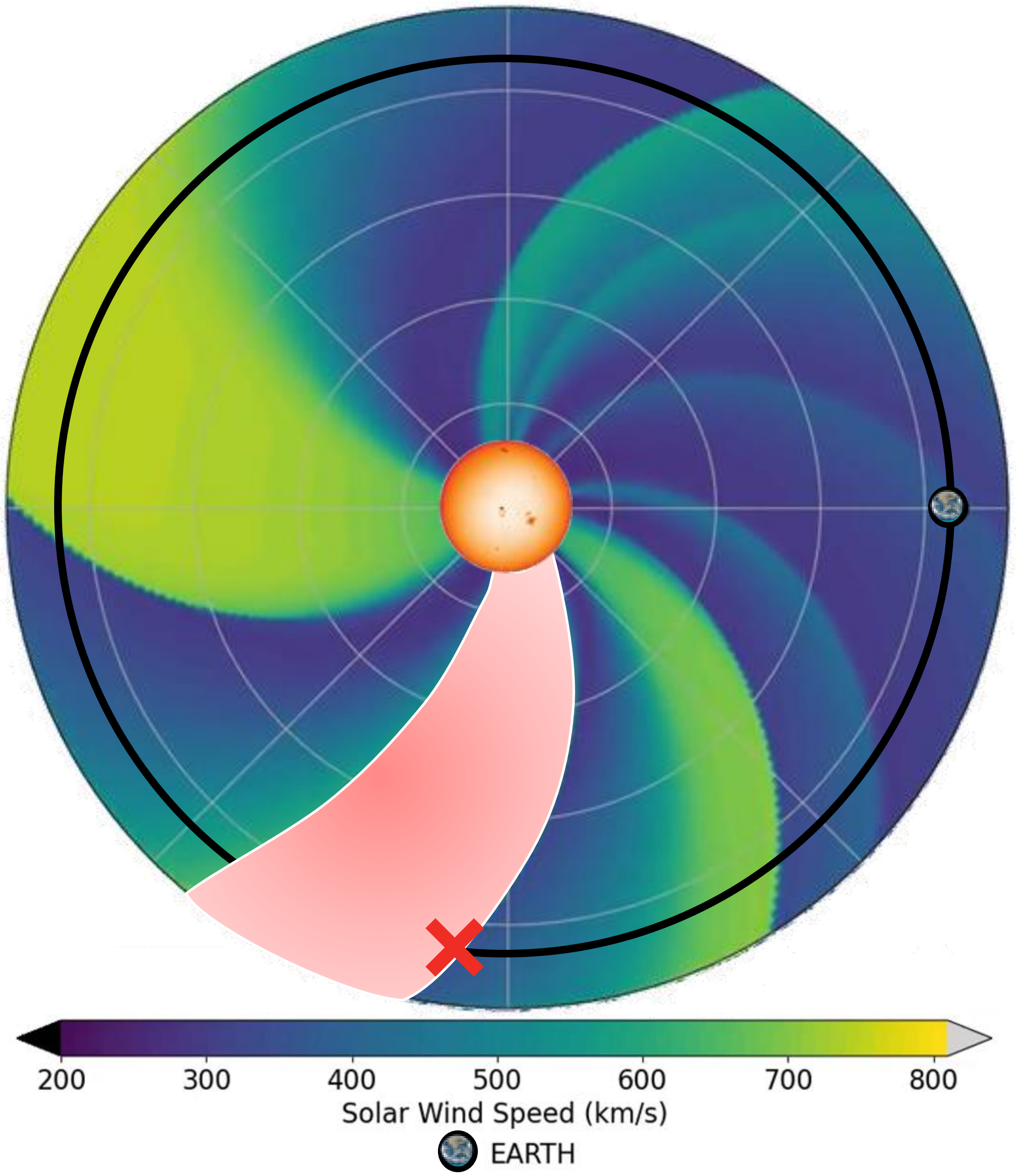
Time = t_0

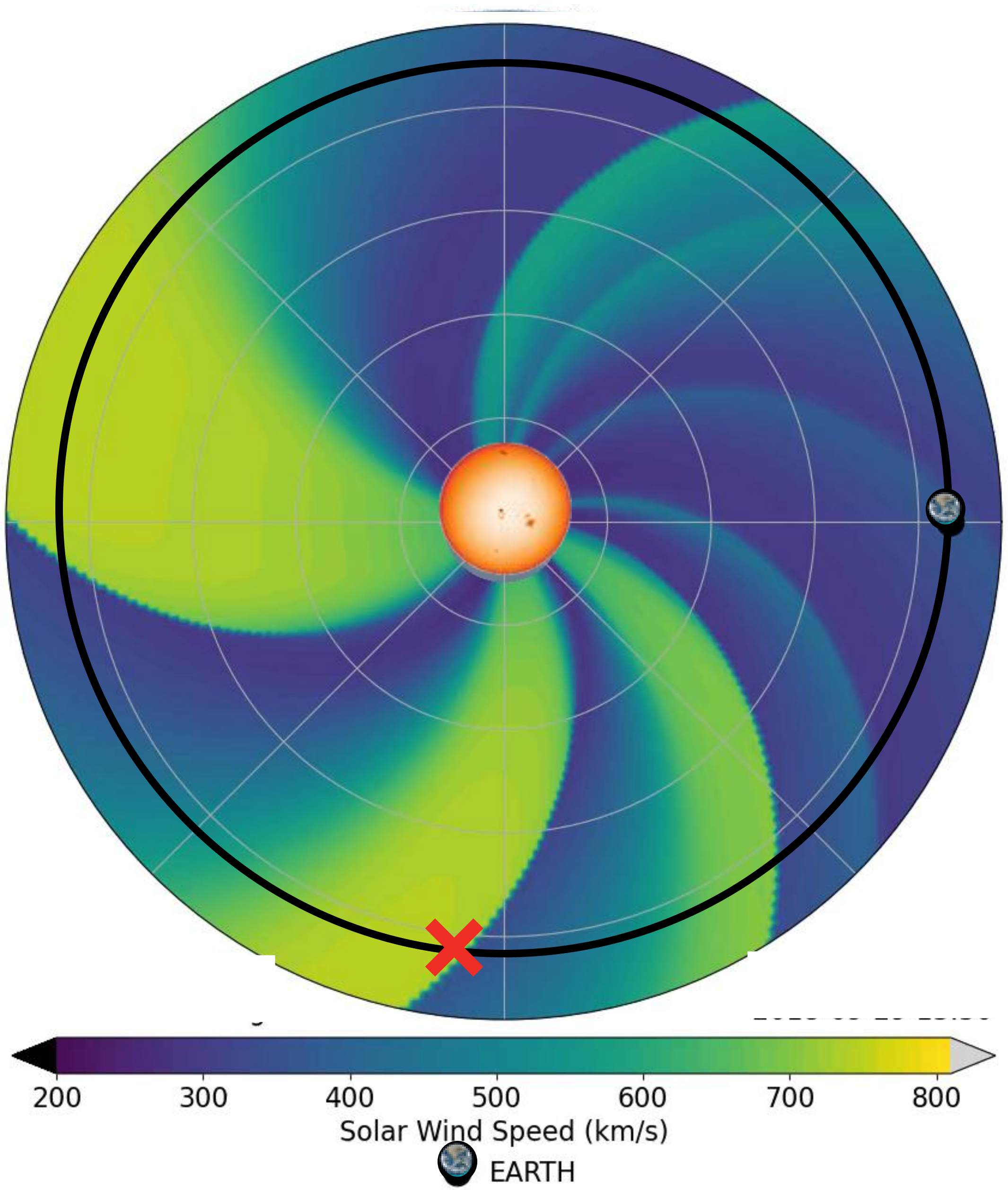
✕ = observation



Time = t_0

✕ = observation



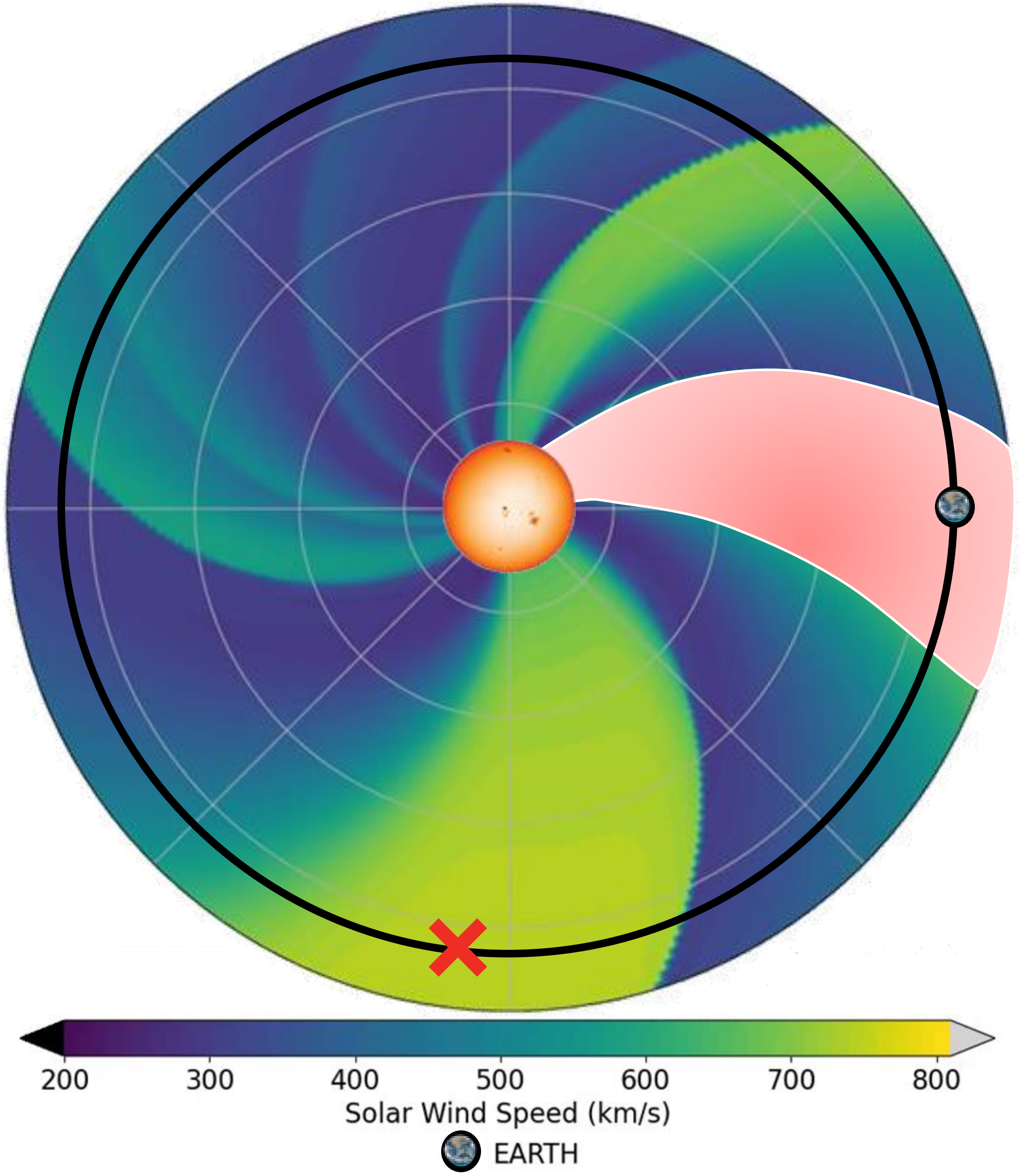


Time = t_0

✖ = observation

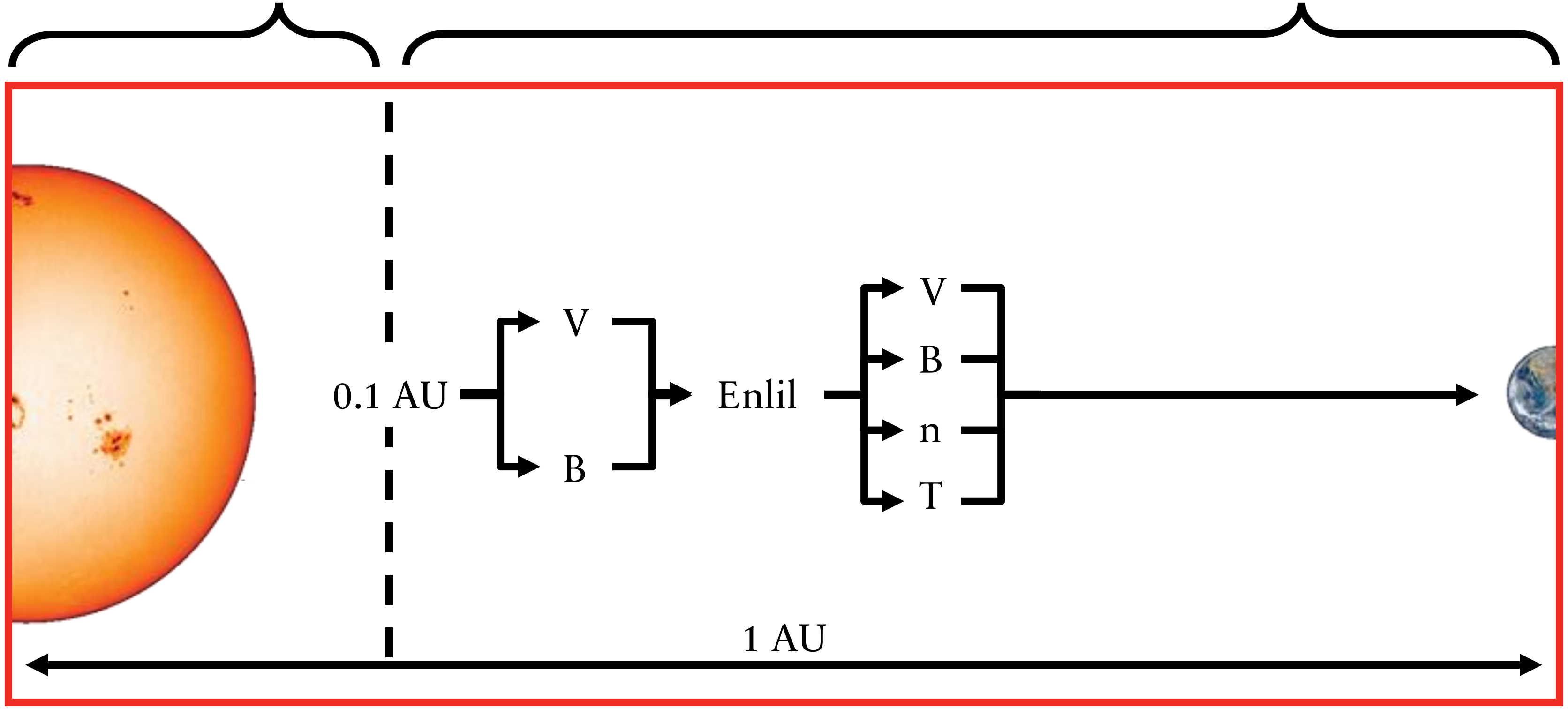
Time = $t_0 + \Delta t$

✕ = observation



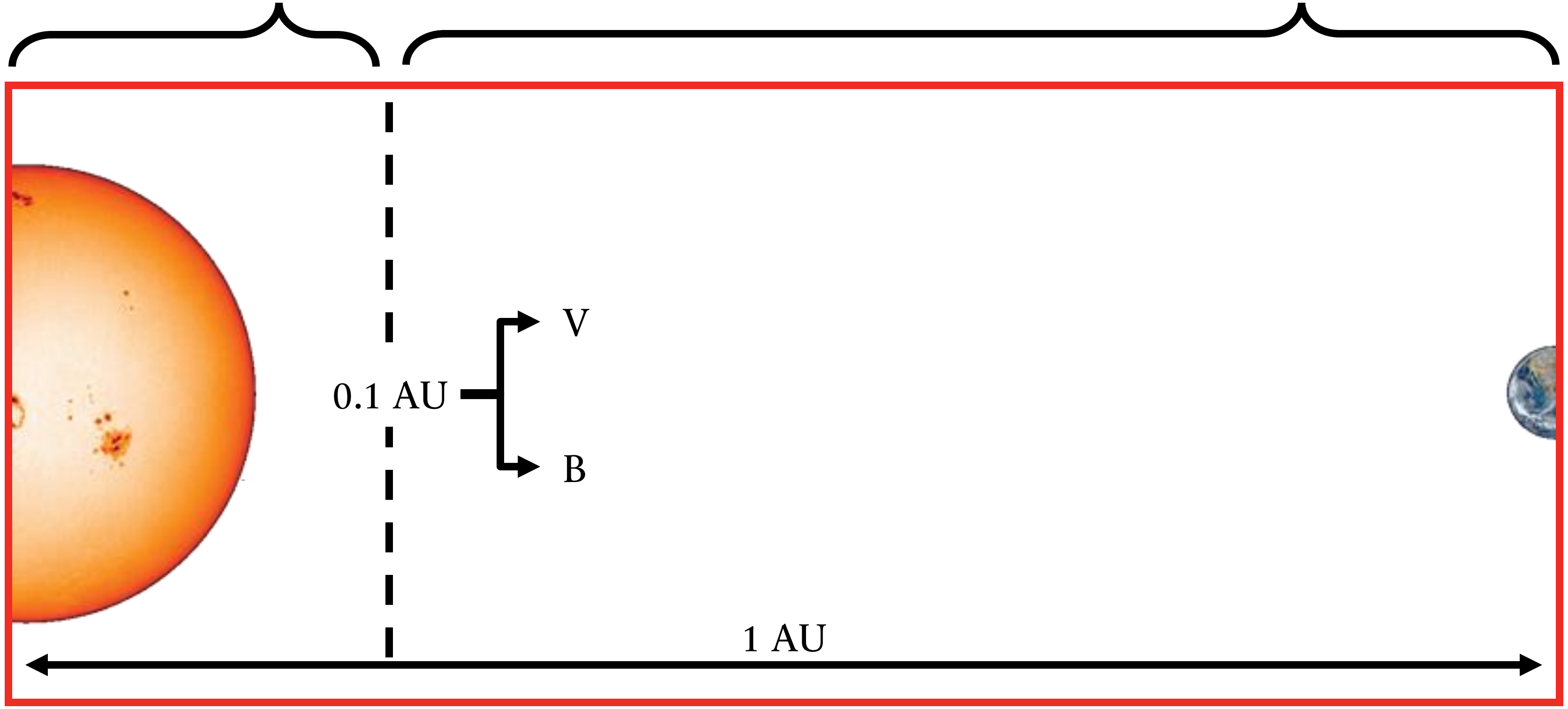
CURRENT FORECASTING

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



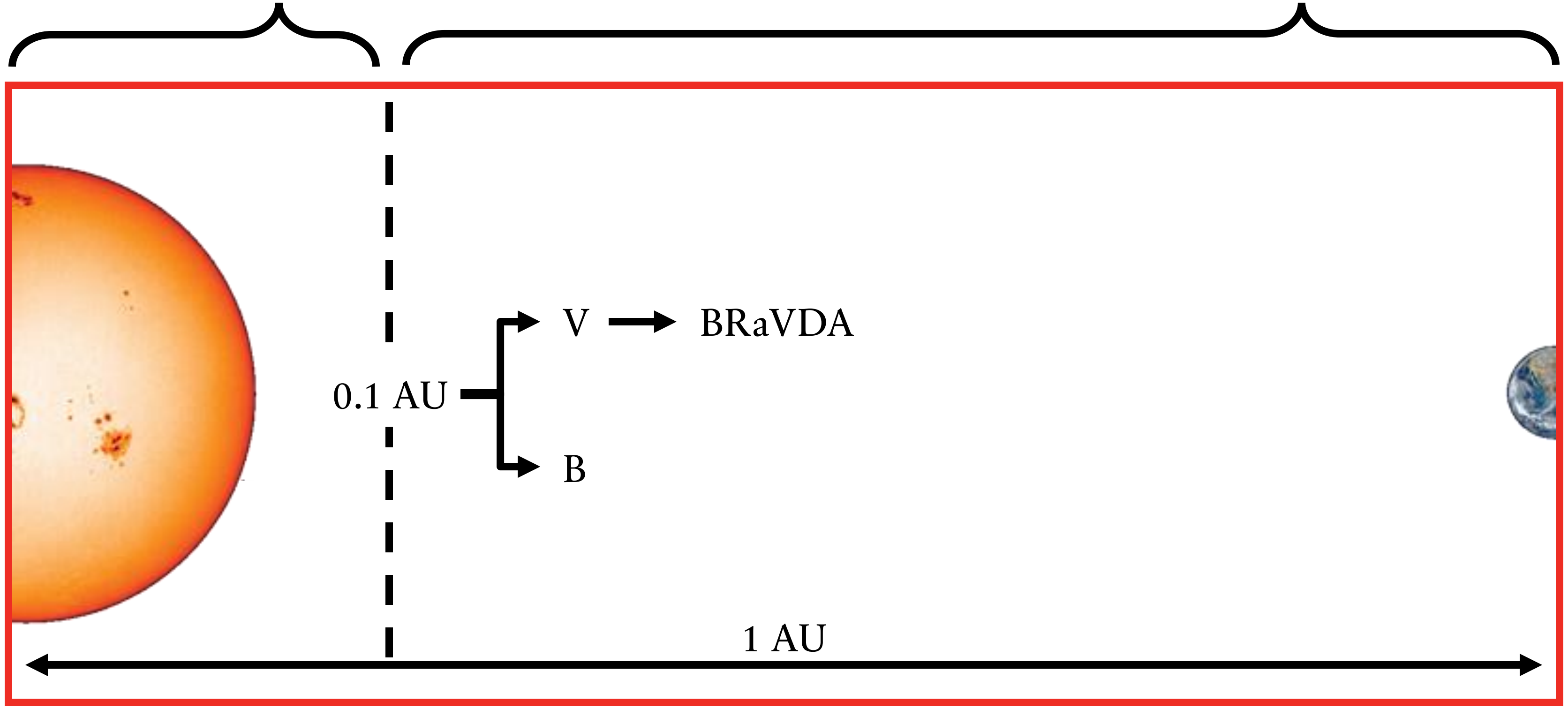
CURRENT DA IMPLEMENTATION

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



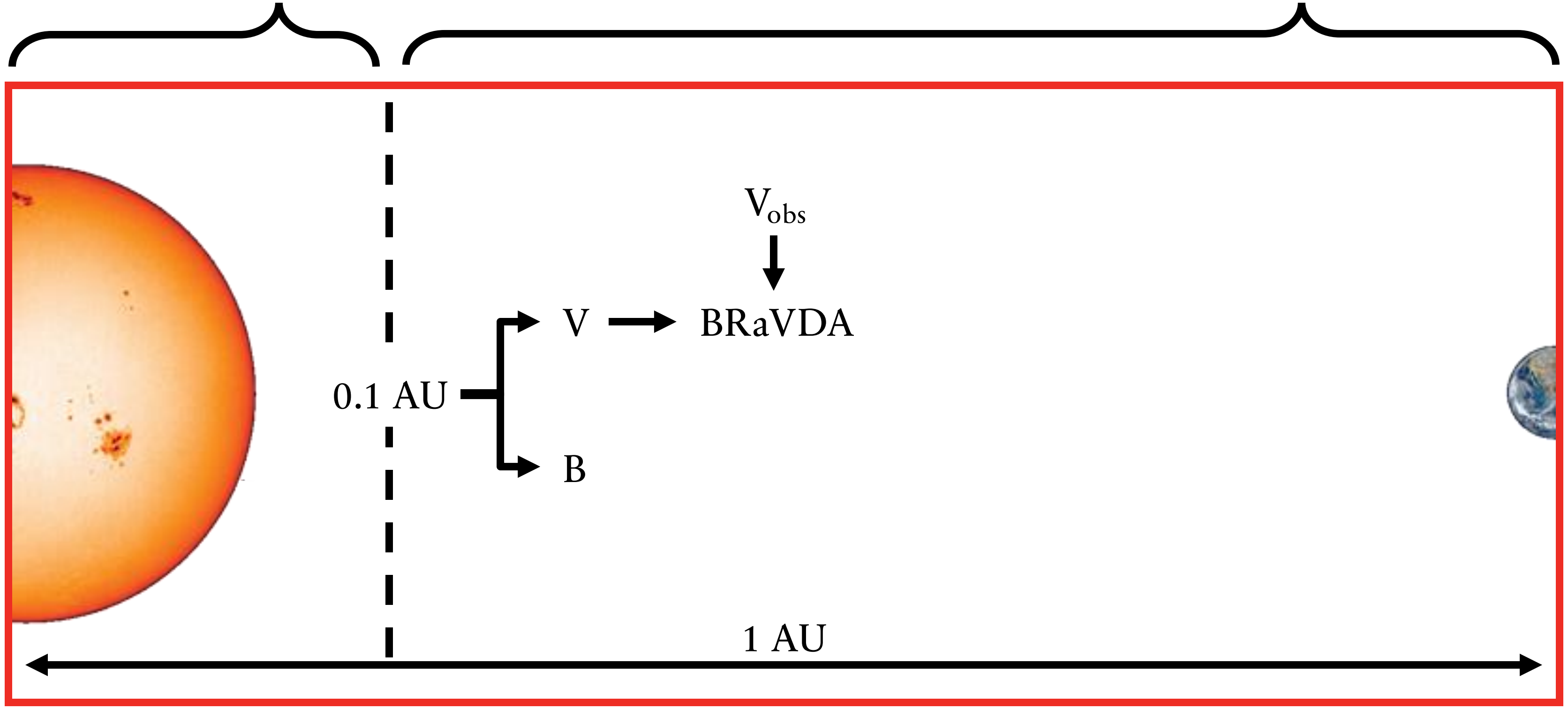
CURRENT DA IMPLEMENTATION

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



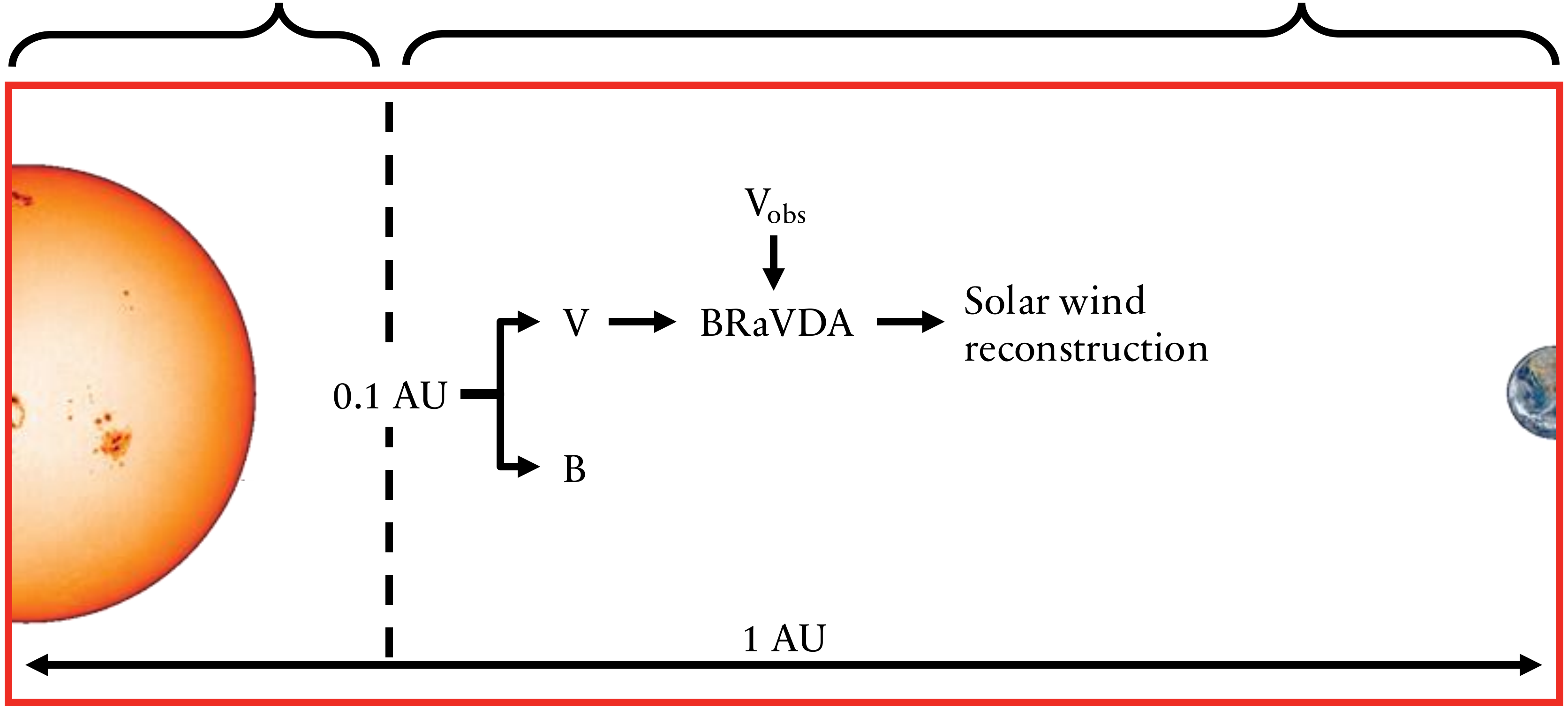
CURRENT DA IMPLEMENTATION

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



CURRENT DA IMPLEMENTATION

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



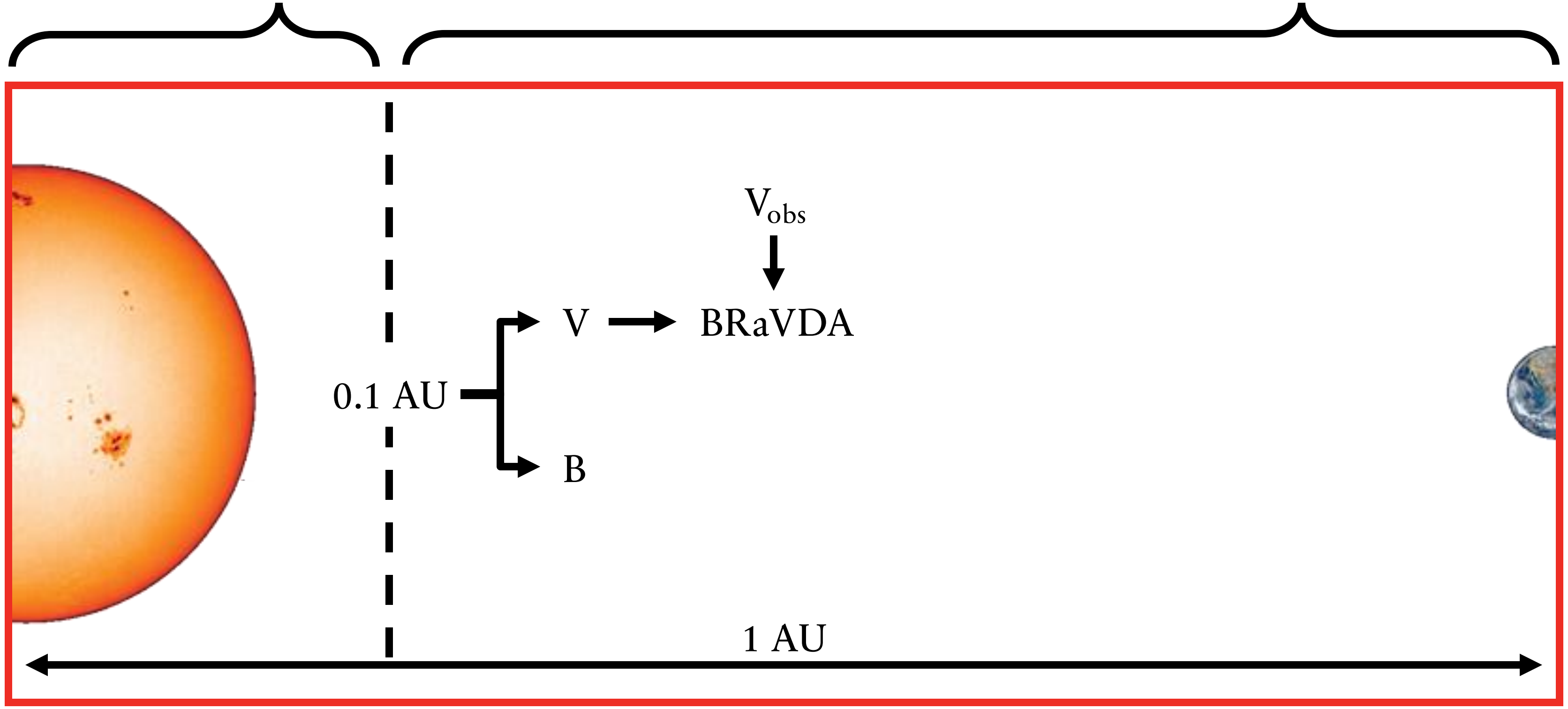
DIVERGENCE OF METHODS

Previous work (Lang et al., 2021) have used the reduced-physics model "HUXt" (Owens et l., 2020) for analysis

For simplicity, I have used corotation – essentially assuming the Sun remains constant as it rotates

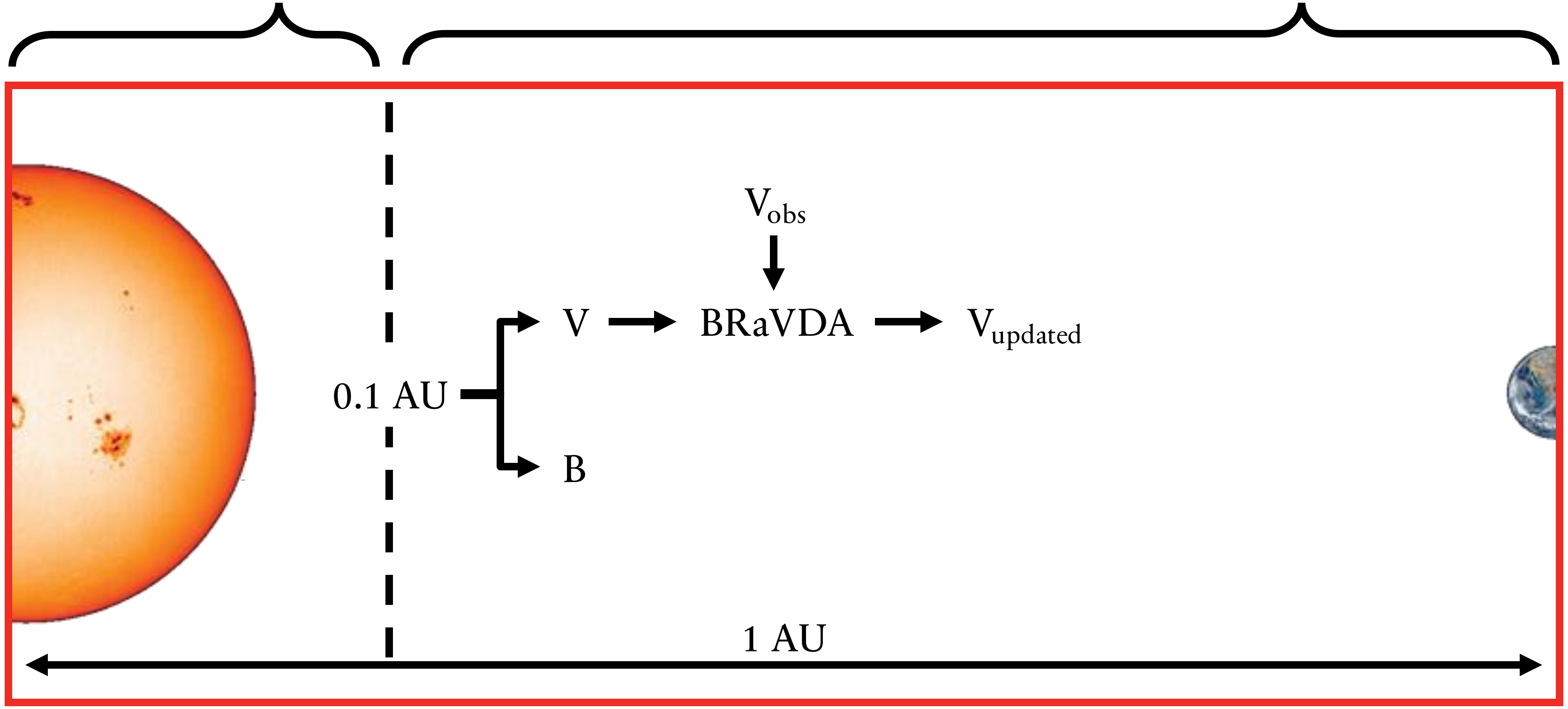
HUXt METHOD

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



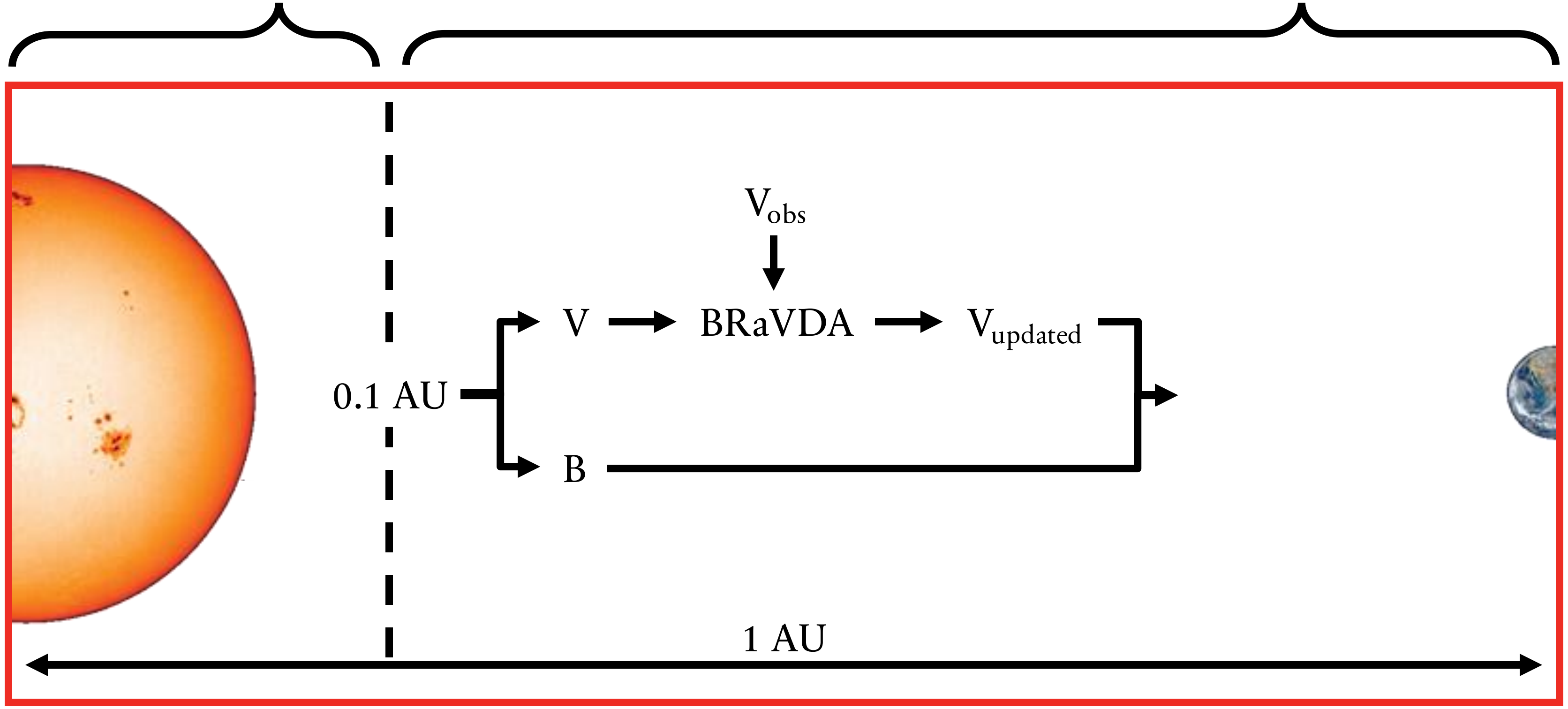
HUXt METHOD

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



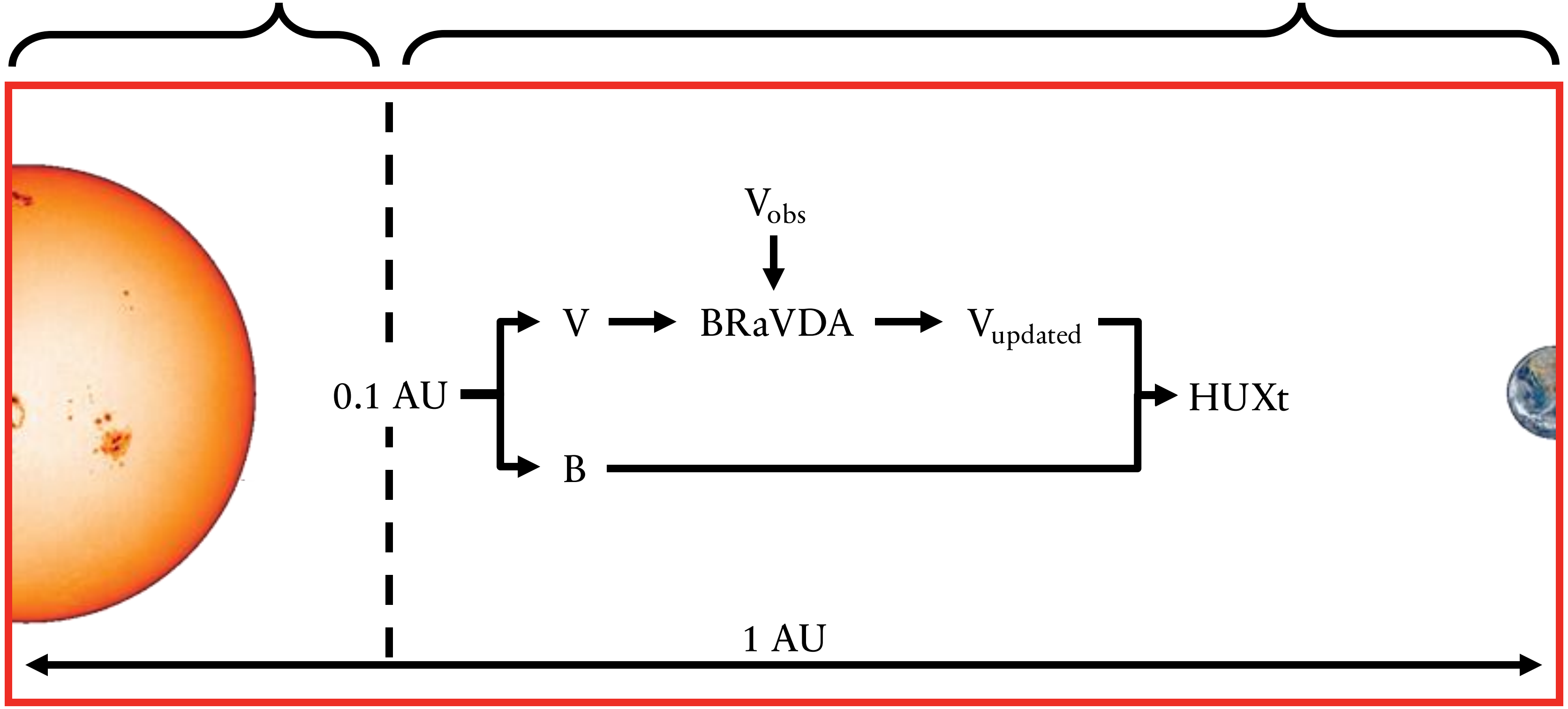
HUXt METHOD

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



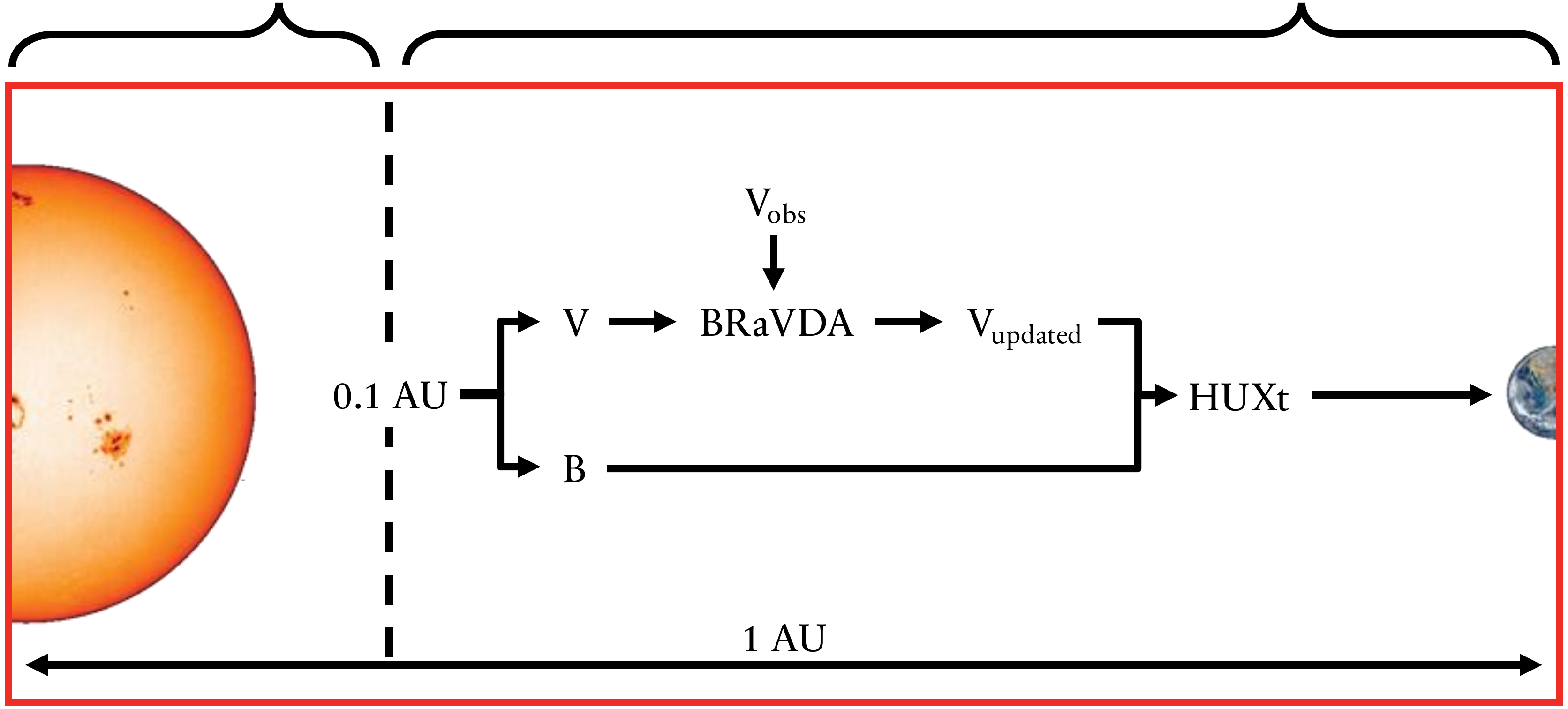
HUXt METHOD

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



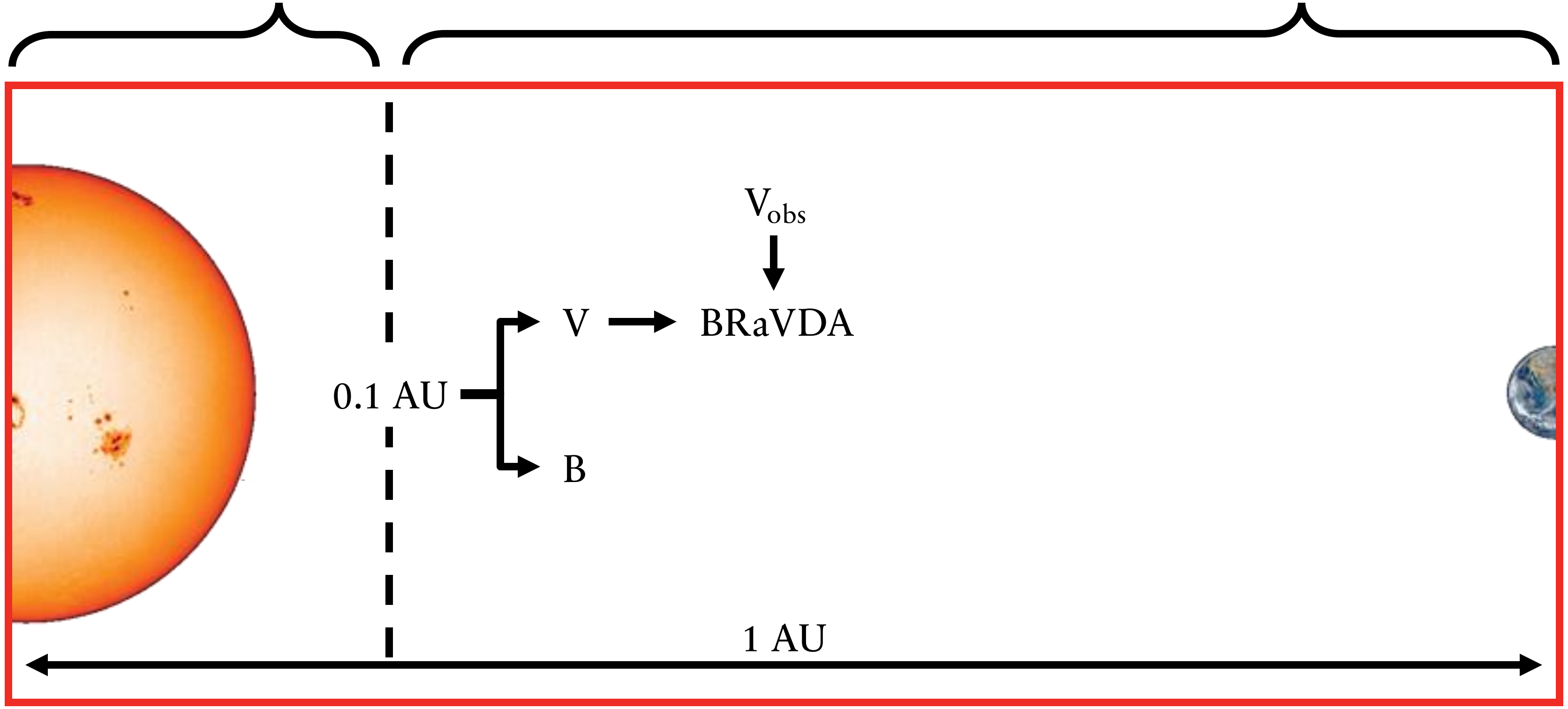
HUXt METHOD

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



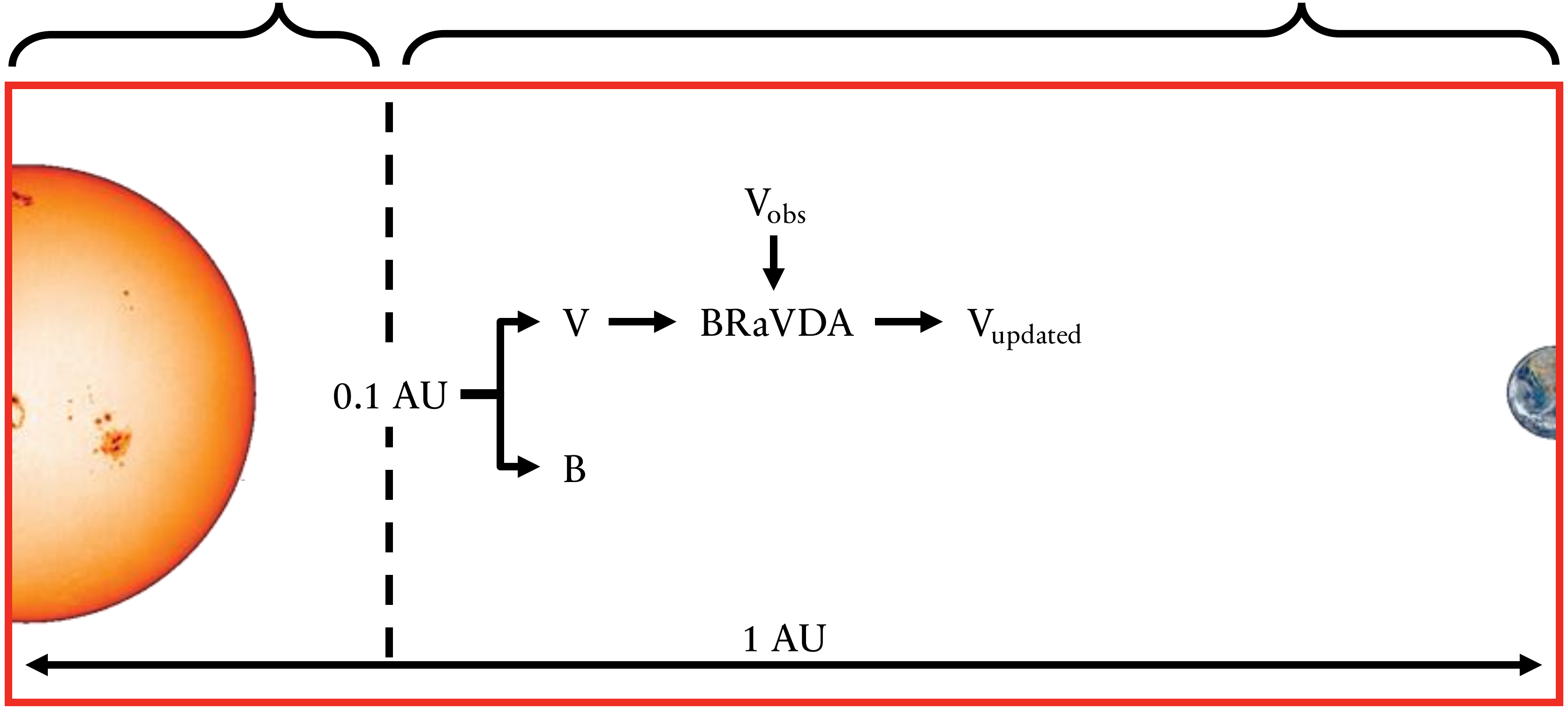
COROTATION METHOD

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



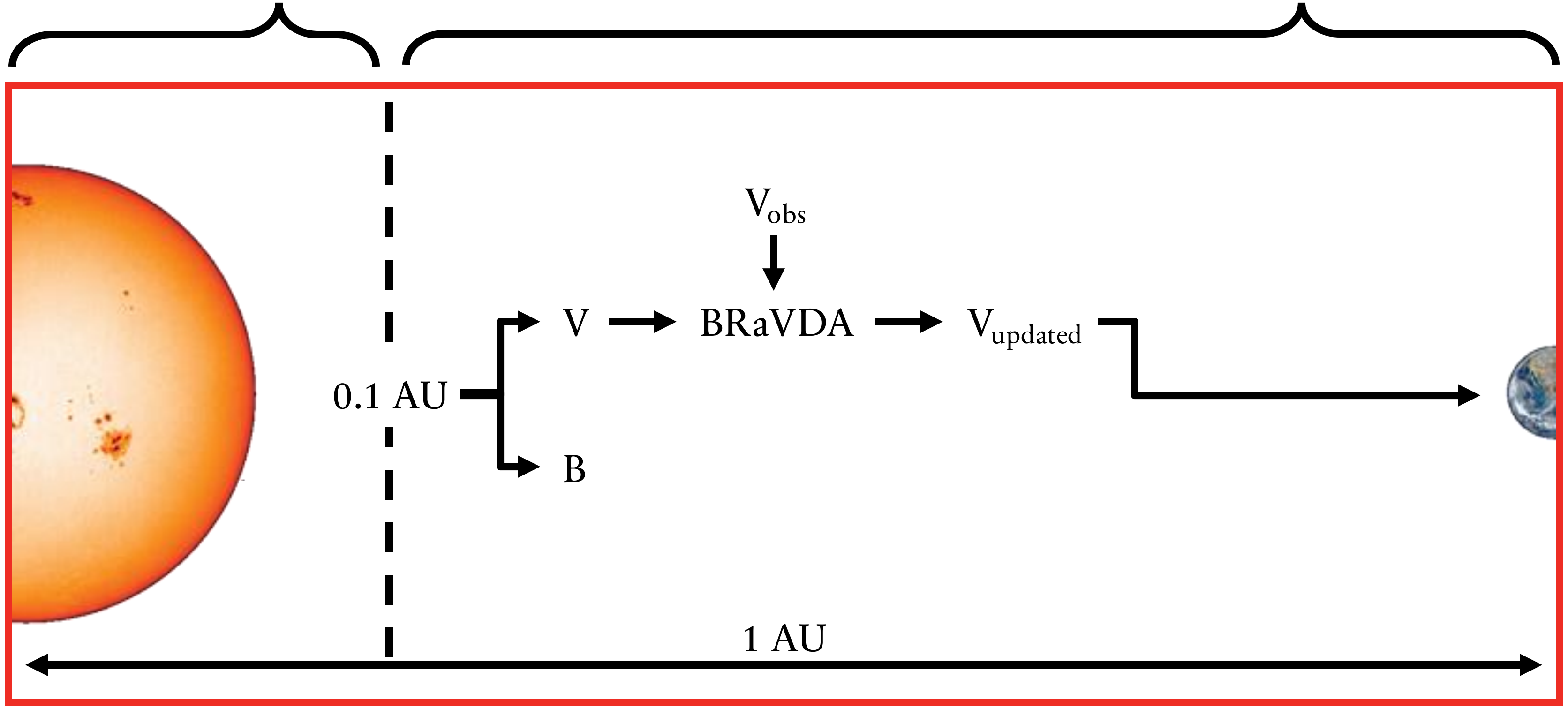
COROTATION METHOD

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



COROTATION METHOD

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



OBSERVATIONS – STEREO

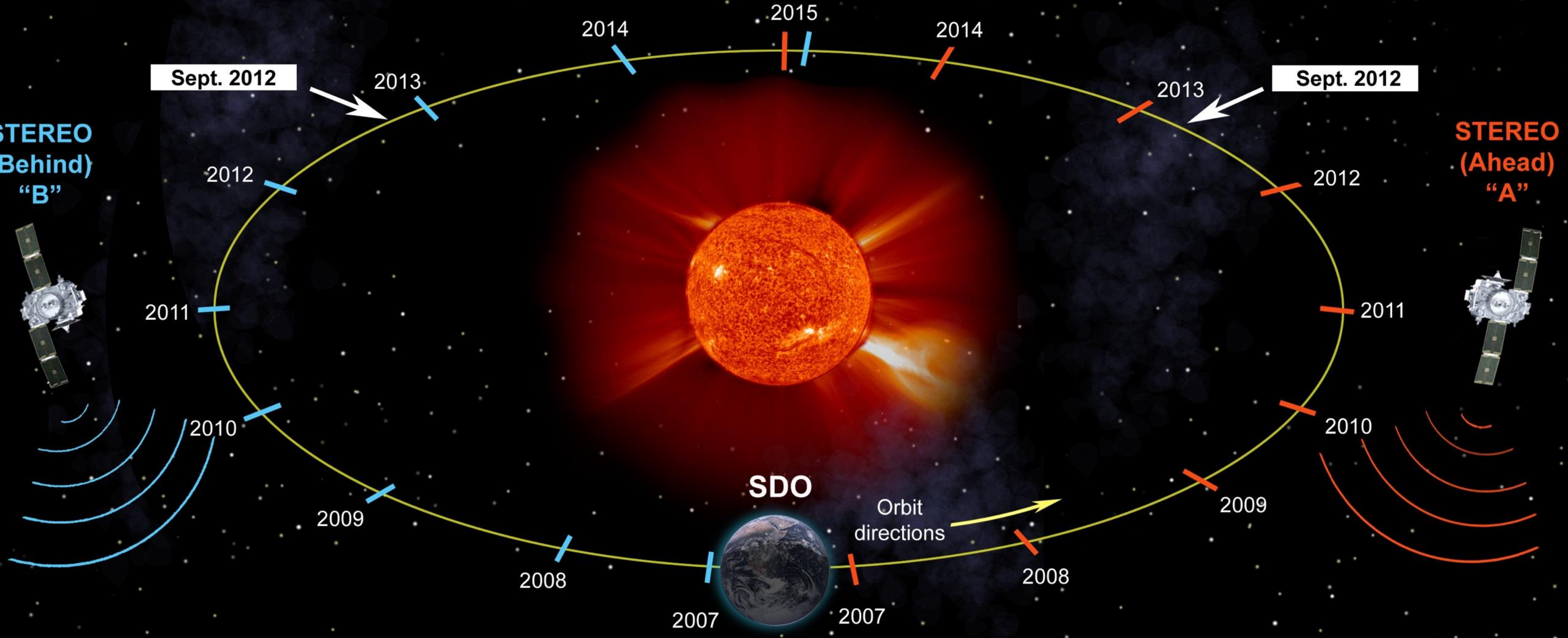
Solar Terrestrial Relations Observatory Ahead and Behind – STEREO-A and B

Earth-like orbits, but separating in longitude

Launched in 2007

Communication with STEREO-B lost in 2014

NASA's STEREO (with SDO) Sees the Entire Sun



The two **STEREO** spacecraft reach equidistant positions between themselves and Earth on Sept. 1, 2012.

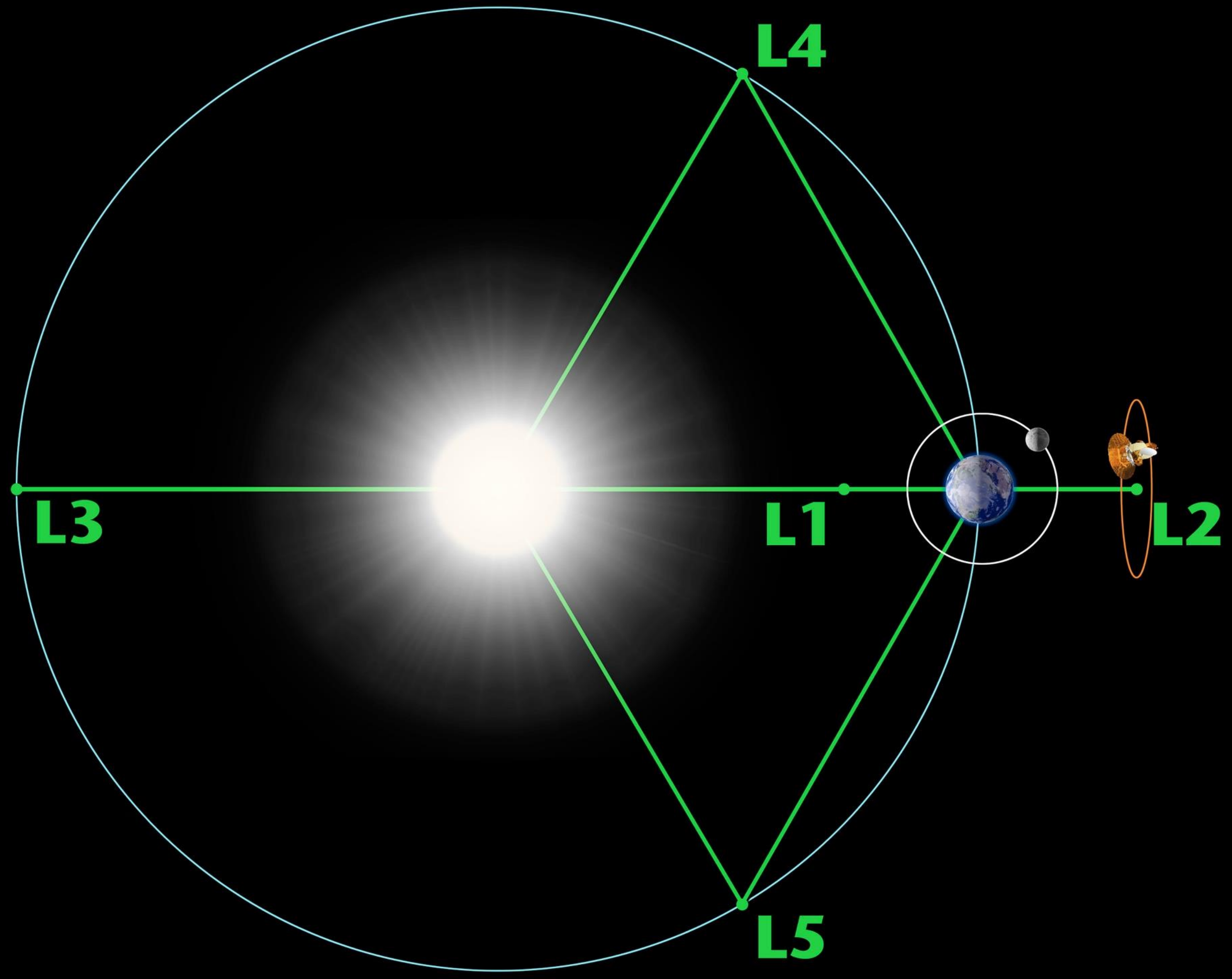
Drawing gives the relative orbital positions of both STEREO spacecraft for each year from June 2007 to June 2015.
(Not to scale)

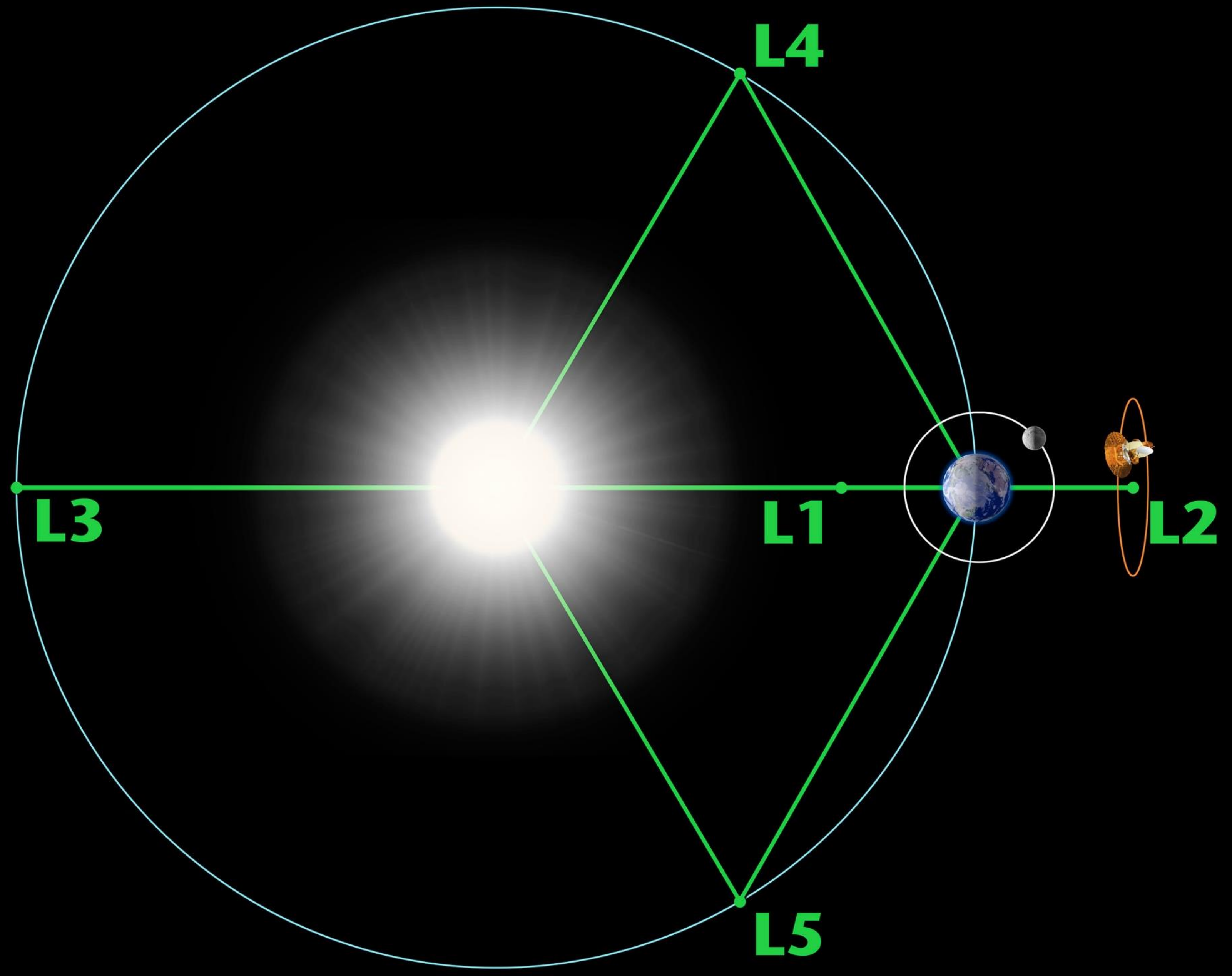
OBSERVATIONS – ACE & DSCOVR

Advanced Composition Explorer – ACE (launched 1997)

Deep Space Climate Observatory – DSCOVR (launched 2015)

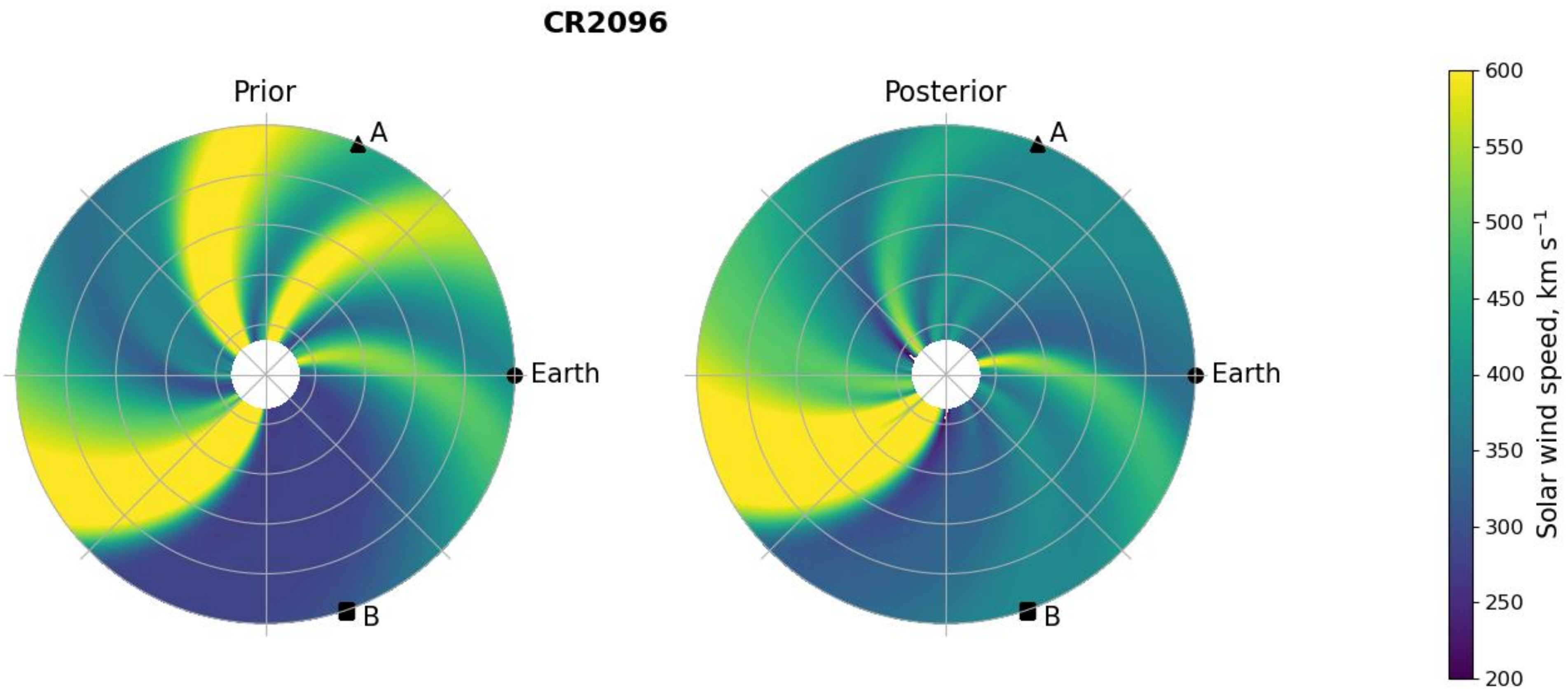
Both give near-Earth observations from L1


L4
L3
L1
L2
L5

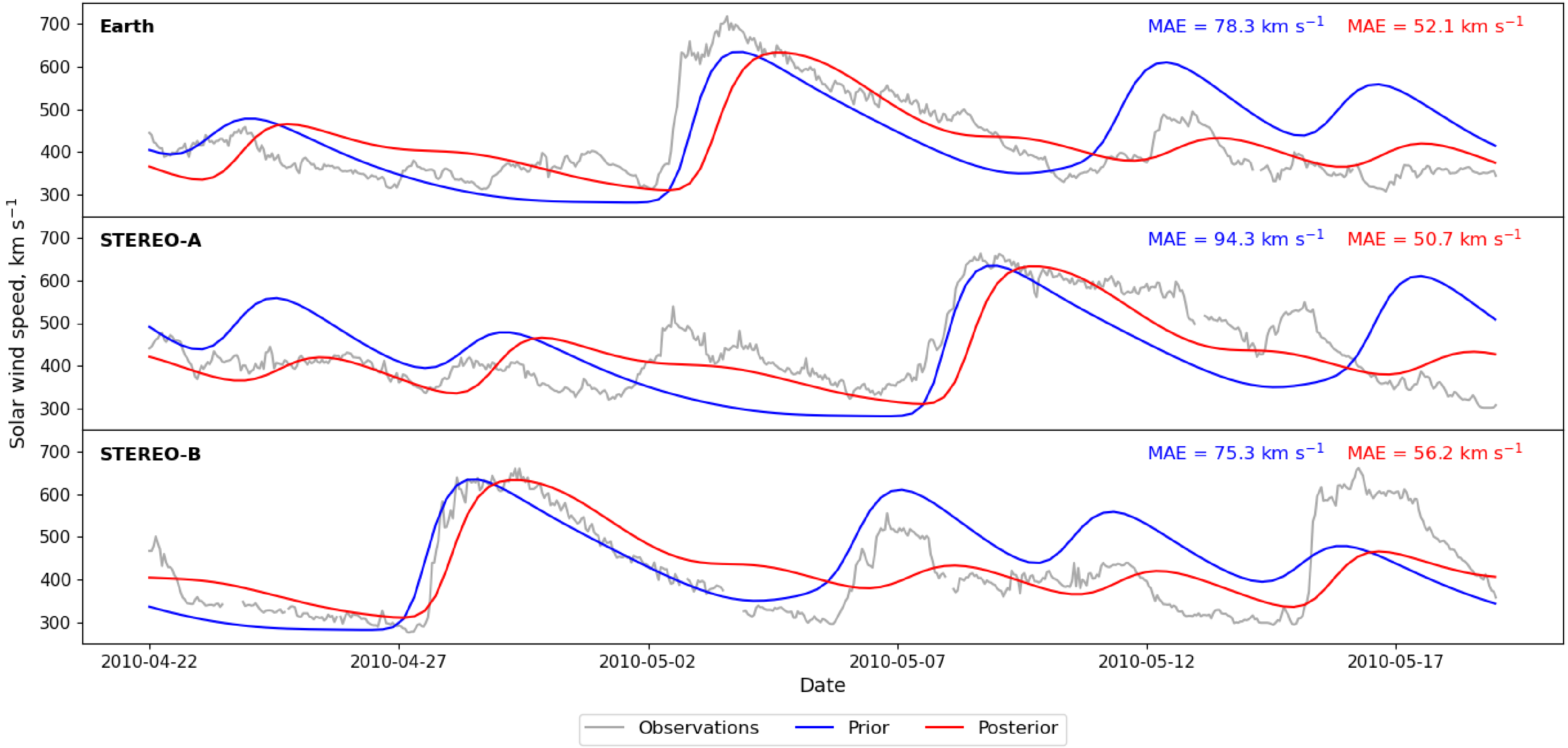


*Not to scale

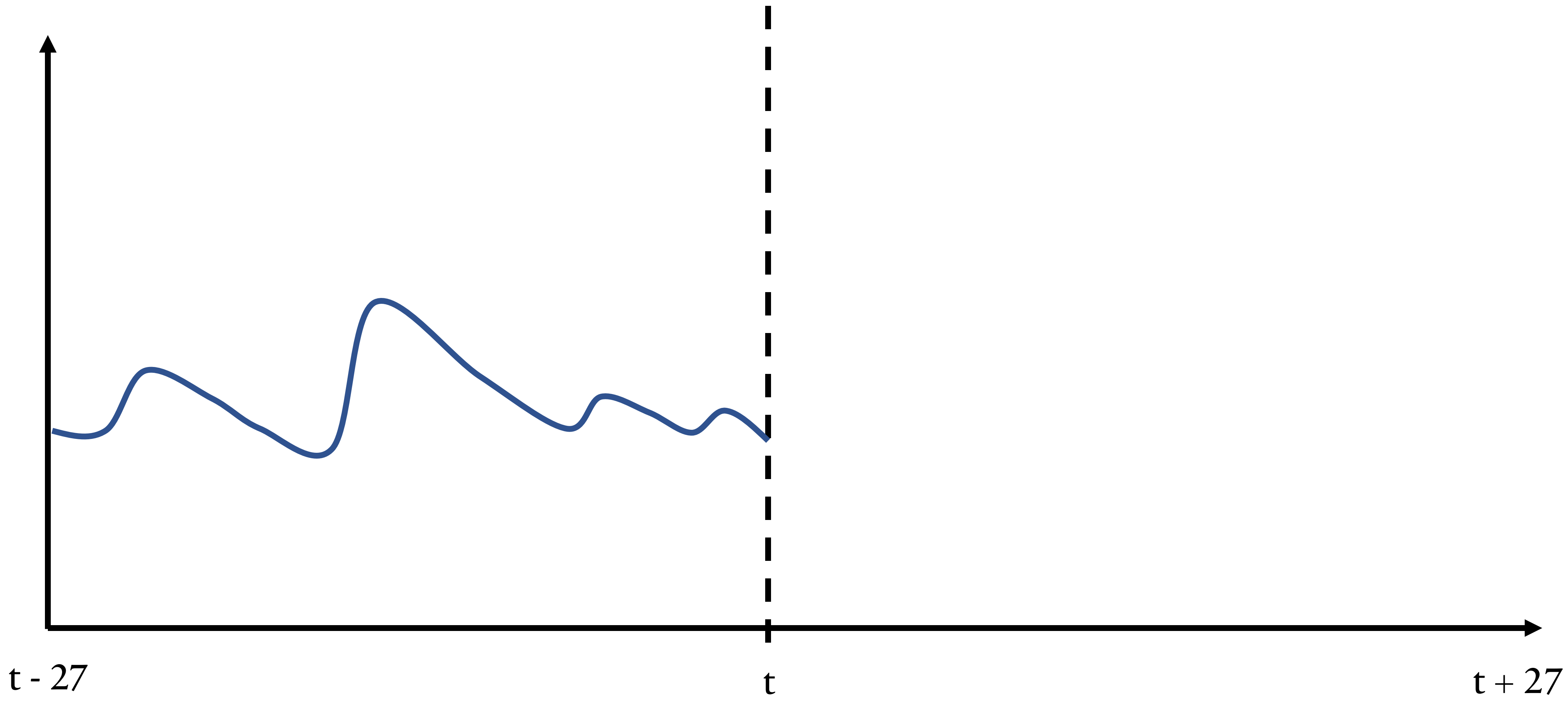
DA OUTPUT – POLAR



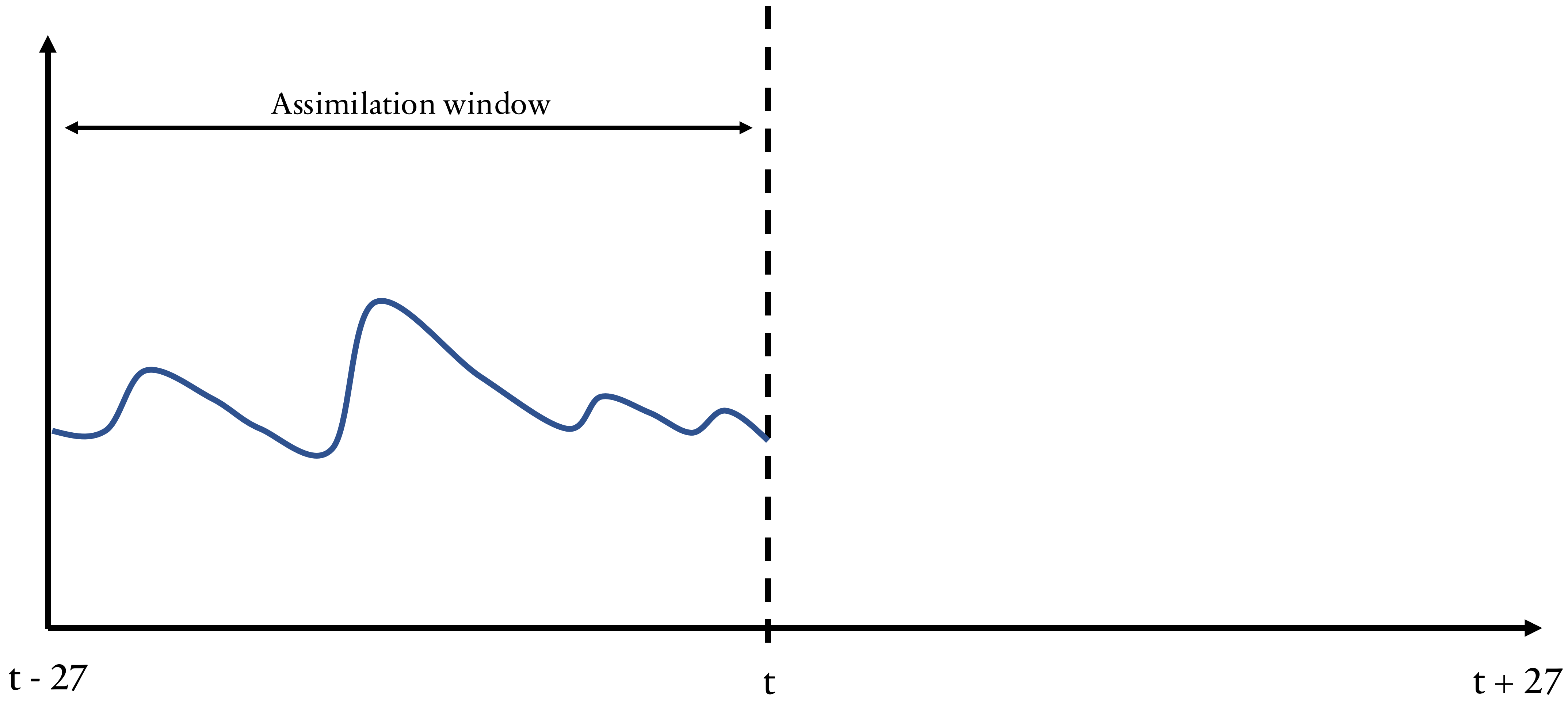
DA OUTPUT – TIME SERIES



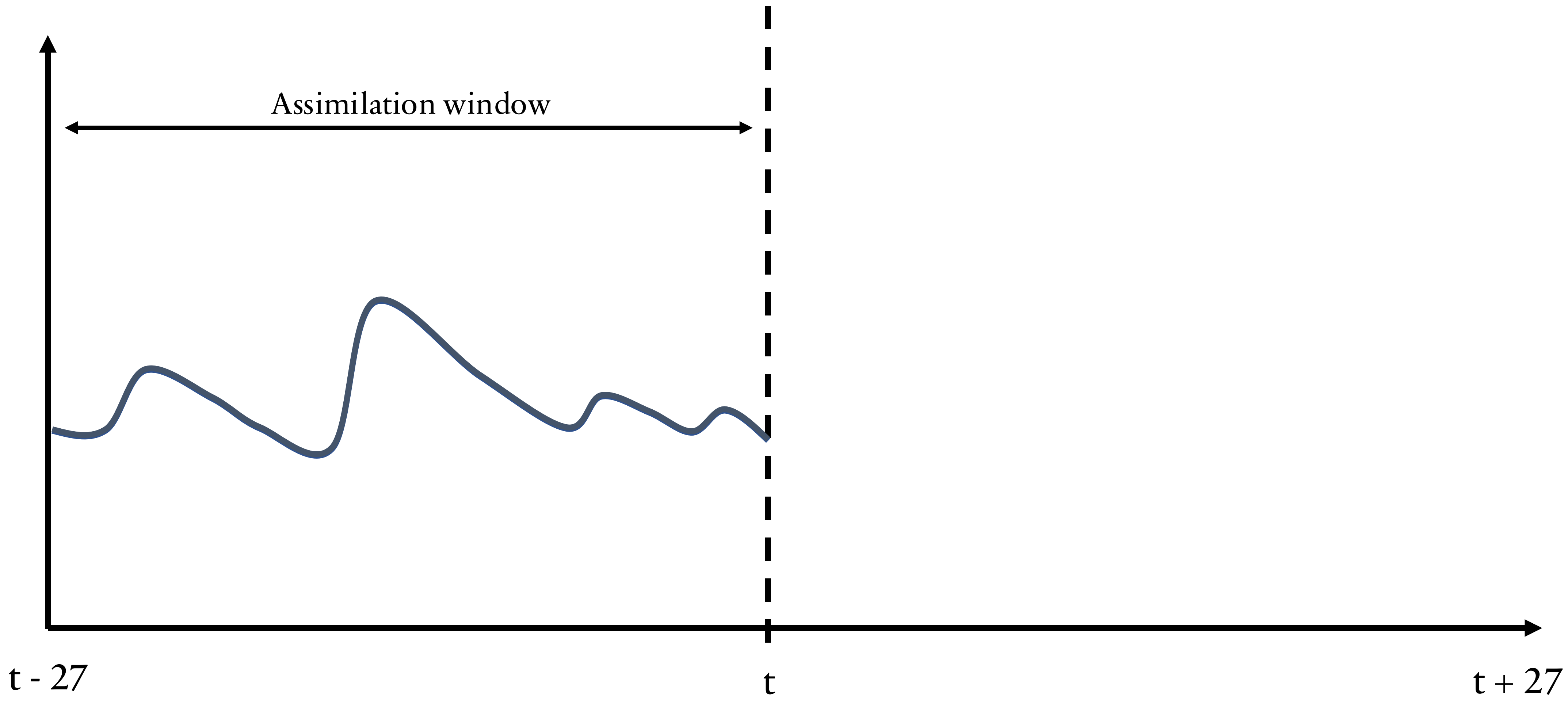
FORECASTING USING OUTPUT



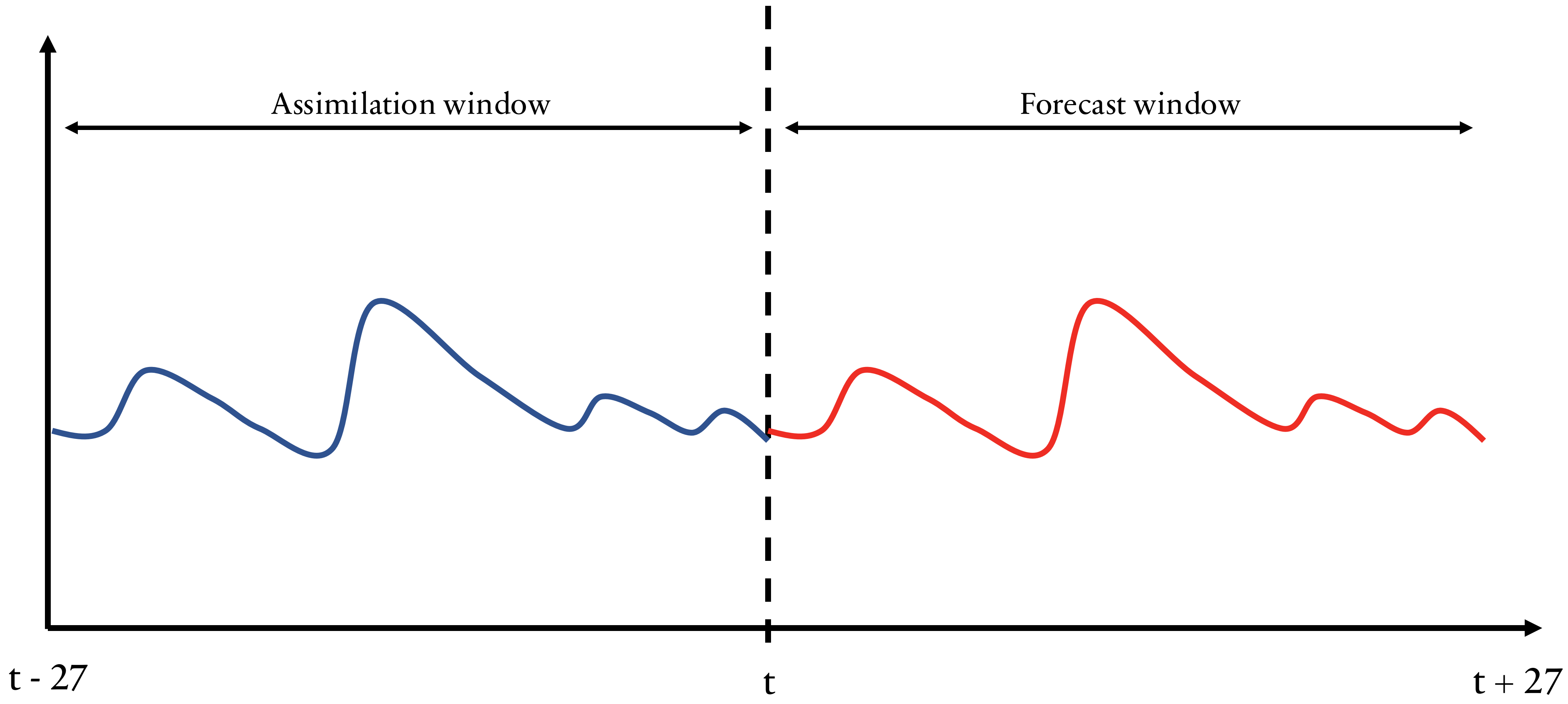
FORECASTING USING OUTPUT



FORECASTING USING OUTPUT



FORECASTING USING OUTPUT



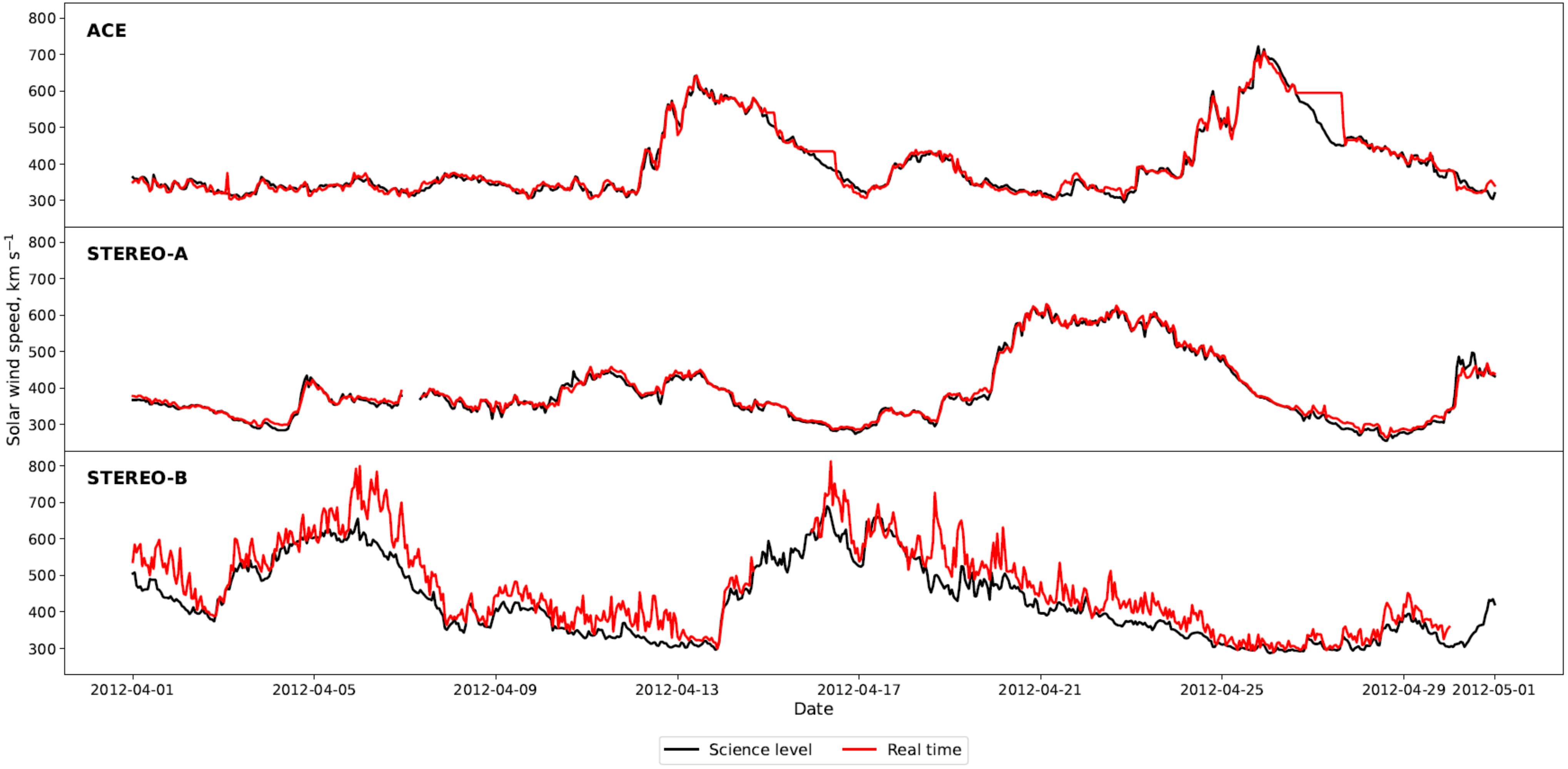
OPERATIONAL SOLAR WIND DA

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

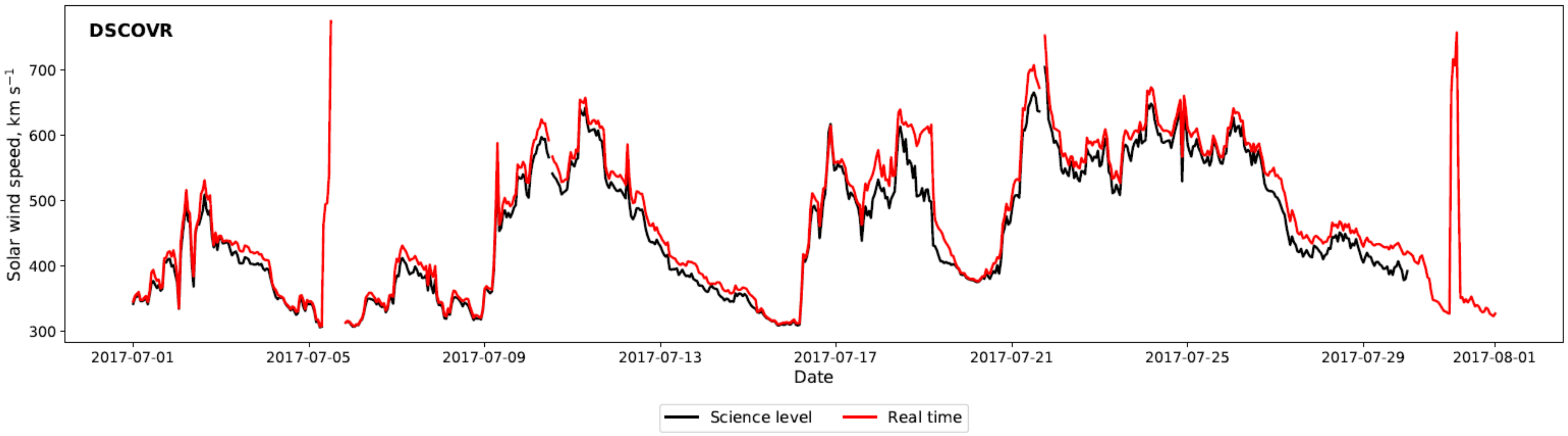
Previous experiments have used science level data, which has been pre-processed to provide a "cleaner" dataset (e.g. Lang et al., 2021 and Turner et al., 2022)

- Removing data gaps, erroneous observations and biases

REAL TIME ISSUES



REAL TIME ISSUES



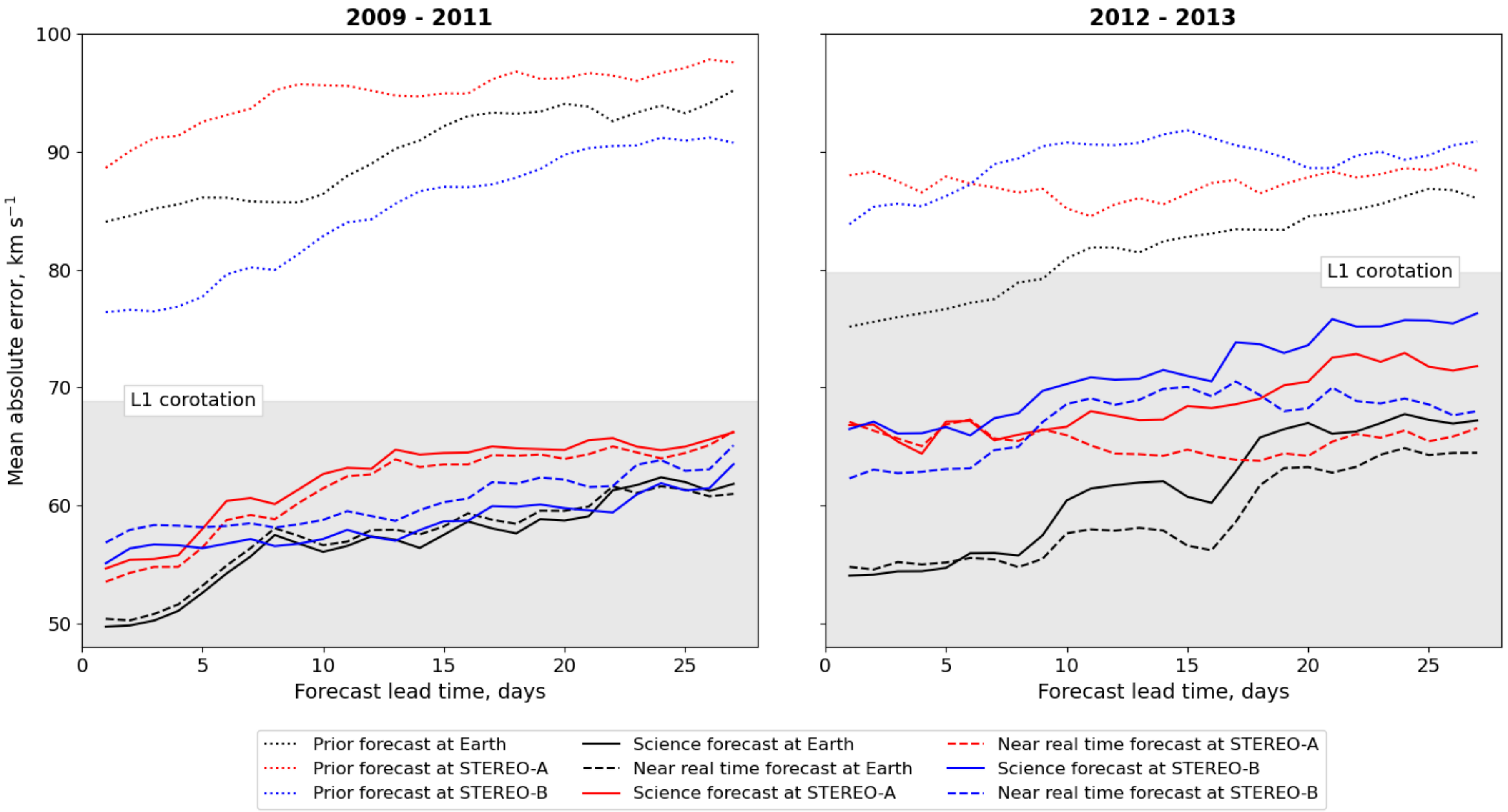
BRaVDA EXPERIMENTS

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

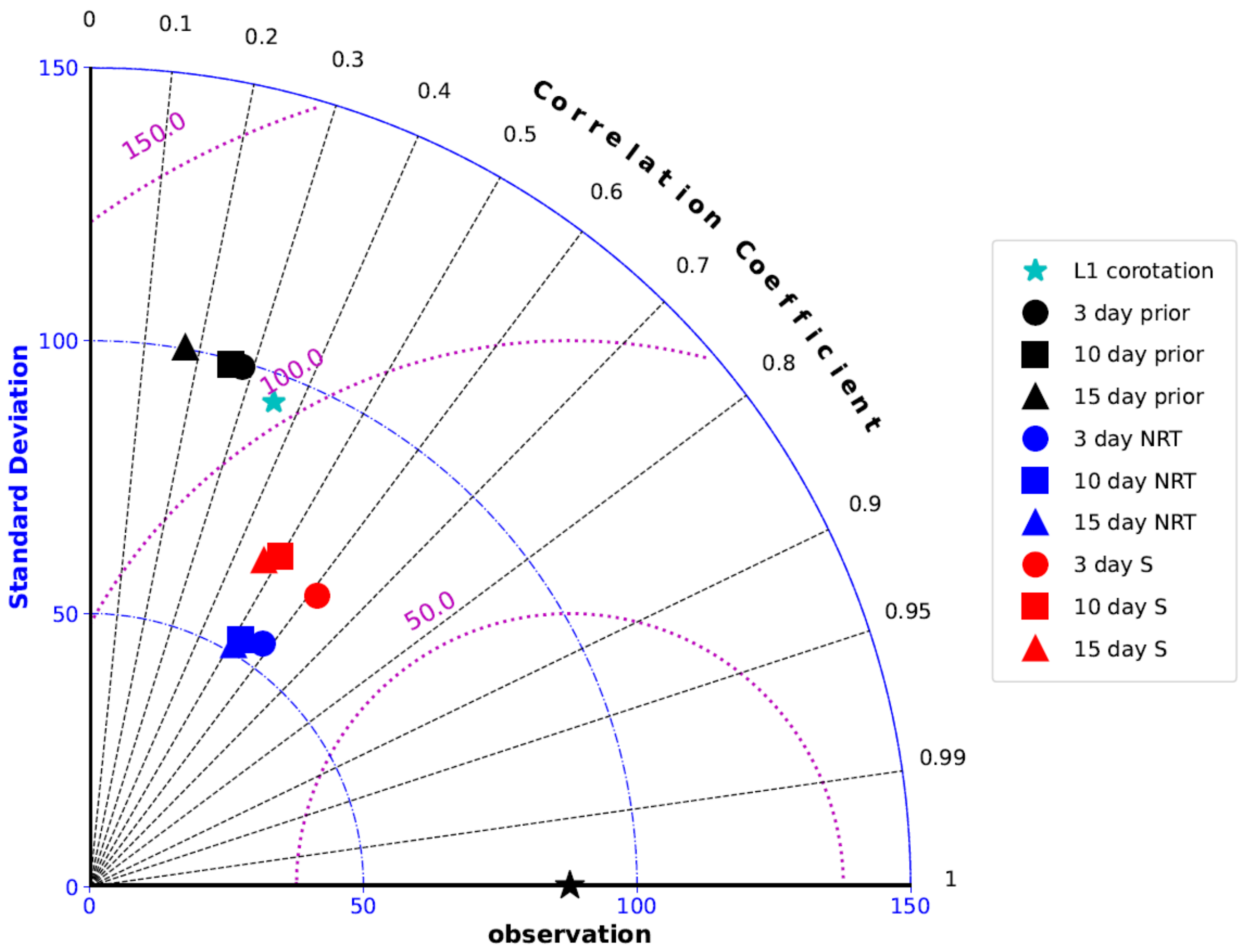
Evaluate the forecast accuracy at the three observation locations – verification time series is the science data

Comparing the prior, real time and science forecasts

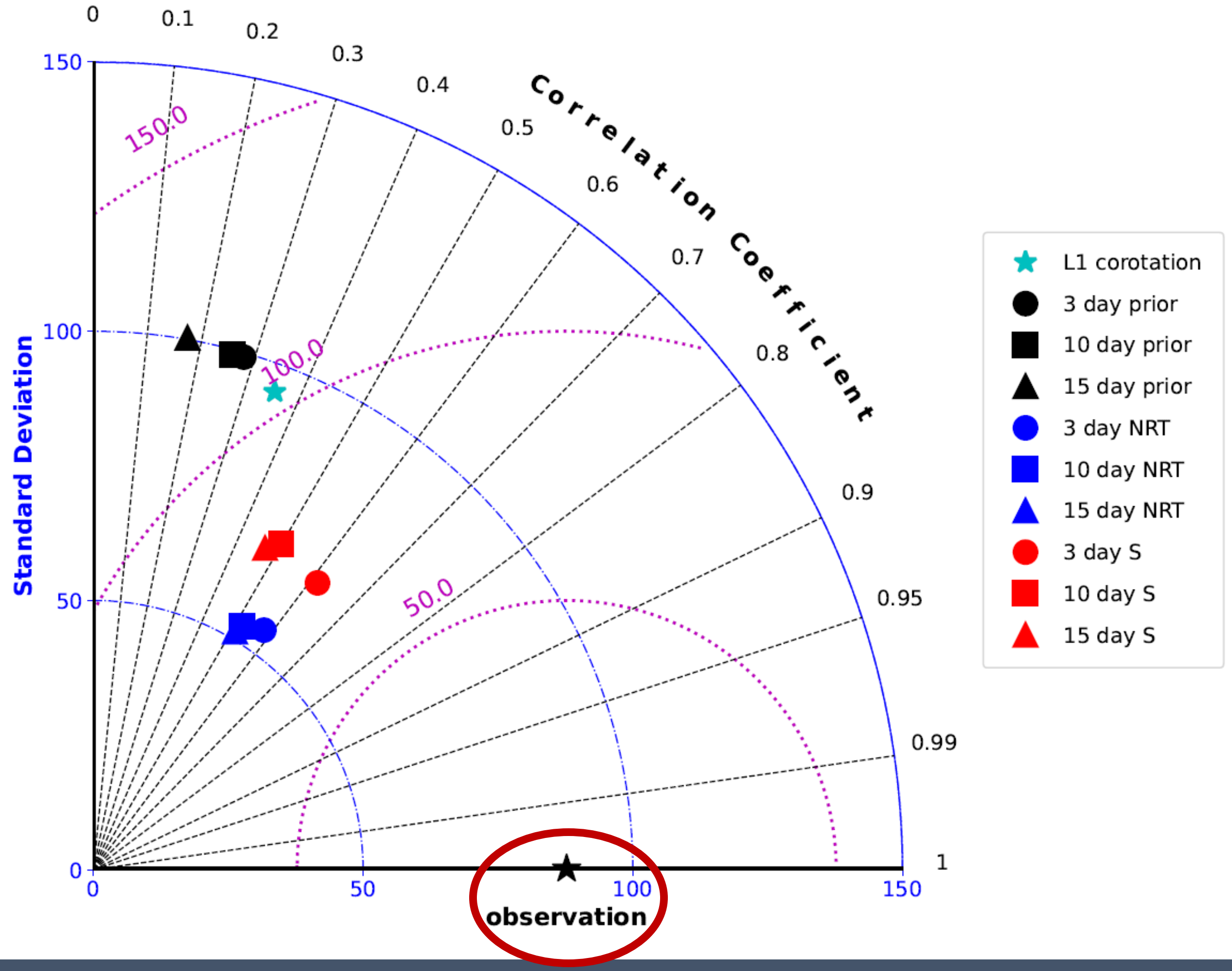
BRaVDA EXPERIMENTS



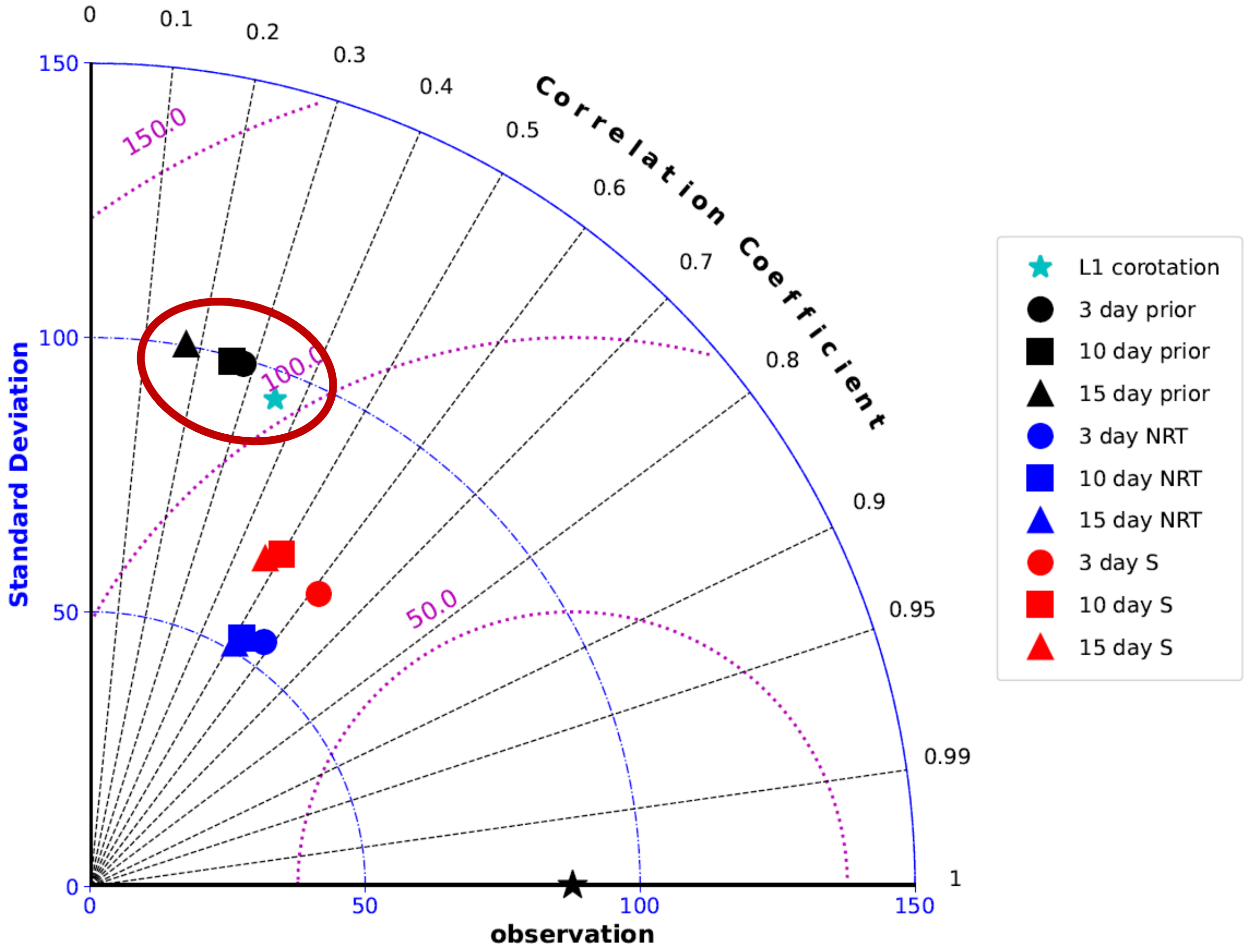
TAYLOR DIAGRAM



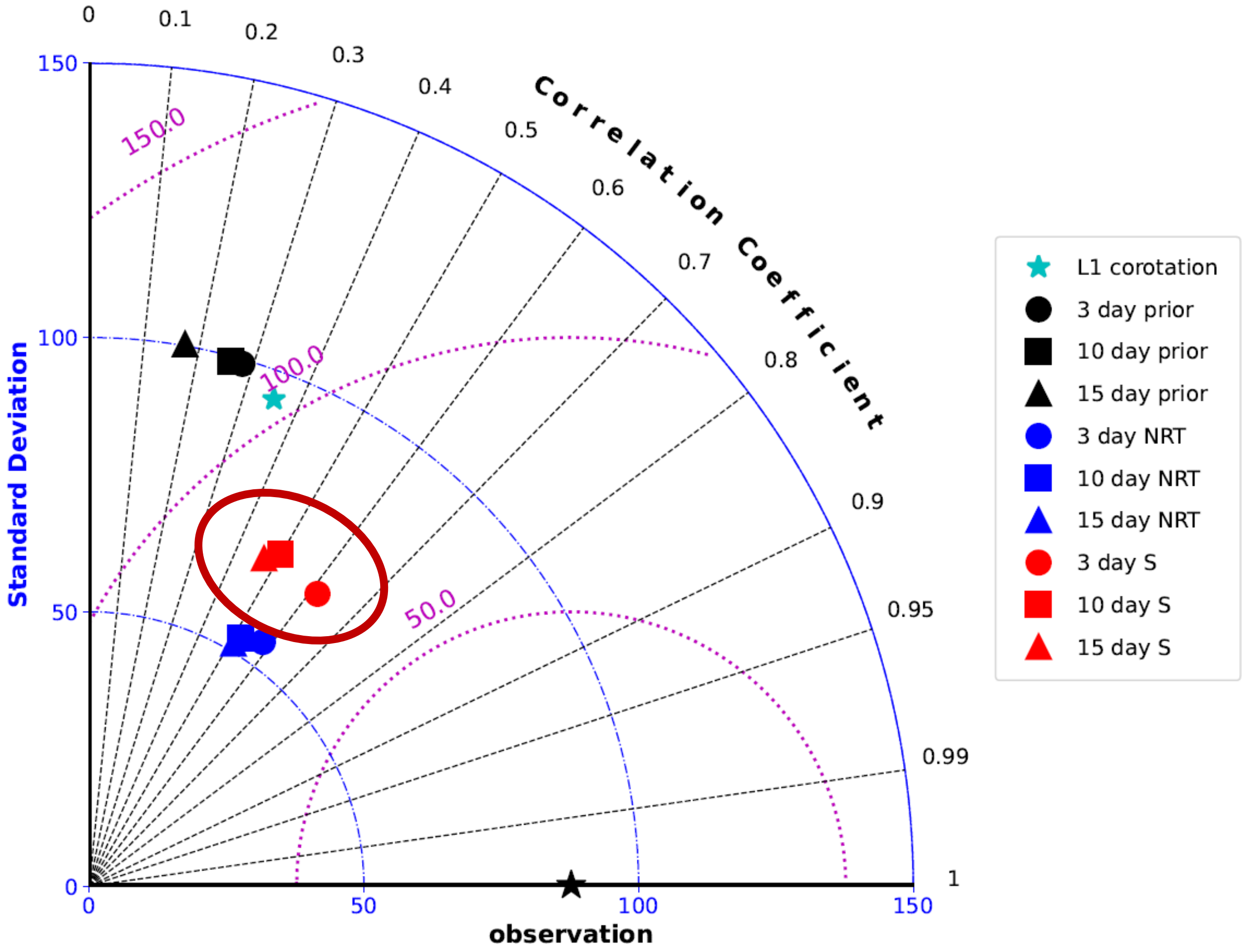
TAYLOR DIAGRAM



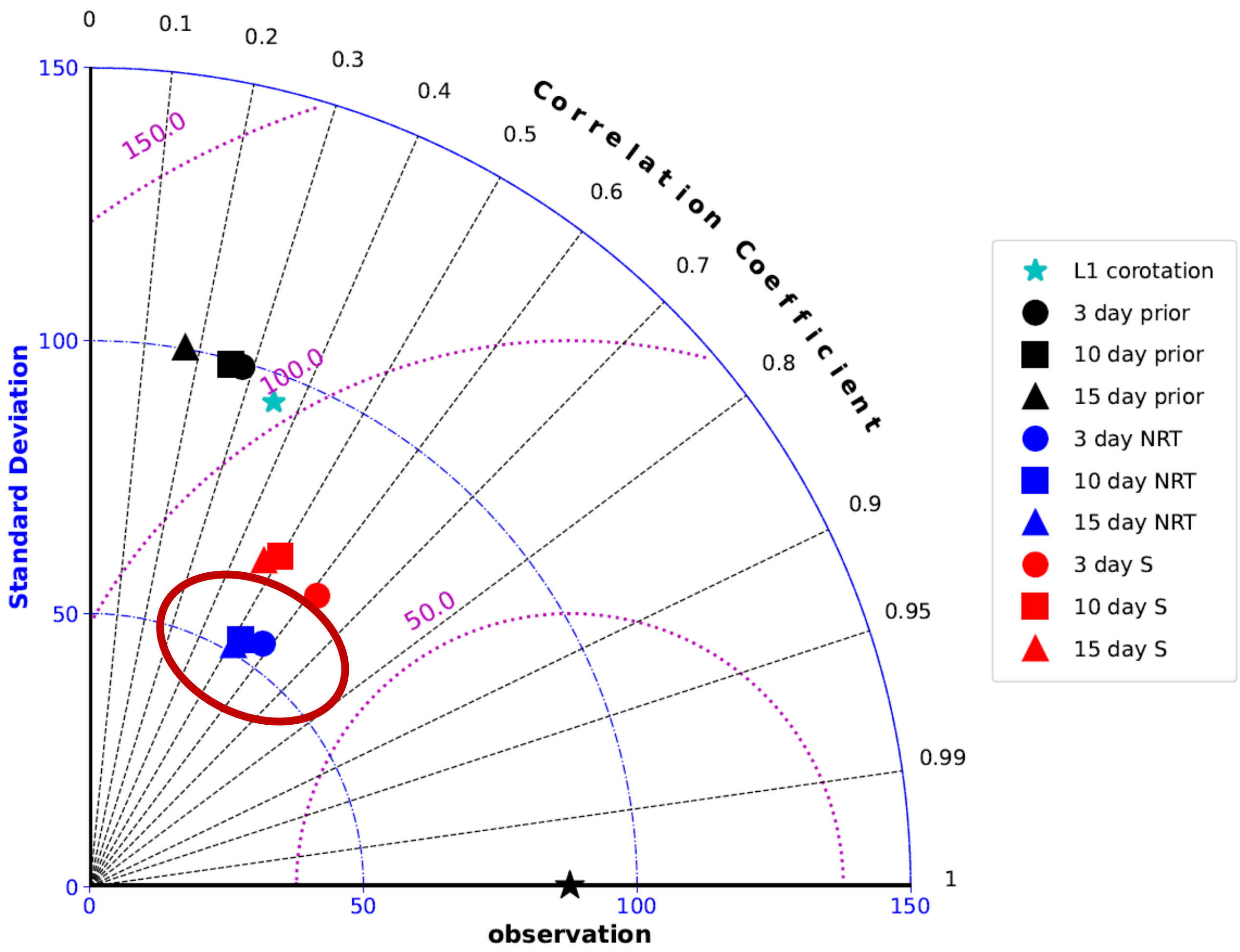
TAYLOR DIAGRAM



TAYLOR DIAGRAM



TAYLOR DIAGRAM



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

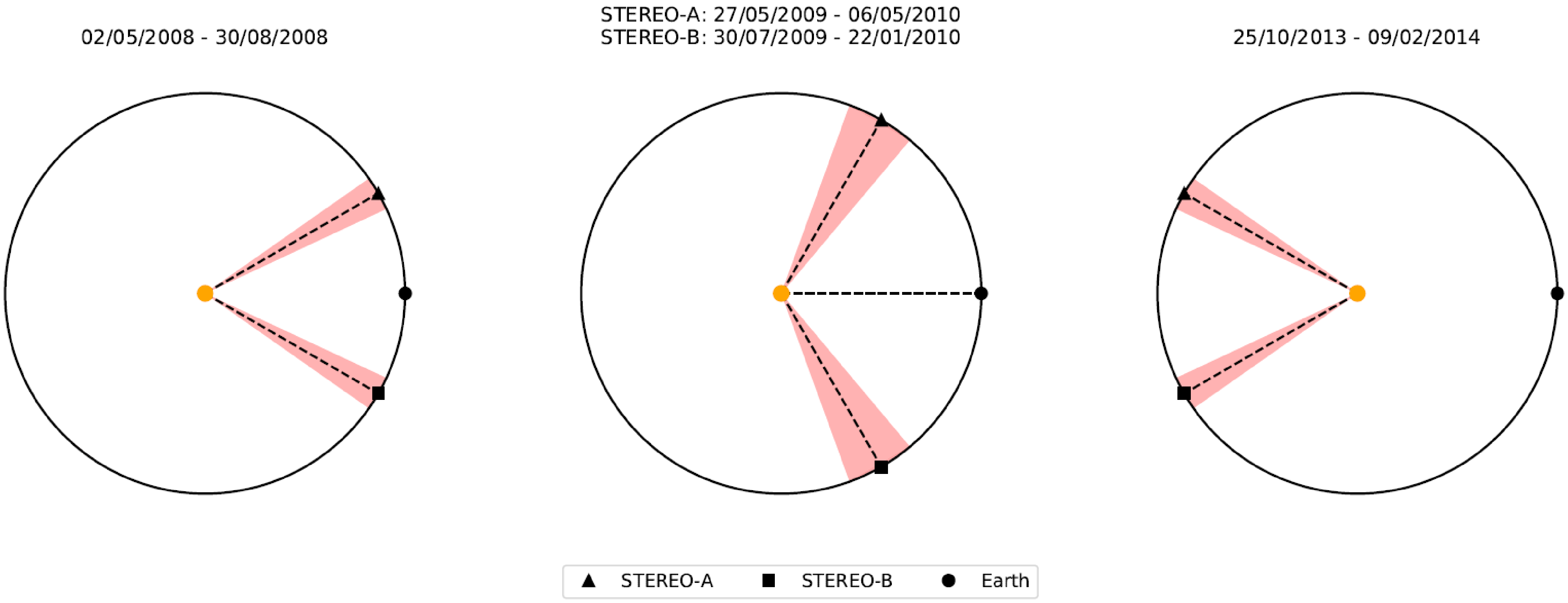
L5 & L1 SIMULATION

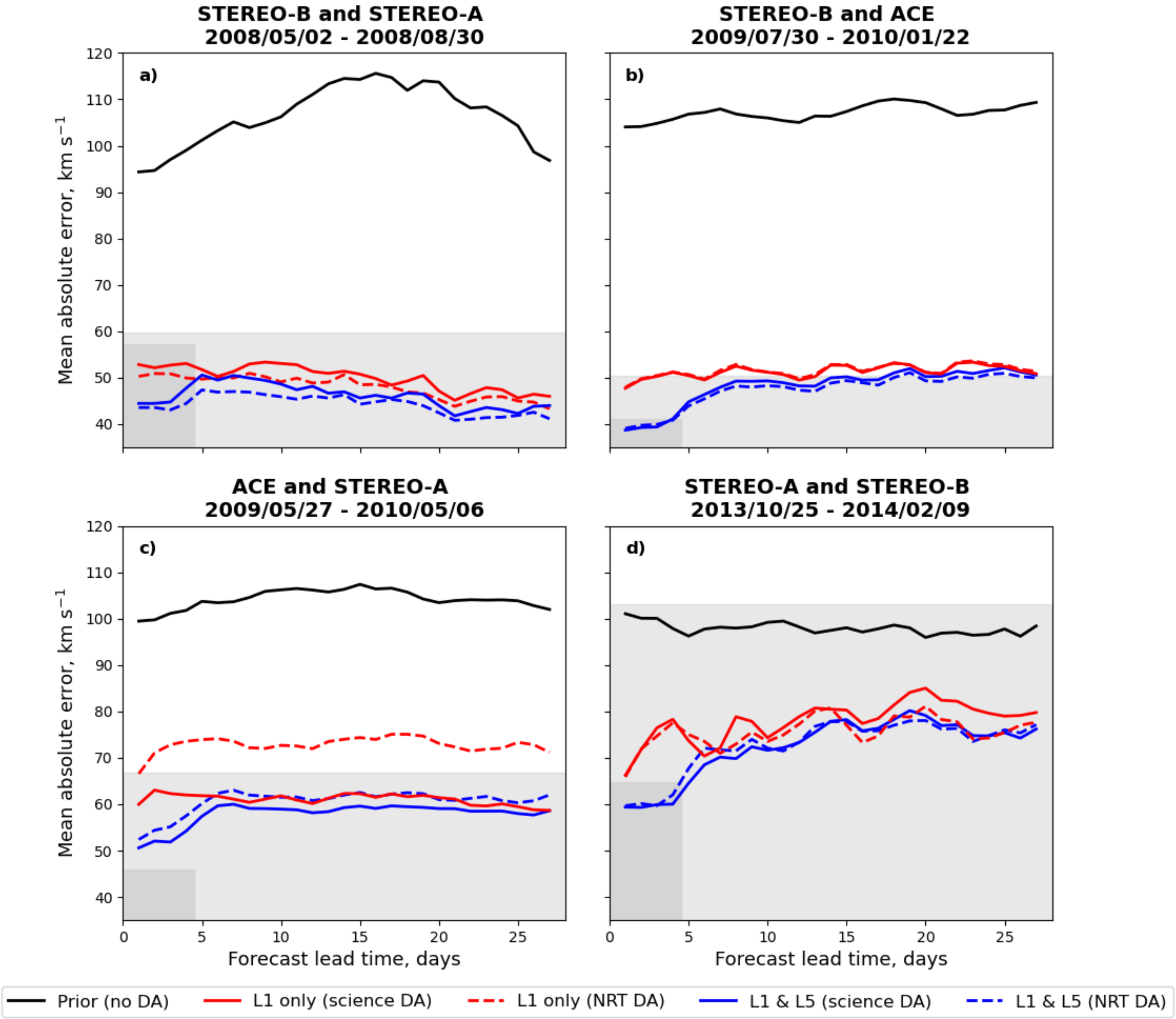
Combinations of spacecraft separated by approximately 60^o in longitude

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

4 time periods

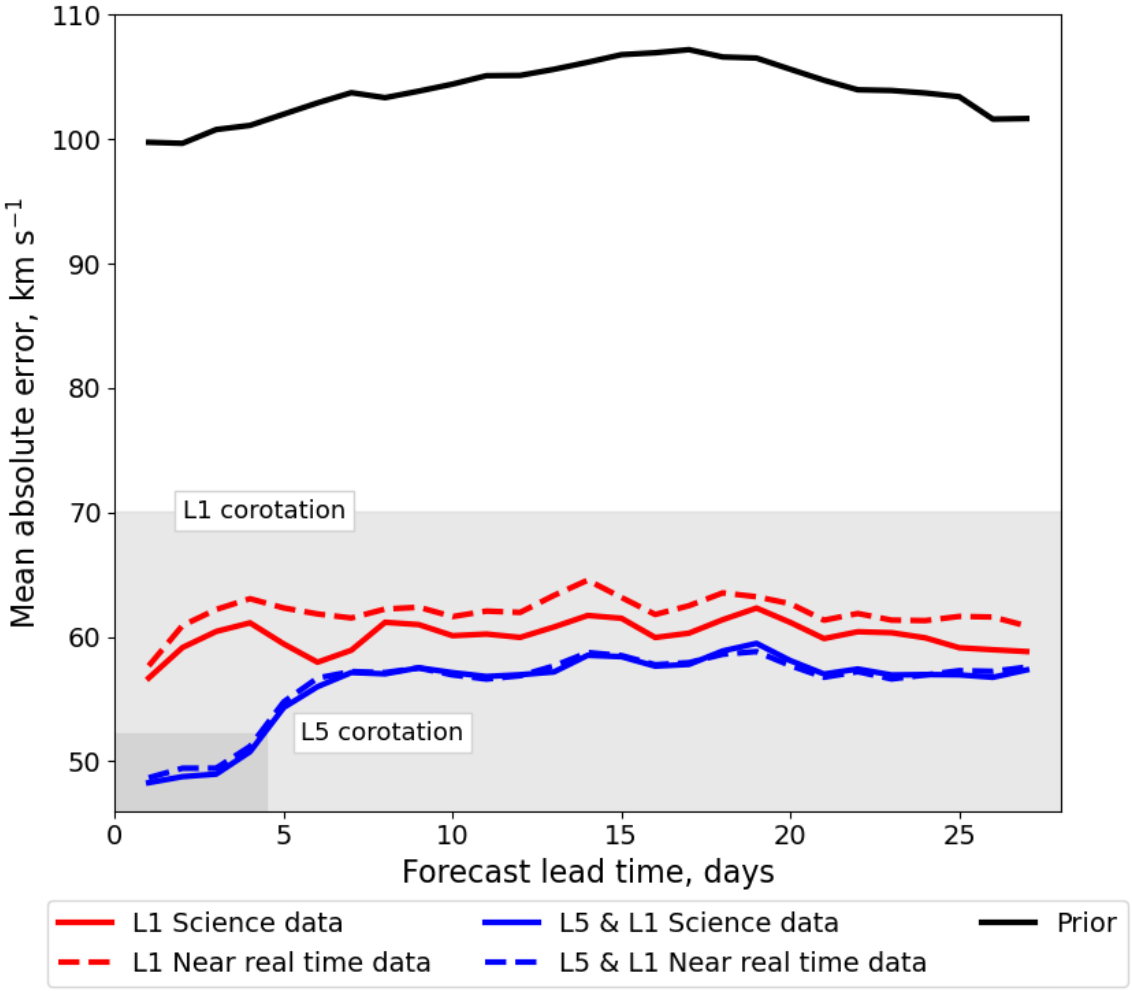
L5 & L1 SIMULATION



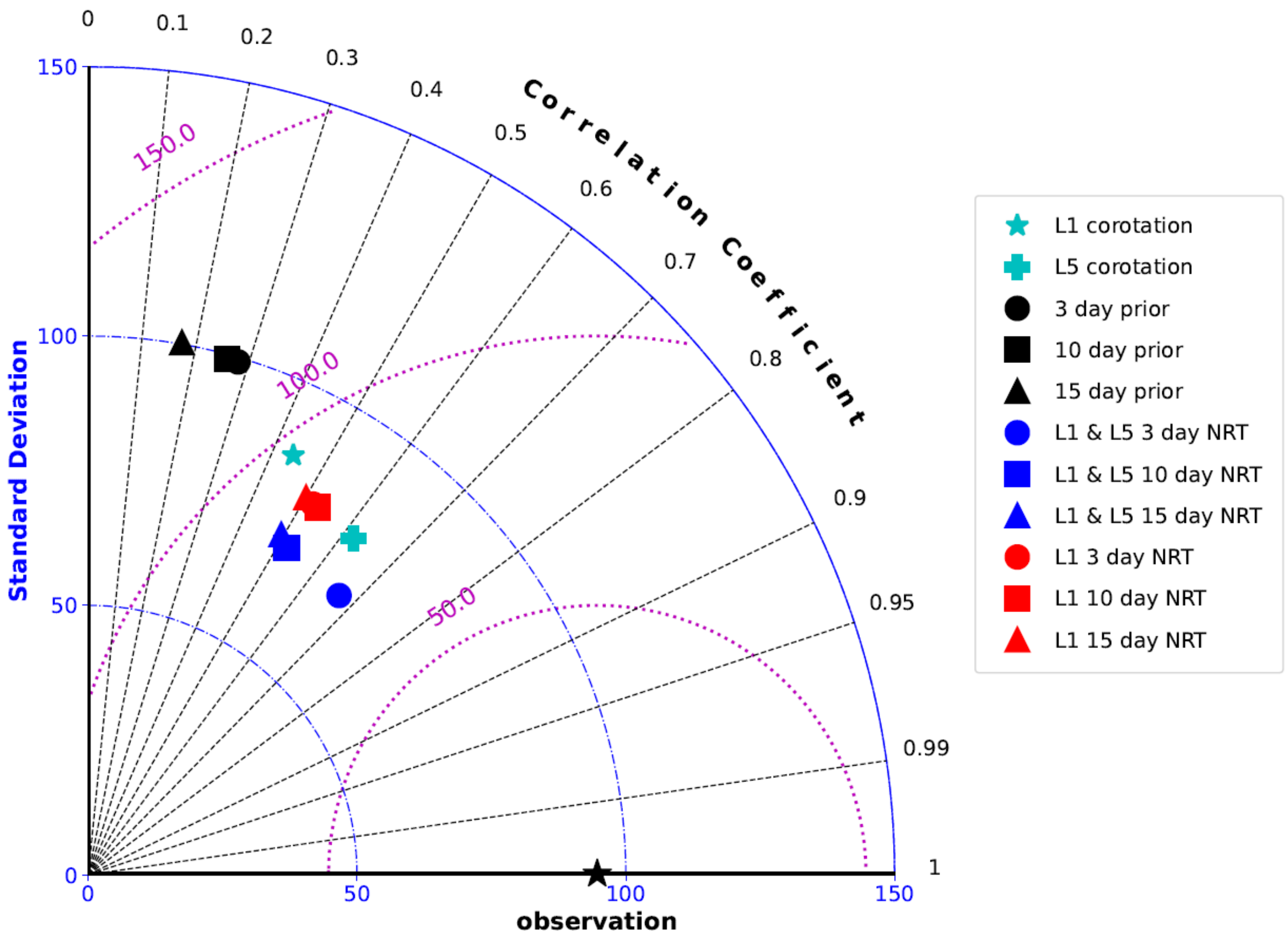


STEREO-B and STEREO-A
2008/05/02 - 2008/08/30
STEREO-B and ACE
2009/07/30 - 2010/01/22
ACE and STEREO-A
2009/05/27 - 2010/05/06
STEREO-A and STEREO-B
2013/10/25 - 2014/02/09
a)
b)
c)
d)
Mean absolute error, km s^{-1}
Forecast lead time, days
Prior (no DA)
L1 only (science DA)
L1 only (NRT DA)
L1 & L5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

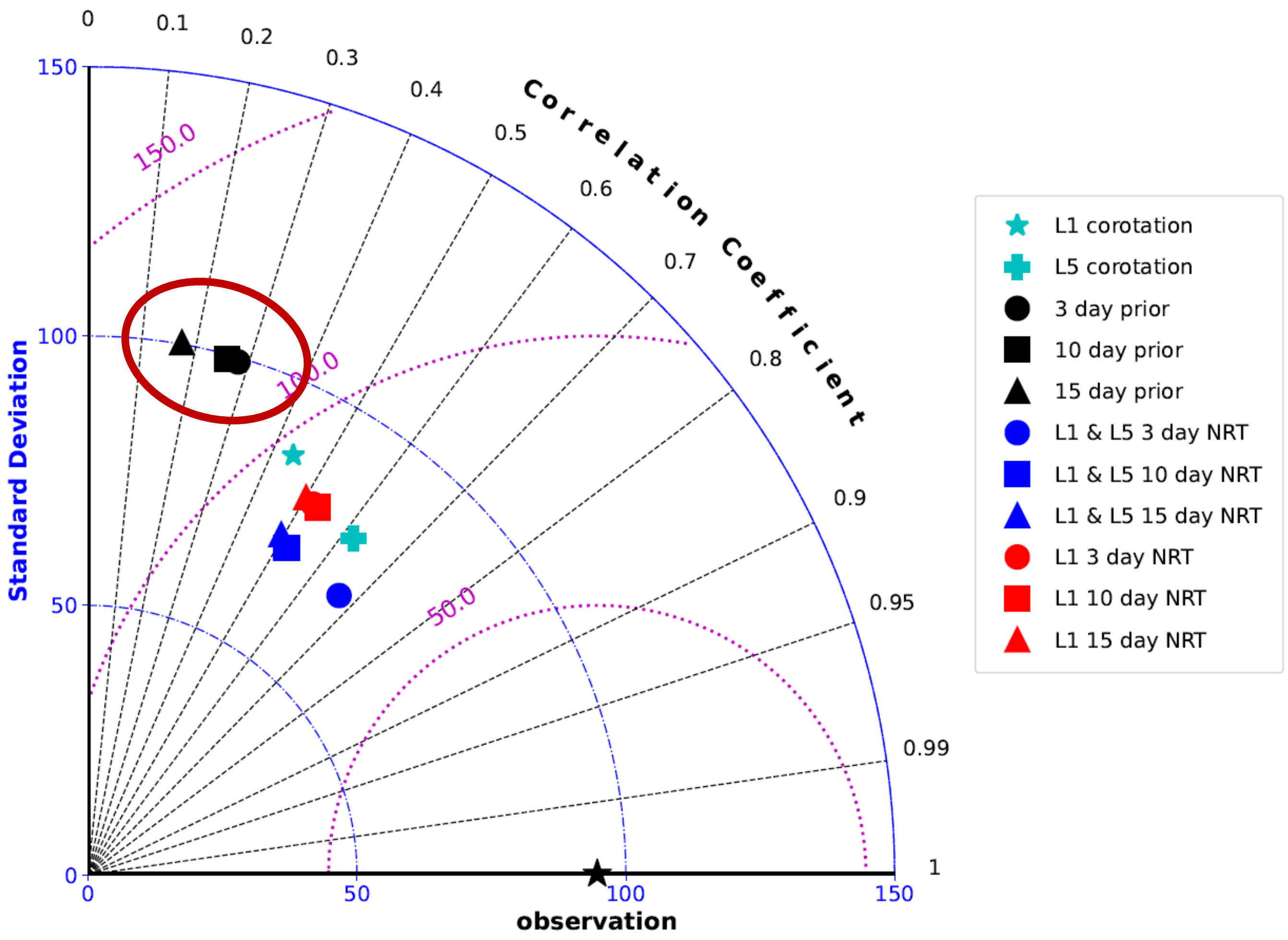
L5 & L1 AVERAGE



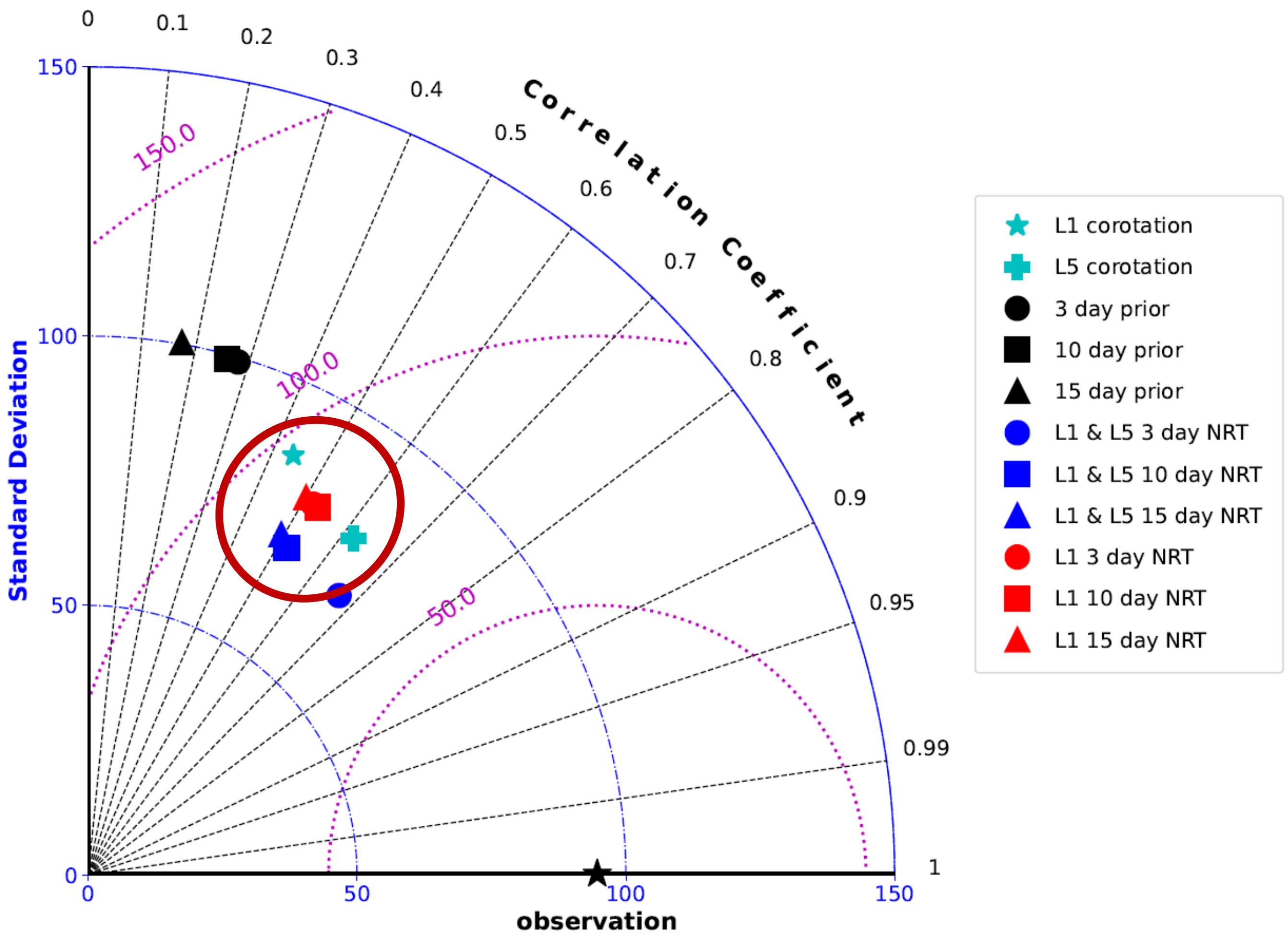
L5 & L1 AVERAGE



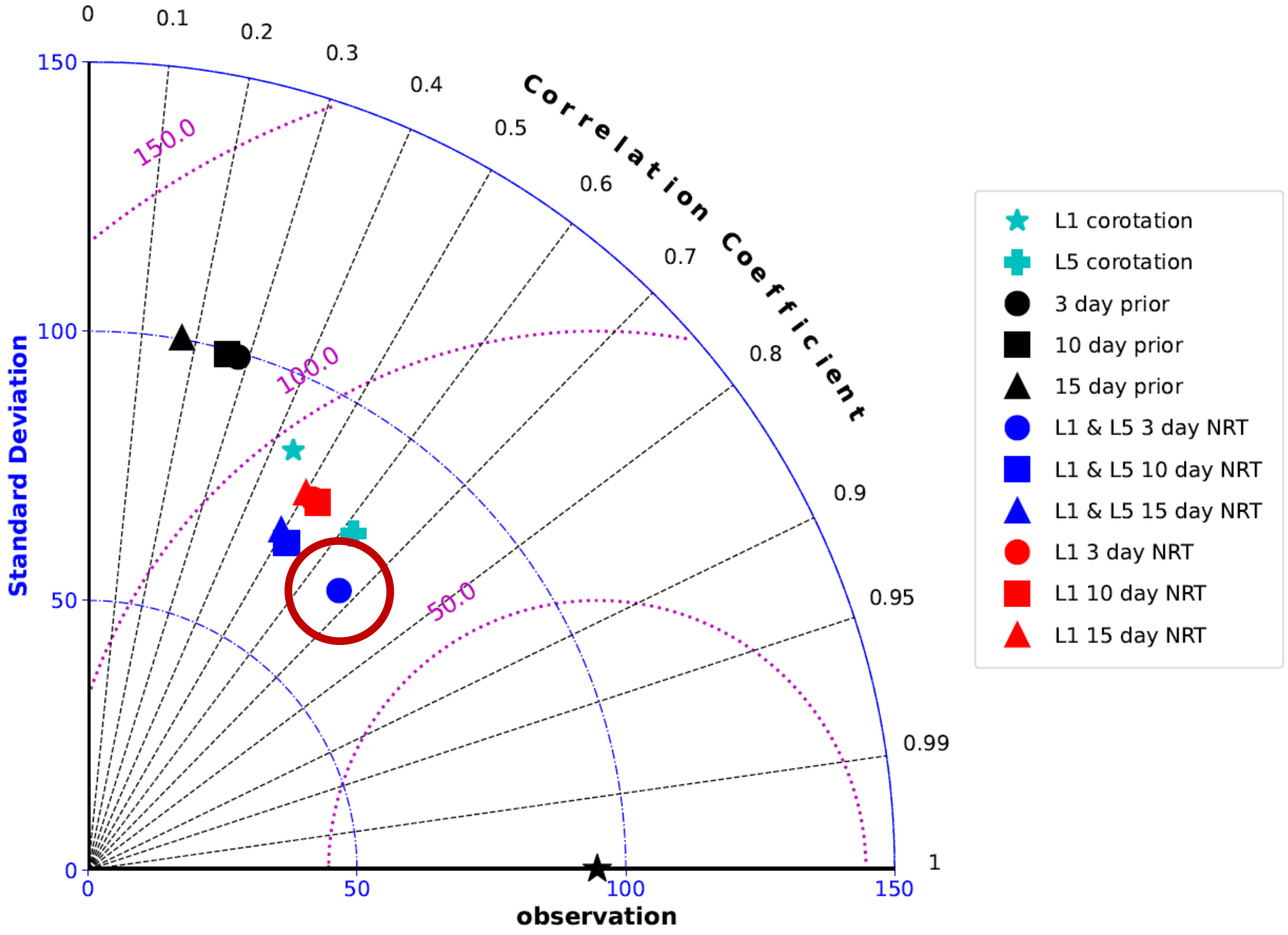
L5 & L1 AVERAGE



L5 & L1 AVERAGE



L5 & L1 AVERAGE



OPERATIONAL FORECASTING

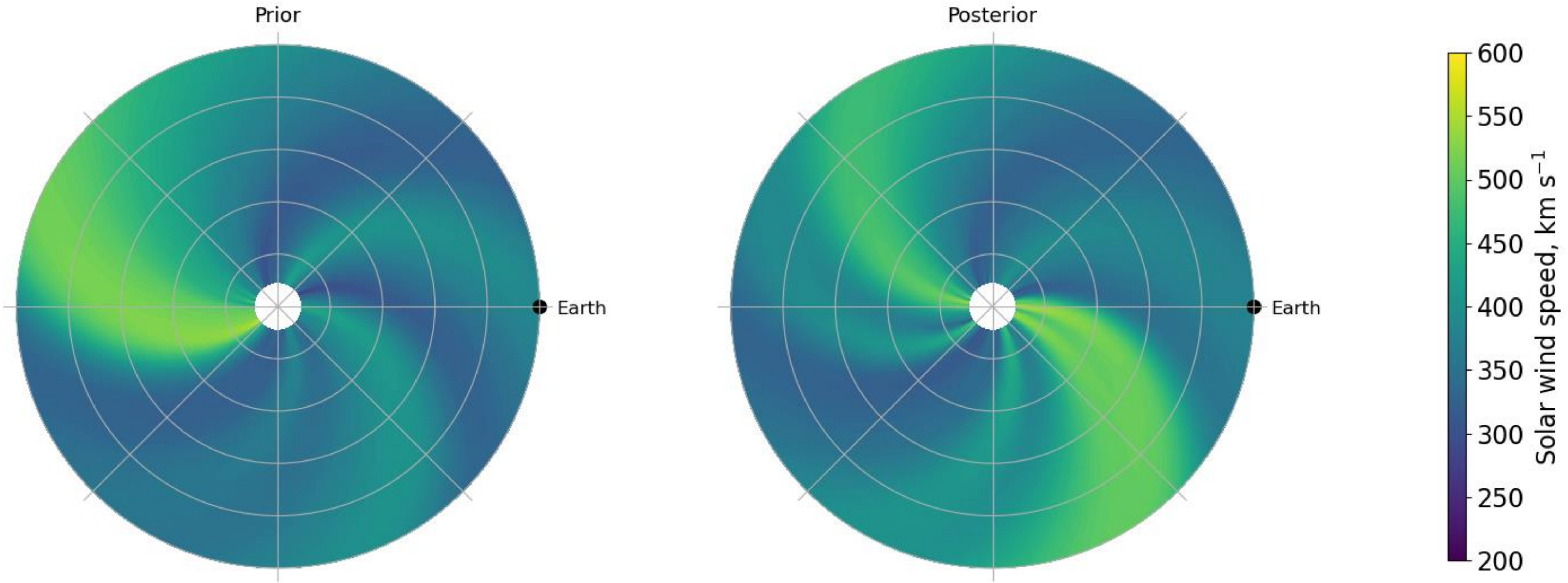
Using files from the Met Office and HUXt, we have got BRaVDA running operationally on a routine basis

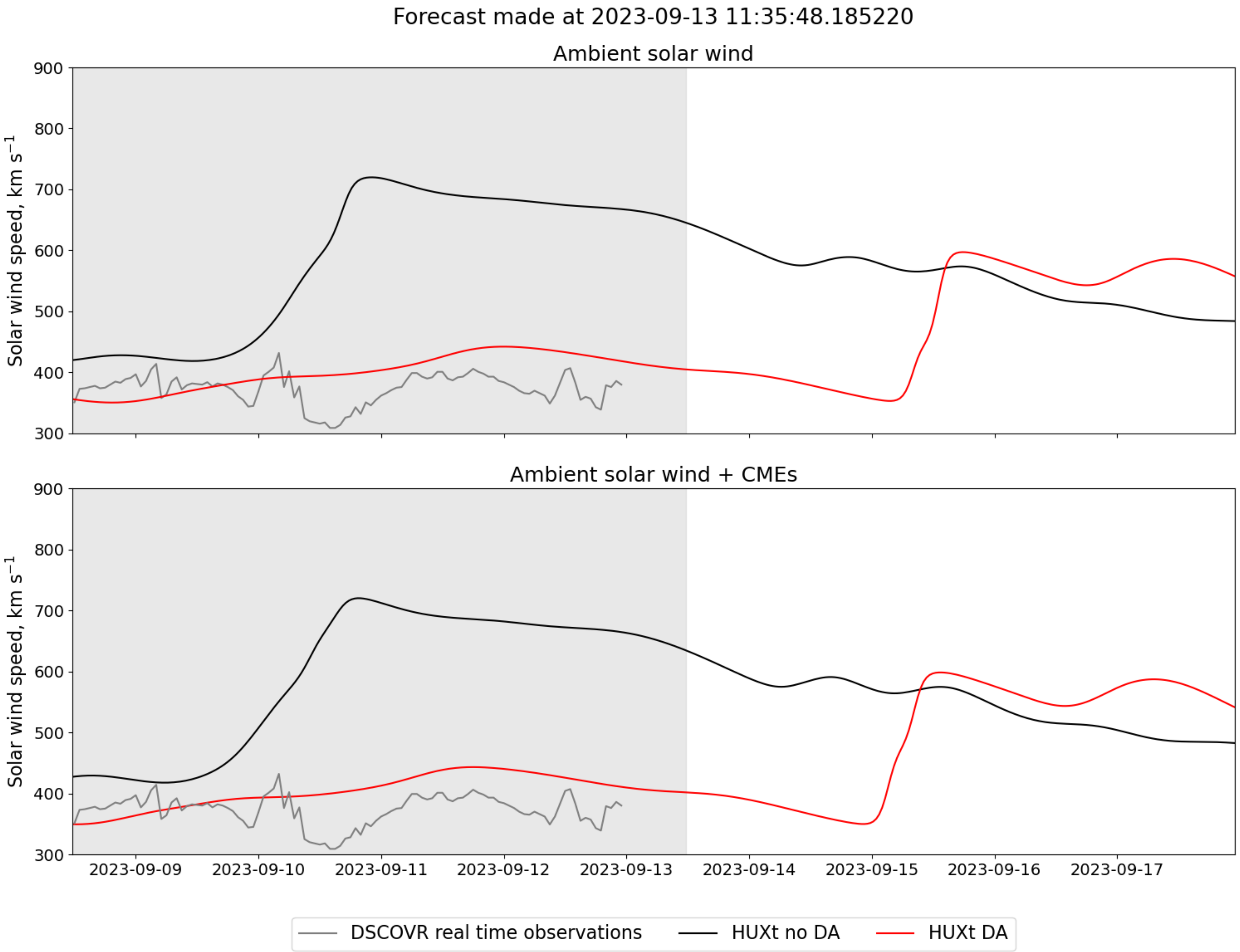
Still being tweaked and isn't verified (yet…), but the initial plots are online

Running CMEs through the improved solar wind to give speed and arrival time updates

A world's first using solar wind DA?

Forecast made at 2023-09-13 11:35:48.185220





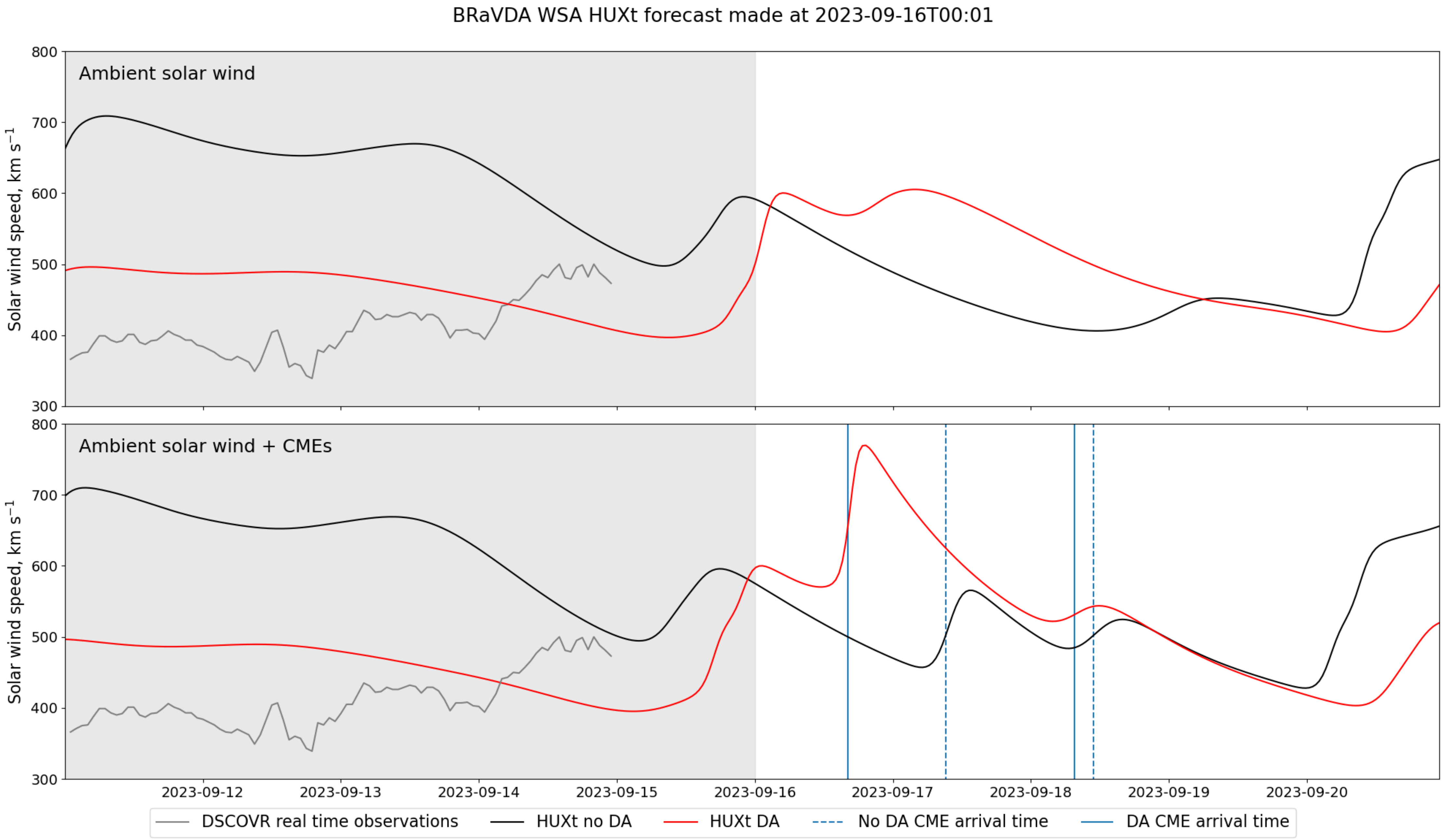
Forecast made at 2023-09-13 11:35:48.185220
Ambient solar wind
Solar wind speed, km s^{-1}
900
800
700
600
500
400
300
Ambient solar wind + CMEs
Solar wind speed, km s^{-1}
900
800
700
600
500
400
300
2023-09-09
2023-09-10
2023-09-11
2023-09-12
2023-09-13
2023-09-14
2023-09-15
2023-09-16
2023-09-17
DSCOVR real time observations
HUXt no DA
HUXt DA

CME EXAMPLE

That example has no CMEs in it, so is a bit boring

The next plot is a forecast from 16th September 2023, which has two CMEs in the Met Office cone file

The CME speed/ arrival time changes are **unverified** because I just *don't have time* right now – this will hopefully form part of my postdoc starting next Spring


BRaVDA WSA HUXt forecast made at 2023-09-16T00:01
Ambient solar wind
Ambient solar wind + CMEs
Solar wind speed, km s^{-1}
800
700
600
500
400
300
2023-09-12
2023-09-13
2023-09-14
2023-09-15
2023-09-16
2023-09-17
2023-09-18
2023-09-19
2023-09-20
DSCOVR real time observations
HUXt no DA
HUXt DA
No DA CME arrival time
DA CME arrival time

FUTURE WORK

Verification of the solar wind DA forecasts, including a large-scale study of CME speed and arrival time predictions

Hopefully see how using the DA boundary conditions would change when used in MHD models (Enlil, maybe EUHFORIA)

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, leading to improved solar wind forecasts

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

BRaVDA is running operationally using HUXt, with future plans to verify the forecasts

REFERENCES

ESA, 2023. URL: https://www.esa.int/Space_Safety/Vigil

Lang, M., & Owens, M. J. (2019). A Variational Approach to Data Assimilation in the Solar Wind. *Space Weather, 17*(1), 59 – 83. DOI: 10.1029/2018SW001857.

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