Splinter Session 8:
Towards a better understanding of cool star magnetised winds and mass-loss rates

Modeling Coronal Mass Ejection Induced Dimmings on Epsilon Eridani and Comparing with HST Far-Ultraviolet Observations

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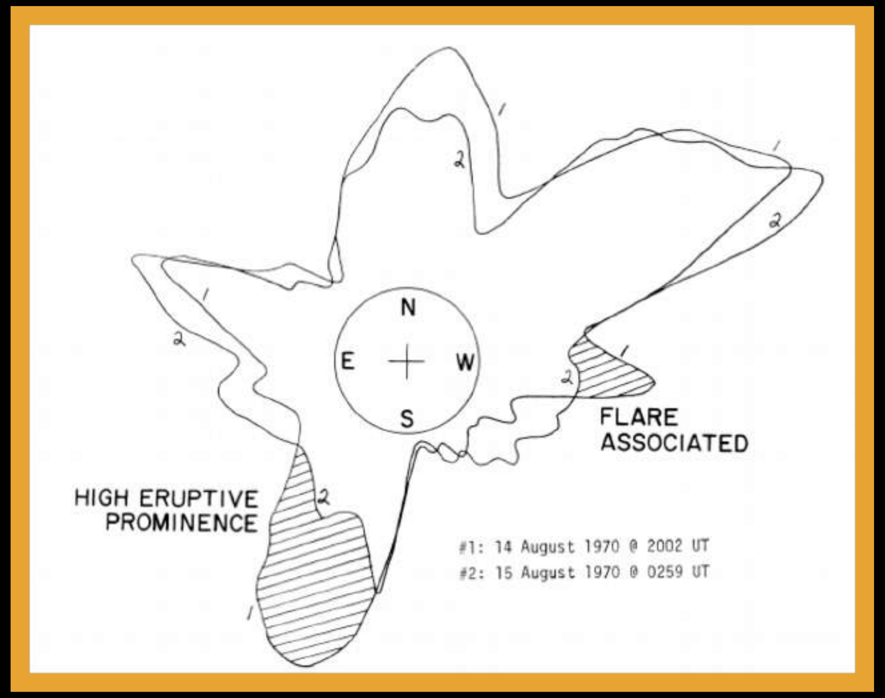
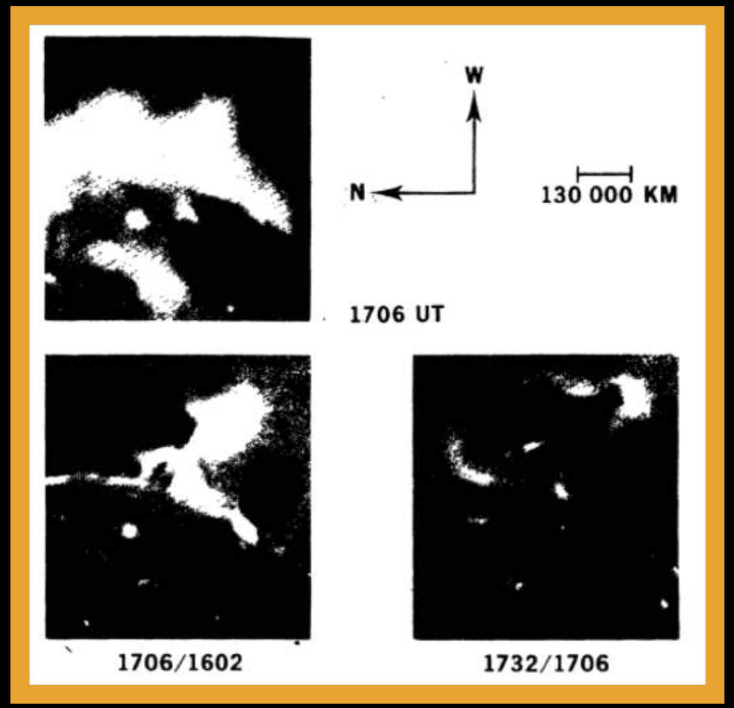
Solar Coronal Dimming

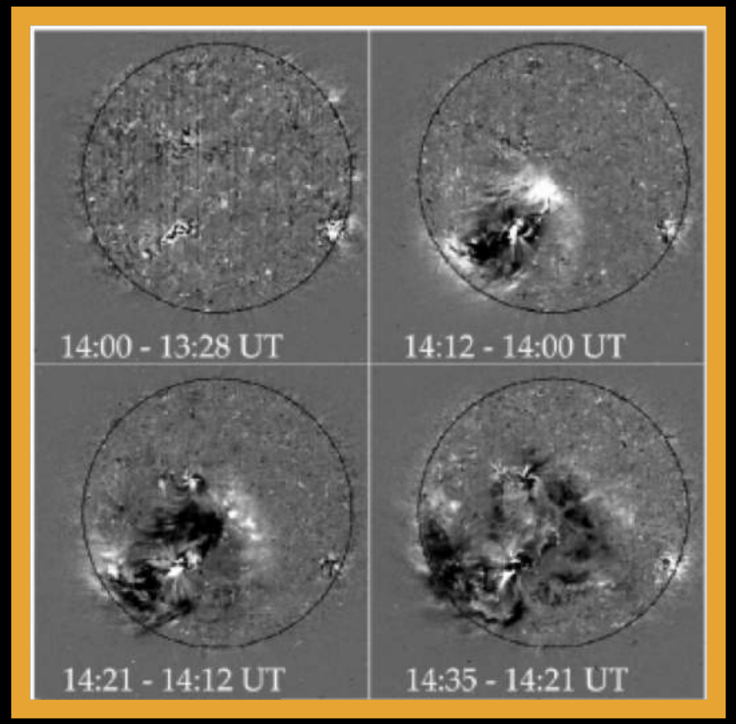
- Coronal dimming is the reduction in intensity on/near the solar disk across a large area, which has been observed in many wavebands (e.g., white-light, X-ray, EUV) of solar observation. And it is usually associated with coronal EUV waves.
- Spectroscopic observations confirmed that the dimmings are regions of up-flowing expanding plasma (e.g., *Harra& Sterling 2001, Harra+2007, Imada+2007, Jin+2009, Attril+2010, Tian+2012*). Both observation and MHD Modeling of solar coronal dimming (e.g., *Cohen+2009, Downs+2012*) suggest that the coronal dimming is mainly caused by the CME-induced plasma evacuation, and the spatial location is well correlated the footpoints of the erupting magnetic flux system (*Downs+2015*).
- Solar observations suggest that all coronal dimmings were associated with CMEs. Therefore, they might encode important information about CME's mass, speed, energy etc. (e.g., *Hudson+1996, Sterling&Hudson 1997, Harrison+2003, Zhukov& Auchere 2004, Aschwanden+2009, Cheng&Qiu 2016, Mason+2016, Krista&Reinard 2017, Dissauer+2018*).
- *Harra+2016* found "coronal dimming is the only signature that could differentiate powerful flares that have CMEs from those that do not". Therefore, dimming might be one of the best candidates to observe the CMEs on distant Sun-like stars.



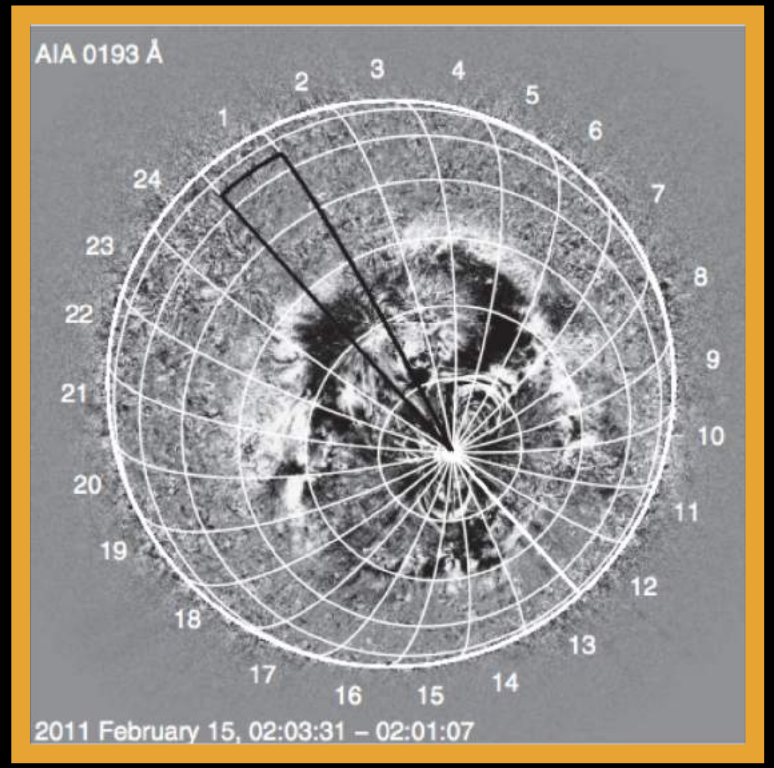
White-light corona "depletion" (Hansen et al. 1974)



X-ray "transient coronal holes" (Rust and Hildner, 1976)



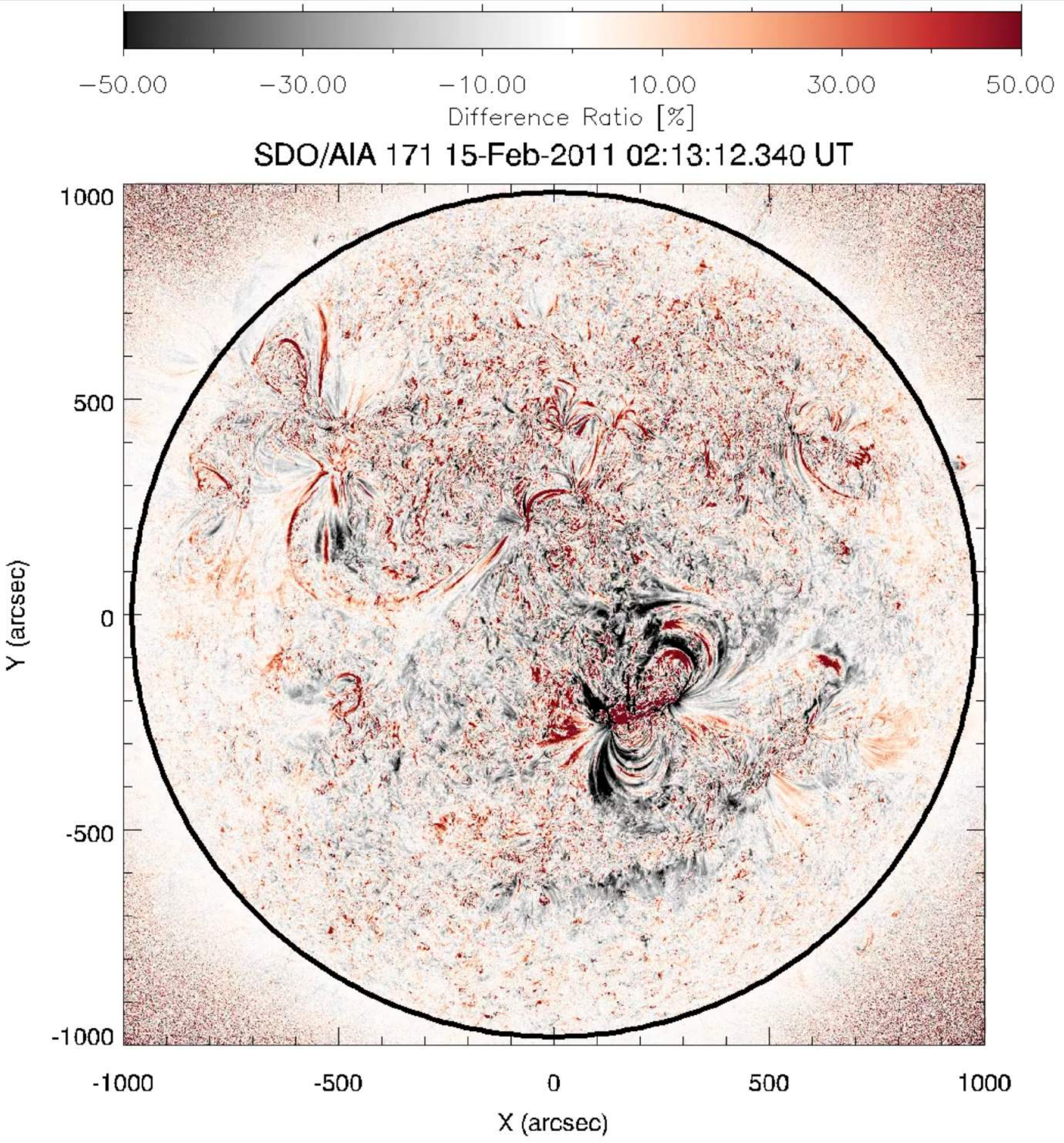
EUV Dimming by SOHO/EIT (Thompson et al. 1999)



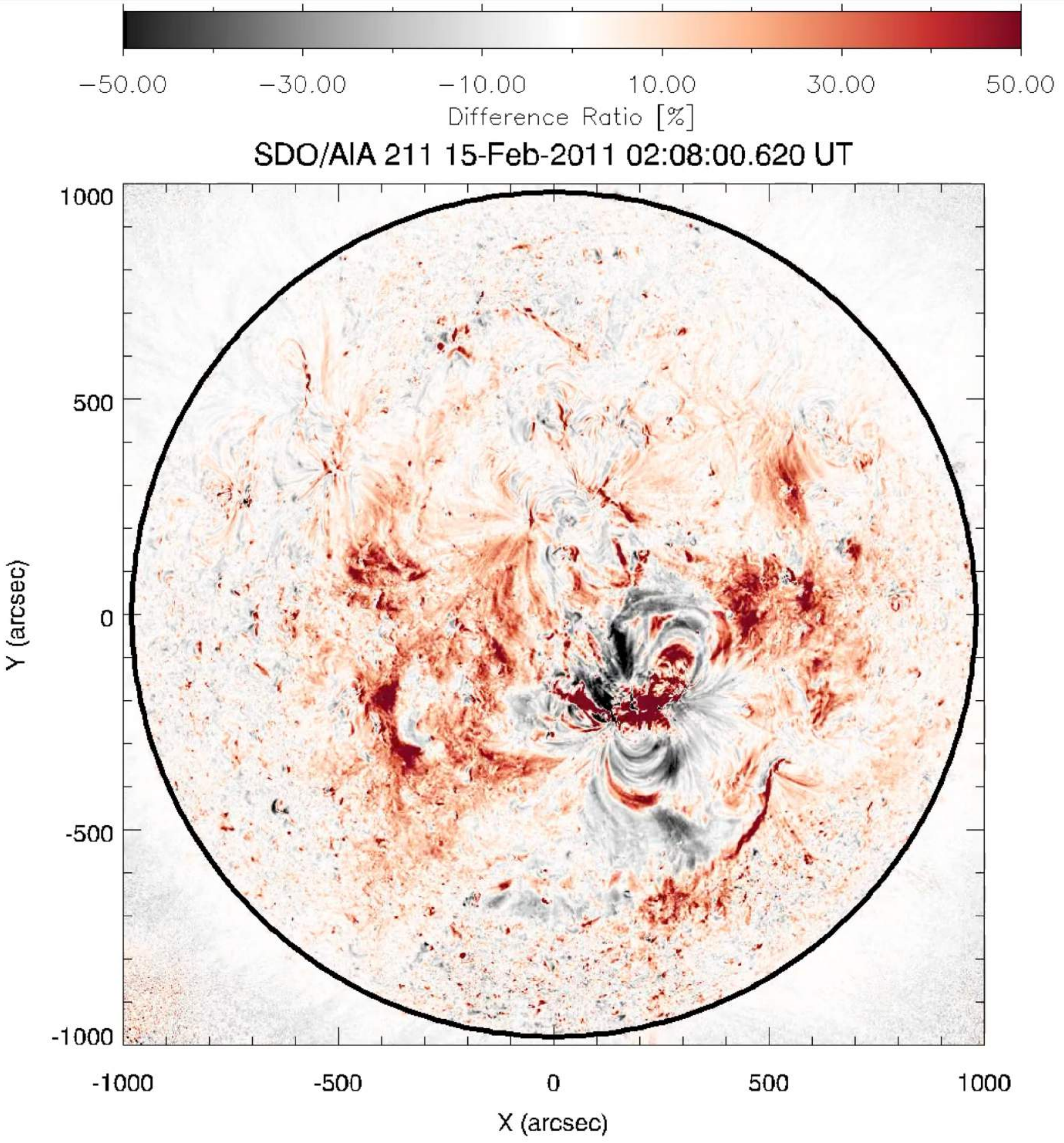
EUV Dimming by SDO/AIA (Nitta et al. 2013)

Coronal Dimming Observed by SDO/AIA

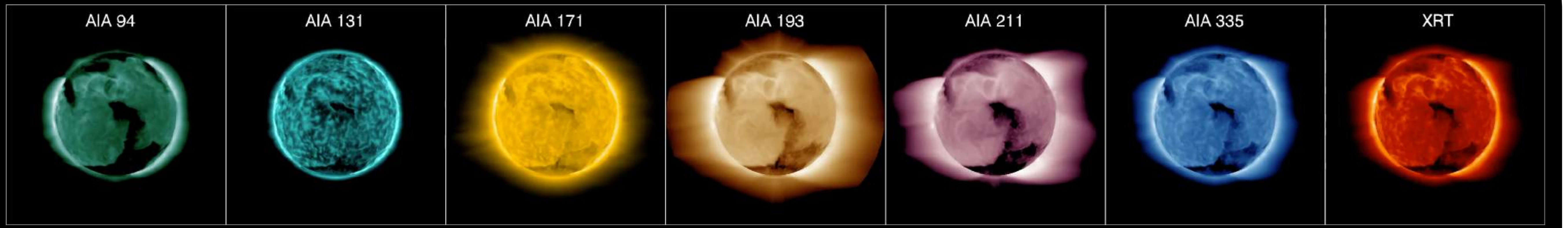
AIA 171 (T = 0.63 MK)



AIA 211 (T = 1.86 MK)

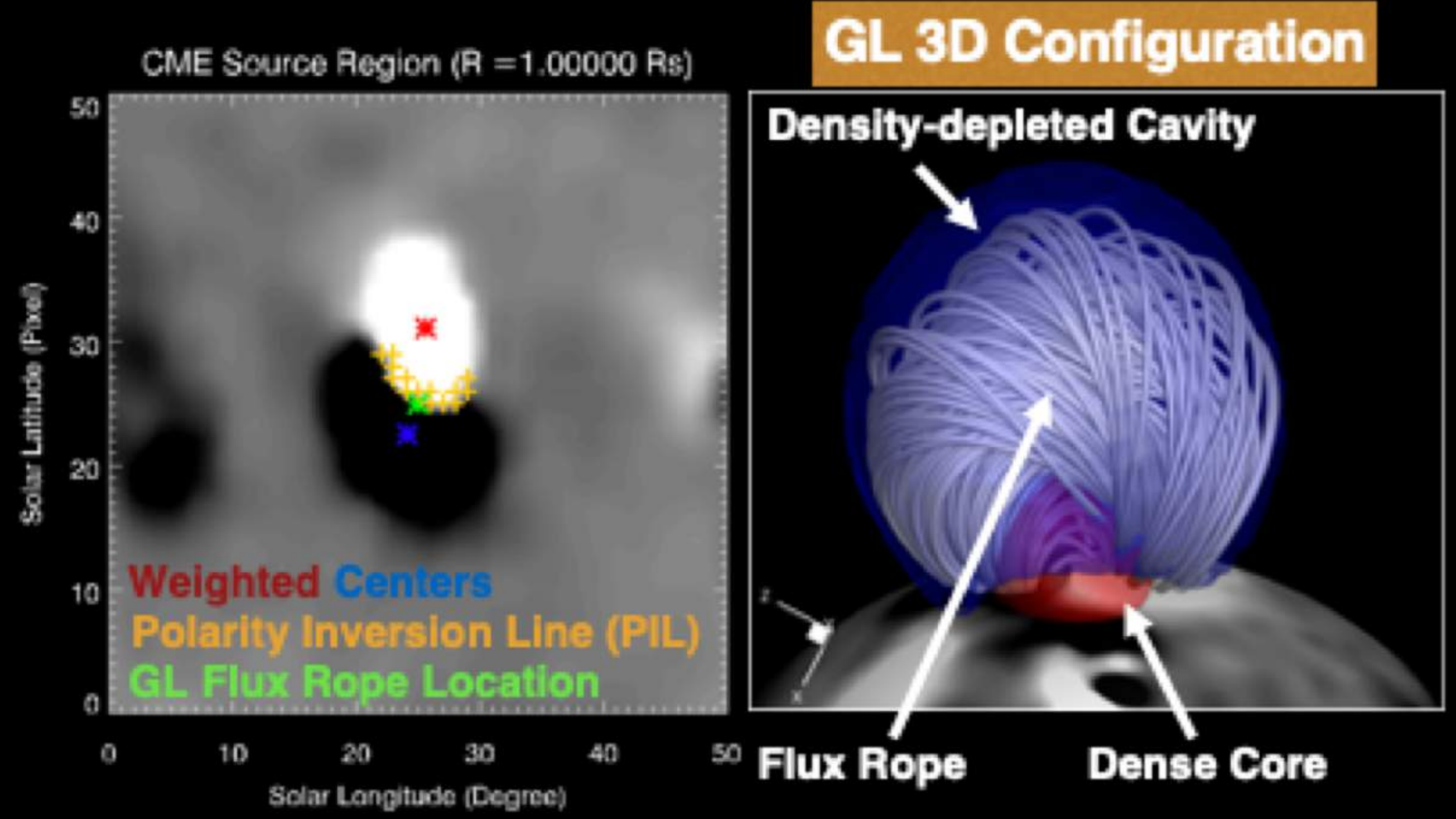


Alfvén Wave Solar Model (AWSoM)



- **AWSoM** (van der Holst et al. 2014) is developed within Space Weather Modeling Framework (**SWMF**; Toth et al. 2012) at U of Michigan.
- Coronal heating and solar wind accelerating by Alfven waves. Separate energy equations for **electrons** and **protons**.
- Model starts from upper chromosphere including **heat conduction** (both collisional and collisionless) and **radiative cooling**. Adaptive mesh refinement (**AMR**) to resolve structures (e.g., current sheets, shocks). **Data-driven boundary condition** from magnetic maps.

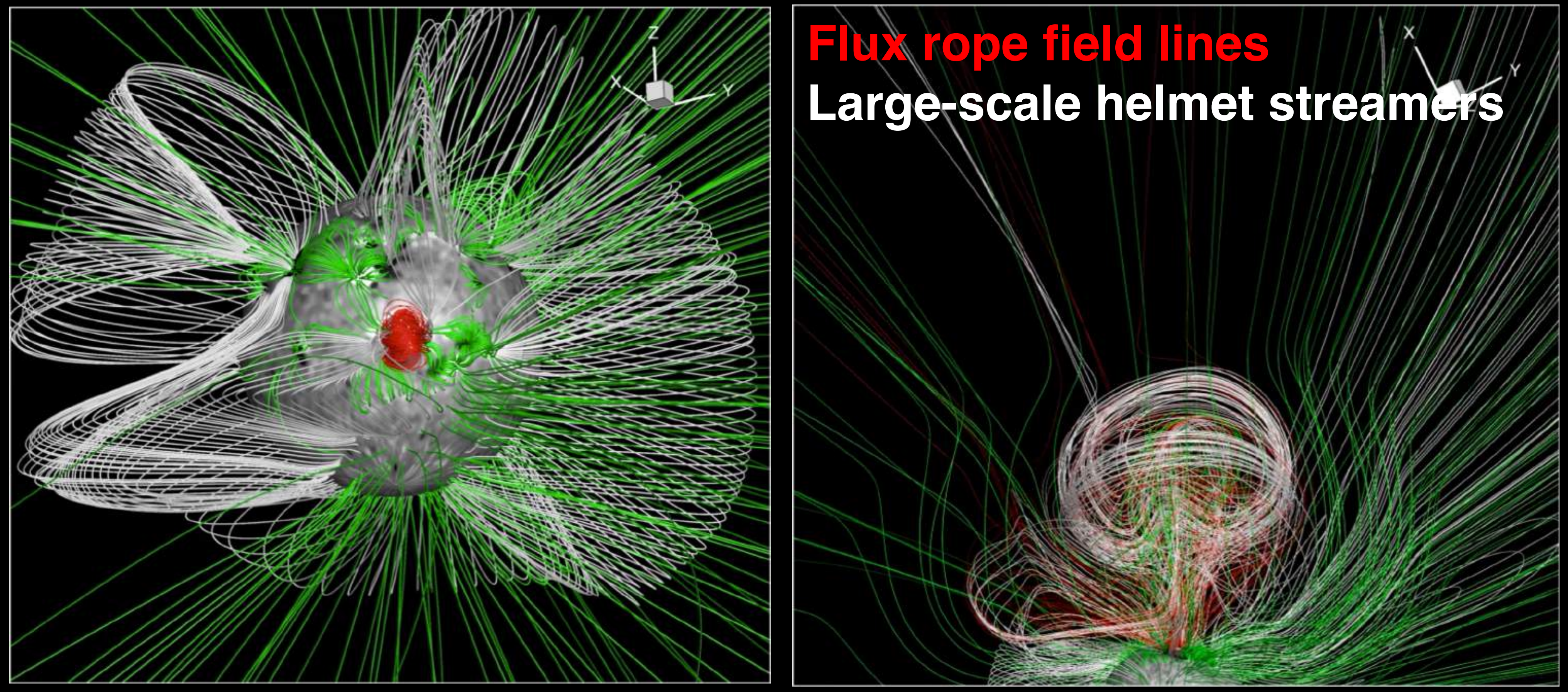
EEGGL: Eruptive Event Generator (Gibson and Low)



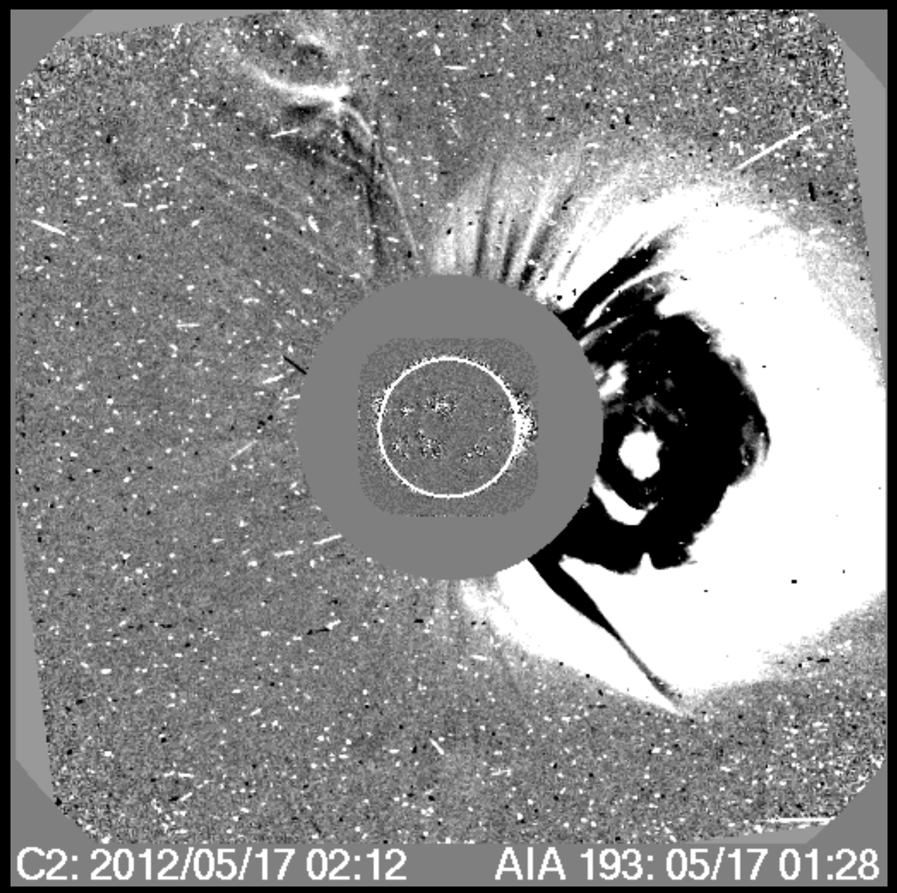
EEGGL uses observational data to calculate input parameters for the GL flux rope model (Gibson & Low 1998) so that it could approximately reproduce observed CME events (Jin et al. 2017).

More information: https://ccmc.gsfc.nasa.gov/eeggl/

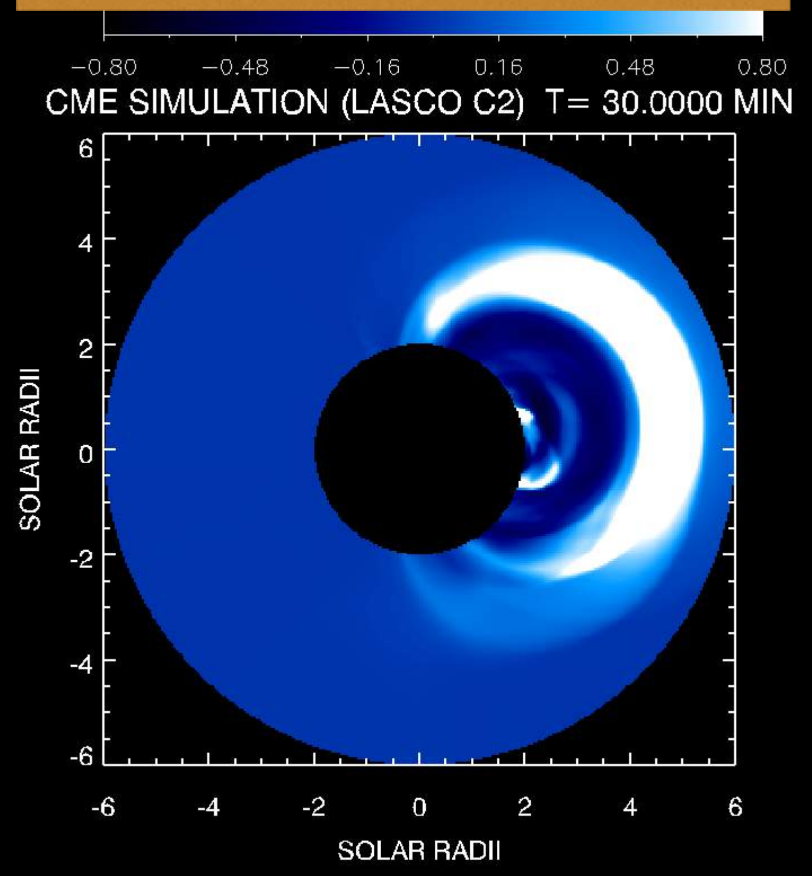
CME Field Evolution in 3D



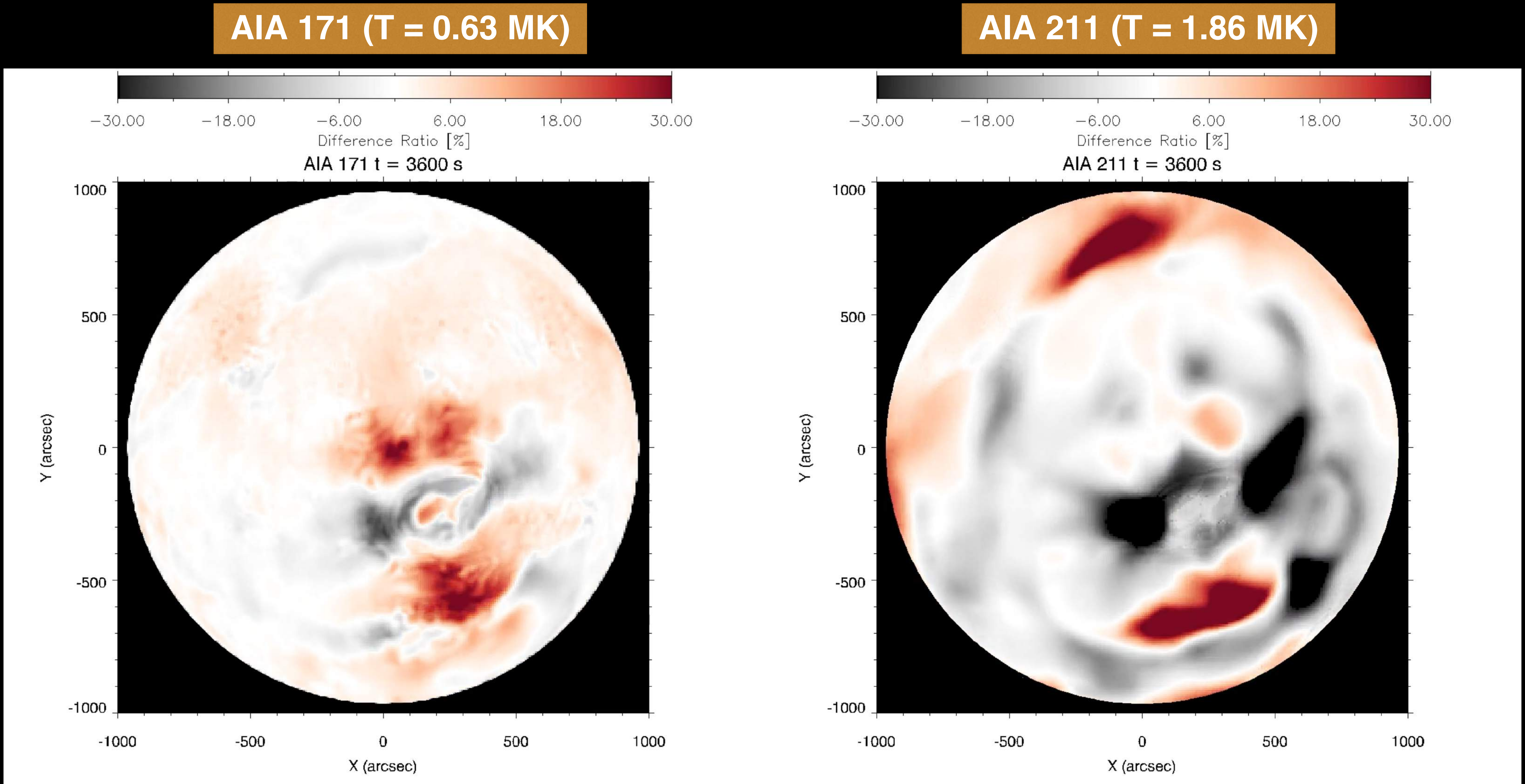
LASCO C2 Observation



Synthetic LASCO C2

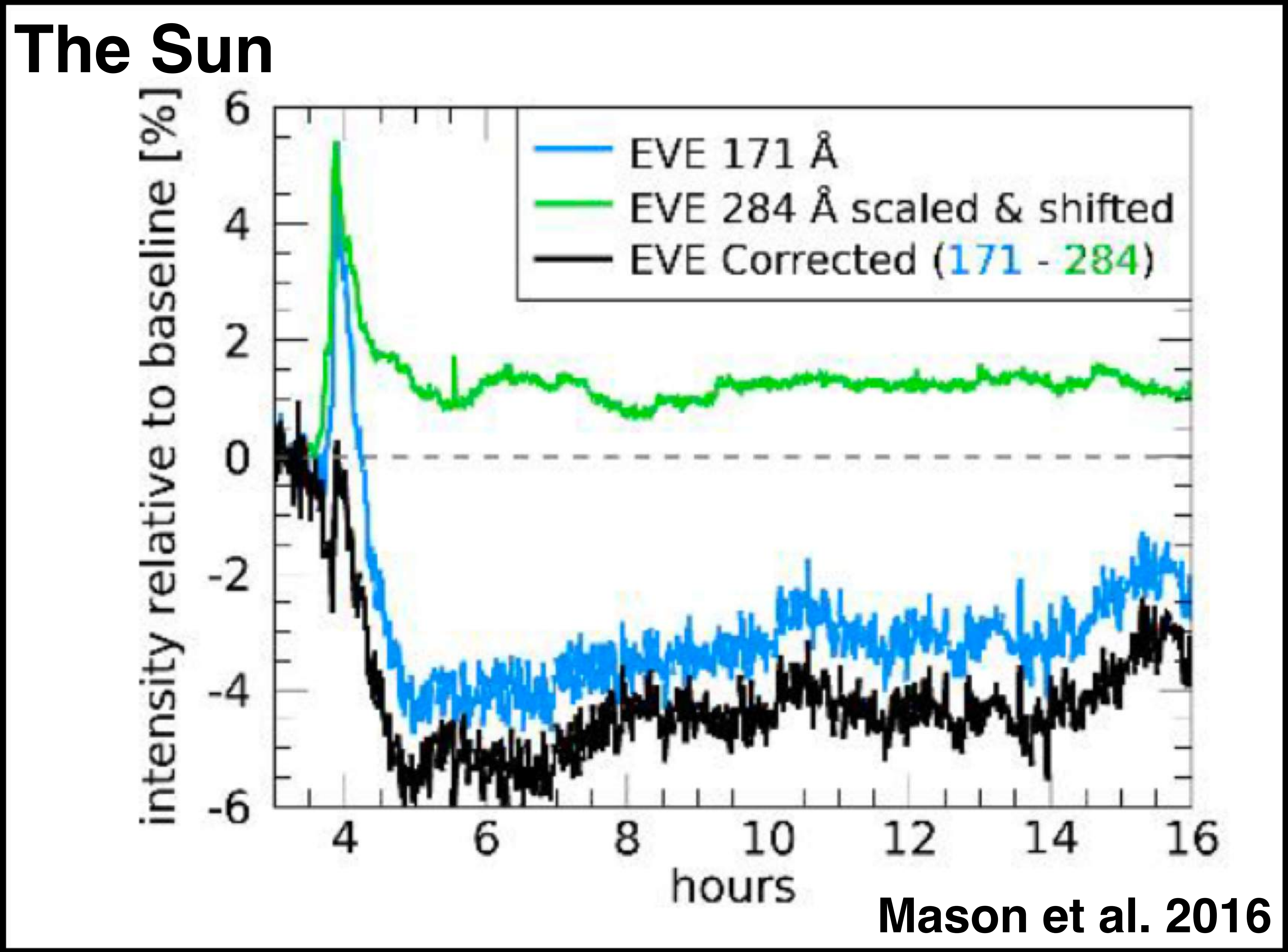


Synthesized Solar Coronal Dimming/Brightening

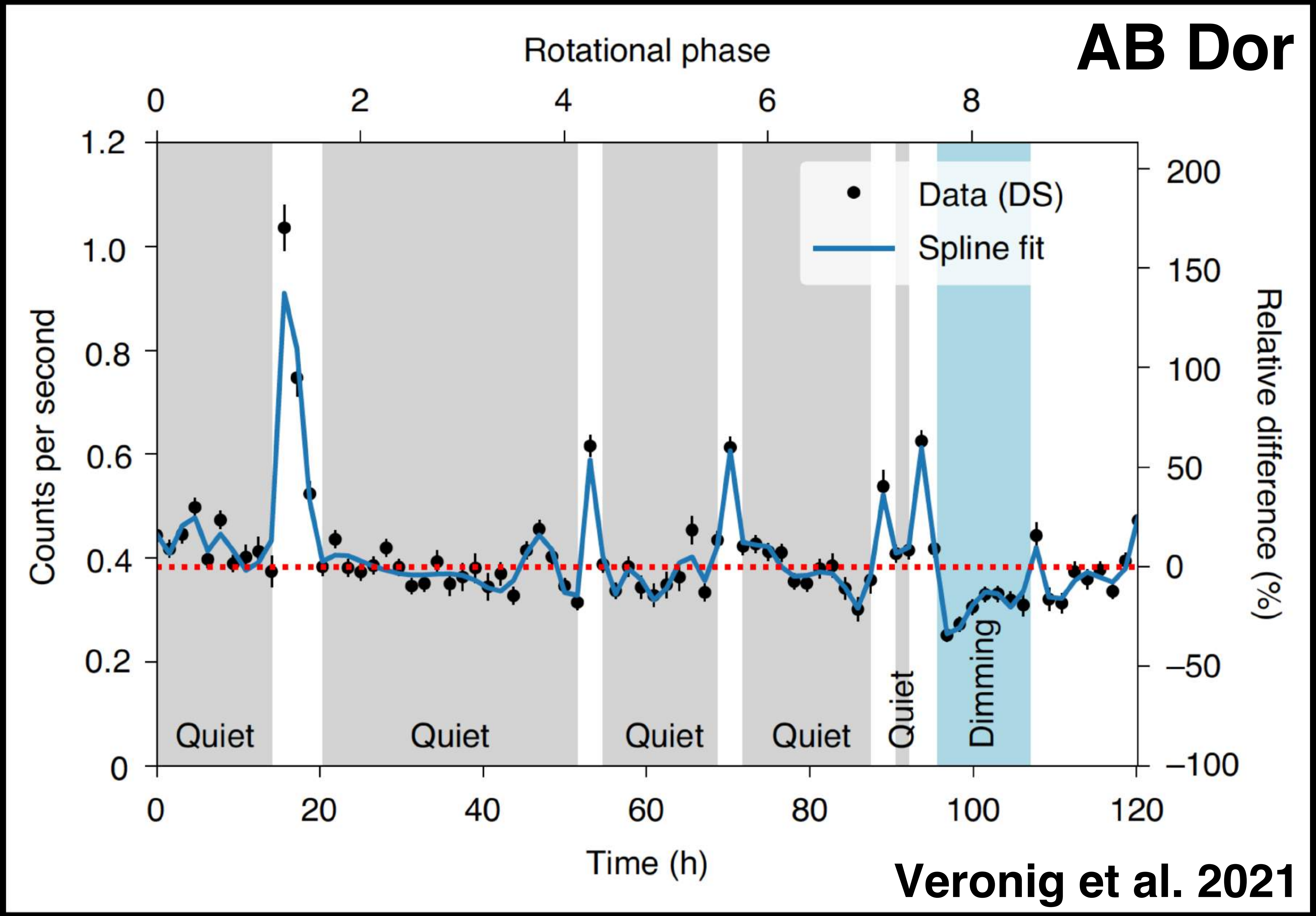


Jin et al. 2022

Coronal Dimming as a Proxy for Stellar CMEs



Mason et al. 2016

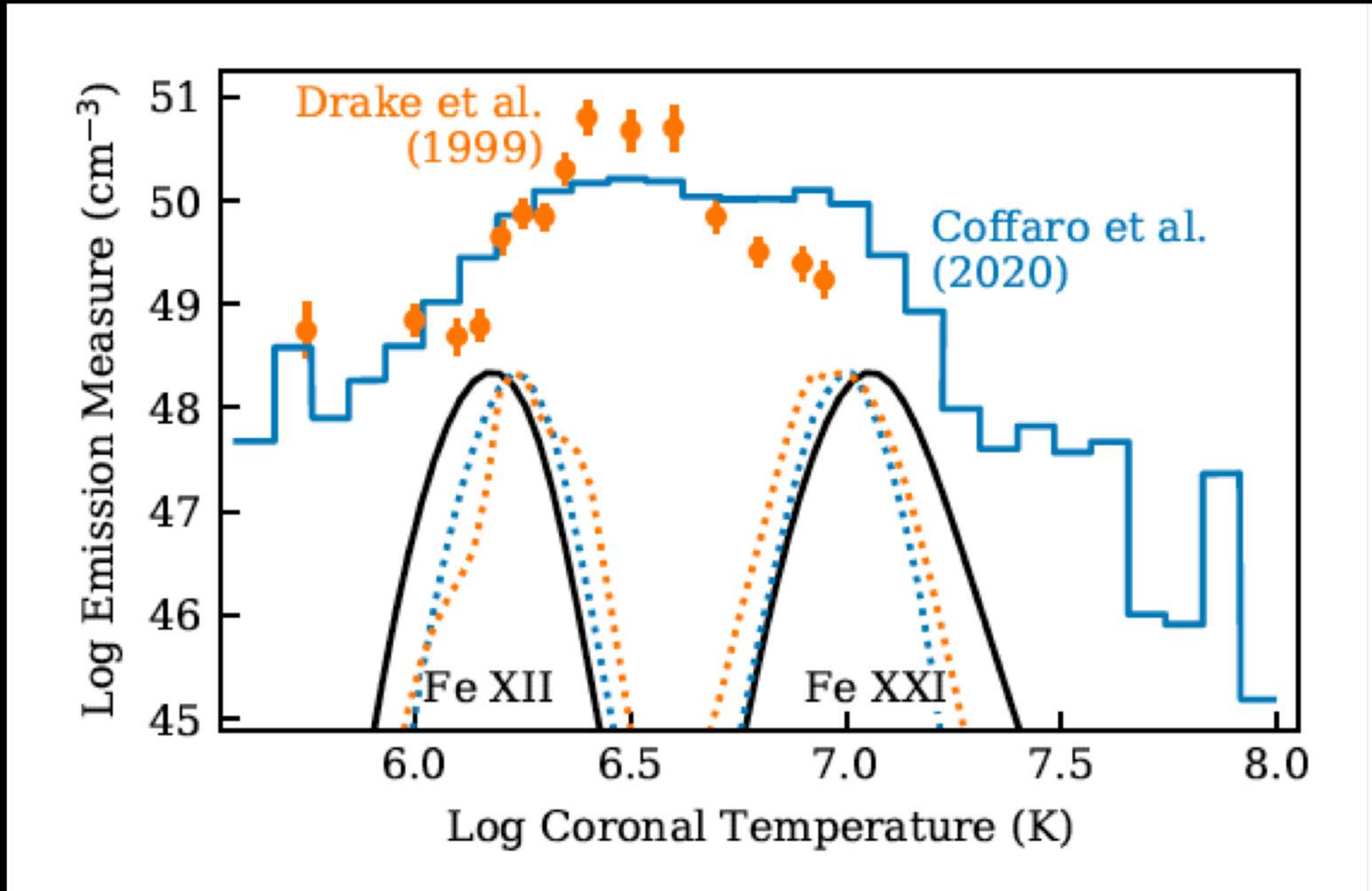


Veronig et al. 2021

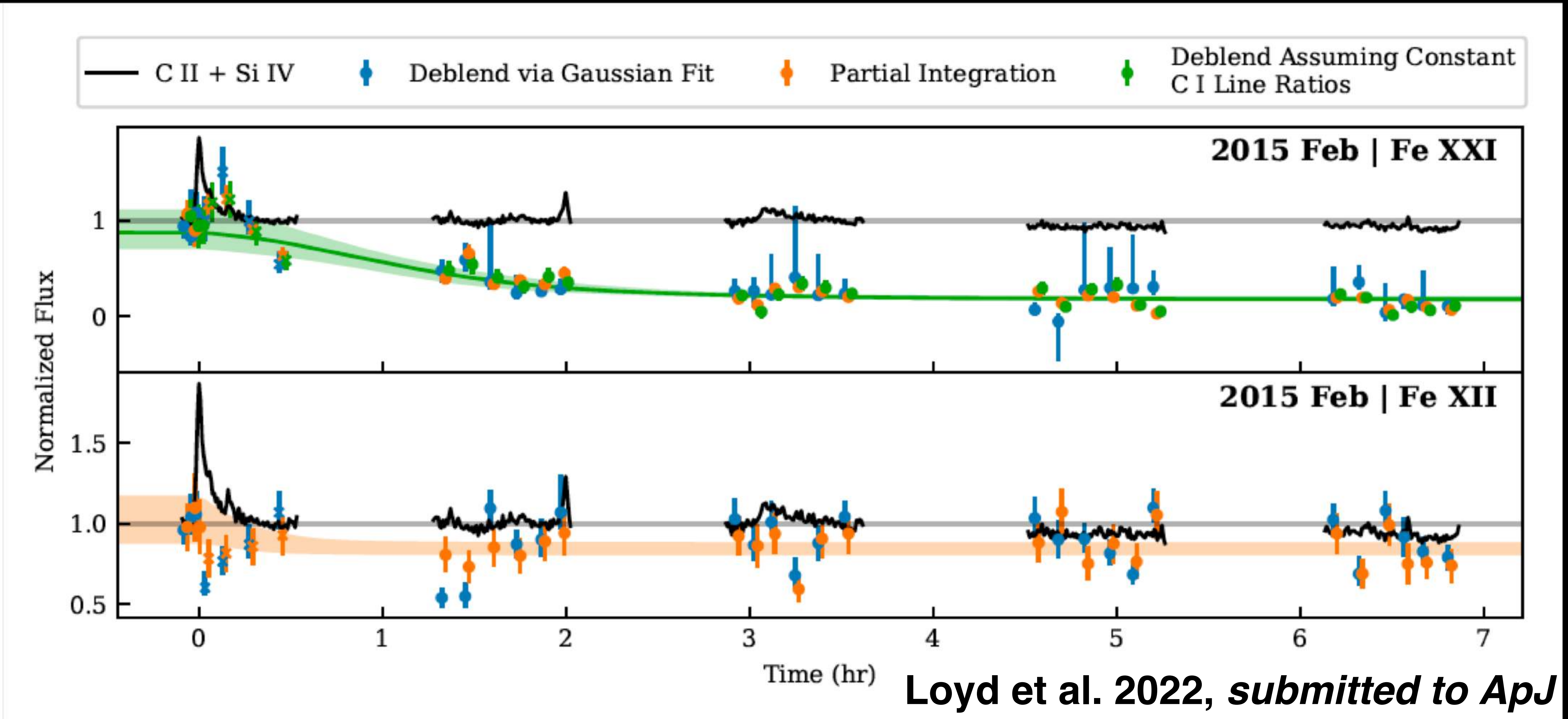
- **For the Sun, we are able to observe CMEs directly with coronagraphs and in-situ measurements. However, these traditional methods may not feasible for stellar CMEs in the near-term.**
- **Based on the solar studies, the coronal dimming is one of the best candidates that can be employed to detect and quantify the CME events on other stars (Harra et al. 2016).**
- **Using historical data from XMM, HST, and EUVE, Veronig et al. (2021) identified 21 stellar dimming events on 13 different stars.**

Far UV Coronal Dimming of Epsilon Eridani

Emission Measure



Far UV Emision

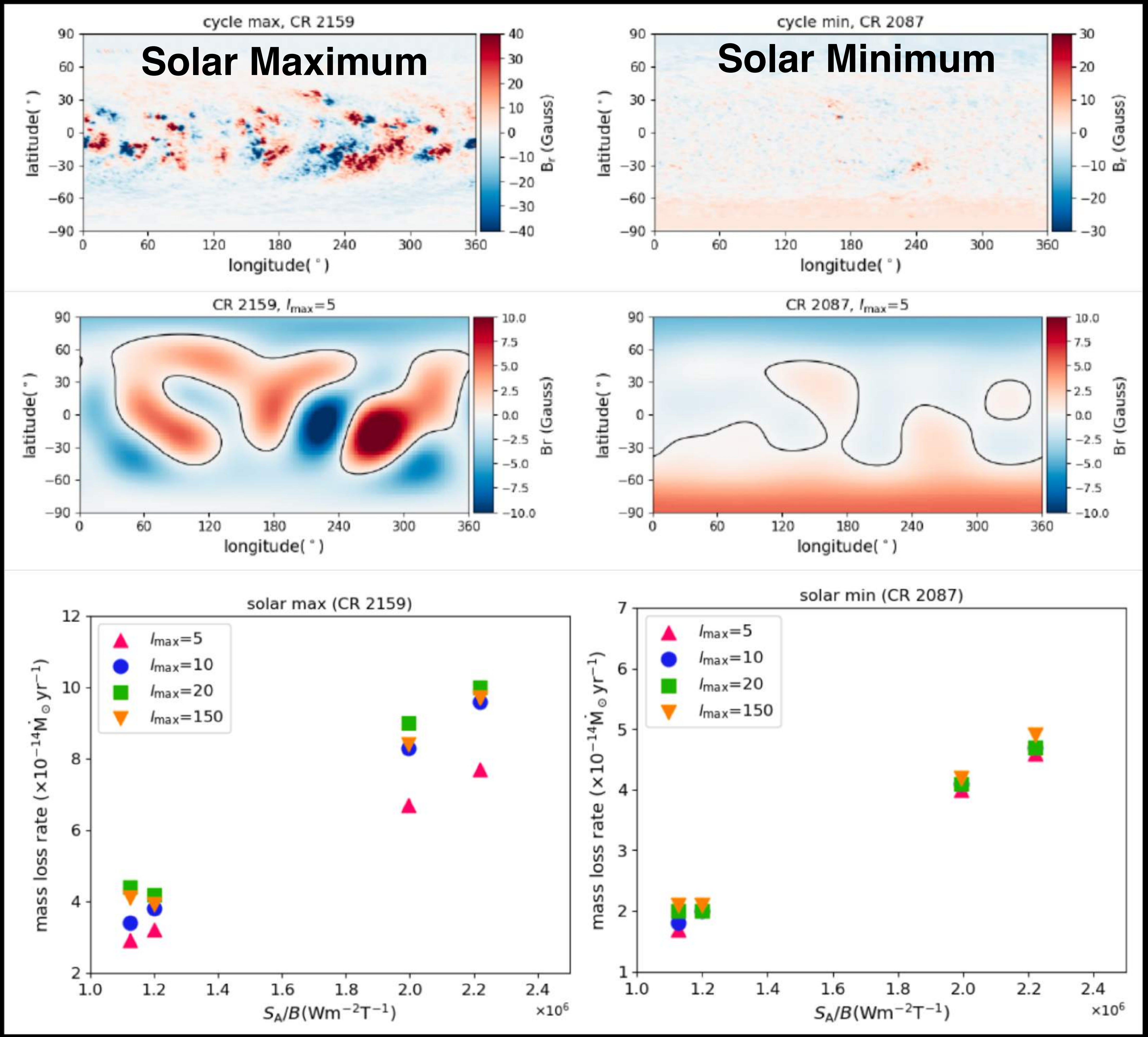


Loyd et al. 2022, *submitted to ApJ*

- Fe XII 1349 A and Fe XXI 1354 A observation from HST's Cosmic Origins Spectrograph archival data.
- Following a flare in February 2015, the Fe XXI emission declined by ~80% (Note that the limited preflare observation allows for the possibility that Fe XXI decline was the decay of an earlier flare).
- Fe XII emission does not show evident dimming signal in this event.

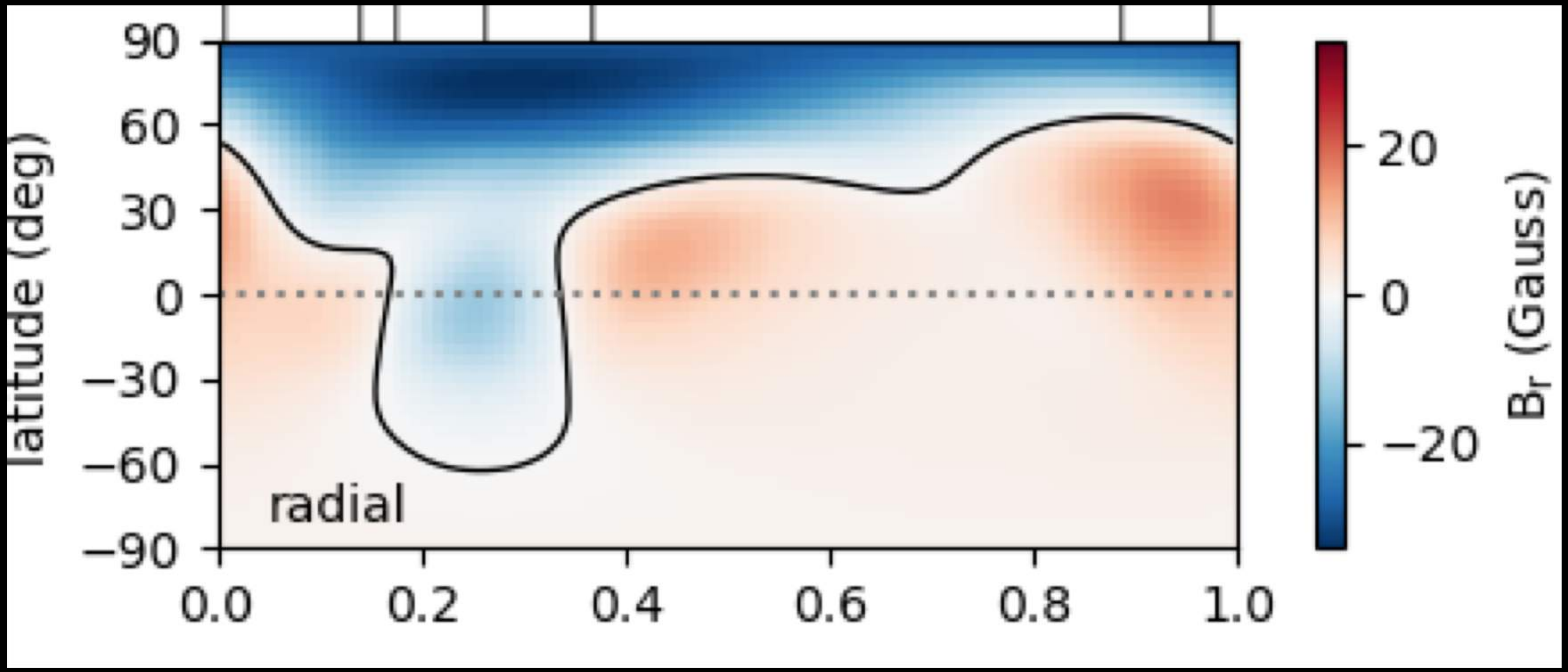
Modeling Steady State Corona of Eps Eri

Model Validation (Solar Case)



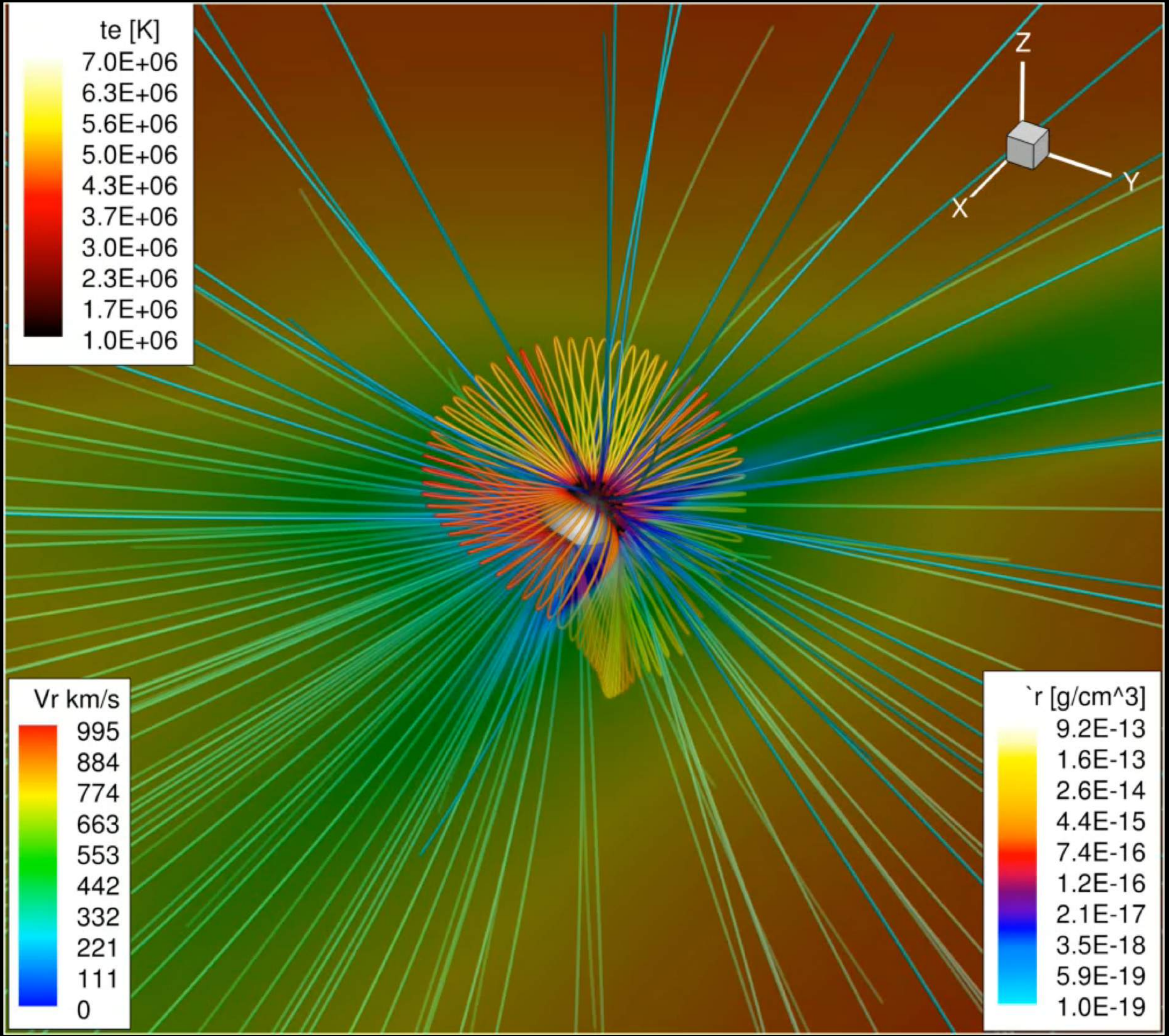
Boro Saikia et al. 2020

ZDI Map of Eps Eri



- The ZDI map reconstructs large-scale structures of the stellar corona therefore providing a reliable estimation on stellar mass loss rate when used to drive global MHD models (e.g., Vidotto et al. 2009, Cohen et al. 2009, Réville et al. 2016).
- Using the ZDI map and the stellar mass loss rate of 30 $\dot{M}_\odot$ estimated from the astrospheric absorption method (Wood et al. 2005), we could better constrain the free parameters of the model and reconstruct the steady state corona of Eps Eri.

Stellar Corona and Wind of Eps Eri



Eps Eri Stellar Parameters
Type: K2V
Age: 400 – 800 Myr
Rotation Period: 11.68 days
Mass: 0.86 M_sun
Radius: 0.75 R_sun

- **The Eps Eri has a hotter, denser corona comparing with the solar case.**
- **The stellar wind from Eps Eri is also faster comparing with the solar wind.**
- **The calculated stellar wind mass loss rate is 3.6E13 g/s, which is ~30 $\dot{M}_{\odot}$.**

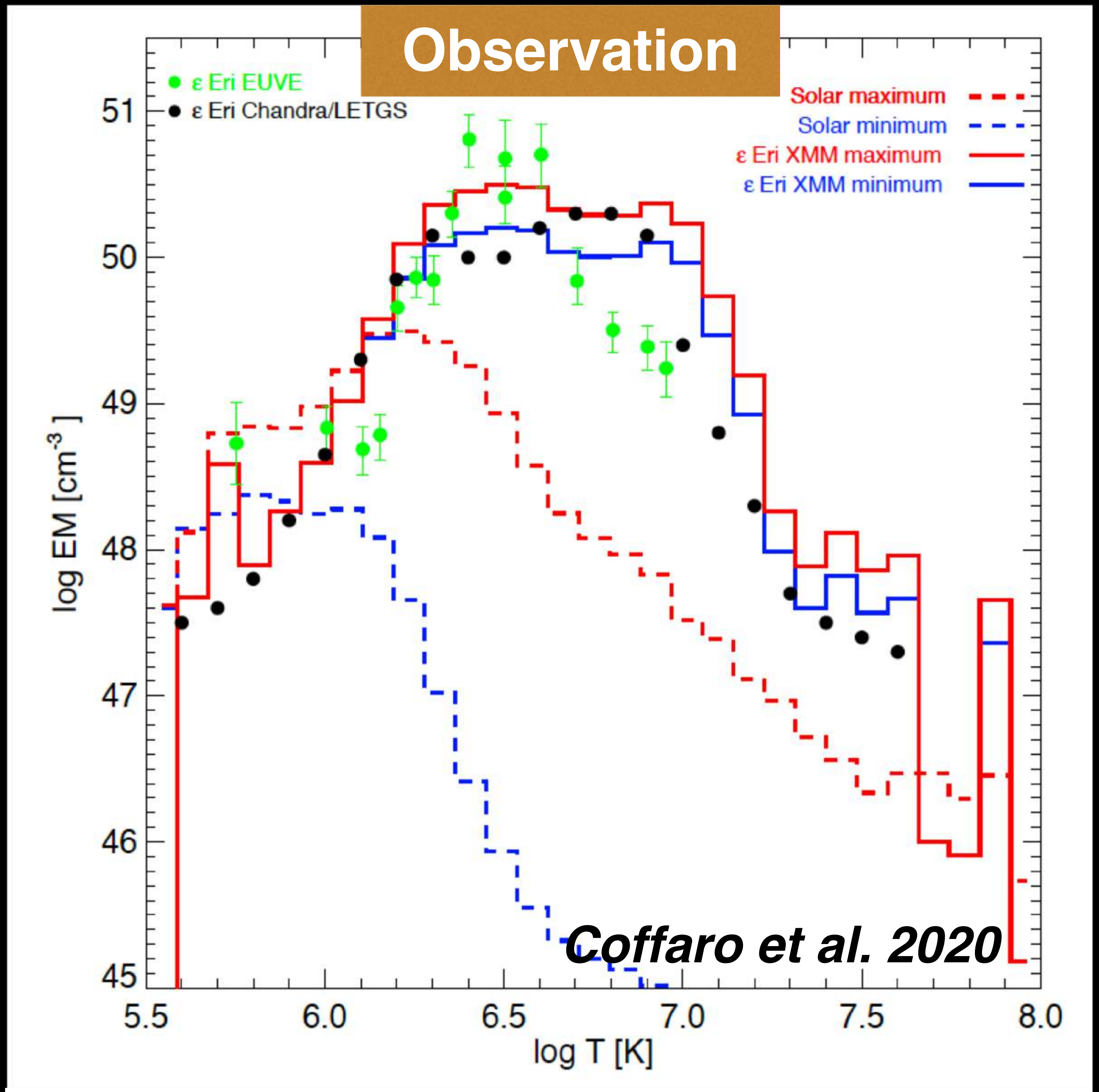
Modeling CME from Eps Eri

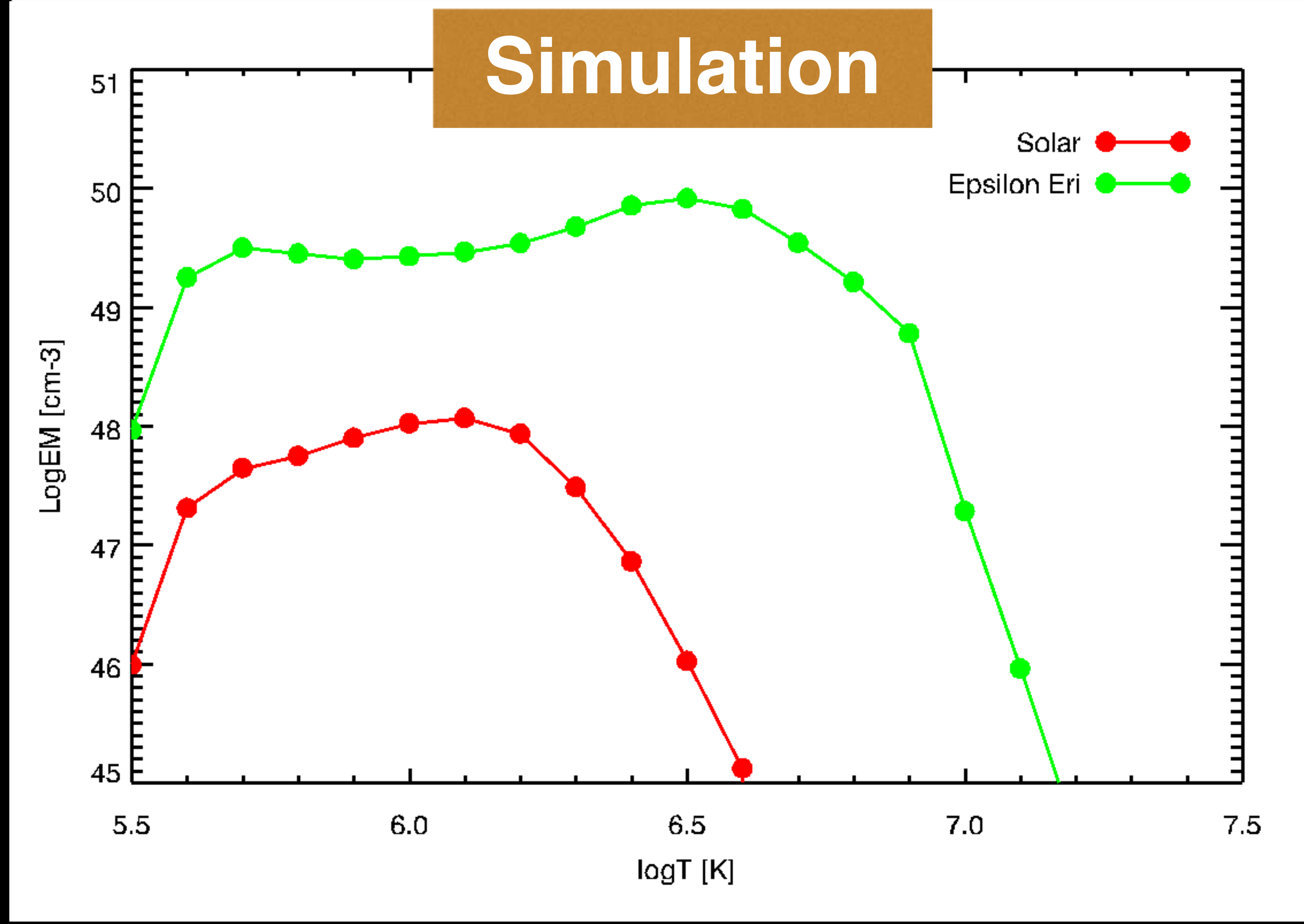
- However, due to the lack of higher harmonics degrees in the ZDI map (l_max < 10), there is no active region structures, which is necessary for modeling CME eruptions.

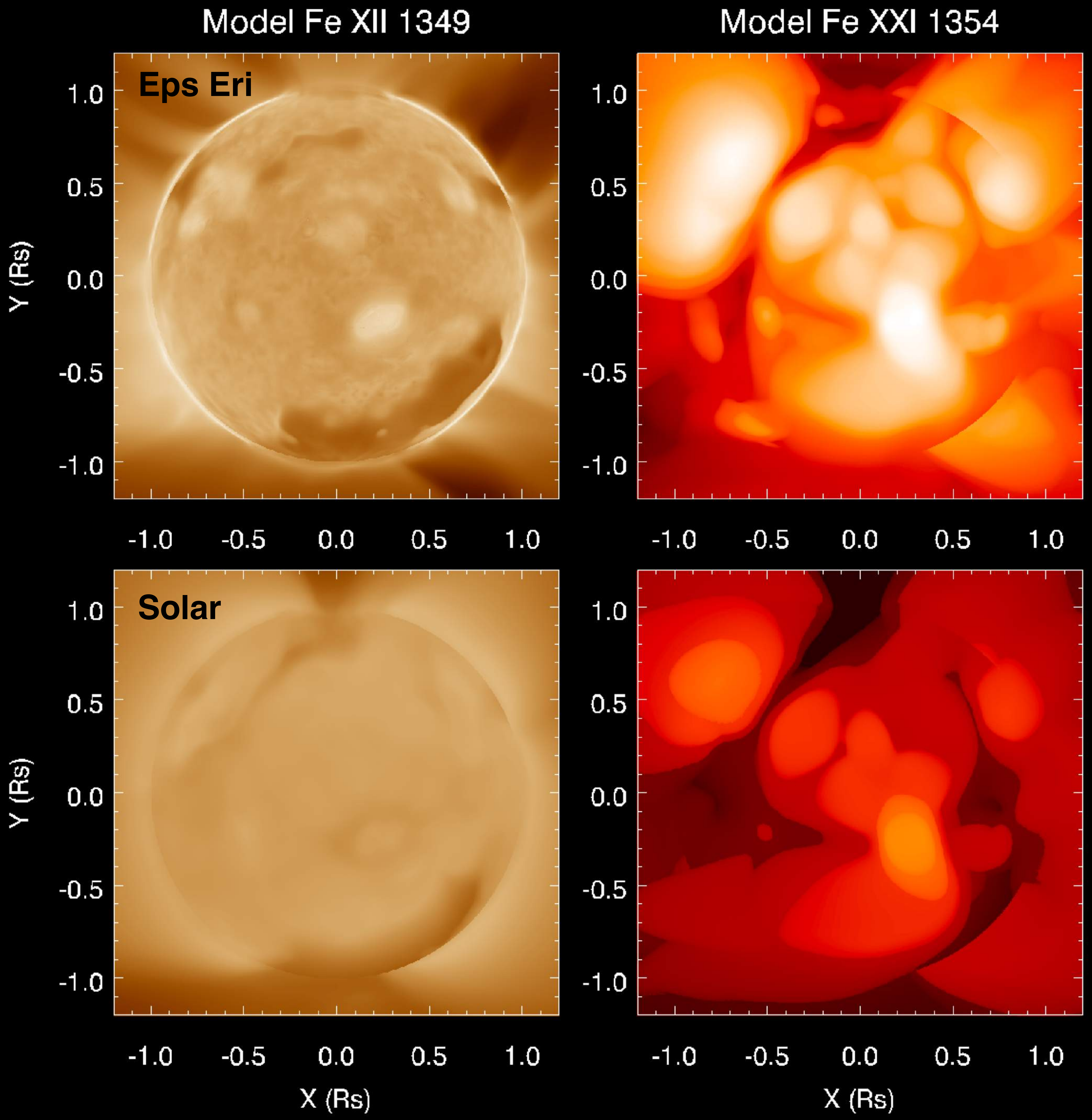
- In addition, the lack of active regions also lead to less high temperature plasmas in the model, which makes the quantitative comparison with the Far-UV observations difficult.

- To model the CMEs from the Eps Eri, we adapt a solar magnetic map and scale the mean magnetic flux density according to the Eps Eri ZDI map while keep the rest of the model parameters the same as used in the steady state stellar wind simulation.

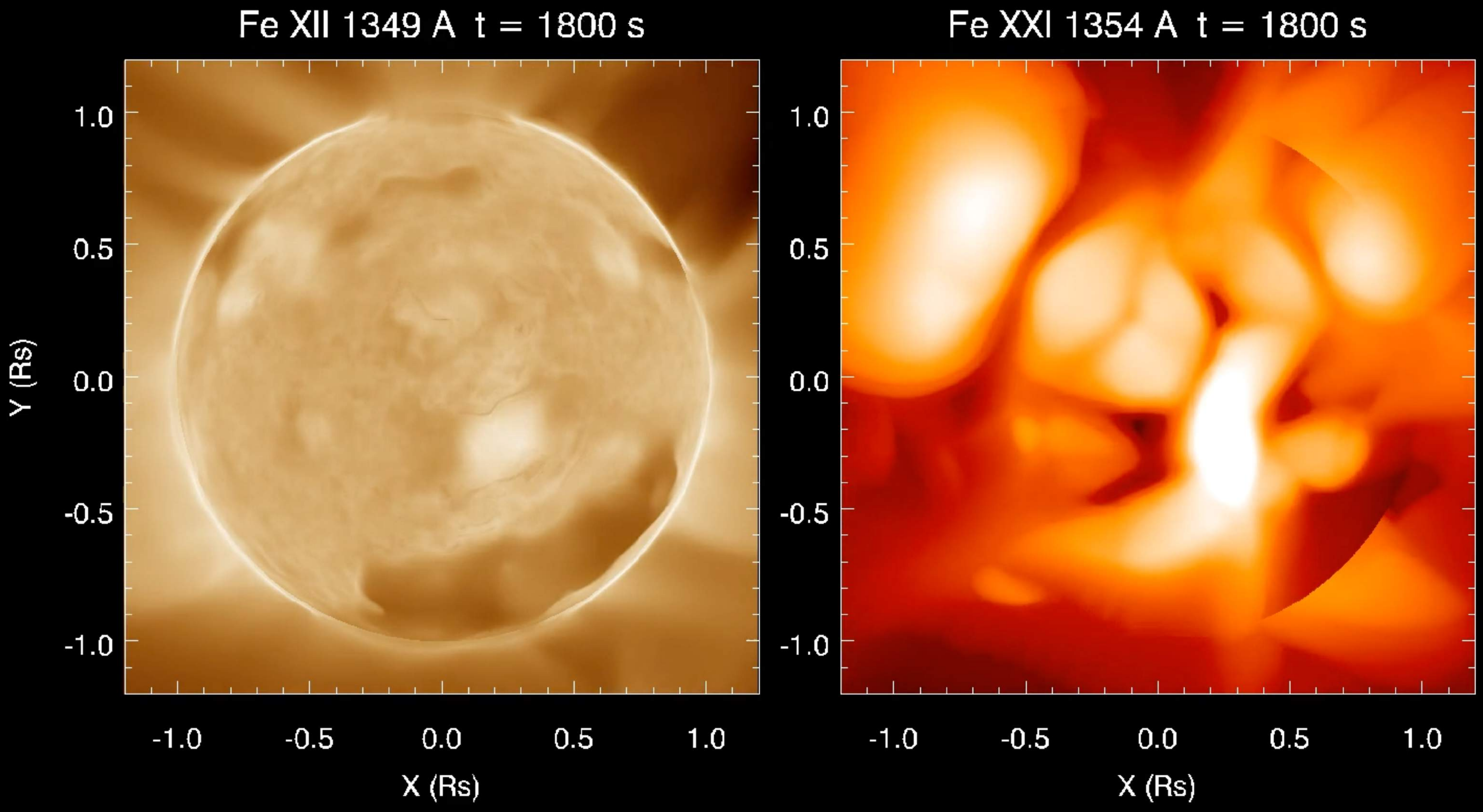
- The CME flux rope energy is chosen to allow a successful eruption without confinement (Alvarado-Gómez et al. 2016) and with a speed considered a fast solar CME. Note that the maximum strength of surface magnetic field (large-scale) was 20-33 Gauss near the 2015 observations (Jeffers et al. 2017), which is only a few times stronger than the solar case.


Observation
ε Eri EUVE
ε Eri Chandra/LETGS
Solar maximum
Solar minimum
ε Eri XMM maximum
ε Eri XMM minimum
log EM [cm^{-3}]
log T [K]
Coffaro et al. 2020

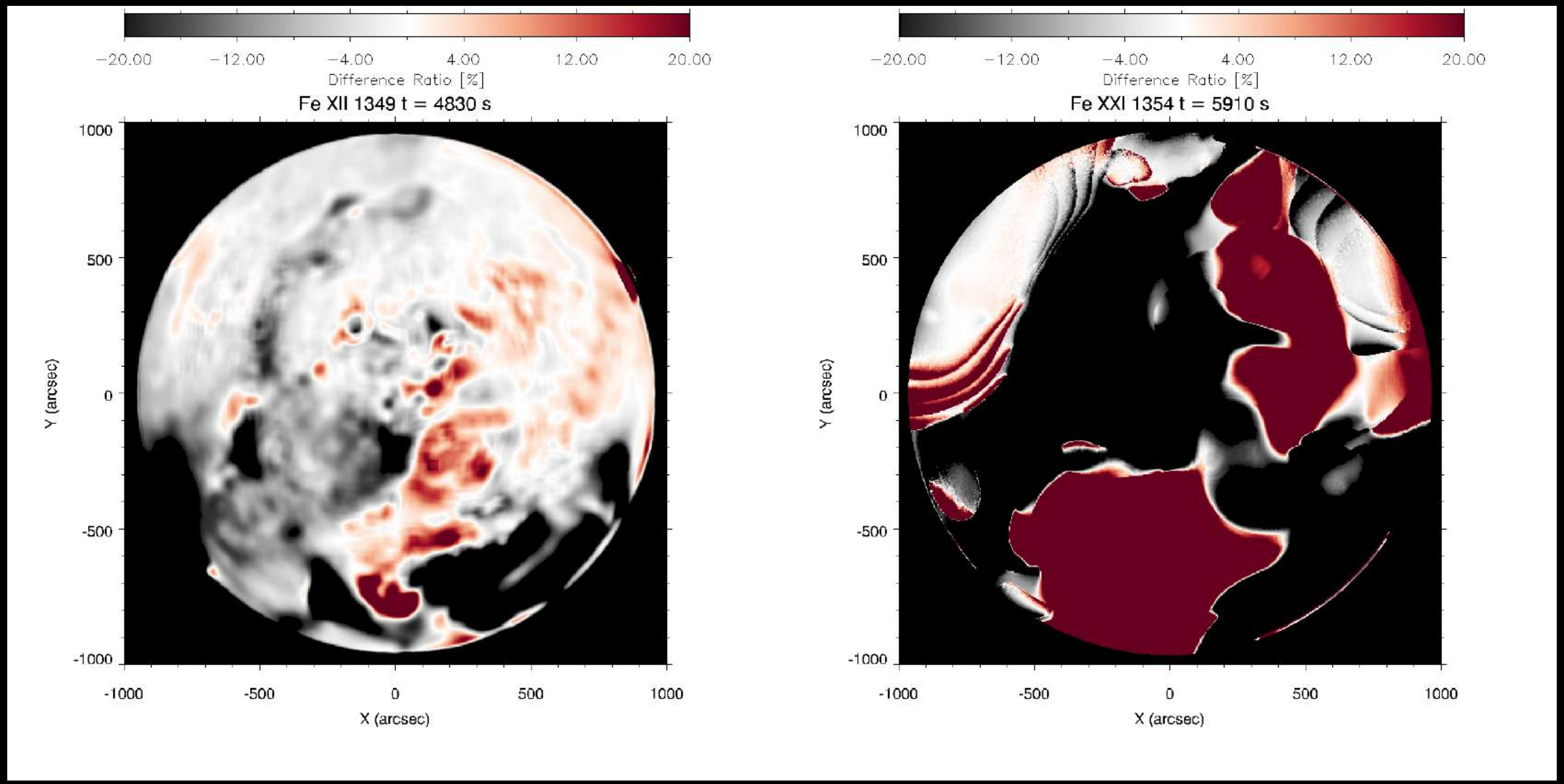

Simulation
Solar
Epsilon Eri
LogEM [cm-3]
logT [K]

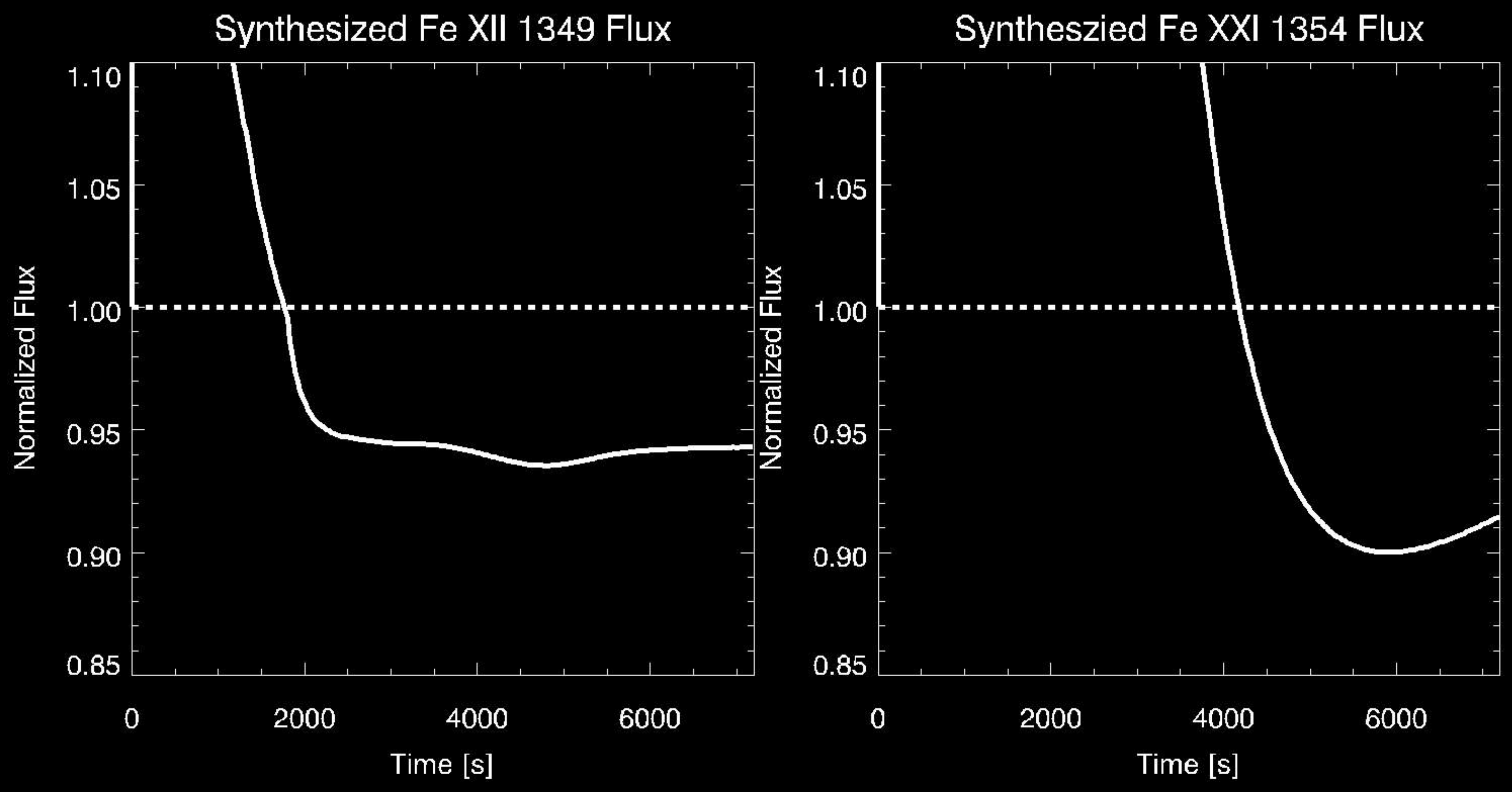

Model Fe XII 1349
Model Fe XXI 1354
Eps Eri
Solar
Y (Rs)
X (Rs)

CME Eruption from Eps Eri Corona



CME-induced Dimming for Eps Eri Case





- The dimming depth in the synthesized Fe XXI emission (~10%) is significantly larger than that in the Fe XII emission (~5%).
- The dimming area is also larger for the Fe XXI line.
- The dimming in Fe XXI starts later than in Fe XII.

CME Properties Estimated from the Model

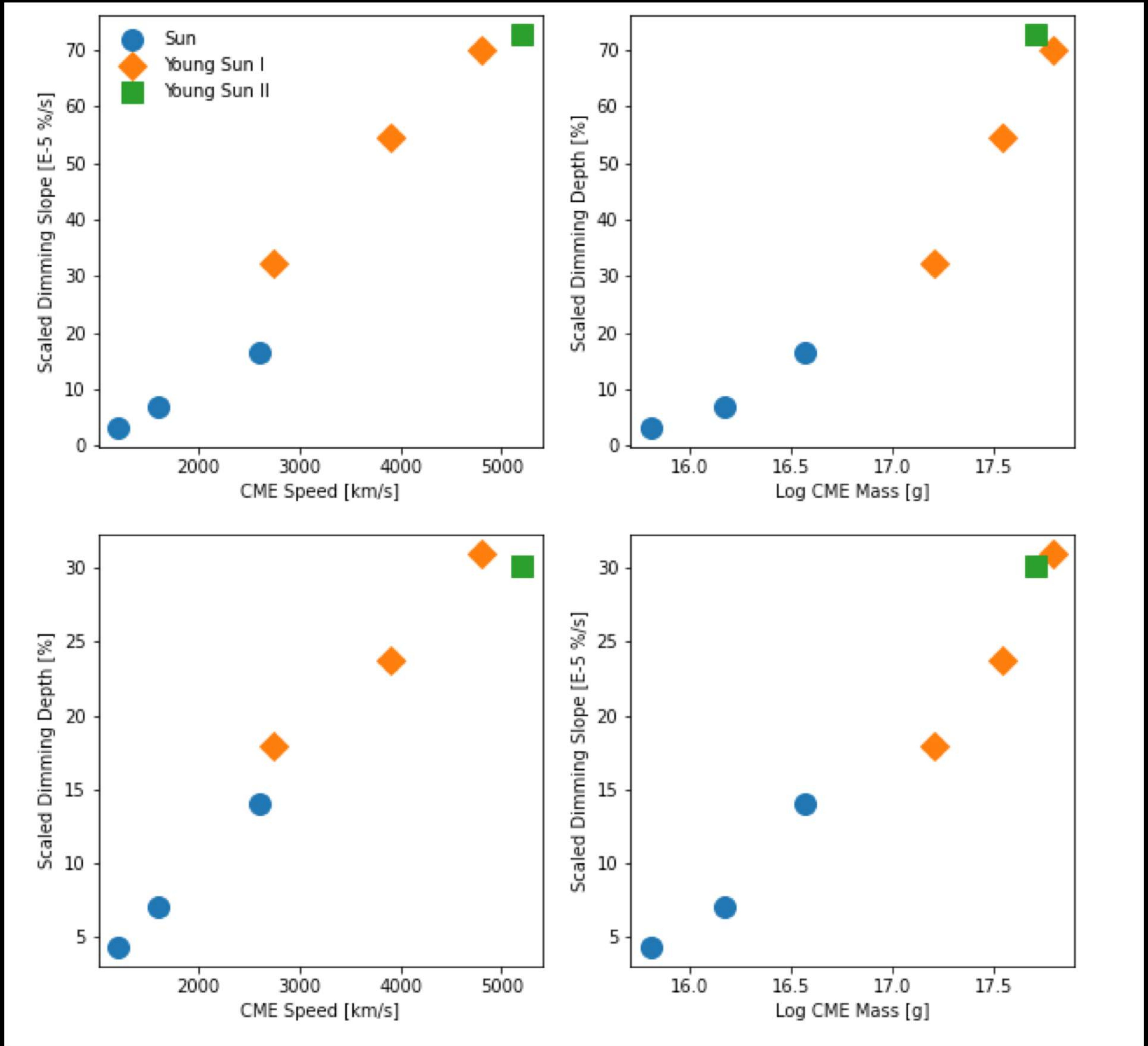
- CME Magnetic Energy: ~1.E33 ergs
- CME Speed: ~3000 km/s
- CME Mass: 1.E17 g
- CME Mass Loss Rate: 2.5E20 g/year (20% of the wind loss rate, assuming 7 events/day)

Eruptive Solar/Young Sun Cases

	Mean Magnetic Flux Density	CME Energy [erg]	CME Mass [g]	CME speed [km/s]	Dimming Depth [%]	Dimming Slope [E-5 %/s]
Young Sun I CME I	25 Gauss	1.5E33	1.6E17	2750	6.2	11.2
Young Sun I CME II	25 Gauss	1.3E34	3.5E17	3900	8.2	18.9
Young Sun I CME III	25 Gauss	2.3E34	6.2E17	4800	10.7	24.2
Young Sun II CME I	50 Gauss	4.9E35	5.0E17	5200	6.6	15.9
Solar CME I	5 Gauss	4.1E31	6.5E15	1216	4.4	3.2
Solar CME II	5 Gauss	1.2E32	1.5E16	1598	7.1	7.0
Solar CME III	5 Gauss	4.2E32	3.7E16	2607	14.0	16.5

**The 3 solar CME cases are from Jin et al. 2022*

Coronal Dimming vs. CME Characteristics (including Young Sun Cases)



- The relationship between the CME and dimming might depend on many factors, but the magnetic strength should be one of the most important factors.
- When taking into account the magnetic field strength of the star, we can get a quasi-linear relationship between the CME speed/mass and the dimming depth and slope among all the cases.
- The relationship is not perfect, which indicate there are other factors that influence the dimming characteristics. But it shows the potential to get useful information of stellar CMEs from their dimming signatures.

Summary

- By applying a solar global MHD model (AWSoM) with stellar conditions, we simulate the Eps Eri stellar wind and CMEs to compare with the HST Far-UV observations.

- The model reproduces the high wind mass loss rate of 30 $\dot{M}_{\odot}$. With stronger magnetic field of Eps Eri therefore enhanced coronal heating, the CME-induced dimming is more evident in the higher temperature lines (e.g., Fe XXI), which follows a similar trend as shown in the HST observation. Based on the modeling result, the CME mass loss rate could account for ~20% of the stellar wind loss rate.

- Solar and stellar coronal dimmings encode important information about the CME properties. By combing observation and modeling efforts, it is possible to derive useful information of CMEs that plays a critical role for habitability of explanatory system.

- Future observations/missions (especially in the EUV wavebands) are needed to better capture the coronal signatures of the stellar CMEs. At the same time, we need to keep improving our knowledge about the physics of solar CMEs and coronal dimmings.