The Sun as a Star:

The discovery of “high-speed prograde flows”

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Outline of presentation

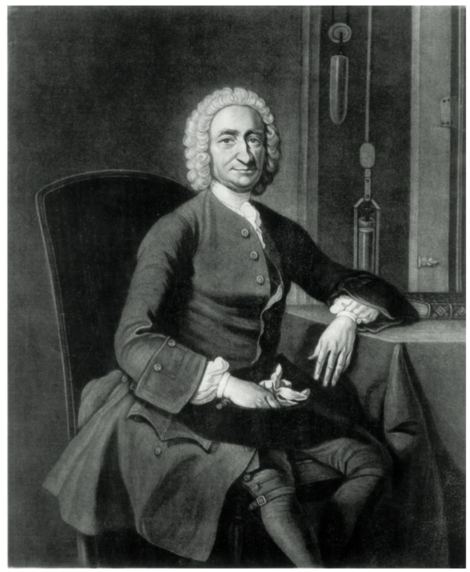
- Why we can learn even while ignoring images (Sun-as-a-star)
- The nature of solar magnetism
- EVE spectroscopy (Sun-as-a-star)
- The “high-speed prograde flows”
- Conclusion

Discovery follows from parameter space

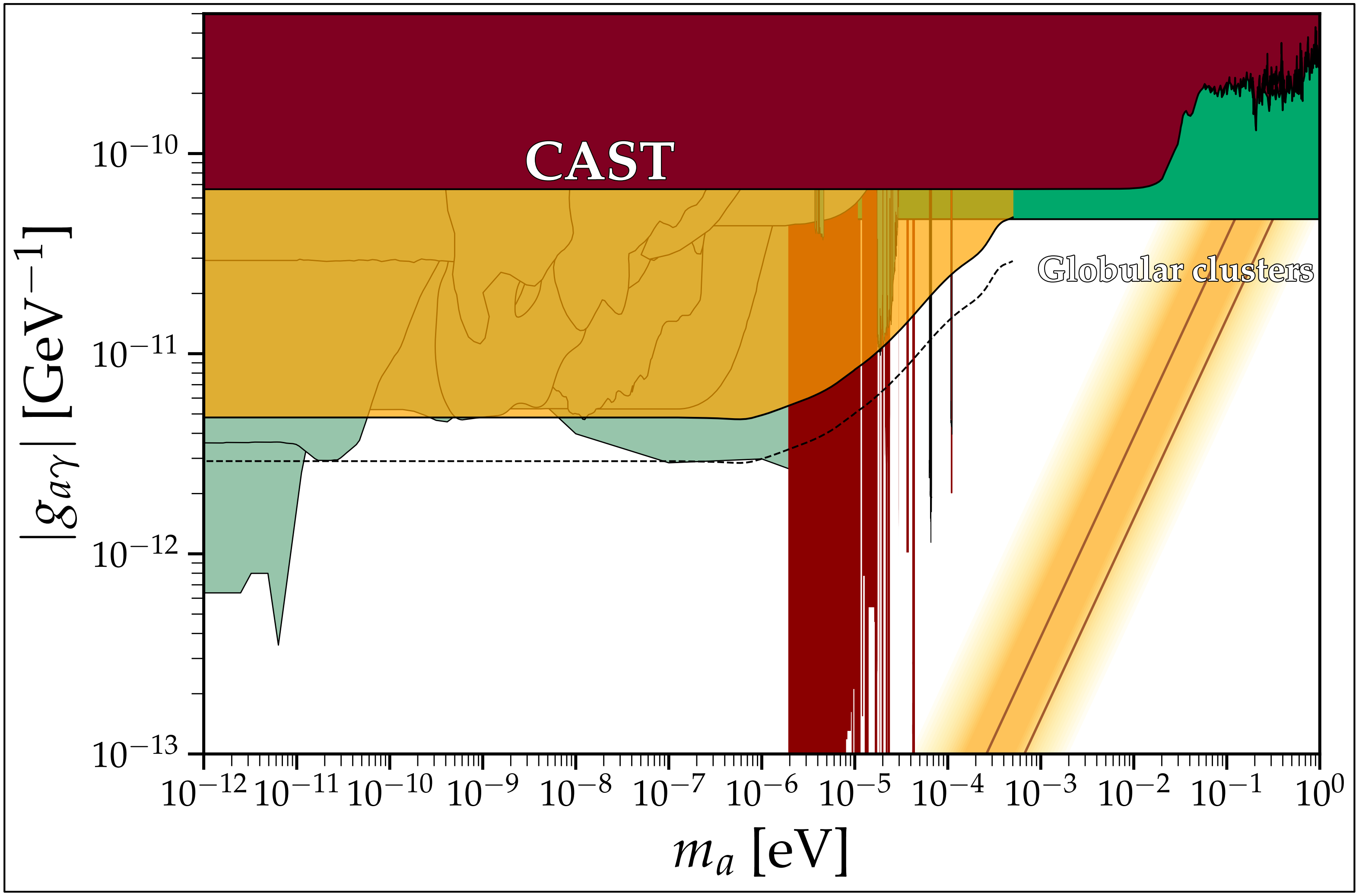
- Harwit, 1981 “Cosmic Discovery” [44]
- Hudson, 1987, “Solar Flare Discovery” [9]
- Harwit, 2019 (re-publication) [5]

Advances in technology lead to discovery.
Note that “multimessenger astronomy” began with the Sun, perhaps in 1722 - G. Graham discovers the geomagnetic diurnal variation.

George Graham (d. 1751)



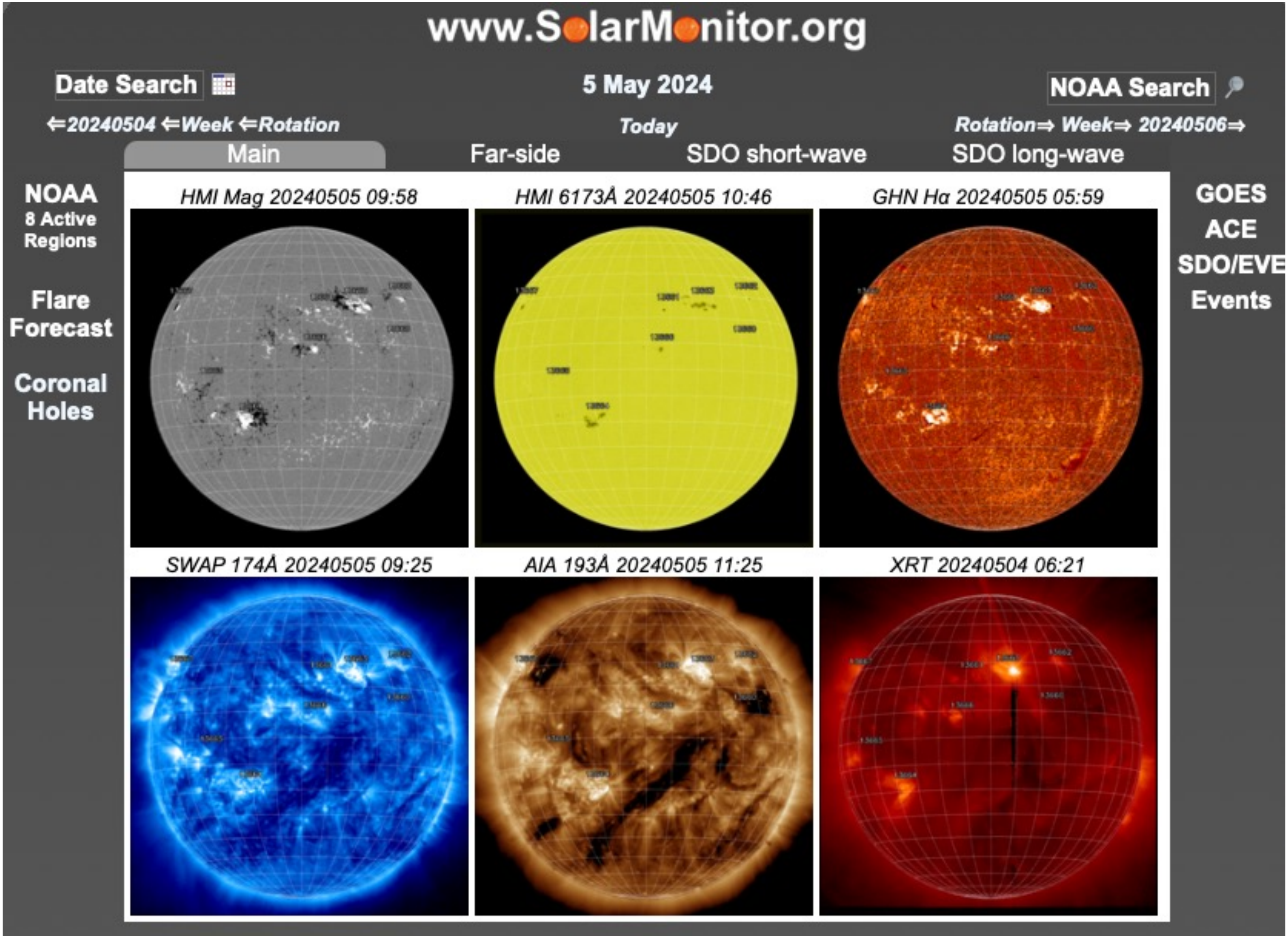
There is solar parameter space for axion discovery



E. Todarello, 2024

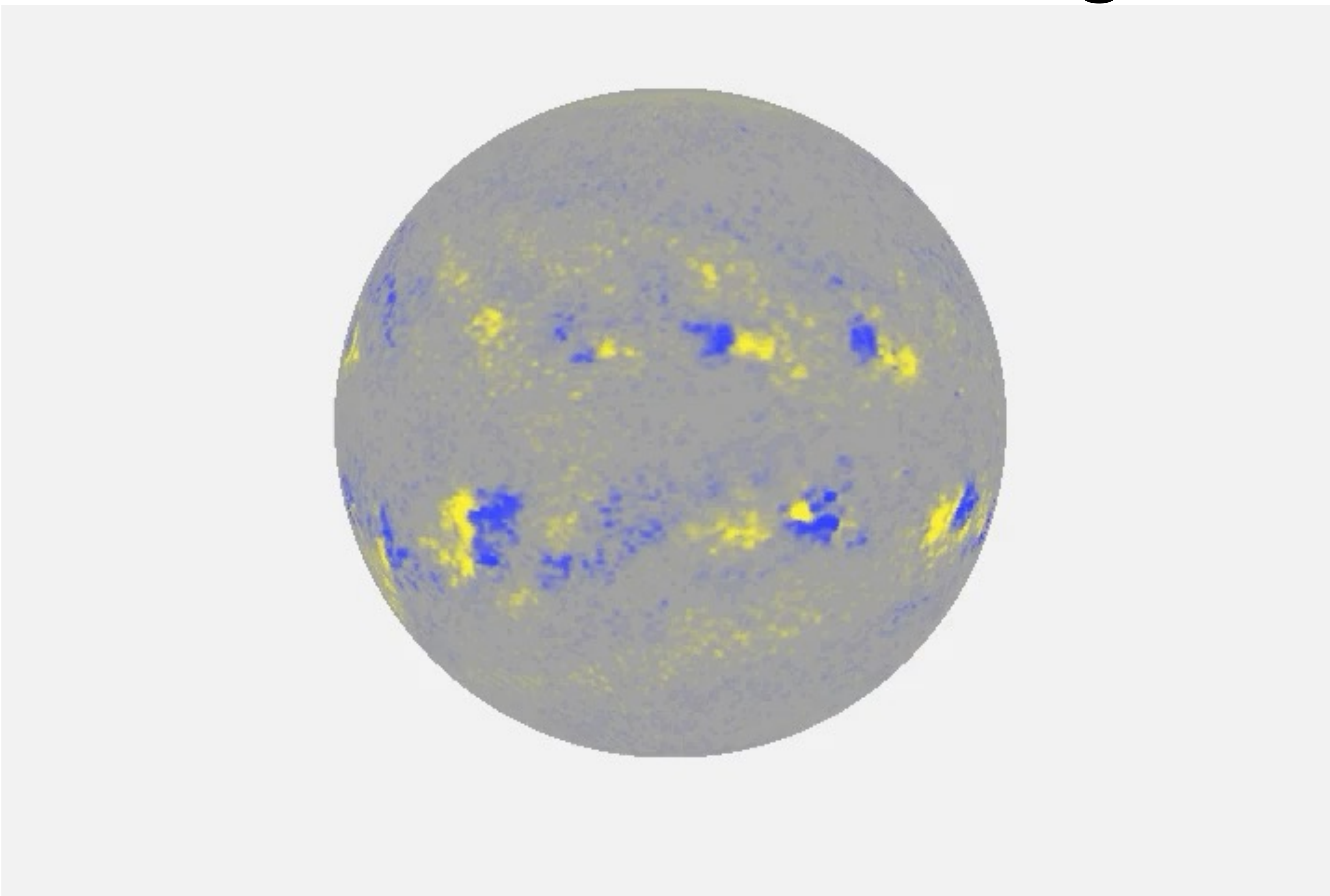
Sun-as-a-star astrophysics

- Of course we can observe the Sun without imaging it; we have 2-3 continua to study:
  - The time domain
  - Spectroscopy (polarization)
- My main involvement has been with
  - The “solar constant” (TSI; 1980s)
  - EVE spectroscopy (2010s to present)
  - GOES soft X-rays (1960s to present)
- If we discover anything, we can turn to the images to help understand it



www.SolarMonitor.org
Date Search
5 May 2024
NOAA Search
⇐20240504 ⇐Week ⇐Rotation
Today
Rotation⇒ Week⇒ 20240506⇒
Main
Far-side
SDO short-wave
SDO long-wave
NOAA
8 Active Regions
Flare Forecast
Coronal Holes
HMI Mag 20240505 09:58
HMI 6173Å 20240505 10:46
GHN Hα 20240505 05:59
SWAP 174Å 20240505 09:25
AIA 193Å 20240505 11:25
XRT 20240504 06:21
GOES
ACE
SDO/EVE
Events

What is a solar active region?



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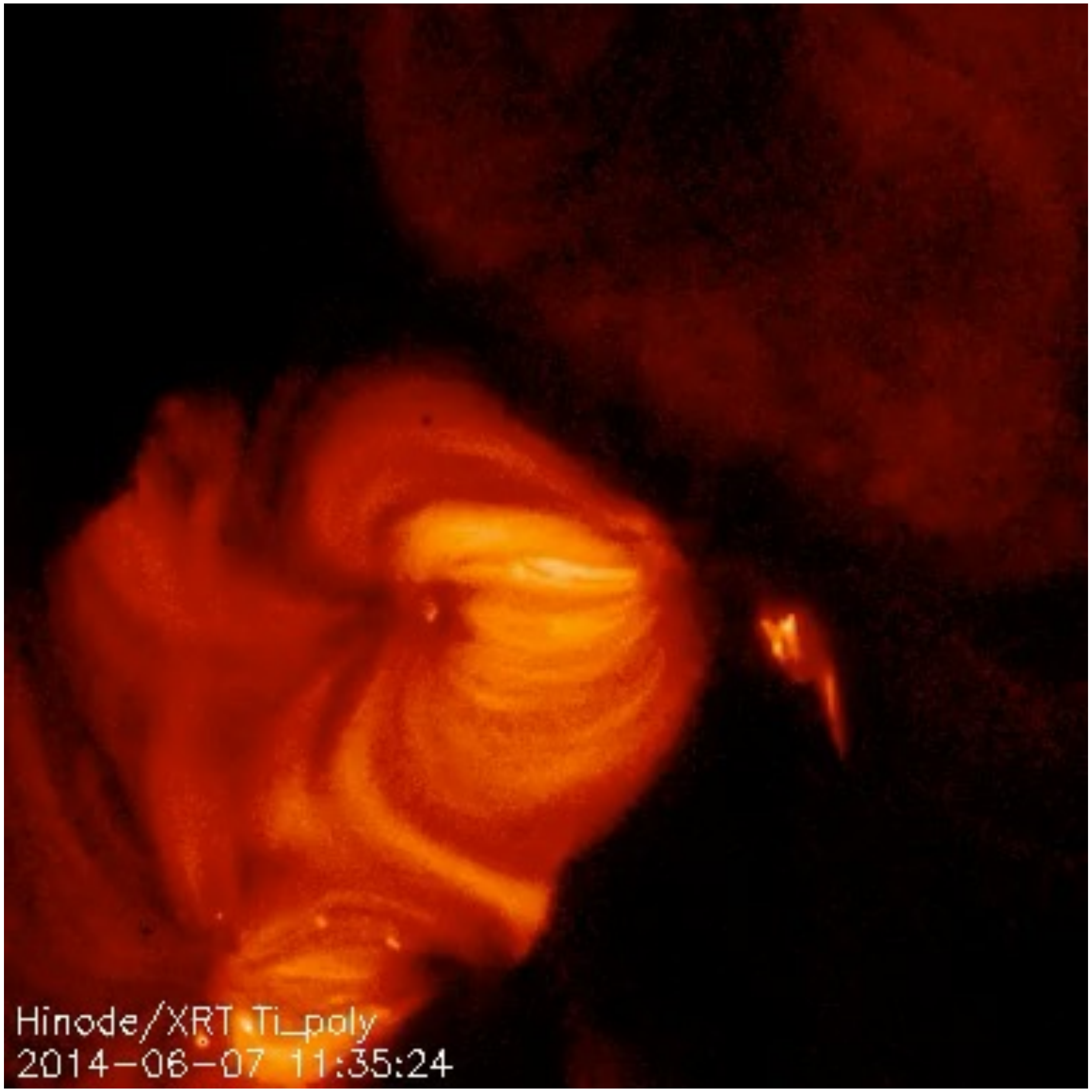
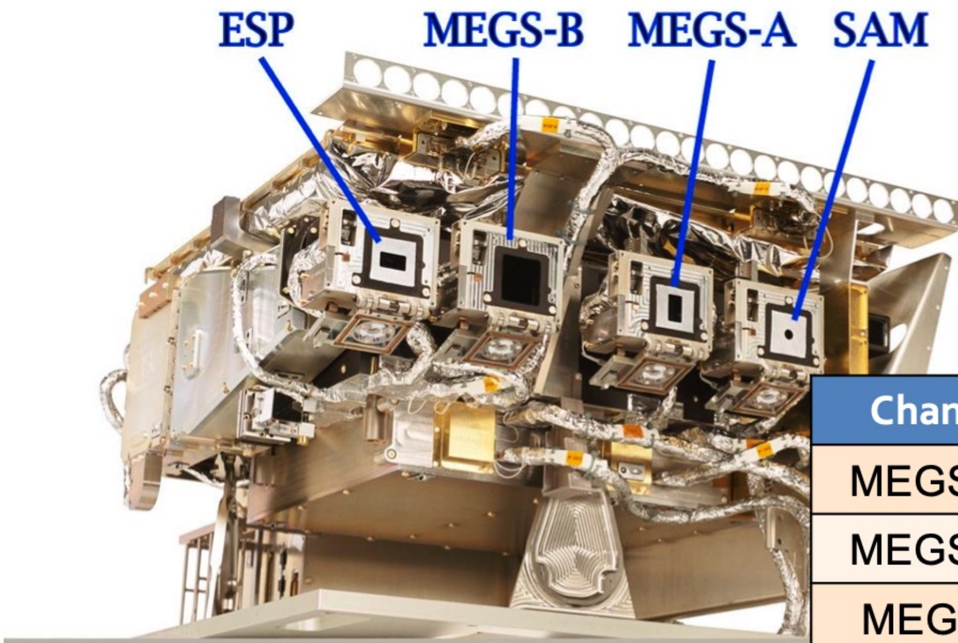
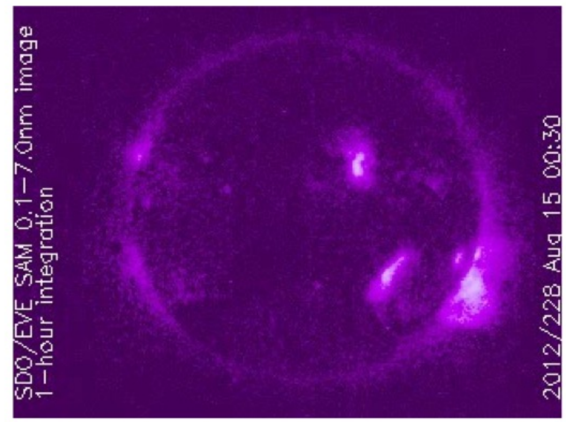


What is EVE?

LASP / USC / MIT-LL / SI built solar EUV irradiance instruments for the EVE suite with significant improvements in spectral resolution (0.1 nm) and time coverage (24/7, 0.25 s -10 s cadence)





SAM is X-ray Imager

Channel	λ Range	Δλ	Δt
MEGS-A1	6-18 nm	0.1 nm	10 sec
MEGS-A2	18-37 nm	0.1 nm	10 sec
MEGS-B	37-106 nm	0.1 nm	10 sec
MEGS-SAM	0.1-7 nm	(1 nm)	10 sec
MEGS-P	121.6 nm	1 nm	0.25 s
ESP	0.1-38 nm	4 nm	0.25 s

EVE Status - Woods

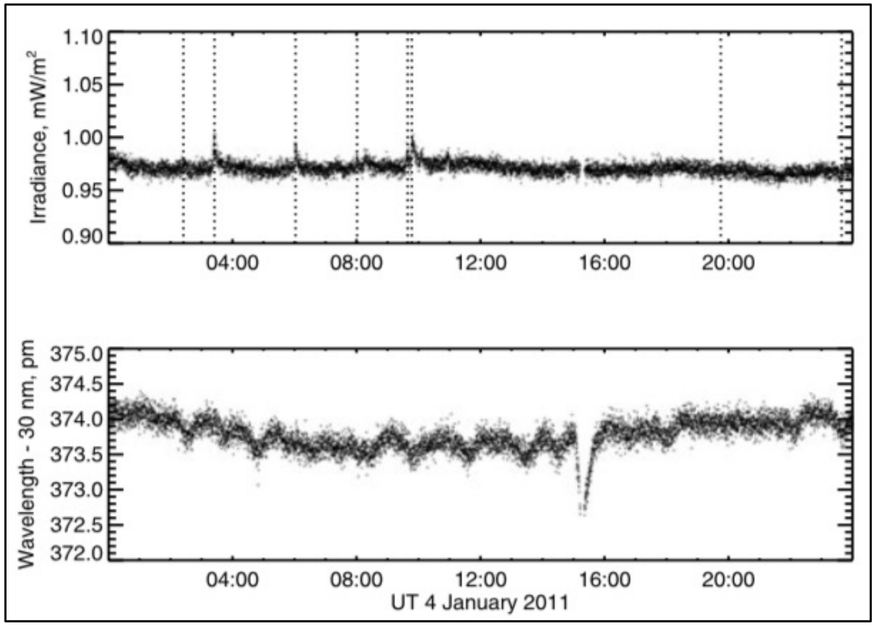
T. Woods 2023

EVE solar history

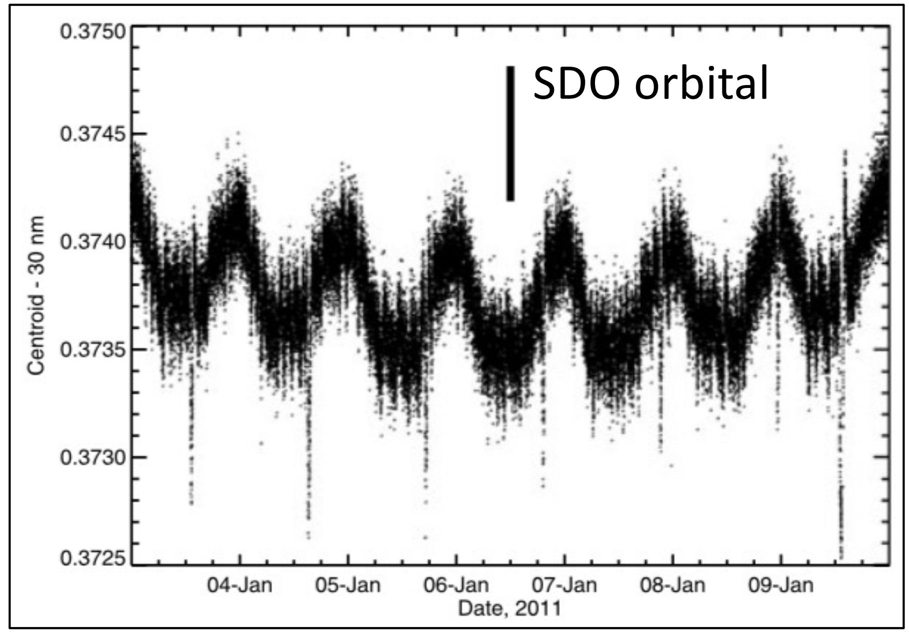
EVE was built to study the terrestrial impacts of solar EUV radiation. But this radiation is of course interesting to solar physicists.

Hudson et al. 2011SoPh..273...69H	***EVE can do Doppler***
Chamberlin 2016SoPh..291.1665C	***MEGS-A astigmatism***
Brown 2016A&A...596A..51B	***Lyman series (MEGS-B)***
Cheng et al. 2019ApJ...875...93C	***MEGS-B Flare Doppler***
Xu et al. 2022ApJ...931...76X	***Ejecta in 3D***
Hudson et al. 2022MNRAS.515L..84H	***Hot prograde flows!***
Fitzpatrick-Hudson 2023SoPh..298....2F	***MEGS-A confirmation***
Otsu-Asai 2024ApJ...964...75O	***EUV-Hα Ejecta***

EVE Doppler capability



One day

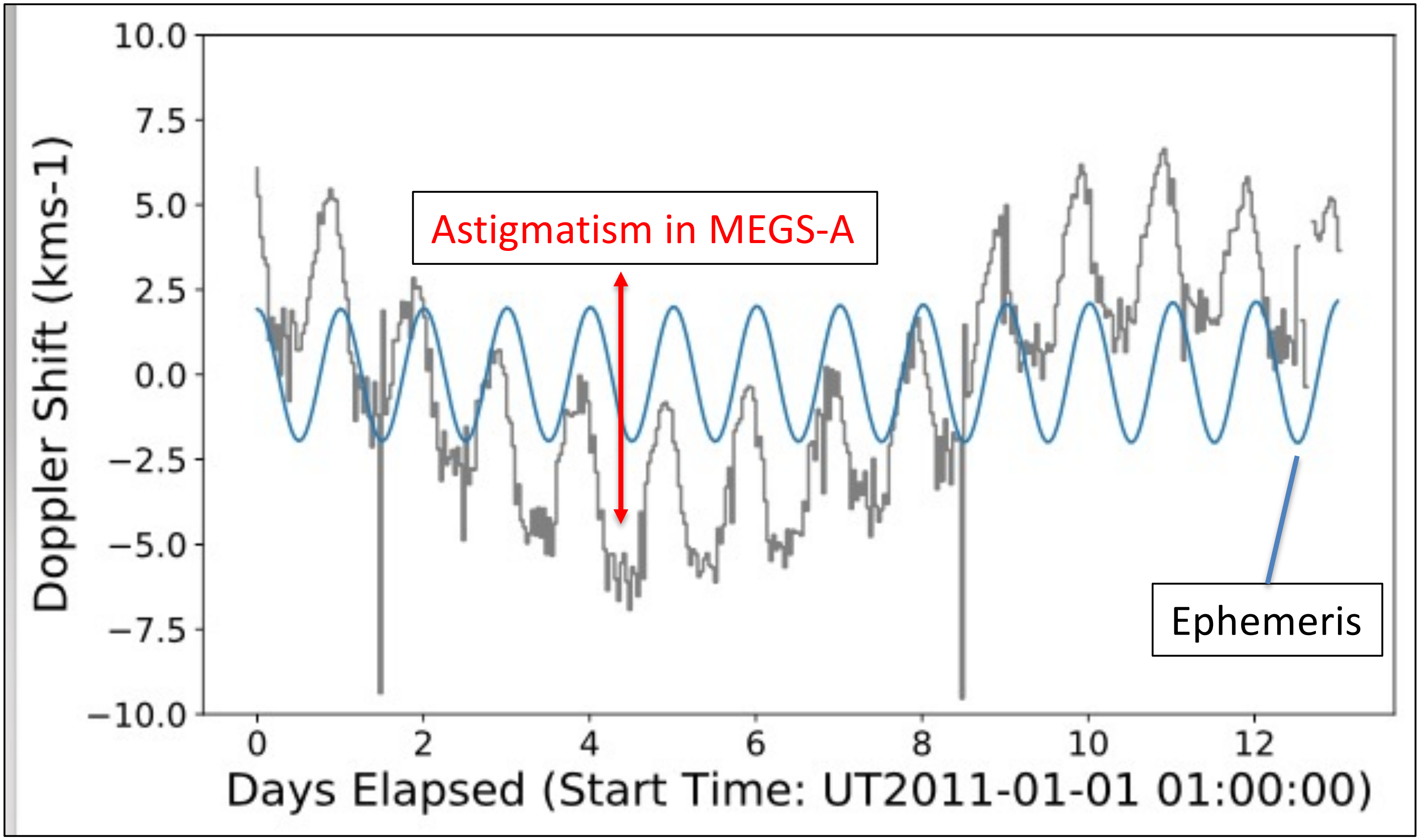


One week

As reported in Hudson et al. (2011)

- A diurnal effect due to spacecraft orbit, plus
- Thermal perturbation at 16:00 UT calibrations
- A few-day “swoop”, unidentified…
- Persistent wiggles at longer periods than the p-modes (5 min), still unidentified…

Doppler 30.4 nm hourly

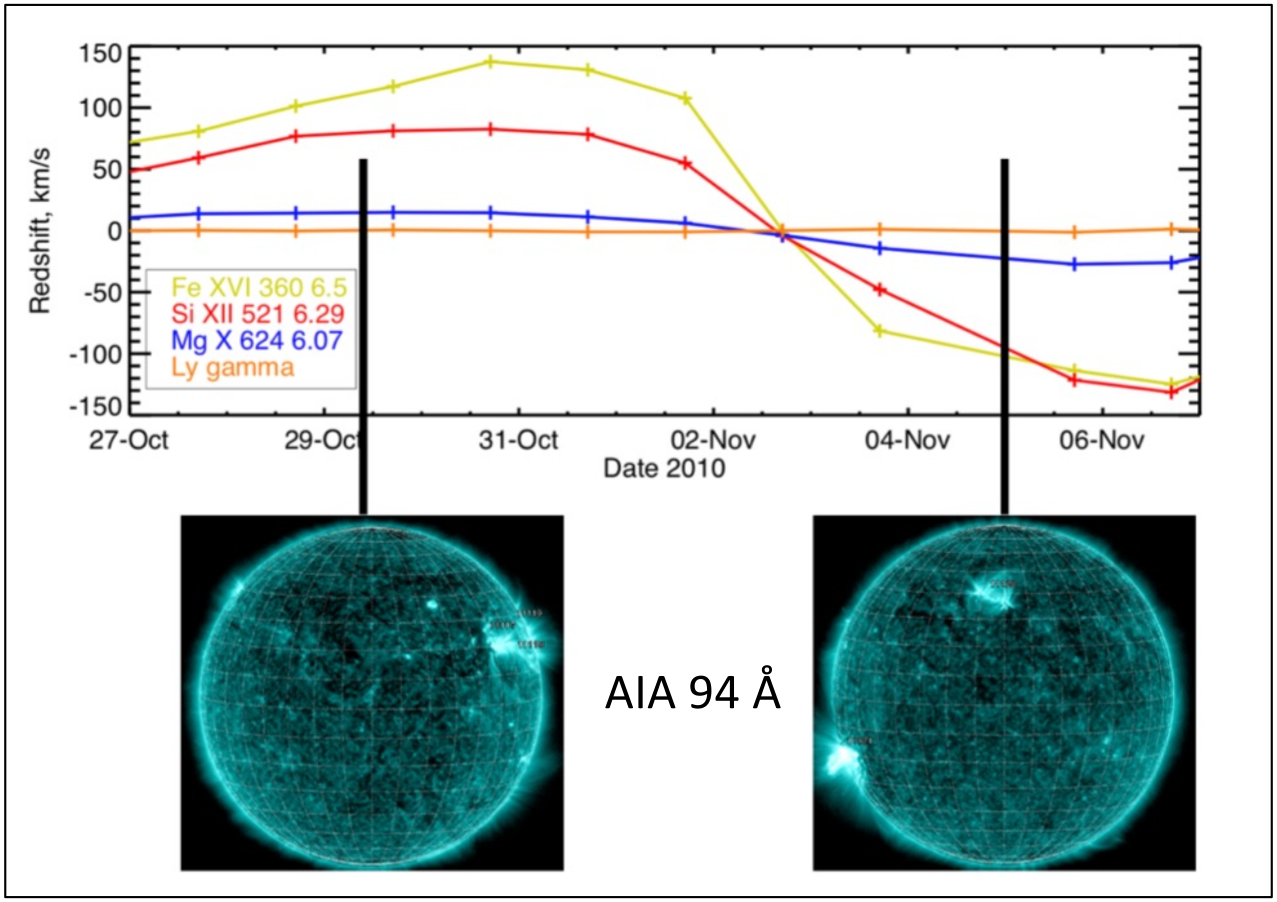


The EVE MEGS-A spectrometer is mildly astigmatic (Chamberlin, 2016): wavelengths depend slightly on image structure

EVE's spectroscopic advantages

- High throughput; excellent SNR
- Excellent stability (geosynchronous orbit)
- Stable wavelength scale
- High time resolution (10 s sampling)
- MEGS-B accurately stigmatic
- Sun-as-a-star, no imaging

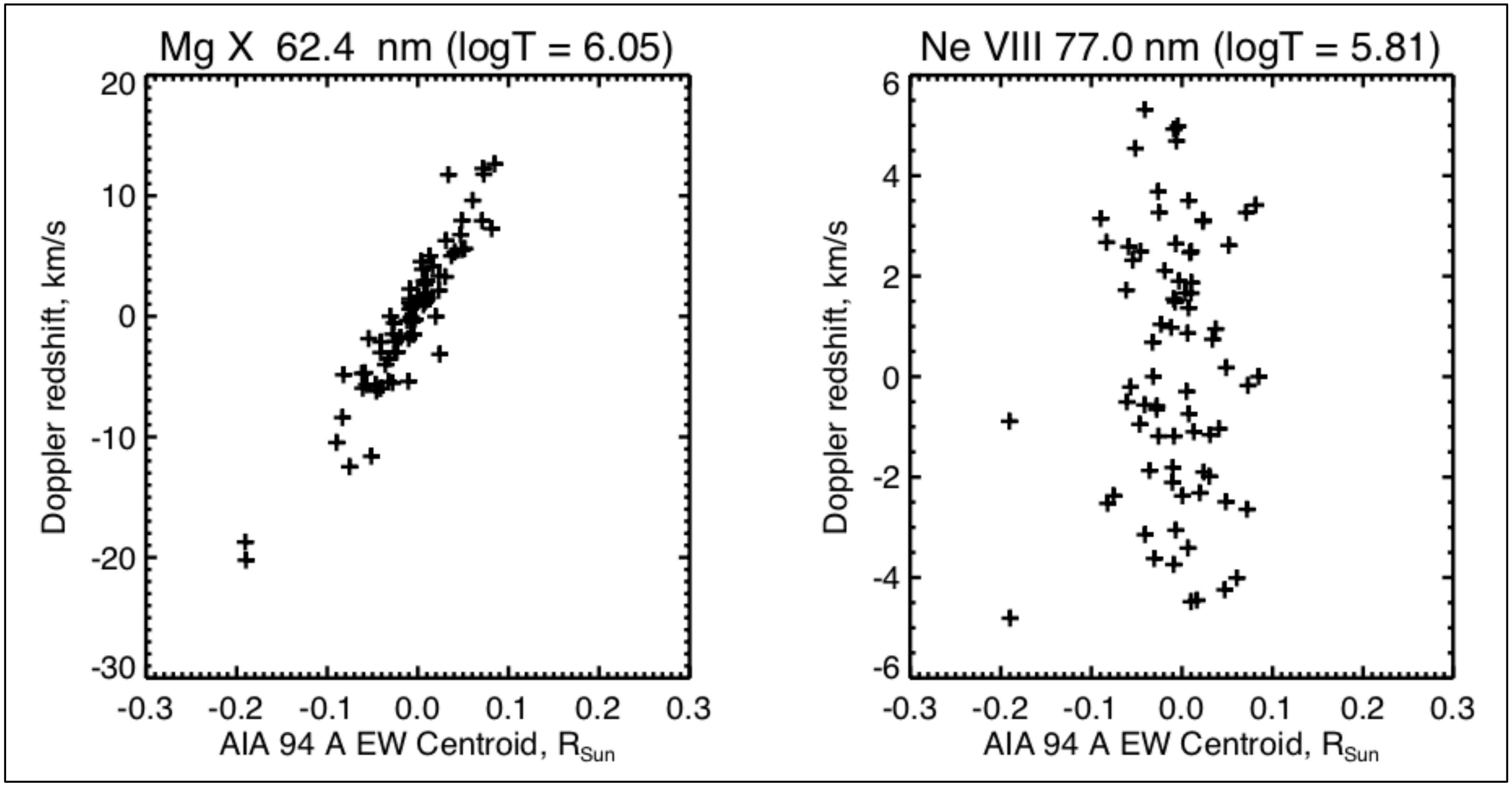
Fast prograde coronal flows



Redshifts from W limb region and blueshifts from E: this means ***prograde flow;*** *It is strongly localized.* This is a MEGS-B result, not compromised by the MEGS-A astigmatism or line blends

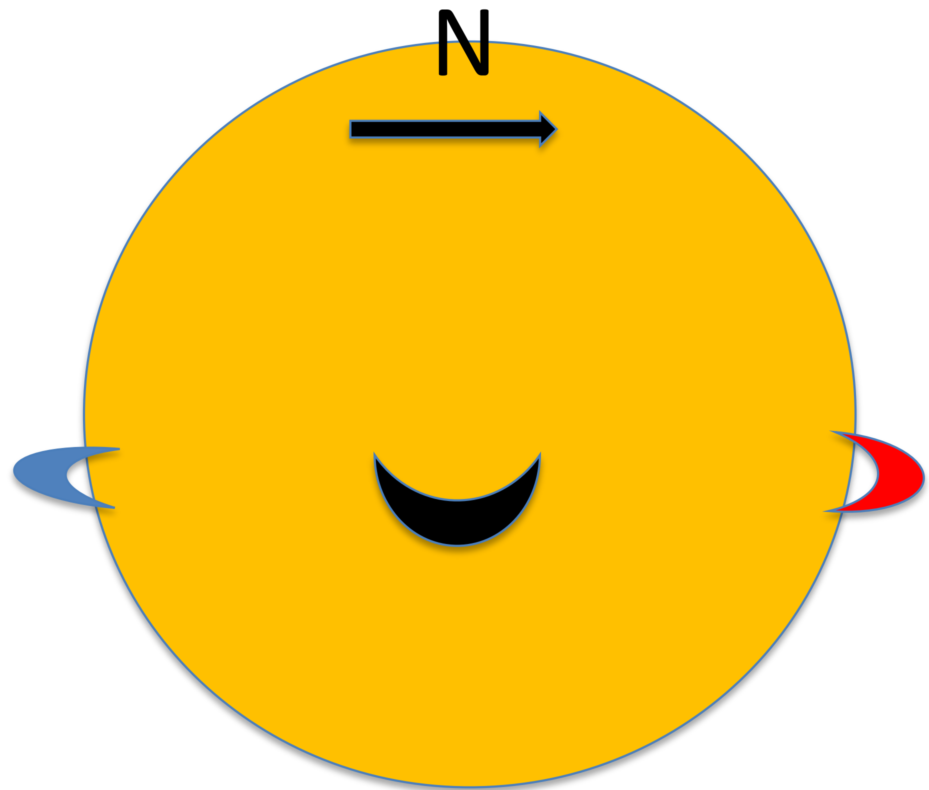
Doppler/image correlations

$$\bar{X} = \frac{\sum X \times I(x,y)}{\sum I(x,y)}$$

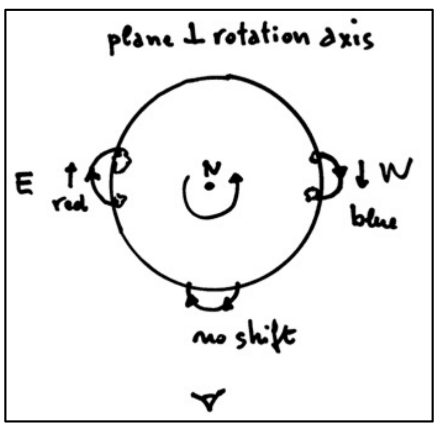


Simple image correlations confirm the prograde flows and show that they depend sensitively on the temperature of formation

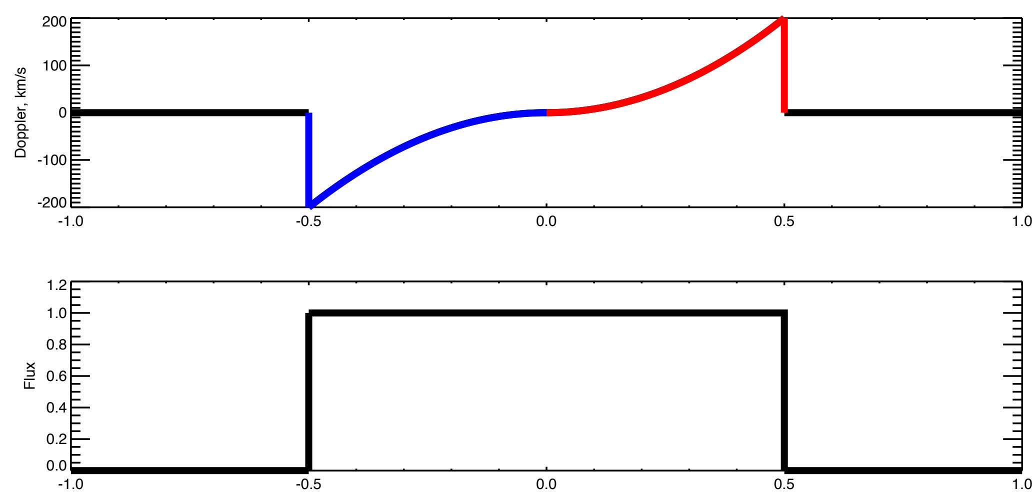
Simplest model: prograde flow in hot lines only



E. Antonucci suggestion of time-series analysis

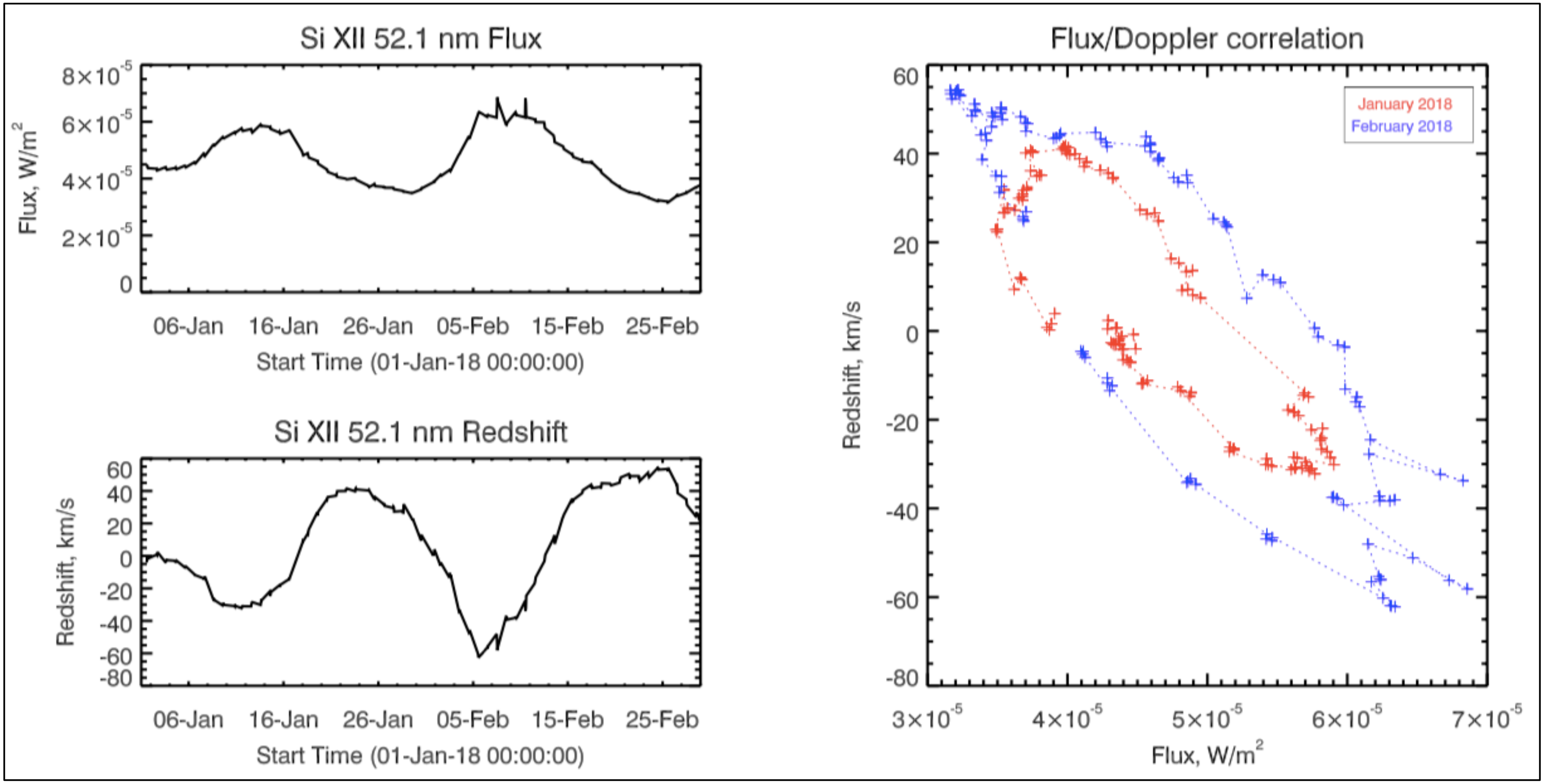


View from S pole



One active region, one full rotation:
the "impulse response" function

Time-series data from early 2018



The correlation between line flux and Doppler signal shows the expected 90^o phase shift

Morphological history of the active-region corona

- The coronal green line (Fe XIV): “*coronal condensations”,* high temperatures
- X-ray imaging (rockets, *Skylab*): magnetic ``loops’’
- X-ray time domain (*Yohkoh/SXT):* some microflares but also stable hot loops at T ~ 2 MK
- **Doppler radiometry (EVE): Fast prograde flows in hot loops, this result**

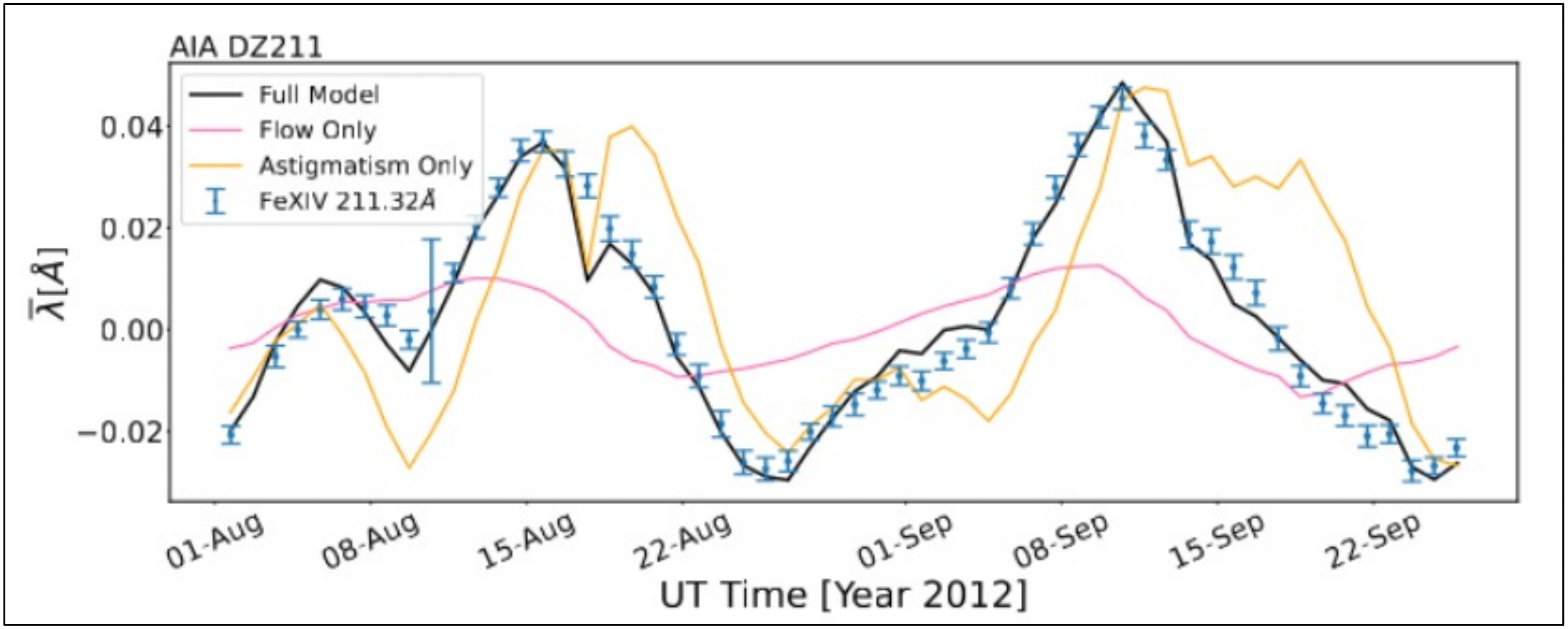
Role of Honours Lab

Modeling astigmatism and Doppler flows simultaneously

$$f(X_{ij}, Y_{ij}) = \underbrace{C_0 Y_{ij} + C_1 X_{ij}^2}_{\text{Astigmatism}} + \underbrace{C_2 F(X_{ij})}_{\text{Flow}} + C_3 t$$

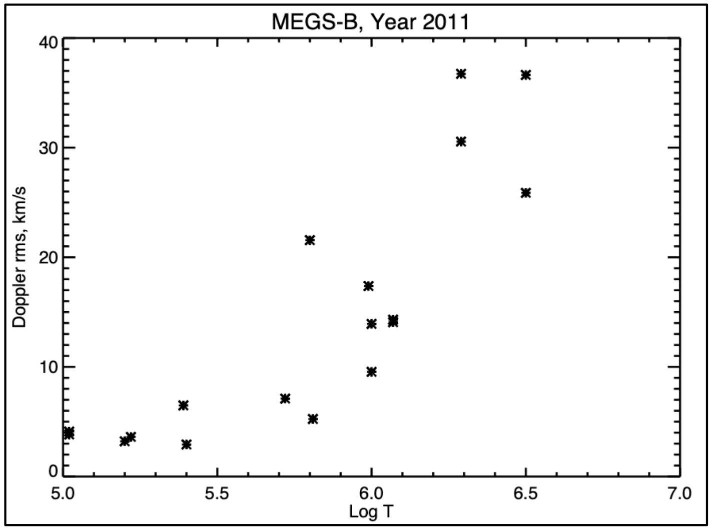
- Astigmatism (C_0, C_1) follows the known form of this effect (Chamberlin) but with adjustable parameters
- Doppler flows follow our super-simple model (C_2)
- Instrument degradation (C_3) is prescribed (using Chamberlin's fits over the EVE history)

Results for Fe XIV 211 A

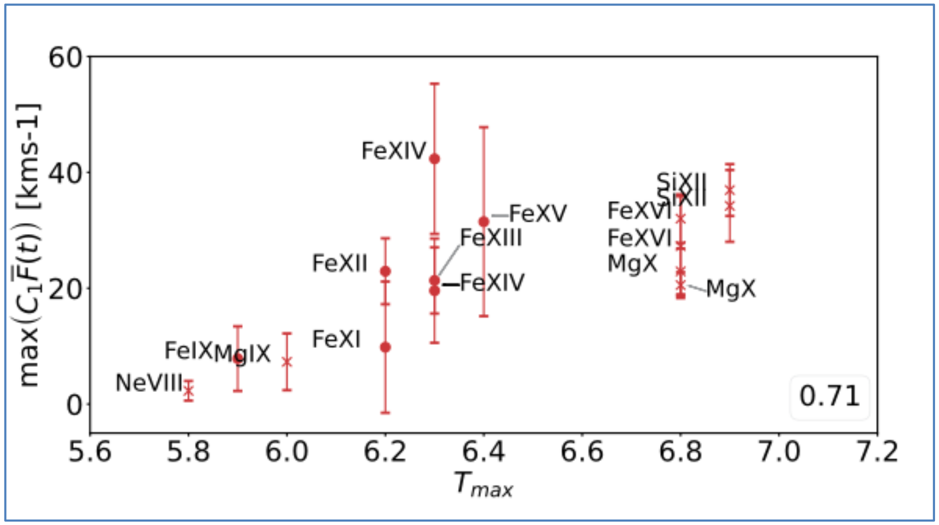


Generally, the MEGS-A results also show the flows and clarify the temperature dependence (Fitzpatrick & Hudson 2023).

Temperature dependence



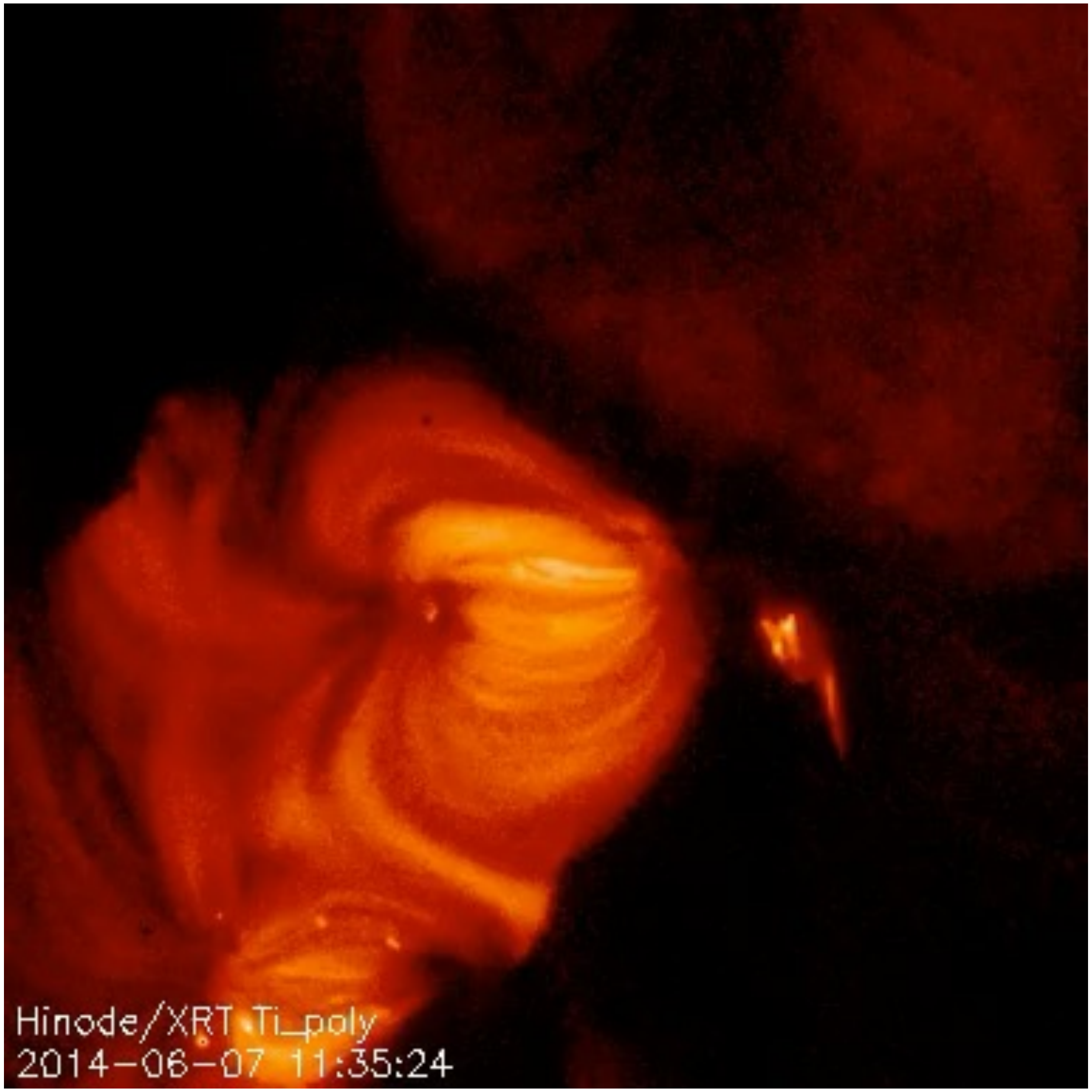
Doppler RMS vs. log(T_{max}):
(MEGS-B; Hudson *et al.)*



Doppler amplitude vs. log(T_{max}):
(MEGS-A; Fitzpatrick-Hudson)

Independent spectrometers analyzed independently confirm the T dependence, but it has puzzling scatter.

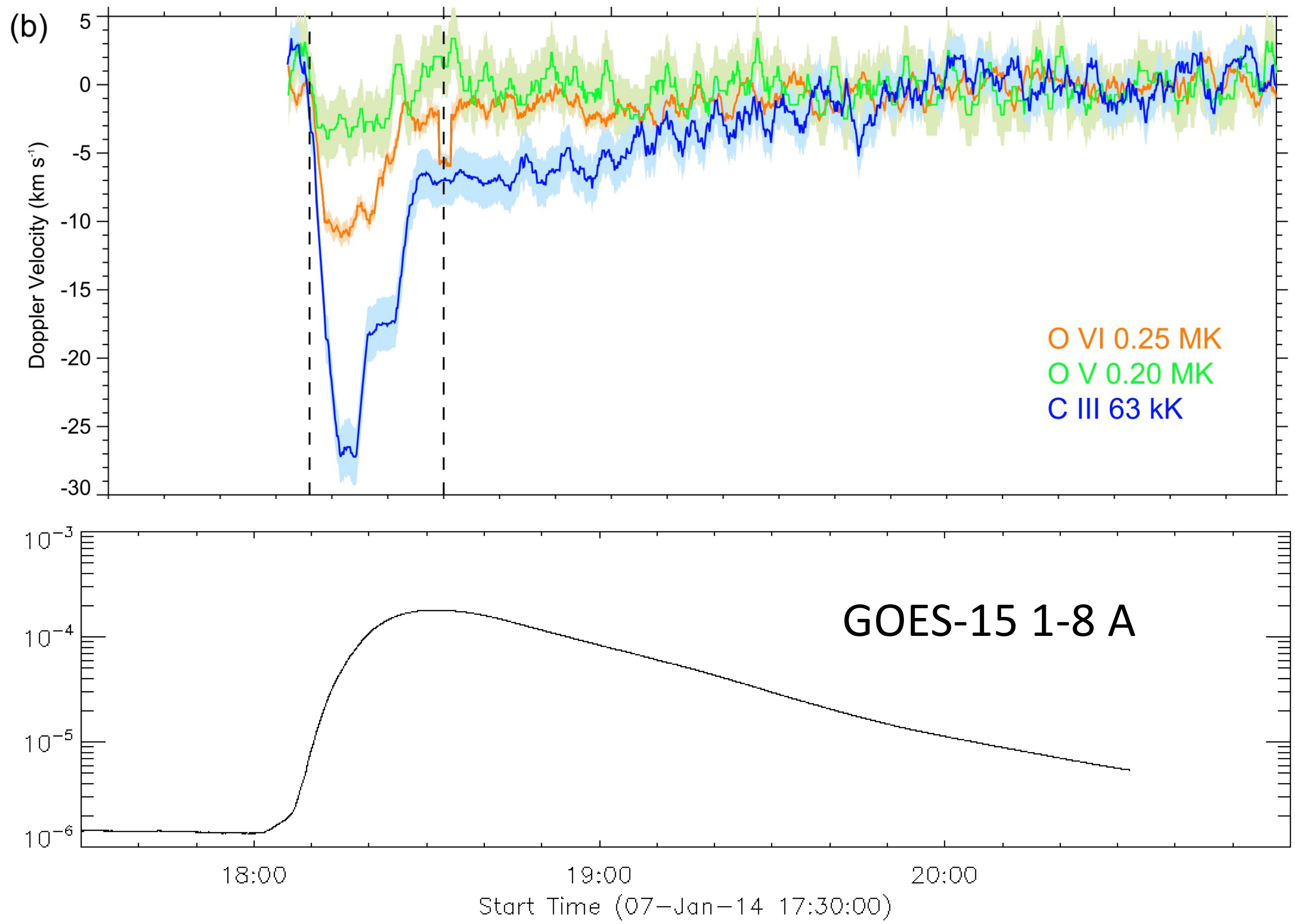
What is a solar active region?



Conclusions

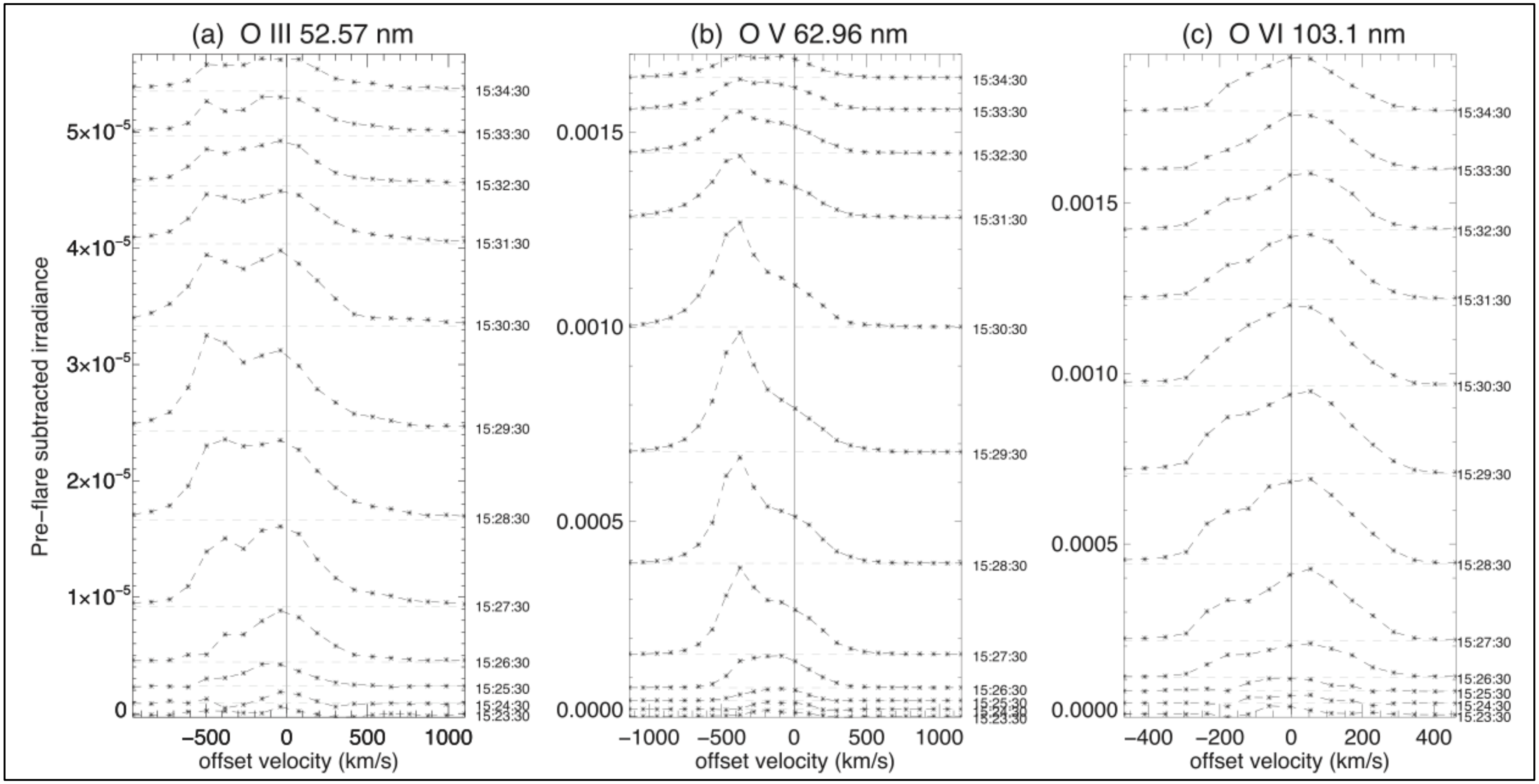
- The EVE Sun-as-a-Star stable EUV spectroscopy has made an unexpected discovery*:* hot lines show prograde flows comparable to the sound speed.
- Theory had not predicted this; no modeling had anticipated it. Nor has there been imaging confirmation!
- We currently have no explanation. The observed flow speeds are lower limits because of projection, dilution, and confusion. The prograde sense matches that expected from leader/follower sunspot asymmetry.

Transition-region flows



SOL2014-01-07 MEGS-B (Cheng et al. 2019):
this is the impulsive-phase evaporation, but
Note the anomalous C III behavior.

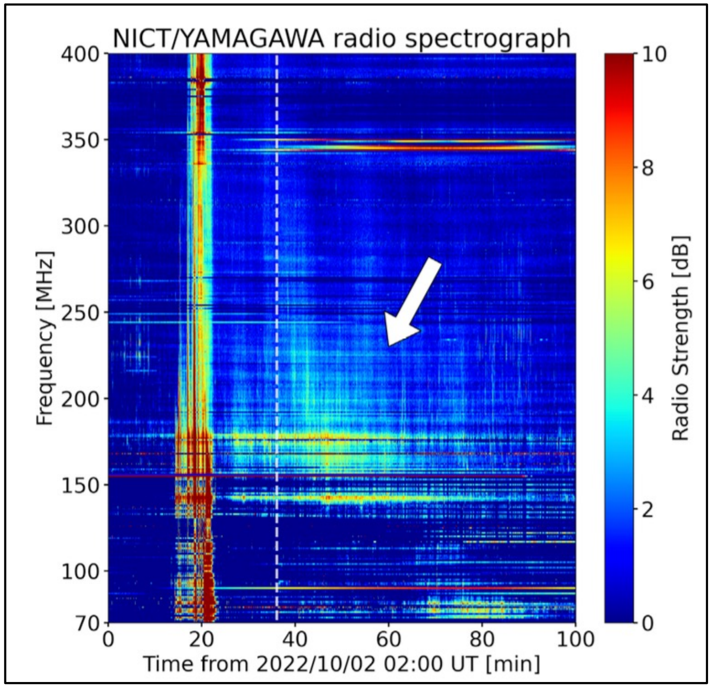
Ejecta seen in 3D

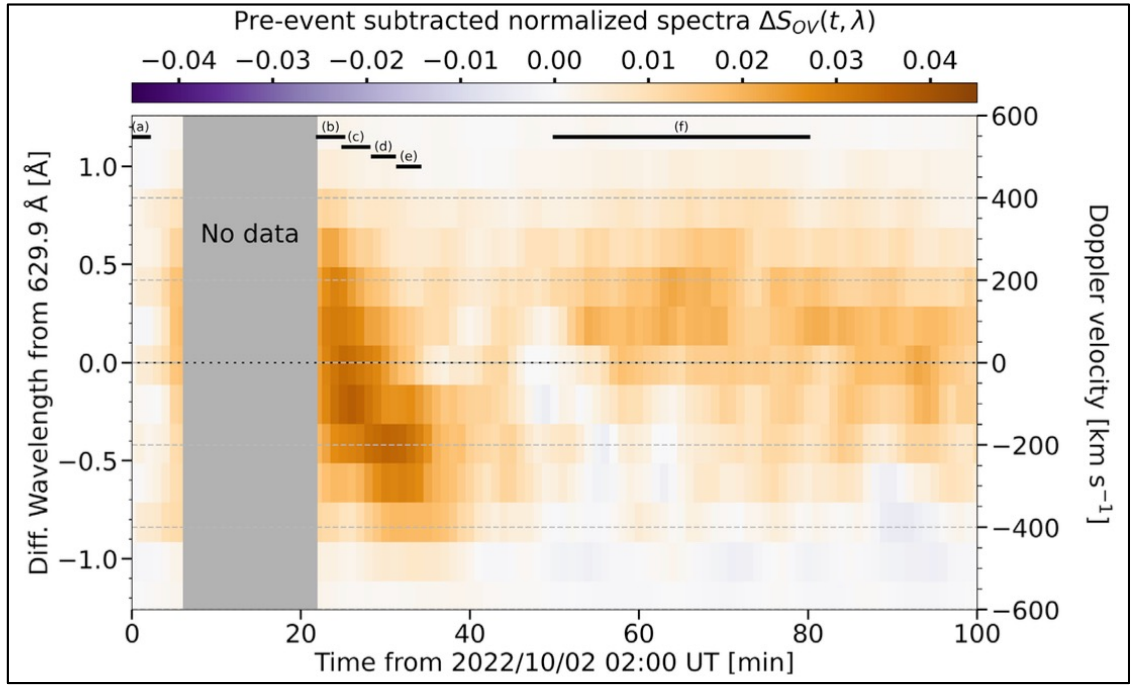


SOL2021-10-28 (Xu et al. 2022): Fast ejecta can be
een in AIA images and EVE Doppler simultaneously

Note the stellar implications of this solar observation

Ejecta in EVE O V and in Hα





Otsu & Asai 2024: Type II burst and EUV spectrogram (O V).
Again, note the stellar implications of this solar observation.

More conclusions

- Sun-as-a-Star stable EUV spectroscopy with high throughput can make many contributions
  - Dimming (CMEs)
  - Flare flows
  - The remarkable hot prograde AR flows
  - 3D reconstructions of ejecta
- All of these should be available for stars with suitable instruments (mainly, large aperture)