D. SEATON, J. M. HUGHES CU/CIRES & NOAA NCEI
N. ALZATE NASA'S GODDARD SPACE FLIGHT CENTER
A. CASPI SOUTHWEST RESEARCH INSTITUTE
D. BERGHMANS, E. D'HUYS, M. WEST ROYAL OBSERVATORY OF BELGIUM
L. GOLUB HARVARD-SMITHSONIAN CENTER FOR ASTROPHYSICS
N. HURLBURT LOCKHEED-MARTIN
J. MASON CU/LASP
L. RACHMELER, S. SAVAGE NASA'S MARSHALL SPACE FLIGHT CENTER
S. TADIKONDA SSAI

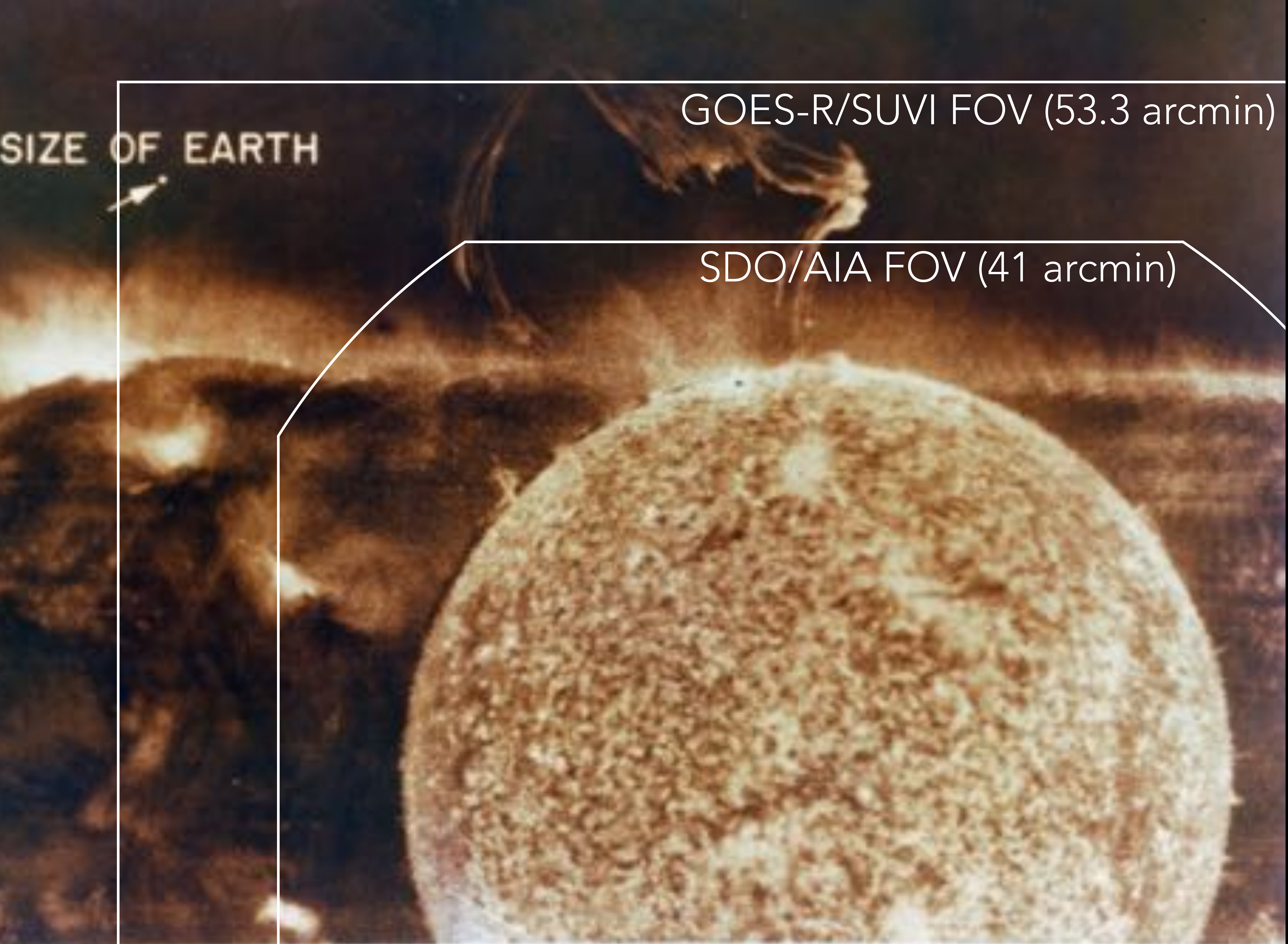
THE PRESENT & FUTURE OF EUV OBSERVATIONS OF THE CORONA ON LARGE SCALES

L5 CONSORTIUM MEETING, STANFORD UNIVERSITY
OCTOBER 3 2019

Slide captions appear at the end of this document.


The Middle Corona?

PROLOGUE: WHY STUDY THE MIDDLE CORONA IN EUV?



Skylab Extreme Ultraviolet Spectroheliograph

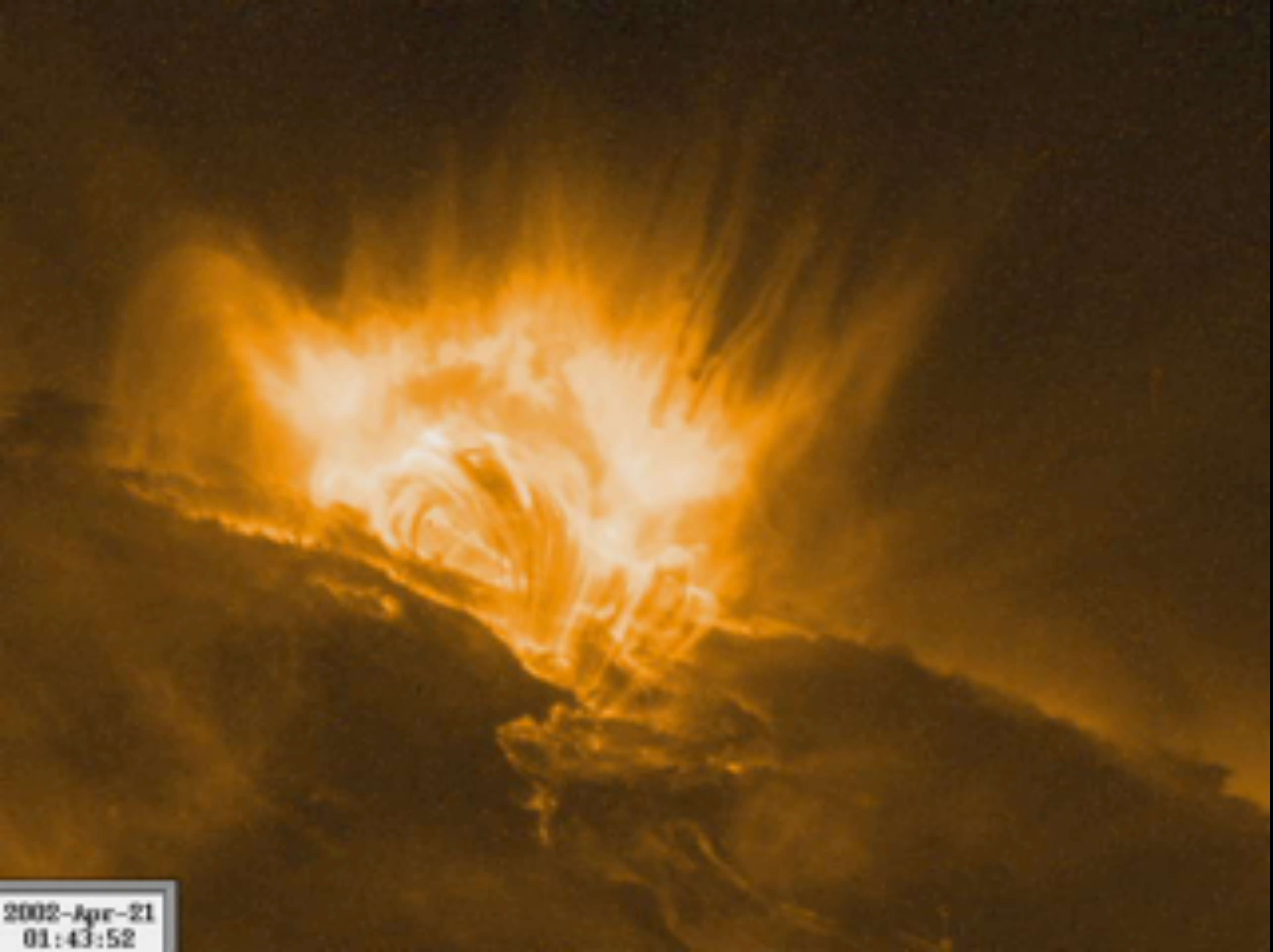
~150–650 Å

Nominal FOV
57 arcmin

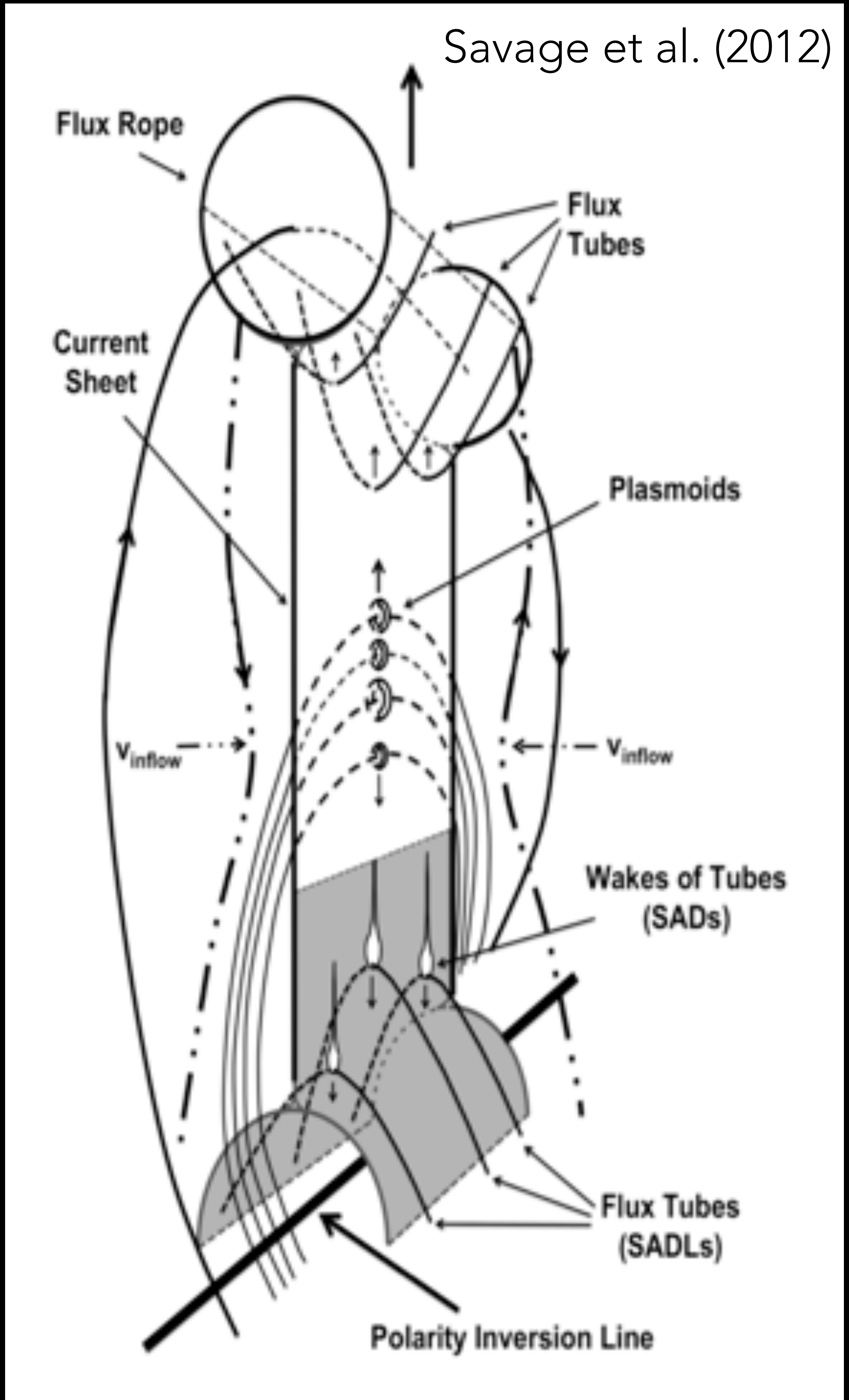
Max observable height above limb with offpoint
36 arcmin

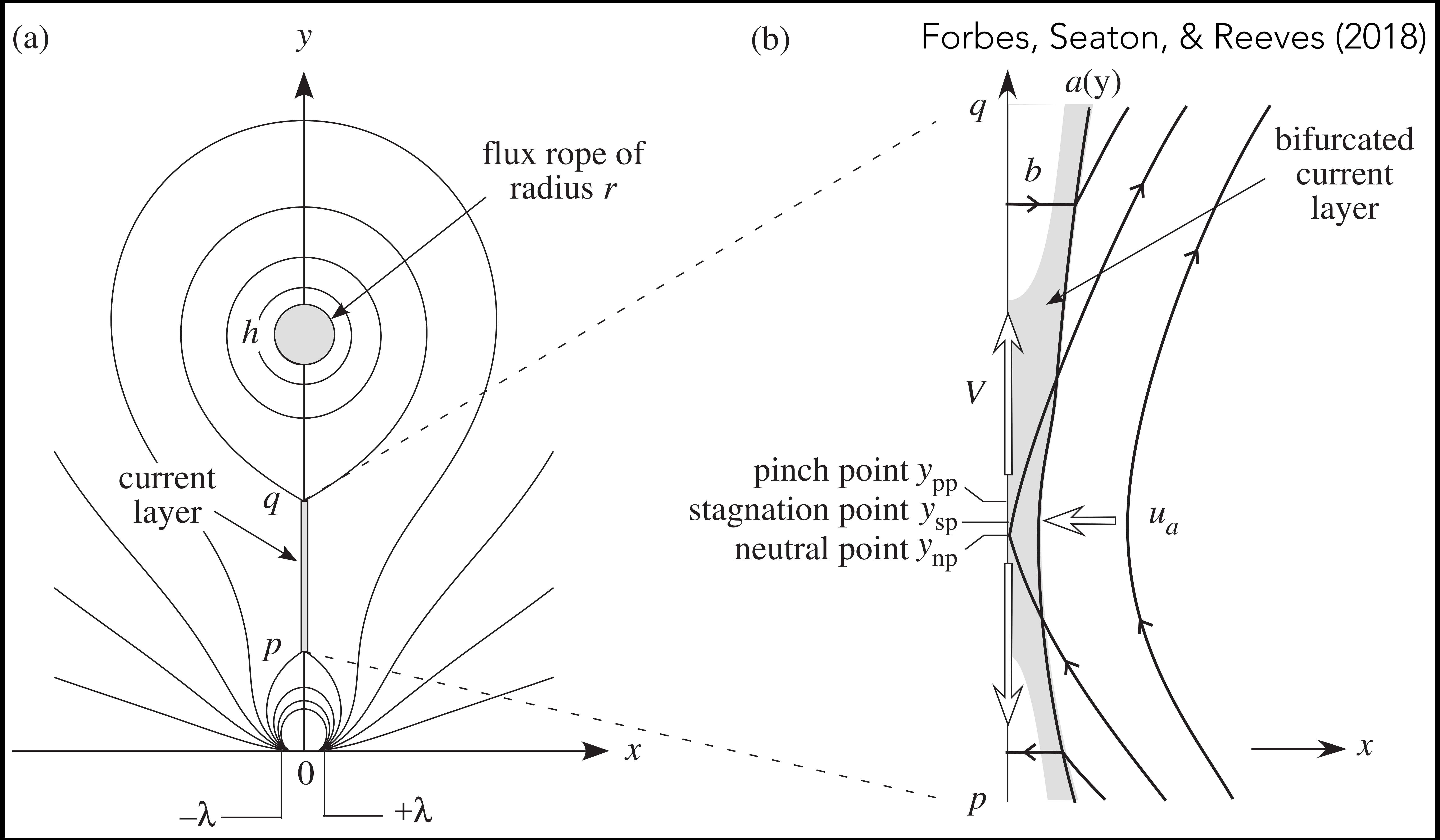
May 1973–
Feb 1974

TRACE



TRACE 195 Å
21 April 2002



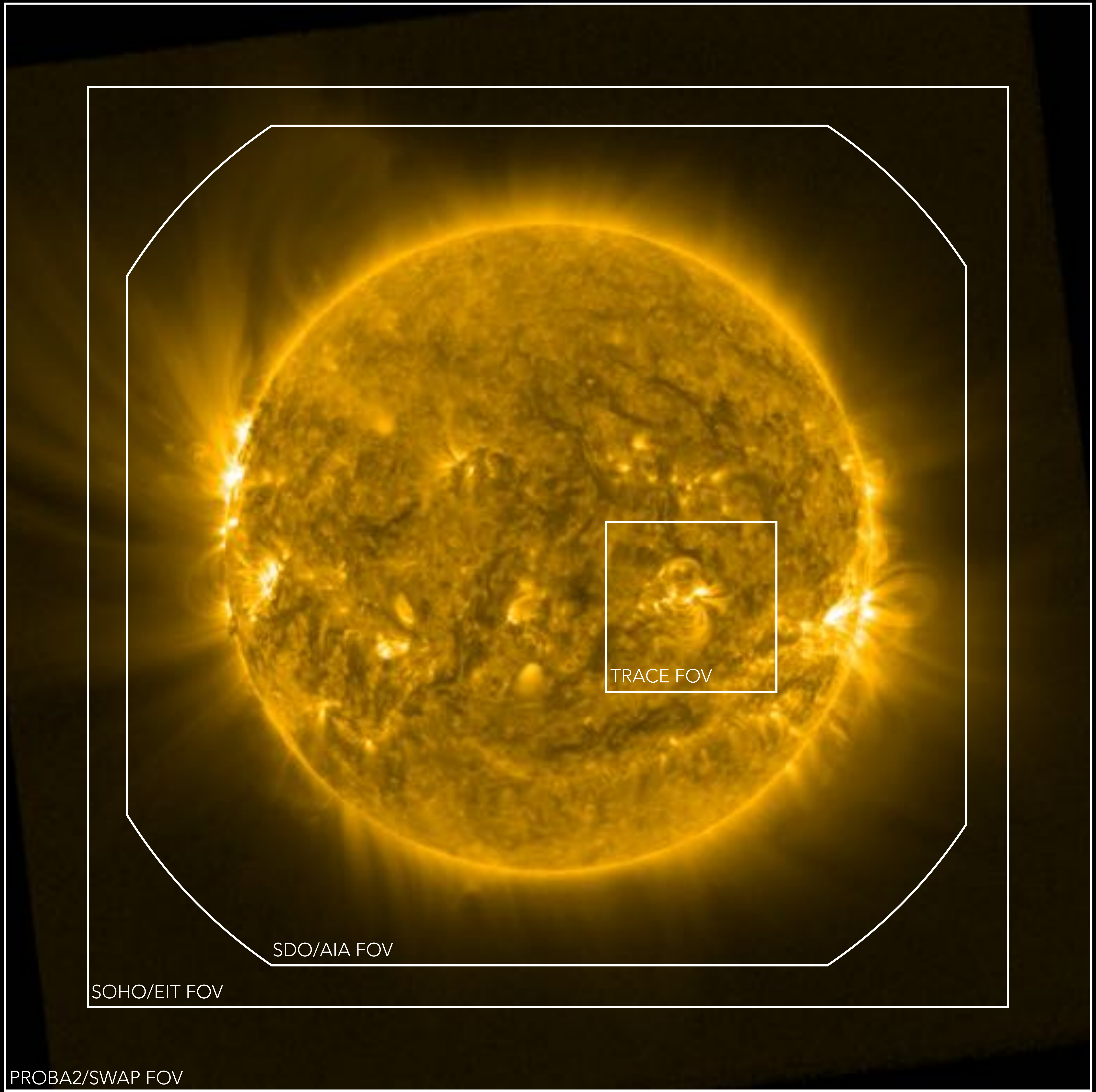


Inflows seen by TRACE represent the bottom of the current layer where reconnection happens.


SDO AIA 131 Å
2014-Feb-25 02:05
Seaton et al. (2017)

SOHO/LASCO C2
SDO/AIA 131 Å
Likely magnetic reconnection region
Current sheet described in Seaton et al. (2017)

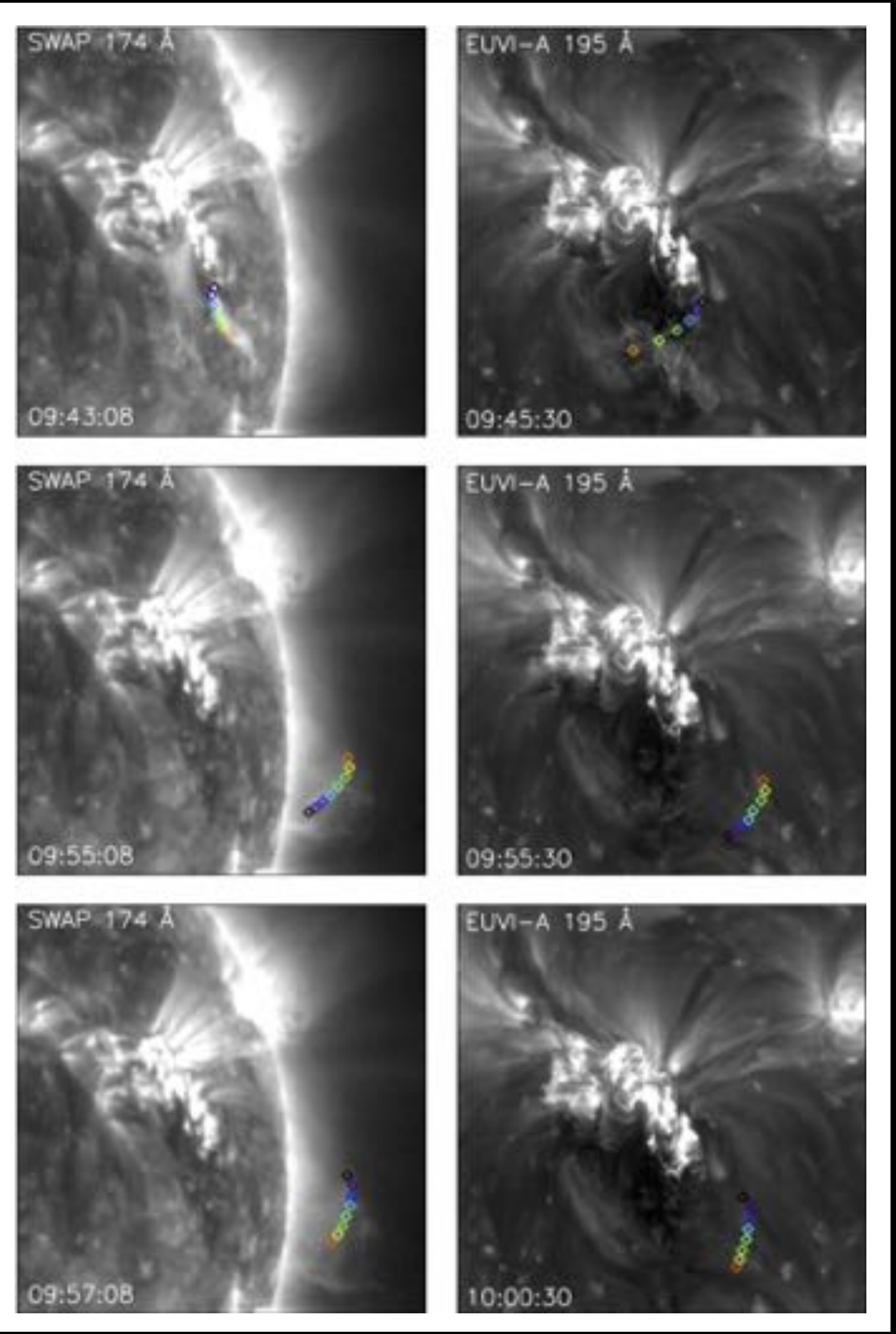
THE PRESENT: PROBA2/SWAP & GOES-R/SUVI

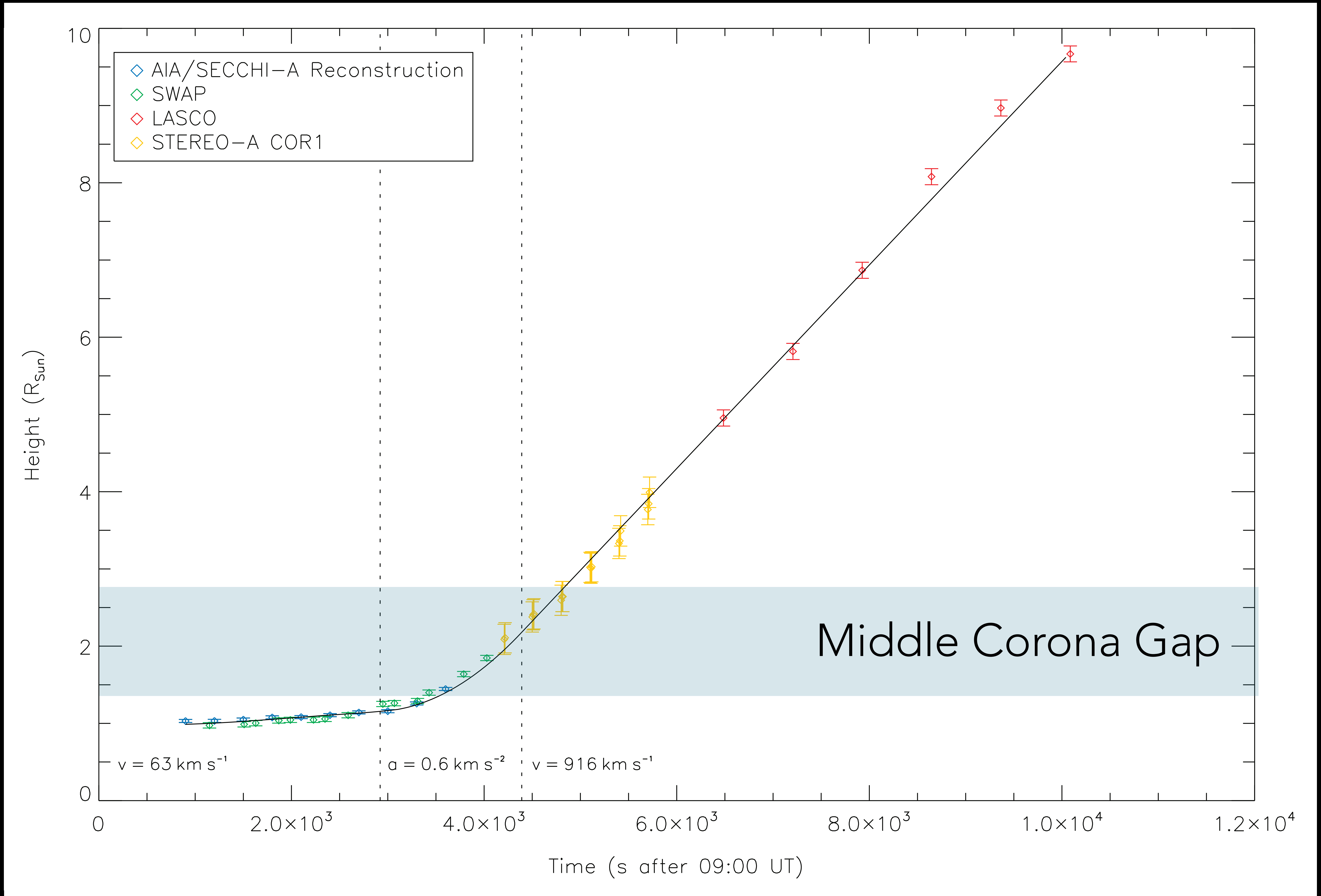


PROBA2/SWAP

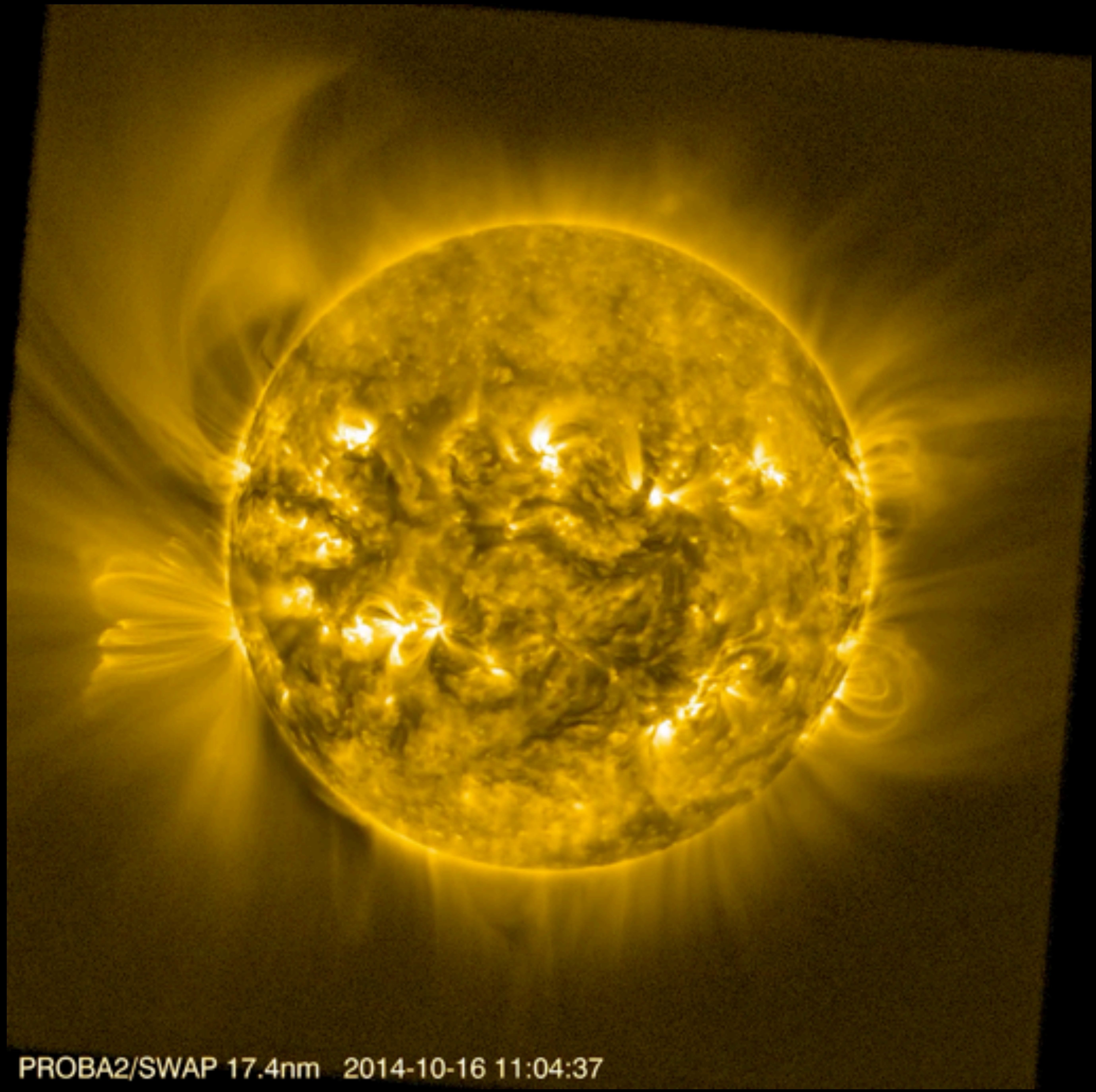

PROBA2/SWAP 2010 April 13
Mierla et al. (2013)

2010 August 10 Eruption

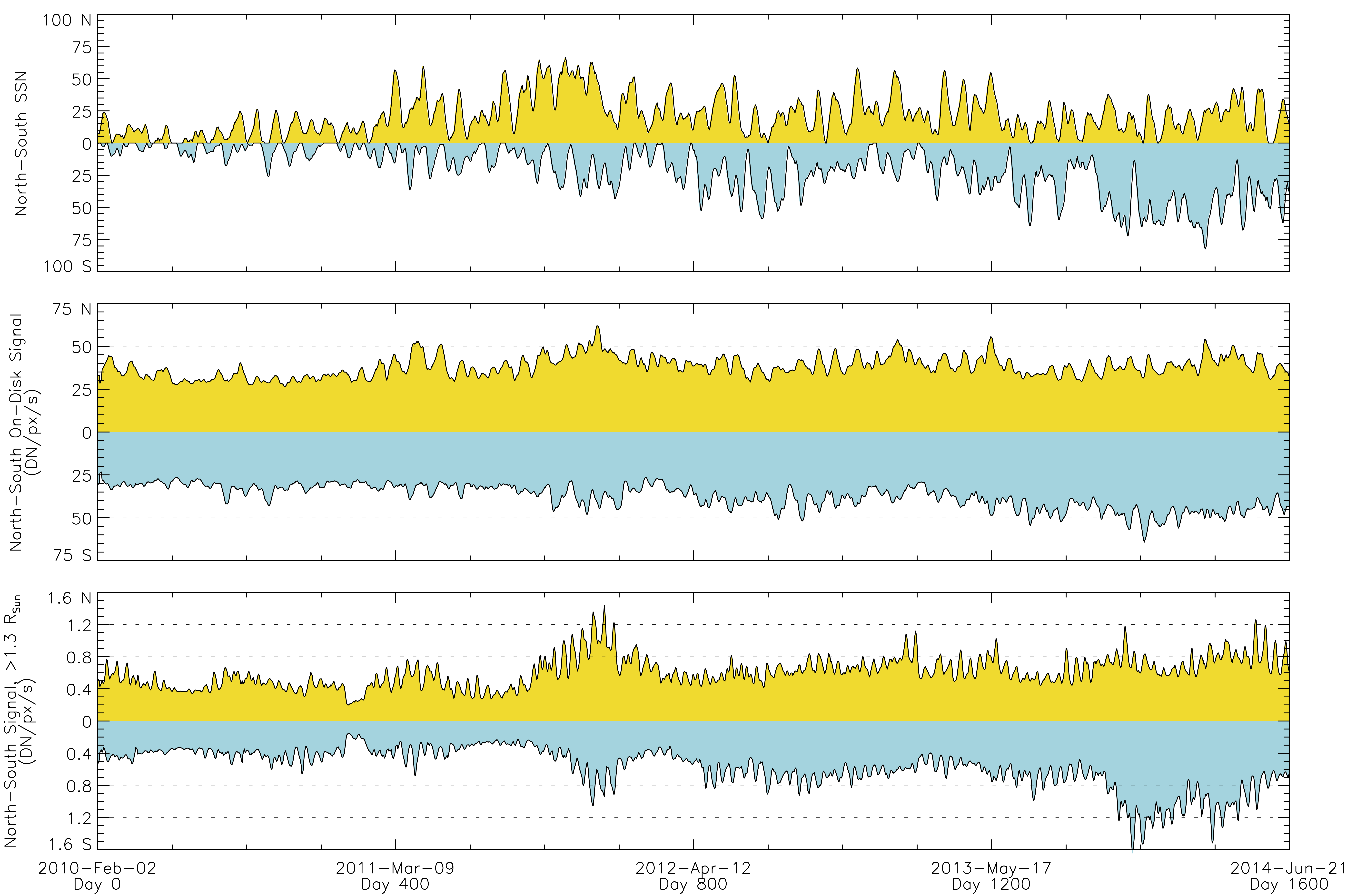




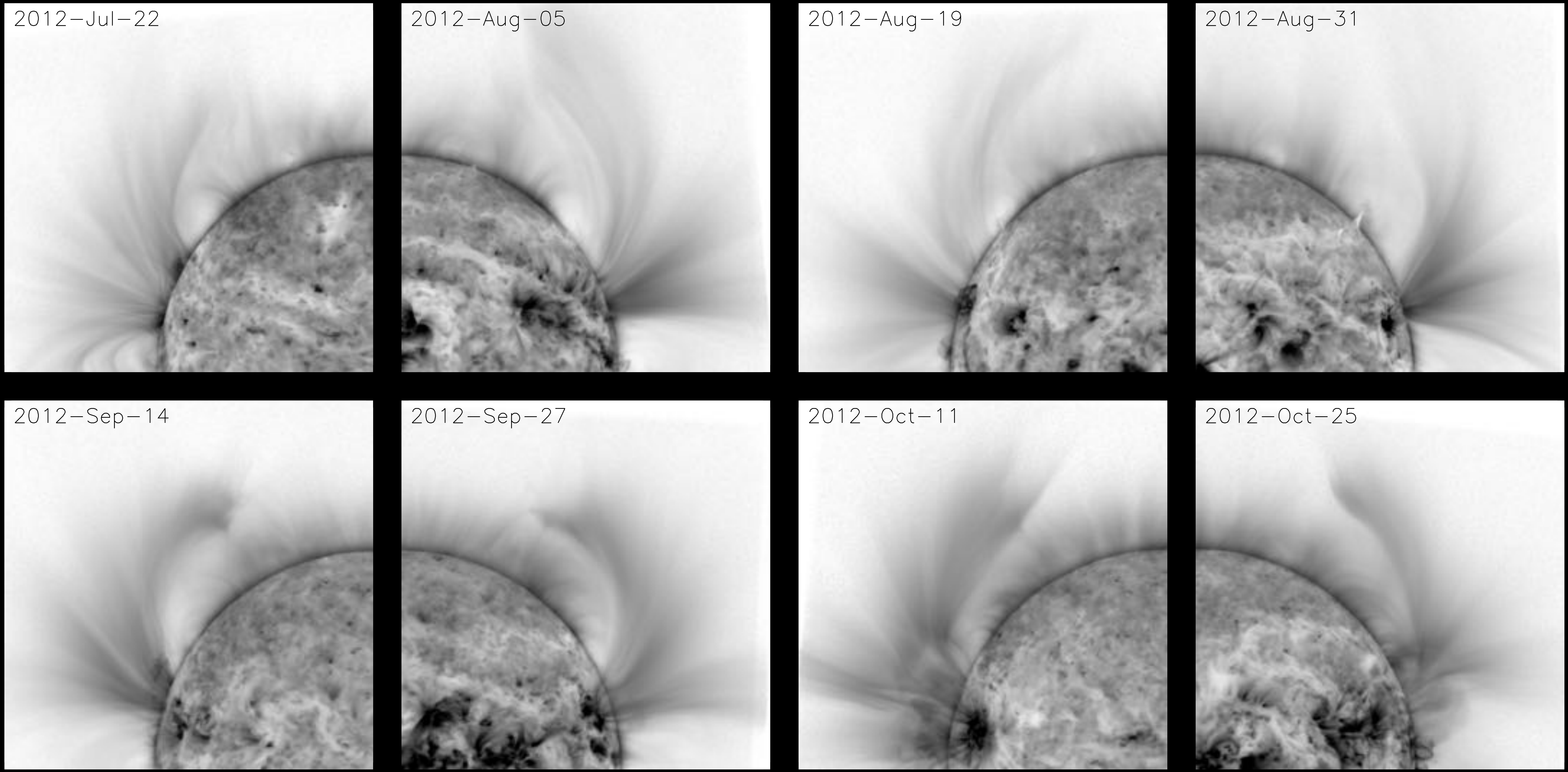
D'Huys et al. (2017)



Devising new ways to clean images, boost signal-to-noise, and filter images to improve contrast allowed us to see structures nobody knew was there.

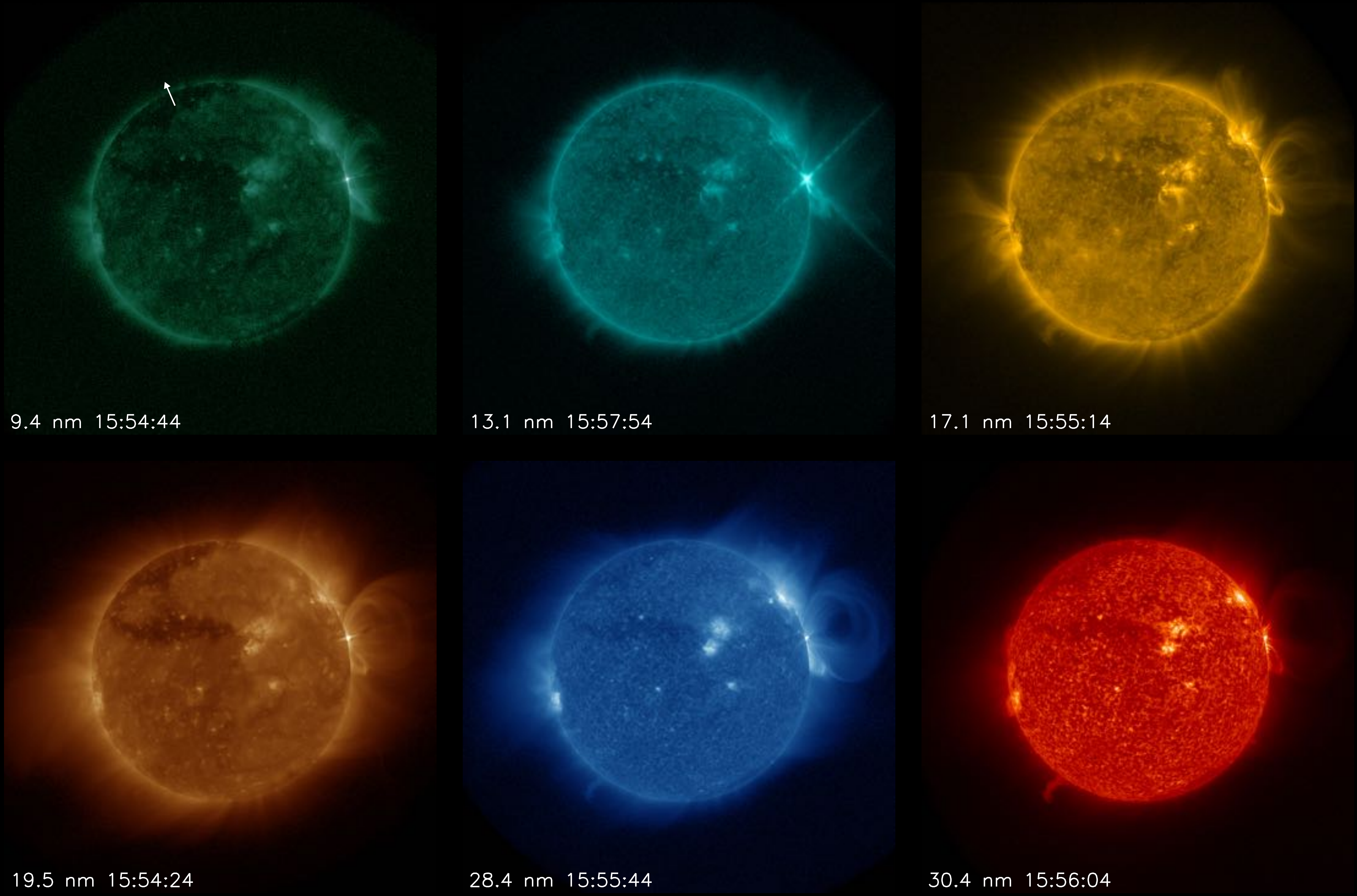


Seaton et al. (2013)



Seaton et al. (2013)

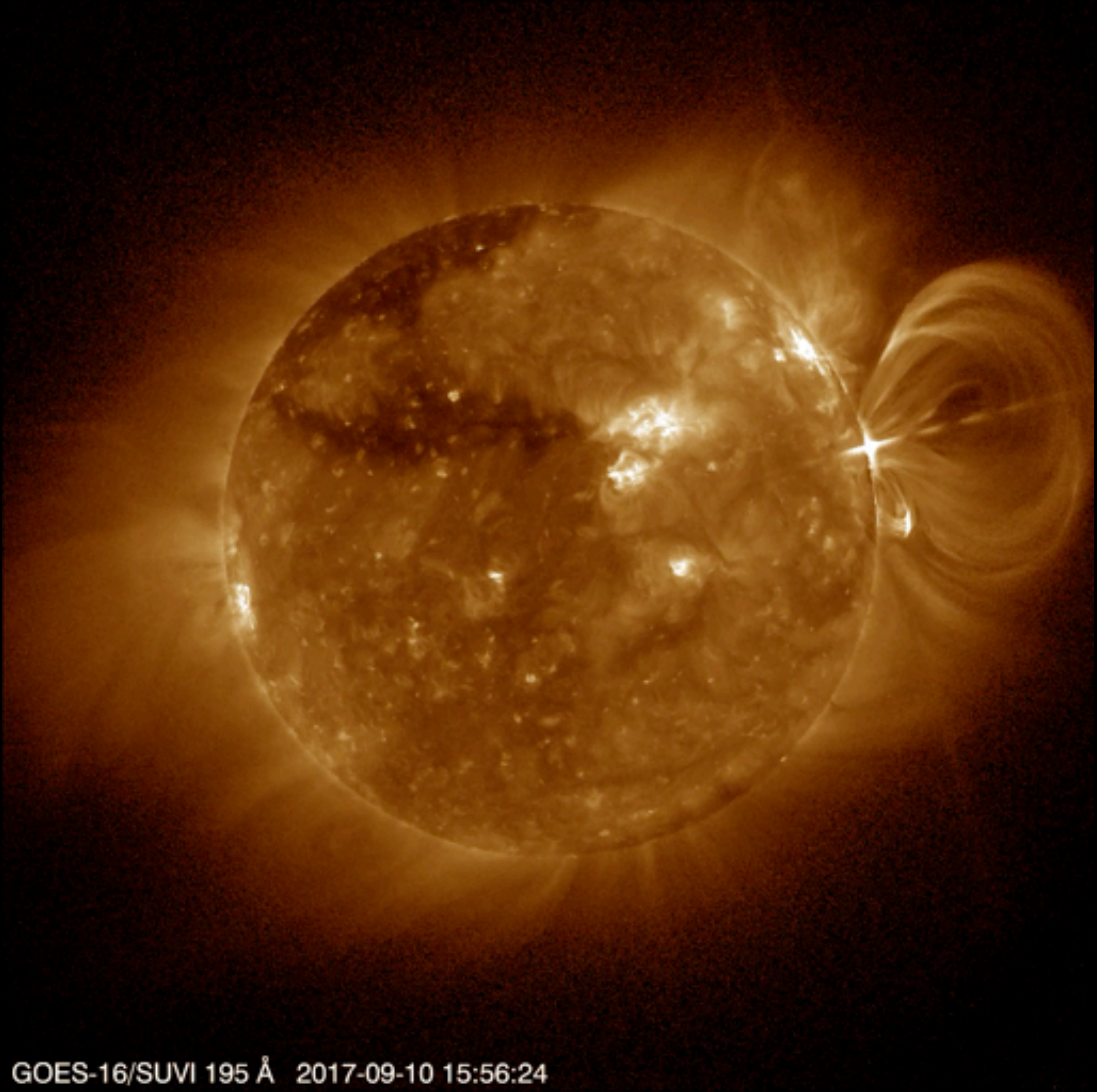
GOES-R Solar Ultraviolet Imager (SUVI)



SUVI:
Six EUV passbands

53.3 arcmin FOV

Temperatures from 50,000 to 10^{10} K



SUVI: X8.2 Flare & CME 2017 Sep 10

A larger field of view reveals eruption impacts in the middle corona.

Seaton & Darnel (2018)

RESEARCH ARTICLE
10.1029/2018SW001959

Special Section:
Space Weather Events of 4-10 September 2017

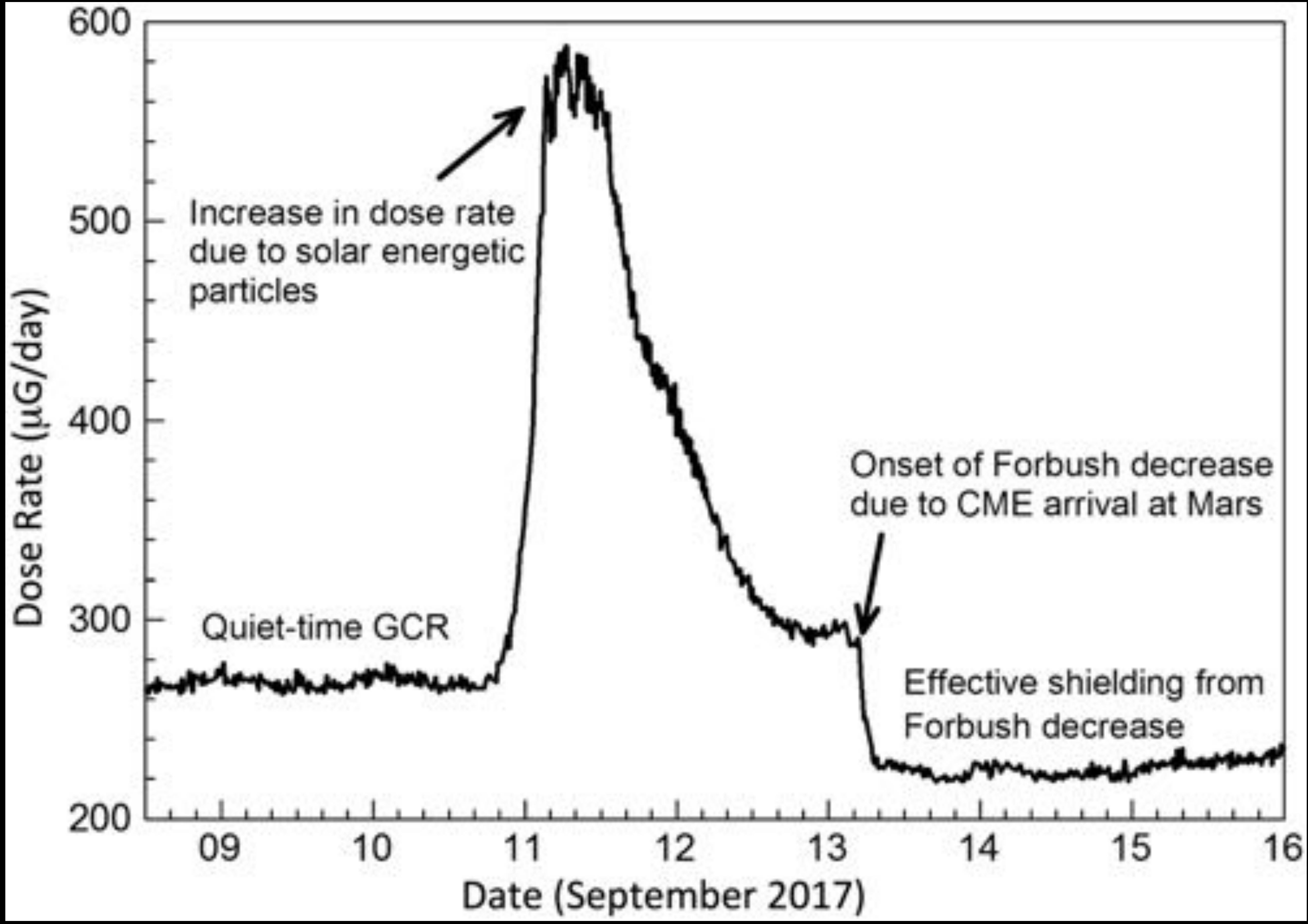
Space Weather on the Surface of Mars: Impact of the September 2017 Events

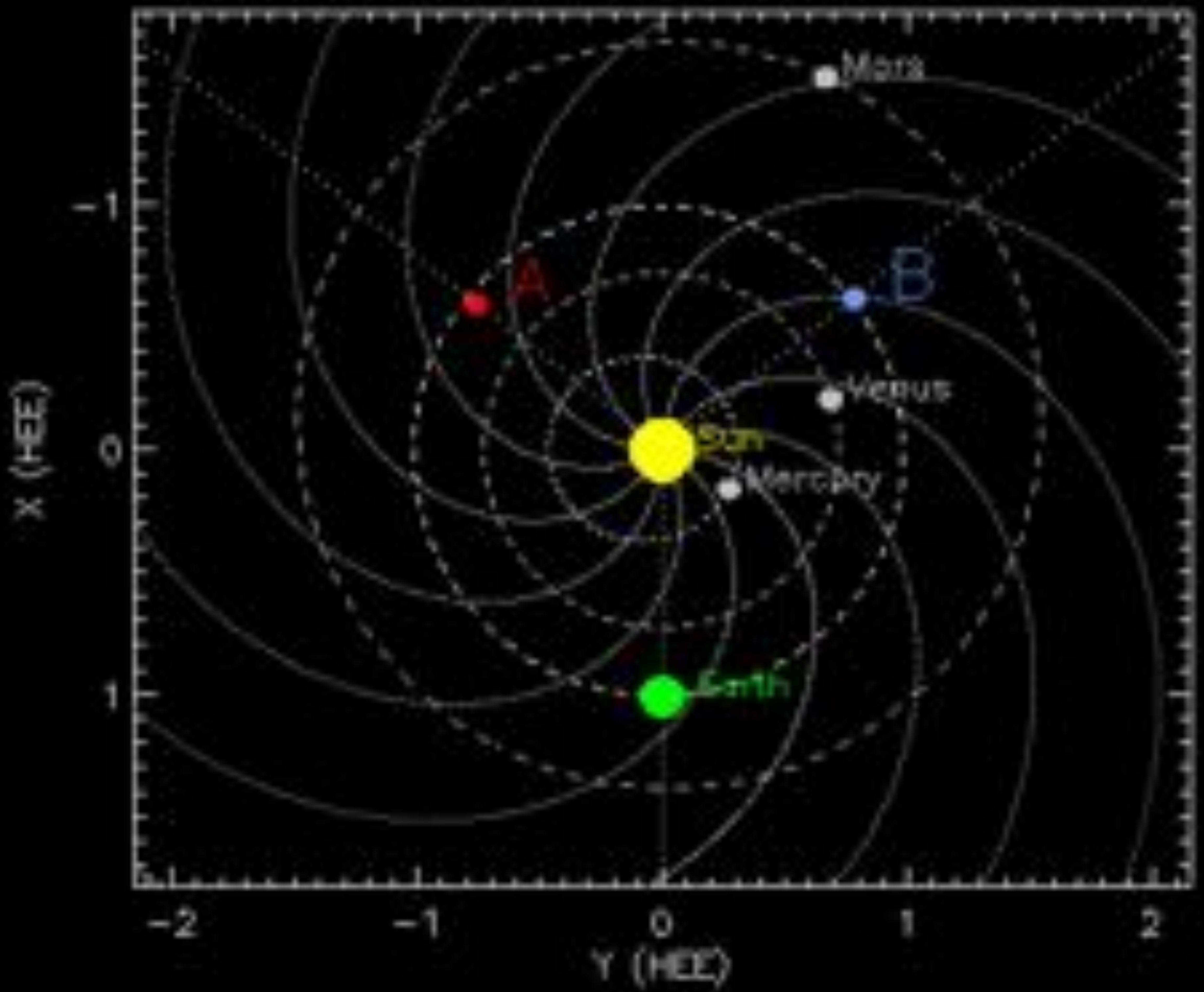
D. M. Hassler[1], C. Zeitlin[2], B. Ehresmann[1], R. F. Wimmer-Schweingruber[3], J. Guo[3], D. Matthiä[4], S. Rafkin[1], T. Berger[4], and G. Reitz[4]

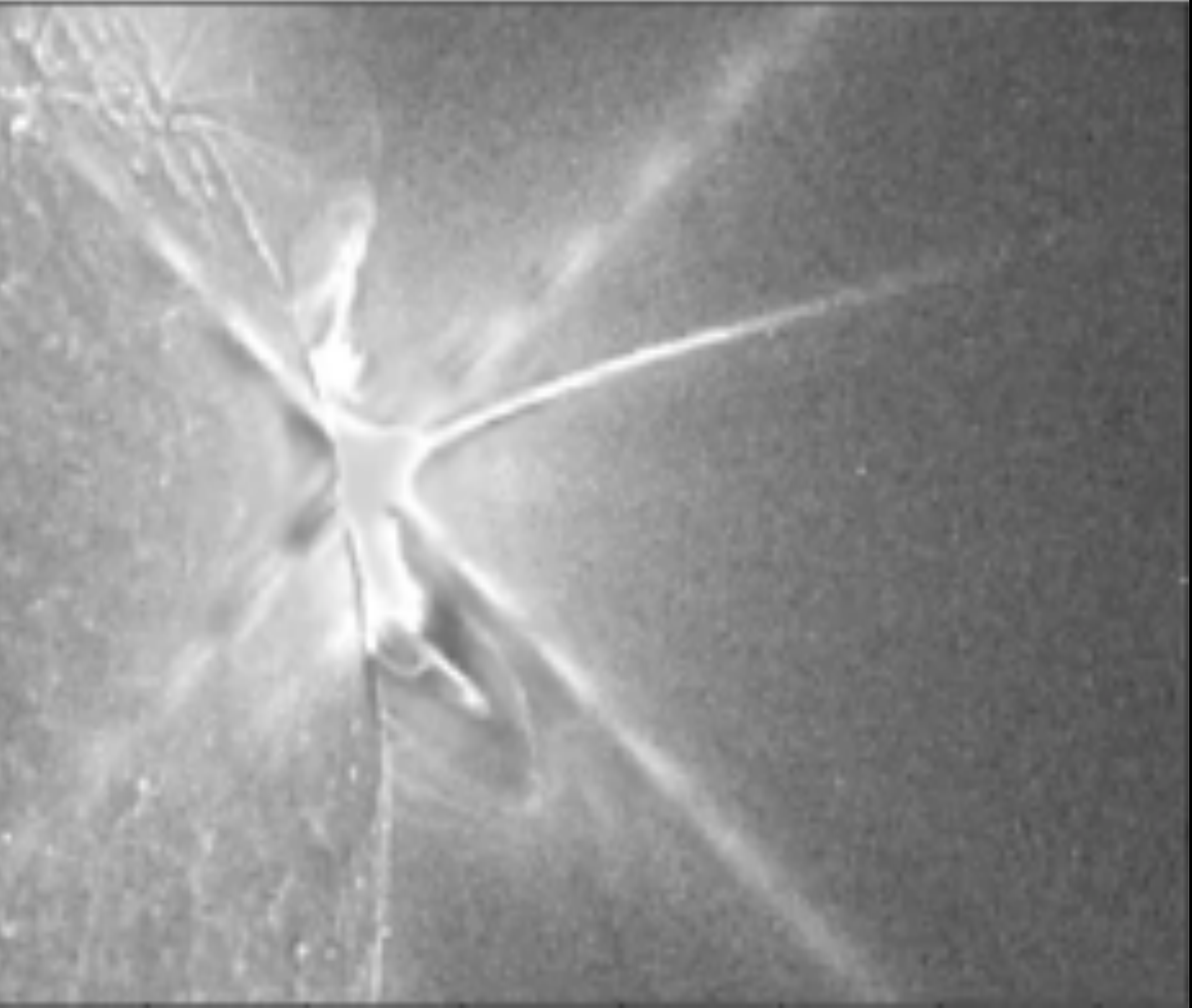
[1]Southwest Research Institute, Boulder, CO, USA, [2]Leidos Innovations Corporation, Houston, TX, USA, [3]Department of Extraterrestrial Physics, Christian Albrechts University, Kiel, Germany, [4]German Aerospace Center (DLR), Institute of Aerospace Medicine, Cologne, Germany

Key Points:

- On 11 September 2017, MSL RAD



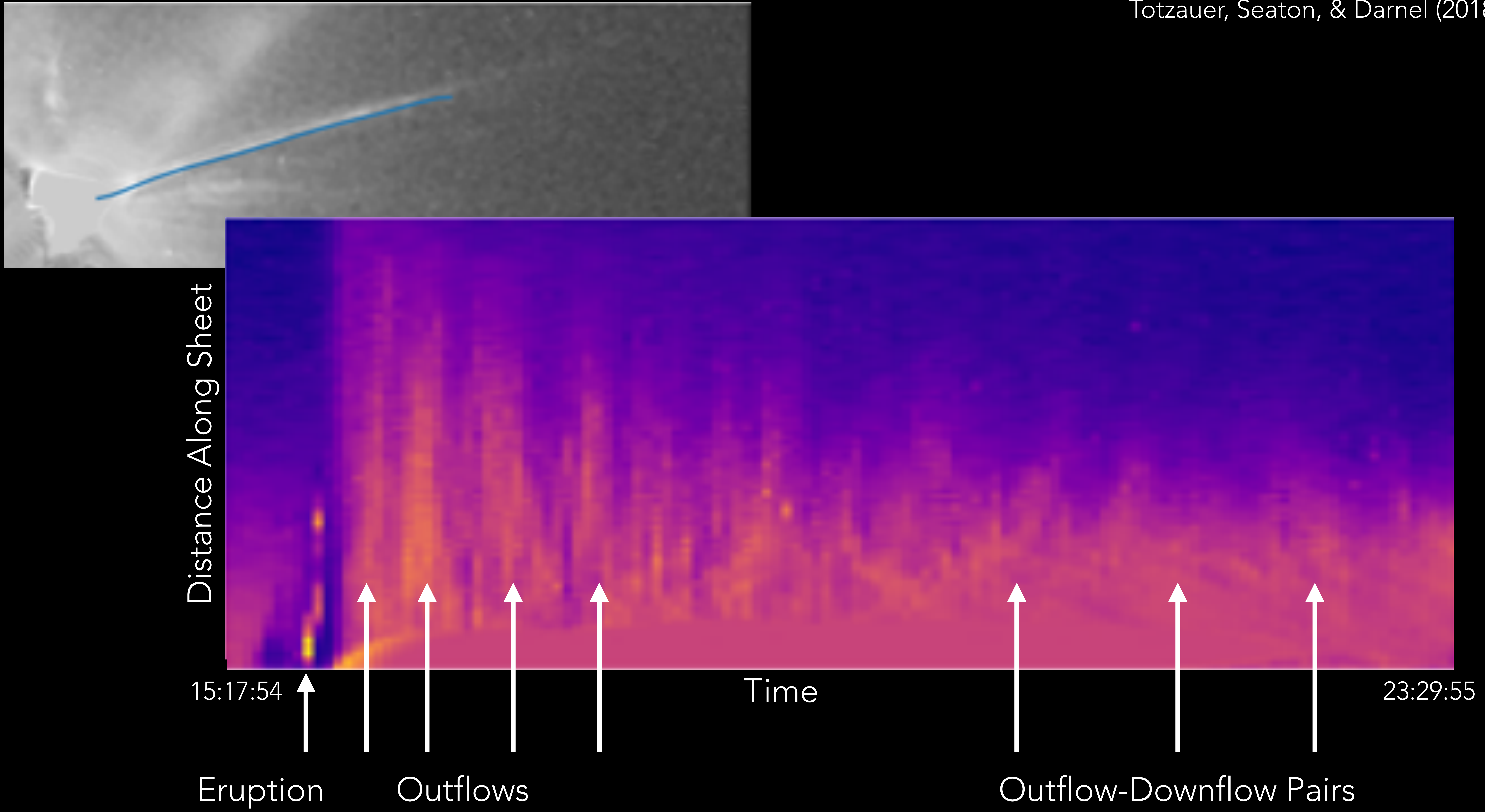




Processed high-temperature observations reveal inflow-outflow pairs.

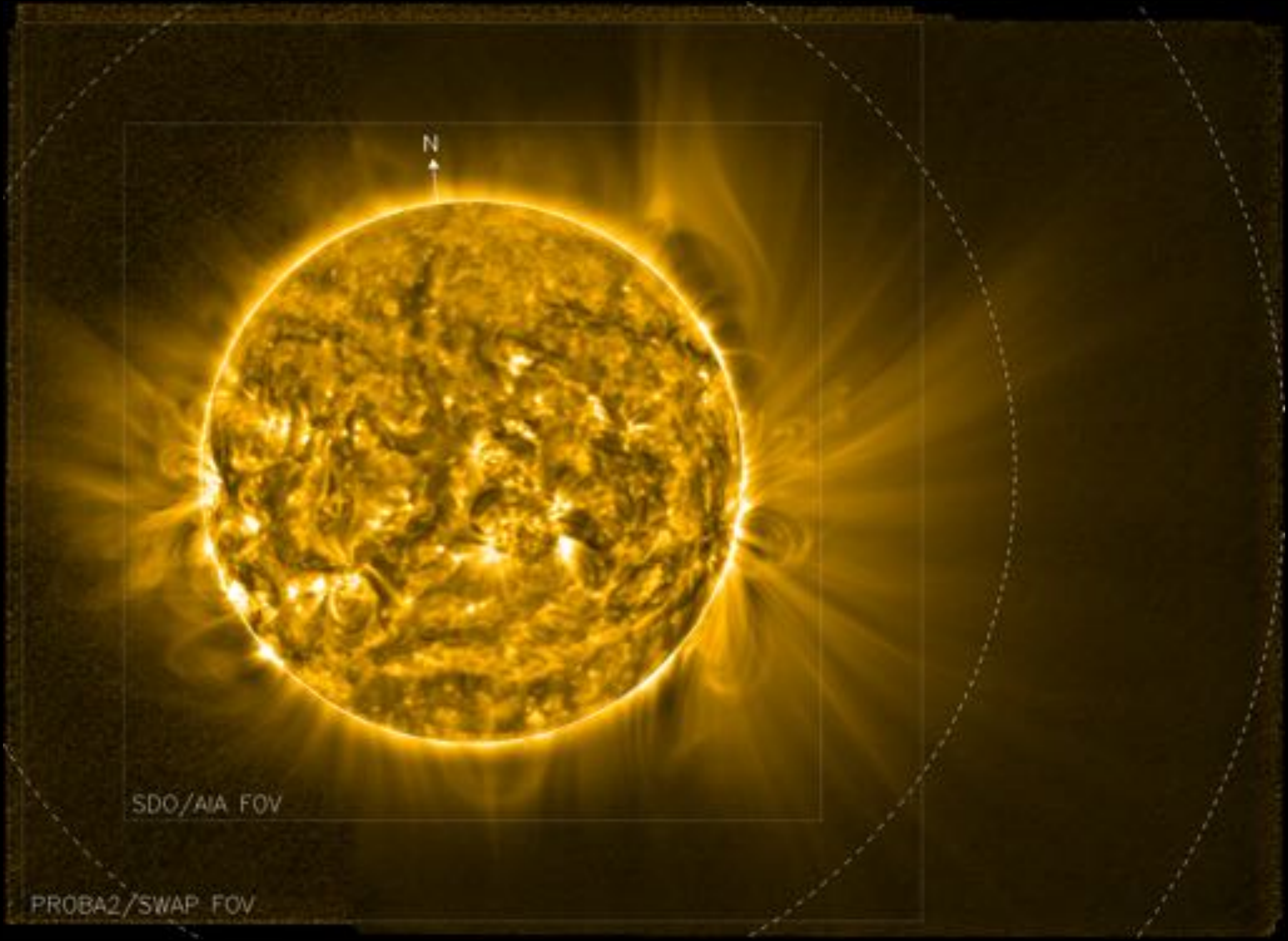
Totzauer, Seaton, & Darnel (2018)

Totzauer, Seaton, & Darnel (2018)



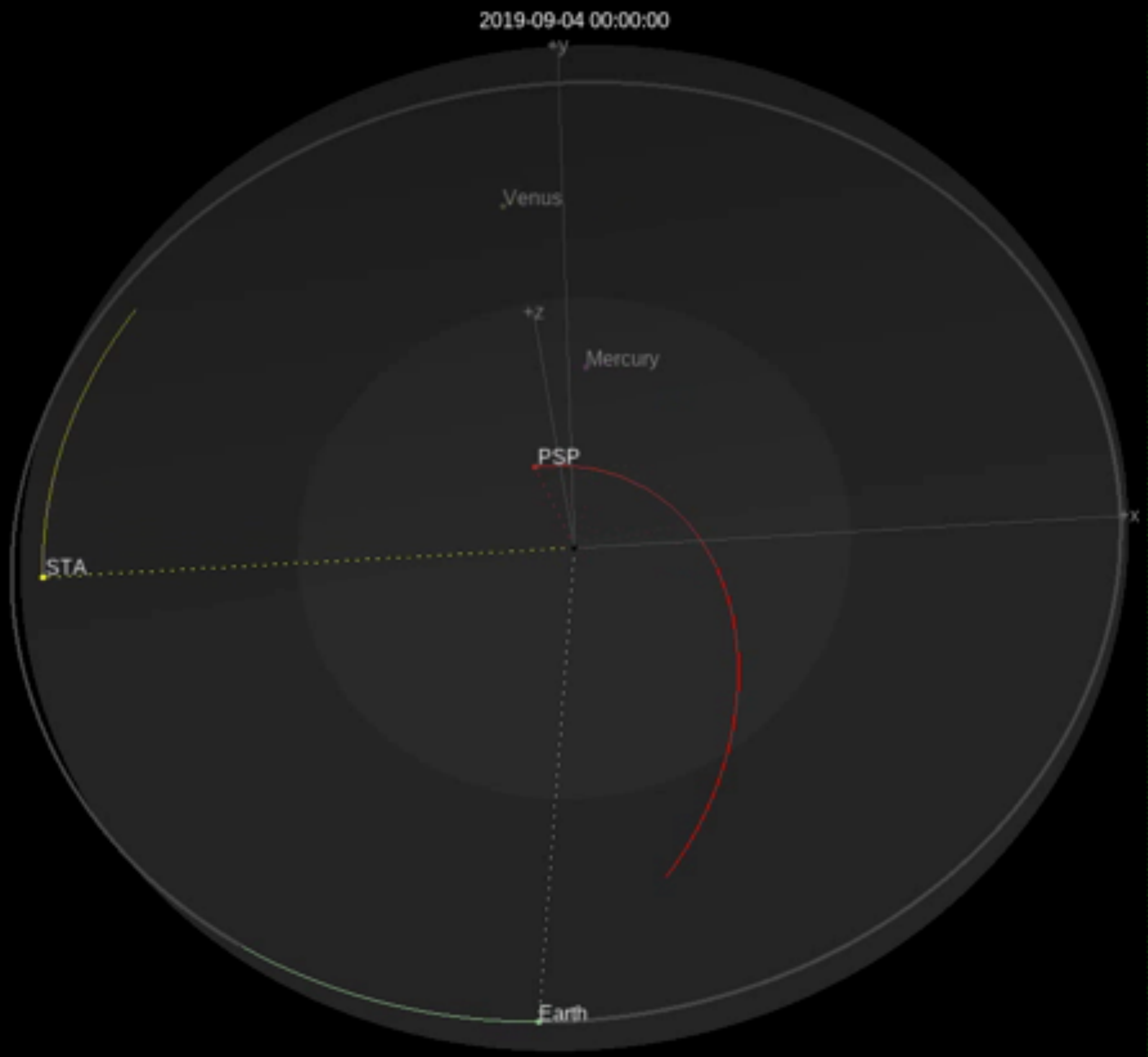
A BRIDGE TO THE FUTURE: GOES-R SUVI EXTENDED CORONAL IMAGING


SOHO/LASCO
2017 Sep 10
(Launched 1995)



PROBA2/SWAP off-points showed potential for EUV observations to large heights.

See Tadikonda et al. (2019) for an early look.
DOI:10.1007/s11207-019-1411-0



SUVI off-points supported Parker Solar Probe Perihelion Pass

Long-term campaign is ongoing (Sep-Nov 2019)

LOOKING AHEAD: WHAT DO WE HAVE? WHAT DO WE NEED?

USING EUV IN THE MIDDLE CORONA, WE HAVE…

- Identified structure and outflows that could be the origins of the solar wind, and which help shape the global corona.
- Identified key features to advance understanding of reconnecting current layers and validate reconnection models.
- Demonstrated the value and viability of imaging this region to solve critical unresolved problems in coronal physics.

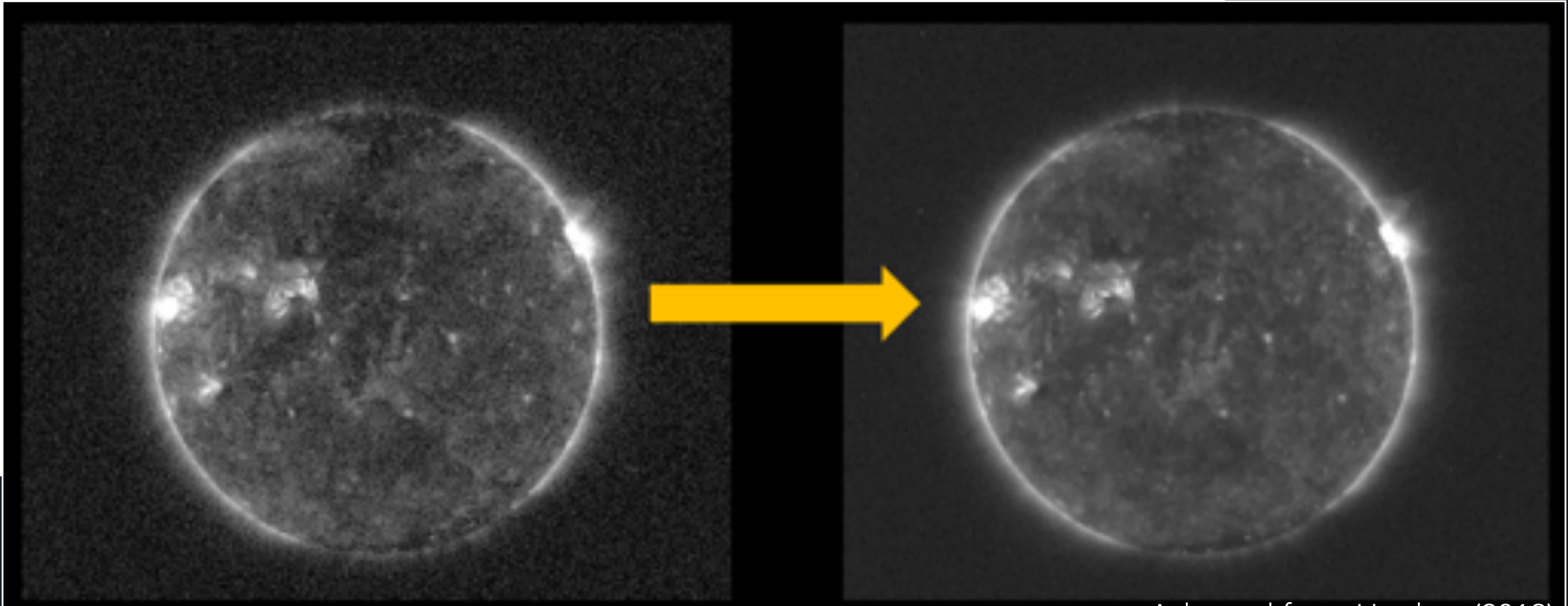
BUT STILL, WE MUST...

- Deploy new image processing techniques to illuminate hard-to-observe structures and dynamics.
- Bring together interdisciplinary teams that can unravel mysteries requiring the coupling of very different physical regimes.
- Develop instruments that fully close the observational gap between coronal domains.
- Build links to new missions (PUNCH, Solar Orbiter, Parker Solar Probe, Lagrange, L5/L*) to create truly global observation sets.

The Astrophysical Journal, 838:155 (10pp), 2017 April 1
https://doi.org/10.3847/1538-4357/aa67f1

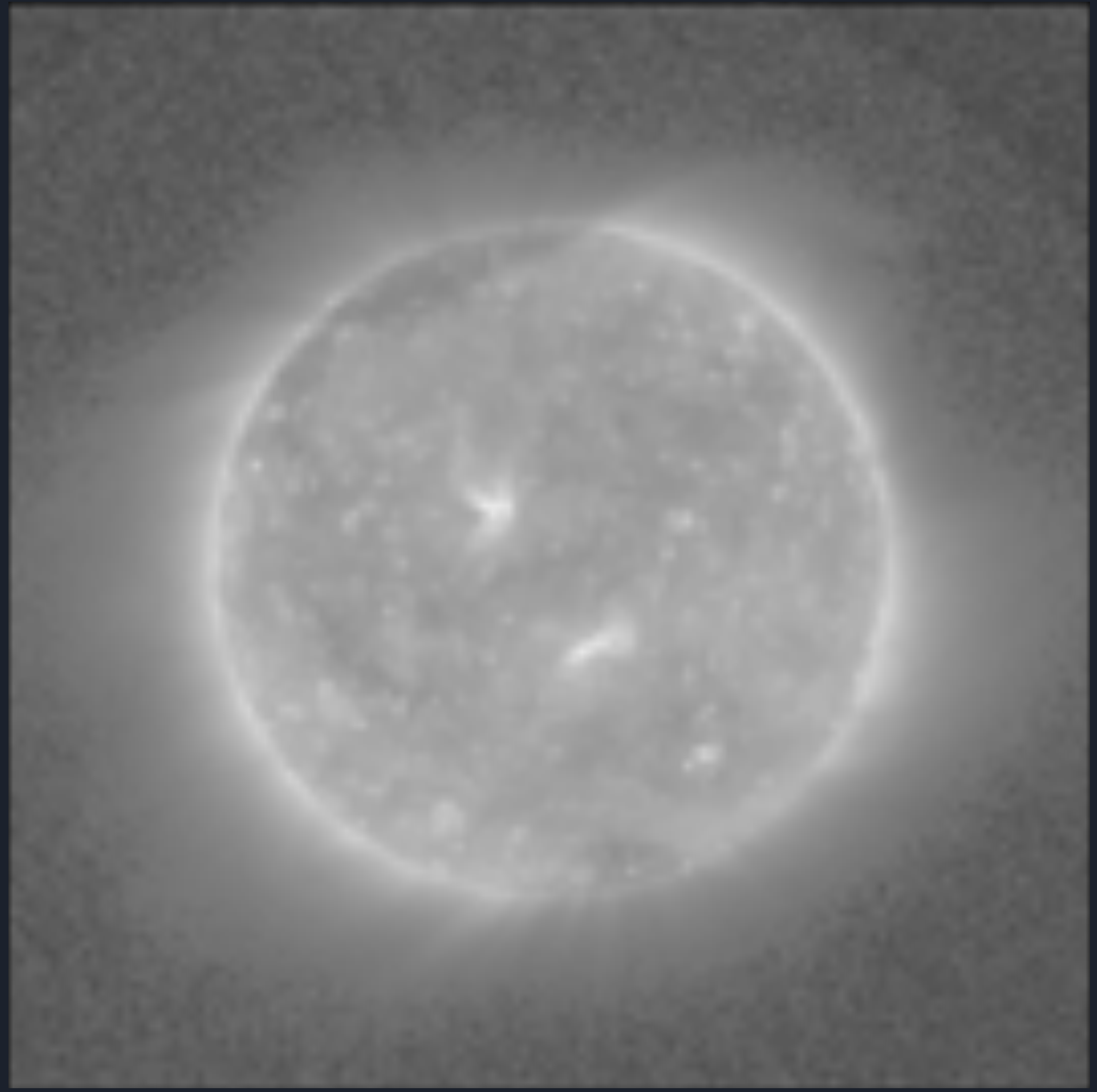
Noise-gating to Clean Astrophysical Image Data

C. E. DeForest
Southwest Research Institute, 1050 Walnut Street, Boulder, CO, USA
Received 2017 February 17; revised 2017 March 17; accepted 2017 March 17; published 2017 April 5

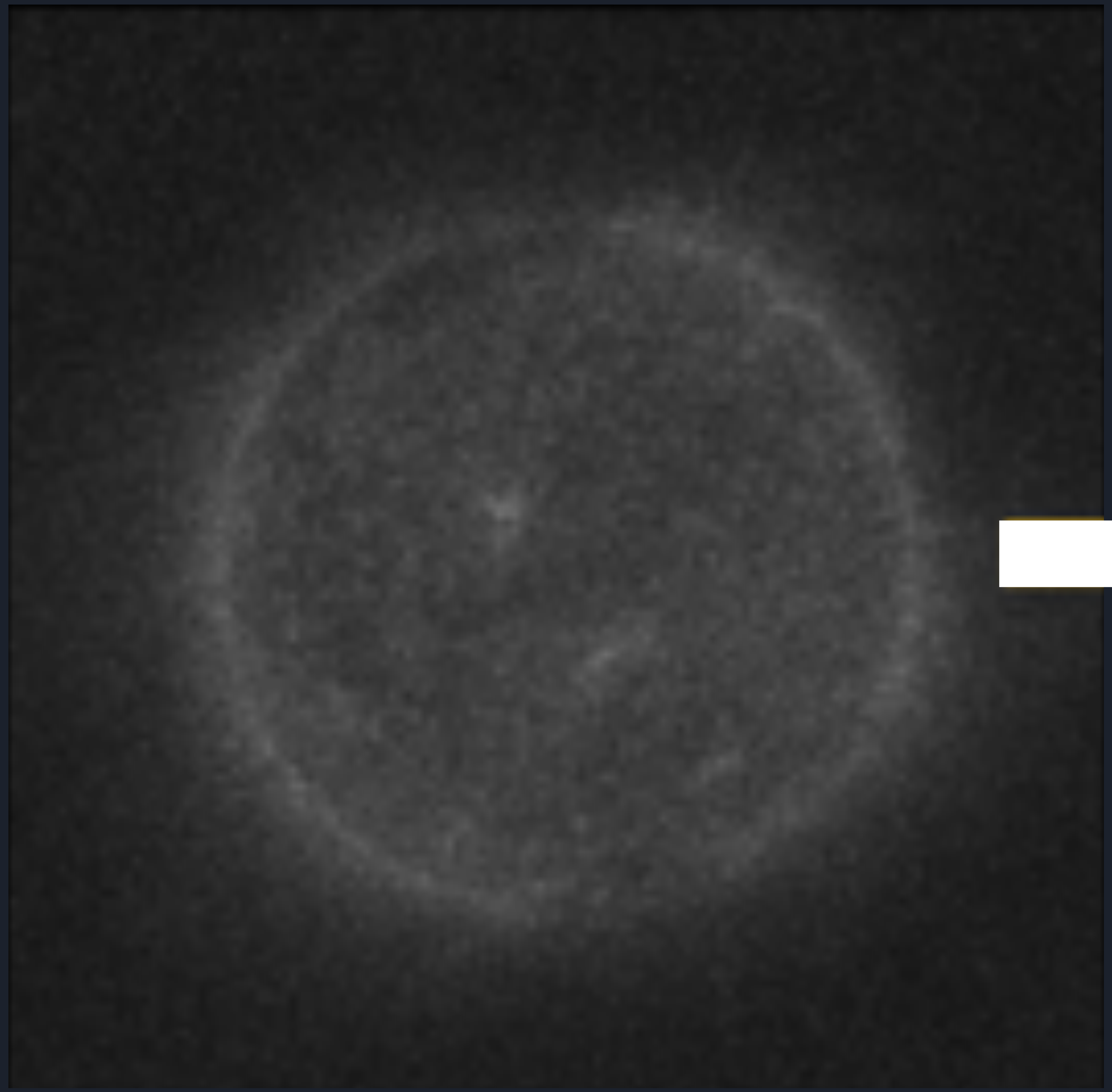


Adapted from Hughes (2019)

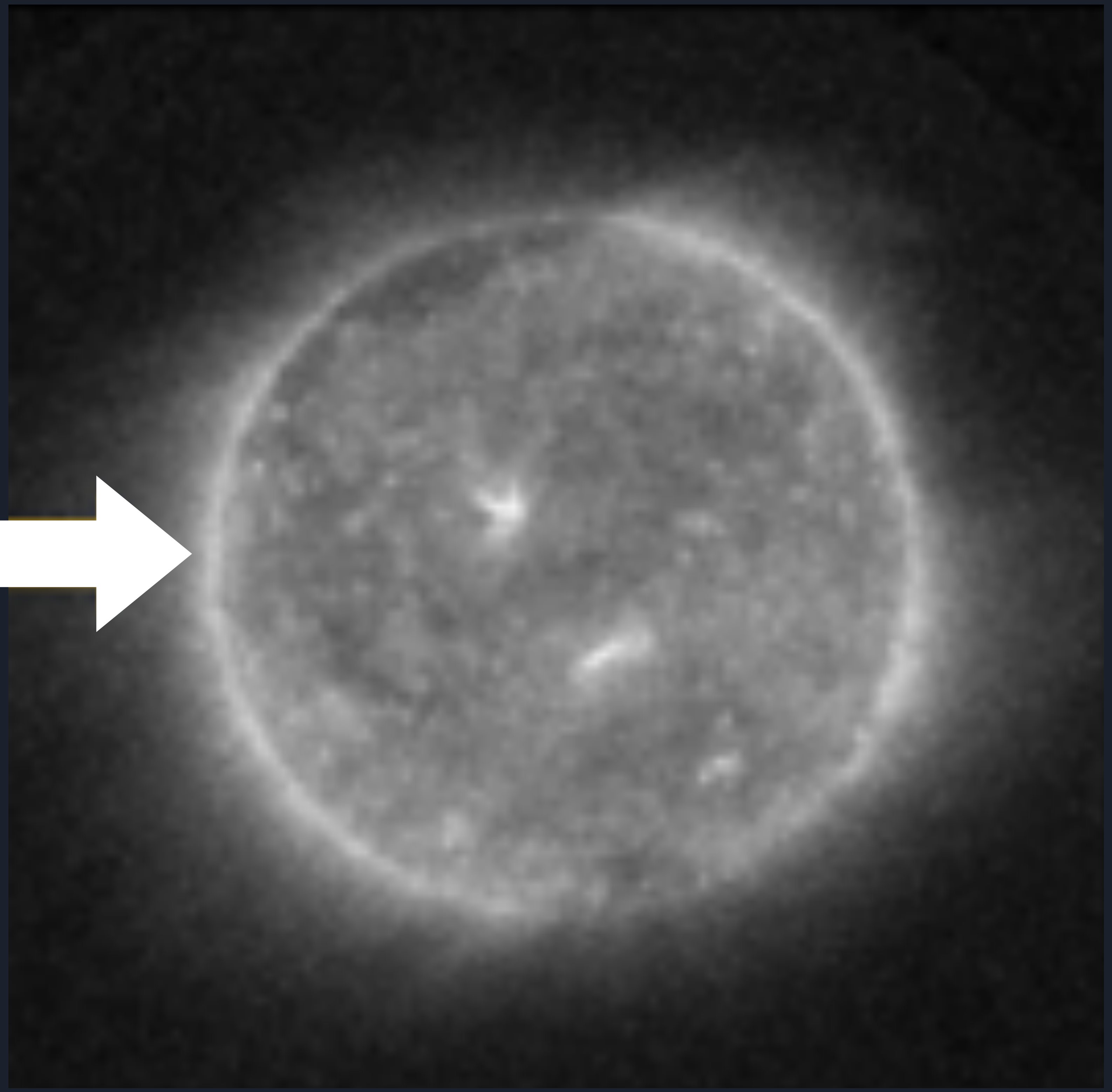
Noise2Self a self-supervised ML framework for blind denoising of high-dimensional measurements. Preliminary tests are promising!



Observation

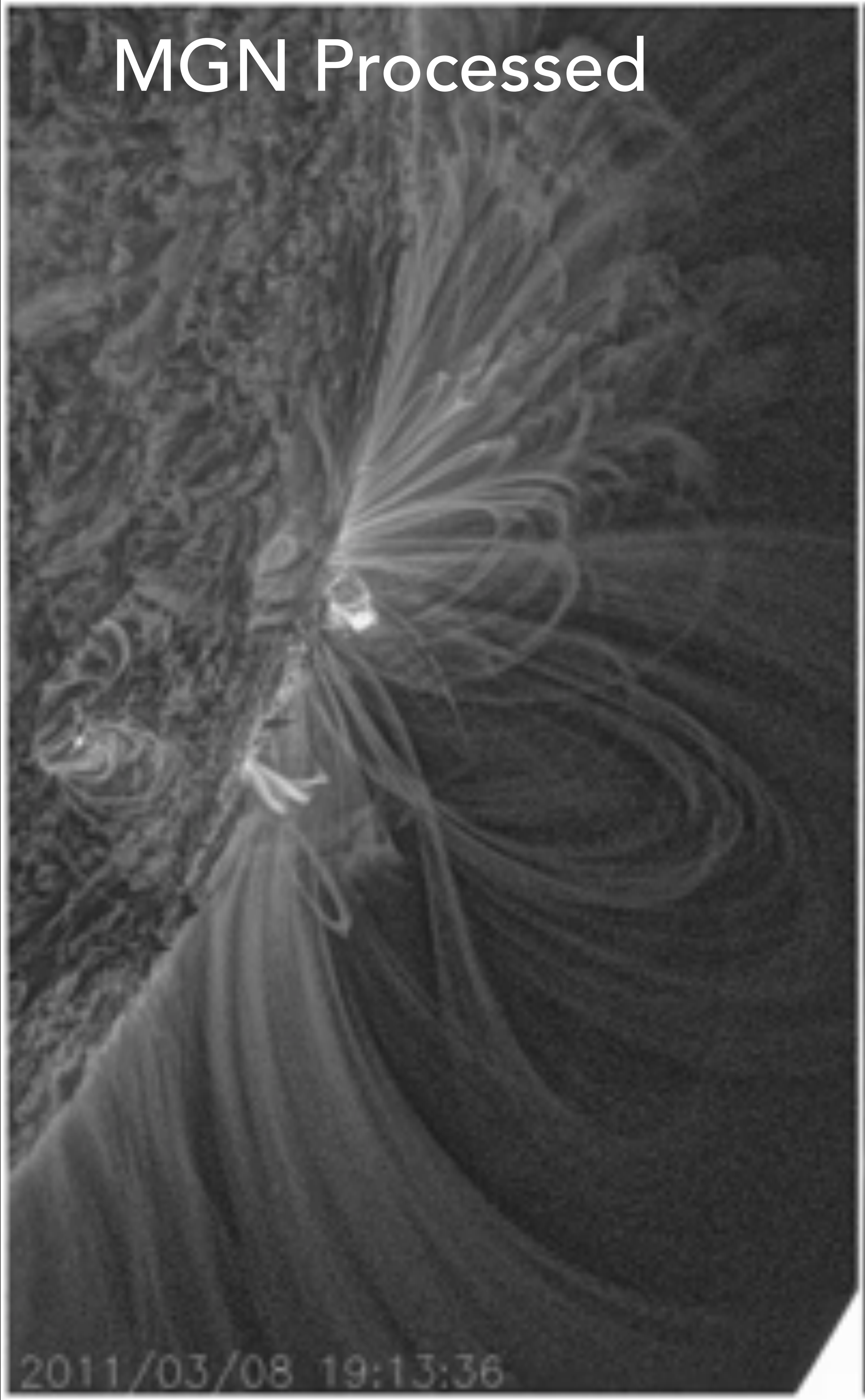


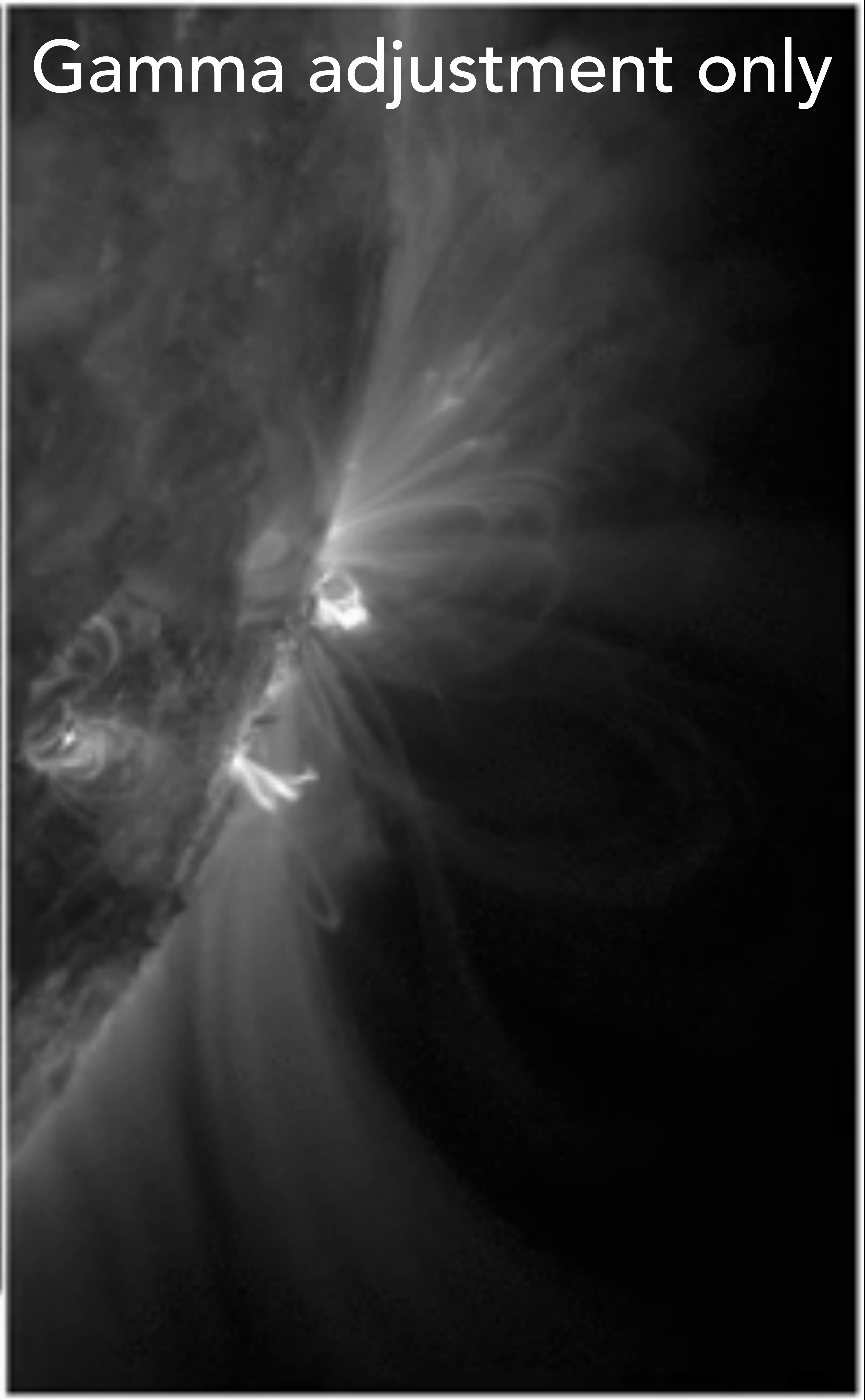
Noisy



Denoised

Adapted from Hughes (2019)





Careful & appropriate image processing can dramatically improve detectability of EUV middle corona structure & dynamics.

For more: Alzate & Morgan (2017)

COHERENT

COrona as a Holistic Environment REsearch NeTwork

NASA AO NNH18ZDA001N-DRIVE

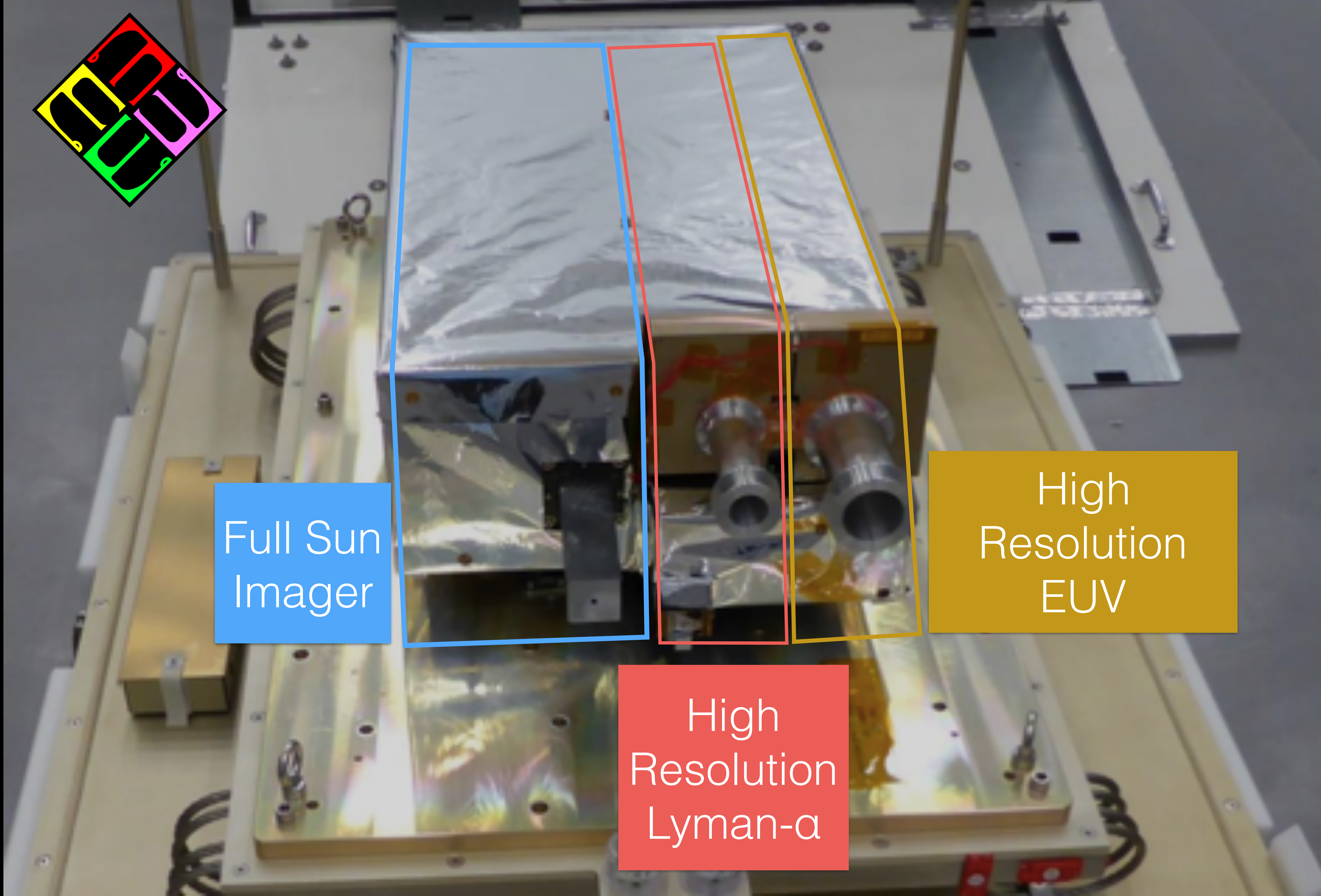
June 28, 2019

NASA

SwRI

Co-Is:
Mark Cheung
Stephen Cranmer
Craig E. DeForest
Giuliana de Toma
Cooper Downs
Heather Elliott
Anne Gold

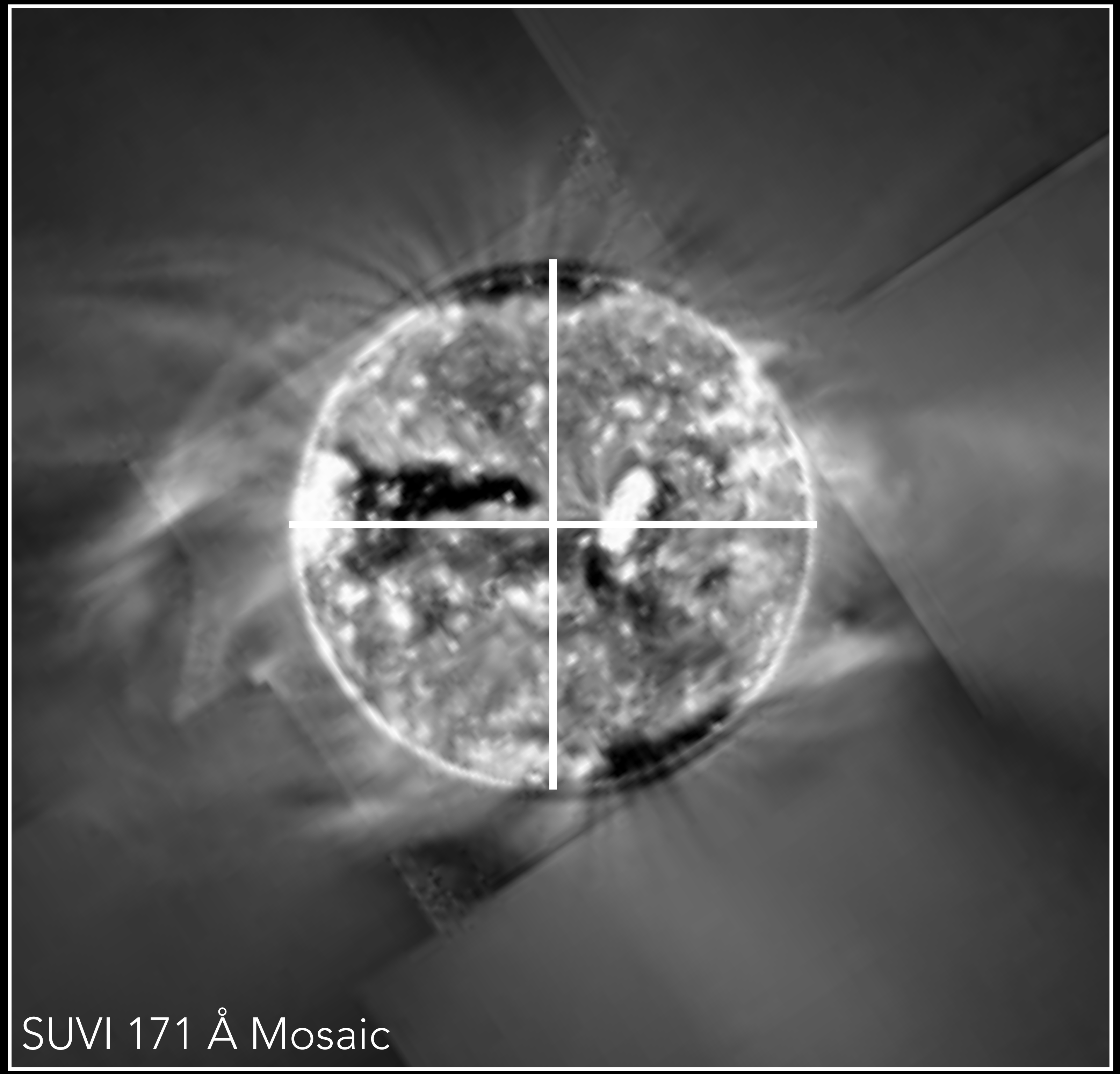
Solar Orbiter Extreme Ultraviolet Imager



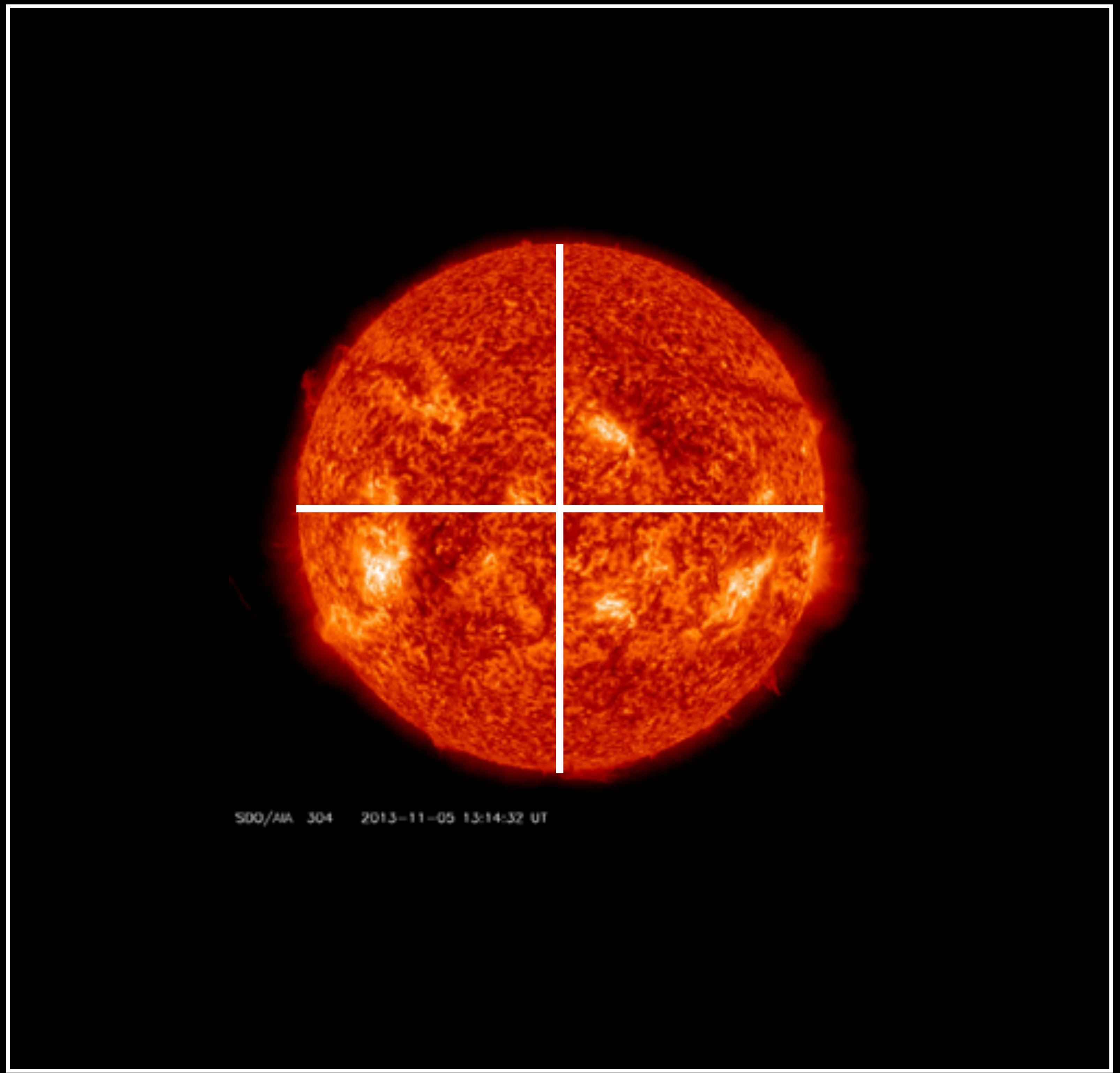
FSI: Full Sun Imager

FOV: 3.8°x3.8°, @ 0.28 AU: 4 Rsun × 4 Rsun

17nm



30.4nm



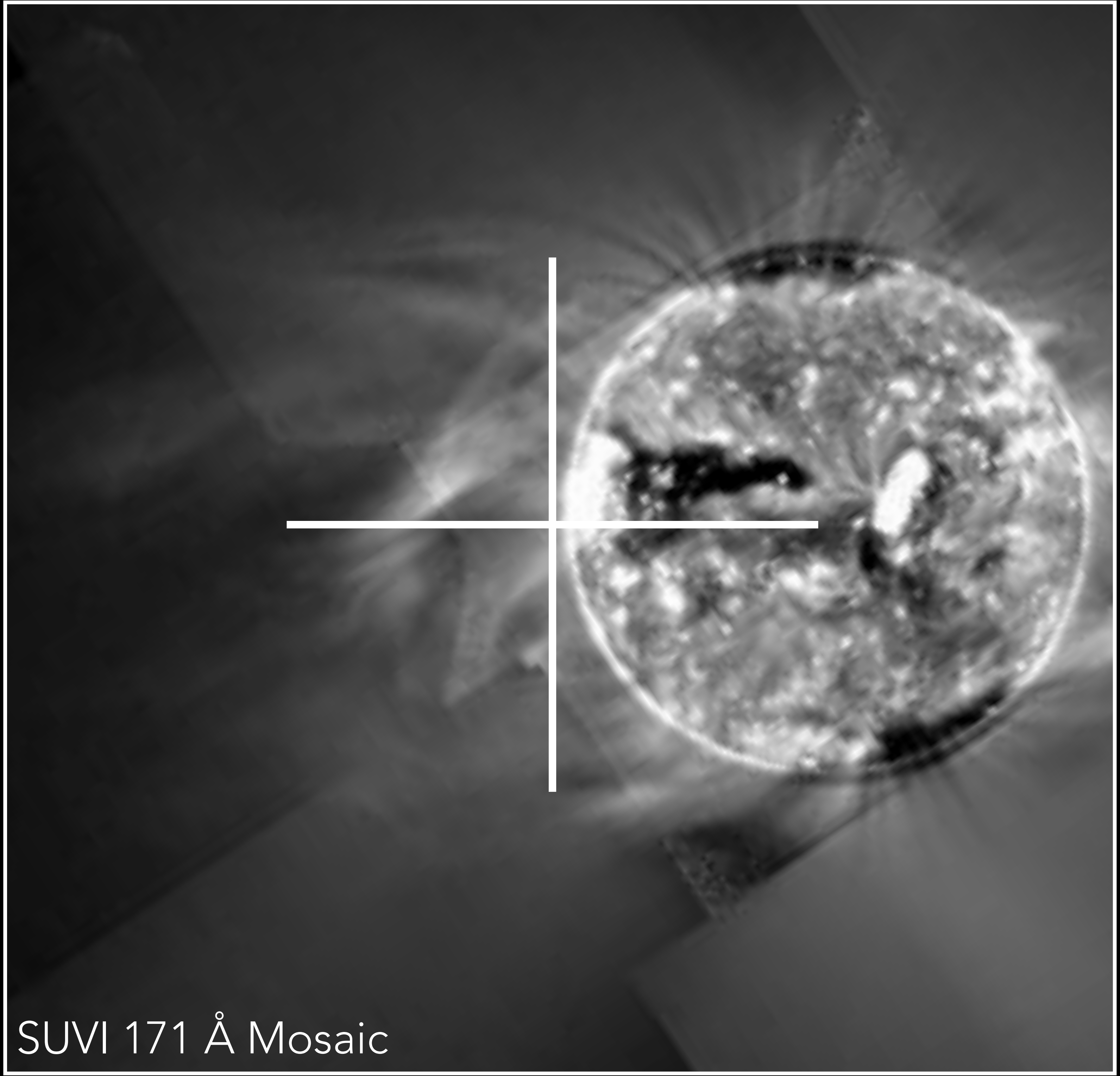
resolution: 9 arcsec on 2 pixels

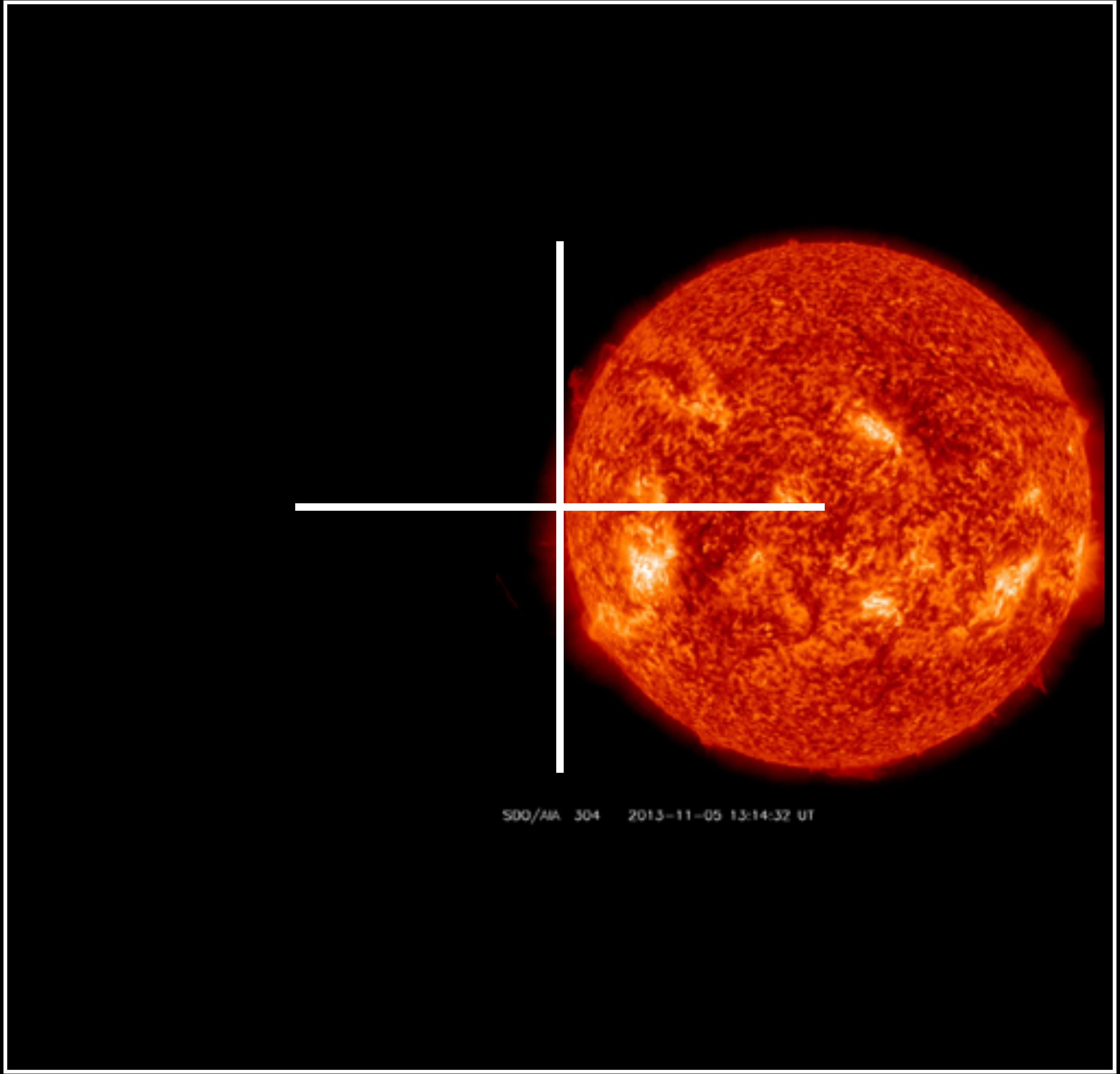
@ 0.28 AU =1830 km on 2 pixels

FSI: Full Sun Imager

FOV: 3.8°x3.8°, @ 0.28 AU: 4 Rsun × 4 Rsun

17nm



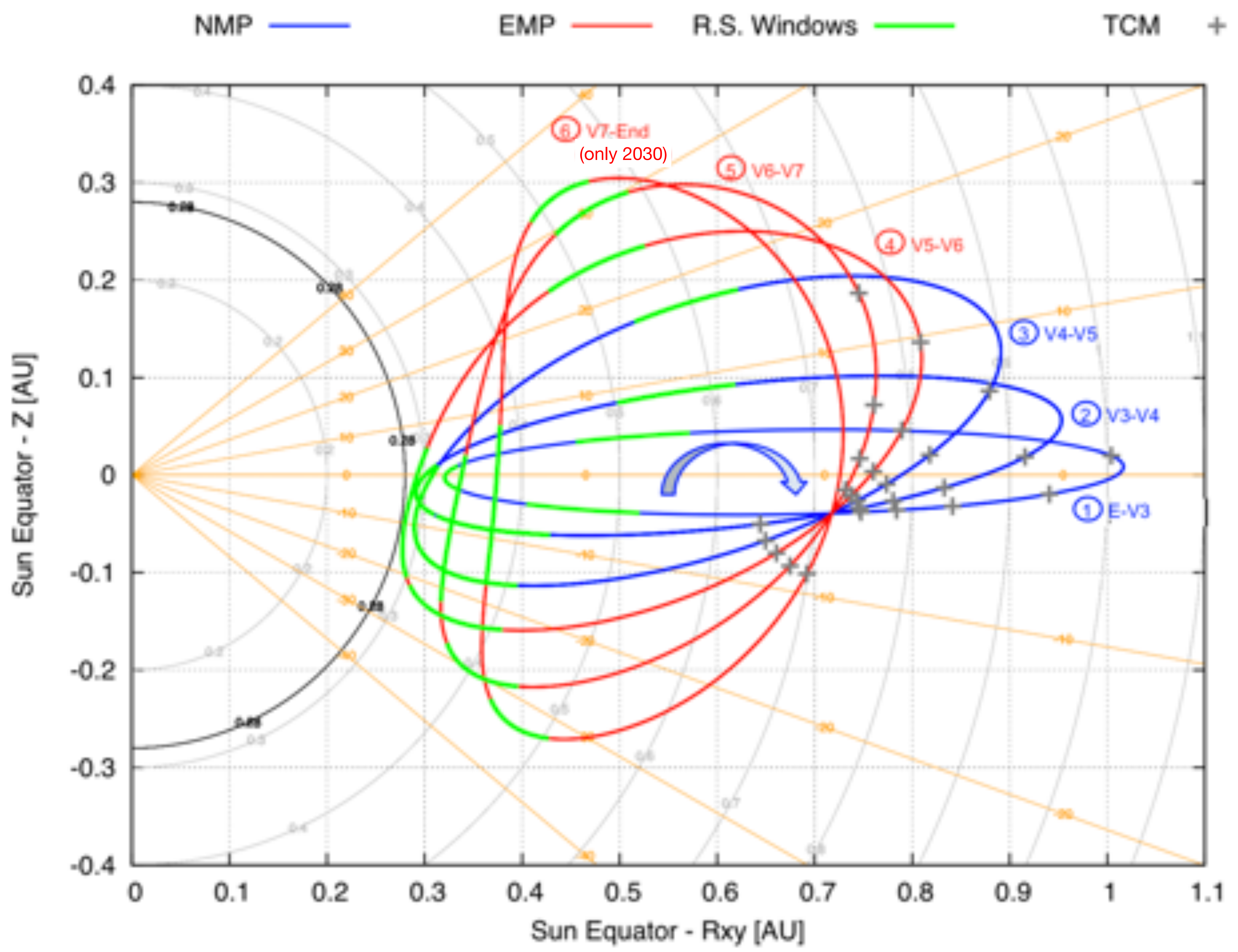


30.4nm

resolution: 9 arcsec on 2 pixels

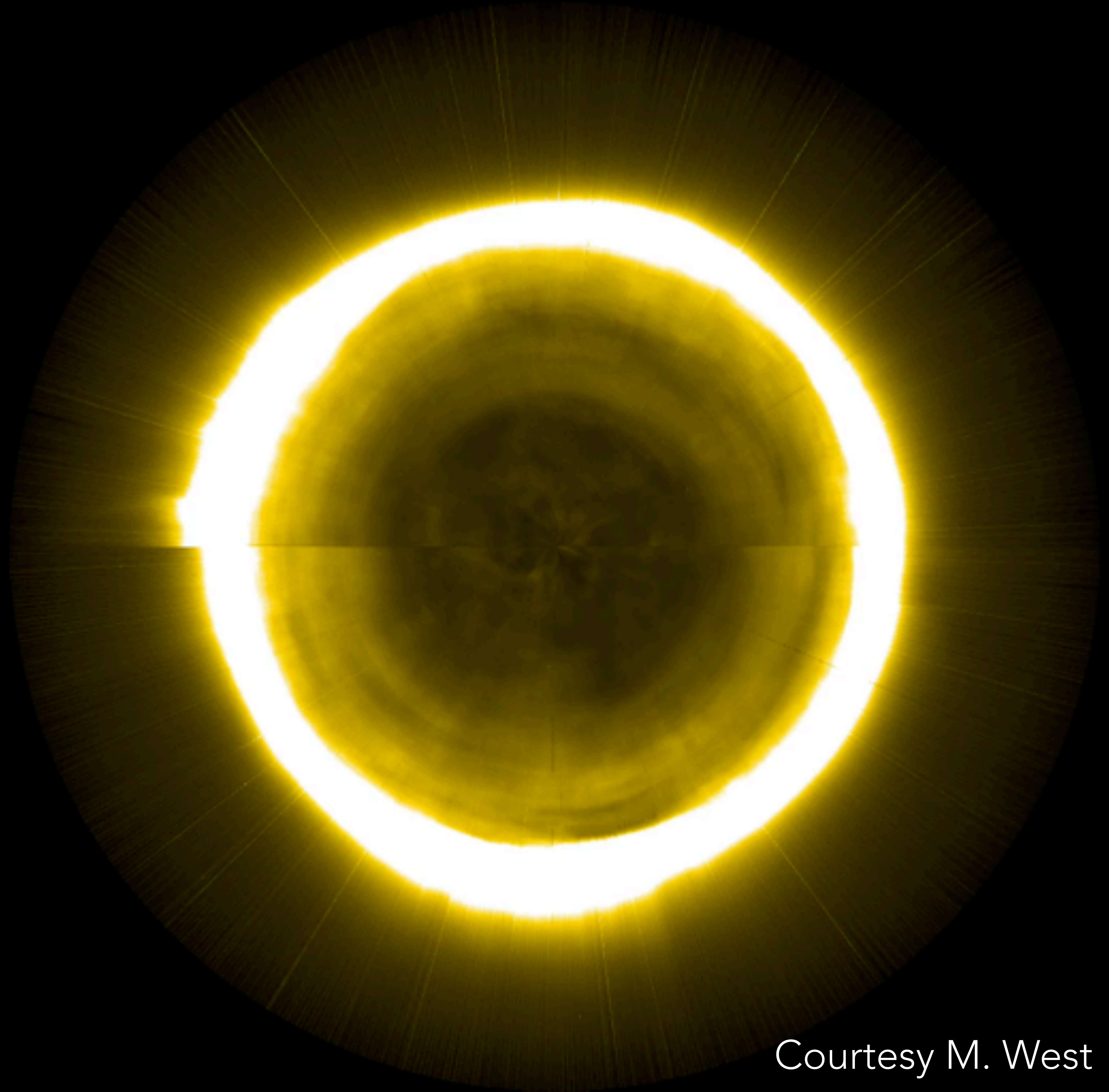
@ 0.28 AU =1830 km on 2 pixels

Solar Orbiter Orbits 4/2020 – 12/2030



PROBA2 SWAP 174 Å
EUV Polar View

June 2018 – September 2018



Courtesy M. West

The Lagrange Mission

Courtesy M. West

THE LAGRANGE MISSION PAYLOAD

Remote Sensing Instruments

Coronagraph

Heliospheric imager (HI)

Magnetograph

EUV imager

X-ray flux monitor

In-situ Instruments

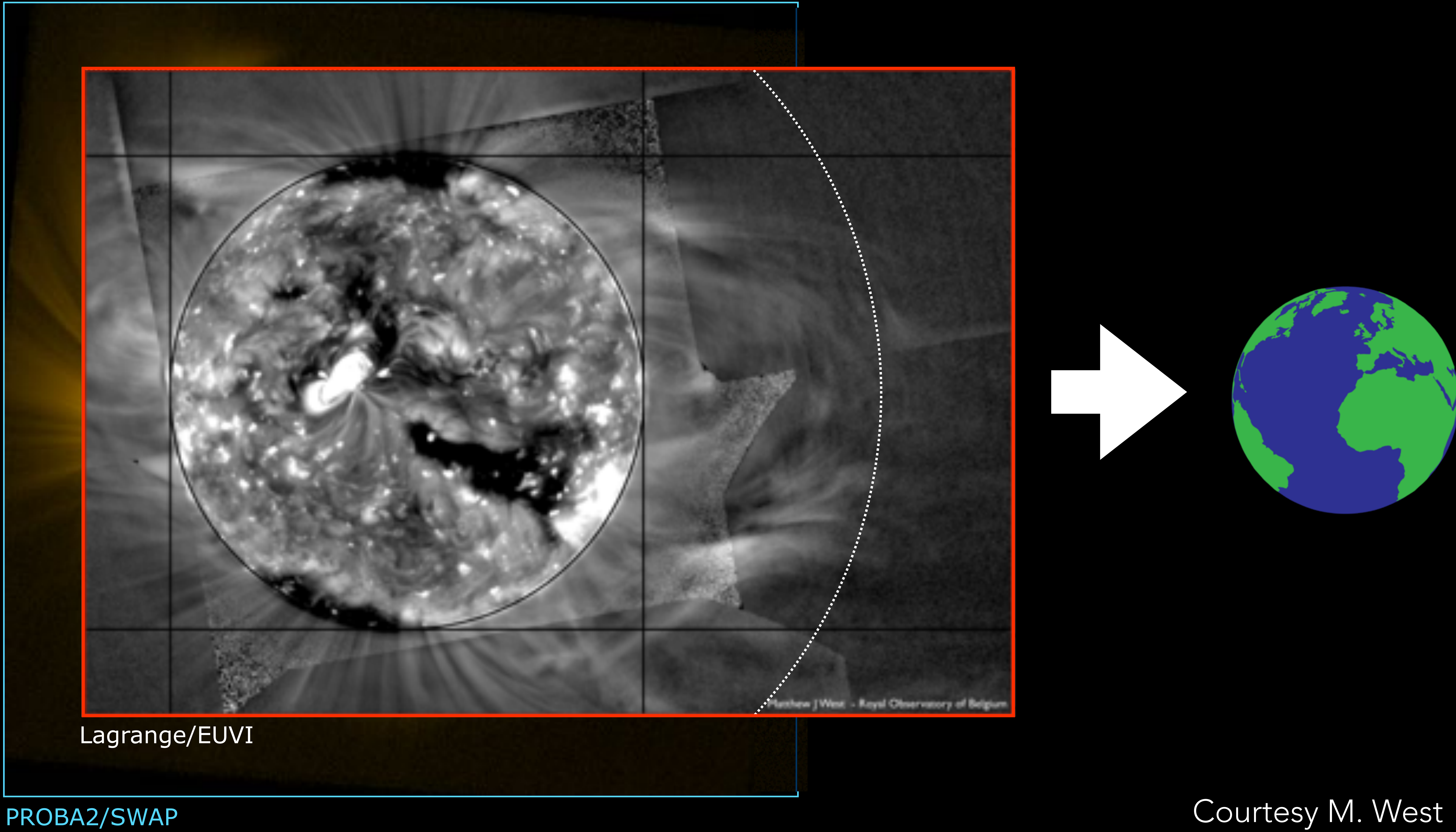
Magnetometer

Plasma analyser

Radiation monitor

Particle spectrometer

Courtesy M. West

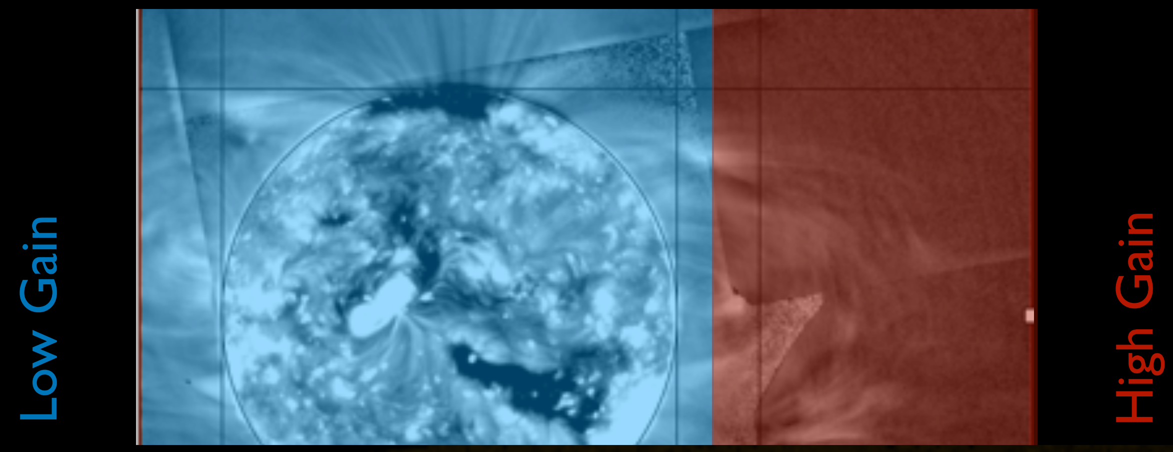


Courtesy M. West

LG

2010-05-04T18:05:29.570

Exposure time - constar

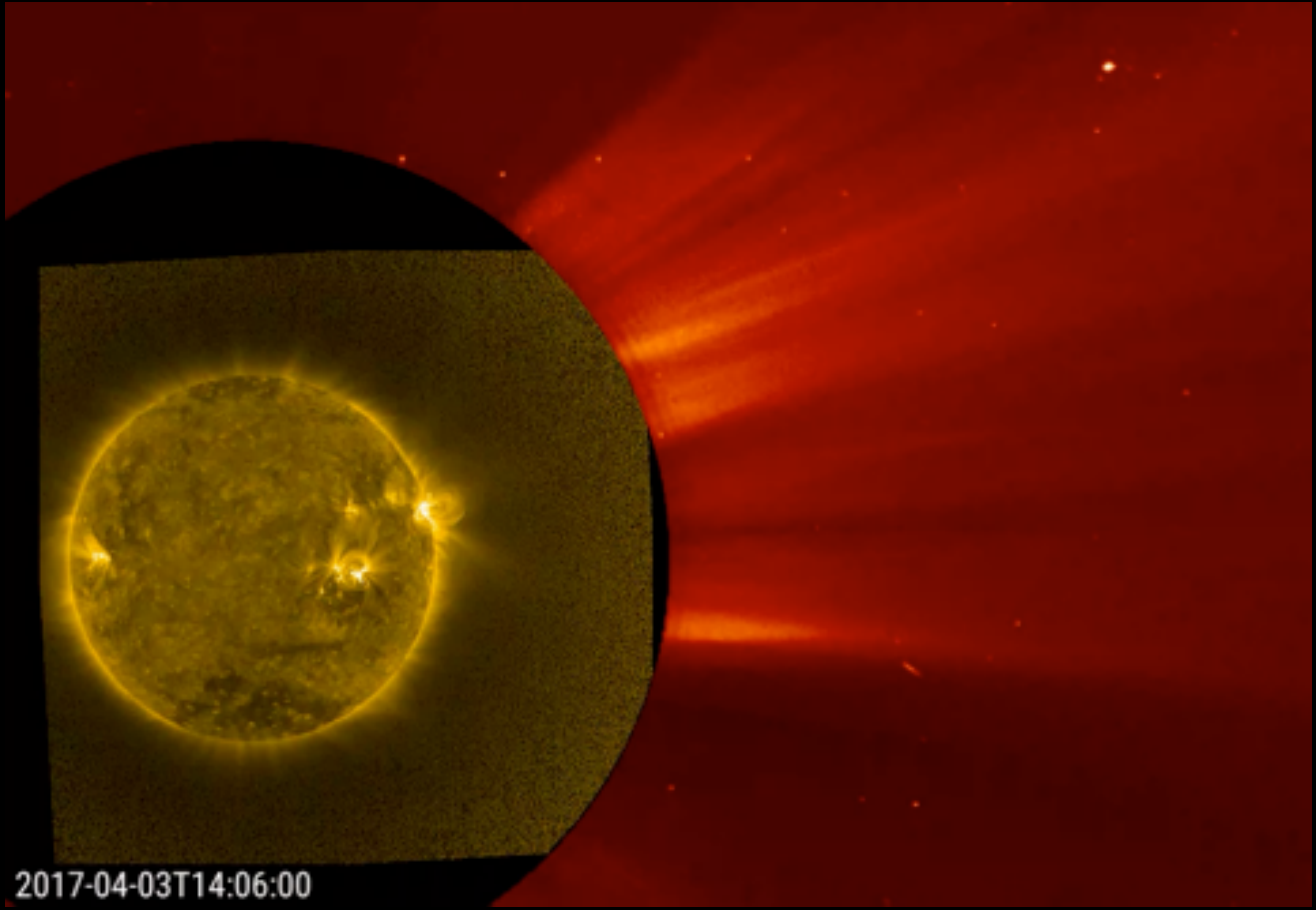


HG

2010-05-04T18:15:54.584

ure time - constant 100s

Courtesy M. West



PROBA2/SWAP Pathfinder Observations

O'Hara (2019)

Courtesy M. West

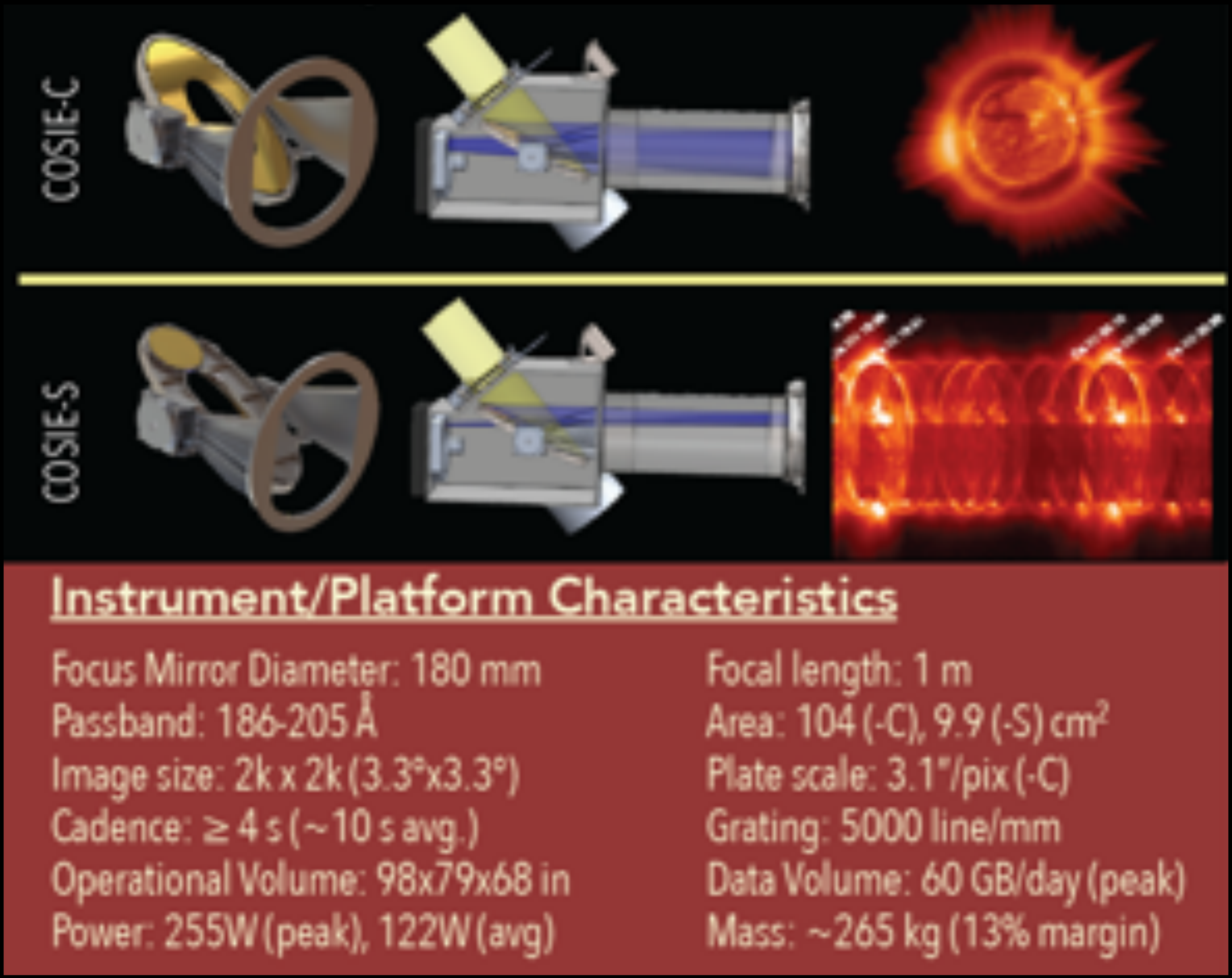
Coronal Spectrographic Imager in the EUV (COSIE)

Wide FOV, high-sensitivity EUV imager and slitless spectrograph.

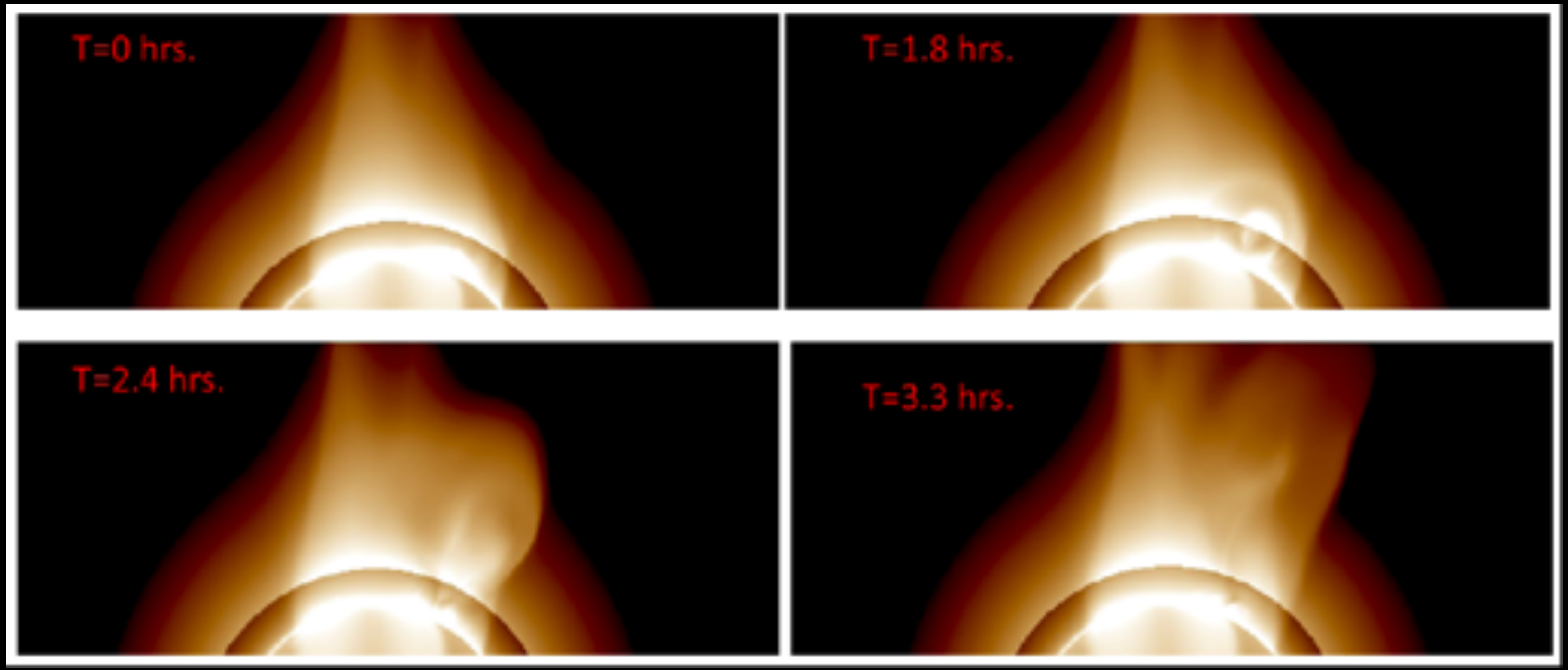
500× AIA Effective area

Channel switch via flipable feed optic

Hosted on ISS



Courtesy L. Golub



CMEs and magnetic connectivity are tracked through the Sun's corona:

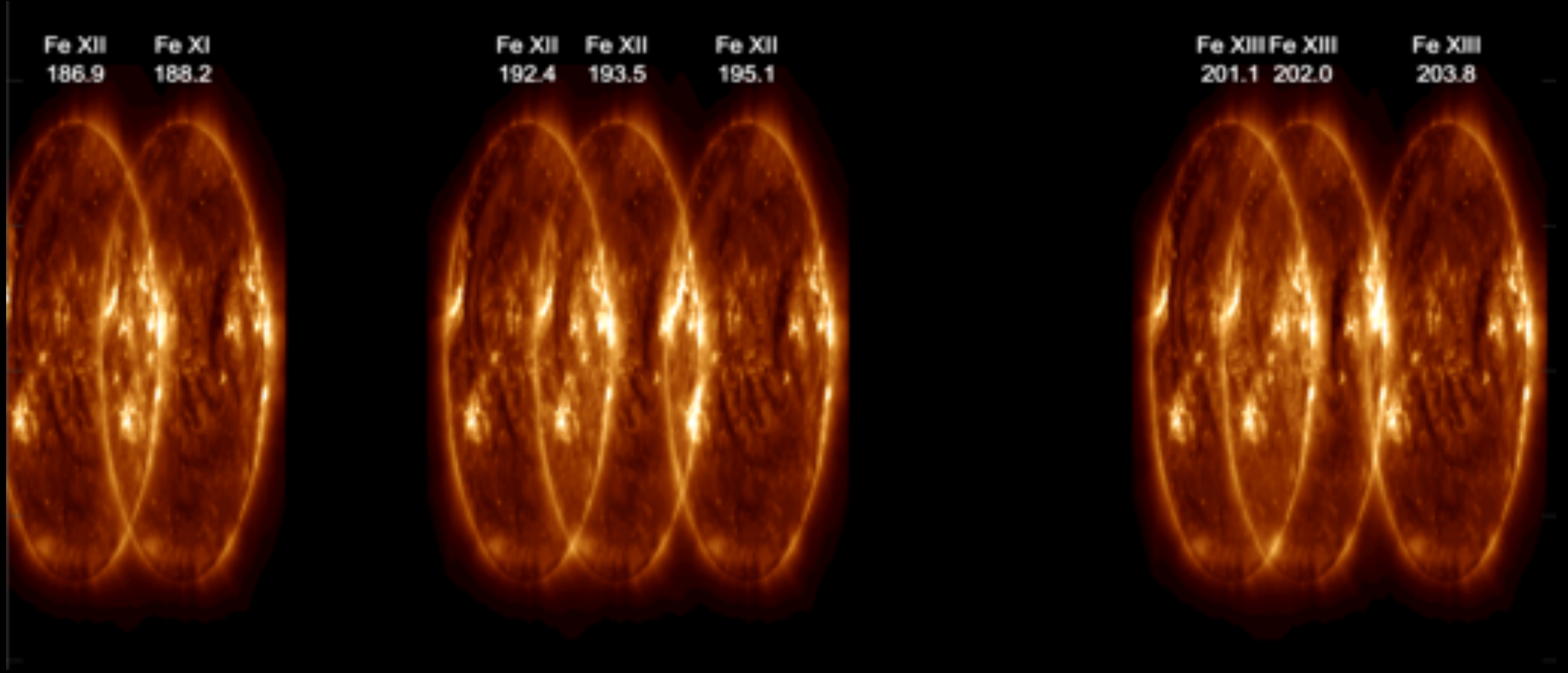
Disk/Coronal brightness varies by a small factor in the EUV (vs. 106 in white light).

EUV coronagraphs allow for simultaneous visibility of the source region and the propagating disturbance.

The Sun emits in discrete EUV spectral lines:

Dispersing the light with a grating results in distinct solar images.

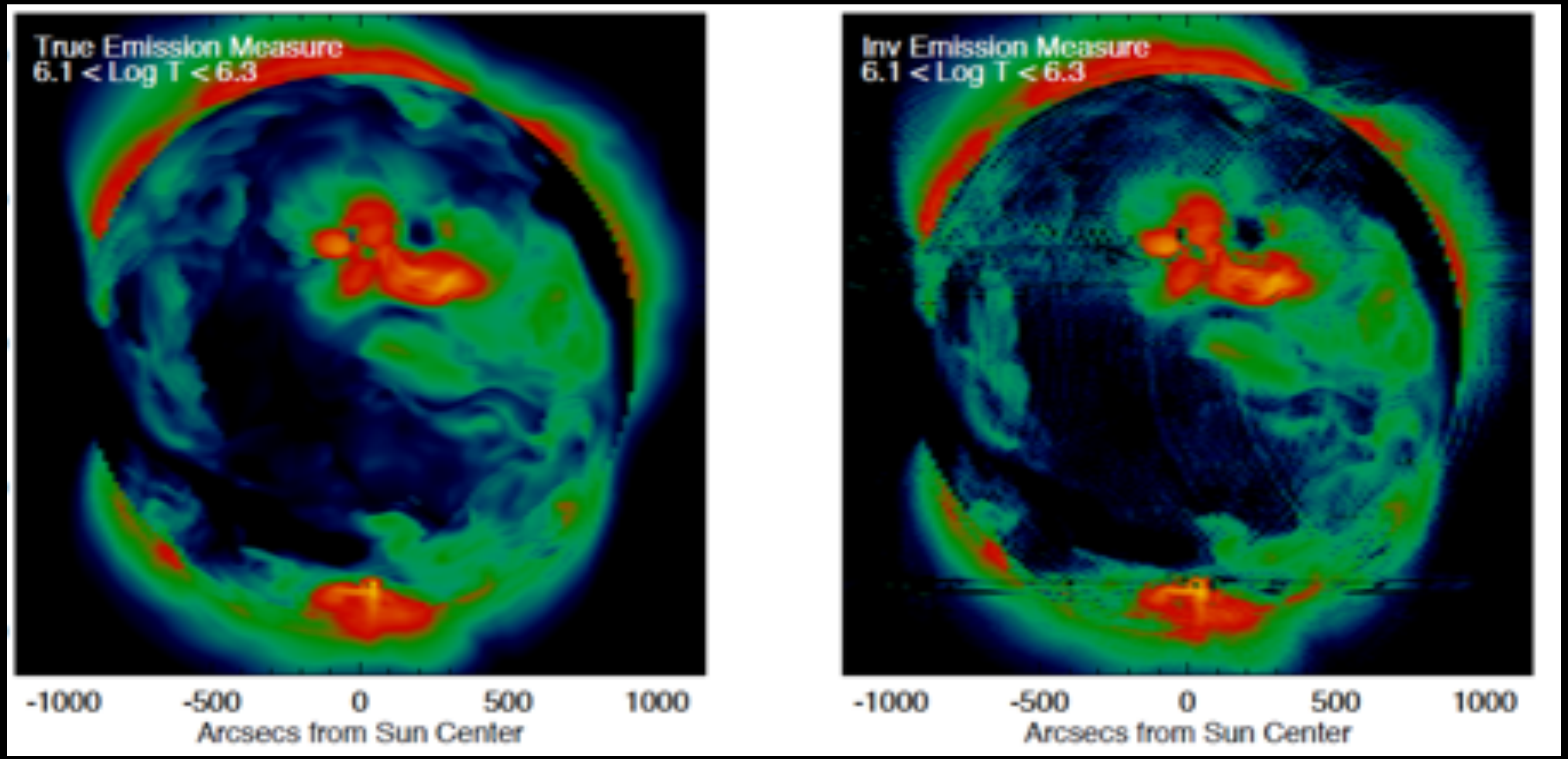
The images provide diagnostics for large solar events (location, strength, speed).



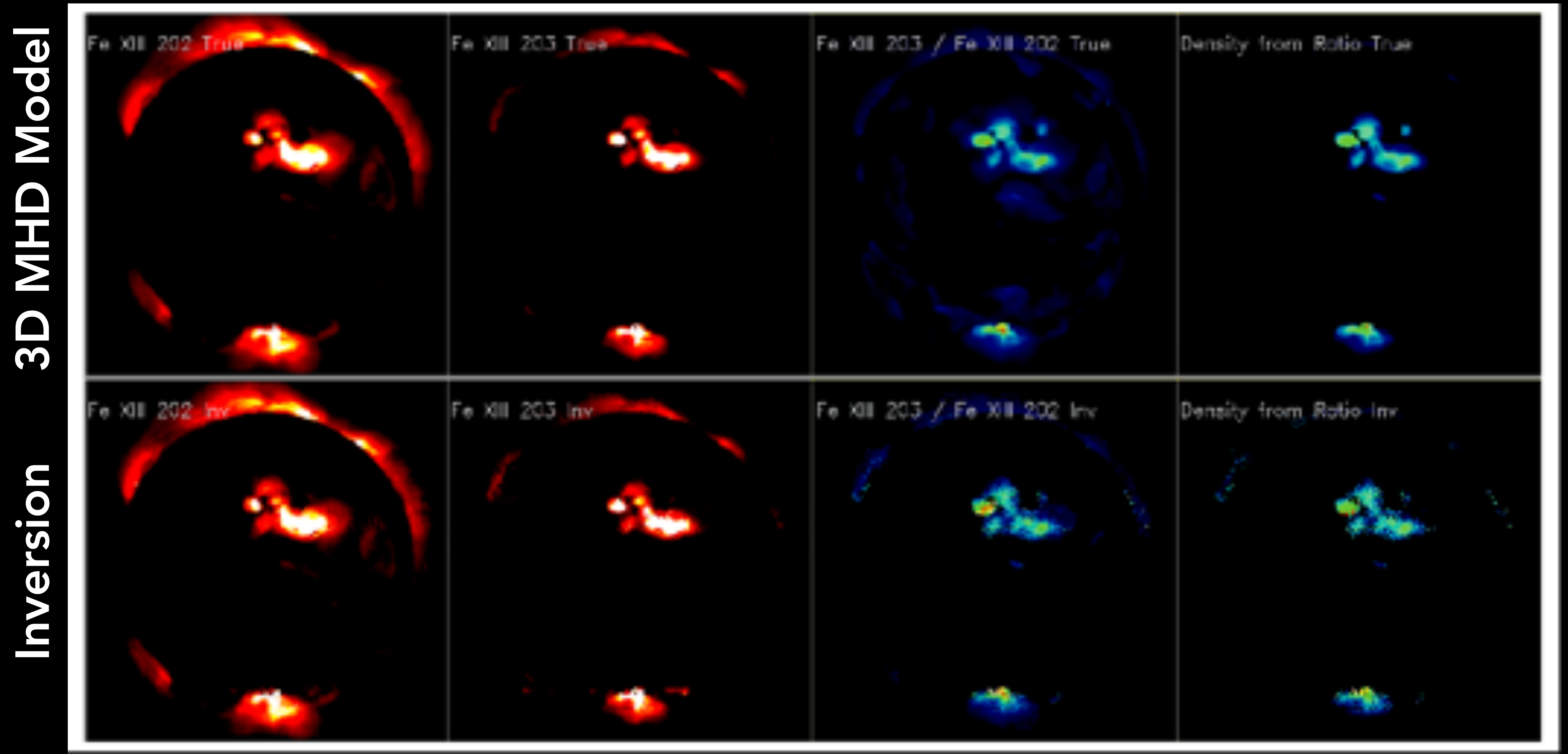
Courtesy L. Golub

Unfolding Overlaping Spectral Images

True versus reconstructed (via direct inversion) emission measure maps for T ~1.2 – 2 MK (Winebarger et al., 2018).



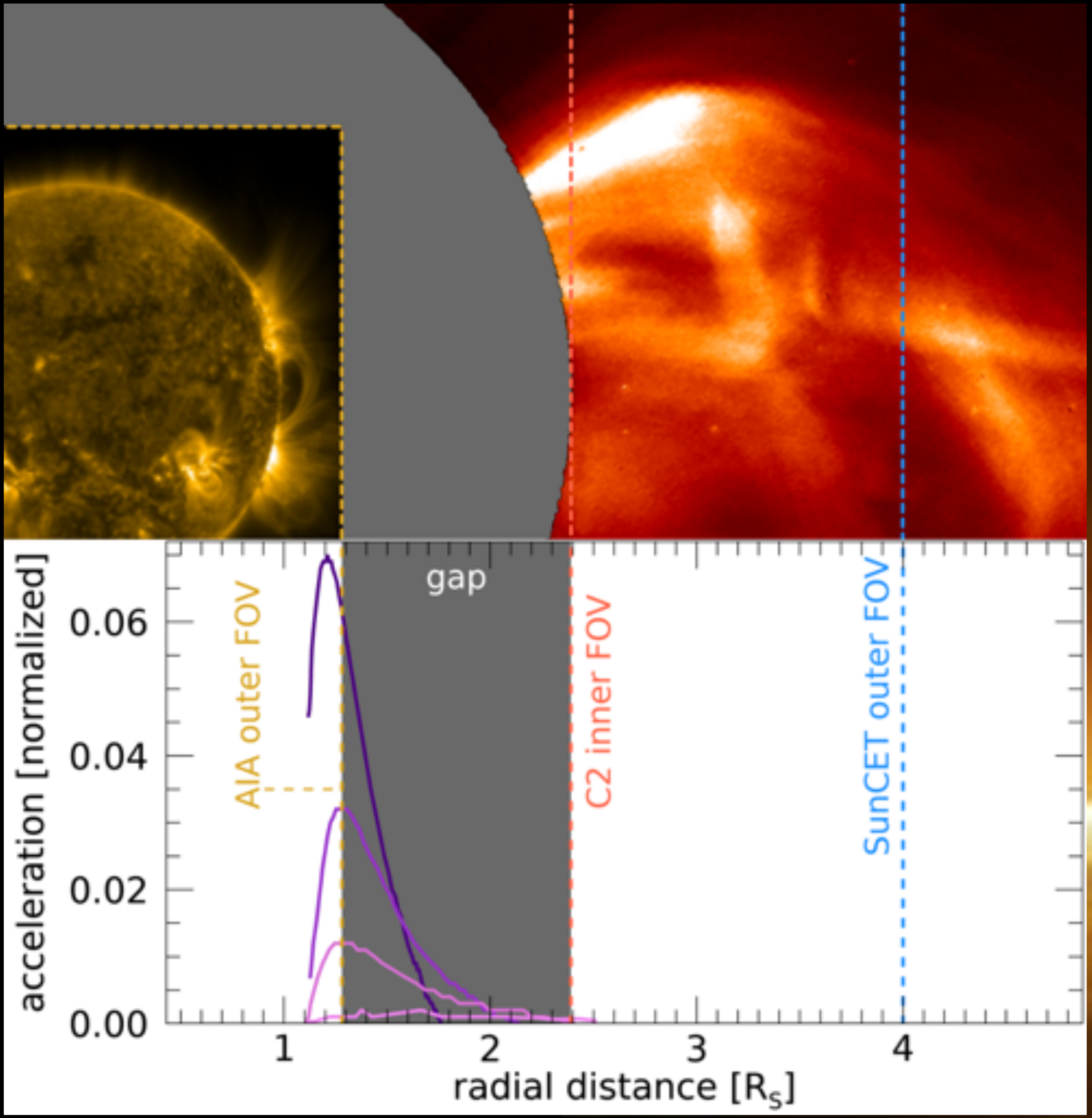
Full Sun intensity maps for Fe XII 203 A and Fe XIII 202 A, and density maps calculated from the ratio of these lines



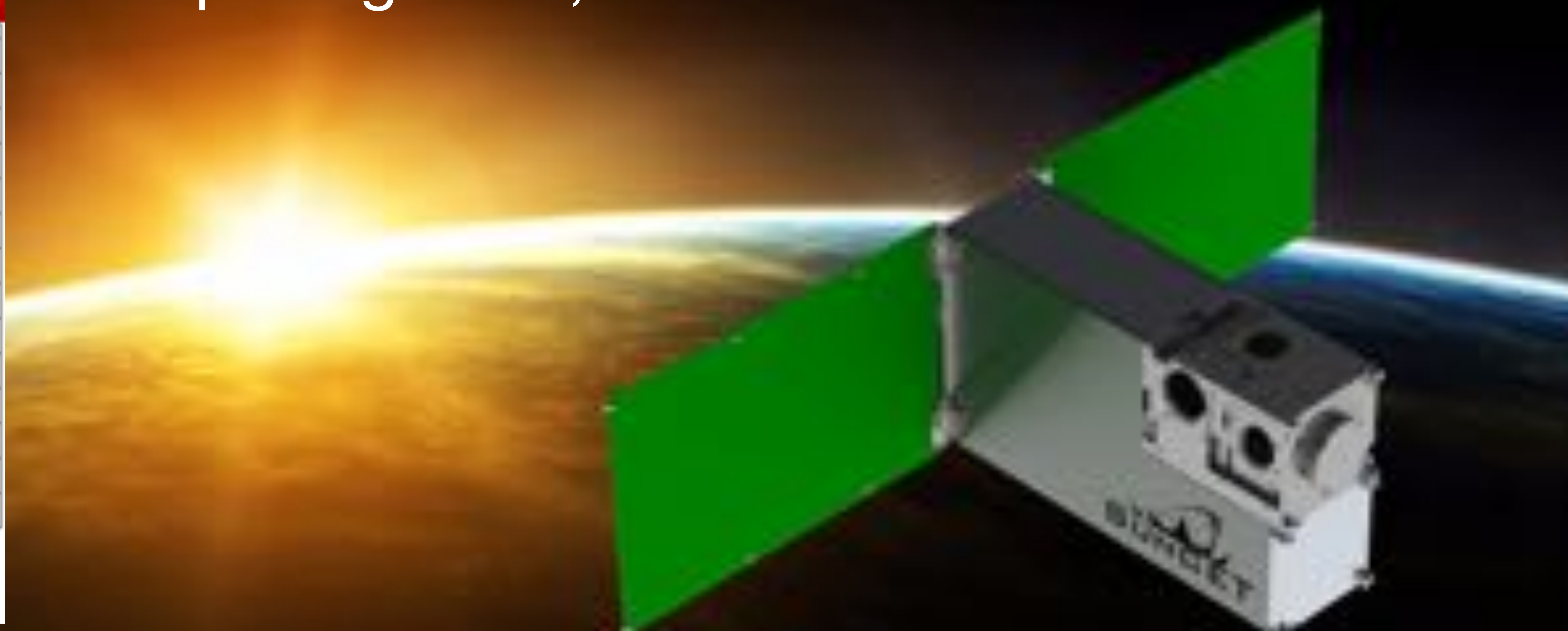
Courtesy L. Golub

Courtesy J. Mason

Sun Coronal Ejection Tracker



- 6U CubeSat
- 0-4 $R_\odot$ field of view
- 170-200 Å bandpass
- Measure the entire CME acceleration profile
- Proposing 2019, launch 2023

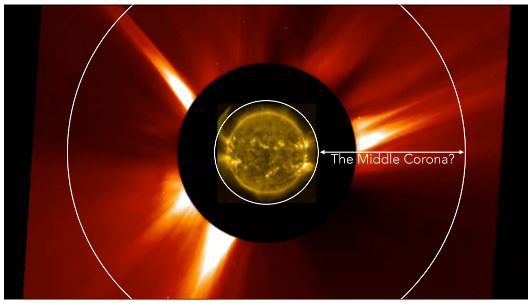


TO UNDERSTAND THE GLOBAL CORONA WE WILL…

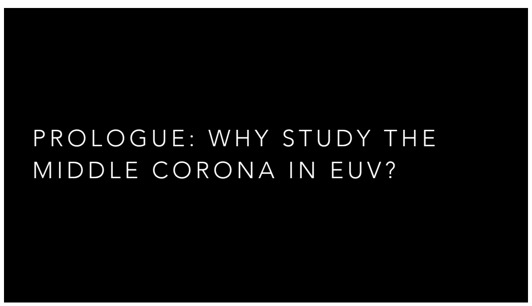
- ✓ Deploy new image processing techniques to illuminate hard-to-observe structures and dynamics.
- ✓ Bring together interdisciplinary teams that can unravel mysteries requiring the coupling of very different physical regimes.
- ✓ Develop instruments that fully close the observational gap between coronal domains.
- ✓ Build links to new missions (PUNCH, Solar Orbiter, Parker Solar Probe, Lagrange) to create truly global observation sets.

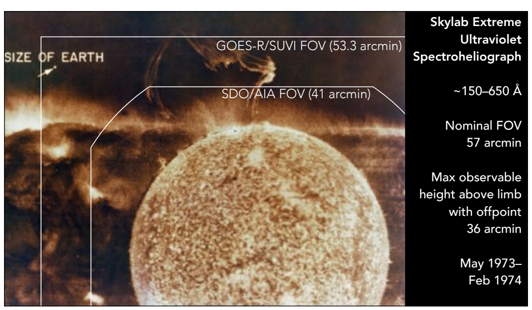
Middle Corona EUV imagers at L5 will allow us to develop coherent observations of the corona/heliosphere that are *required* to answer important questions about coronal physics and the origins space weather phenomena.

These are particularly valuable when coupled with observations from near-Earth and out-of-the-ecliptic vantages.



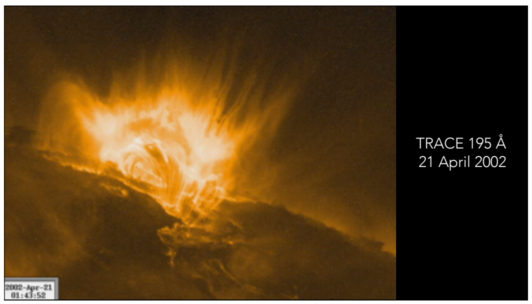
The middle corona is a poorly defined region, between roughly 1.3–5 solar radii, defined by sparse observations and complex transitional physics. It's the region where the corona changes from magnetically dominated to flow dominated, and it's the region where energy is liberated from the Sun's magnetic field to drive flares and eruptions.



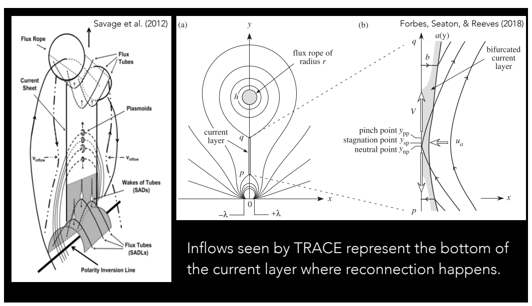


Early observations of the Sun in EUV made use of large fields of view and revealed the structure and dynamics of large-scale eruptions and other features of the corona.

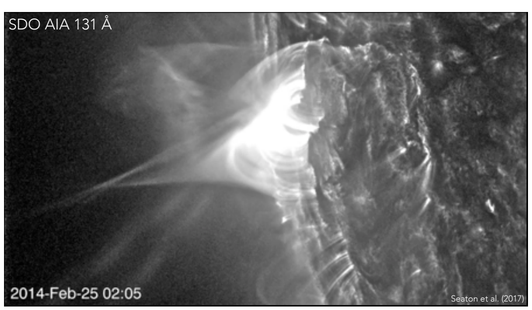
Focusing in on the corona on small scales with imagers like TRACE provided tantalizing glimpses of important features with relevance to the middle corona.



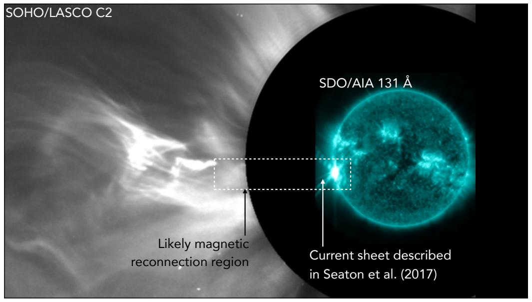
Trace observations of a huge eruption in 2002 shows all sorts of dynamics associated with the process of reconnection, but small fields of view limited the availability of direct observations of the reconnection region.



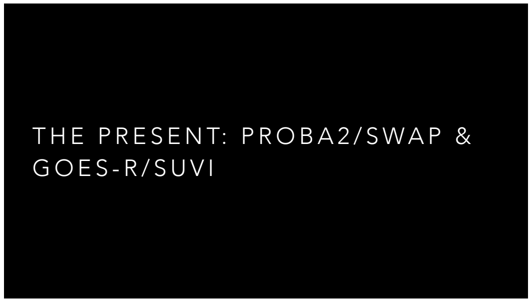
These TRACE inflows are now known to be Supra-Arcade Downflows (SADs), and are linked to processes of reconnection. We have good reconnection models that describe the structure and dynamics of current sheets, but do not have observations that can validate model predictions.

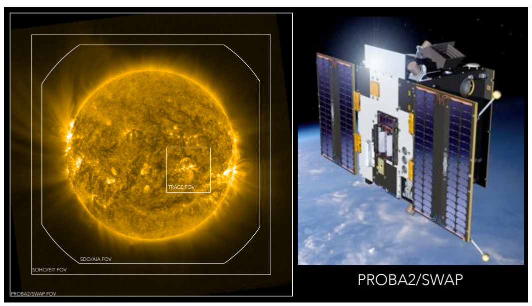


AIA has helped with the reconnection problem, but we still haven't seen the upflow/downflow pairs that are predicted by reconnection models. (Note the view is in profile instead of along the plane of sky like the TRACE movies.)

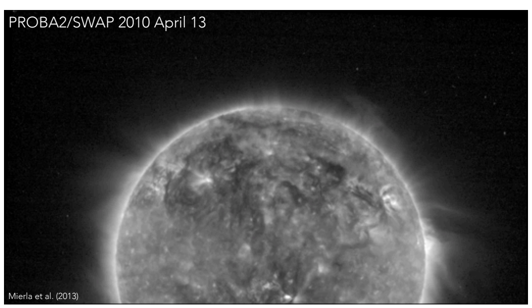


This lack of observations is probably because the outflow region is too high in the corona. So how can we close the gap?

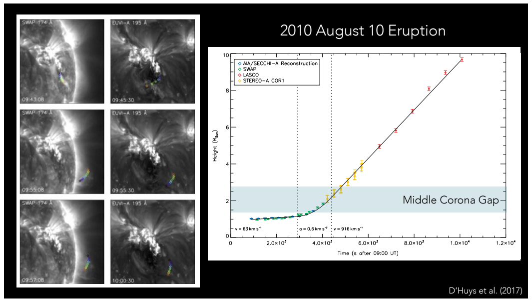




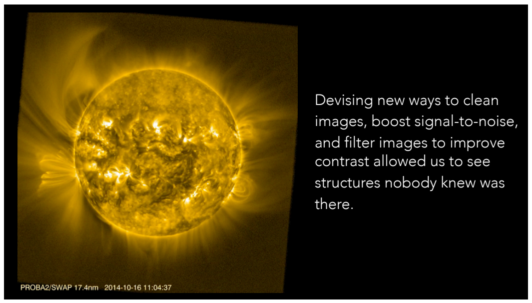
PROBA2/SWAP was one of the first imagers to be used this way, providing 174 Å EUV observations with a field of view much larger than AIA or even EIT.



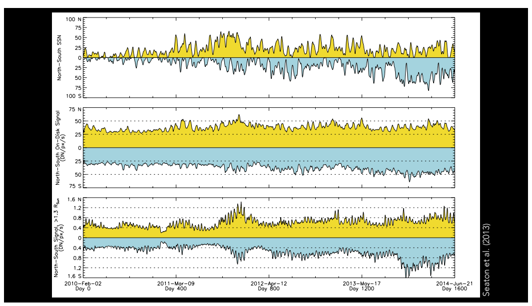
Early observations allowed us to track eruptions high in the corona…



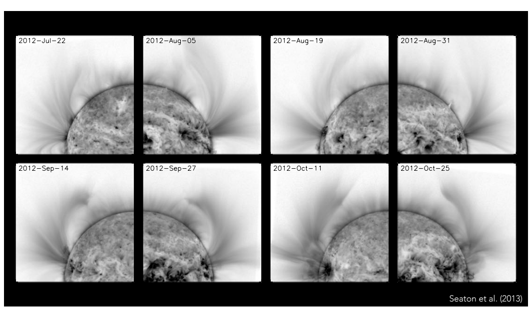
…and, using joint STEREO/PROBA2 reconstructions, track eruptions through the traditional gap region in the middle corona.



More complex image processing techniques allowed us to probe the structure of the middle corona. It is highly dynamic, and not dominate by loops, but rather surfaces, sheets, and broad fans of brightness. (Movie: http://proba2.oma.be/swap/movies/campaign_movies/swap_cr_2152_2158/swap_eclipse_cr_2152_to_2158_comp.mp4)

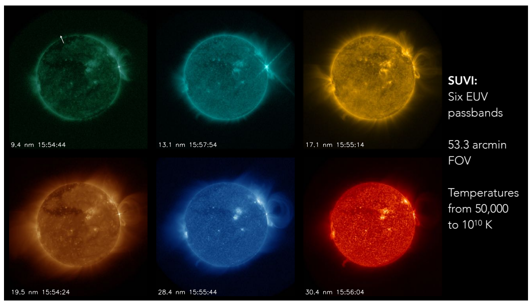


Looking at how irradiance varied at different heights, we saw strong periodic behavior high in the corona that did not really resemble what we saw on disk. What could be responsible for these?

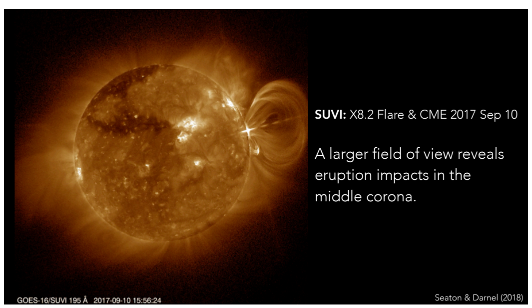


Turns out that these were the signatures of highly extended, long-lived fans, bright open field regions which may be related to the slow solar wind. What drives material/energy into these regions and makes them visible, unlike their open counterparts coronal holes? Why do they appear to form at the boundaries of high-latitude pseudostreamers?

The GOES-R Solar Ultraviolet Imager (SUVI) added to this picture beginning in November 2016.

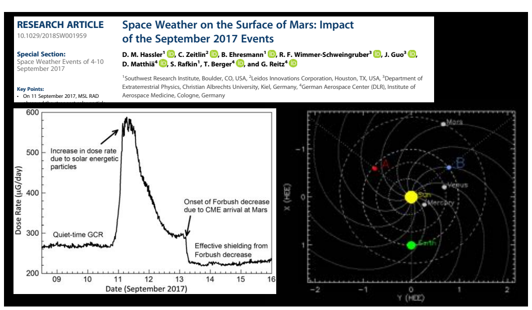


SUVI is much like SWAP, but has 6 passbands rather than 1.

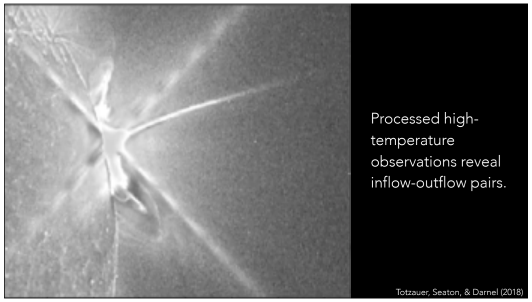


Carefully processed SUVI observations revealed how CME-related shocks/waves are massively global phenomena. This can help explain how…

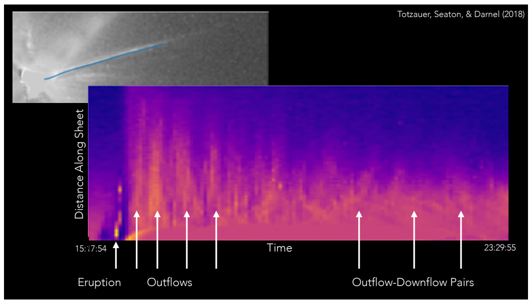
See movies and additional images in Seaton & Darnel (2018; DOI: 10.3847/2041-8213/aaa28e)



…major SEP events can be detected simultaneously at locations throughout the solar system, like this one which was detected both on Mars and as a Ground Level Enhancement on Earth.

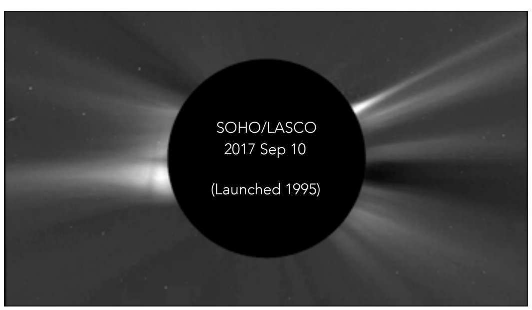


SUVI observations of the same event revealed dynamics along current-sheet-like features…

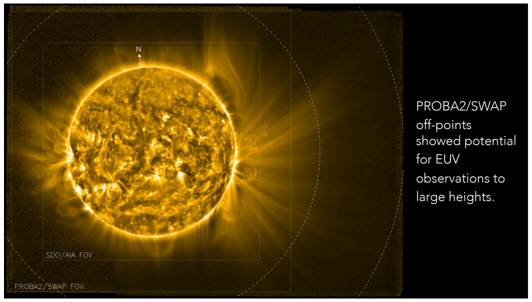


…including, when you look at how brightness propagates along this structure, inflow-outflow pairs that are exactly what reconnection models predict.

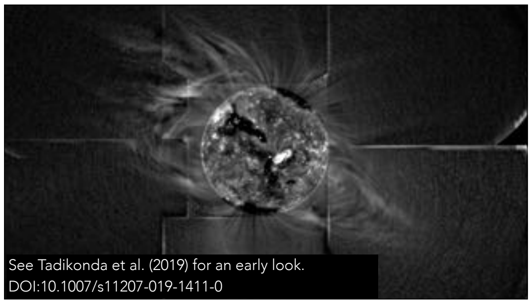
But still, how can we go further?



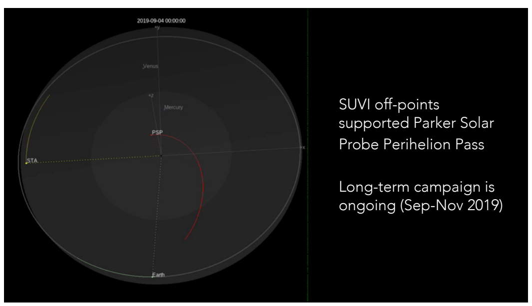
NOAA and the GOES Program started to explore potential ways to mitigate the sudden loss of LASCO data.



We had observed structure far above the limb with SWAP, so decided to see if SUVI off-points could be useful for this.



Results have been promising. Seaton et al. (2019, in prep) will address the dynamics discussed in this presentation; omitted in this presentation.



SUVI ran a month-long campaign in August/September 2018, another three-month campaign is ongoing now, run concurrently with PSP perihelion.

LOOKING AHEAD: WHAT DO WE HAVE? WHAT DO WE NEED?

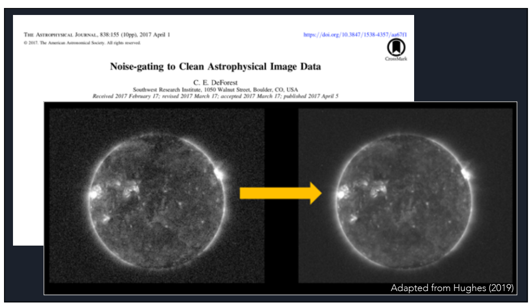
What does the future hold?

USING EUV IN THE MIDDLE CORONA, WE HAVE…

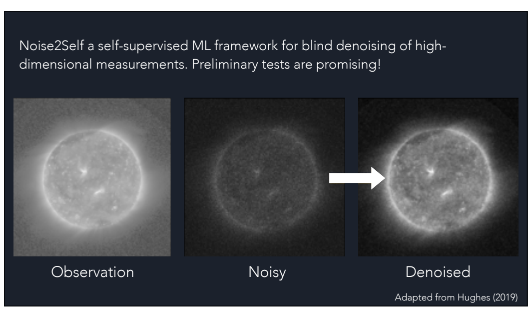
- Identified structure and outflows that could be the origins of the solar wind, and which help shape the global corona.
- Identified key features to advance understanding of reconnecting current layers and validate reconnection models.
- Demonstrated the value and viability of imaging this region to solve critical unresolved problems in coronal physics.

BUT STILL, WE MUST…

- Deploy new image processing techniques to illuminate hard-to-observe structures and dynamics.
- Bring together interdisciplinary teams that can unravel mysteries requiring the coupling of very different physical regimes.
- Develop instruments that fully close the observational gap between coronal domains.
- Build links to new missions (PUNCH, Solar Orbiter, Parker Solar Probe, Lagrange, L5/L*) to create truly global observation sets.



We are developing a variety kinds of new techniques to reduce noise and improve images. These will be invaluable for working on low-signal middle corona observations.



ML-based noise reduction techniques are also very promising.

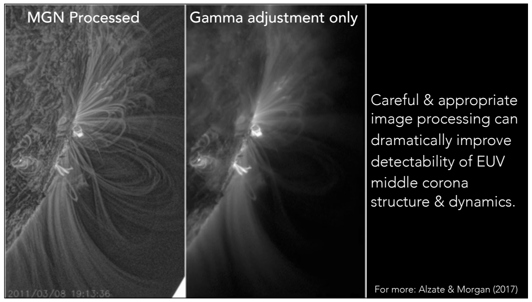
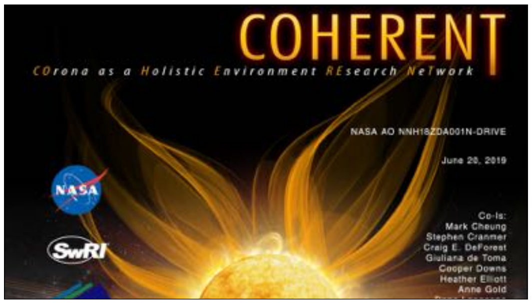
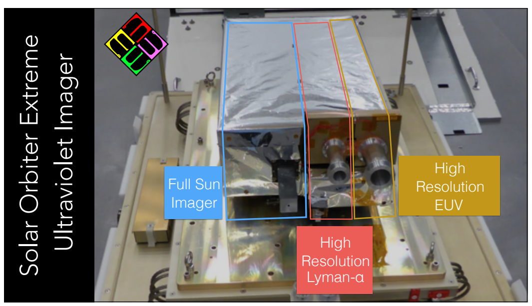


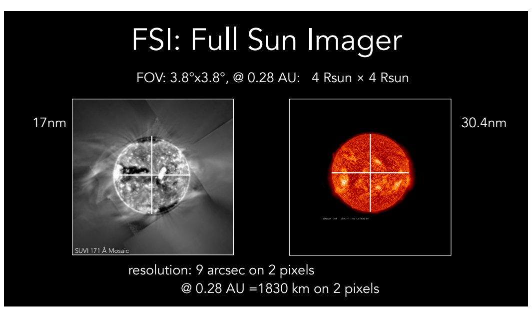
Image processing techniques like Multiscale Gaussian Normalization can reveal faint features that we would otherwise miss. We will need these to study this region!



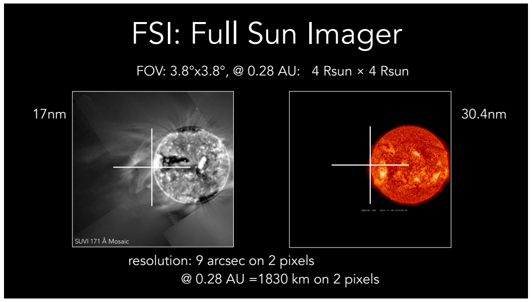
A number of collaborations, interdisciplinary sessions, and other new community efforts are providing the collaborative framework we need to study this region.



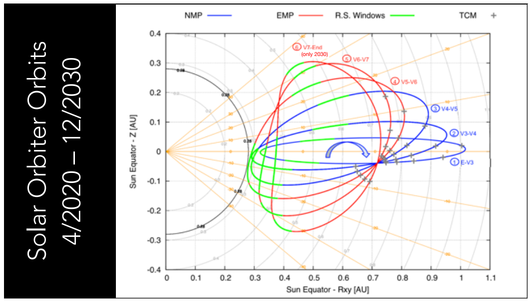
The Full Sun Imager in the EUV Suite on Solar Orbiter will provide useful large-field images of the corona in the EUV.



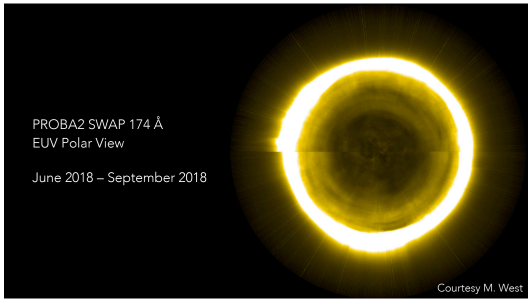
Even at closes approach, Solar Orbiter see a lot of extended EUV corona…



…and it can off-point to get an even wider view.

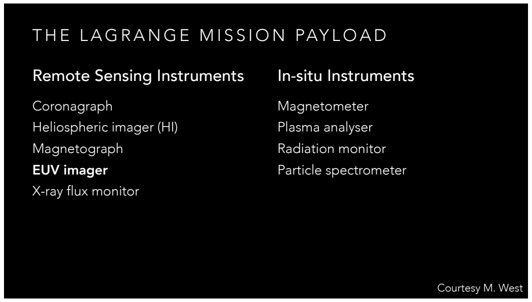


Of course, it will leave the ecliptic and give us a view closer to the poles as well.

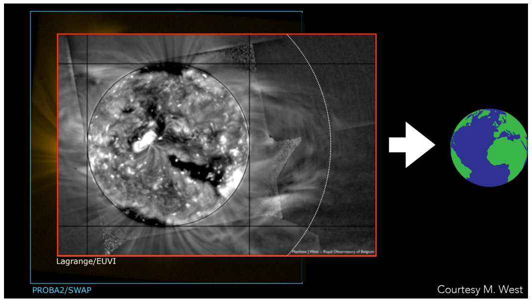


Some experiments with PROBA2/SWAP images give a clue as to what Solar Orbiter will reveal.

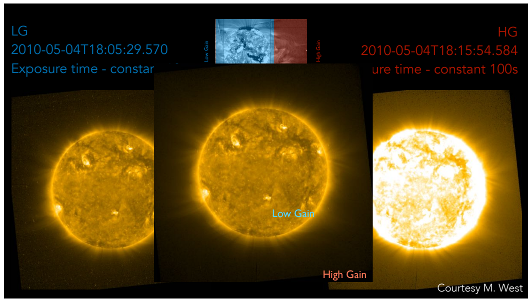
Lots of people spoke about Lagrange at this meeting.



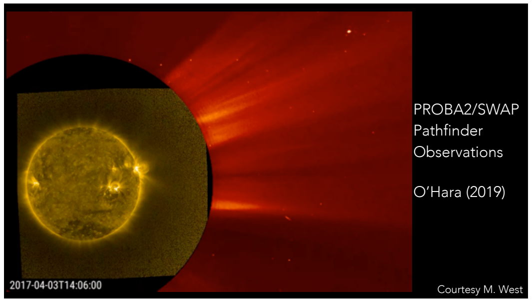
It also has a wide-field EUV imager.

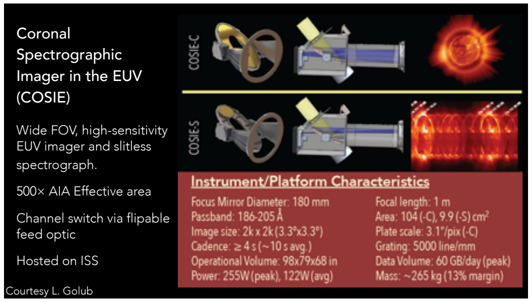


The FOV is offset to allow EUVI to observe well beyond 2 solar radii.

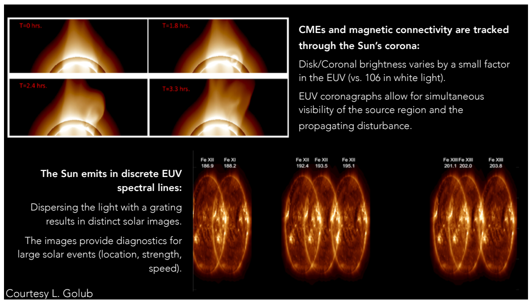


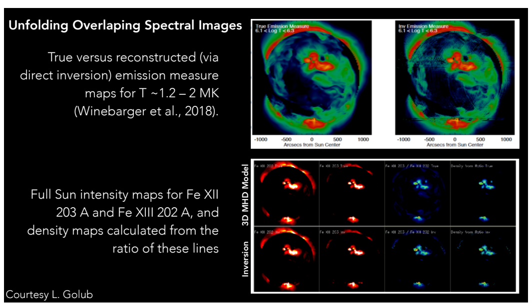
And it will use novel dual-gain imaging to do generate high-dynamic-range images.

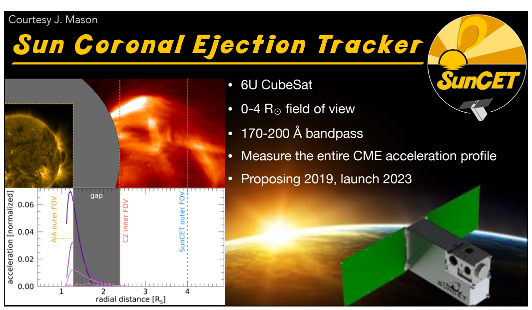




COSIE is another proposed wide field of view imager with some unique capabilities.







SunCET is a large FOV EUV imager proposal led by LASP, which could demonstrate this sort of observation can be miniaturized in a way that would be appropriate for L5/L* observations.

TO UNDERSTAND THE GLOBAL CORONA WE WILL…

- ✓ Deploy new image processing techniques to illuminate hard-to-observe structures and dynamics.
- ✓ Bring together interdisciplinary teams that can unravel mysteries requiring the coupling of very different physical regimes.
- ✓ Develop instruments that fully close the observational gap between coronal domains.
- ✓ Build links to new missions (PUNCH, Solar Orbiter, Parker Solar Probe, Lagrange) to create truly global observation sets.

In fact, these things we need to do are things that we *are* doing.

Middle Corona EUV imagers at L5 will allow us to develop coherent observations of the corona/heliosphere that are *required* to answer important questions about coronal physics and the origins space weather phenomena.

These are particularly valuable when coupled with observations from near-Earth and out-of-the-ecliptic vantages.