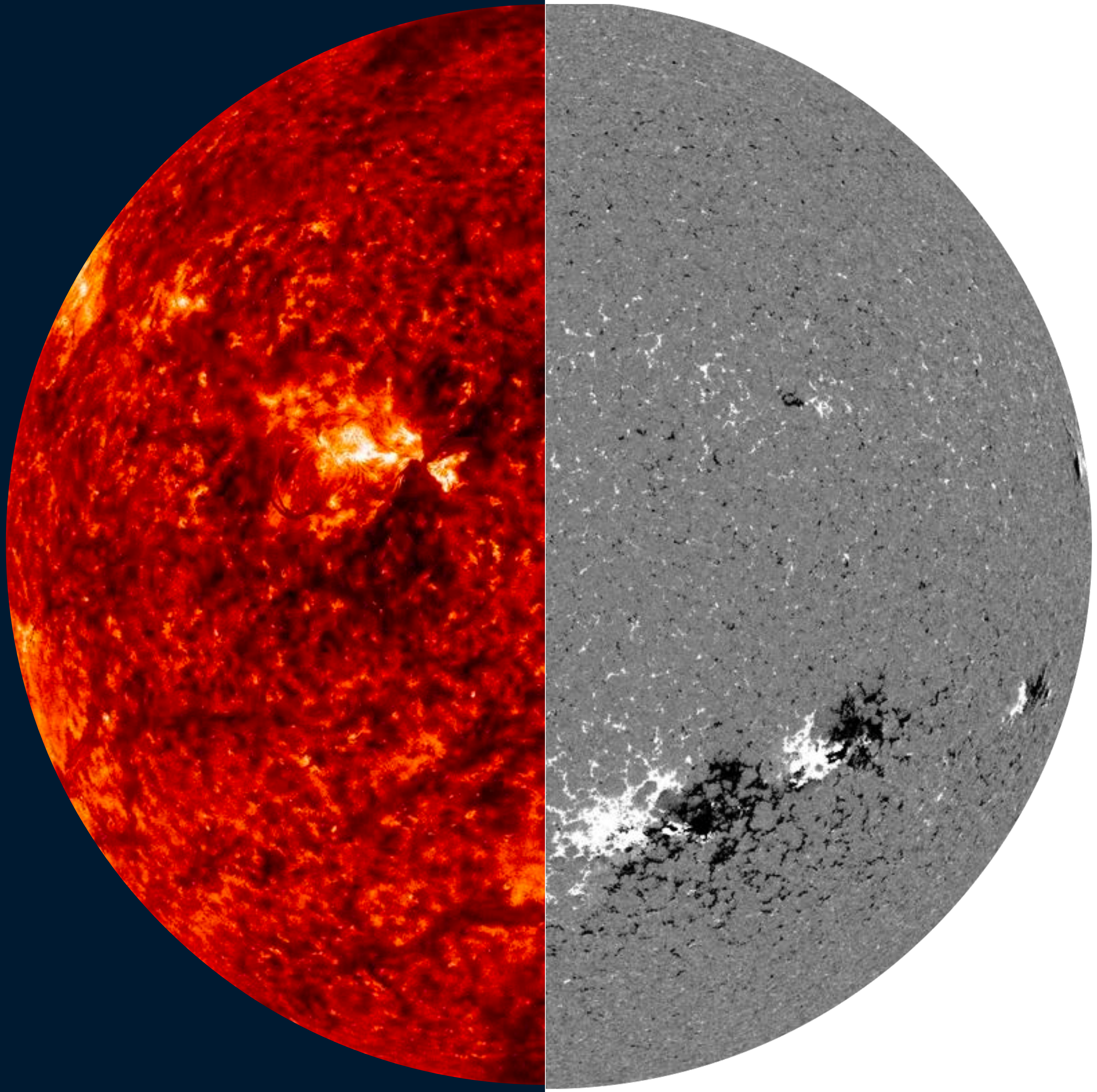
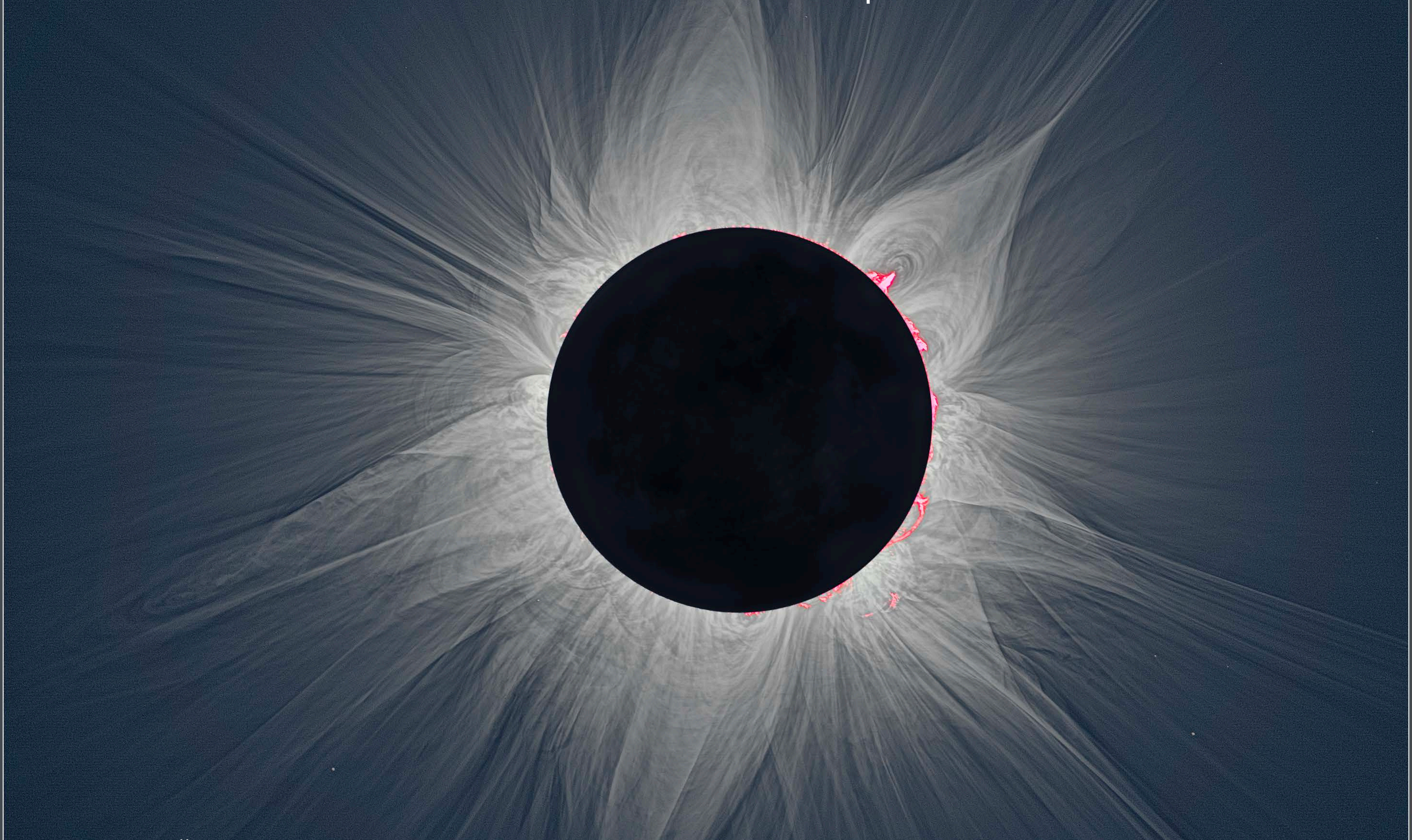
Solar Astronomy with Space-Based Telescopes



Mark Cheung, CSIRO Space & Astronomy

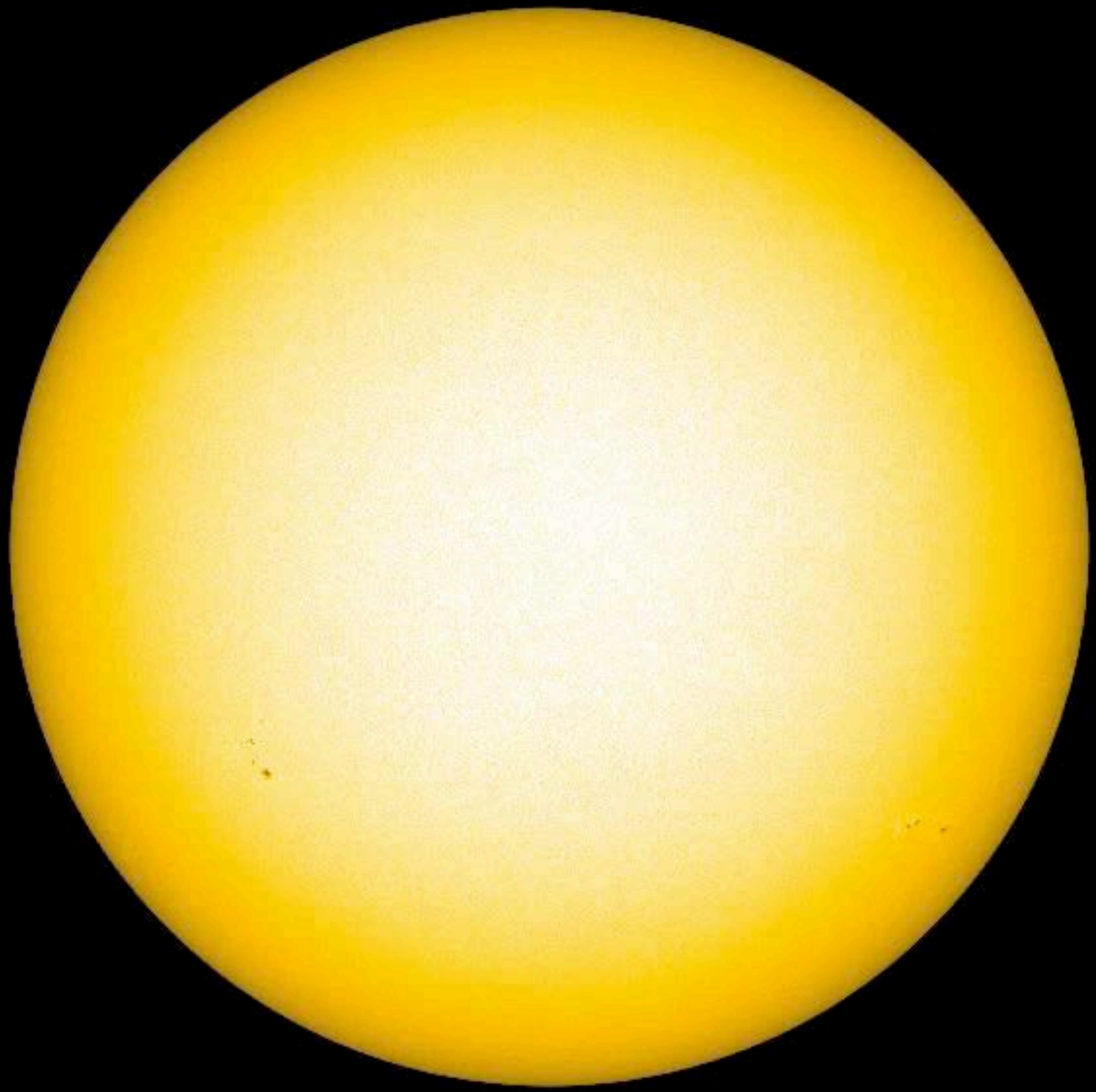
Advancing Australian Participation in Space-based Astronomy

Exmouth, WA on 20th April 2023



Credit: Pavel Štarha, Stadia Habbal, Miroslav Druckmüller

Total Solar Eclipse 2023



The solar corona has temperatures of millions of K.

Science Motivation

<u>Stellar interiors and atmospheres are natural laboratories</u>

<u>for plasma physics:</u>

- Physical processes: magnetohydrodynamic turbulence, particle acceleration, transport mechanisms in plasmas, magnetic reconnection, magnetised shocks, (magneto)convection in highly stratified & rotating bodies, MHD instabilities, multi-fluid effects, radiative transfer, dynamo action, conservation of topological invariants.

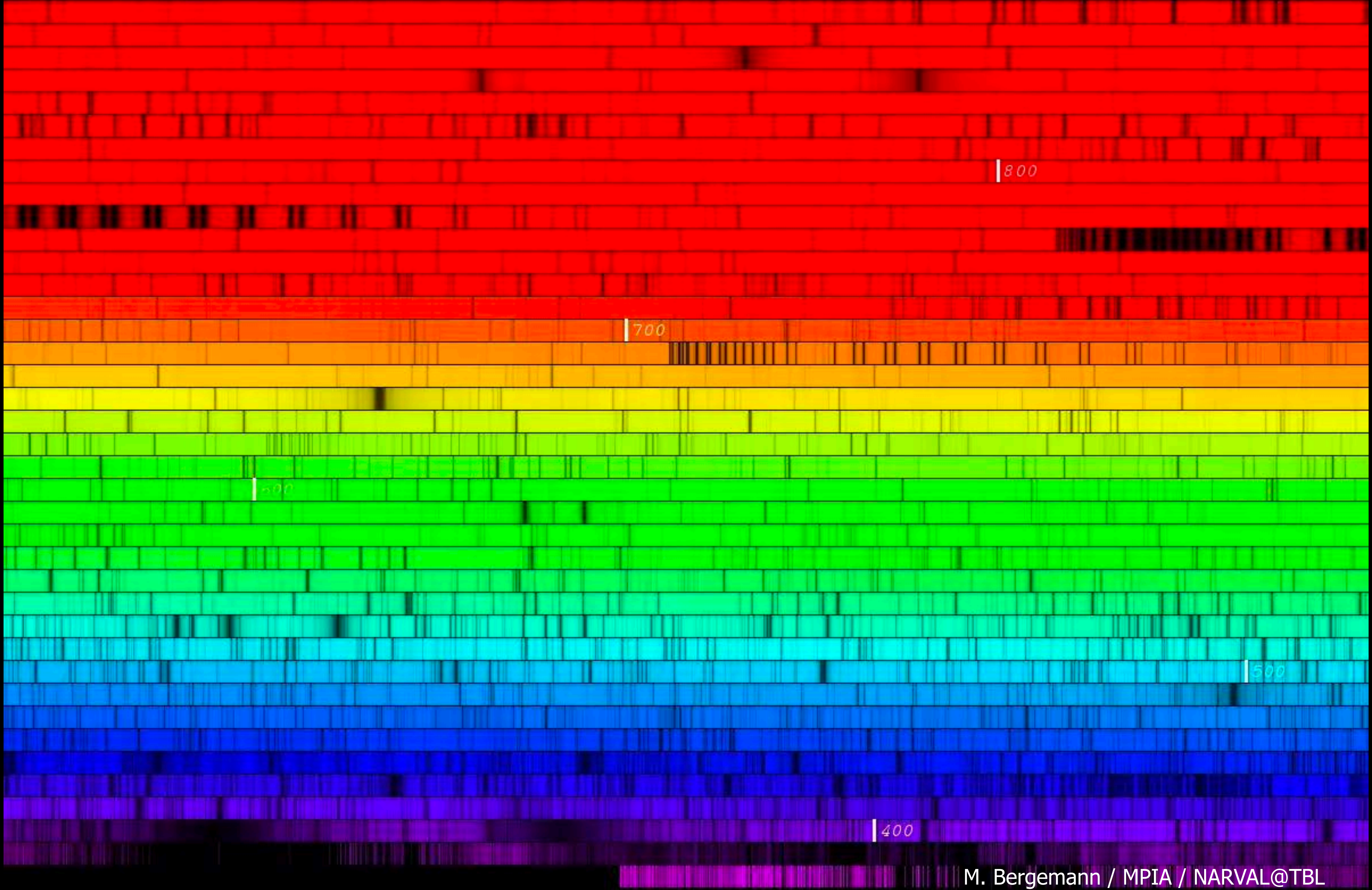
- Astrophysical manifestations: Sun/star-spots, flares, coronal mass ejections, solar/stellar activity cycles, winds, accreting flows, space weather, exoplanet habitability.

- Multi-wavelength (and multi-messenger) observations needed to reveal the richness of the underlying physics.

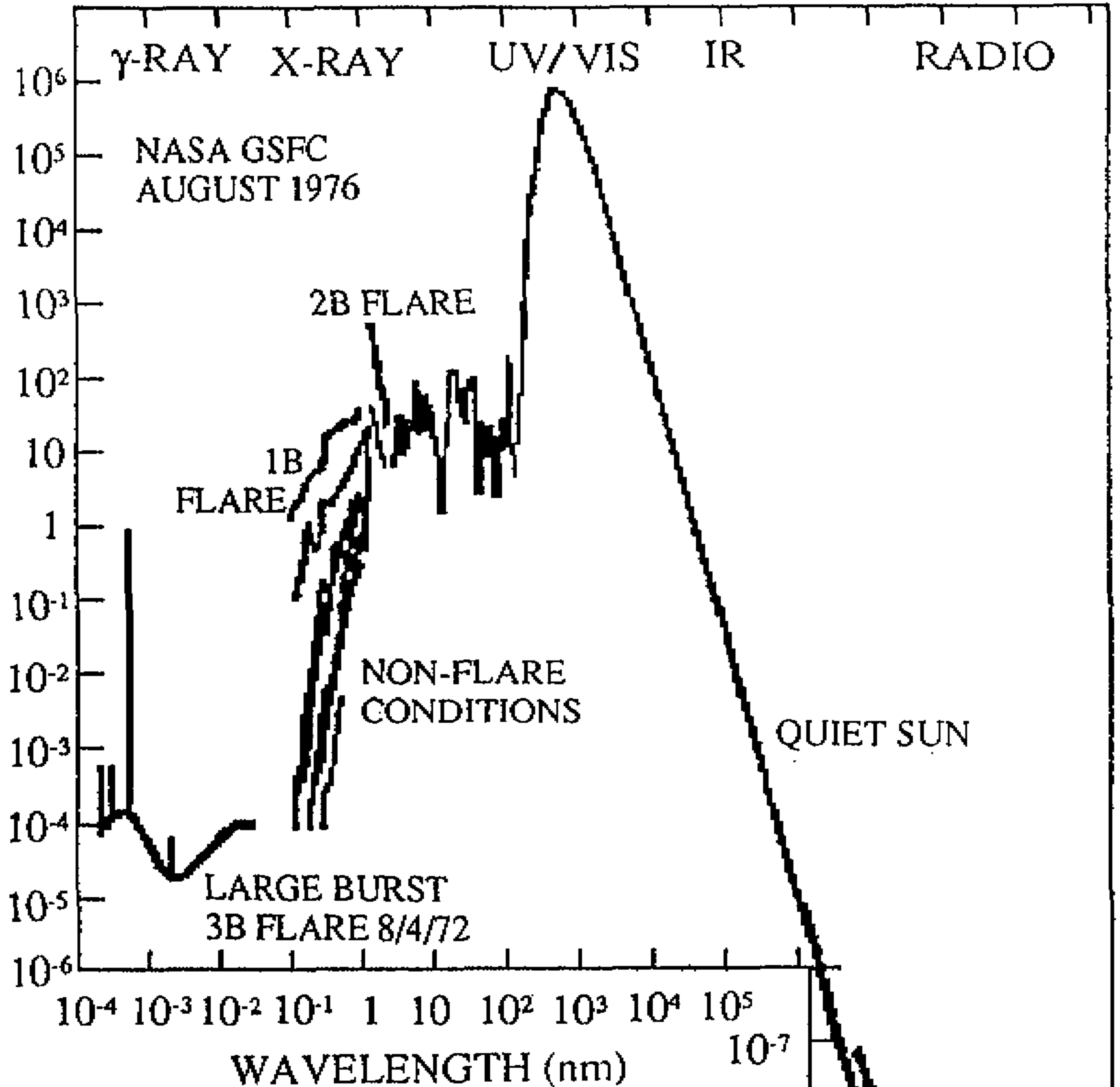
Solar Astronomy 101

<u>Most Salient Observational Features about the Sun</u>

- It rotates, but not as a solid body. The equator rotates faster than the poles (use helioseismology to probe the interior).
- It has sunspots. The number of sunspots waxes and wanes with an eleven year cycle.
- Magnetic fields pervade the entire Sun
- The Sun is a panchromatic astrophysical object.



M. Bergemann / MPIA / NARVAL@TBL



γ-RAY
X-RAY
UV/VIS
IR
RADIO
NASA GSFC
AUGUST 1976
2B FLARE
1B
FLARE
NON-FLARE
CONDITIONS
QUIET SUN
LARGE BURST
3B FLARE 8/4/72
10⁶
10⁵
10⁴
10³
10²
10
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁴ 10⁻³ 10⁻² 10⁻¹ 1 10 10² 10³ 10⁴ 10⁵
WAVELENGTH (nm)

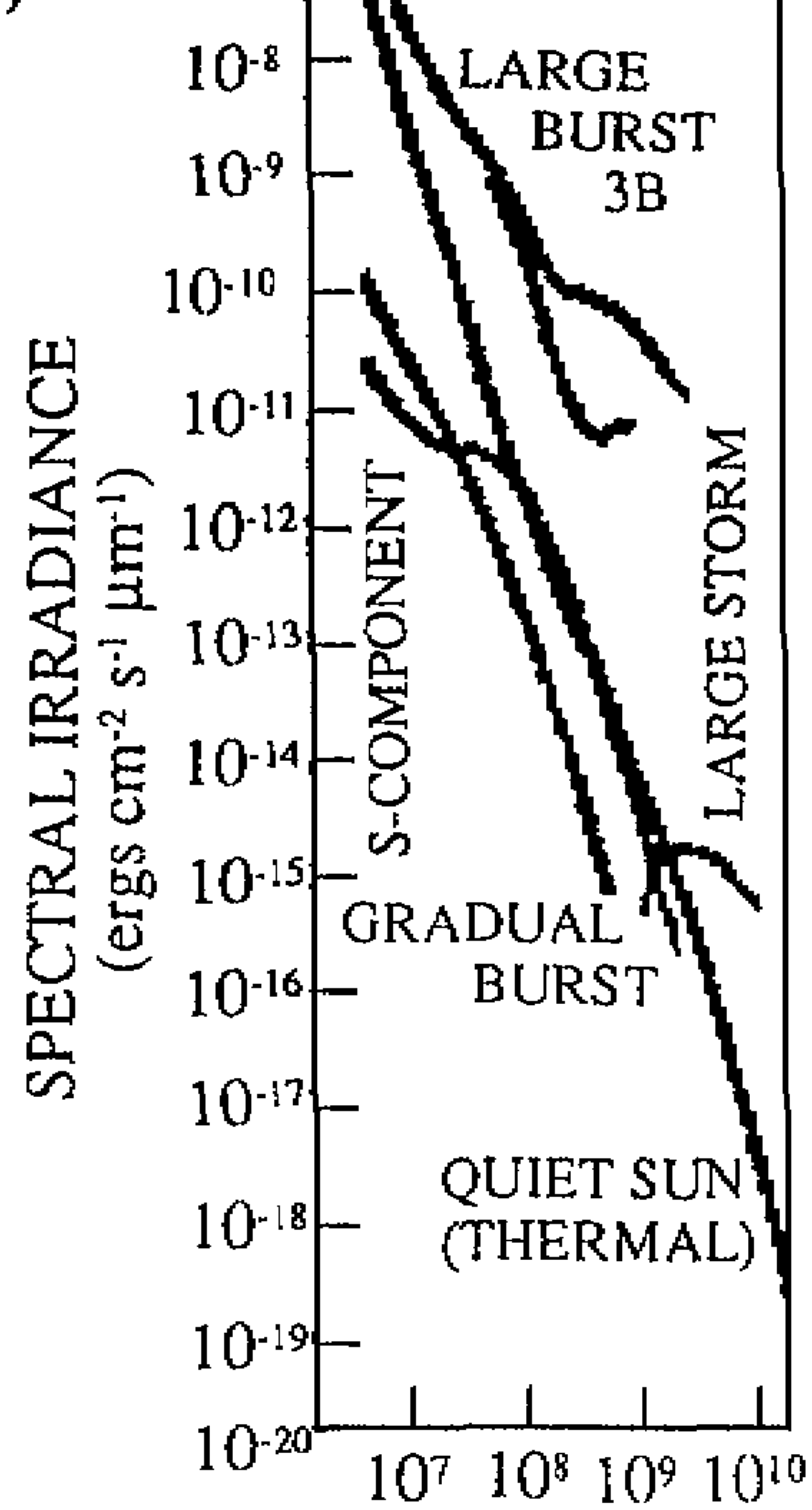


Fig. 3. The solar spectrum from gamma rays to radio wavelengths from *White* [1977].

Solar Astronomy 101

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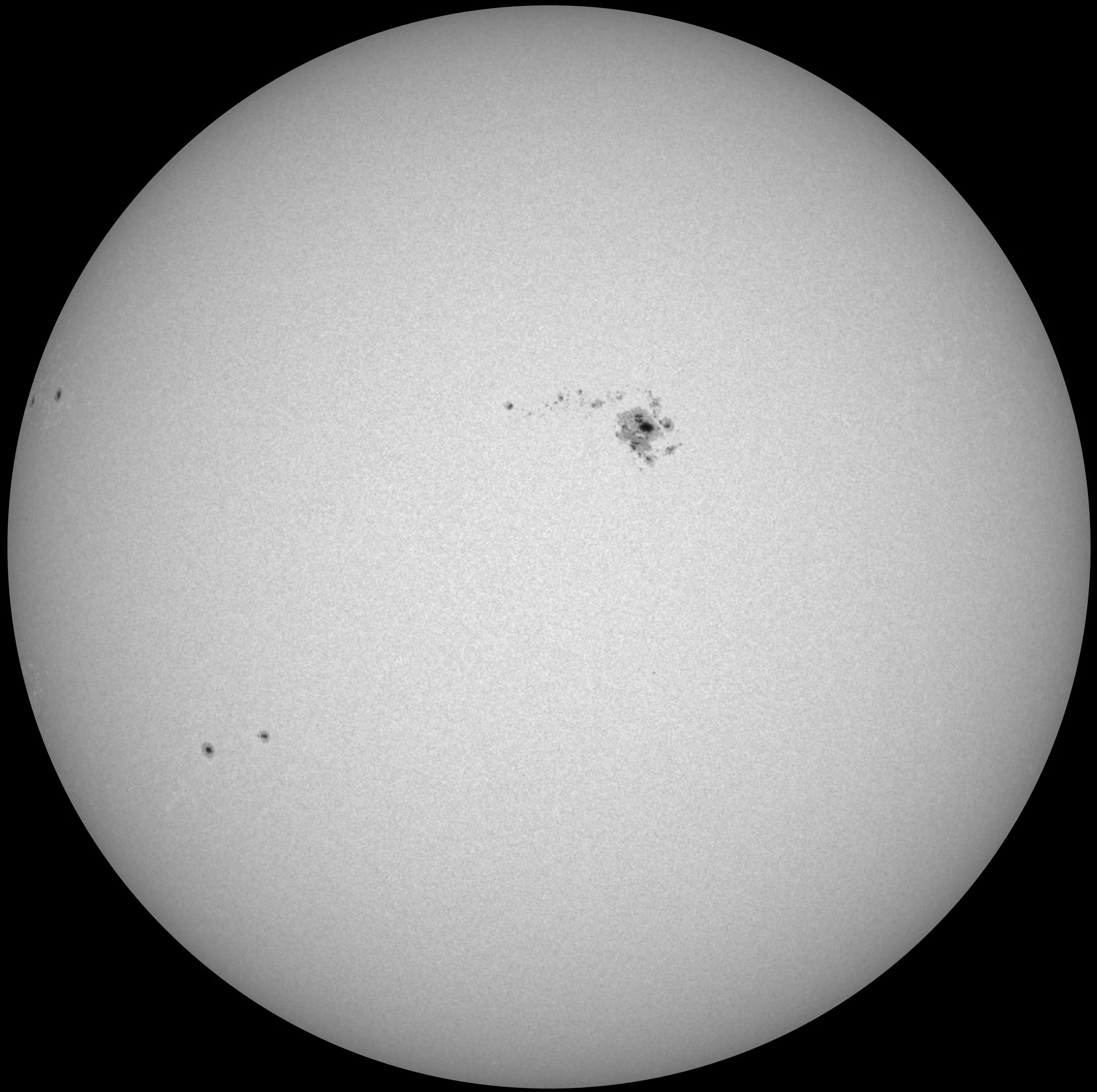
- It has sunspots. The number of sunspots waxes and wanes with an eleven year cycle.
- Magnetic fields pervade the entire Sun.

  The Sun is a panchromatic astrophysical object.
- The hot corona consists of loops anchored at/near sunspots.
- Total eclipses are awesome (partial eclipses less so). 😎

Sunspots are like planet-sized MRI machines

Credit: Swedish Solar Telescope



Credit: Solar Dynamics Observatory / Stanford


HELIOPHYSICS SYSTEM OBSERVATORY
• 20 Operating Missions with 27 Spacecraft
• 14 Missions in Formulation or Implementation
• 1 Under Study
FORMULATION
IMPLEMENTATION
PRIMARY OPS
EXTENDED OPS
Solar Orbiter (ESA)
ACE
Solar Cruiser
SunRISE (6)
SDO
AIM
TRACERS(2)
ICON
EUVST (JAXA)
HERMES (Gateway)
IBEX
AWE (ISS)
THEMIS-ARTEMIS (2)
GOLD (SES)
IMAP
SOHO (ESA)
Parker Solar Probe
WIND
GDC
HelioSwarm (9)
EZIE (3)
TIMED
GLIDE
PUNCH (4)
THEMIS (3)
MMS (4)
STEREO
Hinode (JAXA)
Geotail (JAXA)
IRIS
MUSE
CubeSats
In Development
AEPEX
AERO / VISTA
CIRBE
CURIE
CuSP
Dione
GTOSat
ICOVEX
LAICE
LLITED
CubIXSS
petitSat
REAL
SPORT
PADRE
SunCET
DYNAGLO
WindCube
On Orbit
ELFIN
SORTIE
CuPID
DAILI
Hosted Payloads
In Development
CODEX
LARADO
MinXSS-3
OWLS
STORIE
Voyager (2)
ESCAPADE (2)
RAD
OPERATING & FUTURE

ESA/NASA Solar Orbiter

DE GRUYTER Adv. Opt. Techn. 2014; 3(3): 309–314

Research Article Open Access

Stephen D. Gensemer* and David Farrant

Fabrication and metrology of lithium niobate narrowband optical filters for the solar orbiter

Abstract: We report on the fabrication of custom voltage tunable etalons for the SO/PHI spaceborne solar imaging instrument [A. Gandorfer, S. K. Solanki, J. Woch, V. M. Pillet, A. A. Herrero, and T. Appourchaux, J. Phys.: Conference Series 271, 012086 (2011)]. The etalons were manufactured to place a transmission maximum within 0.3 Å of the FeI emission line at 6175.0 Å. Meeting this specification requires an overall thickness specified to within ±15 nm, over a 60 mm aperture. We describe here the metrology, modelling and coating procedures we developed to achieve this.

Keywords: electrooptic; etalon; Fabry-Perot; filter; lithium niobate; solar.

DOI 10.1515/aot-2014-0016
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1 Introduction

Most astronomical spectral instruments are designed to maximise the light gathering capability, so that their dispersive elements distribute the spectral signal across large detectors. In the case of solar observations, however, imaging can be done with extremely narrow band filters which still pass enough light for high quality images [1–3]. The narrowest band filters, Fabry-Perot etalons, have an extremely high angular dependence of their pass band been a challenge for fabrication. Limitations in the thickness uniformity that is achievable by polishing have led to the development of vapour deposition as a method for correction of thickness nonuniformity, enabling us to produce substrates with thickness variations of <1 nm across 60 mm [4, 5]. Etalons made of lithium niobate ($LiNbO_3$) have the advantage of being tunable by tilting, temperature, and voltage. In addition, their high index of refraction allows them to be made thinner than comparable air-spaced etalons, resulting in low angular sensitivity. This makes them advantageous in telescopic systems, where a wide field of view is desired. Their light weight and stability also make them well suited to spaceborne instrumentation.

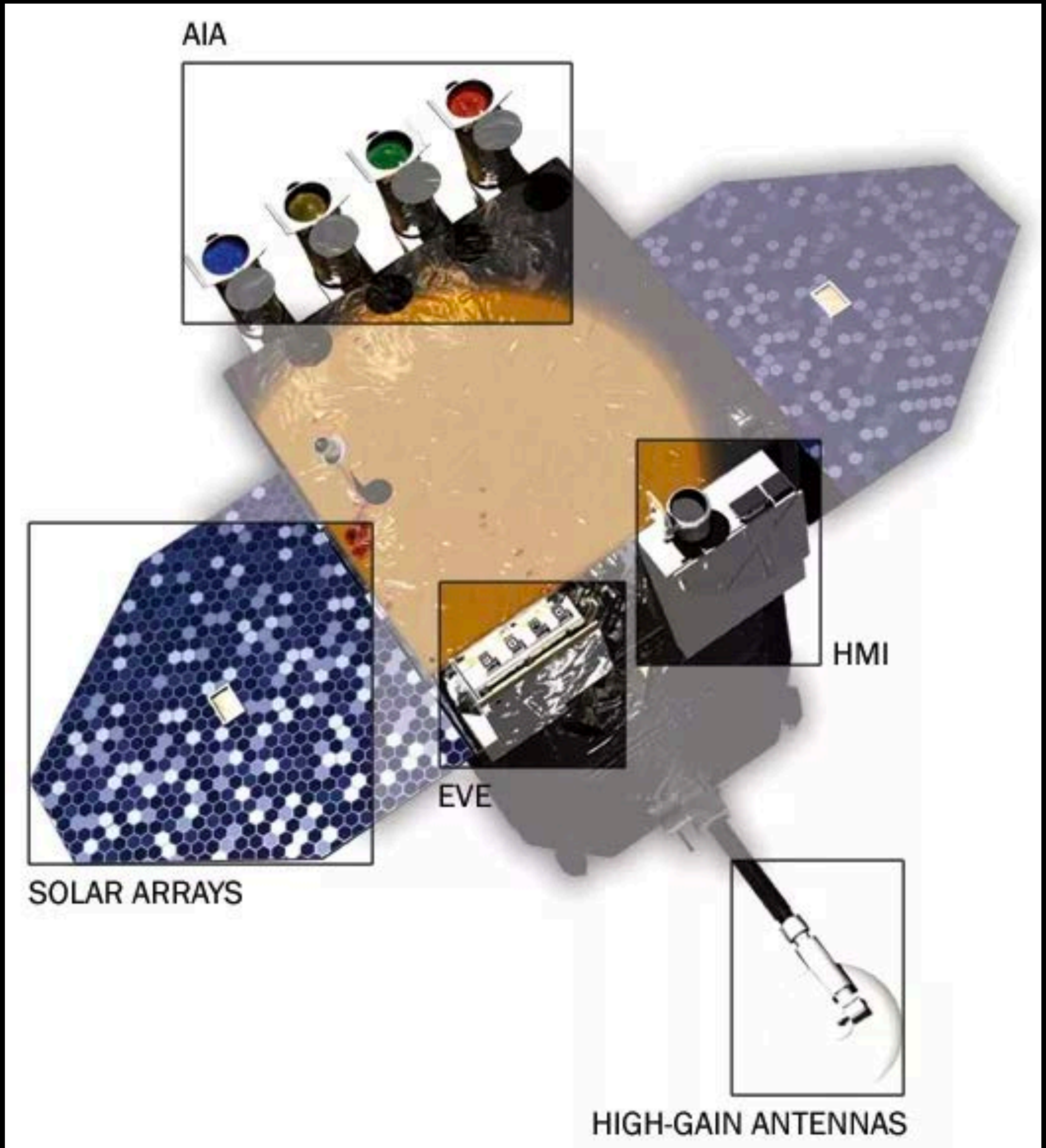
Typically $LiNbO_3$ voltage-tuneable etalons [6] are designed to be tuneable across the entire free spectral range, so that a fringe (transmission maximum) can be placed at any wavelength desired. The tuning range of such an etalon depends primarily on the thickness and the breakdown voltage, above which the crystal structure becomes depoled. The tuning range can be extended by varying the temperature and by tilting the etalon in addition to voltage tuning. However, in the Polarimetric and Helioseismic Imager for the upcoming Solar Orbiter (SO/PHI) [7], the thermal requirements of the satellite make temperature tuning of the etalon impossible, and tilt tuning is avoided to minimise pass band distortions. For these reasons, we are constrained to tunability of only a fraction of the free spectral range. The spectral window of interest is determined by the range of Doppler shifts of interest – a combination of the radial gas velocity

NASA’s Solar Dynamics Observatory

SDO in a Nutshell

3 instruments monitoring the Sun all the time since May 2010.

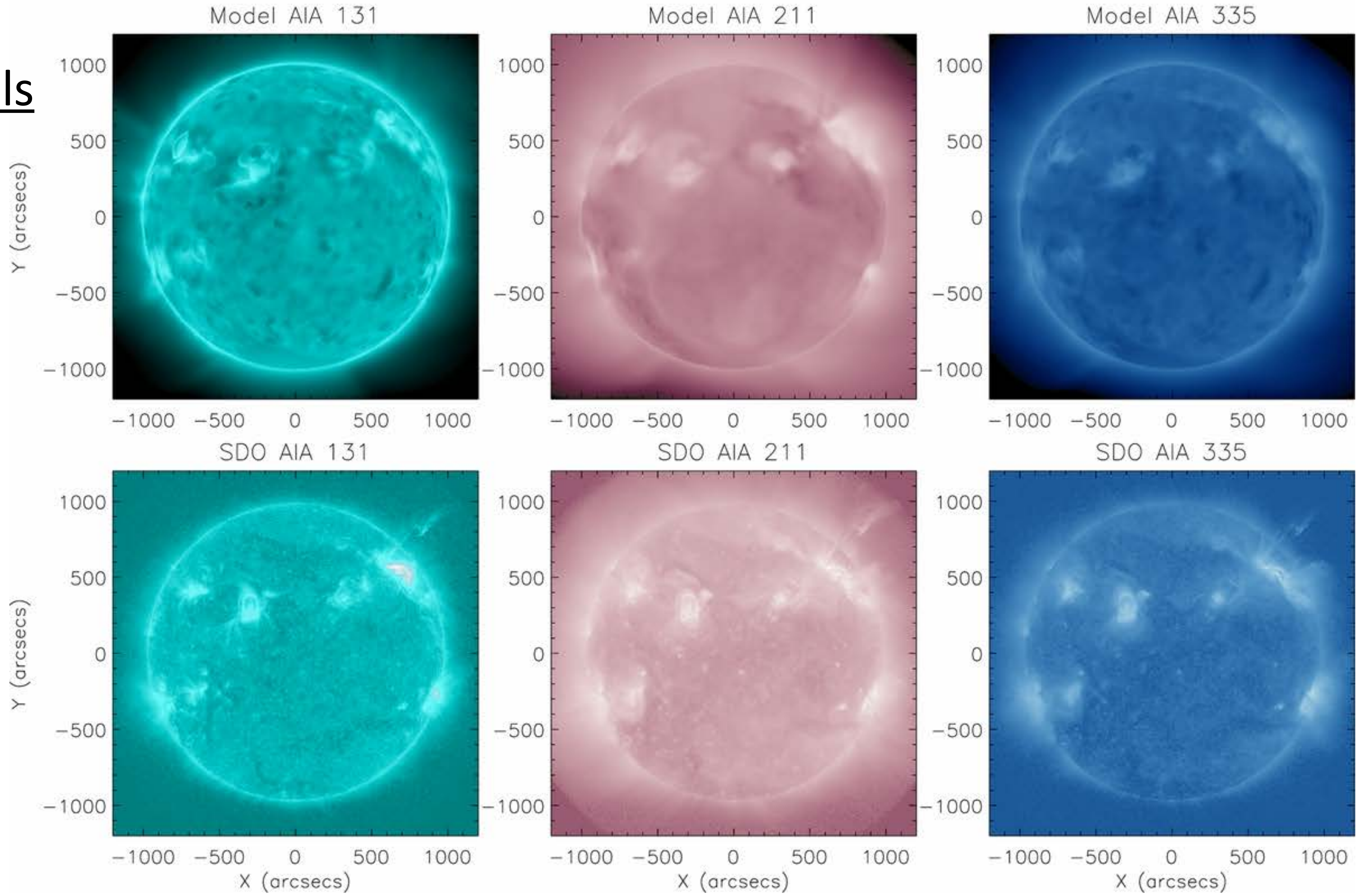
- Atmospheric Imaging Assembly: visible, UV, and EUV full disk images of the photosphere, chromosphere, transition region and corona at 4096x4096 pixels.
- Helioseismic & Magnetic Imager: visible light full disk dopplergrams and magnetograms at 4096x4096 pixels.
- EUV Variability Experiment: disk-integrated EUV irradiance spectra at 1 Å resolution.



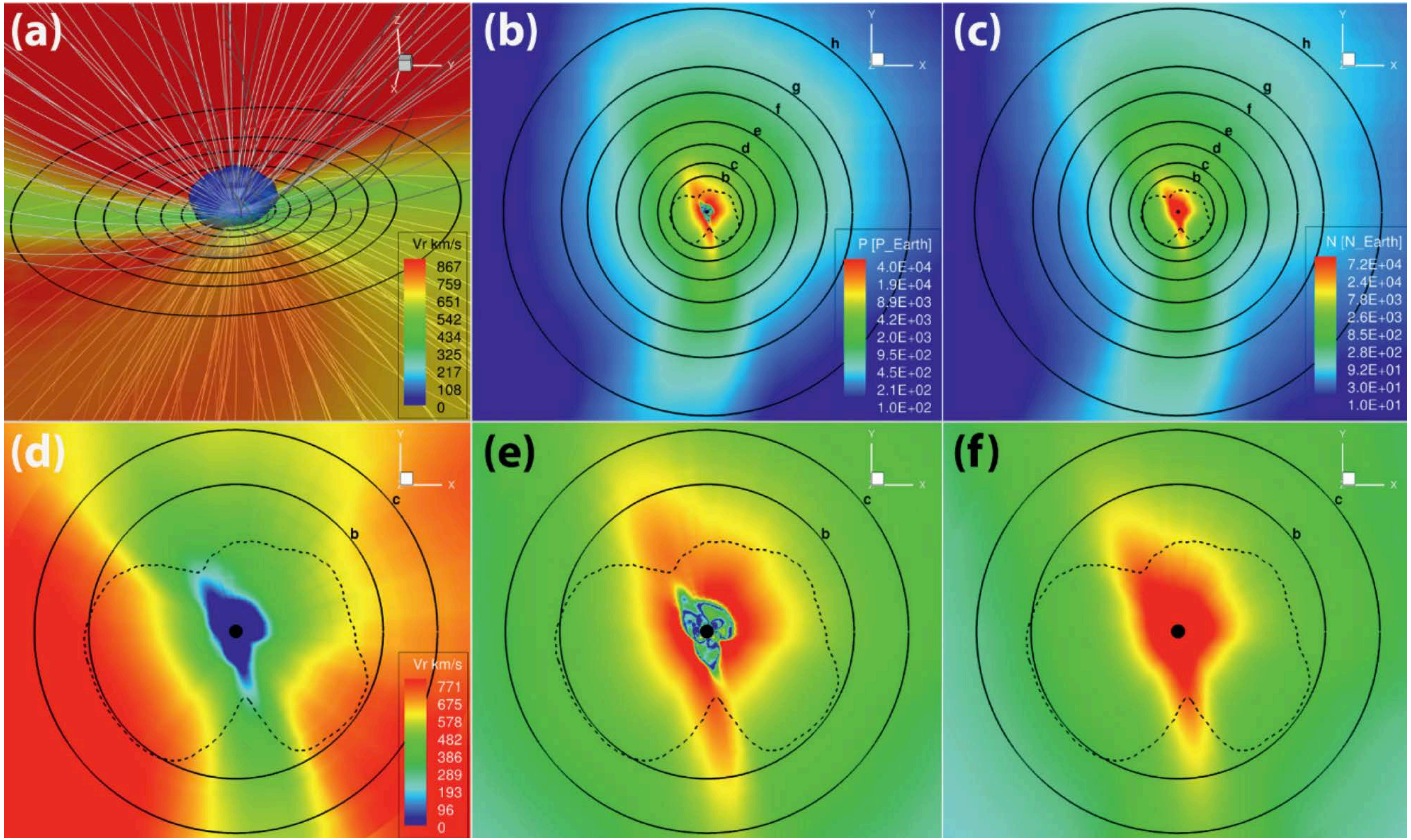
http://svs.gsfc.nasa.gov/4008

EUV constraints on solar/stellar coronal models

- Fully-compressible MHD equations + Alfvén wave propagation and dissipation (van der Holst et al. 2014ApJ...782...81V).
- Used AIA (and STEREO) EUV images to calibrate the Alfvén wave heating mode.
- See Alvarado-Gómez et al. (2016) for application to stellar winds of exoplanet host stars: HD 1237, HD 22049, and HD 147513.



Space Weather at Trappist-1



Dong + (PNAS, 2018)

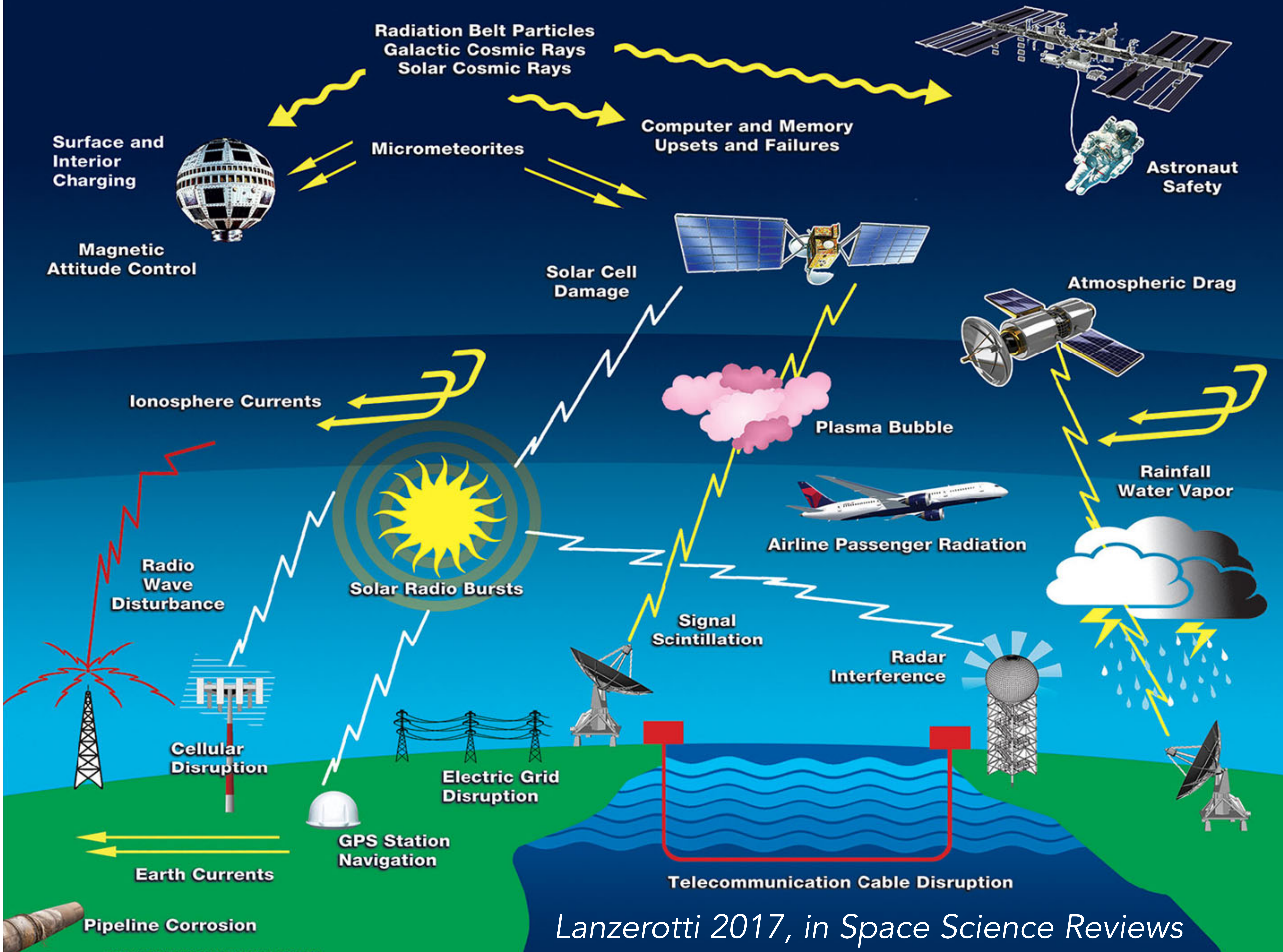
Violent Events on the surface give rise to Coronal Mass Ejections

SOHO / LASCO

Problem: *Space*

svs.gsfc.**nasa.gov**: computer model of a coronal mass ejection and resulting geomagnetic storm

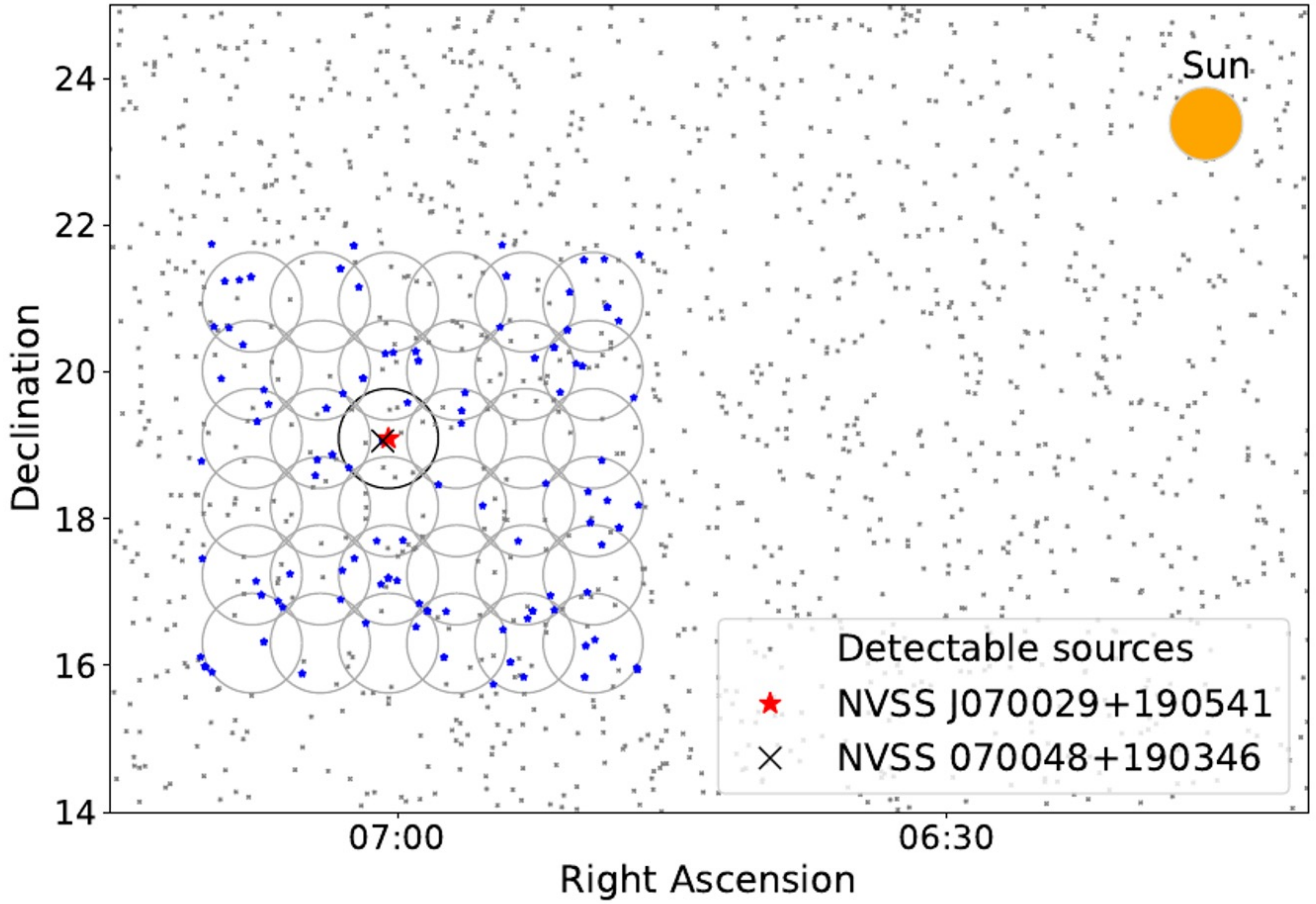
Space Weather



Lanzerotti 2017, in Space Science Reviews

Check out
sws.bom.gov.au

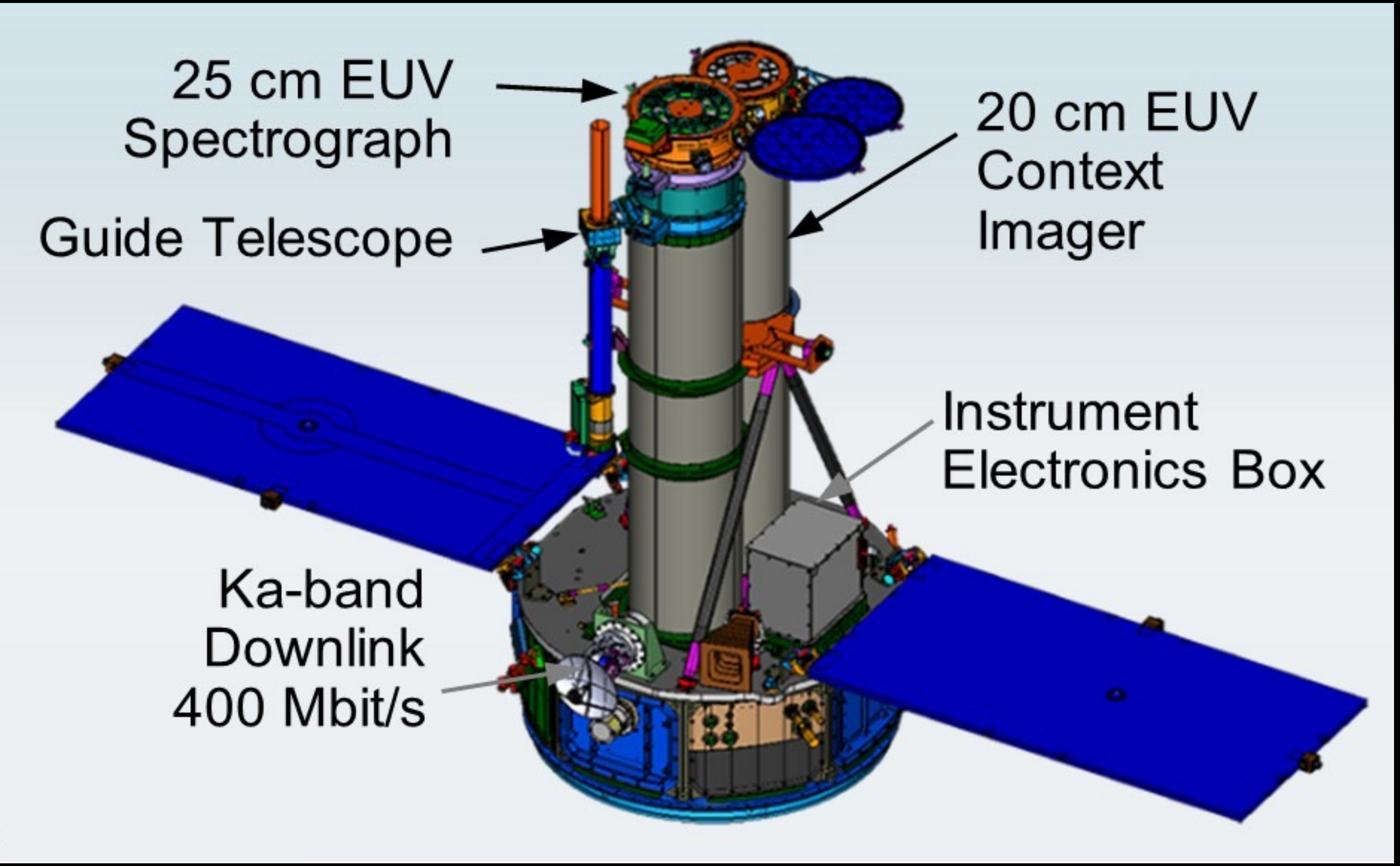
Interplanetary Scintillation Observations



- Japanese Solar Wind Imaging Facility (SWIFT; Tokumaru et al. 2011) observes dozens of IPS sources per day.
- MWA: Probe between ~20 and 30 degrees solar elongation with < 1 source per sq deg; Chhetri et al. 2018)
- ASKAP: Probe between 7 and 12 degrees solar elongation with a very high density of sources (5 per sq deg; Chhetri et al. 2022).

MUSE

MULTISLIT SOLAR EXPLORER



Current status: Passed PDR, KDPc

Launch date: Mid 2027

Mission: 2-year prime mission

Cost cap: ~200M USD

Orbit: sun-synchronous orbit at 600 km for continuous observations

Flight heritage: extensive heritage from IRIS, SDO, Hinode ensures low risk for cost or schedule and high TRL for instrument, spacecraft and mission operations.

Spacecraft: 3-axis stabilised, fine pointing (subarcsecond) using guide telescope, based on IRIS design.

The Astrophysical Journal, 926:52 (36pp), 2022 February 10 https://doi.org/10.3847/1538-4357/ac4222

Probing the Physics of the Solar Atmosphere with the Multi-slit Solar Explorer (MUSE). I. Coronal Heating

Bart De Pontieu[1,2,3], Paola Testa[4], Juan Martínez-Sykora[1,2,3,5], Patrick Antolin[6], Konstantinos Karampelas[6,7], Viggo Hansteen[1,2,3,5], Matthias Rempel[8], Mark C. M. Cheung[1], Fabio Reale[9,10], Sanja Danilovic[11], Paolo Pagano[9,10], Vanessa Polito[1,5], Ineke De Moortel[2,12], Daniel Nóbrega-Siverio[2,3,13,14], Tom Van Doorsselaere[7], Antonino Petralia[10], Mahboubeh Asgari-Targhi[4], Paul Boerner[1], Mats Carlsson[2,3], Georgios Chintzoglou[1,15], Adrian Daw[16], Edward DeLuca[4], Leon Golub[4], Takuma Matsumoto[17], Ignacio Ugarte-Urra[18], and Scott W. McIntosh[8]
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Probing the Physics of the Solar Atmosphere with the Multi-slit Solar Explorer (MUSE). II. Flares and Eruptions

Mark C. M. Cheung[1], Juan Martínez-Sykora[1,2,3,4], Paola Testa[5], Bart De Pontieu[1,3,4], Georgios Chintzoglou[1,6], Matthias Rempel[7], Vanessa Polito[1,2], Graham S. Kerr[8,9], Katharine K. Reeves[5], Lyndsay Fletcher[3,10], Meng Jin[1,11], Daniel Nóbrega-Siverio[3,4,12,13], Sanja Danilovic[14], Patrick Antolin[15], Joel Allred[9], Viggo Hansteen[1,2,3,4], Ignacio Ugarte-Urra[16], Edward DeLuca[5], Dana Longcope[17], Shinsuke Takasao[18], Marc L. DeRosa[1], Paul Boerner[1], Sarah Jaeggli[19], Nariaki V. Nitta[1], Adrian Daw[9], Mats Carlsson[3,4], and Leon Golub[5]
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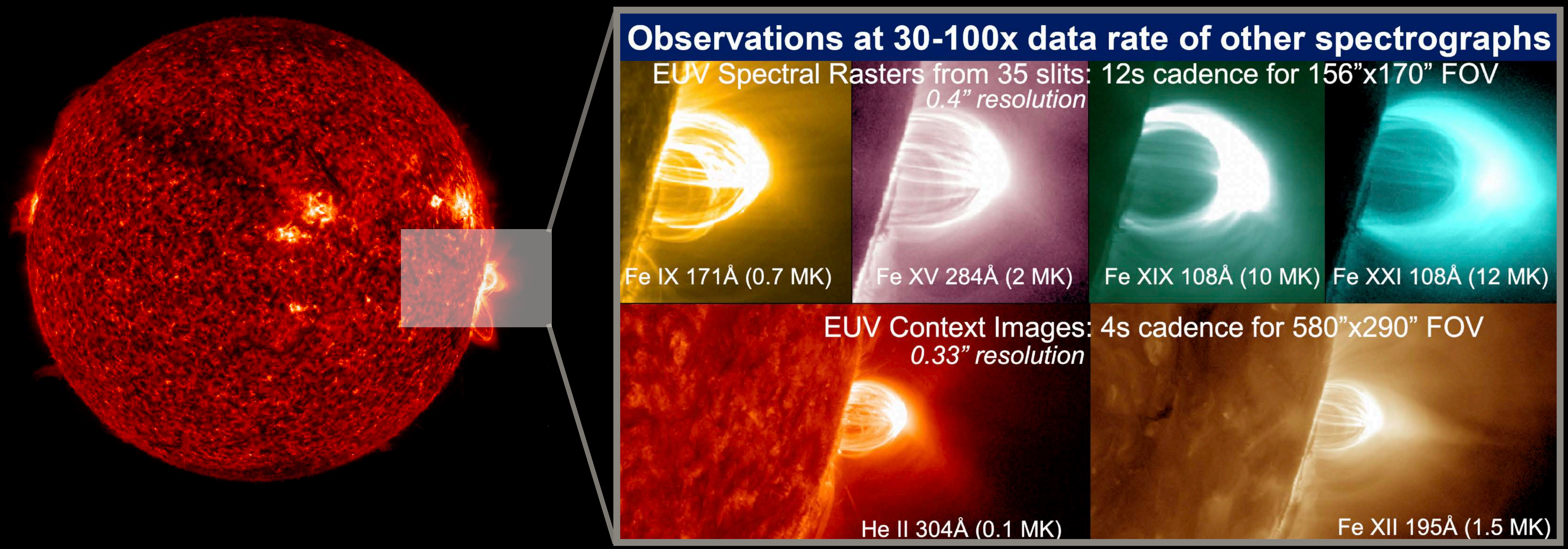
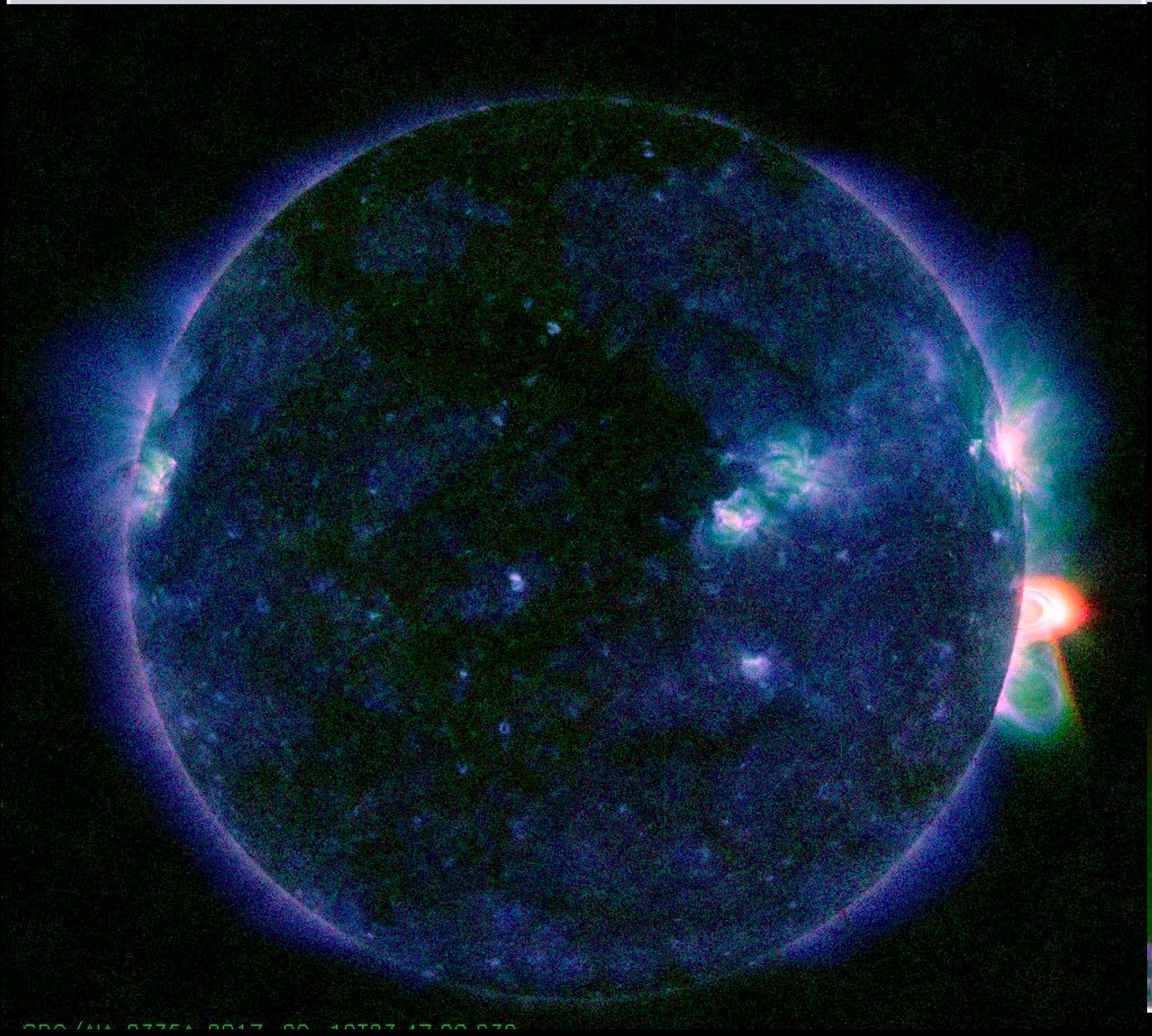
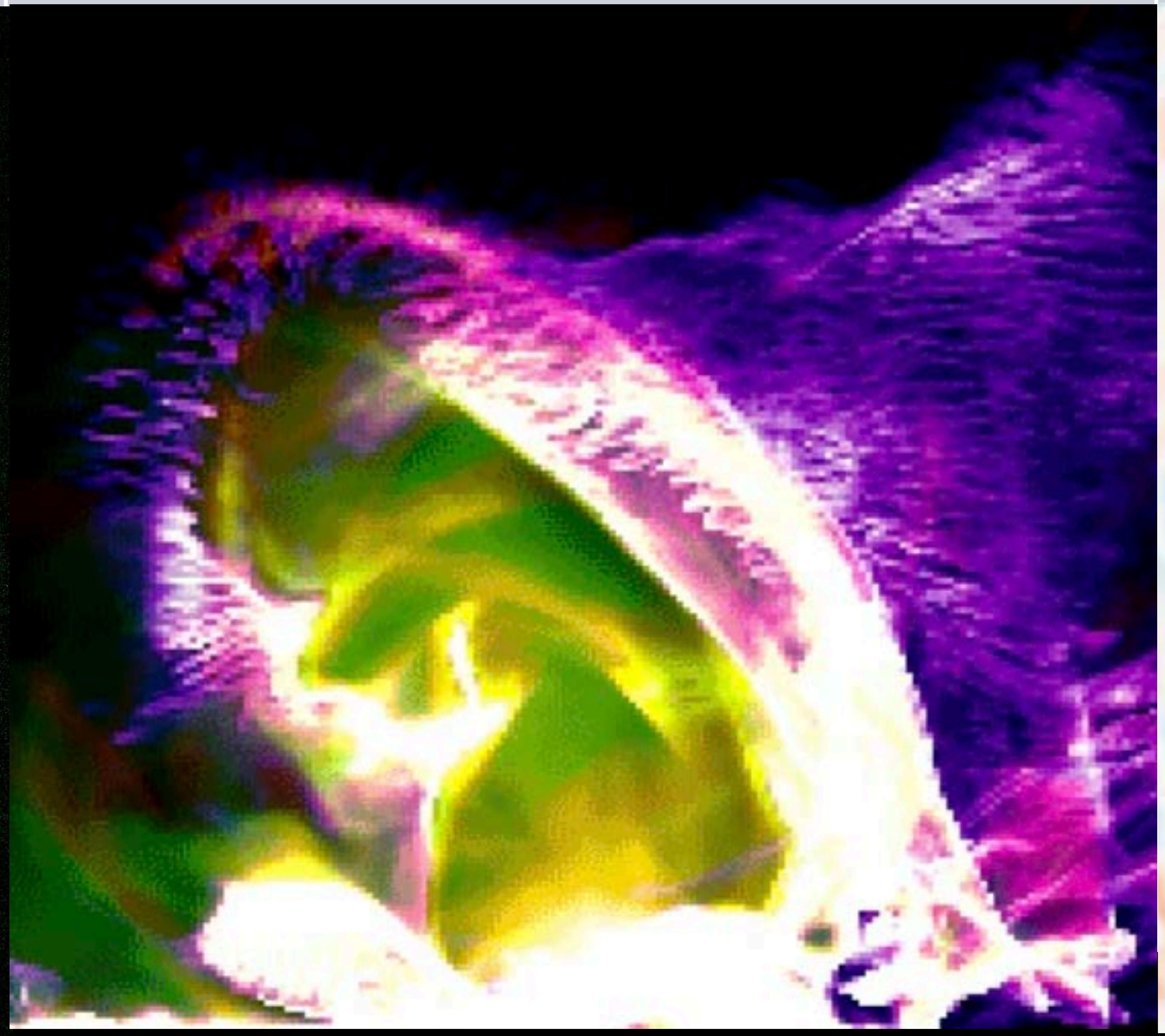
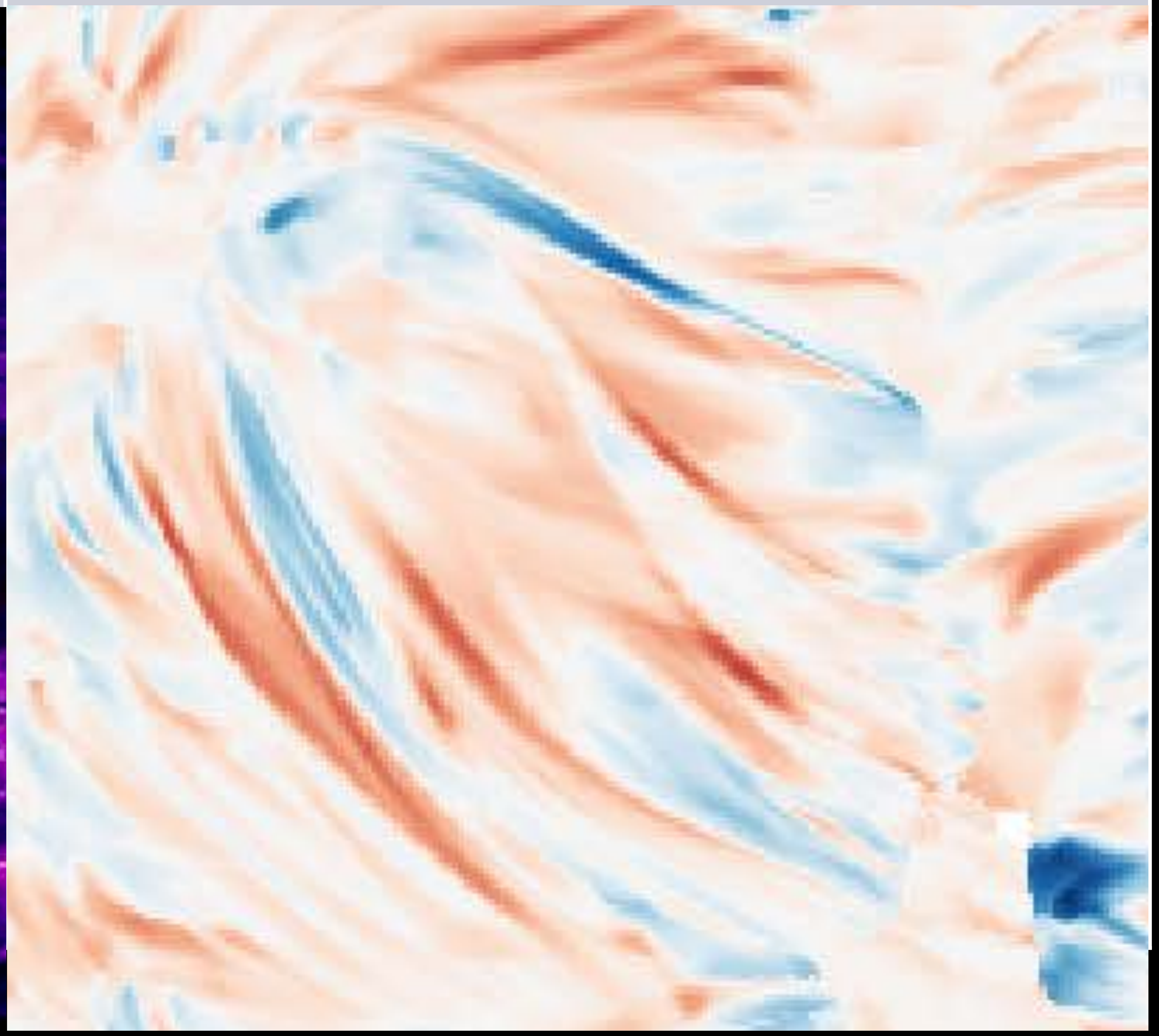


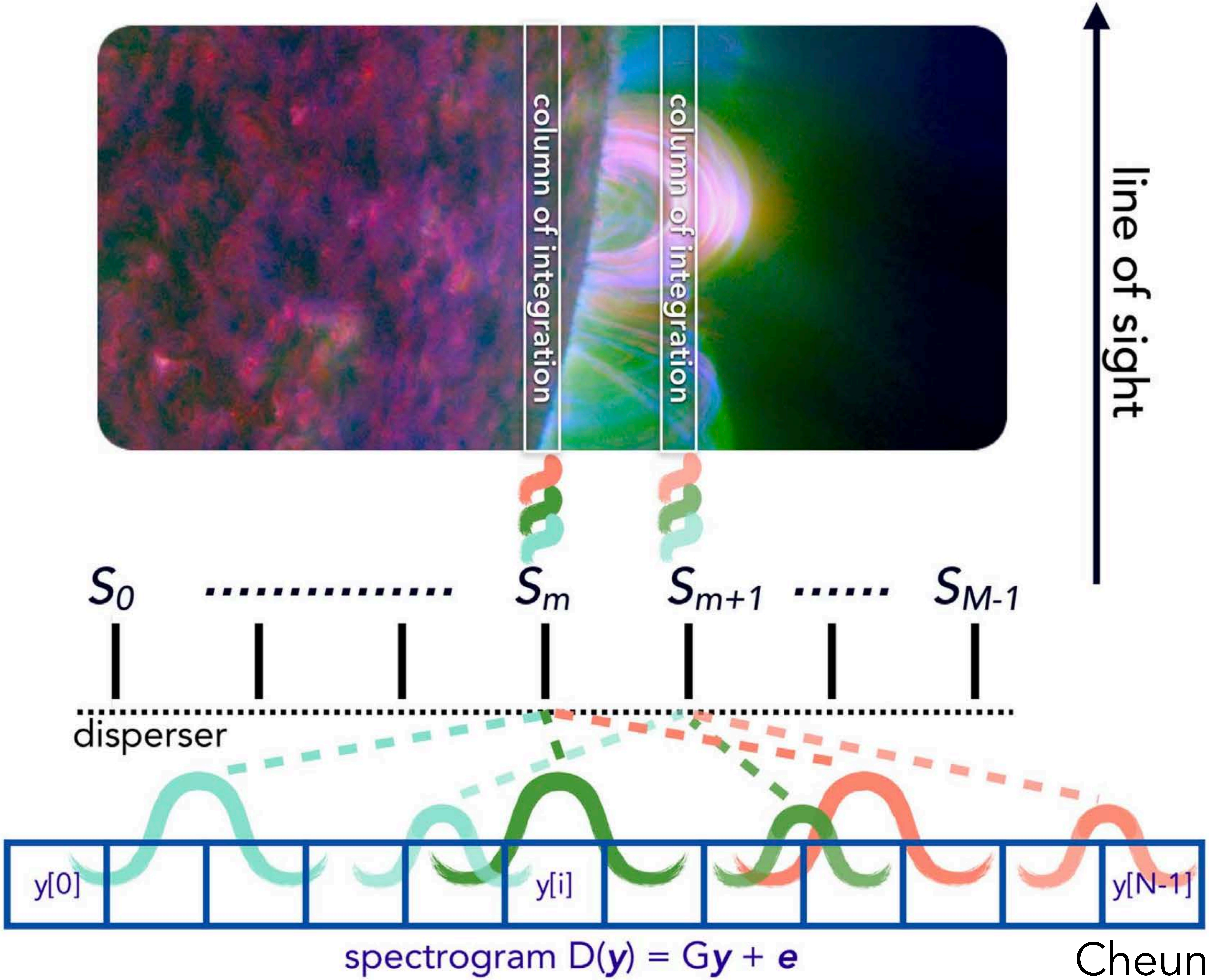
MUSE’s high-throughput, multi-slit spectroscopy reveals processes invisible to imagers (AIA) or single-slit spectrographs (IRIS, EUVST), allowing detailed studies of multi-scale processes driving coronal heating and activity:

- full spatial and simultaneous coverage of hot plasma in current sheets, flare loops and CMEs as well as cooler plasma in coronal loops and flare ribbons, including conjugate footpoints.
- nominal observing mode with 12 step rasters to densely cover 170”x170” at raster cadence of 12s
- special observing modes at very high cadence (<1s) of the impulsive phase of flares and initial stage of coronal mass ejections (CMEs)

MUSE
MULTISLIT SOLAR EXPLORER

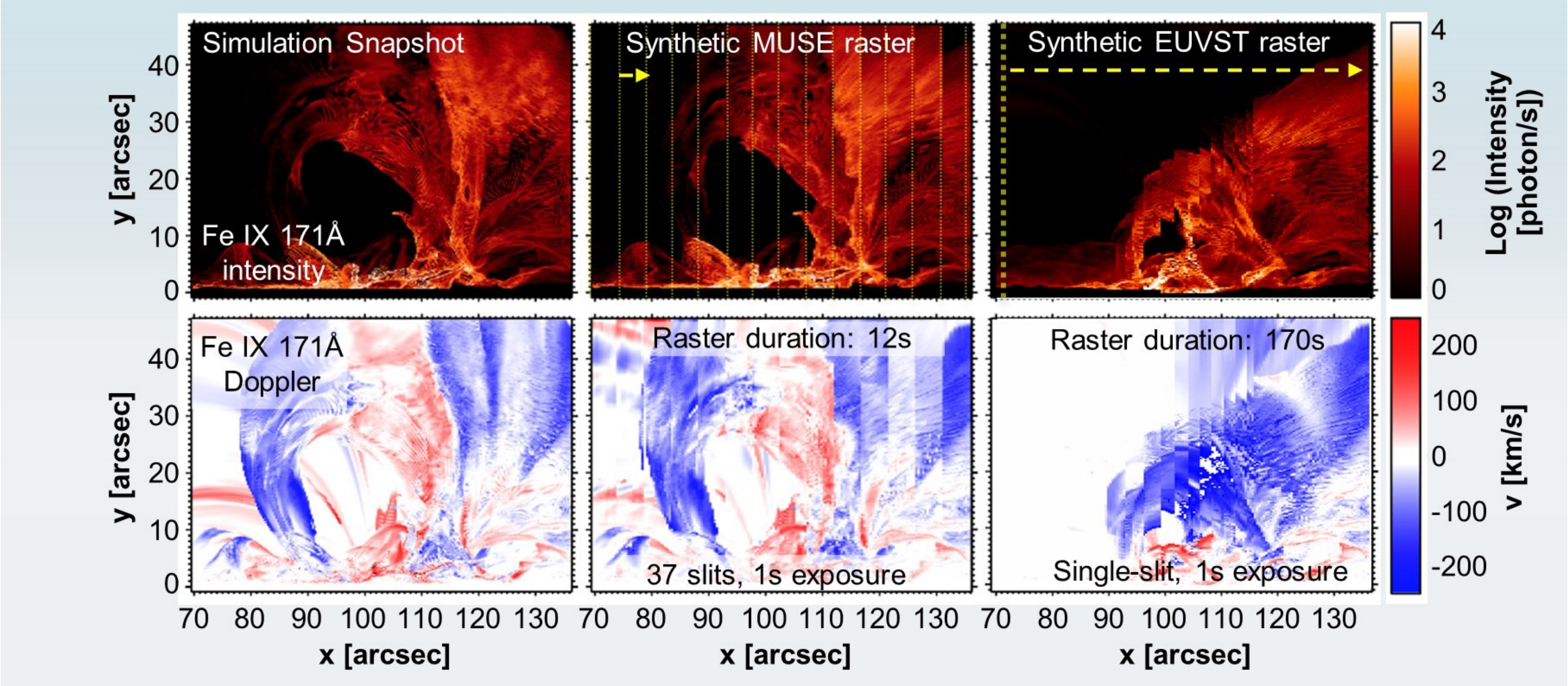
MUSE Science Goals

1. Determine which mechanism(s) heat the solar corona and drive the solar wind	2. Understand the origin and evolution of the unstable solar atmosphere	3. Investigate fundamental physical plasma processes
		



Cheung et al. (2019)

What is unique about MUSE?



- **Breakthrough** in:
  - cadence: 20x-100x faster & larger 2-D FOV than current/planned spectrographs – **will, for the first time, freeze "coronal evolution" under spectrograph slits**
  - spatial resolution: 10x higher than AIA, 25x better than Hinode/EIS or SOLO/SPICE
  - field-of-view: captures, for the first time, the multi-scale nature of solar atmosphere from sub-granular to active region size scales

Take home messages

- The Sun is a natural laboratory for plasma and astrophysical processes.
- Multi-wavelength observations crucial for testing many of the processes.
- A 99% partial solar eclipse is not close to being a total solar eclipse. Prepare for 2028 (path of totality passing through Sydney).
- Australia can make unique contributions to space weather science and forecasting, and space optics.