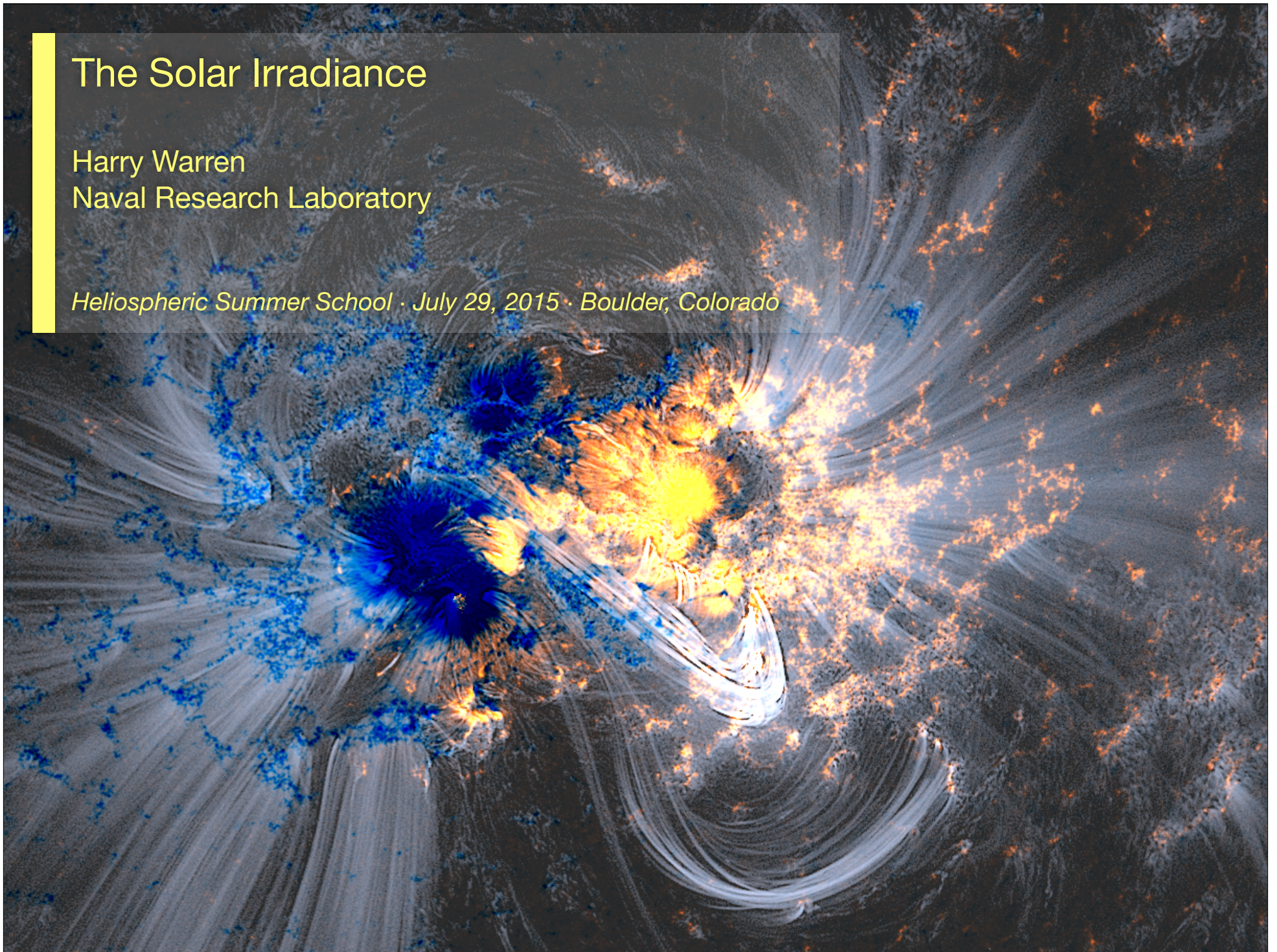
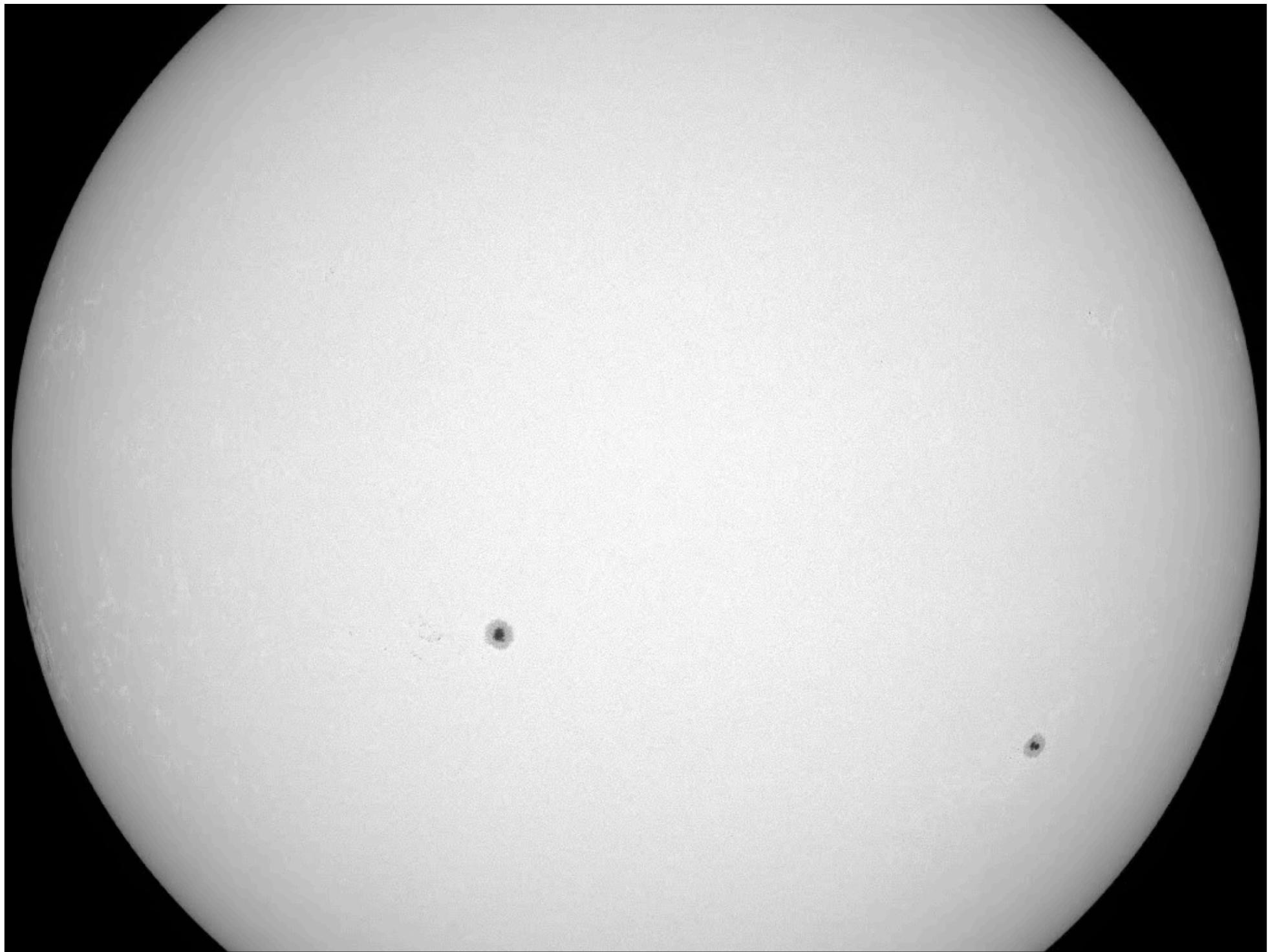


The Solar Irradiance

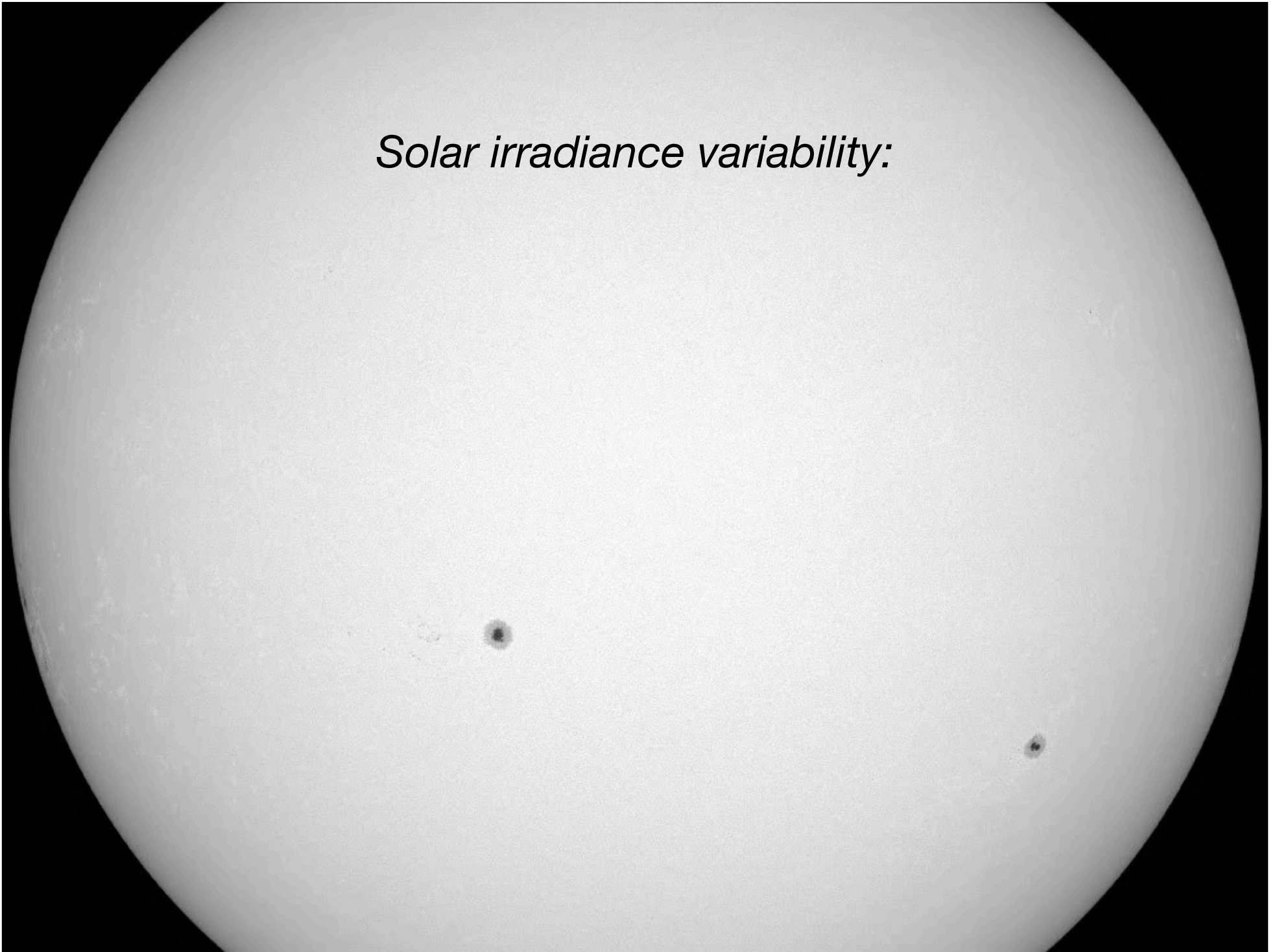
Harry Warren
Naval Research Laboratory

Heliospheric Summer School · July 29, 2015 · Boulder, Colorado

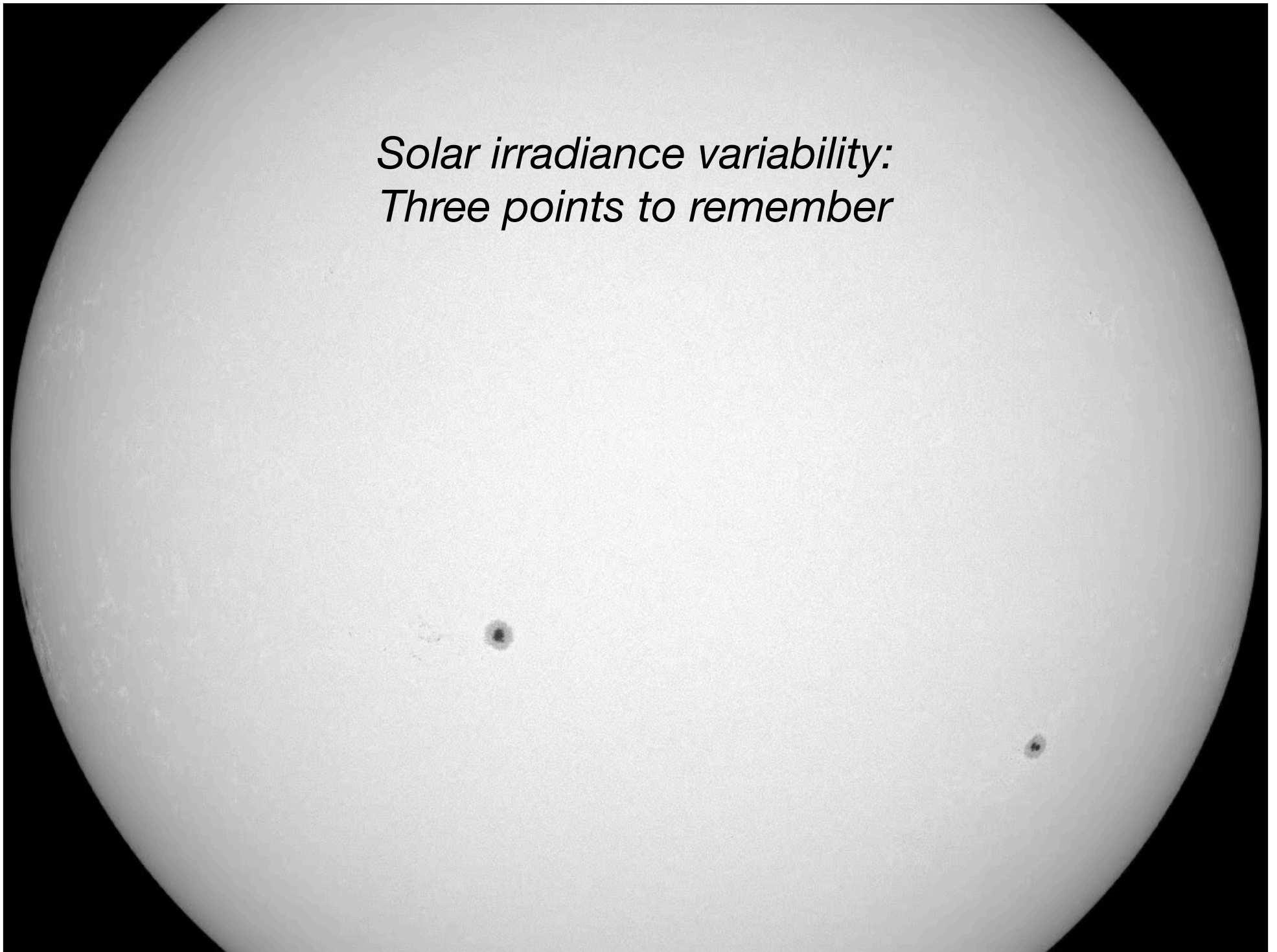




Solar irradiance variability:



*Solar irradiance variability:
Three points to remember*



*Solar irradiance variability:
Three points to remember*

. . . plays an important role in the Earth's upper atmosphere

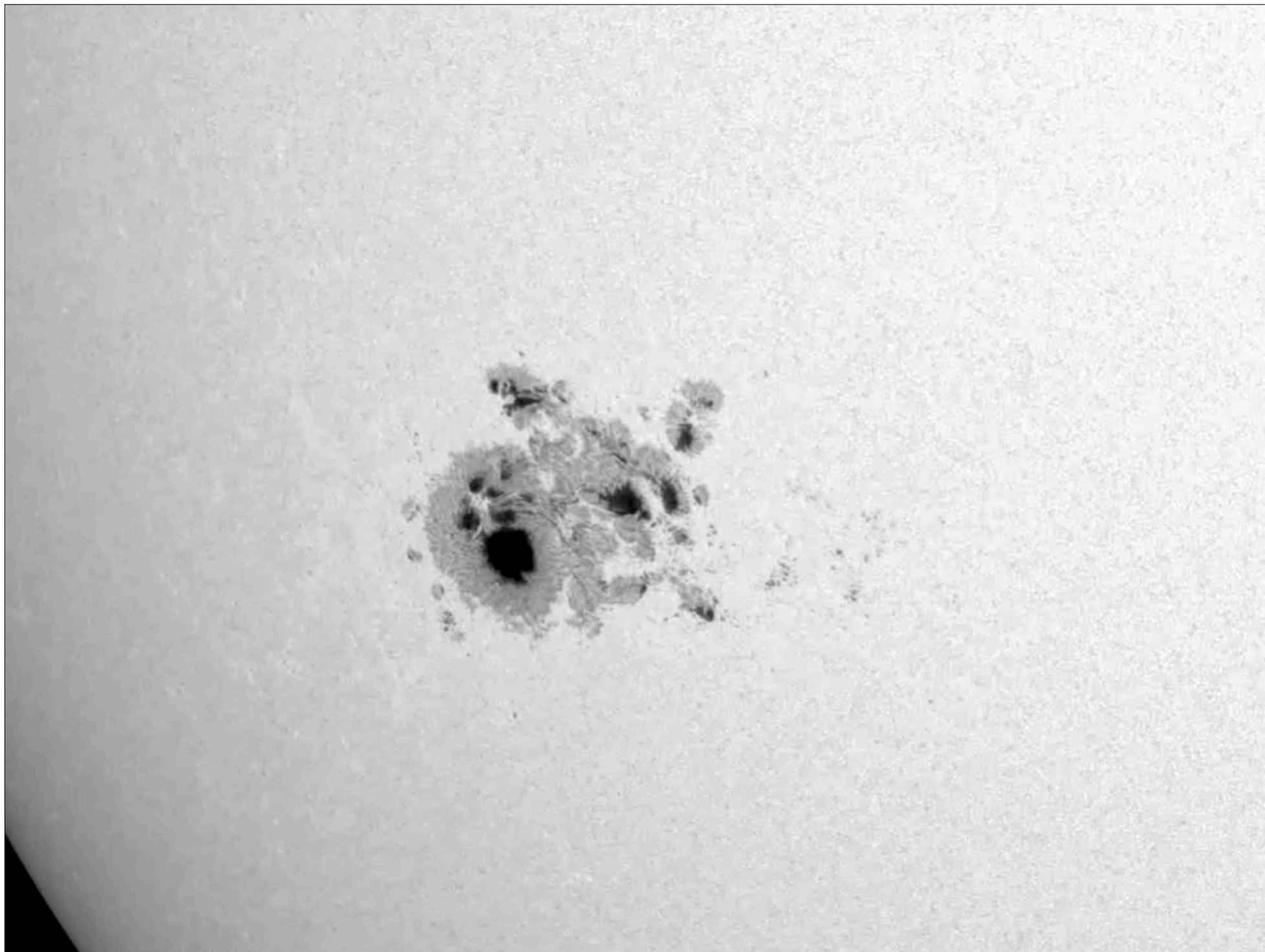
*Solar irradiance variability:
Three points to remember*

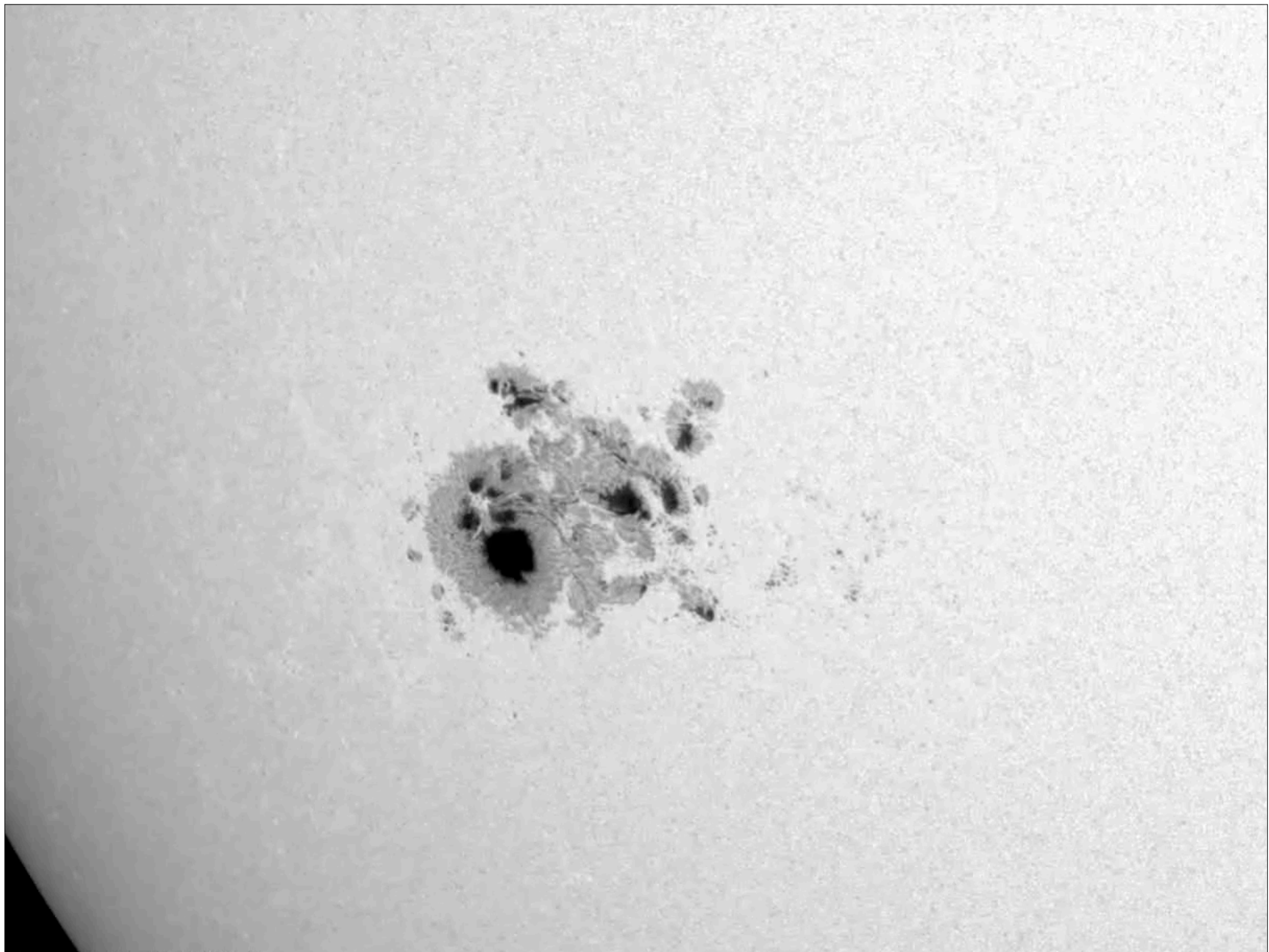
. . . plays an important role in the Earth's upper atmosphere

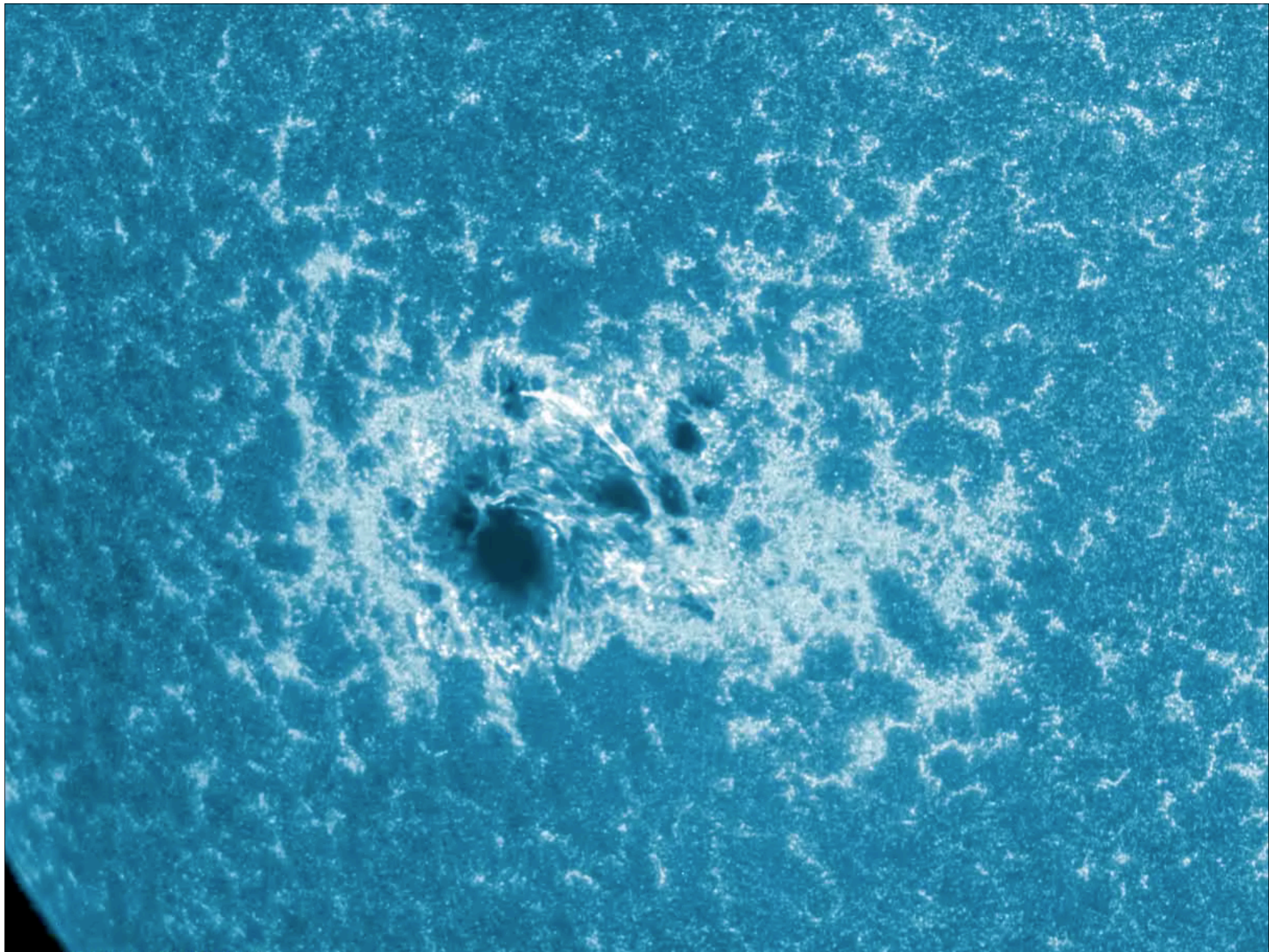
. . . is driven by variations in the magnetic field

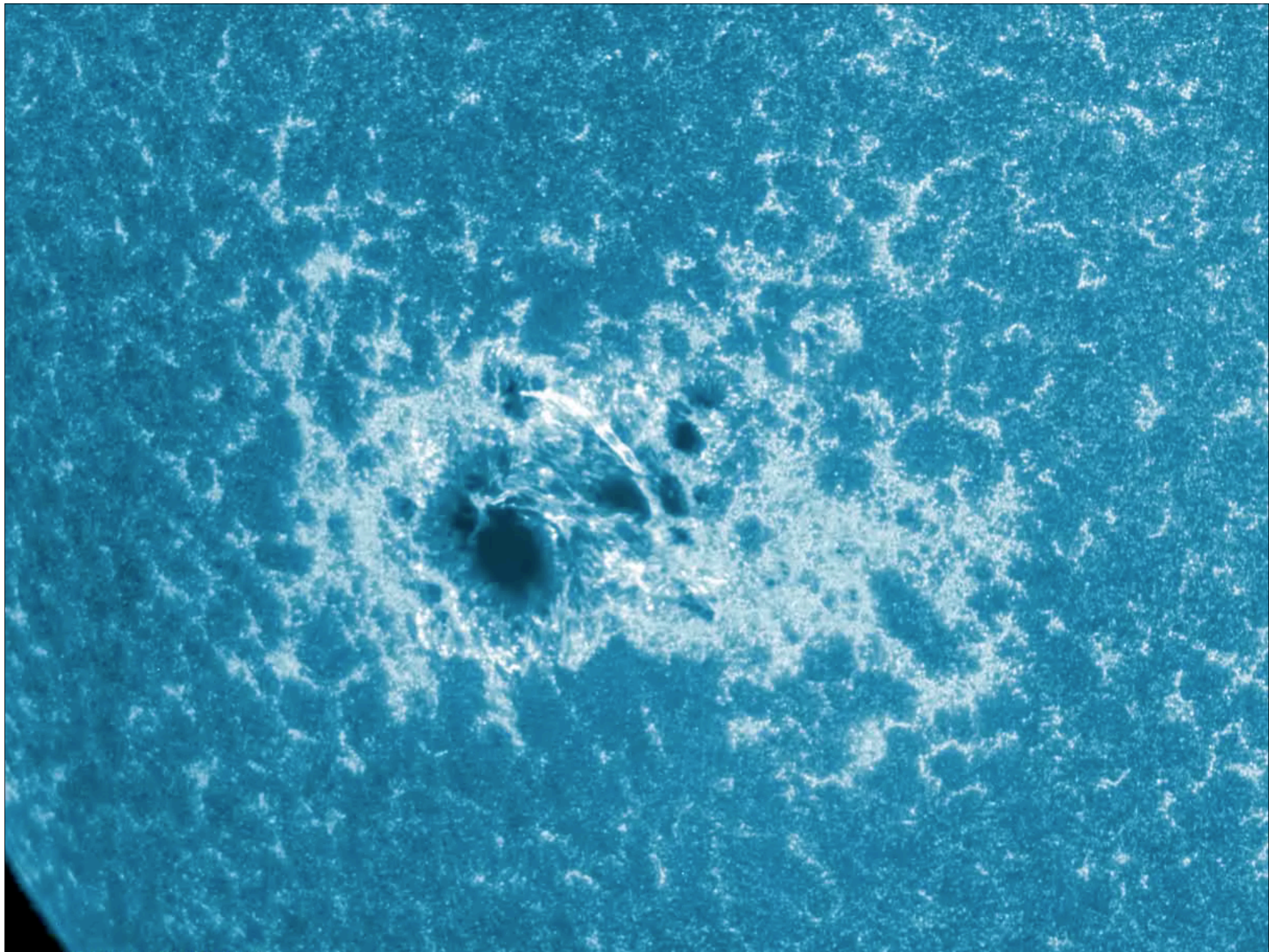
*Solar irradiance variability:
Three points to remember*

- . . . plays an important role in the Earth's upper atmosphere*
- . . . is driven by variations in the magnetic field*
- . . . is determined by the structuring of the solar atmosphere*



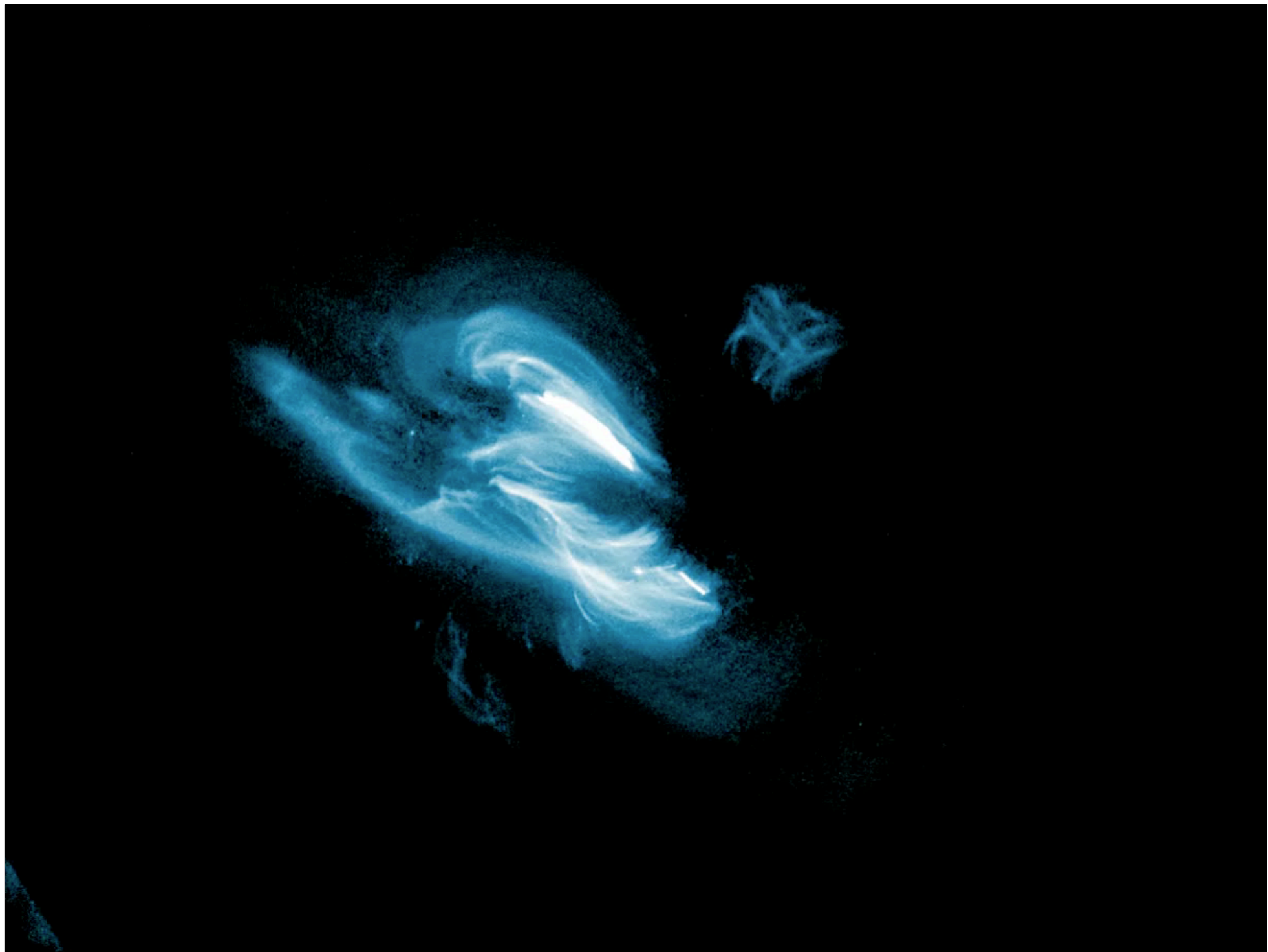


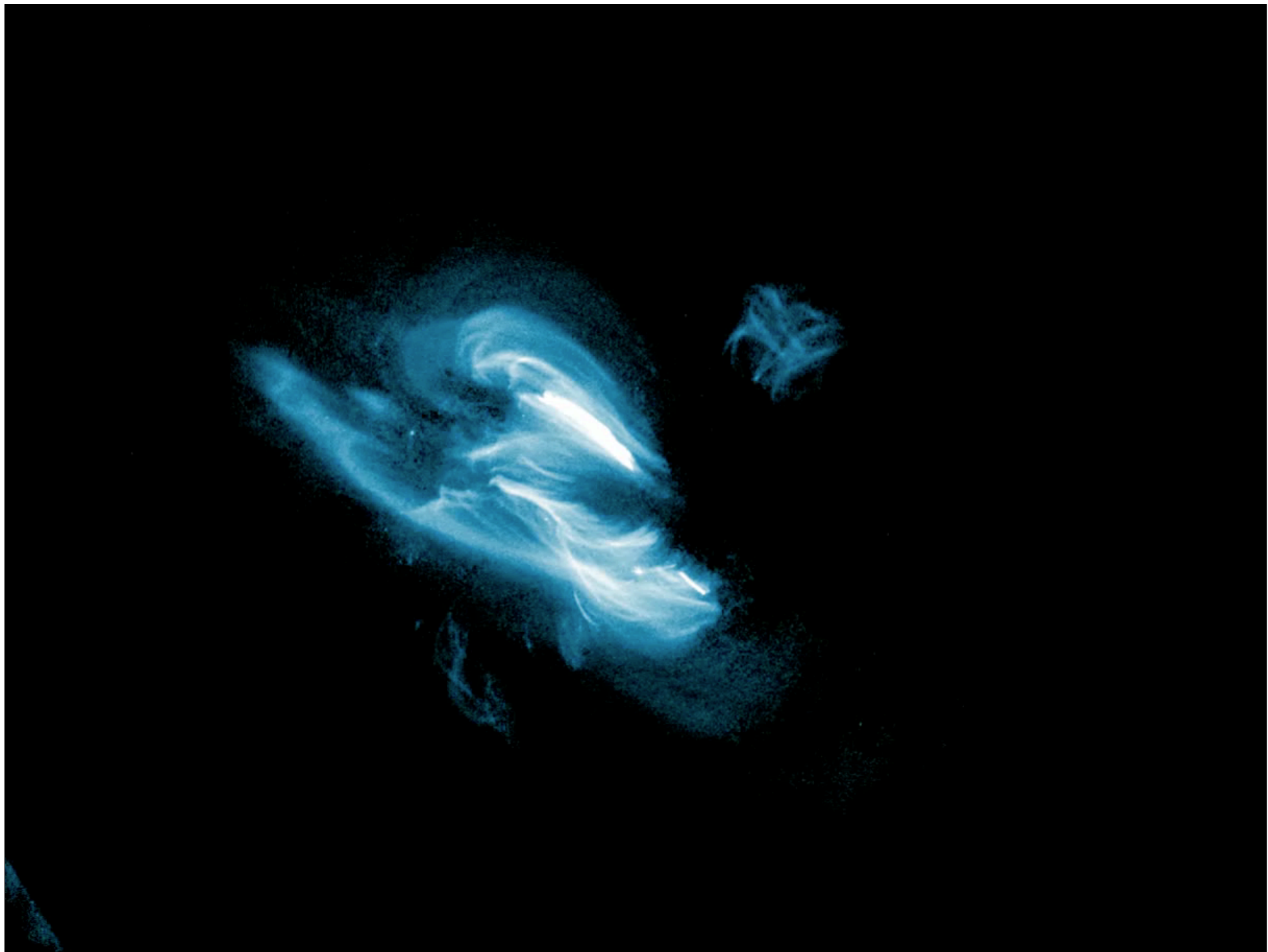


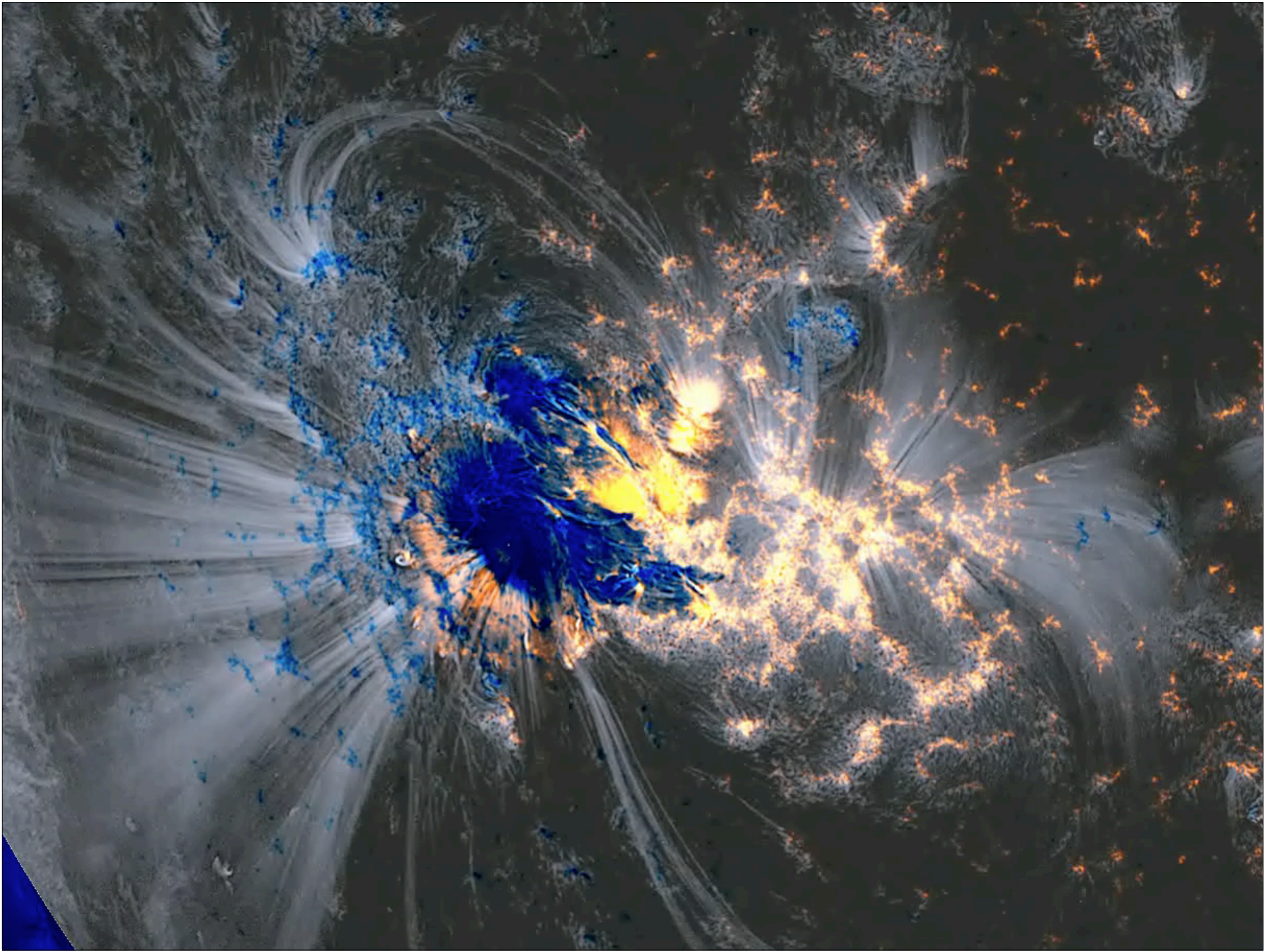


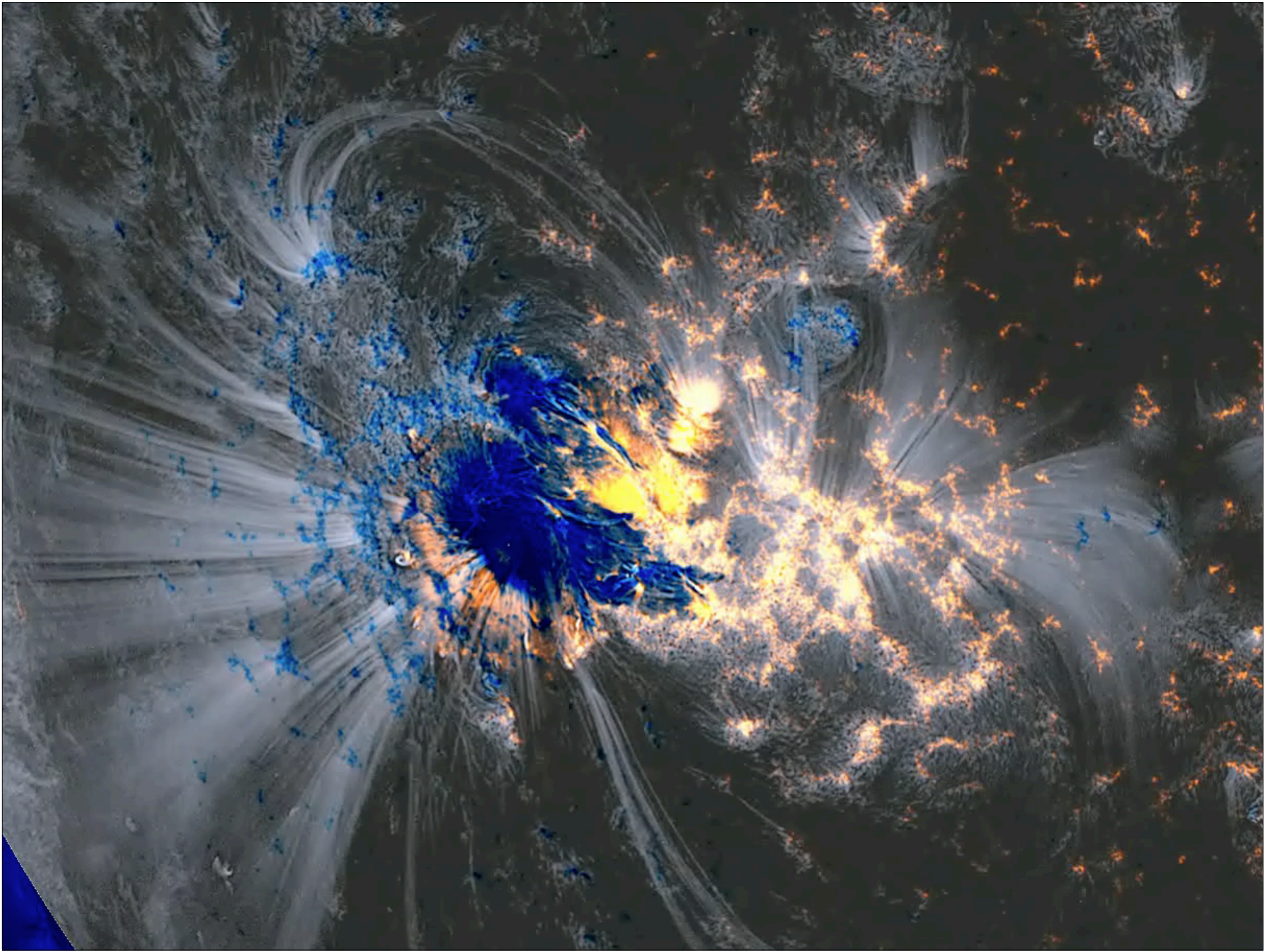












An Application: The Orbital Debris Problem



Video courtesy of Analytical Graphics, Inc. www.agi.com

An Application: The Orbital Debris Problem

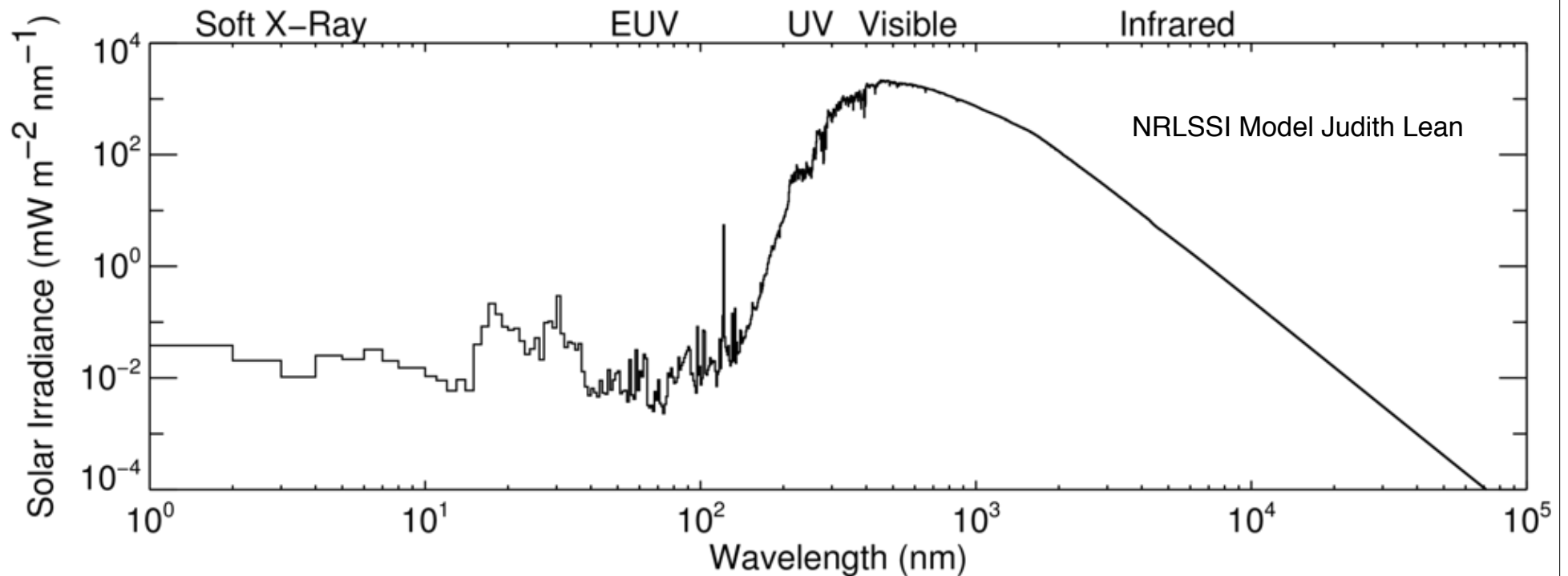


Video courtesy of Analytical Graphics, Inc. www.agi.com

Outline

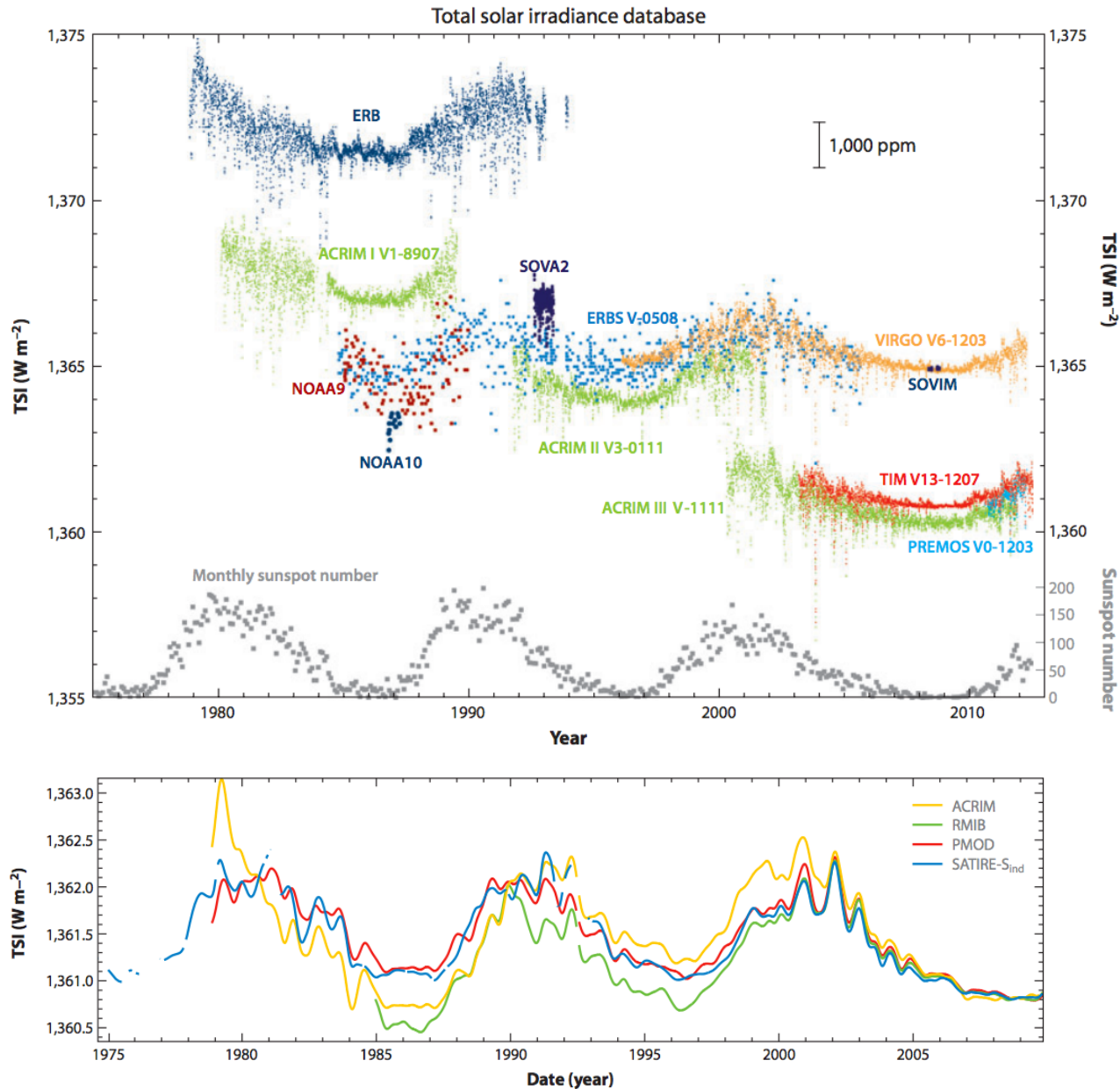
- Total Solar Irradiance
 - Measurements
 - Application to climate change
- Solar Spectral Irradiance
 - The Solar Atmosphere
 - Soft X-rays
 - Extreme Ultraviolet
 - Ultraviolet
 - Visible/Infrared
 - Overview of observations
 - Application to satellite drag
- Common proxies for solar activity
- Proxy irradiance models
- A quick note on regression
 - Training/Test/Validation
 - Gaussian Process Regression
- The magnetic flux as a proxy
- Forecasting solar activity
 - Autoregression
 - Magnetic flux transport
- Emission processes
 - Optically thin line emission
- Semi-empirical models
 - Differential emission measure
- My 2 cents on useful tools and skills

Overview of the Solar Spectral Irradiance



Total Solar Irradiance: The Sun's radiated power integrated over all wavelengths

The Total Solar Irradiance: Measurements and Composites

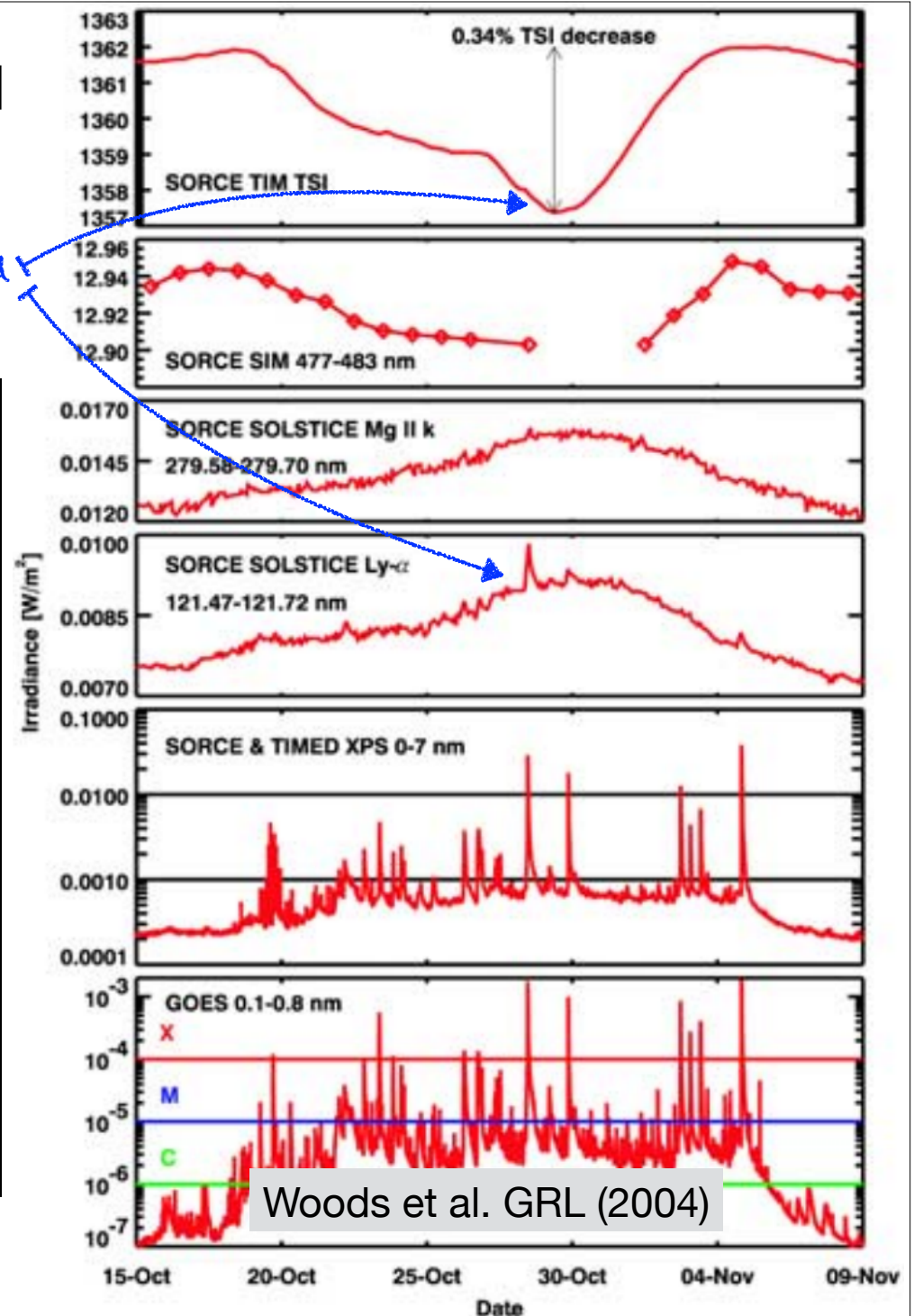


TSI Variations During a Period of Very High Solar Activity

TSI is often anti-correlated
with solar activity



MDI/SoHO
October - November 2003

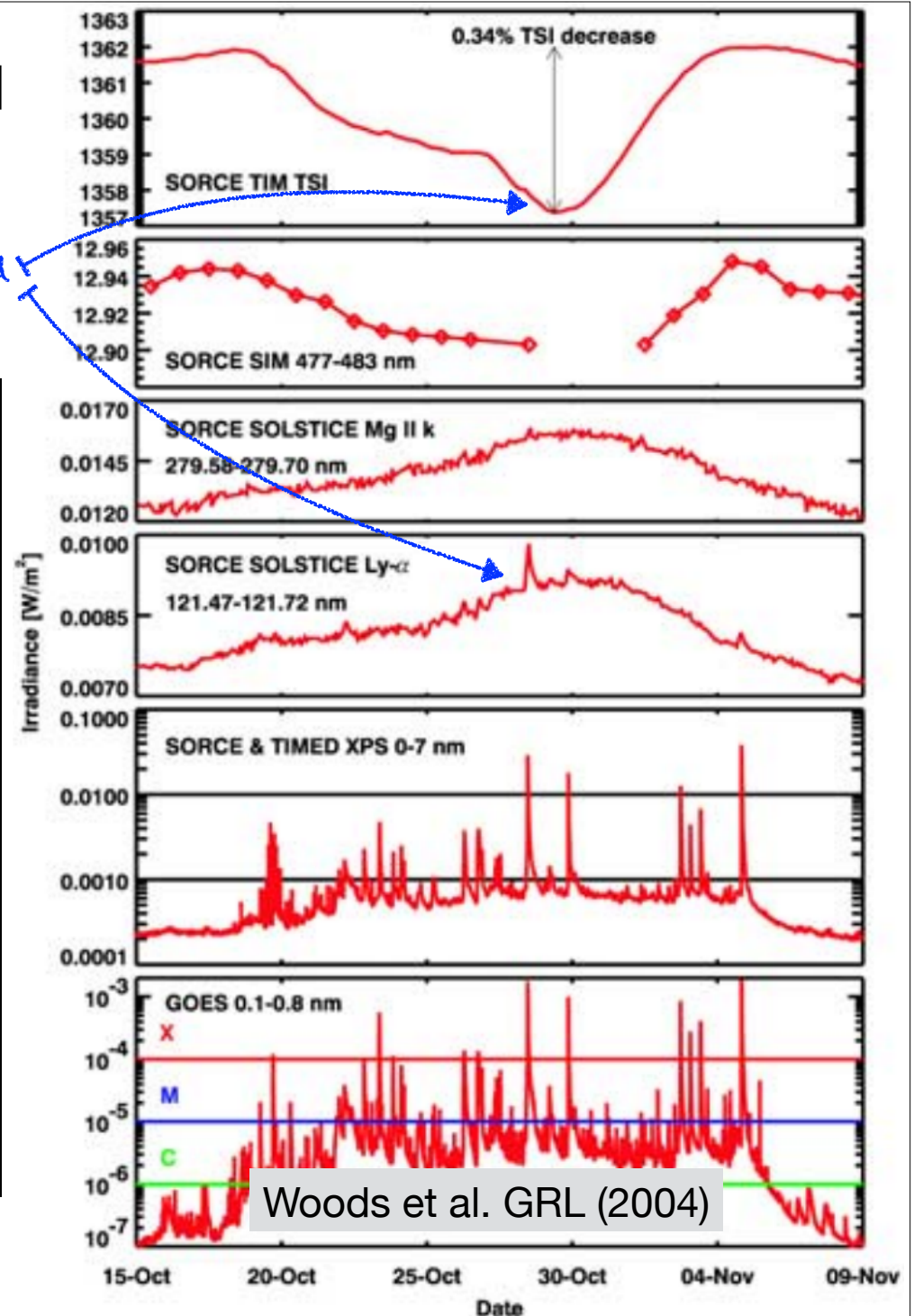


TSI Variations During a Period of Very High Solar Activity

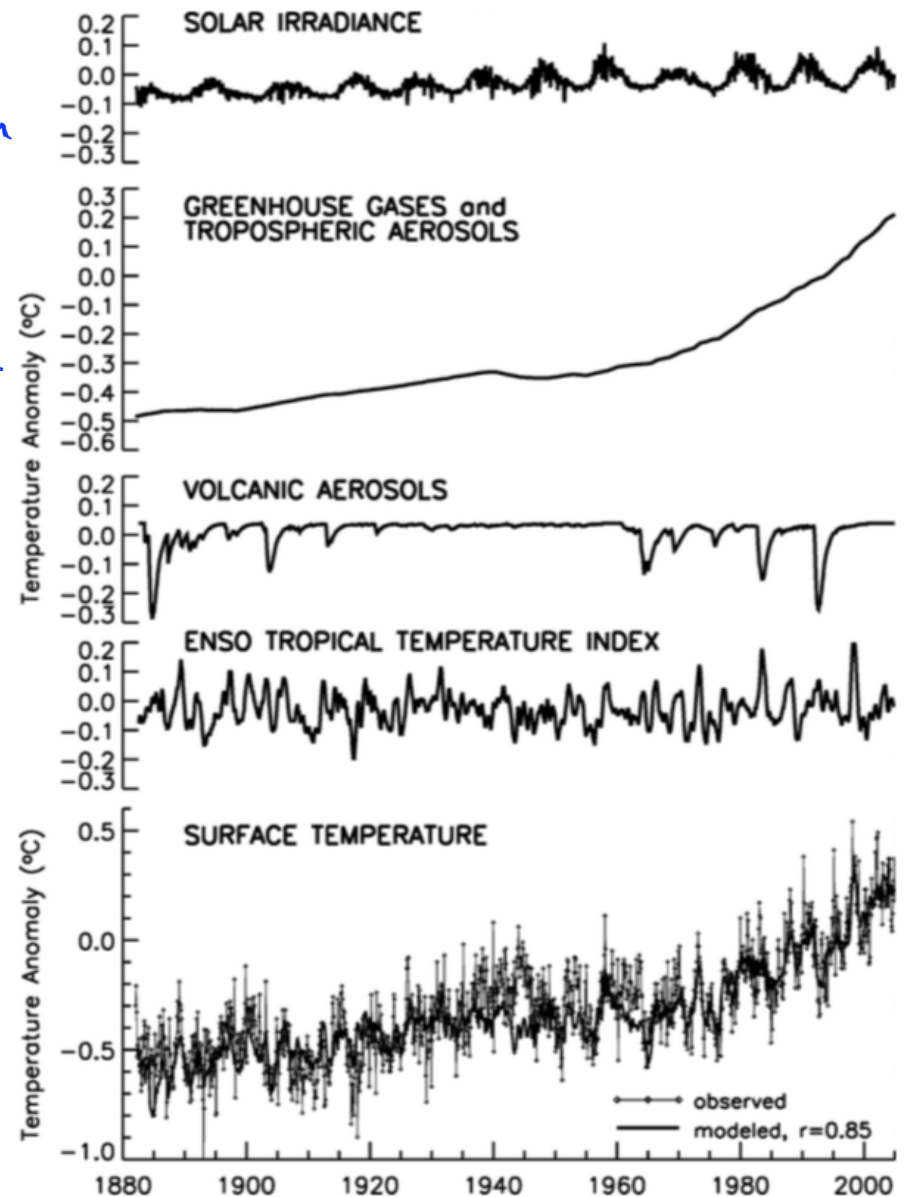
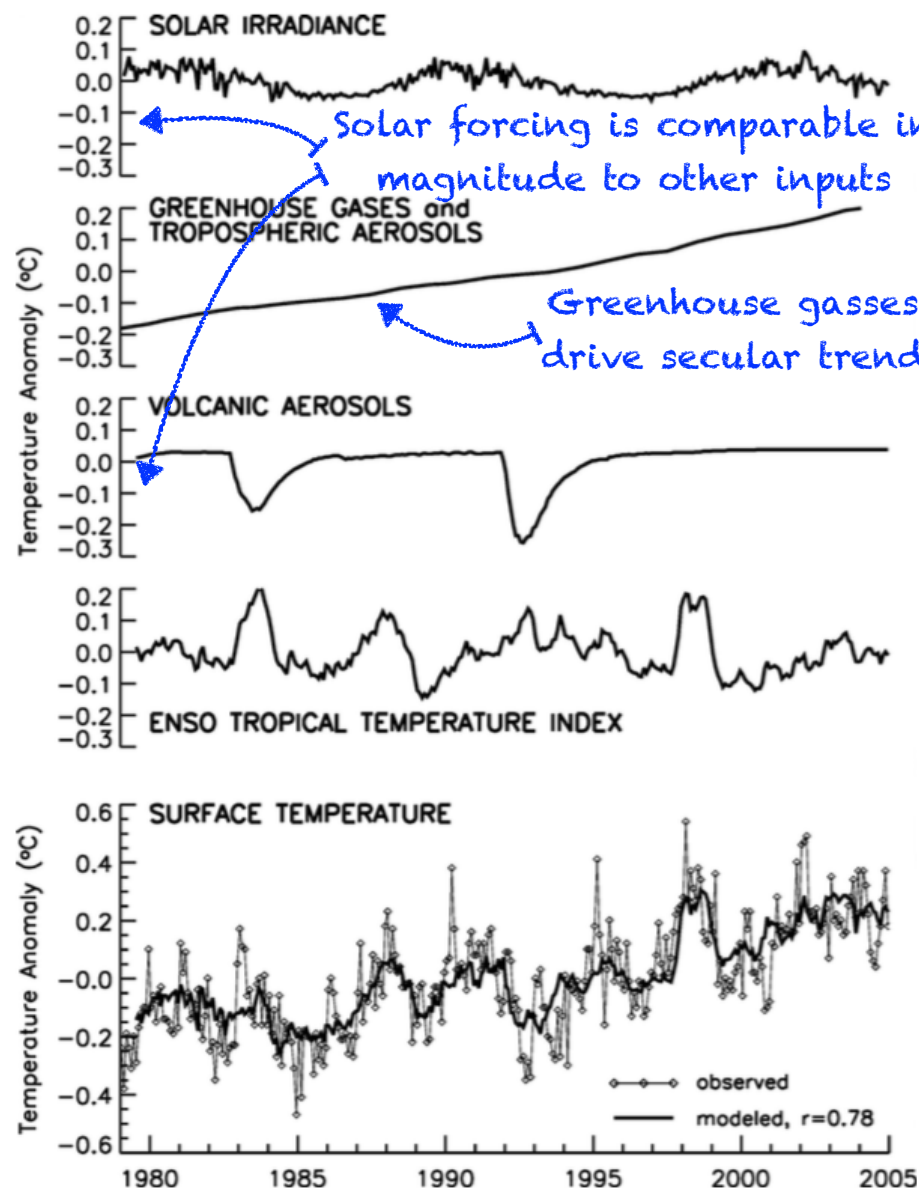
TSI is often anti-correlated
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MDI/SoHO
October - November 2003

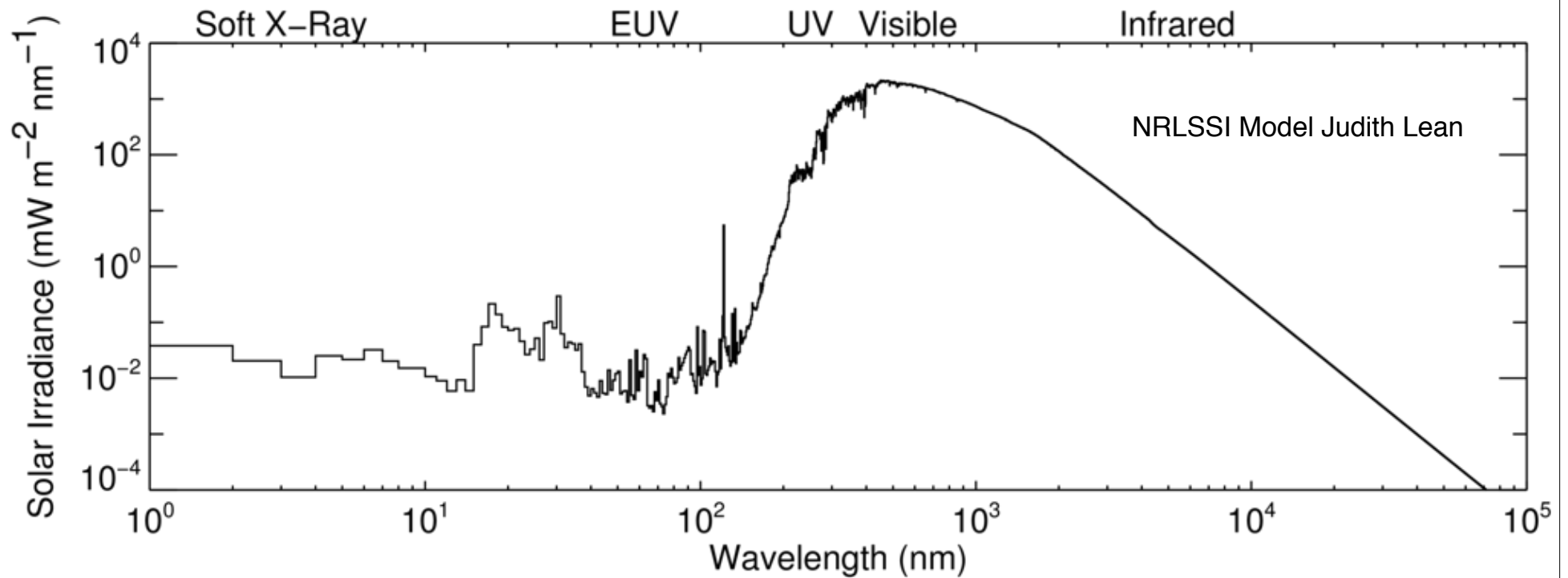


The Total Solar Irradiance: Application to Climate Change

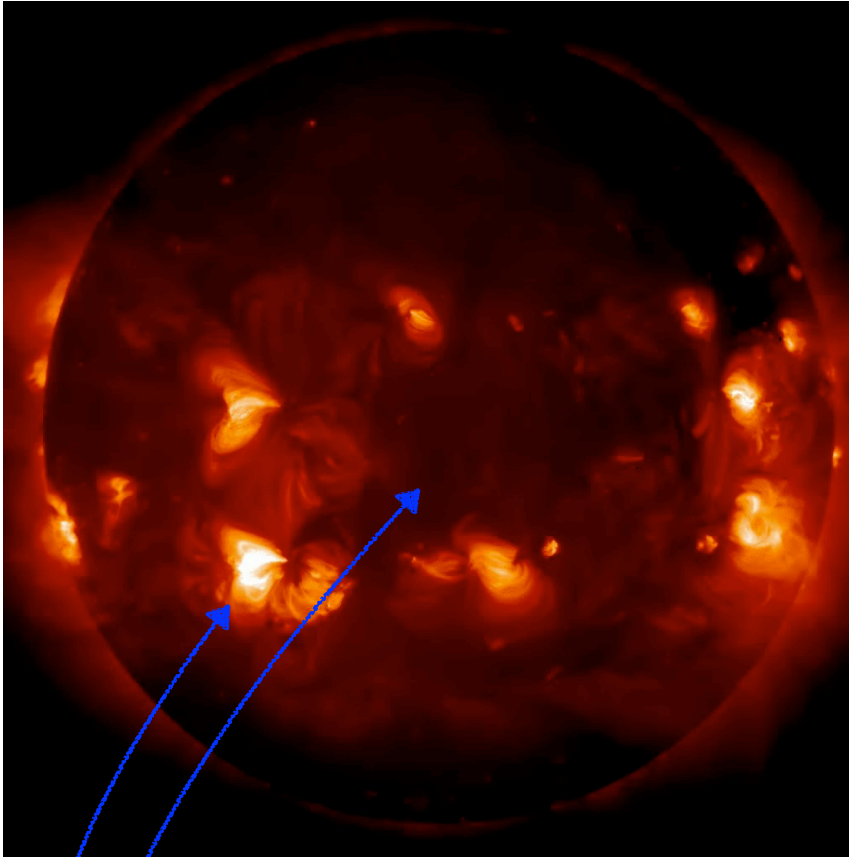


Lean, Solar Physics (2005)

Overview of the Solar Spectral Irradiance



Soft X-Rays: $< 50 \text{ \AA}$

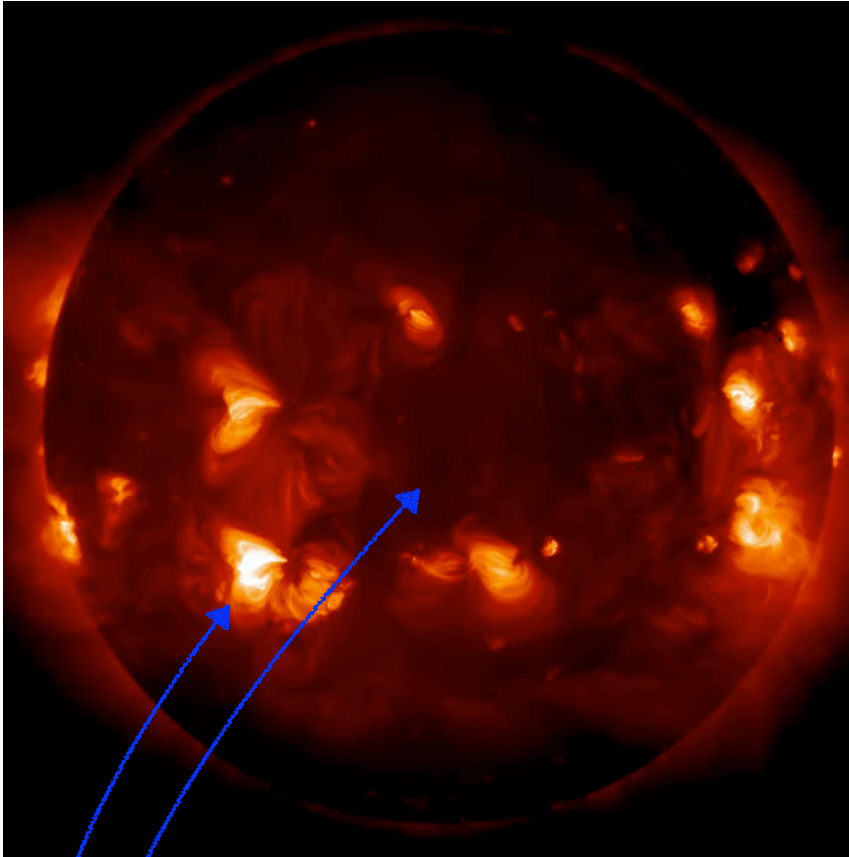


XRT/Hinode
September – November 2014

Very high contrast between
quiet and active Sun

- Generally formed at high temperatures ($> 2\text{MK}$)
- Very high contrast between quiet and active sun $\rightarrow$ strong variation over solar rotation and solar cycle
- Flares contribute significantly to variability
- Optically thin
- Limited measurements

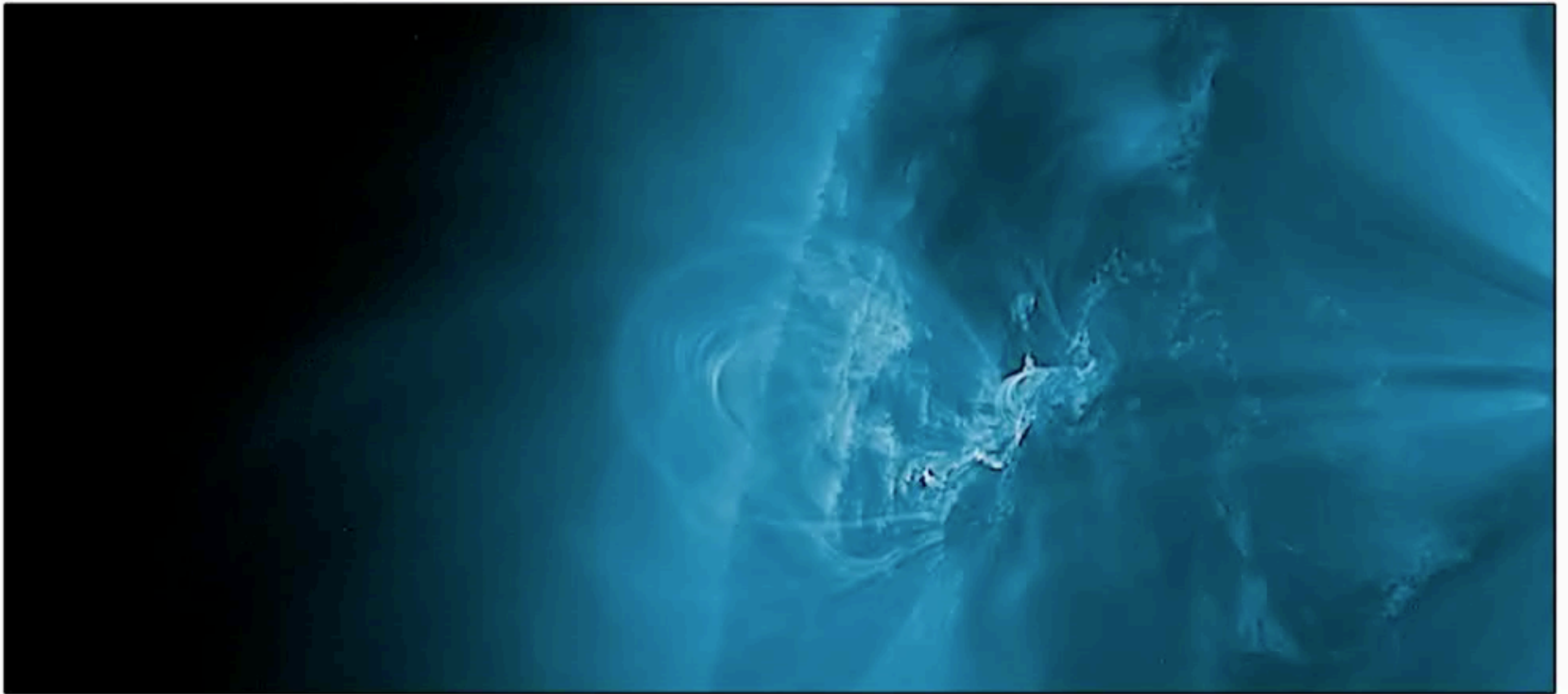
Soft X-Rays: $< 50 \text{ \AA}$



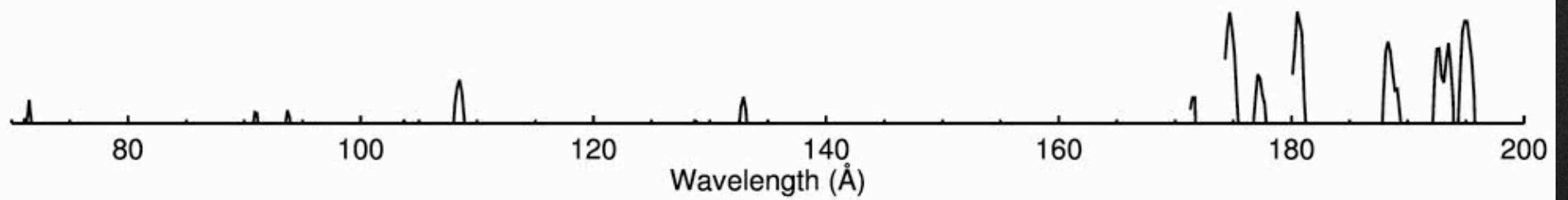
XRT/Hinode
September – November 2014

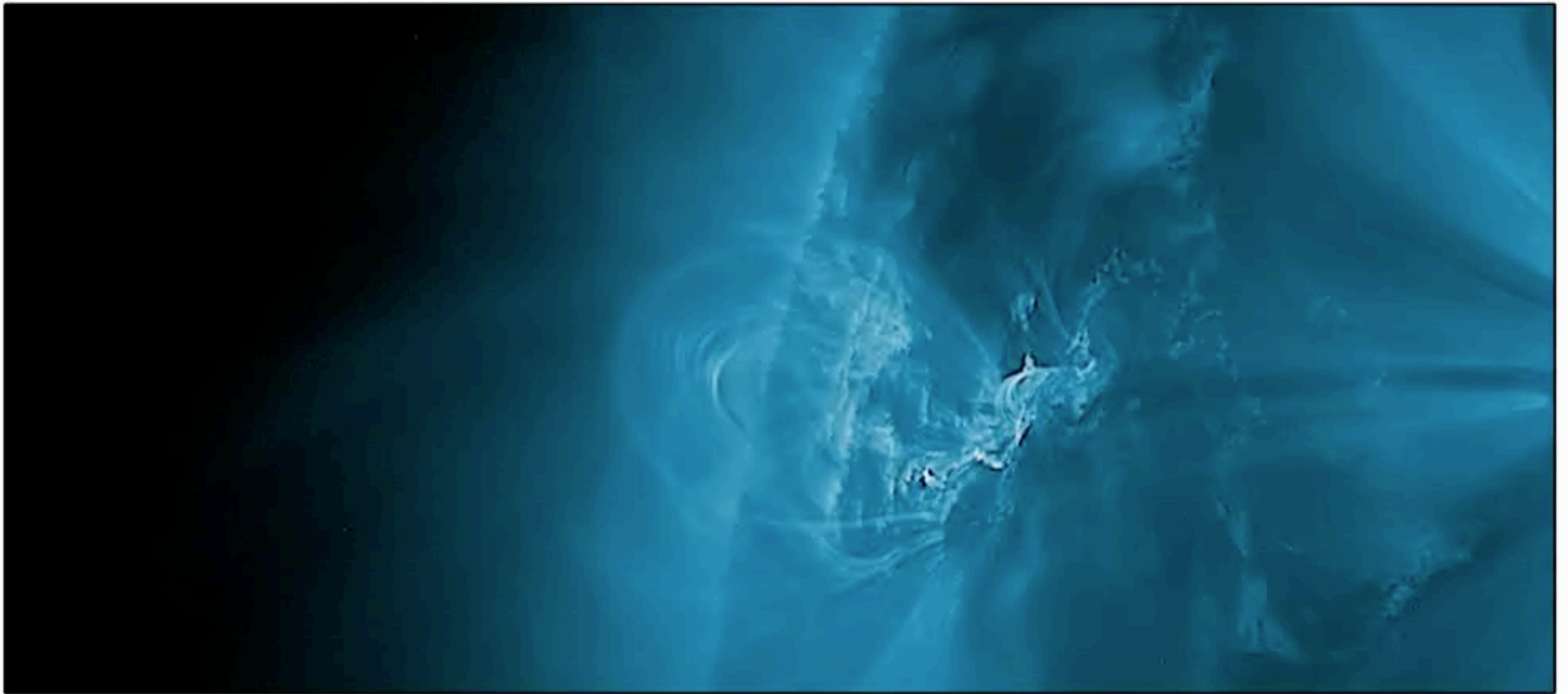
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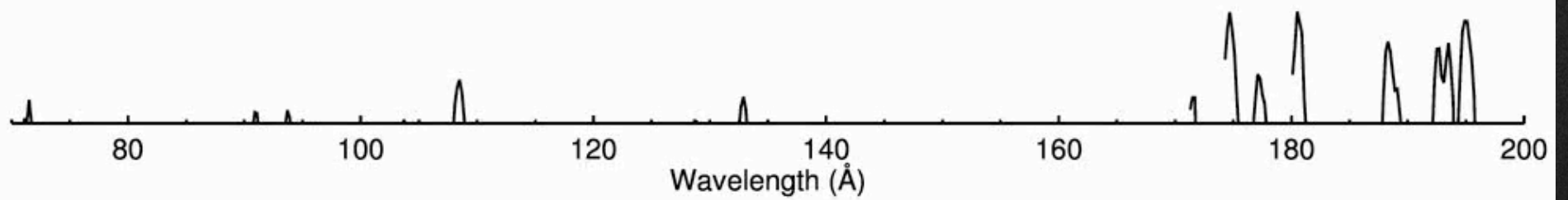


EVE/SDO Flare Irradiance

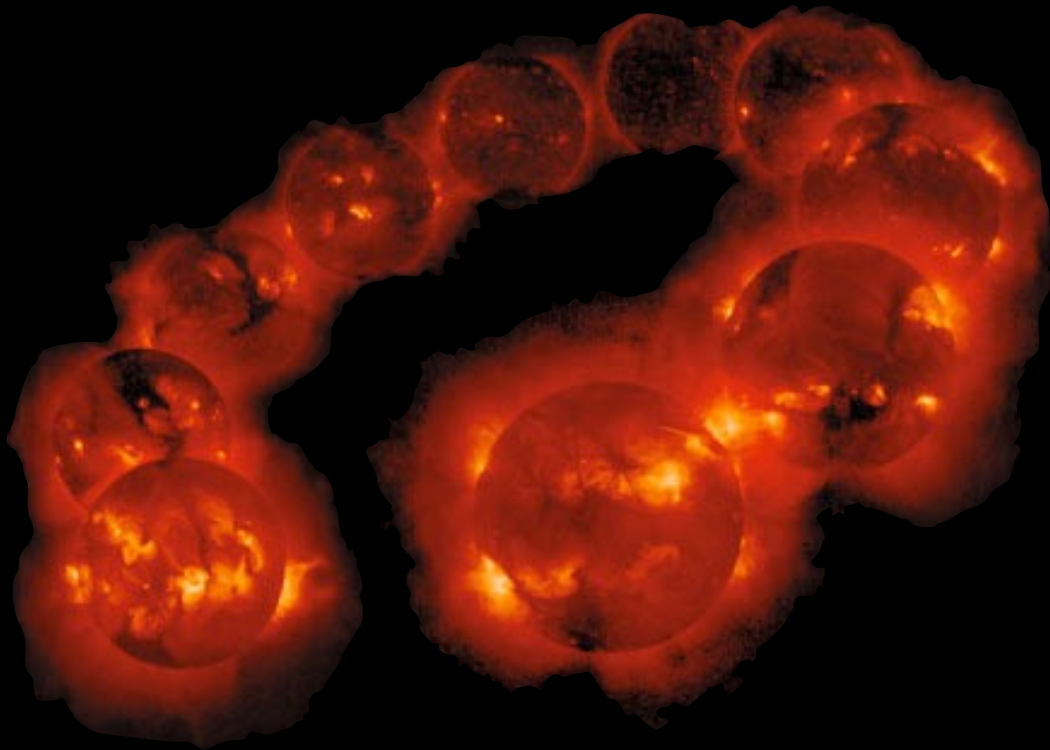




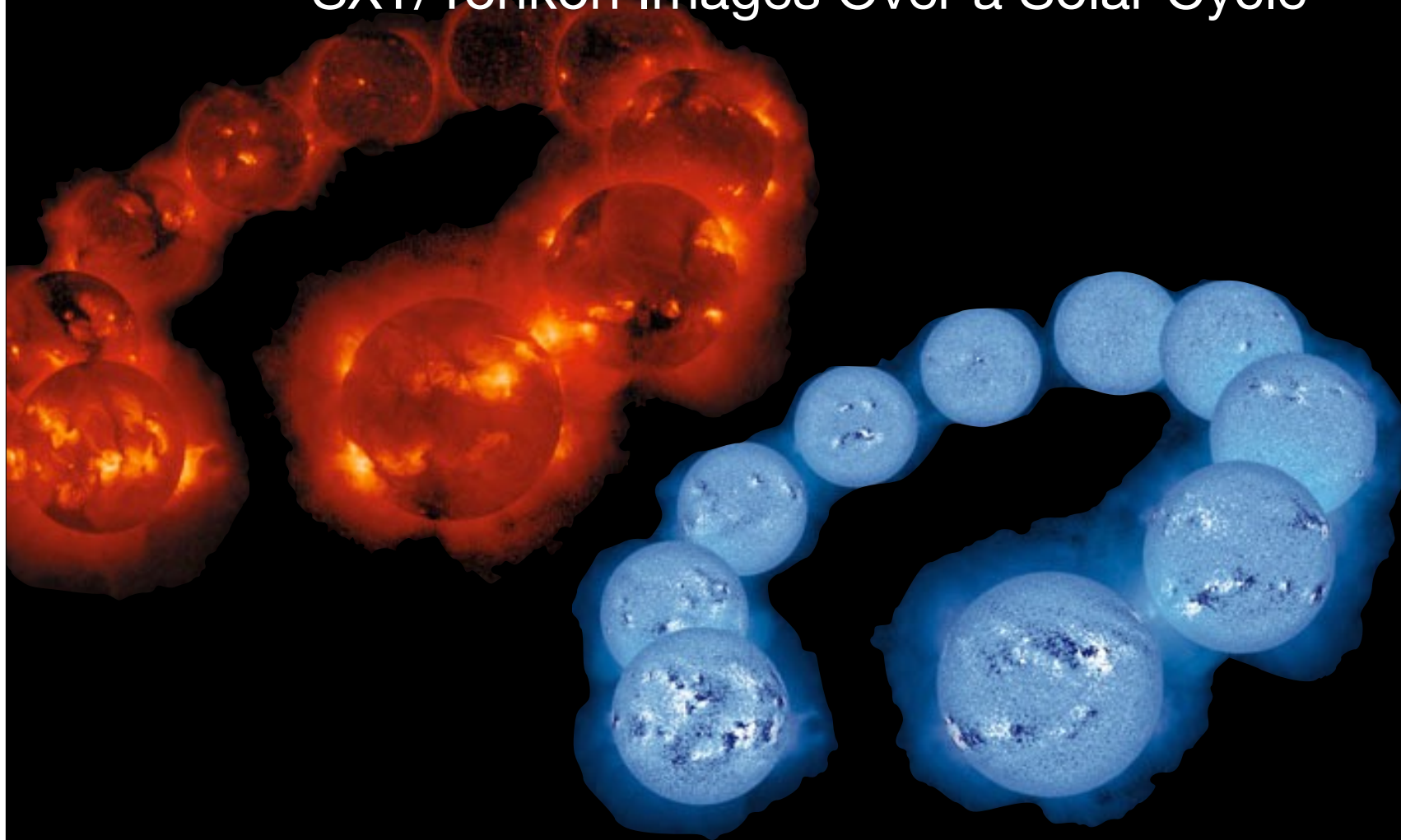
EVE/SDO Flare Irradiance



SXT/Yohkoh Images Over a Solar Cycle

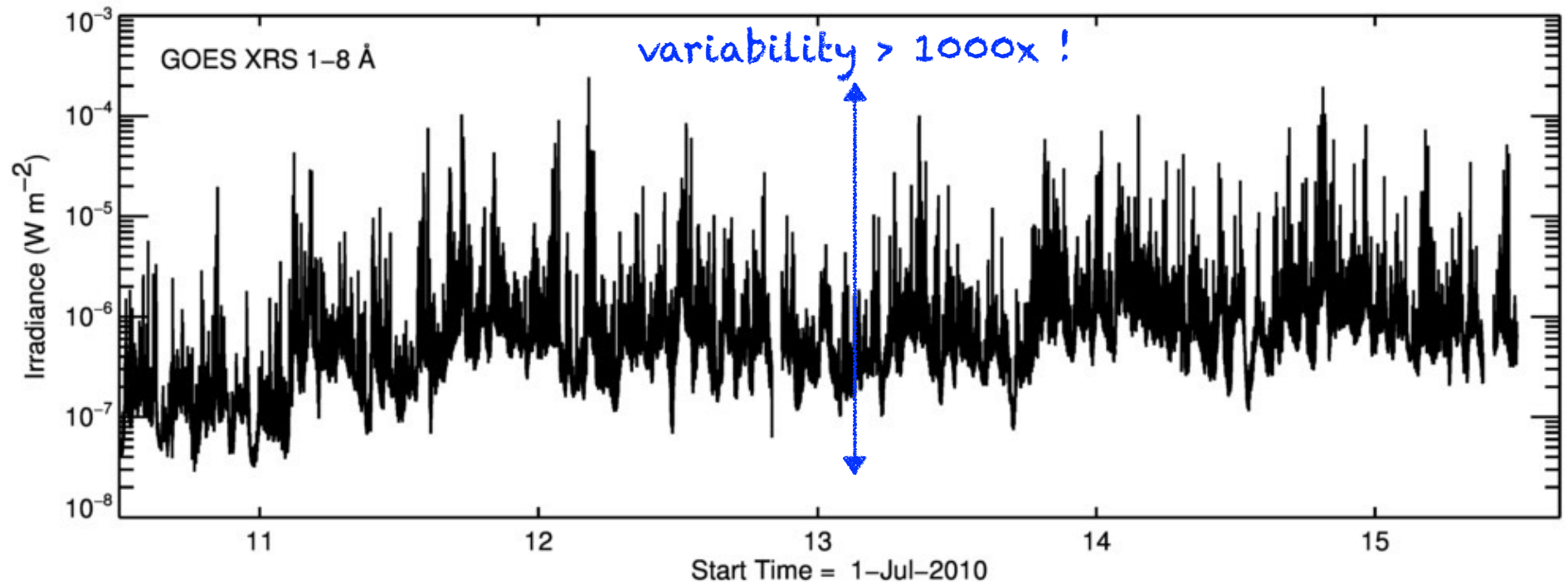


SXT/Yohkoh Images Over a Solar Cycle



Example SXR Irradiance Solar Cycle Time Series

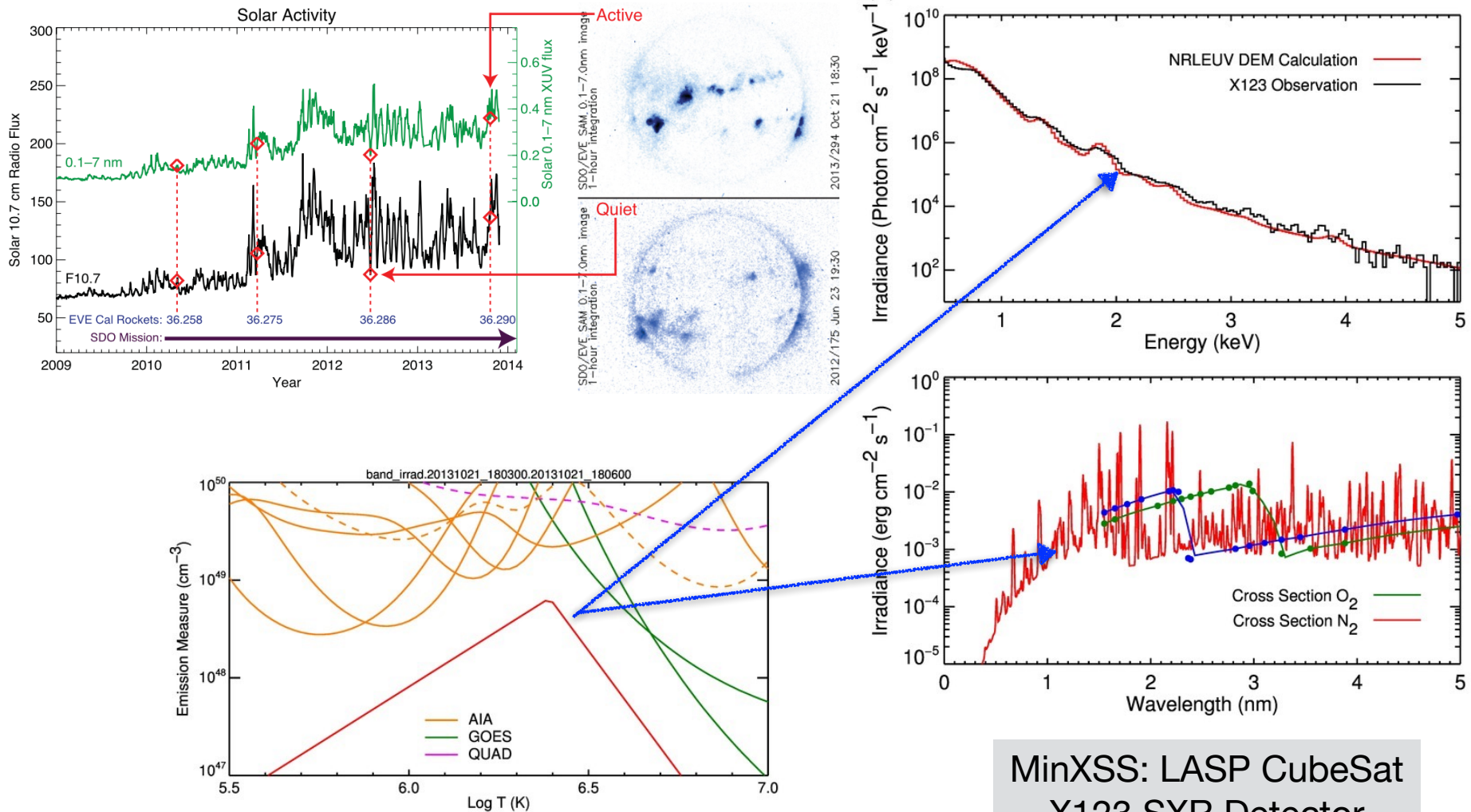
Daily XRS/GOES 1 – 8 Å



*No continuous, spectral irradiance measurements
that completely cover $< 50 \text{ Å}$*

Example SXR Irradiance Spectrum New Observations from X123

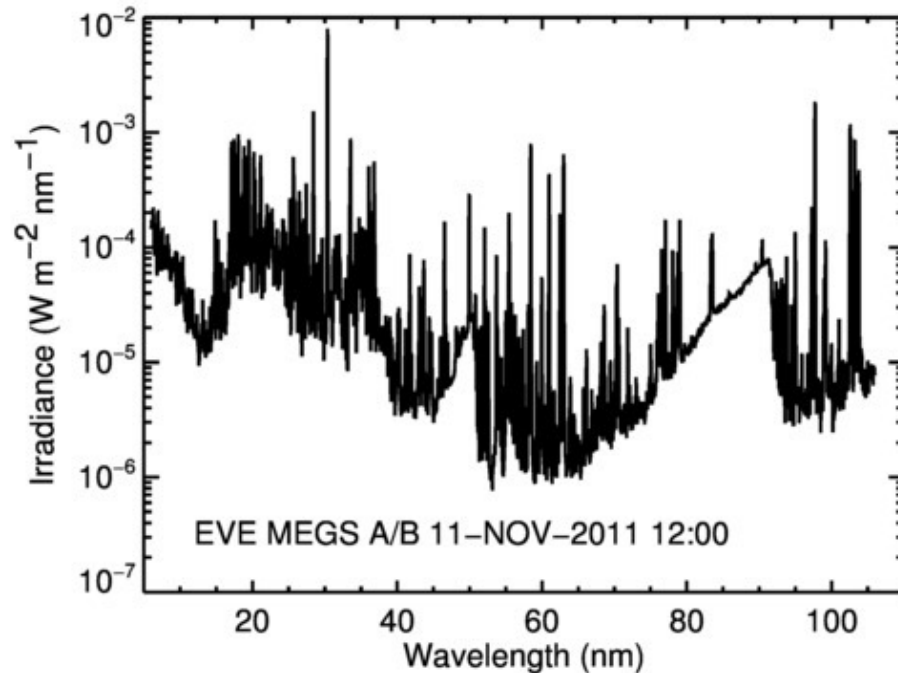
Caspi, Woods, & Warren (2015)



infer spectra from
emission measure model?

MinXSS: LASP CubeSat
X123 SXR Detector
2015 launch

Extreme Ultraviolet: 50 – 1200 Å

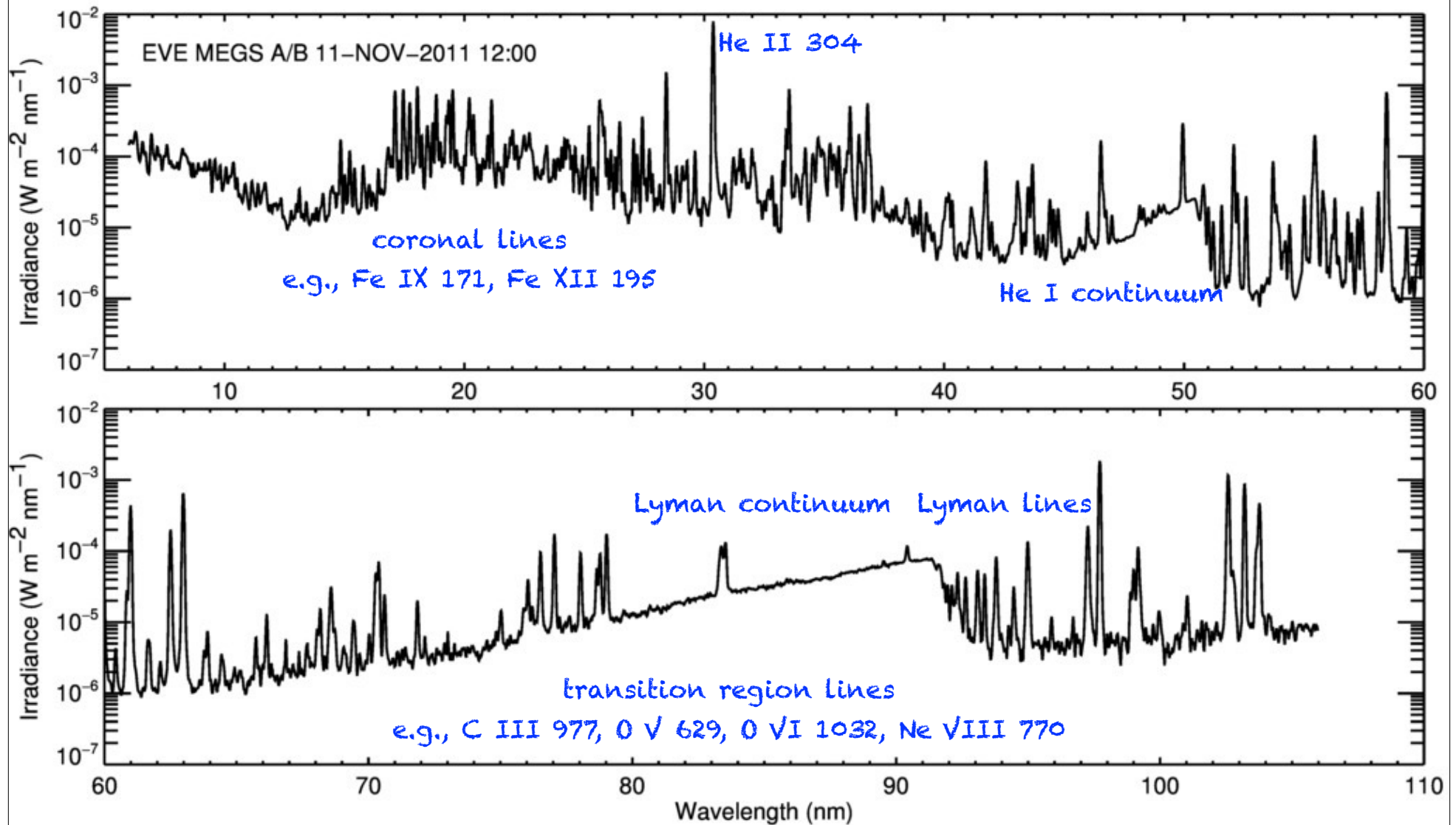


EVE/SDO EUV Spectral Irradiance

1 Å spectral resolution
10s cadence
50-1050 Å coverage
2010 - present

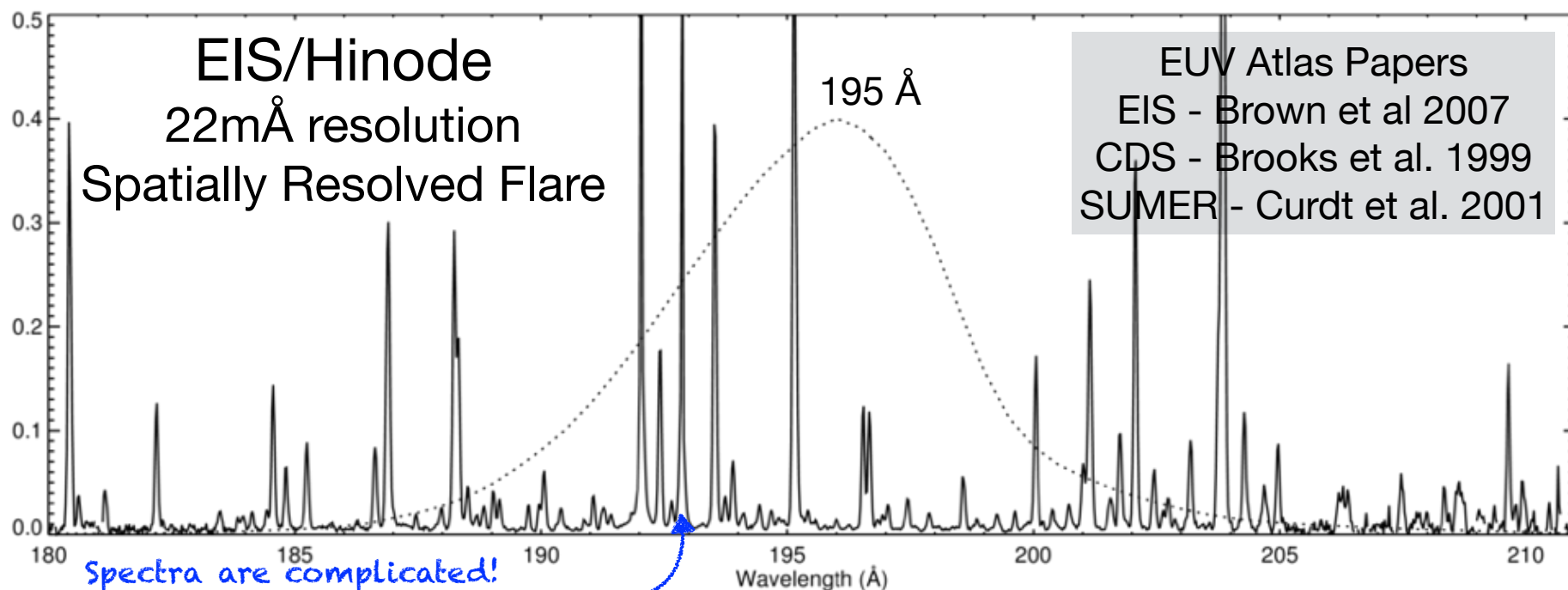
- Formed at chromospheric, transition region, coronal, and flare temperatures
- Optically thin and thick lines and continua
- Moderate contrast between quiet and active sun → moderate variation over solar rotation and solar cycle
- Many measurements

EUV: 50 – 1200 Å: EVE/SDO Irradiance Spectrum

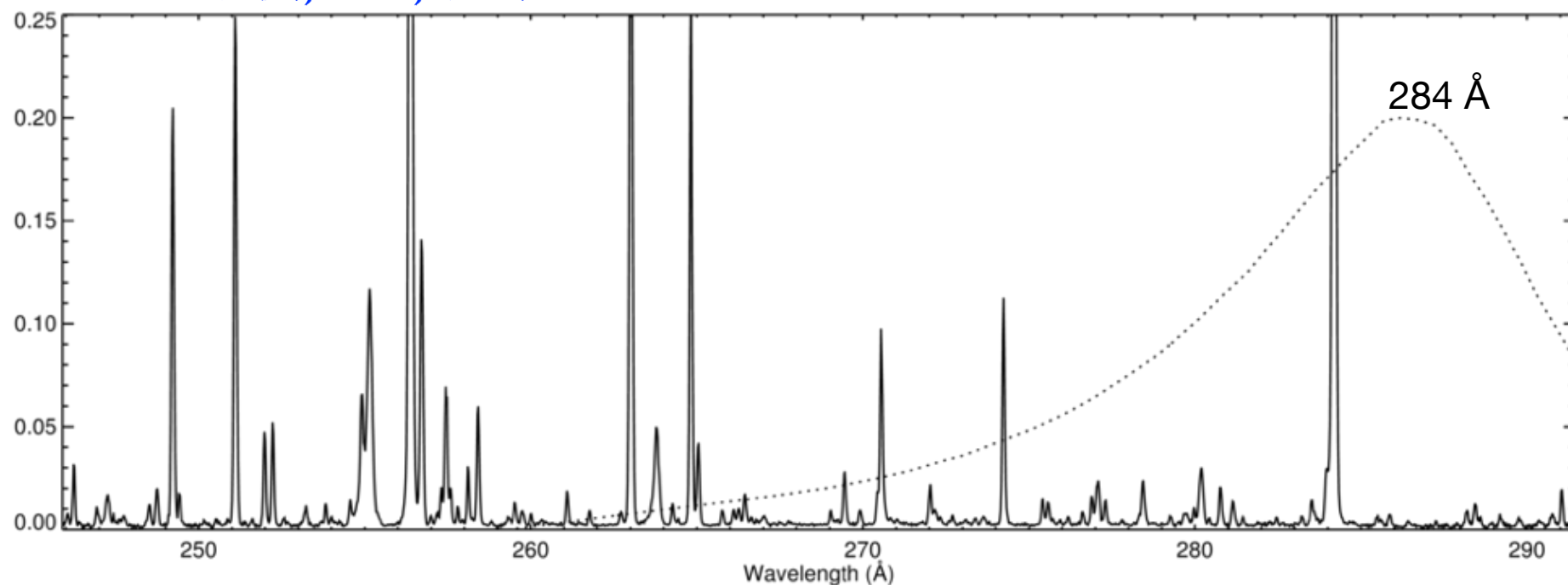


EIS/Hinode
22mÅ resolution
Spatially Resolved Flare

EUV Atlas Papers
EIS - Brown et al 2007
CDS - Brooks et al. 1999
SUMER - Curdt et al. 2001



Spectra are complicated!
within ~ 1 Å O V, Fe XI, Ca XVII

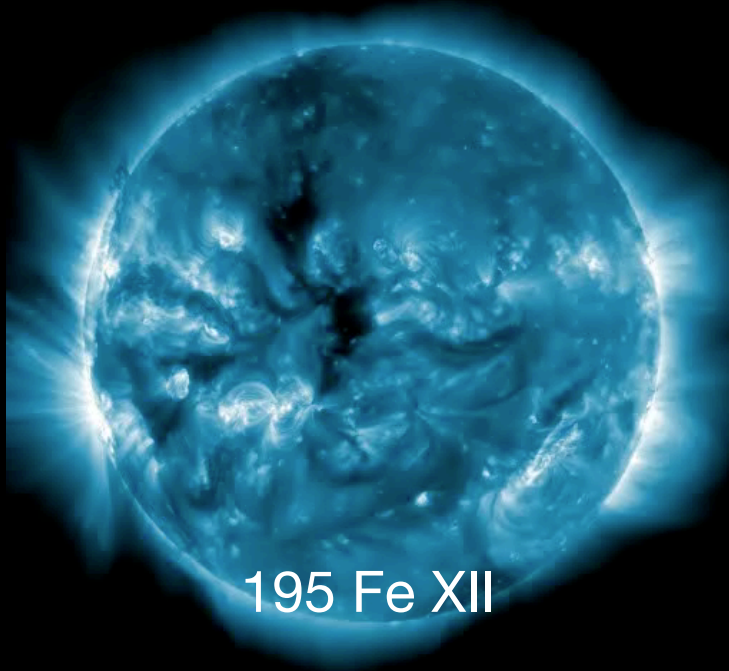




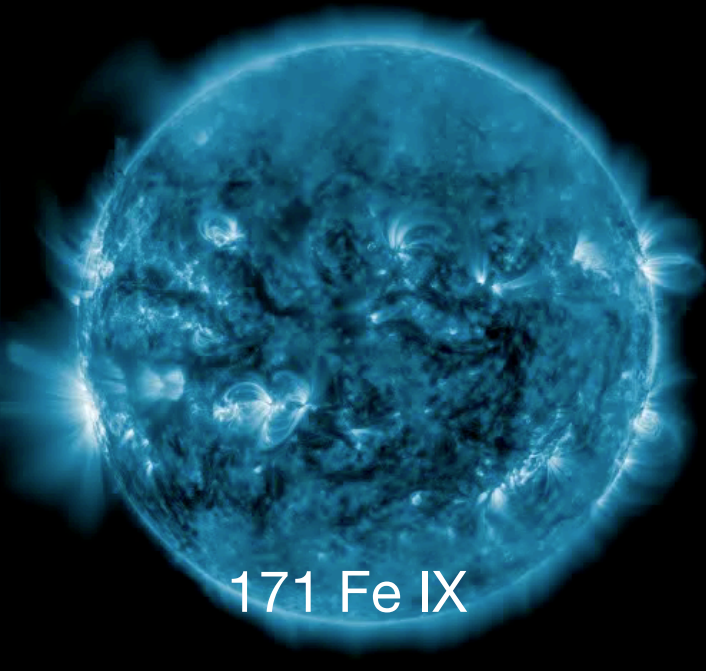
131 Fe VIII/Fe XXIII



94 Fe XVIII



195 Fe XII



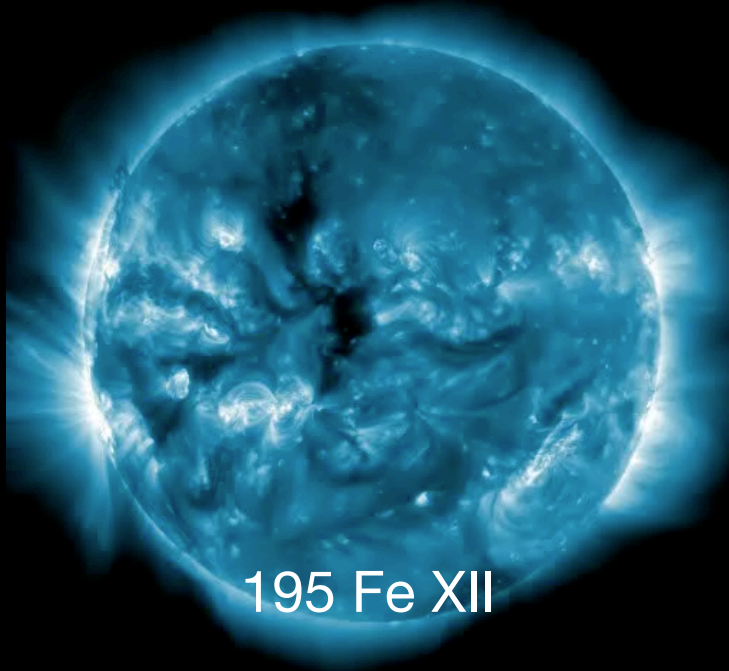
171 Fe IX



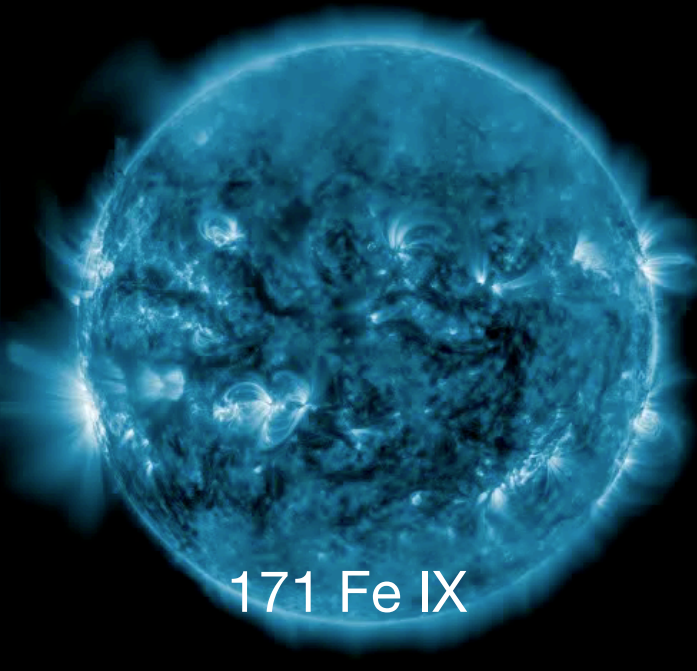
131 Fe VIII/Fe XXIII



94 Fe XVIII



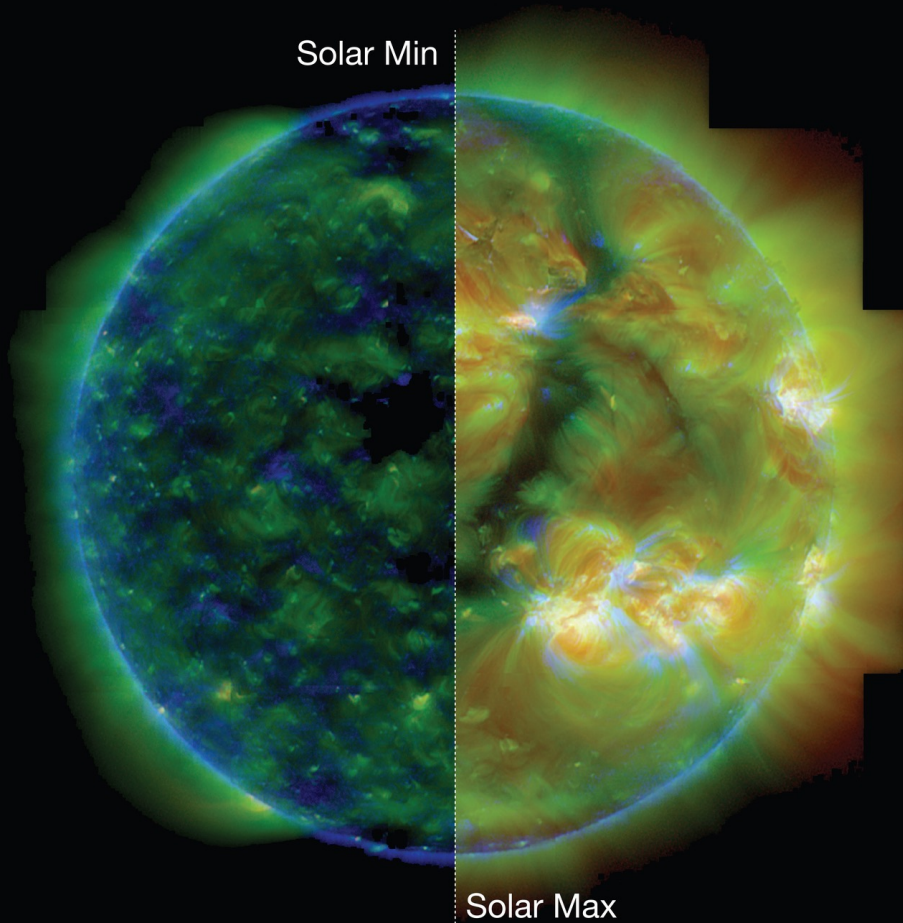
195 Fe XII



171 Fe IX

The Extreme Ultraviolet Imaging Spectrometer on Hinode

Solar Min

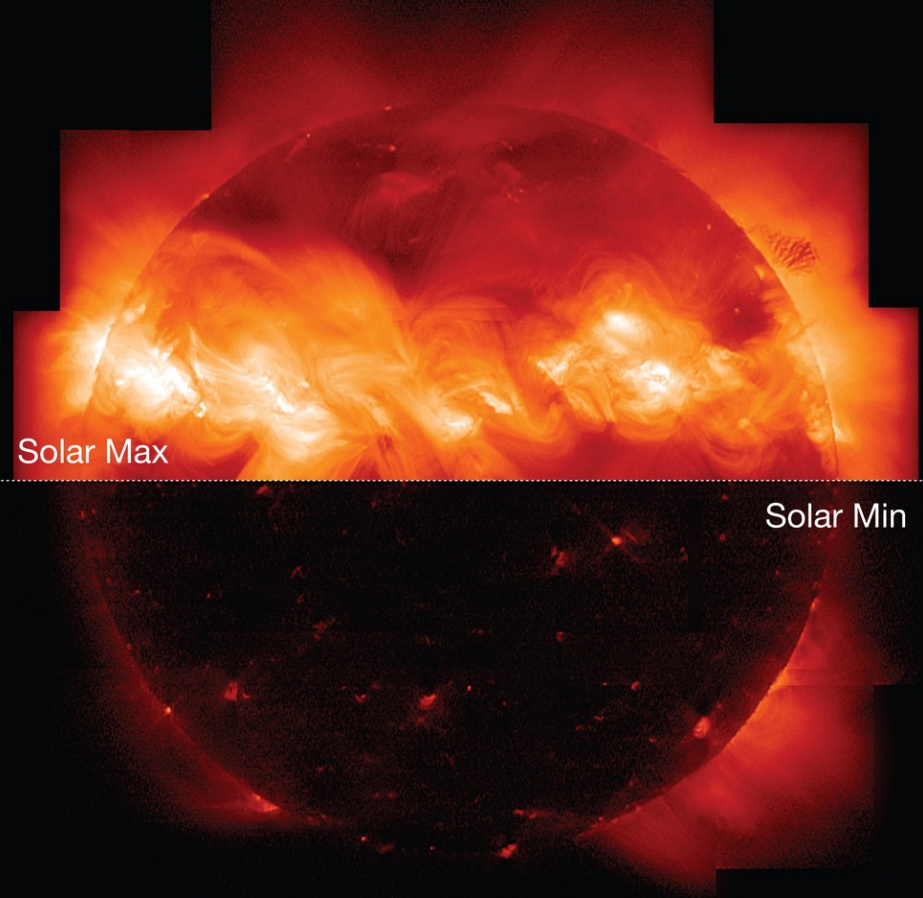


Solar Max

Si VII 275.37 Å
Fe XII 195.12 Å
Fe XV 284.16 Å

The Extreme Ultraviolet Imaging Spectrometer on Hinode

Solar Max

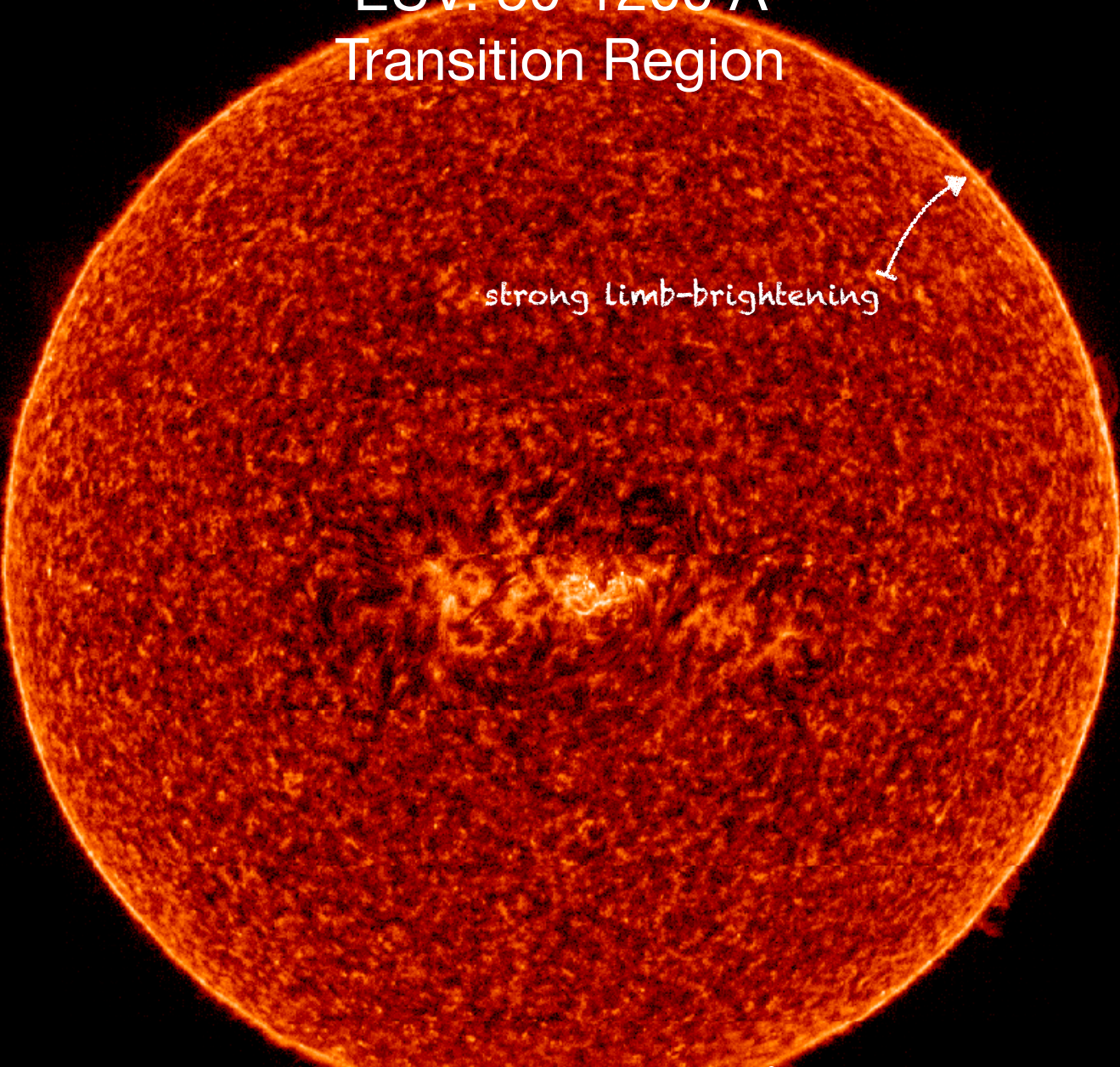


Solar Min

Fe XV 284.16 Å

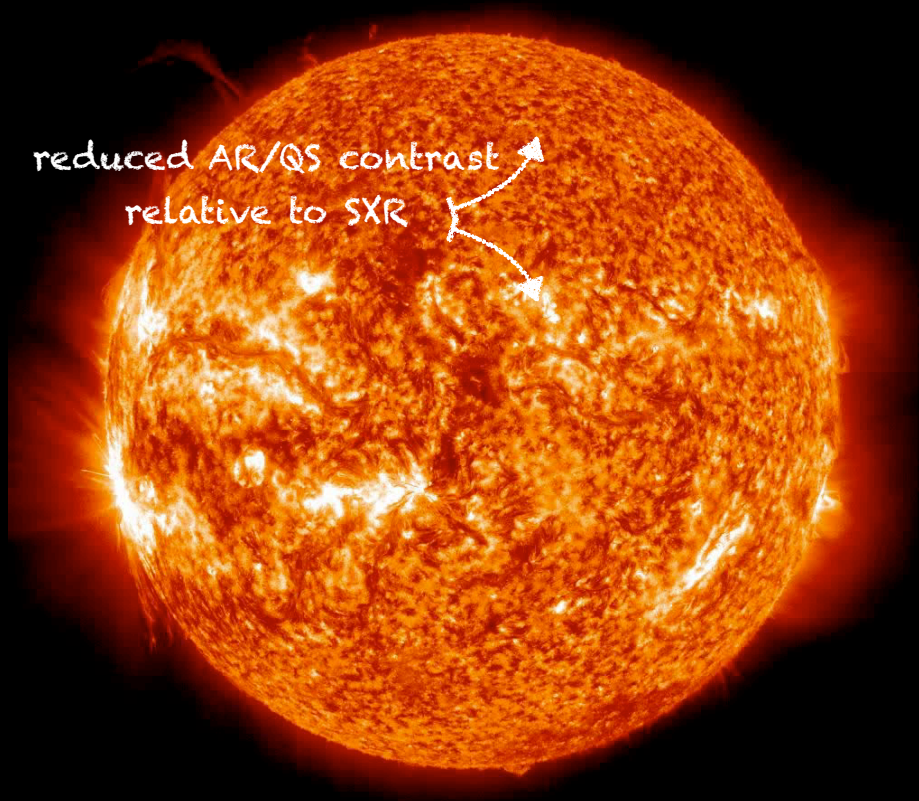
EUV: 50-1200 Å
Transition Region

strong limb-brightening

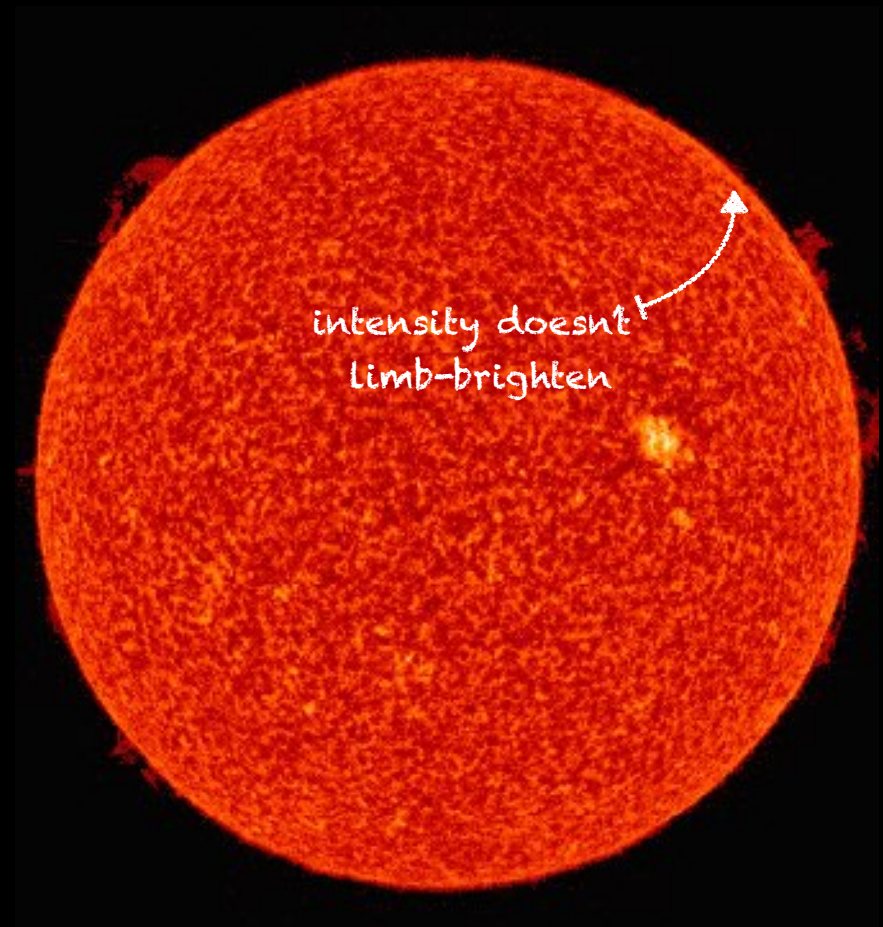
A circular image of the Sun's transition region in EUV light. The image shows a bright, textured disk with a central bright spot. A curved arrow points from the text "strong limb-brightening" to the outer edge of the disk.

SUMER/SoHO S VI 933 Å
May 12 – 13, 1996

EUV: 50 – 1200 Å Chromosphere

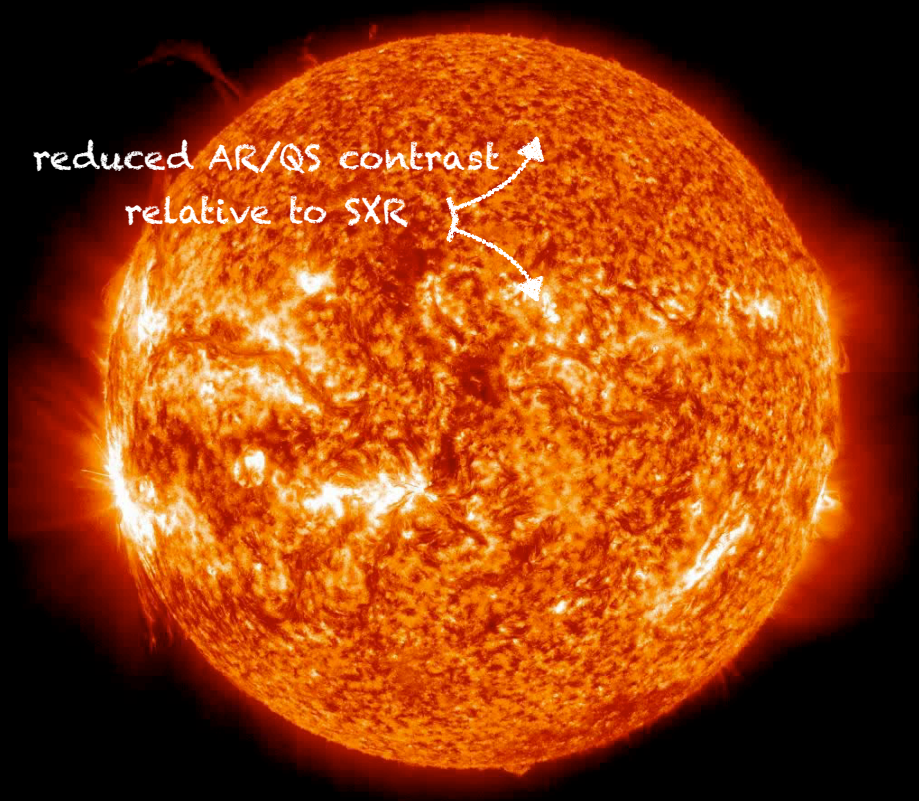


AIA/SDO He II 304 Å
October 2014

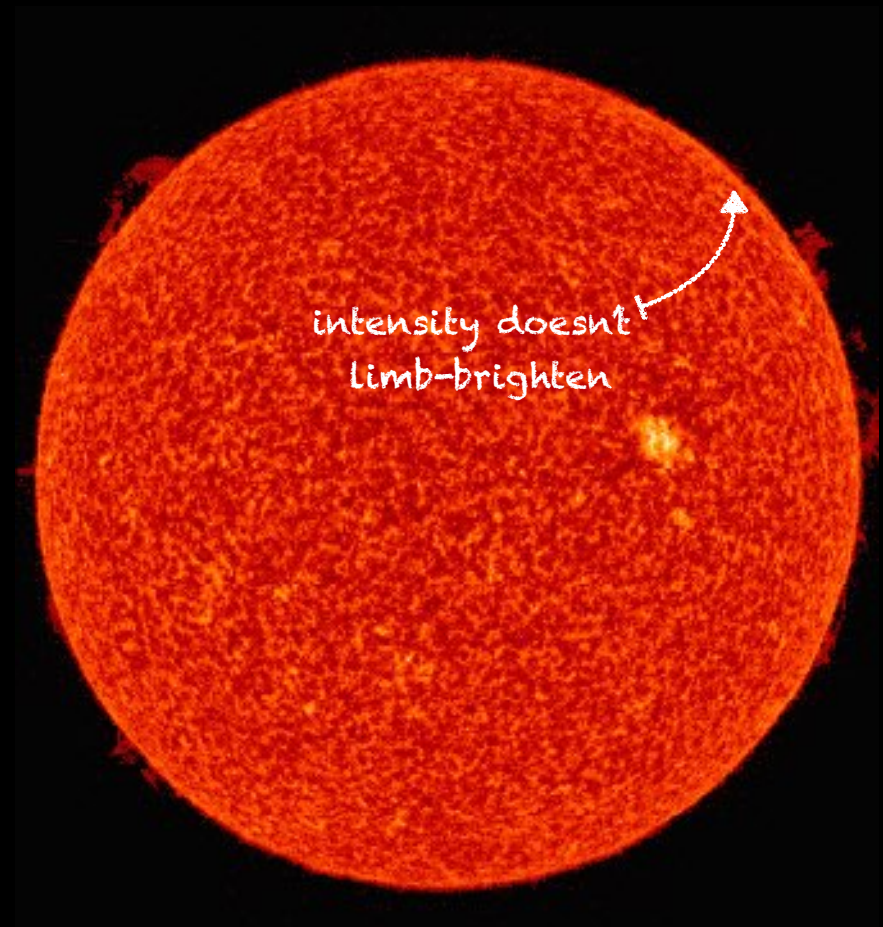


SUMER/SoHO Lyman ε 937 Å
August 11 – 12, 1996

EUV: 50 – 1200 Å Chromosphere

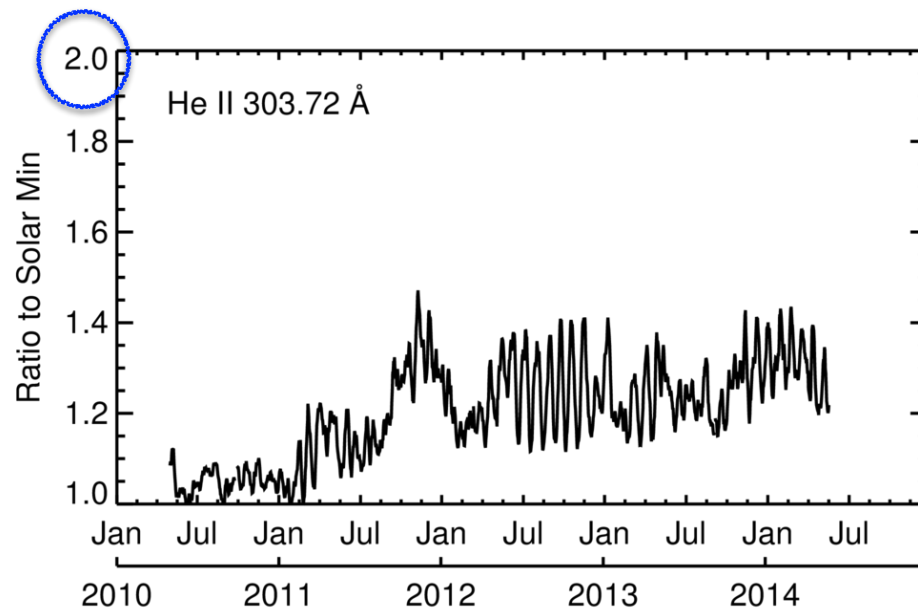
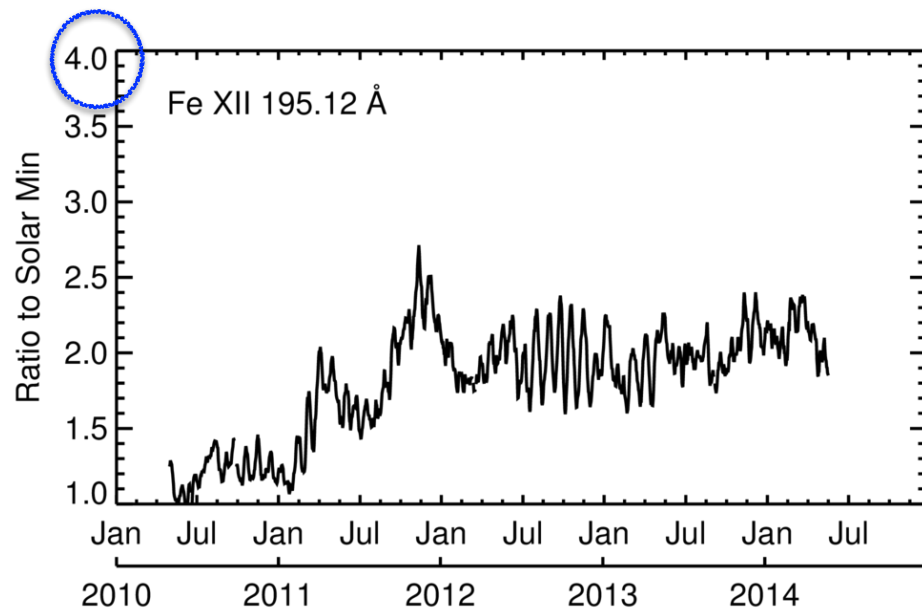
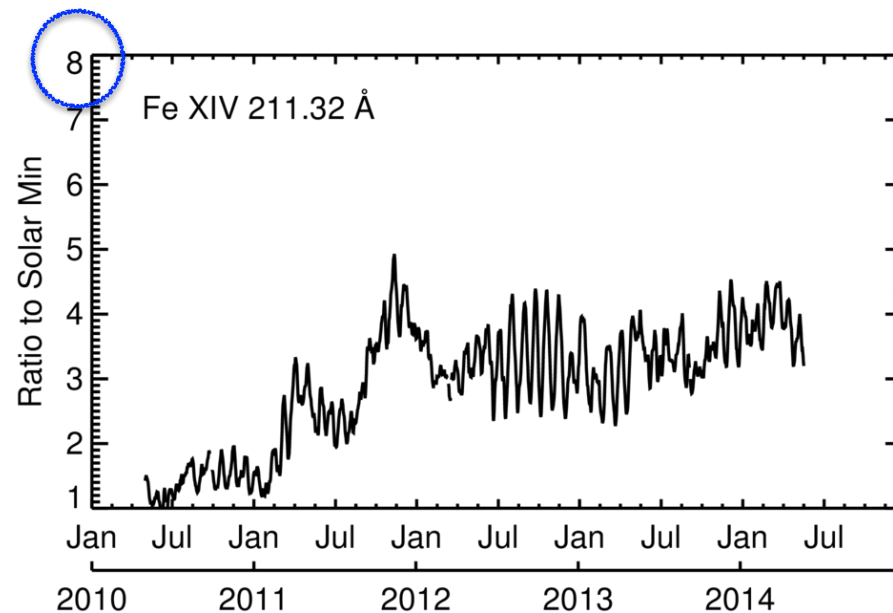
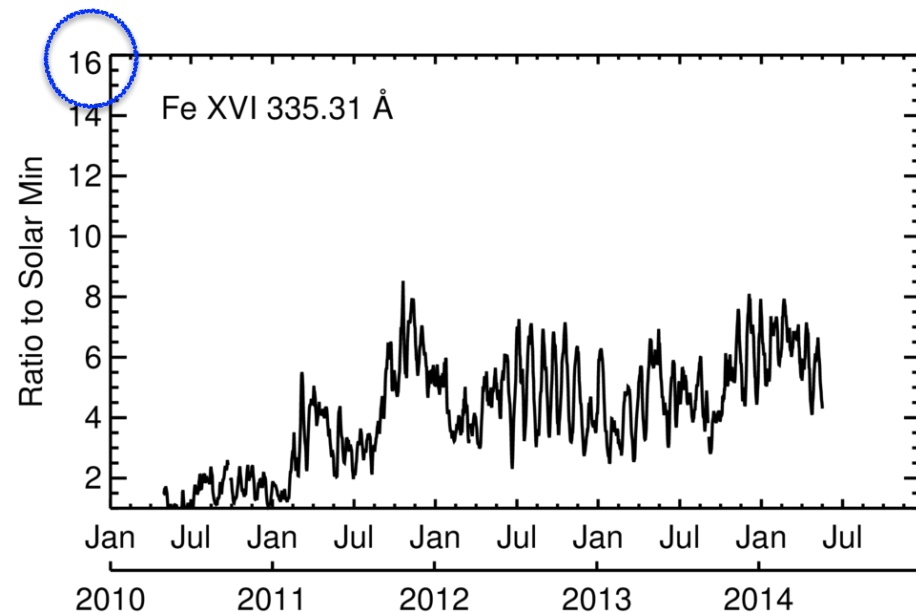


AIA/SDO He II 304 Å
October 2014

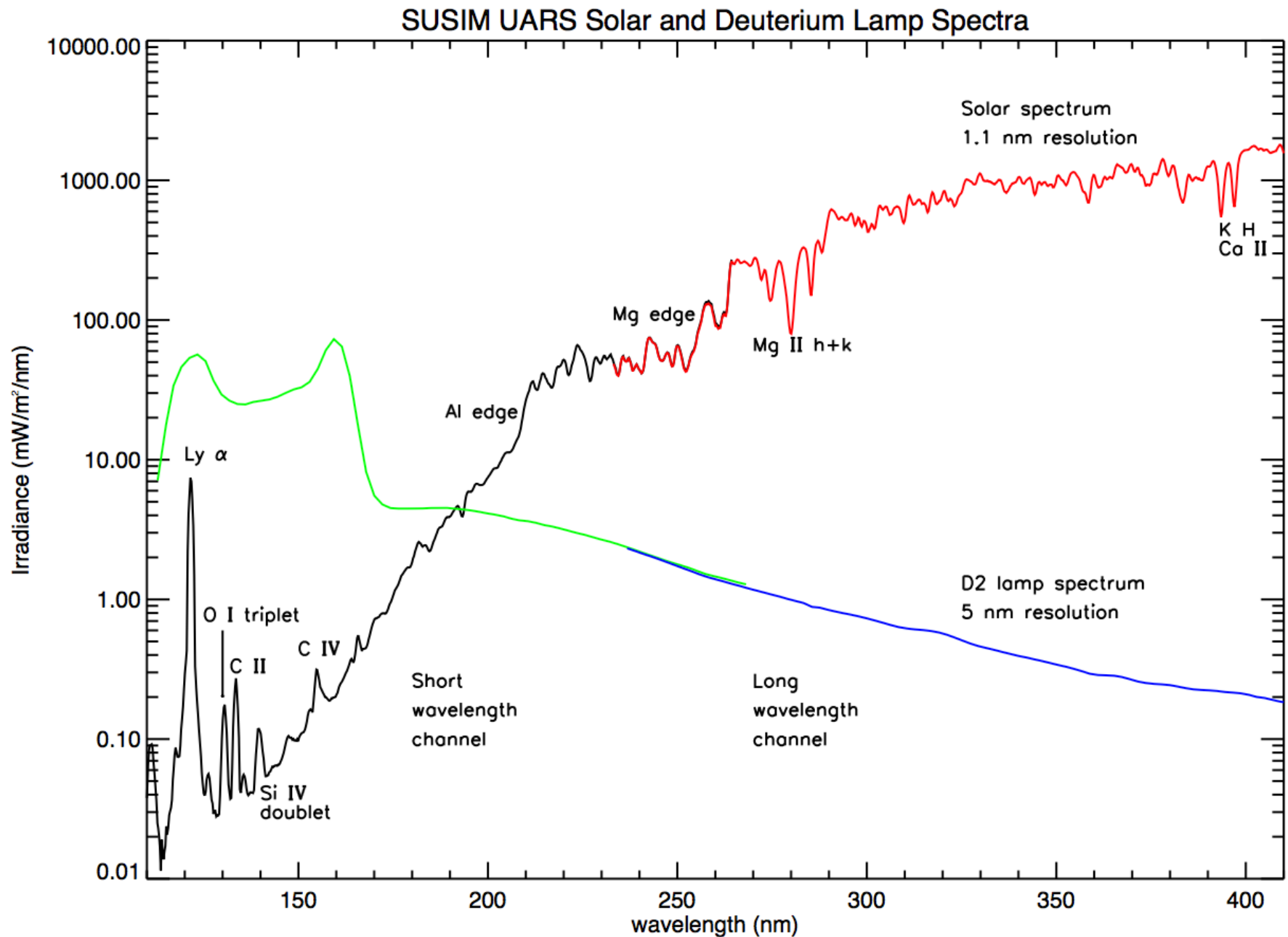


SUMER/SoHO Lyman ε 937 Å
August 11 – 12, 1996

Example EVE/SDO EUV Irradiance Time Series



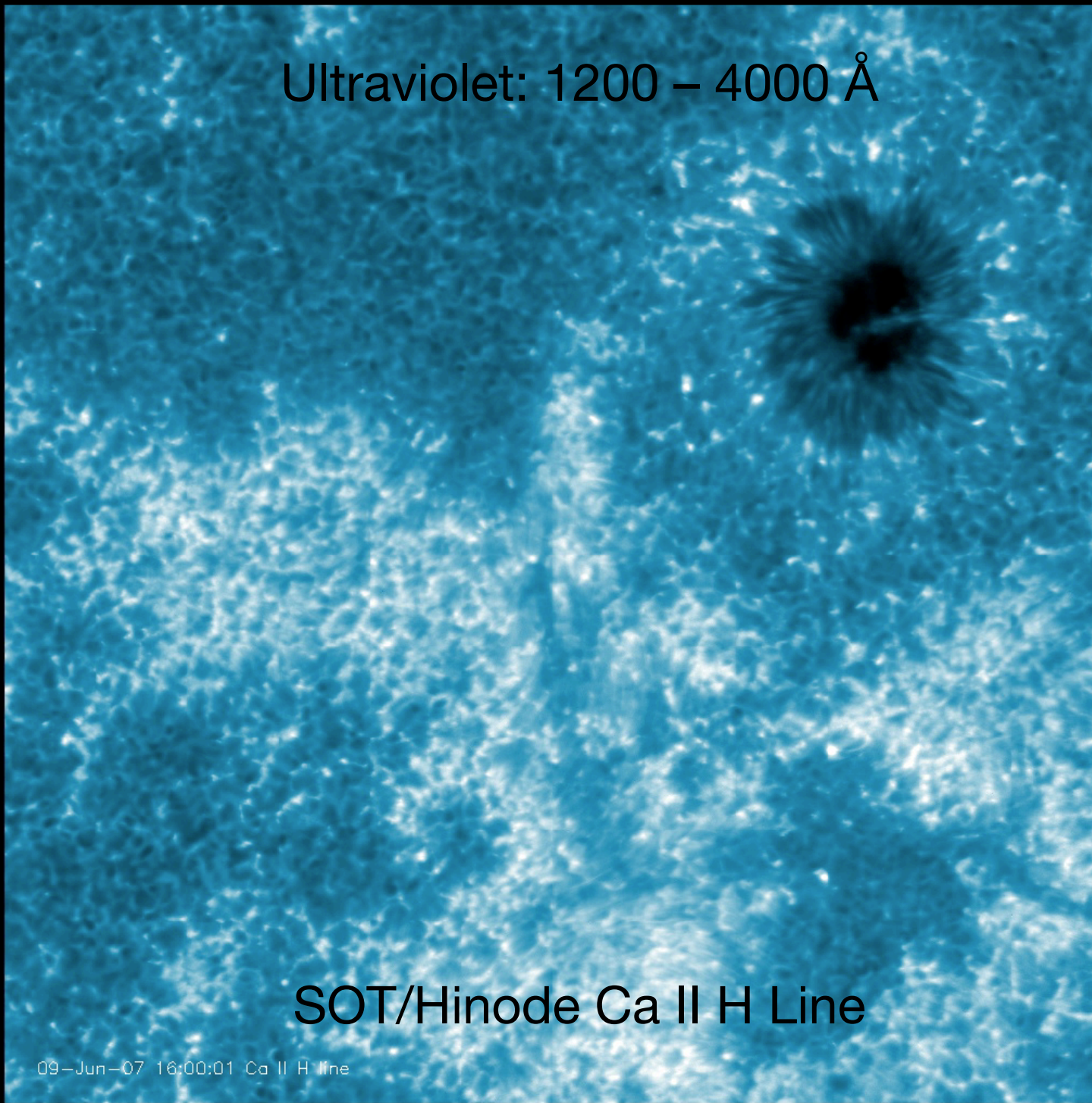
Example Ultraviolet Spectrum: 1200 – 4000 Å



Ultraviolet: 1200 – 4000 Å

SOT/Hinode Ca II H Line

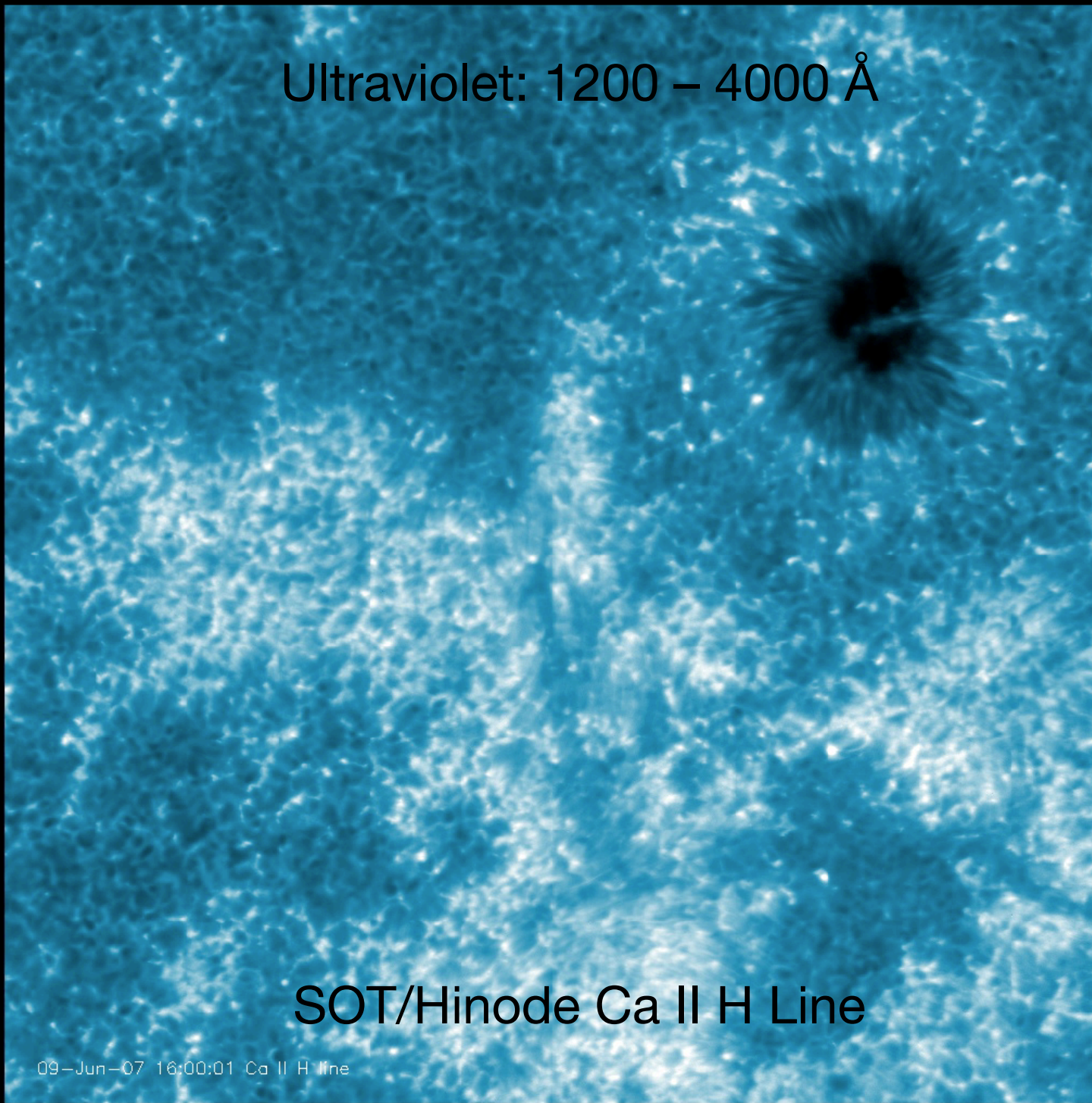
09-Jun-07 16:00:01 Ca II H line



Ultraviolet: 1200 – 4000 Å

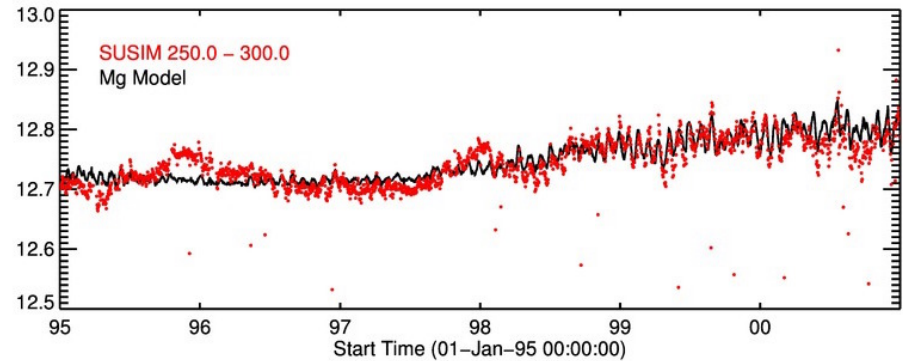
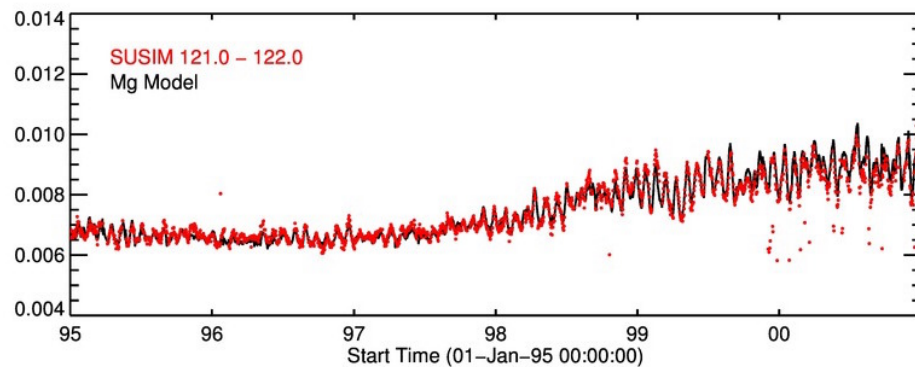
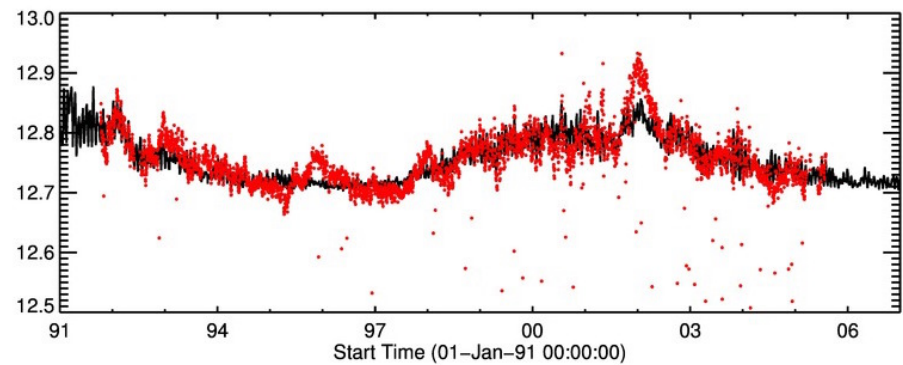
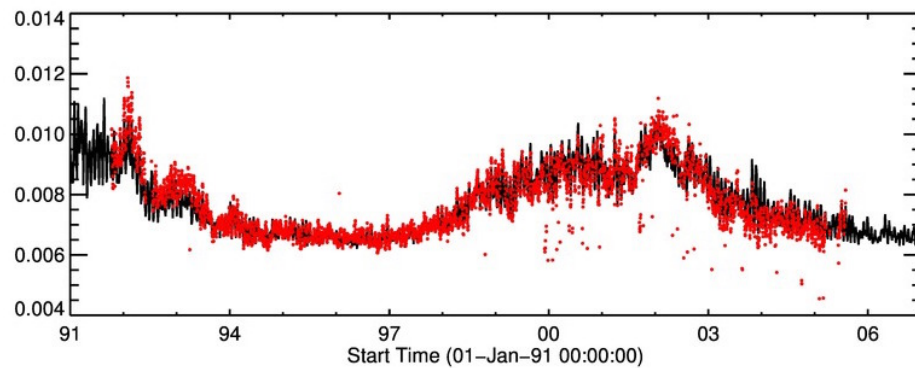
SOT/Hinode Ca II H Line

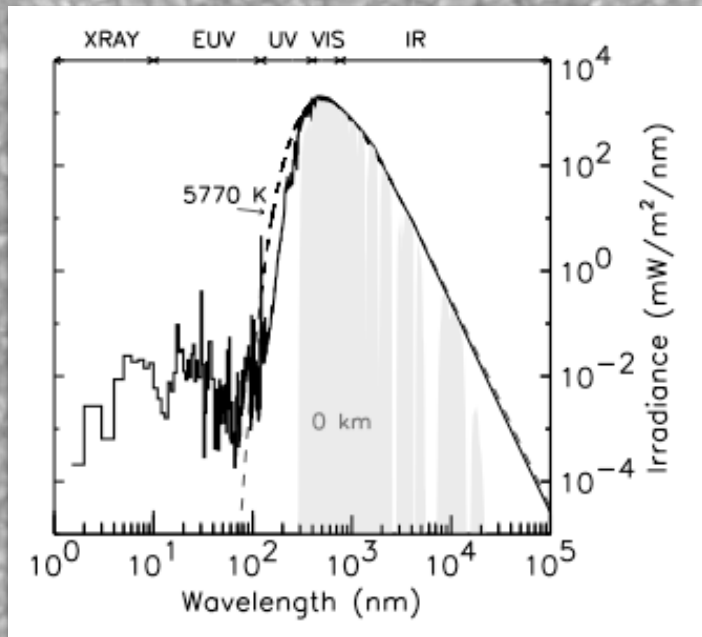
09-Jun-07 16:00:01 Ca II H line



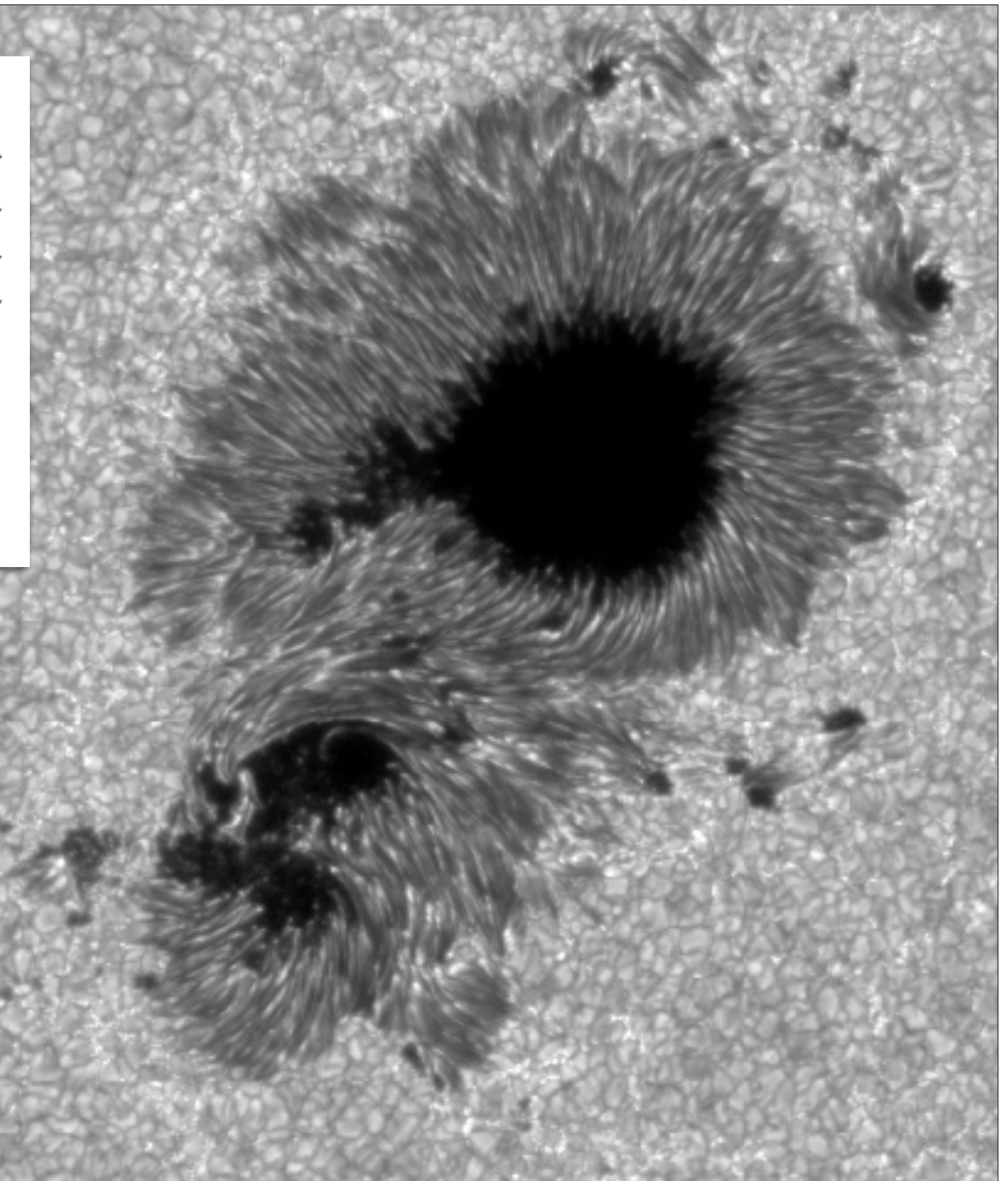
Example UV Irradiance Time Series

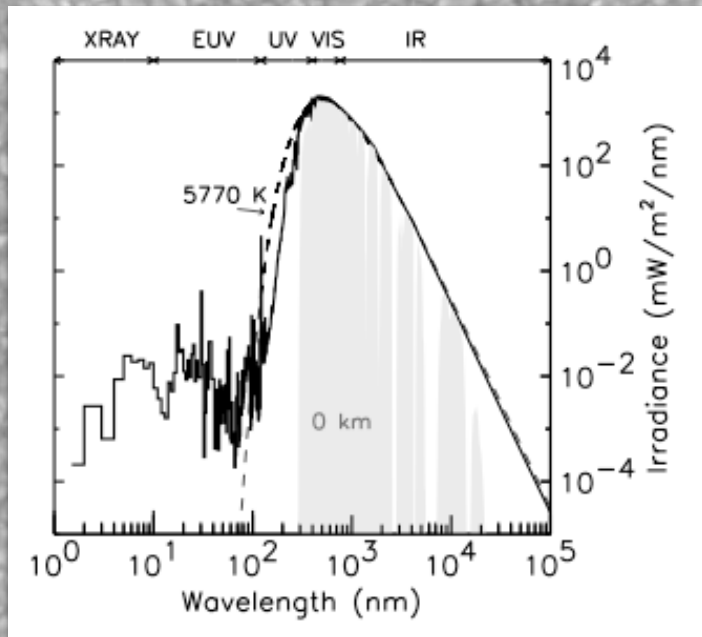
SUSIM/UARS



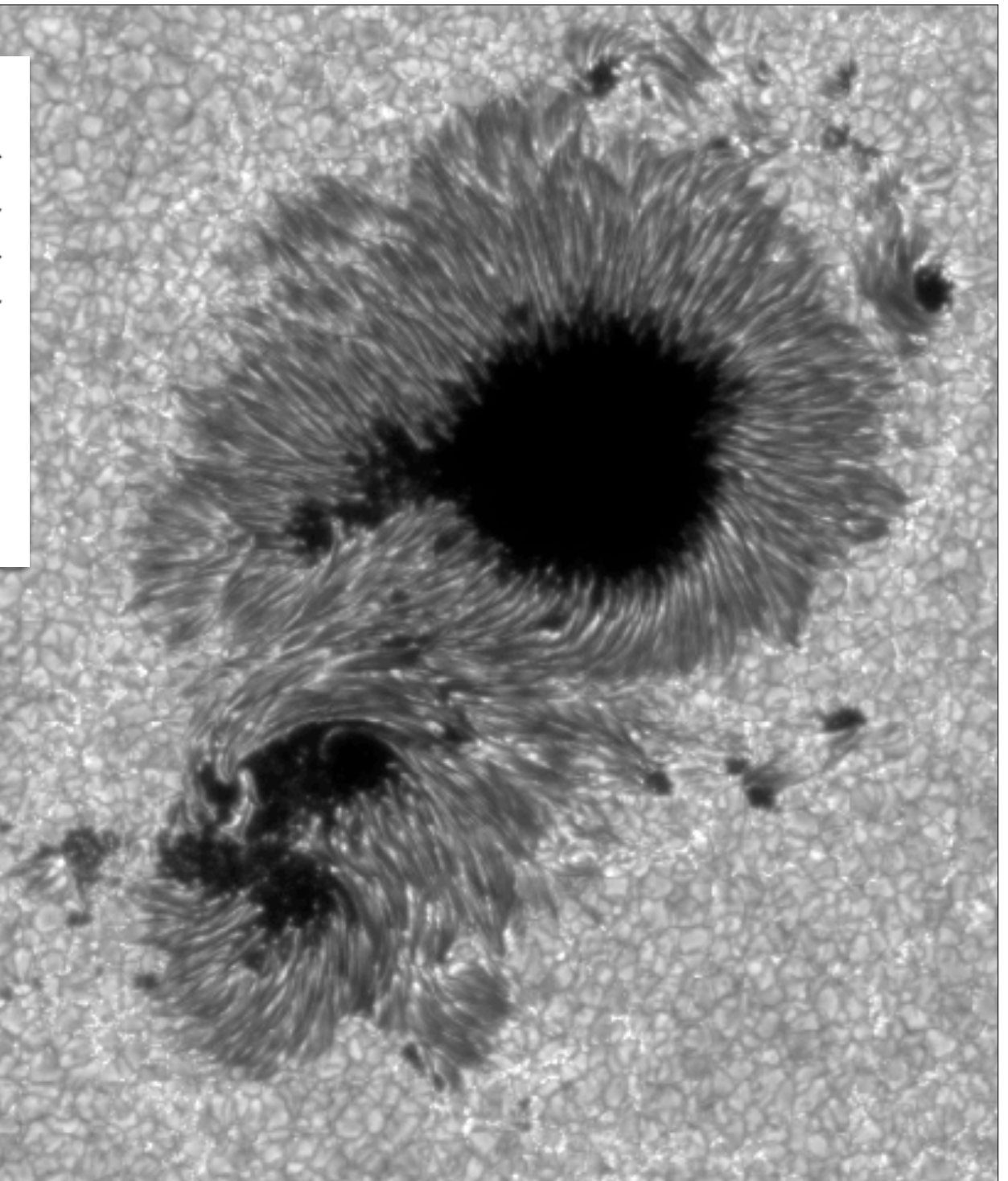


Visible Spectrum:
5770 K Blackbody

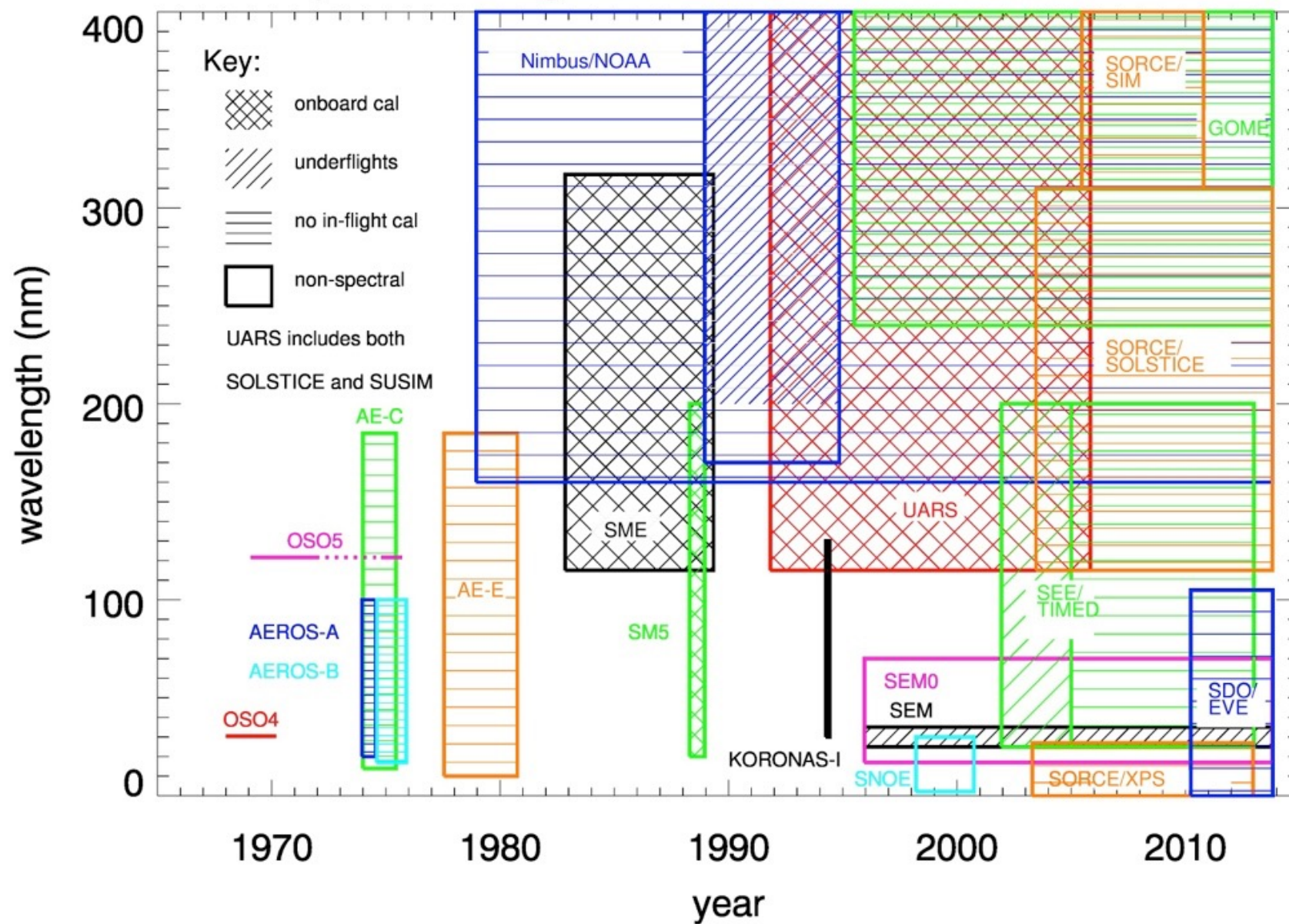




Visible Spectrum:
5770 K Blackbody



Temporal Coverage of Solar UV Irradiance Observations



Jeff Morrill NRL/NASA HQ

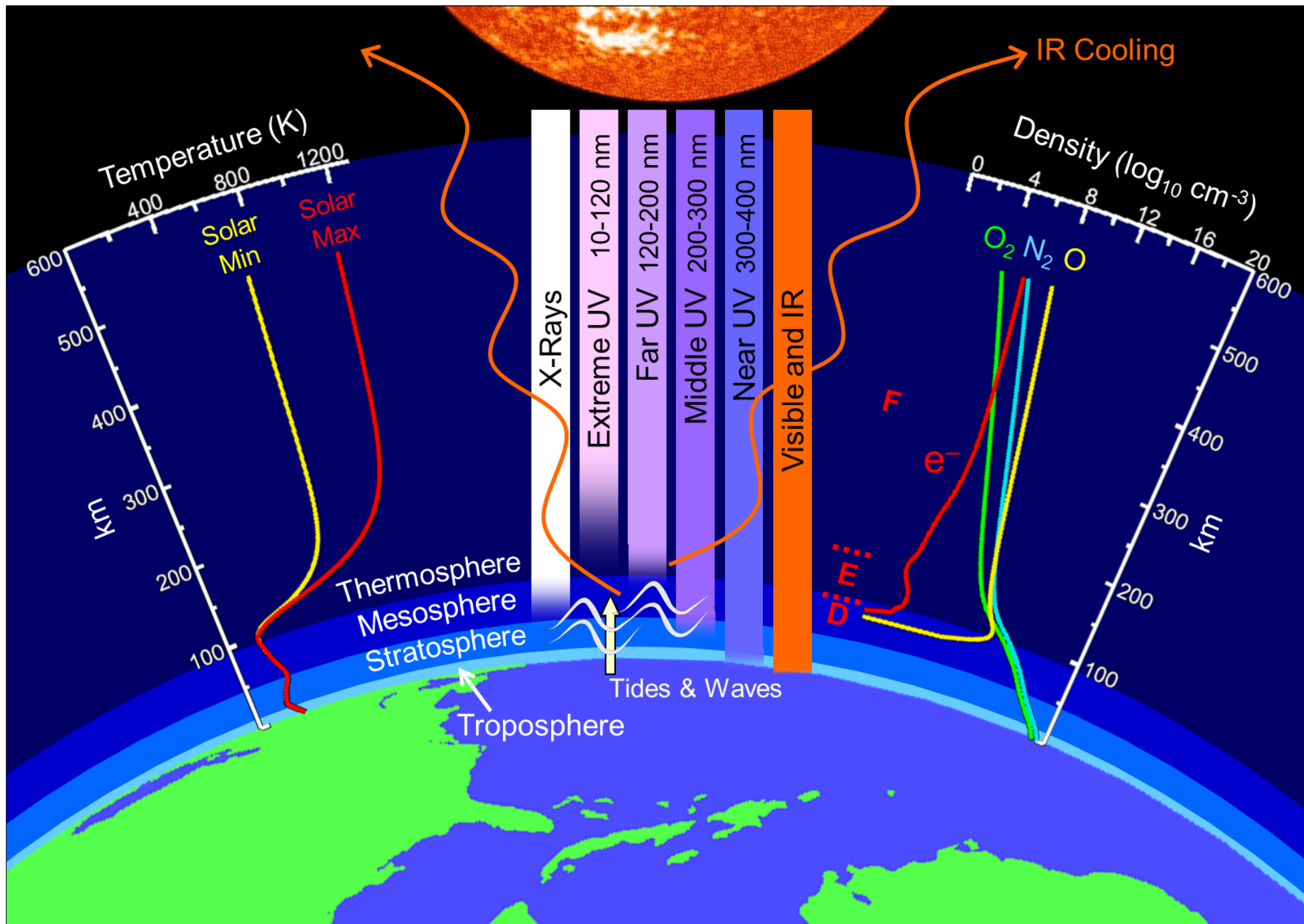


Image courtesy of John Emmert, Naval Research Laboratory

An Application: The Orbital Debris Problem



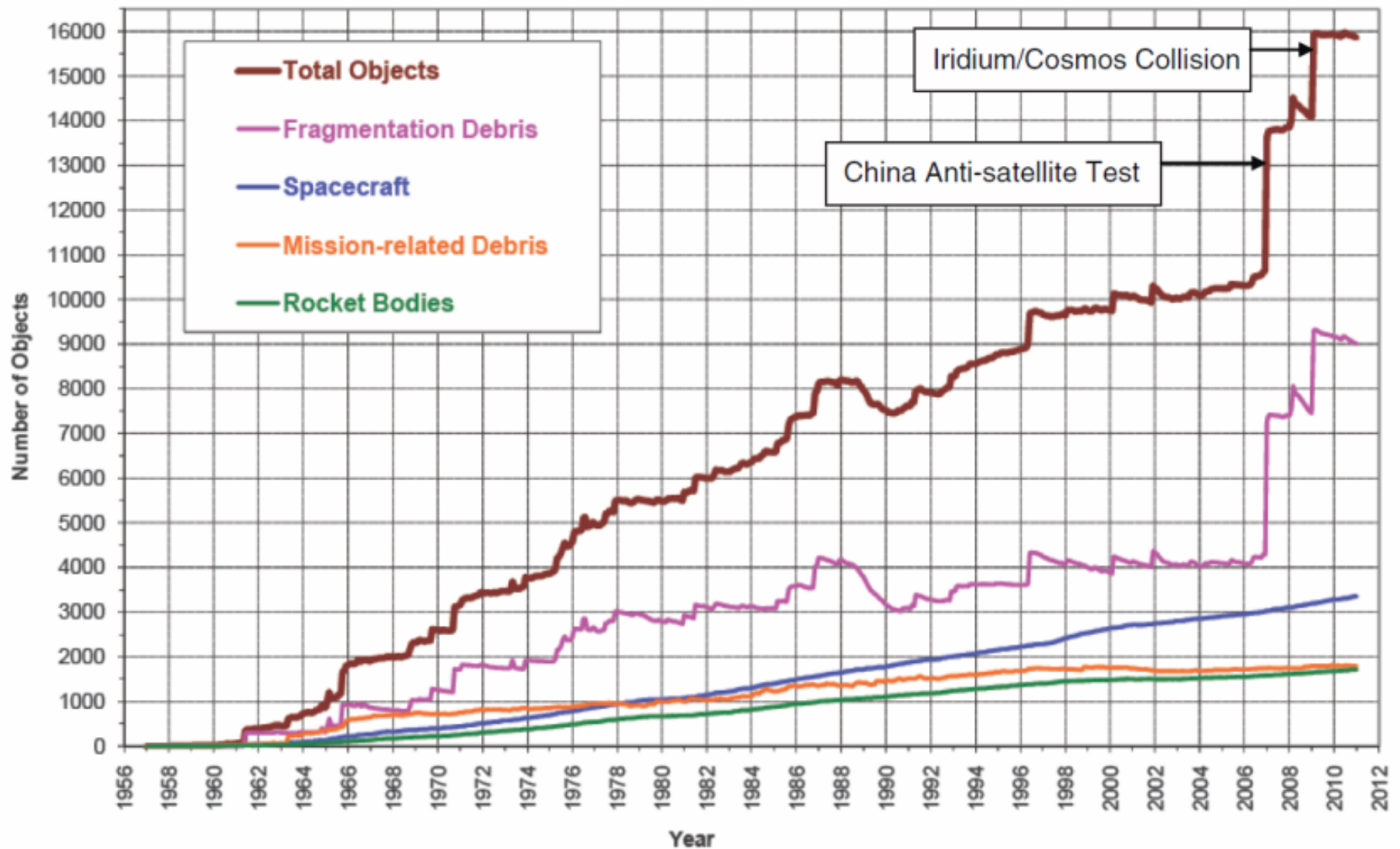
Video courtesy of Analytical Graphics, Inc. www.agi.com

An Application: The Orbital Debris Problem



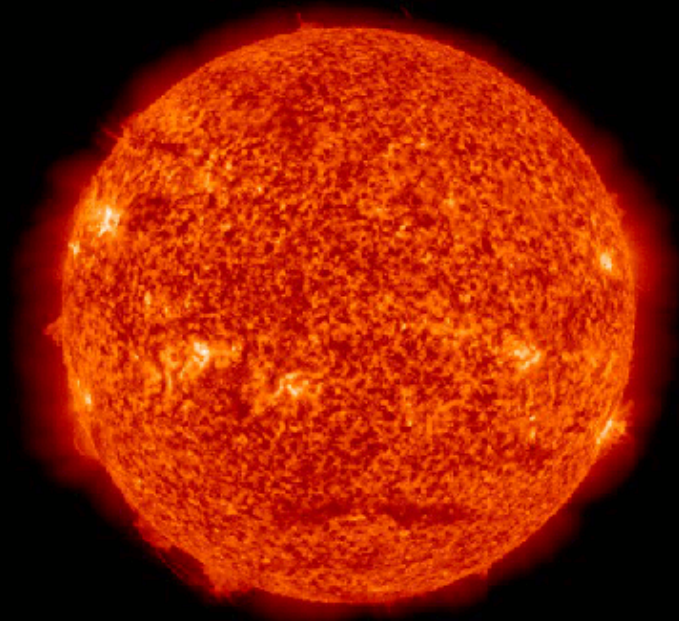
Video courtesy of Analytical Graphics, Inc. www.agi.com

An Application: The Orbital Debris Problem

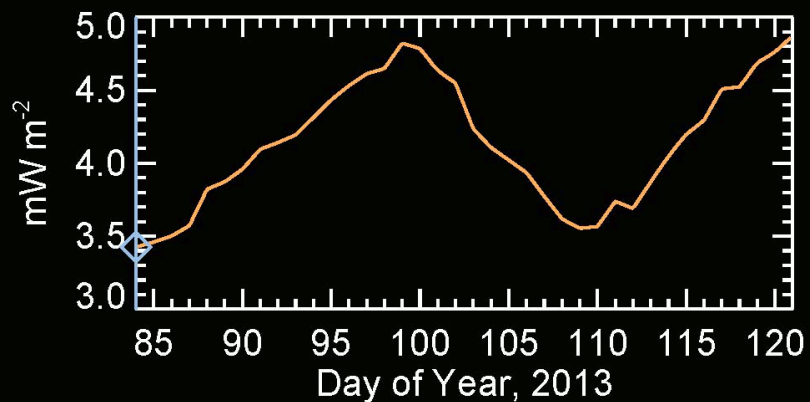


Solar EUV Irradiance Variations

SDO/AIA 30.4 nm

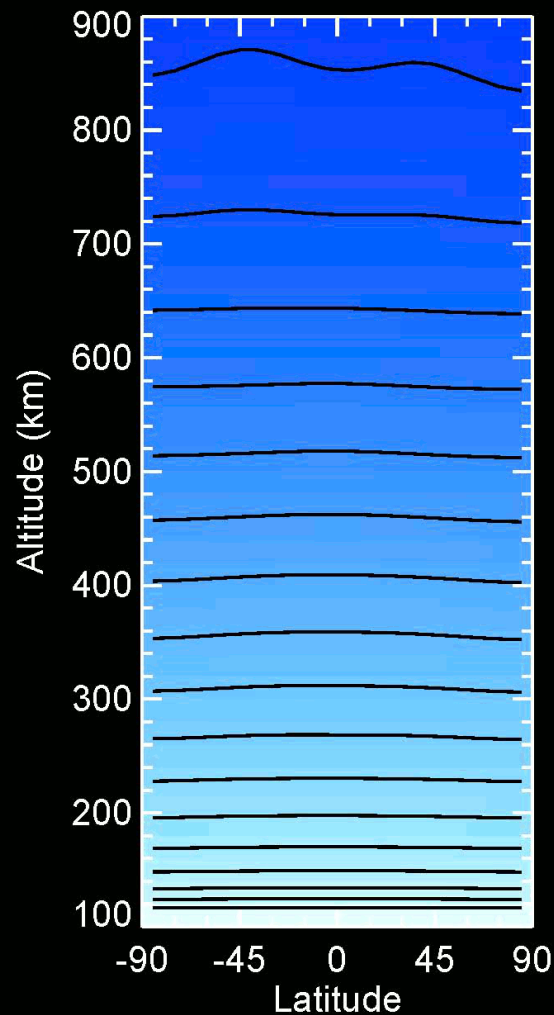


0-103 nm Irradiance (TIMED/SEE)



Thermospheric Density Response NRLMSISE

$\ln \rho$



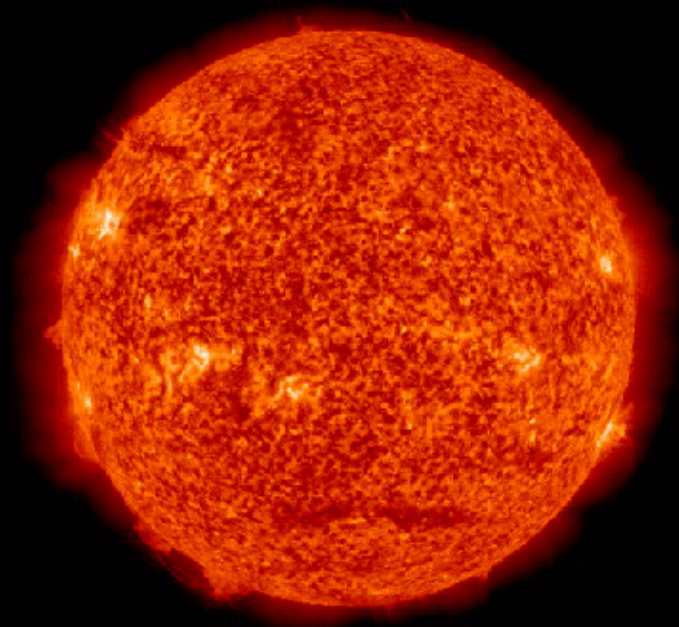
Density Change



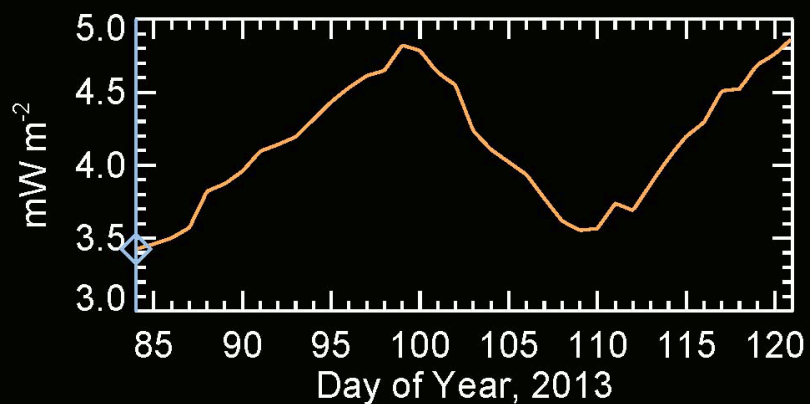
John Emmert, NRL

Solar EUV Irradiance Variations

SDO/AIA 30.4 nm

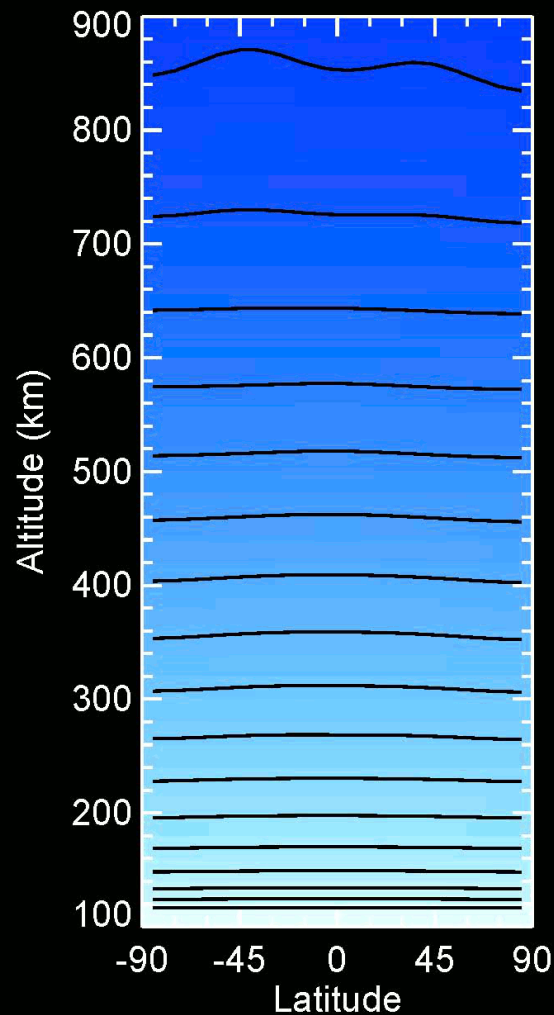


0-103 nm Irradiance (TIMED/SEE)



Thermospheric Density Response NRLMSISE

$\ln \rho$



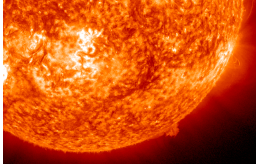
Density Change



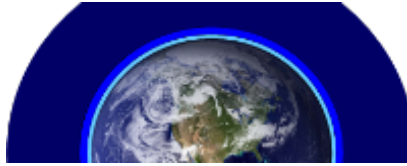
John Emmert, NRL

Connections Among Space Environment Components

**Photons
(+Solar Wind)**



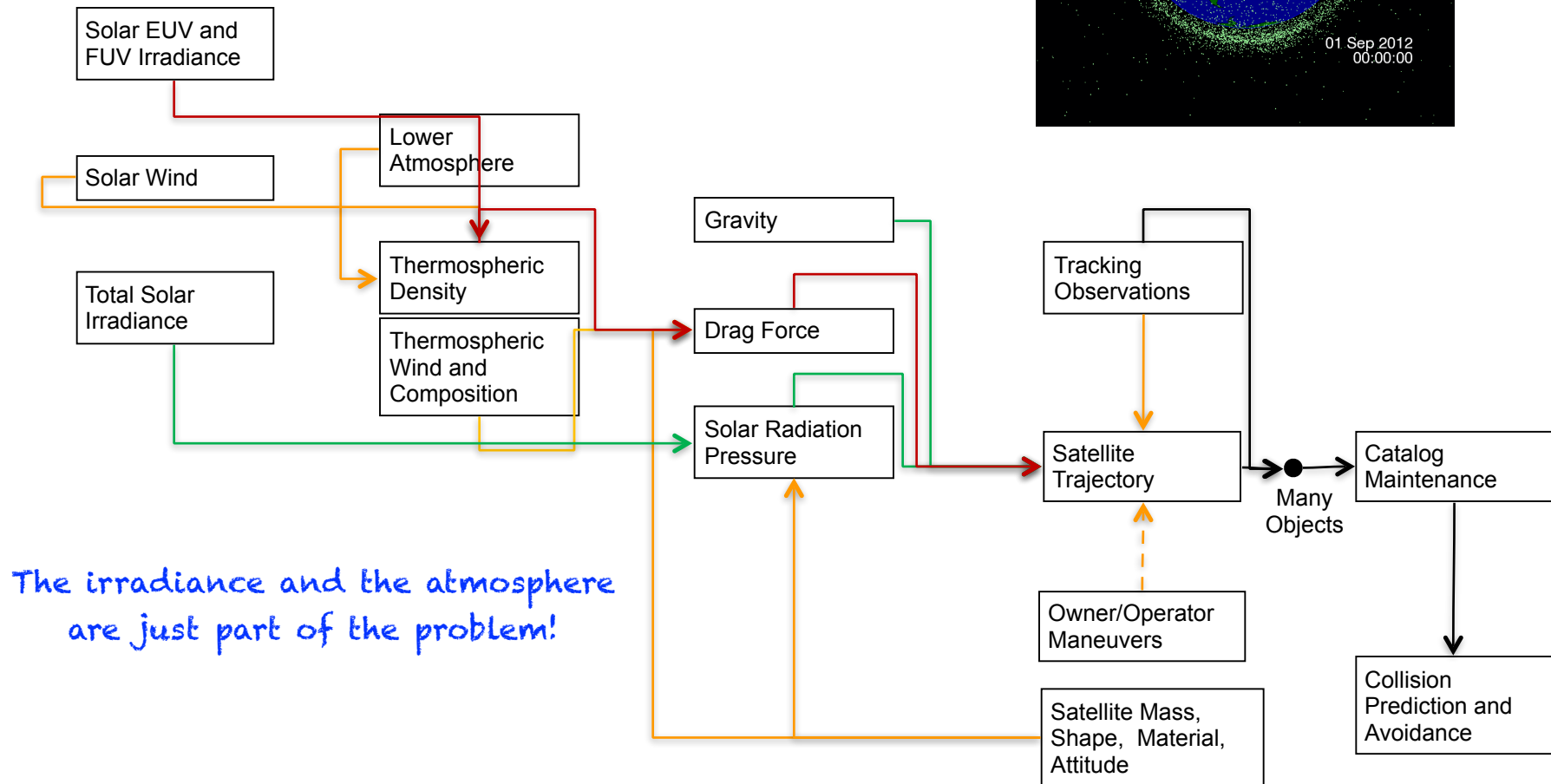
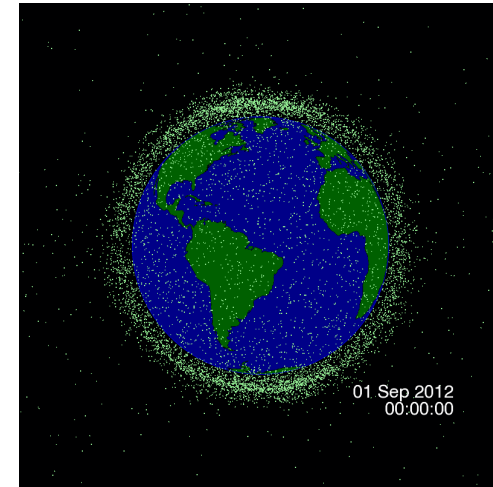
Gas



Forces

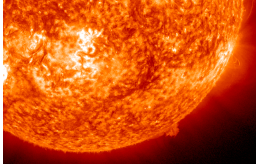


Satellites and Debris

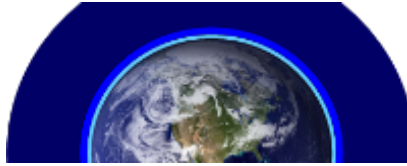


Connections Among Space Environment Components

**Photons
(+Solar Wind)**



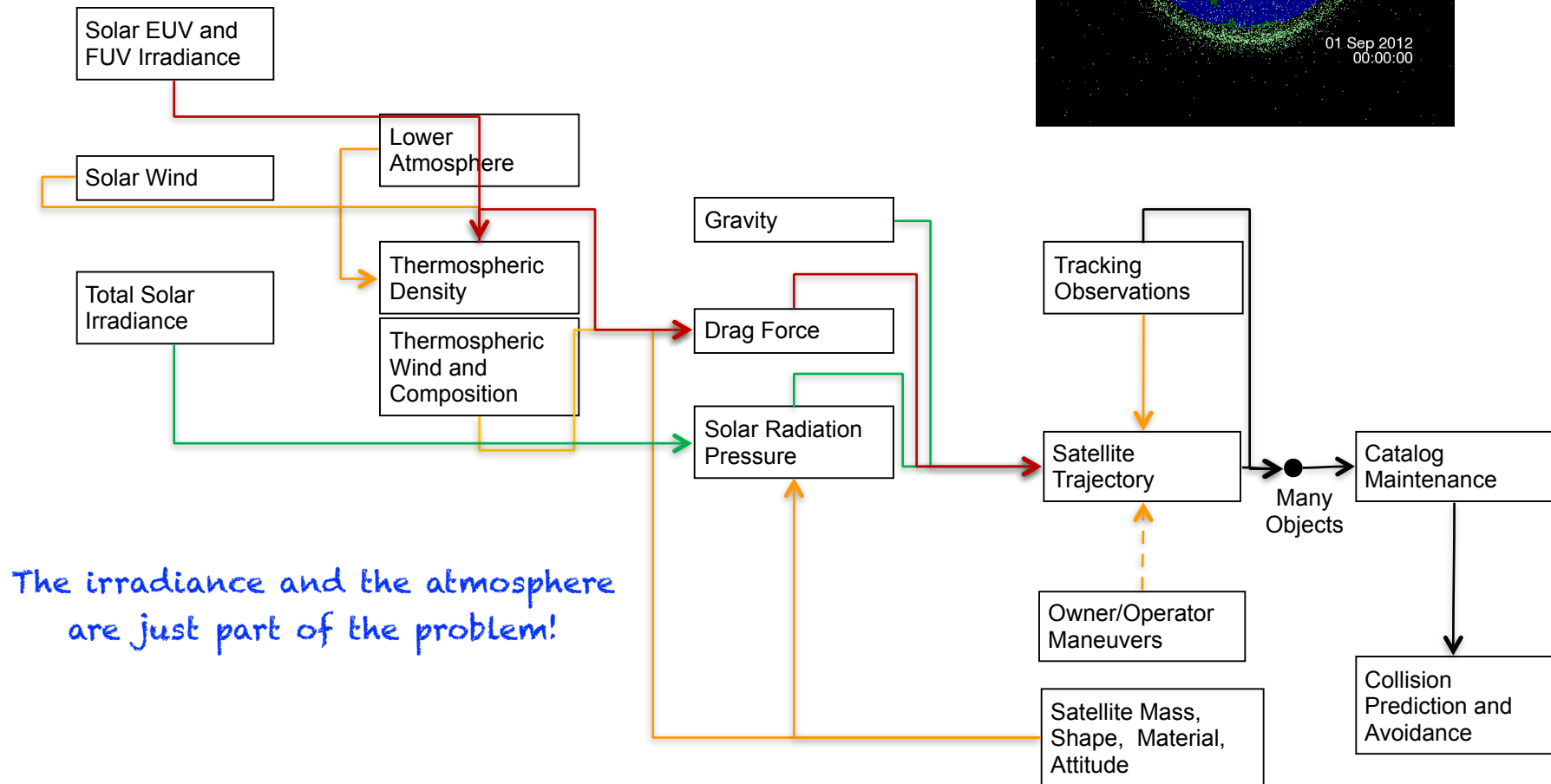
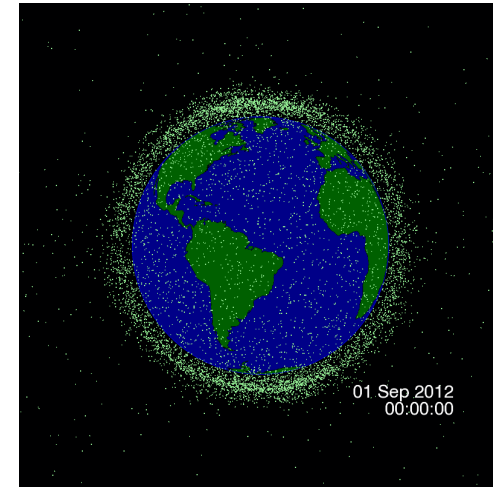
Gas



Forces



Satellites and Debris



Outline

- Total Solar Irradiance
 - Measurements
 - Application to climate change
- Solar Spectral Irradiance
 - The Solar Atmosphere
 - Soft X-rays
 - Extreme Ultraviolet
 - Ultraviolet
 - Visible/Infrared
 - Overview of observations
 - Application to satellite drag
- Common proxies for solar activity
- Proxy irradiance models
- A quick note on regression
 - Training/Test/Validation
 - Gaussian Process Regression
- The magnetic flux as a proxy
- Forecasting solar activity
 - Autoregression
 - Magnetic flux transport
- Emission processes
 - Optically thin line emission
- Semi-empirical models
 - Differential emission measure
- My 2 cents on useful tools and skills