PAST SOLAR ACTIVITY

Natalie Krivova

Thanks to:

T. Chatzistergos, D. Temaj, S.K.Solanki, B. Hofer, A.K. Yadav,

R. Cameron, I. Usoskin, M. Kazachenko, K.L. Yeo, C.J. Wu, ..

MAX PLANCK INSTITUTE
FOR SOLAR SYSTEM RESEARCH

SUN – CLIMATE

http://www.mps.mpg.de/projects/sun-climate

SUN – CLIMATE

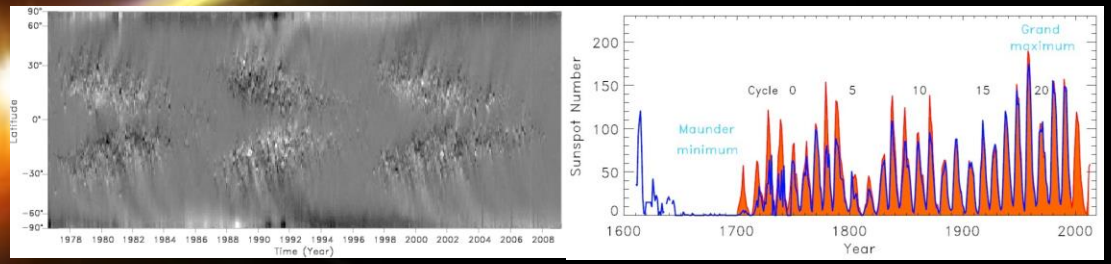
http://www2.mps.mpg.de/projects/sun-climate/

Main Goal

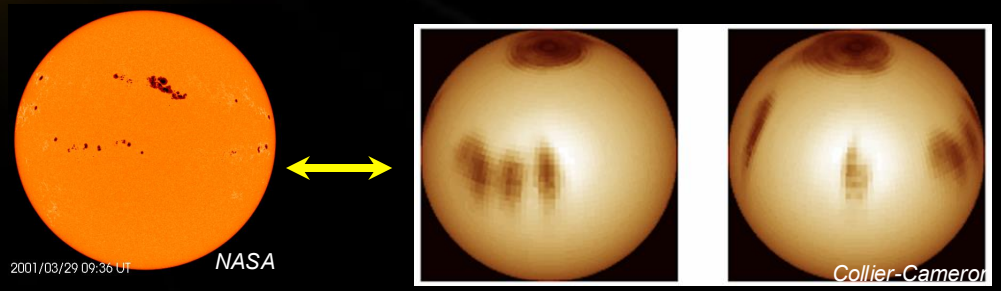
MAX PLANCK INSTITUTE FOR SOLAR SYSTEM RESEARCH

➢ Understanding and modelling solar variability on time scales of days to millennia

• Observed manifestation of solar magnetism and dynamo



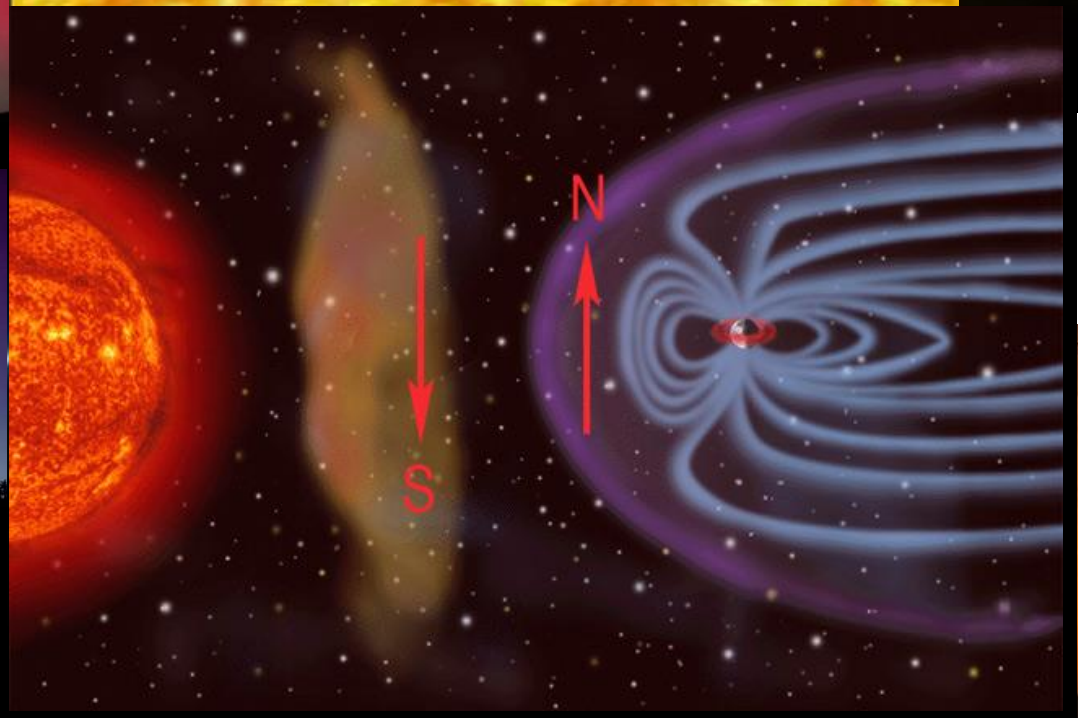
• Prototype of stellar variability, limiting detection of extrasolar planets

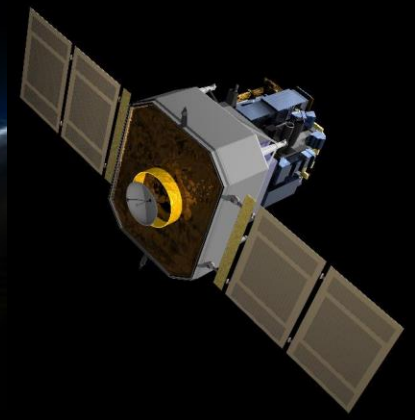


• Impacts Earth and near-Earth space

2024

Space Weather





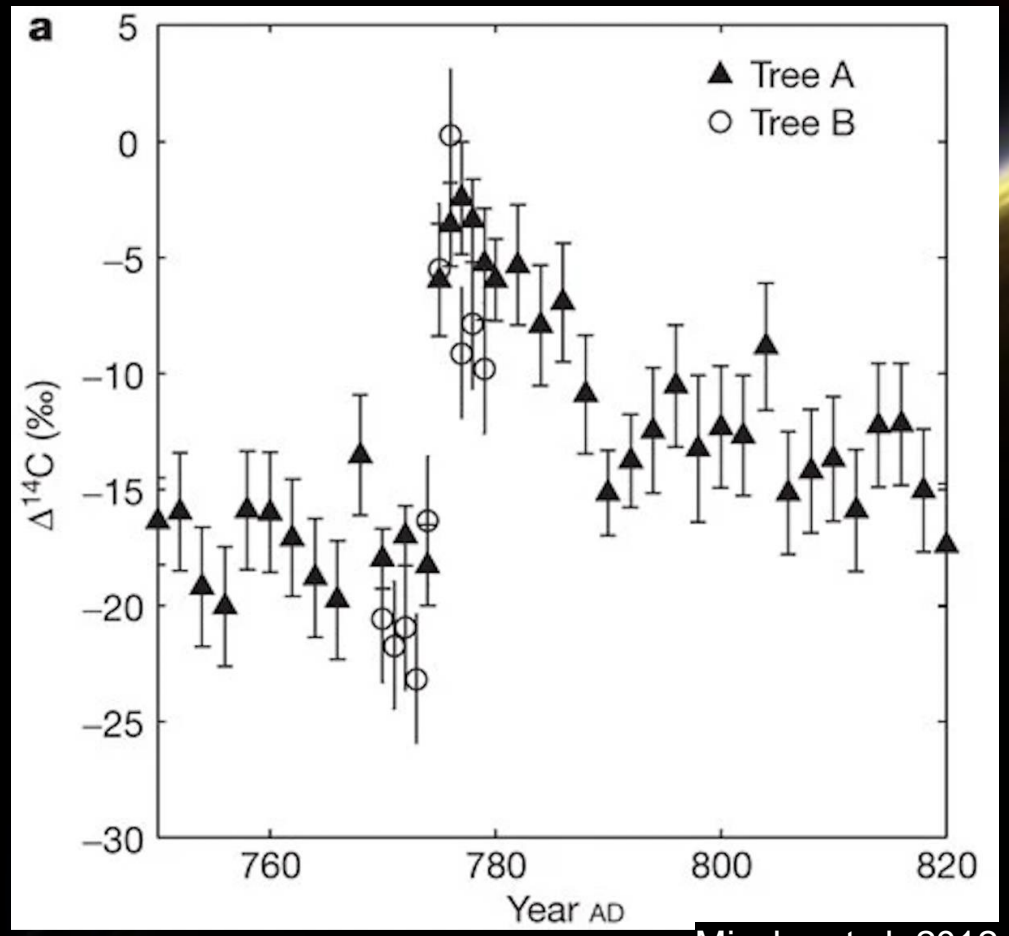
SUN – CLIMATE

http://www2.mps.mpg.de/projects/sun-climate/

Extreme Solar Particles Events: Evidence from radionuclide archives

MAX PLANCK INSTITUTE FOR SOLAR SYSTEM RESEARCH

ESPE



Miyake et al. 2012

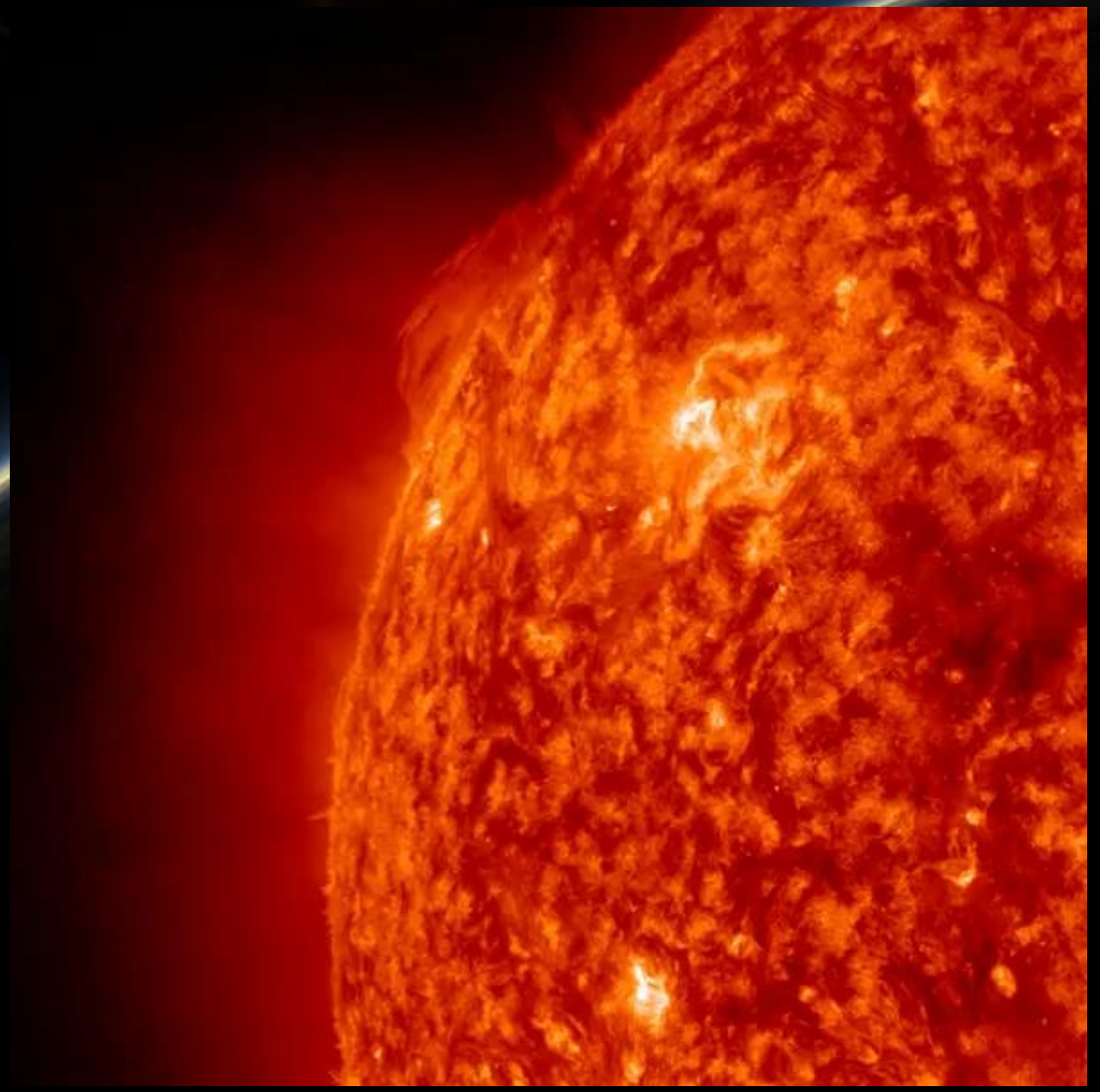
SUN – CLIMATE

http://www2.mps.mpg.de/projects/sun-climate/

Extreme Solar Particles Events: Evidence from radionuclide archives

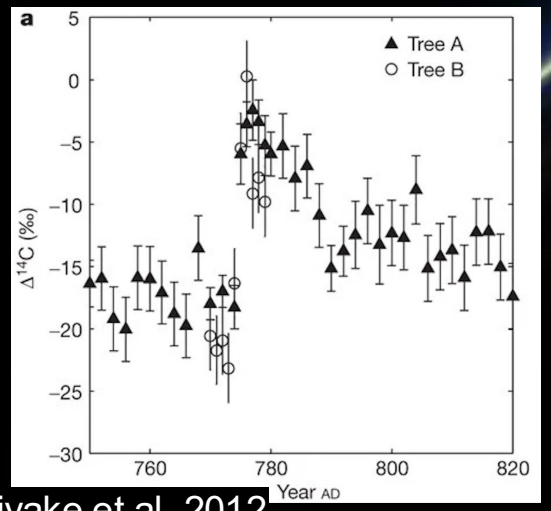
MAX PLANCK INSTITUTE FOR SOLAR SYSTEM RESEARCH

SDO



CME

ESPE



Miyake et al. 2012

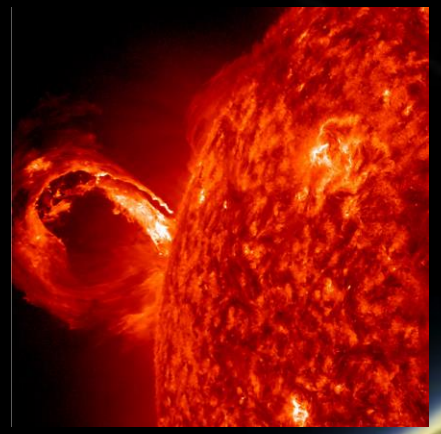
SUN – CLIMATE

http://www2.mps.mpg.de/projects/sun-climate/

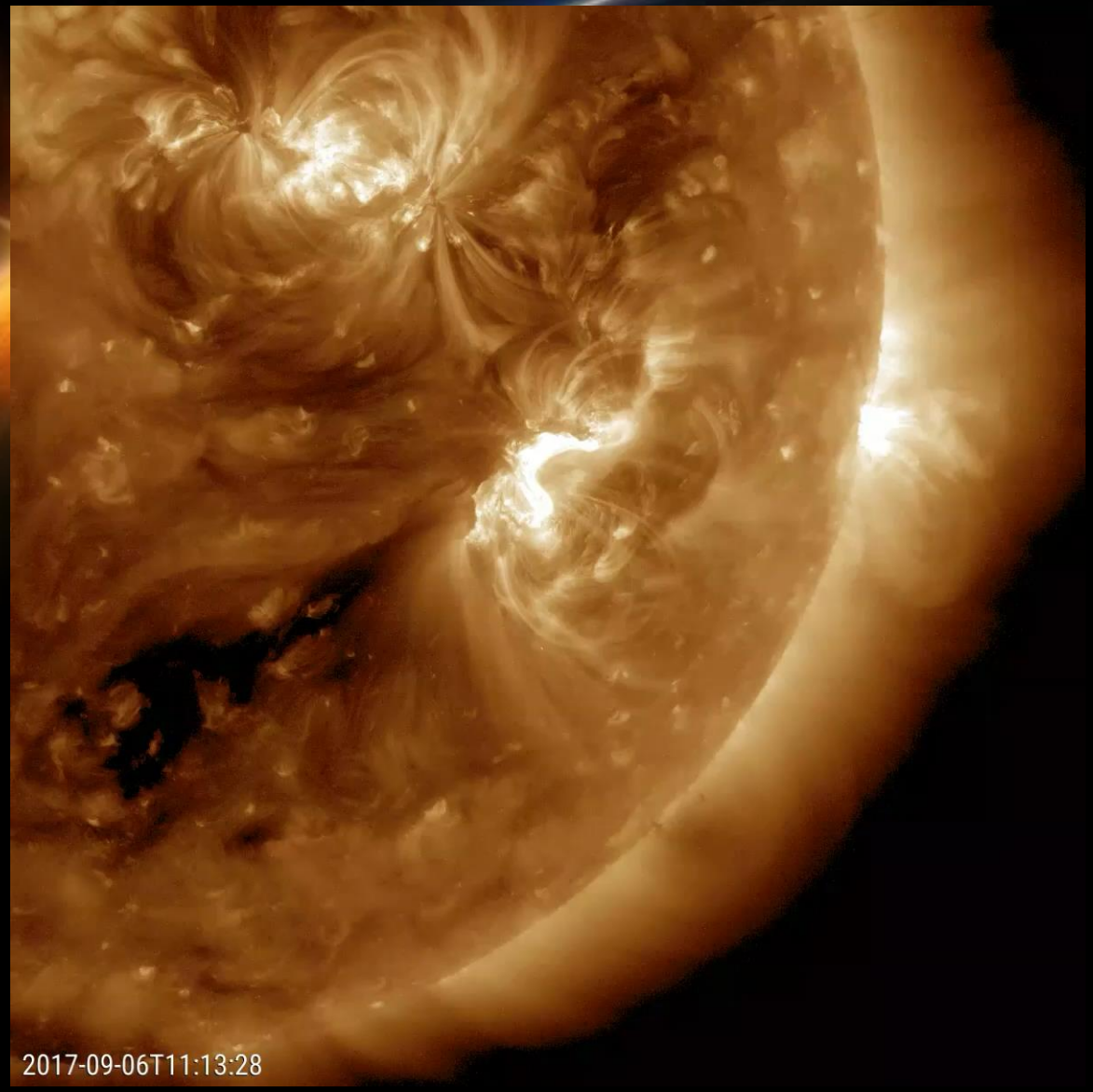
Extreme Solar Particles Events: Evidence from radionuclide archives

MAX PLANCK INSTITUTE FOR SOLAR SYSTEM RESEARCH

SDO



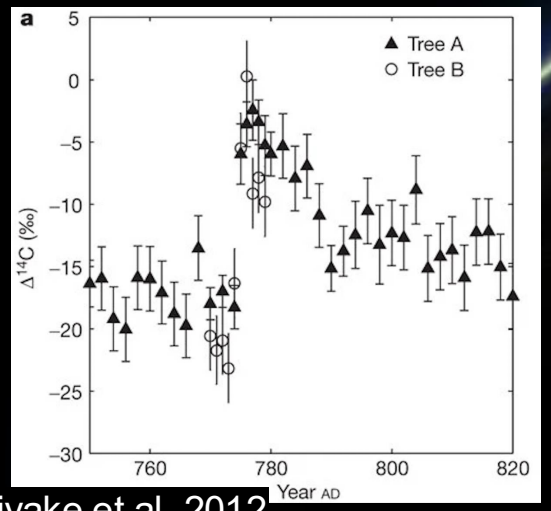
SDO



CME

ESPE

Flare



Miyake et al. 2012

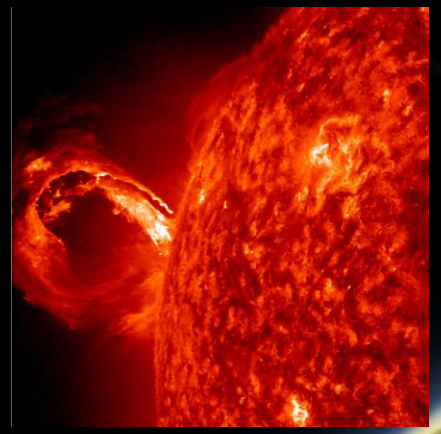
SUN – CLIMATE

http://www2.mps.mpg.de/projects/sun-climate/

Extreme Solar Particles Events: Evidence from radionuclide archives

MAX PLANCK INSTITUTE FOR SOLAR SYSTEM RESEARCH

SDO



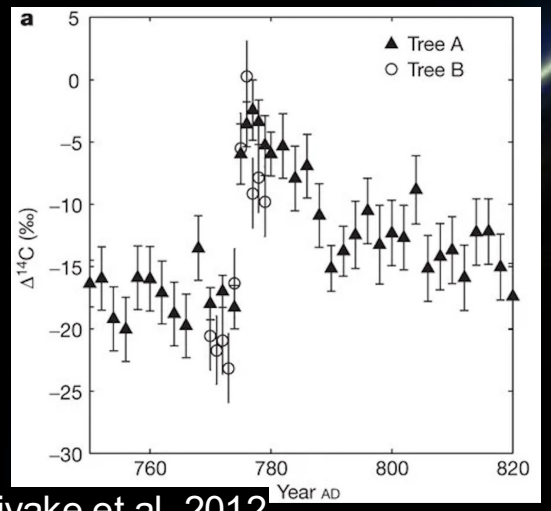
Active Region

Helioviewer / SDO

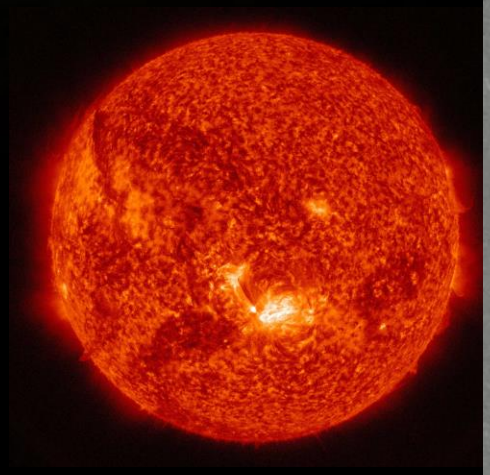
CME

ESPE

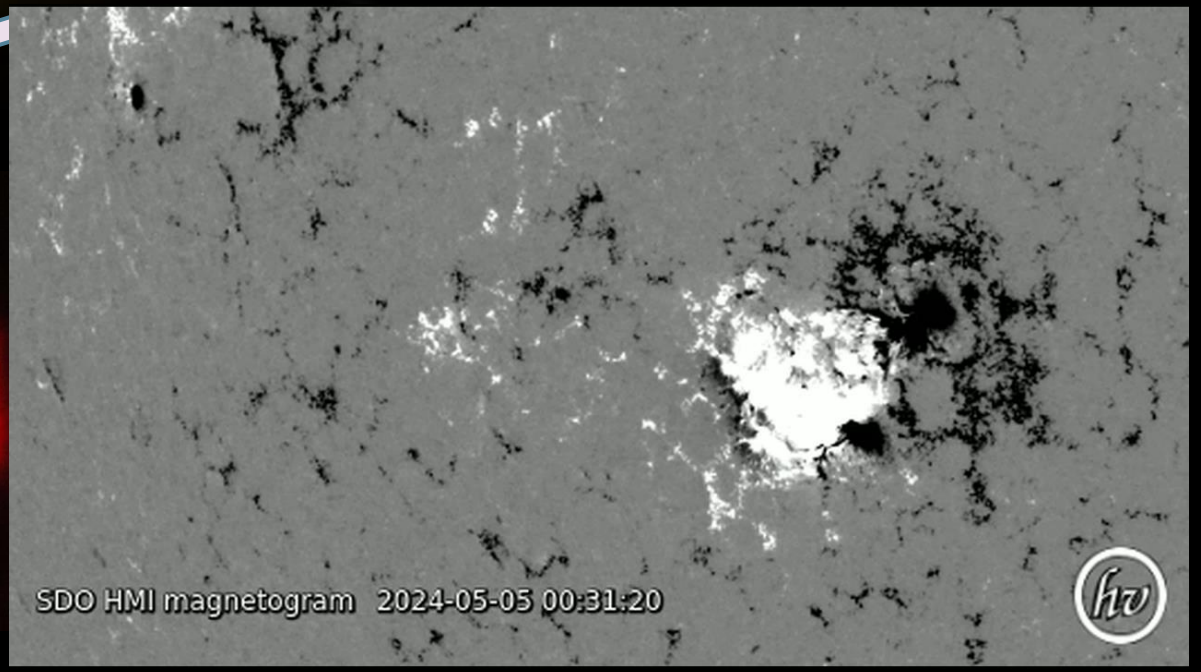
Flare



Miyake et al. 2012



SDO



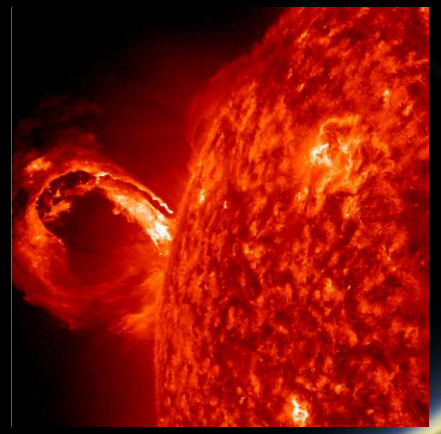
SUN – CLIMATE

http://www2.mps.mpg.de/projects/sun-climate/

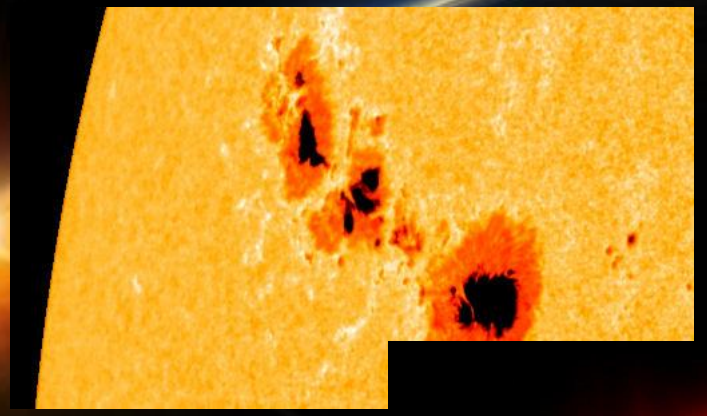
Extreme Solar Particles Events: Evidence from radionuclide archives

MAX PLANCK INSTITUTE FOR SOLAR SYSTEM RESEARCH

SDO



NASA



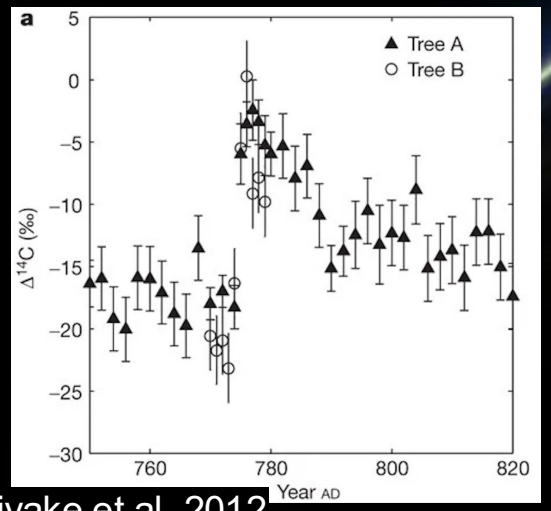
Magnetic Field

CME

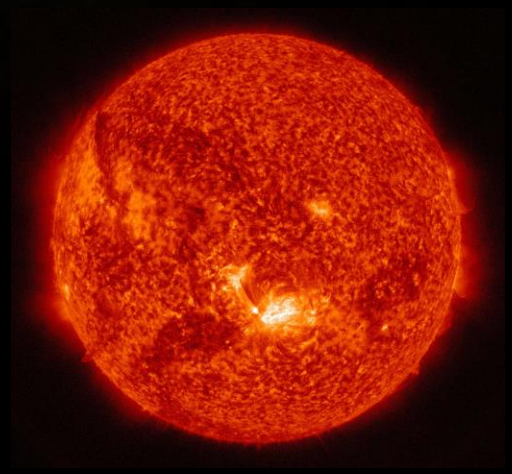
Active Re

ESPE

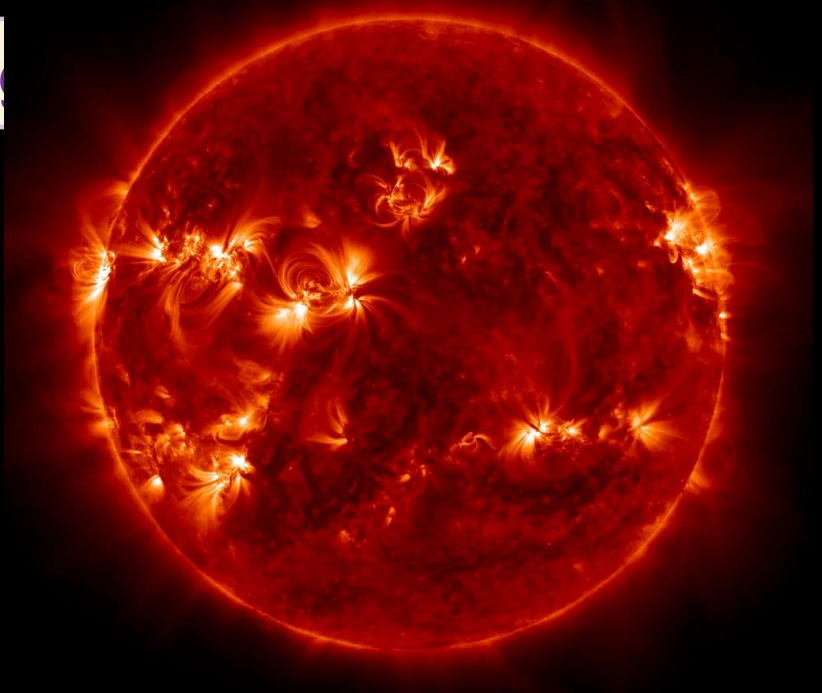
Flare



Miyake et al. 2012



SDO



SDO

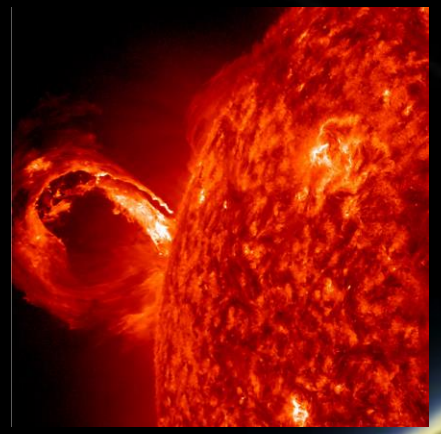
SUN – CLIMATE

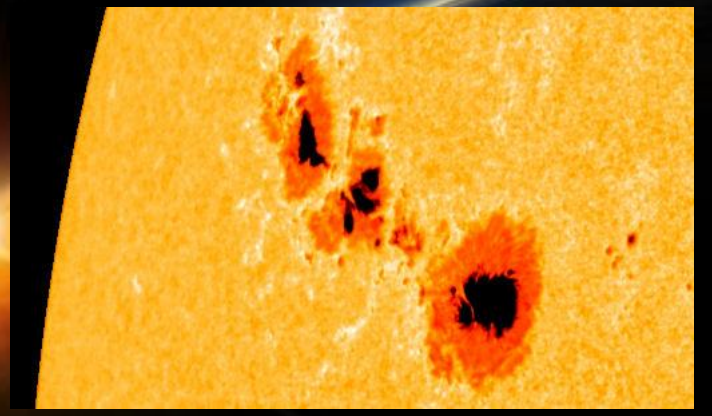
http://www2.mps.mpg.de/projects/sun-climate/

Extreme Solar Particles Events: Evidence from radionuclide archives

MAX PLANCK INSTITUTE FOR SOLAR SYSTEM RESEARCH

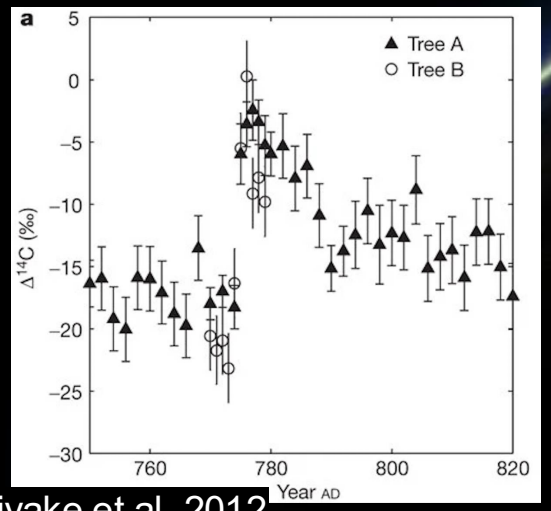
SDO



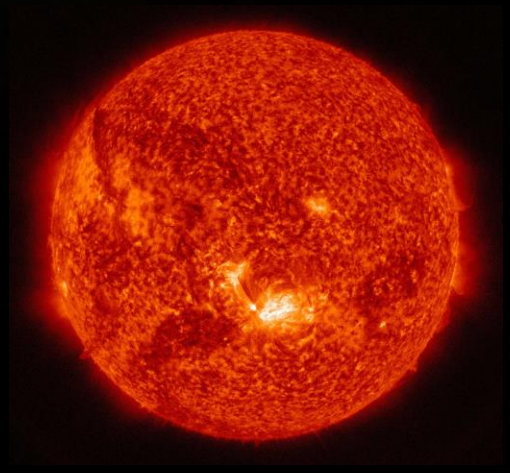


NASA

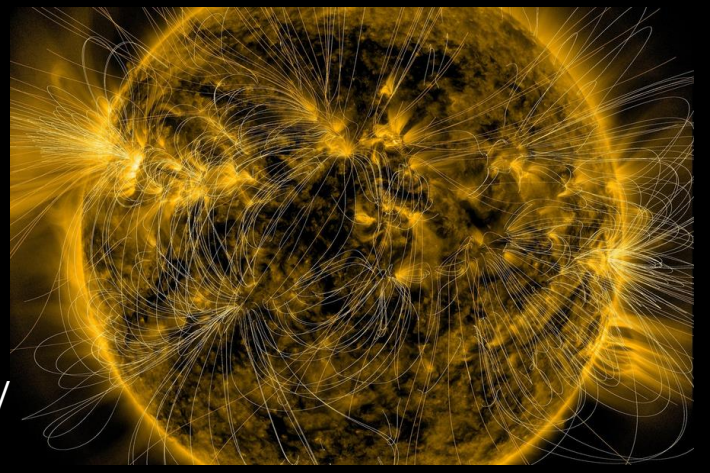
ESPE ← CME ← Flare ← Active Region ← Magnetic Field



Miyake et al. 2012



SDO



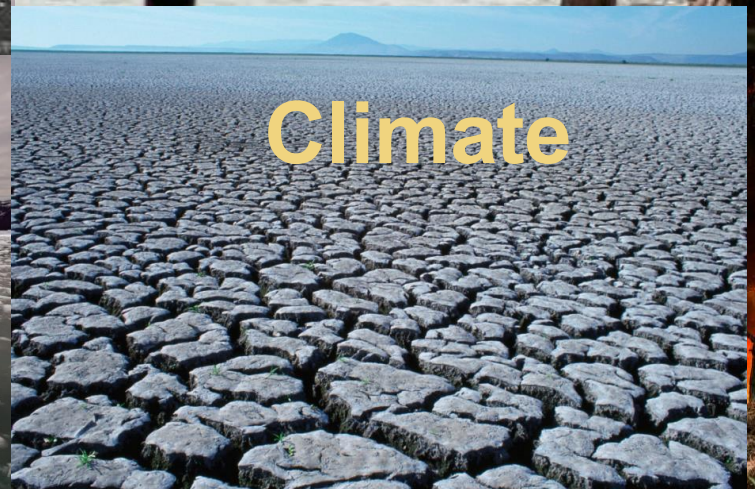
NASA/SDO/ AIA/LMSAL


2020


2025


© Thomas Savert, Oktober 2000


~1900

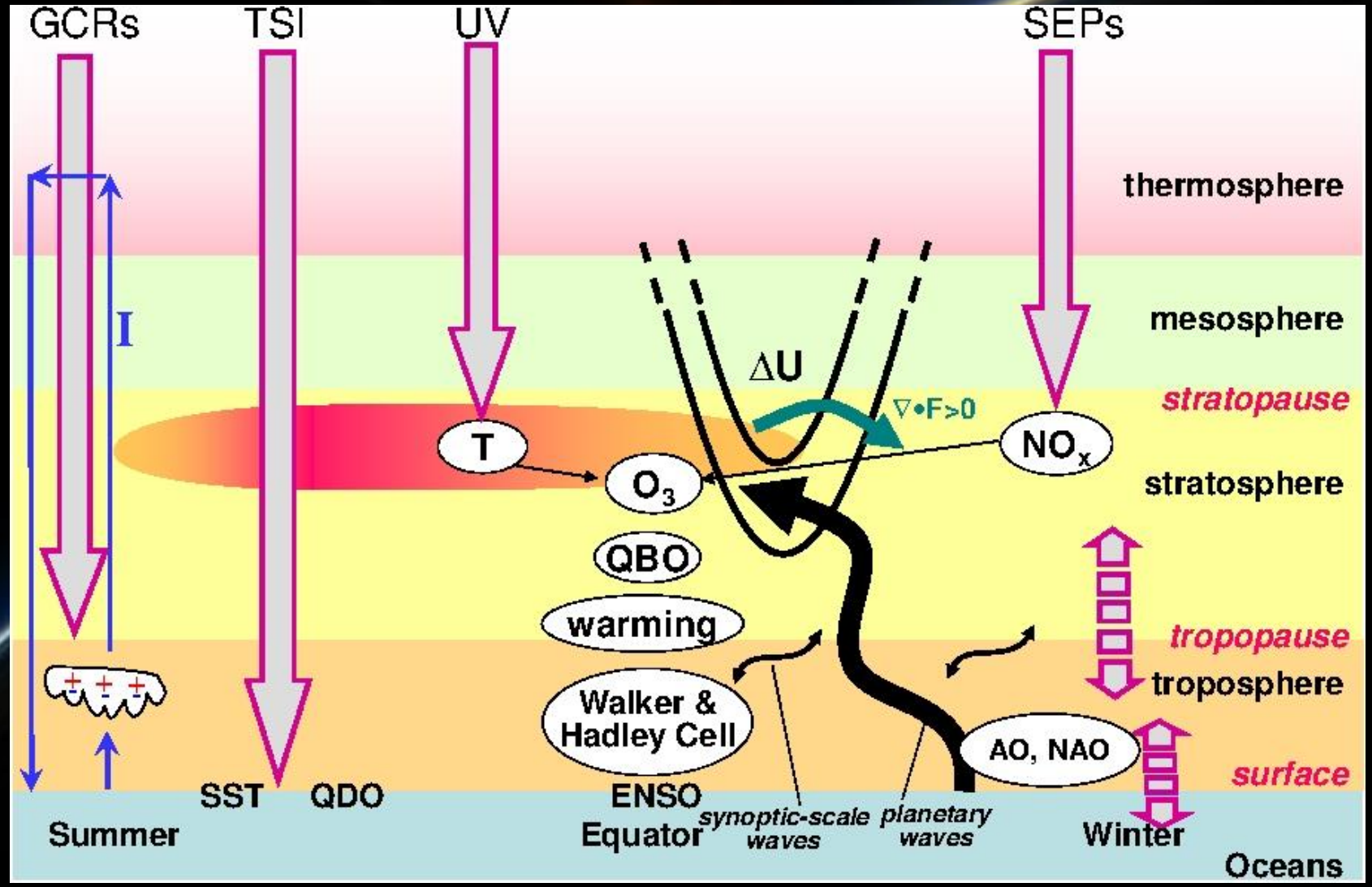

Climate

SUN – CLIMATE

http://www2.mps.mpg.de/projects/sun-climate/

Mechanisms of Solar Influence on Climate

MAX PLANCK INSTITUTE FOR SOLAR SYSTEM RESEARCH



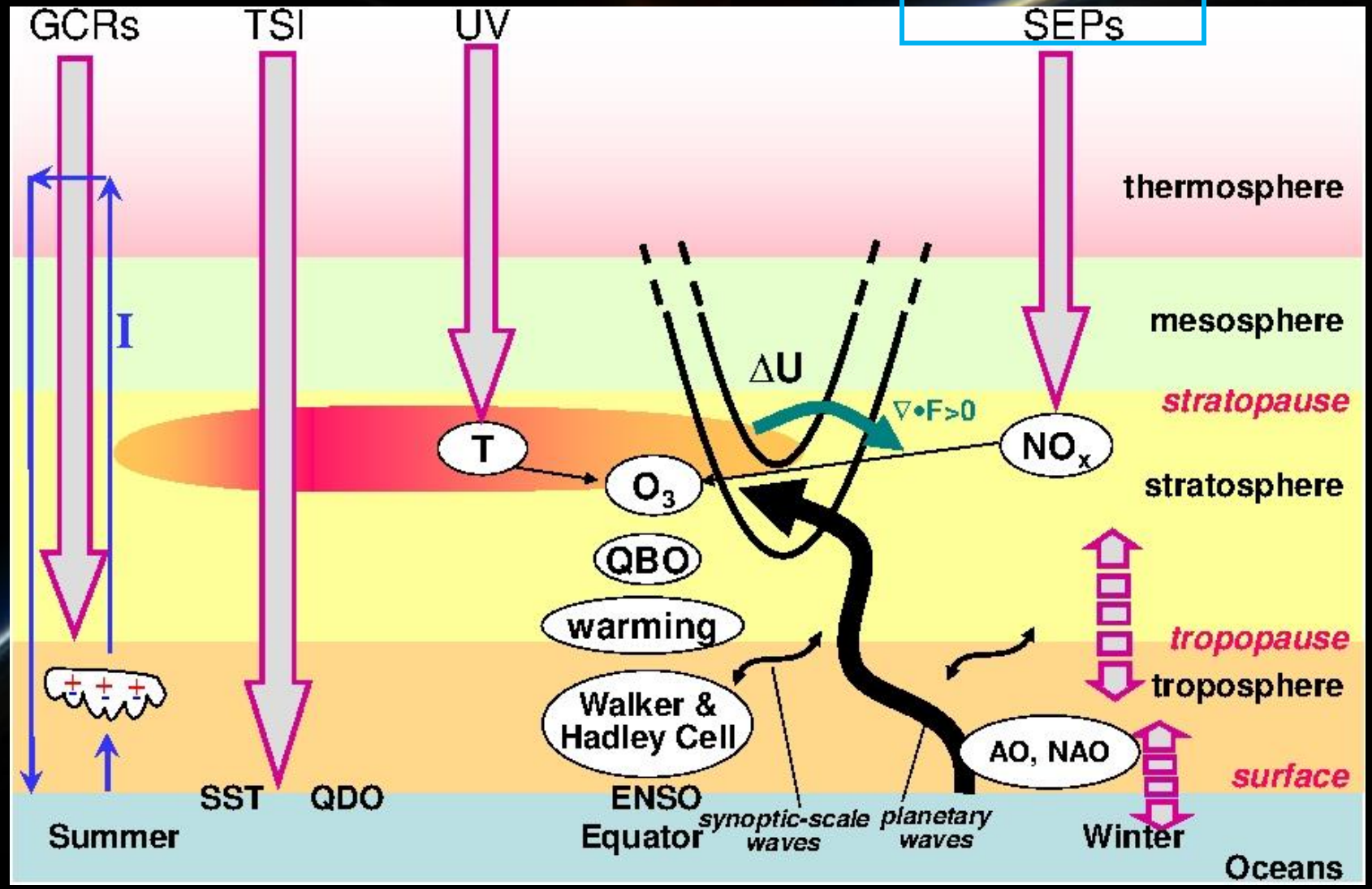
Gray et al. 2010

SUN – CLIMATE

http://www2.mps.mpg.de/projects/sun-climate/

Mechanisms of Solar Influence on Climate

MAX PLANCK INSTITUTE FOR SOLAR SYSTEM RESEARCH



Gray et al. 2010

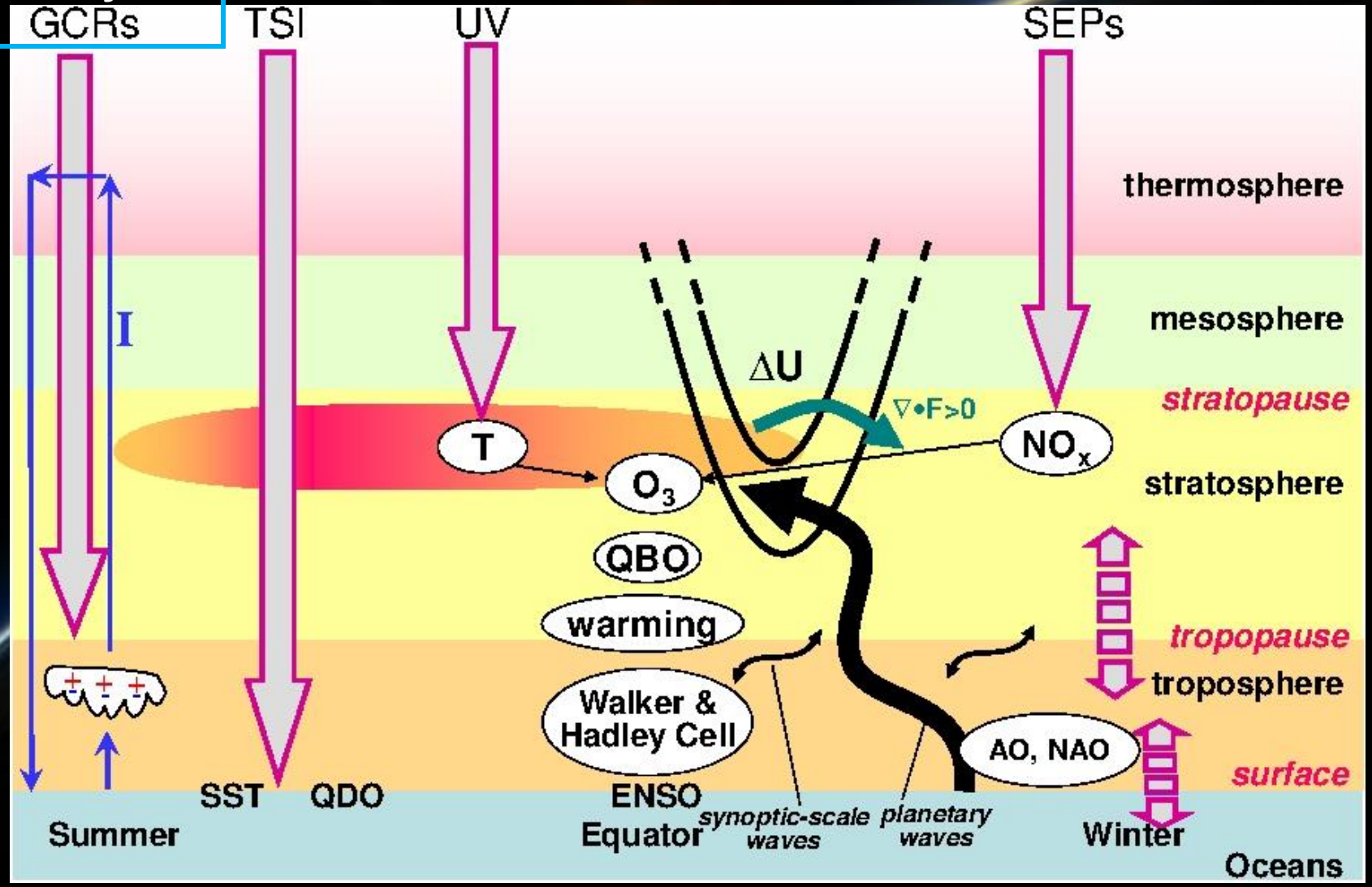
SUN – CLIMATE

http://www2.mps.mpg.de/projects/sun-climate/

Mechanisms of Solar Influence on Climate

MAX PLANCK INSTITUTE FOR SOLAR SYSTEM RESEARCH

Modulation of the Cosmic Ray flux



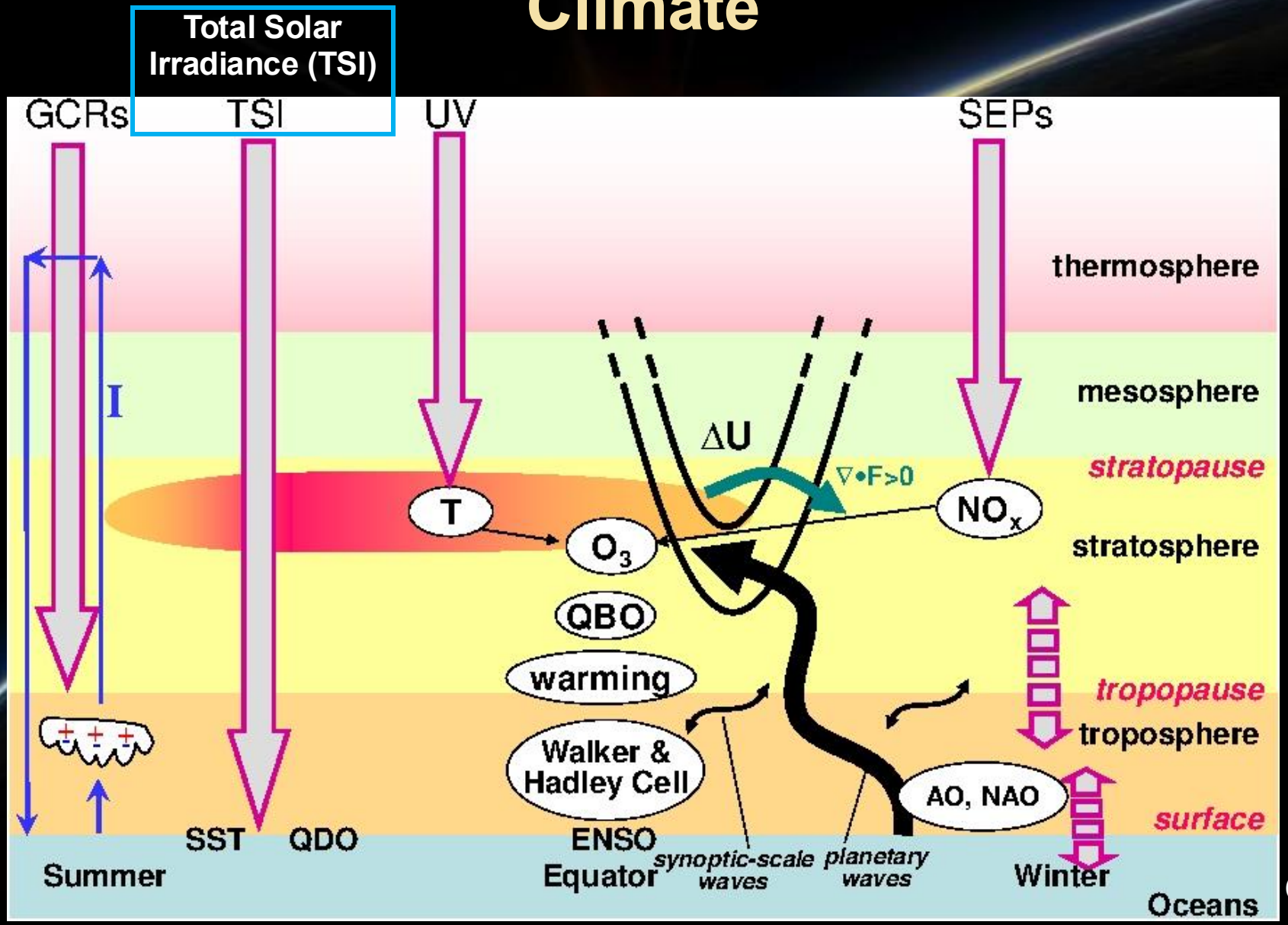
Gray et al. 2010

SUN – CLIMATE

http://www2.mps.mpg.de/projects/sun-climate/

Mechanisms of Solar Influence on Climate

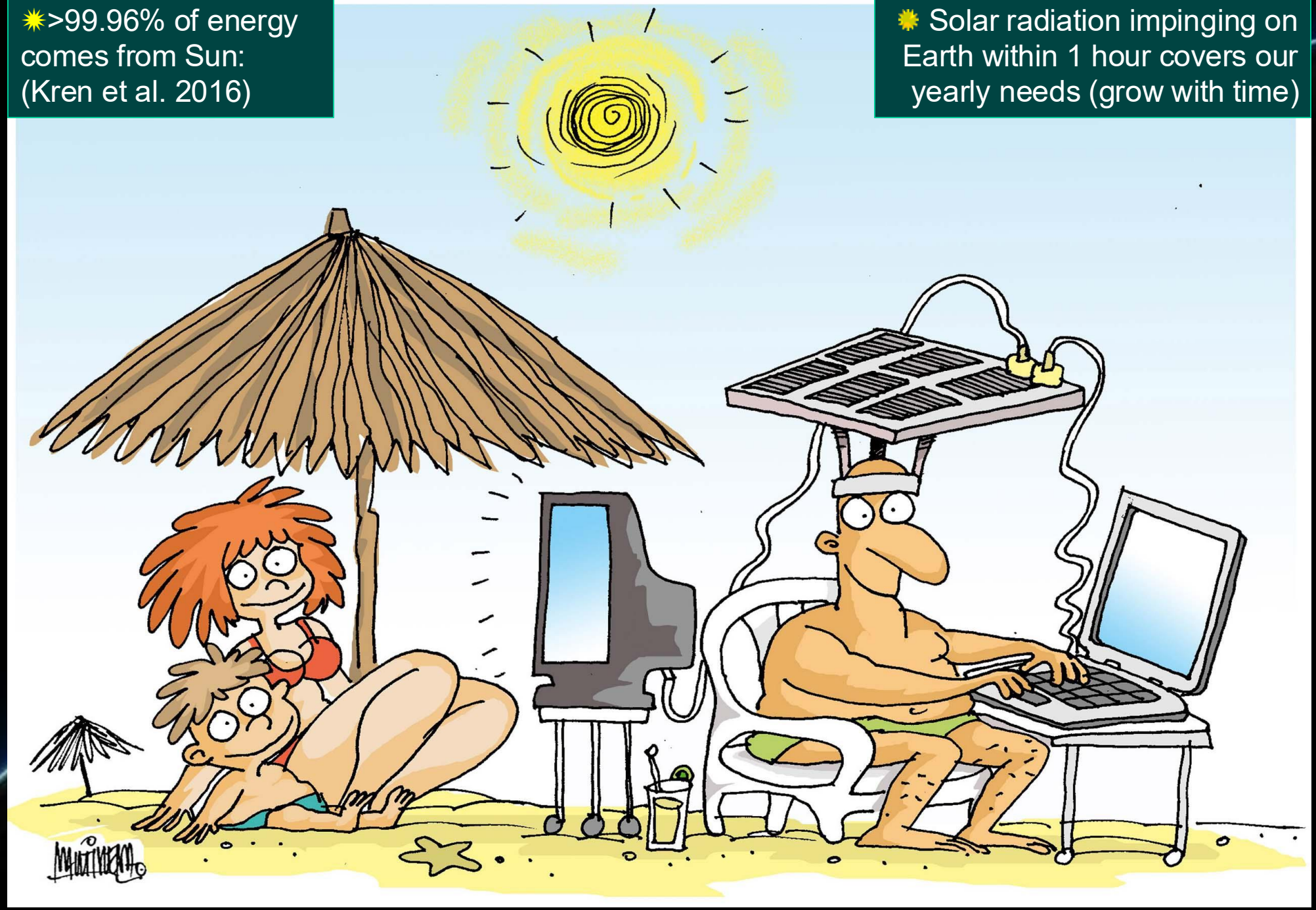
MAX PLANCK INSTITUTE FOR SOLAR SYSTEM RESEARCH



Gray et al. 2010

>99.96% of energy comes from Sun: (Kren et al. 2016)

Solar radiation impinging on Earth within 1 hour covers our yearly needs (grow with time)



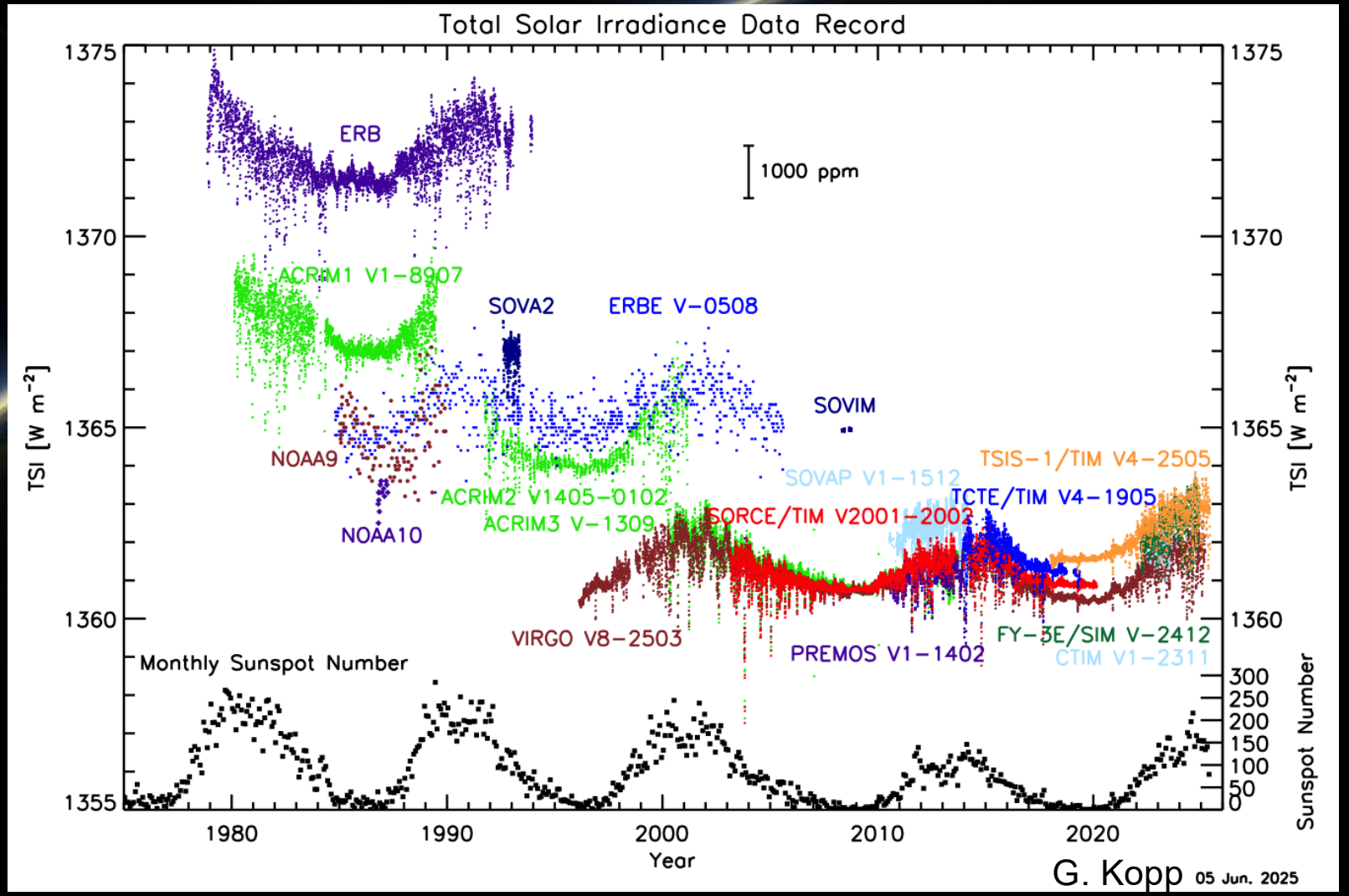
SUN – CLIMATE

http://www2.mps.mpg.de/projects/sun-climate/

Measured Irradiance Variations

MAX PLANCK INSTITUTE FOR SOLAR SYSTEM RESEARCH

- Almost uninterrupted since 1978
- Limited length
- Multiple (>10) instruments
- Cross-calibration is challenging
- Long-term change (> solar cycle) uncertain

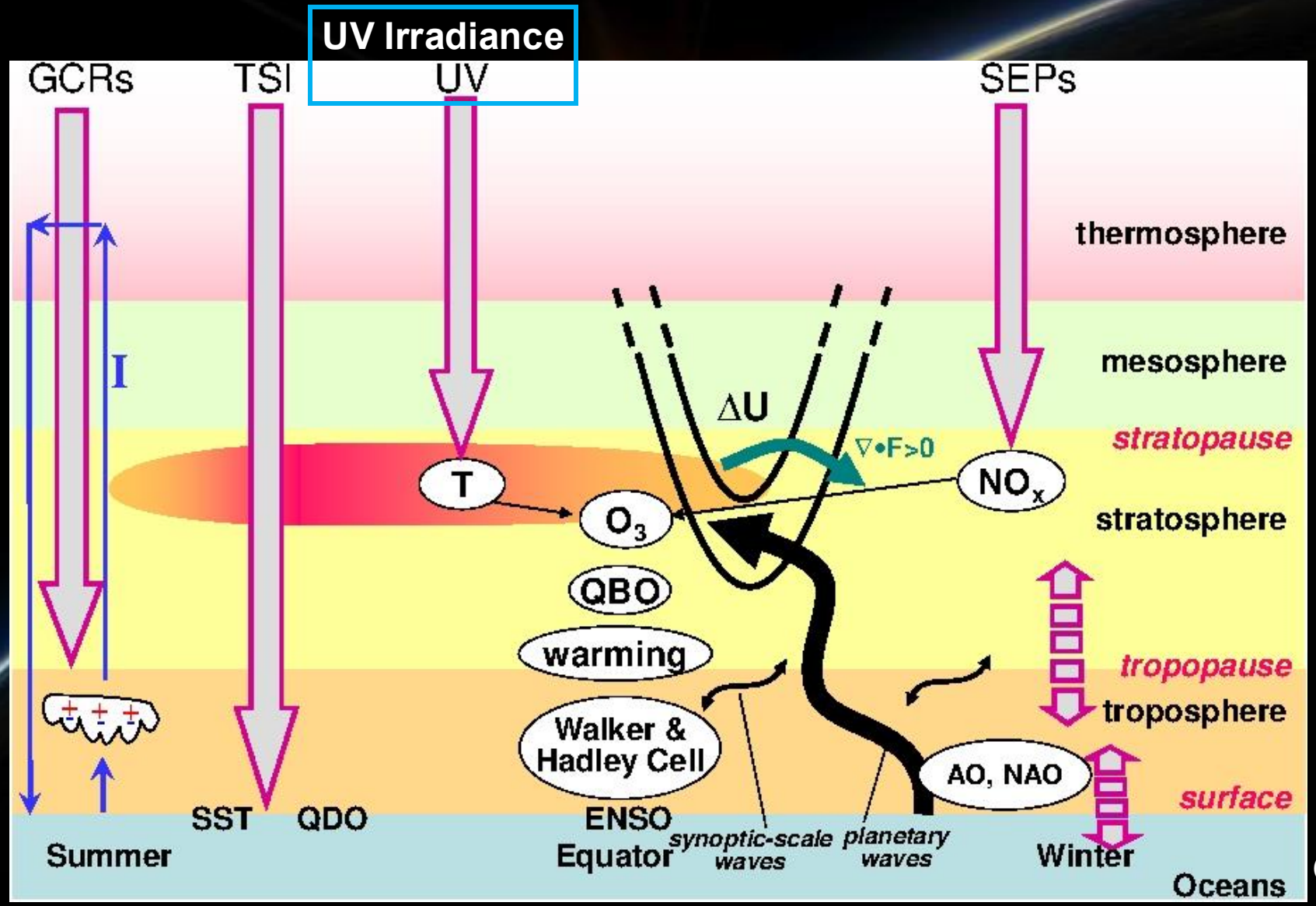


SUN – CLIMATE

http://www2.mps.mpg.de/projects/sun-climate/

Mechanisms of Solar Influence on Climate

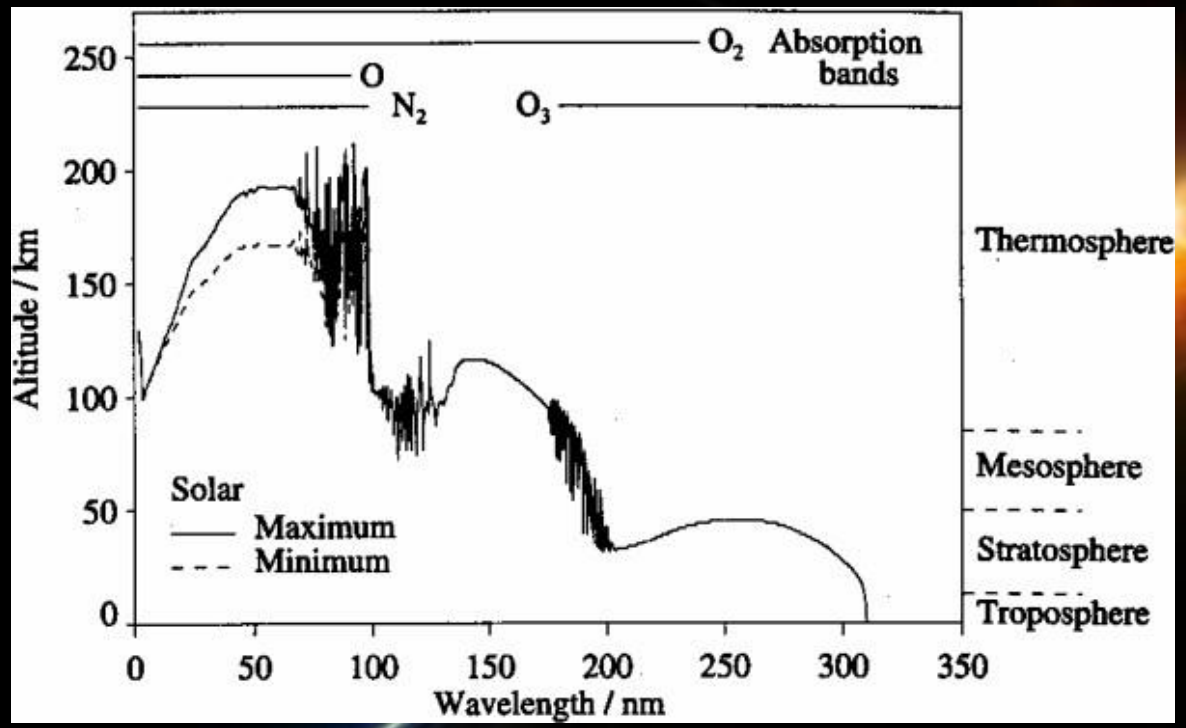
MAX PLANCK INSTITUTE FOR SOLAR SYSTEM RESEARCH



Gray et al. 2010

Absorption of Solar Radiation in the Atmosphere

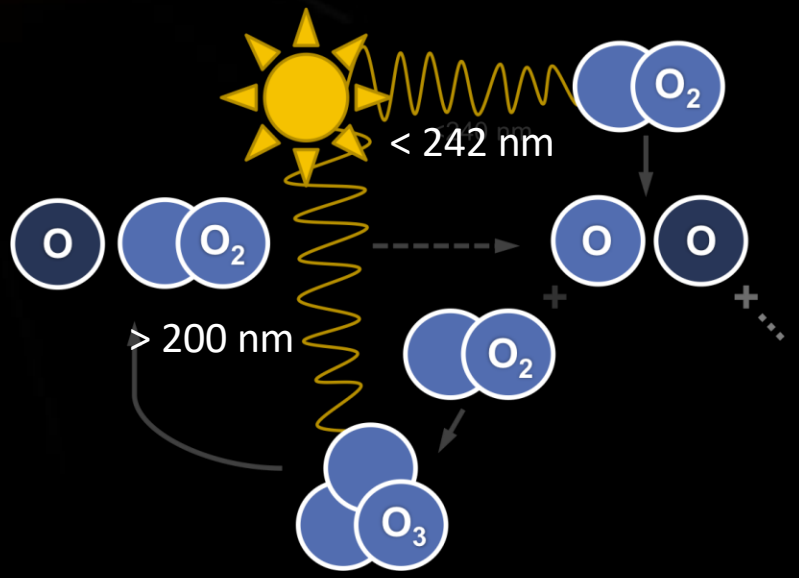
MAX PLANCK INSTITUTE
FOR SOLAR SYSTEM RESEARCH



Andrews 2000, Haigh 2007

200–242 nm:
Oxygen Herzberg continuum

200-350 nm:
Ozone Hartley-Huggins bands



Chemistry in the Stratosphere
Ozone balance

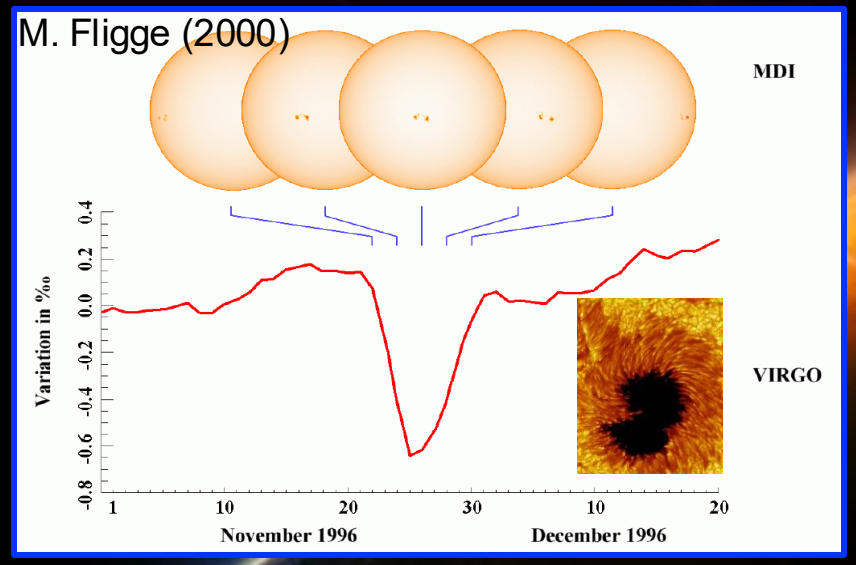
SUN – CLIMATE

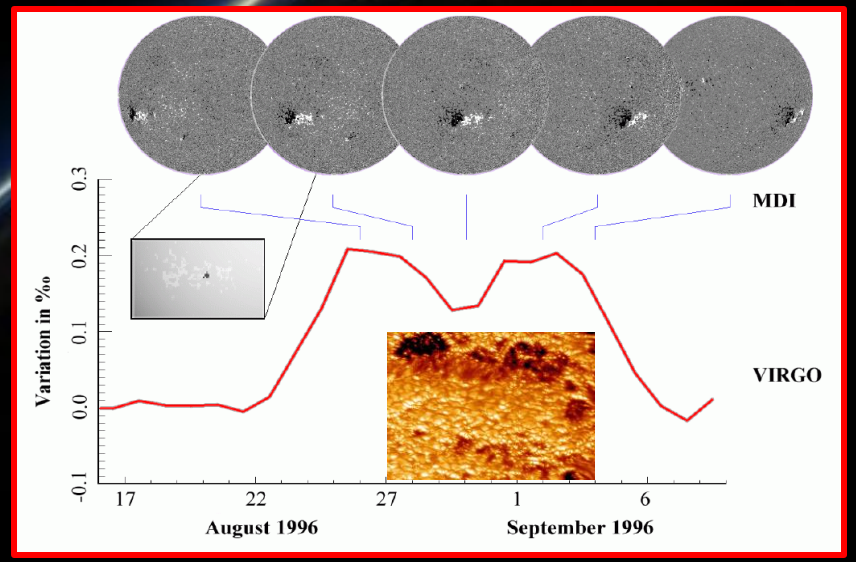
http://www2.mps.mpg.de/projects/sun-climate/

Surface Magnetic Field as Driver of Solar Irradiance Variability

MAX PLANCK INSTITUTE FOR SOLAR SYSTEM RESEARCH

Darkening due to sunspots





Brightening due to faculae

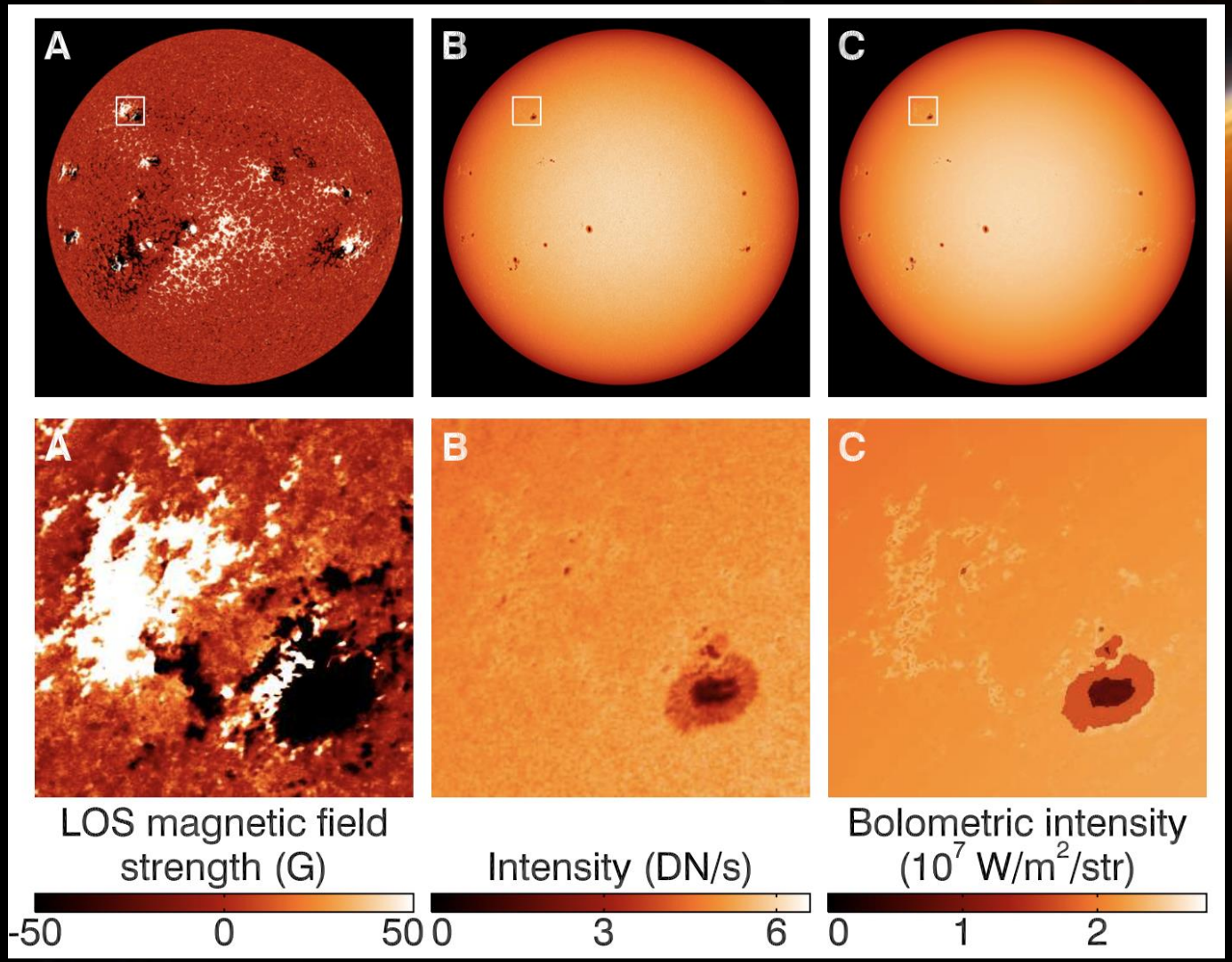
The Sun's surface magnetic field is the dominant cause of irradiance variability on timescales from days to centuries and beyond

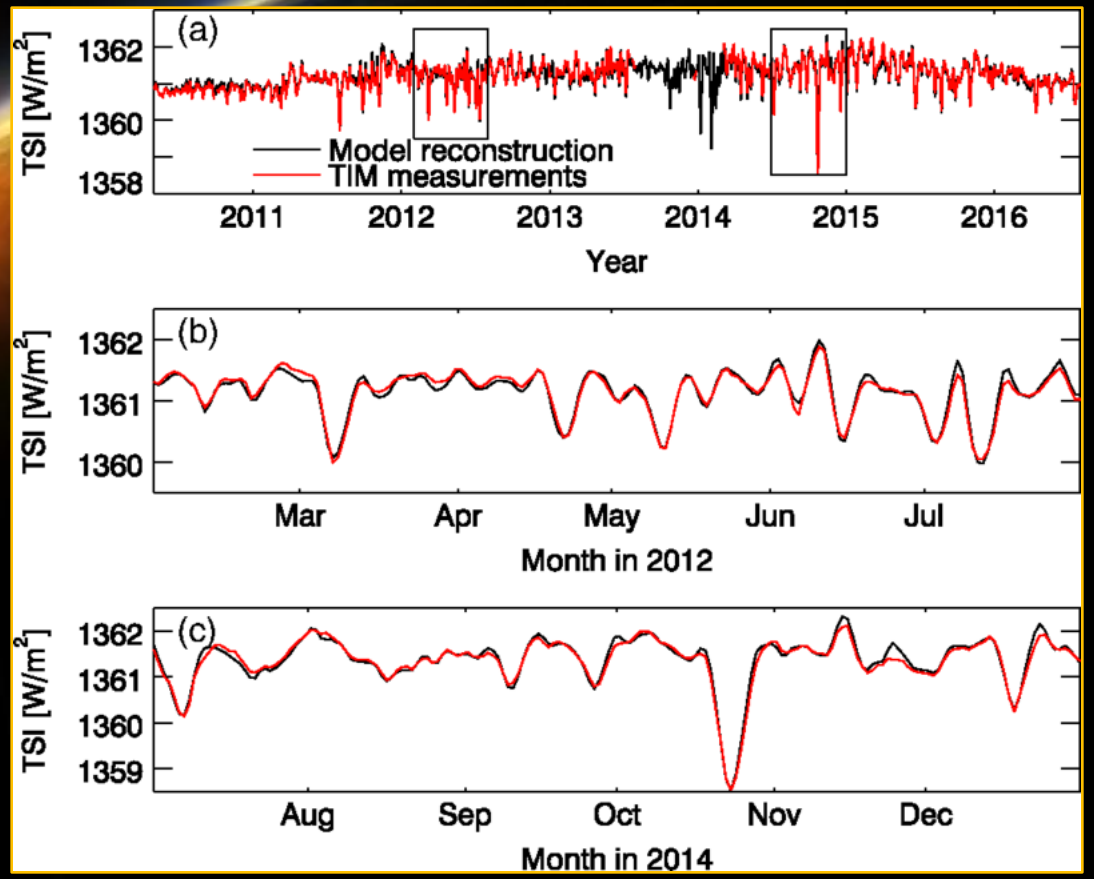
SUN – CLIMATE

http://www2.mps.mpg.de/projects/sun-climate/

Modelling Irradiance Variations

MAX PLANCK INSTITUTE FOR SOLAR SYSTEM RESEARCH





A. HMI magnetogram
B. HMI continuum image
C. Reconstructed image

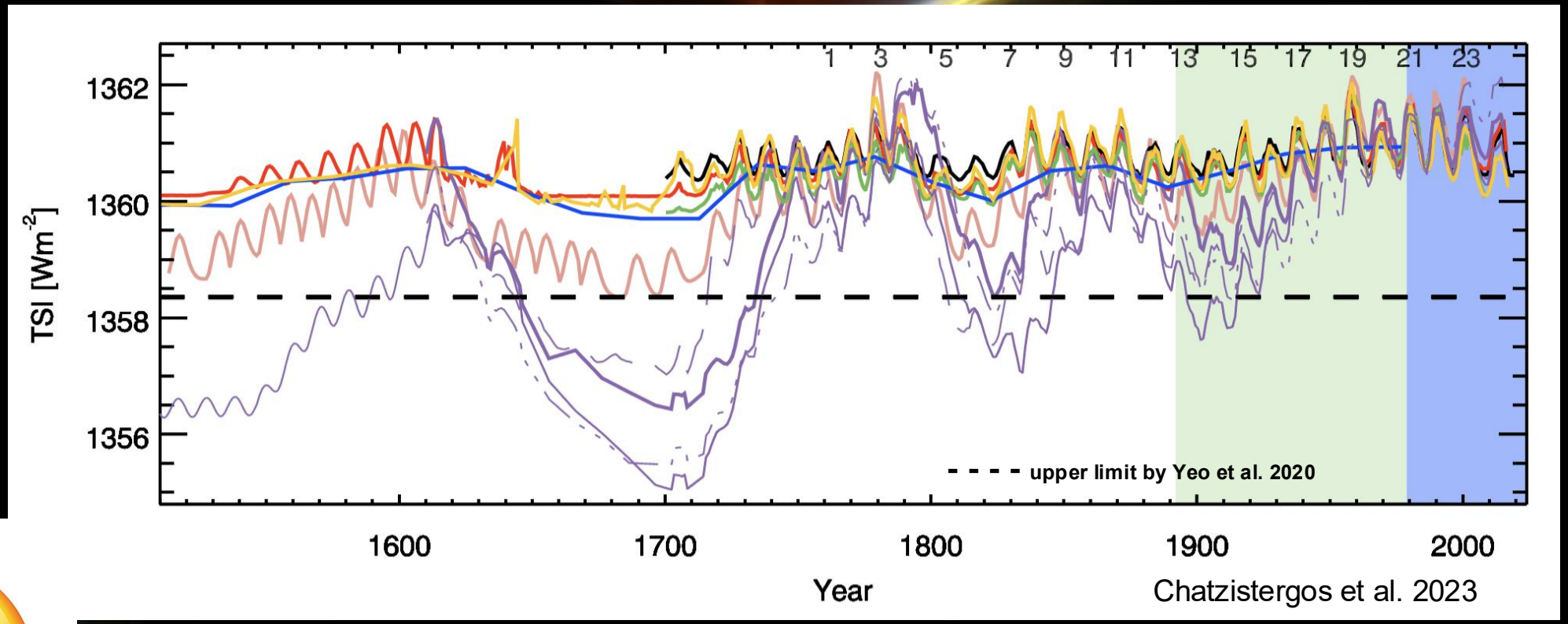
Yeo et al. 2017, PRL

SUN – CLIMATE

http://www2.mps.mpg.de/projects/sun-climate/

MAX PLANCK INSTITUTE
FOR SOLAR SYSTEM RESEARCH

Secular Variability is Highly Uncertain



Chatzistergos et al. 2023

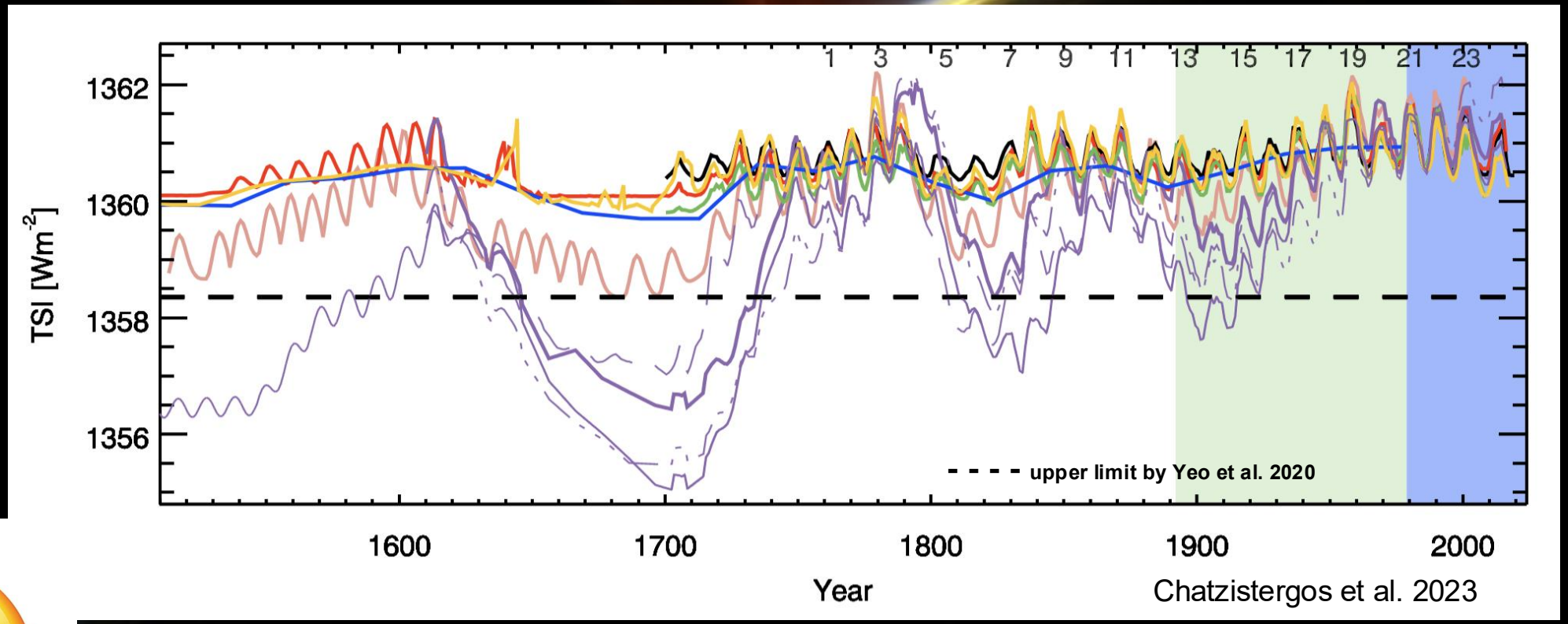
SUN – CLIMATE

http://www2.mps.mpg.de/projects/sun-climate/

Secular Variability is Highly Uncertain

MAX PLANCK INSTITUTE FOR SOLAR SYSTEM RESEARCH

Magnetograms available



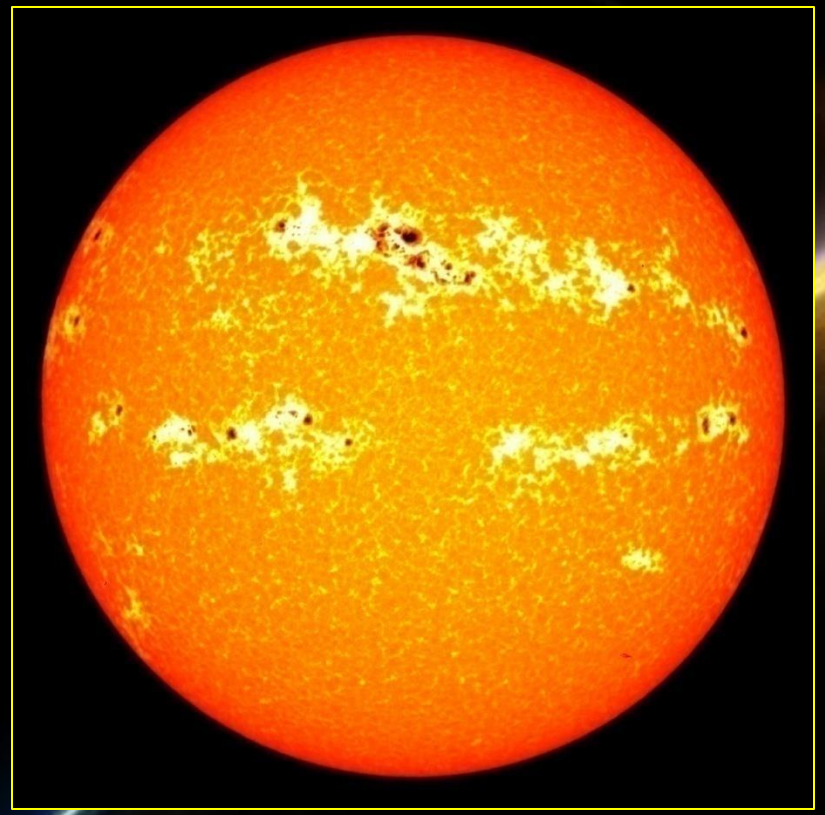
Chatzistergos et al. 2023

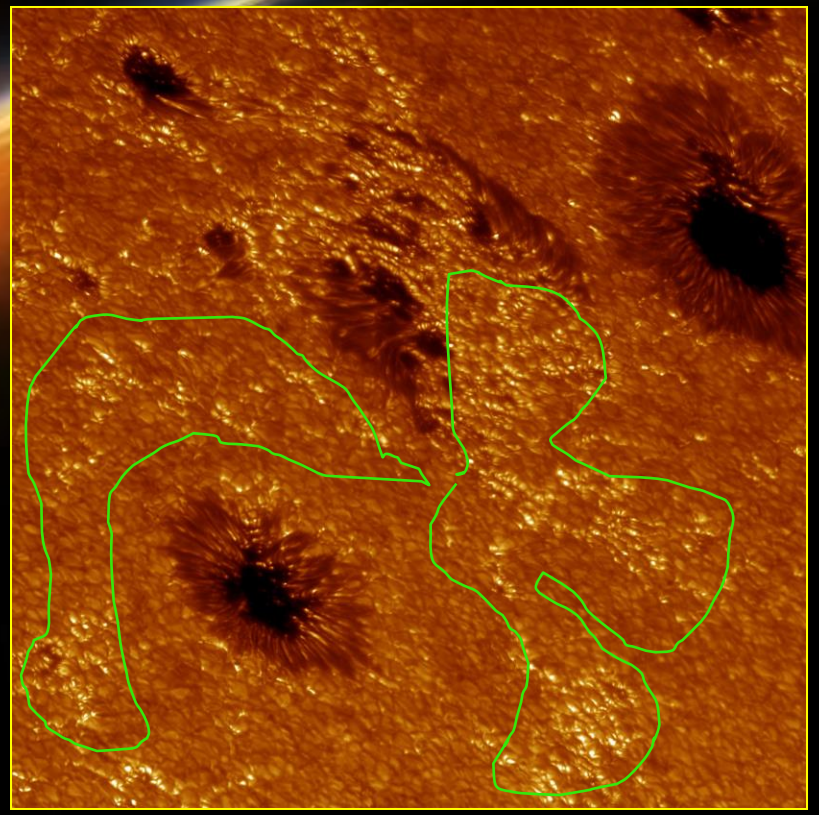
SUN – CLIMATE

http://www2.mps.mpg.de/projects/sun-climate/

Main Problem: Missing Proxy of Facular Evolution in the Past

MAX PLANCK INSTITUTE FOR SOLAR SYSTEM RESEARCH

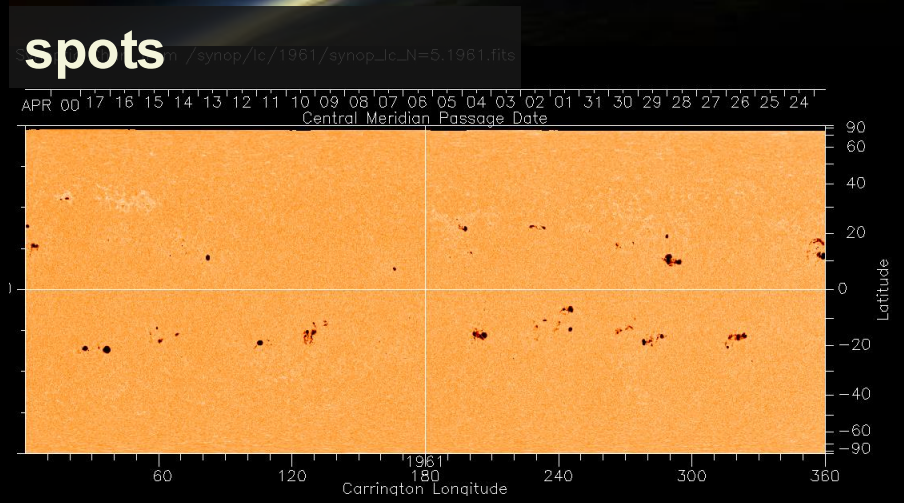




- Need: sunspot darkening & facular brightening
- Available: sunspot observations
- ➤ Sunspots are used to describe facular evolution

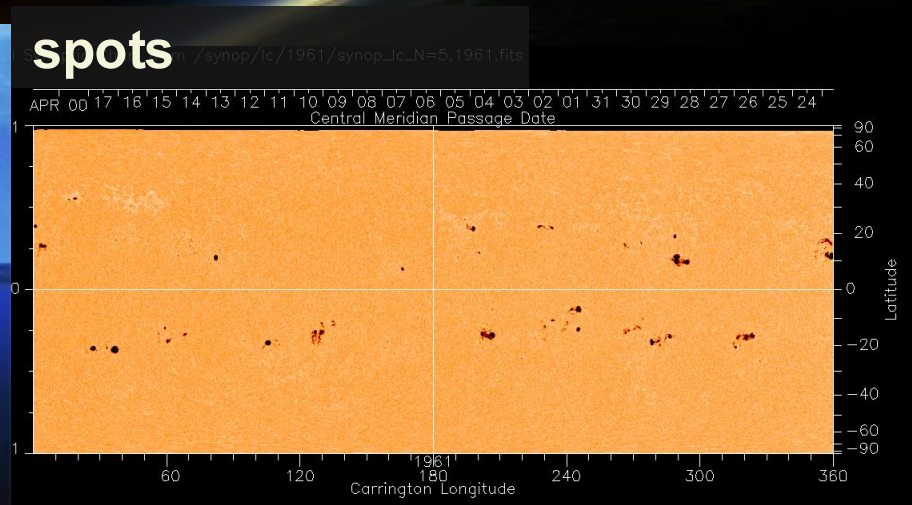
Main problem: proxy of facular evolution in the past

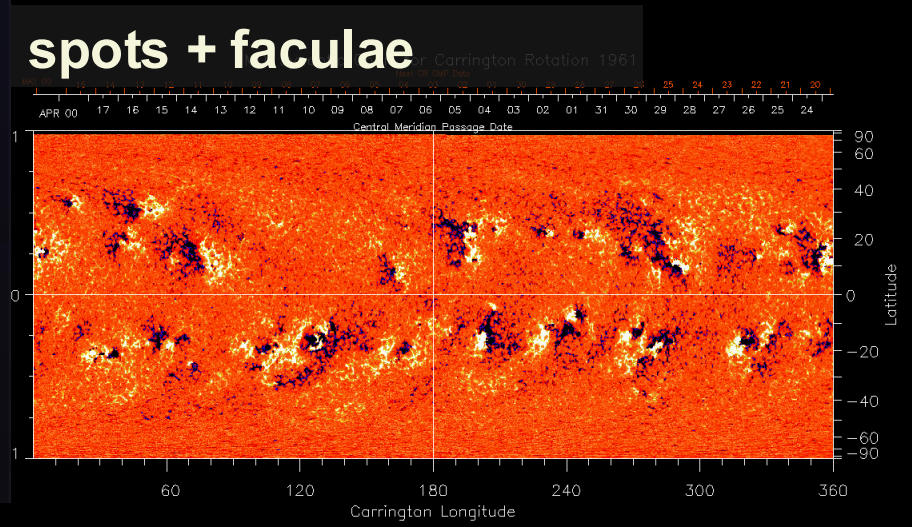
2000, Maximum



Main problem: proxy of facular evolution in the past

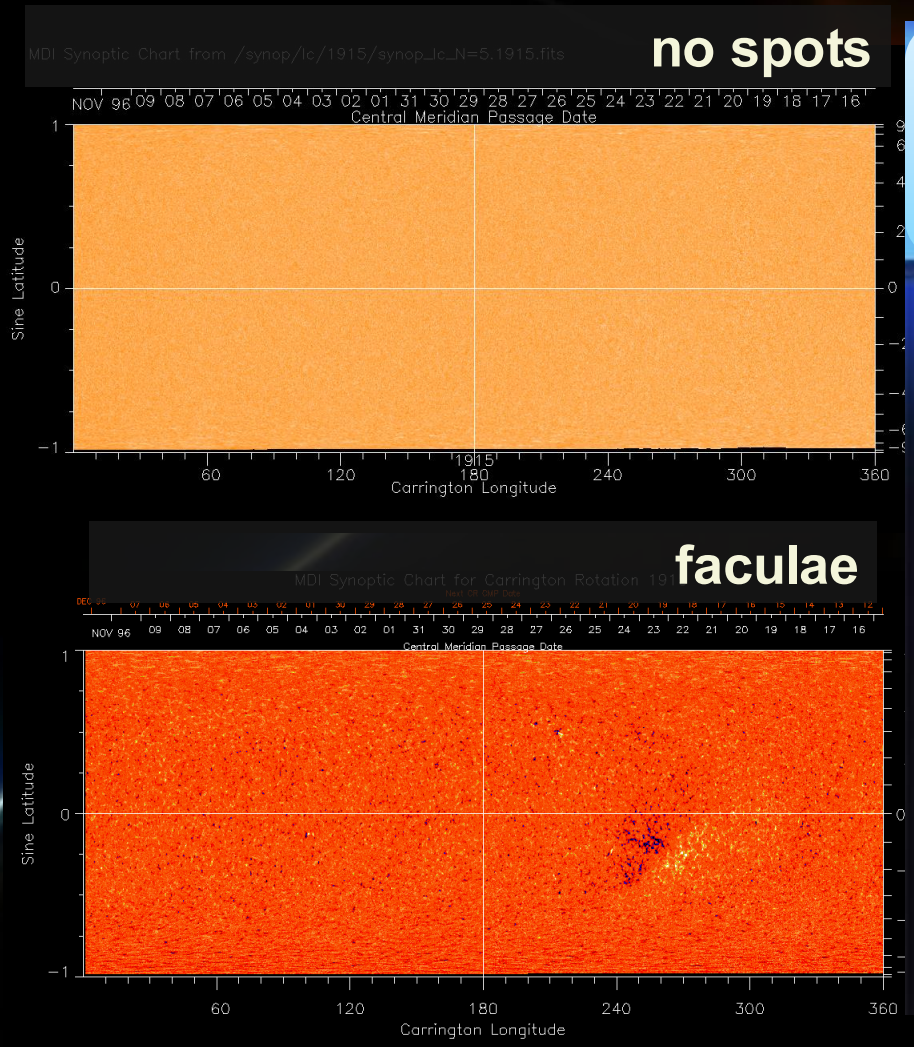
2000, Maximum

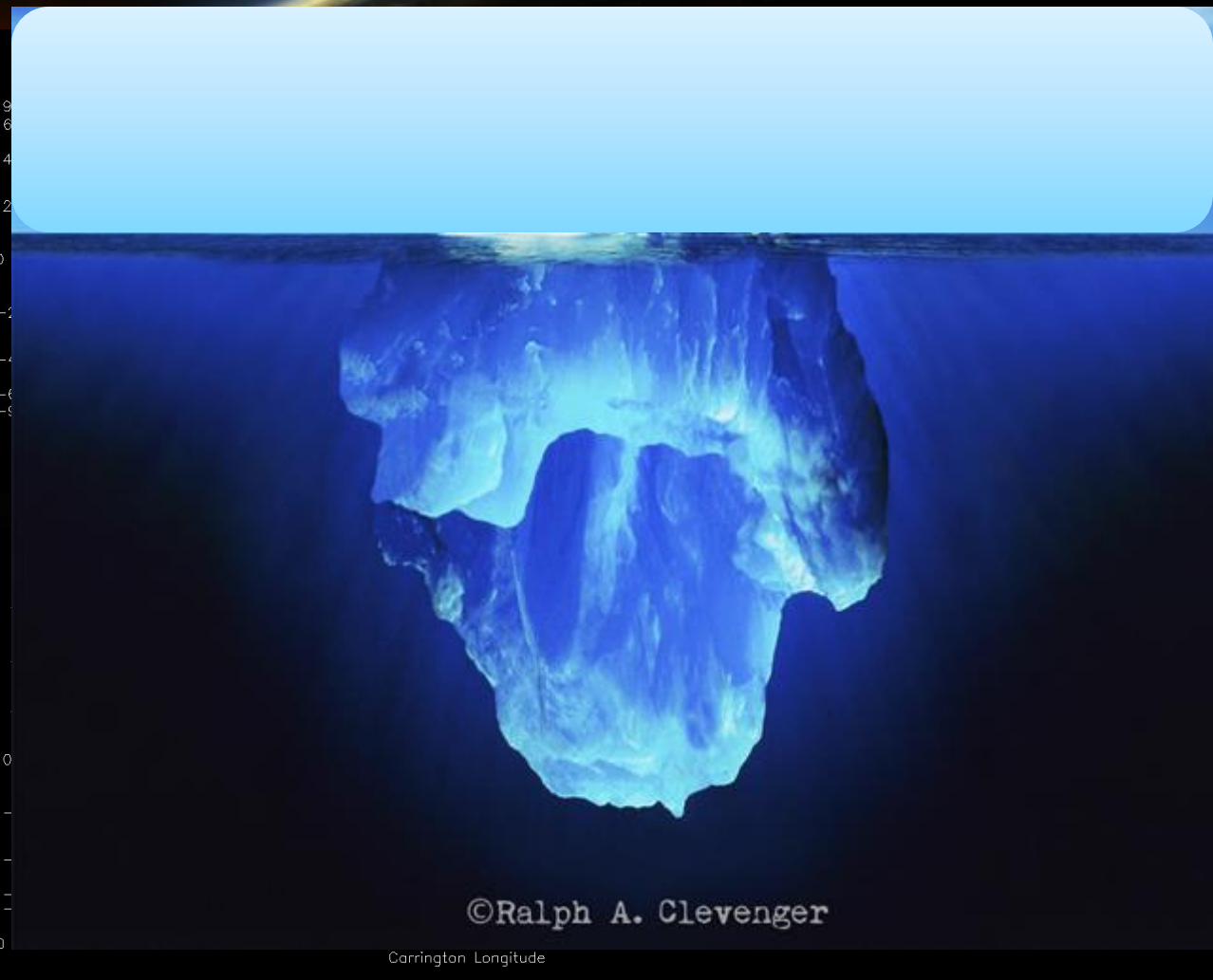




Main problem: proxy of facular evolution in the past

1996, Minimum



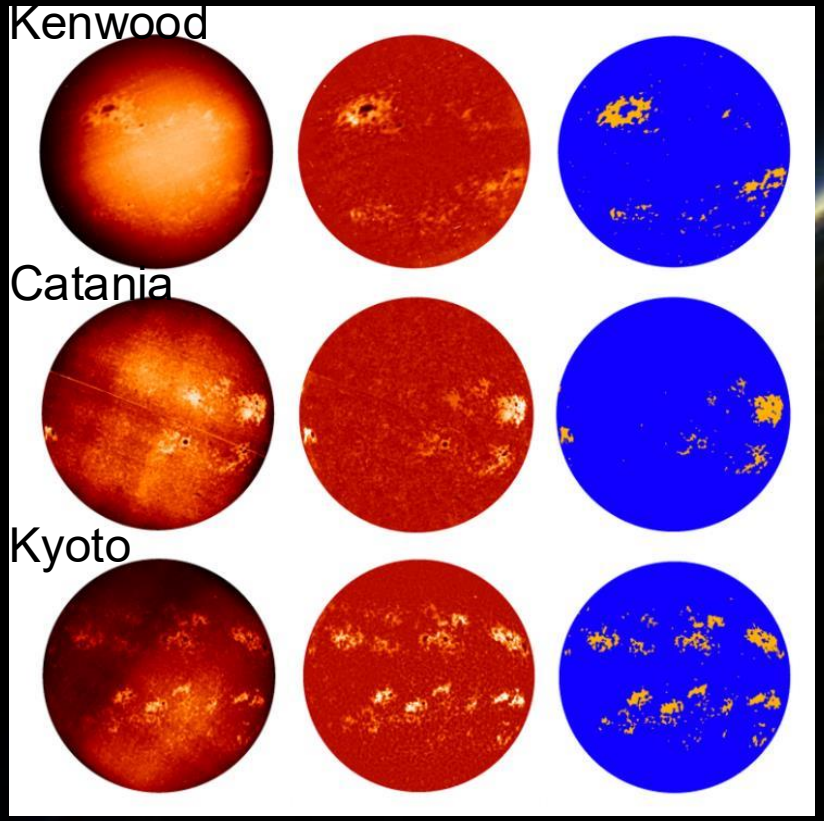


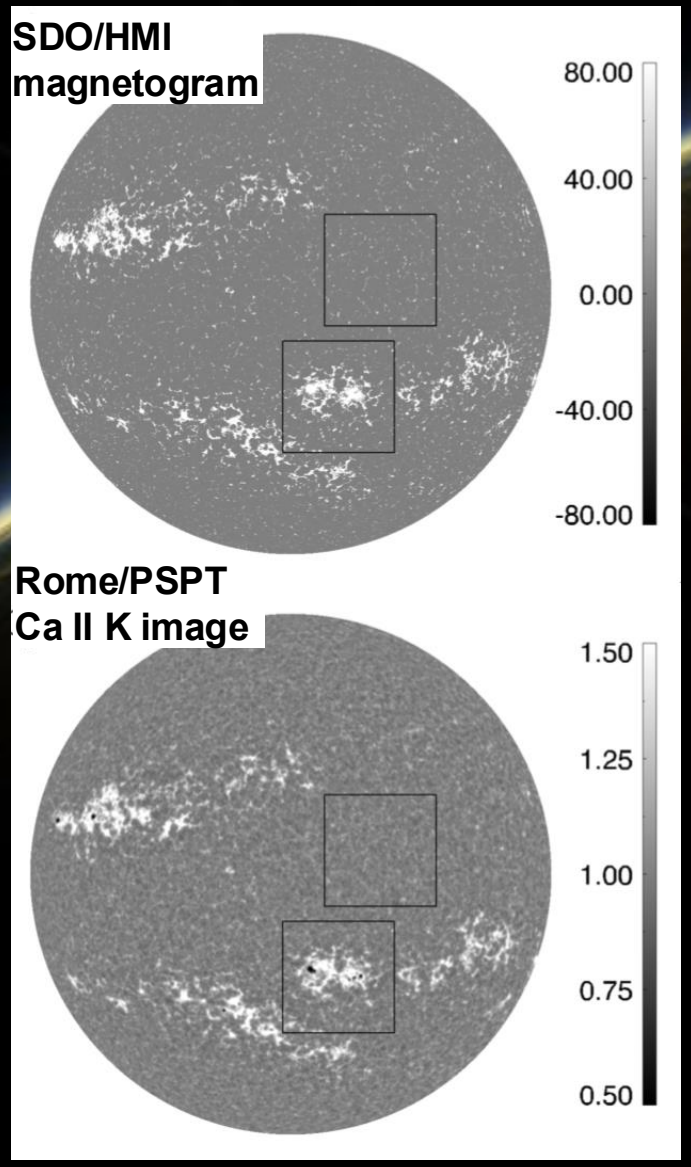
Ca II K Photographic Archives

Uncalibrated

CLV-compen-sated & calibrated

Masks: plage / QS



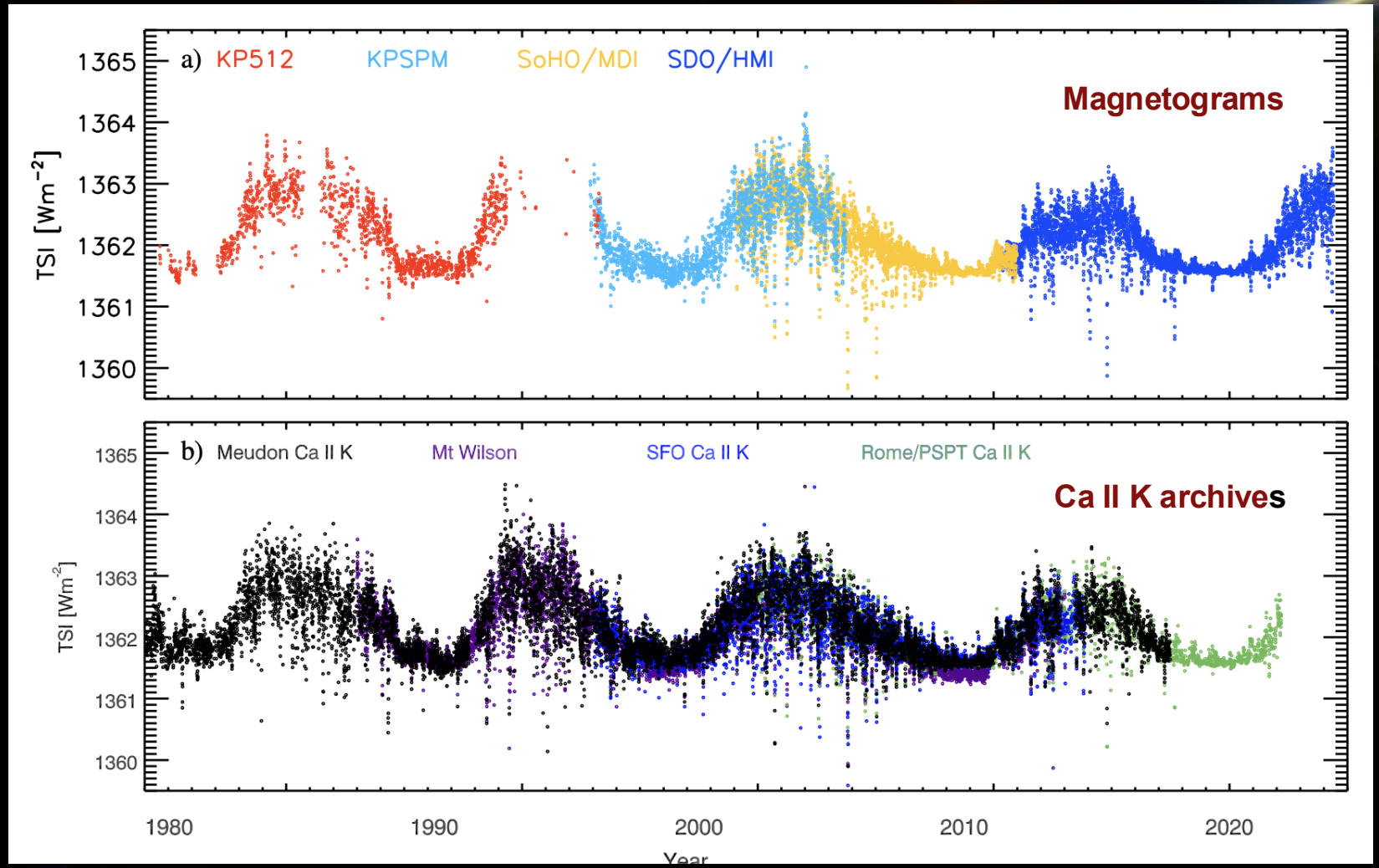


Chatzistergos et al. (2018,2019, 2020, 2021,2022,2023,2024):

- Novel superior method to process historical Ca II K images
- > 300 000 full-disc Ca II K observations from 43 archives
- Most comprehensive plage area composite since 1892 with daily coverage of 88% before 1907 & 98% after 1907
- Strong relationship between Ca II K brightness and the magnetic field strength allows reconstruction of magnetograms back to late 19th century
- Use magnetograms to reconstruct irradiance

Solar irradiance from Ca II K archives

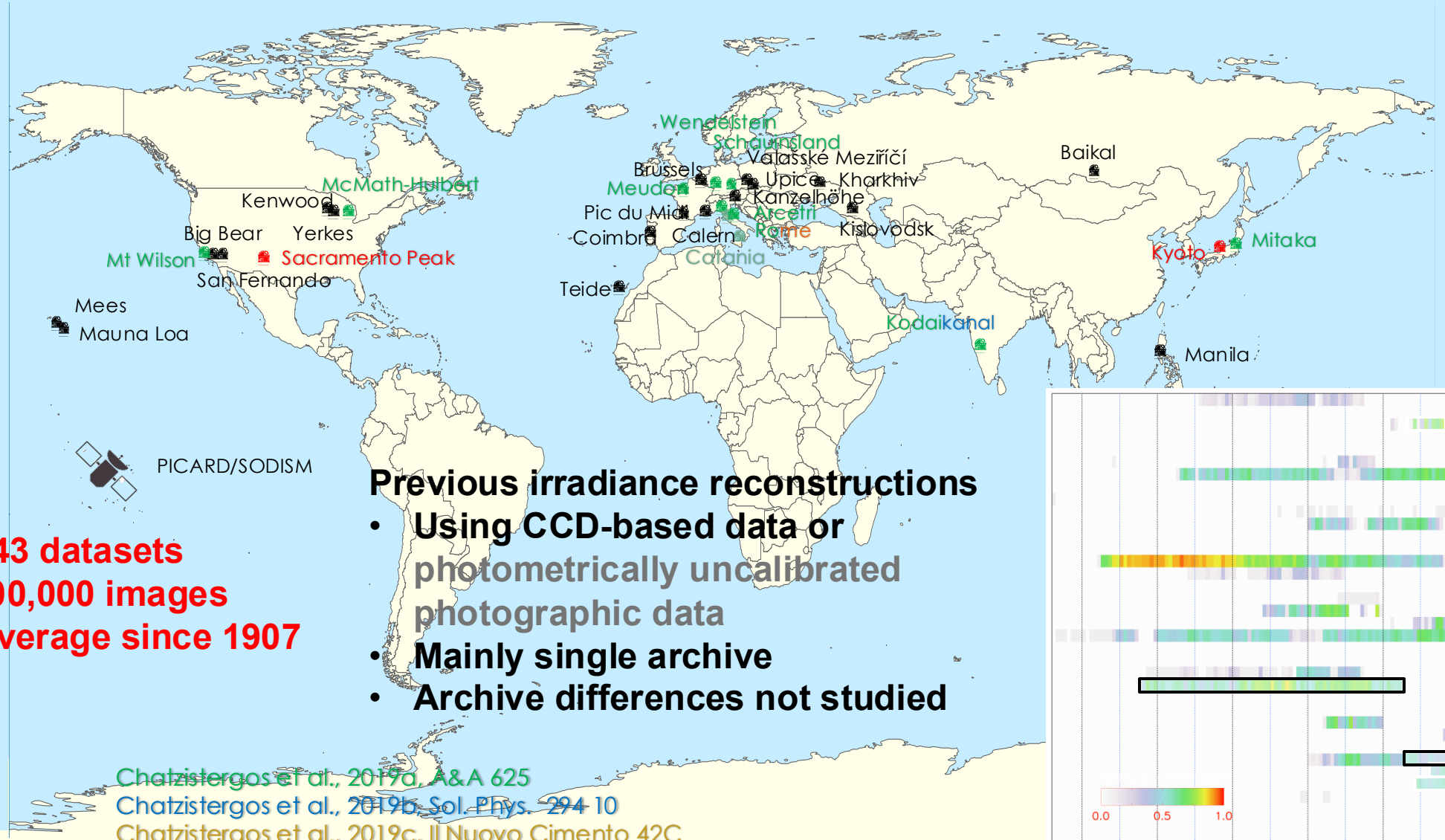
Chatzistergos et al. 2024



Magnetograms recovered from Ca II K images allow nearly as accurate irradiance reconstructions as actual direct magnetograms

Ca II K archives

Courtesy of T. Chatzistergos



43 datasets
~300,000 images
98% coverage since 1907

Previous irradiance reconstructions

- **Using CCD-based data or photometrically uncalibrated photographic data**
- **Mainly single archive**
- **Archive differences not studied**

Chatzistergos et al., 2019a, A&A 625
Chatzistergos et al., 2019b, Sol. Phys. 294 10
Chatzistergos et al., 2019c, Il Nuovo Cimento 42C
Chatzistergos et al., 2020a, J. Phys. Conf. Ser. 1548
Chatzistergos et al., 2020b A&A 639

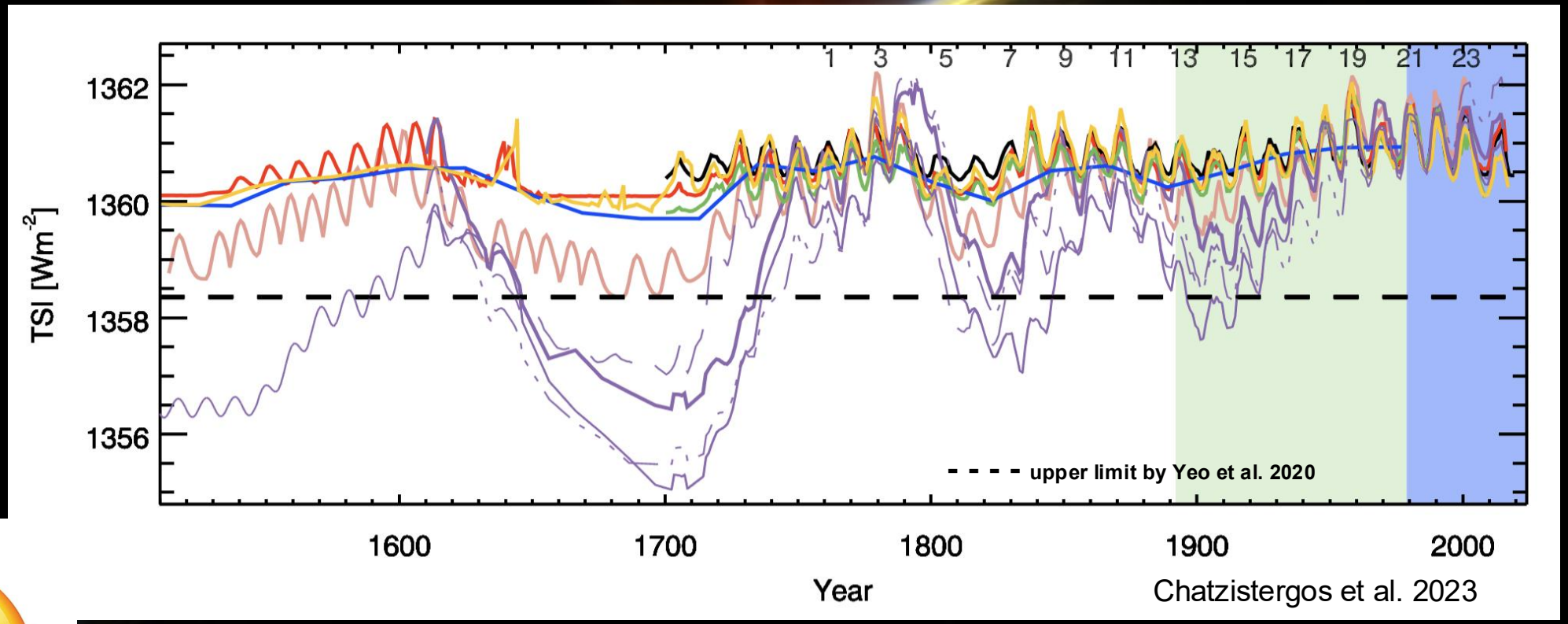
SUN – CLIMATE

http://www2.mps.mpg.de/projects/sun-climate/

MAX PLANCK INSTITUTE FOR SOLAR SYSTEM RESEARCH

Secular Variability is Highly Uncertain

Ca II K images available



Chatzistergos et al. 2023

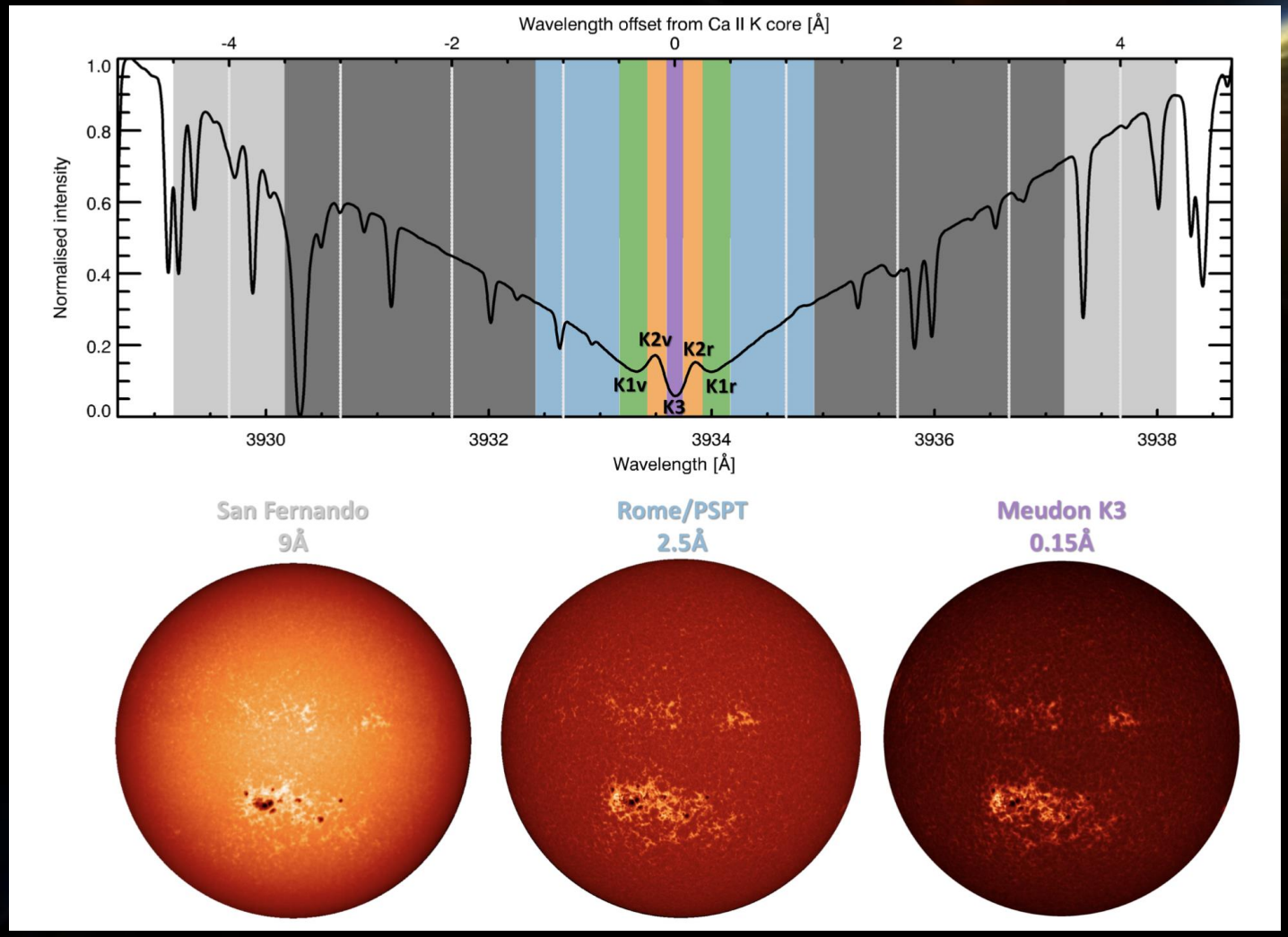
SUN – CLIMATE

http://www2.mps.mpg.de/projects/sun-climate/

Ca II K Archives for Reconstructions of Past Magnetic Activity

MAX PLANCK INSTITUTE FOR SOLAR SYSTEM RESEARCH

Chatzistergos et al. 2024



Cross-calibration of historical photographic archives

- Individual archives taken in various passbands
- Trace different atmospheric layers
- Need careful cross-calibration to avoid artifact trends

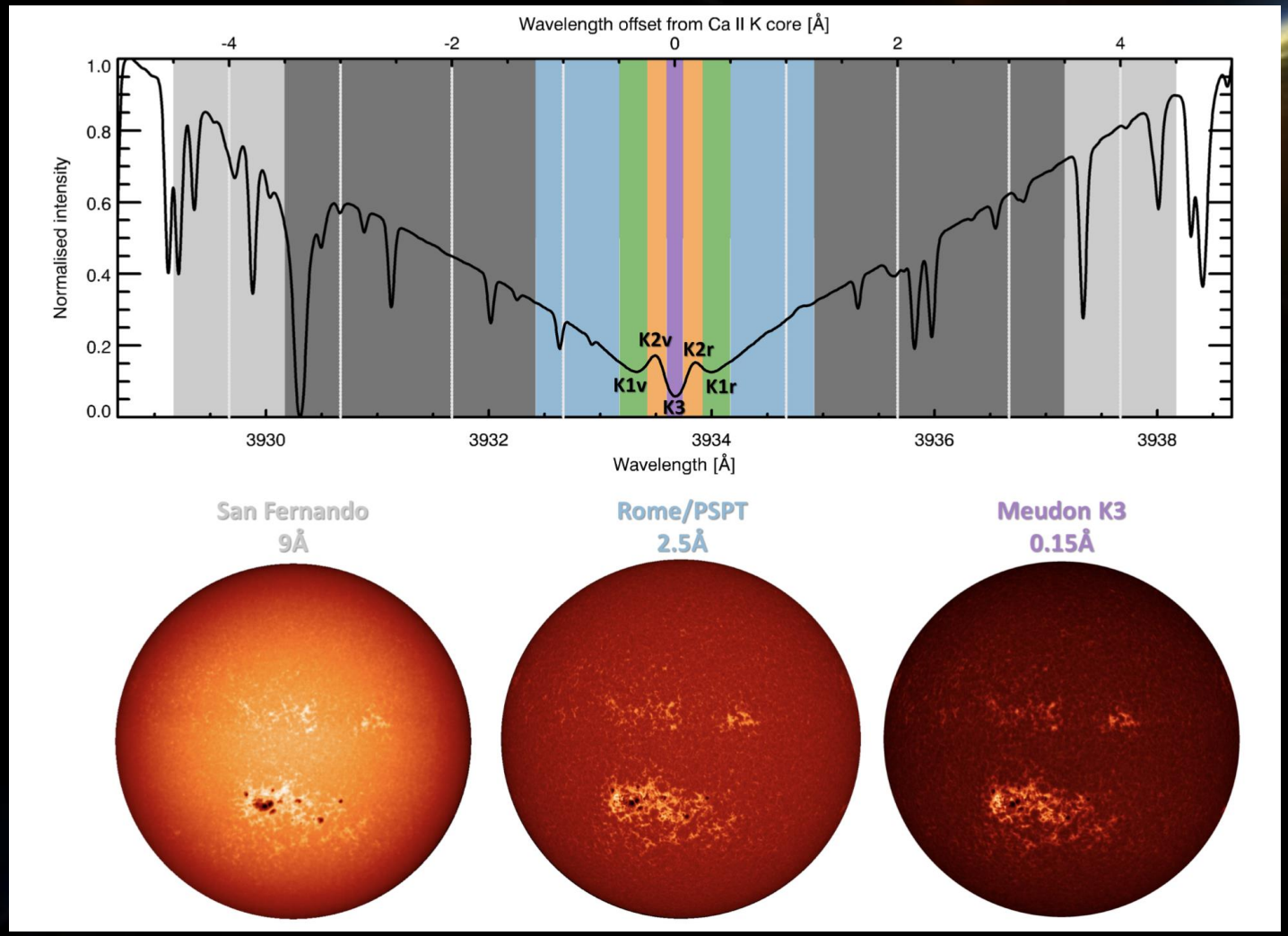
SUN – CLIMATE

http://www2.mps.mpg.de/projects/sun-climate/

Ca II K Archives for Reconstructions of Past Magnetic Activity

MAX PLANCK INSTITUTE FOR SOLAR SYSTEM RESEARCH

Chatzistergos et al. 2024



Cross-calibration of historical photographic archives

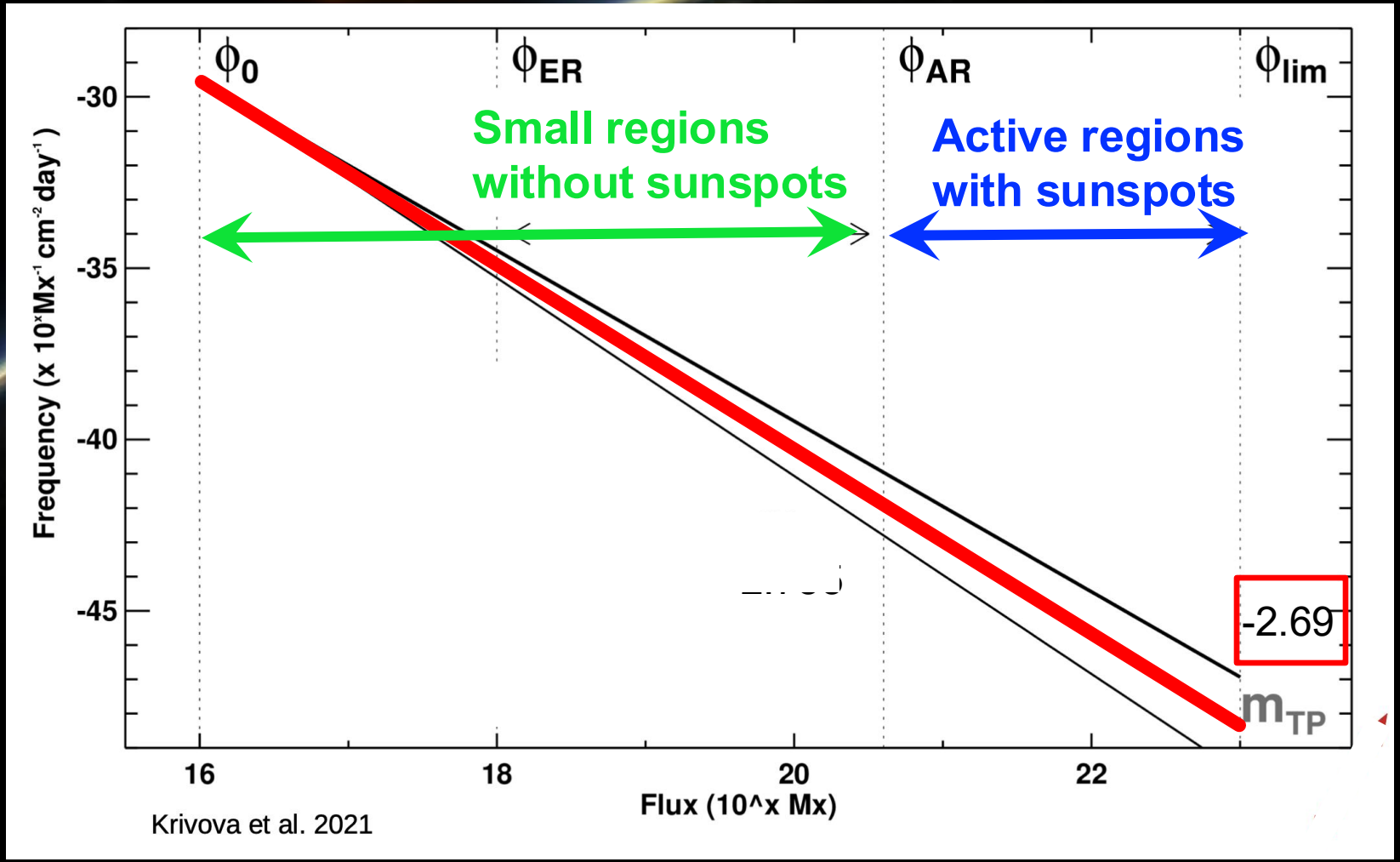
- Individual archives taken in various passbands
- Trace different atmospheric layers
- Need careful cross-calibration to avoid artifact trends
- Use *Sunrise-III* data!

Poster by Ajay Yadav

Accounting for small magnetic regions not represented by the Sunspot Number

MAX PLANCK INSTITUTE
FOR SOLAR SYSTEM RESEARCH

- MF emergence is described by a single power law as observed by Thornton & Parnell (2011)



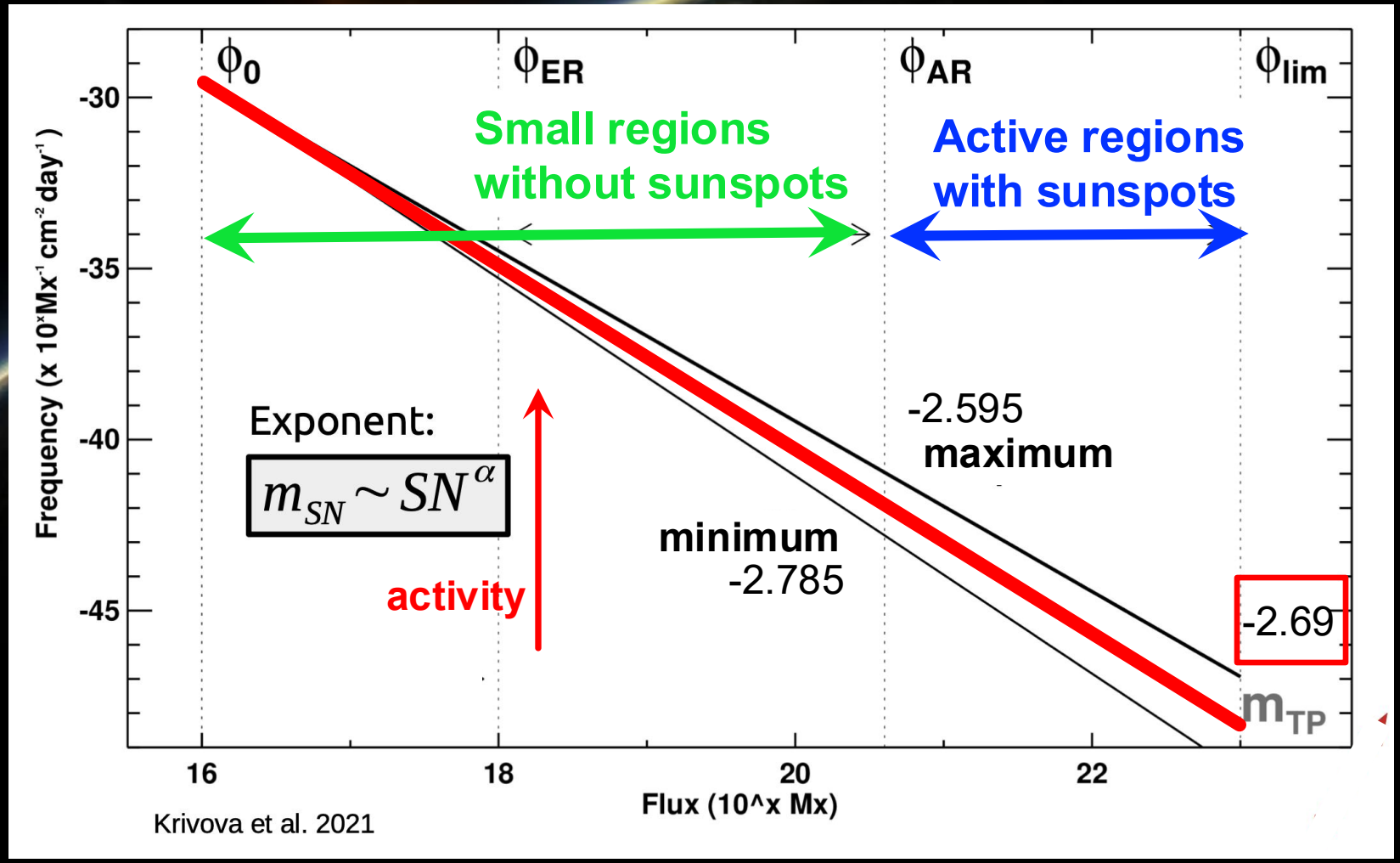
SUN – CLIMATE

http://www2.mps.mpg.de/projects/sun-climate/

MAX PLANCK INSTITUTE FOR SOLAR SYSTEM RESEARCH

Accounting for small magnetic regions not represented by the Sunspot Number

- MF emergence is described by a single power law as observed by Thornton & Parnell (2011)
- Slope varies with activity (that is spot/fac ratio grows with activity), in agreement with various observations



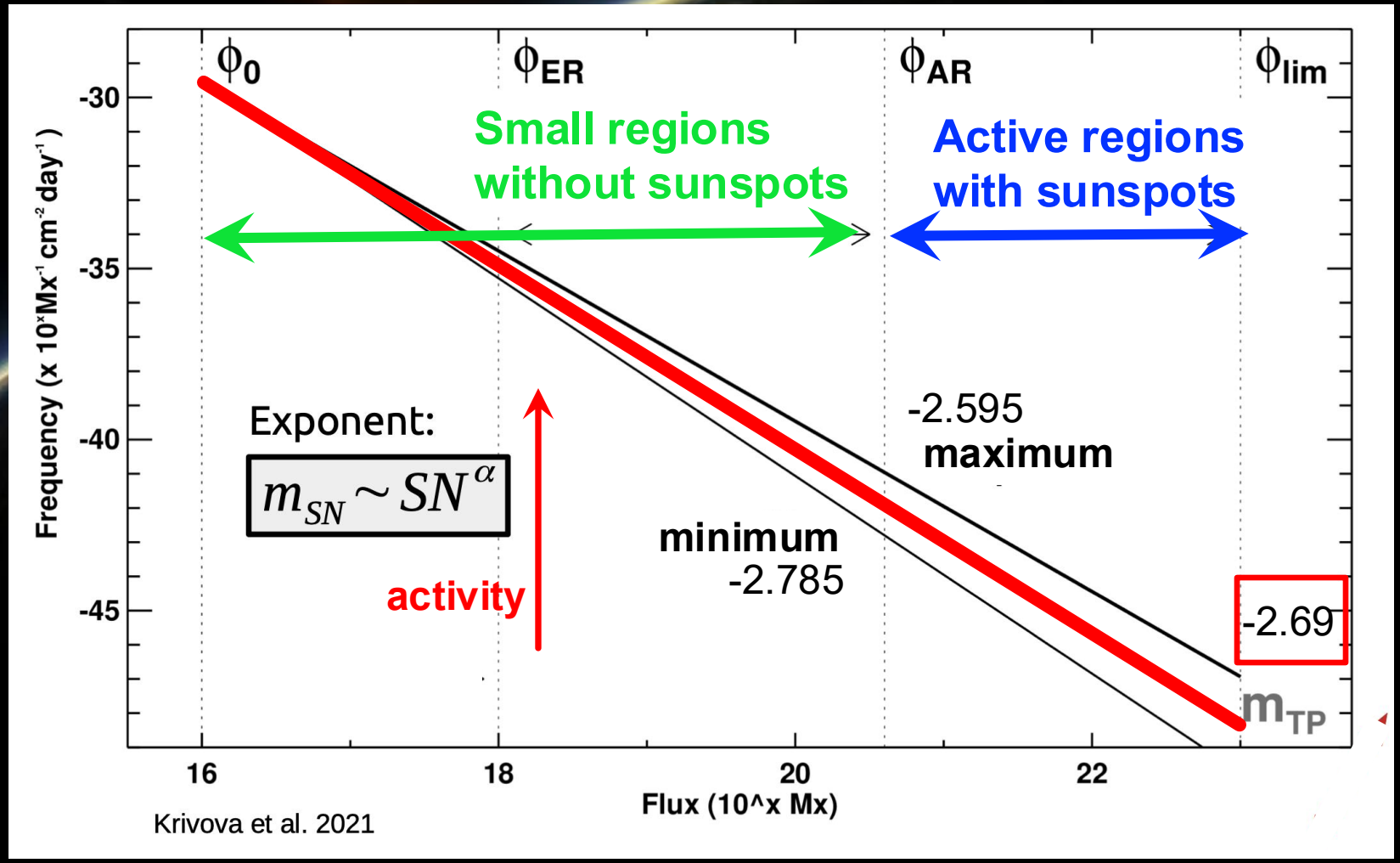
SUN – CLIMATE

http://www2.mps.mpg.de/projects/sun-climate/

MAX PLANCK INSTITUTE FOR SOLAR SYSTEM RESEARCH

Accounting for small magnetic regions not represented by the Sunspot Number

- MF emergence is described by a single power law as observed by Thornton & Parnell (2011)
- Slope varies with activity (that is spot/fac ratio grows with activity), in agreement with various observations
- Accounts for small regions not captured by spot data
- Important for extended minima but also for high cycles (e.g., cycle 19)



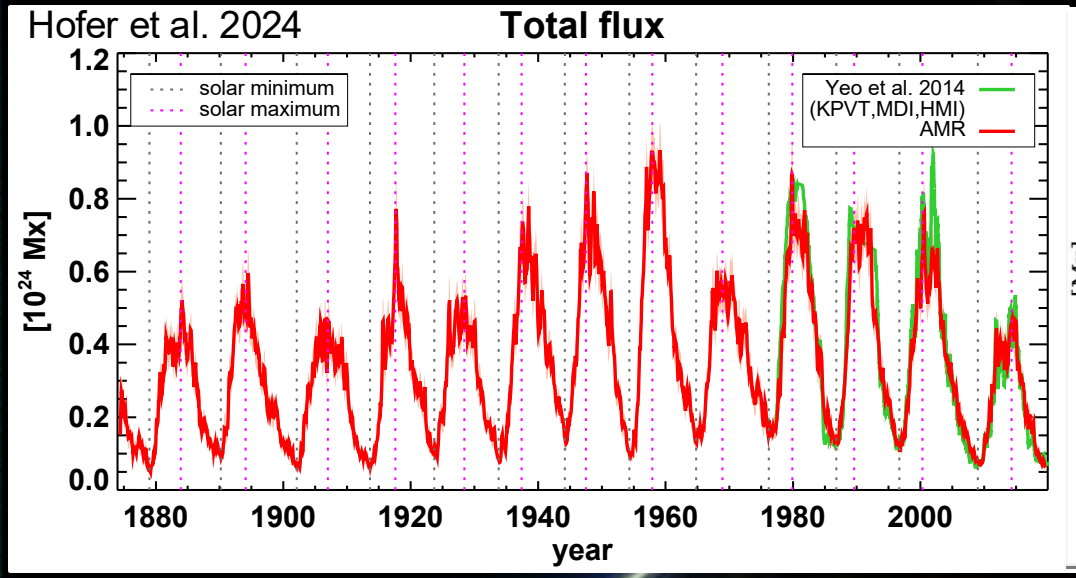
SUN – CLIMATE

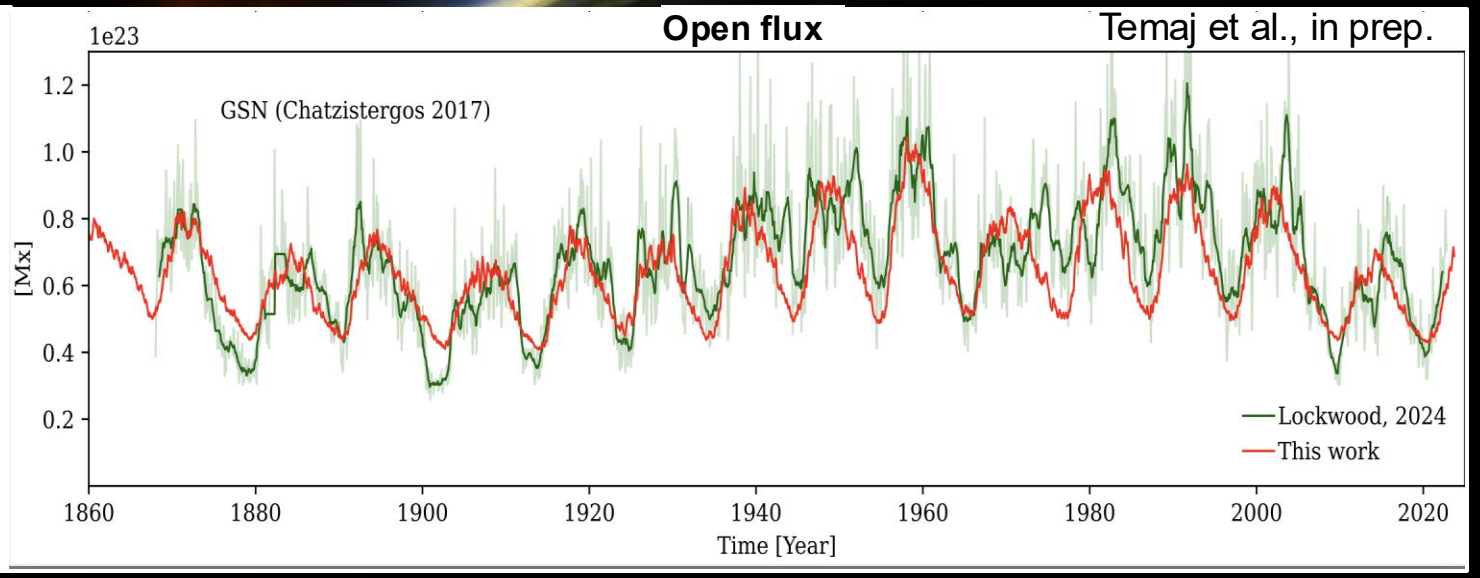
http://www2.mps.mpg.de/projects/sun-climate/

Reconstruction of the total and open MF

MAX PLANCK INSTITUTE FOR SOLAR SYSTEM RESEARCH

Observed or alternative reconstruction/ Modelled



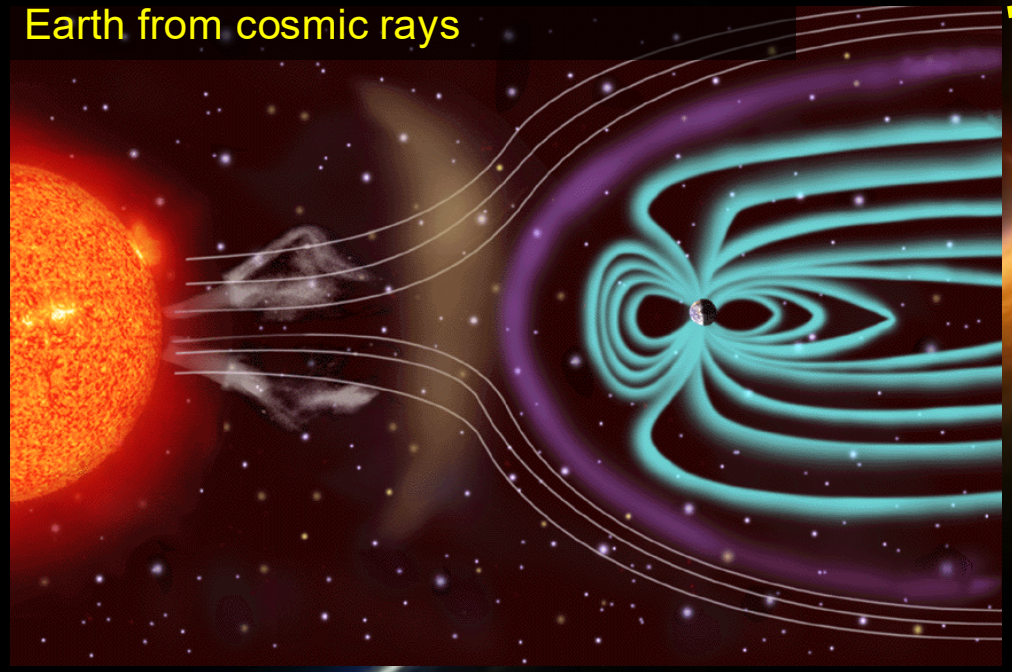


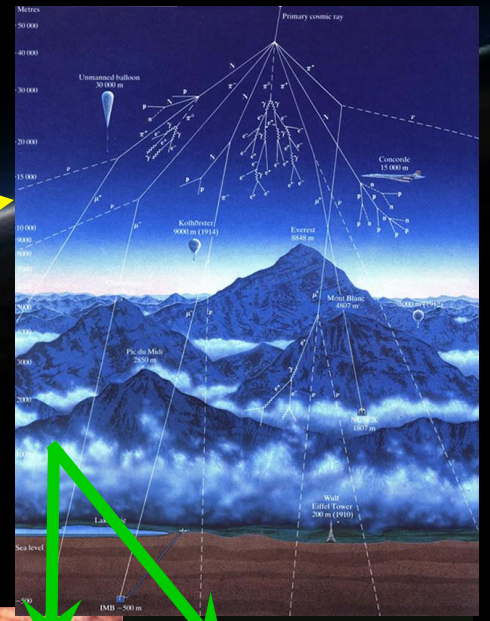
This reconstructed magnetic flux can be used to also compute irradiance variability– Poster by Duresa Temaj

Open flux modulates production of cosmogenic isotopes

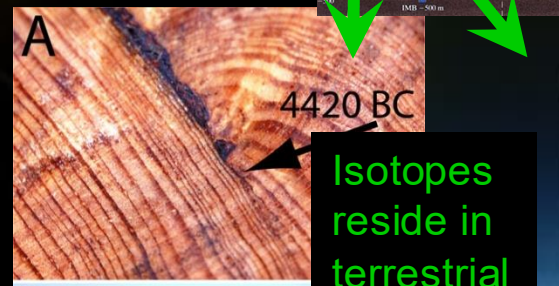
Thus, solar activity modulates the cosmic-ray flux

Sun's and Earth's magnetic field protect Earth from cosmic rays





In the atmosphere, cosmic rays produce cosmogenic isotopes, e.g. ^{14}C and ^{10}Be



^{10}Be

Isotopes reside in terrestrial archives

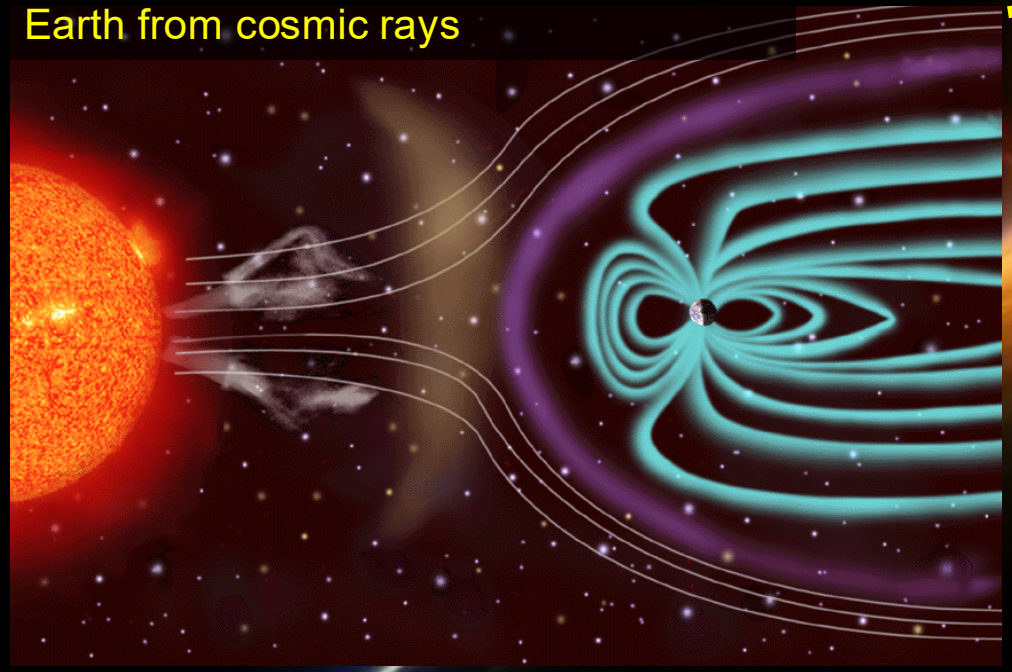
^{14}C

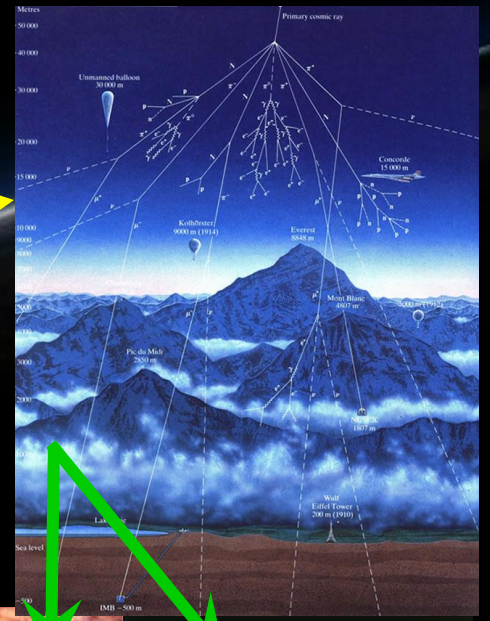
Solar open flux ⇨ GCR modulation ⇨ ^{14}C production rate ⇨ ^{14}C concentrations

We can invert this to get sunspot number from cosmogenic data!

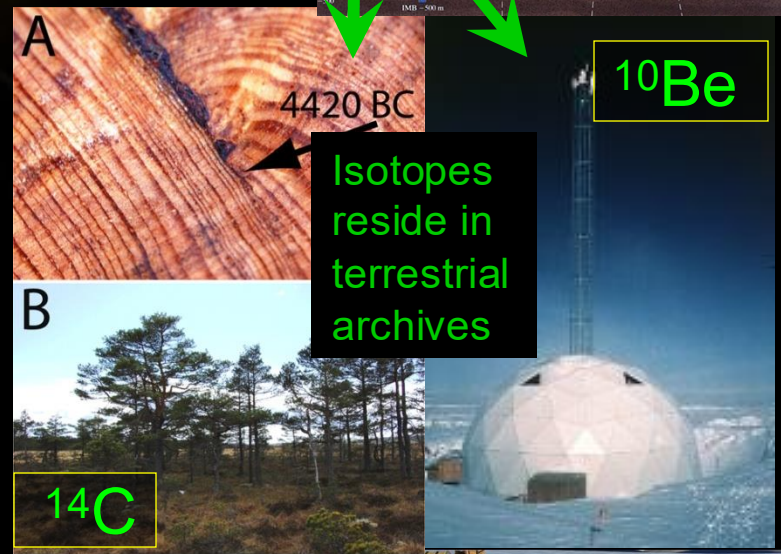
Thus, solar activity modulates the cosmic-ray flux

Sun's and Earth's magnetic field protect Earth from cosmic rays





In the atmosphere, cosmic rays produce cosmogenic isotopes, e.g. ^{14}C and ^{10}Be



Isotopes reside in terrestrial archives

Solar open flux ⇦ GCR modulation ⇦ ^{14}C production rate ⇦ ^{14}C concentrations

SUN – CLIMATE

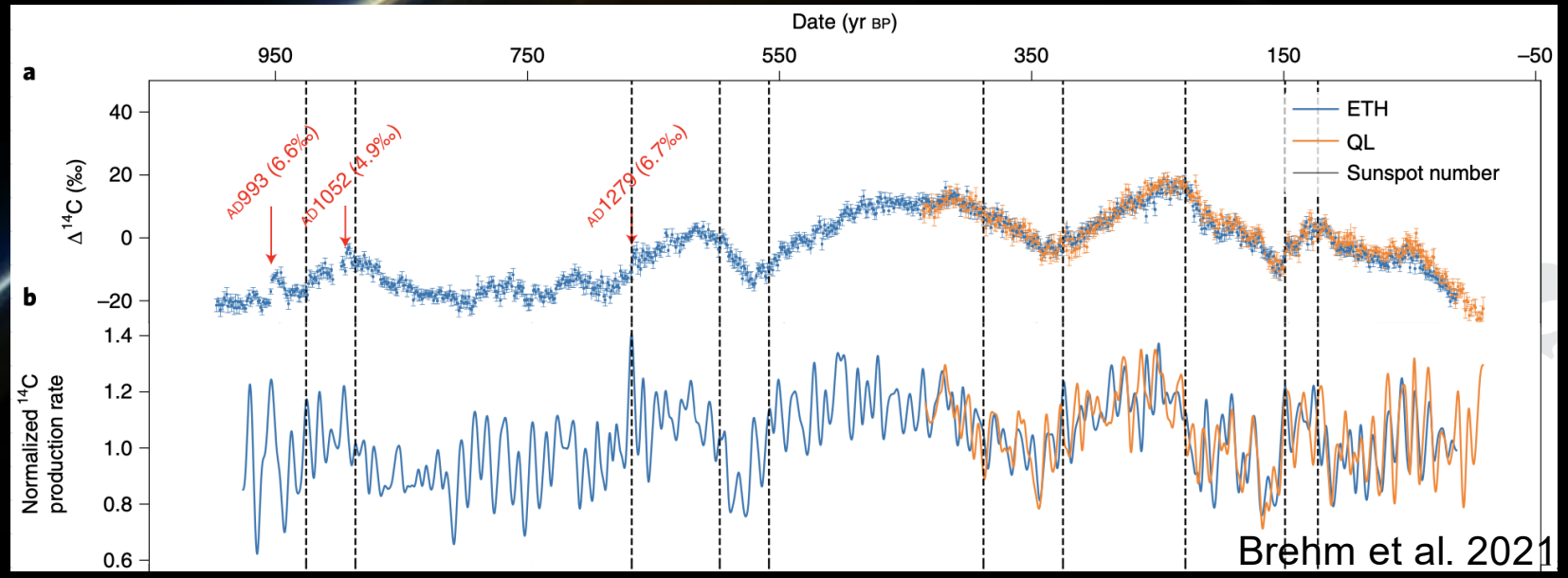
http://www2.mps.mpg.de/projects/sun-climate/

MAX PLANCK INSTITUTE FOR SOLAR SYSTEM RESEARCH

Cosmogenic data with yearly resolution give the Sunspot Number with yearly resolution for the last 1000 years

Usoskin et al. (2021; 2025):

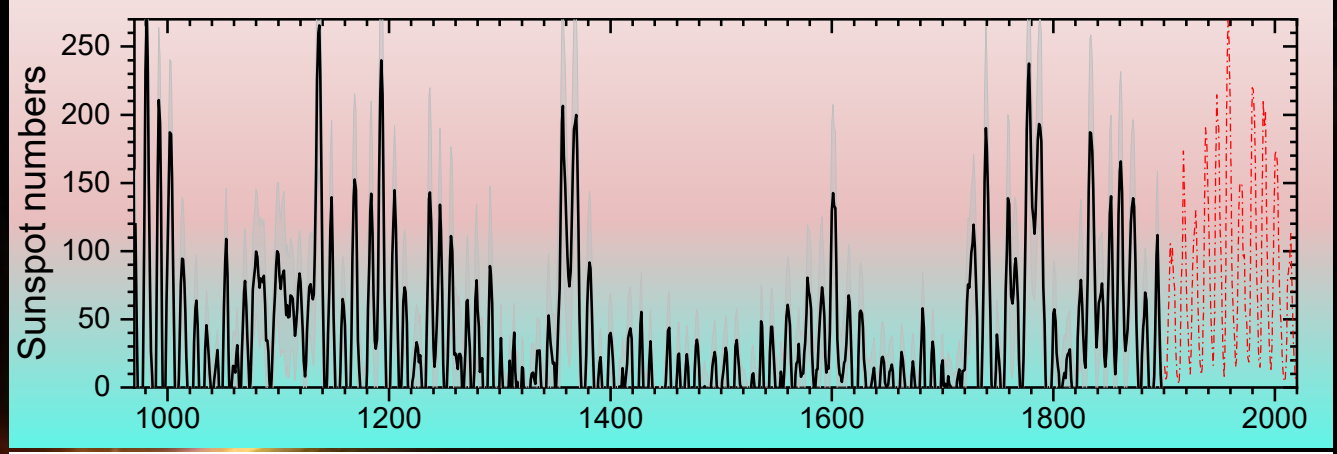
- use ^{14}C from Brehm et al. (2021; 2025) → Open solar flux
- invert the model by Krivova et al. (2021) → Sunspot Number

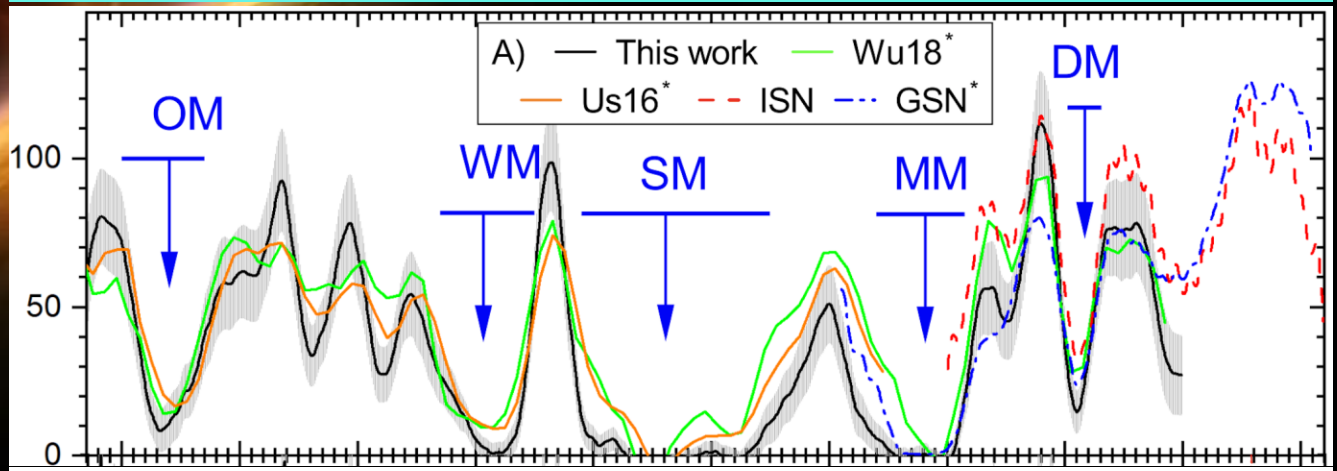


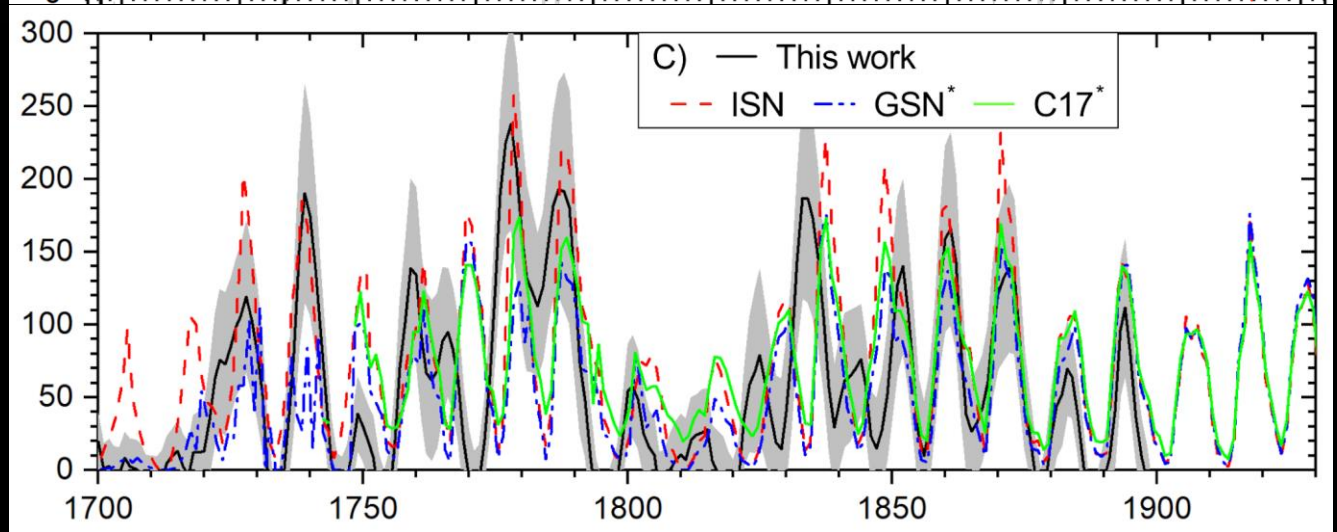
Reconstruction of the annual sunspot number

- Comparison to other (decadal) isotope data:
  - decadal averages agree with earlier decadal ^{14}C and ^{10}Be-based reconstructions
- Telescope era:
  - generally good agreement with telescopic observations;
  - low-activity periods are less certain (low signal-to-noise ratio)

Usoskin et al. 2021







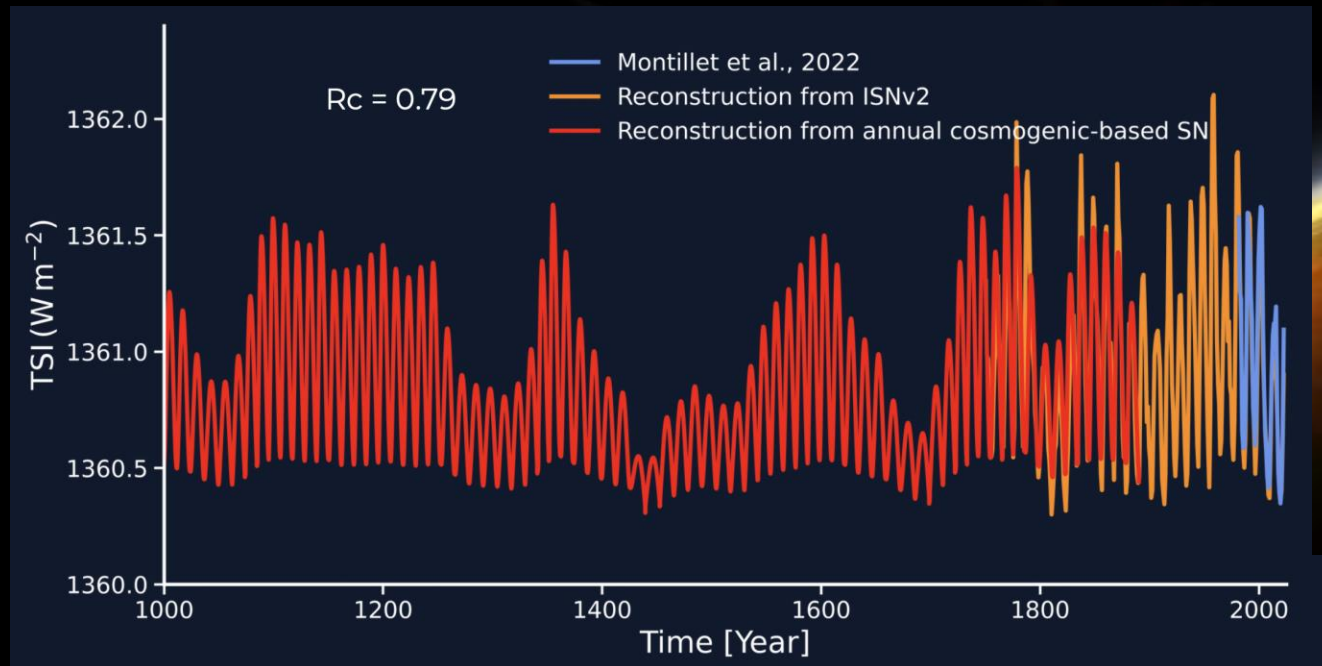
SUN – CLIMATE

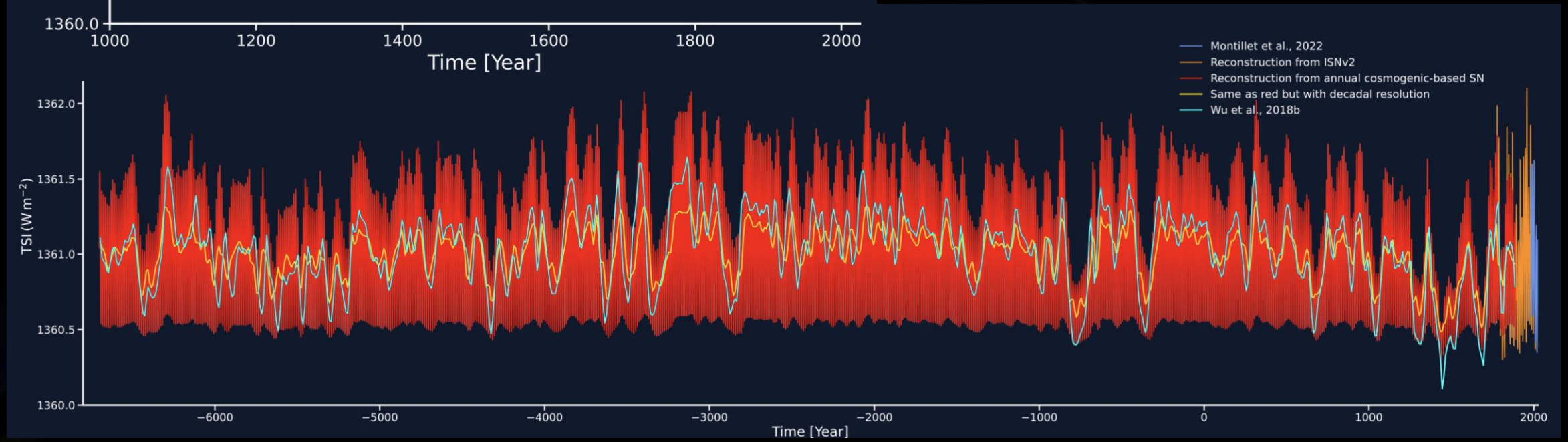
http://www2.mps.mpg.de/projects/sun-climate/

Reconstruction of the annual Solar Irradiance

MAX PLANCK INSTITUTE FOR SOLAR SYSTEM RESEARCH

Poster by Duresa Temaj





Summary

- ✓ On time scales of days to millennia, the solar magnetic field is the main driver of solar variability
- ✓ To reconstruct solar activity, we use
  - ➢ magnetograms – ~50 years
  - ➢ sunspot observations – ~300-400 years
    + Ca II K archives – ~130 years
  - ➢ cosmogenic isotope archives ^{14}C and ^{10}Be – Holocene
- ? Cross-calibration of historical Ca II K observations pending ⟹ key to reliable assessment of secular variability
- ? Go yet further back in time ?