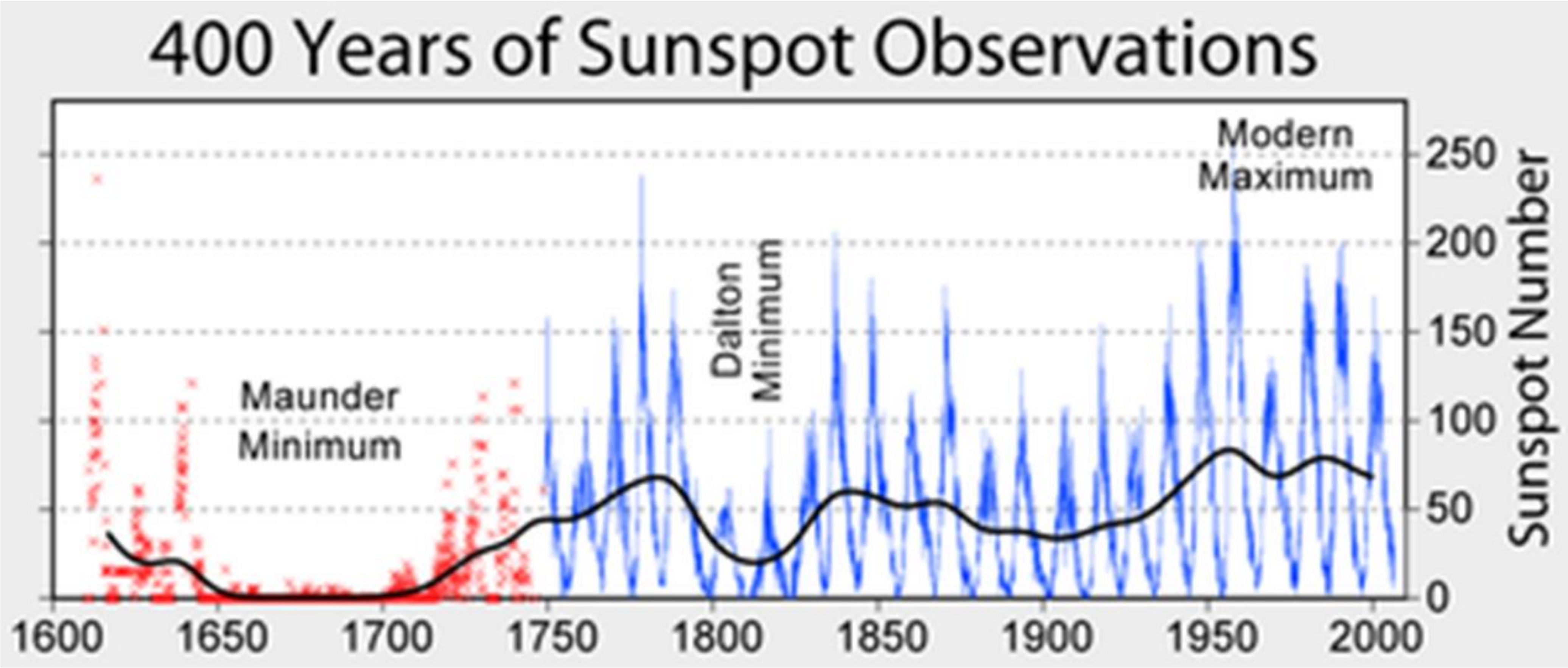
Solar Irradiance

Serena Criscuoli
National Solar Observatory

01/25/2023

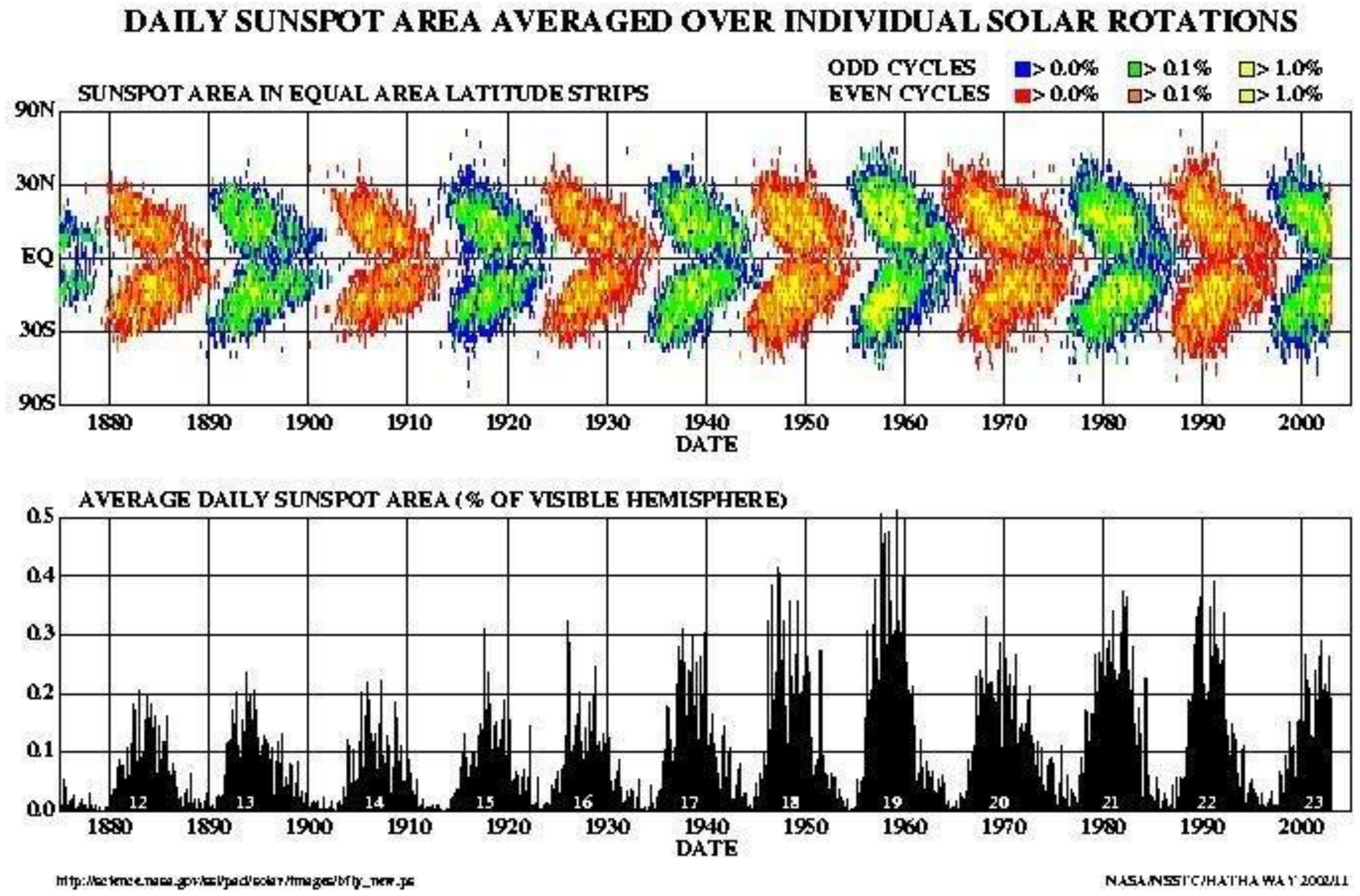
The Solar Cycle(s)



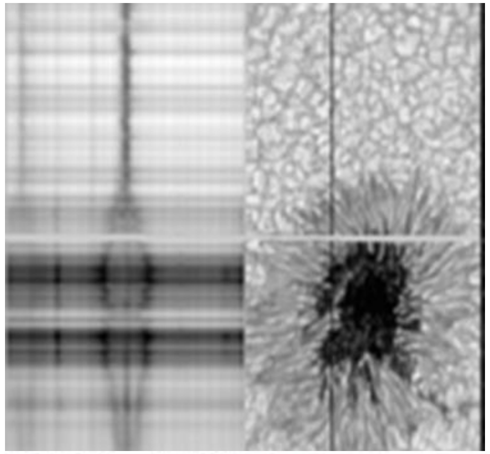
Galileo, 1610
Schwabe, 1844

SILSO
https://www.sidc.be/silso/datafiles

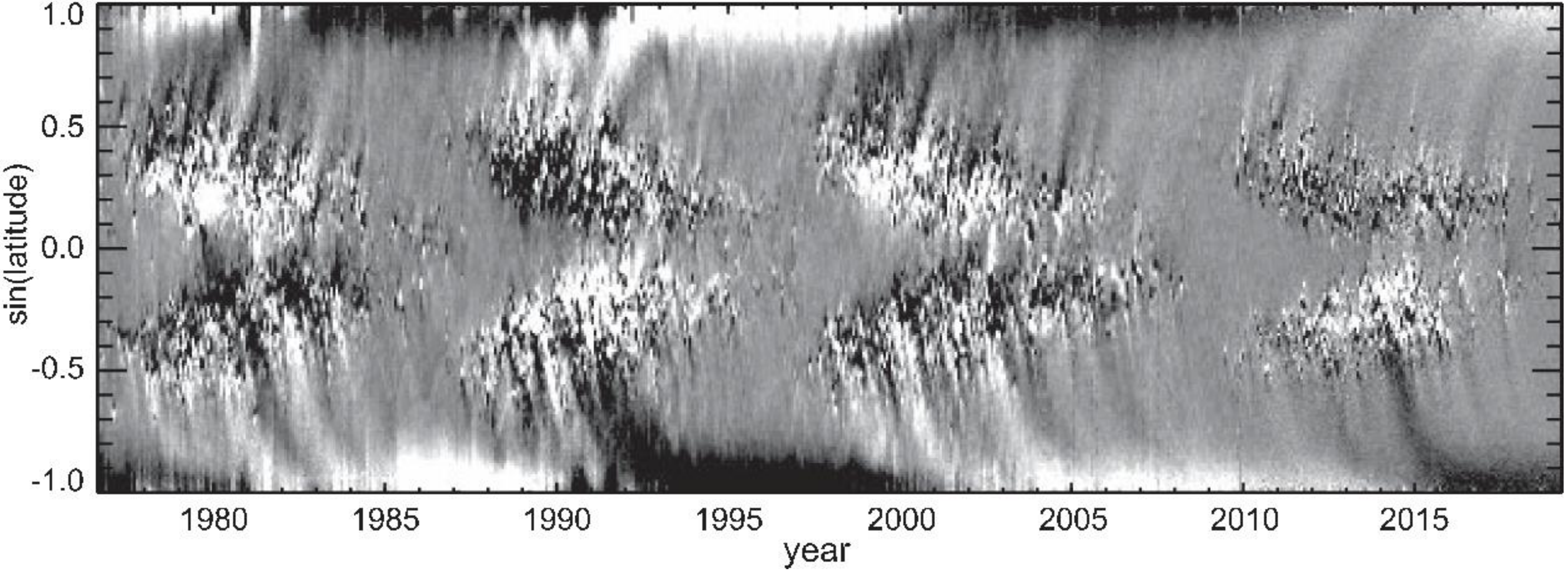
Butterfly Diagram

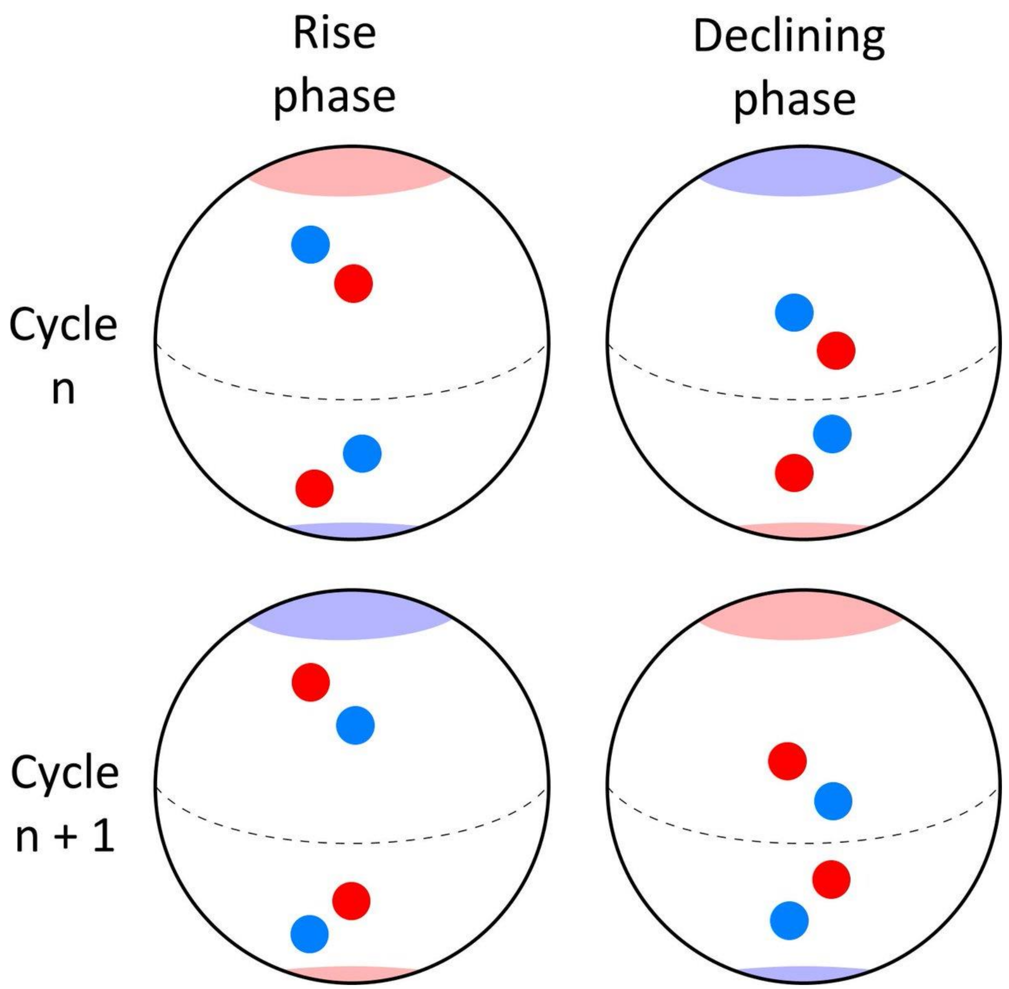


Spörer law: The first spot of each cycle appear at 30°-35° latitude



George Ellery Hale
“On the Probable Existence of a Magnetic Field in Sun-Spots”
Hale, 1908



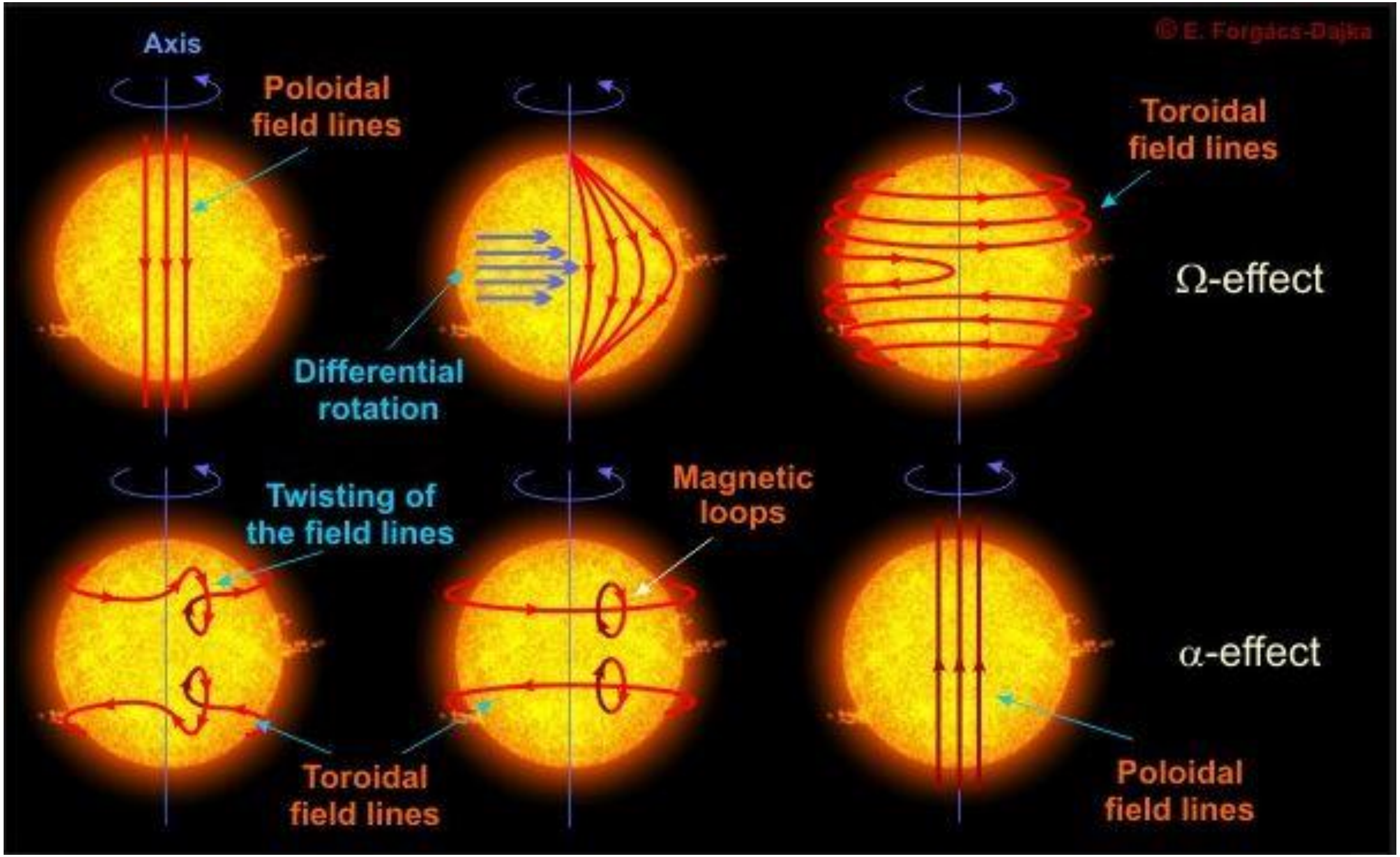


Leading polarities of ARs are the same in a given hemisphere
And opposite in the opposite hemisphere

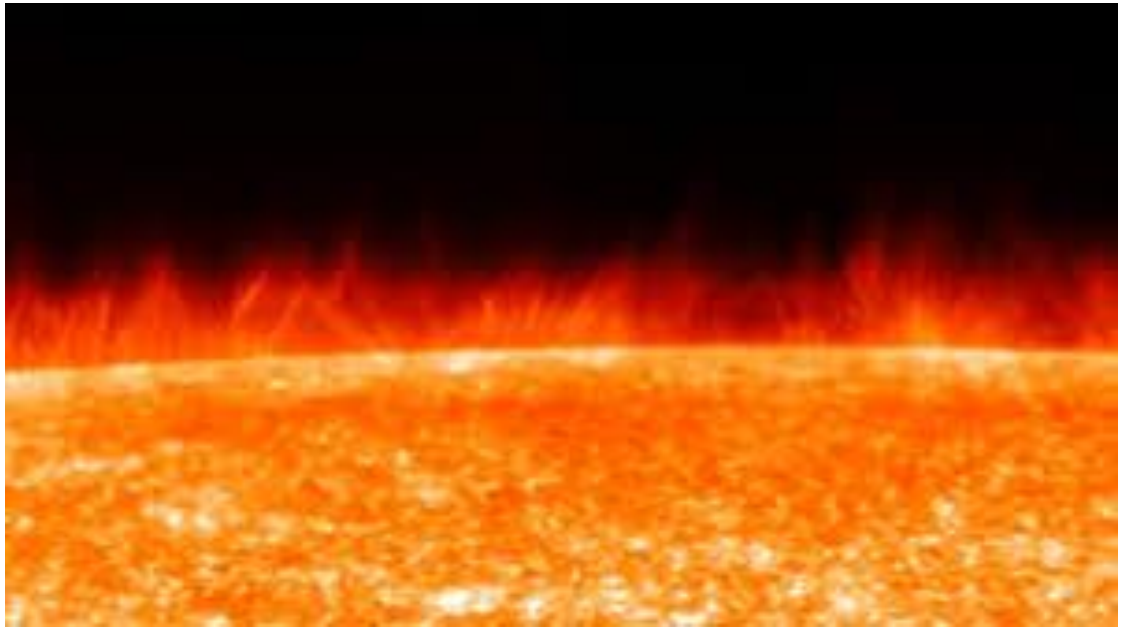
Active regions bi-poles are oriented almost E-W.

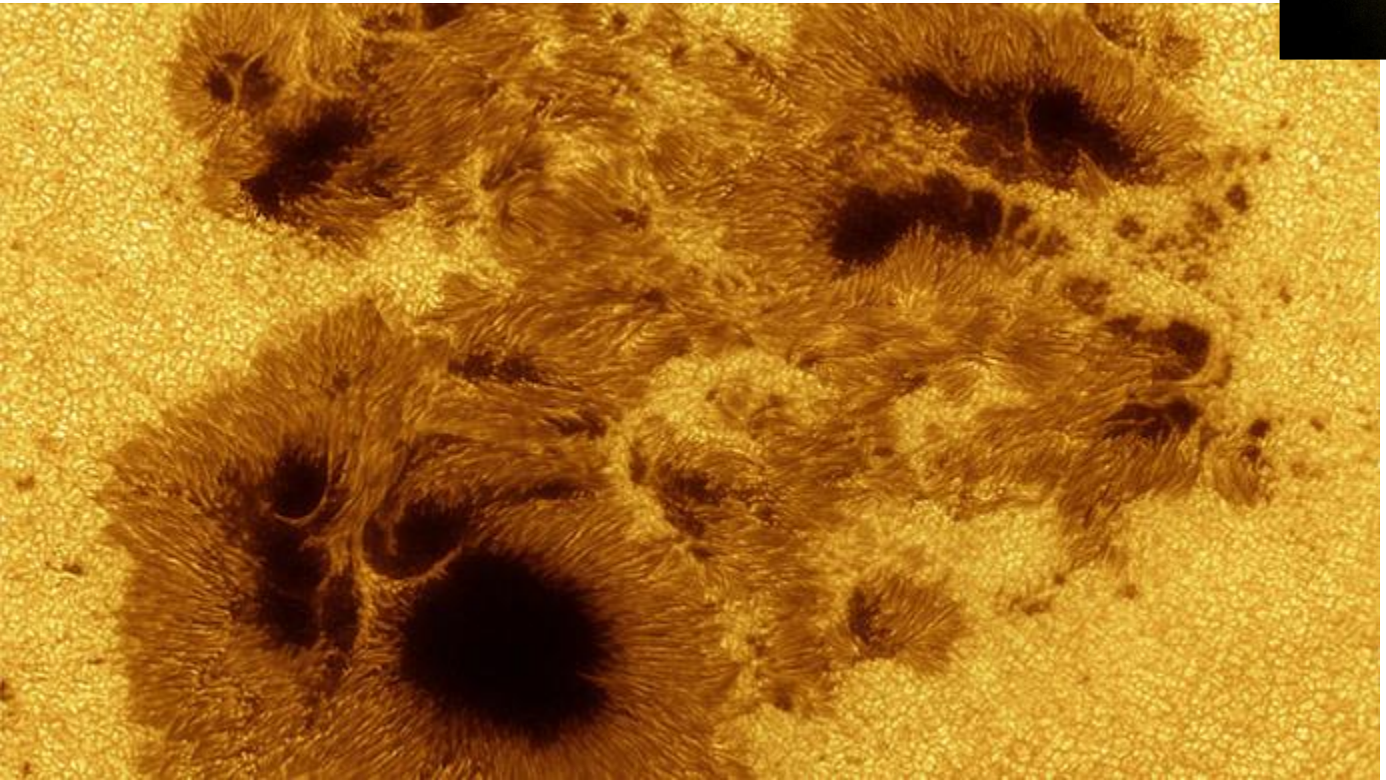
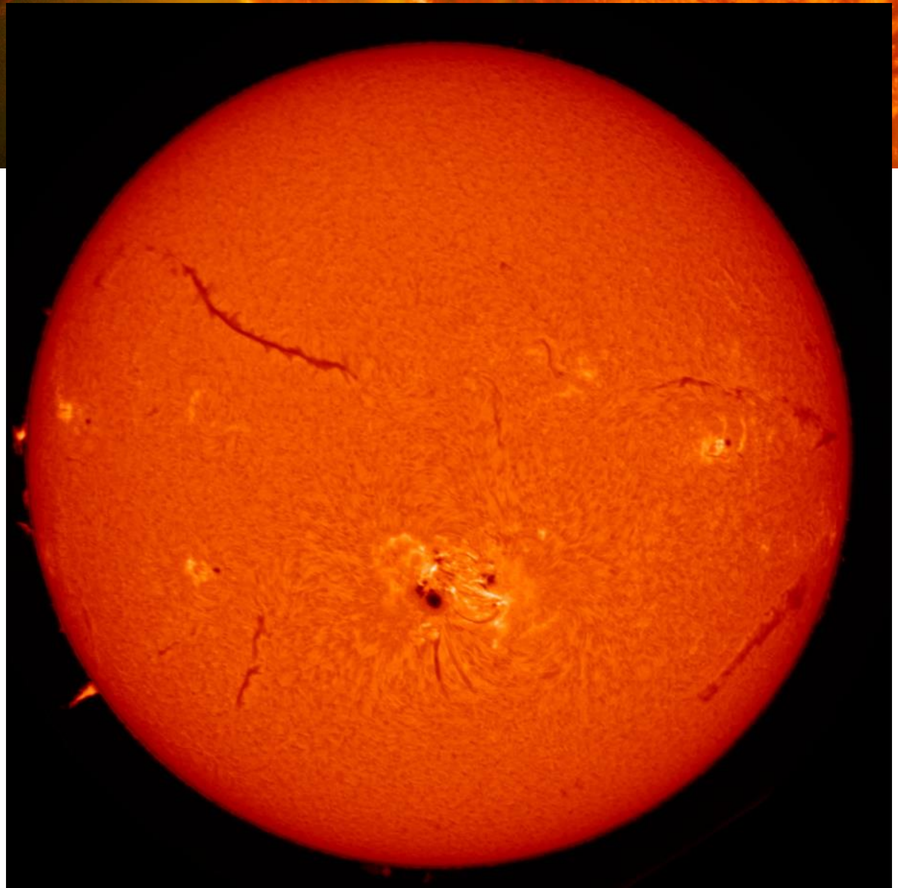
Typically the leading polarity of an AR is closer to the equator.

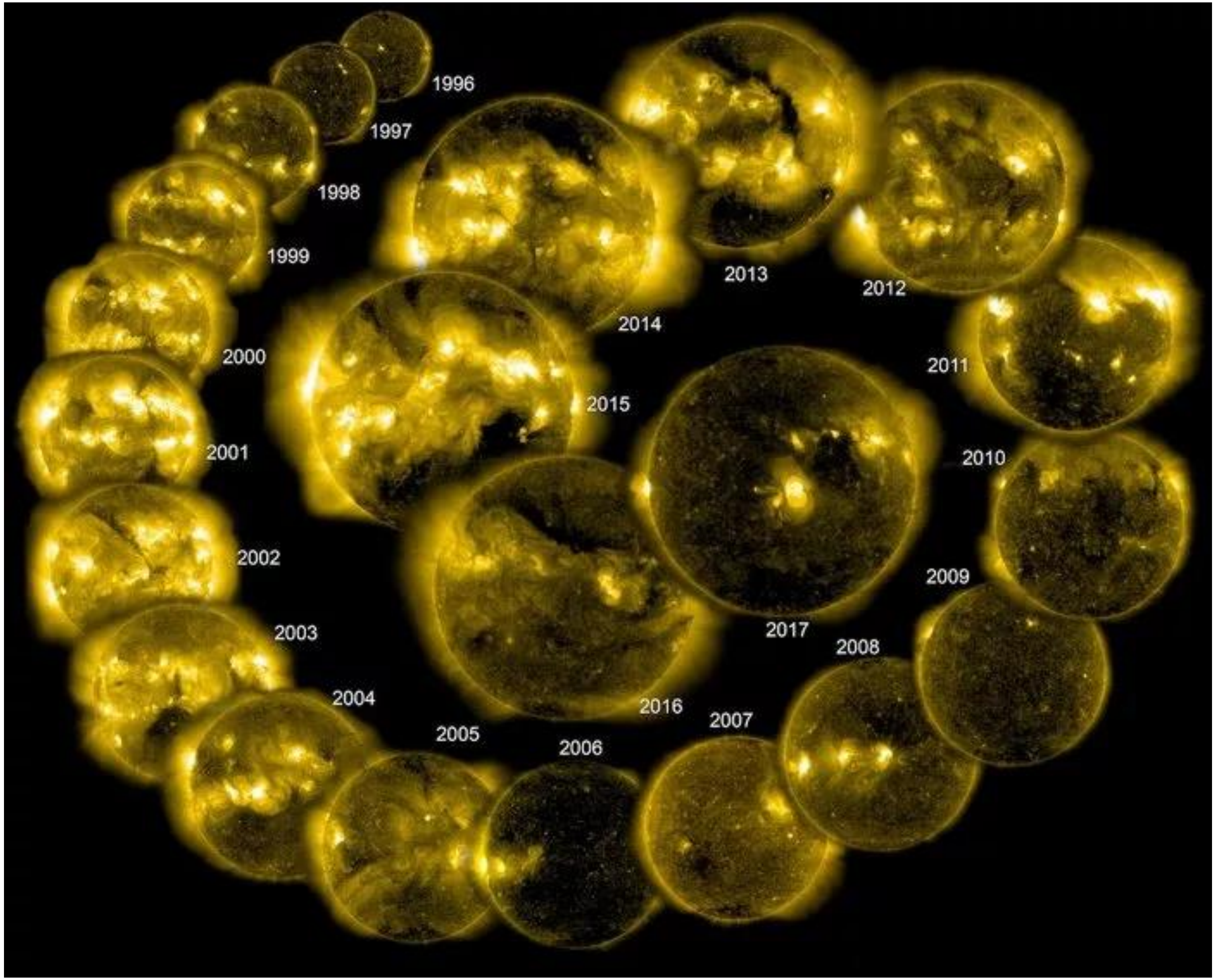
The mean tilt angle between the leading and trailing polarities increases linearly with the latitude.



© E. Forgács-Dajka
Axis
Poloidal
field lines
Differential
rotation
Toroidal
field lines
Ω-effect
Twisting of
the field lines
Magnetic
loops
Toroidal
field lines
α-effect
Poloidal
field lines



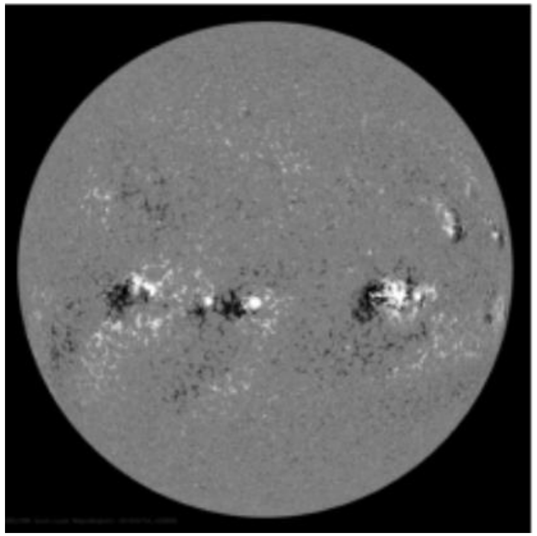




1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017

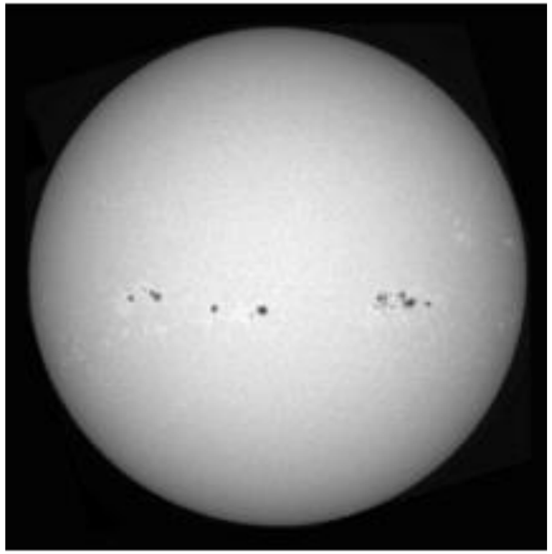
Solar Proxies (of the magnetic field)

Ermolli et al. 2014
https://ui.adsabs.harvard.edu/abs/2014SSRv..186..105E/abstract

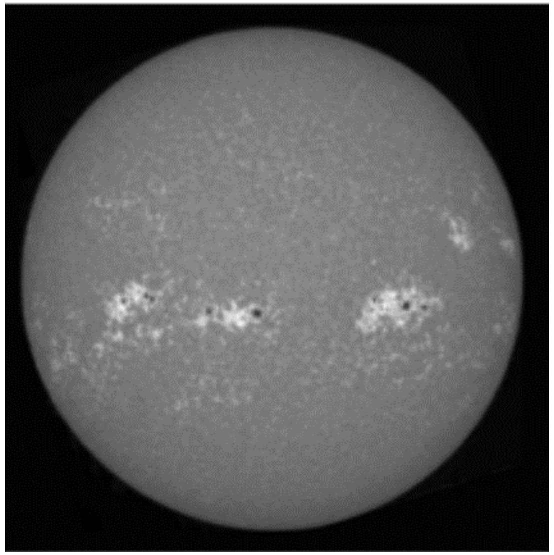
Magnetogram, Fe I 617 nm



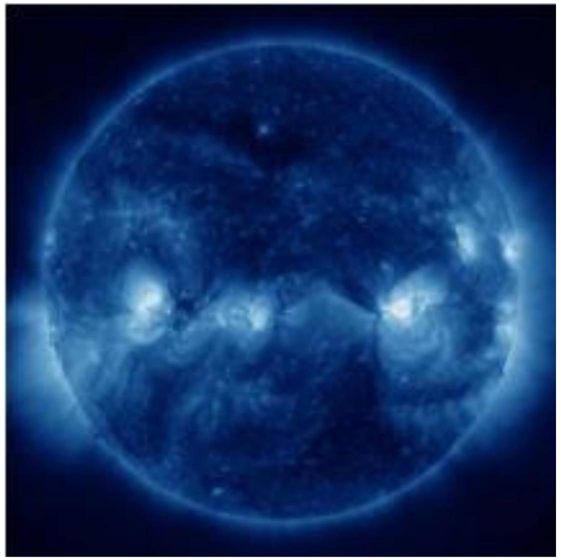
CH band, 434 m



Ca II K, 393 nm

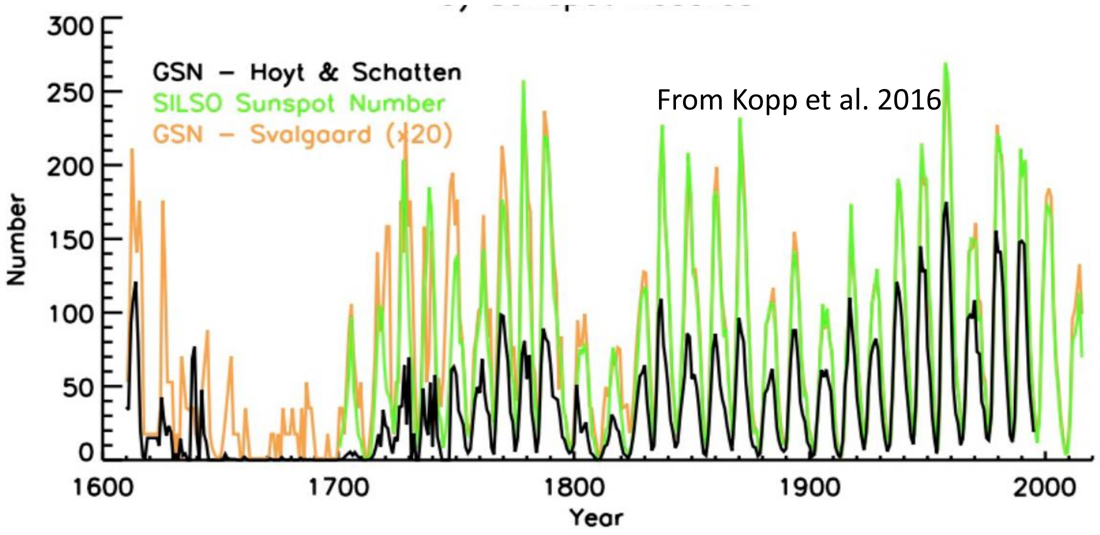


Fe XVI, 33 nm



Photospheric Indices

Sunspot Number (SN)/ Group Sunspot Number (GSN): weighted estimate of individual sunspots and sunspot number as derived from white light full-disk observations.



From Kopp et al. 2016

SILSO
https://www.sidc.be/silso/datafiles

Clette et al. 2014
https://ui.adsabs.harvard.edu/abs/2014SSRv..186...35C/abstract

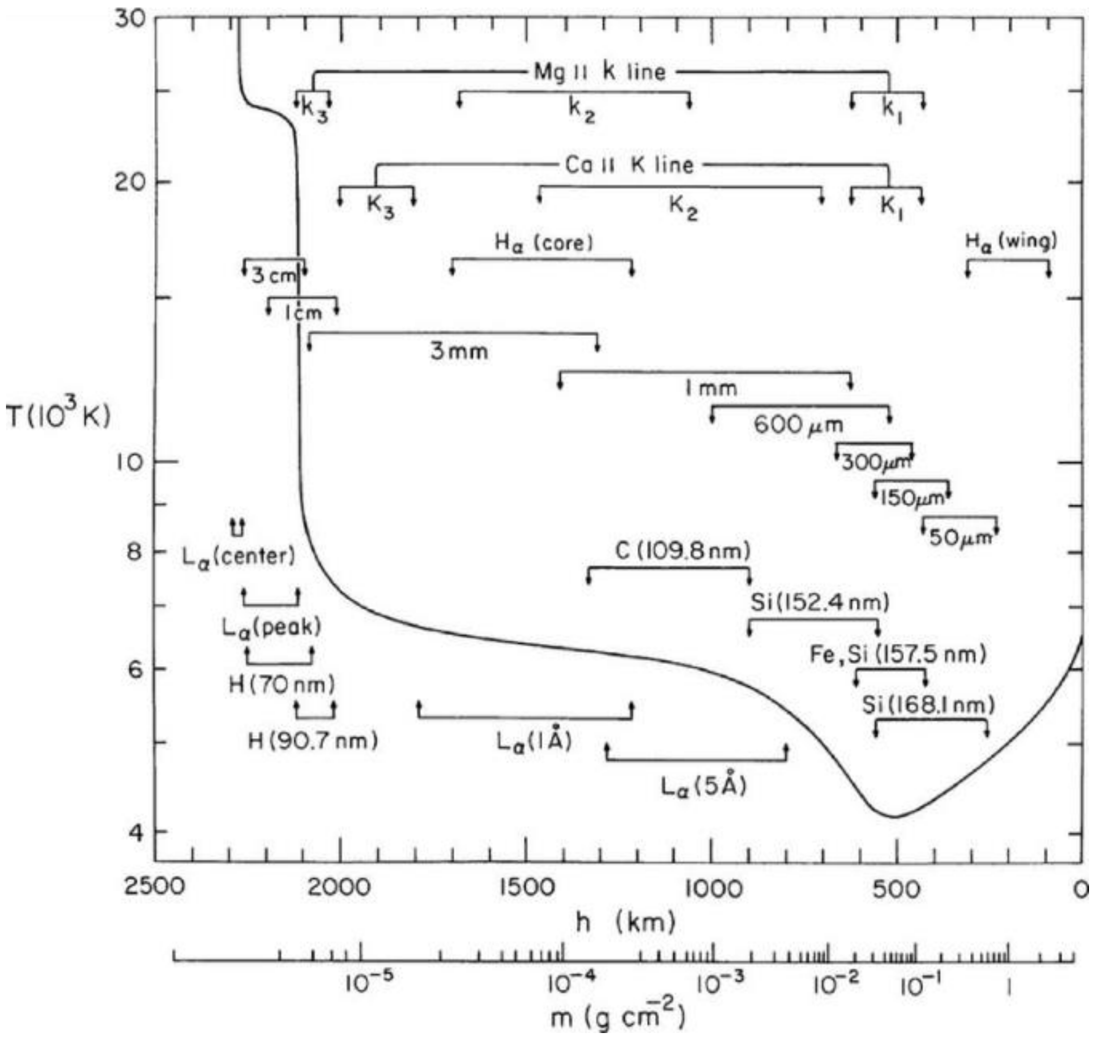
Sunspot Area: even more challenging than SN and GSN, but more meaningful.

Mandal et al. 2020
https://ui.adsabs.harvard.edu/abs/2020A%26A...640A..78M/abstract

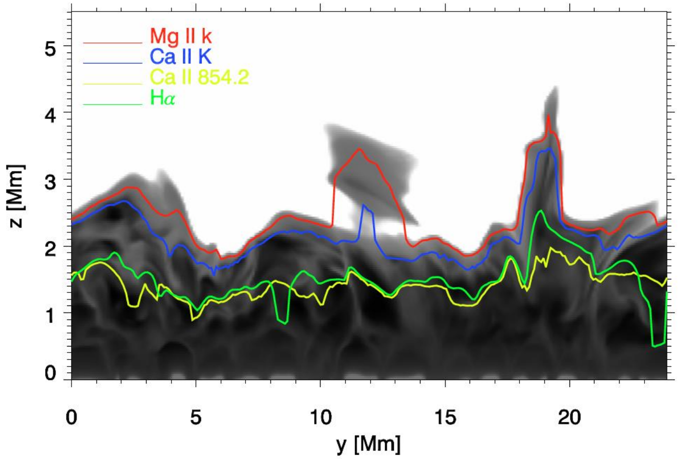
http://www2.mps.mpg.de/projects/sun-climate/data.html

Chromospheric Indices

(see also Linsky 2017, https://ui.adsabs.harvard.edu/abs/2017ARA%26A..55..159L/abstract)



From Leenarts et al. 2013

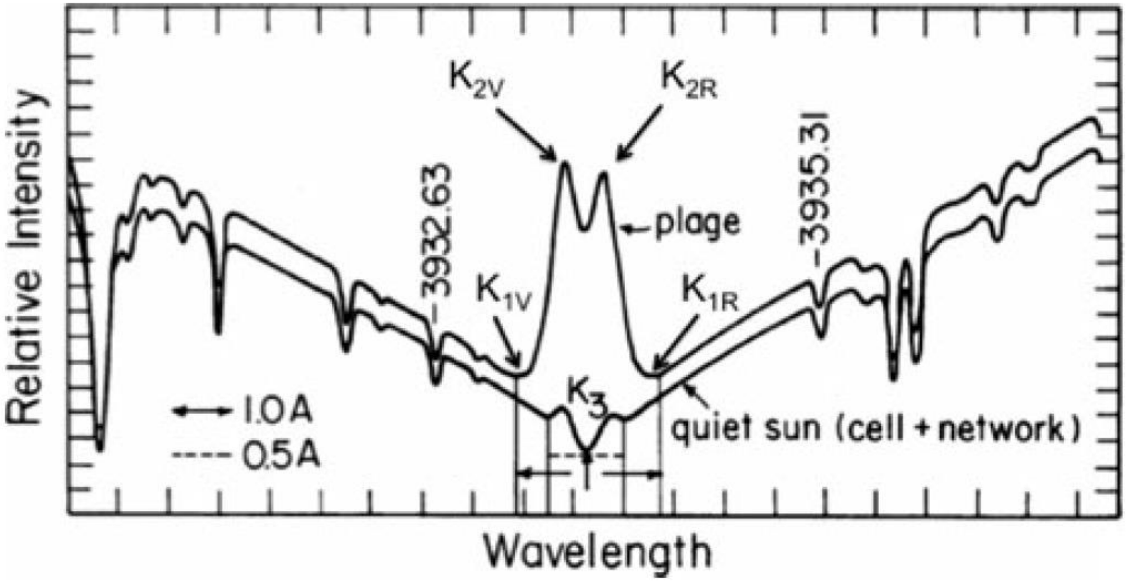


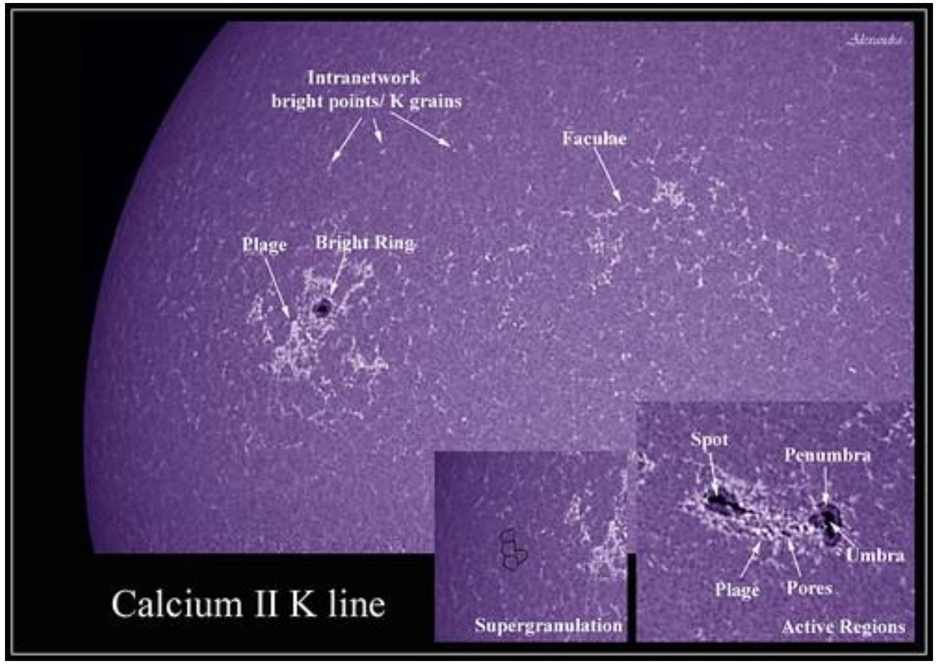
From Radiative Transfer Lectures by R. Rutten
https://ui.adsabs.harvard.edu/abs/2003rtsa.book.....R/abstract

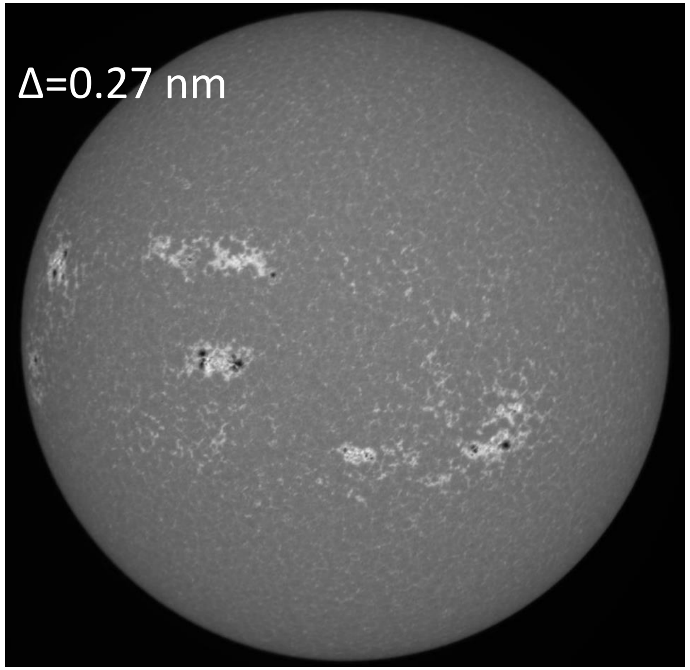
Ca II K 393.37 nm

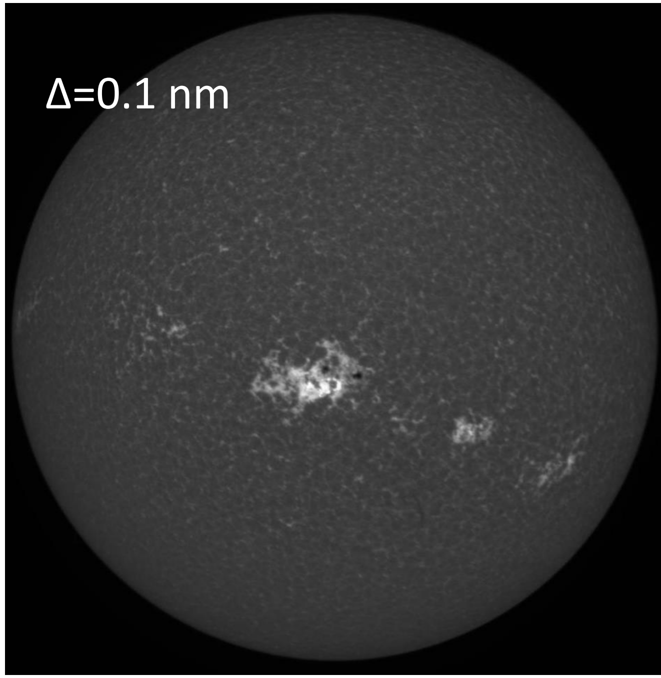
Observed from the ground!
Plethora of observations, dating back to 1904 (Kodaikanal)

Skumanich et al. 1984





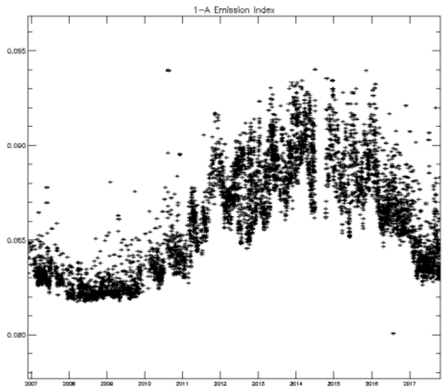




$$log \Delta F_{Ca\ II} = 0.6 log < B > +4.8,$$

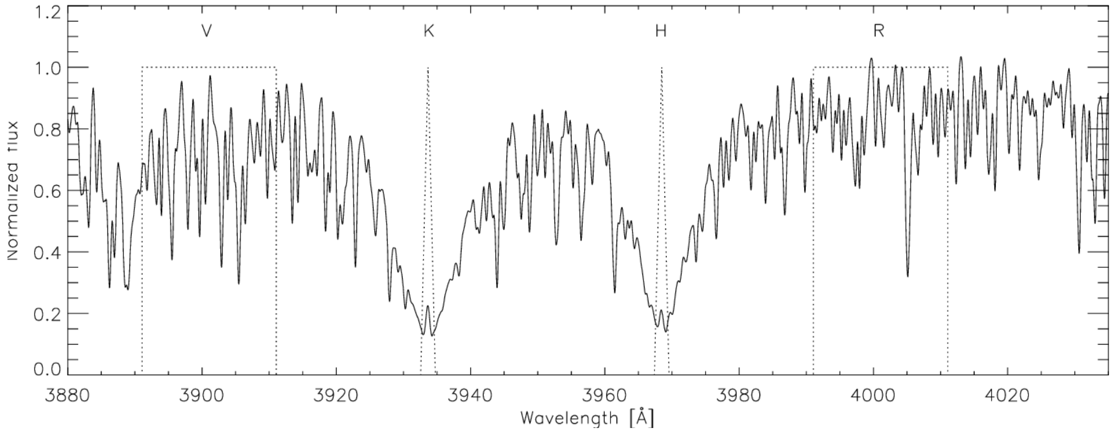
Schrijver et al. 1989

Ca II K 393.37 nm



Sun-as-a-star observations: 1Å, k1,k2,k3

ISS @ SOLIS
https://solis.nso.edu/0/iss/iss_timeseries.html

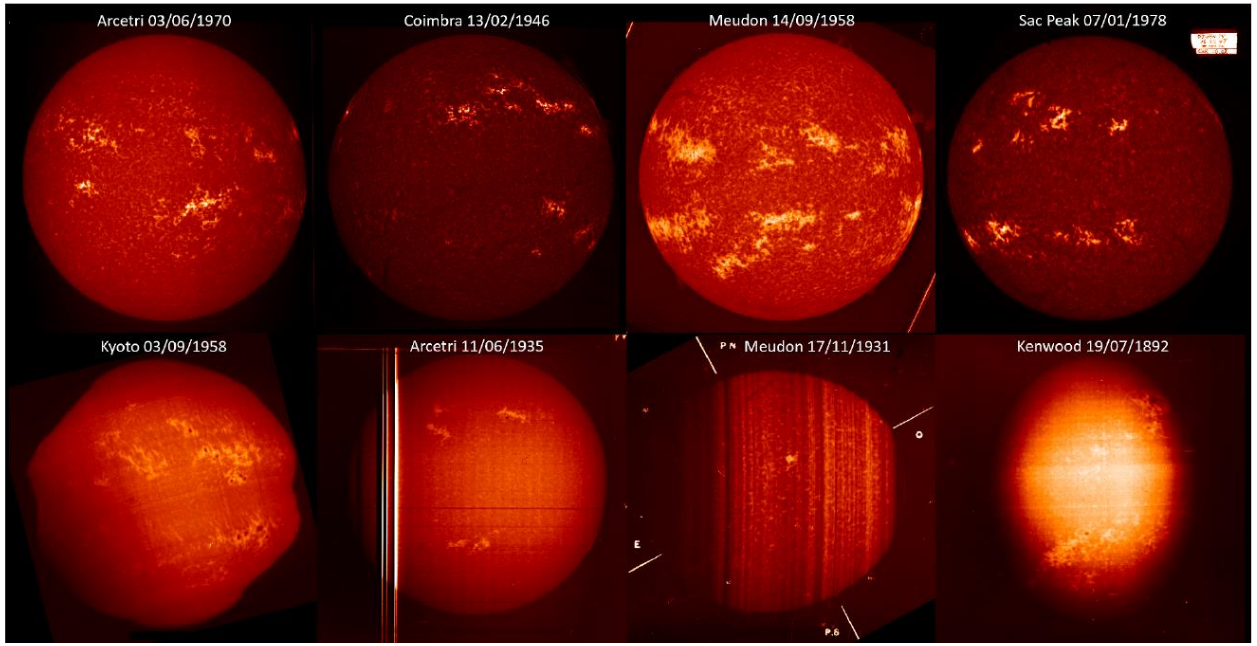


S-index: $$S = \alpha \frac{N_H + N_K}{N_R + N_V}$$

Full disk Observations: Plage index (area of plage).

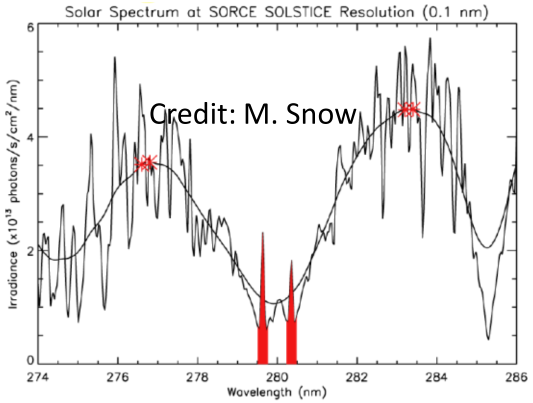
Chatzistergos et al. 2018-2022

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



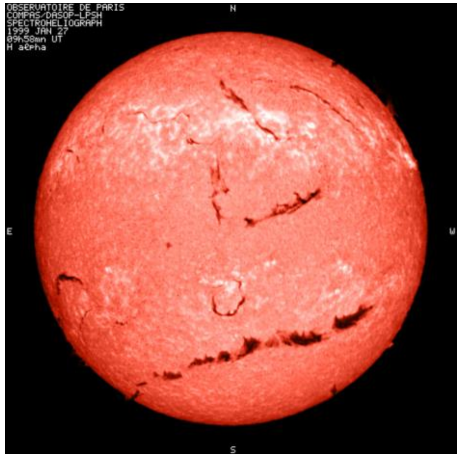
Other Chromospheric/Transition Region/Corona Indices

Mg II-Index: Core-to-wings ratio
Sun-as-a-star
Bremen Index
https://www.iup.uni-bremen.de/UVSAT/Datasets/mgii

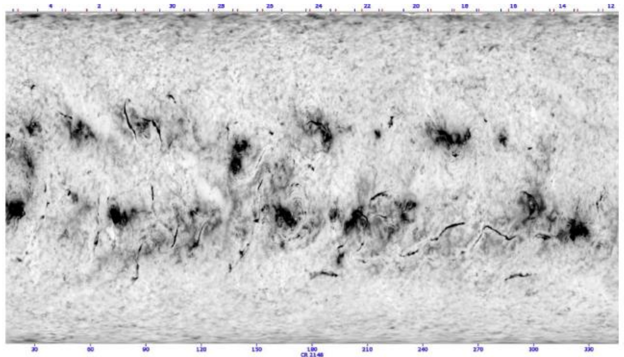


Ha full-disk observations: Prominences, Filaments
Full-disk observations

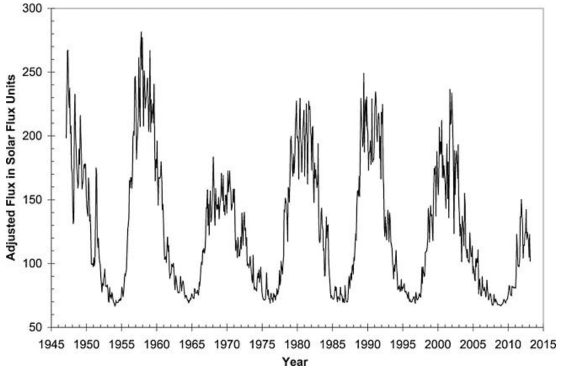
https://bass2000.obspm.fr/home.php



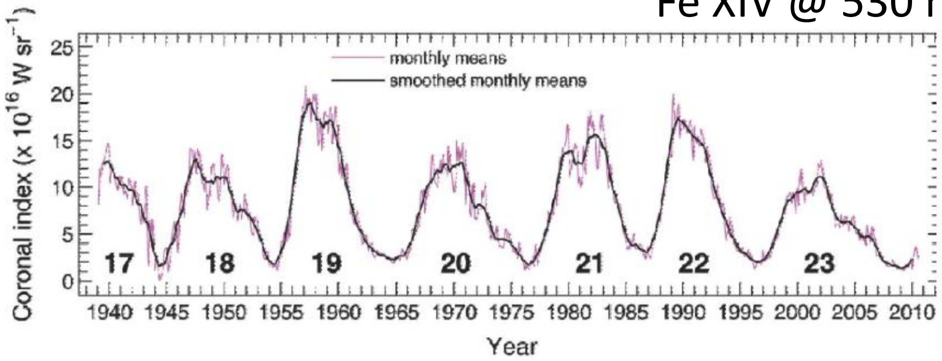
He I 1083 nm



F10.7

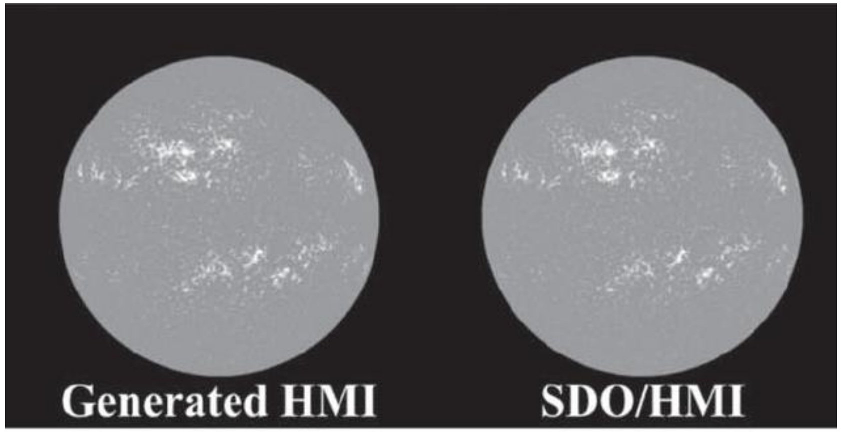


Fe XIV @ 530 nm



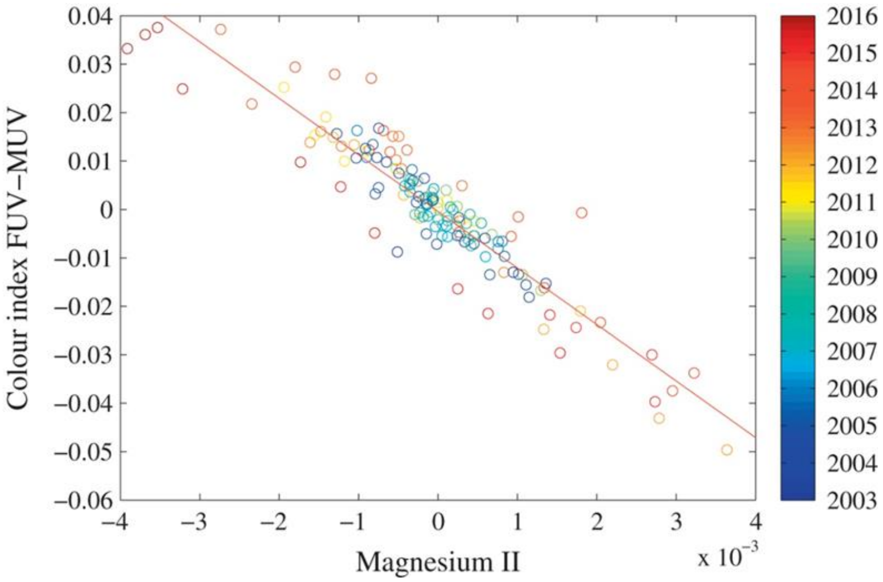
Proxies Applications

Shin et al. 2020



Synthetic (pseudo) magnetograms

Lovric et al. 2017



Estimate other proxies or other properties in lack of measurements

Important in the UV!

Indirect Proxies

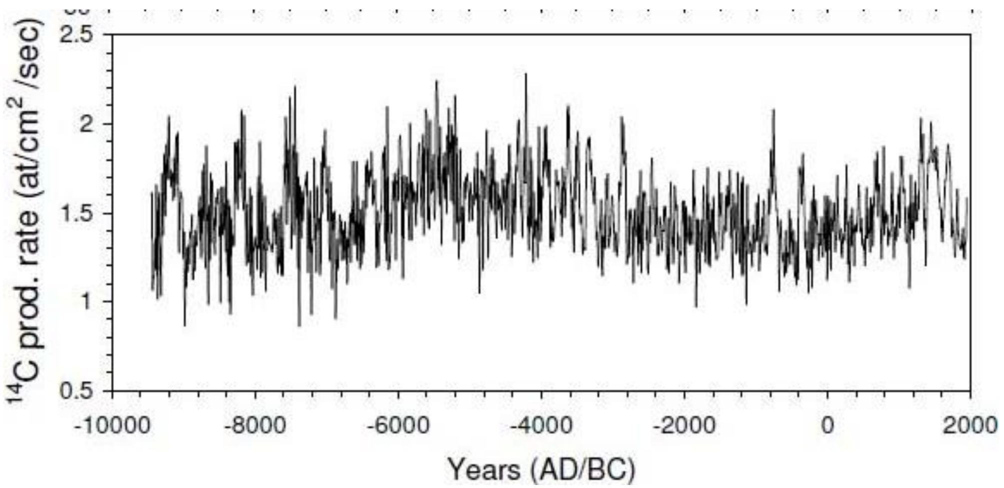
Usoskin 2017
https://ui.adsabs.harvard.edu/abs/2017LRSP...14....3U/abstract

Geomagnetic indices: quantify effects of geomagnetic activity (e.g. Aurorae)

Cosmogenic isotopes, produce by the interaction of galactic cosmic rays (GCRs) with atmospheric molecules.
Modulated by the solar magnetic field, depend on solar activity, Earth climate and magnetic field.

^{14}C (tree rings); ^{10}Be (ice cores)

Usoskin 2013



Steinhilber et al. 2012

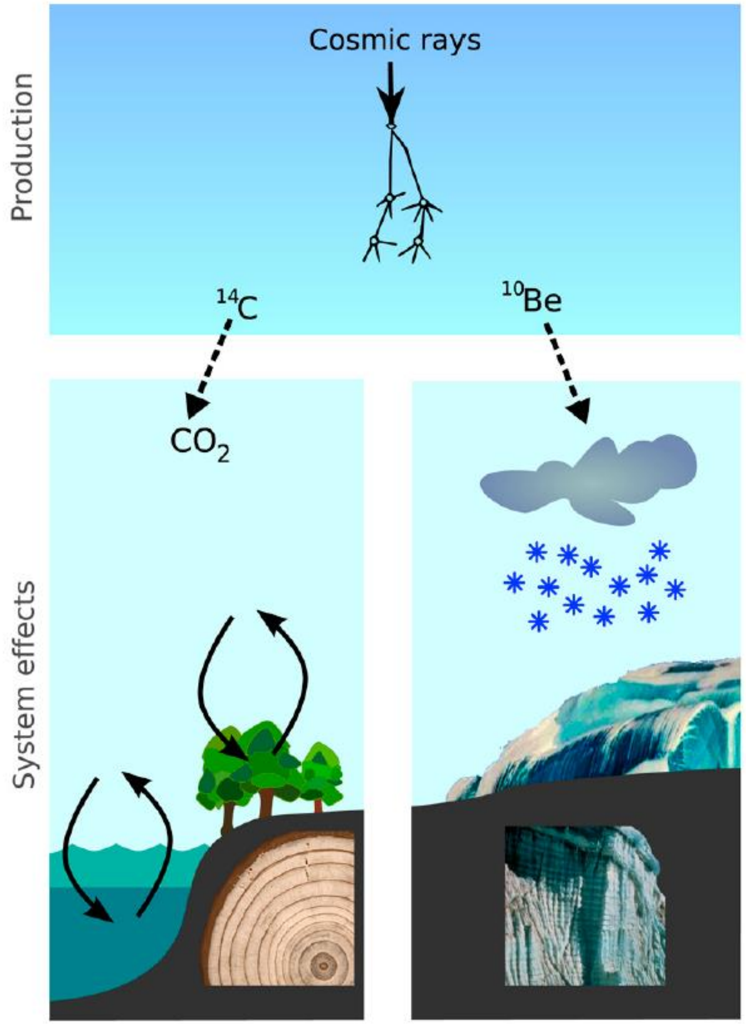
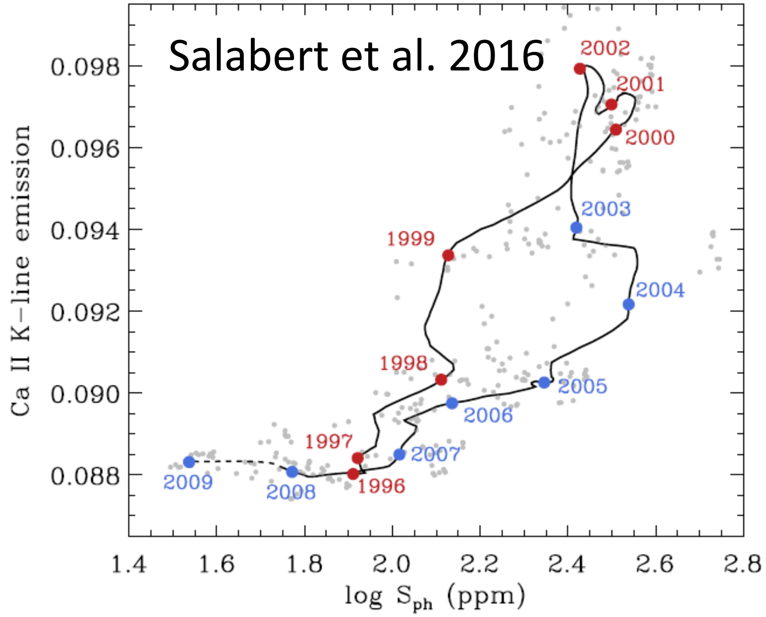


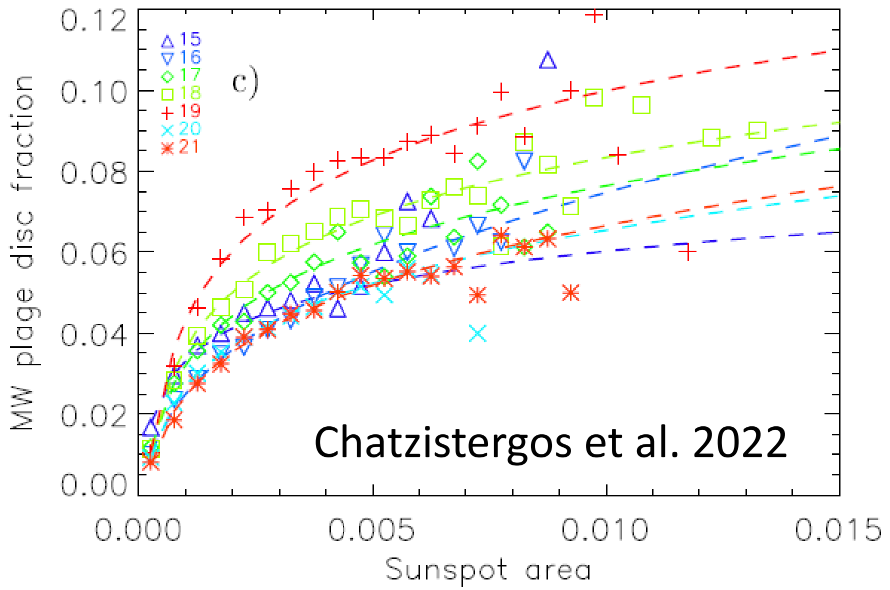
Fig. 1. Cartoon illustrating some basics of the radionuclides ^{14}C and ^{10}Be in the Earth's system. Both radionuclides are produced in a very similar way by nuclear reactions of cosmic ray particles with the atmospheric gases (3). After production, their fate is very different (system effects). ^{10}Be attaches to aerosols and is transported within a few years to ground (34). ^{14}C oxidizes to CO_2 and enters the global carbon cycle, exchanging between atmosphere, biosphere, and the oceans (4).

Solar Indices: complex trends

Indices are often used to estimate magnetic field and other properties. However:

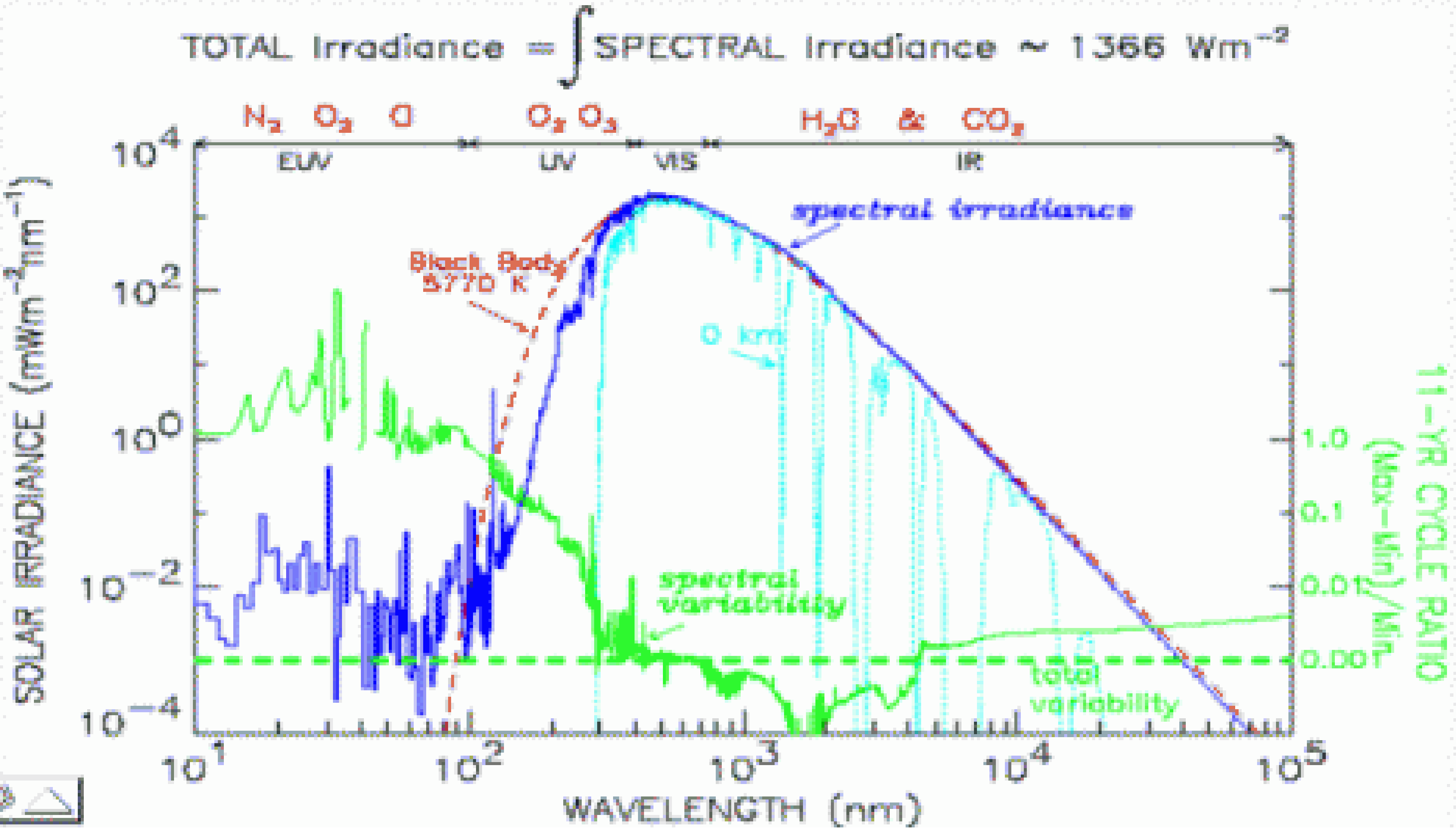
- ❖ Trends may change during the activity cycle
- ❖ Trends may change from cycle to cycle
- ❖ Non-linearity (saturation)
- ❖ Correlation coefficients may depend on the numerical techniques used to extract them
- ❖ Prone to Instrumental effects



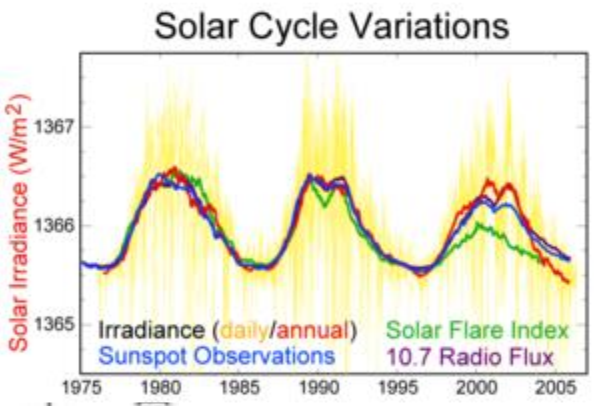


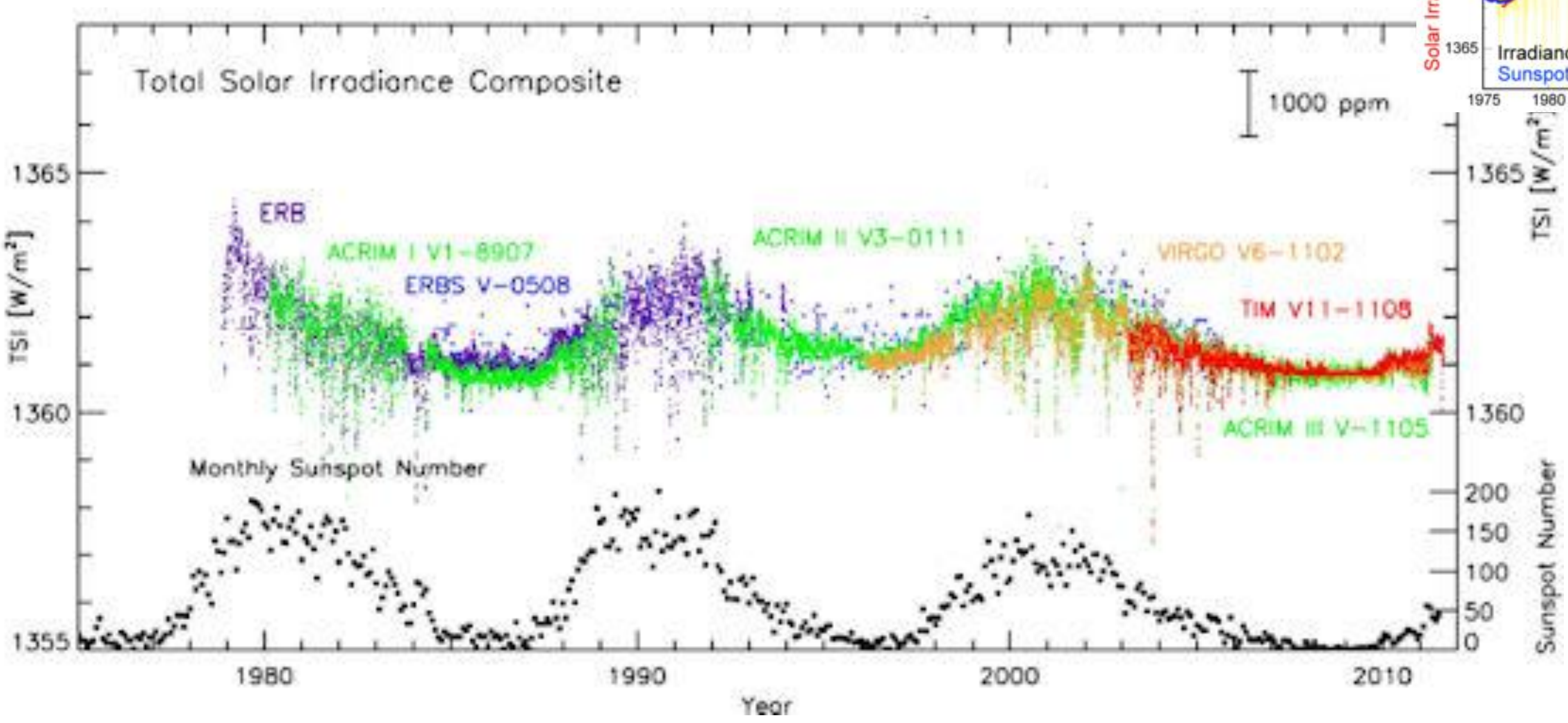
Solar Irradiance

SOLAR SPECTRUM, VARIABILITY and ATMOSPHERIC ABSORPTION

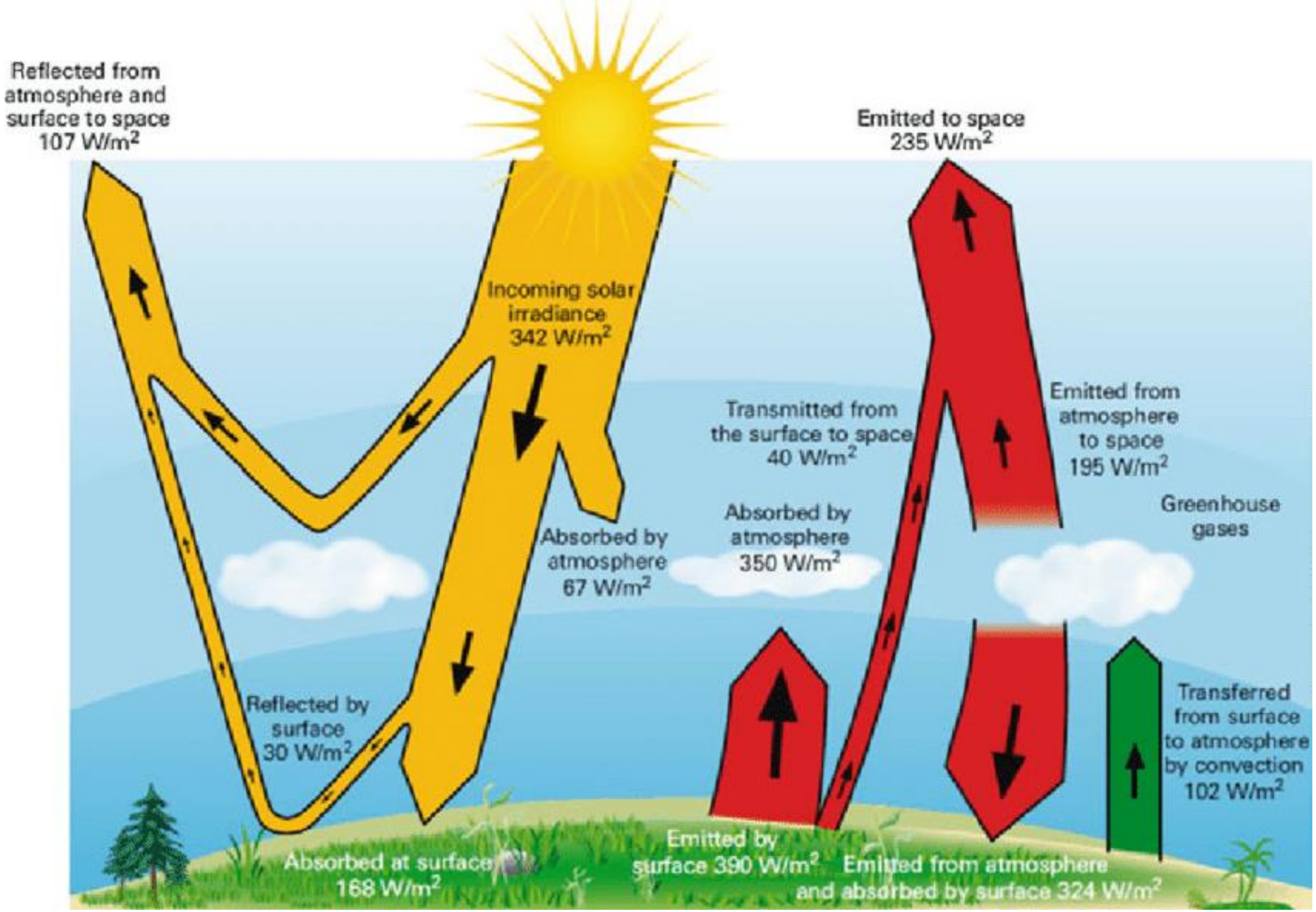


Total Solar Irradiance





Total Solar Irradiance also varies with the solar cycle, typically one part in a thousand (e.g. Hickey et a. 1980)

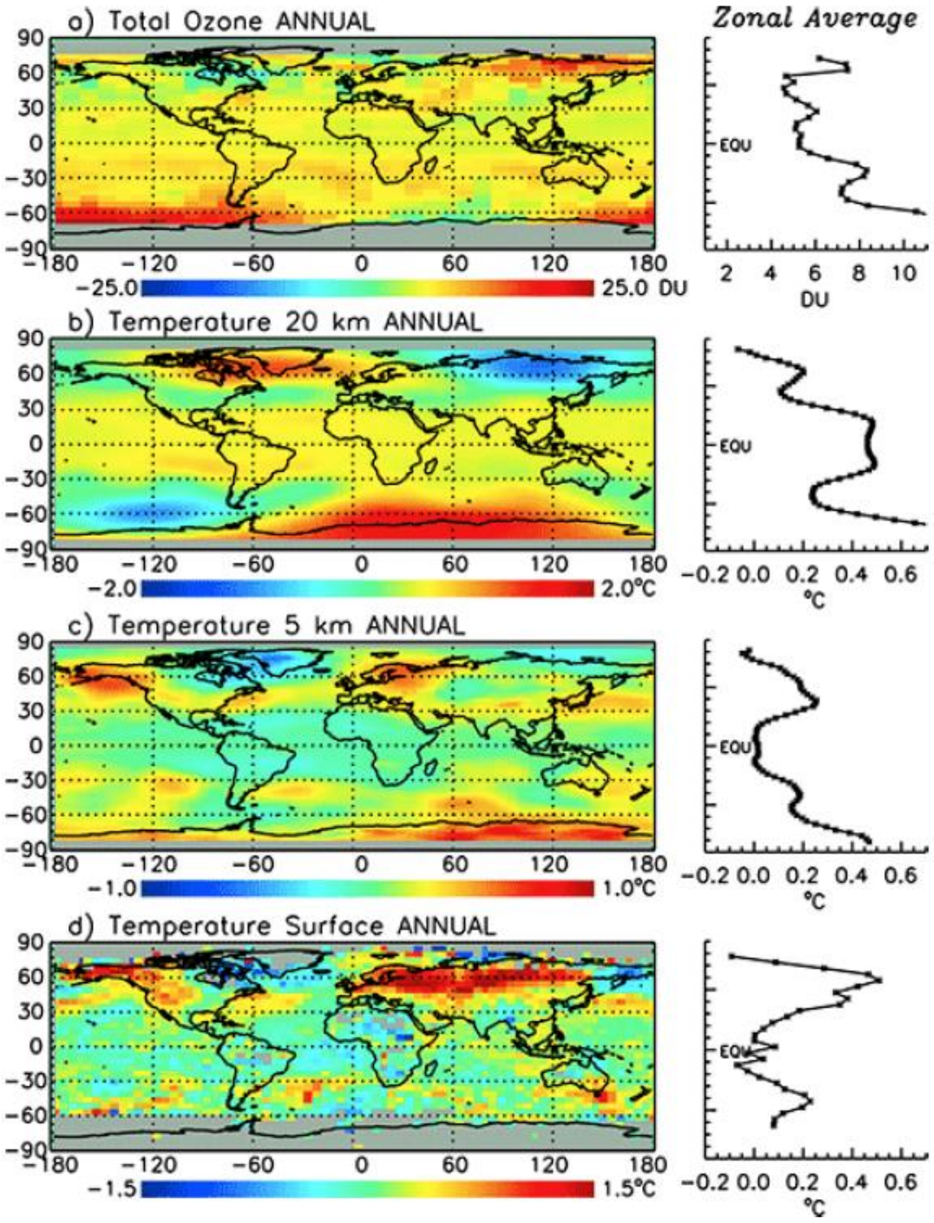


Reflected from atmosphere and surface to space 107 W/m²
Incoming solar irradiance 342 W/m²
Emitted to space 235 W/m²
Transmitted from the surface to space 40 W/m²
Emitted from atmosphere to space 195 W/m²
Absorbed by atmosphere 67 W/m²
Absorbed by atmosphere 350 W/m²
Greenhouse gases
Reflected by surface 30 W/m²
Transferred from surface to atmosphere by convection 102 W/m²
Absorbed at surface 168 W/m²
Emitted by surface 390 W/m²
Emitted from atmosphere and absorbed by surface 324 W/m²

Lean 2017

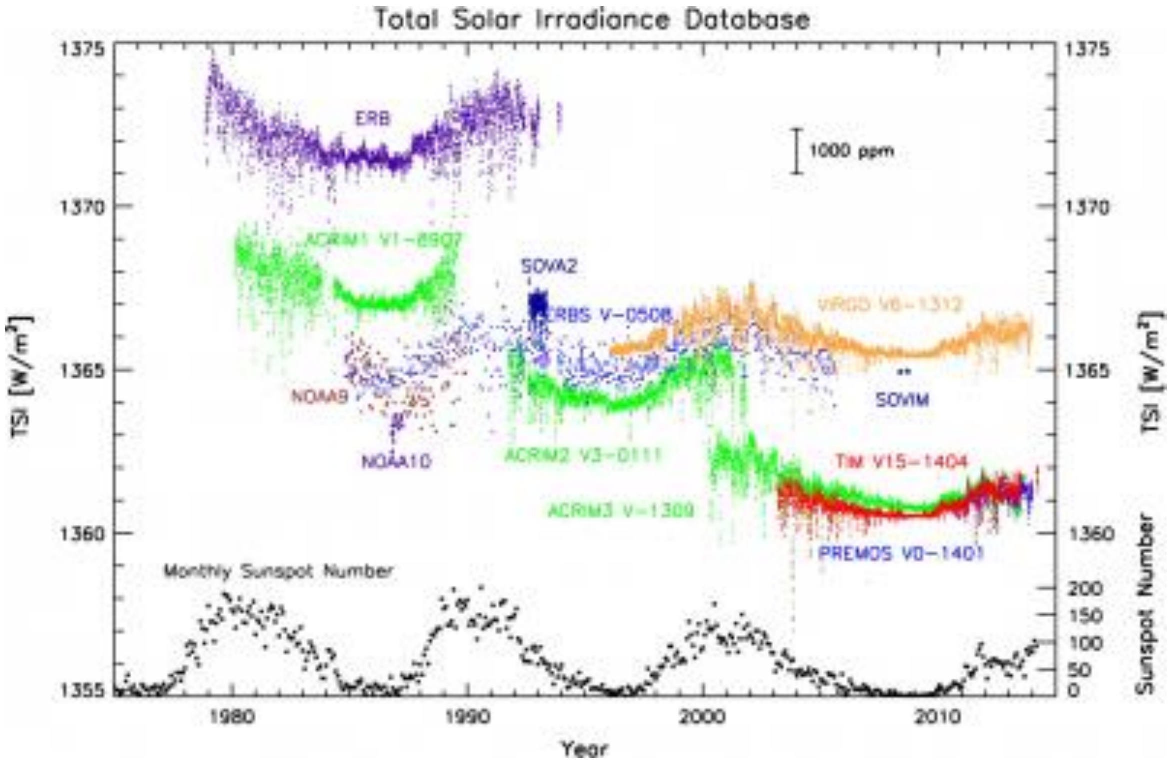
Top-down: UV radiation is absorbed in the higher layers of the atmosphere, affecting ozone abundance, causing heating and affecting atmospheric dynamics and circulation patterns (e.g. Matthes et al. 2017)

Bottom-up: longer wavelengths reach the Earth surface and are absorbed by Oceans, thus affecting global circulation and precipitation patterns (Gray et al. 2010)



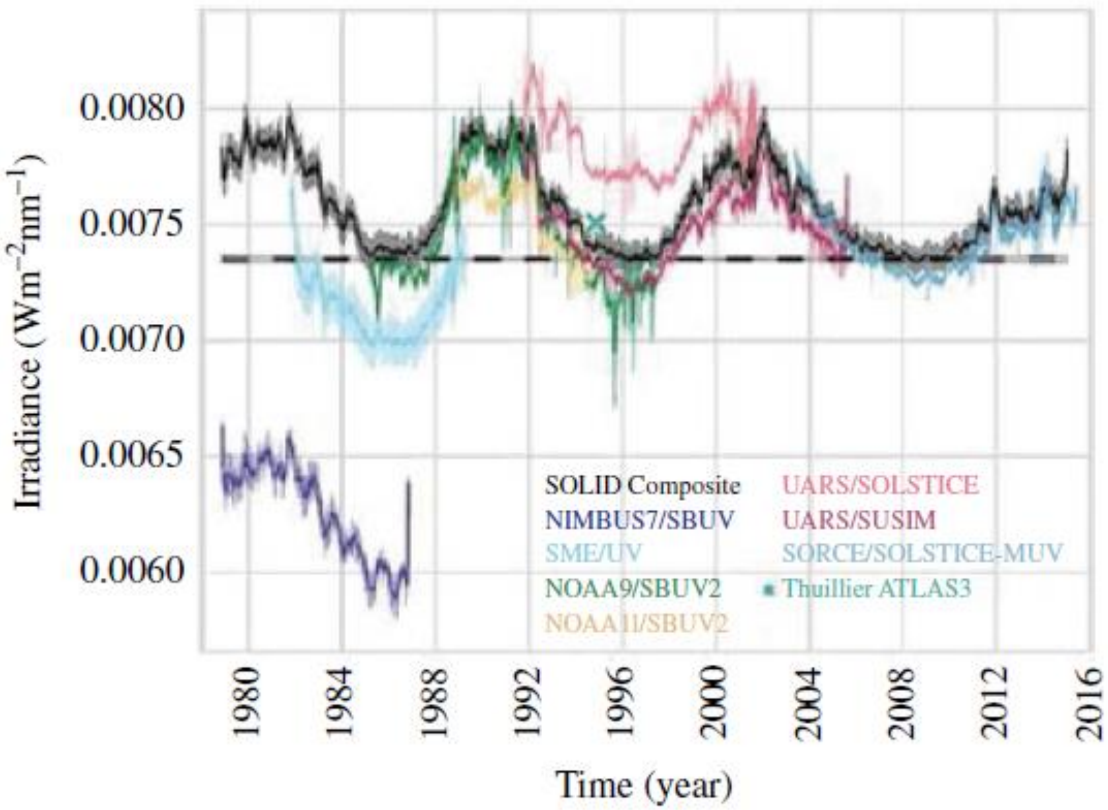
Solar min-to-max variations

Measurements of Solar Irradiance



TSI variations are ~0.1% over the cycle

Irradiance @ 200nm



Date back to the seventies. **We need models!**

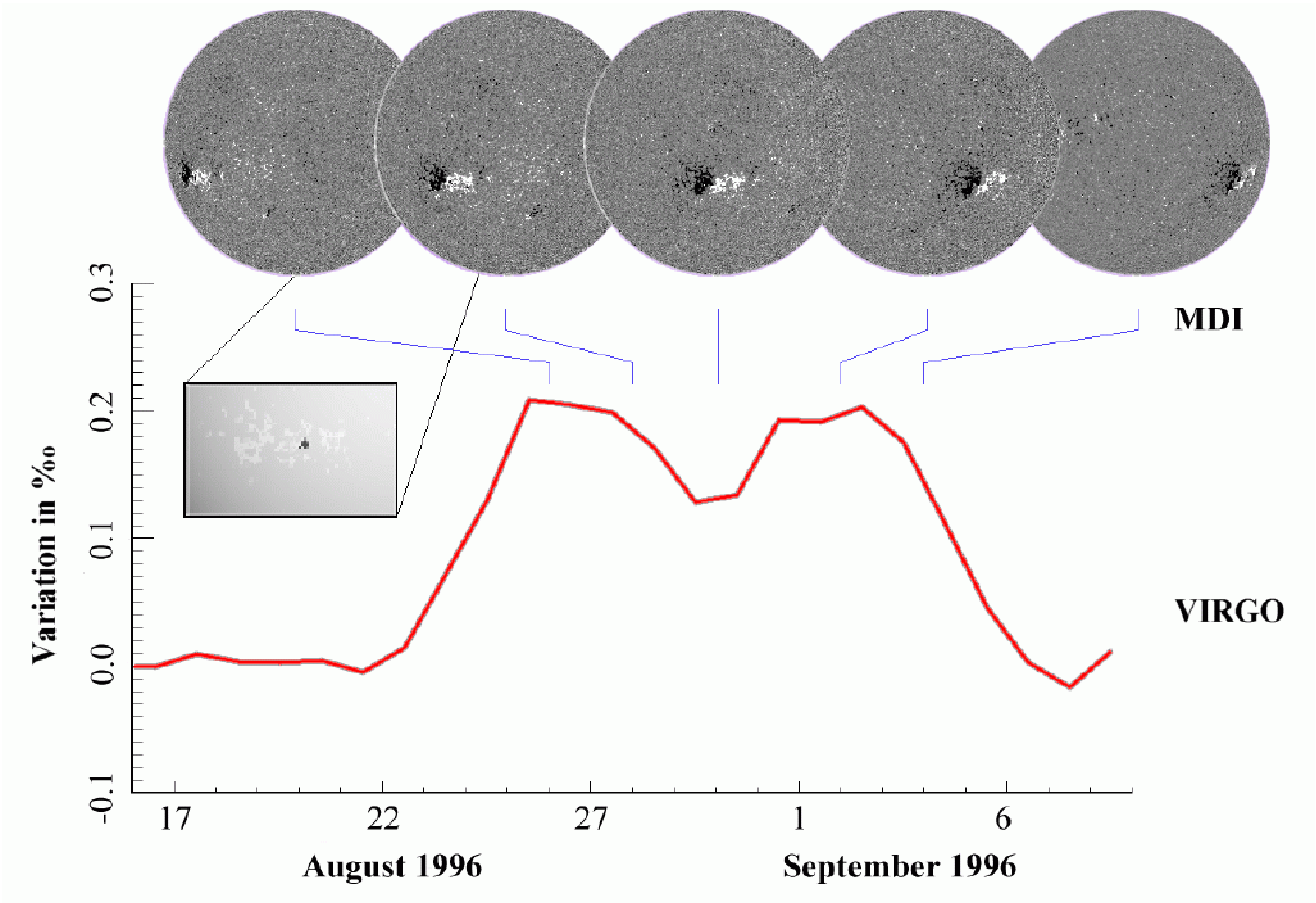
Importance of Modeling Stellar Variability

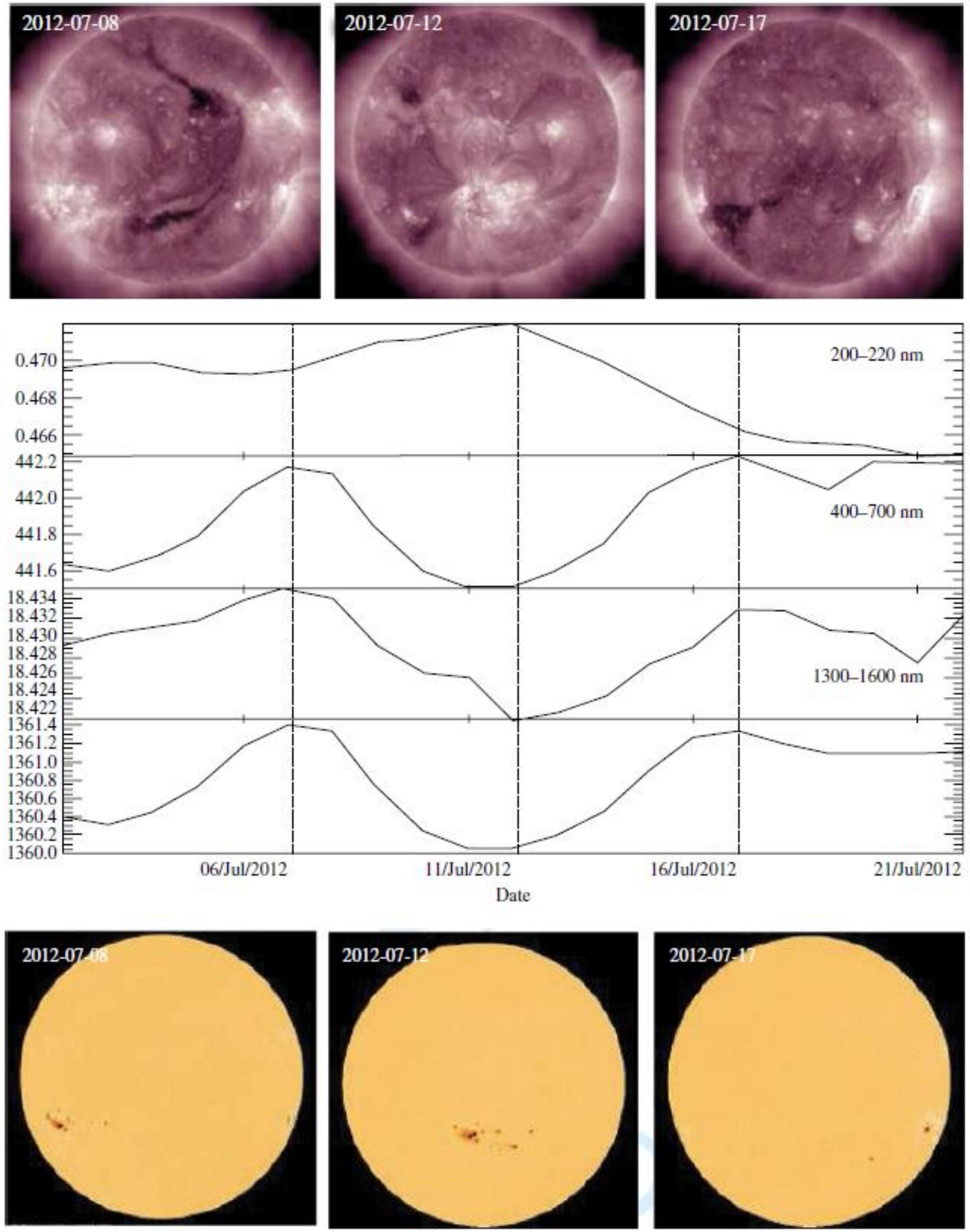
1) Stellar radiation affects exo-planet atmospheres and determine their habitability (e.g. EUV radiation determines the stability of exoplanet atmospheres)
2) Affect the detectability of exoplanets introducing "noise".
3) Affect our capability of determining the atmospheres of exoplanets and presence of life.
(e.g. O_2, O_3, CH_4, CO_2: good bio-markers, but abundances are regulated by Lyα, FUV/NUV ratio. Affect transmission spectroscopy measurements!!!)

"[u]nderstanding of exoplanets is limited by measurements of the properties of the parent stars, including [their]...emergent spectrum and variability"

National Academies of Science, Engineering, and Medicine in its Exoplanet Science Strategy Consensus Study Report, 2018

There is a general consensus on the fact that irradiance variability is (predominantly) caused by changes of surface magnetism (at least on solar cycle scales).

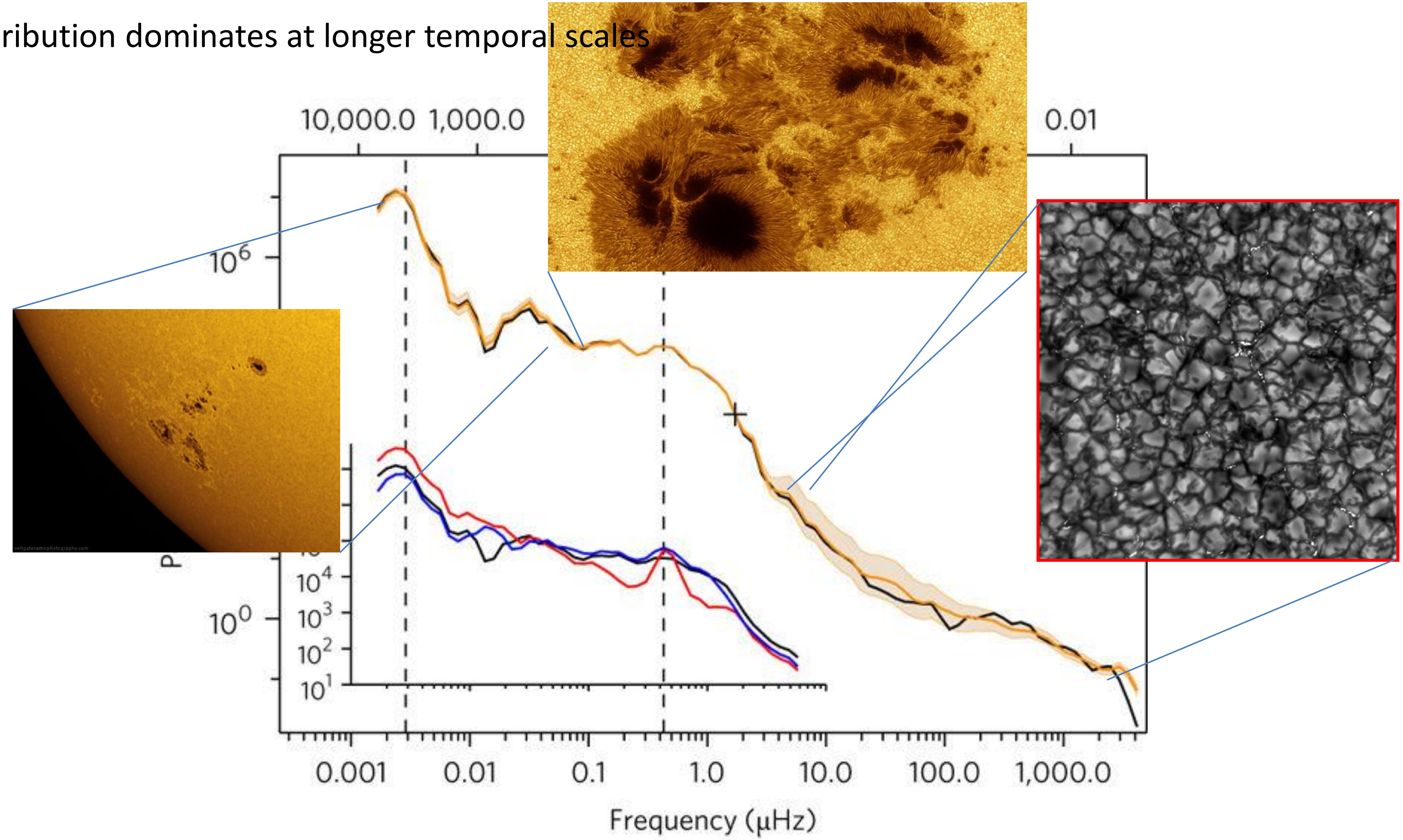




AIA @ 211 nm

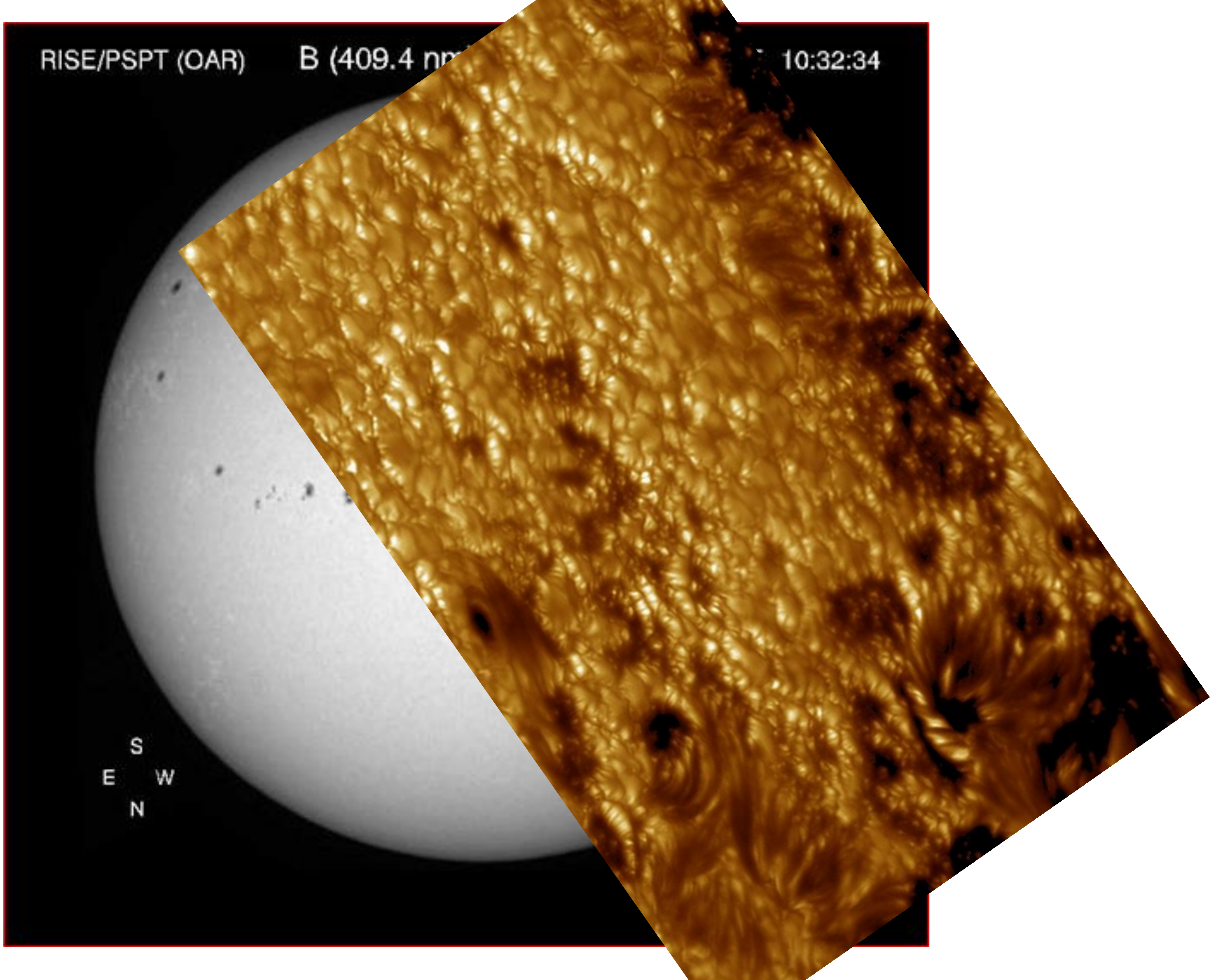
HMI, photosphere

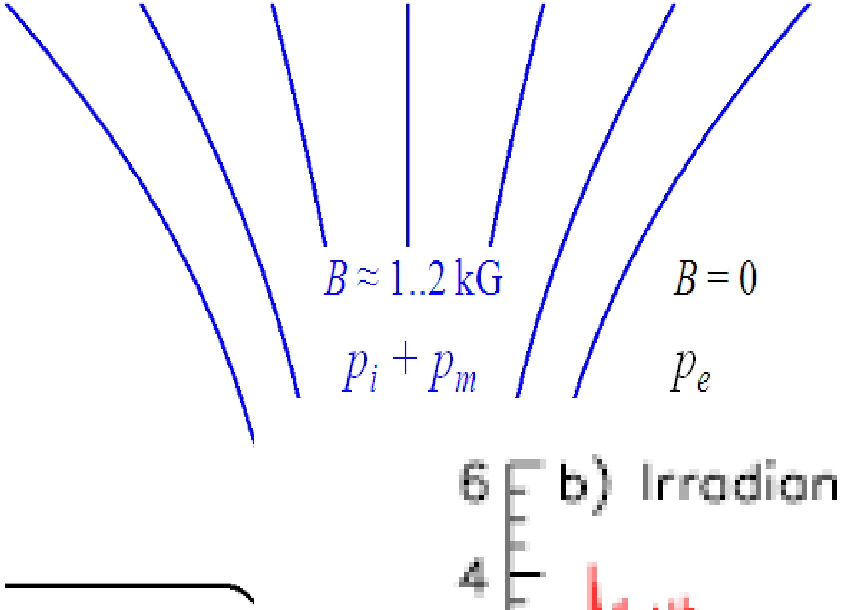
Facular contribution dominates at longer temporal scales



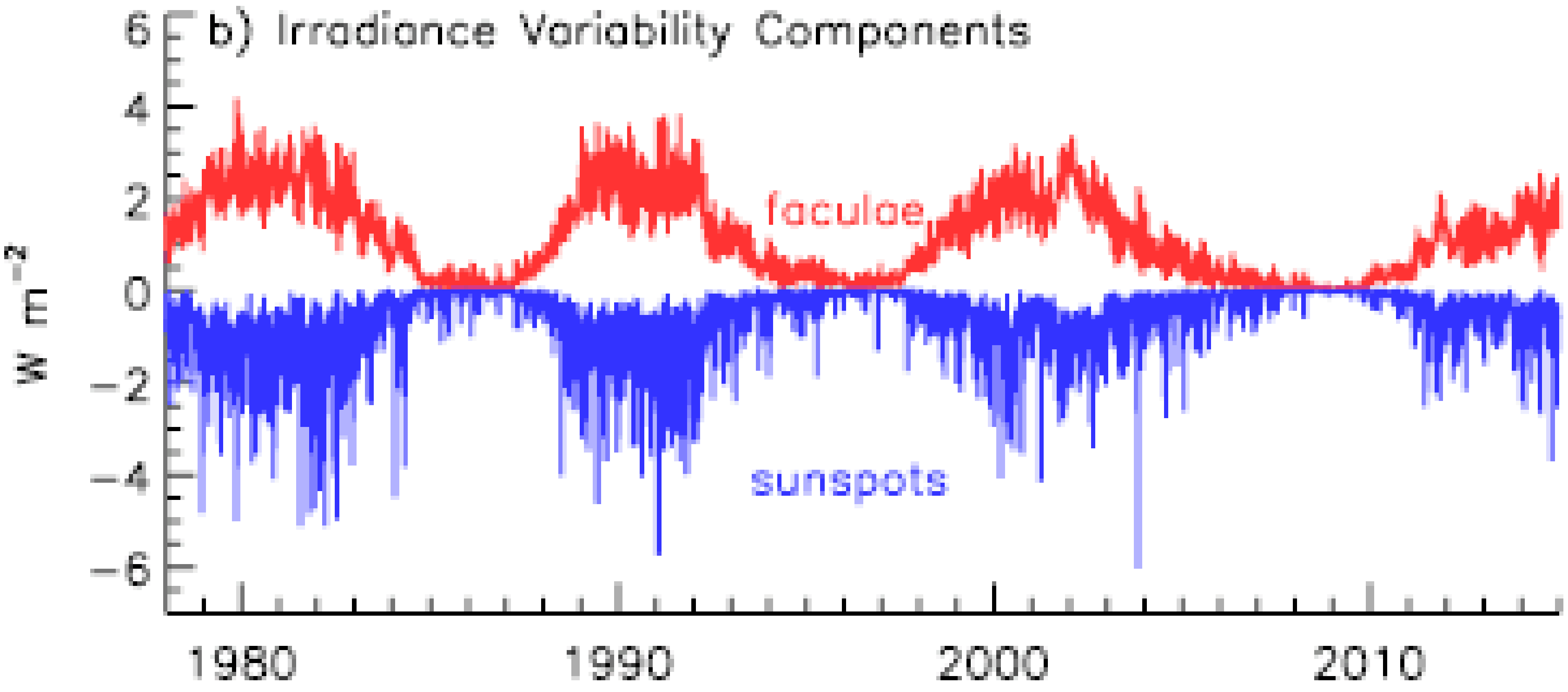
TSI power spectrum from minutes to 19 years

Shapiro et al. 2017


RISE/PSPT (OAR)
10:32:34
S
E
W
N



- The ratio between the size and the horizontal optical depth determine whether a structure is bright or dark.
- Brightness also depends on wavelengths



Three types of modeling:

- Proxies only : sunspot number and area, plage area, CaIIK, Mg II core-to-wing, radio flux at 10.7 cm. The irradiance is fitted via a set of proxies through multiple regression.
- Proxies and modelling: the area coverage of magnetic features is derived from observations and their brightness is prescribed by (semi-empirical) atmosphere models
- Forward modelling: employ results from numerical simulations instead of proxies, radiative flux is derived from models based on observations. (MOCASSIM)

Details depend on the spectral and temporal ranges that the technique aims to reproduce.
None of them is universal!

PROXY MODELS

SAN FERNANDO (e.g. Chapman et al. 1996, 2012, 2013)
Morrill et al. 2011
SCIA (Pagaran et al. 2011)
MGNM (Thuiller et al. 2012)
Tapping et al., 2007, 2013
Woods et al. 2000
Woods et al. 2015
MOCASSIM (Bolduc et al. 2012)
NRL-TSI/SSI -1/2 (e.g. Lean 2000, Coddington 2016)
EMPIRE (Yeo, Krivova, Solanki 2017)

Naval Research Laboratory
Total Solar Irradiance
Spectral Solar Irradiance
v.2

(Lean et al. 1997; Lean 2000; Coddington et al. 2016)

TSI $T(t) = T_Q + \Delta T_F(t) + \Delta T_S(t)$

SSI $I(\lambda,t) = I_Q(\lambda) + \Delta I_F(\lambda,t) + \Delta I_S(\lambda,t)$

Q= baseline/reference value determined from measurements

T_Q from TIM measurements
$I_Q(\lambda)$ from SORCE (<300 nm) /SOLSPEC (300-1000nm)/SIM measurements (1-2.µm)/Kurucz model (>2. µm)

<u>INPUTS</u>:

- MgII index Bremen composite
- RGO and SOON sunspot area

- SIM/SOLSTICE measurements
- TIM measurements

- ❑ Facular and Sunspot contributions are determined by ***linear regression*** with SIM measurements over rotational scales.

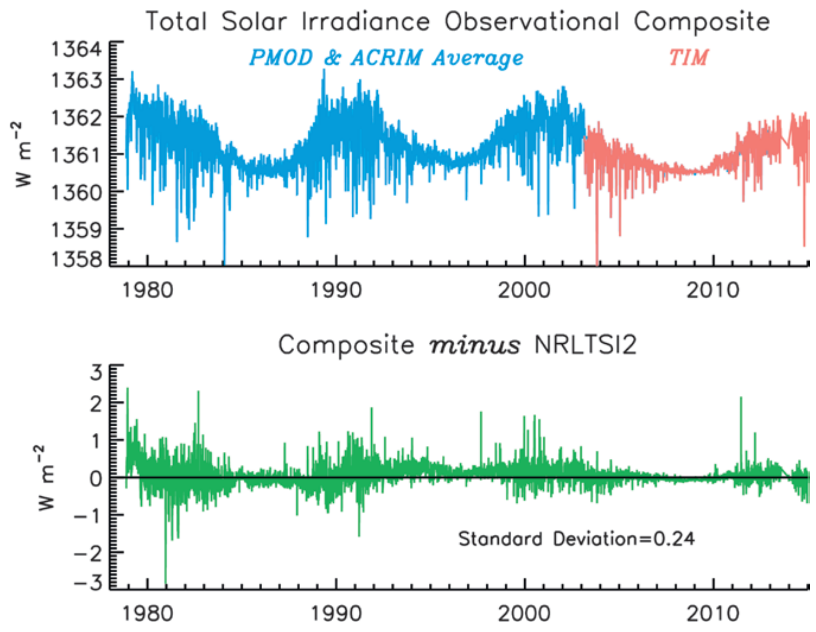
- ❑ For TSI, linear regression is comprises the whole mission as measurements are considered more reliable

- ❑ Empirical correction factors applied to derived SSI coefficients to compensate for long-term variations.

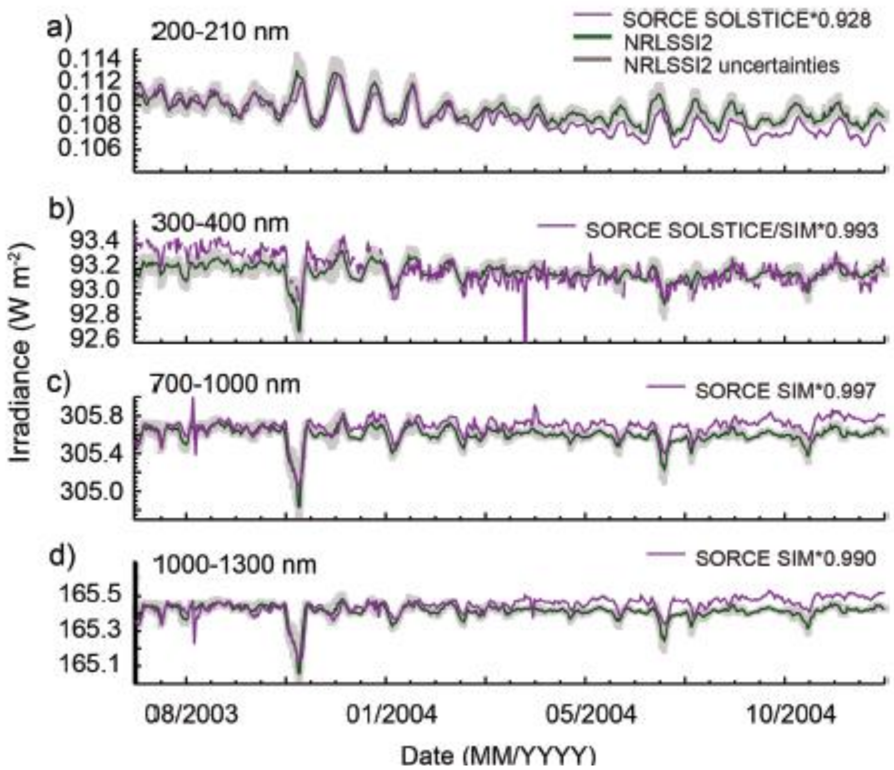
- ❑ Sum of spectral facular and sunspot contribution must match TSI facular and sunspot contributions

➡ It provides uncertainties, detailed versioning, manual, consistency of inputs

Proxy Models



Explains 92% of TSI / TIM variability



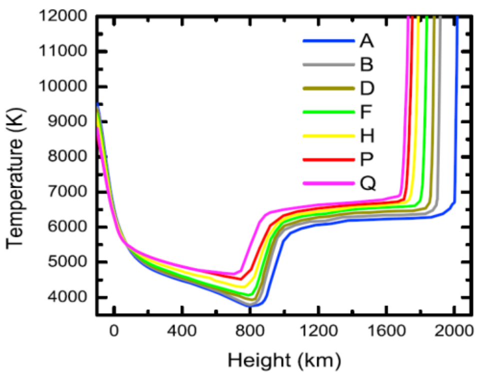
Still discrepancies with SORCE-SSI

- UV variability smaller than other models
- The agreement depends on wavelength and time.

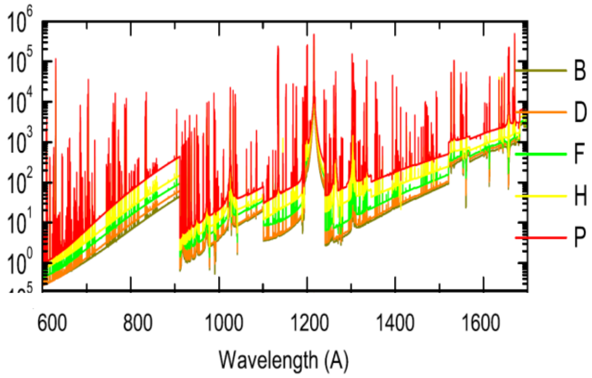
SEMI-EMPIRICAL MODELS

SATIRE-S/T (e.g. Krivova2003,Yeo2014);
COSI (Shapiro et al. 2010; 2011);
SEA (Shapiro et al. 2011)
OAR(e.g. Ermolli et al. 2011; Ermolli et al. 2013);
SRPM (e.g. Fontenla 2011; Fontenla 2015)

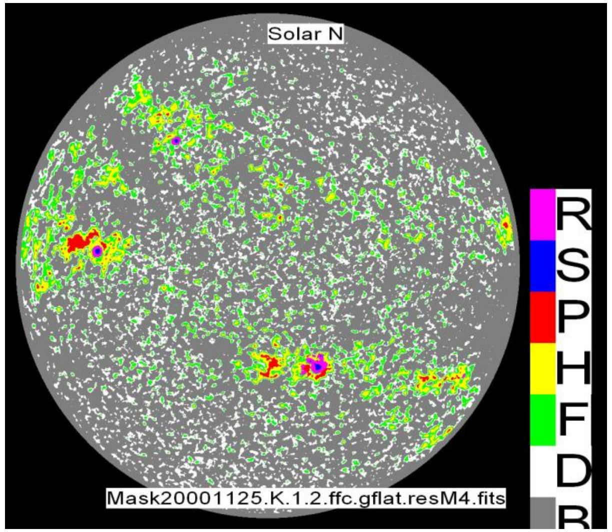
Reconstruction of Solar (Stellar) Irradiance variability

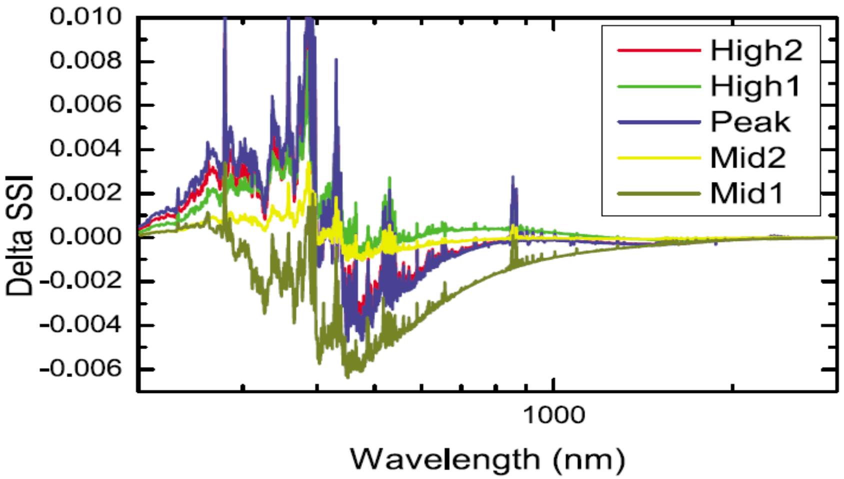


Fontenla et al., ApJ, 2011

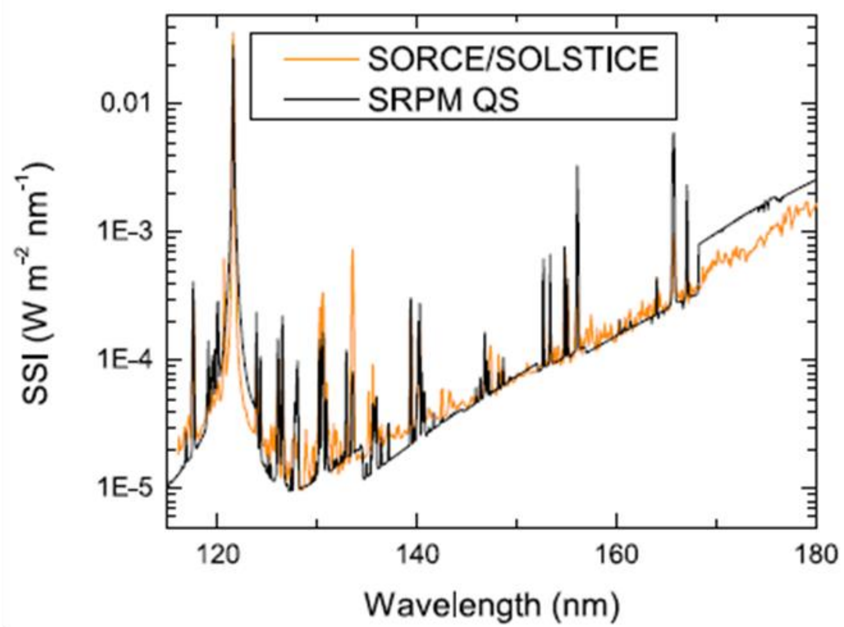


Irradiance variations are computed by weighing pre-computed spectra of archetypal magnetic features with the temporal variation of their area coverage. Spectra are computed using *1D, static, atmosphere models* of magnetic and quiet features. More recently *3D MHD* models have been employed.





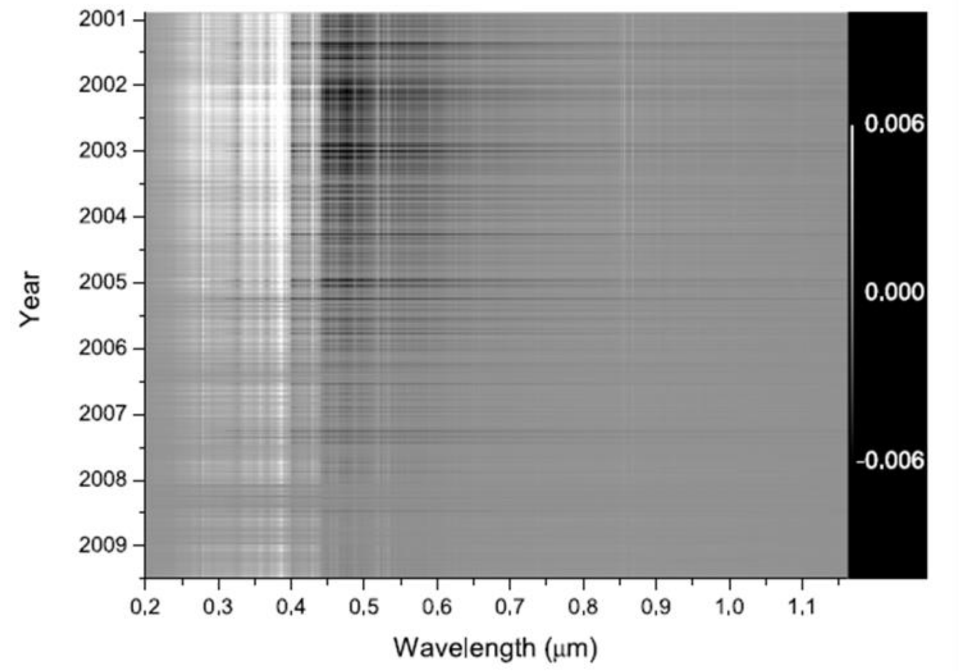
Semi-Empirical Models

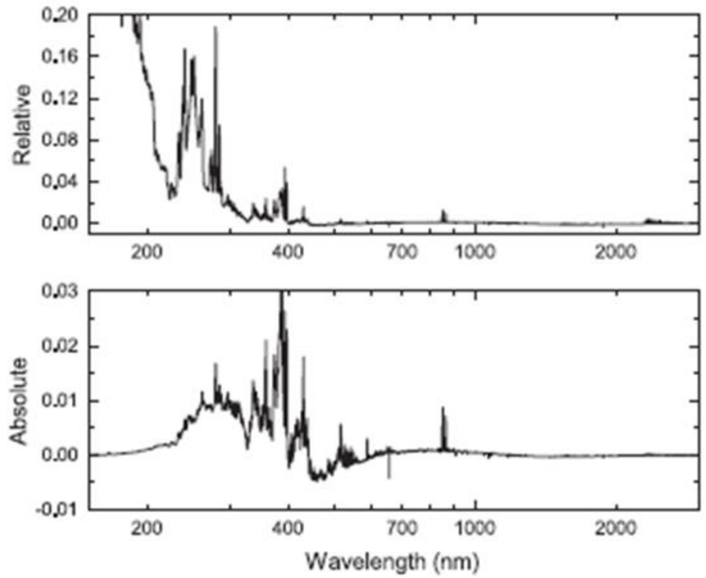


The Solar Spectrum is reproduced well

<u>TSI variations were NOT reproduced in 2011 version</u>

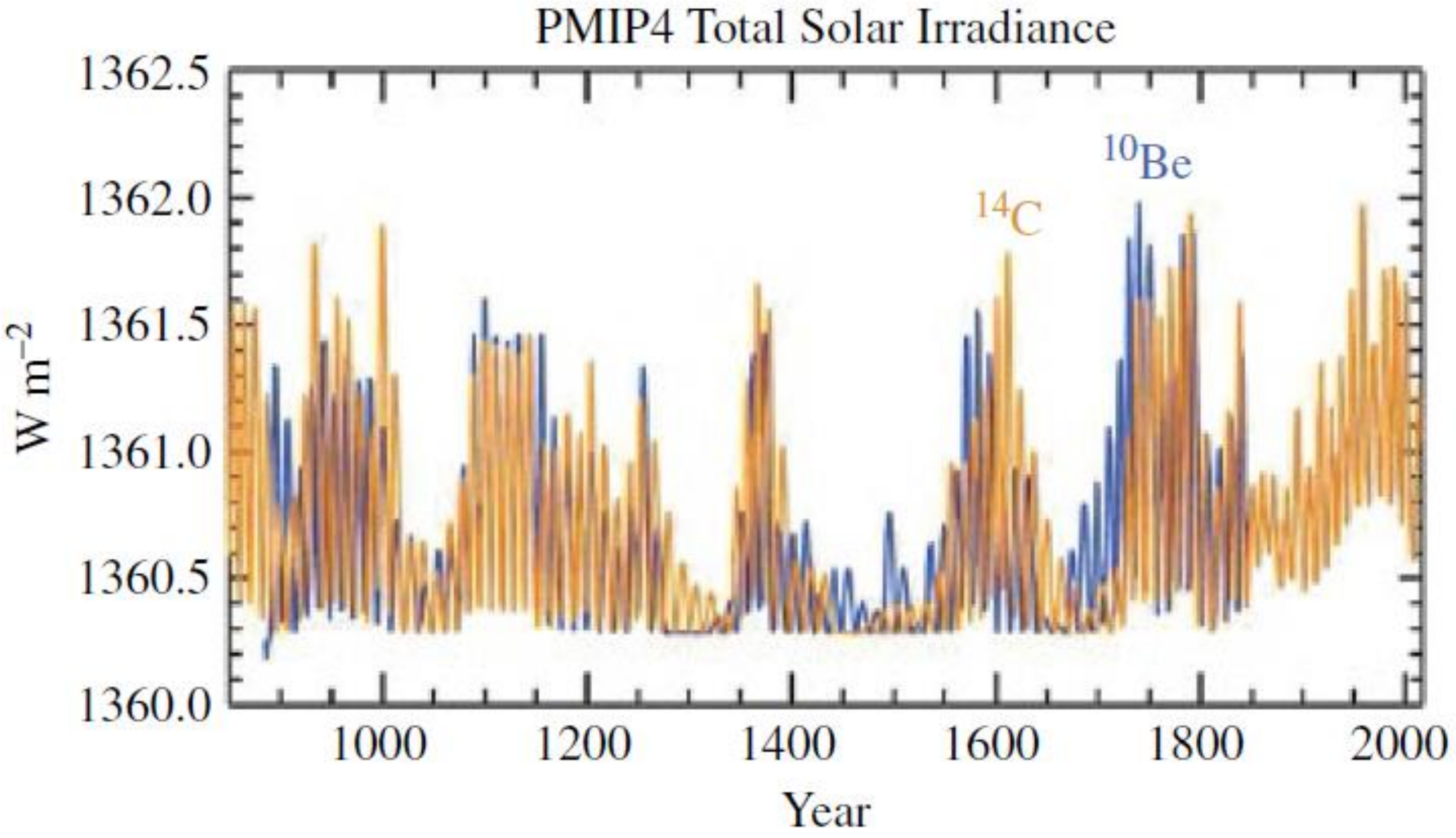
<u>TSI IS reproduced in 2015 version</u>





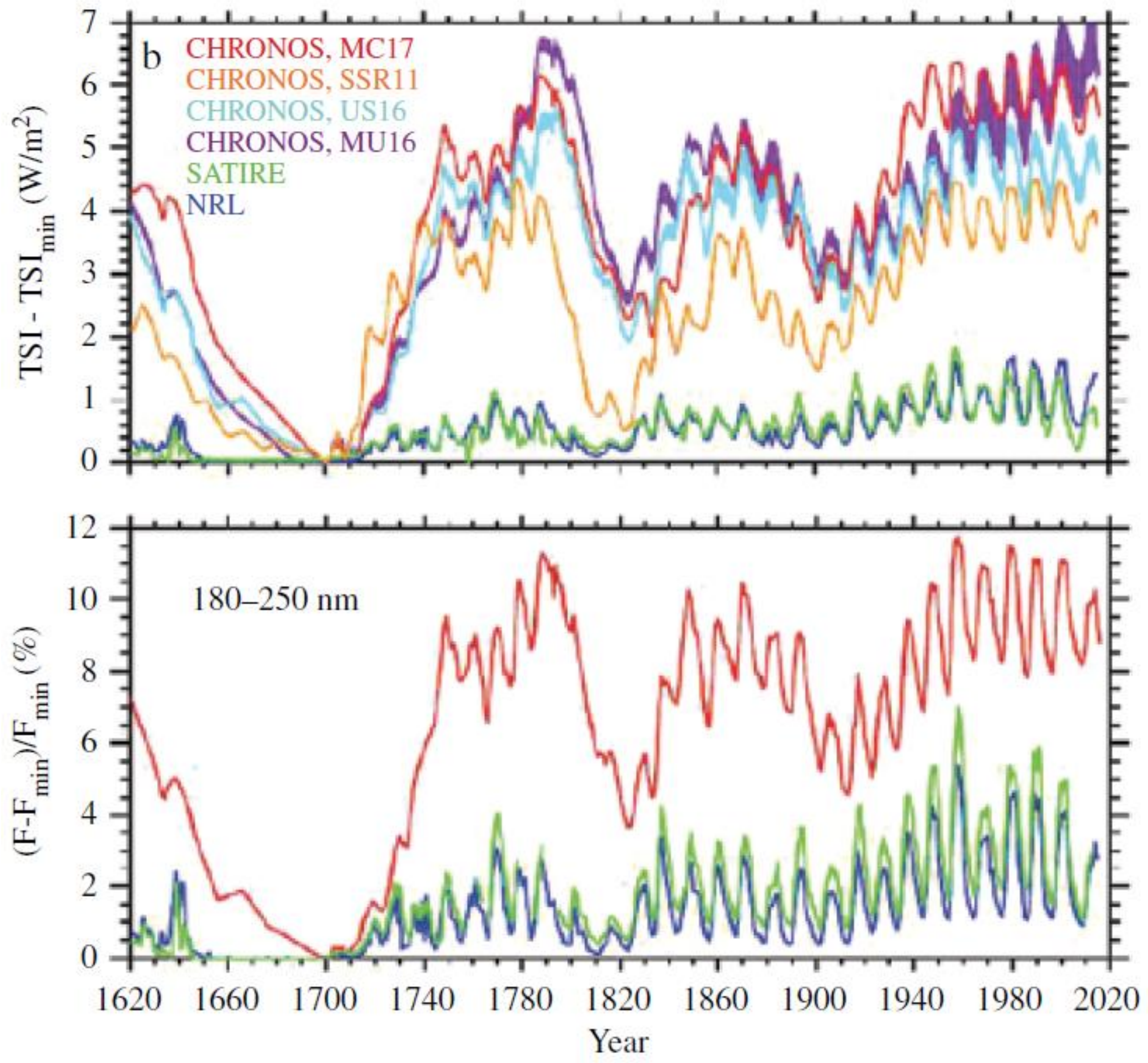
SIM VIS and IR signal in counter-phase is reproduced in both 2011 and 2015 versions.

Historical reconstructions

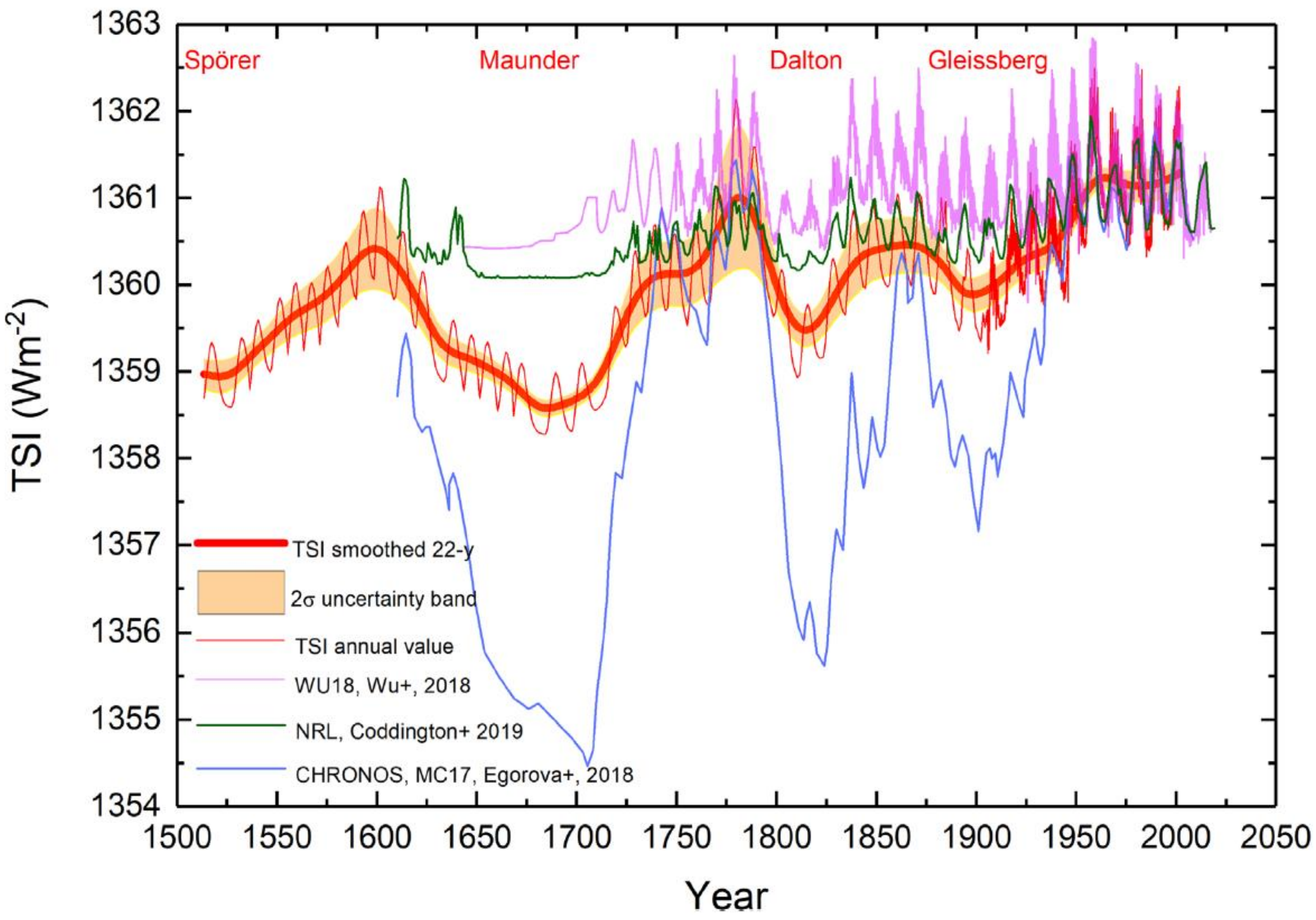


Lean 2018

Is there a long-trend in the quiet Sun component?



Egorova et al. 2018



Between 0.1-0.3K T Earth , that is 8-30% of global warming

Shortcomings of Irradiance reconstruction models

- All irradiance reconstructions depend on assimilating data, either proxies (e.g. sunspot number, Mg II c/w ratio, …), images (e.g. Ca II H), or magnetograms (MDI, HMI, …)

- No model has true predictive power

- Many models neglect NLTE effects (exceptions COSI, SRPM)

- Models have one or more free parameters

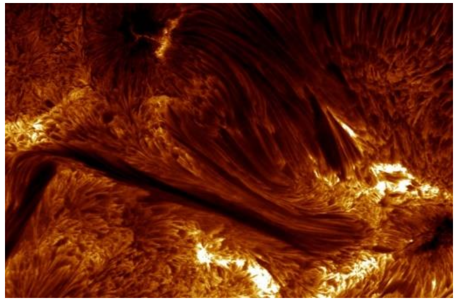
- **The disagreement of the models in the UV is relevant for Earth climate studies.(Thuiller et al. 2014) and for the characterization of stellar habitability zone.**

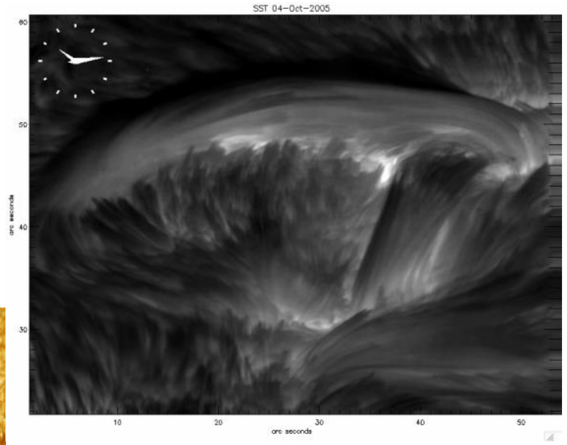
- Even small differences in the algorithms and assumptions may lead to significant discrepancy

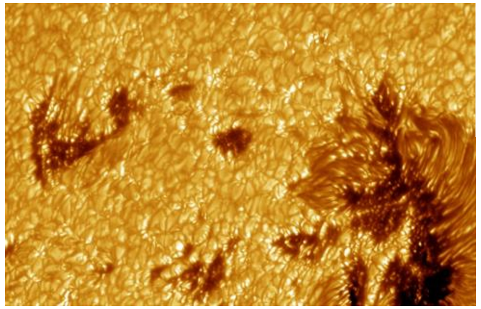
- Semi-empirical models have not been tested sufficiently versus independent measurements

- **Do not take into account 3D, small-scale, highly dynamic nature of solar atmosphere**

1 D models: Drawbacks







a) **Semi-empirical** models do not necessarily reproduce portions of the spectrum, or variability other than those they were derived from.

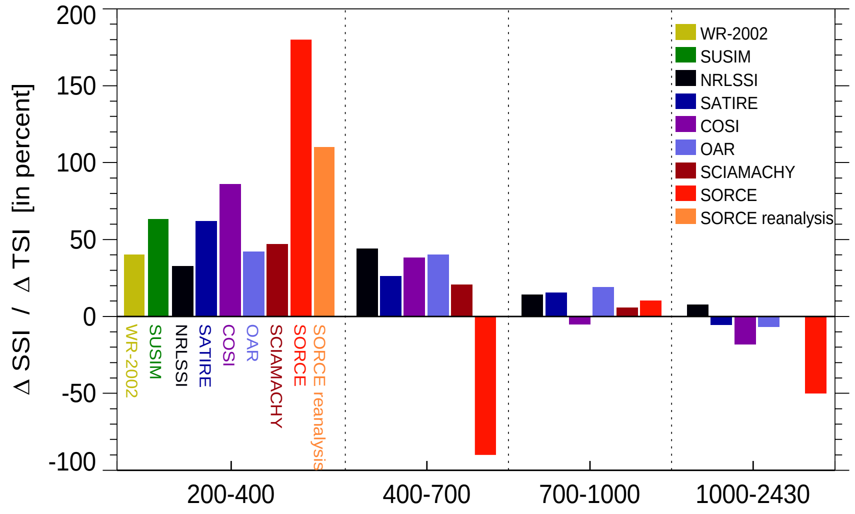
(e.g. FAL2011 did not reproduce TSI variations)

b) **Semi-empirical** models do not necessarily reproduce photometric observations

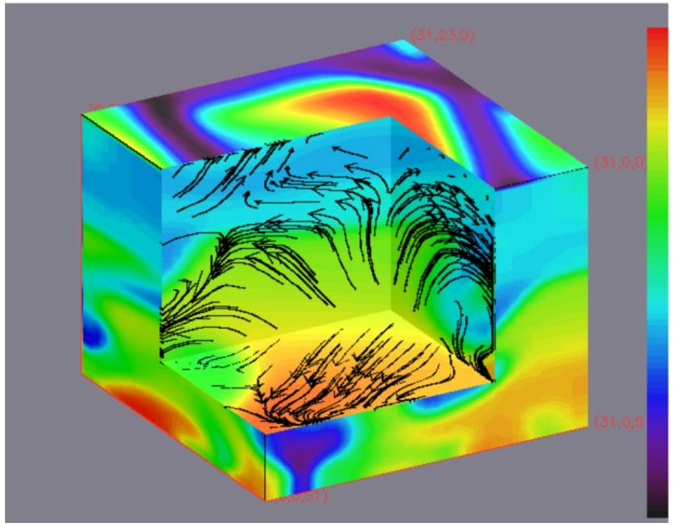
(e.g. FAL2009 do not reproduce CaIIK PSPT photometric contrasts)

c) **1D static atmosphere** models do not reproduce the complex fine and dynamic nature of the solar atmosphere

d) **Discrepancy between irradiance reconstruction models**



Forward modeling: 3D MHD simulations



Stein & Nordlund 1998

Box-in-a star regime

A small portion of the solar atmosphere is reproduced in a box.
Typically x,y contain few granules (10x10Mm), z extends between 12-15 Pressure scale height.

Solve time-dependent magneto-fluid-hydrodynamics equations for compressible fluids

- Energy
- Momentum
- Continuity
- Induction
- Gauss Law of Magnetism

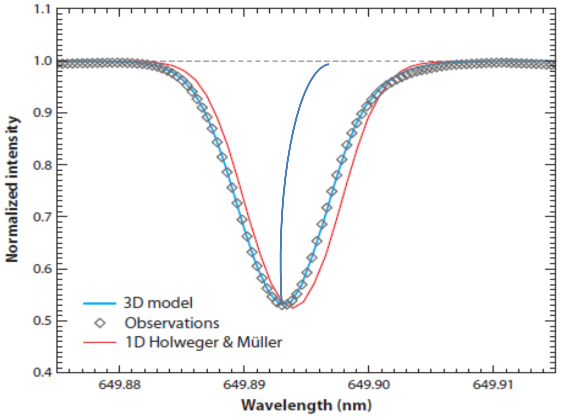
Codes

STAGGER
MURaM
CO5BOLD
SolarBox
Pencil
Bifrost
Antares

Internal energy takes into account of ionization and dissociation processes
Radiative processes are very important in the energy budget.

3D MHD models of the solar PHOTOSPHERE reproduce observations better than 1D models

Asplund et al. 2009

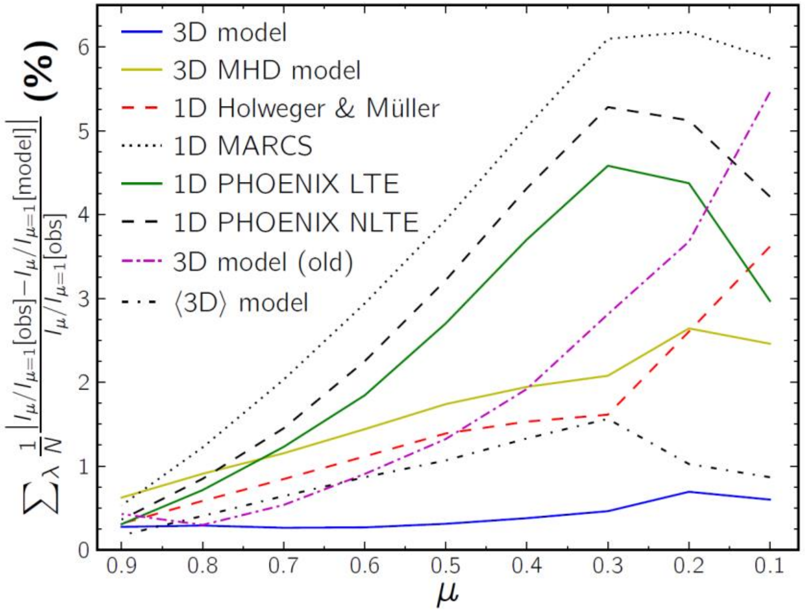


Properties of photospheric lines (revision of abundances)

Micro and Macro-turbulence are no longer needed

CLV of continuum intensity

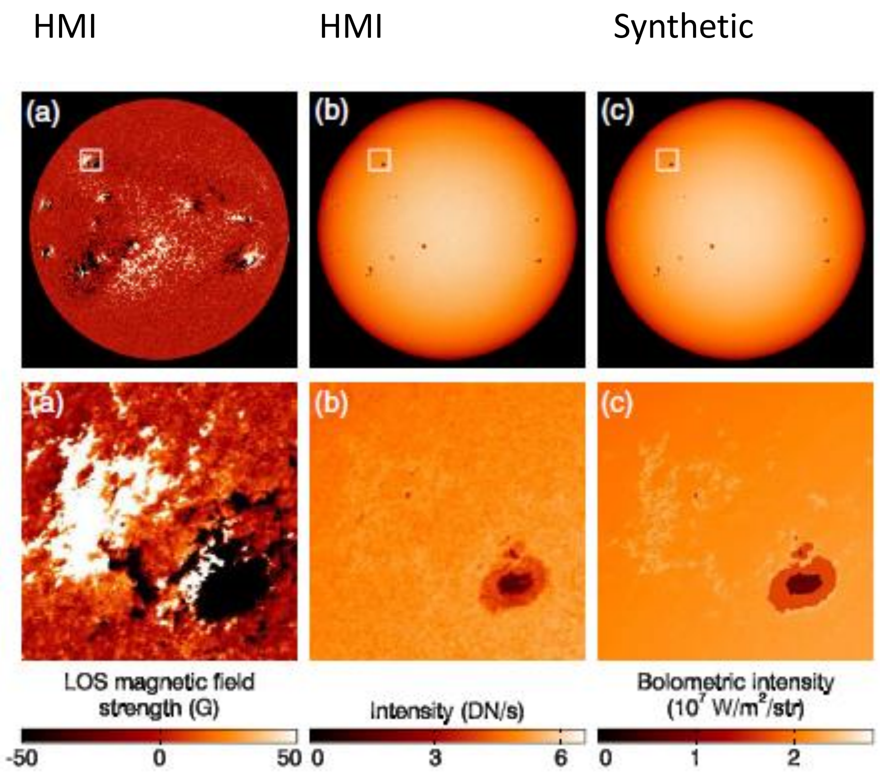
Pereira et al. 2013



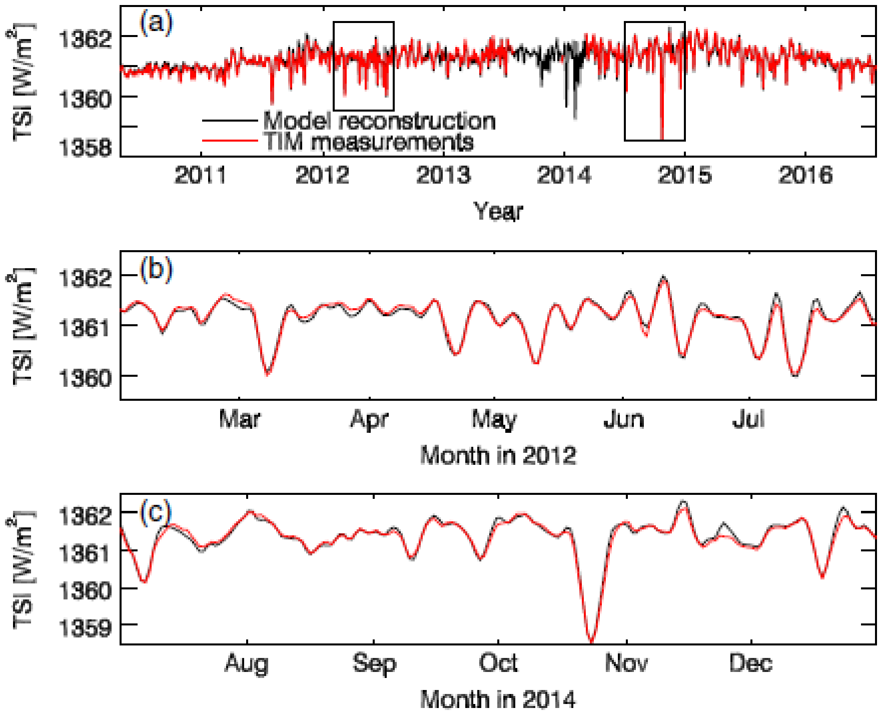
First reconstruction of TSI

Yeo et al. 2017

40 MURaM snapshots: 0G, 100G, 200G, 300G
Compute bolometric flux.
Simulate HMI magnetograms and Intensitygram.
TSI is reconstructed comparing synthetic data with daily HMI observations.
Note that sunspot contribution is still represented using a 1D model.



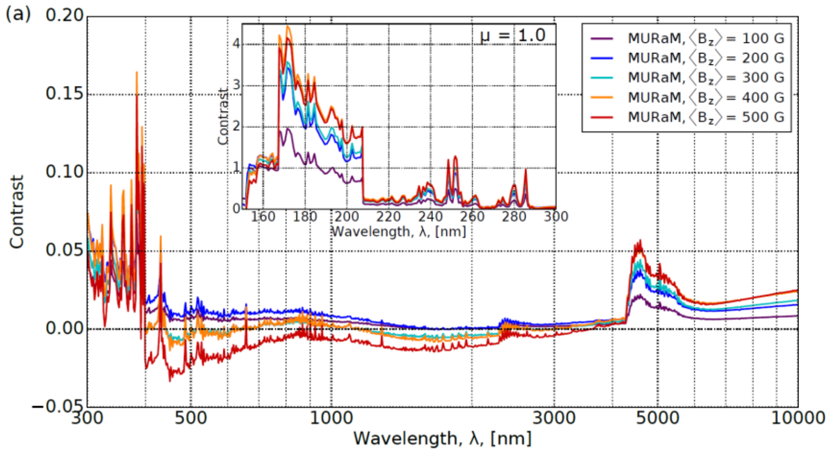
Time series	R	rms difference (W/m^2)
Model and TIM	0.976	0.0836
Model and VIRGO	0.968	0.0941
TIM and VIRGO	0.975	0.0865



3D Models Drawbacks:

1) Computationally expensive-- Thanks to the development of supercomputers, and massive parallelization, time sequences produced by different codes are publicly available or can be obtained under request.

Norris et al. 2017 Atlas9 opacities



2) Radiative Transfer is prohibitive, especially in NLTE
However, LTE is possible using some numerical approximations

Modeling the Chromosphere

An important fraction of the Spectral Irradiance variability that impacts the Earth atmosphere originates from the chromosphere. Several Irradiance proxies are Chromospheric.

The chromosphere is a complex region where transition between different regime occur:
'thick'→ 'thin'; plasma dominated→ B dominated; Local → Non-Local; partially→ fully ionized
Highly dynamic, conversion of modes

1)Numerical stability: Acoustic waves generated in the photosphere grow in amplitude. Shocks propagate, creating sharp gradients

2)Time step: is determined by the Alfvén speed, order of milliseconds, I which is about 100 times smaller than in the photosphere.

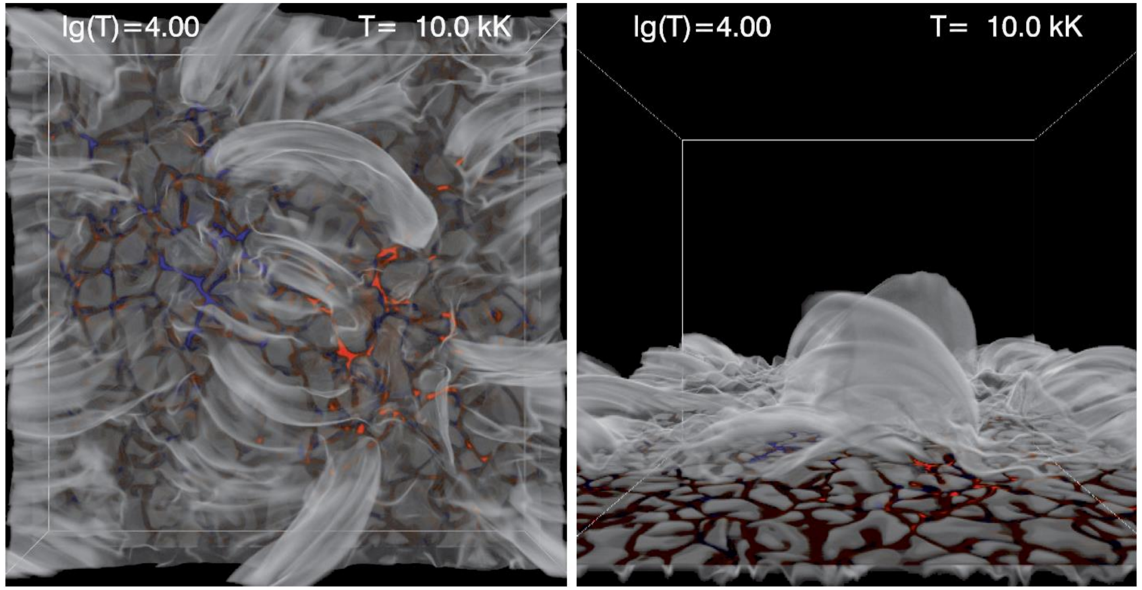
3)Non Local Radiative Transfer: Radiative losses require NLTE radiative transfer, and scattering is also important in the energy balance.

4)Non-equilibrium processes: ionization and photodissociation are time-dependent.

5)Heat conduction is important at T>10000K

6)B dominated: Multi-fluid description is necessary.

Very few snapshots available to the community.



References

Lean, 2017
Sun-Climate Connections
https://ui.adsabs.harvard.edu/abs/2017orec.bookE...1L/abstract

Petrie, Criscuoli, Bertello 2021
Solar Magnetism and Radiation
https://ui.adsabs.harvard.edu/abs/2021GMS...258...83P/abstract

Assignment

The purpose of this assignment is two fold: 1) make the students familiar with how to access solar irradiance and solar indices dataset; 2) understand how the correlation between solar irradiance and other indices changes with the indices and with time.

The LISIRD/LASP database is the most complete currently available (https://lasp.colorado.edu/lisird/).
Get familiar with it. Visualize and compare how different irradiance dataset, including spectral irradiance at different spectral ranges, change with time.

-Download one of the available sunspot number dataset (no CSUN!).
-Download one of the available TSI time series.
-After interpolating on a common temporal grid study and compare: a) the correlation over the entire dataset; 2) the correlation for different cycles; 3) the correlation for the ascending phases and the descending phases.
-Download the sunspot area from and repeat the computations above.
-Note the differences and if possible coCSUNmpare with results published in the literature.

The Extended Solar Cycle

https://www.frontiersin.org/articles/10.3389/fspas.2018.00038/full

‘The latitudinal dependence of the solar activity markers smaller in scale than sunspots (like, for example, bright points, granulation, diffuse coronal emissions, filaments/prominences, etc.) show a narrow concentration of activity that appears at higher latitudes (around 55°) just after solar maximum.’