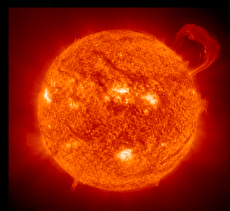
MODELS OF SOLAR IRRADIANCE

and their reliance on data

Natalie Krivova

MPS

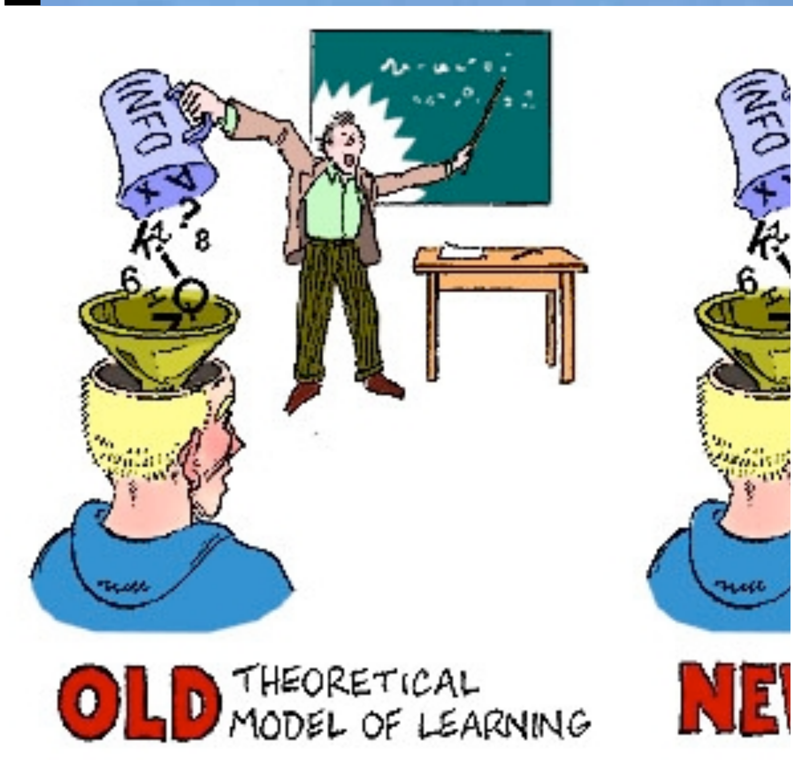


SUN – CLIMATE

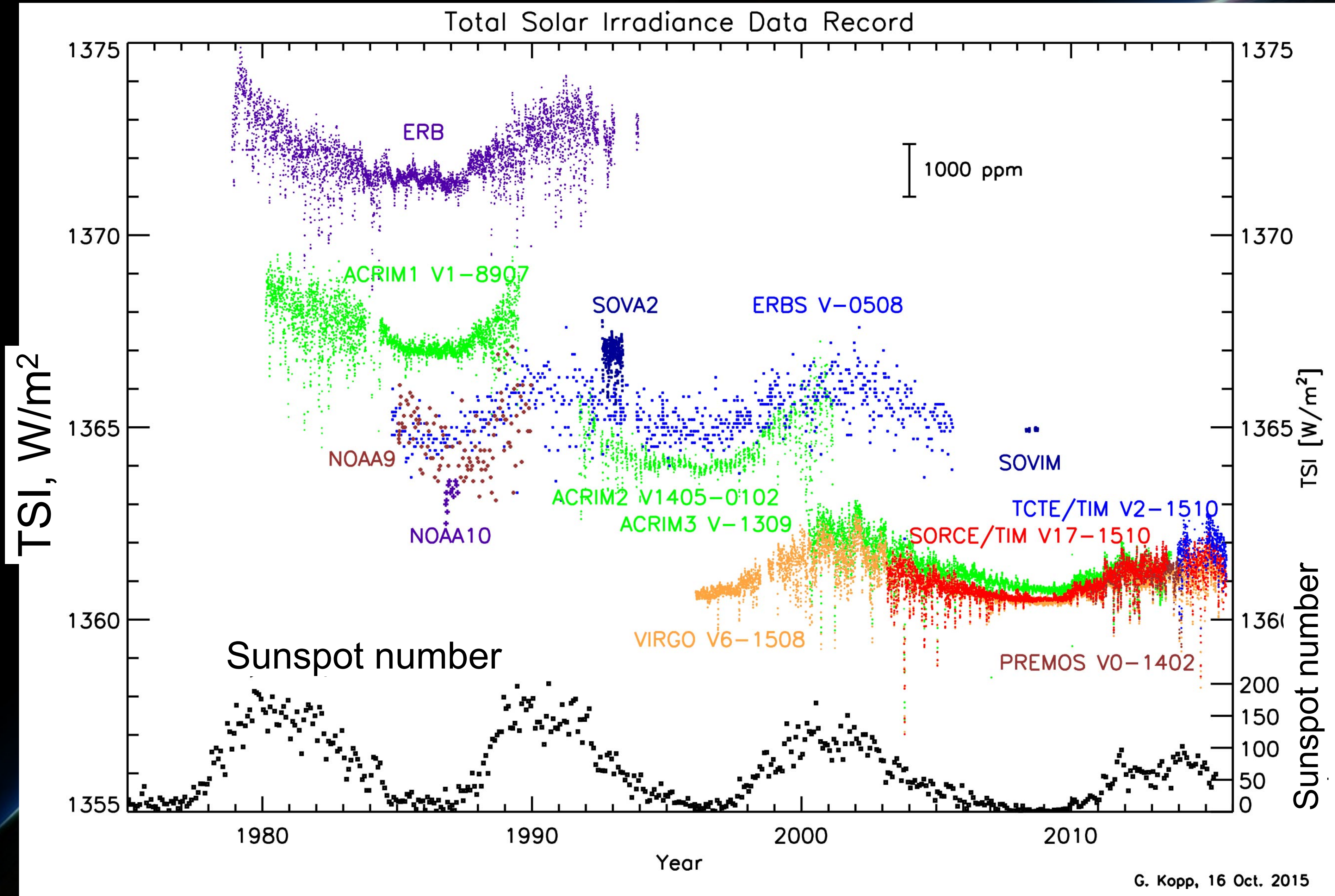
http://www.mps.mpg.de/projects/sun-climate/

IRRADIANCE


WELCOME TO
COLORFUL
COLORADO

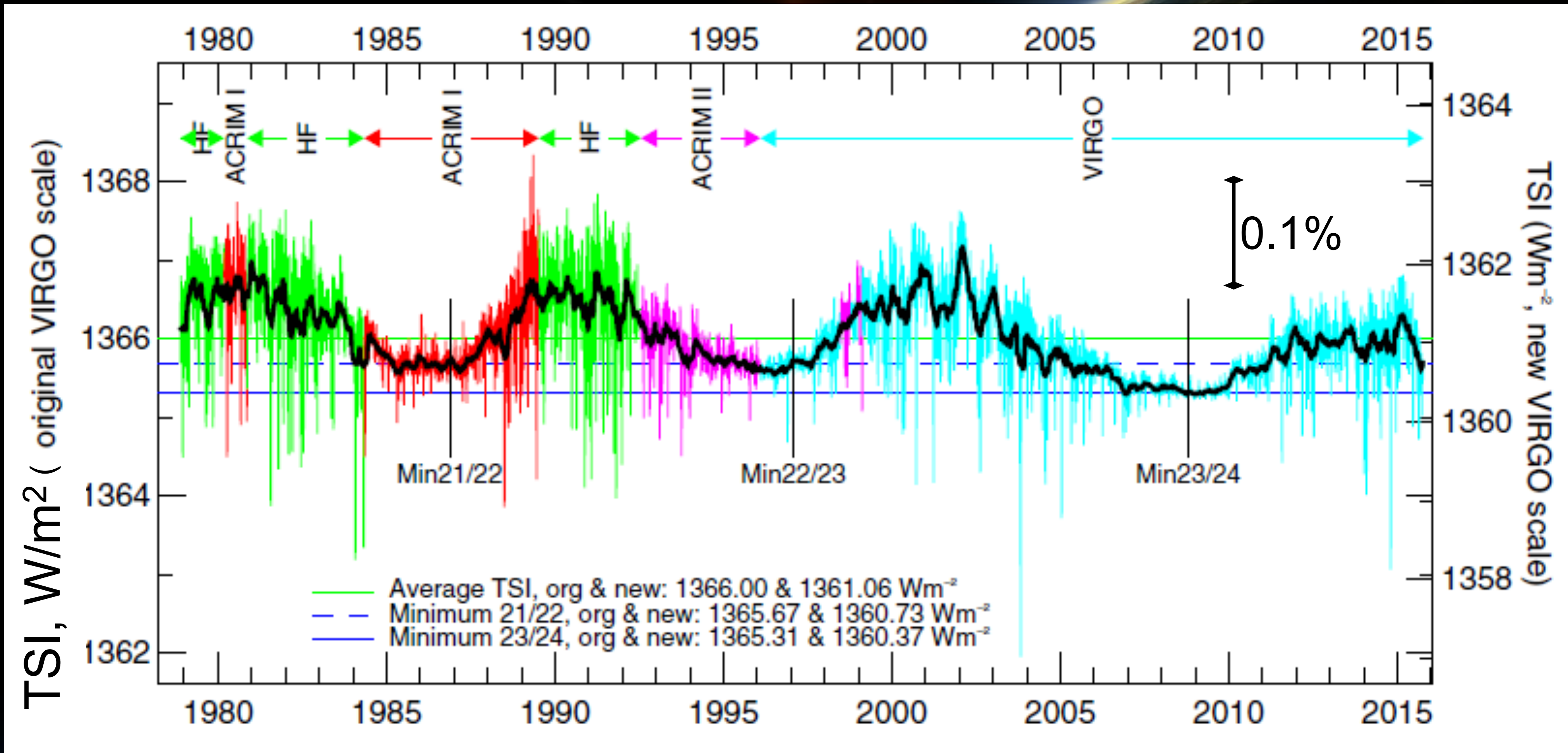

INFO
OLD THEORETICAL MODEL OF LEARNING

Solar Irradiance (TSI): Measurements



Greg Kopp

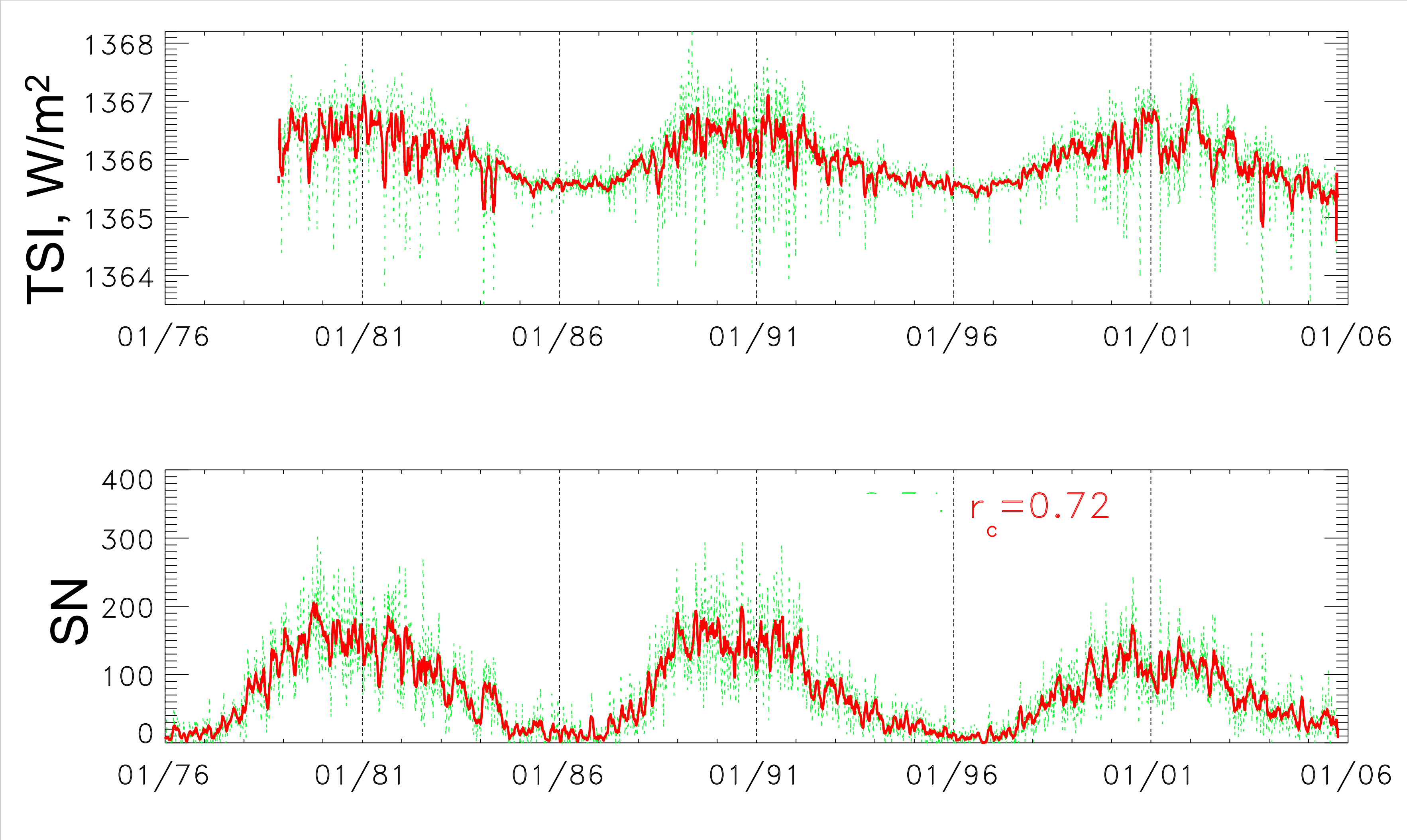
Solar Irradiance (TSI): Measurements



TSI composite
Physicalisch-Meteoroligisches Observatorium Davos (PMOD; C. Fröhlich)

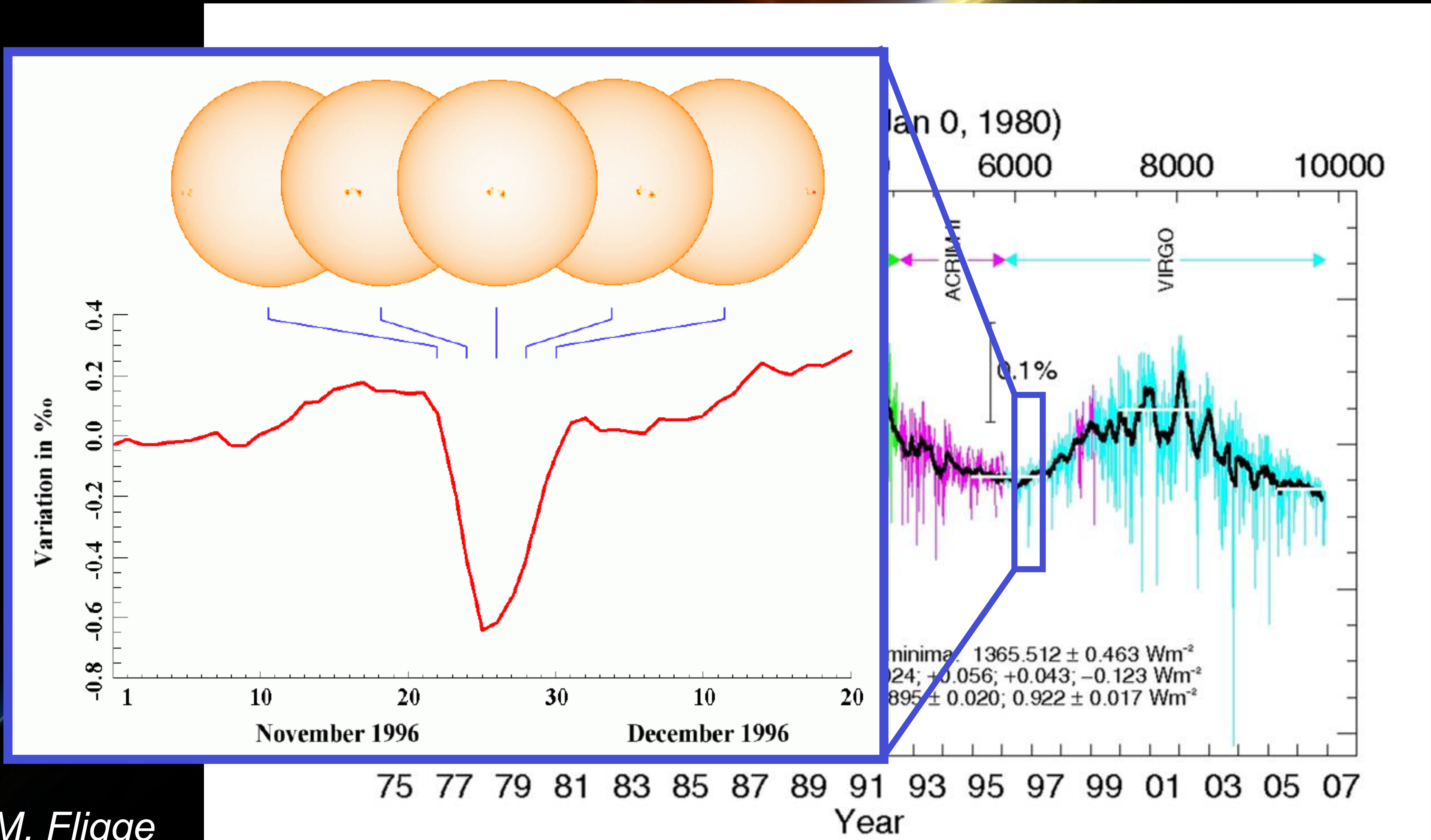
Solar Irradiance (TSI): Variability

Solar cycle



Solar Irradiance: Variability

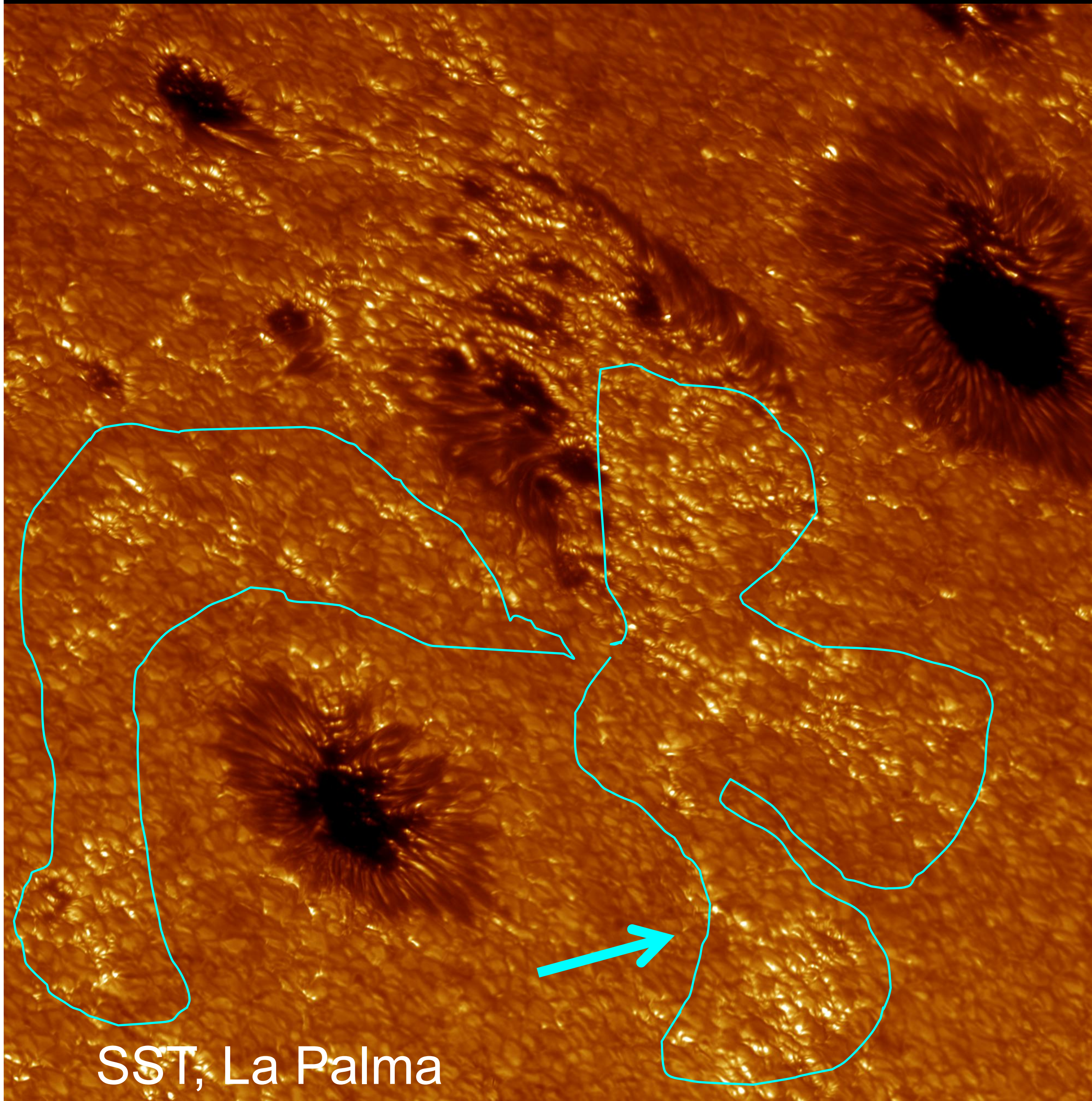
Solar rotation

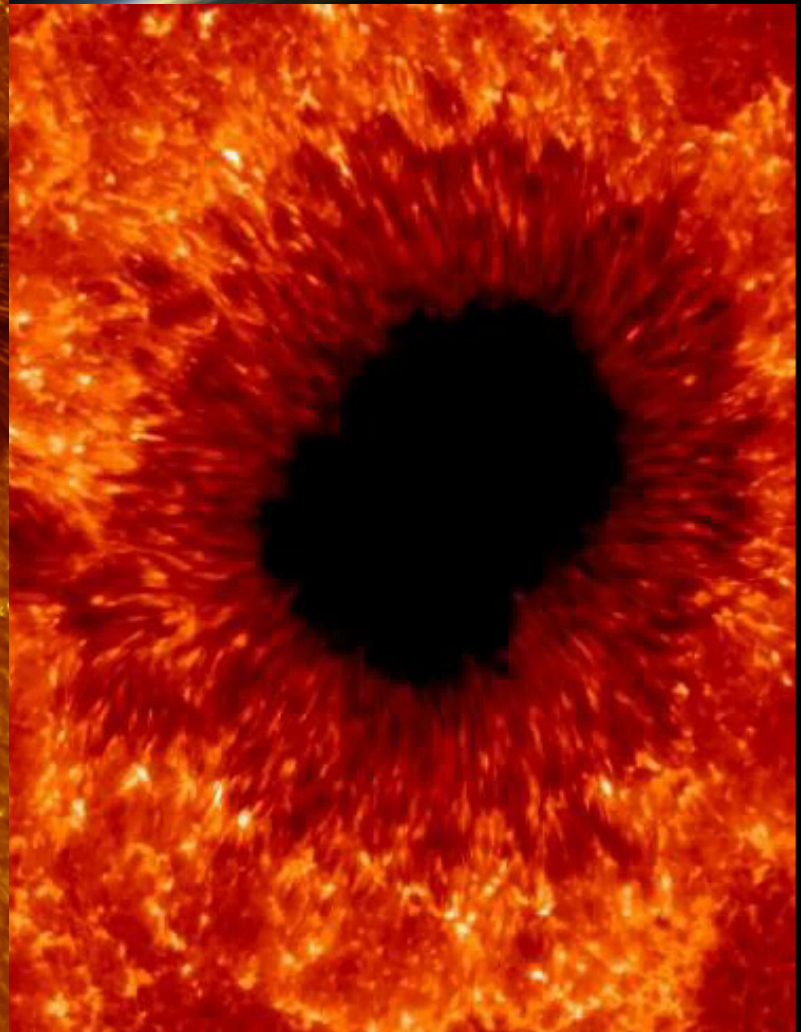


M. Fligge

Solar Irradiance: Variability

Spots vs. faculae

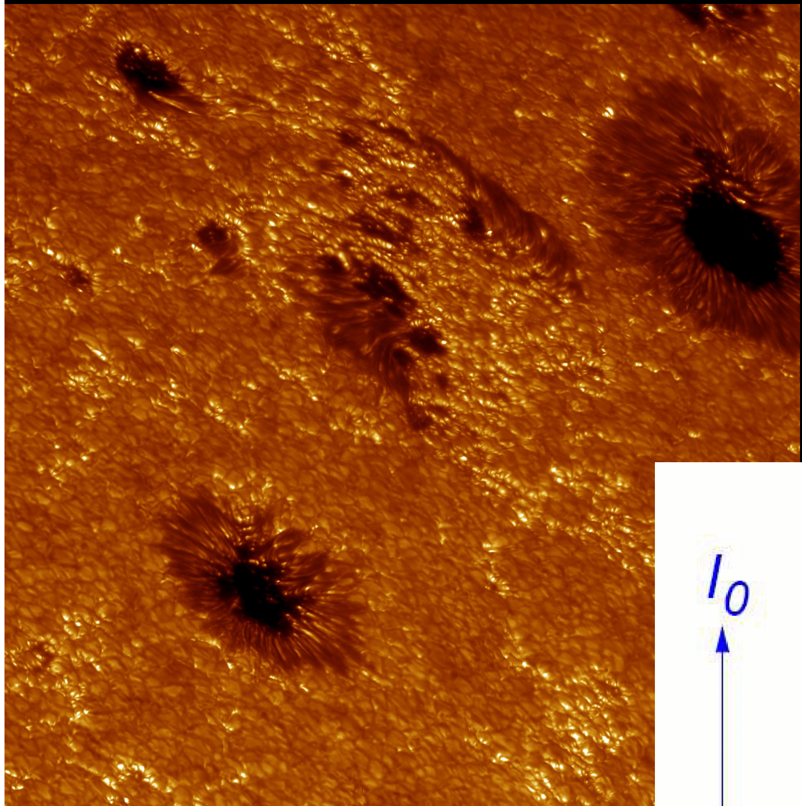


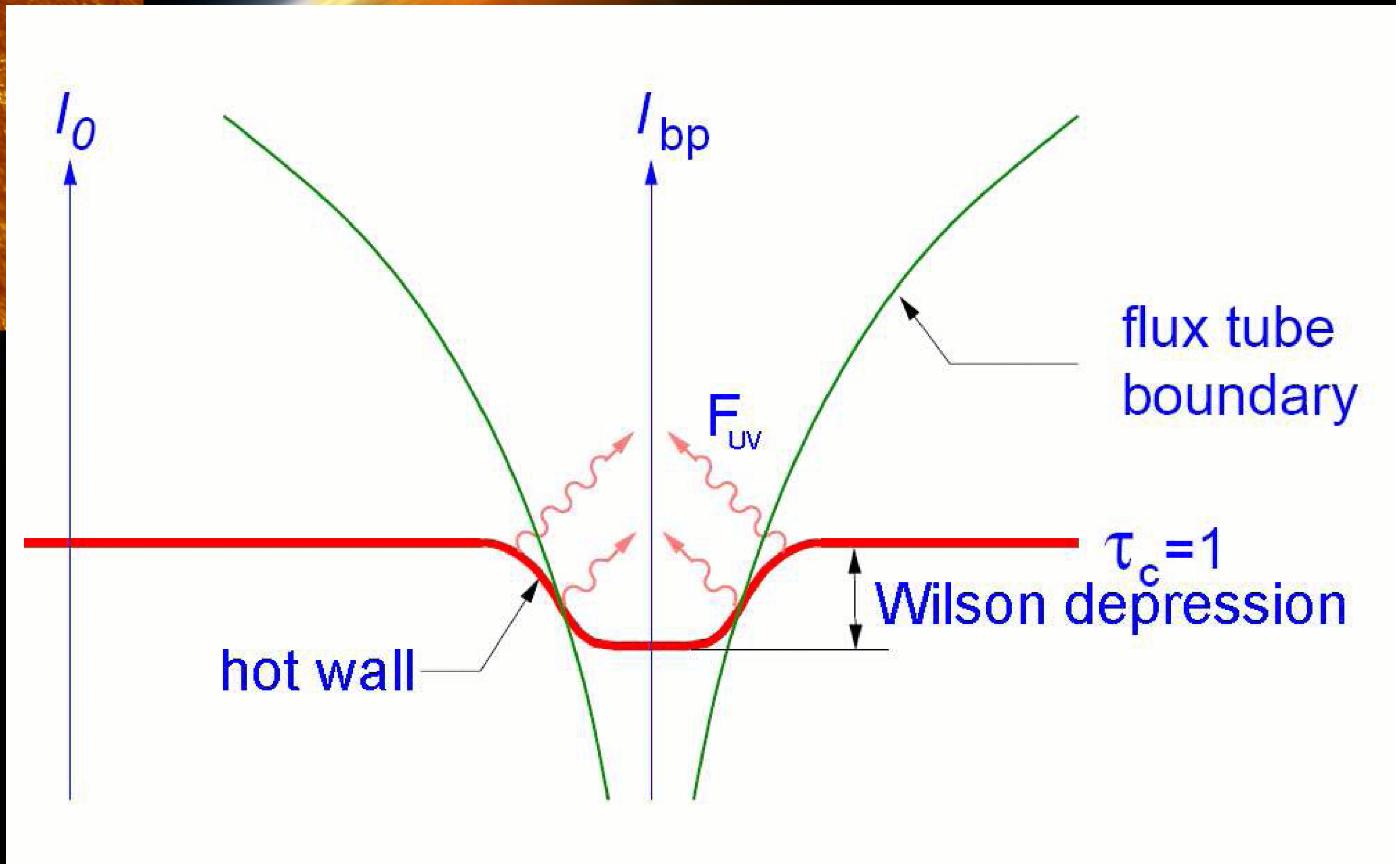


Hinode

Solar Irradiance: Variability

Spots vs. faculae





Solar Irradiance: Variability

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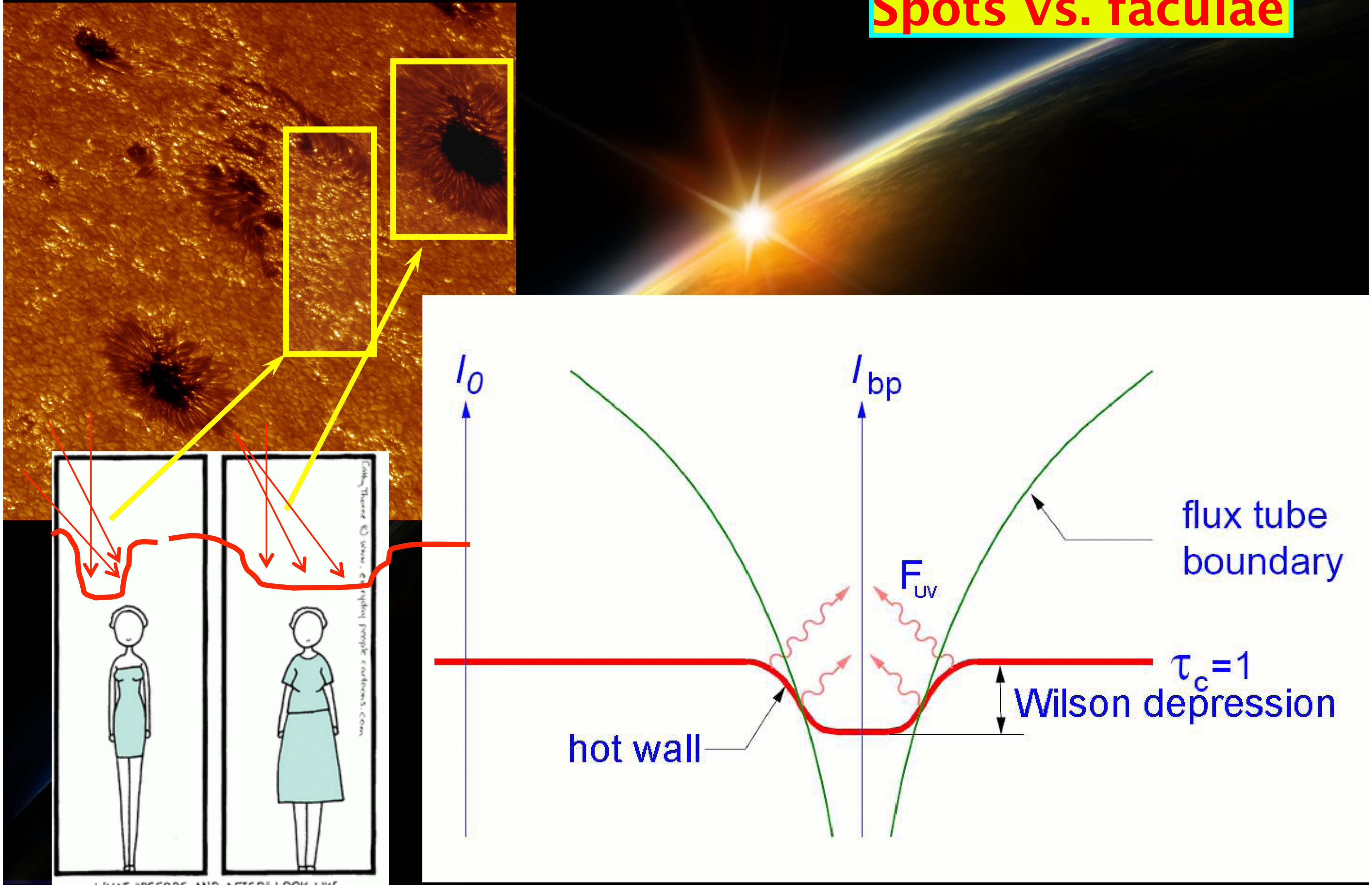
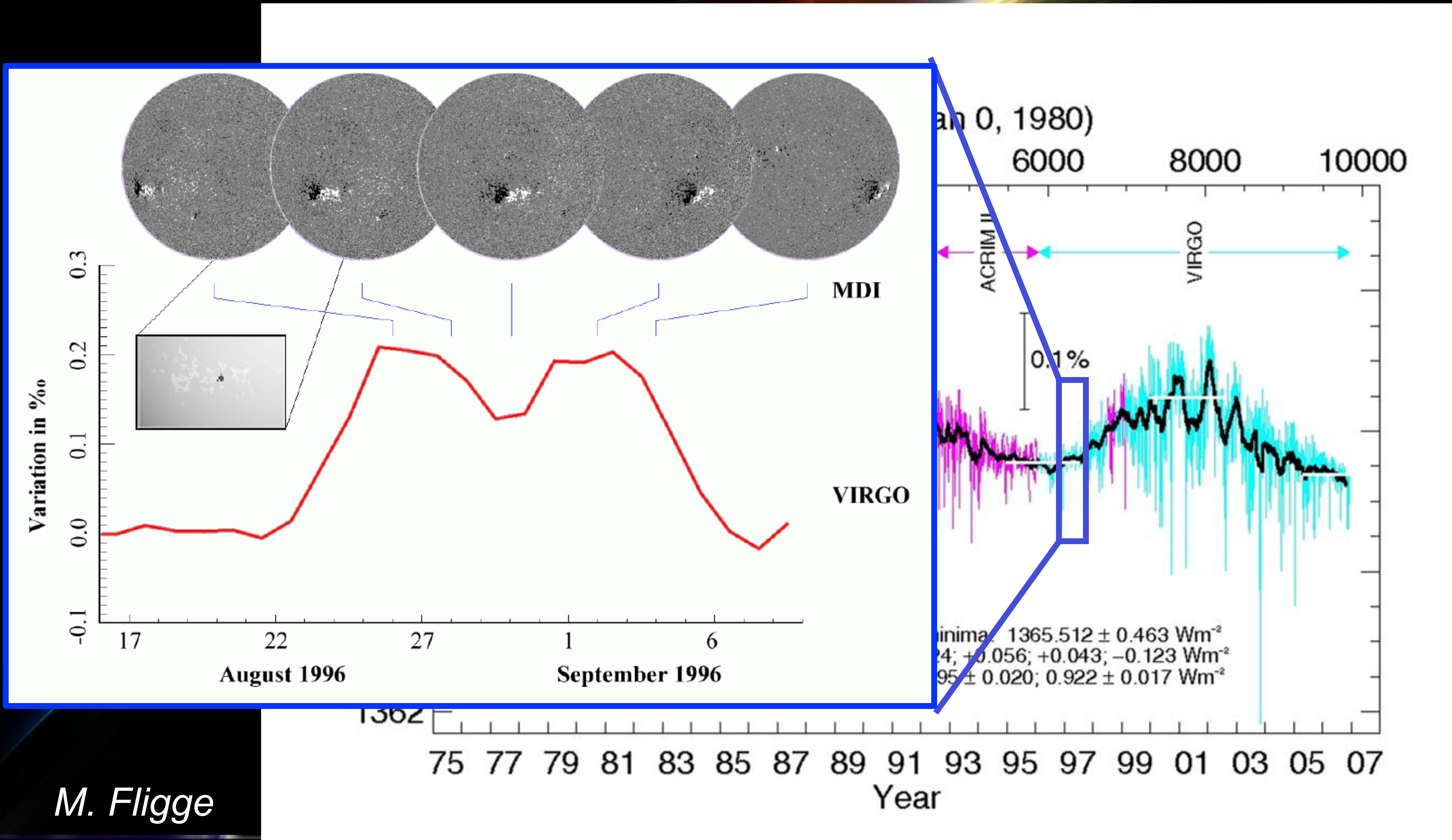


Solar Irradiance: Variability

Solar rotation



M. Fligge

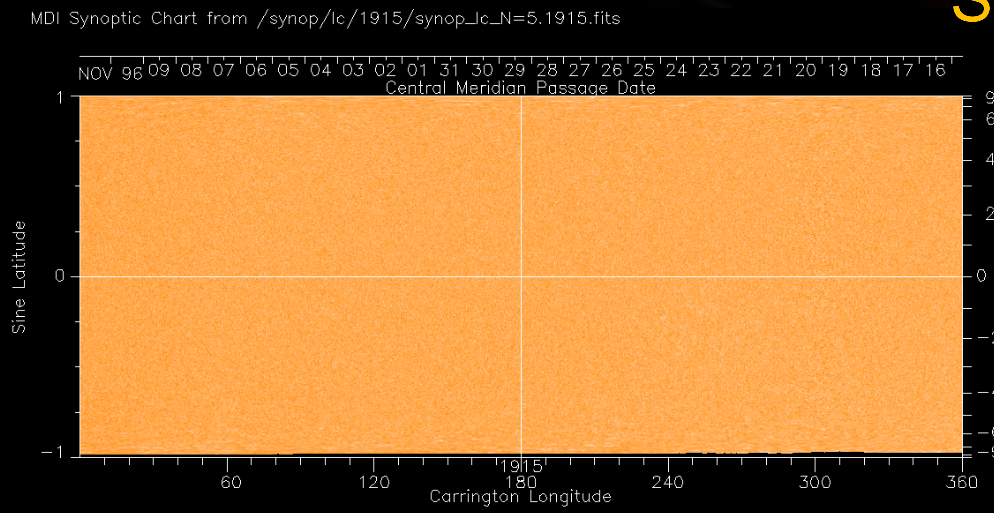
Solar Irradiance Variability

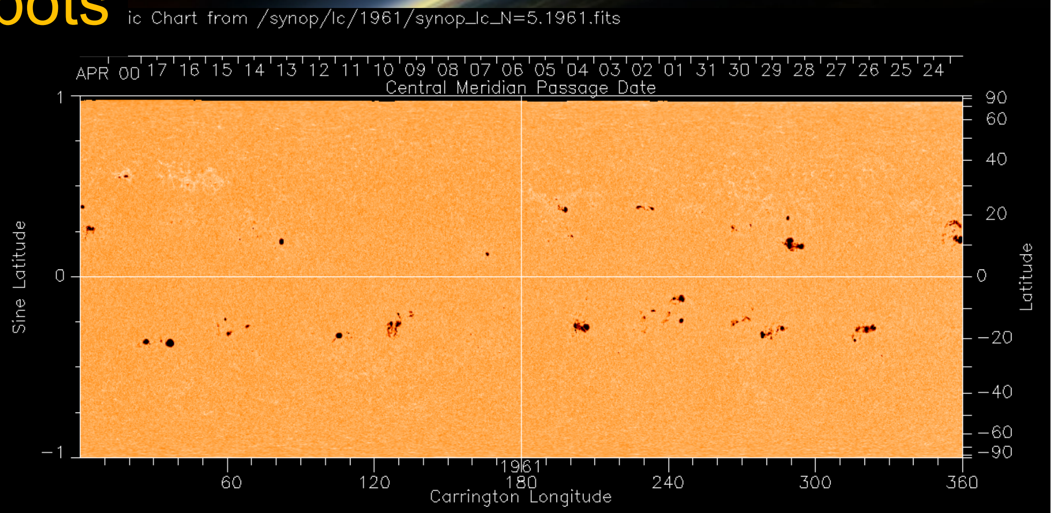
Spots vs. faculae

1996, Minimum

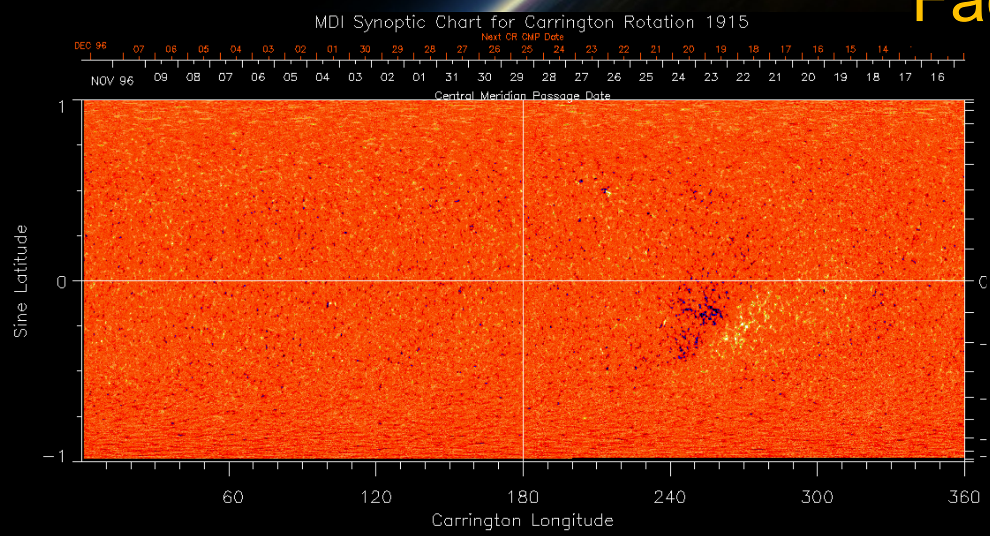
2000, Maximum

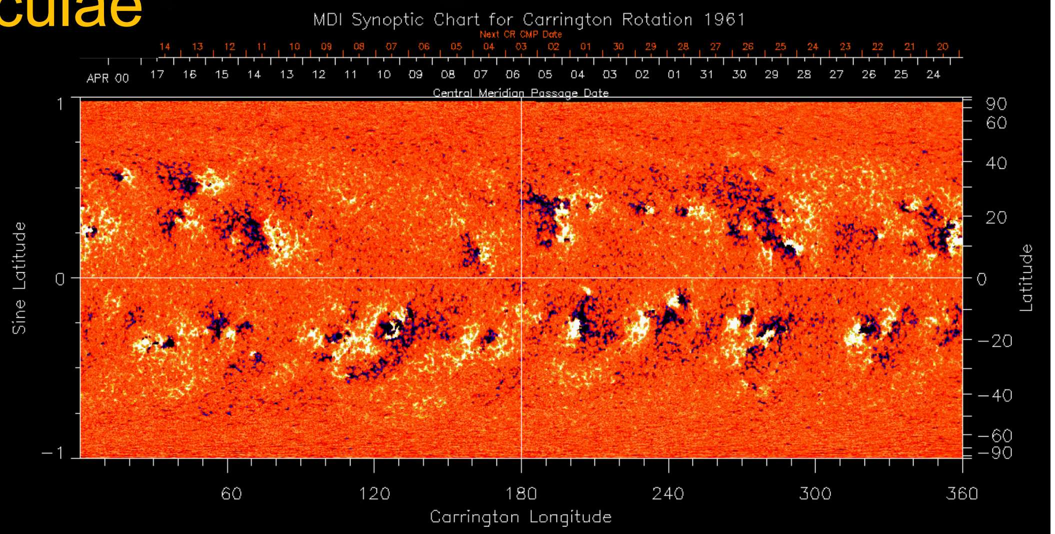
Spots





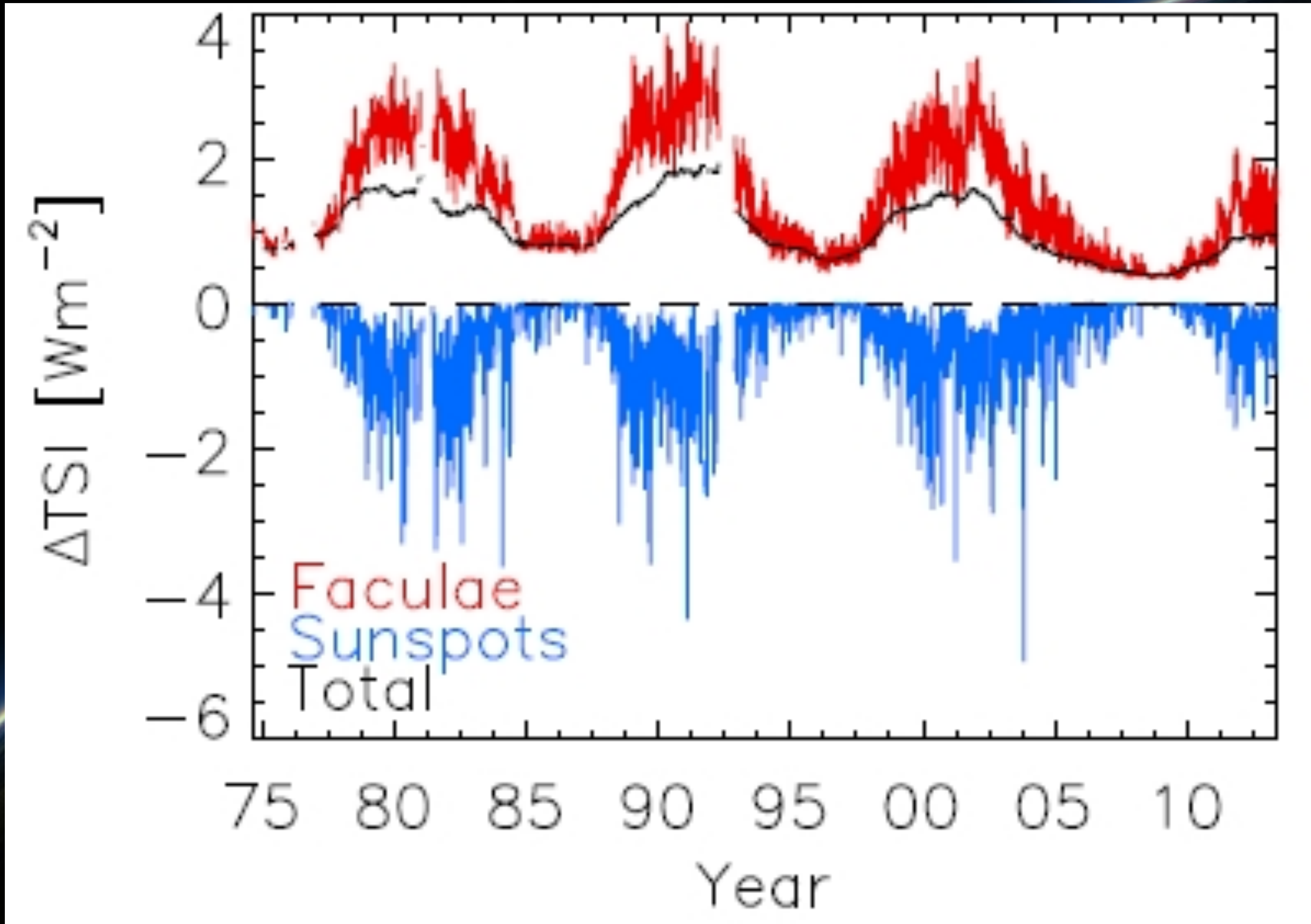
Faculae





Data: SoHO/MDI

Basis for Irradiance Modelling

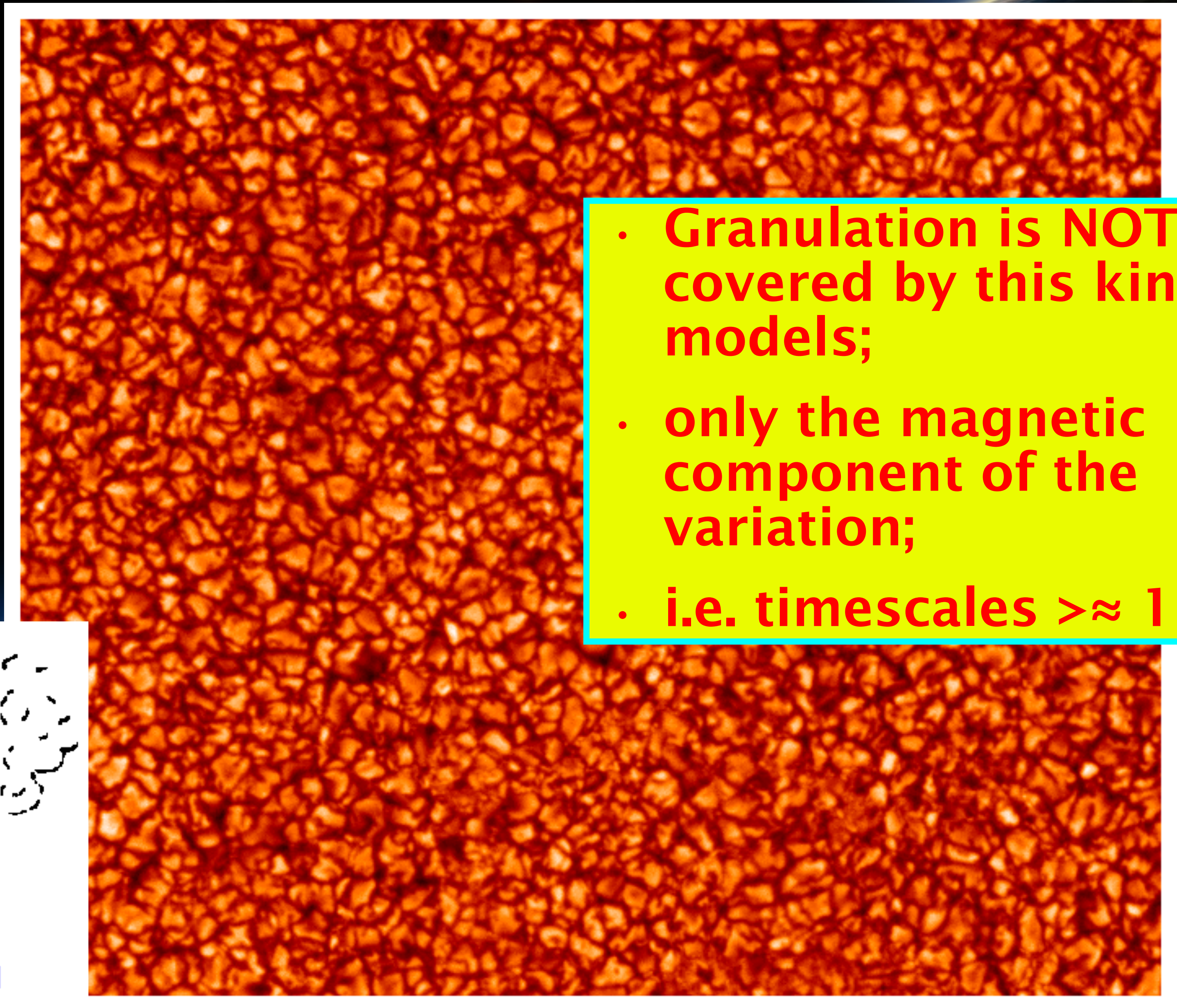


Yeo et al. 2014

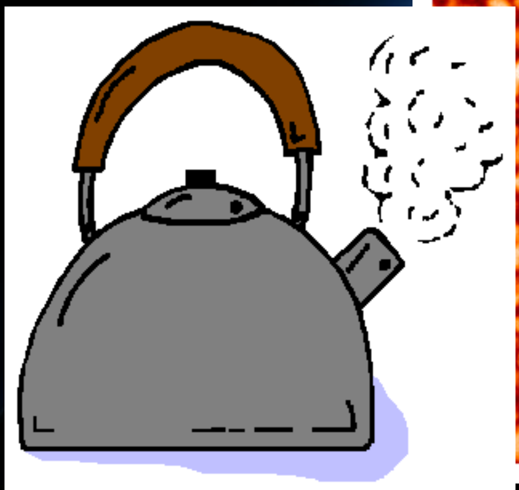
$$\Delta S(t) = \Delta S_s(t) + \Delta S_f(t)$$

Solar Irradiance (TSI): Variability

Minutes to hours: granulation



- Granulation is NOT covered by this kind of models;
- only the magnetic component of the variation;
- i.e. timescales >≈ 1 day



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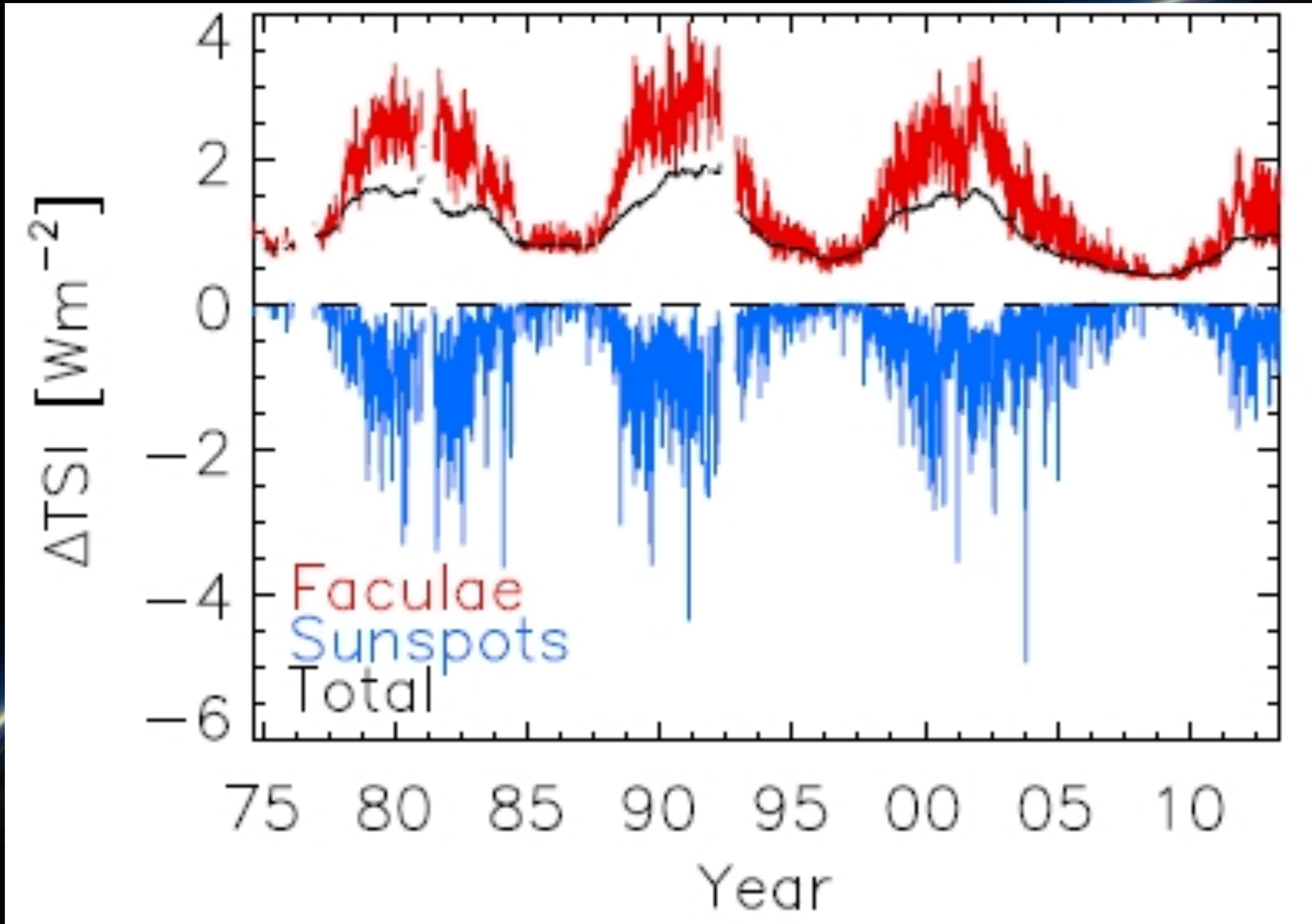

Yeo et al. 2014

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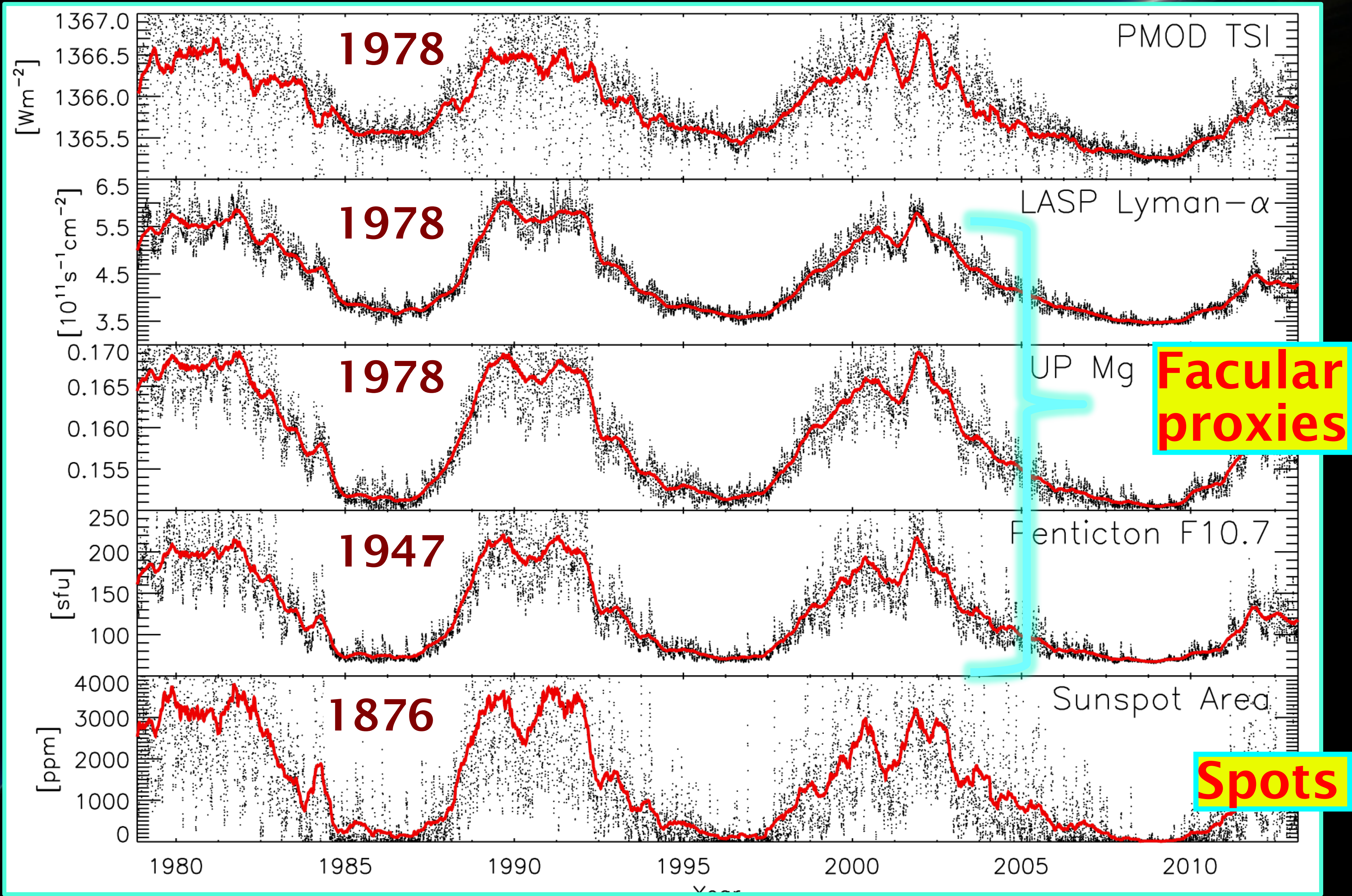
TSI & Solar Magnetic Activity Proxies

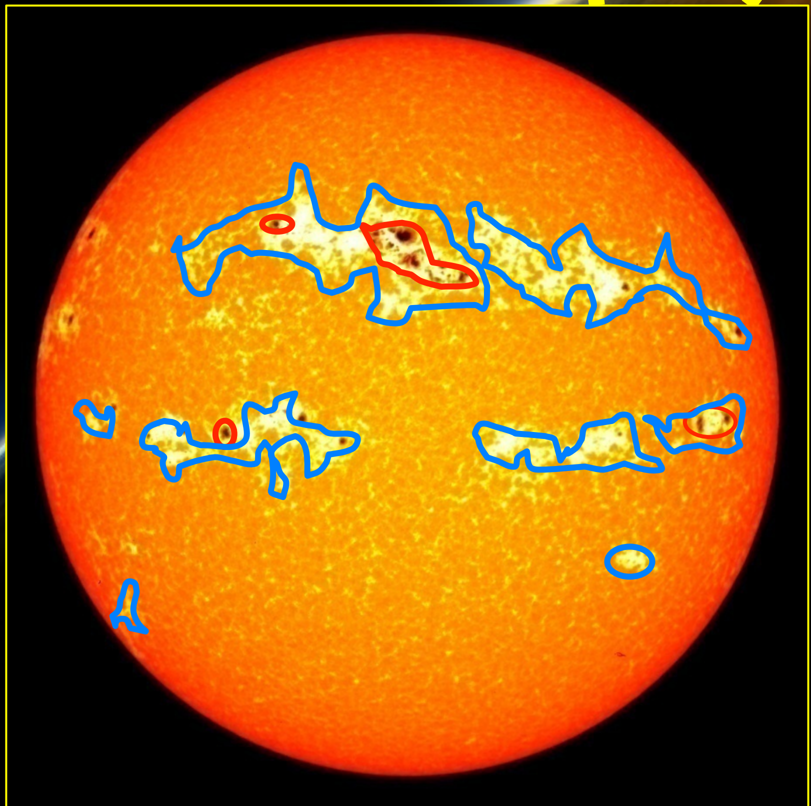


PROXY MODELS

Combine sunspot darkening, e.g. PSI, with facular/plage/network brightening, Facular Proxy (e.g. Mg index, Ca II, F10.7) via linear or multiple regressions

$$S\,(t) = \kappa_1 PSI(t) + \kappa_2 FP(t)$$

≥ 2 free param.



SEMI-EMPIRICAL MODELS

1. Surface area coverage (filling factors) and ideally positions *(function of time)*

2. Brightness of each component *(function of wavelength and disc position)* calculated from semi-empirical model atmospheres

(e.g., Kurucz models, Fontenla et al. 1999, 2009, 2011; Unruh et al. 1999; Shapiro et al. 2010)

using spectral synthesis codes

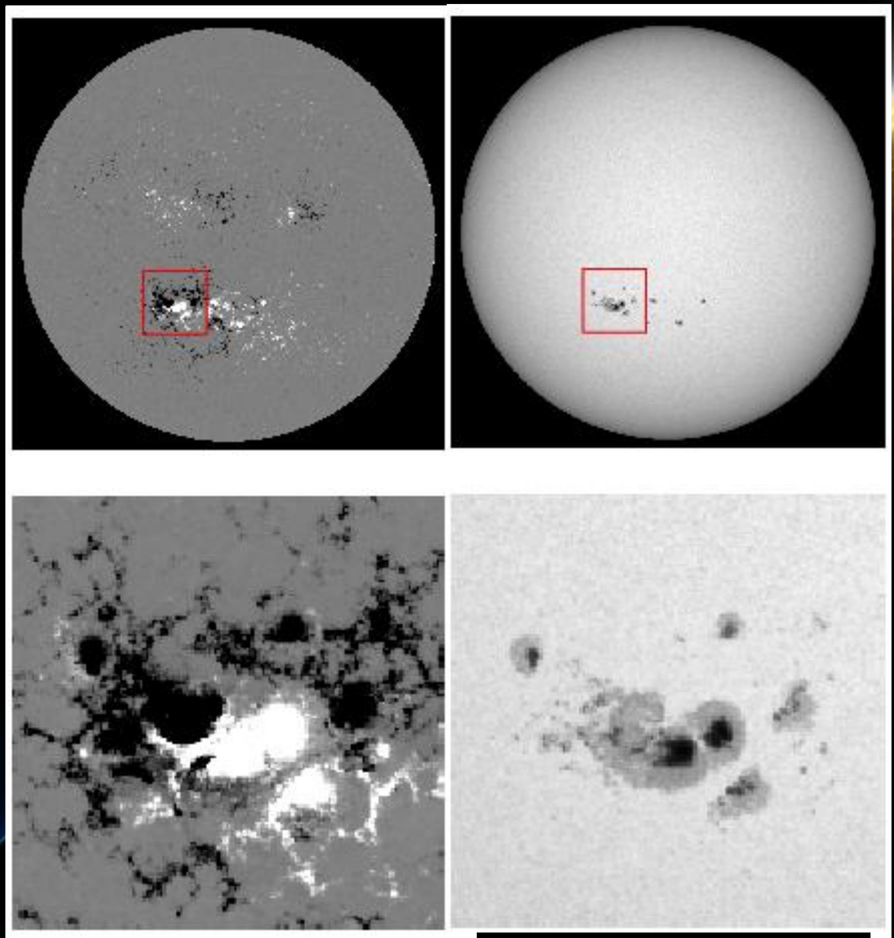
(e.g., SRPM, NESSY or ATLAS9, the latter uses LTE)

≥ 1 free param.

Spectral And Total Irradiance Reconstructions for the Satellite era (SATIRE-S)

Magnetograms and continuum images
KP/512, KP/SPM, SoHO/MDI, SDO/HMI

Intensity spectra from semi-empirical model atmospheres *Unruh et al. 1999*



Yeo et al. 2014

$$S(\lambda,t) = \Sigma_{i=0,N} \left(\alpha_i(t,\mu)\, I_i(\lambda,\mu)\right)$$

$$S(t) = \int S(\lambda,t)\, d\lambda$$

Components *(i)***:**
quiet Sun
sunspot umbrae
sunspot penumbrae
faculae & network

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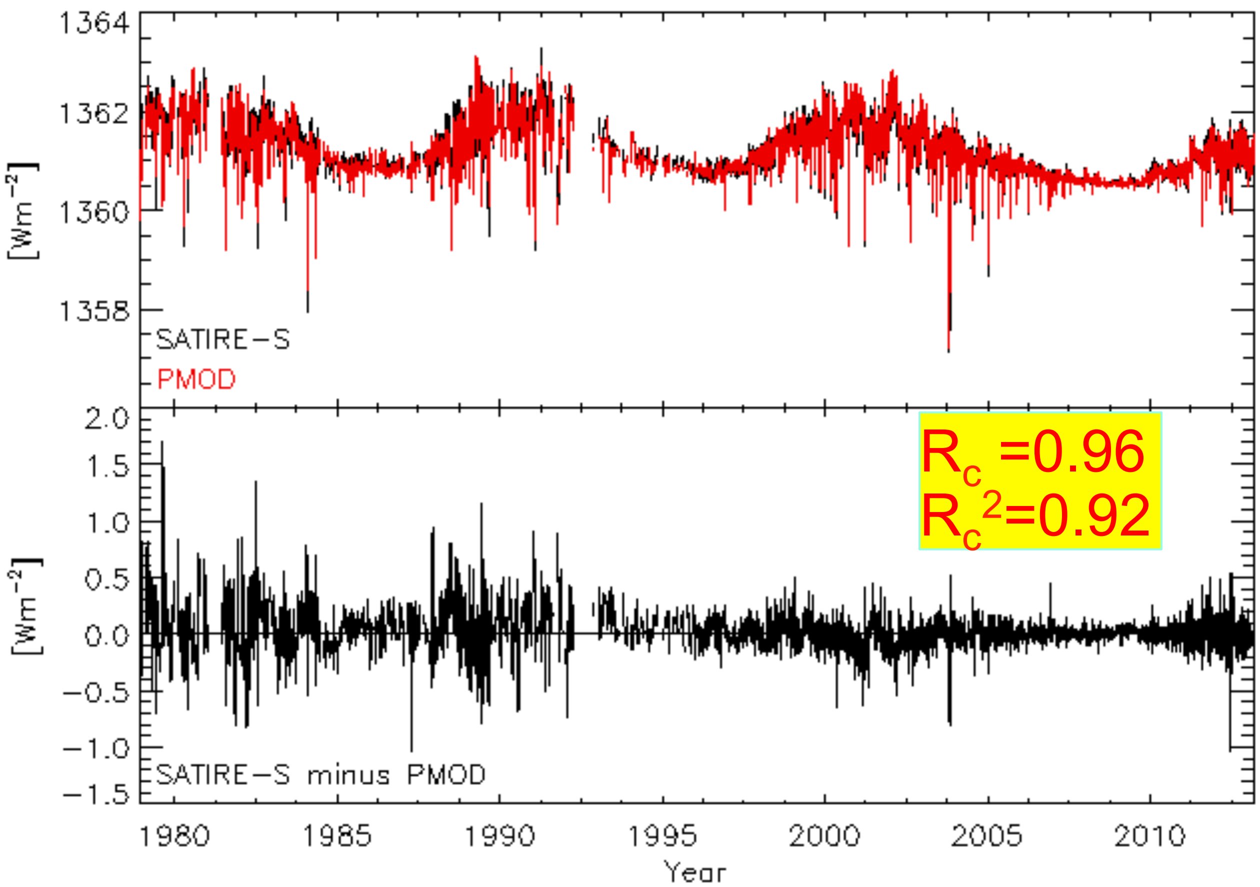

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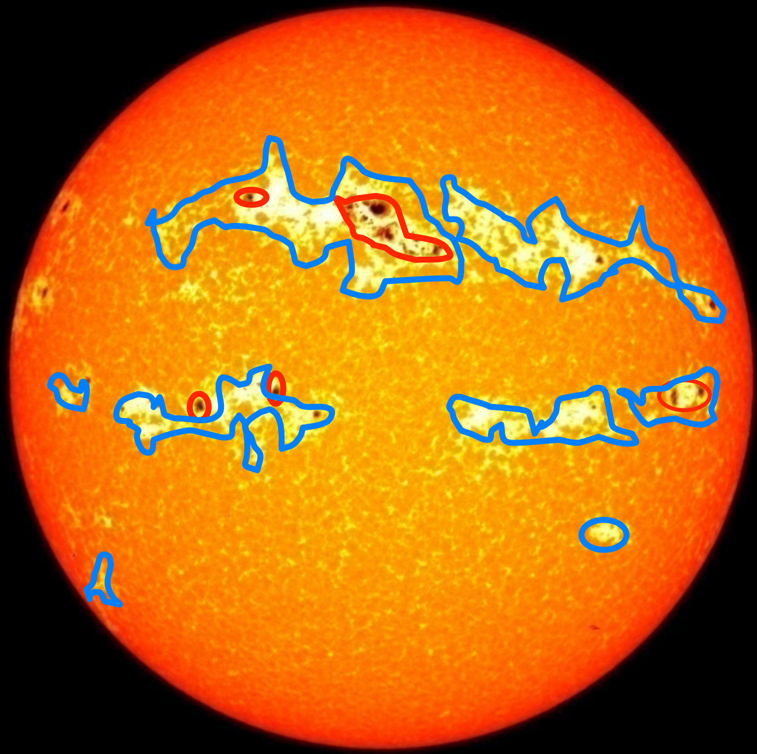
Yeo et al. 2014

Solar Data as Input to Irradiance Models



ALL CURRENT MODELS USE DATA:

to describe surface coverage and the distribution of different features *as a function of time*

• disc-integrated proxies:
sunspot number, area, plage area, Mg index, Ca II, F10.7, ^{10}Be, ^{14}C....

(NRLSSI, also SATIRE-T & SATIRE-H – i.e. before 1974, Shapiro et al. 2012)

• spatially resolved maps of the full disc:
magnetograms, continuum images, Ca II images...

(SATIRE-S, Fontenla et al. 2009, 2011, SFO & OAR models)

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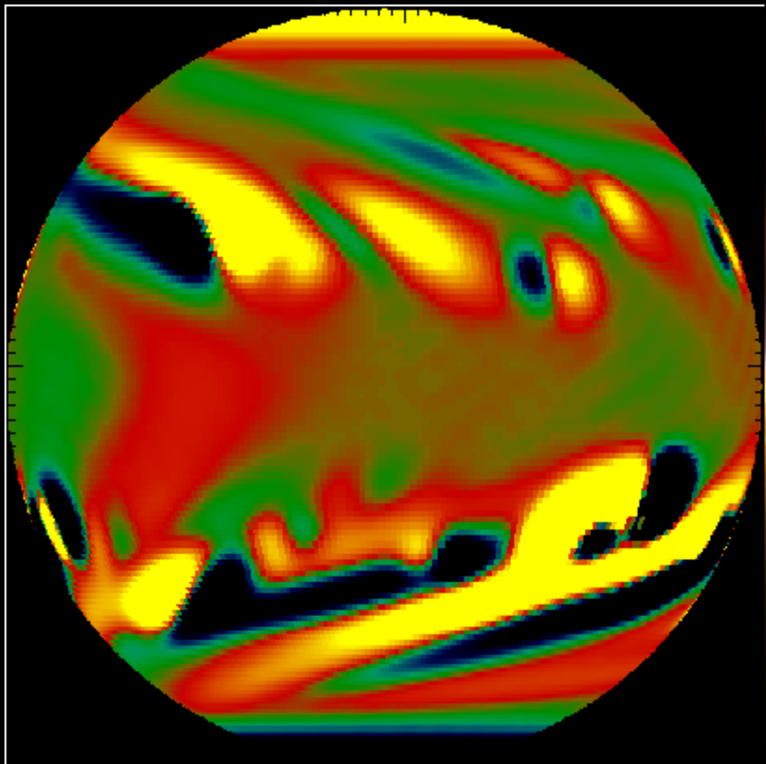

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Do not need to be from observations directly:

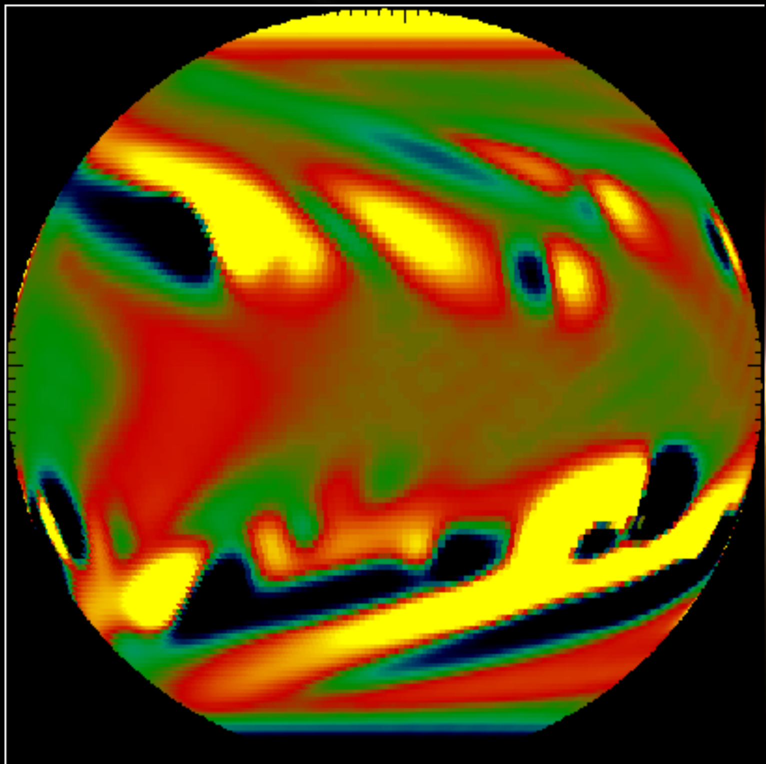
- Surface Flux Transport simulations

(Wang et al. 2005, Jiang et al. 2011, Dasi et al. 2014, 2016)

- Monte Carlo simulations

(Crouch et al. 2008, Bolduc et al. 2012)

Solar Data as Input to Irradiance Models



ALL CURRENT MODELS USE DATA:

to describe surface coverage and the distribution of different features *as a function of time*

But they are still fed with solar data, such as sunspot numbers, areas, positions...

(NR… , SATIRE-T & SATIRE-H – i.e. before 1974, Shapiro et al. 2012)

• spatially resolved maps of the full disc:
magnetograms, continuum images, Ca II images...

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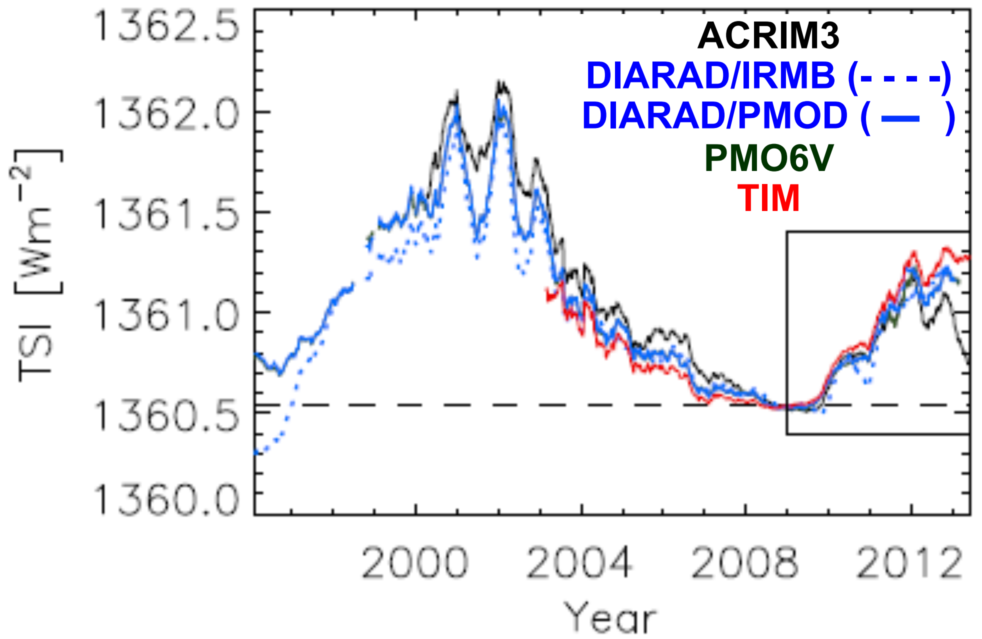
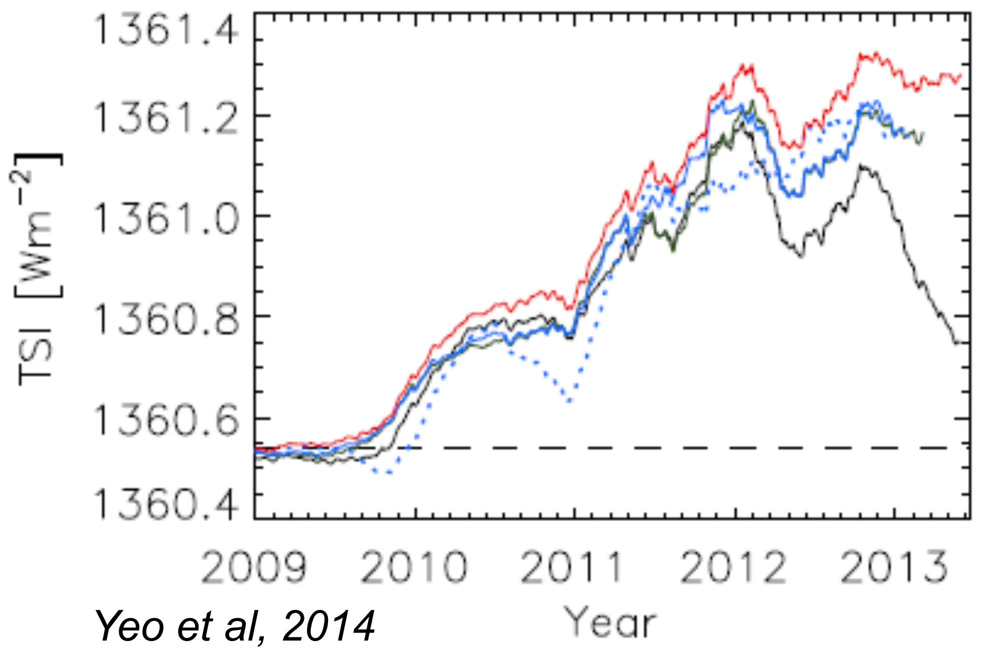
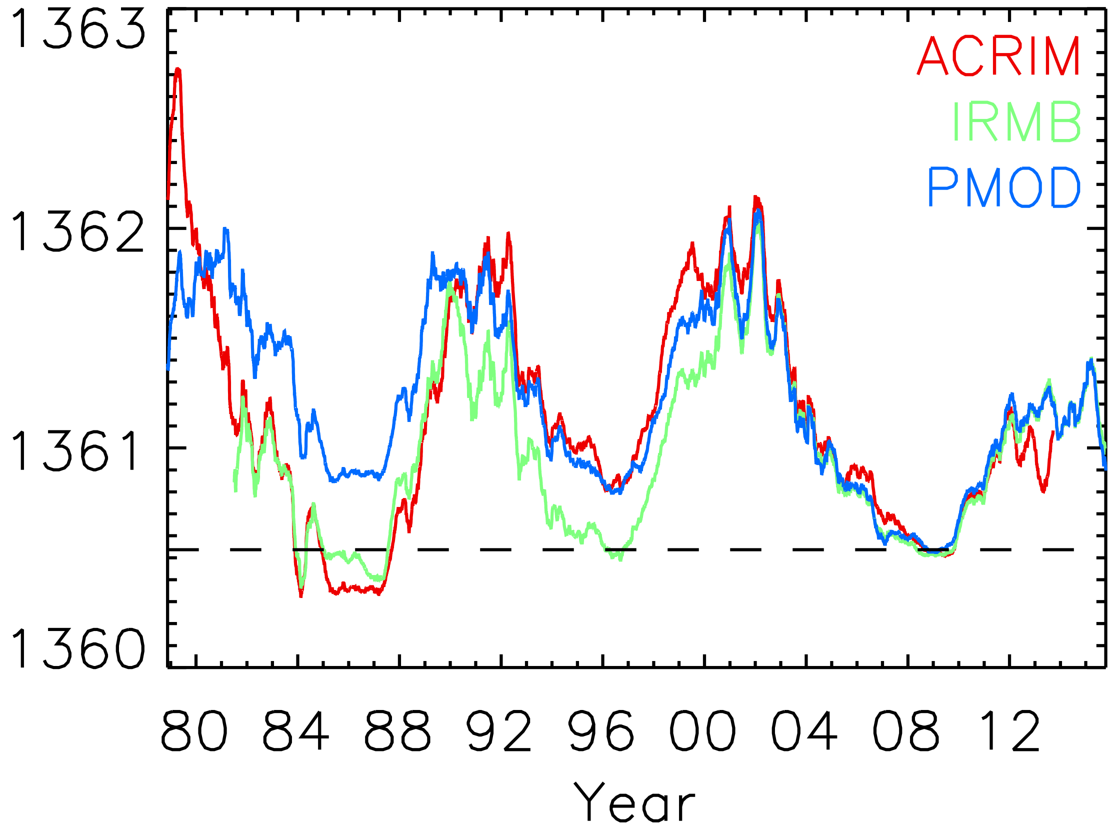
Models vs. Measurements



Free parameter(s) are fixed from comparisons with irradiance measurements



Yeo et al, 2014



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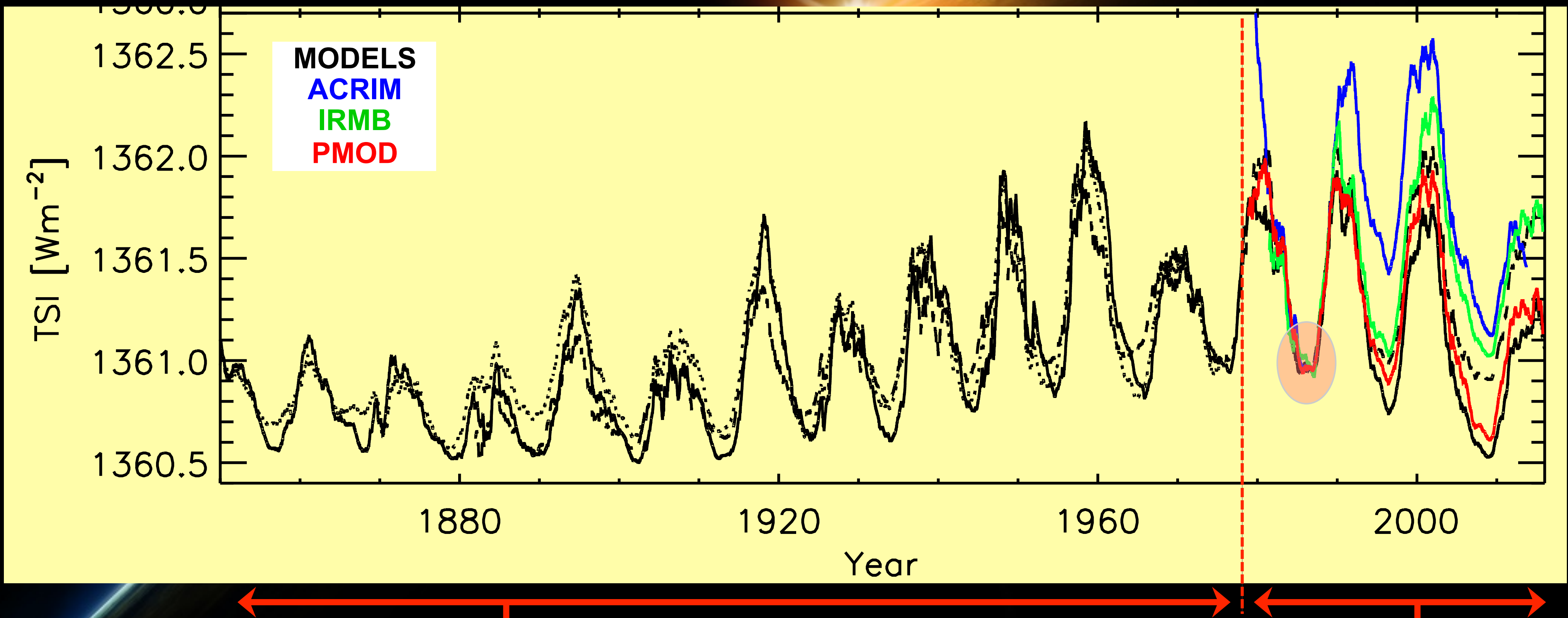
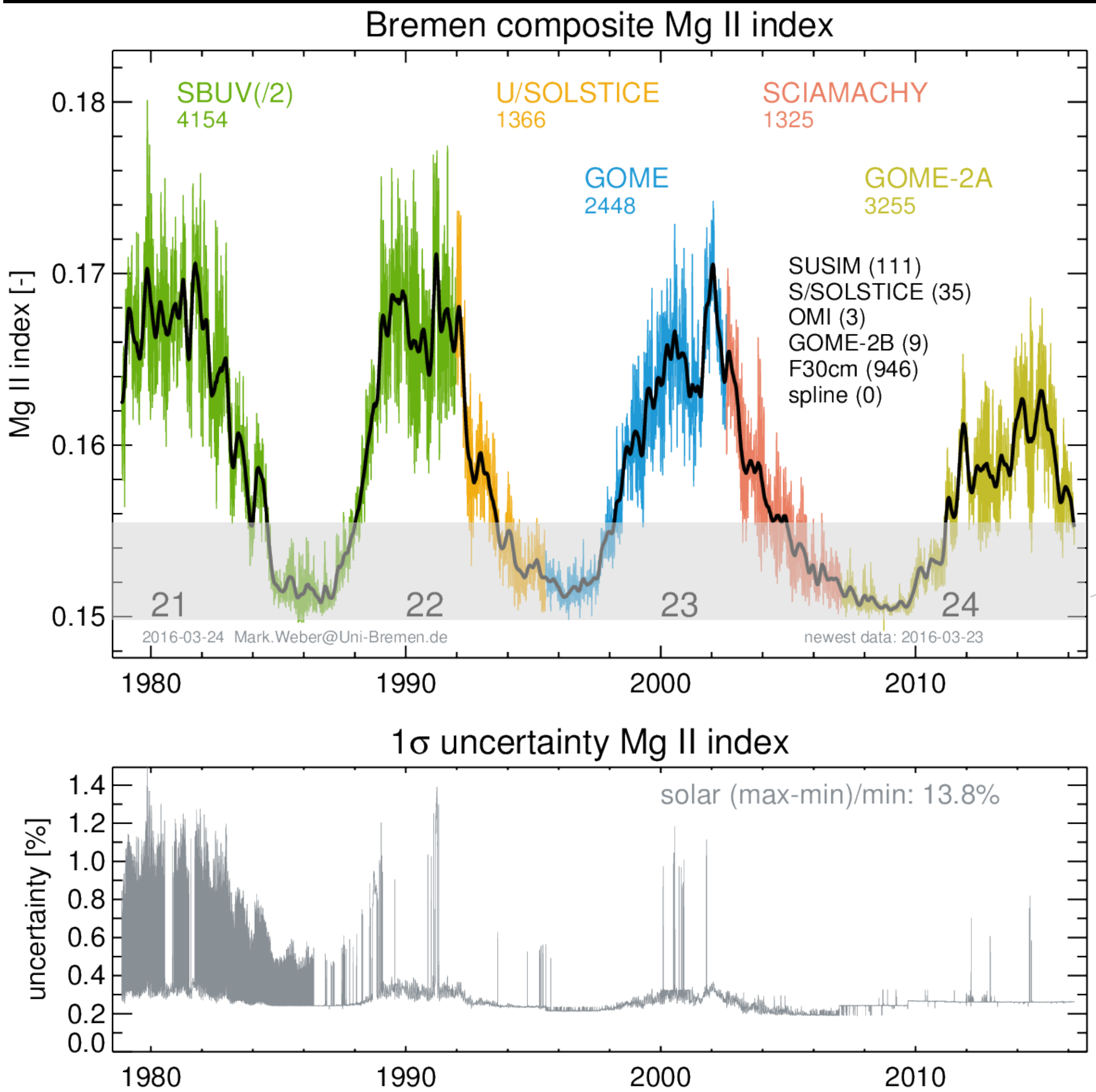


Sunspot Areas

Dashed: Sunspot Areas + Mg II
Solid: Mag. field (magnetograms)

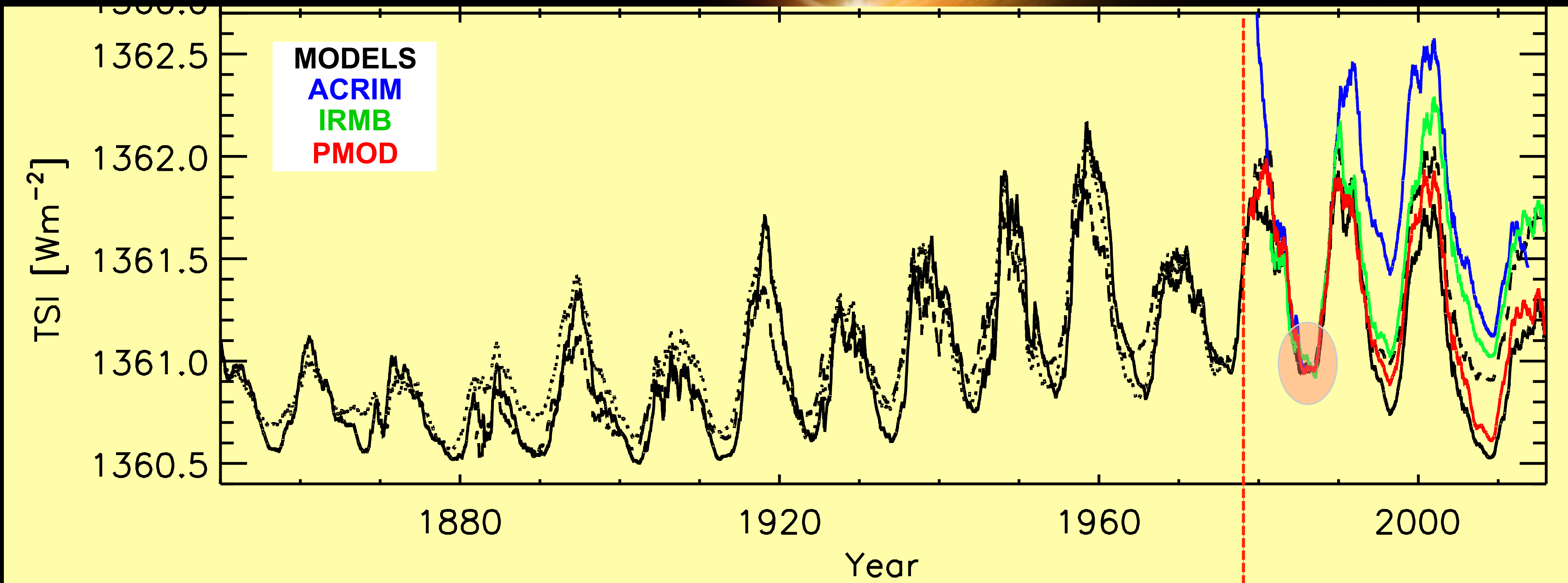
Long-term trend in Mg index



M. Weber

Models vs. Measurements

Different secular trends are primarily due to different inputs used (proxy vs. MF observations)



Sunspot Areas

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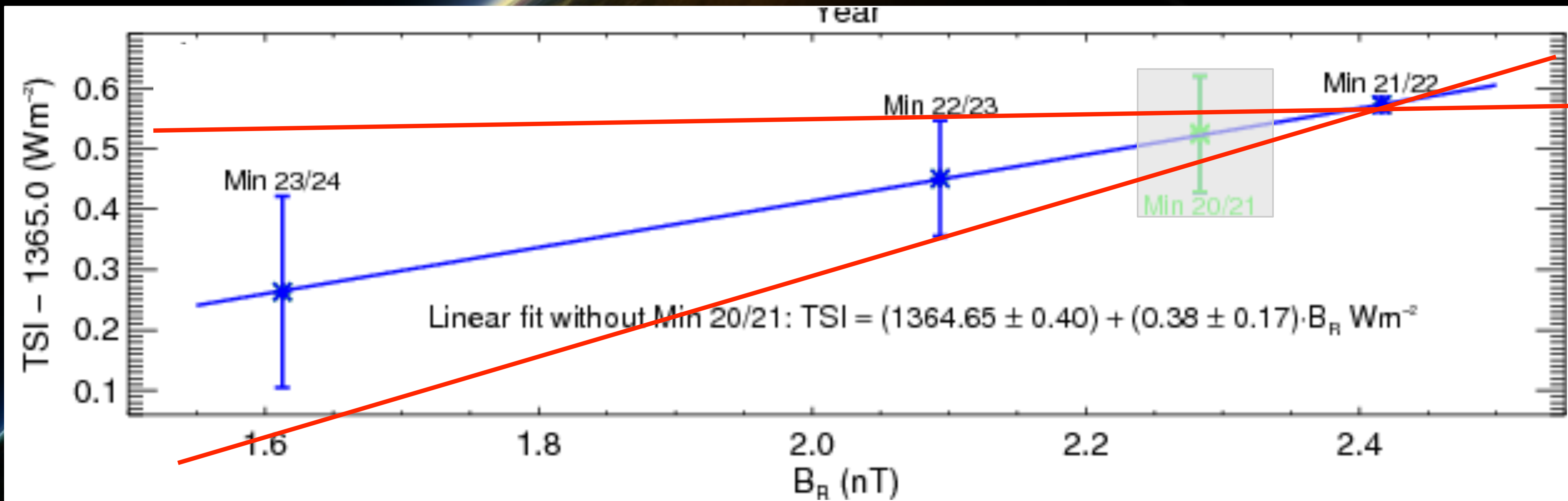
Models vs. Measurements: Long Term Extrapolations

Free parameter(s) are fixed from comparisons with irradiance measurements

Steinhilber et al. 2009: use linear relationship between the TSI and OF during last 3 minima



Models vs. Measurements: Long Term Extrapolations

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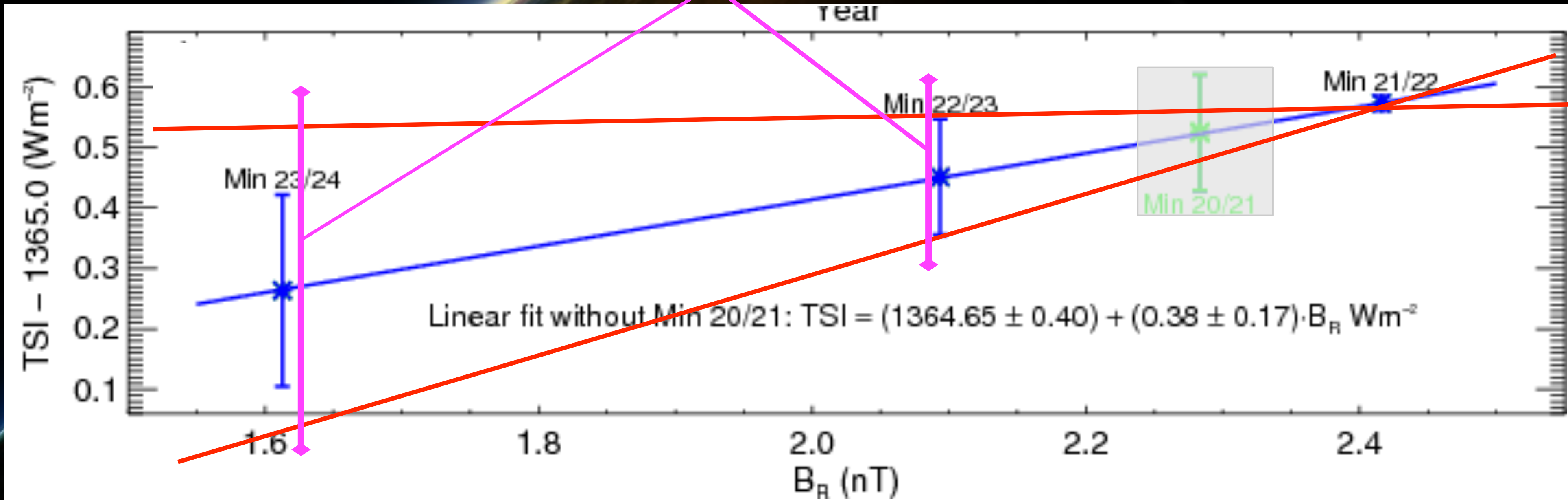
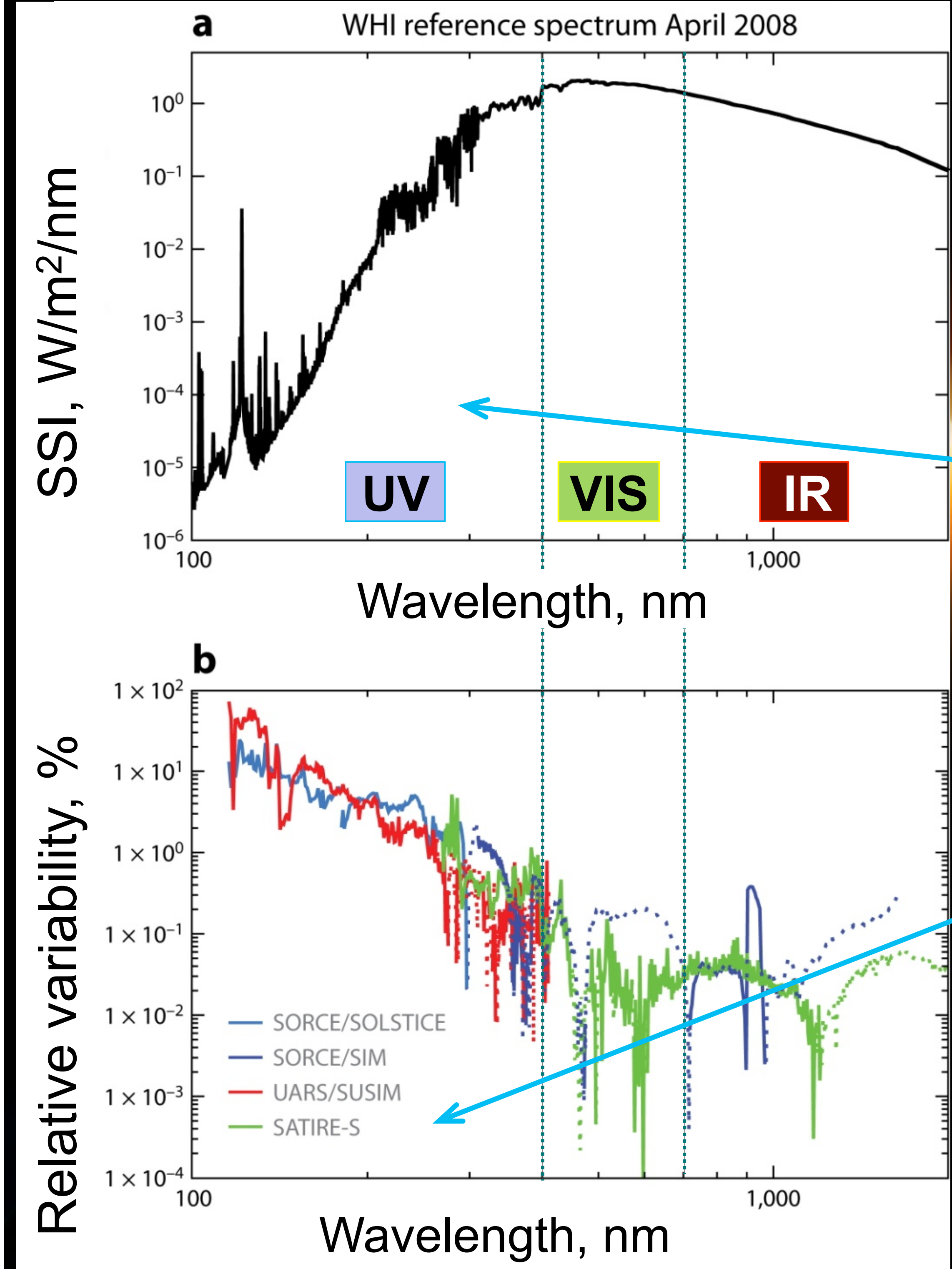
Difference between composites



Spectral Distribution of Irradiance Variability



Total energy:
<10%

Contribution to Variability:
ca.60%

Spectral Irradiance

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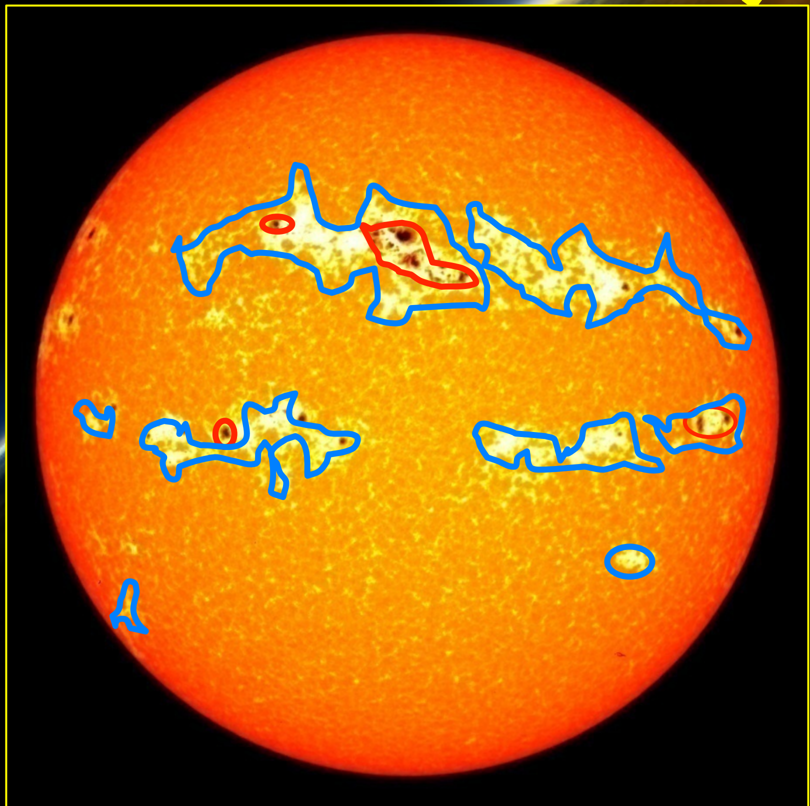


≥ 1 free param.

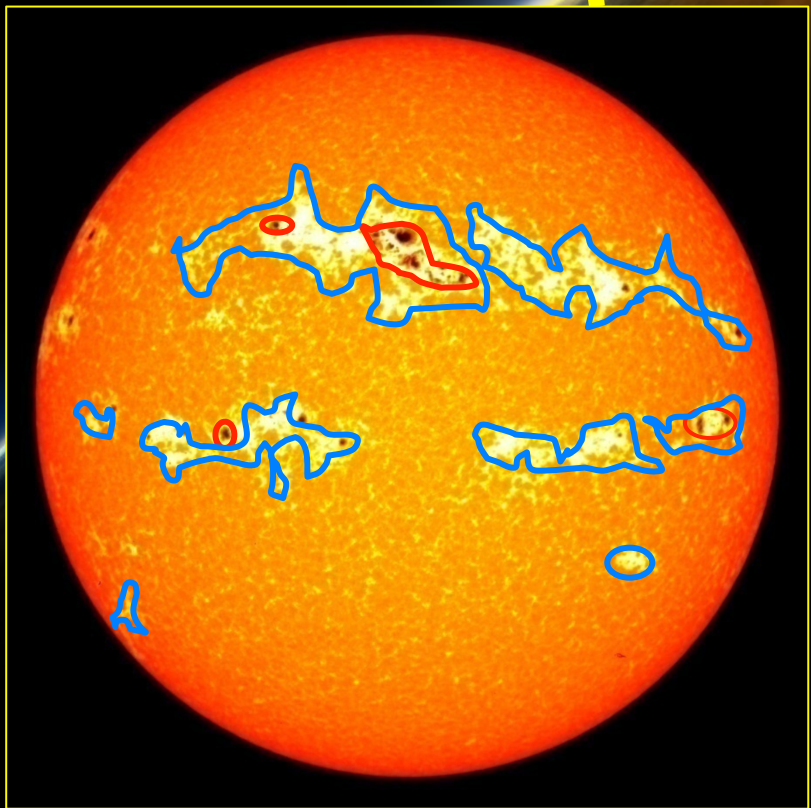
PROXY MODELS

Spectral Irradiance

Combine sunspot darkening, e.g. PSI, with facular/plage/network brightening, Facular Proxy (e.g. Mg index, Ca II, F10.7) via linear or multiple regressions

$$S(t) = \kappa_1 PSI(t) + \kappa_2 FP(t)$$

≥ 2 free param.



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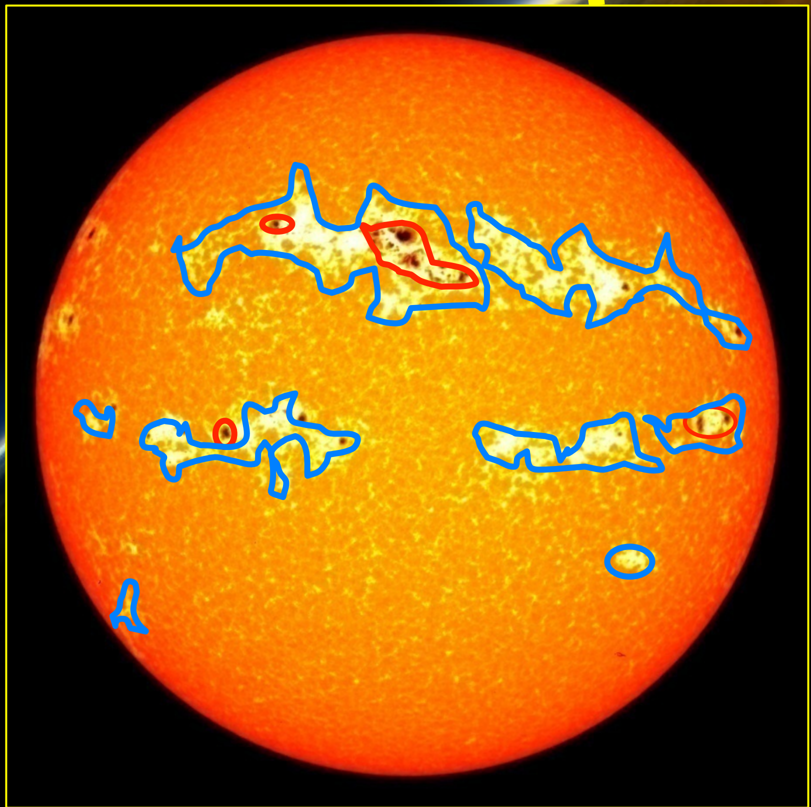
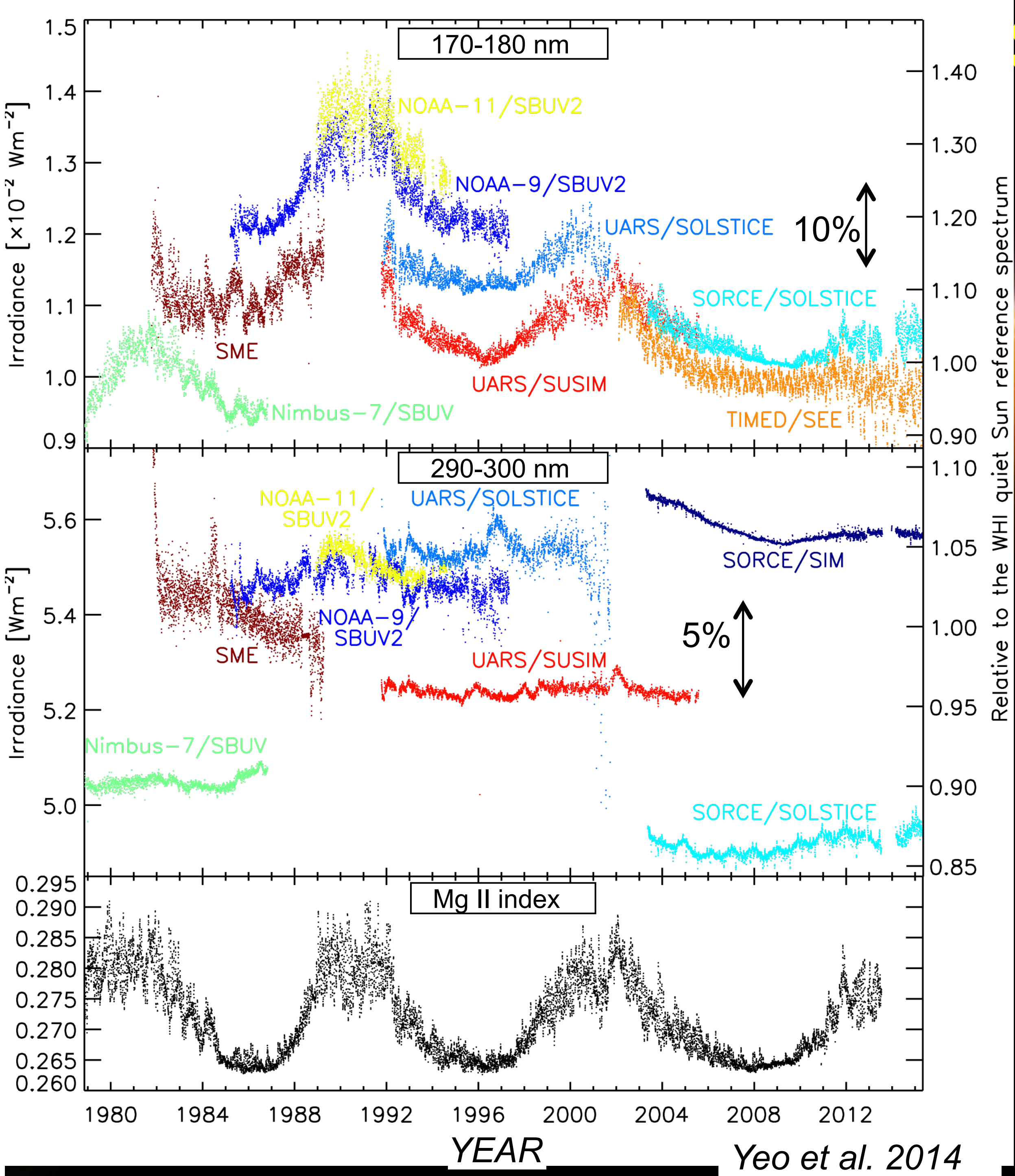
$$S(\lambda,t)=\kappa_1(\lambda)PSI(t)+\kappa_2(\lambda)FP(t)$$

≥ 2 free param. at each λ



- **Proxy** models use SSI observations;
- Need measurements at each wavelength;
- Have multiple free parameters;

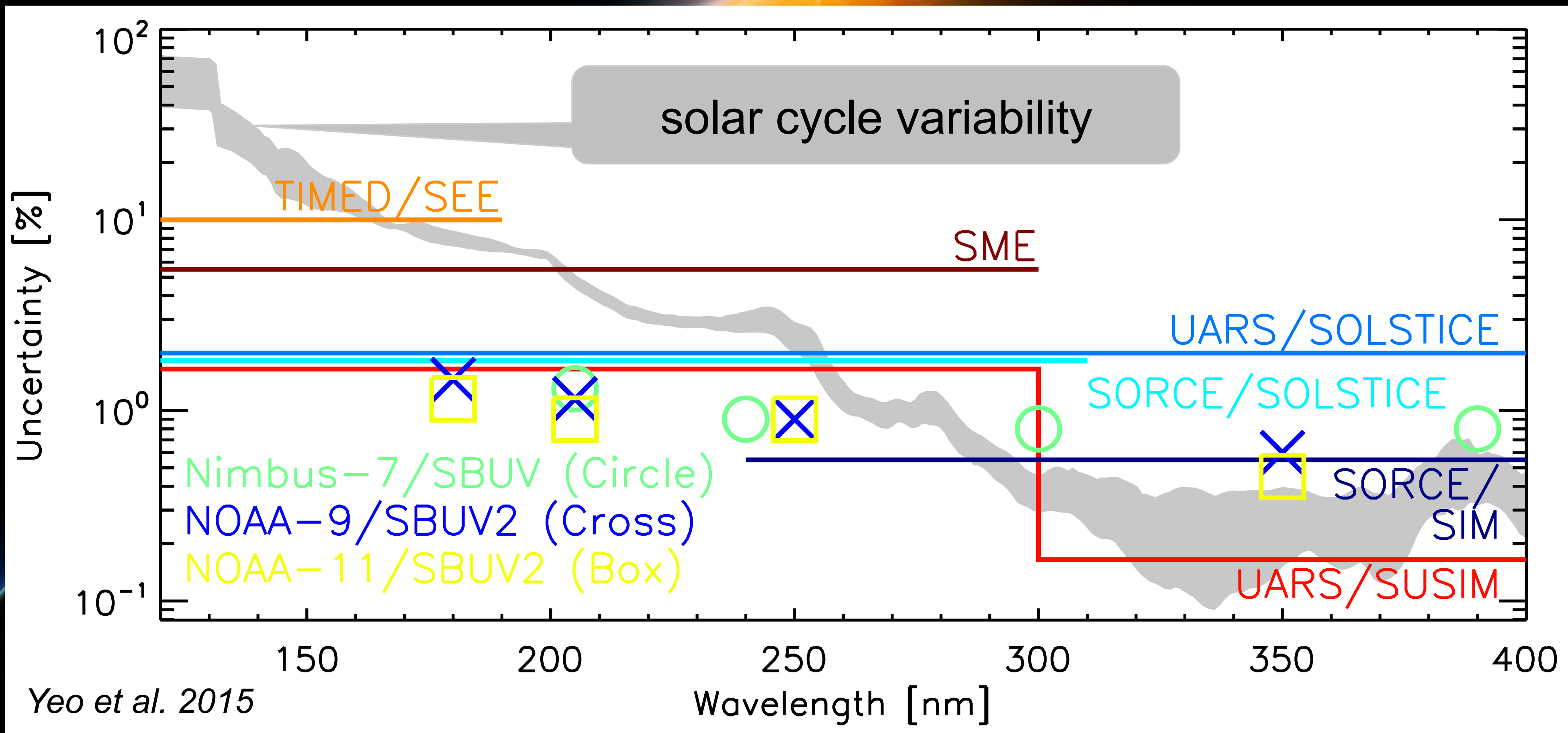
Spectral Irradiance: Measurements



- SSI changes;
- In the UV – in phase with the solar cycle;
- In the VIS - ?

Spectral Irradiance: Measurements

- Solar cycle variability above 250-300 nm ≤ uncertainty, for all instruments



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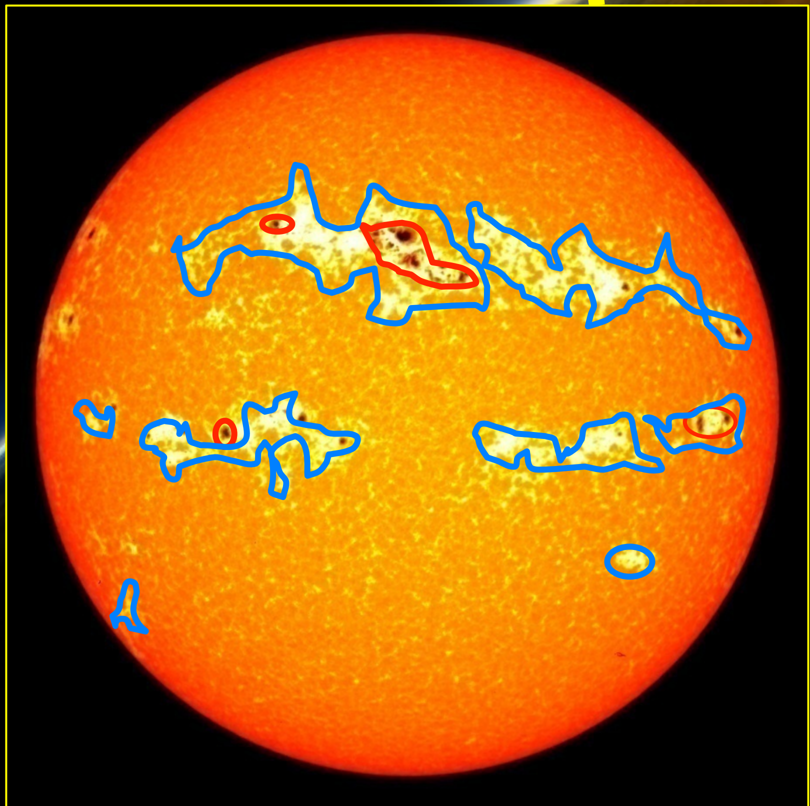
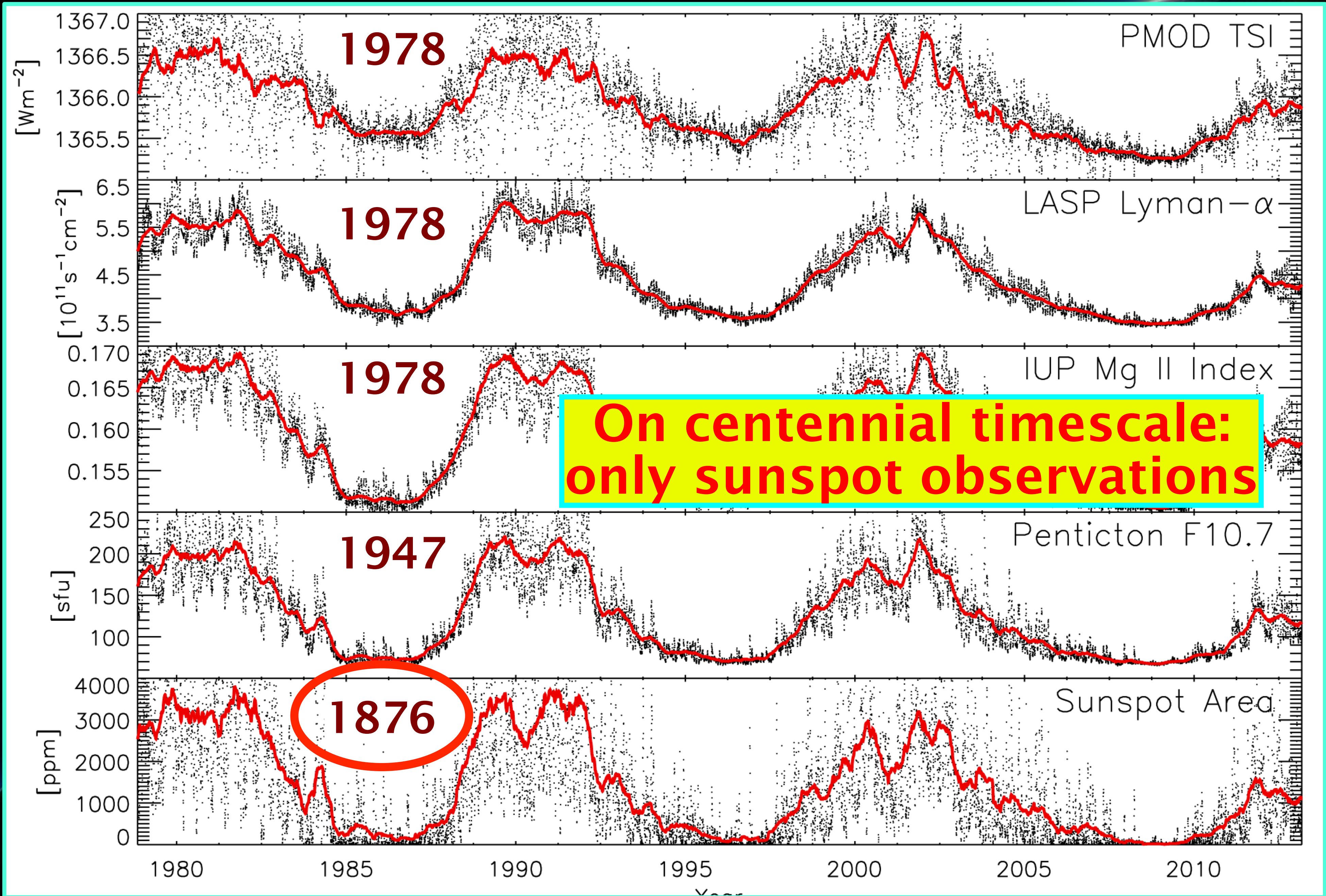


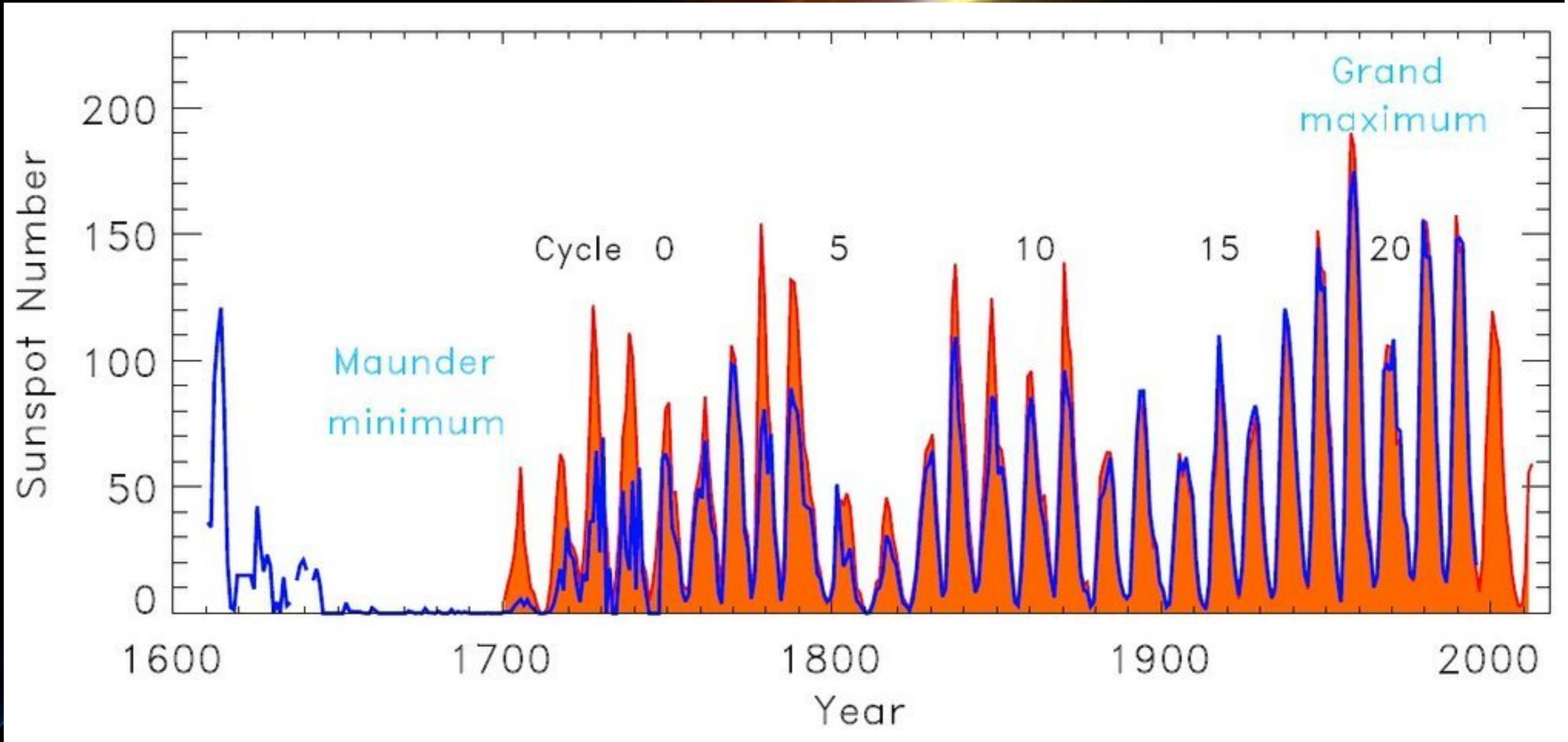
- **Proxy** models use SSI observations;
- Need measurements at each wavelength;
- Have multiple free parameters;
- Strongly dependent on measurement noise;
- Above 250 nm they have to assume that the rotational variability scales to longer time scales.

Going Back To The Maunder Minimum



Going Back To The Maunder Minimum

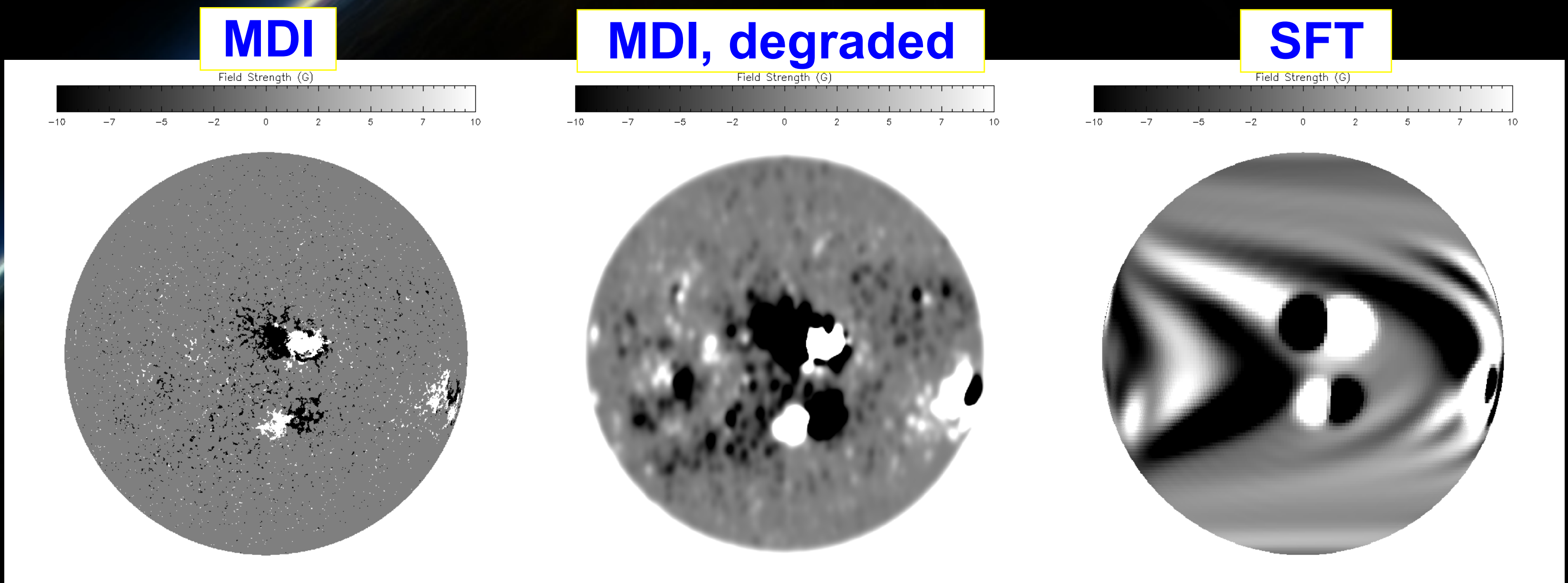
- **Sunspot number is the only available record**
- **Need to know the distribution of the total magnetic field on the surface**



Going Back To The Maunder Minimum

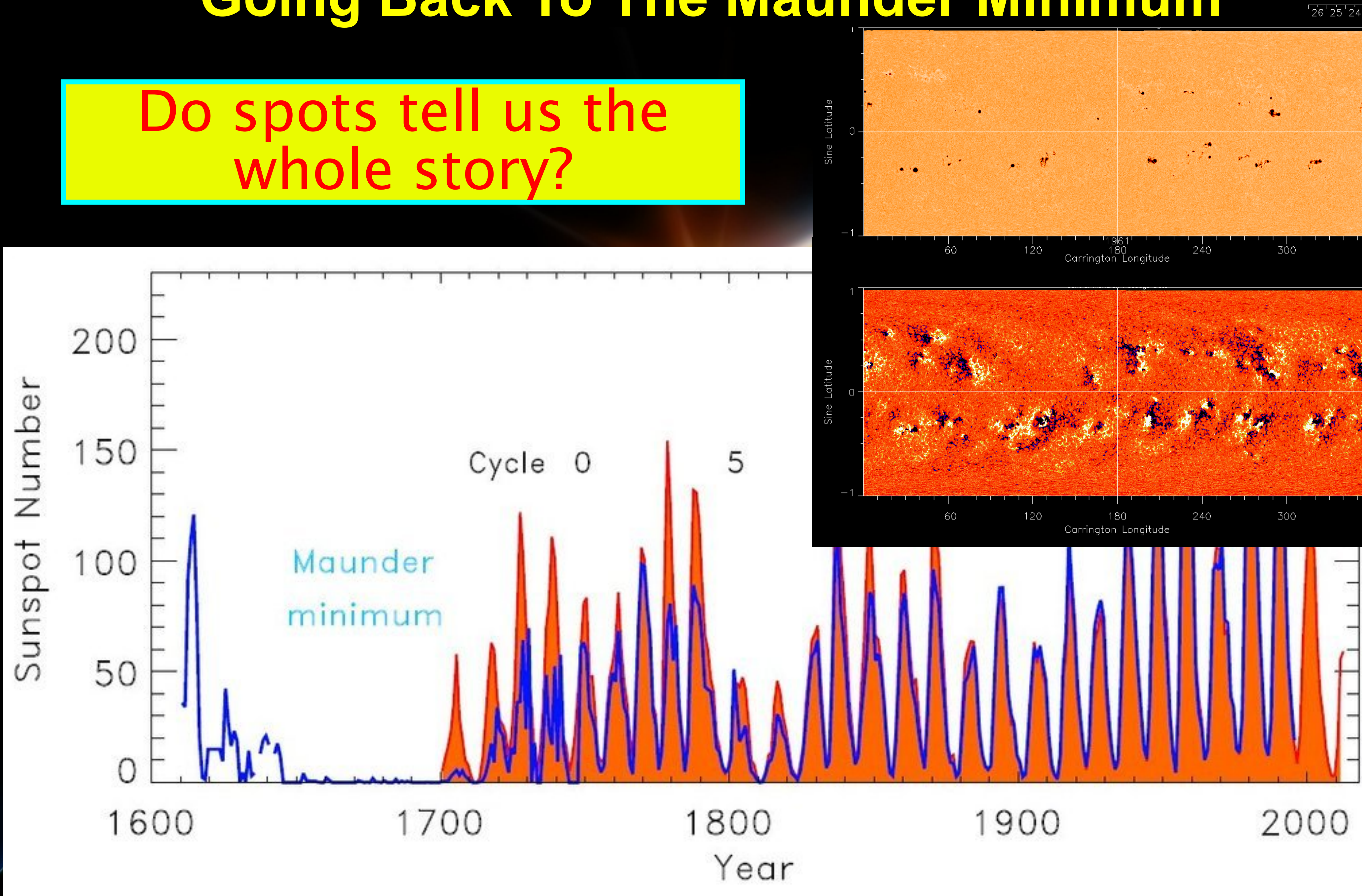
Magnetic flux in active regions

- Emergence is well described by sunspots;
- Evolution:
  - simple statistical relationships;
  - more sophisticated response functions;
  - Monte Carlo simulations;
  - more physical techniques:
    - ordinary differential equations or
    - Surface flux transport simulations



Going Back To The Maunder Minimum

Do spots tell us the whole story?



Going Back To The Maunder Minimum

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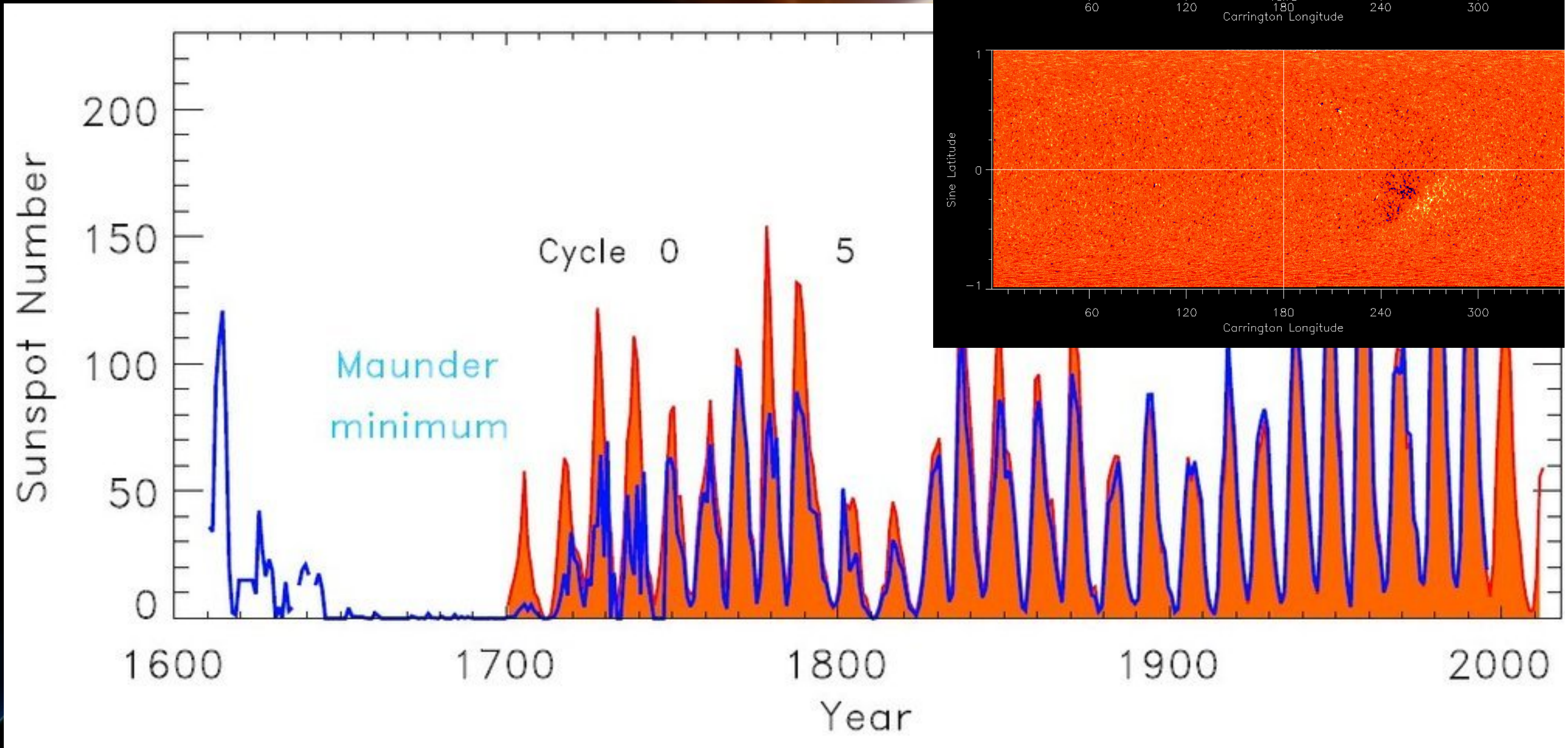
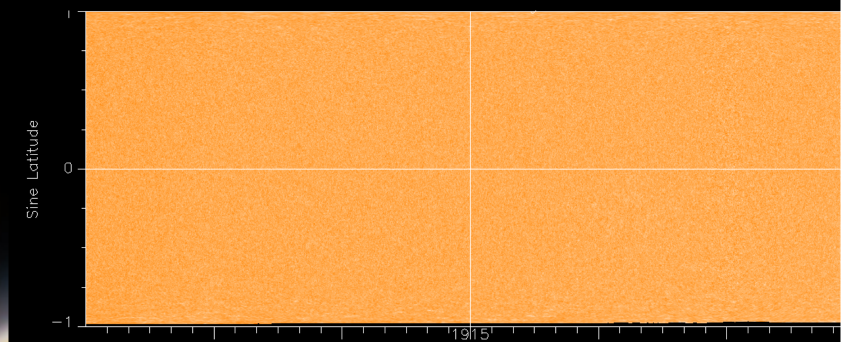


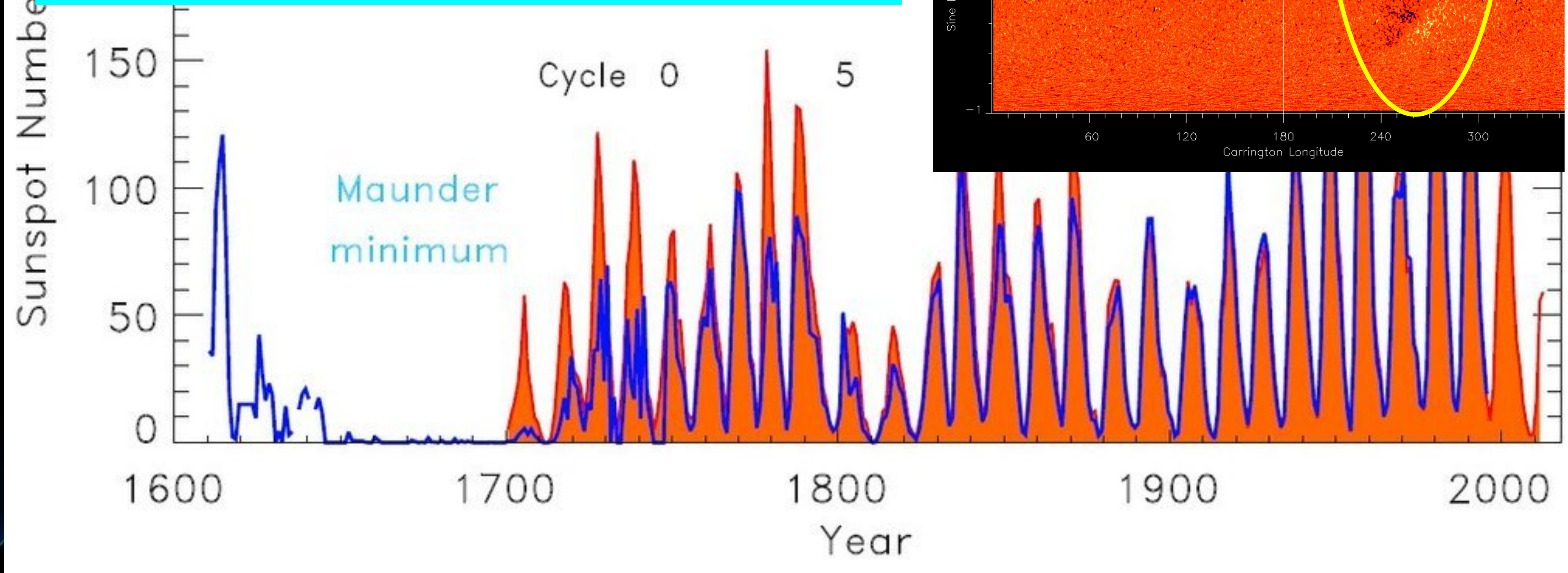


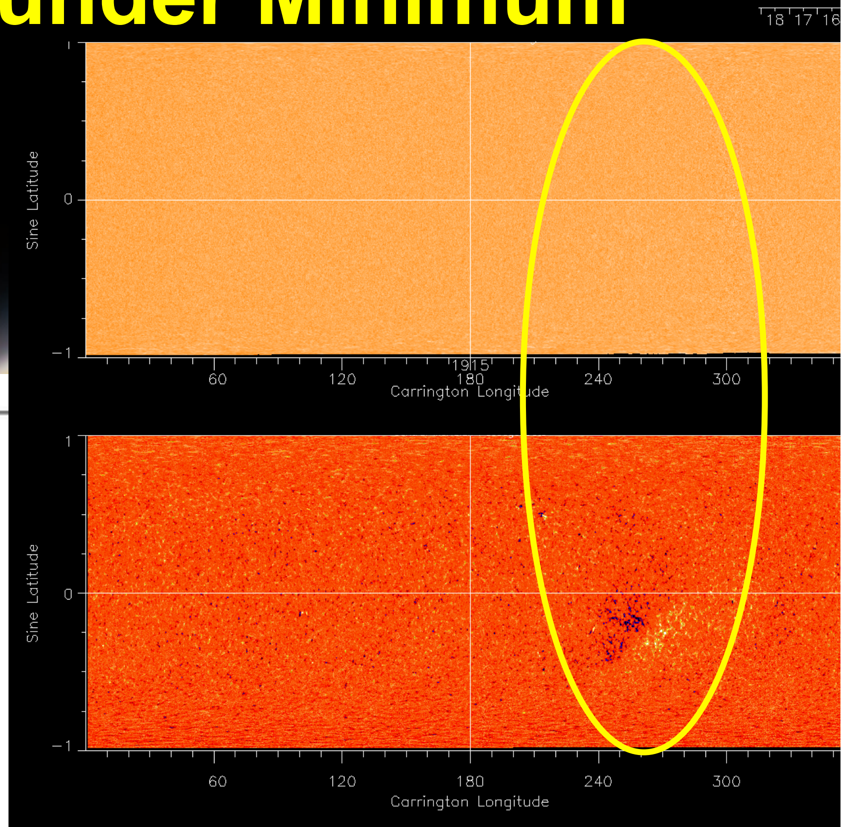
Going Back To The Maunder Minimum

Minima are particularly challenging

⬇

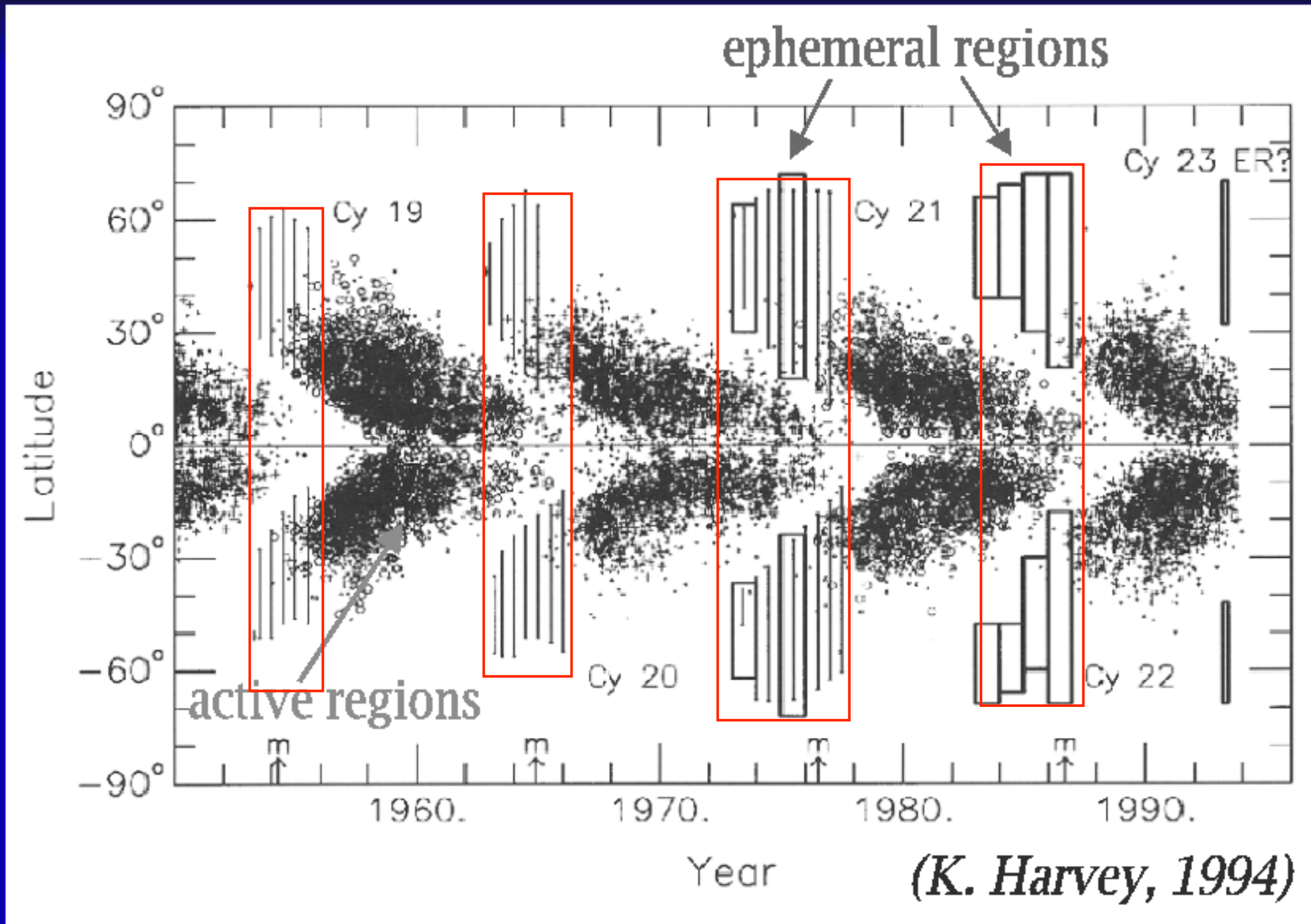
NO secular change, not even in the surface flux trasport models





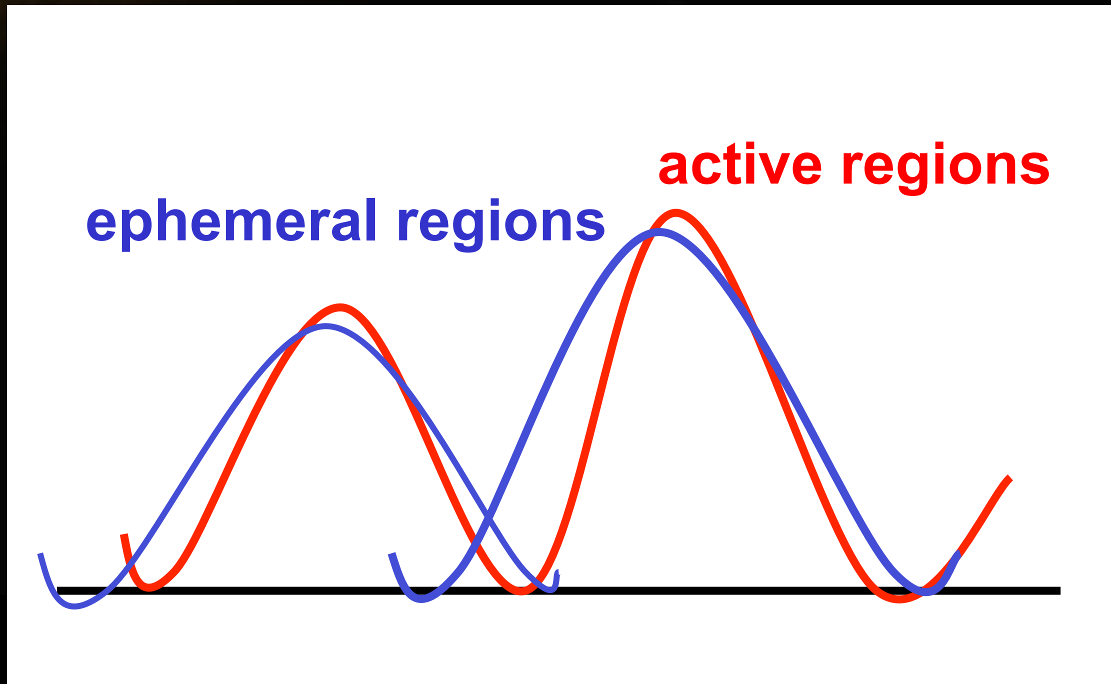
Modelling the secular change

Solar cycle:
sunspots vs. ephemeral regions



Modelling the secular change

- Cyclic flux emergence in active regions
- Take sunspot number as a `proxy´
- Cyclic flux emergence in ephemeral regions
- Extended and thus overlapping ER cycles



Solanki et al. 2002

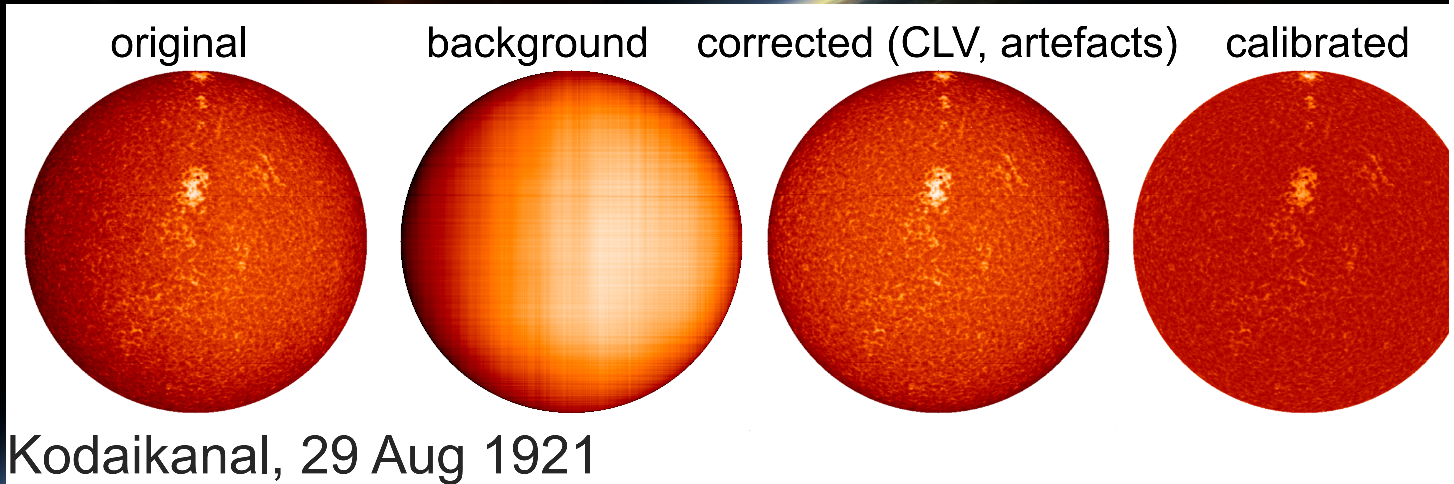
Modelling the secular change

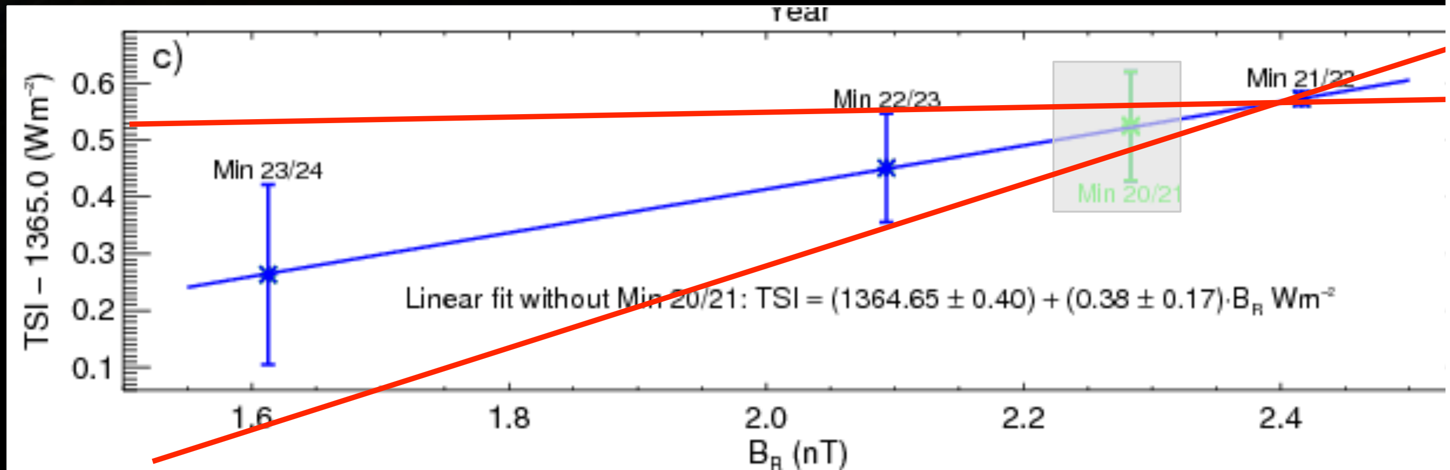
Alternatives:

- [Outlook] Analysis of historical Ca II images *(Th. Chatzistergos)*;

  must be properly processed and calibrated!

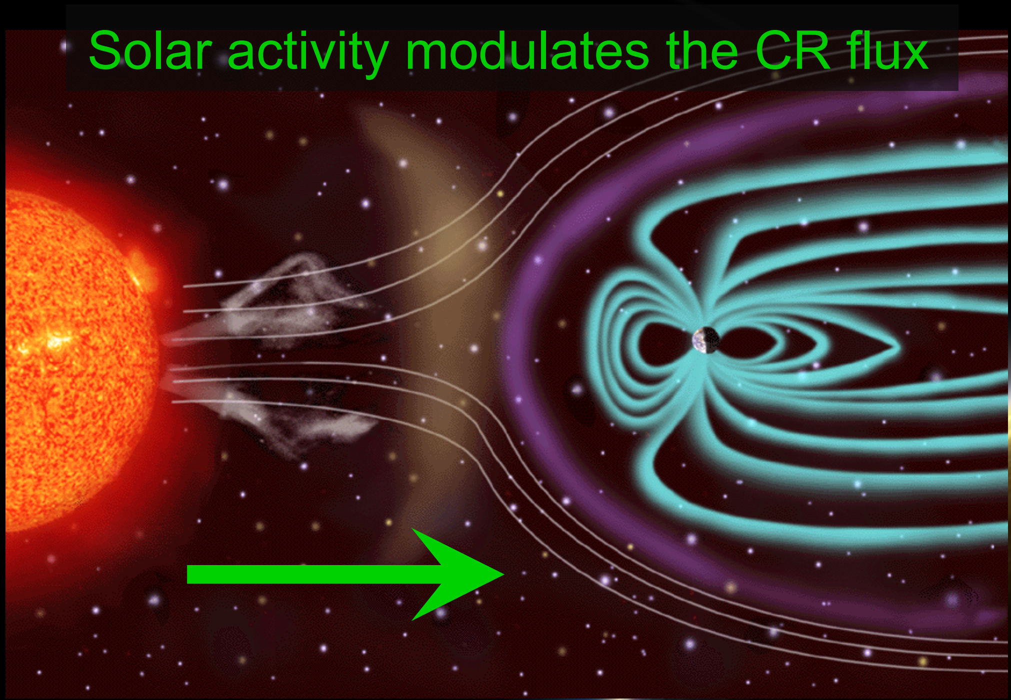
- Reconstructions from cosmogenic isotope data *(K. McCracken)*; but no simple linear regressions!



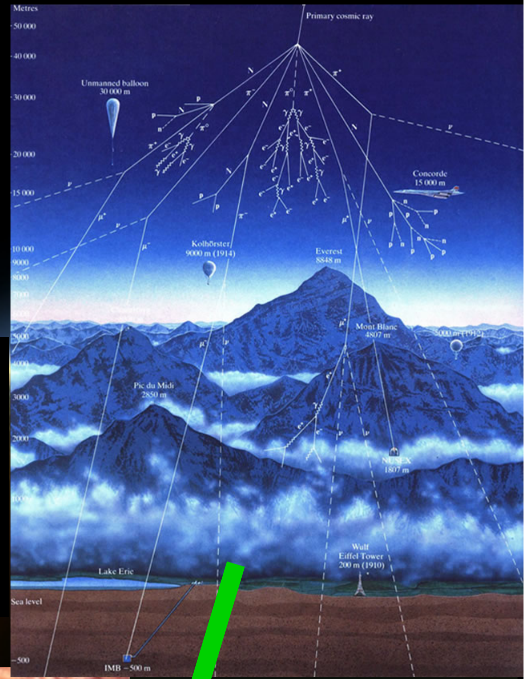


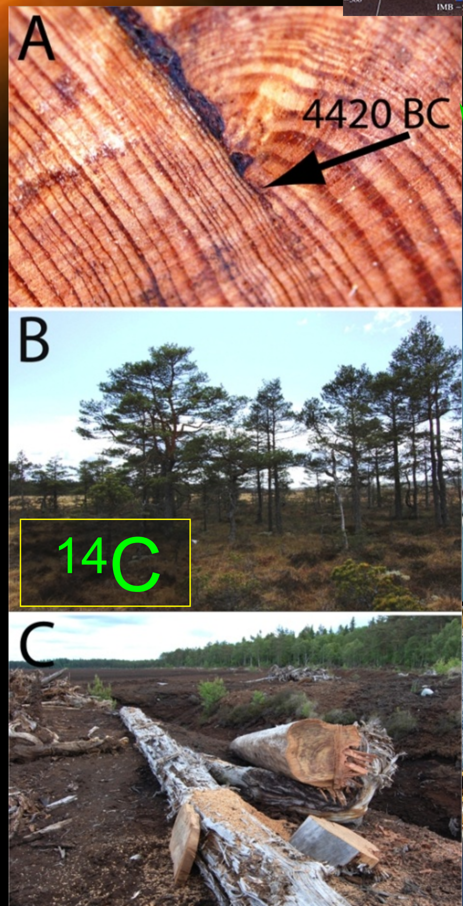
Millennial timescales

Solar activity modulates the CR flux

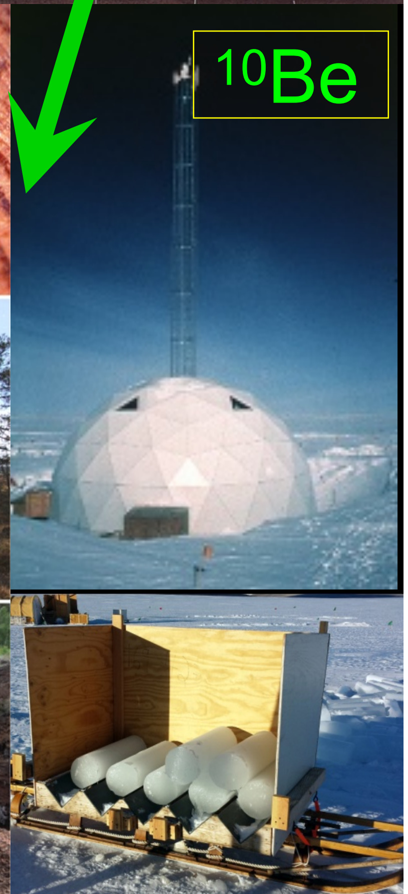


Production of cosmogenic isotopes, e.g. ^{14}C and ^{10}Be



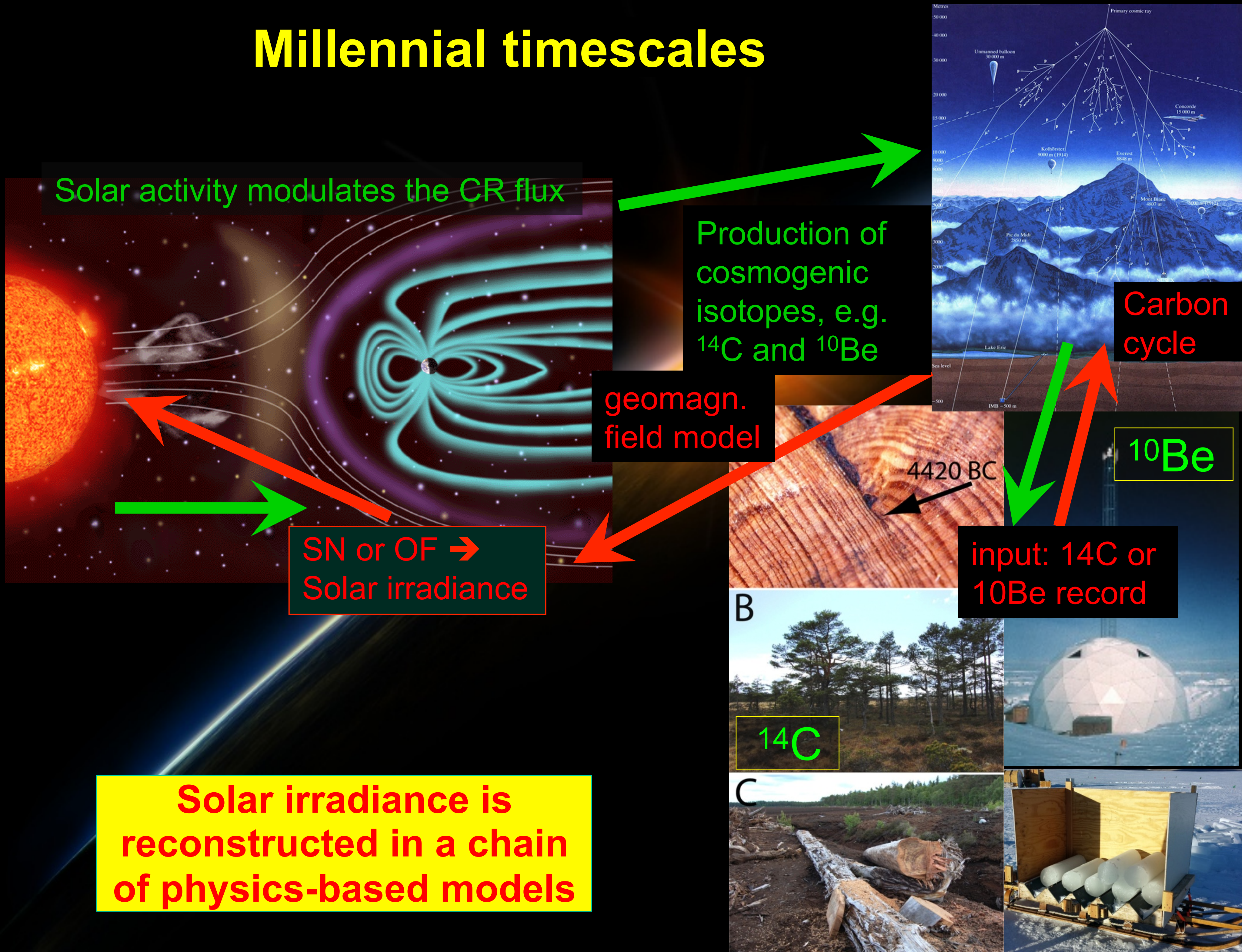


^{14}C



^{10}Be

Millennial timescales

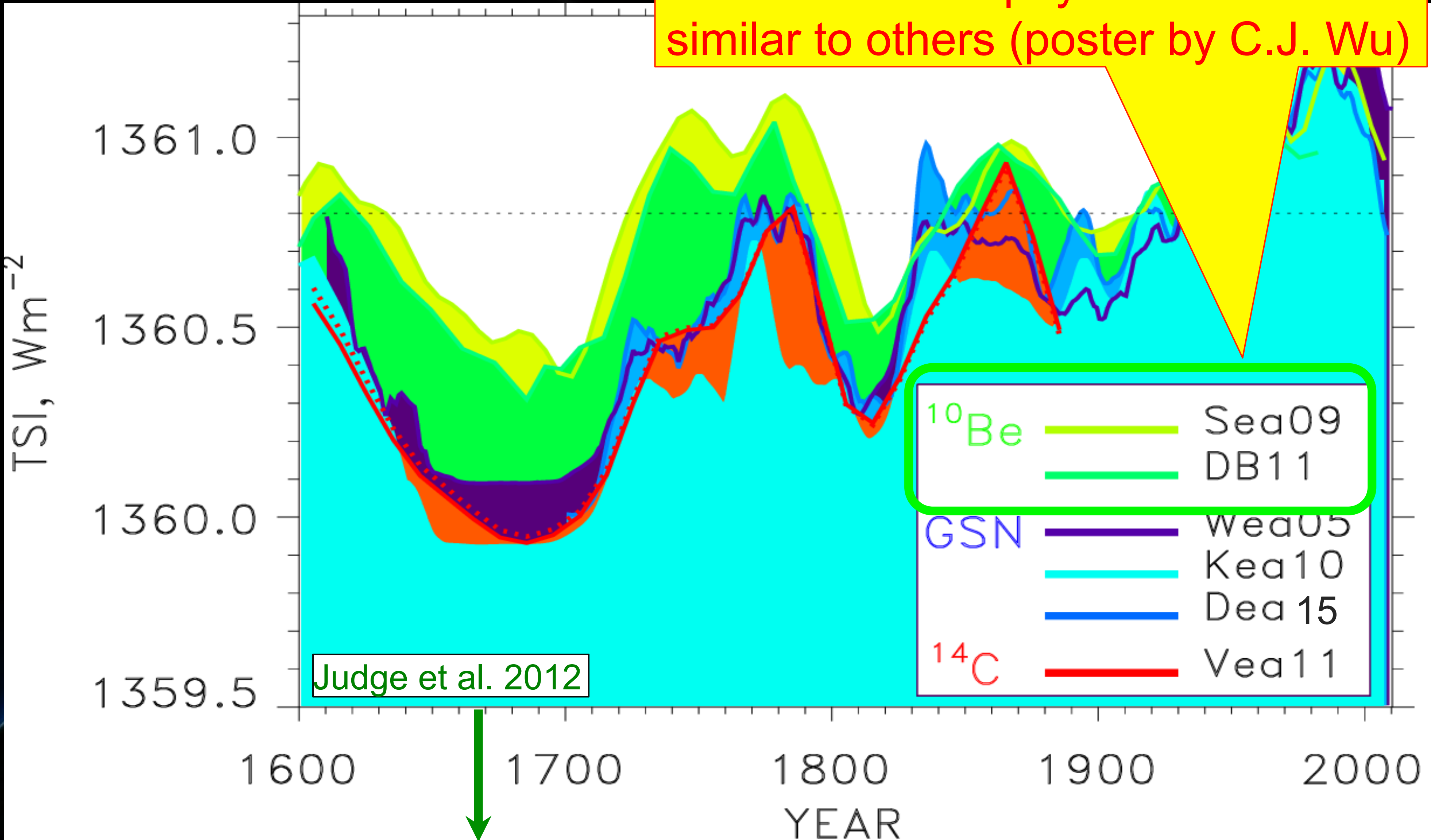


Solar irradiance is reconstructed in a chain of physics-based models

TSI since the Maunder Minimum

Both 10Be-based models are linear regressions;

When used in a physical model - similar to others (poster by C.J. Wu)



Summary

- All existing irradiance models use data:
  - as input
    - space era - solar images / magnetic maps, Mg II index, F10.7;
    - telescope era - sunspot areas, numbers;
    - Holocene - cosmogenic isotopes
  - or to fix their free parameters
    - TSI in all models;
    - + SSI in empirical models
- ... thus taking over their uncertainties
- partly amplifying them (purely empirical models)
- but partly also reducing (more physics-based models)


Thank You!