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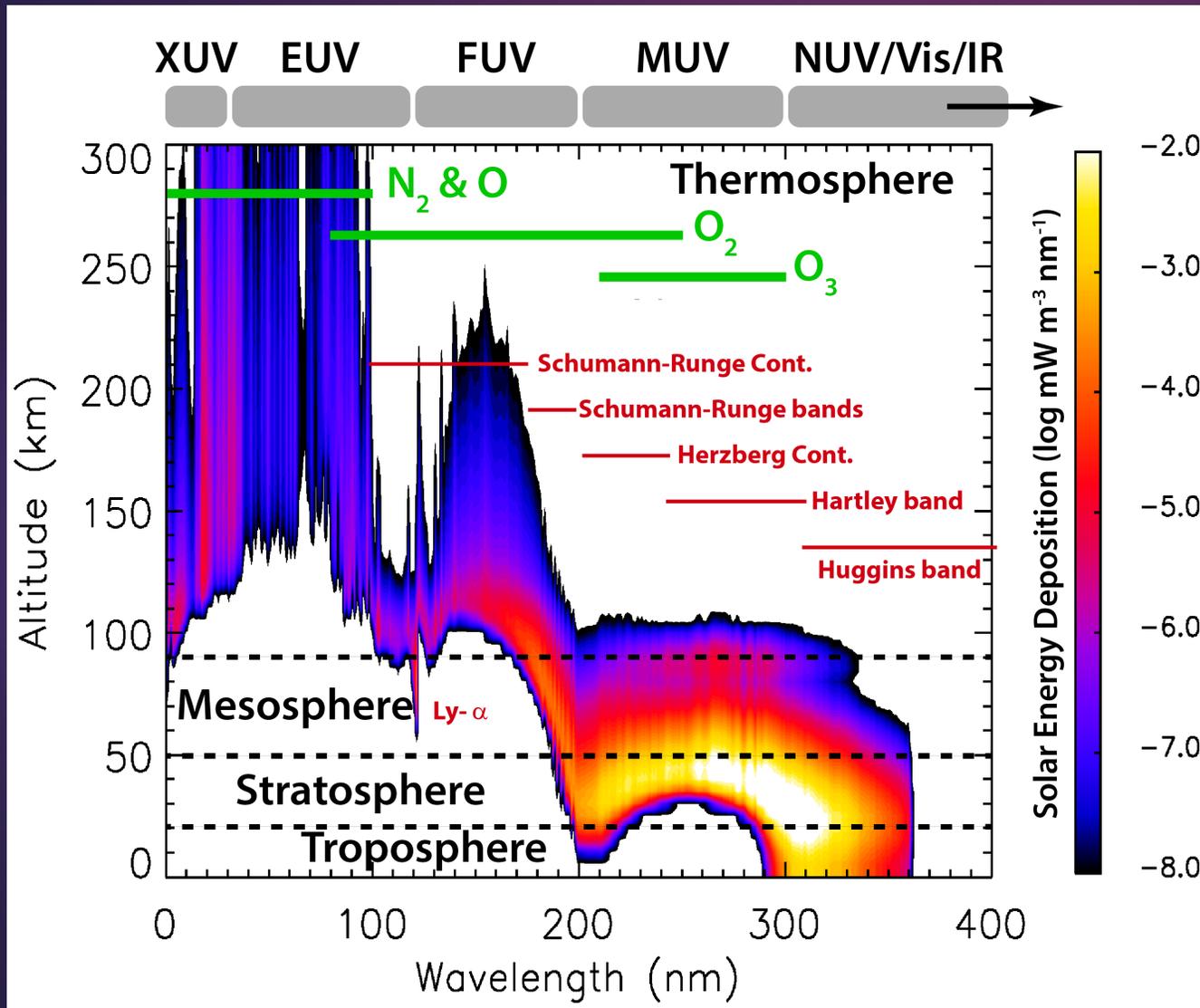


# Recent and Historical reconstructions of Solar UV variability

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# The importance of UV radiation



EUV-UV radiation is absorbed from the higher layers of the Earth atmosphere.

UV is responsible for photochemistry of molecular oxygen.

Generation of heating that produces winds, affecting the Troposphere. (Matthes 2017)

For similar reasons, it is important for the modeling of Exoplanets



EUV ionizes H, favoring atmospheric escape (stability of atmospheres)

O<sub>2</sub>, O<sub>3</sub>, CH<sub>4</sub>, CO<sub>2</sub>: good bio-markers, but abundances are regulated by Lya, FUV/NUV ratio. (e.g. Tian et al. 2014)

Recent Prebiotic studies indicate UV as favorable for life (origin of chirality, synthesis of amino acids, polymerization of RNA) (e.g. Ranjan et al. 2017)

UV spectra may provide signature of star-planet interaction (e.g. France et al. 2018)

Presence of planetary magnetospheres (e.g. Culey et al. 2015)

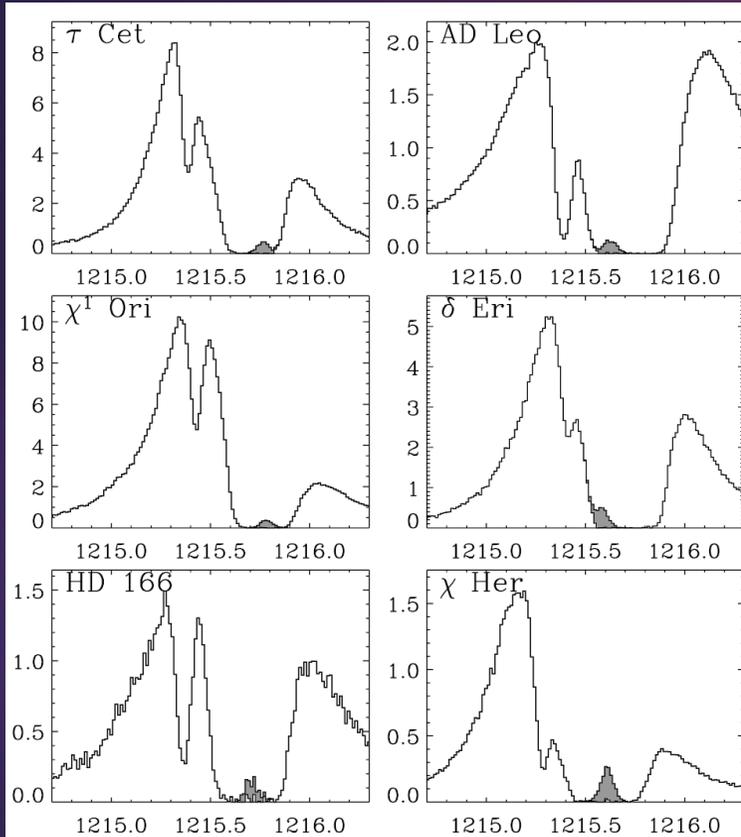
# Measuring UV, especially its variability, is extremely difficult!

## The Sun:

- Calibration and instrument degradation issues, hamper long-term studies.
- Measurements available only from space-era.

## The stellar case:

- Measurements are scarce (e.g. MUSCLE survey only includes less than 100 objects)
- Photospheric UV continuum is very low, very hard to observe
- Interstellar medium absorbs large part of the radiation, measurements strongly rely on models
- After Hubble, no mission scheduled in the near future to directly observe UV radiation



From Wood et al. 2005

# The UV color-index

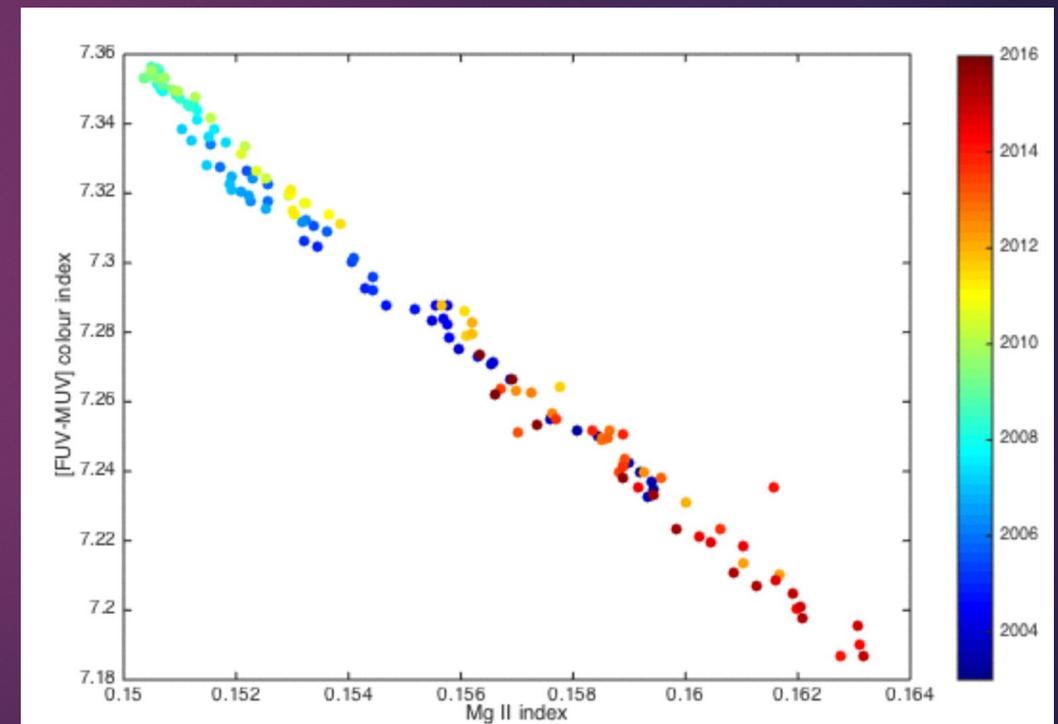
$$[FUV-MUV] = -2.5 \cdot \log \frac{F_{FUV}}{F_{MUV}}$$

FUV= [115-180 nm]

MUV = [180 – 310 nm]

The color index measures the slope of the Solar Spectral Energy Distribution in UV

The UV color index computed from SORCE observations well correlates with the Bremen MgII index.

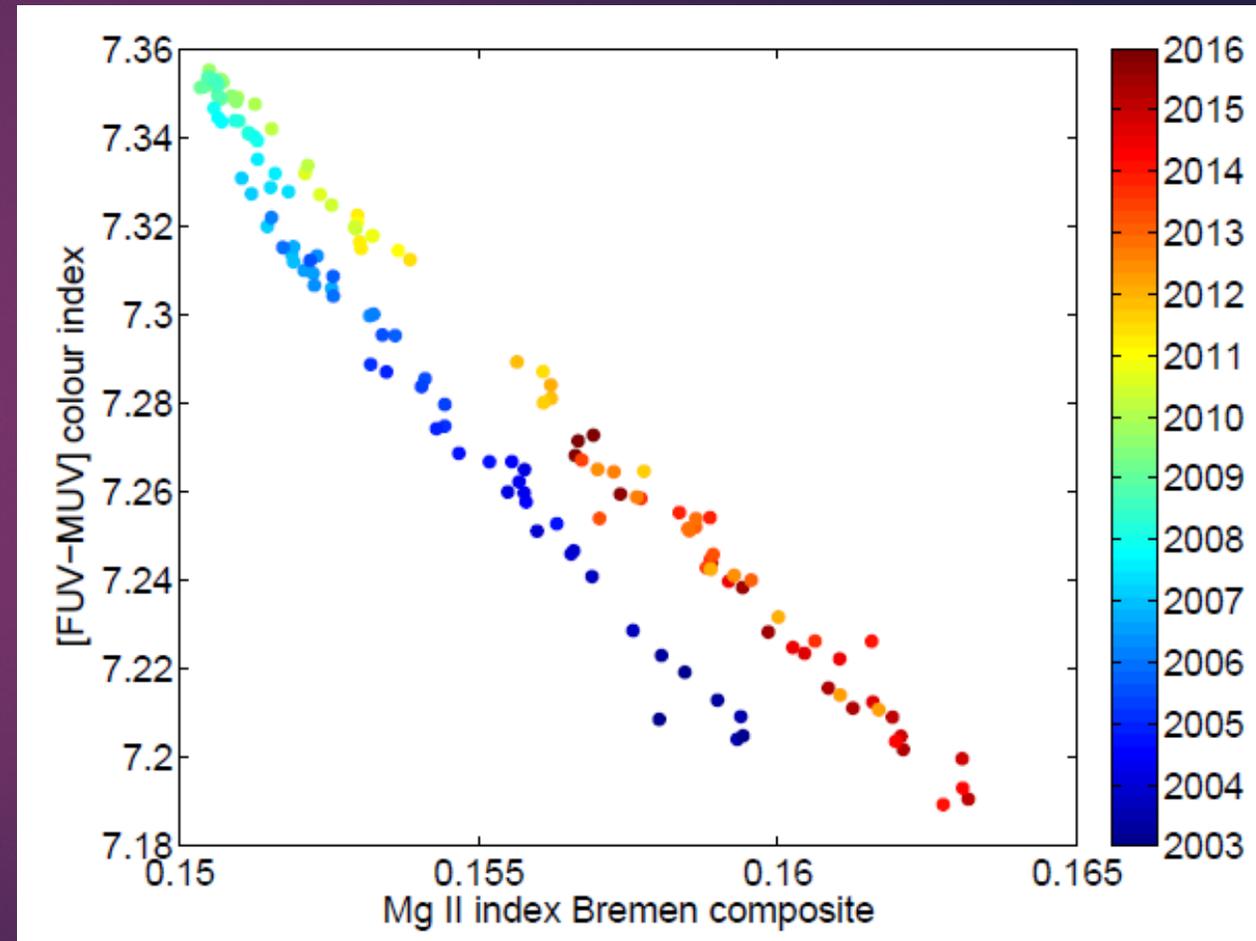


Lovric et al. 2017

With the aim of

- 1) Verifying the introduced age correction of SORCE data does not over-compensate the observations
- 2) Verify the relation holds for several cycles
- 3) Understanding the physical mechanisms that produce such high correlation

We **modelled** the observations using a **semi-empirical approach** similar to SRPM



# Adopted semi-empirical approach

$$F(\lambda) = \sum_j \alpha_j F_j(\lambda)$$

$j$ : different types of quiet and magnetic features

$\alpha_j$  area covered by the feature, derived from Full-Disk Observations

$F_j(\lambda)$  Flux estimated with a radiative transfer code and assuming a set of model atmospheres

## Observations

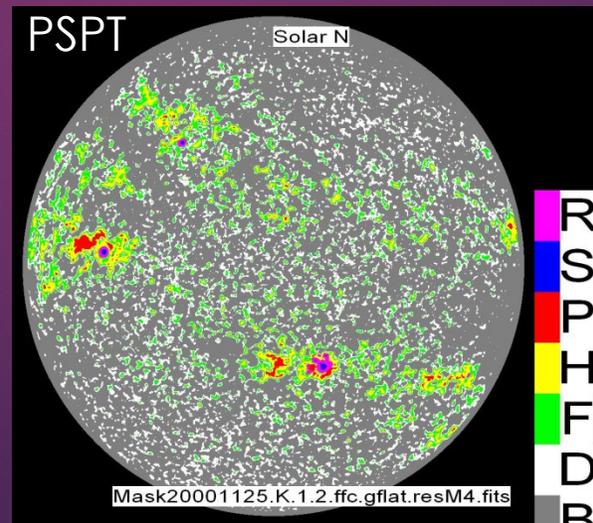
PSPT-Hawaii, CalK and Red from 2005 to 2015 (courtesy of J. Harder).

SFO, CalK and Red from 1988 to 2004

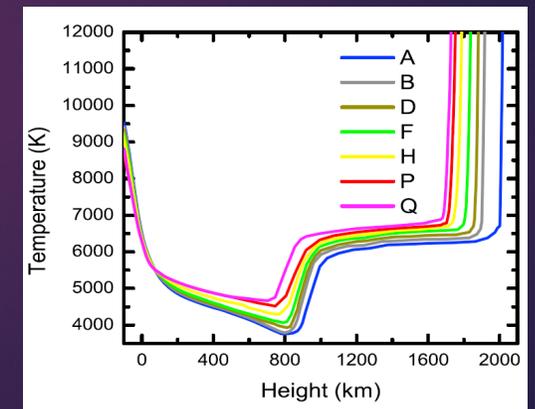
## Synthesis

Set of FAL2011 atmosphere models

RH code  
SPECTRUM code



Fontenla et al., ApJ, 2011

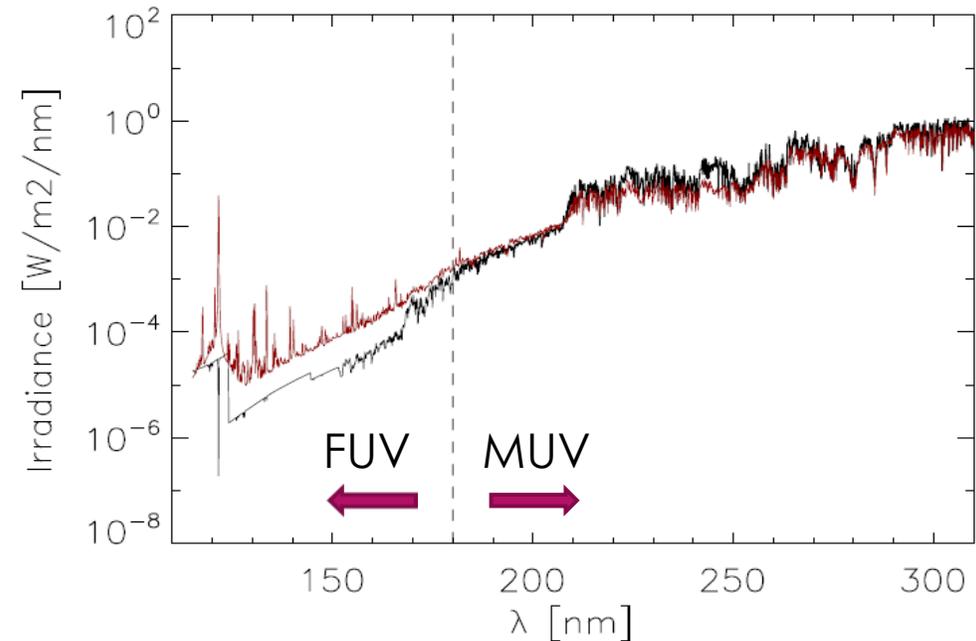
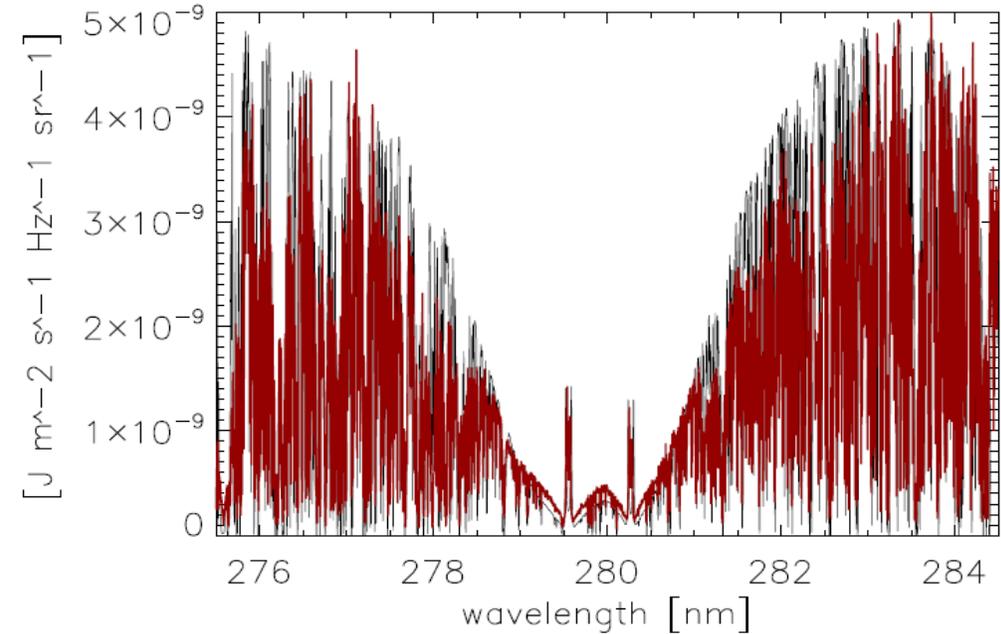


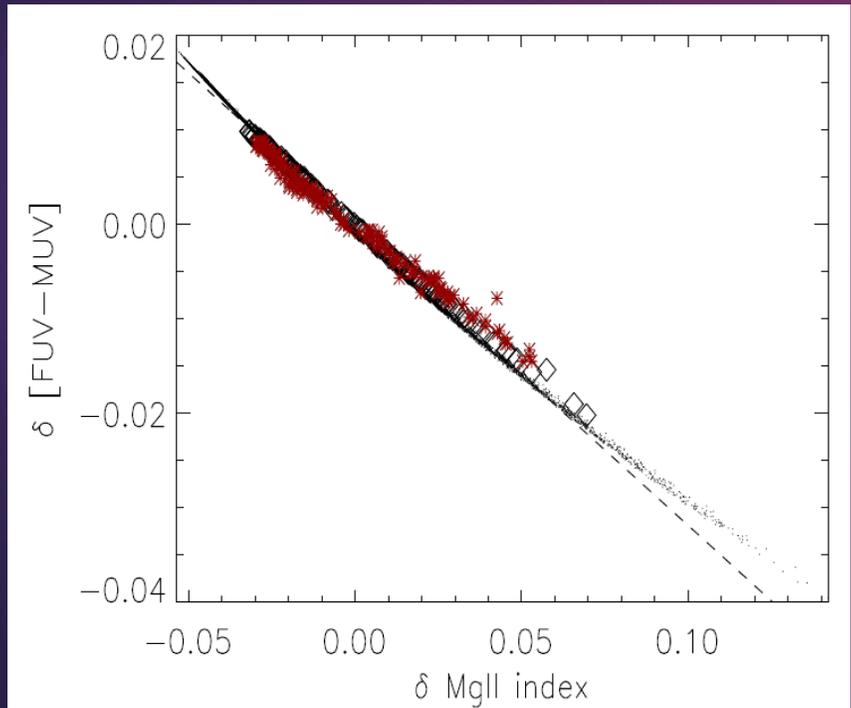
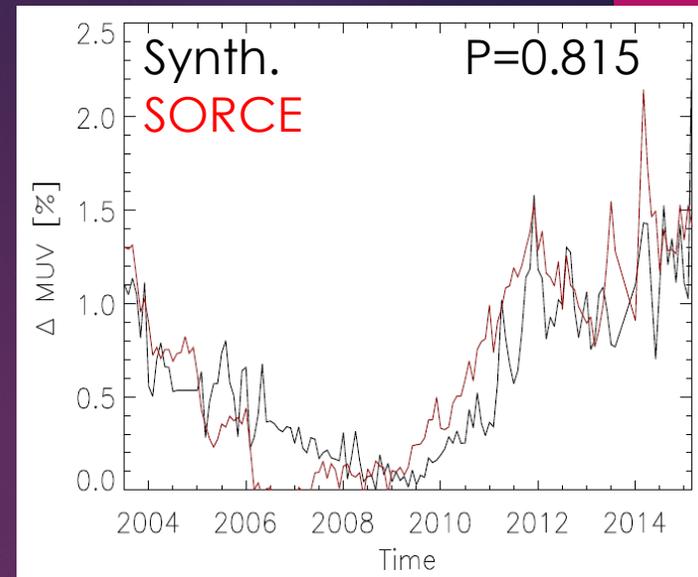
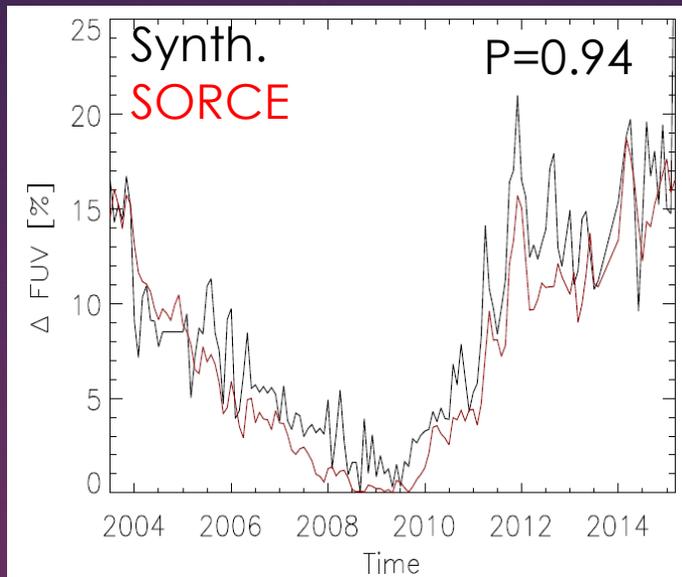
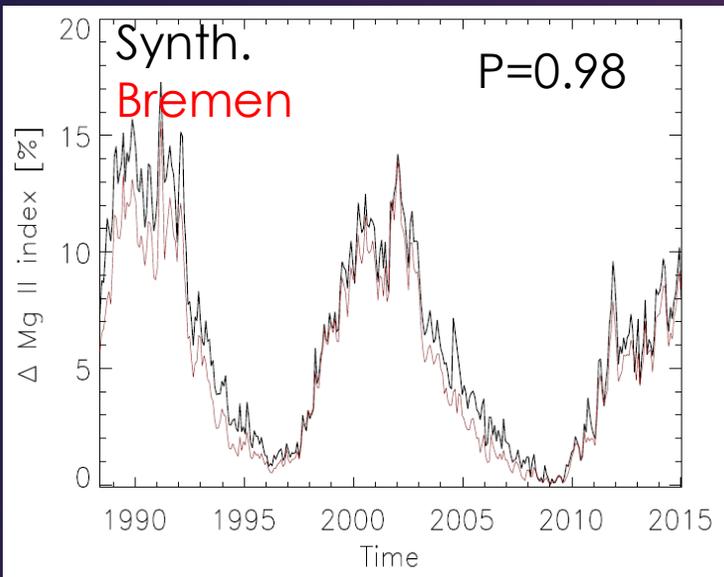
MgII lines synthesized in NLTE using RH code (Uitenbroek 2001)

FUV and MUV in LTE with SPECTRUM code

For the LTE synthesis the atmosphere temperature profiles were truncated at the temperature minimum and prolonged with a linear function (similar to SATIRE-Unruh 1999)

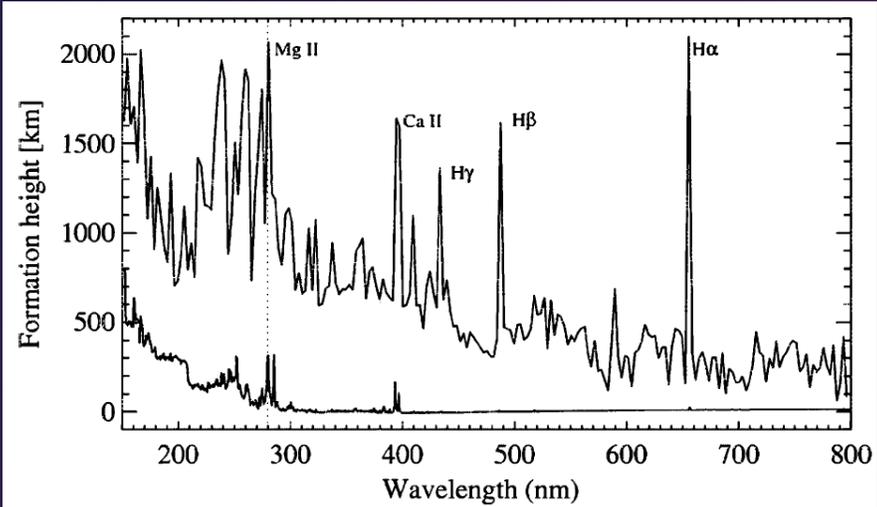
Black= Synthesis  
Red= Observations:  
top- Hawaii UV Atlas (Allen 1977)  
bottom-WHI ref. spectrum (Woods et al. 2008)





Black dots: reconstruction 1988-2015  
 Black diamonds: reconstruction over the SORCE observation period  
 Red Stars: SORCE observations/Bremen index 2003-2015

- ➔ UV-Color scales linearly with MgII index over two cycles (although note the small deviation at high activity level)
- ➔ The correction for the aging effect of SORCE observations seems correct.



Most of the variability:

in MUV is from the lower to middle  
chromosphere :800-1200 km (+ some  
photosphere)

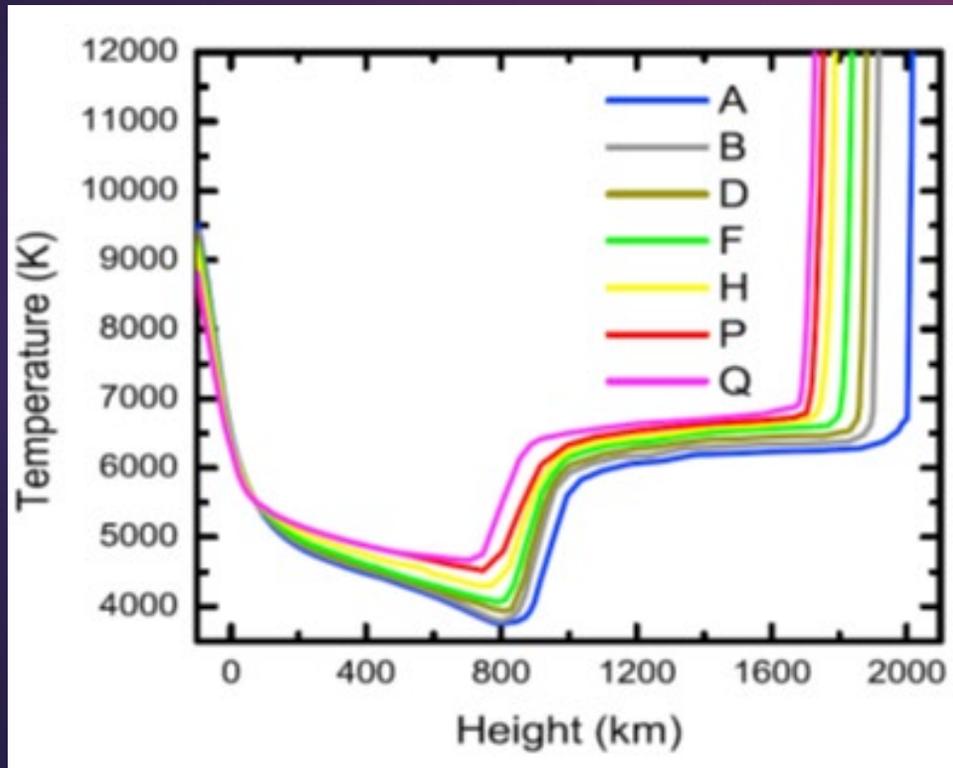
In FUV is from higher layers (continuum is above  
the temperature minimum at  $\lambda < 160$  nm)

Under the assumption that the integrated intensity  
over the FUV and MUV ranges is described by a  
Plank function, and expanding at first order:

$$(\text{UV color}) + \Delta(\text{UV color}) = 2.5 \log \frac{M + K_m \Delta T}{F + K_F \Delta T} \approx \left( \frac{K_m}{M} - \frac{K_F}{F} \right) \Delta T$$

Because all the models have similar T gradients, both  
 $\Delta FUV$  and  $\Delta MUV$  are affected by the same  $\Delta T$ . Therefore the UV  
color at first order scales linearly with T.

The same reasoning can be applied to the  
core-to-wing MgII index ratio.



# Historical Reconstruction of UV indices:

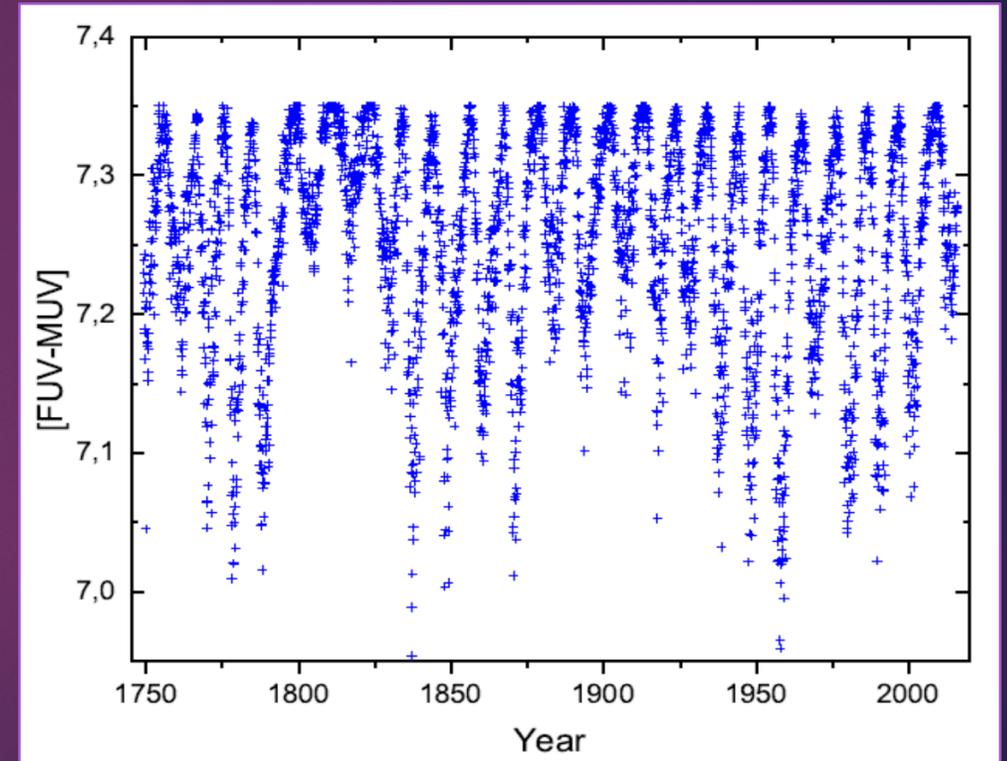
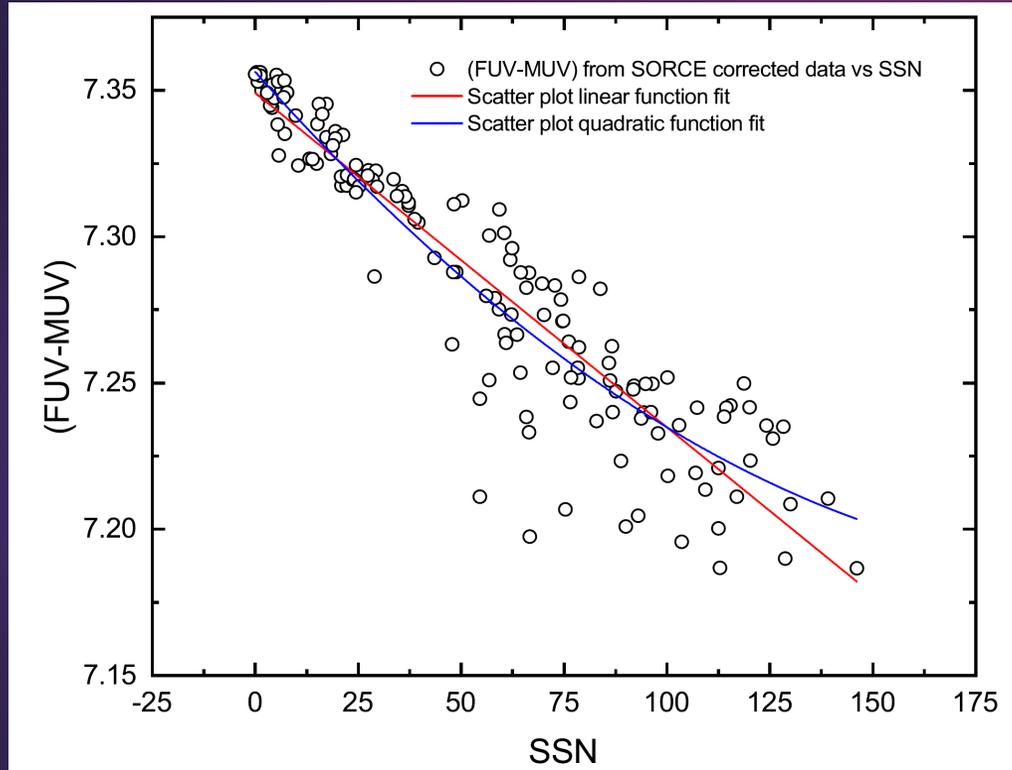
**MgII** core-to-wing and **CaII** Emission Index

**MgII:** core-to-wing excellent indicator of chromospheric activity, relatively long time series. Deep lines span higher photosphere to transition region.

**CaII:** long records, even for stars. Largely used proxy for chromospheric activity proxy, derivation of chromospheric models, observable used for stellar dynamo models. Deep line spans from photosphere to chromosphere.

# Step 1: reconstruct the UV color index from the Sunspot Number

SSN from SILSO database



$$(FUV - MUV) = -0.00114 \times SSN + 7.35$$

## Step 2: reconstruct the Area coverage of magnetic features

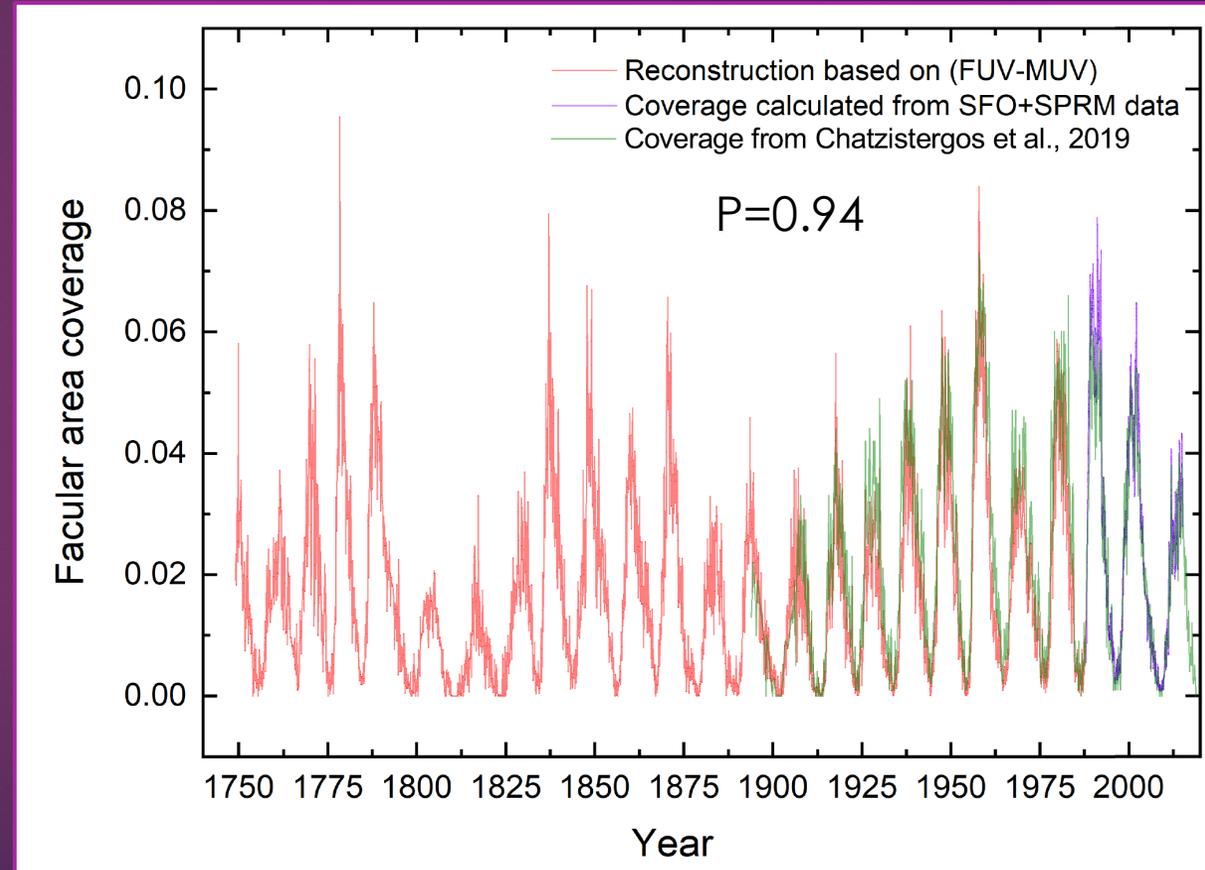
### Step 2a: reconstruct the Area of faculae

We assume that Faculae are the major contributors to UV variability at long temporal scales

$$(FUV - MUV) = -2.5 \log\left(\frac{F_{FUV}}{F_{MUV}}\right) = -2.5 \log\left(\frac{\alpha_f F_{FUV}^f + (1 - \alpha_f) F_{FUV}^q}{\alpha_f F_{MUV}^f + (1 - \alpha_f) F_{MUV}^q}\right)$$

$$\alpha_f = \frac{10^{2(C_q - C)/5} - 1}{\delta_{FUV} - 10^{2(C_q - C)/5} \delta_{MUV}}$$

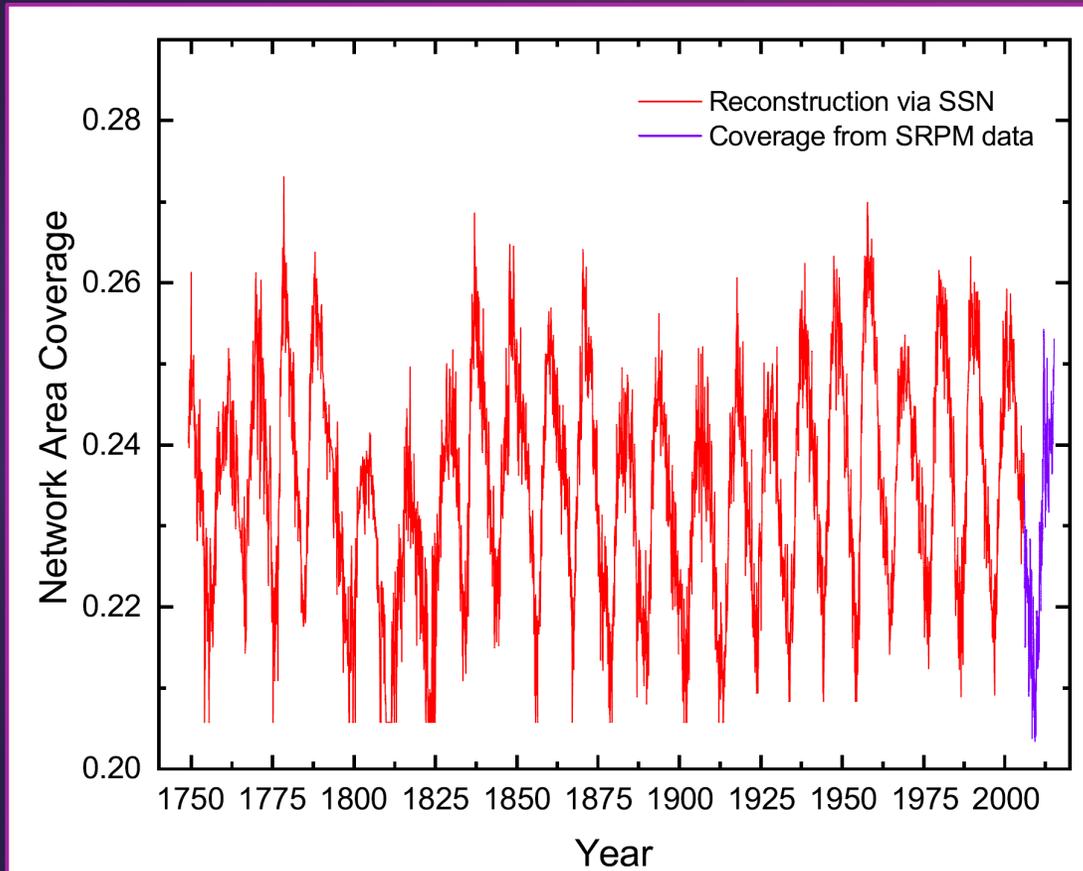
C = the reconstructed color (from Step 1),  
C<sub>q</sub> = the color of the quiet Sun,  
δ<sub>MUV</sub> and δ<sub>FUV</sub> = the contrast of faculae in MUV and FUV.  
C<sub>q</sub>, δ<sub>MUV</sub> and δ<sub>FUV</sub> derived by spectral synthesis using quiet and facular atmosphere semiempirical models (Fontenla et al. 2011).



## Step 2b: reconstruct the Area of Network

$$\alpha_n = d \cdot SSN^f + g$$

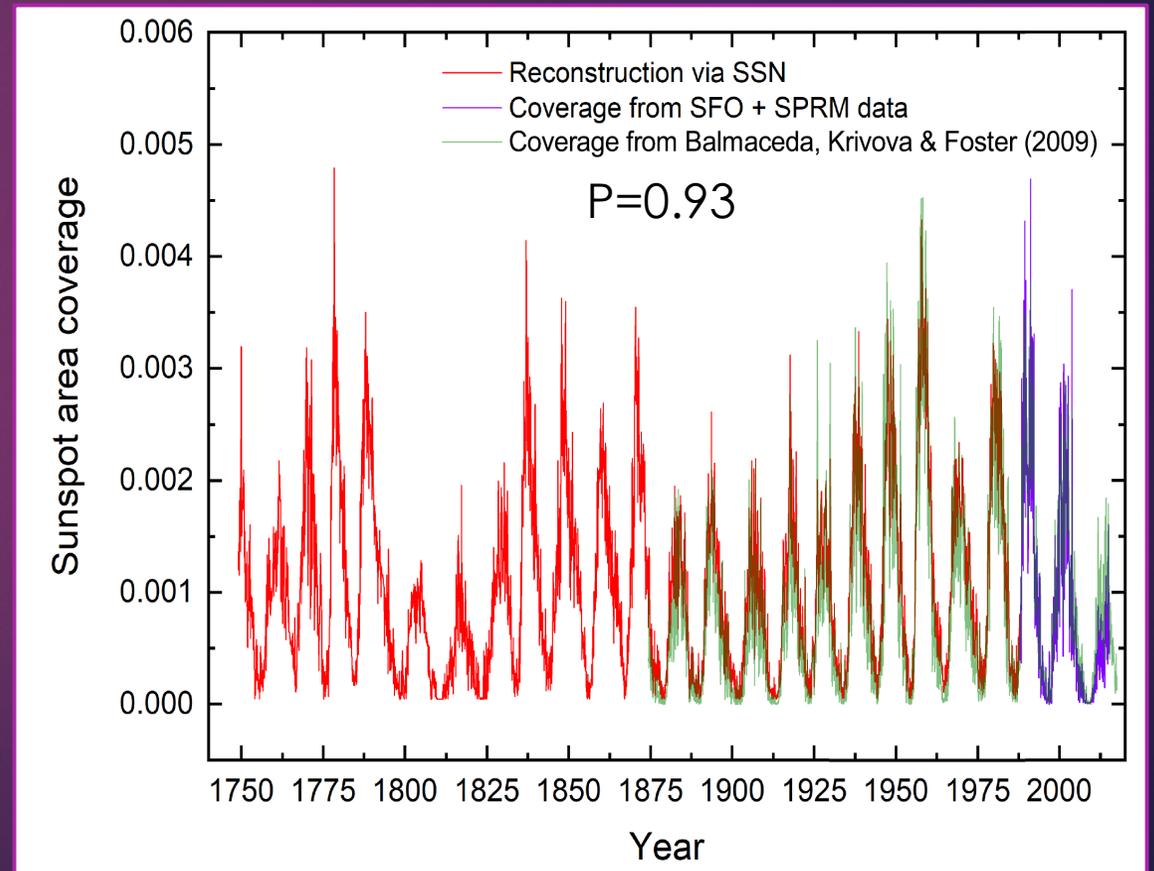
Network area from full-disk PSPT images  
 $d = 1.047 \times 10^{-3}$ ,  $f=0.712$  and  $g=0.212$



## Step 2bc: reconstruct the Area of Sunspots

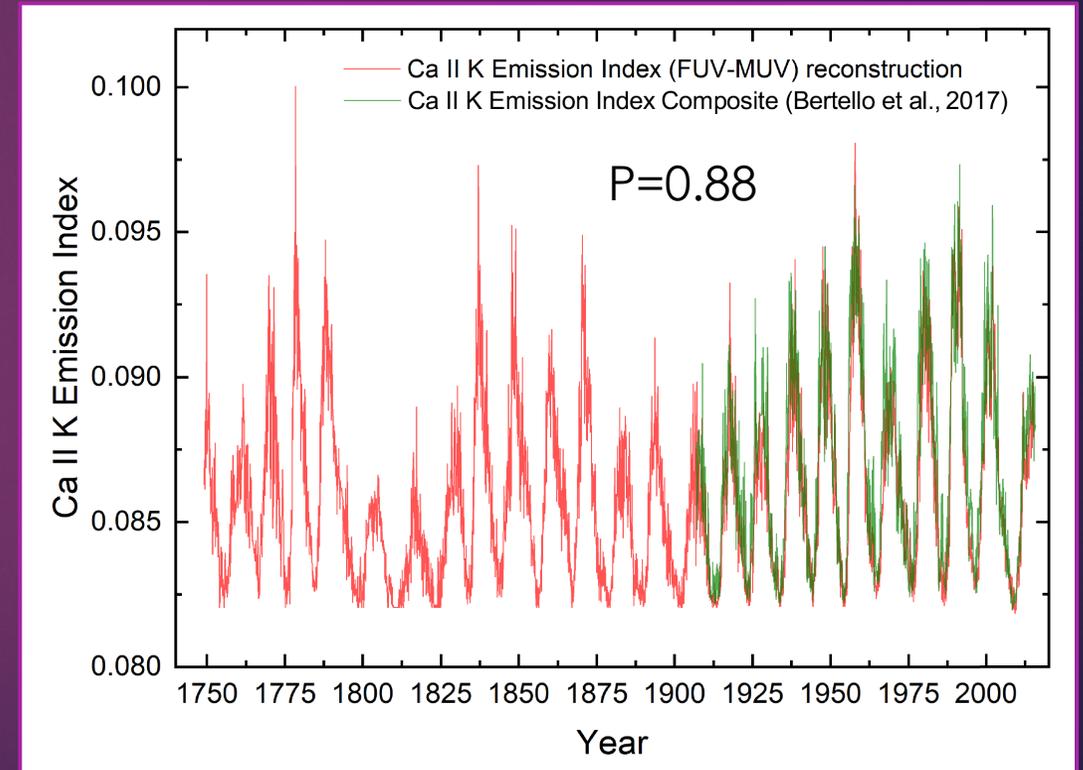
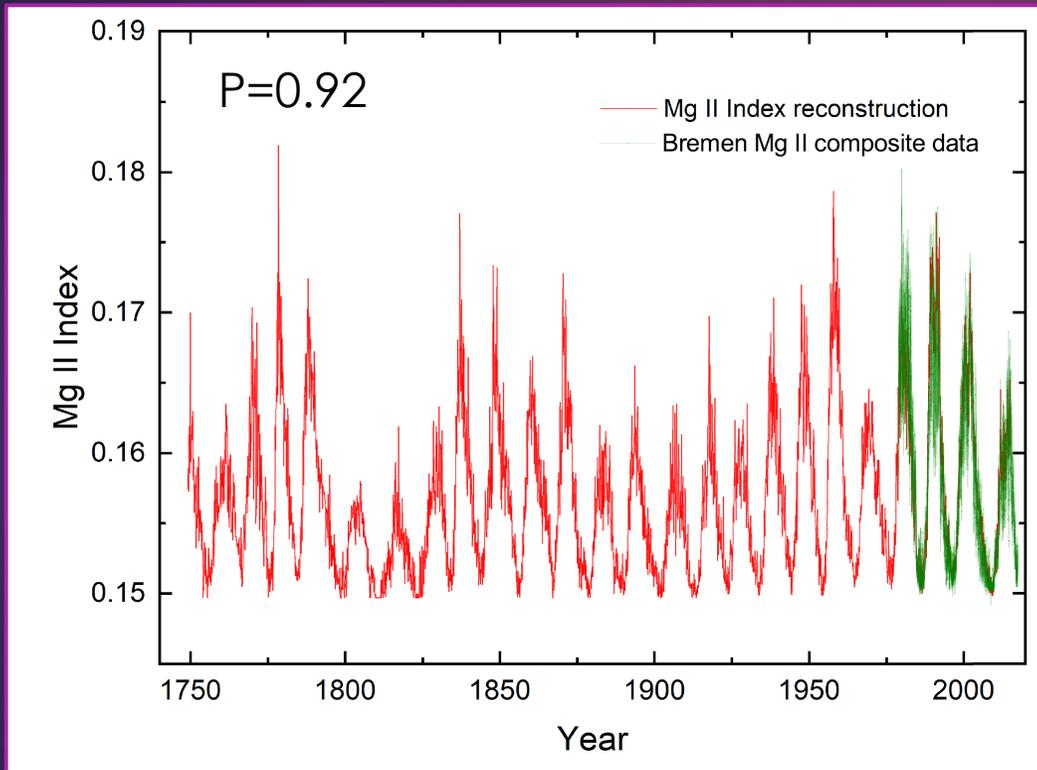
$$\alpha_s = a \cdot SSN^b$$

Sunspot area from full-disk PSPT and SFO images  
 $a = 1.246 \times 10^{-6}$  and  $b=1.418$



### Step 3: Reconstruct Ca and MgII Indices by combining area coverages and spectral synthesis

Spectral synthesis performed with RH in NLTE using FAL2011 atmosphere models



# Conclusions

- ▶ Our modern reconstruction reproduces well the observations (SORCE and Bremen index).
  - ▶ Our modern reconstructions reproduce well the MgII index and UV color relation.
  - ▶ It allowed to verify that our aging correction to SORCE data is reasonable.
  - ▶ Provides a theoretical explanation of observed trends.
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- ▶ Our method provides reliable reconstruction of area coverage of magnetic features
  - ▶ Our (simple) method provides reliable reconstruction of CaII and MgII indices

## Work in progress

- ▶ Historical reconstruction of TSI
- ▶ Investigate stellar variability