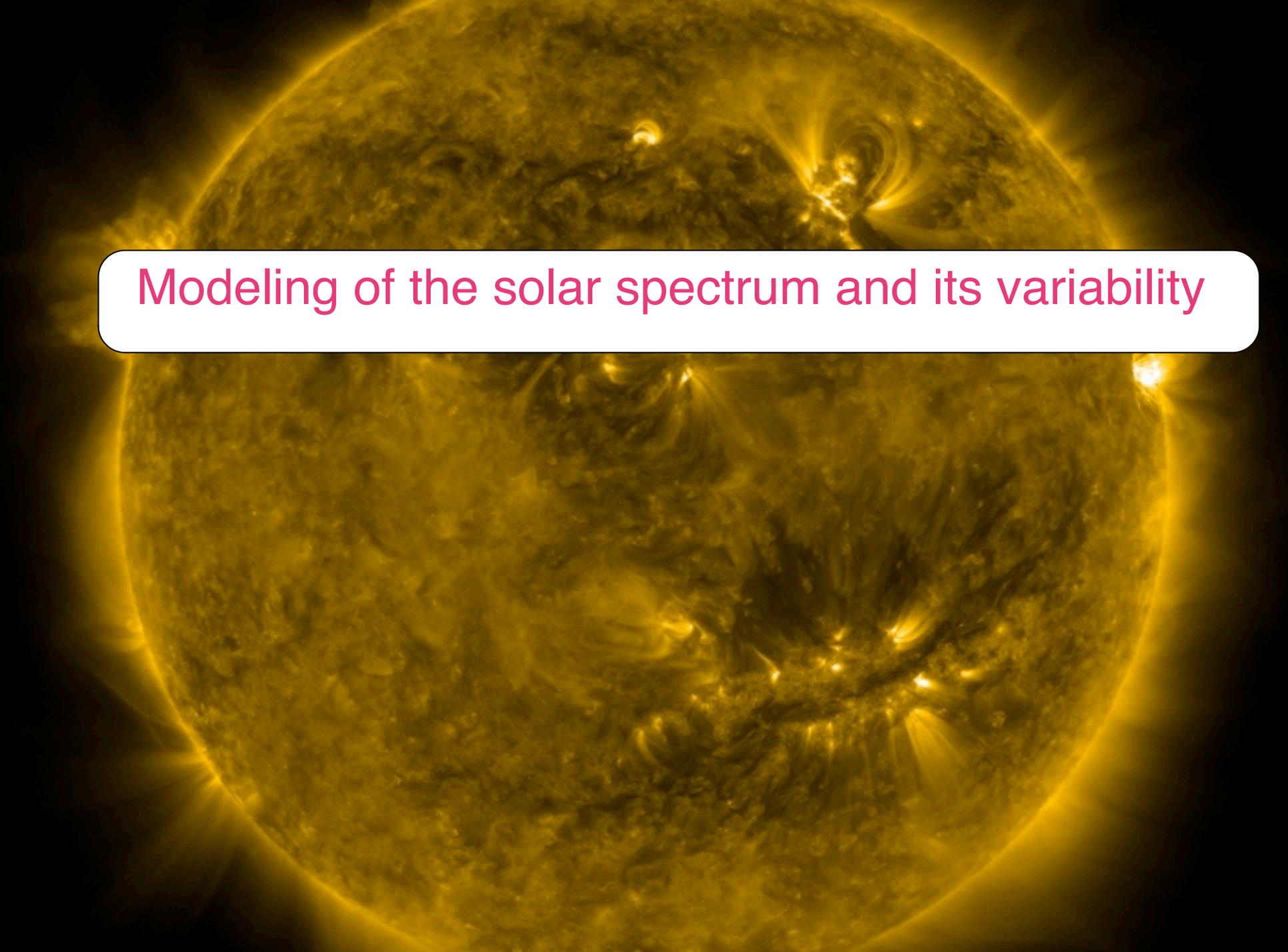


The Sun can also smile :))



Modeling of the solar spectrum and its variability

Outline

- Formation of the solar spectrum
- rotation cycle
- activity cycle
- secular time-scale

Outline

- Formation of the solar spectrum
- rotation cycle
- activity cycle
- secular time-scale



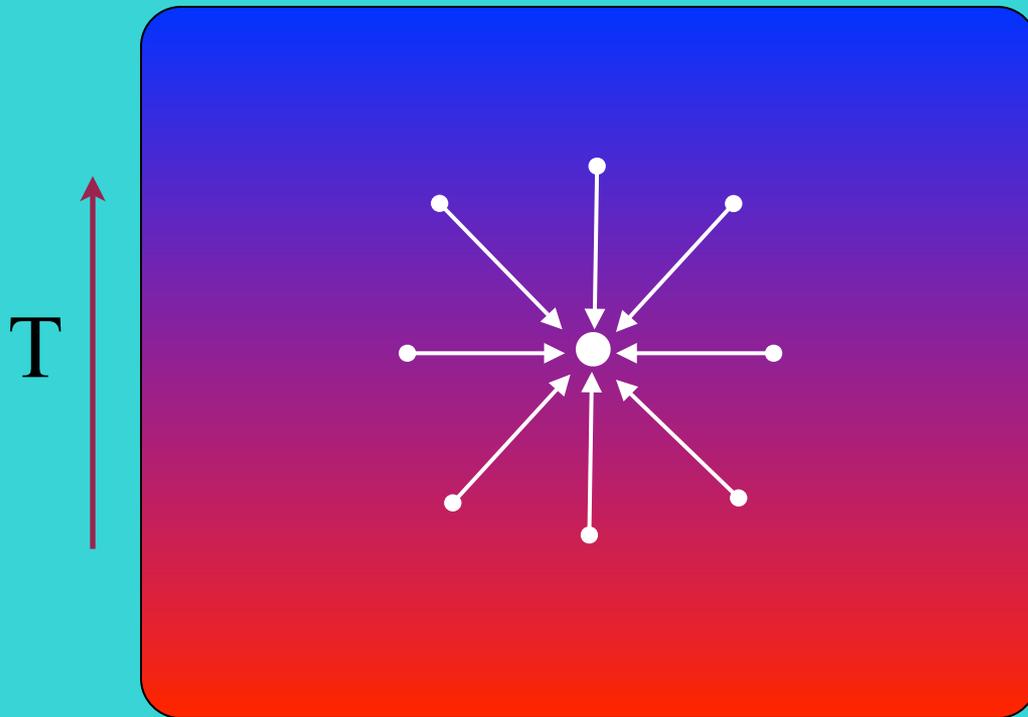
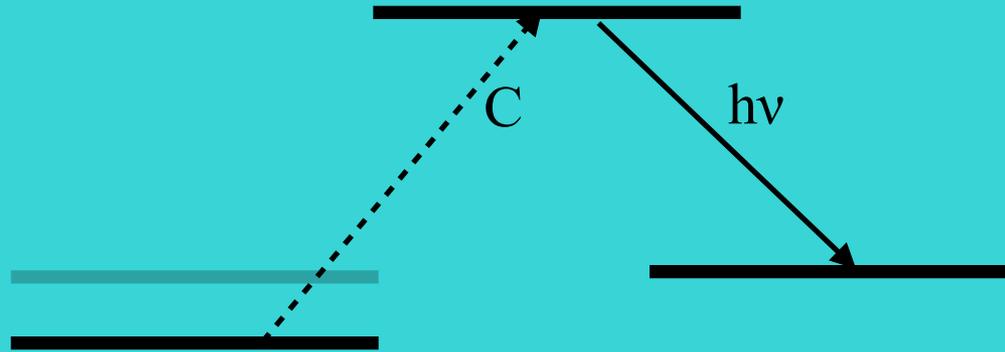
Calculations of the solar spectrum

Millions of atomic and molecular transitions

Non-local thermodynamic equilibrium

Radiative Transfer Codes

Non Local Thermodynamic Equilibrium (NLTE)

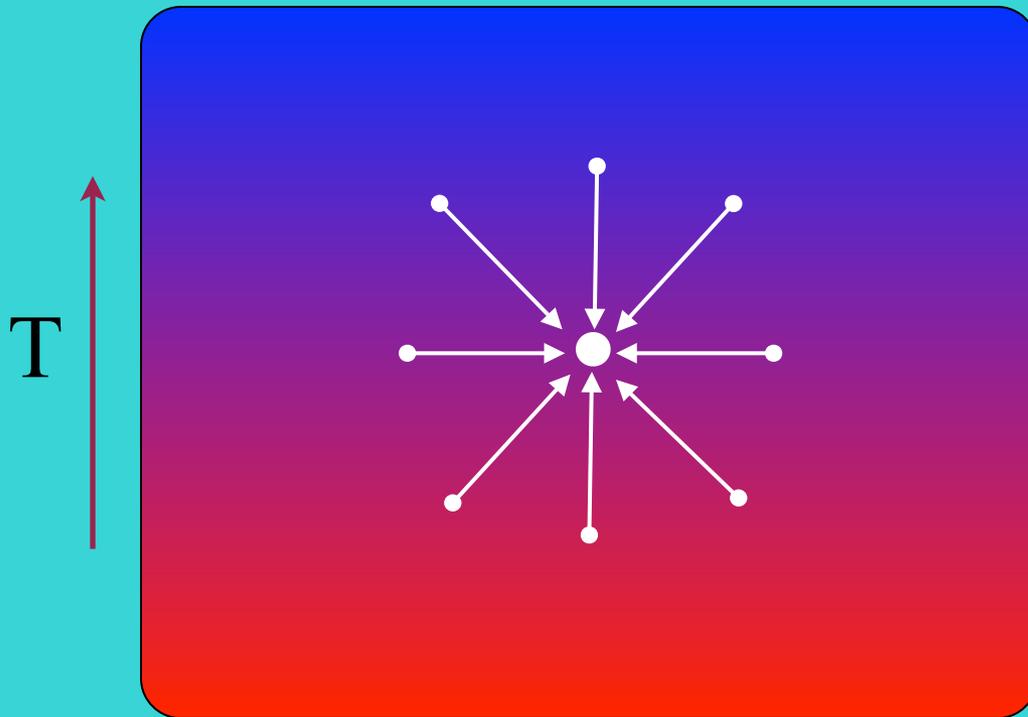
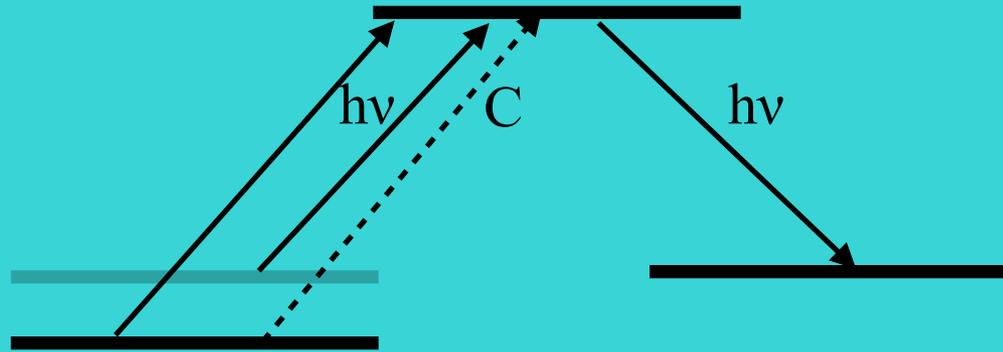


Maxwell-Boltzmann
distribution

Saha ionization
equation

Source function obeys
the Planck's law

Non Local Thermodynamic Equilibrium (NLTE)

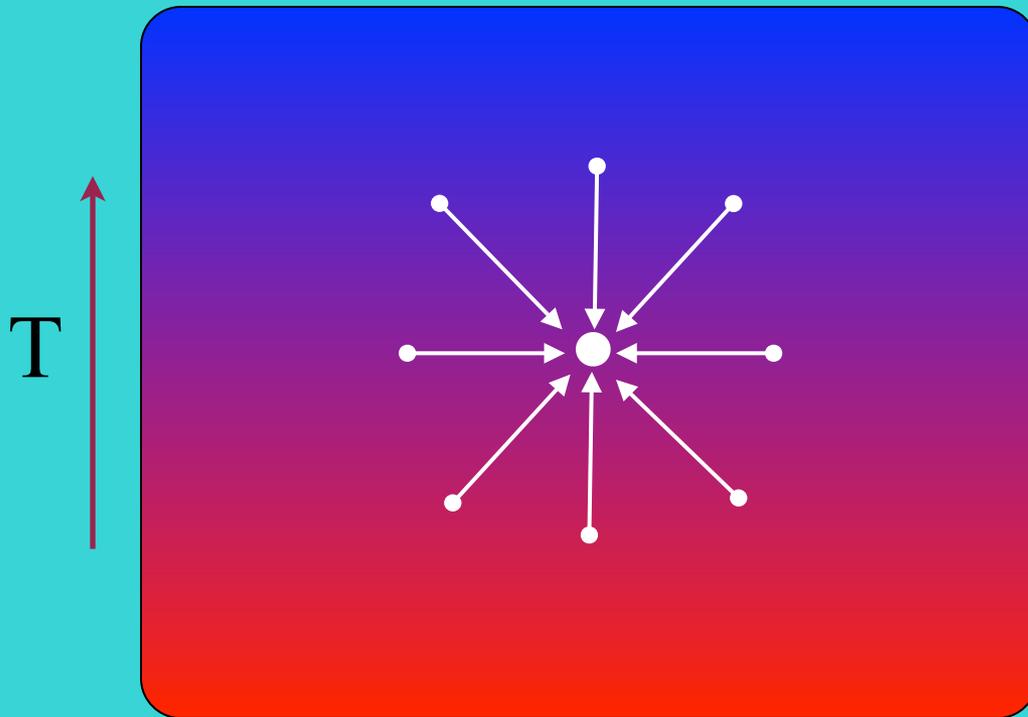
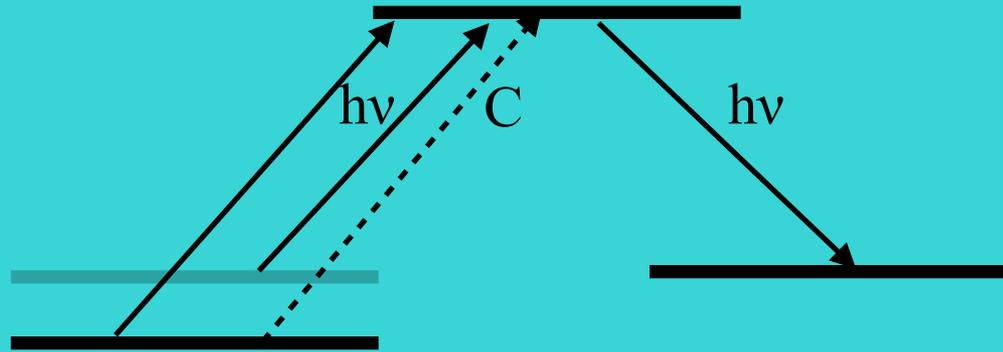


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Non Local Thermodynamic Equilibrium (NLTE)

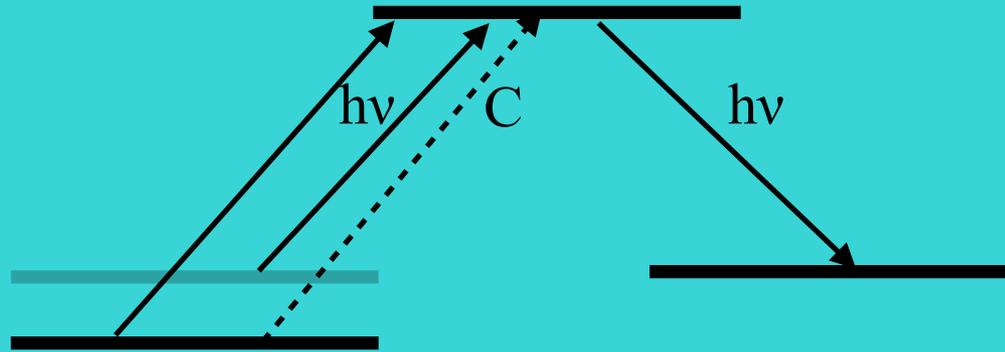


~~Maxwell-Boltzmann
distribution~~

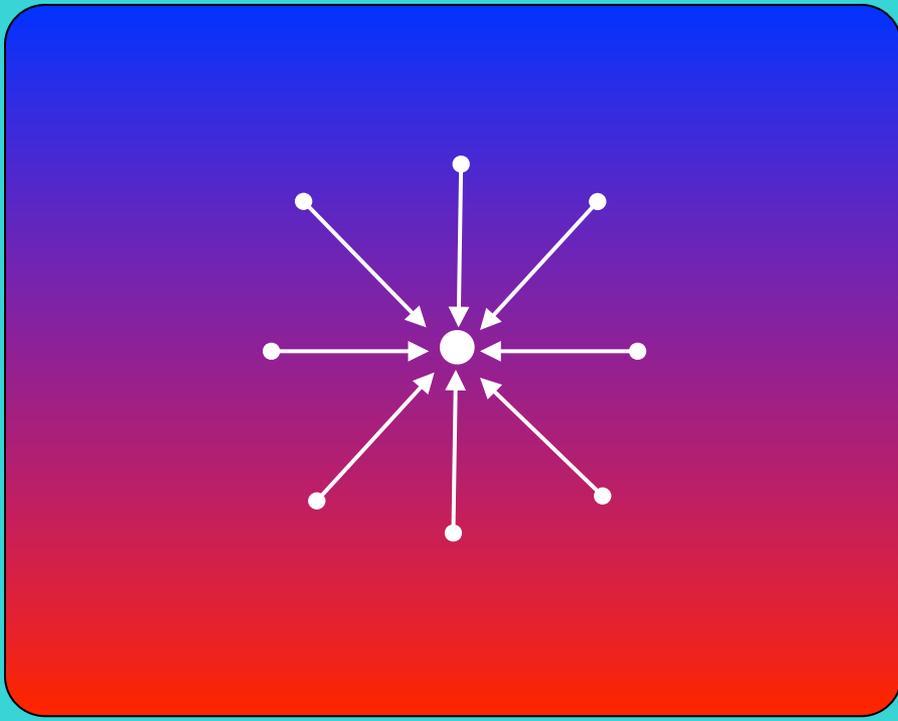
~~Saha ionization
equation~~

~~Source function obeys
the Planck's law~~

Non Local Thermodynamic Equilibrium (NLTE)



T ↑



~~Maxwell-Boltzmann
distribution~~

Statistical
Equilibrium
Equations

Radiative transfer codes

MULTI Carlsson (1986)

ATLAS Kurucz (1991); Unruh et al. (1999) SATIRE

PHOENIX Hauschildt and Baron (1999)

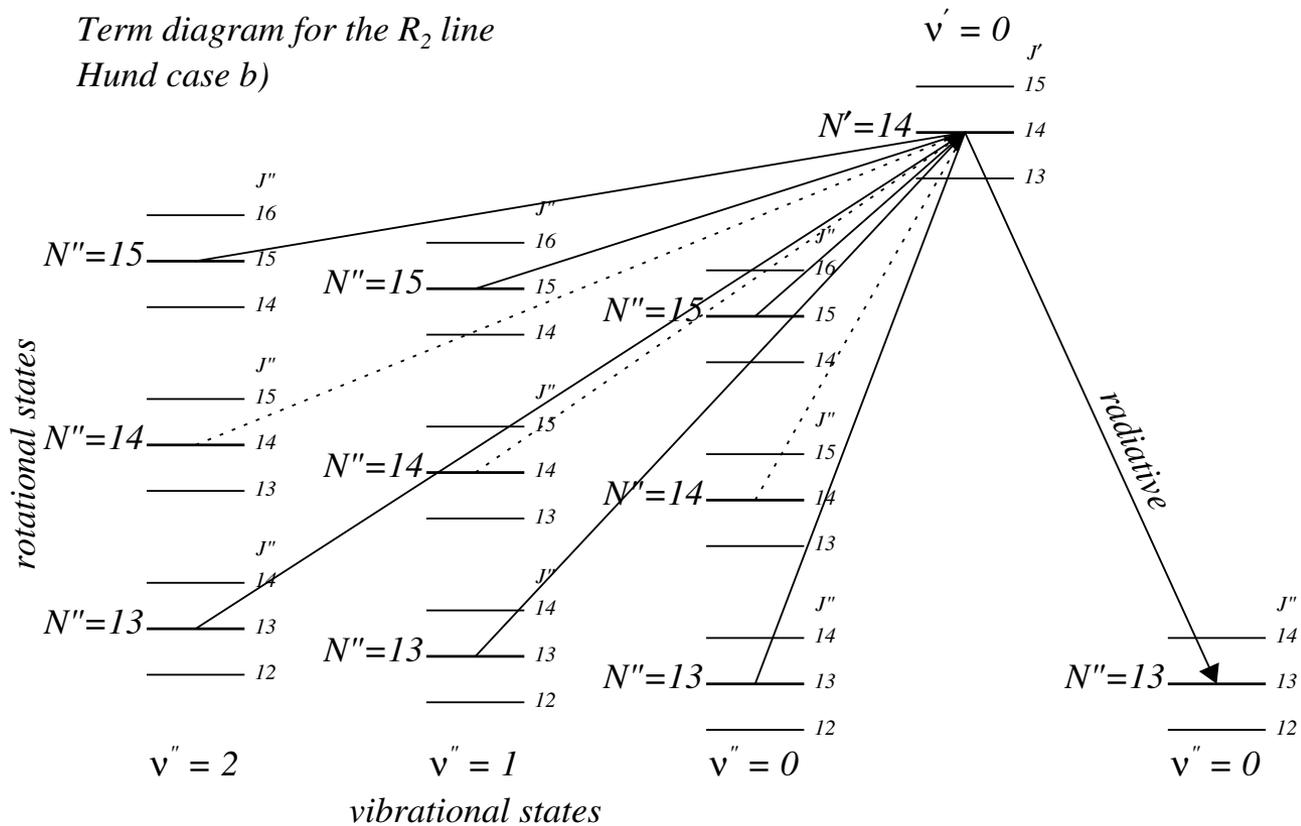
SRPM Fontenla et al. (1999, 2005, 2009, 2011)

RH Uitenbroek (2001)

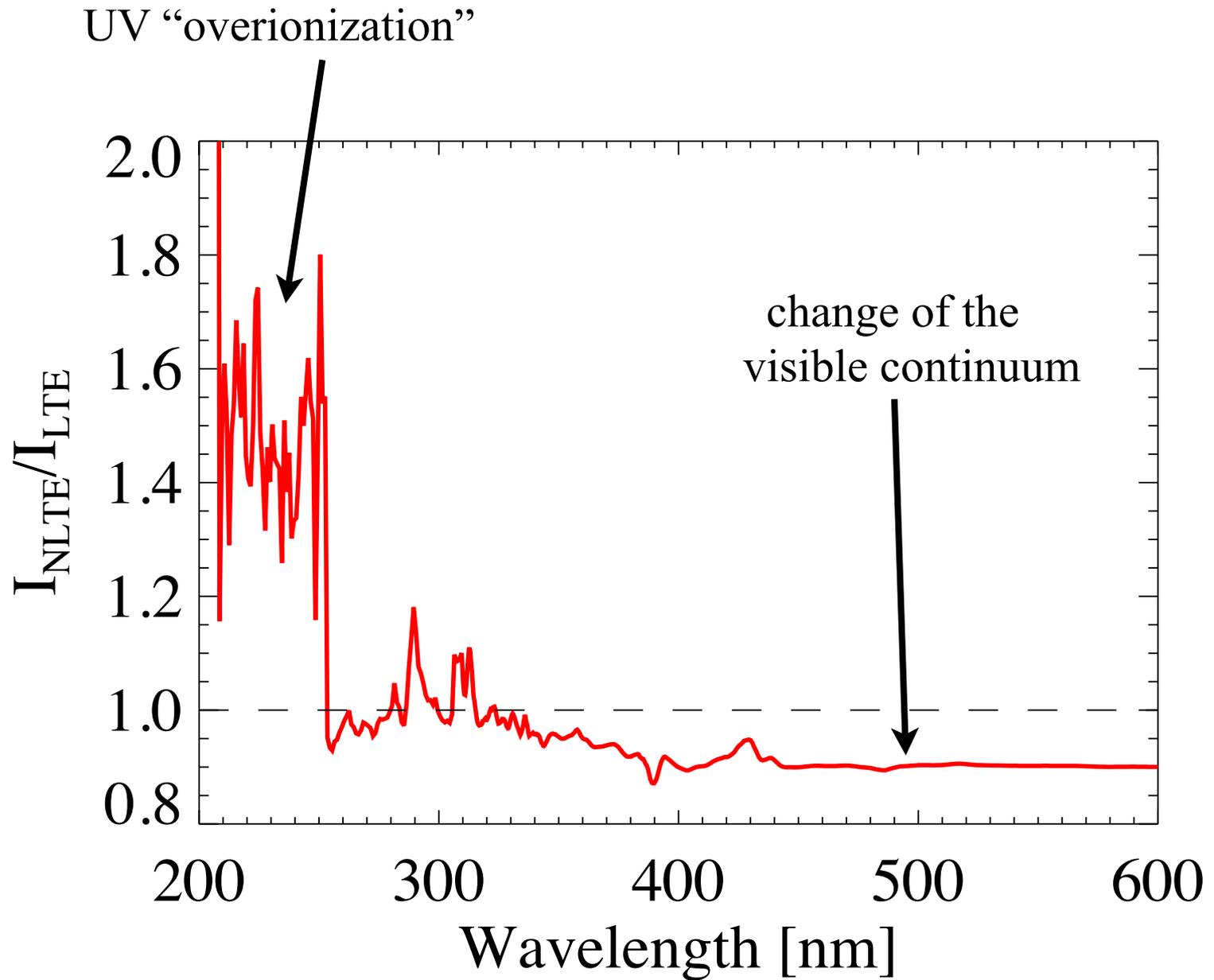
POLY Fluri&Stenflo (2003); Shapiro et al. (2011)

COSI Haberreiter et al. (2008); Shapiro et al. (2010)

Term diagram for the R_2 line
Hund case b)

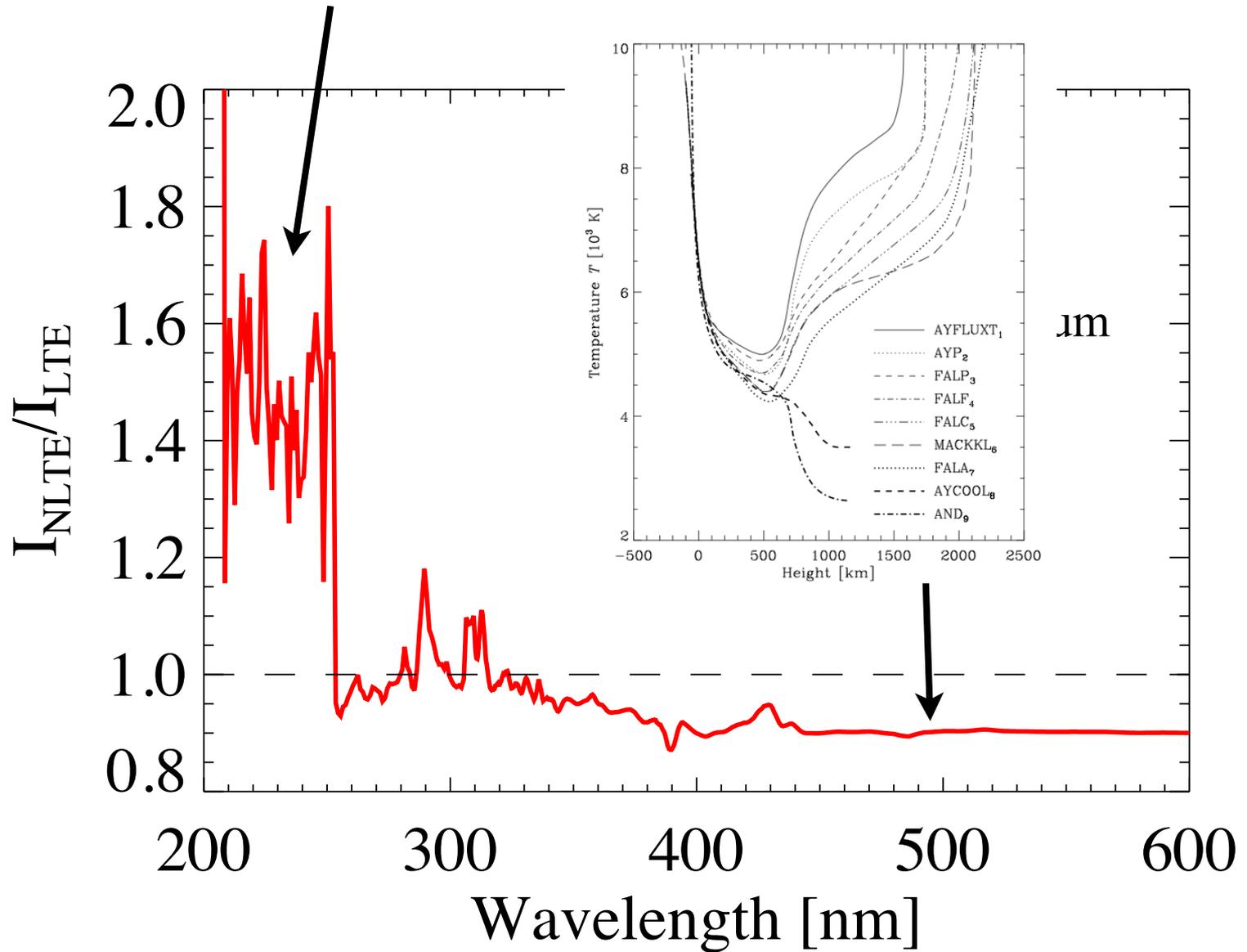


NLTE effects



NLTE effects

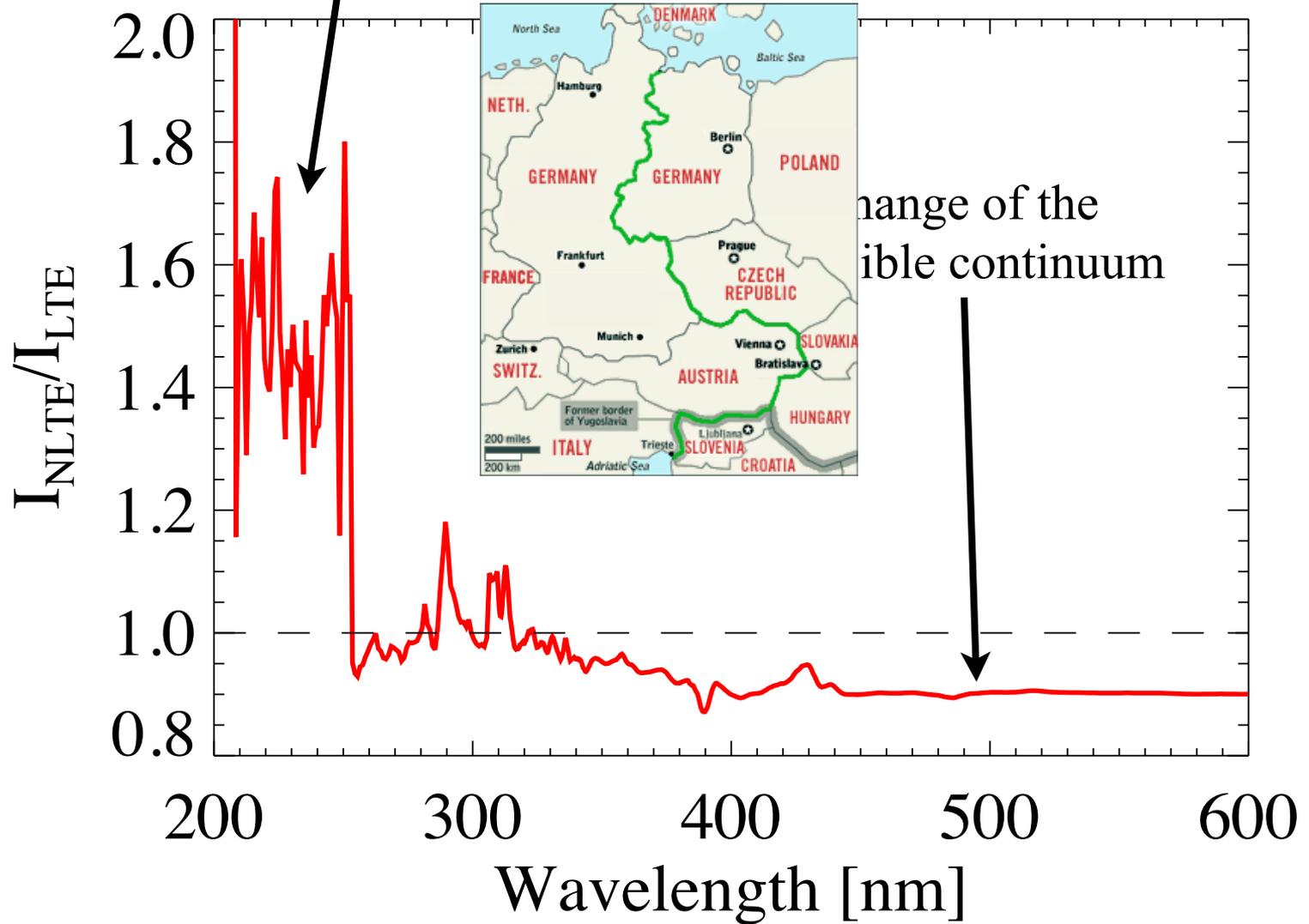
UV “overionization”



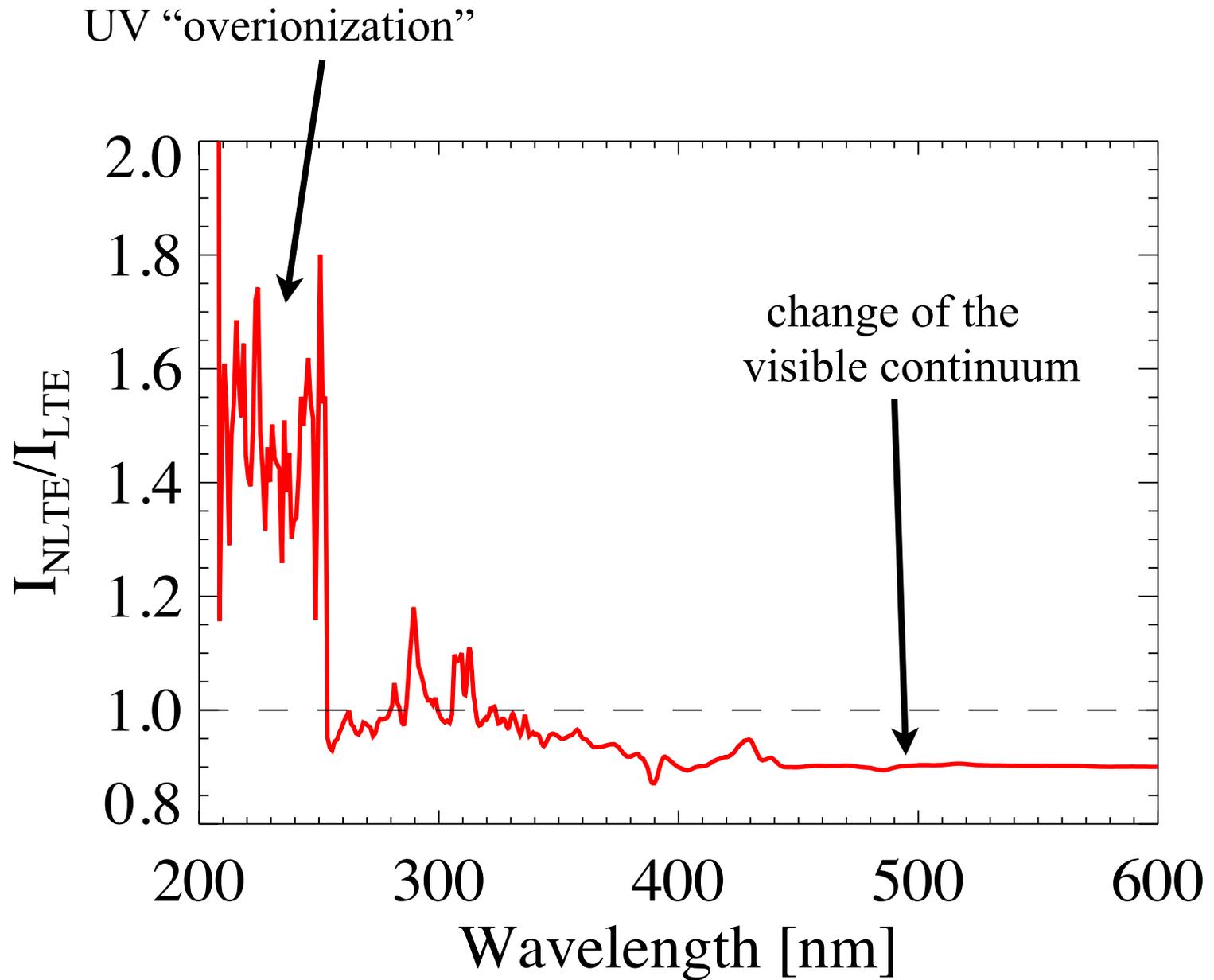
NLTE effects

UV “overionization”

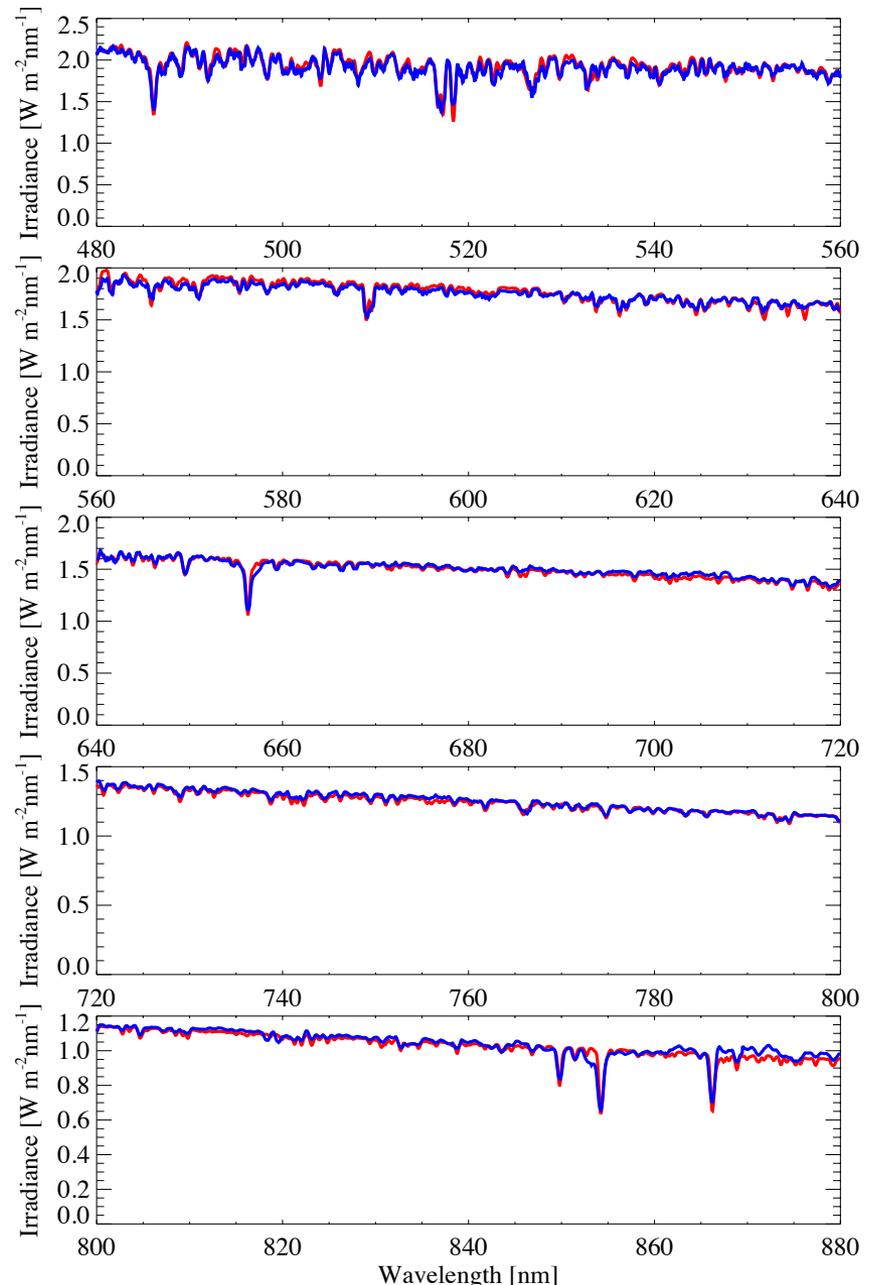
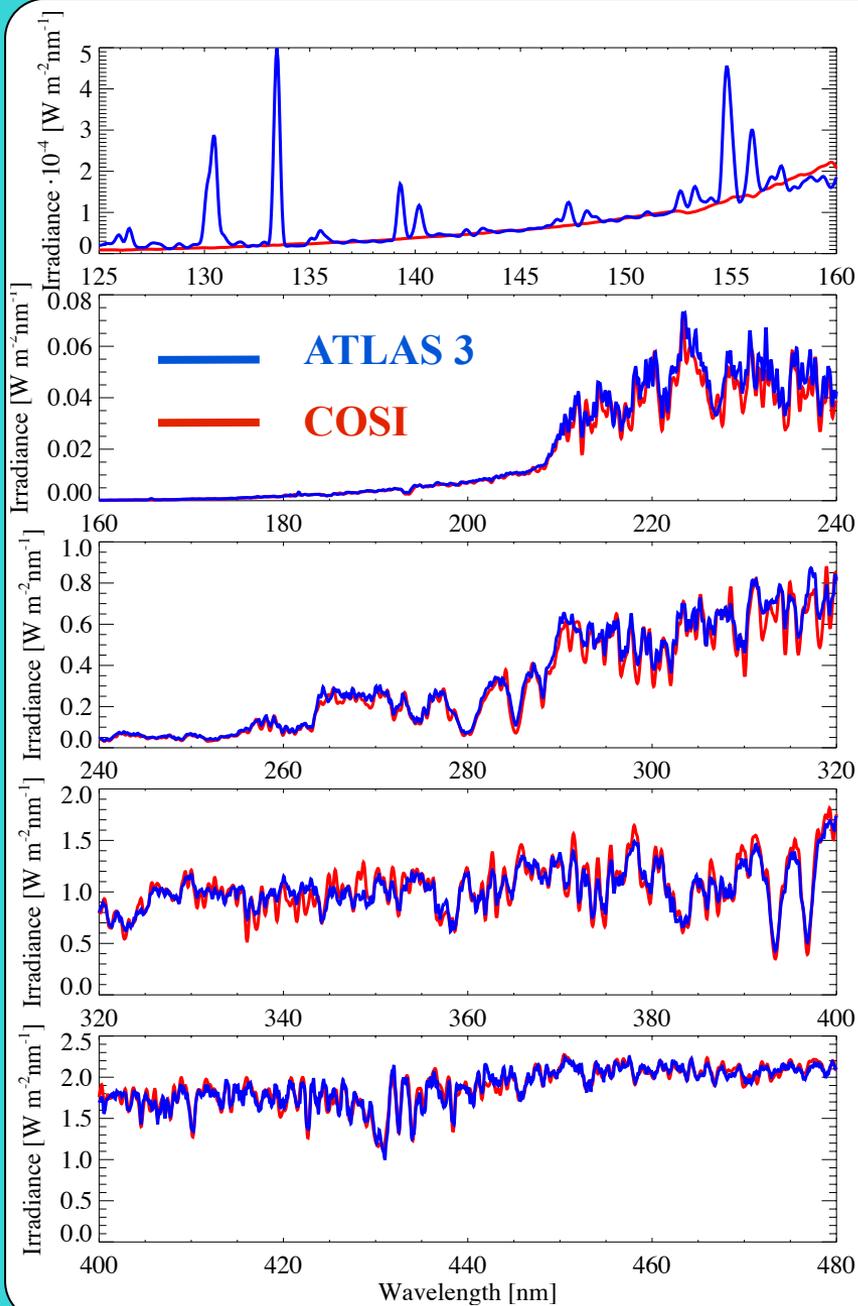
Lifting of the iron curtain



NLTE effects



Comparison with ATLAS 3



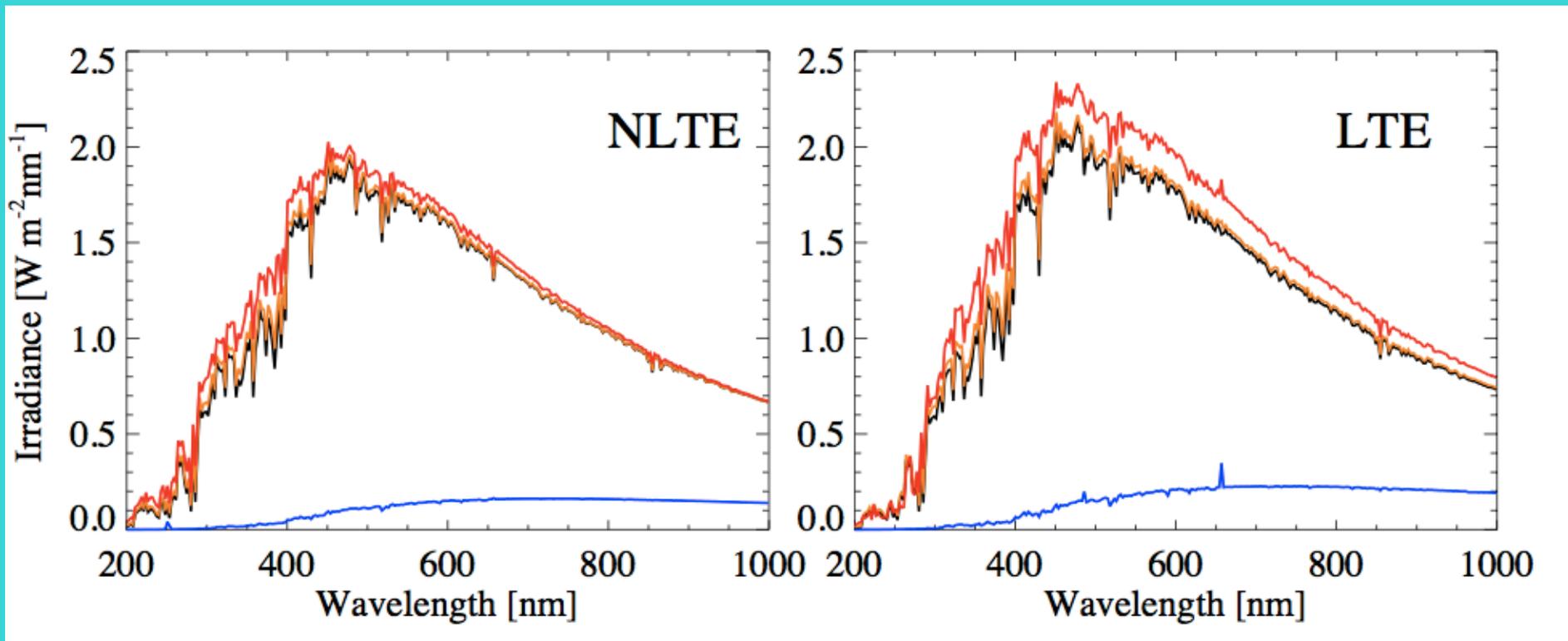
Irradiance from the active solar components

Plage

Quiet Sun

Bright network

Sunspot



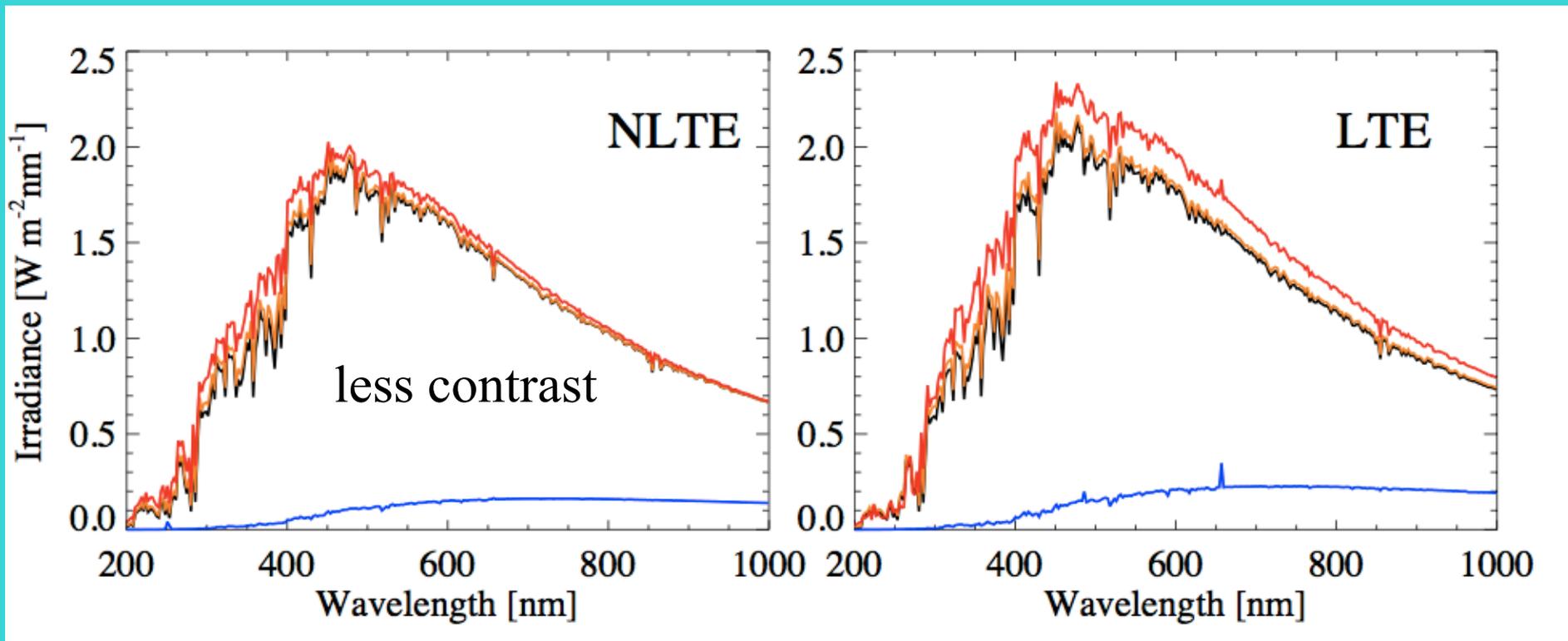
Irradiance from the active solar components

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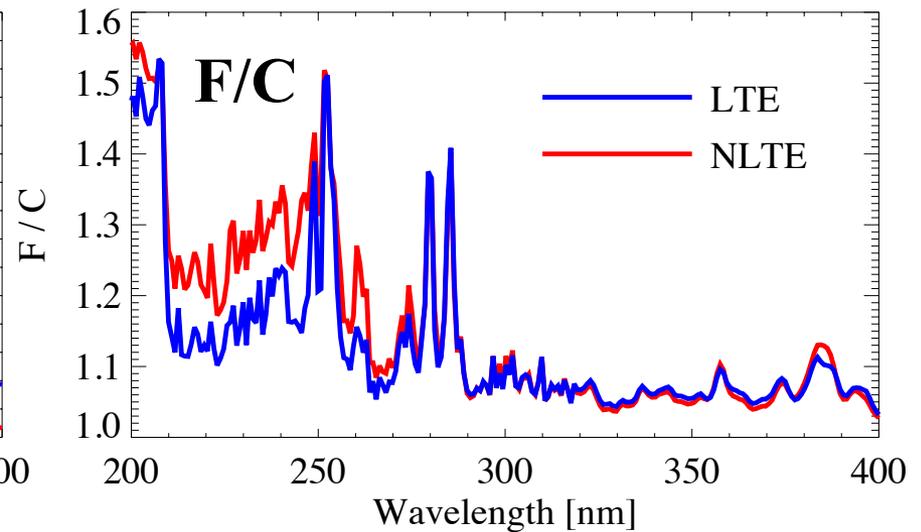
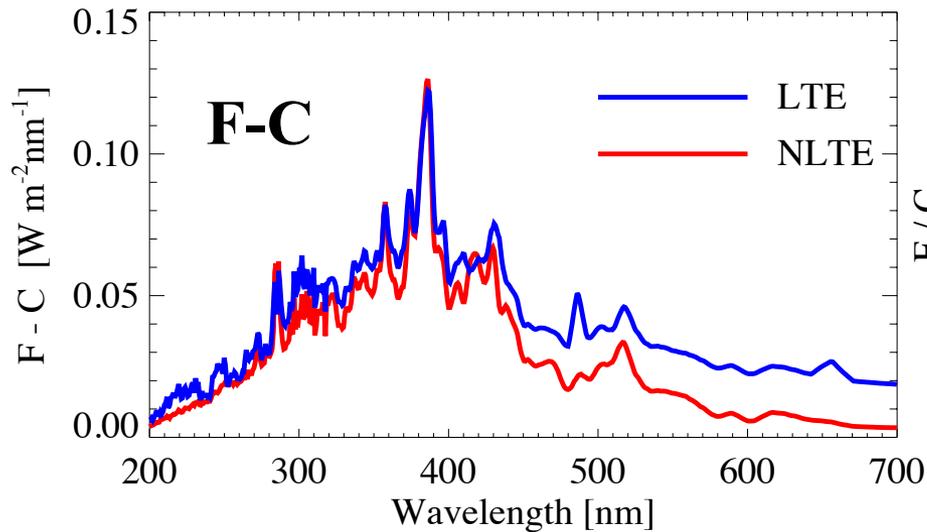
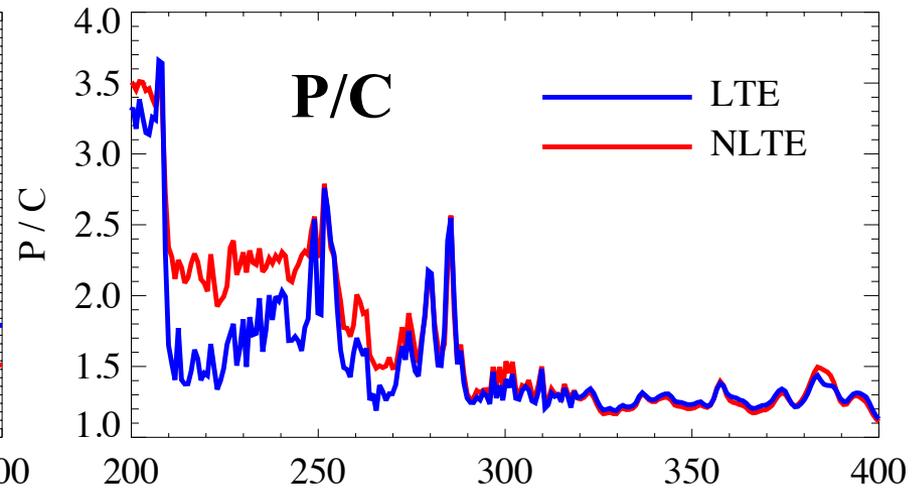
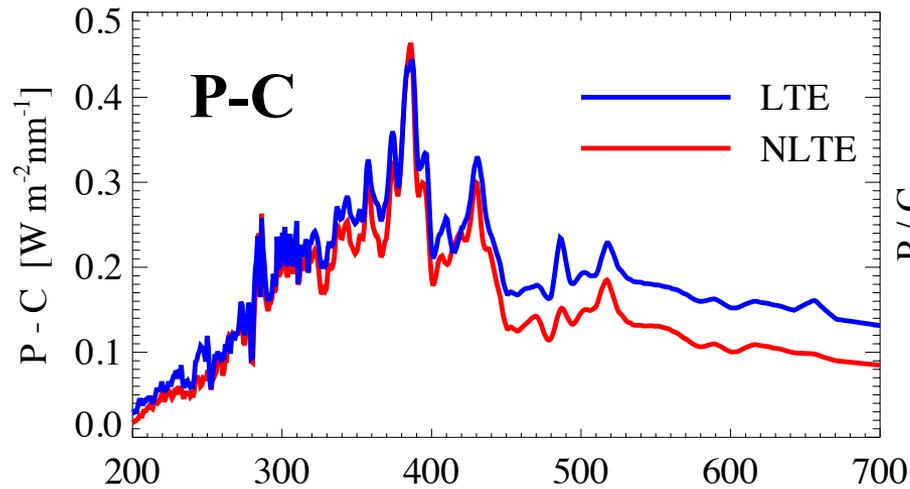


Contrasts

P - plage

F - bright network

C - quiet Sun

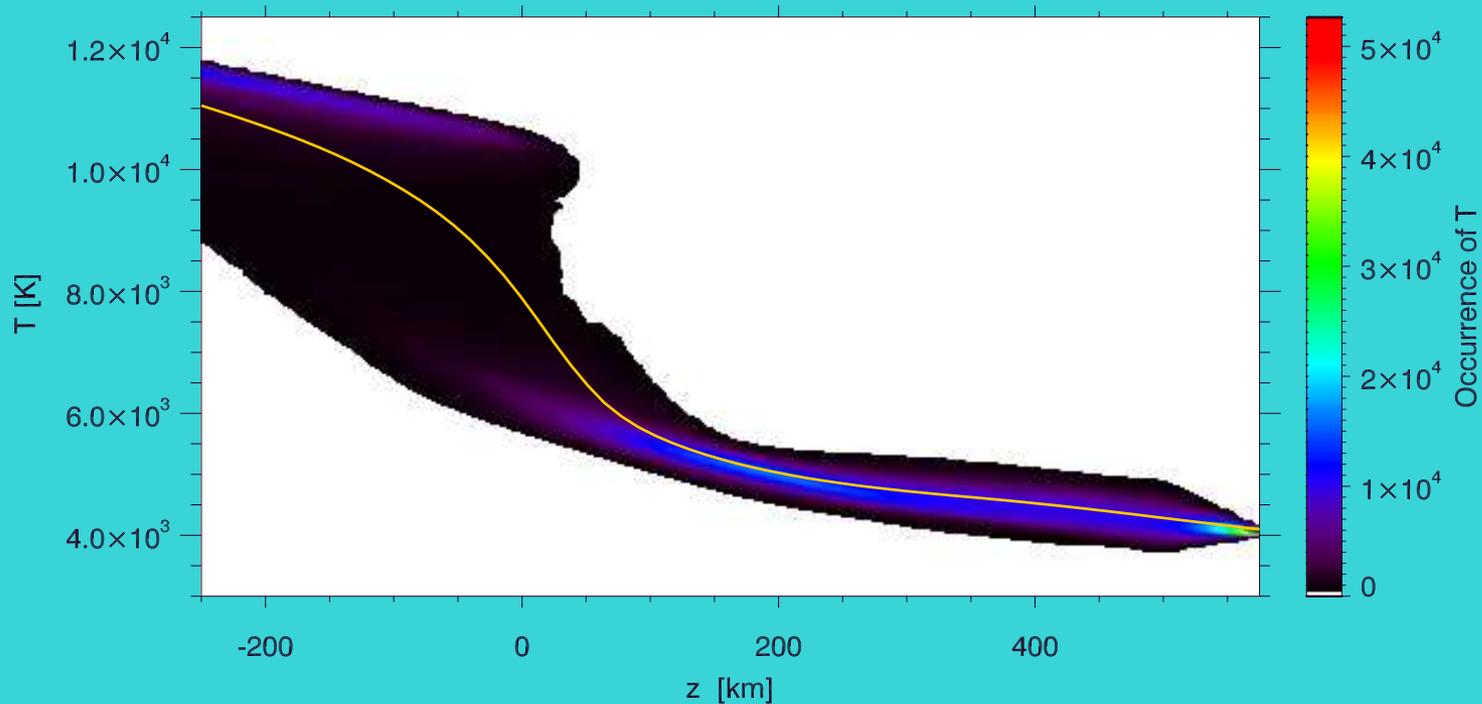


What is next?

Do we need something better than this?

3D

MHD



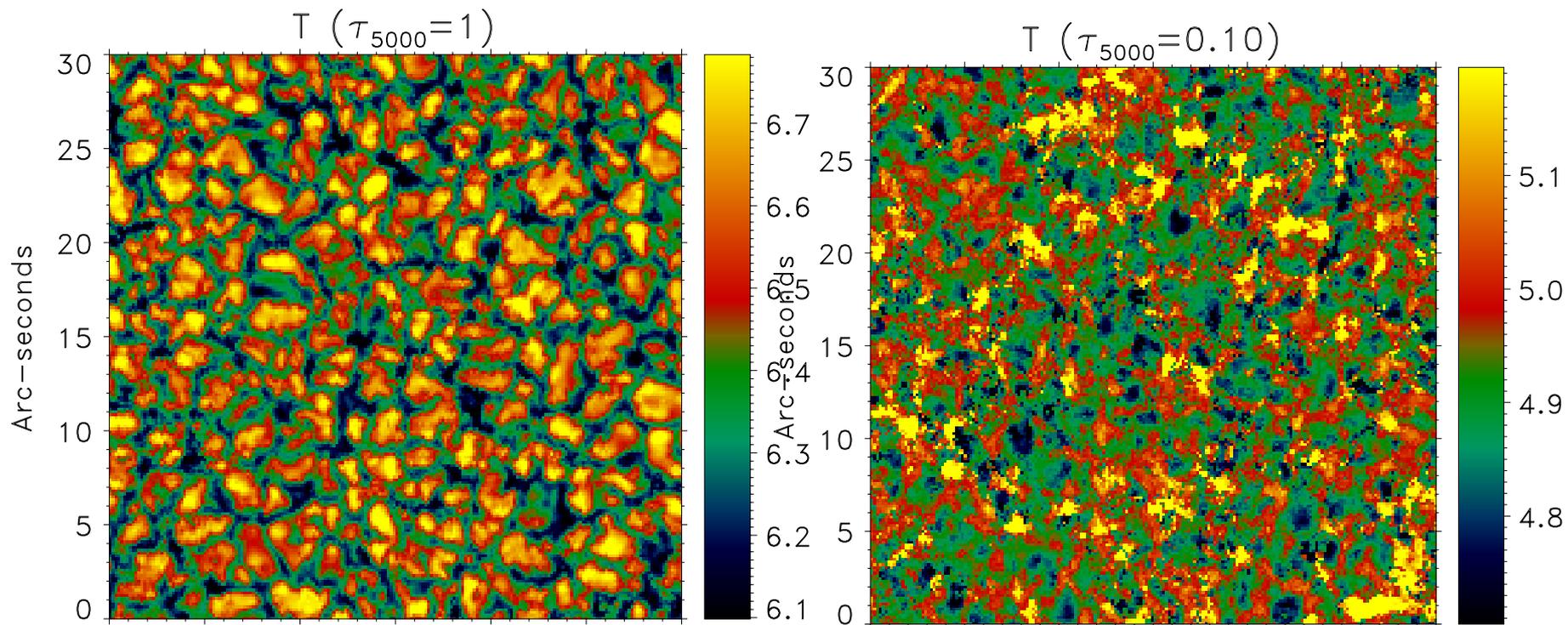
from Uitenbroek (2011)

What is next?

Do we need something better than this?

3D

MHD



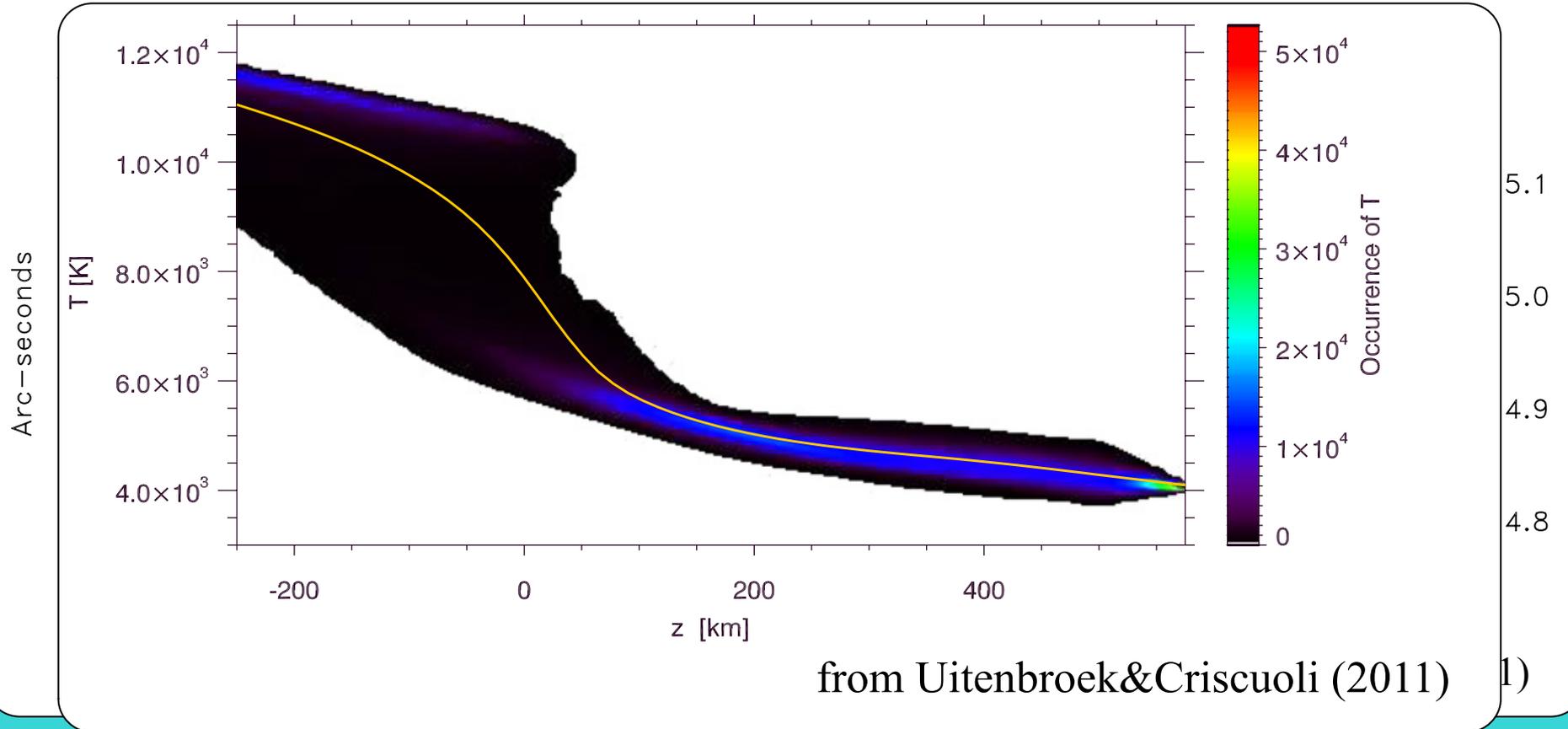
from Socas-Navarro et al. (2011)

What is next?

Do we need something better than this?

3D

MHD



5.1

5.0

4.9

4.8

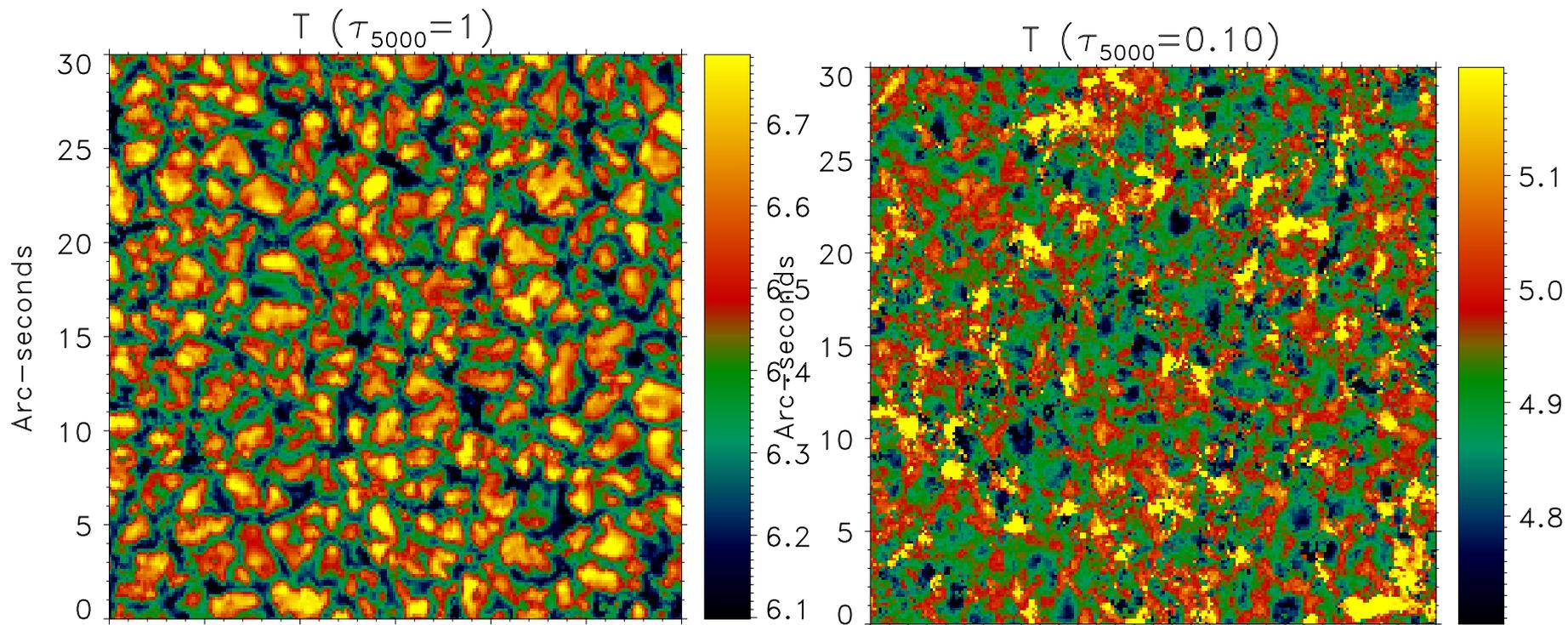
1)

What is next?

Do we need something better than this?

3D

MHD



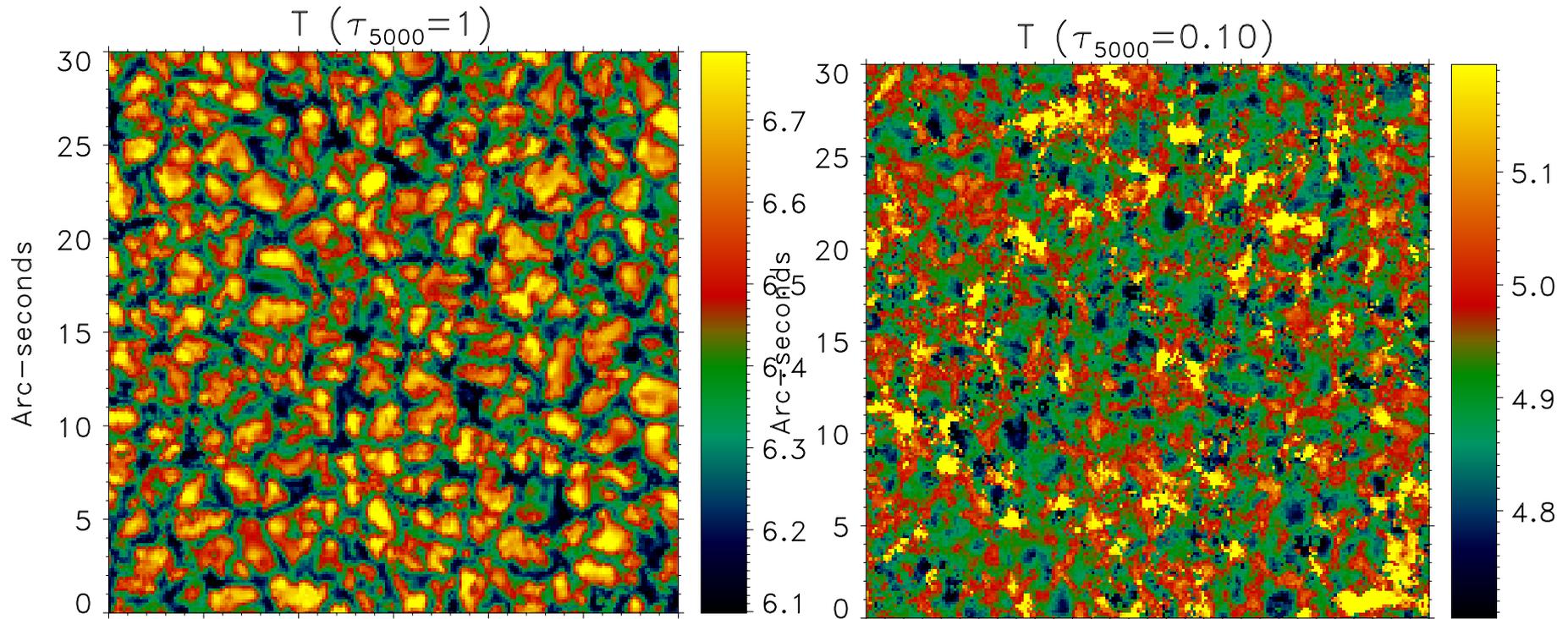
from Socas-Navarro et al. (2011)

What is next?

Do we need something better than this?

3D

MHD



from Socas-Navarro et al. (2011)

Hirzberger et al. (2010), Afram et al. (2011) MURaM vs. HINODE and SUNRISE

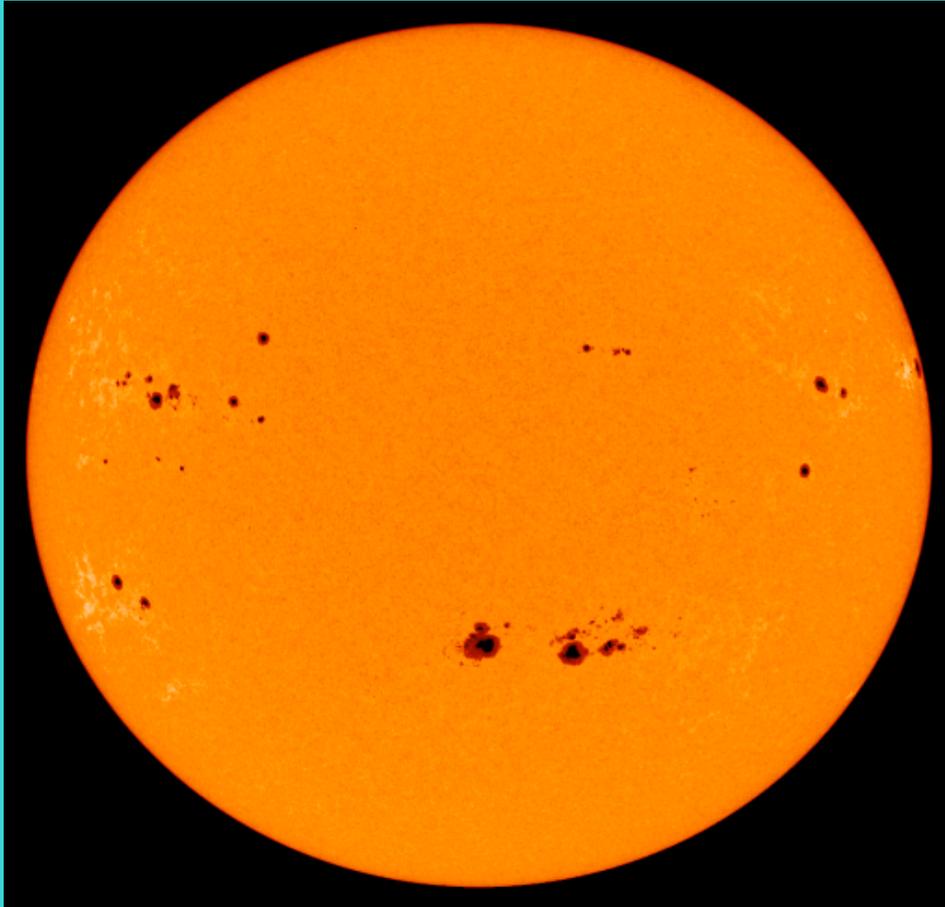
The analysis of the simulations uncovers a potentially more realistic centre-to-limb behavior than calculations based on 1-D model atmospheres. (Afram et al. 2011)

Outline

- Formation of the solar spectrum
- Variability of the solar spectrum
 - rotation cycle (27 days)
 - activity cycle (11 years)
 - secular time-scale

Modeling of the solar variability

Main assumption. Variations in the solar irradiance are directly related to the evolution of surface magnetic flux



Sunspot Model S

Plage Model P

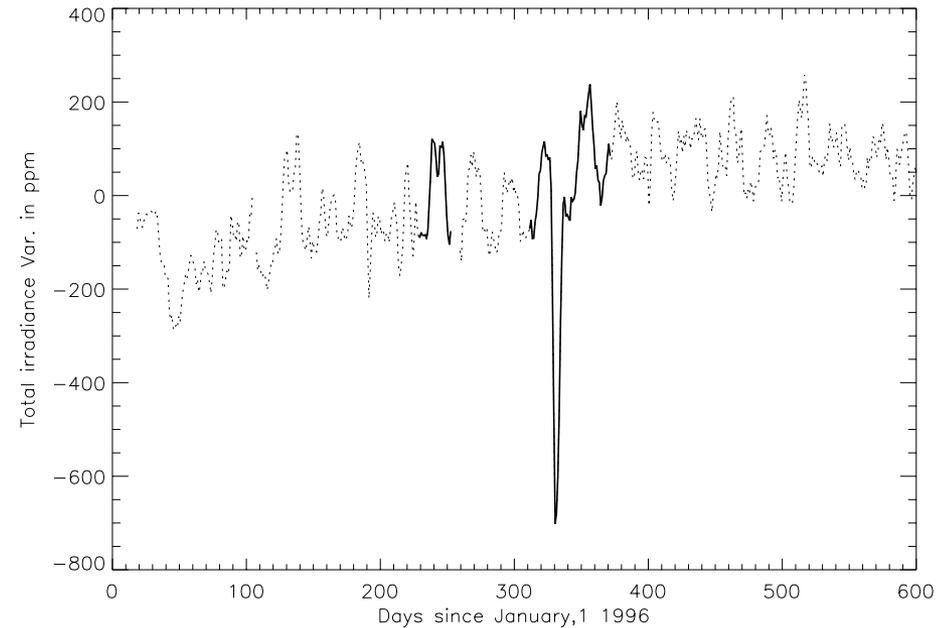
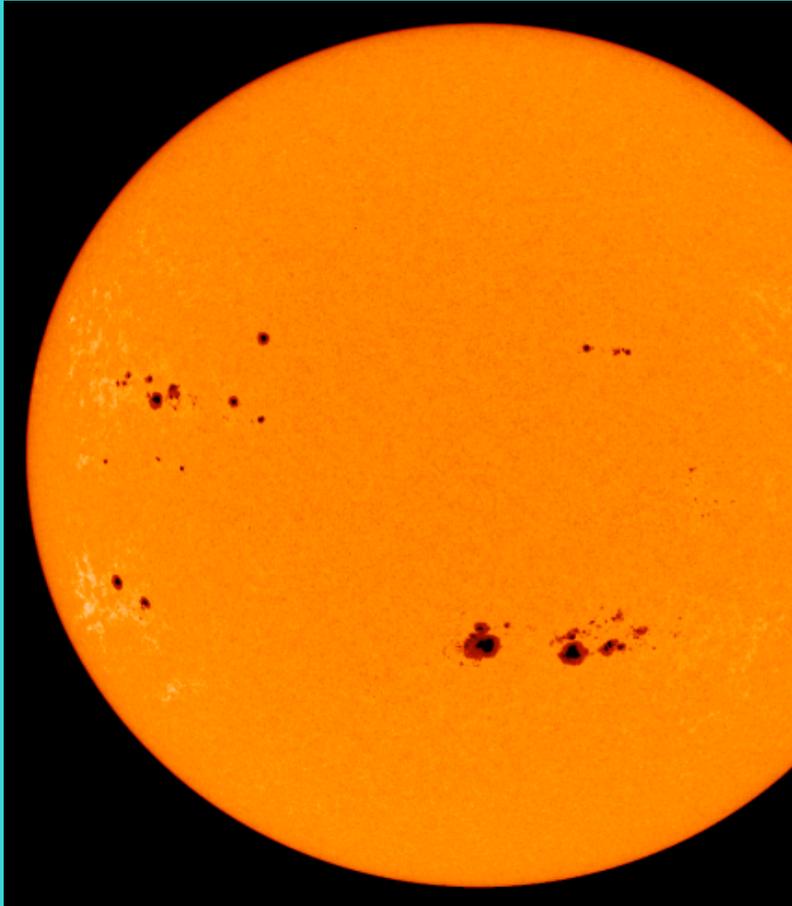
Bright network Model F

Quiet Sun Model C

$$I(\lambda, t) = \sum_k (\alpha_{\text{QS}}(\mu_k, t) I_{\text{QS}}(\lambda, \mu_k) + \alpha_{\text{S}}(\mu_k, t) I_{\text{S}}(\lambda, \mu_k) + \alpha_{\text{AN}}(\mu_k, t) I_{\text{AN}}(\lambda, \mu_k) + \alpha_{\text{P}}(\mu_k, t) I_{\text{P}}(\lambda, \mu_k)),$$

Modeling of the solar variability

Main assumption. Variations in the solar irradiance are directly related to the evolution of surface magnetic flux

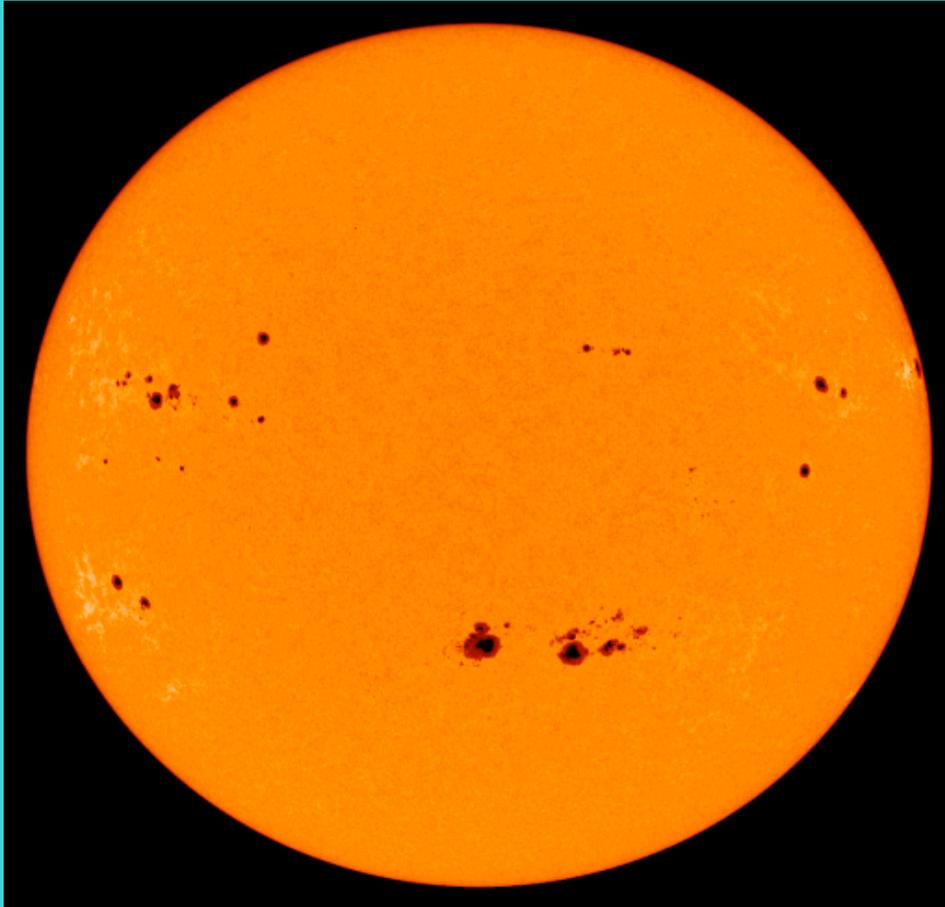


from Fligge et al. (2000)

$$I(\lambda, t) = \sum_k (\alpha_{QS}(\mu_k, t) I_{QS}(\lambda, \mu_k) + \alpha_S(\mu_k, t) I_S(\lambda, \mu_k) + \alpha_{AN}(\mu_k, t) I_{AN}(\lambda, \mu_k) + \alpha_P(\mu_k, t) I_P(\lambda, \mu_k)),$$

Modeling of the solar variability

Main assumption. Variations in the solar irradiance are directly related to the evolution of surface magnetic flux



Sunspot Model S

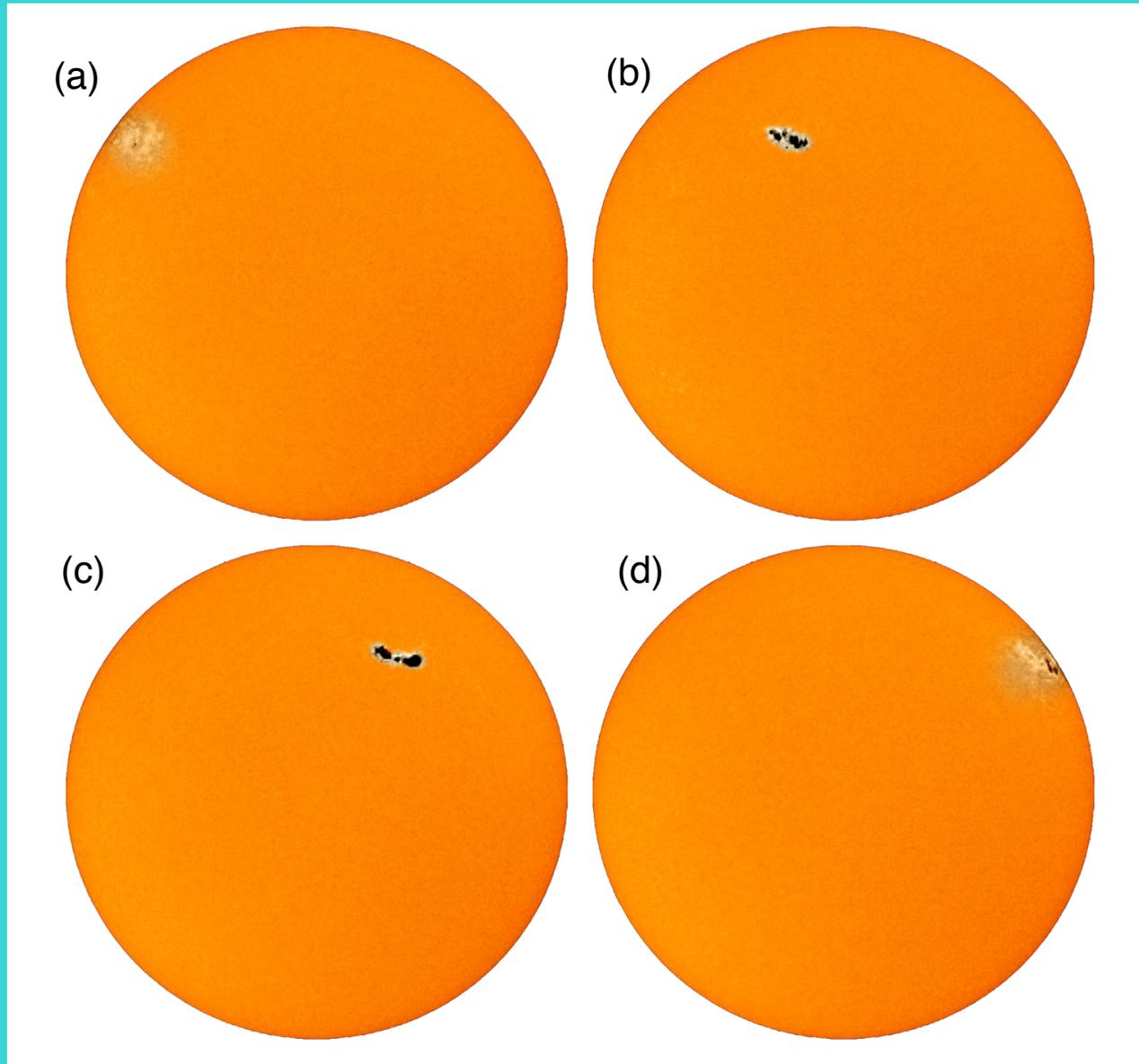
Plage Model P

**Bright network
Model F**

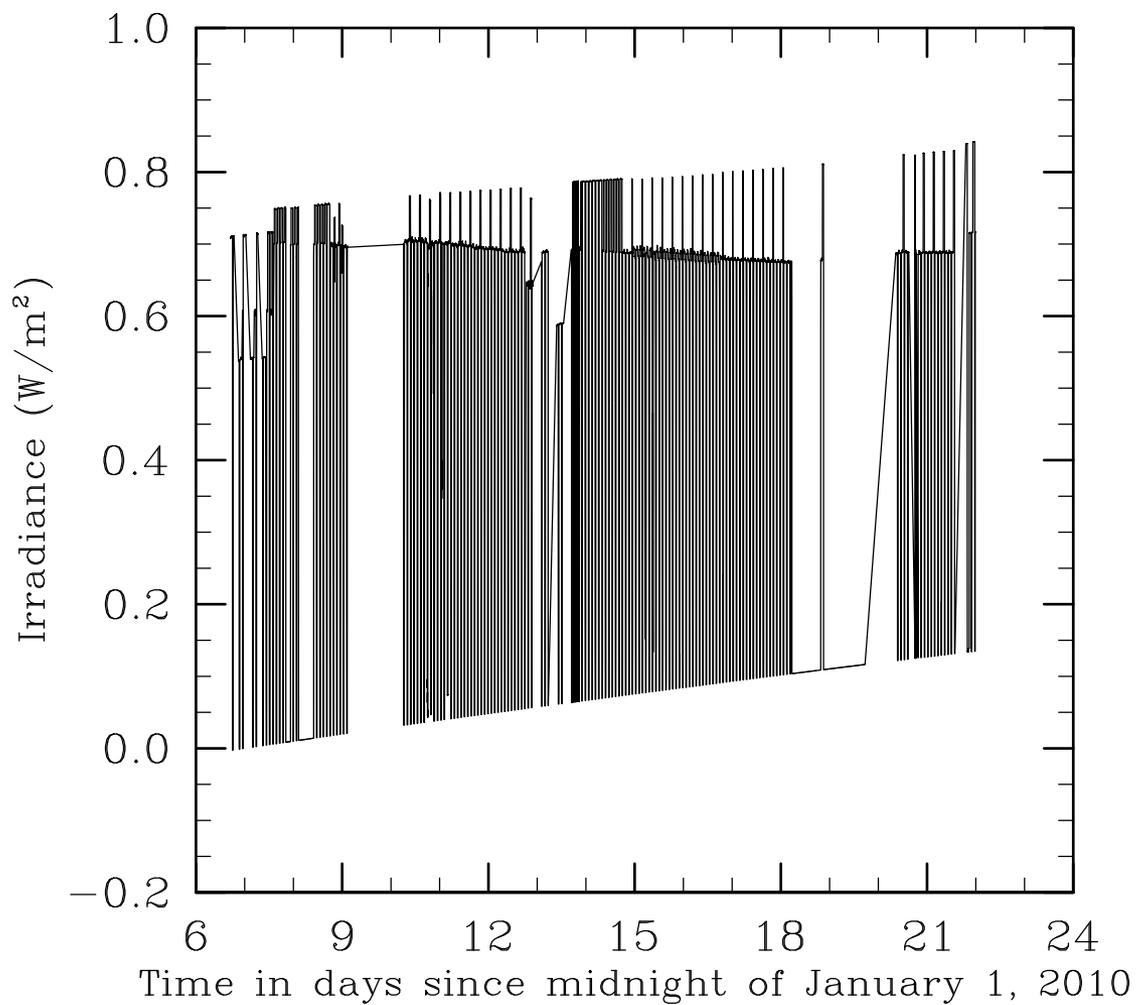
Quiet Sun Model C

$$I(\lambda, t) = \sum_k (\alpha_{QS}(\mu_k, t) I_{QS}(\lambda, \mu_k) + \alpha_S(\mu_k, t) I_S(\lambda, \mu_k) + \alpha_{AN}(\mu_k, t) I_{AN}(\lambda, \mu_k) + \alpha_P(\mu_k, t) I_P(\lambda, \mu_k)),$$

Rotational cycle. LYRA/PROBA2 measurements



Rotational cycle. LYRA/PROBA2 measurements

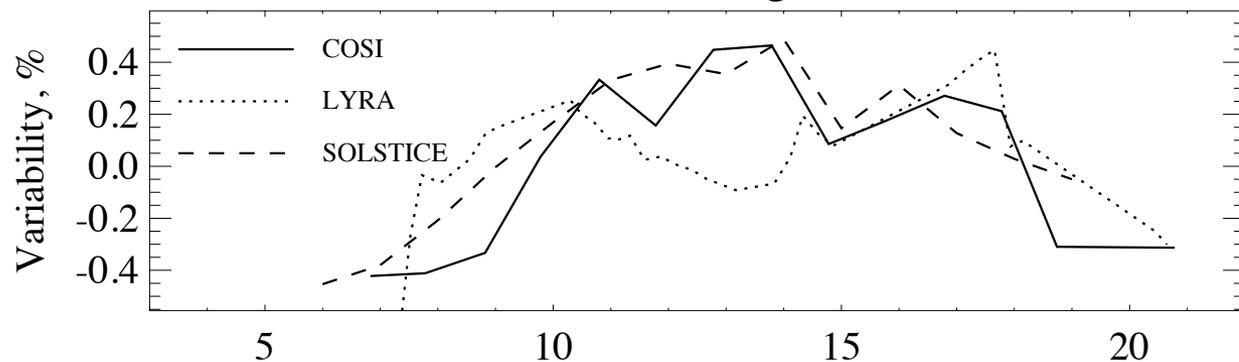


Rotational cycle. LYRA/PROBA2 measurements

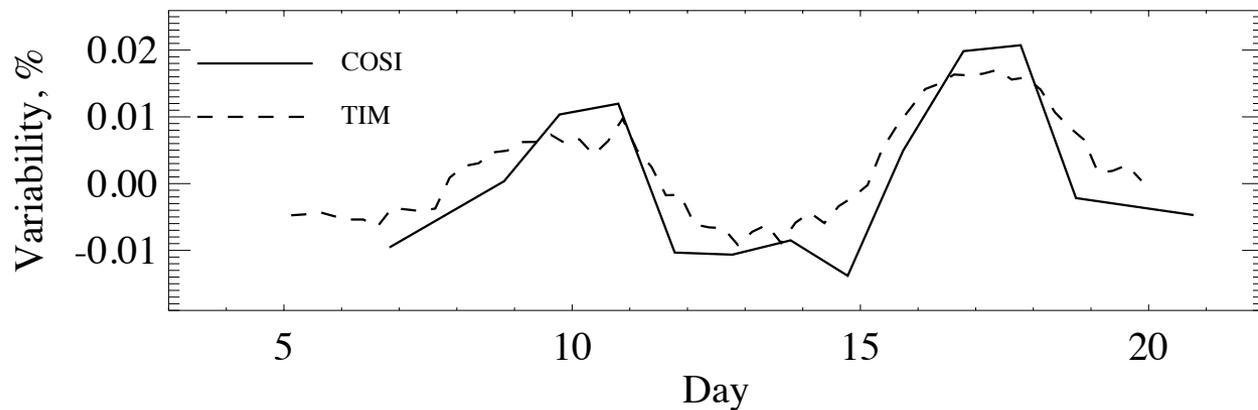
(a)

(b)

Herzberg

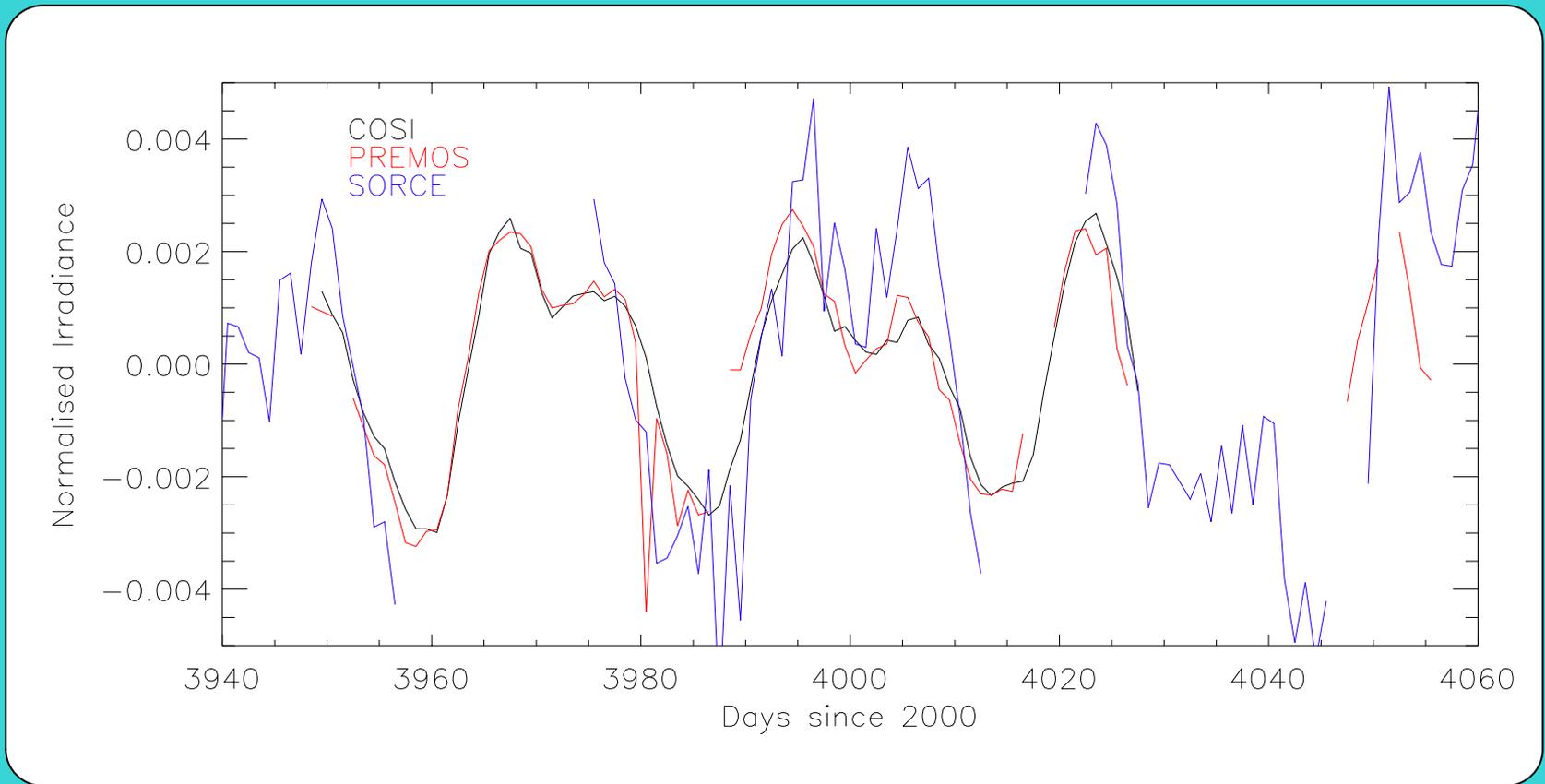


TSI



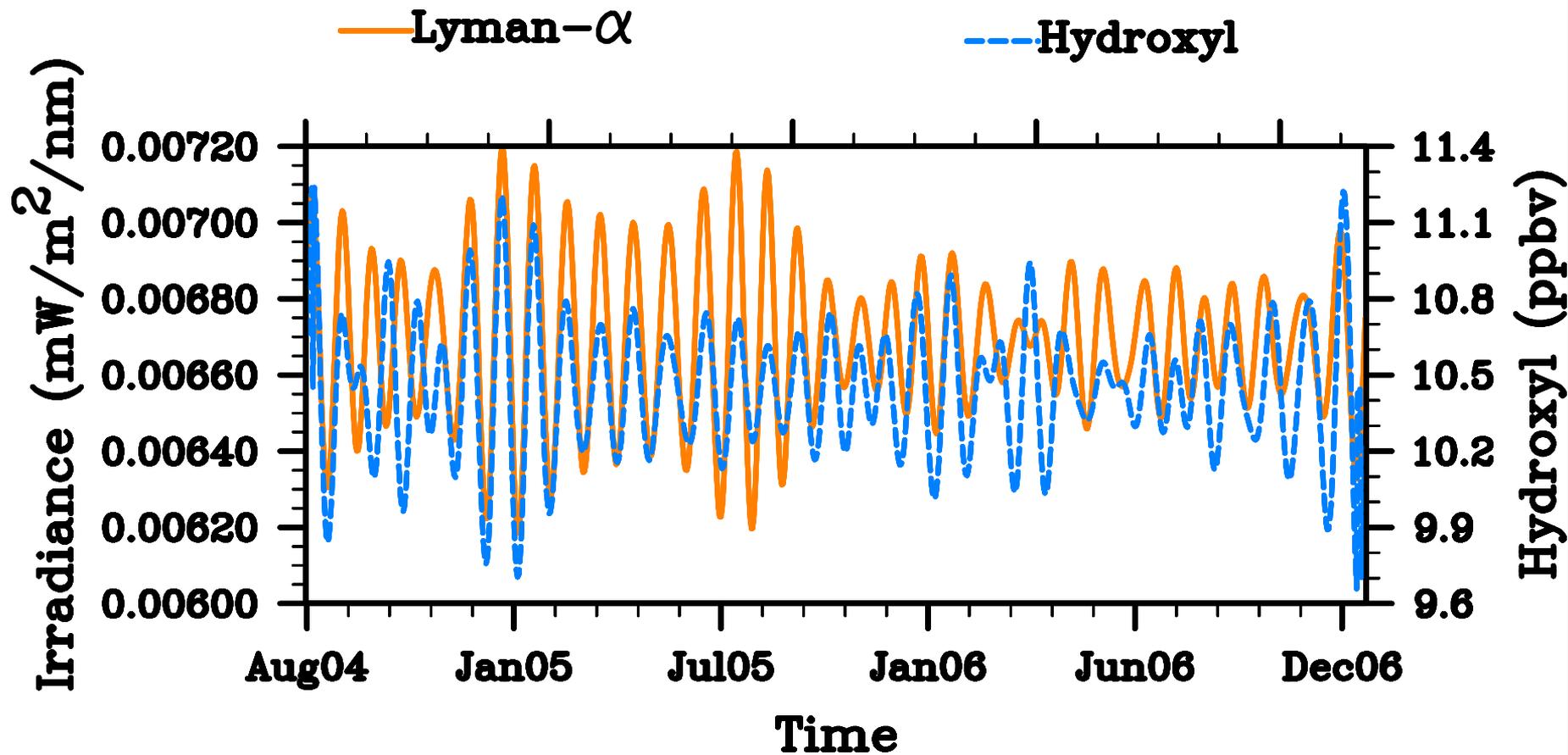
PSPT
images

Rotational cycle. PREMOS/PICARD measurements



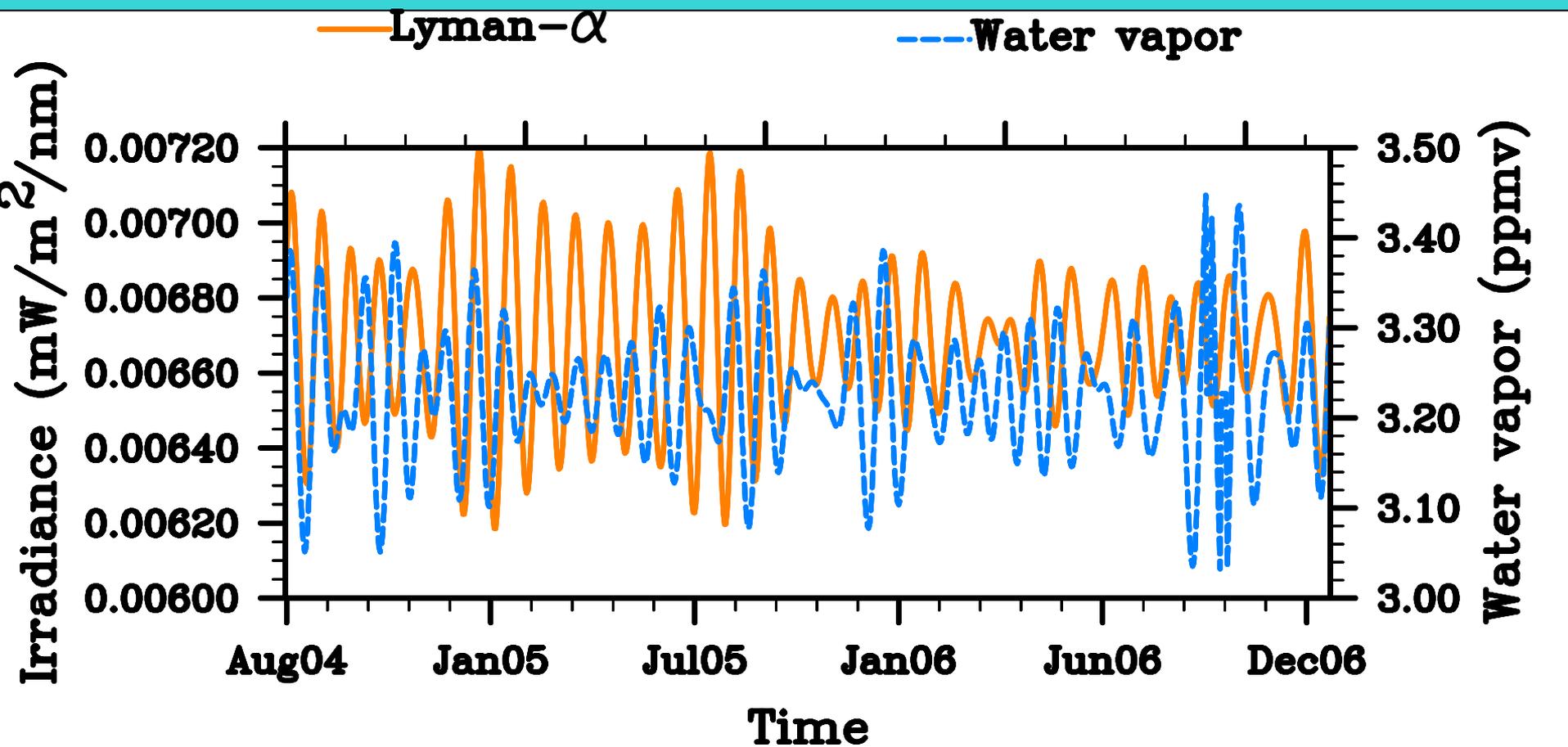
HMI filling factors

Atmospheric response



Hydroxyl

Atmospheric response

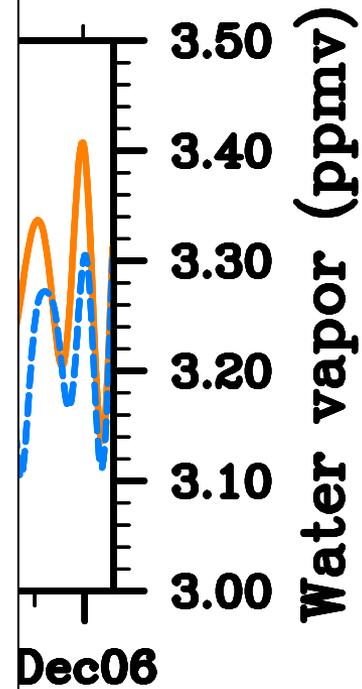
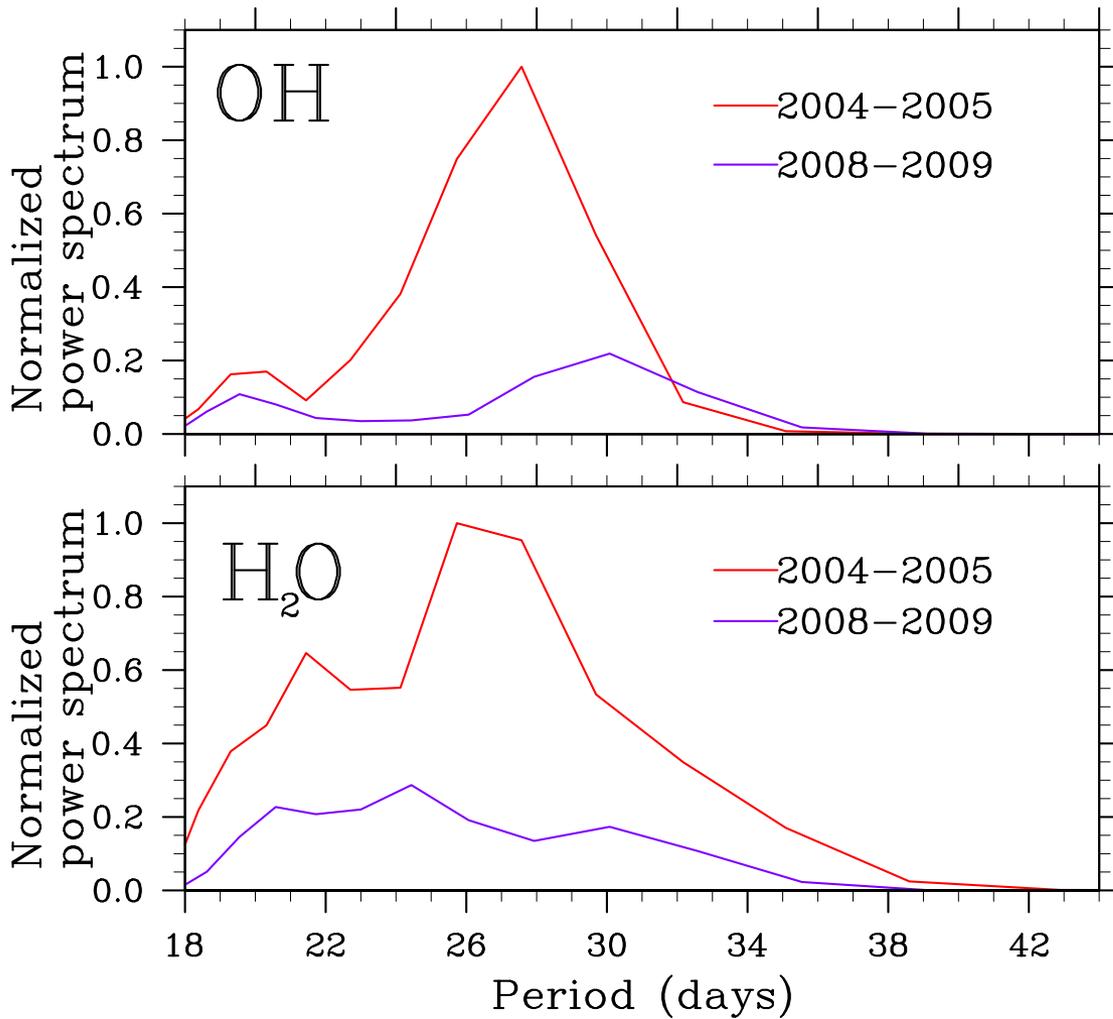


Water vapor

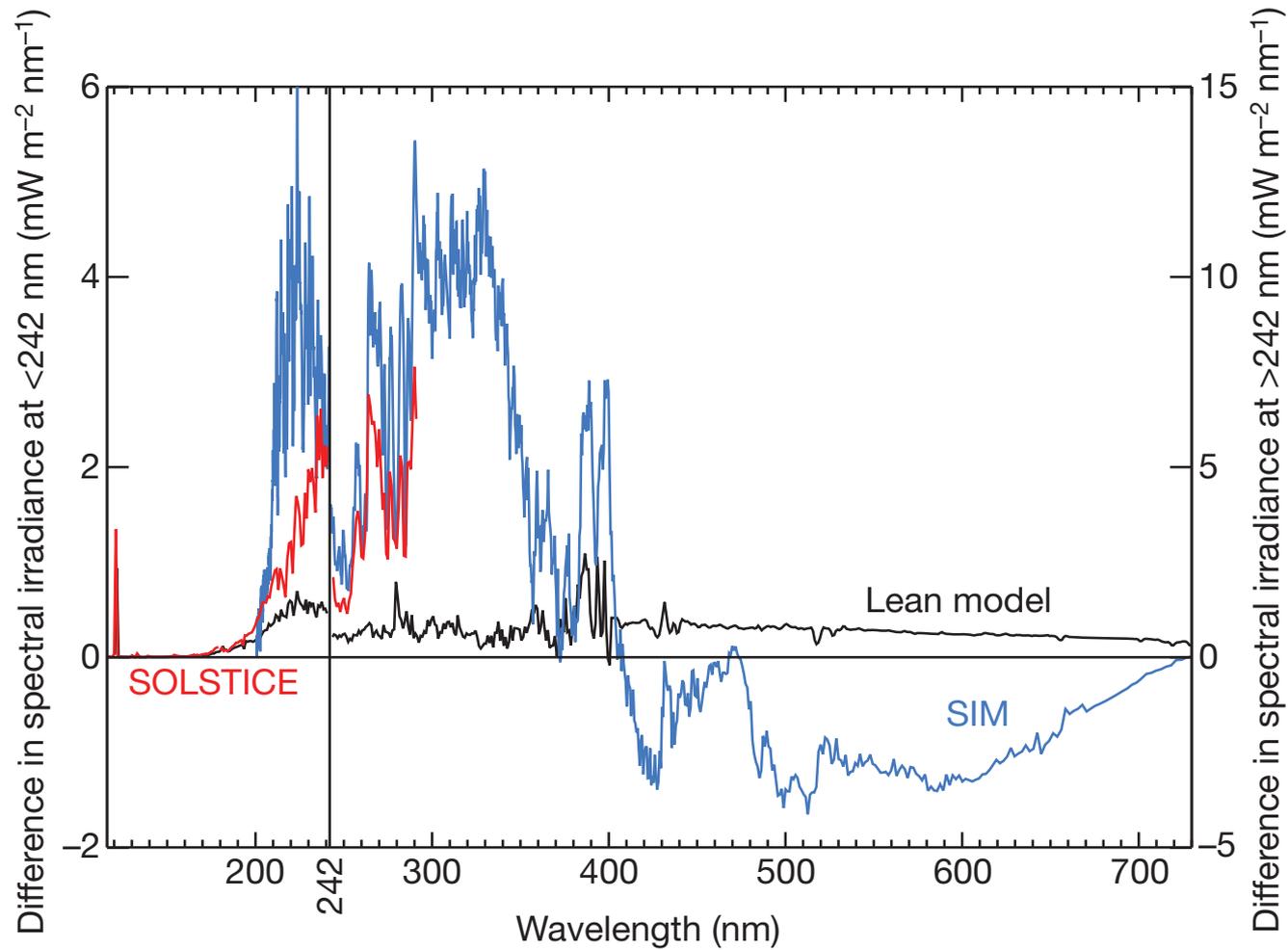
Atmospheric response

Irradiance ($\text{mW}/\text{m}^2/\text{nm}$)

0.00720
0.00700
0.00680
0.00660
0.00640
0.00620
0.00600

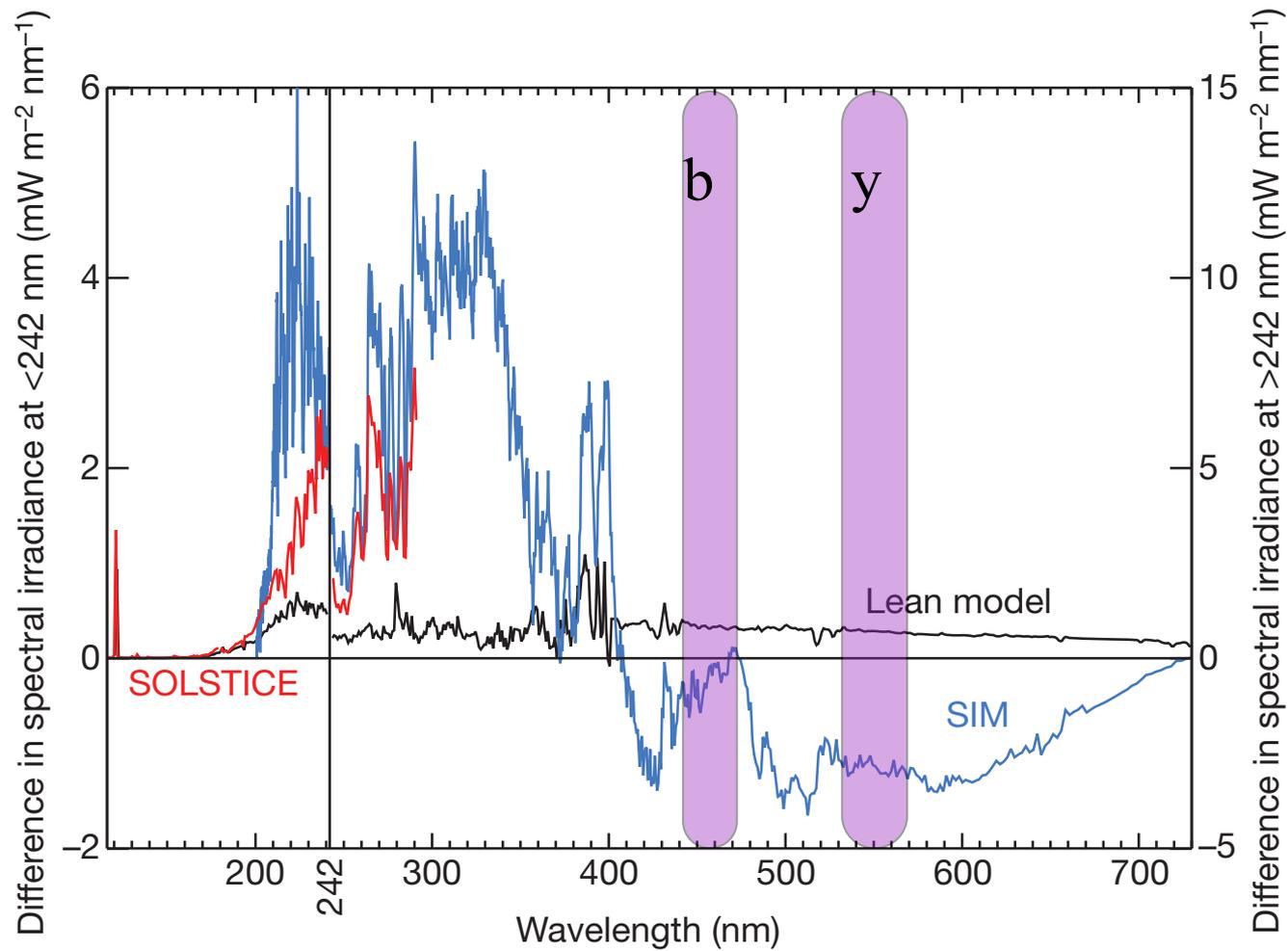


SIM+SOLSTICE/SORCE measurements



from Haigh et al. (2010)

SIM+SOLSTICE/SORCE measurements



from Haigh et al. (2010)

Synoptic Program

Search for the variations of quiet Sun magnetism with the solar cycle

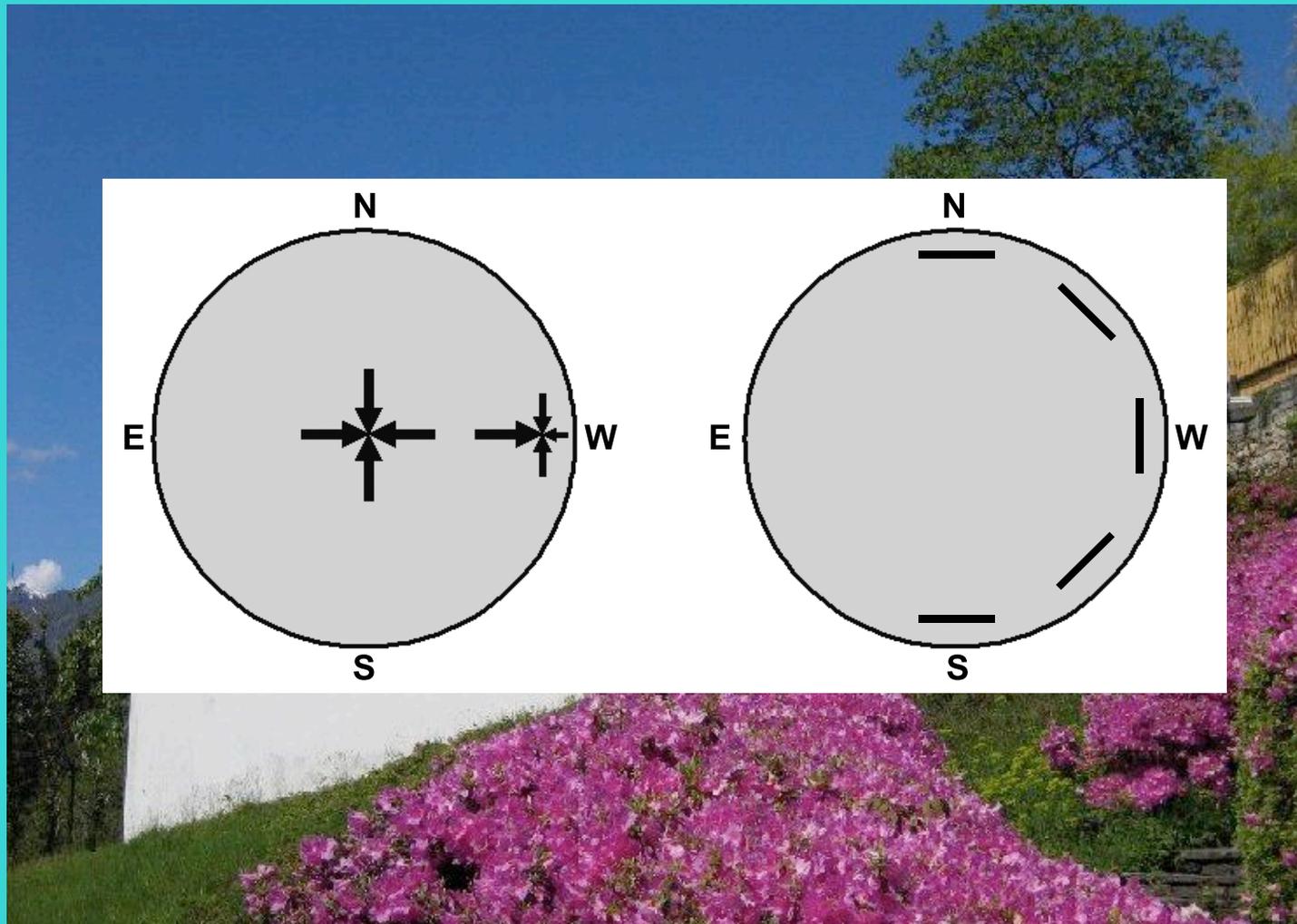
Measurements of the scattering polarization close to the solar limb



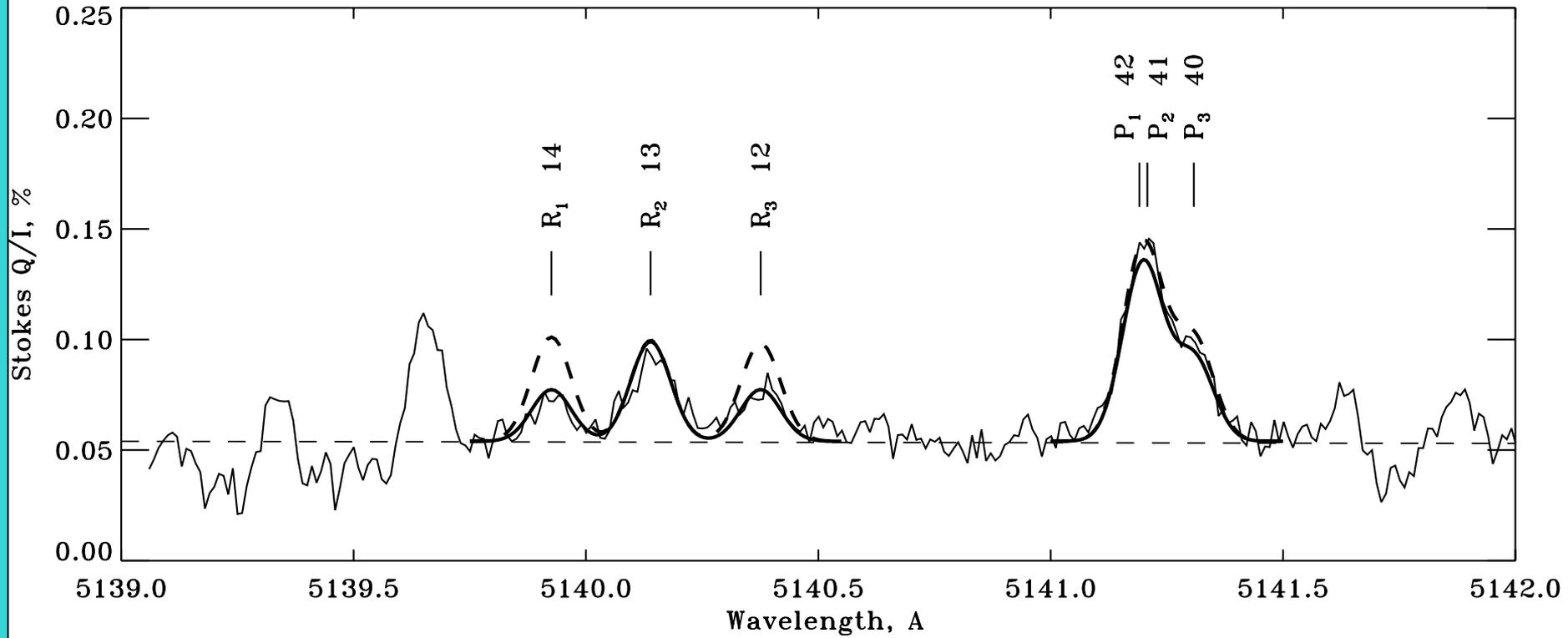
Synoptic Program

Search for the variations of quiet Sun magnetism with the solar cycle

Measurements of the scattering polarization close to the solar limb

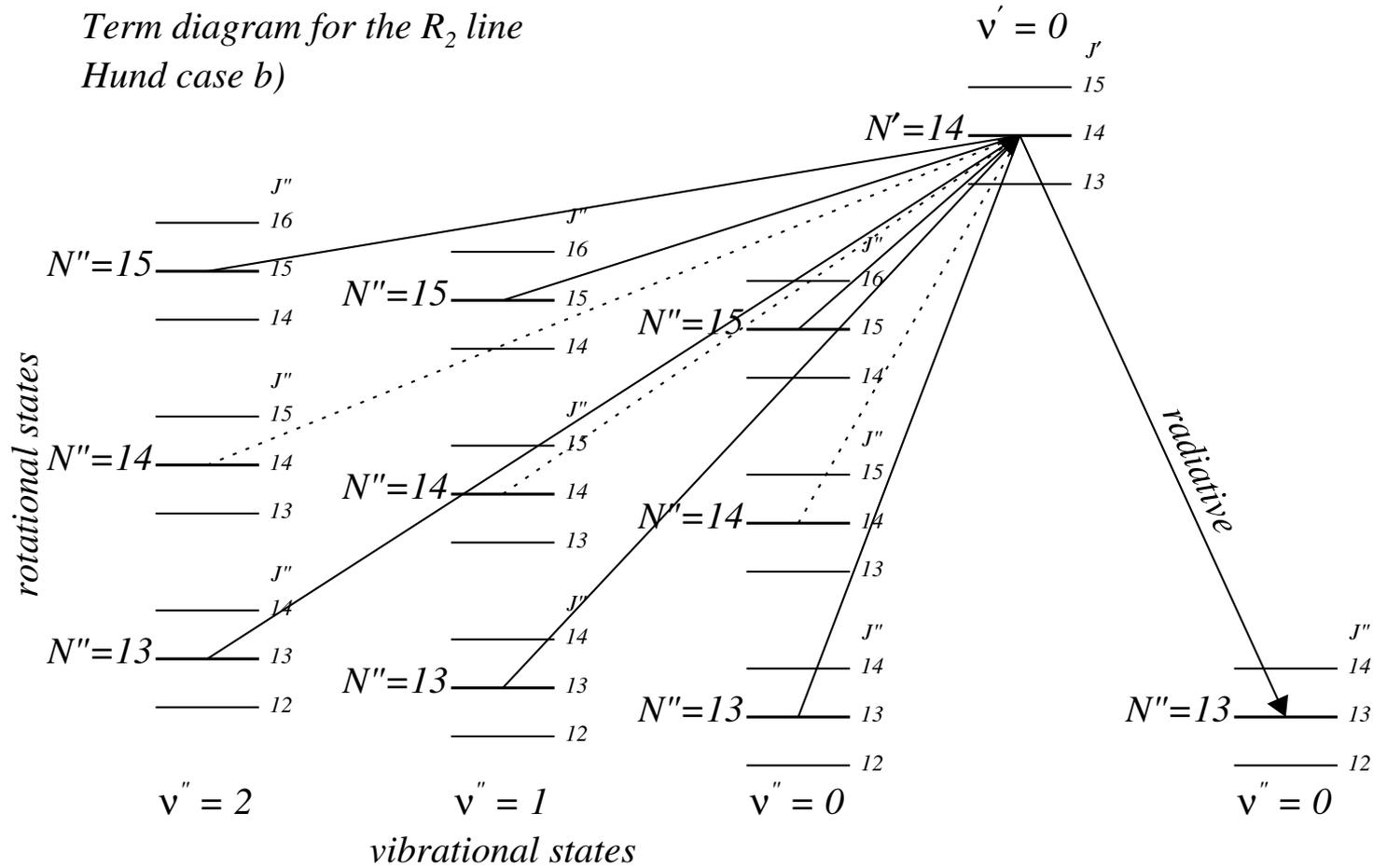


Polarization in C₂ lines

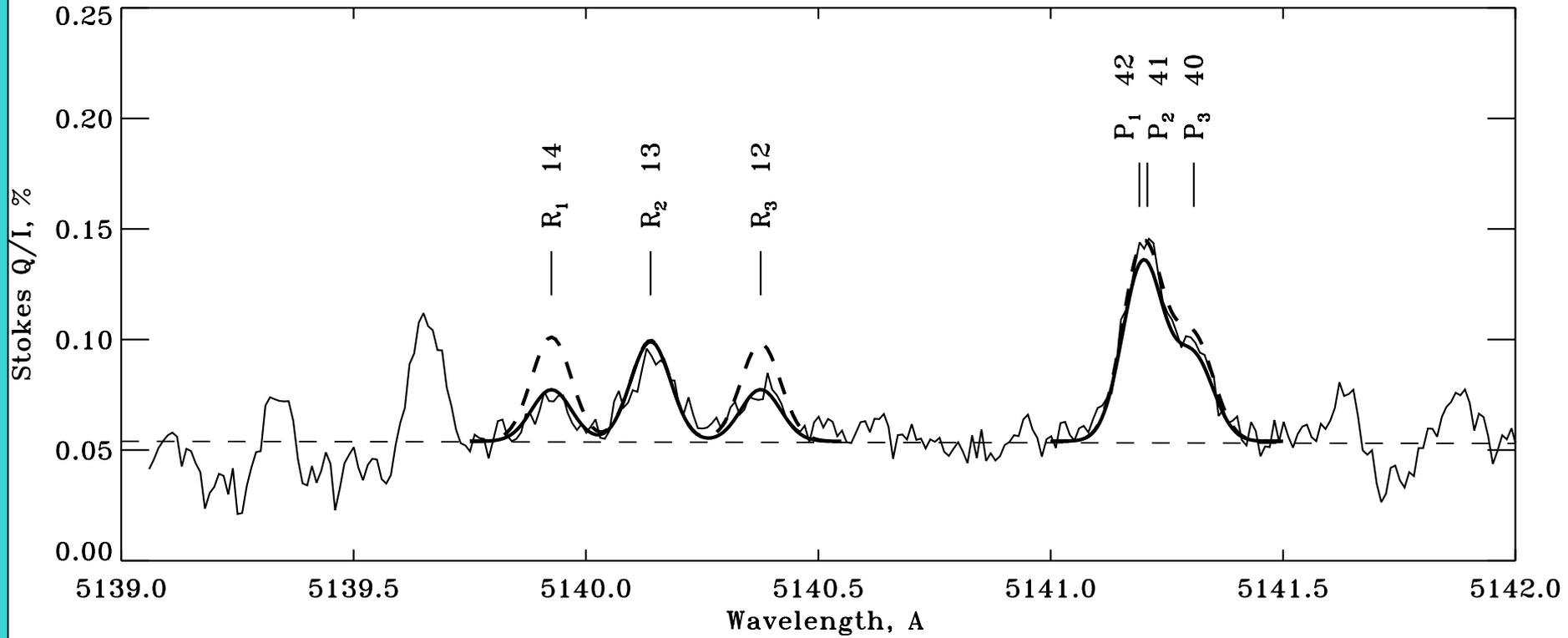


Polarization in C₂ lines

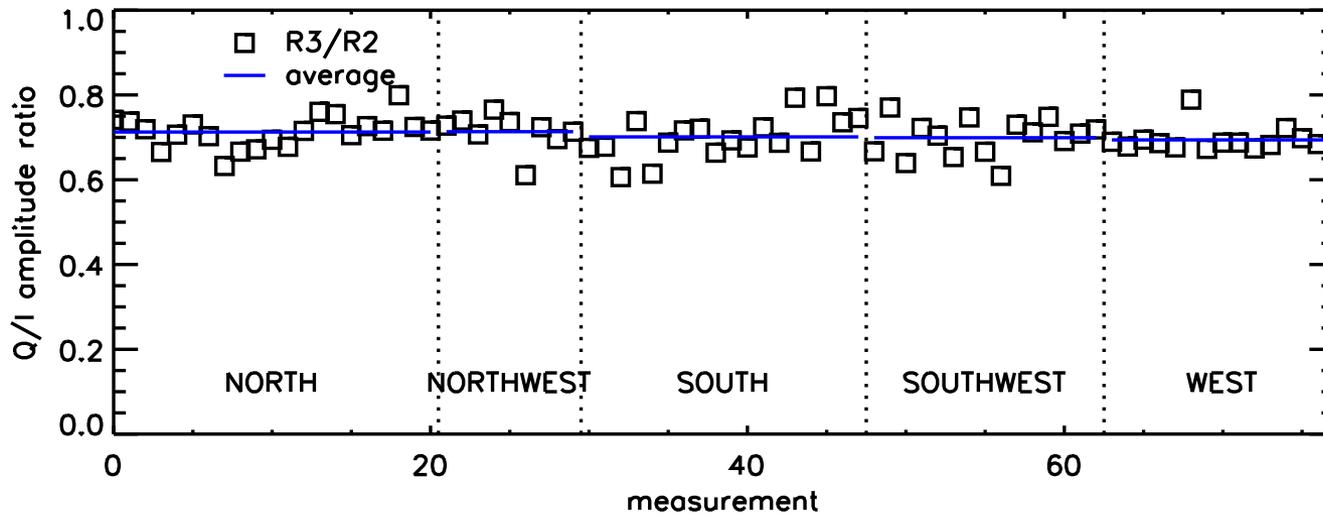
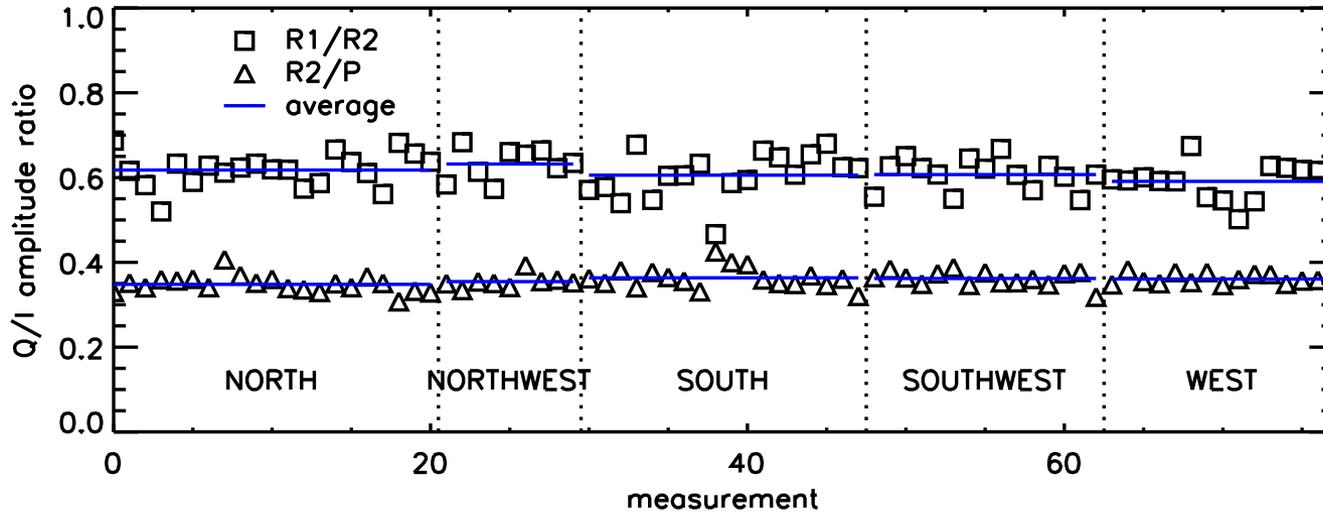
Term diagram for the R₂ line
Hund case b)



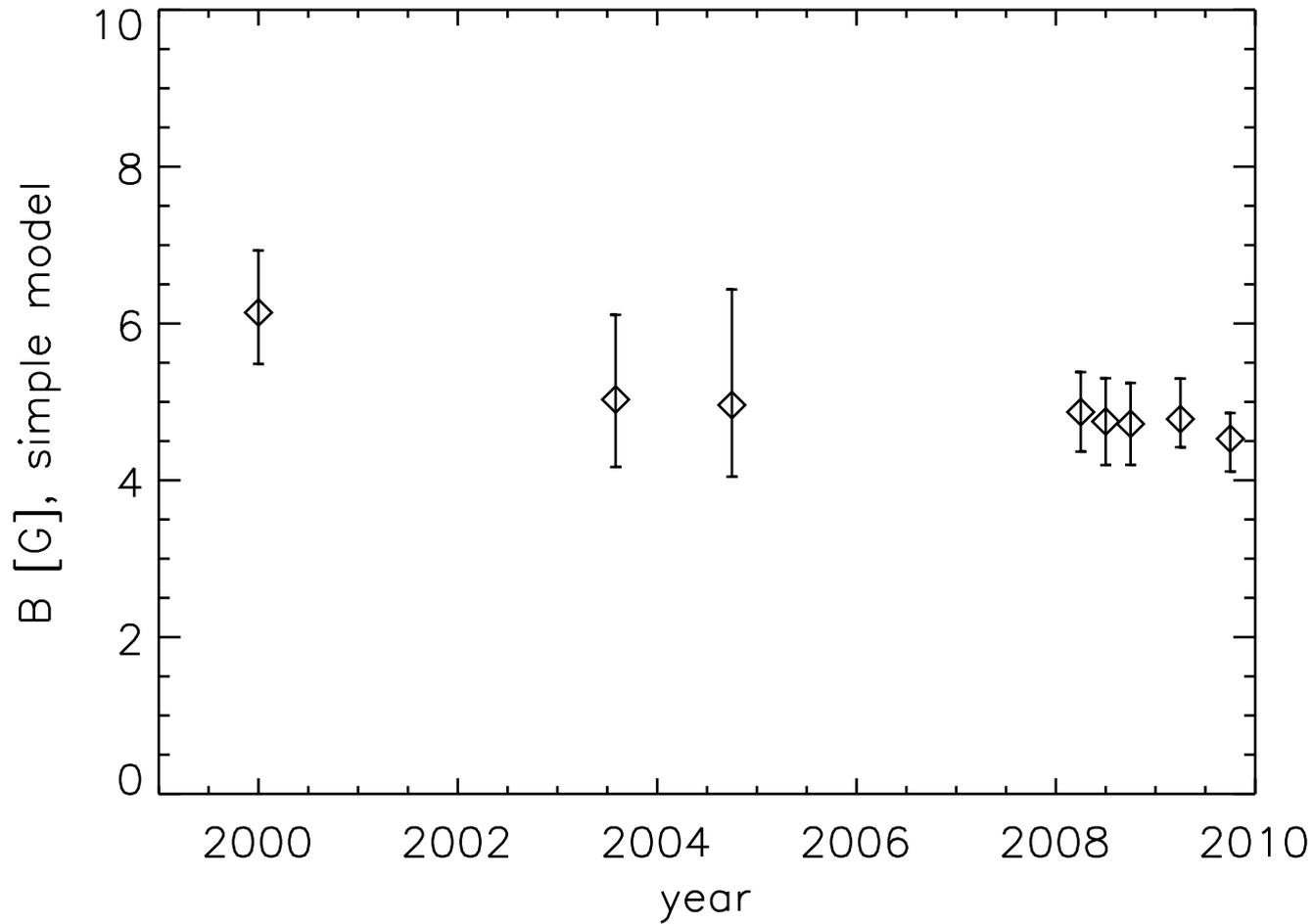
Polarization in C₂ lines



Distribution on the disc

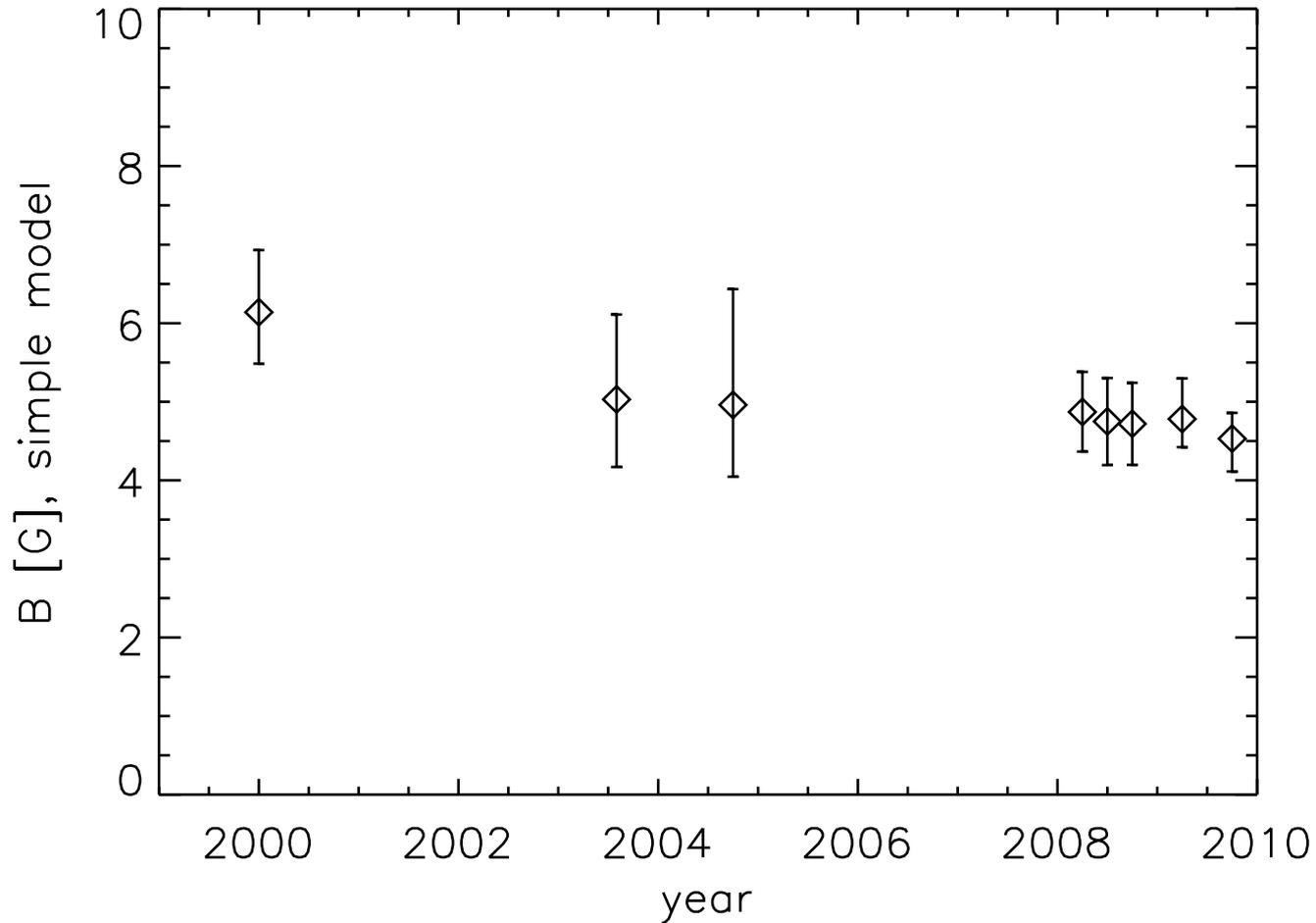


Evolution of the Quiet Sun



from Kleint et al. (2010)

Evolution of the Quiet Sun



from Kleint et al. (2010)

The quiet Sun magnetism is probably modulated by the solar cycle

Modulation

observation	B [G]	ρ_C	ρ_J
Syn. obs.*	7.41 ± 0.09	0.054 ± 0.001	1.58 ± 0.03
stddev σ	0.76	0.010	0.23
Atlas	9.1 ± 1.5	0.045 ± 0.006	1.2 ± 0.2
ms ₀₈₀₅₀₉	8.1 ± 0.8	0.047 ± 0.003	1.4 ± 0.1

Modulation

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min

max

Modulation

observation	B [G]	ρ_C	ρ_J	
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stddev σ	0.76	0.010	0.23	
Atlas	9.1 ± 1.5	0.045 ± 0.006	1.2 ± 0.2	max
ms080509	8.1 ± 0.8	0.047 ± 0.003	1.4 ± 0.1	

The quiet Sun magnetism is probably modulated by the solar cycle

VERY SPECULATIVE...

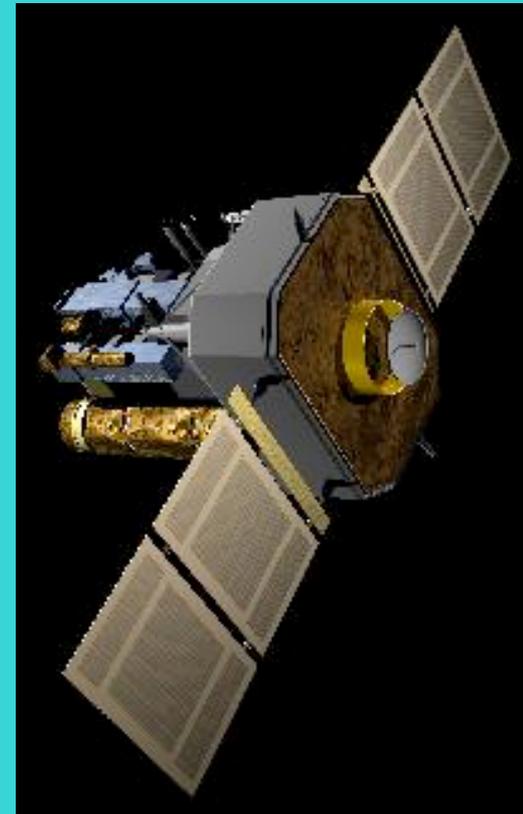
The Sun today

TIM/SORCE



1361.1 W/m²

VIRGO/SOHO



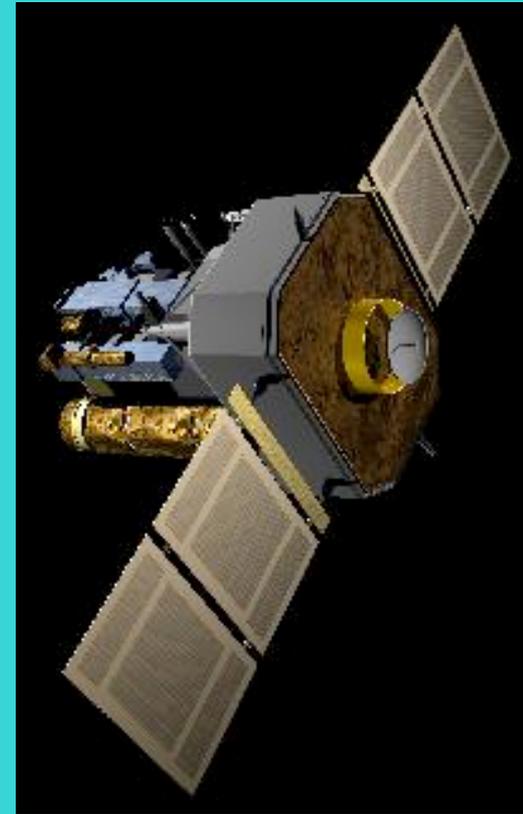
1365.1 W/m²

The Sun today

TIM/SORCE



VIRGO/SOHO



1361.1 W/m²



1365.1 W/m²



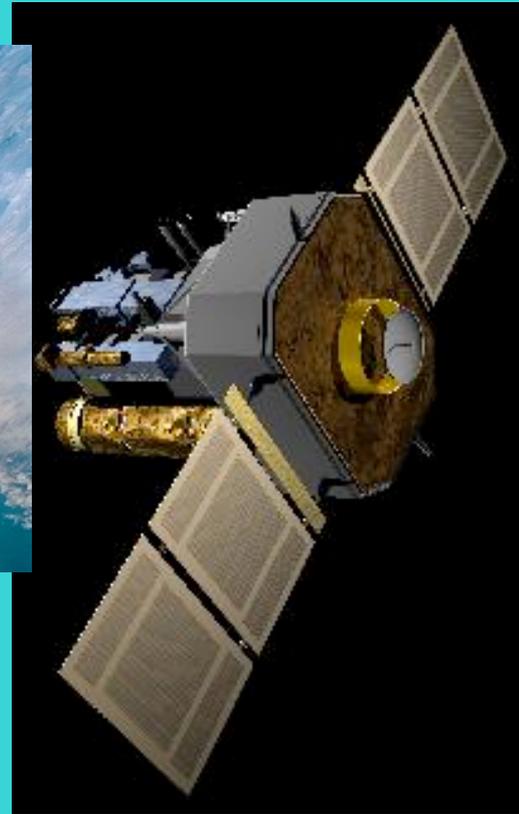
$D \approx 220000 \text{ km}$

The Sun today

TIM/SORCE

PREMOS/PICARD

VIRGO/SOHO



1361.7 W/m²

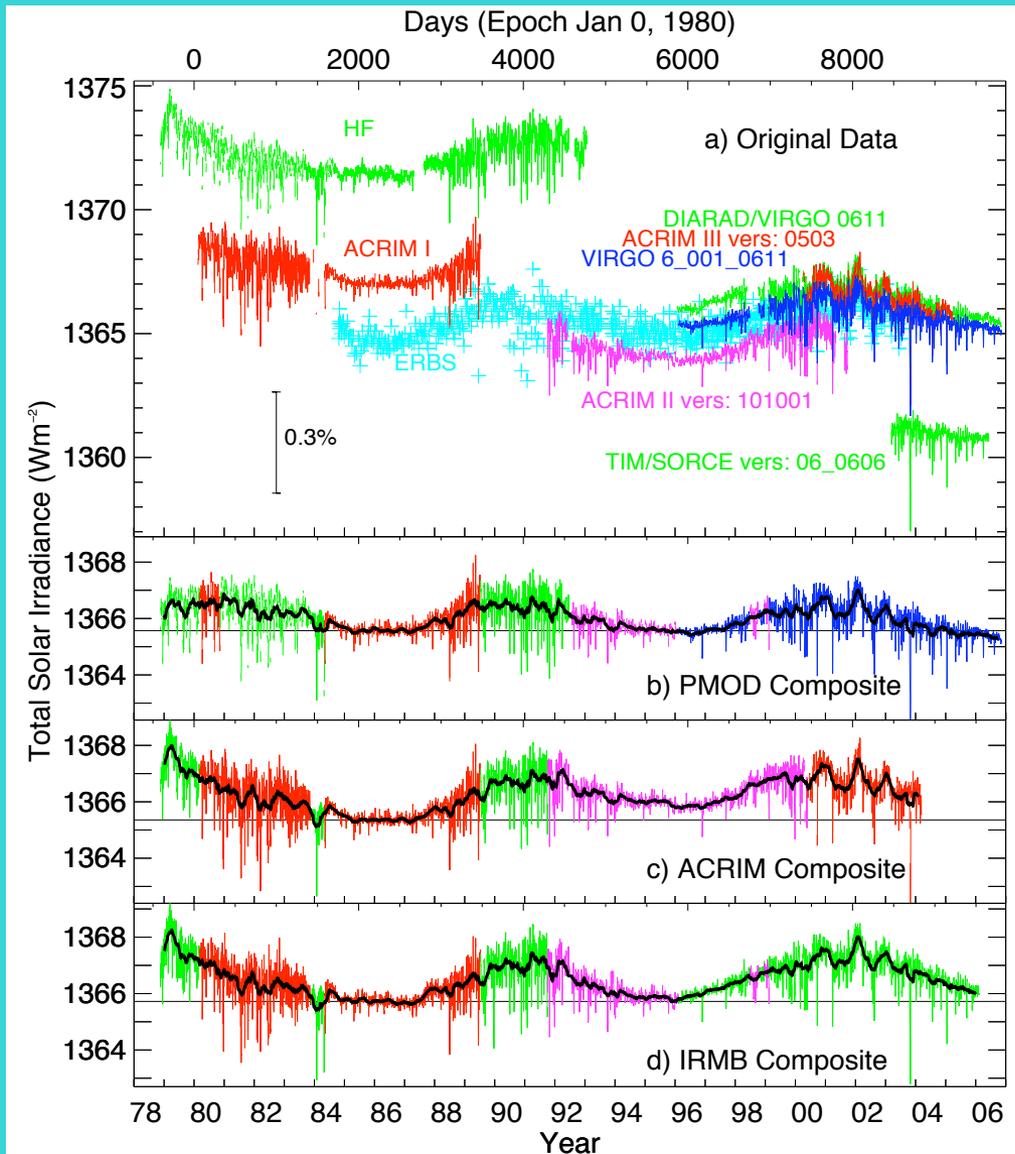
1361.1 W/m²

1365.1 W/m²



D ≈ 220000 km

TSI reconstruction for the satellite period



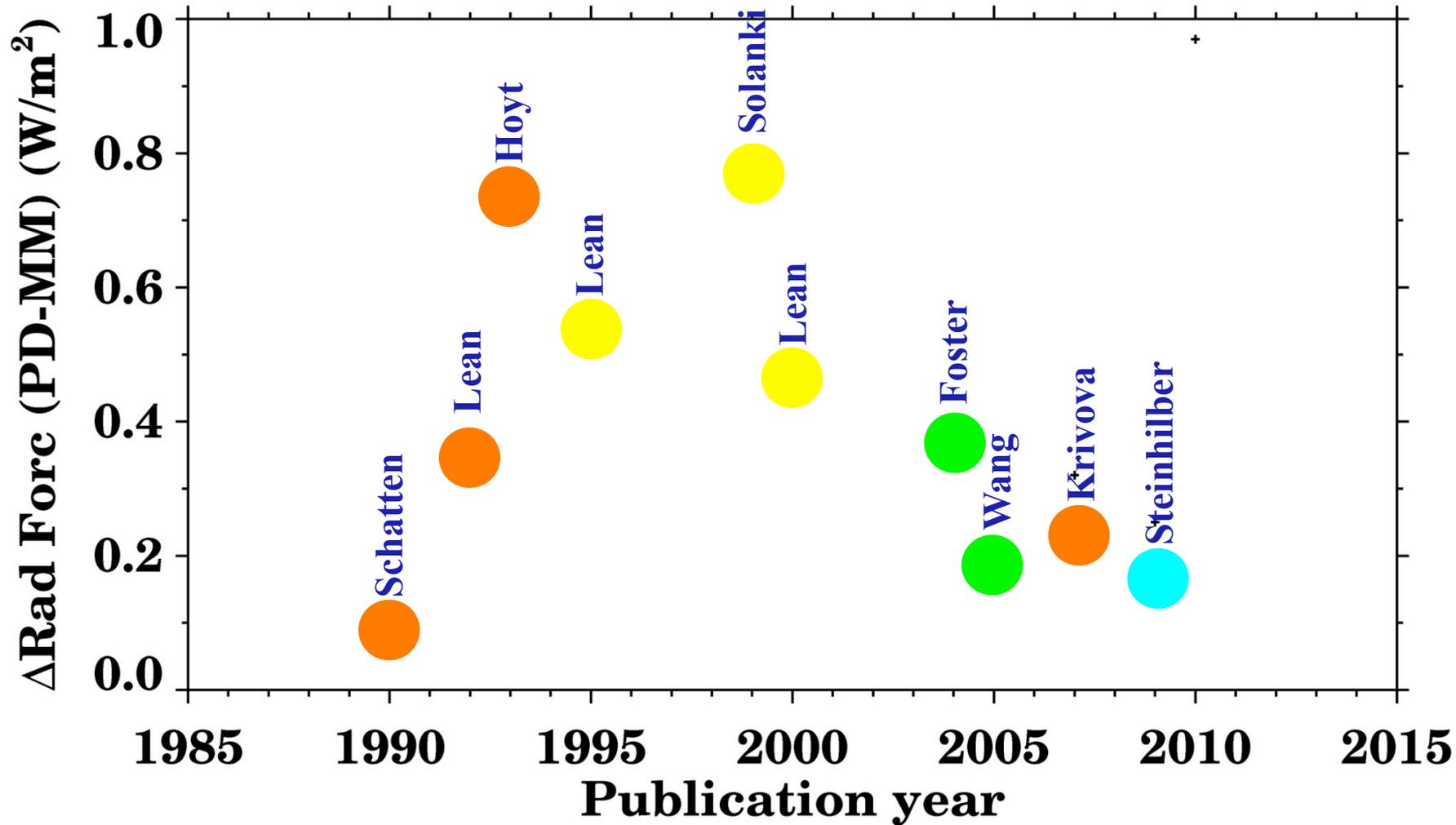
Scafetta & Willson (2009)

Fröhlich (2009)

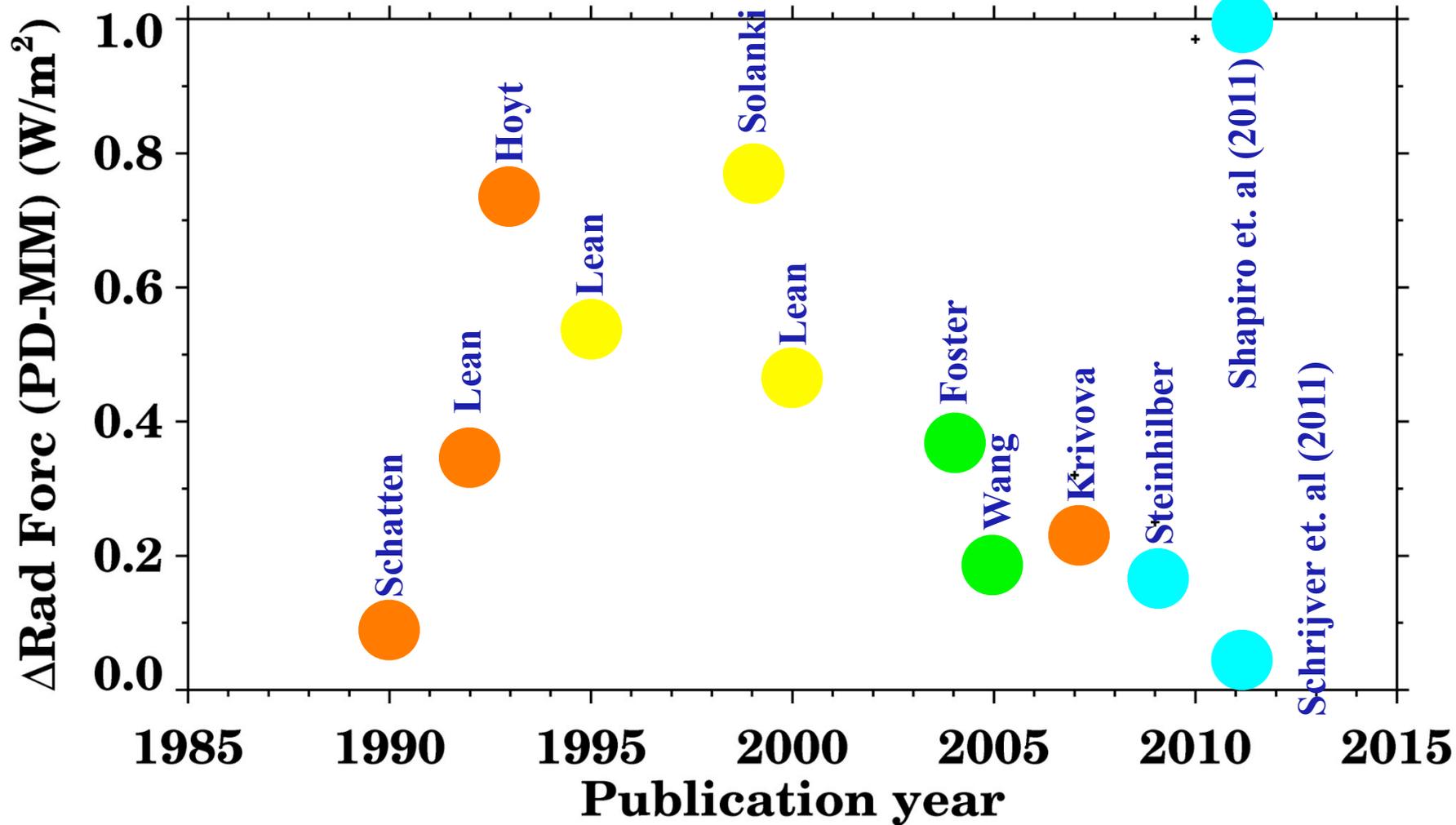
Krivova et al. (2009)

Krivova, Solanki & Schmutz (2011)

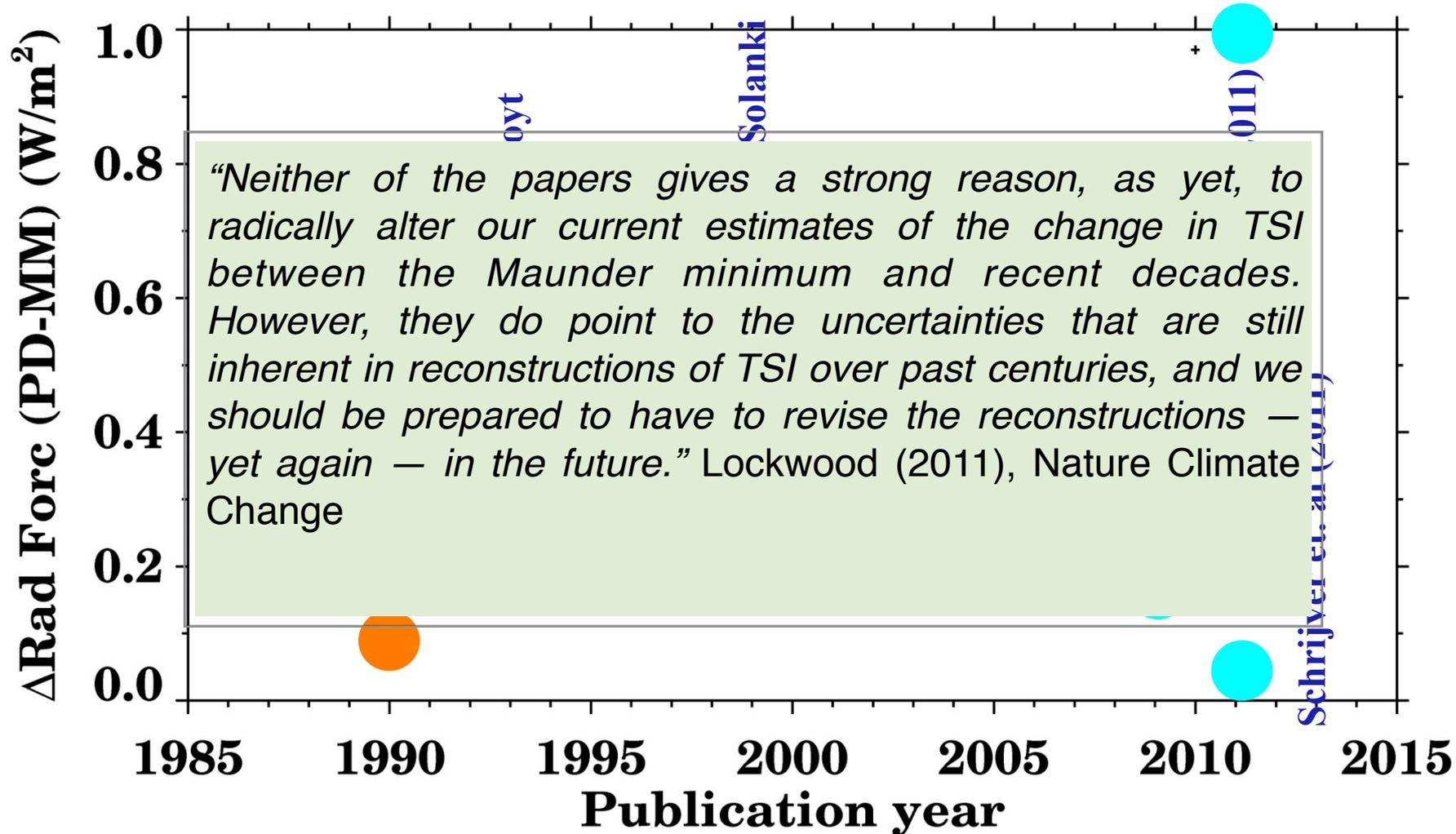
Different approaches



Different approaches

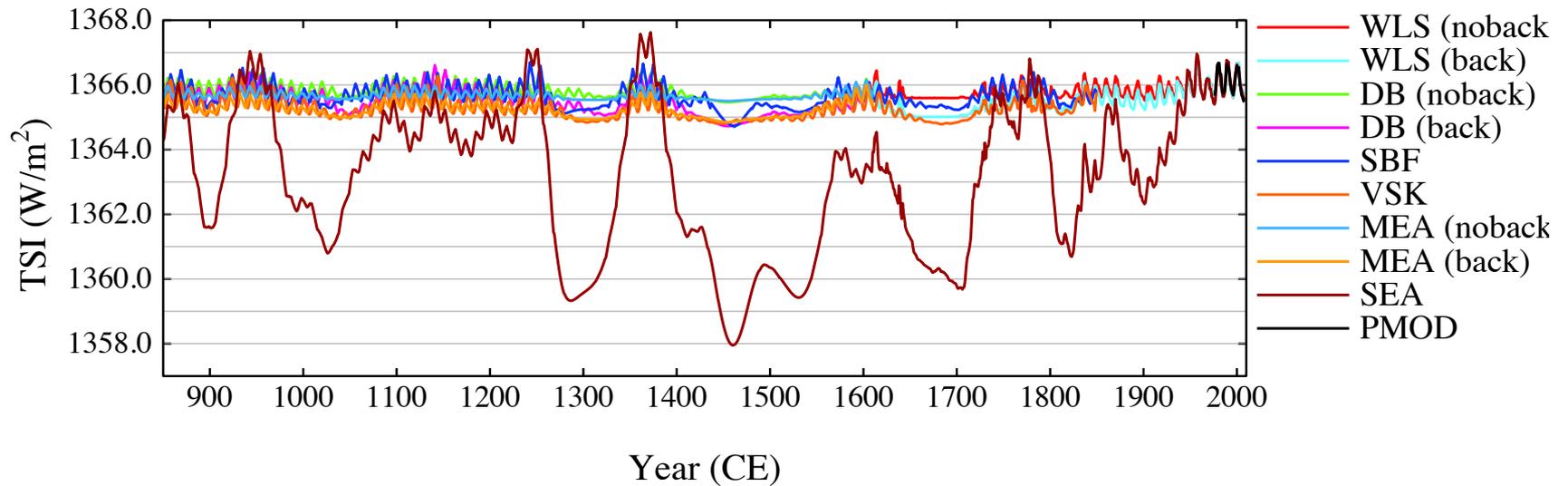


Different approaches



TSI reconstructions

Total Solar Irradiance Reconstructions



from Schmidt et al. (2011)

Secular variability

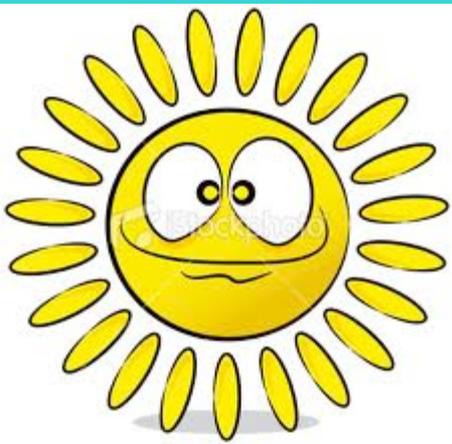


Minimum
Sun



Present
Sun

Secular variability



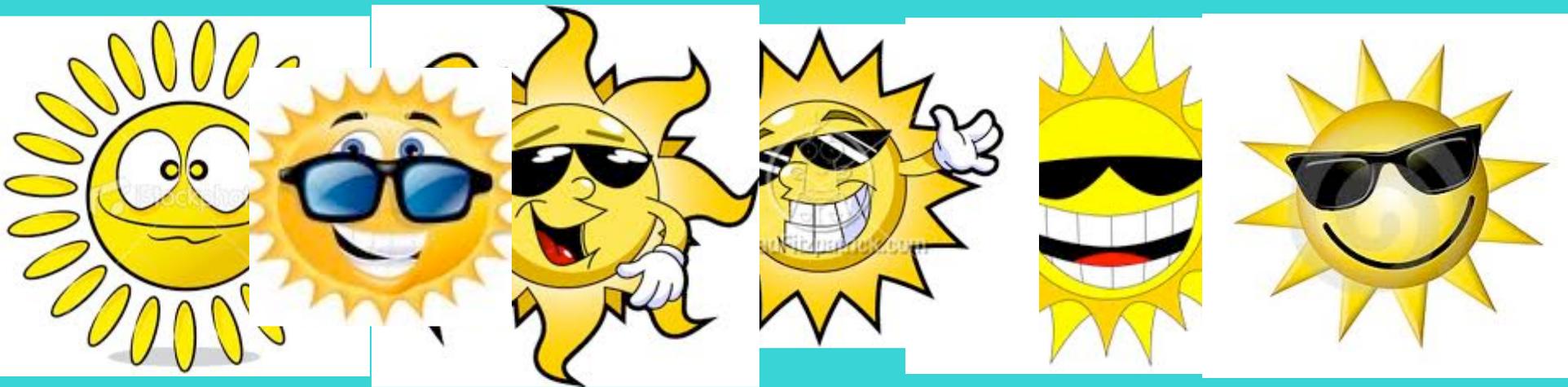
Minimum
Sun



Present
Sun

←—————→
Linear interpolation using
available proxies of the solar
activity

Secular variability



Minimum
Sun



Linear interpolation using
available proxies of the solar
activity

Present
Sun

Secular variability

$$\text{SSI}(\lambda, t)$$

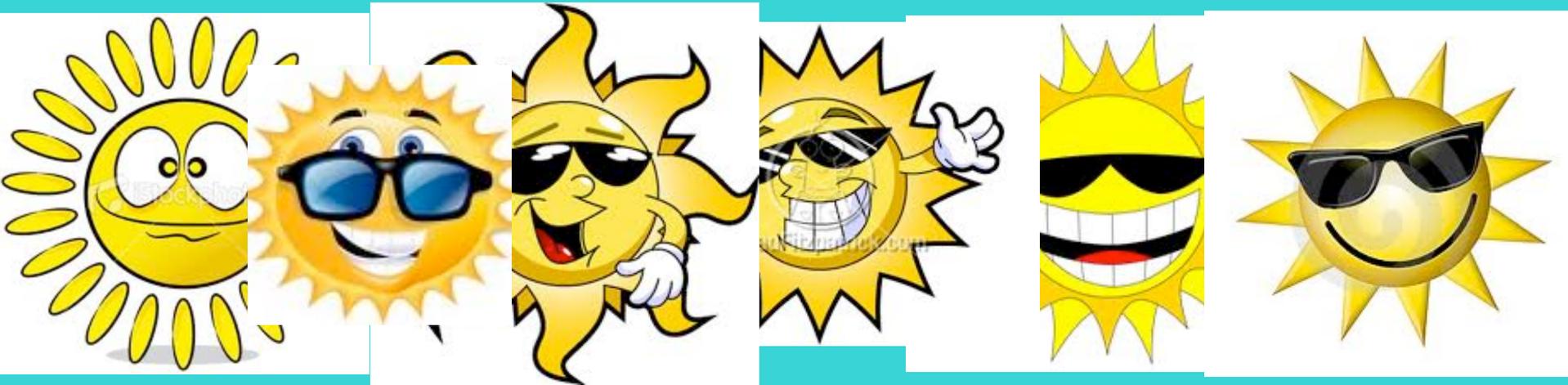


Minimum
Sun

Present
Sun

Linear interpolation using
available proxies of the solar
activity

Shapiro et al. (2011) approach

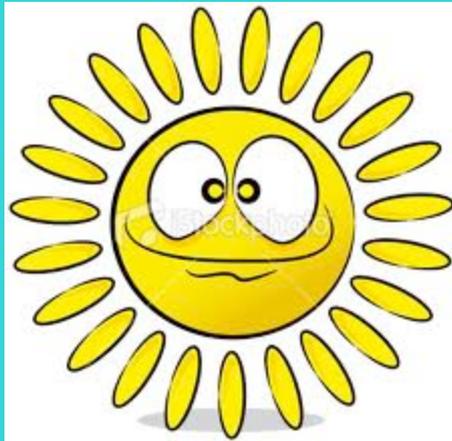


Minimum
Sun



Present
Sun

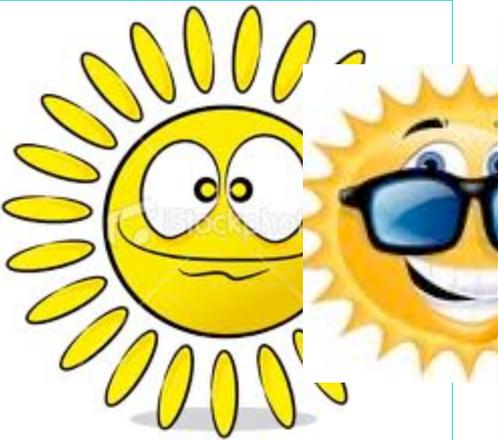
Linear interpolation using
available proxies of the solar
activity



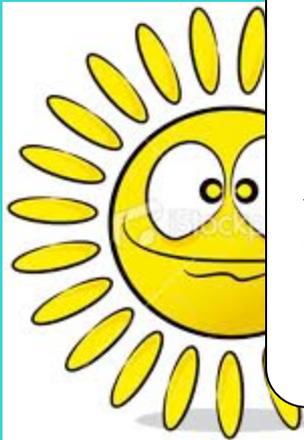
=

**quietest areas on the
present Sun**

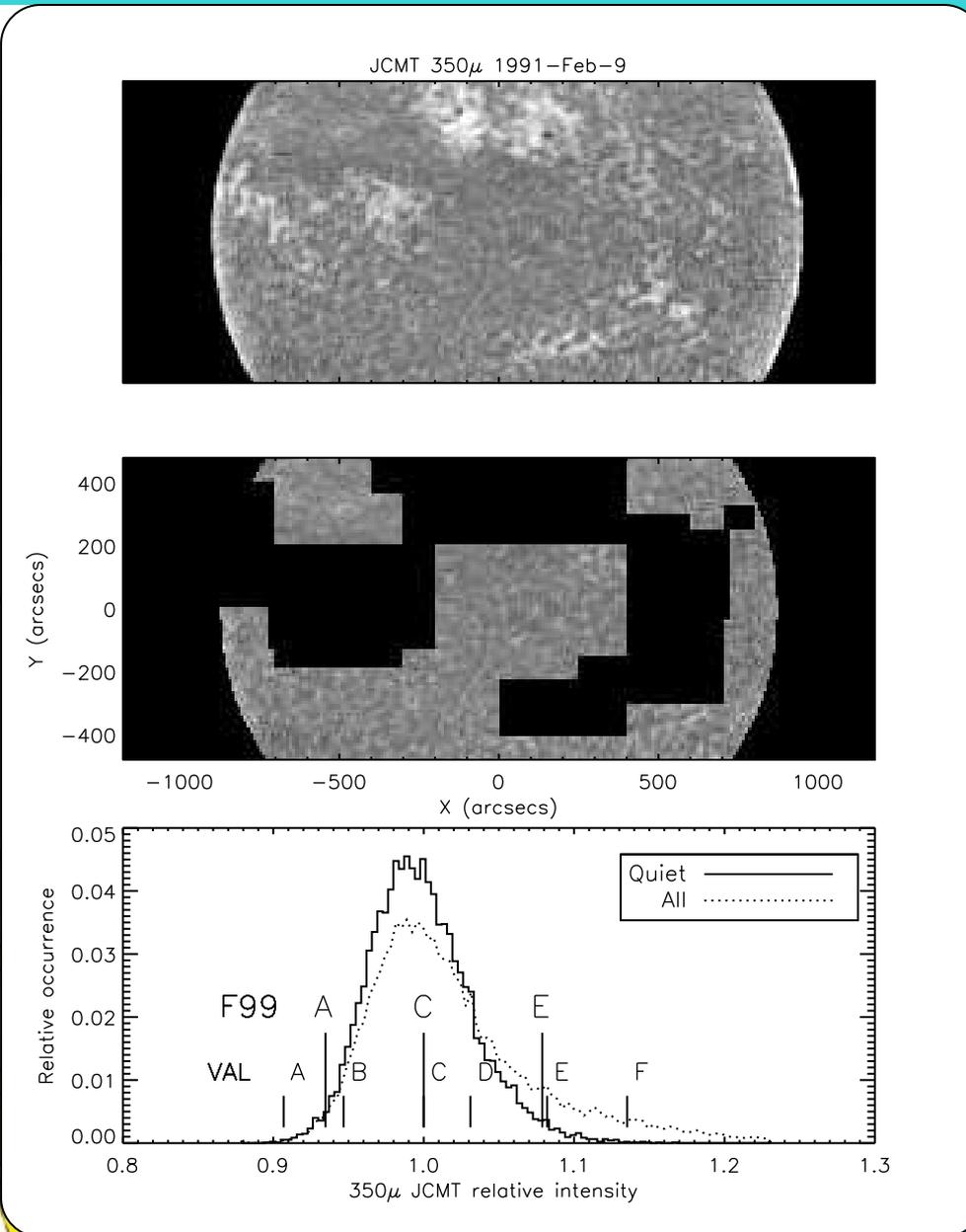
Shapiro et al. (2011) approach



Minimum
Sun

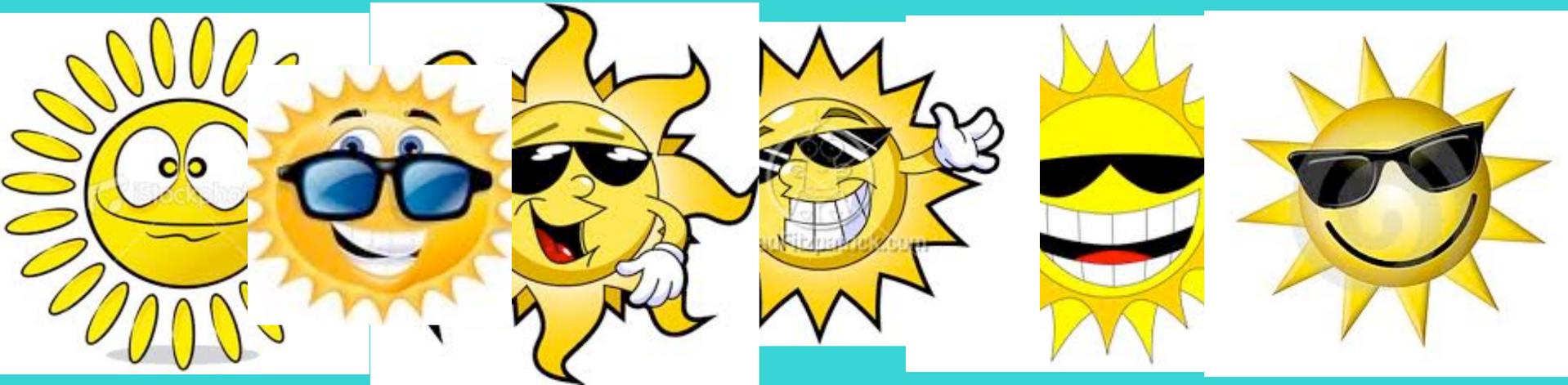


Present
Sun



s on the

Schrijver et al. (2011) approach

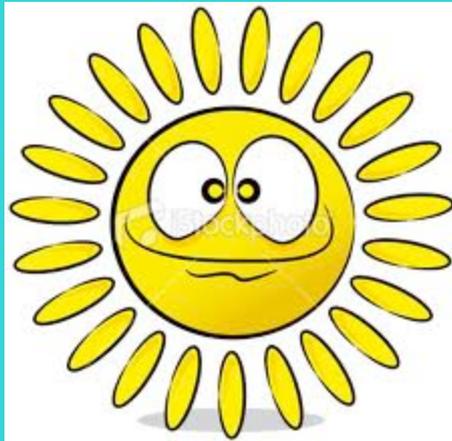


Minimum
Sun



Present
Sun

Linear interpolation using
available proxies of the solar
activity

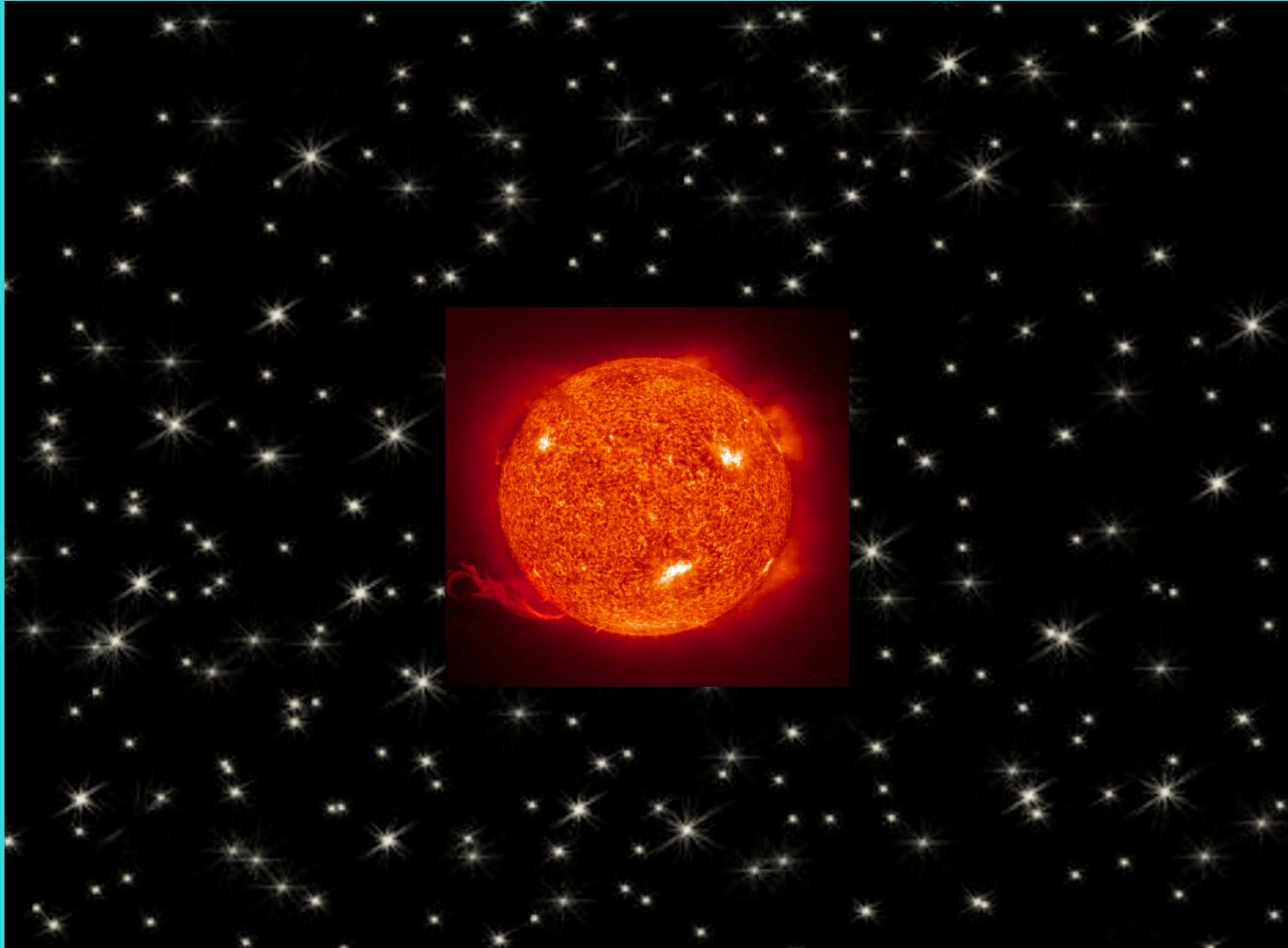


=



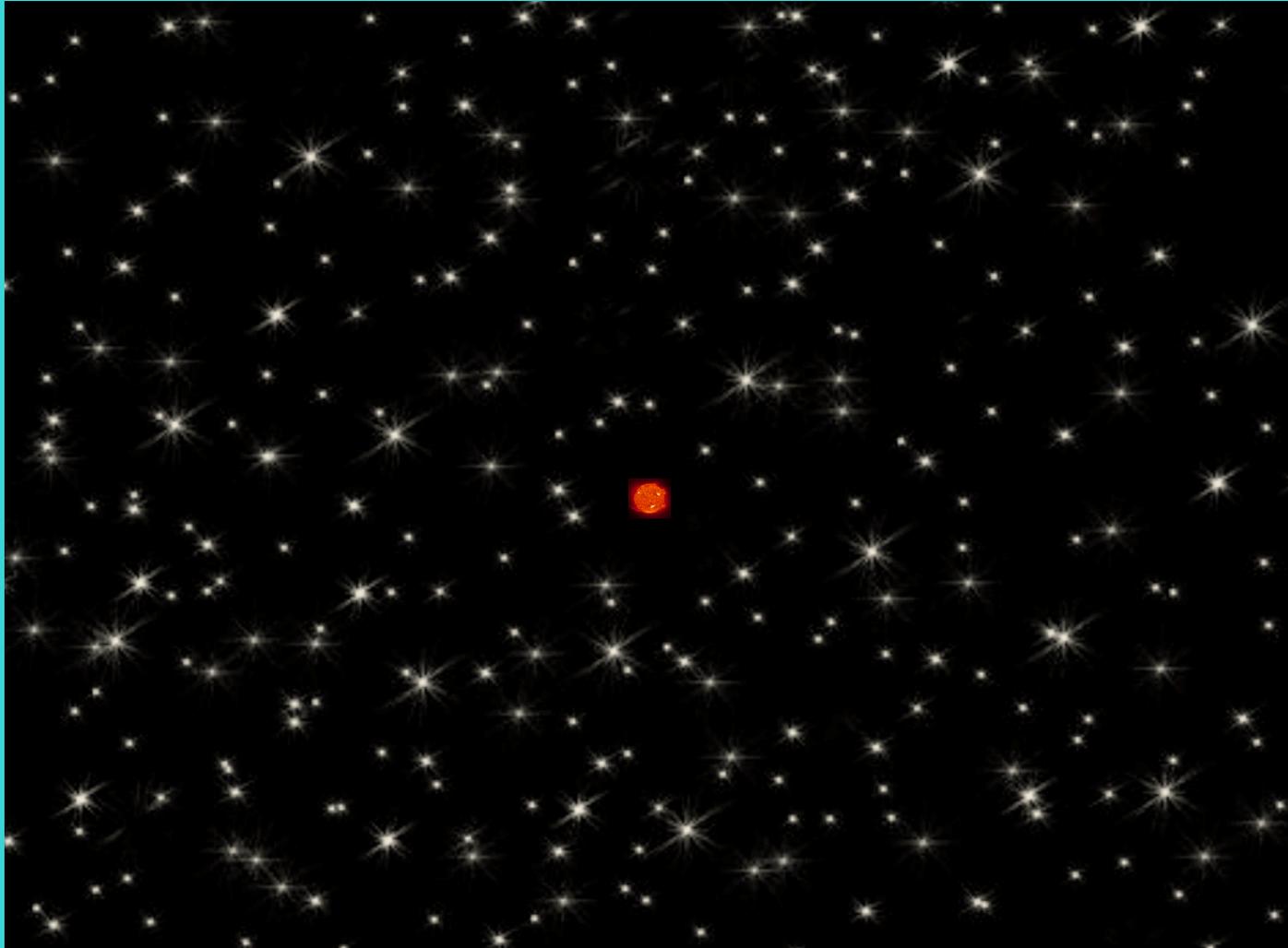
Solar variability

The Sun: a typical star or an outlier among its stellar cohort?

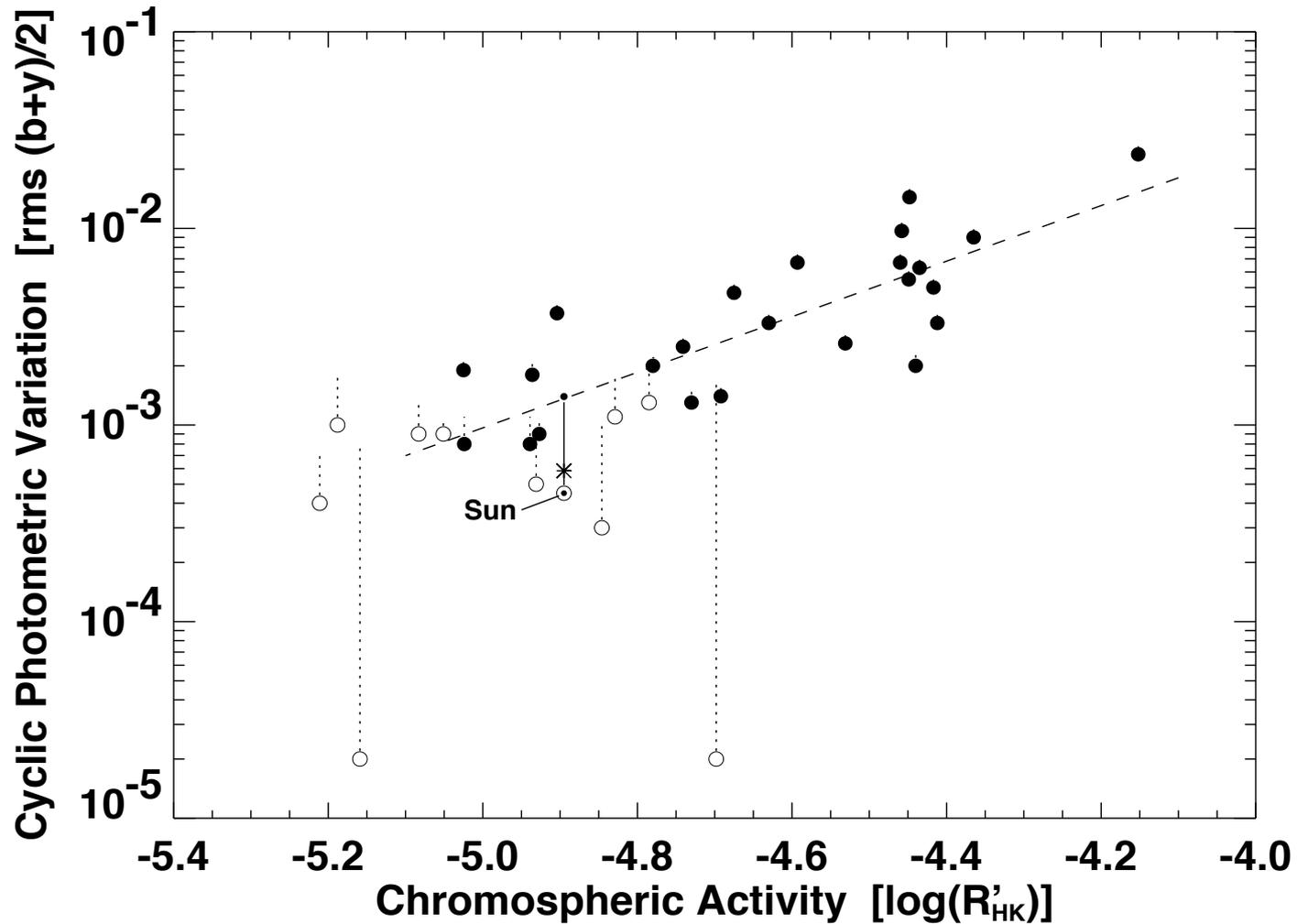


Solar variability

The Sun: a typical star or an outlier among its stellar cohort?

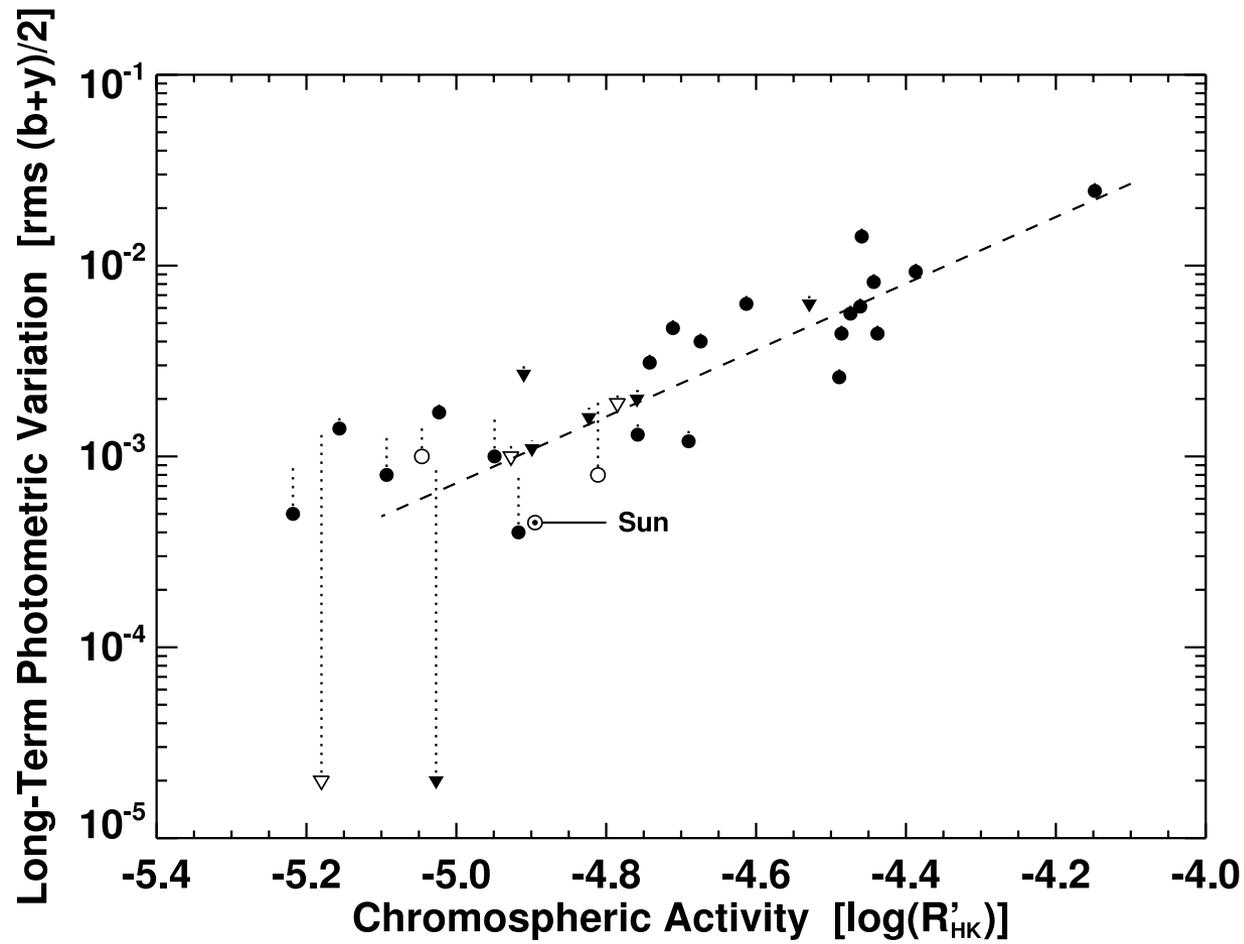


The Sun among its stellar cohort



Radick et al. (1998)

The Sun among its stellar cohort

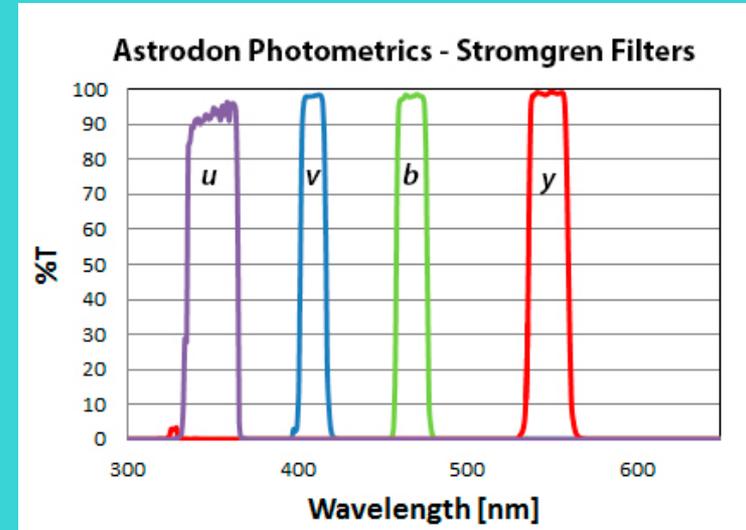


Lockwood et al. (2007)

Where to put the *present* Sun?

Stellar photometry - Stromgren (b+y)/2

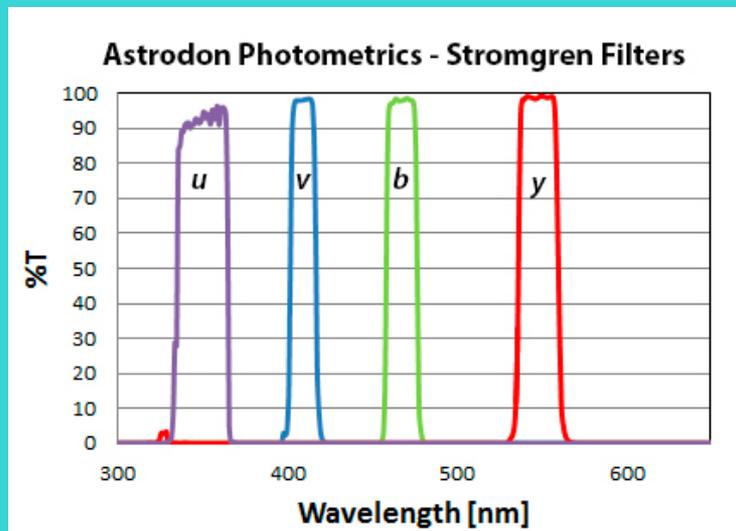
There is no long-term records of the solar irradiance in the visible spectrum



Where to put the *present* Sun?

Stellar photometry - Stromgren $(b+y)/2$

There is no long-term records of the solar irradiance in the visible spectrum



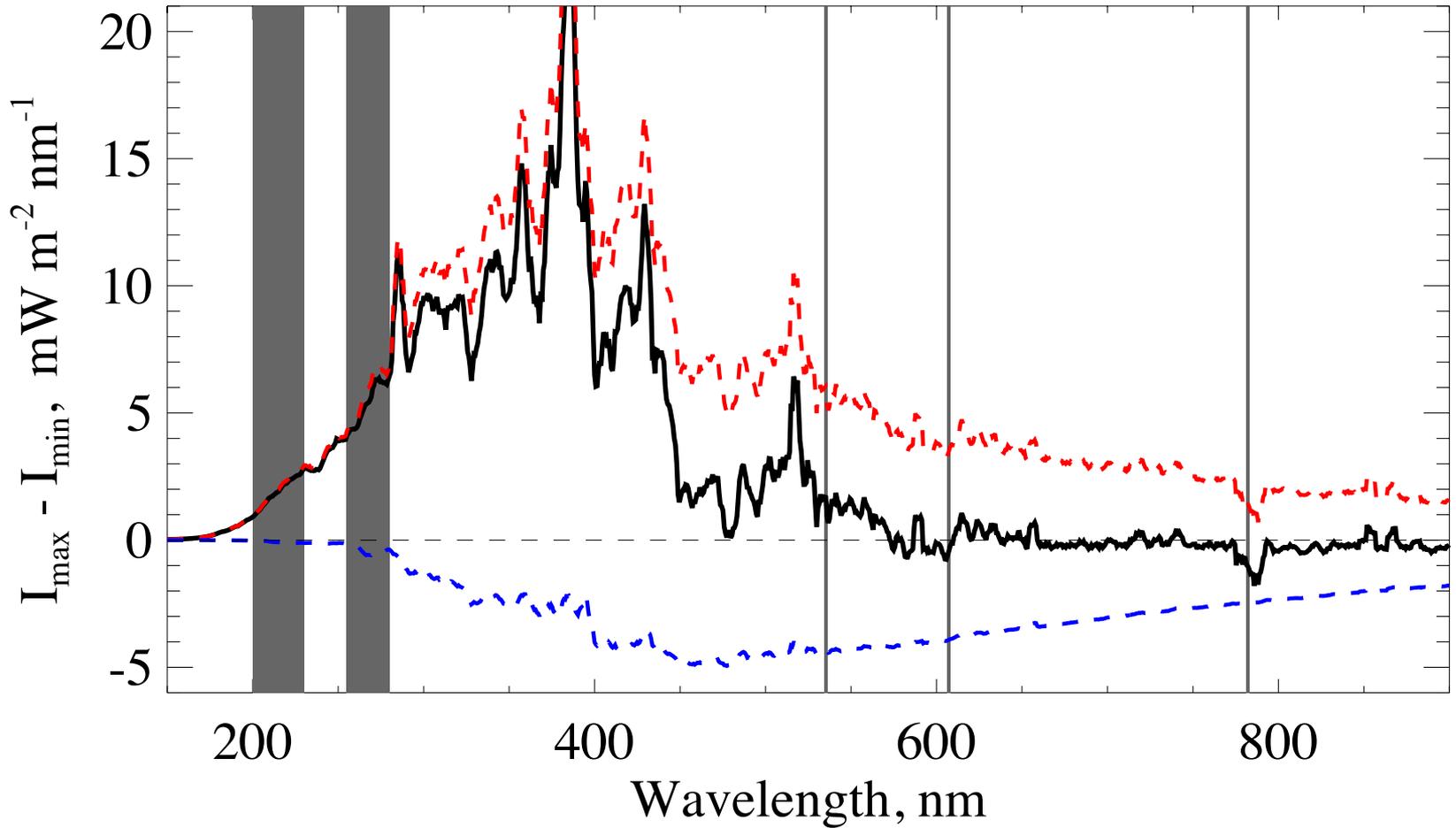
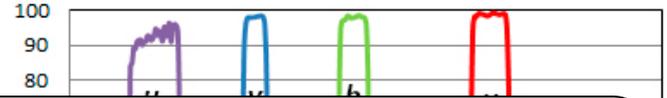
Radick et al. (1998) - **0.00044 mag**

They assumed that TSI and photometric variabilities are connected as if they are caused by change of the solar effective temperature

Where to put the *present* Sun?

Stellar photometry - Stromgren (b+v)/2

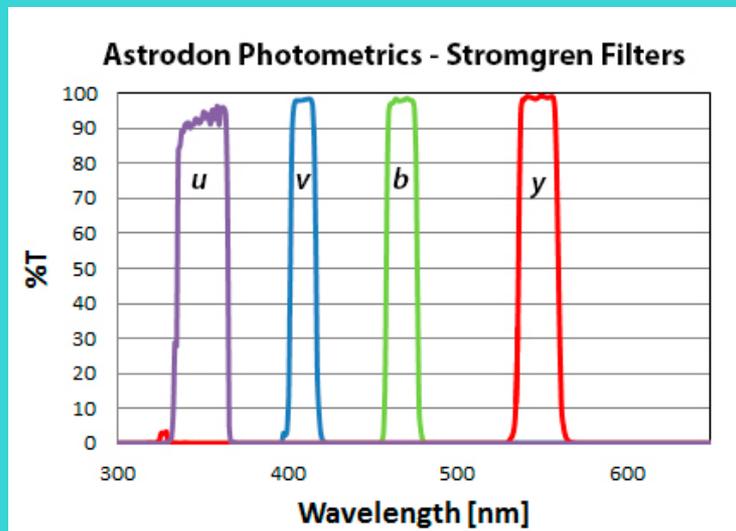
Astrodon Photometrics - Stromgren Filters



Where to put the *present* Sun?

Stellar photometry - Stromgren (b+y)/2

There is no long-term records of the solar irradiance in the visible spectrum



Radick et al. (1998) - **0.00044 mag**

They assumed that TSI and photometric variabilities are connected as if they are caused by change of the solar effective temperature

Lean et al. 2005 - **0.00027 mag**

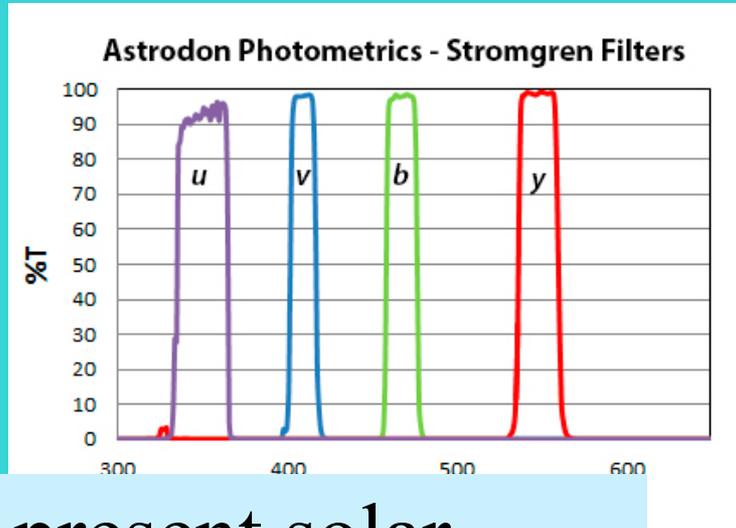
Krivova et al. 2010 - **0.00017 mag**

Shapiro et al. 2011 - **0.00017 mag**

Where to put the *present* Sun?

Stellar photometry - Stromgren (b+y)/2

There is no long-term records of the solar irradiance in the visible spectrum



R
T “Stellar” papers overestimate present solar
variability

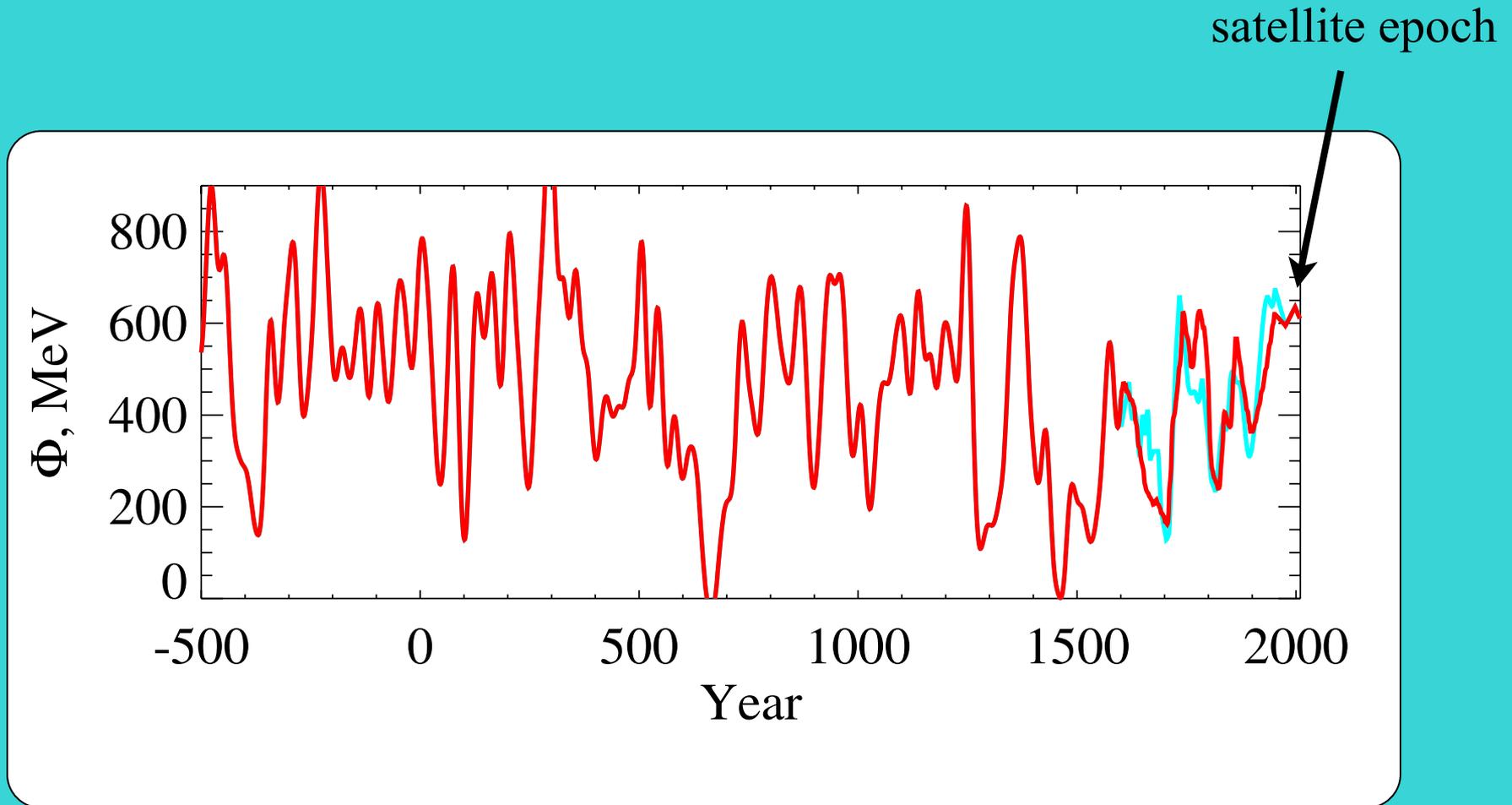
they are caused by change of the solar effective temperature

Lean et al. 2005 - **0.00027 mag**

Krivova et al. 2010 - **0.00017 mag**

Shapiro et al. 2011 - **0.00017 mag**

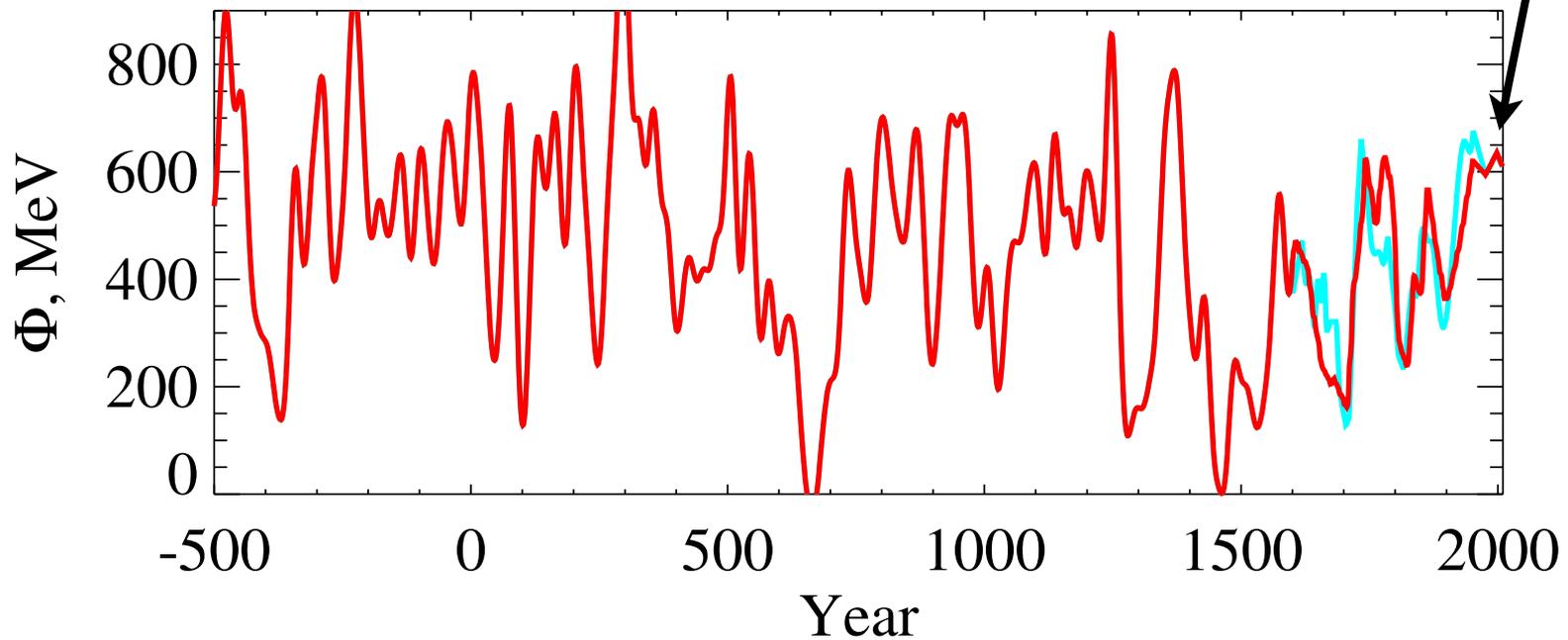
Can we use present solar location for comparison?



Can we use present solar location for comparison?

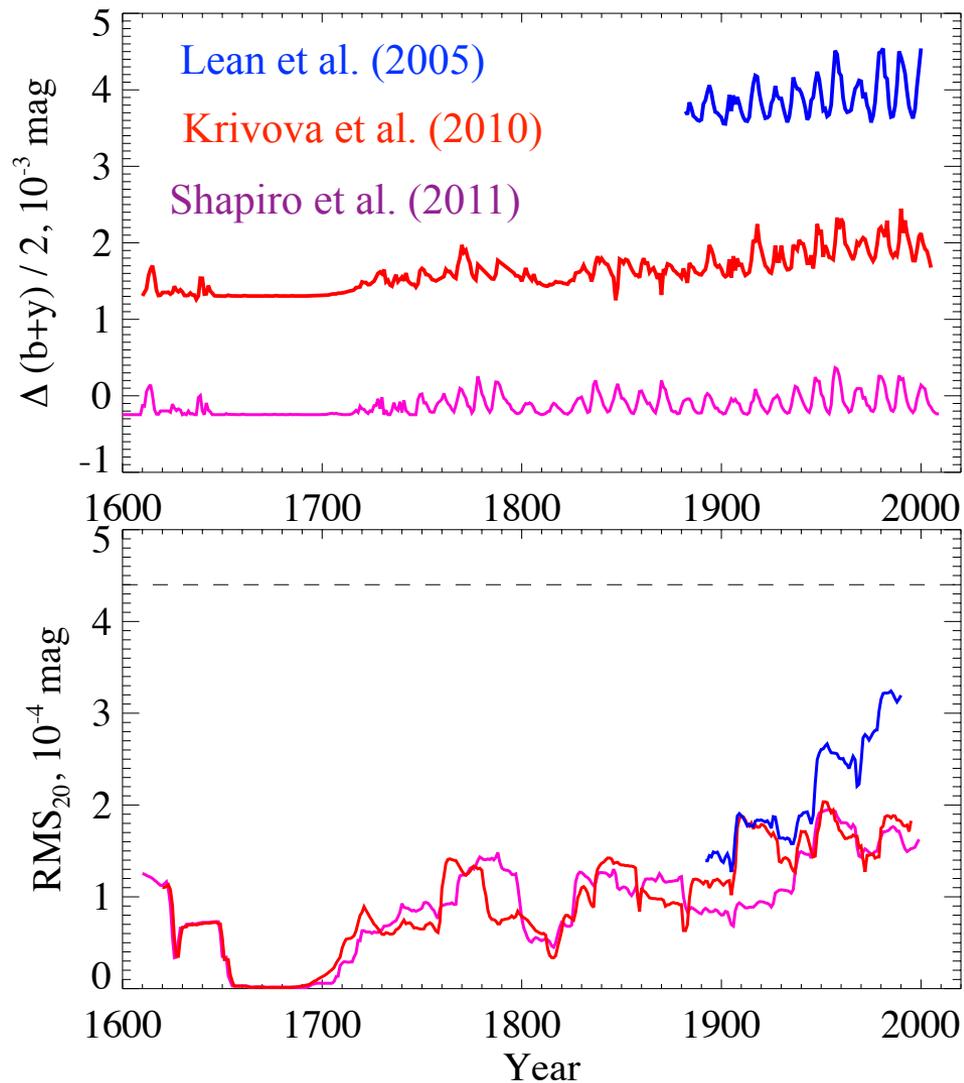
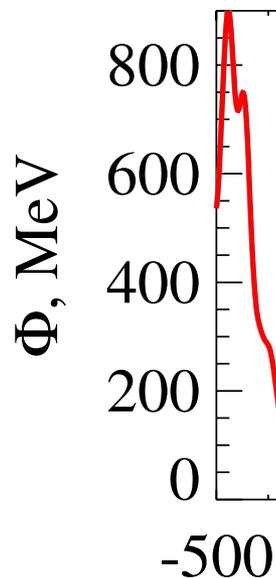
Present solar location is rather peculiar

satellite epoch

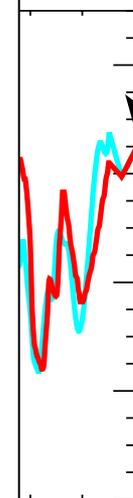
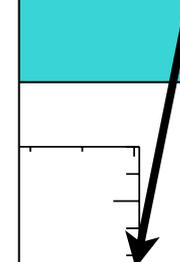


Can we use present solar location for comparison?

P



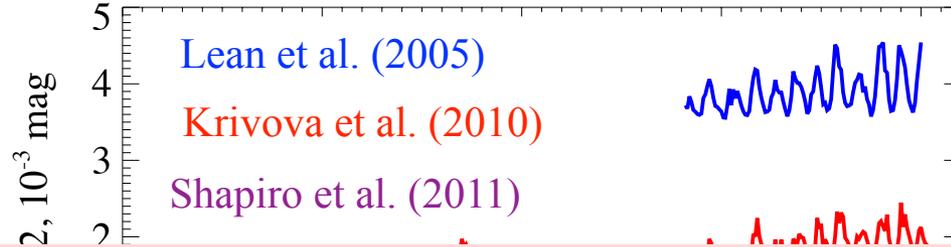
satellite epoch



2000

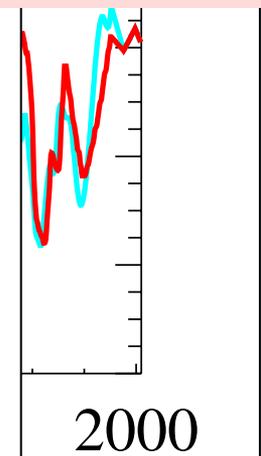
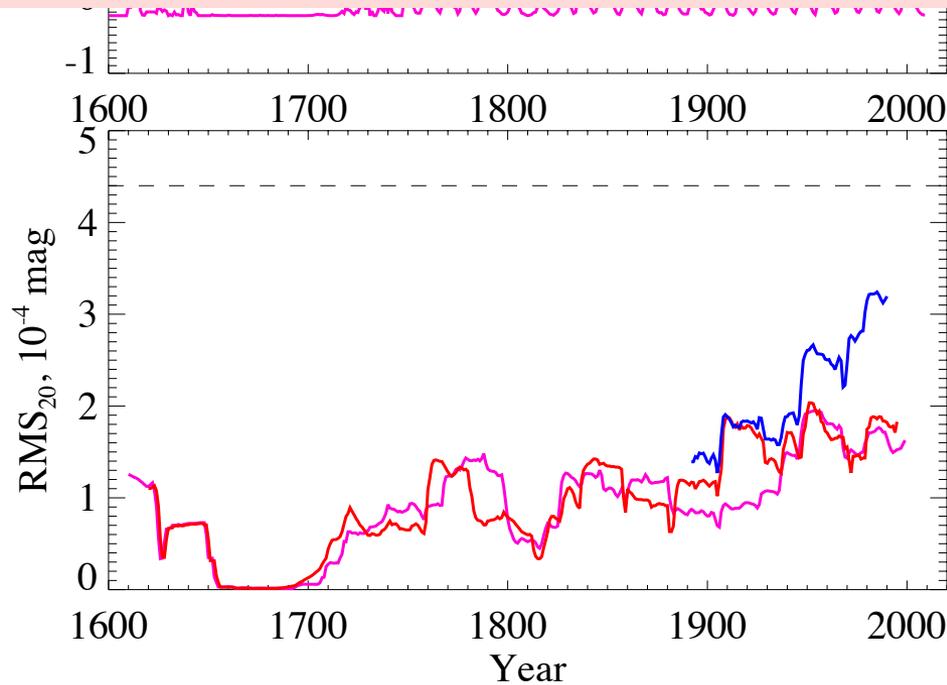
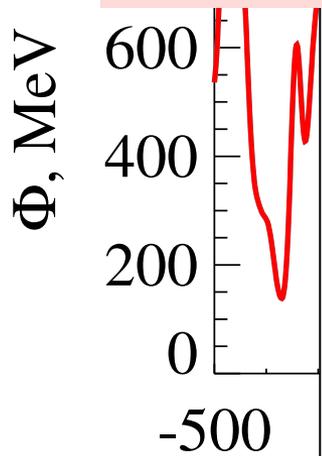
Can we use present solar location for comparison?

P



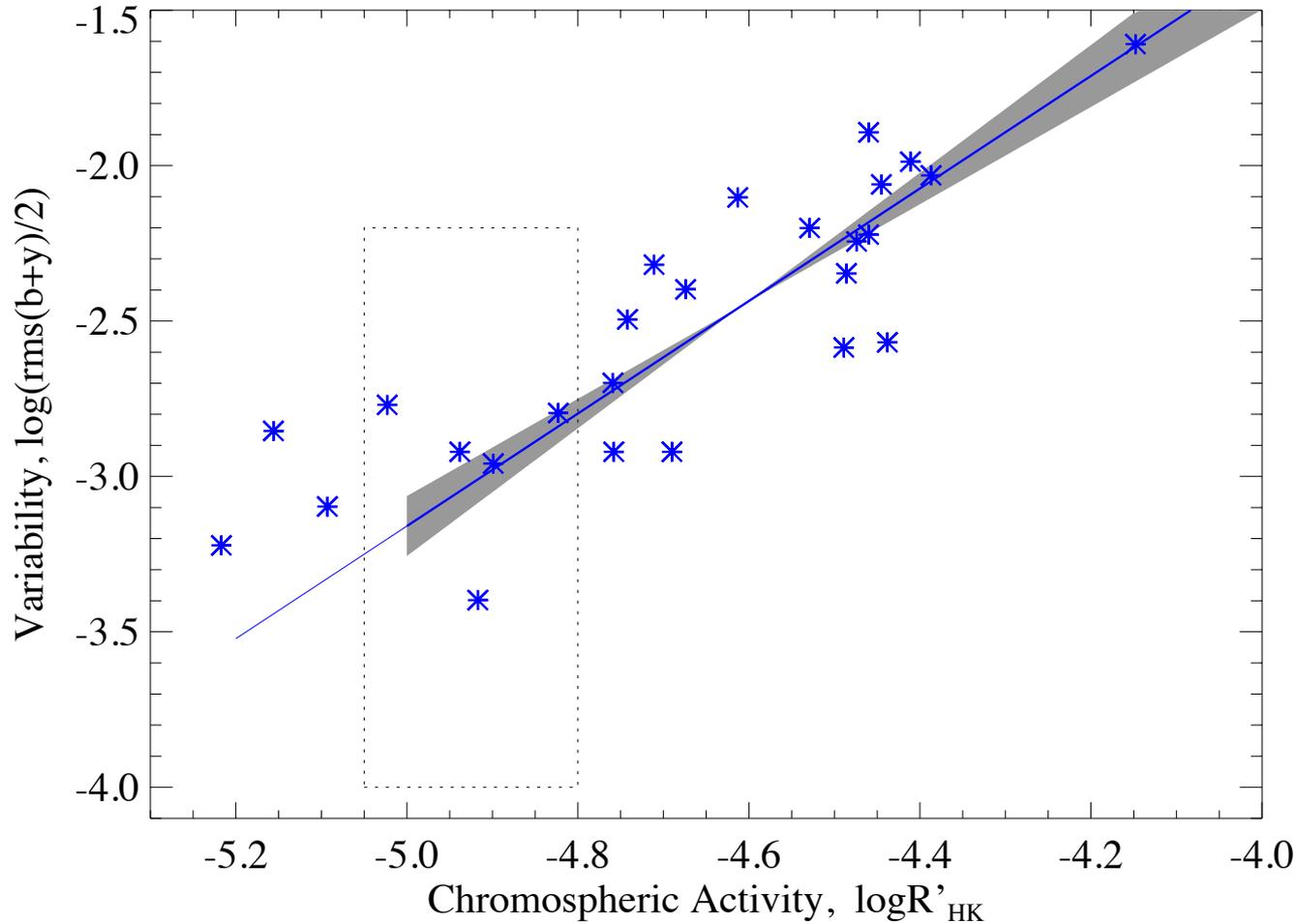
satellite epoch

temporal mean of the solar variability is *approximately 2 times smaller* than presently measured



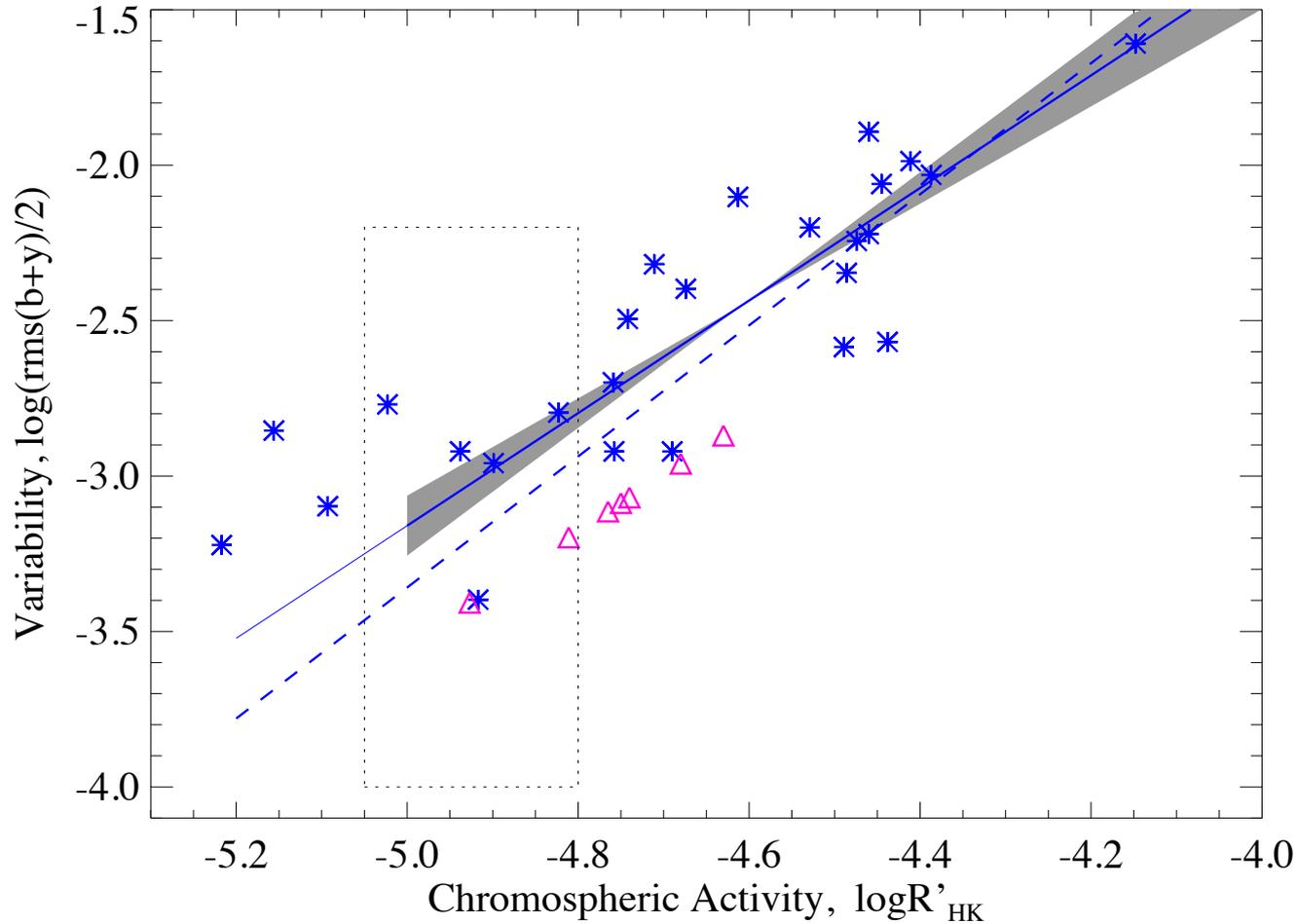
Activity vs. Variability

Lockwood et al. (2007)



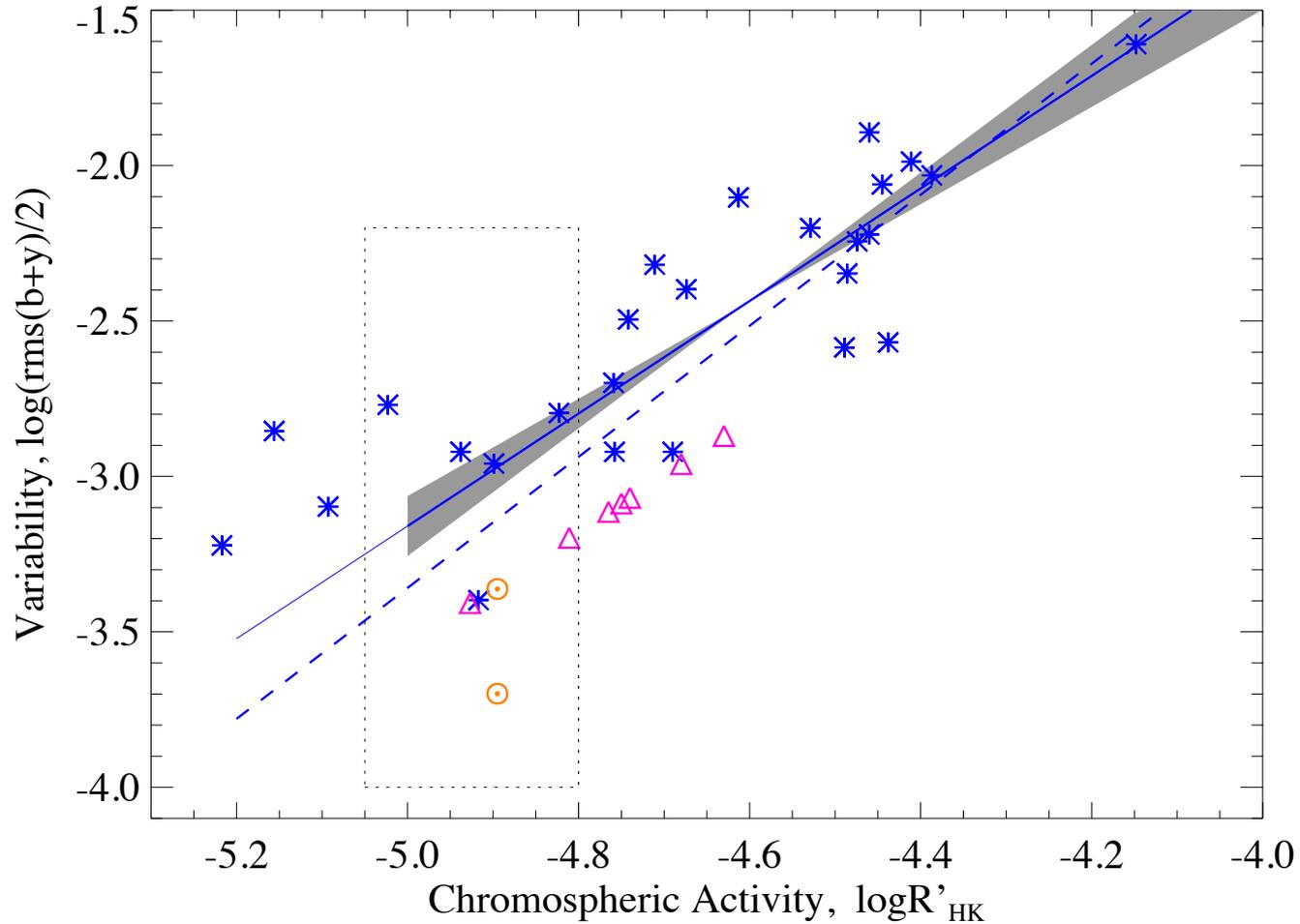
Activity vs. Variability

Lockwood et al. (2007) + stars with unconfirmed variability



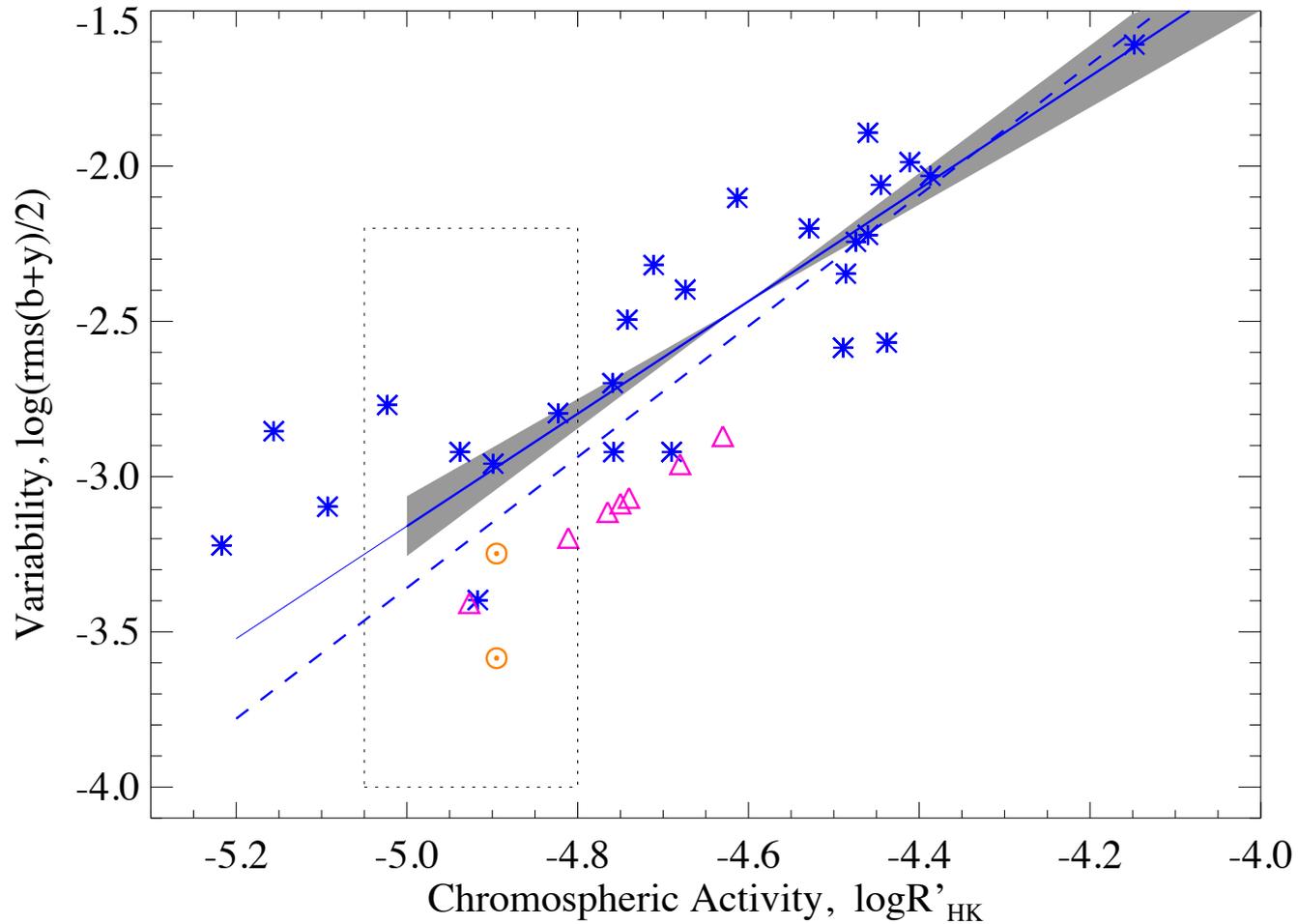
Activity vs. Variability

Lockwood et al. (2007) + stars with unconfirmed variability



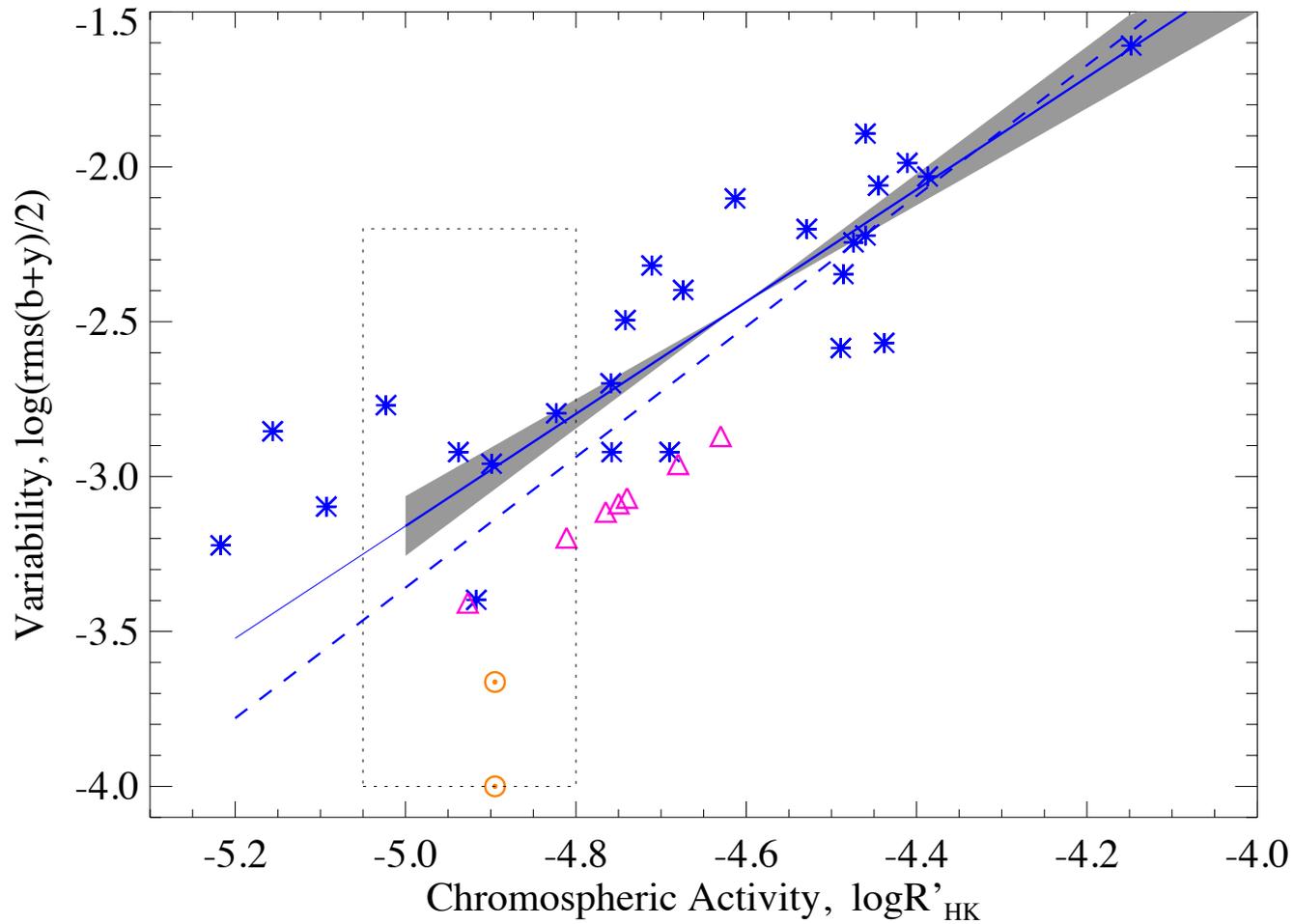
Activity vs. Variability

inclination effect from Knaack et al. (2001)



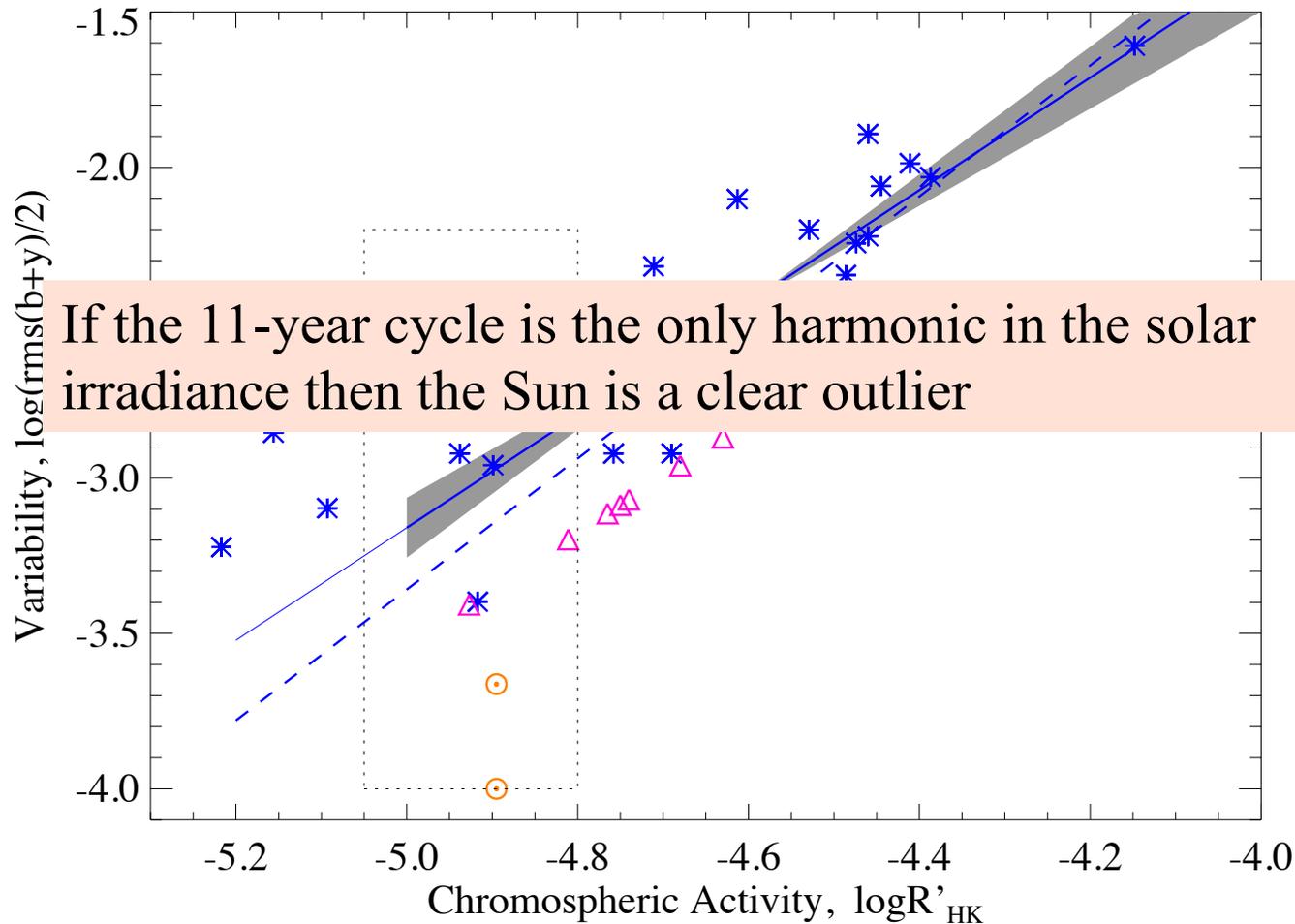
Activity vs. Variability

temporal mean position

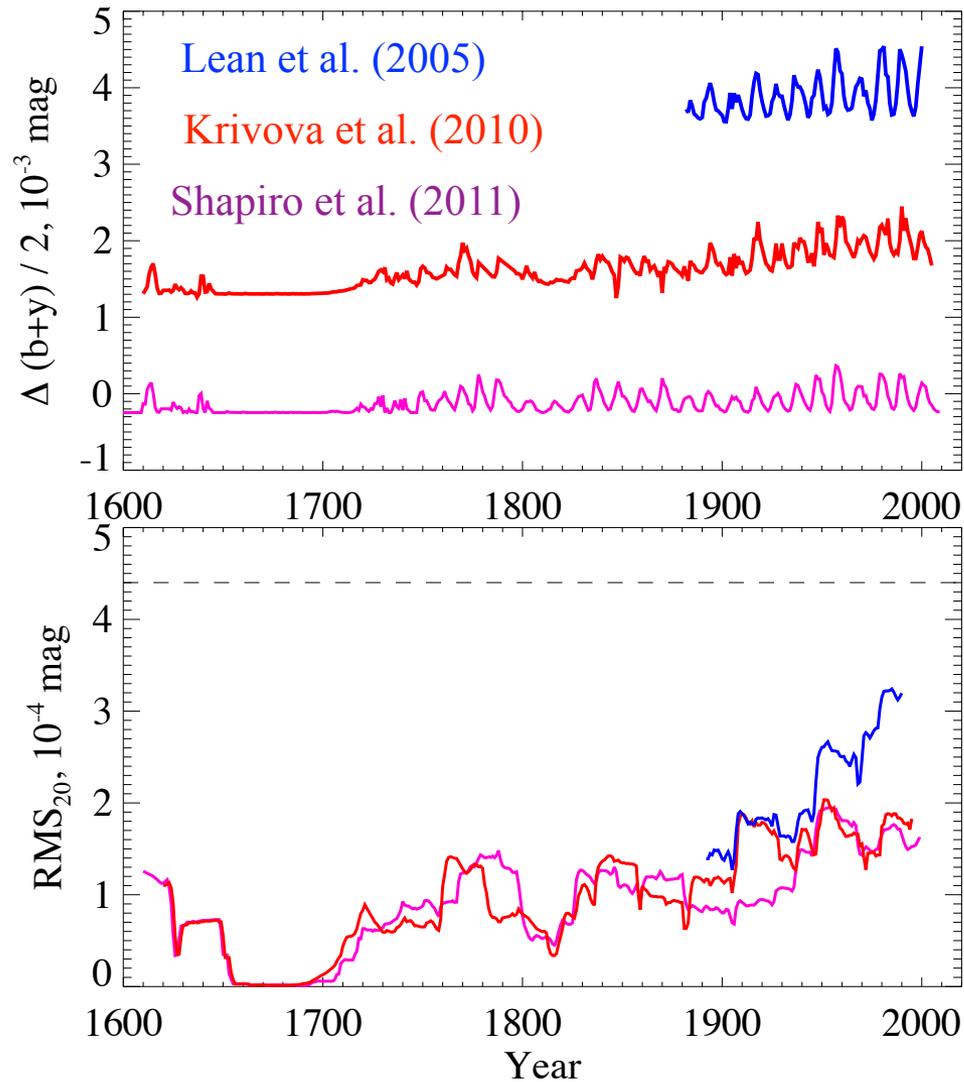


Activity vs. Variability

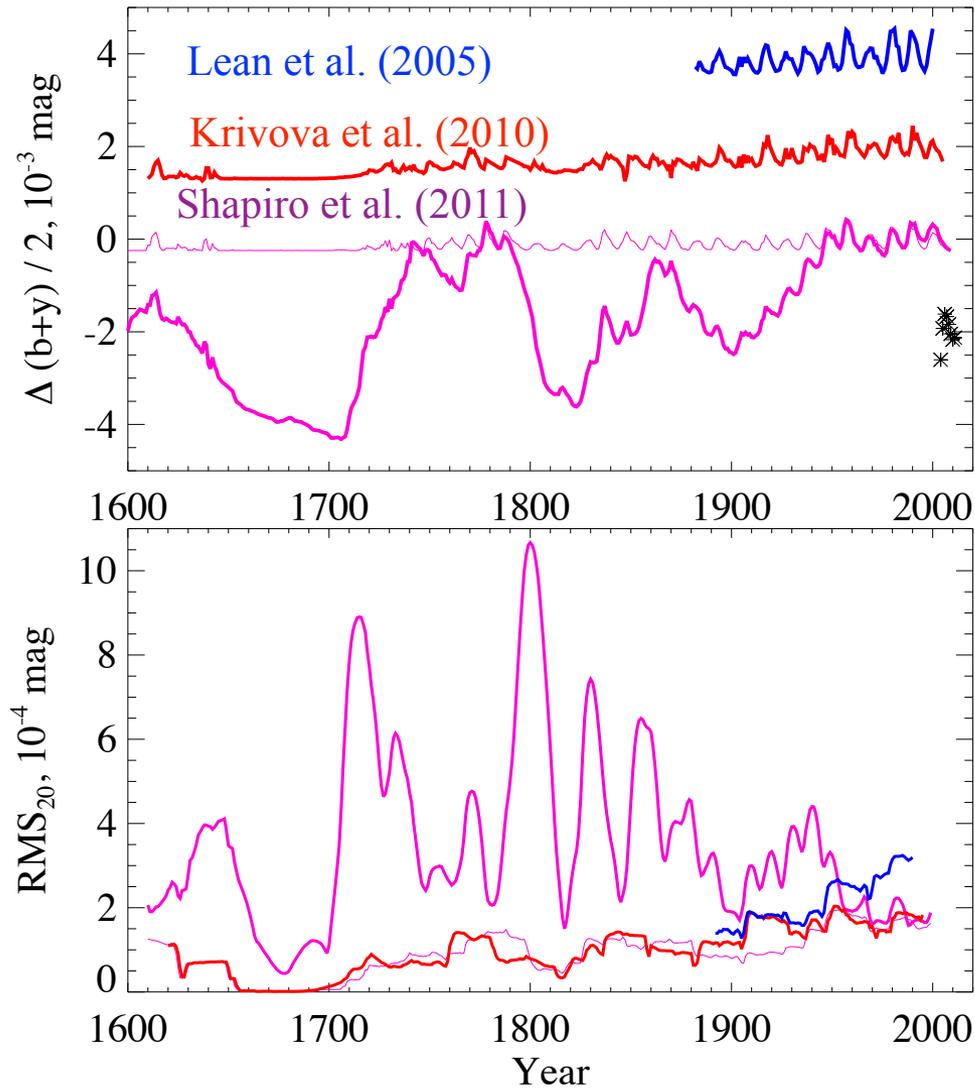
temporal mean position



Long-term trend in the solar irradiance



Long-term trend in the solar irradiance

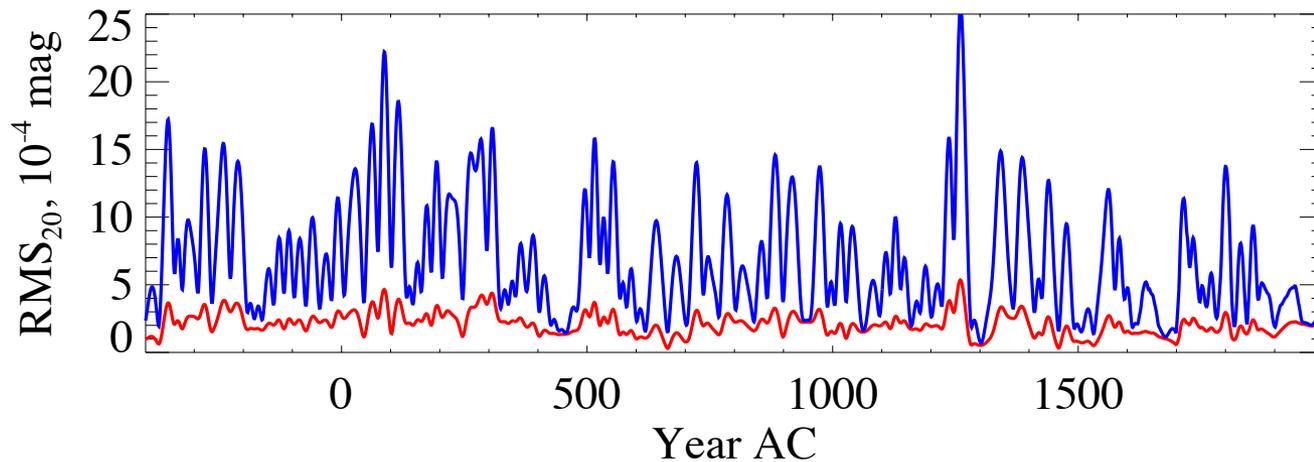


Solar variability back in time

two free parameters

amplitude of the 11-year cycle, V_{11}

amplitude of the long-term trend, V_{LT}

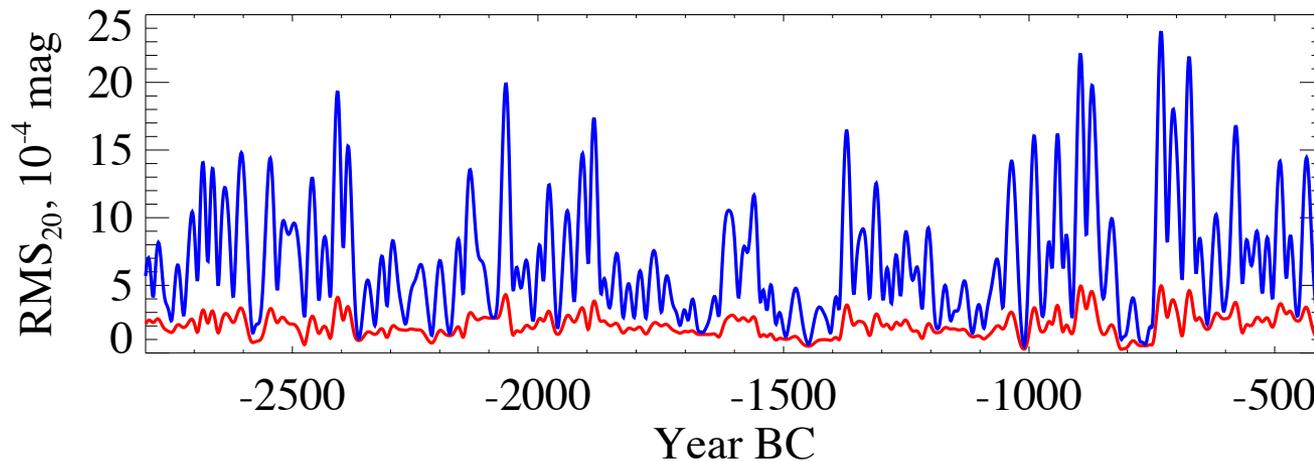


$V_{11}=0.0002$ mag

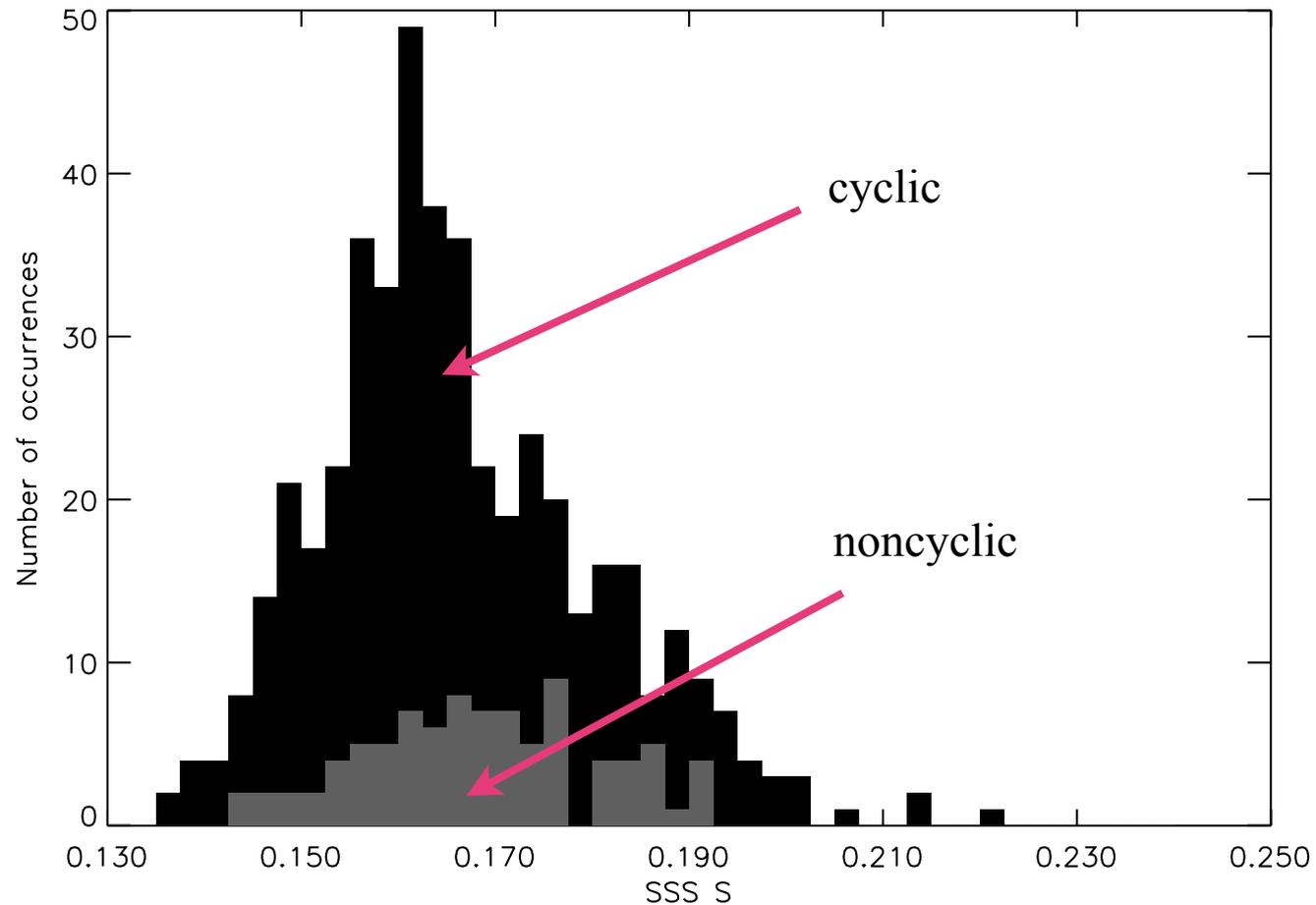
$V_{LT}=0.005$

$V_{11}=0.0002$ mag

$V_{LT}=0.001$



Chromospheric activity



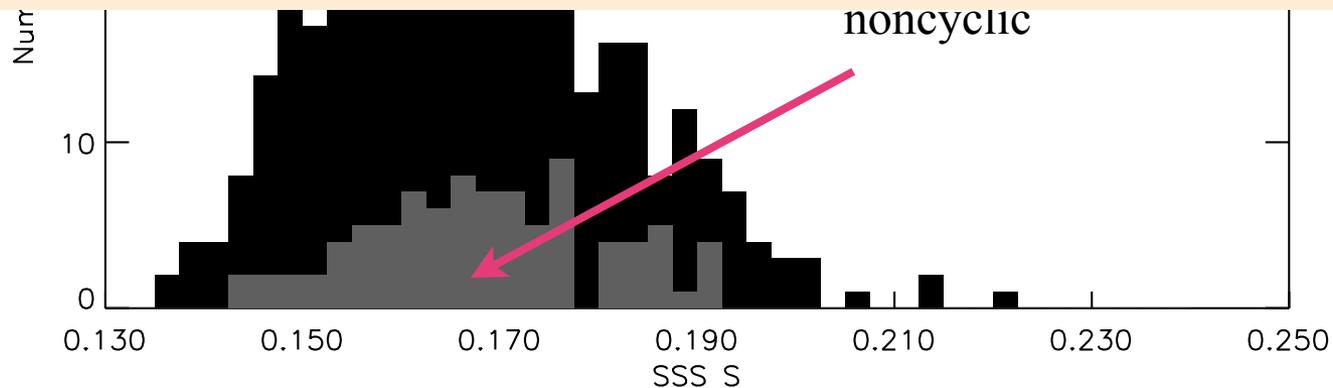
from Hall and Lockwood (2004)

Chromospheric activity

chromospheric activity of the flat-activity stars is not systematically lower than the chromospheric activity of the cycling stars.



minimum chromospheric activity of the stars with solar metallicity corresponds to $\log R_{HK}' = -5.08$ (Saar 2006)



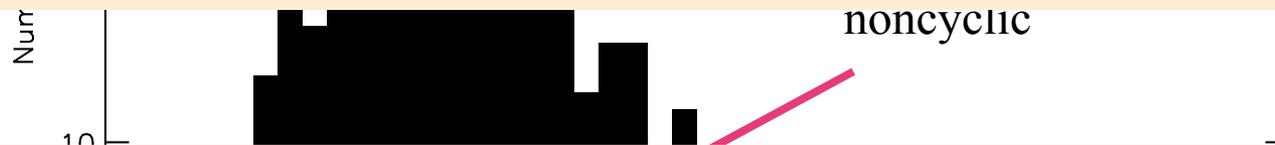
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Chromospheric activity

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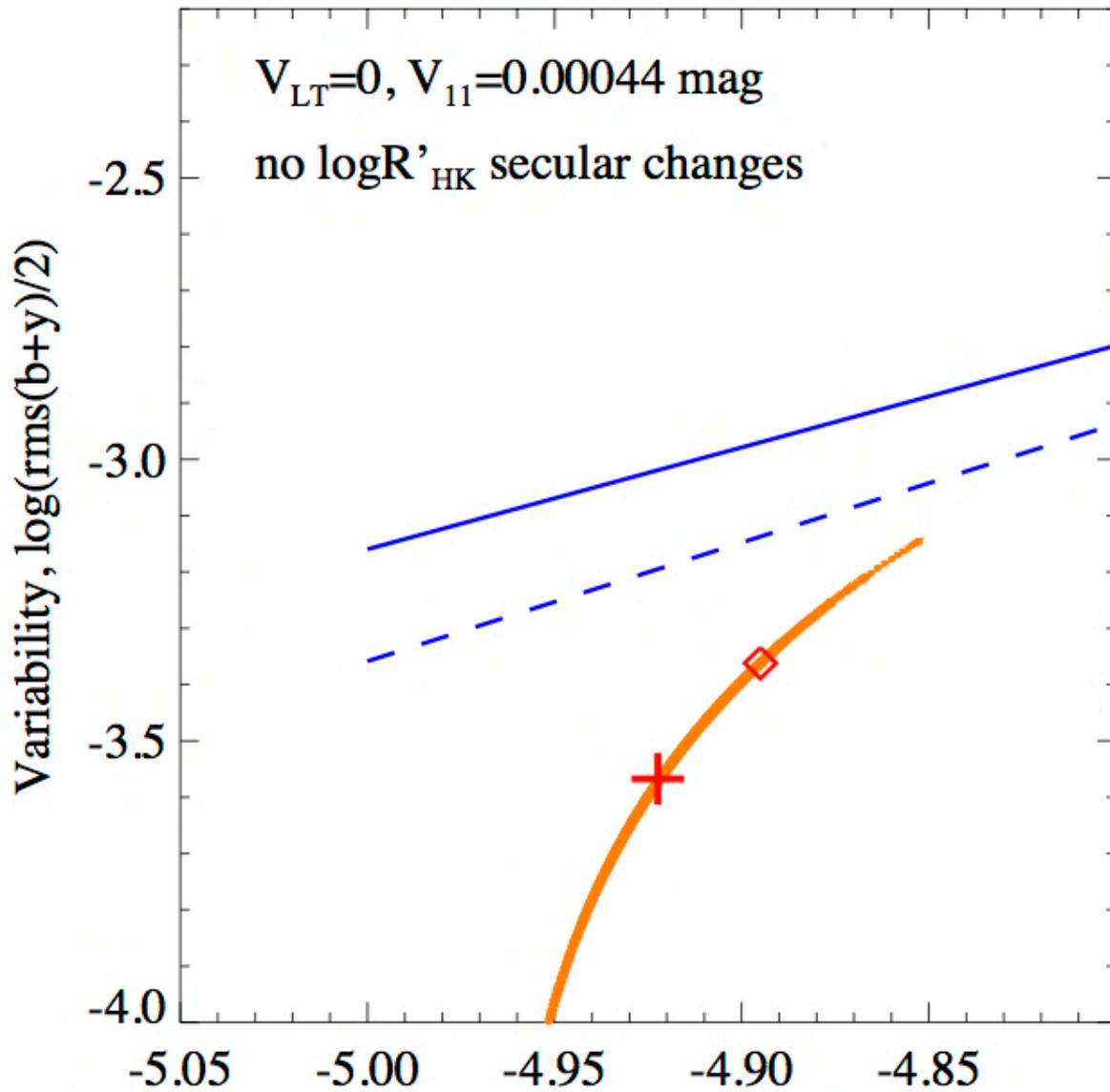
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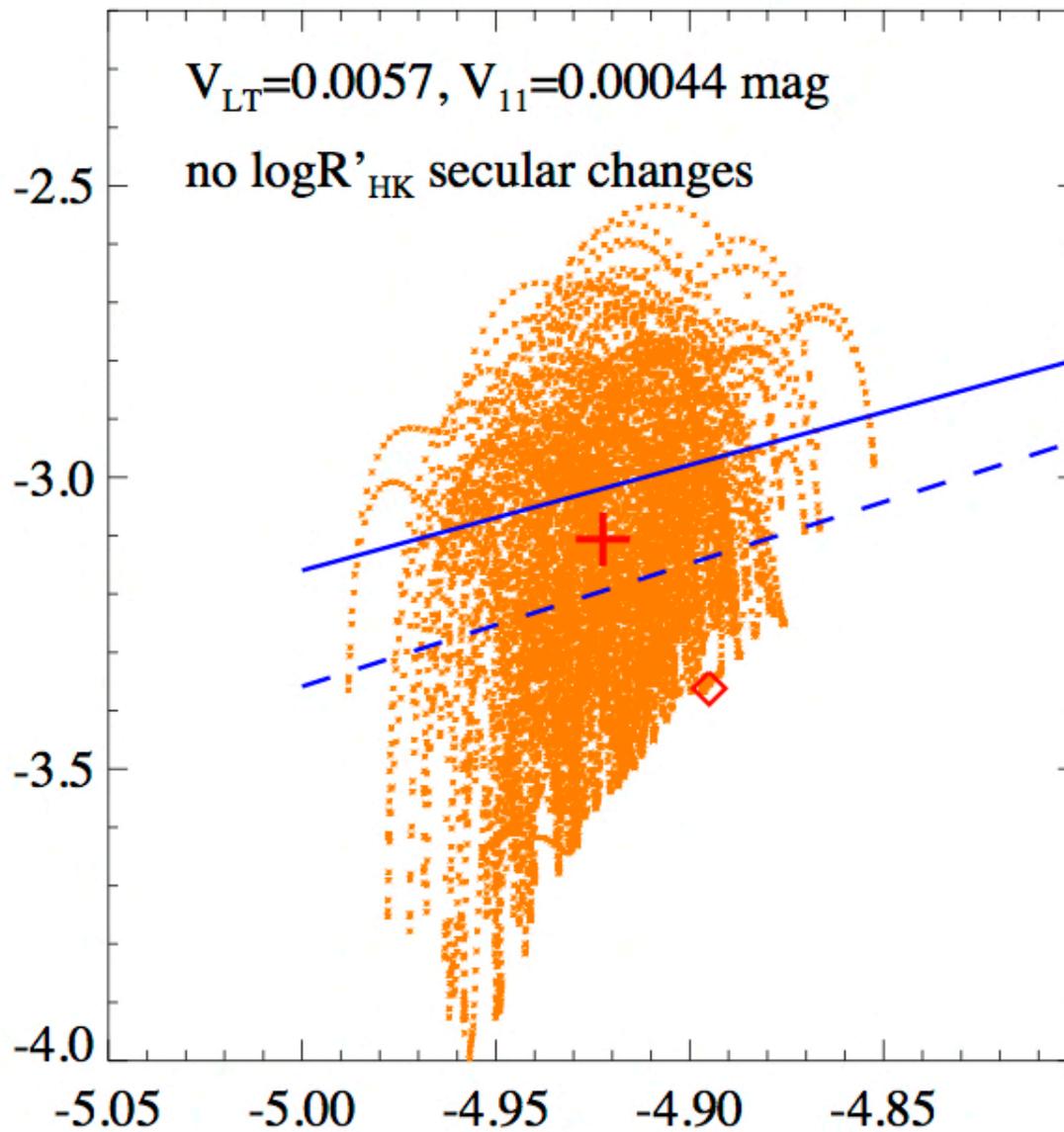
two scenarios: no secular changes in the chromospheric activity;
strong secular changes in the chromospheric activity
($\log R_{HK}'$ reaches Saar 2006 limit)

from Hall and Lockwood (2004)

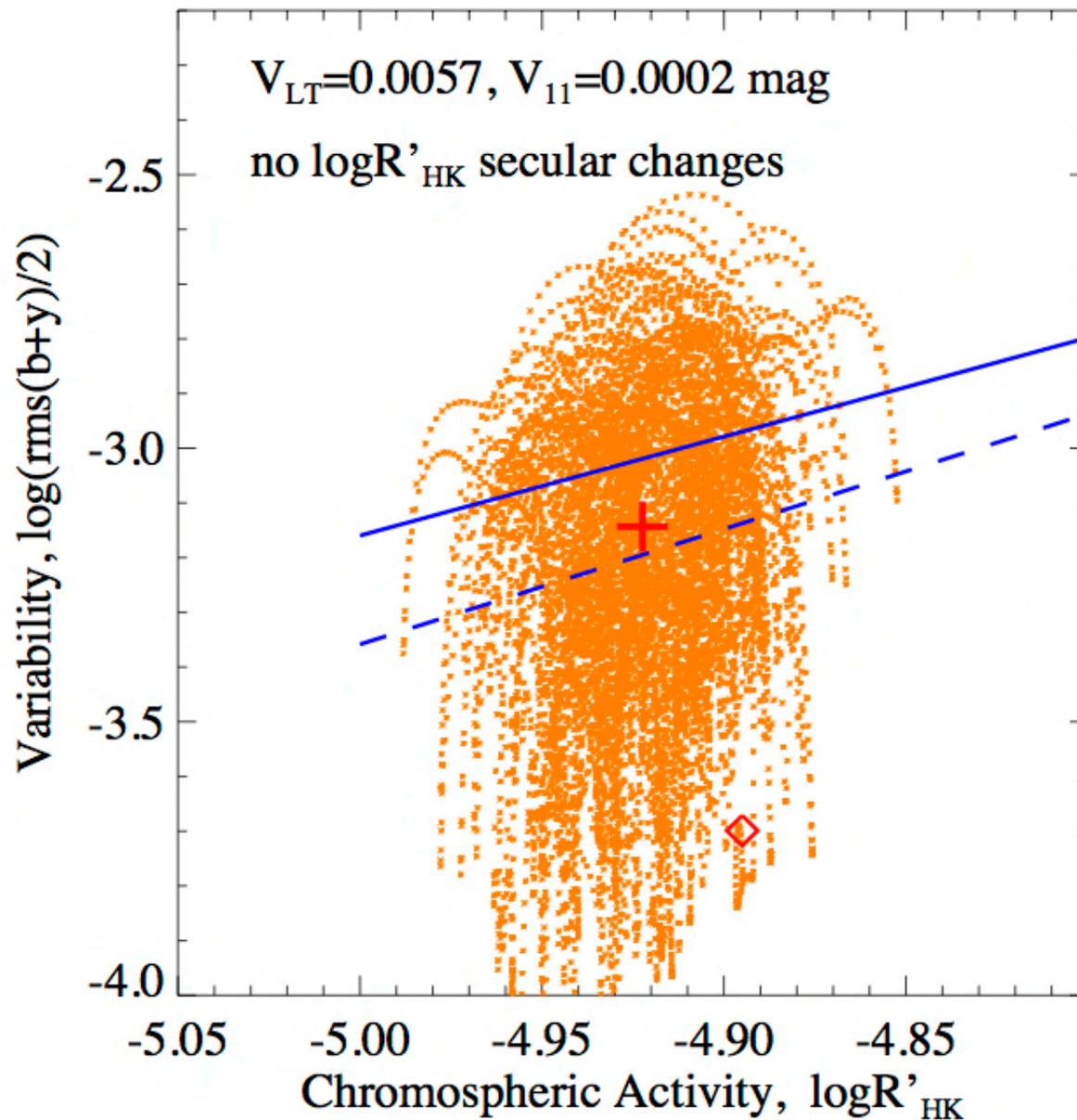
Different scenarios for the solar trajectory



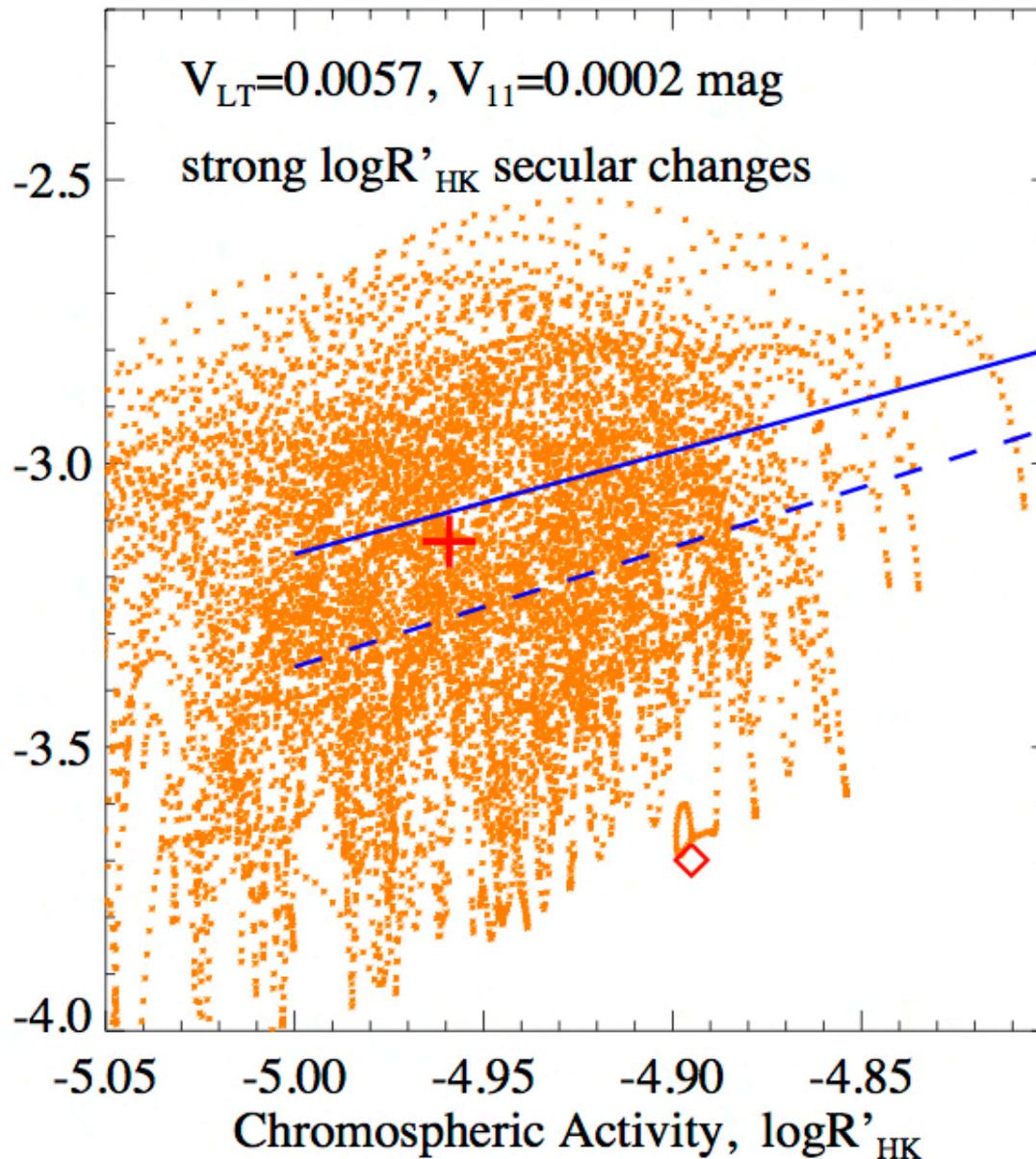
Different scenarios for the solar trajectory



Different scenarios for the solar trajectory



Different scenarios for the solar trajectory



Possible constrains on the historical solar variability

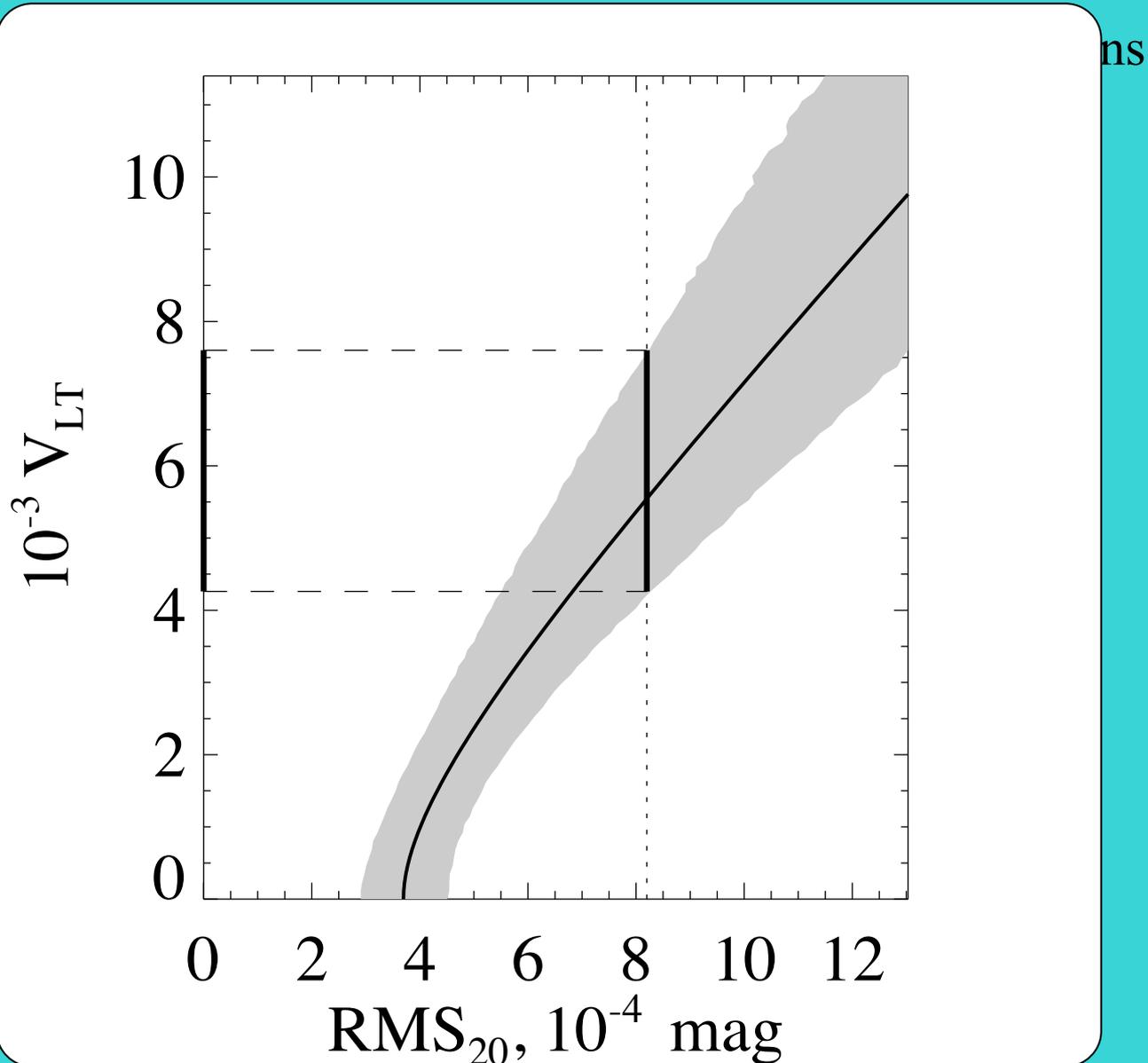
The Sun

30 years of observations

25 Sun-like stars \times 20 years of observations = 500 years

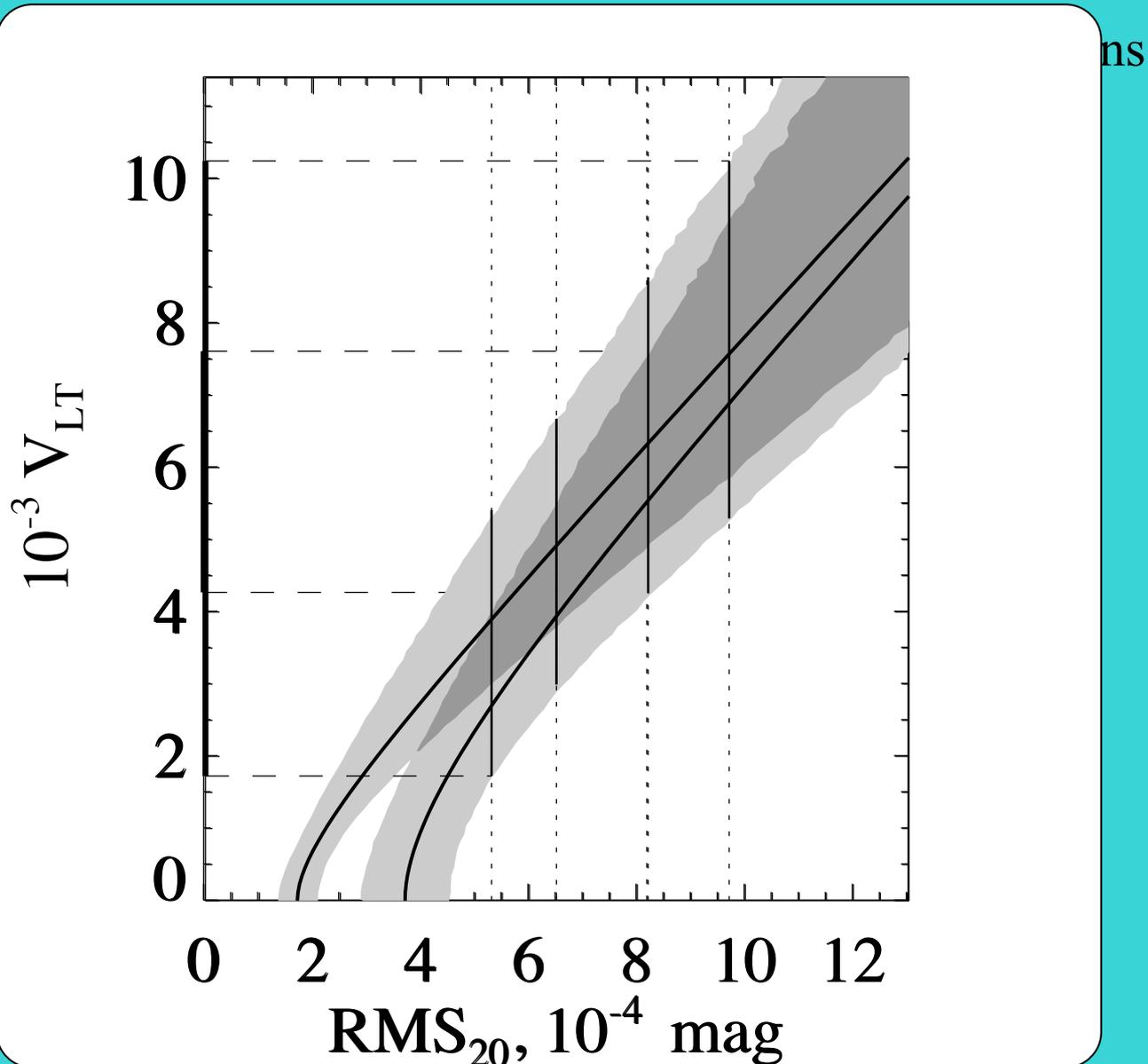
Possible constraints on the historical solar variability

25 Su



Possible constraints on the historical solar variability

25 Su



Possible constraints on the historical solar variability

25 Su

10

0.17% change in Stromgren (b+y) between the Maunder minimum and present

$10^{-3} V_I$

6
4

corresponds to 1.9-2.7 W/m² TSI change

2
0

0 2 4 6 8 10 12

RMS₂₀, 10⁻⁴ mag

ns

Possible constraints on the historical solar variability

25 Su

10

0.17% change in Stromgren (b+y) between the Maunder minimum and present

$10^{-3} V_I$

6
4

corresponds to 1.9-2.7 W/m² TSI change

2

0

THANK YOU!

RMS₂₀, 10⁻⁷ mag