Modelling of the solar spectral irradiance (SSI) in the UV: empirical approach

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Why should we care about the SSI in the UV?

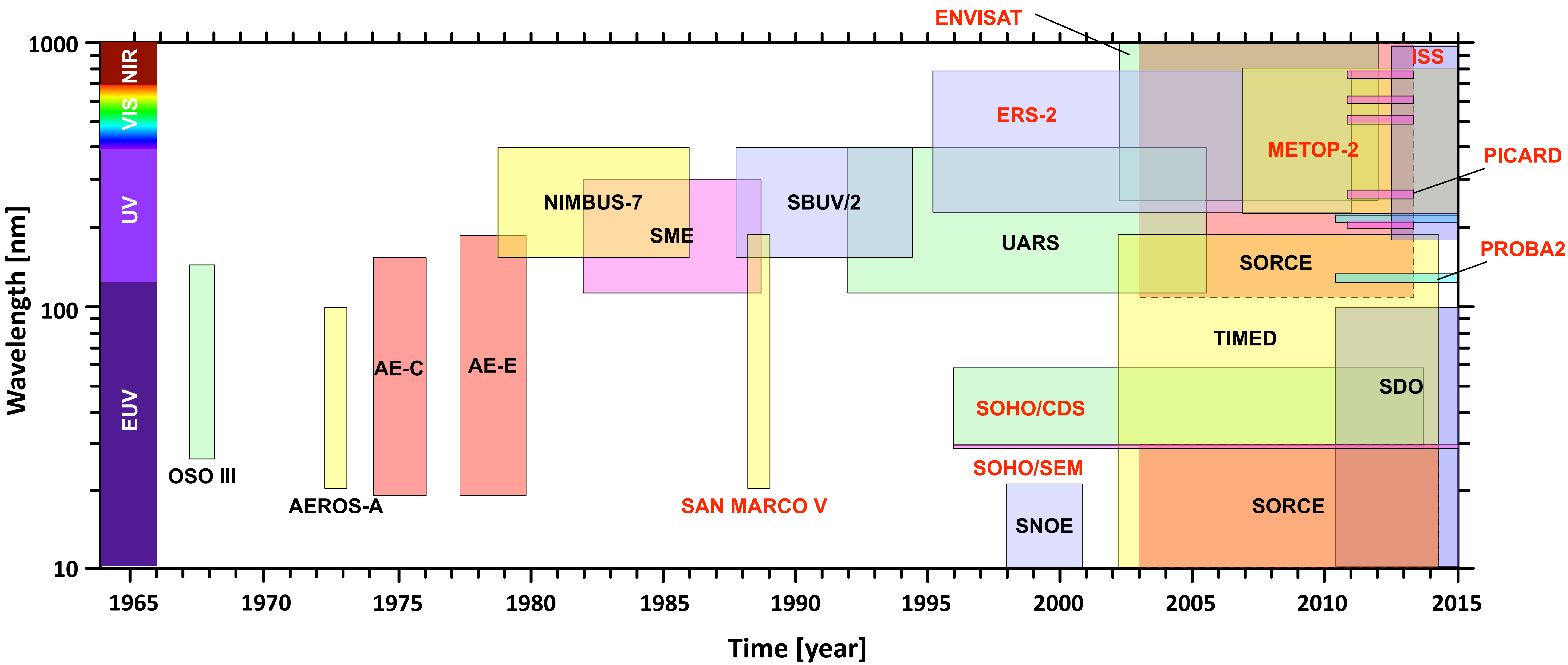
- Incomplete physical knowledge about the processes which lead to the formation of emissions at different wavelengths.

- Spectral irradiance in UV band directly affects the state of the Earth's middle and upper atmosphere.

- On the short timescale: increases the satellite drag due to heating of the thermosphere; perturbs the ground-satellite communications due to changes in the ionospheric electron density.

- On the long timescale: forces climate.

Available SSI observations.

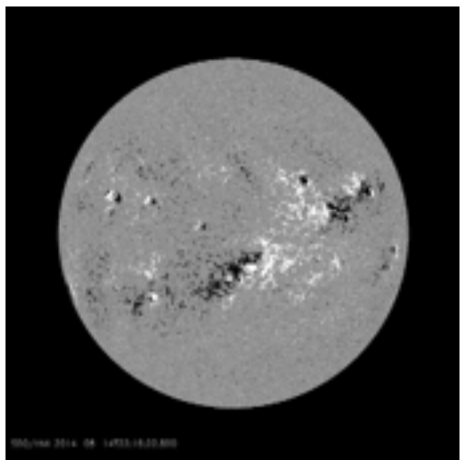


Gaps in both spectral coverage and time domain!
Moreover, data from different instruments often disagree.

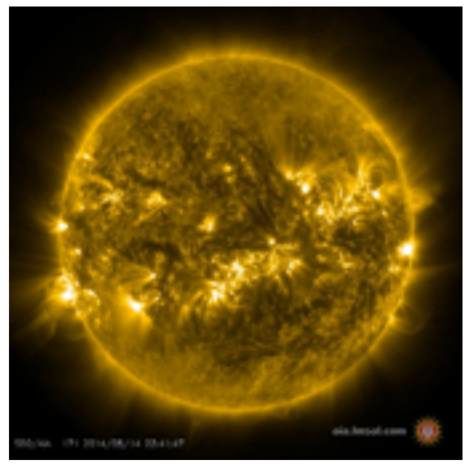
Modelling of the SSI.

physical models	proxy-based models	semi-empirical models
none	use statistical relation between the SSI and different indices of solar activity like f10.7, Mg II etc. (e.g. NRLSSI)	based on assumption that the SSI variability are driven by the evolution of the surface magnetic field. (e.g. SATIRE, COSI, SRPM)
	are as good as proxies lack of physical interpretation	sensitive to absolute data calibration require solar atmosphere model spectra

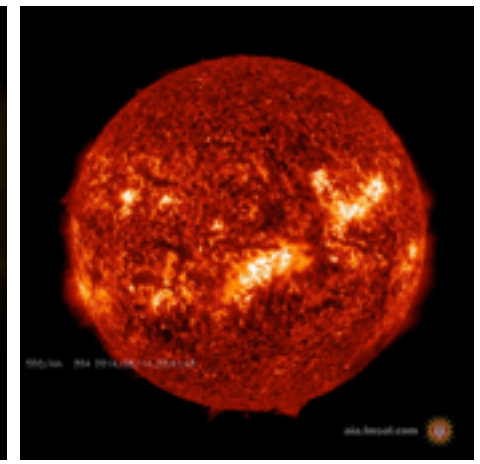
Semi-empirical models.



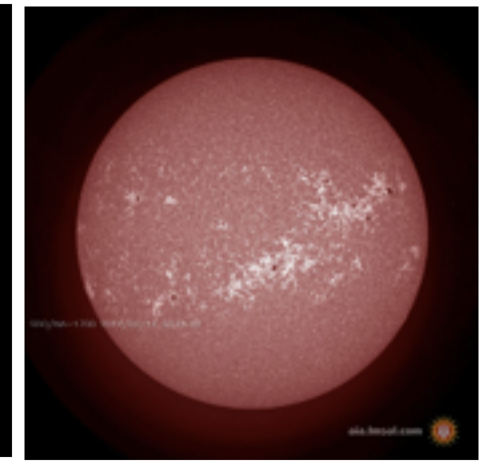
magnetogram



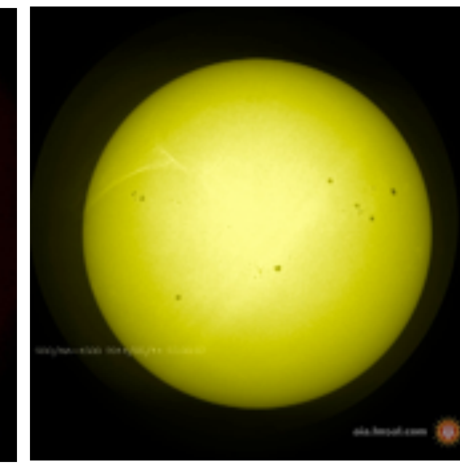
17.1 nm



30.5 nm



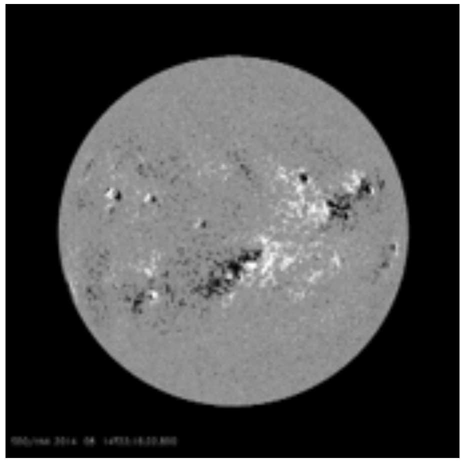
170 nm



450 nm

Semi-empirical models.

Assumption: SSI variability is driven by the evolution of surface magnetic field.



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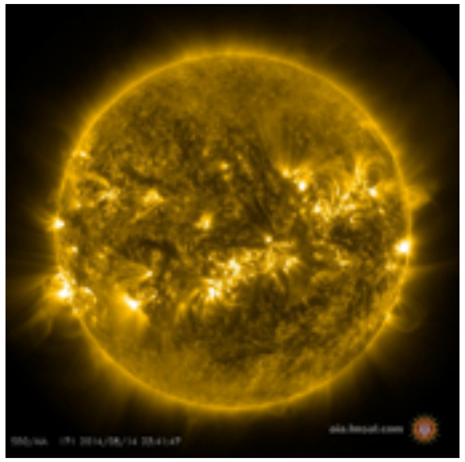

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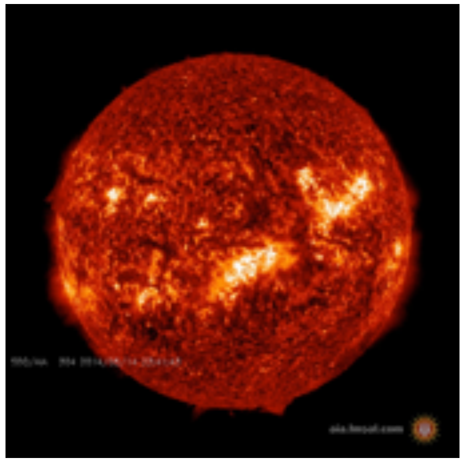

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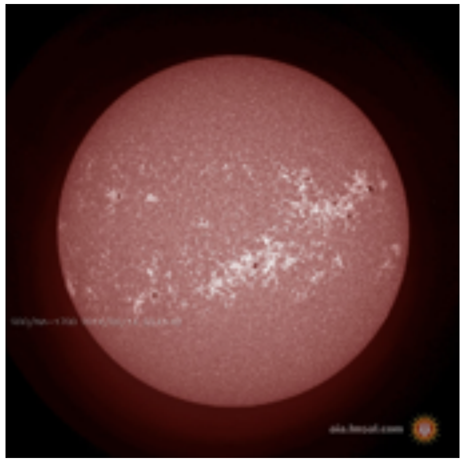

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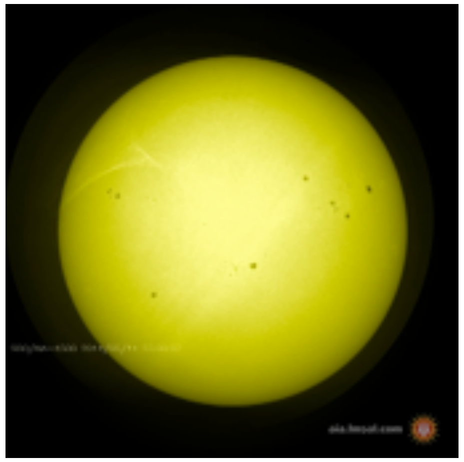

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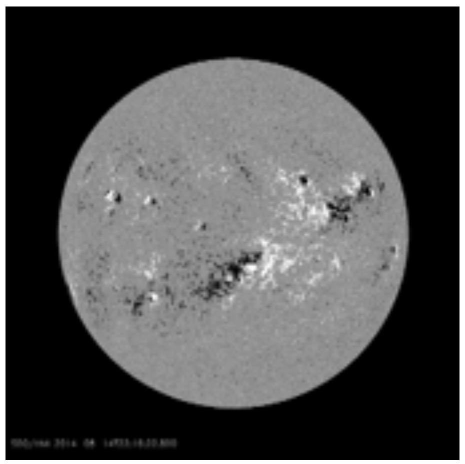

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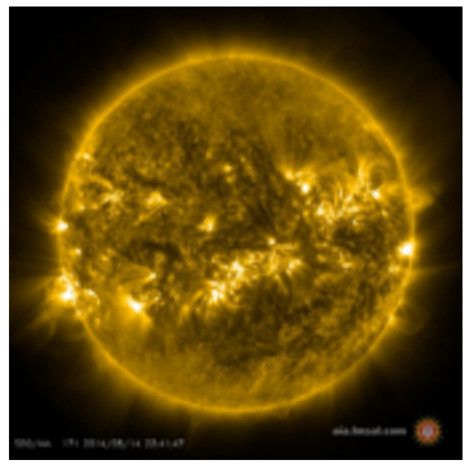

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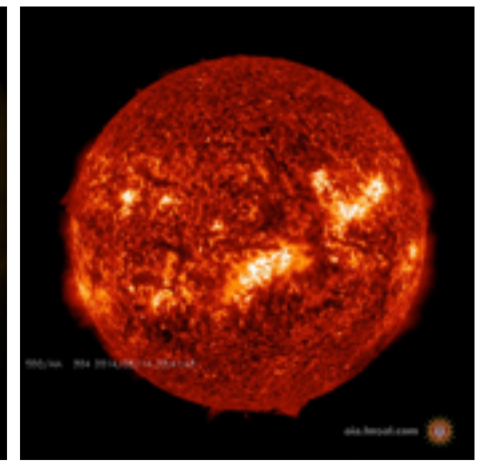

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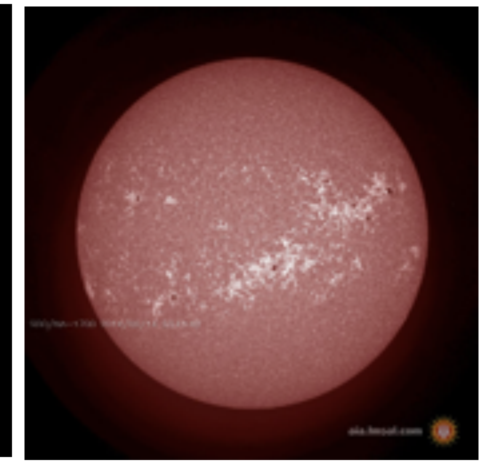

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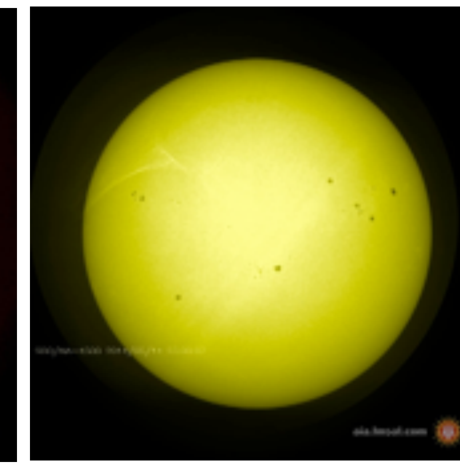

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characteristic spectra +

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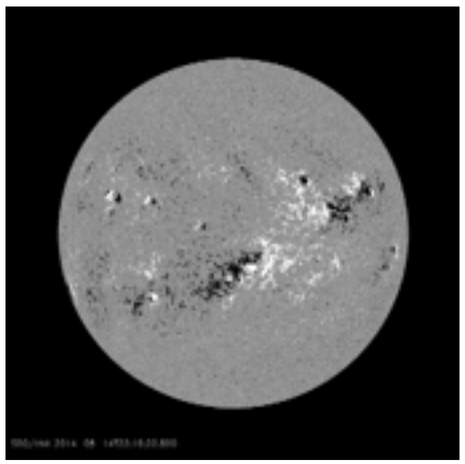

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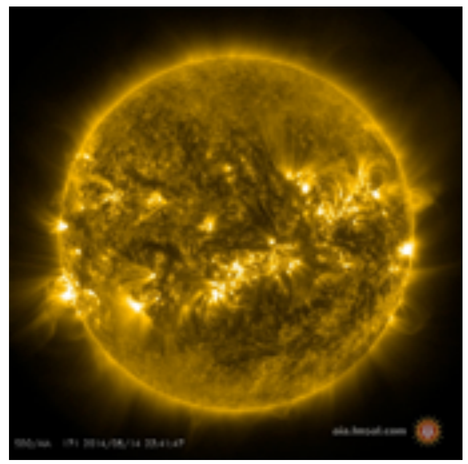

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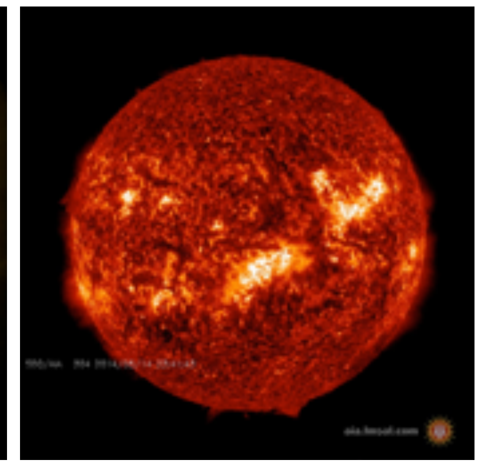

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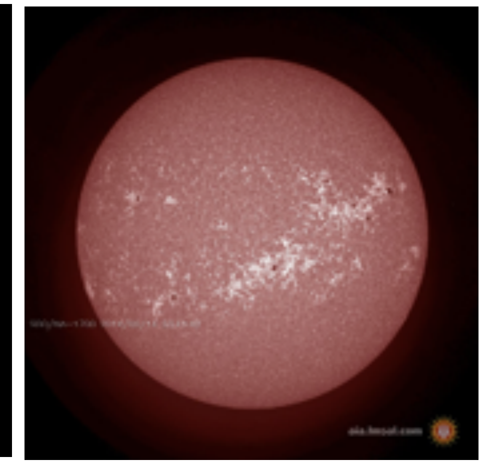

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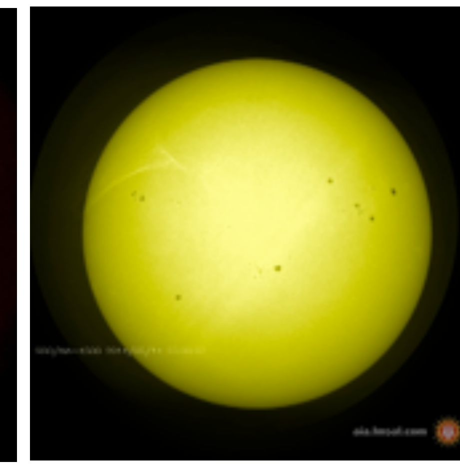

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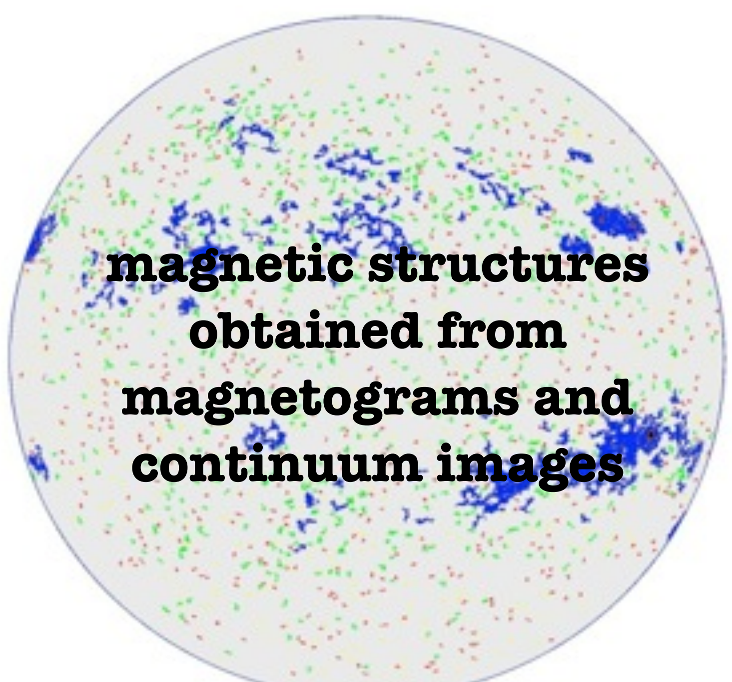

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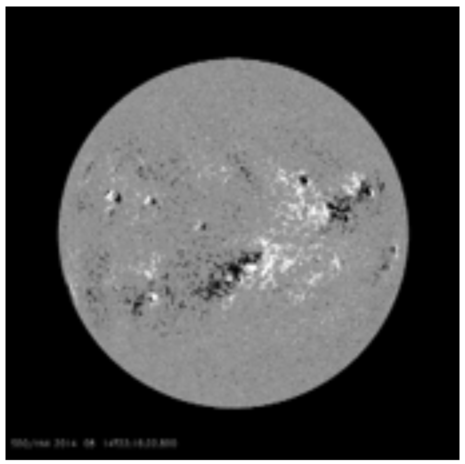
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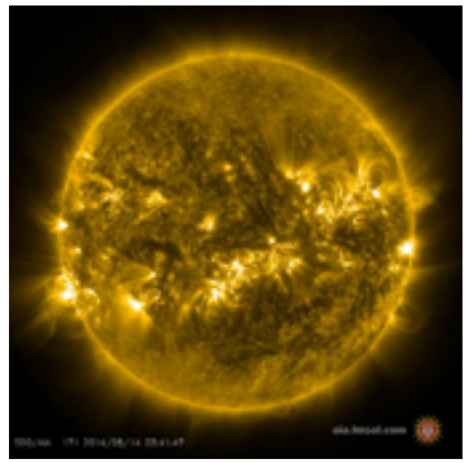
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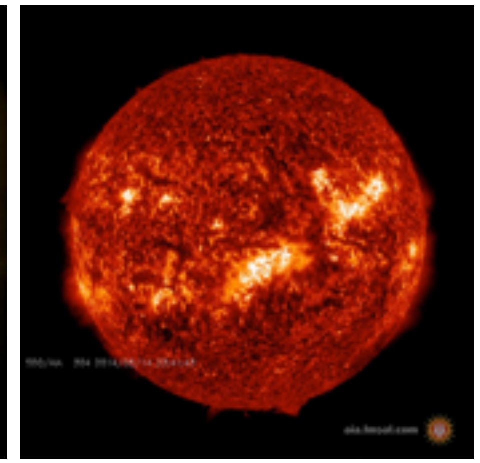
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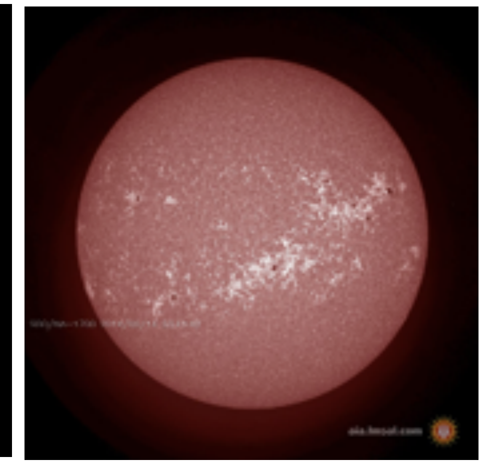
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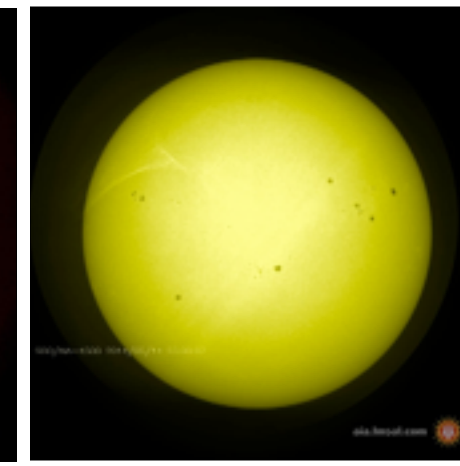
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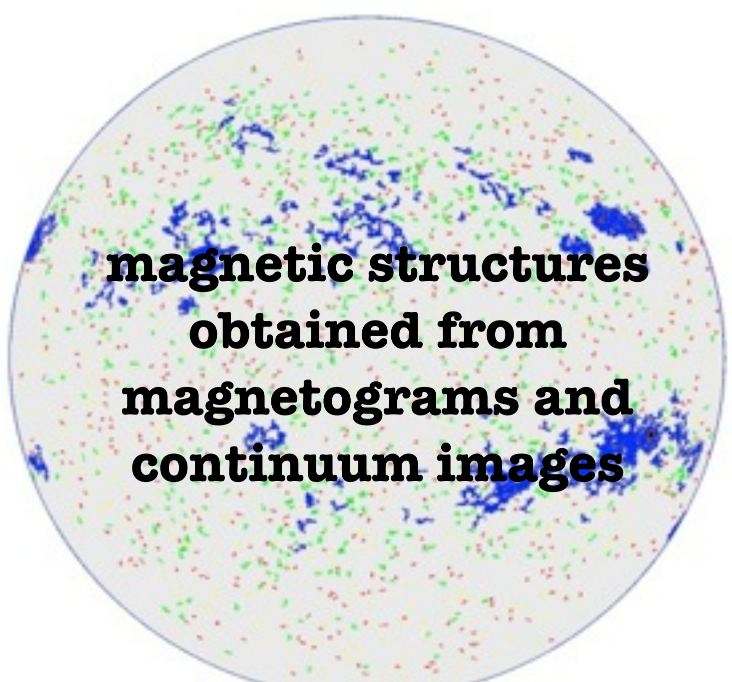

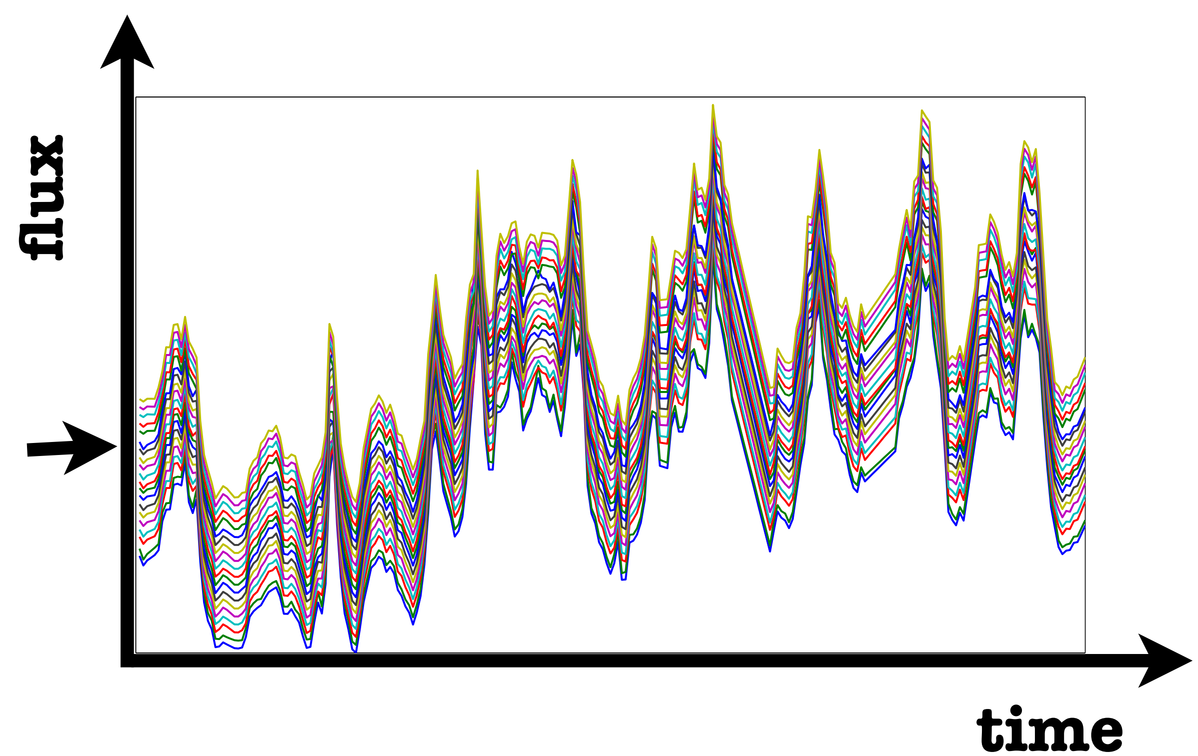

Issues.

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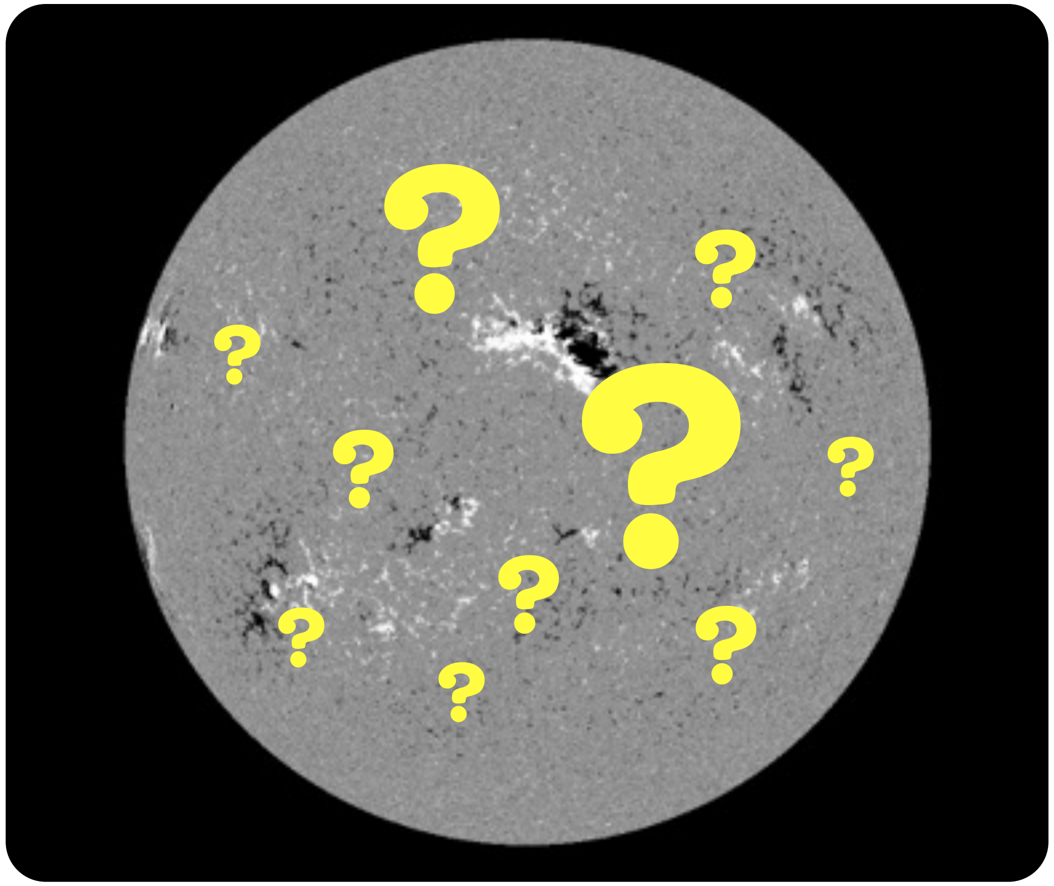
- How should the magnetic structures be defined?



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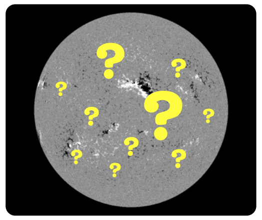

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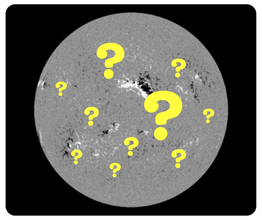

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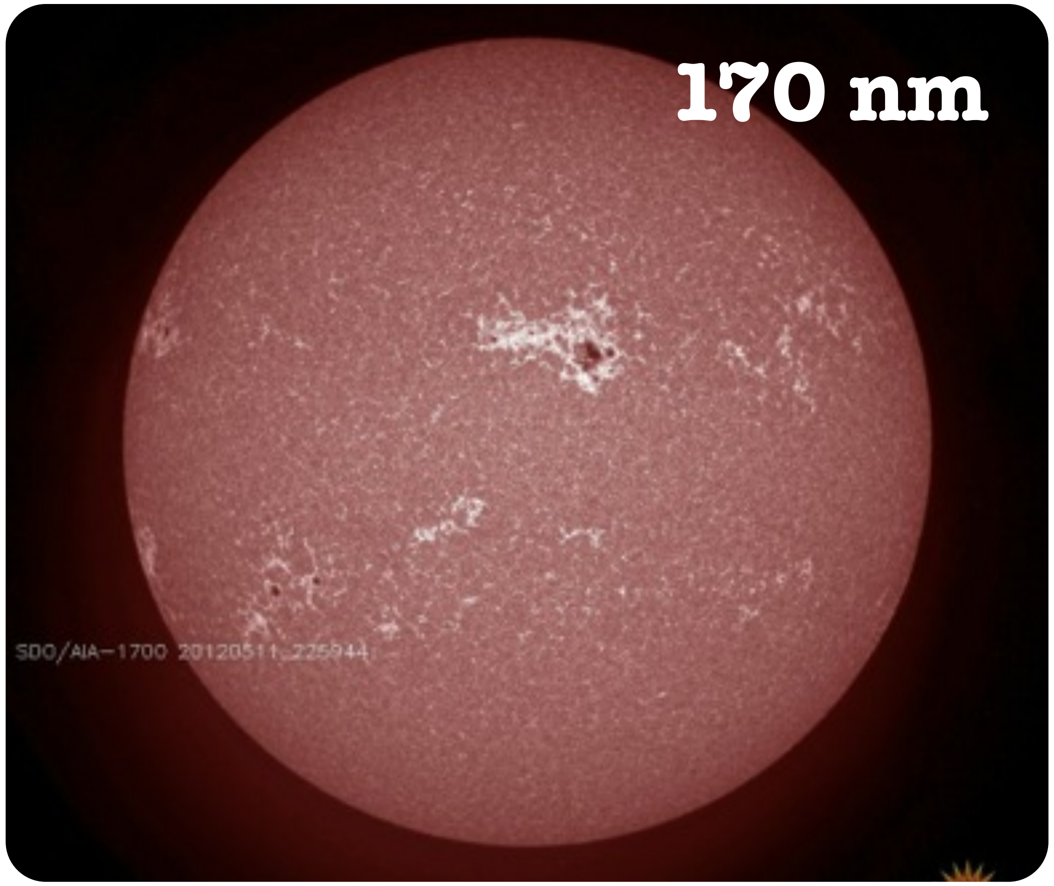
- How important is the center-to-limb (CLV) effect?



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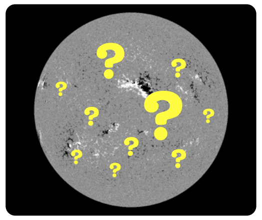

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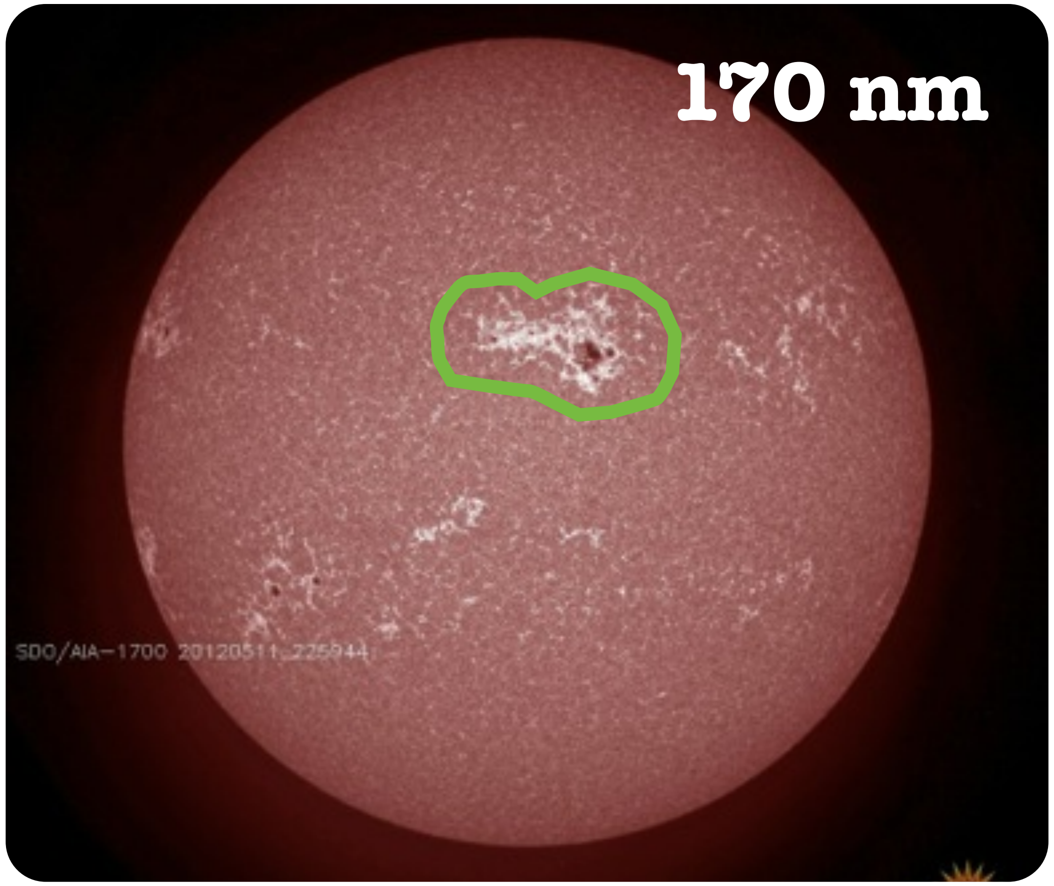

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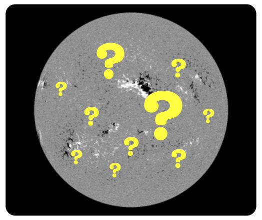

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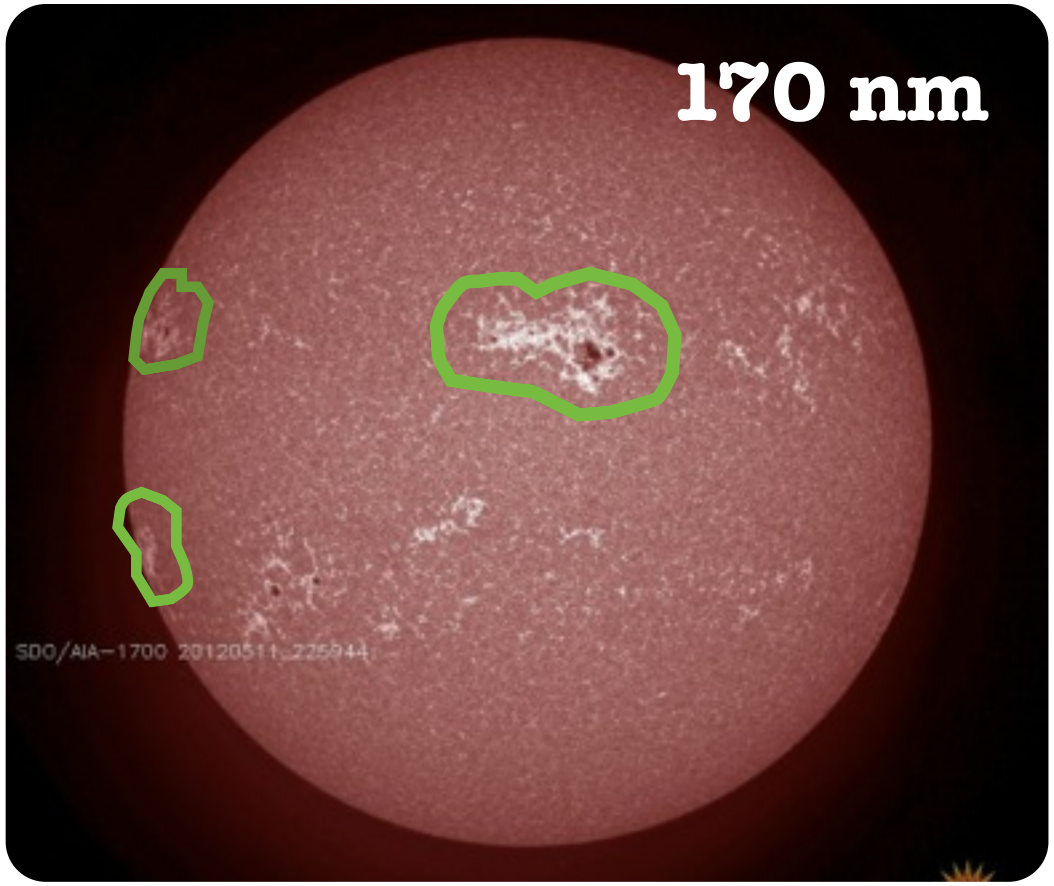

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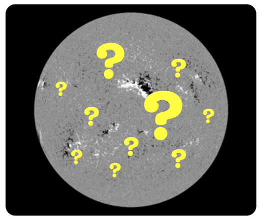

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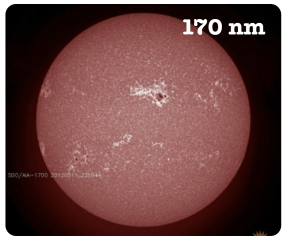

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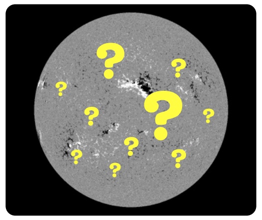

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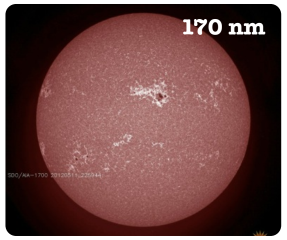

- What is the contribution of magnetic structures to the SSI?

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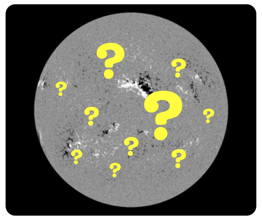

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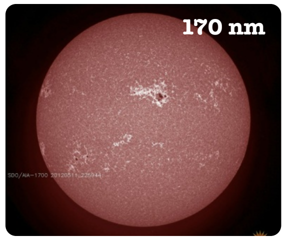

- How important is the center-to-limb (CLV) effect?

- What is the contribution of magnetic structures to the SSI?

To answer these questions consider an empirical ("less biased") approach. No assumptions on atmospherical models.

Our empirical model.

Linear SATIRE-like model:

$$I\left(\lambda,t\right)=\sum_{f}\sum_{r}S_{f,r}\left(\lambda\right)F_{f,r}\left(t\right)+S_{QS}\left(\lambda\right)F_{QS}(t)+\xi\left(\lambda,t\right)$$

$I\left(\lambda,t\right)$ - spectral irradiance
$S_{f,r}\left(\lambda\right)$ - spectral profile of magnetic structures that belong to class f
$F_{f,r}\left(t\right)$ - filling factor of magnetic structures that belong to class f
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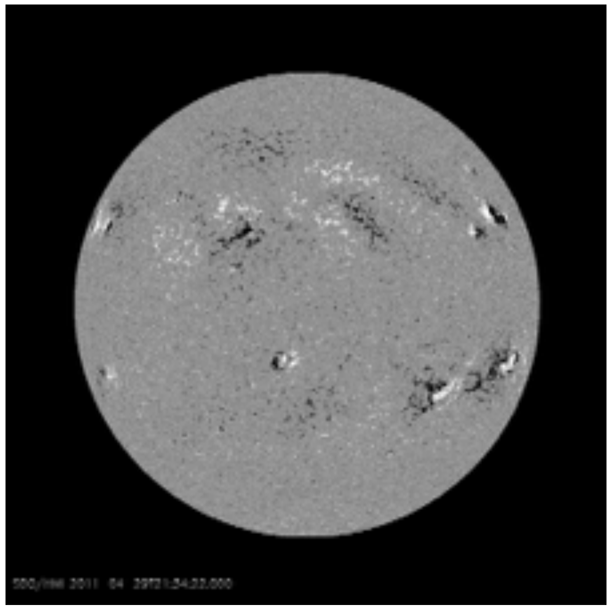

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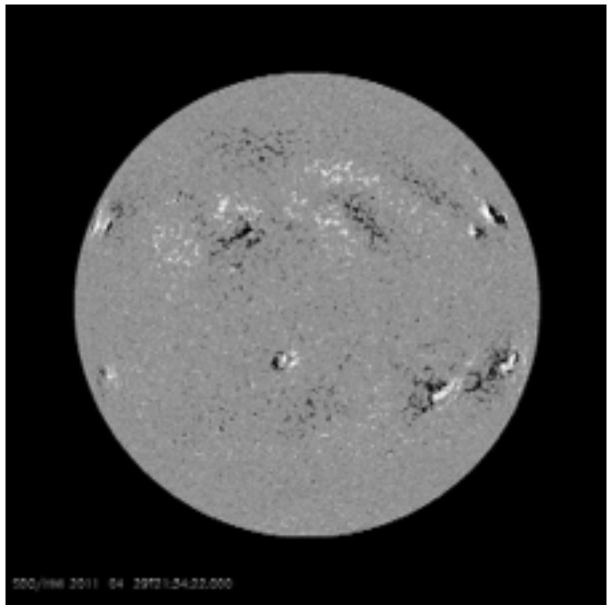

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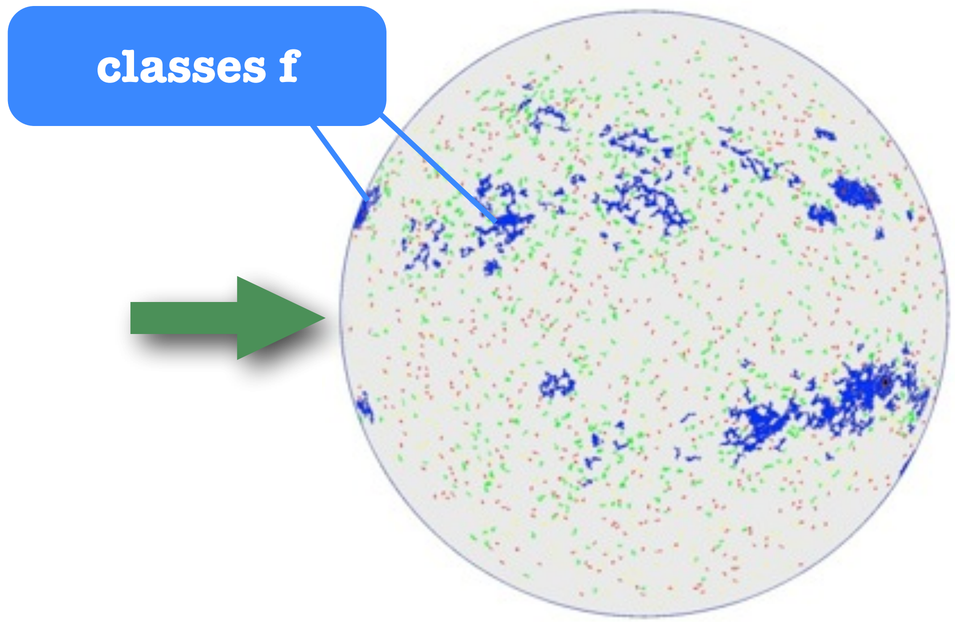

segmentation map

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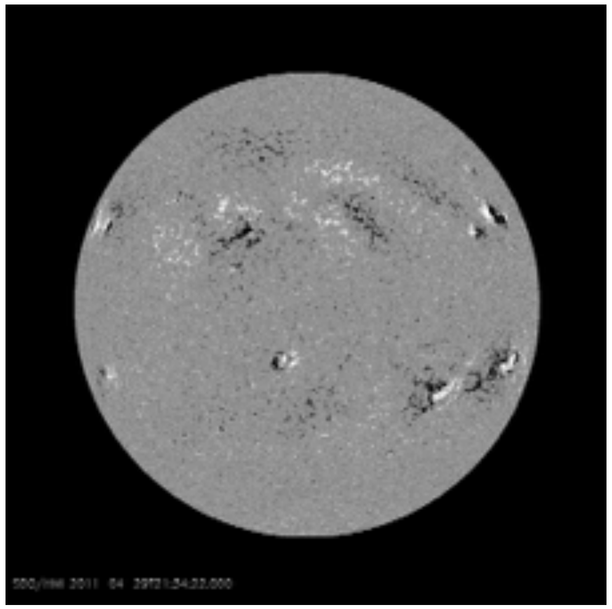

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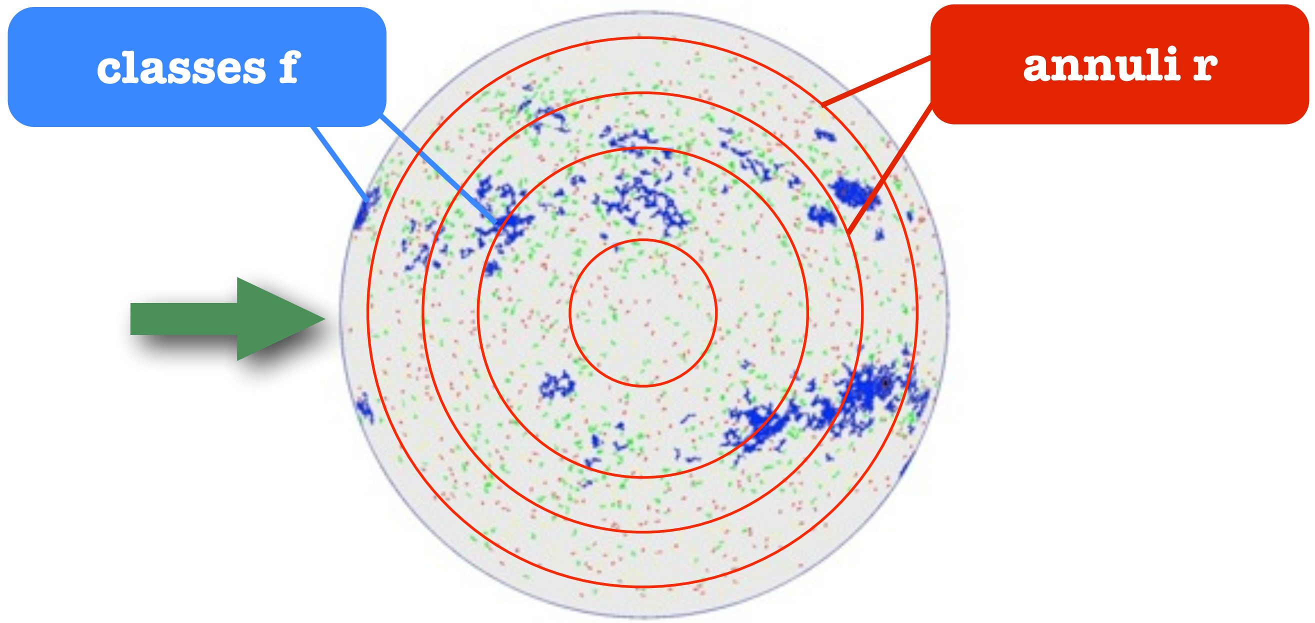

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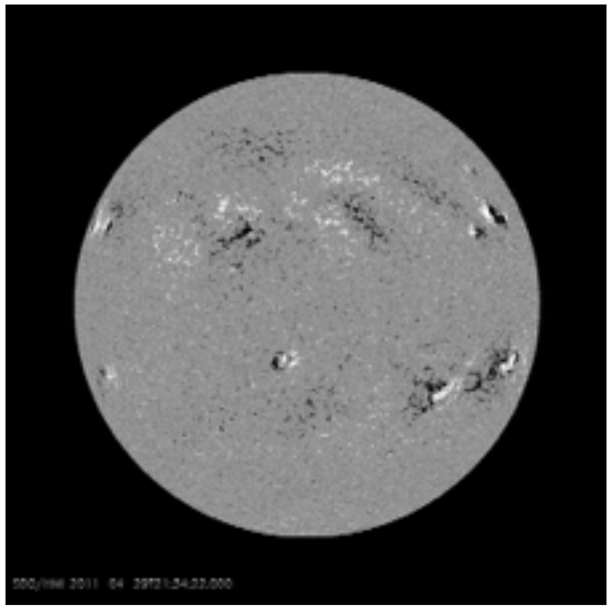

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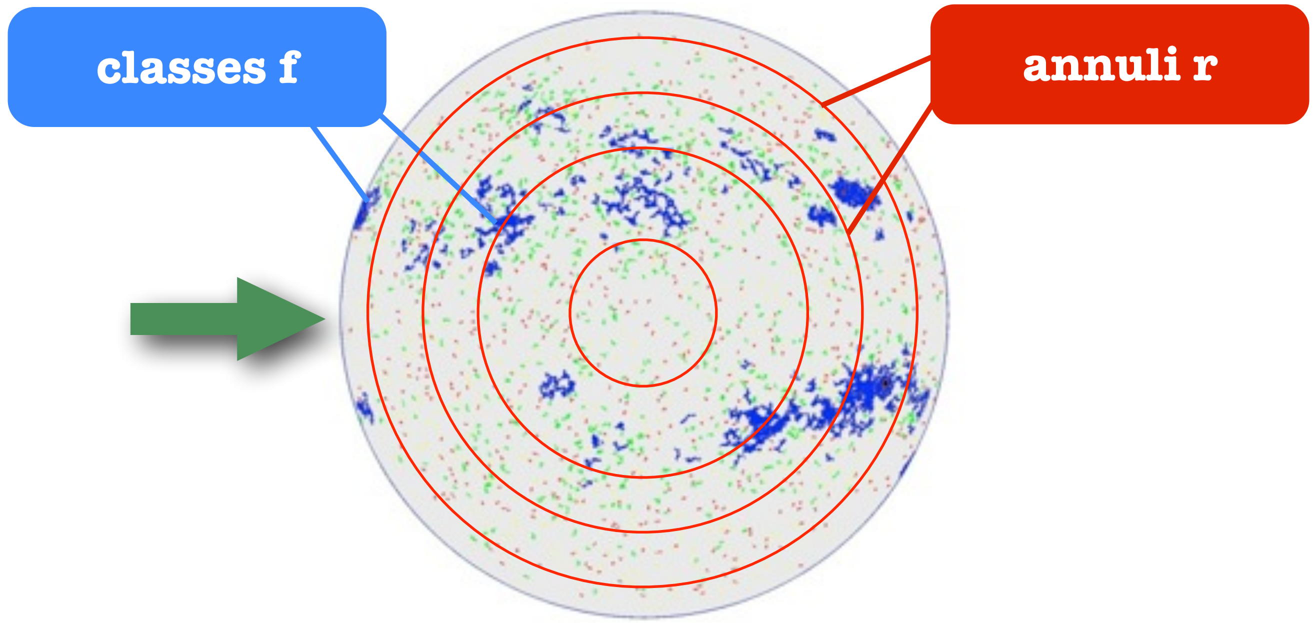


segmentation map

Linea

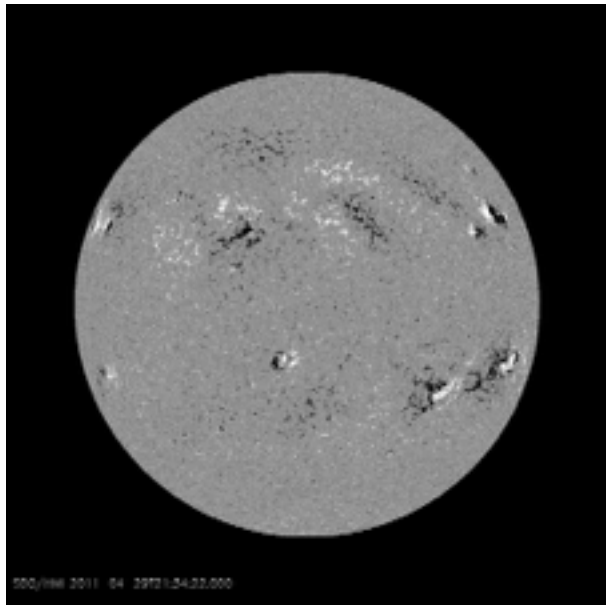
$I(\lambda,$

$I(\lambda, t)$ -
$S_{f,r}(\lambda)$ -
$F_{f,r}(t)$ -
$S_{QS}(\lambda)$ -
$F_{QS}(\lambda)$ -
$\xi(\lambda, t)$ - residuals

Difference!

- spectra S are not imposed.
- number of classes f is not imposed.
- threshold levels between classes f are not pre-defined.
- number of annuli r is not imposed.
- segmentation of magnetograms according to the area of magnetic structures.

Our empirical model.



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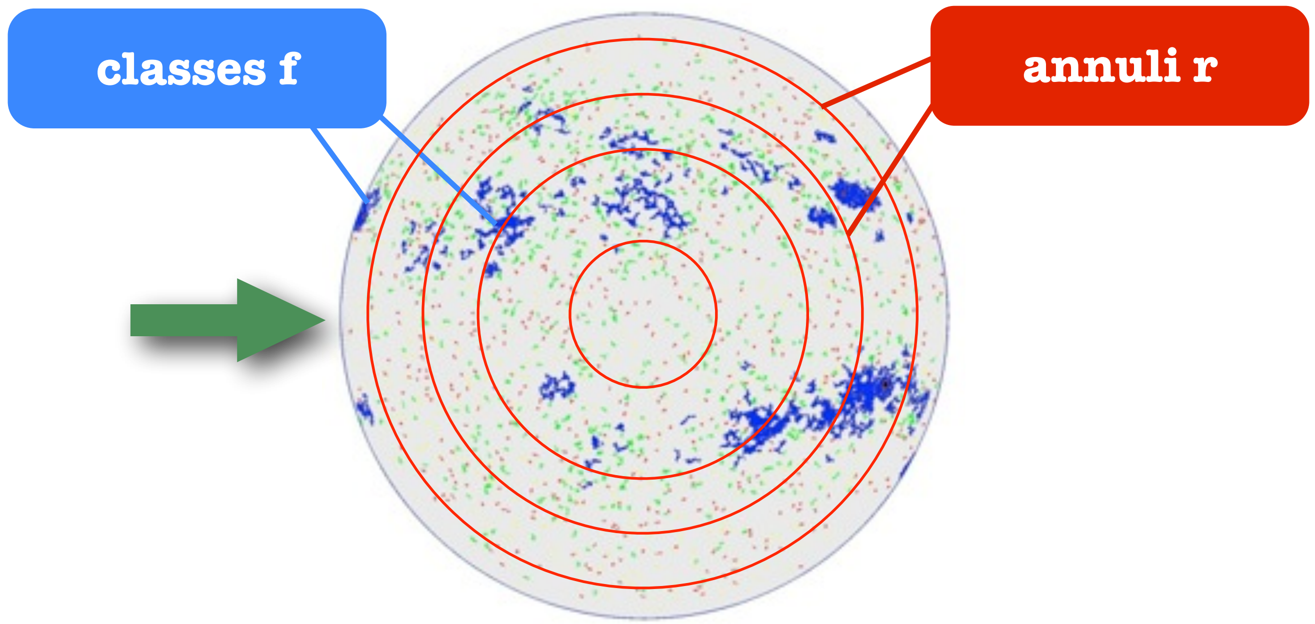

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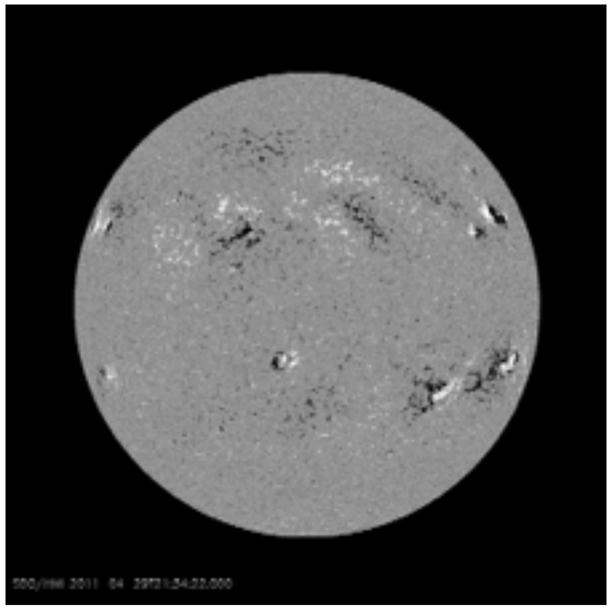

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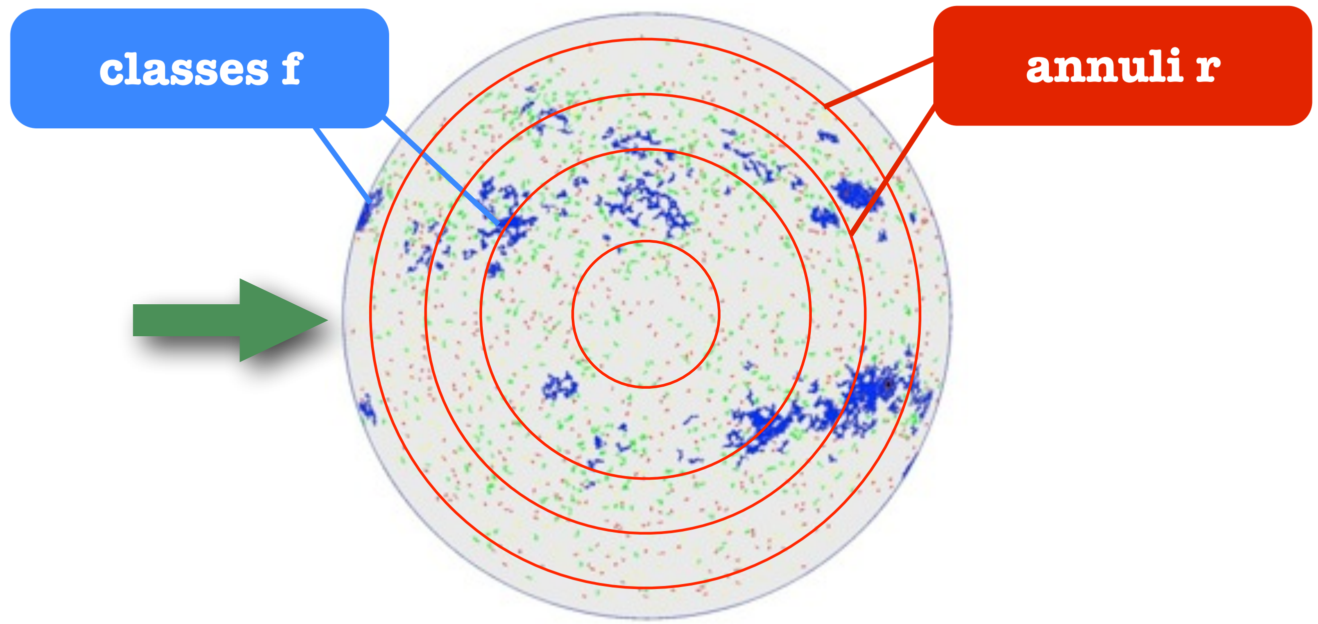

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$$I(\lambda,t) = \sum\sum S_{f,r}(\lambda)\,F_{f,r}(t) + S_{QS}(\lambda)\,F_{QS}(t) + \xi(\lambda,t)$$

$S = I\,F^{-1}$

S - atmosphere model

I - spectral irradiance observations

F -filling factors

$\xi(\lambda,t)$ - residuals

Data.

Data.

- Model is selected and calibrated with SSI observations (daily averages).

Instrument	Wavelength, nm	Spectral band
SDO/EVE	6.5-9.5	XUV
SDO/EVE	10.5-35.5	EUV
TIMED/SEE	36.5-115.5	EUV
SORCE/SOLSTICE	121.5	LyA
SORCE/SOLSTICE	116.5-200.5	FUV
SORCE/SOLSTICE	280.5	MgII
SORCE/SOLSTICE	200.5-300.5	MUV

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SORCE/SOLSTICE	116.5-200.5	FUV
SORCE/SOLSTICE	280.5	MgII
SORCE/SOLSTICE	200.5-300.5	MUV

- Magnetic structures extracted from SDO/HMI magnetograms (4096x4096 pxls compressed to 2048x2048 pxls)

Data.

- Model is selected and calibrated with SSI observations (daily averages).

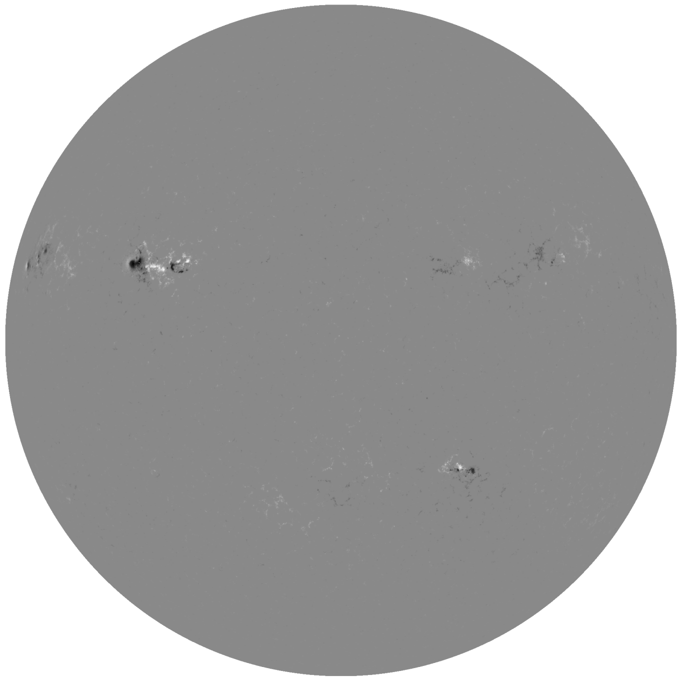
Instrument	Wavelength, nm	Spectral band
SDO/EVE	6.5-9.5	XUV
SDO/EVE	10.5-35.5	EUV
TIMED/SEE	36.5-115.5	EUV
SORCE/SOLSTICE	121.5	LyA
SORCE/SOLSTICE	116.5-200.5	FUV
SORCE/SOLSTICE	280.5	MgII
SORCE/SOLSTICE	200.5-300.5	MUV

- Magnetic structures extracted from SDO/HMI magnetograms (4096x4096 pxls compressed to 2048x2048 pxls)

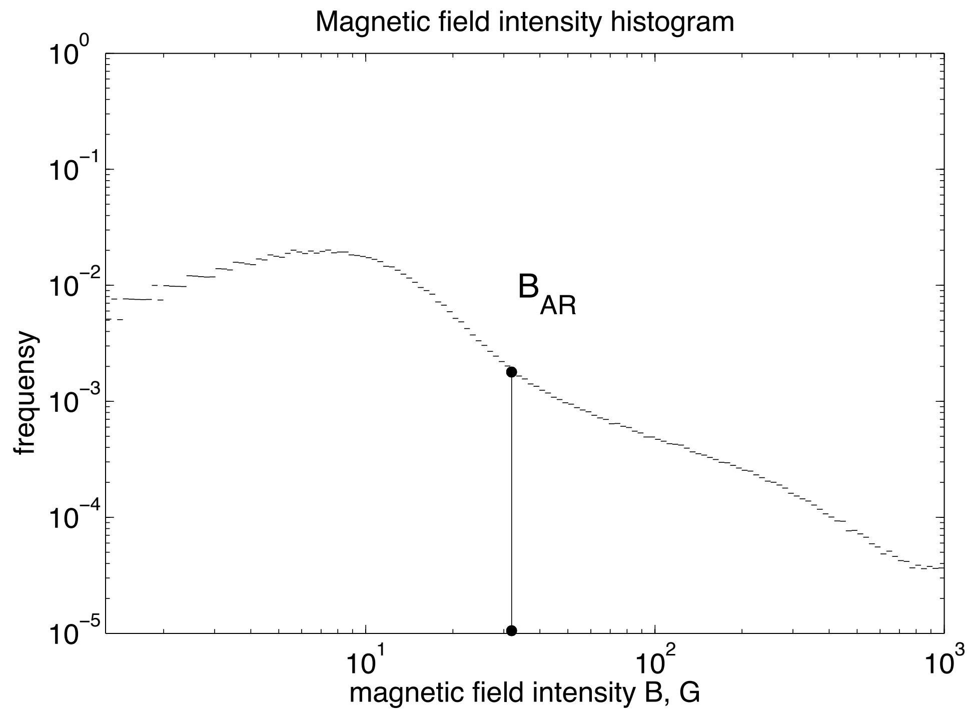
Time interval: 24/04/2010 - 01/07/2013 (rising phase of cycle 24)

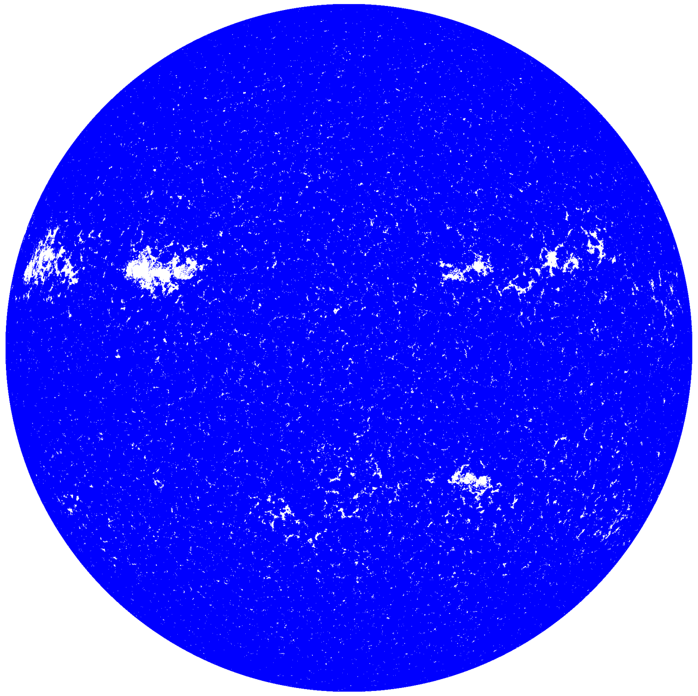
Extraction of magnetically active regions.

To proceed with the classification of magnetically active regions we have to separate them from the surrounding quiet Sun area.



magnetogram





binary mask of magnetically active regions

Classification of magnetically active regions by area.

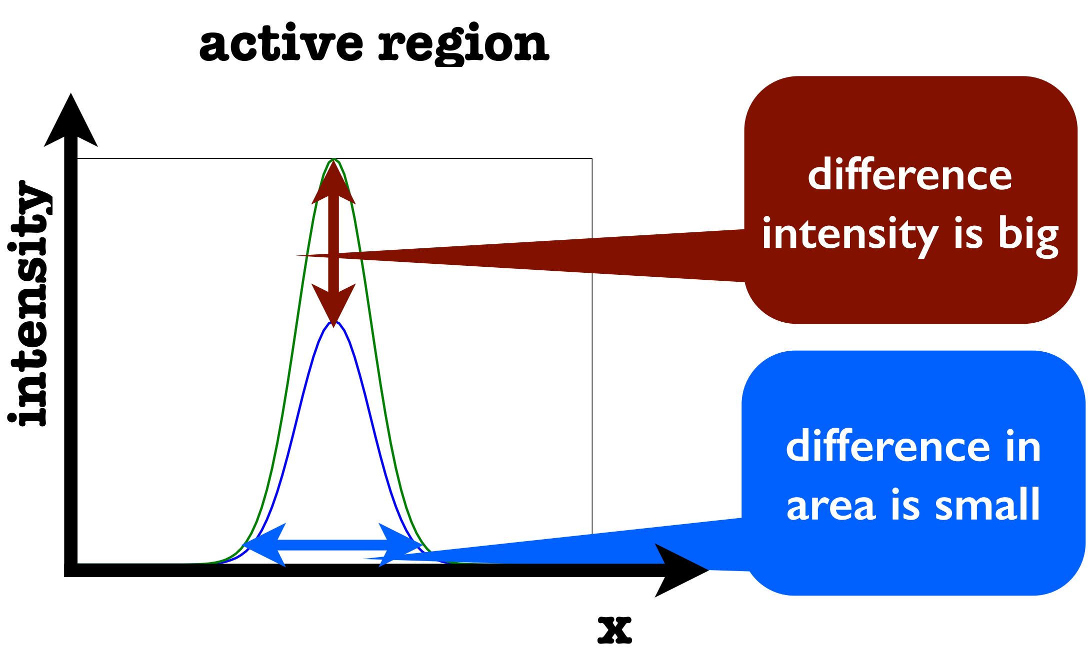
Common approach: classification by the magnetic field intensity.
Disadvantages:

Our approach: classification by the size.
Disadvantage: merging of active regions that are located close to each other.

Classification of magnetically active regions by area.

Common approach: classification by the magnetic field intensity.
Disadvantages:

Absolute calibration

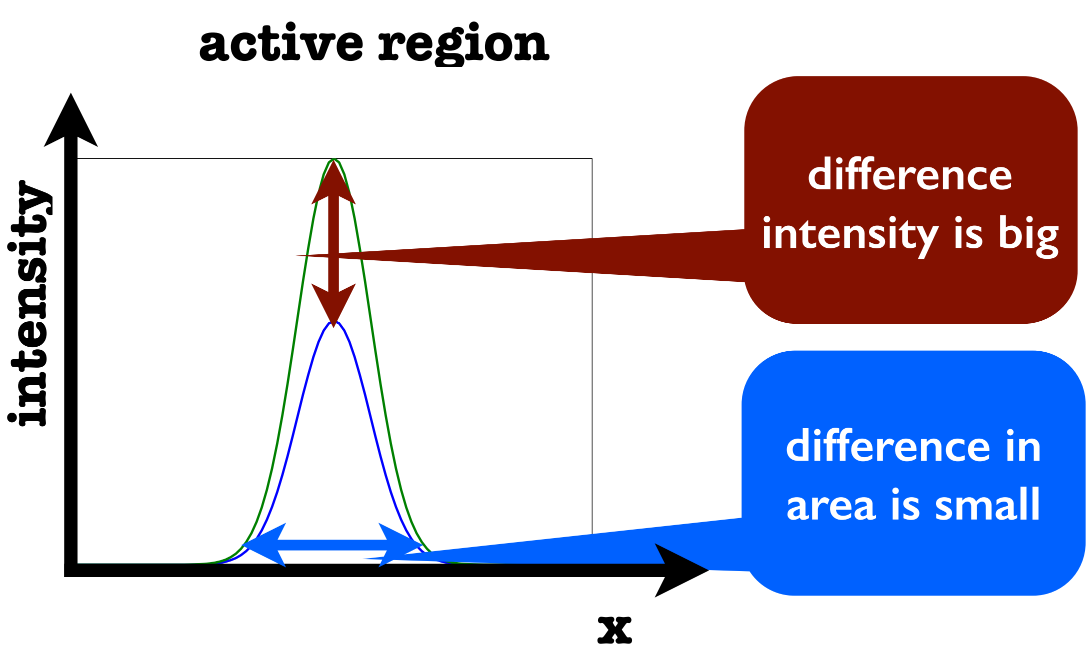


Our approach: classification by the size.
Disadvantage: merging of active regions that are located close to each other.

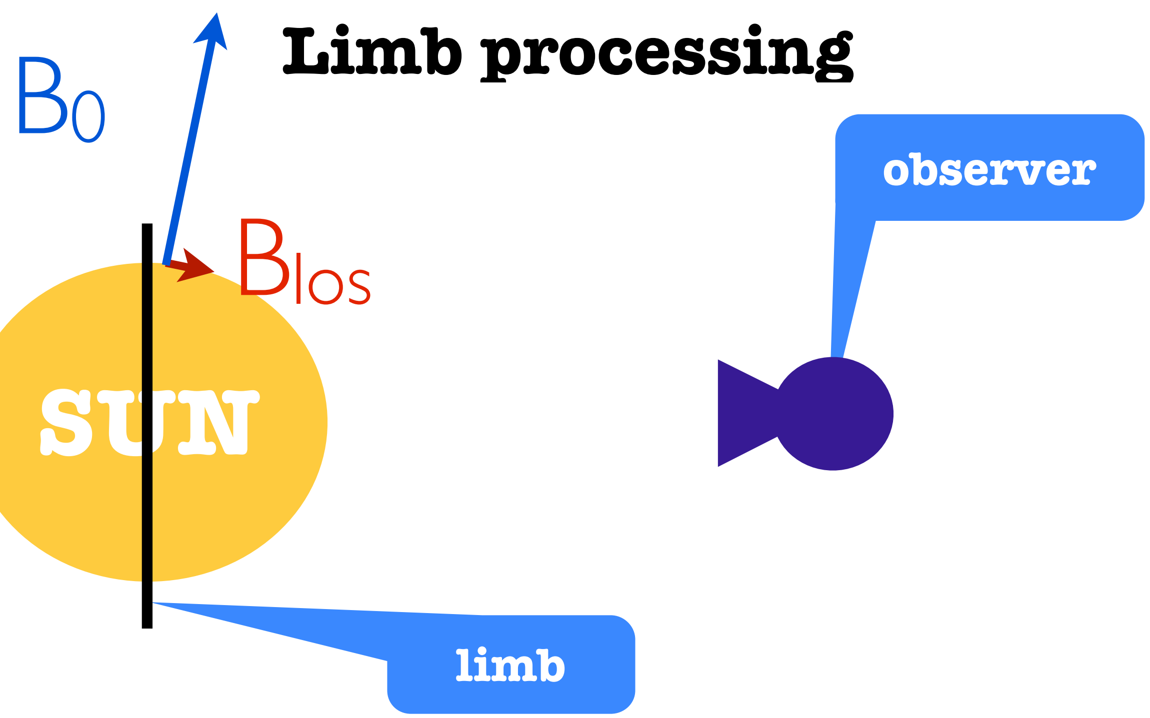
Classification of magnetically active regions by area.

Common approach: classification by the magnetic field intensity.
Disadvantages:

Absolute calibration



Limb processing



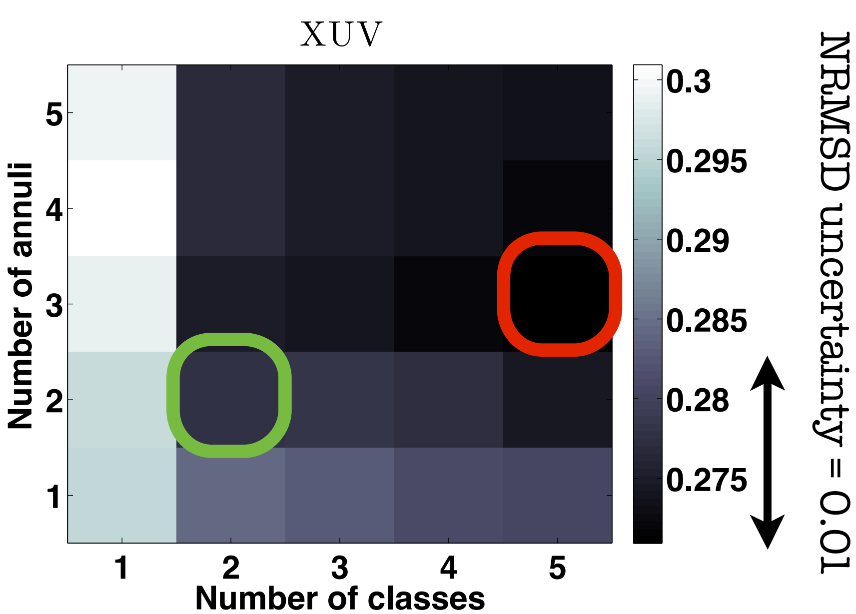
Our approach: classification by the size.
Disadvantage: merging of active regions that are located close to each other.

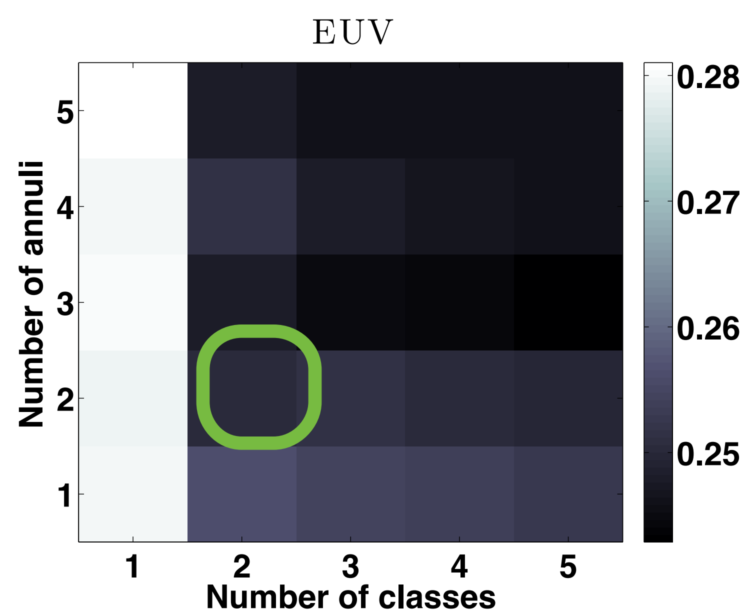
Model selection and calibration.

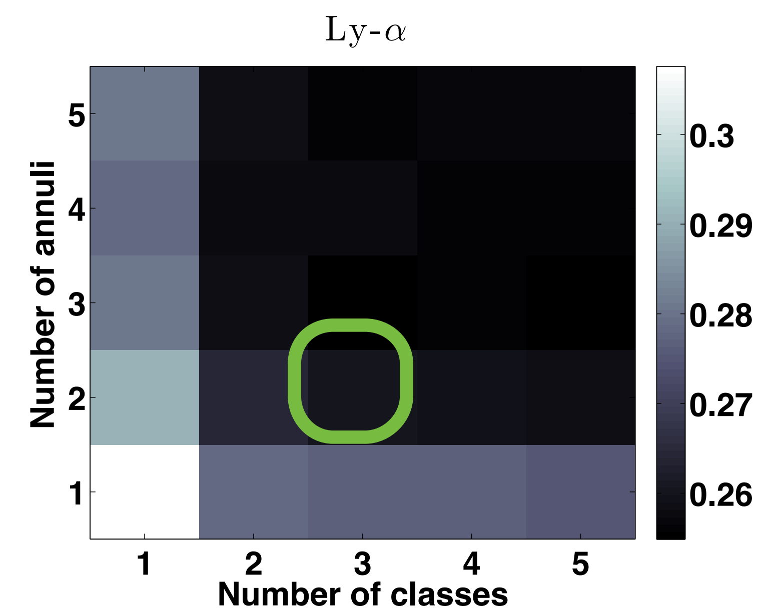
Model quality is quantified using the NRMSD error. NRMSD tells what fraction of variance of observations is NOT explained by the model.

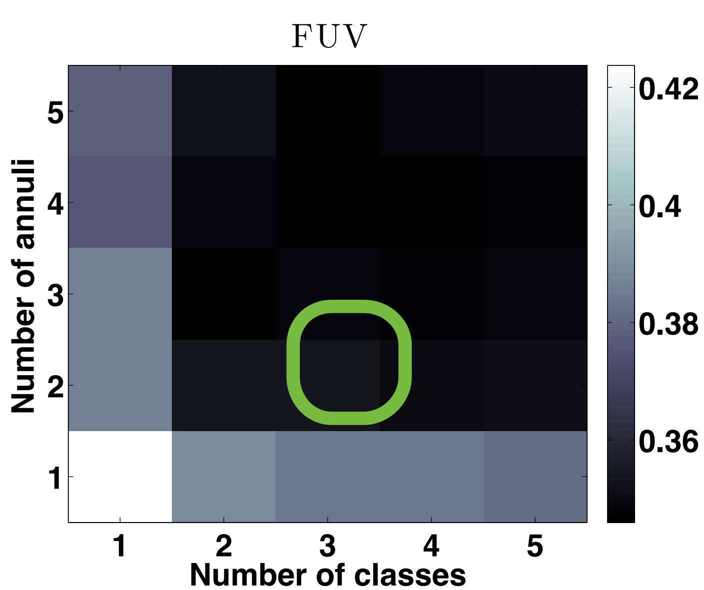
$$\mathrm{NRMSD}(\lambda) = \frac{\sqrt{\frac{1}{N}\sum_t (I_t(\lambda) - \hat{I}_t(\lambda))^2}}{\sigma_I}$$

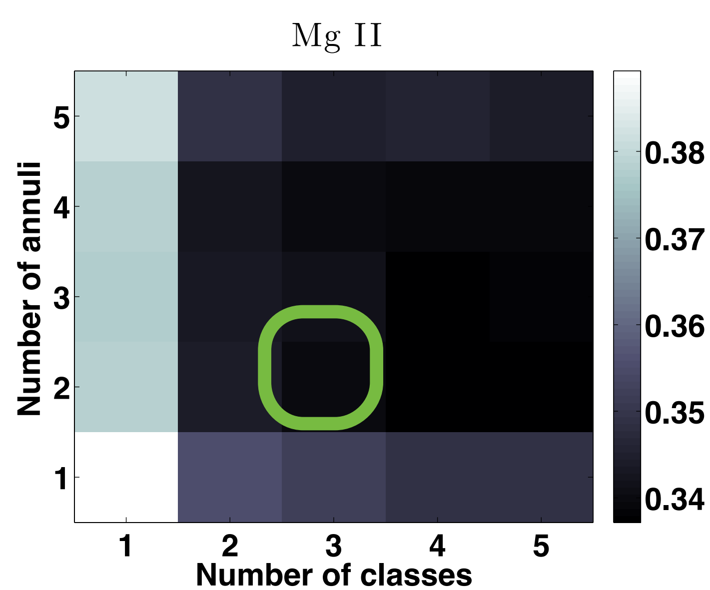
To find the optimum values of number of classes and number of annuli, we vary both parameters from 1 to 5 and compare the model quality.







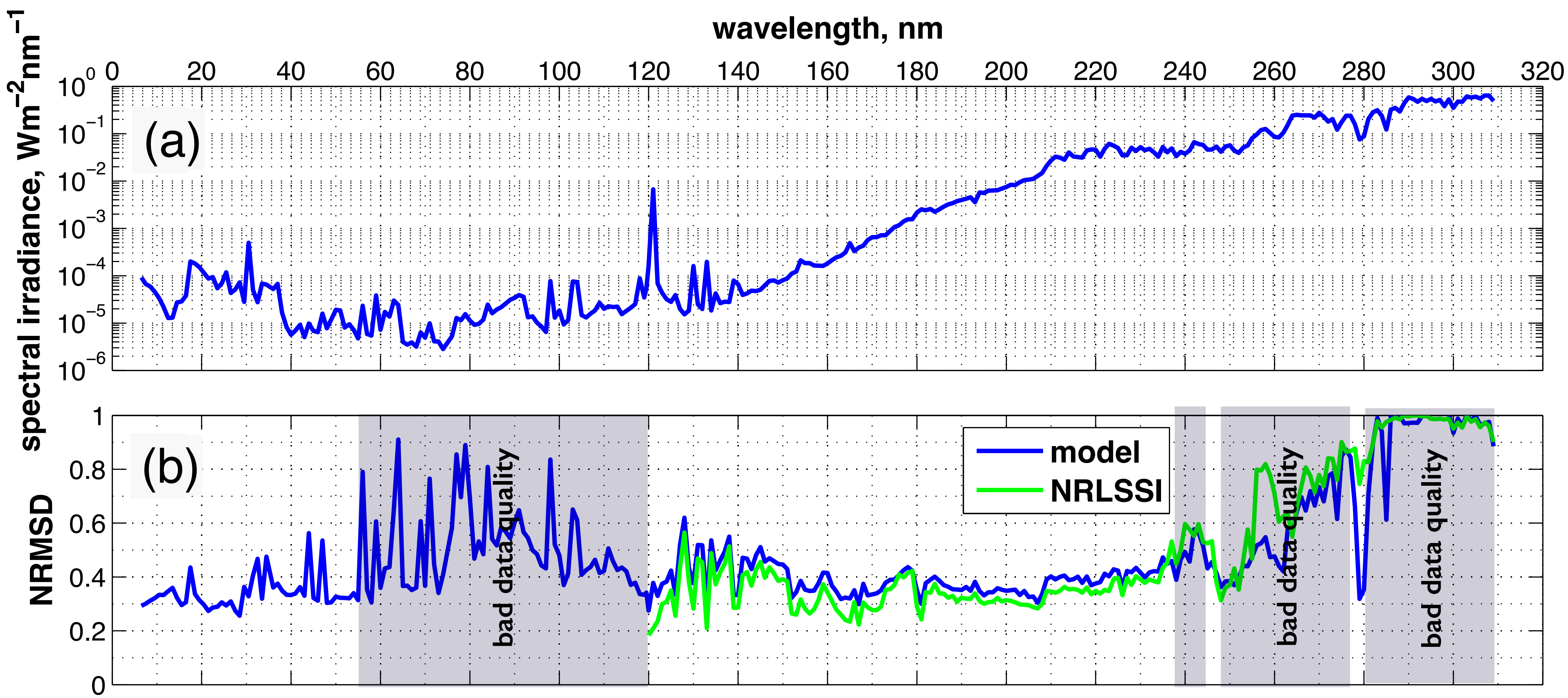




The optimum model has:
2 classes and
3 annuli.
These classes we call small and large structures respectively.

Model quality.

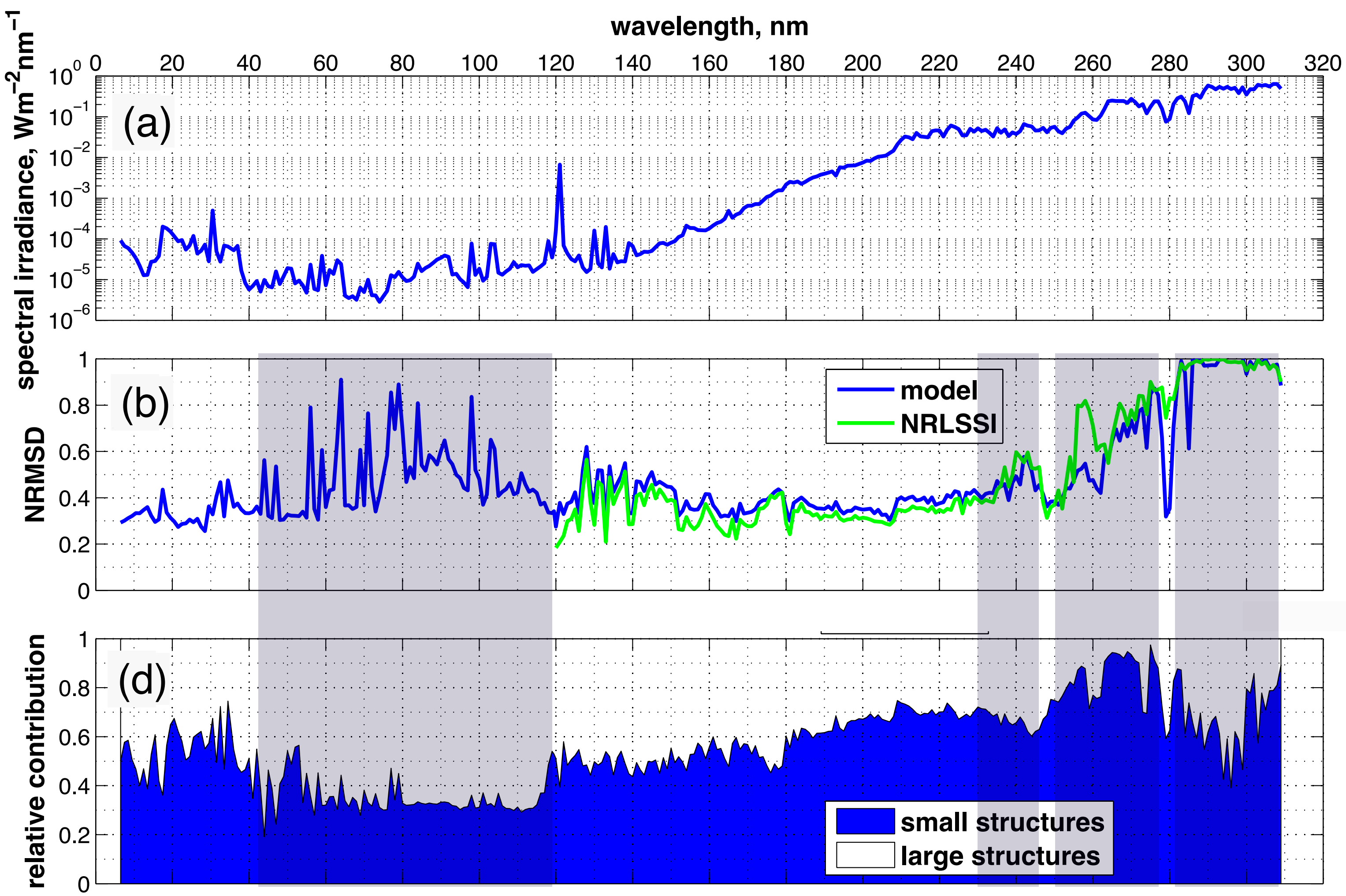
As a reference we use the NRLSSI model.

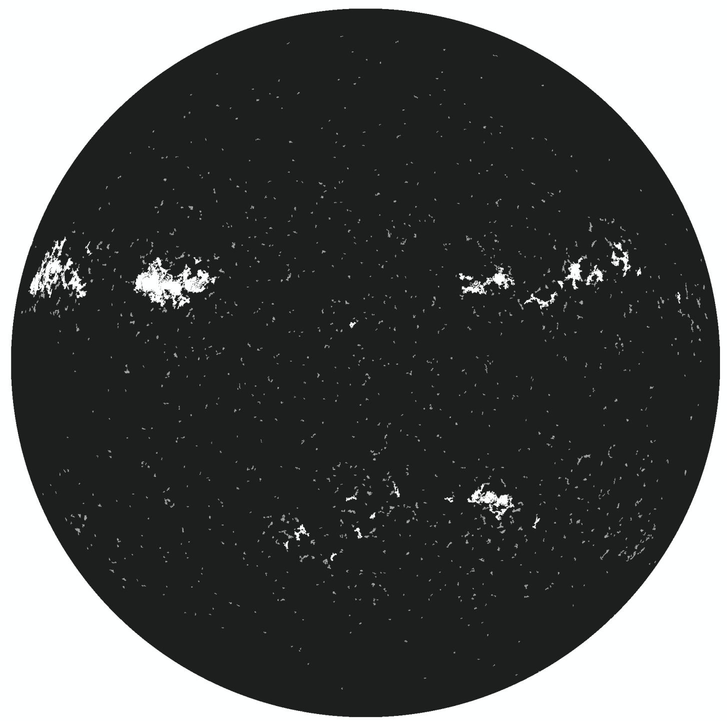


Our model has a comparable reconstruction quality to the NRLSSI. However the error is typically 3-5% higher.

The models allow to reconstruct the XUV band, 10.5-46.5 nm range in the EUV, 120.5 - 199.5 nm range in the FUV and 200.5 - 255.5 in the MUV with few exceptions. The bends with low quality are explained by degradation of instruments and spurious noise patterns.

Contribution of different magnetic structures to the SSI.





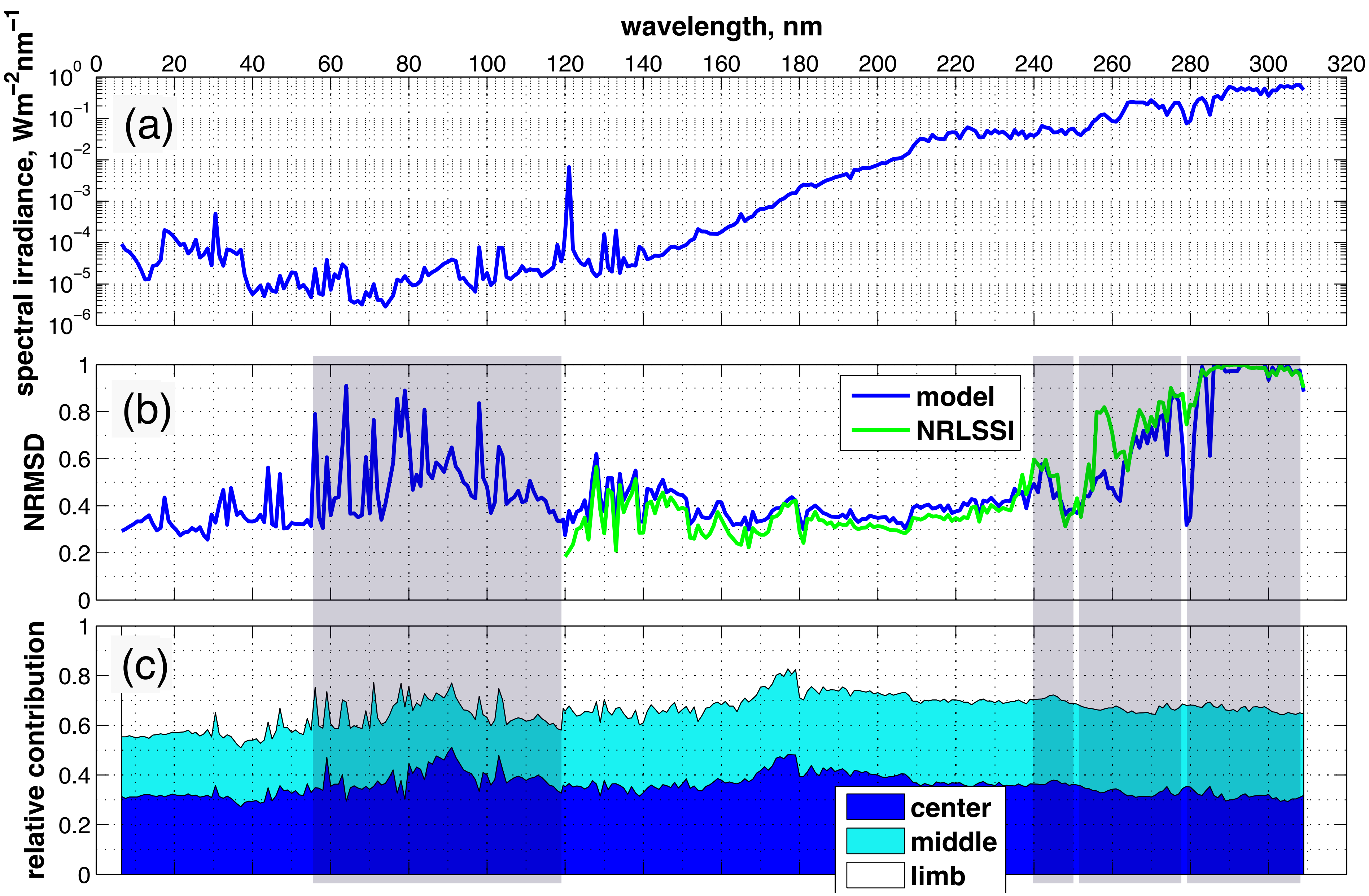
Large structures = plages
Small structures = network
Quiet sun

Small structures = footpoints of the small loops that expand not higher than the transition region.

Large structures = footpoints of the large loops that reach up to the corona.

The small structures contribute more to long-wavelength emissions, and the large ones contribute more to short-wavelengths.
The rapid decrease of contribution form the large structures in FUV is associated with the sunspot darkening.

How important the CLV is?



Large contribution from the limb ring = limb brightening in the XUV/EUV.

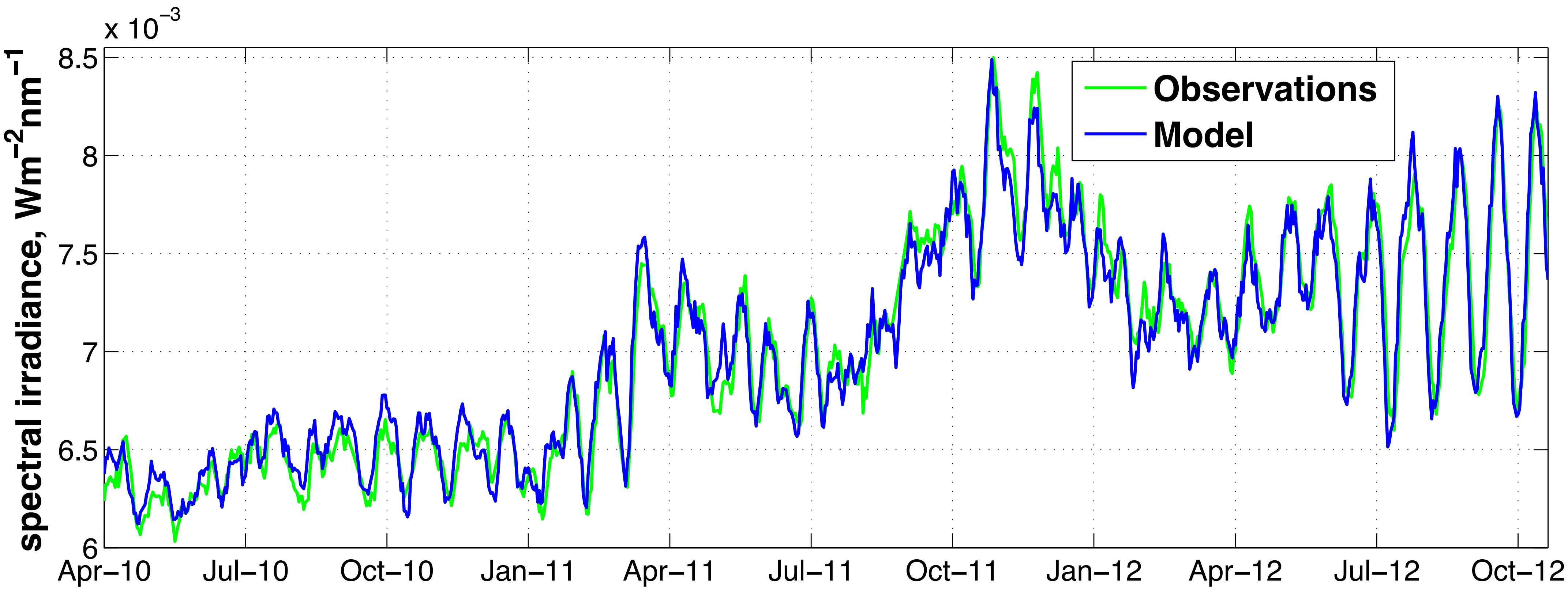
121.5 - 150 nm (FUV): weak limb darkening.

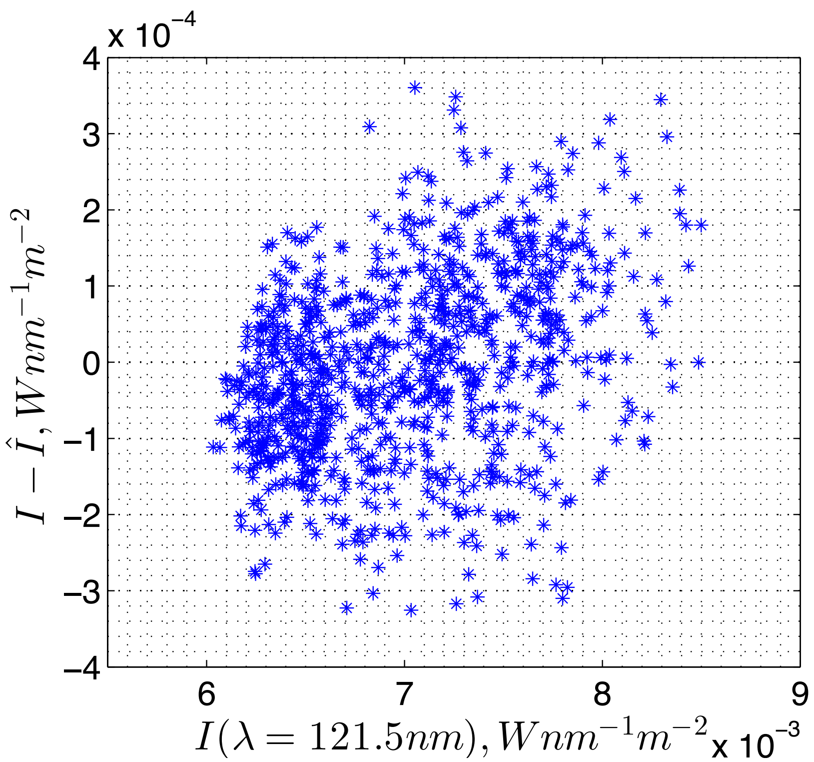
160-180 nm (FUV): strong limb darkening.

180-230 nm (FUV/MUV): weak limb brightening.

The centre-to-limb variation is of most importance for the optically thin emissions in XUV/EUV (strong limb contribution) and optically thick 160-180 nm band in FUV (strong limb darkening).

Reconstruction example: Ly-alpha line.

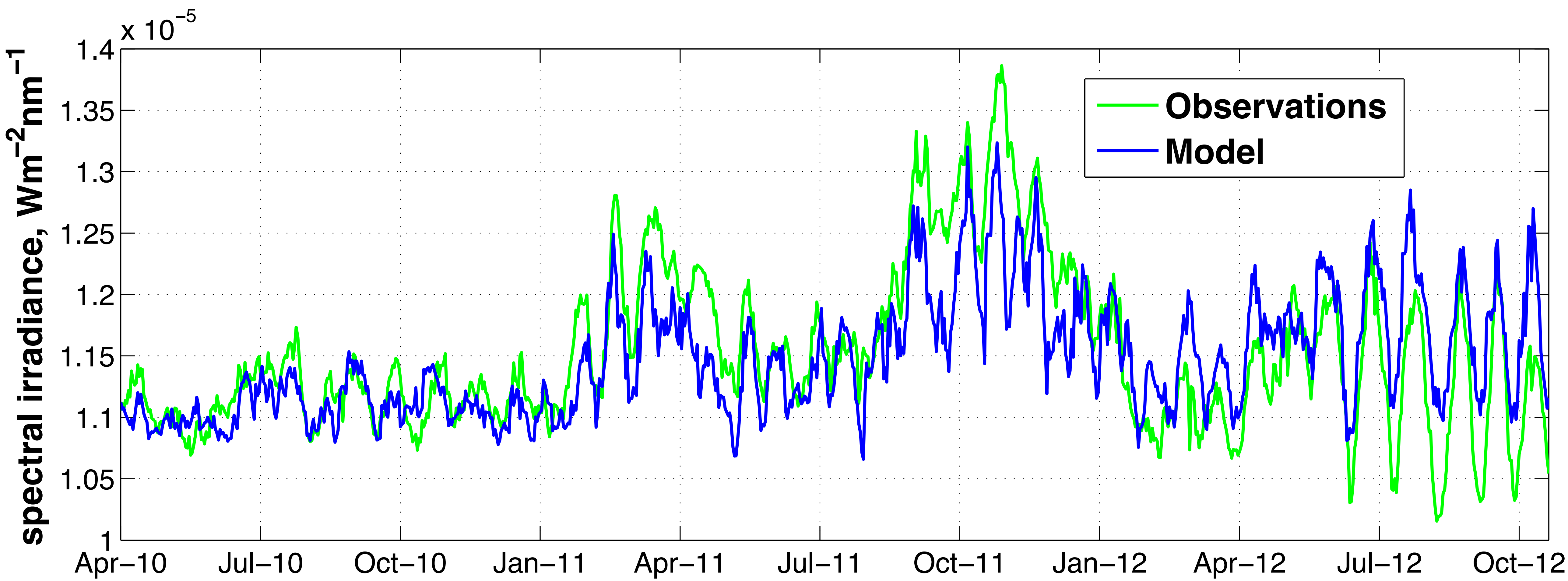




The reconstruction is visually good.

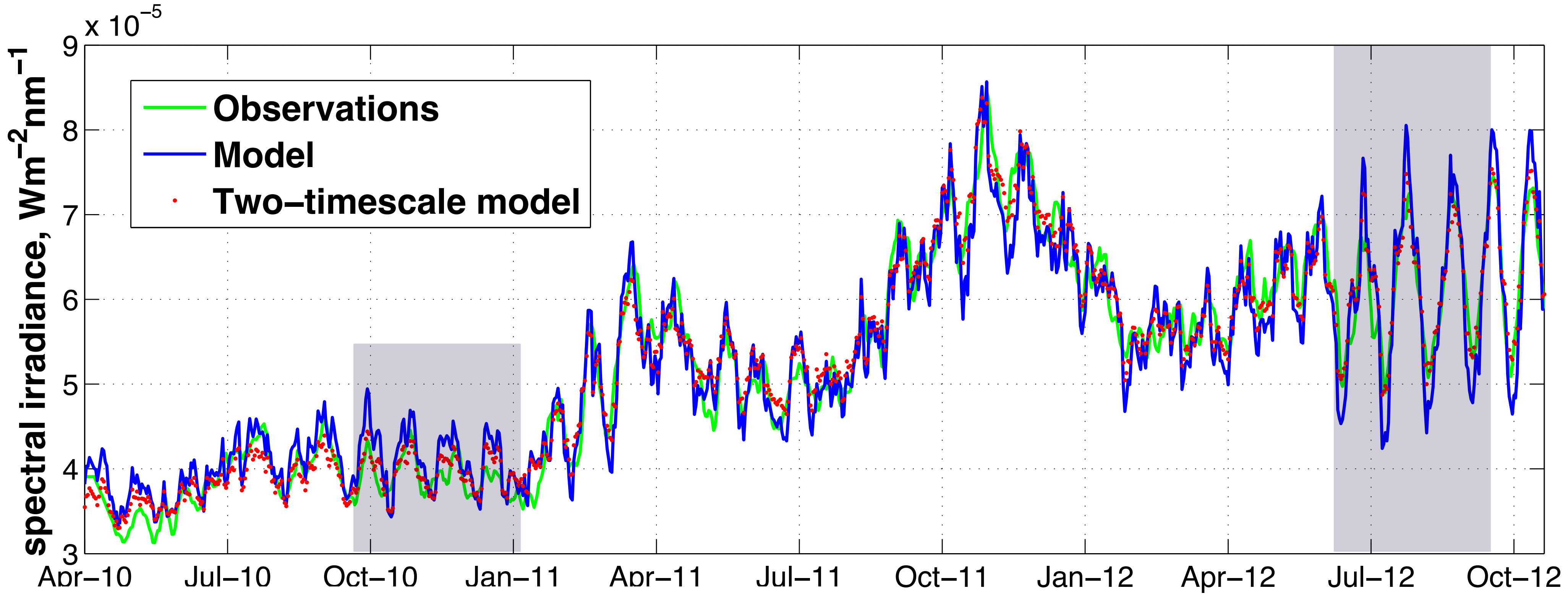
No significant patterns in the model residuals found.

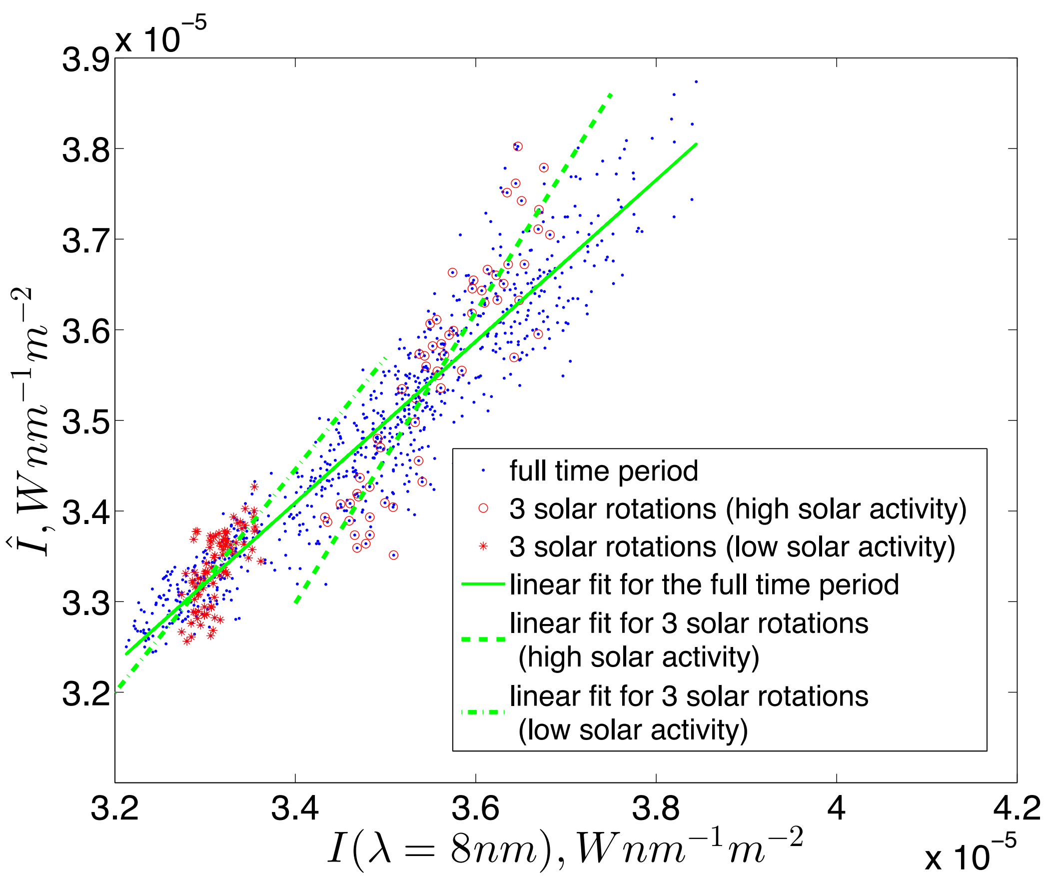
Reconstruction example: 78 nm (EUV).



The long-term trend of the observations is in antiphase with the 11-year solar cycle, which is not realistic, and, thus, can not be reproduced by the model.

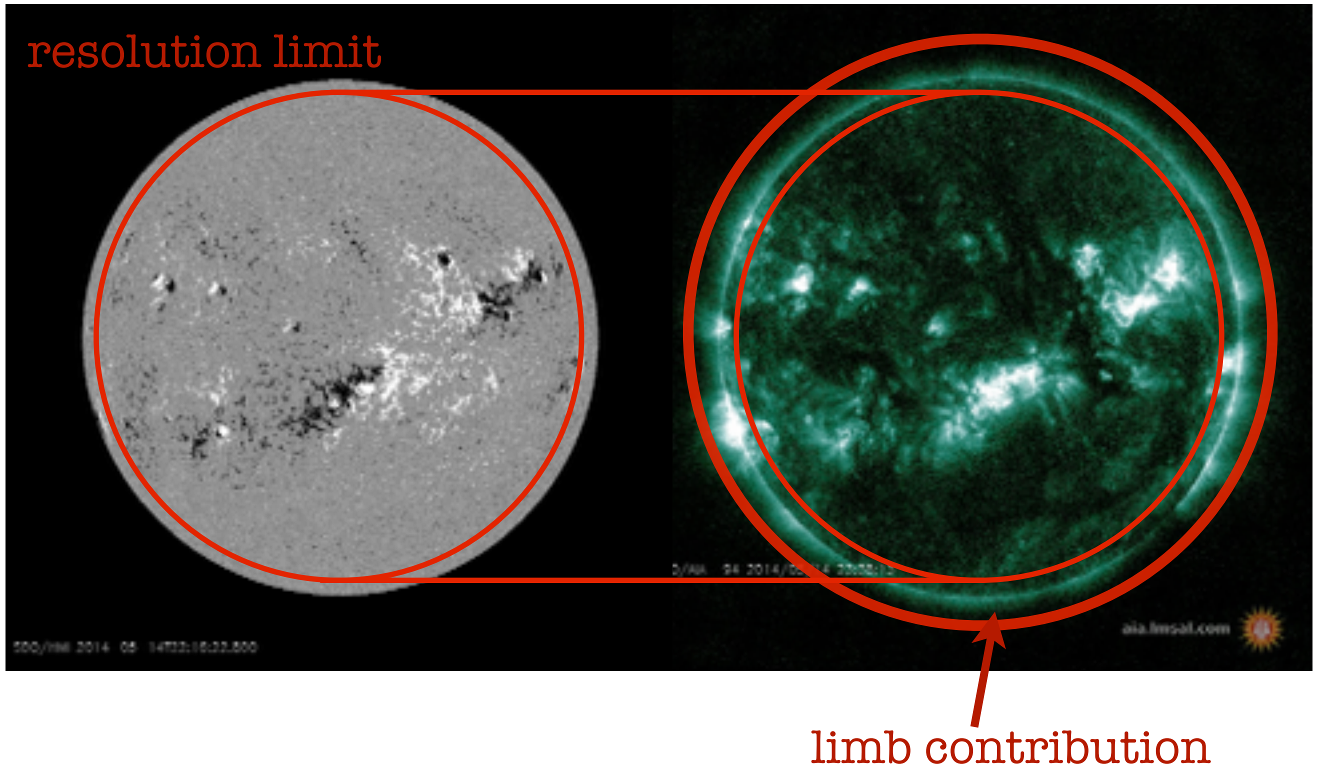
Reconstruction example: 8 nm (XUV).

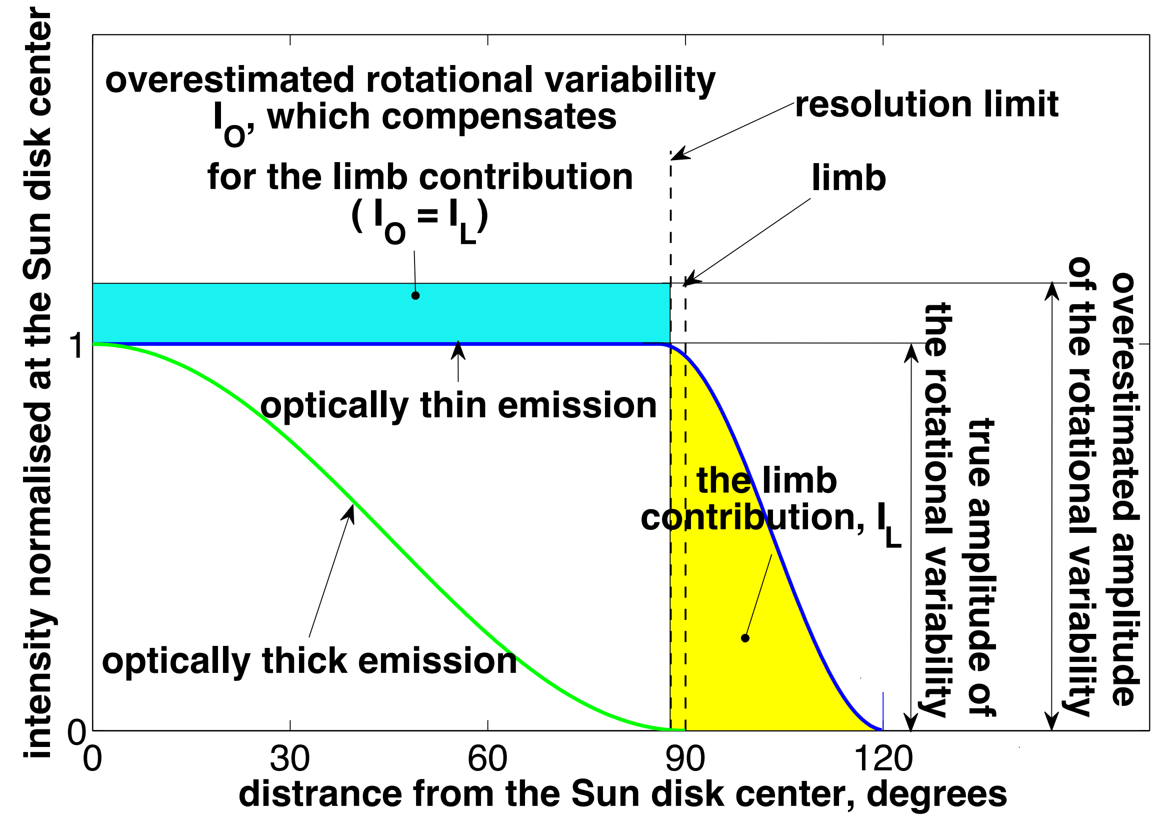


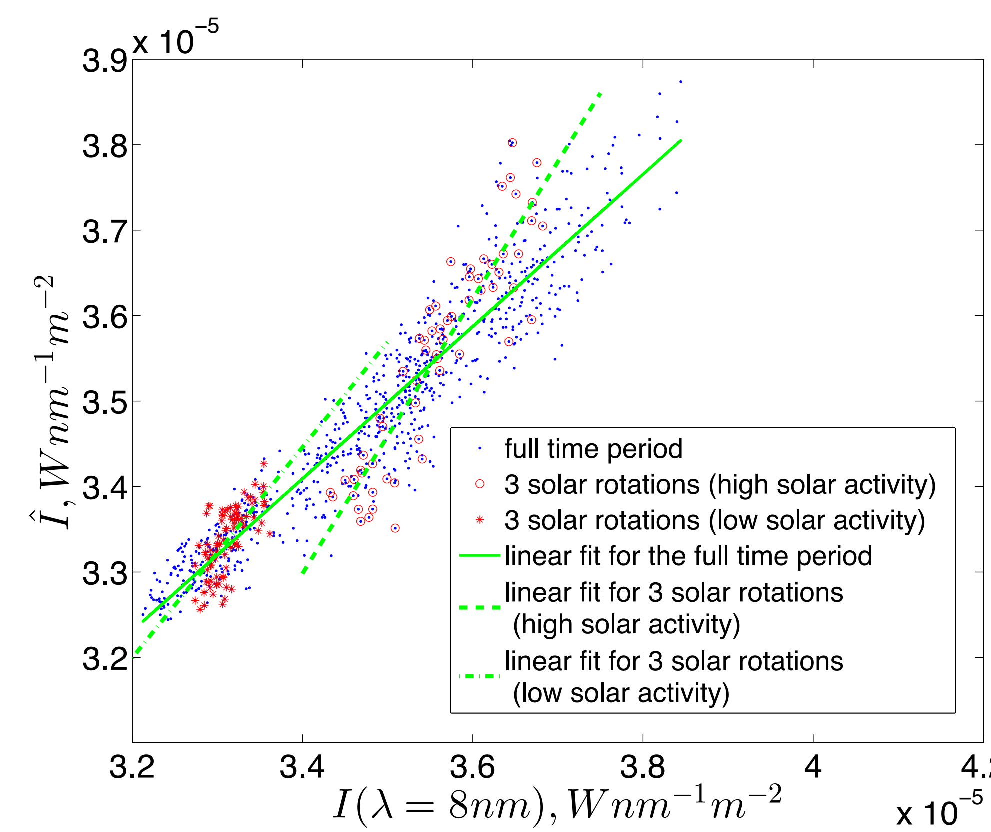


The model does not reproduce accurately the solar rotation timescale.
This suggest that the contribution of magnetic structures to the SSI variability on different timescales is not equal.

The off-limb contribution







The significant limb contribution comes from optically thin lines (XUV/EUV).

A single-timescale linear model tends to overestimate the solar rotation variability to preserve the 11-year cycle.

Two-timescales model.

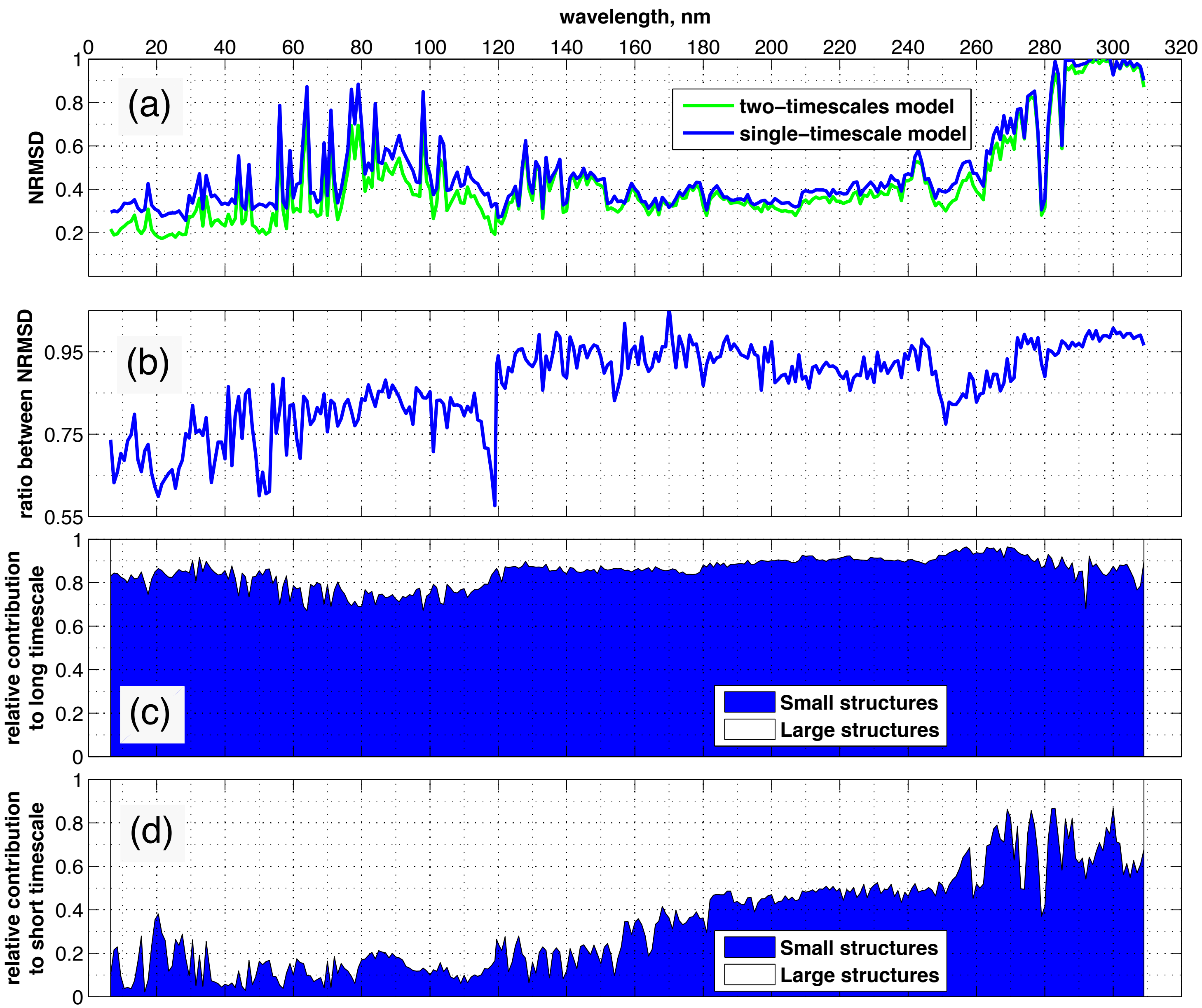
$$I(\lambda,t)=\sum_f\sum_r S_{Lf,r}(\lambda)\,F_{Lf,r}(t)+\sum_f\sum_r S_{Sf,r}(\lambda)\,F_{Sf,r}(t)+S_{QS}(\lambda)\,F_{QS}(t)+\xi(\lambda,t)$$

$$F_{f,r}(t)=F_{Lf,r}(t)+F_{Sf,r}(t)$$

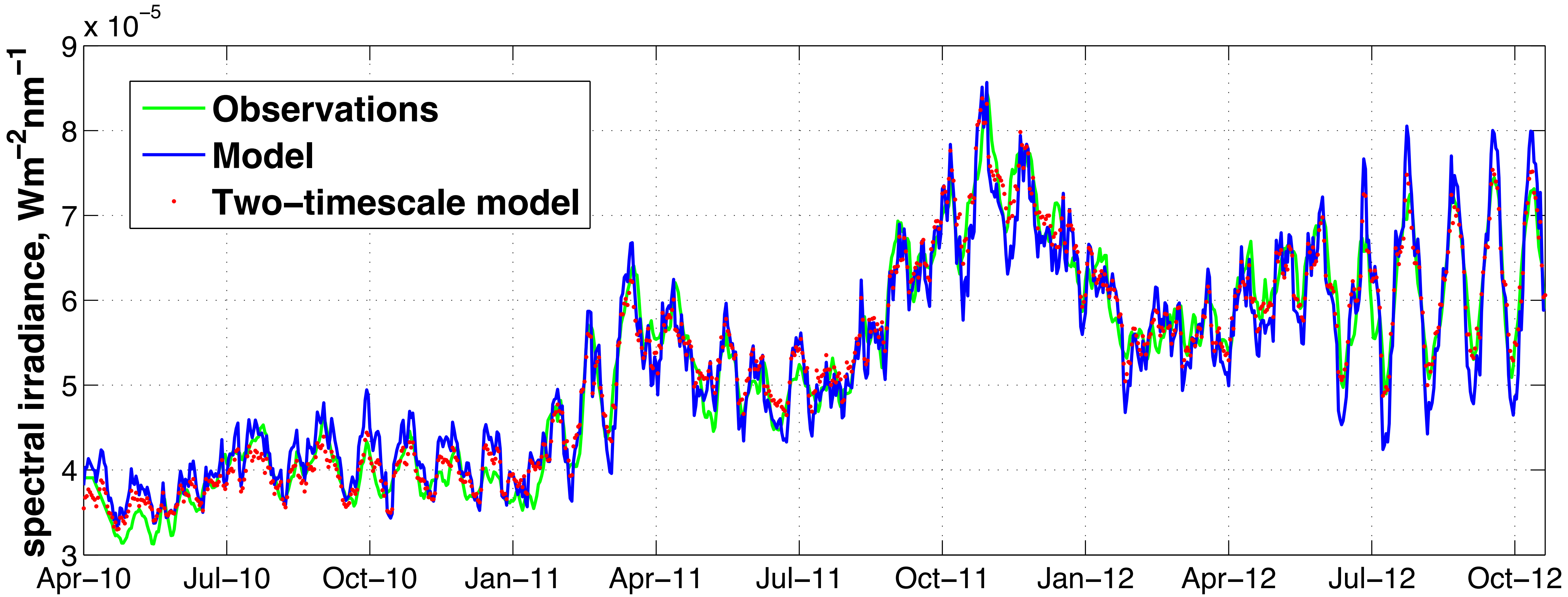
The filling factors are split into two timescales with a cut-off period of 90 days.

The long-timescale (11-year cycle) variability is dominated by the small structures.

On the contrary, the short timescale variability (solar rotation) is driven by the large structures.



Improvement example: 8 nm.



The two-timescale model reproduces solar rotation variability more accurately.

Conclusions.

- We find 3 principal classes of magnetic structures (large magnetic structures ≈ faculae, small magnetic structures ≈ active network, and the quiet Sun) that suffice to reconstruct up to 80% the SSI variability in the UV.

- Large magnetic structures have size greater than 512'' x 512''.

- Small magnetic structures have size from 32'' x 32'' to 512'' x 512 ''.

- Small magnetic structures contribute more to emissions from the chromosphere and photosphere.

- Large magnetic structures contribute more to coronal emissions.

- Centre-to-limb variation plays significant role for MUV/FUV emissions in range from 170 to 265 nm and in the XUV/EUV.

- A two-timescale model is needed to reproduce accurately optically thin emissions in XUV/EUV due to the off-limb contribution.

- Small structures are important to properly reproduce the 11-year cycle, whereas the large structures are of importance for the solar rotation variability.


See Vuiets et al., 2014, submitted to A&A
Thank you!