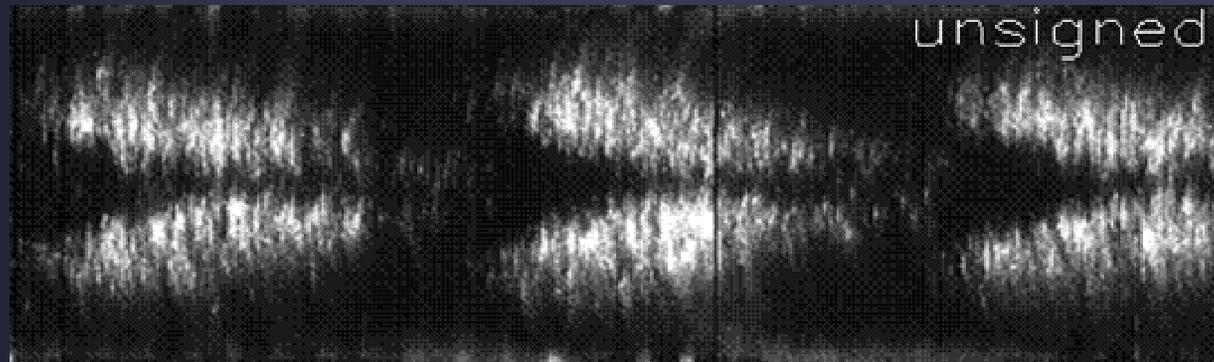


Surface magnetic field-based irradiance models



Sami K. Solanki



Max-Planck-Institut for Solar System Research,
Katlenburg-Lindau, Germany

Why bother? To answer the most pressing questions raised in the media!

BILD beantwortet die wichtigsten Fragen zum Sommer

Ist die Sonne stärker als früher?

Autsch! Dieses Foto tut schon beim Anschauen weh. Gastwirt Paul Witwicki (55) aus Fürth (Bayern) saß drei Stunden in der prallen Sonne. „Ich hatte mich zwar eingecremt, sah danach aber aus wie ein Krebs!“ Die wichtigsten Fragen zum Hitze-Sommer – BILD beantwortet sie.

● Ist die Sonne heute stärker als früher? Sami K. Solanki (48), Max-Planck-Insti-

verbrennen? Prof. Dr. Eggert Stockfleth (43), Berliner Charité: „Ja! Bis zu 50 Prozent der UV-Strahlen werden durch Staub und Luftteilchen dorthin reflektiert.“

● Kann die Sonne auch durch ein T-Shirt die Haut verbrennen? Prof. Stockfleth: „Nein, Kleidung blockt sie ab.“

● Muss man sich 30 Minuten vorher eincremen? Britta Klebon (40), L’Oreal-For-

● Macht nacktes Radfahren

● Darf ich mit Flipflops Auto fahren? Versicherungsexpertin Katrin Rüter de Escobar (42): „Ja. Bei Unfällen zahlt die Versicherung unabhängig vom Schuhwerk.“

● Geht mein Handy in der prallen Sonne kaputt? Christina Bohlmann (38), NO-KIA: „Ja. Hohe Temperaturen können die Lebensdauer des Gerätes verkürzen, Akkus beschädigen, Kunststoffteile verformen.“

arbeiter sorgen. Z. B. mit einer längeren Mittagspause.“

● Was tun, wenn ich meinen Chef beim FKK treffe? Jan Schaumann (38), Stiltrainer: „Freundlich begrüßen, ein paar unverfängliche Worte wechseln. Und nicht auf intime Stellen starren!“

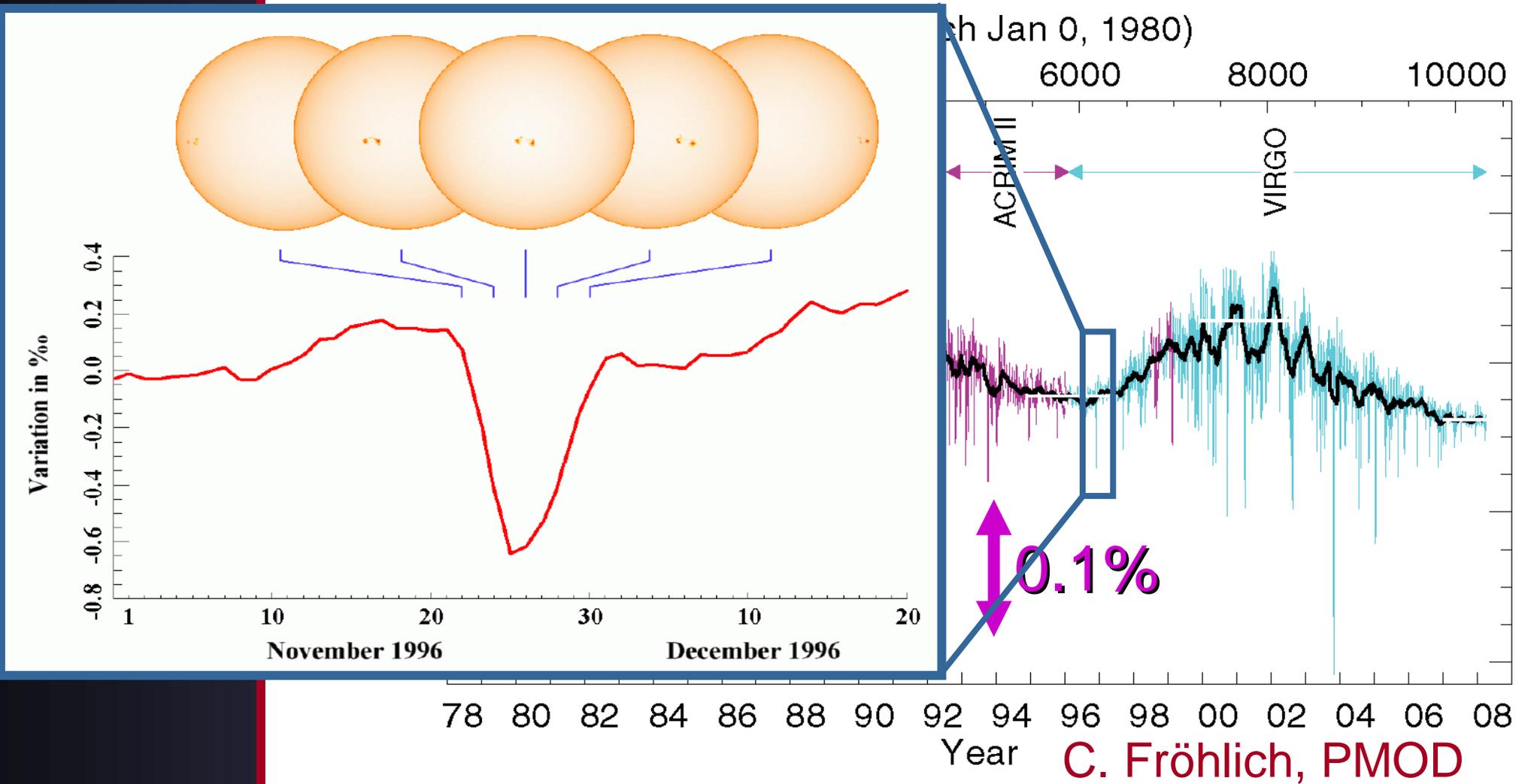
● Wie lange kann ich den Hund im Auto lassen? Dr. Jan Groth (49), Tierarzt: „Bei über 25 Grad

Trotz Sonnenschutzes hat sich Paul Witwicki (55) aus Fürth Bauch und Brust verbrannt. „Ich saß drei Stunden in der Sonne, hab immer wieder nachgcremt“, sagt er. Ein Bekannter fotografierte

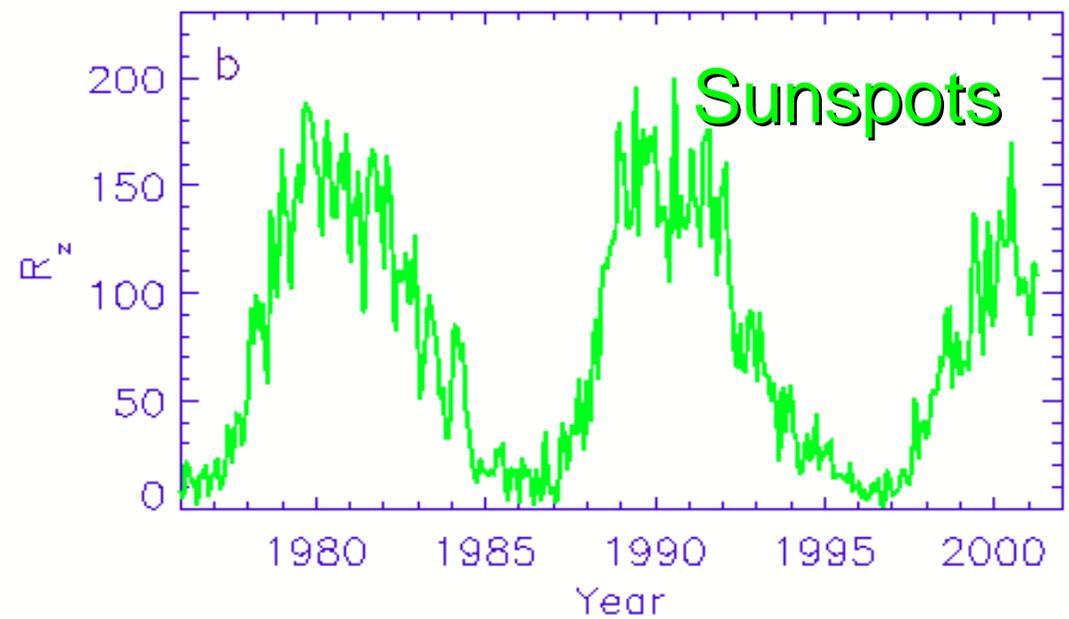
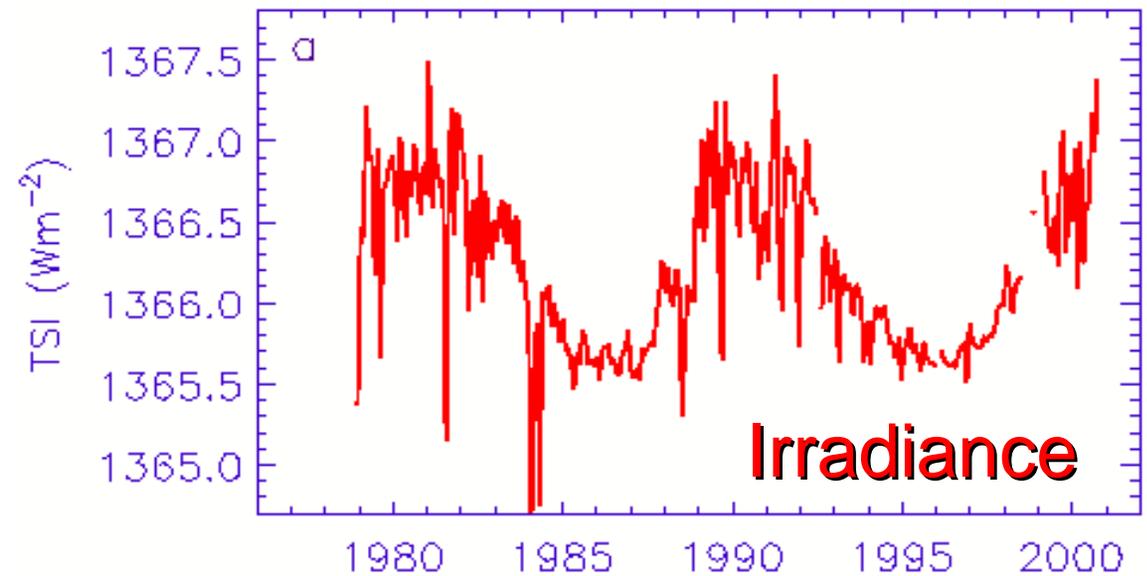
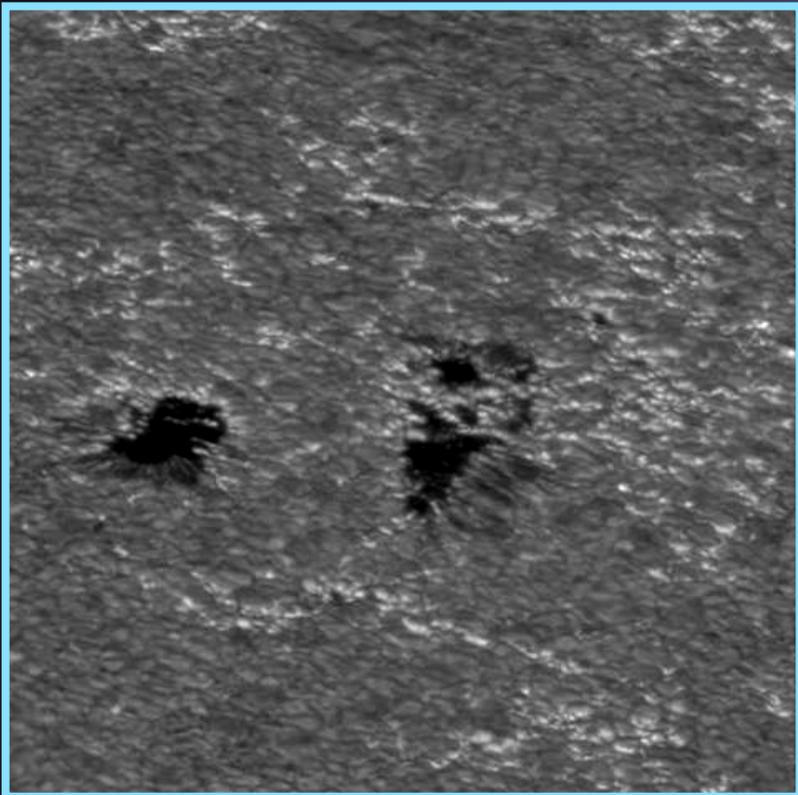


Darin

Measured total irradiance: sunspots

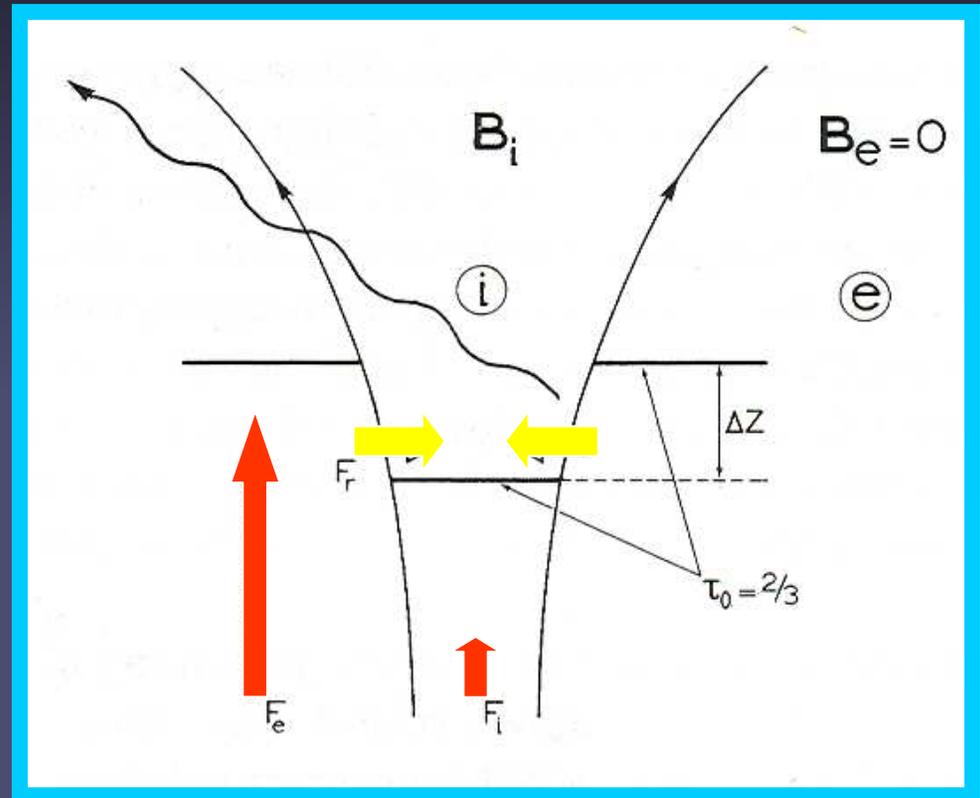


Importance of faculae



Influence of magnetic features in photosphere on energy flux

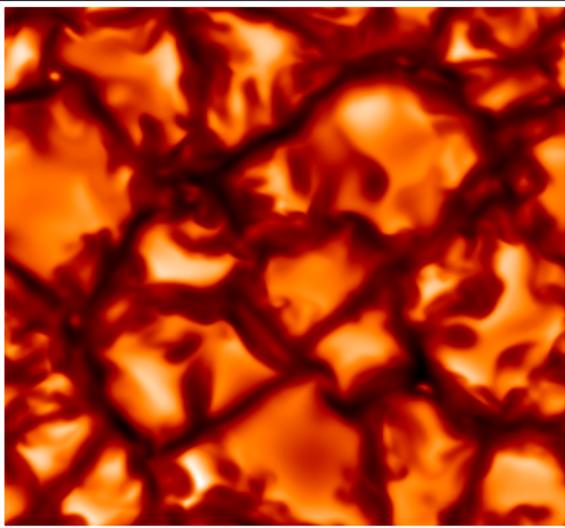
- **Sunspots:** B in spot **blocks energy transport**. Blocked energy is distributed over CZ on convective time scale (\approx month). Stored energy is released over 10^5 years on thermal equilibrium time scale (Spruit 1982) \rightarrow only weak bright rings around spots (Waldmeier 1938; Rast et al. 01)



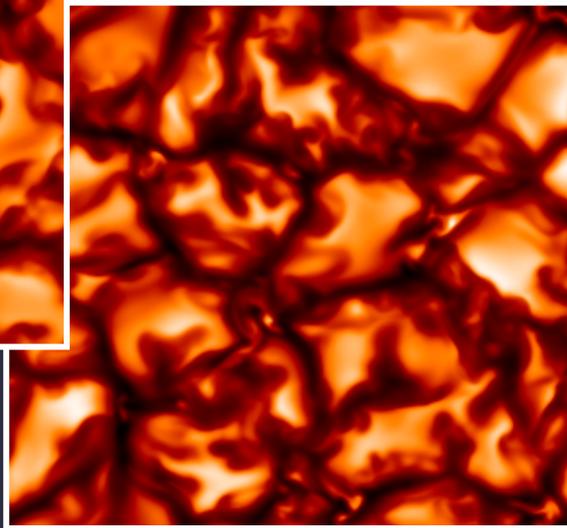
- **Faculae:** Faculae **increase solar surface area** (via Wilson depression) \rightarrow enhanced emission. Excess flux taken from CZ on convective time scale (Spruit 1976; Deinzer et al. 1984)

MHD simulations: from quiet Sun to strong plage

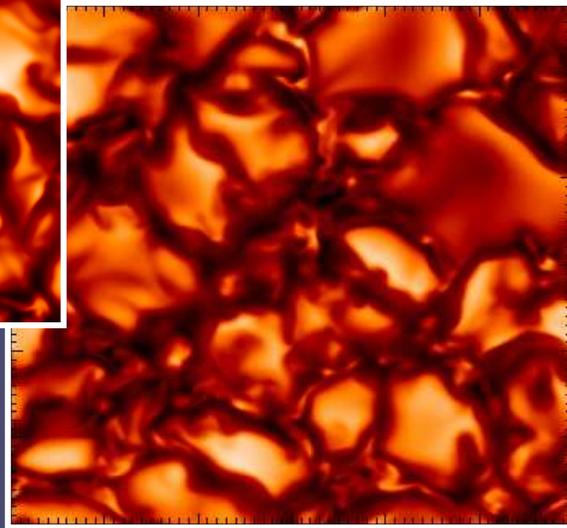
0 G



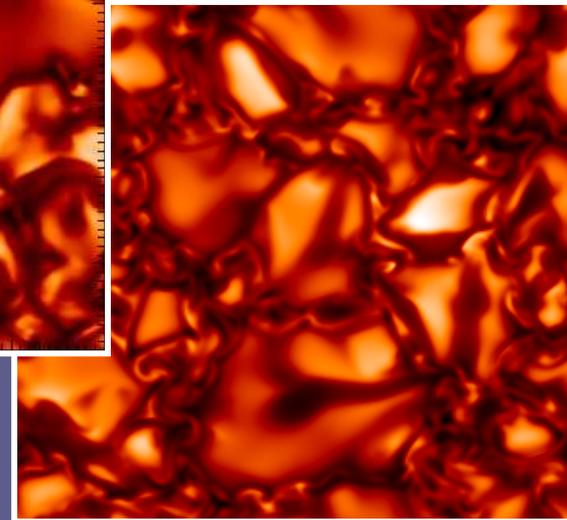
50 G



200 G



400 G



Vögler et al. 2005

6000x6000x1400 km box,
20km grid

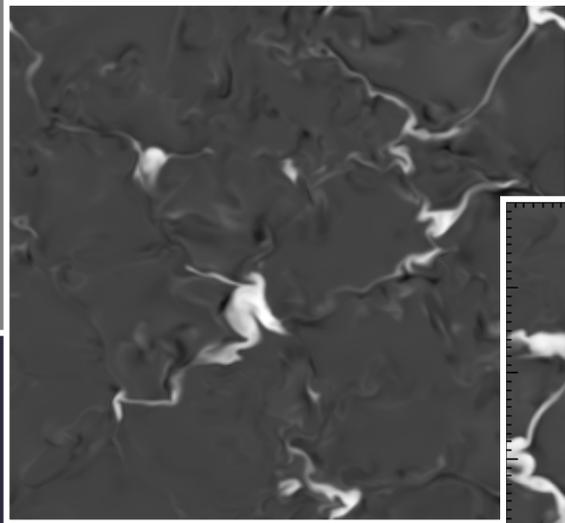
Radiation MHD simulations of solar surface layers. Open lower boundary with fixed value of entropy for bottom inflow (i.e. assume irradiance changes in surface layers)

MHD simulations: from quiet Sun to strong plage

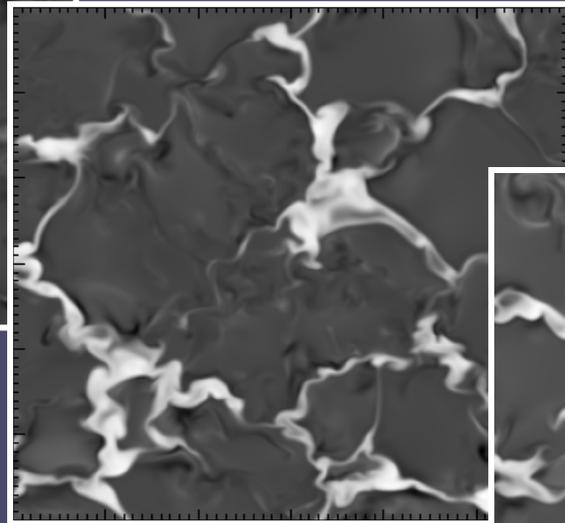
0 G



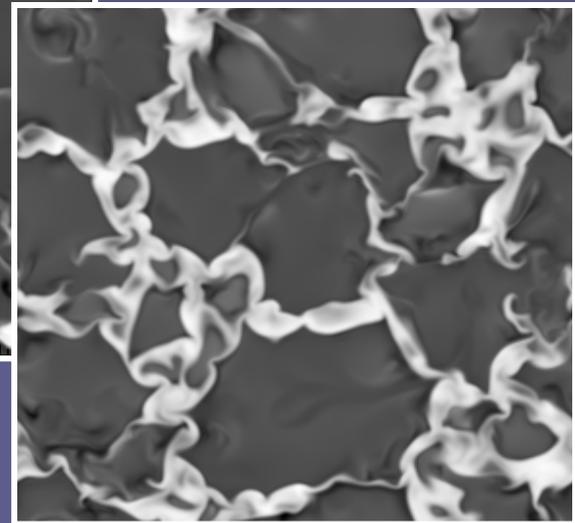
50 G



200 G



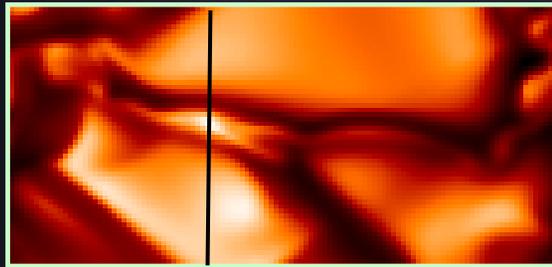
400 G



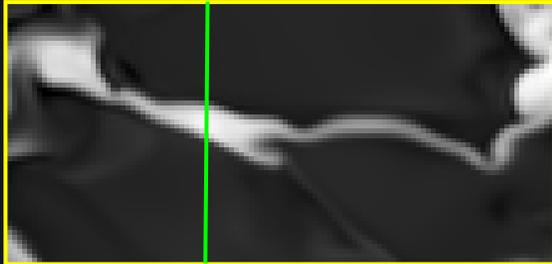
Magnetic field



Vertical cut through a sheet-like structure



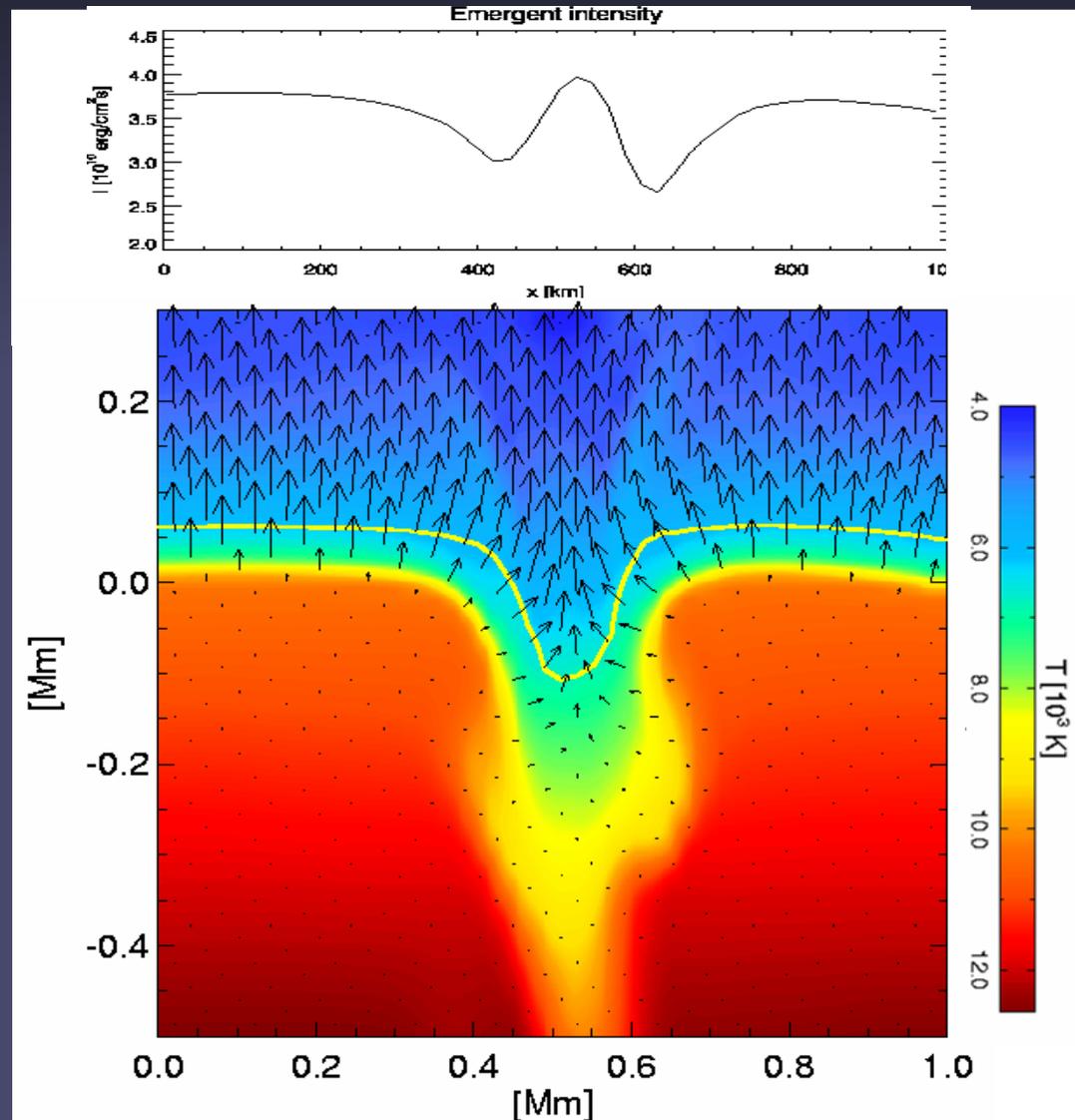
I



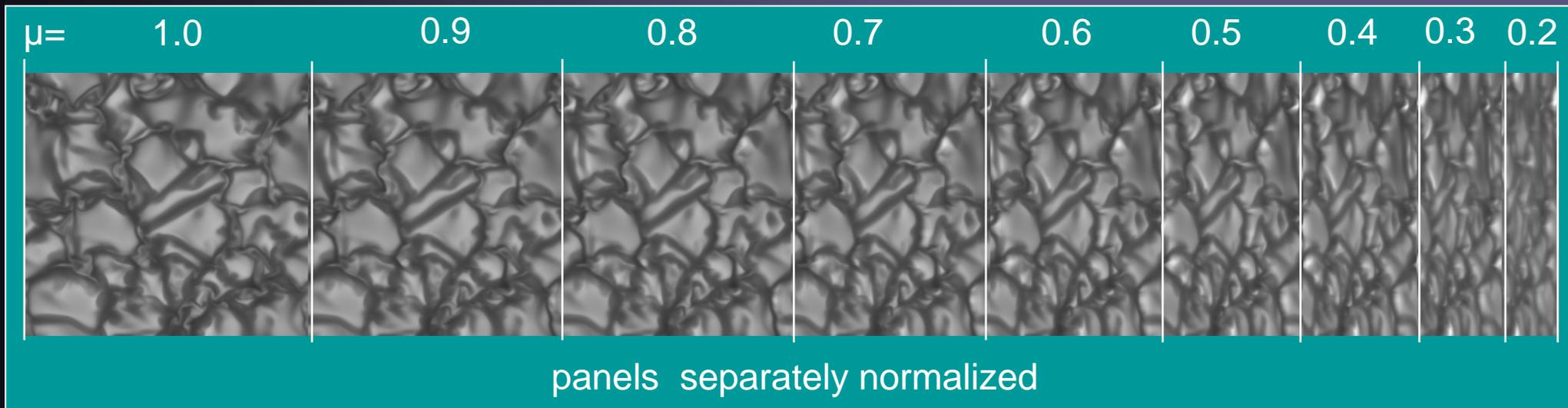
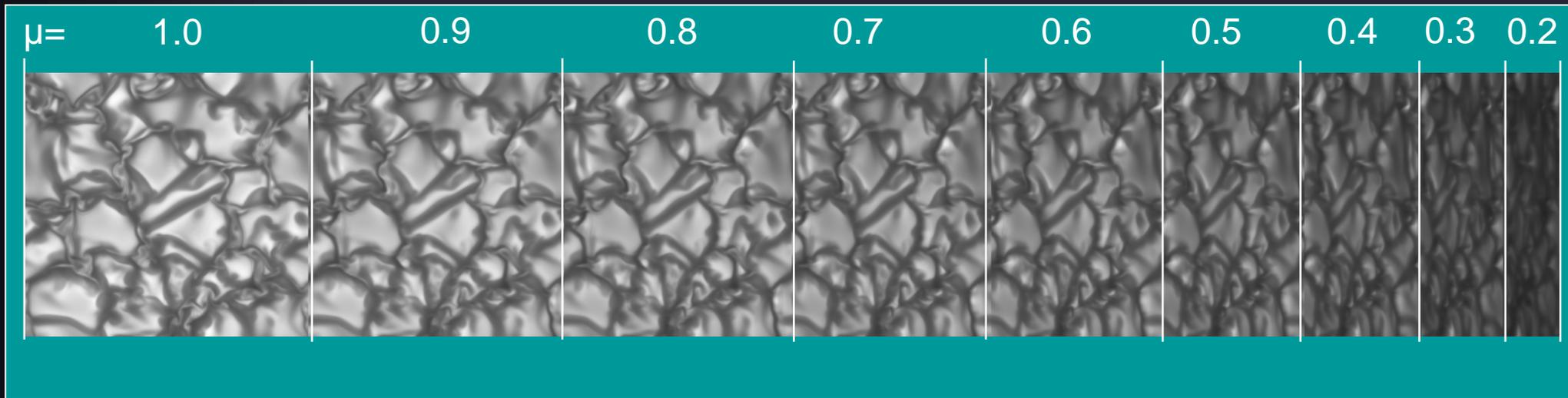
B_z

- partial evacuation leads to a depression of the $\tau=1$ level
- lateral heating from hot walls (Spruit 1976)
- ➔ Brightness enhancement of small structures

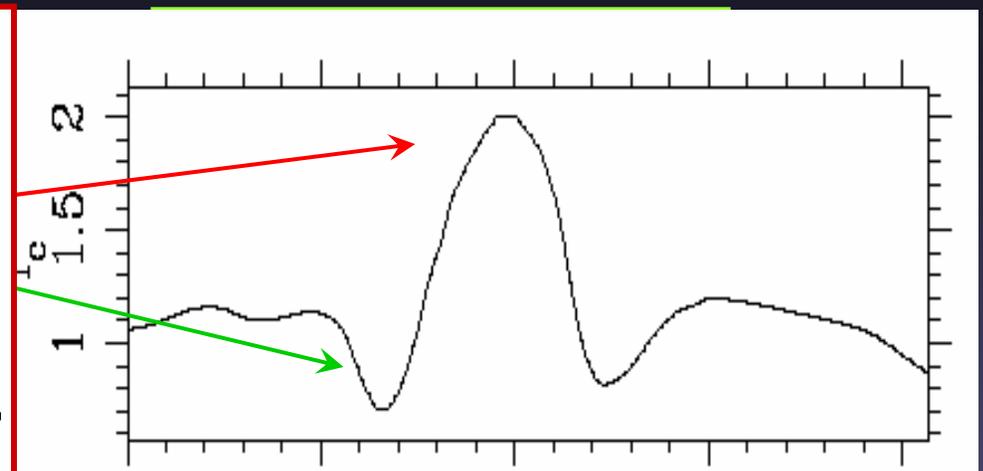
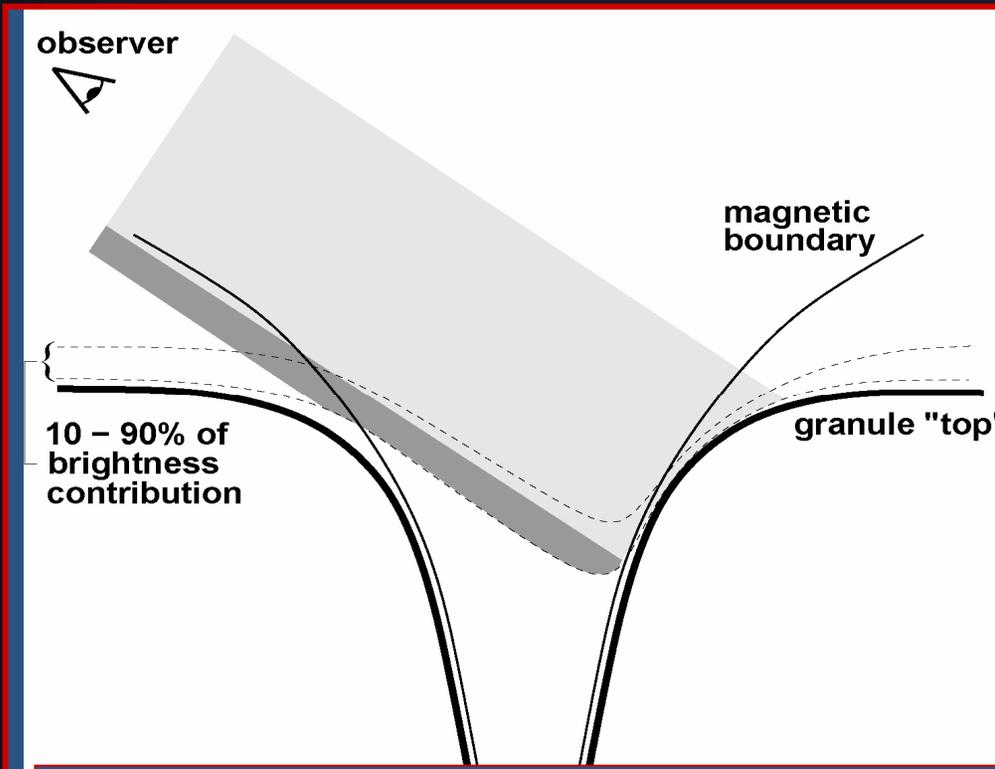
Radiation flux vectors & temperature



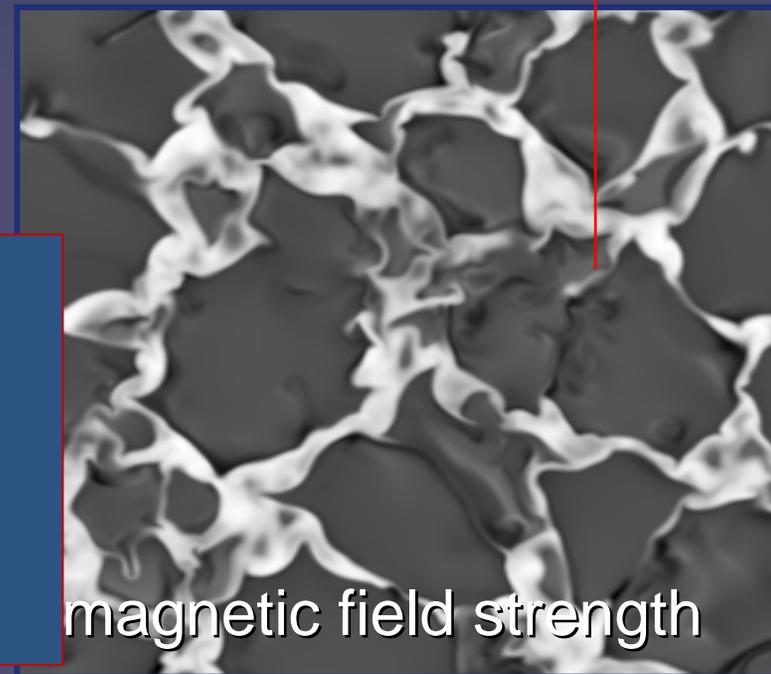
$B_0=200$ G: CLV of wavelength-integrated brightness



Facular brightening



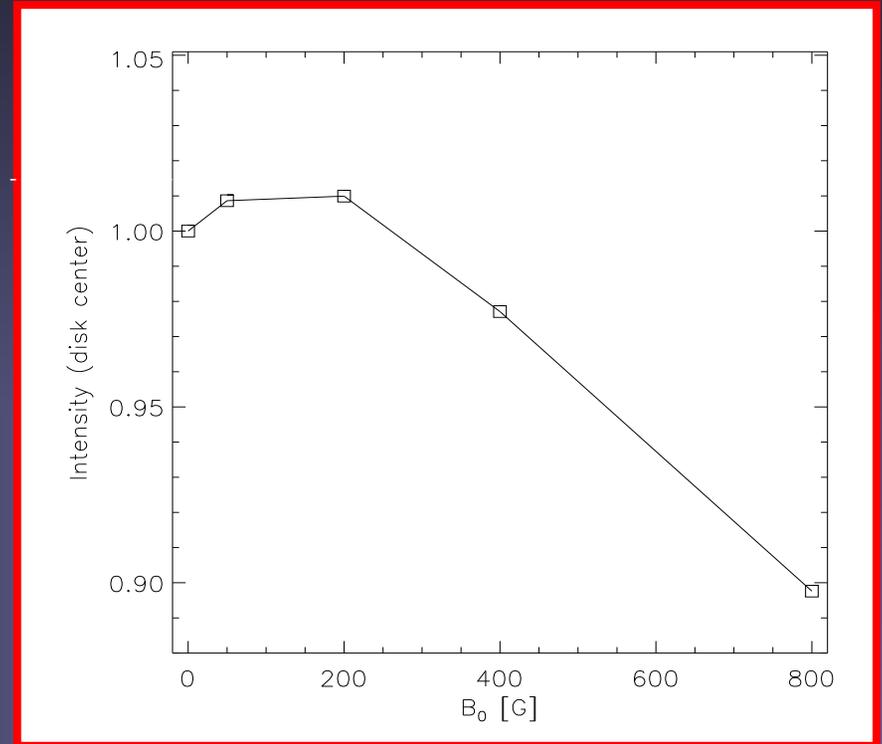
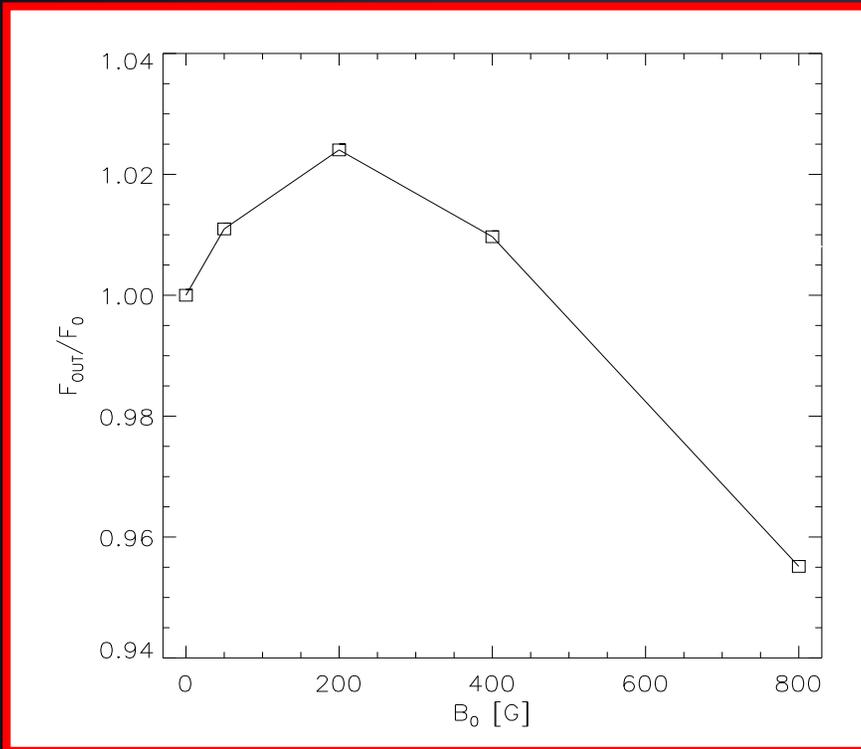
- Facula:** narrow layer of hot material on side and top of adjacent granule
- Dark lane:**
- cool & tenuous material in adjacent flux concentration
 - cool & dense material above neighbouring granule



(Keller et al. 2004)

From quiet Sun to strong plage

Photometric properties (normalized to case $B_0=0$)

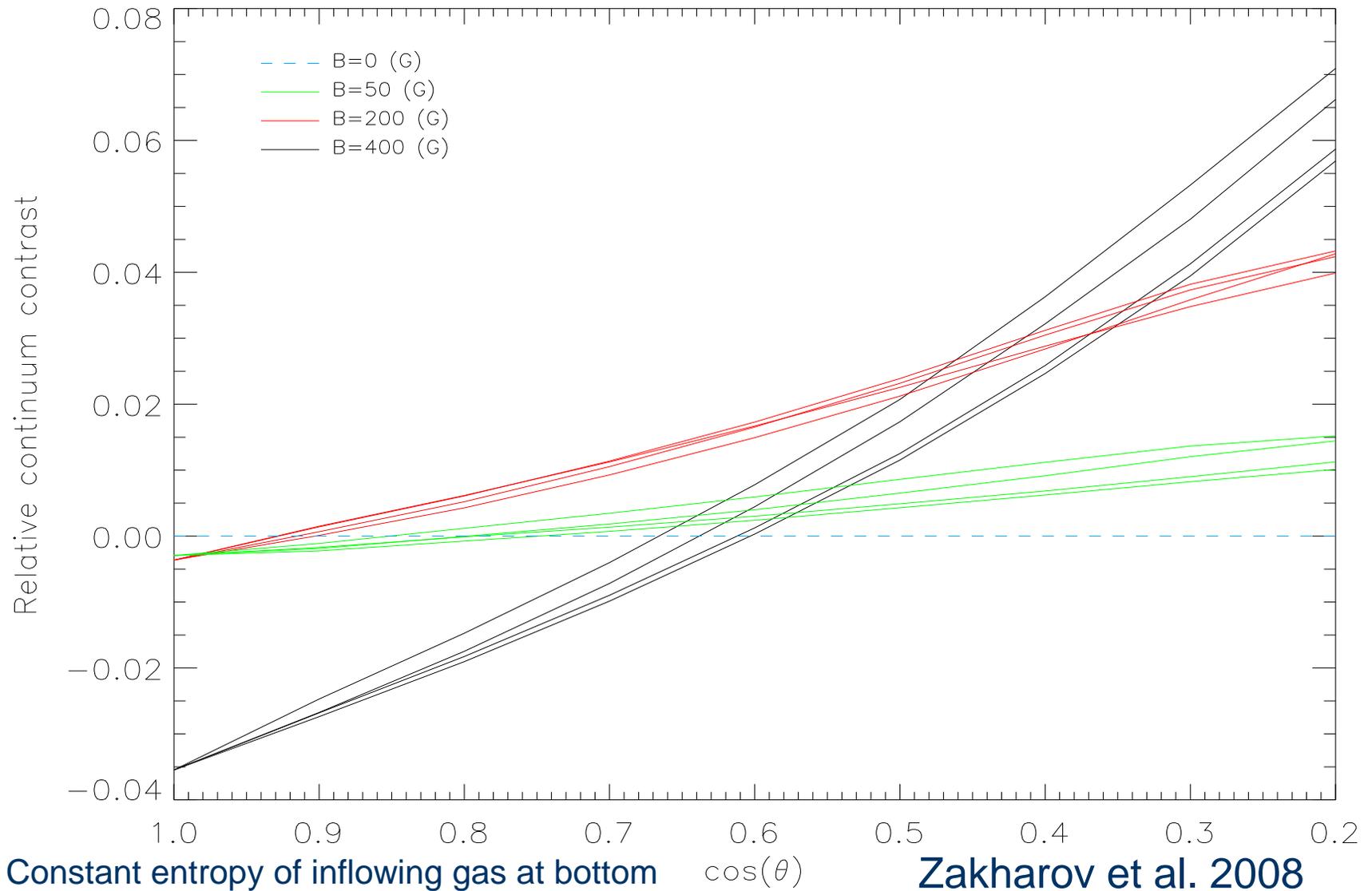


Total emerging energy flux

Mean disk center λ -integrated intensity

Constant entropy of inflowing gas at the bottom

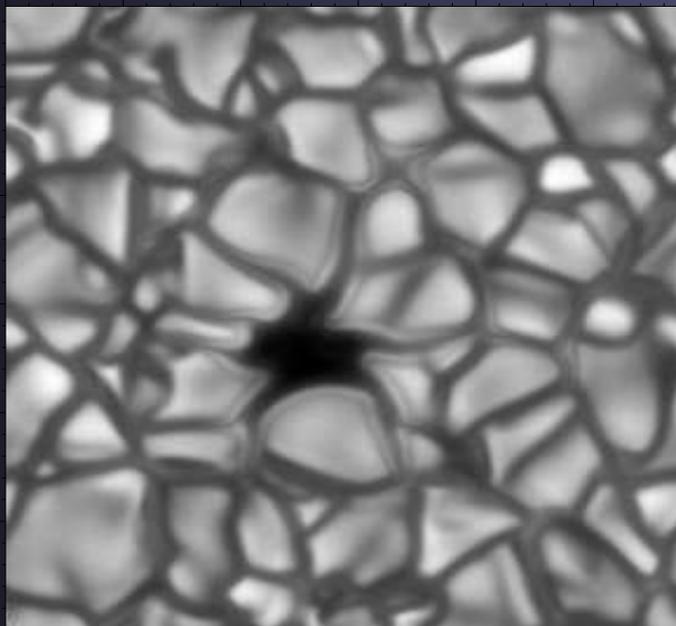
CLV of continuum intensity at 676.8 nm



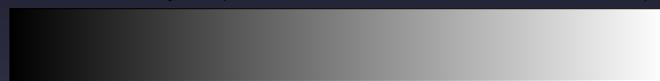
Pore simulation: brightening near the limb

Pore appears brighter near limb due to Wilson depression: hot walls become visible, dark bottom is hidden

$\mu=1$

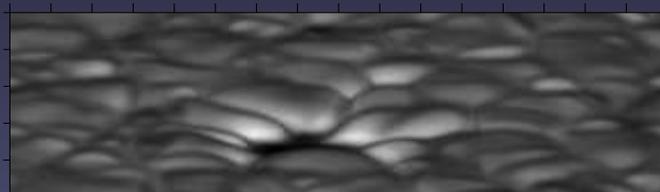


Intensity (normalized, 500nm)

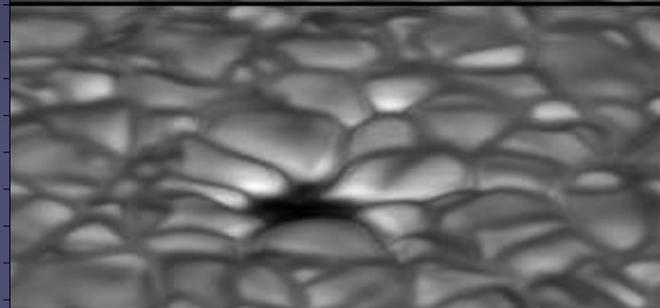


0.2 0.4 0.6 0.8 1.0 1.2 1.4

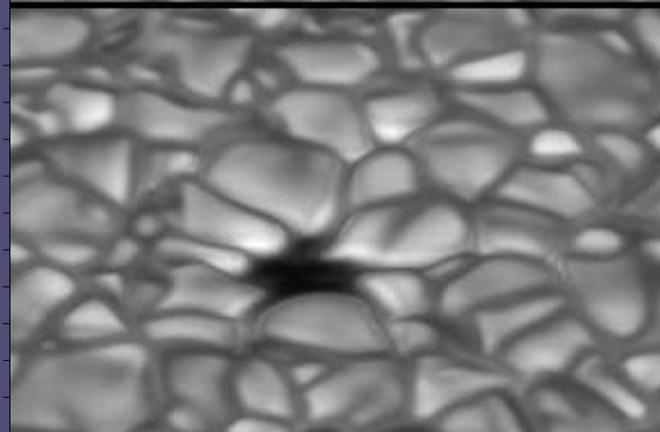
$\mu=0.3$



$\mu=0.5$



$\mu=0.7$



1''

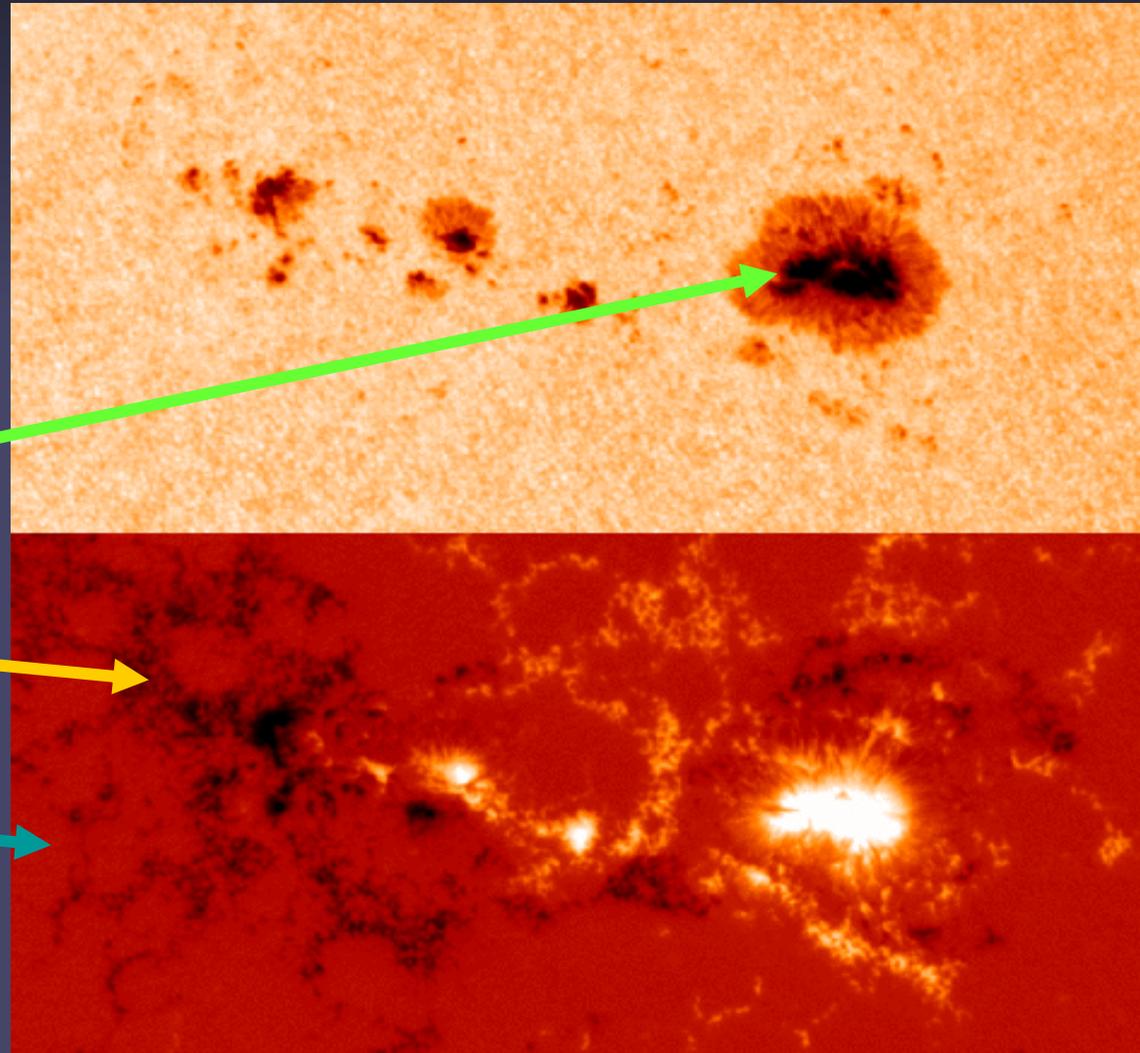
SATIRE: Spectral And Total Irradiance REconstruction

Semi-empirical model
with main assumption:
B-field at solar surface
causes TSI + SSI
variations in UV,vis,IR

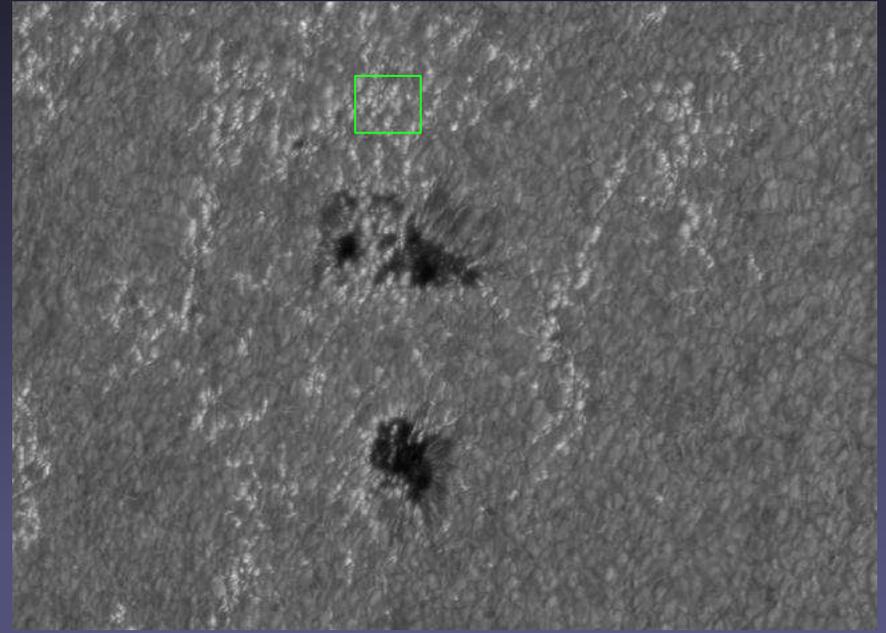
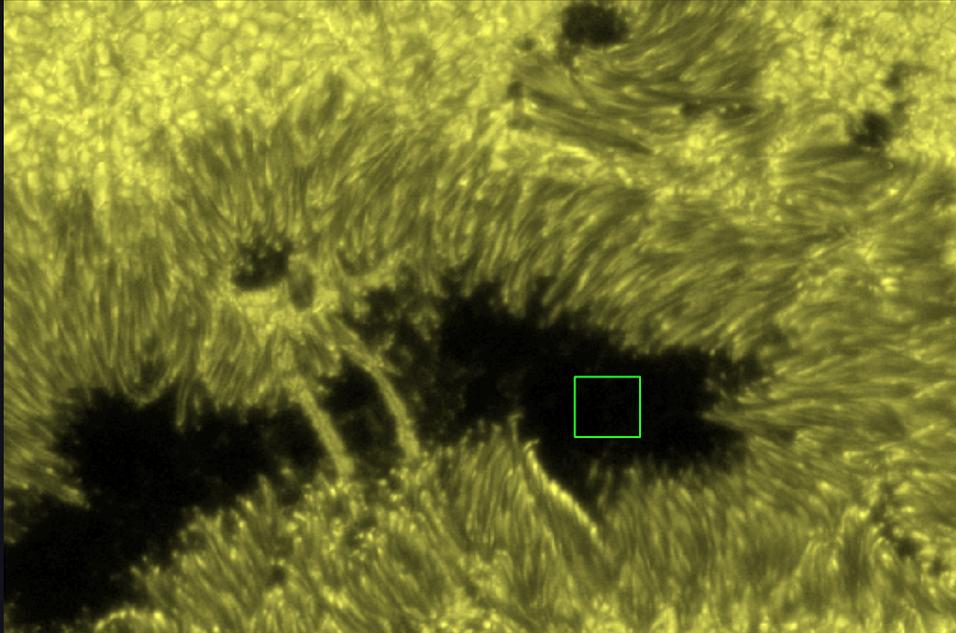
Components: Spots
(contin. images),
faculae + network
(magnetograms), quiet
Sun

Model atmospheres

1 free parameter

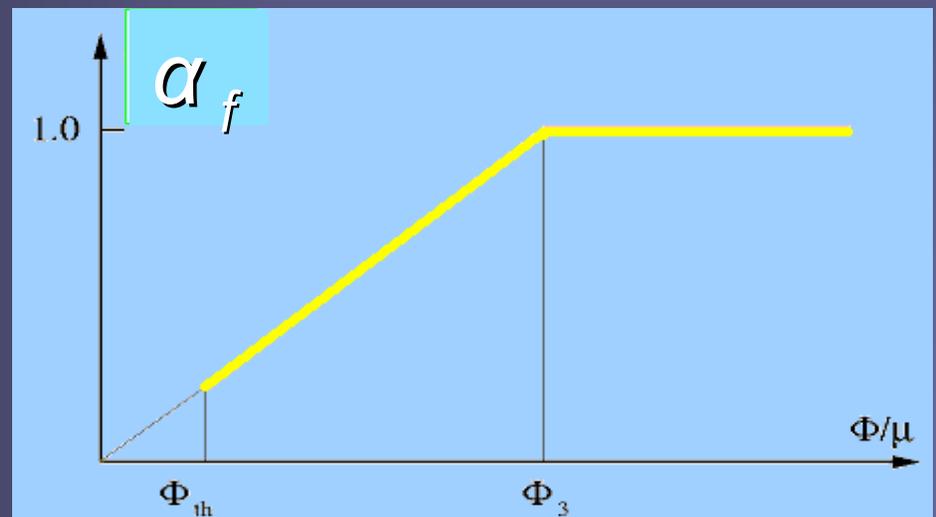


Filling Factors

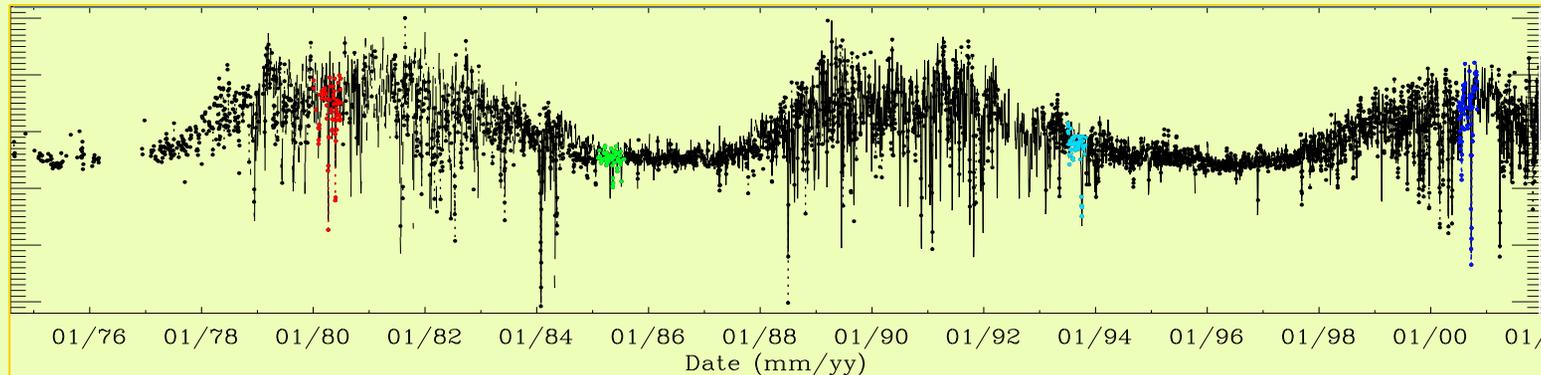


$$\alpha_s = 1 \text{ (or } 0)$$

$$\alpha_q = 1 - \alpha_s - \alpha_f$$

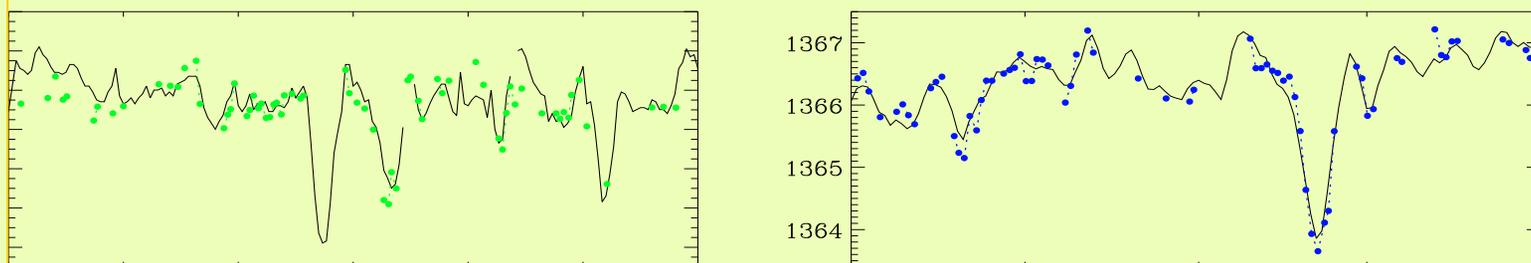


SATIRE TSI vs. PMOD composite



>90% of solar irradiance variations on time scales days to solar cycle caused by surface magnetism.

Caveat: There is a free parameter in the model



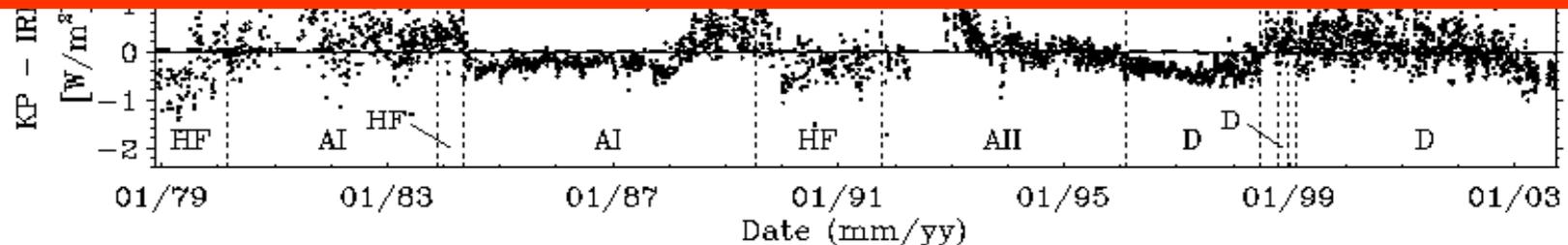
Wenzler et al. 2006, A&A

What about other TSI composites?

- 3 composites available: PMOD (Fröhlich), ACRIM (Willson), IRMB (DeWitte et al.).
- Differ in employed data sets + corrections: trends

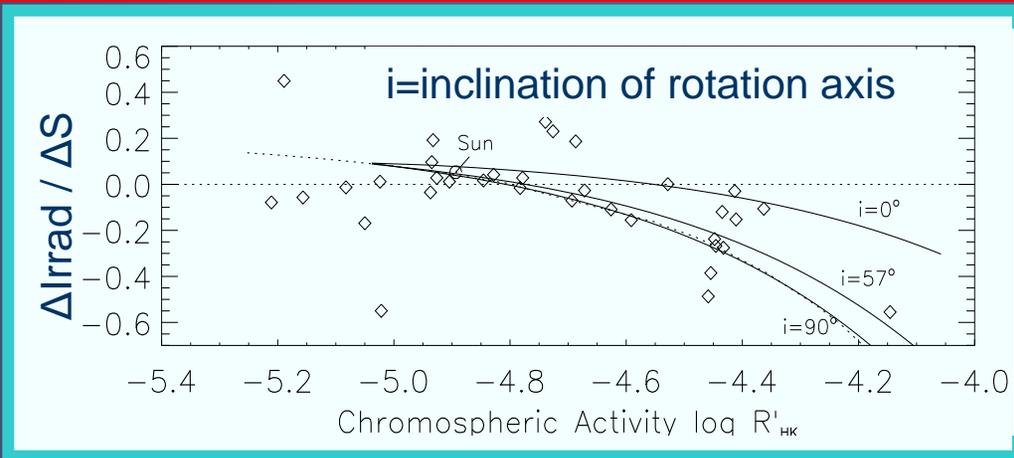
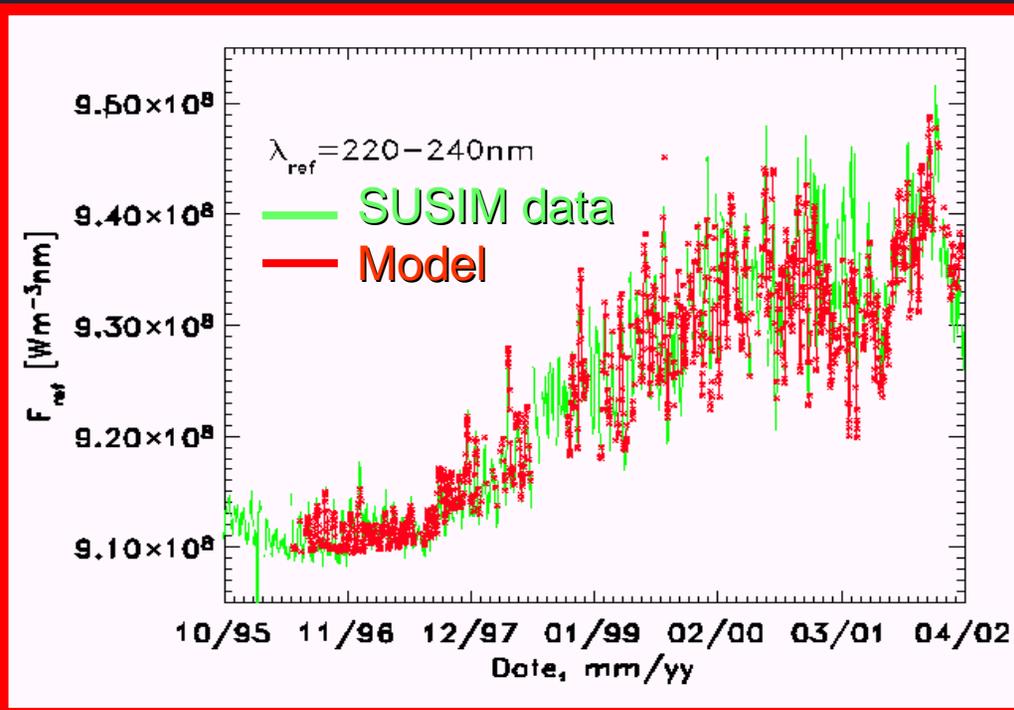


SATIRE model gives best agreement with Fröhlich's TSI composite. Thus, if another composite, e.g. of Willson, were to be correct, then the secular trend present in that composite cannot be caused by surface magnetic fields.

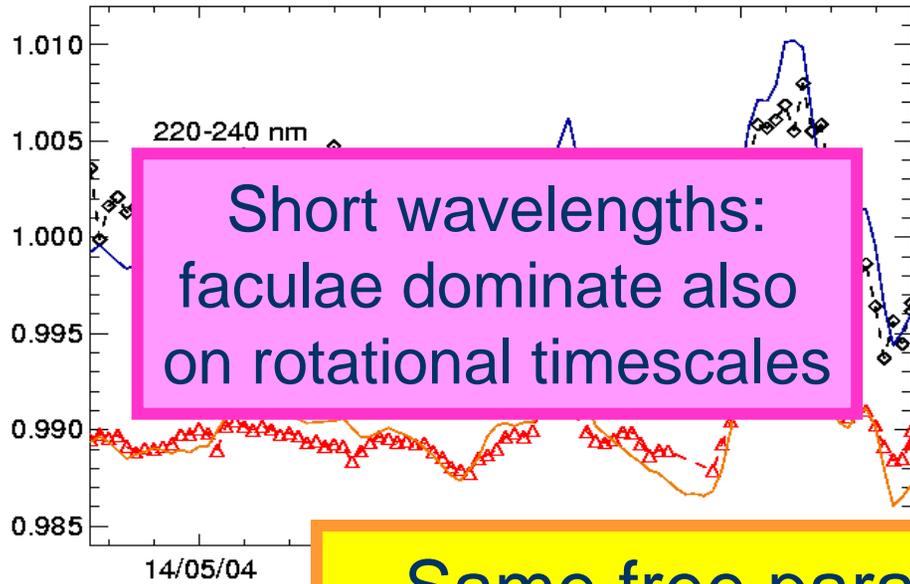


Further Applications of SATIRE

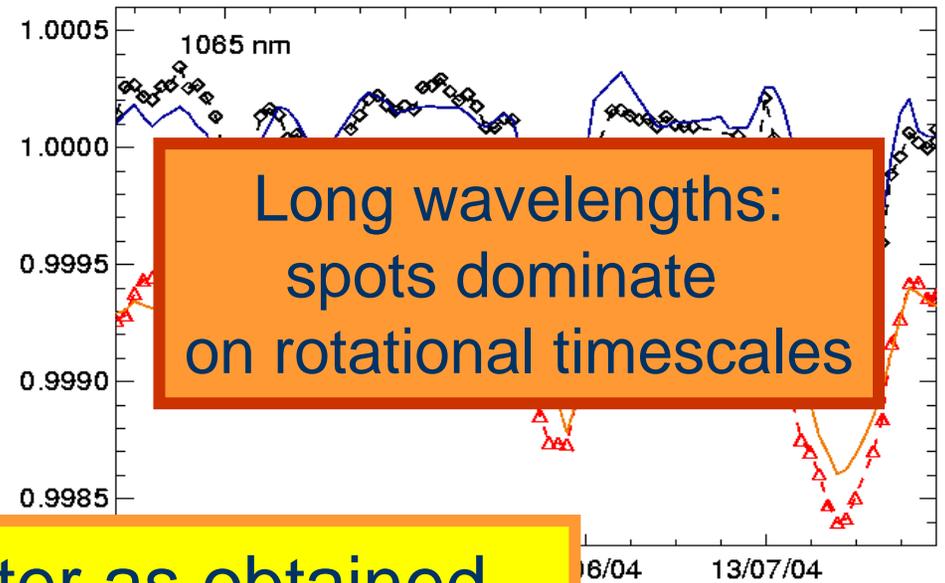
- SATIRE also reproduces, spectral irradiance changes over time (Krivova et al. 06, 08; Unruh et al. 99, 08), and variation of spectral lines over solar cycle (Danilovic et al. 2008) with same value of free parameter!
- Same model also reproduces the change from facular to spot dominated irradiance variations with increasing stellar activity (Knaack et al. 2008)



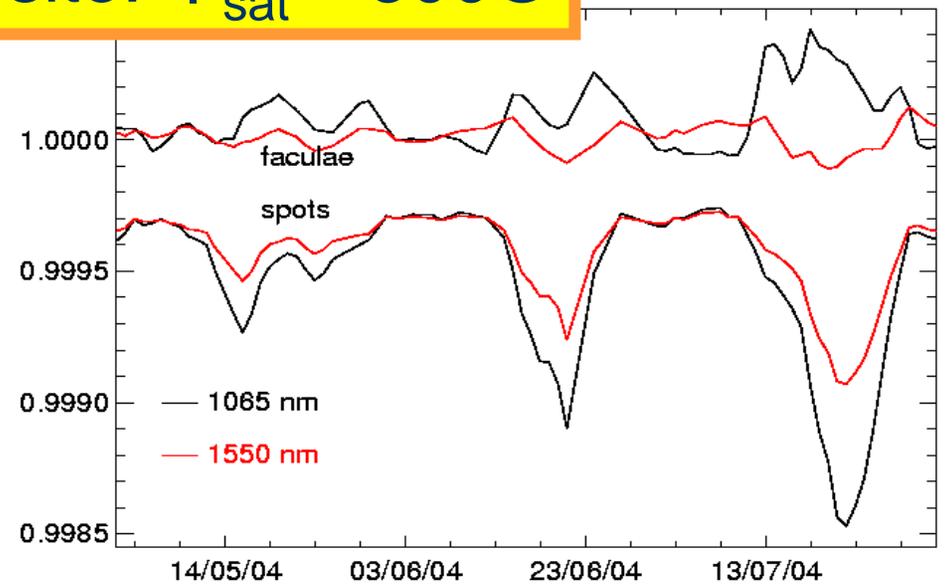
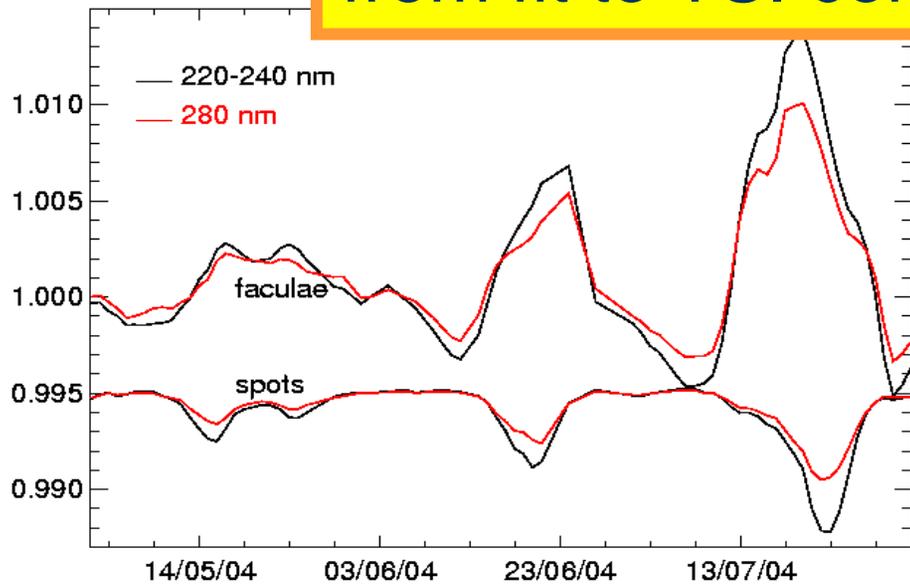
220-240 nm and 280 nm flux



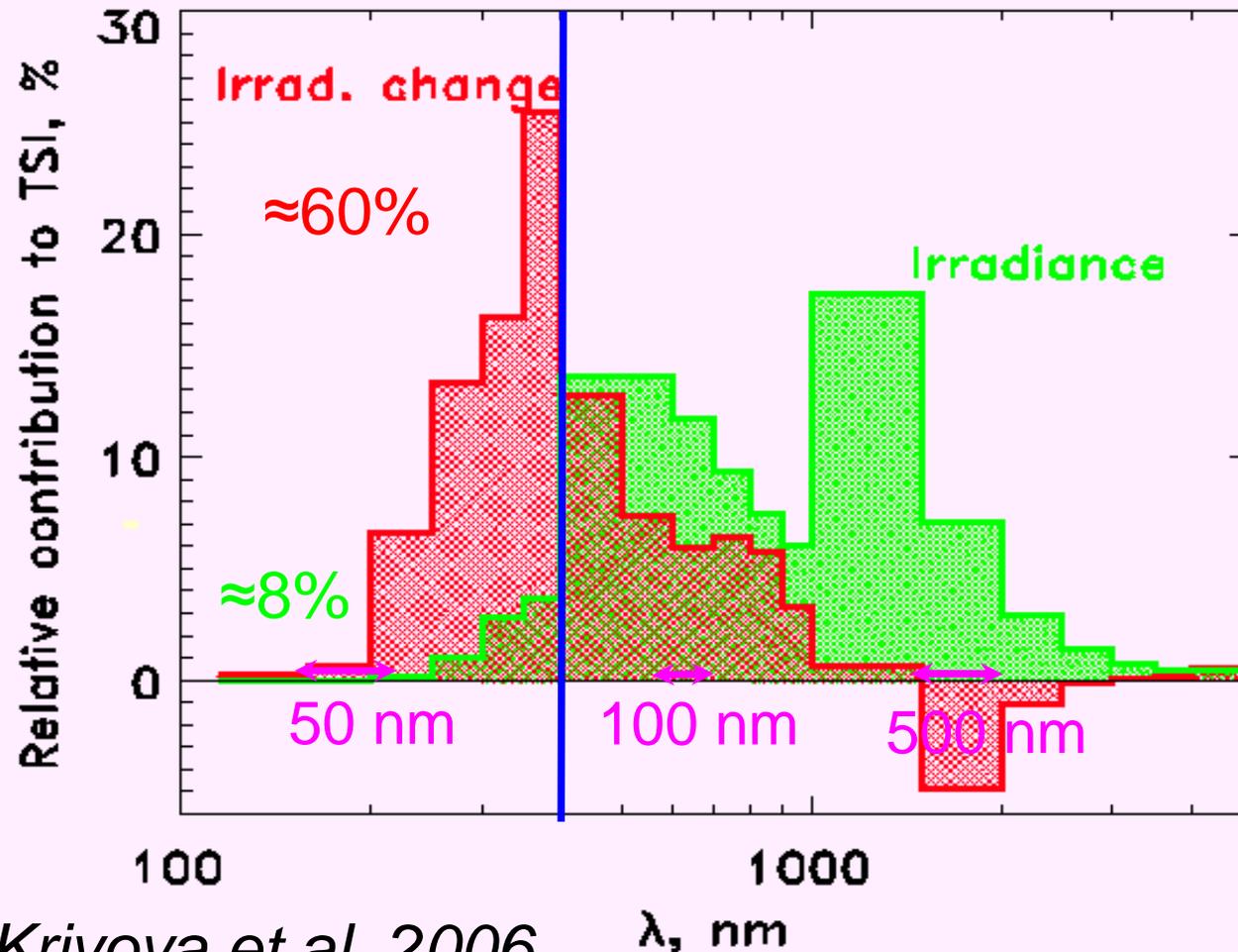
1065 and 1550 nm



Same free parameter as obtained
from fit to TSI composite: $\Phi_{\text{sat}} = 300\text{G}$



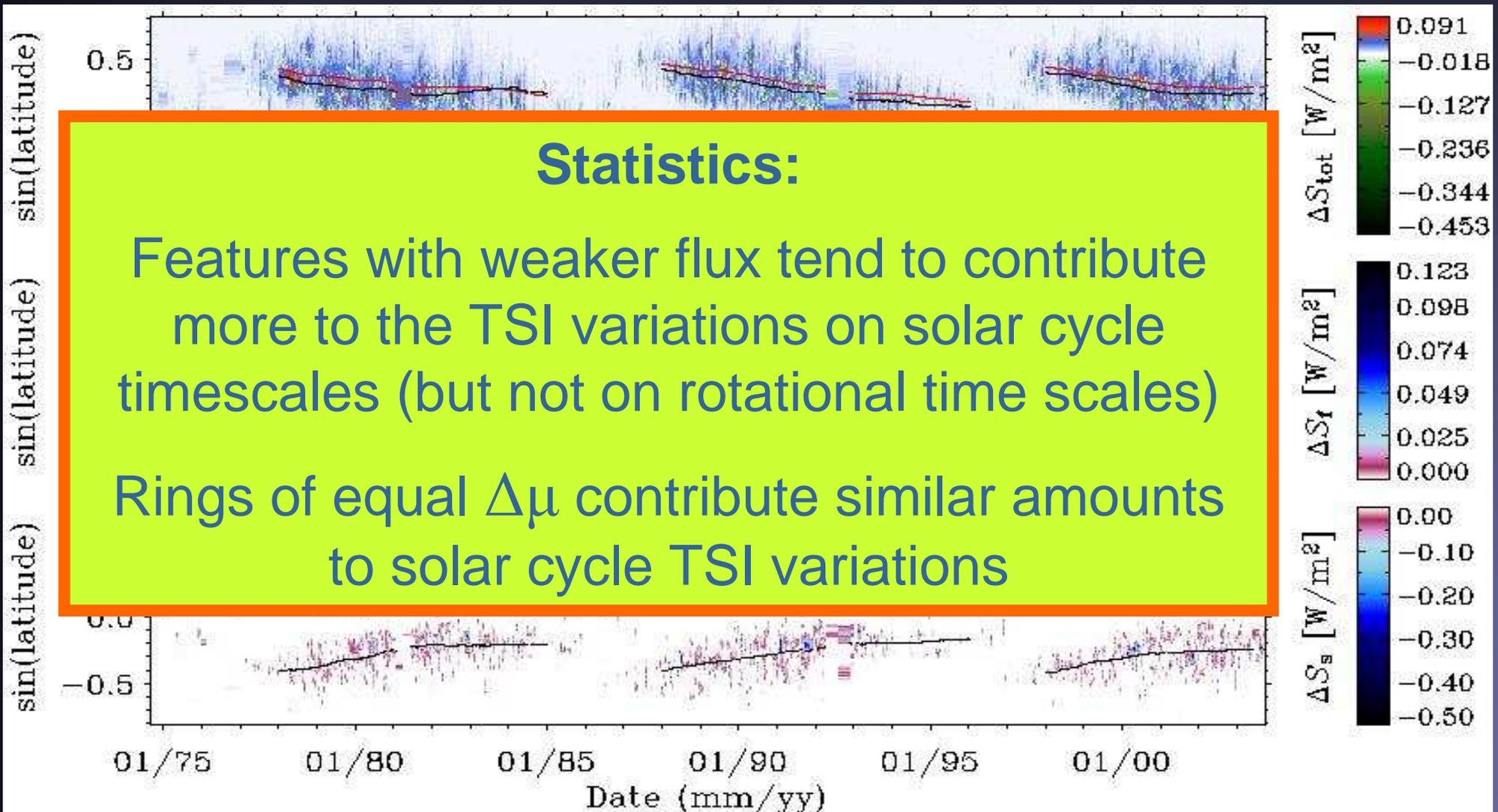
How strongly do different wavelengths contribute to TSI and TSI variations?



Krivova et al. 2006

λ , nm

Irradiance butterfly diagram

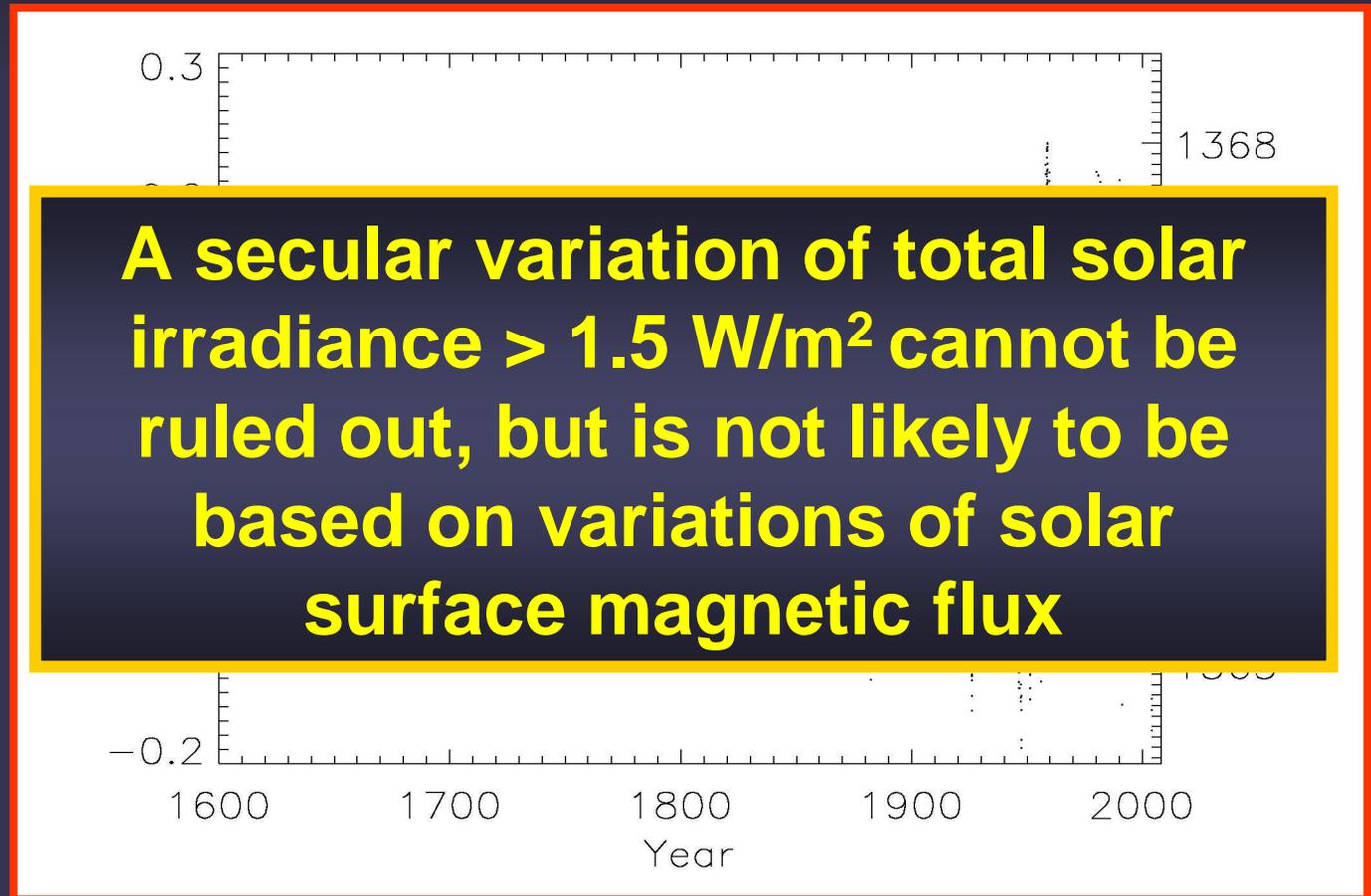


Solar Irradiance Since 1610 Based on Magnetic Field Reconstruction

Model agrees with: obs. TSI, total & open magn. flux

→ estimates of secular rise in TSI since Maunder minimum

≈0.9-1.5 W/m²



Krivova et al. 2007

Outlook: Improve sunspot models

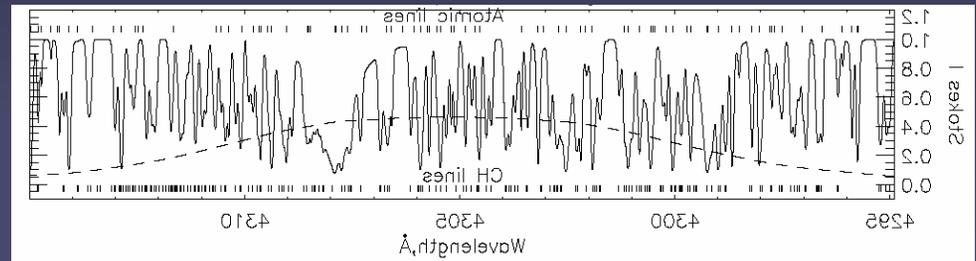
- Incorporate new knowledge: sunspot intensity depends strongly on size (Mathew et al. 2007)

- Correlation
improvement

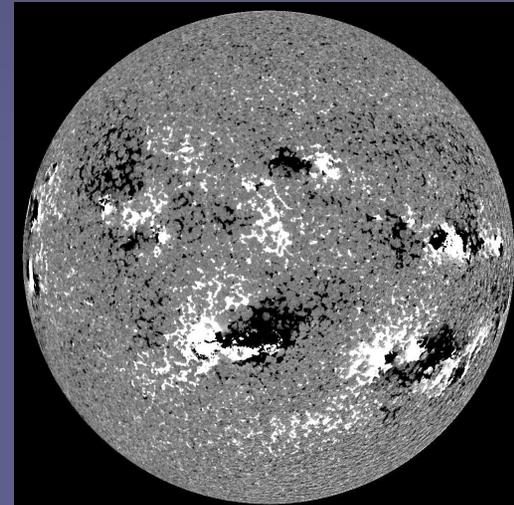


Outlook: improved treatment of faculae, improved magnetograms

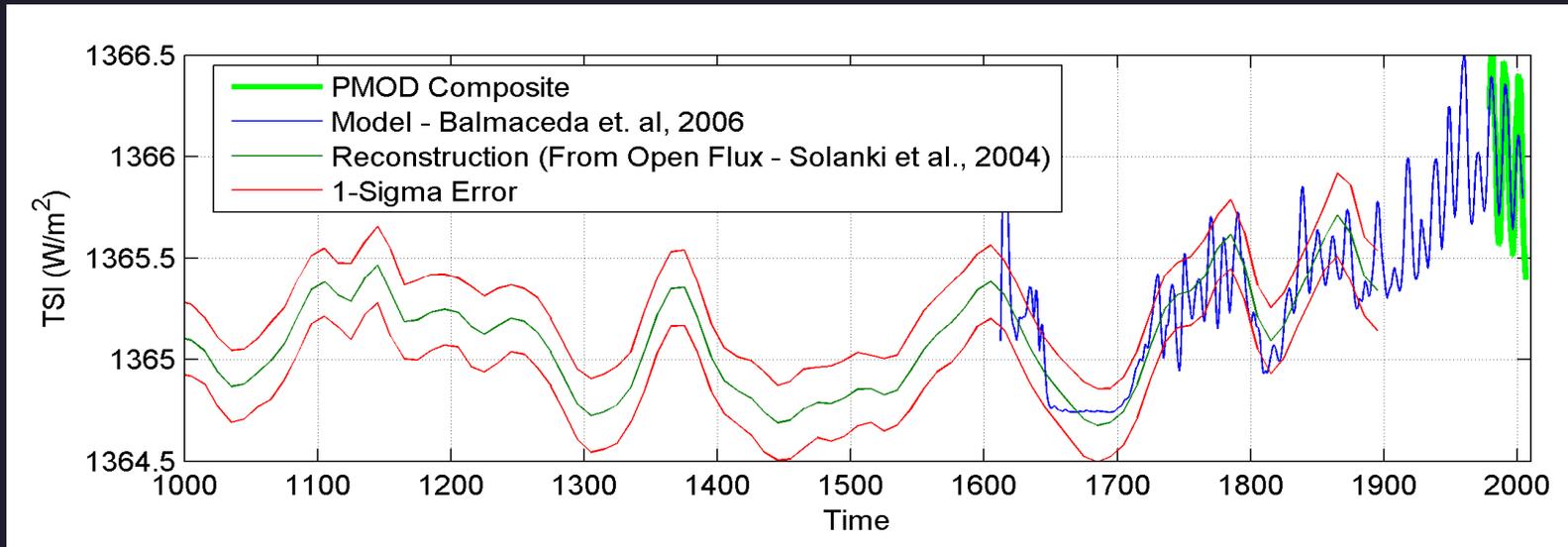
- Compute spectra from **3D radiation MHD simulations** and use these to determine total and spectral irradiance
→ no free parameter needed anymore.



- Employ **lower noise magnetograms** available from **SOLIS** and hopefully from **SDO** (allow also brightening from weaker fields to be included, in particular also near the limb).



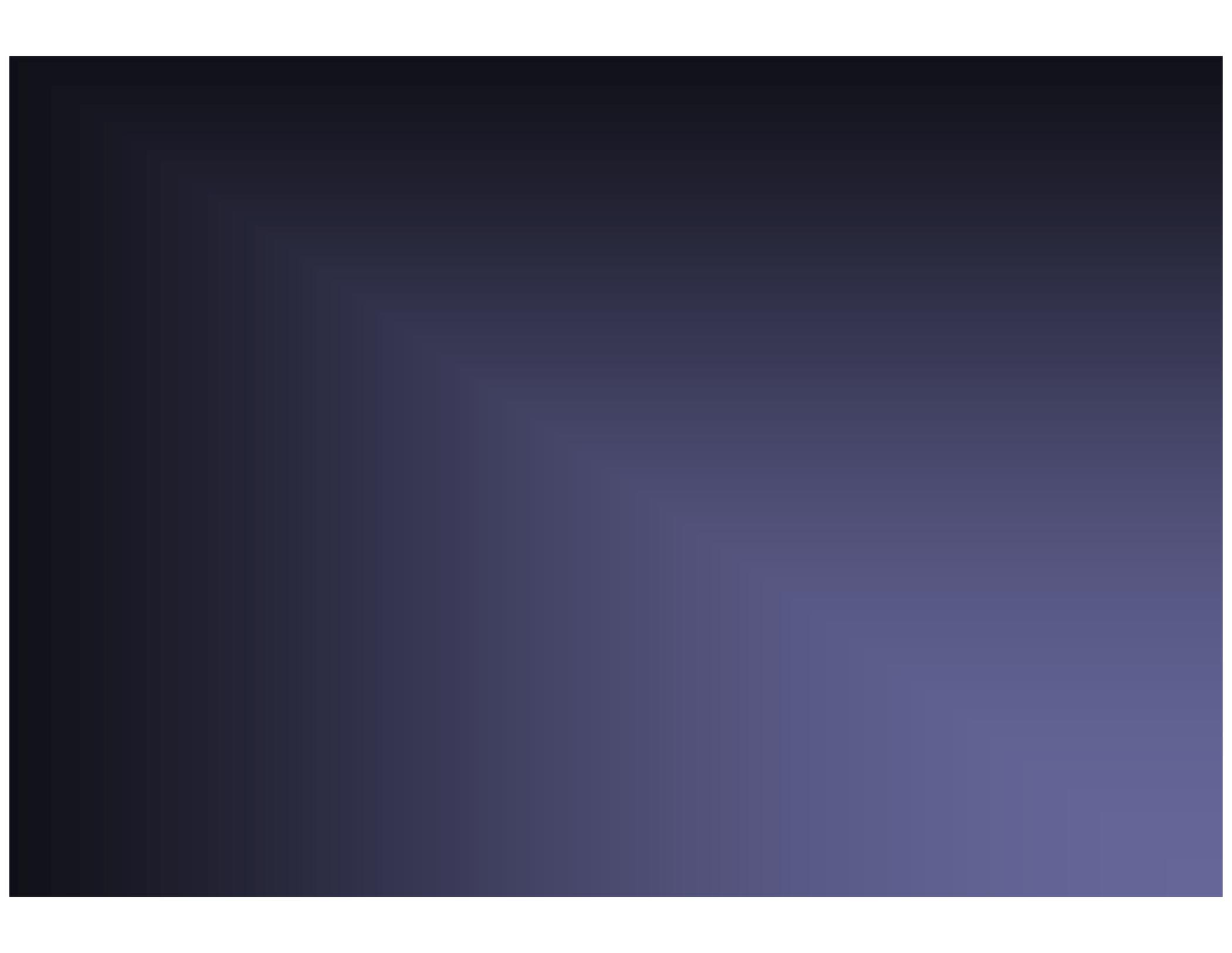
Outlook: Irradiance over 11 kyr



Vieira et al. in preparation

- Use SN obtained from ¹⁴C data (cf. Usoskin et al. talk on wed) to reconstruct TSI over 11400 years
- Only cycle averages can be reconstructed with ¹⁴C data
- Make use of near-linear relationship betw. 10-year avges. of SN and of reconstructed TSI since Maunder minimum

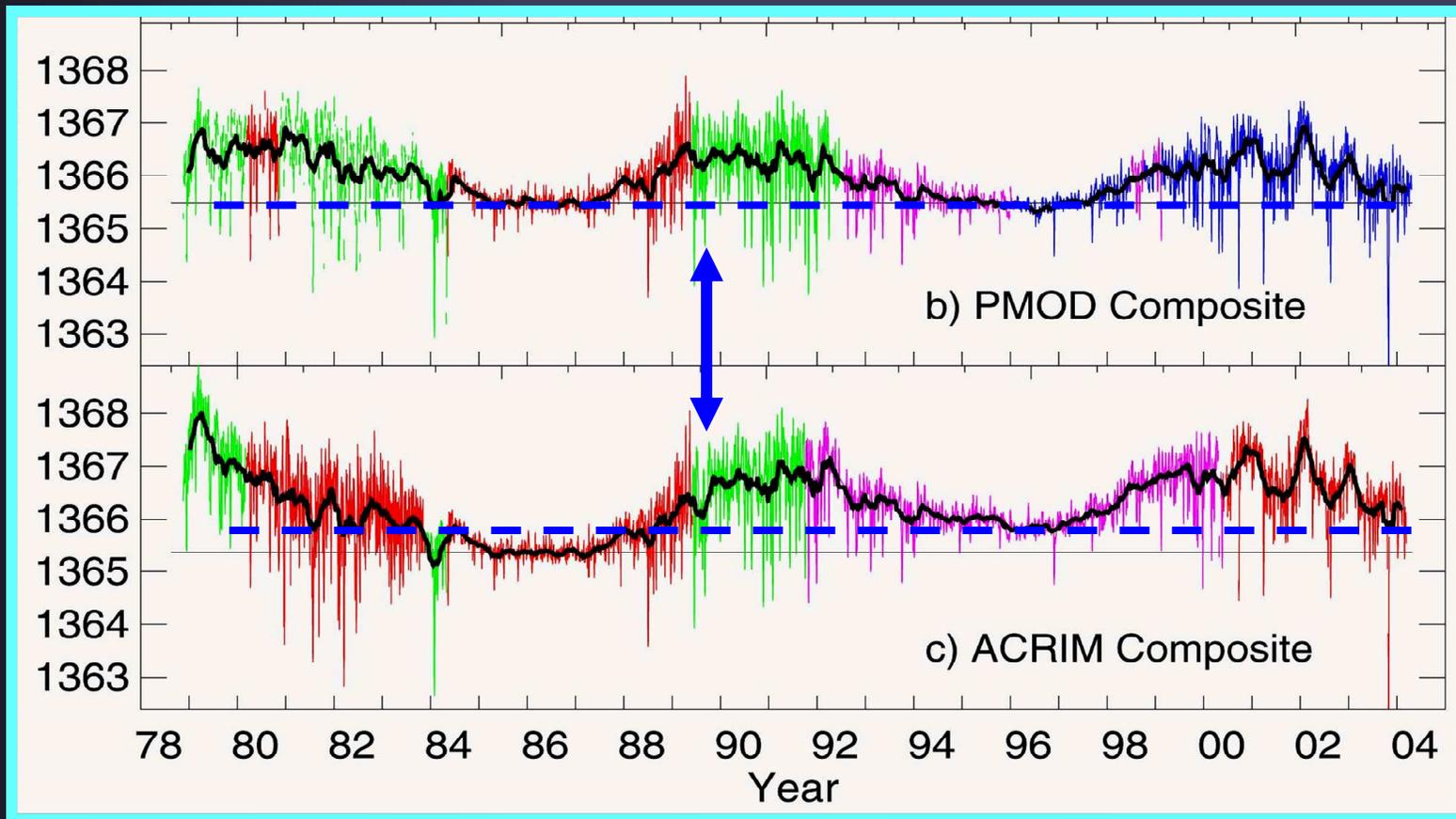






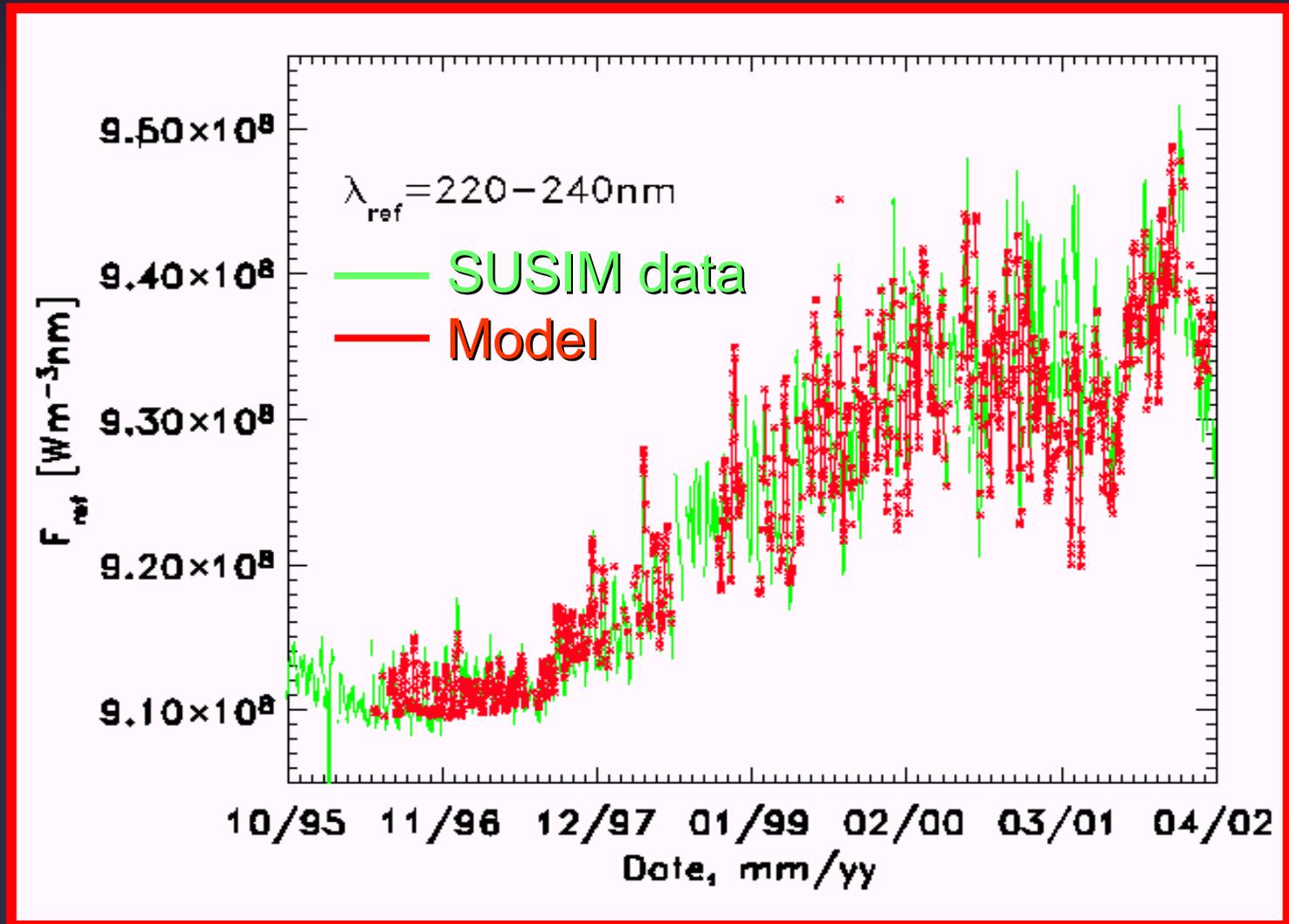
What about other composites?

- 3 composites available: PMOD (Fröhlich), ACRIM (Willson), IRMB (DeWitte).
- Differ in employed data sets + corrections: trends



SATIRE UV irradiance vs. SUSUM

Reconstruction of spectral irradiance based on the same model as for total irradiance, with **same value of free parameter!**



Krivova and Solanki 2006 A&A

Spectral Irradiance: SATIRE vs. SUSIM

Relative difference between UV irradiance at activity max & min



Other models with more detailed radiative transfer have been and are being constructed by Haberreiter et al. 2005, Haberreiter 2006; Fontenla et al. 2004, 2006.

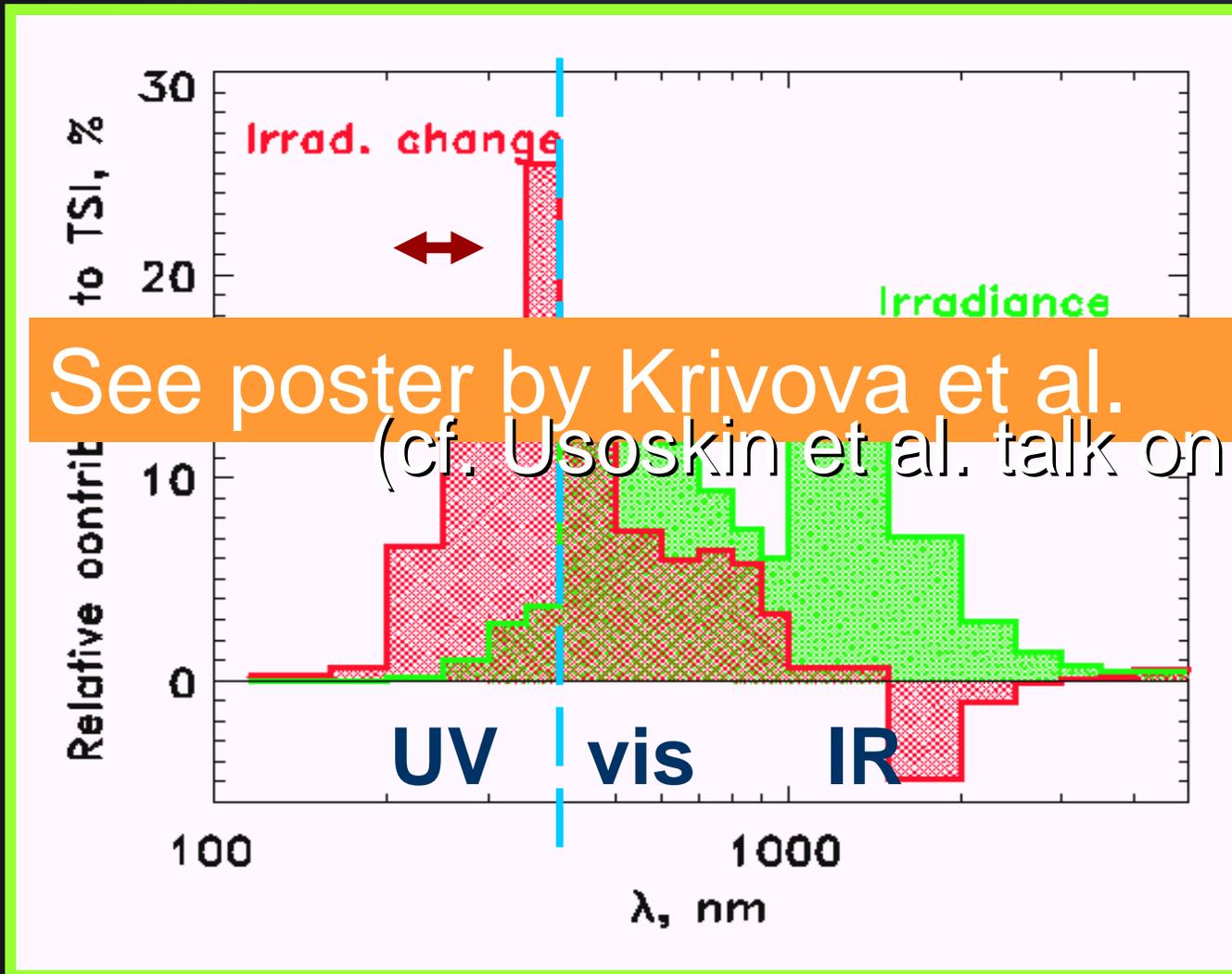
They will eventually improve on these reconstructions.

100
Krivova and Solanki 2005

λ , nm

1000

Spectral Irradiance over Cycle



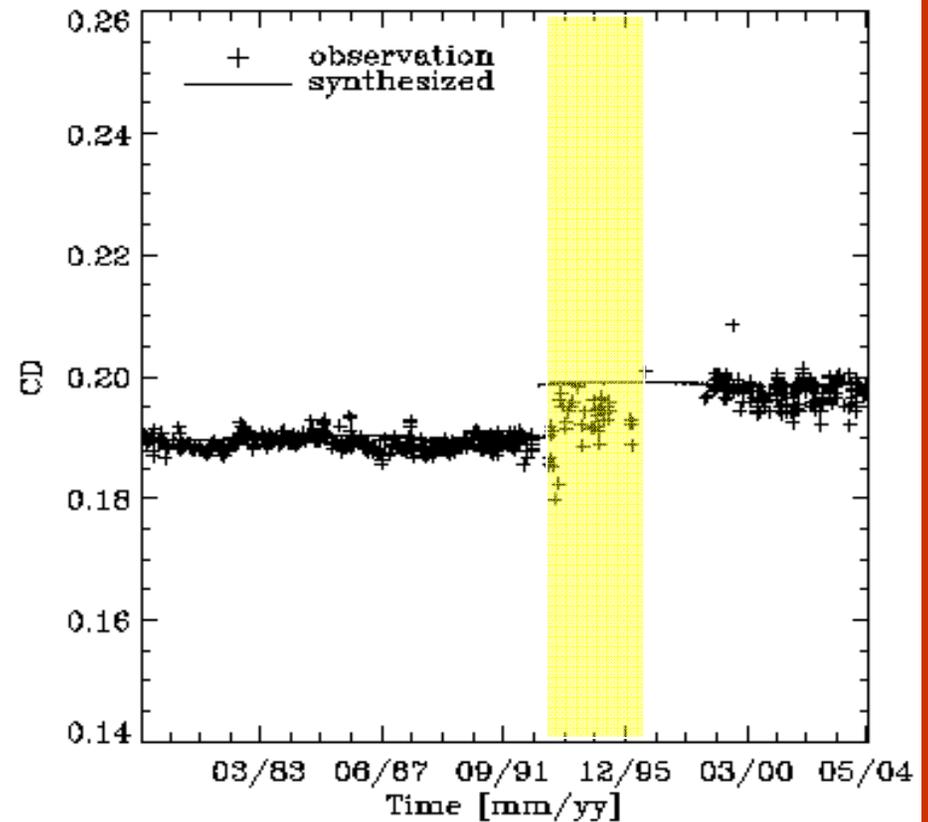
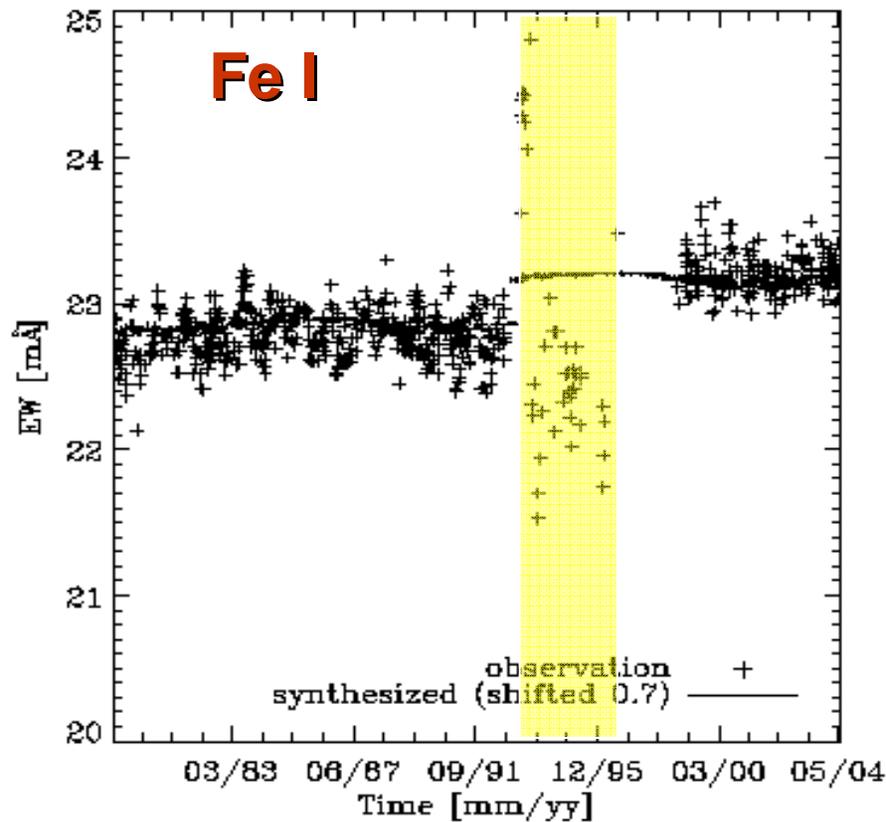
Although UV provides only a minor contribution to total irradiance, it produces $\approx 60\%$ of TSI change over a solar cycle



Stratospheric chemistry.

Krivova and Solanki 2006 A&A

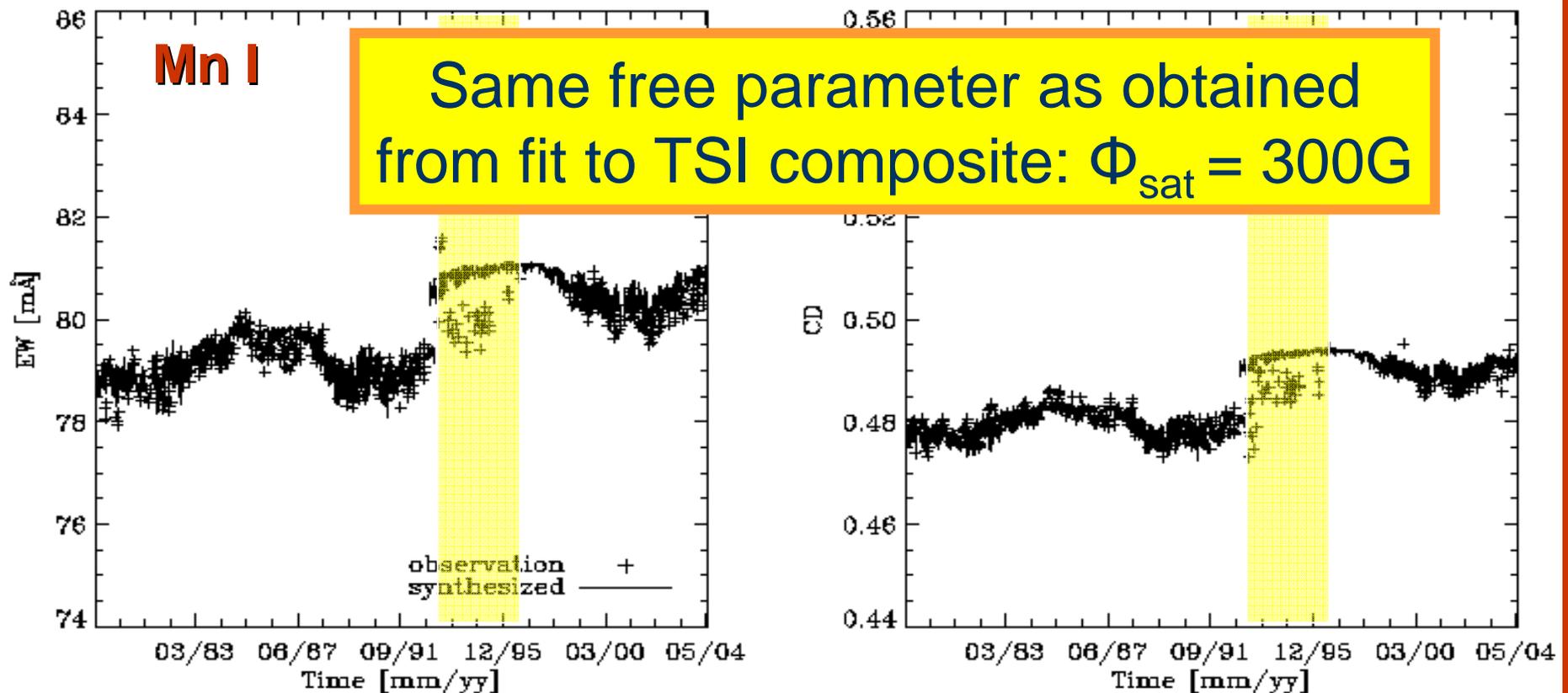
New tests of SATIRE II: Livingston's line observations



Solar cycle variation is absent

Danilovic et al. 2006

New tests of SATIRE II: Livingston's line observations



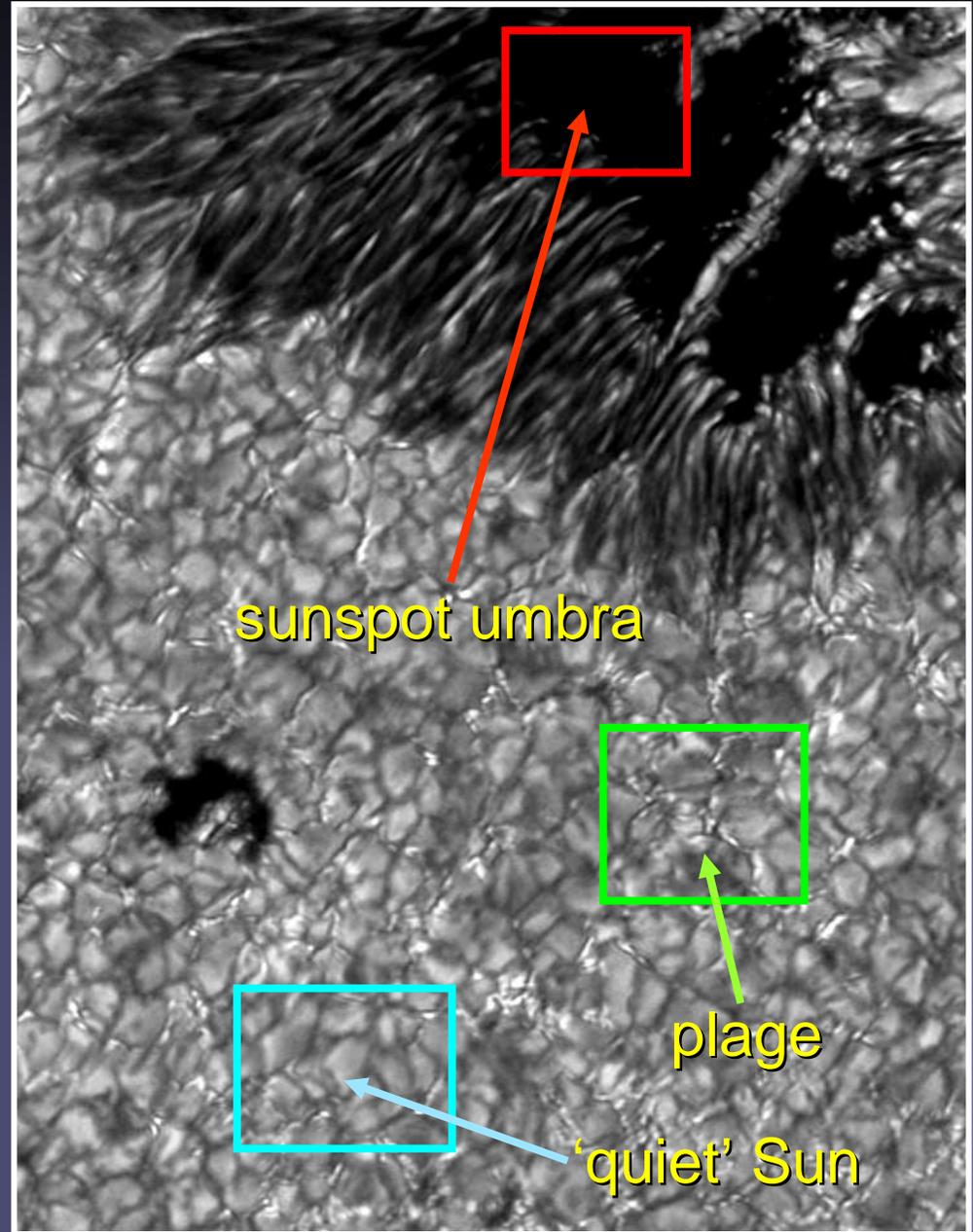
Significant solar cycle variation

Danilovic et al. 2006

Regimes of solar magnetoconvection



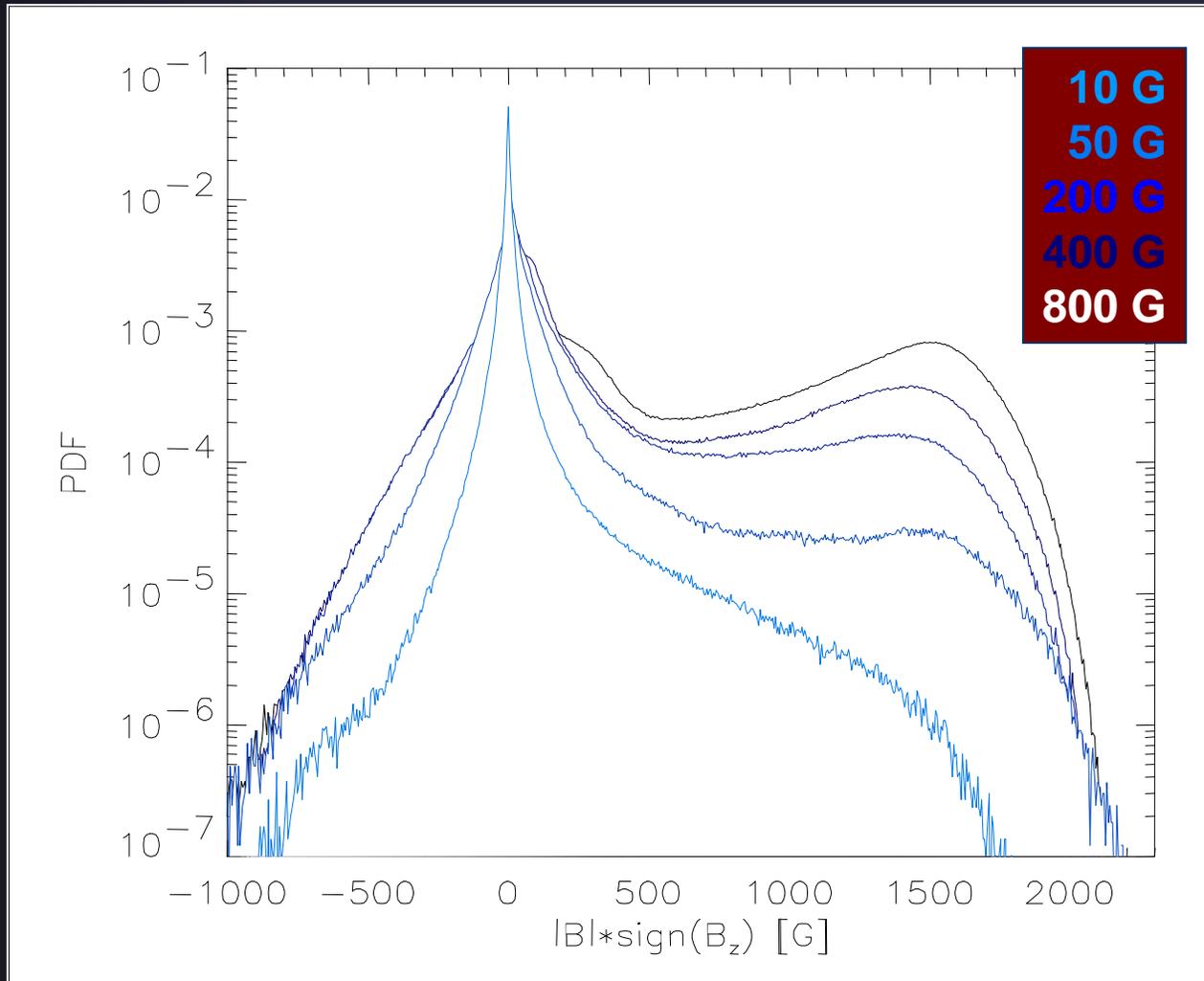
- horizontal scale of convection decreases
- convective energy transport decreases



G-band image: KIS/VTT, Tenerife

From quiet Sun to strong plage

Probability density function of field strength around $\alpha=1$

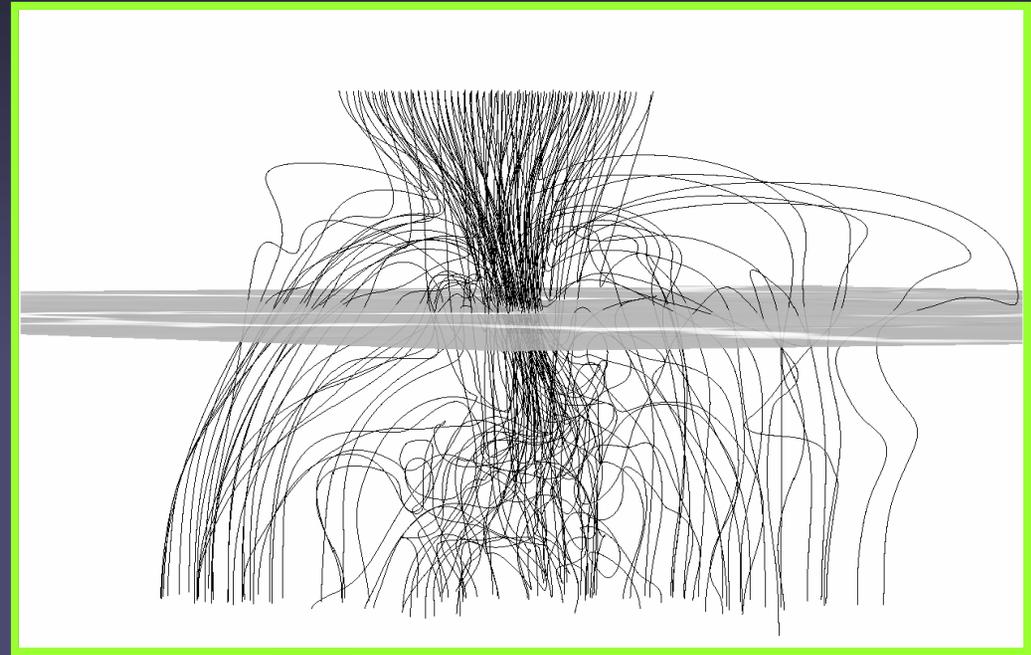
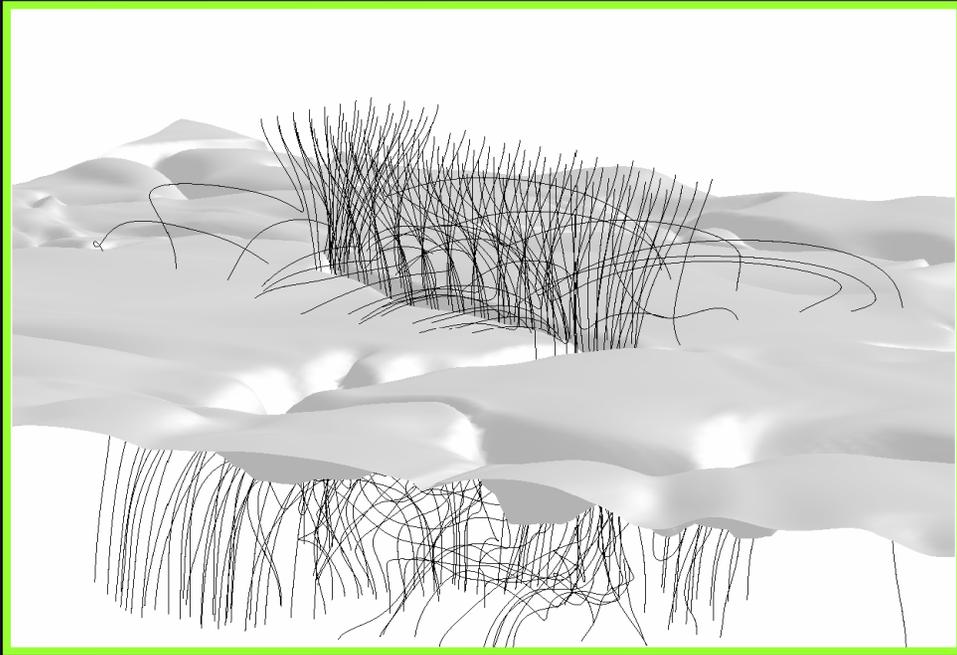


□ Weak fields:
exponential

□ Strong fields:
Gaussian

□ Efficiency of convective
field intensification de-
creases for small B_0

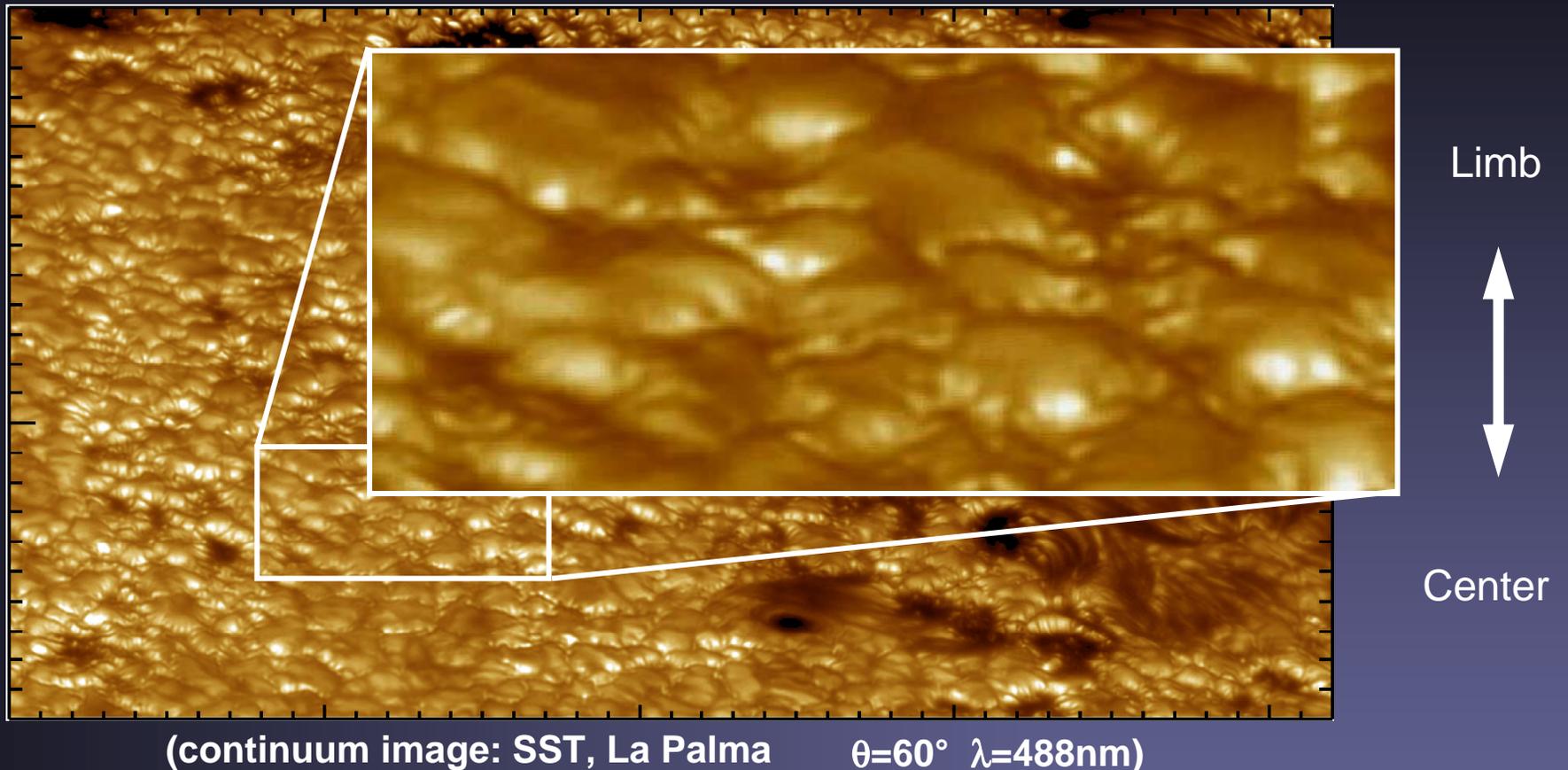
3D view of a thin flux sheet



Face-on view

- Quasi 2-dimensional above the surface
- Loss of coherence beneath the surface

Facular brightening

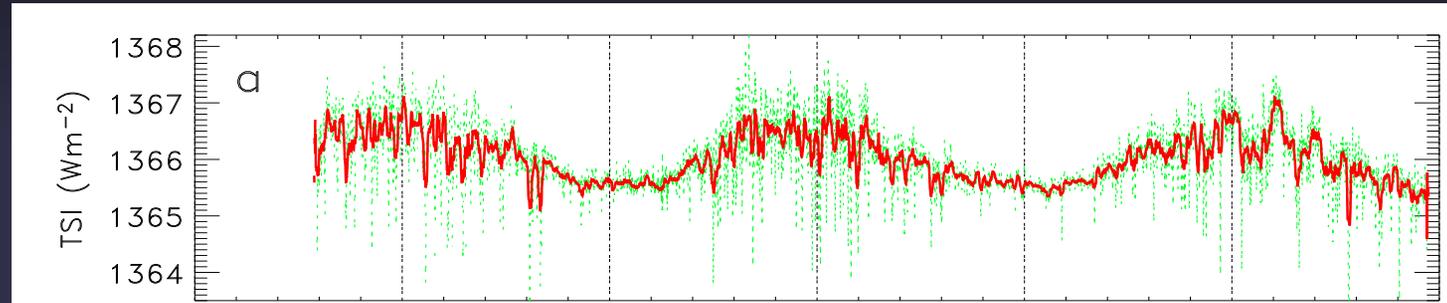


Recent observations reveal:
(Lites et al. 2004)

- 3D appearance of faculae
- extension up to $0.5''$
- narrow dark lanes centerward of faculae

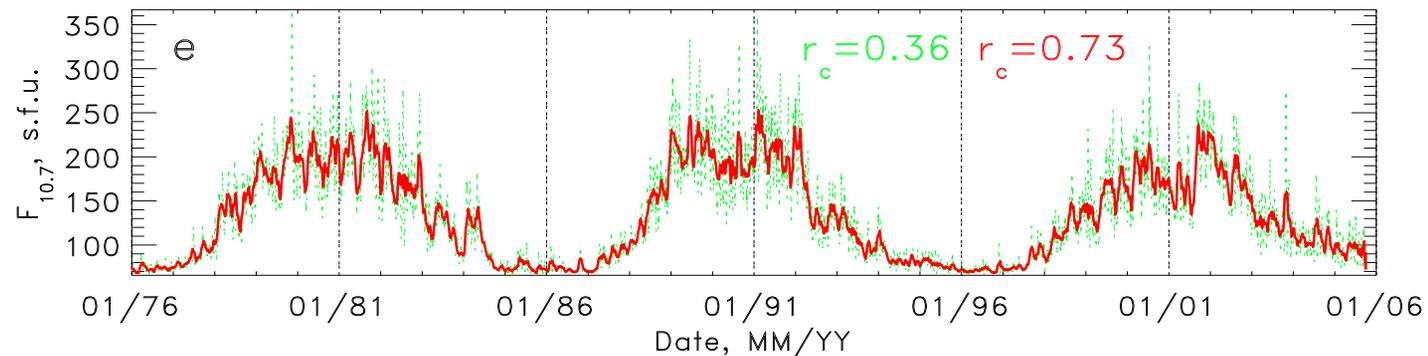
Irradiances from different layers

TSI: reference
daily curve;
monthly
smoothed



Photospheric irradiance has both spot and facular contributions; chromospheric and coronal irradiance has mainly facular contribution

F10.7 cm:
daily: 0.36
monthly: 0.73

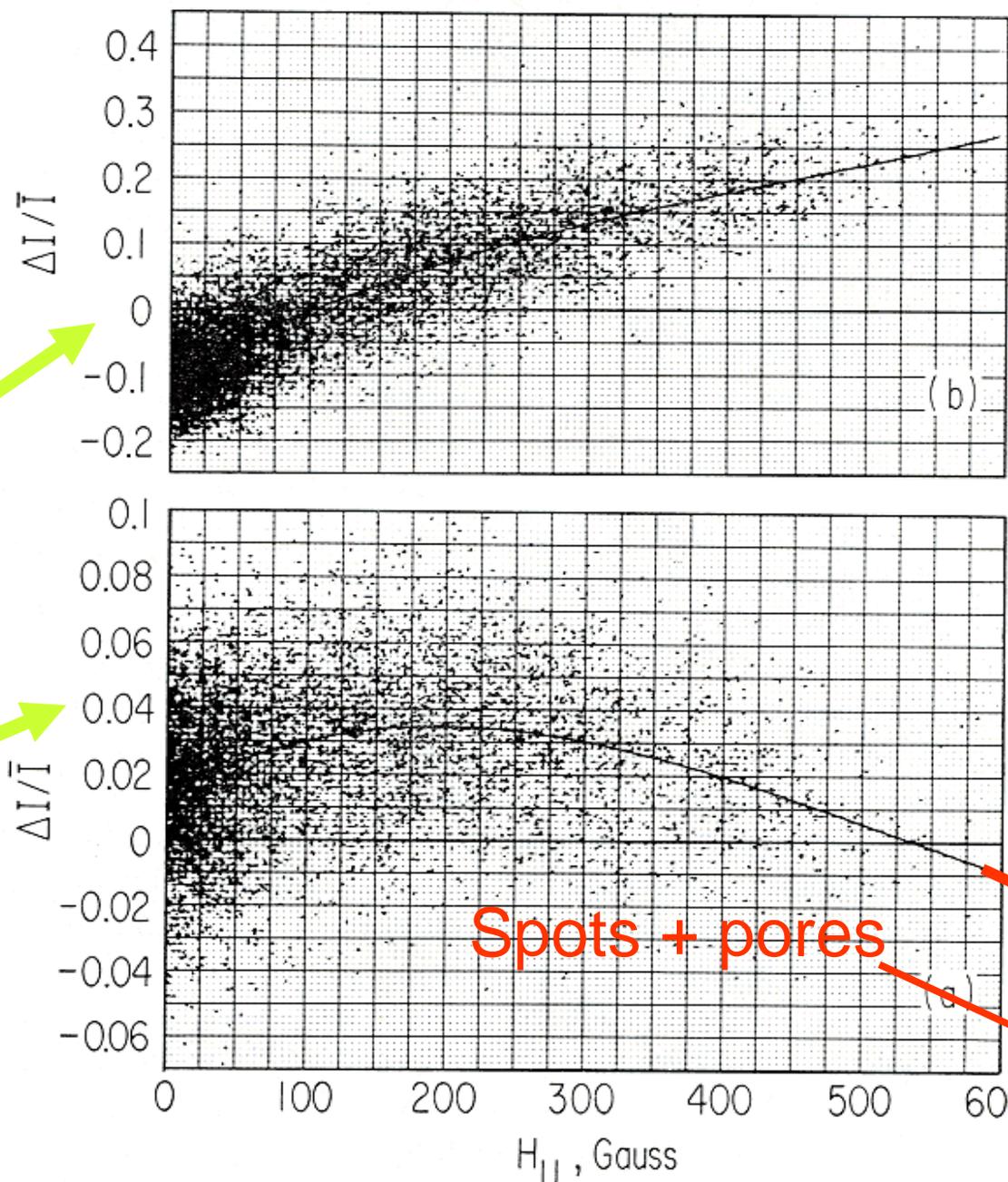


Contrast of magnetic features

Chromosphere
(Ca II K)

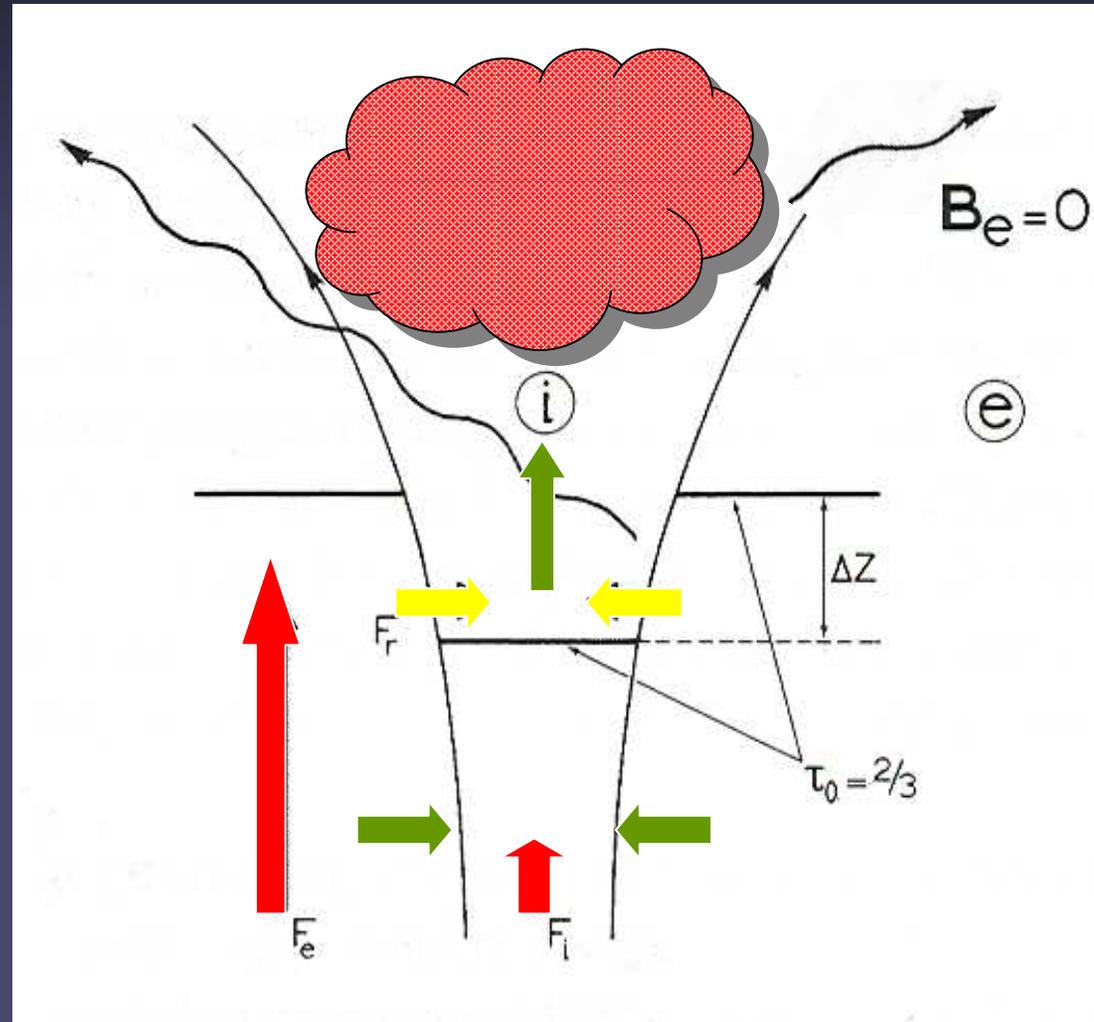
Photosphere
($\lambda \approx 5251 \text{ \AA}$, contin)

Frazier (1971)



Influence of magnetic features in chromosphere

- **Photosphere:** heat blocking & release at solar surface
- **Chromosphere:** release of excess energy stored in field or channelled by field to higher layers (e.g. MHD wave dissipation, or in current sheets).
- **Sunspots:** dark in photosph+lower chromo; neutral-bright in upper chromosphere + TR



Irradiance Modelling

Many models involving radiative proxies of B, e.g. Fröhlich & Lean 1998, Fligge et al. 1998, DeToma et al. 2004 (Mg c/w); Ermolli et al. 2003, Fontenla et al. 2004 (PSPT); Preminger et al. 2002, 2005, 2006 (SFO, spots); Foster 2004, Jain & Hasan 2004 (Φ).

SATIRE model discussed here is based on magnetic field at solar surface. It has 1 free parameter.

Fligge et al. (2000); Krivova et al. (2003); Wenzler et al. (2004, 2005, 2006); Haberreiter et al. (2005); Unruh et al. (2006); Danilovic et al. (2006)