Space Climate 6
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# The dynamo origin of solar spectral irradiance variations


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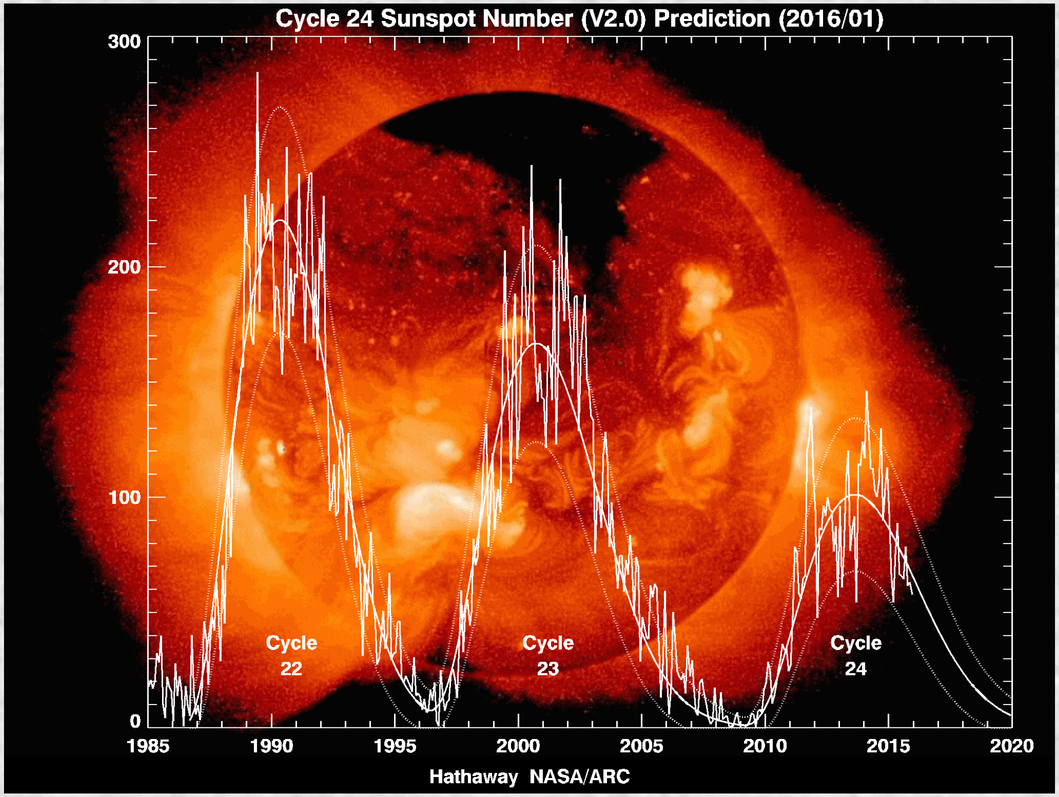
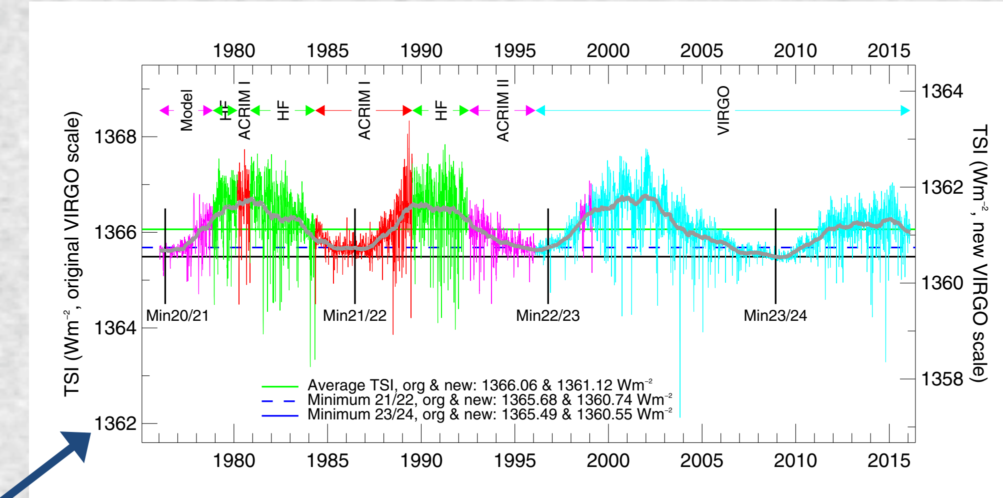


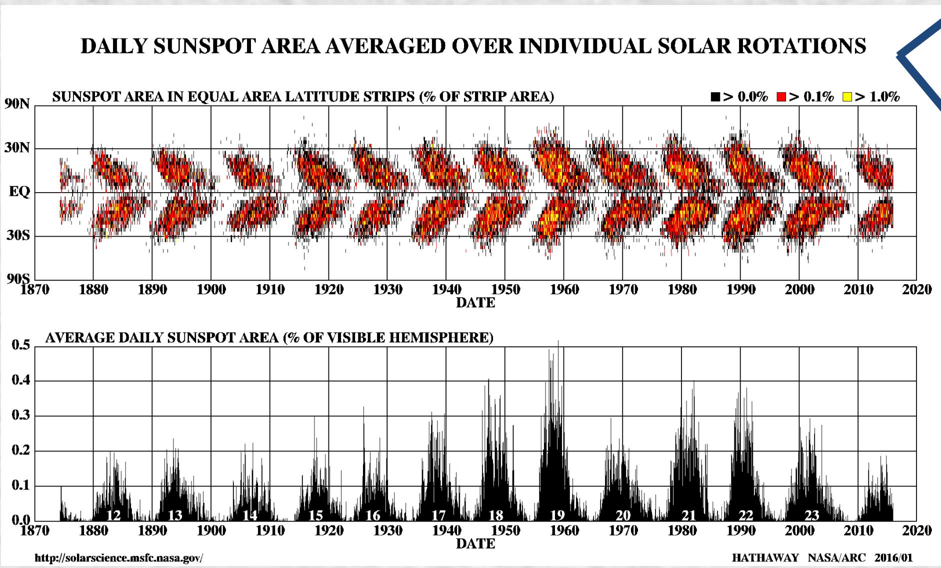

Courtesy D. Hathaway

# Goal:

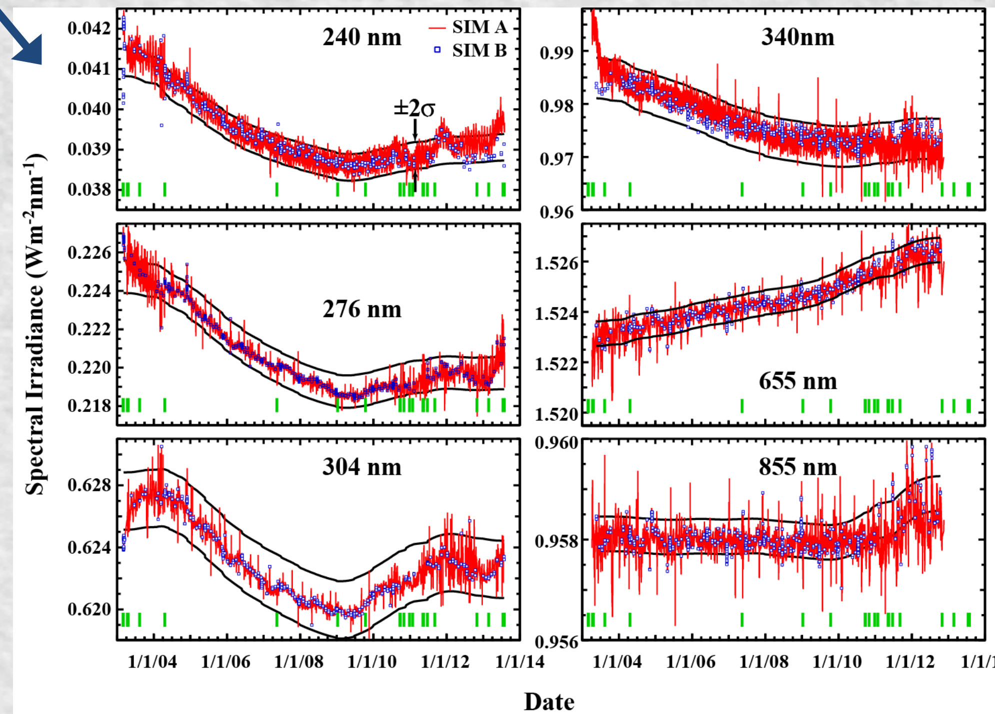
Understanding of dynamo ⟹ Total and spectral irradiance




Courtesy PMOD WRC




Courtesy D. Hathaway

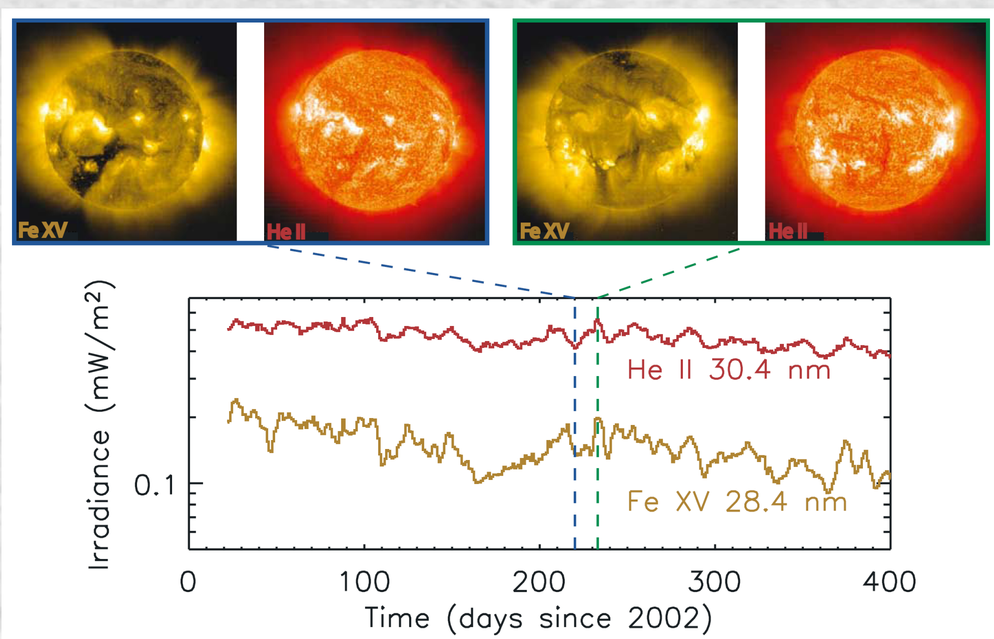



Courtesy J. Harder

# Challenge:

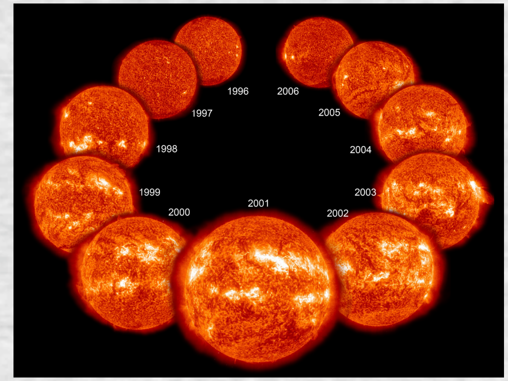
- Dynamo processes likely producing field at all scales
- Non-dynamo interaction of field with convective motions
- Formation of somewhat discrete magnetic structures
- Reconfiguration of solar atmosphere
- $\mu$ and $\lambda$ dependent radiative output due to inhomogeneity

$\Longrightarrow$ Disk integrated spectral irradiance

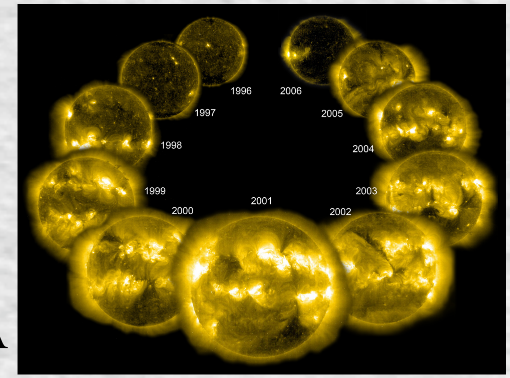



Woods et al. 2005, JGR 110, A01312

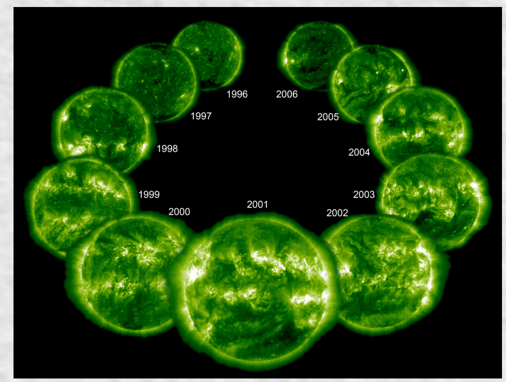
SOHO EIT: (courtesy S. Hill)



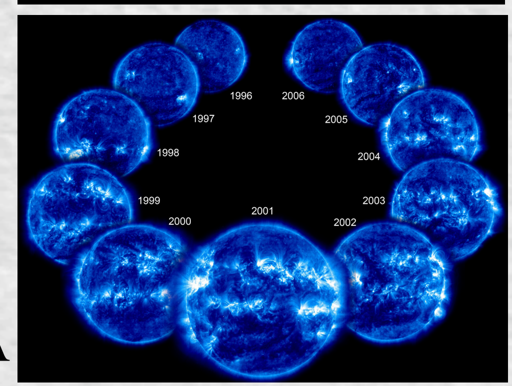
He II 304 Å



Fe XV 284 Å



Fe XII 195Å



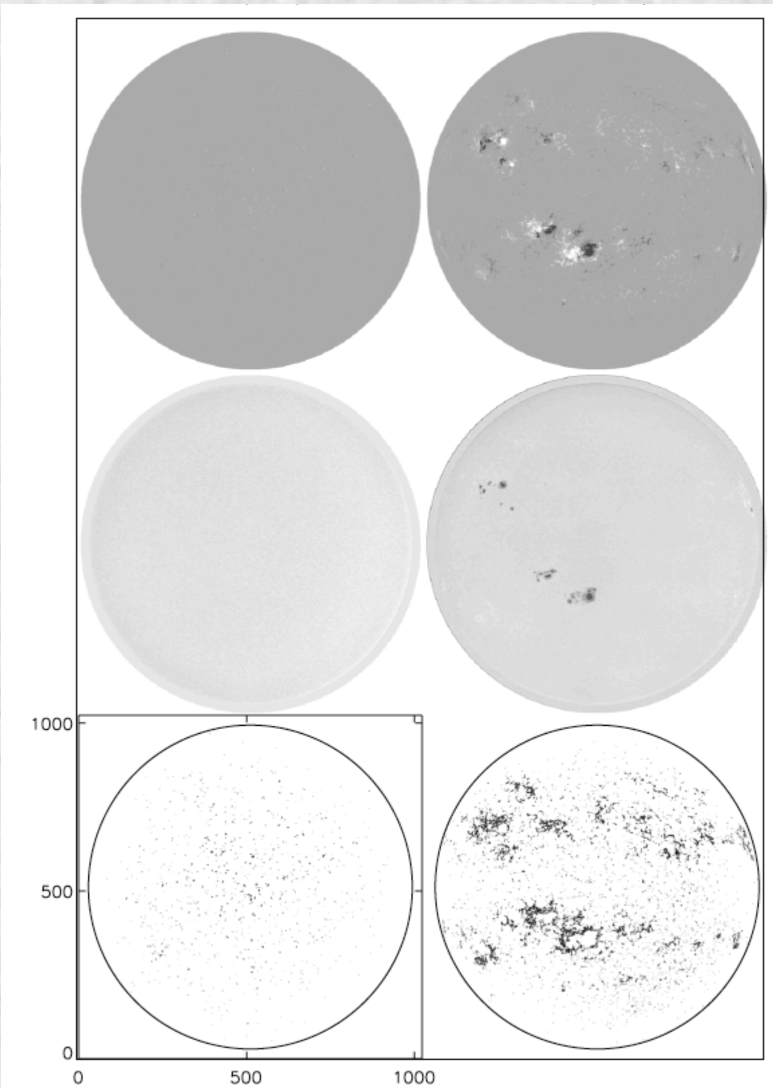
Fe IX/X 171Å

# Uncertainty:

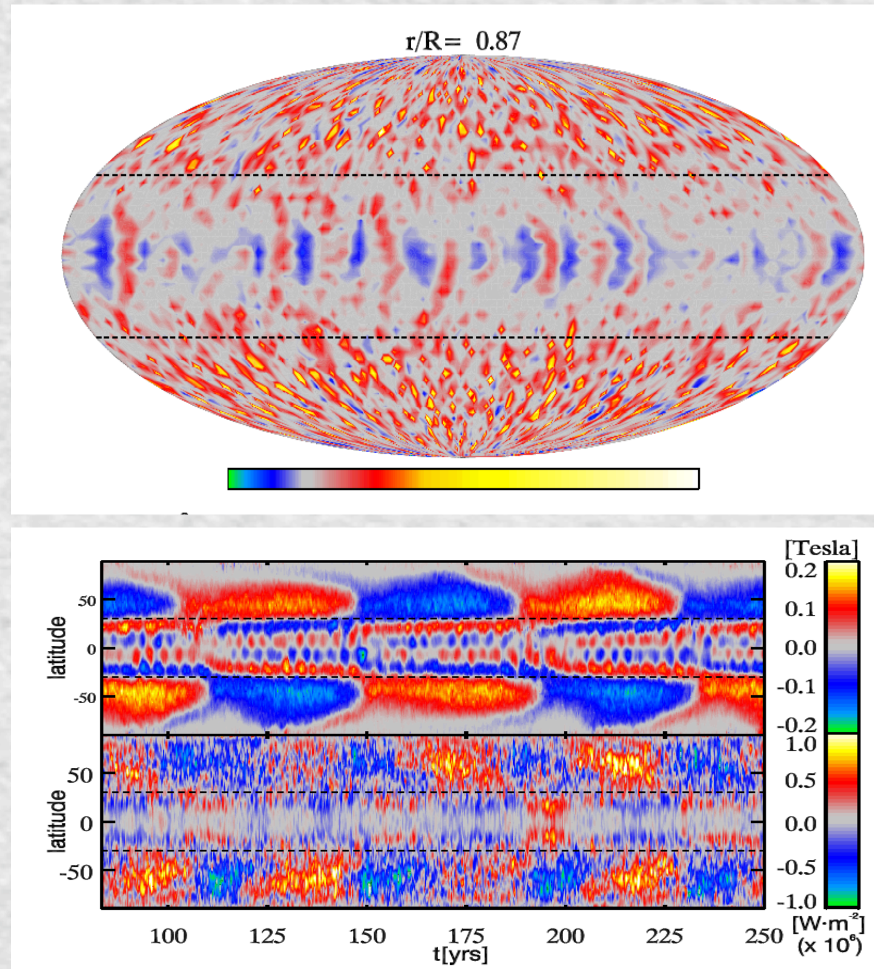
All irradiance variations are the result of changes in the surface photospheric magnetic flux

or (and?)

Changes in the Sun's deep-seated convective flow contribute to global modulation of the Sun's internal thermal structure and variations in the solar irradiance on decadal time scales and longer




Ortiz et al. 2006, A&A 452, 311

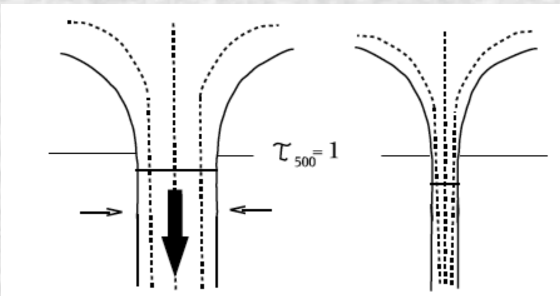


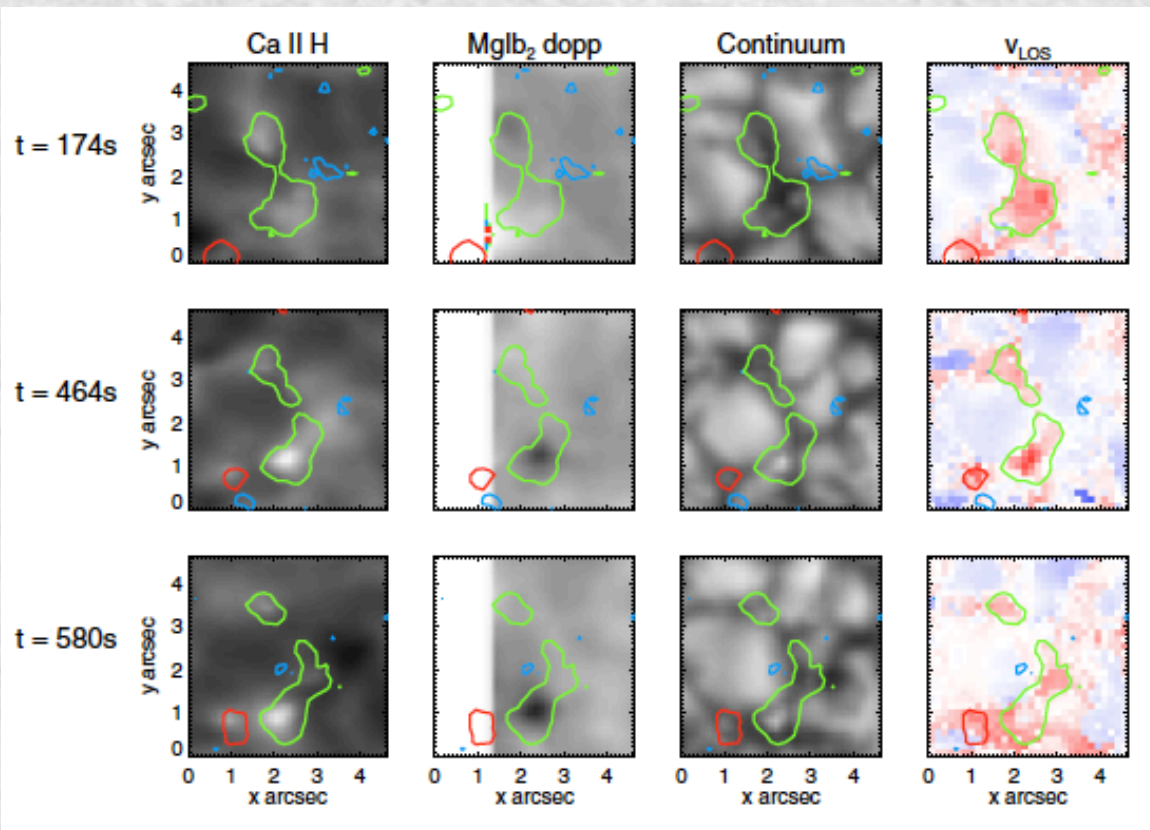

Cossette et al. 2013, ApJ 777, L29

# First possibility:

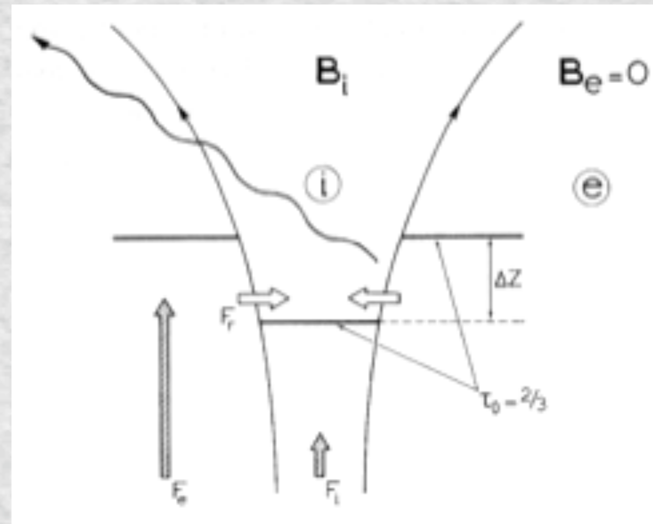
All irradiance variations are the result of changes in the surface photospheric magnetic flux

From the dynamo point of view need to know origin of photospheric magnetic elements and how they influence convective and radiative transport



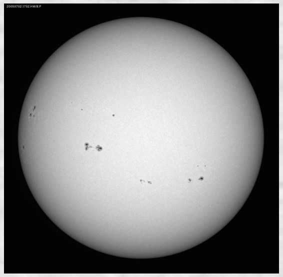



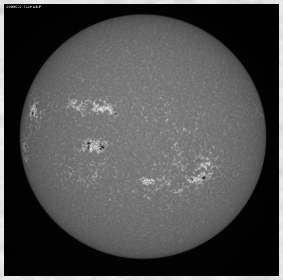

from Fischer et al. 2009



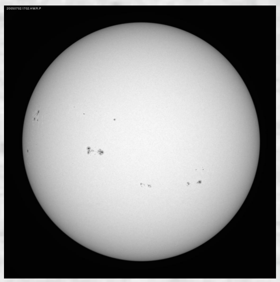

from Schrijver & Zwaan 2000

409.4nm



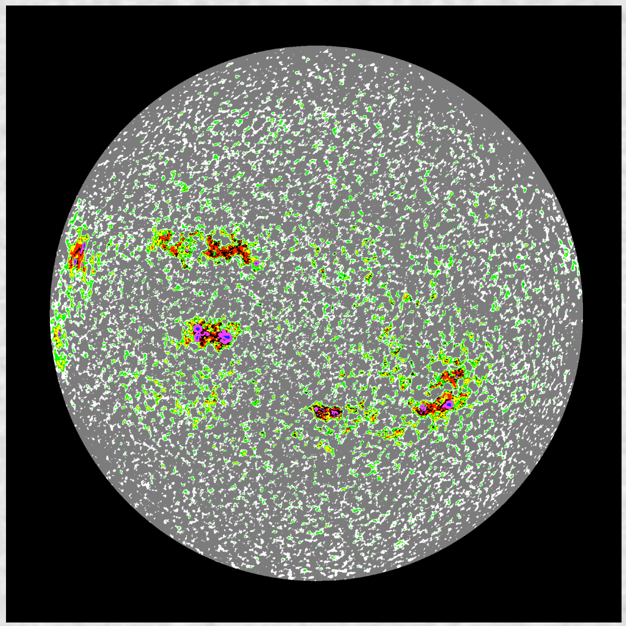


393.4nm

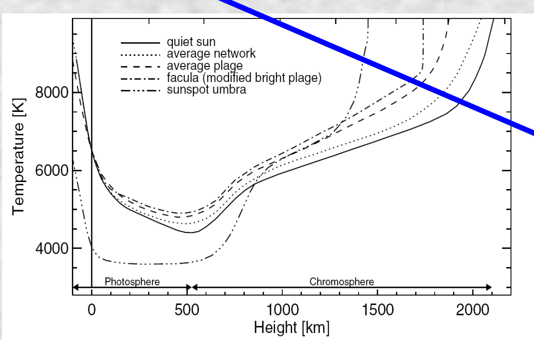


607.1nm

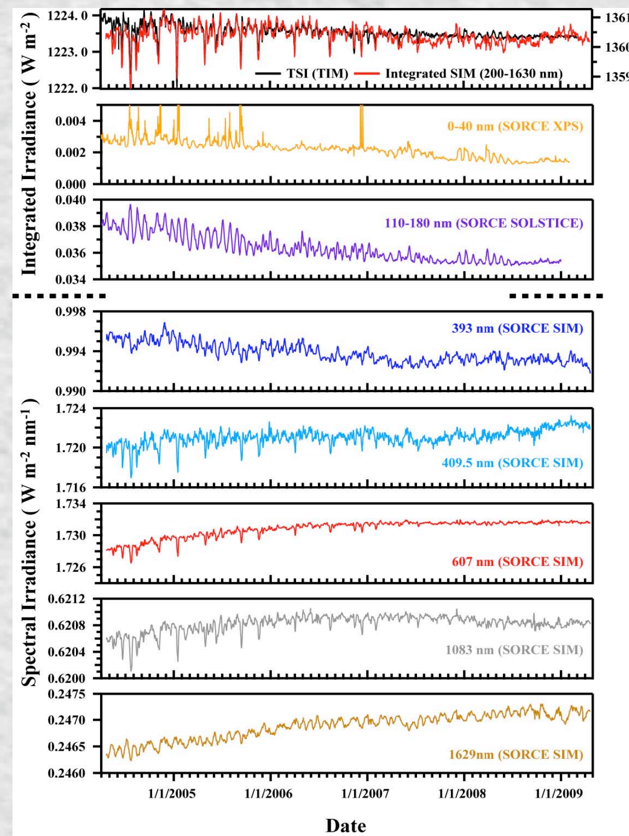
Magnetic structure definition: based magnetograms or contrasts at particular wavelengths such as Ca II K



surface distribution of magnetic field

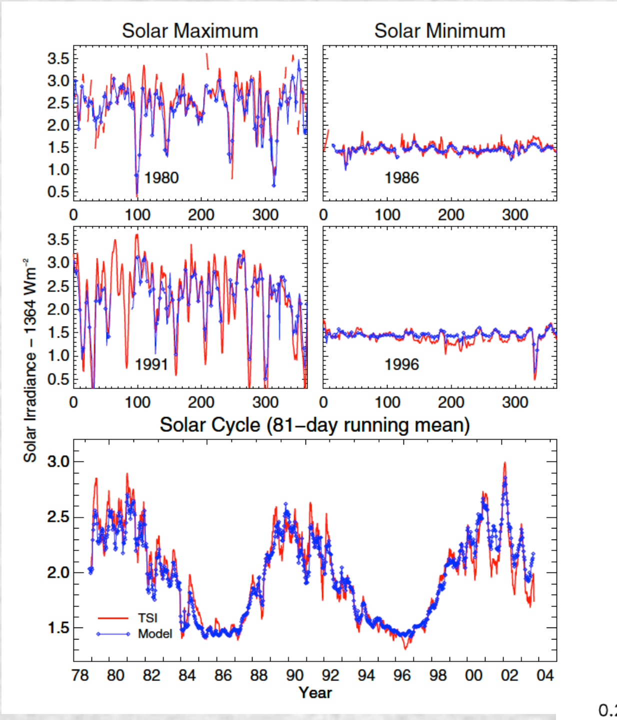



model atmospheres

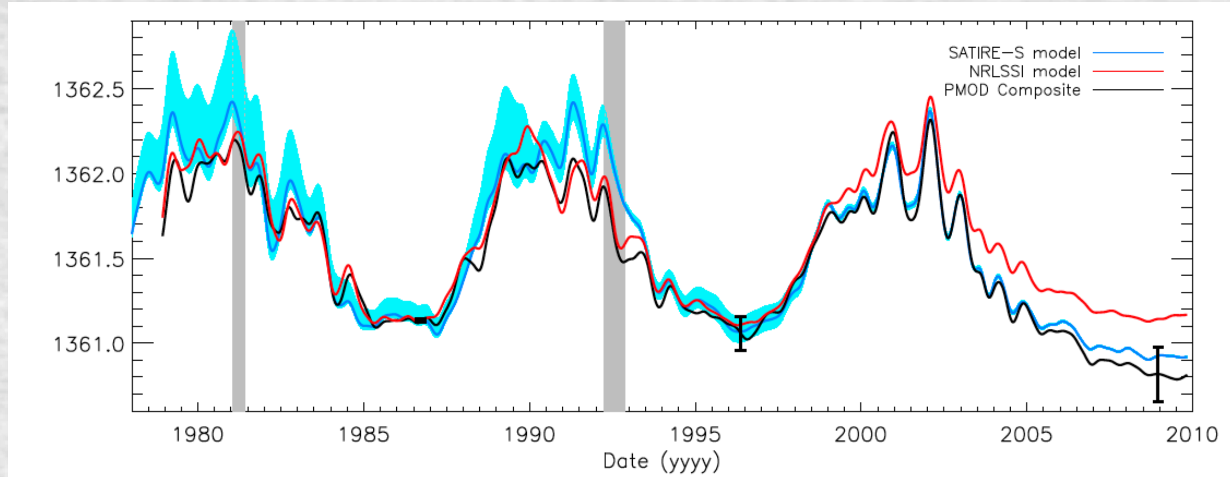



Total and spectral irradiance variation

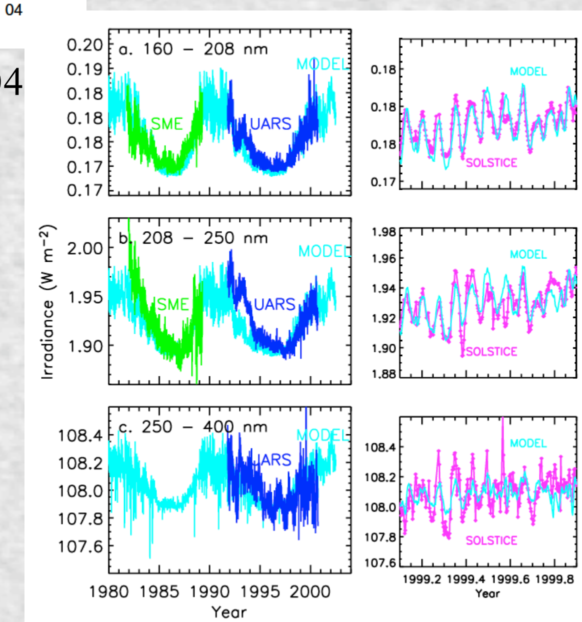
- Such models do quite well accounting for TSI variability
- Generally fit to spectral variability better at shorter wavelengths than longer

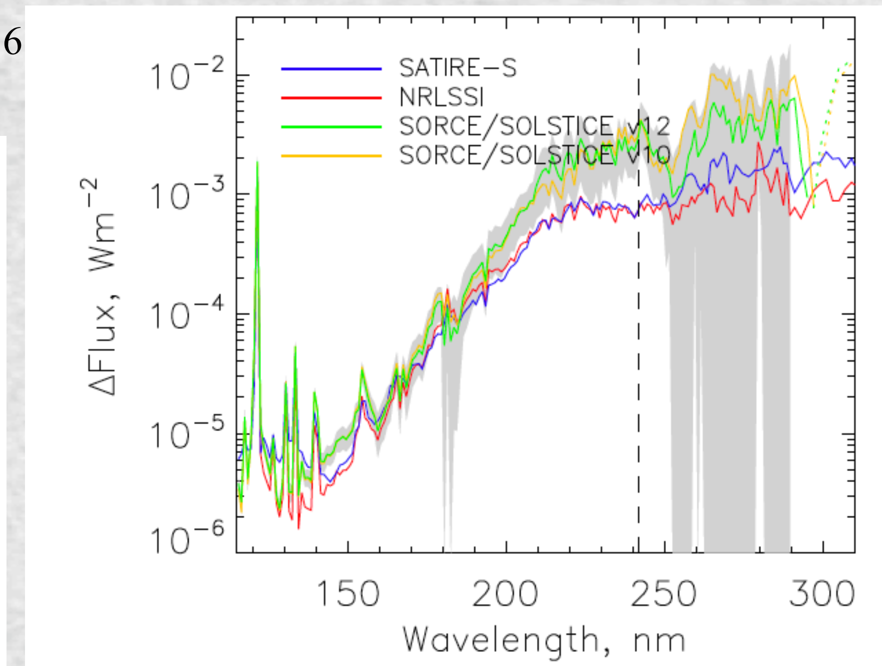



Fröhlich & Lean 2004

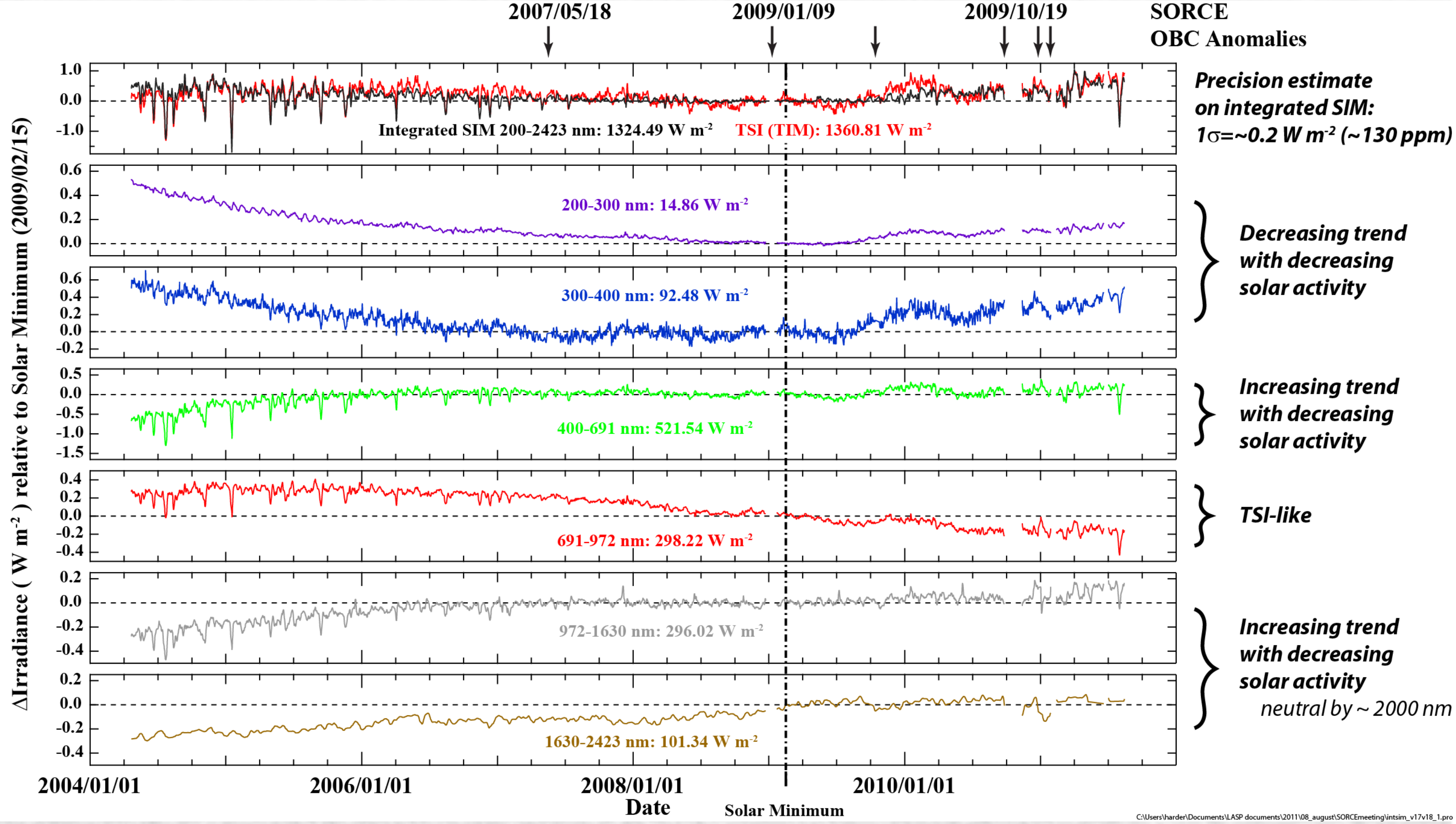



Ball et al. 2014, JAS 71, 4086



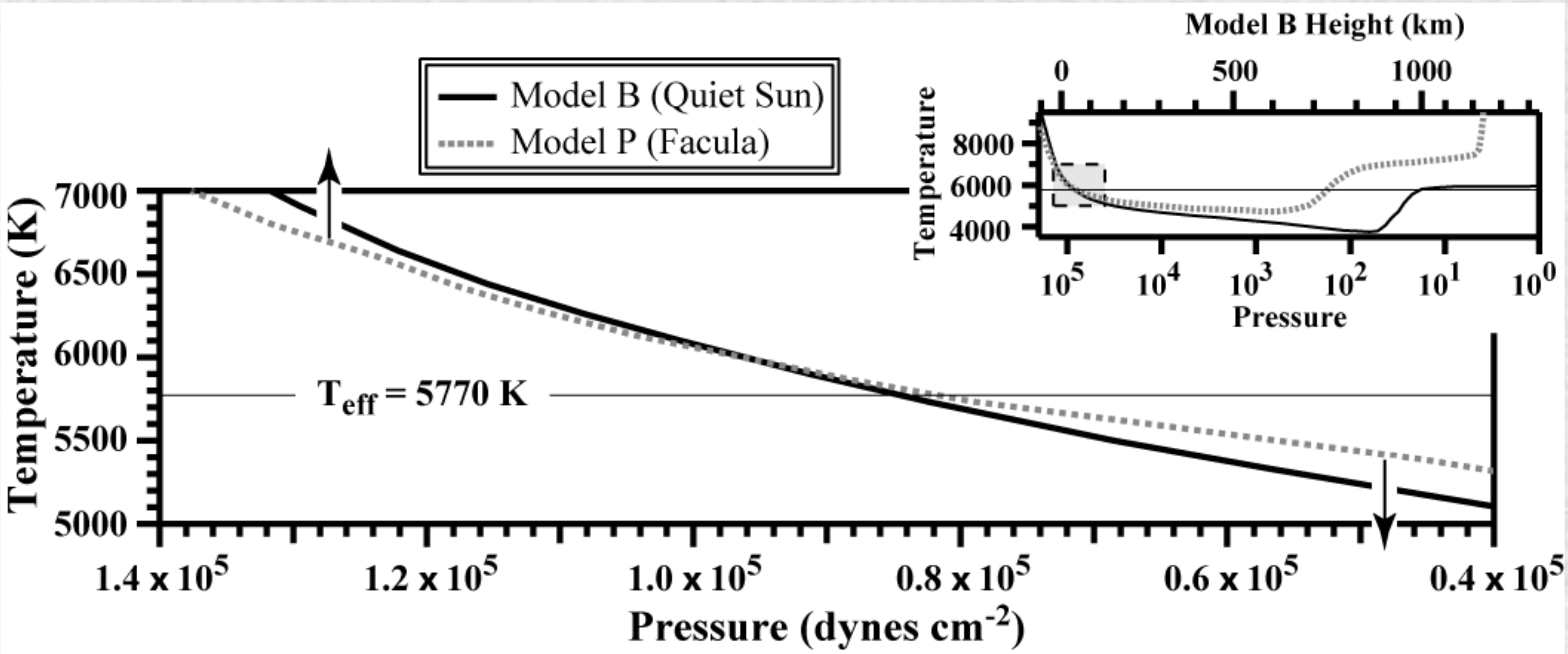
# Time series of solar spectral variability from SORCE:




courtesy J. Harder

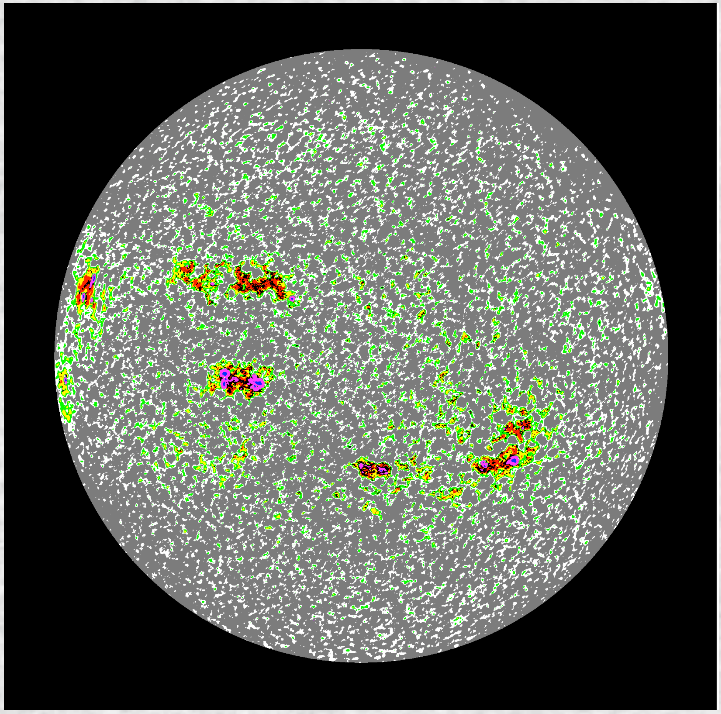
- SIM observations are consistent with an overall decrease in the temperature gradient in the active (magnetic) solar atmosphere

- Crossing point occurs in the solar atmospheric layers that are close to the $T_{eff}$ value

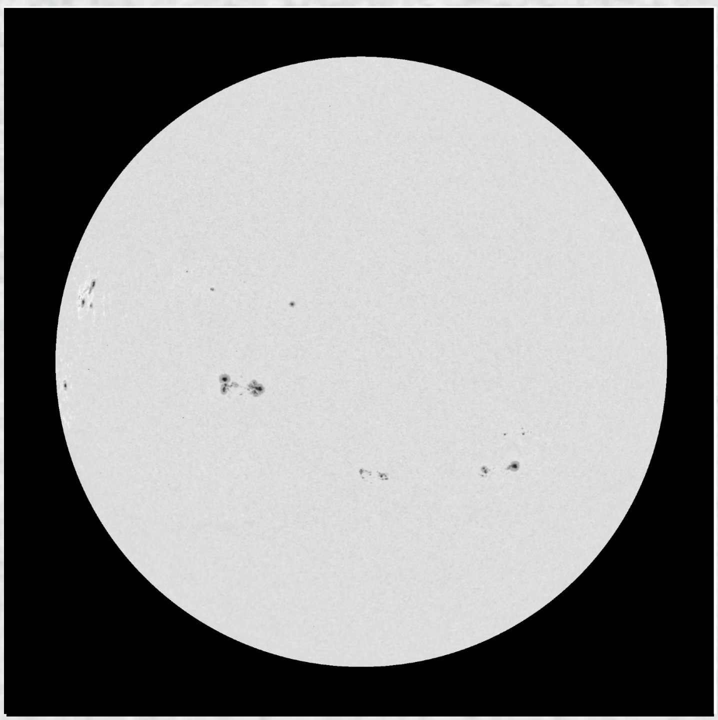


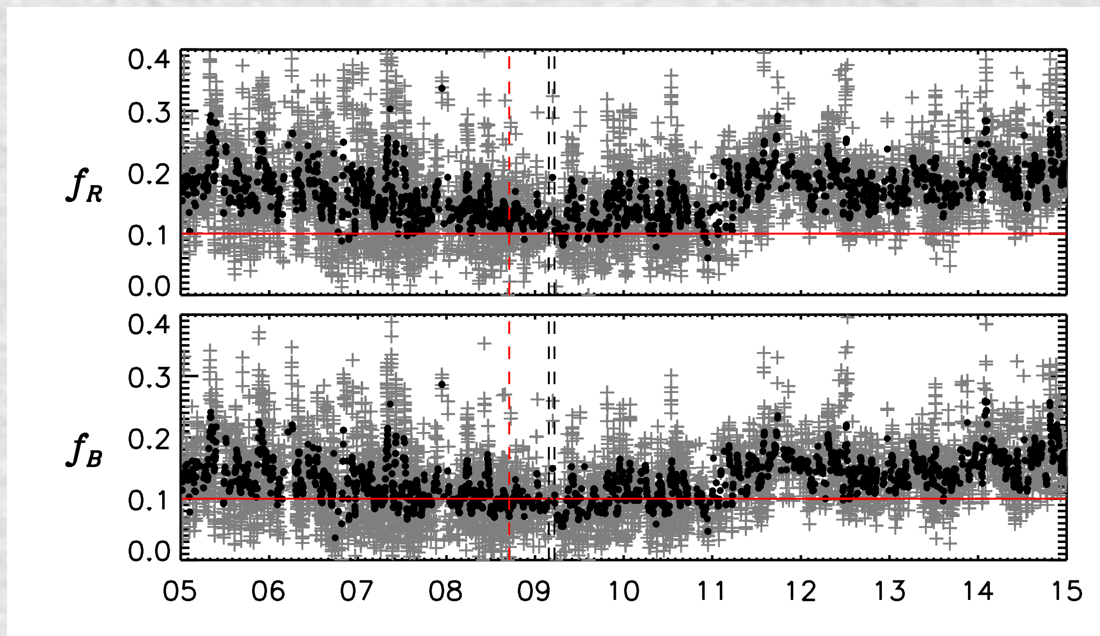

Harder et al. 2009

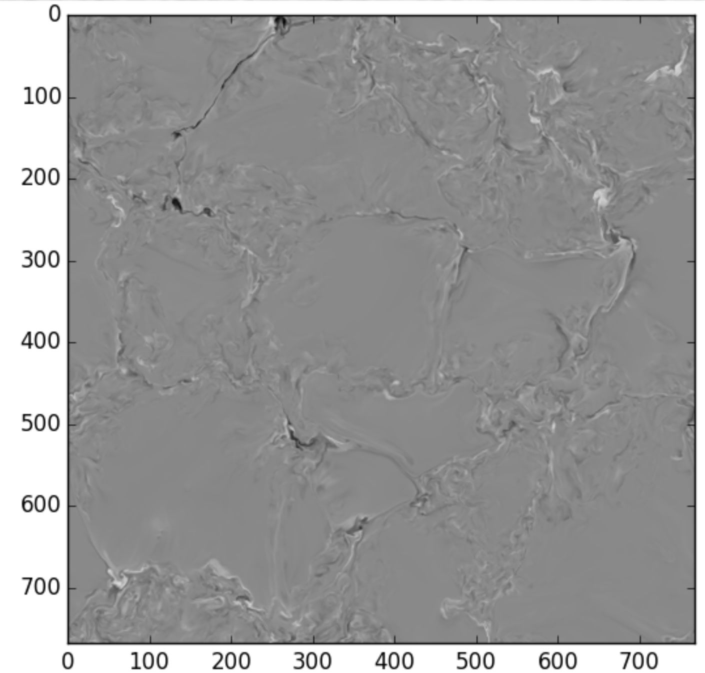
## Not all magnetic structures in the same class have the same contrast

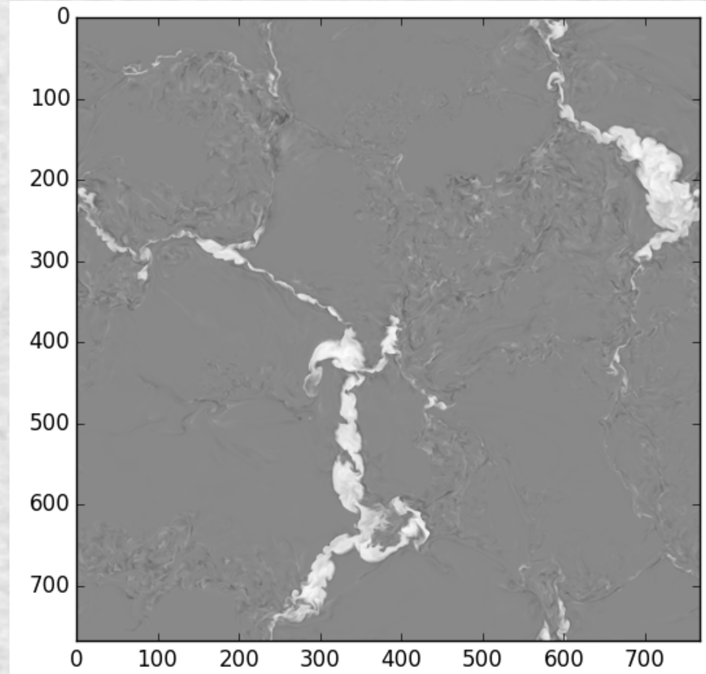


- Some faculae and plage have negative contrast at red continuum wavelengths
- The position of dark faculae on the disk is not a simple function of heliocentric angle
- The fraction of dark faculae decreases into the last minimum and increases out of it








courtesy M. Rempel

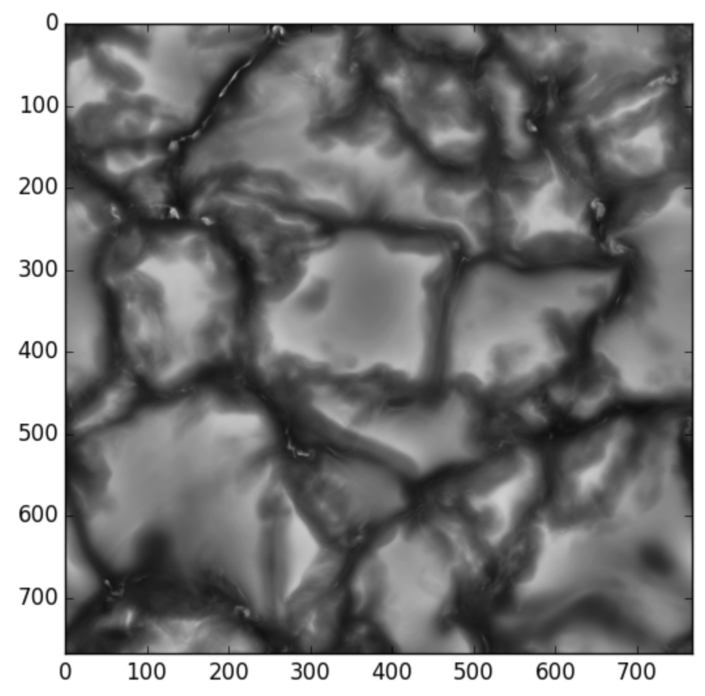
MURaM

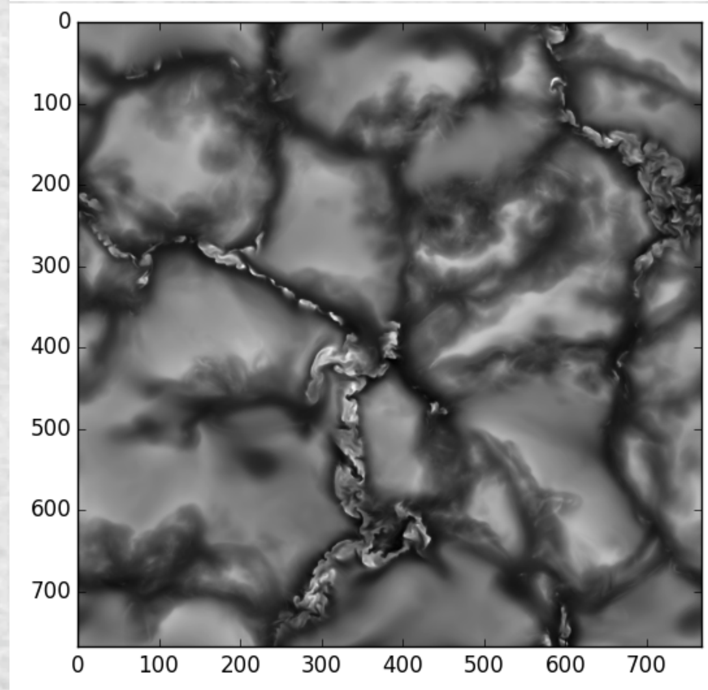
6x6 Mm, 8km grid

Local Dynamo:
80G mean field
(unsigned) in photosphere

Mean field (80G) imposed:
120G mean field
(unsigned) in photosphere

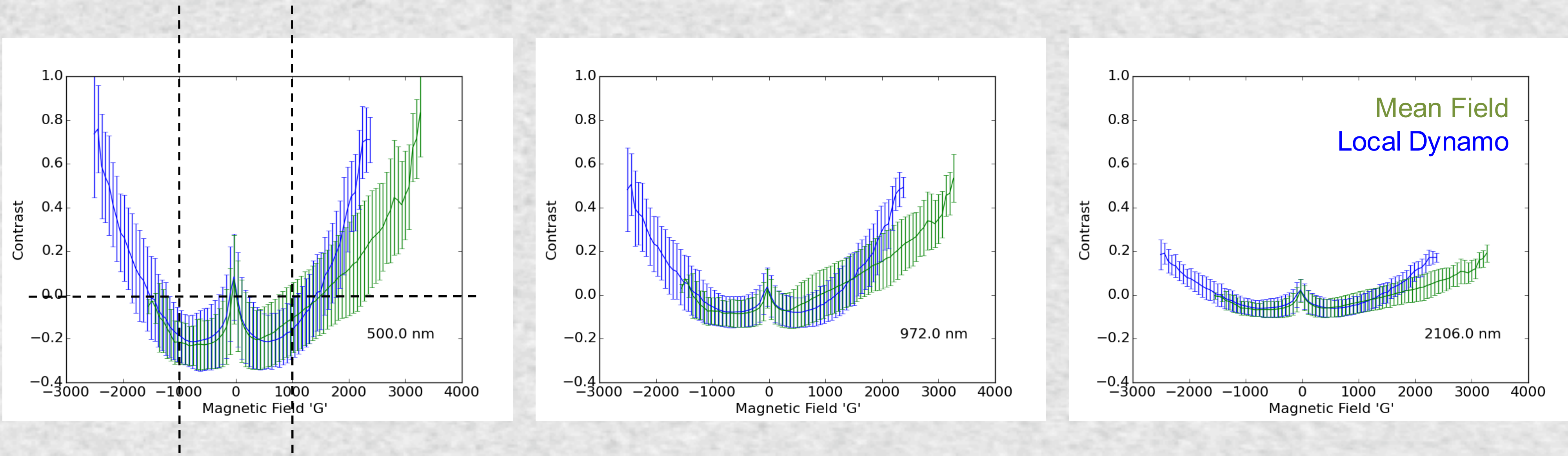
Can 1D model atmospheres capture the spectral irradiance contributions of these structures?



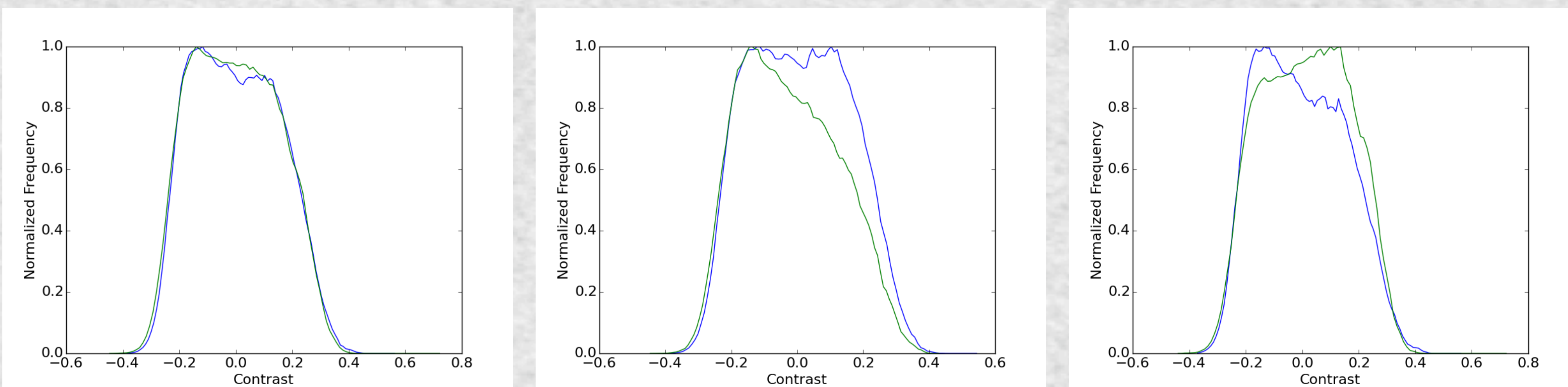



# Radiative output of simulated magnetic structures:

(see poster of Courtney Peck, collaboration with S. Criscuoli)




The contrast of pixels of a given magnetic field strength depends on the "environment" within they are found.




|B| < 1000G    B < 1000G    B > 1000G

# Second possibility:

Changes in the Sun's deep-seated convective flow contribute to global modulation of the Sun's internal thermal structure and variations in the solar irradiance on decadal time scales and longer → From the dynamo point of view need to know how the magnetic field back reacts on the convective transport

Significant constraints on thermal effects:

Thermal time scale (Kelvin-Helmholtz):

- the time it takes for the structure of the solar envelope to adjust to changes in flux

$\tau_t = U/L$

| | | |
|---|---|---|
| for Sun as a whole: | $\tau_t = 10^{41}\,\mathrm{J}/10^{26}\,\mathrm{W}$ | $= 10^7\,\mathrm{yr}$ |
| for convection zone: | $z = 2\times10^5\,\mathrm{km}$ | $\tau_t = 10^5\,\mathrm{yr}$ |
| supergranulation: | $z = 2\times10^4\,\mathrm{km}$ | $\tau_t = 10\,\mathrm{yr}$ |
| granulation: | $z = 2000\,\mathrm{km}$ | $\tau_t = 10\,\mathrm{hr}$ |
| | $z = 1000\,\mathrm{km}$ | $\tau_t = 1\,\mathrm{hr}$ |

The Sun has an enormous heat capacity and consequently enormous thermal inertia

Difussive time scale:

- the time it takes for perturbations to equilibrate by thermal diffusion in the solar convection zone

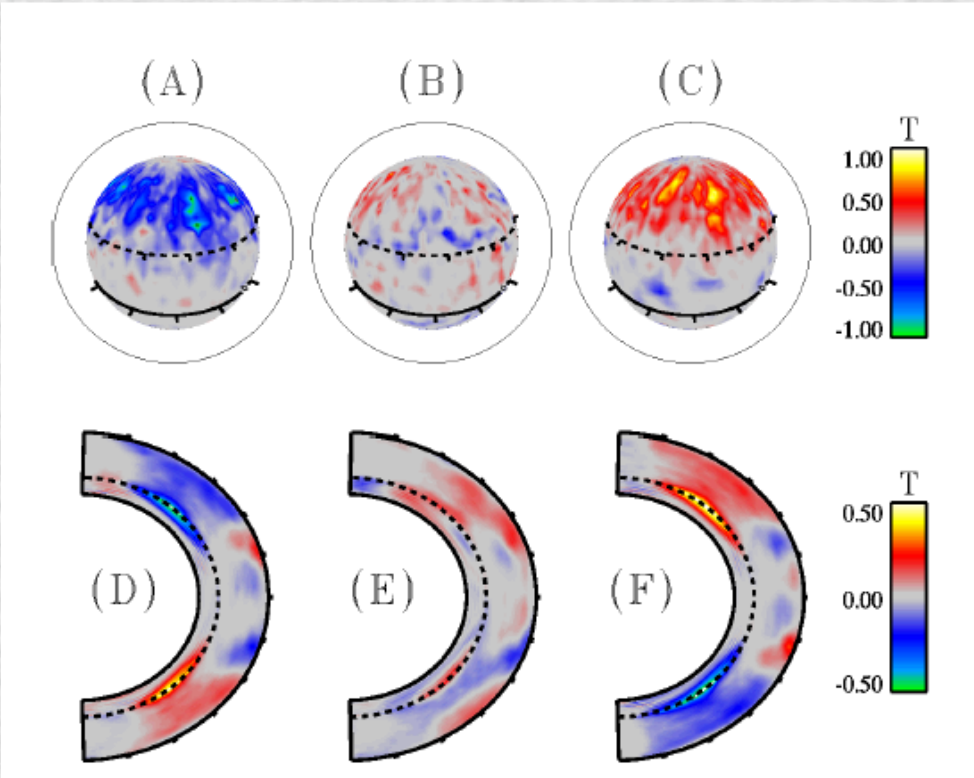
$\tau_d = d^2/\kappa_t$

| | | |
|---|---|---|
| for convection zone: | $d = 2\times10^5\,\mathrm{km}$ | $\tau_d = 1\,\mathrm{yr}$ |
| supergranulation: | $d = 2\times10^4\,\mathrm{km}$ | $\tau_d = 5\,\mathrm{d}$ |
| granulation: | $d = 2000\,\mathrm{km}$ | $\tau_d = 1\,\mathrm{hr}$ |
| | $d = 1000\,\mathrm{km}$ | $\tau_d = 15\,\mathrm{min}$ |

Turbulent diffusion is extremely efficient in the solar convection zone.

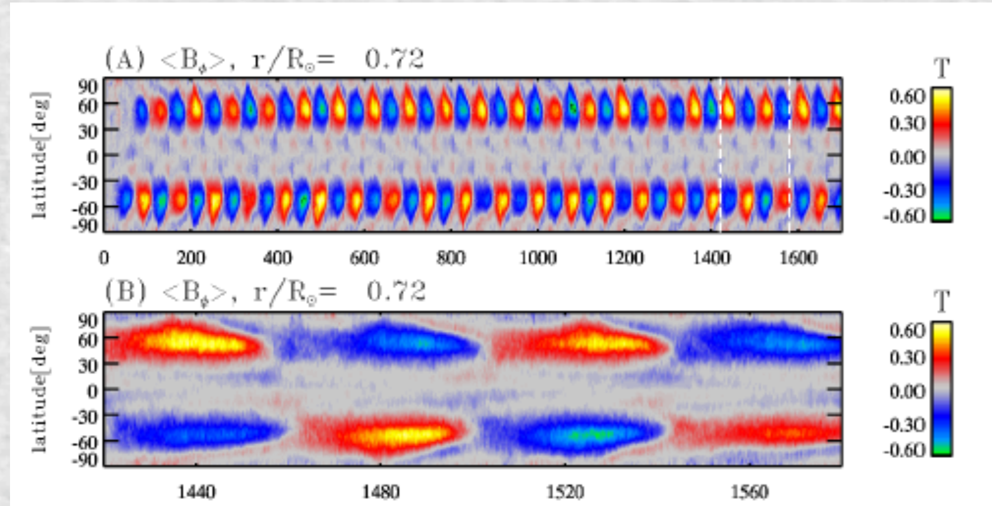
# Global simulations of cyclic dynamo (EULAG – MHD code):

(Cossette et al. 2013, Cossette et al. 2016)



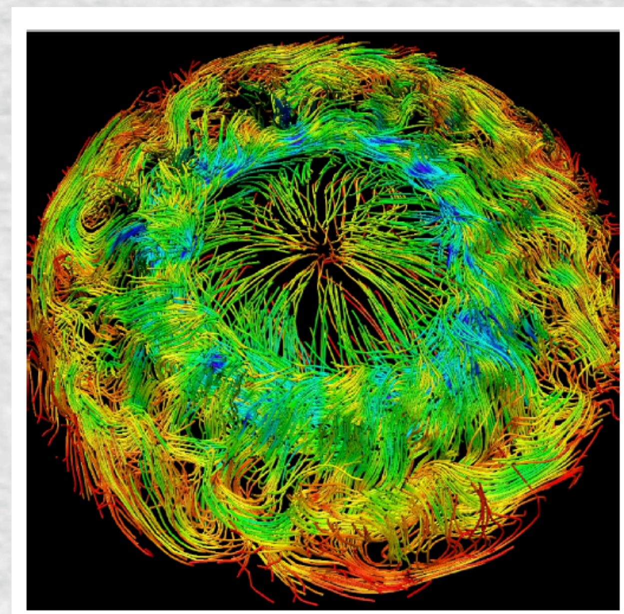

Toroidal field at the bottom of the convective layer (top)

Meridional cross sections of the zonally averaged toroidal field (bottom)

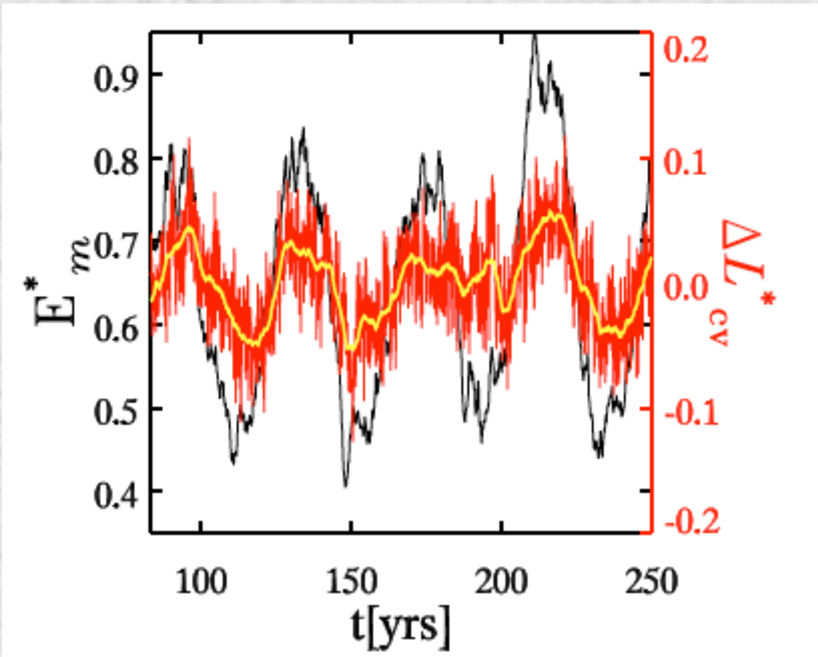


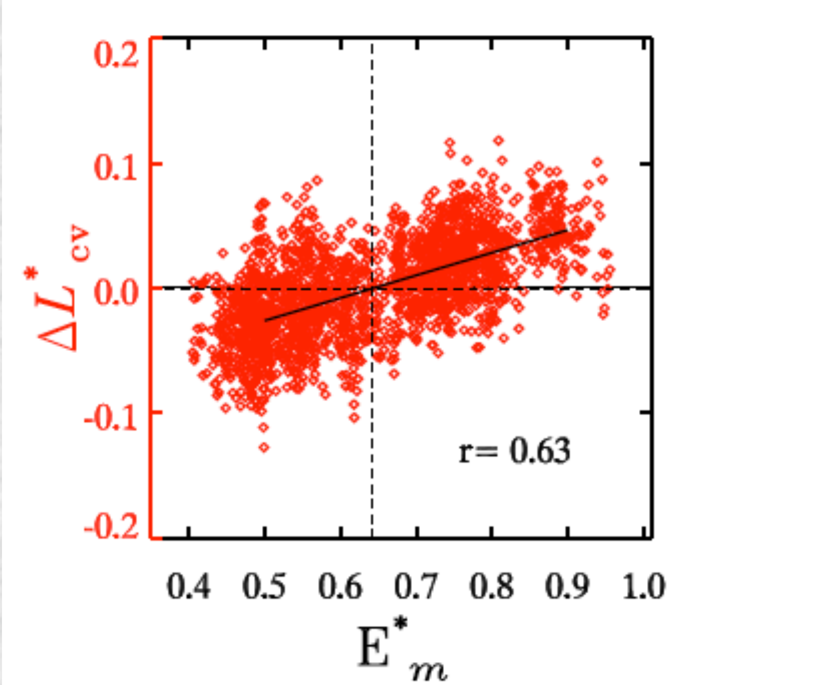

Zonally averaged toroidal magnetic field as fuction of time at the bottom of the convective layer

Periodically reversing kilogauss toroidal flux system at mid/high latitude, peaking in the convective interface



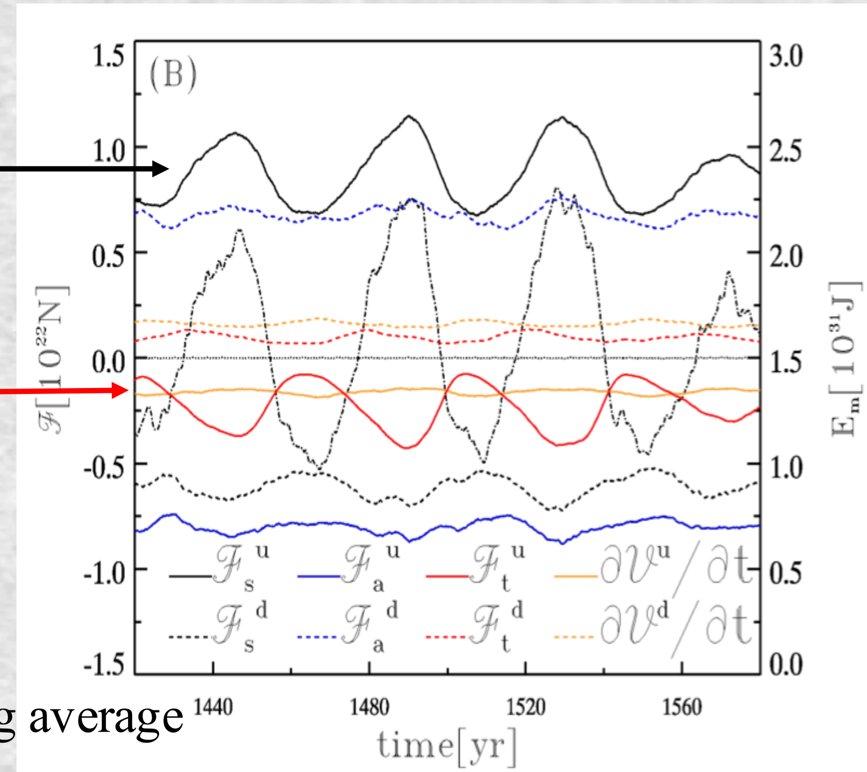
# Magnetically modulated heat transport:




Integrated buoyancy force in upflows

Integrated tension force in upflows




5 year running average
$r=0.76R_{Sun}$

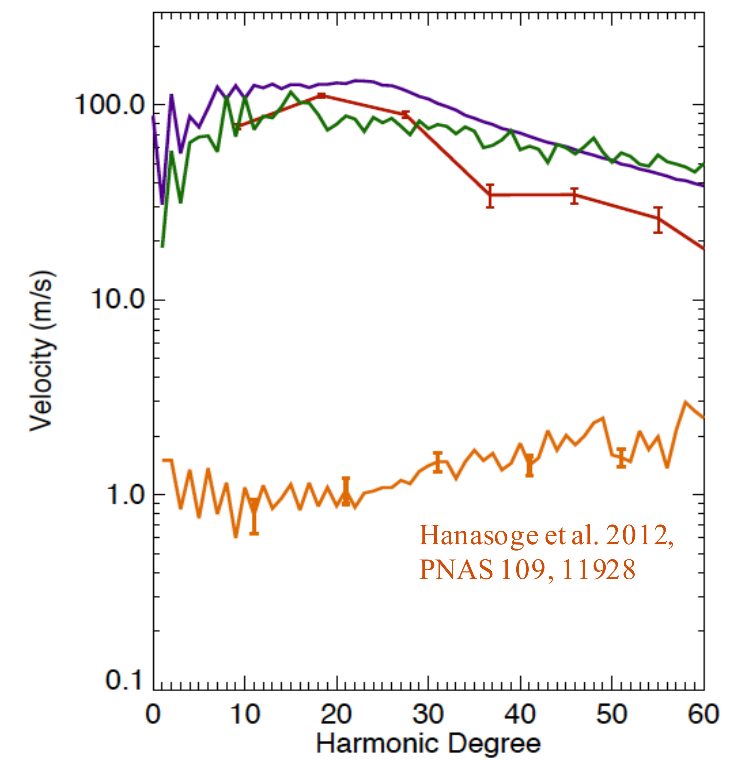
In this simulation

Thermodynamics is slave to dynamics

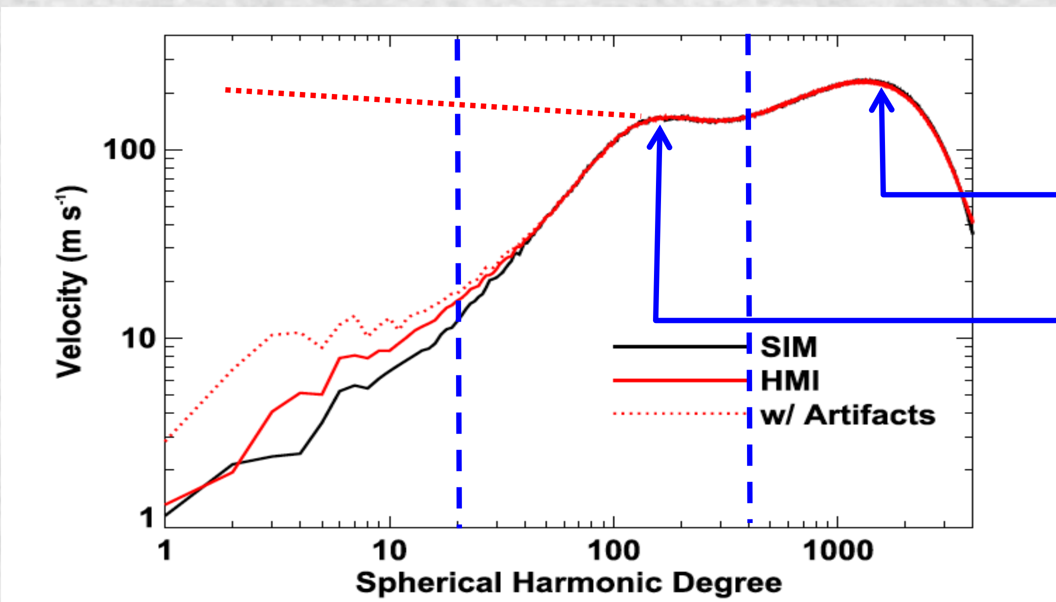
Magnetic tension imbalance inside upflows and downflows perturbs their respective contributions to heat transport enhancing the total convective heat flux at cycle maximum.

# All global and local area models get amplitude of large scale convective motions wrong:

- Models all show increasing horizontal flow amplitudes toward low wavenumber (Giant cell problem)
- Global do not get amplitude of the motions correct at solar rotation rate and luminosity (Rossby number problem)
- Some helioseismic results suggest increase of low wavenumber amplitudes with depth -- all models show decreasing power with depth




Greer et al. 2015, ApJ 803, L17




Hathaway et al. 2015, ApJ 811, 105

Granulation: ~1.2Mm, $\ell$ = 3500

Supergranulation: ~35Mm, $\ell$ = 120

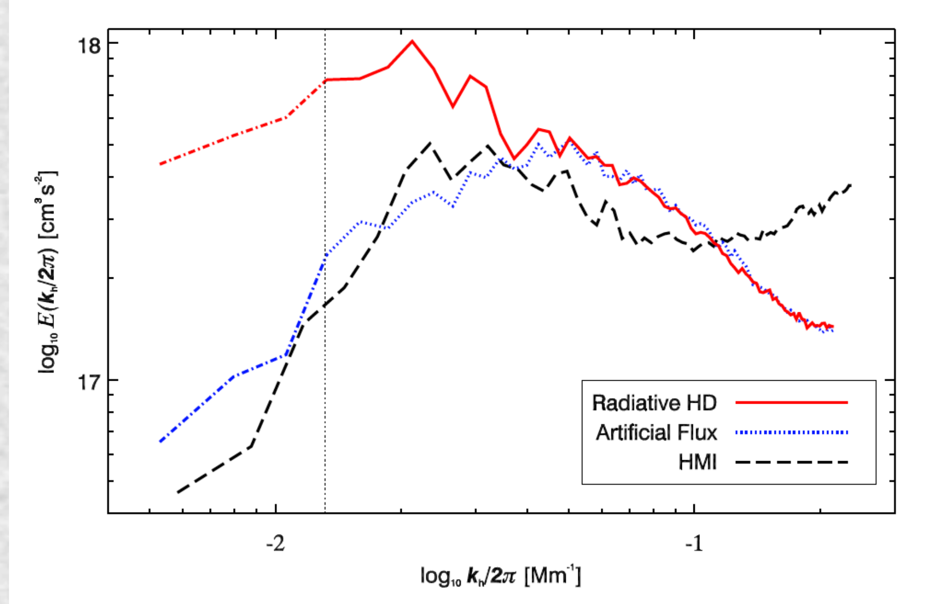
(Mesogranulation: ~10.5Mm, $\ell$ = 400)

Giant Cells: ~210Mm, $\ell$ = 20

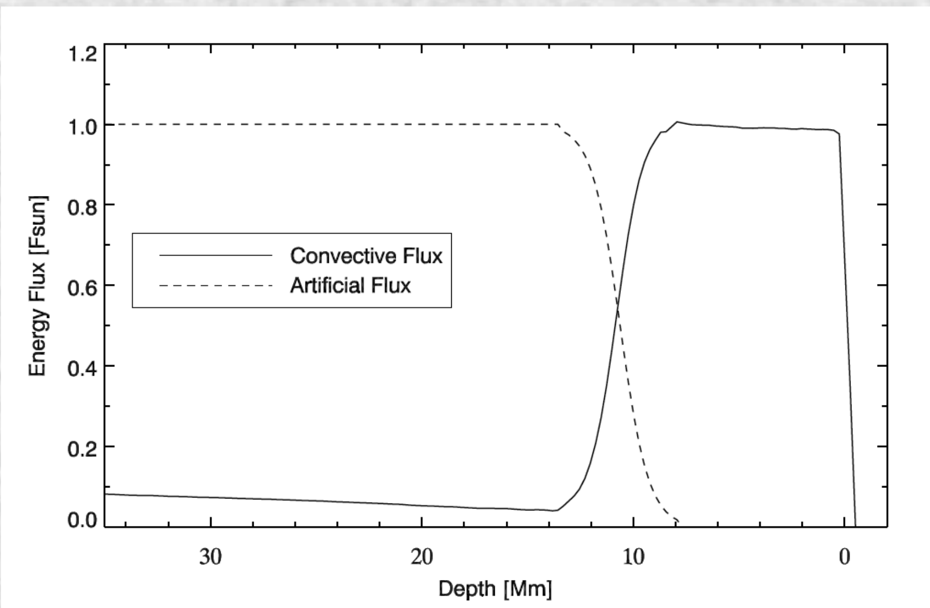
# MURaM Experiment:

(Lord et al. 2014, ApJ 793, 24 )

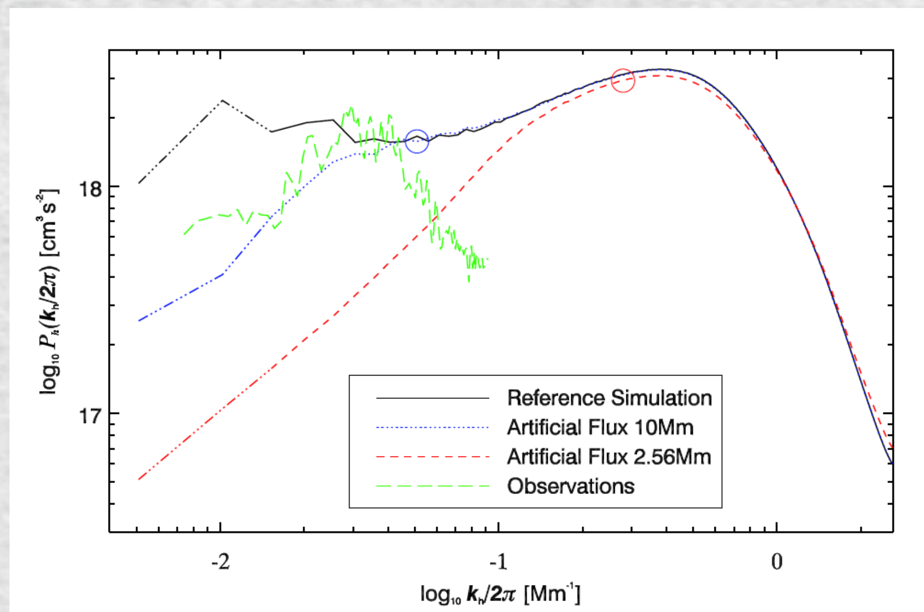
- In stratified convection large scale modes are driven deep (integral scale is ~4 times the local density scale height)
- If Sun is super-adiabatic only in the upper 10Mm ($4H_{rho}$= 20Mm) then observed surface amplitudes are recovered.




Identical structure tracking on data and observations




Artificial flux profile




Turn spectrum over at that scale that corresponds to $4H_{rho}$ bottom of unstable layer

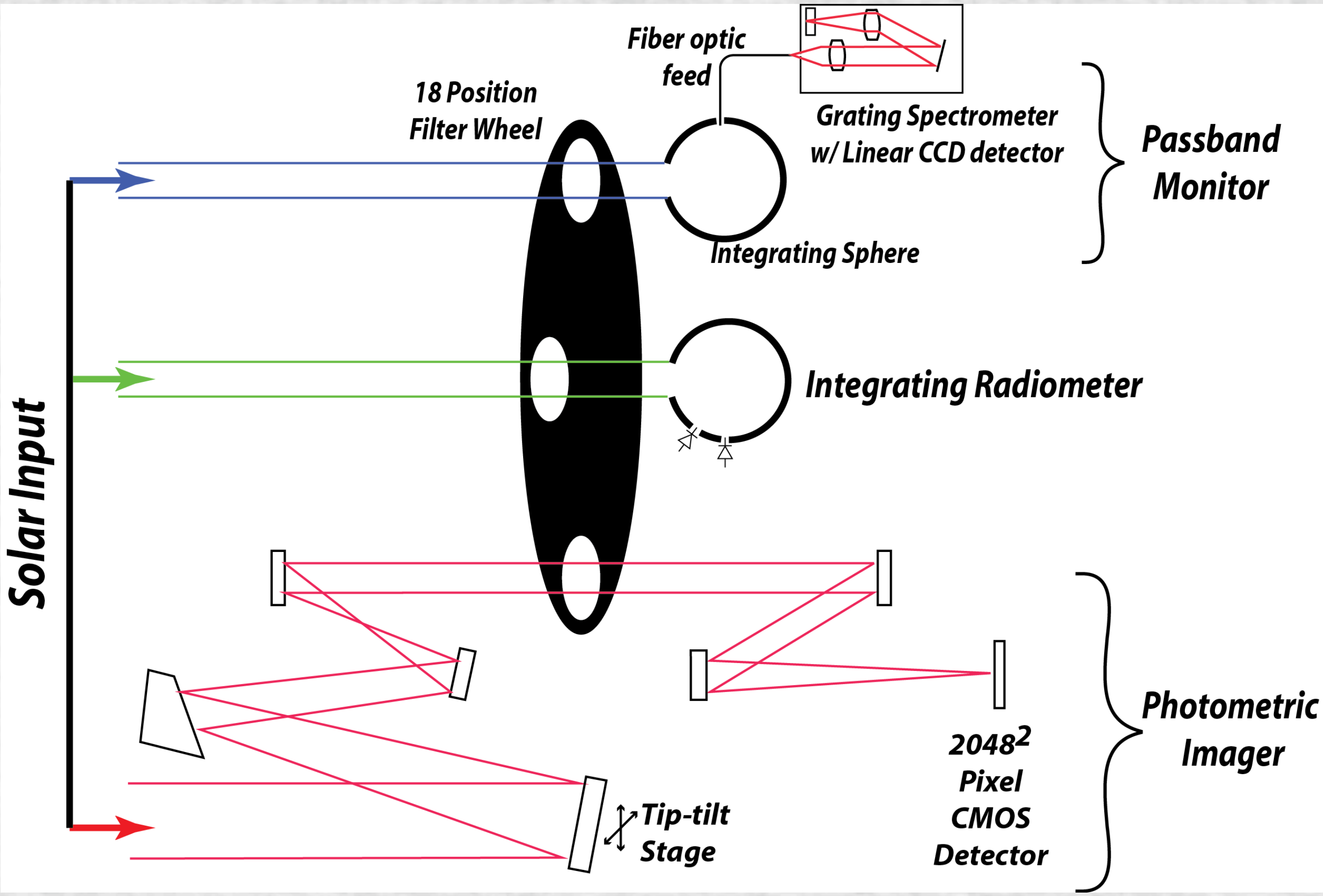
Conclusions:

- Spectral irradiance variations depend on dynamo processes at all scales, non-dynamo interactions of the magnetic field with the flow in the photosphere , and the response of the atmospheric layers

- Irradiance models face fundamental challenges
    - Surface models do not yet account for the significant variability in spectral output if elements that share the same identifying features
    - Global models struggle to reproduce the solar convective spectrum and disagree on irradiance implications of cyclic solutions

# New class of observations needed:

The true center-to-limb profiles of magnetic structures, their contributions to solar cycle irradiance trends, and the role of the quiet-Sun itself can only be determined via absolute radiometric imaging.




Requires balloon or spacecraft platform.

The idea is to normalize an image that has good pixel to pixel relative photometry using the absolute integrated intensity of the light that *should* have come through the filter.