SOLAR LIMB DARKENING: OBSERVATIONS AND MODELS

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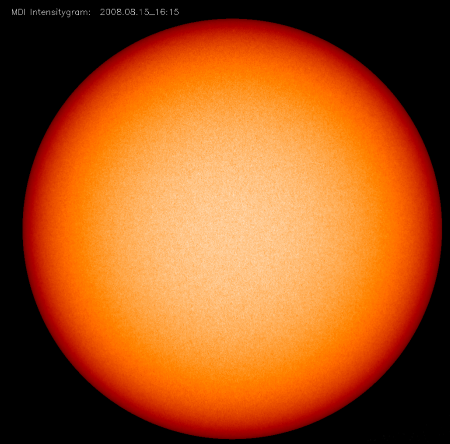
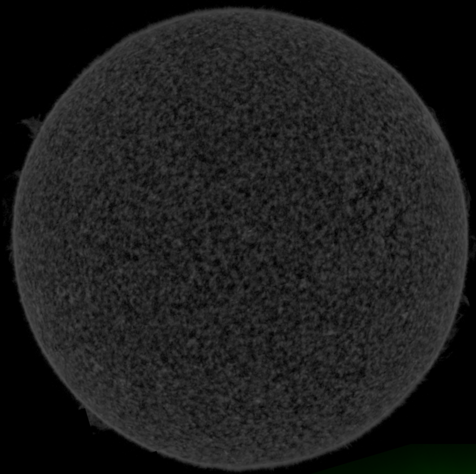
Limb darkening?

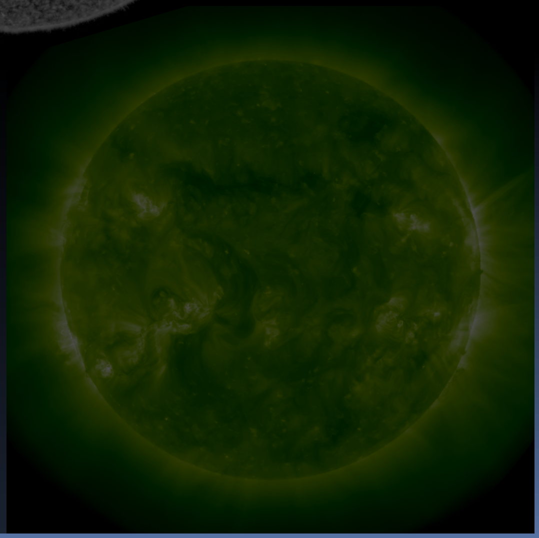
- Limb darkening is very strongly wavelength dependent
- In UV it becomes limb brightening (partly due to the fact that radiation becomes optically thin, partly because temperature above the photosphere increases with height)
- Coronal radiation also comes from above limb: roughly double the brightness



6768 Å continuum (SOHO/MDI)



C IV 1549 Å (SOHO/SUMER)



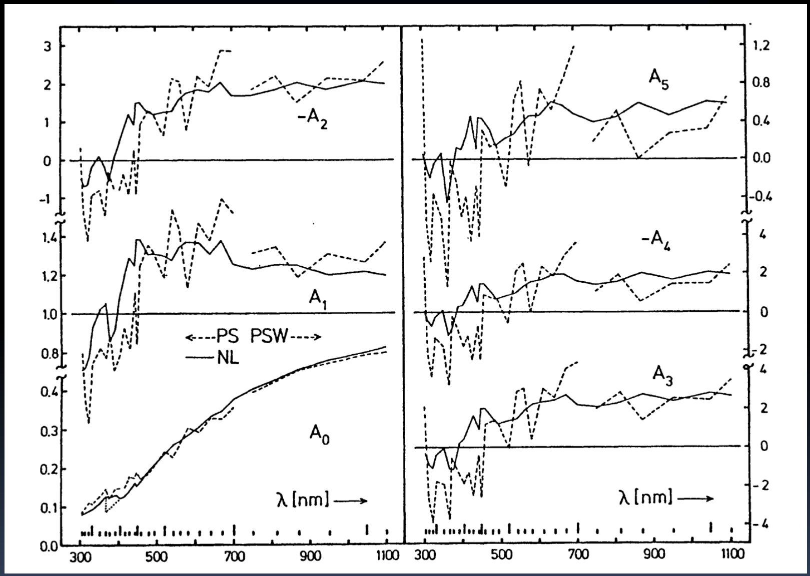
Fe XI 193 Å (SDO/AIA)

Classical observations of limb darkening

- Neckel & Labs 1984, 1994: limb darkening betw. 3033 and 10989 Å (cf. Pierce & Slaughter 1977; Pierce+ 1977, Neckel 1996, 2003, 2005)
- Limb darkening described by 5th order polynomial in μ:

$$\frac{I(\mu)}{I(\mu=1)} = A_0 + A_1\mu + A_2\mu^2 + A_3\mu^3 + A_4\mu^4 + A_5\mu^5$$

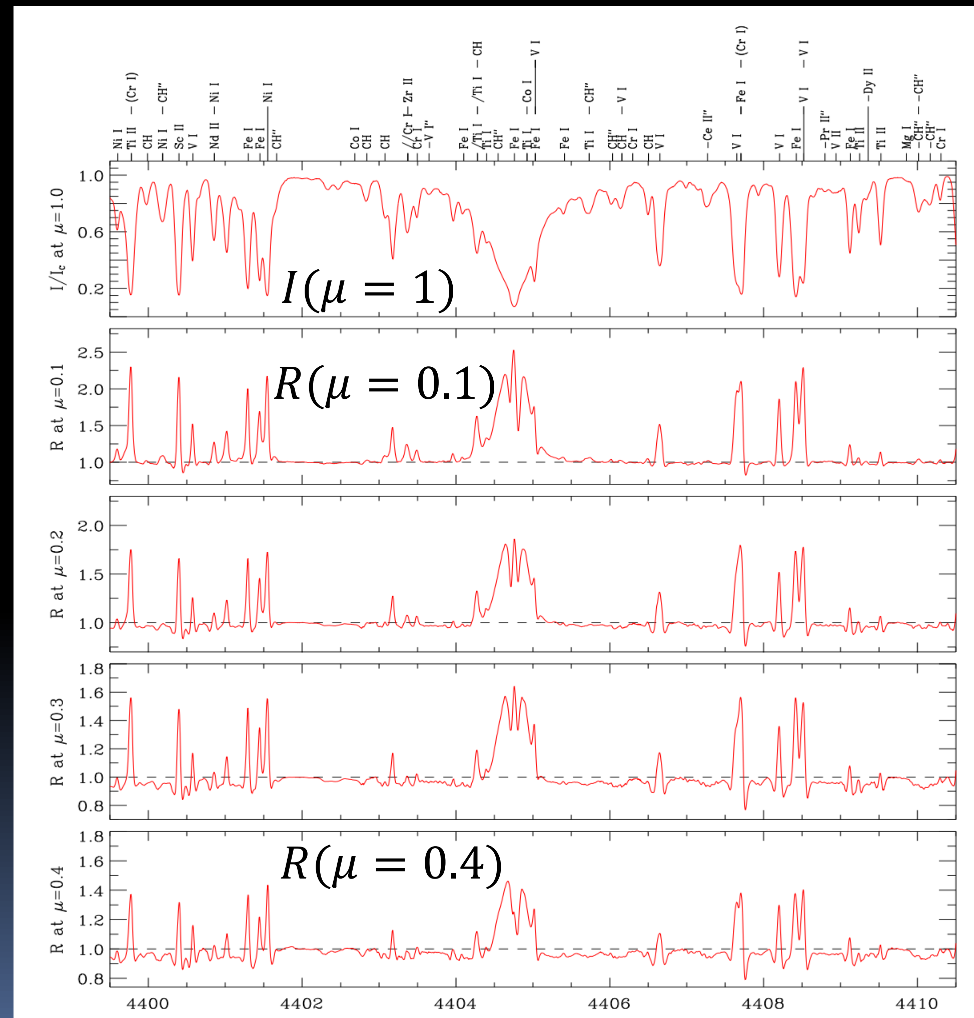
- Careful work. Straylight etc. removed
- Nonetheless this work is 25 years old. Limb darkening is seen as boring and solar scientists are in general not keen to redo such measurements



Neckel+Labs 1994
Solid: their obs,
dashed: Pierce data

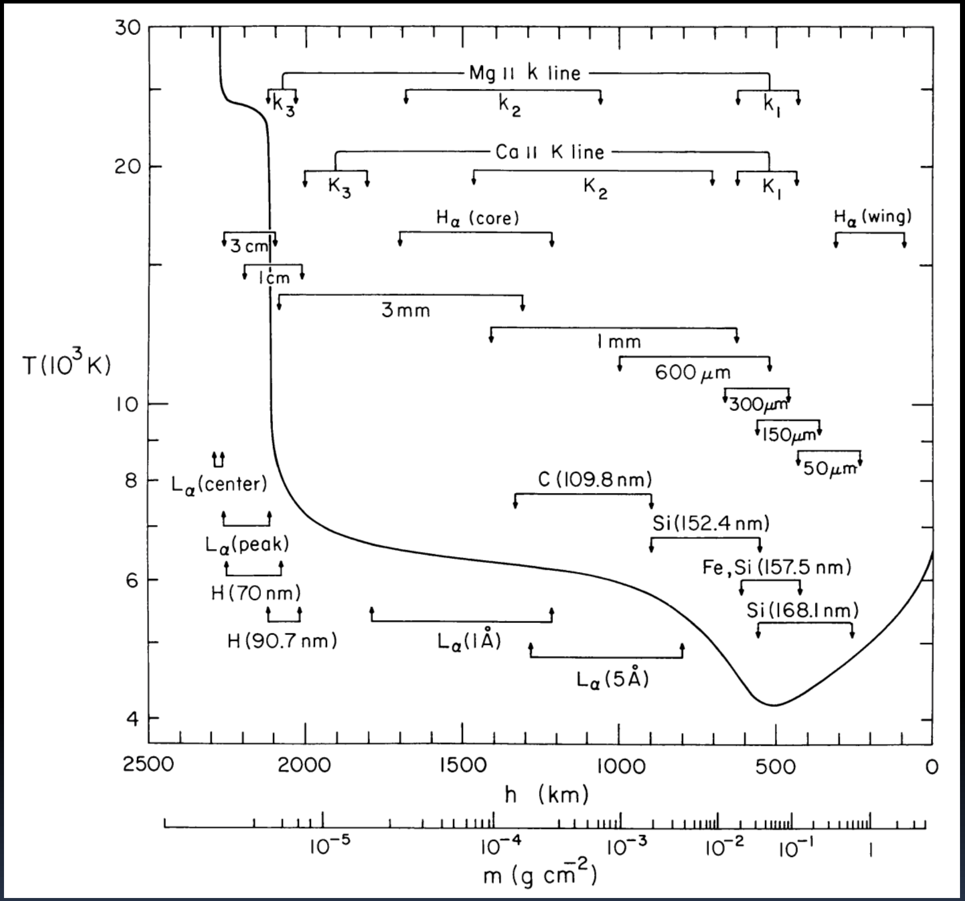
CLV of spectral lines

- Stenflo 2015, Ramelli+2017, 2018
- Determine and plot $R(\mu,\lambda) = \frac{I(\mu,\lambda)}{I(\mu=1,\lambda)}$
- R is a measure of the difference in line depth and width near the limb
- Typically spectral lines are less deep (flatter temp gradient) and broader (large horizontal granular flows) near limb



Atmospheric structure associated with limb darkening

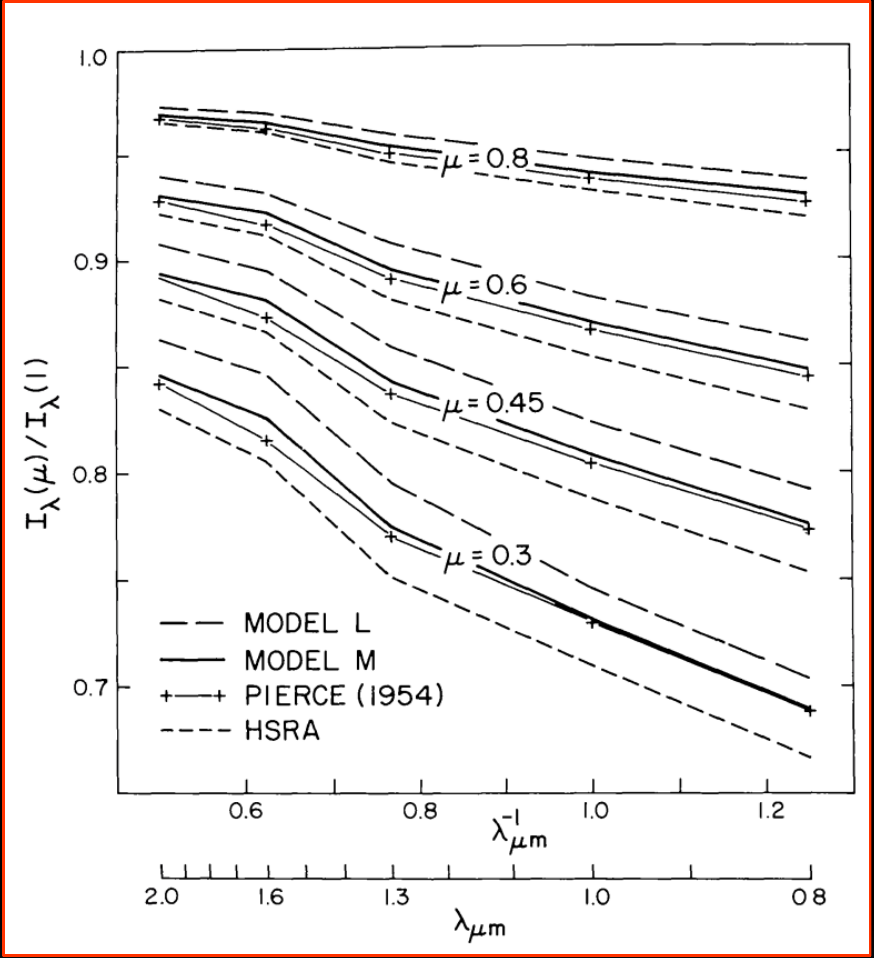
- Drop in temp. with height in photosphere is physical reason for limb darkening
- Reduced line depth near limb due to reduced temperature gradient in upper photosphere
- Above the temperature minimum, the temperature plays a less dominant role in determining the CLV (NLTE effects, including PRD effects)



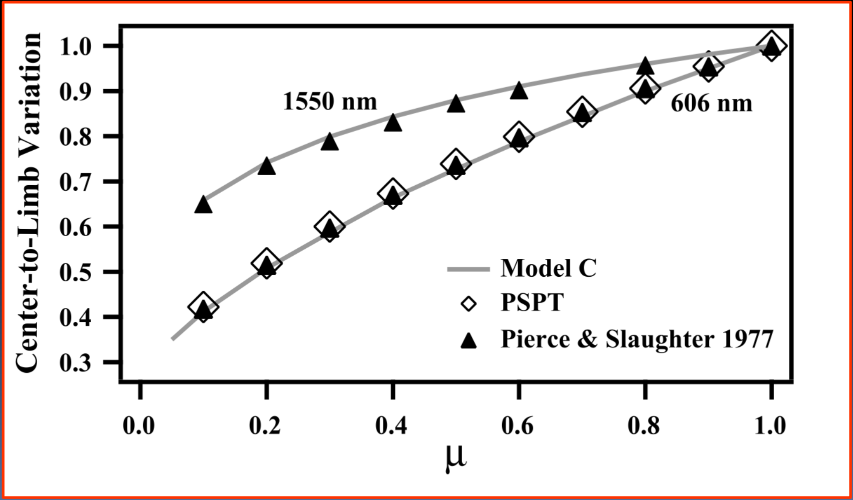
VAL-C: avge quiet Sun model atmosphere
Vernazza+ 1981

1D models

- 1D semi-empirical model atmospheres by Vernazza+, Fontenla+ etc. reproduce limb darkening in red & IR reasonably, but not perfectly
- For MARCS model results (e.g., Gustafsson+ 08, Plez 08) see talk by Bertrand Plez



VAL: Vernazza+ 1976



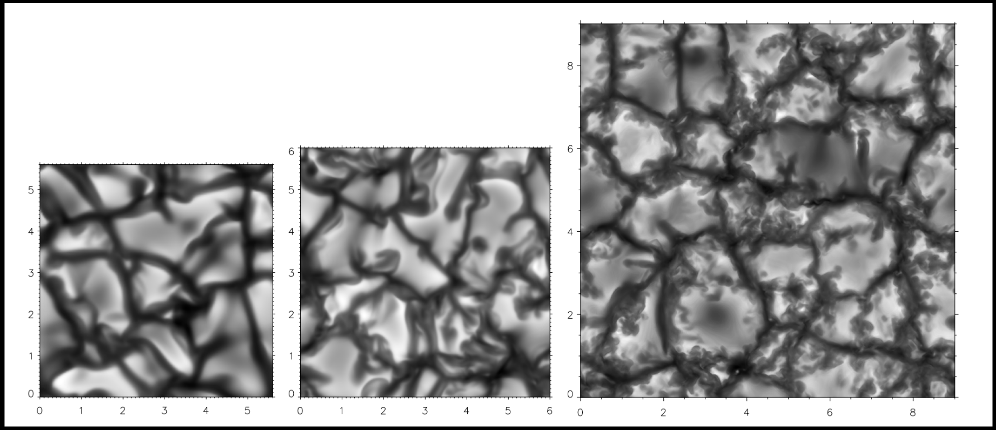
Fontenla+ 2006

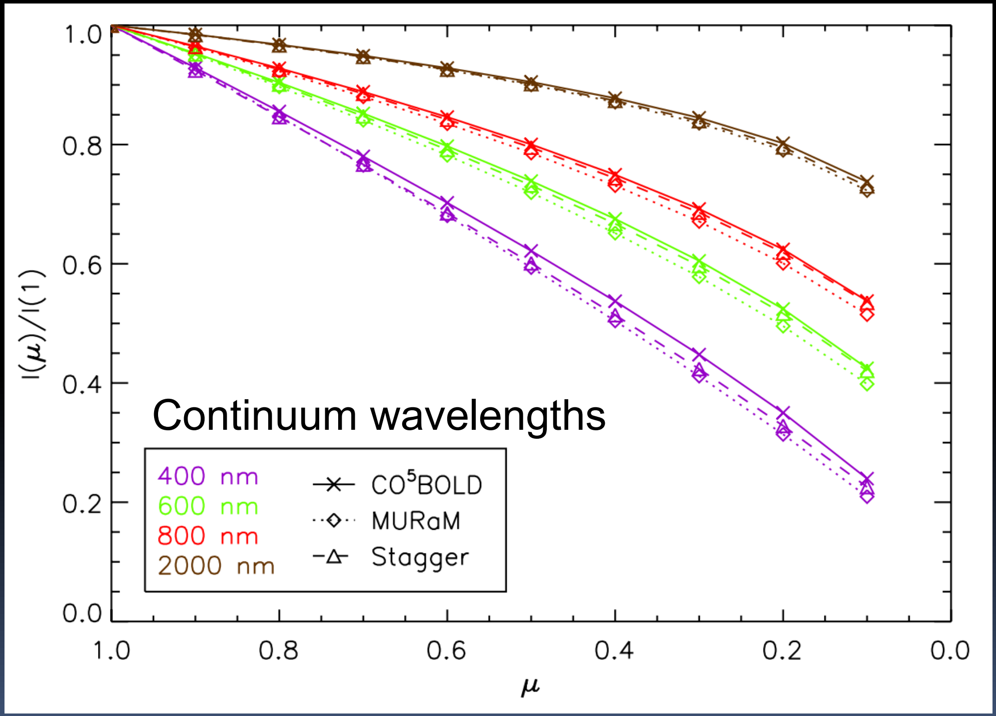
Kurucz atmosphere models: see next slide

Difference between 3D simulations

- Beeck+ 2012: compared CO^{5}BOLD, Stagger and MURaM solar hydro cubes
- Mostly similar results
- Differences: different spatial grids. Horiz. grid: 17.6 km (MURaM), 40 km (CO^{5}BOLD)
- or RT: 4 opacity bins 12 rays in MURaM vs. 12 bins 17 rays for CO^{5}BOLD & 9 rays for Stagger)
- or abundances → Shapiro

CO5BOLD Stagger MURaM

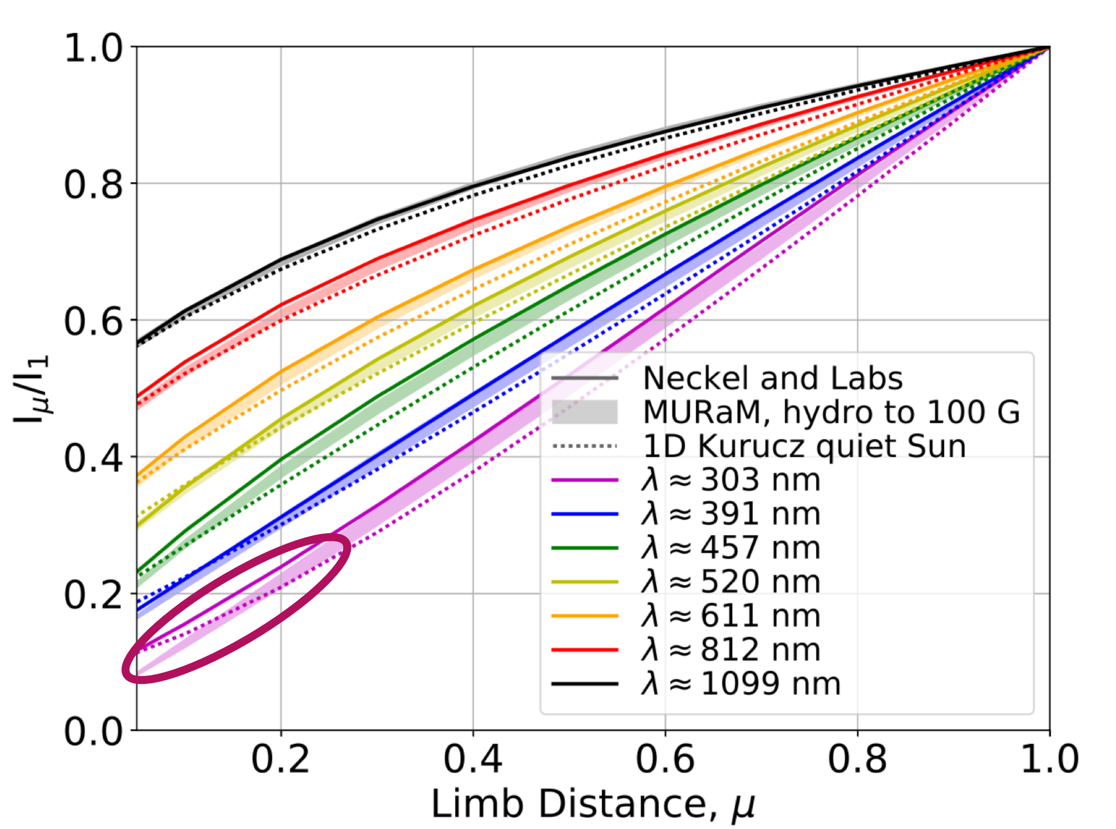




Beeck+ 2012: limb darkening from the 3 tested HD simulations

3D models

- 3D HD/MHD simulation codes Stagger, MURaM, CO^5BOLD were used to compute limb darkening in LTE
- Solar example from MURaM, compared with Kurucz models & Neckel+Labs obs.
- More on 3D limb darkening (e.g. Koesterke+ 2008; Lind+2017, cf. talk by Remo Collet)



Solid lines: Neckel and Labs 1994 limb darkening polynomials

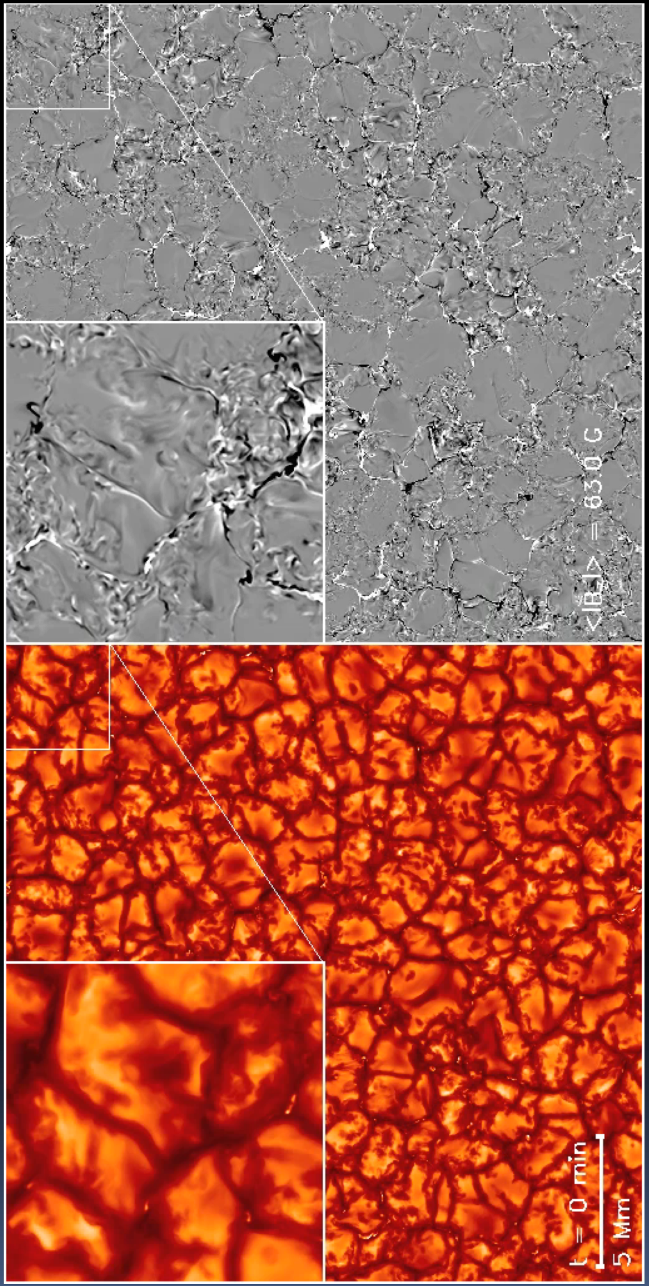
Shaded region: range covered by 0G and 100 G MURaM MHD simulations

Dotted lines: limb darkening from 1D solar Kurucz model

Norris+ 2017; Norris+ in prep

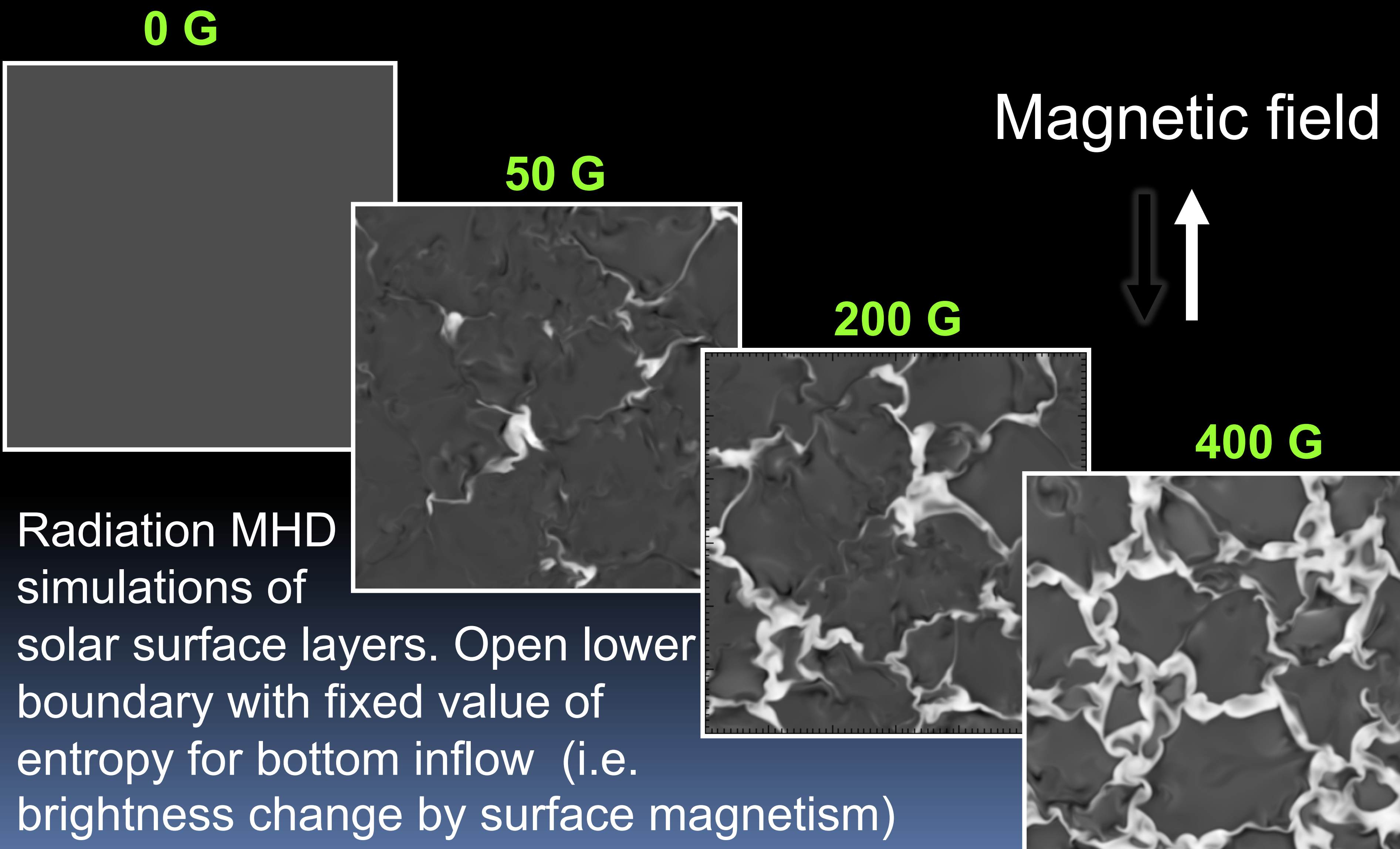
100 G in the quiet Sun?

- Small-scale turbulent dynamo (Schüssler & Vögler 2007; Vögler & Schüssler2007; Rempel 2014, 2018)
- Even when starting with a very weak seed field, a turbulent field on the order of 100 G is built up (Rempel 2014)
- Observational evidence of ubiquitous fields of on average around 100 G: Trujillo Bueno+ 2004; Danilovic+ 2016
- All observations also show a magnetic network on the surface of the Sun



M. Rempel 2014

Effect of magnetic field in 3D MHD simulations



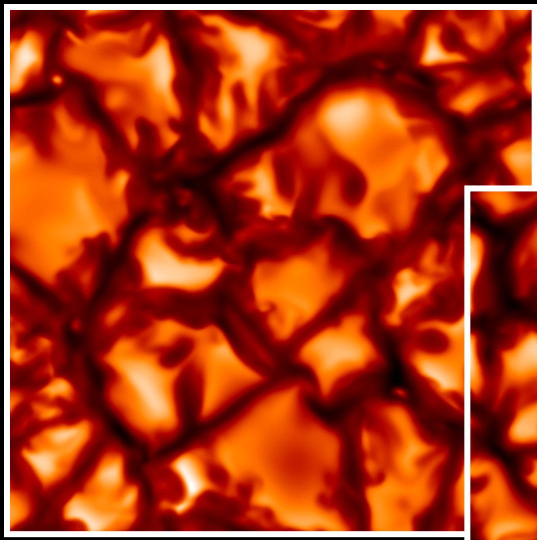
Radiation MHD simulations of solar surface layers. Open lower boundary with fixed value of entropy for bottom inflow (i.e. brightness change by surface magnetism)

Effect of magnetic field in 3D MHD simulations

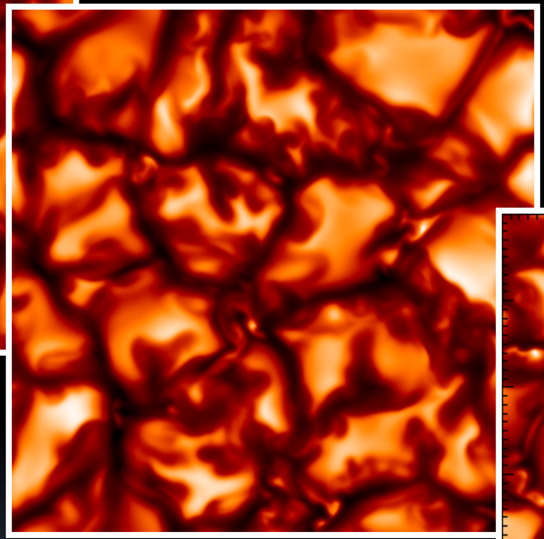
MURaM code, Vögler+ 2005;
Norris+ 2017

Intensity

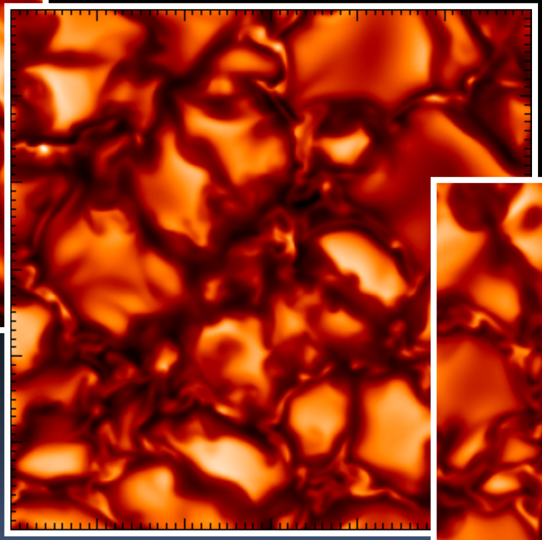
0 G



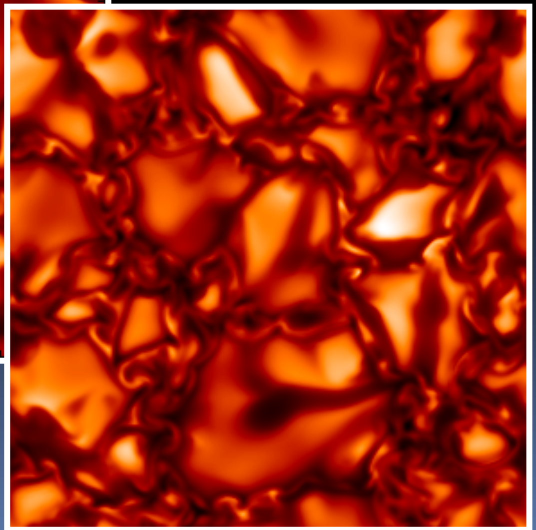
50 G



200 G



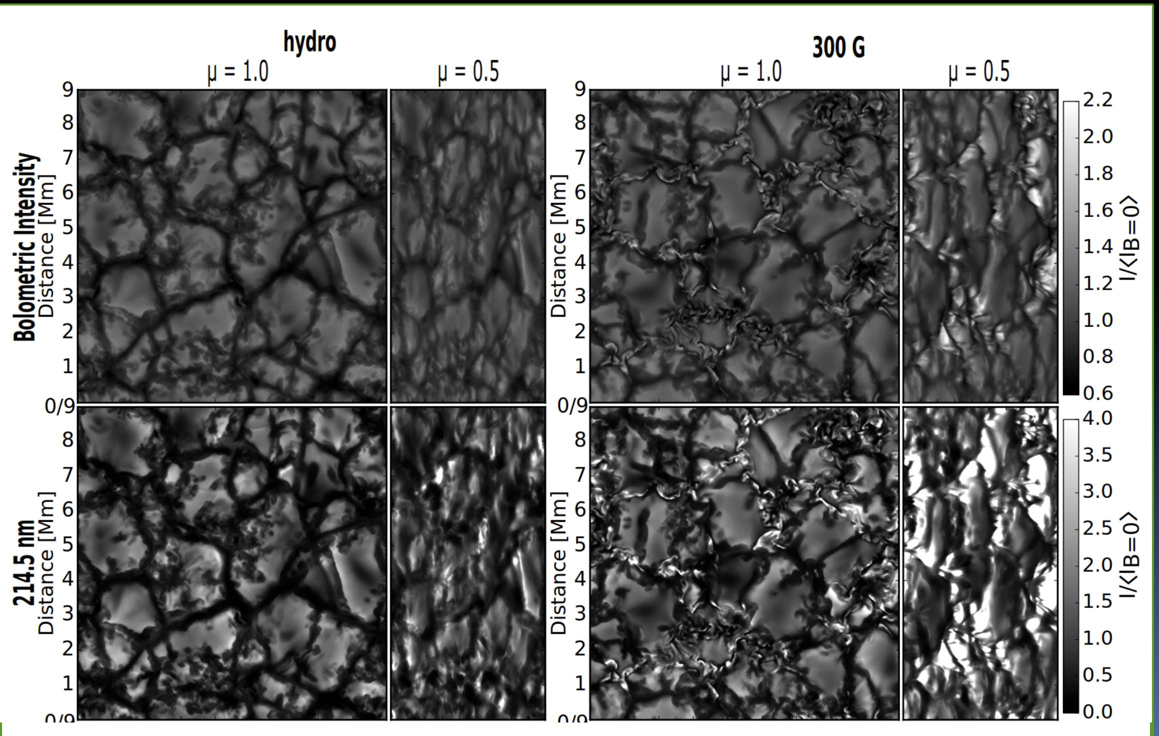
400 G

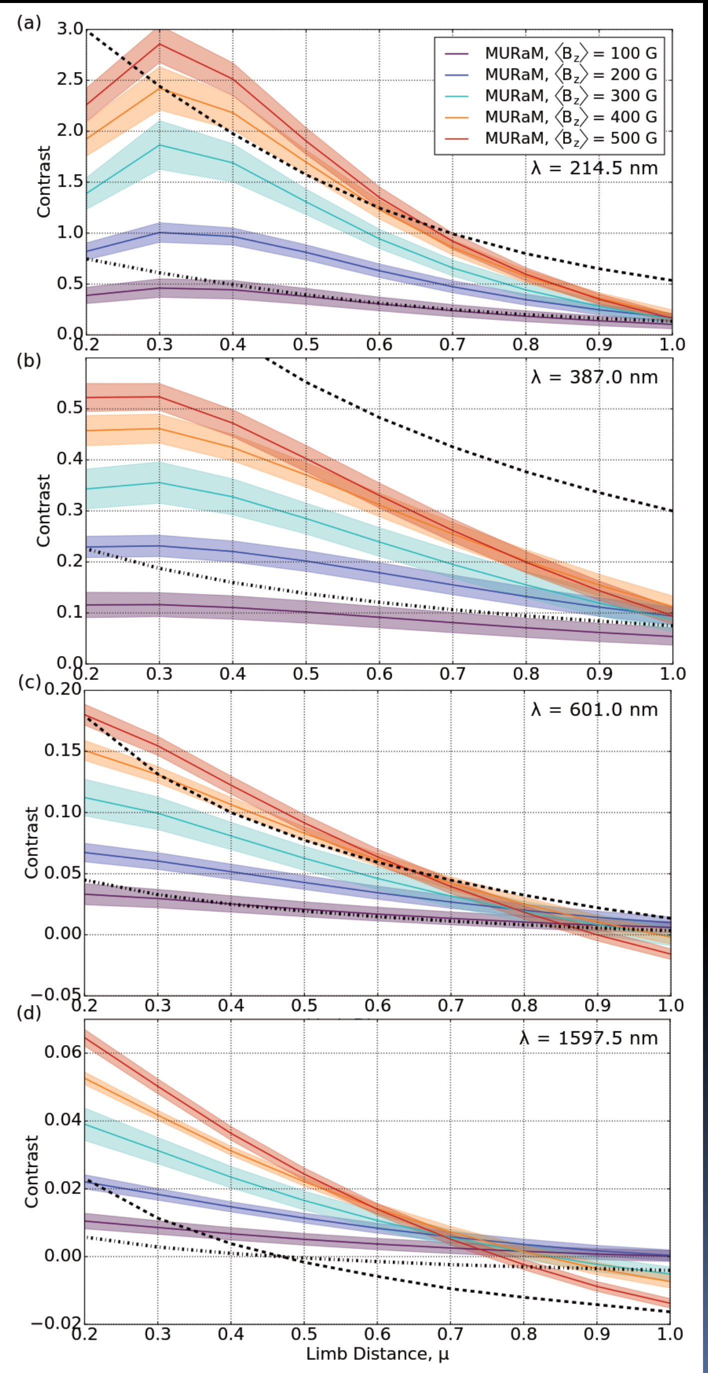


Radiation MHD simulations of solar surface layers. Open lower boundary with fixed value of entropy for bottom inflow (i.e. brightness change by surface magnetism)

Effect of magnetic field in 3D MHD simulations

- Two main effects of small-scale fields: brightening near limb (in continuum) + weakening of spectral lines (all over disc)
- Norris+ 2017

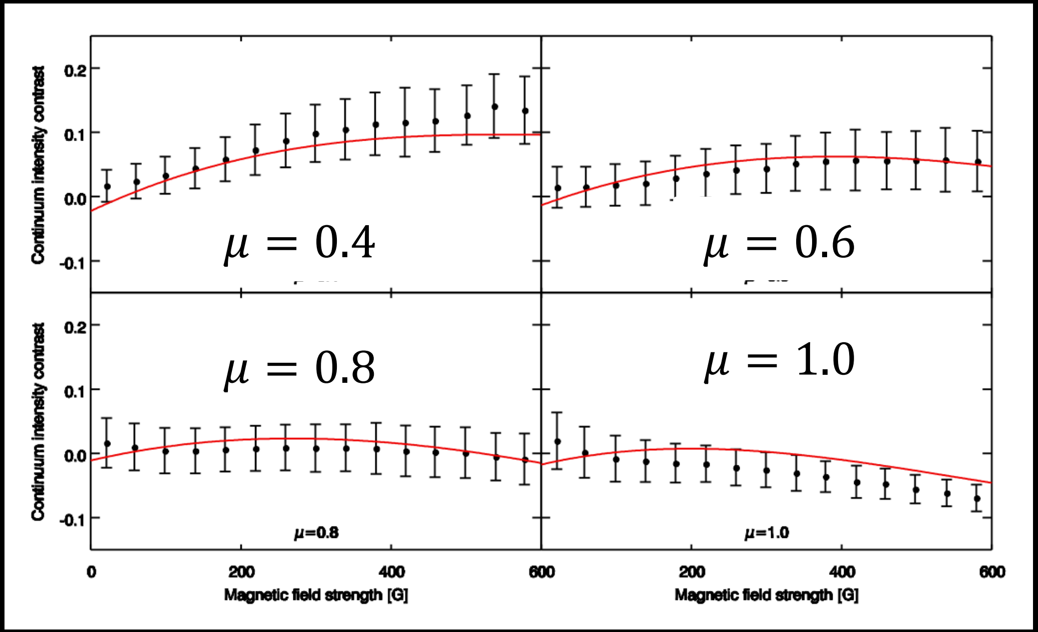




Synthic vs. observed contrast

- Compare the computed intensity contrast in the HMI continuum channel (6173 Å) with observed values
- E.g. plot contrast vs. B for different μ values.
- Put all pixels with similar $B_{\mathrm{magnetogram}}$ in all snapshots of all simulation runs (with different initial $\langle B \rangle$ values) into a single bin

Yeo et al. 2017



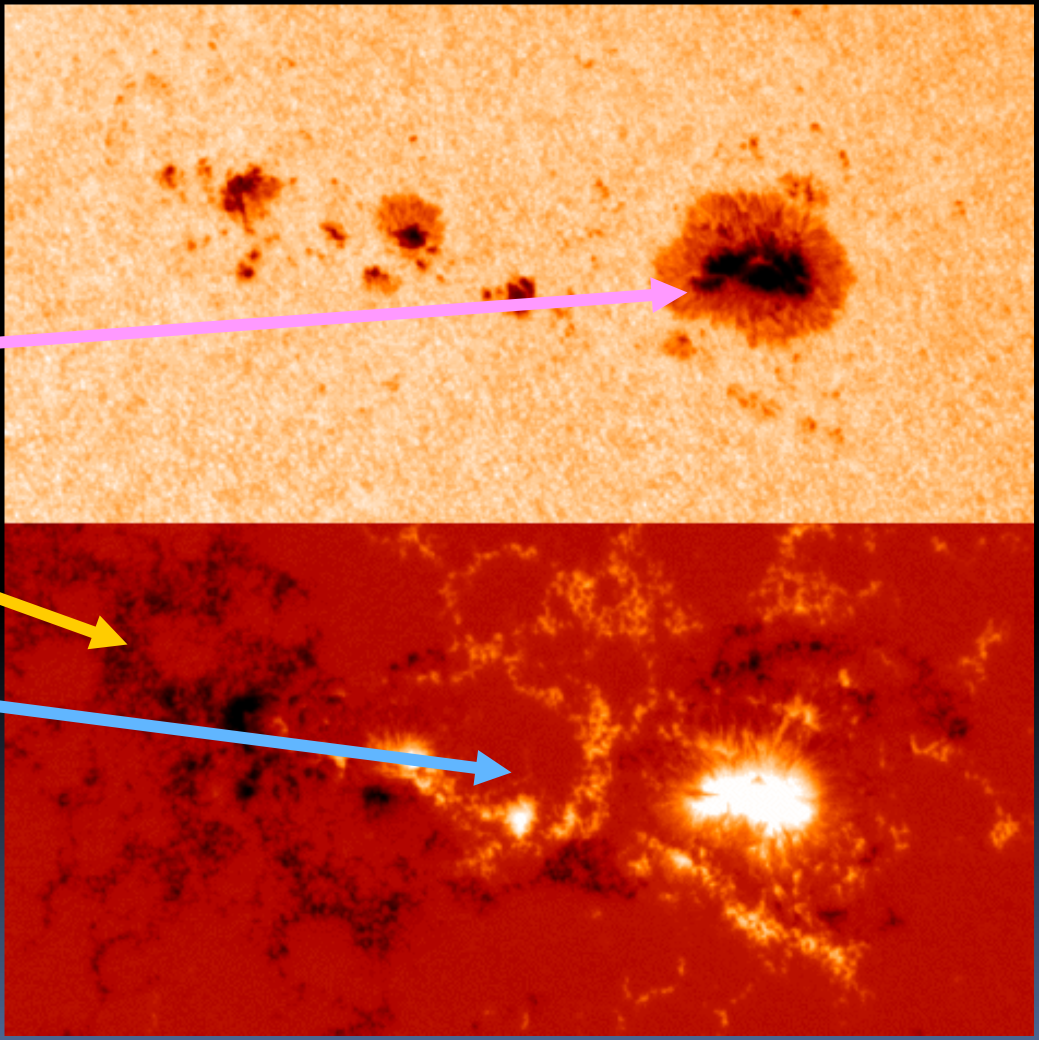
- Red line: fit to observations
- Black symbols: synthetic values + standard deviation
- Agreement between obs & simulations is encouraging

Testing effect of magnetic features. SATIRE: Spectral And Total Irradiance REconstruction

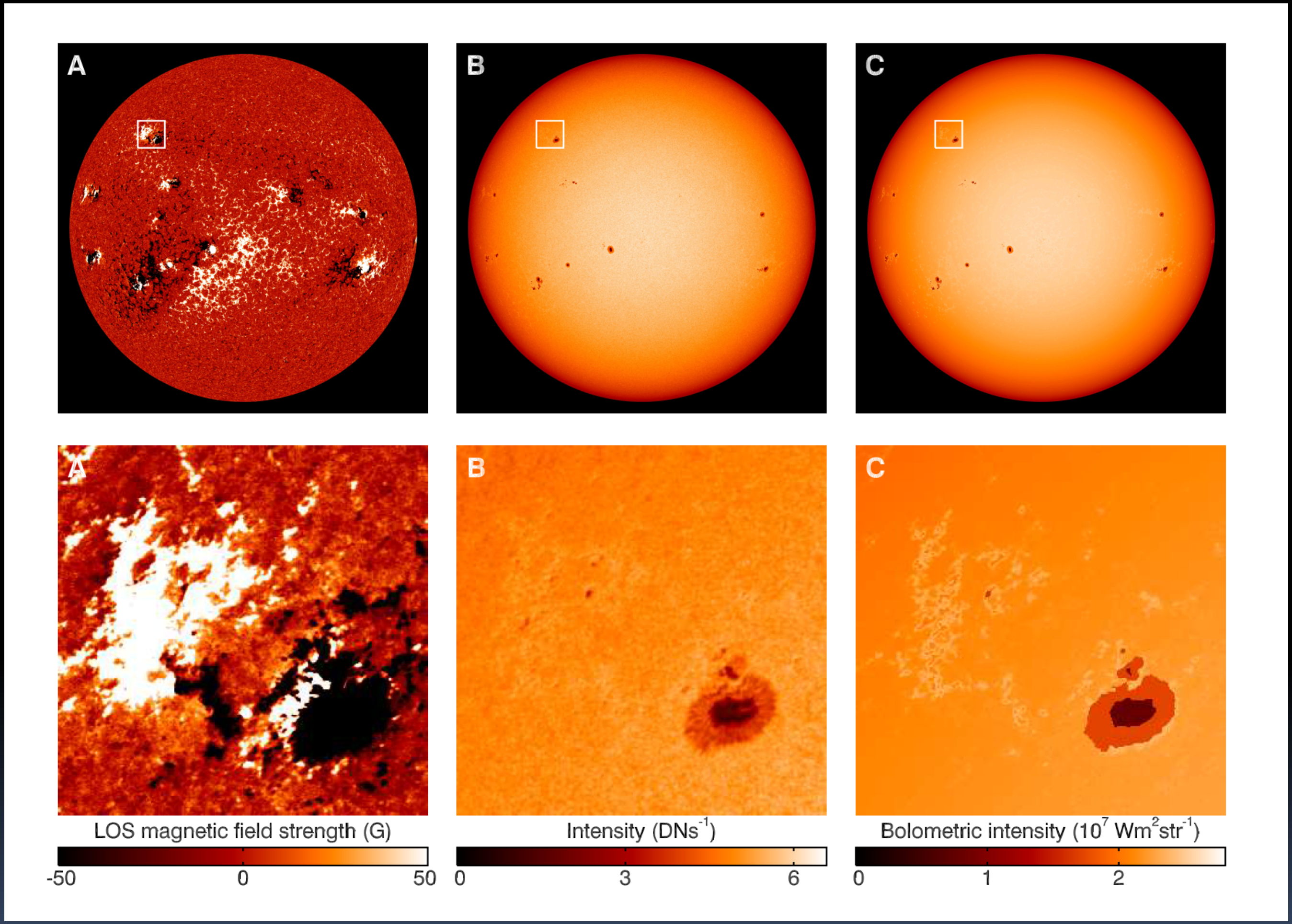
Semi-empirical model with main assumption: B-field at solar surface causes irradiance variations

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

Originally, 1D model atmospheres. More recently replaced by 3D MURaM atmosphere models



From HMI magnetograms to irradiance



HMI Magnetogram

HMI 6173 Å intensity

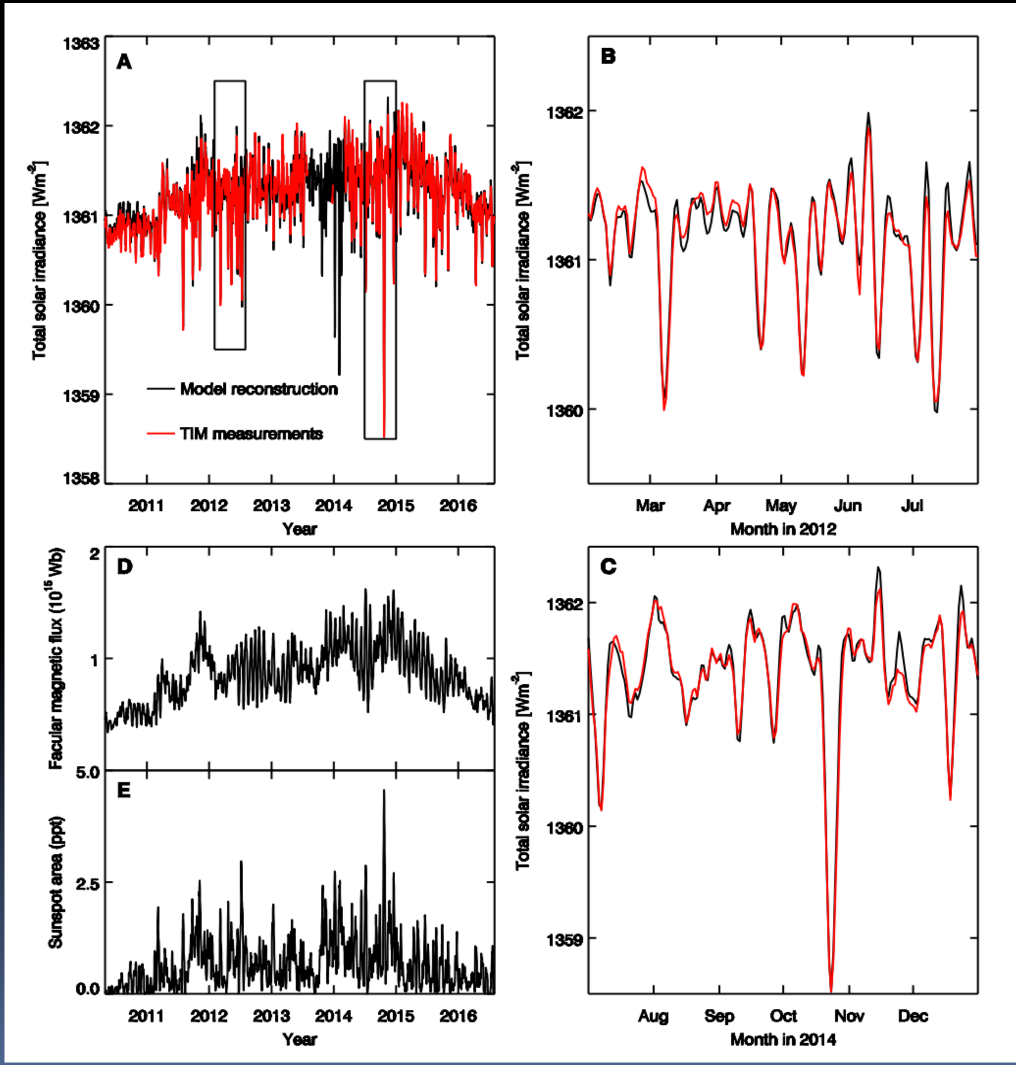
SATIRE 3D bolometric intensity

TSI reconstructions using MHD simulations + HMI manetograms

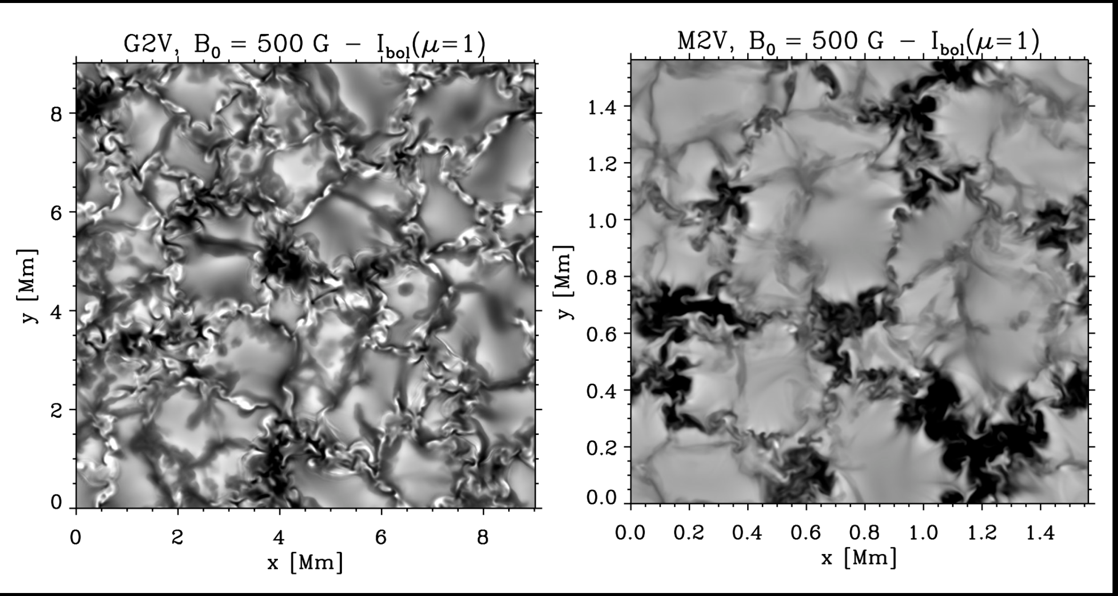
- Using spectra obtained from MHD simulations for different B and μ and SDO/HMI magnetograms, reconstruct the TSI variations without a free parameter

- The reconstruction reproduces TSI data from the SORCE/TIM instrument rather well

Yeo et al. 2017, Phys Rev Lett



Other cool stars



- Large grids of 1D stellar atmospheres and spectra available; computed by MARCS (Gustafsson+2008), ATLAS (Bessell+ 1998, Castelli+Kurucz 2004), Phoenix (Hauschild+ 1999, Husser+ 2013) → Bertrand
- Stellar 3D hydrodynamic model atmosphere grids available; computed by Stagger (Magic+ 2015) & CO^5BOLD → Remo
- Stellar 3D MHD model atmospheres available; computed by CO^5BOLD and MURaM (Norris+ in prep)

Thank you for listening