Towards the next generation of solar irradiance models

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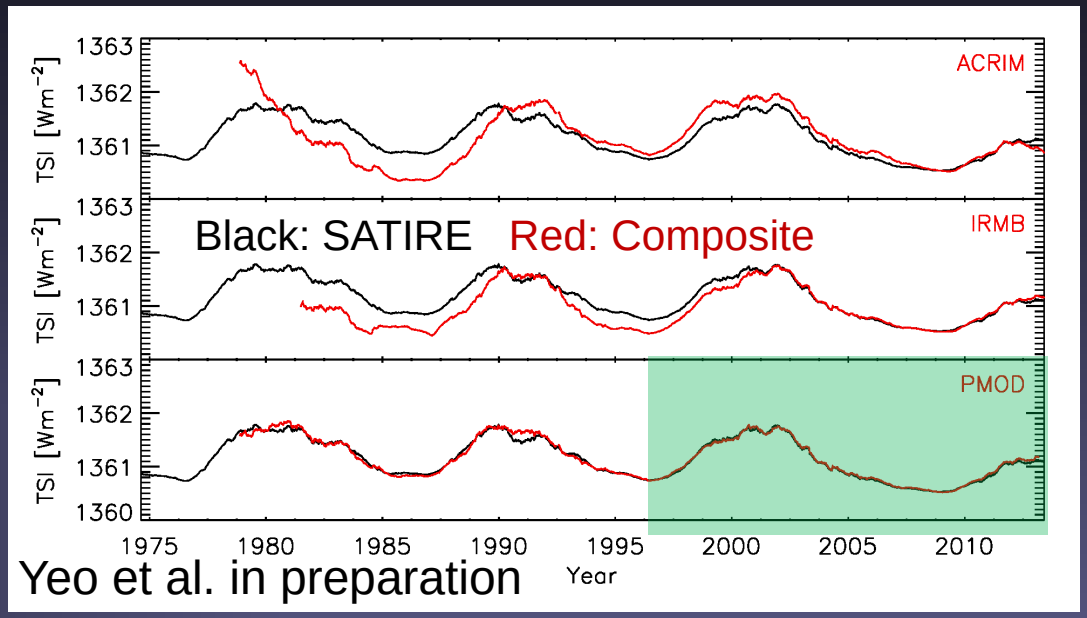
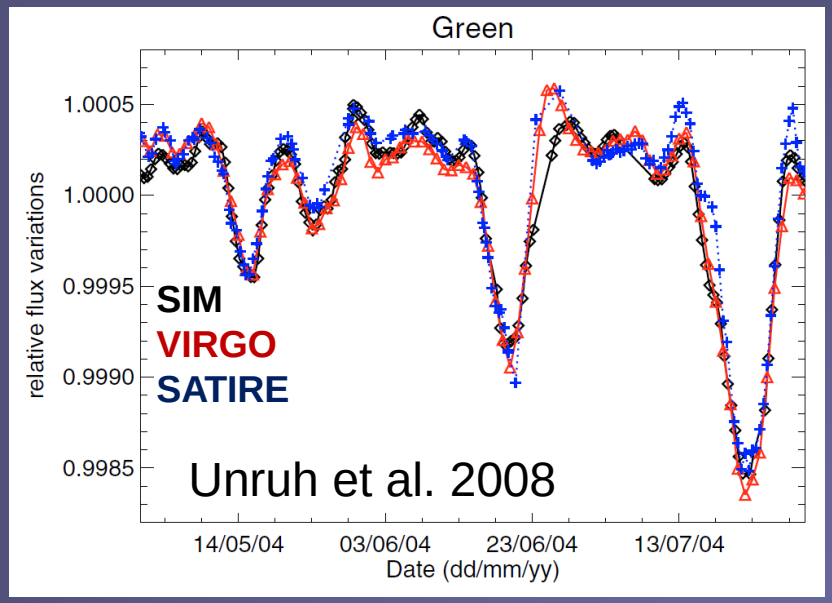
Achievements of modern irradiance models

- > 92% of variations in TSI during the satellite era are reproduced by surface magnetic features (assuming PMOD composite is correct). > 95% of VIRGO TSI variability



- SSI is well reproduced on solar rotation timescale & some time series also over the solar cycle
- Spectral line variations over solar cycle are reproduced
- Correct sign of variability of radiative flux over stellar cycles



Shortcomings of modern irradiance models

- All irradiance reconstructions depend on assimilating data, either proxies (e.g. sunspot number, Mg II c/w ratio, …), images (e.g. Ca II H), or magnetograms (MDI, HMI, …)
- No model has true predictive power
- Many models neglect NLTE effects (exceptions COSI, SRPM)
- Models have one or more free parameters
- Models neglect the 3D structure of the Sun
- All models that accurately reproduce TSI variations, disagree with SIM

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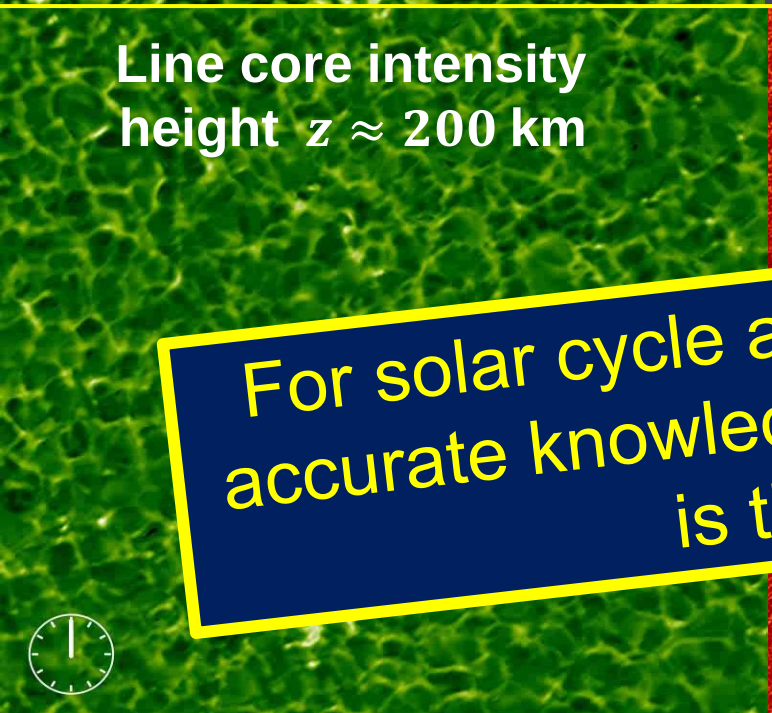
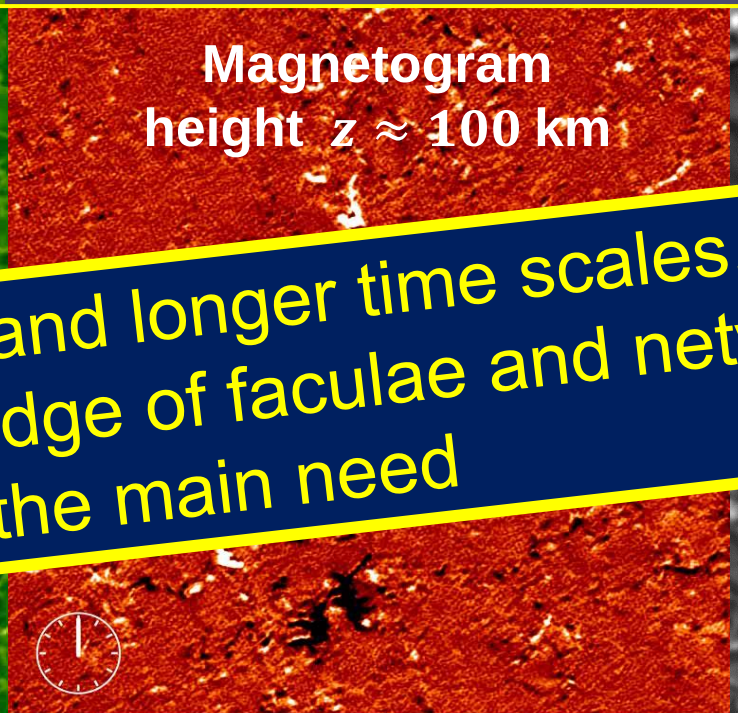
Do away with 1D model atmospheres!

The solar photosphere: Not a 1D place

Movies of quiet Sun recorded by the Sunrise stratospheric observatory

Highest resolution data available that are undisturbed by Earth's atmosphere

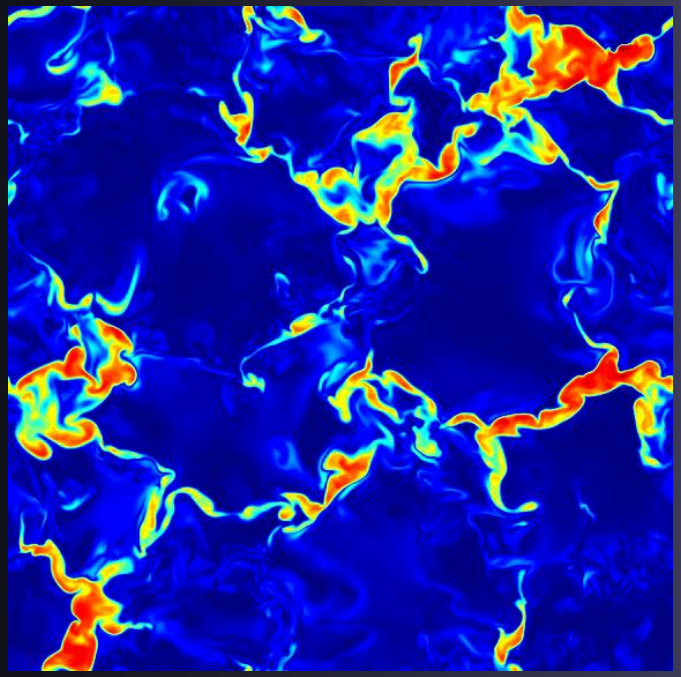




For solar cycle and longer time scales, an accurate knowledge of faculae and network is the main need

Realistic computations of faculae

- One way of studying faculae and network in detail is to consider 3D radiation MHD simulations, such as those with the MURAM code (Vögler et al. 2005)
- Simulate evolution of gas dynamics and magnetic field over a “small” box (5-50 Mm horizontal, 1.4-8 Mm depth) containing the solar surface



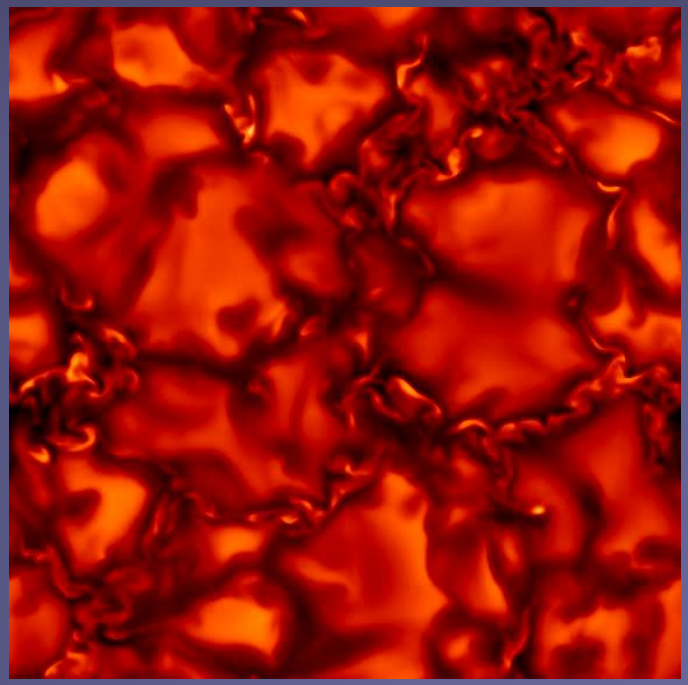
Simulation run with

10 km spatial grid

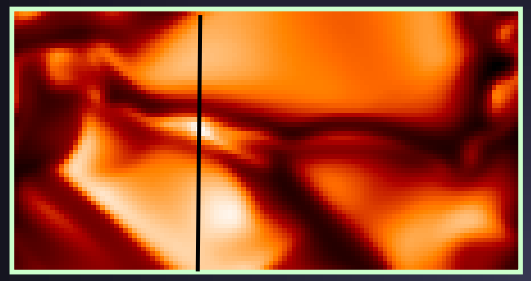
6 Mm spatial size

Homogeneous 200 G vertical initial magnetic field

← B_z I_c →



Vertical cut through a sheet-like structure



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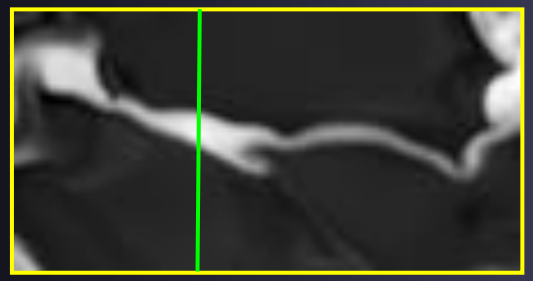
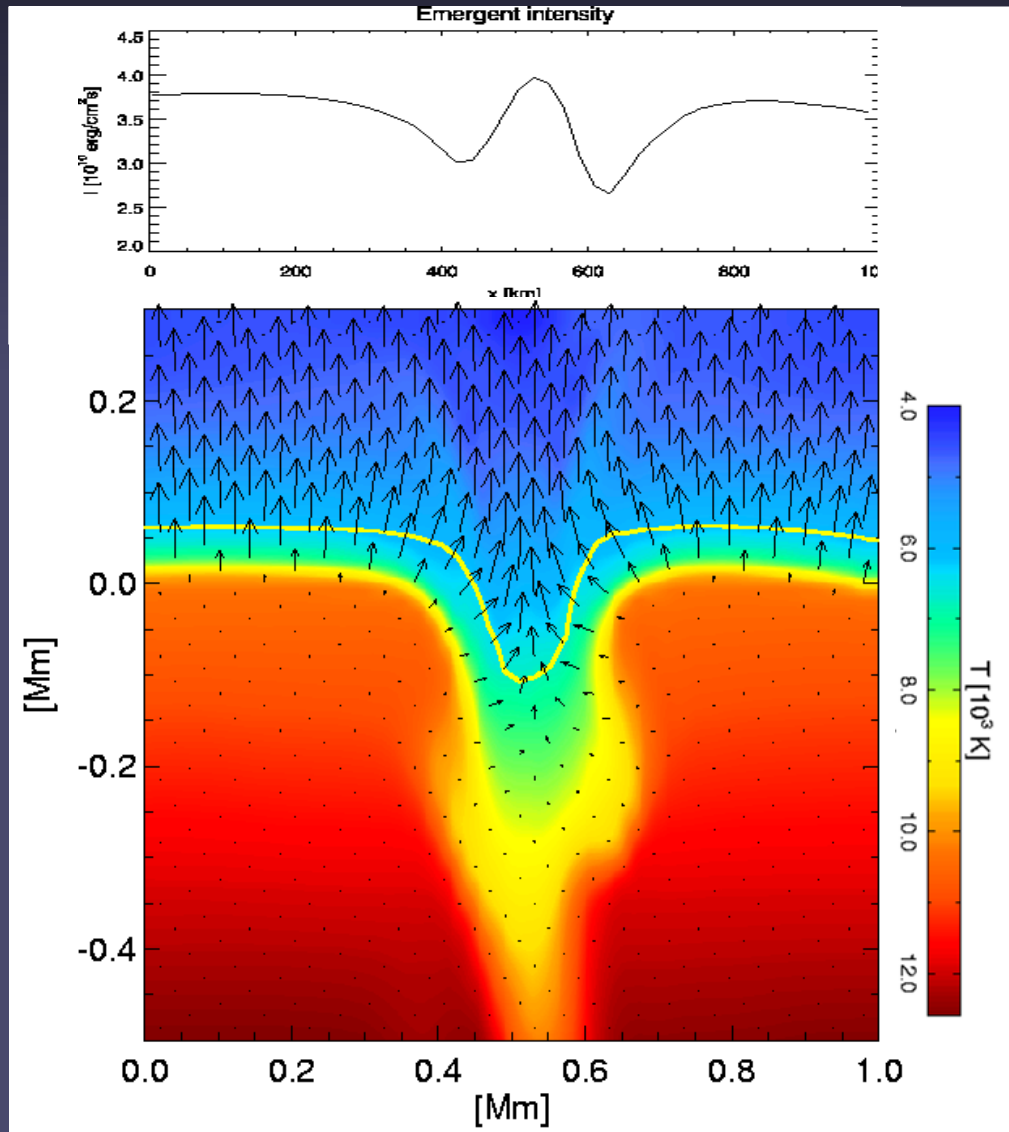


B_z

- B-field → magnetic pressure → evacuation → depression of the solar surface
- Lateral heating from hot walls (Spruit 1976)

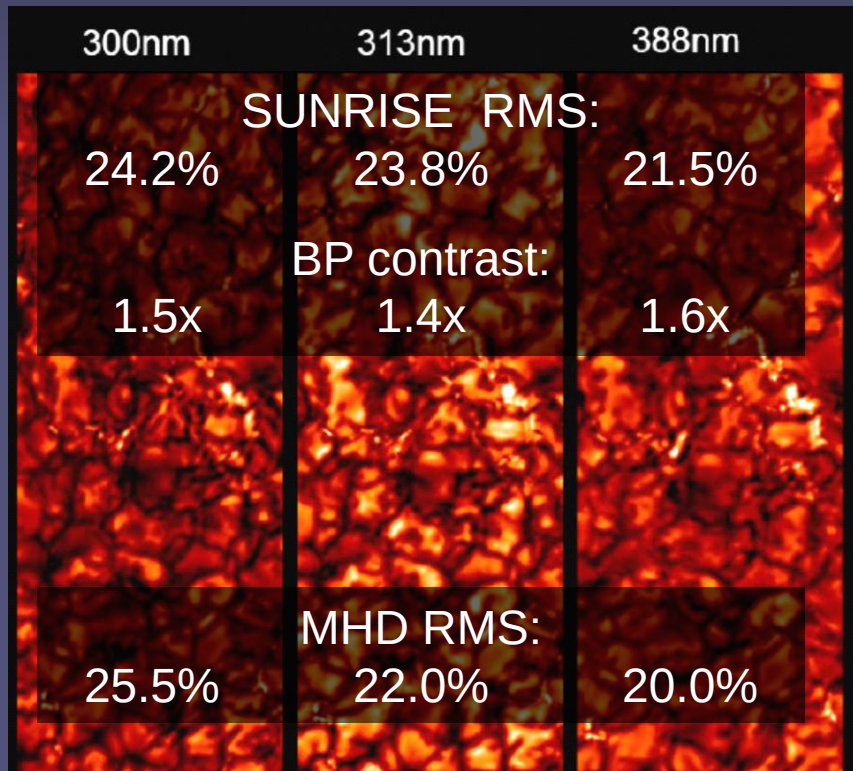
→Brightness enhancement of small structures

Radiation flux vectors & intensity



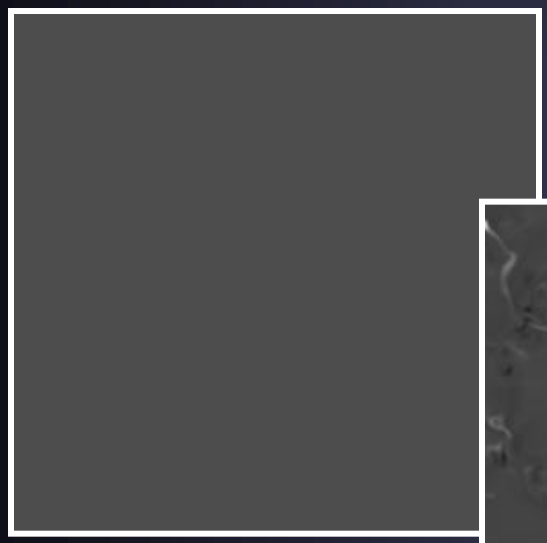
MURAM MHD simulations vs. observations

- MURAM 3D radiation **MHD simulations were successfully tested** vs. many observational constraints. They reproduce:
  - Kilo-Gauss field strengths of magnetic features (Shelyag+ 07)
  - Detailed centre-to-limb variation (CLV) of magnetic features (Keller+ 04)
  - CLV of rms variations, mainly granulation (Afram+ 11)
  - MBP Contrasts in visible (Schüssler+ 03) and in UV (Riethmüller+ 10) by stratospheric observatory SUNRISE
  - Global & local properties of sunspots & pores (Rempel+ 09)

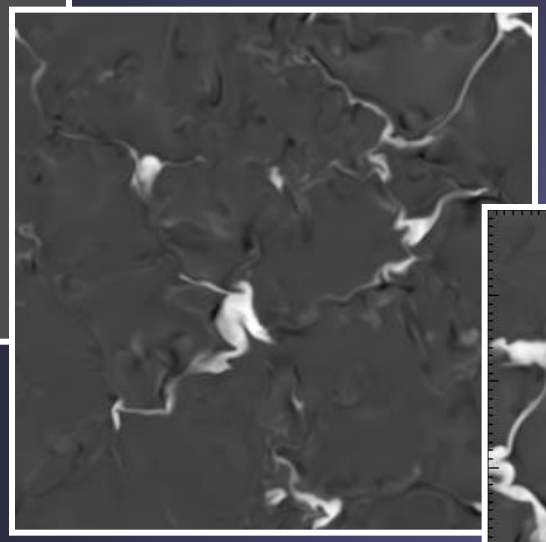


MHD simulations: from quiet Sun to plage

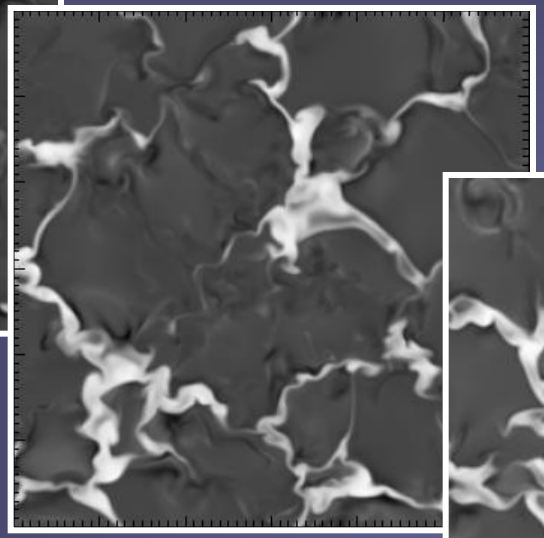
0 G



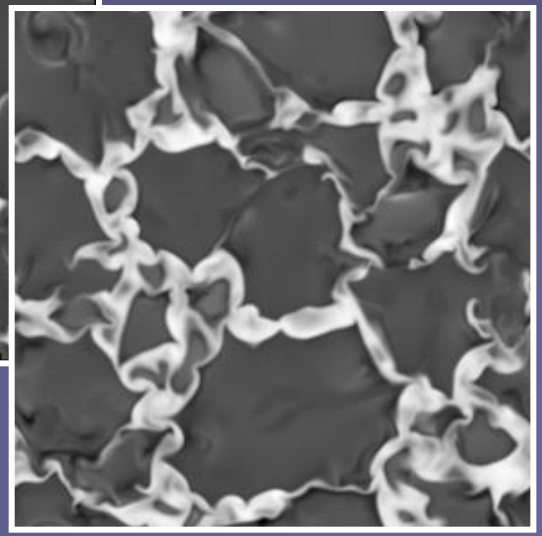
50 G



200 G



400 G



Magnetic field

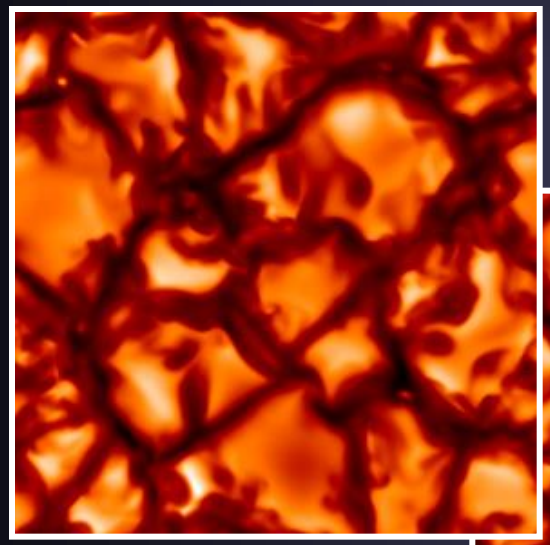
Radiation MHD simulations of solar surface layers. Open lower boundary with fixed value of entropy for bottom inflow (i.e. assume irradiance changes in surface layers)

MHD simulations: from quiet Sun to plage

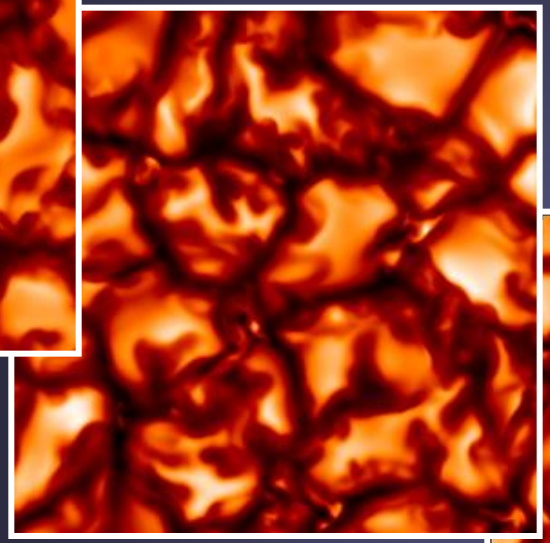
Vögler et al. 2005

Intensity

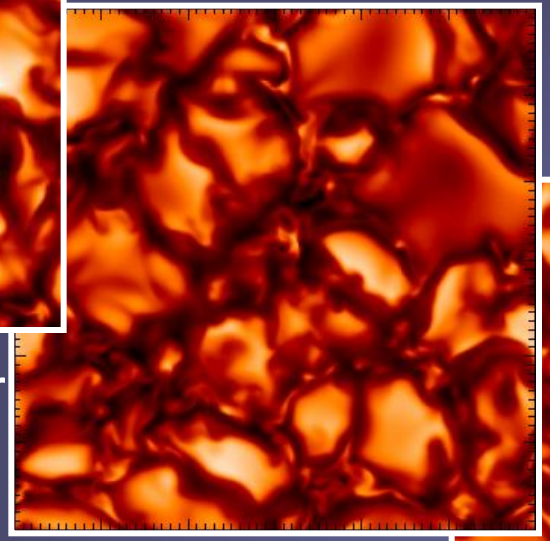
0 G



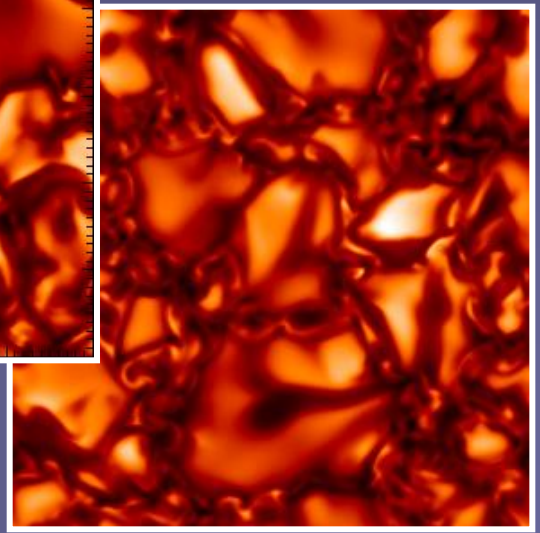
50 G



200 G



400 G



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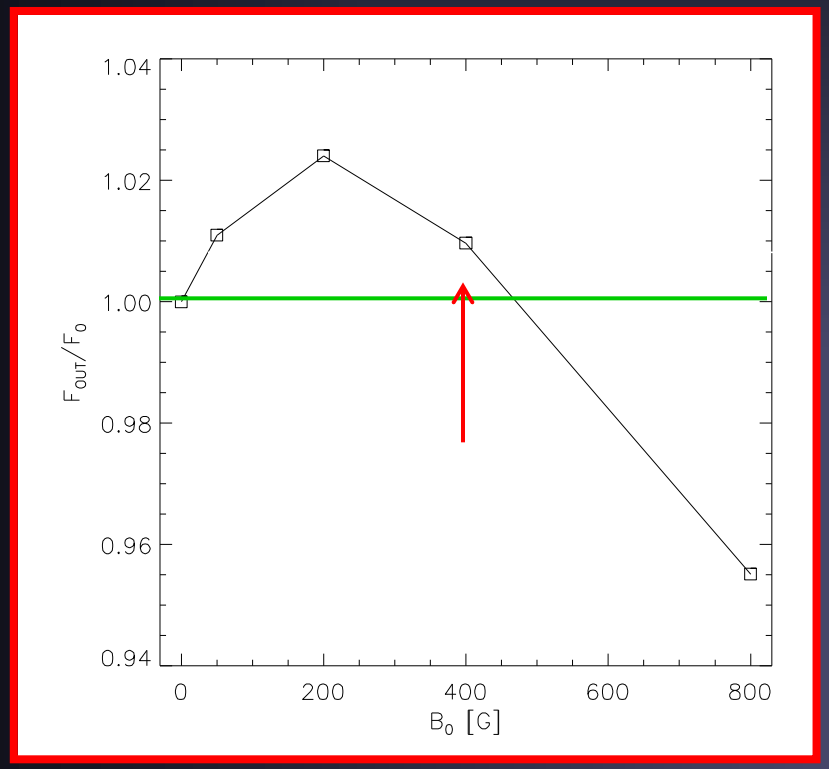
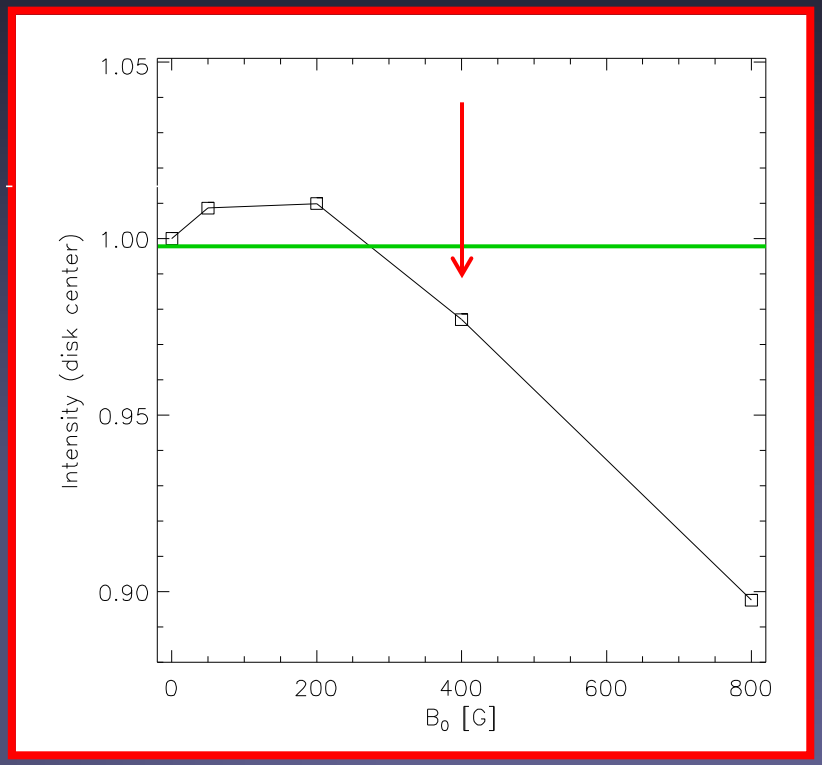
MHD simulations: from quiet Sun to plage

Global photometric properties (contrast relative to B_0=0)



Total emitted energy flux: integrated over all λ and angles



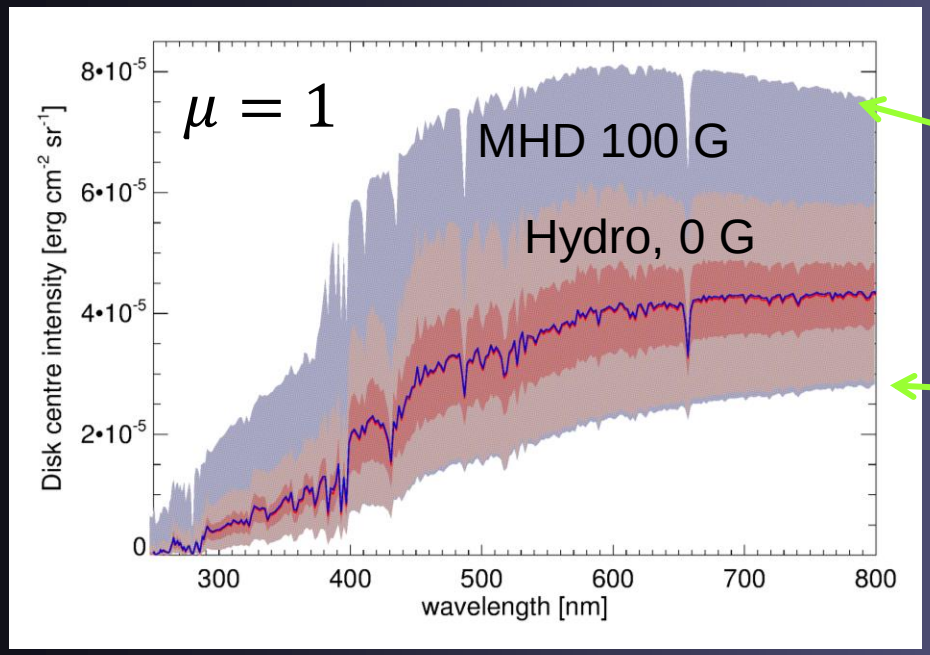
Mean disk center λ-integrated intensity (i.e. emitted vertically)

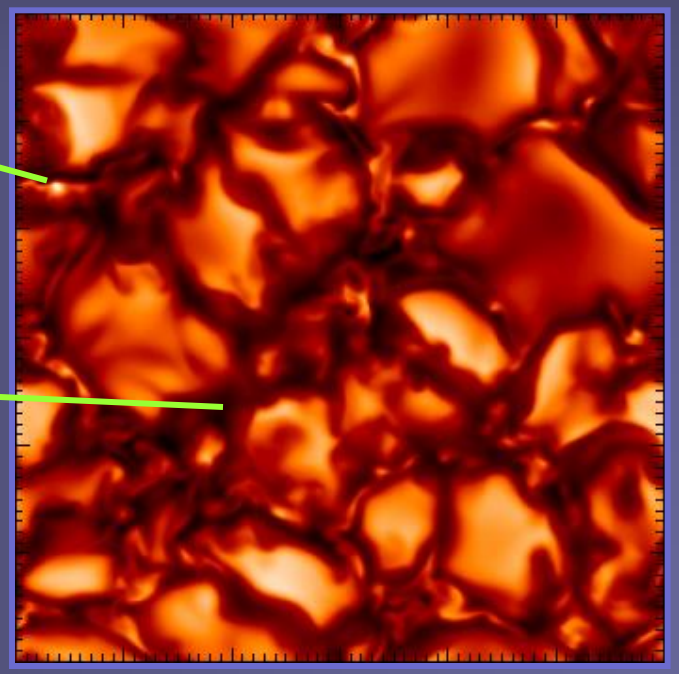
Constant entropy of inflowing gas at bottom of computational box

Vögler (2005)

Spectrum computed for each pixel

- Compute low-resolution (ODF-based) spectrum for each pixel of the MHD box
- Large range of variations of the spectrum from pixel to pixel
- $B \neq 0$: larger variation due to magnetic bright points
- However, the spectra averaged over a complete snapshot turn out to be rather similar (strong blue and red lines)





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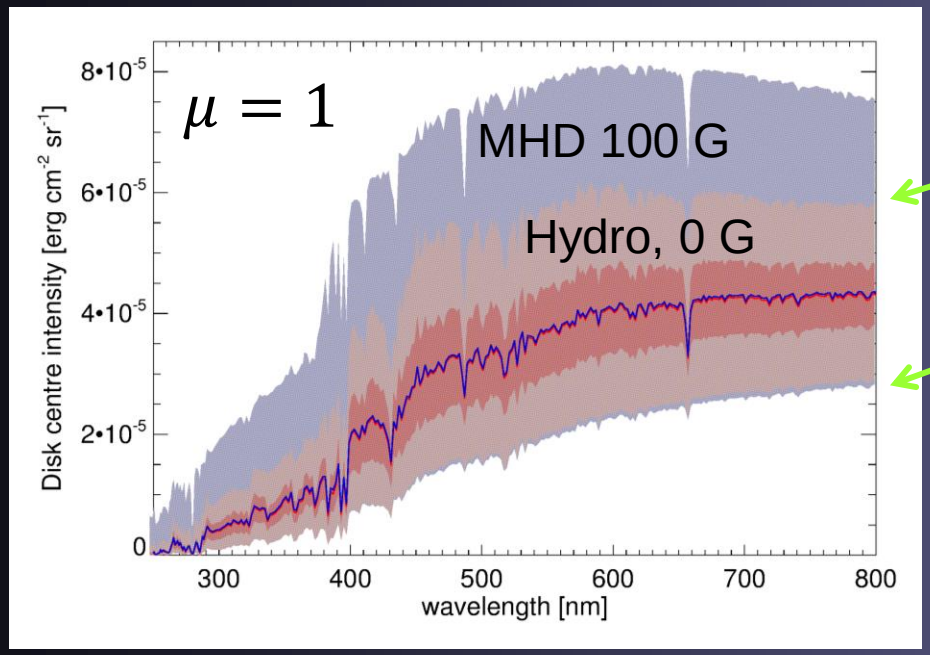
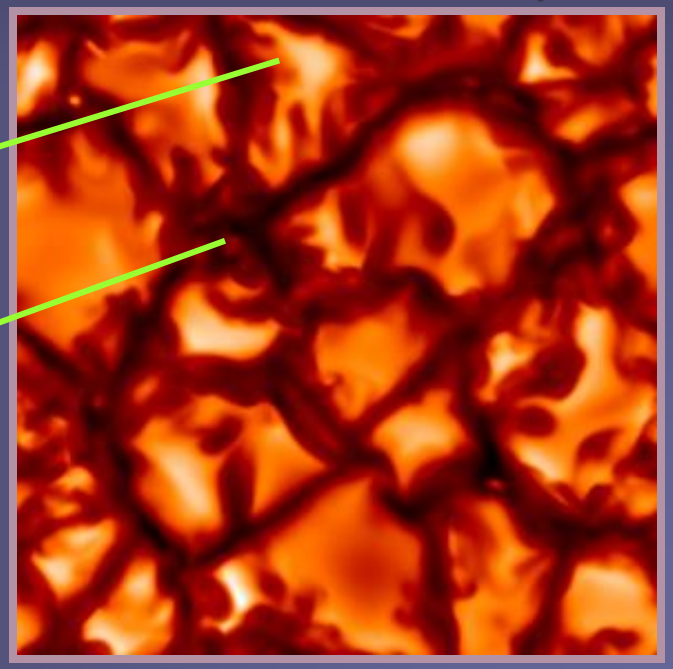
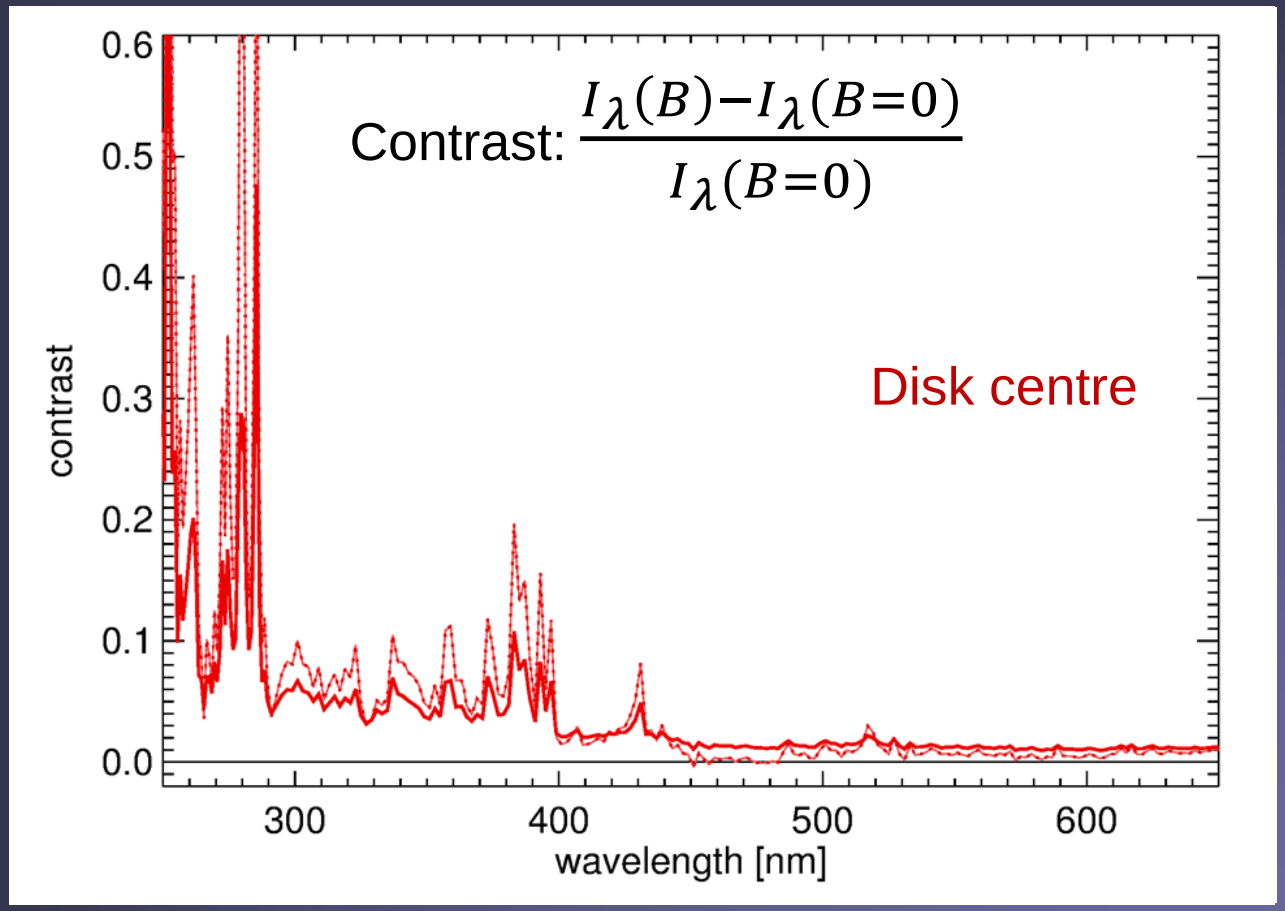




Spectra averaged over whole simulated box

- Averaged spectra from MHD simulations roughly agree with models of Unruh et al. (1999) at disk centre, with some diffs
- MHD CLV is much less steep → closer to actual obs.
- Since spectra from MHD simulations are associated with a given B-field, there is (in theory) no need for a free parameter for irradiance reconstructions



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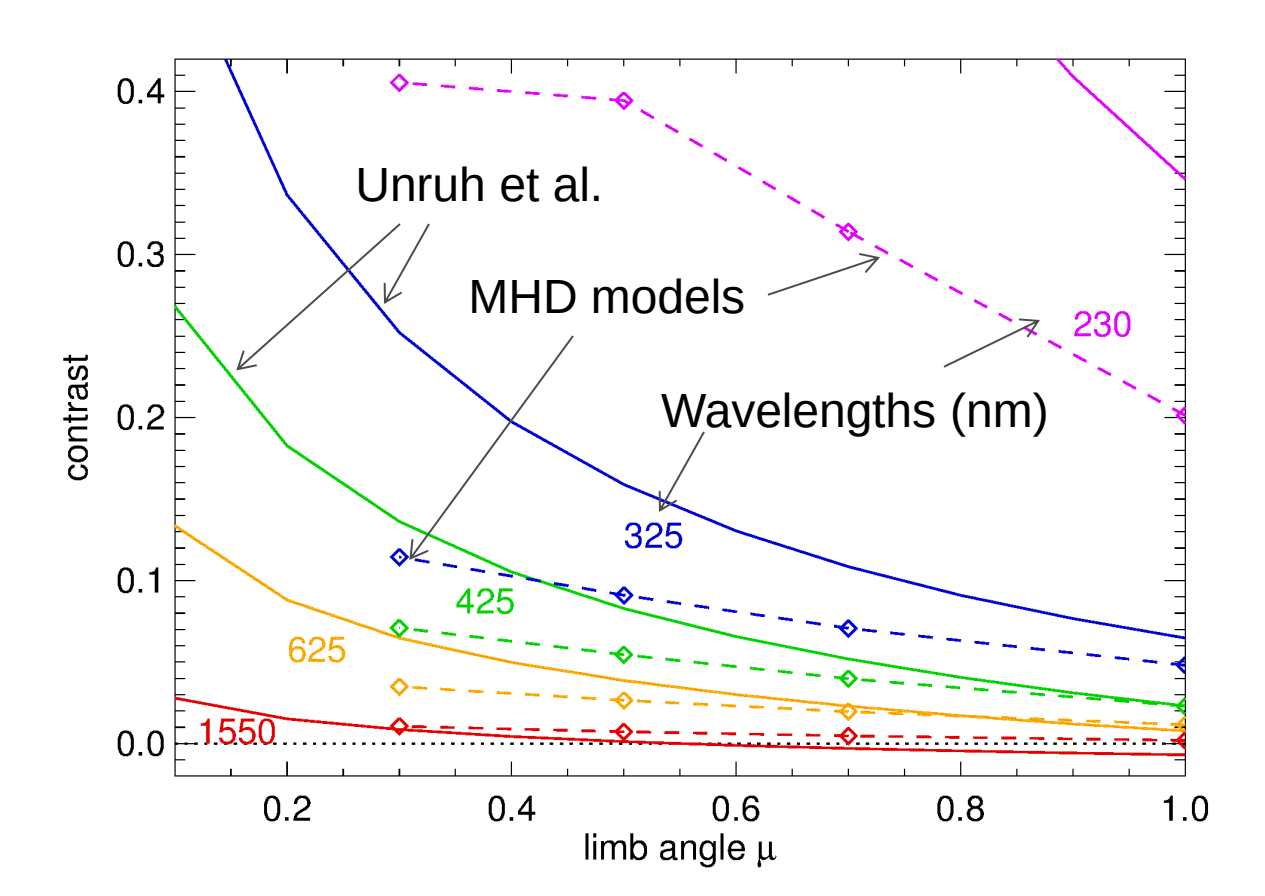


Conclusions I

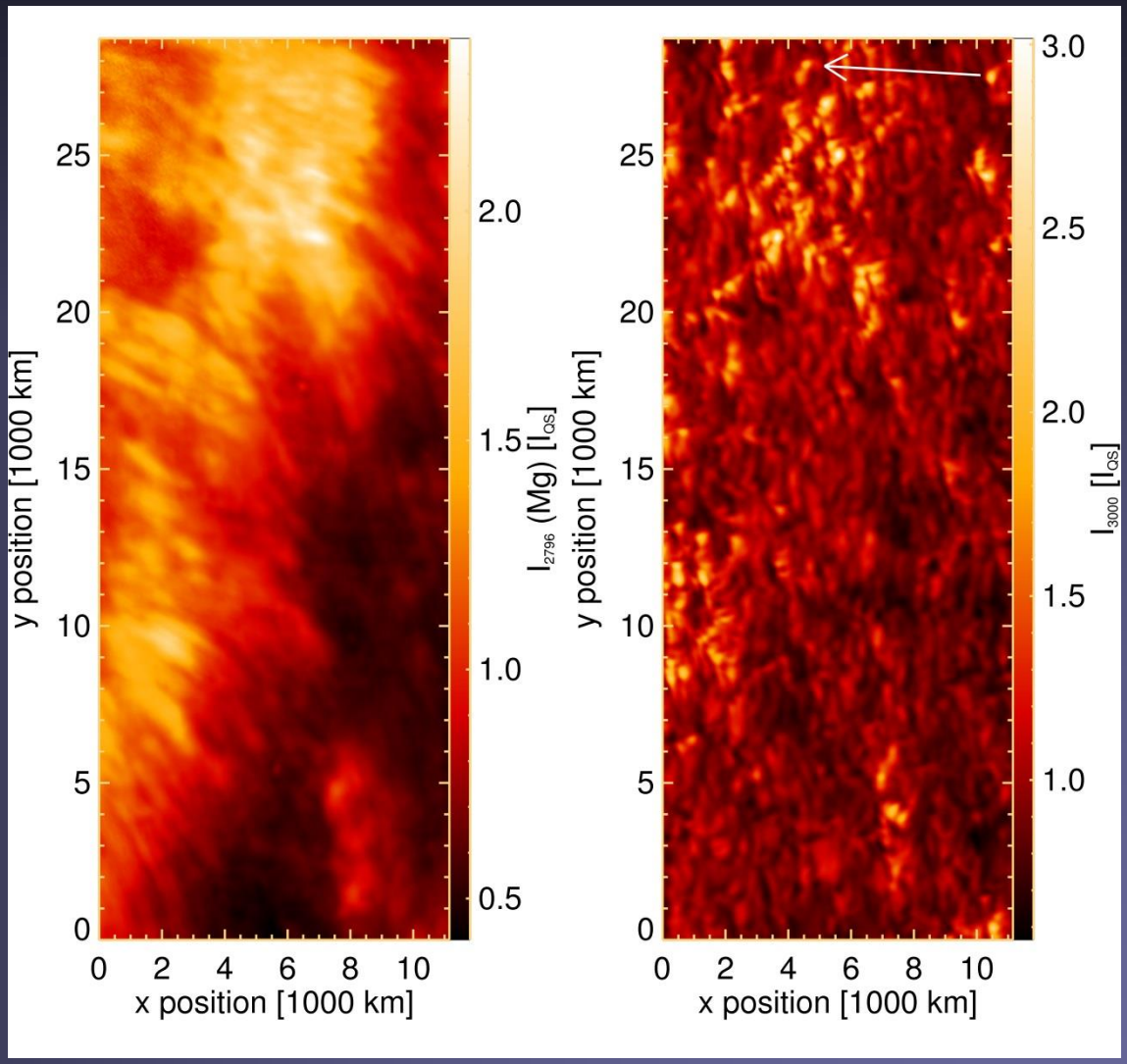
- **Positive points:**
  - 3D radiation MHD simulations are much closer to reality than the 1D models used so far. Spectral syntheses with ODFs are feasible
  - The spectra have similarity with the successful model of Unruh et al. (1999), although there are differences
  - The CLV of the intensity contrast from the MHD simulations is less steep and hence closer to observations
  - Solar irradiance reconstructions using such spectra have the potential to do away with the single free parameter of SATIRE (but see next slides)

Conclusions II

- **Not so positive points:**
  - Full spectrum synthesis, e.g. in NLTE, is prohibitively expensive
  - Very preliminary: MURAM + ODF spectral synthesis: Discrepancy with SIM is unlikely due to use of 1-D models
  - MHD simulations are robust in photosphere, less so in chromosphere (only one code currently treats chromosphere properly). More work needed
  - Full-disk magnetograms such as HMI probably sample only a small fraction of the Sun's magnetic flux
  - We are just at the beginning and have a long way to go!

Chromospheric vs. photospheric structure

- Images taken during the 2013 flight of Sunrise
- First high-resolution images in Mg II h & k
- Chromospheric structure is totally different from that in the photosphere, especially in active regions



Mg II h + k

300 nm

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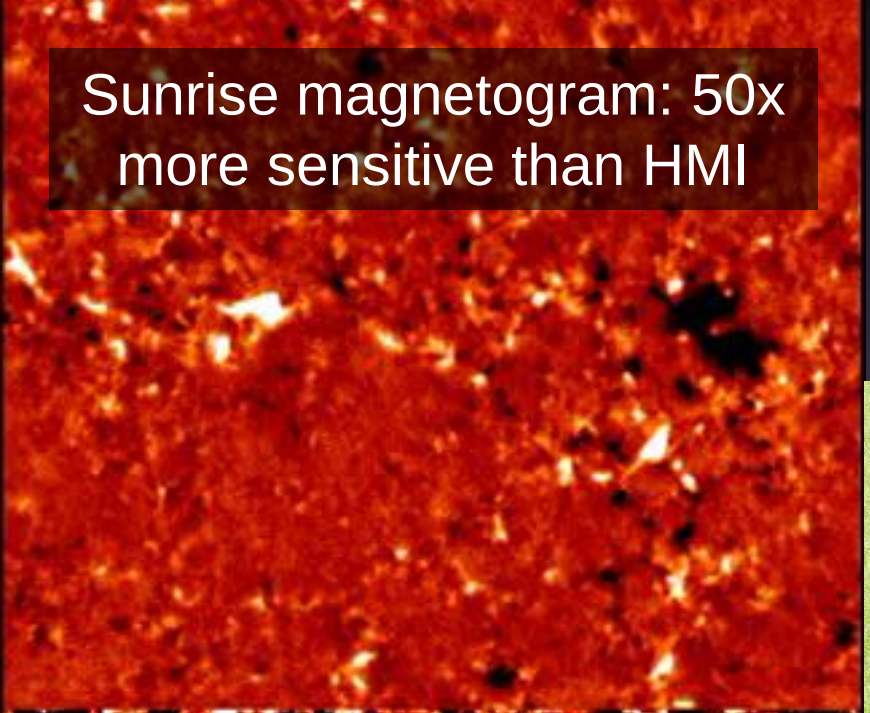
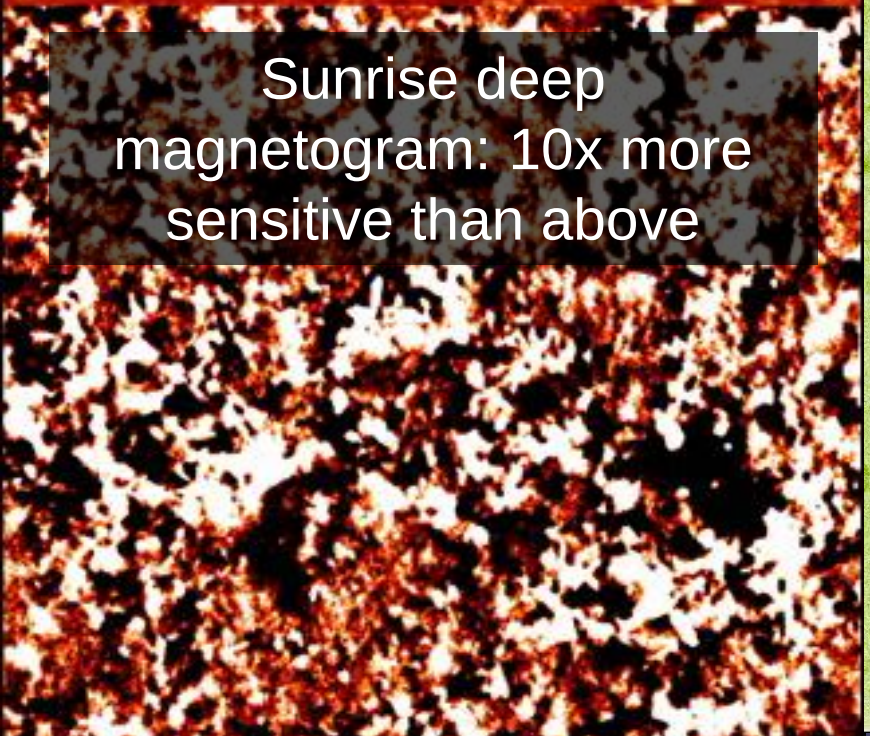
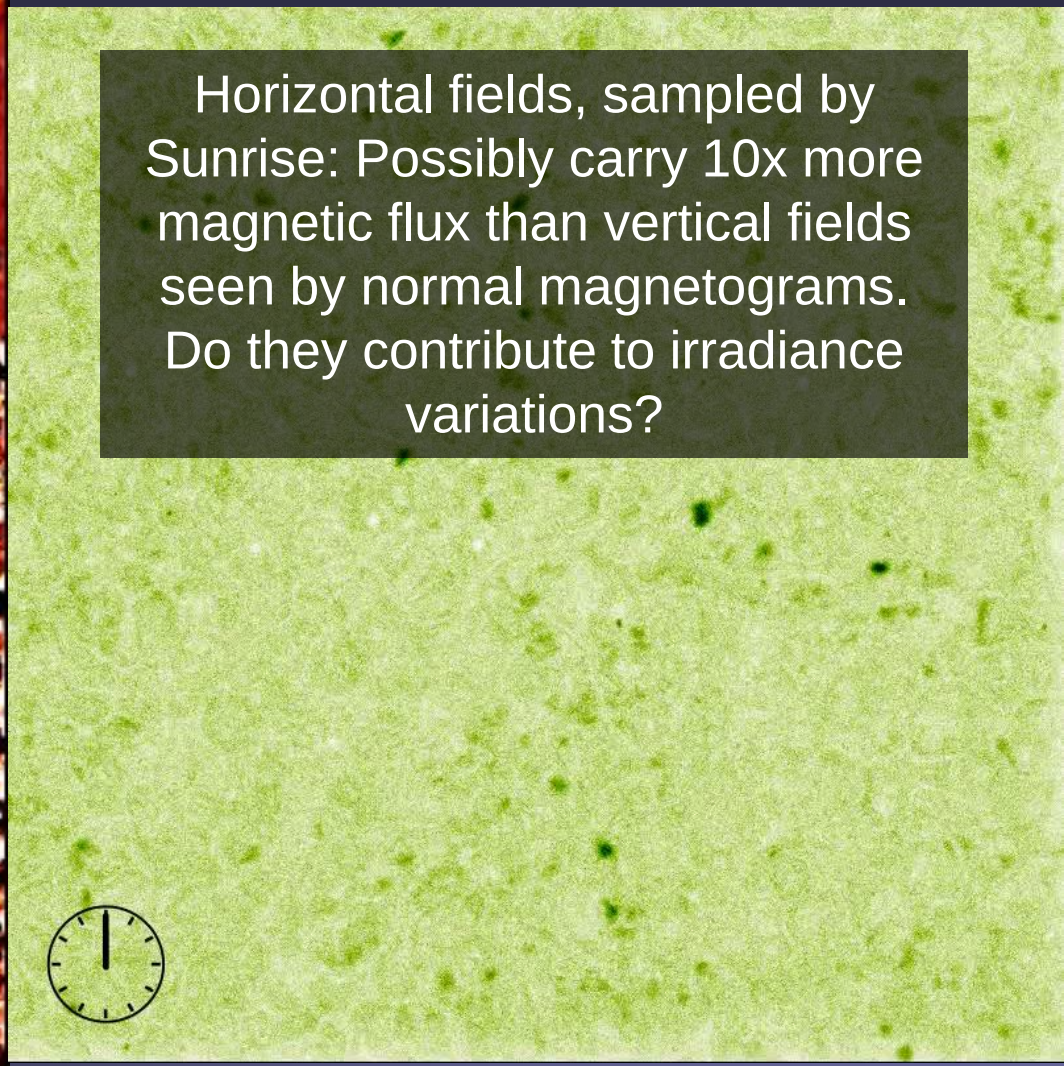
Do standard magnetograms catch all the magnetic flux?



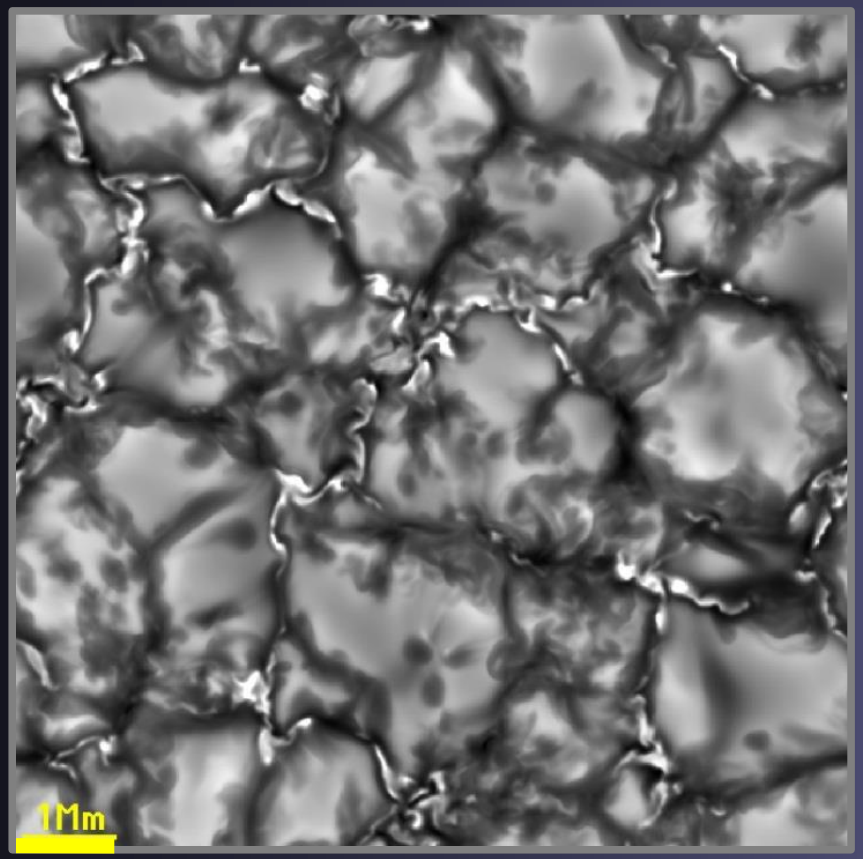




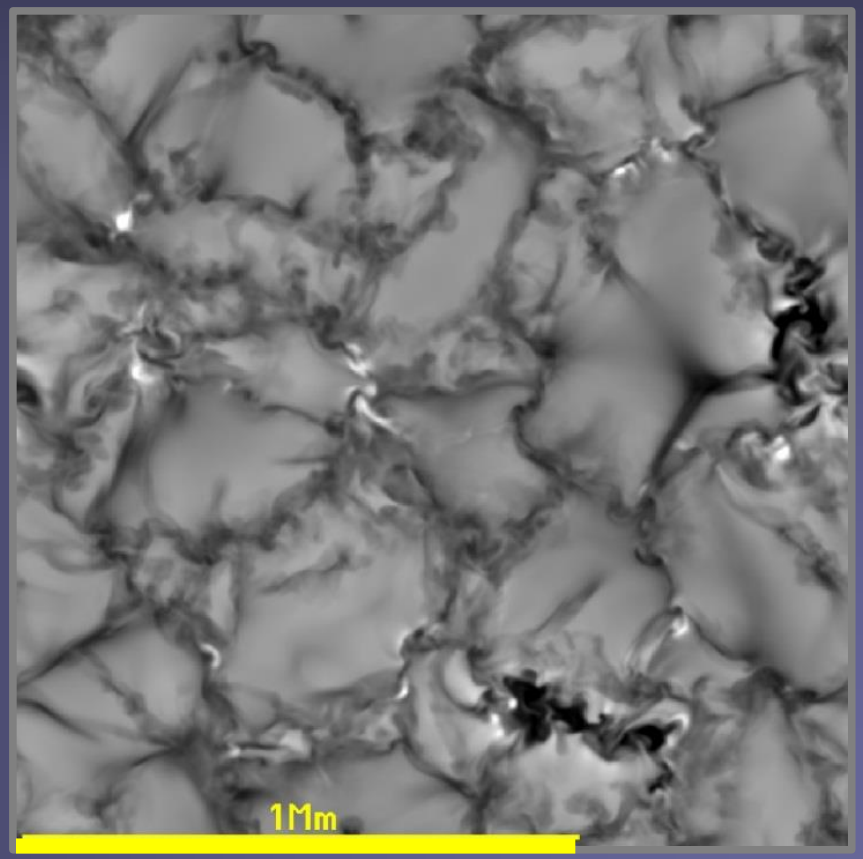
Application to other stars

Emergent flux & contrasts show spectral type dependence
Such models can be used to compare with Kepler data

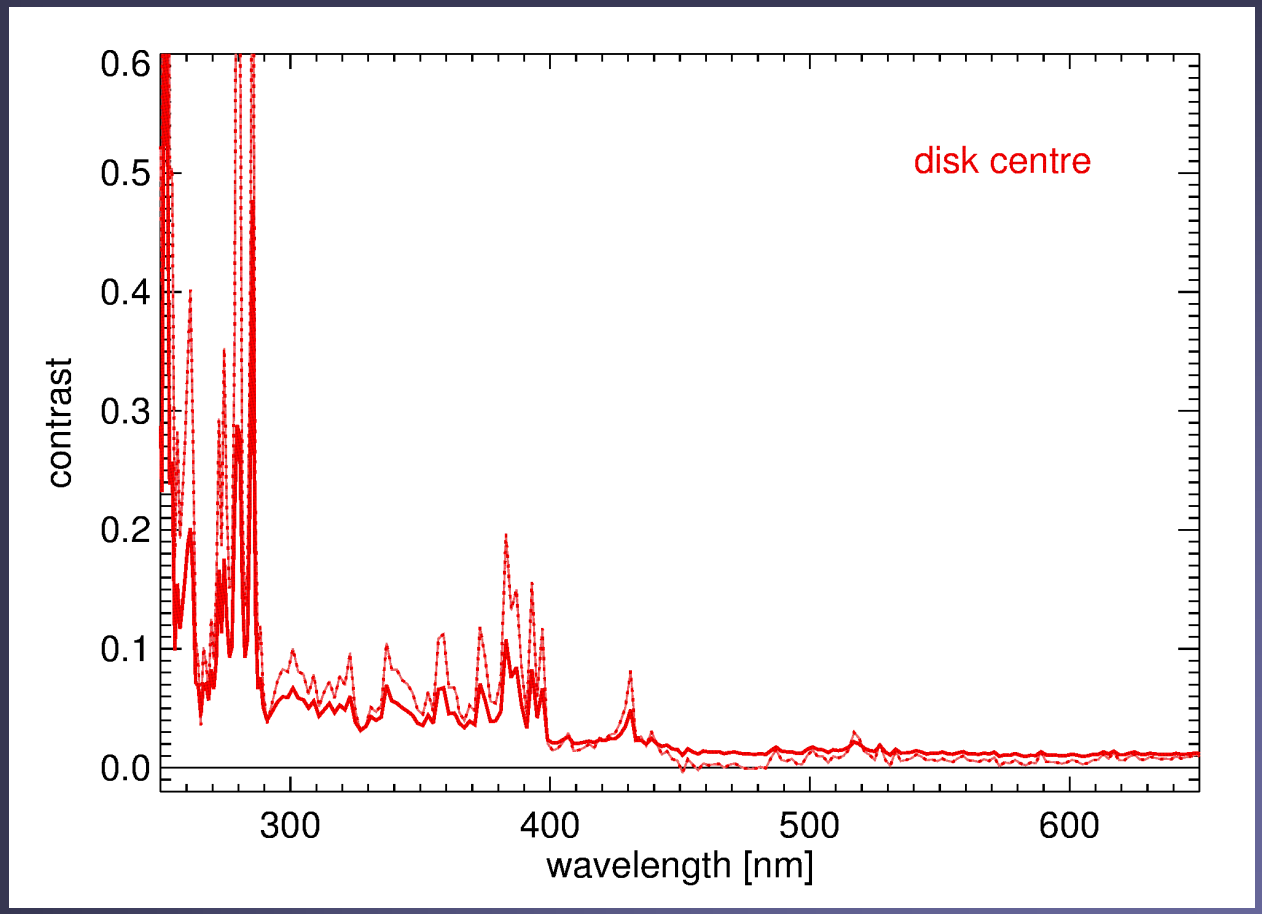
G2 (100 G)

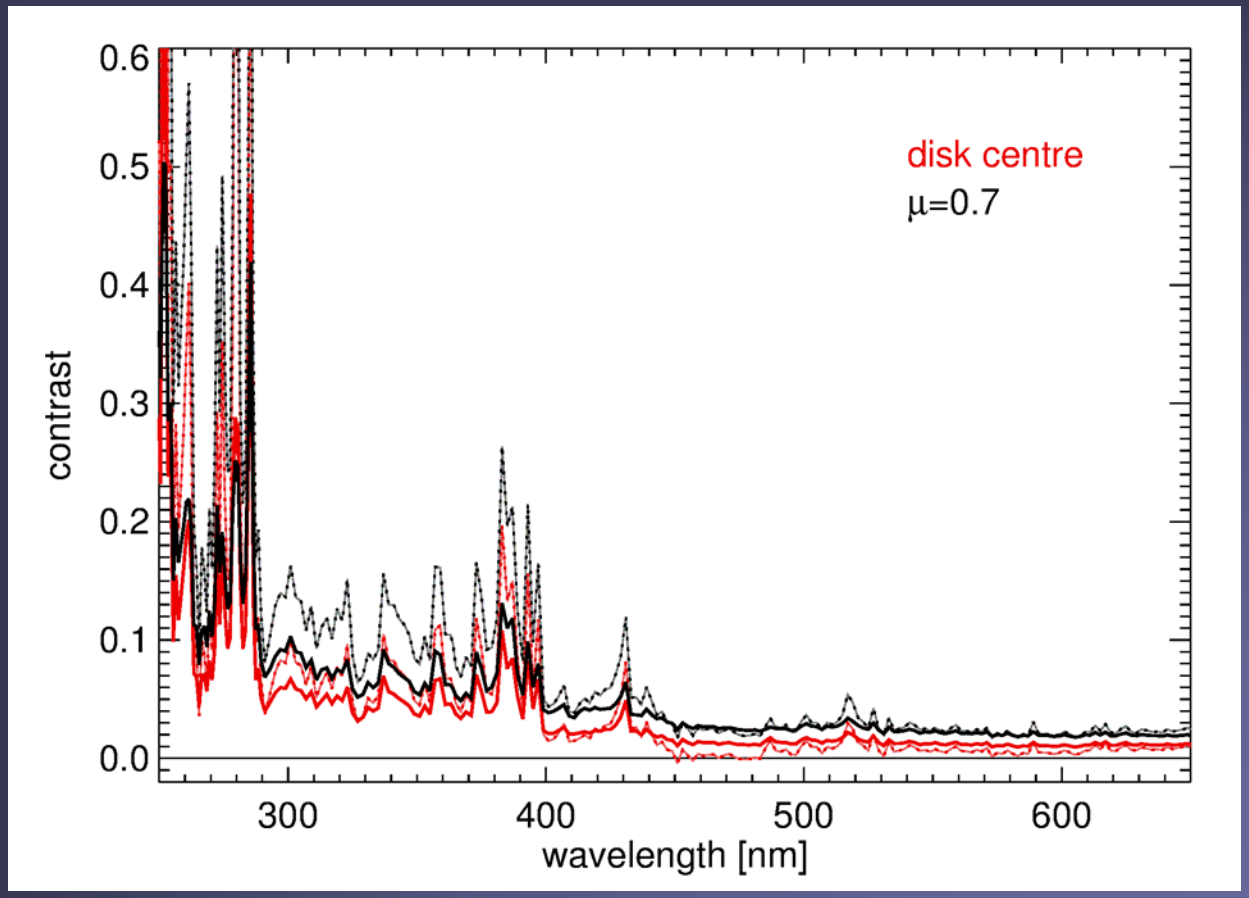


M2 (100G)



19 slides !!!


disk centre
contrast
0.6
0.5
0.4
0.3
0.2
0.1
0.0
300
400
500
600
wavelength [nm]


disk centre
μ=0.7
contrast
0.0
0.1
0.2
0.3
0.4
0.5
0.6
300
400
500
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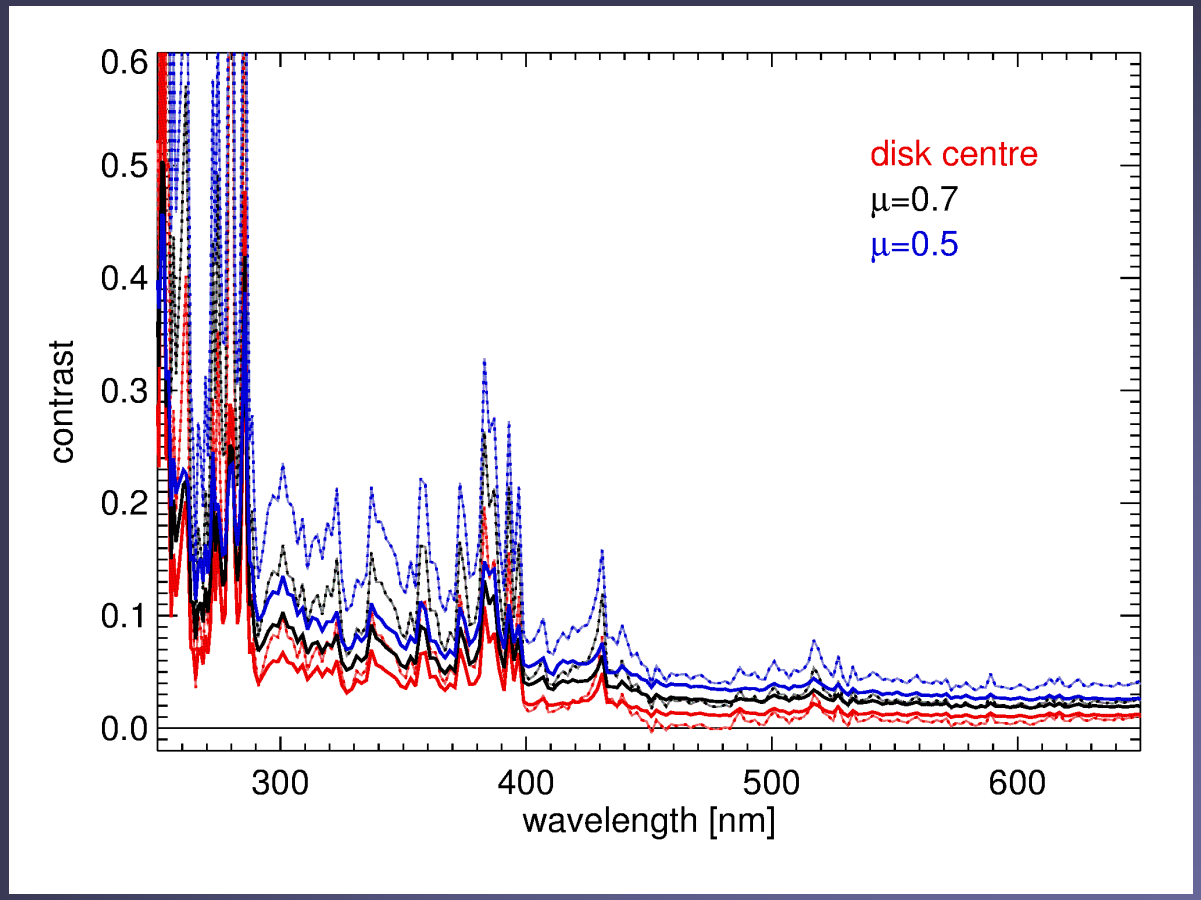
wavelength [nm]


disk centre
μ=0.7
μ=0.5
contrast
0.0
0.1
0.2
0.3
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wavelength [nm]