Simulated observations of waves in the solar atmosphere

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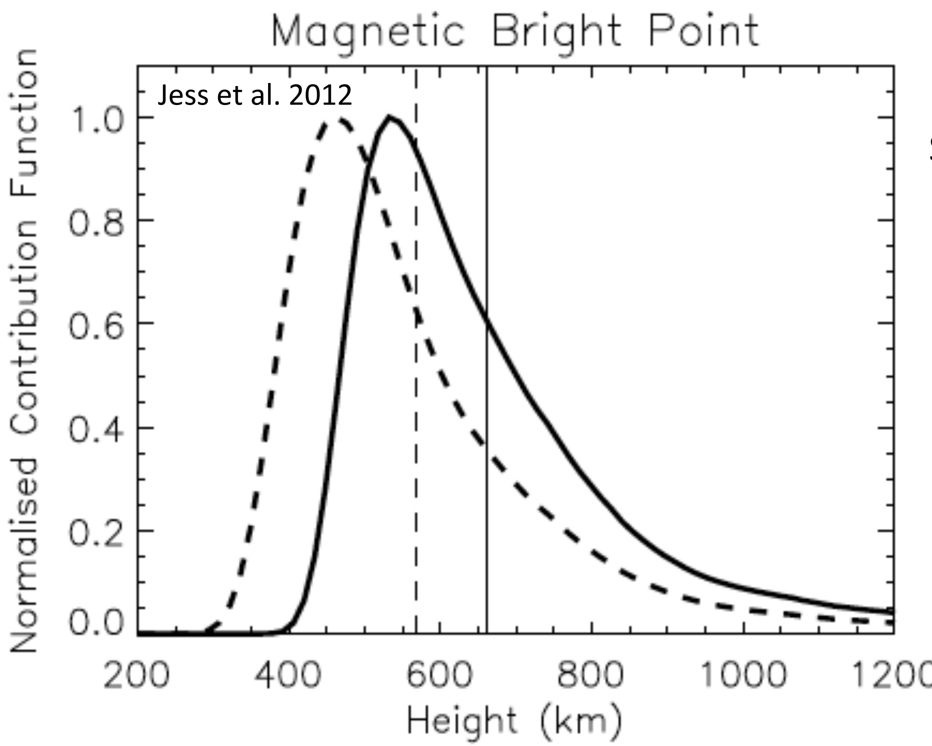
Introduction

- Why do we need simulated observations of waves at all
- What do we get from them, or what the simulations can do

1. Non-locality of radiative transport: contribution function in photosphere

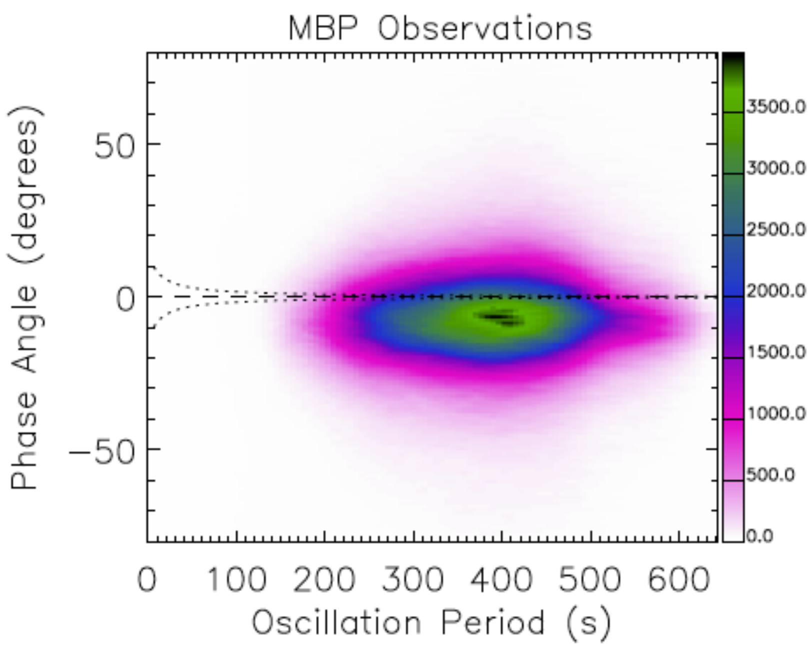


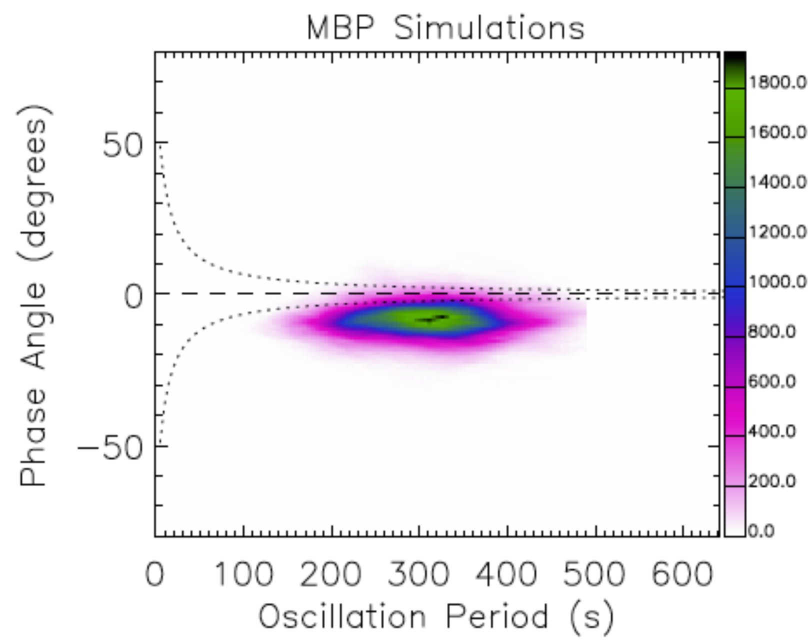
Dashed – 417nm continuum
Solid – 430.5-431.5nm G-band

The radiation is formed between 500 and 1000 km. Within this range:

- Density and pressure change by ~2 orders of magnitude
- Temperature changes by ~4000K
- Plasma β changes from ~5 to ~0.1
- **Helpful: formation height difference between 417nm and G-band is about 100 km.**

Simultaneous ROSA observations and simulations in 417 nm and G band: oscillation phase difference





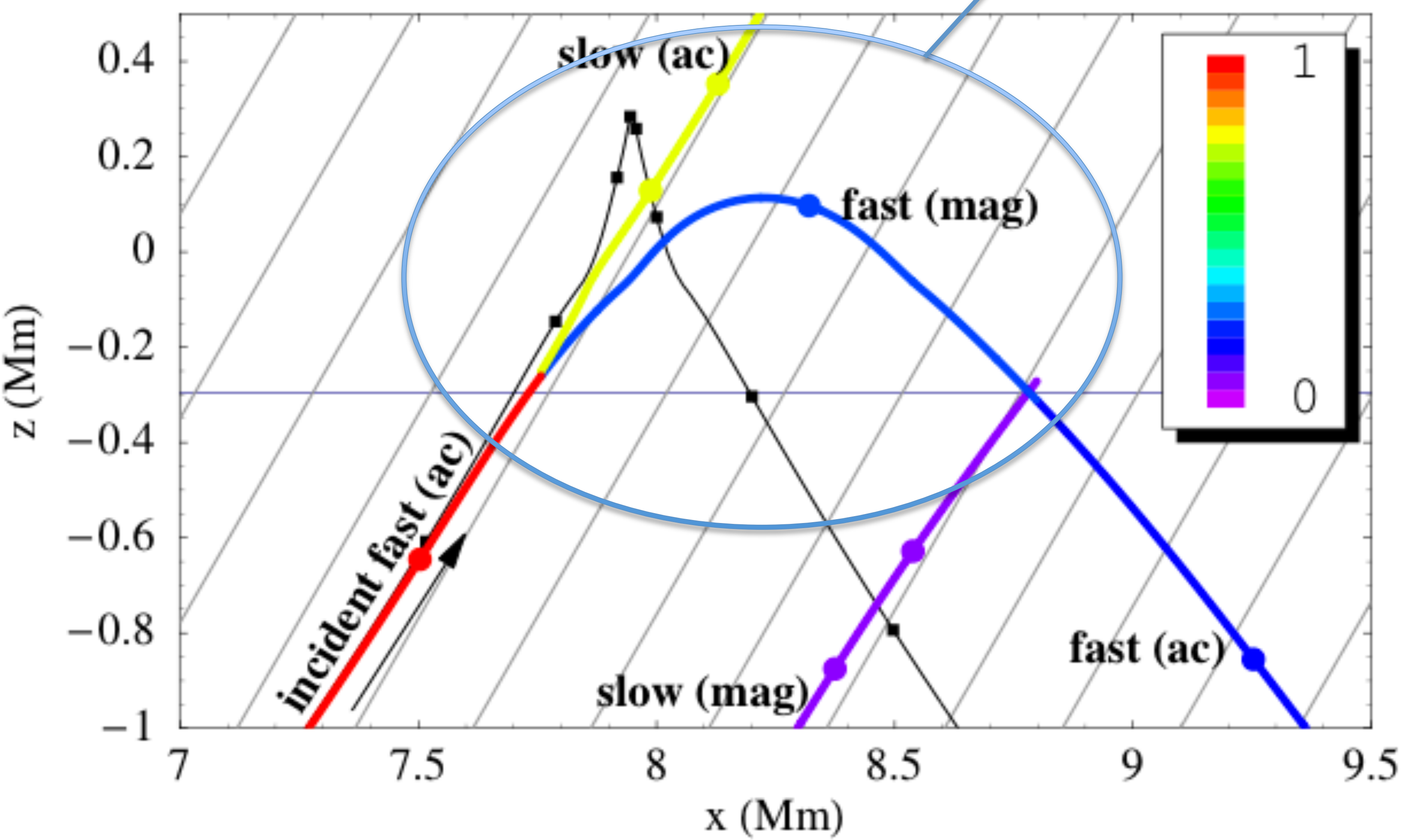
Both occurrence plots show a phase shift of about 8 degrees between 417 nm and G-band filters for wide range of periods, giving the oscillation phase speed of about 8 km/s. Simulated oscillations are not induced and occur naturally as a property of the model.

Jess et al. ApJ 2012

Implications for helioseismology

Famous picture by Paul Cally:

All this can be within the line formation region, but affects travel times



Implications for solar atmospheric energy balance: Poynting flux

10G horizontal

200G vertical

200G mixed

10G vertical

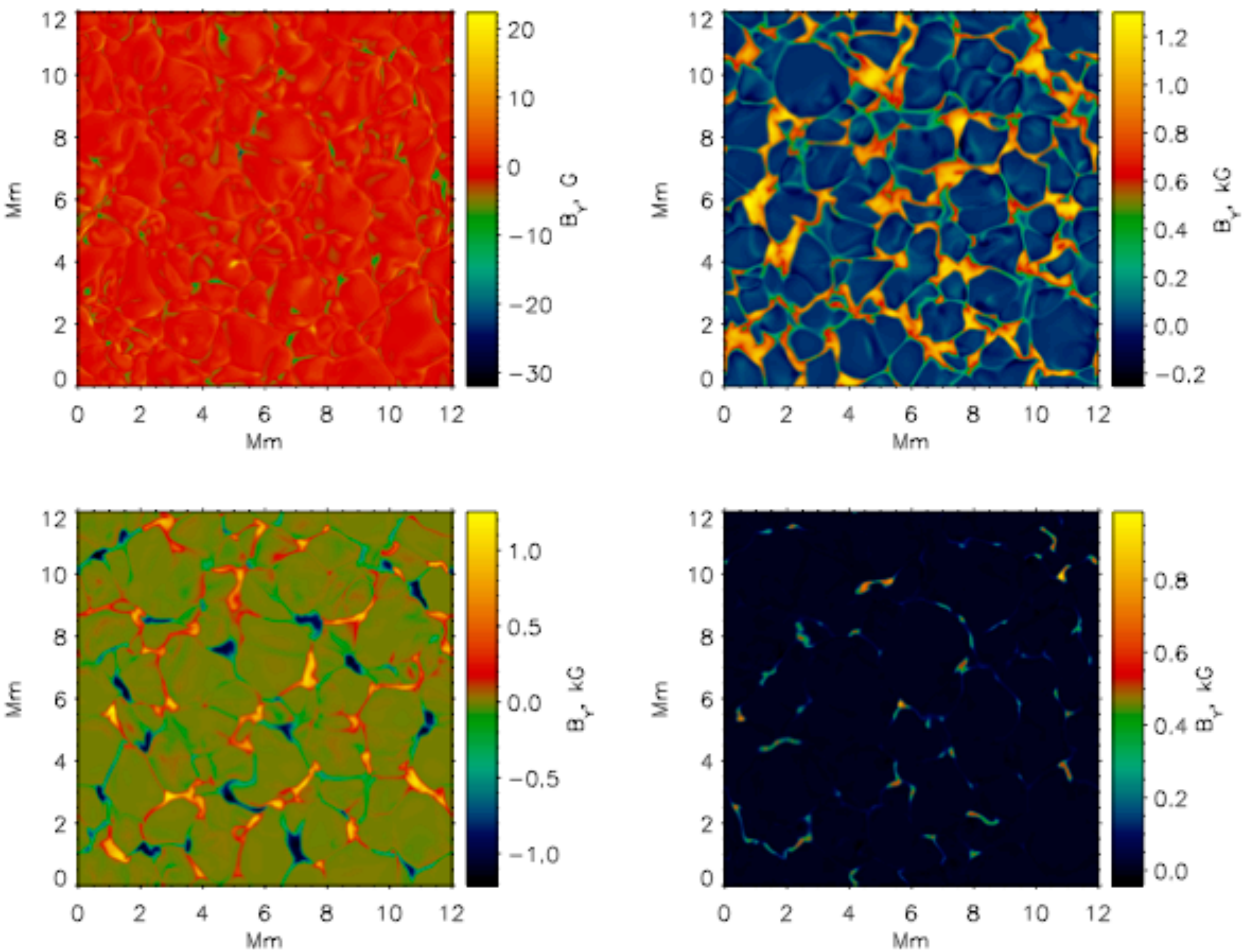
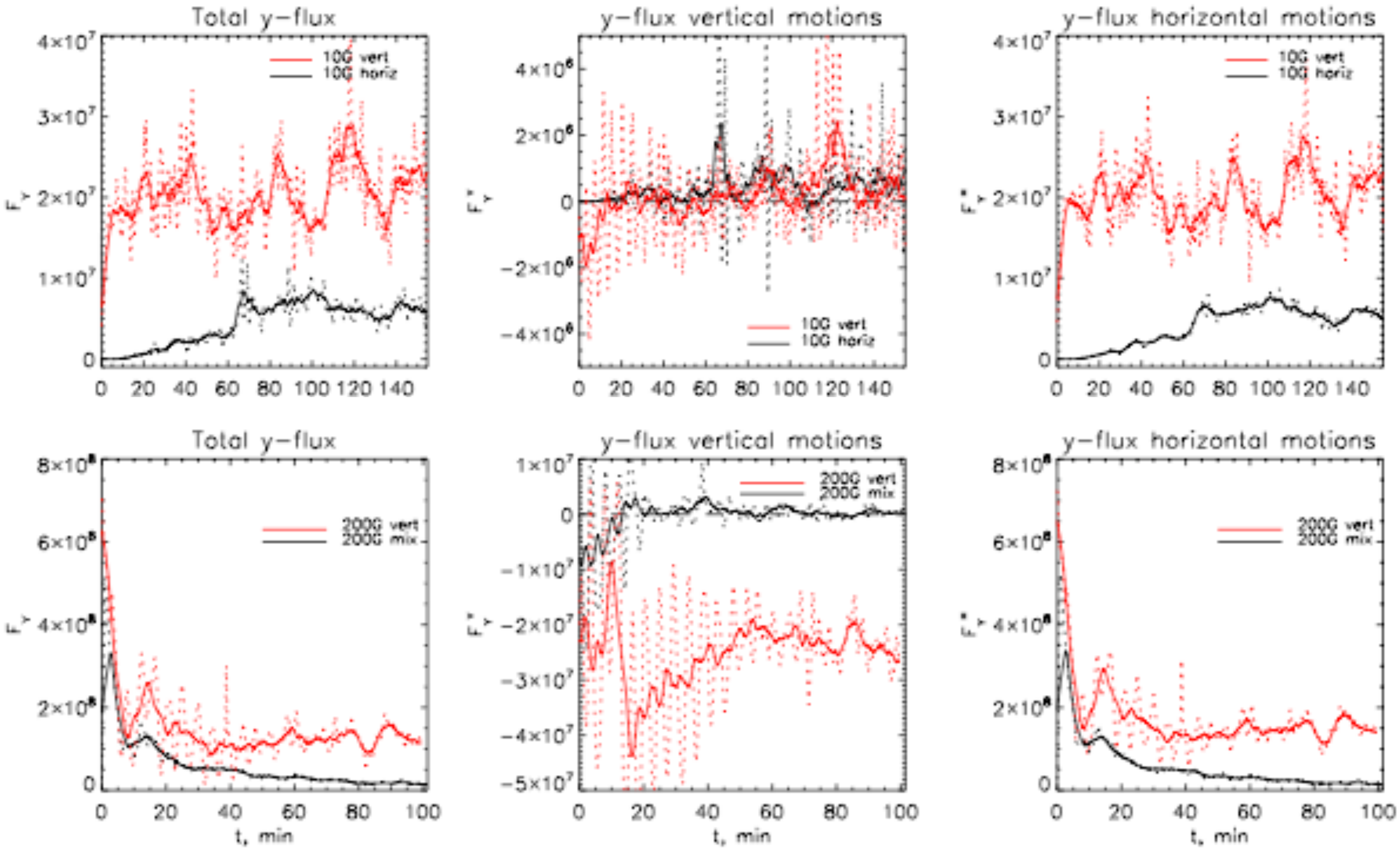


Image from Shelyag et al. (2012)

Net Poynting flux, different B configurations

$$\mathbf{F} = \frac{1}{4\pi}\mathbf{B} \times (\mathbf{v} \times \mathbf{B})$$

$$F_y = \frac{1}{4\pi}\left(v_y\left(B_x^2 + B_z^2\right) - B_y\left(v_x B_x + v_z B_z\right)\right) = F_y^v + F_y^h$$

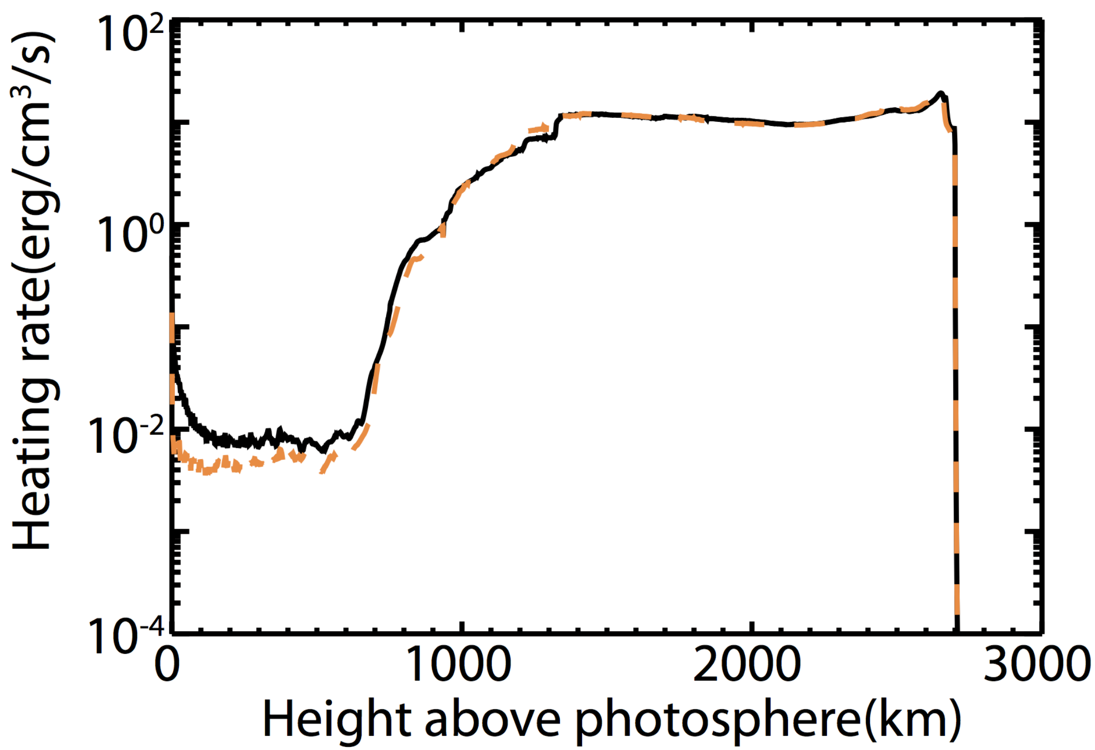


Shelyag et al. (2012)

Chromospheric heating

- Is possible with waves due to non-ideal resistive mechanisms.

- Alfvén turbulence. 1.5D simulations, AW with broad spectrum are fed through the bottom boundary.



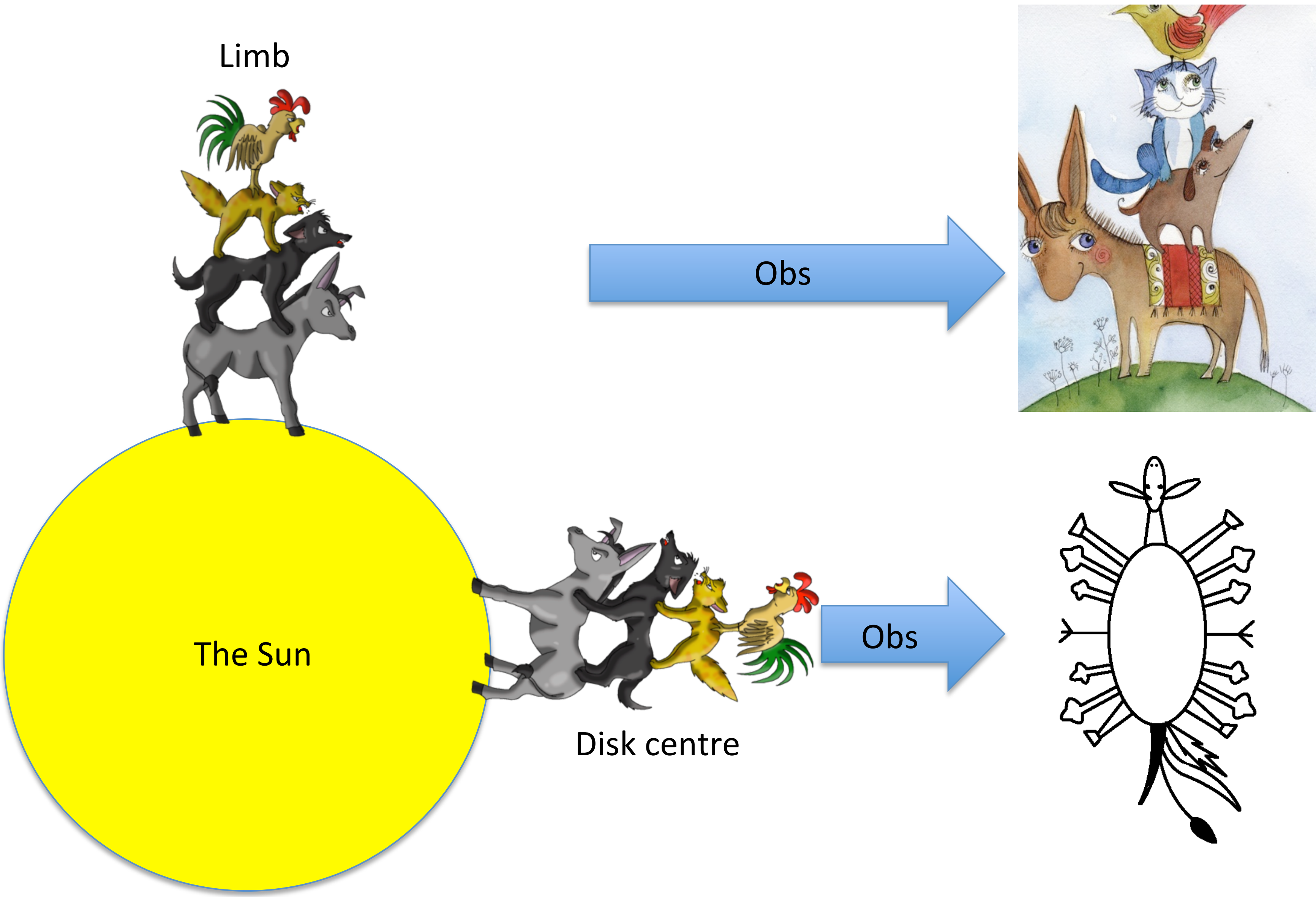
Arber et al 2015, submitted

Net Poynting flux

In ideal magneto-convection simulations, enough energy flux is produced in the photosphere to heat everything one needs, there are also mechanisms to convert and absorb. The major part of PF comes from horizontal, torsional motions at very small, intergranular scales:

- difficult to observe.
- needs observational confirmation, but how and where to look?

2. Limb vs disk solar observations



Limb vs disk solar observations

Of course, it is not as simple and nice as that – mainly due to non-locality of radiative transport in optically thick regime + nLTE effects.

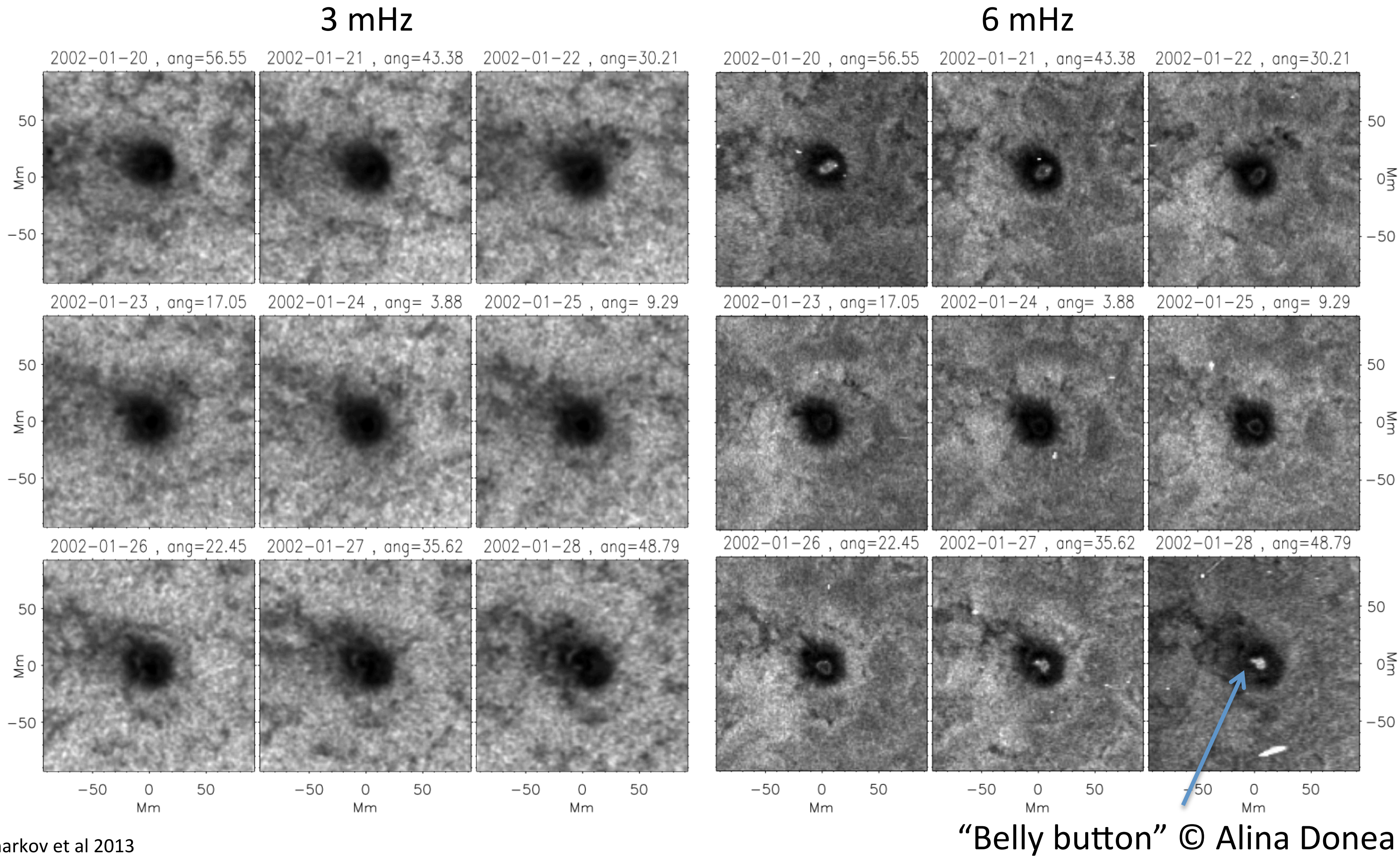
But:

- Horizontal flows become line-of-sight
- Horizontal magnetic fields become Stokes-V measurable
- Radial structure becomes (probably) more apparent than at the disk centre

Generally, limb and disk observations together give 3D structure of the solar atmosphere

Observations: acoustic power variability on the position at the solar disk

AR9787, SOHO MDI, NiI 6787A Doppler, analysis by Sergei Zharkov



Zharkov et al 2013

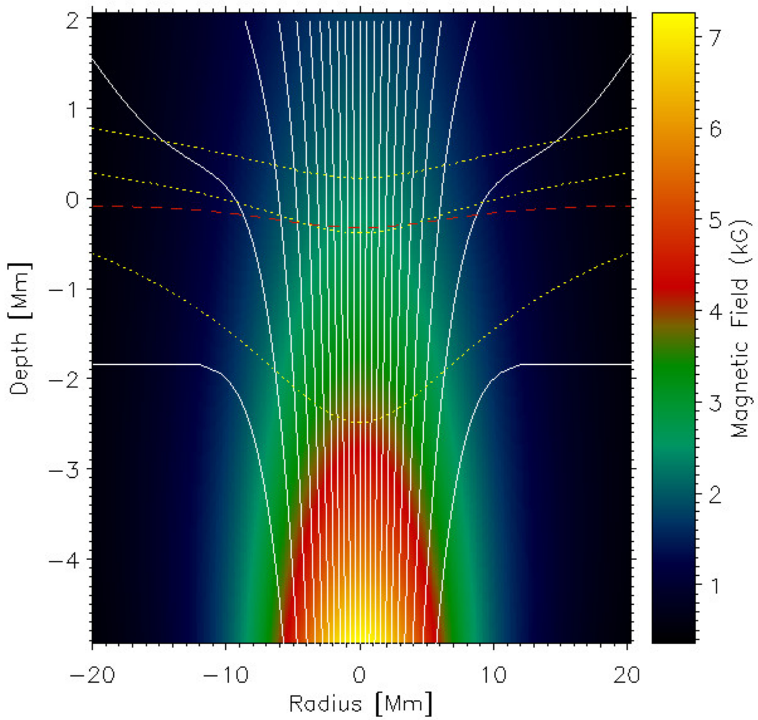
“realistic” 3D sunspot

Model requirements:

• Stable for linear MHD simulations.
• ‘Looks’ real with spectral synthesis.
• Adjustable.

Based on the Khomenko et al. (2009) Model:
• A self-similar solution in the lower layers
•A semi-empirical solution in the upper layers

Creates a convectively stable quiet Sun and umbral distribution of temperature, pressure and density, then solves hydrostatic equilibrium with an enforced non-negative Brunt-Väisälä frequency.

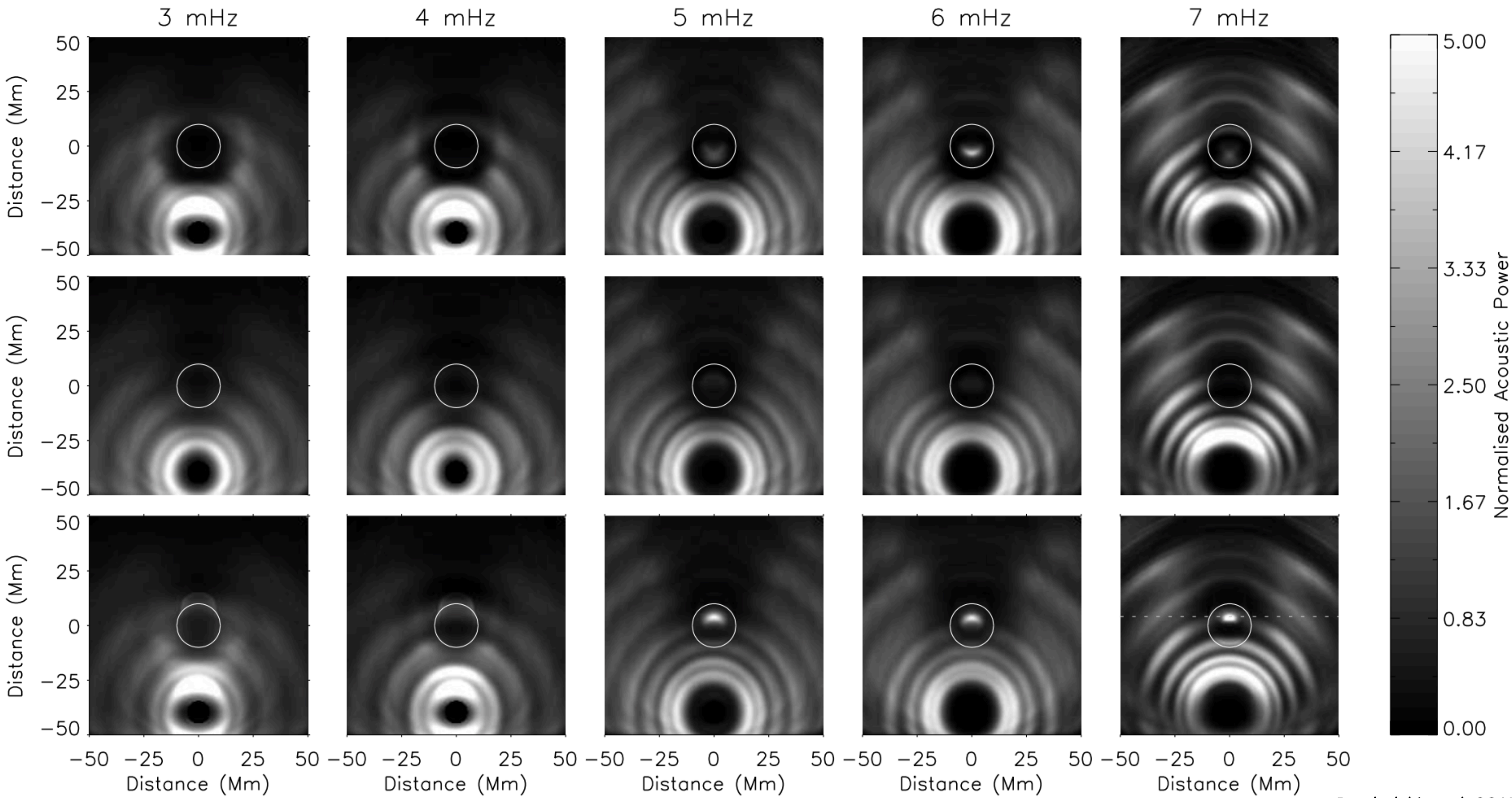


For more details and simulations please send an email to Damien Przybylski:

damien.przybylski@monash.edu

Simulations: acoustic power variability on the position at the solar disk

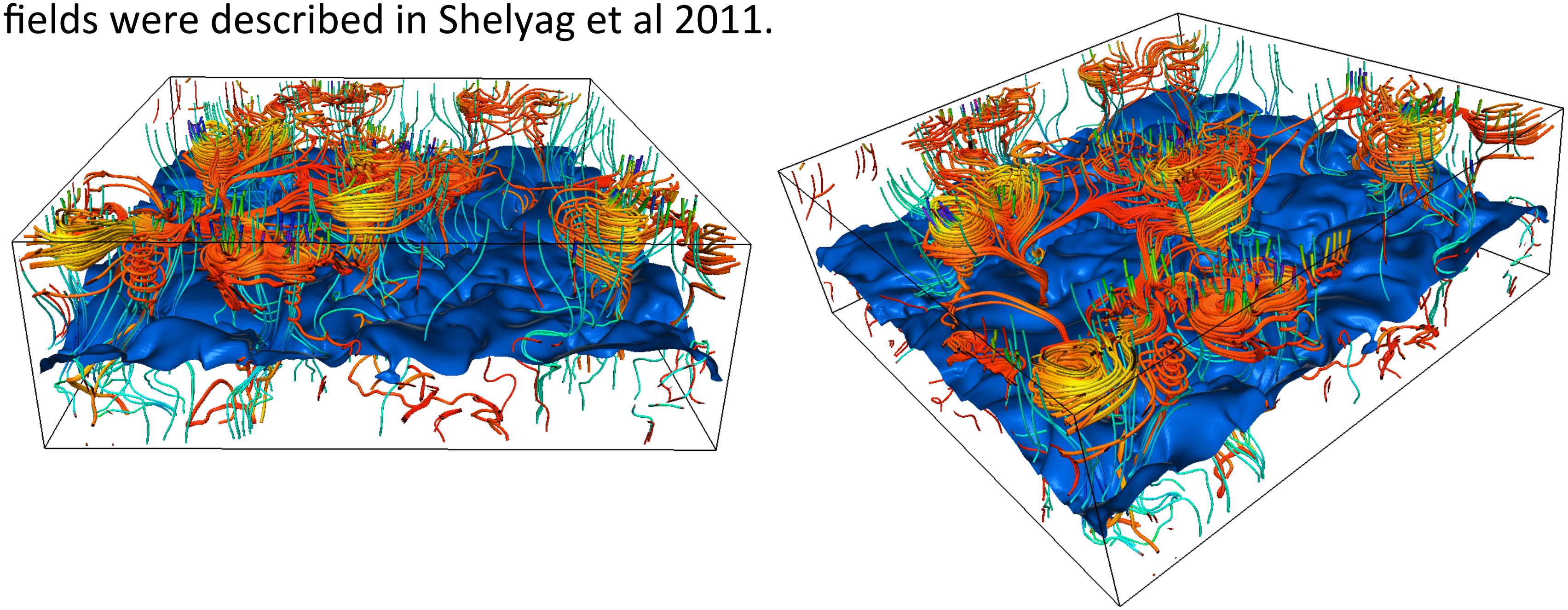
FeI 6173A line core Doppler shift, acoustic power maps
We see slow MAWs. Line wing does not show it.



Przybylski et al, 2015

Torsional motions in intergranular lanes

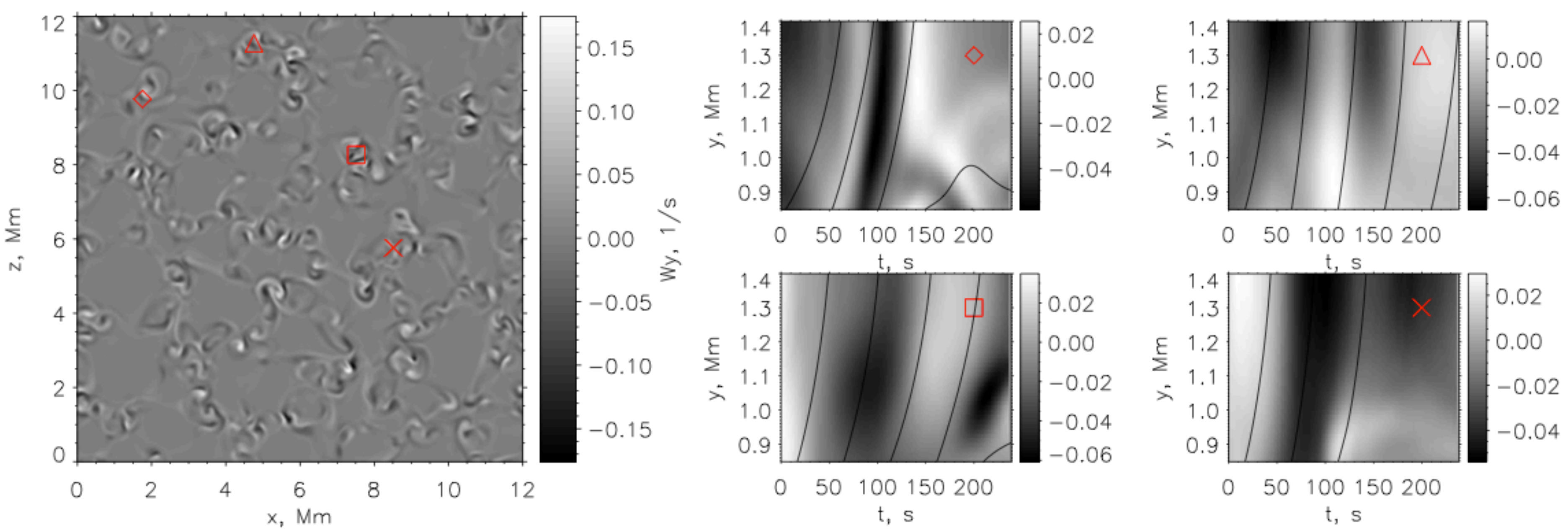
-MURaM code (Vögler et al 2005)
-Domain size is 12x12x3.2 Mm resolved by 480x480x320 grid cells
-50G / 200G unipolar initial magnetic field / bottom-boundary B advection
-Photospheric "vortices" generation and their links to strong photospheric magnetic fields were described in Shelyag et al 2011.



Velocity field lines show vortex structures in strong magnetic field regions.
Single-fluid ideal MHD: magnetic field is frozen into plasma.
Why the magnetic field lines do not show the same structures?
Because the velocity field is not steady-state: it is an oscillation

Alfvén waves

To identify wave types, we plot time-distance diagrams for the vertical component of vorticity in vortex structures. Also, overplot tracks for test particles moving with the local time-dependent Alfvén speed.



Shelyag et al, ApJL 2013

- The domain is filled with the structures exhibiting rapid vertical propagation of vorticity perturbation. No preferred frequency; possibly resolution-dependent.
- Alfvén speed can reach 70 km/s, normally about 40 km/s in higher photosphere in the magnetic field regions. Flow speeds never exceed 5-15 km/s. Propagation of vorticity perturbation cannot be explained with flows. It propagates with Alfvén speed.

"Vortices" do not generate Alfvén waves: they look like they are Alfvén waves themselves.

Without observational confirmation, it is still unclear if there are small-scale AW. Also, experts in non-ideal plasma physics say there could be no.

Need observational confirmation, where to look?

Off-centre simulated spectropolarimetry

NICOLE code by Hector Socas-Navarro (IAC, Spain) is used to compute the Stokes profiles. Different viewing angles are achieved by shifting the layers of the MHD box and recalculating LOS and perp. magnetic field and LOS velocity.

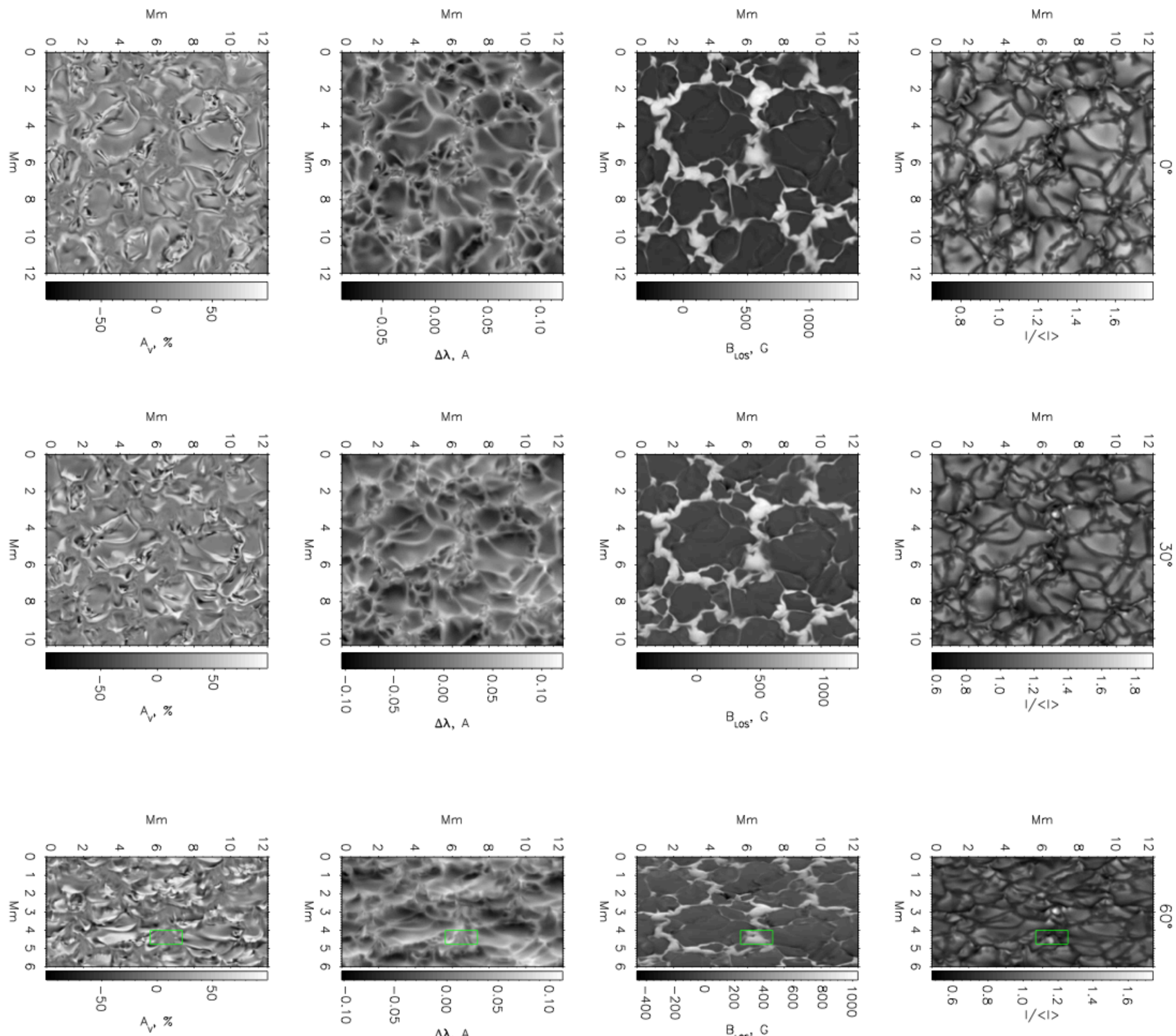
FeI 6302.5A line

Av | Δλ | Blos | Ic

0°

30°

60°



Shelyag&Przybylski, PASJ, 2014

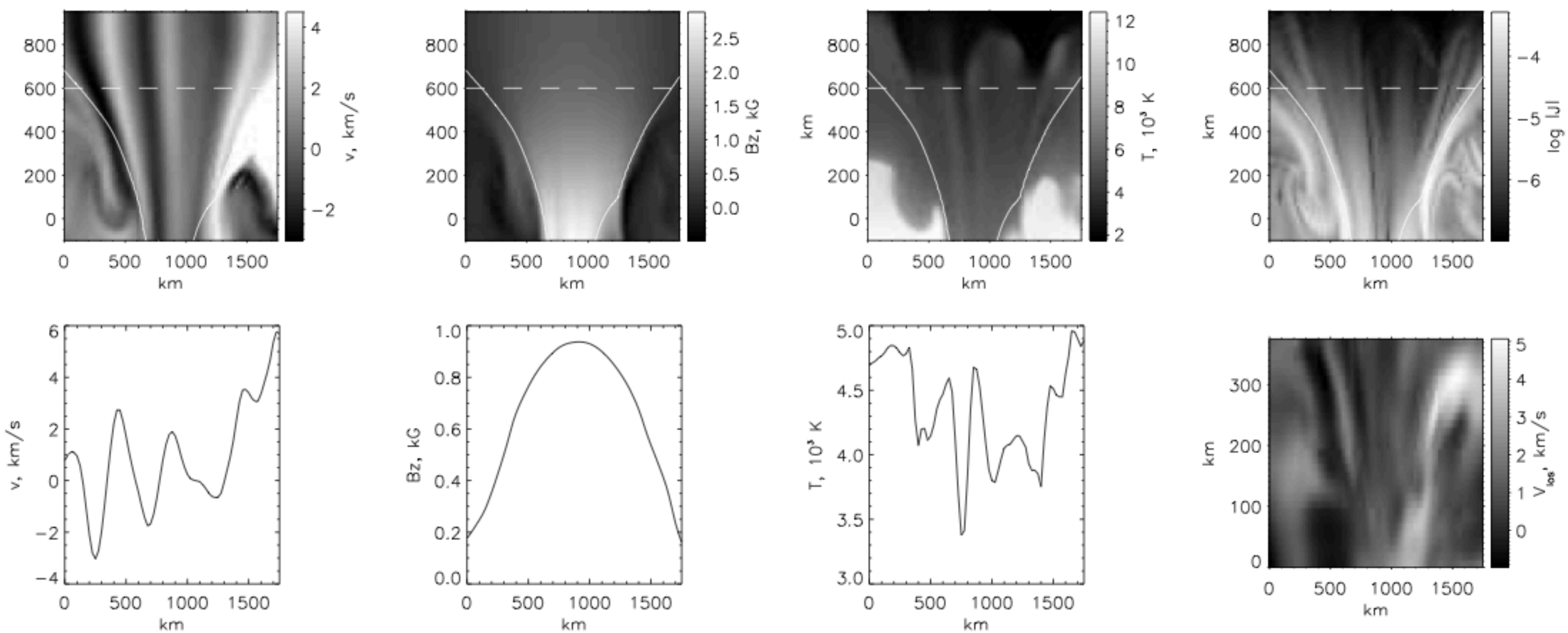
Plasma parameters and FeI 6302.5A line

Horizontal velocity

Vertical B

Temperature

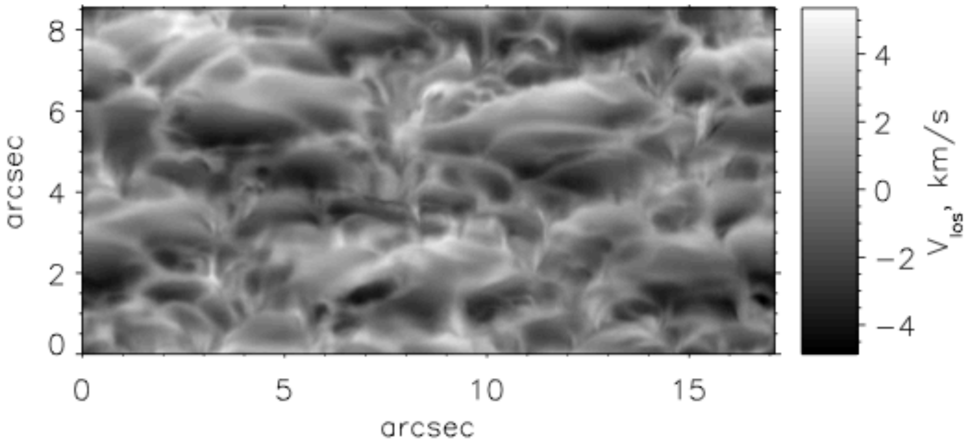
Current



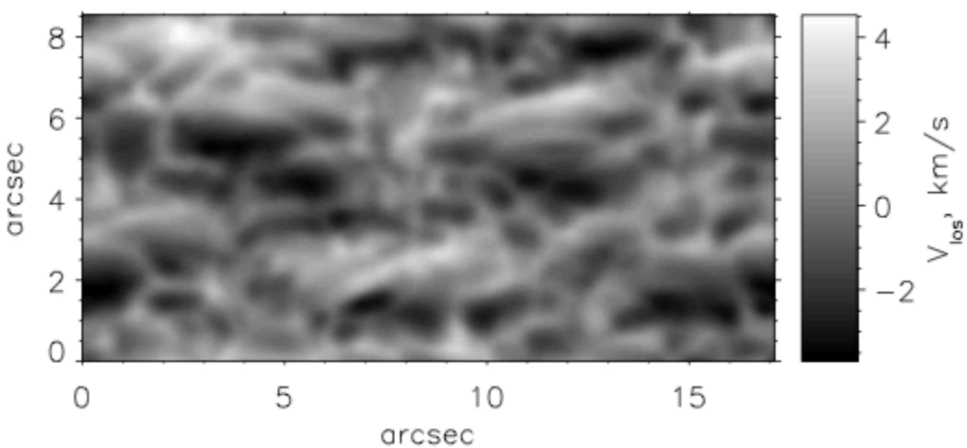
Vlos

Shelyag&Przybylski, PASJ, 2014

V_{LOS} from FeI 6302 at 60 degrees



Original resolution, 25 km

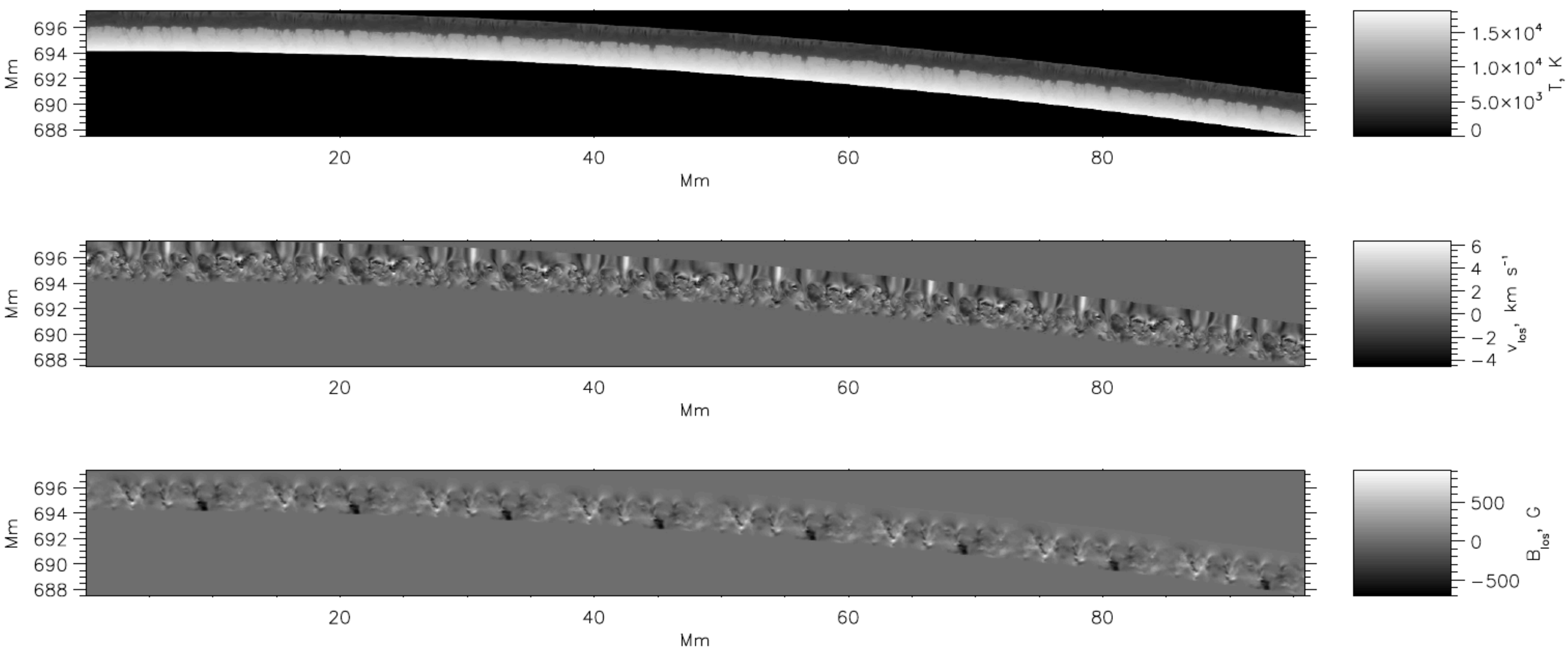


Degraded with Hinode PSF

Shelyag&Przybylski, PASJ, 2014

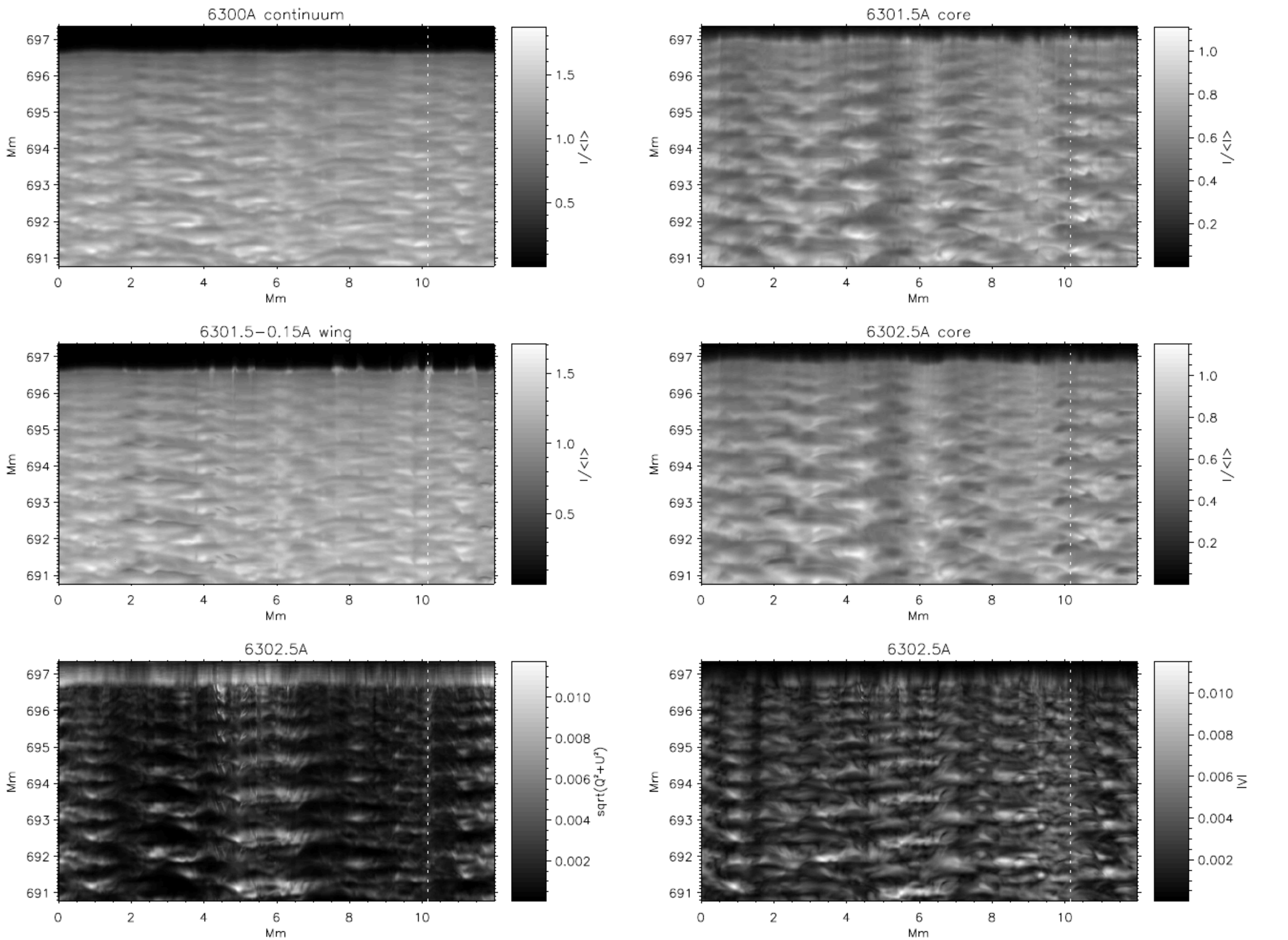
The limb simulation

16 MURaM models are stacked together and then curved to make the “spherical” (cylindrical, in fact) solar surface. Velocity and magnetic field are recalculated accordingly.



Shelyag, ApJ, 2015

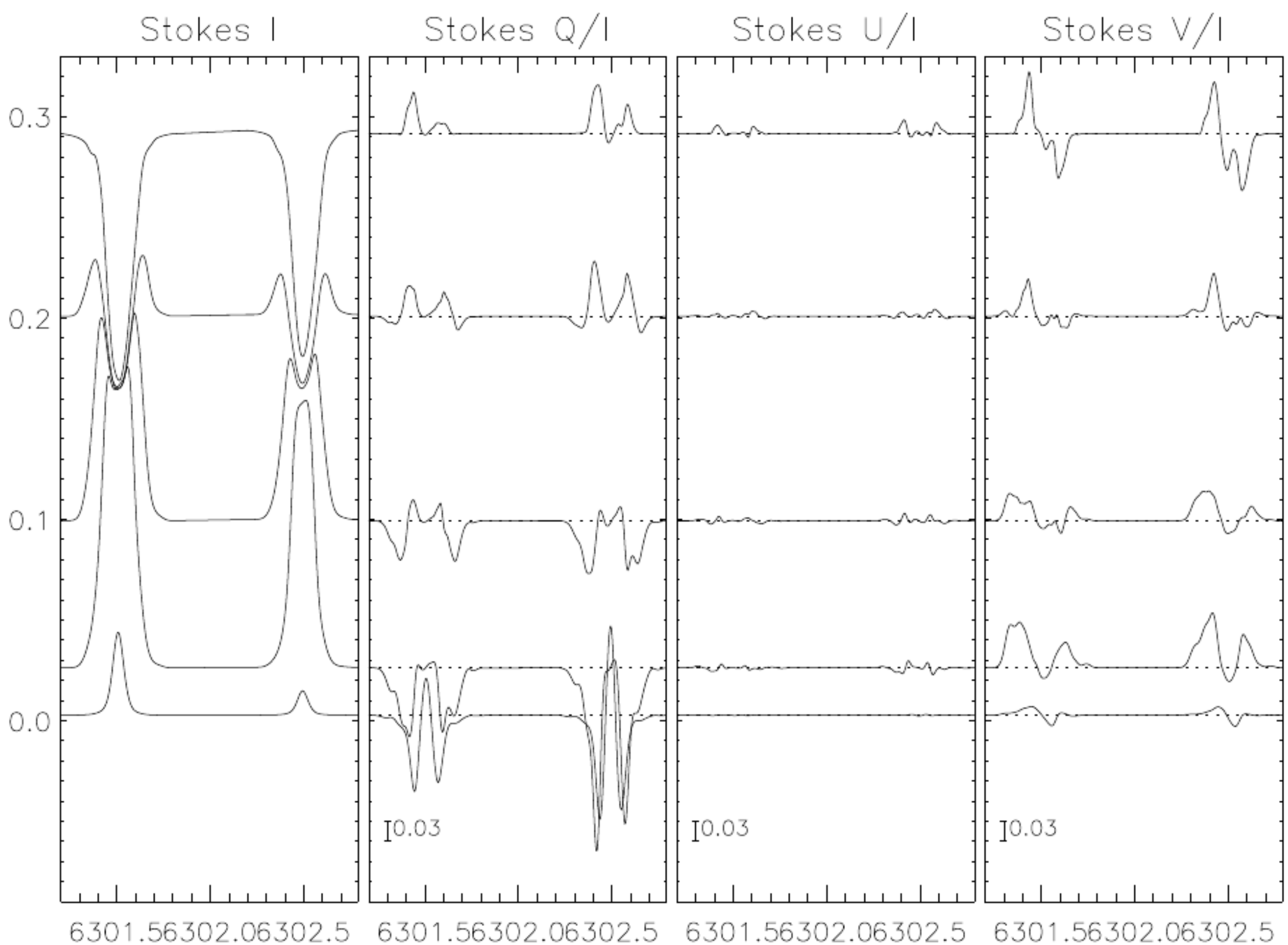
Simulated limb, images



Shelyag, ApJ, 2015

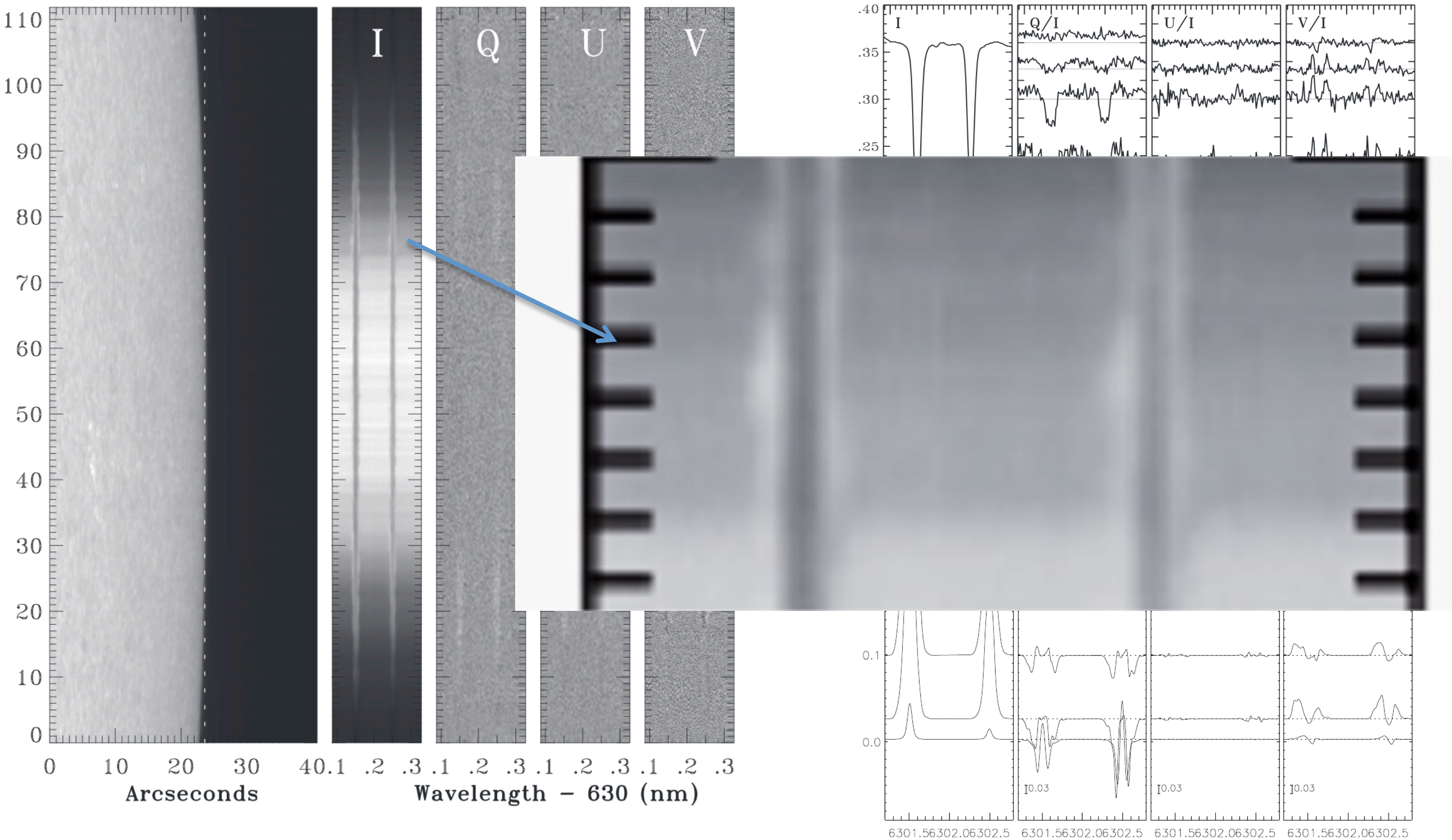
Simulated limb, average profiles

The 6302A line profiles go into emission. But the wings rise first.



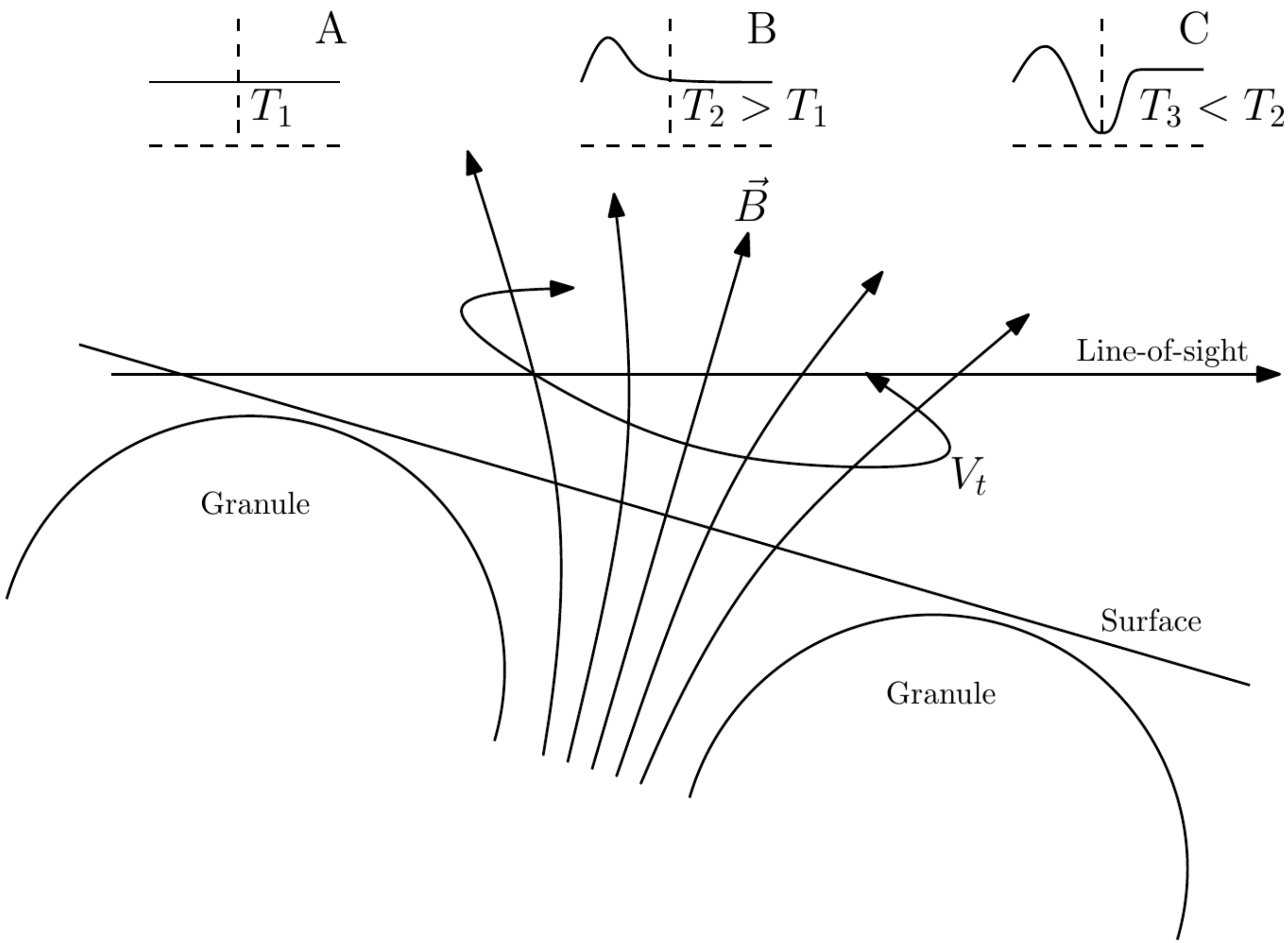
Shelyag, ApJ, 2015

S-p observation of the limb, Hinode, Lites et al 2010



Lites et al (2010) show similar profiles. They say emission in the wings is due to 3D non-LTE scattering. Apparently, not only – I used 1D LTE.

How the emission-absorption profiles are formed



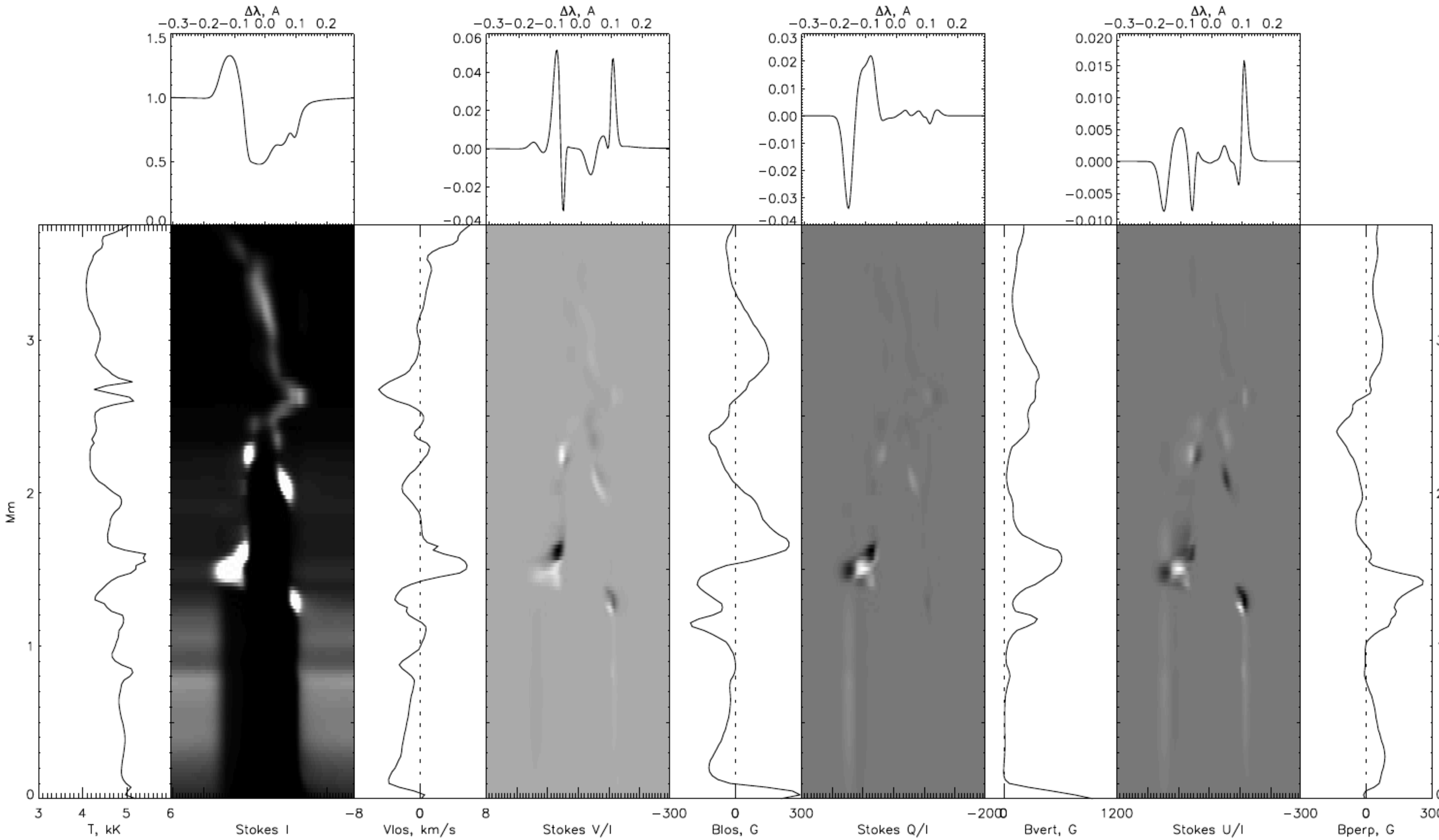
Here, absorption-emission profiles are formed in three stages: (A) – continuum formation, (B) – Doppler-shifted emission profile in the positive T-gradient with torsional flow, (C) – normal absorption profile.

Shelyag, ApJ, 2015

Conclusions

- Simulations have been shown to be widely successful in simulating a variety of photospheric effects – including waves
- Simulations (if you believe them) can give you a hint on where to look and what to expect in observations
- If you don't believe them, there is a plenty of space to improve
- If you are interested in some of those results/models, let me know

Simulated limb, 6302A FeI response functions



Shelyag, ApJ, 2015