Transmission and conversion of magneto-acoustic waves in the quiet solar chromosphere.

I. Kontogiannis, G. Tsiropoula & K. Tziotziou

IASARS, NOA

Chromospheric fine structure and the magnetic field

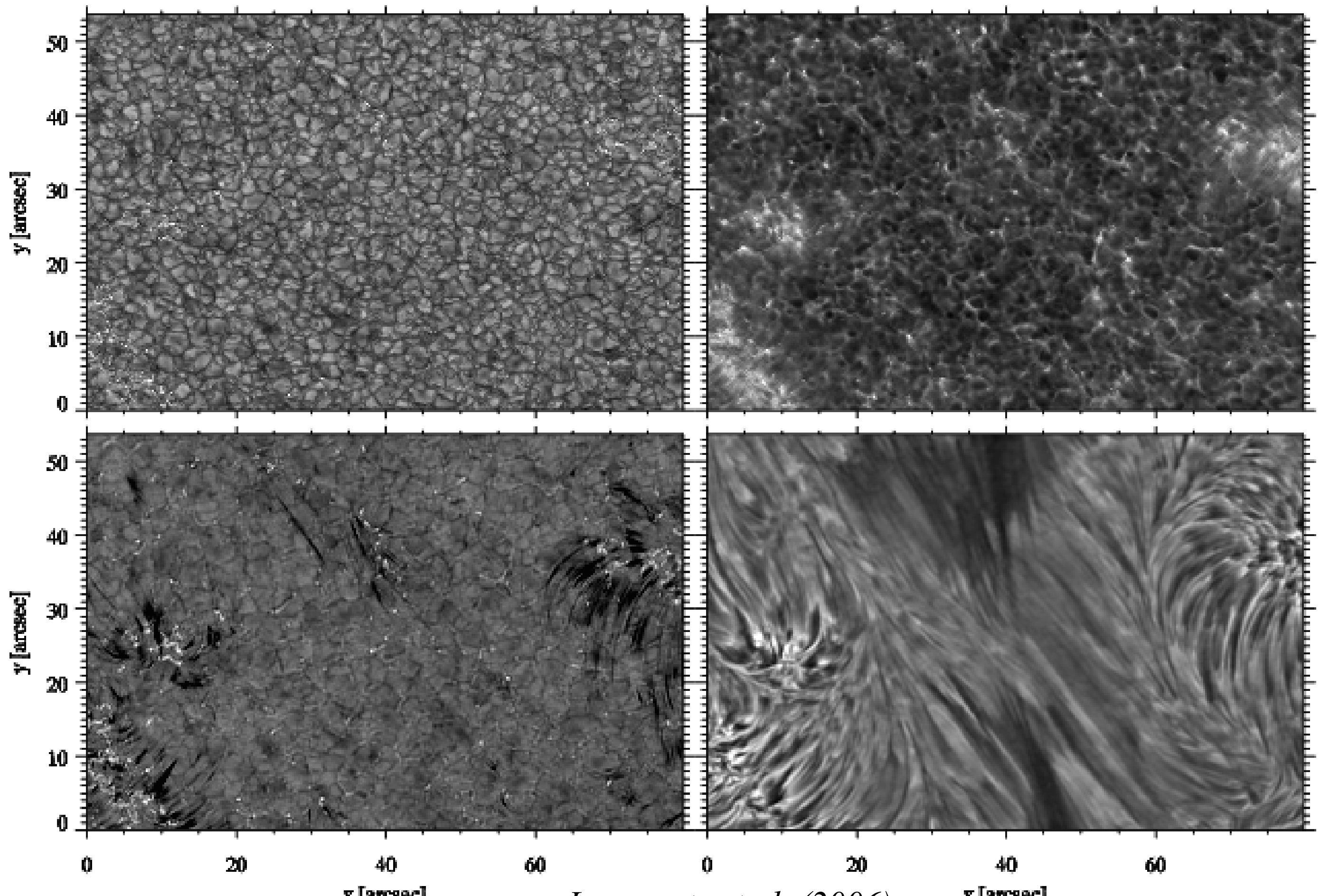
Mottles:

Length: ~10 000 km

Life time: ~ 3 – 15 min ?

Temperature:
10 000 – 15 000 K

Density: 1.1 10^{-13} g/cm^3



Leenaarts et al. (2006)

Tsiropoula, G., Tziotziou, K., Kontogiannis, I., Madjarska, M. S., Doyle, J. G., Suematsu, Y., 2012,
Space Science Reviews, Volume 169, Issue 1-4, pp. 181-244

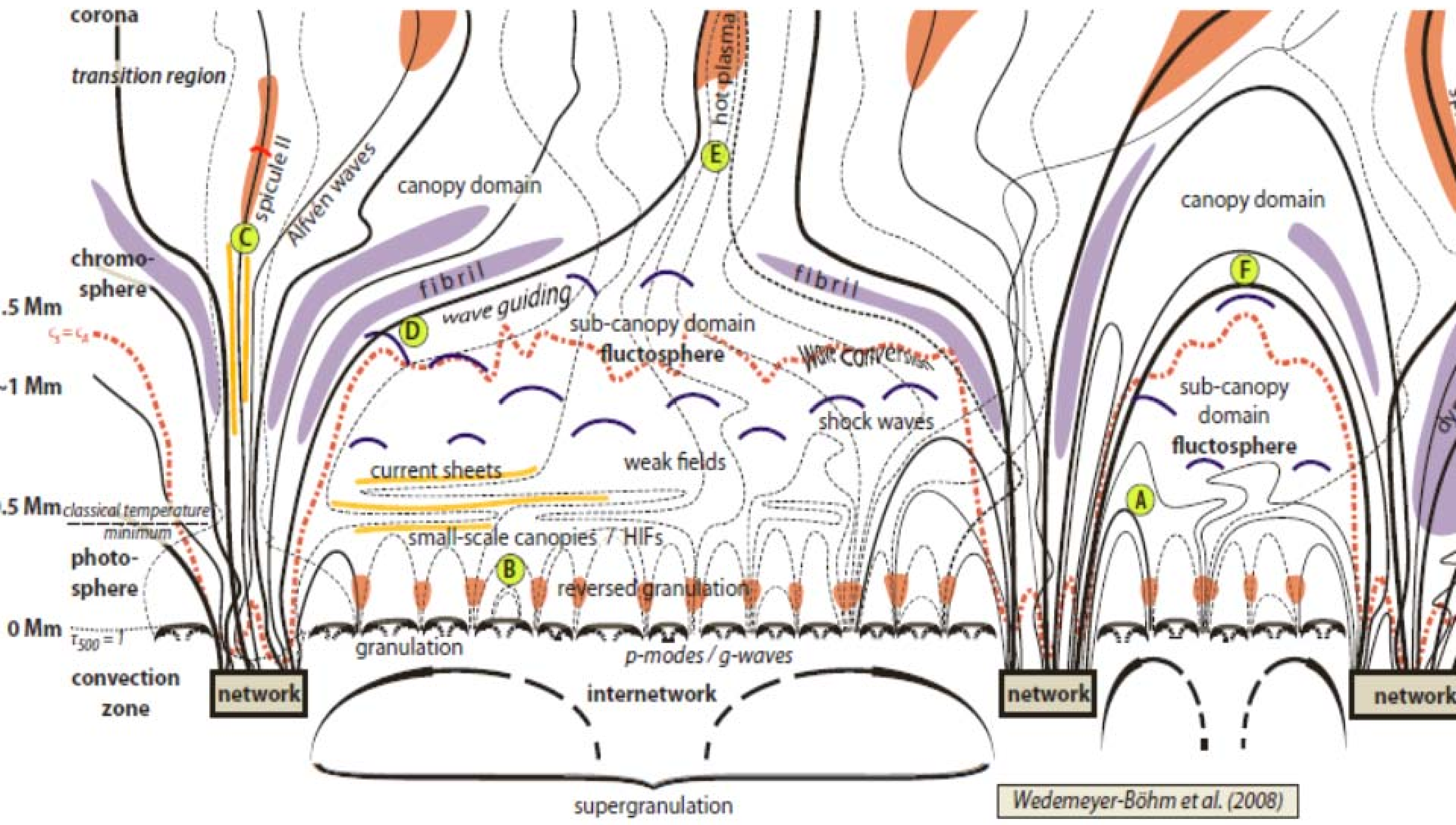
The magnetic canopy

$$\beta = \frac{P_{gas}}{P_{mag}}$$

Magnetic canopy: β ~ 1 or approximately where $V_{sound} = V_{Alfven}$

$\beta > 1$: thermal motions (P_{gas}) dominate (quiet photosphere)

$\beta < 1$: magnetic field (P_{mag}) dominates (chromosphere, network)

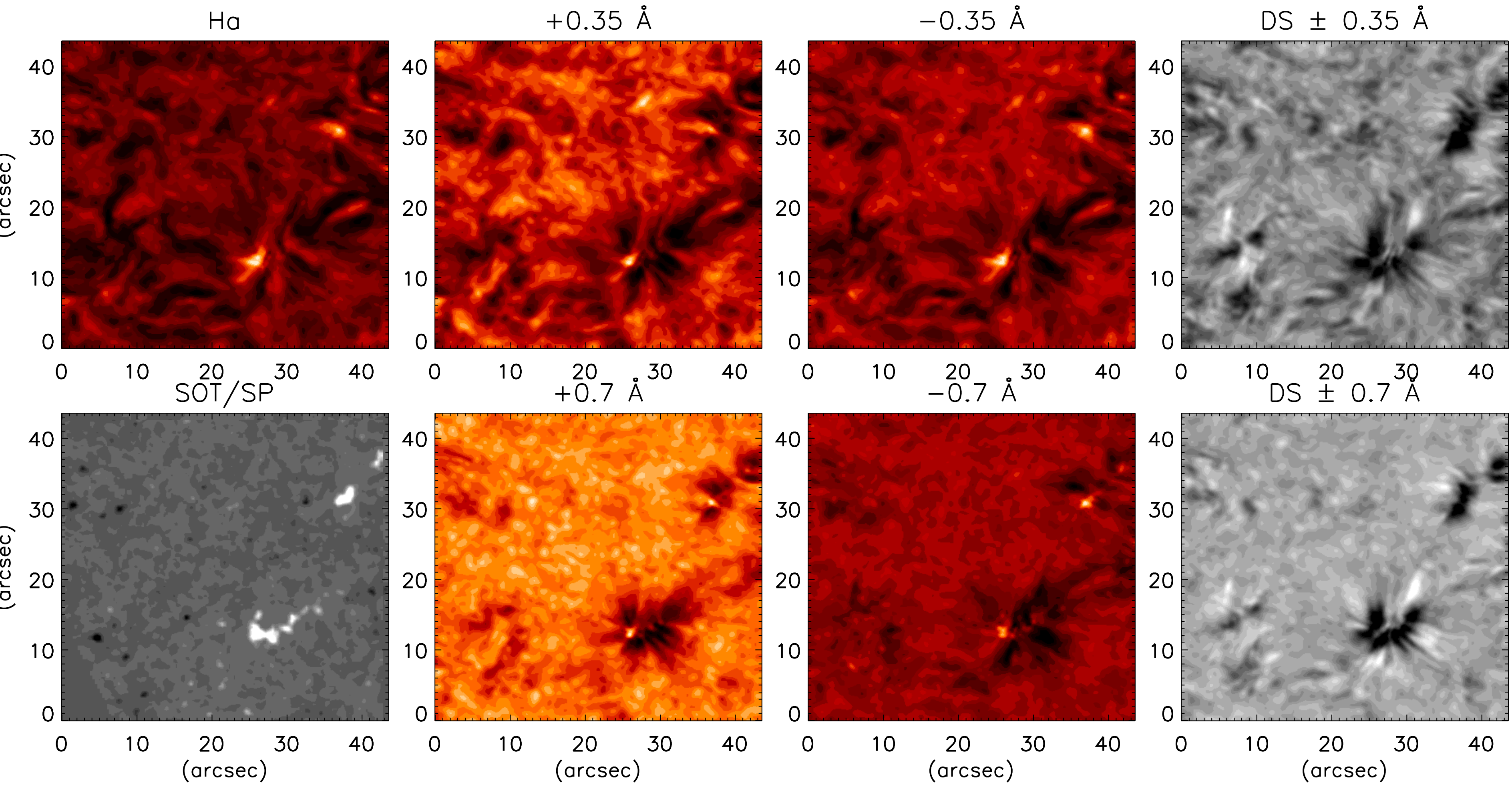


Wedemeyer-Böhm et al. (2008)

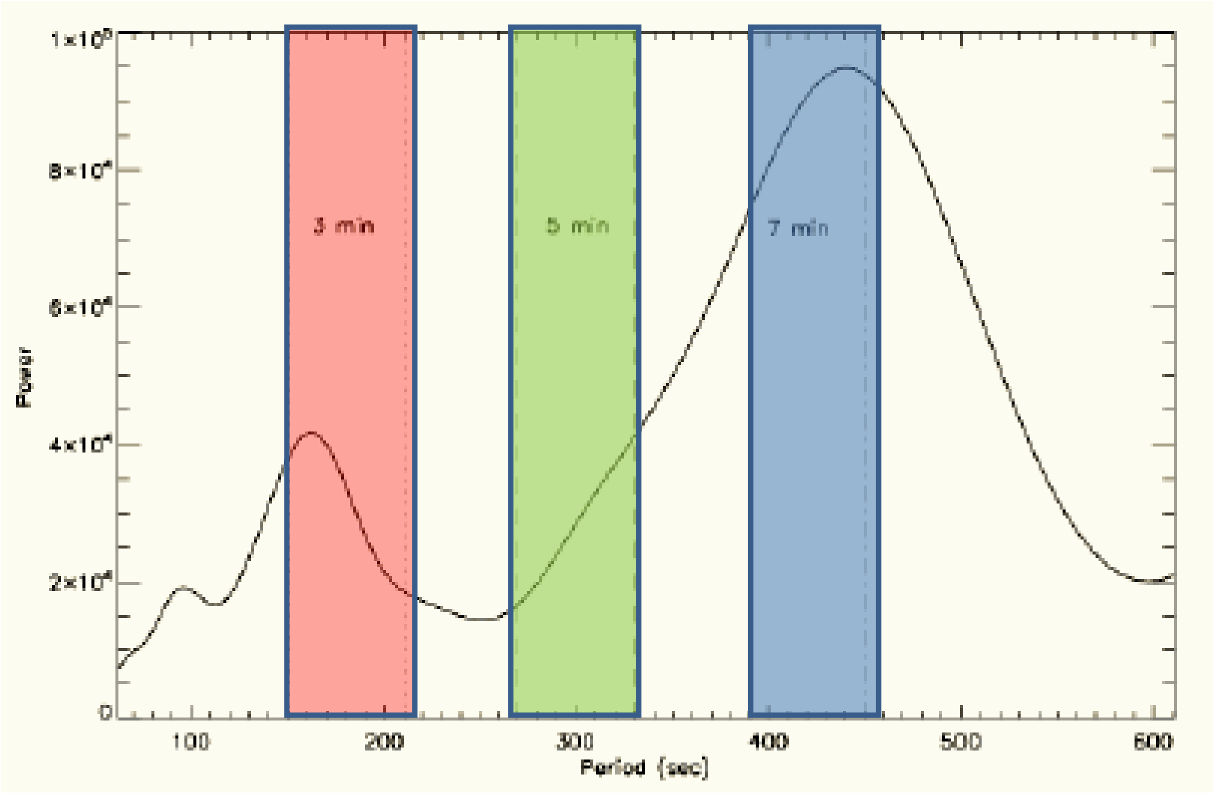
Observations

Dutch Open Telescope (DOT): **Hα (5 wavelengths along the profile)**
(30 s cadence, 30 min time series, 0.1'' resolution)

HINODE/SP : **2 high resolution vector magnetograms**
(0.32'' resolution)



Wavelet Analysis



Global Wavelet Spectrum for every pixel of the FOV → 2-d power maps:

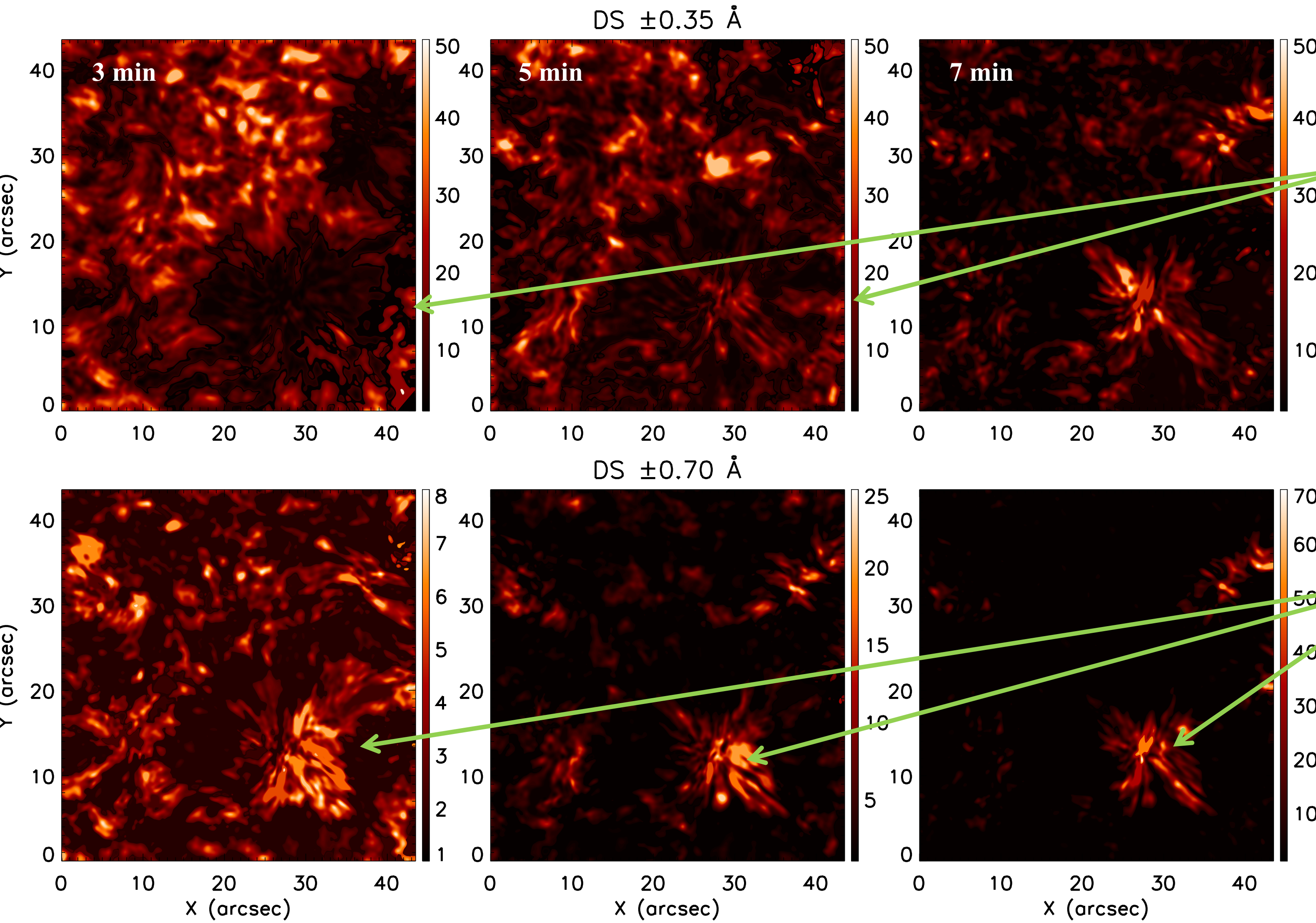
Phase difference and coherence

$$\delta\phi(s) = \arctan\left(\frac{\mathrm{Im}\{<s^{-1}W_{XY}(s)>\}}{\mathrm{Re}\{<s^{-1}W_{XY}(s)>\}}\right)$$

$$R^2(s) = \frac{|<s^{-1}W_{XY}(s)>|^2}{<s^{-1}|W_X(s)|^2><s^{-1}|W_Y(s)|^2>}$$

Vertical wave propagation between two heights

3, 5 and 7 min power distribution in Hα chromosphere



Magnetic Shadow

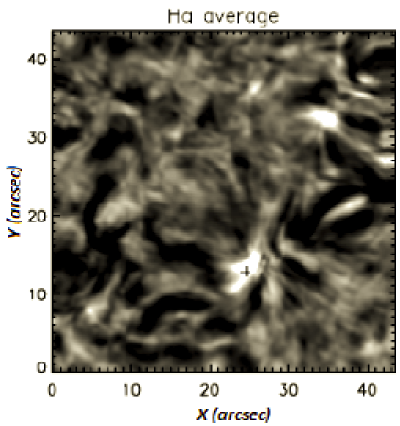
(Judge et al. 2001
Vecchio et al. 2007

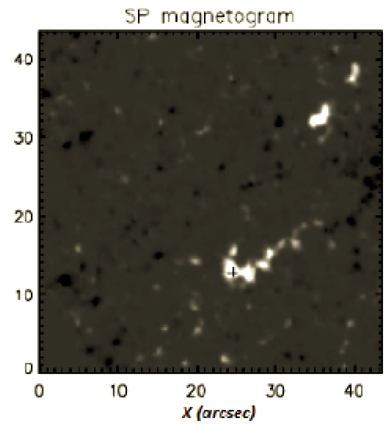
Power Halo

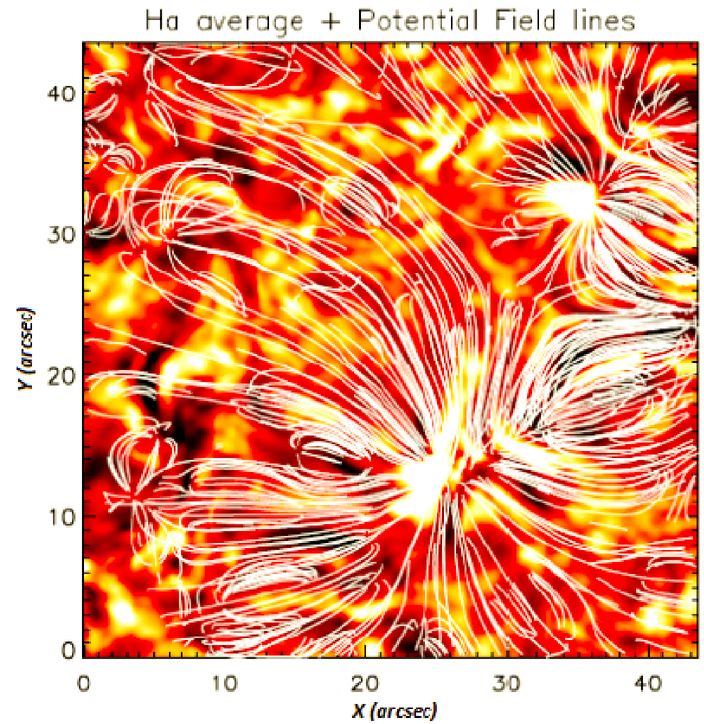
(Braun et al. 1992,
Krijger et al. 2001,
Jain & Haber 2002

(*Kontogiannis. Tsiropoula, Tziotziou 2010, A&A, 510, A41*)

Hα and chromospheric magnetic field







<u>Calculating the height of the magnetic canopy</u>

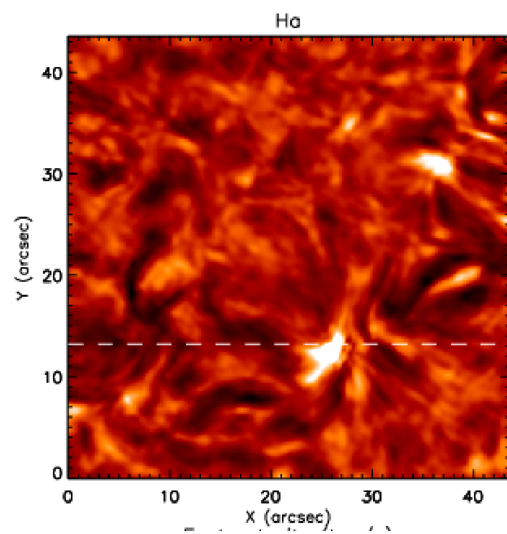
Magnetic field extrapolation (Pmag)

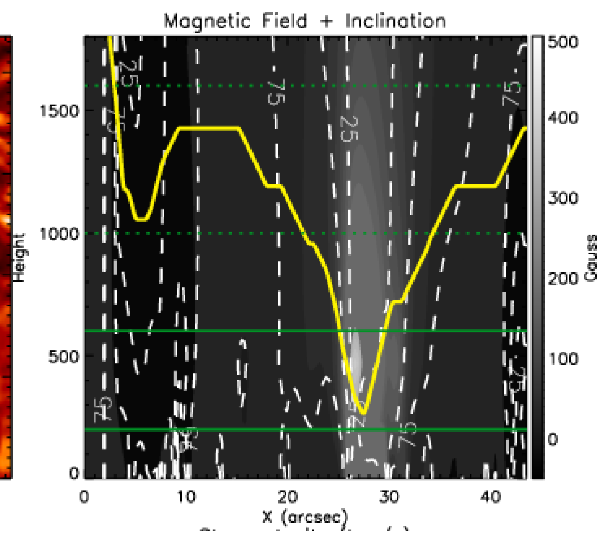
(current-free or potential field assumption)
(Schmidt 1964, Alissandrakis 1981)

Atmospheric model (Pgas)
(Vernazza et al. 1981 (VAL)

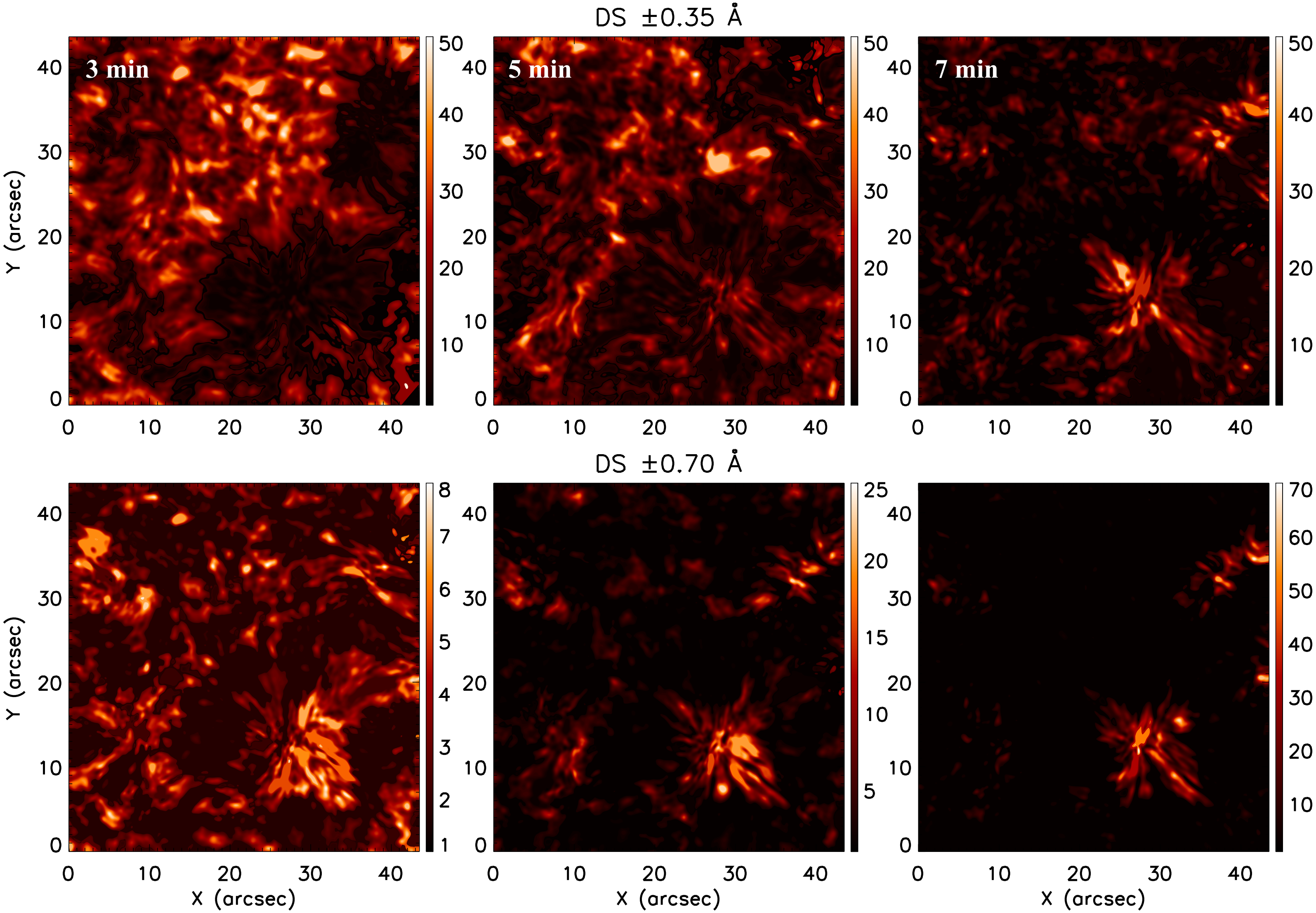
$$\beta = \frac{P_{gas}}{P_{mag}}$$

Magnetic canopy:
the height where β ~ 1

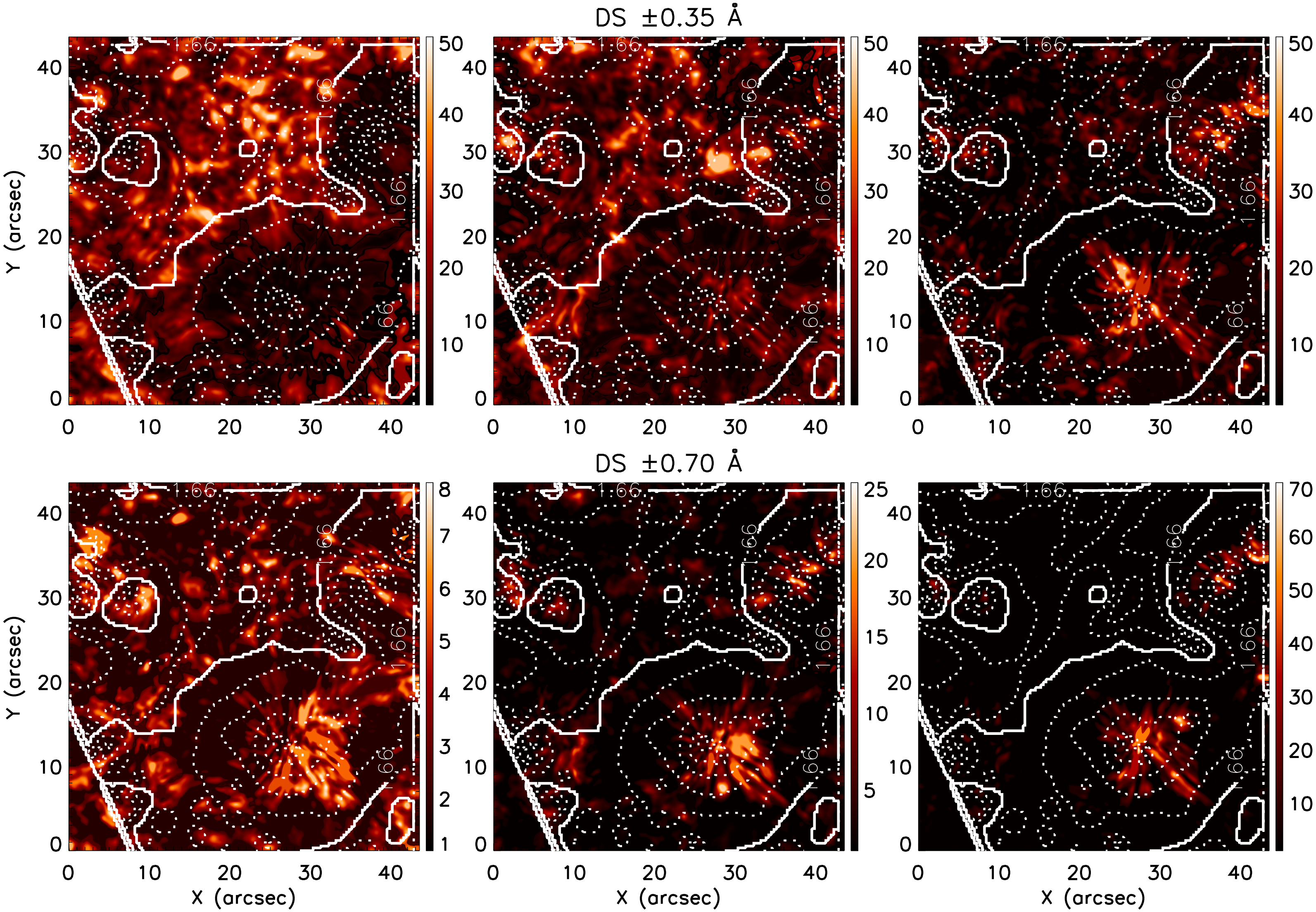




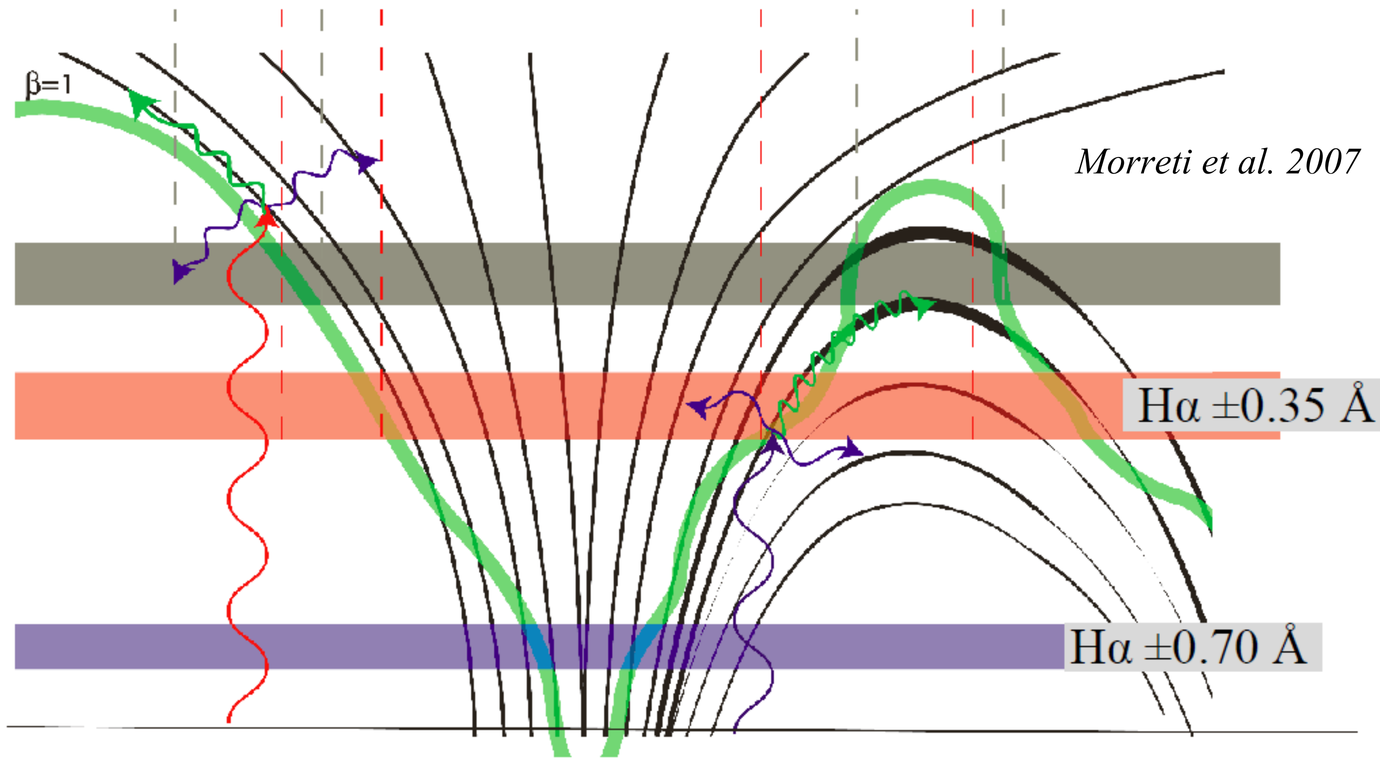
3, 5 and 7 min power distribution in Hα chromosphere + canopy height



3, 5 and 7 min power distribution in Hα chromosphere + canopy height



Conclusion: Magnetic shadow and power halo phenomena in Hα are due to the interaction between the acoustic oscillations and the magnetic canopy:



-Canopy Height < Formation Height → Magnetic Shadow

-Canopy Height > Formation Height → Power Halo

-The magnetic canopy is formed by the magnetic flux tubes that constitute mottles.

(*Kontogiannis. Tsiropoula, Tziotziou & Georgoulis. 2010, A&A, 524, A12*)

These flux tubes are probably the loci of **mode conversion**

Acoustic oscillations and magneto-acoustic waves

p- modes or “5 min oscillations” (Leighton 1962)

$\mathbf{f_0 > 5.2\ mHz}$ (P < 3 min) → **vertical propagation (else evanescent)**

But!!!
In Chromospheric Mottles: 5 min (Tziotziou et al. 2004, Tsiropoula et al. 2009)

How can long period waves propagate up to the chromosphere?

Inclined magnetic fields: increase the acoustic cut-off period (Michalitsanos 1973, Bel & Leroy 1977)
“p-mode leakage” (De Pontieu et al. 2004), **“ramp effect”**
“magneto-acoustic portals”, (Jefferies et al. 2006)

$$f = f_0 \cos\theta$$

Magneto-acoustic waves (pressure gradient and Lorentz Force):

$$\upsilon_f = \sqrt{\frac{1}{2}\left(\upsilon_A^2 + c_s^2\right) + \frac{1}{2}\sqrt{\left(\upsilon_A^2 + c_s^2\right)^2 - 4\cdot\upsilon_A^2\cdot c_s^2\cos^2\vartheta}}$$

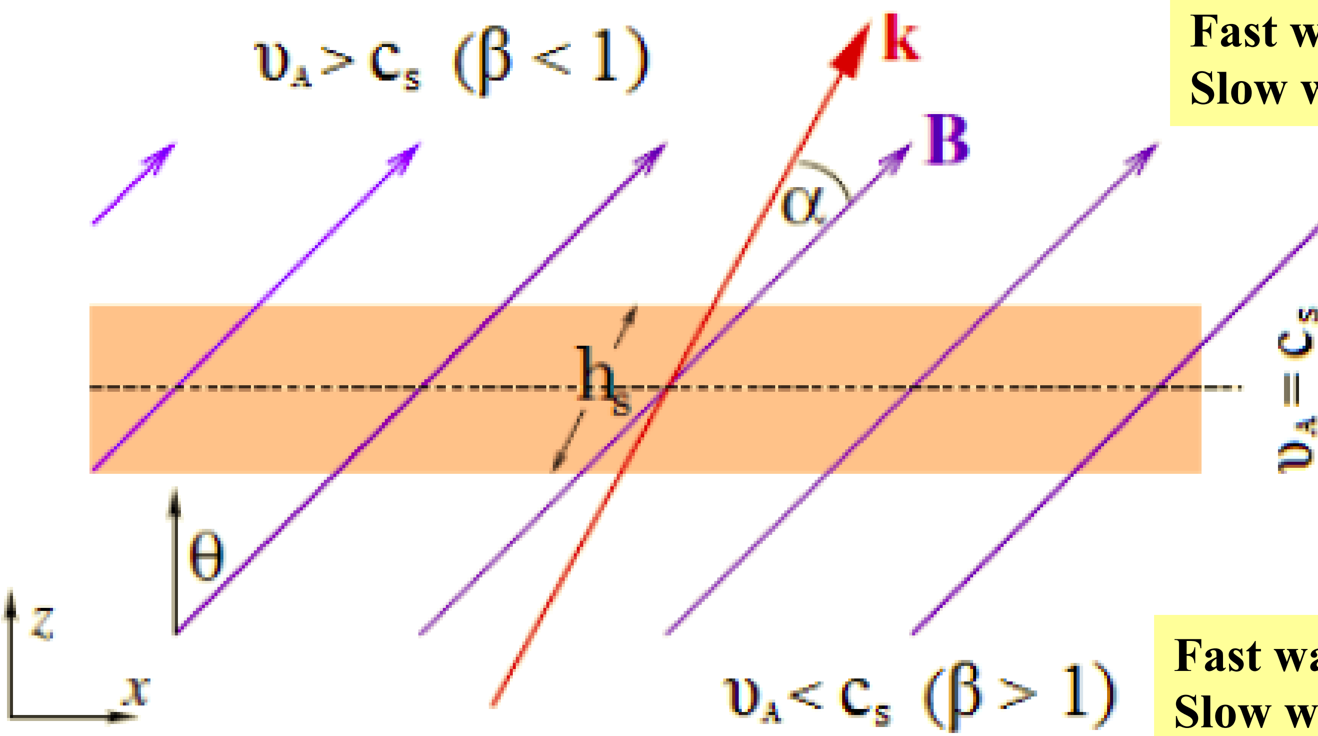
In phase: **fast mode/wave**

$$\upsilon_s = \sqrt{\frac{1}{2}\left(\upsilon_A^2 + c_s^2\right) - \frac{1}{2}\sqrt{\left(\upsilon_A^2 + c_s^2\right)^2 - 4\cdot\upsilon_A^2\cdot c_s^2\cos^2\vartheta}}$$

In anti-phase: **slow mode/wave**

$$\upsilon_A = \frac{B}{\sqrt{\mu_0\rho}} \qquad c_s = \sqrt{\frac{\gamma\cdot P}{\rho}}$$

Wave propagation around the magnetic canopy (2-d model)



Fast wave: magnetic wave $\perp$ B
Slow wave: acoustic wave // B

β = 1 (magnetic canopy)
mode coupling,
energy transfer

Fast wave : acoustic wave
Slow wave: Alfvén wave along B

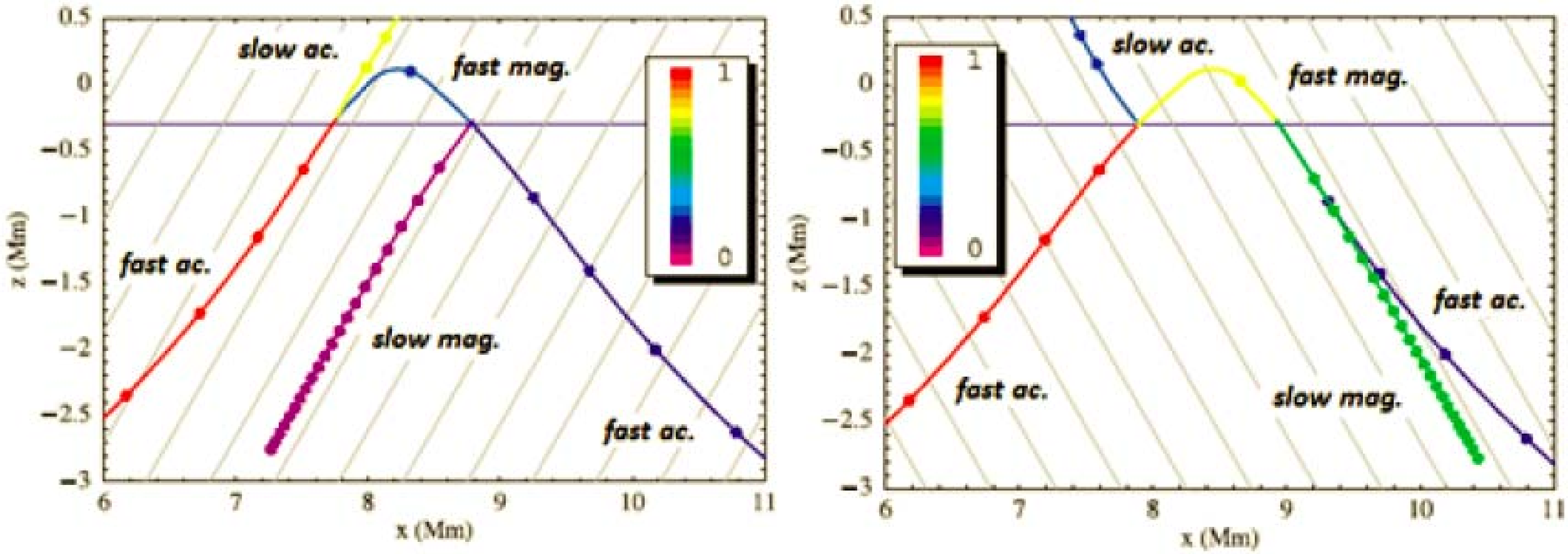
Two processes
Transmission to a slow magnetoacoustic wave
(T, small α, low f)
Conversion to a fast magnetoacoustic wave
(C, large α, high f)

$$T = \exp(-\pi k h_s \sin^2 \alpha)$$

$$T + C = 1.$$

Schunker & Cally 2006, Cally 2007

Wave propagation around the magnetic canopy (2-d model)



1. **Directional filtering of the waves above the canopy**
   α) slow magneto-acoustic waves along the magnetic field lines
   β) reflection of fast magneto-acoustic waves towards the solar surface

Stangalini et al. 2011:

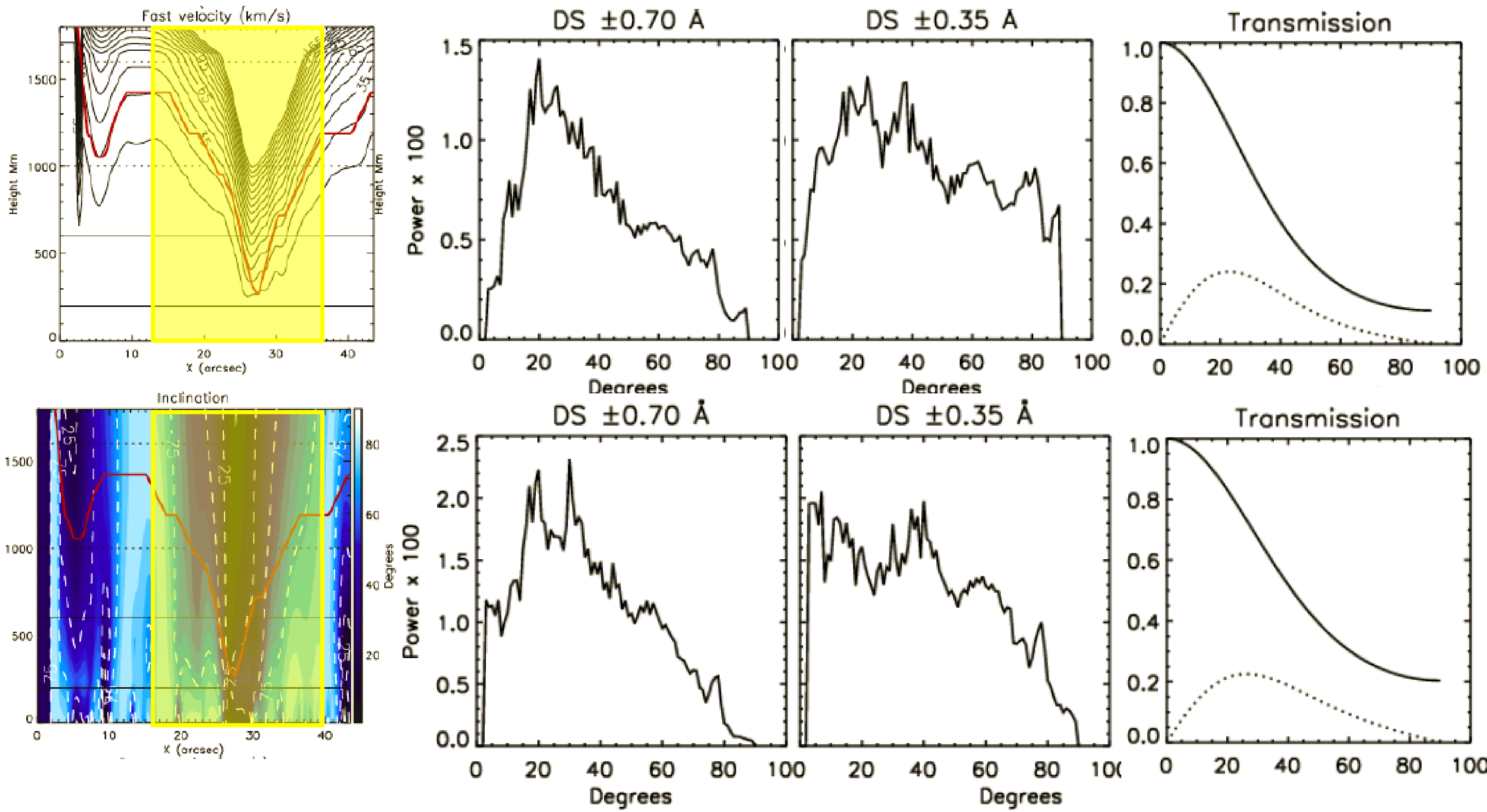
ramp effect

$$T' = T \cdot [1 - \exp(-\theta / \theta_0)] \cdot \cos\theta$$

Projection effects

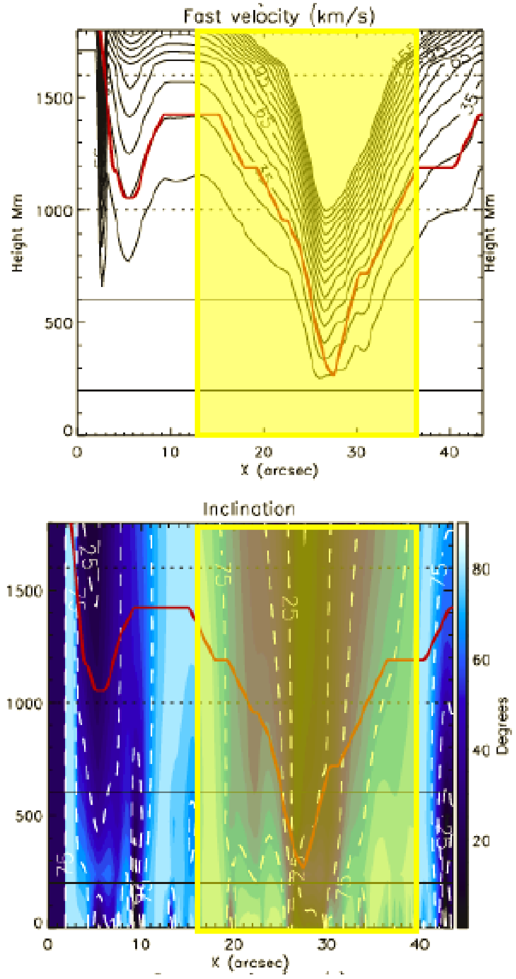
2. **Reduced travel times (phase differences)** at the magnetic canopy due to partial conversion to fast magneto-acoustic waves.

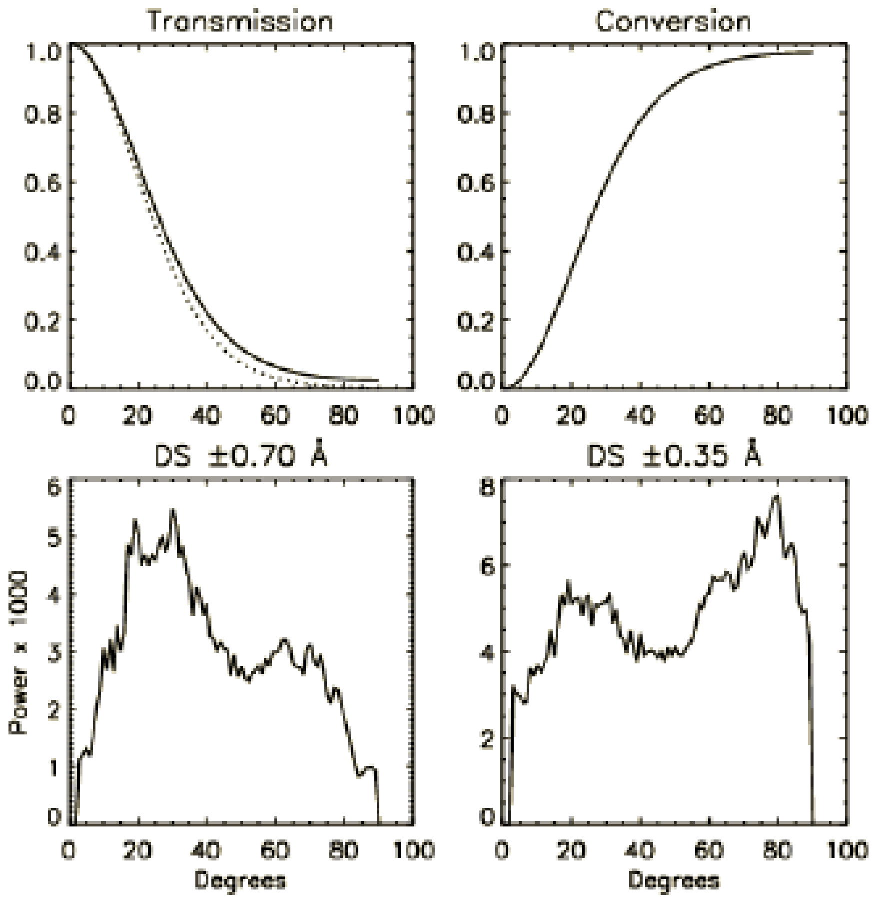
Wave propagation around the magnetic canopy (5 and 7 min Power vs inclination)



Kontogiannis, Tsiropoula & Tziotziou (in preparation)

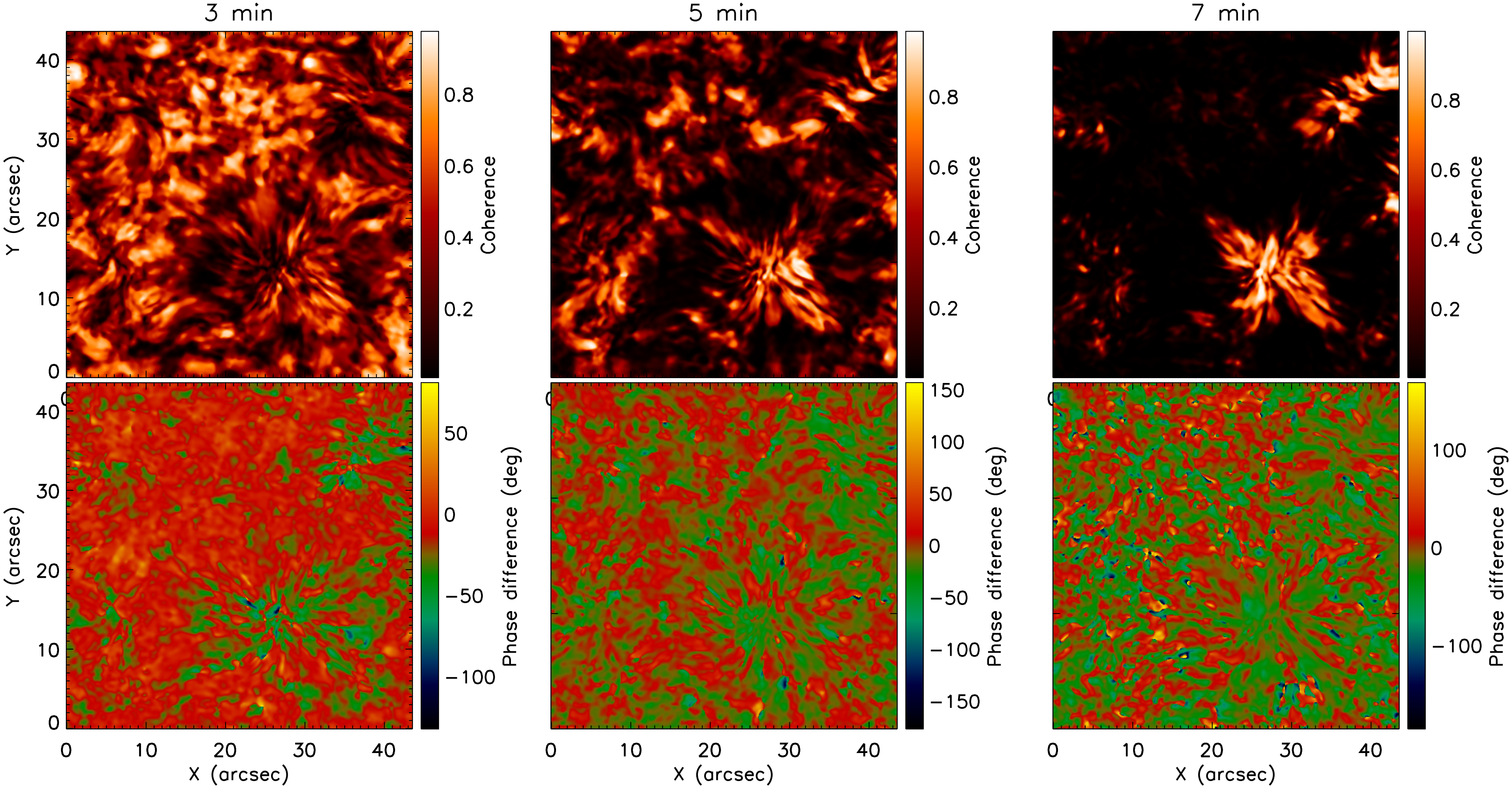
Wave propagation around the magnetic canopy (3 min Power vs inclination)





Kontogiannis, Tsiropoula & Tziotziou (in preparation)

Wave propagation around the magnetic canopy (Phase differences)

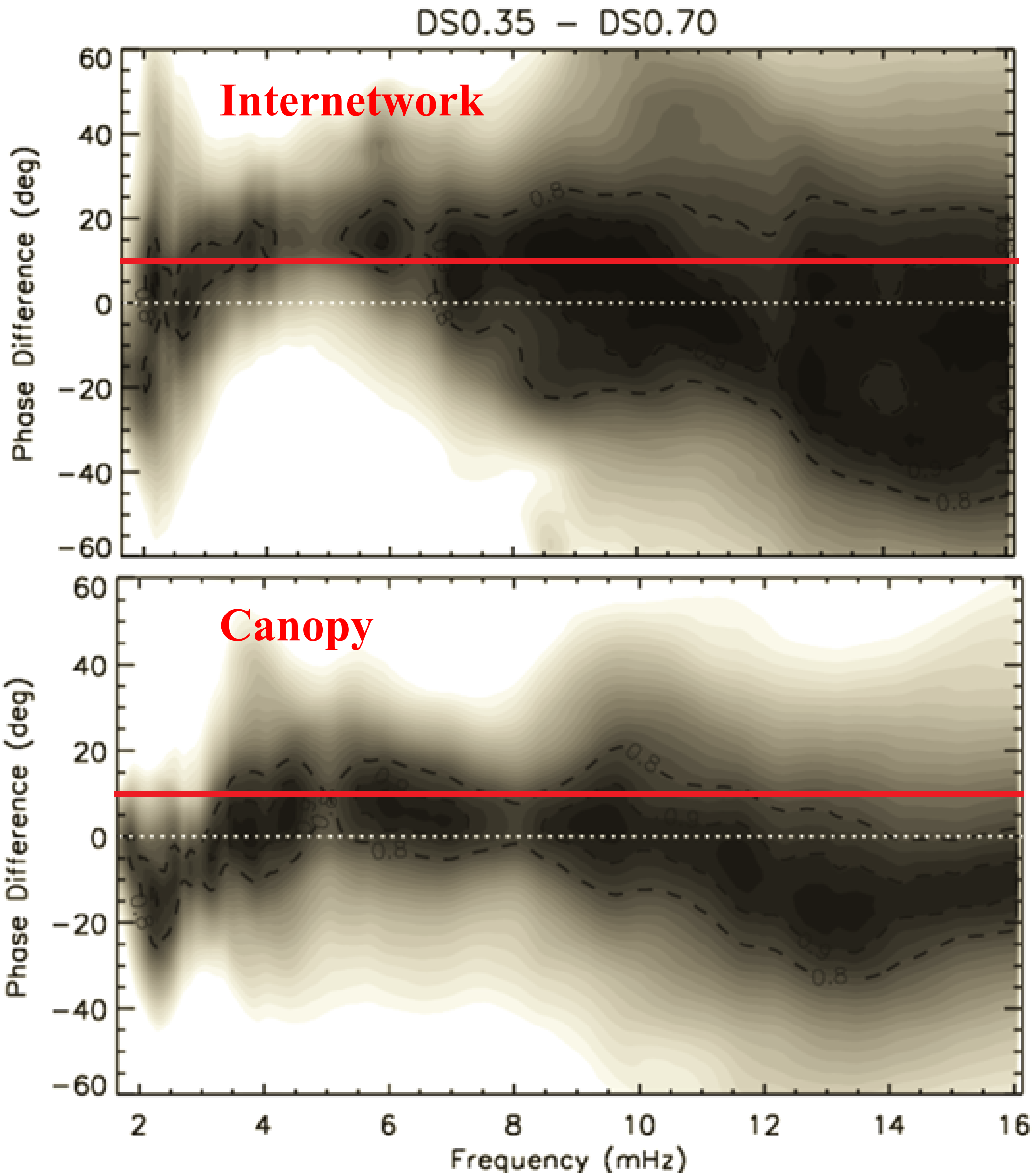


Very small phase differences → large phase speeds

Lower coherence inside the rosette (non vertigal propagation)

Negative phase differences (possible downward propagation)

Wave propagation around the magnetic canopy (Phase differences)



No clear signs of wave propagation

At the canopy:
Most power around **smaller** phase differences

<u>High frequencies:</u>
Most power at negative phases (downward propagation)

In summary:

1. On the magnetic canopy, acoustic waves convert into slow and fast magneto-acoustic waves. The first ones propagate along the (slanted) magnetic field lines, while the latter vertical to the magnetic field and reflect to the photosphere.

2. Hα magnetic shadow is a result of non-vertical propagation of the slow waves while power halo is due to the reflection of the fast waves on the magnetic carpet.

Future Work:

1. Extend our study to upper and intermediate atmospheric layers using more spectral lines and bandpasses.

2. Study wave propagation along the magnetic field lines.

3. Estimate the flux carried by the slow waves to the upper chromospheric layers.

4. Compare the results with those of MHD simulations.

Thank You!