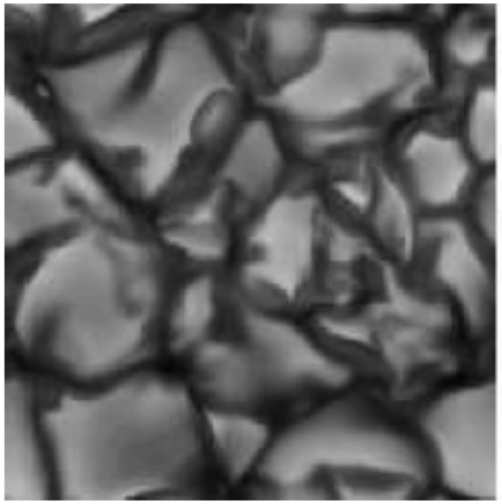
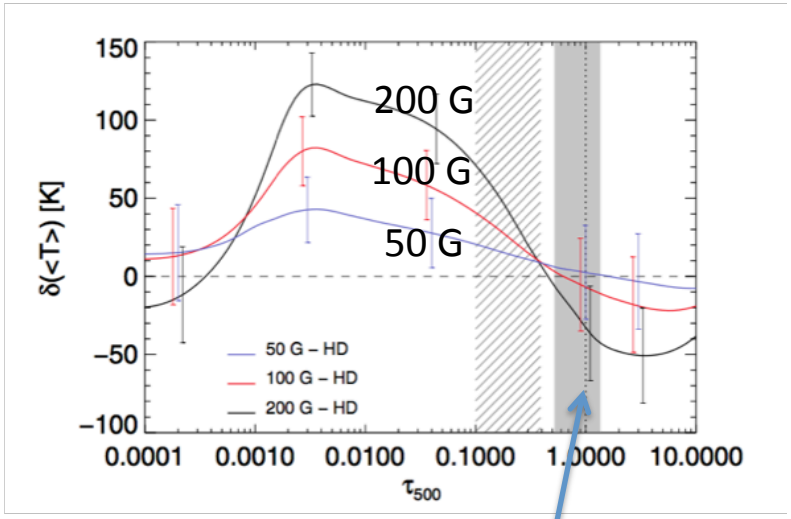
Variation of the photospheric temperature gradient with solar activity

Marianne Faurobert & Gilbert Ricort
University Cote d'Azur
Rahul Balasubramanian
Indian Institute of Technology Madras

Variation of T-gradient in 3D-MHD simulations



Numerical simulations of the granulation at various magnetic flux (Criscuoli & Uitenbroek, A&A 2014)



Steepening of T-gradient and temperature decrease in the **low photosphere** with increasing magnetic flux

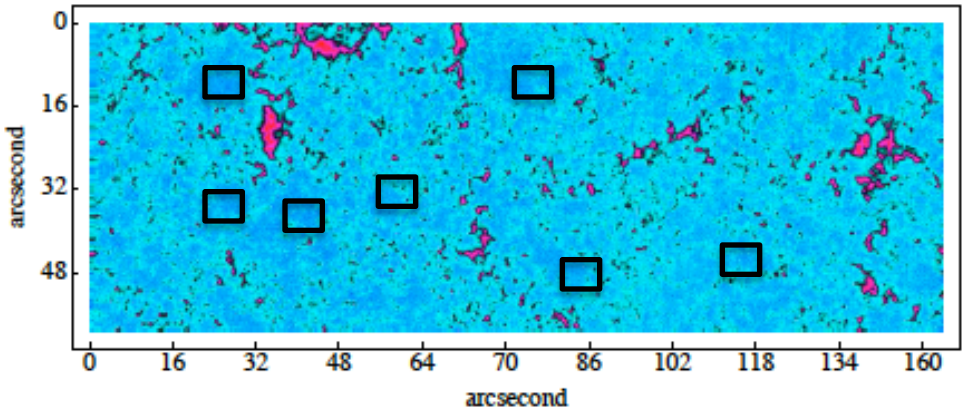
Is it possible to measure this effect?

Outline

- How do we measure a temperature gradient?
- Implementing the method on Hinode SOT/SP data
- Results on two data sets (at solar max and solar min)
- What is next?

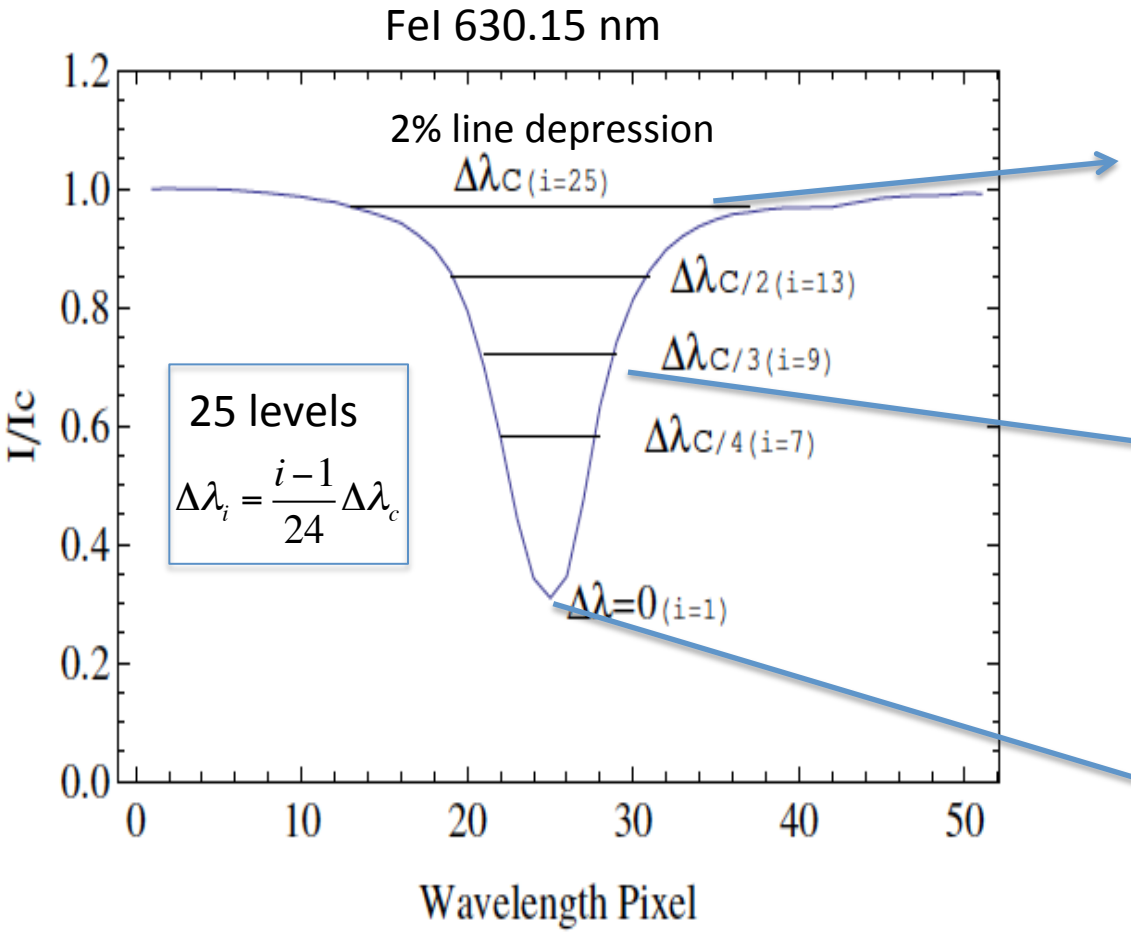
Quiet Sun Internetwork

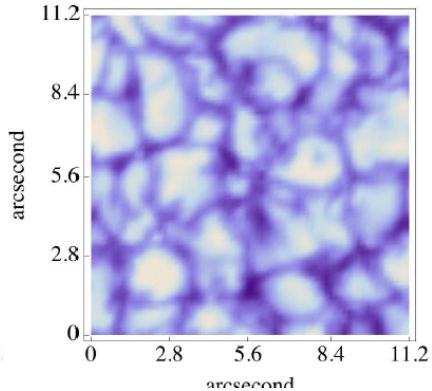
We select (10'' x 10'') regions at various latitudes in the internetwork around local minima of the polarization map.



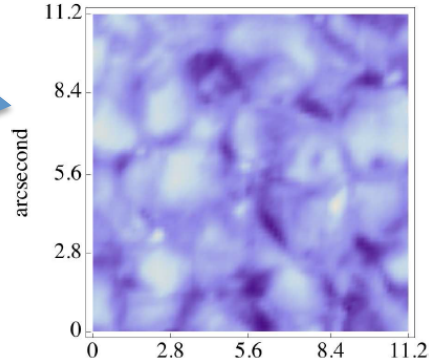
How do we measure temperature gradients ?

Photospheric images at different line levels

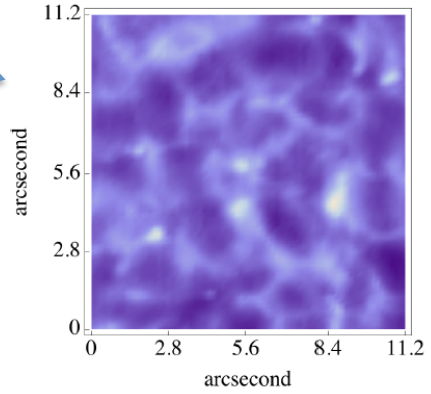




continuum



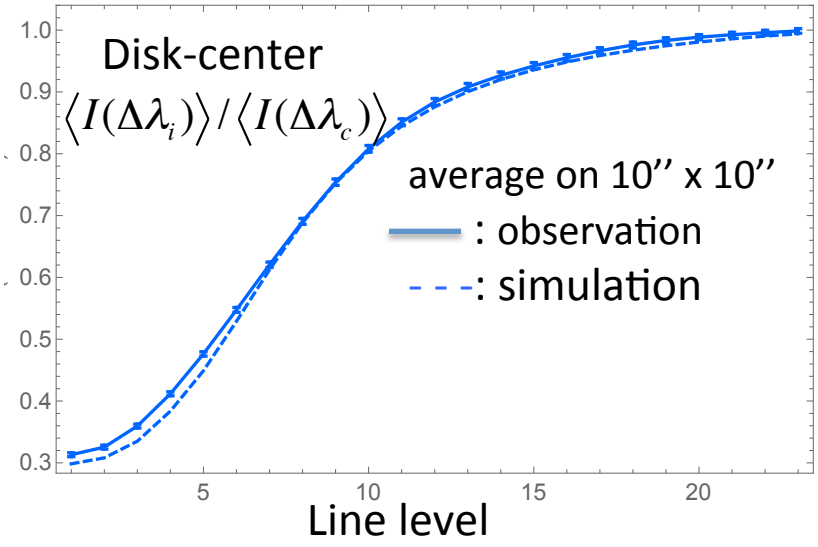
Line wing

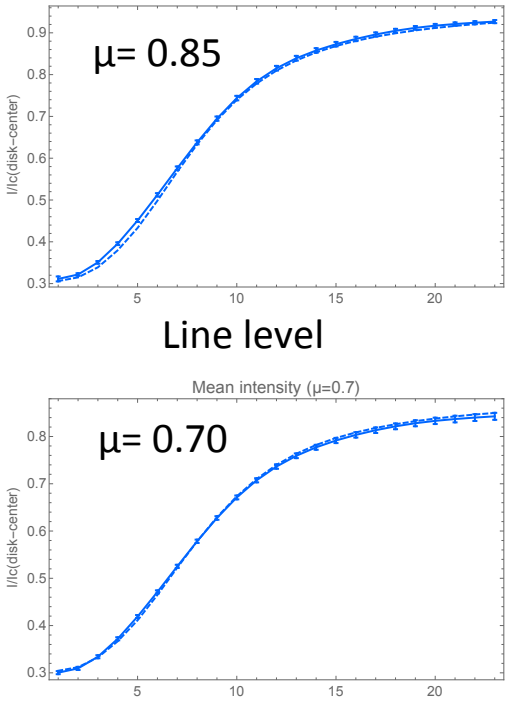


Line core

In the line damping wings, the images are formed on constant continuum opacity surfaces

Average intensity in 10'' x 10'' regions
Comparison with 3D RHD simulations
Stagger code (with A. Chiavassa)
FeI 630.15 nm in LTE





Observations: Hinode SOT/SP (2007-12-19)

The average intensity at different line-levels is well recovered under the assumption of Local Thermodynamic Equilibrium.

Local Thermodynamic Equilibrium (LTE)

Black body radiation law:

$$\left\langle I(\Delta\lambda_i)\right\rangle = B_\lambda(T_i) = \frac{2hc^2/\lambda^5}{\exp\left(\frac{hc}{\lambda k T_i}\right)-1}$$

Power of emitted radiation per surface unit

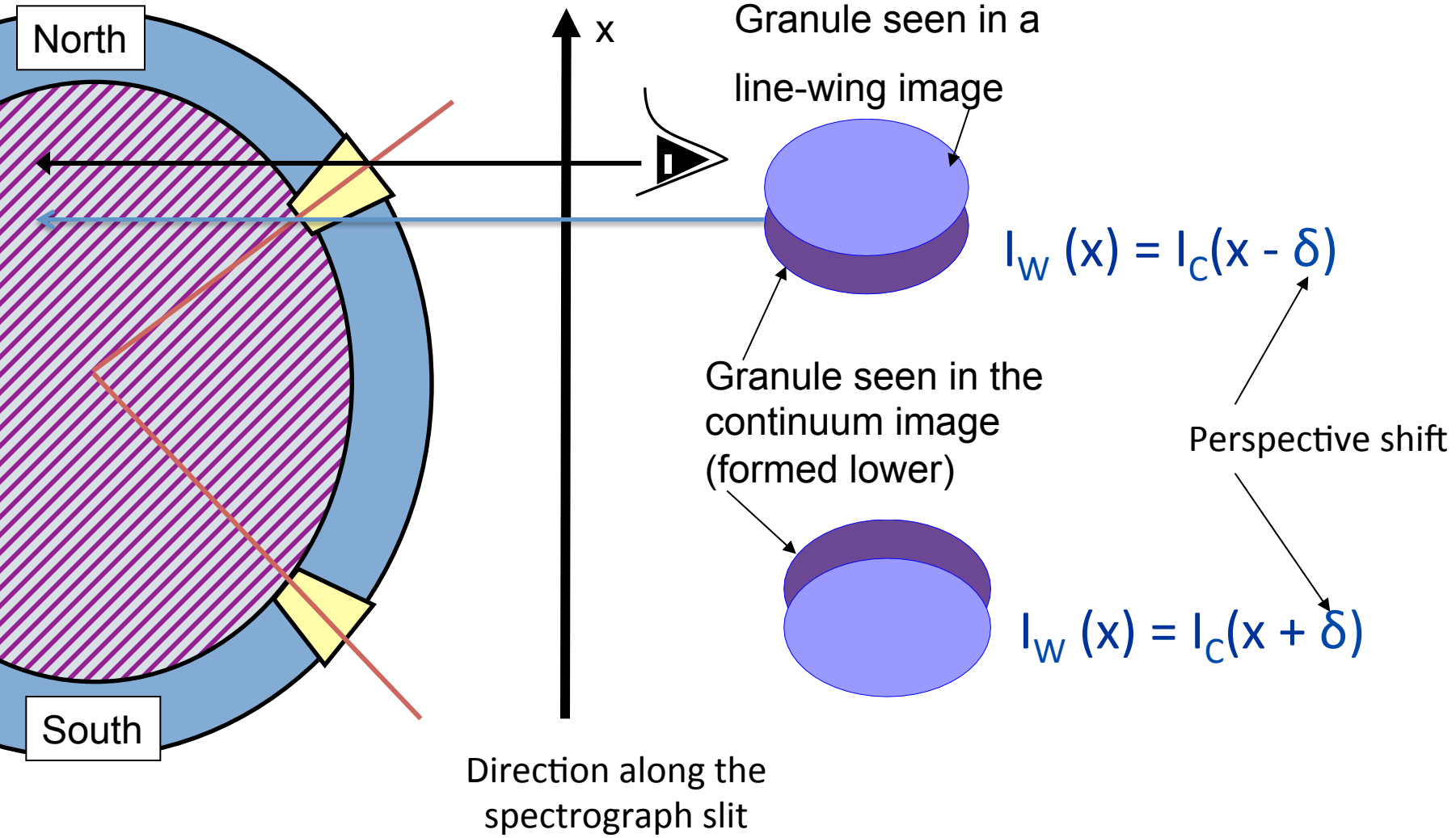
Gives the « local » average temperature on 10'' x 10'' surfaces

Calibration is needed.

We use the continuum intensity at disk-center given by the FALC model.

How do we measure the depth difference between the images?

We measure the perspective shifts between images formed at different depths



The cross-correlation of continuum and line-wing spectrograms

Fourier transforms of the images

$$\widehat{I}_i(u) \sim \widehat{I}_c(u)\exp(2i\pi u\delta)$$

u: spatial frequency variable, in arcsec $^{-1}$

Cross-spectrum of the images

< > : ensemble average on
a large number of spectrograms

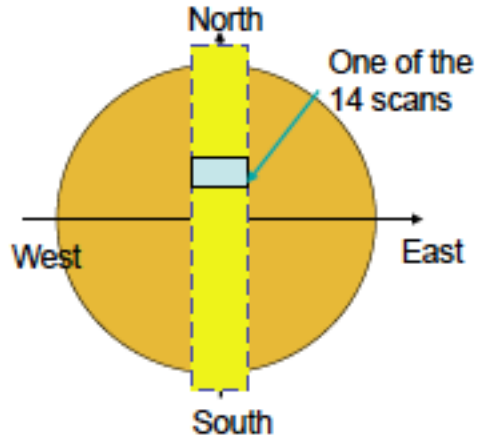
$$\widehat{Q}_{ci}(u) = <\widehat{I}_c(u)\widehat{I}_i^*(u)> \sim <|\widehat{I}_c(u)|^2> e^{-2i\pi\delta u}$$

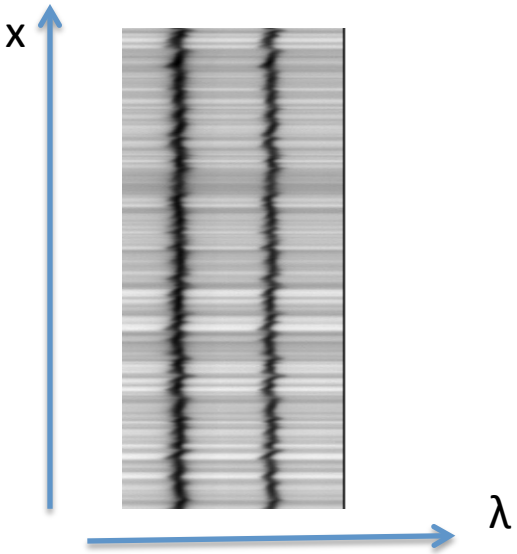
Linear phase term

The slope of the phase term gives the perspective shift in arcsec

Implementing the method on Hinode SOT/SP data

Center-to-limb scans with SOT/SP

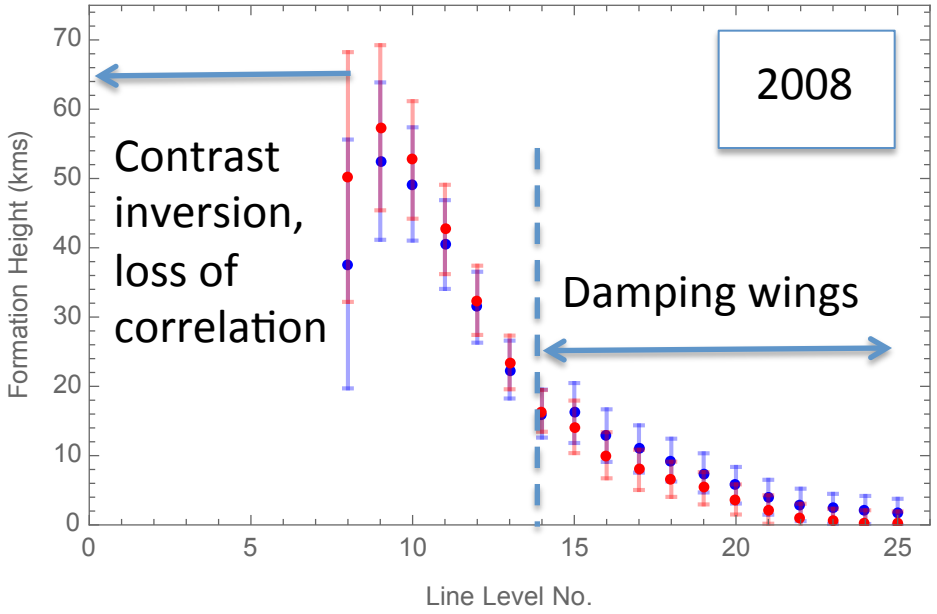




Irradiance program: 130'' x 30'' scans at 20 positions along the N/S axis.
On October 22, 2008 (solar minimum) and May 5, 2014 (solar maximum)
In each data set we select 144 (10'' x 10'') internetwork regions

Two spectral lines FeI 630.15 nm, 630.25 nm
4 Stokes parameters (I,Q,U,V)
2.1 pm /px in wavelength.

Formation heights of the images at successive line-levels

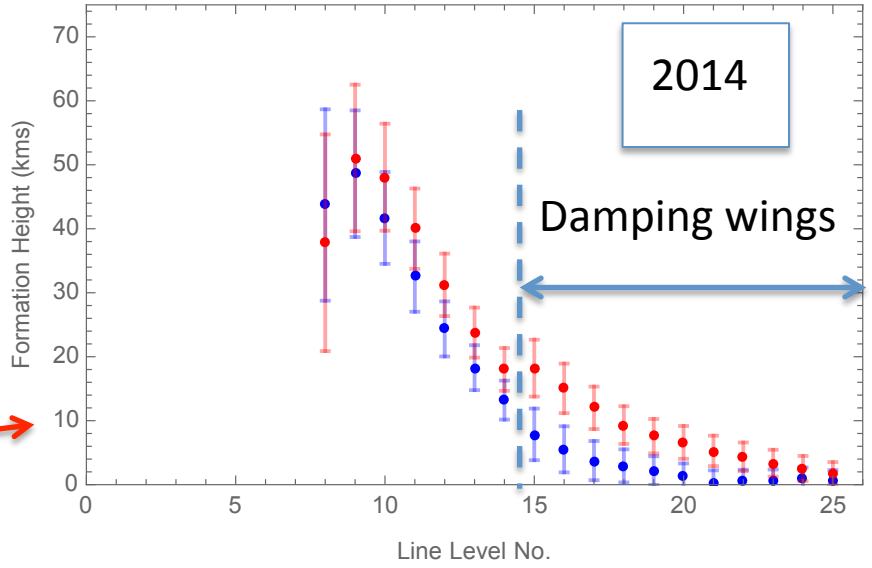


North

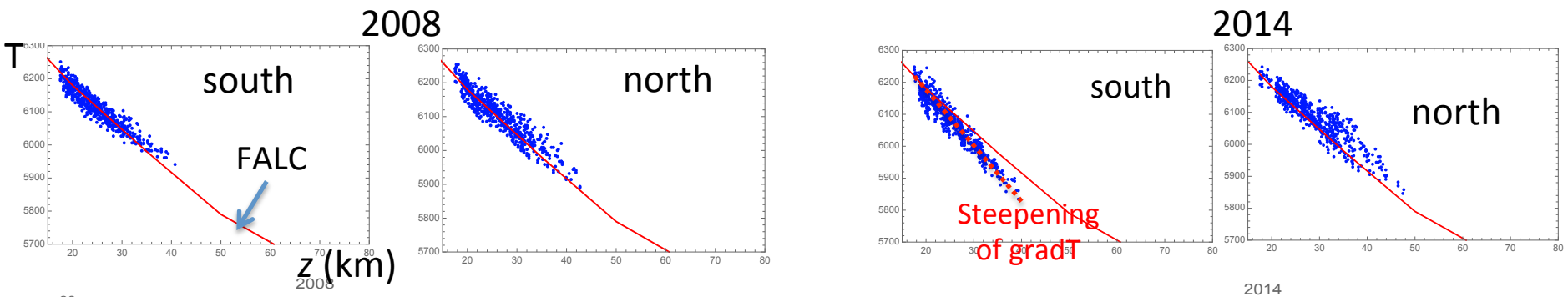
South

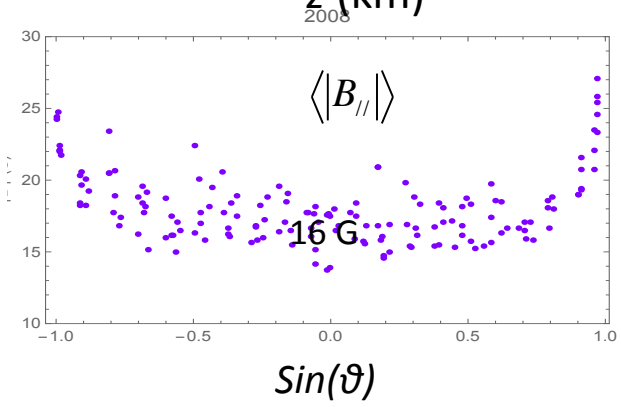
We ‘ll consider line-levels 15 to 22
Damping wings

Look at the height scale!
We can measure a few kms …
(less than 0.01’’ …)

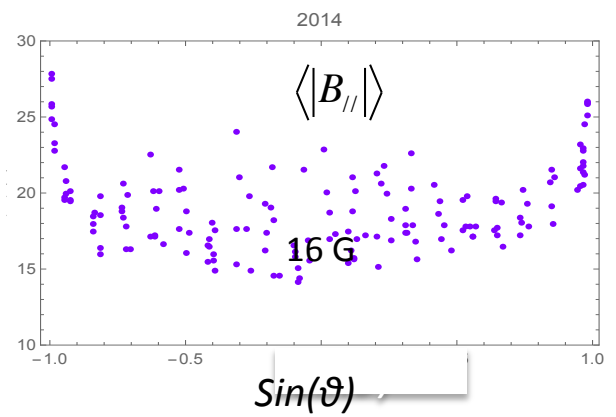


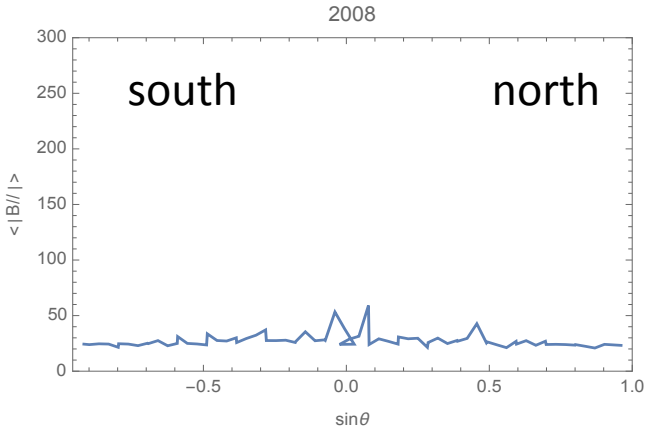
Gathering all measurements
(-50°< θ < 50°, line-levels 15 to 22)



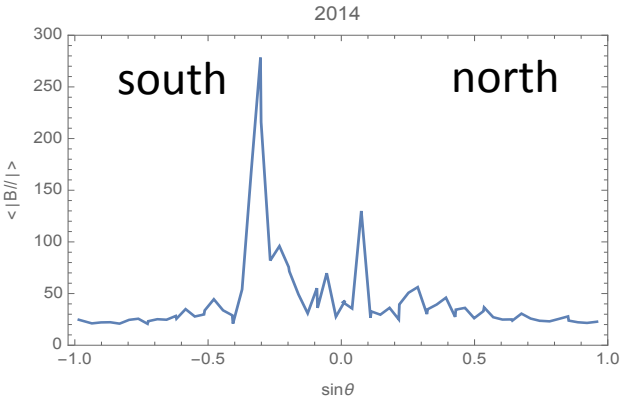


Average unsigned magnetic flux in the selected IN regions





Magnetic context: Quiet-Sun average unsigned magnetic flux in 30''x 30'' regions along S/N axis



Conclusion

- **New method** for measuring the temperature gradient in the low photosphere
  Direct measurements (no radiative transfer computation with semi-empirical models)
  First tests on good quality Hinode spectroscopic data

- The results show the steepening effect found in 3D MHD simulations, and an important North/South asymmetry of magnetic flux distribution in the quiet Sun at solar maximum

- **Perspectives:**
  Apply the method on larger data sets with systematic measurements along the solar cycle.