PHYS 7810: Solar Physics with DKIST

Lecture 26: Hanle effect and vector magnetic fields

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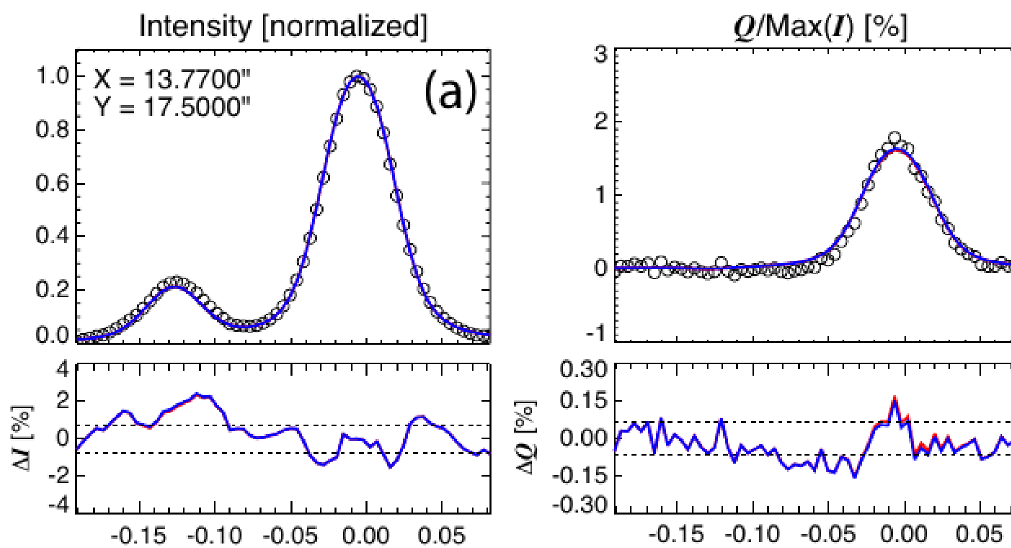

Previous lecture

- We made a phenomenological argument that anisotropy determines the amount of scattering polarization
- We saw a simplified treatment for the so called resonance lines
- We saw what the so called microturbulent Hanle effect is
- We will quickly review these, and move on to the vector magnetic field

So, in a 1D atmosphere, without the magnetic field...

- The problem is axially symmetric - that is why we use μ instead of the two angles
- There is no reason for *U* and *V* to exist – when we study the scattering polarization we will separate Zeeman effect

$$\frac{dI_\lambda}{d\tau_\lambda} = I_\lambda - S_\lambda^I$$
$$\frac{dQ_\lambda}{d\tau_\lambda} = Q_\lambda - S_\lambda^Q$$

Where the source functions for I and Q are:

- From Trujillo Bueno (2003) – Generation and Transfer of Polarized radiation
- There is a lot to unpack here:

Collisional depolariation

Intrinsic line polarizability

Hanle depolarization

$$S_\lambda^I = \epsilon B + (1-\epsilon)\left(J_0^0 + w^c w^H w^2 \frac{1}{2\sqrt{2}}(3\mu^2 - 1)J_0^2\right)$$

$$S_\lambda^Q = (1-\epsilon) w^c w^H w^2 \frac{3}{2\sqrt{2}}(\mu^2 - 1)J_0^2$$

$$J_0^2 = \frac{1}{4\sqrt{2}}\int_0^\infty \int_{-1}^1 I_\lambda(\mu')(3\mu'^2 - 1)d\mu' \phi_\lambda d\lambda$$

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$$J_0^2 = \frac{1}{4\sqrt{2}} \int_0^\infty \int_{-1}^1 I_\lambda(\mu')(3\mu'^2 - 1) d\mu' \phi_\lambda d\lambda$$

- Source function is **anisotropic**
- Anisotropy modifies the “pure intensity” too!
- Sensitivity to the magnetic field
- More NLTE → more polarization
- Very, very, interesting and subtle

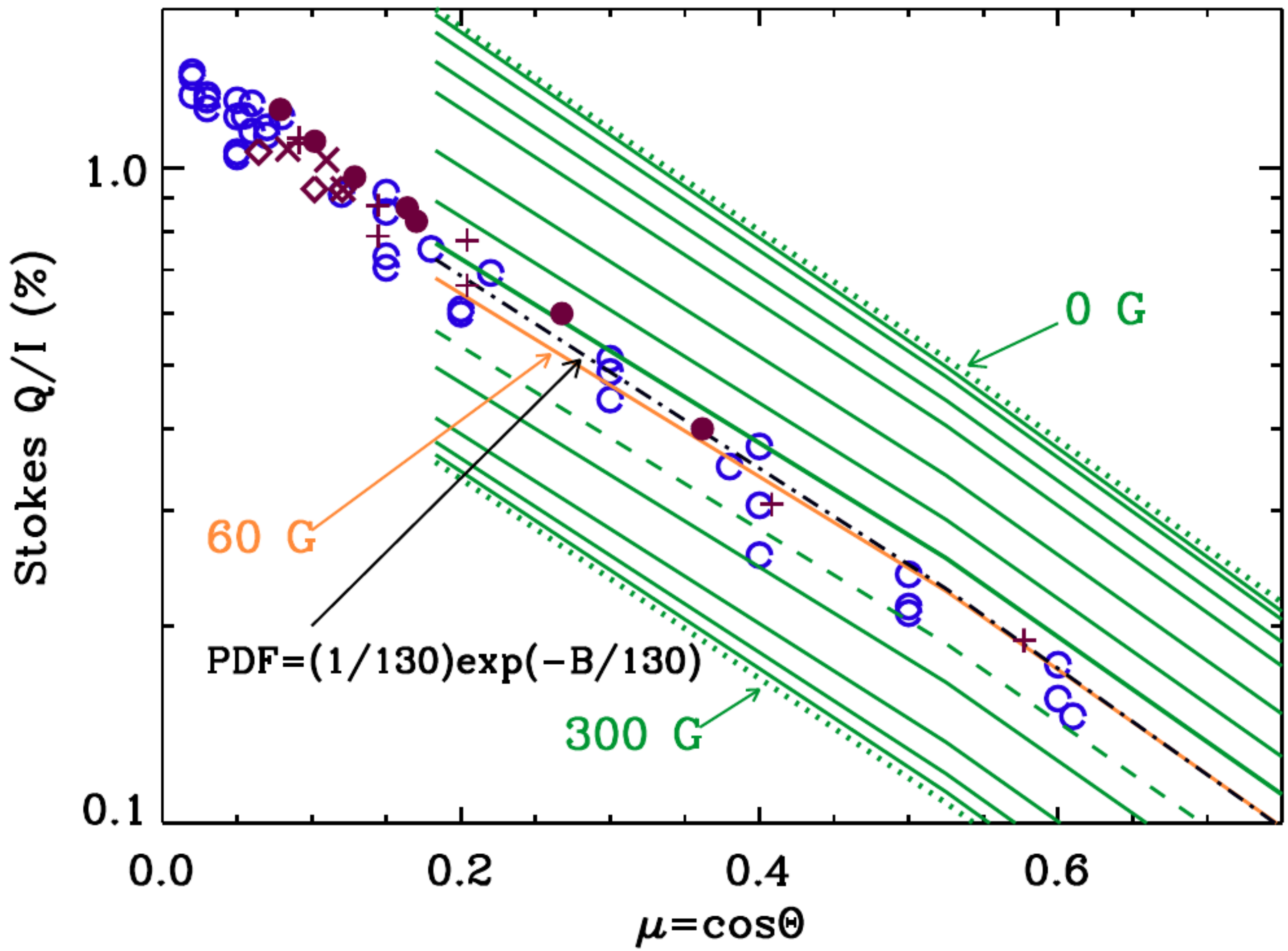
“Microturbulent” Hanle effect

- Mixed polarity fields in a pixel would not be seen by Zeeman polarization (convince yourself of that)
- But, with Hanle:

$$w^H = 1 - \frac{2}{5}\left(\frac{\Gamma_H^2}{1+\Gamma_H^2} + \frac{4\Gamma_H^2}{1+4\Gamma_H^2}\right)$$

$$\Gamma_H = 0.88\frac{gB}{A_{ul} + \Gamma_{\mathrm{depolarizing}}}$$

The famous TB et al Nature paper, again using Sr 4607



Truth be told, I started with microturbulent Hanle because equations are simpler…

- This presumes the magnetic field is mixed, randomly oriented and with random strength on scaller smaller than the photon mean free path (hence the term “microturbulent”)

- Equations I have shown you come from the so called scattering matrix:

$$\begin{pmatrix} I \\ Q \\ U \end{pmatrix}^{\mathrm{out}} = \hat{M}(\theta, \phi, \theta', \phi') \begin{pmatrix} I \\ Q \\ U \end{pmatrix}^{\mathrm{in}}$$

Incoming direction

Outgoing direction

Polarized source function

- The total outgoing intensity is going to be:

$$\hat{I}^{\mathrm{out}}(\theta,\phi) = \frac{1}{4\pi}\oint \hat{M}(\theta,\phi,\theta',\phi')\hat{I}^{\mathrm{in}}(\theta',\phi')\sin\theta' d\theta' d\phi'$$

- And this can be factorized as:

$$\hat{I}^{\mathrm{out}}(\theta,\phi) = \hat{M}(\theta,\phi)\frac{1}{4\pi}\oint \hat{M}'(\theta',\phi')\hat{I}^{\mathrm{in}}(\theta',\phi')\sin\theta' d\theta' d\phi'$$

- Or more briefly as:

$$\boxed{\hat{I}(\theta,\phi) = \hat{M}(\theta,\phi)\hat{J}}$$

But this is just what happens localy…

- To get the full picture in the optically thick medium we have to integrate over the full atmosphere:

$$\cos\theta \frac{d\hat{I}(\theta,\phi)}{d\tau} = \hat{I}(\theta,\phi) - \hat{S}(\theta,\phi)$$

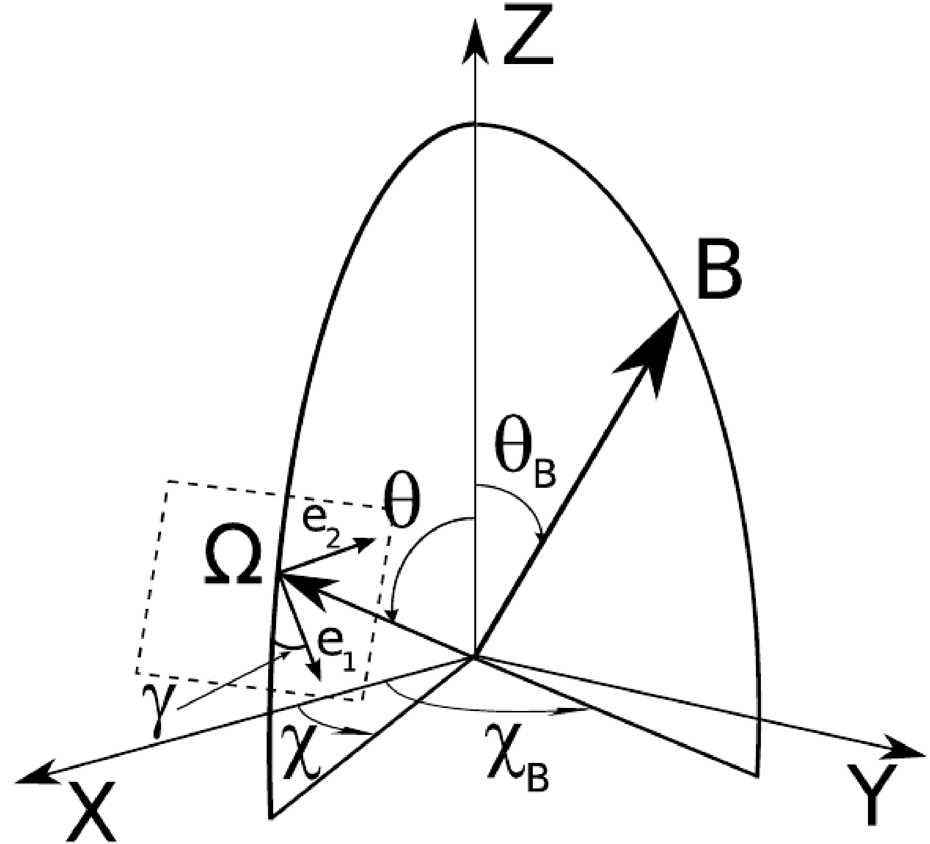
- Where the source function is the combination of thermal contribution and the scattering

$$\hat{S}(\theta,\phi) = \epsilon\hat{B} + (1-\epsilon)\hat{M}(\theta,\phi)\hat{J}$$

- In 1D atmosphere everything is azimuth invariant, so dependency on azimuth disappears, and so does U.
- Also, scattering cannot create circular polarization – no Stokes V.

But...

- Even though the atmosphere is 1D, magnetic field can make it anisotropic and destroy axial symmetry
- This will create source function for Stokes U:



Asensio Ramos et al. (2008)

$$\hat{S}(\theta,\phi) = \epsilon\hat{B} + (1-\epsilon)\hat{M}_B(\theta,\phi,\vec{B})\hat{J}$$

Hanle effect

- Clasically – precession of the scattering electrons due to the presence of the magnetic field
- QM – magnetic field changes the axis of quantization and changes the atomic alignment and orientation induced by the anisotropic radiation field
- Complicated, and very cumbersome to describe
- But, again, very interesting.
- The quantity that determines the strength of Hanle effect:

Magnetic field

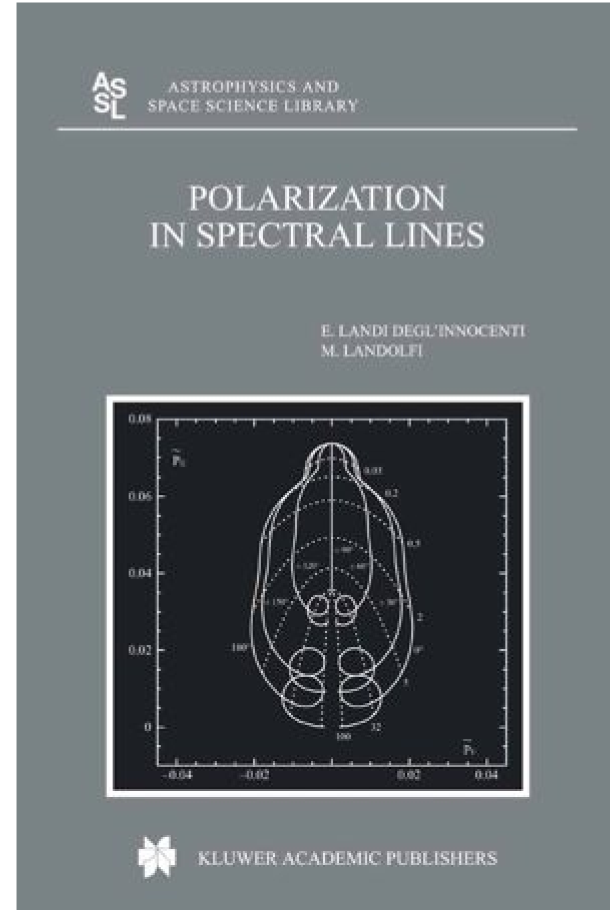
Lande factor, order of a few

$$\Gamma_H \approx \frac{g_L\, B}{A_{ul}} \times 10^7$$

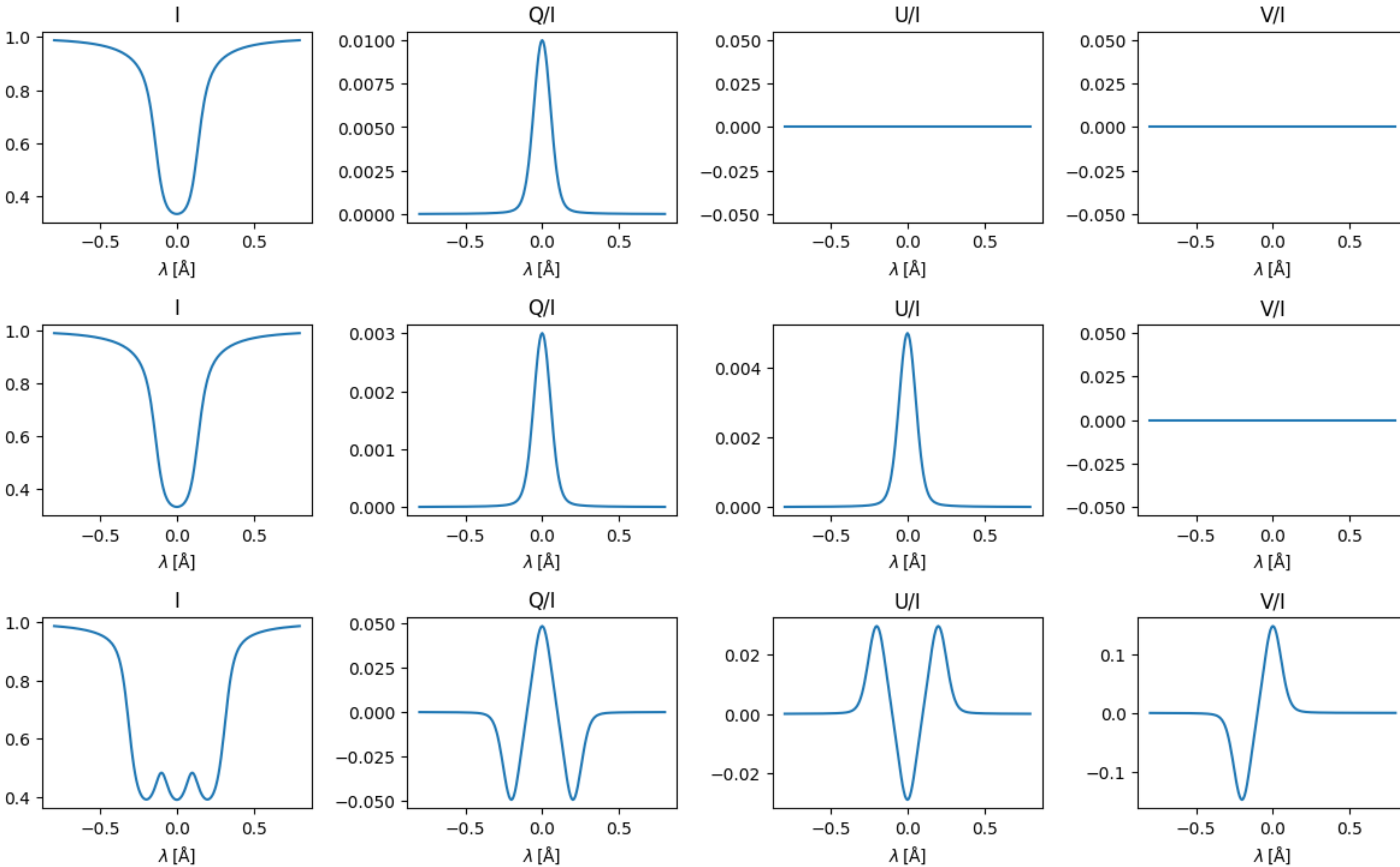
Einstein coefficient of emission, 10^5 - 10^8

If you want to fully model this – density matrix

- A complete theory must account for many other details
- The story is quantum, the approach is one using the density matrix
- Time to move to a monastery and read this book? :)
- With simple analogies, density matrix approach to scattering matrix approach is what full multi-level problem is to the simple 2-level NLTE problem
- In general we want a theory that accounts for scattering, nlte, Hanle, Zeeman - simultaneously



Finally, Zeeman vs Hanle



Pure scattering, no magnetic field

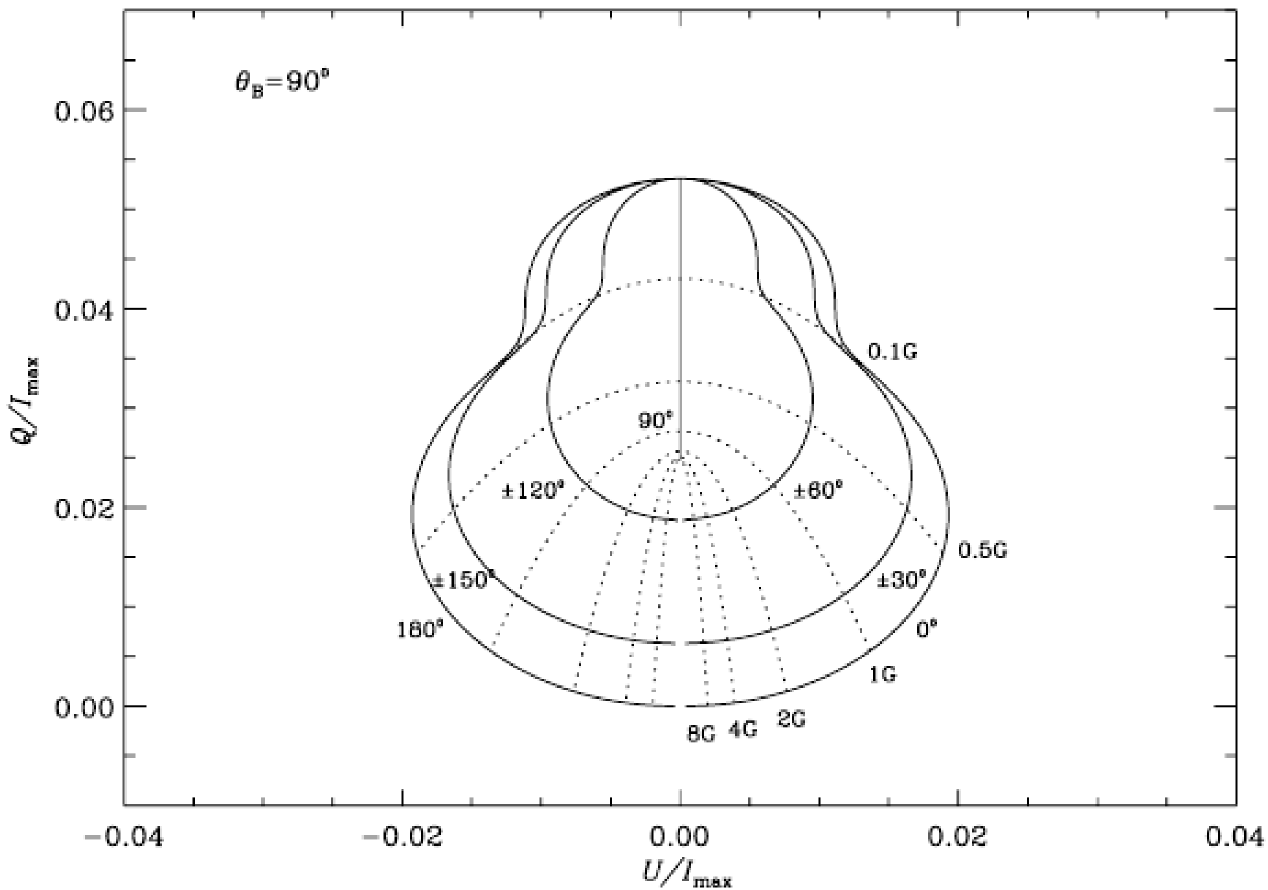
Weak magnetic field

$$\frac{0.88 g B \times 10^5}{A_{ul}} \approx 1$$

Strong magnetic field

$$\Delta\lambda_{\mathrm{Zeeman}} > \Delta\lambda_{\mathrm{Dopp}}$$

Polarization diagrams



From Merenda et al. (2006): Full lines are iso-asimuth, and dotted are iso-B. The inclination of the magnetic field is fixed. Note the ambiguities!

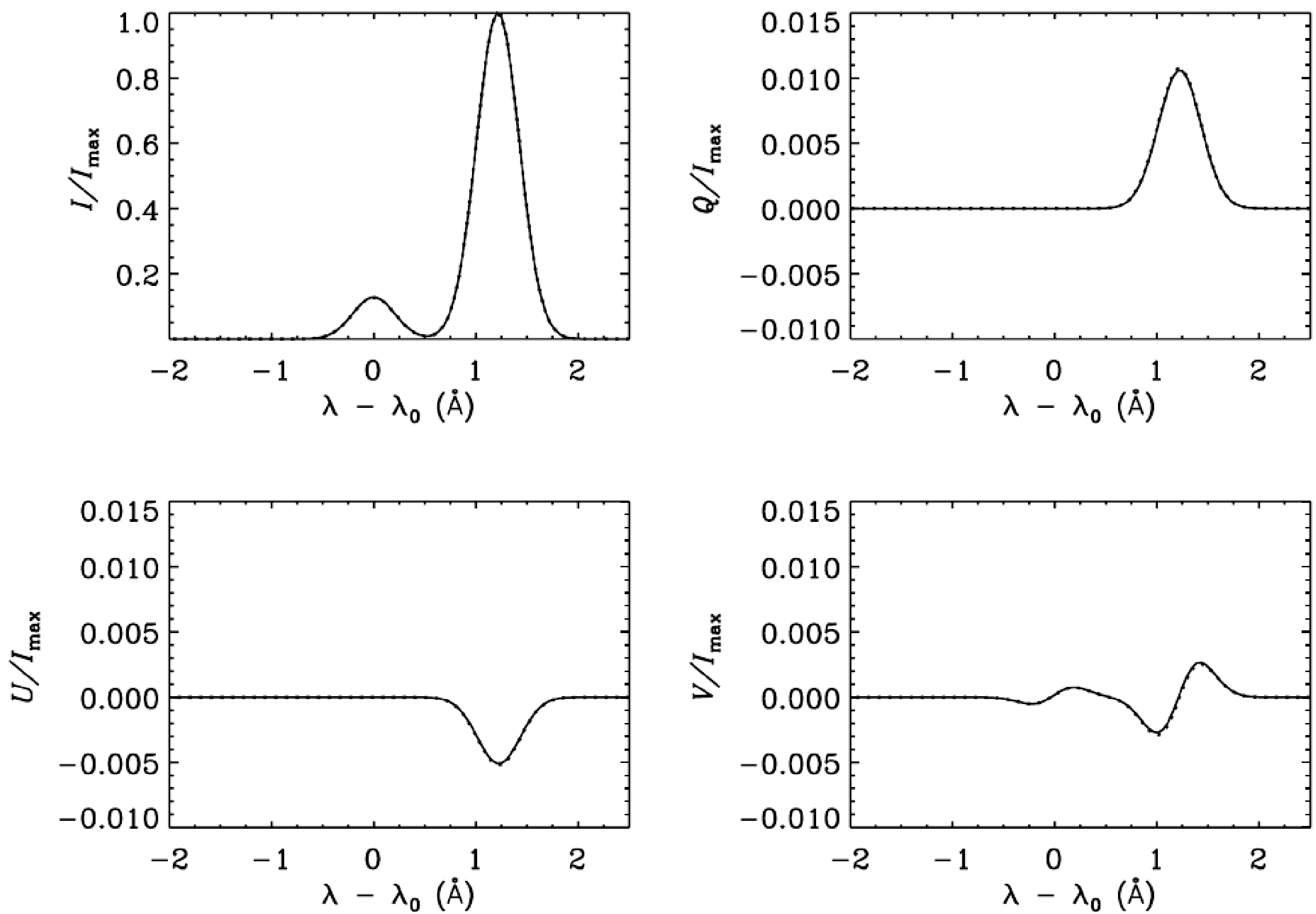
Hanle effect is ambiguous (degenerate) by nature

- Different magnetic field orientations (and strengths) produce the same signals!

$$\theta_b = \pi - \theta_B$$
$$\phi_B = -\phi_B$$

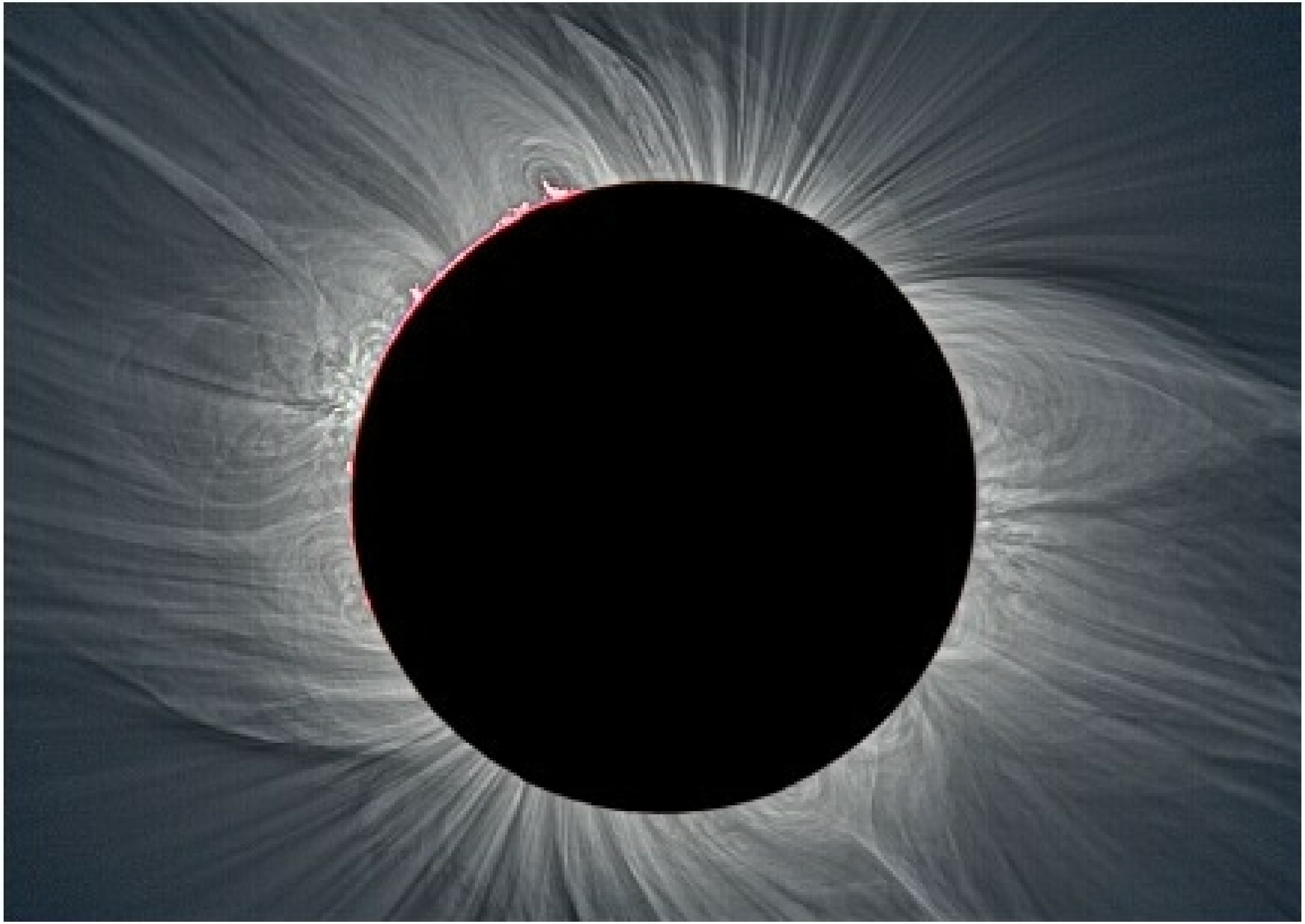
- Plus there are different values that give the same polarization.
- 4 different combinations producing the same polarization
- This comes from the equations directly!

Hanle effect ambiguity

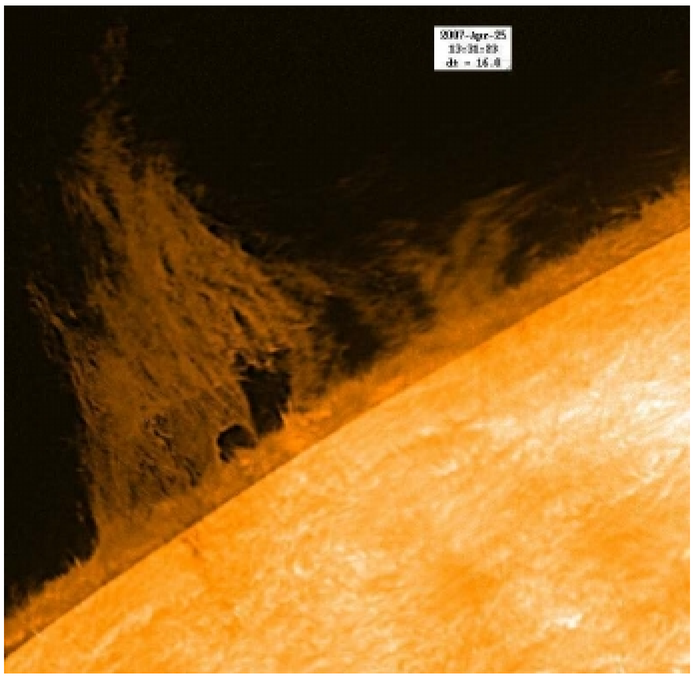


From Merenda et al. (2006): Two overlapping lines have different magnetic field values (not only orientation but strength too!)

Application – solar prominences



Solar prominences



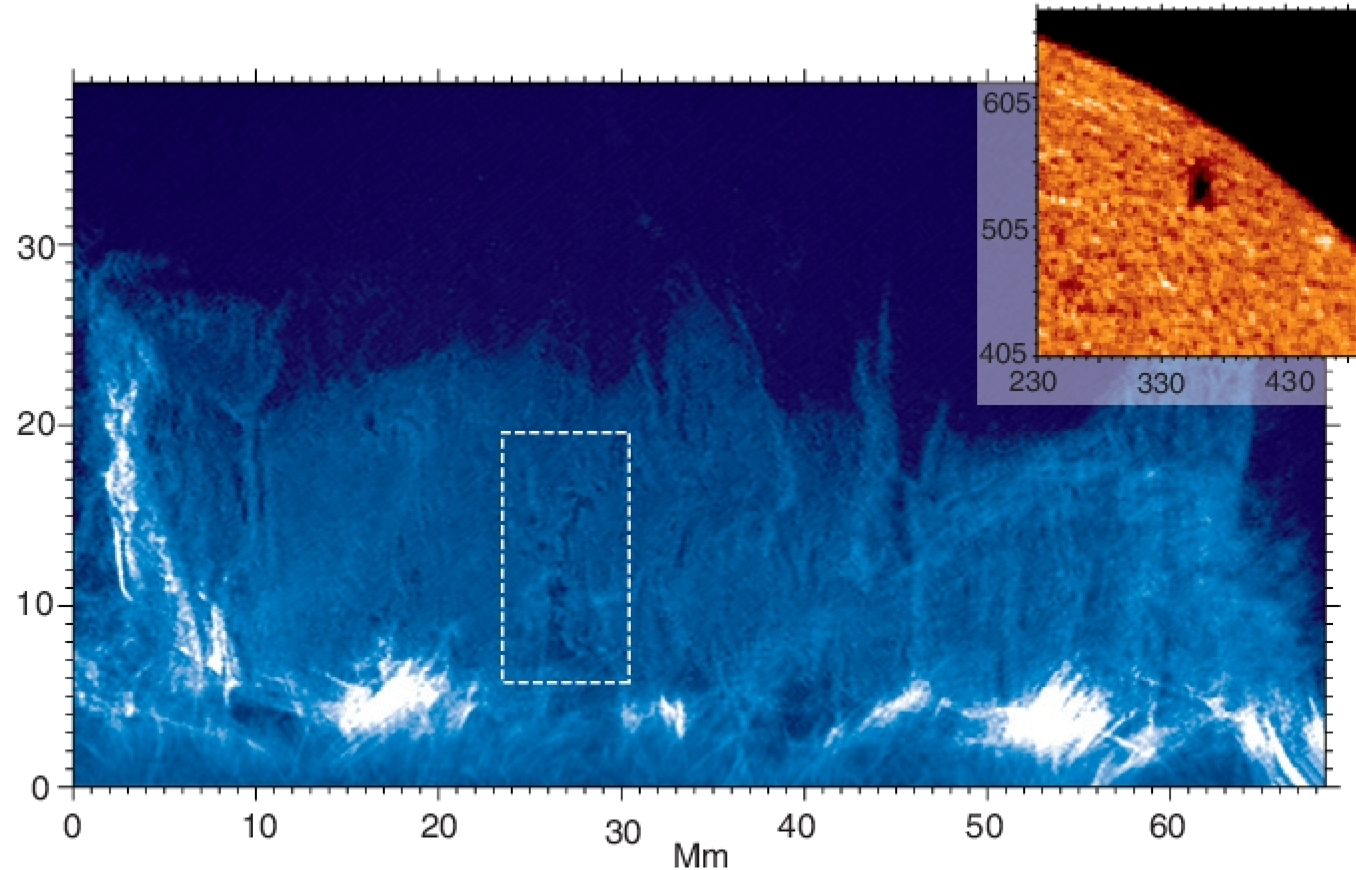


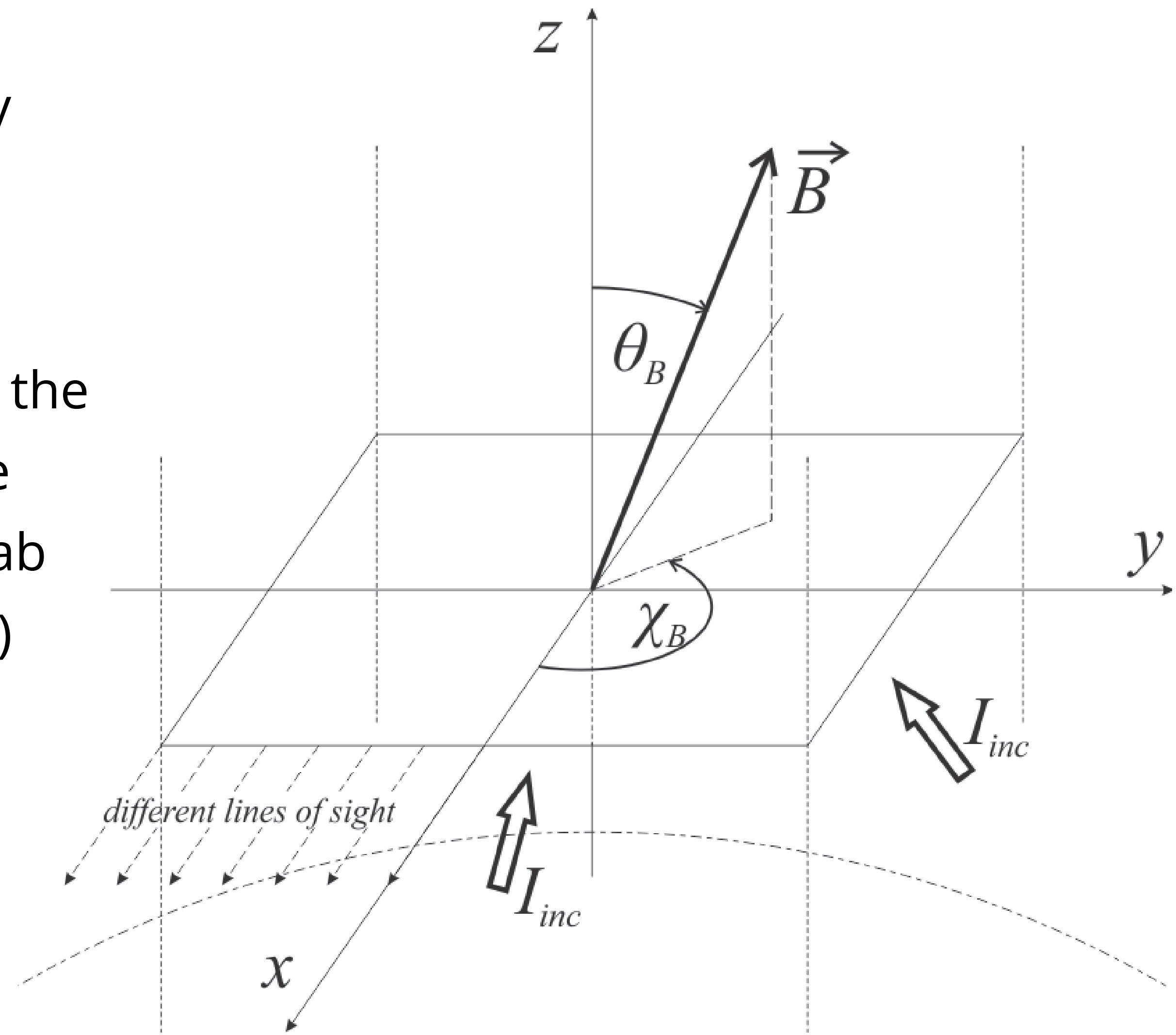
Figure 1. Quiescent solar prominence observed on 2006 November 30 04:23:30

Heinzel and Anzer, 2009

Berger et al., 2010

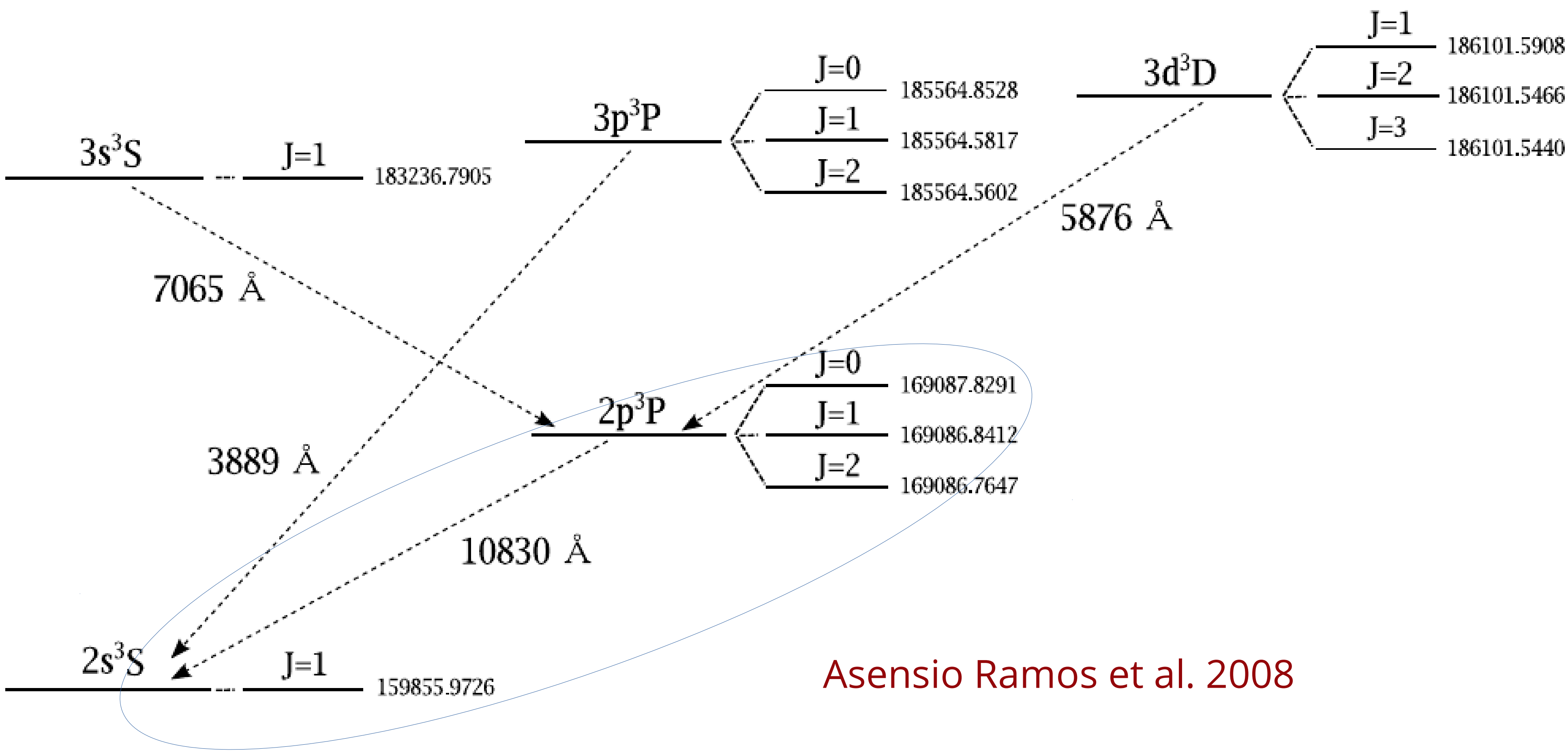
Prominence radiation and polarization

- Incoming radiation described by the limb darkening on the appropriate frequency
- To calculate mean intensity and the anisotropy we need to know the height and the velocity of the slab (Doppler dimming / brightening)
- Magnetic fields breaks the anisotropy



Milic et al. 2016

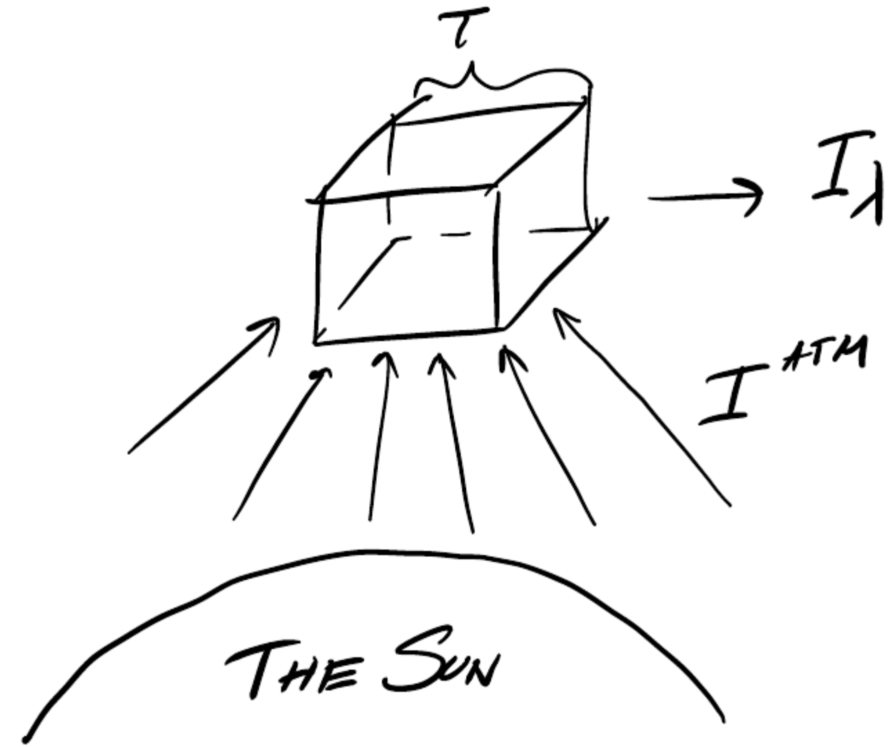
He I 10830 in prominences



Asensio Ramos et al. 2008

Model parameters – He 10830 I case

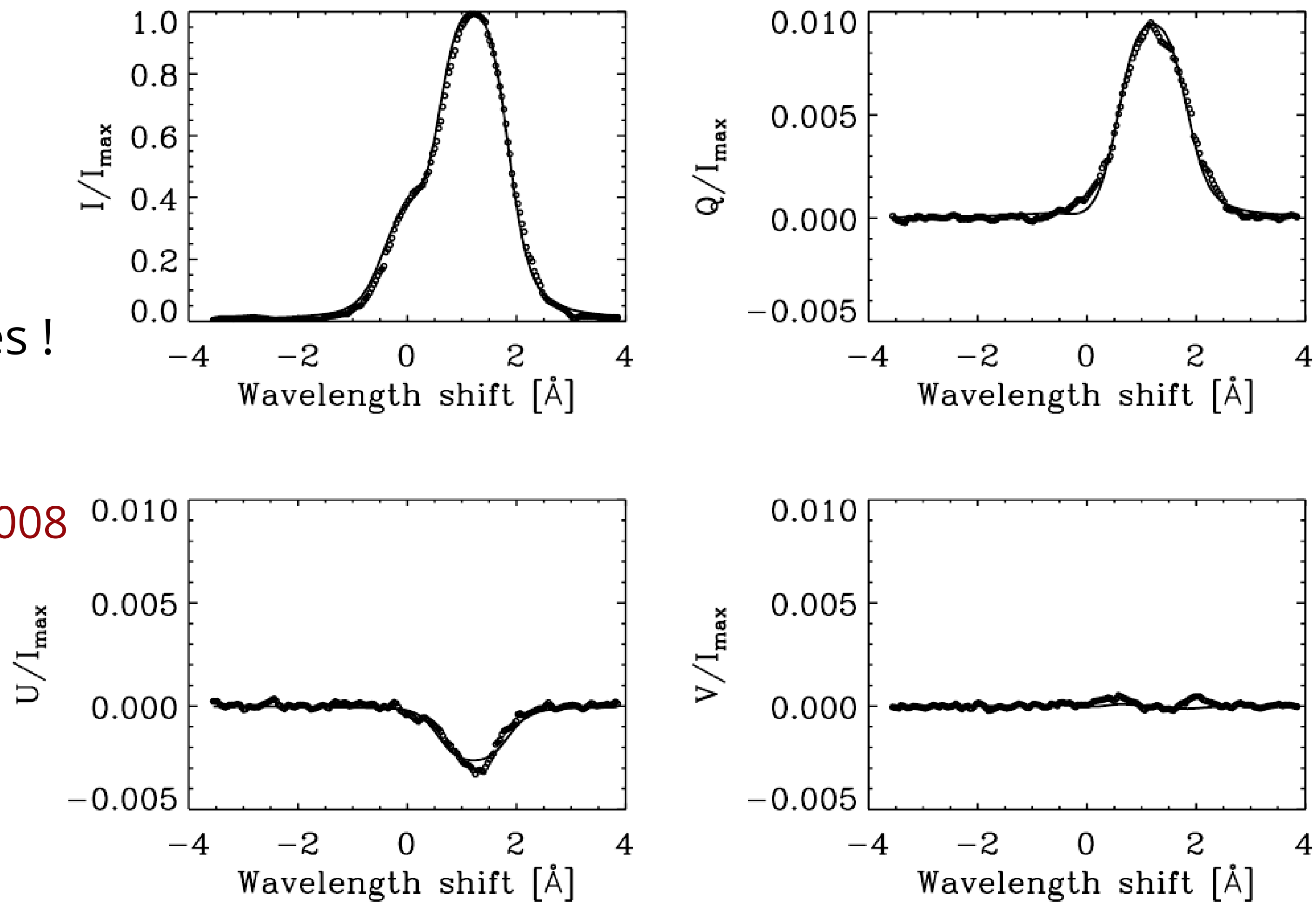
- Optical depth of the slab at the line center
- Absorption/emission profile : center, Doppler width, damping
- Magnetic field vector
- Height above the sun – fixed from the observations



Example prominence spectrum in He I 10830

- Let's try and understand why the intensity and the polarization have these shapes !

Asensio Ramos et al. 2008

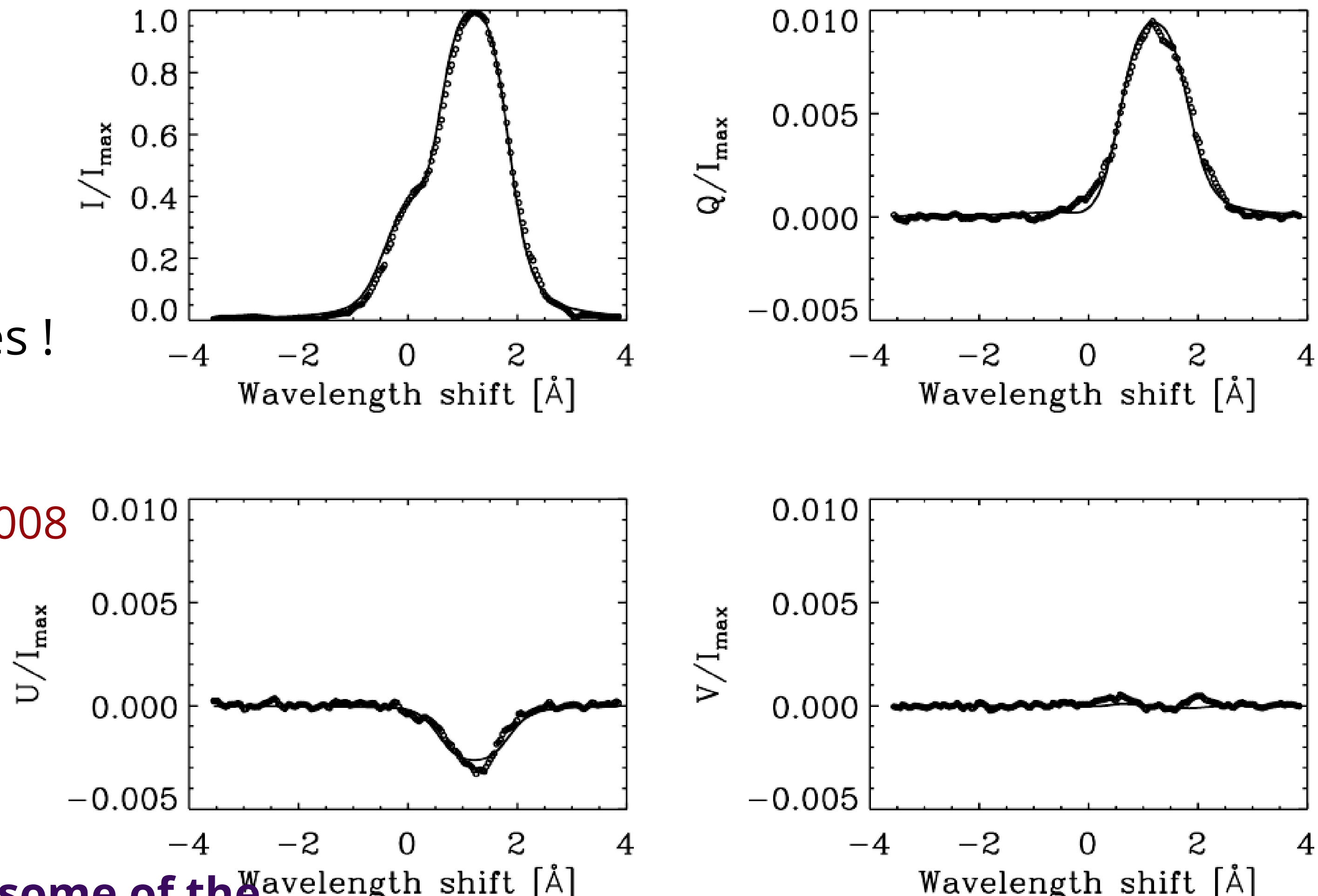


Line scattering on an optically thin slab – 3 lines of different strengths.

Scattering polarization – note different line polarizabilities

- Let's try and understand why the intensity and the polarization have these shapes !

Asensio Ramos et al. 2008

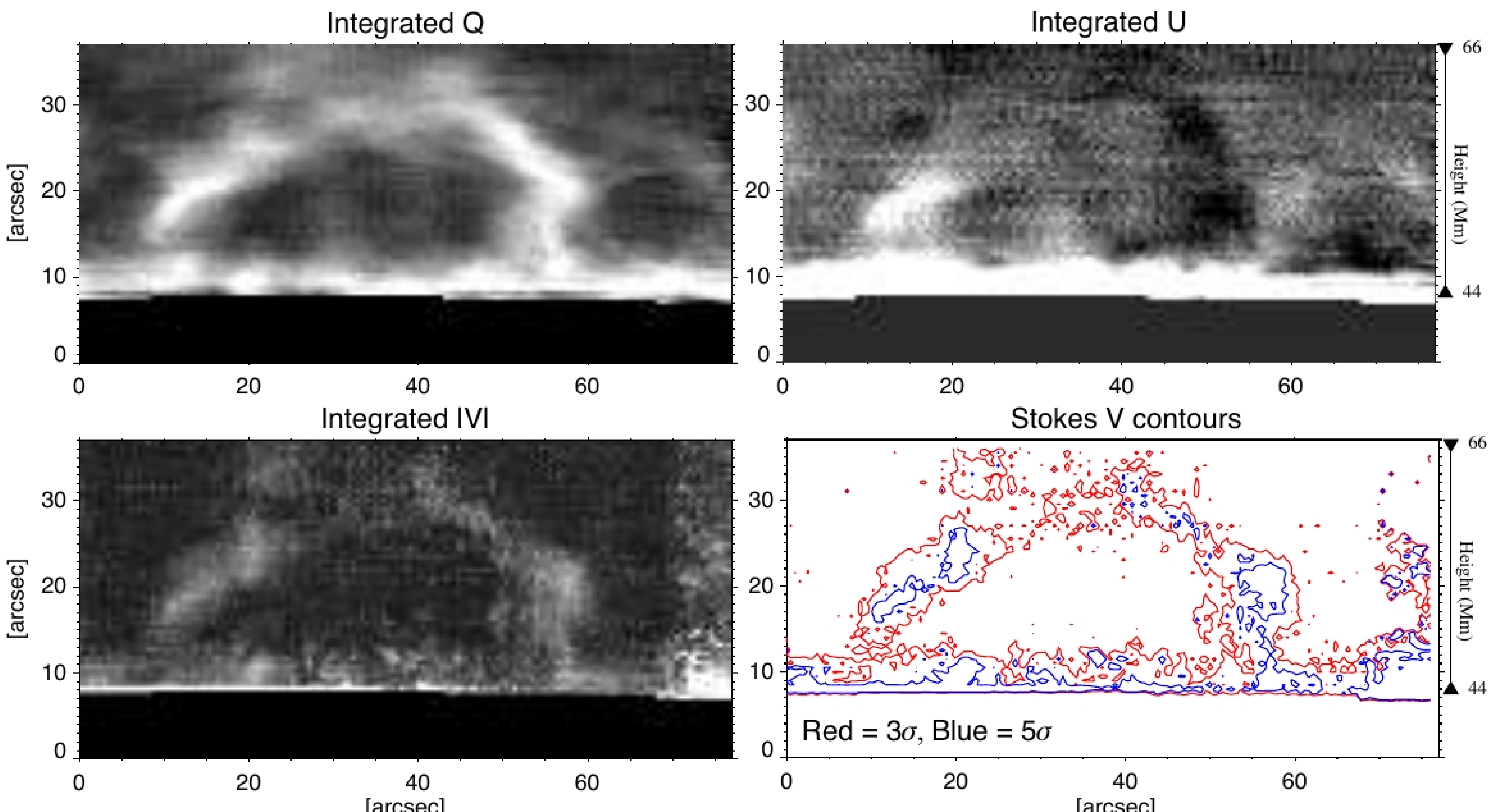


Hanle effect rotating some of the Stokes Q into Stokes U

Zeeman effect (weak)

A prominence map

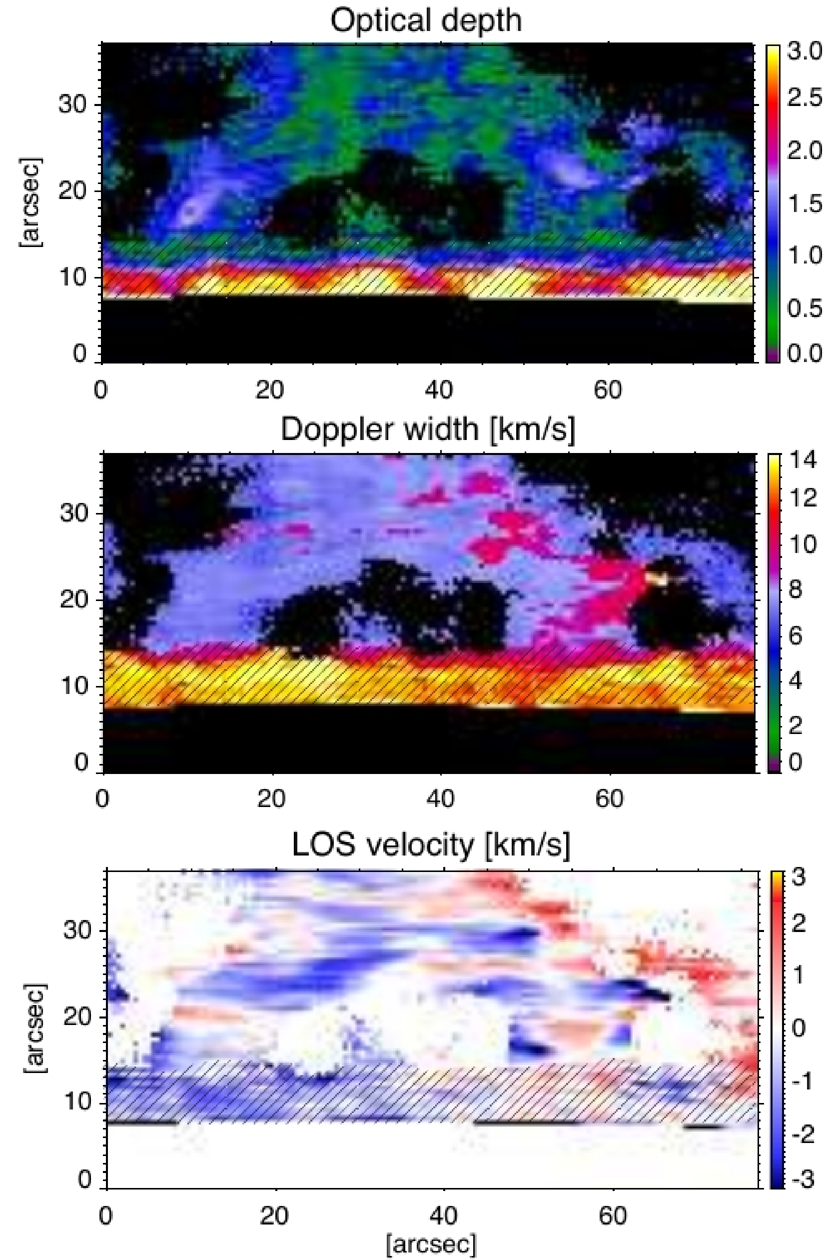
Orozco Suarez et al, 2014



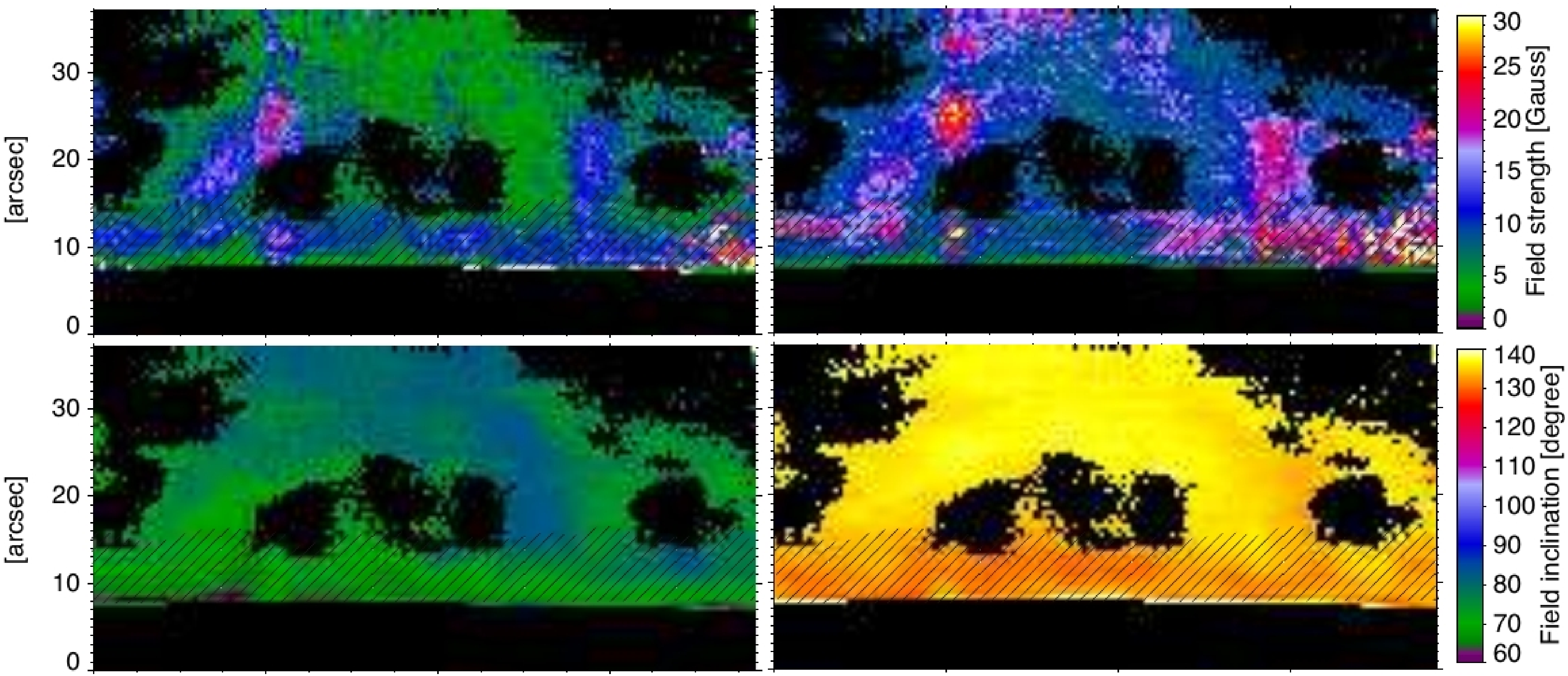
An inverted prominence map

- Works in an identical way to the on the disk inversions
- We get map of the parameters
- Keep in mind some of these parameters are “nuisance” in a way
- We can’t completely uncover what Doppler width and optical depth imply physically

Orozco Suarez et al, 2014

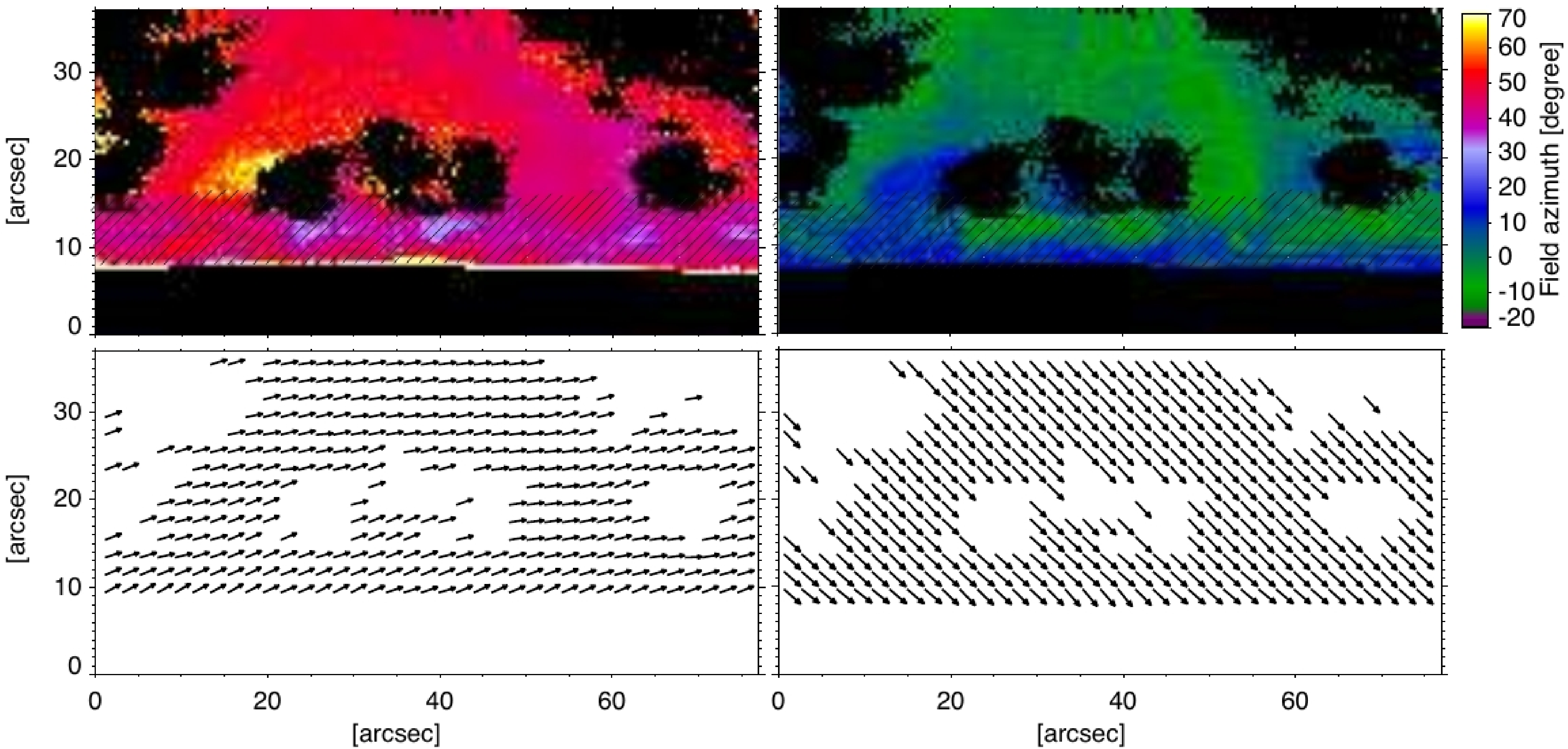


Magnetic field map – ambiguous



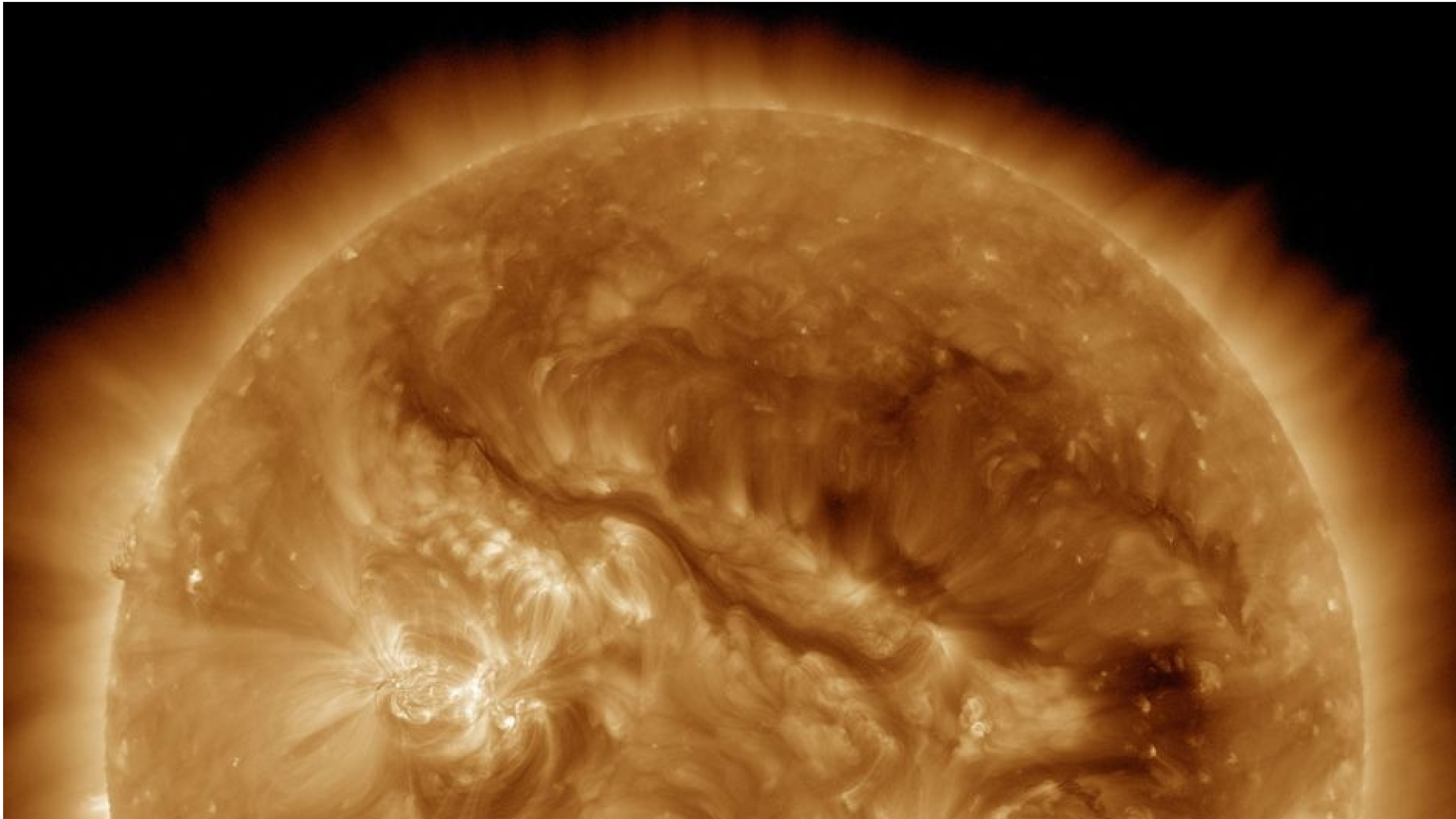
Orozco Suarez et al, 2014

Magnetic field map – ambiguous



Orozco Suarez et al, 2014

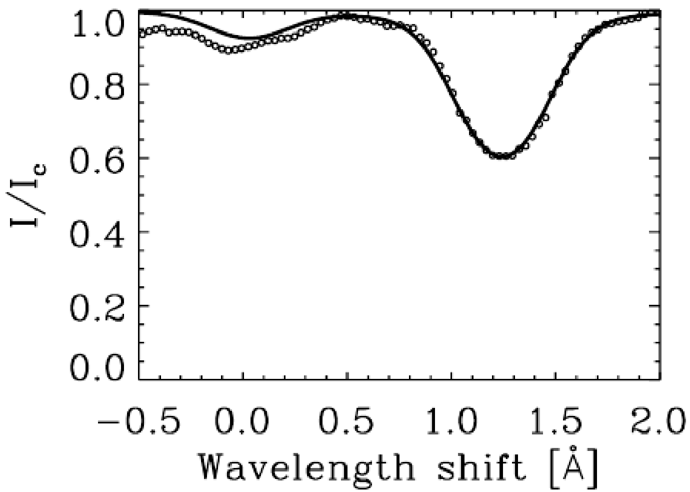
Filaments – prominences from above



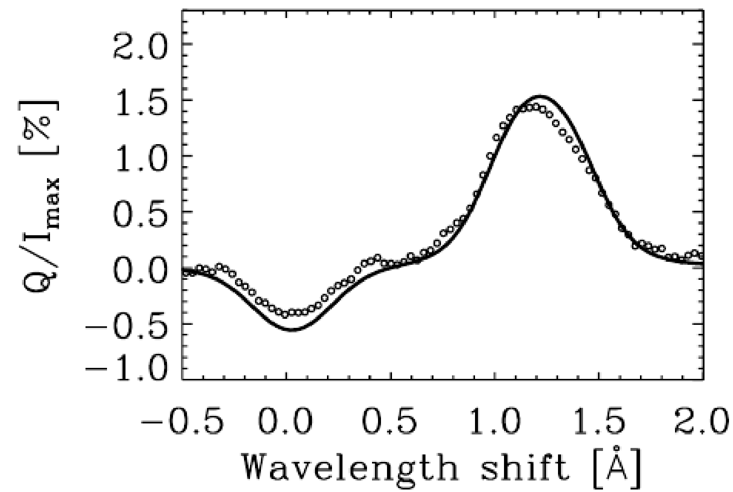
Credits: NASA / SDO

Example spectrum

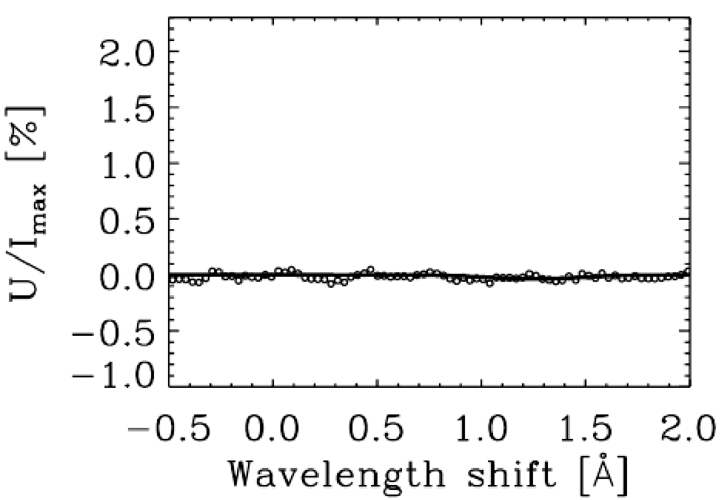
Absorption instead of the emission line



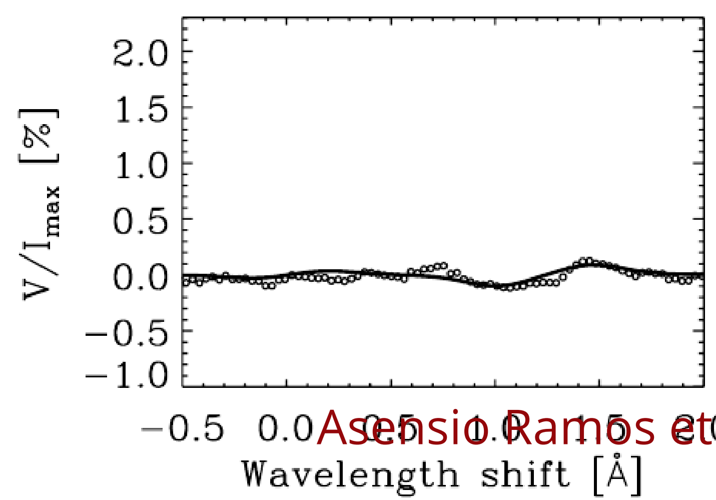
Different optical depth, blue component visible, note the sign!



Magnetic field orientation is such that there is no U



Some weak Zeeman again



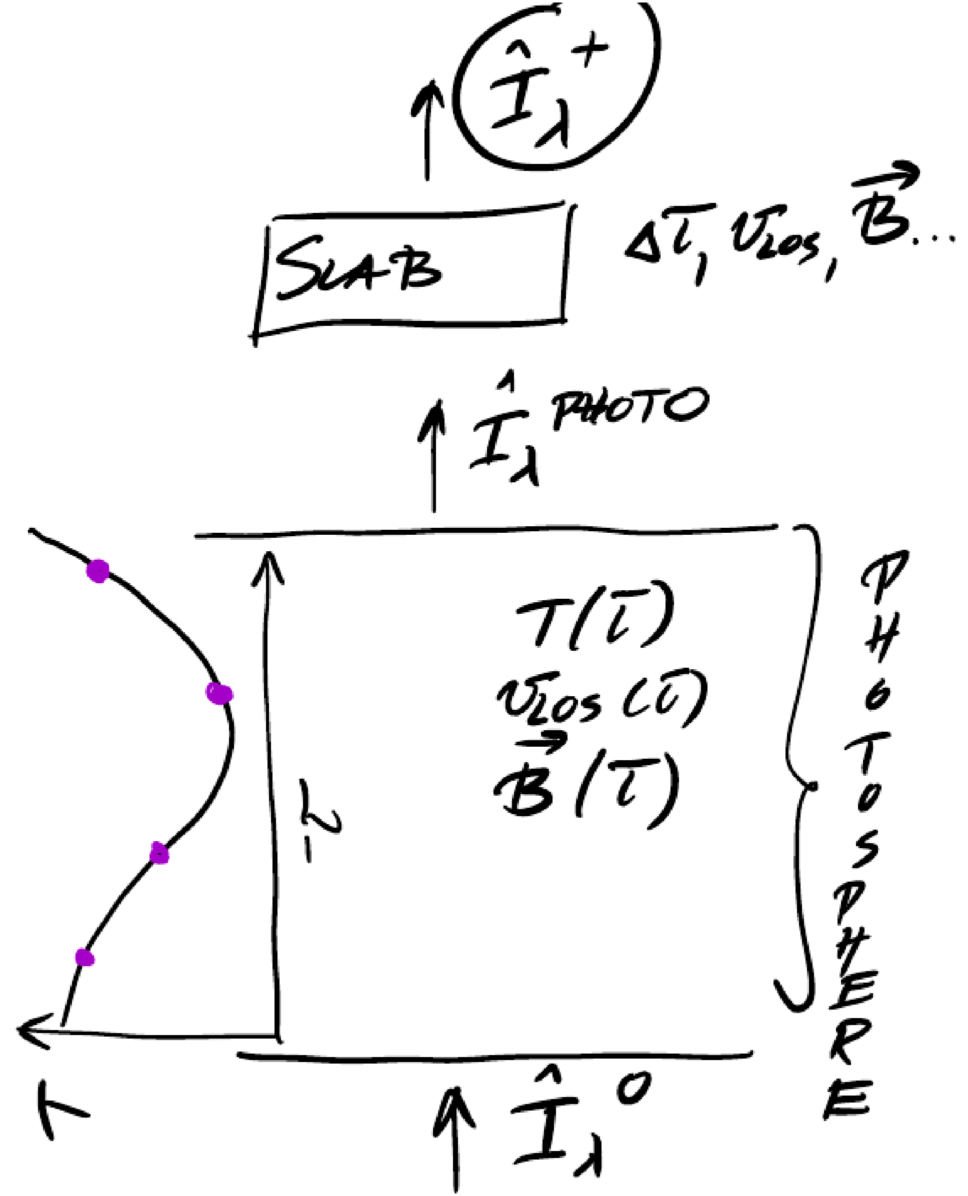
Asensio Ramos et al. 2008

Hazel(2) – He I inversion code

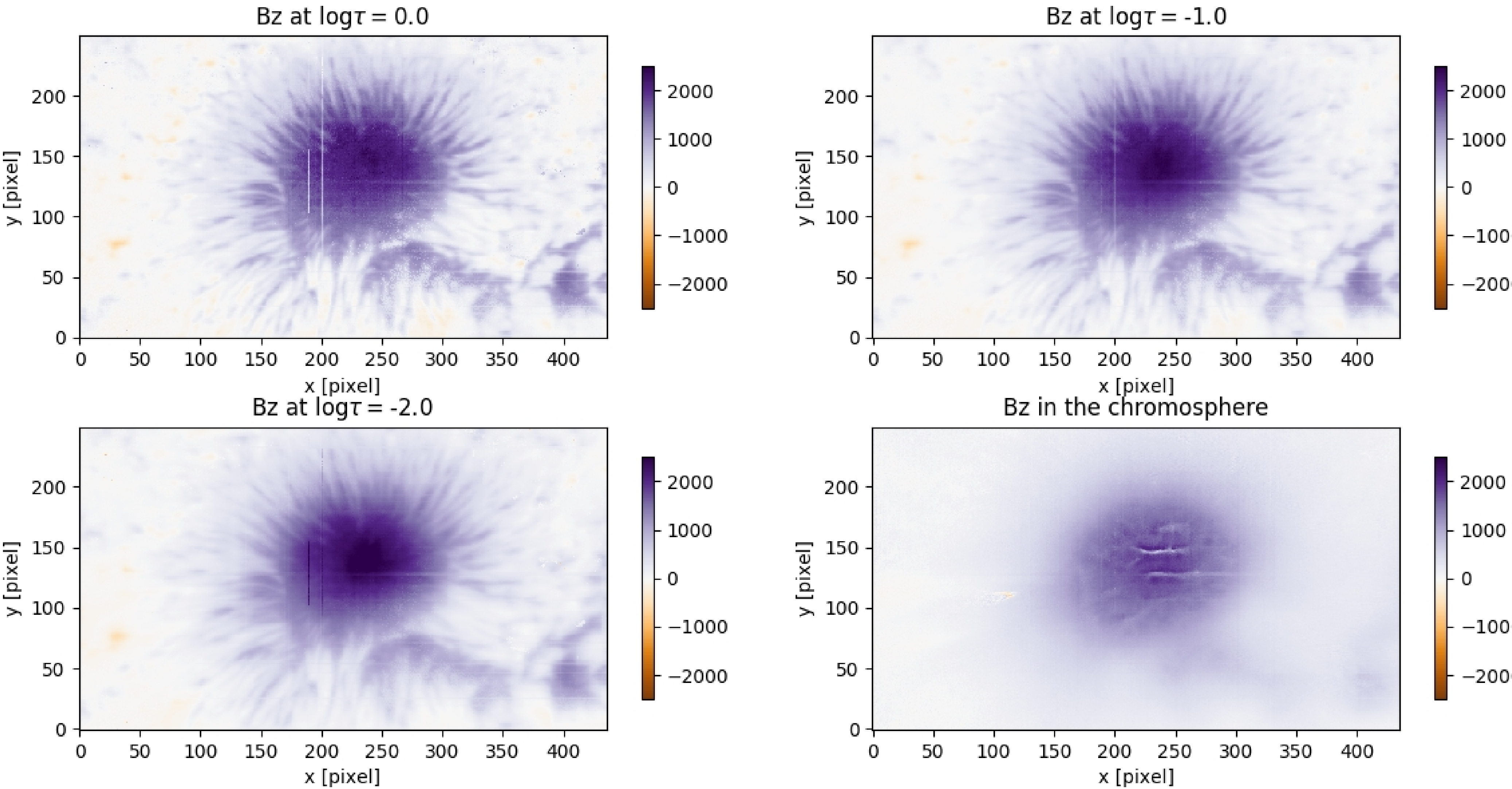
- Hanle and Zeeman Light – HAZEL :)
- Given boundary conditions, and observed spectrum the code retrieves the model parameters
- Applied to prominences, fillaments, active regions, flux emergence, sunspots, even extra-solar applications.

Our level 2 pipeline will use Haze

- We will even be able to invert photosphere and chromosphere together!
- Fully stratified photosphere, parametrized by nodes
- Resulting spectrum is the input for slab.
- Model parameters: **node values + parameters**
- Photosphere is, naturally, in LTE



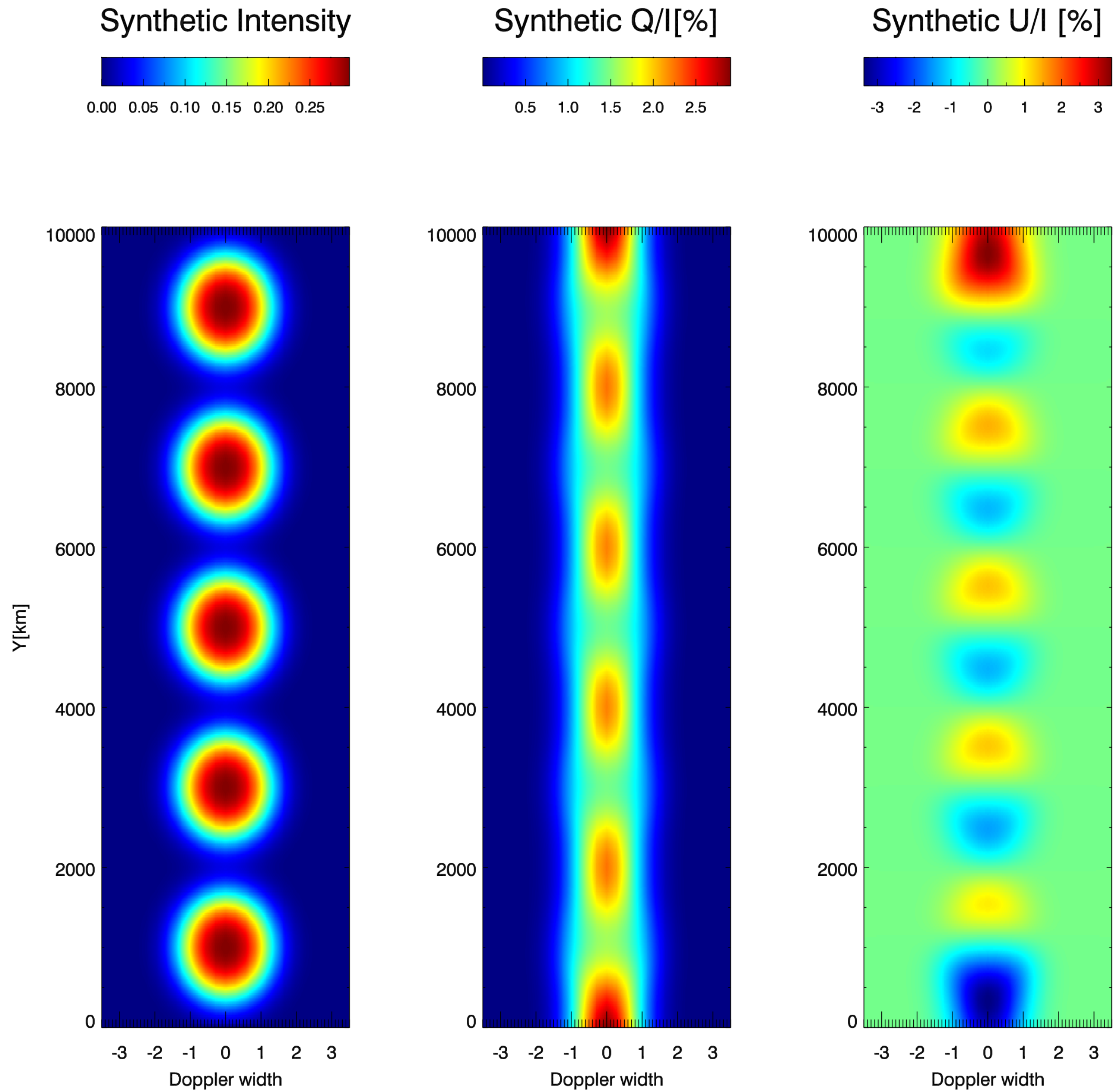
Line of sight magnetic field



So, to recoup:

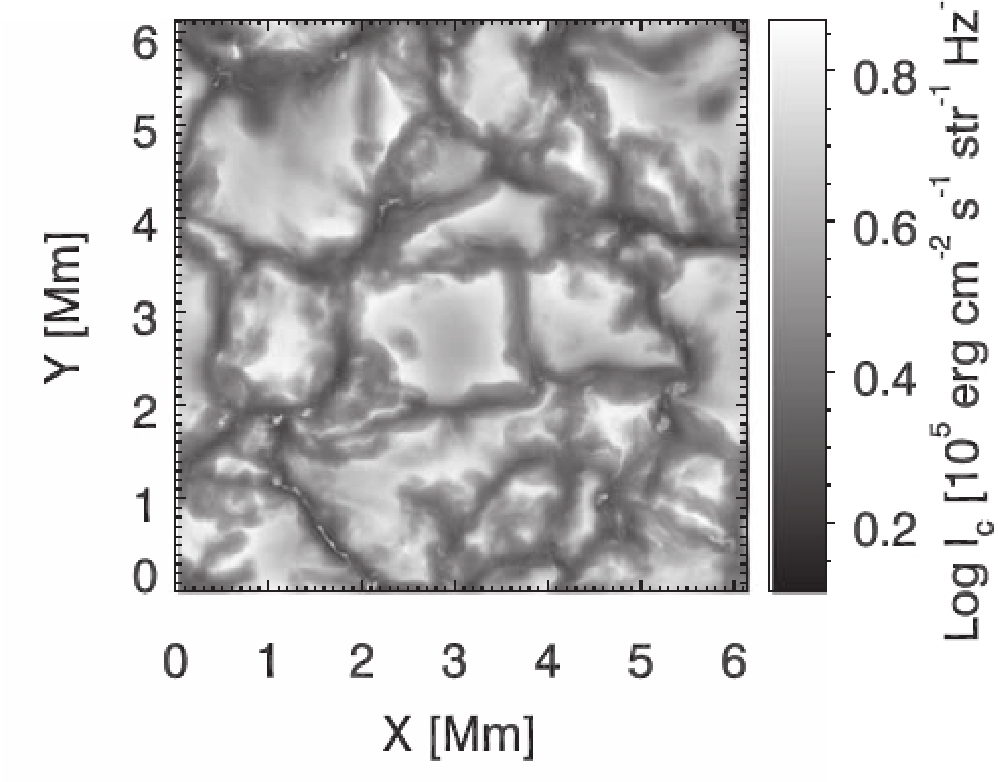
- Vertical anisotropy creates Stokes Q in scattering processes
- Magnetic field “rotates” some of the source function for Q into U
- Full theory accounts for complete radiation ↔ levels interaction : density matrix formalism
- However, radiation does not have to be axially symmetric.
- **This effect is, essentially multiD (pixels talk to each other)**

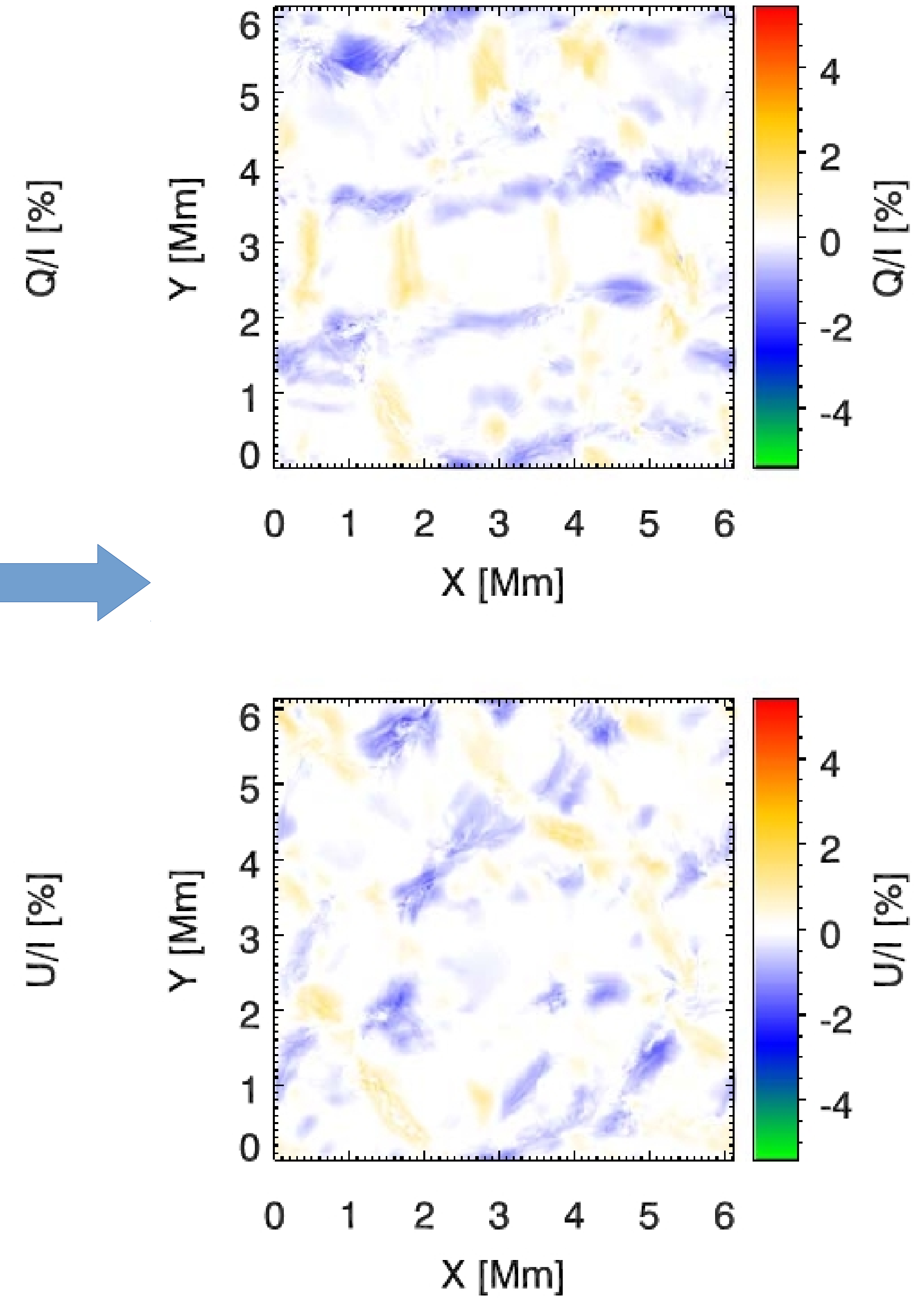
A toy model – a 2D slab with periodic overdensities



Milic et al. 2016

Realistic case, Sr 4607 polarization from a MURAM cube



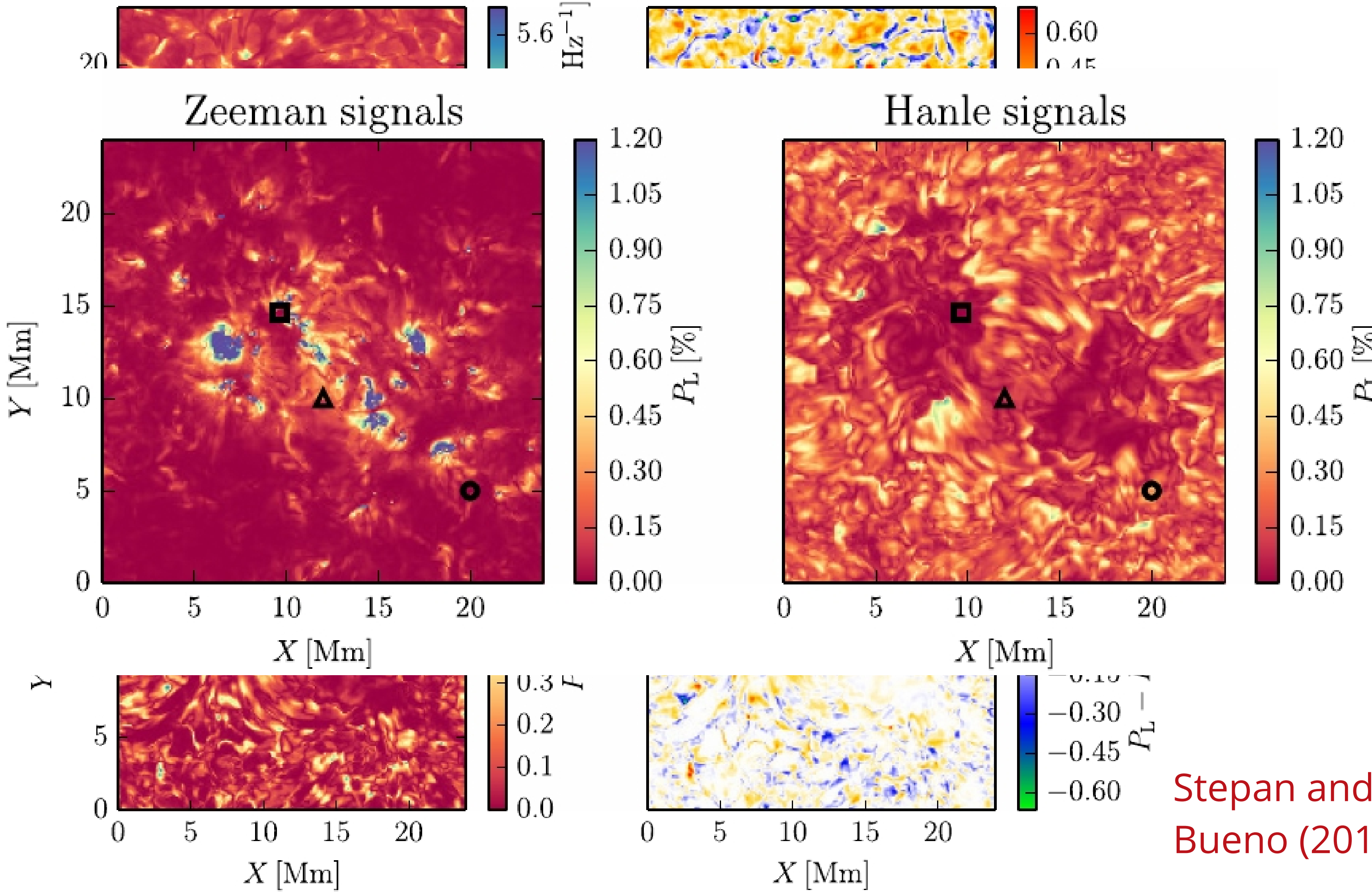


From del Pino Aleman et al. (2018)

Sr 4607 is a magical line

- Contrary to everything I have said so far ,this line is formed in the photosphere
- Extremely large Einstein Coefficient of Emission – a lot of scattering
- Exhibits multi-D effects but also compliments 6300 lines
- Very simple atomic model (resonance line, Zeeman triplet) – scattering polarization is manageable
- Very high degrees of polarization

How strong is the Hanle effect for chromospheric lines?- Ca II 8542



Stepan and Trujillo Bueno (2016)

Summary

- Scattering polarization and the Hanle effect produce very interesting polarization patterns that are fundamentally different from Zeeman
- The problem is essentially NLTE – modeling is complicated
- A lot of matrices, vectors, angular integration etc… even in the simplest case!
- Full treatment – density matrix formalism, out of our scope
- A degenerate problem (4 identical solutions)
- Application – prominences, spicules, highly scattering lines (chromosphere and TR)
- Using DKIST as a "photon bucket" might give us some **new detections**