Inferring physical properties of solar atmosphere from spectropolarimetric observations

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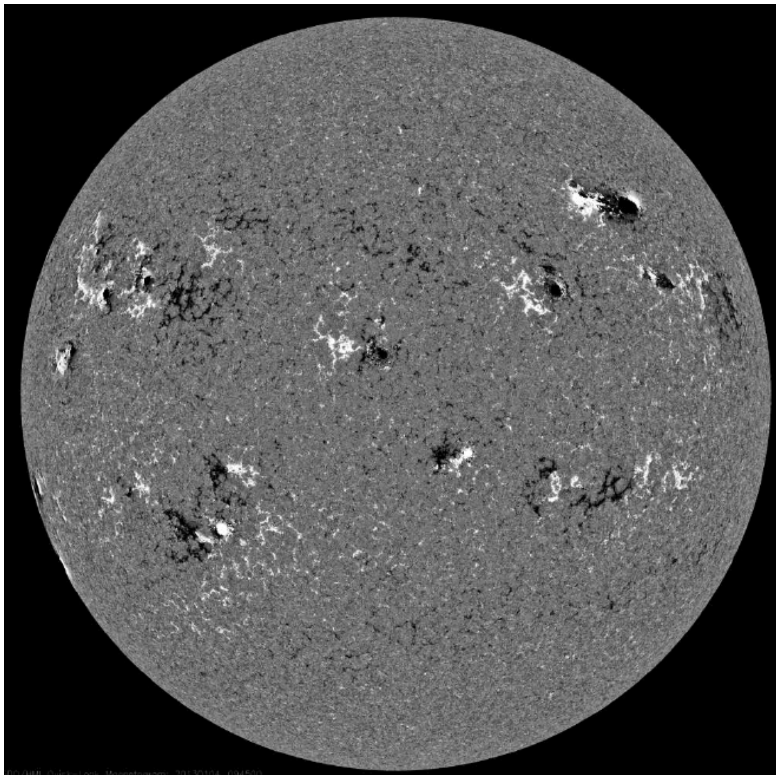
Outline

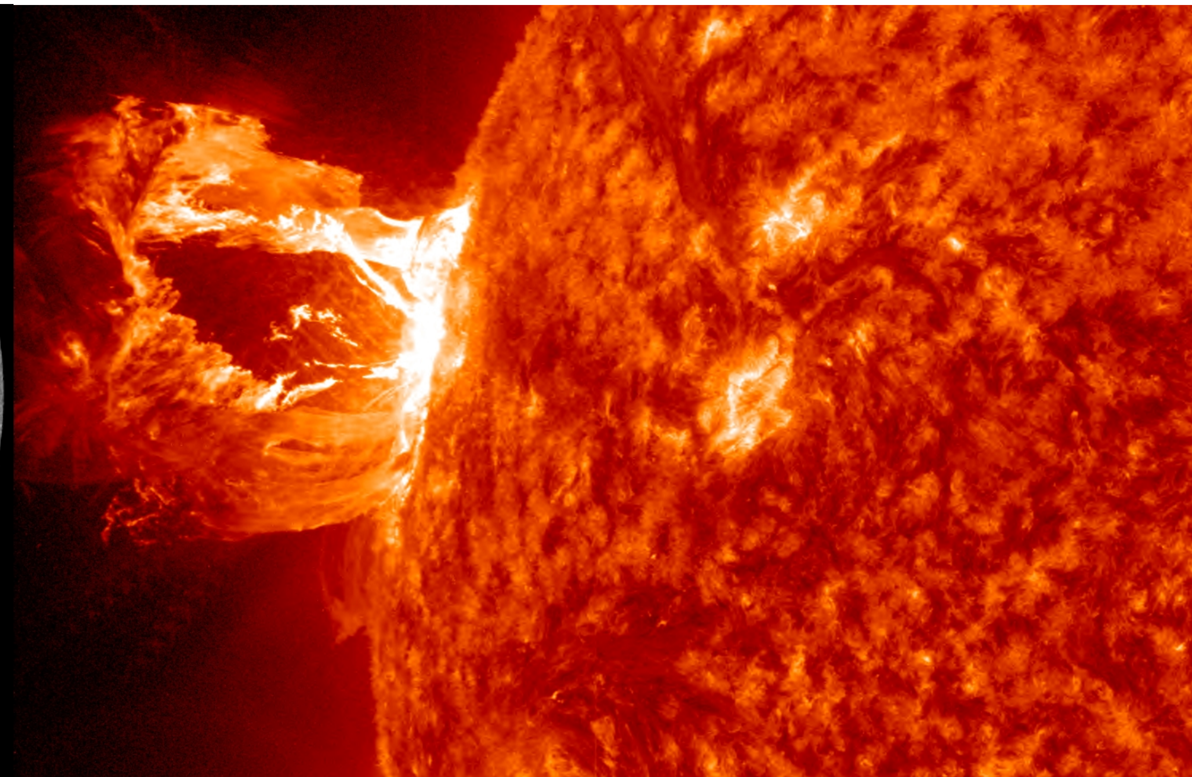
- What do we want to find out?
- What are „signatures“ of these phenomena on our observables?
- Can we measure them?
- *Can we interpret them and how?* (Zeeman and Hanle effects, different generative models)

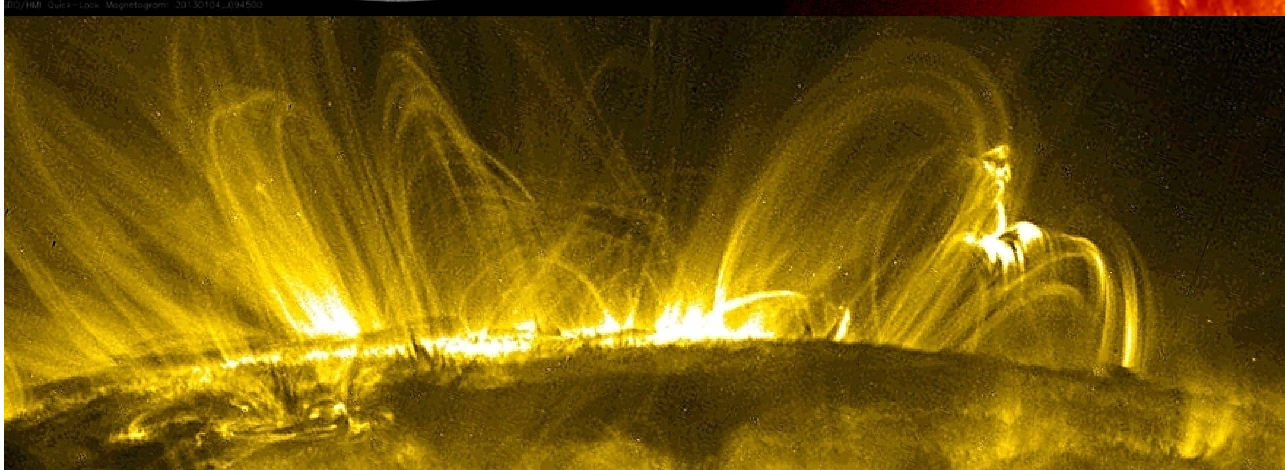
Messages

- Our most reliable tool is spectropolarimetry
- This kind of inference requires knowledge of radiative transfer
- Parameters are degenerate
- Noise is still **high**
- The scientific questions are interesting, but inference methods are as well

It is almost obvious that magnetic field pervades the solar atmosphere

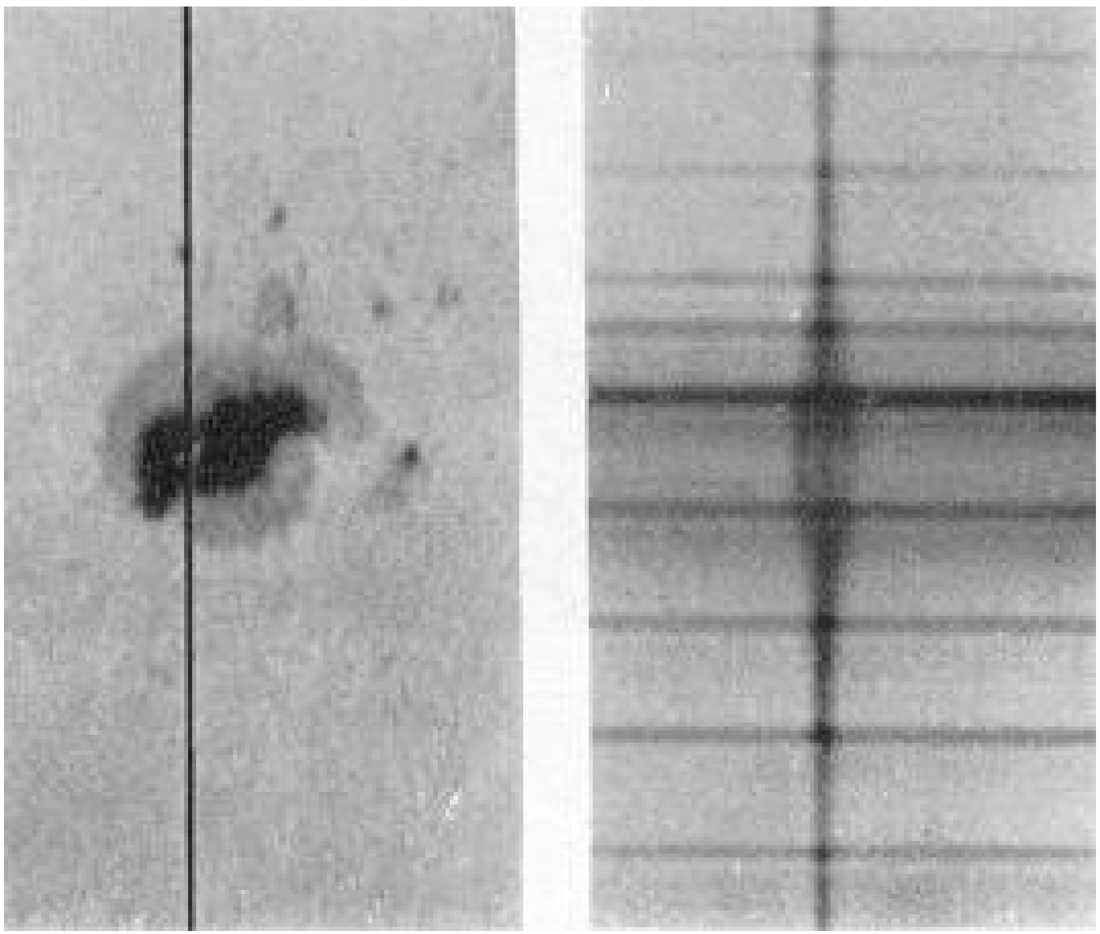






Can we be sure?

G. E. Hale – Observations of Zeeman split lines

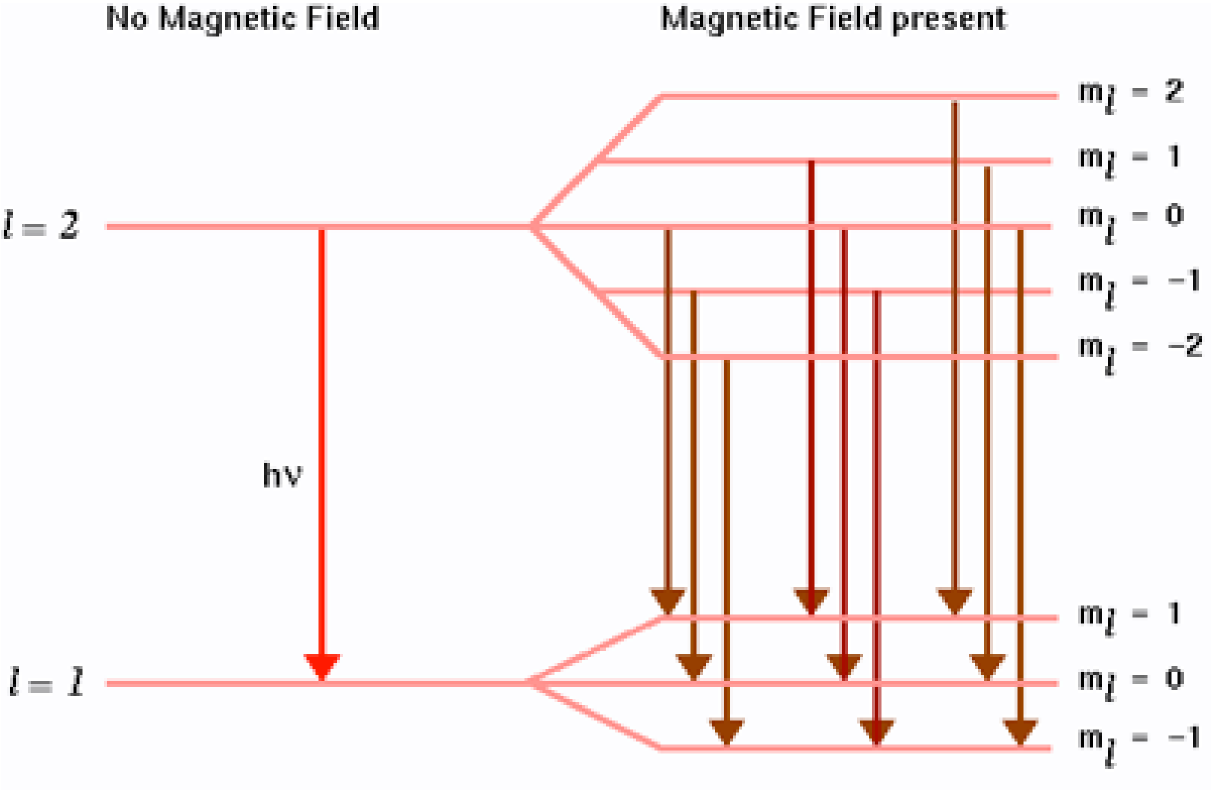


From Hale *et al.* (1919)

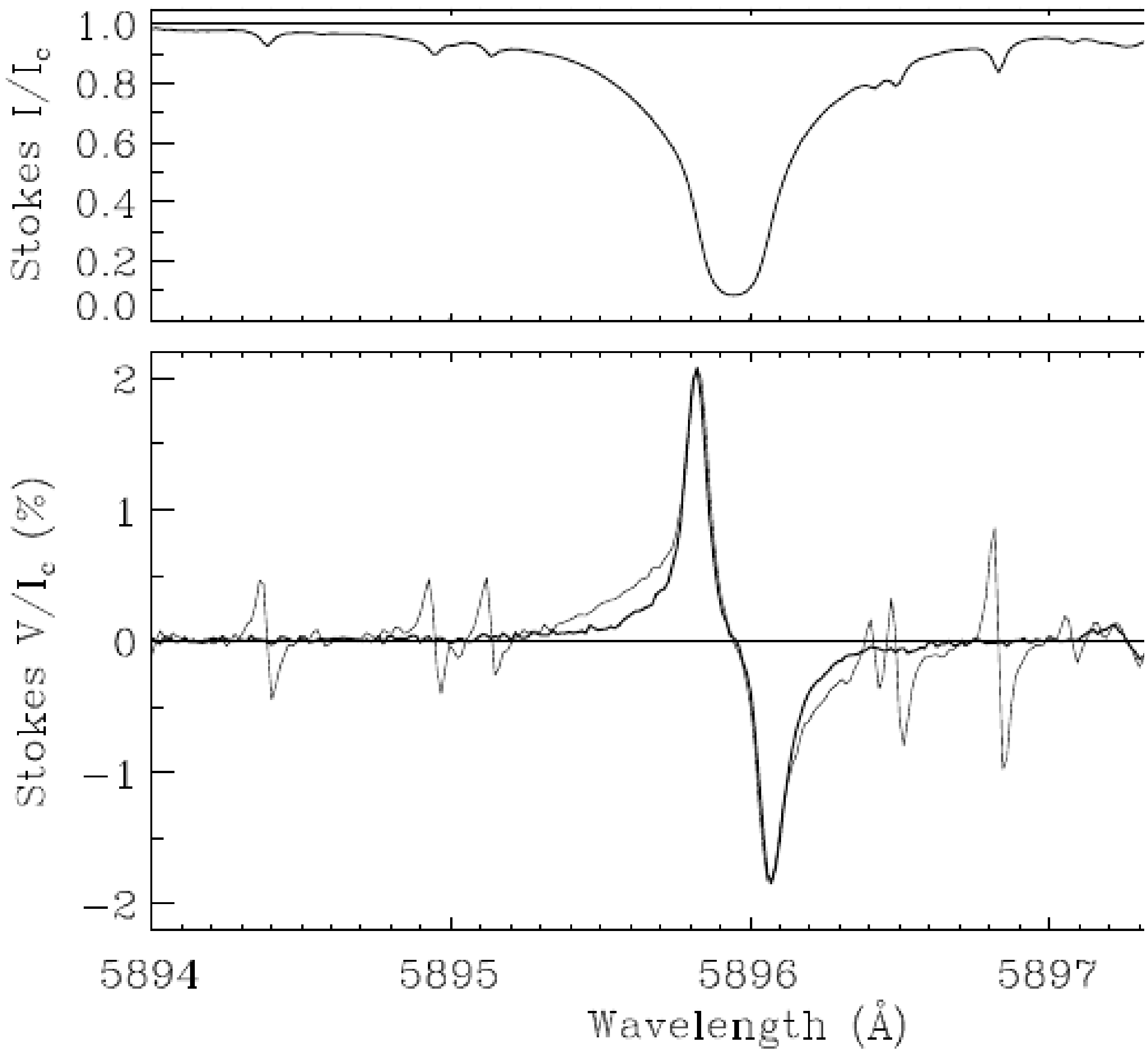
How to interpret these observations?

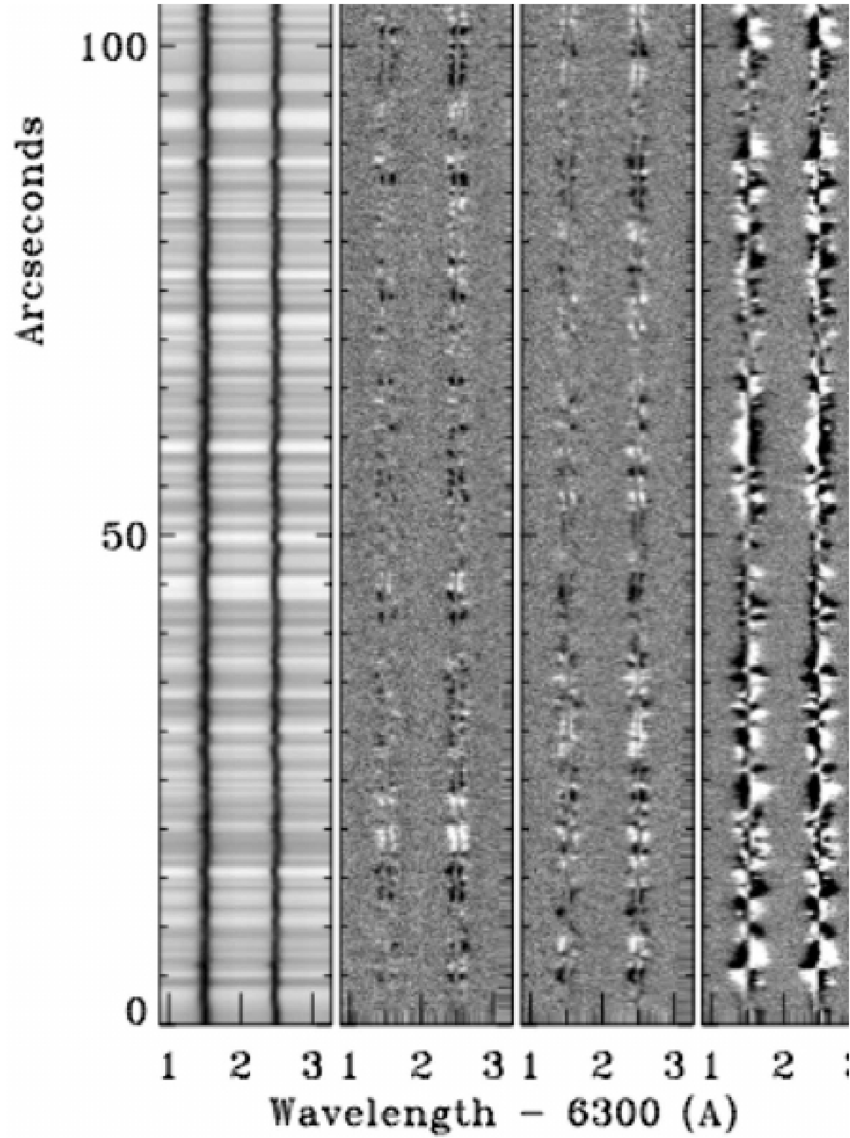
- **Zeeman effect** – splitting of the energy levels in the presence of the magnetic field.

$$\Delta\lambda_H = zg\lambda^2 B$$



However, Zeeman effect also predicts polarization… which we **do** see





From Stenflo (1984) and Lites et al (2008)

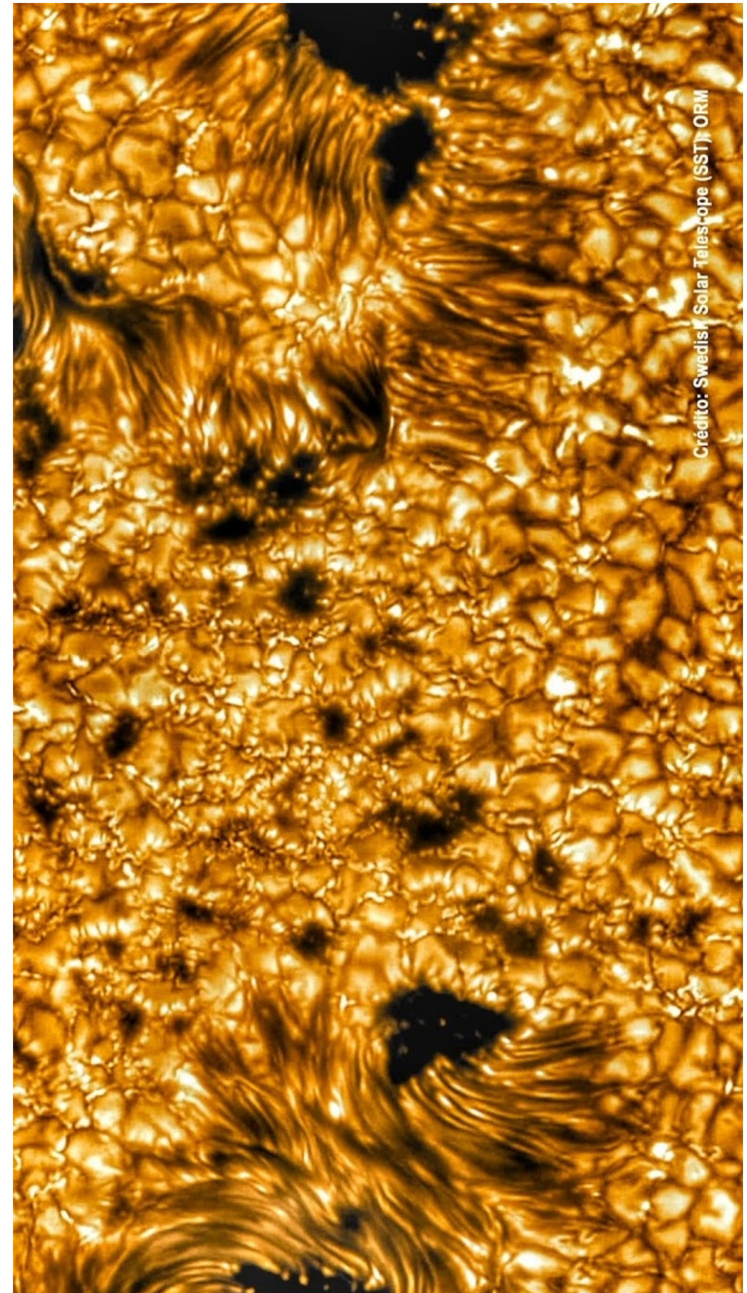
The weak field approximation

$$V \approx -\Delta\lambda_H \, \partial I_0 / \partial\lambda$$

- From this we can derive the Zeeman splitting and then the magnetic field.
- Implicit assumption: magnetic field is constant in the observed „element“
- Q: What magnetic field are we measuring this way?

What exactly are we observing?

- In the case of slit spectrometry: we are observing an array of 1D atmospheres
- Tunable filtergraph: 2D array of 1D atmospheres



So, our observable is:

Wavelength distribution of the four Stokes parameters coming from one (or more) one-dimensional, plane-paralell atmospheres

What is our model then?

- Set of, generally depth dependent, atmospheric parameters: temperature, pressure, microturbulent velocity, macroscopic velocity, magnetic field vector
- However, we want to describe the atmosphere with not too many parameters **or** to simply fix some parameters in advance.

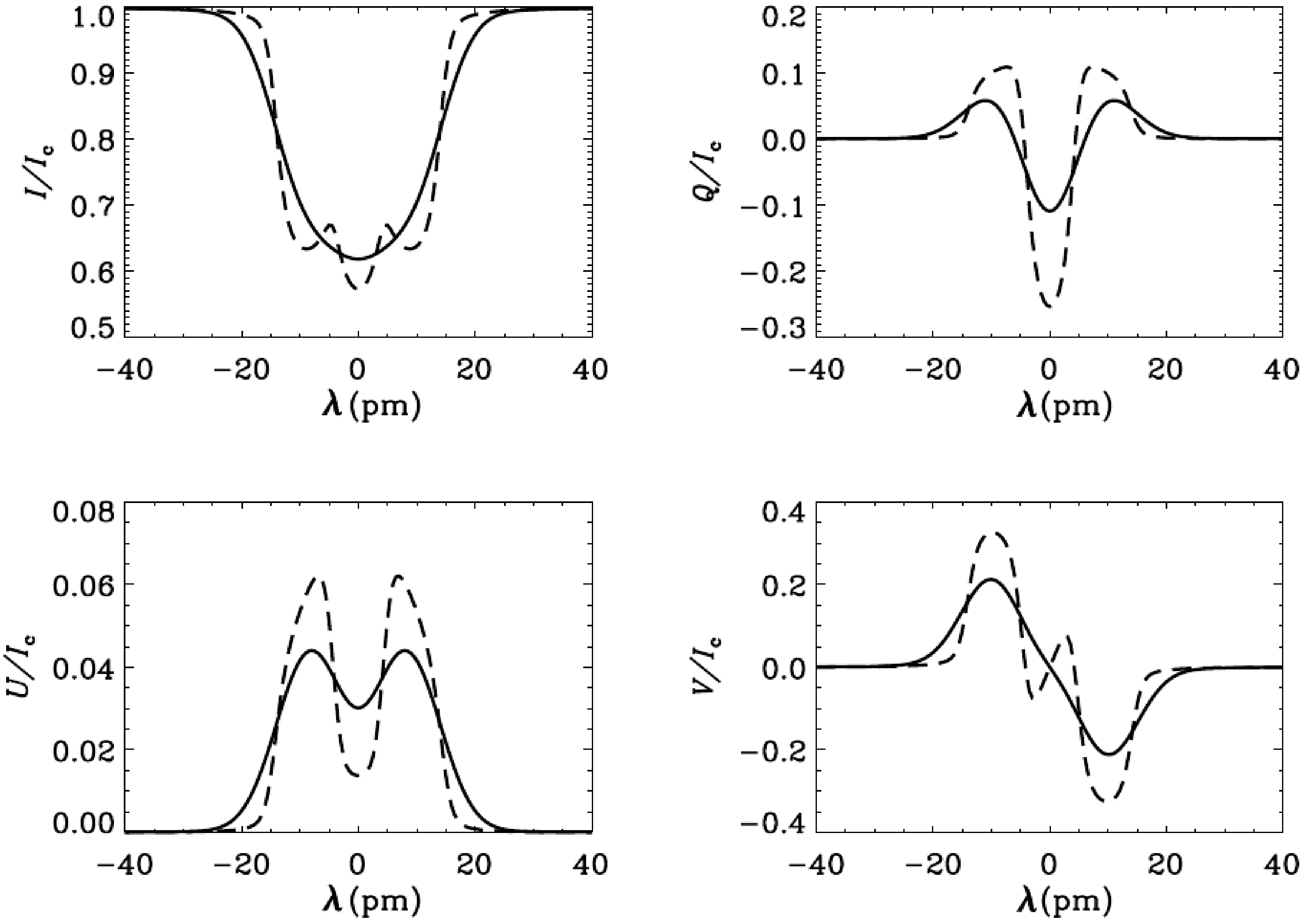
How do we relate them?

$$\frac{\mathrm{d}}{\mathrm{d}z}\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = -\begin{pmatrix} \eta_I & \eta_Q & \eta_U & \eta_V \\ \eta_Q & \eta_I & \rho_V & -\rho_U \\ \eta_U & -\rho_V & \eta_I & \rho_Q \\ \eta_V & \rho_U & -\rho_Q & \eta_I \end{pmatrix}\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}$$

$$\boldsymbol{I}(0) = \int_0^\infty \mathbf{O}(0, \tau_\mathrm{c})\mathbf{K}(\tau_\mathrm{c})\boldsymbol{S}(\tau_\mathrm{c})\mathrm{d}\tau_\mathrm{c}$$

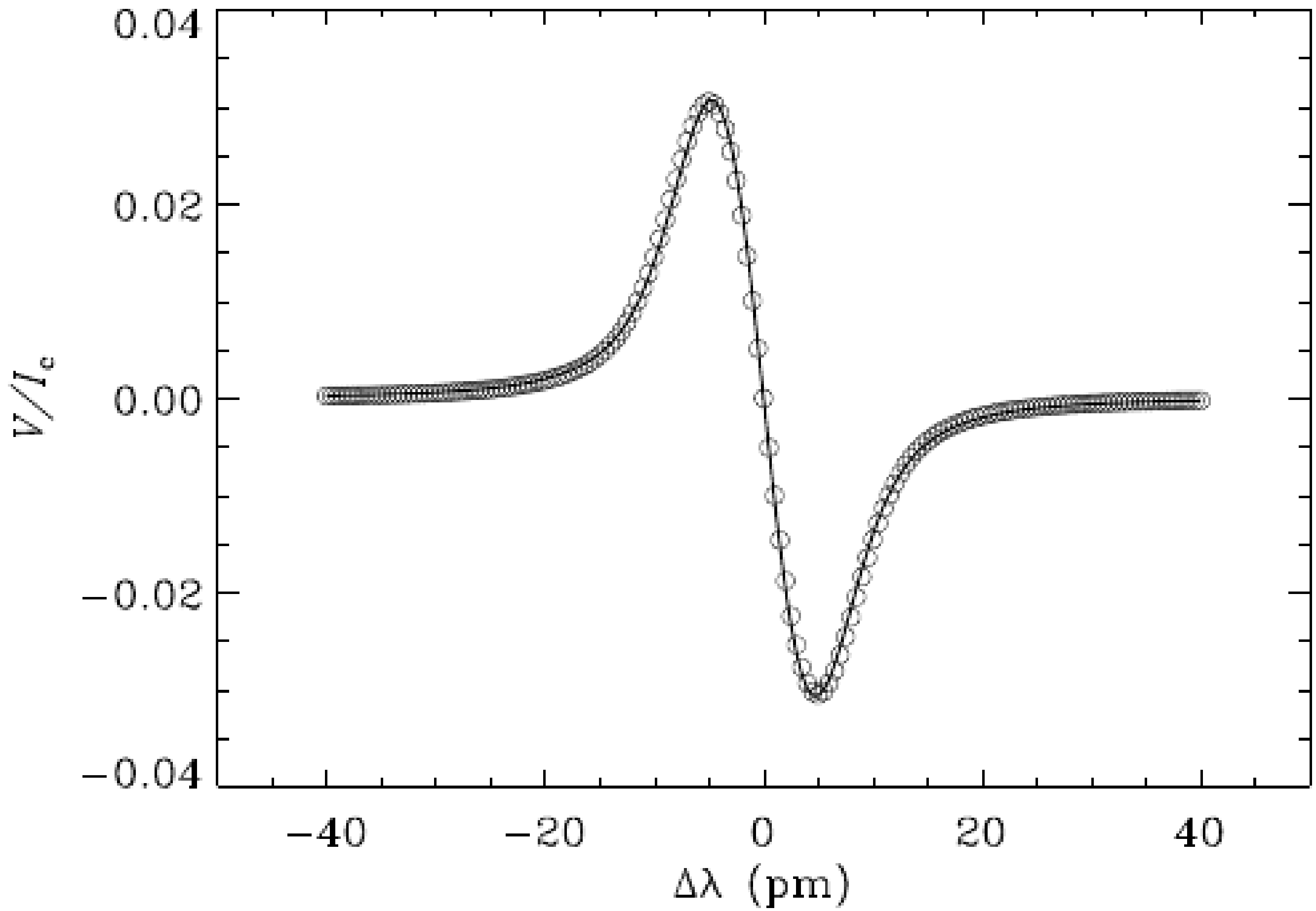
If we know O (the kernel), this problem (solving an integral equation of this form) is known as *inversion*.

Forward modeling



From del Toro Iniesta (2003)

Forward modeling



From del Toro Iniesta (2003)

Two atmospheres (difference in T of 2000 K and in B of 800 G) yield the same result!

Spectropolarimetric inversions

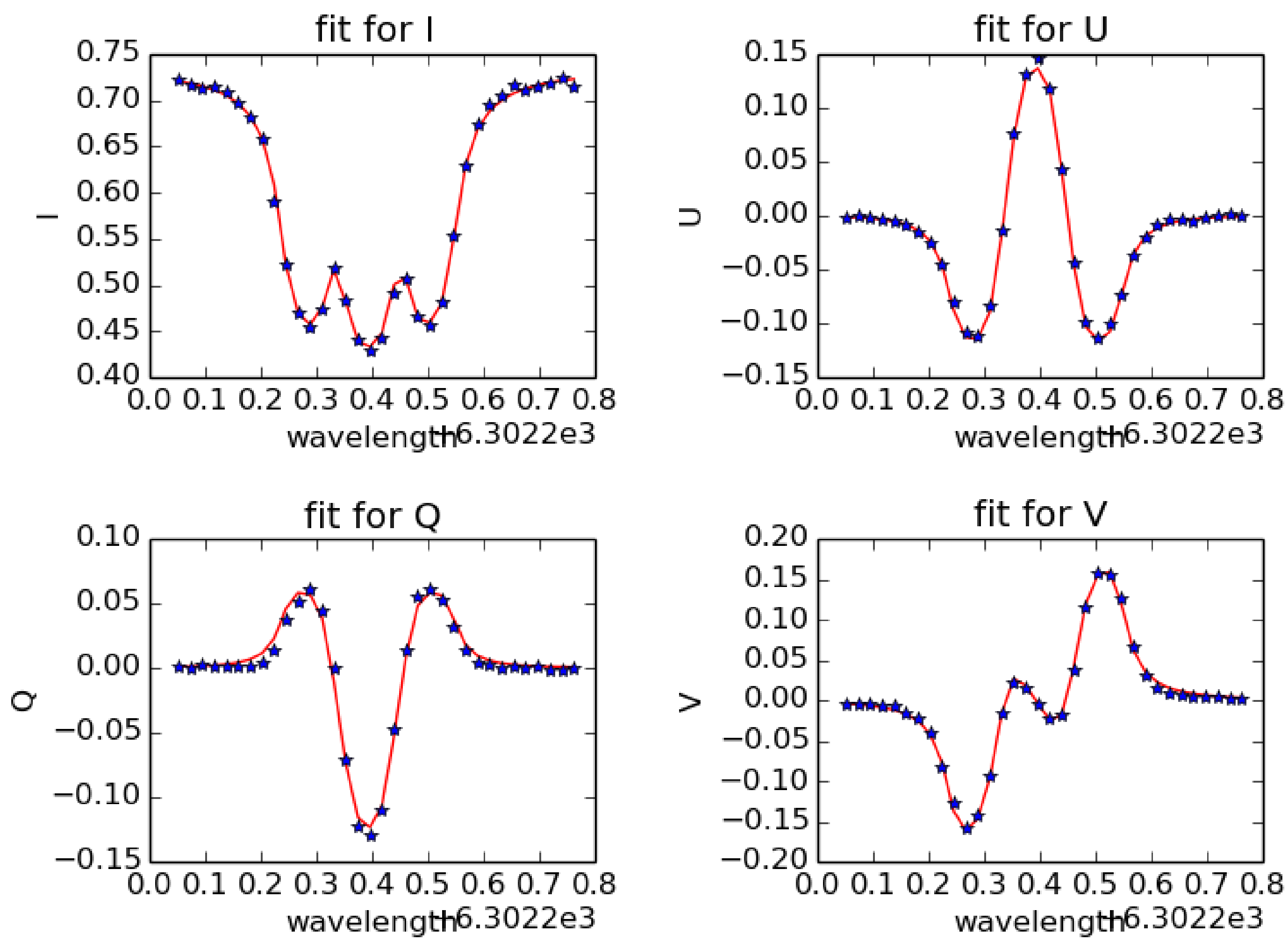
- The aim is to assume the model and then tune parameters in order to find the best fit to the observed Stokes spectrum.

$$\chi^2(\boldsymbol{x}) \equiv \frac{1}{\nu} \sum_{s=0}^{3} \sum_{i=1}^{q} \left[I_s^{\mathrm{obs}}(\lambda_i) - I_s^{\mathrm{syn}}(\lambda_i; \boldsymbol{x}) \right]^2 w_{s,i}^2$$

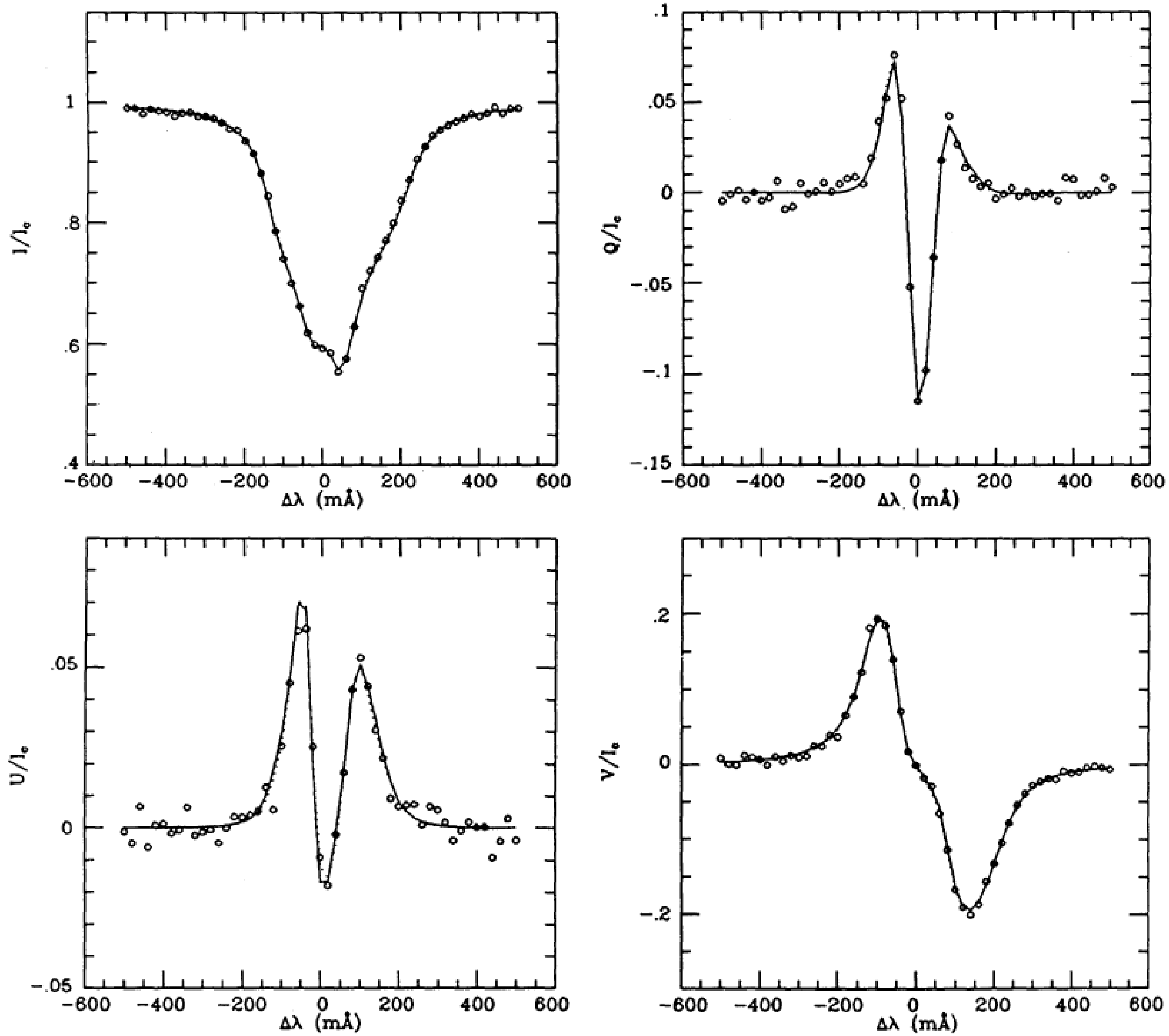
- A most common approach is to employ some gradient based minimization to find the minimum of the merit function.

Milne-Eddington atmosphere

Set all the parameters constant except the source function which is assumed to be linear.

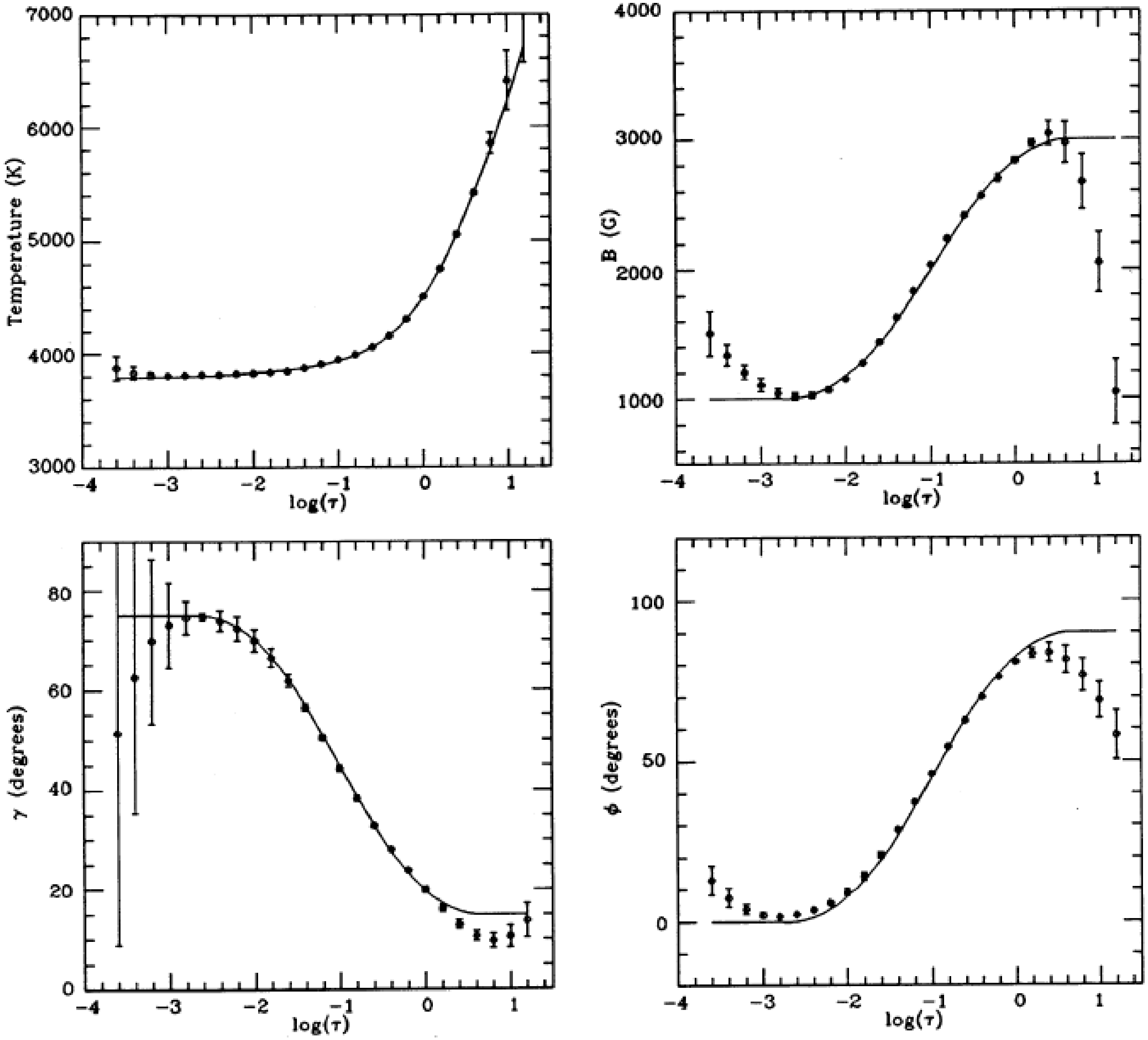


Depth dependent atmosphere



From Ruiz Cobo & del Toro Iniesta (1992)

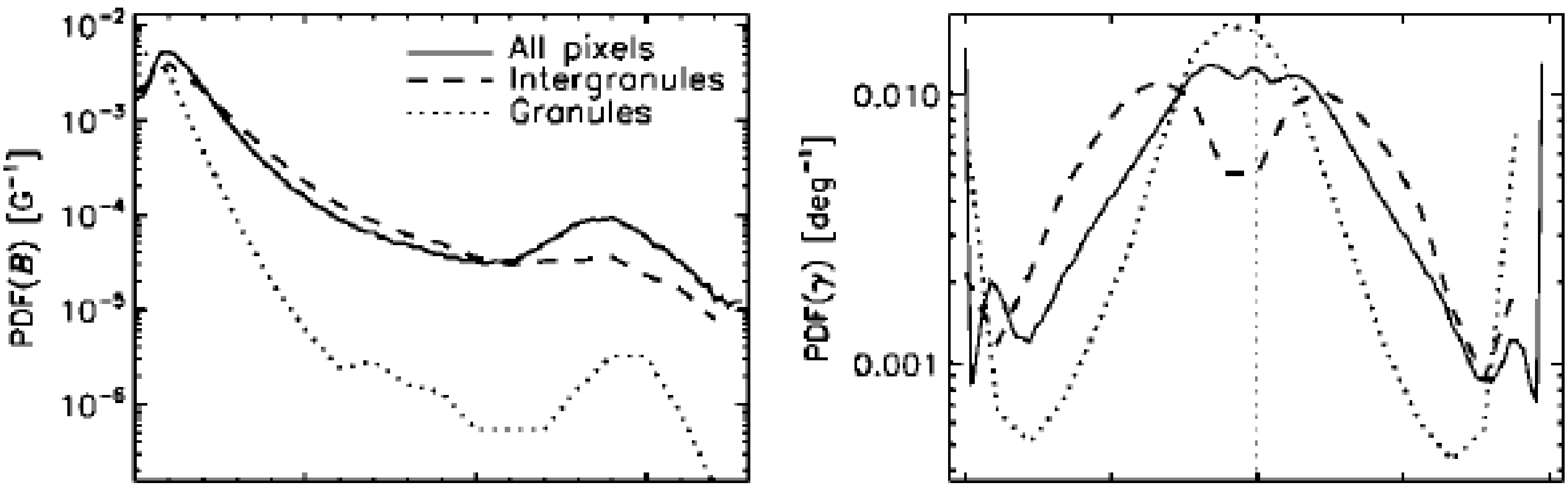
Depth dependent atmosphere



From Ruiz Cobo & del Toro Iniesta (1992)

Example 1: Quiet Sun magnetic fields inclination

- It is hard to invert QS observations because linear polarization is dominated by noise → bias toward vertical fields!

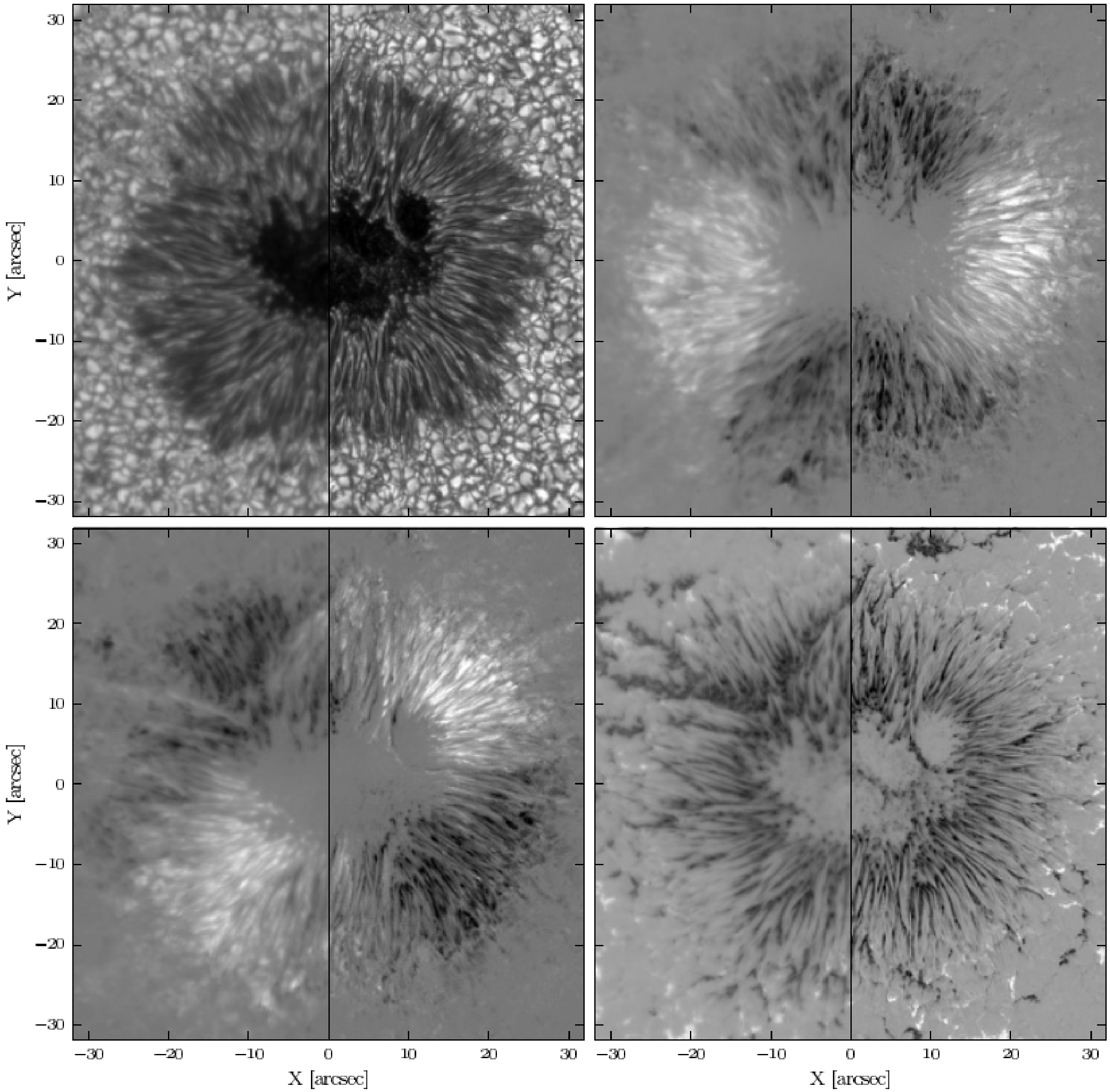


From Orozco Suarez *et al.* (2007)

Example 2: Spatially coupled inversion

- Pixels „talk“ to each other because of the PSF of the telescope. If you know PSF…
- You can represent your 3D cube (x,y, wavelength) as an action of two operators on your 3D cube of atmospheric parameters
- First operator: Radiative transfer
- Second operator: Spatial coupling because of the PSF

Spatially coupled inversion



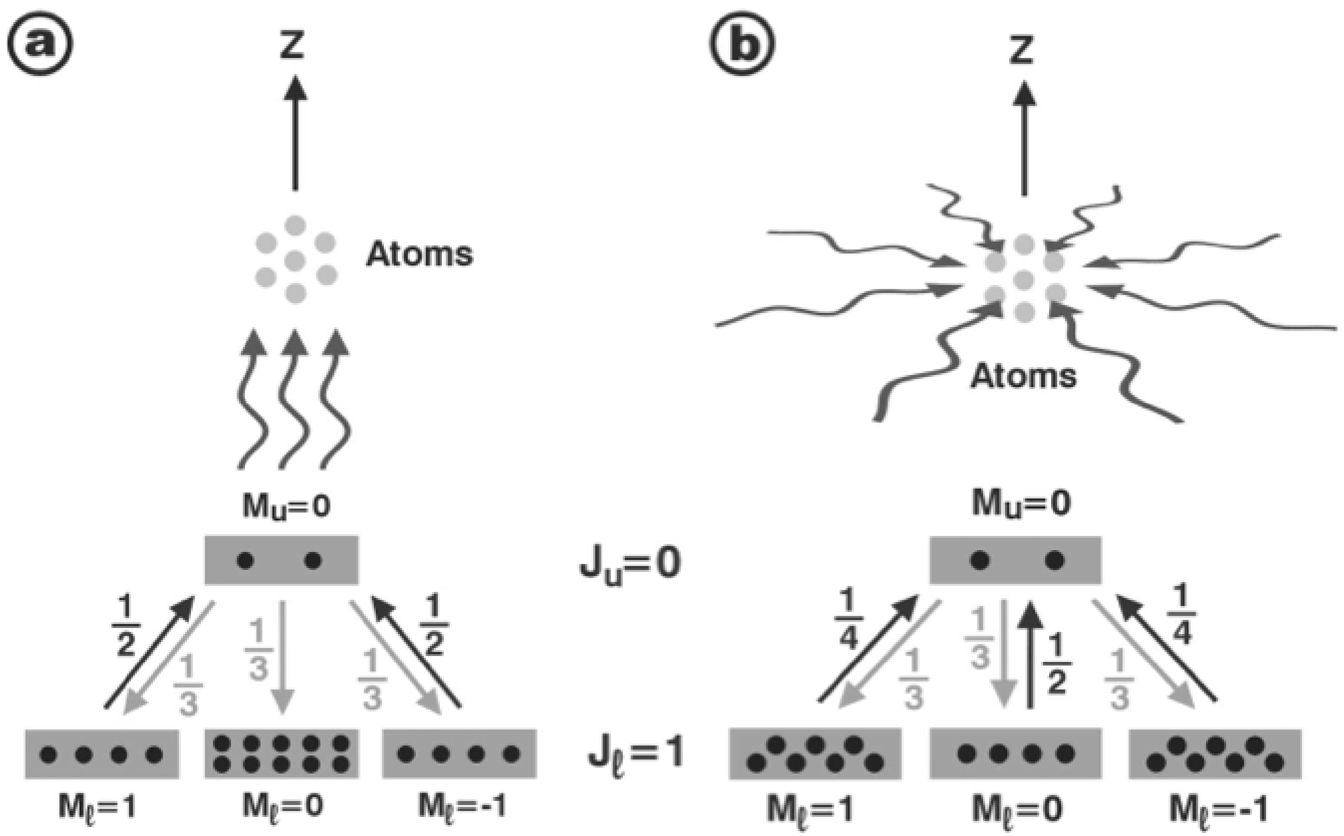
From van Noort (2012)

Non-mainstream topics:

Magnetic field diagnostics
using Hanle effect

Scattering polarization in spectral lines

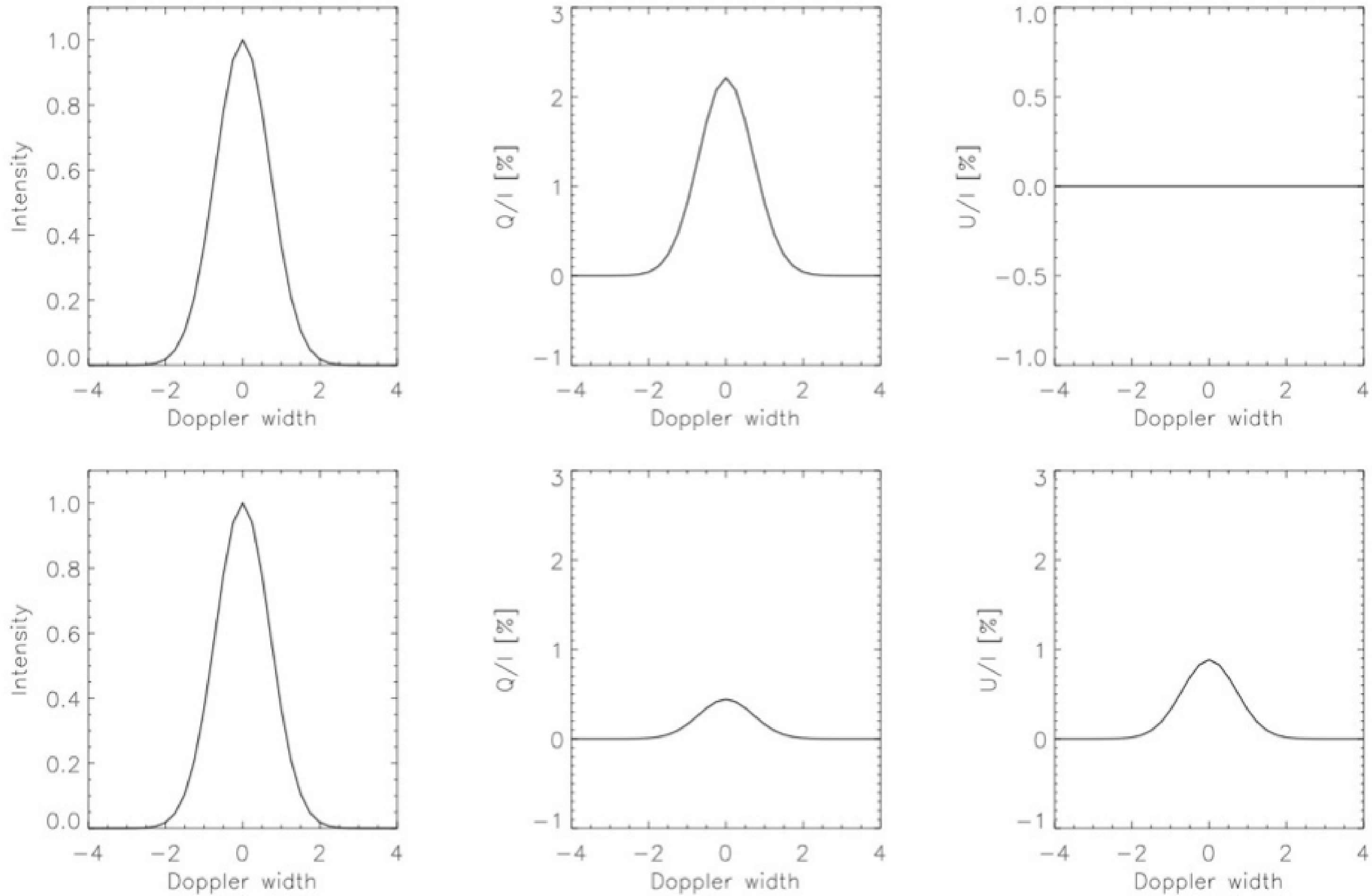
Linear polarization caused by the illumination of scattering atoms by anisotropic radiation field.



From Trujillo Bueno (2003)

Hanle effect

Magnetic field is inclined with respect to symmetry axis → rotation and depolarization.



Following example from Landi degl'Innocenti & Landolfi (2004)

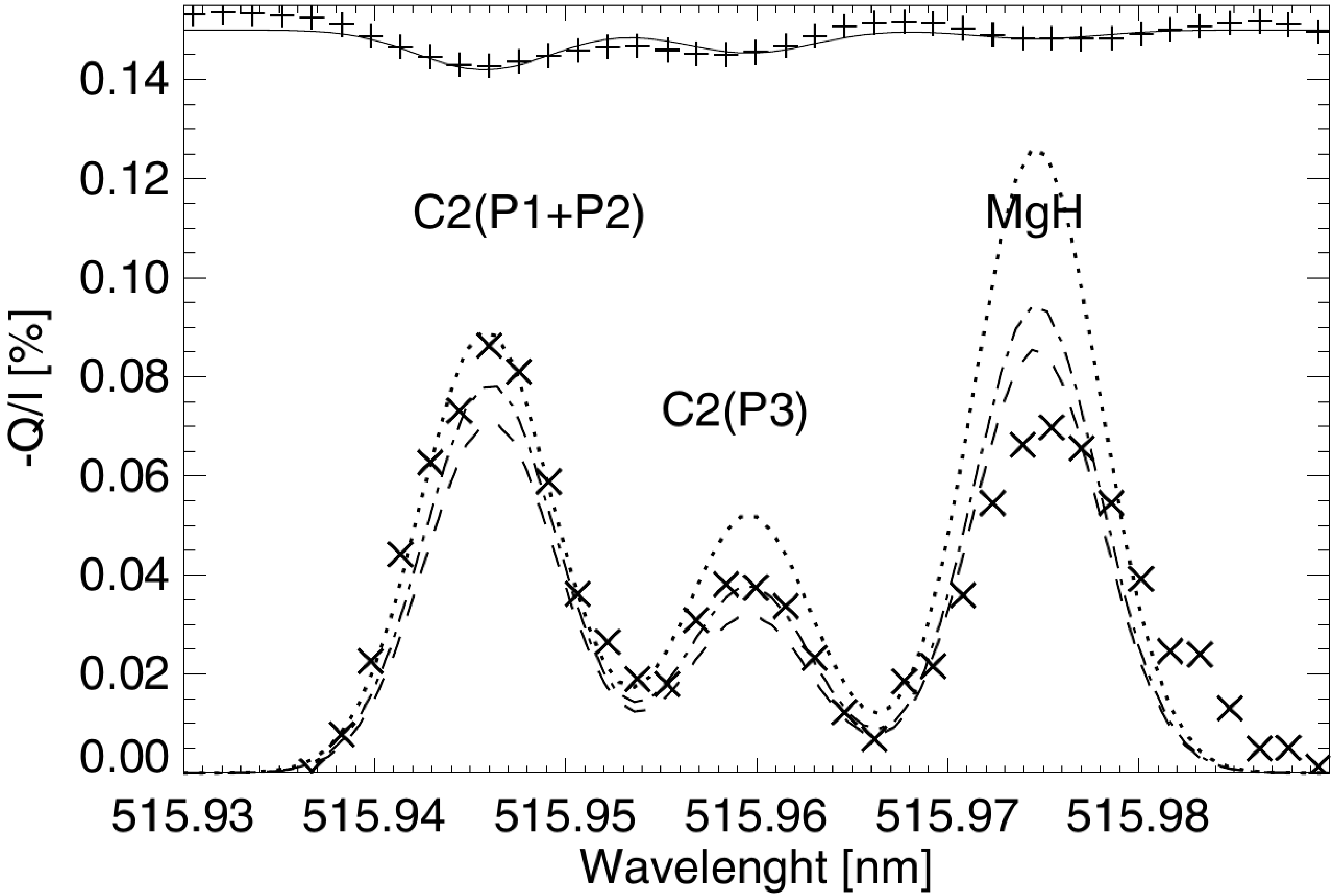
Sensitivity to Hanle effect

- Line has to be formed by scattering – NLTE line
- Needs to be magnetically sensitive
- And also sensitive to magnitude of fields we are trying to diagnose

$$\Gamma_H = 0.88 \frac{gB}{\Gamma_r + C_{ul} + D^{(2)}}.$$

What happens if the magnetic field is „turbulent“?

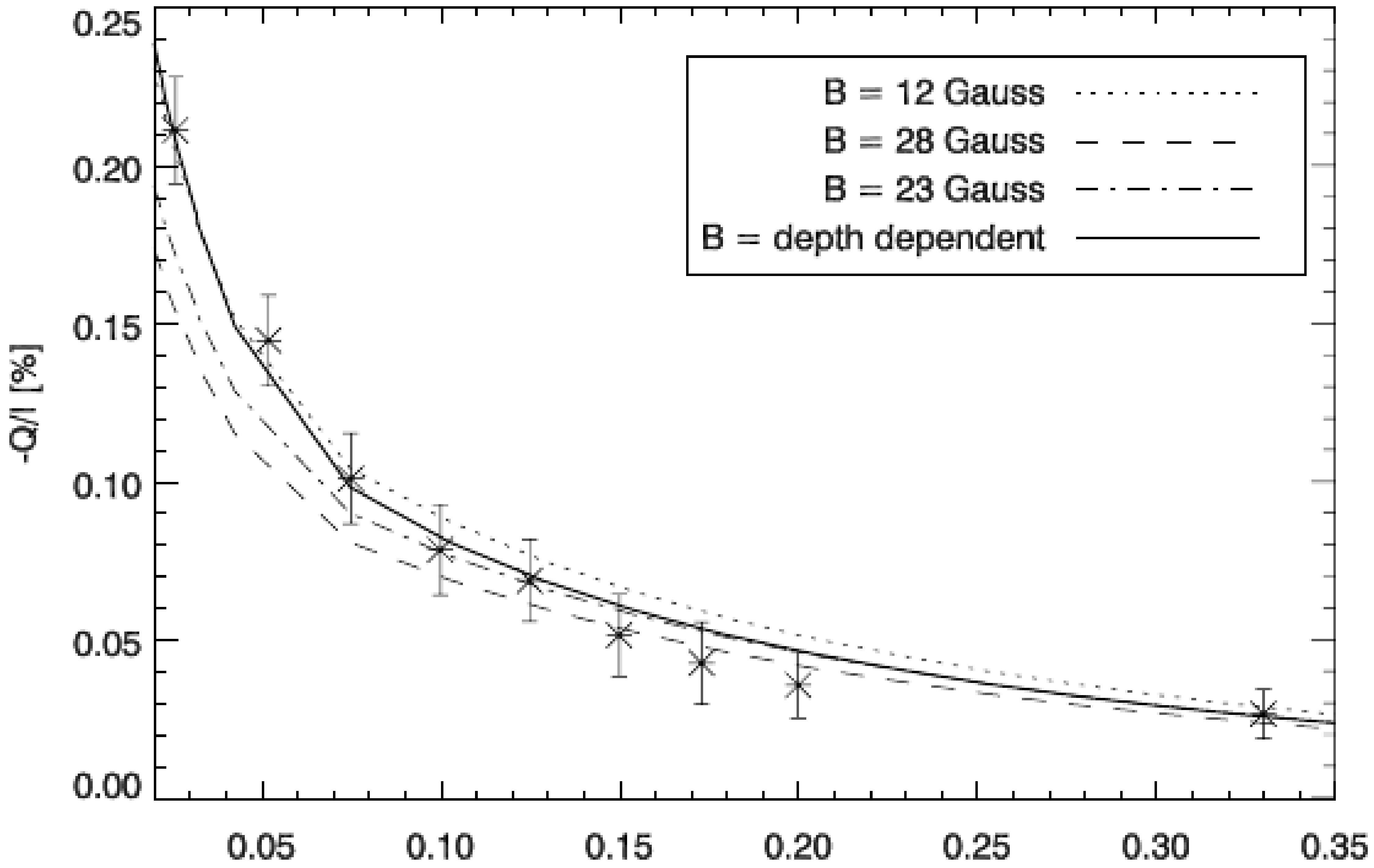
- Rotations will cancel, but depolarization will not.
- Total scattering polarization will be reduced.
- **Problem:** Magnetic field competes with other depolarizing process: elastic collisions
- *Differential Hanle effect*



From Milić & Faurobert (2012)

Example 3: Diagnosing depth-dependent fields

- Interpretations of Sr and MgH lines yield B of around 60 Gauss, while interpretation of C2 molecule results in B < 10 Gauss
- We attempt to make peace between these results by invoking a depth-dependent field.
- Simultaneous fit of line-center polarization in three lines + inference of collisional rates + observations at different limb positions



From Milić & Faurobert (2012)

Problems

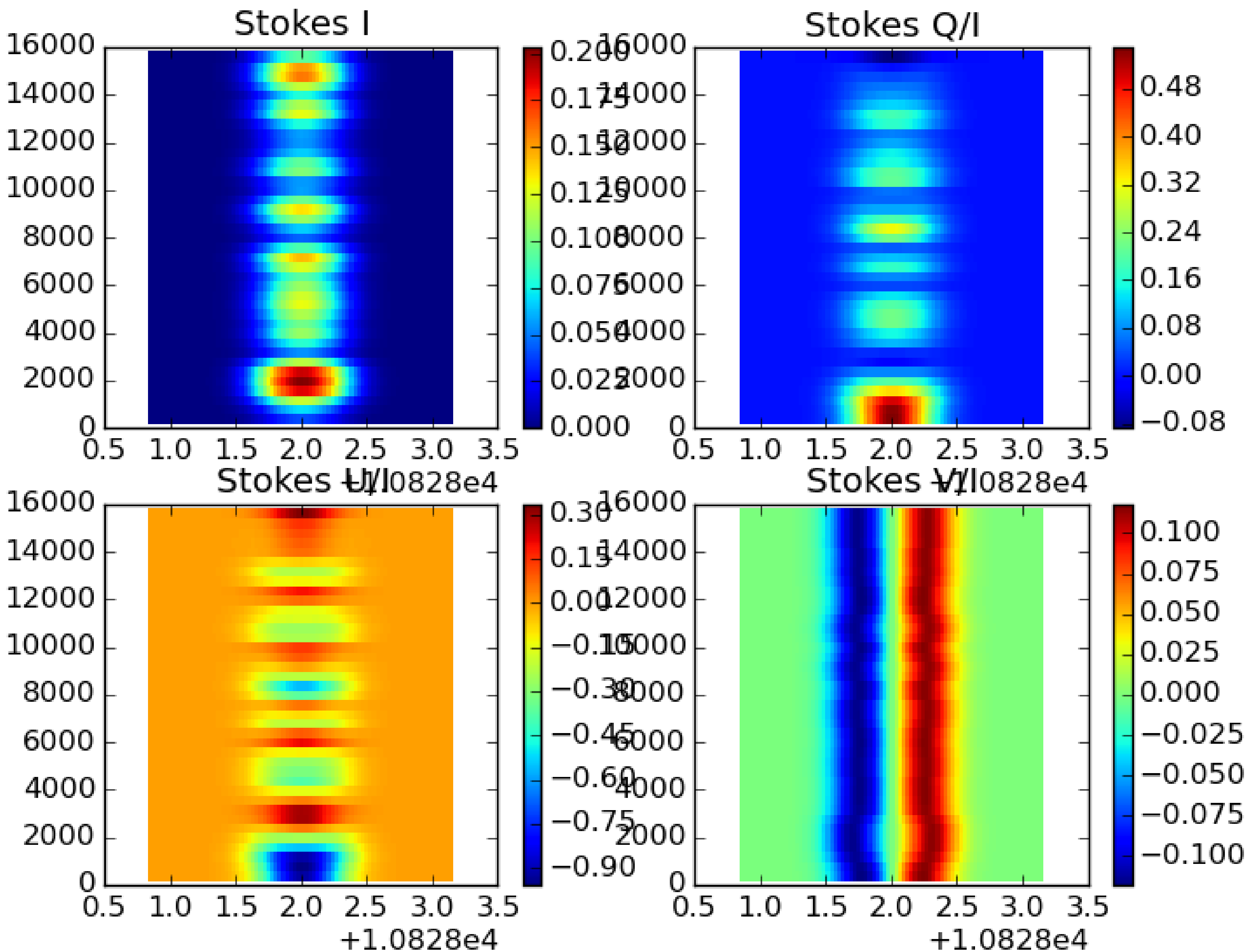
- The interpretation assumes that Solar atmosphere is 1D, and it certainly is not so
- How can one invert a 3D model? (*No way!*)
- However, remember spatially coupled inversion of van Noort (2012) from few slides go

Example 4: Multidimensional effects in prominences

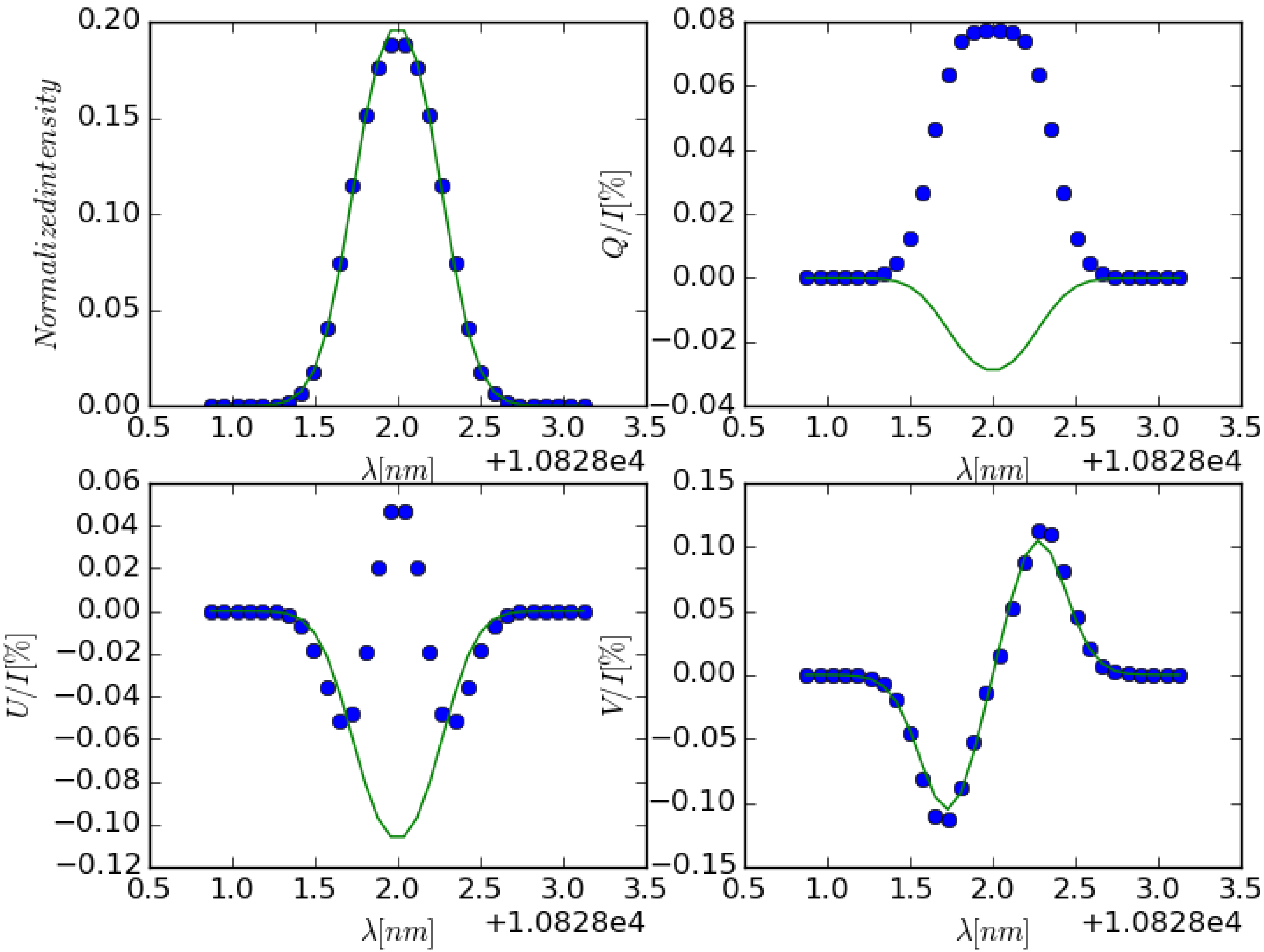
What happens then we assume a simple model for something that **is** complicated?

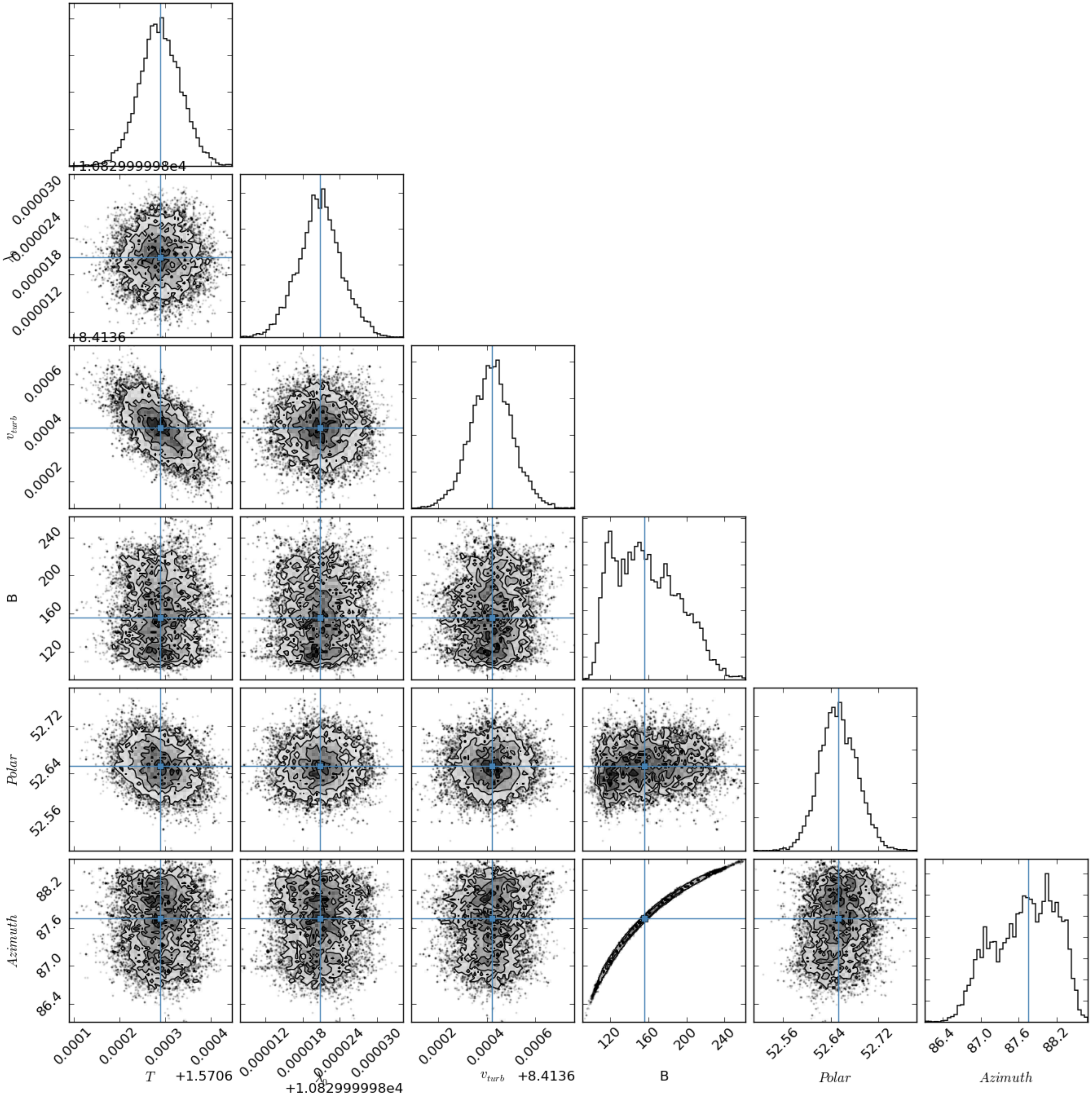
Image by Joseph Brimacrombe

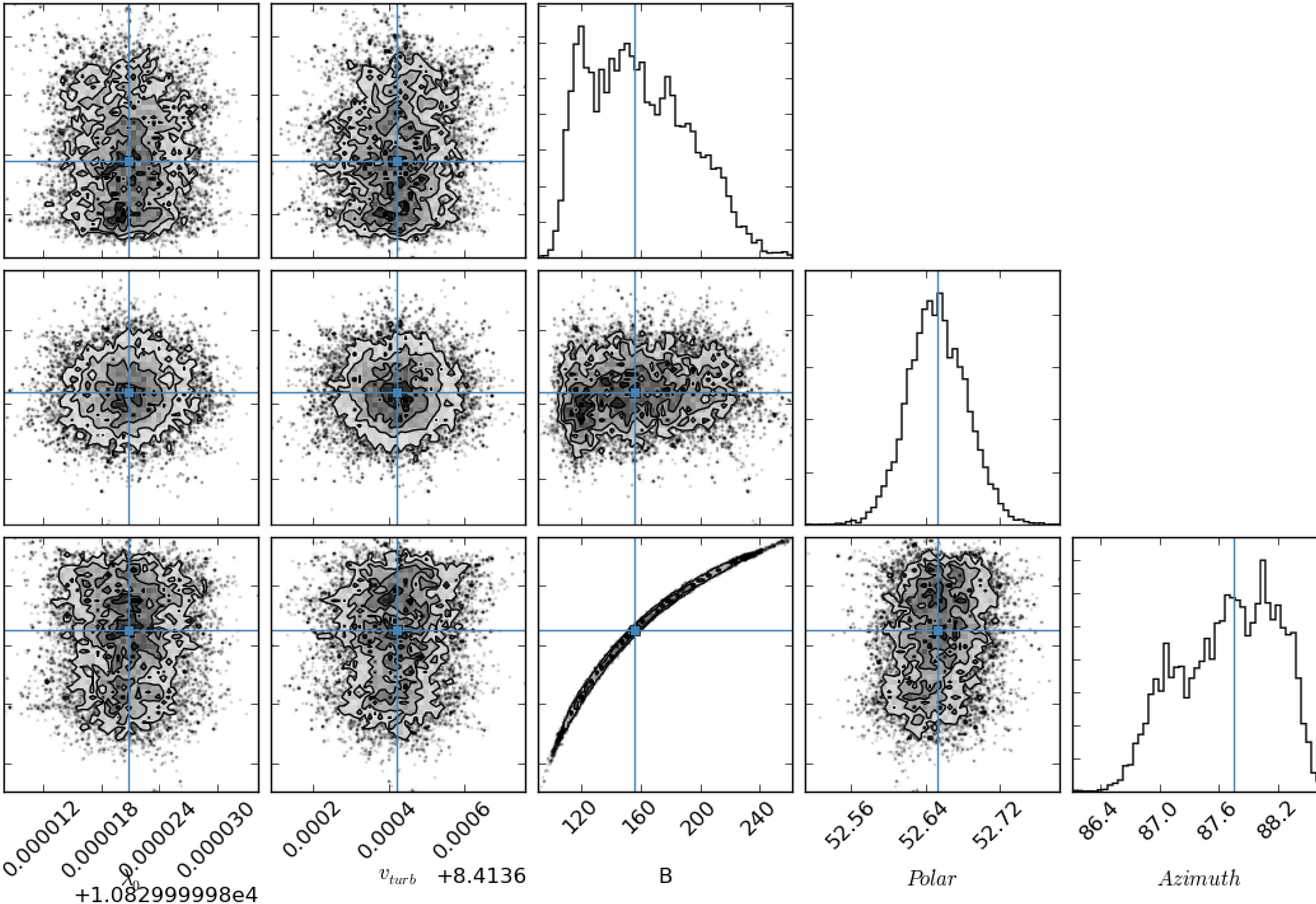
We make a toy model and investigate

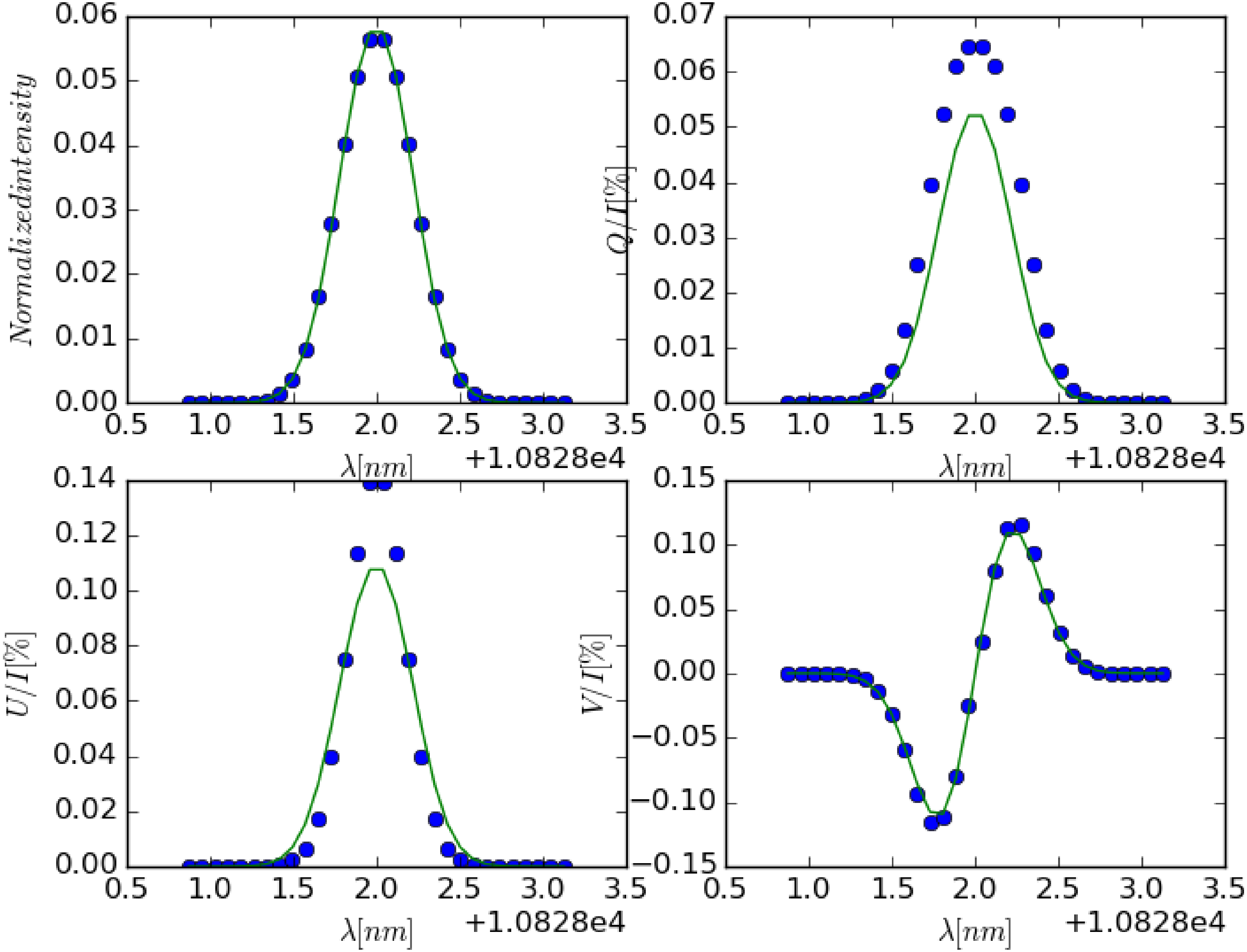


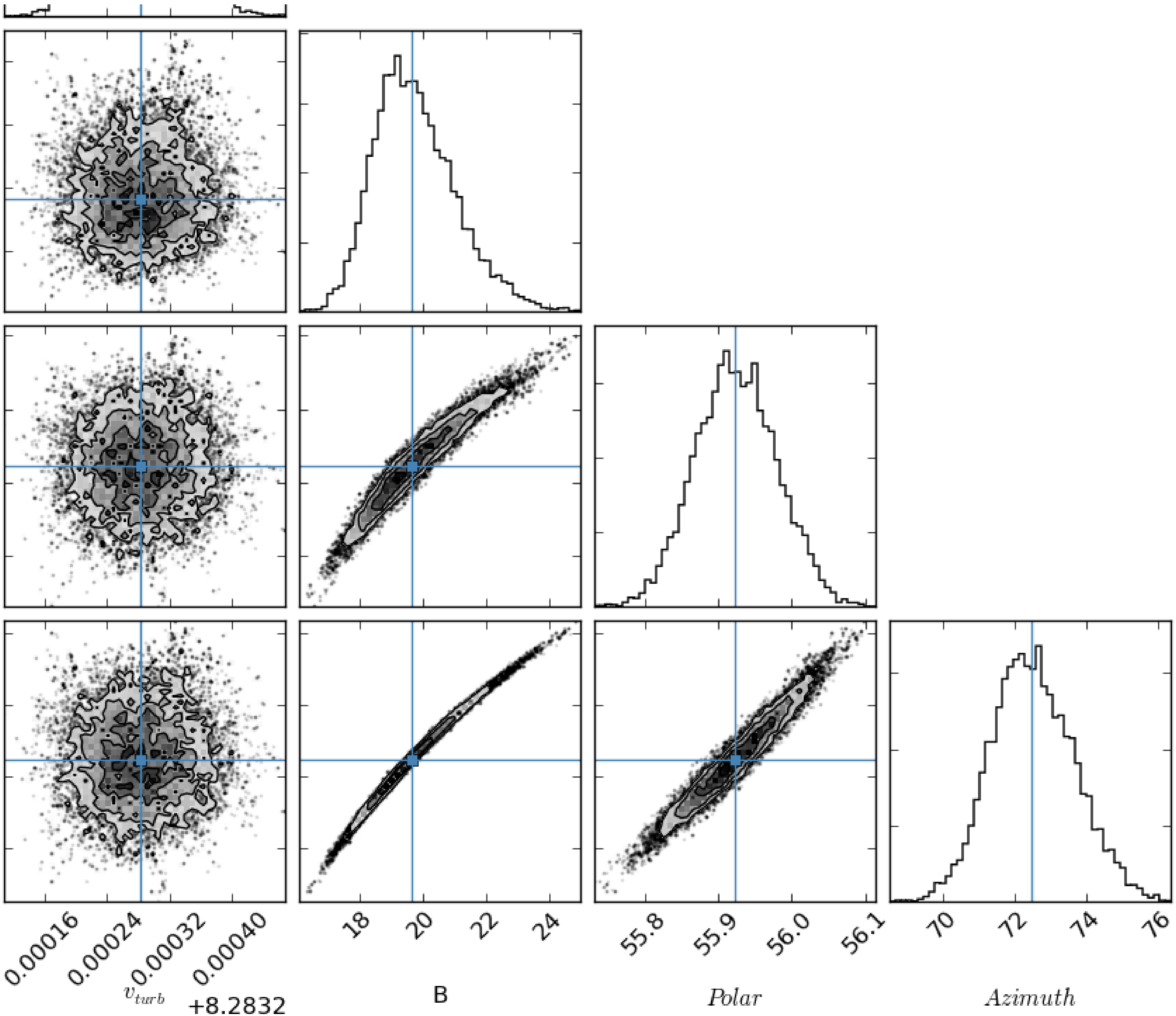
We make a toy model and investigate




+1.082999998e4
+8.4136
λ
v_{turb}
B
$Polar$
$Azimuth$
T +1.5706
+1.082999998e4
v_{turb} +8.4136


0.000012
0.000018
0.000024
0.000030
λ_0
+1.082999998e4
0.0002
0.0004
0.0006
v_{turb}
+8.4136
120
160
200
240
B
52.56
52.64
52.72
Polar
86.4
87.0
87.6
88.2
Azimuth


Normalizedintensity
Q/I[%]
U/I[%]
V/I[%]
λ[nm]
+1.0828e4


0.00016
0.00024
0.00032
0.00040
v_{turb}
+8.2832
18
20
22
24
B
55.8
55.9
56.0
56.1
Polar
70
72
74
76
Azimuth

Can this be remedied?

- Optically thin cases should not cause such problems.
- However, this might be really severe in other objects: spicules, filaments…
- *Is there a solution?*
- In principle, multidimensional inversion **is** possible, one should just describe the „communication“ between the pixels

Some more conclusions

- Inversions are probably the only way to gain quantitative information on atmospheric parameters
- However, they are ill-posed and far from direct measurement
- Extensive inference studies are hard because forward computation is expensive
- ANNs? ML? Catalogs from MHD simulations?