# Hale Collage

## Spectropolarimetric Diagnostic Techniques

Rebecca Centeno

*March 1 - 8, 2016*

# Degree of polarization

The degree of polarization is defined as: $p = \frac{Q^2 + U^2 + V^2}{I^2}$

In a purely absorptive medium (no emission): $\frac{d\vec{I}}{d\tau} = \mathbf{K}\vec{I}$

It can be demonstrated that:

- If $\eta_Q = \eta_U = \eta_V = 0$ unpolarized light remains unpolarized.
- If $\eta_I =$ constant, the degree of polarization, p, increases asymptotically.

Absorption and dispersion processes are non-depolarizing.
Depolarizing effects can only appear through emission processes.

# Today

- Symmetry properties of the Stokes profiles
  - Net Circular Polarization

- Longitudinal magnetograms

- Quiet Sun magnetic fields
  - Unsigned magnetic flux density
  - Effects of spatial resolution

- Shortcomings of the Zeeman effect

- Scattering polarization and the Hanle effect
  - Second solar spectrum

# Symmetry properties of the Stokes profiles

What happens to the propagation matrix when we do a change of variable: ($\lambda$ - $\lambda_0$) → ($\lambda_0$ - $\lambda$)?

$$\mathbf{K} = \begin{pmatrix} \eta_I & \eta_Q & \eta_U & \eta_V \\ \eta_Q & \eta_I & \rho_V & -\rho_U \\ \eta_U & -\rho_V & \eta_I & \rho_Q \\ \eta_V & \rho_U & -\rho_Q & \eta_I \end{pmatrix} \longrightarrow \mathbf{K}' = \begin{pmatrix} \eta_I & \eta_Q & \eta_U & -\eta_V \\ \eta_Q & \eta_I & \rho_V & \rho_U \\ \eta_U & -\rho_V & \eta_I & -\rho_Q \\ -\eta_V & -\rho_U & \rho_Q & \eta_I \end{pmatrix}$$

Zeeman shift

Voigt profile:

$$\phi_\alpha = \frac{1}{\sqrt{\pi}} \sum_i S_{\alpha,i} H(u_0 + u_{B,\alpha,i} - u_{LOS}, a)$$

central wavelength

LOS velocity

In the absence of velocity gradients, this transformation is a constant modification of **K** regarding the symmetry of wavelengths with respect to ($u_0$ - $u_{LOS}$).

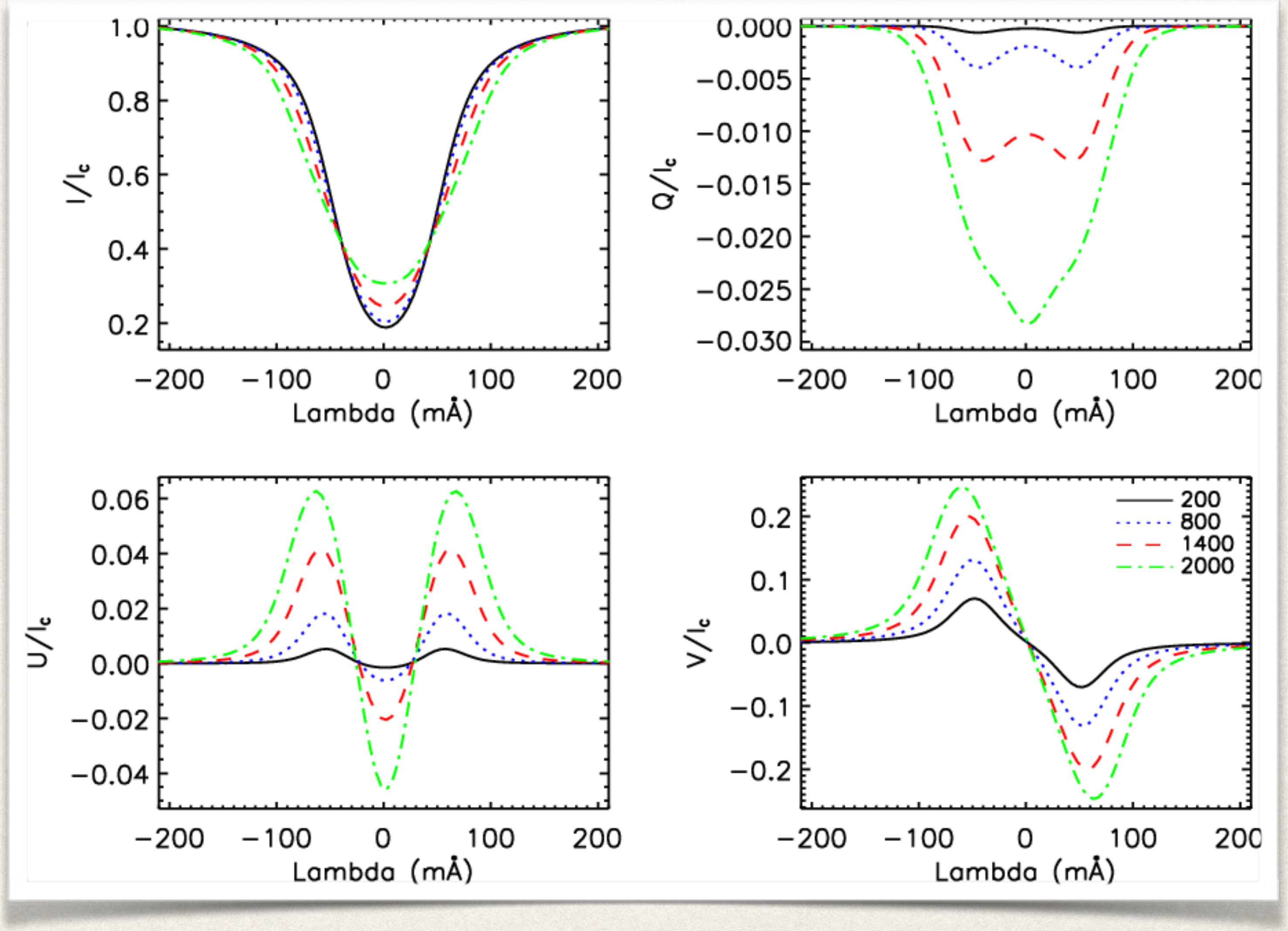
# Symmetry properties of the Stokes profiles

So the RTE transforms like this:

$$\frac{d}{d\tau_c}\vec{I}(\lambda-\lambda_0)=\mathbf{K}(\vec{I}(\lambda-\lambda_0)-\vec{S}) \longrightarrow \frac{d}{d\tau_c}\vec{I}(\lambda_0-\lambda)=\mathbf{K}'(\vec{I}(\lambda_0-\lambda)-\vec{S})$$

$$\boxed{\begin{aligned}I(\lambda_0-\lambda)&=I(\lambda-\lambda_0)\\Q(\lambda_0-\lambda)&=Q(\lambda-\lambda_0)\\U(\lambda_0-\lambda)&=U(\lambda-\lambda_0)\\V(\lambda_0-\lambda)&=-V(\lambda-\lambda_0)\end{aligned}}$$

Stokes I, Q and U are *symmetric* with respect to their central wavelength, while Stokes V is *antisymmetric*.



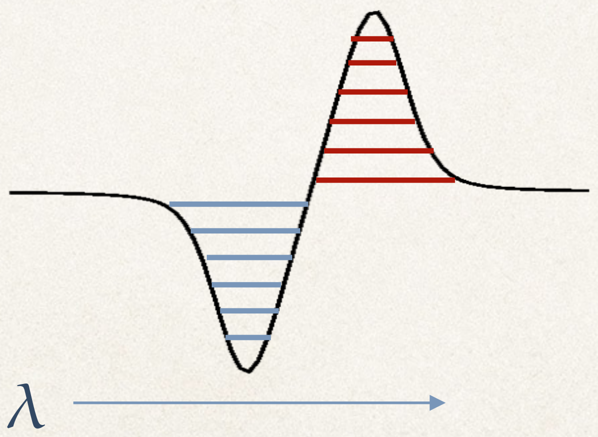
from Orozco Suarez et al, 2006

# Net Circular Polarization

Net circular polarization: integral of Stokes V over the wavelength span (W) of the spectral line

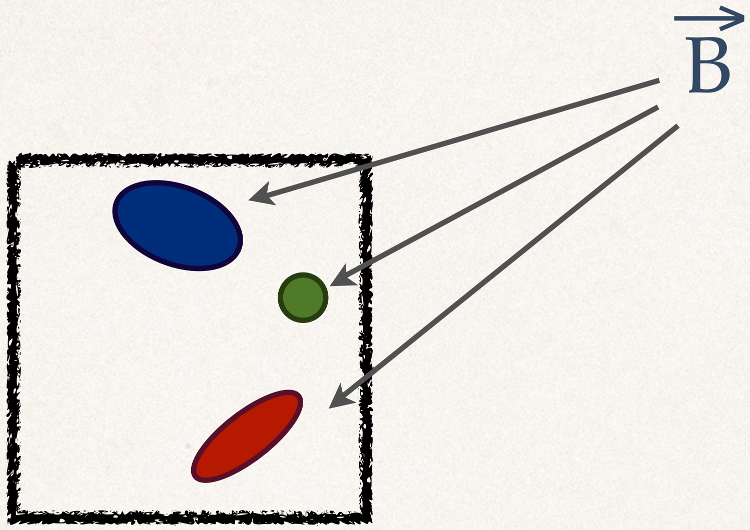
$$\mathrm{NCP} = \int_W V_{\mathrm{obs}}(\lambda)d\lambda$$

It is zero in the absence of velocity gradients!



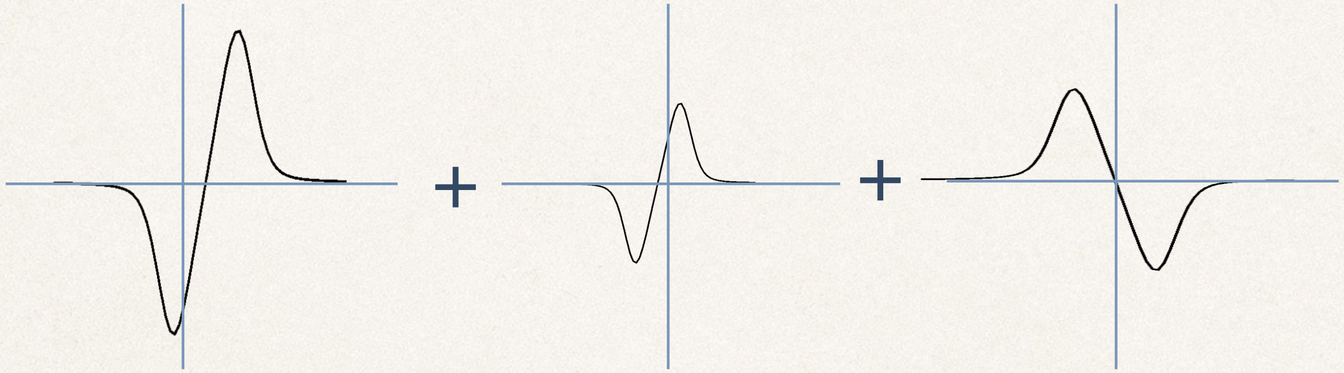
blue - red = 0

# Net Circular Polarization



resolution element

A fraction of the pixel is non-magnetic: no contribution to Stokes V

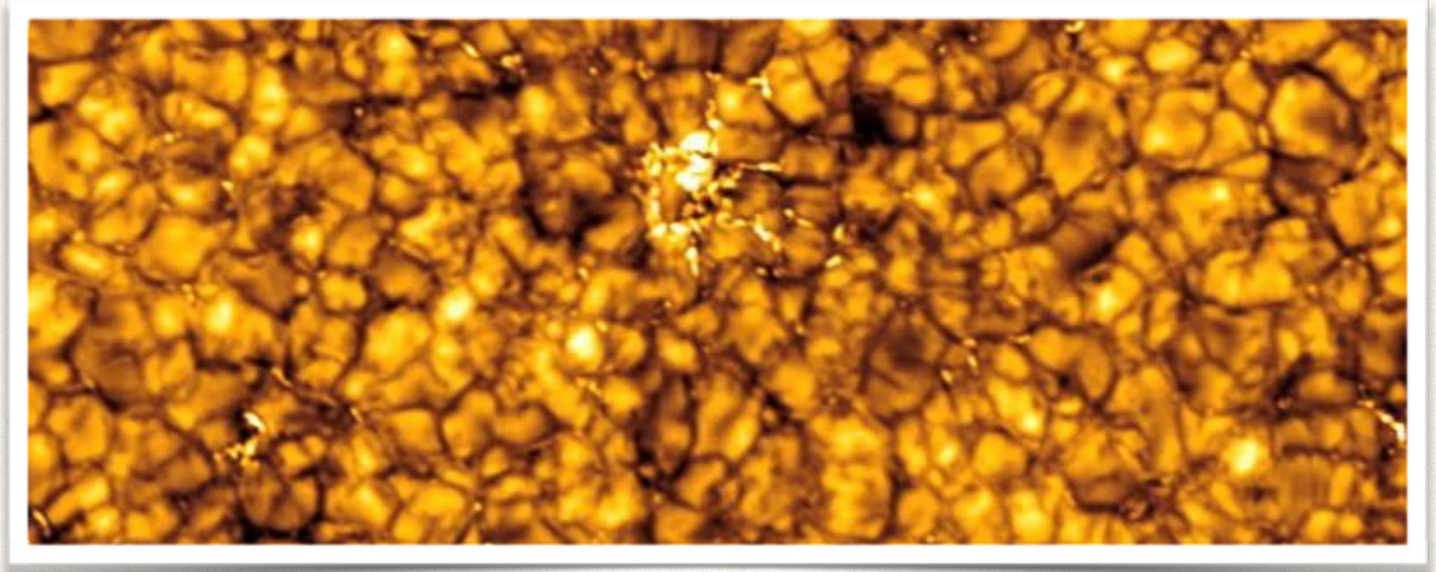


= asymmetric

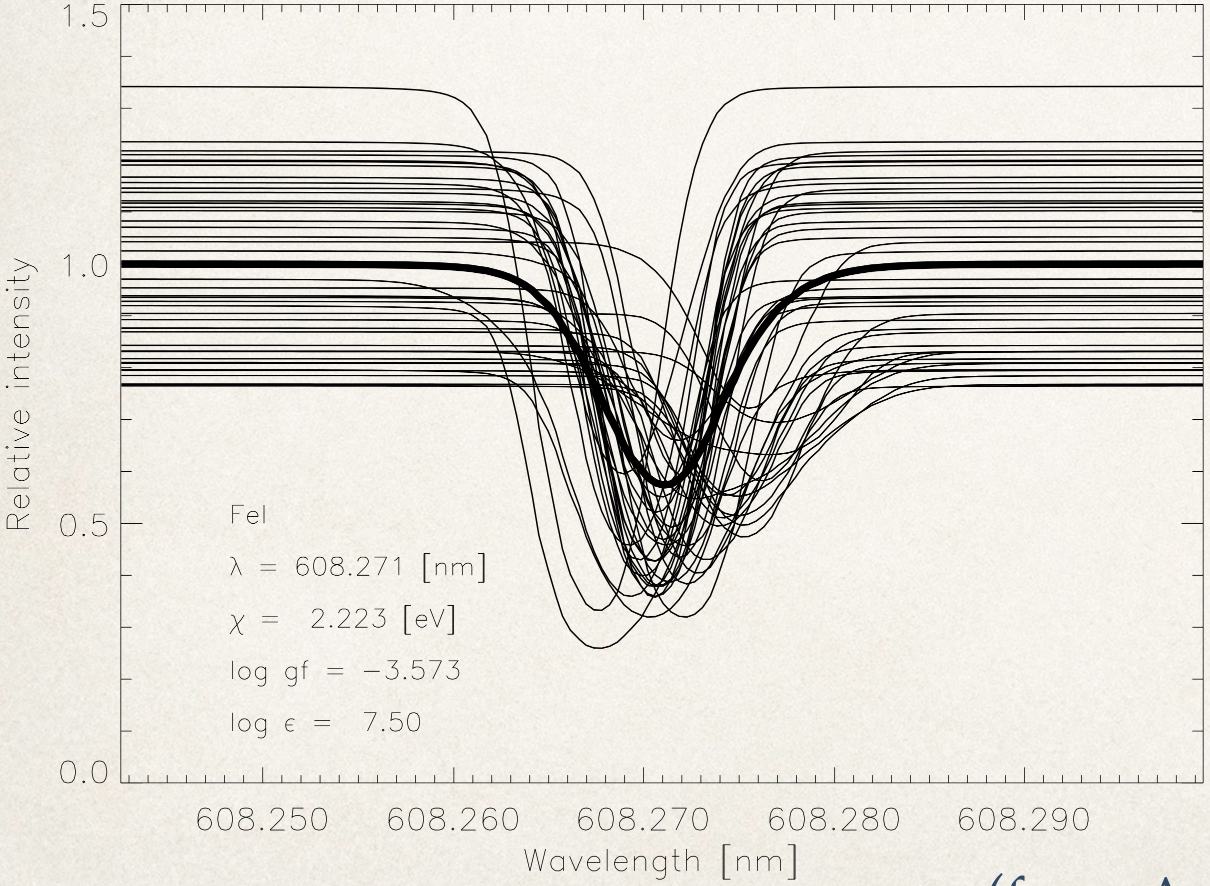
A fraction of the pixel is magnetized, with different field strengths, spatial extensions, plasma velocities… If we assume no velocity gradients, each Stokes V is still antisymmetric, but the sum might not.

However, the total NCP = 0!

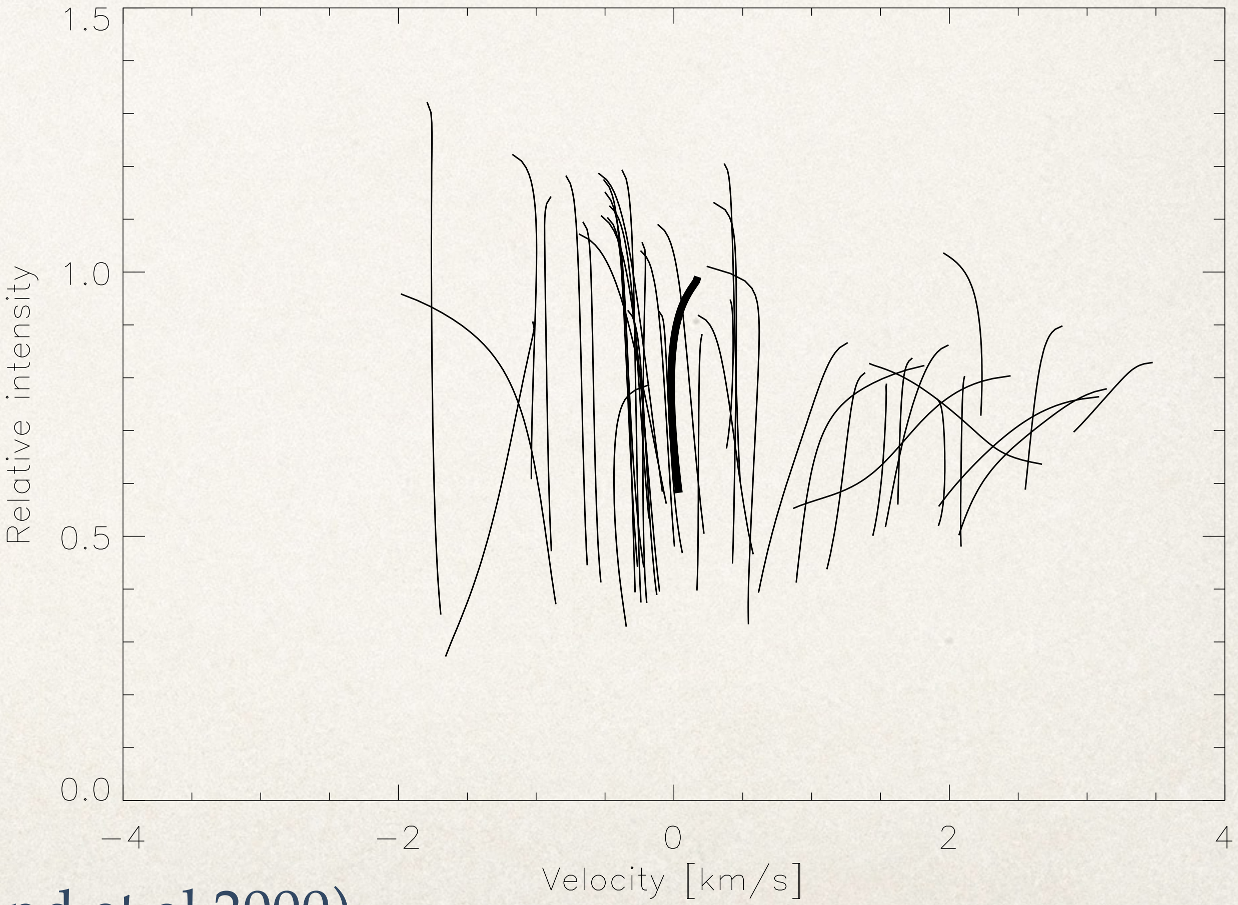
# Line Bisectors and Convective Blueshift



line profiles



bisectors

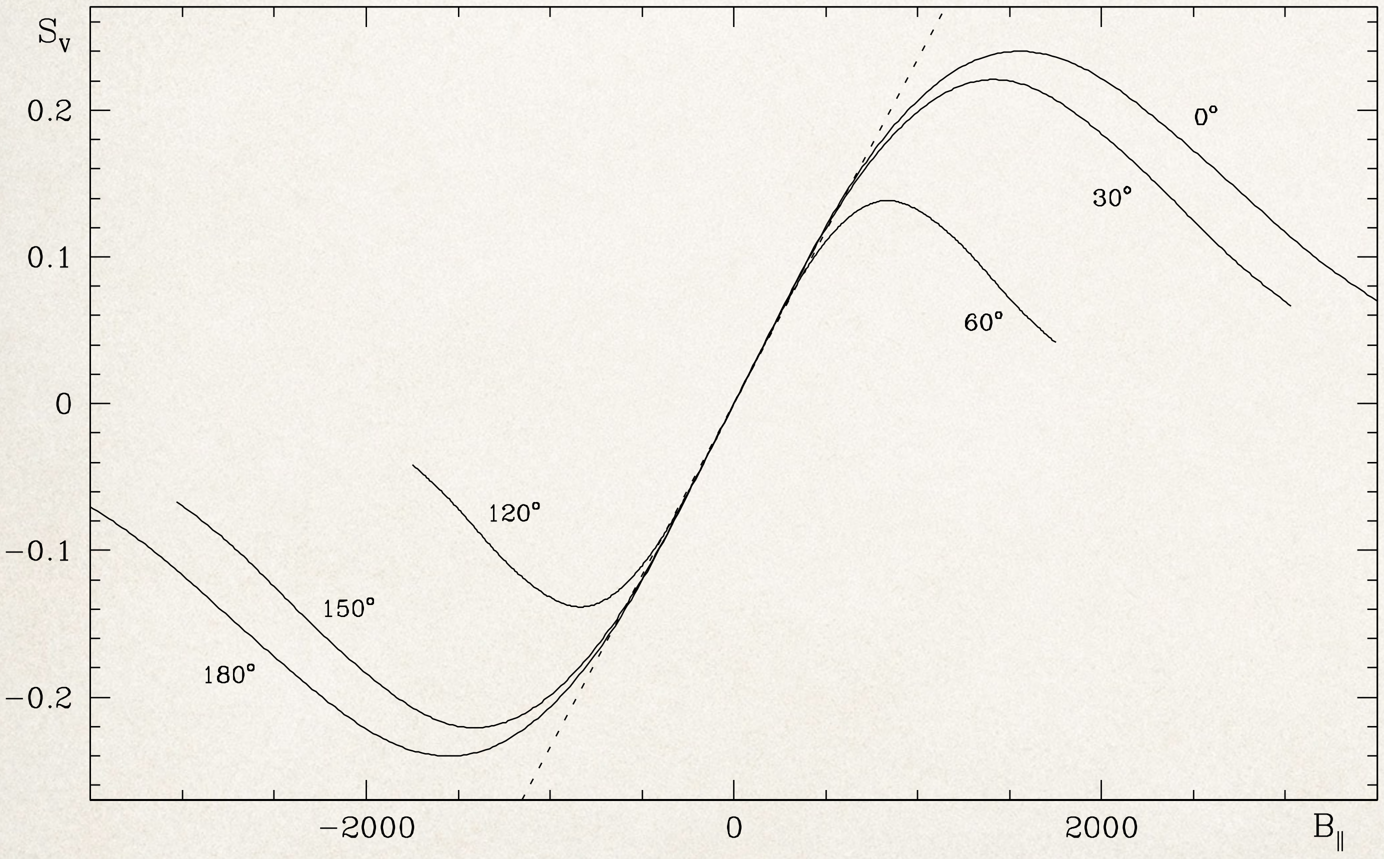


(from Asplund et al 2000)

# Longitudinal magnetograms

Based on the weak-field approximation:

$$V(\lambda) = -C g_{\mathrm{eff}} \overset{\text{BLOS}}{\boxed{B \cos\theta}} \frac{\partial I(\lambda)}{\partial \lambda}$$



Magnetograph signal as a function of BLOS strength and inclination angle for a spectral line with geff = 2.5.

From Landi Degl'Innocenti & Landolfi "Polarization in spectral lines"

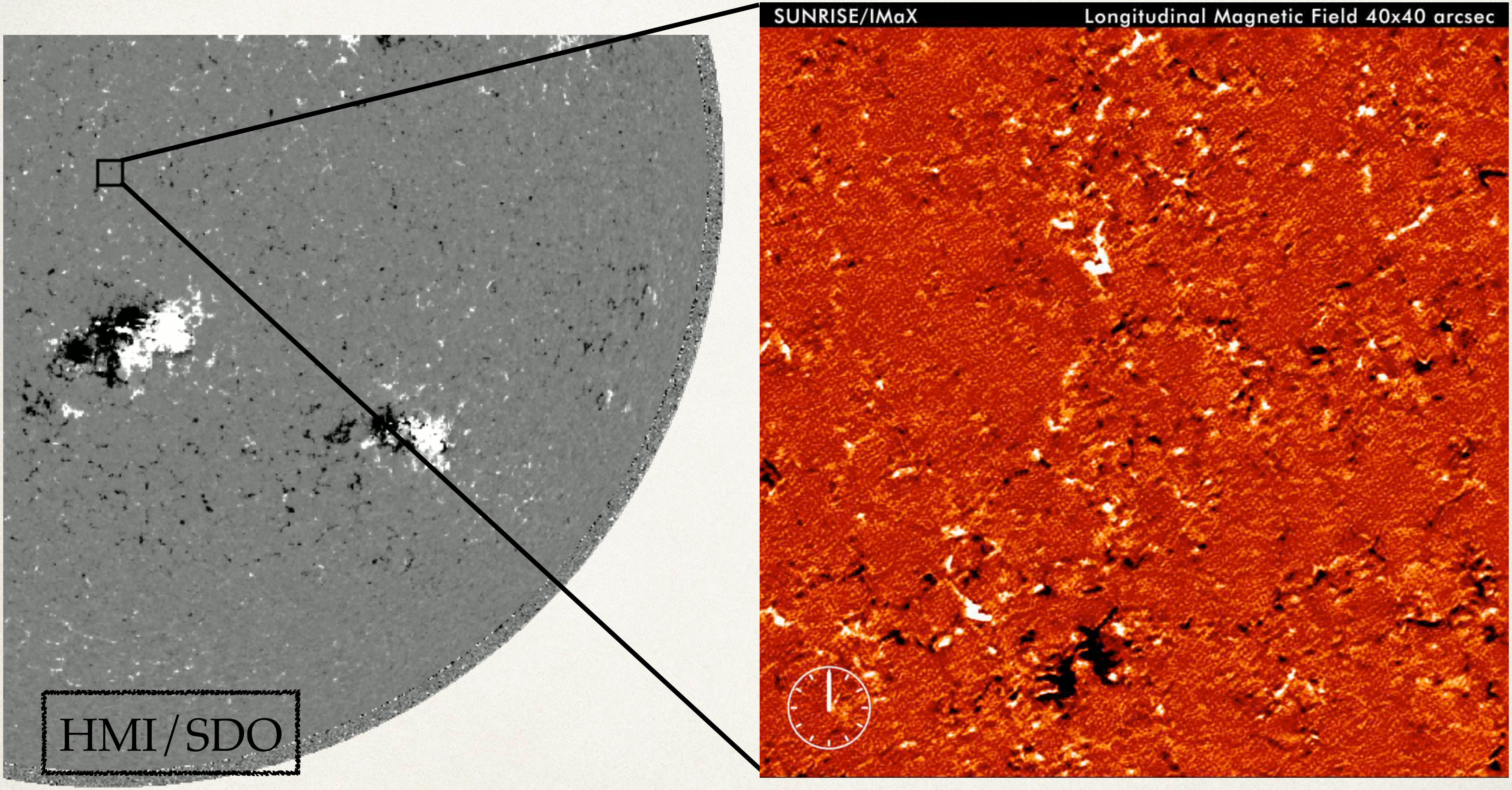
# Longitudinal magnetograms

- Only valid for weak fields (no effect on Stokes I)
- Assumes magnetic field has no gradients along LOS
- Only gives the component of the magnetic field along the LOS

Yet line-of-sight magnetograms are by far the most popular measurement of magnetic fields in Solar Physics.

Magnetograms give us the **net longitudinal** component of the magnetic field, $B_z$, averaged over each resolution element.

# Quiet Sun magnetic fields



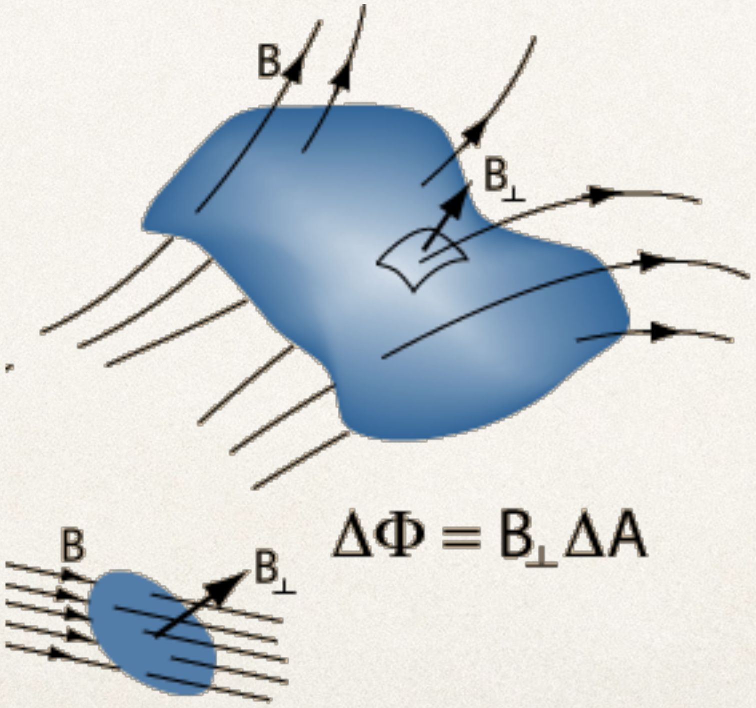
(IMaX - SUNRISE, courtesy of V. Martínez Pillet)

# Unsigned magnetic flux density

The unsigned magnetic flux density:

$$\phi_{\mathrm{B}} = \frac{\int_A |\mathrm{B_z}| dA}{\int_A dA}$$

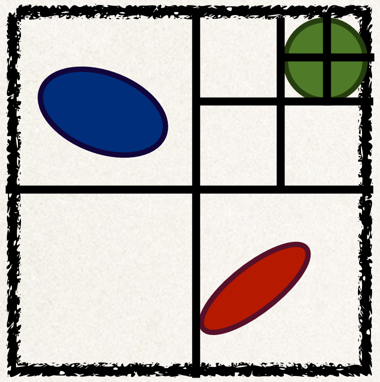
$\mathrm{B_z}$ = component of the magnetic field vector projected along the LOS.



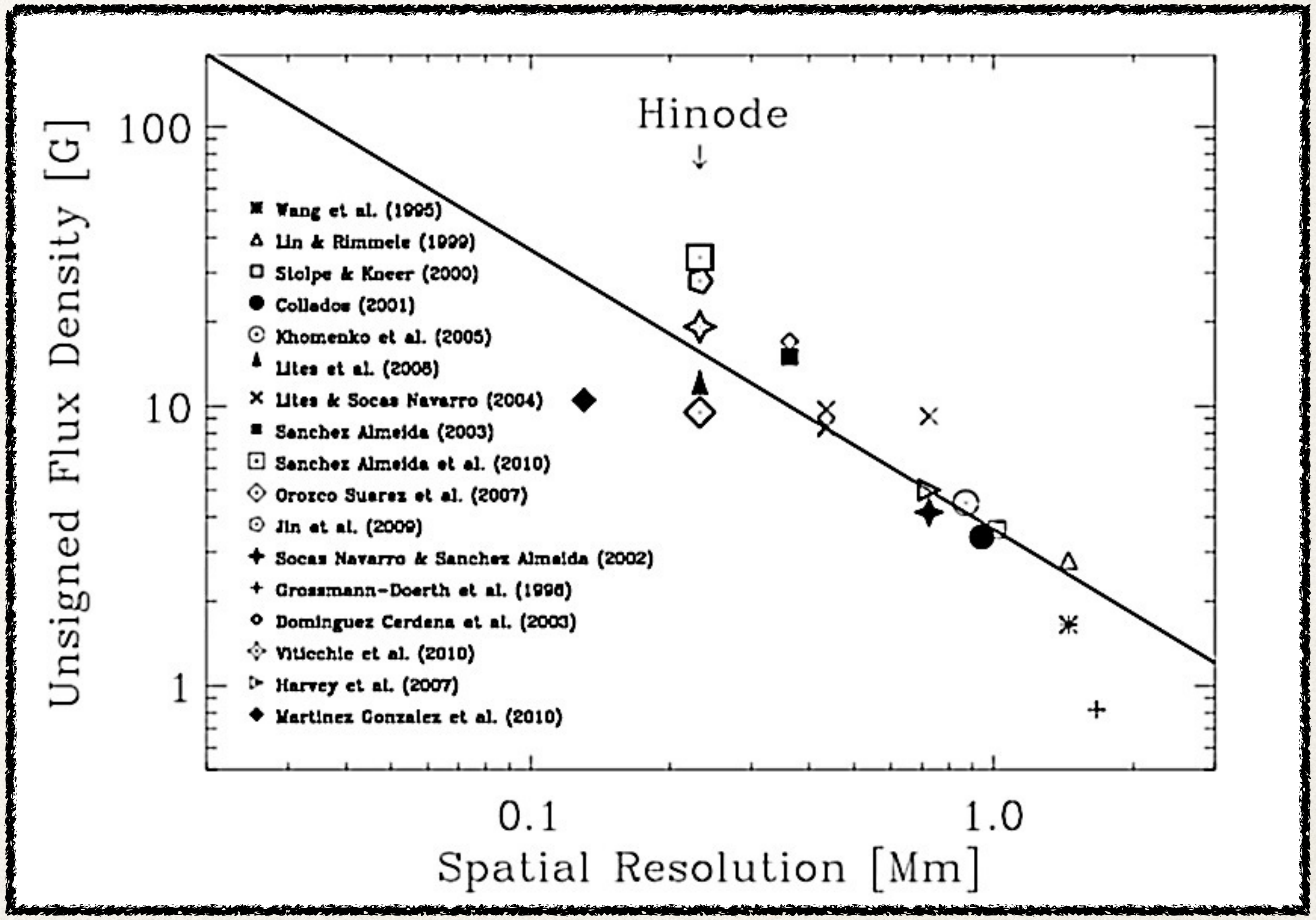
In general:
$\mathrm{B_z} \neq \mathrm{B_{radial}}$

# Effects of spatial resolution on Quiet Sun magnetic fields

How do measurements of unsigned magnetic flux change with increasing spatial resolution?



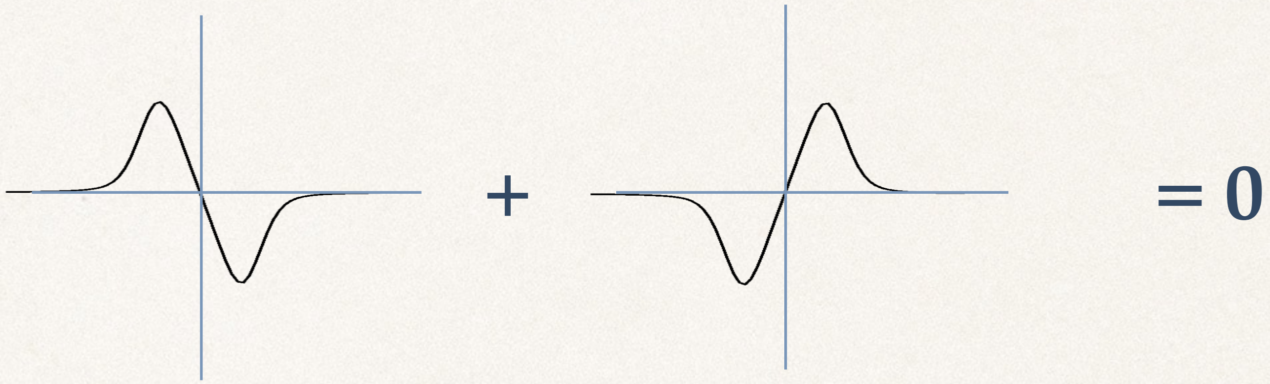
resolution element



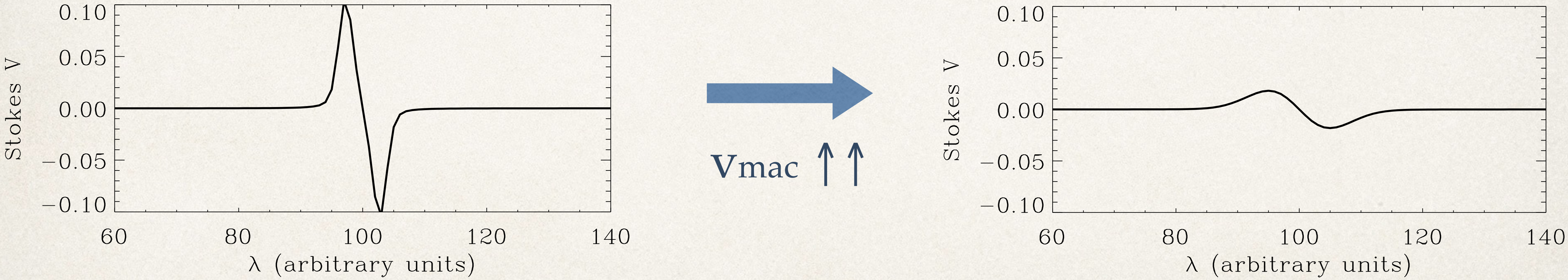
(from Sánchez Almeida & Martínez González 2011)

# Shortcomings of the Zeeman Effect

The Zeeman Effect polarization signals cancel out when tangled magnetic fields are present at sub-pixel spatial scales.



Very weak magnetic fields do not produce measurable magnetic signals (when the Zeeman splitting is much smaller than the width of the spectral line).



$B = 100$ G, $\theta = 0$ deg

# Shortcomings of the Zeeman Effect

There is a 180 degree azimuth ambiguity, in the plane perpendicular to the LOS.

$$\eta_Q = \frac{\eta_0}{2}\{\phi_0 - \frac{1}{2}[\phi_{+1} + \phi_{-1}] sin^2\theta cos2\phi\}$$

$$\eta_U = \frac{\eta_0}{2}\{\phi_0 - \frac{1}{2}[\phi_{+1} + \phi_{-1}] sin^2\theta sin2\phi\}$$

When converting from LOS into a solar reference frame:

Anywhere but at disk center:

The azimuth ambiguity in the LOS reference frame translates into an inclination (with respect to the solar radial direction) and an azimuth ambiguity in the local solar frame.

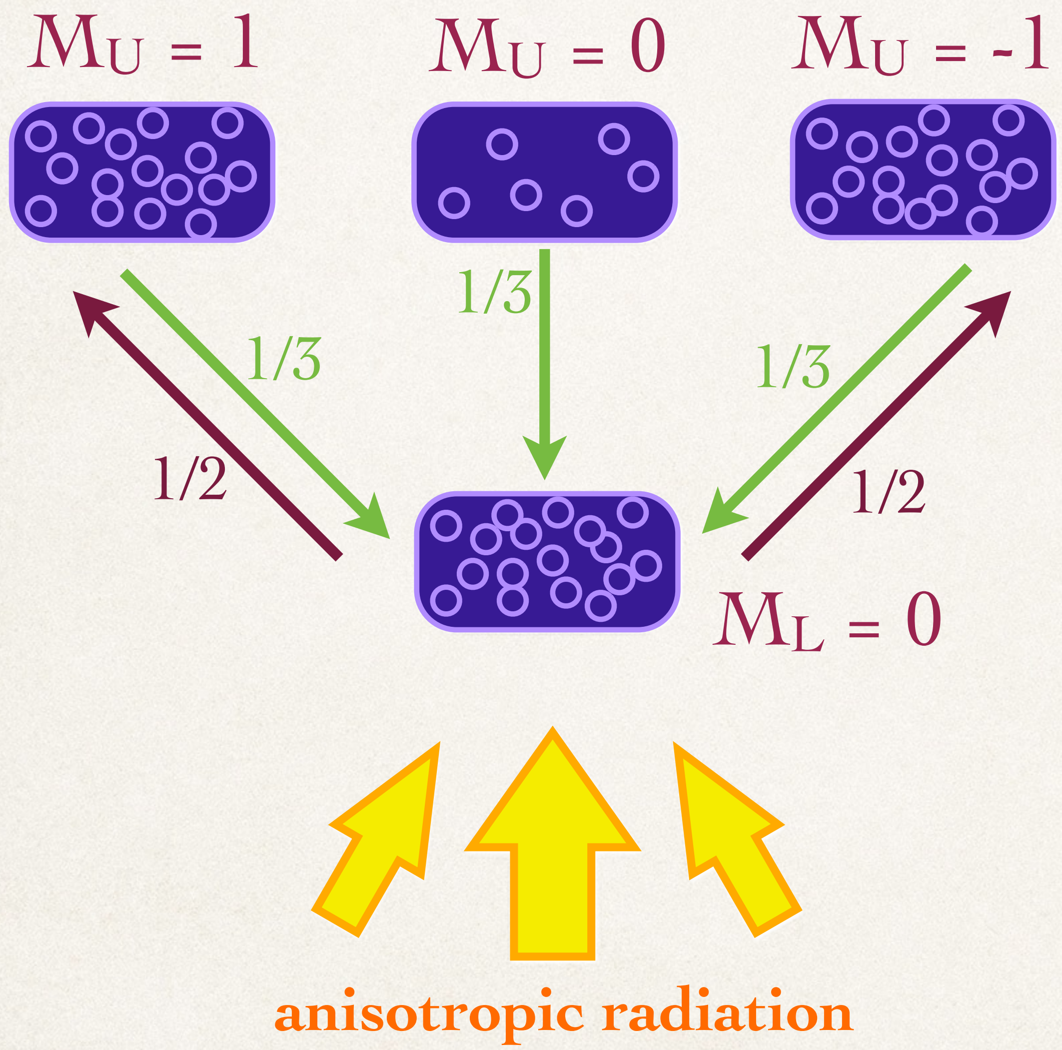
Disambiguation methods are based on continuity and minimizing currents.

# Mechanisms that produce polarization in spectral lines

- Anisotropy in the excitation mechanism of the atom
    - Impact polarization
    - Optical pumping
- External field breaking the axis of symmetry
    - Electric field
    - Magnetic field

# Atomic polarization

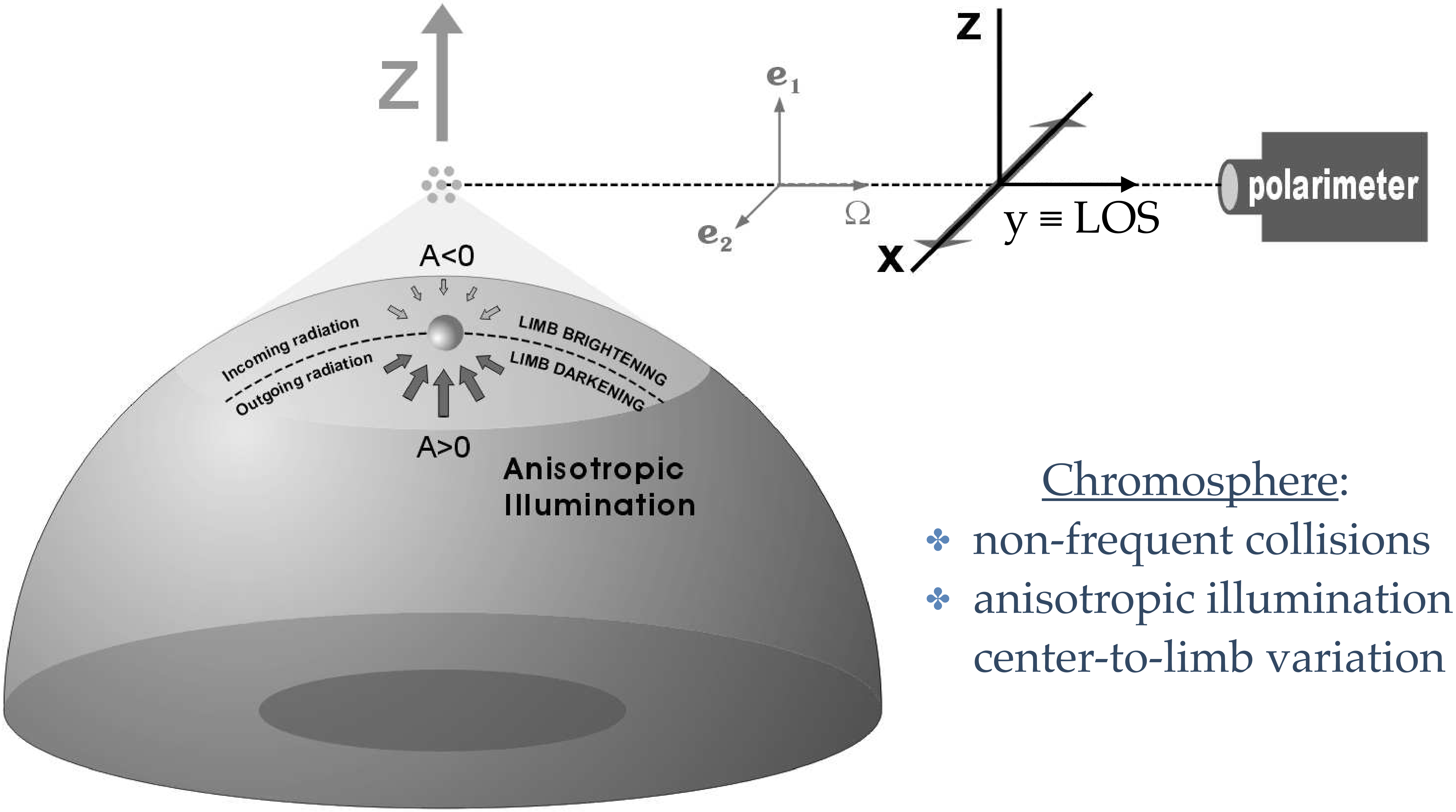
$$\eta_Q = \frac{\eta_0}{2}\{\overset{\overset{w_\pi}{\downarrow}}{\phi_0} - \frac{1}{2}[\overset{\overset{w_R}{\downarrow}}{\phi_{+1}} + \overset{\overset{w_B}{\downarrow}}{\phi_{-1}}]sin^2\theta cos2\phi\}$$



If the number of π-transitions does not "compensate" the number of σ-transitions per unit volume and time, we will get a linear polarization signal.

Anisotropic illumination induces population imbalances between the magnetic energy sub-levels of an atom.

# Atomic polarization

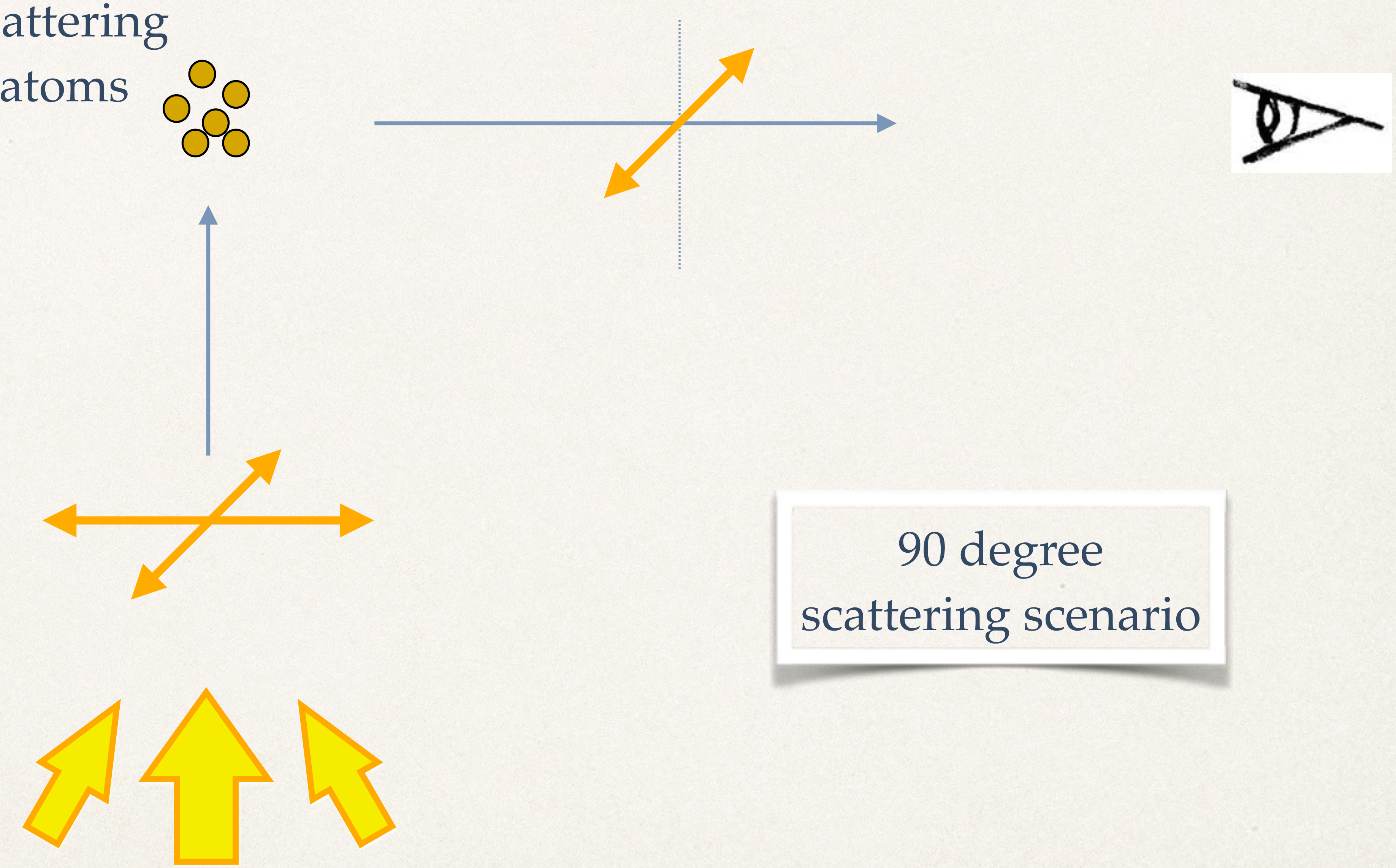


Chromosphere:

- non-frequent collisions
- anisotropic illumination: center-to-limb variation

(from Trujillo Bueno 2006)

# Atomic polarization



linearly polarized radiation

scattering atoms

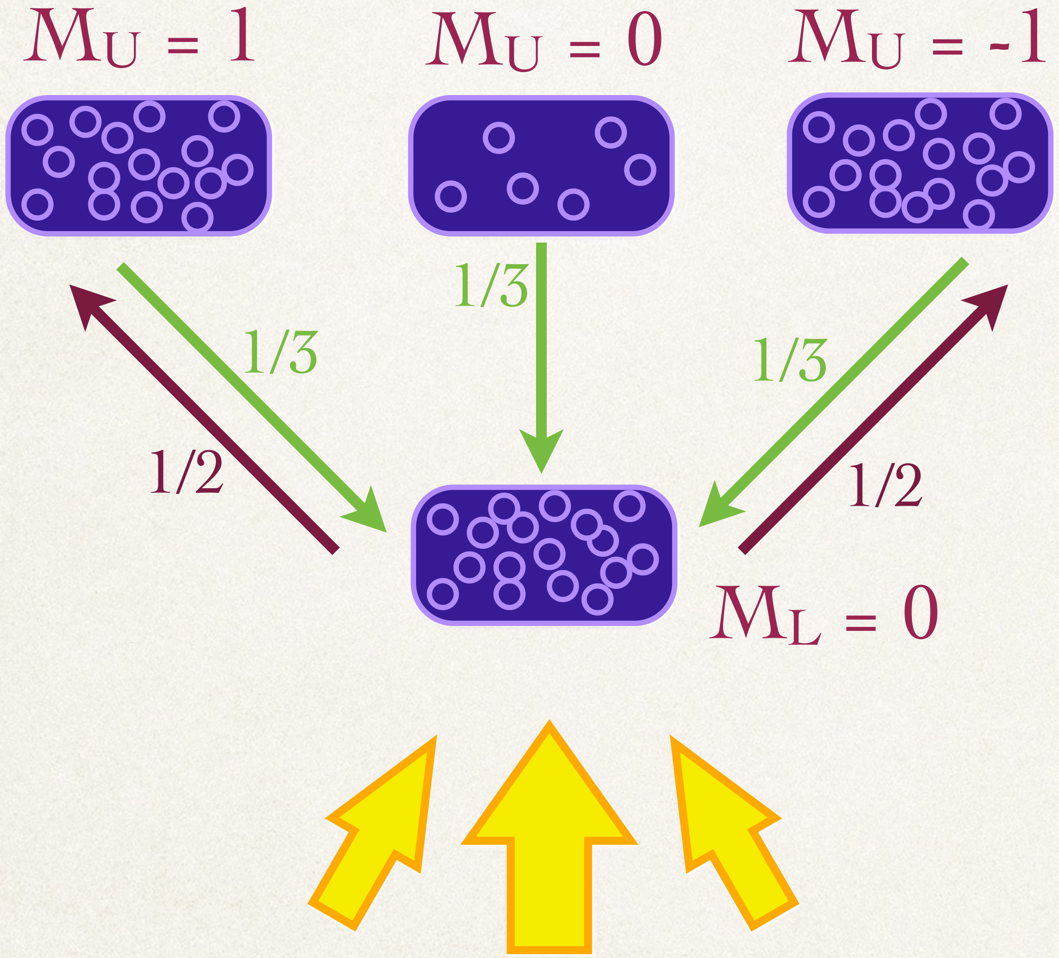
unpolarized radiation

90 degree scattering scenario

**anisotropic radiation**

# Atomic polarization

$$\eta_Q = \frac{\eta_0}{2}\{\overset{\overset{w_\pi}{\downarrow}}{\phi_0} - \frac{1}{2}[\overset{\overset{w_R}{\downarrow}}{\phi_{+1}} + \overset{\overset{w_B}{\downarrow}}{\phi_{-1}}] sin^2\theta cos2\phi\}$$



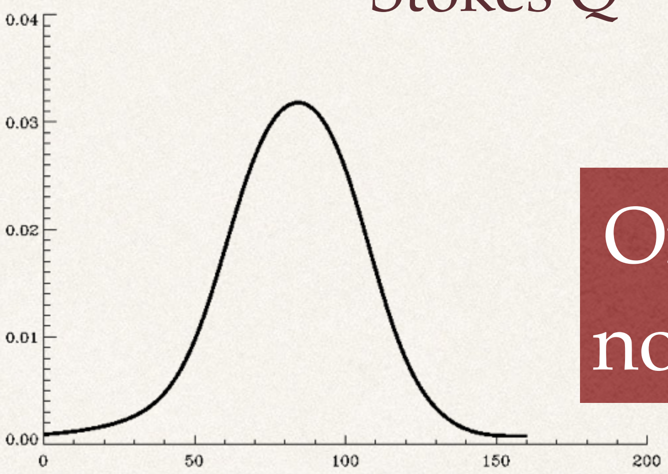
$M_U = 1$ $M_U = 0$ $M_U = -1$

$M_L = 0$

**anisotropic radiation**

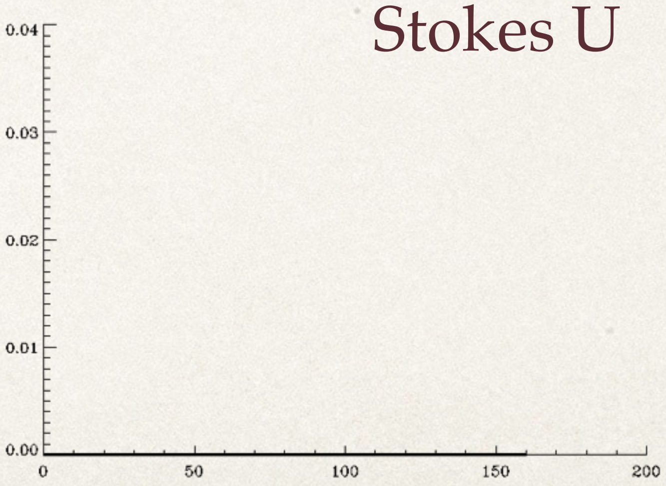
**B = 0**

Stokes Q

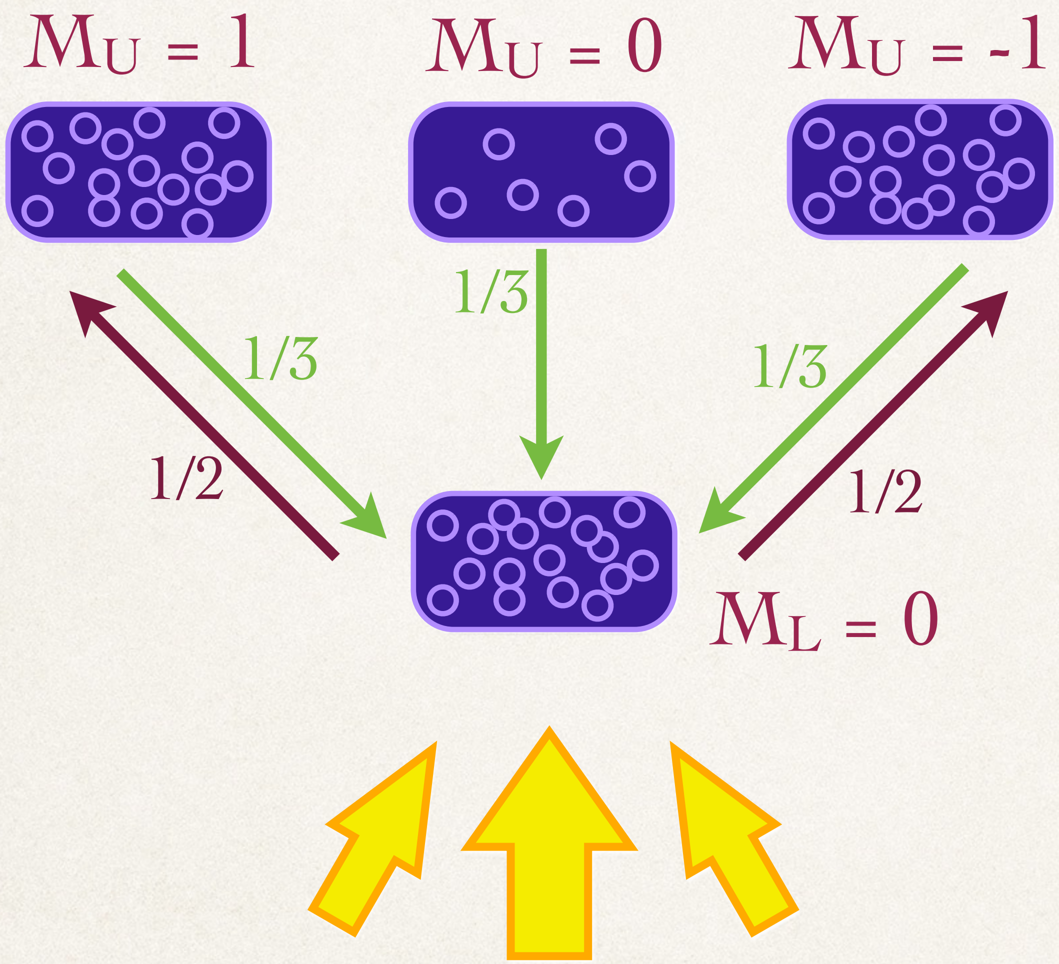


One lobe, not three!!

Stokes U



# Atomic polarization and the Hanle Effect



$M_U = 1$

$M_U = 0$

$M_U = -1$

1/3

1/3

1/3

1/2

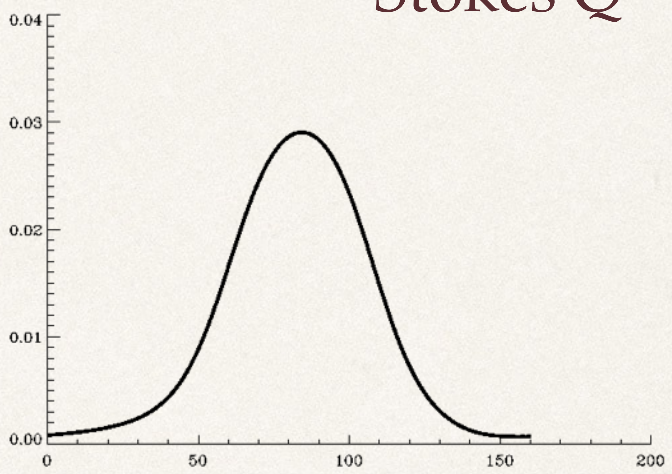
1/2

$M_L = 0$

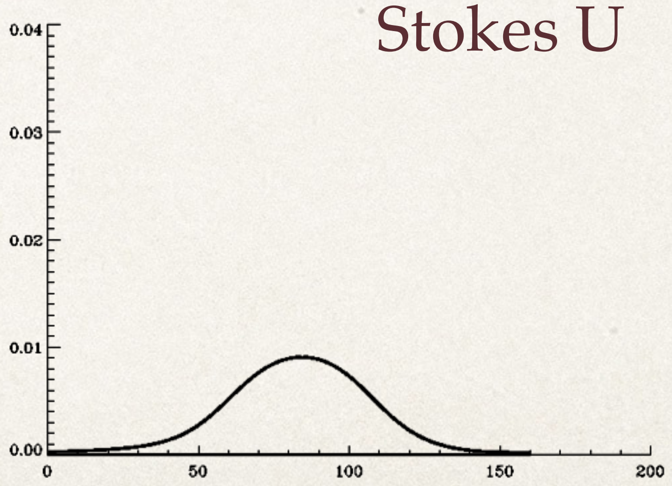
**anisotropic radiation**

**B ≠ 0 and inclined with respect to the axis of symmetry of the radiation**

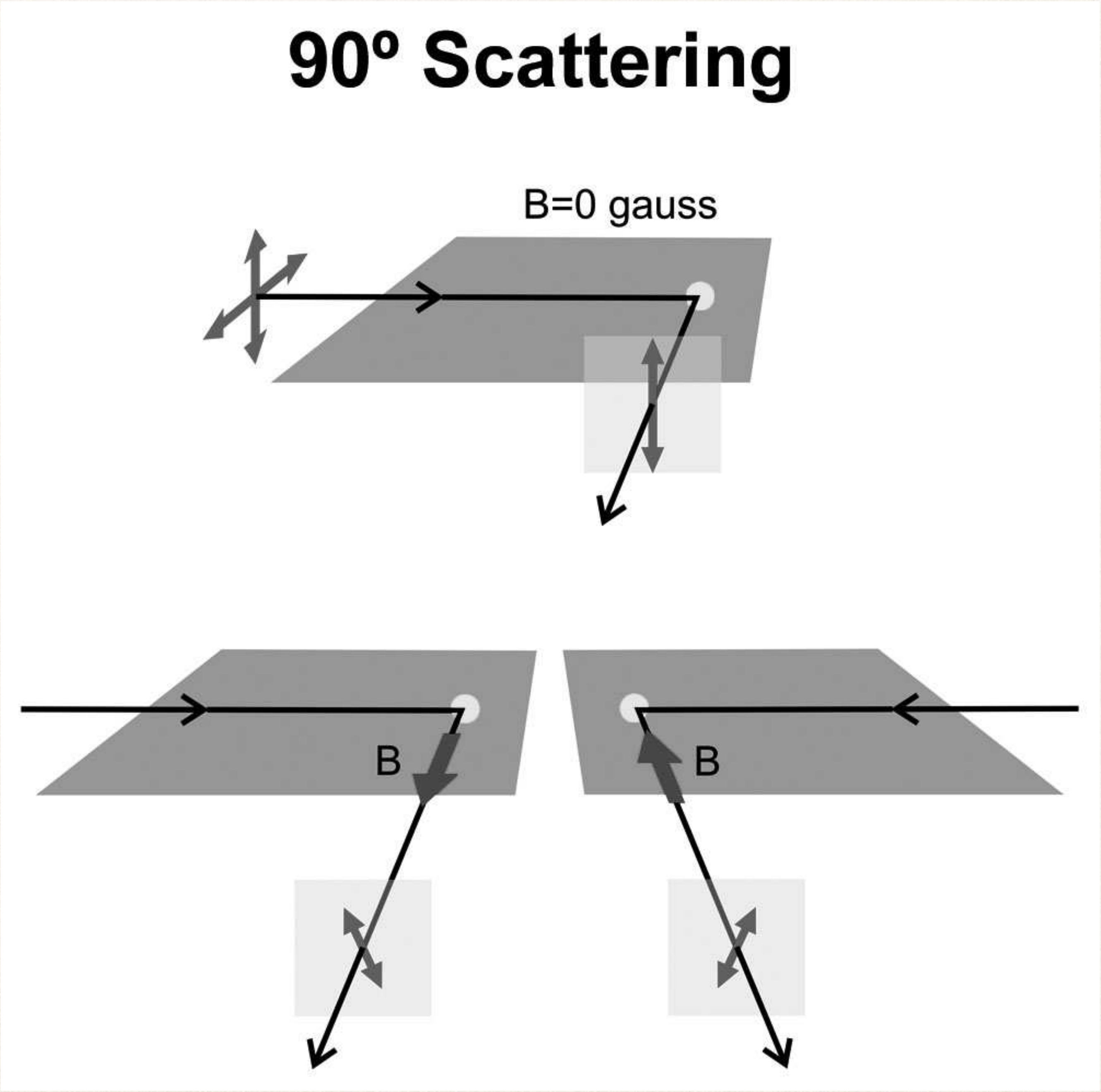
Stokes Q



Stokes U



# Atomic polarization and the Hanle Effect



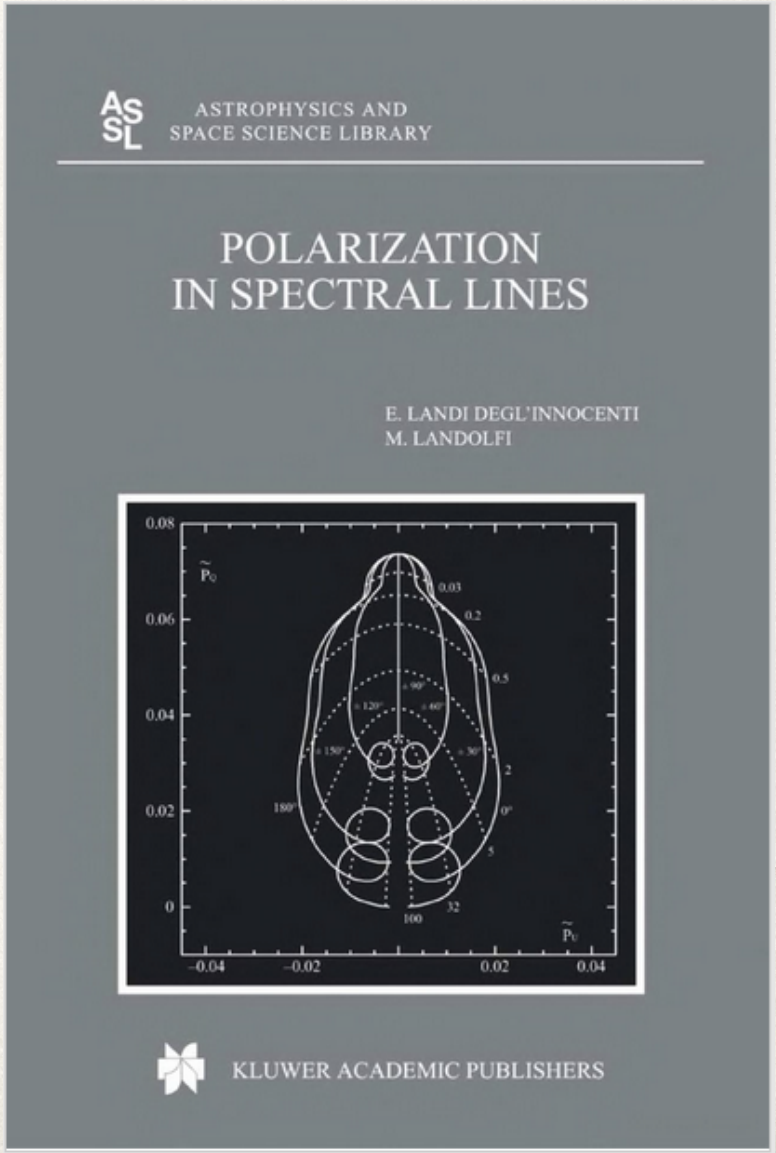
(from Trujillo Bueno, 2006)

# Atomic polarization and the Hanle Effect

The Hanle Effect can be sensitive to very weak magnetic fields, depending on the spectral line (from milligauss to hectogauss).

$$B_H = 1.137 \times 10^{-7} / (t_{\rm life}\, g_J)$$

It is also sensitive to tangled magnetic fields at sub-pixel scales, so it doesn't cancel out as the Zeeman polarization signals would.



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POLARIZATION
IN SPECTRAL LINES

E. LANDI DEGL'INNOCENTI
M. LANDOLFI

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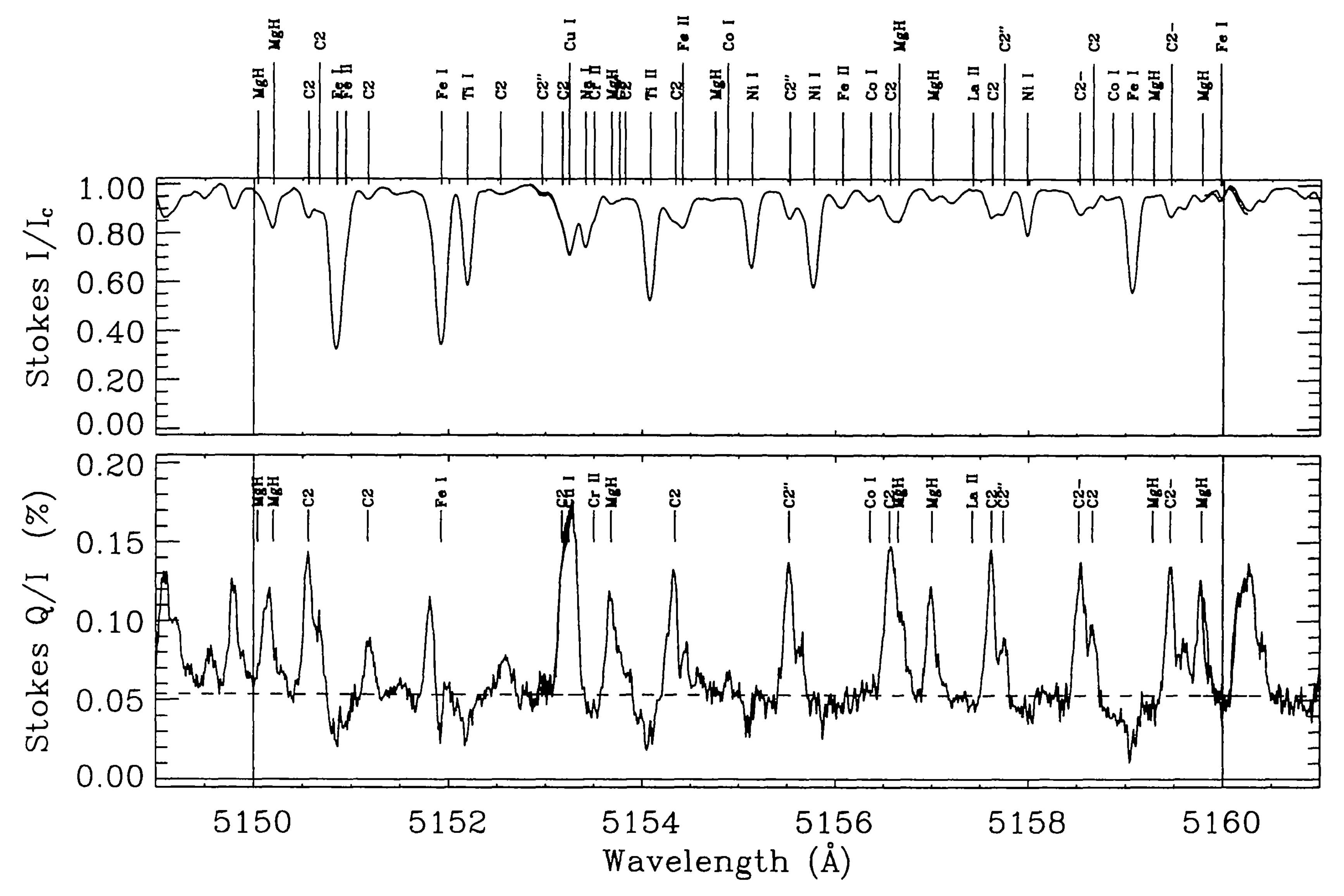
Hanle techniques suffer from a saturation effect, so there is an upper limit for the magnetic field strength sensitivity.

It has to be treated within the frame of the quantum theory of polarization.

# The Second Solar Spectrum



(Gandorfer, 2001)

# Next time

- Simple solutions to the RTE
  - Milne-Eddington approximation
  - LTE approximation

- The general inversion problem

- Spectral line inversion algorithms
  - Levenberg-Marquardt techniques
  - Principal Component Analysis