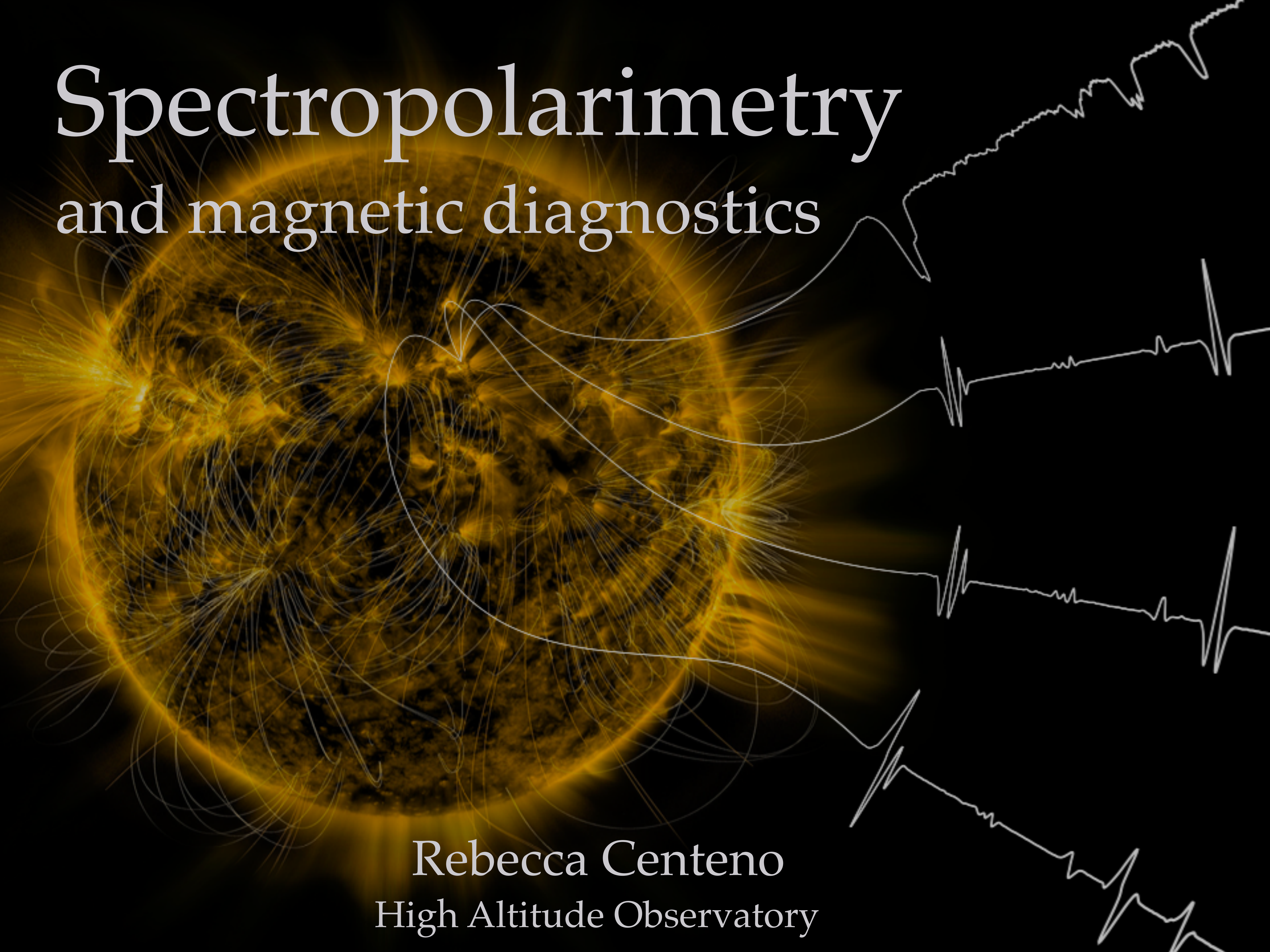
Spectropolarimetry

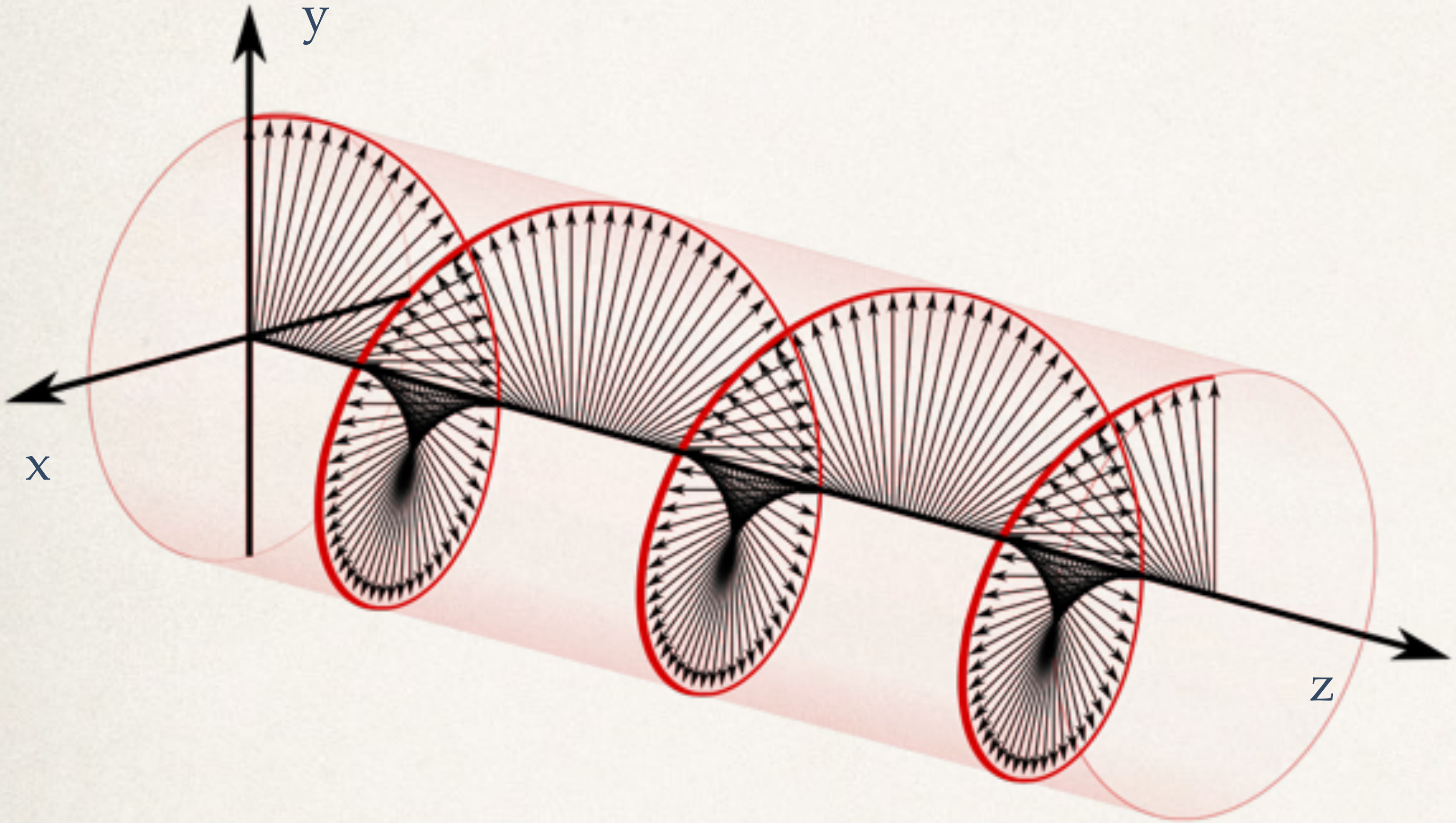
and magnetic diagnostics



Rebecca Centeno

High Altitude Observatory

Polarization of light



$$E_x(t) = \varepsilon_x(t)\, e^{i\delta_{x(t)}}\, e^{-2\pi i\nu_0 t}$$

$$E_y(t) = \varepsilon_y(t)\, e^{i\delta_{y(t)}}\, e^{-2\pi i\nu_0 t}$$

$$\boxed{\begin{aligned}
I &= \kappa\,(\langle\varepsilon_x{}^2\rangle+\langle\varepsilon_y{}^2\rangle)\\
Q &= \kappa\,(\langle\varepsilon_x{}^2\rangle-\langle\varepsilon_y{}^2\rangle)\\
U &= 2\kappa\,\langle\varepsilon_x\,\varepsilon_y \cos\delta(t)\rangle\\
V &= 2\kappa\,\langle\varepsilon_x\,\varepsilon_y \sin\delta(t)\rangle
\end{aligned}}$$

where $\delta(t) = \delta_x(t) - \delta_y(t)$

Stokes Parameters:

Spectropolarimetry

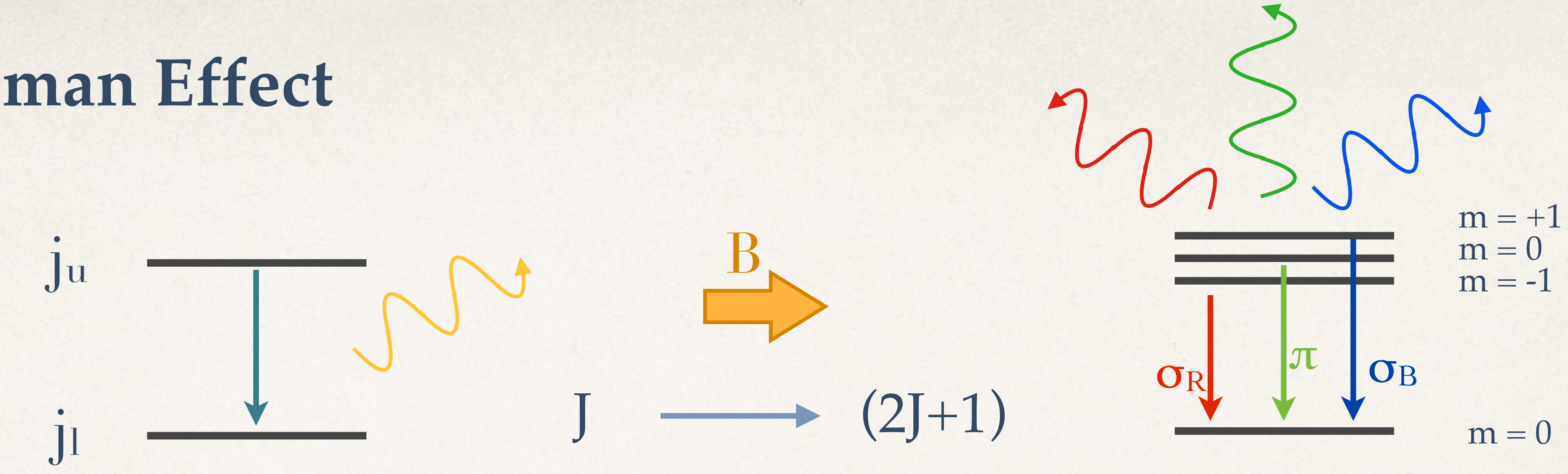
Spectropolarimetry **is the measurement of the distribution of energy and polarization of light as a function of frequency**

It is an incredibly powerful tool for **remote sensing** of **magnetic fields** in the Sun's atmosphere!

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

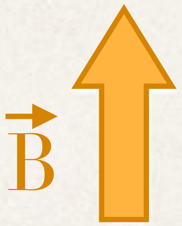
Zeeman Effect



$$\Delta\lambda_B = (m_l\, g_l - m_u\, g_u)\, \lambda_B$$

where: $\boxed{\lambda_B = 4.67 \times 10^{-13}\, \lambda_0^2\, B}$

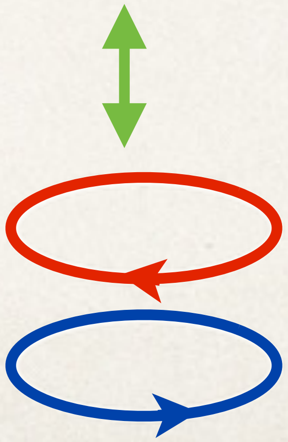
B (gauss), λ_0 and λ_B (angstroms)



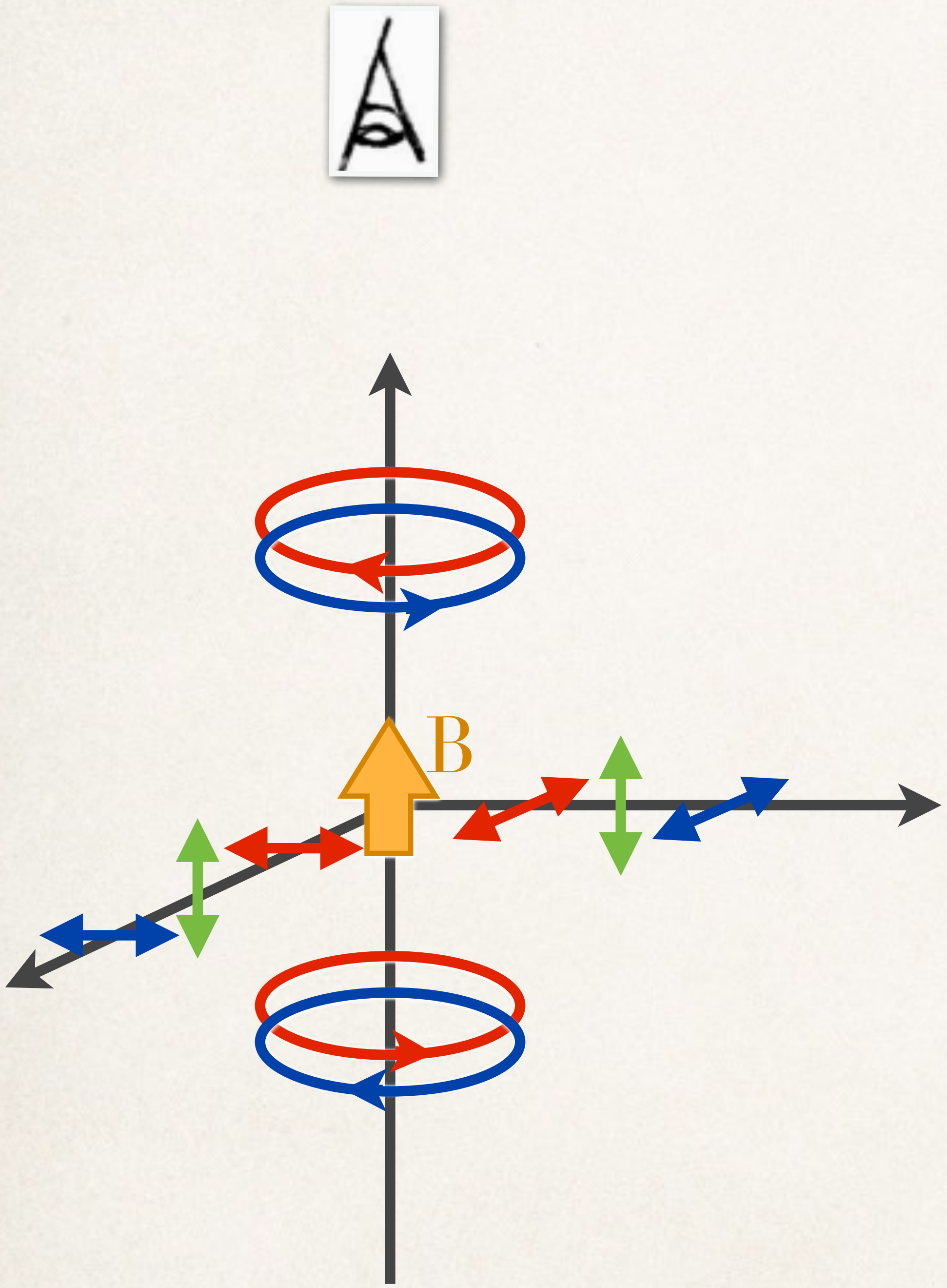
$\pi \equiv \Delta m = 0$ linearly polarized light $\parallel$ B

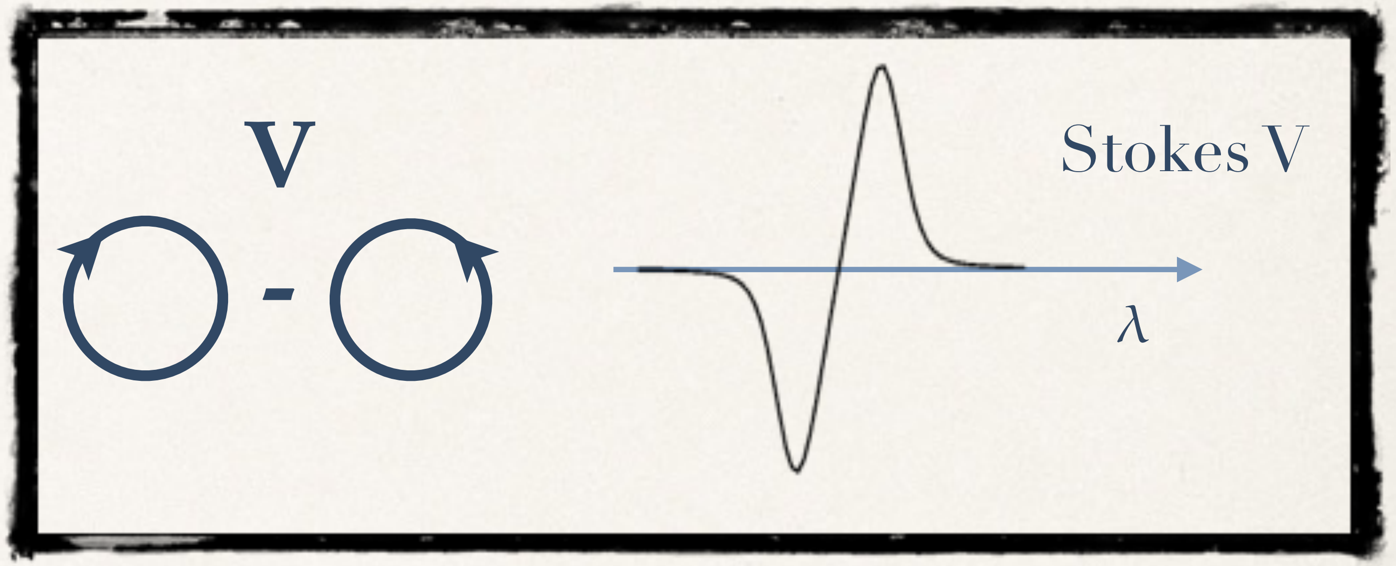
$\sigma_R \equiv \Delta m = +1$ right-handed circularly polarized light

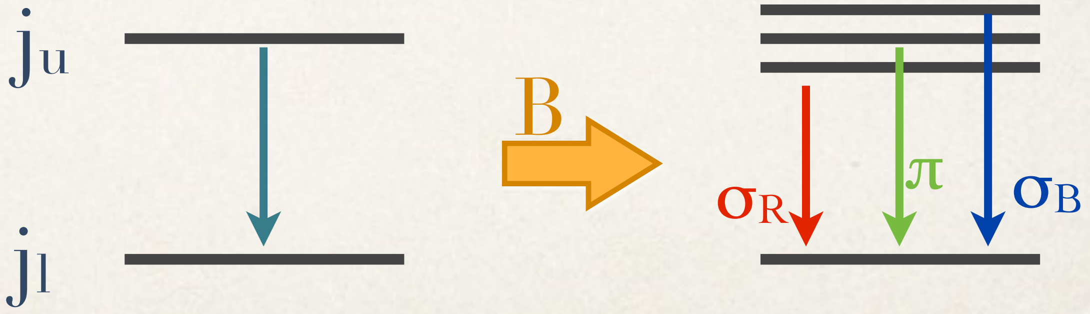
$\sigma_B \equiv \Delta m = -1$ left-handed circularly polarized light



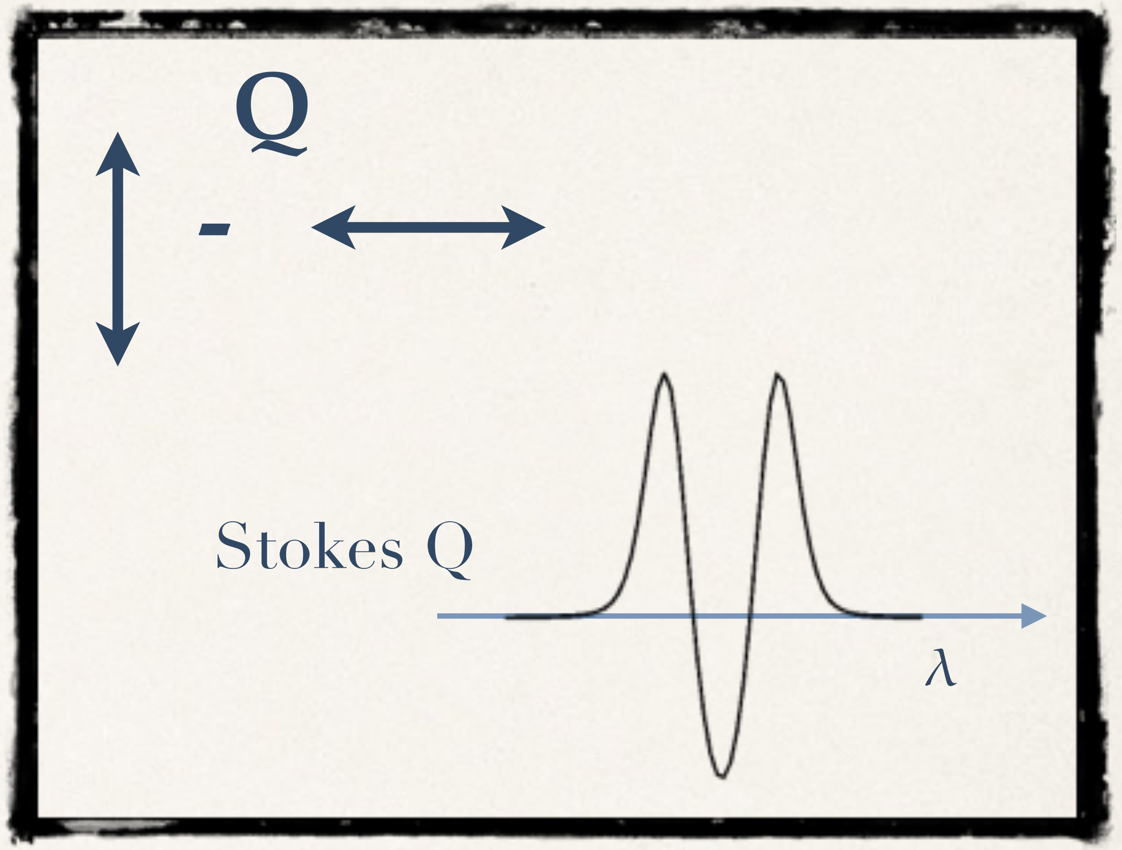
Polarization spectra

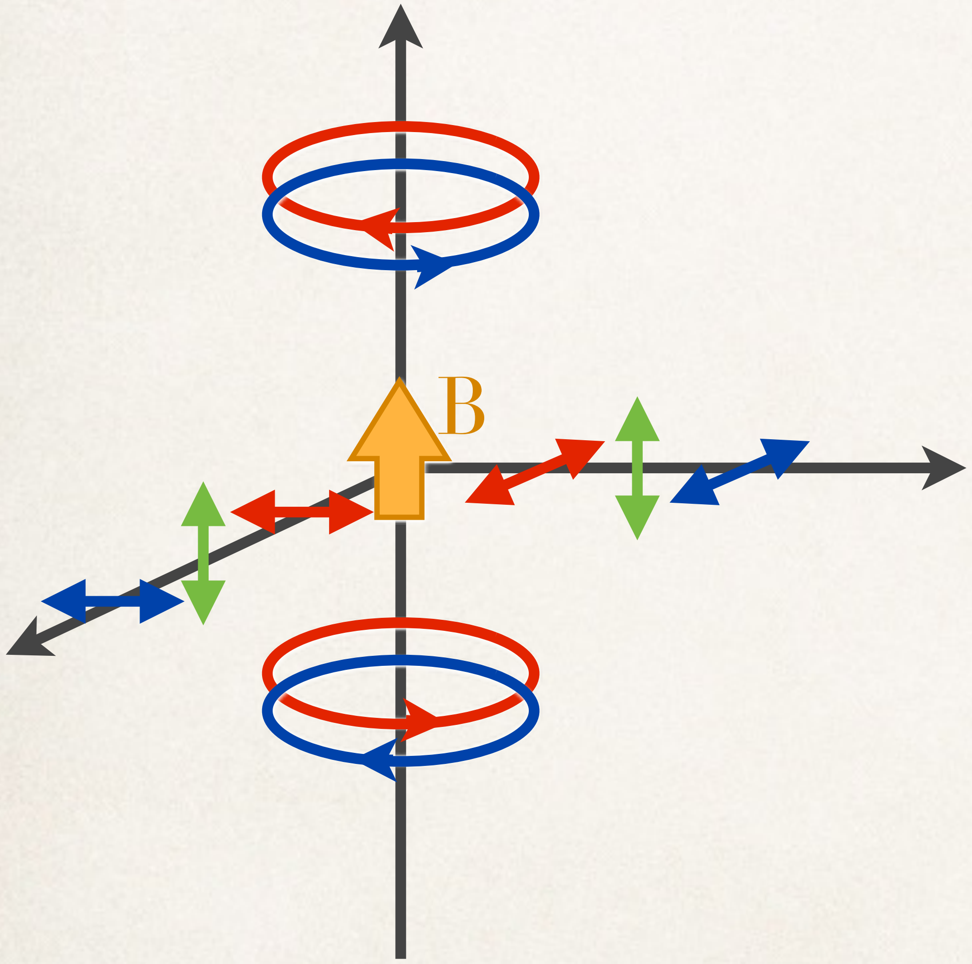


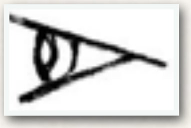


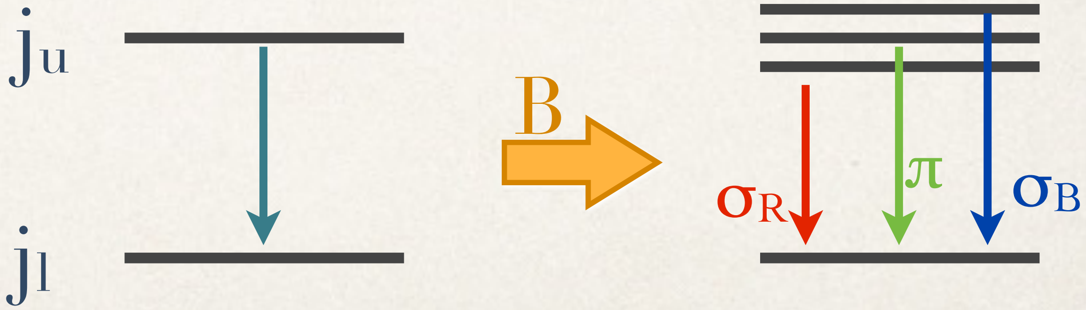


Polarization spectra









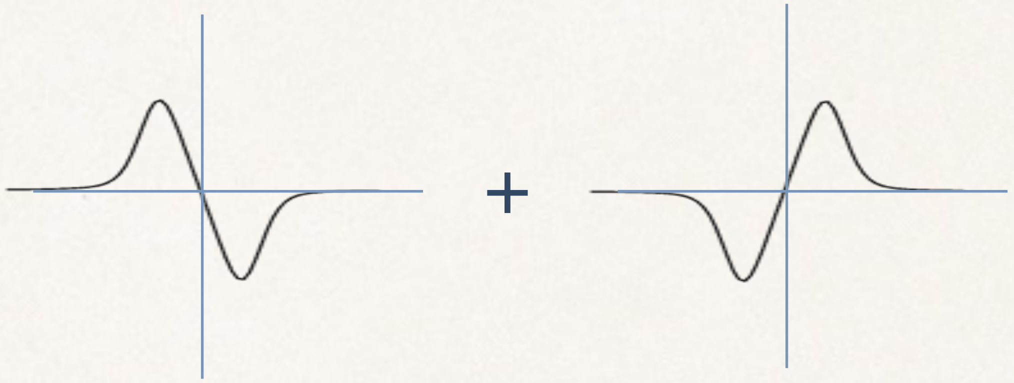
Zeeman Effect

The polarization signals due to the Zeeman effect only arise because of the wavelength shift between the pi and sigma components of the spectral line.

If there is no magnetic field, there is no polarization.

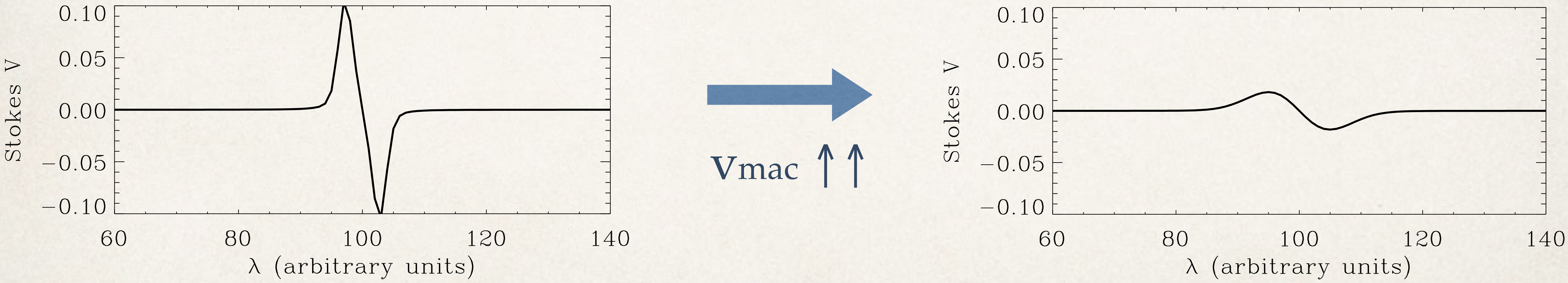
Shortcomings of the Zeeman Effect

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



= 0

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

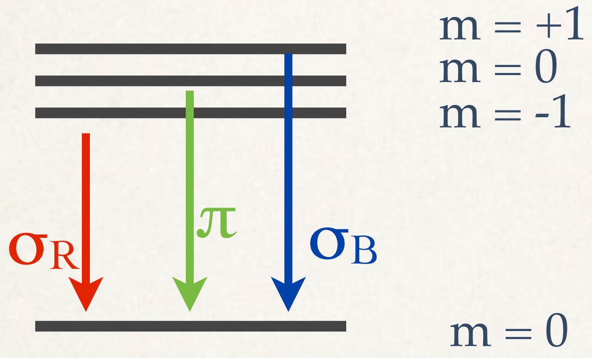


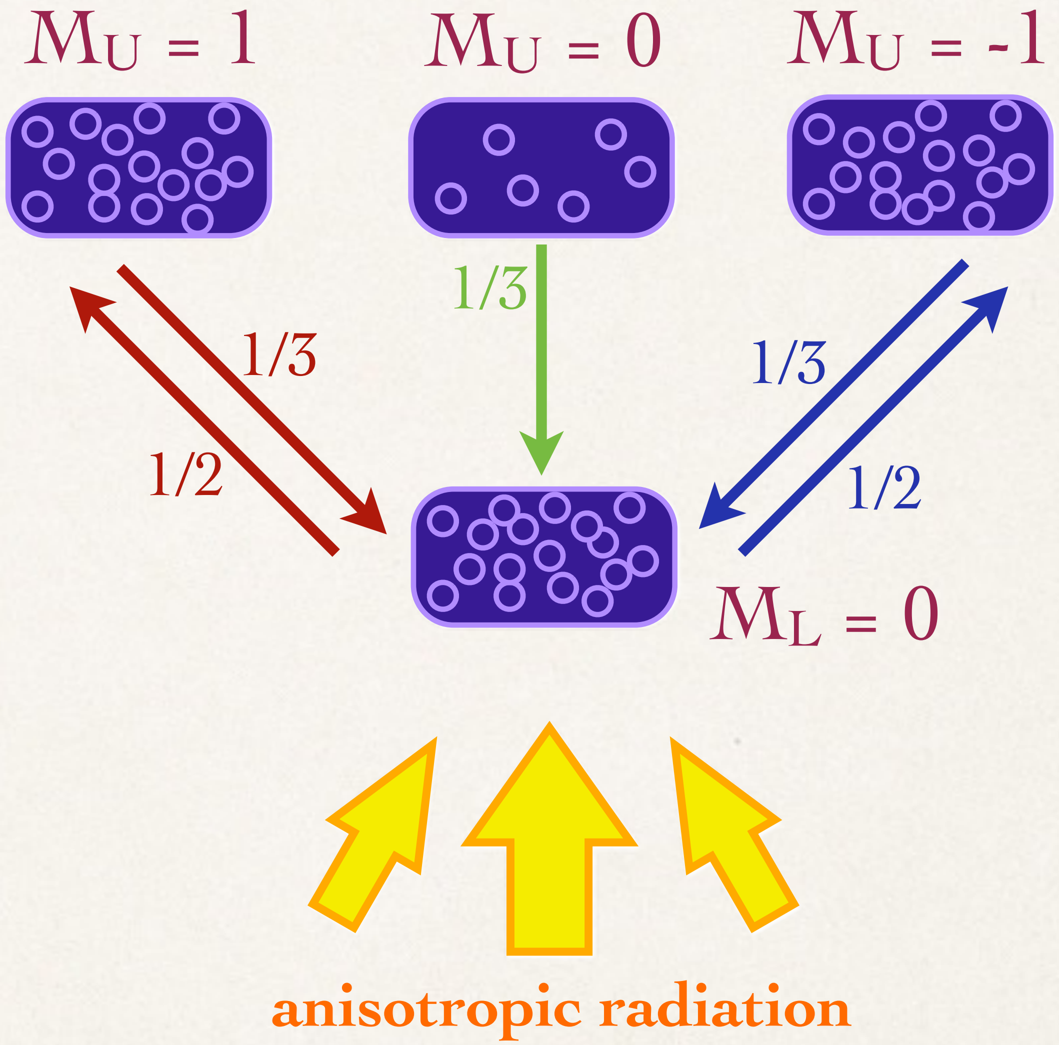
B = 100 G, θ = 0 deg

Mechanisms that produce polarization in spectral lines

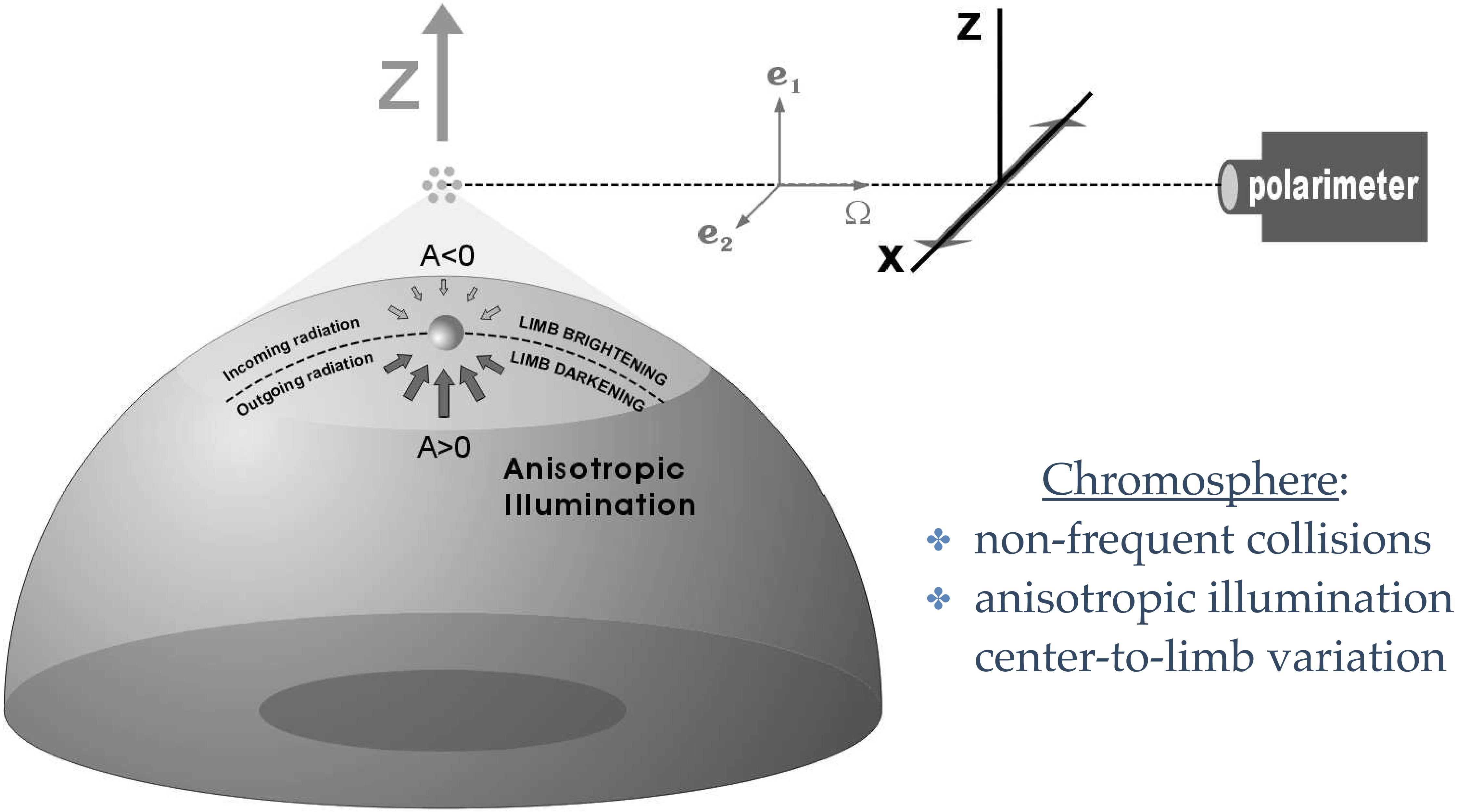
- Anisotropy in the excitation mechanism of the atom
    - Impact polarization
    - Optical pumping
- External field breaking the axis of symmetry
    - Electric field
    - Magnetic field

Atomic Polarization and the Hanle Effect





Optical Pumping

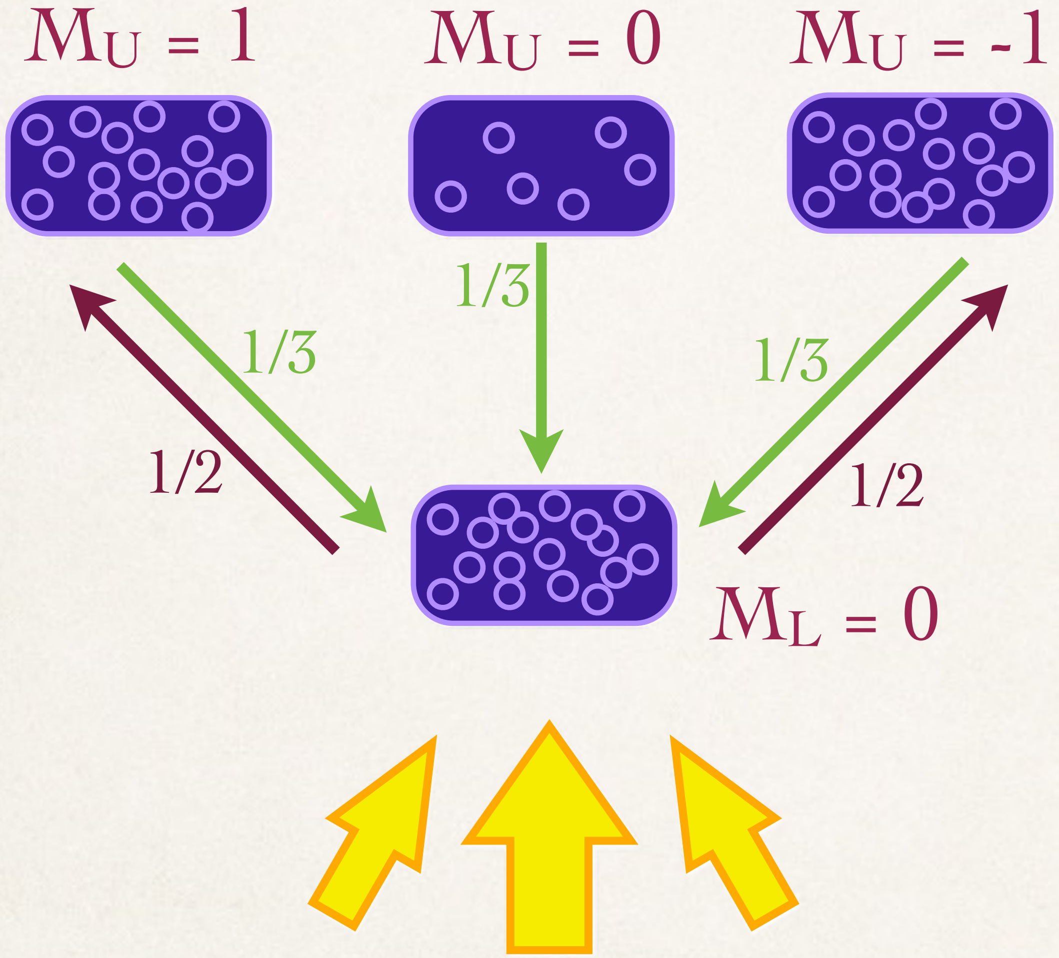


Chromosphere:

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

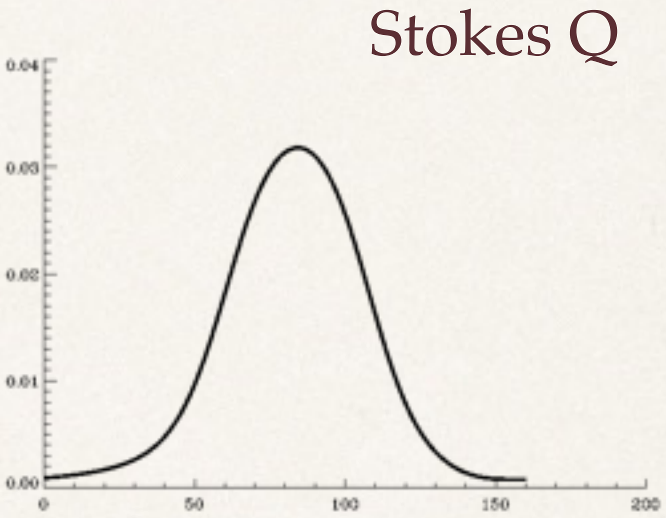
(from Trujillo Bueno 2006)

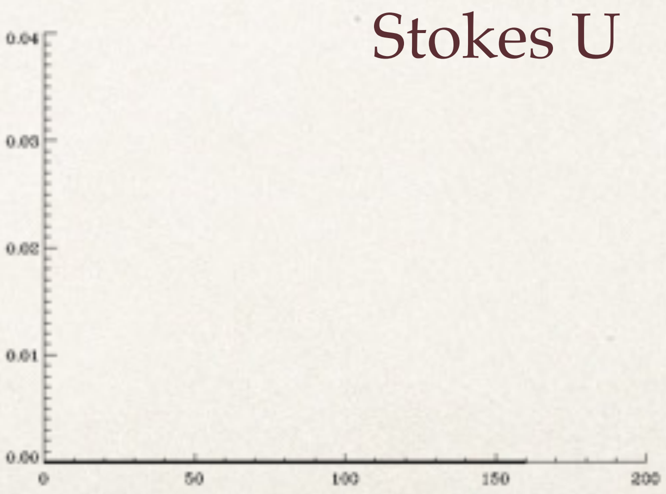
Atomic Polarization and the Hanle Effect



anisotropic radiation

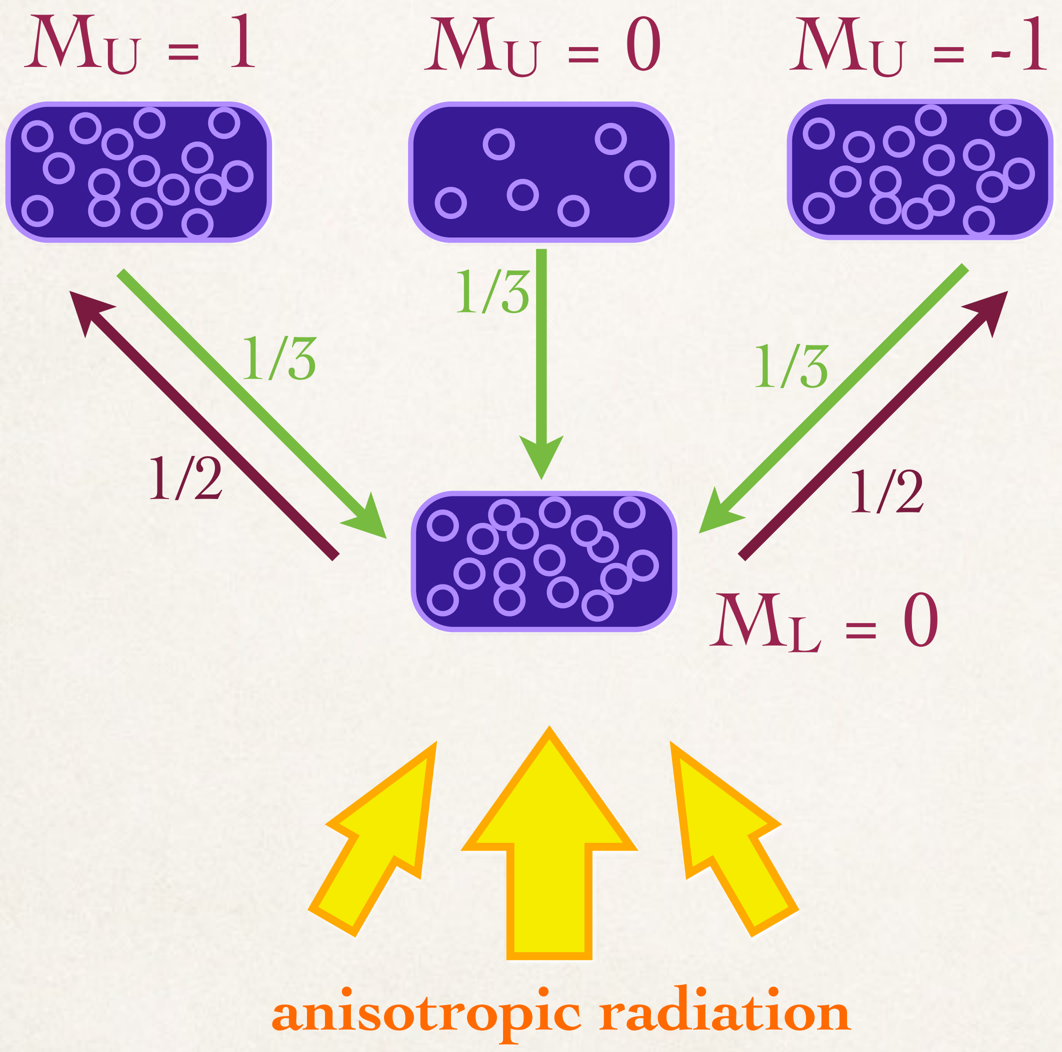
B = 0


Stokes Q

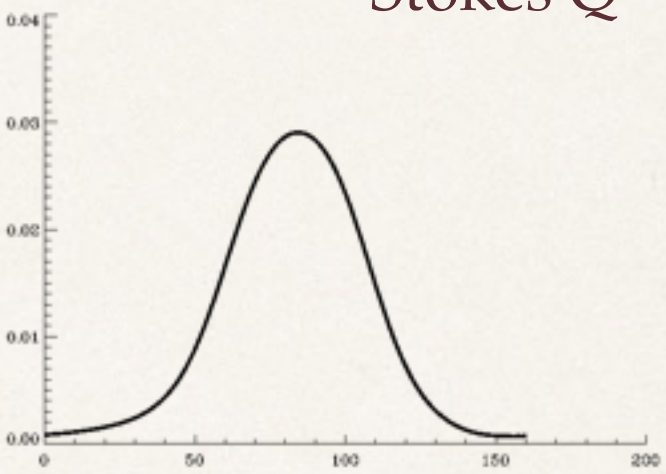

Stokes U

Atomic Polarization and the Hanle Effect

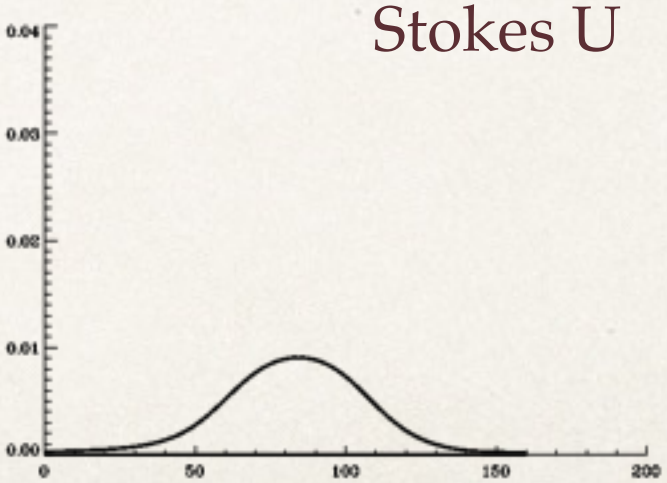
B ≠ 0 and inclined with respect to the axis of symmetry of the radiation



Stokes Q



Stokes U



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).

$$\boxed{B_H = 1.137\times10^{-7}/(t_{\mathrm{life}}\, g_J)}$$

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

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

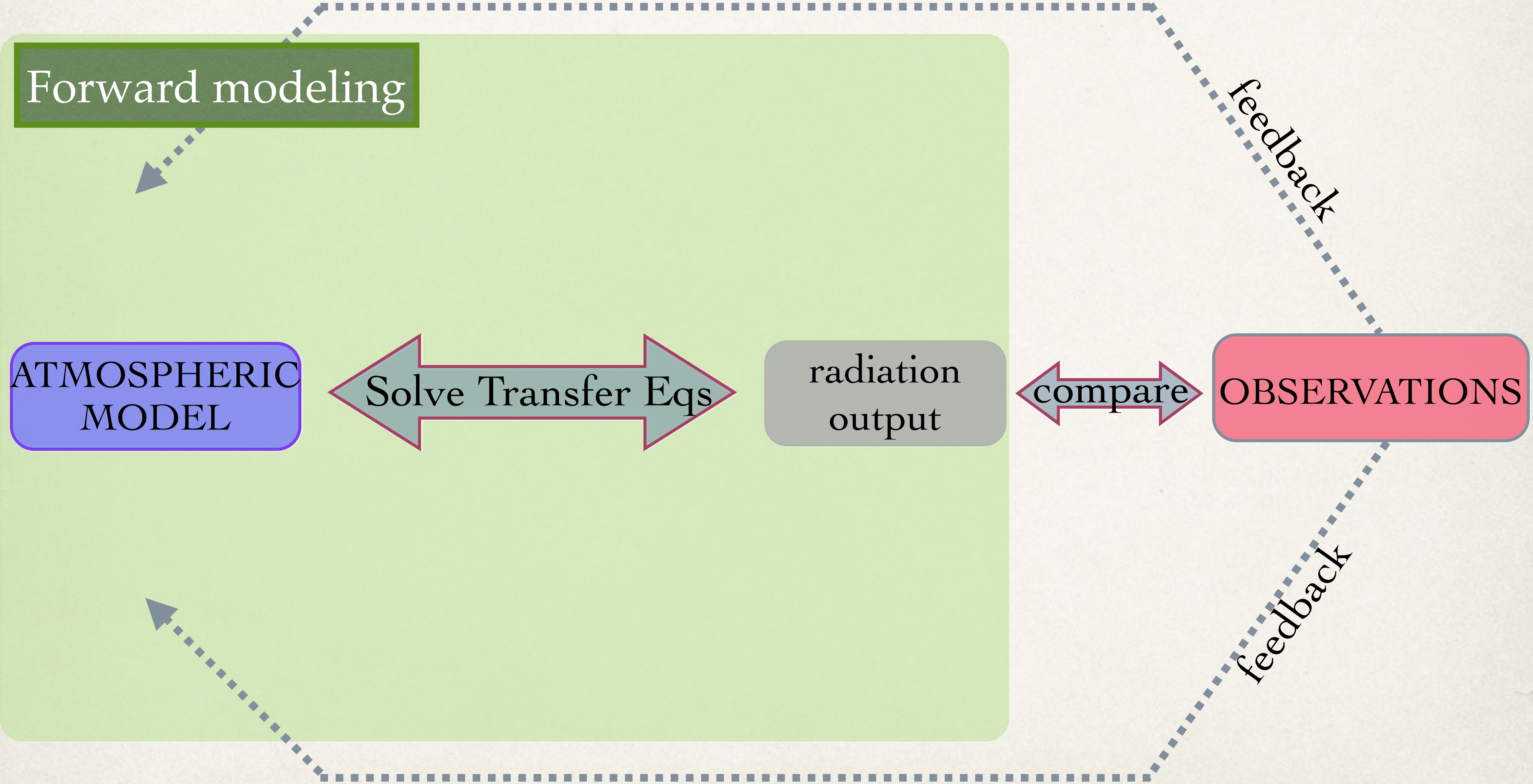
It has to be treated within the framework of the quantum theory of polarization.

Zeeman vs. Hanle

	Zeeman Effect	**Scatt. polarization Hanle Effect**
Prevalent in	Photosphere & Chromosphere	Chromosphere & Corona
Weak fields	✗	✓
Strong fields	✓	✗
Small-scale **mixed polarities**	✗	✓
Ambiguities	✗	✗
Computationally/ Conceptually	✓	✗

How do we use this knowledge to extract information about the magnetic field?

Spectral Line Inversions



Forward modeling

ATMOSPHERIC MODEL

Solve Transfer Eqs

radiation output

compare

OBSERVATIONS

feedback

feedback

Forward modeling approaches

Forward modeling

ATMOSPHERIC MODEL

RADIATIVE TRANSFER

solve

radiation output

Milne-Eddington:

Constant semi-infinite atmosphere

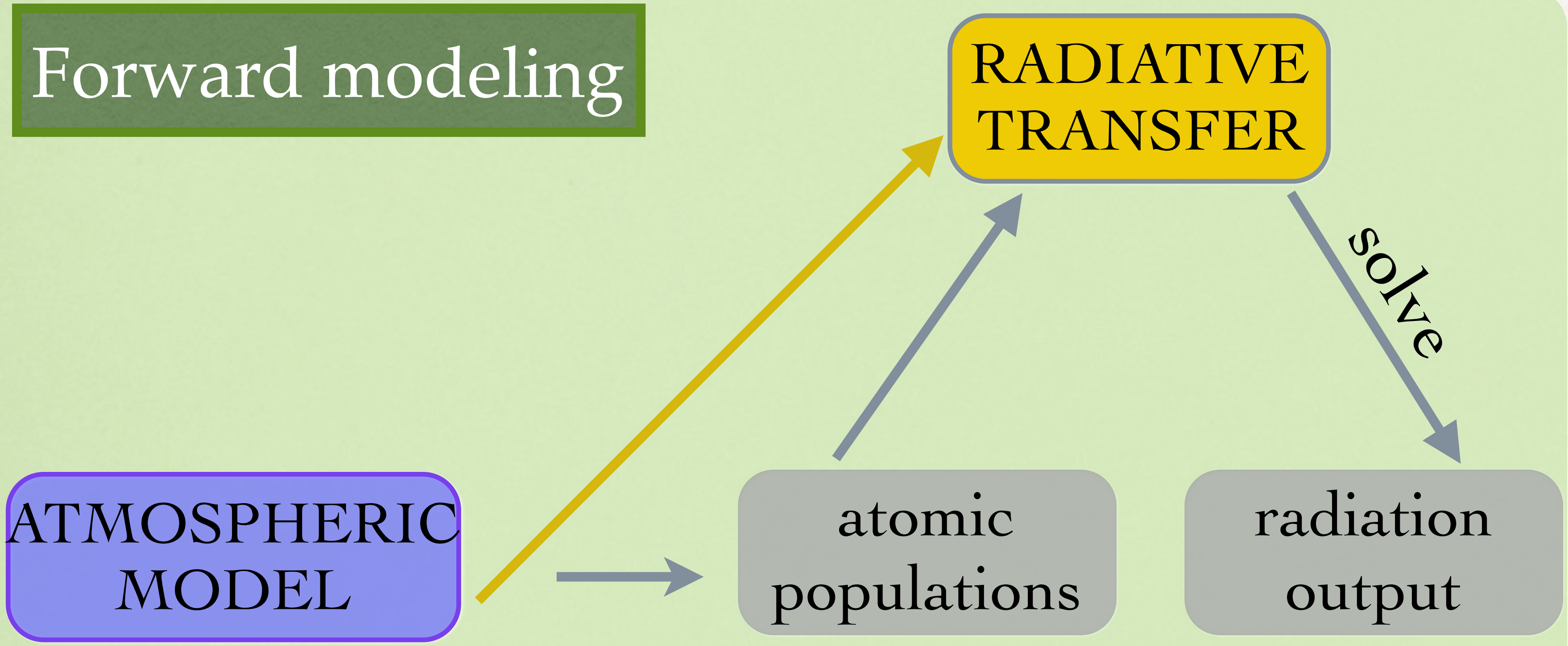
Linear source function

Zeeman polarization

No gradients/line asymmetries

No thermodynamical variables

Forward modeling approaches



Forward modeling

RADIATIVE TRANSFER

solve

ATMOSPHERIC MODEL

atomic populations

radiation output

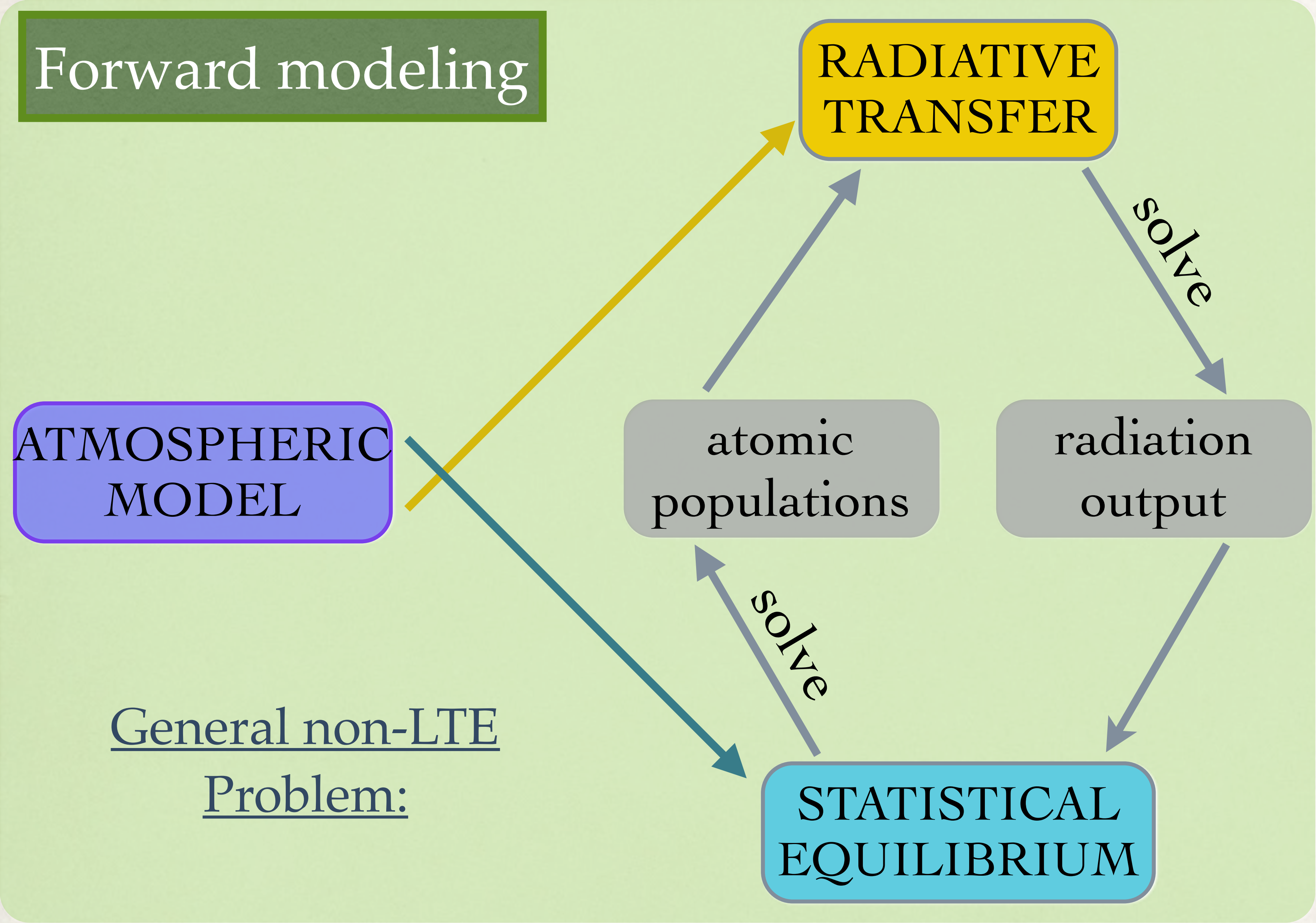
LTE:

Stratified atmosphere/line asymmetries

Thermodynamical variables (T, P, ϱ…)

Zeeman polarization

Forward modeling approaches



Forward modeling

ATMOSPHERIC MODEL

RADIATIVE TRANSFER

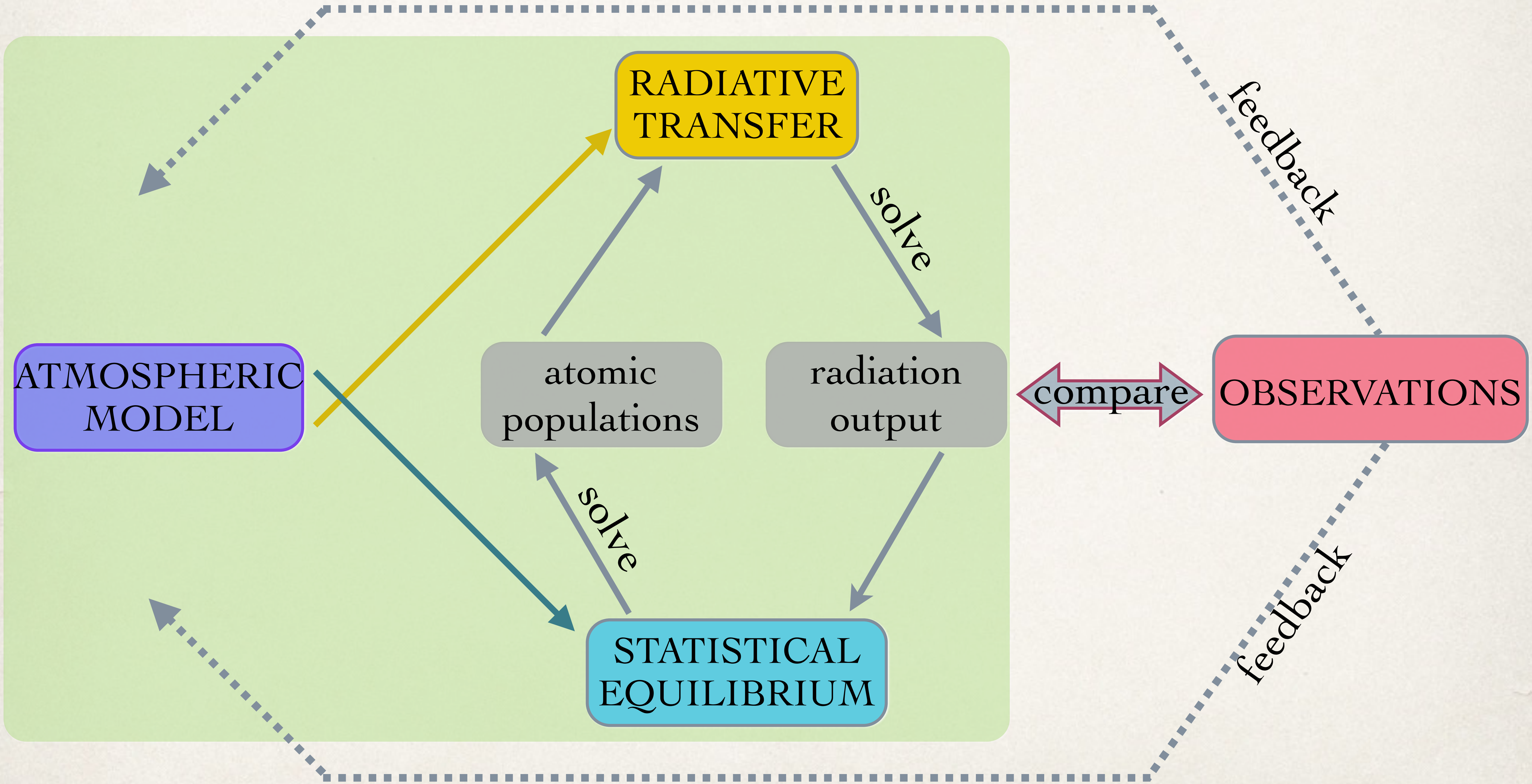
atomic populations

radiation output

STATISTICAL EQUILIBRIUM

General non-LTE Problem:

Spectral Line Inversions



RADIATIVE TRANSFER

solve

atomic populations

radiation output

compare

OBSERVATIONS

ATMOSPHERIC MODEL

solve

STATISTICAL EQUILIBRIUM

feedback

feedback

Inversion Methods

Let's assume we know how to solve the RTE.

Blind trial and error?!?!

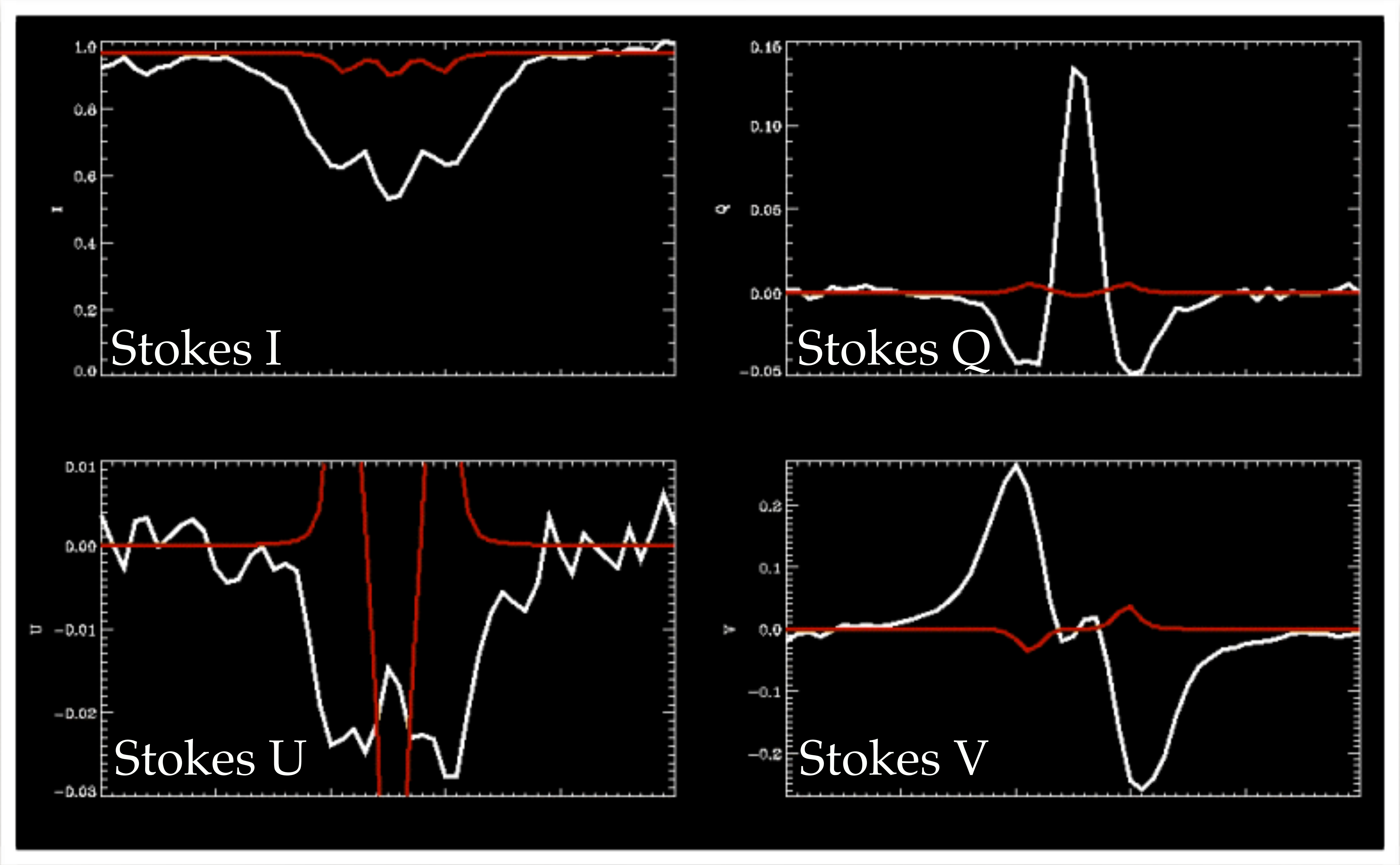
Least squares fitting:
Levenberg Marquardt

Bayesian approaches

Genetic algorithms:
Pikaia

Pattern recognition techniques:
Principal Component Analysis

Inversions: Levenberg-Marquardt Techniques



white = observations red = synthetic fit

	Photosphere	Chromosphere
Regime	LTE	non-LTE, PRD, 3D RT…
Scattering	No	Yes
Polarization	Zeeman	Zeeman/Hanle Scattering polariz.
Magnetic fields	Stronger	Weaker
Polarization signals	10^{-1} - 10^{-3} Icont	10^{-3} - 10^{-5} Icont
Spectral Lines	Many (optical/IR spectrum)	Few (optical/IR spectrum)
Computationally/ Conceptually	Acceptable/Easy	Expensive/Complex
Inversions	Milne-Eddington, LTE	Milne-Eddington, slab, non-LTE

Spectral Diagnostics: Photosphere

Zeeman splitting:

$\Delta\lambda_B = (m_l\, g_l - m_u\, g_u)\, \lambda_B$

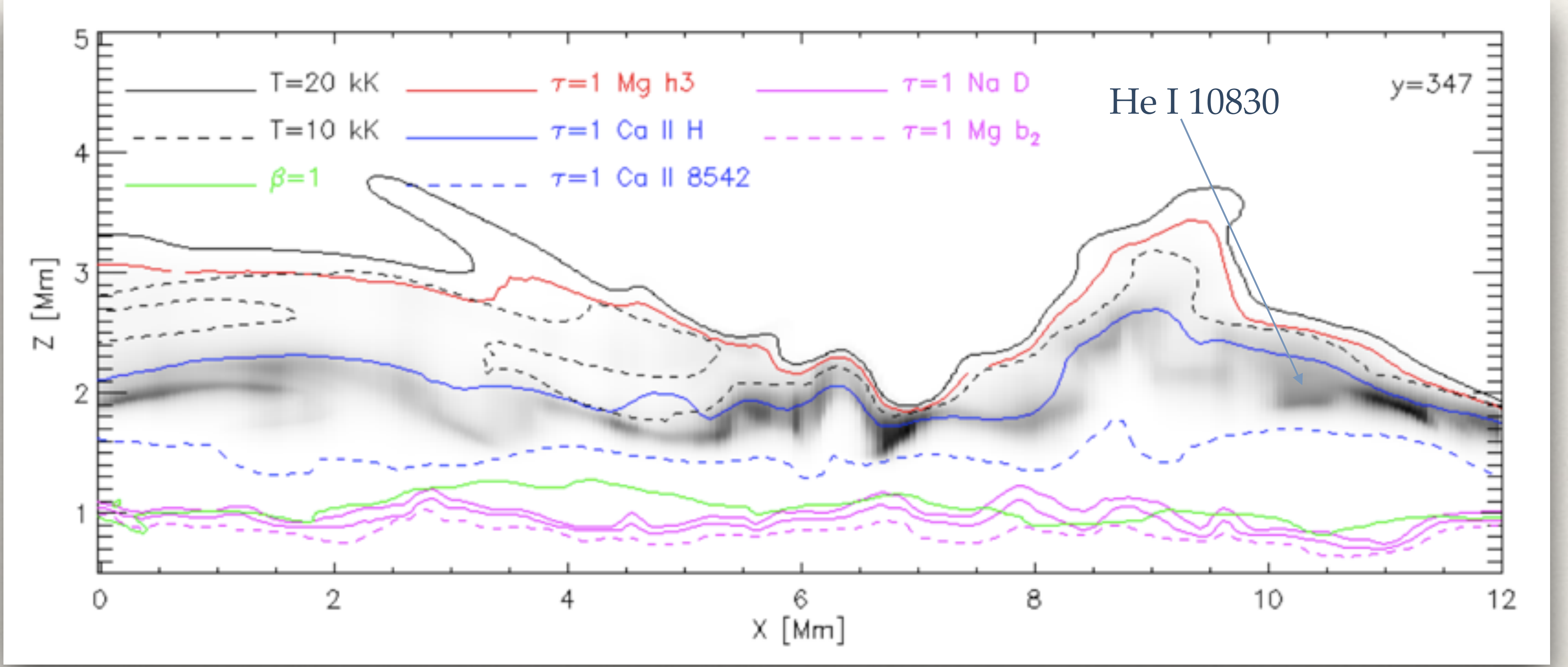
where: $\boxed{\lambda_B = 4.67 \times 10^{-13}\, \lambda_0^2\, B}$

B (gauss), λ_0 and λ_B (angstroms)

Some typical *magnetically sensitive* photospheric diagnostics

Fe I 5247, 5250 Å (line ratio techniques, Sunrise IMaX)
Fe I 6301.5 , 6302.5 Å (Hinode spectropolarimeter)
Fe I 6173 Å (SDO / HMI)
Fe I 15648, 15650 Å (IR, large Lande factor == high magnetic sensitivity)
Si I 10827 Å (next to He I 10830 Å)

Spectral Diagnostics: Chromosphere



From de la Cruz Rodriguez & van Noort, 2017, figure from M. Carlsson

Most common diagnostics in the visible and IR:

- Ca II H & K, Ca II IR triplet (~8500 Å),
- H-alpha (6563 Å)
- He I D3 (5876 Å) and He I 10830 Å

Inversion Codes

Non-LTE Forward modeling:

- Hanle-RT (Roberto Casini, HAO)
- RH (Han Uitenbroek, NSO)

Milne-Eddington:

- VFISV / HMI code (Juanma Borrero, KIS)
- MERLIN / Hinode (José García, Bruce Lites, HAO)
- MILOS (David Orozco Suárez, IAA)

LTE codes (1D):

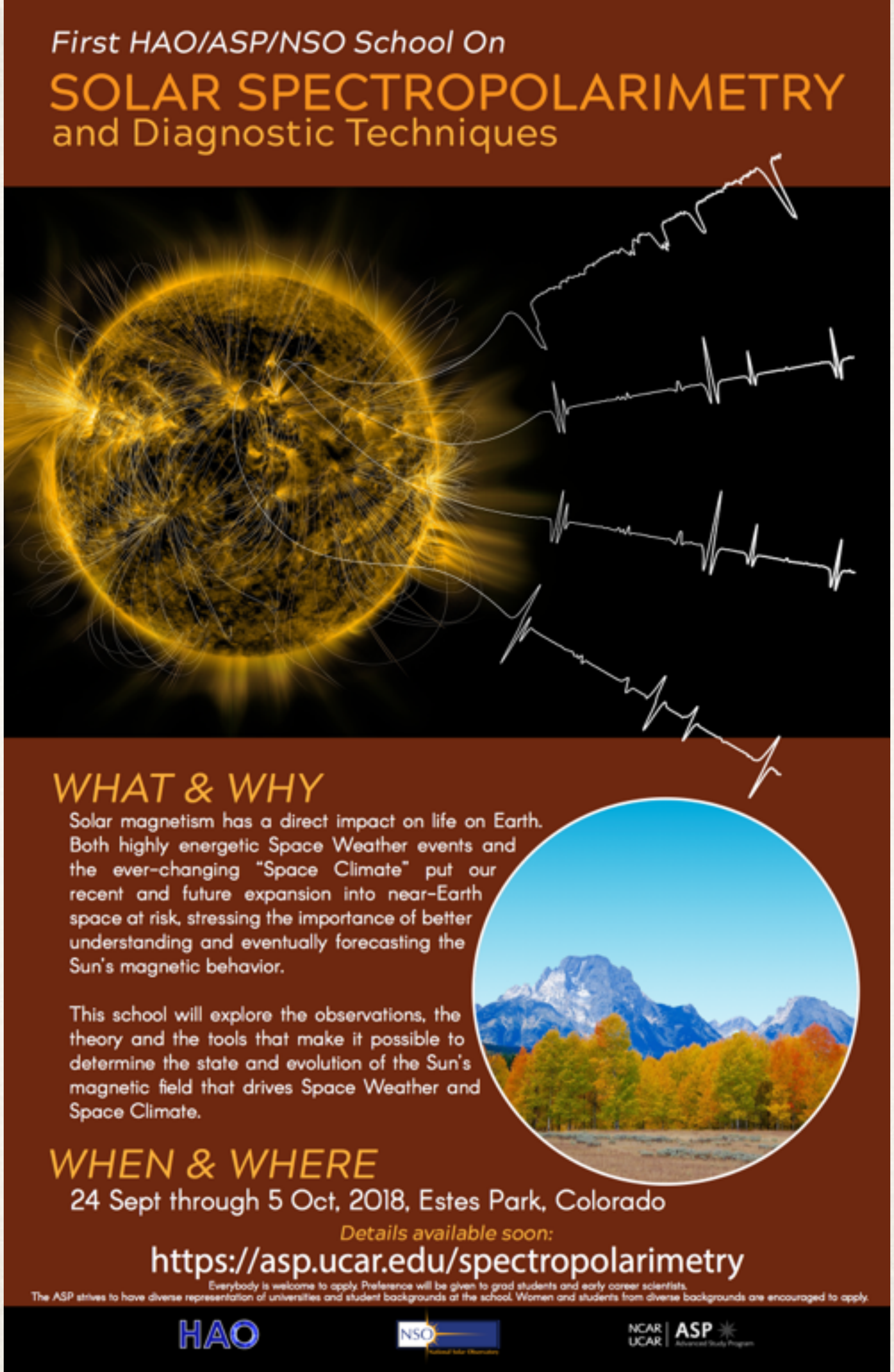
- SIR (Basilio Ruiz Cobo, IAC): https://github.com/BasilioRuiz/SIR-code
- HELIX (Andreas Lagg, MPS)

Constant slab model, optical pumping, atomic level polarization, Zeeman+Hanle

- HAZEL (Andrés Asensio Ramos, IAC): https://github.com/aasensio/hazel

Non-LTE (1D, no scattering polarization yet)

- NICOLE (Héctor Socas-Navarro, IAC): https://github.com/hsocasnavarro/NICOLE
- STIC (Jaime de la Cruz Rodríguez, Stockholm U.): in development



First HAO/ASP/NSO School On

SOLAR SPECTROPOLARIMETRY and Diagnostic Techniques

WHAT & WHY

Solar magnetism has a direct impact on life on Earth. Both highly energetic Space Weather events and the ever-changing "Space Climate" put our recent and future expansion into near-Earth space at risk, stressing the importance of better understanding and eventually forecasting the Sun's magnetic behavior.

This school will explore the observations, the theory and the tools that make it possible to determine the state and evolution of the Sun's magnetic field that drives Space Weather and Space Climate.

WHEN & WHERE

24 Sept through 5 Oct, 2018, Estes Park, Colorado

Details available soon:

https://asp.ucar.edu/spectropolarimetry

Everybody is welcome to apply. Preference will be given to grad students and early career scientists.
The ASP strives to have diverse representation of universities and student backgrounds at the school. Women and students from diverse backgrounds are encouraged to apply.