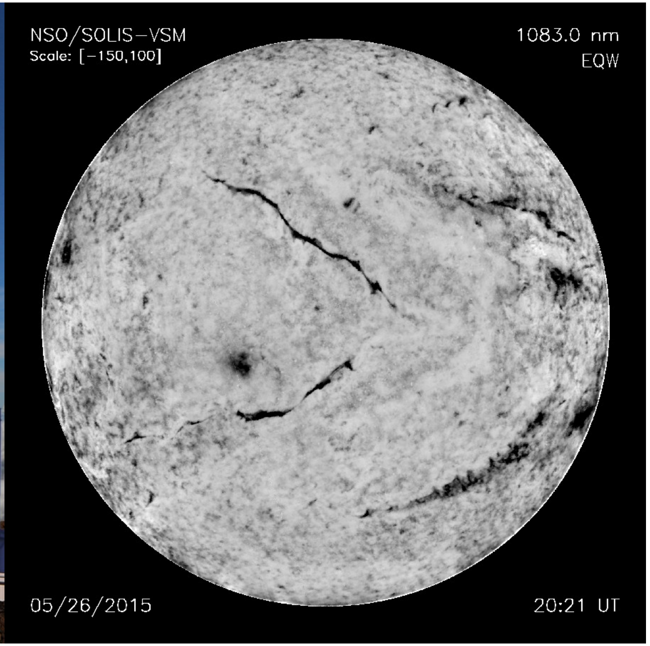
5th NCSP DKIST Data-Training Workshop:
He I Diagnostics in the Solar Atmosphere

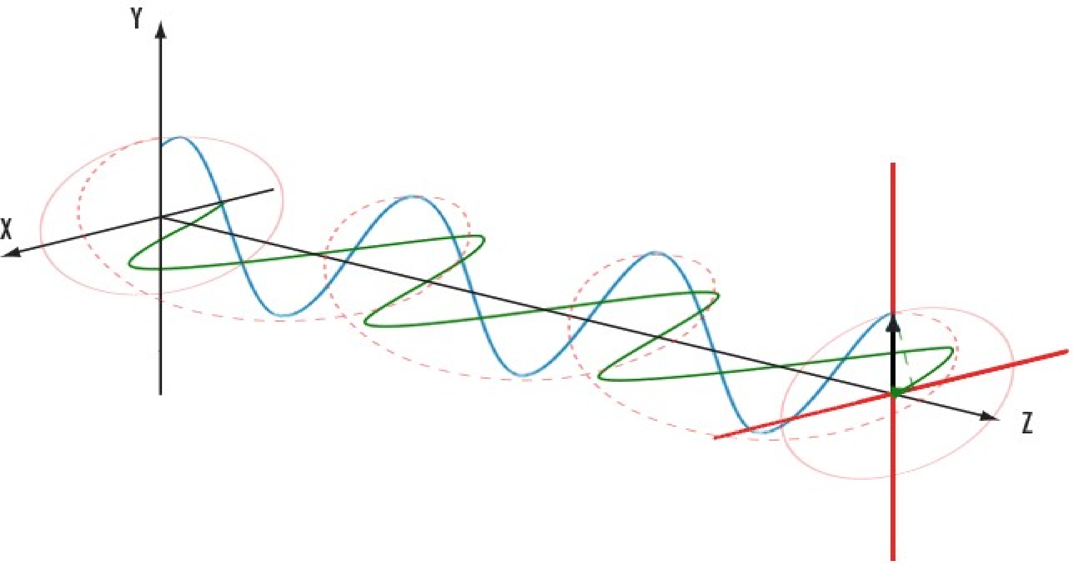
Scattering Polarization and Hanle effect in He 10830

Ivan Milic (CU Boulder / LASP) ; ivan.milic (at) colorado.edu

Scattering and polarization are like pizza and tomato

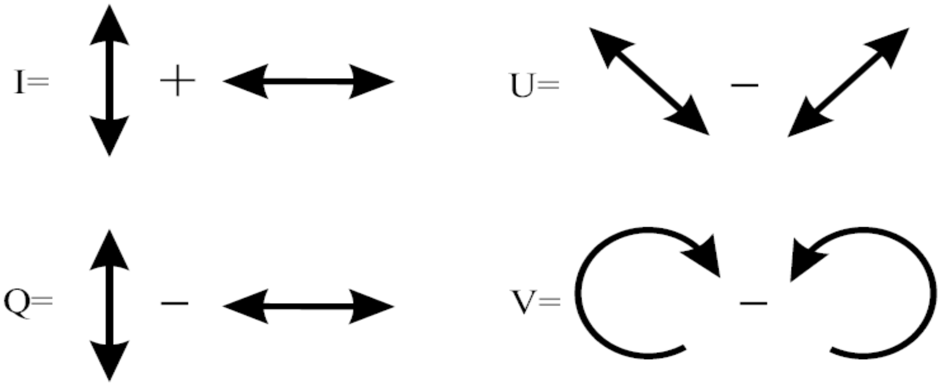
- The “slabs” (i.e. prominences and filaments), are not very dense, so they purely scatter the light.
- Scattering automatically creates the polarization.
- Polarization is a very powerful tool, it probes geometry, spatial anisotropy (or anisotropies), as well as the magnetic field.
- In the same way we can look at the variation of the intensity with the wavelength (i.e. **the spectrum**), we can look at the variation of the polarization state of the light with the wavelength (i.e. **polarized spectrum,** in case of Stokes Q only, **second solar spectrum**).

How do we describe the polarization of the light?

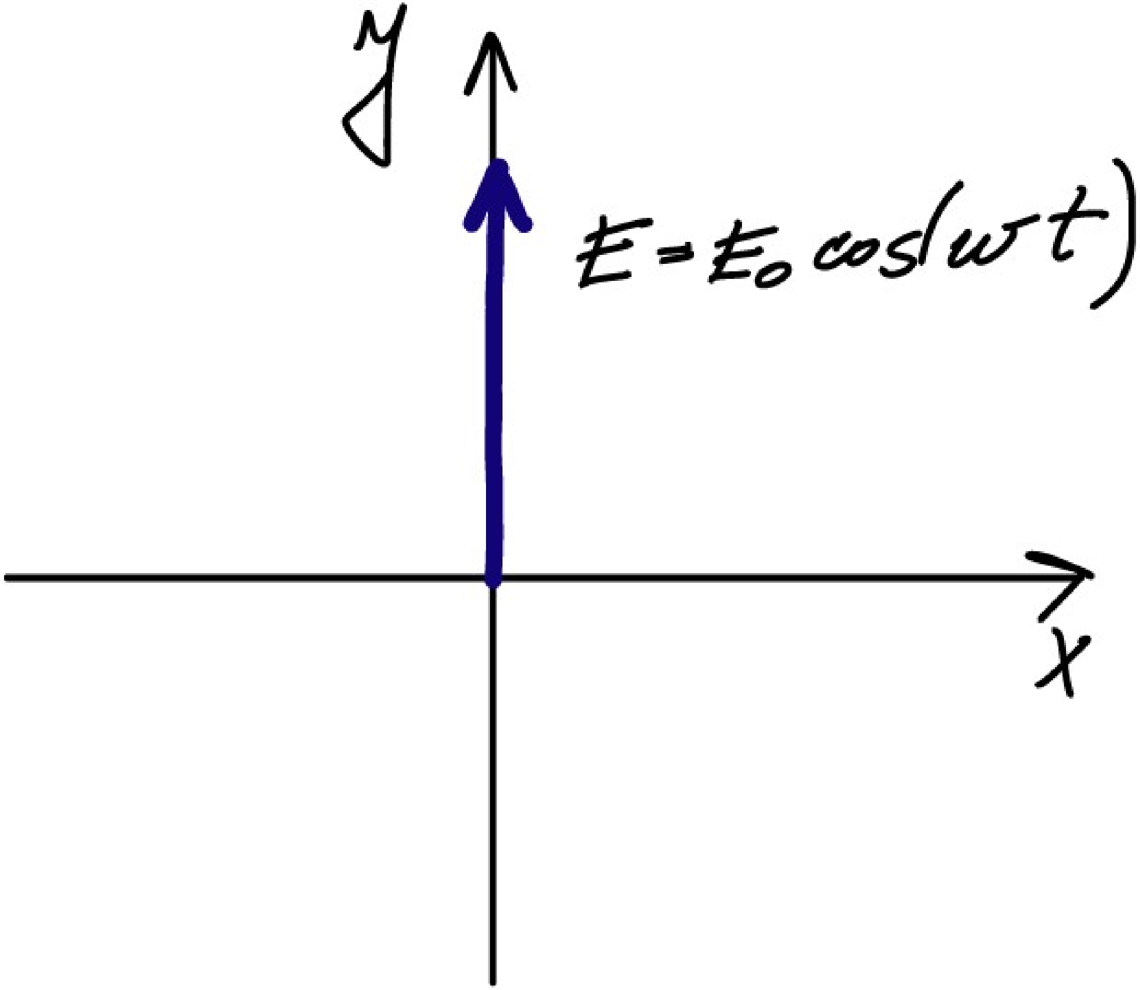


Credits: www.edmundoptics.com

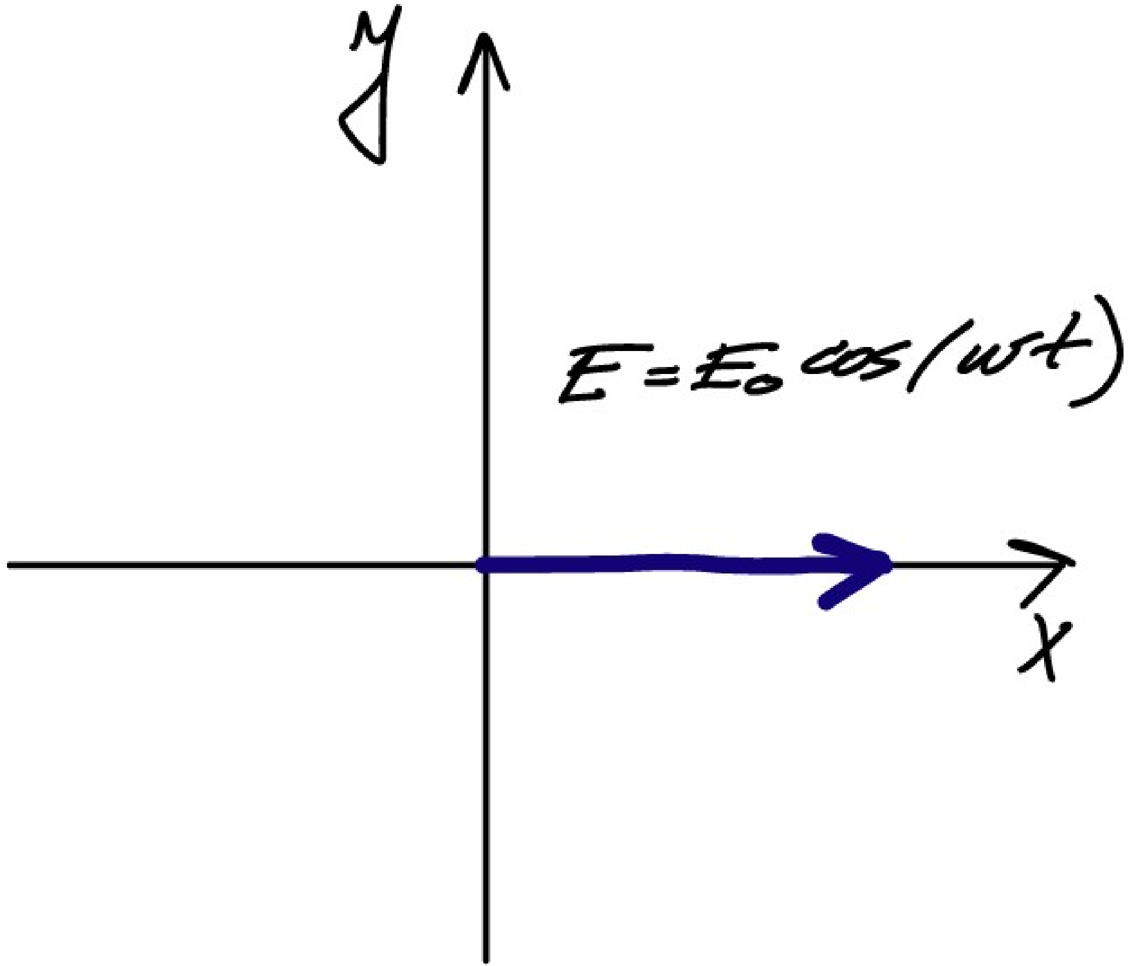
“Instrumental” definition of Stokes parameters:



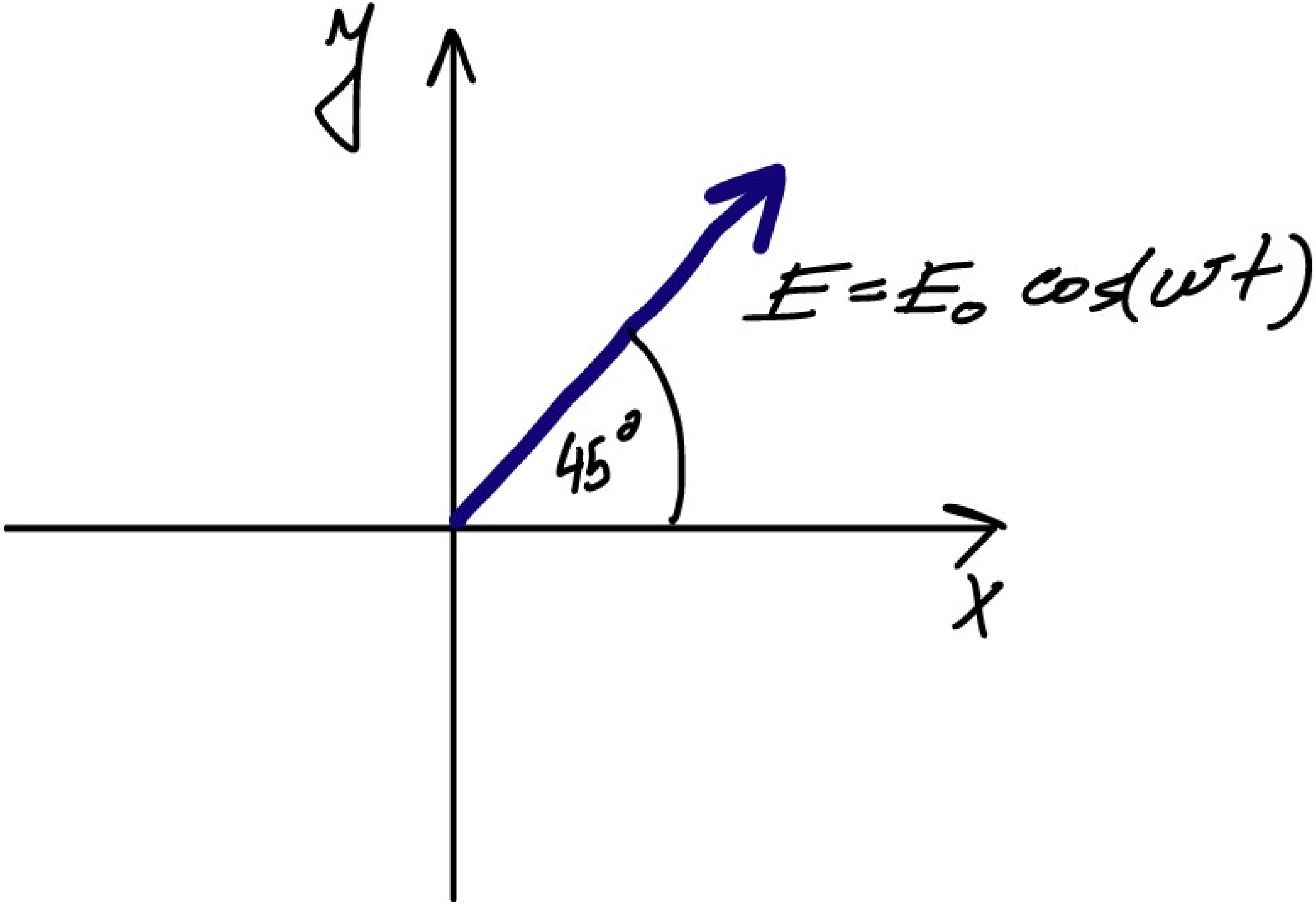
So let's have some questions! Is this positive Q or negative Q?



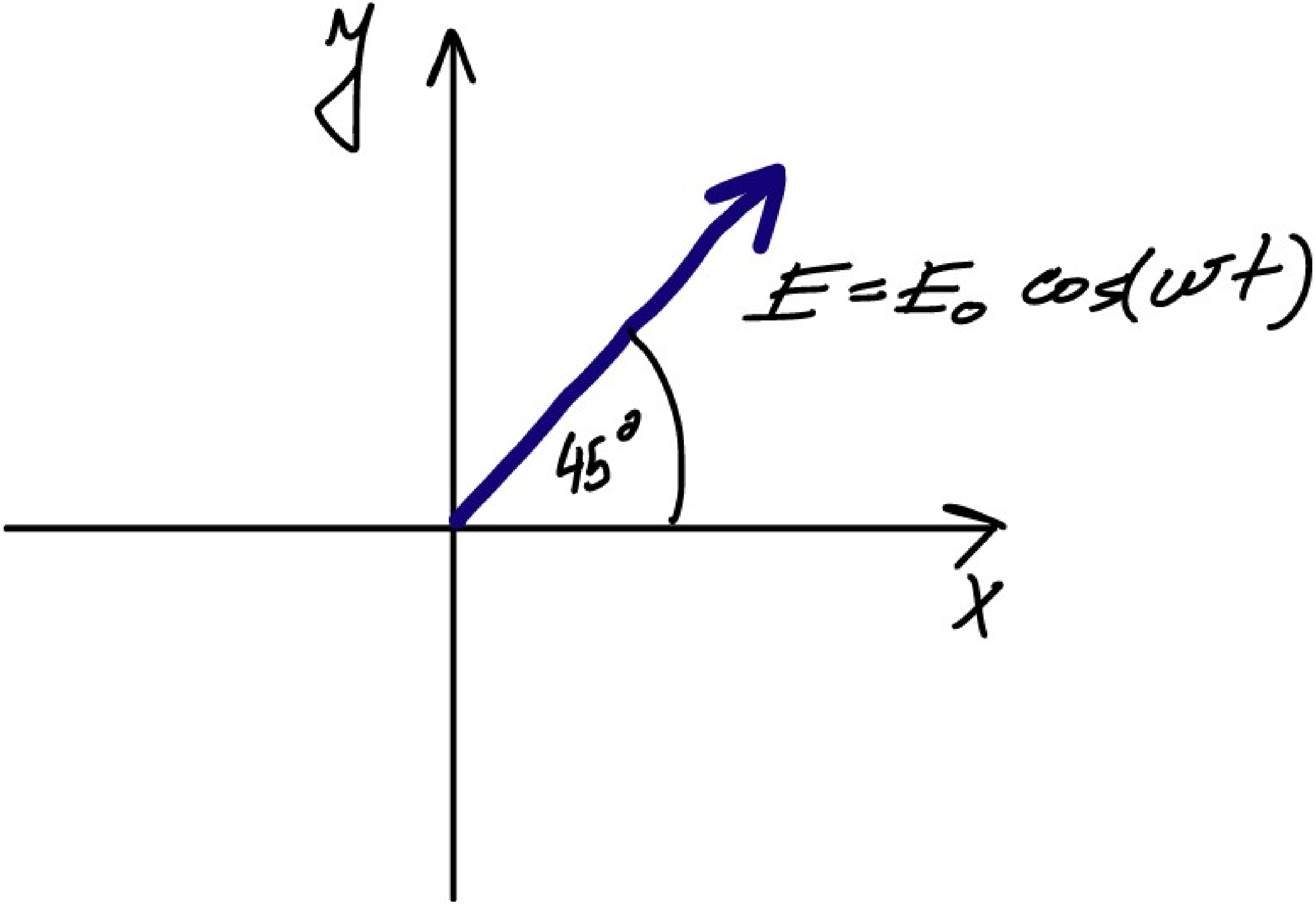
How about this?



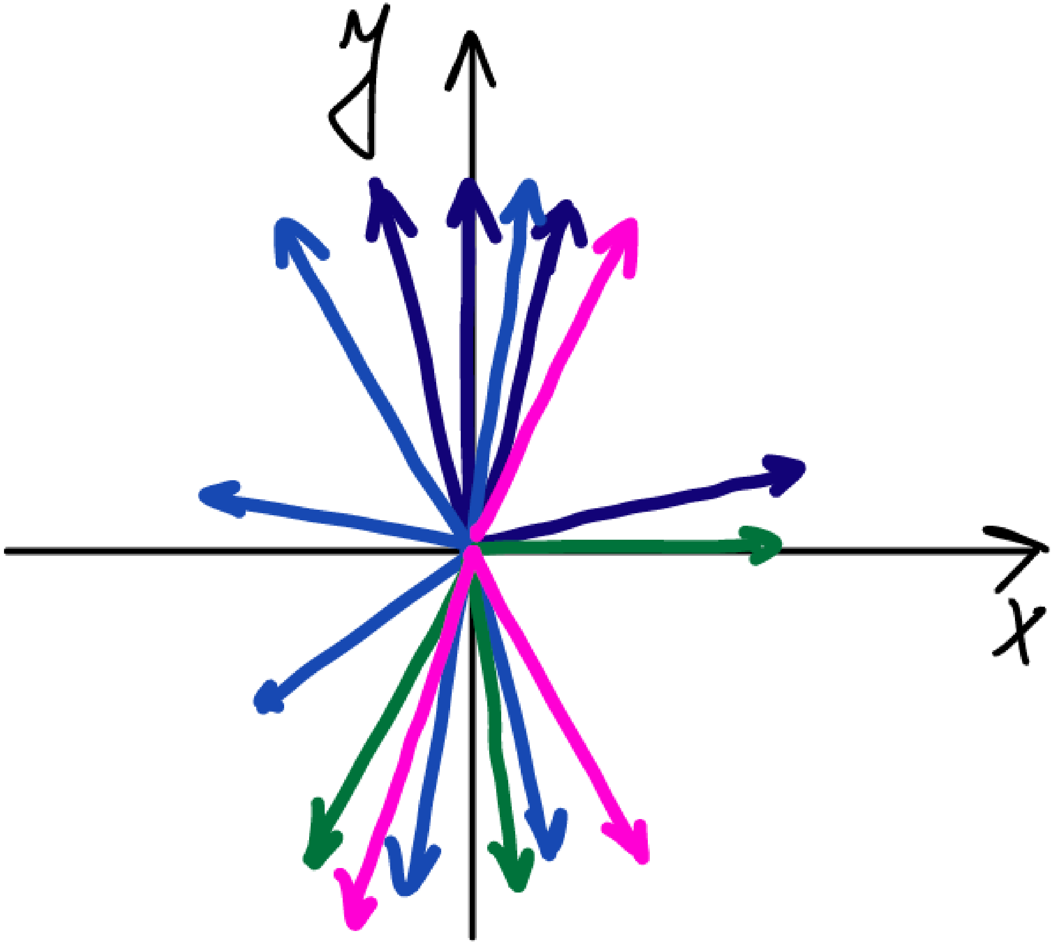
And this?



And this? That’s right, this is zero Q but negative U



Here we have an incoherent superposition of many wavepackets. Is Q positive or negative? How about U?



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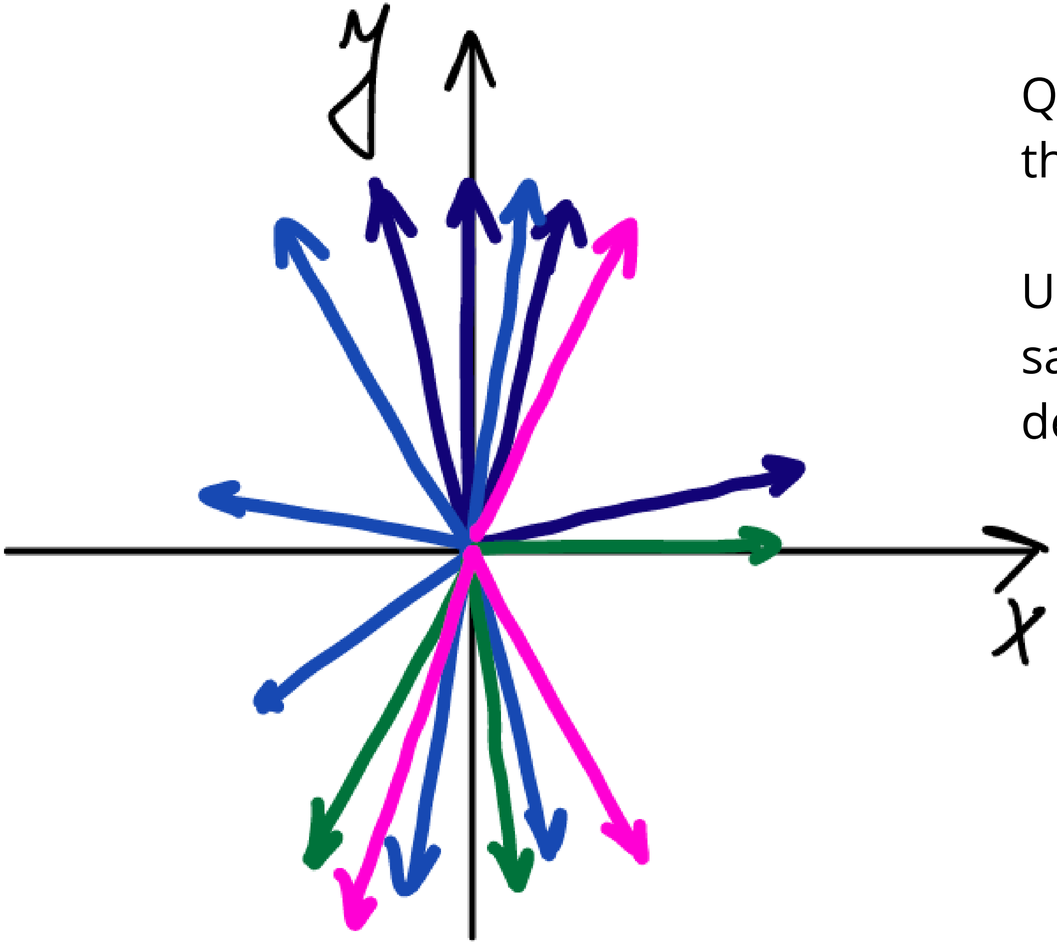


Q **positive –** more vertical than horizontal waves

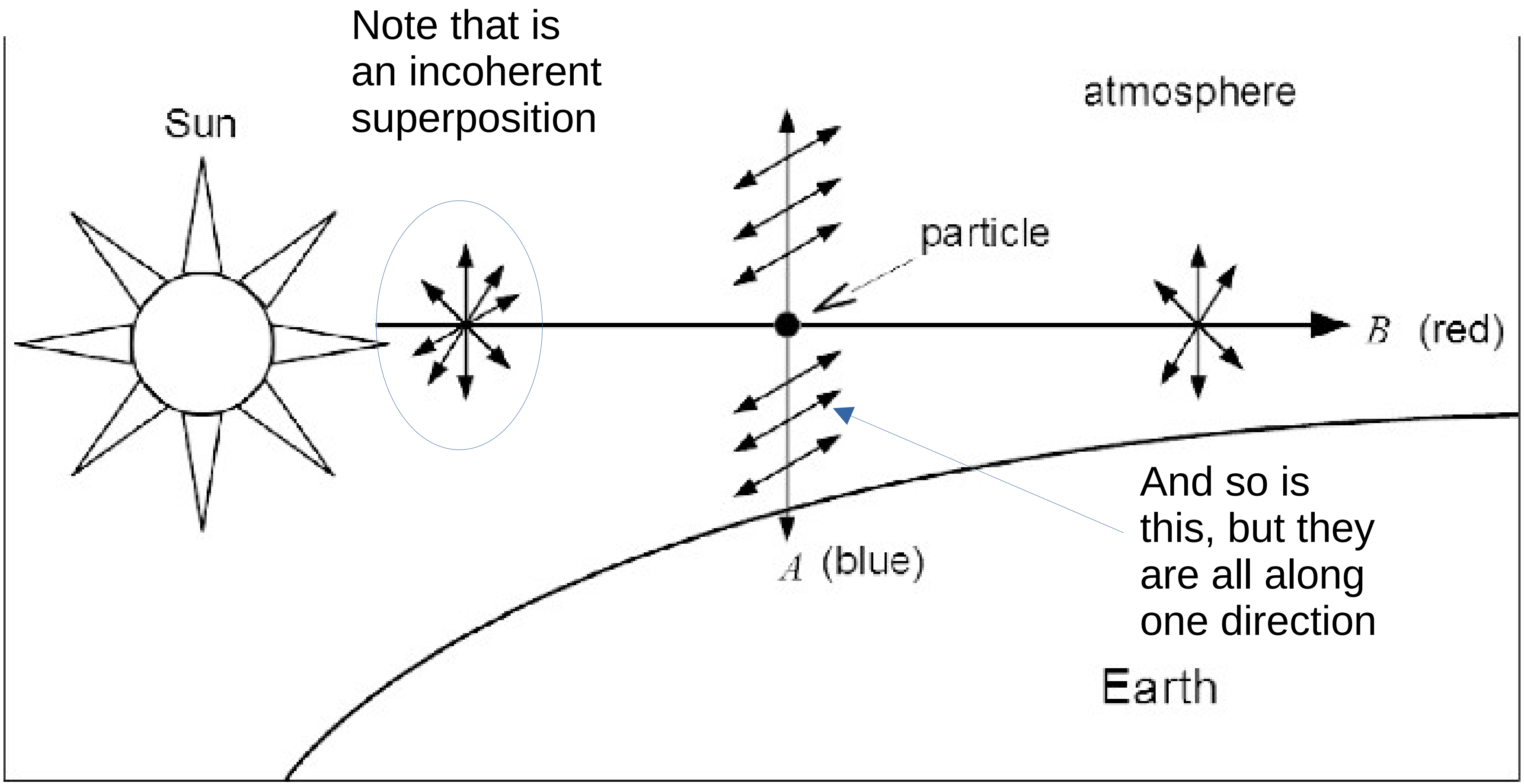
U **zero –** approximately same amount at 135 degrees and 45 degrees

Reminders about Stokes formalism:

- Stokes formalism describes intensities
- I is total intensity of the light (counting photons not caring about their orientation)
- Other 3 are differences between number of photons with specific polarizations
- Note that if light was really monochromatic plane wave, sum of of squares of Q,U,V would be equal to square of I.
- It is not (again, the light we see is an incoherent superposition of many short wavepackets)

Classical coherent (continuum) scattering

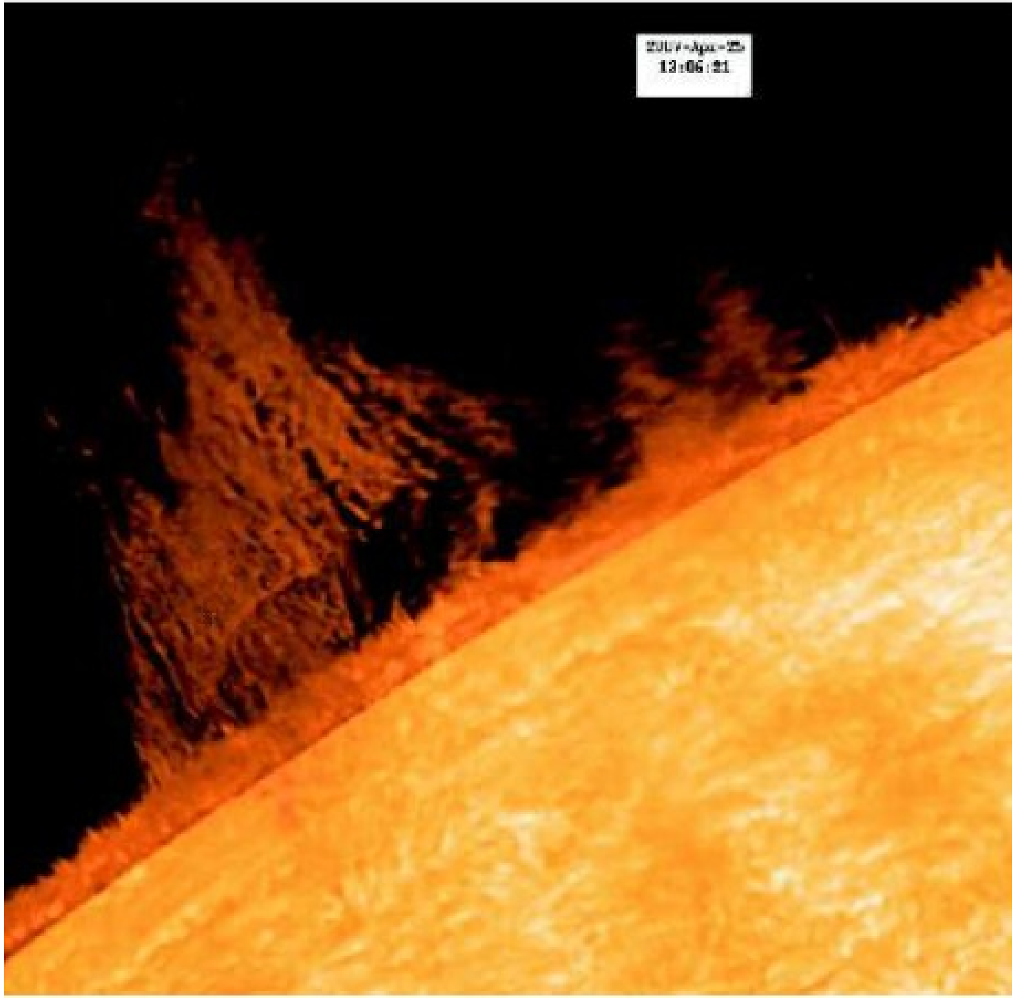
Classical coherent (continuum) scattering



Credits: Soga et al. 2018

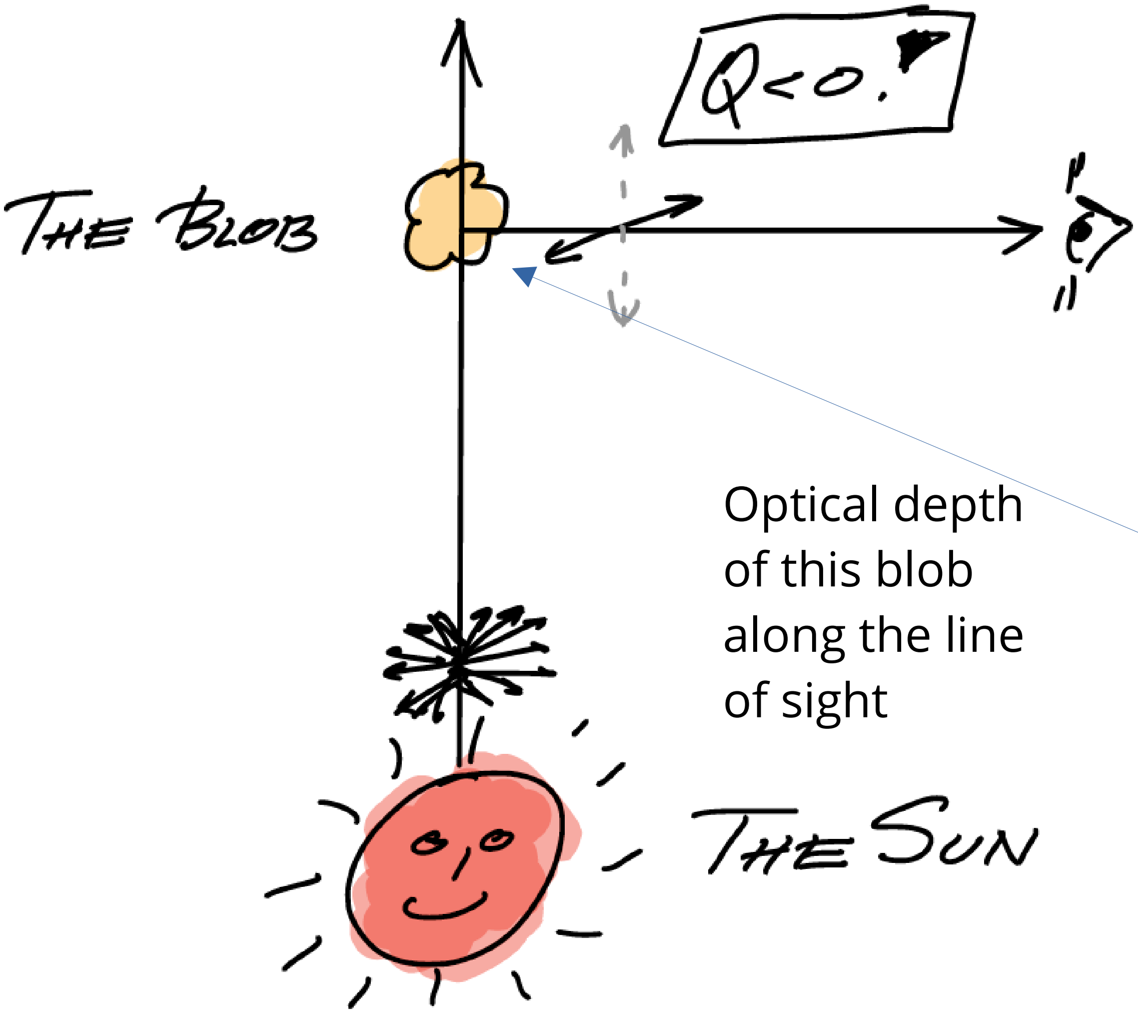
Let's go back to prominences

- We agreed that prominences scatter the light and that is why we see them.
- They are more dense than the surrounding corona so we see them even out of the eclipse
- Easy way to model brightness of this prominence would be to split it in little 'blobs' and say that each blob scatters light



HINODE NFI observations of a prominence in H alpha, Henzel et al. 2008.

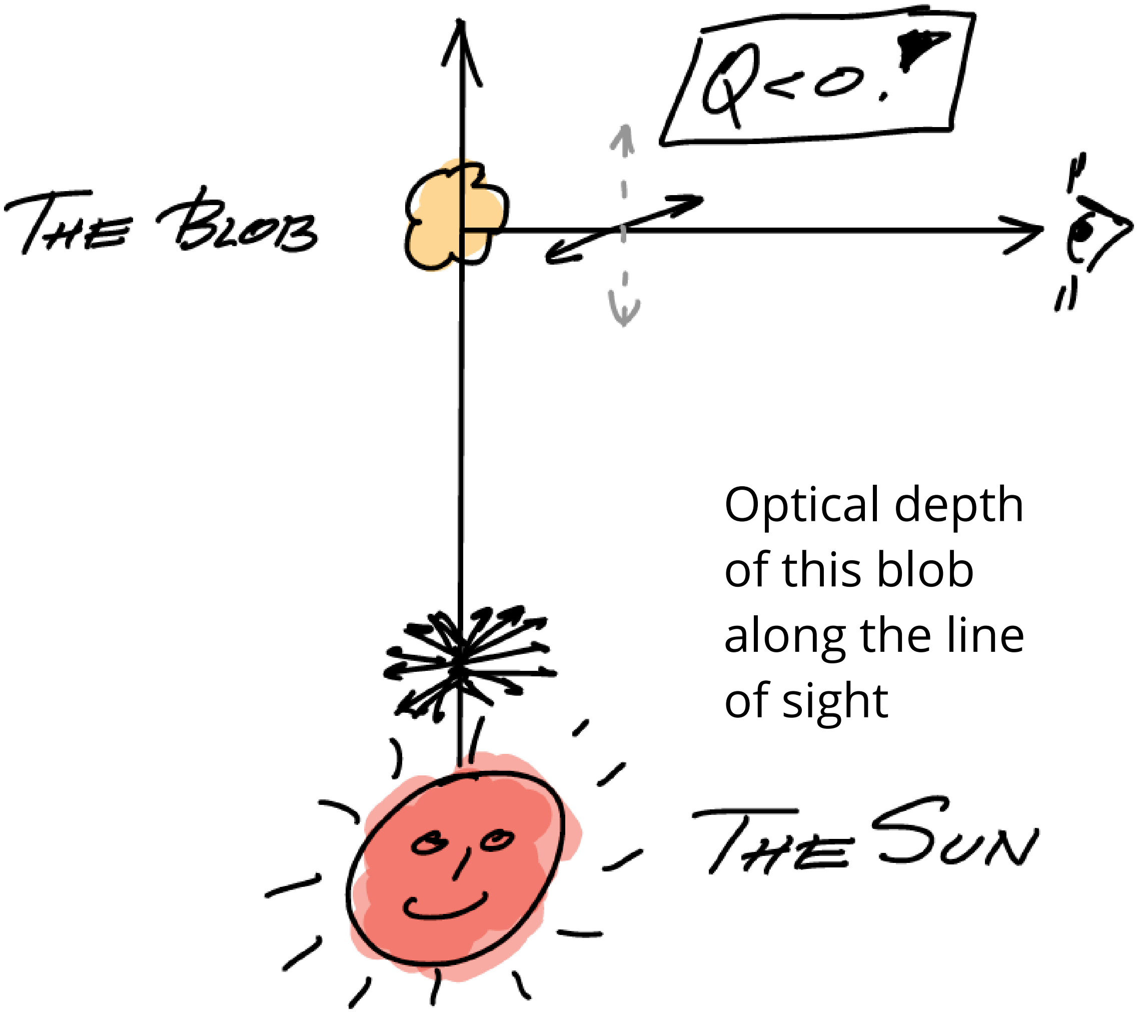
Let’s imagine a Blob very far away from the Sun



- In this (extreme) case, all the light is linearly polarized “parallel to the limb”
- Can we also agree that **I = |Q|** in this case?
- And, separately from that, in the optically thin limit:

$$I_\lambda = S\tau_\lambda = S\tau\phi_\lambda$$

Now let's complicate things a little:



Optical depth of this blob along the line of sight

- Since I wrote RTE (simple one but still a RTE), for stokes I, can we all agree to write one for Q too?
- After all Q is some sort of intensity too!

$$\boxed{\begin{aligned} I_\lambda &= S_I \tau_\lambda \\ Q_\lambda &= S_Q \tau_\lambda \end{aligned}}$$

RTE for scattering polarization

- In principle, I could have went in a bit more detail:

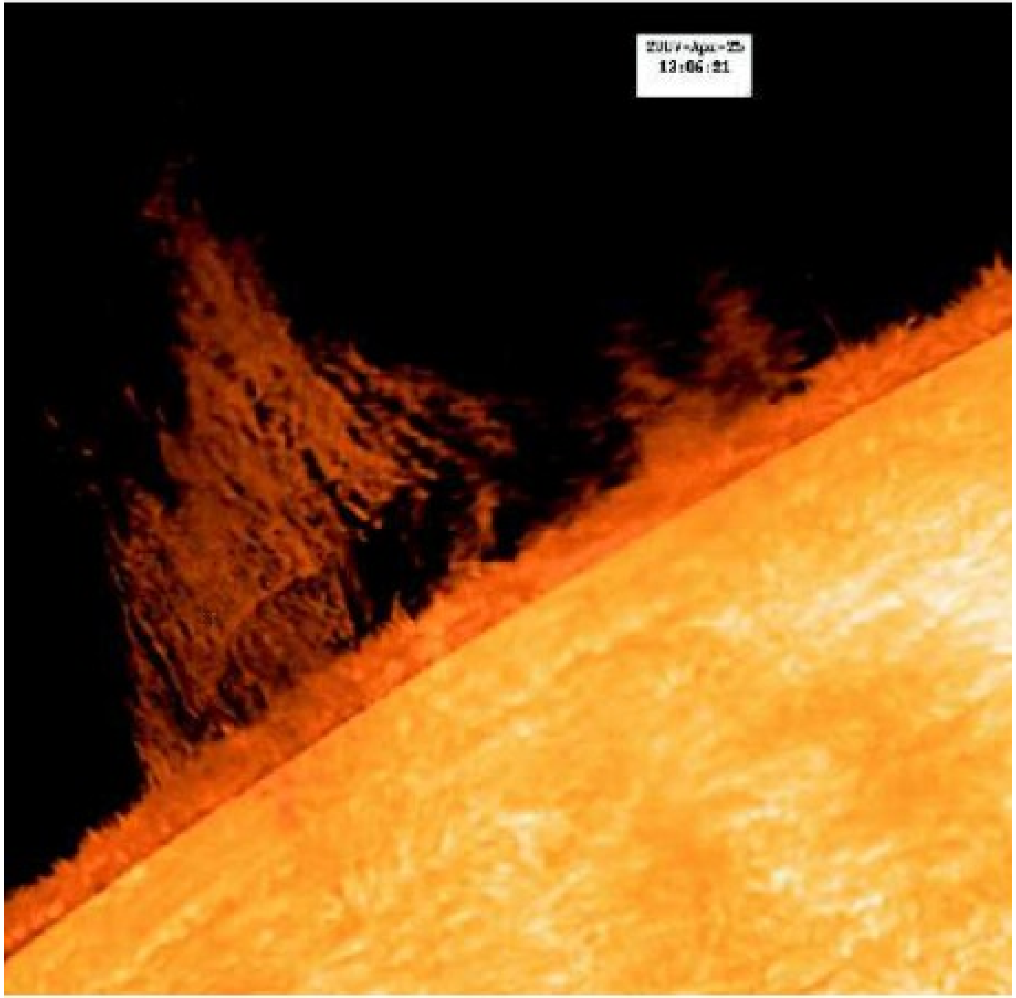
$$\frac{dI_\lambda}{d\tau_\lambda} = I_\lambda - S_I$$

$$\frac{dQ_\lambda}{d\tau_\lambda} = Q_\lambda - S_Q$$

- Two radiative transfer equations, for two components, each of these has it's own Source function.
- This implies that both Stokes I and Q "experience" the same absorption coefficient
- What would be source function for S in general?

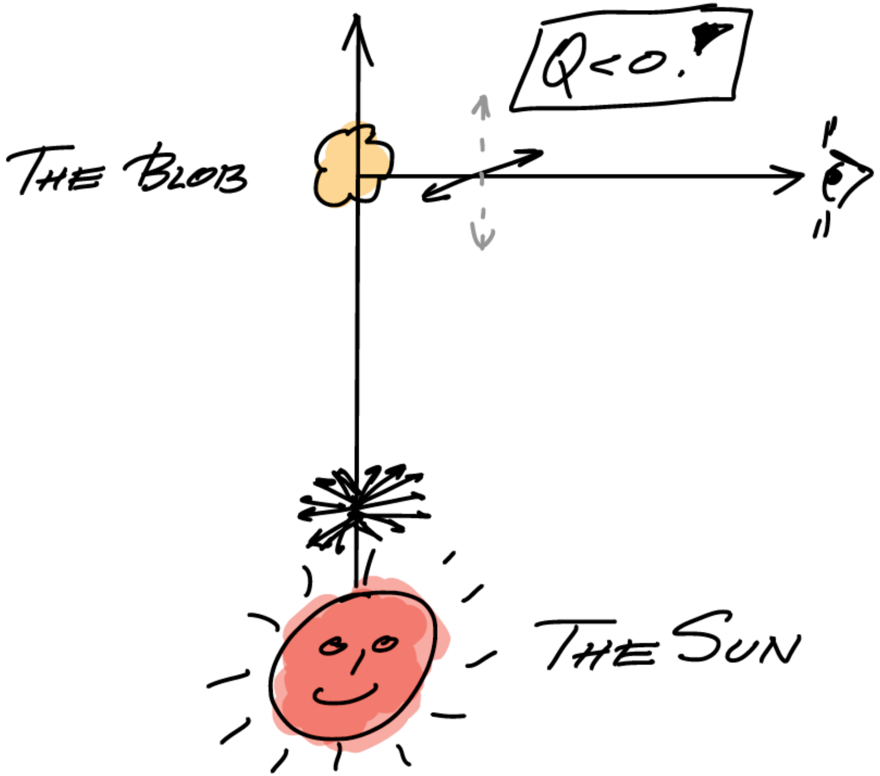
Prominence again

- These prominences are not suspended super super high above the Sun
- That is, they are not illuminated only from one direction
- They are illuminated by a cone of radiation, as we saw yesterday
- How do we proceed now?

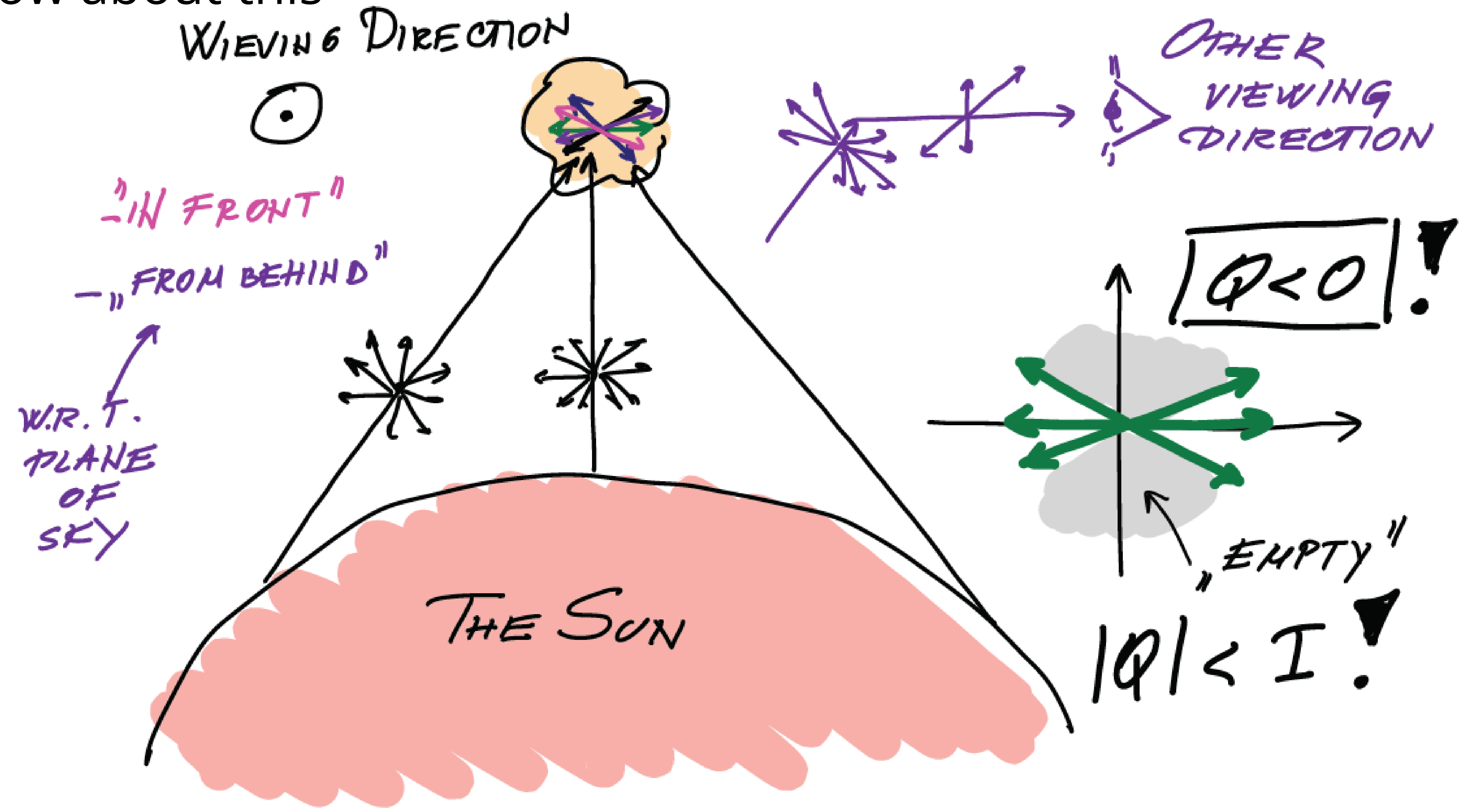


HINODE NFI observations of a prominence in H alpha, Henzel et al. 2008.

Now, take pen, paper and 5 mins and make a sketch similar to this one but for when the prominence is slose to the surface. What is the sign of Q? Is Q still equal to I?
(Hint: You might want to change the “orientation” to make it more obvious. i.e. make the plane of the sky be the plane of you notebook)



How about this



It turns out that (continuum, so no wavelength for now)

$$S_I \approx \frac{1}{2}\int_{-1}^{1} I(\mu')d\mu'$$

$$S_Q \approx \frac{3(\mu^2-1)}{16}\int_{-1}^{1} I(\mu')(3\mu'^2-1)d\mu'$$

- These follow from Rayleigh's scattering. **Note that the Source function for Q is direction-dependent!**
- Can someone tell me difference between mu and mu' ?
- These directions are with respect to the blob
- Let's use the equation to answer some more questions!

What is Source function for Q for isotropic radiation?

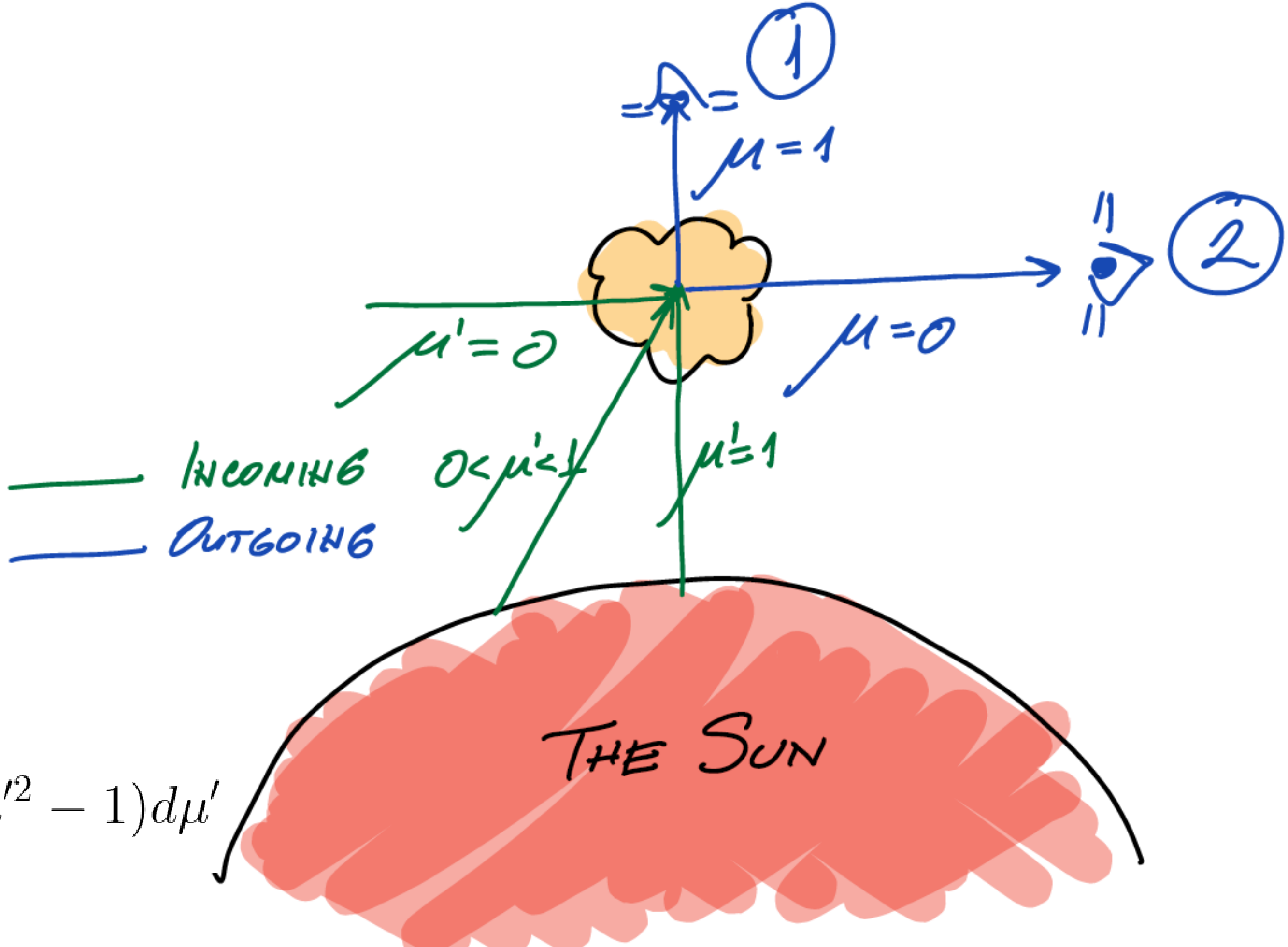
- 3 mins to try and calculate this one

$$S_I \approx \frac{1}{2}\int_{-1}^{1} I(\mu')d\mu'$$

$$S_Q \approx \frac{3(\mu^2 - 1)}{16}\int_{-1}^{1} I(\mu')(3\mu'^2 - 1)d\mu'$$

- We very often refer to S_Q (up to a constant) as a measure of anisotropy of the radiation
- Scattering polarization is a consequence of scattering of light by anisotropically illuminated particles (lot of bold text here)

What is polarization for observer **1?** What sign is polarization for observer **2**?



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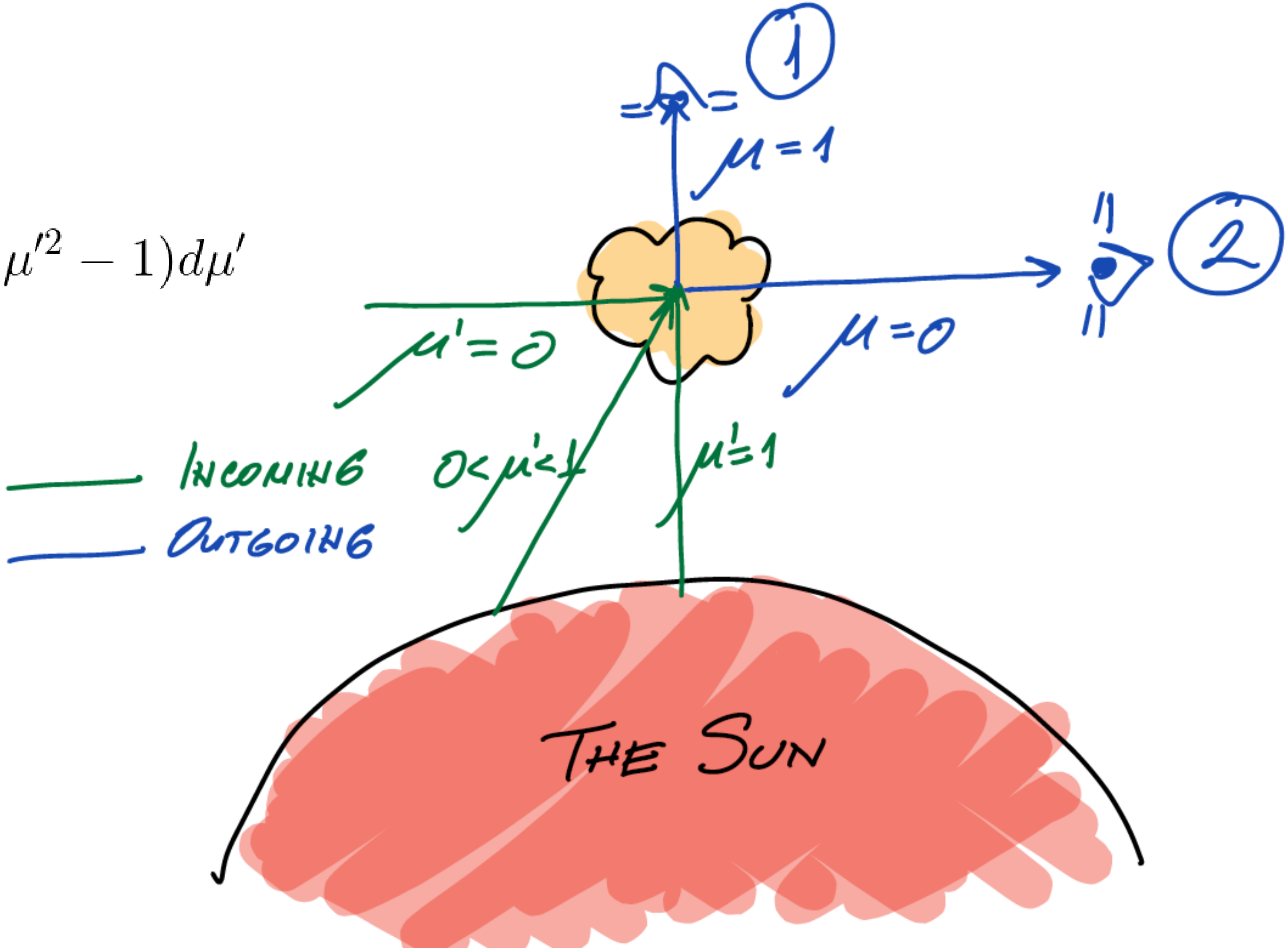


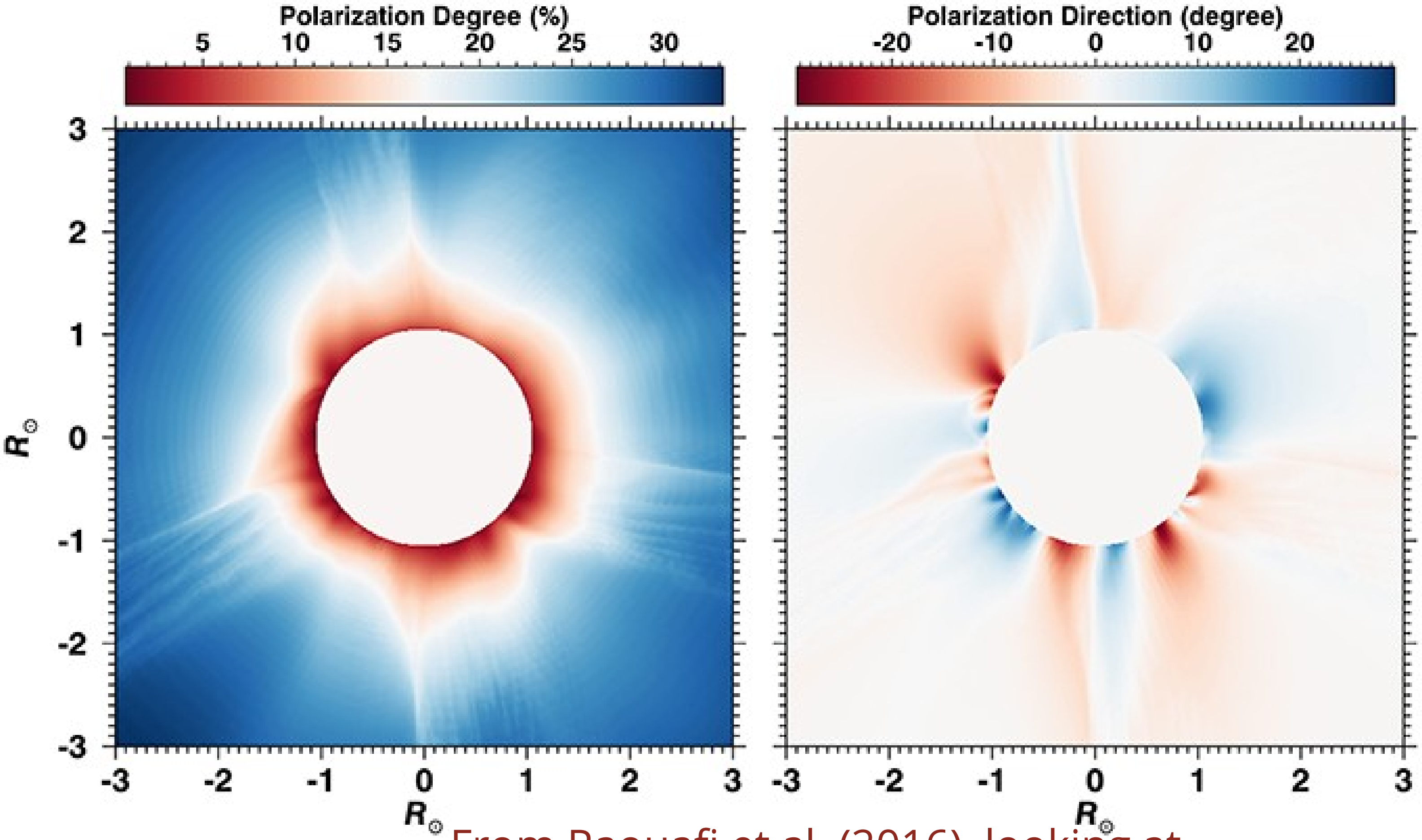
For Observer **1**: Zero, no matter how big the anisotropy is

For Observer **2**: Q<0, since the term in front is negative

Summary of scattering polarization

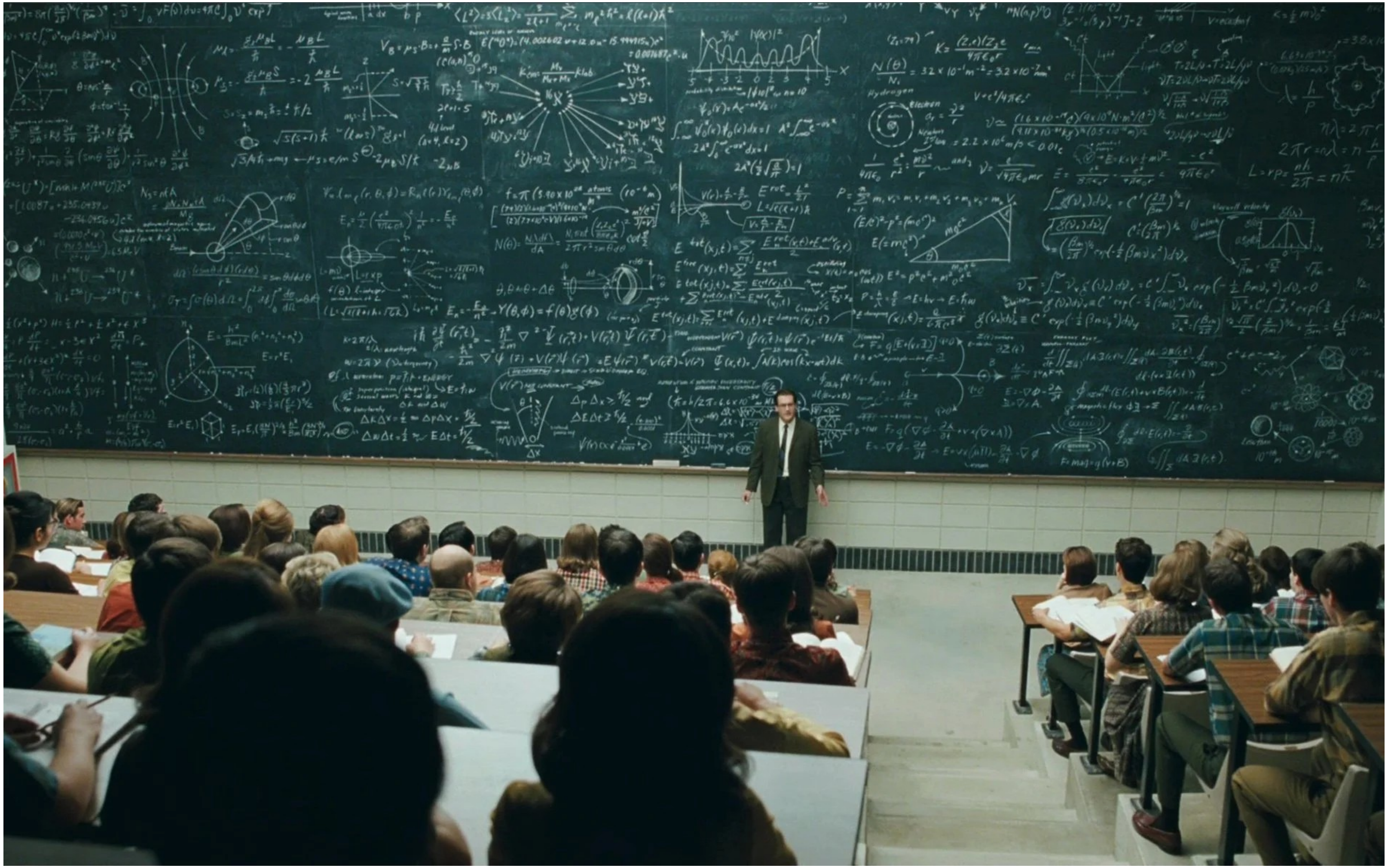
- It appears when, we have, well, scattering
- It is a measure of anisotropy. More anisotropically illuminated the scattering material is , more polarization
- But it is also a function of geometry: We have to be in a convenient viewing direction (no polarization at the disk center)
- There is more to this when you take into account stuff is 3D, but let’s leave that to some other workshop (HAO workshop 2022 !?)

All this is also applicable to corona



From Raouafi et al. (2016), looking at 10830 He line – forward modeling

Now, the spectral lines! (Serious man, Cohen & Cohen, 2009)



Now, the spectral line

Additional integration over wavelength since the line redistributes the light

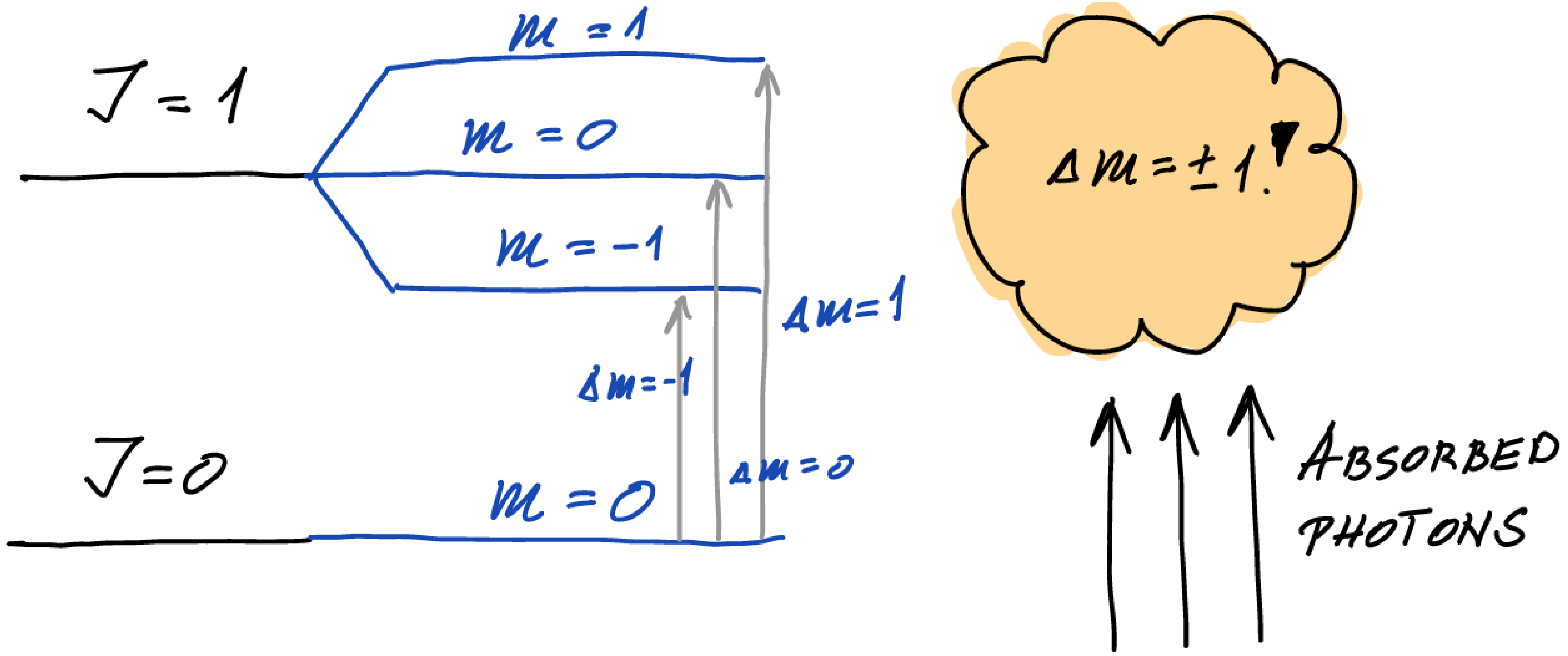
$$S_I \approx \frac{1}{2}\int_{-1}^{1}\int_{-\infty}^{\infty} I(\mu', \lambda)\phi_\lambda d\lambda d\mu'$$

$$S_Q \approx \frac{3(\mu^2-1)}{16}\frac{1}{1+\delta/\Gamma_R} w_0^2 \int_{-1}^{1}\int_{-\infty}^{\infty} I(\mu', \lambda)(3\mu'^2-1)\phi_\lambda d\lambda d\mu'$$

Collisional depolarization, something like line damping

Intrinsic line polarizability.

Why are spectral lines polarized due to scattering?



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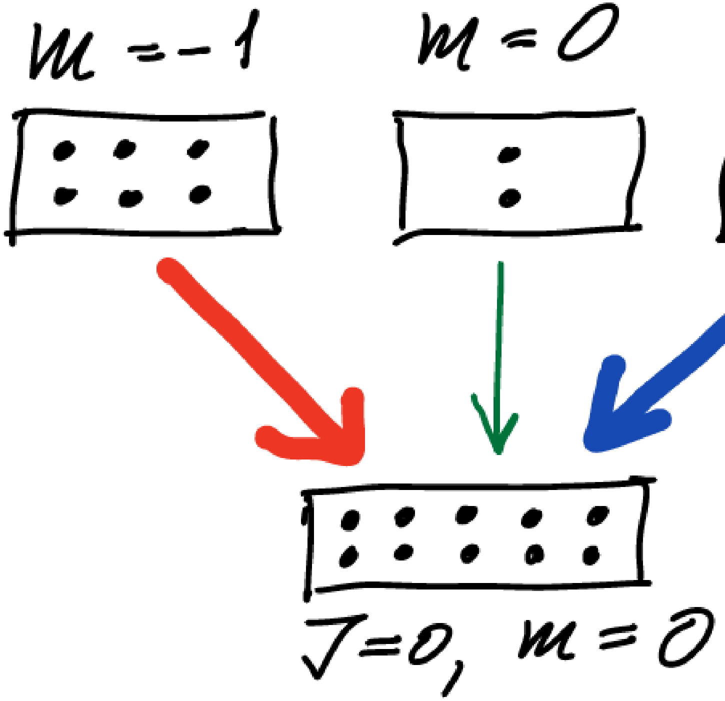
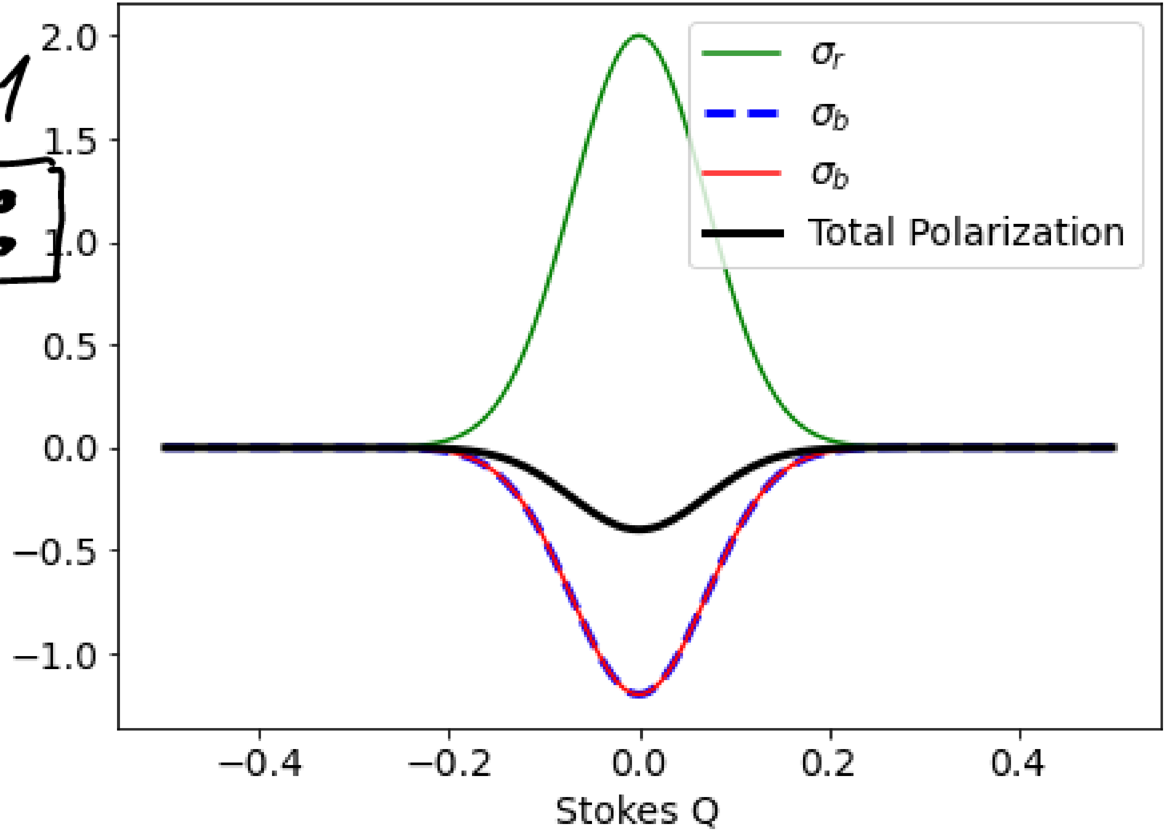




Let's say I want to calculate I,Q (U), what do I do?

$$\hat{J} = (J_0^0, J_0^2, J\_2^2, J\_1^2, J_1^2, J_2^2)^\dagger$$

$$\hat{S} = (S_I, S_Q, S_U)^\dagger$$

$$\hat{I}_\lambda = (I_\lambda, Q_\lambda, U_\lambda)^\dagger = \hat{S}\tau_\lambda$$

- It turns out that:

"Projection" matrix. Takes care of angular dependence of the outgoing radiation

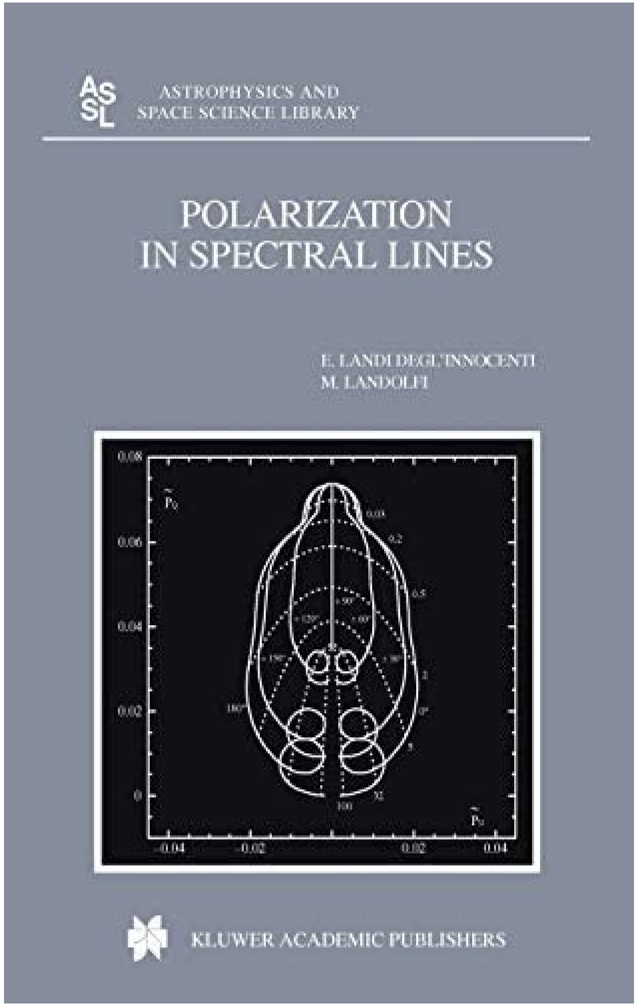
$$\hat{S} = \hat{P}(\mu)\hat{W}\hat{W}_{\rm dep}\hat{J}$$

Collisional depolarization. For some lines negligible, for some lines actually an interesting diagnostic tool! - diagonal matrix

Intrinsic line polarizability – diagonal matrix

The ultimate text: Polarization in Spectral Lines

- A texbook that starts from first principles and derives spectral line polarization via density matrices and proper quantum mechanics
- Not for faint of heart
- Also includes magnetic fields and their effect (i.e. Hanle effect)
- Very little “radiative transfer” in the sense that the goal is to understand the atoms

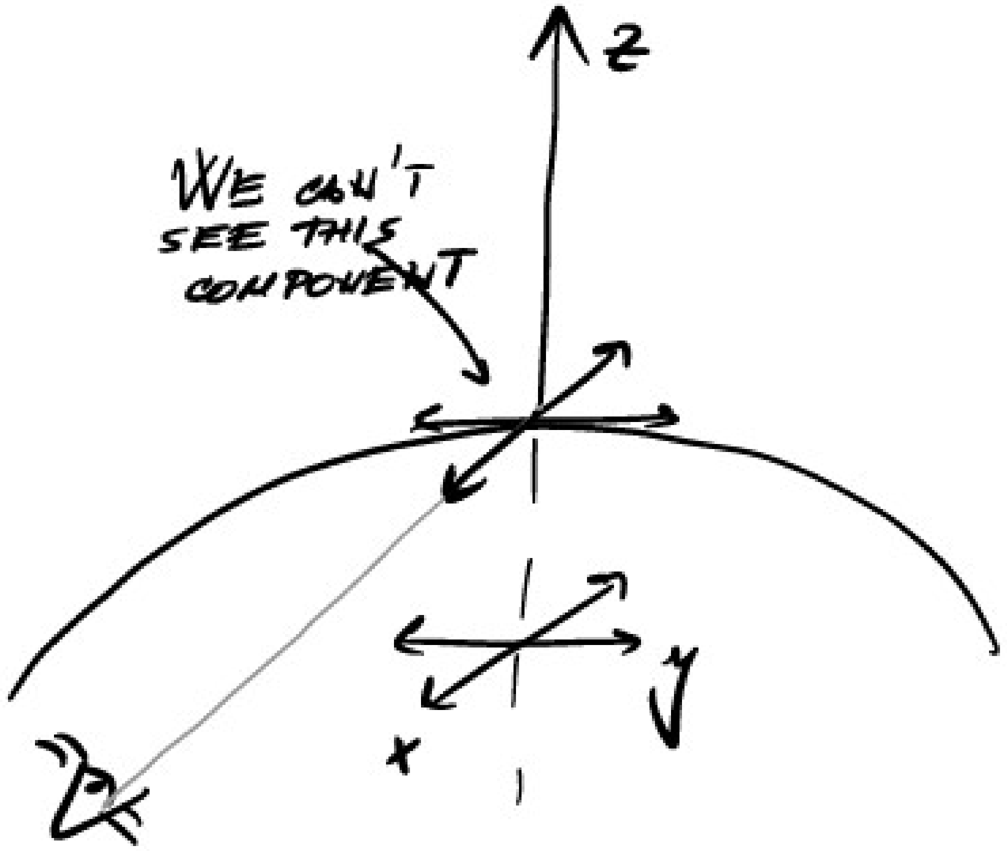


What is this “Hanle effect”?

- Hanle effect is a consequence of interaction between the magnetic fields and “polarized” Zeeman sublevels
- Instead of shifting them completely, magnetic field “shuffles” the Zeeman level coherences around / changes the referent axis
- Two important consequences:
- **Decrease of polarization (depolarization)**
- **Rotation of polarization (Some Q goes into U)**
- **Another way to look at this is classically: The oscillator precesses around the magnetic field axis.**

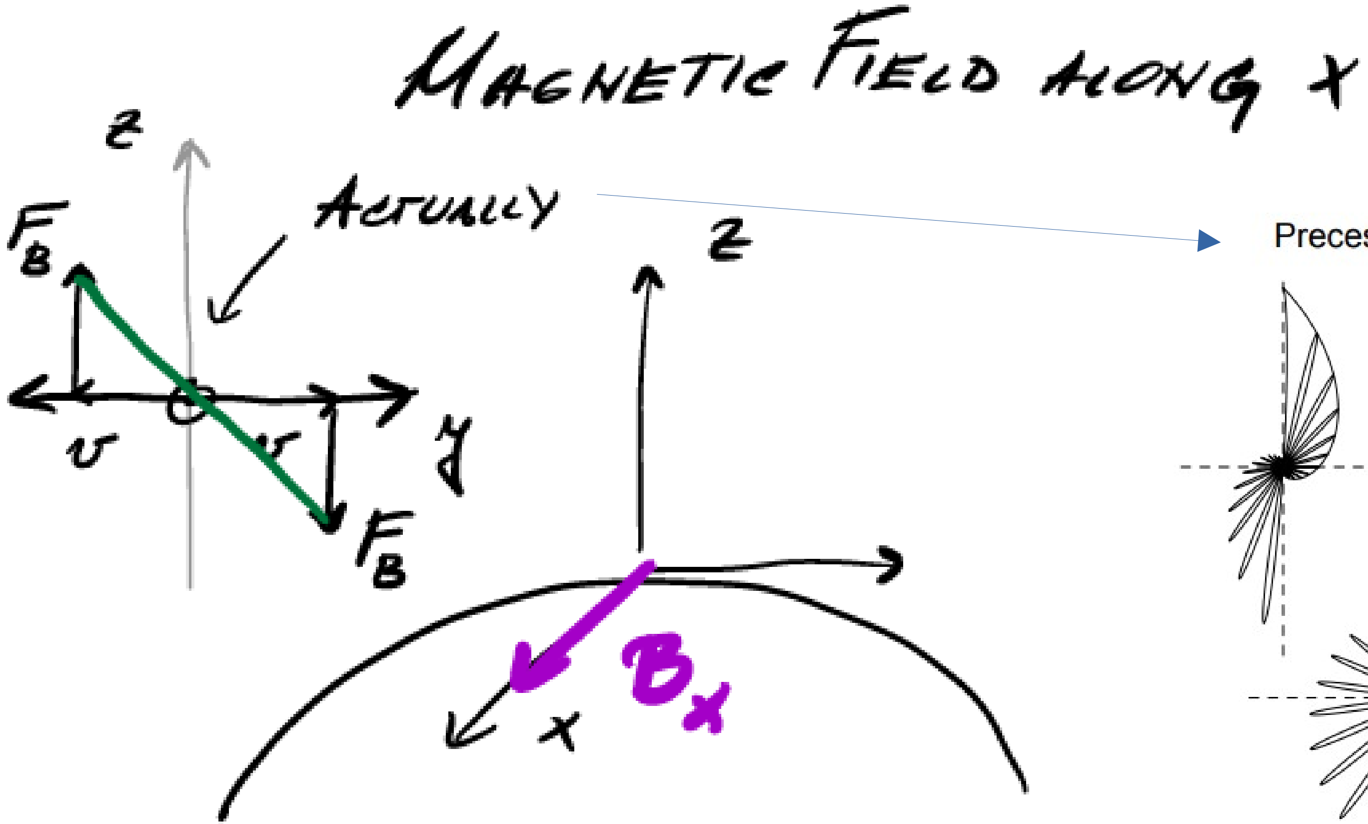
So let's look at it classicaly:

- To simplify the situation, let's consider scattering at the limb, and the radiation is coming directly from below.
- In that case, E oscillates in x and y only (incoherently), and we only can see the y component because we are looking along y

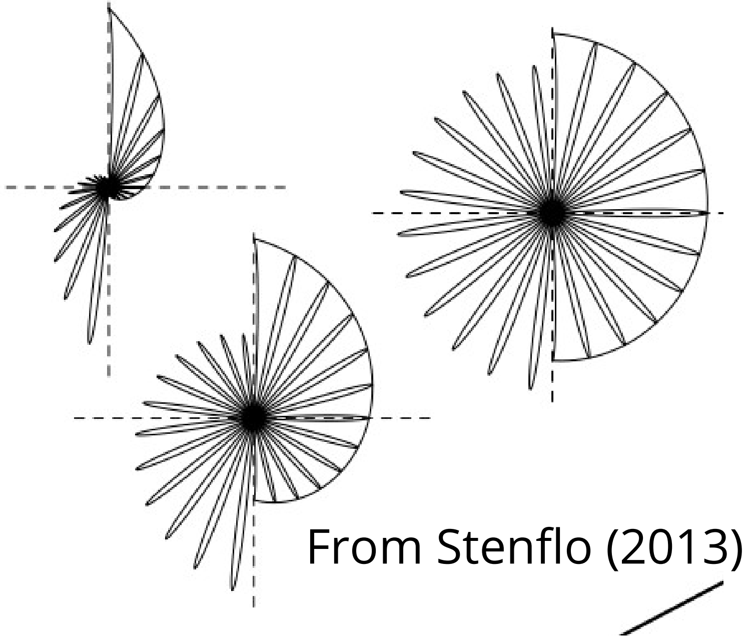


Now let's add the magnetic field along **x**

following Trujillo Bueno 2001 ("Atomic polarization and the Hanle effect")



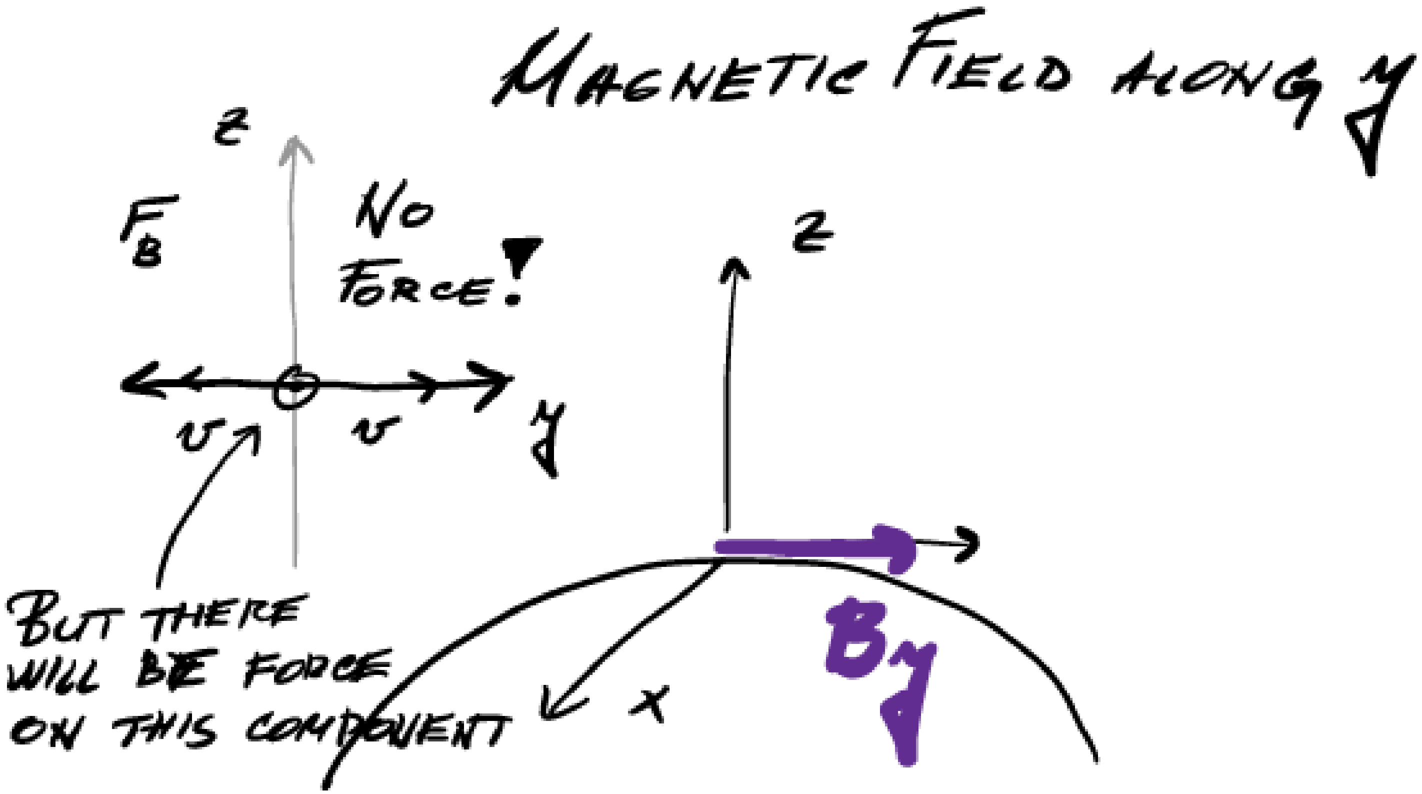
Precessing classical oscillator



From Stenflo (2013)

Now let's add the magnetic field along **y**

following Trujillo Bueno 2001 ("Atomic polarization and the Hanle effect")



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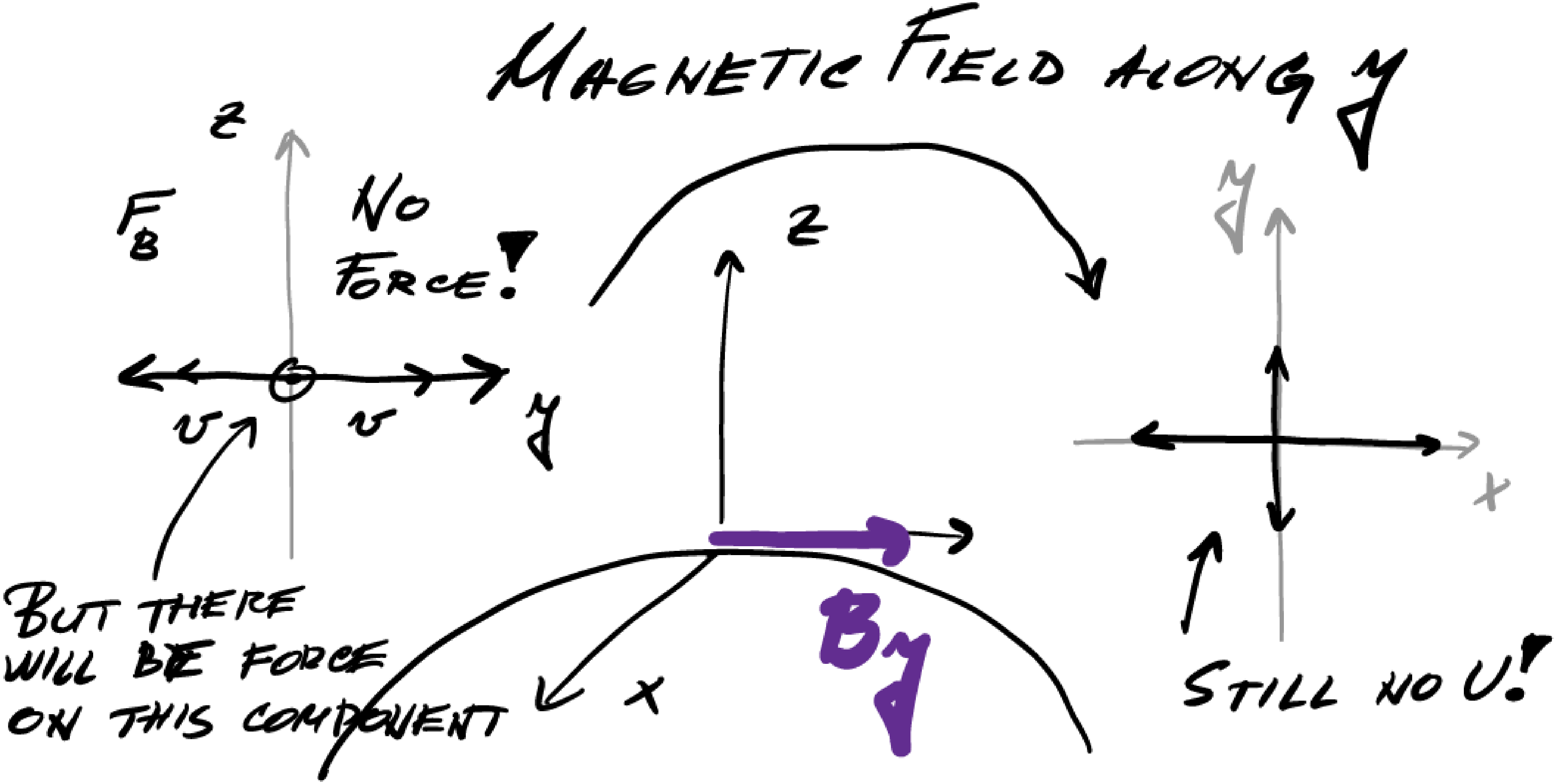


Formal (but simplified) way to illustrate this would be:

Polarized RTE

$$\frac{\hat{I}_\lambda}{d\tau} = \hat{I}_\lambda - \hat{S}_\lambda$$

$$\hat{S}_\lambda = \hat{H}\hat{J}_\lambda$$

“Hanle Matrix”, rotates and decreases polarized sources. Becomes important at:

$$\frac{0.88 g B \times 10^7}{A_{ul}} \approx 1$$

$$\hat{I} = (I, Q, U)^\dagger$$

Polarized Source Function

$$\hat{S} = (S_I, S_Q, S_U)^\dagger$$

$$\hat{J} = (J_I, J_Q, J_U)^\dagger$$

Zero in the absence of horizontal anisotropy

Mean intensity

Vertical anisotropy

Or, talking in our new language (6-vectors and 3-vectors)

- There is an additional, “Hanle matrix” that multiplies (rotates and diminishes) our mean intensity six-vector
- Contrary to other matrices in the story this one is non-diagonal and it “shuffles” components. Eventually this results in some of “vertical” anisotropy, that would regularly produce only Stokes Q, to produce some Stokes U!

$$\hat{S} = \hat{P}(\mu)\,\hat{W}\,\hat{W}_{\rm dep}\hat{W}_H\hat{J}$$

Or in the specific case of He 10830

- To find the polarized intensity we need polarized source function:

$$\hat{I}_\lambda = \hat{S}_\lambda \tau_\lambda = \hat{S}_\lambda \, \tau \, H_\lambda(a, \Delta\lambda_D, \lambda_0)$$

Constant, depends on the boundary condition

$$\hat{S} = \hat{P}(\mu)\hat{W}\hat{W}_{\mathrm{dep}}\hat{W}_H\hat{J}$$

Constant, comes from Rayleigh scattering law

Constant, depends on the spectral line

Can be ignored for He 10830

Depends on the magnetic field vector, **so three parameters**

Sensitivity to Hanle effect

- Can we just neglect Hanle and rely on Zeeman?
- The difference is in the sensitivity!
- Recall that Zeeman broadening is:

$$\Delta\lambda_{\mathrm{Zeeman}} = 4.67 \times 10^{-13}\lambda^2 g B$$

- And Doppler broadening is:

$$\Delta\lambda_D = \frac{v_{\mathrm{random}}}{c}\lambda$$

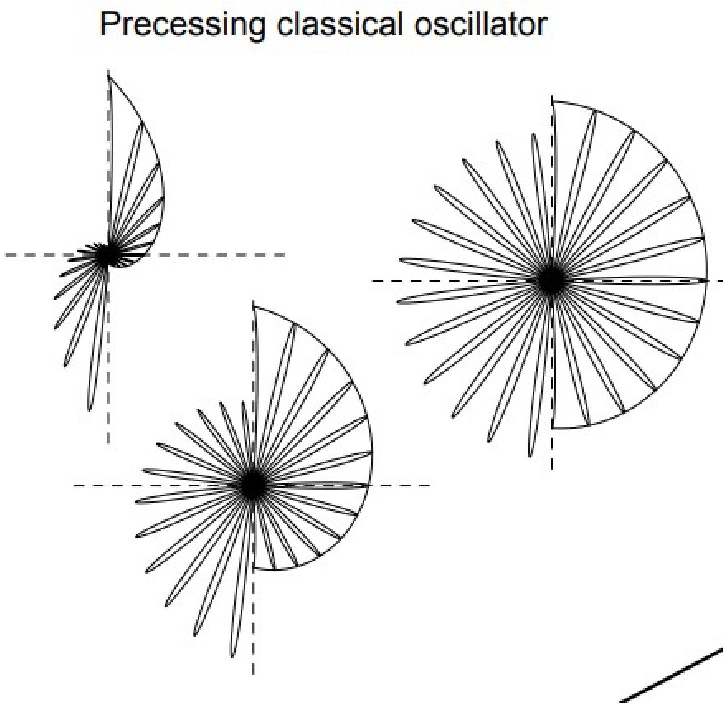
- And critical Hanle field $$\frac{0.88 g B \times 10^7}{A_{ul}} \approx 1$$

In the classical sense:

Precession period due to the presence of the magnetic field

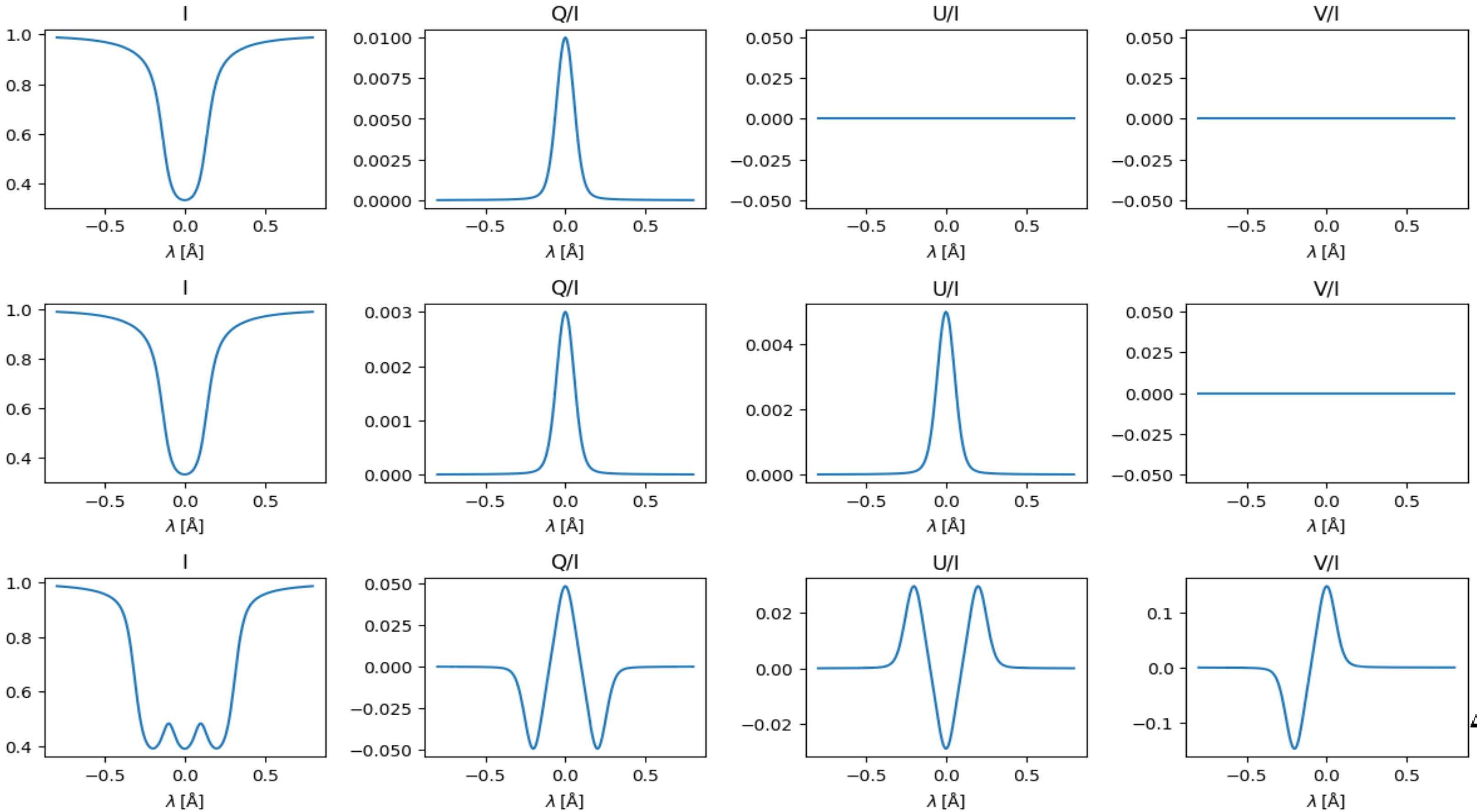
$$\frac{0.88gB \times 10^7}{A_{ul}} \approx 1$$

Damping scale of the damped classical oscillator



In limb scattering, if this is much larger than 1, polarization is completely destroyed!
(Because the oscillator oscillates equally in all the planes)

Three regimes of spectral line polarization



Pure scattering, no magnetic field

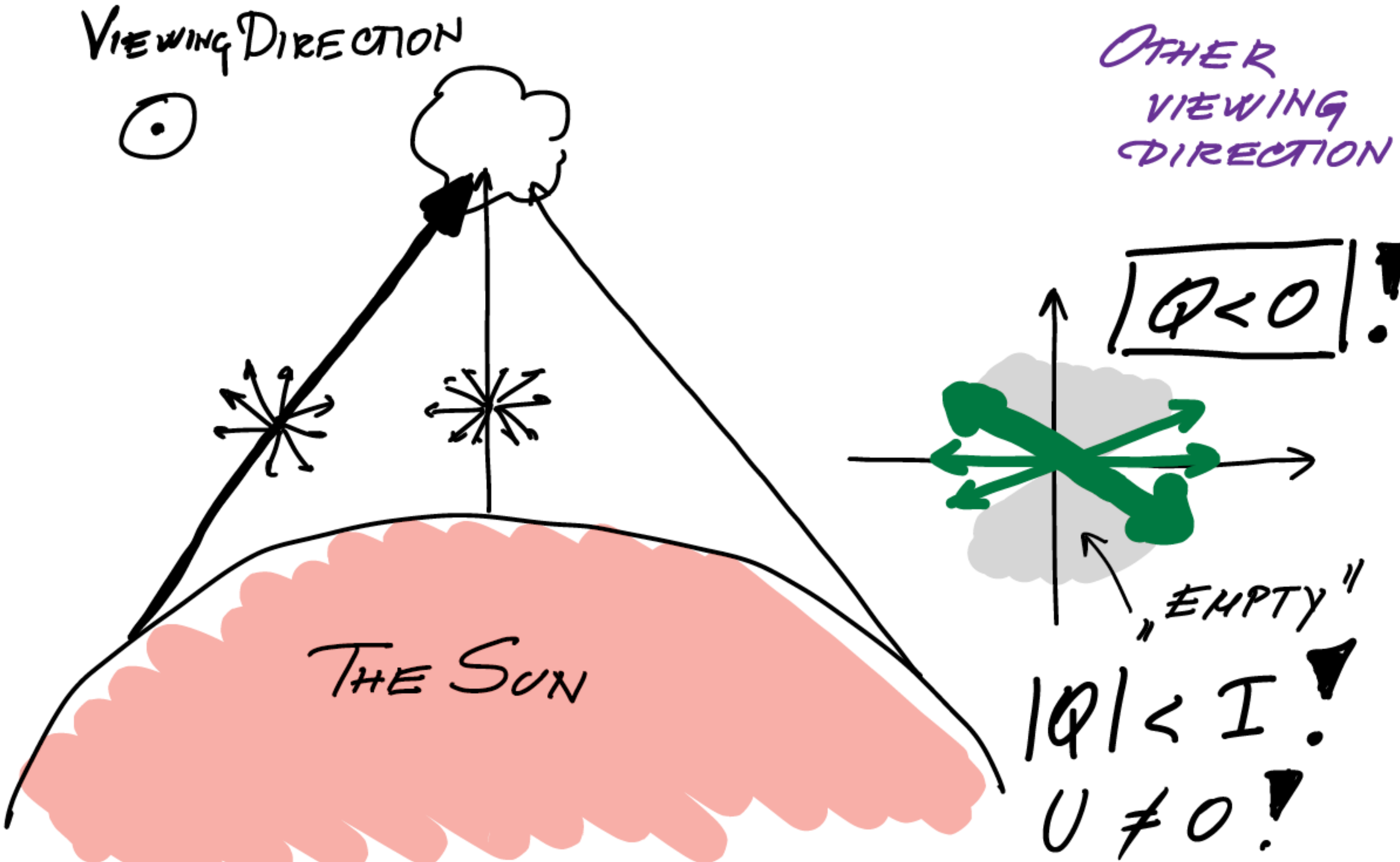
Weak magnetic field

$$\frac{0.88 g B \times 10^{7}}{A_{ul}} \approx 1$$

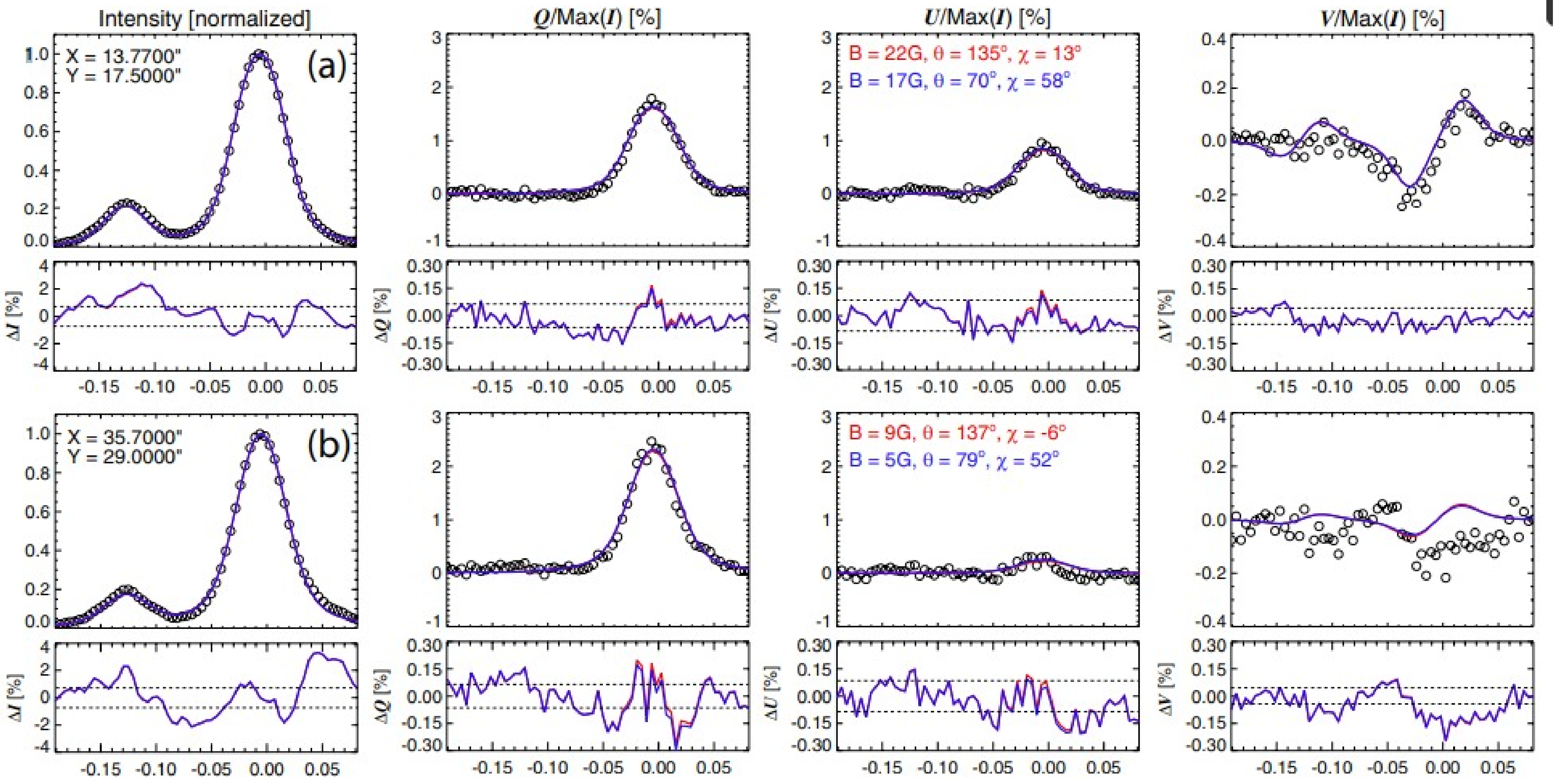
Strong magnetic field

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

Of course in principle, spatial anisotropy could create U, too



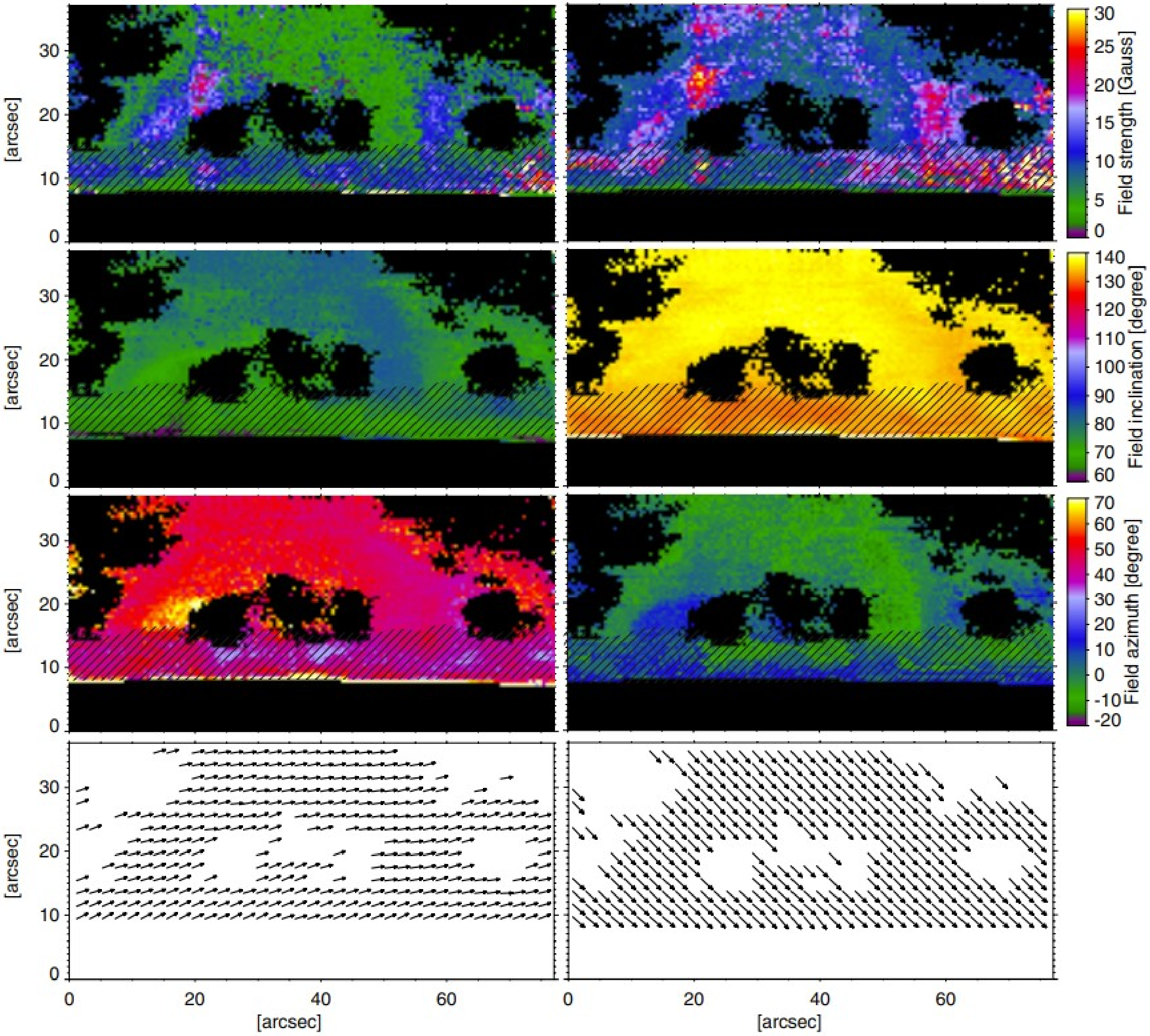
Fitting the observed profiles allows us to infer the weak magnetic field (Orozco Suarez et al. 2014)



Ambiguity

- Equations that describe the rotation (that we did not see in detail, but if you want to- let me know), yield identical polarization for multiple values of the magnetic field strengths and orientations

- This is the ambiguity that always yield two different solutions



Summary:

- Scattering polarization comes naturally with the scattering of the light
- It is sensitive to the viewing geometry and the anisotropy of the incoming radiation
- Hanle effect then depolarizes (or sometimes, polarizes), and rotates this polarization
- To infer the magnetic field responsible for Hanle effect, **we need to know the zero case, i.e. parameters that determine the scattering polarization.**
- Now let’s go to a jypyter notebook and make some examples!