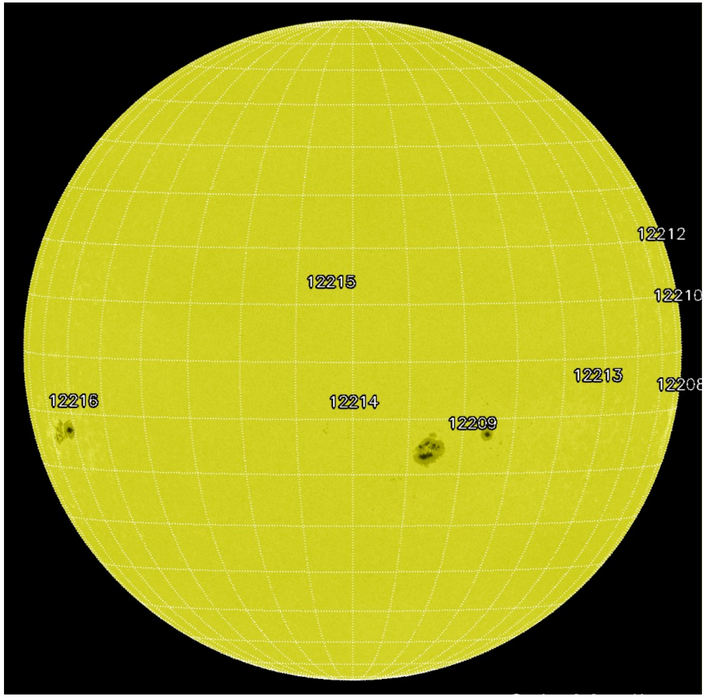
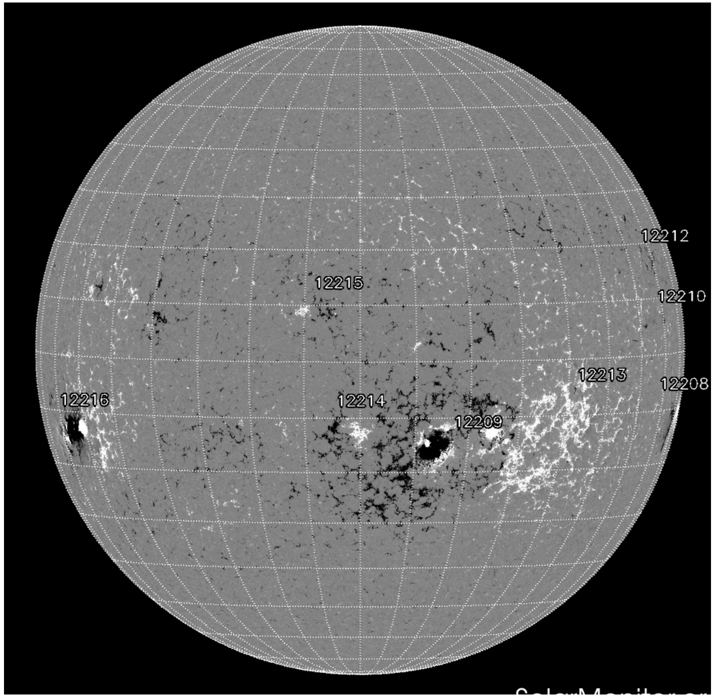




Inferring properties of the solar atmosphere from the spectropolarimetric observations using neural networks

Ivan Milić – Leibniz Institute for Solar Physics (KIS) and University of Belgrade

Workshop on Deep Learning Algorithms for Space Research and Data Imaging; 23/02/2023

Takeaways

- Sun is the only star we can see in high spatial resolution. We combine this with the spectral information – imaging spectroscopy / spectropolarimetry
- We want to interpret spectra at each observed pixel and map the solar atmosphere in 3D
- Forward problem (spectra calculation) is hard because the physics is complicated
- In addition to the spectrum formation, we also care about the polarization (Zeeman effect, scattering, Hanle effect)
- The inverse problem is even harder. But it’s worth it.
- Traditionally, this is where we intersect with convex optimization, today, we hope that DNNs can help us to increase:

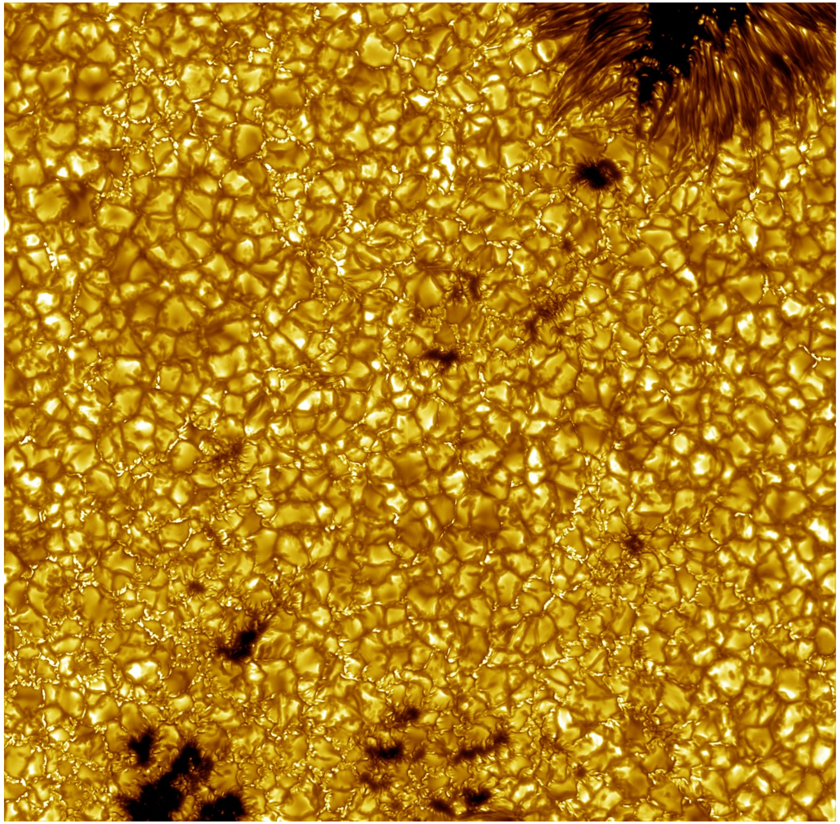
  Speed, Realism and Precision

- The goal of this talk is to give you a theoretical introduction to the problem and hint at the current trends

Why is the Sun so special?

$$\theta = 1.22\frac{\lambda}{D} = 0.012\,''$$

$$\rho = R_\odot/d = 0.004''$$



$$\theta = 1.22\frac{\lambda}{D} = 0.083\,''$$

$$\Delta x = \theta \times 1\mathrm{AU} = 61\,\mathrm{km}$$

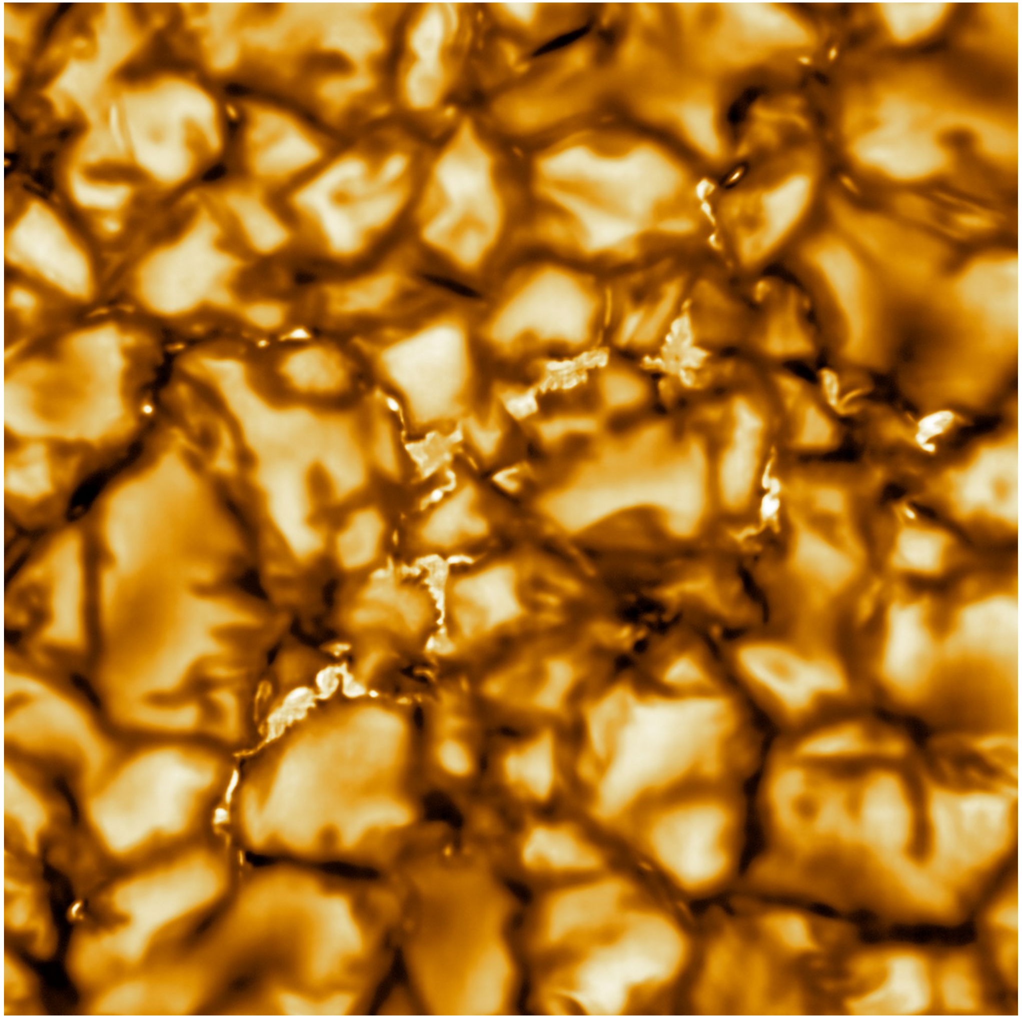
Now we can do even better

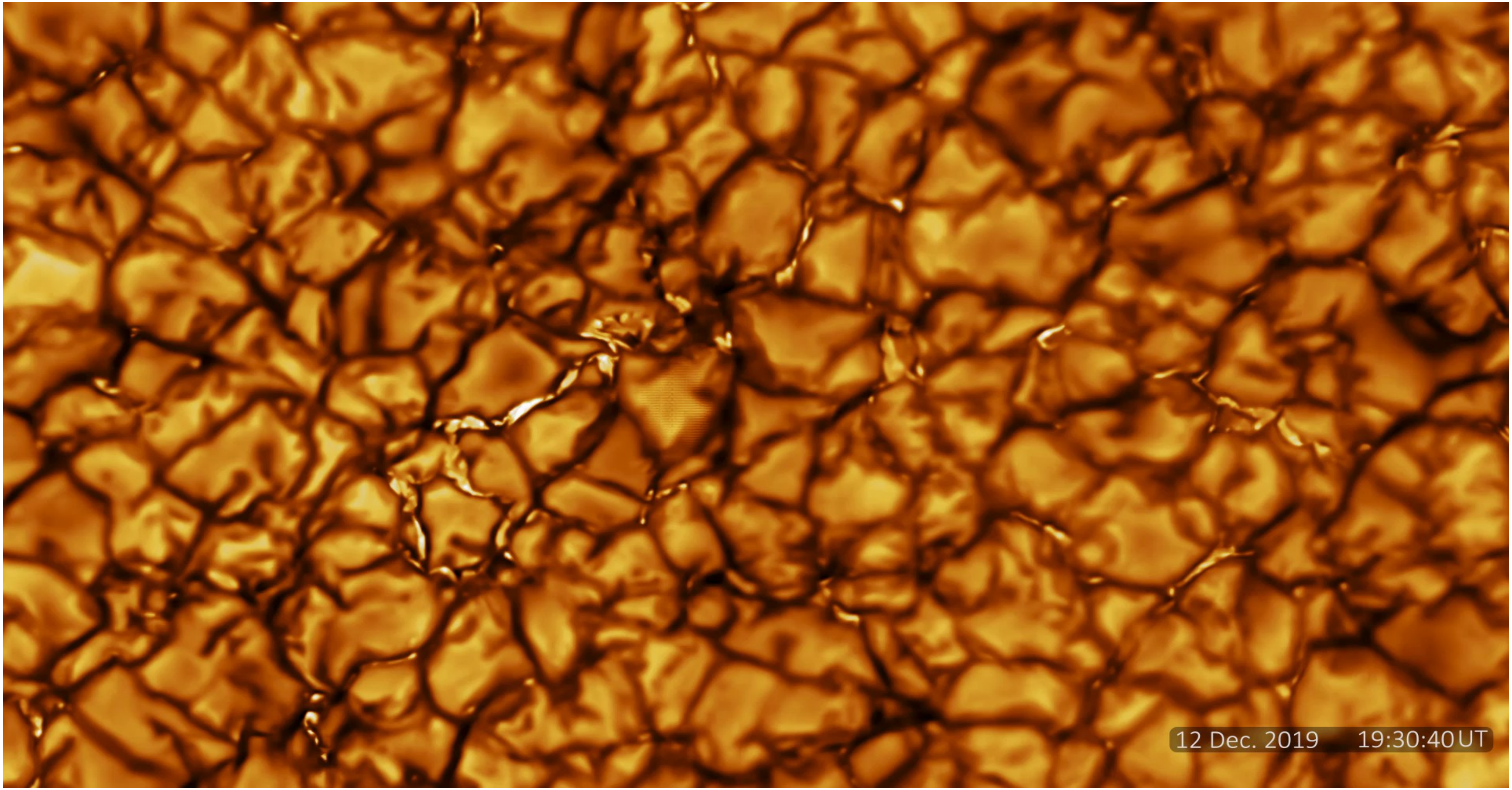
- **Right:** First broadband images of solar granulation by the DKIST (4m solar telescope operated by **NSO**).
- Pixels on this image are ~ 20km. This is big deal as we actually see the structure on this order of sizes.
- **Ideally,** we will have a spectrum at each point.
- DKIST has a suite of instruments to do that:

  Visible Spectropolarimeter (ViSP, slit spectrograph)

  Diffraction Limited Near Infrared Spectropolarimeter (DL-NIRSP, IFU)

  Visible Tunable Filter (VTF, Fabry-Perot)

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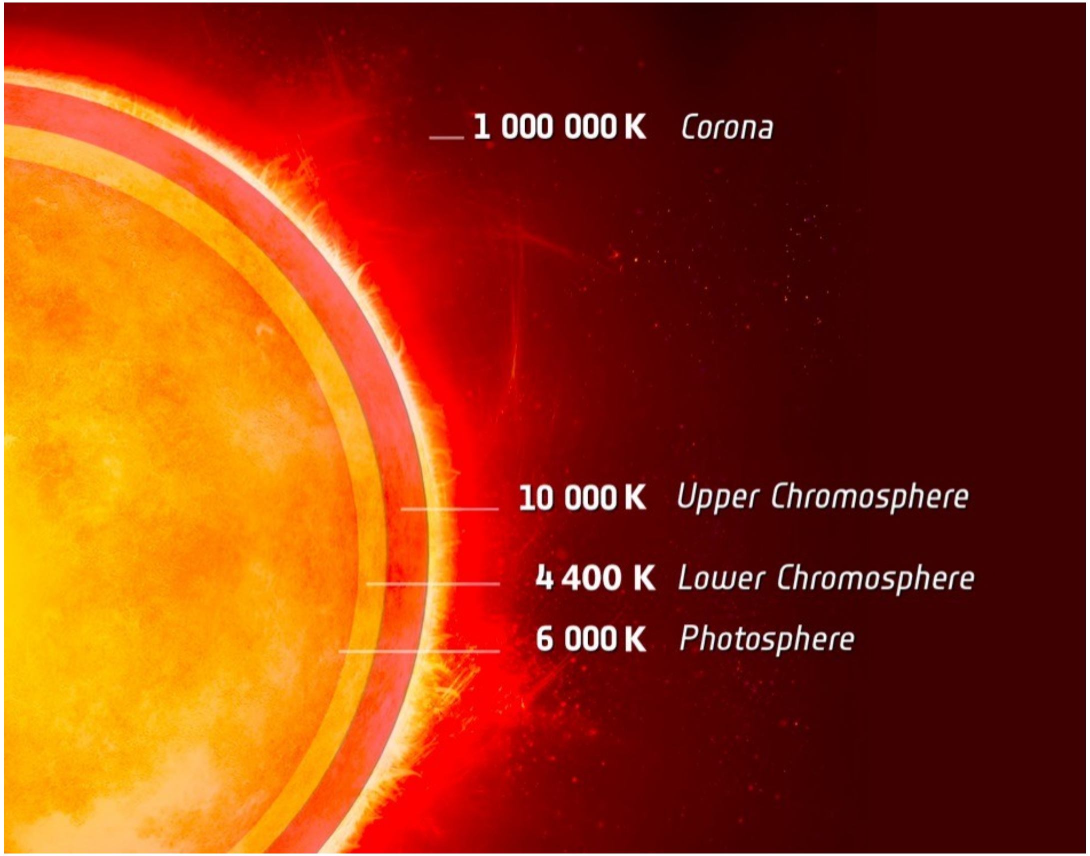
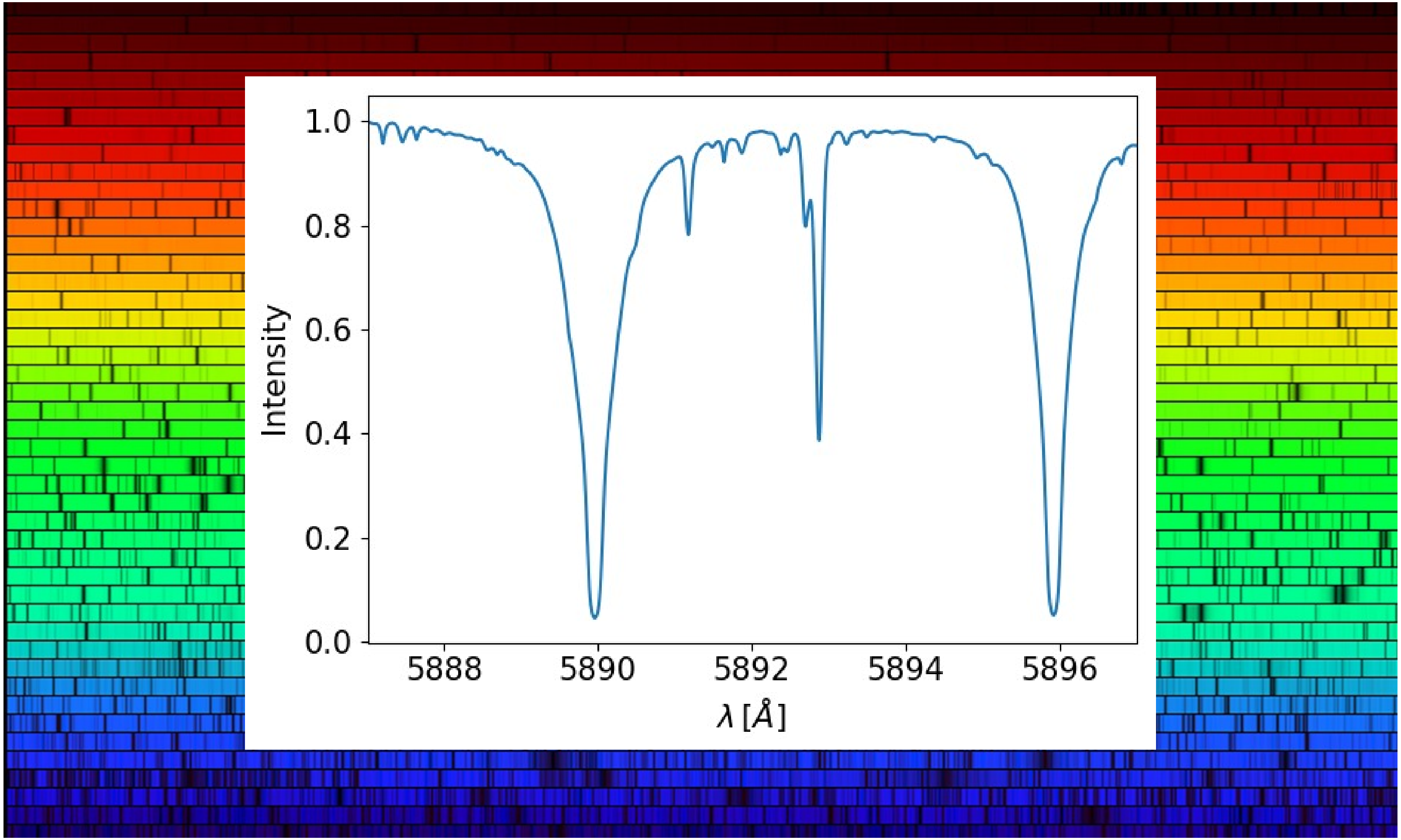
What do we actually see: solar atmosphere

- **What is the solar atmosphere?**
- There is no sharp distinction: atmosphere begins at the point where the photons start escaping
- *„Why would anyone want to study a stellar atmosphere? It takes only a 10^{-10} of the total mass of the star. Surely such a small fraction cannot have any influence on the star as a whole!“*
(Edward Salpeter to Dmitri Mihalas)
- Short answer: Because we cannot see deeper!

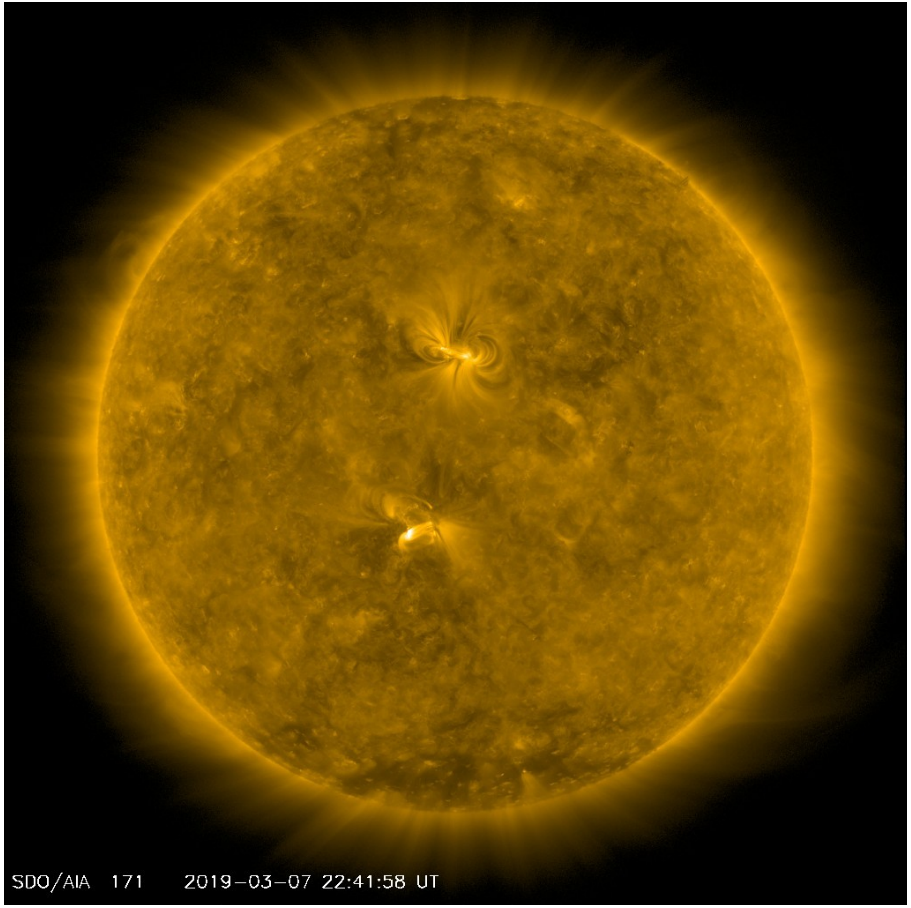


Solar Spectrum

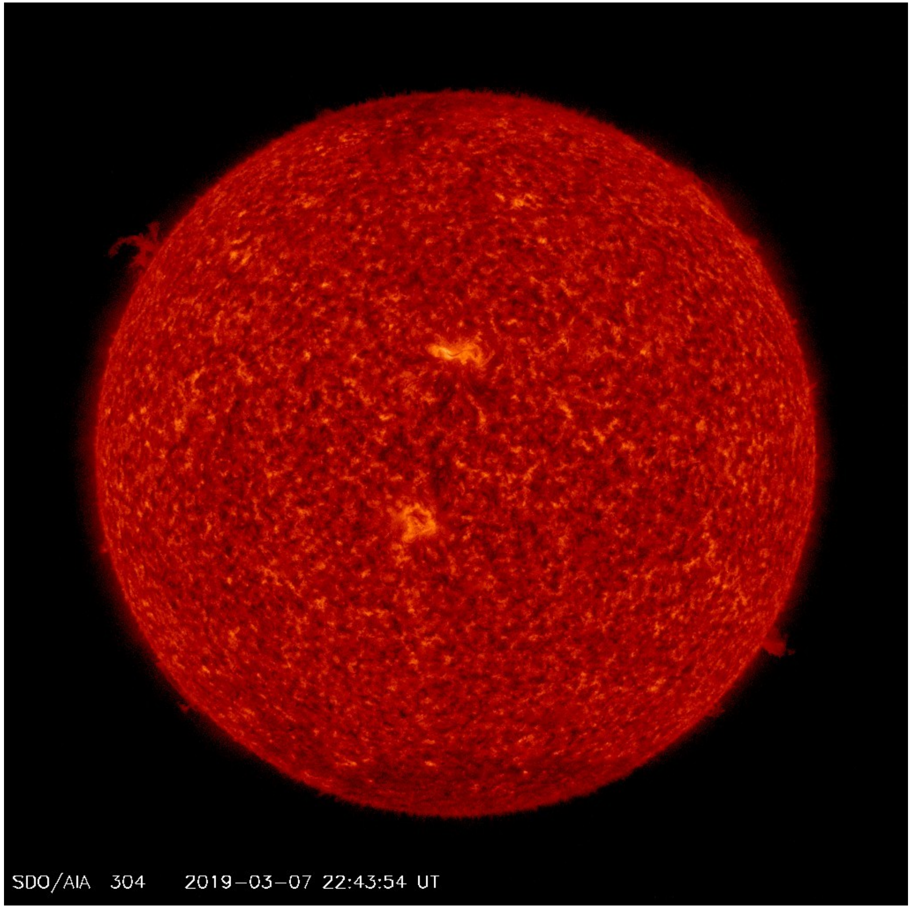


N.A.Sharp, NOAO/NSO/Kitt Peak FTS/AURA/NSF

The solar atmosphere is inhomogeneous



171 Angstrom

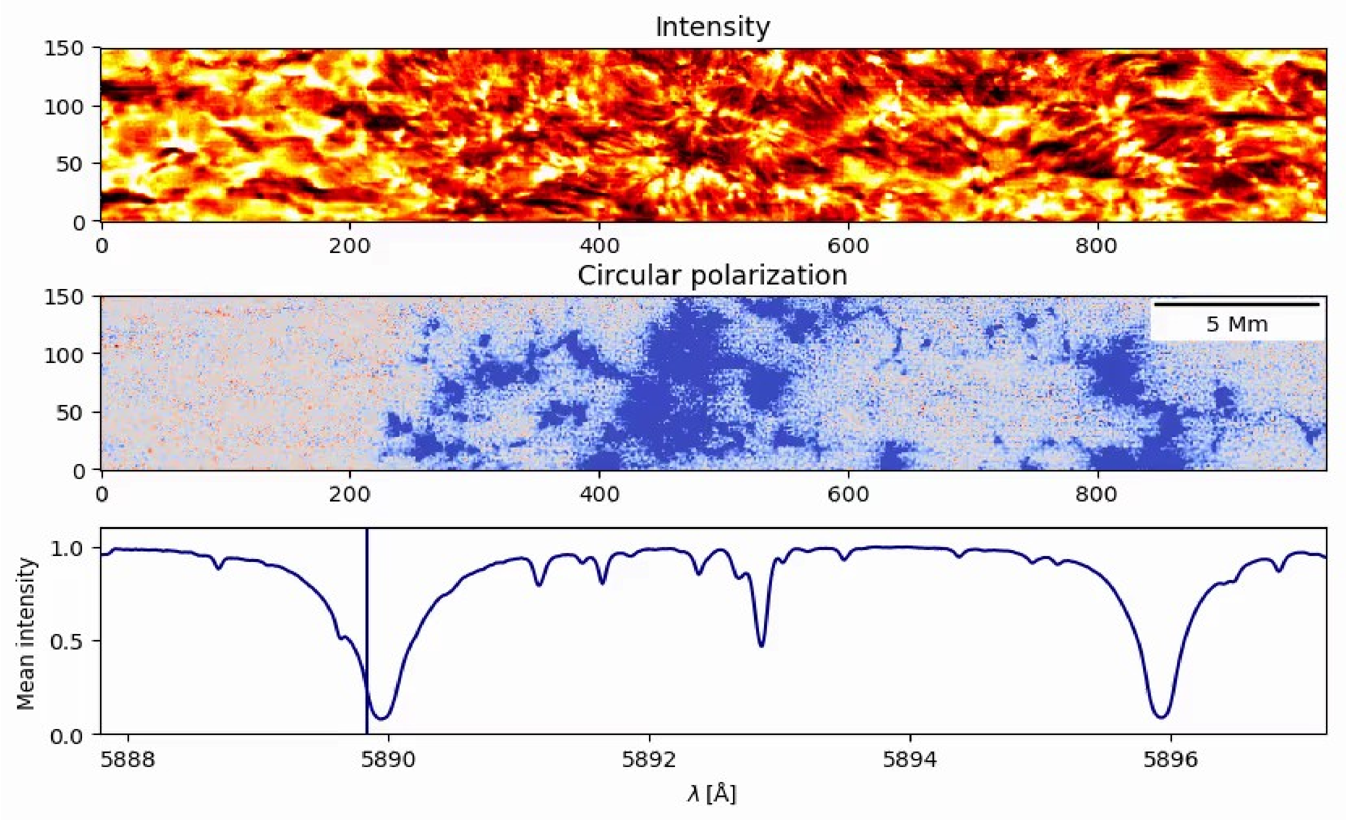


304 Angstrom

Credits: SDO/AIA

The solar atmosphere is inhomogeneous on various scales

~ 6 Mm

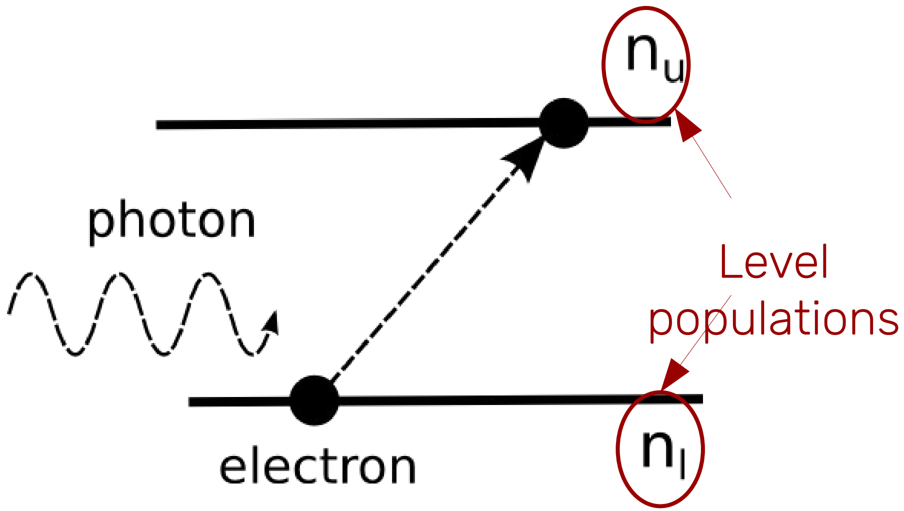


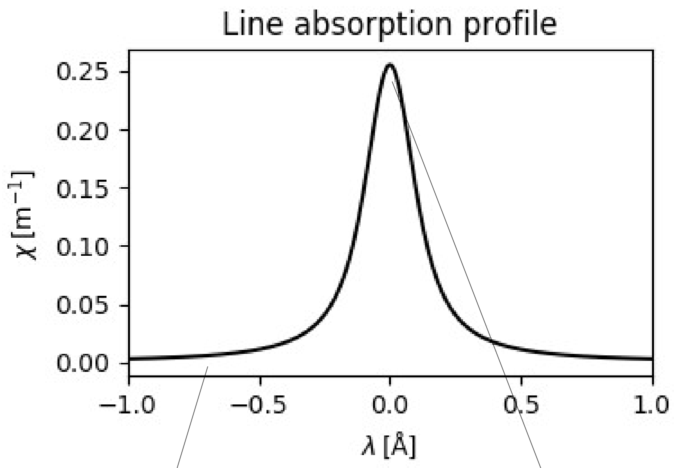
Time → Wavelength; Data obtained at Swedish Solar Telescope (van Noort, 2017)

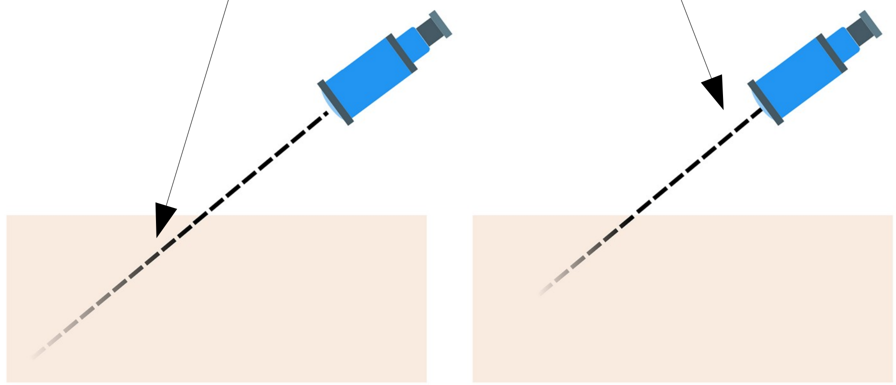
The scientific question now is:

Can we somehow estimate / measure / infer physical properties of the solar atmosphere from these observations?

A brief introduction to the spectral line formation:







Einstein coefficients

$$j(\lambda) = \frac{hc}{4\pi\lambda} n_u A_{ul} \phi(\lambda)$$

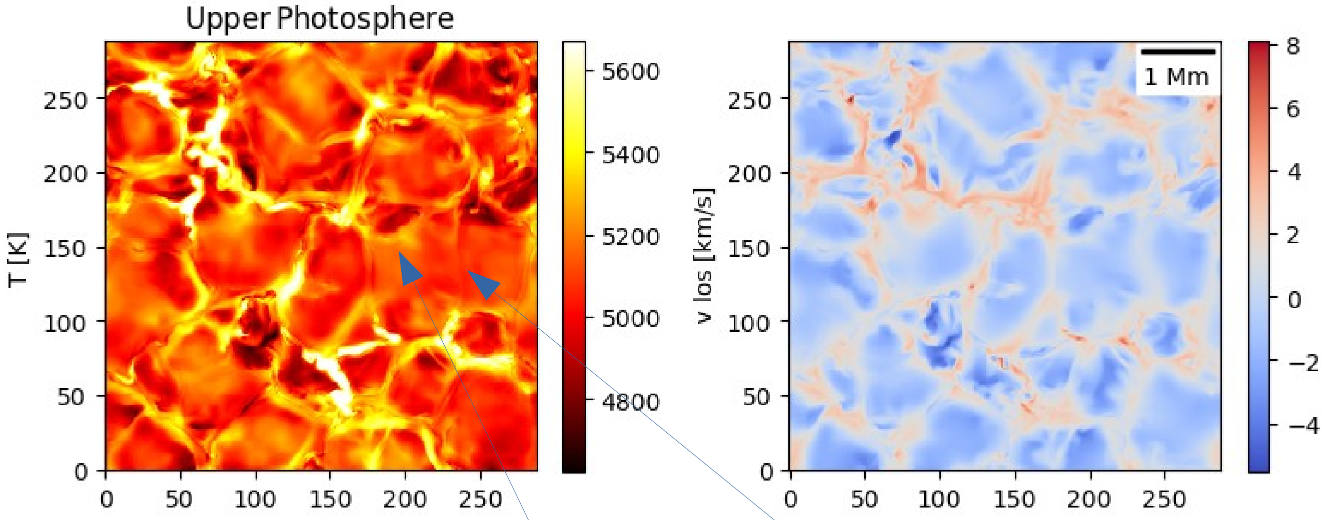
$$\chi(\lambda) = \frac{hc}{4\pi\lambda} (n_l B_{lu} - n_u B_{ul}) \phi(\lambda)$$

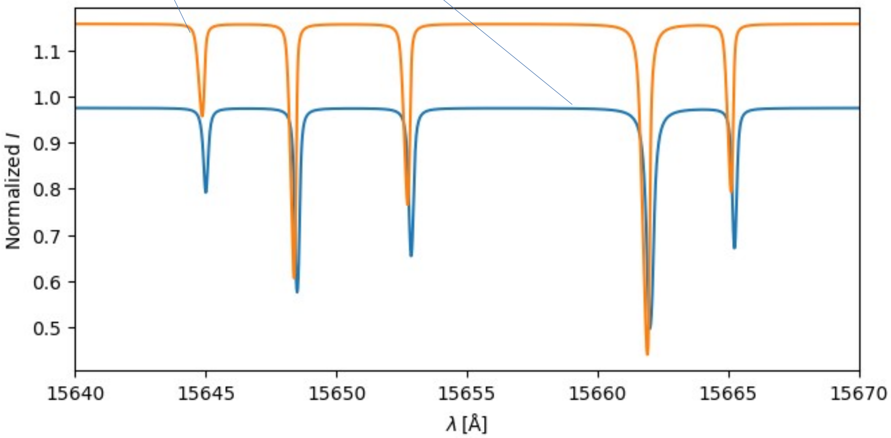
Emergent spectrum samples a range of depths

$$j(\lambda) = \frac{hc}{4\pi\lambda} n_u A_{ul} \phi(\lambda)$$

$$\chi(\lambda) = \frac{hc}{4\pi\lambda} (n_l B_{lu} - n_u B_{ul}) \phi(\lambda)$$

$$\frac{dI(z,\lambda)}{dz} = -\chi(z,\lambda) I(z,\lambda) + \eta(z,\lambda)$$





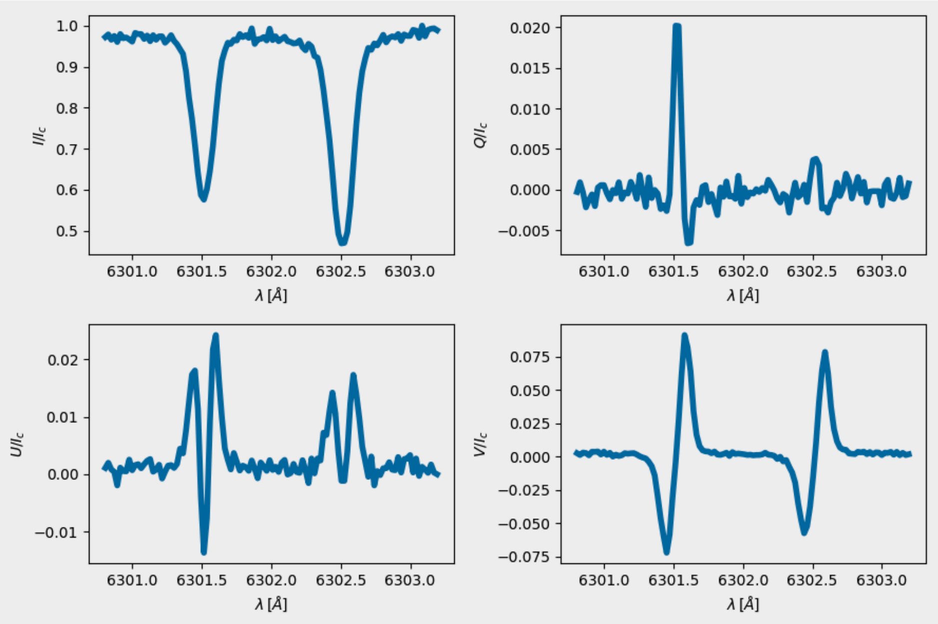
MURAM quiet Sun simulation, courtesy of T. Riethmüller

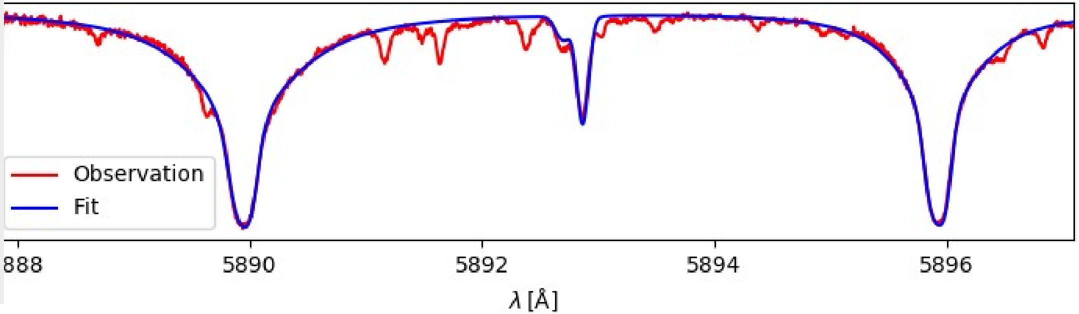
Where is the physics?

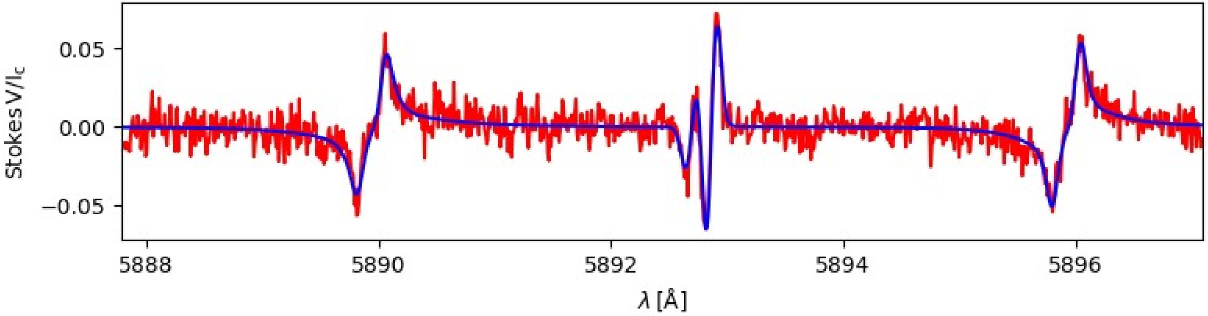
$$\frac{dI(z,\lambda)}{dz} = -\chi(z,\lambda)I(z,\lambda) + \eta(z,\lambda)$$

- All the physical parameters: temperature, pressure, velocities, magnetic field enter in the story through the coefficients of absorption and emission.
- **Temperature** determines ionization and excitation state of the atoms and ions, and the broadening of the spectral lines
- **Pressure** determines the total available pool of particles, and broadening of the spectral lines
- **Velocity** influences line shifts and widths
- We know the **solution** this differential equation and now we need to infer the coefficients – **inversion**

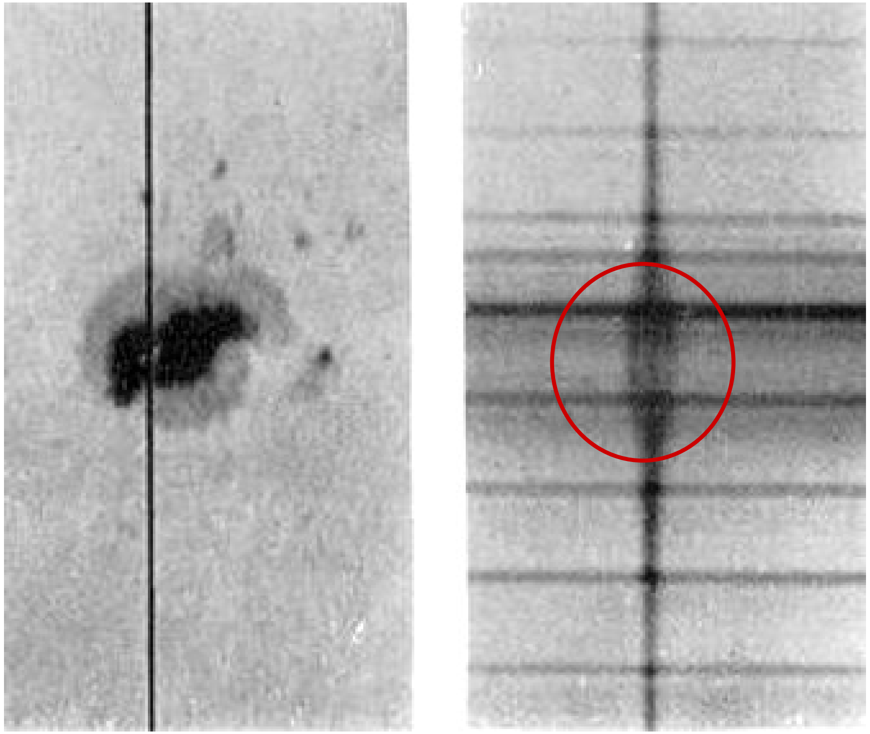
But wait, there is more – spectral line polarization





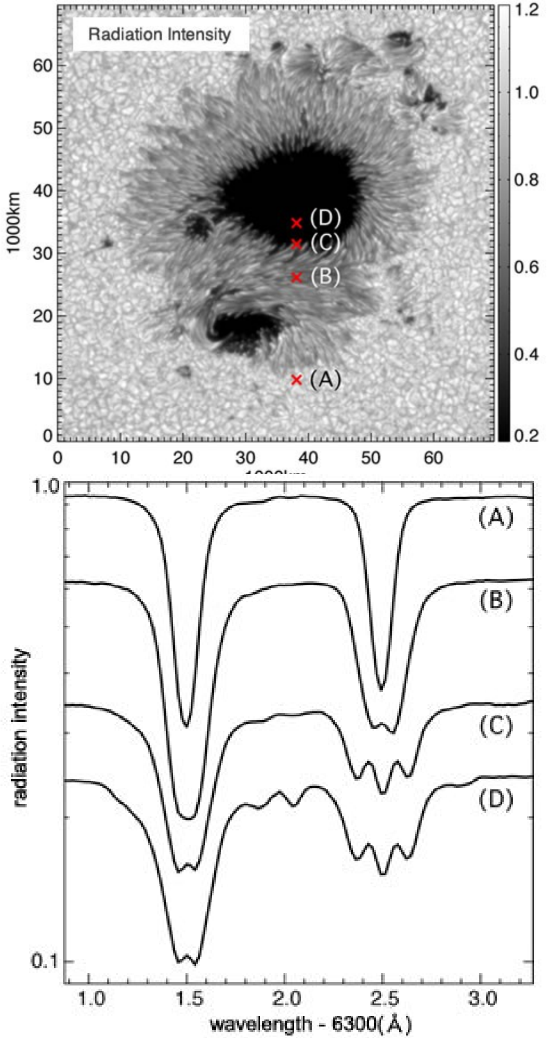


Zeeman effect

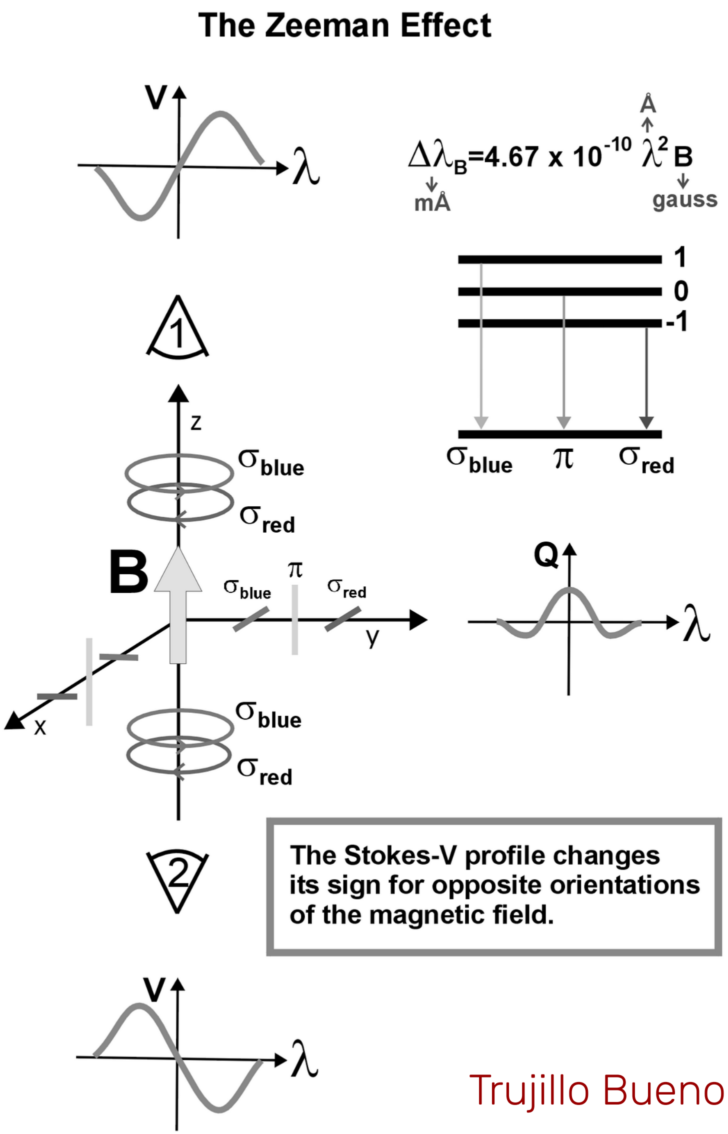


G.E. Hale, F. Ellerman, S.B. Nicholson, and A.H. Joy (ApJ, 1919)

Credits: Yukio Katsukawa

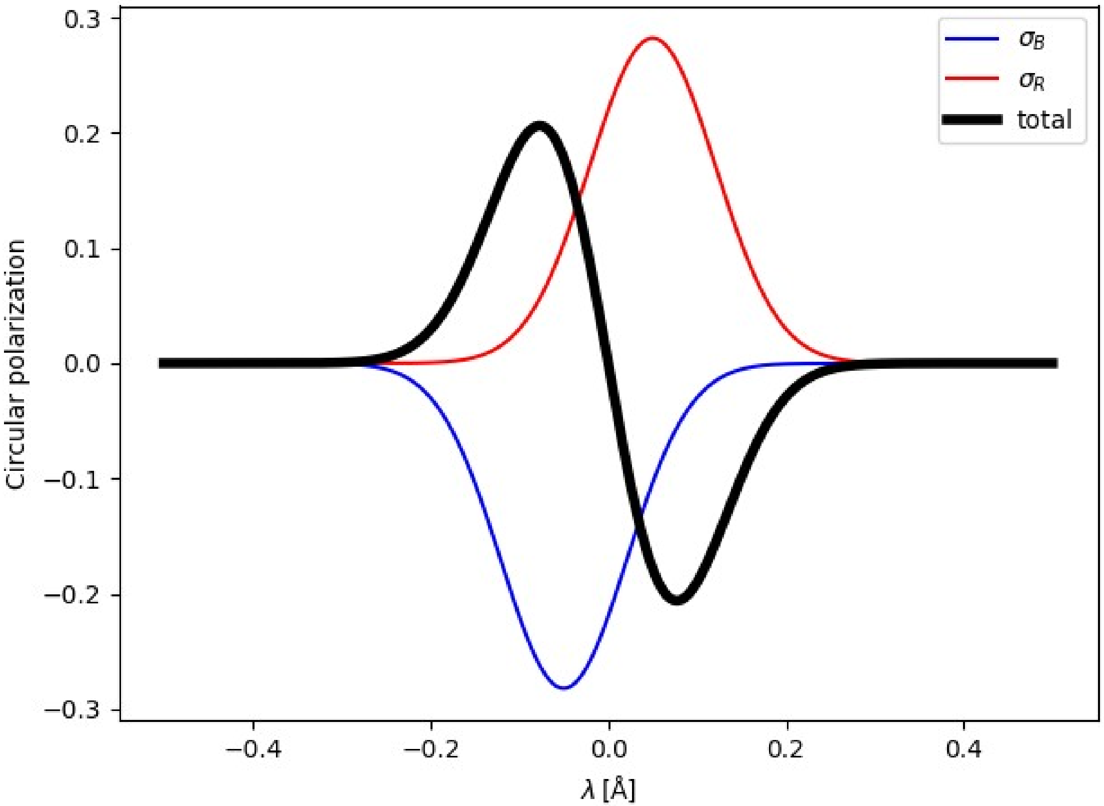


Why the polarization?

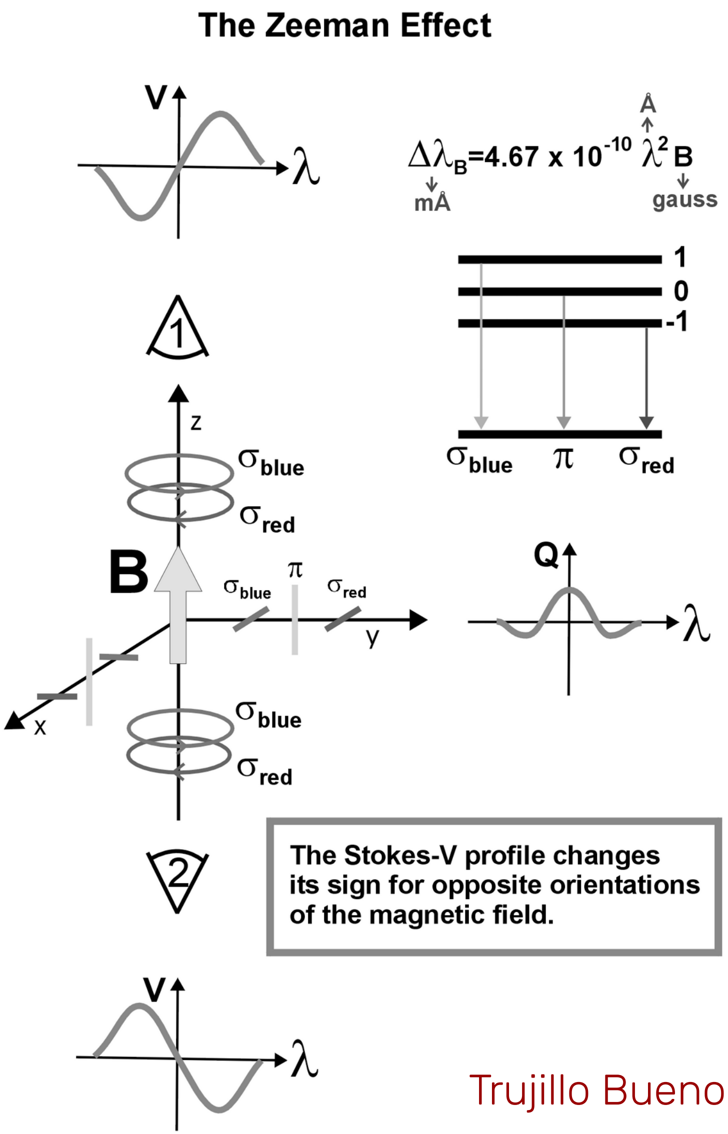


The Stokes-V profile changes its sign for opposite orientations of the magnetic field.

Trujillo Bueno (2006)



Why the polarization?



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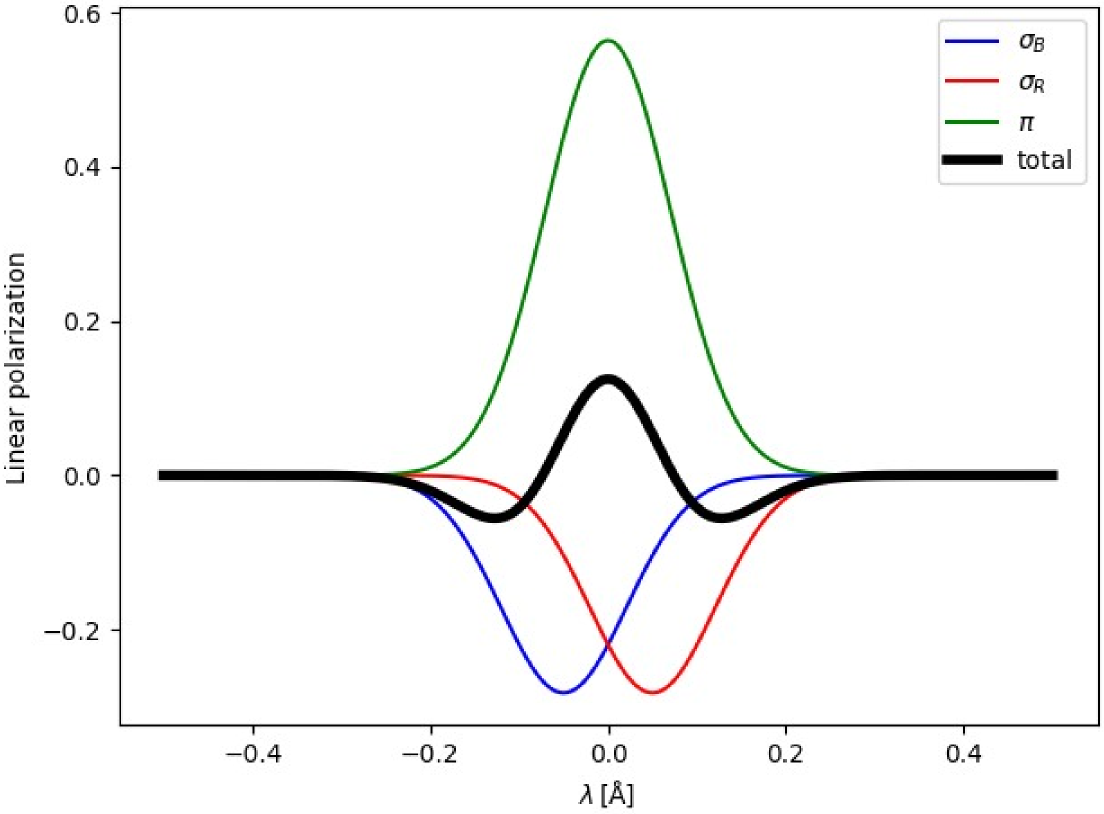
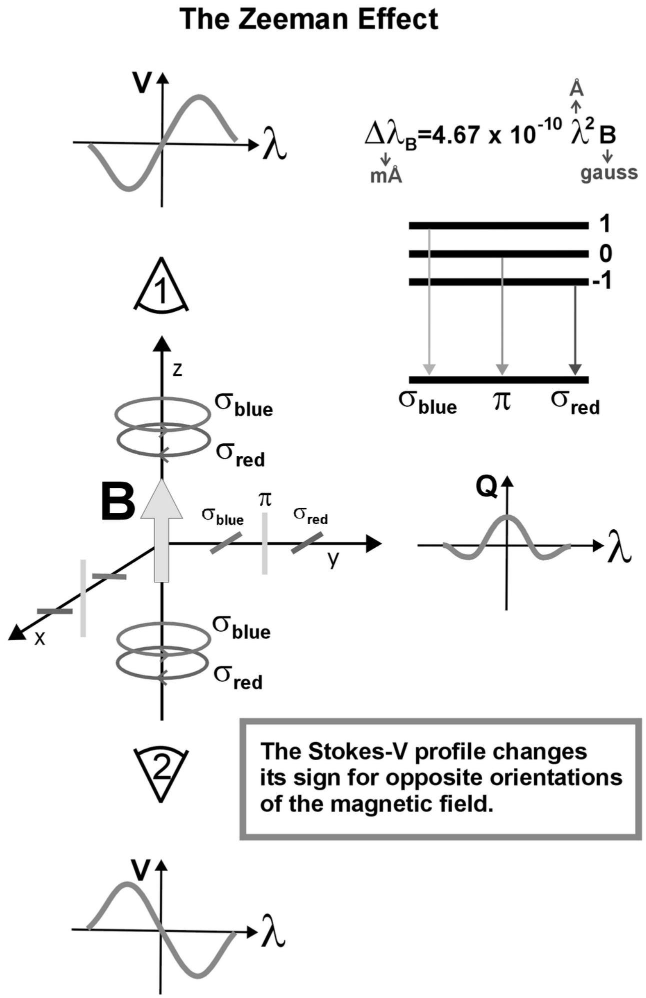
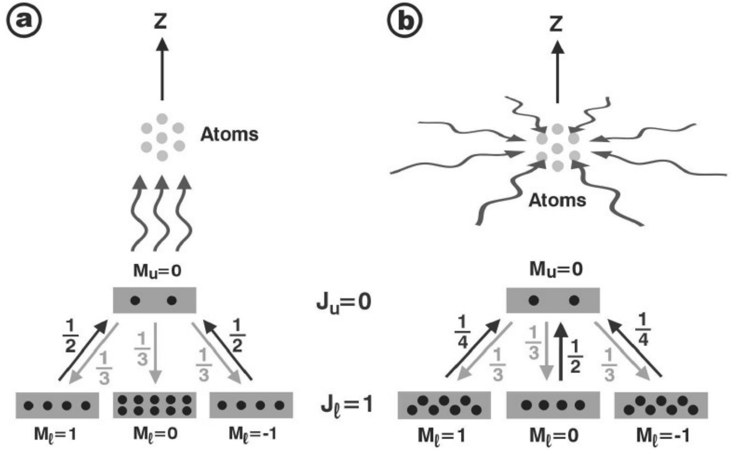


The full story



To get the emergent polarized intensity, we need to solve **polarized** RTE:

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



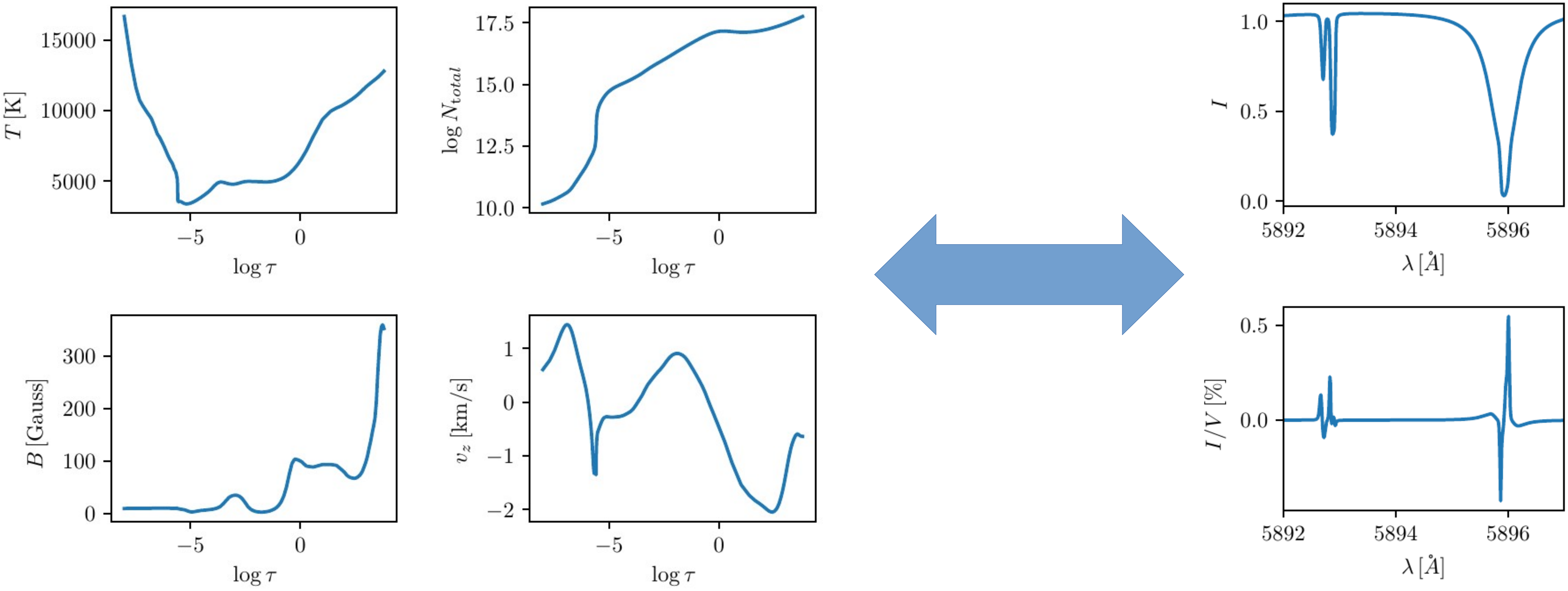
Now when we know the physics behind, the question is:

We have a given set of observations of spectral lines.

We know the relevant physics and have an atmosphere model
(say, a 1D discretized model atmosphere)

To get the maximum amount of quantitative information, we want to fit our atmosphere model to the observed polarized spectra →
Spectropolarimetric inversions

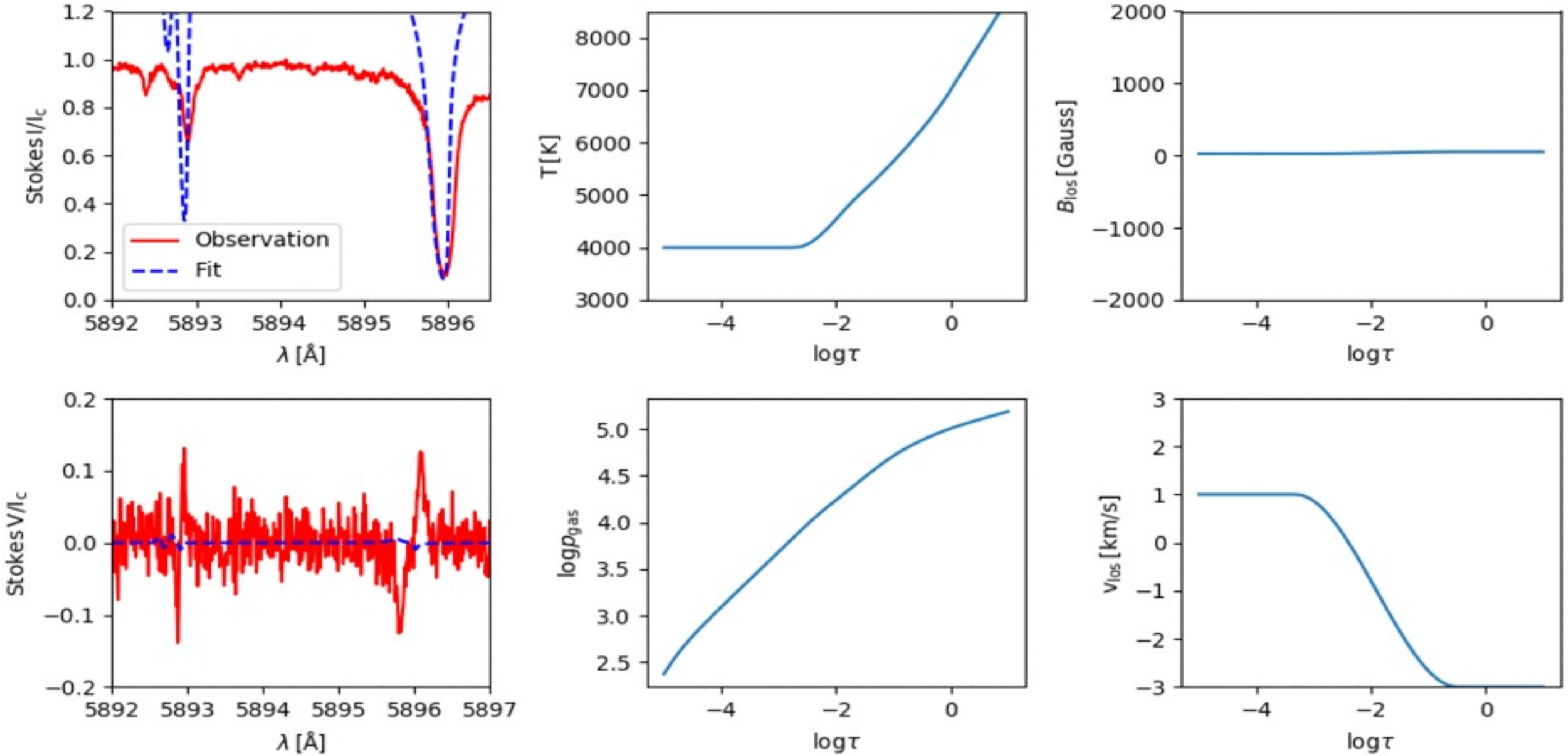
Spectropolarimetric inversion



Left: Stratification of one pixel from a BIFROST MHD simulation (Carlsson et al. 2016); Right: resulting spectra around Sodium D1 line.

Given the observations of the right, we want to perform an inverse mapping to the depth-dependent atmospheric structure.

Spectropolarimetric inversion



$$\frac{dI_\lambda}{dz} = -\chi_\lambda I_\lambda + j_\lambda$$

Inversion: Fitting a model atmosphere to the observed polarized spectrum. They are connected via **R**adiate **T**ransfer **E**quation. Physics hides in these two coefficients.

To summarize once again

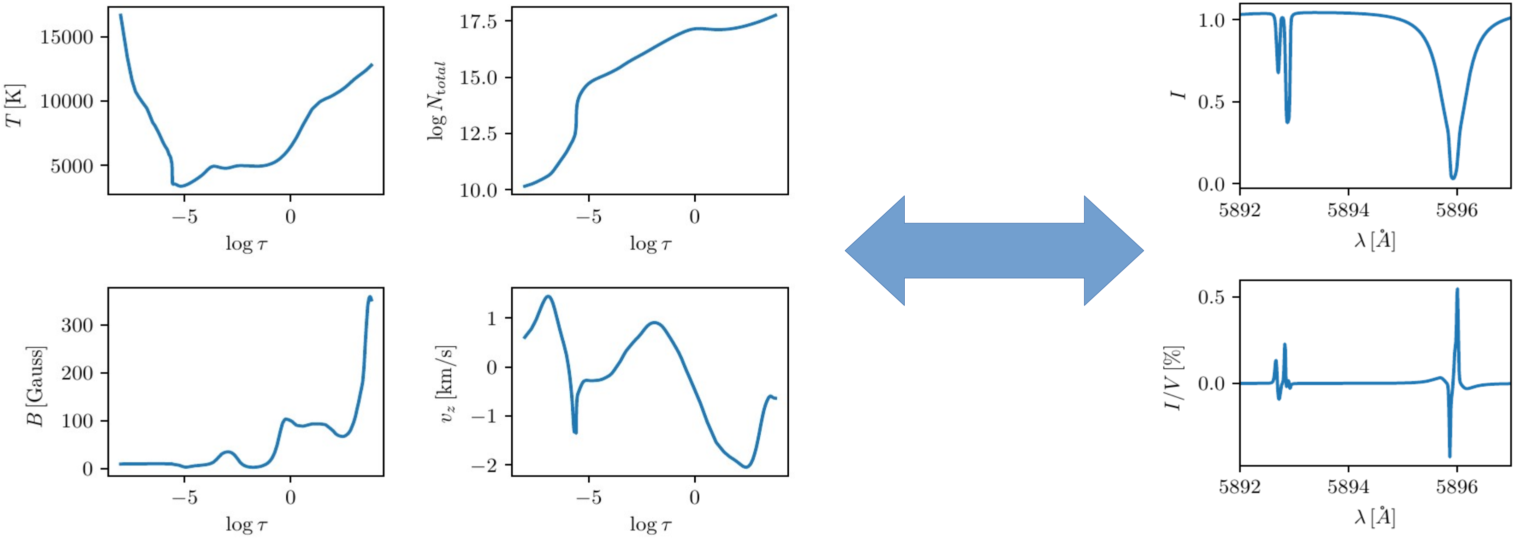
- The solar atmosphere is a 3D cube of different physical parameters
- This 3D cube maps, via **complicated physical processes** onto a 3D cube of (polarized) intensity
- In this mapping, height is somehow mapped onto wavelength.
- Nearby pixels can also “talk” to each other: 3D scattering, or just instrumental effects.

  Inversions try to perform the inverse of this mapping

- Inversions are like “mini-simulations” embedded into iterative procedures, that aim to fit well the observed spectra
- By doing this pixel-by-pixel, we form a 3D model of the observed region
- This process is messy, often unstable, **and extremely numerically demanding**

That is why we recently we tried to turn to Neural Networks

- NNs are, universal function (mapping) approximators
- We can hope that, given a suitable training set, they will be able to learn mapping from **the spectra to the atmospheres** and thus greatly increase the speed
- Another advantage: in the training set we can account for much wider range of physical effects – increasing realism
- Also wider range of instrumental effects – further increasing realism



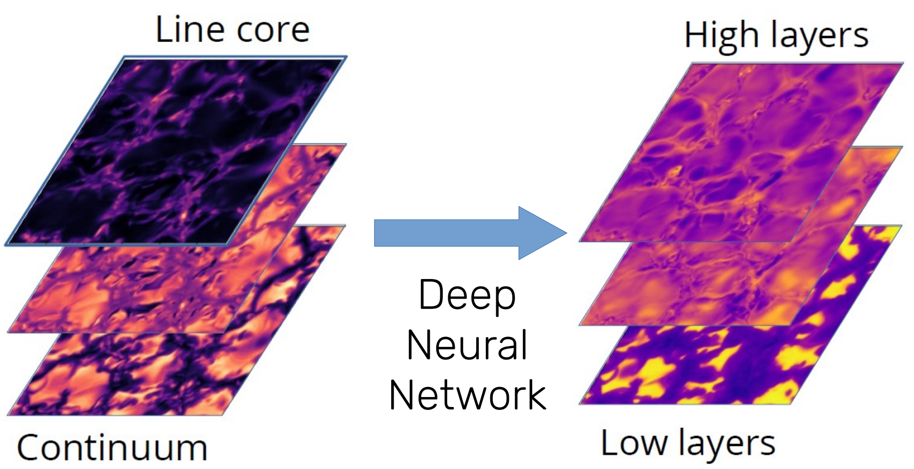
Machine Learning inversions (reconstructions)

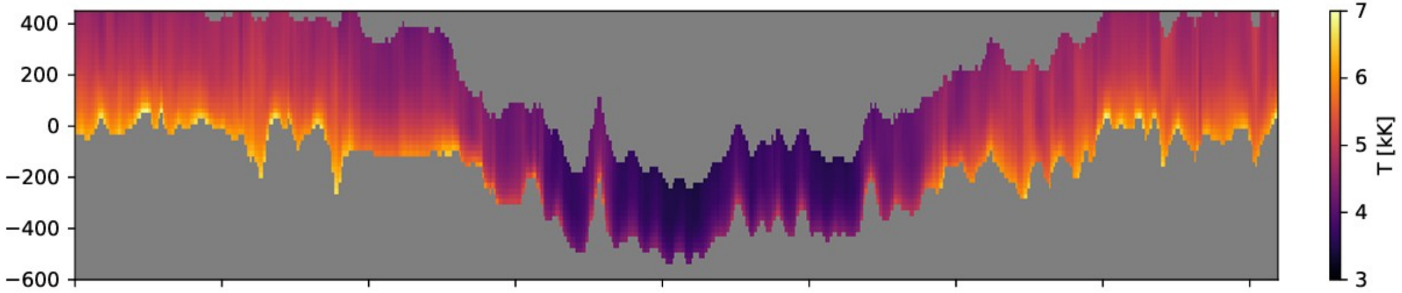
- Spatially resolved, multi-wavelength observations probe structure in depth:

$$I(x, y, \lambda) = \mathcal{F}\left[T(x, y, z), \vec{v}(x, y, z)\right]$$

- Deep Neural Networks (DNNs) can be trained on the state-of-the-art simulations and used to invert the simulations

- **We gt 3D models of the solar atmosphere,** inferred directly from the observations.



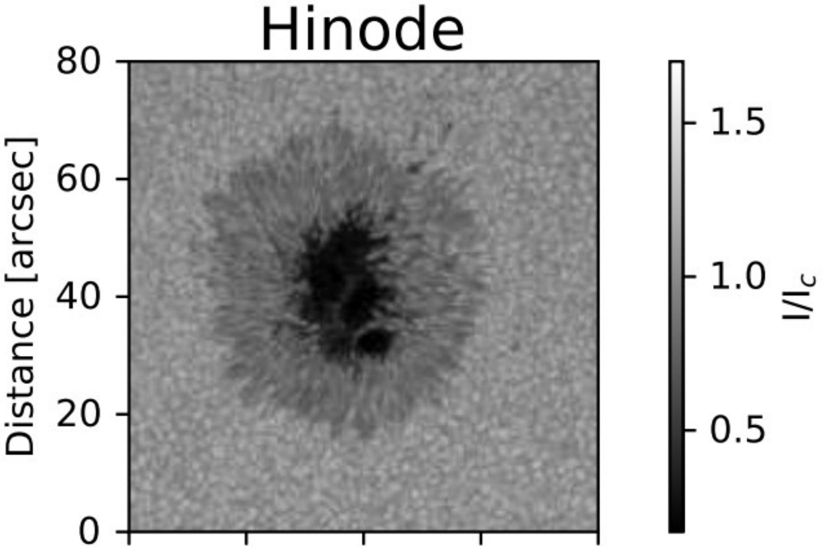


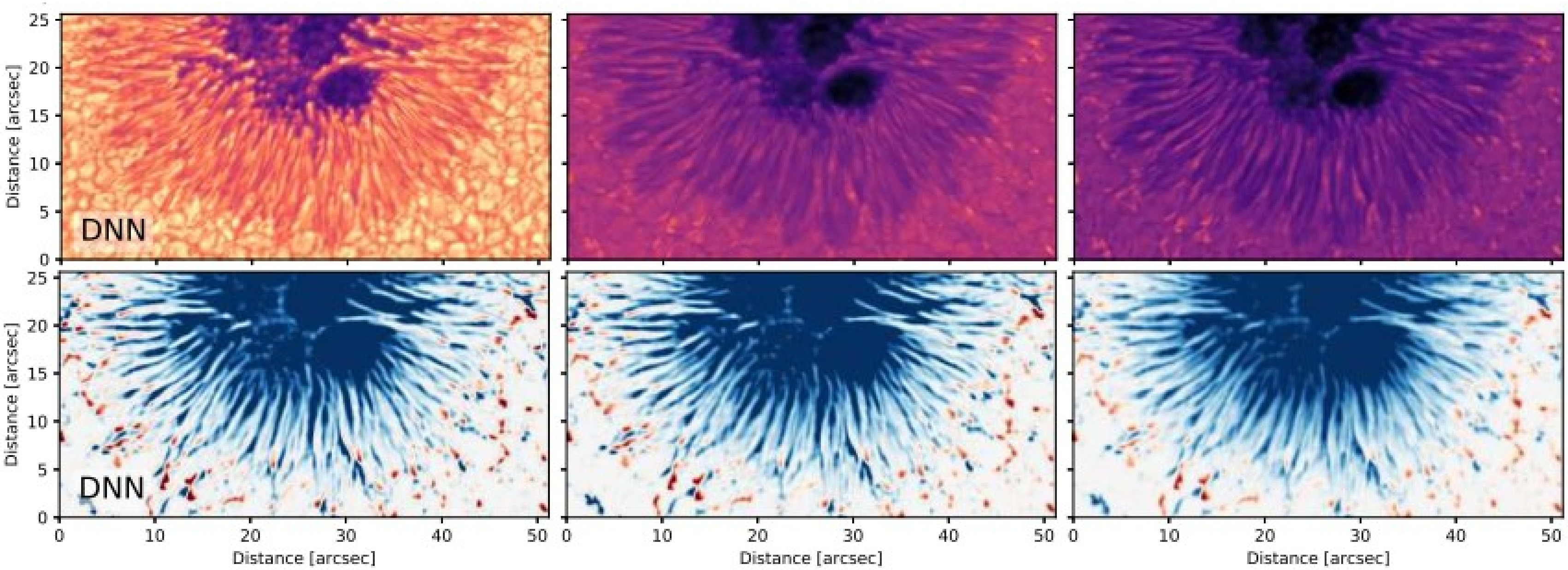
Up: Mapping between the 3D spectral cubes and 3D thermal structure of a photospheric region

Left: Depth structure of a sunspot, obtained by a DNN inversion, Asensio Ramos and Diaz Baso (2019).

Stokes inversion using CNNs

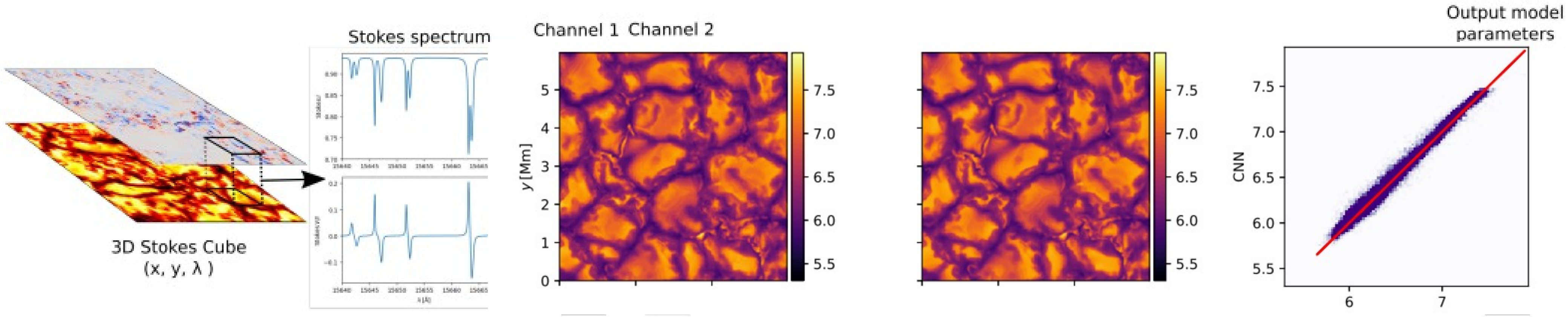
- AR 10933, observed by Hinode SOT/SP:
- Below, results of the CNN inversion (obtained in a fraction of the time standard methods need, Asensio Ramos & Diaz Baso, 2019)
- These inversions are based on the simulated training sets





Or we can train on the results of existing inversions

- We can use a standard diagnostic method on a representative sub-set of our data
- We can then train a network to match the observations to the inferred parameters
- And use that on the remaining data
- As the training typically lasts **much less** than the inversion itself, this gives a significant speed-up
- In Milic & Gafeira (2020) and Gafeira et al (2021), we showed that this really works:



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