The magnetism of the solar atmosphere as revealed by the Hanle effect

L. Belluzzi

Istituto Ricerche Solari Locarno (Locarno Monti, Switzerland)

Kiepenheuer-Institut für Sonnenphysik (Freiburg, Germany)

1st Swiss SCOSTEP Workshop

Bern, 4-5 October 2016

Why speaking about the Hanle effect in a SCOSTEP meeting?

- High-energy phenomena (e.g., *flares* and *CMEs*) may have a strong impact on our environment

- The magnetic field is a key physical ingredient at the origin of such phenomena

- Our empirical knowledge of the magnetic fields present in the outer layers of the solar atmosphere (i.e., *chromosphere* and *transition region*) is still unsatisfactory

- The Zeeman effect turns out to be of limited utility for investigating the *weak* and *highly structured* fields present in the outer solar atmosphere

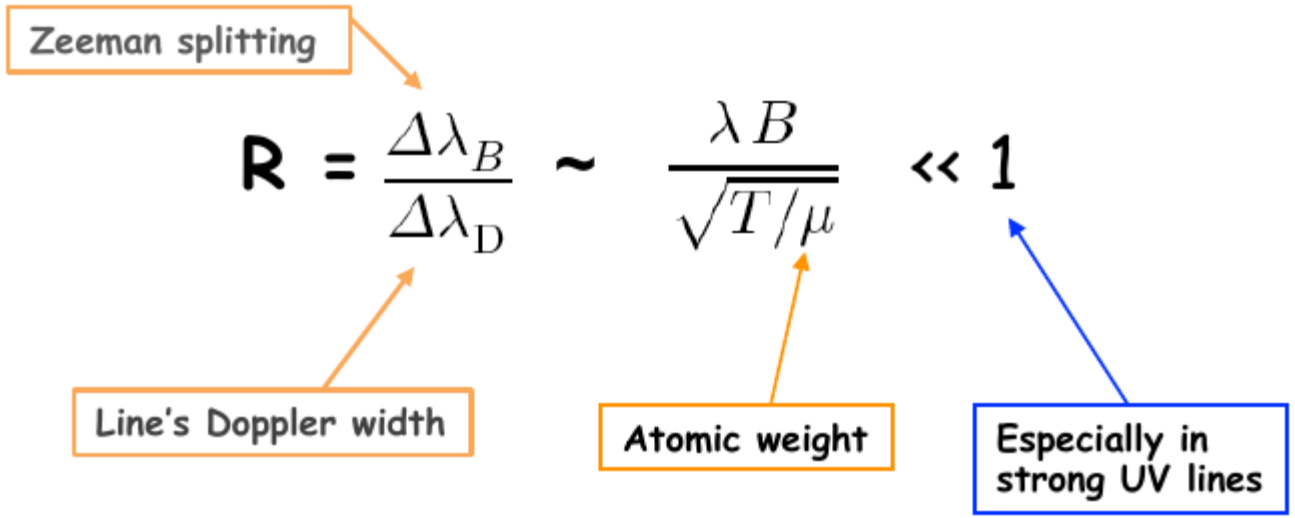
- The Zeeman effect is not the only way through which the magnetic field modifies the polarization of the e.m. radiation: **Hanle effect**!

The Zeeman effect polarization

The Zeeman signals are proportional to the ratio R (for V) and R^2 (for Q and U), between the magnetic splitting and the Doppler line width:

$V_{Zeeman} \sim R$

$Q, U_{Zeeman} \sim R^2$



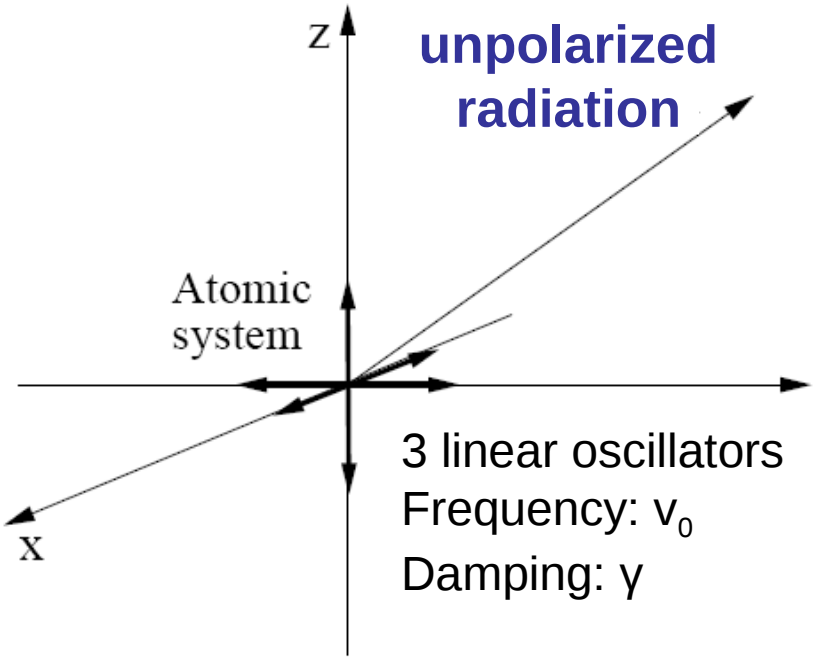
1) For the same magnetic field strength, the Zeeman signals becomes smaller when the temperature increases, and going from the IR to the UV.

E.g., HI Ly-α at 1216Å, assuming T=10000K, and B=10G ⟶ R ~ 0.0001

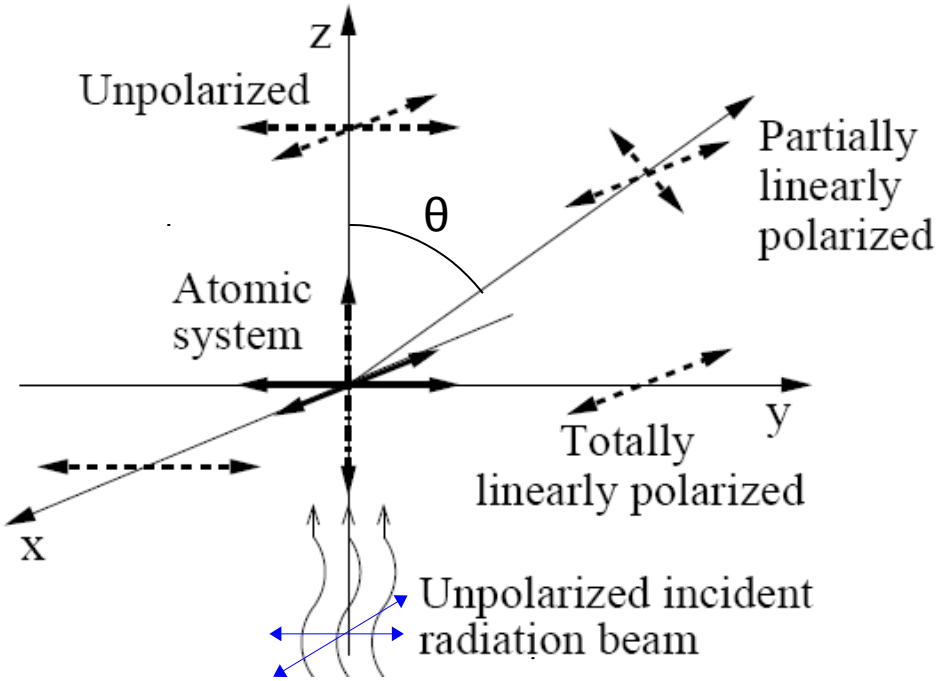
2) The Zeeman effect is blind to fields showing opposite polarities on spatial scales smaller than the resolution element

The physics of scattering polarization
(classical approach)

Isotropic excitation

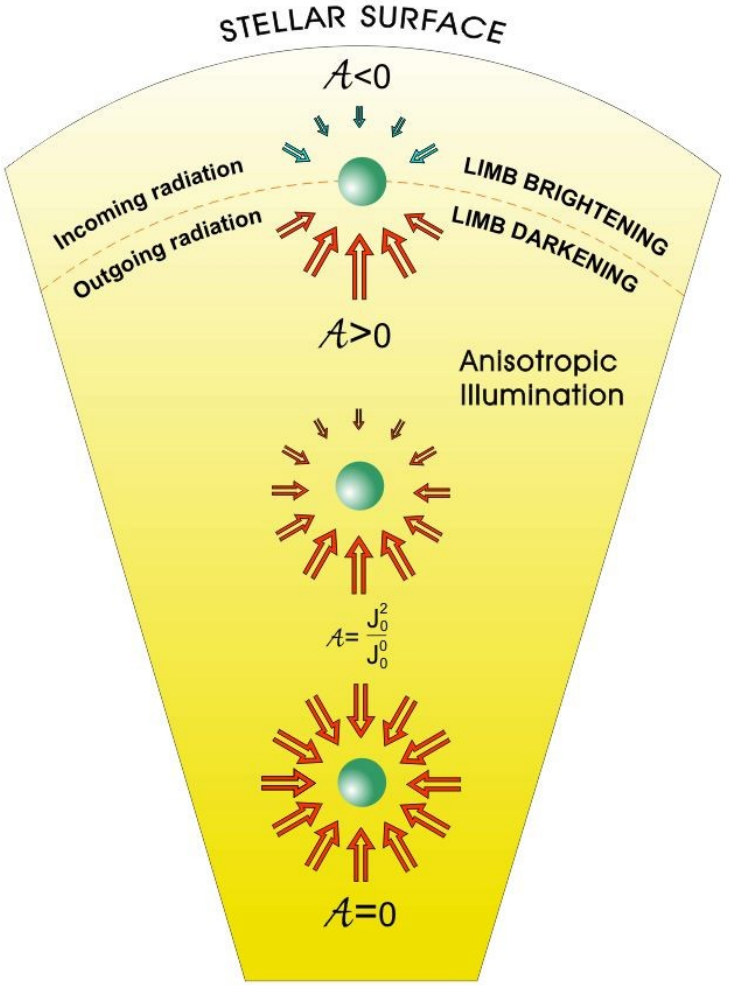


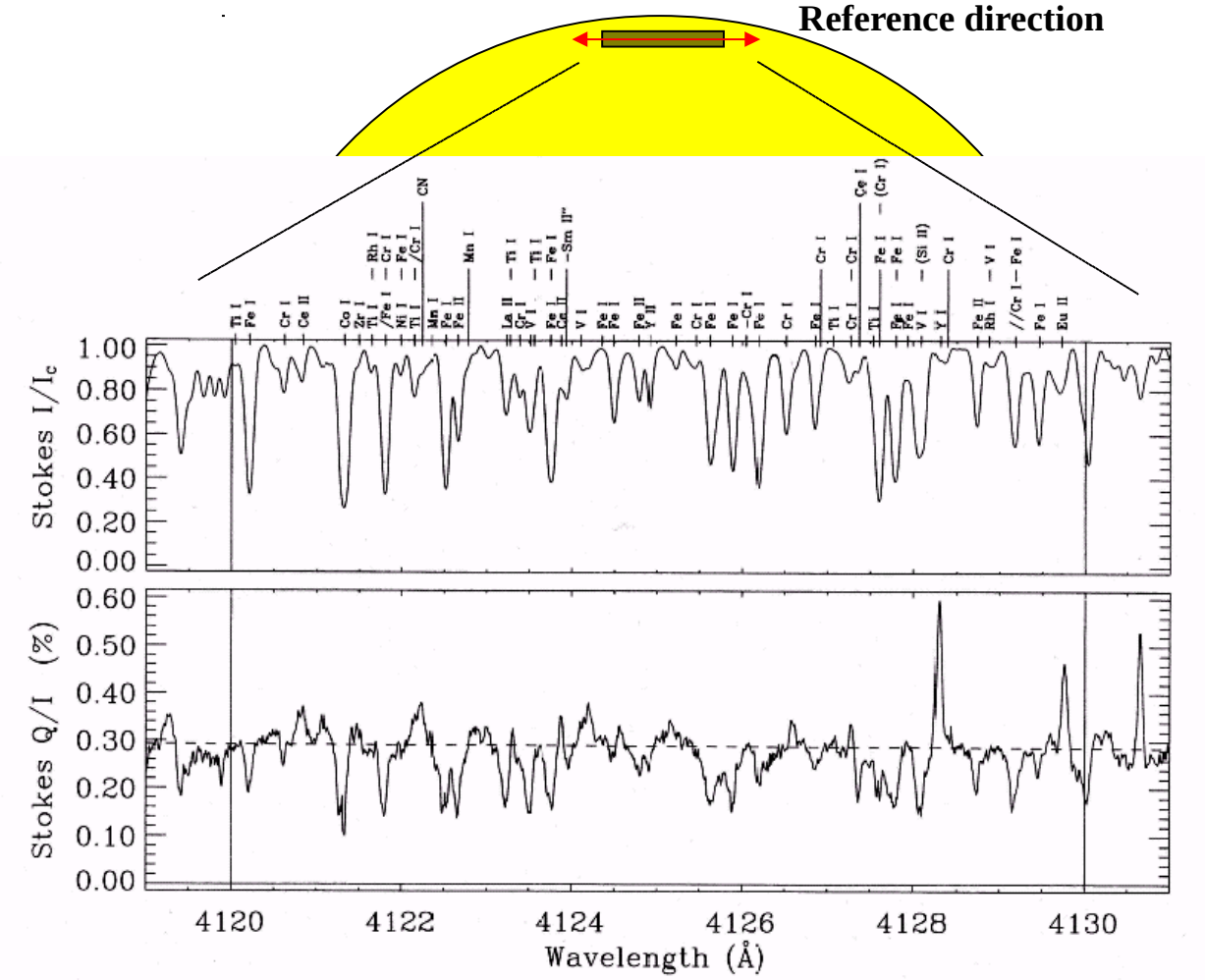
Anisotropic excitation



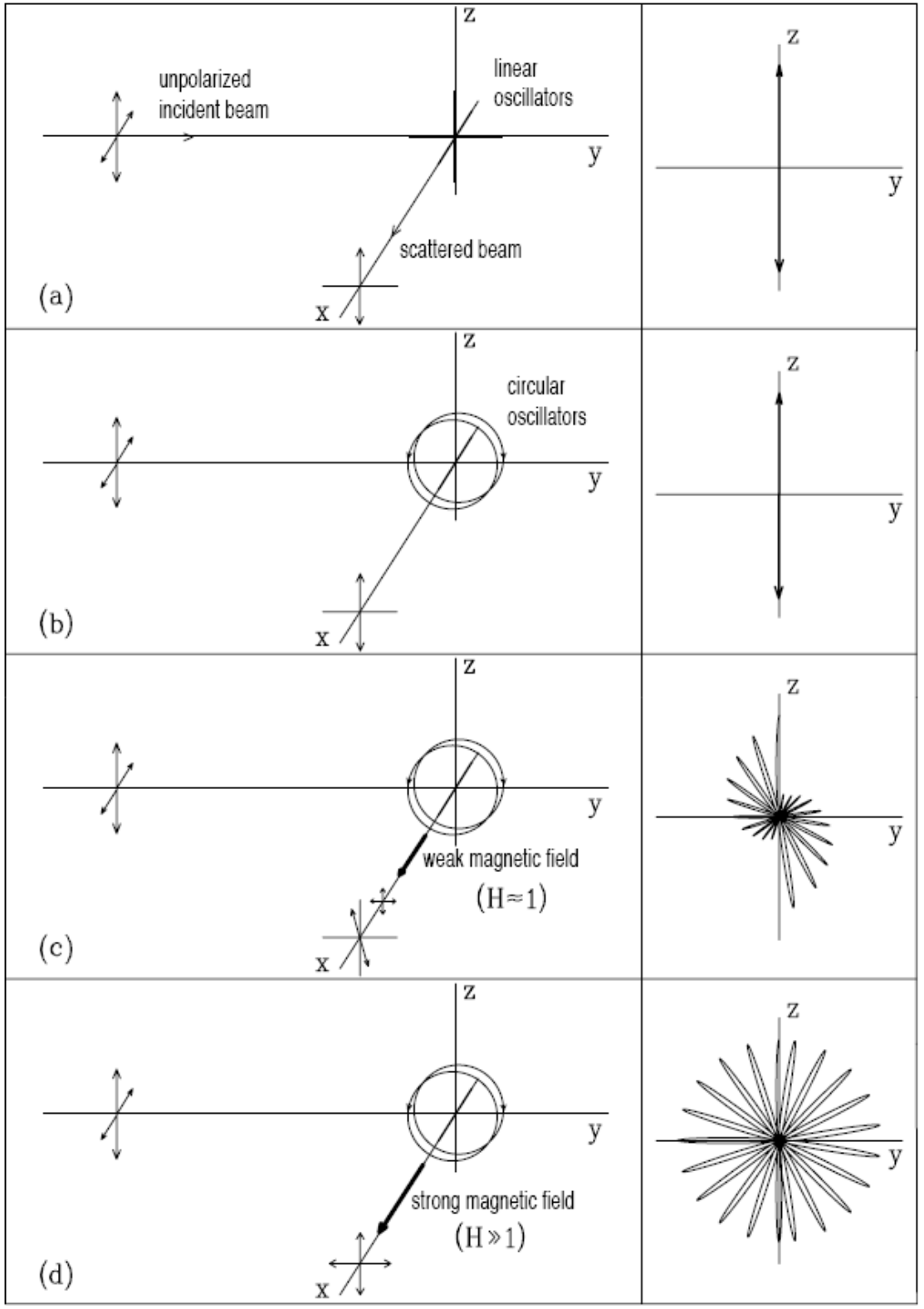
Scattering polarization

The Second Solar Spectrum





Second Solar Spectrum



The Hanle effect

Equivalent description:
linear oscillator (ν_0) along z-axis

⇩

two circular oscillators, σ_+ σ_-, (ν_0)
with well-defined PHASE RELATION
(so that the oscillation is along the z-axis)

Presence of a magnetic field along x:

$\sigma_+ \longrightarrow (\nu_0 + \nu_L)$

$\sigma_- \longrightarrow (\nu_0 - \nu_L)$

⇩

PHASE RELATION LOST

⇩

"Rosetta pattern"

Weak field ($H = 2\pi\nu_L / \gamma \sim 1$)

⇩

Depolarization and rotation of the plane of linear polarization

Strong field ($H = 2\pi\nu_L / \gamma \gg 1$)

⇩

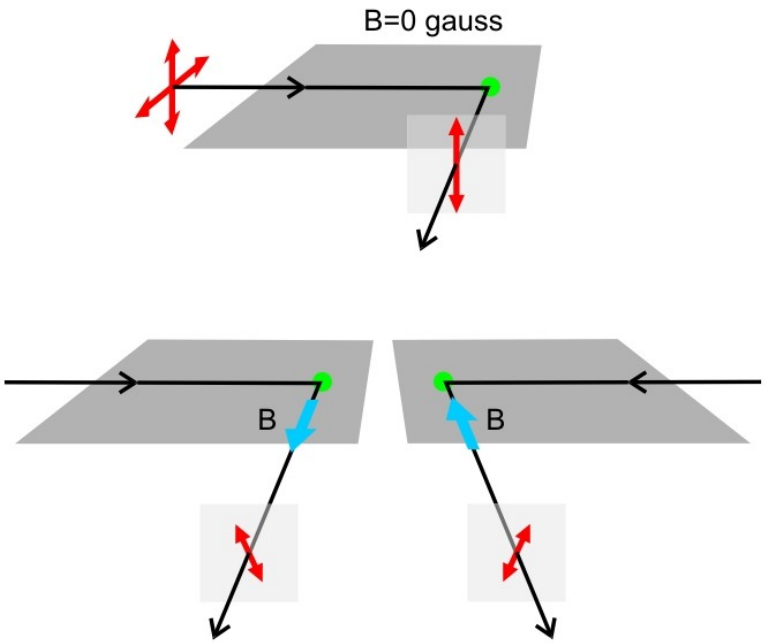
Depolarization ("daisy pattern")

The Hanle effect

Scattering polarization is sensitive to the presence of a magnetic field through the so-called Hanle effect.

Observational signatures of the Hanle effect:

1) Rotation of the plane of linear polarization



2) Modification (in general decrease) of the degree of linear polarization

Pros and Cons of the Hanle effect

PROS

- The Hanle effect is sensitive to magnetic fields showing opposite polarities below the resolution element (to which the Zeeman effect is blind).

- It is sensitive to weaker magnetic fields with respect to those that can be investigated with the Zeeman effect.

Rough estimate of the sensitivity to the Hanle effect:

$$0.2\ B_H < B < 5\ B_H$$

The Hanle critical field B_H is the field for which the magnetic splitting of the upper level of the line is of the same order of magnitude as its natural width

$$B_H\,[G] = A_{ul}\,[\text{units of } 10^7\ s^{-1}] / 0.879\ g_u$$

- The Hanle effect does not depend on the Doppler width of the line and it can be applied from the IR to the UV

Pros and Cons of the Hanle effect

CONS

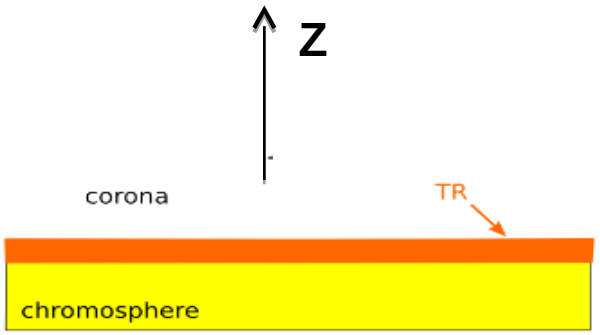
The physics of scattering polarization has revealed to be quite complicated

Robust quantum approaches are, however, today available, and new ones are under development.

Scattering polarization is also sensitive to the depolarizing effect of collisions with neutral perturbers and to other symmetry-breaking effects (e.g., presence of horizontal inhomogeneities in the solar plasma).

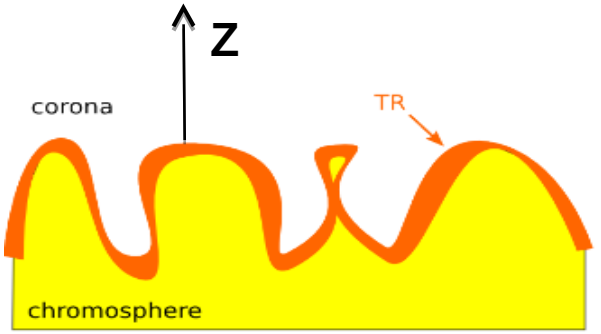
1D plane-parallel model

Cylindrical symmetry



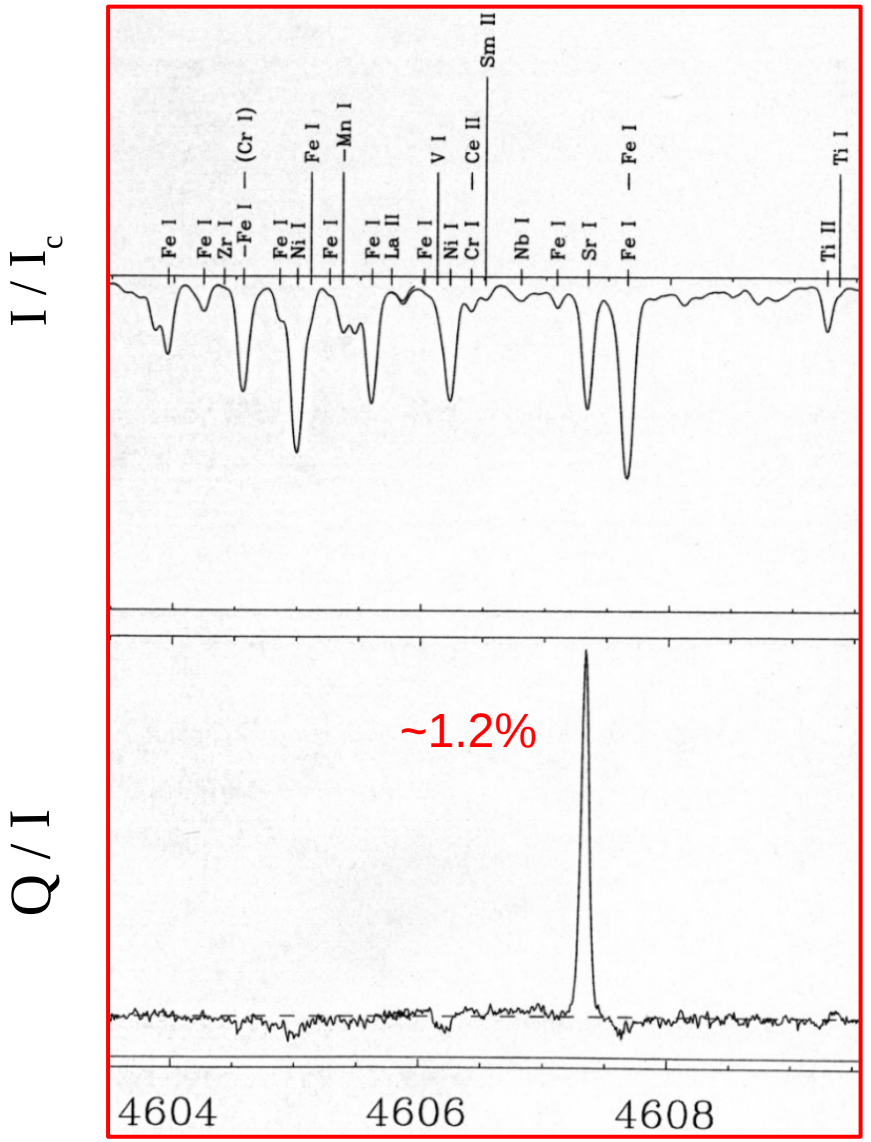
3D model

Symmetry breaking



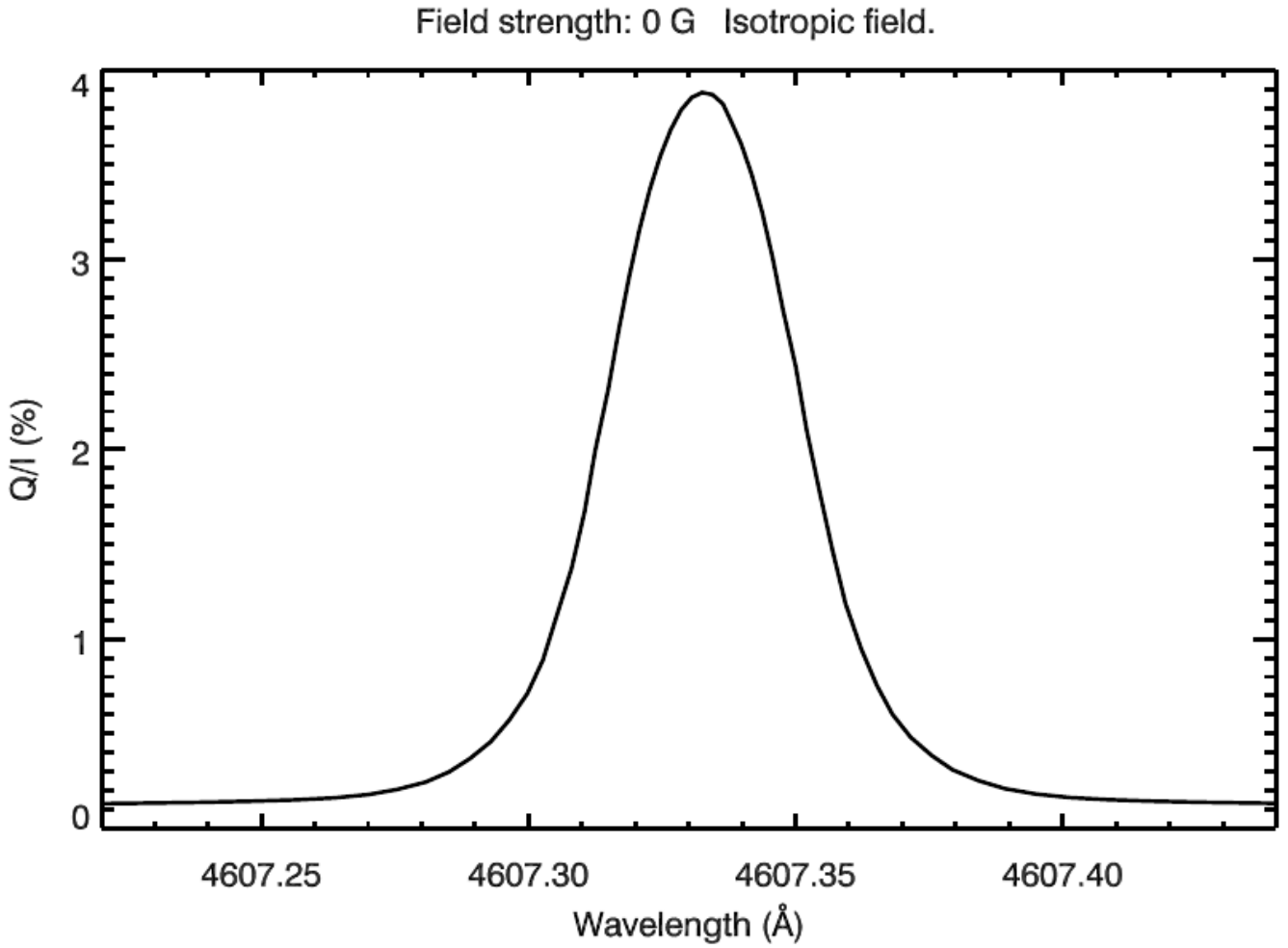
Realistic 3D MHD models of the solar atmosphere + development of numerical codes capable of modeling the generation and transfer of polarized radiation in 3D

The Hanle effect in the SrI line at 4607Å

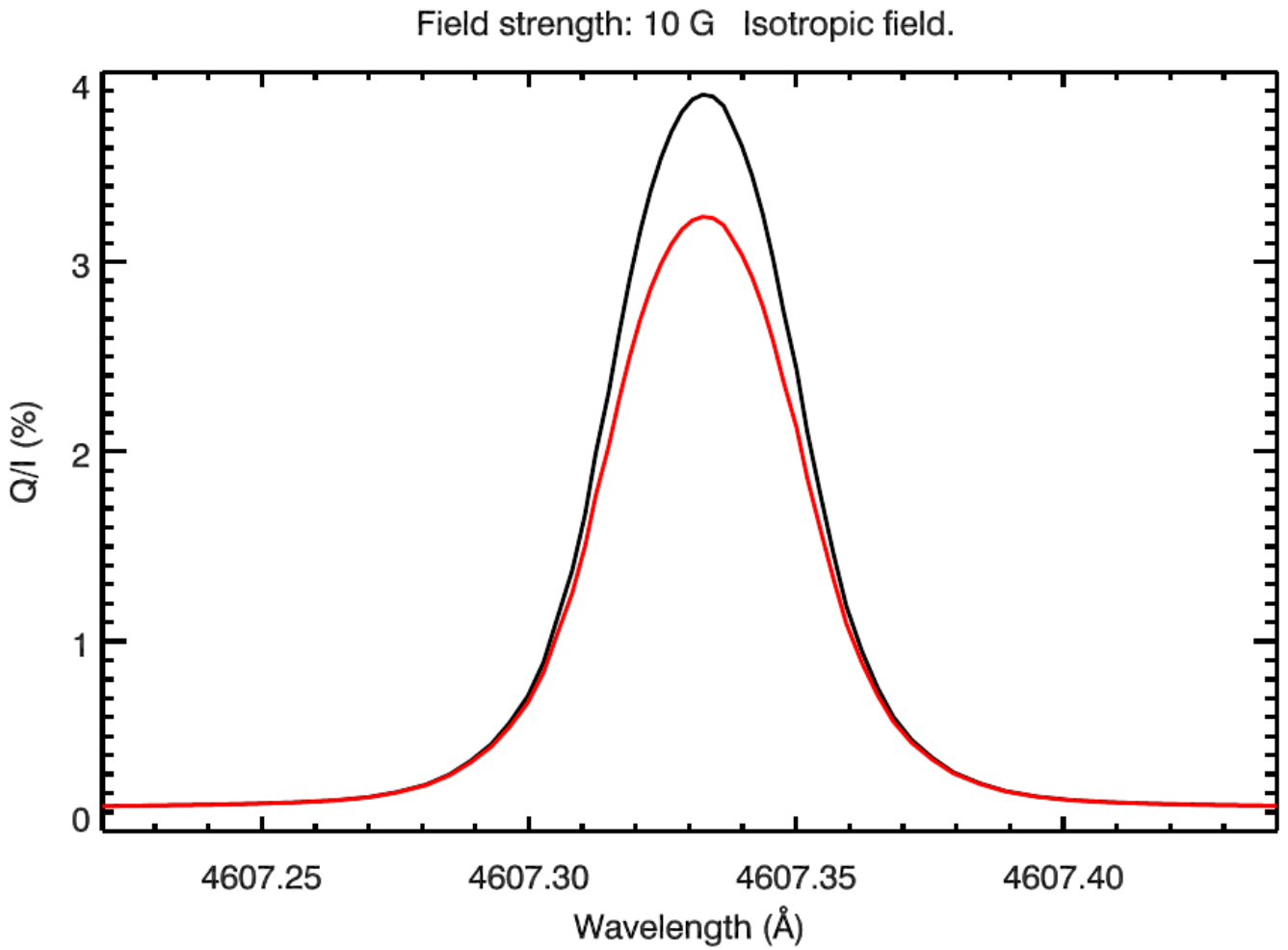


Atlas of the Second Solar Spectrum (Gandorfer, 2002)

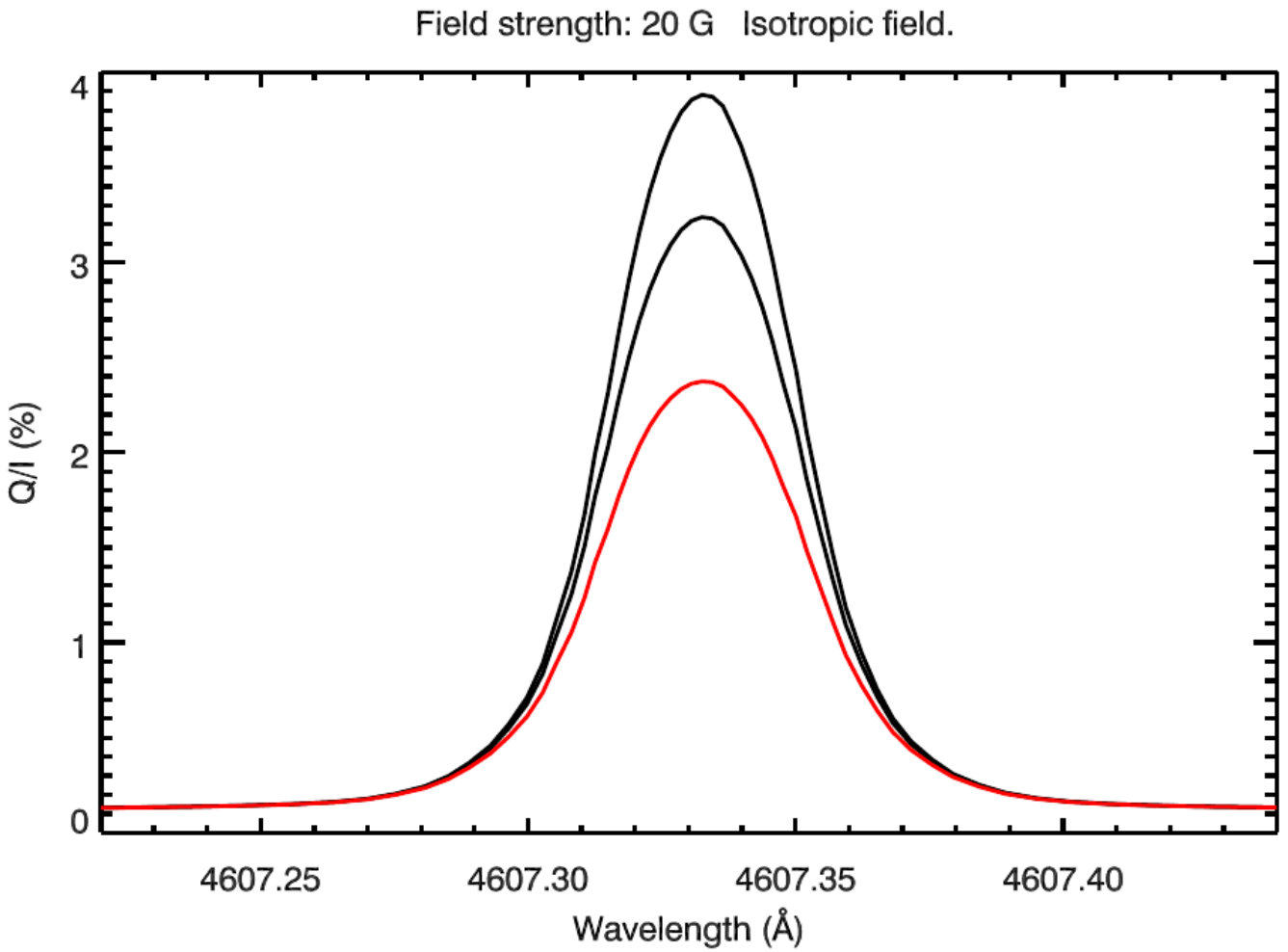
The Hanle effect in the SrI line at 4607Å



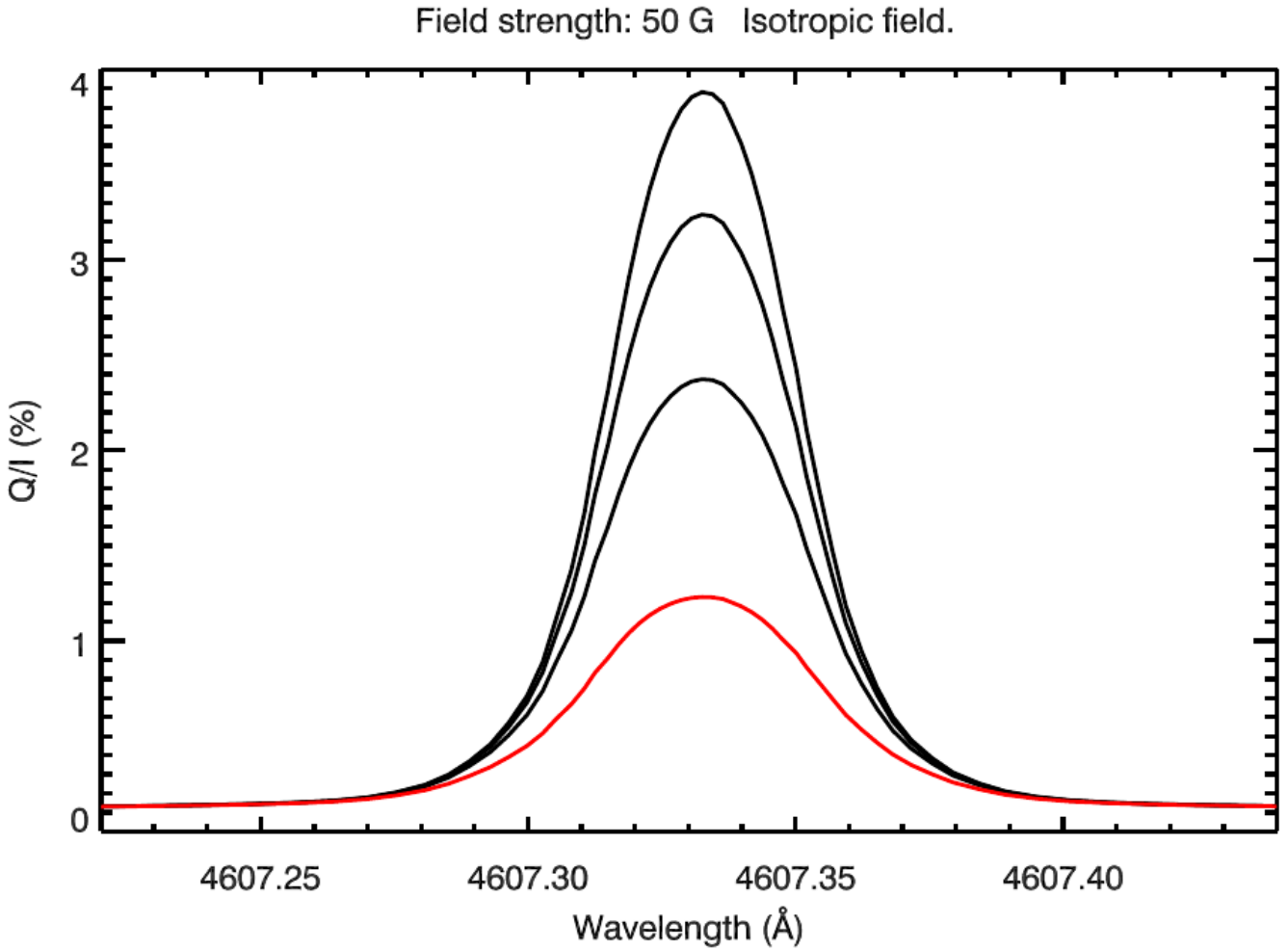
The Hanle effect in the SrI line at 4607Å



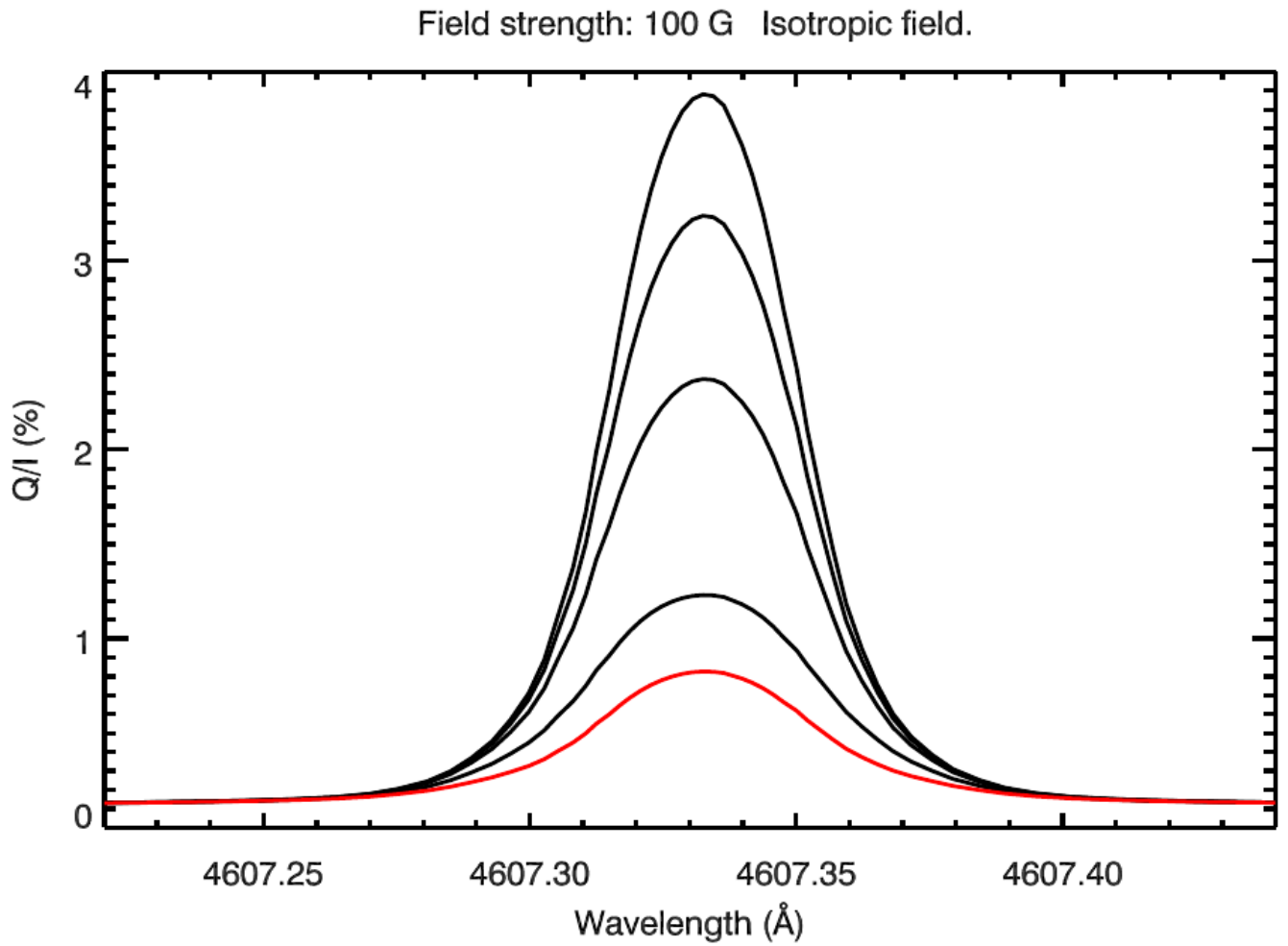
The Hanle effect in the SrI line at 4607Å



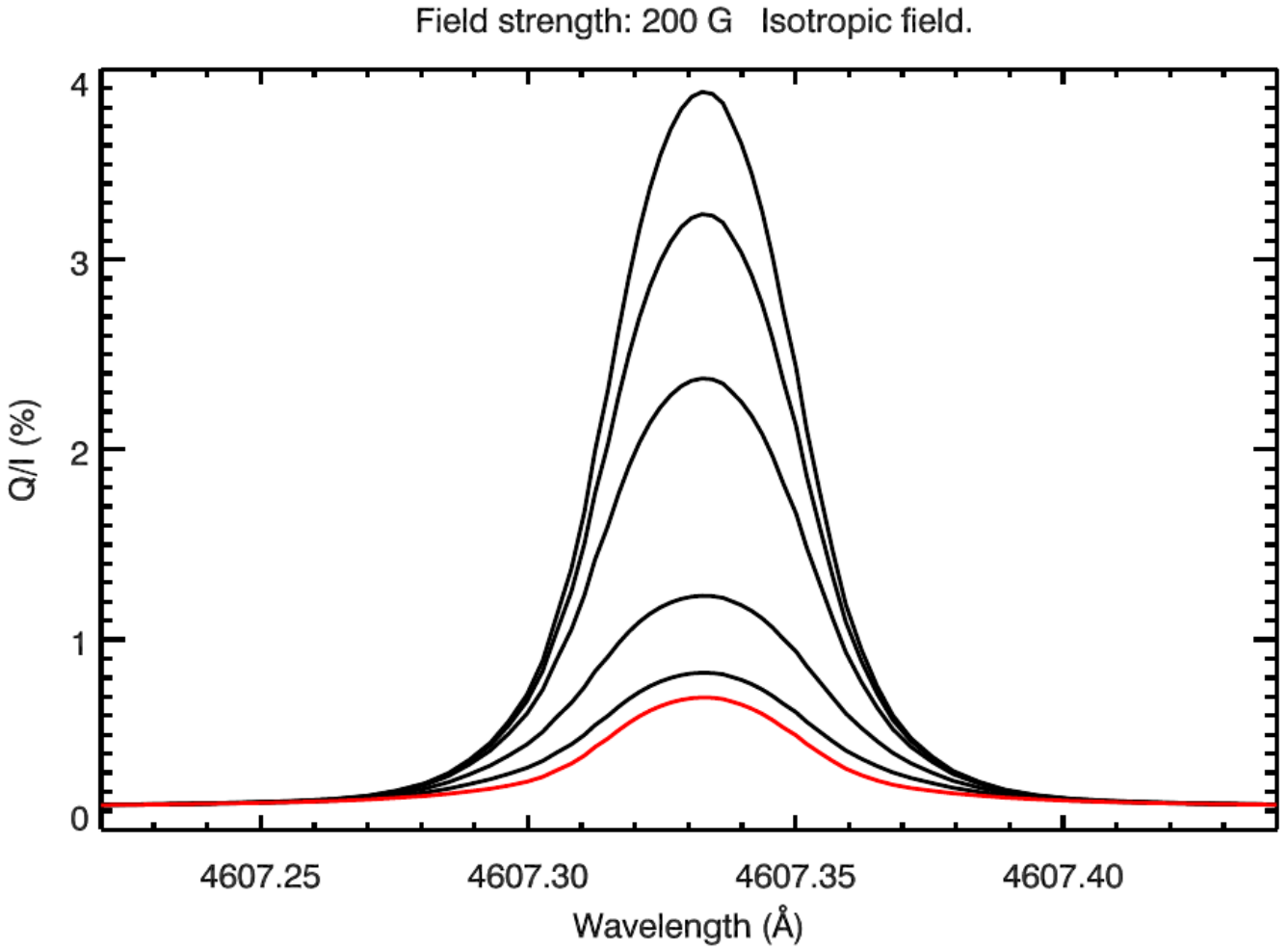
The Hanle effect in the SrI line at 4607Å



The Hanle effect in the SrI line at 4607Å



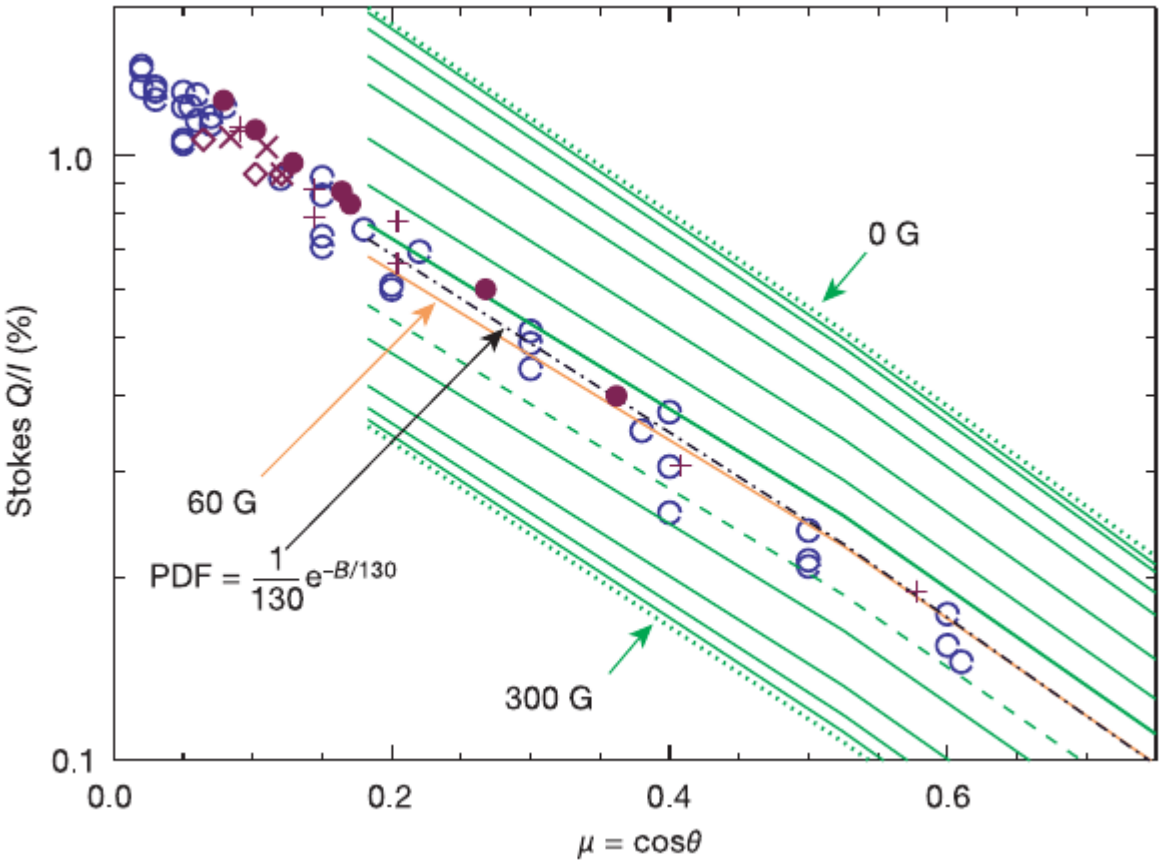
The Hanle effect in the SrI line at 4607Å



The Hanle effect in the SrI line at 4607Å

Investigating the hidden magnetism of the quiet solar photosphere

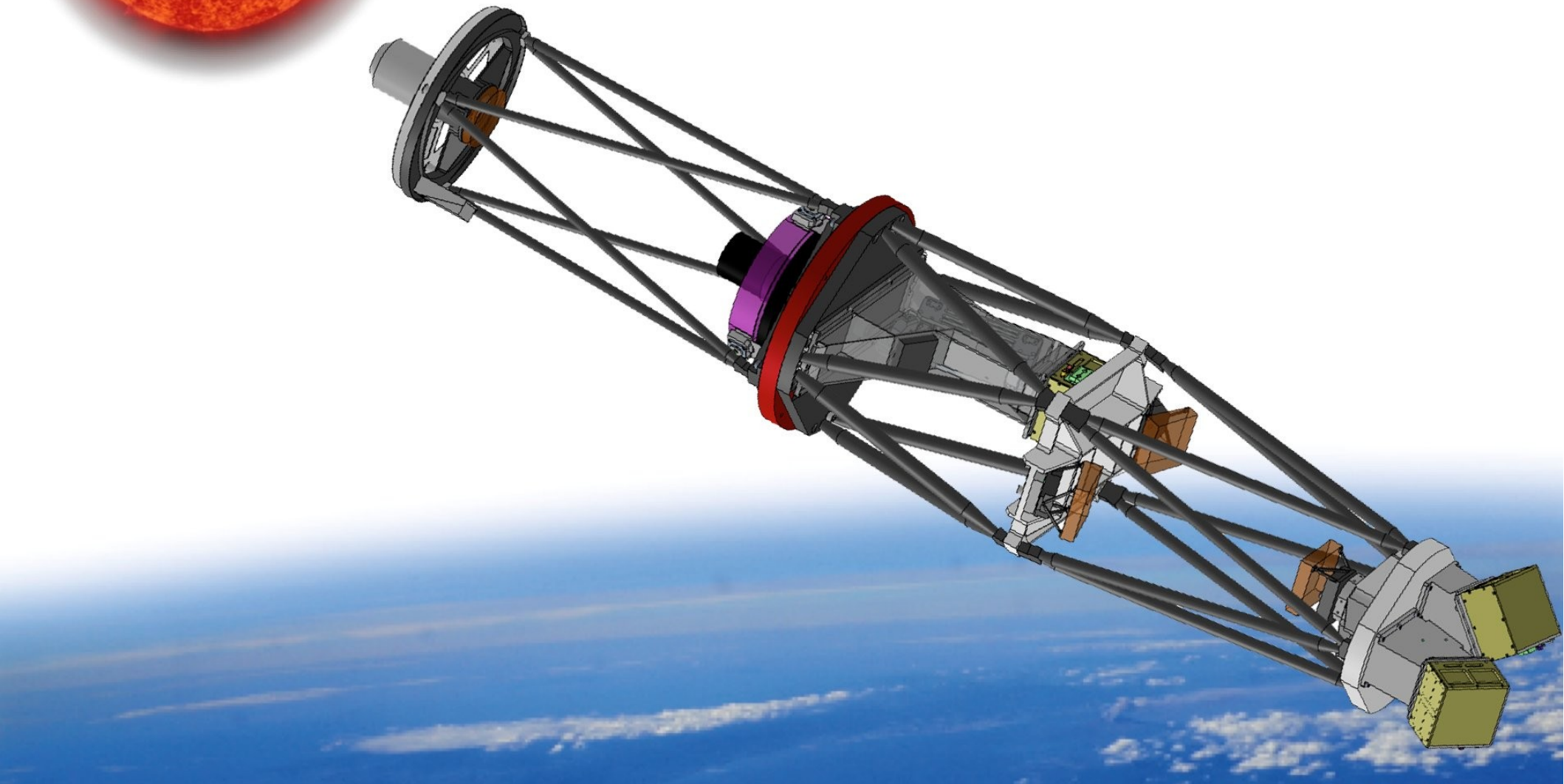
Modeling vs observations

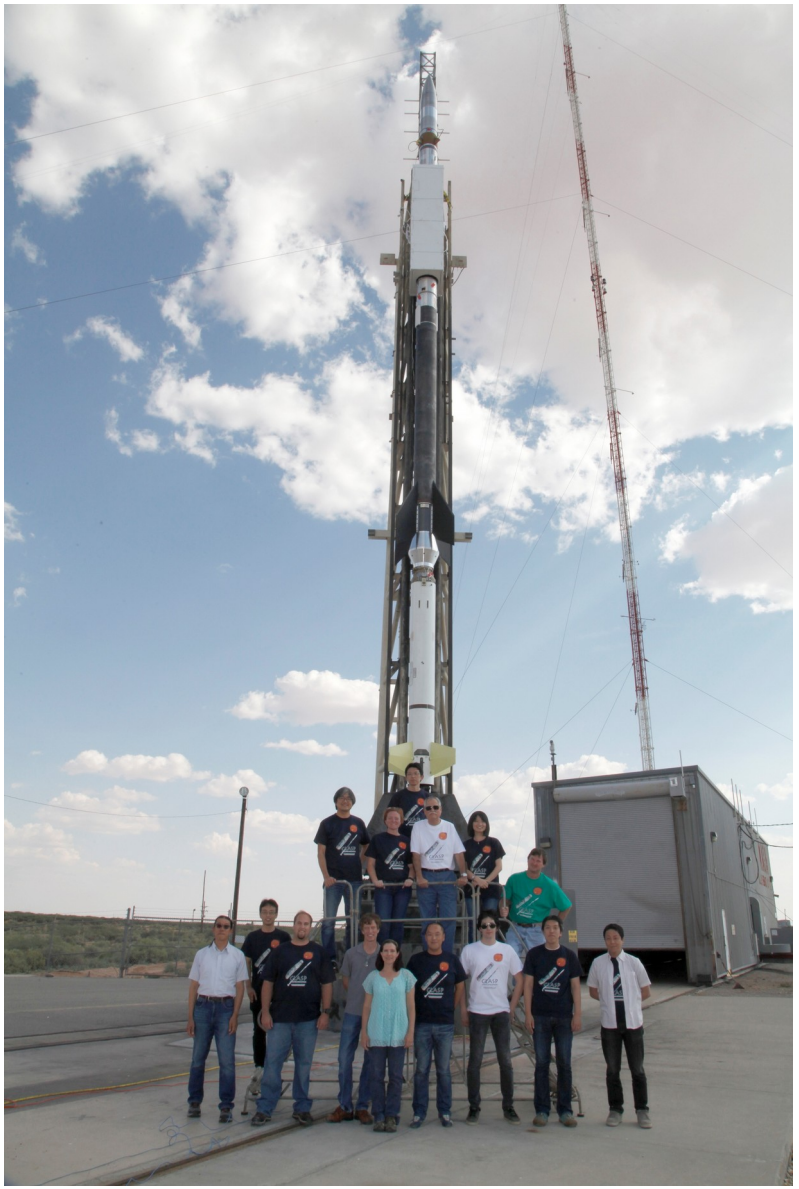


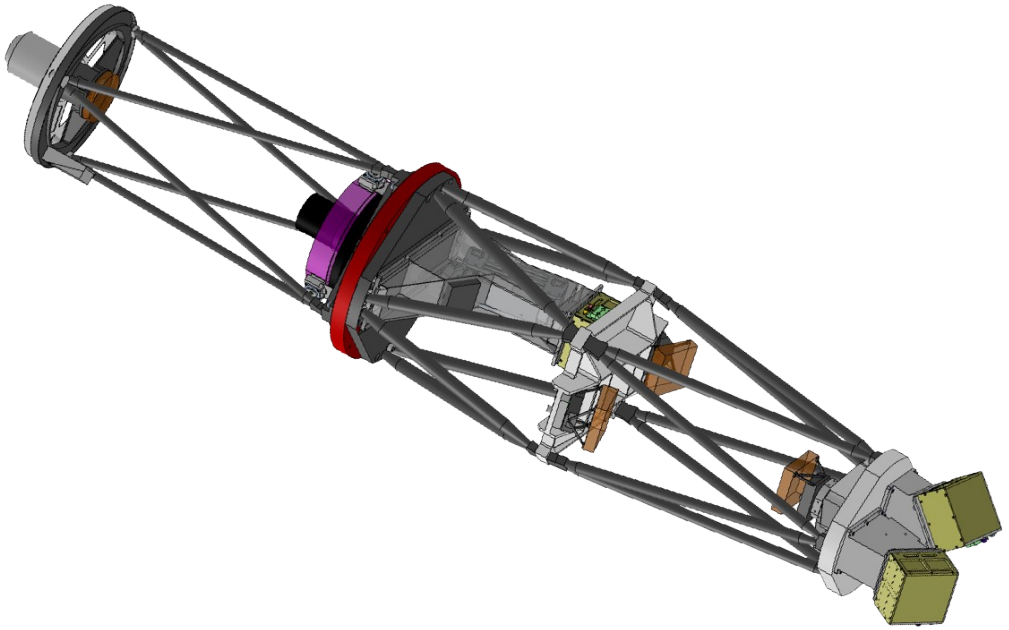
(Trujillo Bueno et al. 2004, Nature, 430, 326)

Best fit assuming volume-filling, isotropic, unimodal micro-turbulent magnetic field: 60G

The Chromospheric Lyman-alpha Spectropolarimeter (CLASP)







International collaboration:

US (NASA)
Japan (JAXA)
Europe (IAC, CNRS, **IRSOL**, ASCR, Univ. Oslo)

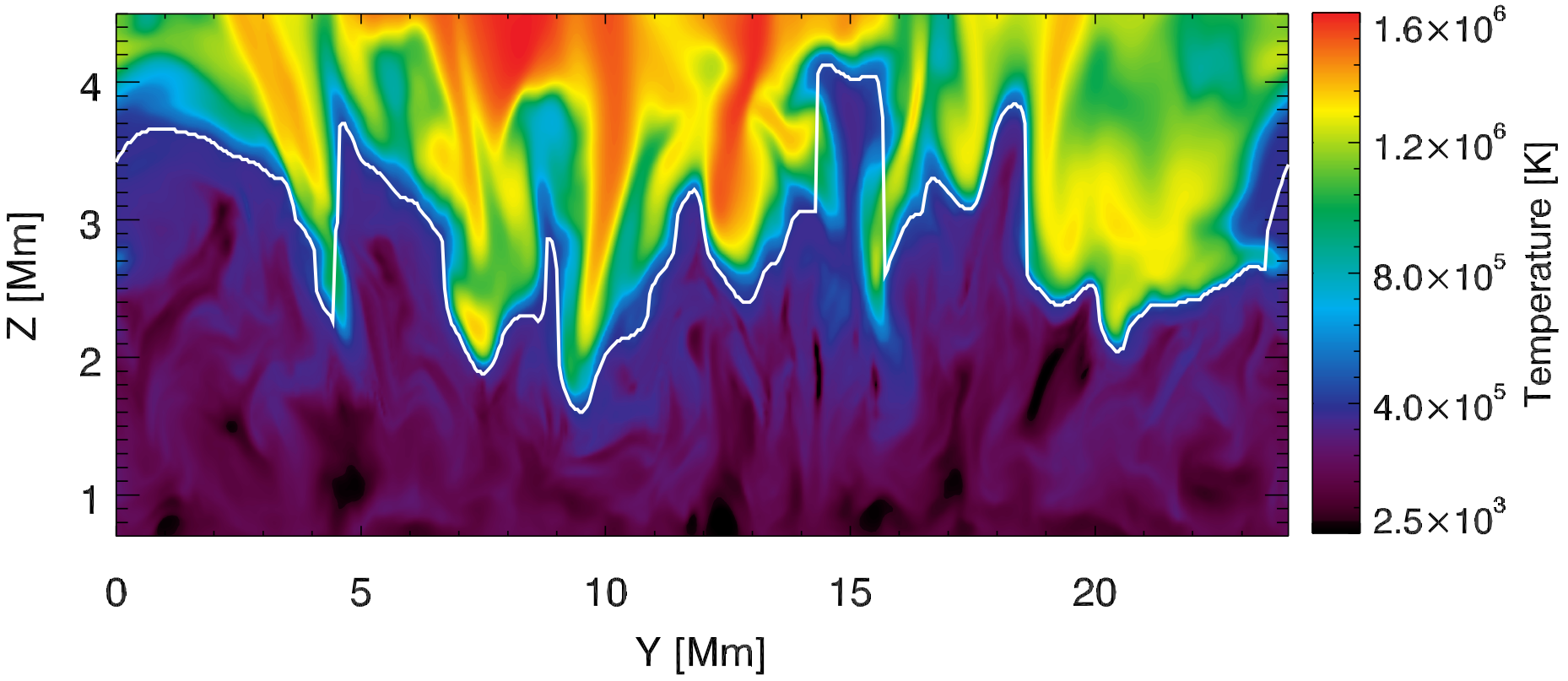
Aims of CLASP:

- measure the intensity and scattering polarization profiles of the hydrogen Ly-alpha line at 1216Å

- possibly exploit them to get information (through the Hanle effect) on the magnetic fields present in the high chromosphere

CLASP: theoretical predictions

Height of formation of the HI Ly-α line

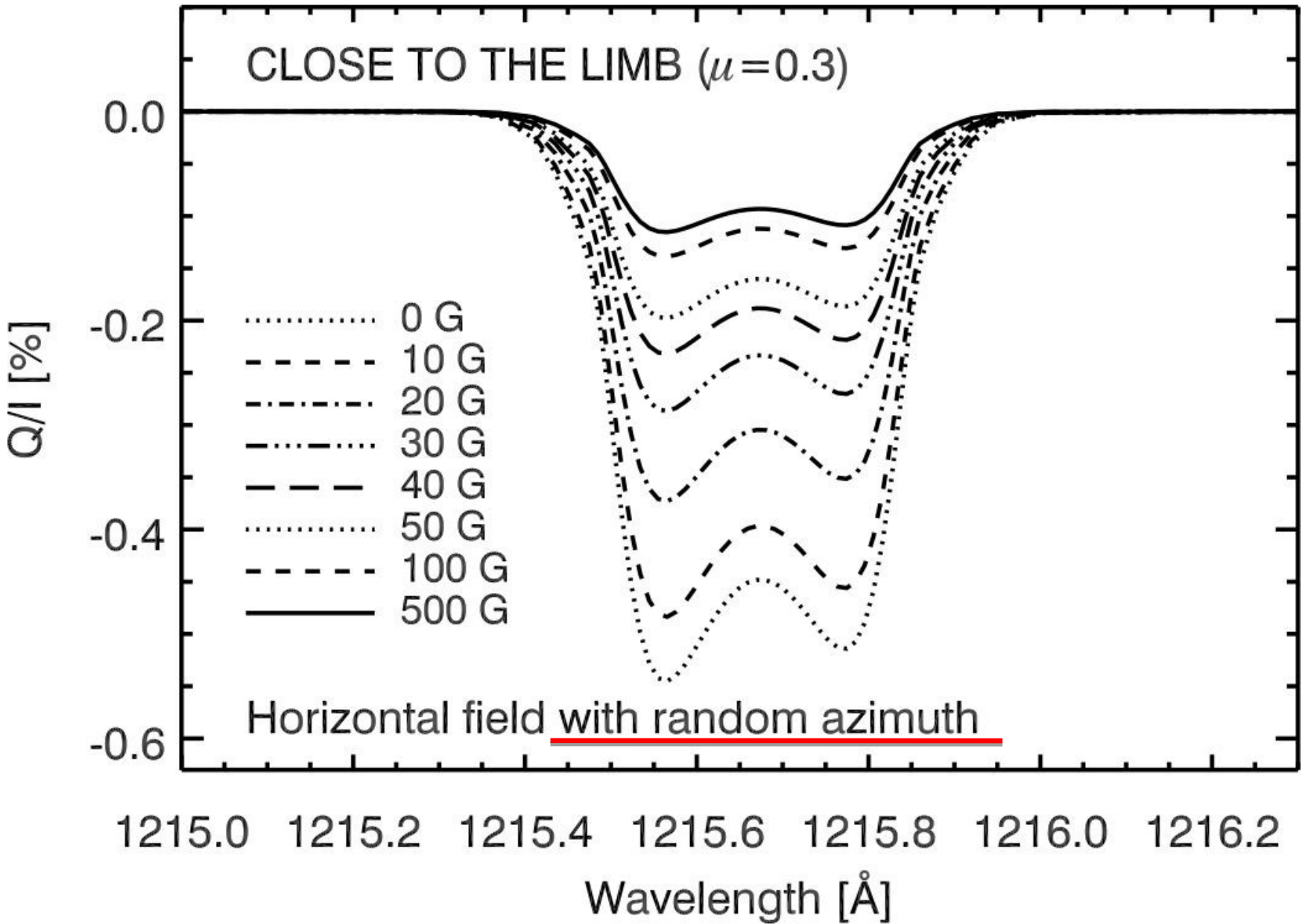


Three-dimensional models resulting from MHD simulations (see Stepan, Trujillo Bueno, Leenaarts & Carlsson 2015; ApJ)

CLASP: theoretical predictions

The Hanle effect in Ly-alpha (CRD calculations, FAL-C model)

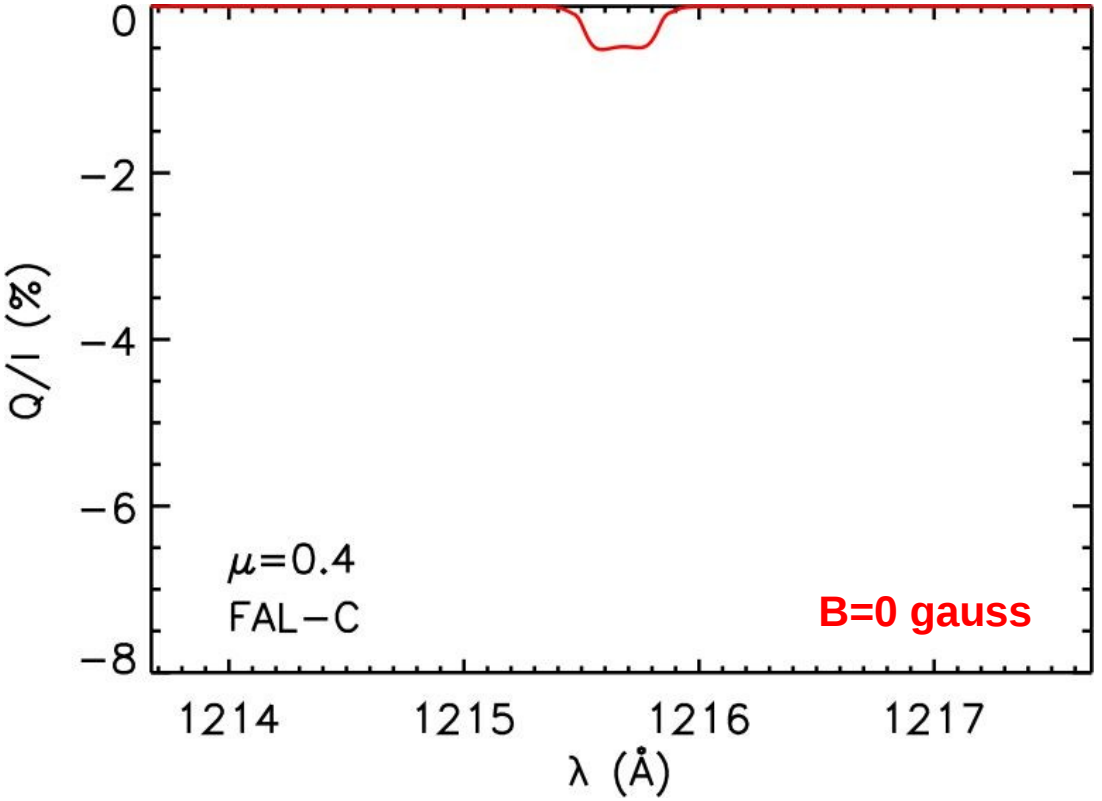
Trujillo Bueno, Stepan & Casini (2011; ApJ Letters)



CLASP: theoretical predictions

The impact of partial frequency redistribution (PRD) effects

CRD calculations

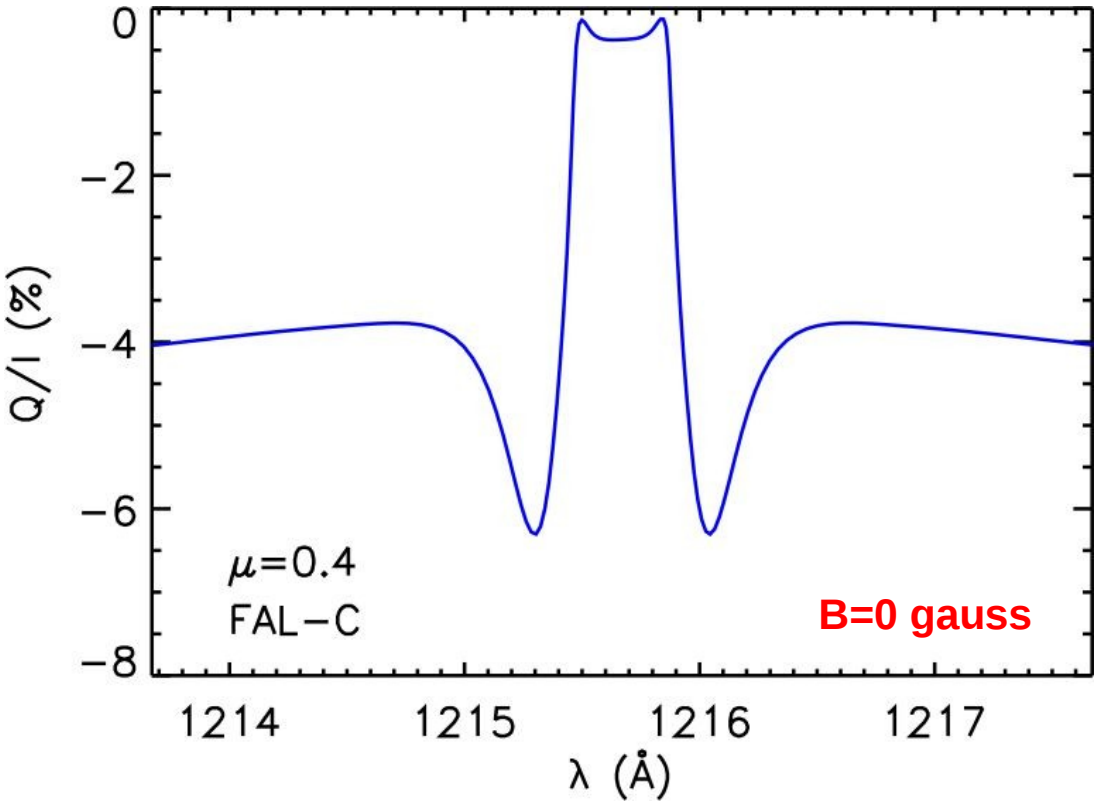


Trujillo Bueno, Stepan & Casini (2011; ApJ Letters)

CLASP: theoretical predictions

The impact of partial frequency redistribution (PRD) effects

PRD calculations



Belluzzi, Trujillo Bueno & Stepan (2012; ApJ Letters)

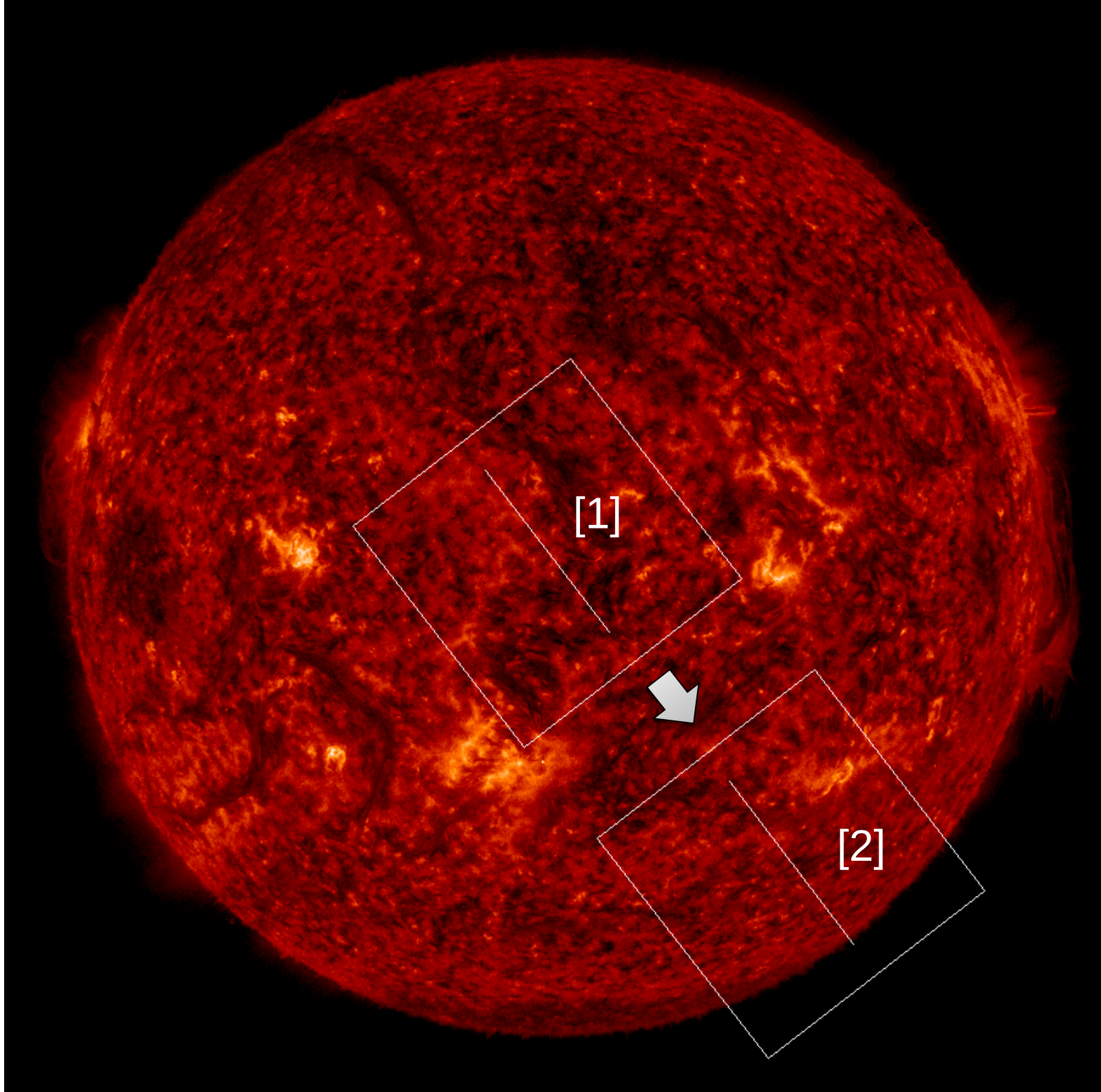
Launch of CLASP (September 3, 2015)

TARGETS SELECTED:

QUIET REGIONS

[1] Disk CENTER

[2] LIMB with radial slit from 20” off-limb till 380” on disk

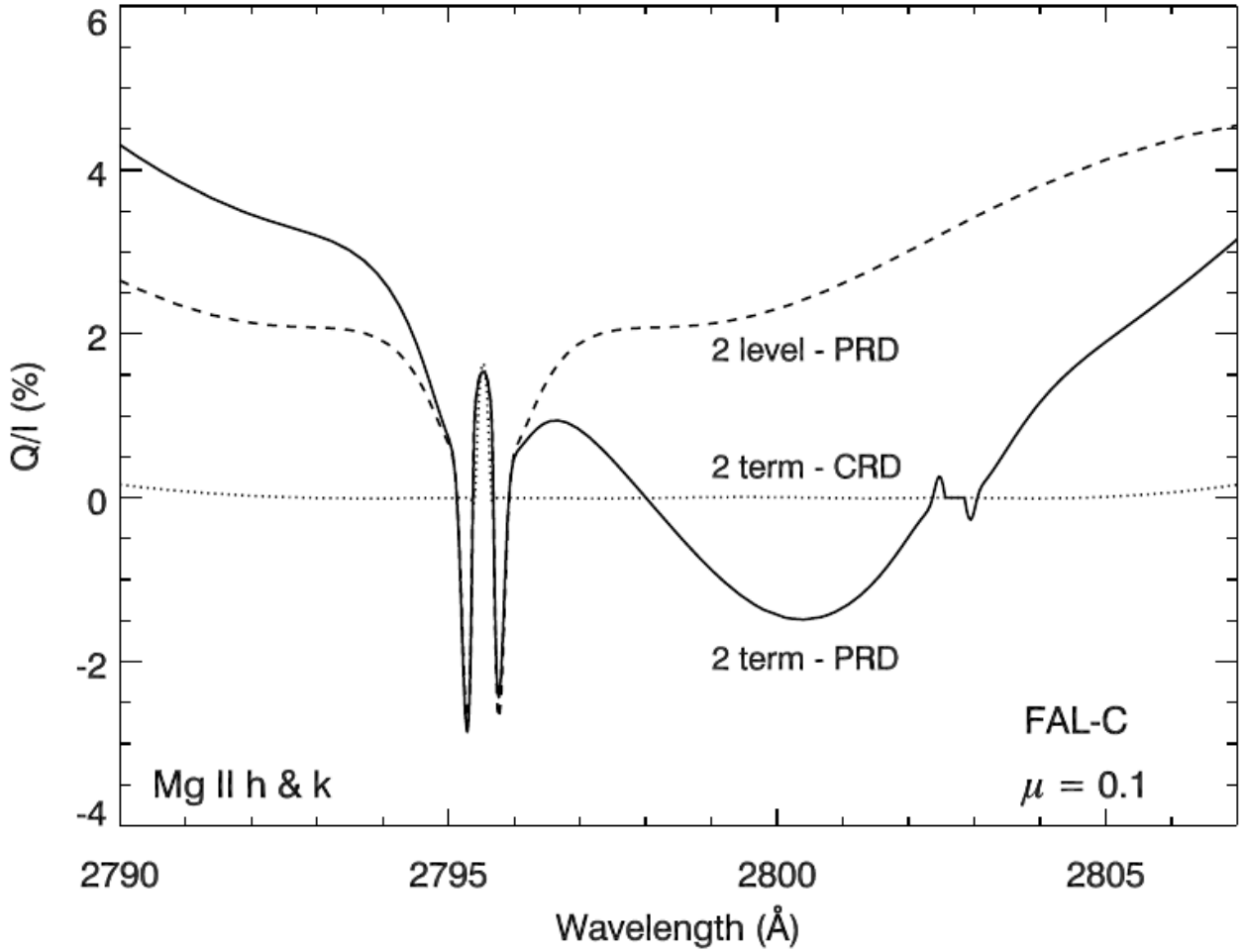


CLASP-2 Chromospheric Layer Spectro-Polarimeter

New sounding rocket experiment focused on the MgII h and k lines at 2800Å

Proposal submitted to NASA on June 2016.

Unmagnetized reference case



Belluzzi & Trujillo Bueno (2012; ApJ Letters)