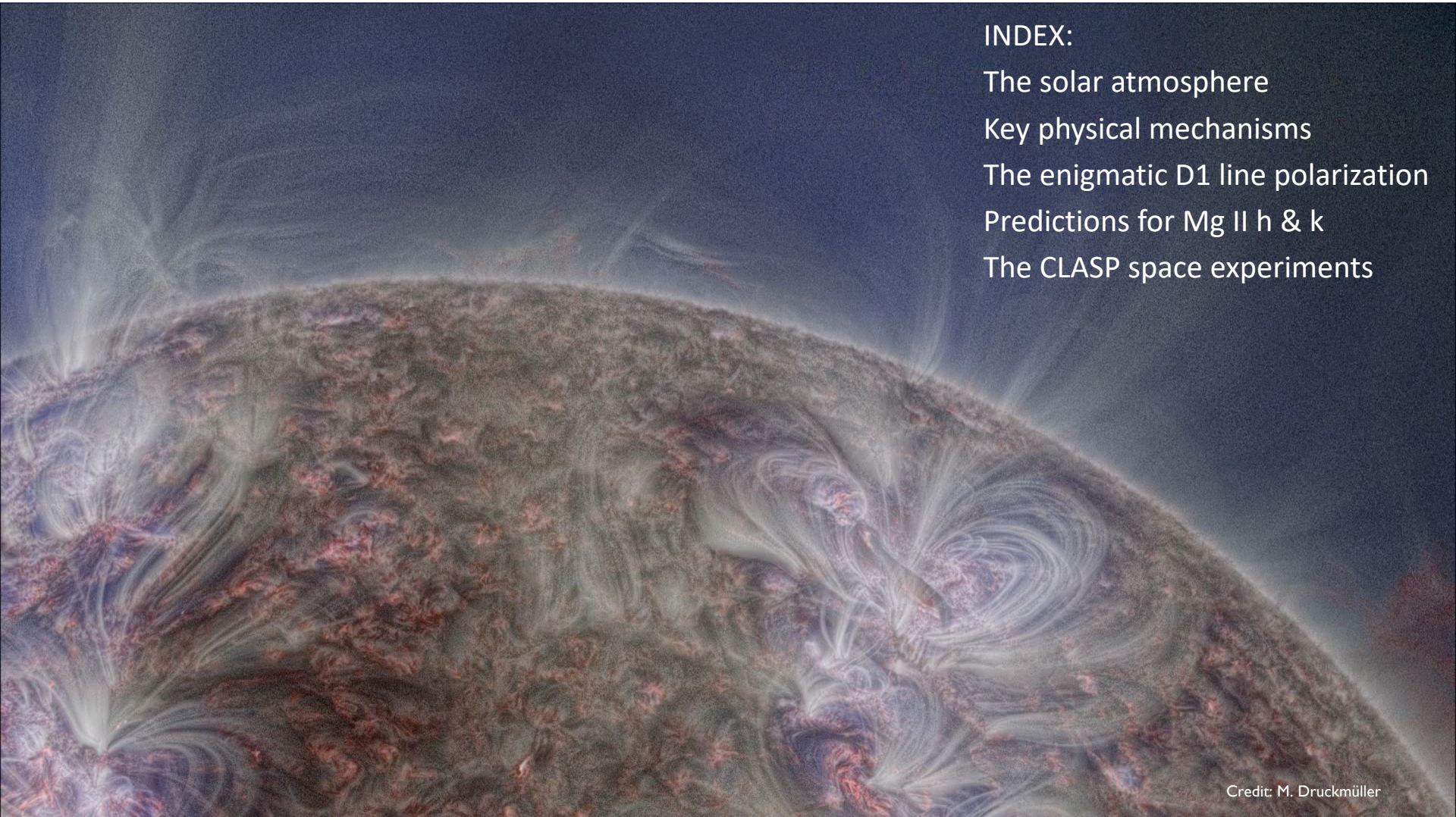
The Sun as a Rosetta Stone for the Physics of Atom-Photon Interactions

Javier Trujillo Bueno
(IAC, Tenerife, Spain)

Movie credit: M. Druckmüller



INDEX:

The solar atmosphere

Key physical mechanisms

The enigmatic D1 line polarization

Predictions for Mg II h & k

The CLASP space experiments

Credit: M. Druckmüller

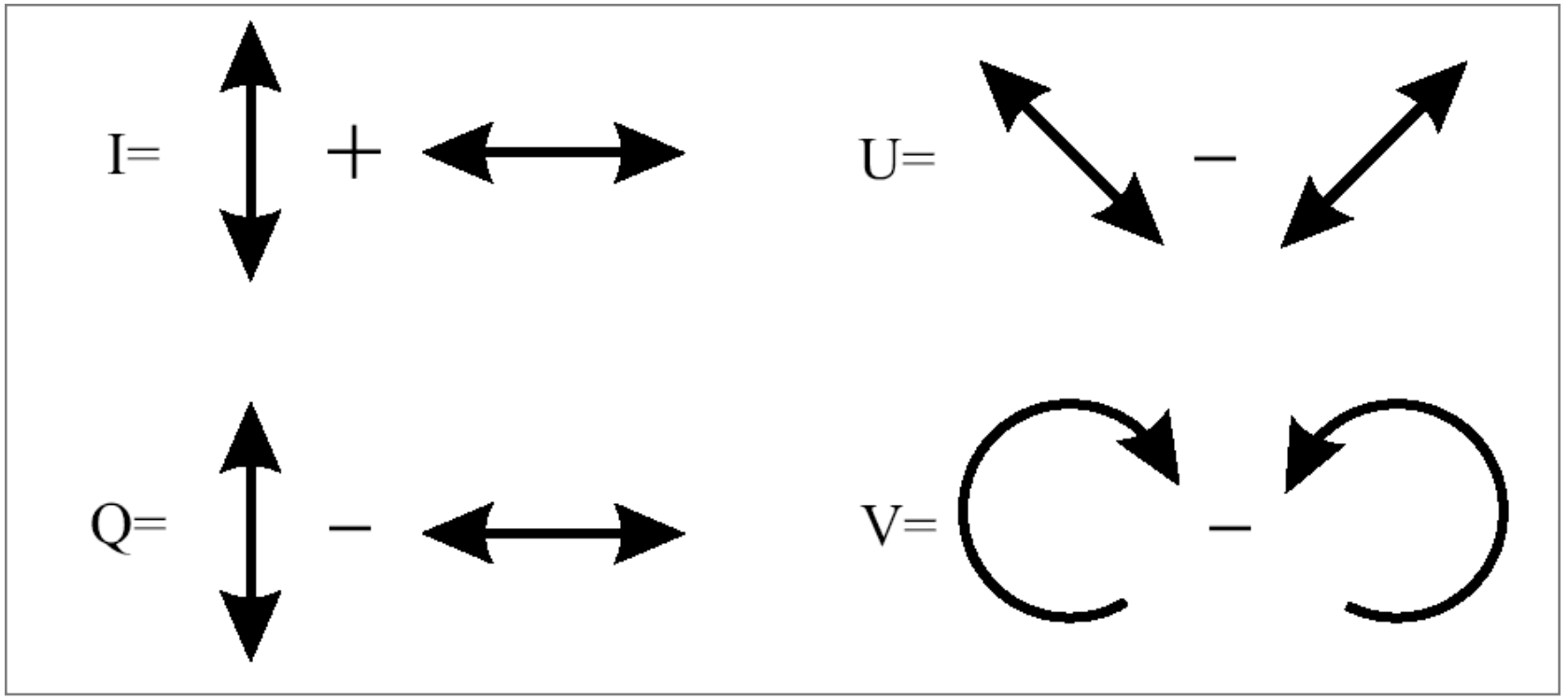
The solar atmosphere: a very complex physical system

- Large spatial dimensions
- Large temperature and density gradients
- Spatially inhomogeneous and time dependent
- Very dynamic, with waves and shocks
- Complex magnetic fields

J. Trujillo Bueno (2023, Solarnet-S3 meeting)

The magnetic field information

The POLARIZATION of the solar spectrum



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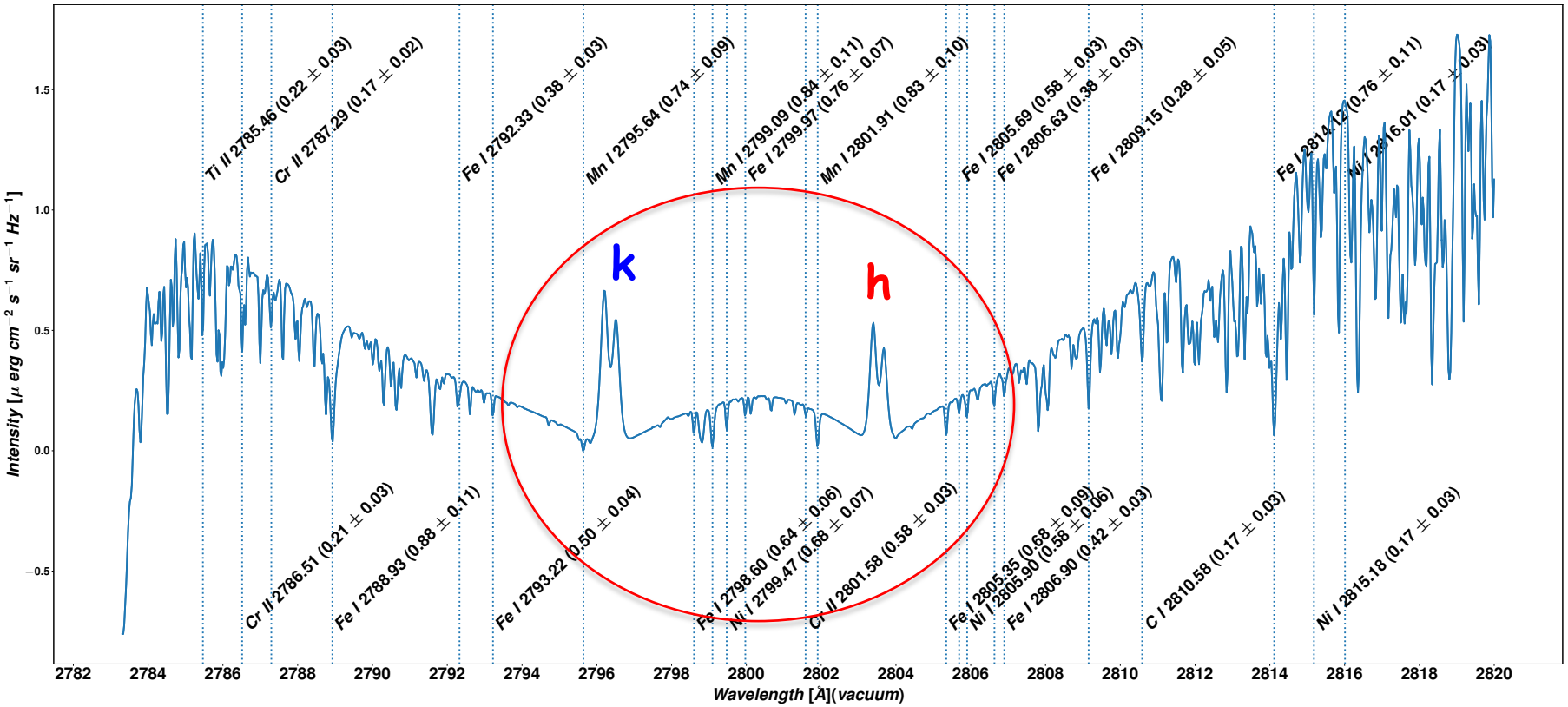
The near-UV spectrum around 280 nm

The spectral region of the Mg II h & k lines

IRIS observation of the INTENSITY spectrum



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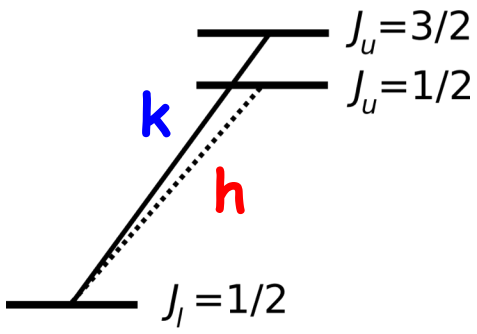
Theoretical predictions for the Mg II h & k lines

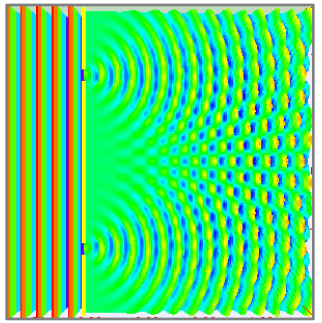
(applying a rigorous quantum theory of atom-photon interactions)

Belluzzi & Trujillo Bueno (2012; ApJ)
Alsina Ballester et al. (2016; ApJ)
del Pino Alemán et al. (2016, ApJ)
Trujillo Bueno et al. (2017)
del Pino Alemán et al. (2020; ApJ)

PRD → correlations between the incoming and outgoing photons

J-state interference →



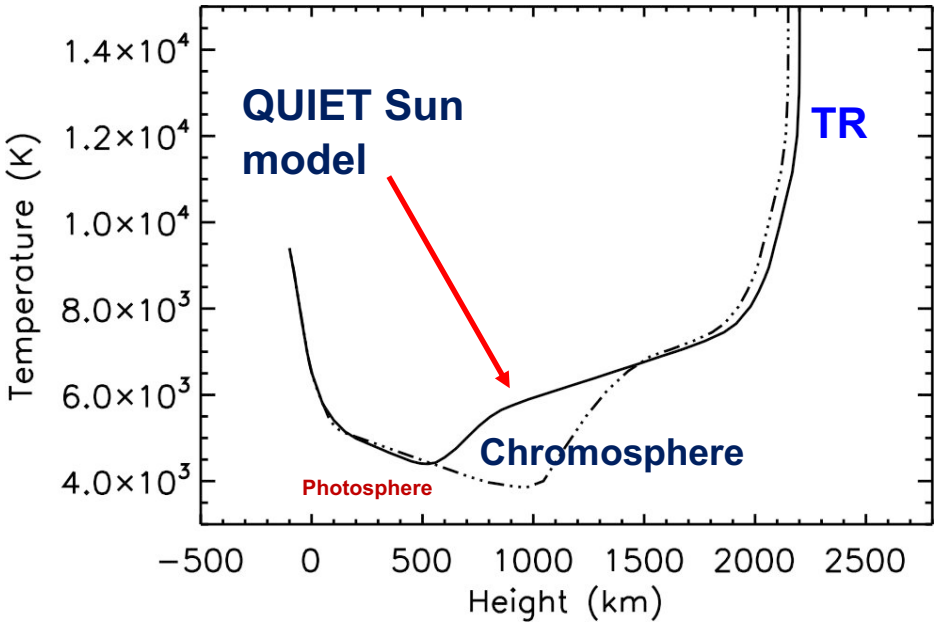


Magnetic fields → joint action of Hanle, Zeeman and MO effects

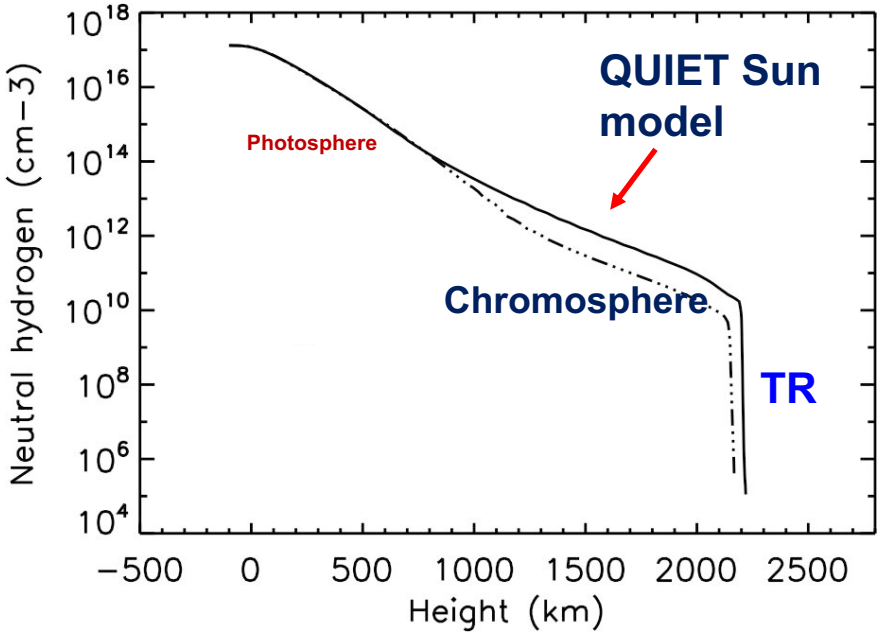
Theoretical predictions from radiative transfer calculations in models of the solar atmosphere

Semi-empirical models of the QUIET SUN atmosphere

TEMPERATURE vs. HEIGHT



H I number density vs. HEIGHT



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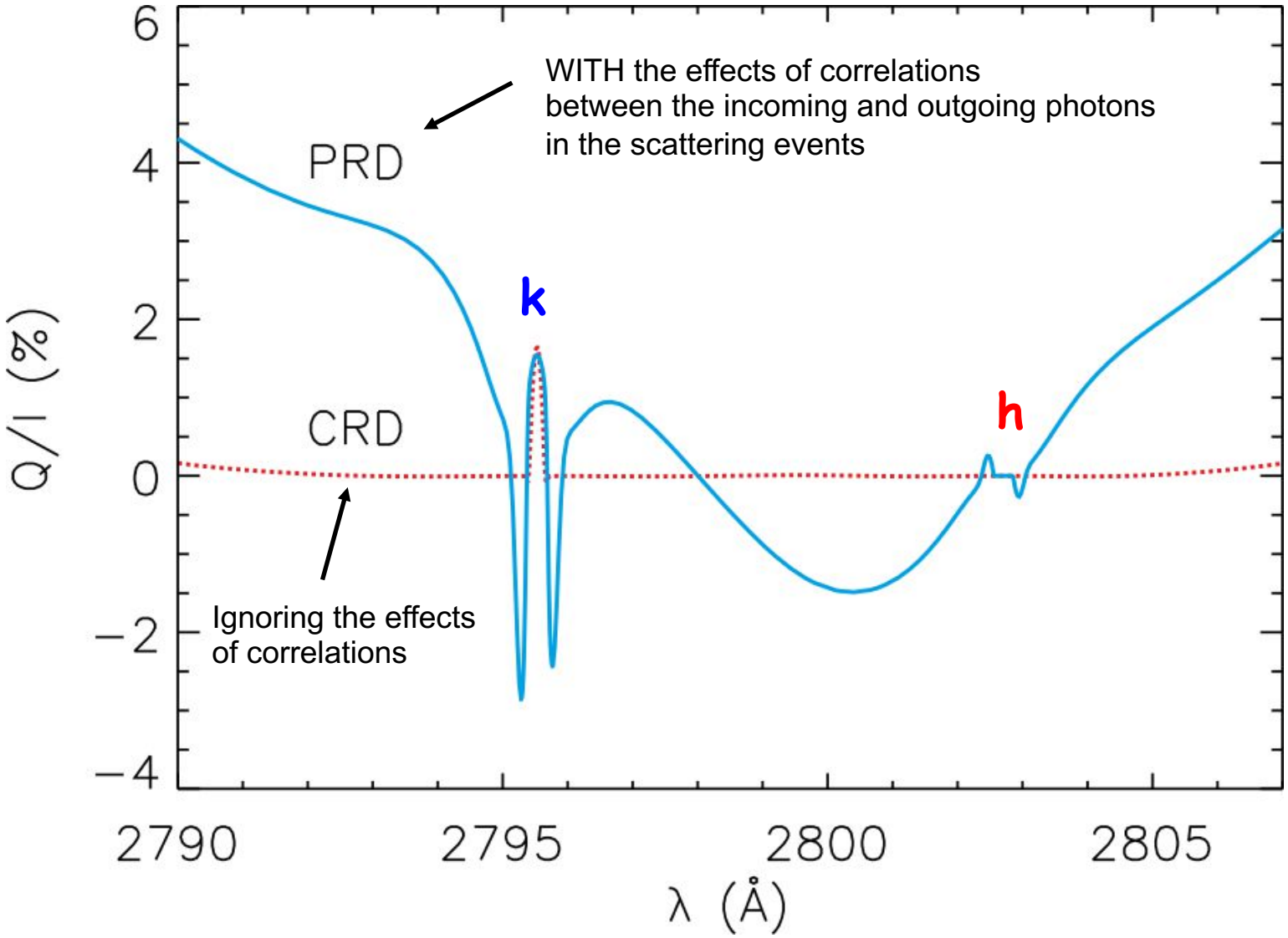
(1) Impact of PRD on the scattering polarization of the Mg II h & k lines



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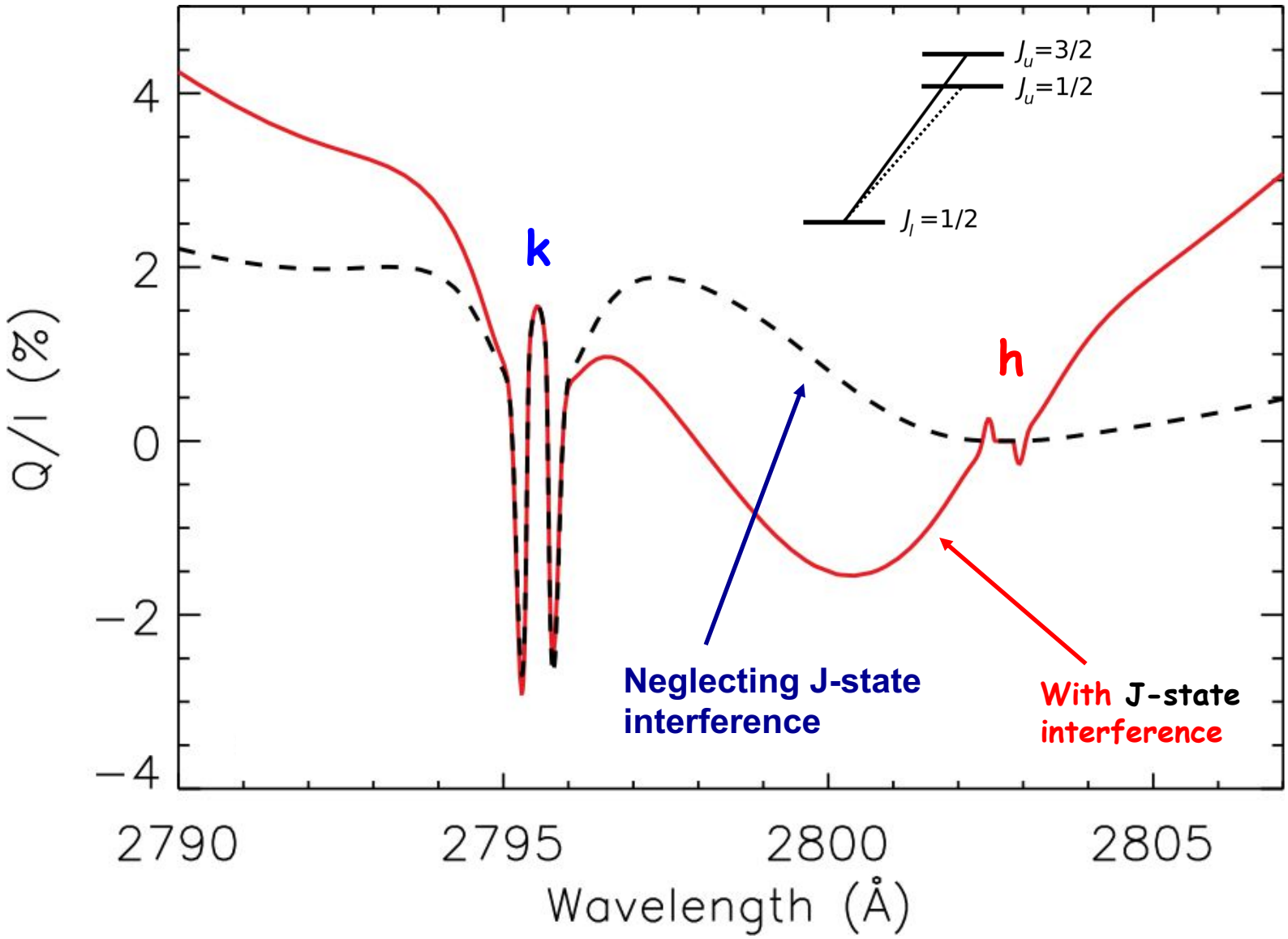
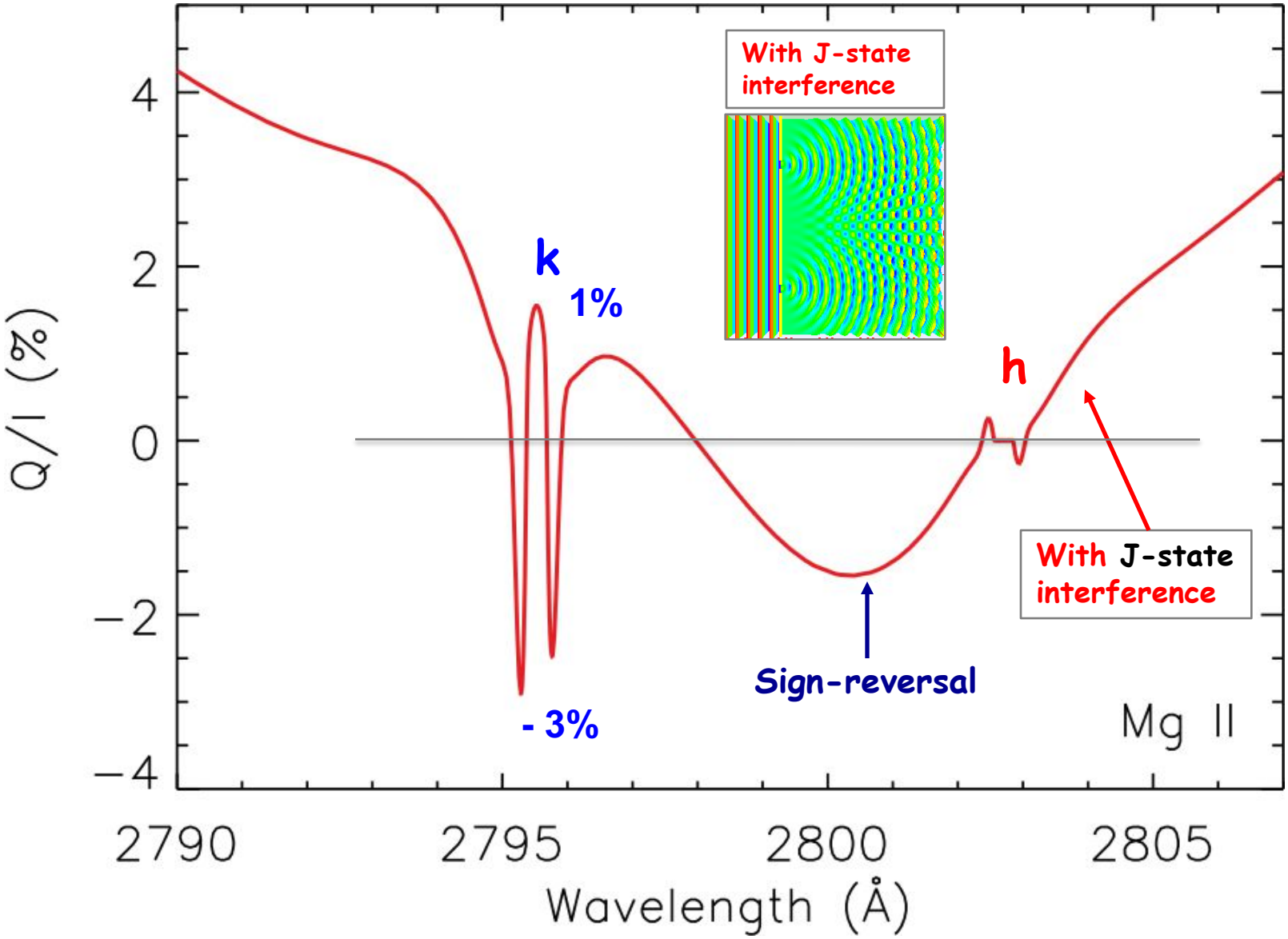
(2) The impact of J-state interference on the scattering polarization of the Mg II h & k lines



J. Trujillo Bueno (2023, Solarnet-S3 meeting)

(2) The impact of J-state interference on the scattering polarization of the Mg II h & k lines



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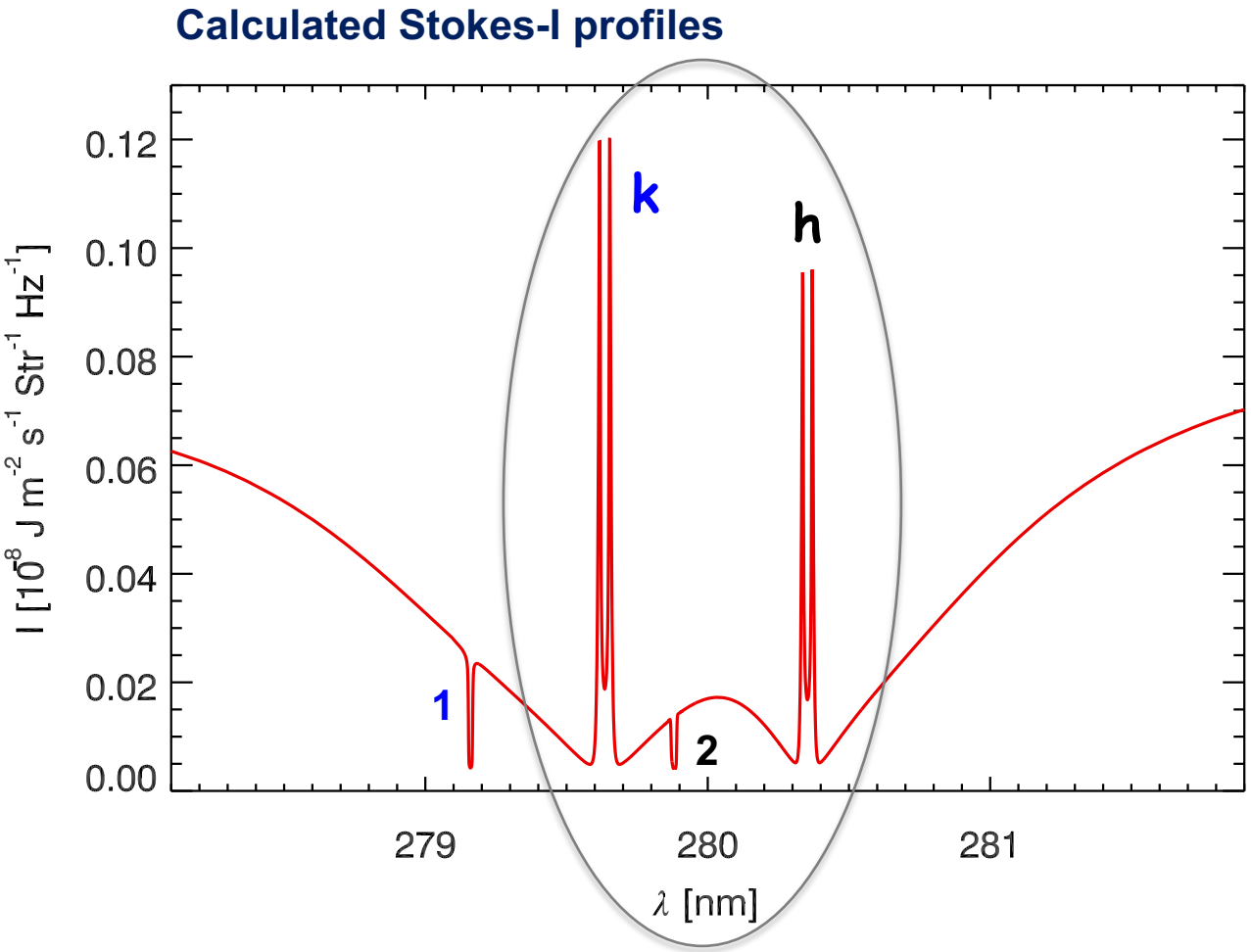
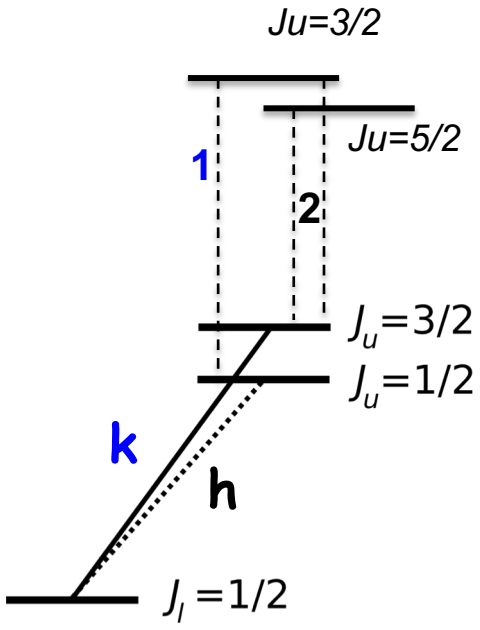
(3) The impact of magnetic fields

Let us now show

- The intensity profiles: Stokes-I
- The circular polarization: V/I
- The linear polarization: Q/I and U/I

The INTENSITY of the Mg II lines





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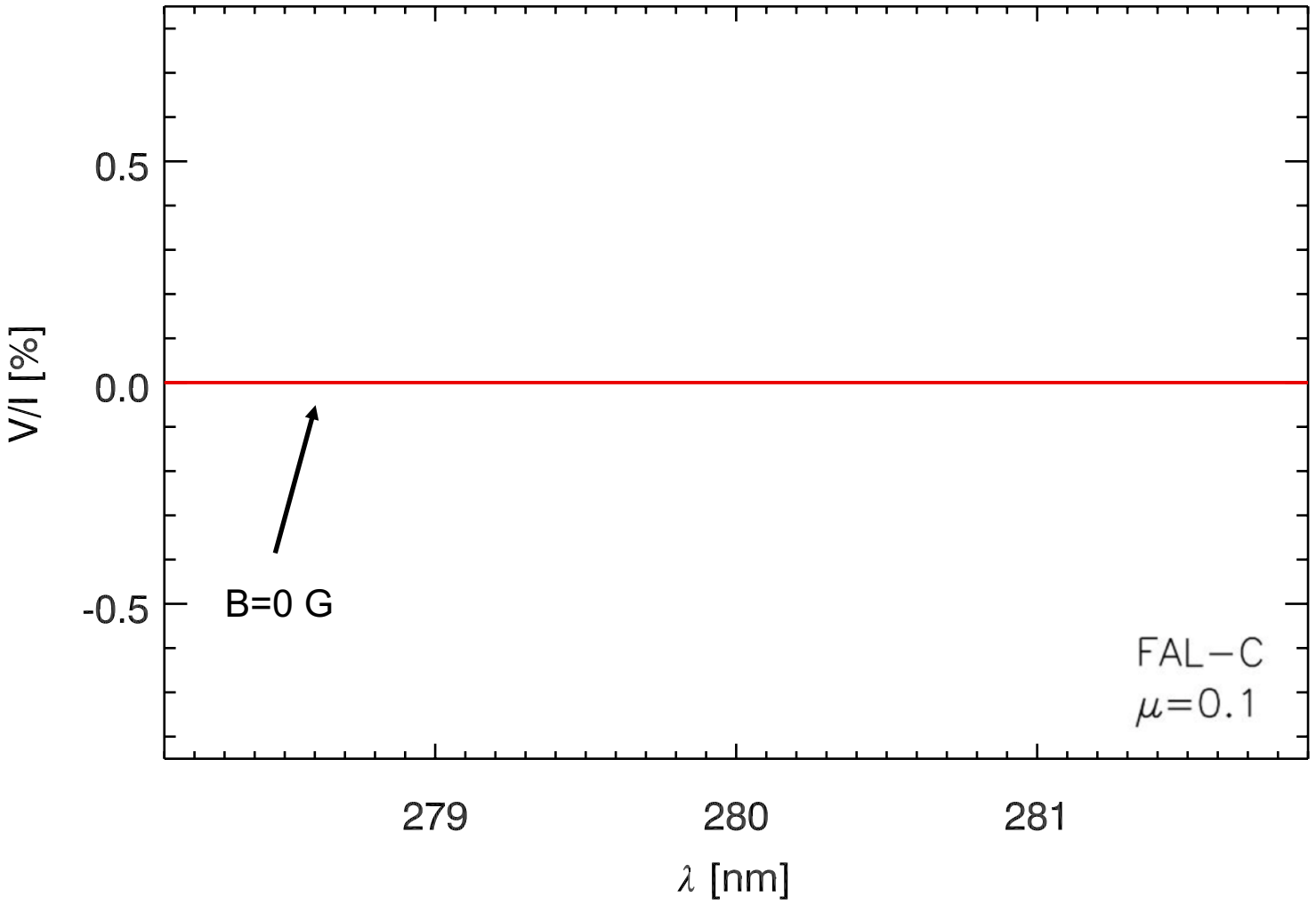
The **CIRCULAR** polarization (Zeeman effect)

(Horizontal field pointing almost towards the observer)



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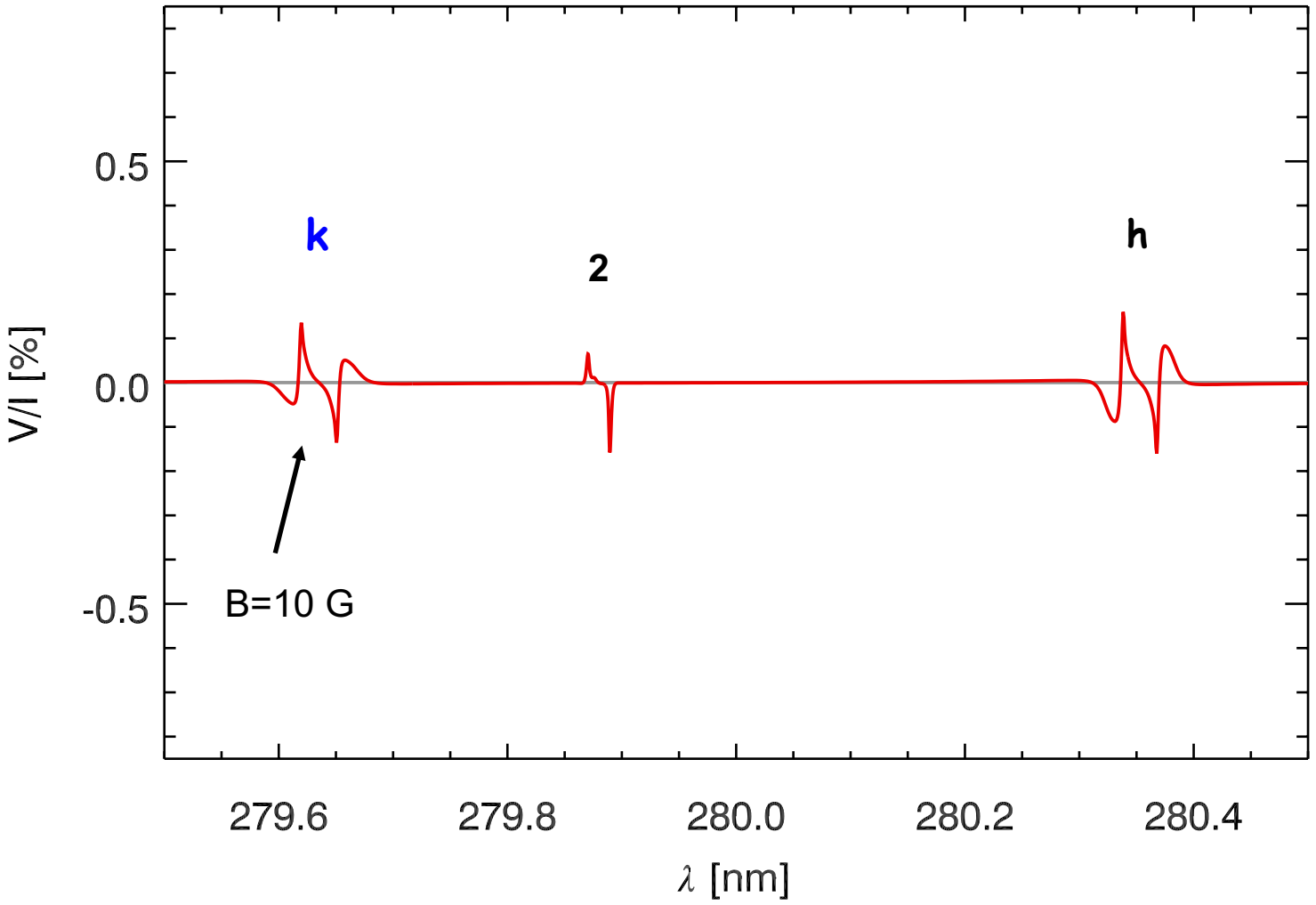

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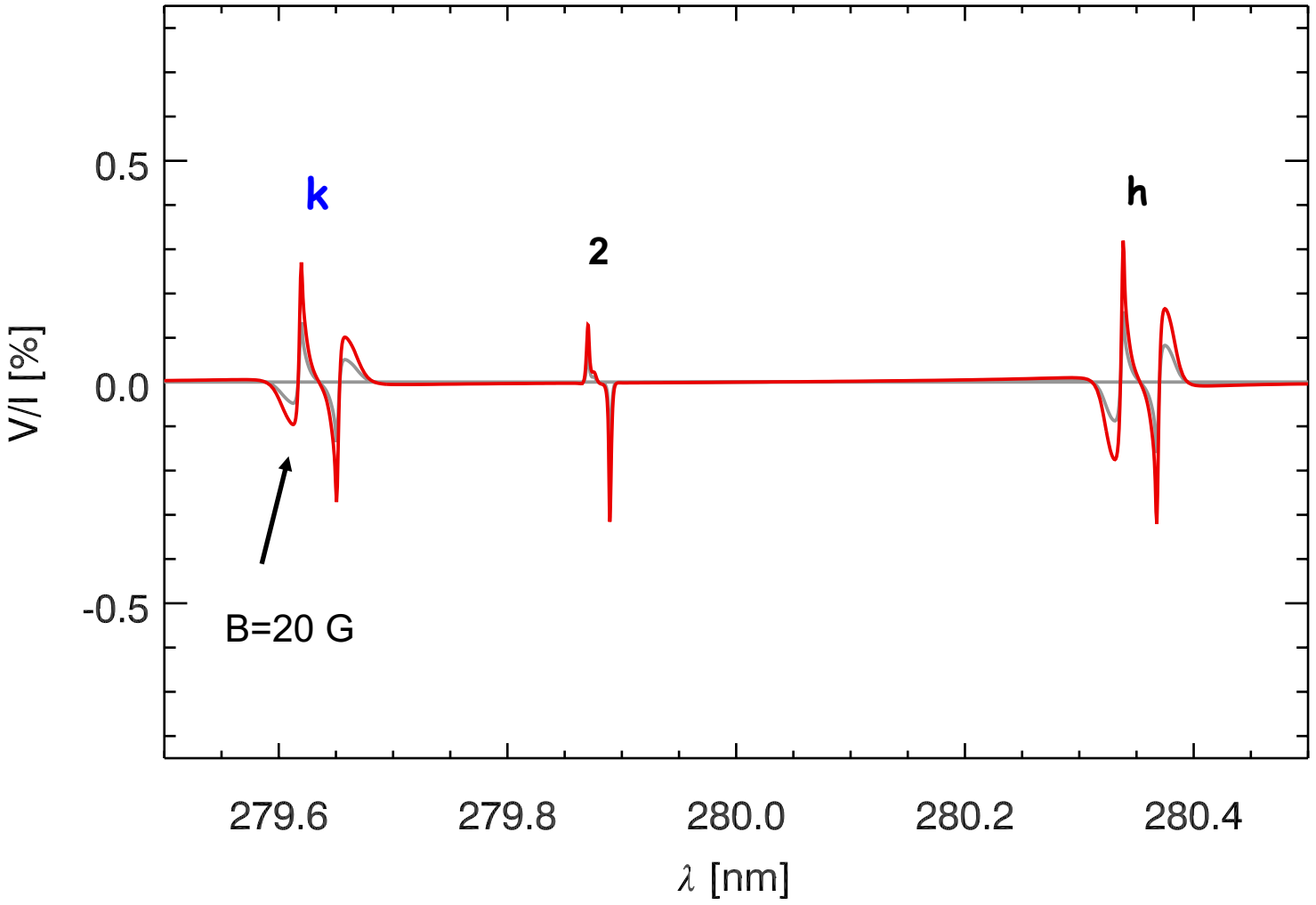

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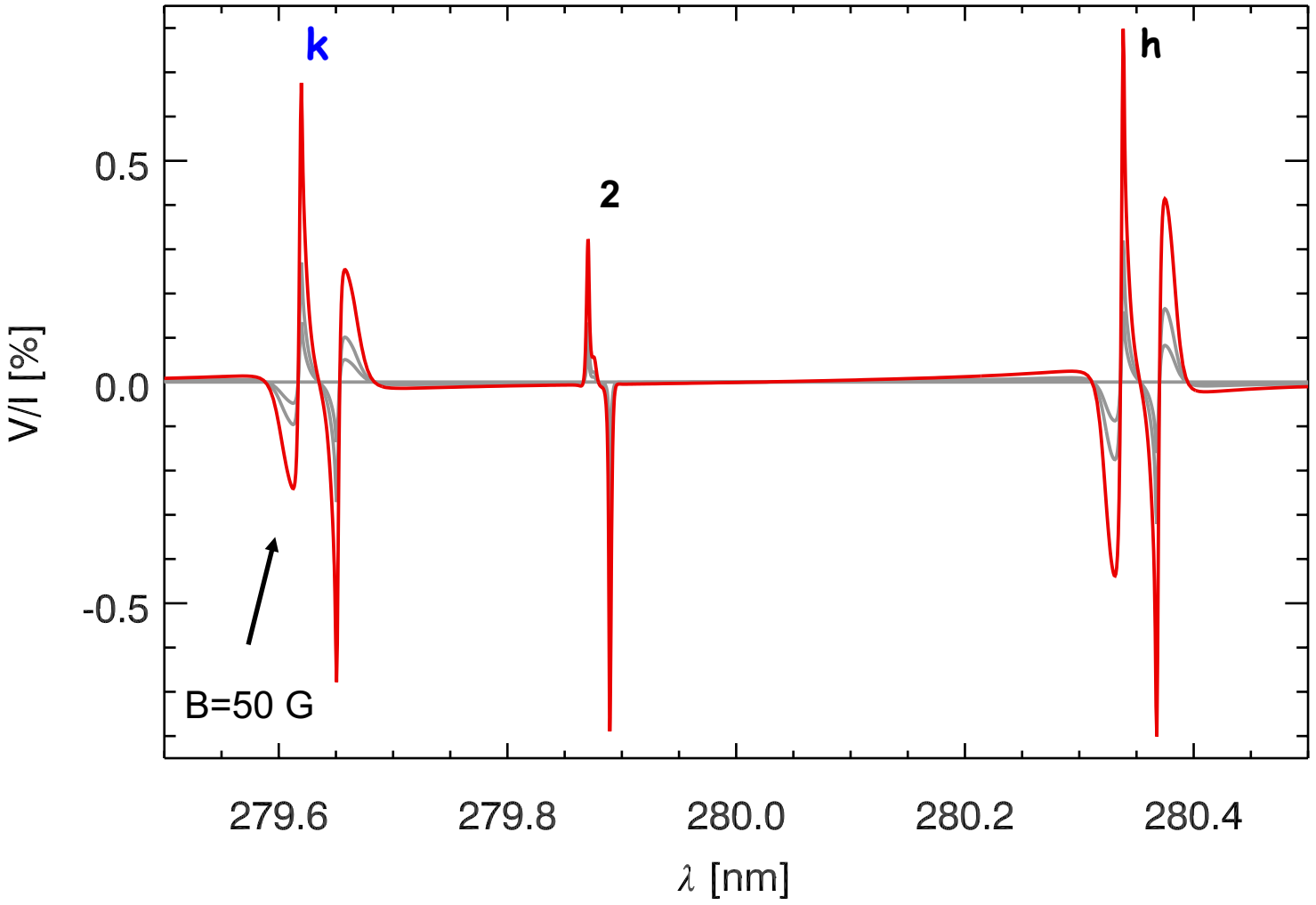
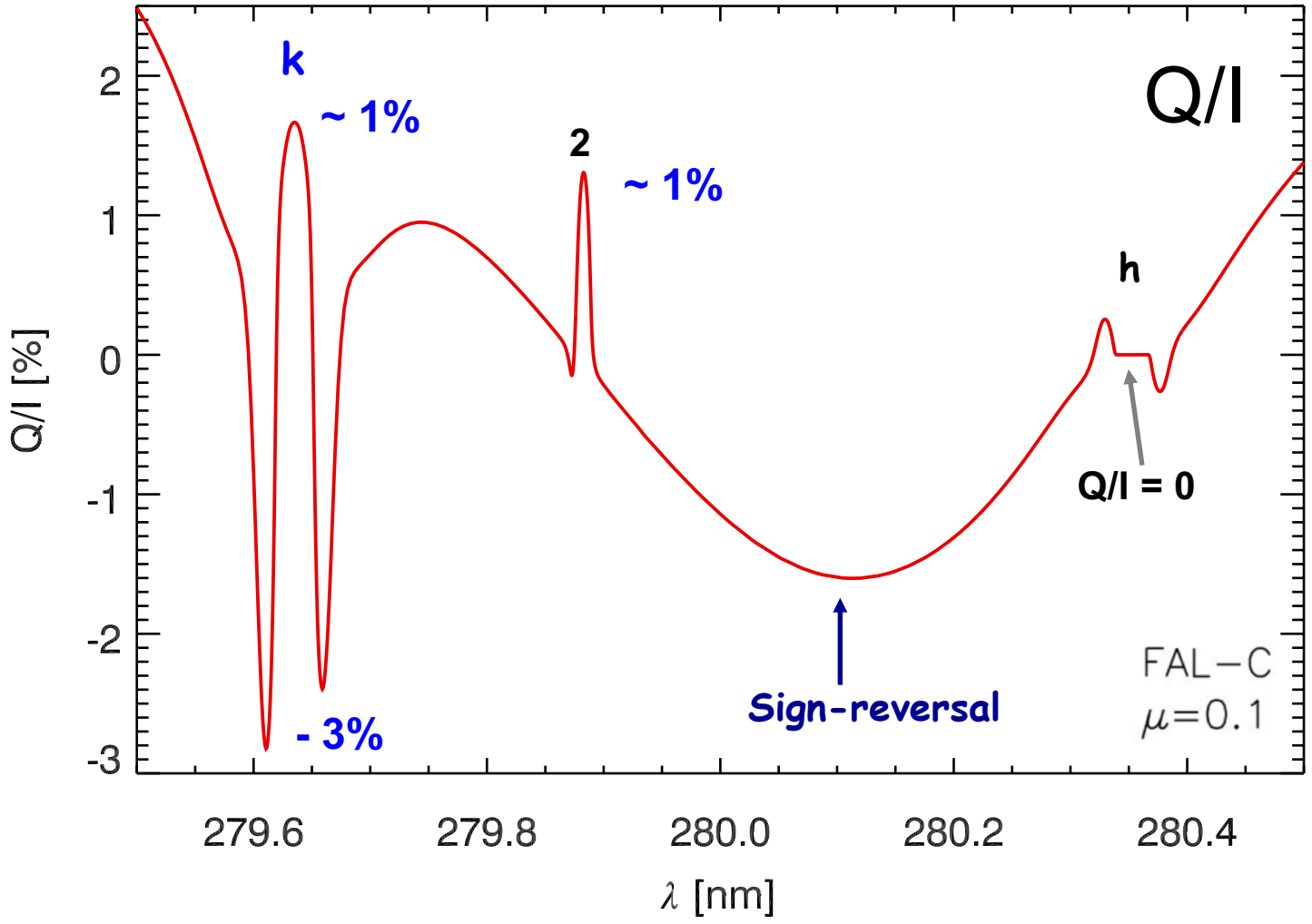


J. Trujillo Bueno (2023, Solarnet-S3 meeting)

The fractional **LINEAR** polarization: Q/I

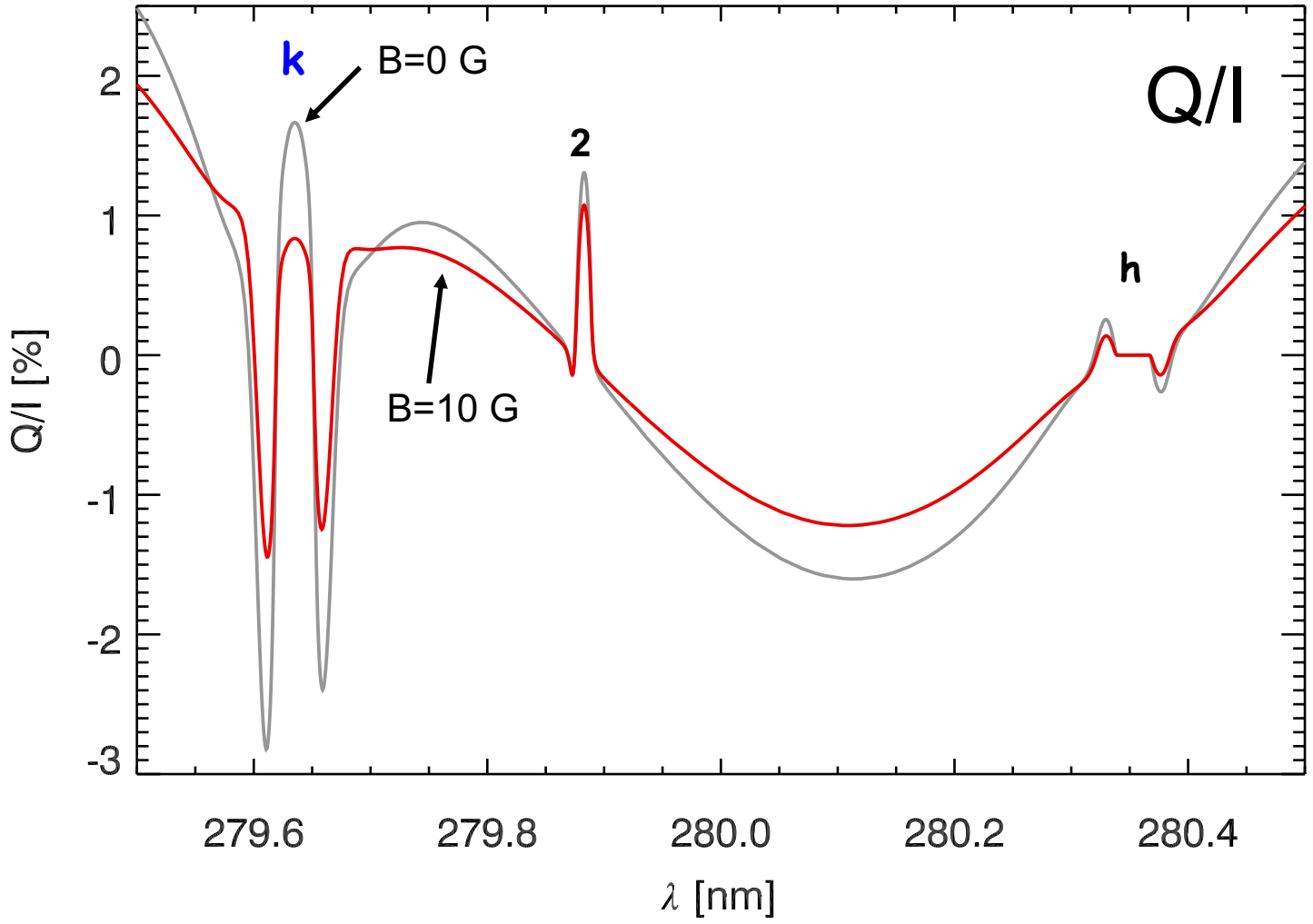
(WITHOUT magnetic fields**)**



J. Trujillo Bueno (2023, Solarnet-S3 meeting)

Q/I **WITH** magnetic fields

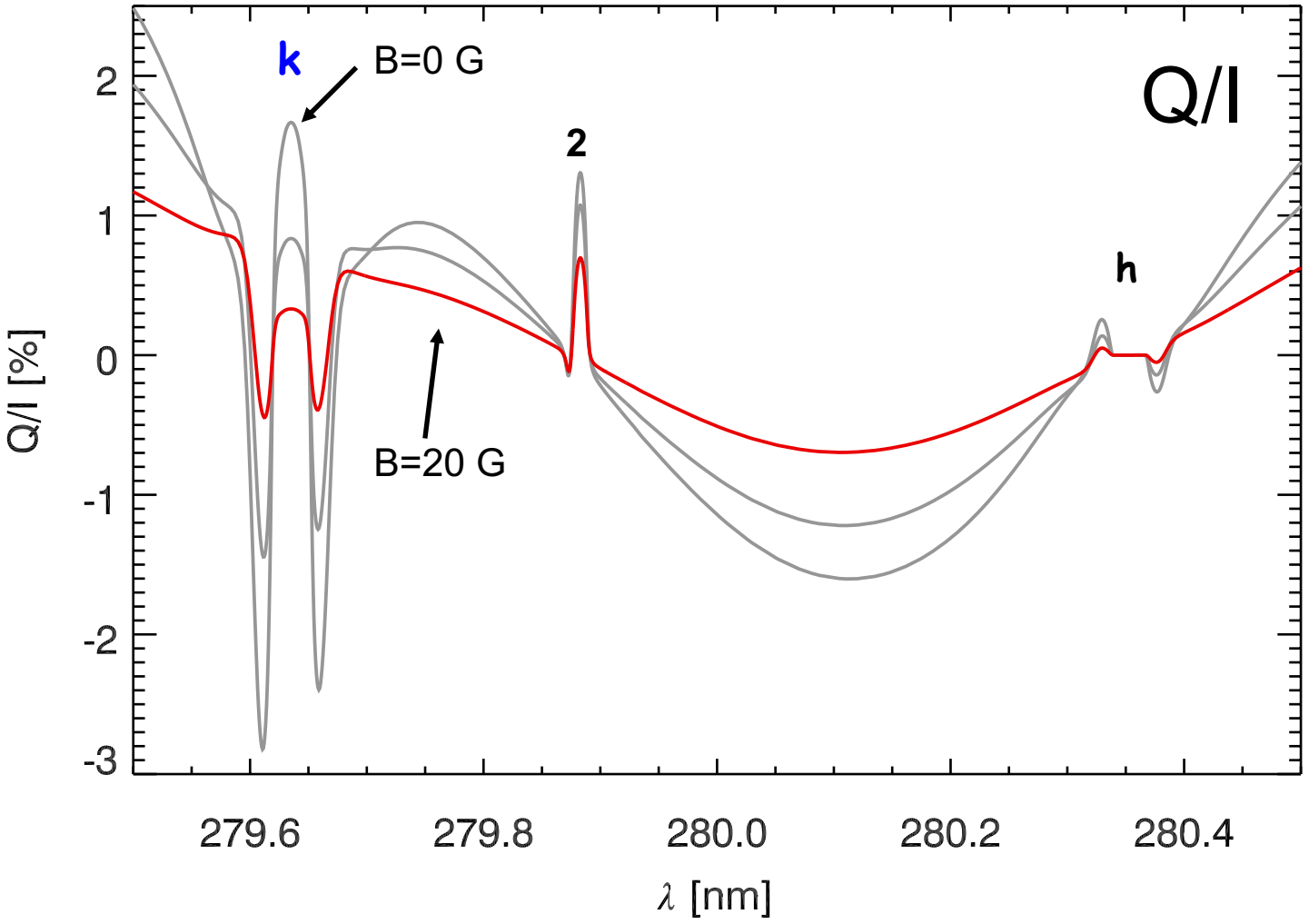
(Horizontal field pointing almost towards the observer)



J. Trujillo Bueno (2023, Solarnet-S3 meeting)

Q/I **WITH** magnetic fields

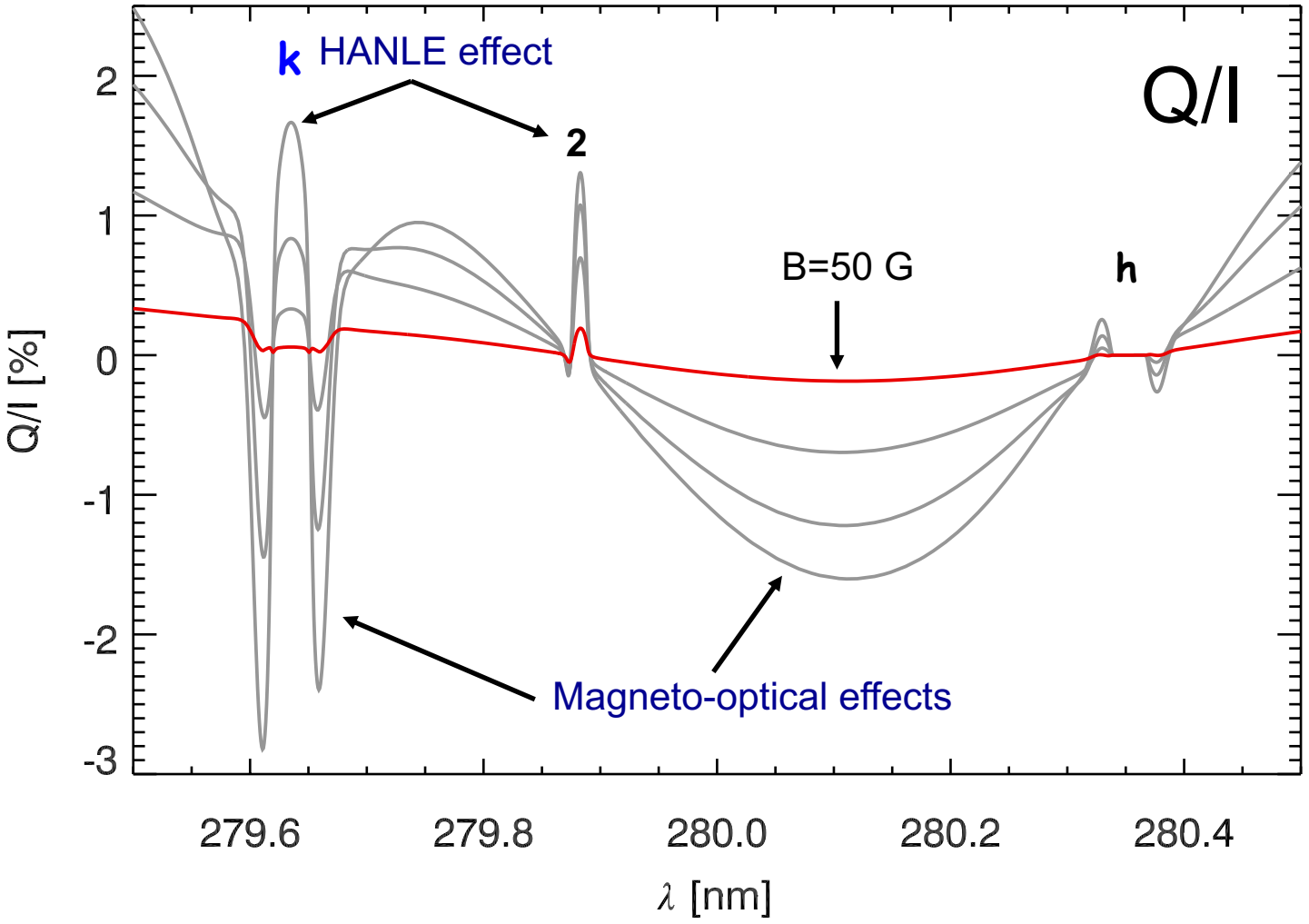
(Horizontal field pointing almost towards the observer)



J. Trujillo Bueno (2023, Solarnet-S3 meeting)

Q/I **WITH** magnetic fields

(Horizontal field pointing almost towards the observer)



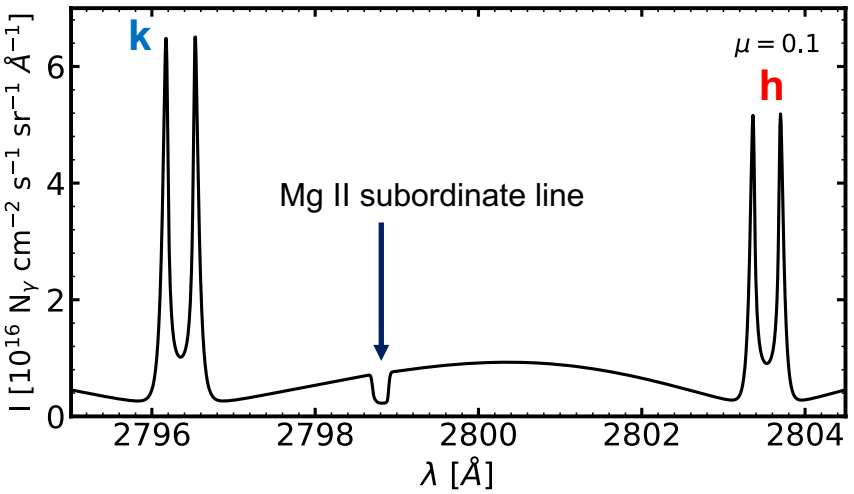
J. Trujillo Bueno (2023, Solarnet-S3 meeting)

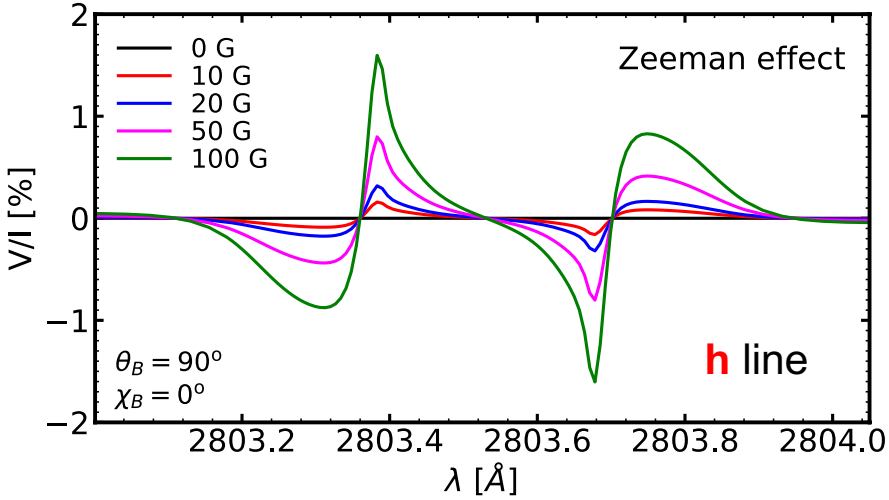
The magnetic sensitivity of the Mg II lines

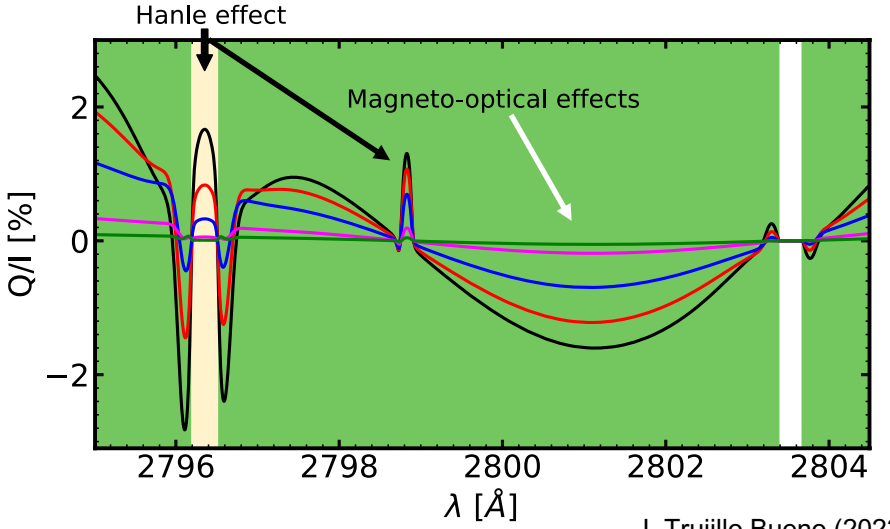
Alsina Ballester et al. (2016; ApJ)

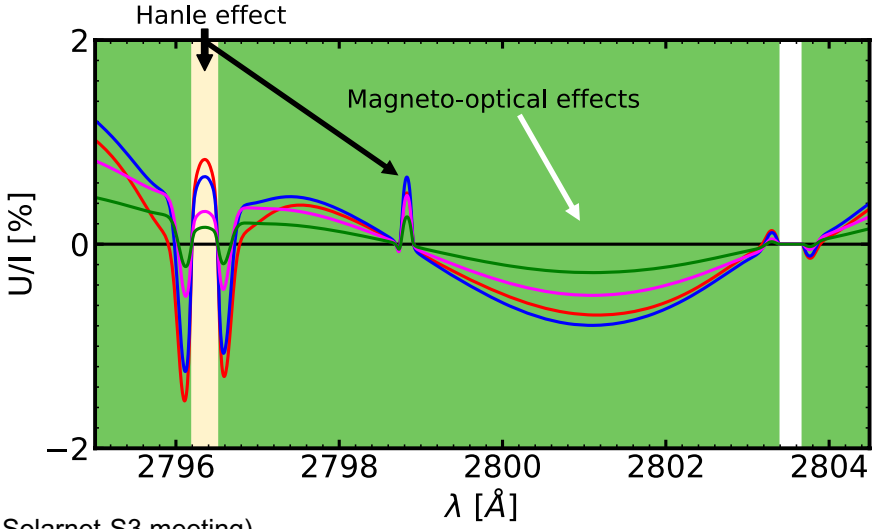
del Pino Alemán et al. (2016, 2020; ApJ)

Trujillo Bueno & del Pino Alemán (2022; Annual Review Astronomy & Astrophysics)









Physical mechanisms responsible of the polarization in chromospheric spectral lines

. **The Zeeman effect** → mainly **V**

. **The scattering of anisotropic radiation** → **Q and U**

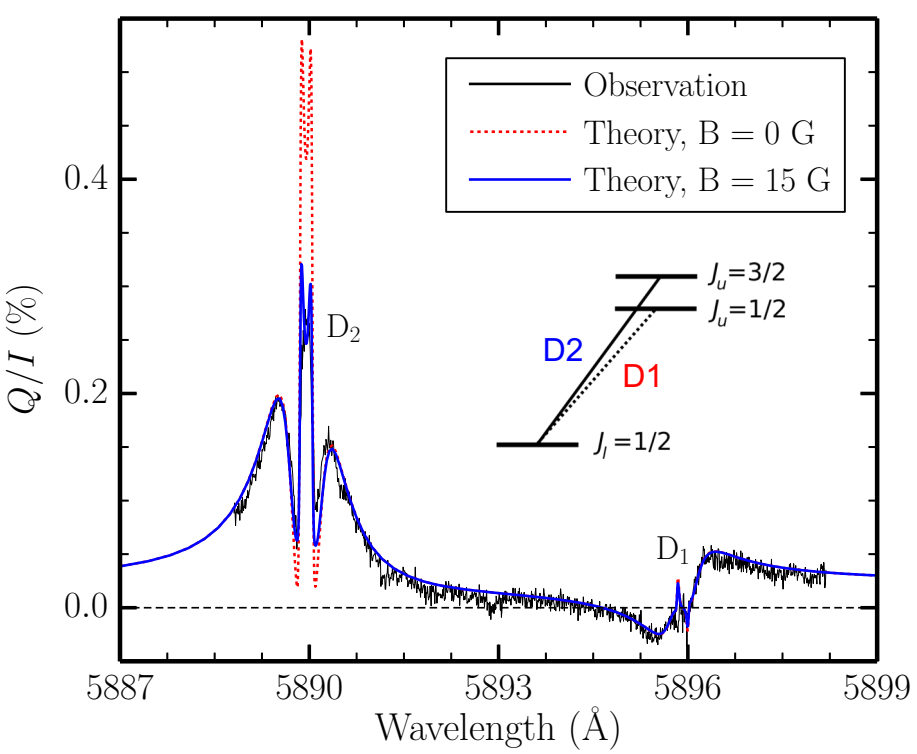
. **The Hanle effect at the center of Q and U**

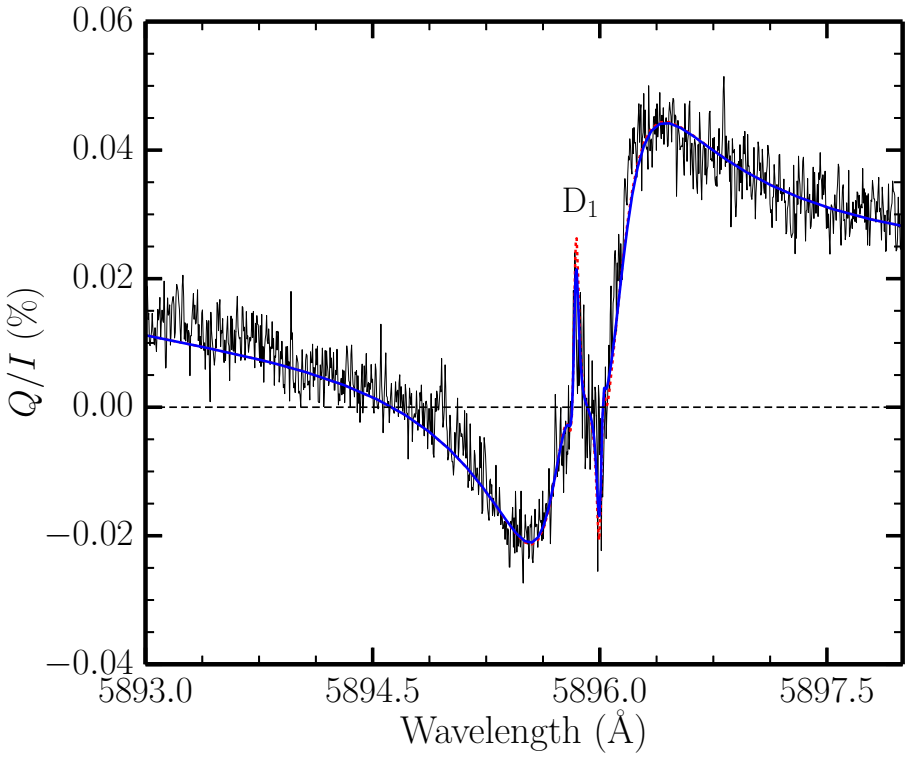
. **Magneto-Optical (MO) effects in the wings of Q and U**

Trujillo Bueno & del Pino Alemán (2022; Annual Review Astronomy & Astrophysics)

RT modeling the enigmatic polarization of the sodium D1 line

Alsina Ballester, Belluzzi and Trujillo Bueno (2021; Physical Review Letters)





Taking into account the **hyperfine structure** of sodium, **PRD**, **J-state interference**, and the Hanle, Zeeman and MO effects.

The CLASP suborbital space experiments

Measuring the polarization of the UV spectrum around 1216 Å and 2800 Å

An international project led by USA, Japan, France and Spain

CLASP-1 (2015)

CLASP-2 (2019)

CLASP-2.1 (2021)

Stokes I Q U	*Spectro-polarimetry*	**Stokes I Q U V**
Ly-α (1216 Å)	*Spectral region*	**Mg II k & h (2800 Å)**
0.1 Å	*Spectral resolution*	**0.1 Å**
3 arcsec	*Spatial resolution*	**2 arcsec**
400 arcsec	*Spectrograph's SLIT*	**200 arcsec**

J. Trujillo Bueno (2023, Solarnet-S3 meeting)

Credit : US Army Photos

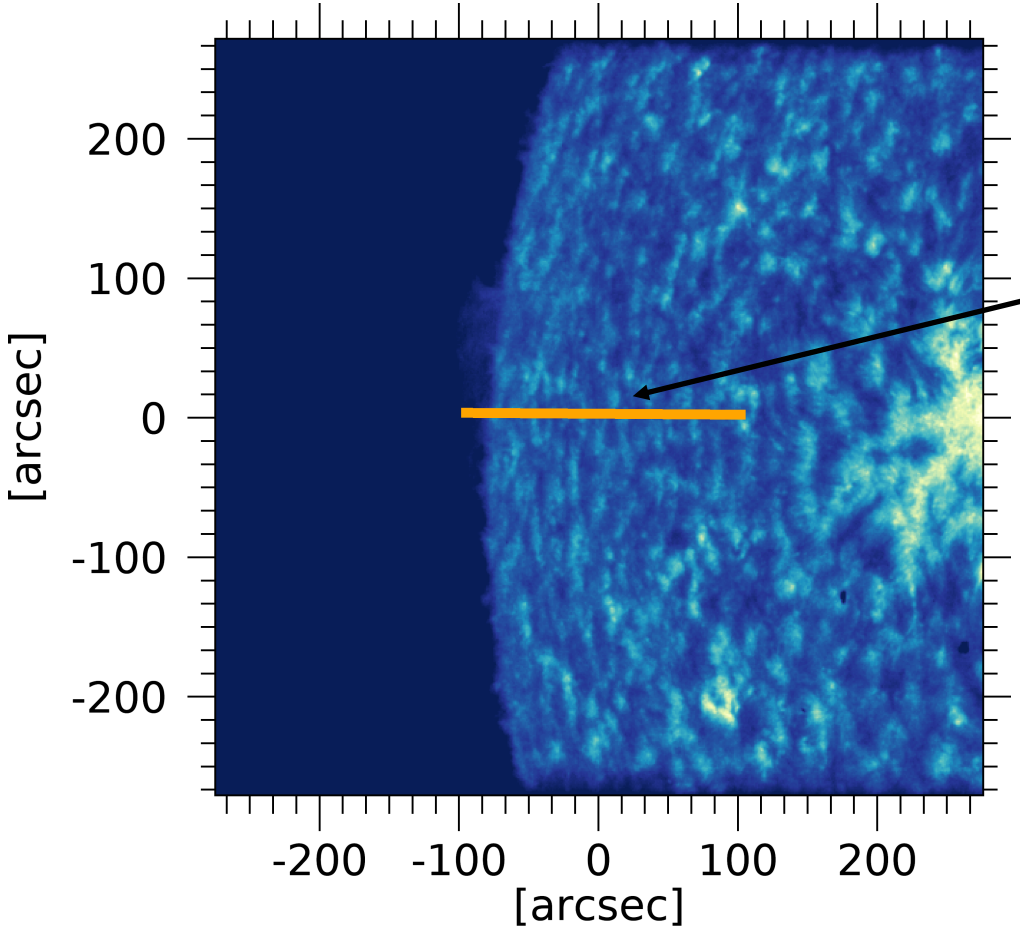
The CLASP2 (2019) observations: QUIET region

Rachmeler, Trujillo Bueno, McKenzie et al. (2022; ApJ)

The Mg II h & k lines

QUIET REGION CLOSE TO THE LIMB

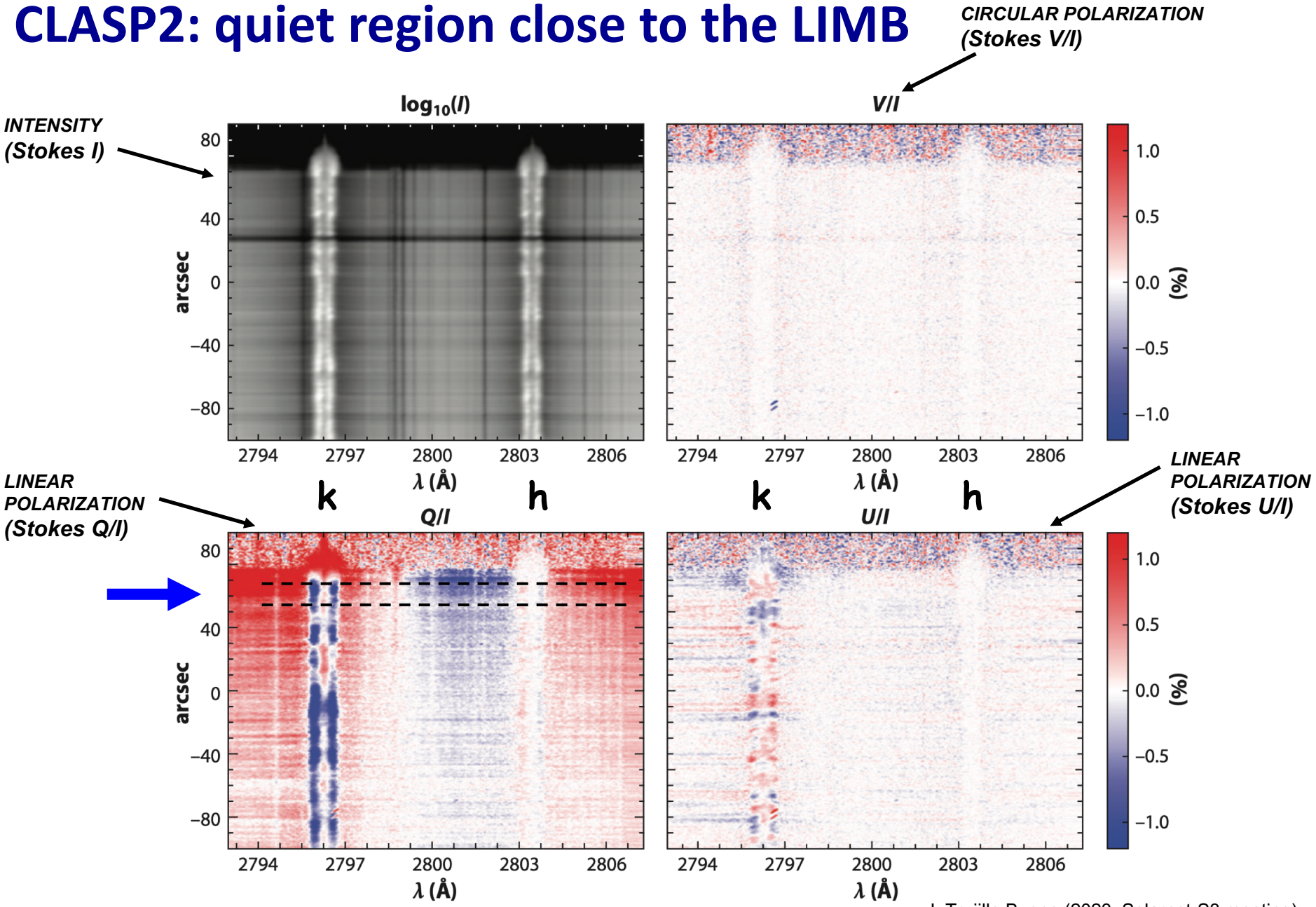
Observing time: 134 sec



SLIT of the spectro-polarimeter

CLASP2 context image taken by the slit-jaw instrument

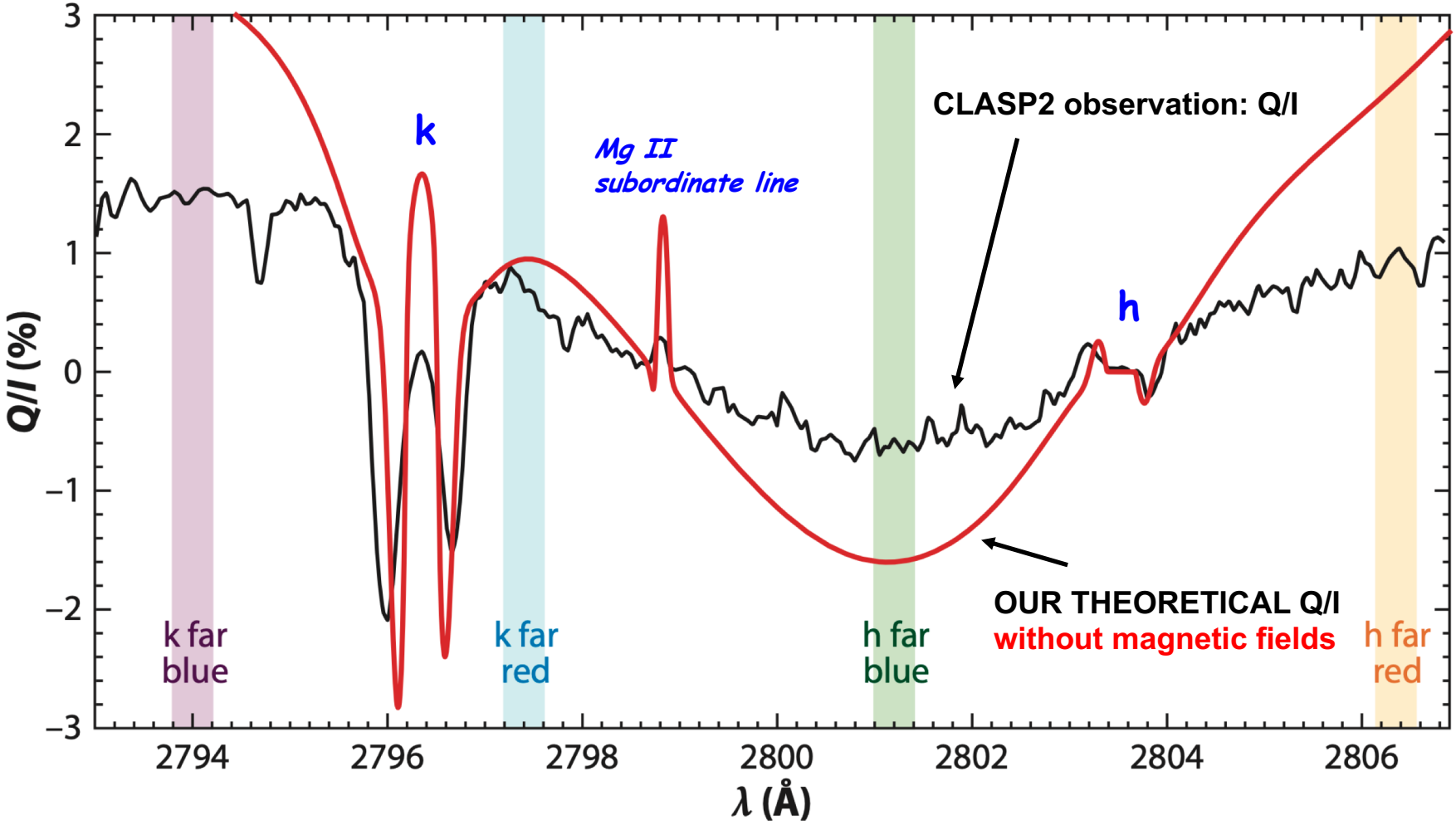
CLASP2: quiet region close to the LIMB



J. Trujillo Bueno (2023, Solarnet-S3 meeting)

CLASP2: quiet region

Figure from Trujillo Bueno & del Pino Alemán (2022; Annual Review Astronomy & Astrophysics)



J. Trujillo Bueno (2023, Solarnet-S3 meeting)

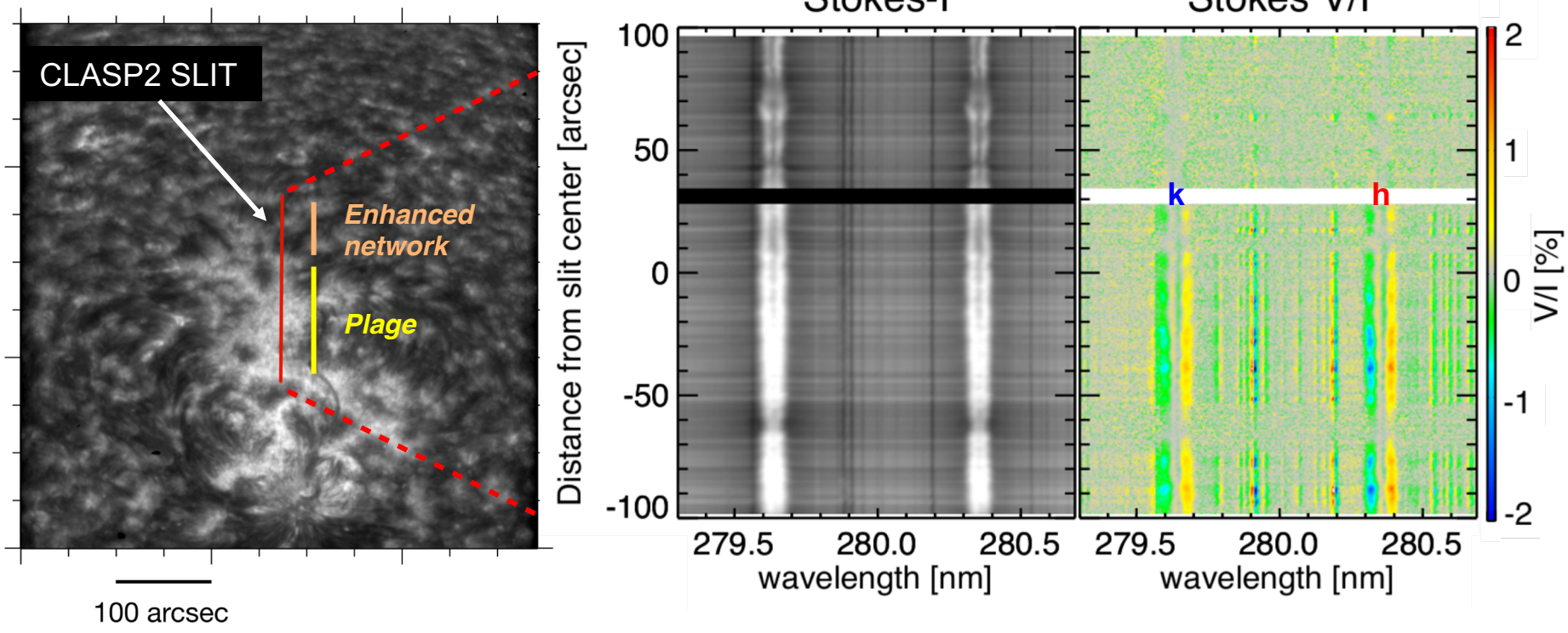
CLASP2: active region PLAGE

Ishikawa et al. (2021) and Li et al. (2023)

The near-UV region of the Mg II h & k lines

Observing time: 155 sec

Zeeman
circular polarization signals



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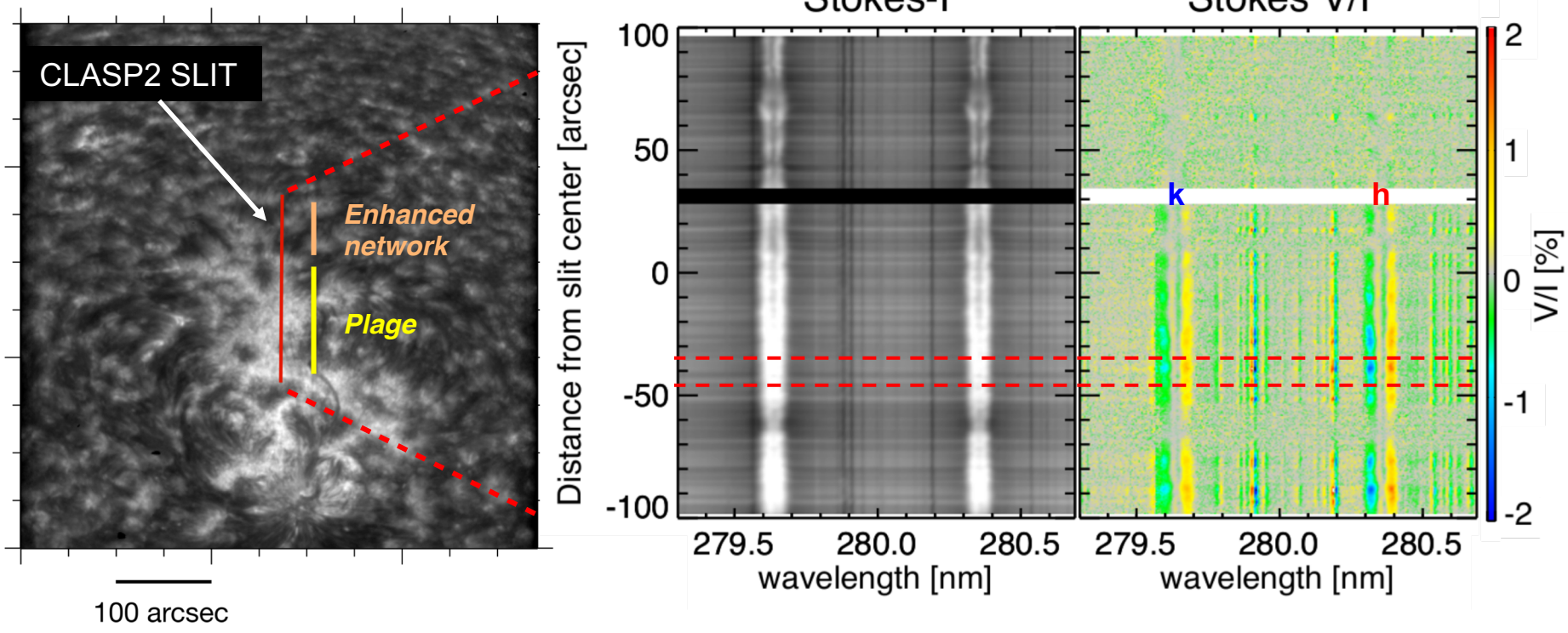
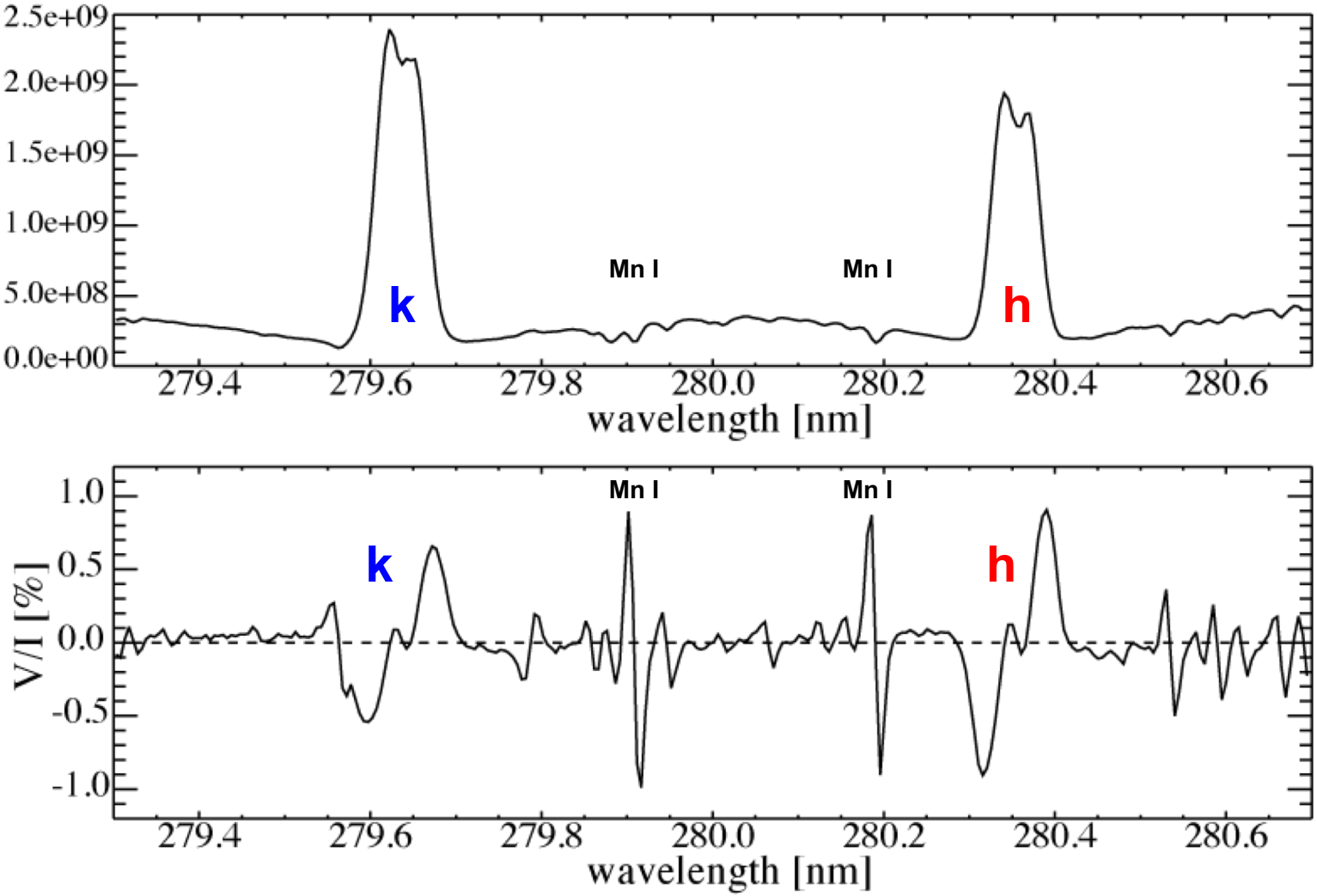


J. Trujillo Bueno (2023, Solarnet-S3 meeting)

Example of the observed Stokes I and V profiles



J. Trujillo Bueno (2023, Solarnet-S3 meeting)

Tenerife Inversion Code (TIC)

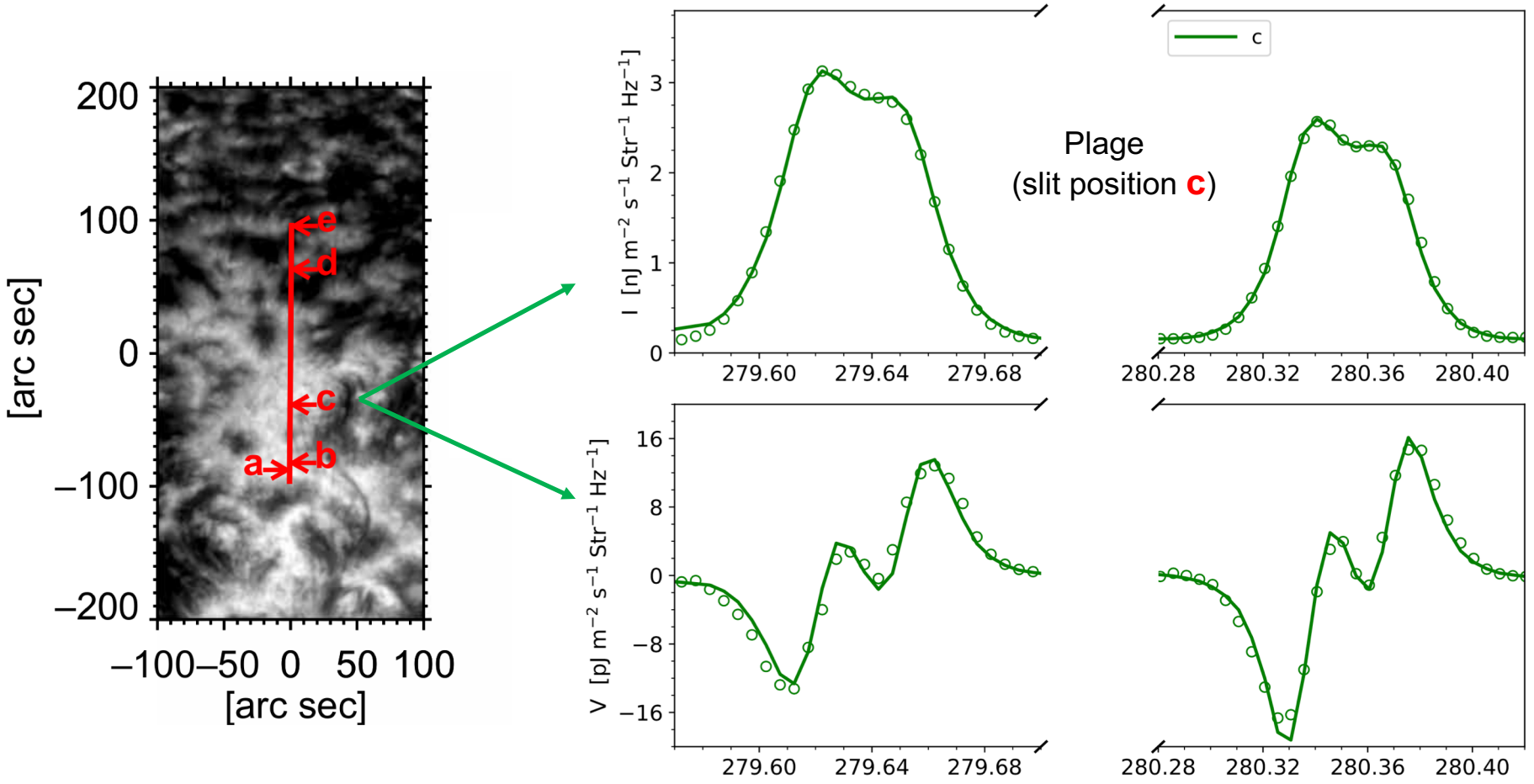
Li, del Pino Alemán, Trujillo Bueno and Casini (2022; ApJ)

- Radiative transfer in 1D model atmospheres with arbitrary magnetic fields

- Scattering processes
- PRD and J-state interference
- Hanle effect
- Zeeman effect
- Magneto-optical effects

Applying the Tenerife Inversion Code (Li et al. 2023; ApJ)

Determining the magnetic field at different heights in the chromosphere



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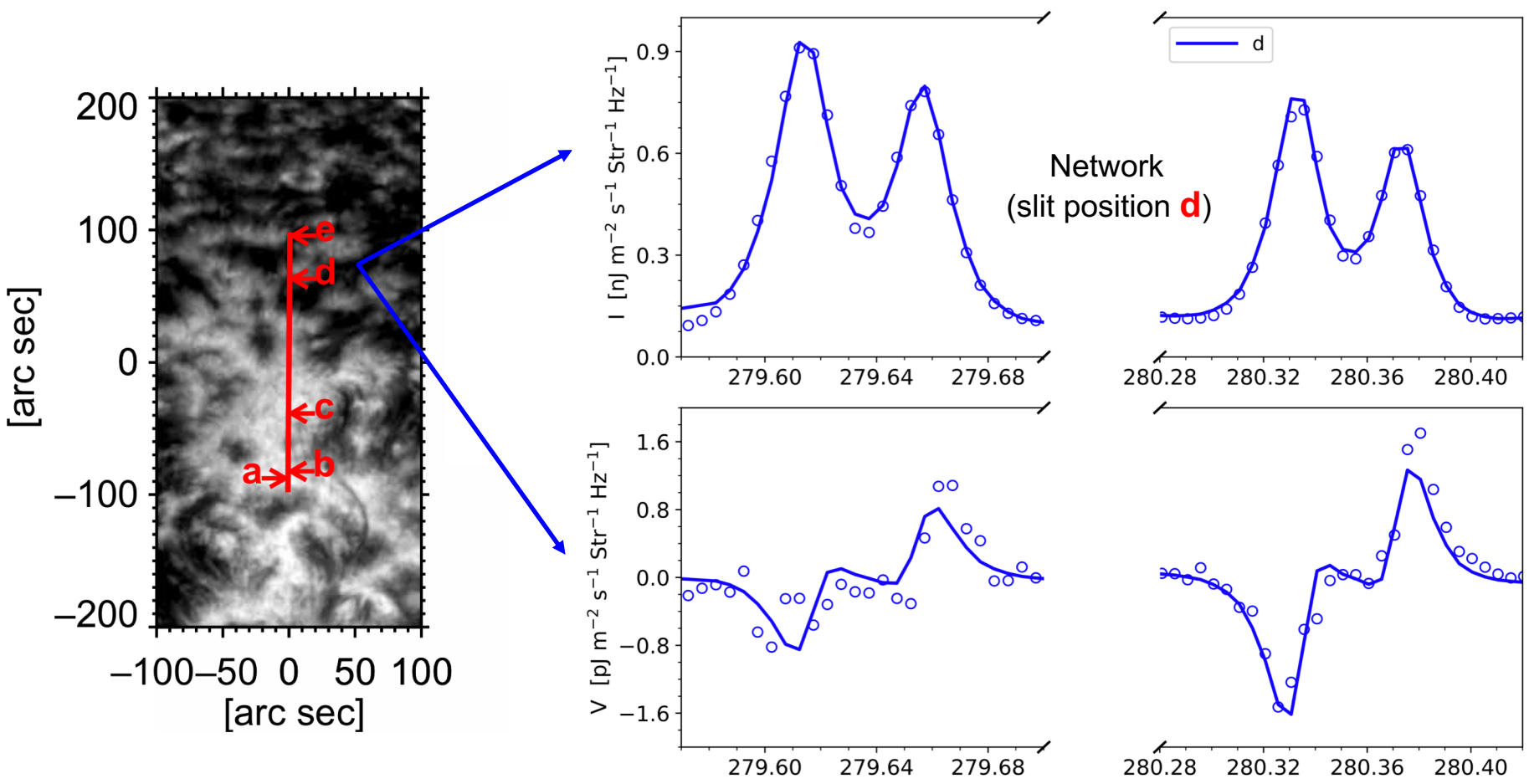

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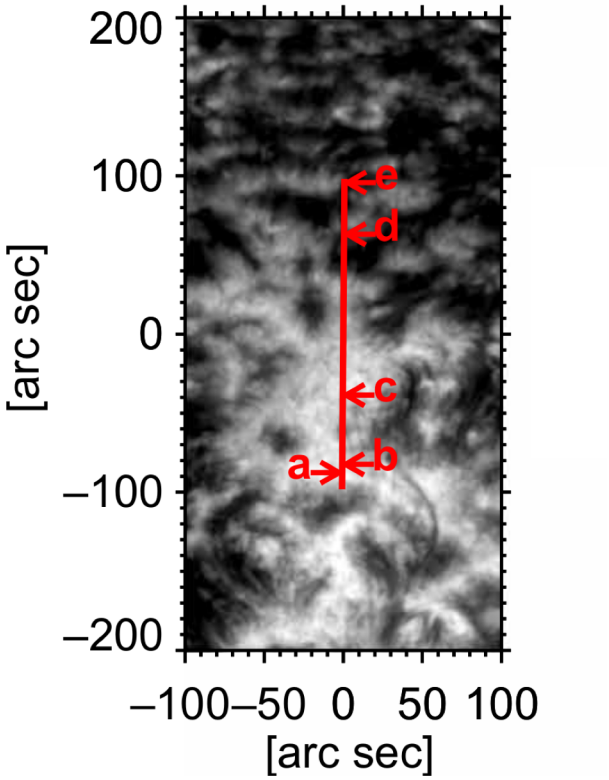

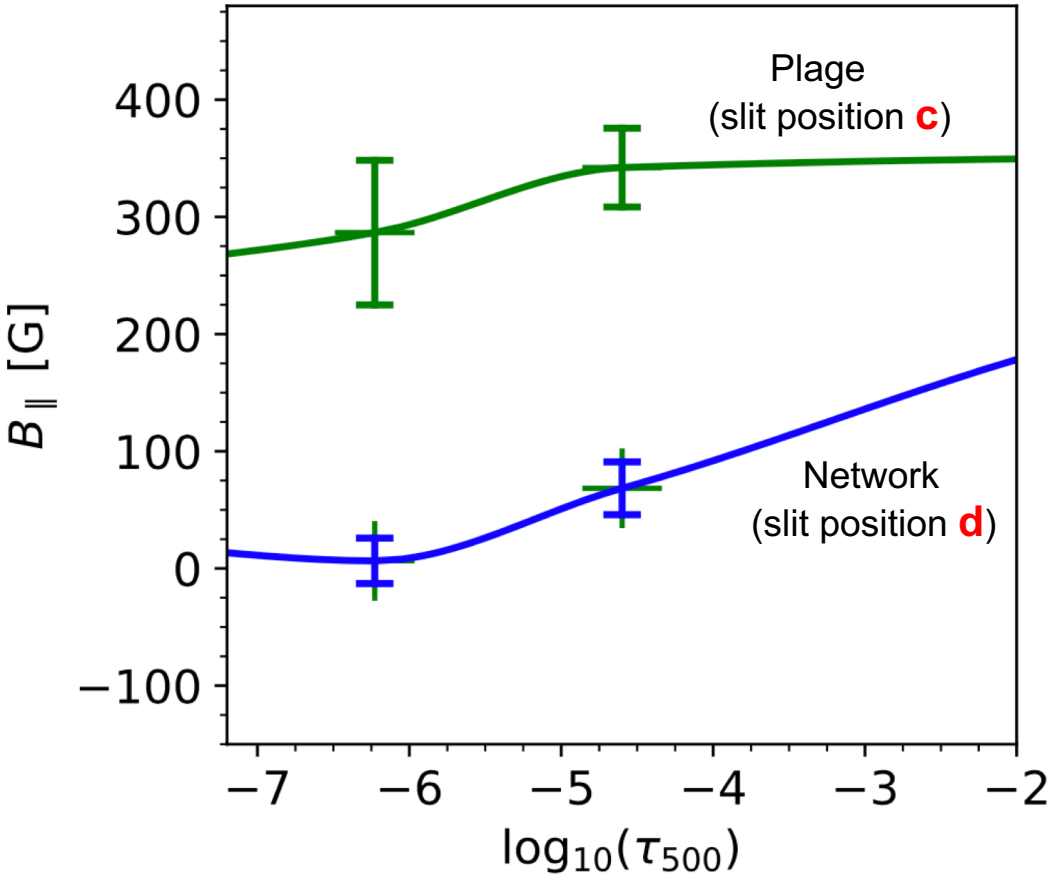

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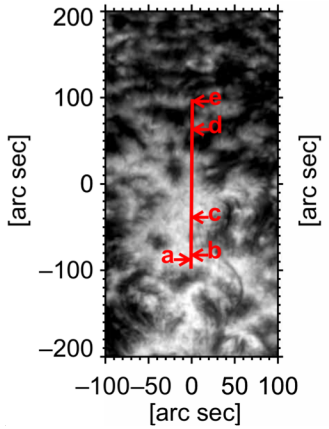
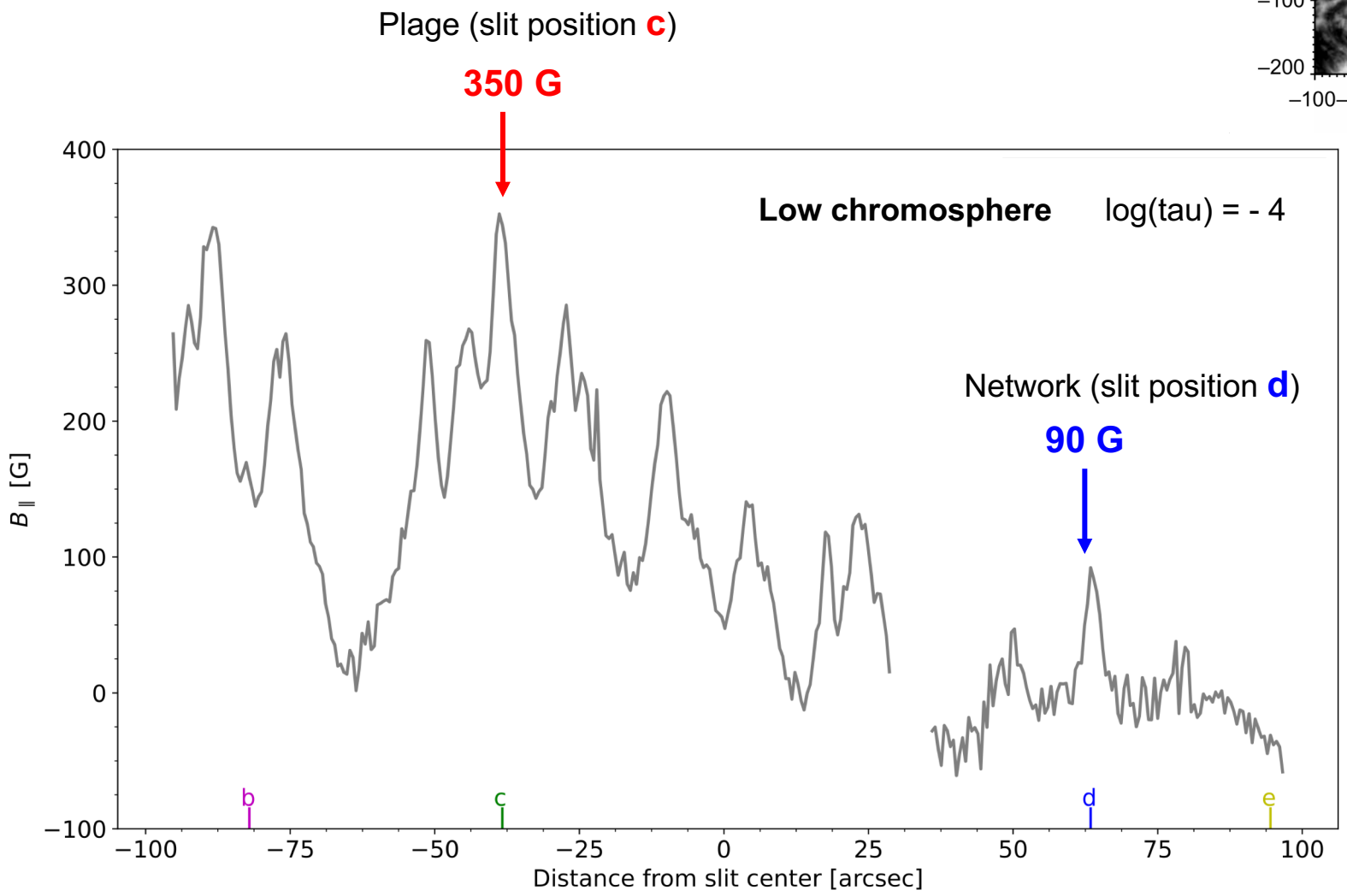
(Li et al. 2023; ApJ)





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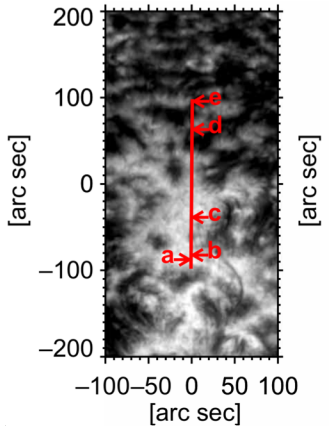

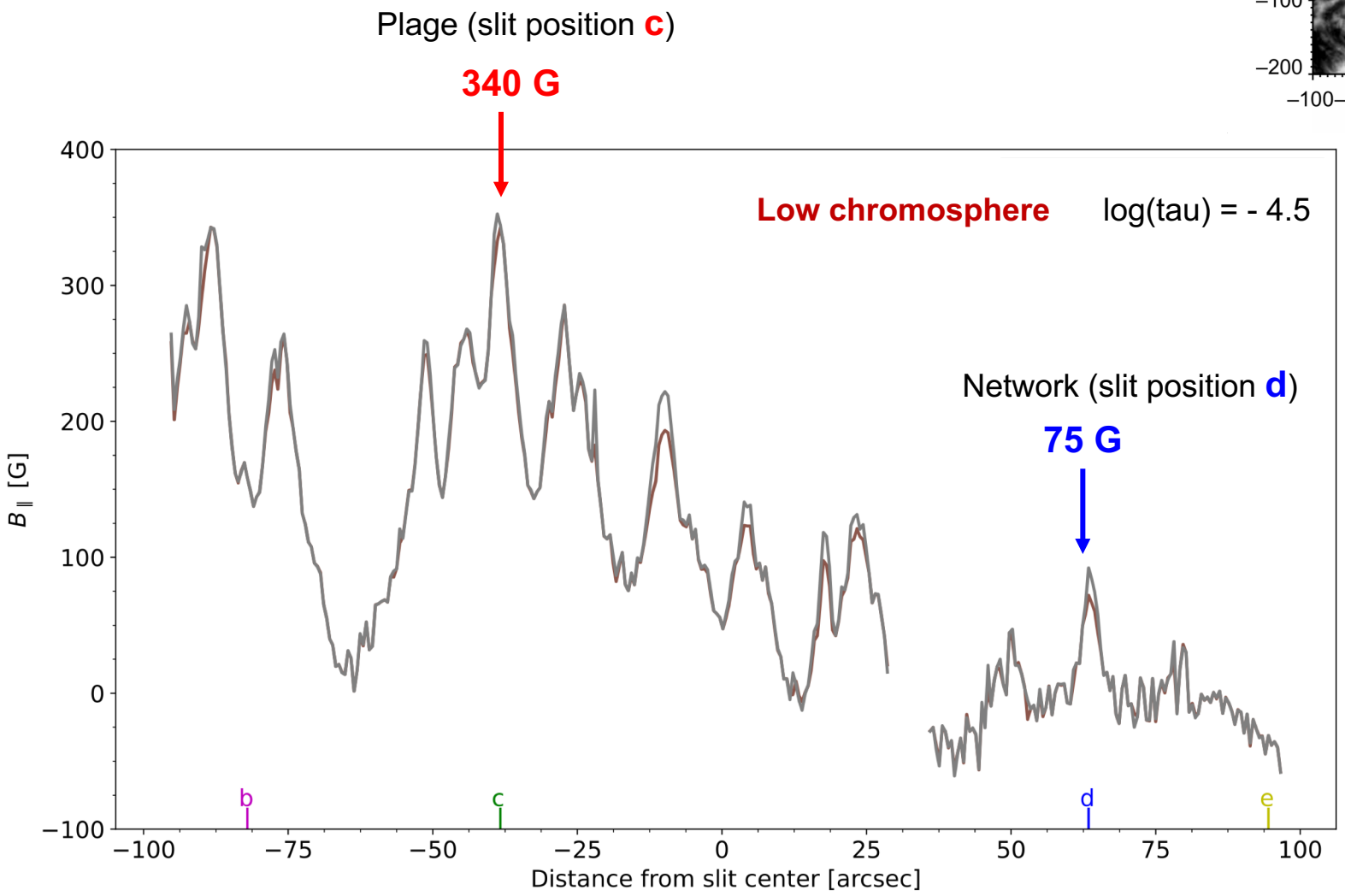

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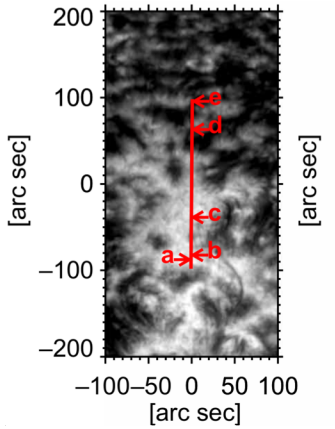

Plage (slit position **c**)

330 G

Mid chromosphere log(tau) = - 5

Network (slit position **d**)

50 G

$B_{\parallel}$ [G]

Distance from slit center [arcsec]

J. Trujillo Bueno (2023, Solarnet-S3 meeting)

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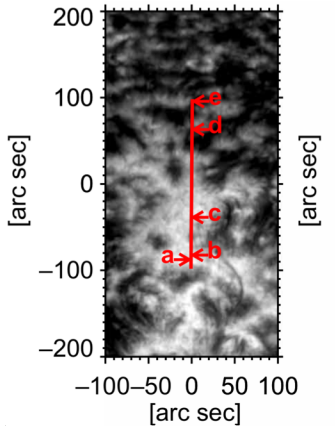

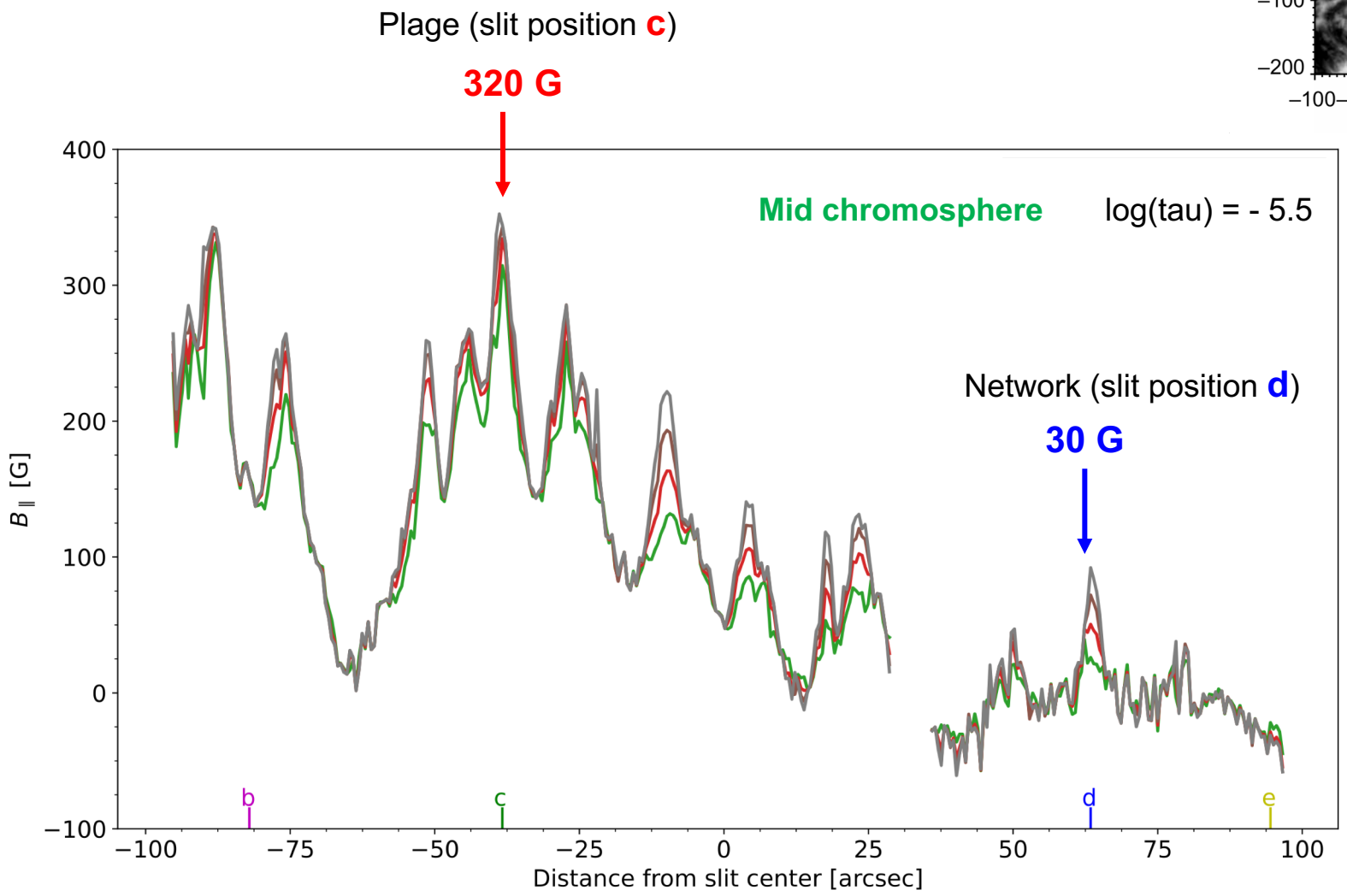

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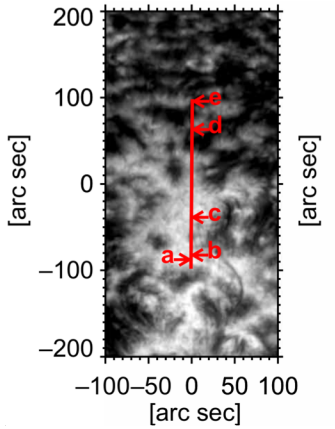
(Li et al. 2023; ApJ)



Plage (slit position **c**)

280 G

Upper chromosphere log(tau) = - 6

Network (slit position **d**)

10 G

$B_{\parallel}$ [G]

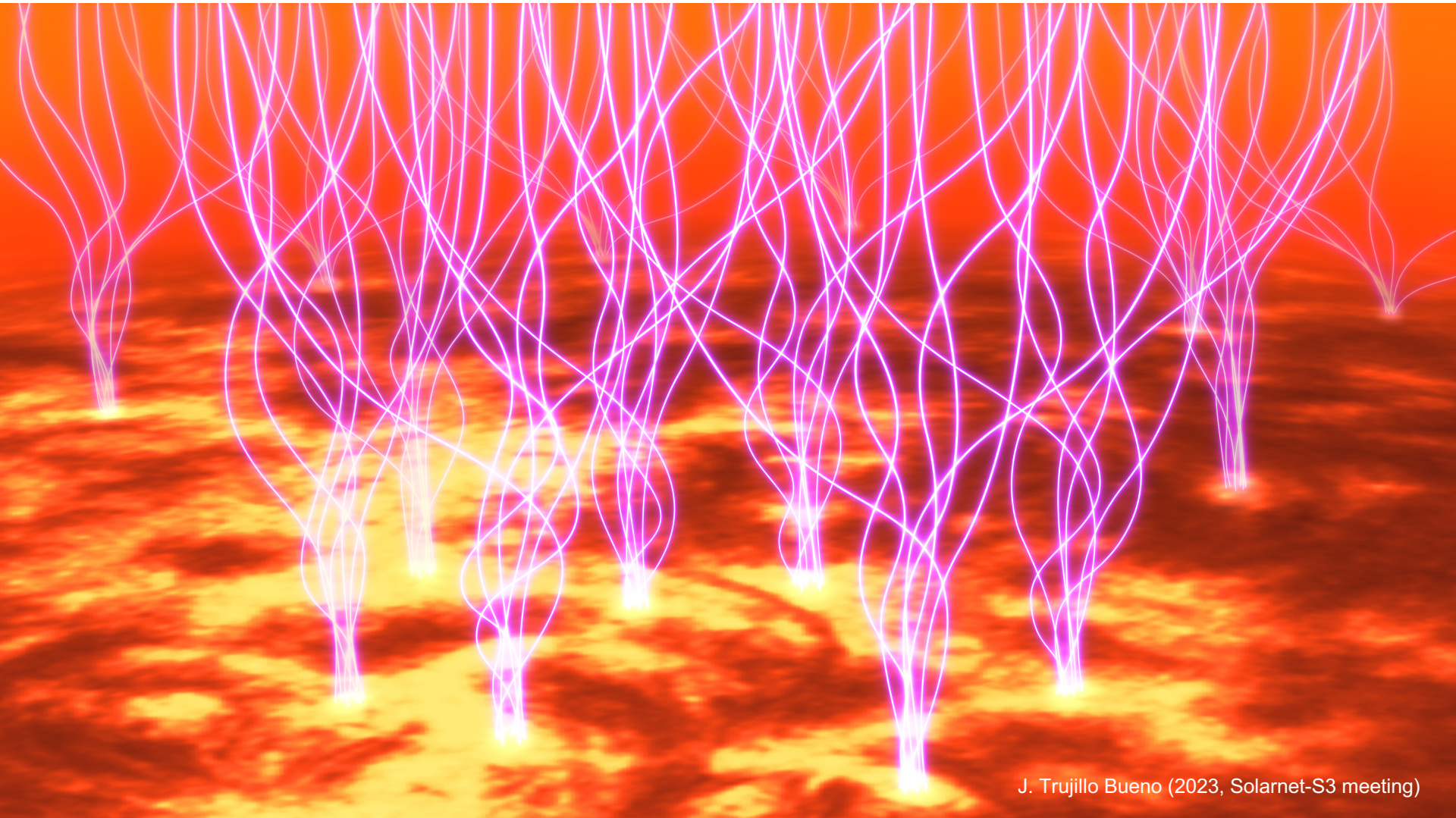
Distance from slit center [arcsec]

J. Trujillo Bueno (2023, Solarnet-S3 meeting)

Mapping solar magnetic fields from the photosphere to the base of the corona

Ishikawa, Trujillo Bueno, del Pino Alemán and the CLASP2 team (2021; Science Advances)

Li, del Pino Alemán, Trujillo Bueno and the CLASP2 team (2023; ApJ)



J. Trujillo Bueno (2023, Solarnet-S3 meeting)

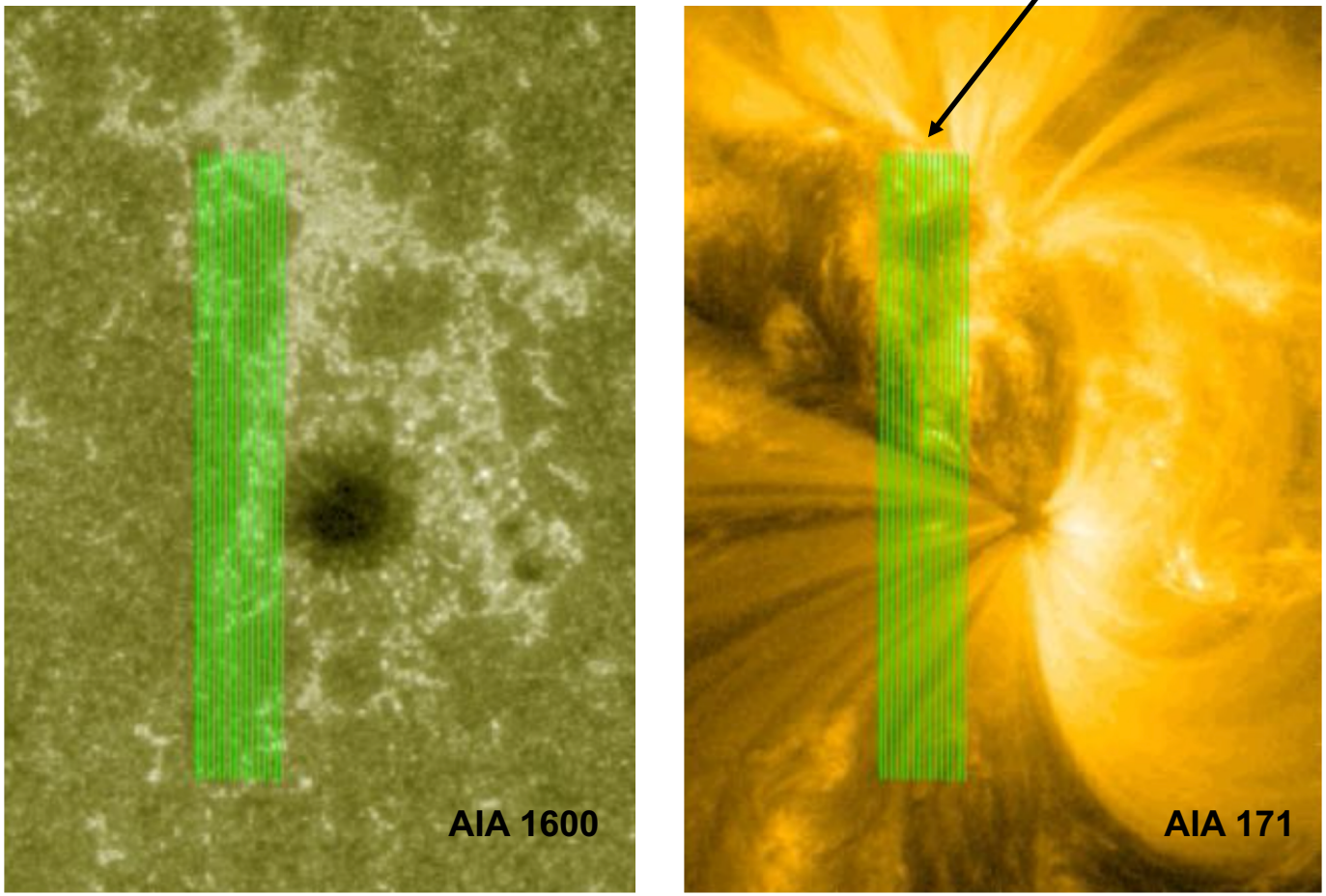
The CLASP2.1 (2021) observations: 2D spectropolarimetry

The Mg II h & k lines

Observing time: 330 sec

Scanning SLIT positions
(200 x 30 arcsec)

OBSERVED ACTIVE REGION PLAGE

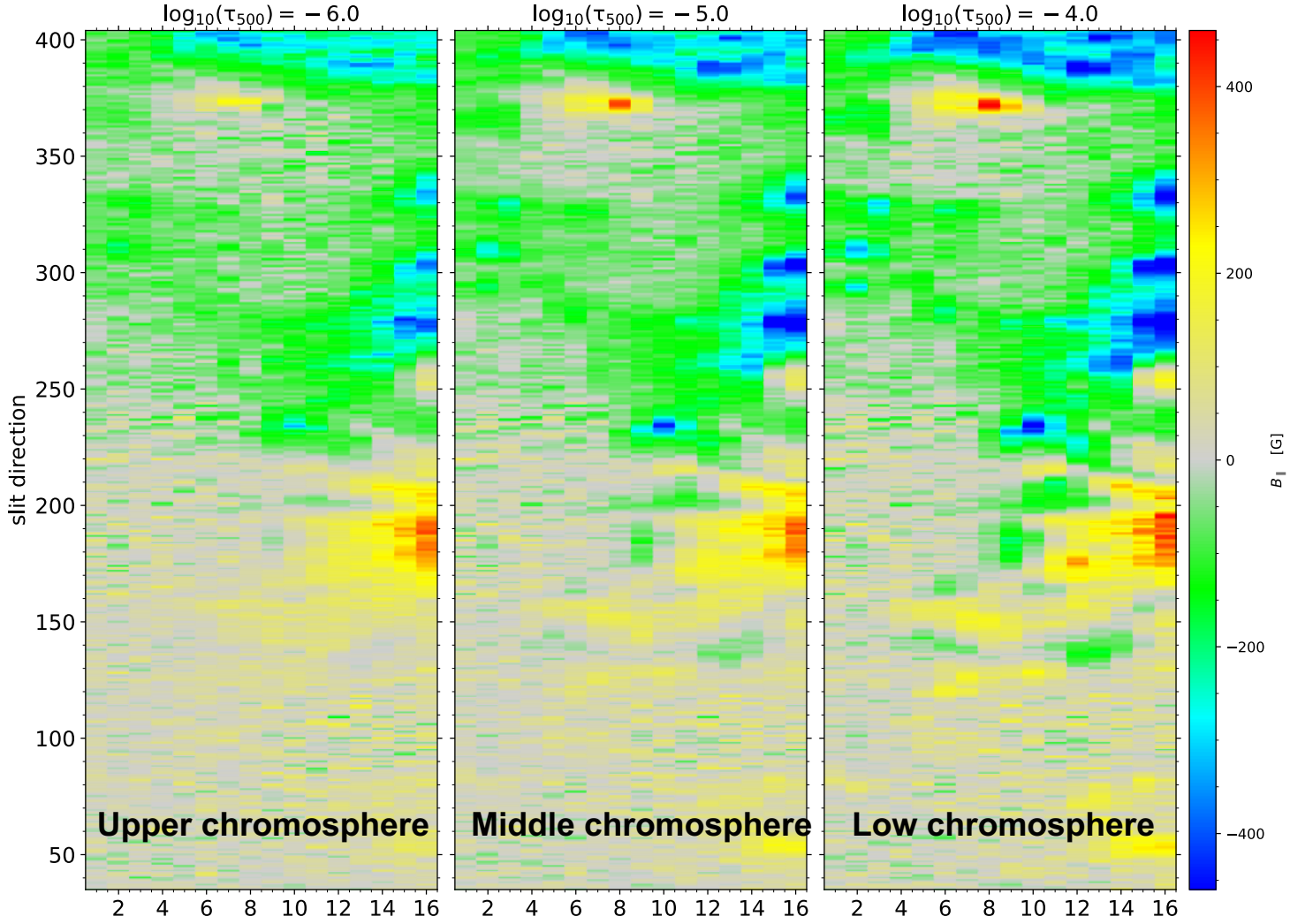


J. Trujillo Bueno (2023, Solarnet-S3 meeting)

Applying the Tenerife Inversion Code

Mapping chromospheric **MAGNETIC FIELDS** over an extended area of the solar disk

(Li, del Pino Alemán, Trujillo Bueno and the CLASP2.1 team 2023; in preparation)

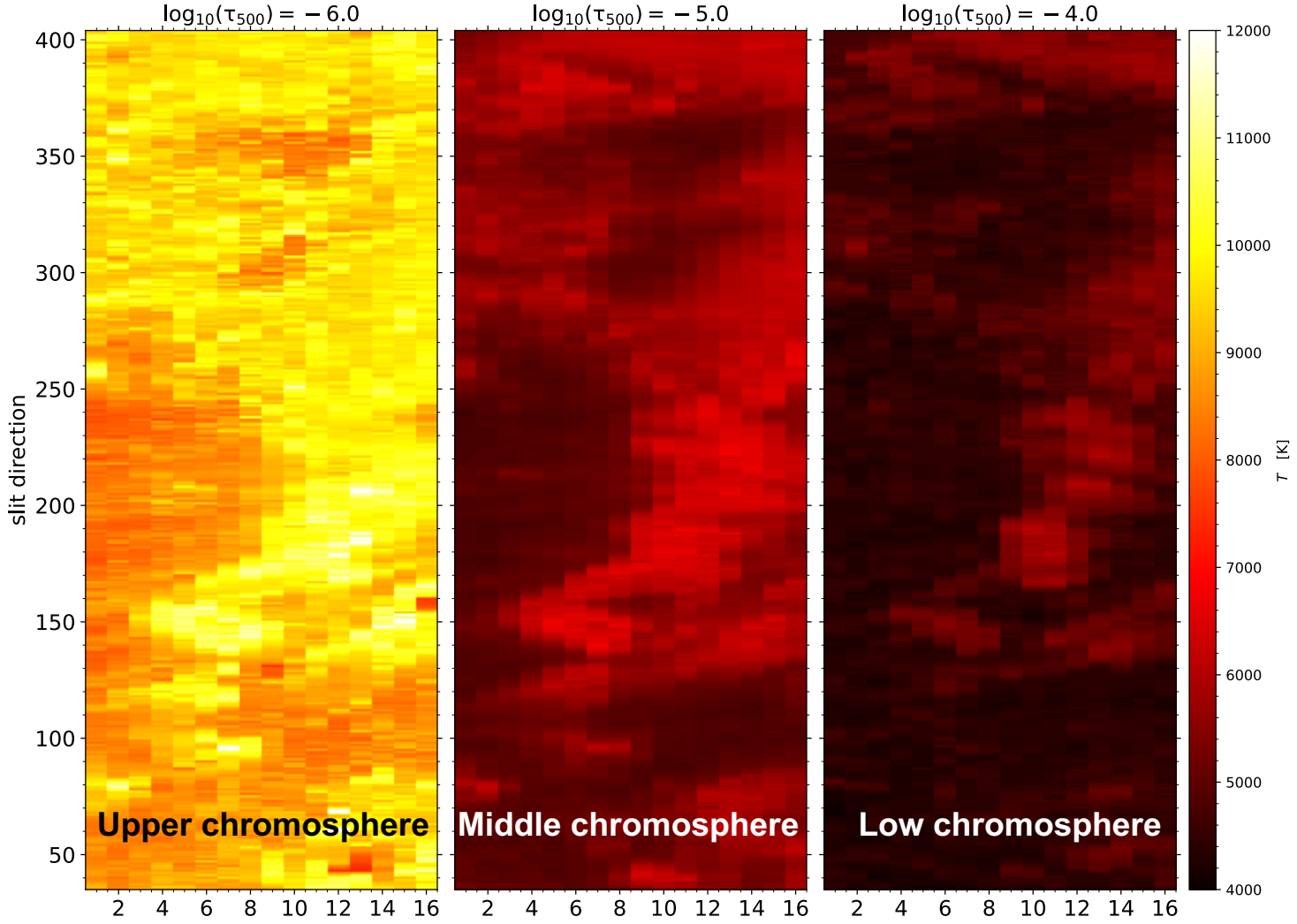


J. Trujillo Bueno (2023, Solarnet-S3 meeting)

Applying the Tenerife Inversion Code

Mapping chromospheric **TEMPERATURES** over an extended area of the solar disk

(Li, del Pino Alemán, Trujillo Bueno and the CLASP2.1 team 2023; in preparation)



J. Trujillo Bueno (2023, Solarnet-S3 meeting)

The Sun is indeed

the Rosetta stone of Astrophysics

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http://www.iac.es/proyecto/polmag/