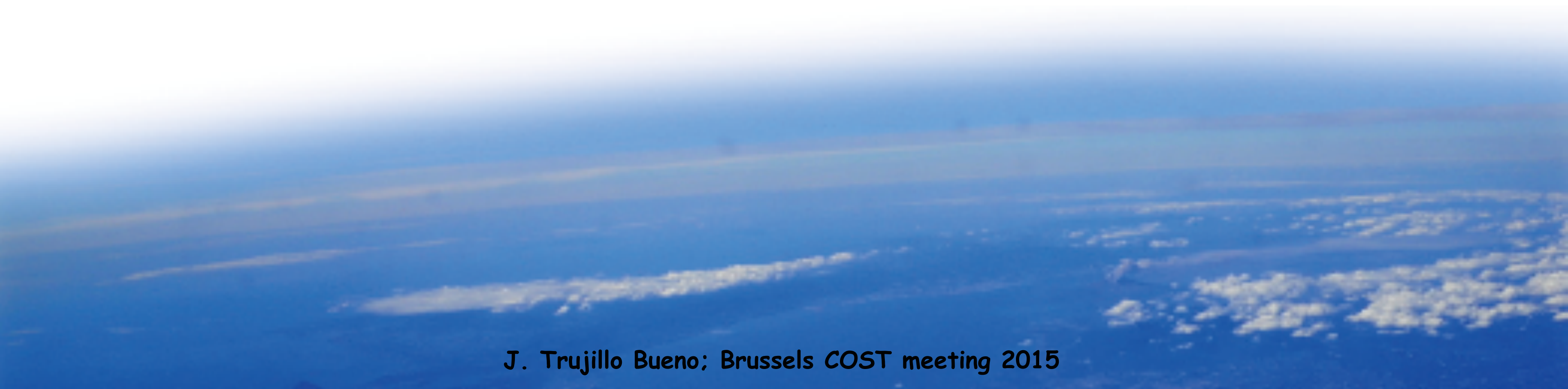
Solar UV Spectropolarimetry

Javier Trujillo Bueno
(IAC; Tenerife; Spain)



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- **Introduction**

- **Theoretical calculations of the Lyman-alpha polarization signals expected for on-disk observations of the Sun**

  (a) CRD without J-state interference

  (b) PRD with J-state interference

- **The Chromospheric Lyman-alpha Spectropolarimeter**

- **Concluding comments**

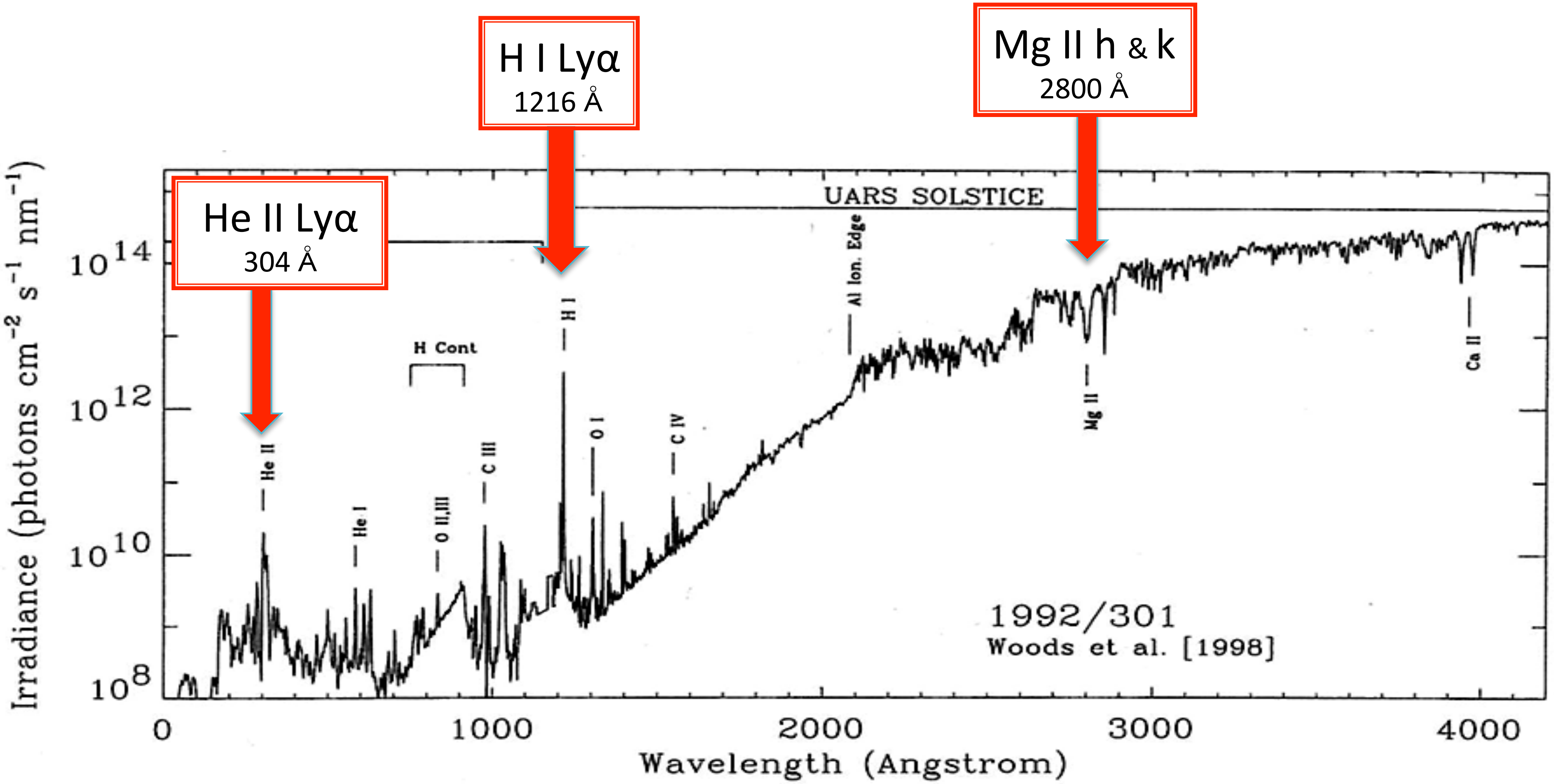
Why Solar UV Spectropolarimetry ?

- To probe the physics of the upper chromosphere, transition region and corona

- To explore virgin territory in solar physics

- To facilitate similar developments in other branches of astrophysics

The primary emission of the upper chromosphere and transition region is in the FUV and EUV spectral regions



He II Lyα
304 Å

H I Lyα
1216 Å

Mg II h & k
2800 Å

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Exposure time T needed for detecting 0.1% polarization signals

Number of photons
we need to accumulate
for detecting 0.1% signals

$$T = \frac{10^7}{\epsilon\,(\mathrm{PIXEL})^2\,(2.35\times 10^{-11})\,[\pi D^2/4]\,N_{\mathrm{photons}}\,\Delta\lambda}$$

Instrumental
THROUGHPUT

Telescope
DIAMETER

Wavelength
interval in
Angstroms

PIXEL = 1 → **for 1 arcsec pixels**

PIXEL = X → **for X arcsec pixels**

Solar photons per
square cm, per sec,
per sr, per Angstrom

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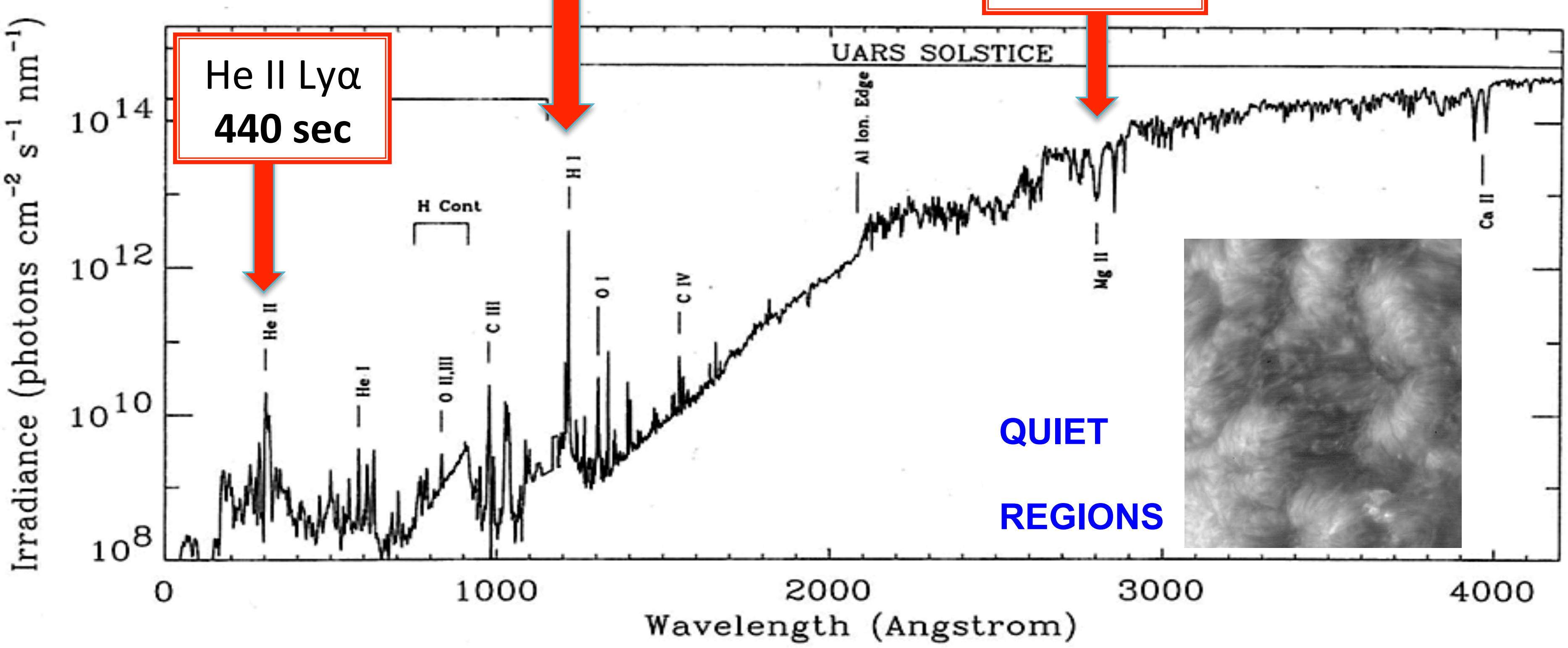
Estimation of the EXPOSURE TIME needed for detecting 0.1% line-center Q/I signals with a 1m telescope, assuming 1” pixels, a wavelength interval of 0.01 nm and an instrumental throughput of 1%

In QUIET regions !



H I Lyα

80 sec

Mg II h & k

8 sec

He II Lyα

440 sec

QUIET

REGIONS

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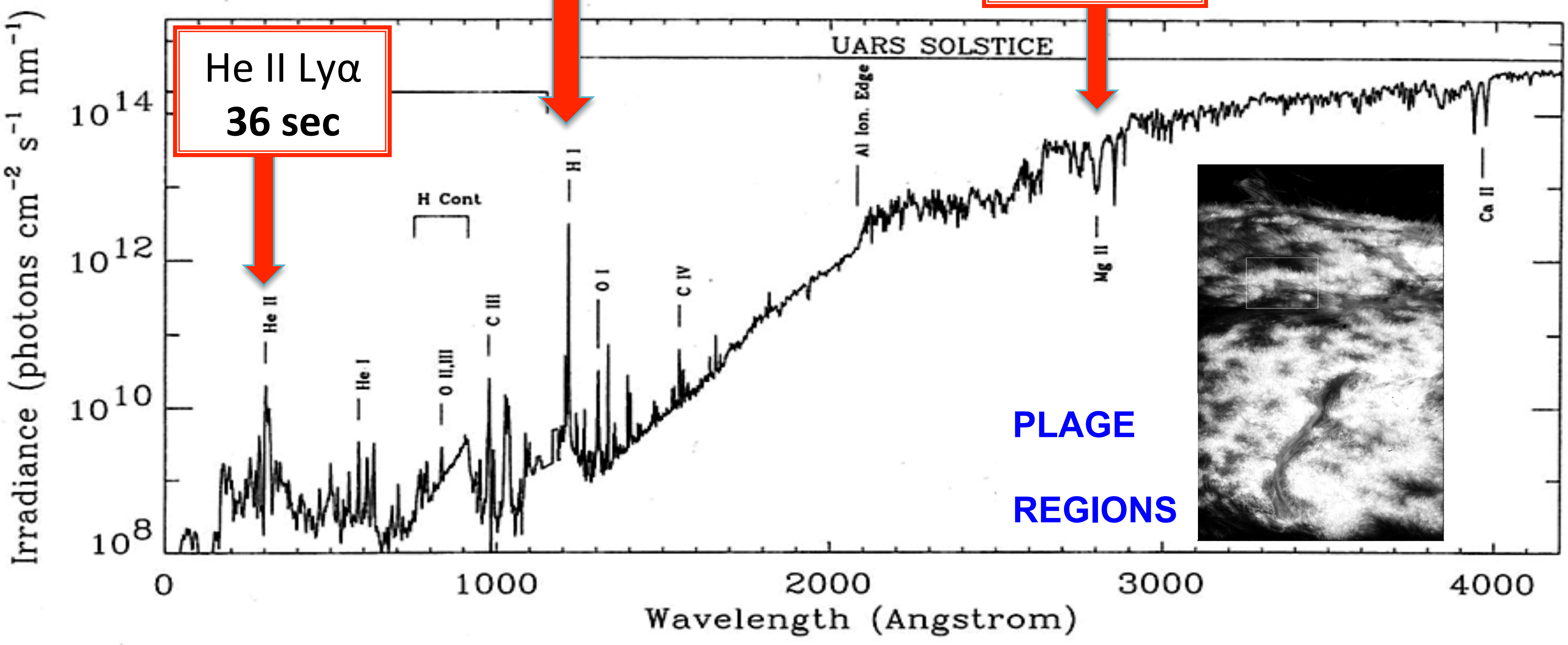
Estimation of the EXPOSURE TIME needed for detecting 0.1% line-center Q/I signals with a 1m telescope, assuming 1” pixels, a wavelength interval of 0.01 nm and an instrumental throughput of 1%

In PLAGE regions !



He II Lyα
36 sec

H I Lyα
10 sec

Mg II h & k
2 sec

PLAGE

REGIONS

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The physical mechanisms

- The Zeeman effect
- The Stark effect
- Scattering processes
- The Hanle effect of a magnetic field
- The Hanle effect in the presence of magnetic and/or electric fields

(1) The Zeeman effect polarization:

Stokes V ~ R

Stokes Q & U ~ R^2

$$R = \frac{\Delta\lambda_B}{\Delta\lambda_{\rm D}} \sim \frac{\lambda B}{\sqrt{T/\mu}} \ll 1$$

Zeeman splitting

Line's Doppler width

Atomic weight

Especially in strong UV lines

(1) The Zeeman effect polarization:

Stokes V ~ R

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Zeeman splitting

$$R = \frac{\Delta\lambda_B}{\Delta\lambda_{\rm D}} \sim \frac{\lambda B}{\sqrt{T/\mu}} \ll 1$$

Line's Doppler width

Atomic weight

Especially in strong UV lines

For Lyman-alpha at 1216 Angstroms,

assuming T=10000 K and B=10 gauss

R ~ 0.0001

(2) The Stark effect polarization:

STARK splitting

Stokes Q & U ~ R

$$R = \frac{\Delta\lambda_S}{\Delta\lambda_D} \lll\lll 1$$

Line's Doppler width

- The linear Stark effect occurs only in hydrogen-like atoms, where the splitting of the energy levels is roughly proportional to the square of the principal quantum number.

(2) The Stark effect polarization:

Stokes Q & U ~ R

STARK splitting

$$R = \frac{\Delta\lambda_S}{\Delta\lambda_D} <<<< 1$$

Line's Doppler width

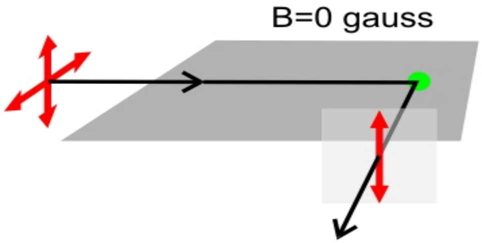
For Lyman-alpha at 1216 Angstroms,

assuming T=10000 K and E=1 volt/cm

R ~ 0.00001

(3) Spectral line polarization due to scattering processes

It is caused by the atomic level polarization (population imbalances and quantum coherence between pairs of M-sublevels) that results from the absorption and scattering of **anisotropic radiation**.



(3) Spectral line polarization due to scattering processes

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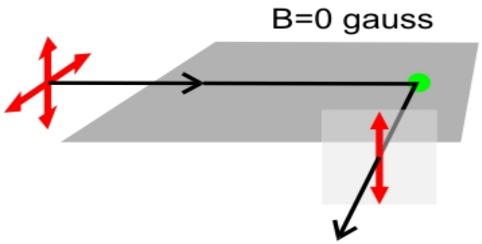
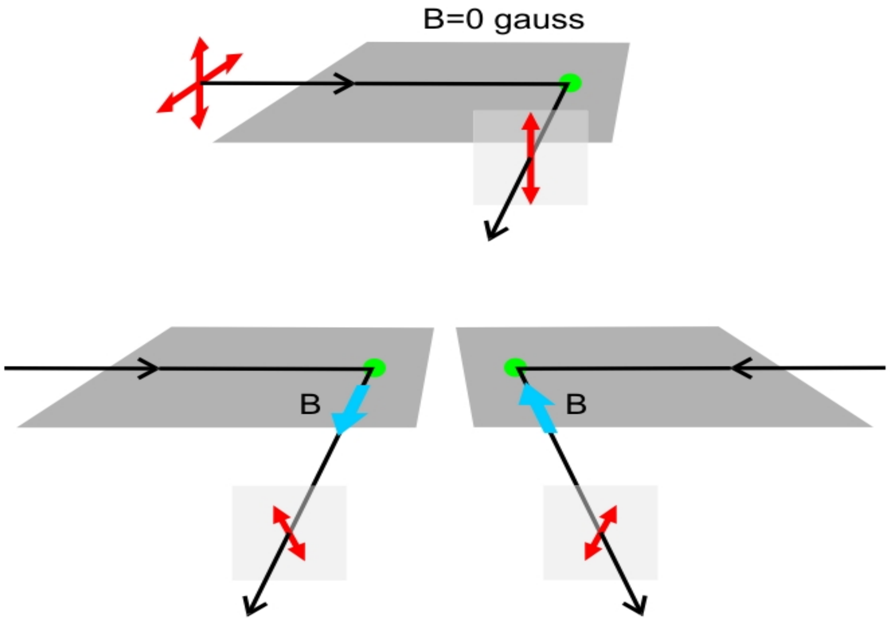


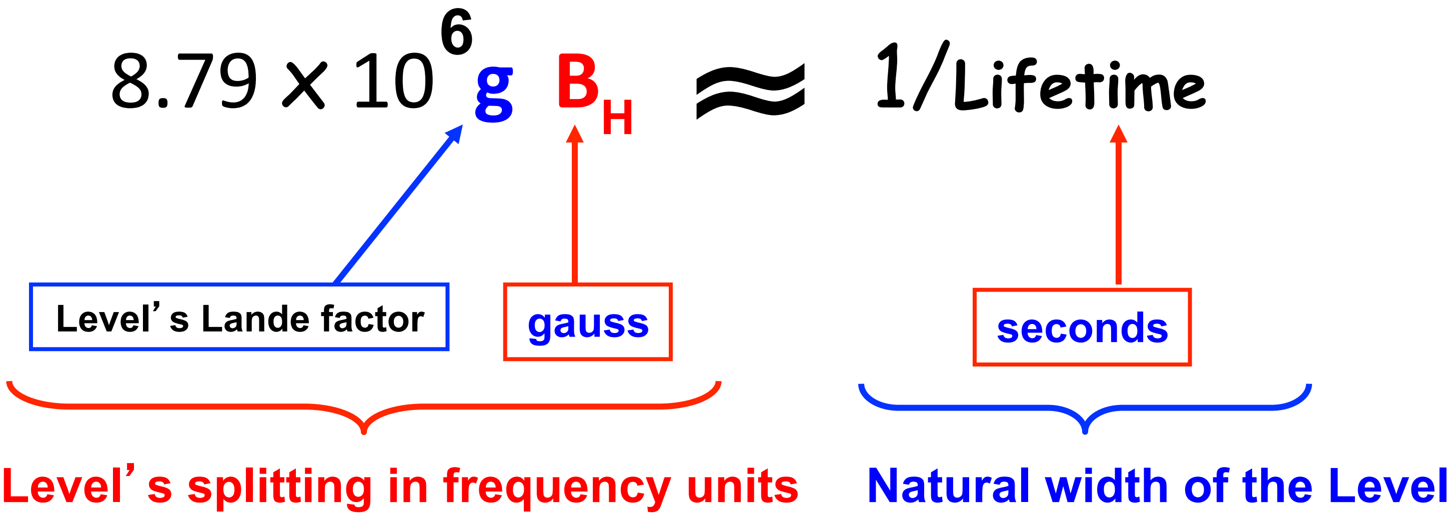
It does NOT need a magnetic field !

(4) The Hanle effect of a magnetic field

The MODIFICATION of the scattering line polarization due to the presence of magnetic fields inclined with respect to the symmetry axis of the incident radiation field.



Magnetic sensitivity (due to the Hanle effect) of the scattering line polarization



$$\underbrace{8.79 \times 10^{6}\, \underset{\text{Level's Lande factor}}{g}\; \underset{\text{gauss}}{B_H}}_{\text{Level's splitting in frequency units}} \approx \underbrace{1/\underset{\text{seconds}}{\text{Lifetime}}}_{\text{Natural width of the Level}}$$

Typically, the Hanle-effect sensitivity is from: $0.2\, B_H$ to $5\, B_H$

Magnetic sensitivity (due to the Hanle effect) of the scattering line polarization

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Typically, the Hanle-effect sensitivity is from: $0.2\, B_H$ to $5\, B_H$

$$\boxed{\begin{array}{c} B_H = 53\ \text{G} \\ \\ \text{(Ly-alpha of H I)} \end{array}}$$

(5) The Hanle effect in the presence of magnetic and/or ELECTRIC fields

- **In principle, an electric field (electrostatic, or isotropic or motional) can have a significant influence on the linear and/or circular polarization of the scattered radiation (Favati et al. 1987; Casini 2005; Casini & Manso Sainz 2006).**

- **However, the available estimations suggest that in order to have a measurable effect on the linear and/or circular polarization of the hydrogen Lyman-alpha line electric fields much stronger than those expected for the upper chromosphere of the quiet Sun are needed (i.e., much stronger than 1 volt/cm).**

- **Critical electric field E_c ~ 300 volt/cm for hydrogen Lyman-alpha**

The physical mechanisms

- Scattering processes
- The Hanle effect of a magnetic field

The approach

- **Radiative Transfer modeling of the intensity and polarization of the emergent spectral line radiation → the essential link between theory and observations**

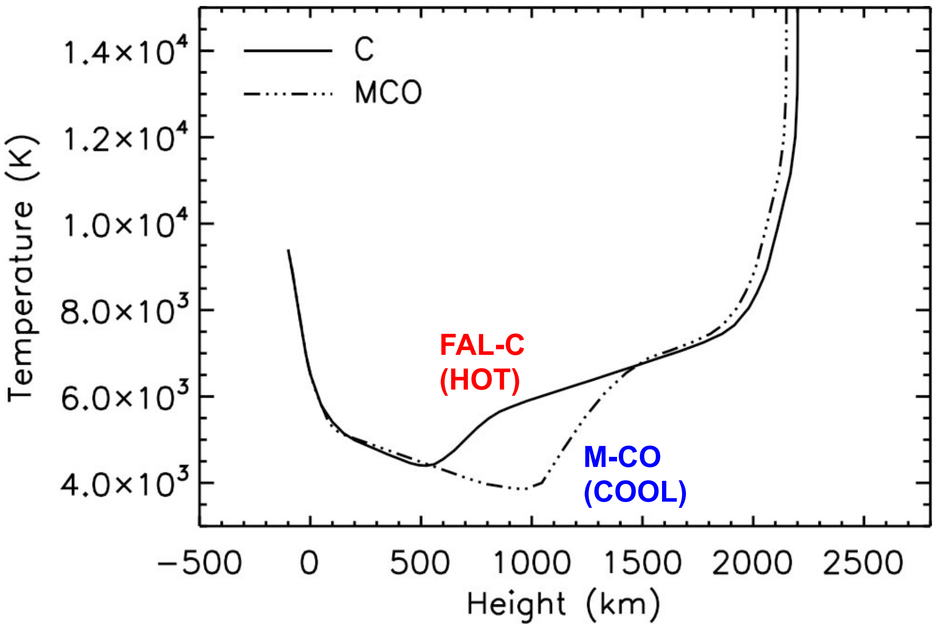
- **The problem's equations (the SEE and the RT equations) are formulated within the framework of QED theories of spectral line polarization.**

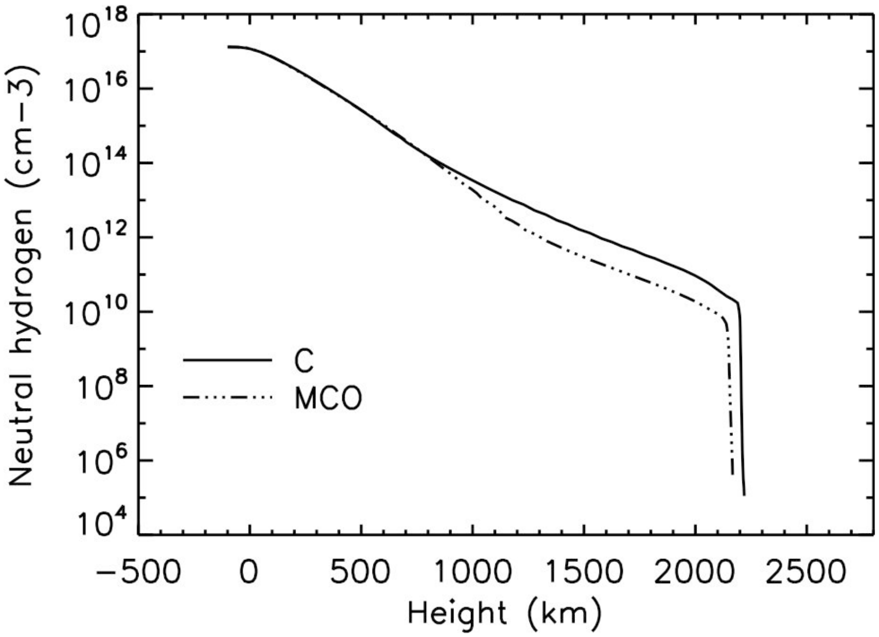
- **We consider the linear polarization due to scattering processes in UV resonance lines and its modification by the Hanle effect of a magnetic field. We also include the circular polarization due to the Zeeman effect** (to determine the minimum B needed to measure it).

The approach

- **We consider the following models of the solar atmosphere :**

- ***One-dimensional semi-empirical models***





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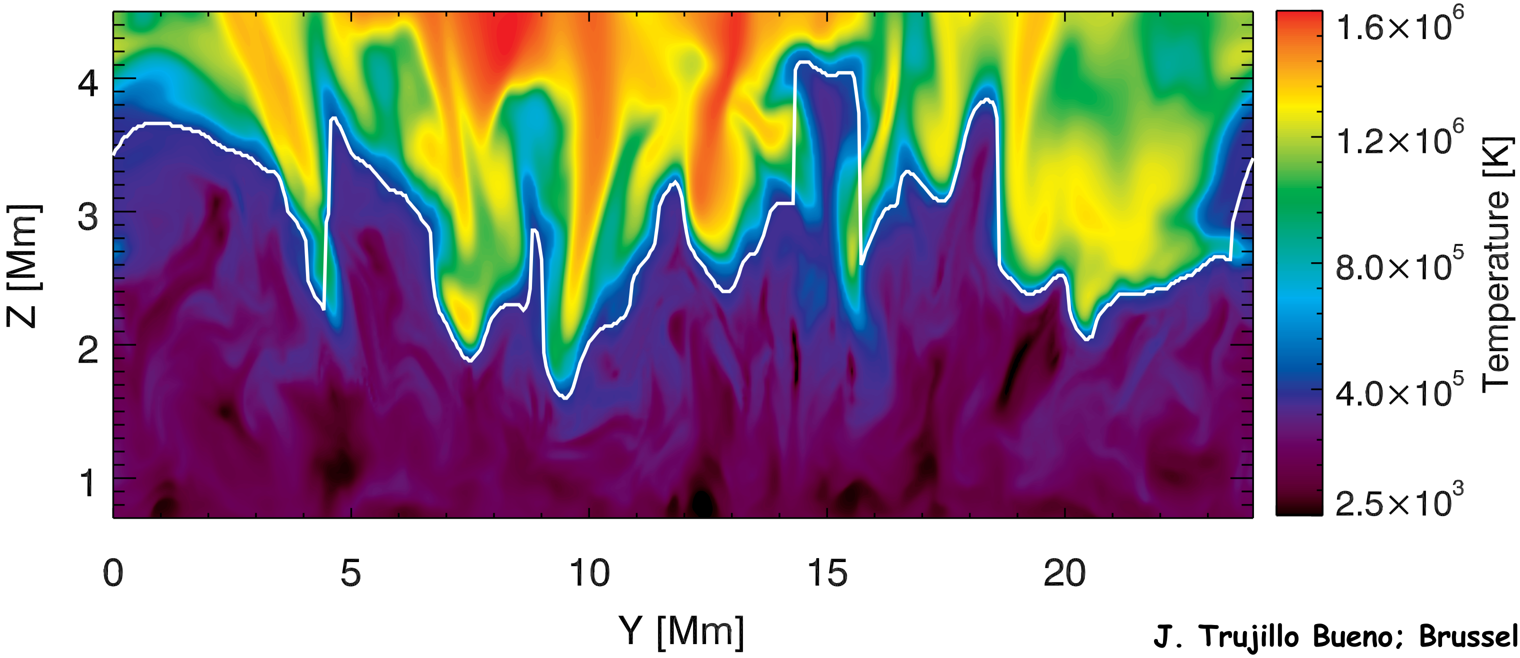
The approach

- **We consider the following models of the solar atmosphere :**

- One-dimensional models

- **Three-dimensional models resulting from MHD simulations**

(see Stepan, Trujillo Bueno, Leenaarts & Carlsson 2015; ApJ)



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The approach

- **The (non-LTE) problem of the generation and transfer of polarized radiation is highly non-local and non-linear. We solve it developing and applying accurate formal solvers of the Stokes-vector transfer equation and highly convergent iterative schemes.**

  For example, see:

  1) Stepan & Trujillo Bueno 2013, PORTA: A 3D Multilevel Radiative Transfer Code for Modeling the Intensity and Polarization of Spectral Lines with Massively Parallel Computers, A&A 557, 143

  2) Belluzzi & Trujillo Bueno 2014, The Transfer of Resonance Line Polarization with Partial Frequency Redistribution and J-state Interference, A&A, 564, 16

For detailed information see the following papers:

(1) Trujillo Bueno, Stepan & Casini 2011, ApJ, 738, L11

(2) Trujillo Bueno, Stepan & Belluzzi 2011, ApJ, 746, L9

(3) Belluzzi, Trujillo Bueno & Stepan 2012, ApJ, 755, L2

(4) Belluzzi & Trujillo Bueno 2012, ApJ, 750, L11

(5) Stepan, Trujillo Bueno, Carlsson & Leenaarts 2012, ApJ, 758, L43

(6) Stepan & Trujillo Bueno 2013, A&A, 557, 143

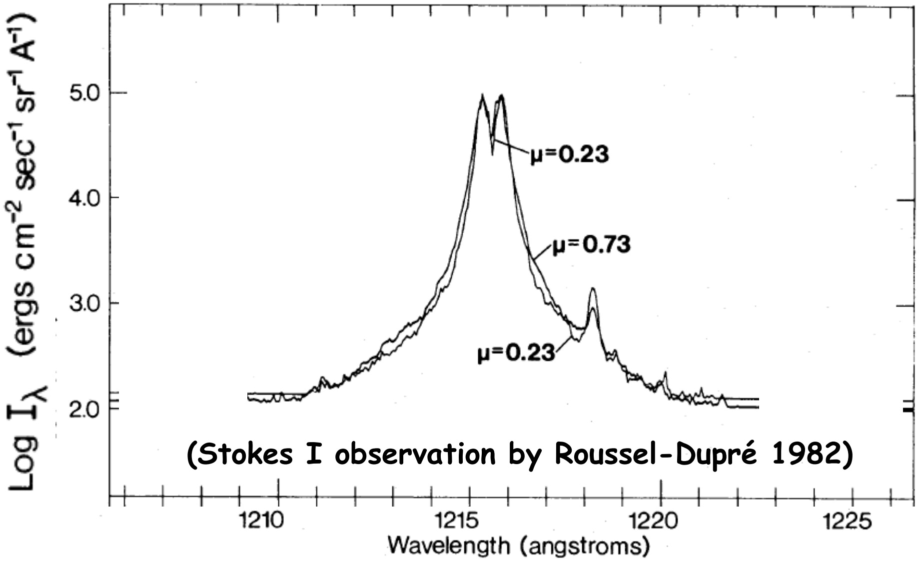
(7) Belluzzi & Trujillo Bueno 2014, A&A, 564, 16

(8) Stepan, Trujillo Bueno, Leenaarts & Carlsson 2015, ApJ,803, 65

Trujillo Bueno 2014 (SPW7 review paper, in ASP Conf. Ser. 489, 137)

The hydrogen Ly-alpha line

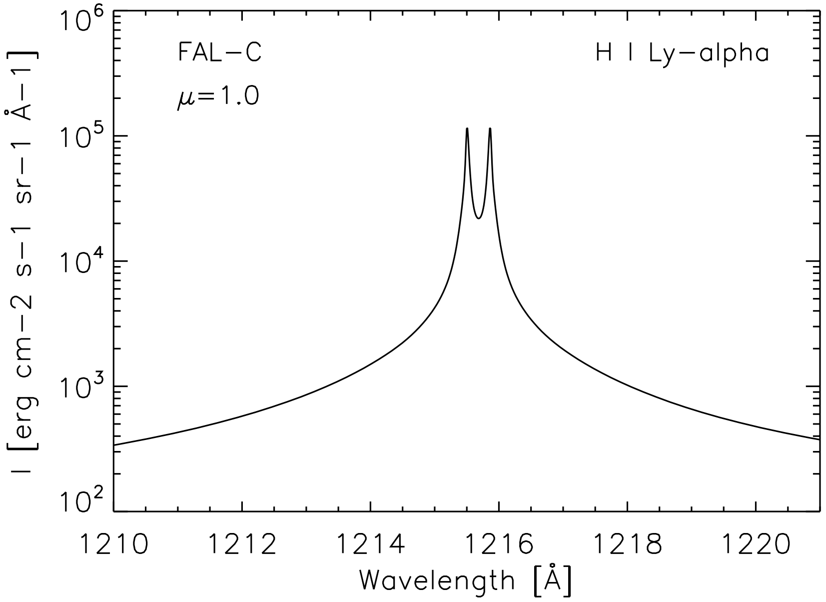
H I Lyα
1216 Å



(Stokes I observation by Roussel-Dupré 1982)

Observed on the quiet Sun disk

H I Lyα
1216 Å



RT synthesis in 1D semi-empirical model

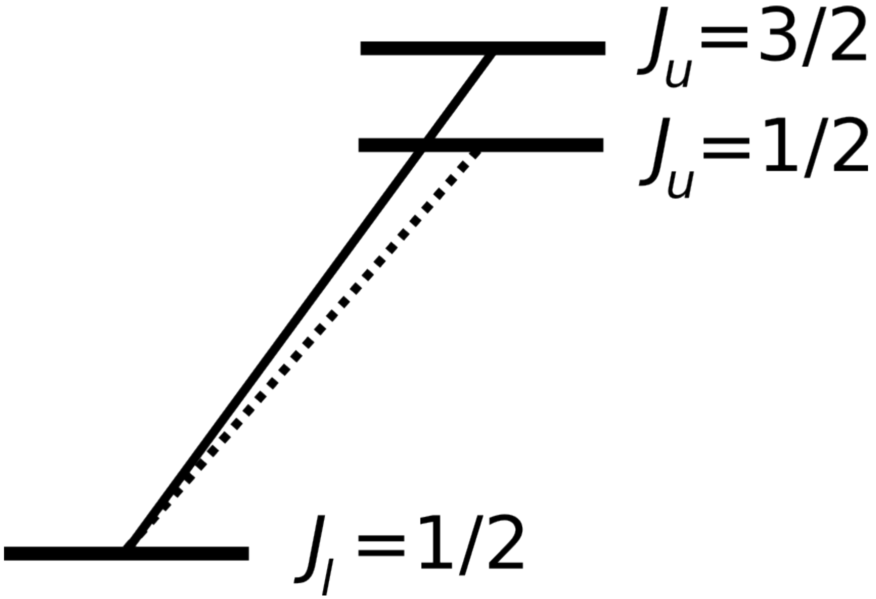
The approach

- **First step:** **CRD without J-state interference**

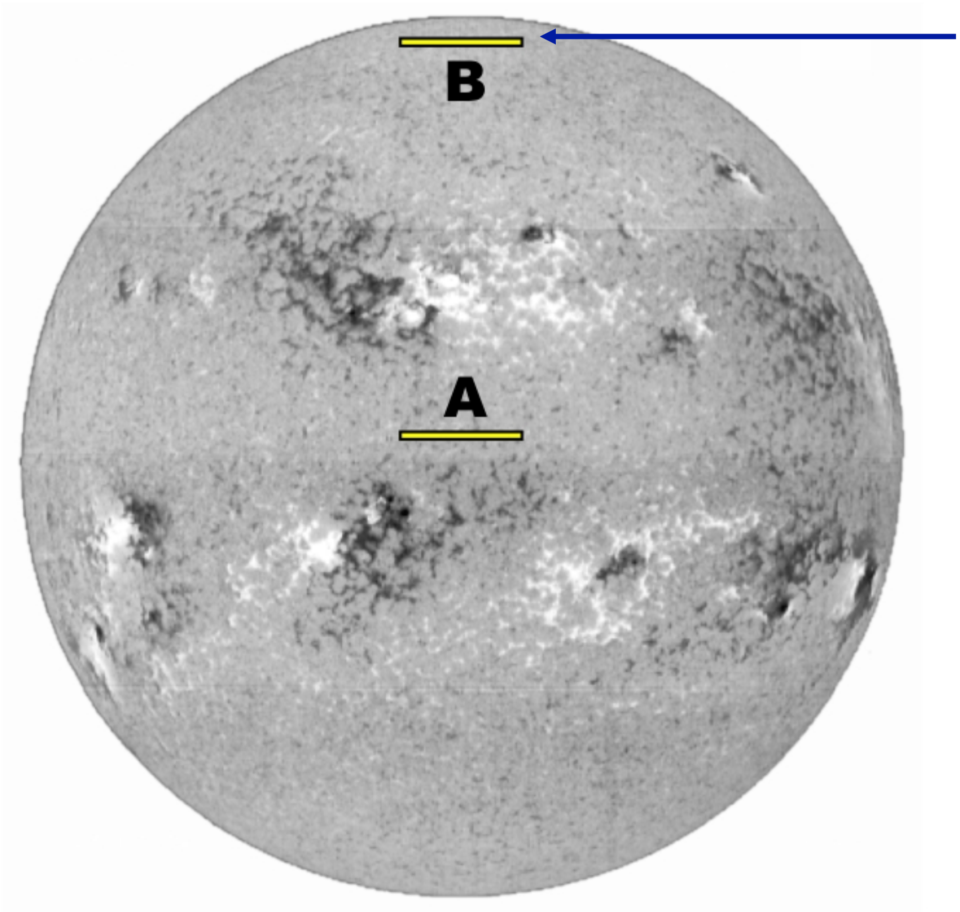
  Theory applied: see the monograph by Landi Degl'Innocenti & Landolfi (2004)

- **Second step:** **PRD with J-state interference**

  Theory applied: a generalization of the metalevels theory proposed by Landi Degl'Innocenti et al. (1997)

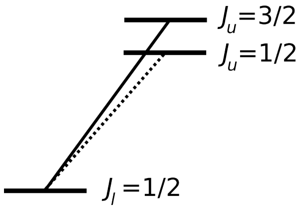


The scattering polarization calculated in a semi-empirical solar model atmosphere



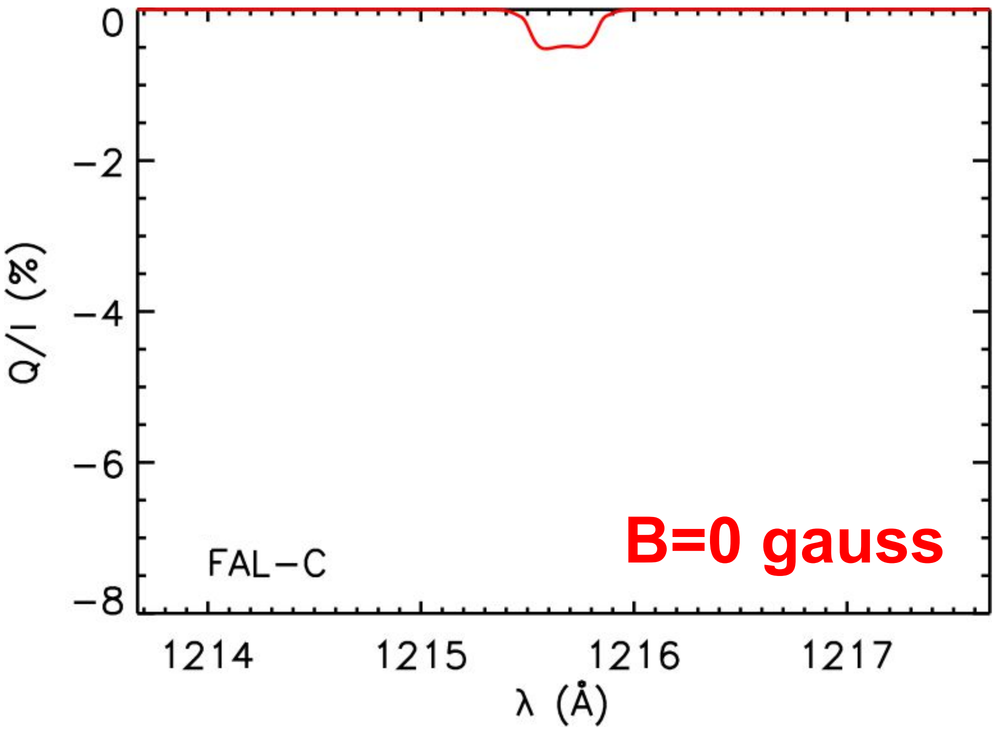
$\mu = \cos\theta$ = 0.3

The Ly-alpha Q/I profile



CRD without J-state interference

Zoom around line core (4 Angstroms interval)



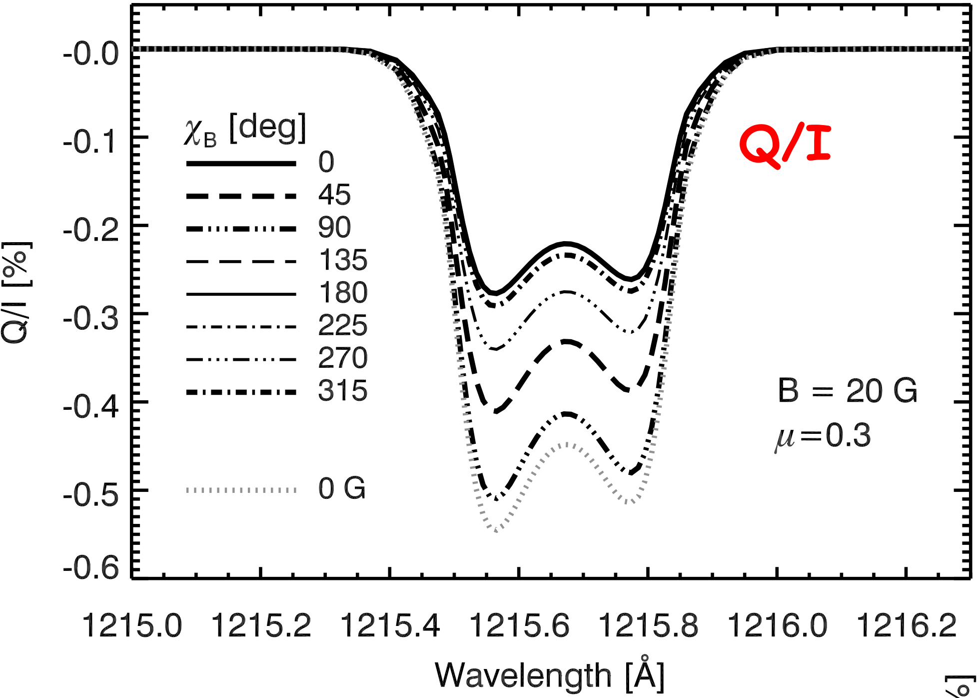
B=0 gauss

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

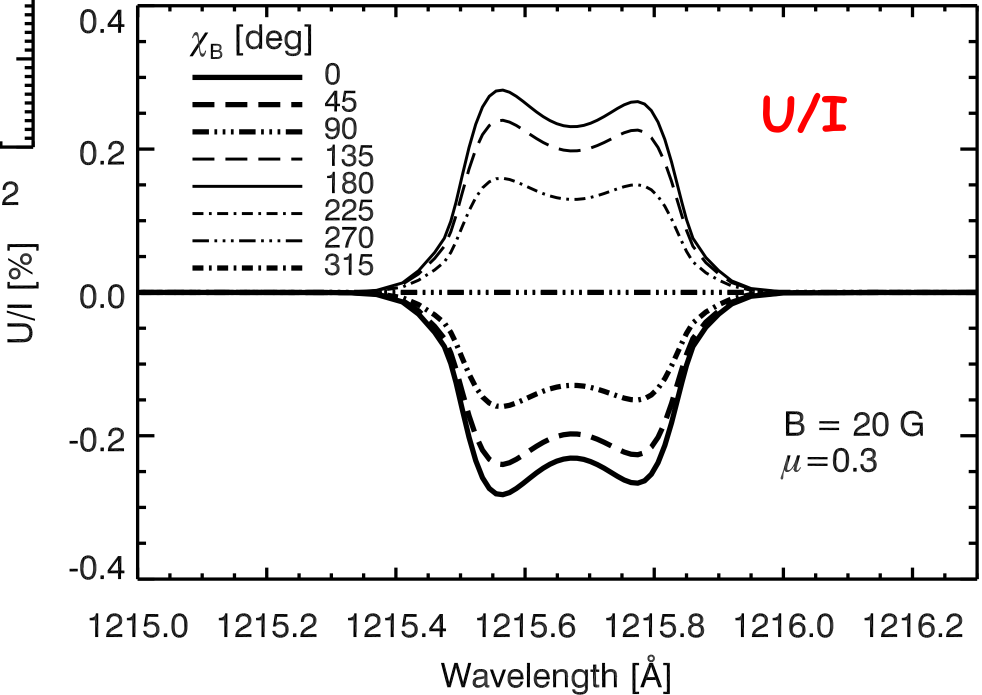
The Hanle effect in the Ly-alpha line

CASE 1: horizontal magnetic field with a given azimuth and B=20 G

Close to the limb LOS: mu=0.3



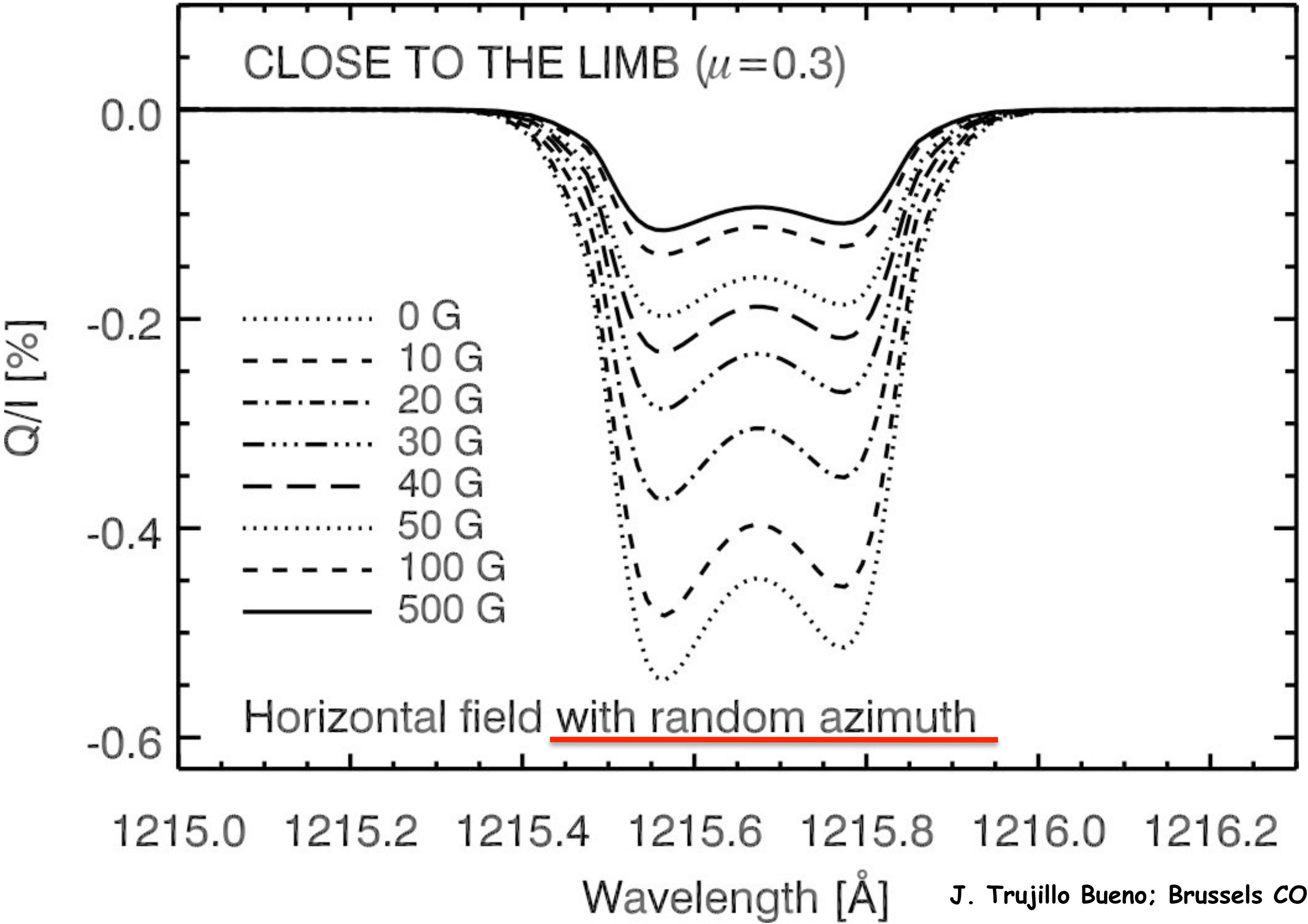
Close to the limb LOS: mu=0.3



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

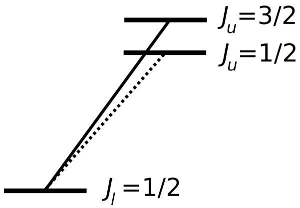
The Hanle effect in the Ly-alpha line

CASE 2: horizontal field with unresolved azimuth (LOS with mu=0.3)



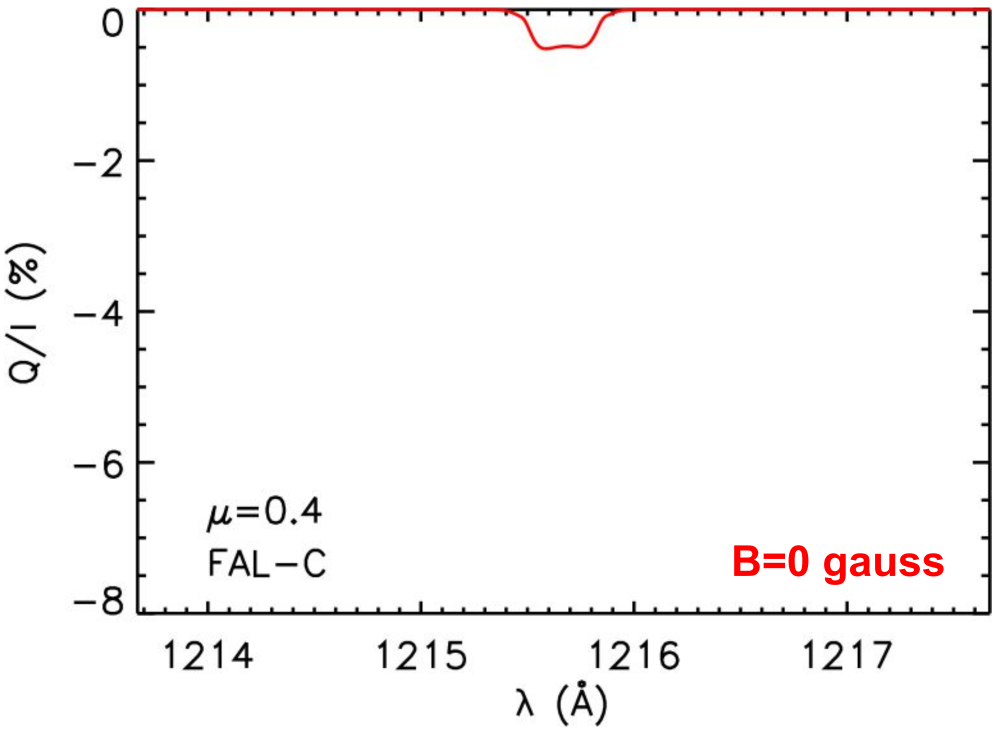
J. Trujillo Bueno; Brussels COST meeting 2015

The Ly-alpha Q/I profile



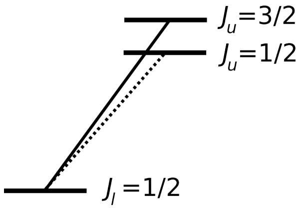
CRD without J-state interference

Zoom around line core (4 Angstroms interval)

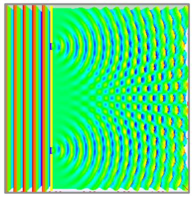


Trujillo Bueno, Stepan & Casini (2011; ApJ Letters)

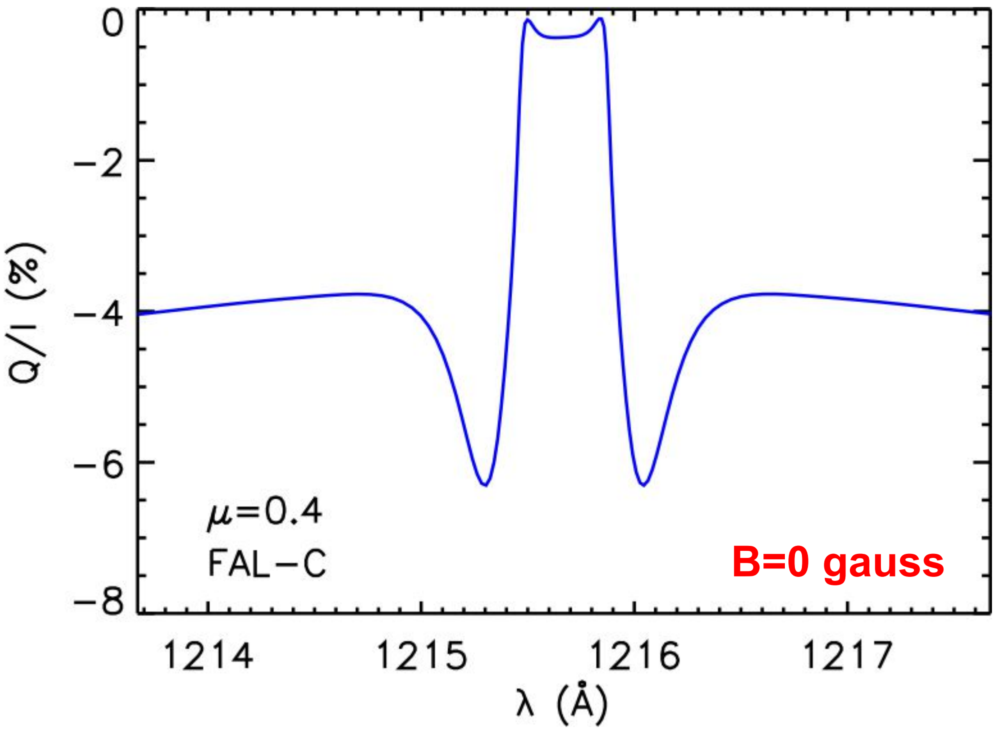
The Ly-alpha Q/I profile



PRD with J-state interference

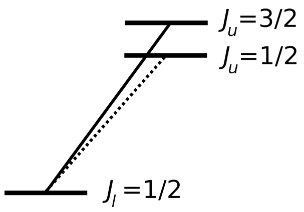


Zoom around line core (4 Angstroms interval)

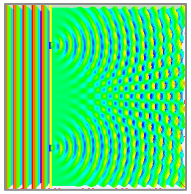


Belluzzi, Trujillo Bueno & Stepan (2012; ApJ Letters)

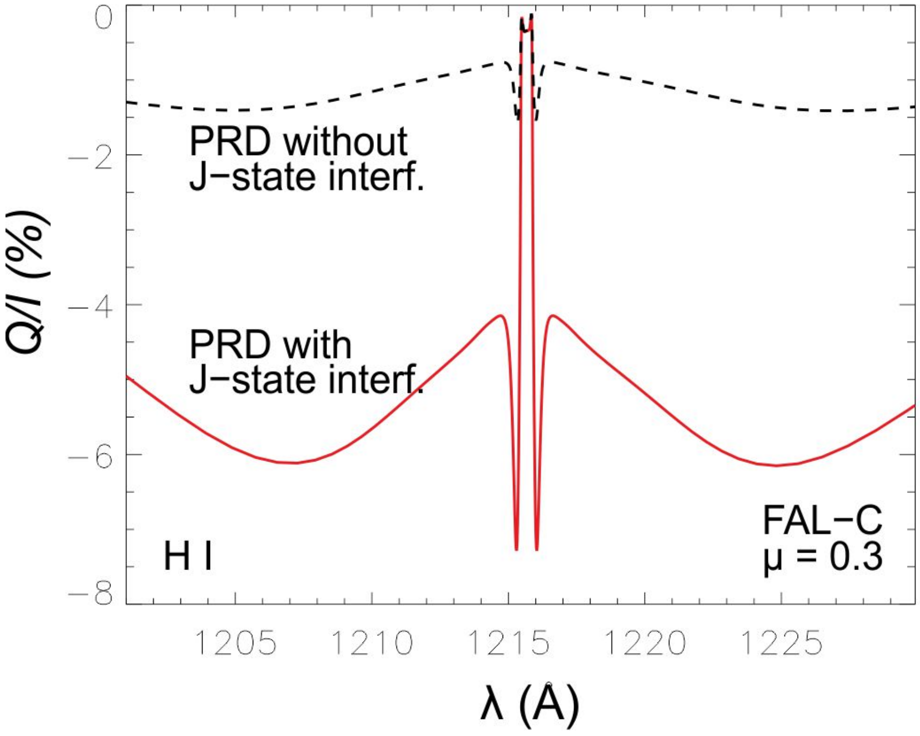
The Ly-alpha Q/I profile for mu=0.3



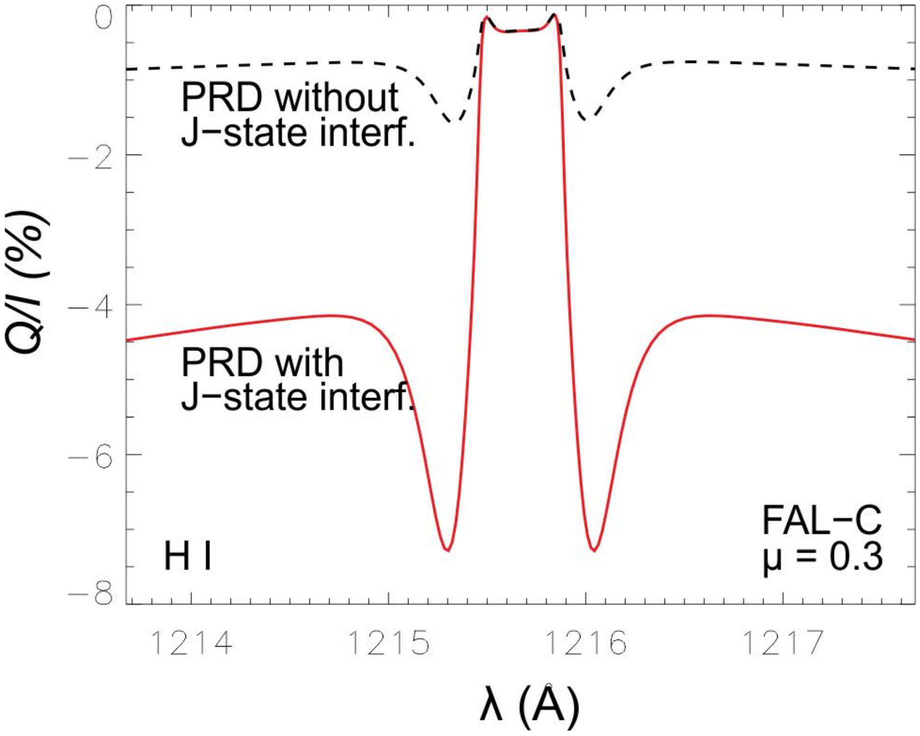
(The impact of **J-state** interference)



Overall Q/I pattern (30 Angstroms interval)



Zoom around line core (4 Angstroms interval)



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

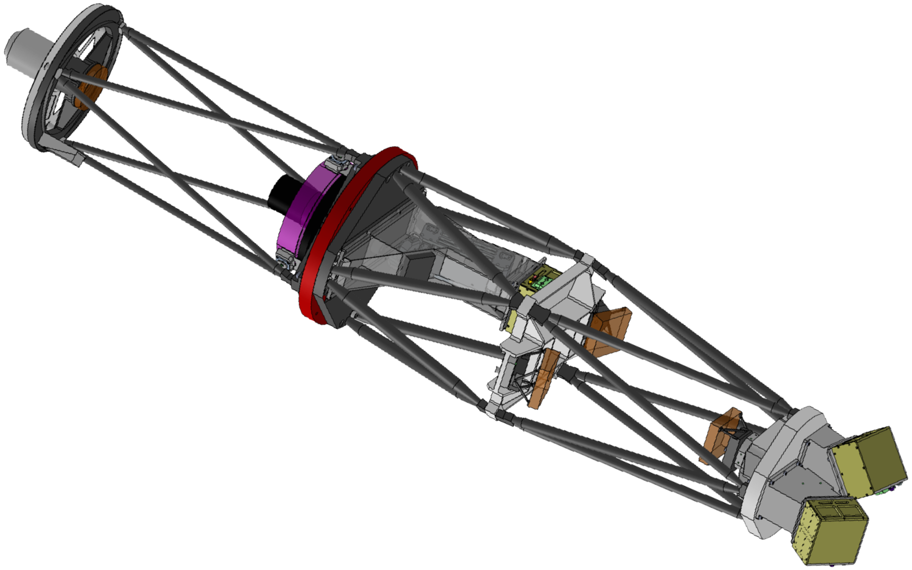
Conclusion

PRD + J-state interference produce Q/I profiles with extended wings.

Relatively high Q/I values (of the order of a few percent) are found in the line wings. They are mainly due to J-state interference.

CRD without J-state interference is suitable only for estimating the scattering polarization amplitudes at the center of the line, which is where the Hanle effect in Ly-alpha operates.

The Chromospheric Lyman-alpha Spectropolarimeter (CLASP)



Chromospheric Ly-Alpha SPectropolarimeter

CLASP: measure I, Q, U of hydrogen Lyman-alpha with a vacuum UV telescope and a spectropolarimeter launched by a NASA sounding rocket

CLASP aims at acting as a trailblazer for the exploration of the outer solar/stellar atmosphere via UV spectropolarimetric observations from space.

Rocket + CCD cameras

USA

A. Weinebarger (MSFC. PI)

T. Holloway (MSFC)* - **PM**

K. Kobayashi - PS

J. Cirtain (MSFC)†

B. De Pontieu (LMSAL) *

R. Casini (HAO) †

France

F. Auchère (IAS, Co-PI) ‡ GRATING

Telescope + Polarimeter

Japan

R. Kano (NAOJ, Co-PI) ‡

S. Tsuneta (NAOJ)‡

N. Narukage (JAXA)‡ - **IS**

M. Kubo (NAOJ)‡

T. Sakao (JAXA) ‡

Y. Suematsu (NAOJ)‡

T. Shimizu (JAXA) ‡

T. Bando (NAOJ)‡ - **PM**

R. Ishikawa (NAOJ) ‡ - **PS**

Y. Katsukawa (NAOJ) ‡

H. Hara (NAOJ) ‡

K. Ichimoto (Kyoto) ‡

G. Ono (NAOJ)

Theory & Modeling

Spain

J. Trujillo Bueno (IAC, Co-PI)‡

R. Manso Sainz (IAC) ‡

L. Belluzzi (IAC) ‡

A. Asensio Ramos (IAC) ‡

Czech Republic

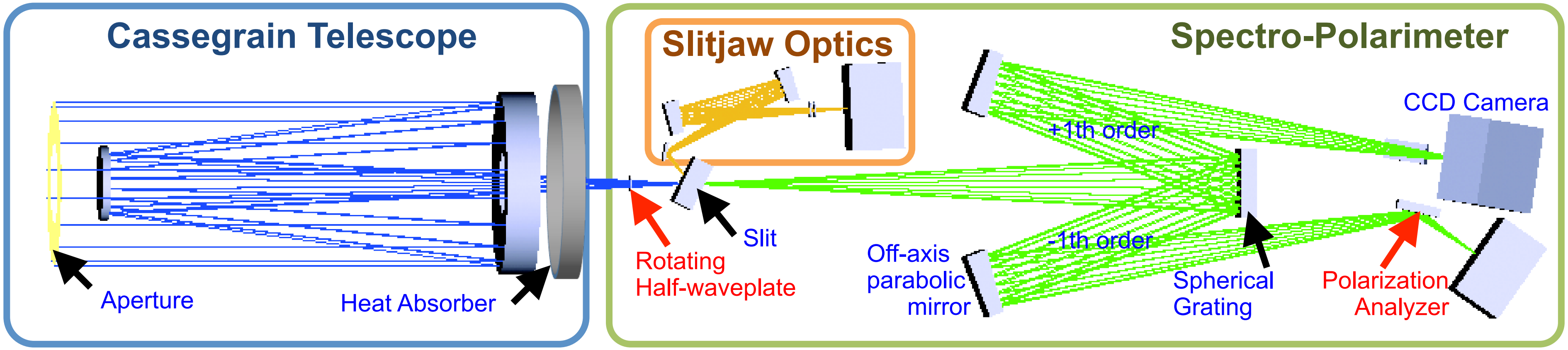
J. Stěpán (ASCR) ‡

Norway

M. Carlsson (Univ. of Oslo) ‡

The CLASP instrument

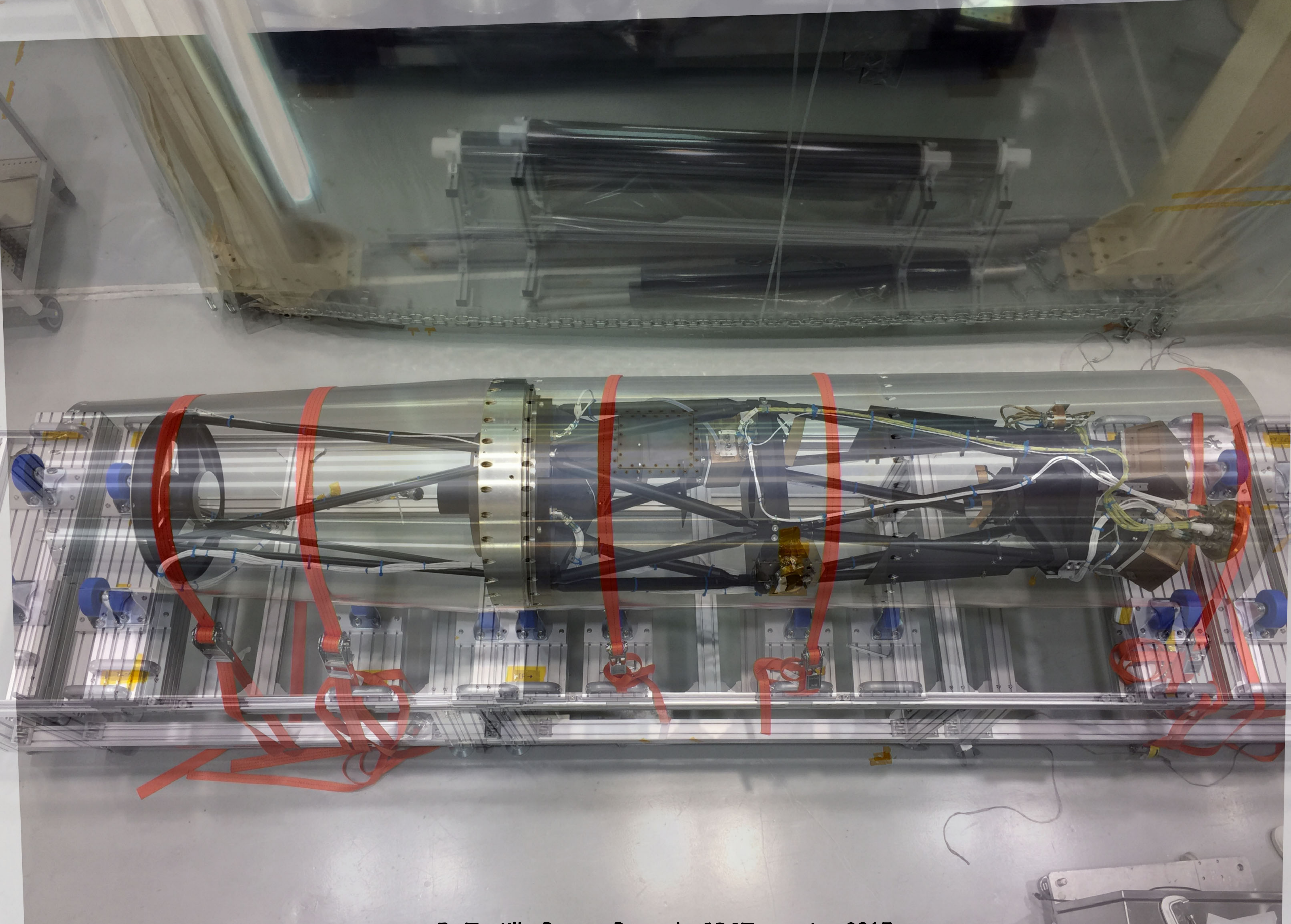
(Kobayashi et al. 2012; Narukage et al. 2015)



Cassegrain Telescope	
Aperture	ϕ270.0 mm
Effective Focal Length	2614 mm (F/9.68)
Visible light rejection	"Cold Mirror" coating on primary mirror

Slitjaw Optics	
Wavelength	121.567 nm (narrowband filter)
Plate scale	1.03''/pixel
FoV	527''×527''

Spectro-Polarimeter		
Optics	**Optically symmetric dual channel**	
Wavelength	121.567 ± 0.61 nm	
Slit	1.45'' (width), 400'' (length)	
Grating	Spherical constant-line-spacing, 3000 lines/mm	
CCD camera	512×512 pixel	13μm/pixel
Plate scale	0.0048 nm/pixel	1.11''/pixel
Resolution	0.01nm	3''



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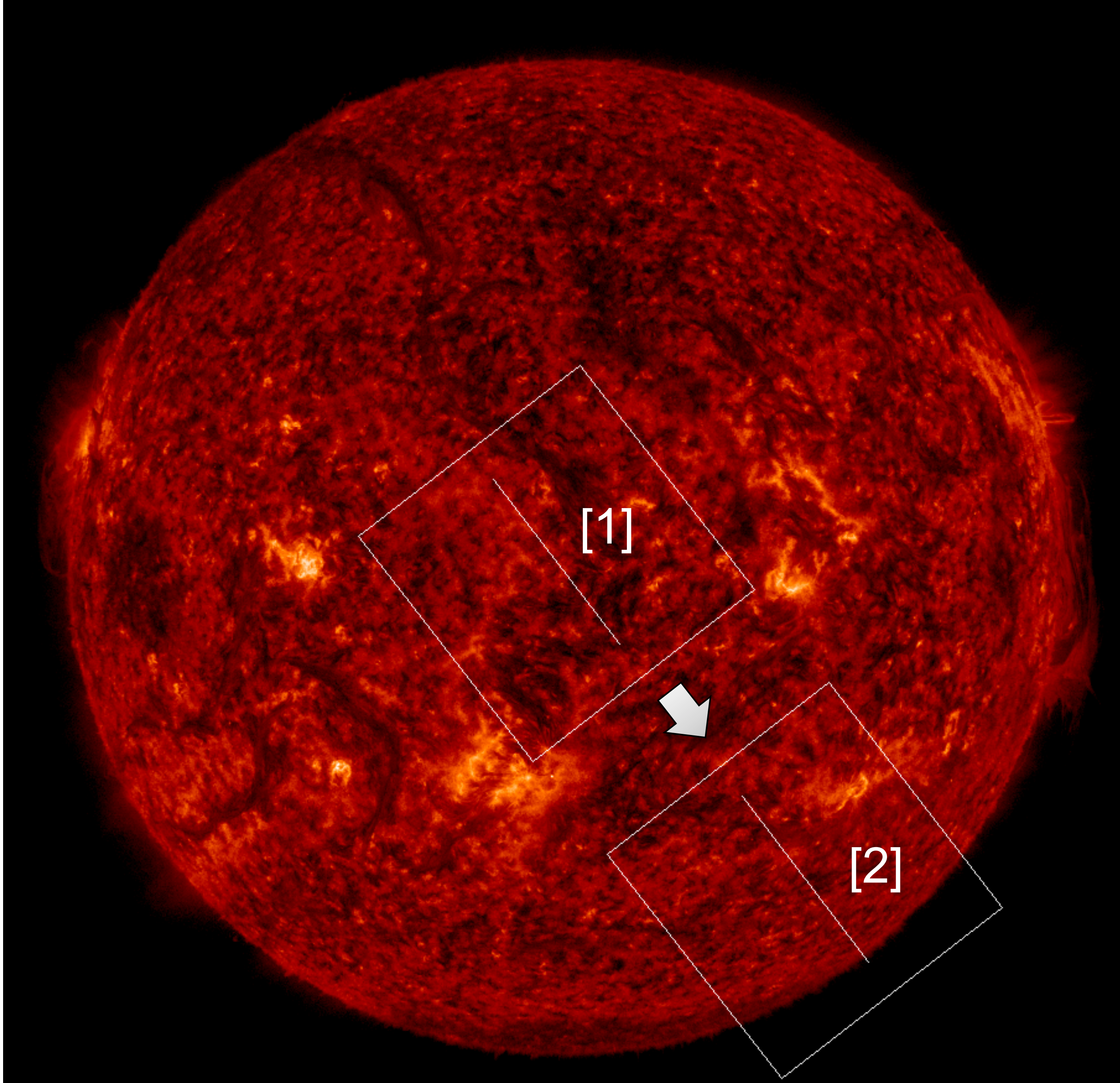
Launch of CLASP (September 3, 2015)

TARGETS SELECTED:

QUIET REGIONS

[1] Disk CENTER

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



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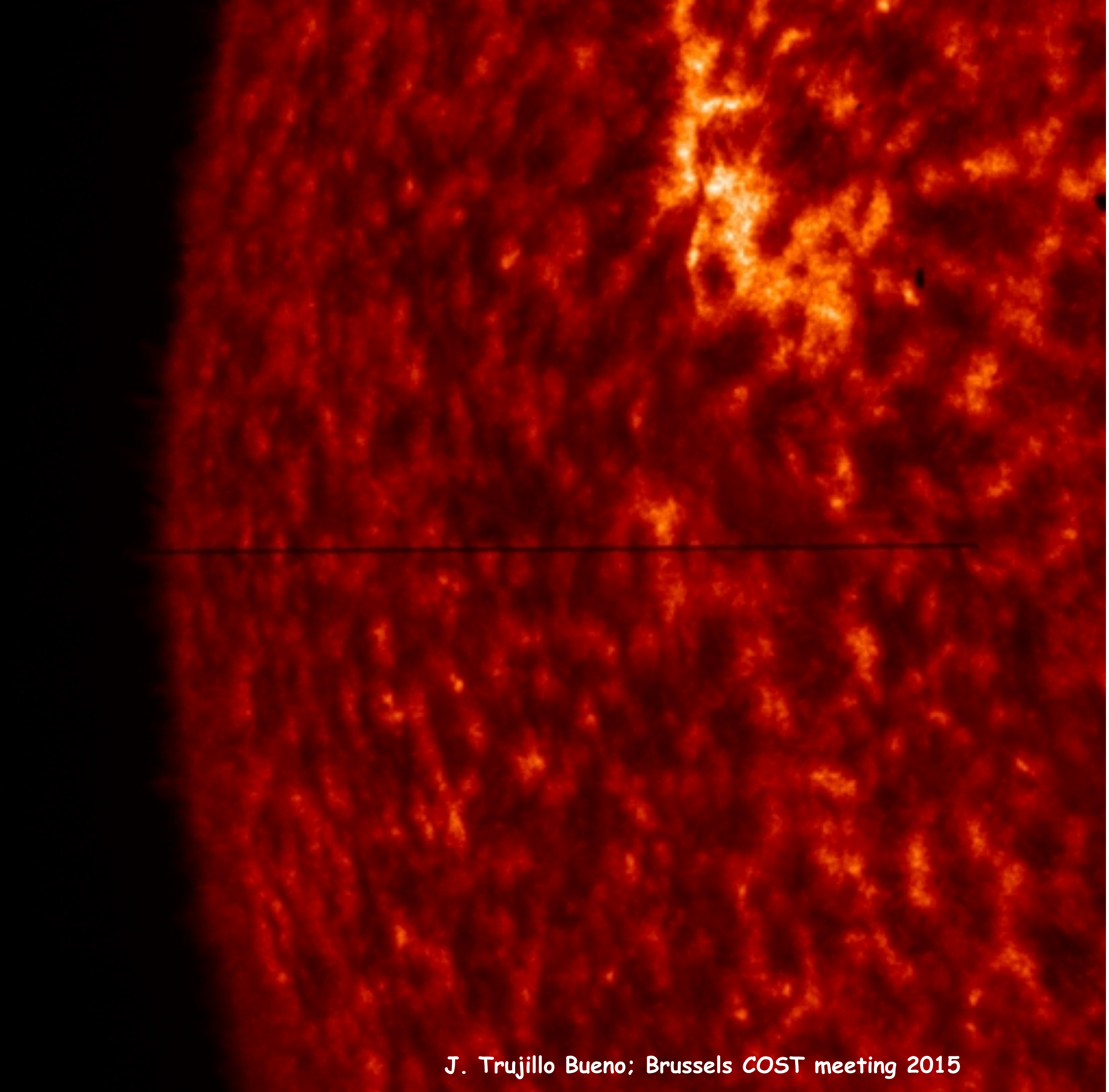

Slit-jaw image during the CLASP observations

All went fine and CLASP got very good data we are studying carefully !

Concluding comments

- The "measurement" of the magnetic field in the outer solar atmosphere (chromosphere, TR and corona) is a very important challenge in astrophysics.

- Spectropolarimetry in FUV and EUV lines can only be done from space. However, we must pursue this goal because vacuum UV polarimetry might be our key gateway to the magnetism of the outer atmospheres of the Sun and of other stars.

- CLASP is a significant step in this advancement, which we will continue with CLASP-2 (whose objective is I,Q,U and V in the Mg II h & k lines)

- We also need new breakthroughs in the development of polarized radiation diagnostics. To this end, we should combine and expand expertise on atomic physics, on the quantum theory of polarization, on advanced methods in numerical radiative transfer, and on the confrontation of spectropolarimetric observations with spectral synthesis in increasingly realistic models of the extended solar atmosphere.