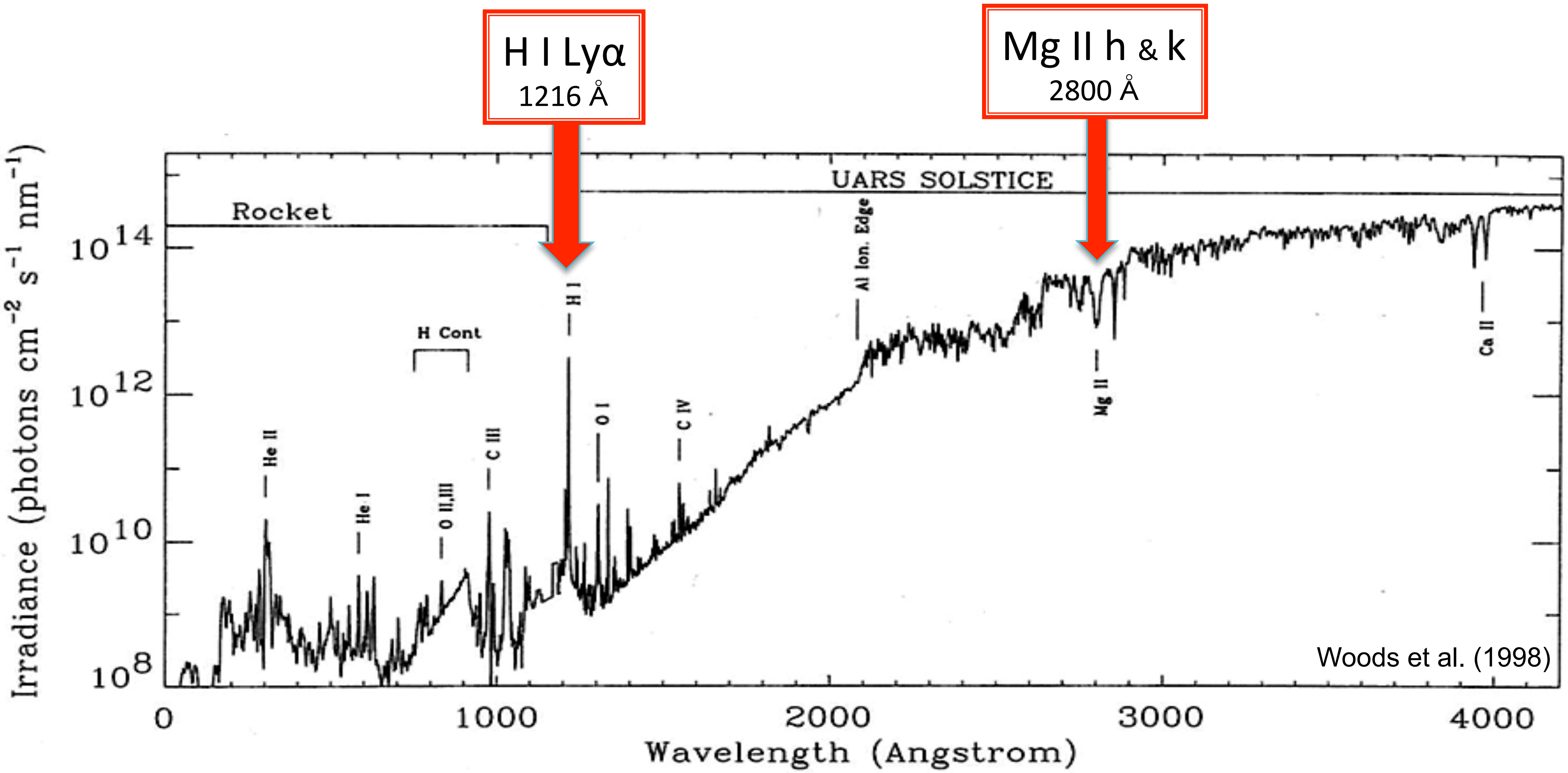
The Polarization and Magnetic Sensitivity of UV Resonance Lines
Mg II *h* & *k* vs. Ly-alpha

J. Trujillo Bueno (IAC; Tenerife)
with
L. Belluzzi (IRSOL), **T. del Pino Alemán** (HAO; Boulder) and **J. Stepan** (ASCR; Prague)



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

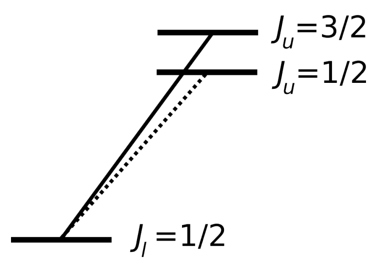
INDEX

- **The physical mechanisms**

- **RT calculations of the Stokes profiles and their magnetic sensitivity**

(a) Lyman-alpha

(b) Mg II h & k



- **The 3D world**

- **Conclusions**

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

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(1) The Zeeman effect polarization:

Stokes V ~ R

Stokes Q & U ~ R^2

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

Zeeman splitting

Line's Doppler width

Atomic weight

Especially in strong UV lines

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For **Lyman-alpha at 1216 Angstroms**,

assuming T=10000 K and B=10 gauss

R ~ 0.0001 → **Stokes V/I ~ 0.01%** → **VERY difficult !**

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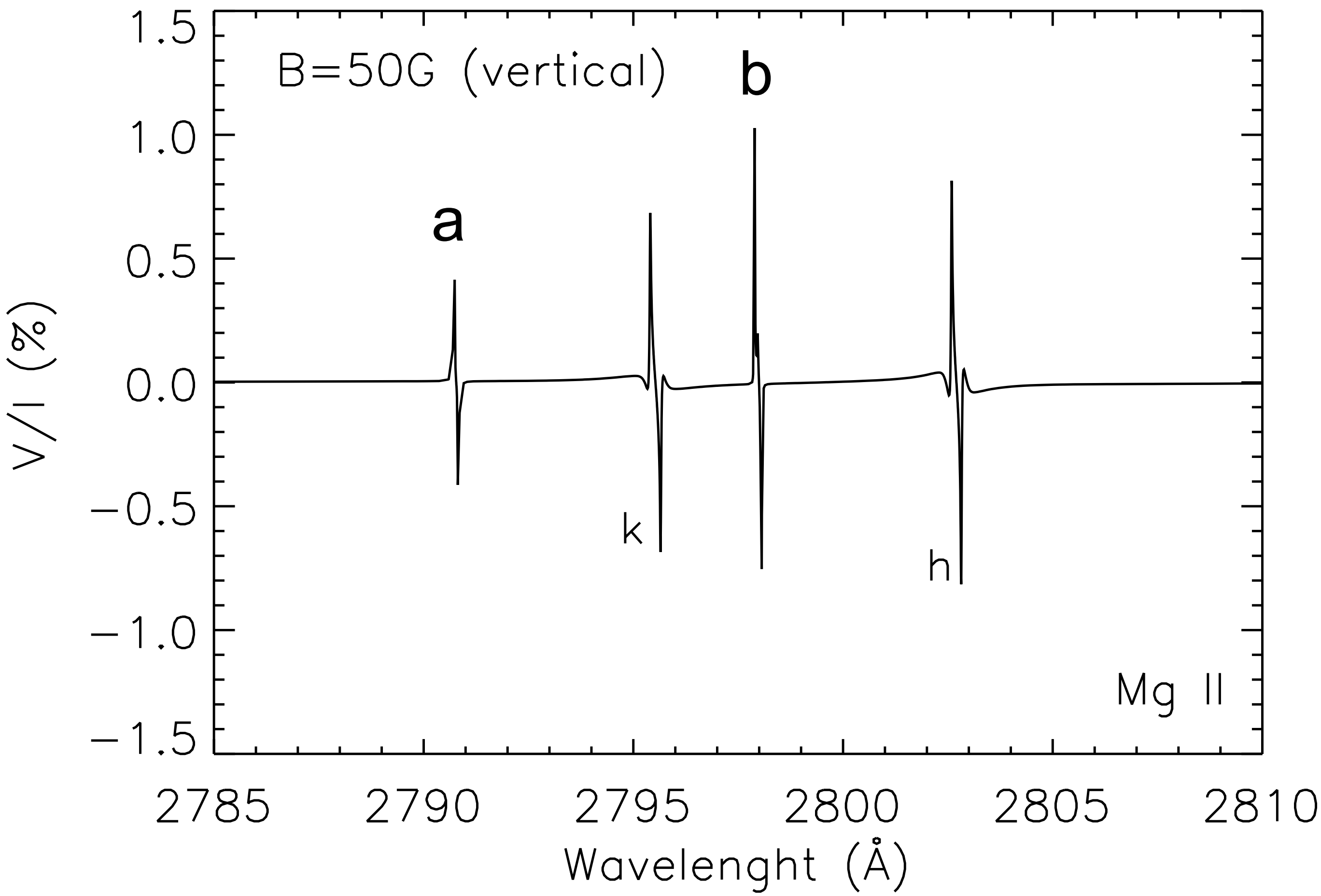
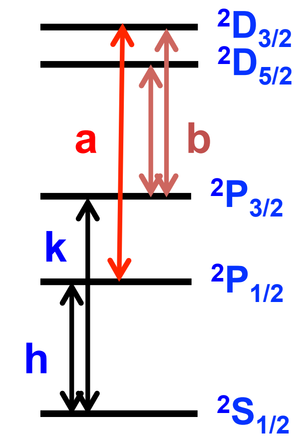
For **Mg II h & k at 2800 Angstroms**,

assuming T=10000 K and B=10 gauss

R ~ 0.001 ⟶ **Stokes V/I ~ 0.1 %** ⟶ **Feasible !**

The Zeeman effect in the Mg II lines

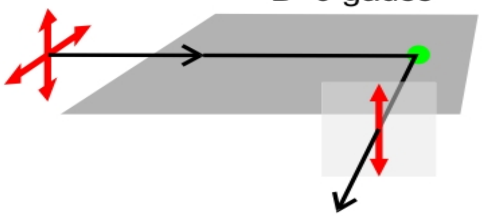




Belluzzi & Trujillo Bueno (2012; ApJ)

(2) The scattering line polarization

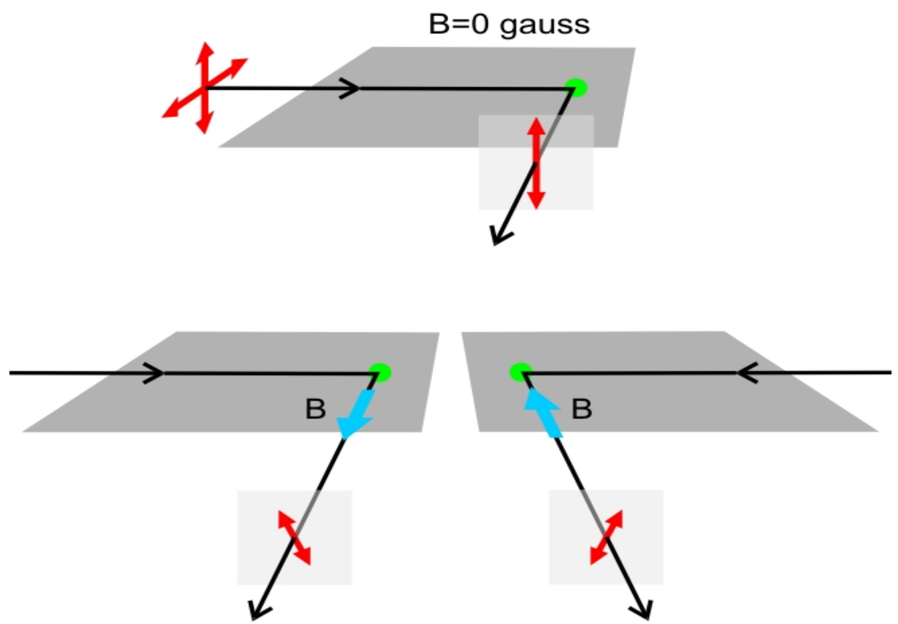
It is the linear polarization in a spectral line produced by the scattering of anisotropic radiation:



It does NOT need of a magnetic field !

(3) The Hanle effect of a magnetic field

The MODIFICATION of the scattering line polarization due to the presence of a magnetic field



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

$$8.79 \times 10^{6}\, g\, B_H = 1/\text{Lifetime} \approx A_{ul}$$

Level's Lande factor

gauss

seconds

Level's splitting in frequency units

Natural width of the Level

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

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$B_H = 850$ G	$B_H = 290$ G	$B_H = 53$ G	$B_H = 20$ G
He II line at 304 Å	Si III line at 1206 Å	Ly-alpha of H I	k-line of Mg II

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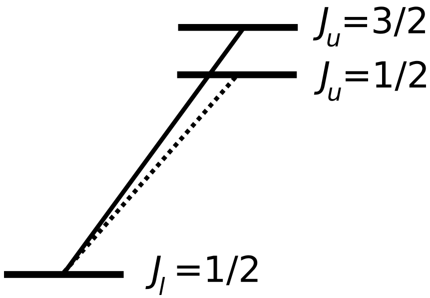
Ly-alpha of H I

$B_H = 20$ G

k-line of Mg II

This atomic model:

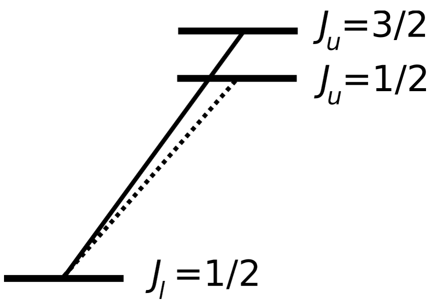


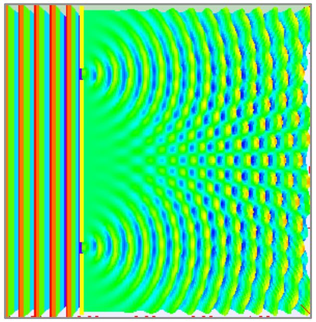
is suitable for understanding the polarization in these lines.

It allows us to take into account:

- Frequency correlations between the incoming and outgoing photons (PRD)

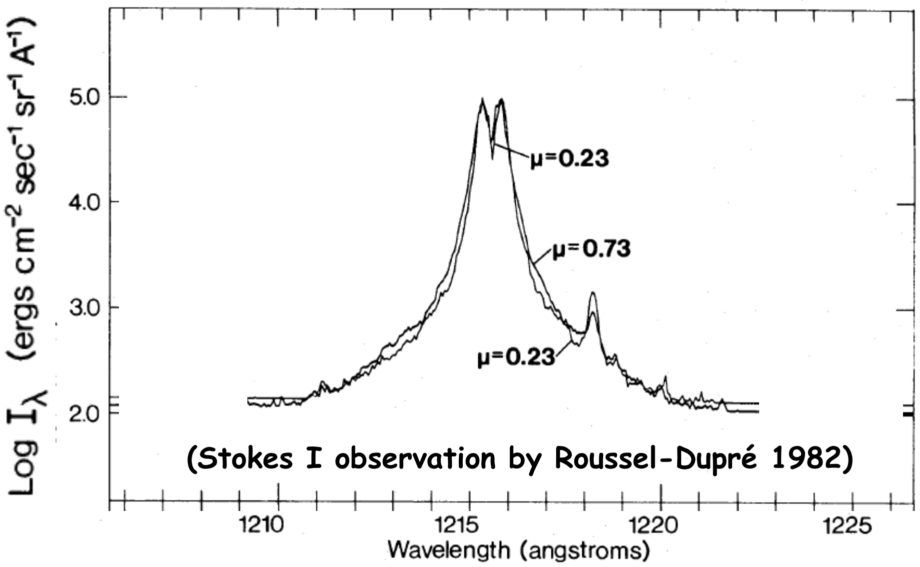
- Quantum interference between the two upper J-levels (J-state interference):





The hydrogen Ly-alpha line

H I Lyα
1216 Å



Observed on the quiet Sun disk

H I Lyα
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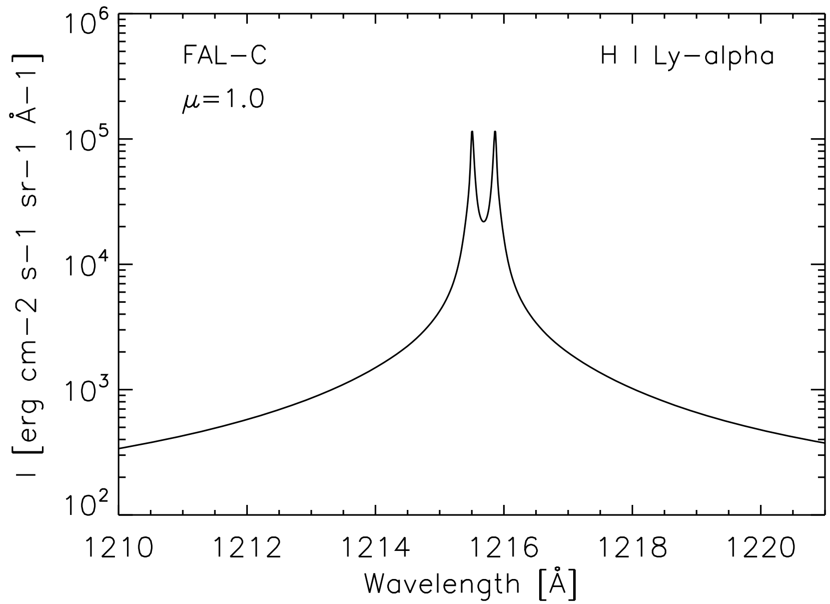
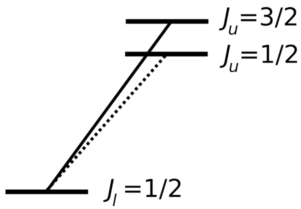
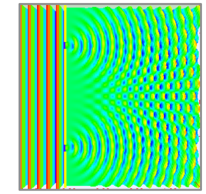


RT synthesis in 1D semi-empirical model

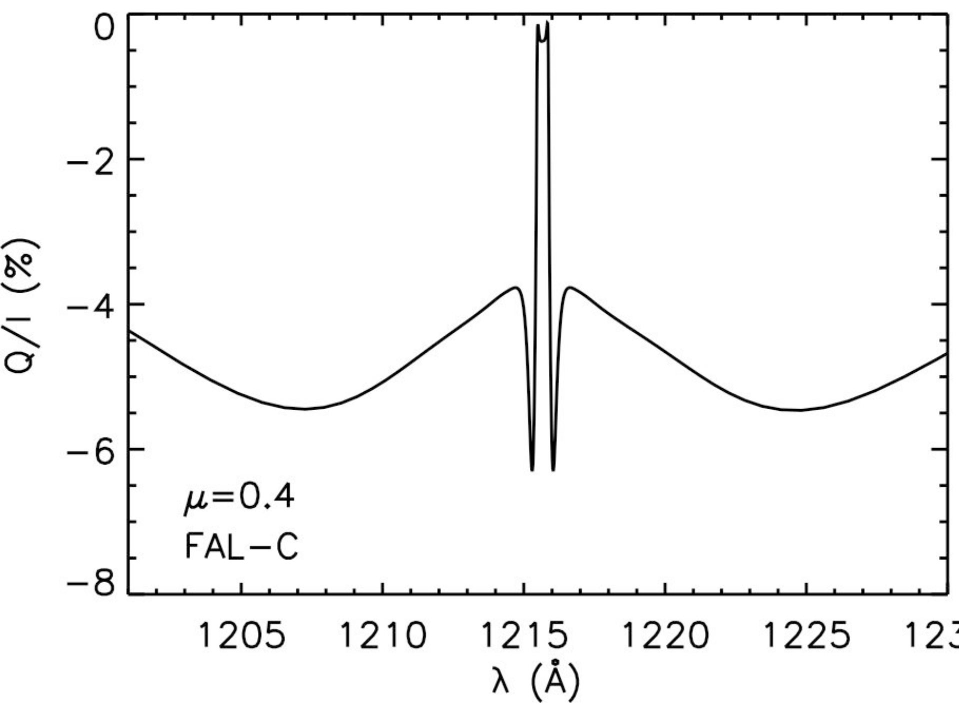
The Ly-alpha Q/I profile for mu=0.4



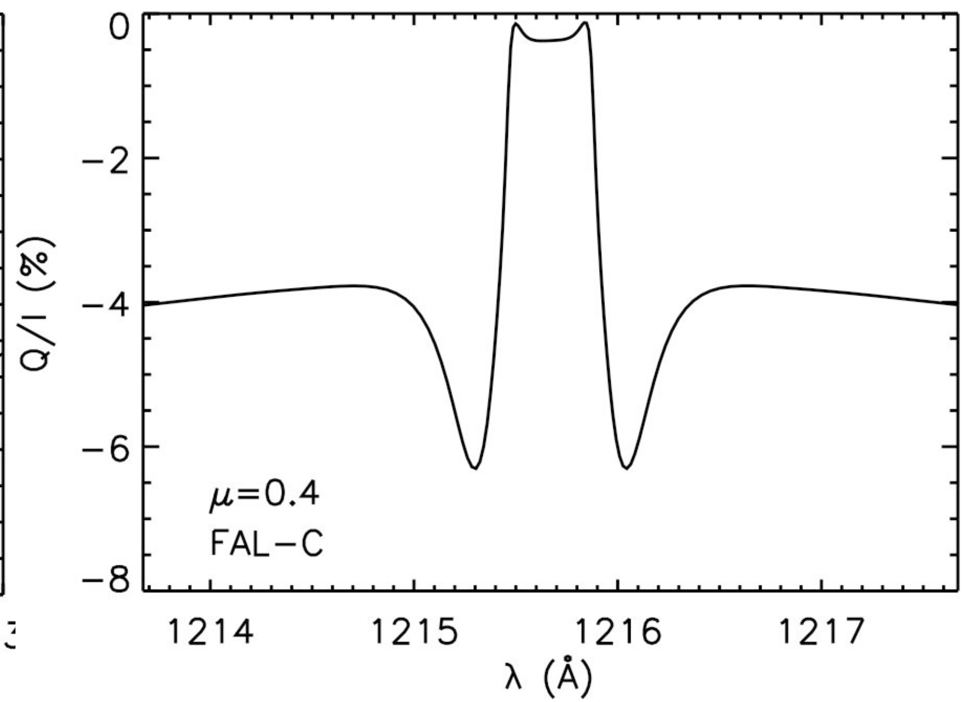
(With PRD + J-state interference)



Overall Q/I pattern (30 Angstroms interval)



Zoom around line core (4 Angstroms interval)



Belluzzi, Trujillo Bueno & Stepan (2012, ApJ)

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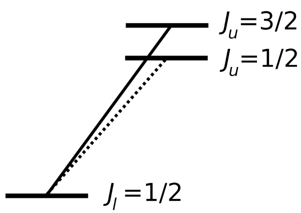
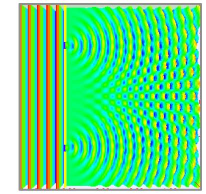


(The impact of J-state interference)



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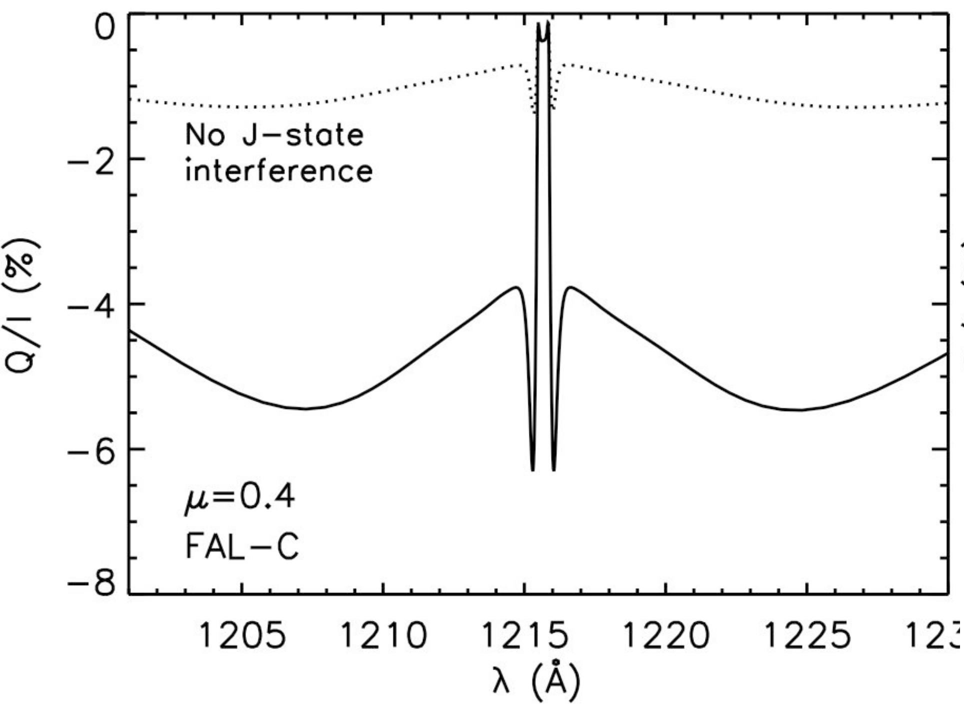
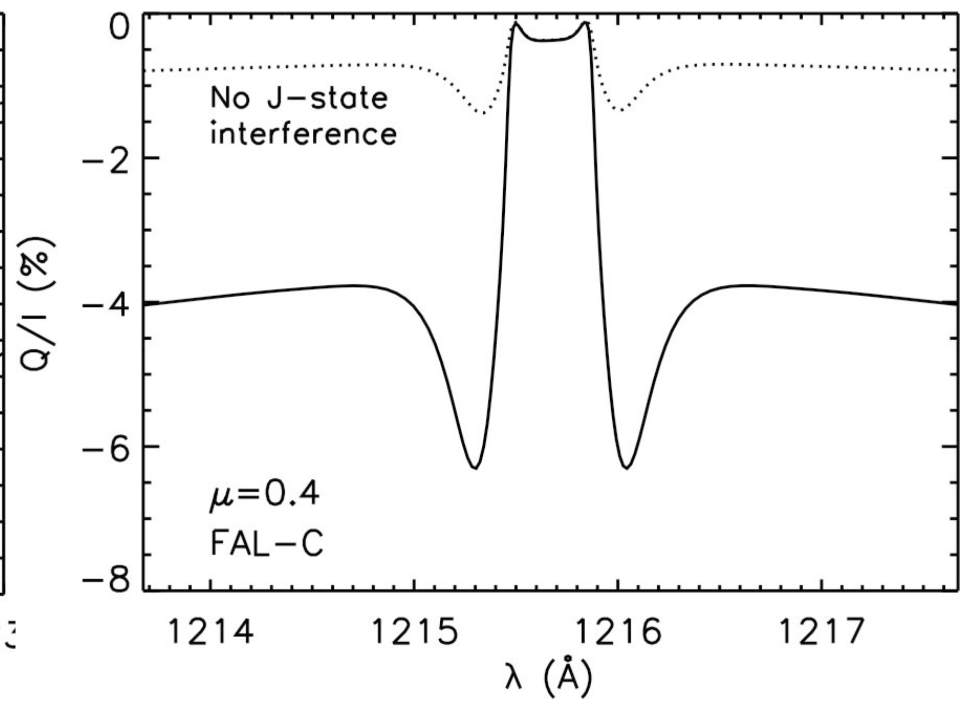
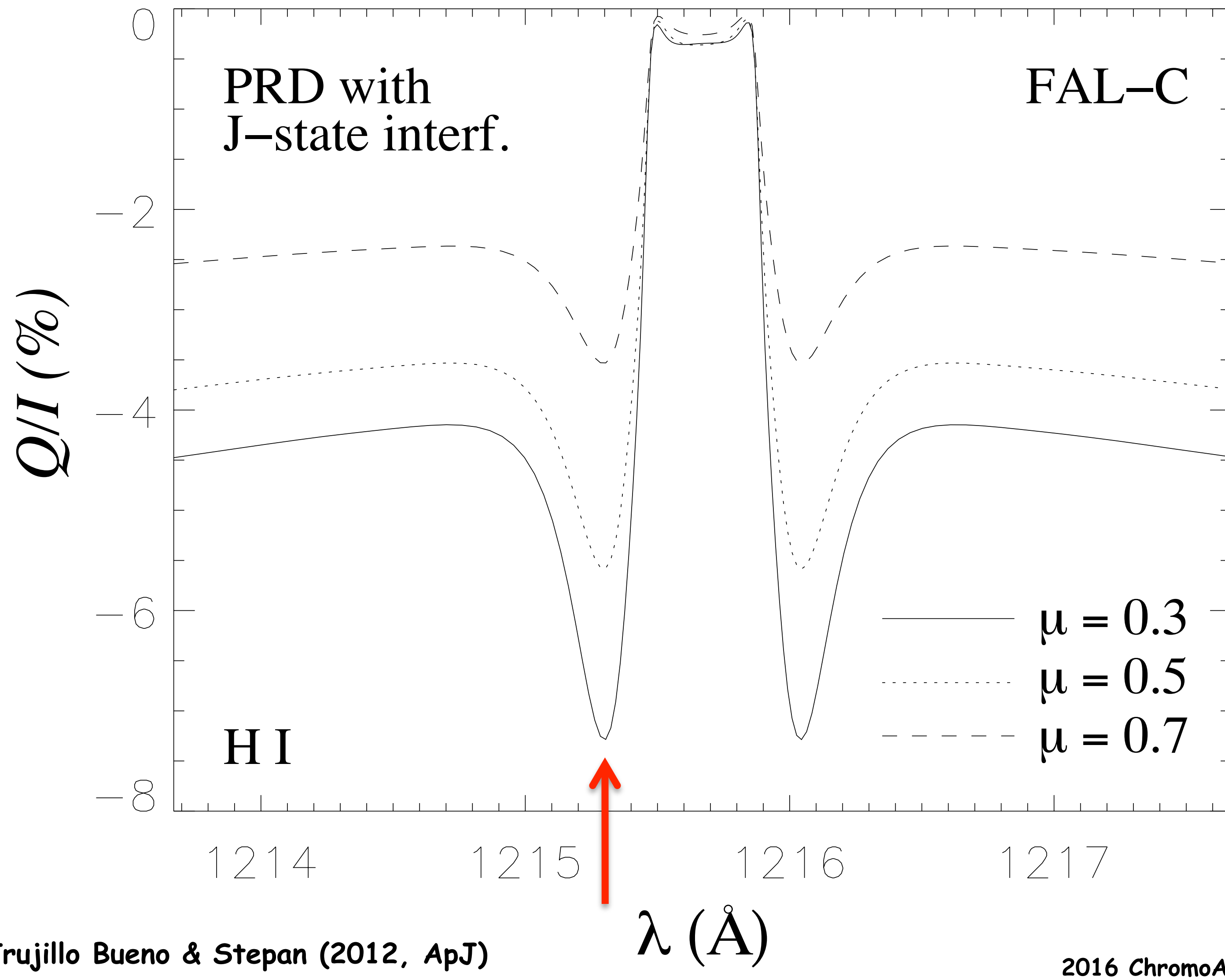




Belluzzi, Trujillo Bueno & Stepan (2012, ApJ)

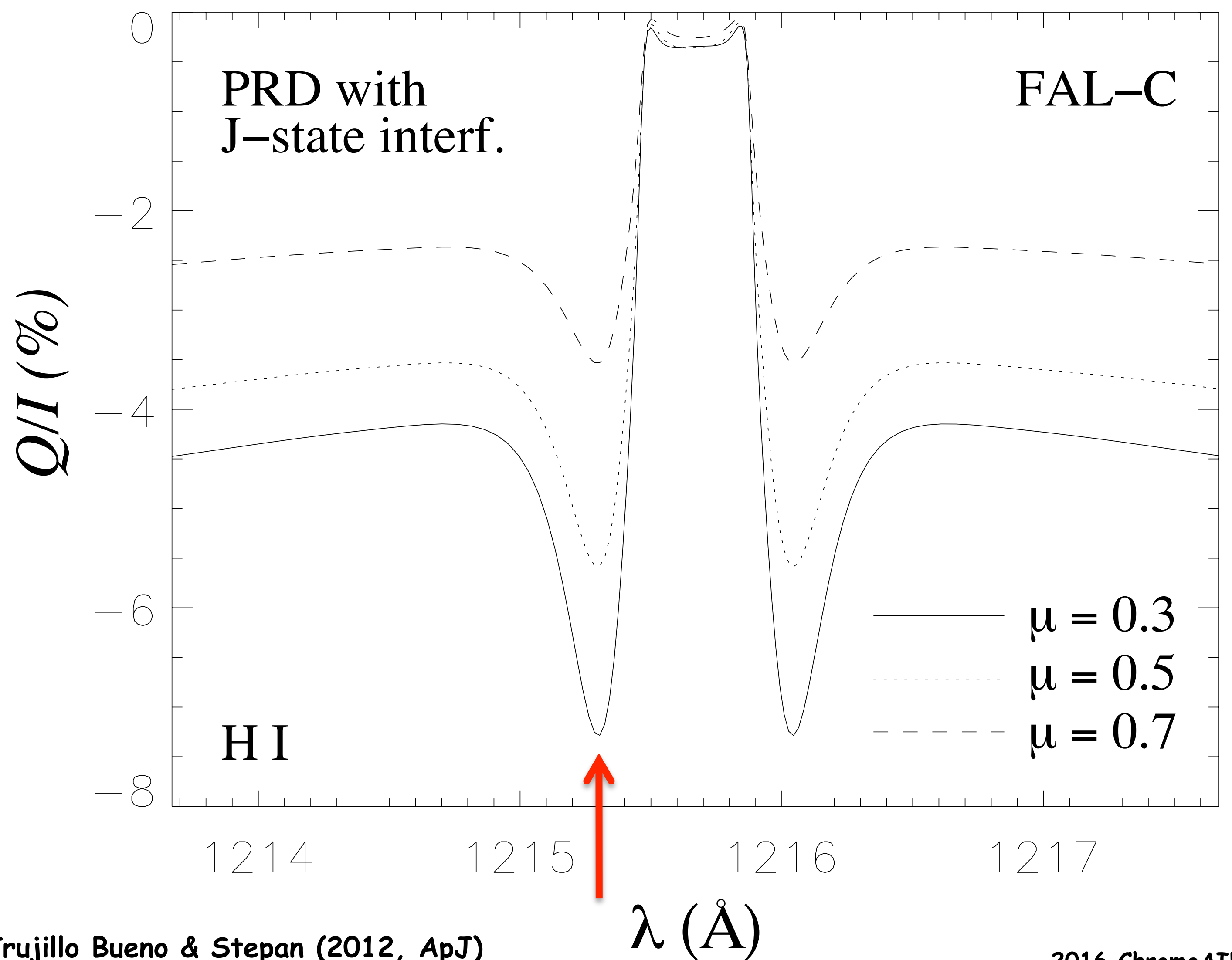
CLV of Q/I



Belluzzi, Trujillo Bueno & Stepan (2012, ApJ)

See CLASP observations in the talk by Ishikawa et al. next Thursday !

CLV of Q/I



Belluzzi, Trujillo Bueno & Stepan (2012, ApJ)

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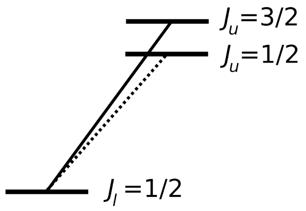
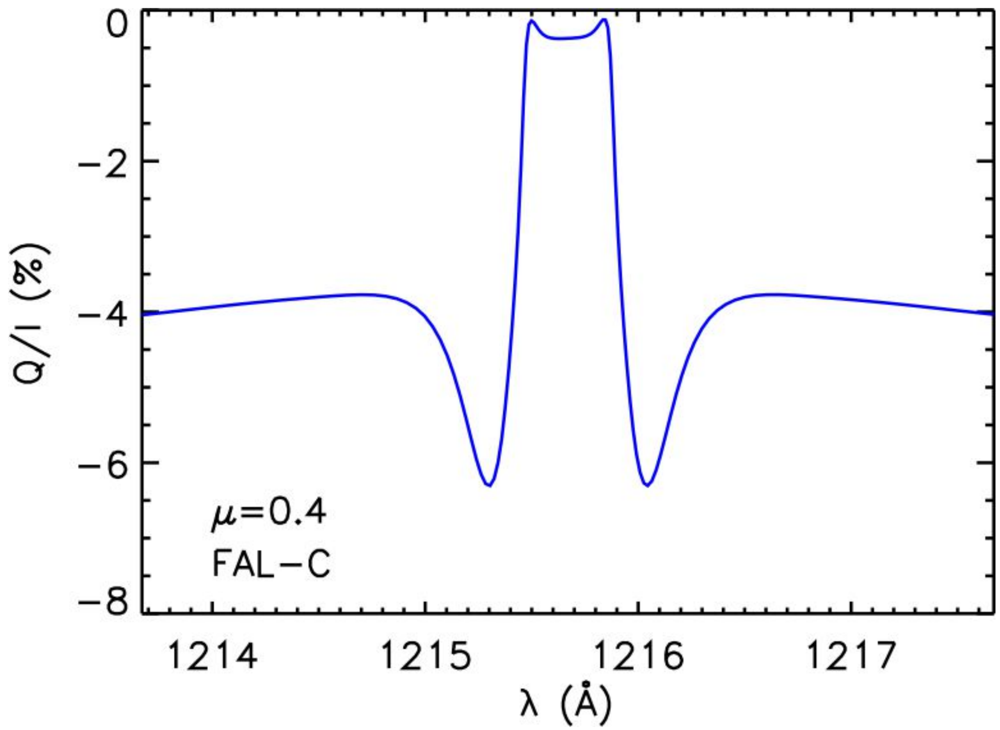


(PRD)

Zoom around line core (4 Angstroms interval)



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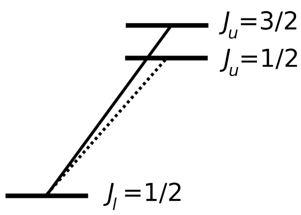

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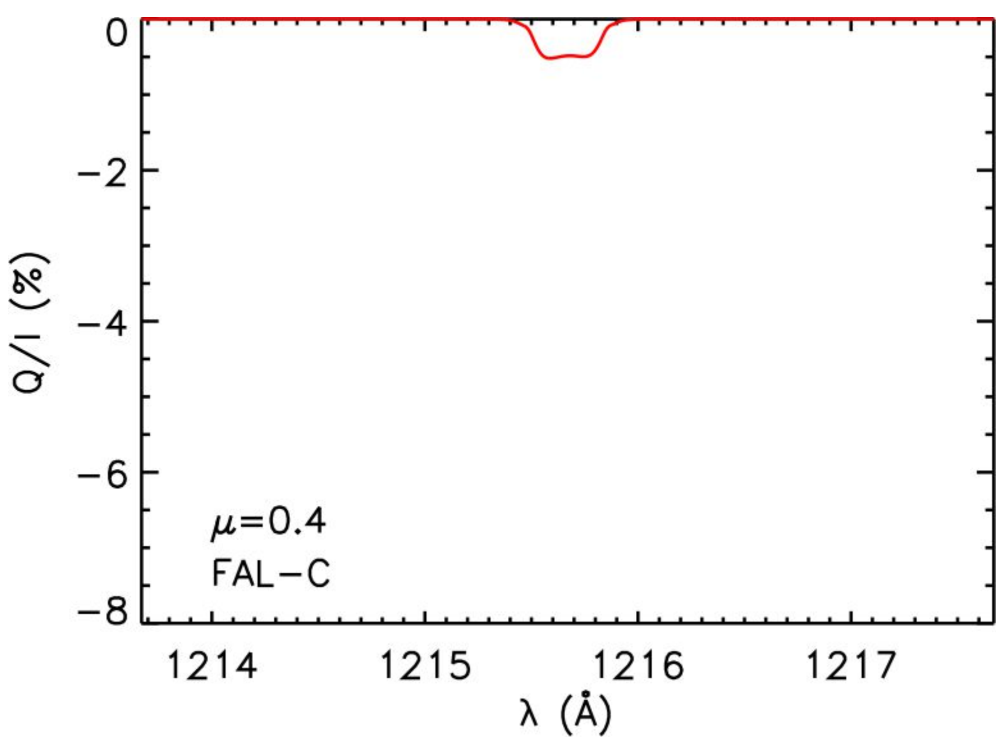
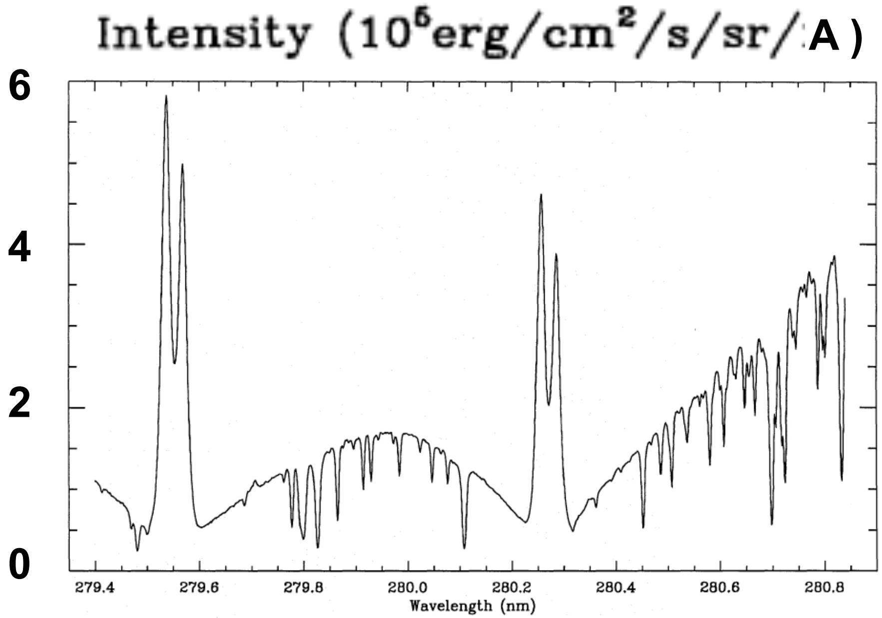


The Mg II h & k Lines



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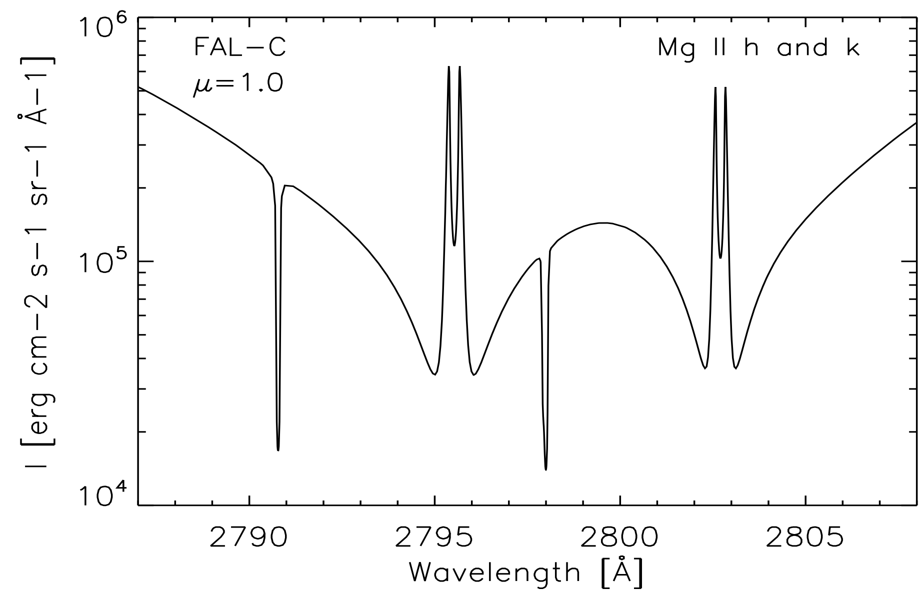
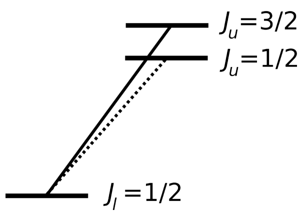
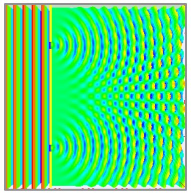


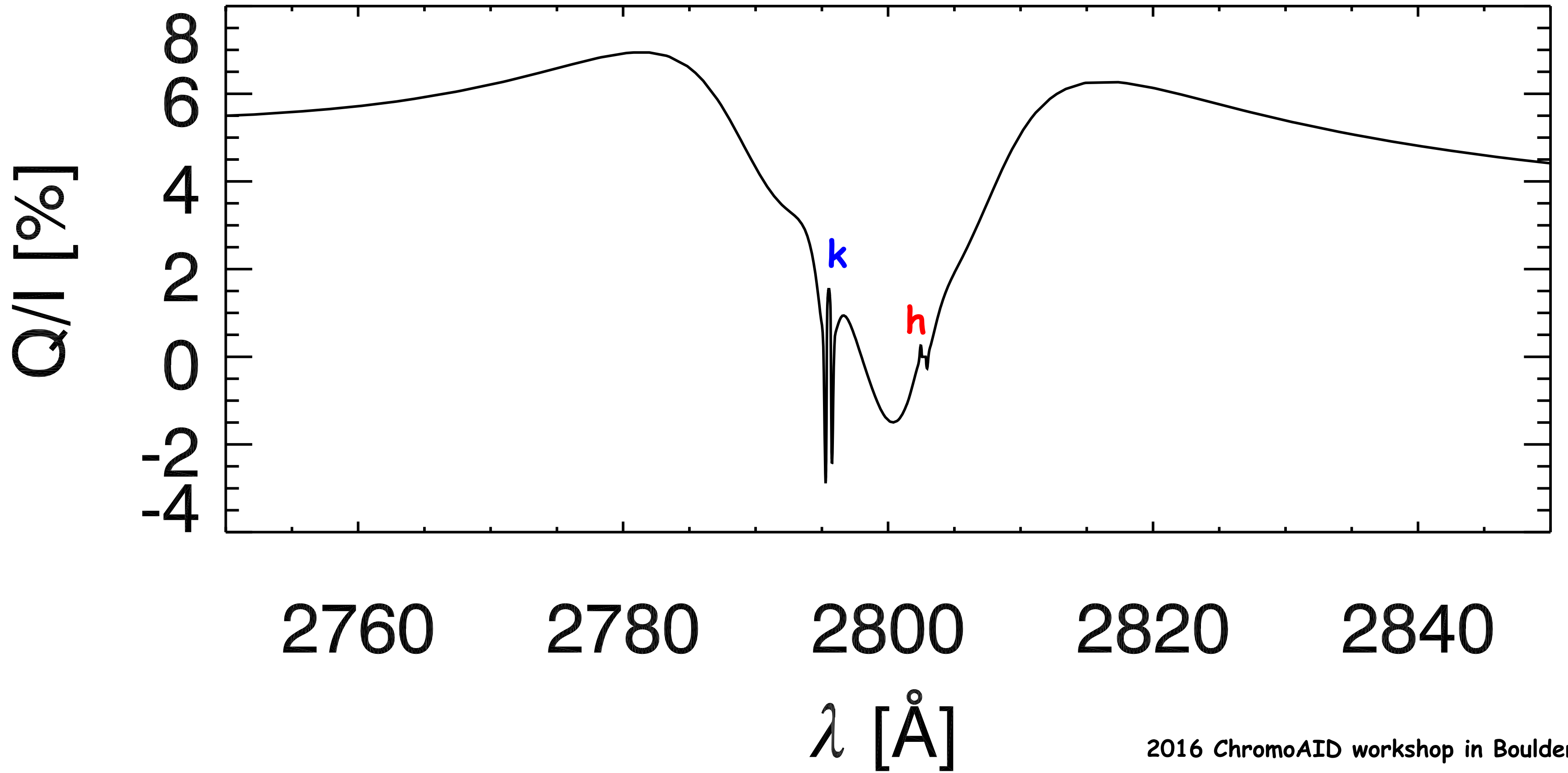
RT synthesis in 1D semi-empirical model

The Q/I of Mg II h & k for mu=0.1



(With PRD + J-state interference)





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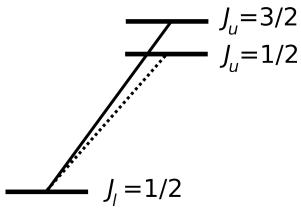

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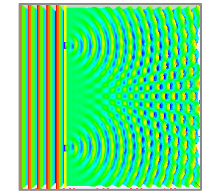
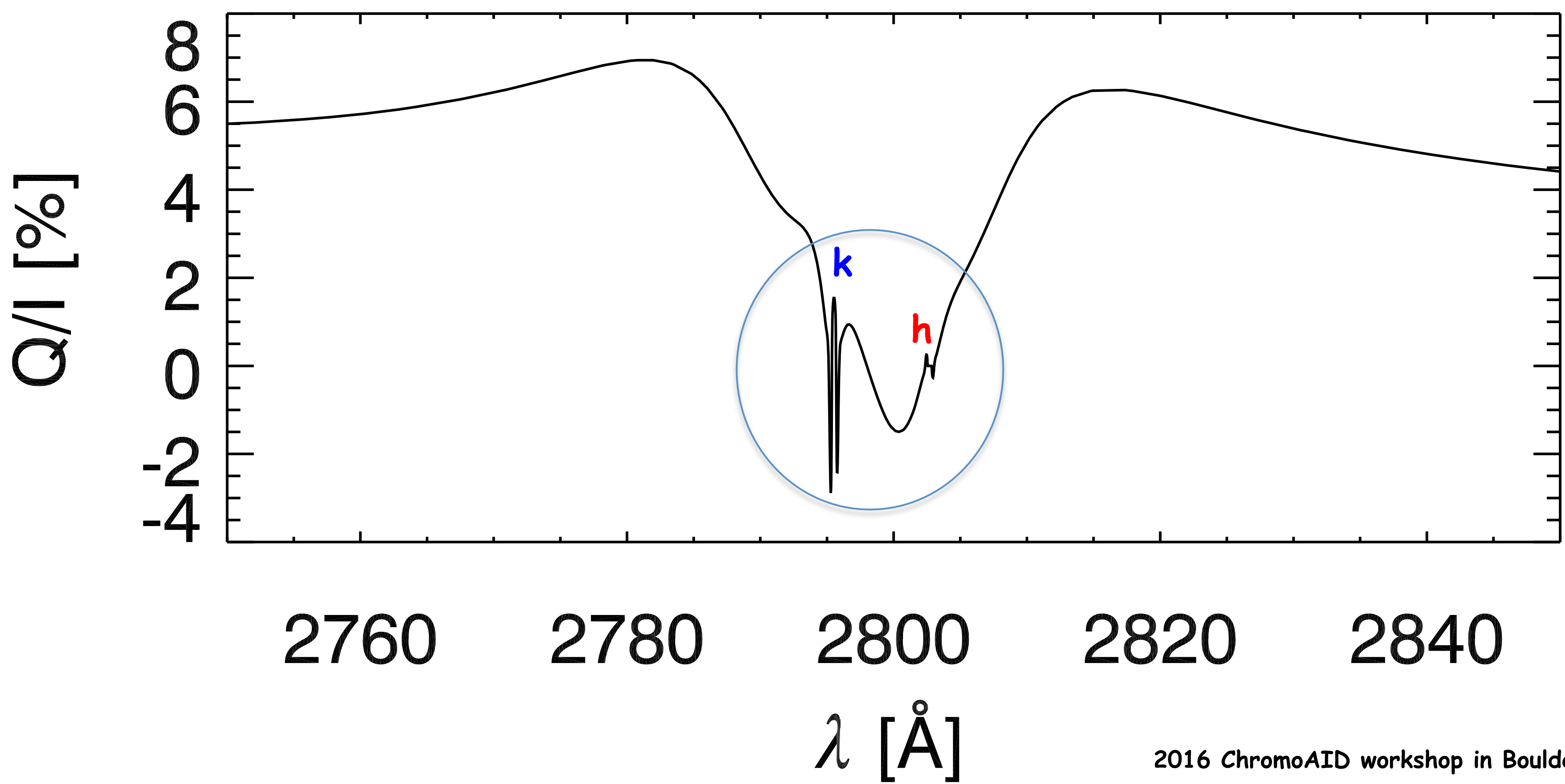
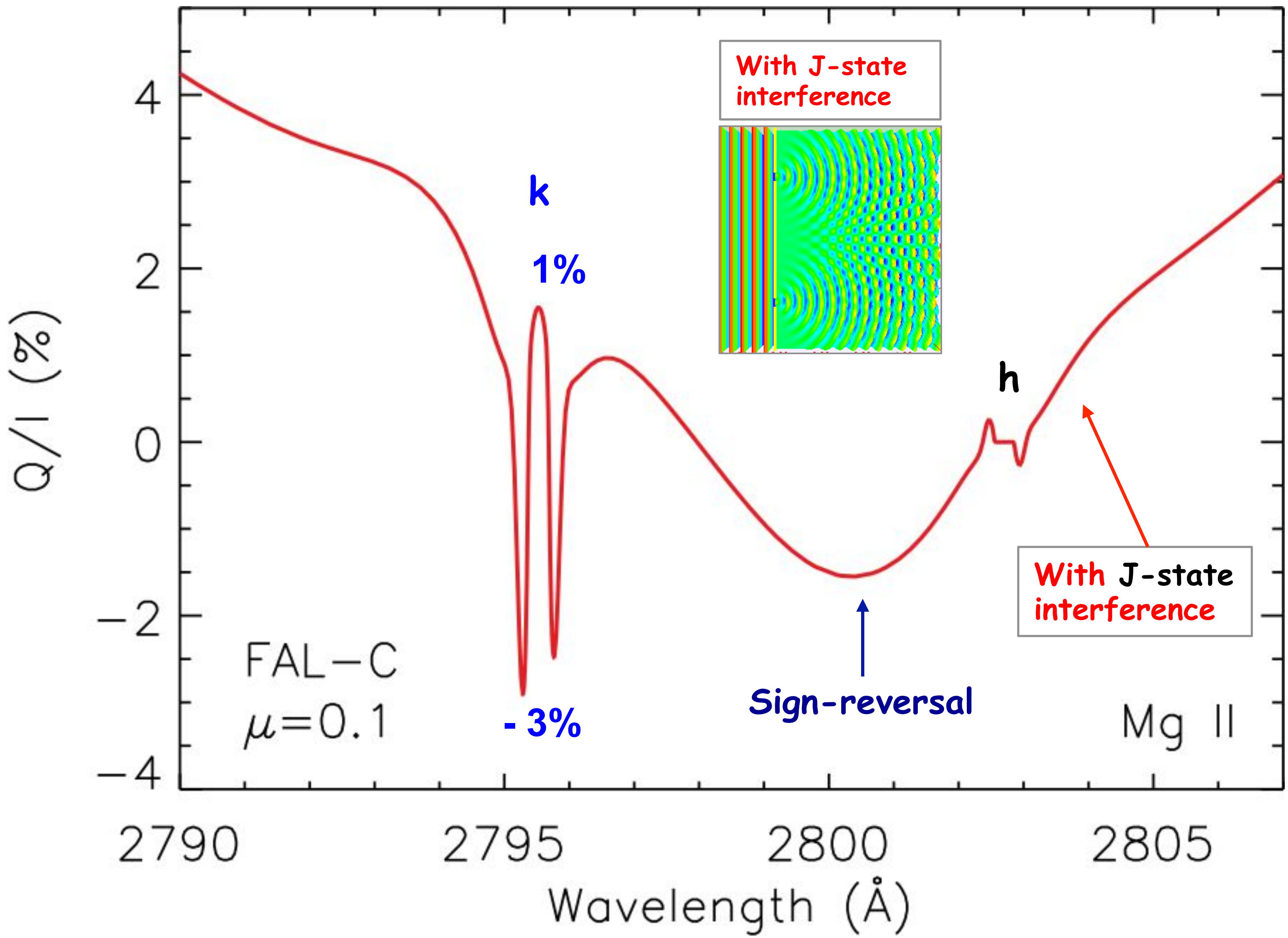




The calculated Q/I signals in the CORE of the Mg II Lines



Belluzzi & Trujillo Bueno (2012; ApJ)

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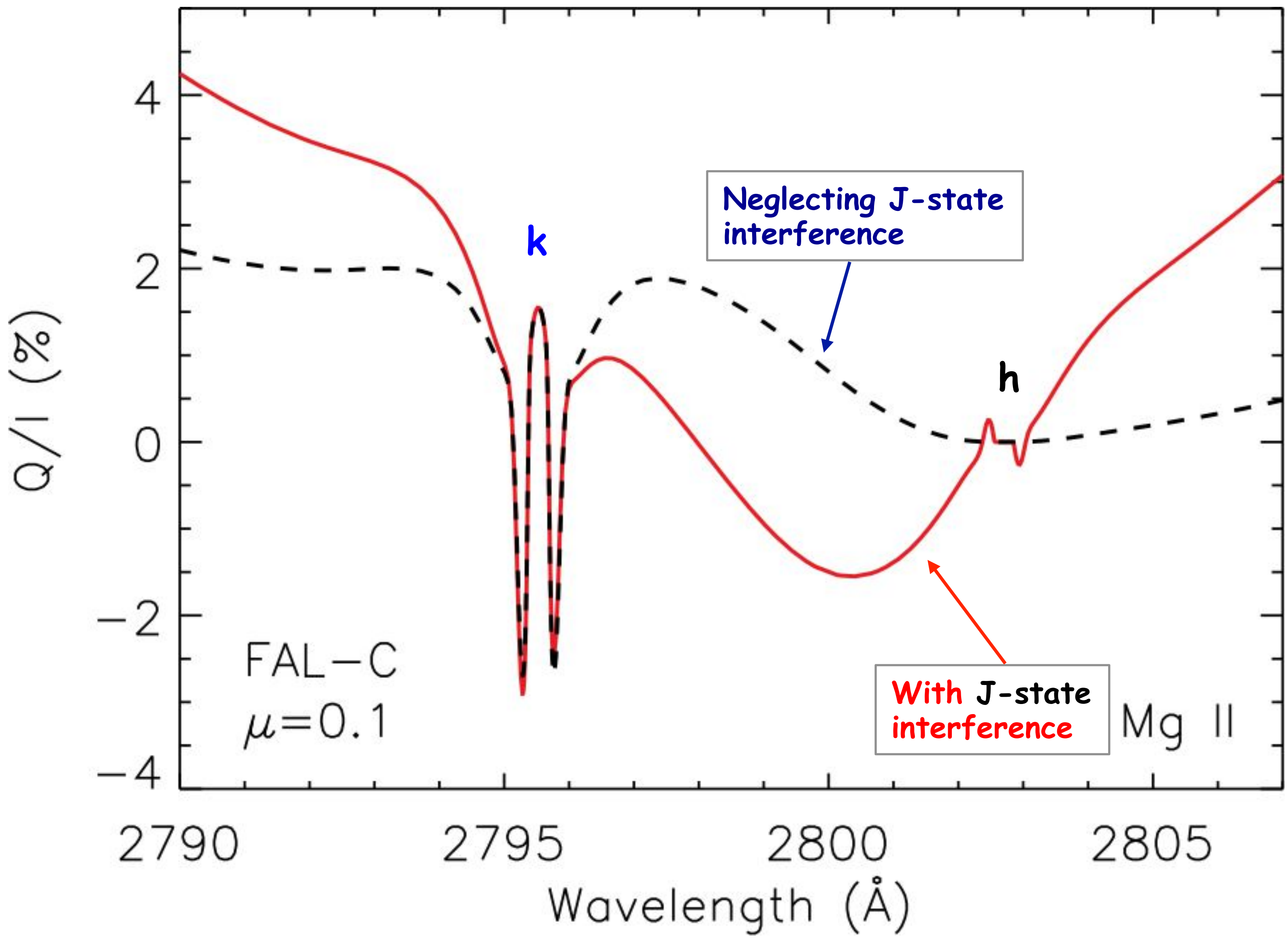
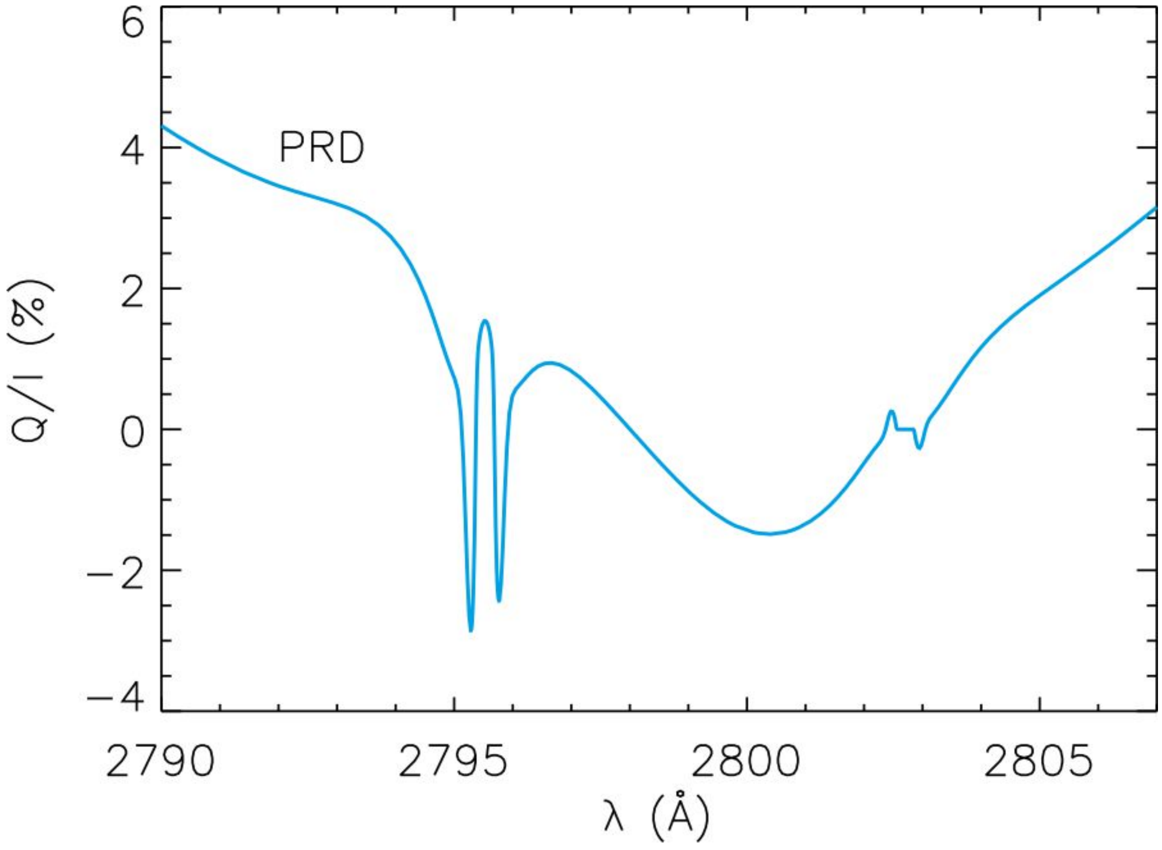


Belluzzi & Trujillo Bueno (2012; ApJ)

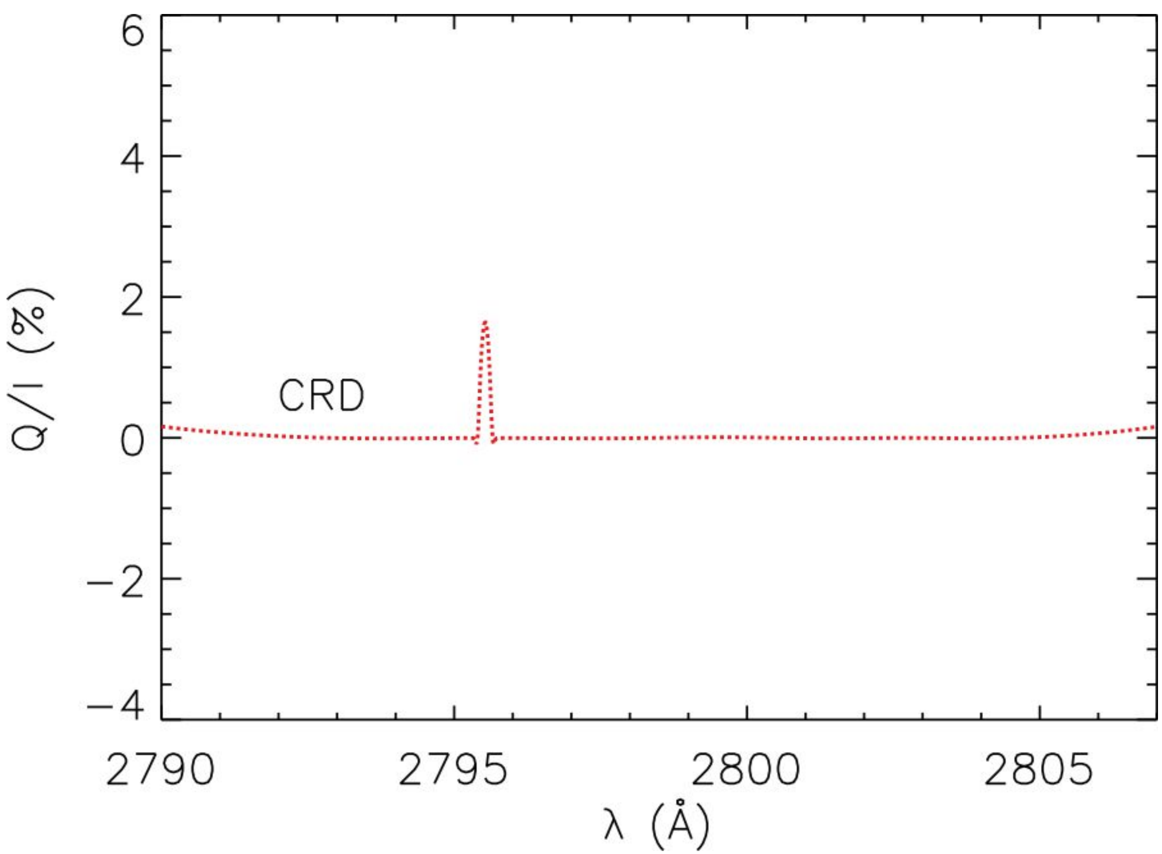
The Q/I of Mg II h & k for mu=0.1

(PRD)



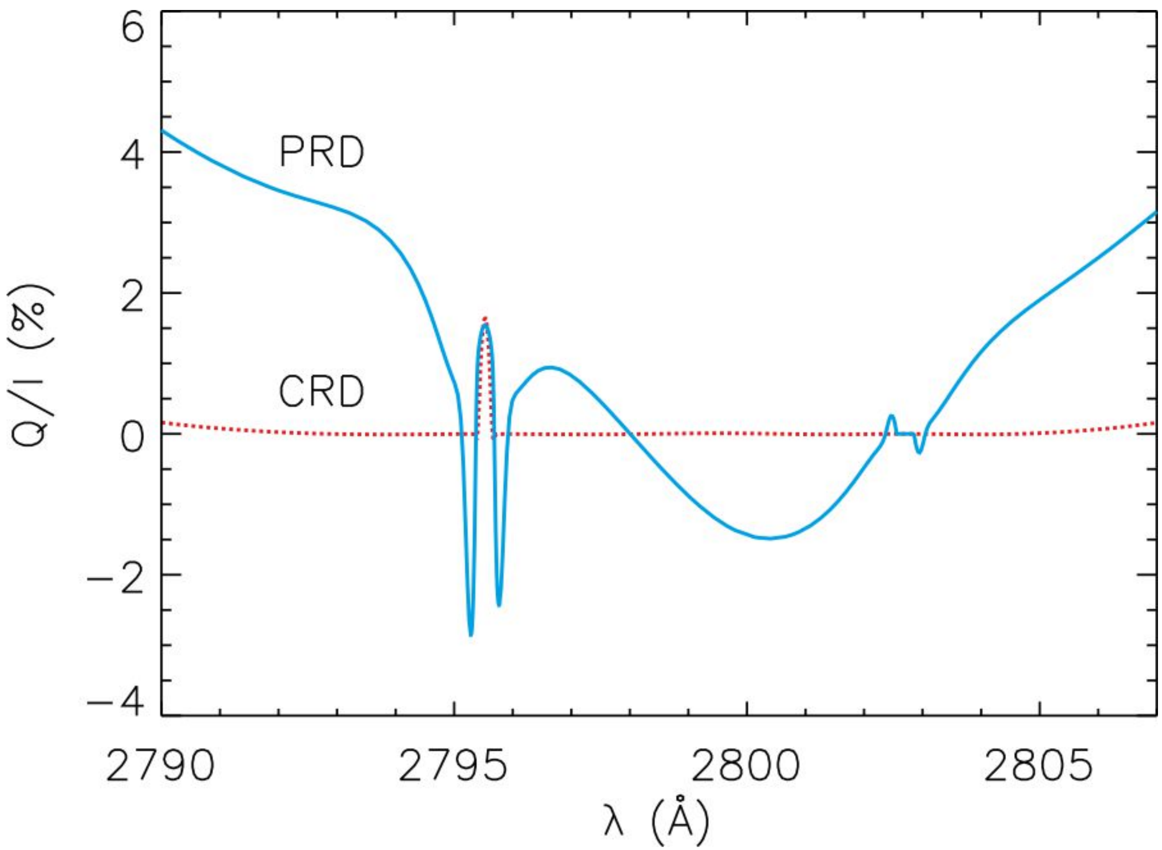
The Q/I of Mg II h & k for mu=0.1

(CRD)



The Q/I of Mg II h & k for mu=0.1

(PRD vs. CRD)



How are the line-center scattering polarization signals of Ly-alpha and Mg II k in a 3D MHD model ?

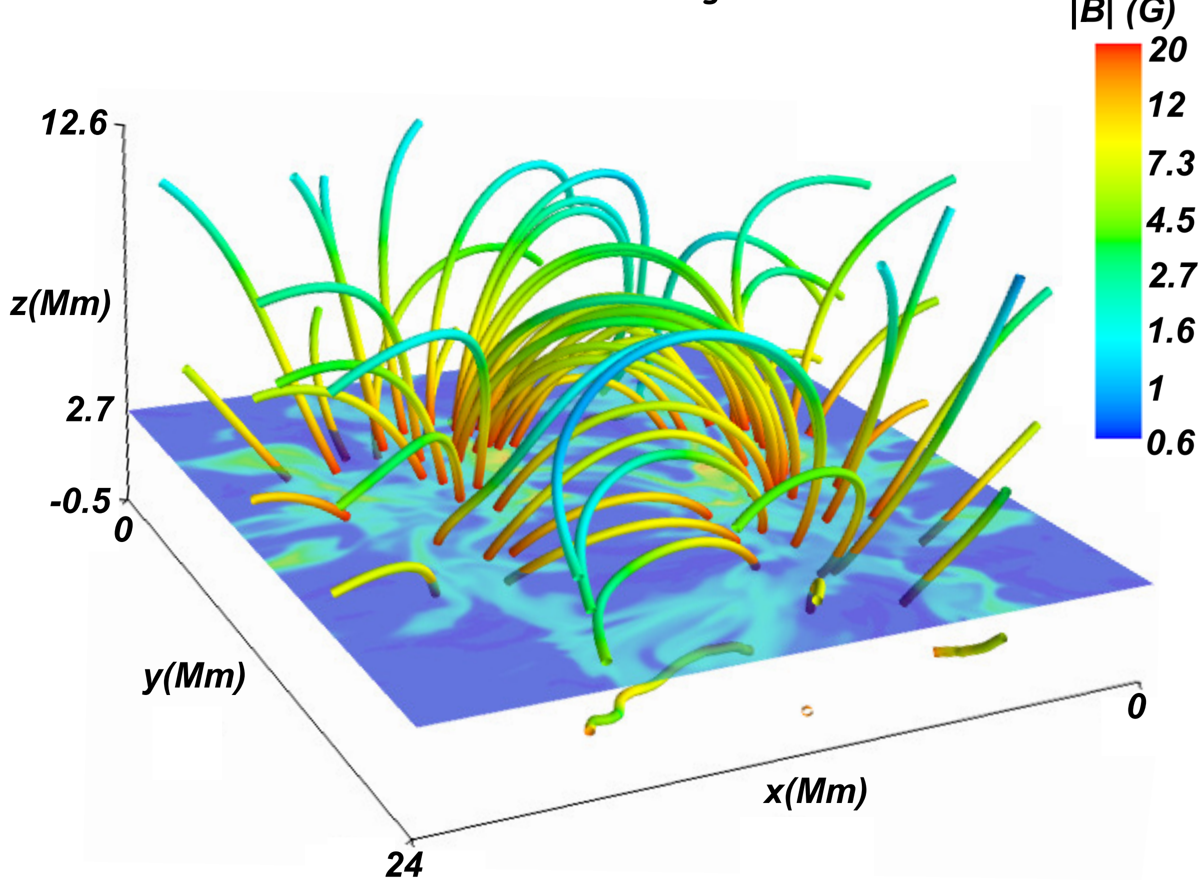
3D model of an enhanced network region, 24 x 24 x 17 Mm (see Carlsson et al. 2015).

Resulting from a MHD simulation with the bifrost code (Gudiksen et al. 2011).

State of the art MHD simulation with non-equilibrium hydrogen ionization.

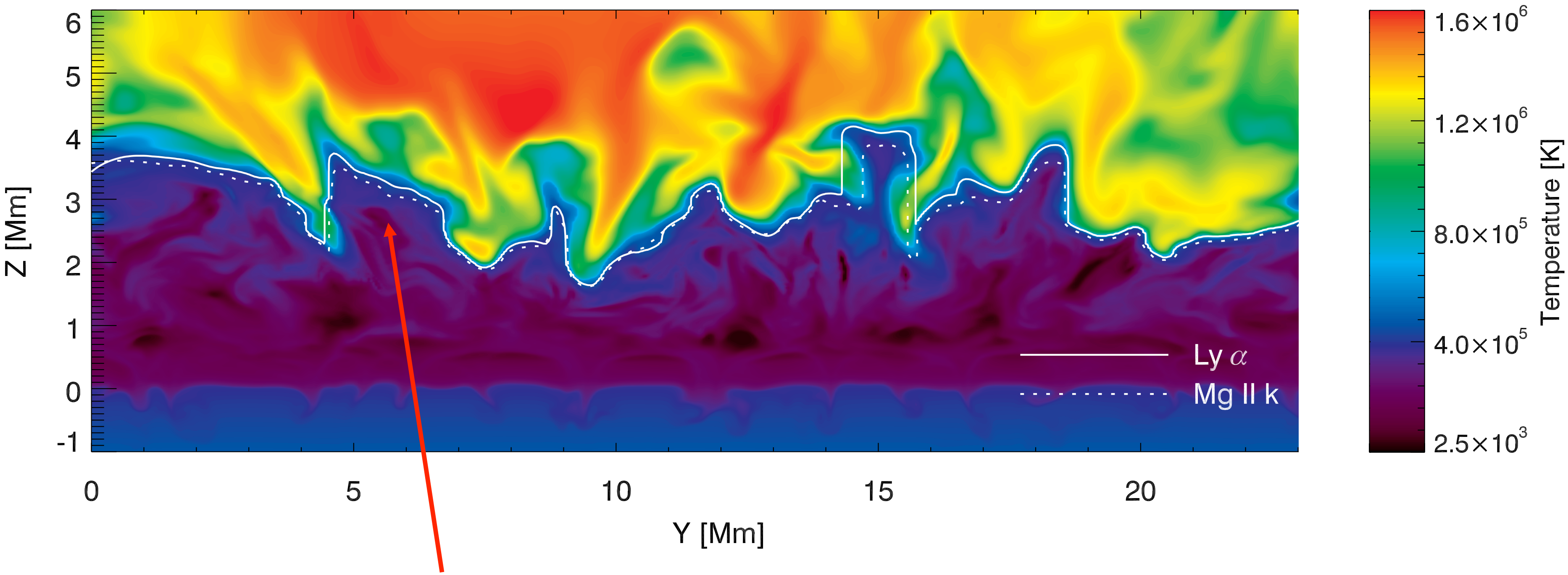
3D radiative transfer code PORTA (see Stepan & Trujillo Bueno 2013) for modeling the spectral line intensity and polarization

Visualization of the model's magnetic field lines



In this MHD model the magnetic field has a predominantly bipolar structure

The 3D world

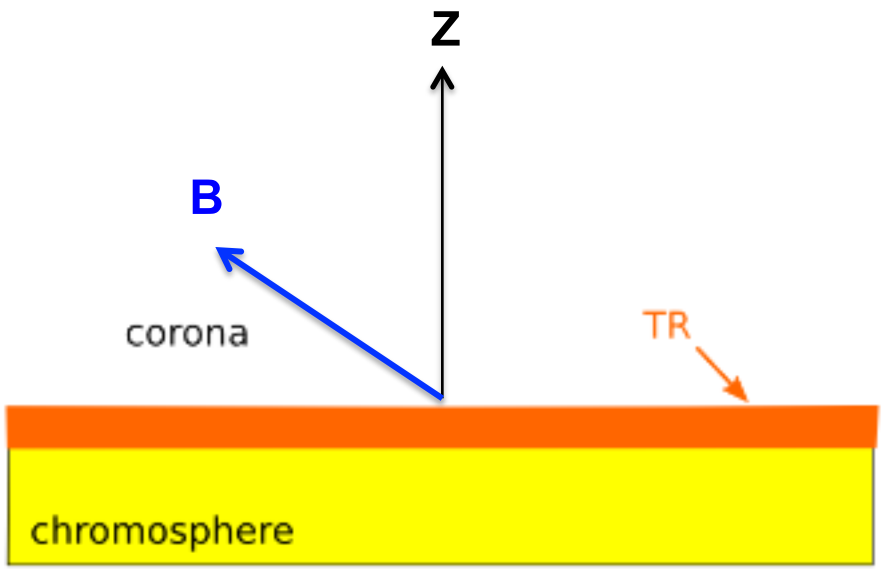


Atmospheric heights where the line-center optical depth along the LOS is unity

The mean magnetic field strength is <B> ~ 15 gauss at the corrugated boundary that delineates the Transition Region

1D

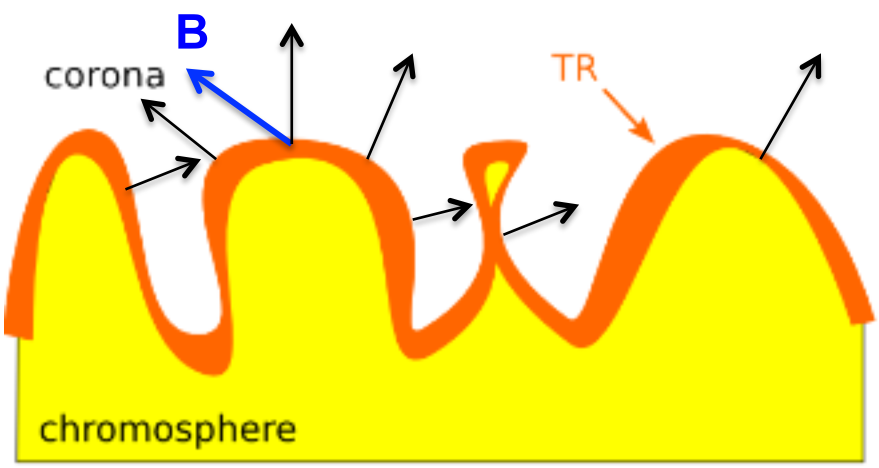
B breaks the symmetry



1D plane-parallel model

3D

Symmetry breaking always



3D model

For resonance lines like Ly-alpha:

$$\frac{\mathrm{d}}{\mathrm{d}\tau}\mathrm{I} = \mathrm{I} - S_{\mathrm{I}}$$

$$\mathrm{d}\tau = -\eta_{\mathrm{I}}\,\mathrm{d}s$$

Monochromatic optical distance along the ray

$$\frac{\mathrm{d}}{\mathrm{d}\tau}\mathrm{Q} = \mathrm{Q} - S_{\mathrm{Q}}$$

$$\frac{\mathrm{d}}{\mathrm{d}\tau}\mathrm{U} = \mathrm{U} - S_{\mathrm{U}}$$

In 3D the line contribution to the source function components:

S_I^{line} ~ S_0^0

$$S_Q^{line} = w_{J_u J_l}^{(2)} \Big\{ \frac{3}{2\sqrt{2}}(\mu^2 - 1) S_0^2 - \sqrt{3}\mu\sqrt{1-\mu^2}(\cos\chi \tilde{S}_1^2 - \sin\chi \hat{S}_1^2)$$

$$- \frac{\sqrt{3}}{2}(1+\mu^2)(\cos 2\chi\, \tilde{S}_2^2 - \sin 2\chi\, \hat{S}_2^2) \Big\}$$

Real part

Imaginary part

$$S_U^{line} = w_{J_u J_l}^{(2)} \sqrt{3} \Big\{ \sqrt{1-\mu^2}(\sin\chi \tilde{S}_1^2 + \cos\chi \hat{S}_1^2)$$

$$+ \mu(\sin 2\chi\, \tilde{S}_2^2 + \cos 2\chi\, \hat{S}_2^2) \Big\}$$

Expressions for scattering polarization and the Hanle effect in 3D:

$$S^0_0 = (1-\epsilon)\, J^0_0 + \epsilon\, B_\nu$$

This is the MAGNETIC kernel !

$$[1+\delta(1-\epsilon)] \begin{pmatrix} S^2_0 \\ \tilde{S}^2_1 \\ \hat{S}^2_1 \\ \tilde{S}^2_2 \\ \hat{S}^2_2 \end{pmatrix} = (1-\epsilon)\, w^{(2)}_{J_u J_l} \begin{pmatrix} \bar{J}^2_0 \\ \tilde{J}^2_1 \\ -\hat{J}^2_1 \\ \tilde{J}^2_2 \\ -\hat{J}^2_2 \end{pmatrix} -(1-\epsilon)\Gamma_u \begin{pmatrix} 0 & M_{12} & M_{13} & M_{14} & M_{15} \\ M_{21} & 0 & M_{23} & M_{24} & M_{25} \\ M_{31} & M_{32} & 0 & M_{34} & M_{35} \\ M_{41} & M_{42} & M_{43} & 0 & M_{45} \\ M_{51} & M_{52} & M_{53} & M_{54} & 0 \end{pmatrix} \begin{pmatrix} S^2_0 \\ \tilde{S}^2_1 \\ \hat{S}^2_1 \\ \tilde{S}^2_2 \\ \hat{S}^2_2 \end{pmatrix}$$

Population imbalances and coherence

$\Gamma_u = 8.79 \times 10^6 g_{J_u} B/A_{ul}$ (with B in gauss and A_{ul} in s^{-1})

These are the radiation field tensors

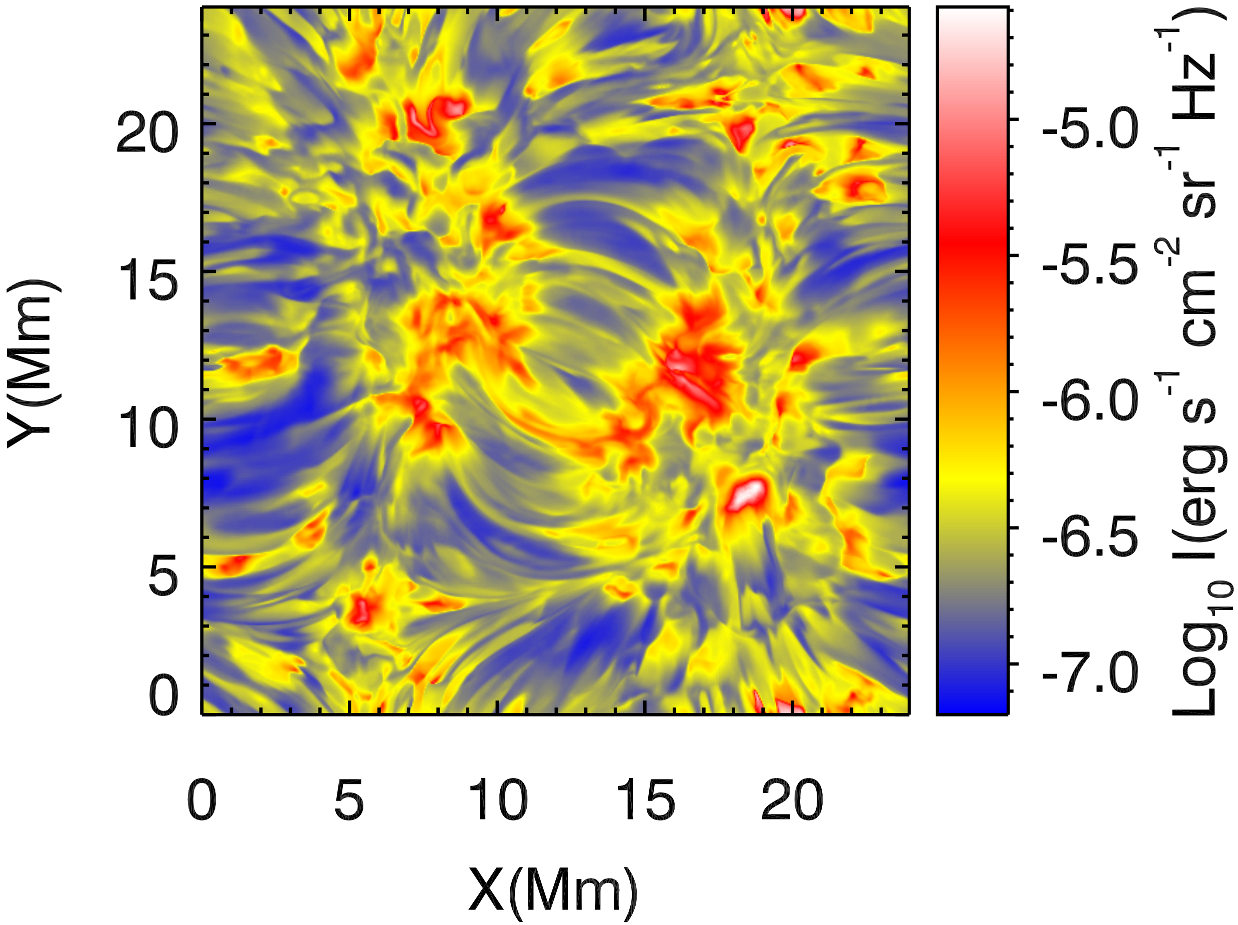
$$\bar{J}^2_0 = \int \mathrm{d}x \oint \phi_x \frac{\mathrm{d}\vec{\Omega}}{4\pi} \frac{1}{2\sqrt{2}} \left[(3\mu^2-1) I_{x\vec{\Omega}} + 3(\mu^2-1) Q_{x\vec{\Omega}}\right] ,$$

$$\bar{J}^2_1 = \int \mathrm{d}x \oint \phi_x \frac{\mathrm{d}\vec{\Omega}}{4\pi} \frac{\sqrt{3}}{2} e^{i\chi} \sqrt{1-\mu^2} \left[-\mu \left(I_{x\vec{\Omega}} + Q_{x\vec{\Omega}}\right) - iU_{x\vec{\Omega}}\right] ,$$

$$\bar{J}^2_2 = \int \mathrm{d}x \oint \phi_x \frac{\mathrm{d}\vec{\Omega}}{4\pi} \frac{\sqrt{3}}{2} e^{2i\chi} \left[\frac{1}{2}(1-\mu^2) I_{x\vec{\Omega}} - \frac{1}{2}(1+\mu^2) Q_{x\vec{\Omega}} - i\mu U_{x\vec{\Omega}}\right] ,$$

Mg II k

Line center intensity (upper chromosphere)

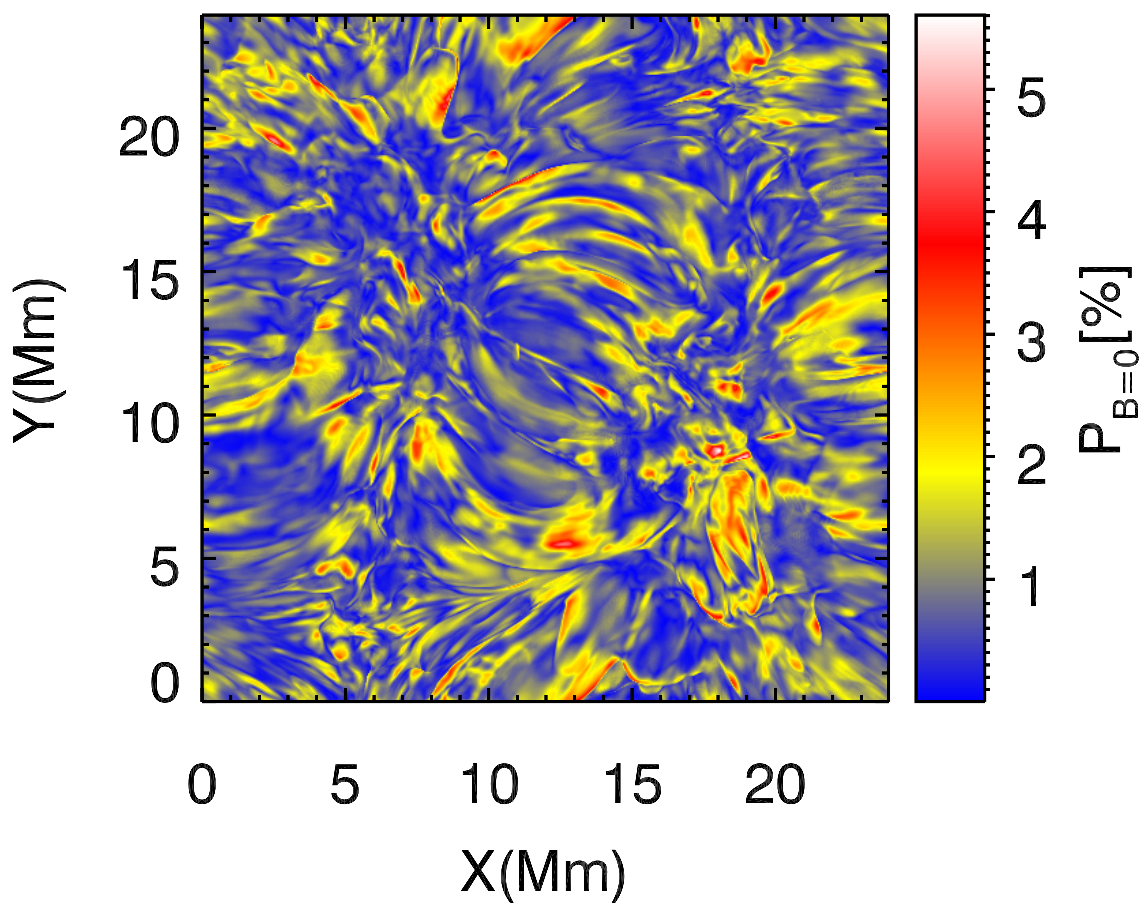


del Pino Alemán et al. (2016; in preparation)

The TOTAL fractional linear polarization for a disk-center observation

B = 0 gauss

$$P = \sqrt{Q^2 + U^2} \;/\; I$$



Mg II k

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The TOTAL fractional linear polarization for a disk-center observation

B = model's B

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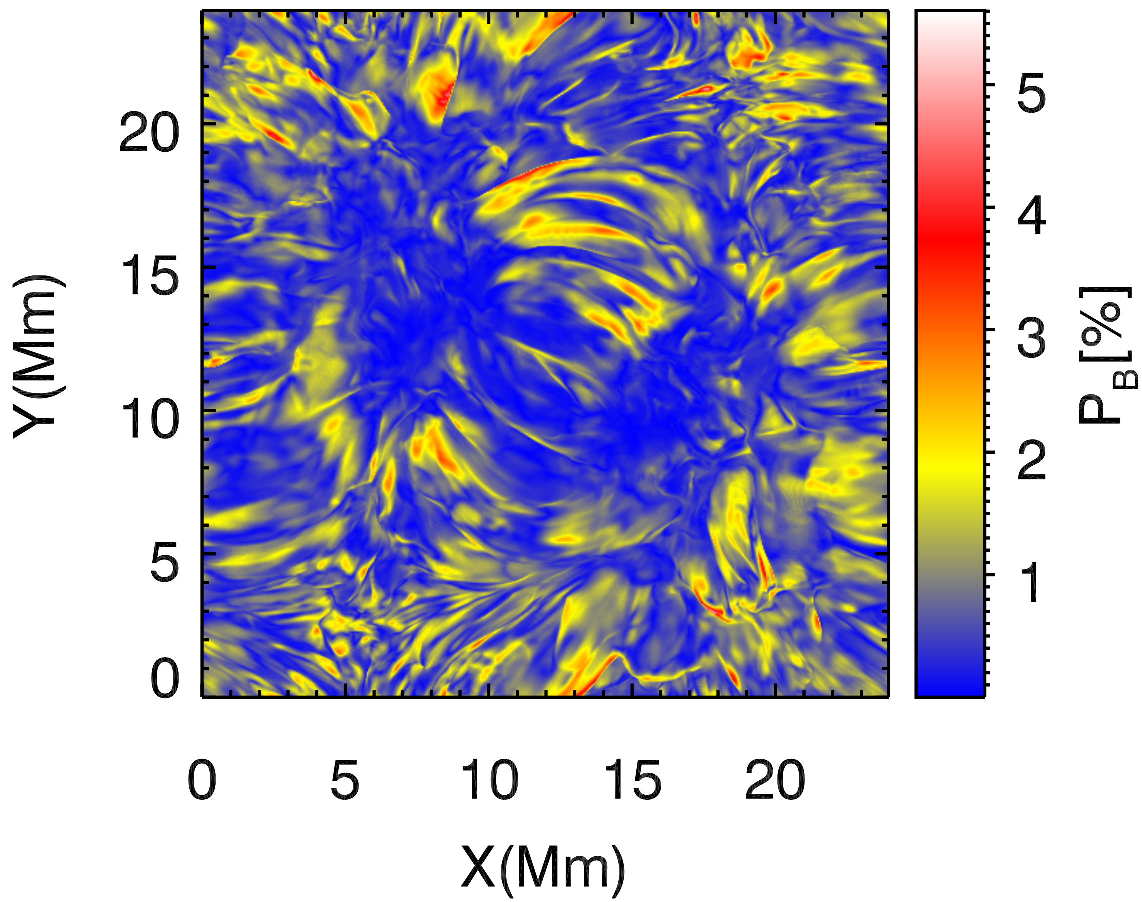


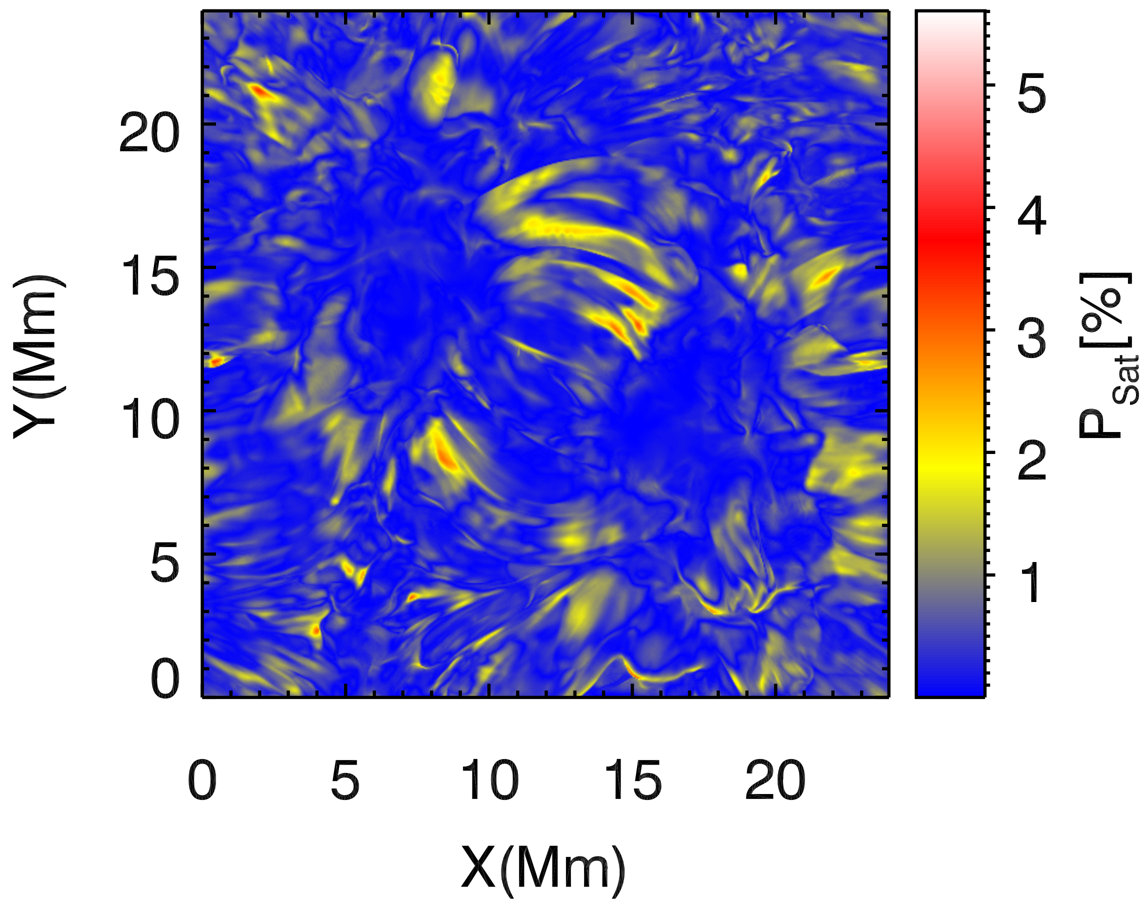
Mg II k

del Pino Alemán et al. (2016; in preparation)

The TOTAL fractional linear polarization for a disk-center observation

B > 100 gauss

$$P = \sqrt{Q^2 + U^2} \; / \; I$$



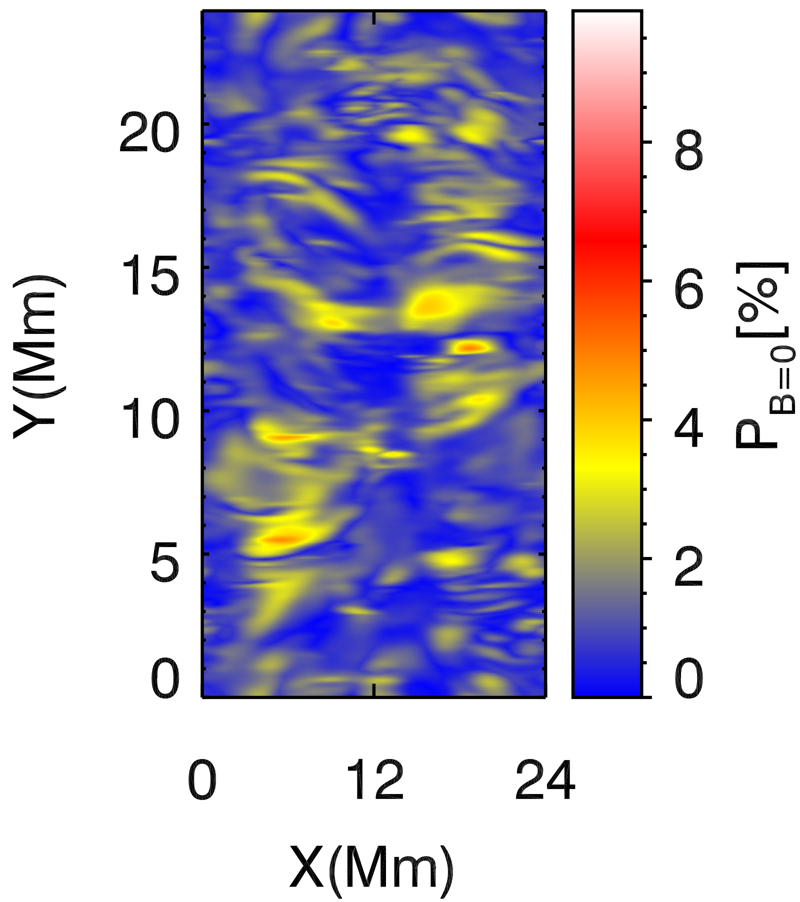
Mg II k

del Pino Alemán et al. (2016; in preparation)

The TOTAL fractional linear polarization for mu=0.5

B = 0 gauss

$$P = \sqrt{Q^2 + U^2} \; / \; I$$



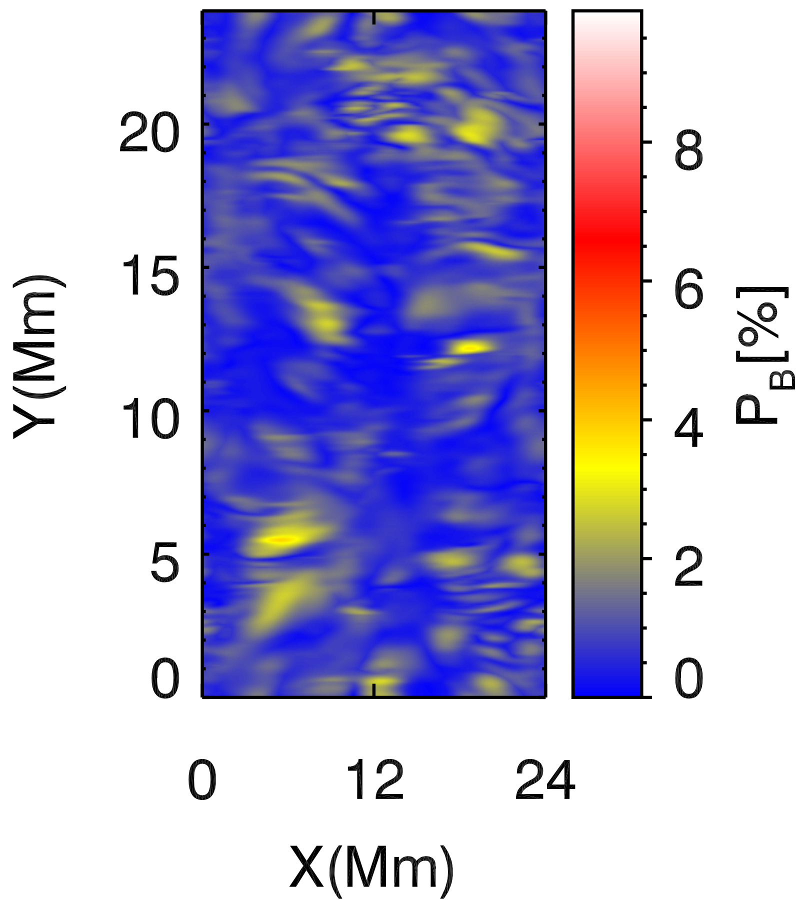
Mg II k

del Pino Alemán et al. (2016; in preparation)

The TOTAL fractional linear polarization for mu=0.5

B = model's B

$$P = \sqrt{Q^2 + U^2} \, / \, I$$

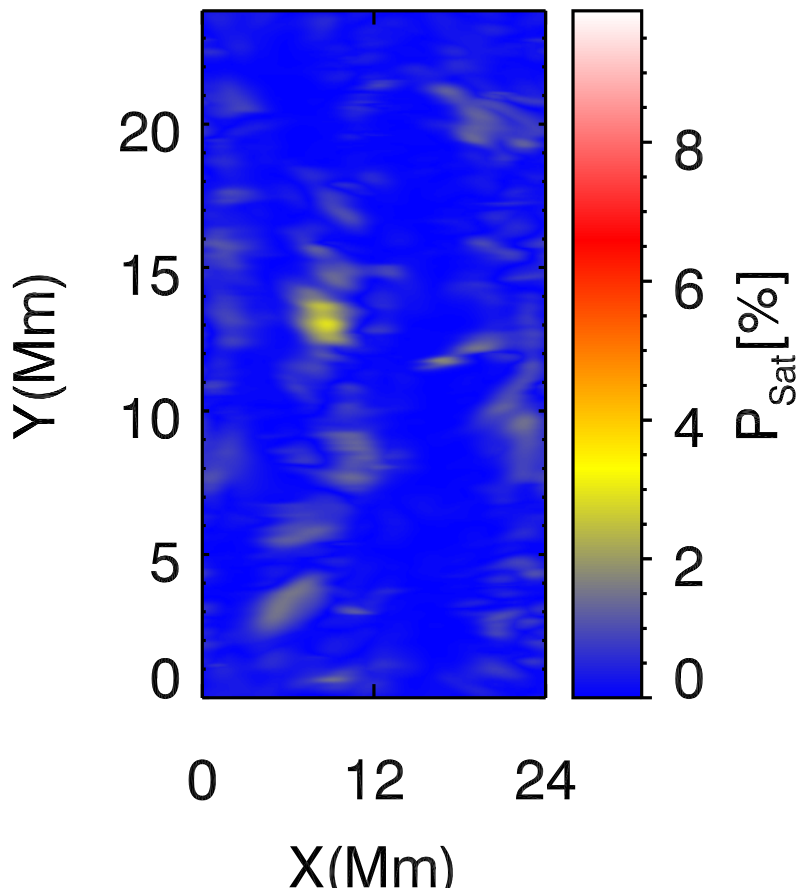


Mg II k

The TOTAL fractional linear polarization for mu=0.5

B > 100 gauss

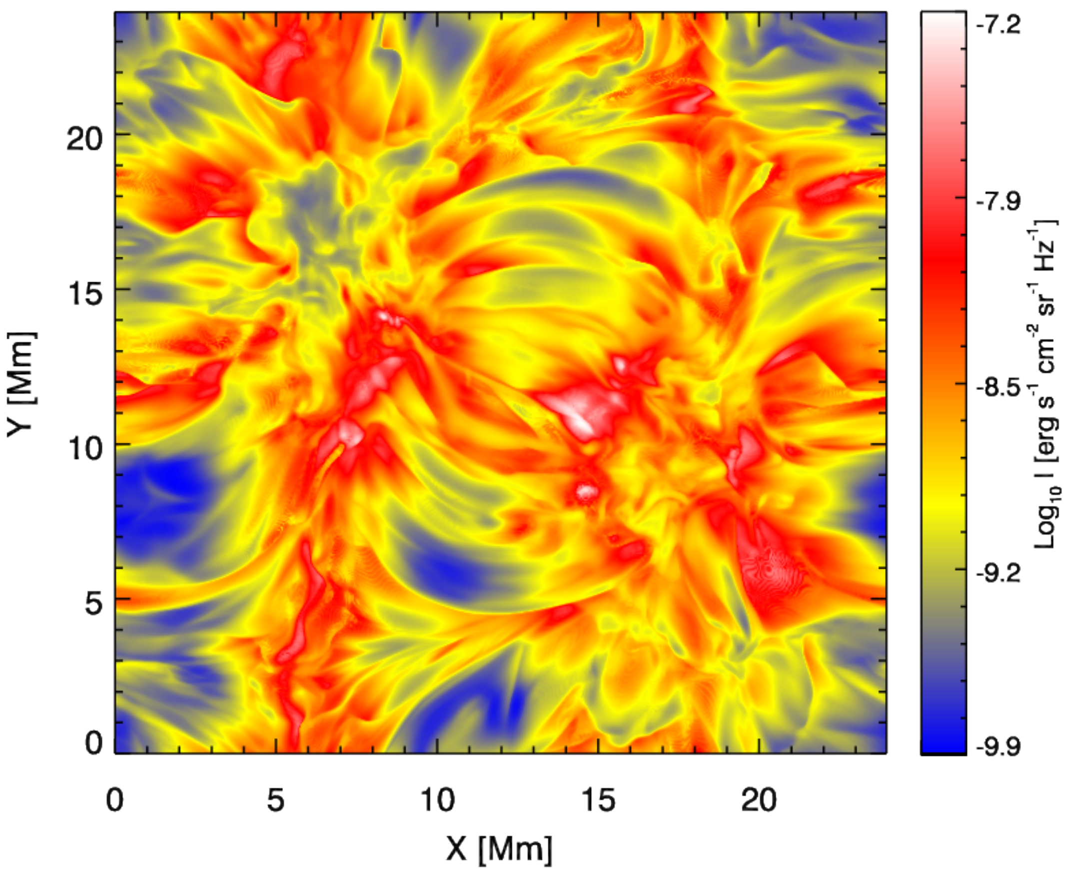
$$P = \sqrt{Q^2 + U^2} \; / \; I$$



Mg II k

del Pino Alemán et al. (2016; in preparation)

Lyman-alpha

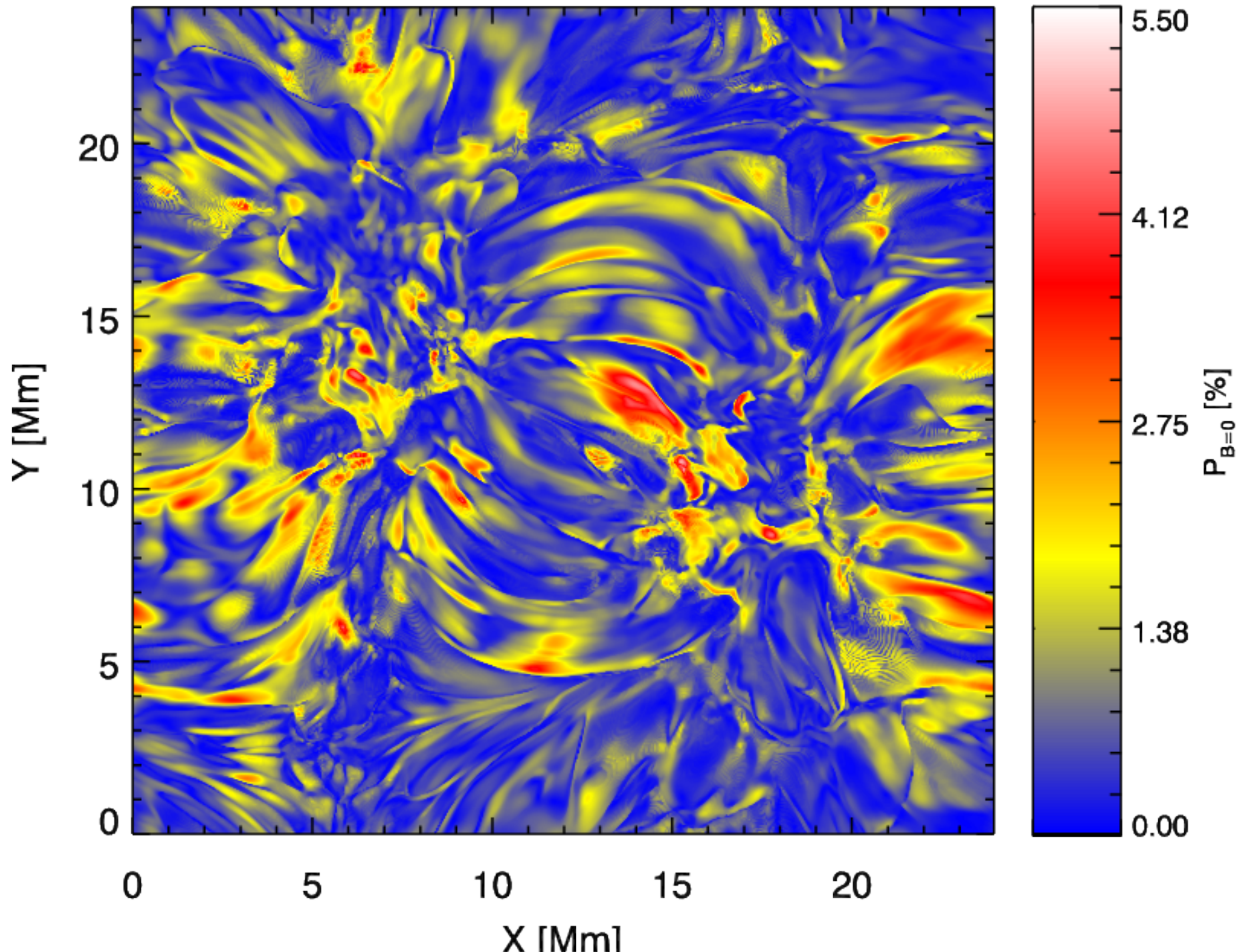


See Stepan, Trujillo Bueno, Leenaarts, Carlsson (2015; ApJ)

The TOTAL fractional linear polarization for a disk-center observation

$$P = \sqrt{Q^2 + U^2} \;/\; I$$

B = 0 gauss



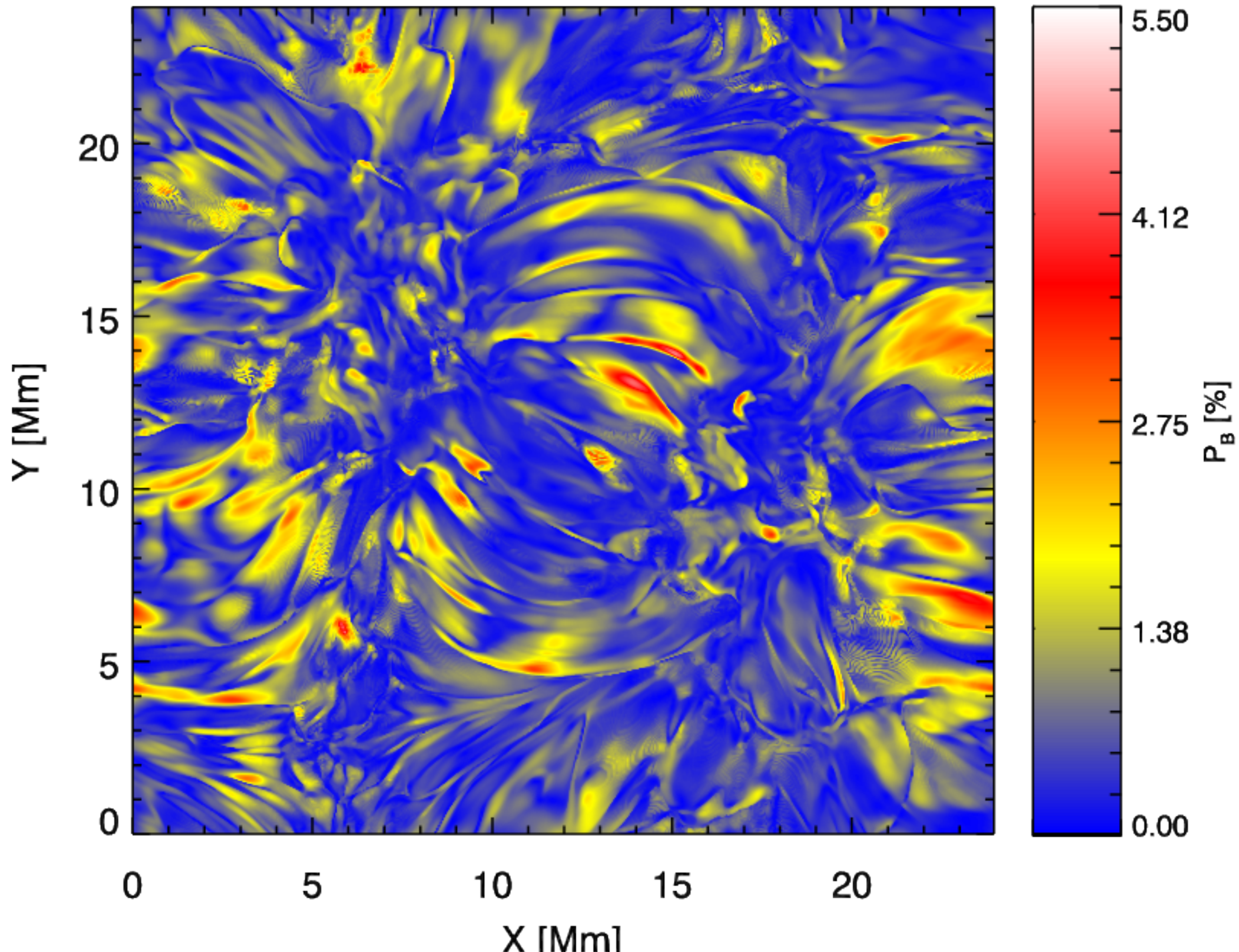
Ly-alpha

See Stepan, Trujillo Bueno, Leenaarts, Carlsson (2015; ApJ)

The TOTAL fractional linear polarization for a disk-center observation

$$P = \sqrt{Q^2 + U^2} \, / \, I$$

B = model's B



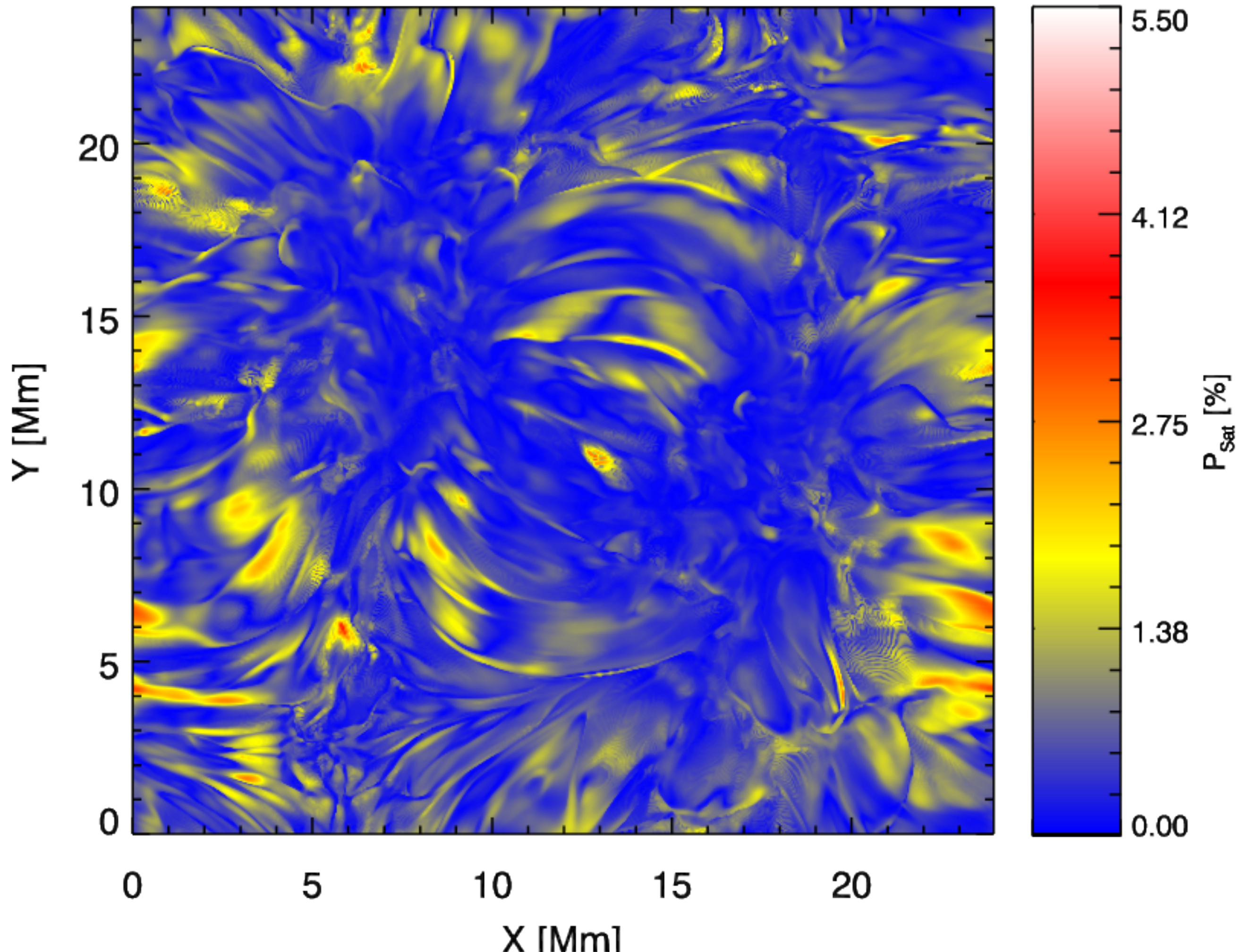
Ly-alpha

See Stepan, Trujillo Bueno, Leenaarts, Carlsson (2015; ApJ)

The TOTAL fractional linear polarization for a disk-center observation

$$P = \sqrt{Q^2 + U^2} \, / \, I$$

B > 250 gauss



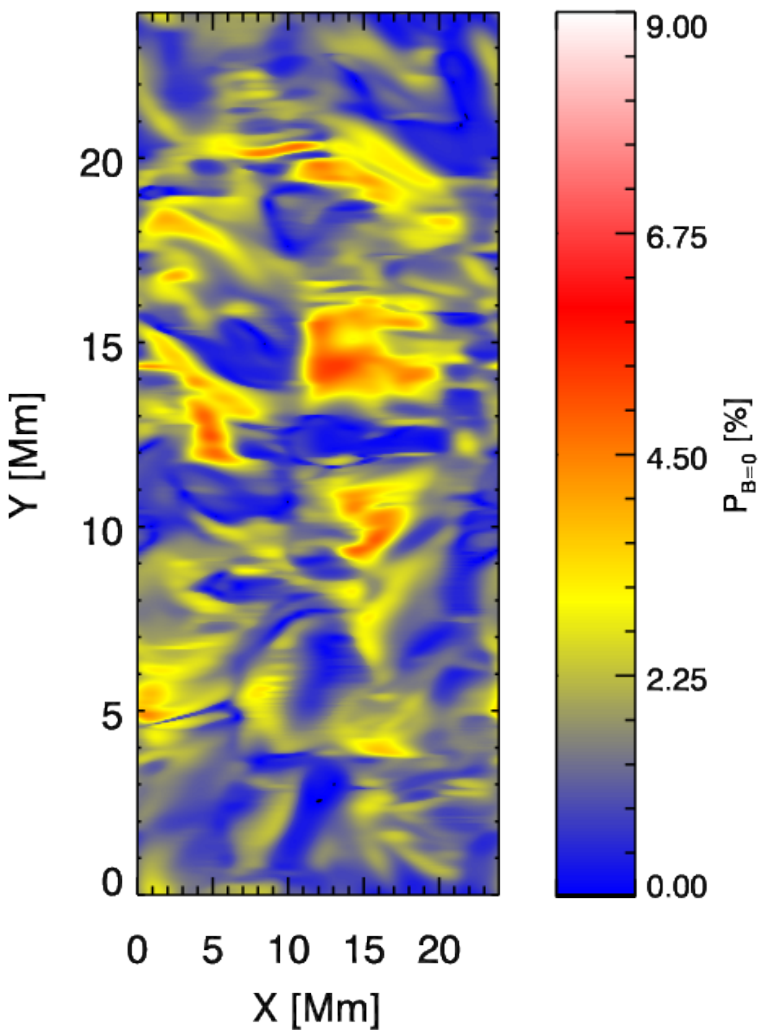
Ly-alpha

See Stepan, Trujillo Bueno, Leenaarts, Carlsson (2015; ApJ)

The TOTAL fractional linear polarization for mu=0.4

$$P = \sqrt{Q^2 + U^2} \; / \; I$$

B = 0 gauss



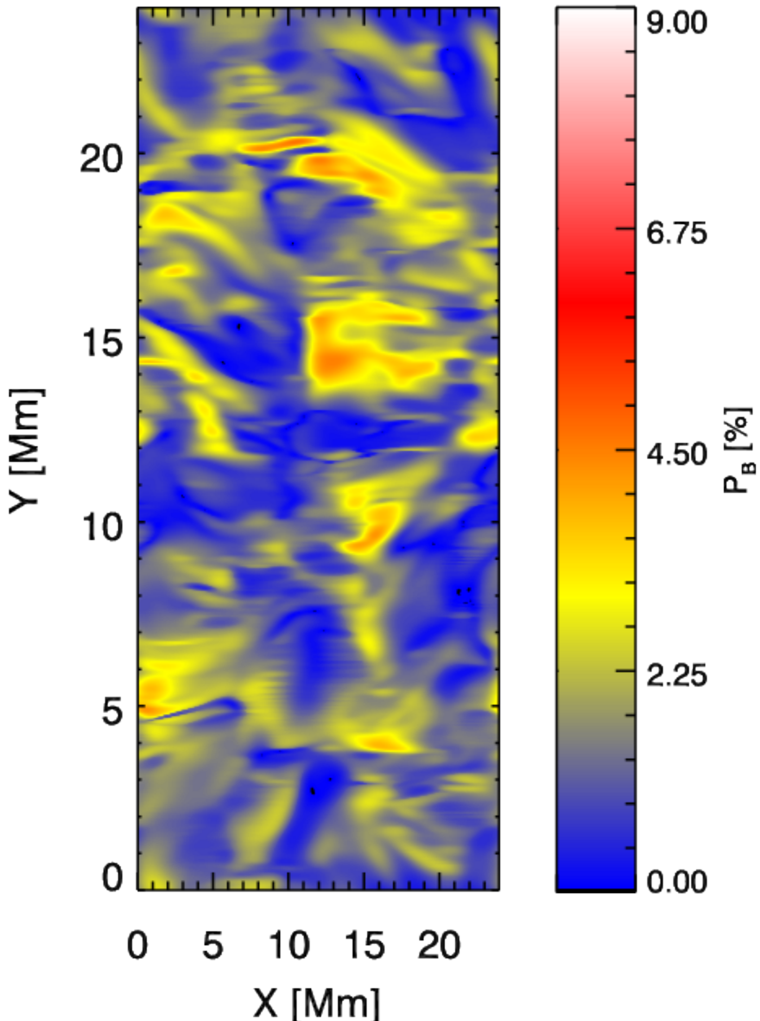
Ly-alpha

See Stepan, Trujillo Bueno, Leenaarts, Carlsson (2015; ApJ)

The TOTAL fractional linear polarization for mu=0.4

$$P = \sqrt{Q^2 + U^2} \; / \; I$$

B = model's B



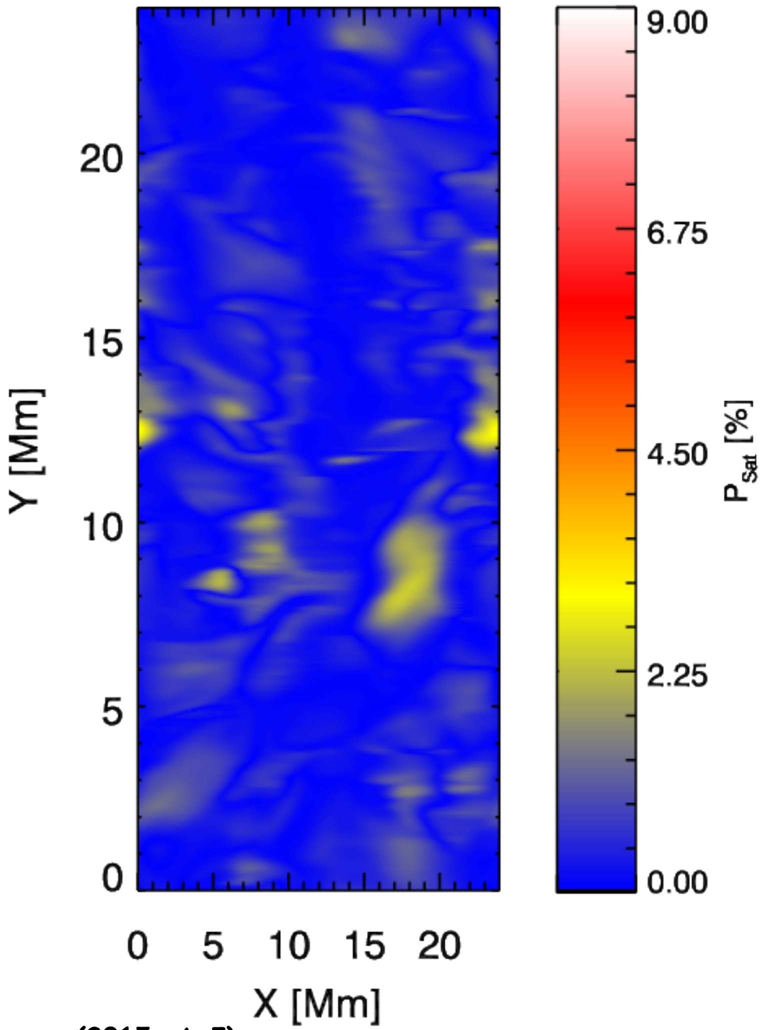
Ly-alpha

See Stepan, Trujillo Bueno, Leenaarts, Carlsson (2015; ApJ)

The TOTAL fractional linear polarization for mu=0.4

$$P = \sqrt{Q^2 + U^2} \;/\; I$$

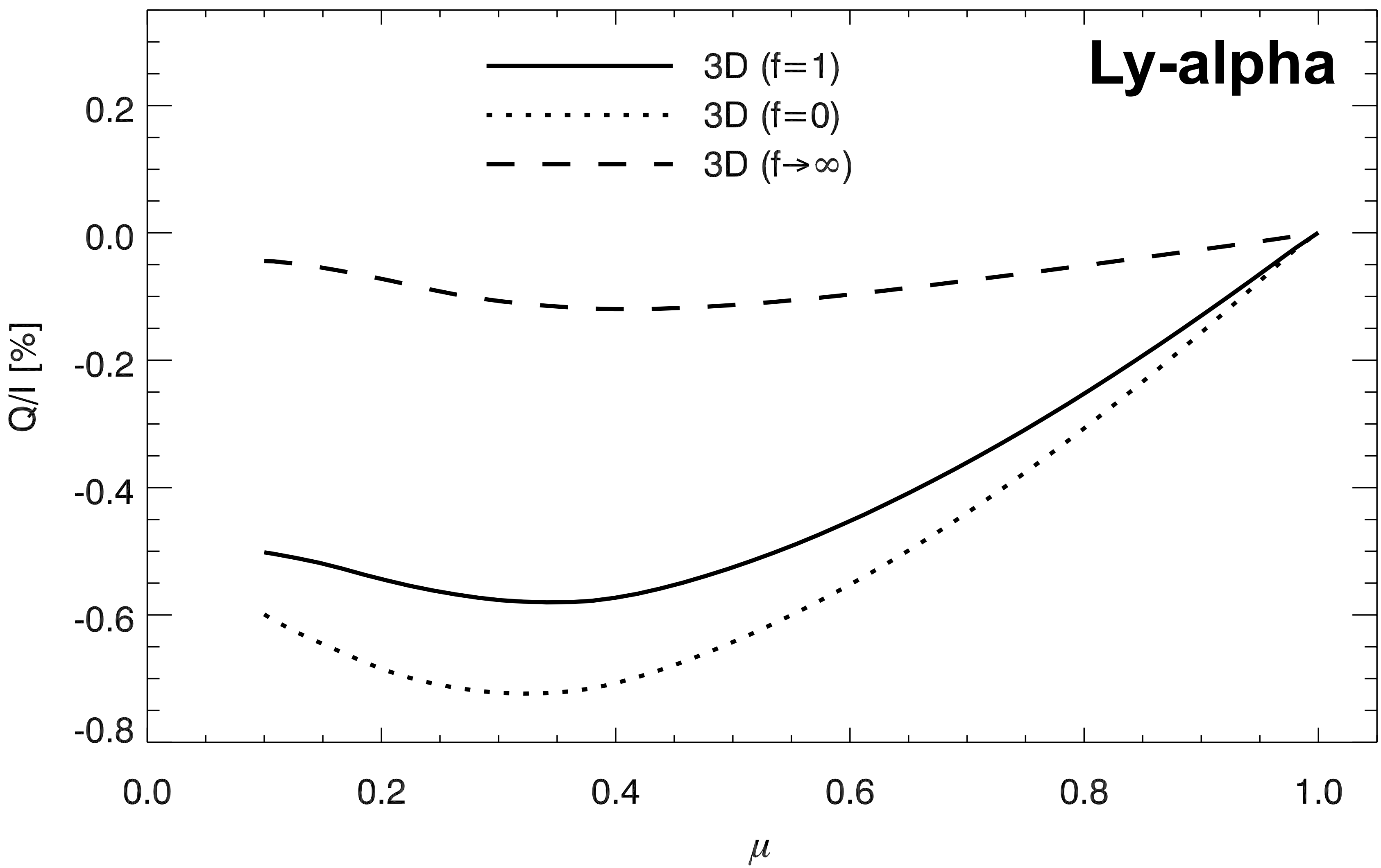
B > 250 gauss



Ly-alpha

See Stepan, Trujillo Bueno, Leenaarts, Carlsson (2015; ApJ)

The spatially-averaged CLV of Q/I calculated in the 3D model



See Stepan, Trujillo Bueno, Leenaarts, Carlsson (2015; ApJ)

Concluding comments

The scattering polarization in UV resonance lines encodes valuable information on the magnetization and geometrical complexity of the upper chromosphere and transition region.

A promising space-based spectropolarimeter would be one capable of measuring simultaneously a few lines with different magnetic sensitivities:

Ly-alpha + Si III 1206 and Mg II h & k

Dear MHD friends, please, develop:

“Realistic” 3D models with SPICULES !

Centeno et al. (2010; ApJ) modeled spectropolarimetric observations of quiet Sun spicules by exploiting the Hanle and Zeeman effects in the He I 10830 Å triplet and concluded:

“Magnetic fields as strong as 50 G were detected, which could represent a possible lower value of the field strength of organized network spicules”