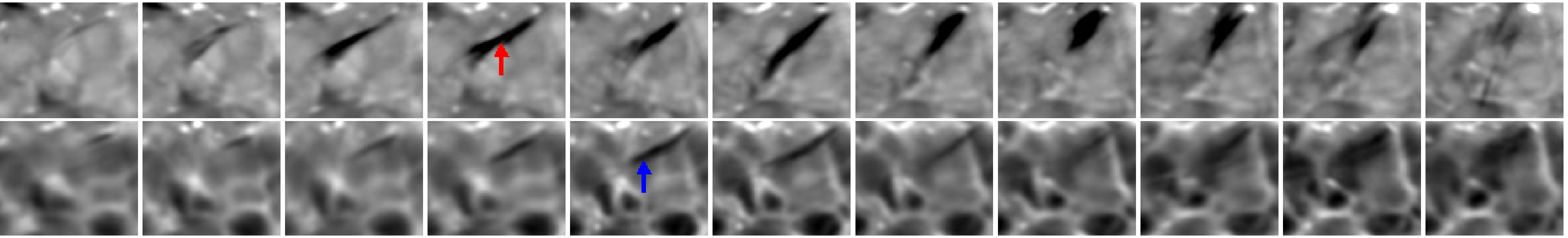

# Spectral Inversion of the Hα and Ca II 8542 Å Lines Observed by SST/CRISP in Chromospheric Jet

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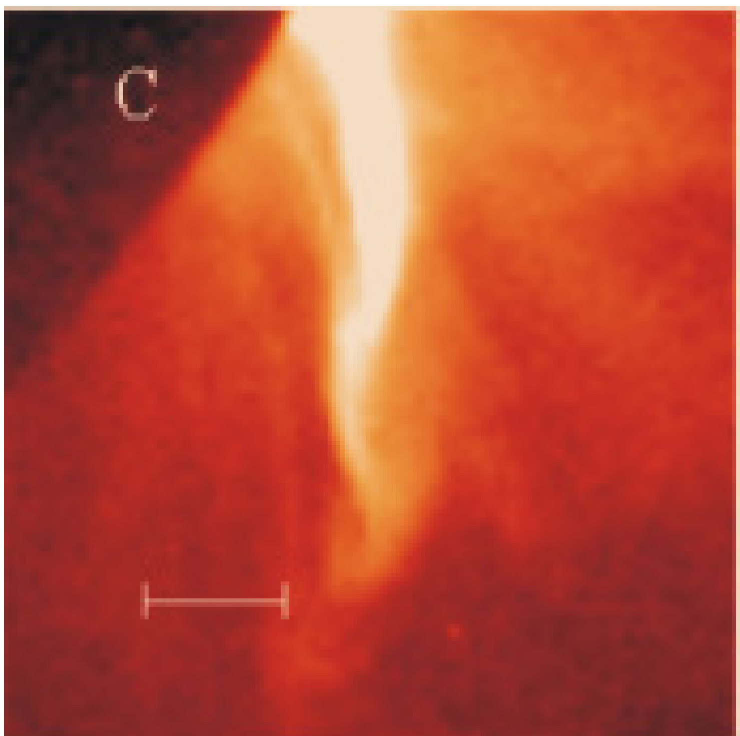
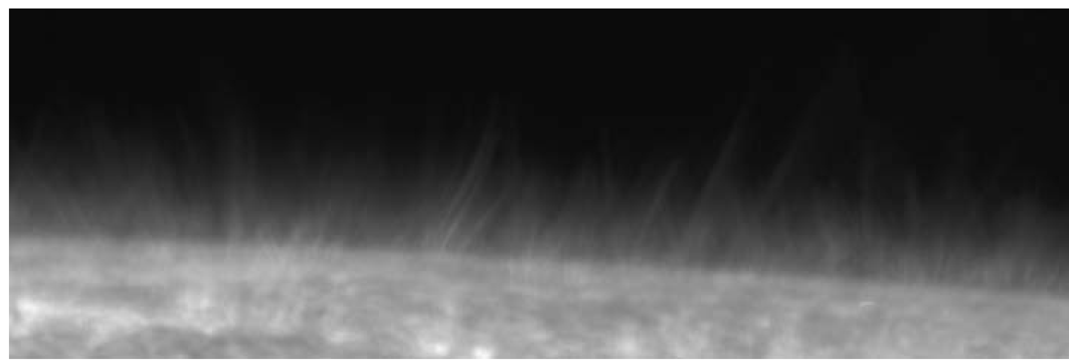
EST Meeting, Bairisch Kölldorf, Austria, 9 - 11 October 2017

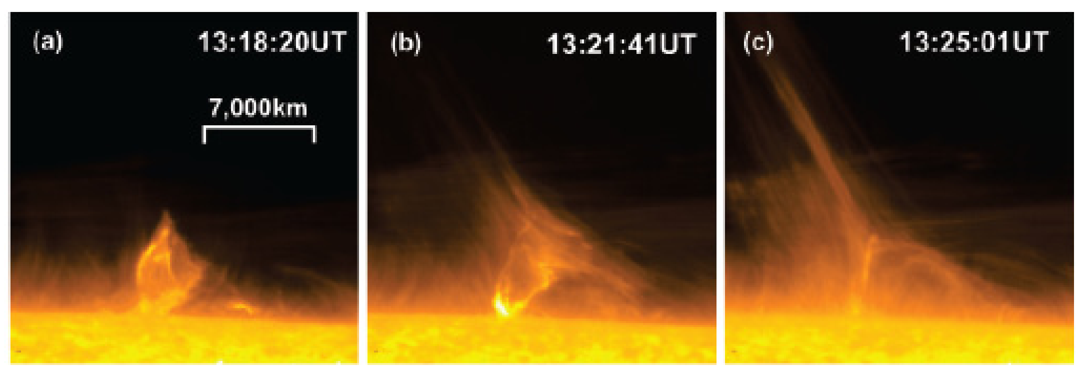
# Jets in the Solar Atmosphere

Observations show various kinds of jets in the solar atmosphere:

- type I spicules : 20 - 25 km/s (Beckers 1968)
- type II spicules: 50 - 100 km/s (De Pontieu et al. 2007)
- RBEs/RREs: 50 - 100 km/s (Rouppe van der Voort et al. 2009)
- chromospheric anemone jets: 10 - 20 km/s (Shibata et al. 2007)
- macrospicules: 100 - 150 km/s (Pike and Mason 1998)
- Hα surges: 50 - 200 km/s (Canfield et al. 1996)
- X-ray jets: 200 - 600 km/s (Shibata et al. 1992)





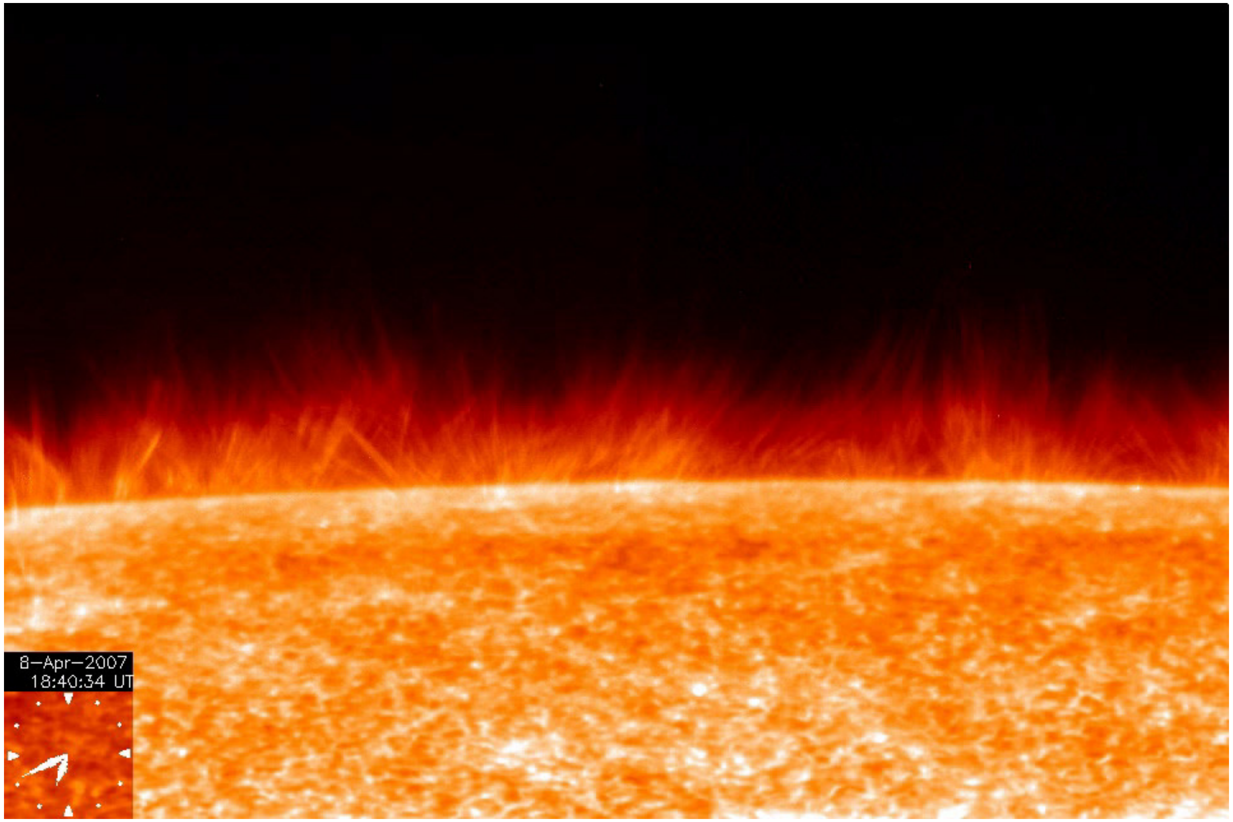
# Type I and Type II Spicules

Type I spicules (Beckers 1972)

diameter: 400 - 1500 km
speed: 20 - 25 km/s
lifetime: 5 - 15 min

Type II spicules (De Pontieu et al. 2007)
RBEs (Rouppe van der Voort et al. 2009)

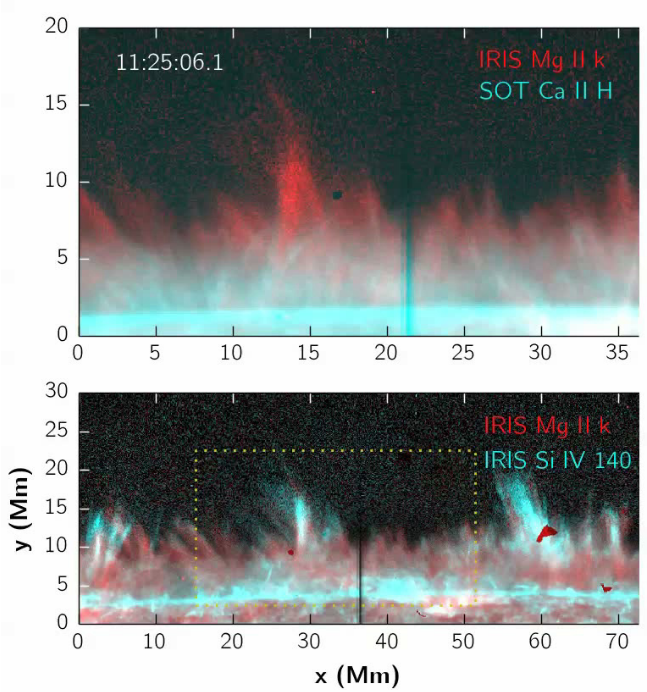
diameter: < 200 km
speed: 50 - 100 km/s
lifetime: 10 - 150 s



# Heating Mechanisms of Type II Spicules

Short life time: fast heating to transition region temperatures (De Pontieu et al. 2007)?

Further supported by IRIS (Pereira et al. 2014).

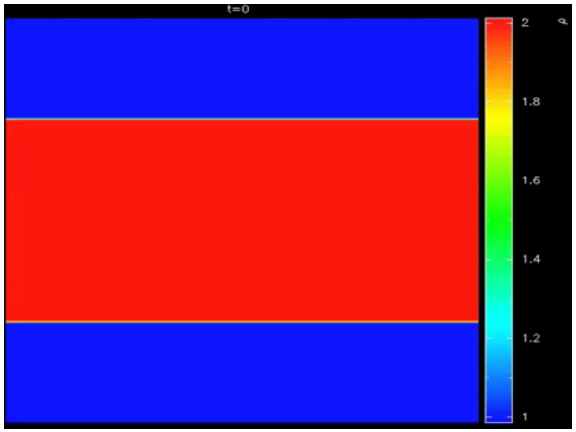



Mechanism for the fast heating remains unknown.

Thermal conduction: hours
Joule heating (spatial scale ≈ 200 km): days
Viscosity (spatial scale ≈ 200 km): months
Ion-neutral collisions (spatial scale ≈ 200 km ): 1 hour

Ion-neutral collisions lead to fastest heating, but spatial scales must be smaller!

Energy of flow must be transferred to smaller scales, where it may dissipate and heat the structure.




Kelvin – Helmholtz Instabilities?
Kuridze et al. 2016
Zaqarashvili et al. 2010, 2014
Soler et al. 2012

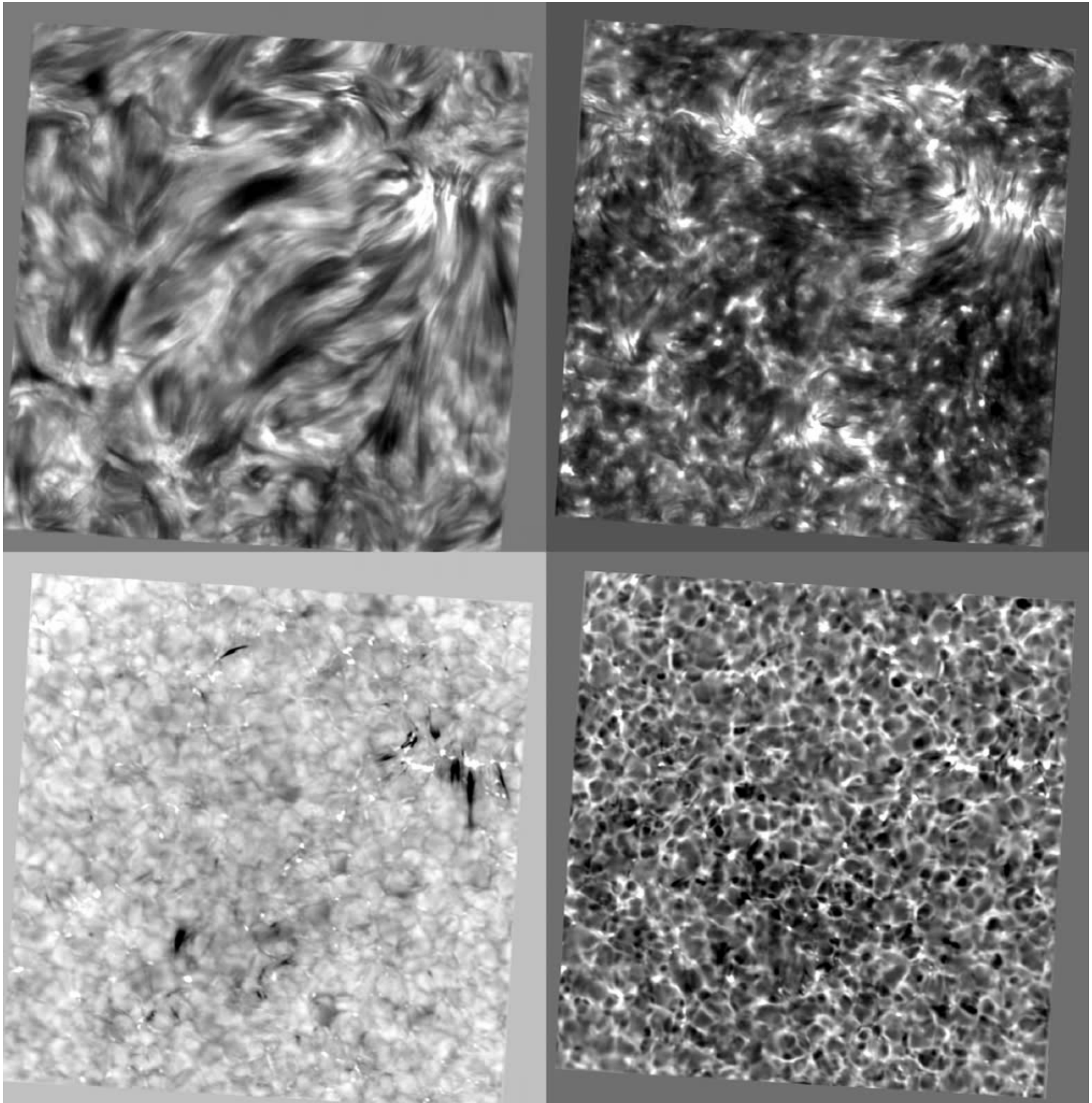
# Aims of This Study

- to identify chromosheric jets in on-disk data obtained by the CRisp Imaging Spectropolarimeter (CRISP) on the Swedish 1-m Solar Telescope
- to infer physical characteristics of a typical jet with **a modified cloud model** (Liu & Ding 2001) yielding:
  - the Source function S
  - the Line center optical thickness $\tau_0$
  - the Doppler width $\Delta\lambda_D$
  - the Line-of-sight velocity $v_{LOS}$
- to prepare basis for spectral inversions of large volumes of CRISP data aiming:
  - to infer temporal evolution of S, $\tau_0$, $\Delta\lambda_D$, and $v_{LOS}$ for large sample of chromospheric jets,
  - to look for the Kelvin-Helmholtz Instabilities manifesting through increased non-thermal broadening of spectral lines.

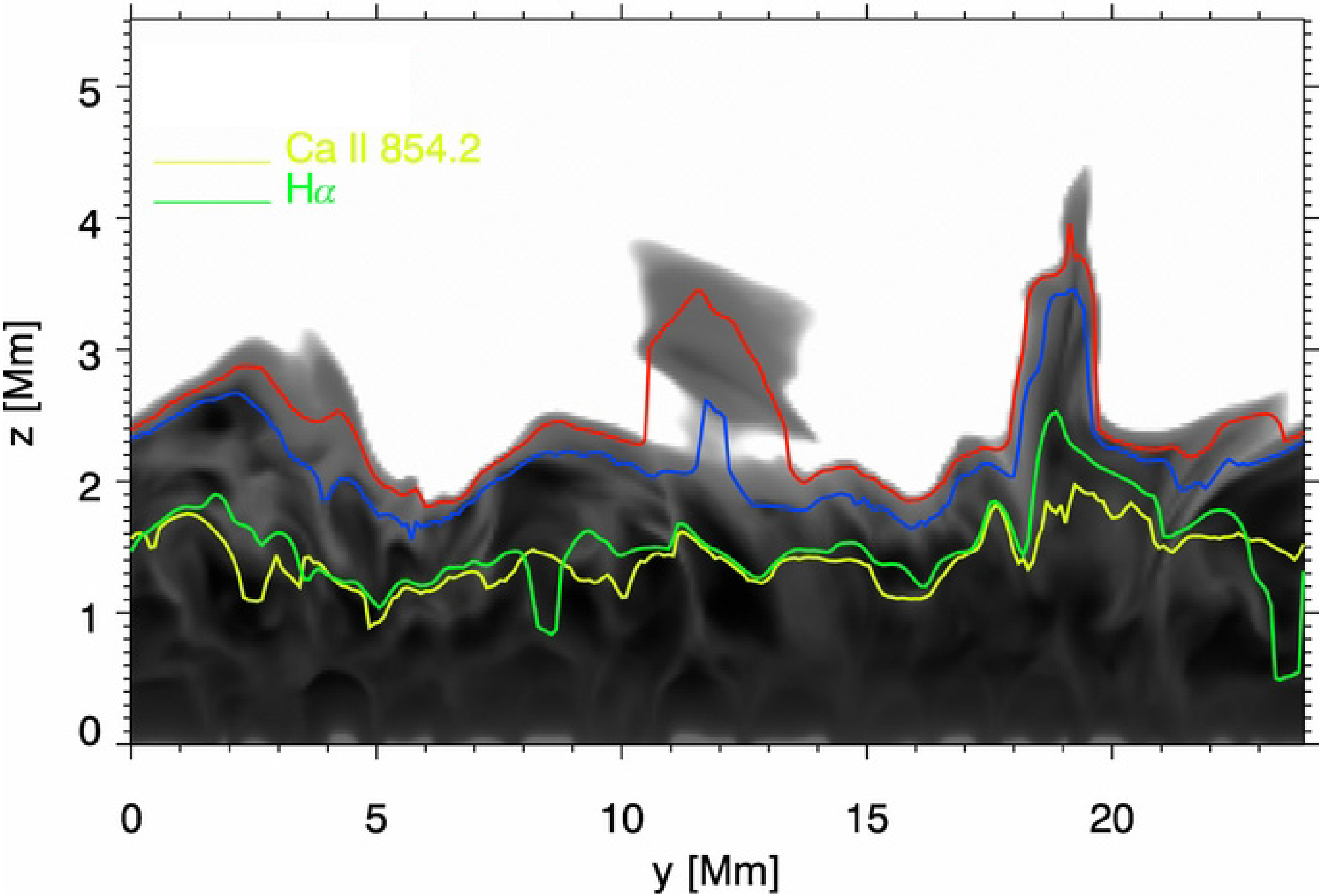
# Observations and Data Reduction

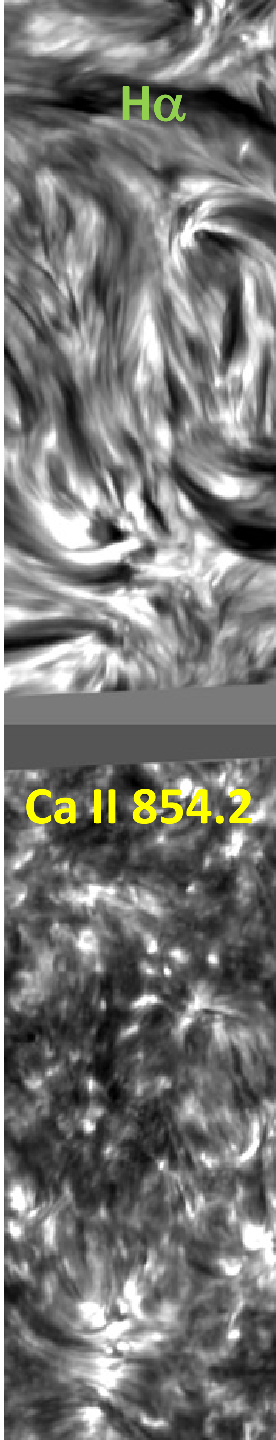
- coordinated SST-IRIS campaign in 13 - 19 May 2016 **supported through SOLARNET**
- data taken on 13 May 2016 between 08:46 UT and 10:02 UT in the quiet chromosphere close to disk center by SST/CRISP
- H$\alpha$ scanned in the range ±1.4 Å around center in 15 points separated 0.2 Å
- Ca II 8542 Å scanned in the range ±1.2 Å around center in 25 points separated 0.1 Å with one extra point at –1.5 Å
- temporal cadence of the H$\alpha$ and Ca II 8542 Å line scans: 12.4 s
- data reduction: Luc Rouppe van der Voort, the CRISPRED pipeline (de la Cruz Rodríguez et al. 2015) and MOMFBD (van Noort et al. 2005)

SOLARNET



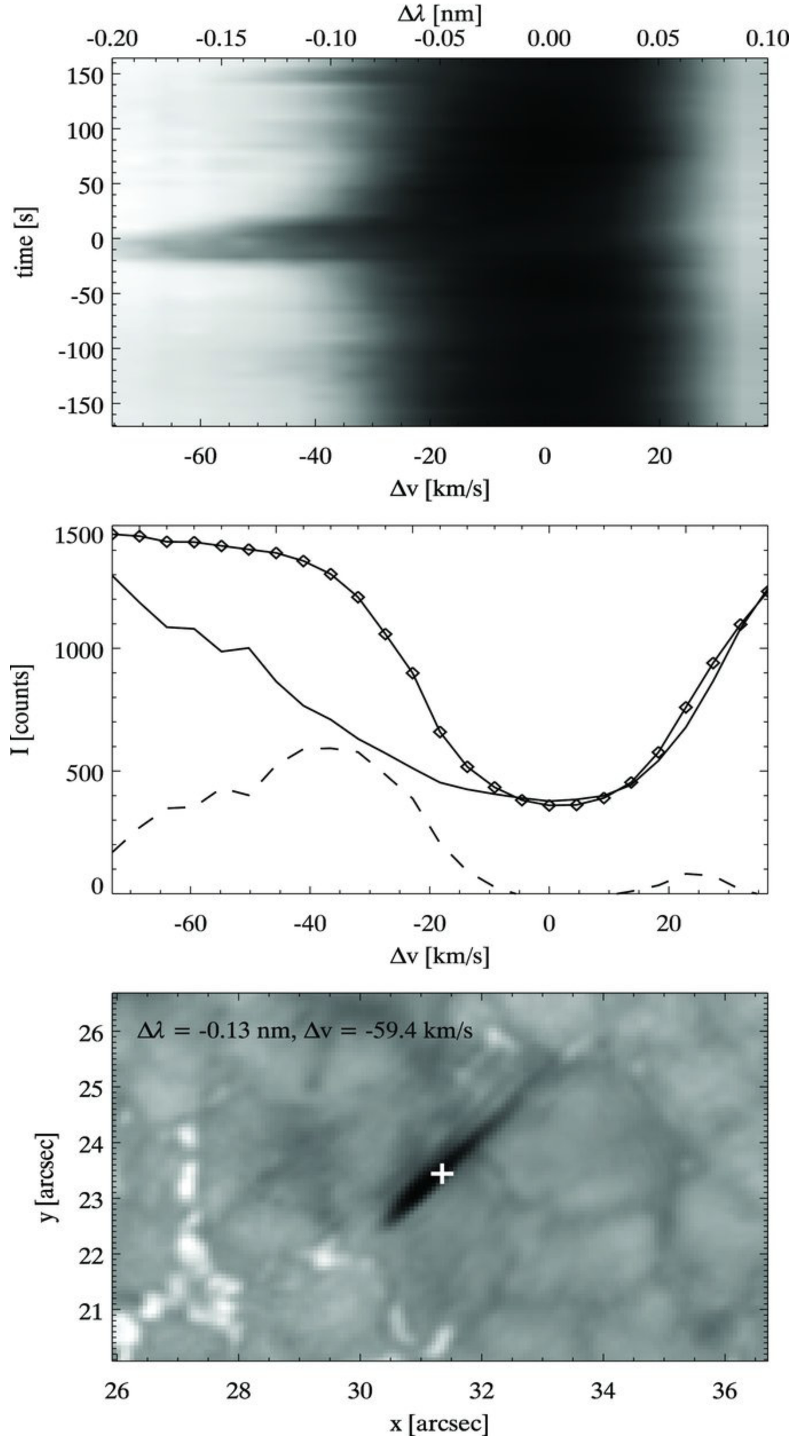
# Differences between $\tau = 1$ Heights of Ca II 8542 Å and Hα




Leenaarts et al. (2013)

# Typical Spectral Manifestation of Rapid Blue Excursion (RBE)




RBE ≡ chromospheric jet

Rouppe van der Voort et al. (2009)

# Spectral Inversion by Cloud Model

## The classical cloud model

In this model by Beckers (1964), the line intensity $I(\Delta\lambda)$ at $\Delta\lambda$ from the line center is given by the formula:

$$I(\Delta\lambda) = I_0(\Delta\lambda)e^{-\tau(\Delta\lambda)} + S\left[1 - e^{-\tau(\Delta\lambda)}\right]$$

where: $I_0(\Delta\lambda)$ is the intensity of background profile

$S$ is the constant source function

$\tau(\Delta\lambda)$ is the optical thickness given by: $\tau(\Delta\lambda) = \tau_0\varphi(\Delta\lambda, \Delta\lambda_D, v_{LOS})$

where: $\tau_0$ is the line center optical thickness

$\varphi$ is the absorption profile (Gaussian or Voigt function)

$\Delta\lambda_D$ is the Doppler width

$v_{LOS}$ is the line-of-sight velocity

The model adopts a mean profile over the quiet chromosphere as the background profile $I_0(\Delta\lambda)$.

## The modified cloud model

Liu & Ding (2001) introduced the modified cloud model, in which the background profile $I_0(\Delta\lambda)$ is eliminated assuming its symmetry $I_0(\Delta\lambda) = I_0(-\Delta\lambda)$. In this model **the observed asymmetry** of the line profile $\boldsymbol{A(\Delta\lambda) = I(\Delta\lambda) - I(-\Delta\lambda)}$ is given as:

$$A(\Delta\lambda) = I(\Delta\lambda) - I(-\Delta\lambda) = \left[I(\Delta\lambda) - S\right]\left[1 - e^{\tau(\Delta\lambda)-\tau(-\Delta\lambda)}\right]$$

# Spectral Inversion by Cloud Model

In this study we employ the modified cloud model, but assuming that:

- the background profile is asymmetric,
- the asymmetry of the background profile can be represented by asymmetry of mean profile.

Then the observed asymmetry $A(\Delta\lambda)$ of line profile is given by the formula

$$A(\Delta\lambda) = [I(\Delta\lambda) - S][1 - e^{\tau(\Delta\lambda) - \tau(-\Delta\lambda)}] + a(\Delta\lambda)e^{-\tau(-\Delta\lambda)}$$

where $a(\Delta\lambda)$ is the asymmetry of the mean profile.

Then from the observables $A(\Delta\lambda)$, $I(\Delta\lambda)$, and $a(\Delta\lambda)$ one can compute $S$, $\tau_0$, $\Delta\lambda_D$, and $v_{LOS}$ by the Levenberg–Marquardt least-squares minimization method (Markwardt 2009).

# Remarks on Cloud Model

**The classical cloud model** (Beckers 1964) is very sensitive on the background profile $I_0(\Delta\lambda)$.

This problems solves **the modified cloud model** (Liu & Ding 2001), in which the background profile is eliminated assuming its symmetry.

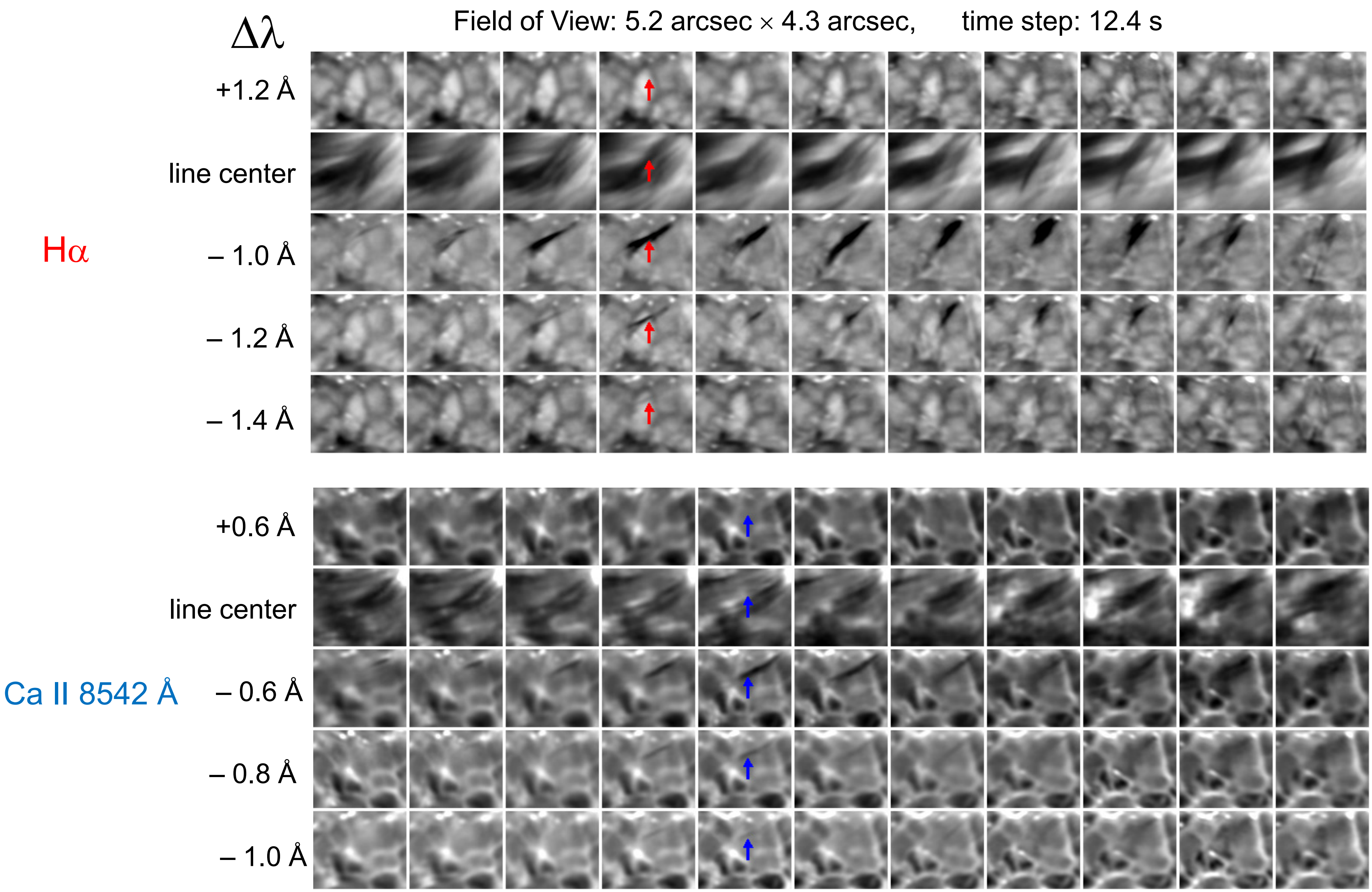
The model is predestined for highly asymmetric line profiles observed in **flares** and also in various **chromospheric jets**, in particularly in RBEs/RREs.

We suggests **the new version of the modified cloud model**, which assumes that the background profile is asymmetric and its asymmetry can be represented by asymmetry of mean profile.

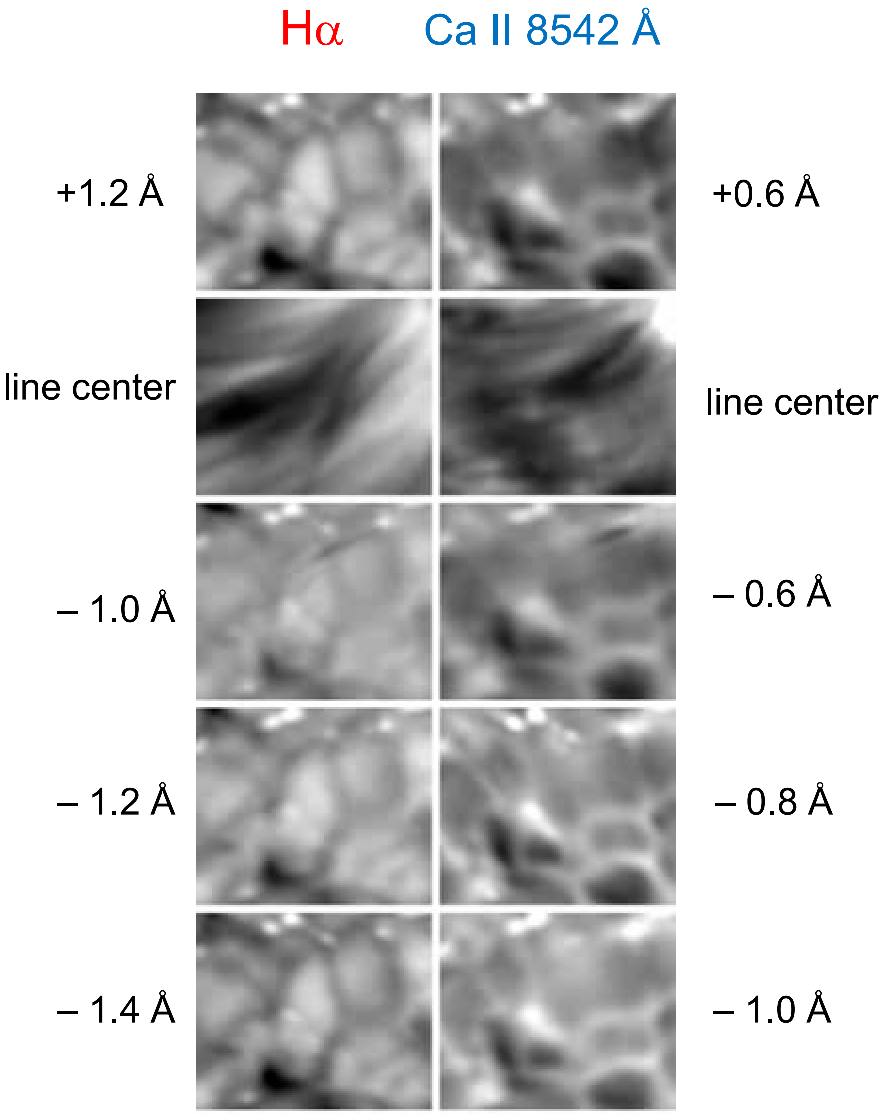
The model works well in those parts of a line profile showing some asymmetry (line flanks), but fails in the line center and far wings with small or zero asymmetry.

**General problem** in application of single-component cloud model inversion is the overlapping of chromospheric structures (Rouppe van der Voort et al. 2009).

# Evolution of selected chromospheric jet

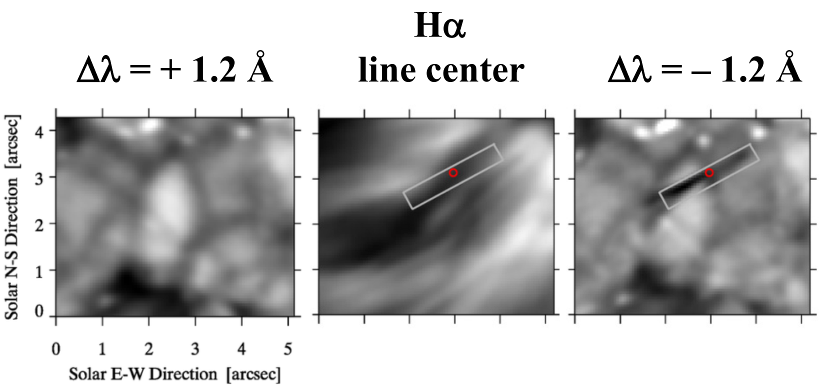


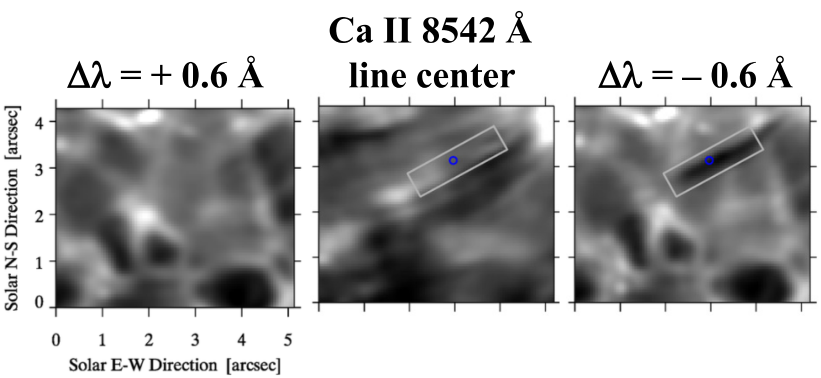
# Evolution of selected chromospheric jet

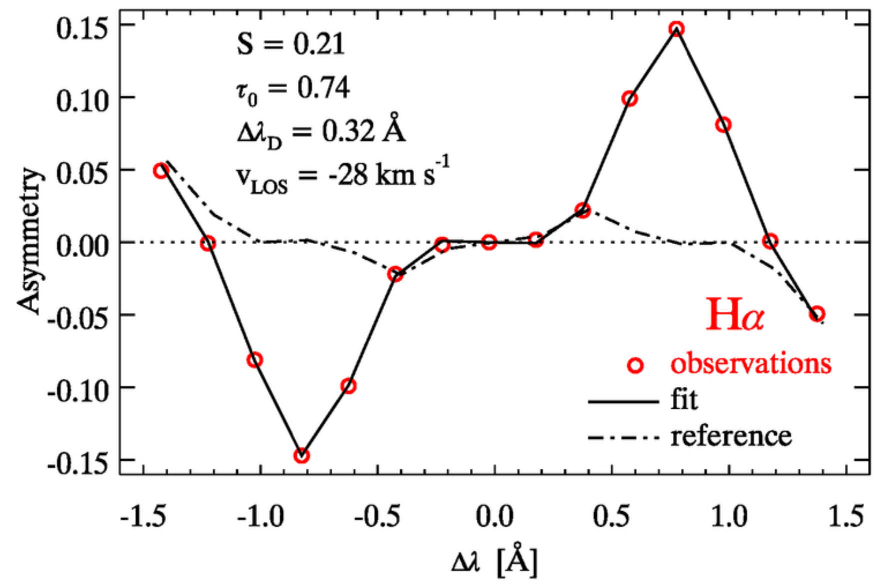


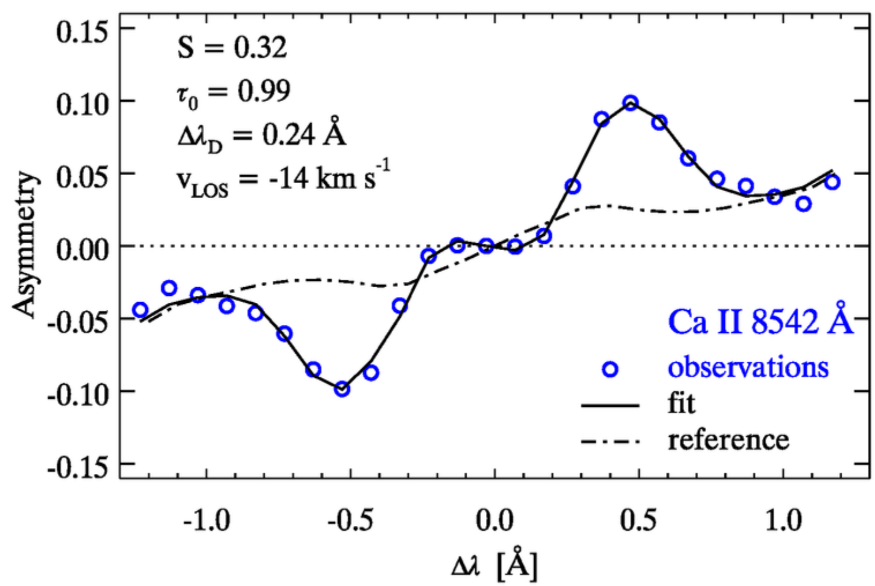

transverse motion

# Example of the Hα and Ca II 8542 Å profile asymmetries



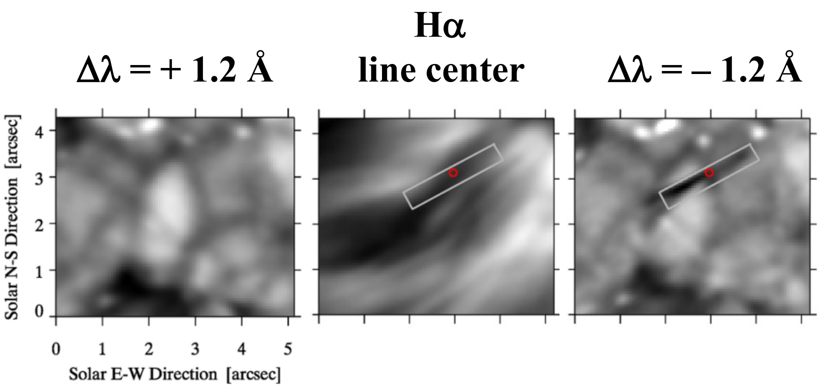



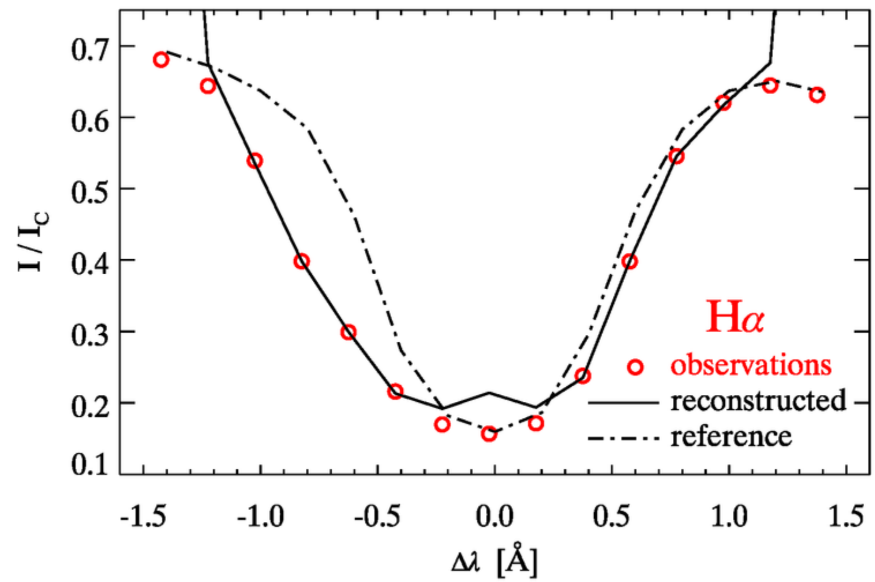



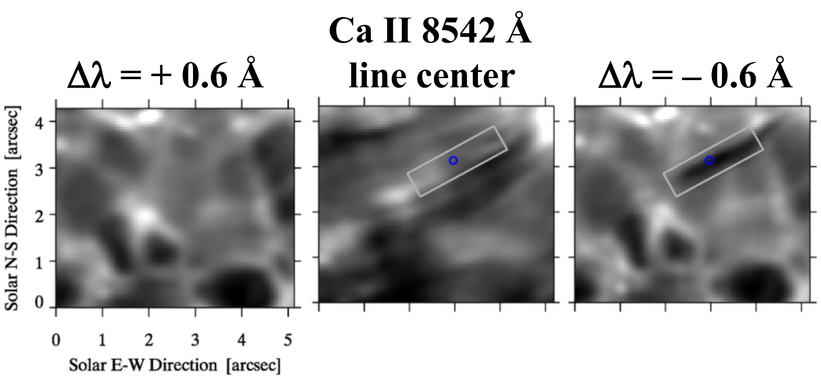



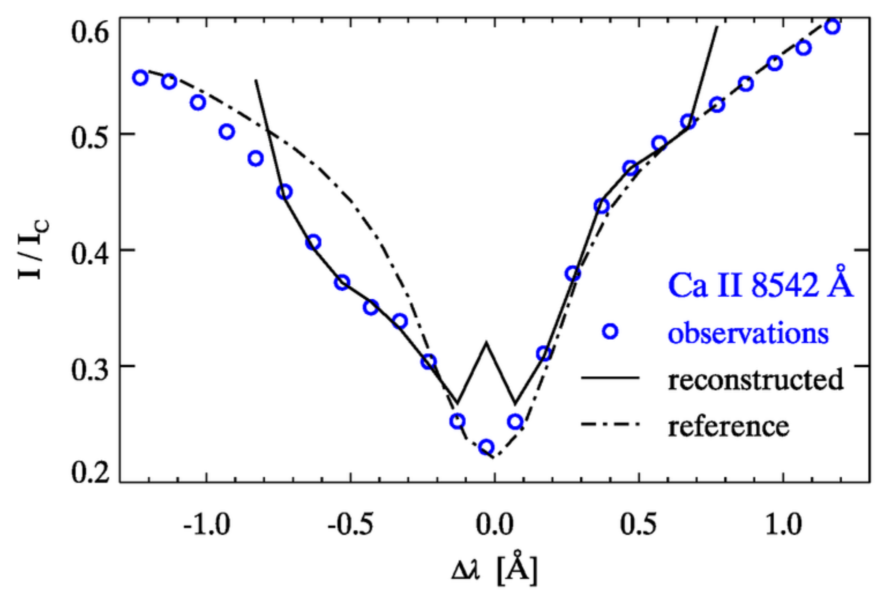

fit = cloud model fit
reference = asymmetry of reference profile
(spatial average over full FoV)

# Example of the Hα and Ca II 8542 Å line profiles



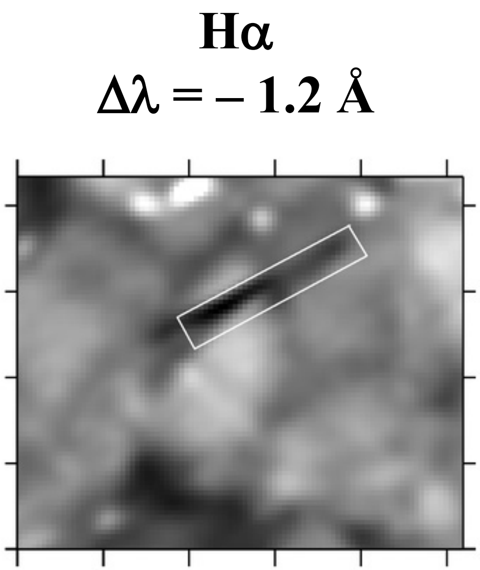



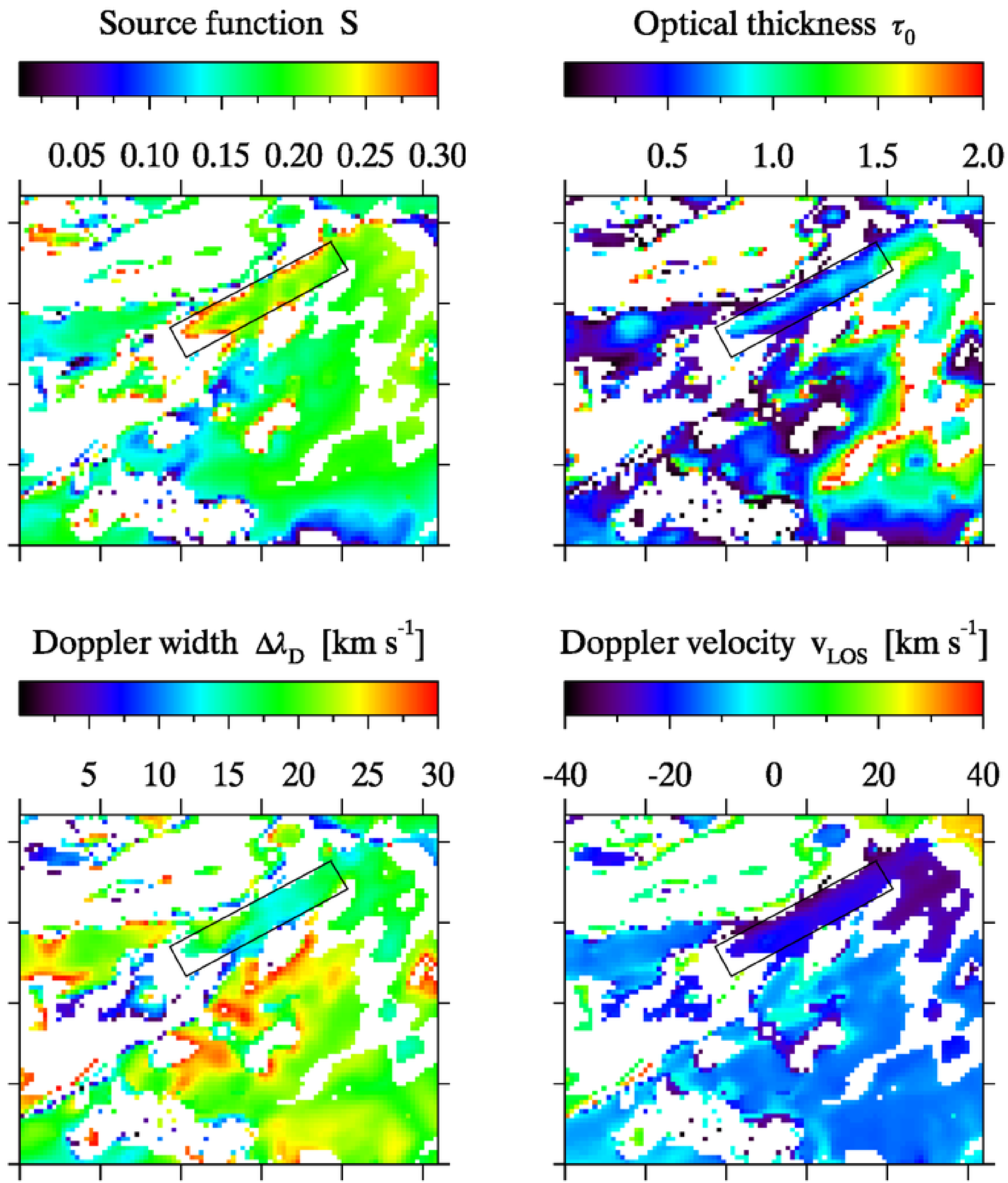




reconstructed = profile computed from cloud model parameters

reference = spatial average over full FoV

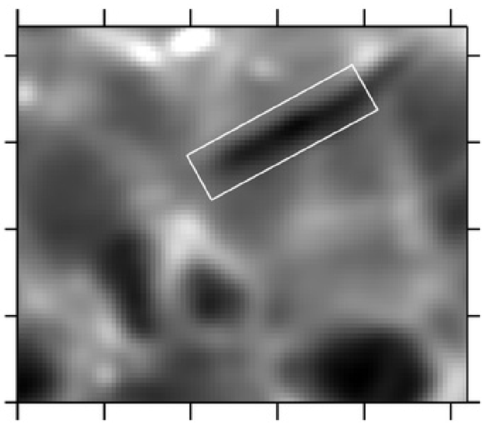
# Structure of chromospheric jet in Hα



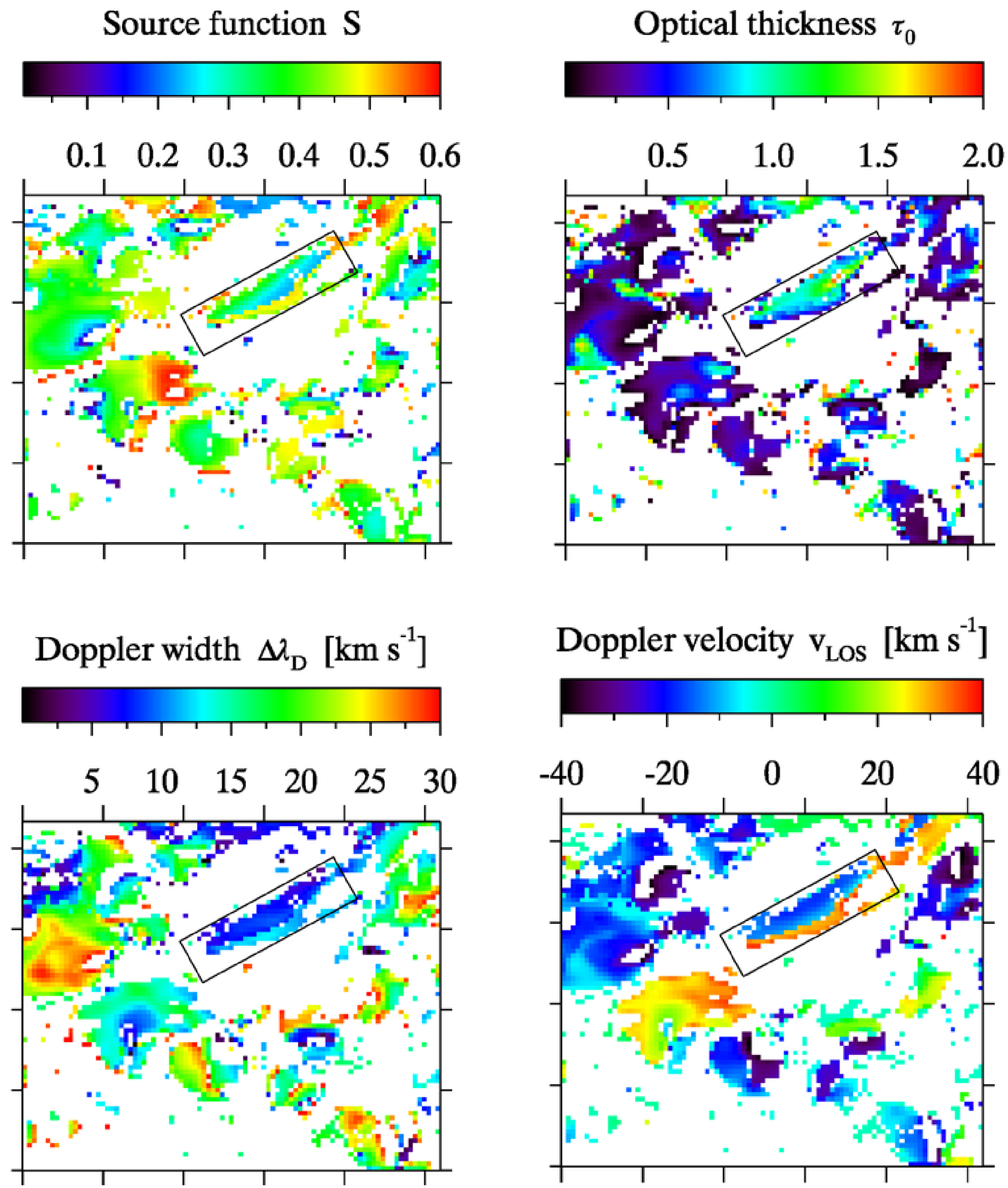



# Structure of chromospheric jet in Ca II 8542 Å

**Ca II 8542 Å**
**Δλ = – 0.6 Å**

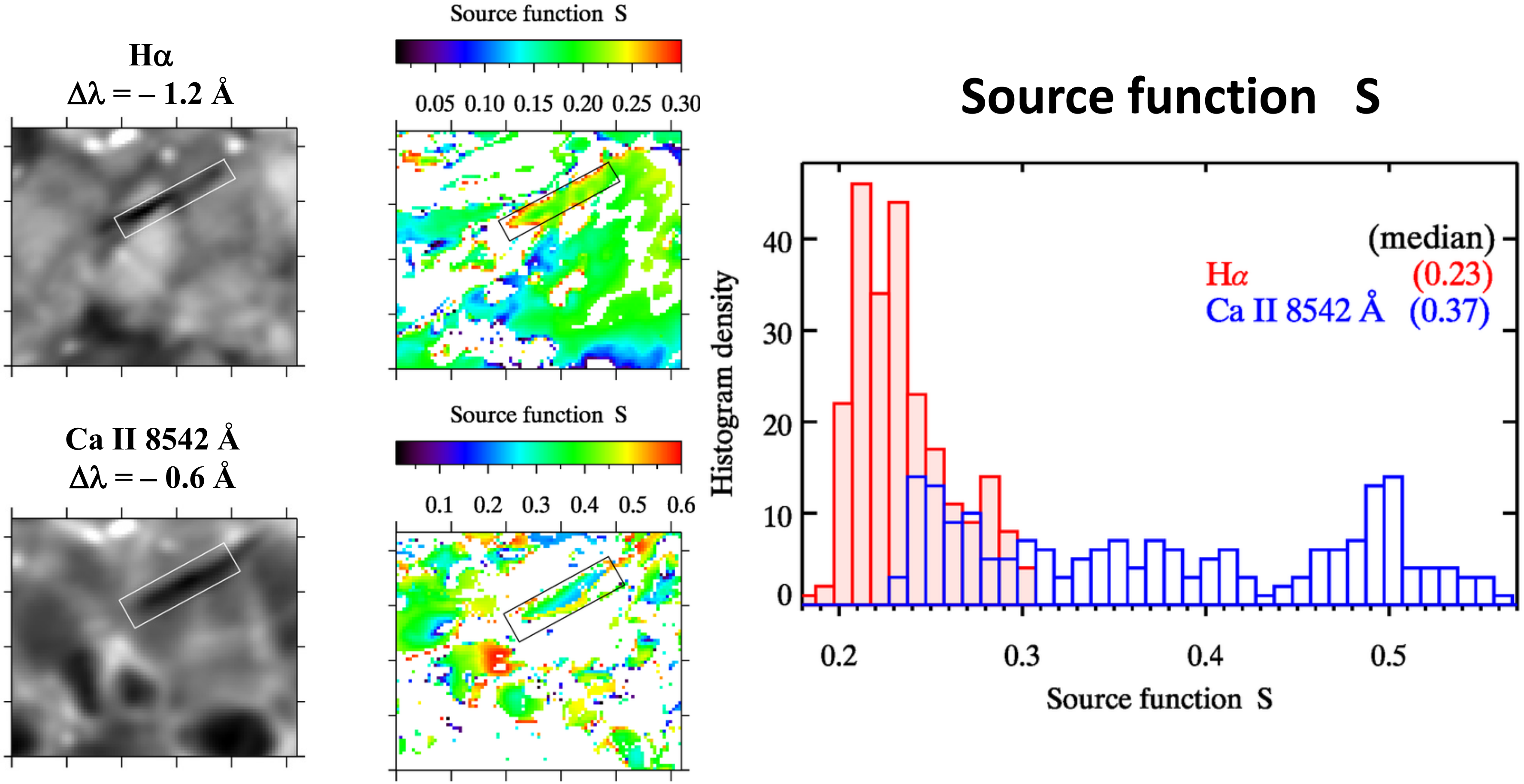


Correlations of the parameters
$S \quad \tau_0 \quad \Delta\lambda_D \quad v_{LOS}$



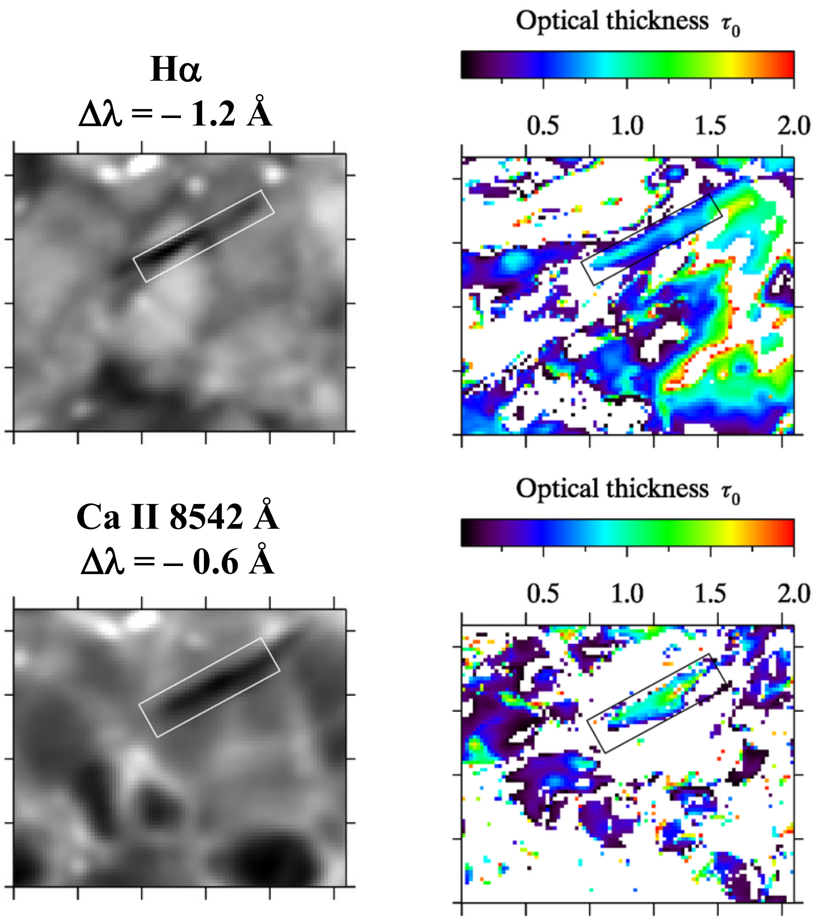

bi-directional flow?

# Structure of chromospheric jet in Hα and Ca II 8542 Å

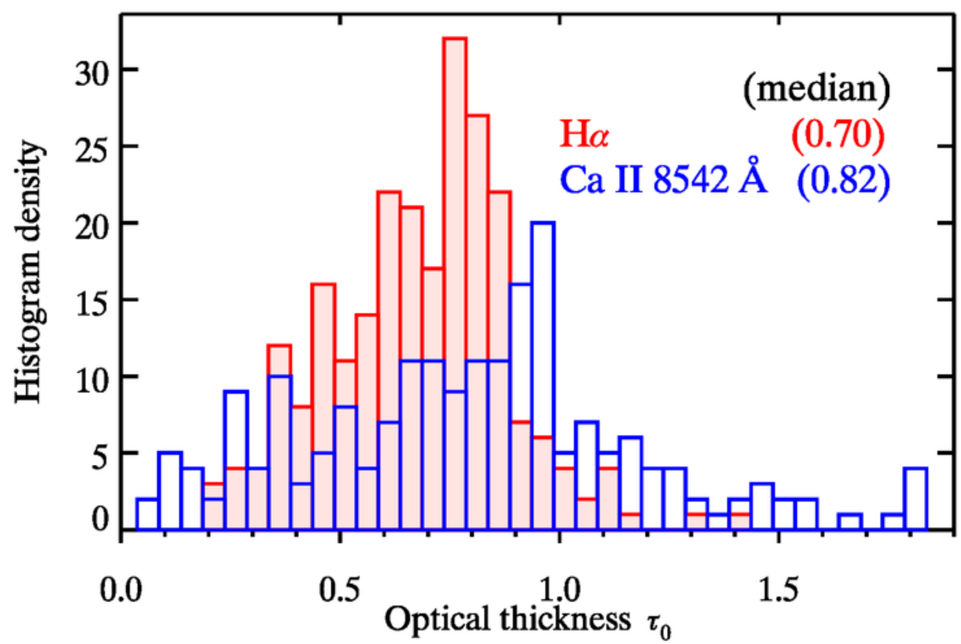



| | |
|---|---|
| Hα | - S increases from the jet core towards its outer limits from S ≈ 0.2 to S ≥ 0.3<br>- prominent peak in the histogram at S ≈ 0.23 |
| Ca II 8542 Å | - S increases from the jet core towards its outer limits from S ≈ 0.25 to 0.45<br>- the histogram suggests flat distribution of S |

# Structure of chromospheric jet in Hα and Ca II 8542 Å




## Line center optical thickness $\tau_0$

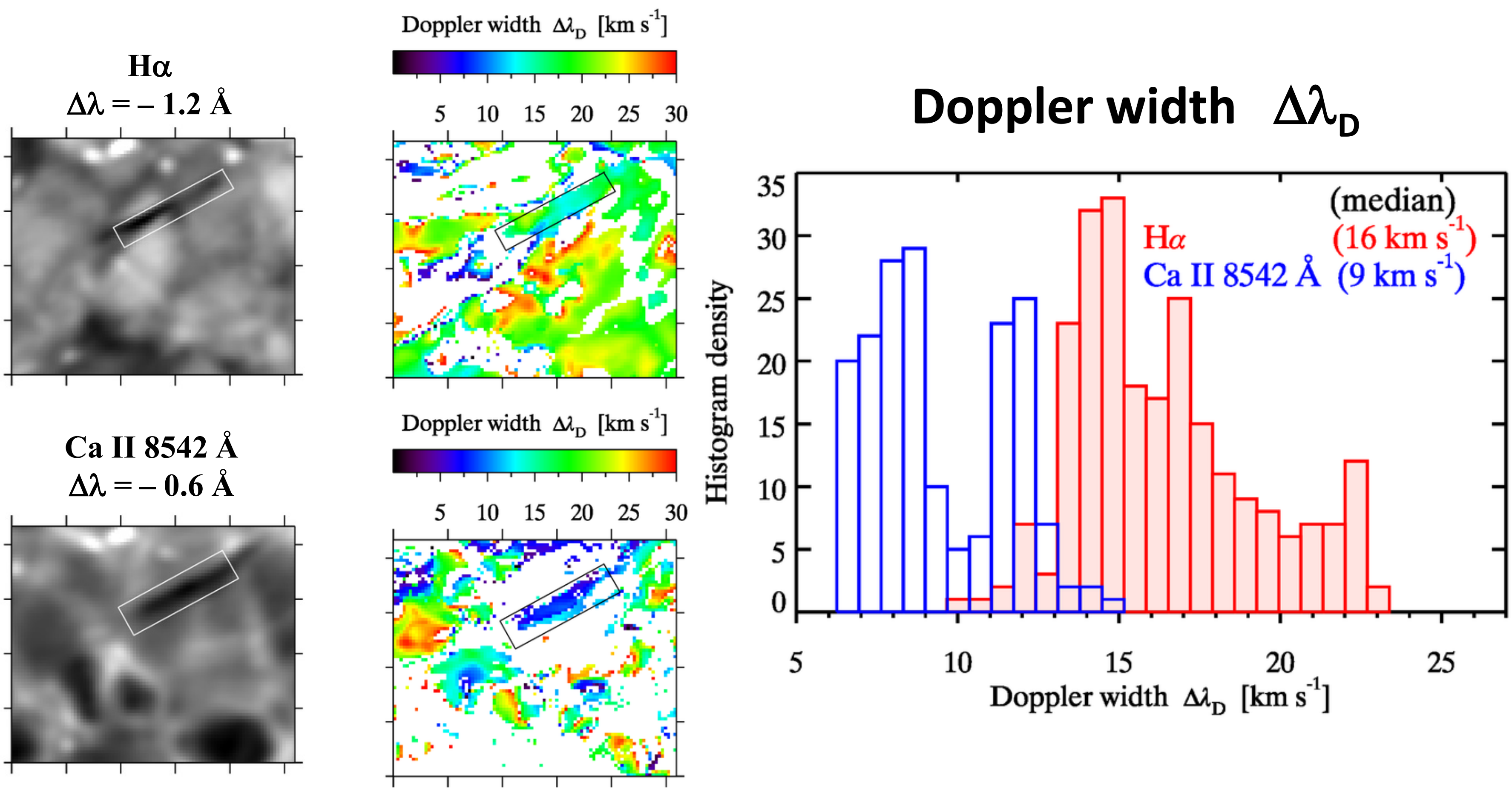



Hα - $\tau_0$ decreases from the jet core towards its outer limits from $\tau_0 \approx 0.8$ to 0.5

Ca II 8542 Å - $\tau_0$ decreases from the jet core towards its outer limits from $\tau_0 \approx 1.2$ to 0.5

**Can be the jet considered as optically thin?**

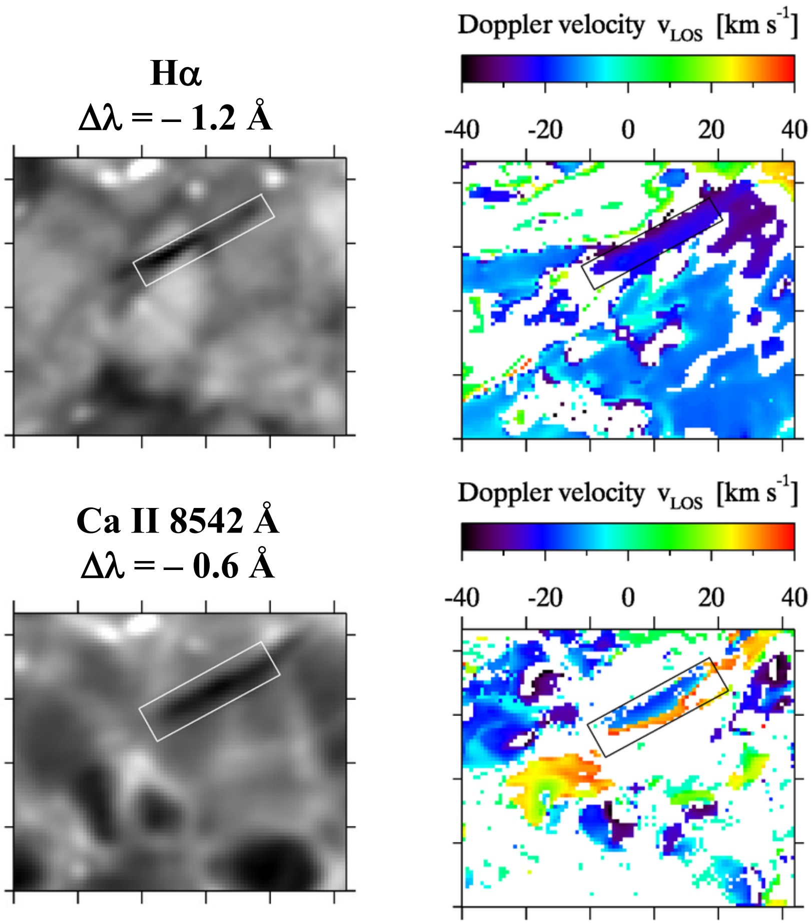
# Structure of chromospheric jet in Hα and Ca II 8542 Å



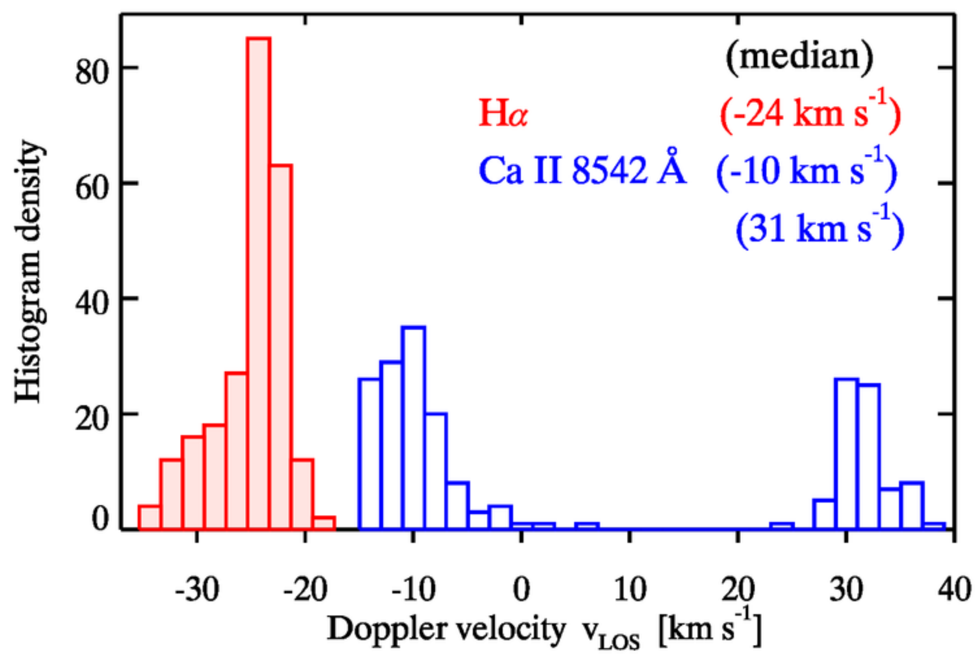

Single-peak distribution of $\Delta\lambda_D$ for Hα but double-peak distribution for Ca II 8542 Å.

The first peak at 8 $kms^{-1}$ suggests very cold jet plasma and/or very small non-thermal broadening.

# Structure of chromospheric jet in Hα and Ca II 8542 Å



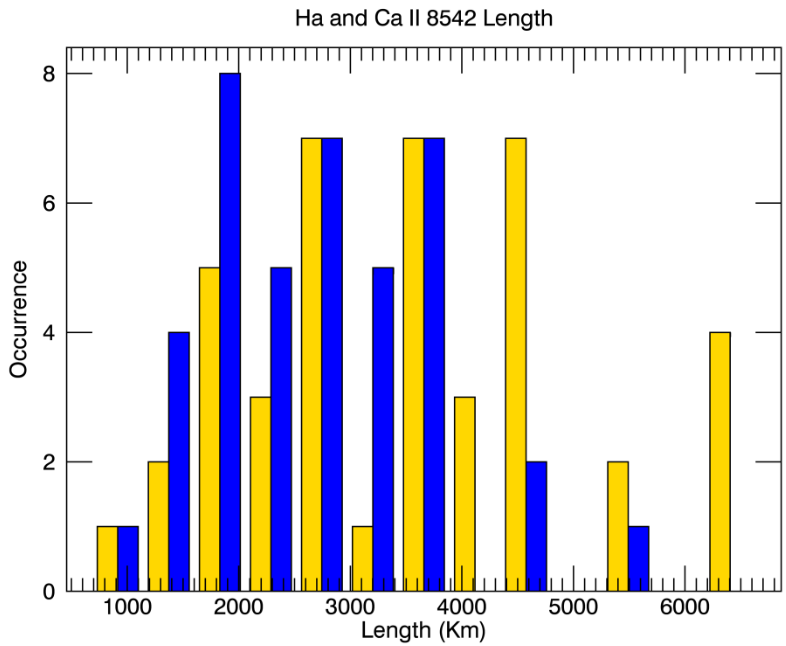

## Doppler velocity $v_{LOS}$

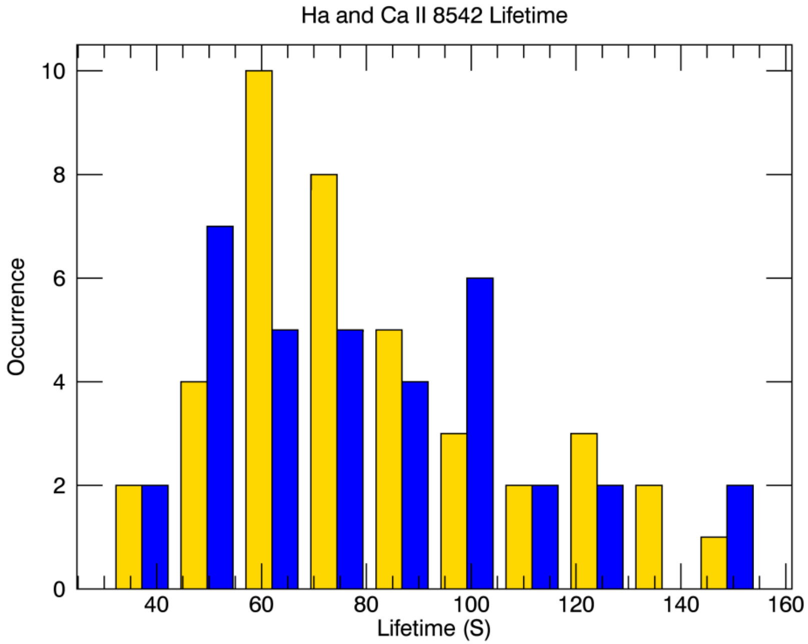



Larger $v_{LOS}$ measured in Hα than in Ca II 8542 Å.

Ca II 8542 Å - signature of bi-directional flow
- sharp boundary between up- and downflows

# Lengths and lifetimes of chromospheric jets



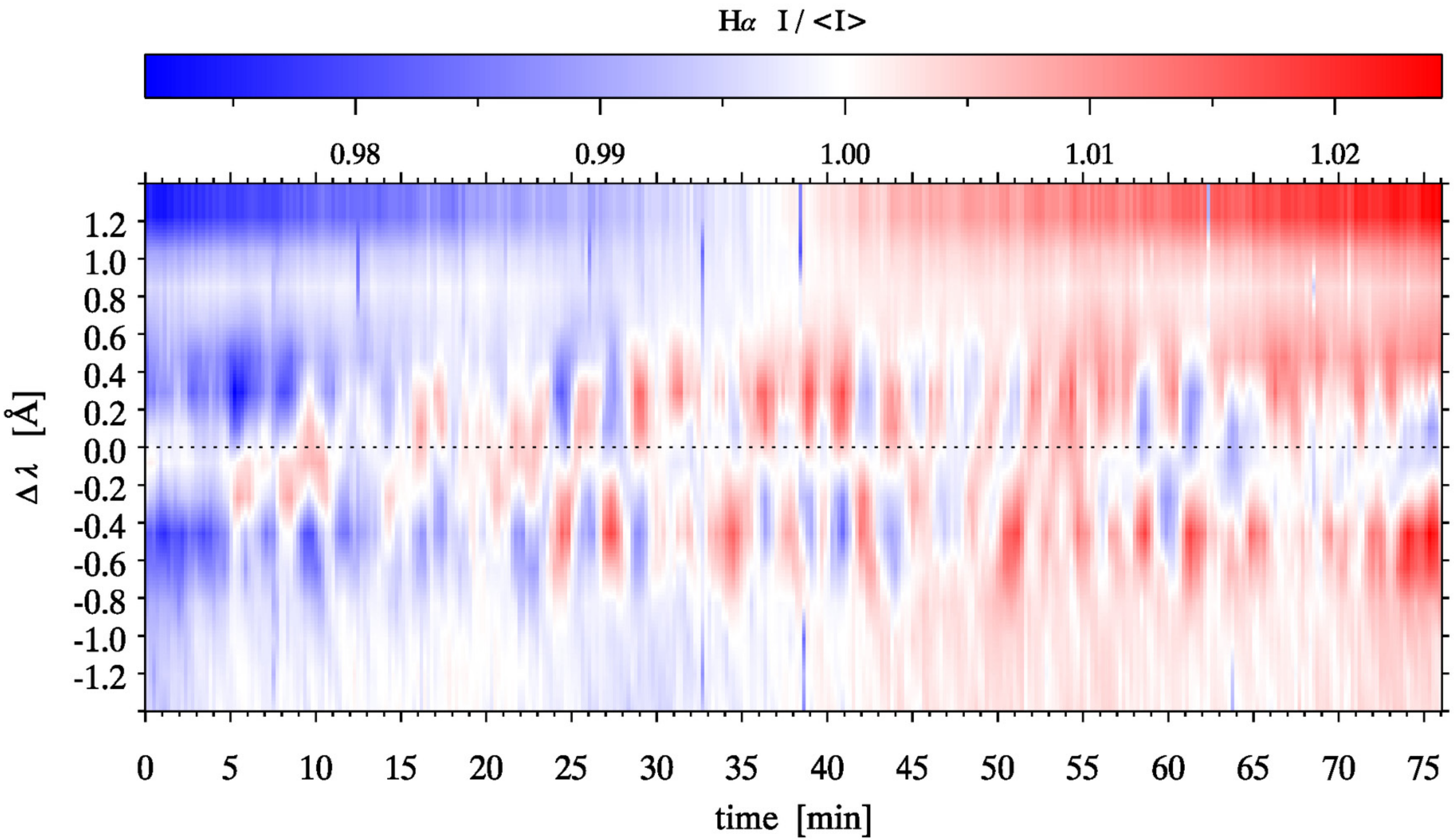




**yellow** = Hα, **blue** = Ca II 8542 Å

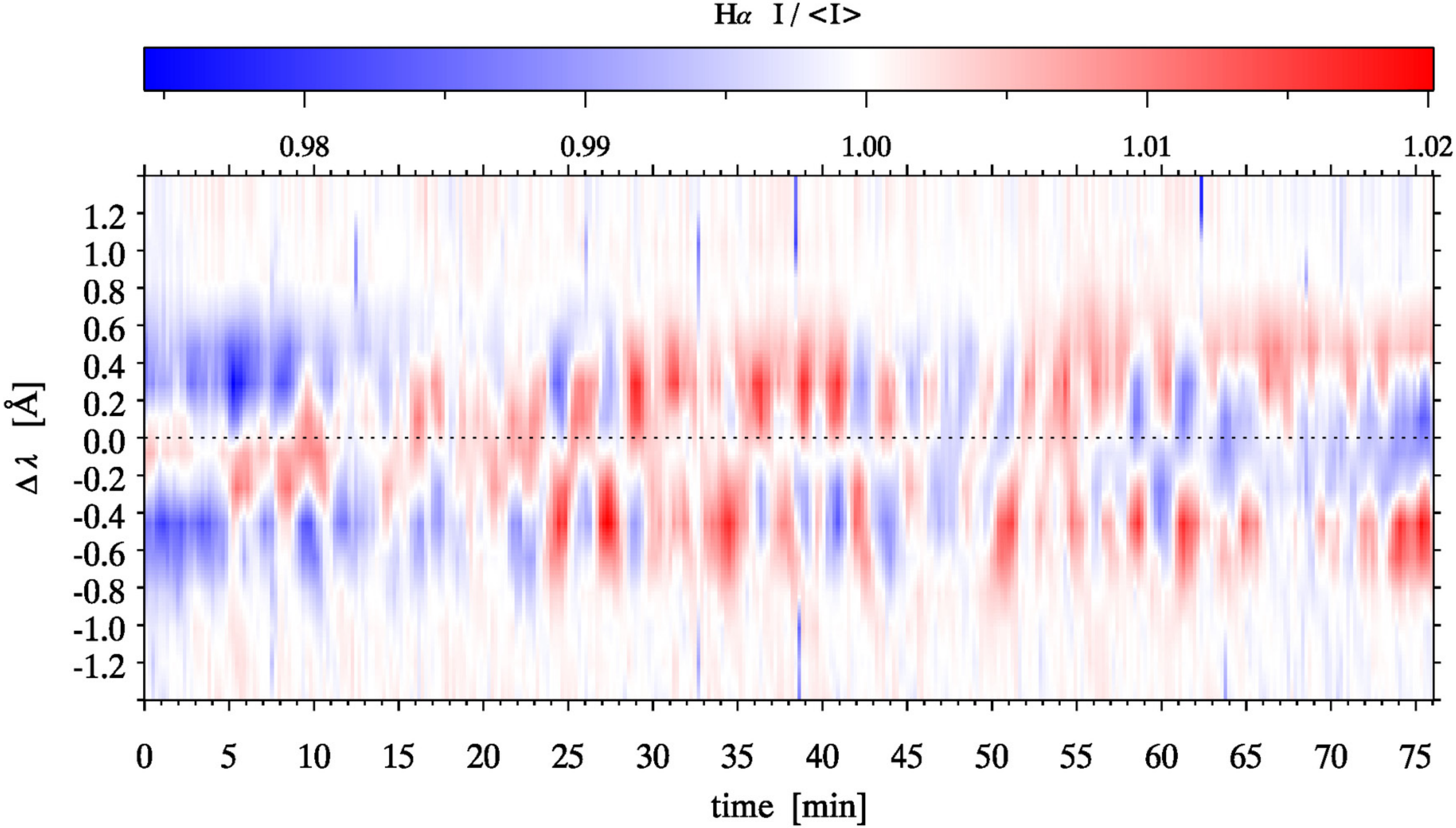
- lengths and lifetimes of 40 jets prepared for spectral inversion
- measured by CRISPEX graphical tool (Vissers & Rouppe van der Voort 2012)

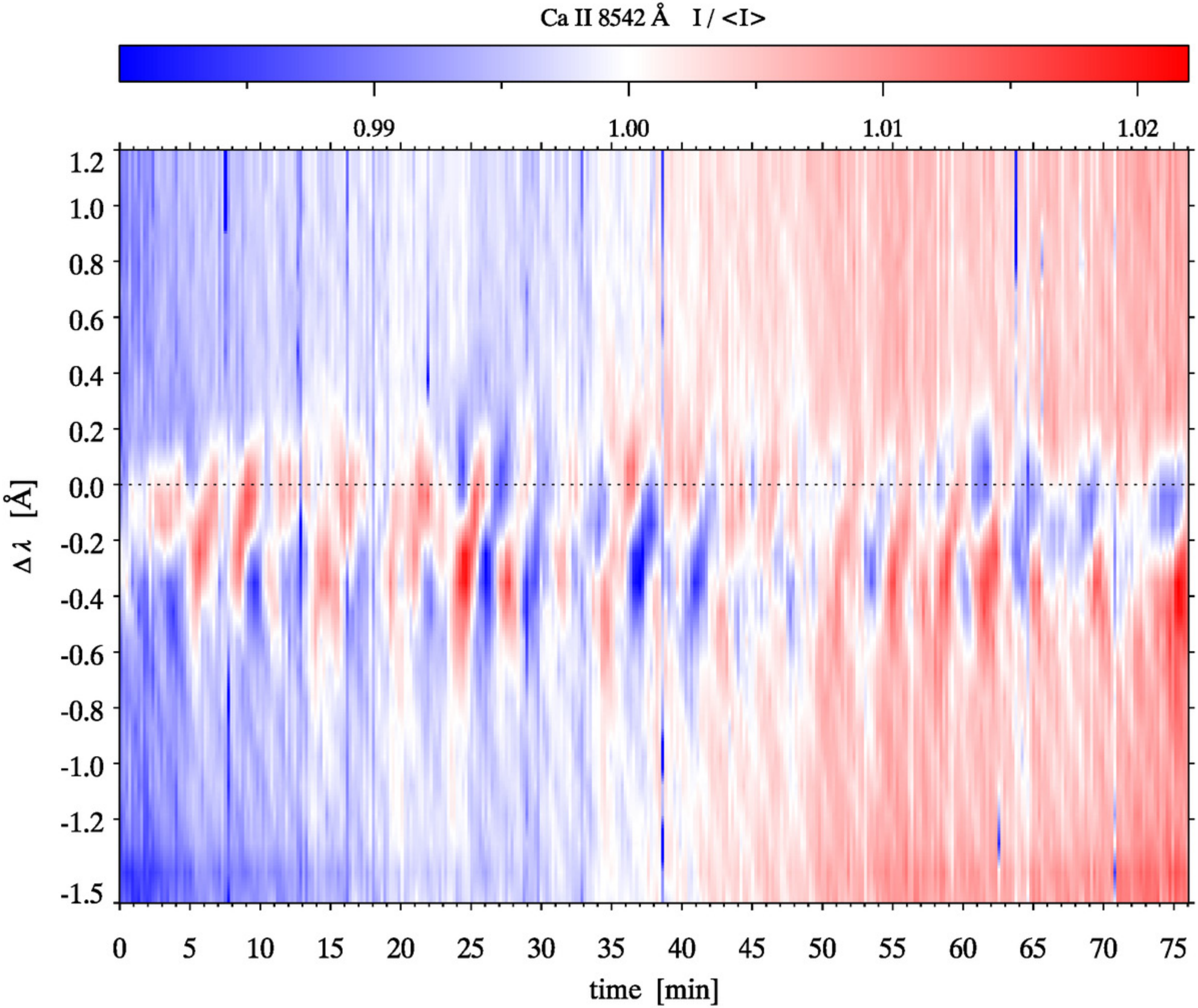
| Medians | Length | Lifetime |
|---|---|---|
| Hα | 3540 km | 81 s |
| Ca II 8542 Å | 2700 km | 80 s |

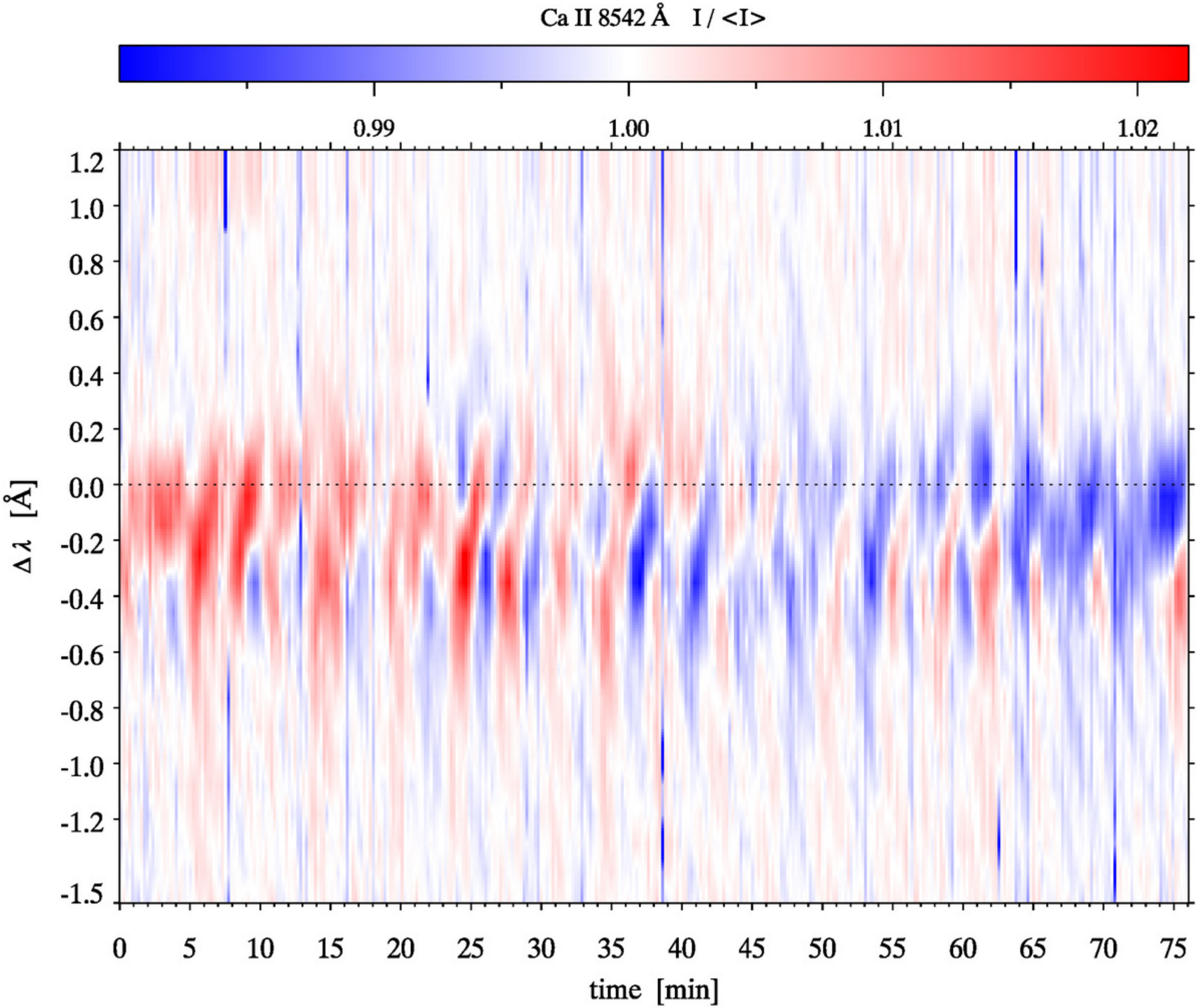
# Discussion of data uncertainties



# Discussion of data uncertainties




Ca II 8542 Å I / <I>
0.99
1.00
1.01
1.02
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
-1.5
Δλ [Å]
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
time [min]

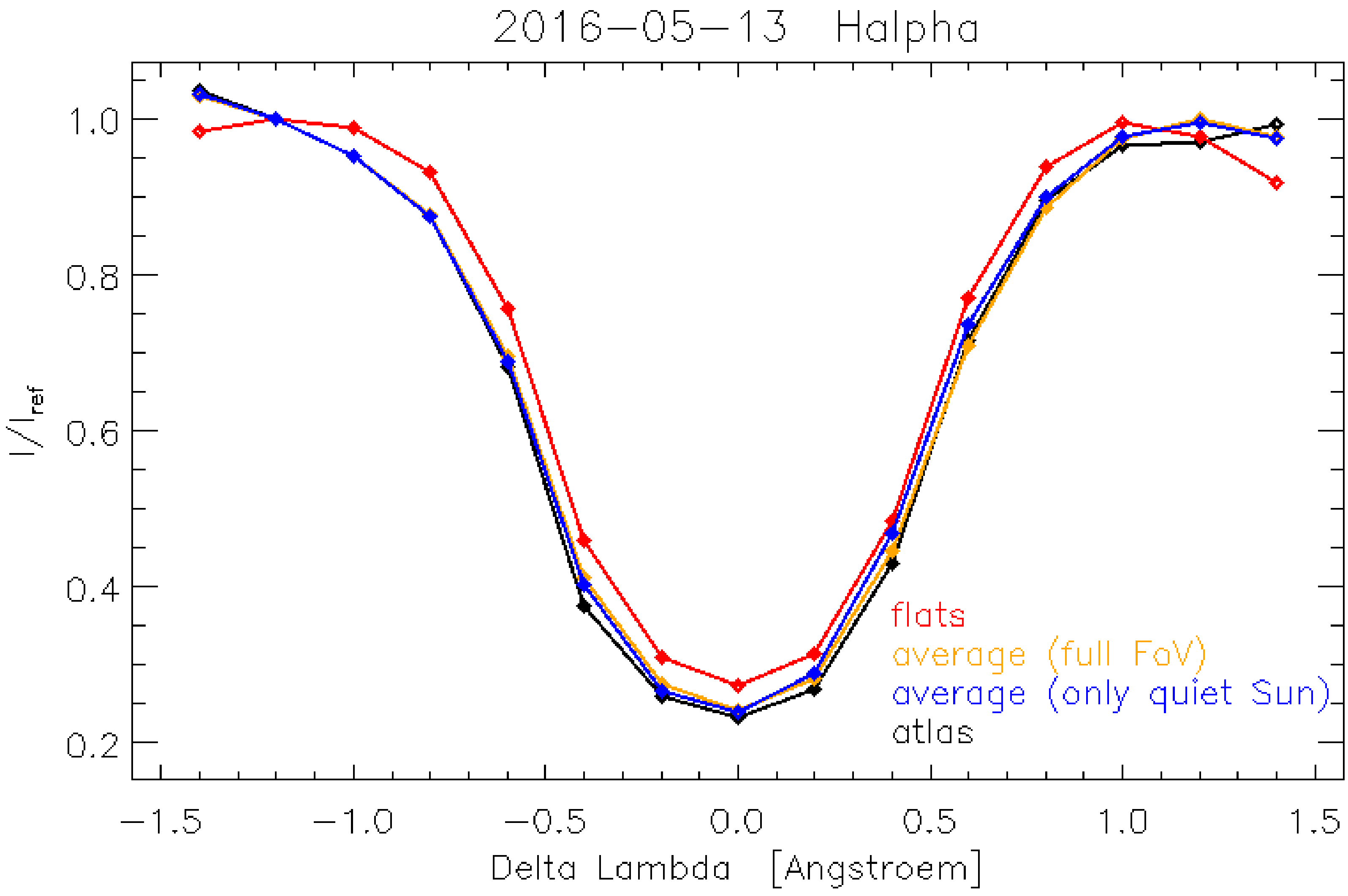


Ca II 8542 Å I / <I>
0.99
1.00
1.01
1.02
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
-1.5
Δλ [Å]
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
time [min]

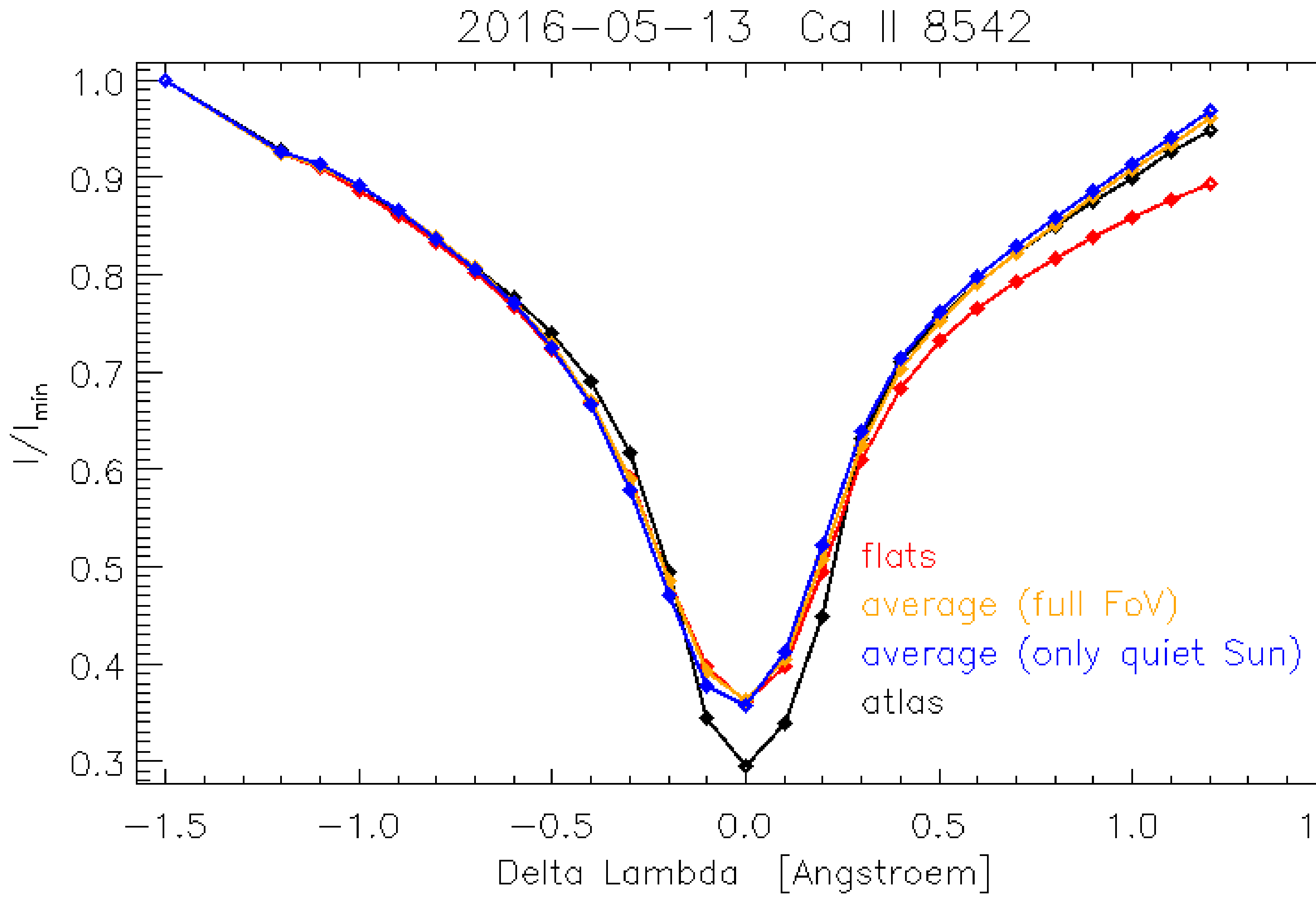
# Discussion of data uncertainties

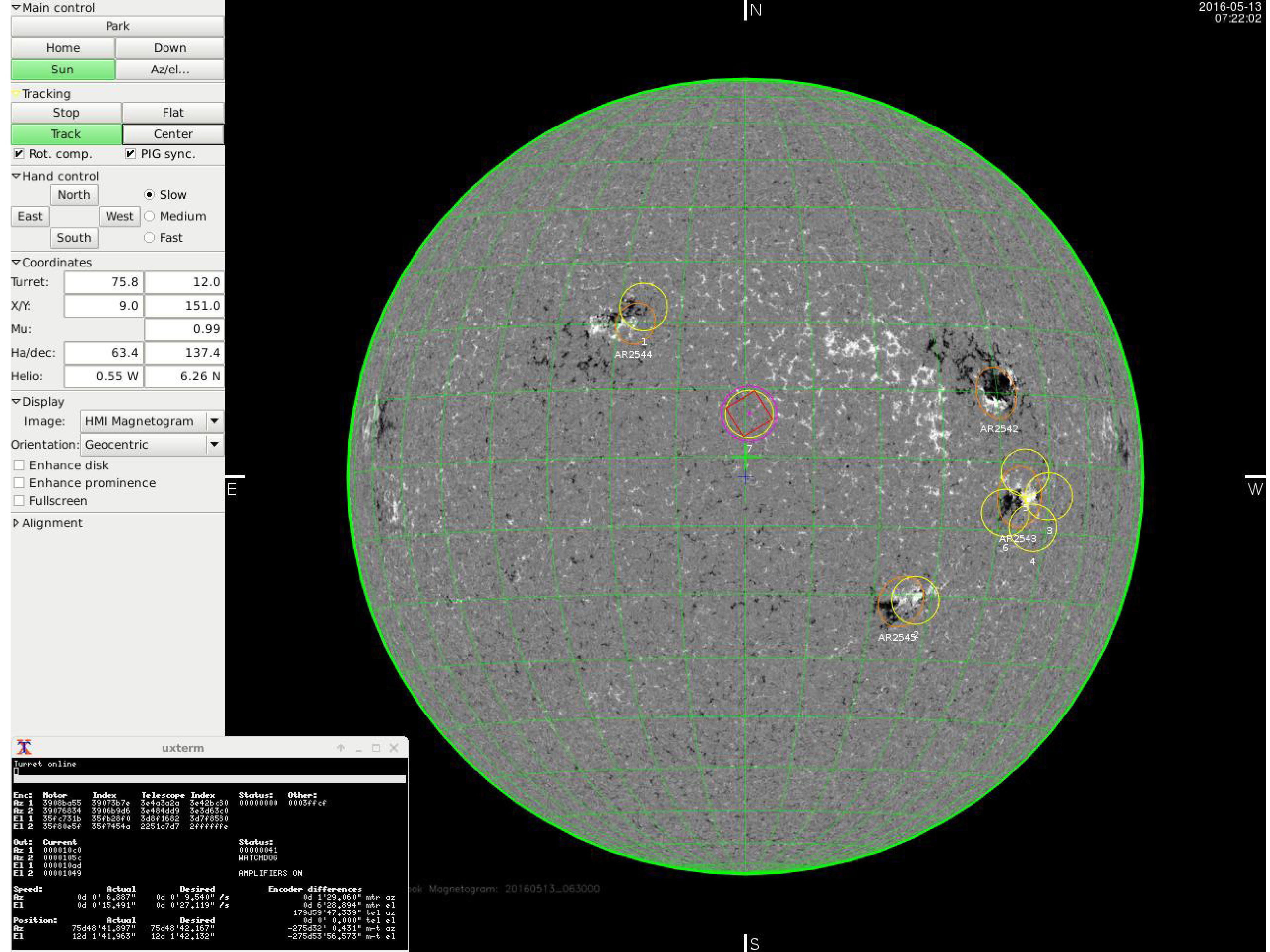
General uncertainty of the Hα and Ca II 8542 Å line profiles intensities, most likely due to global oscillation modes, is about **±2%**.

# Discussion of data uncertainties



# Discussion of data uncertainties





Main control
Park
Home
Down
Sun
Az/el...
Tracking
Stop
Flat
Track
Center
Rot. comp.
PIG sync.
Hand control
North
Slow
East
West
Medium
South
Fast
Coordinates
Turret: 75.8 12.0
X/Y: 9.0 151.0
Mu: 0.99
Ha/dec: 63.4 137.4
Helio: 0.55 W 6.26 N
Display
Image: HMI Magnetogram
Orientation: Geocentric
Enhance disk
Enhance prominence
Fullscreen
Alignment
N
S
E
W
2016-05-13
07:22:02
AR2544
AR2542
AR2543
AR2545
uxterm
Turret online
Enc: Motor Index Telescope Index Status: Other:
Az 1 3908ba55 39073b7e 3e4a3a2a 3e42bc80 00000000 0003ffcf
Az 2 39076834 3906b9d6 3e484dd9 3e3d63c0
El 1 35fc731b 35fb28f0 3d8f1682 3d7f8580
El 2 35f80e5f 35f7454a 2251a7d7 2ffffffe
Out: Current Status:
Az 1 000010c0 00000041
Az 2 0000105c WATCHDOG
El 1 000010ad
El 2 00001049 AMPLIFIERS ON
Speed: Actual Desired Encoder differences
Az 0d 0' 6,887" 0d 0' 9,540" /s 0d 1'29,060" mtr az
El 0d 0'15,491" 0d 0'27,119" /s 0d 6'28,894" mtr el
179d59'47,339" tel az
Position: Actual Desired 0d 0' 0,000" tel el
Az 75d48'41,897" 75d48'42,167" -275d32' 0,431" m-t az
El 12d 1'41,963" 12d 1'42,132" -275d53'56,573" m-t el

# Results summary

- the new version of the modified cloud model by Liu & Ding (2001) was applied to infer parameters of chromospheric jet observed simultaneously in the H$\alpha$ and Ca II 8542
- the source functions of H$\alpha$ and Ca II 8542 Å **increase** from the jet core towards its outer limits
- the line center optical thicknesses of H$\alpha$ and Ca II 8542 Å **decrease** from the jet core outwards
- the jet is optically thicker in Ca II 8542 Å ($\tau_0 \approx 0.82$) than in H$\alpha$ ($\tau_0 \approx 0.7$)
- the jet shows single-peak distribution of the Doppler width $\Delta\lambda_D$ for H$\alpha$ but double-peak distribution for Ca II 8542 Å.
- larger Doppler velocity $v_{LOS}$ measured in H$\alpha$ than in Ca II 8542 Å
- signature of **bi-directional flow** in Ca II 8542 Å Doppler velocity

# Special thanks to

EU-7FP-SOLARNET Transnational Access and Service Programme
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SST/CRISP data processing: Luc Rouppe van der Voort

(Institute of Theoretical Astrophysics, University of Oslo)