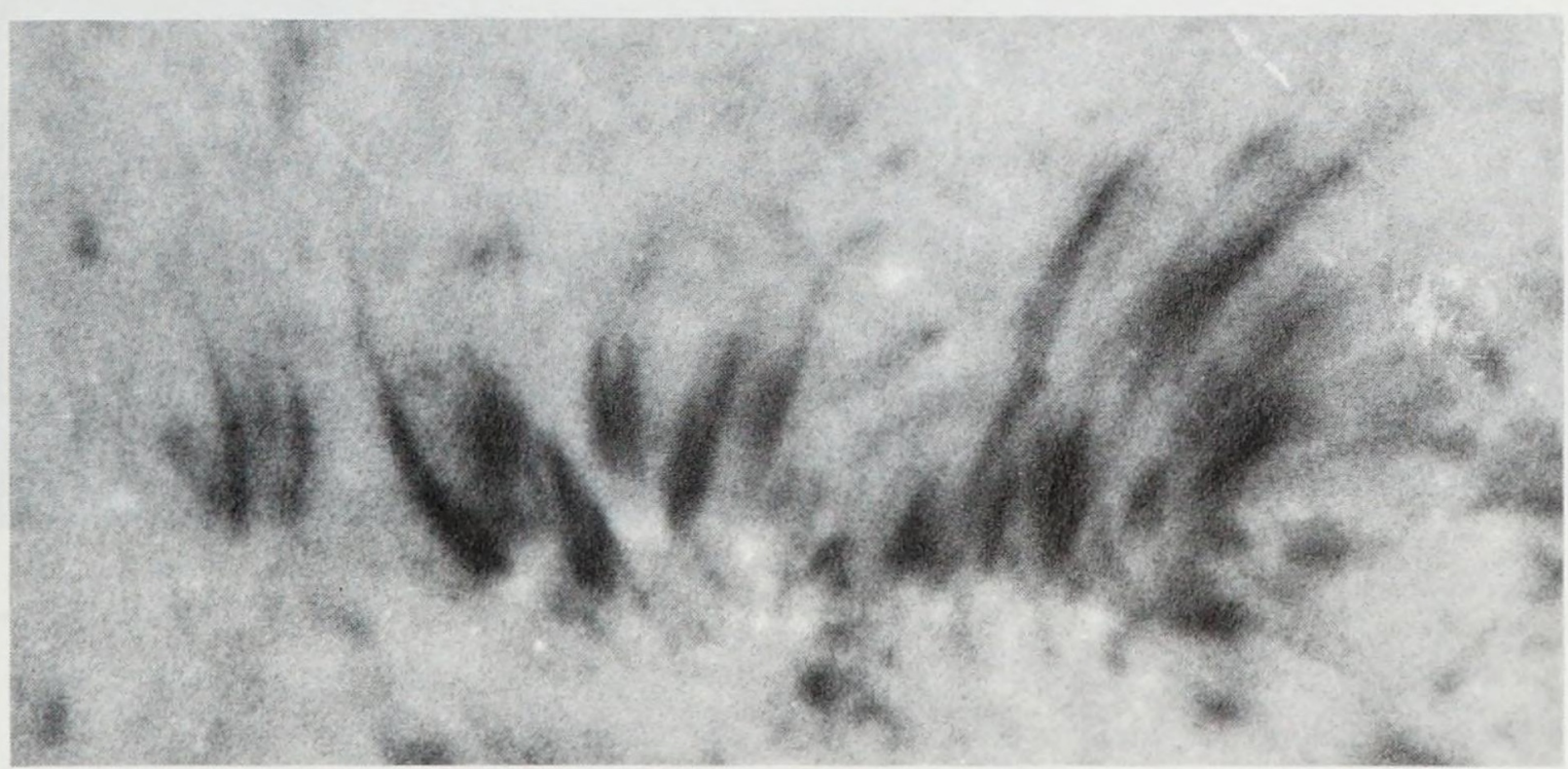


Dynamics of the Solar Chromosphere

Kevin Reardon

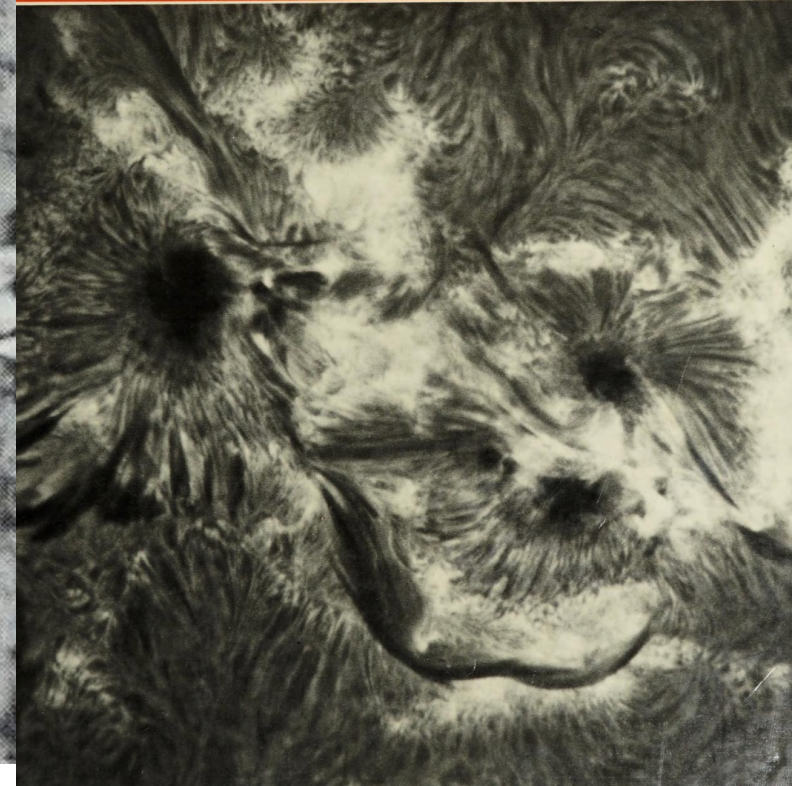
National Solar Observatory

5 SEP 1971



ASTROPHYSICS OF THE SUN

HAROLD ZIRIN





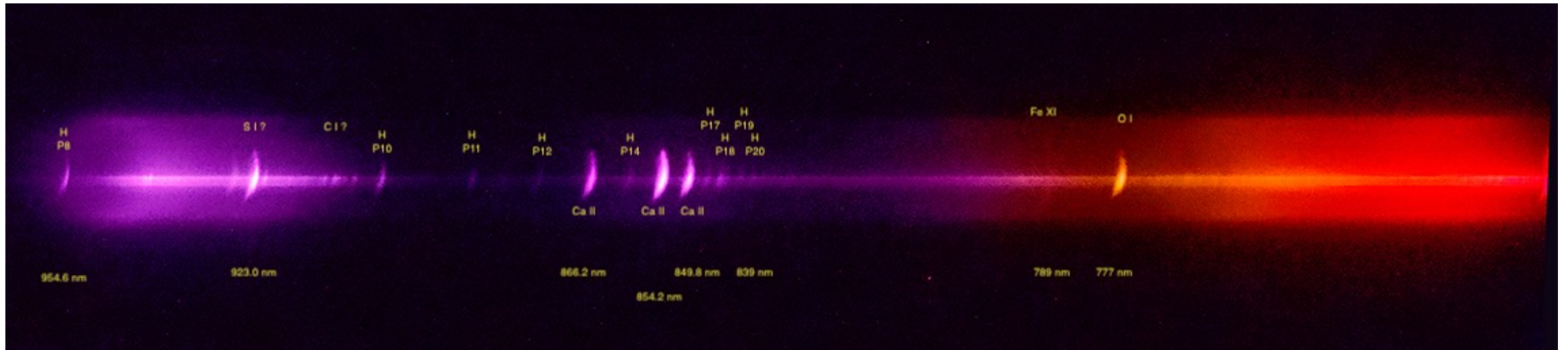
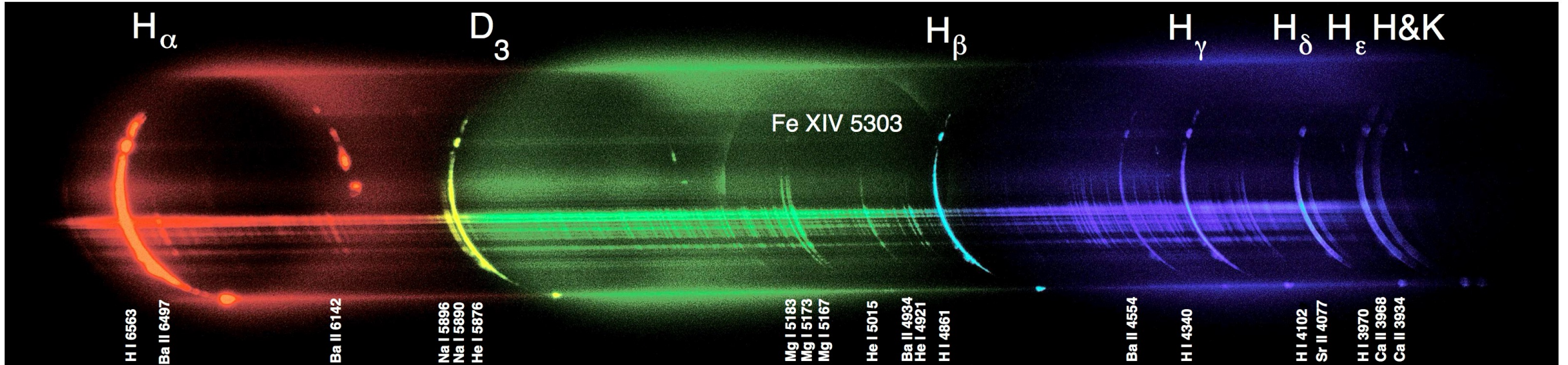
What we're going to talk about

- What are some dominant dynamic behaviors in the chromosphere?
- What are some of the key (ground-based) diagnostics of the chromosphere?
- What are the key parameters that we want measure or derive?
- How does the chromosphere conspire to make this all very confusing?

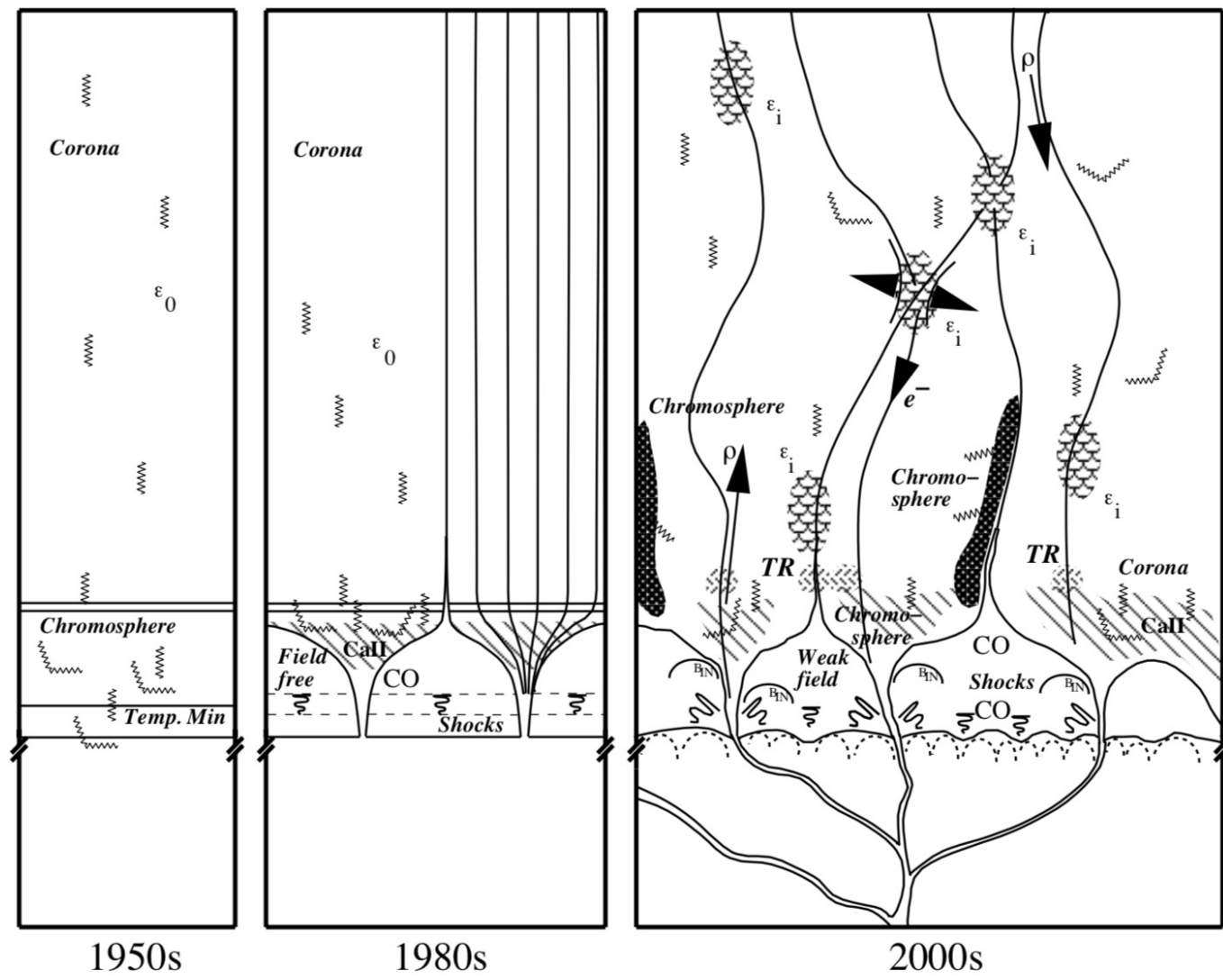
Emphasis on ground-based diagnostics

Flares and polarimetry already covered

The Chromosphere, Our Colorful Friend

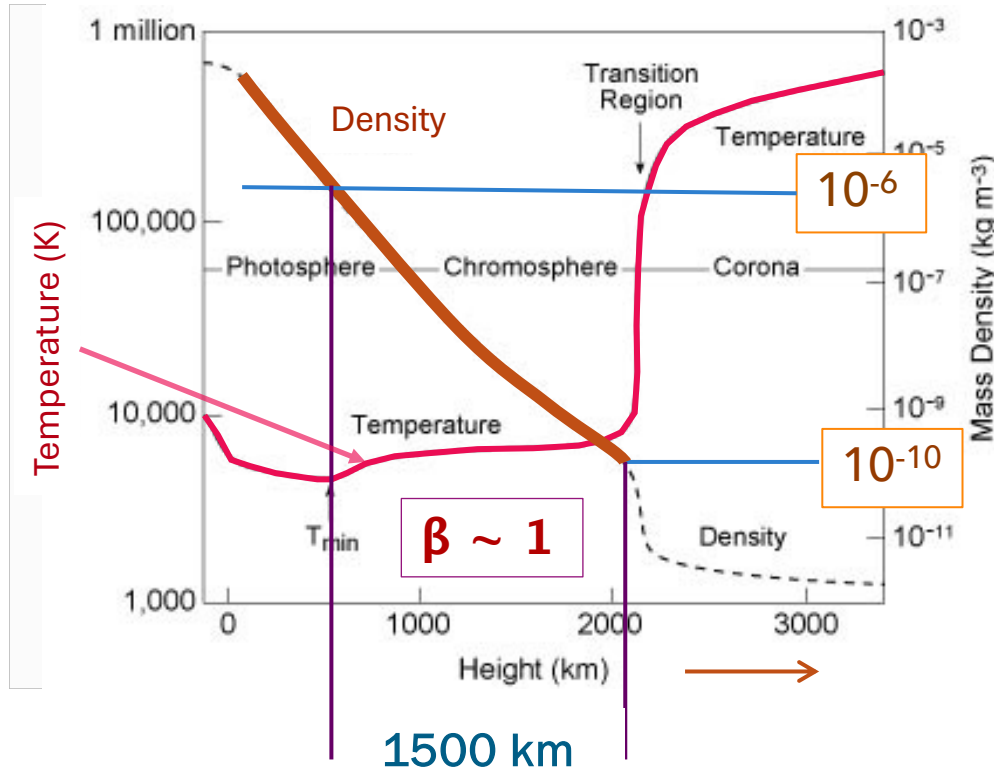


The evolving chromosphere



Cartoon courtesy Carl Schrijver

Chromospheric Density Decrease

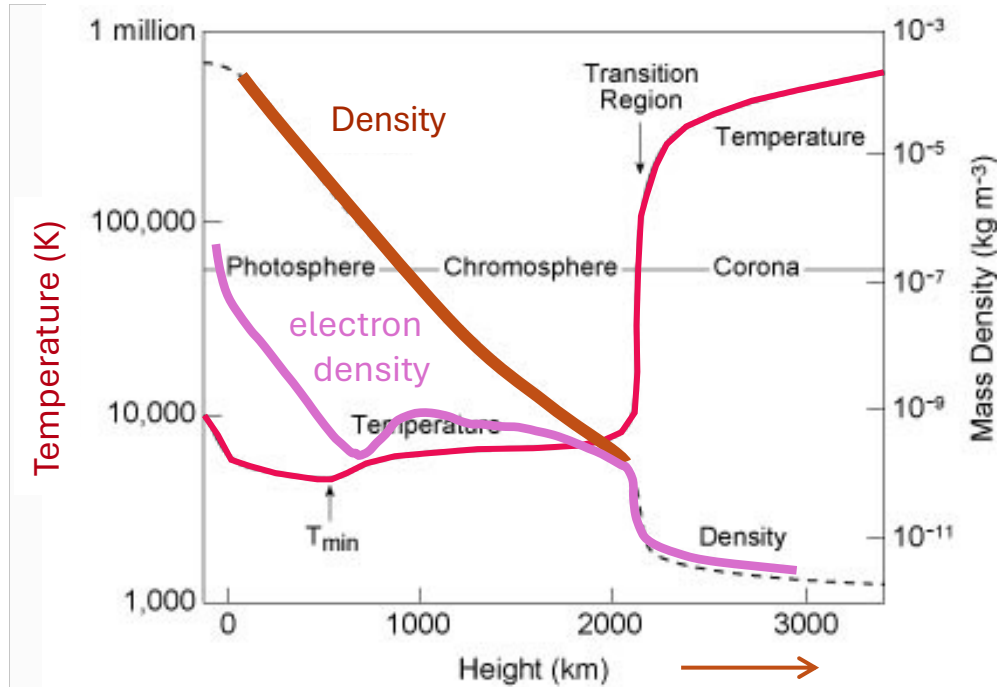


Balance between magnetic field and gas pressure changes (plasma β):

$$\beta = \frac{2\mu_0 P}{B^2}$$

As pressure decreases,
 $\beta < 1$,
magnetic field dominates
over plasma pressure.

Chromospheric Density Decrease

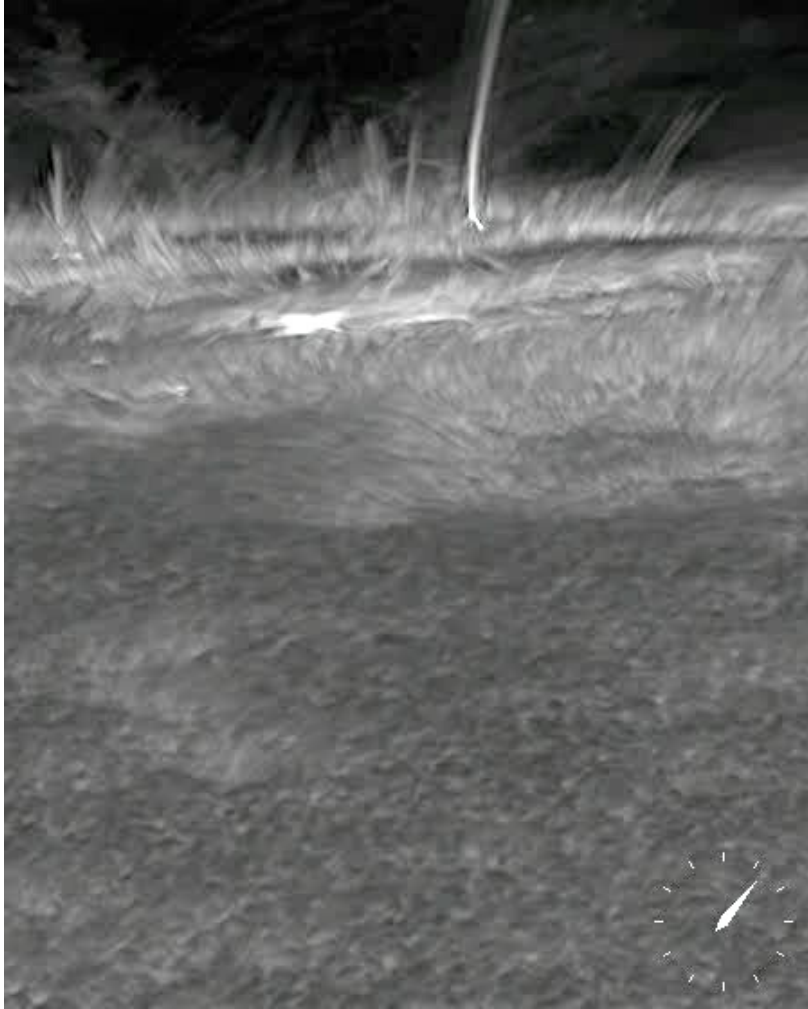


Balance between magnetic field and gas pressure changes (plasma β):

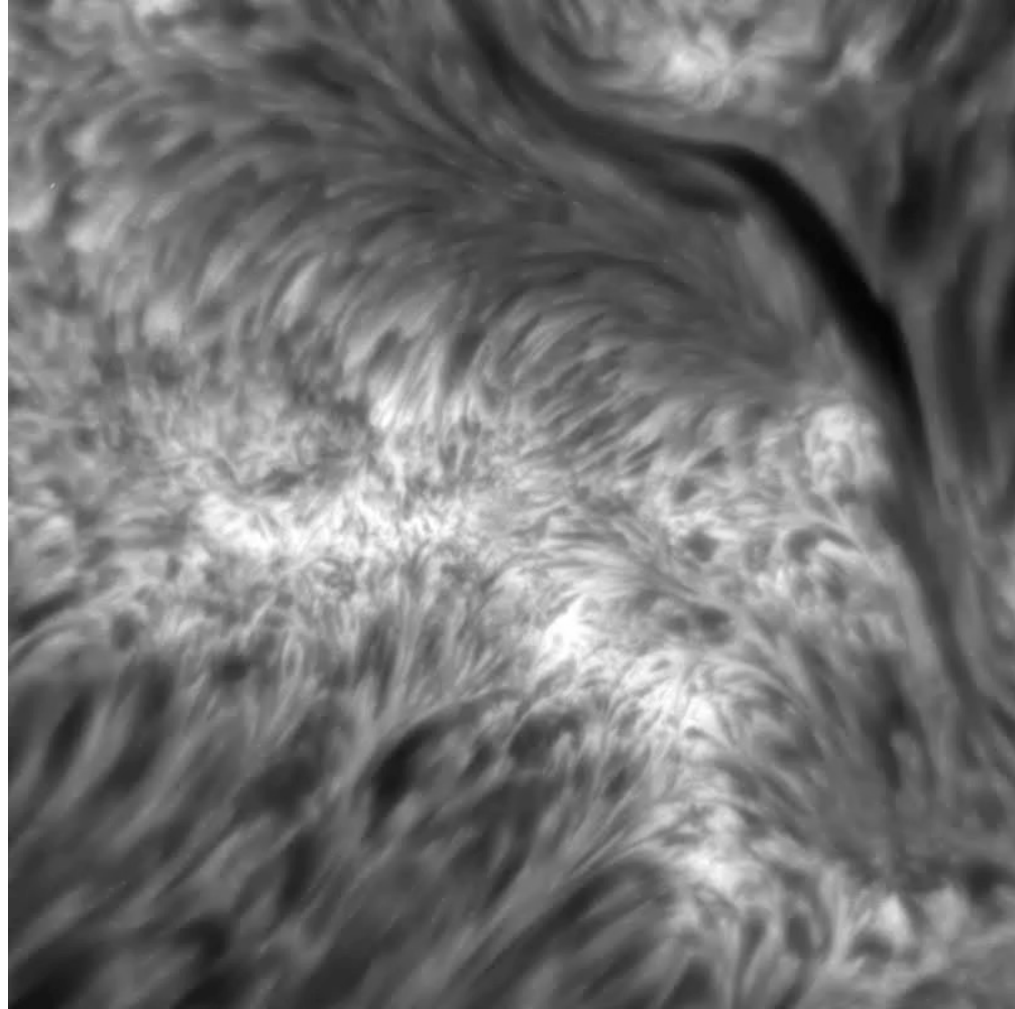
$$\beta = \frac{2\mu_0 P}{B^2}$$

As pressure decreases,
 $\beta < 1$,
magnetic field dominates
over plasma pressure.

The dynamic chromosphere

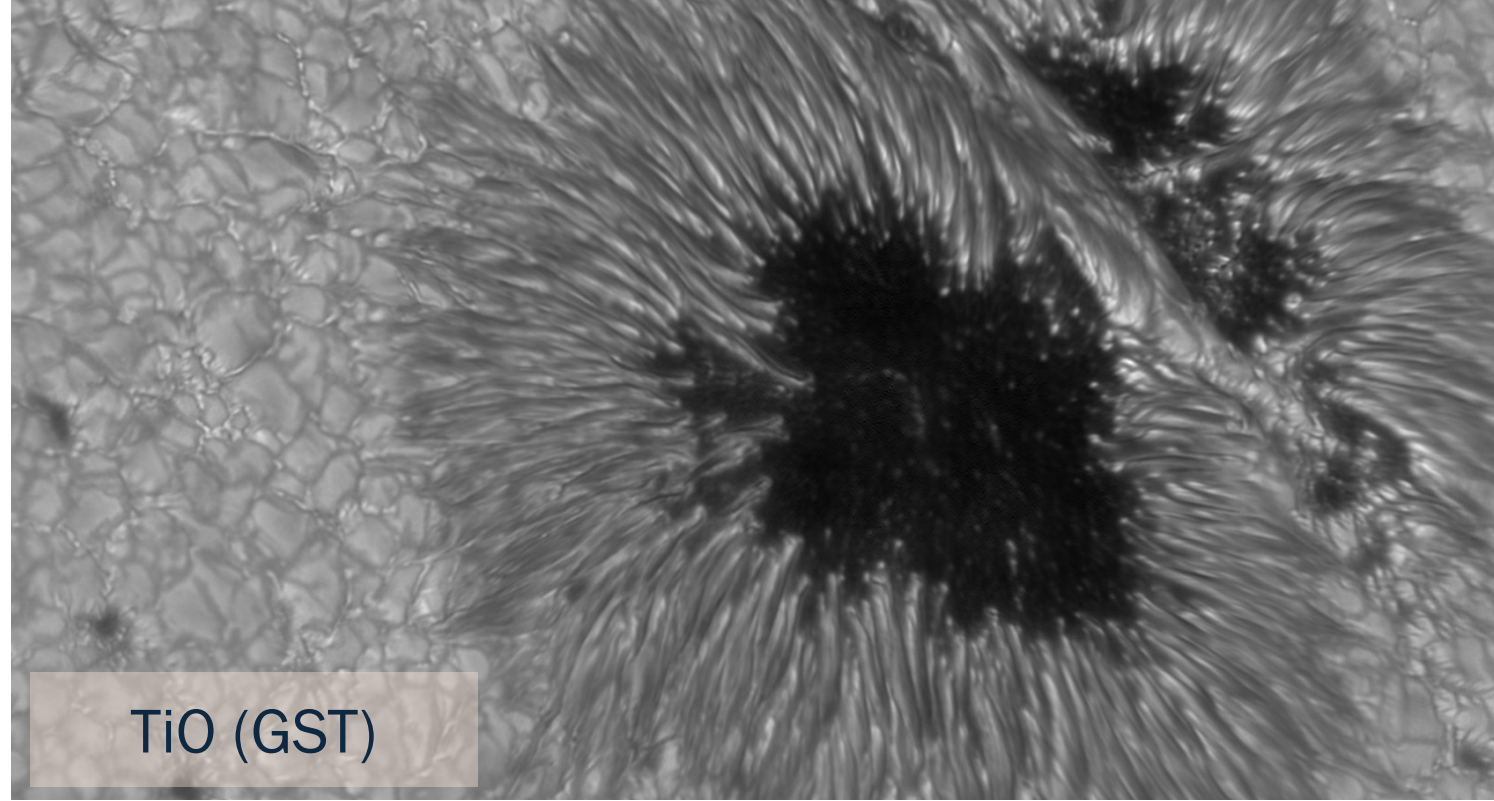
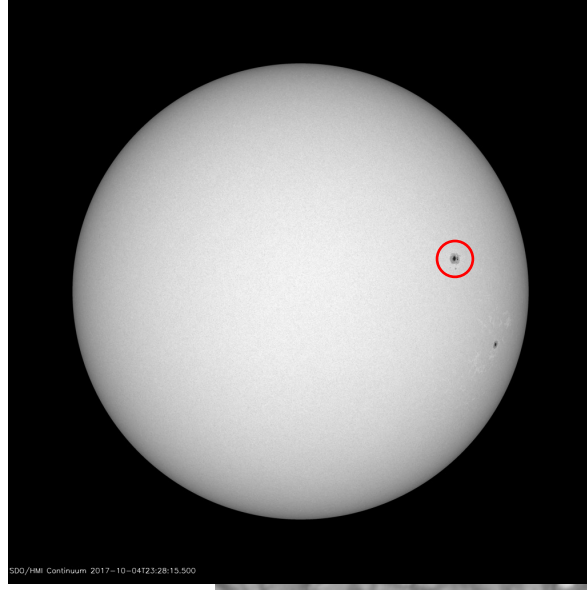


Ca II H (Hinode/SOT)

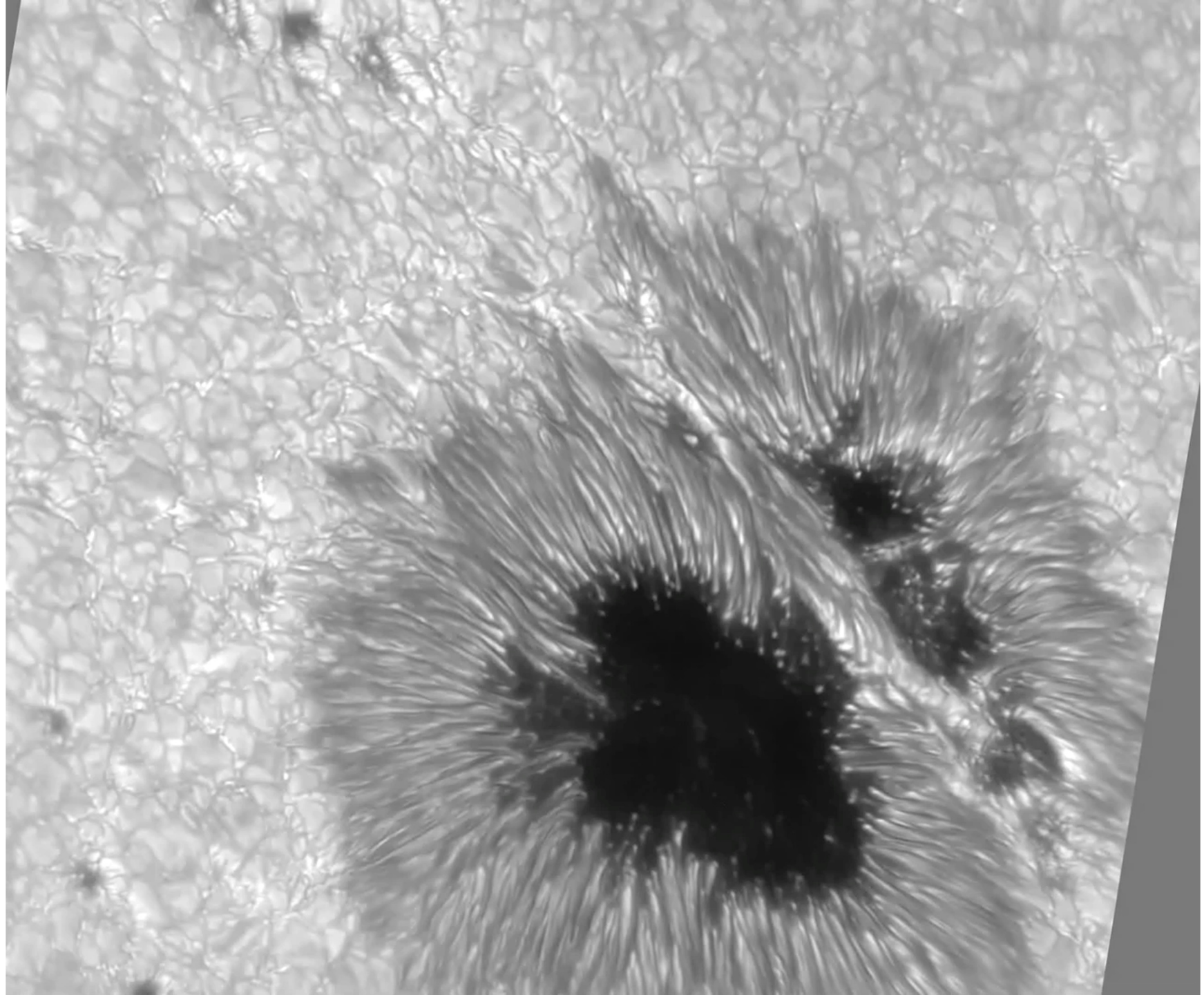


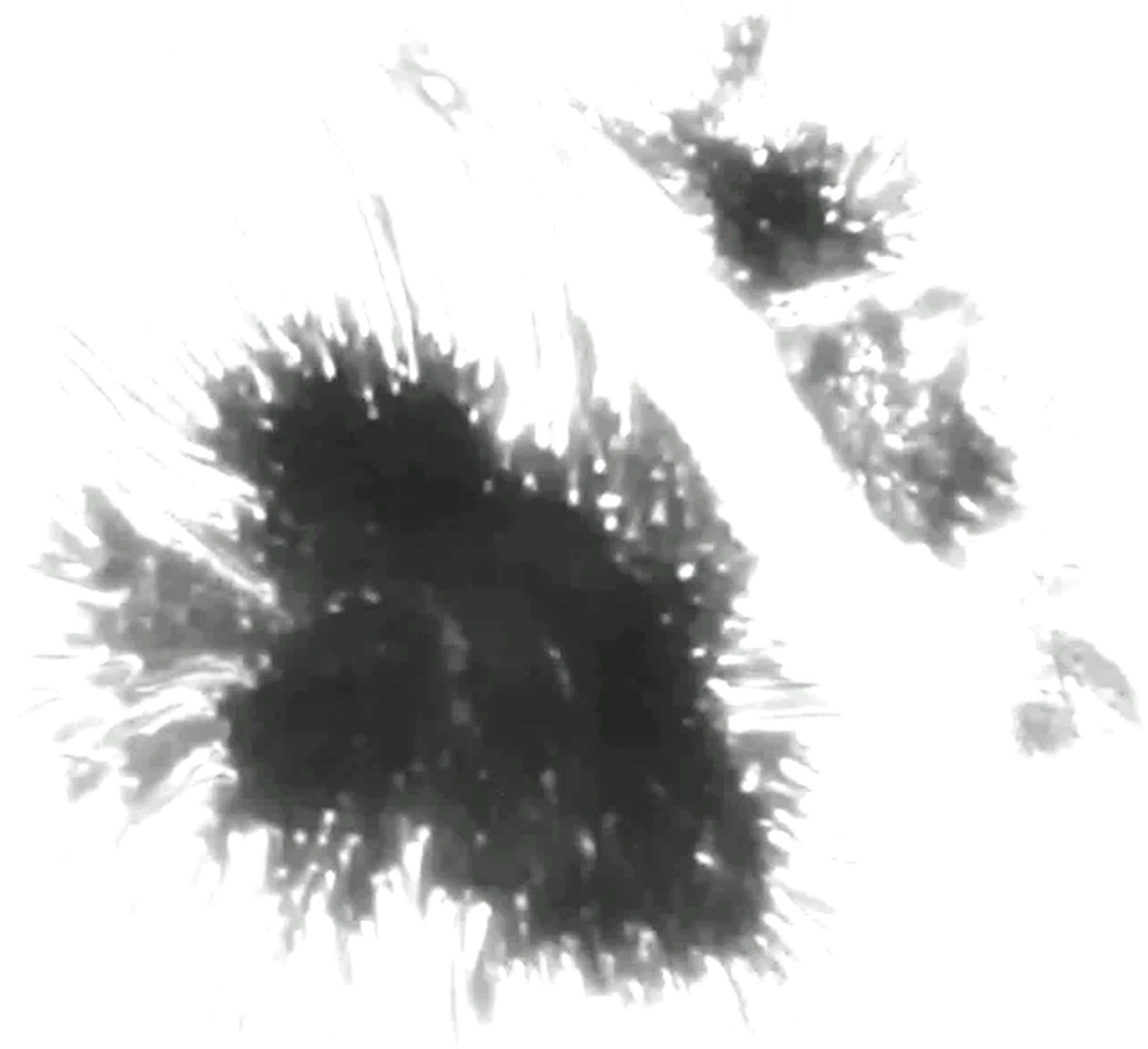
H α (DST/IBIS)

04 Oct, 2018

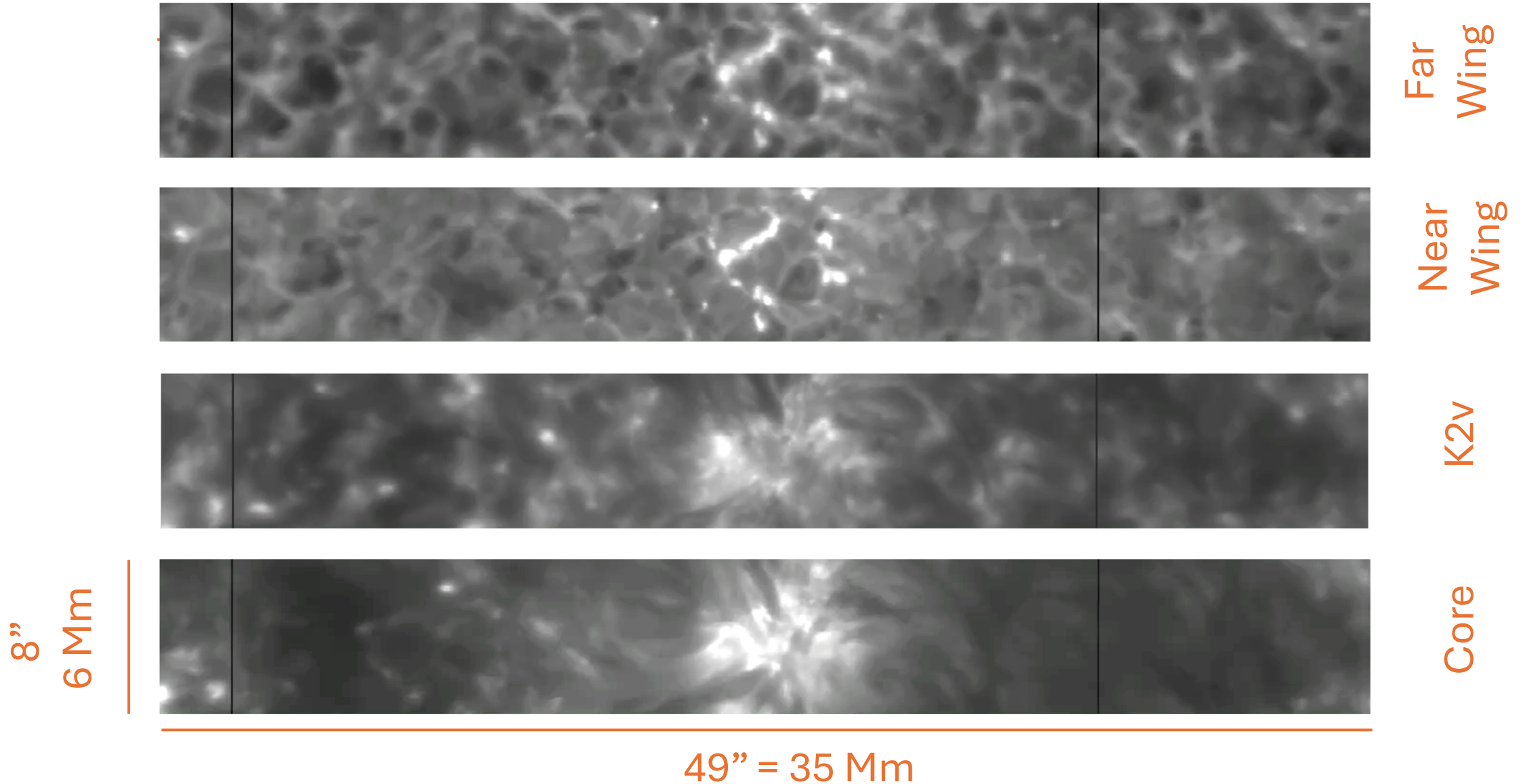


43" = 31 Mm

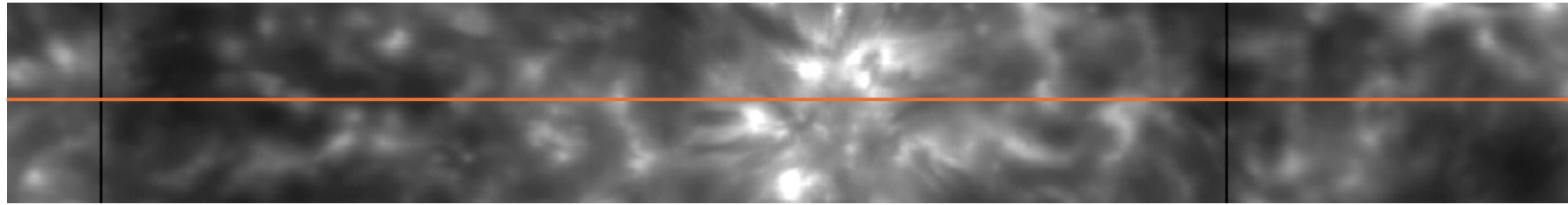




DKIST/ViSP Ca II K Scan Sequence



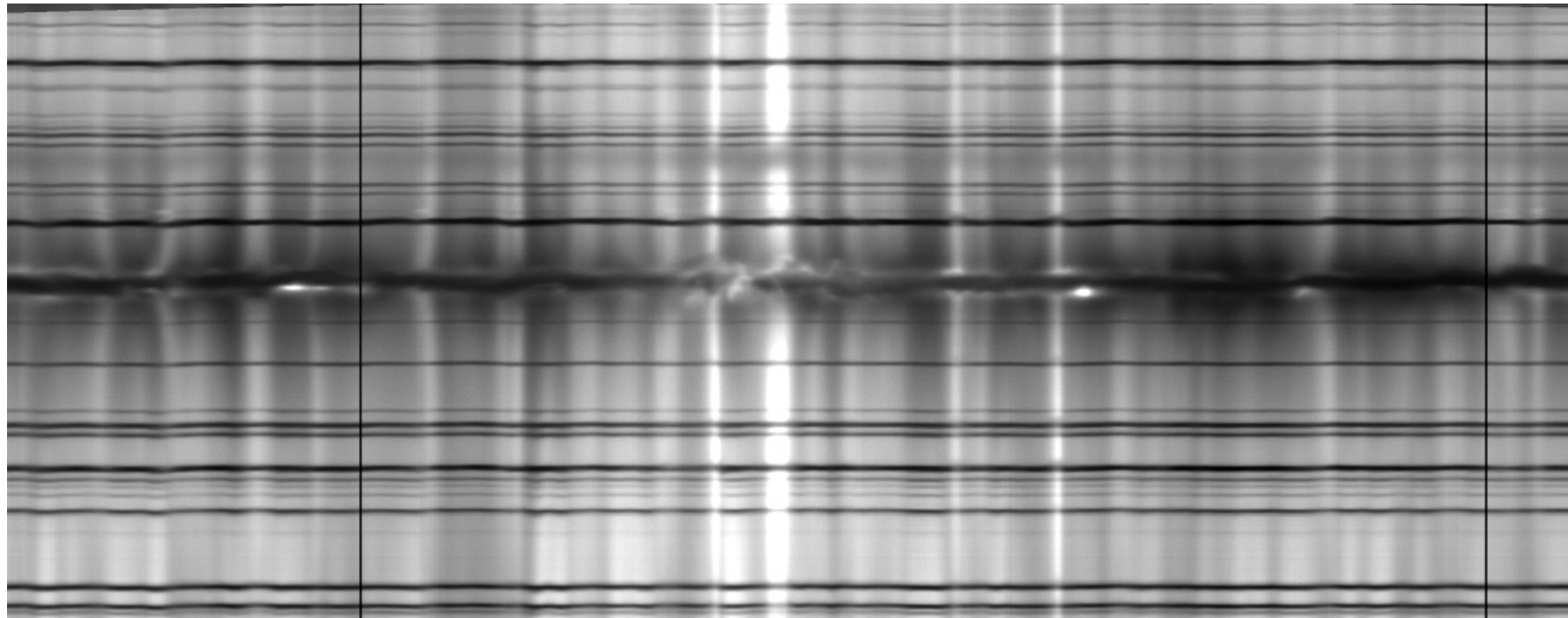
DKIST/ViSP Ca II K Fixed Slit Time Series



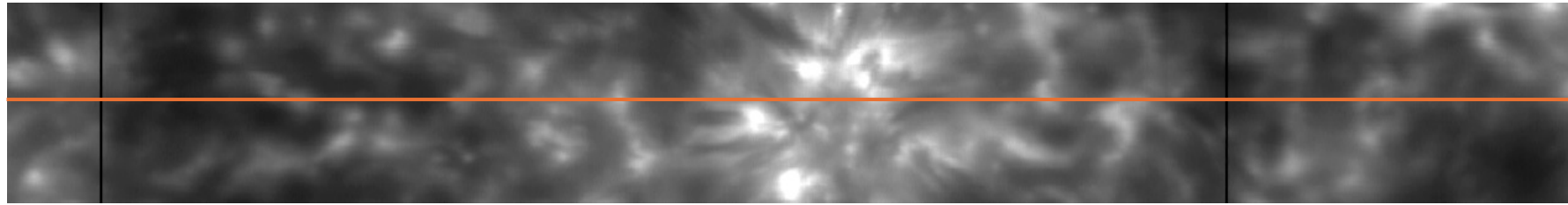
8"
6 Mm

49" = 35 Mm

6 Å



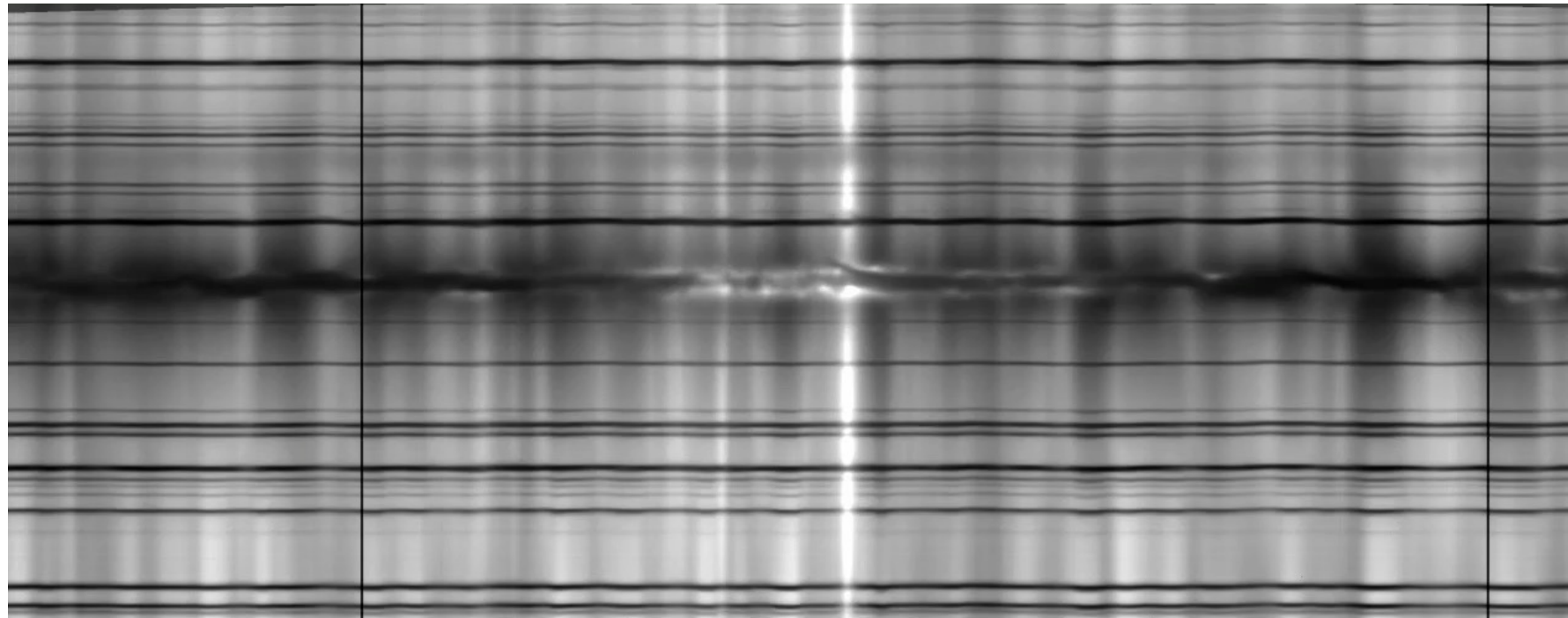
DKIST/ViSP Ca II K Fixed Slit Time Series



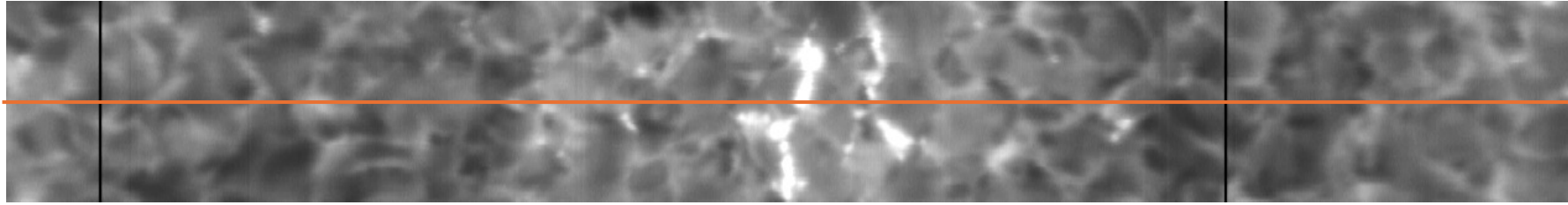
8"
6 Mm

49" = 35 Mm

6 Å



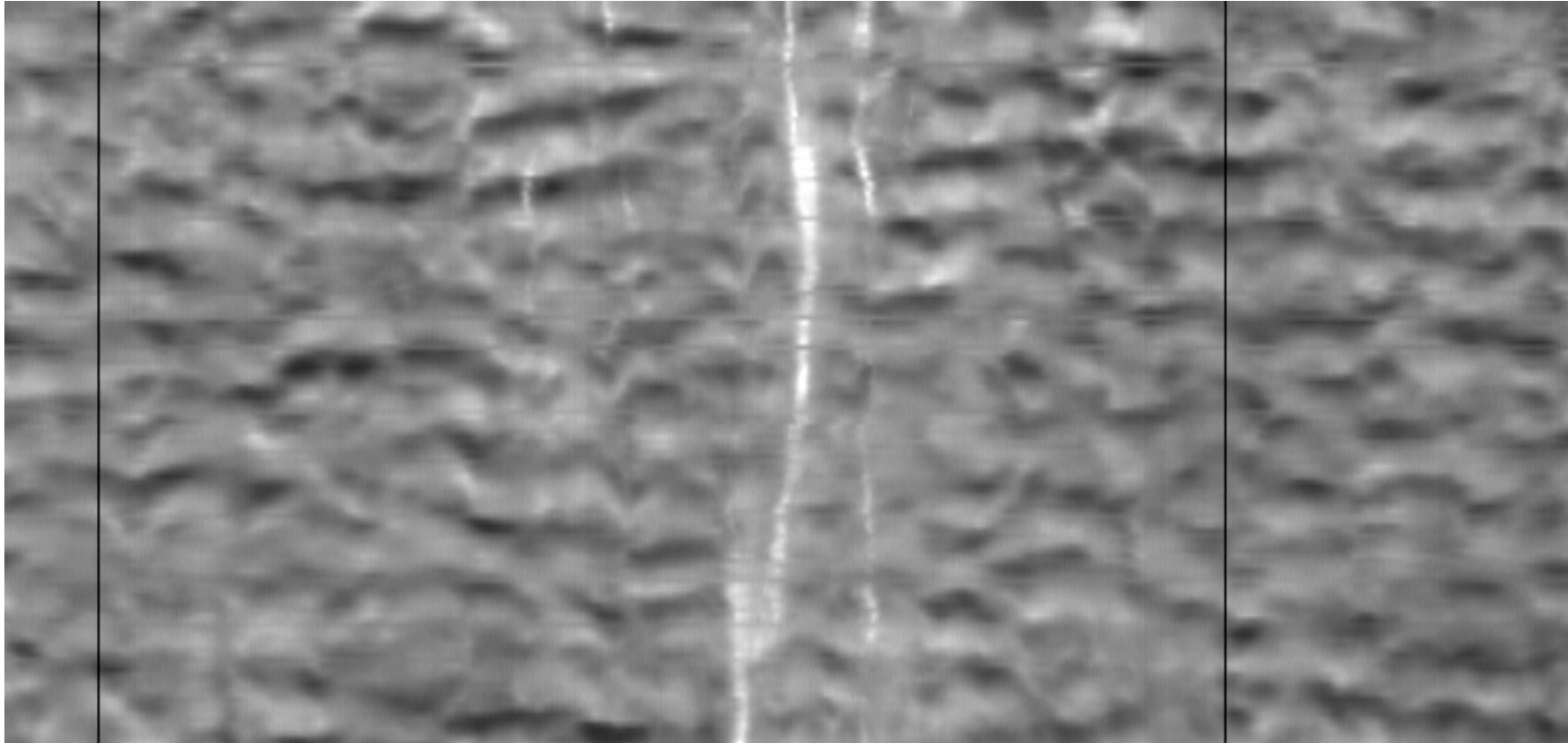
Ca II K Line Wing Intensity (Photosphere)



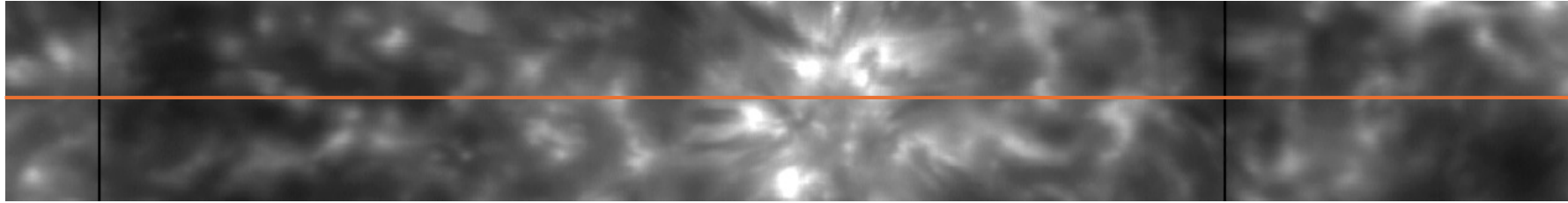
49" = 35 Mm

49" = 35 Mm

47 min



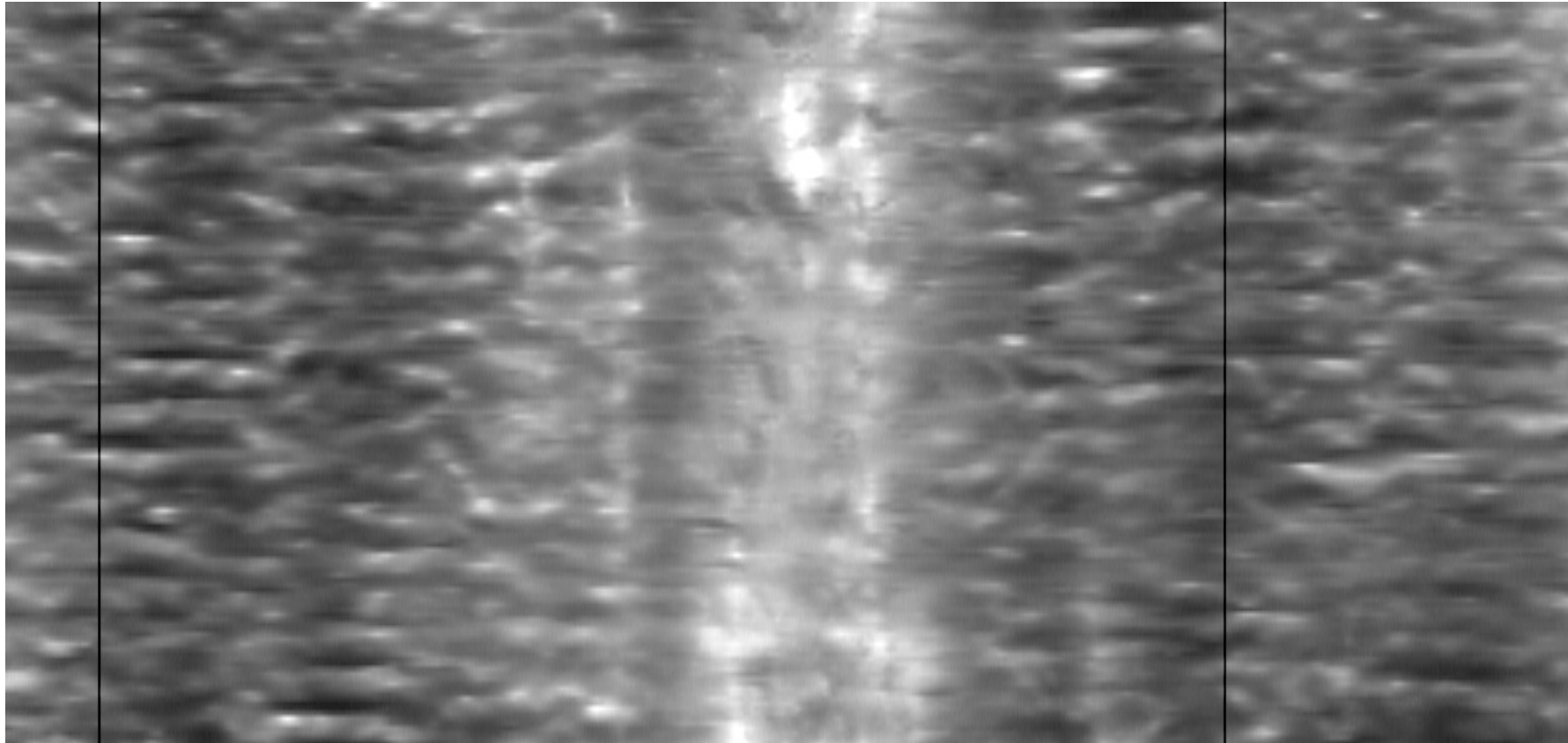
Ca II K k2v Intensity (Chromosphere)



49" = 35 Mm

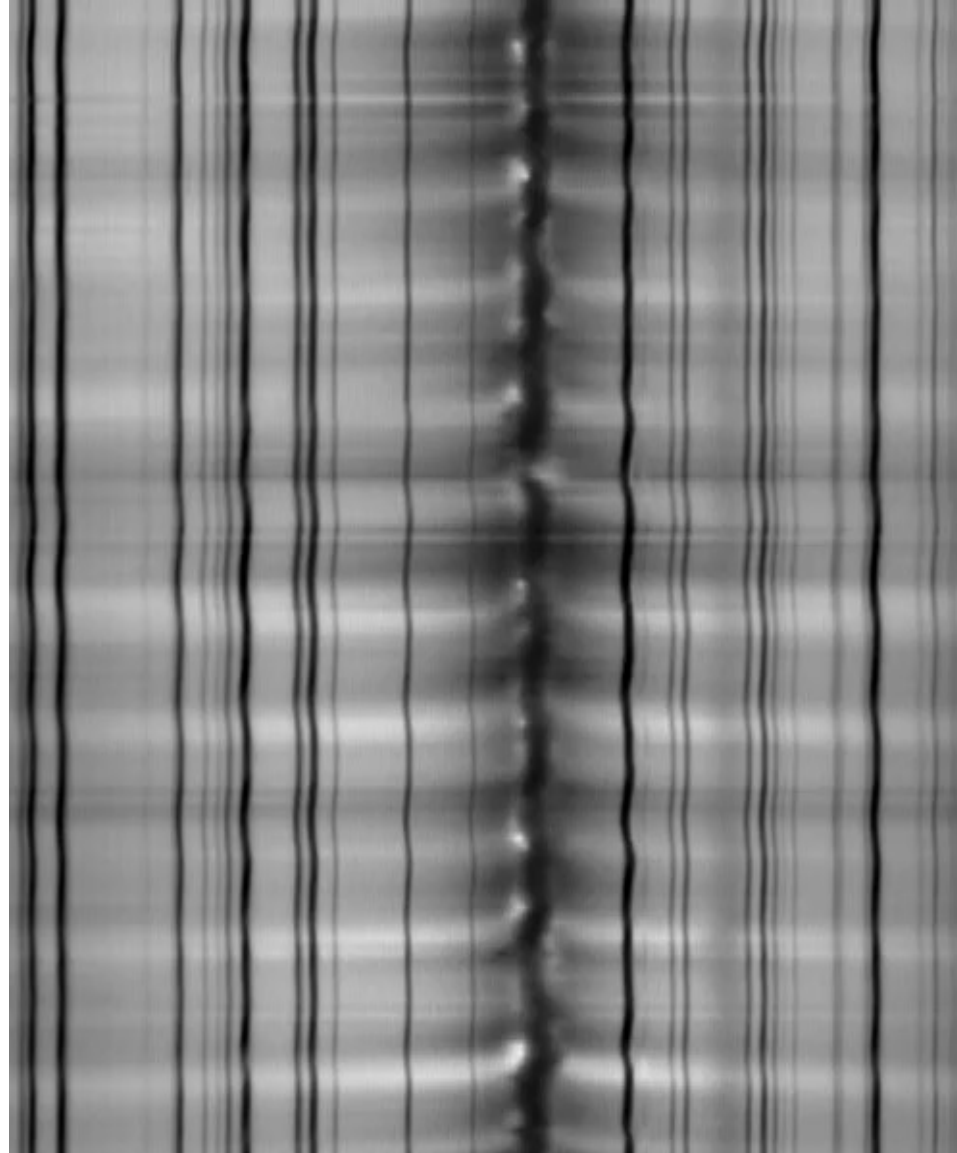
49" = 35 Mm

47 min



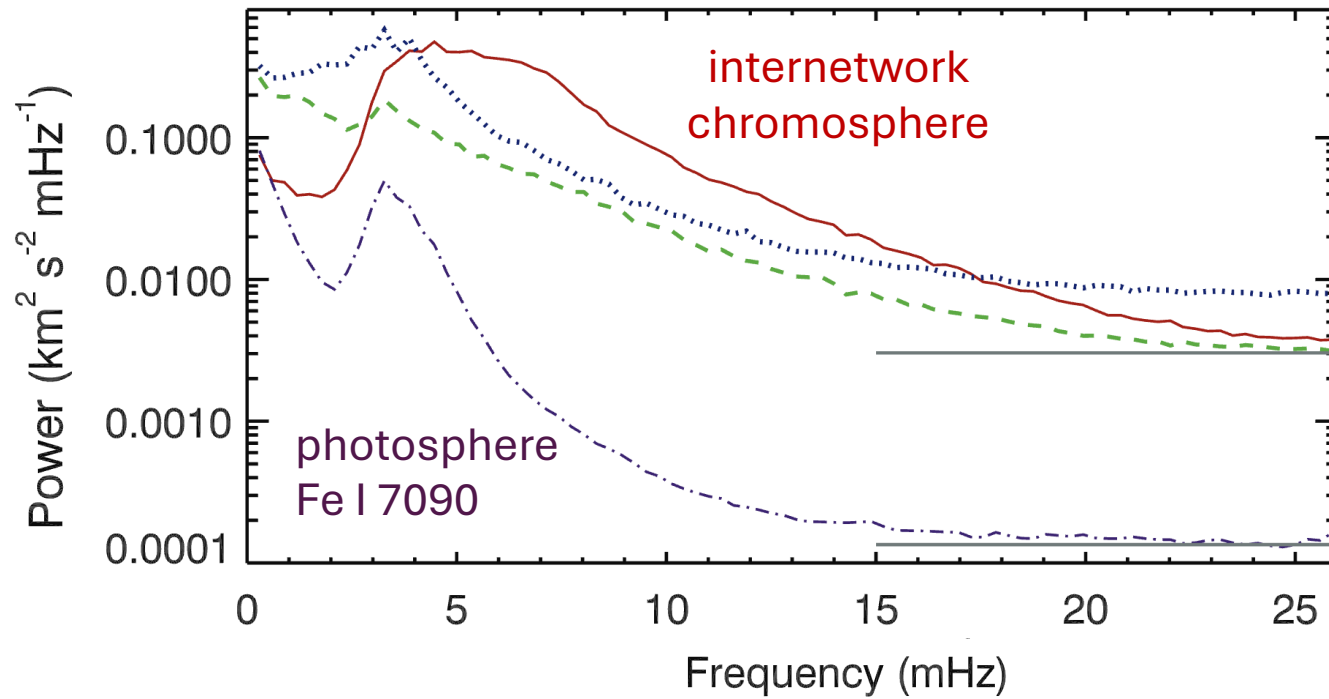
Ca II K Spectral Time Series

47 minutes

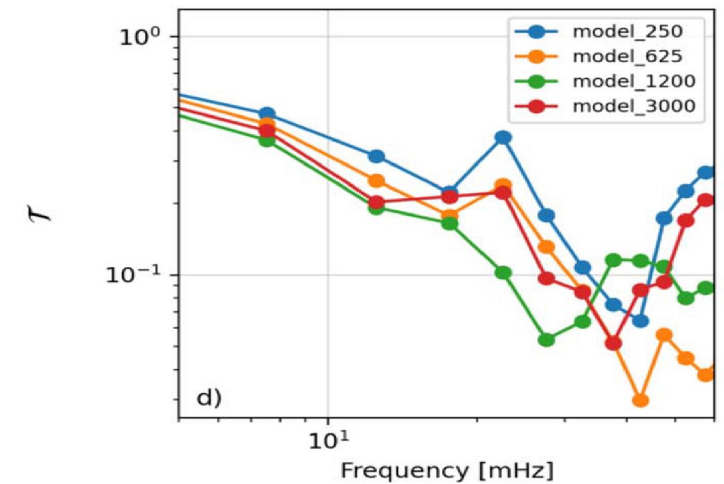
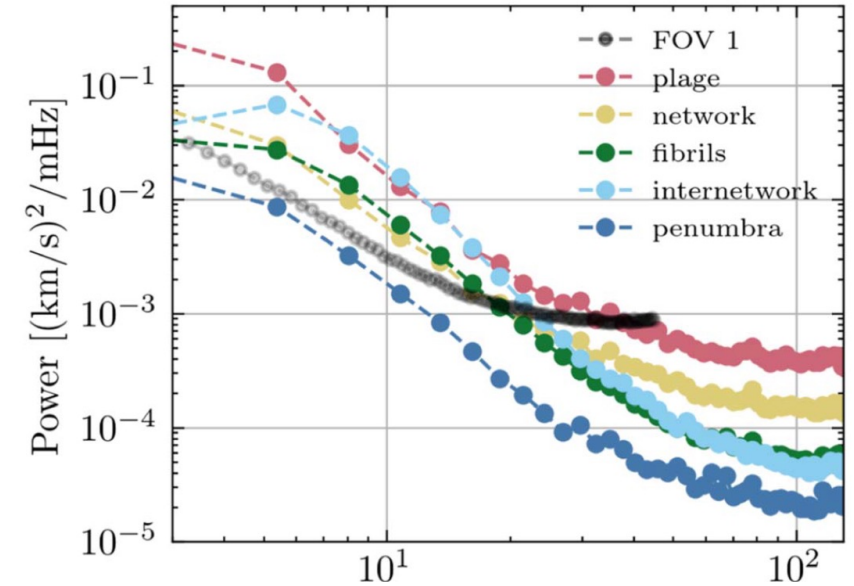


Chromospheric Wave Periods

Ca II 8542 Velocity Power Spectrum

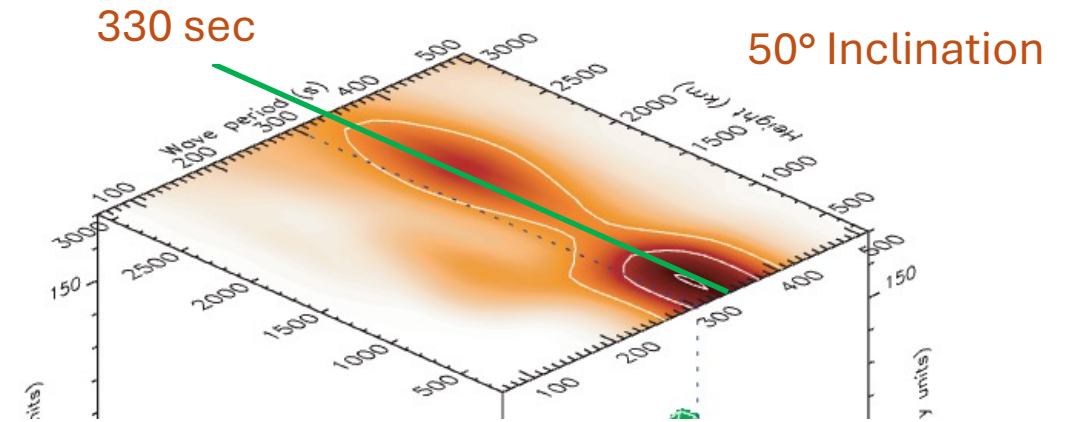
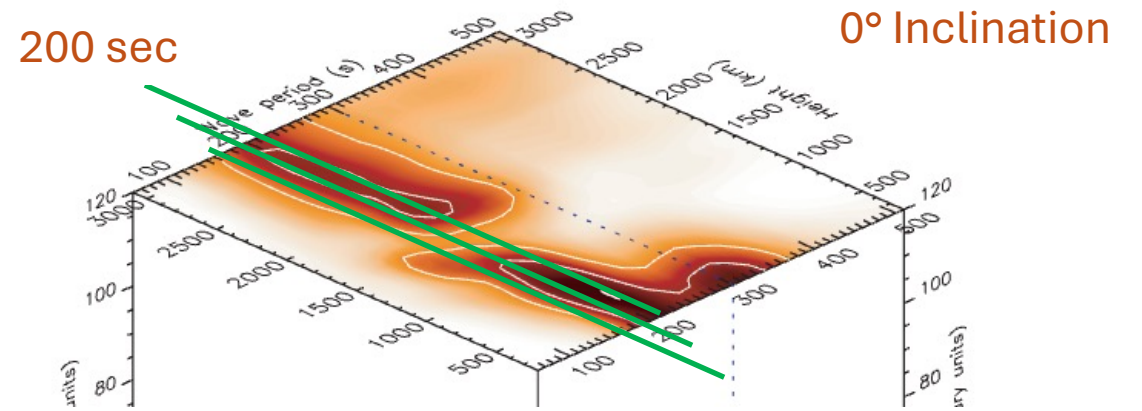
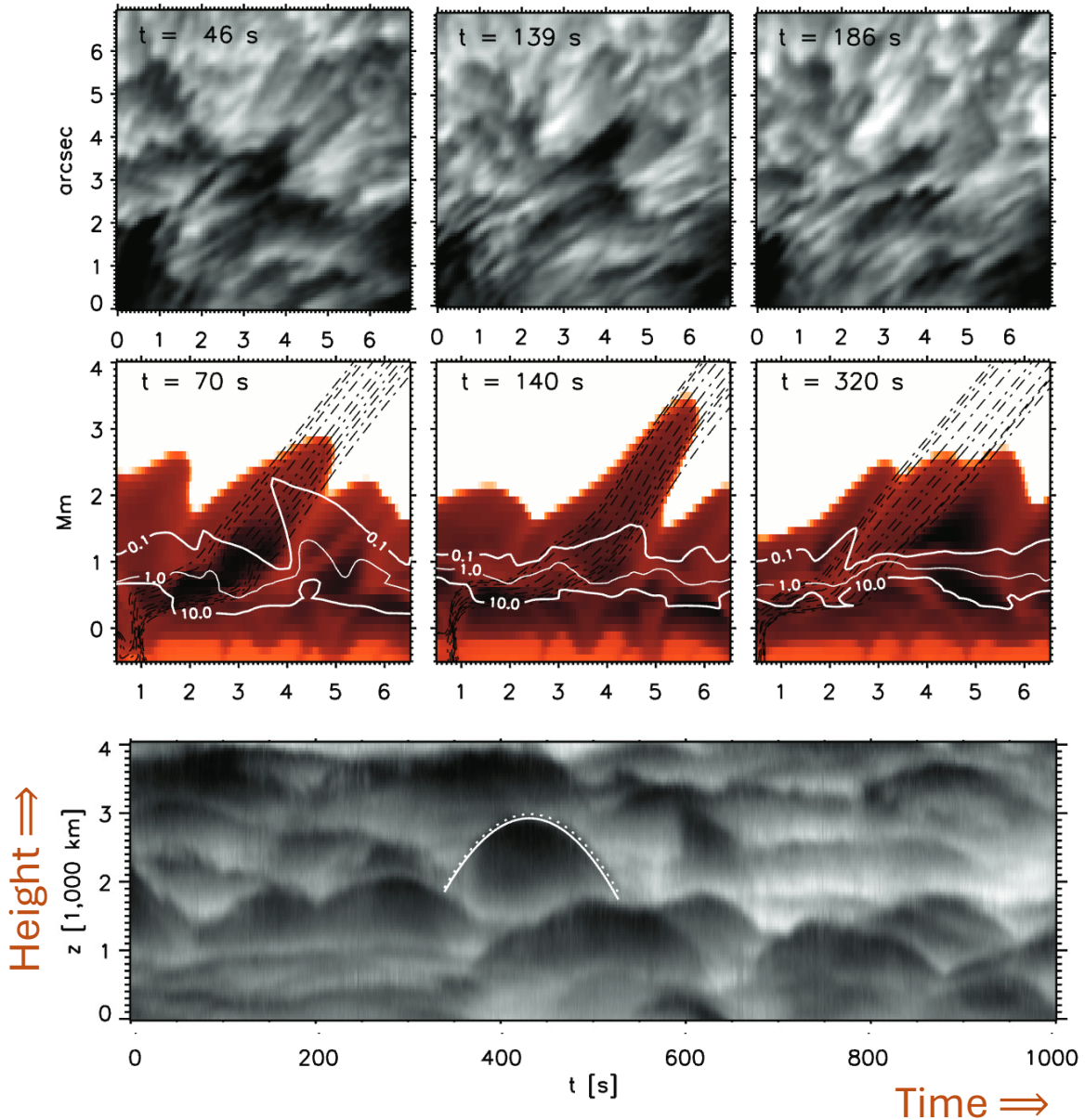


Reardon et al., 2008



Molnar et al., 2021

Power Leakage and Dynamic Fibrils (Type I Spicules)



Hansteen et al., 2006

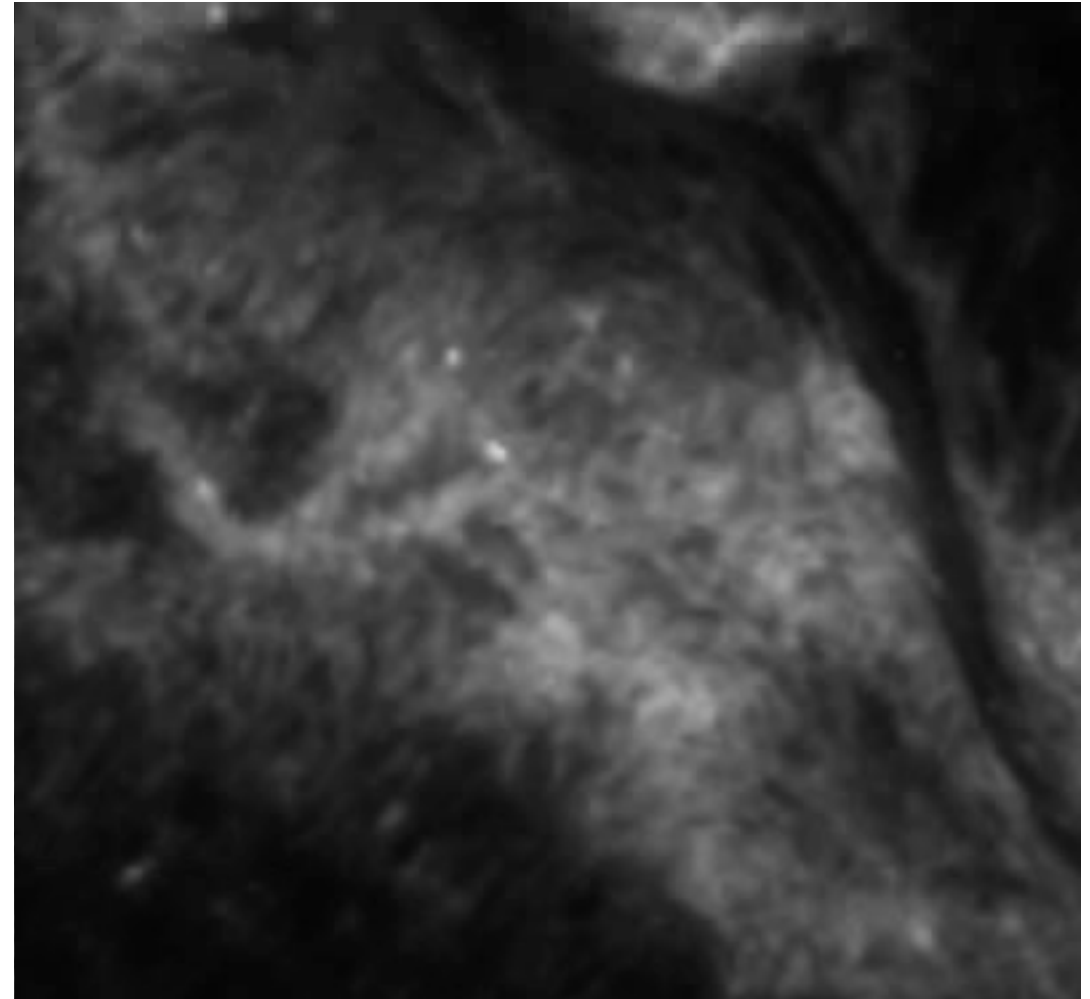
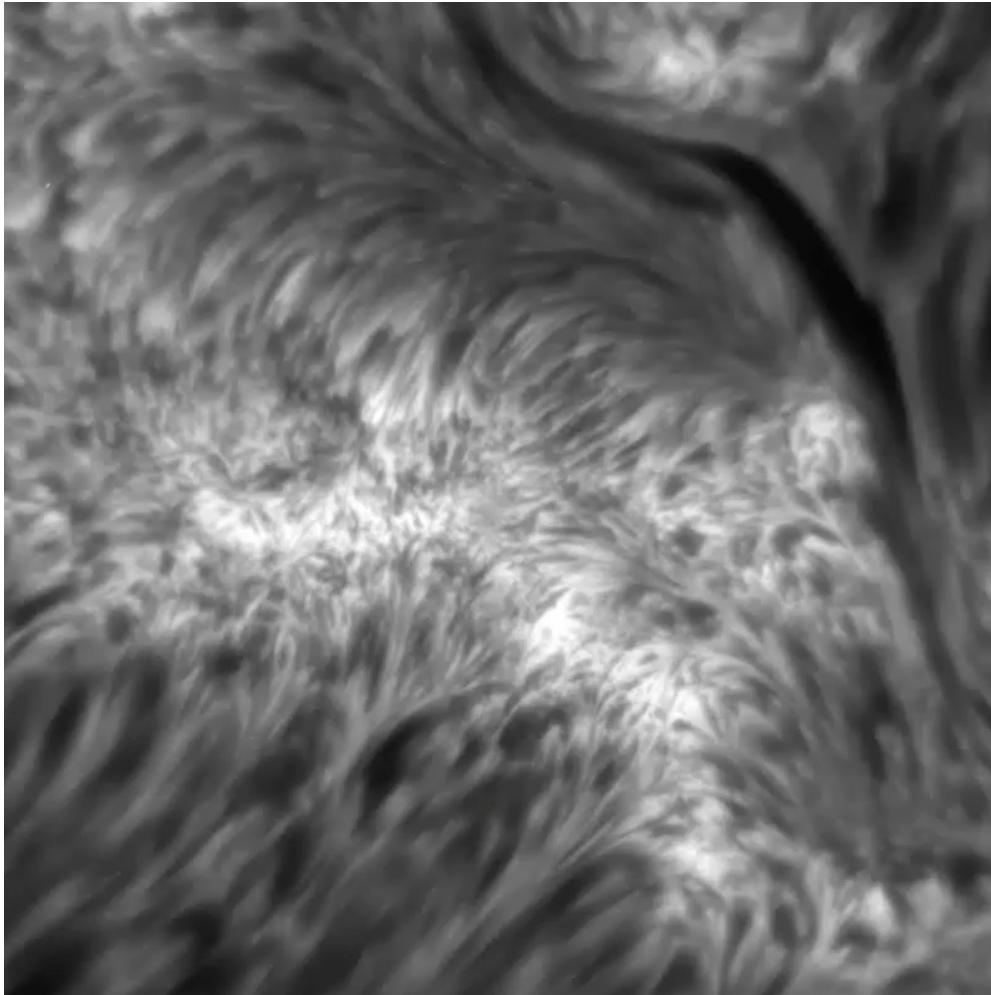
De Pontieu et al., 2004

Power Leakage and Dynamic Fibrils (Type I Spicules)

IBIS – H α

SDO/AIA – He II 304 Å

78 arcsec



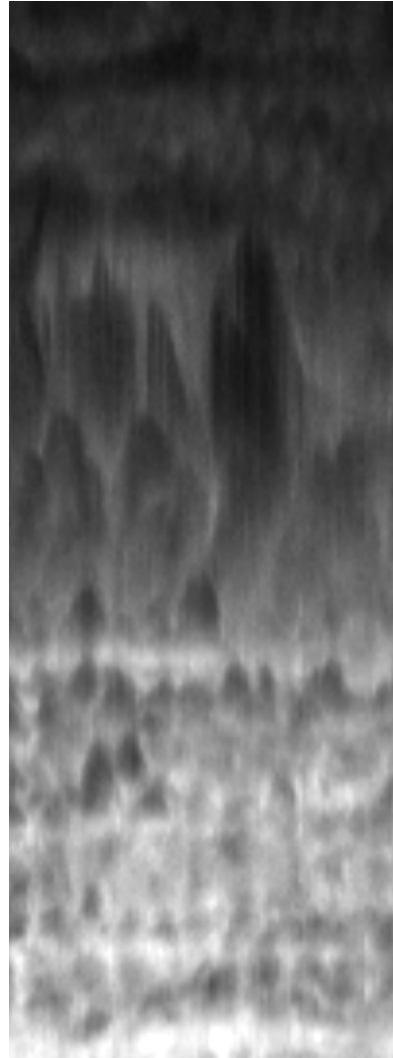
22 sec cadence

30 minute duration

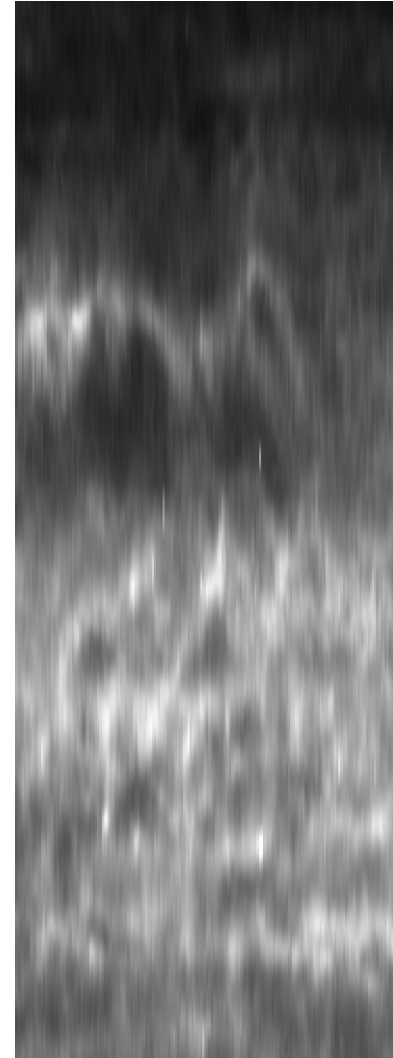
12 sec cadence

Power Leakage and Dynamic Fibrils (Type I Spicules)

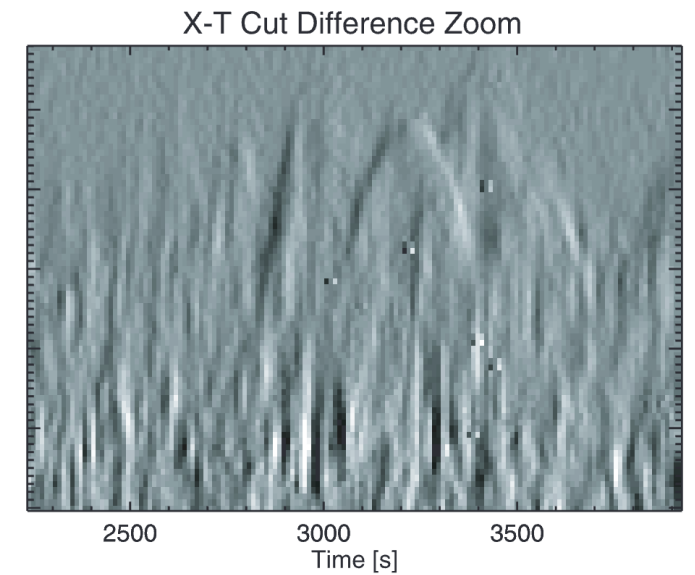
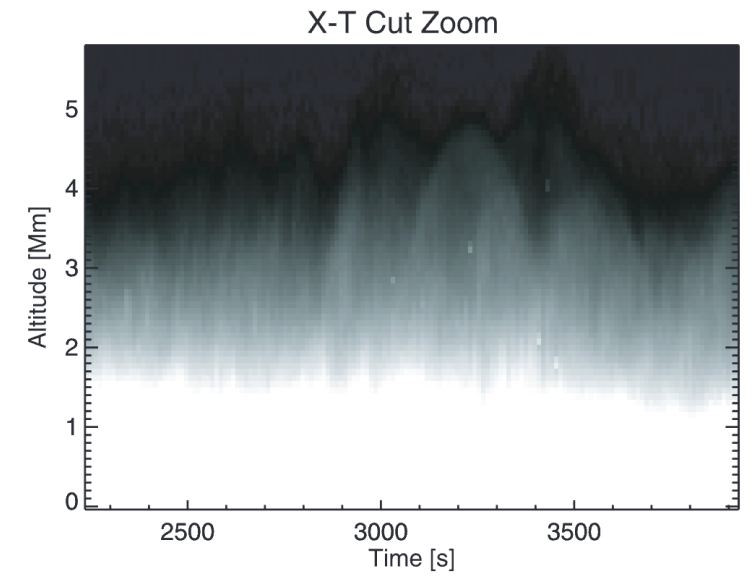
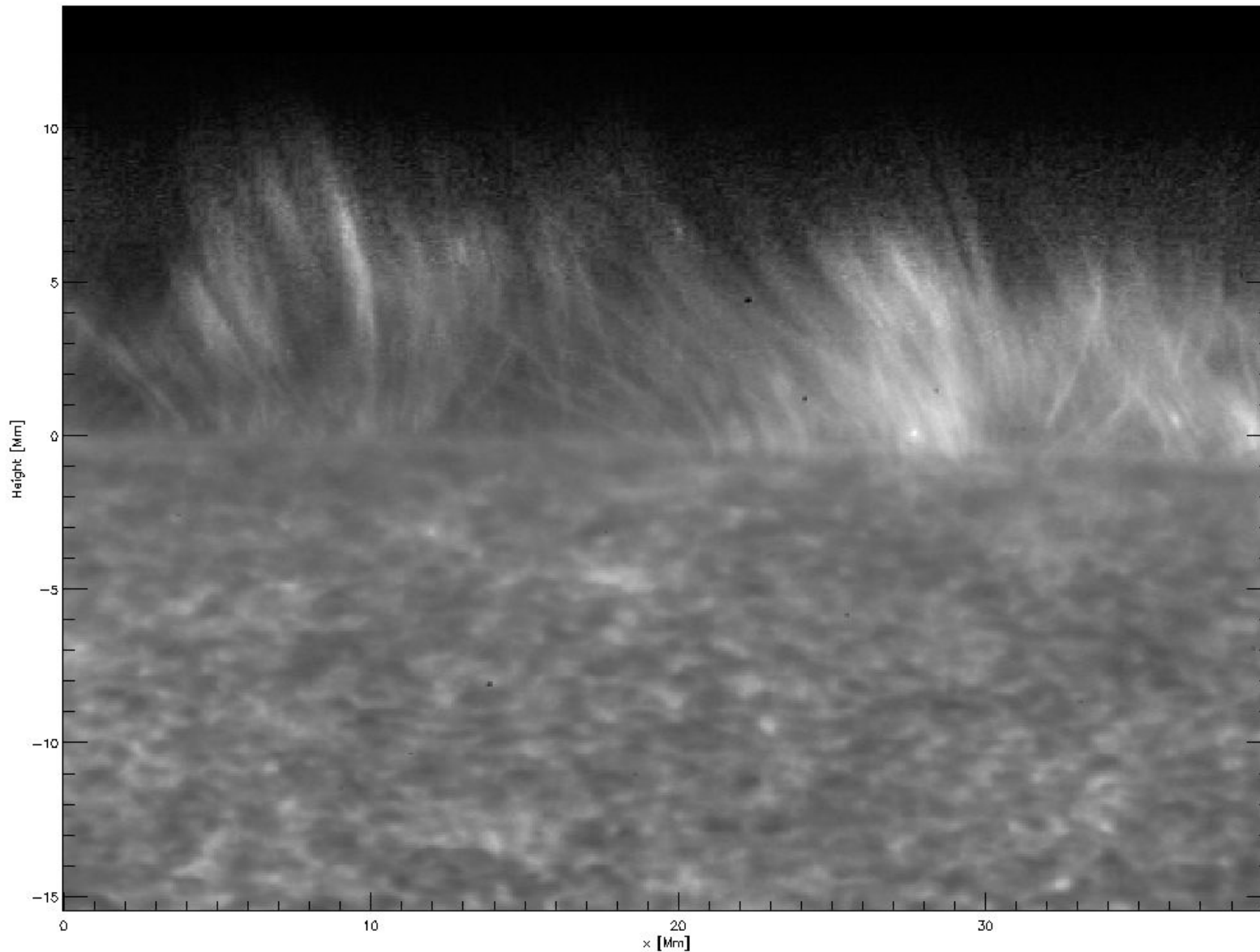
IBIS
H α Line Core



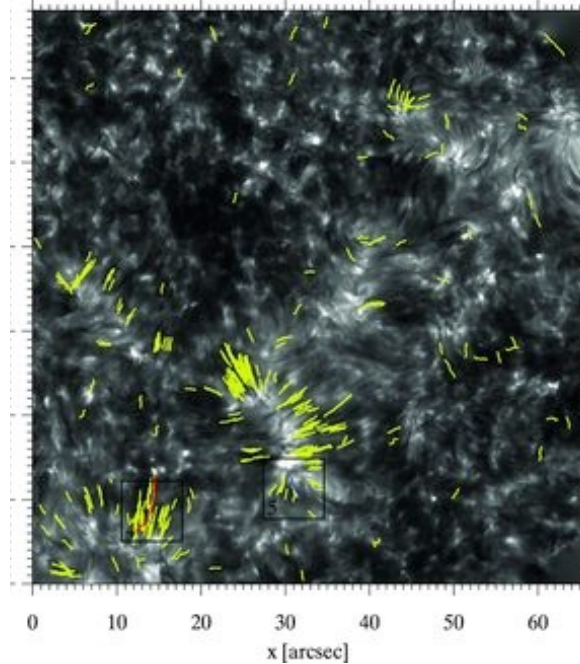
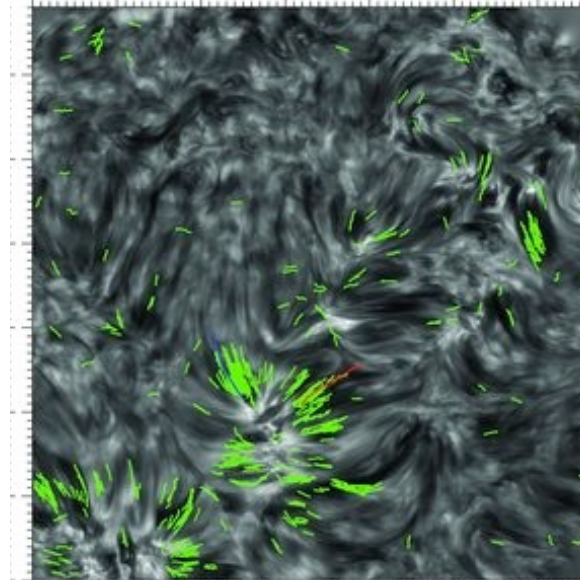
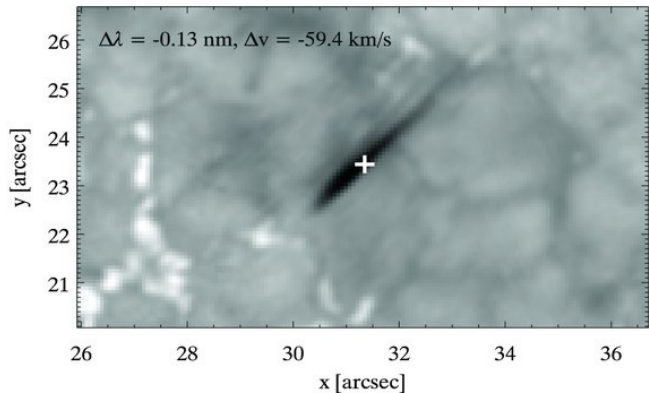
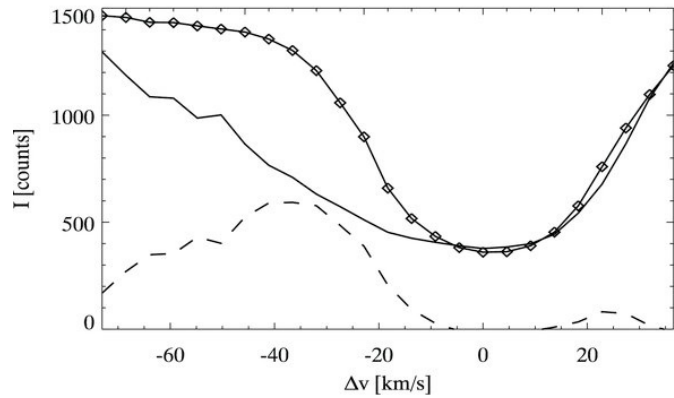
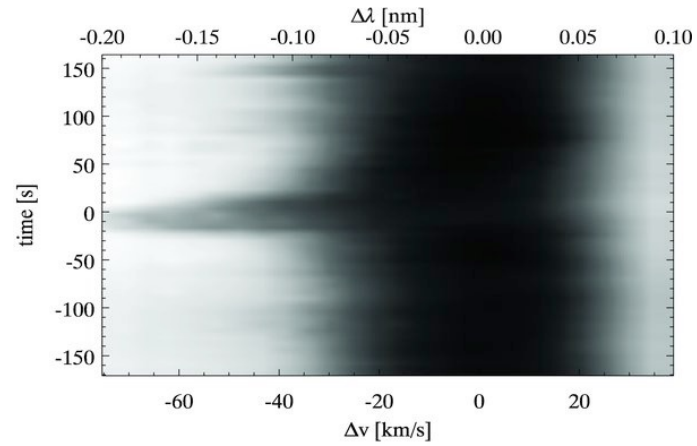
SDO/AIA
304 Å



Type II Spicules

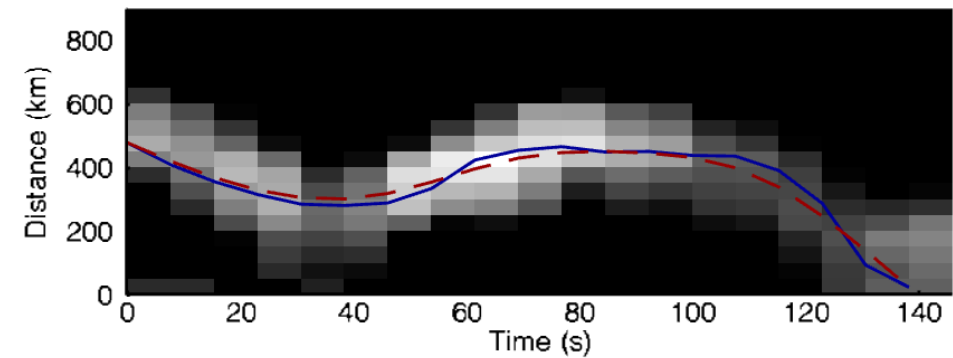
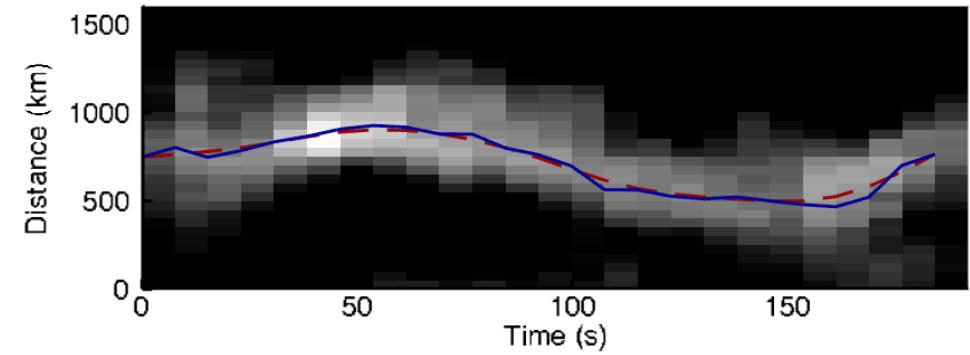
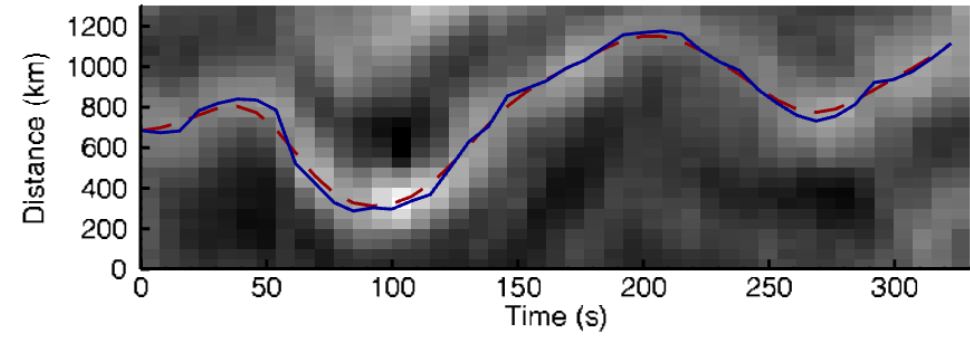
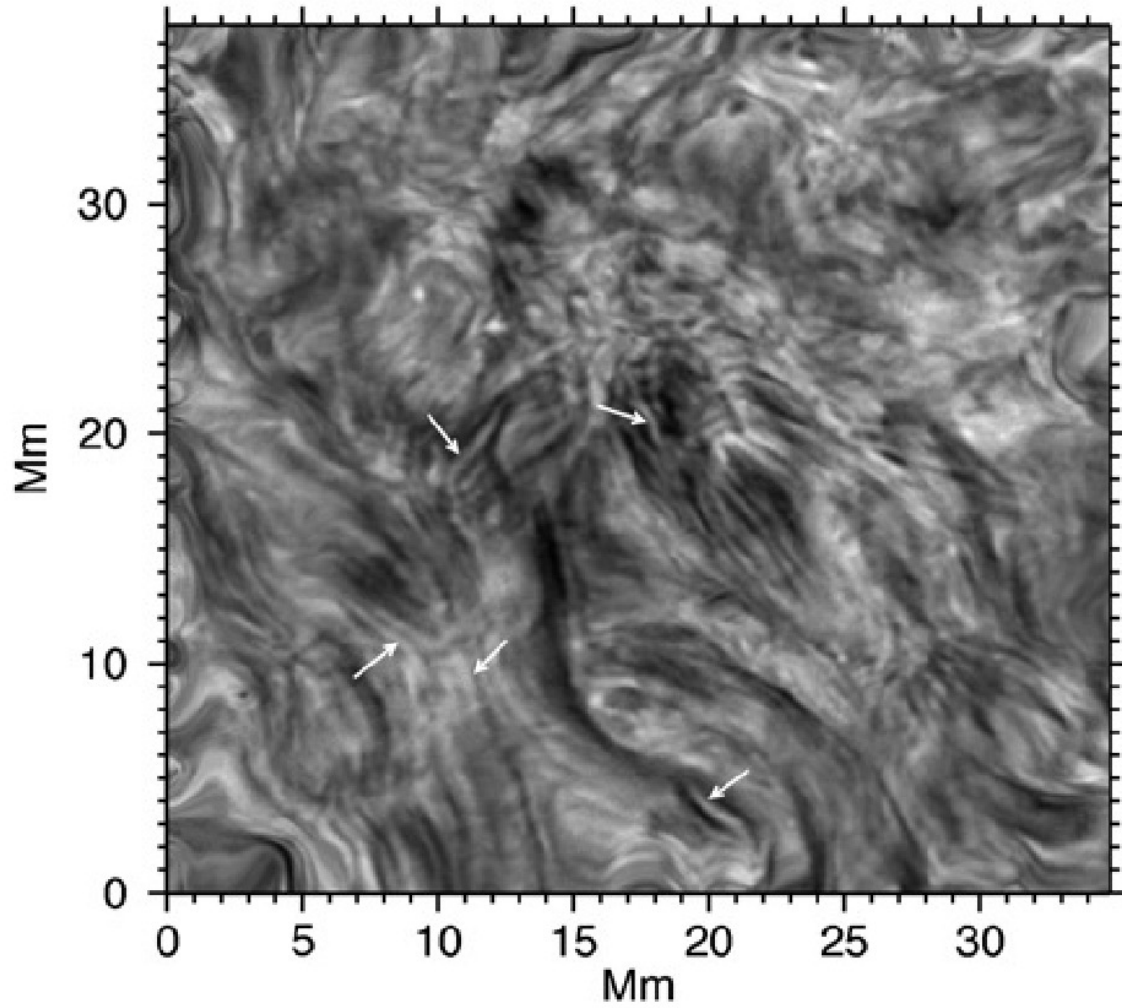


On-disk Counterparts of Type II Spicules

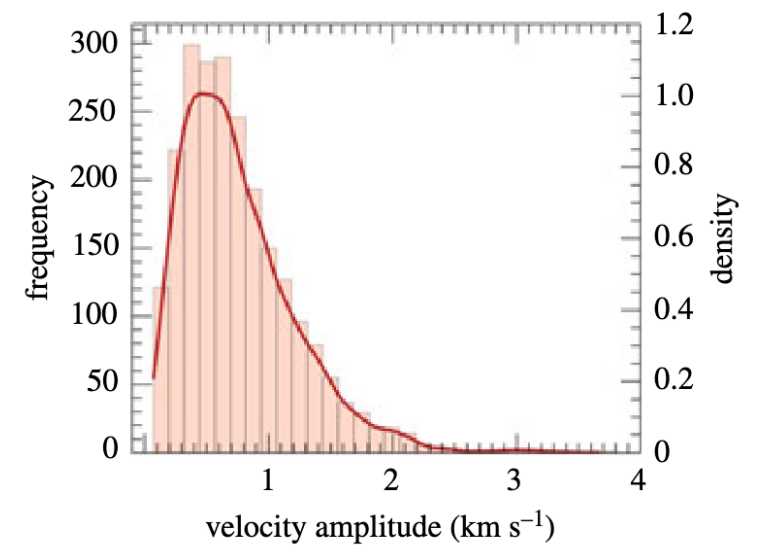
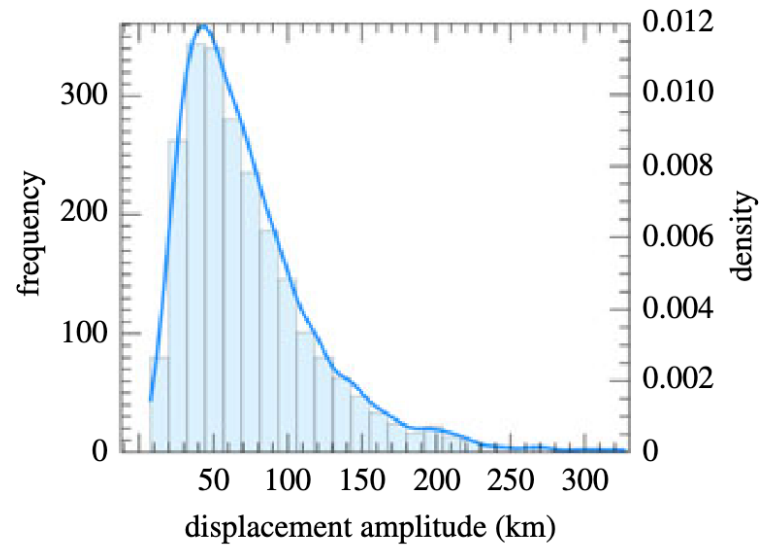
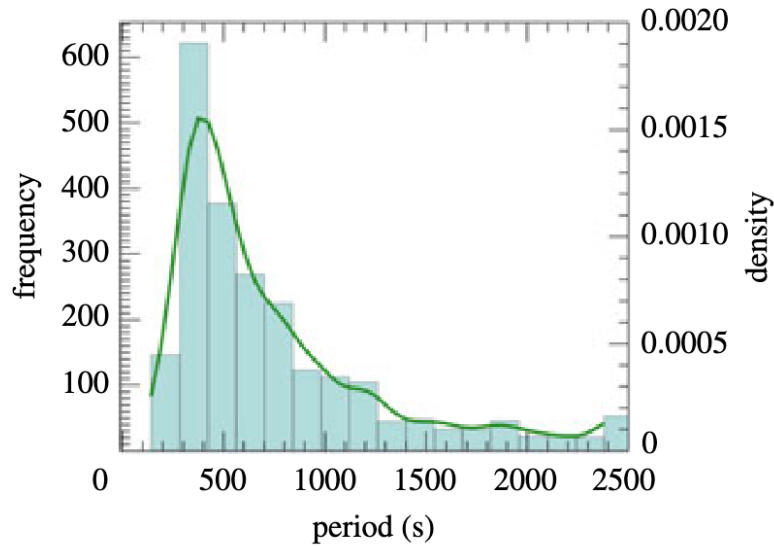
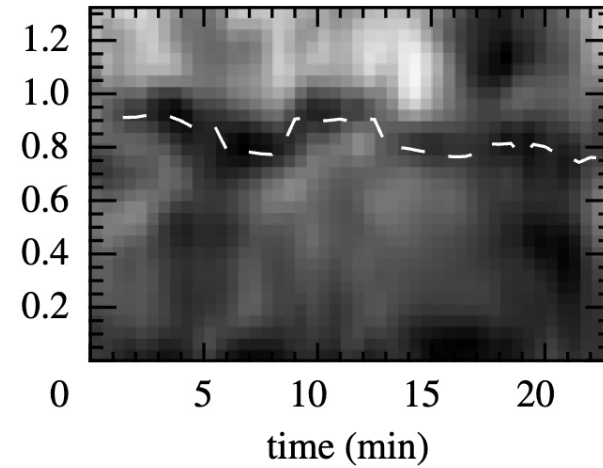
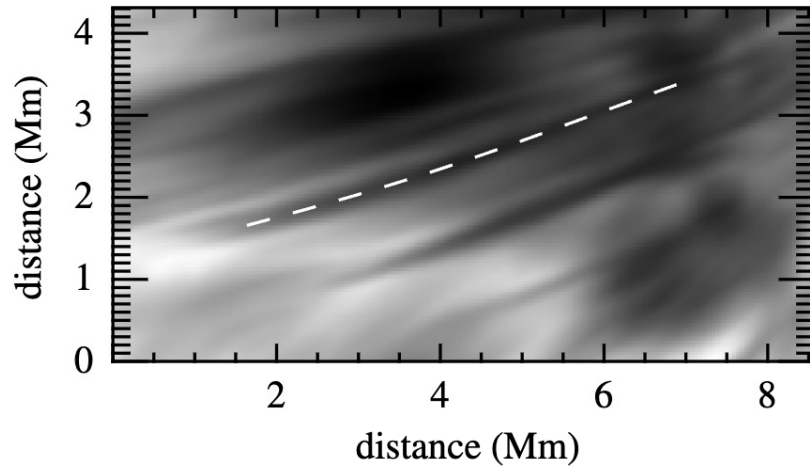


Roupe van der Voort et al. 2009

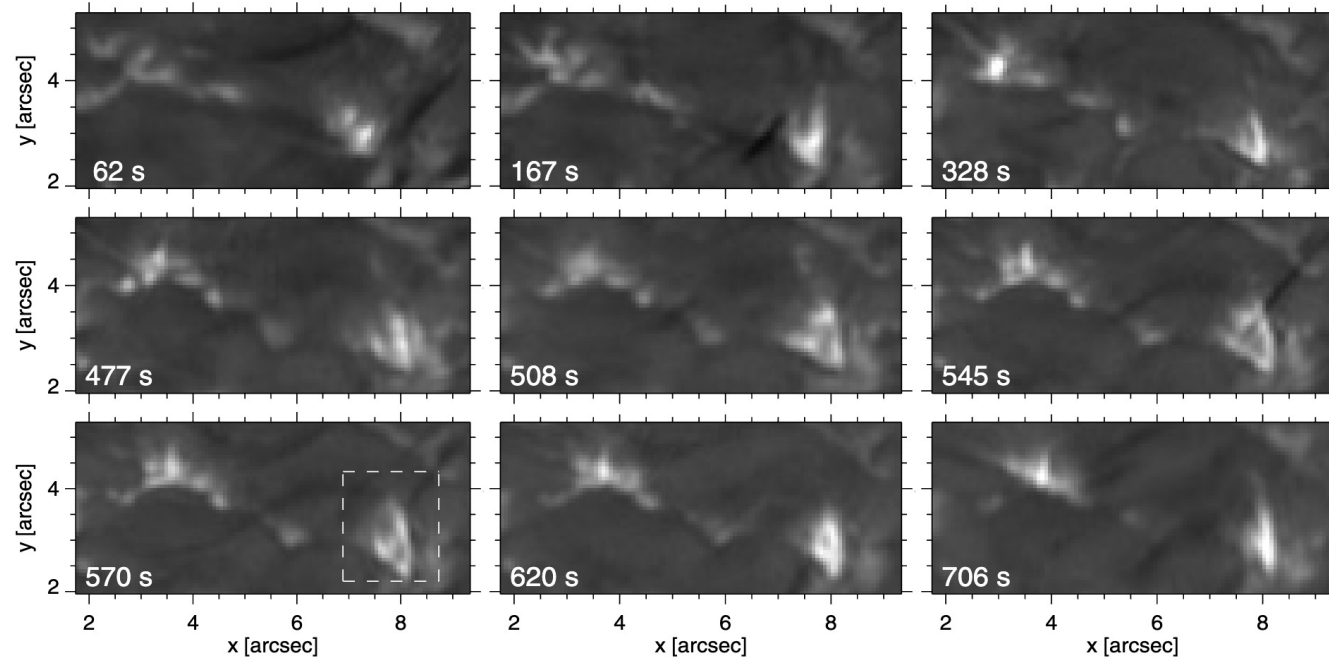
Transverse Motions



Transverse Motions



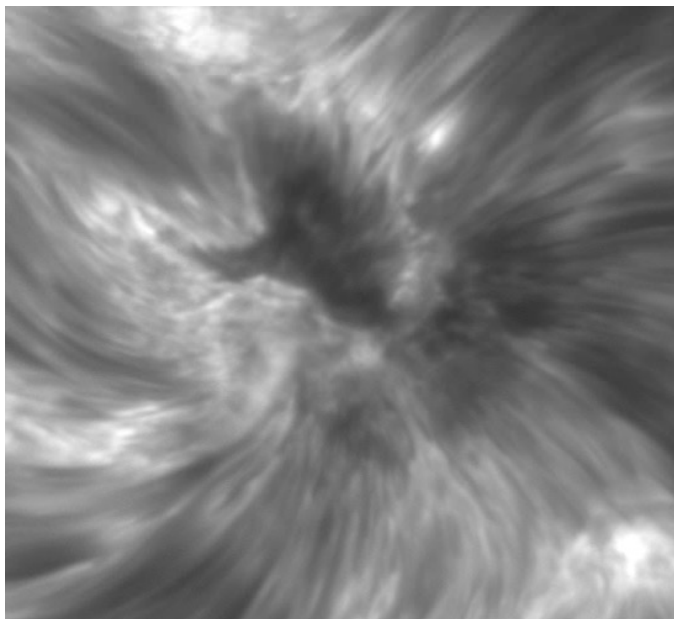
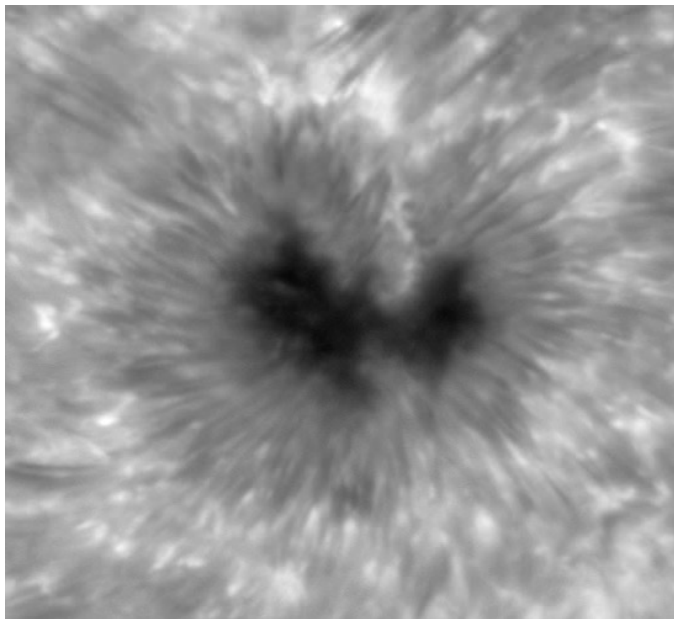
Ellerman Bombs



Watanabe et al., 2011

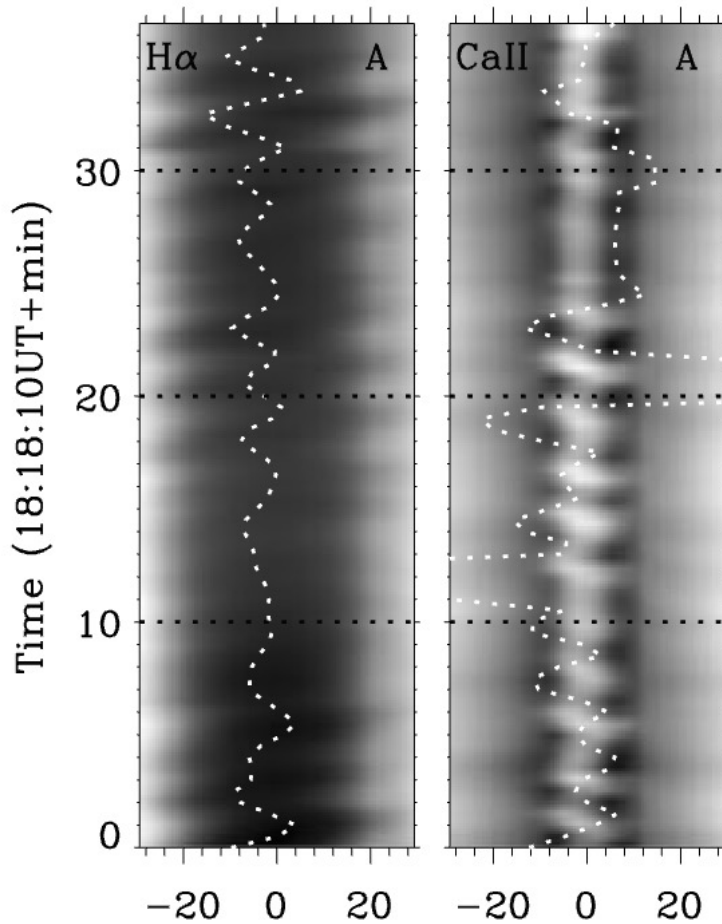
Umbral Oscillations

IBIS



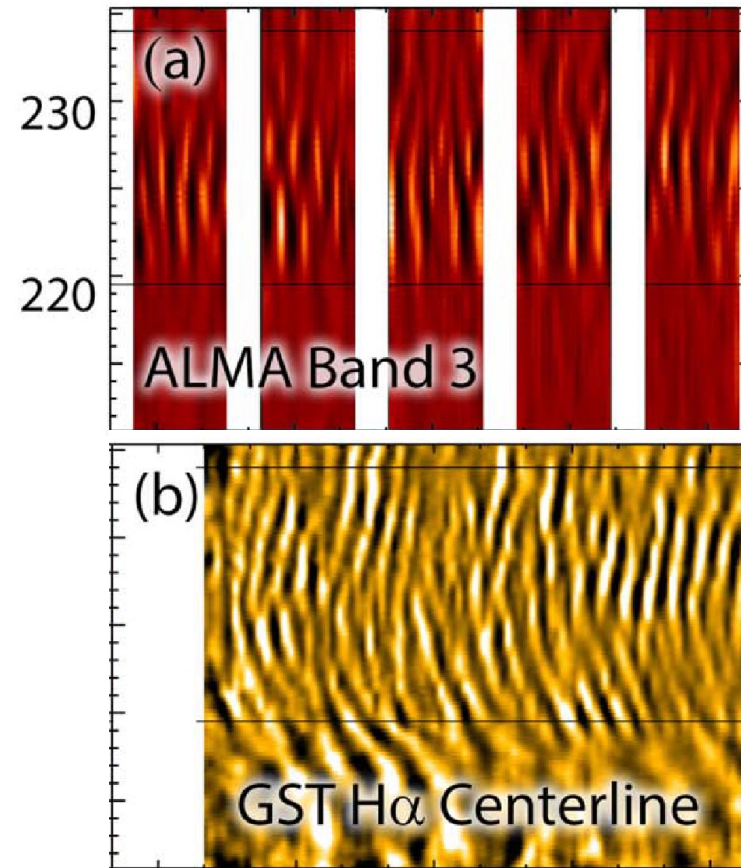
Reardon et al., 2013

FISS



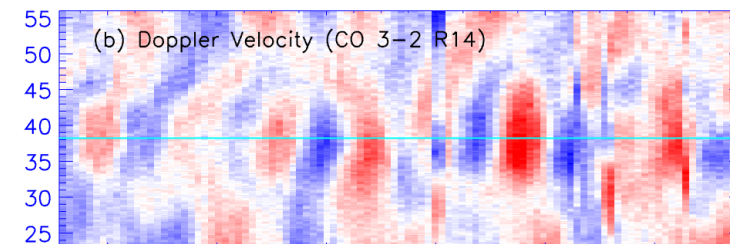
Maurya et al., 2013

ALMA + GST/VIS



Chai et al., 2022

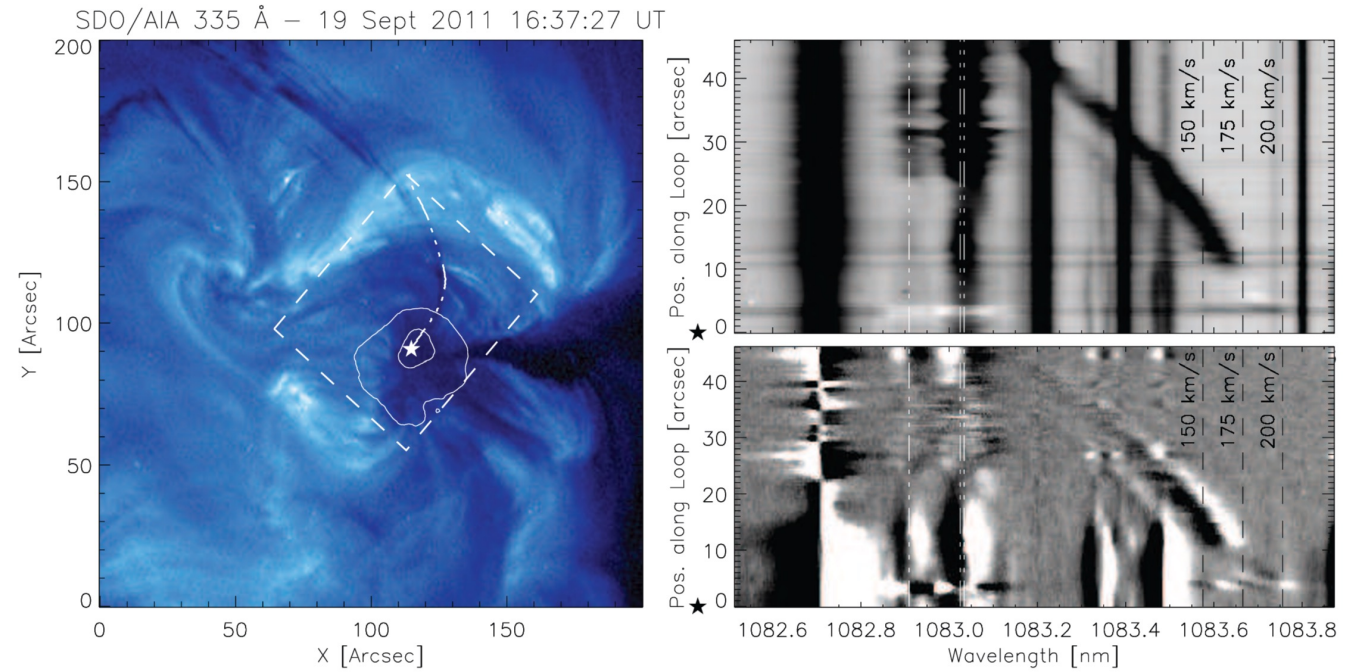
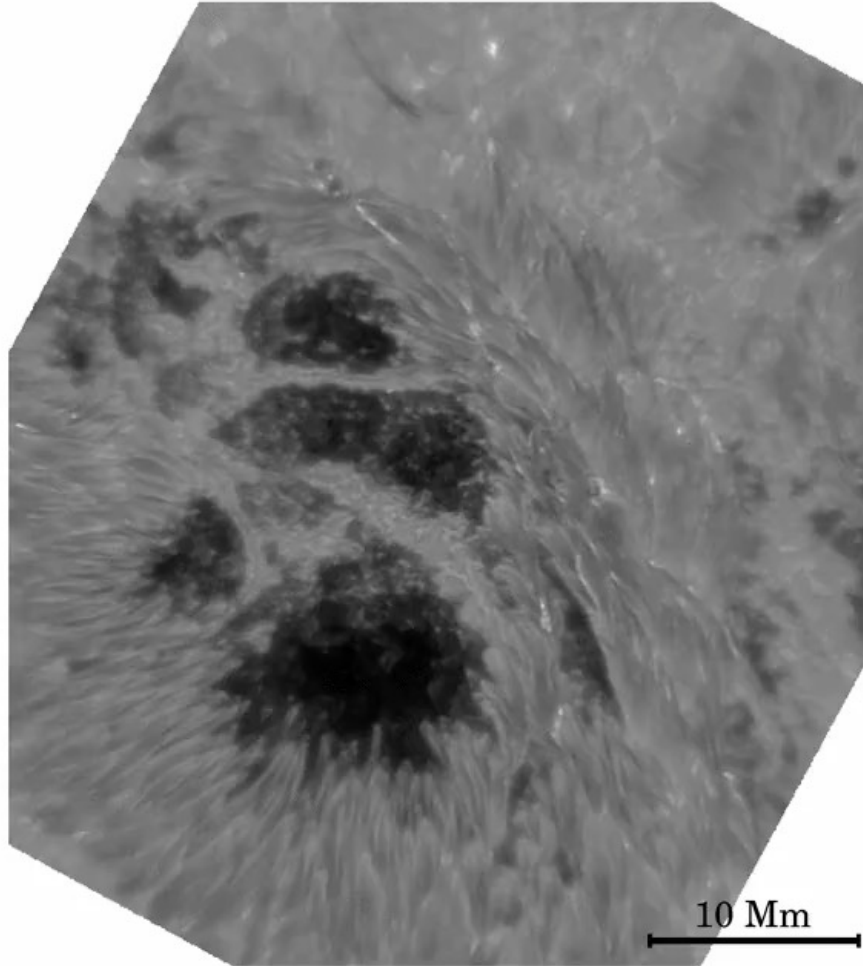
CYRA



Li et al., 2020

Things come down – Coronal Rain

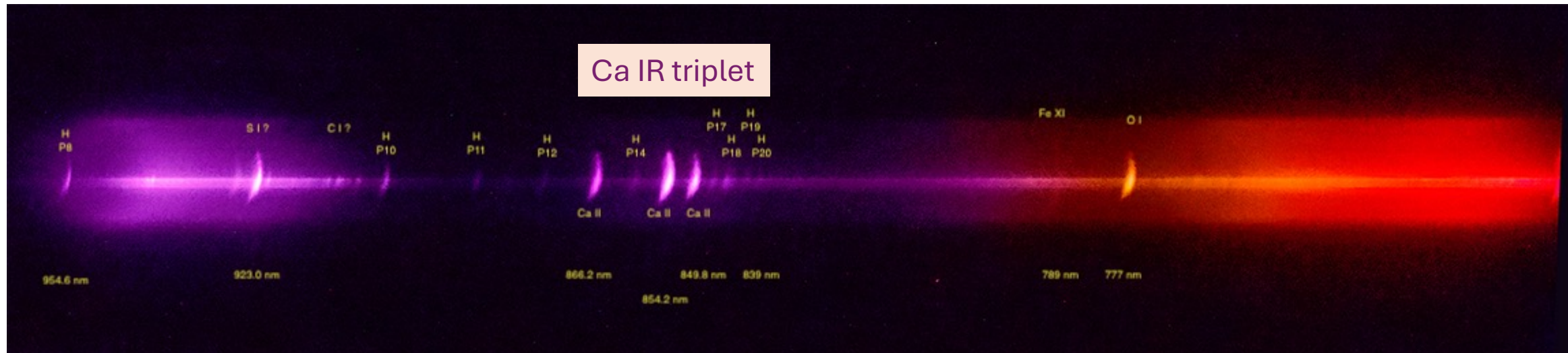
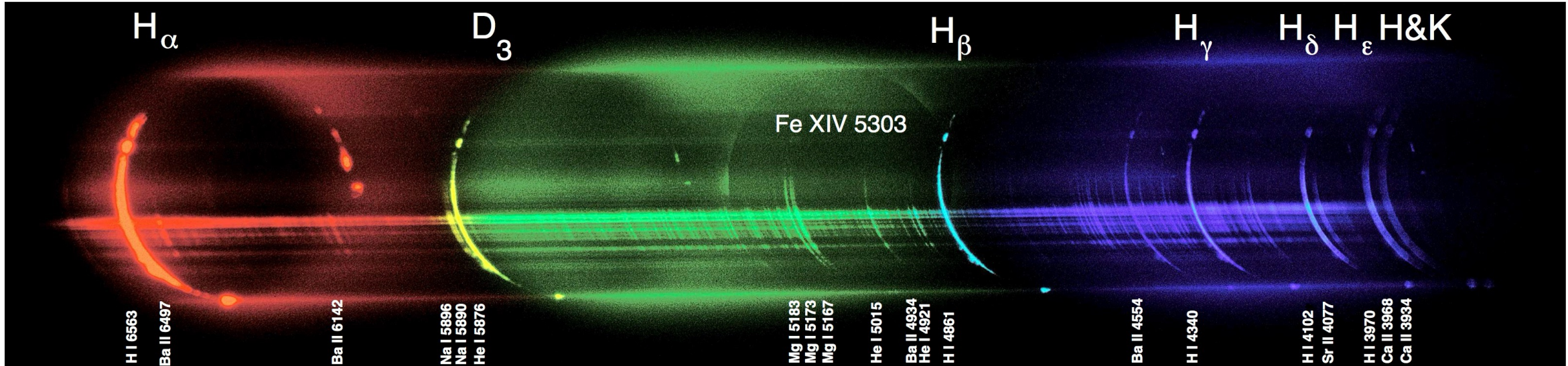
Jing et al., 2016



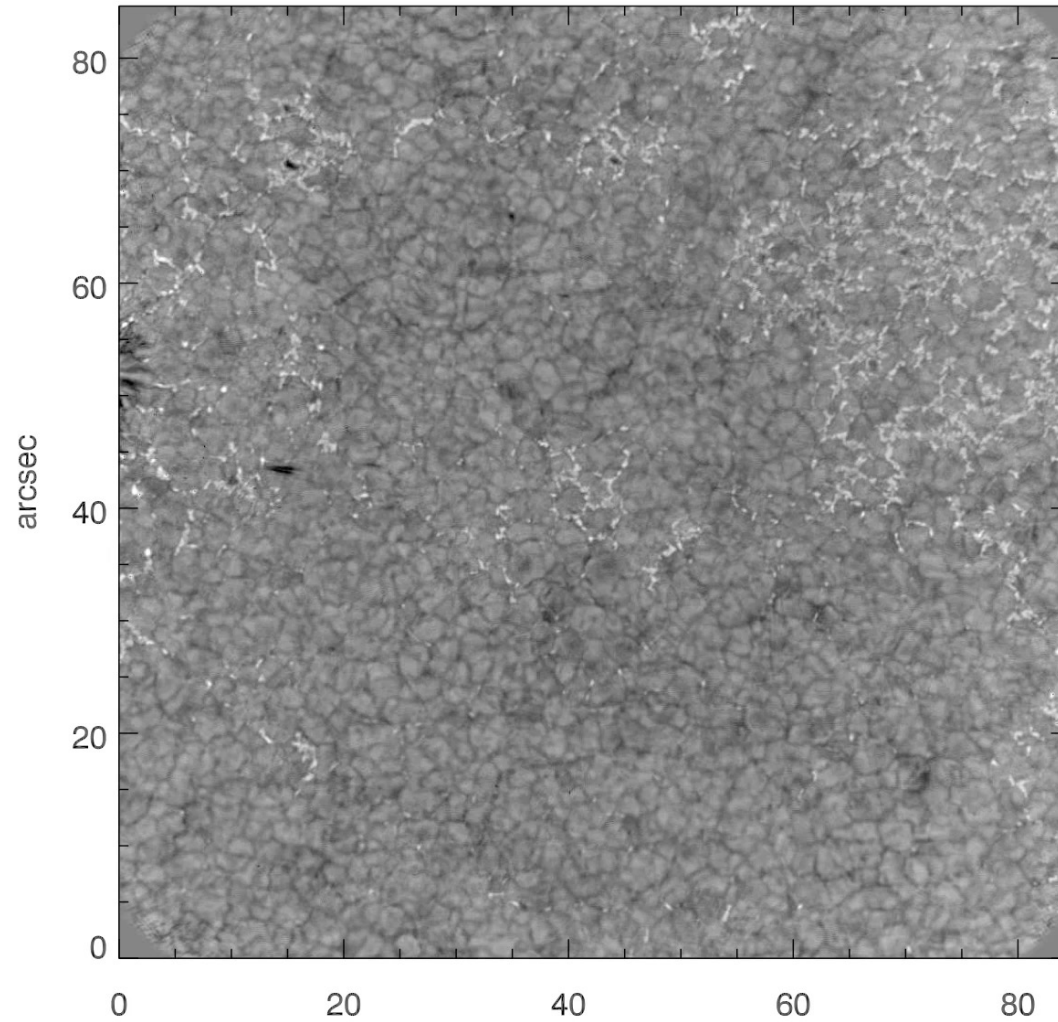
Schad et al., 2012

What are our diagnostic tools?

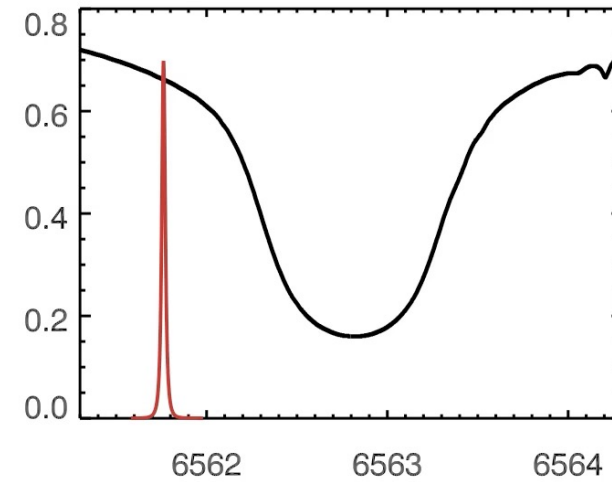
The Chromosphere, Our Colorful Friend



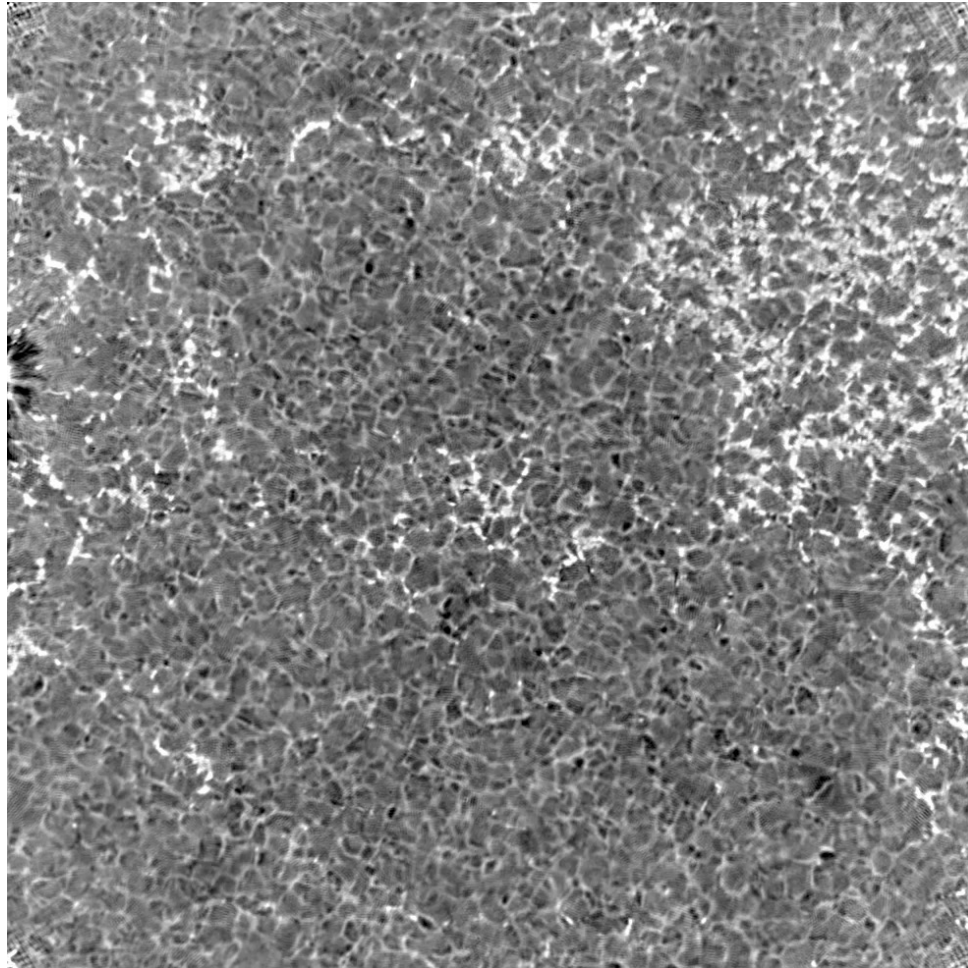
H-alpha 6563 Spectral Scan



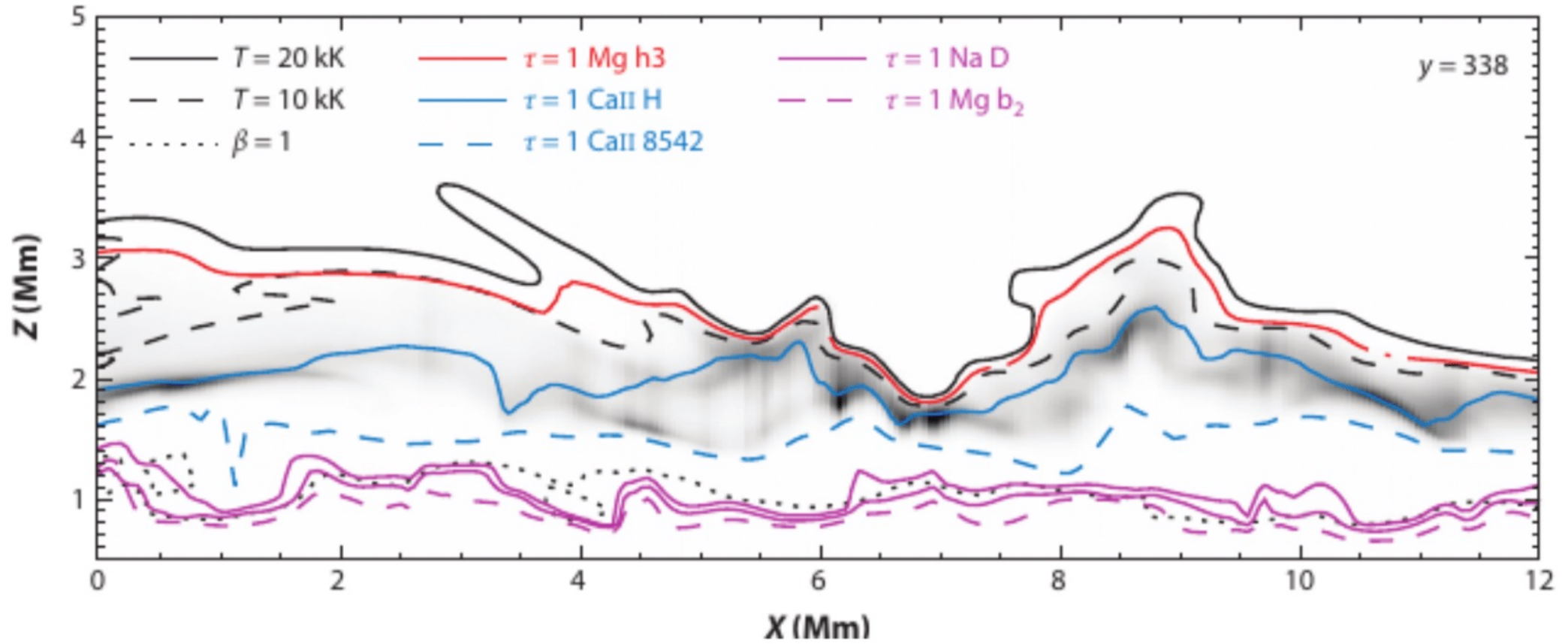
IBIS
23 April 2017



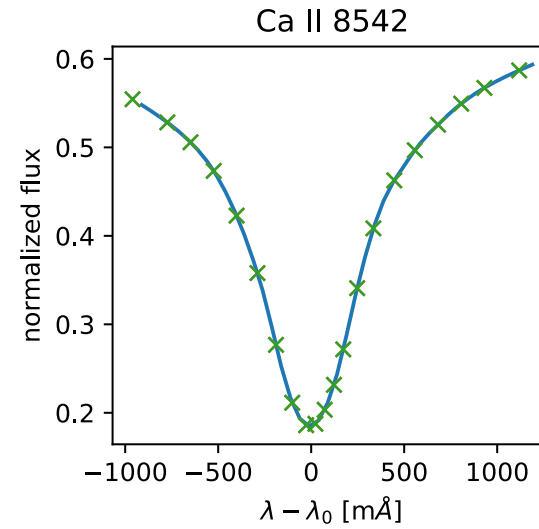
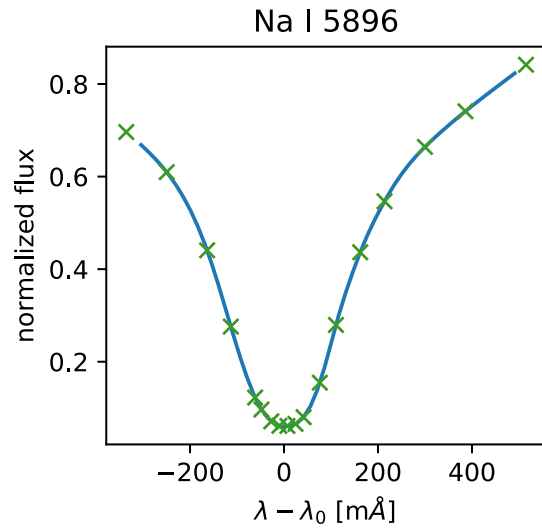
Ca II 8542 Spectral Scan



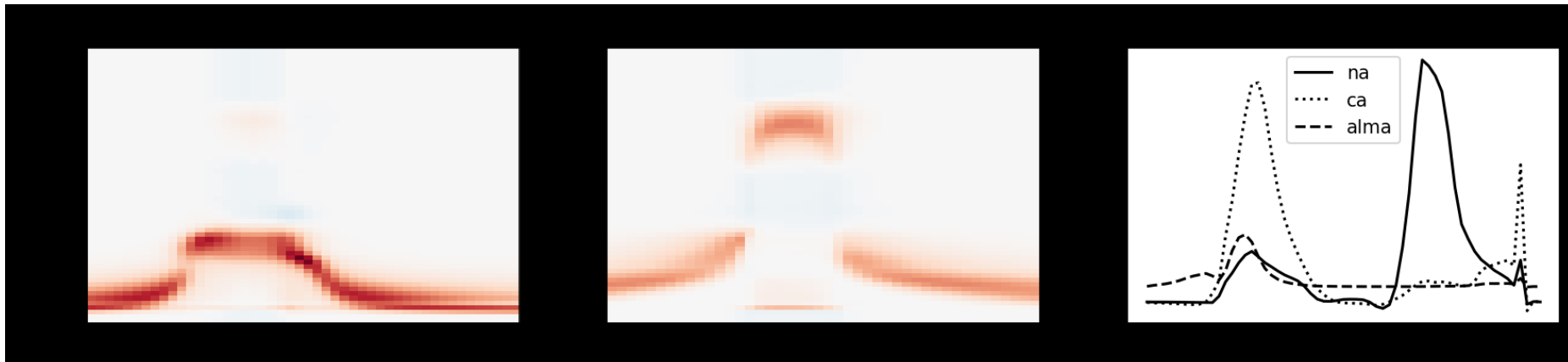
“Heights” of Formation



Spectral Inversions with IBIS & ALMA

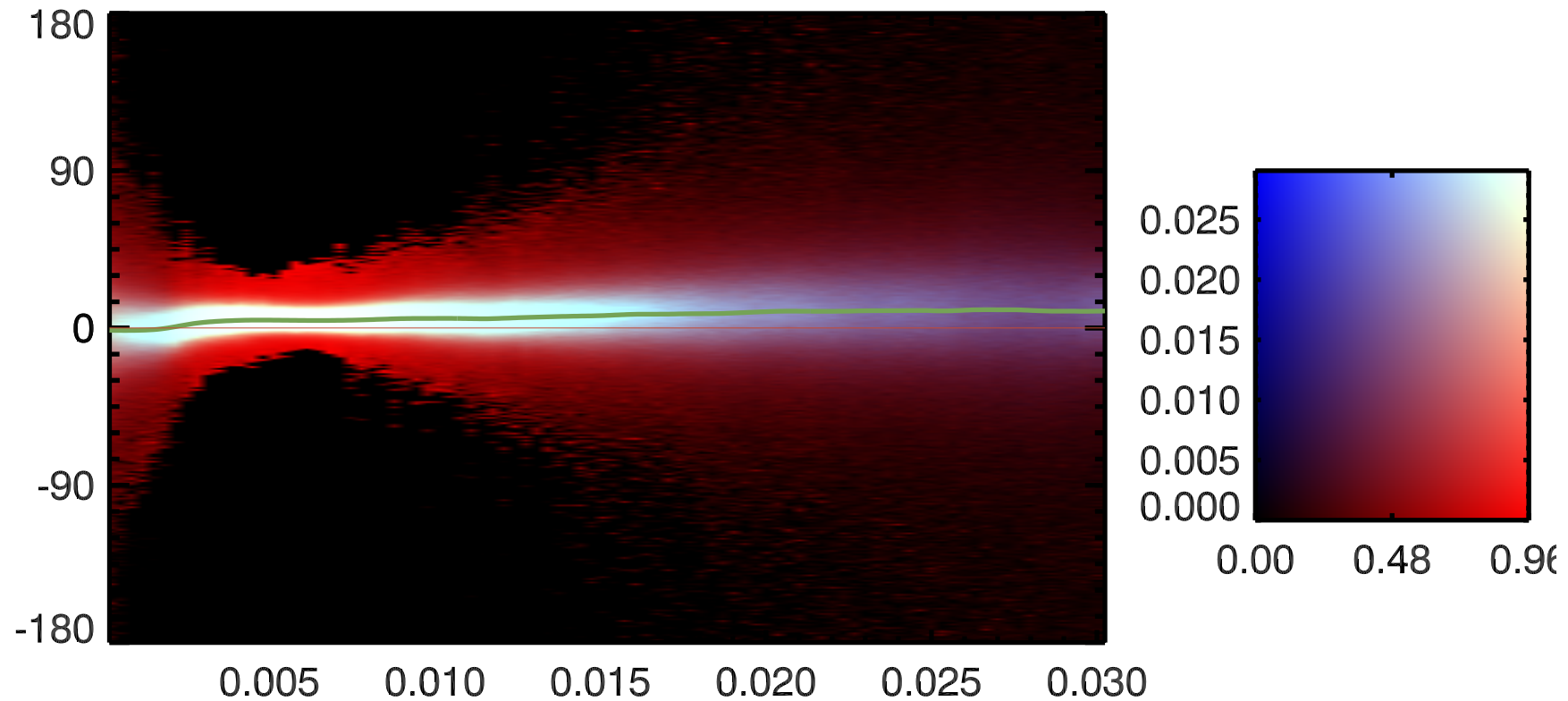


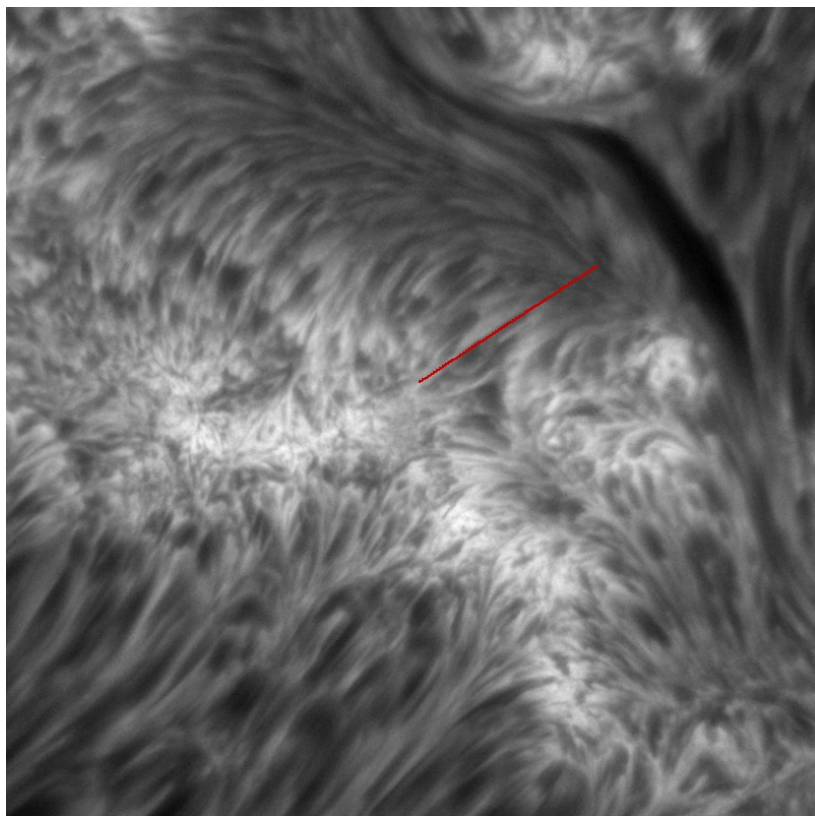
Response Functions



Chromospheric Confounding

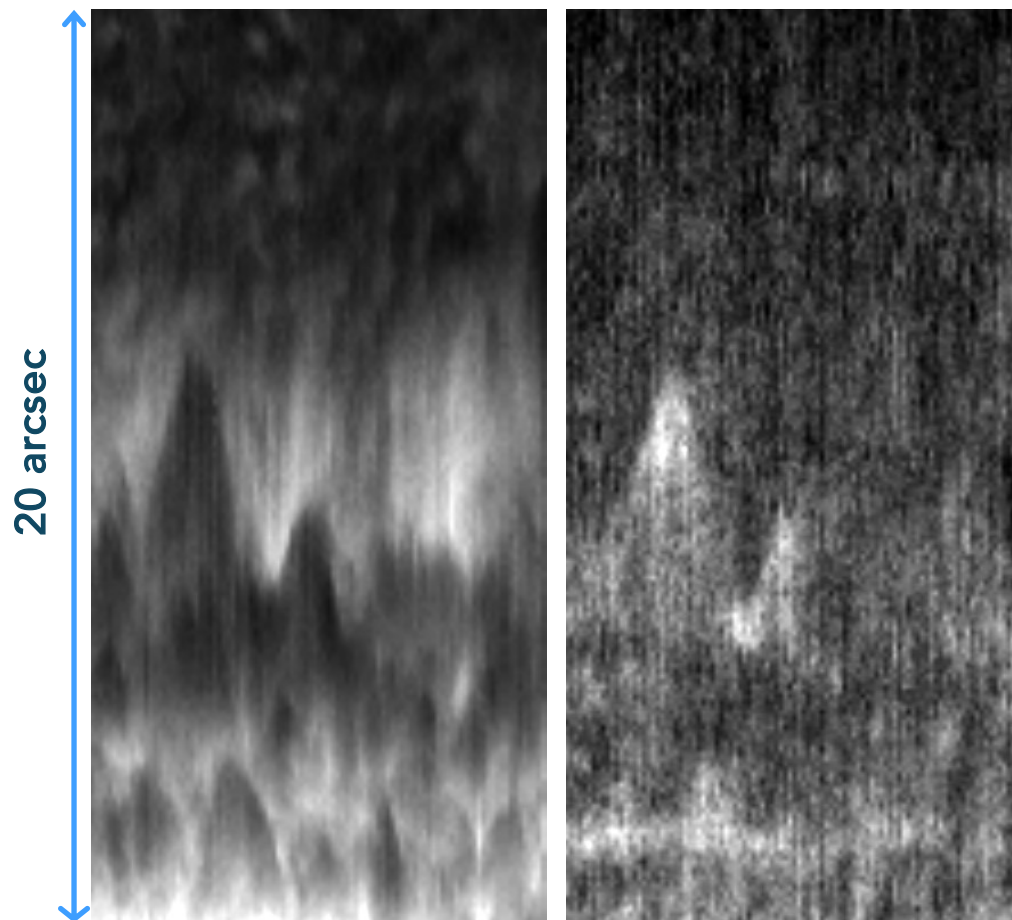
- Heights of formation – corrugation





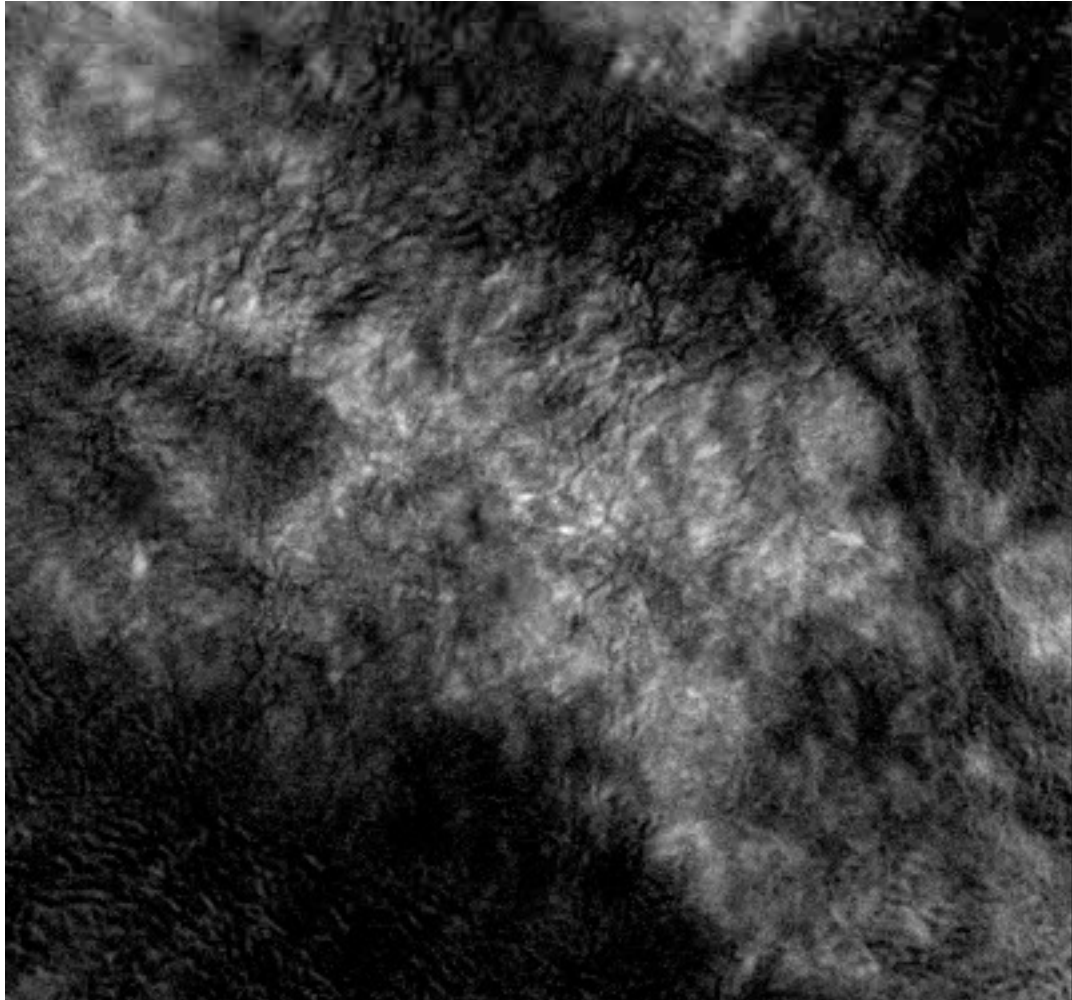
IBIS
H α Line Core

IBIS
He I D₃



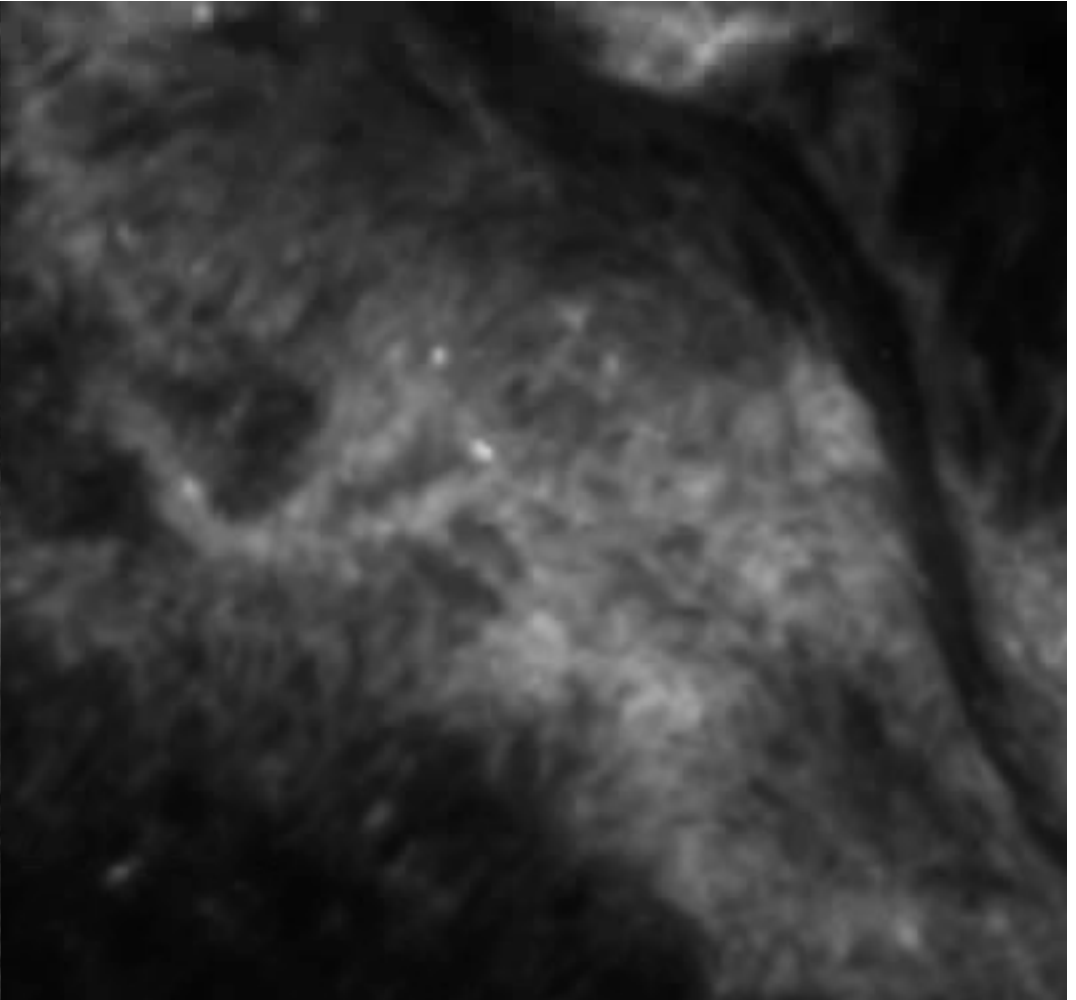
30 minutes

IBIS
He I D₃



22 sec cadence

SDO/AIA
He II 304 Å

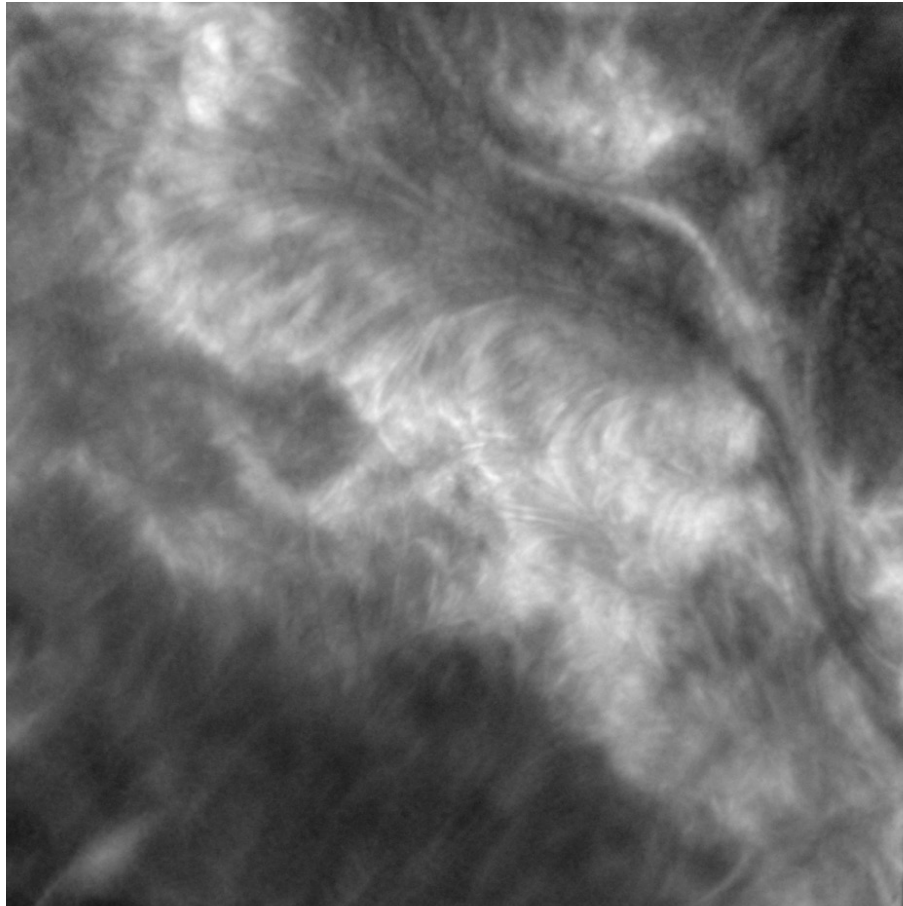


12 sec cadence

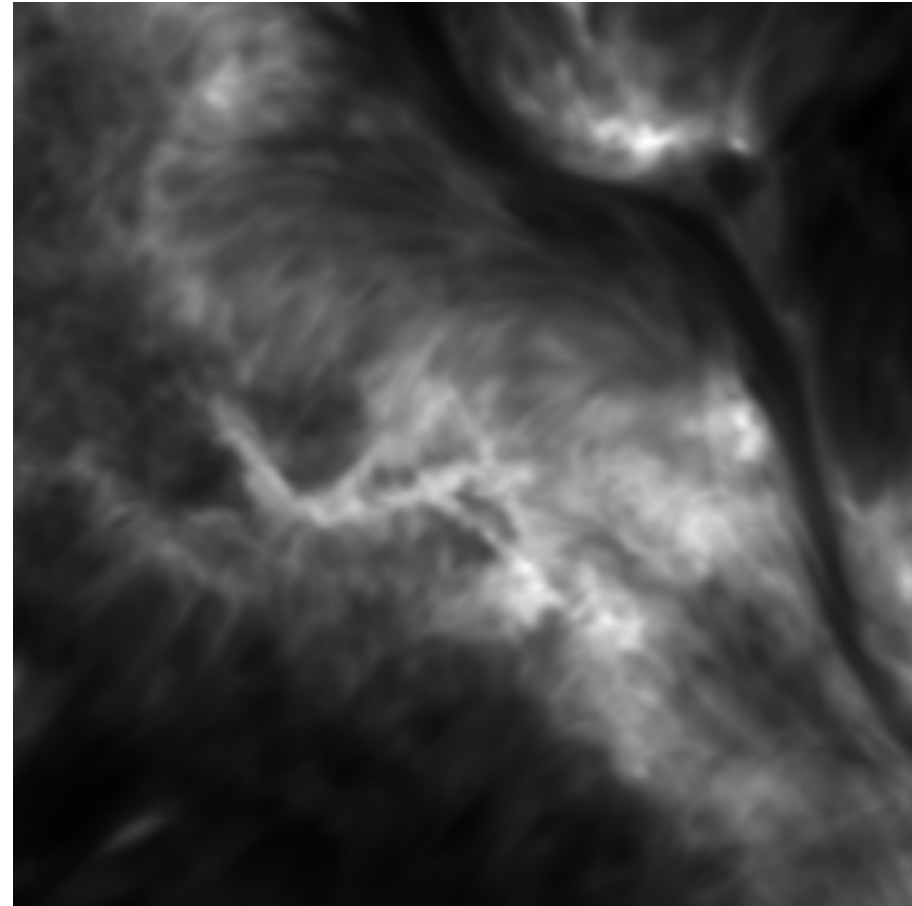
30 minute duration

Chromosphere to TR Connection

IBIS He I D₃

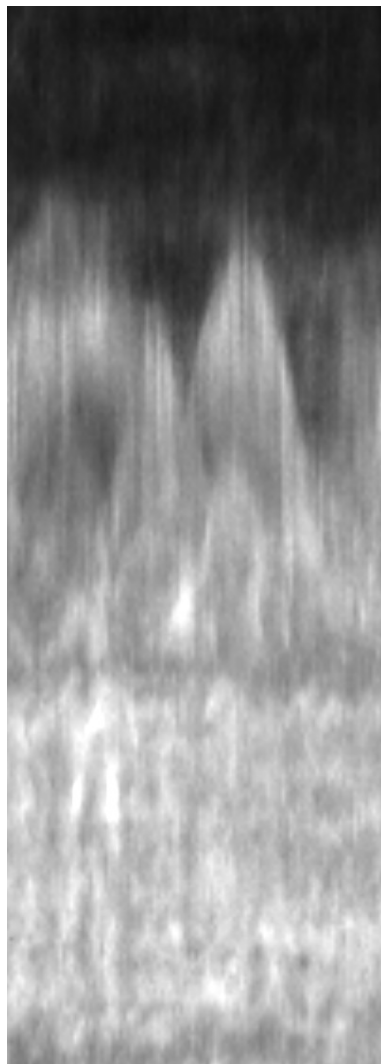


SDO/AIA
He II 304 Å

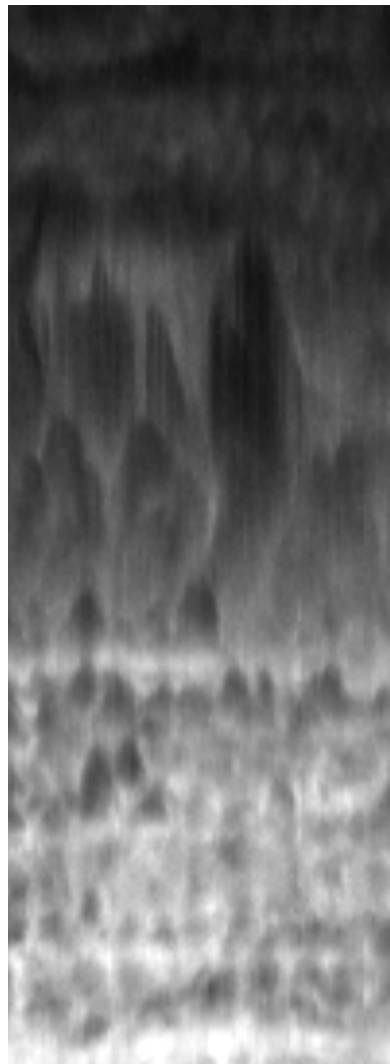


78 arcsec

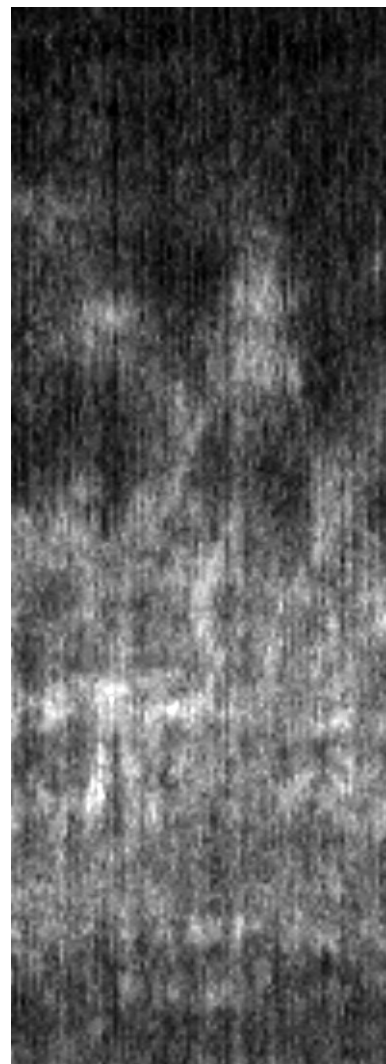
IBIS
H α Line Width



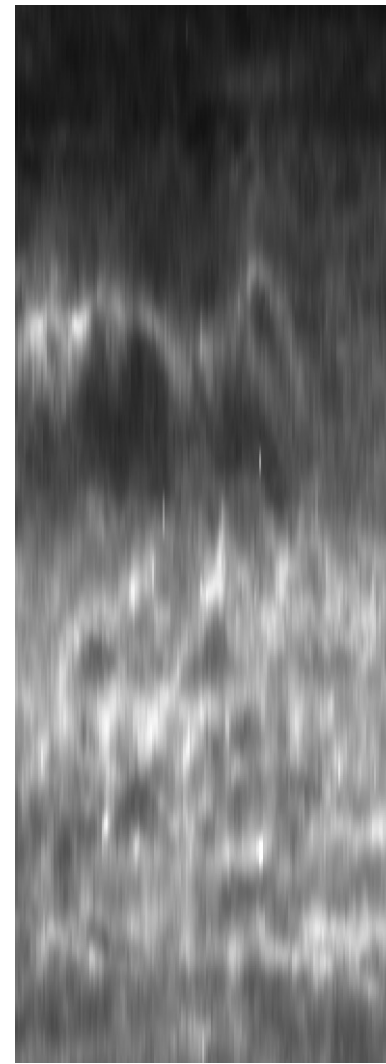
IBIS
H α Line Core



IBIS
He I D $_3$

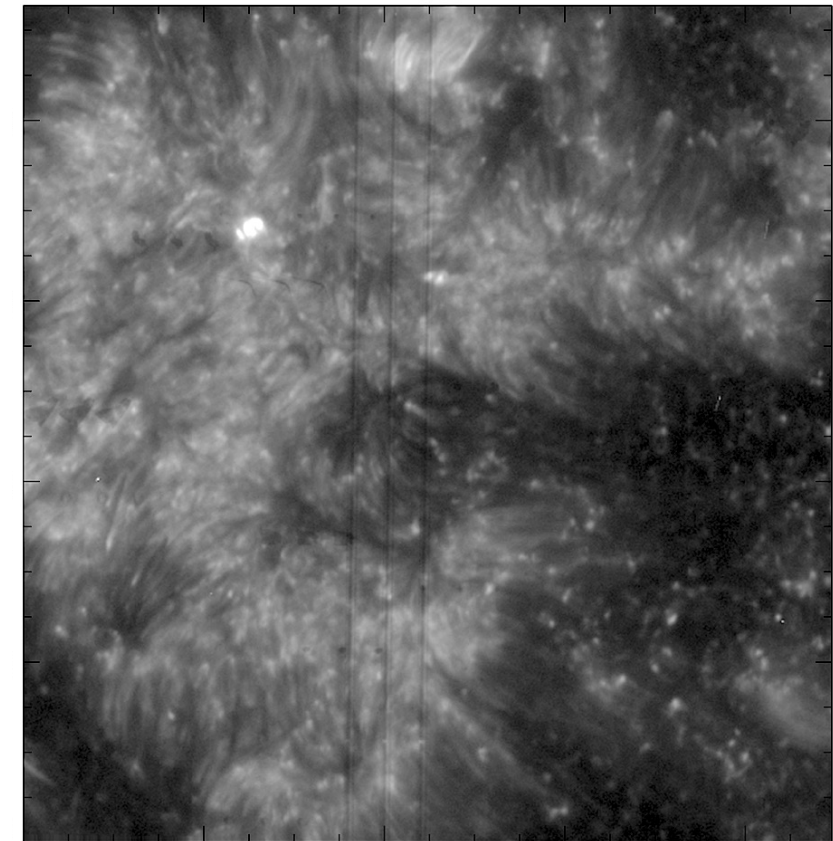


SDO/AIA
304 Å



What diagnostics do we have

IRIS Slit Jaw - 1330 Å

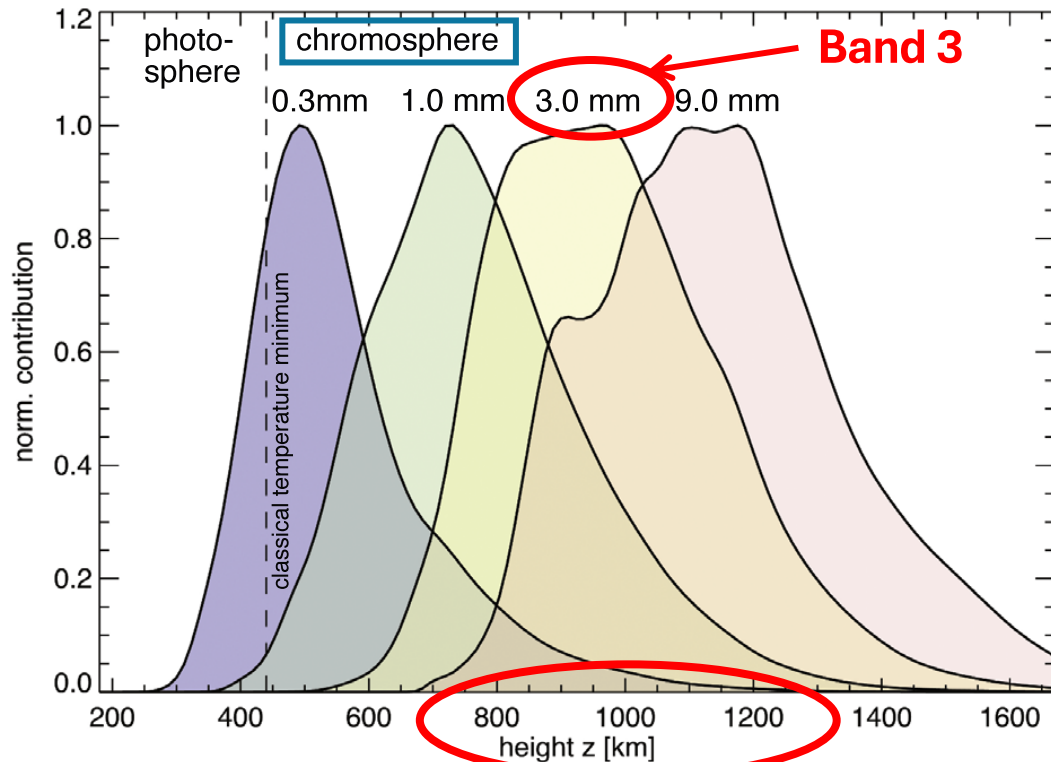


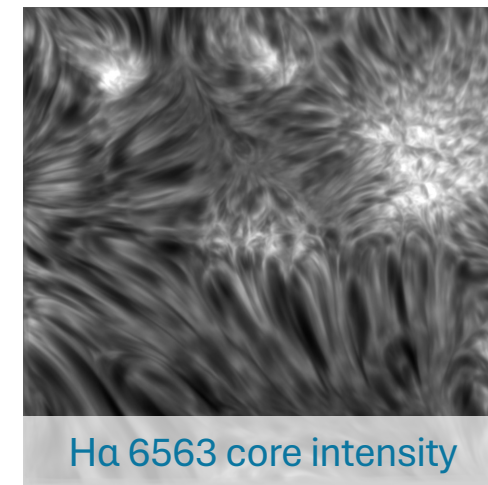
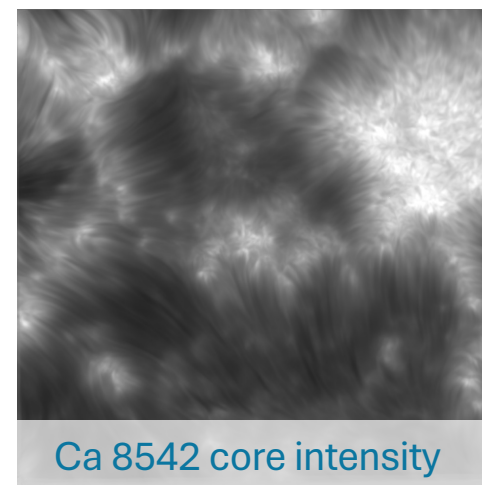
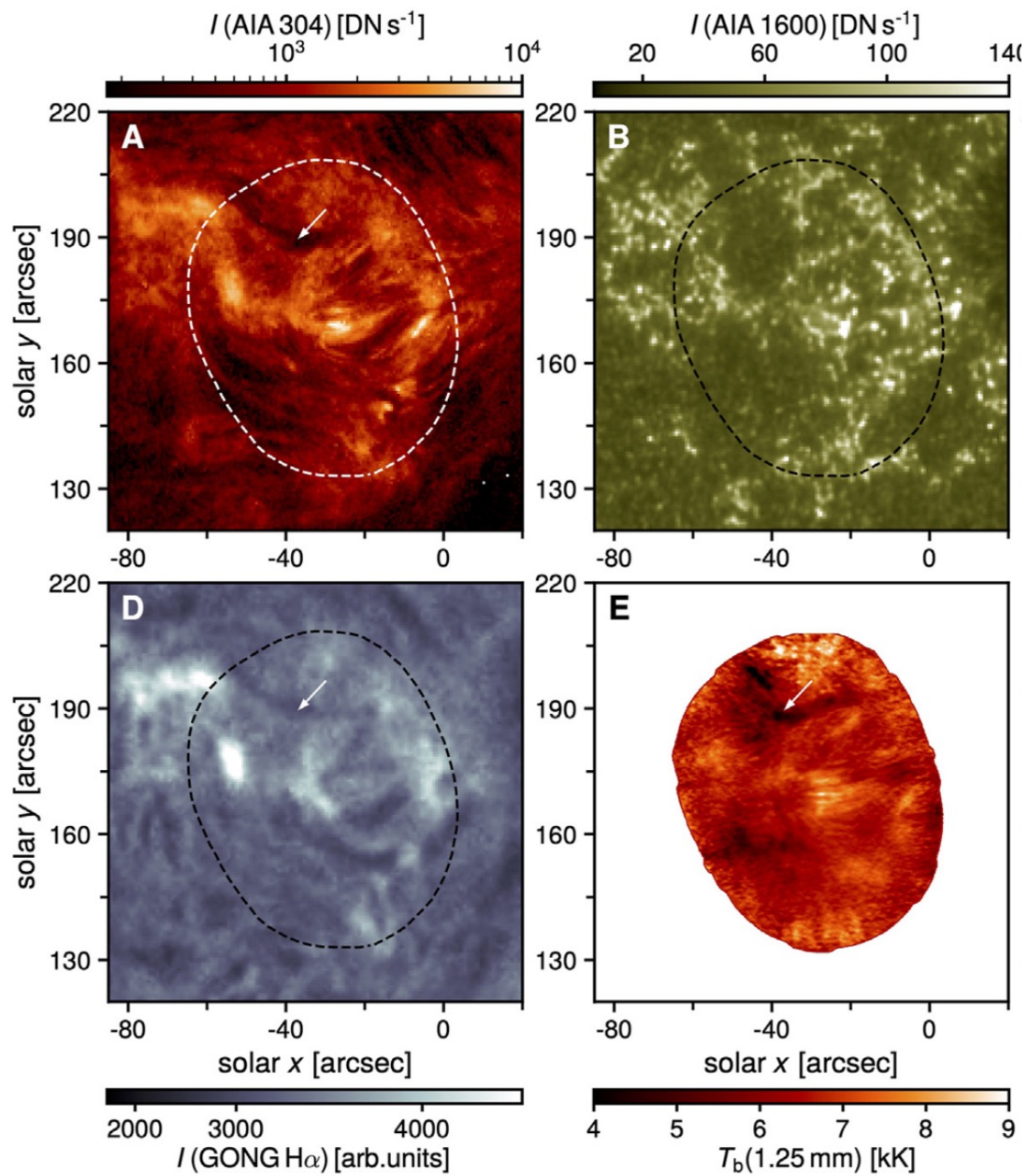
0 20 40 60 80
[arcsec]



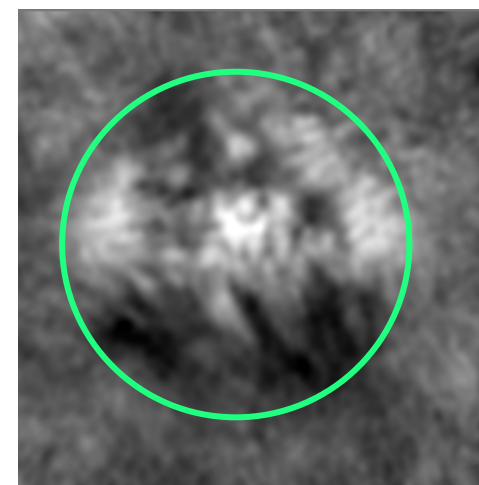
ALMA Arrives

- 1) Millimeter continuum radiation forms in LTE conditions
simple radiative transfer
- 2) In the Rayleigh-Jeans regime - continuum brightness is **linearly** related to electron temperature
- 3) More antennas, larger array
= higher spatial resolution

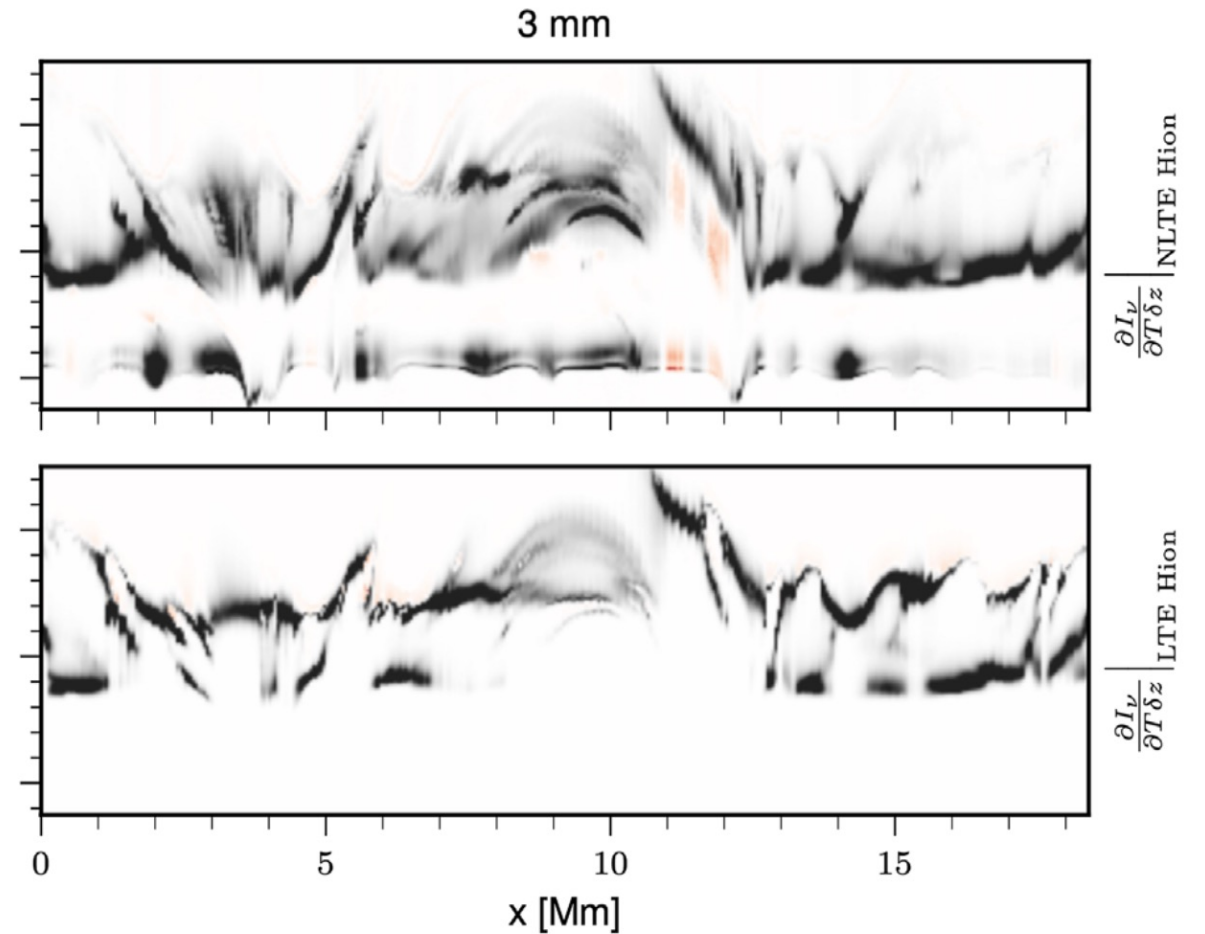
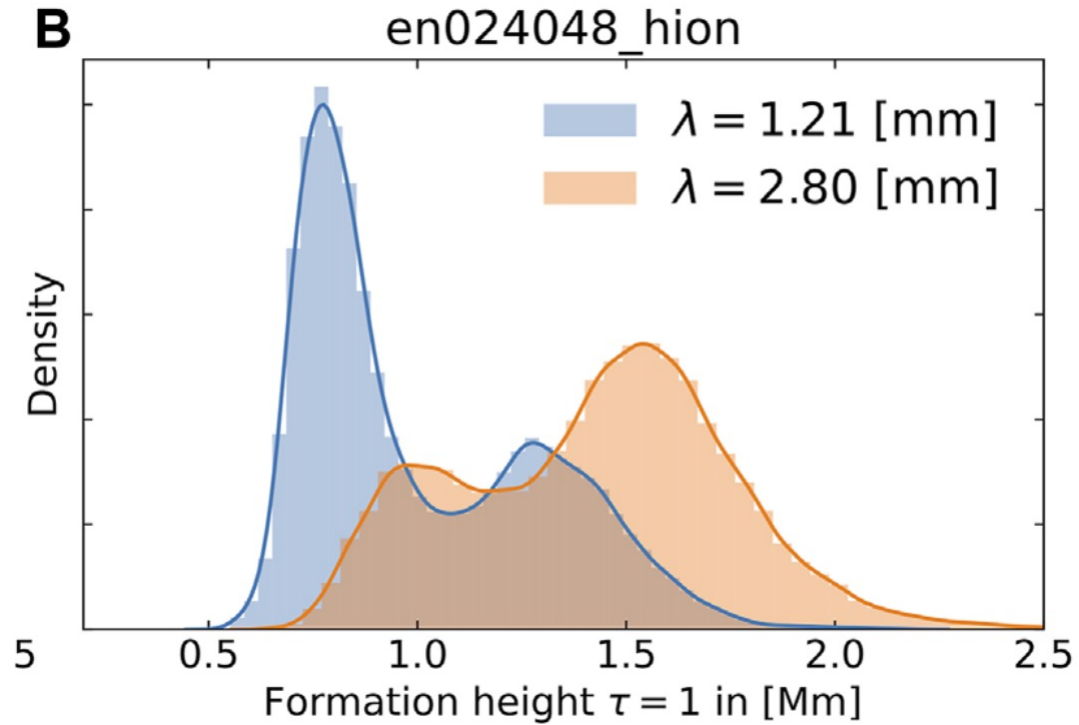




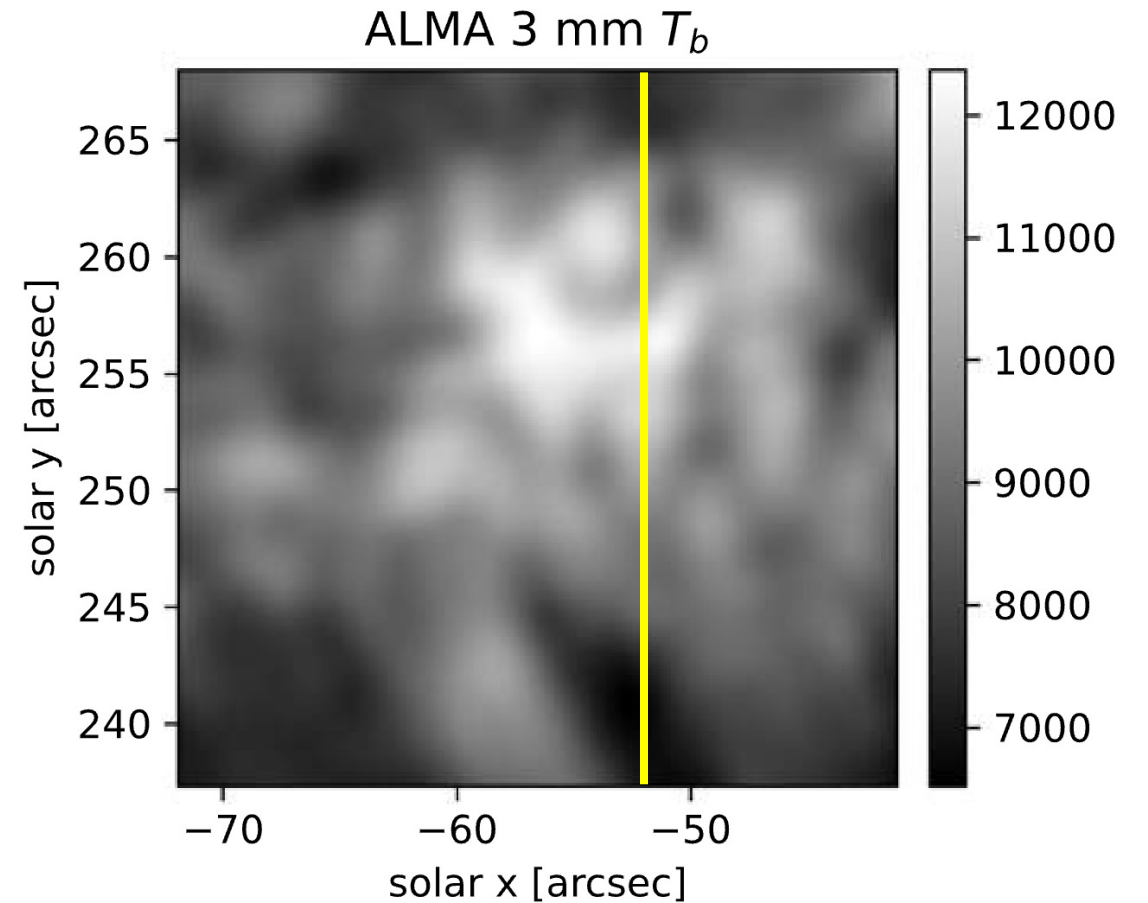
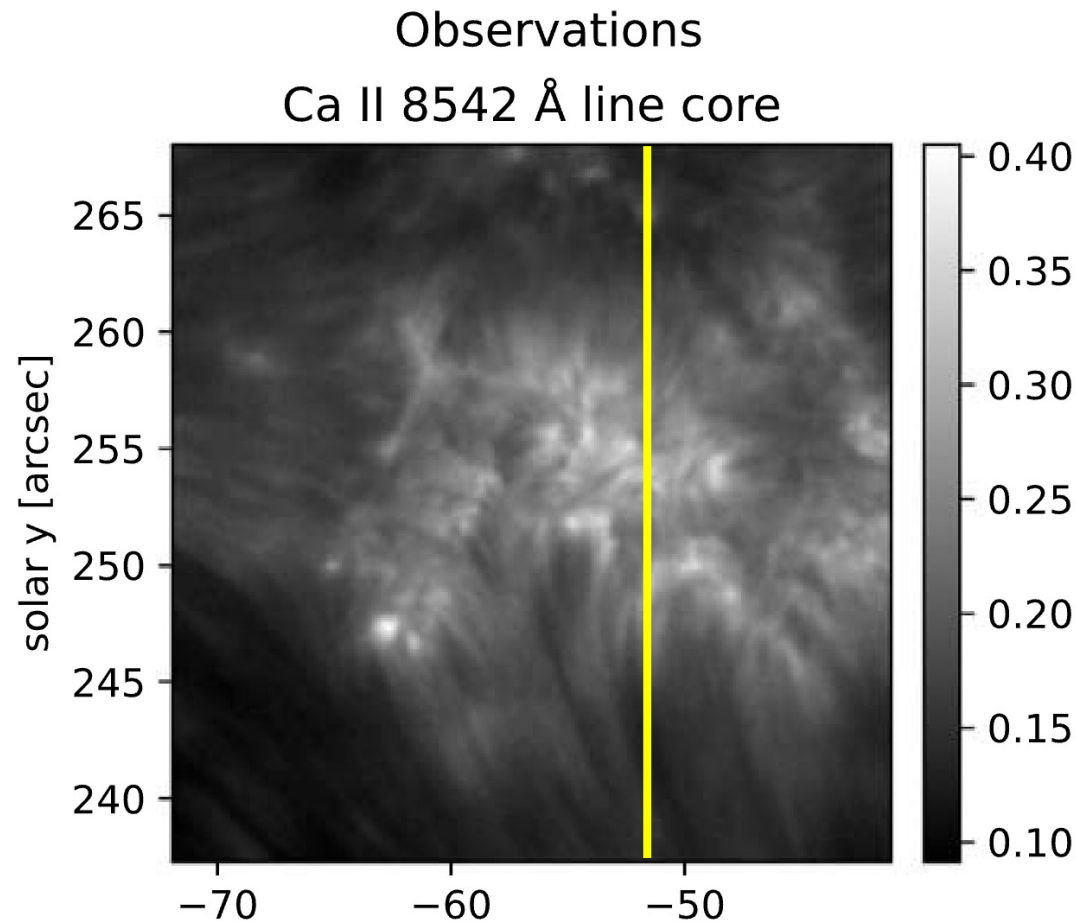
ALMA Band 3 = 3 mm



Extended Heights of Formation



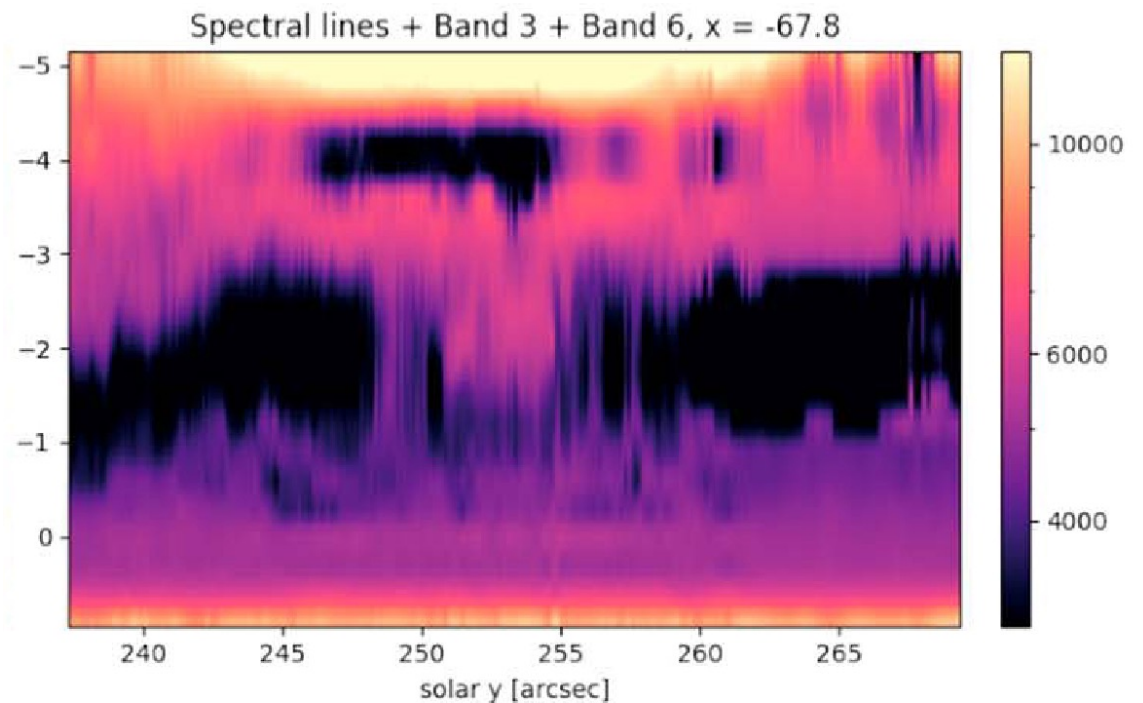
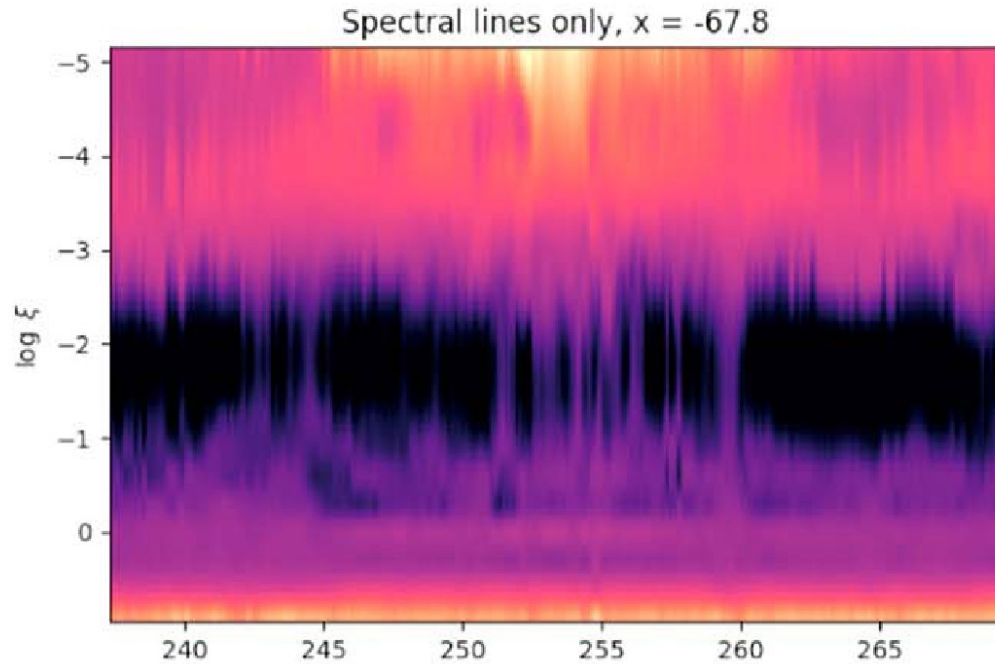
Spectral Inversions with ALMA



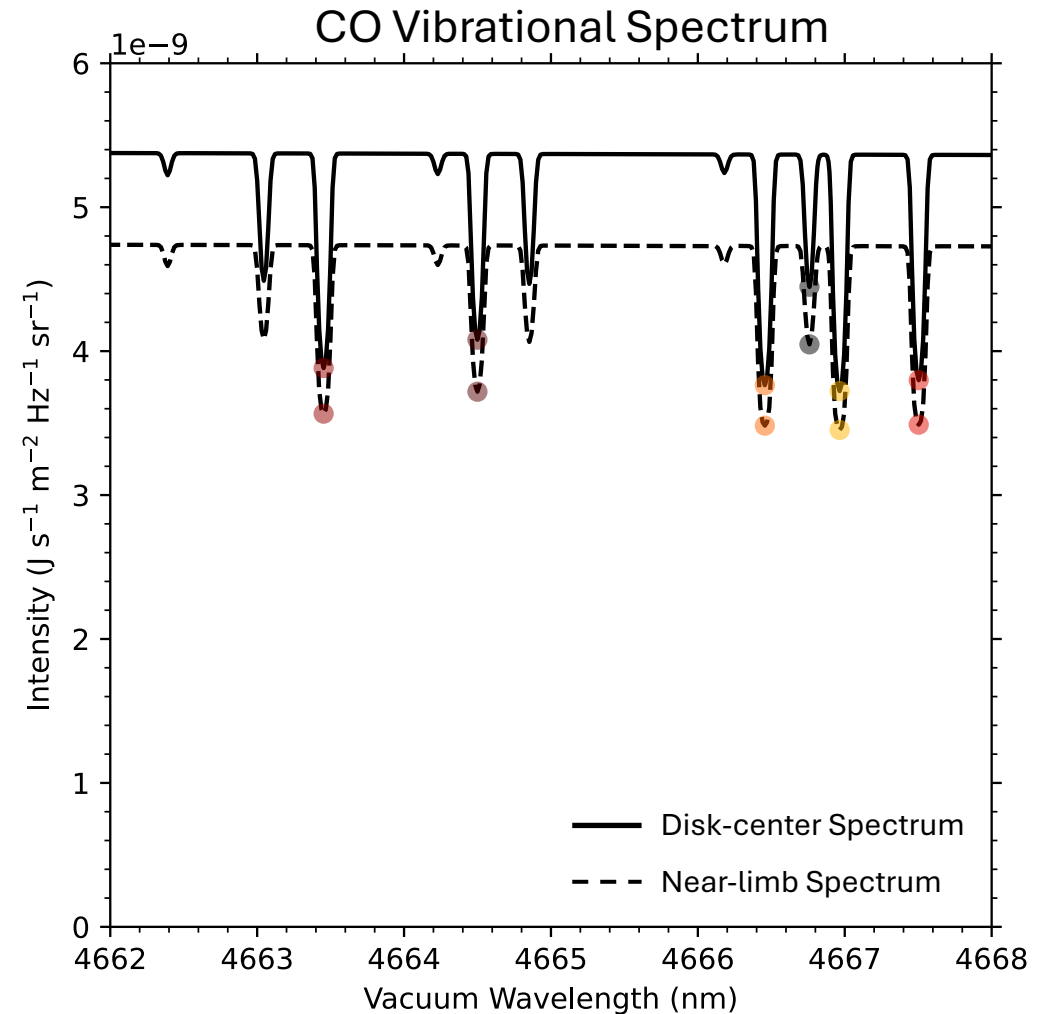
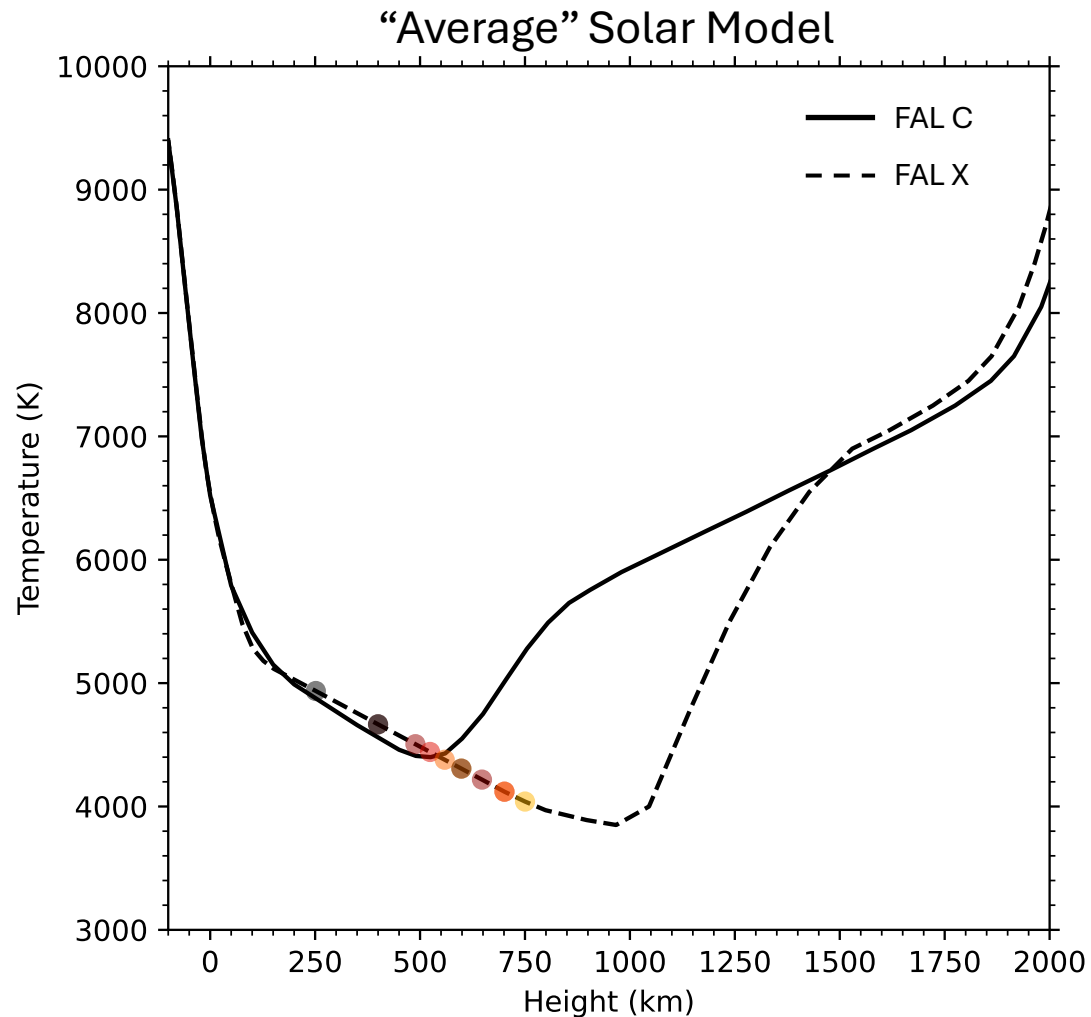
Spectral Inversions with ALMA - problematic

Inversions with atomic lines only
Ca II 8542 + Na D1 5896

Inversions with atomic lines and ALMA
Ca II 8542 + Na D1 5896 + Band 3 & 6



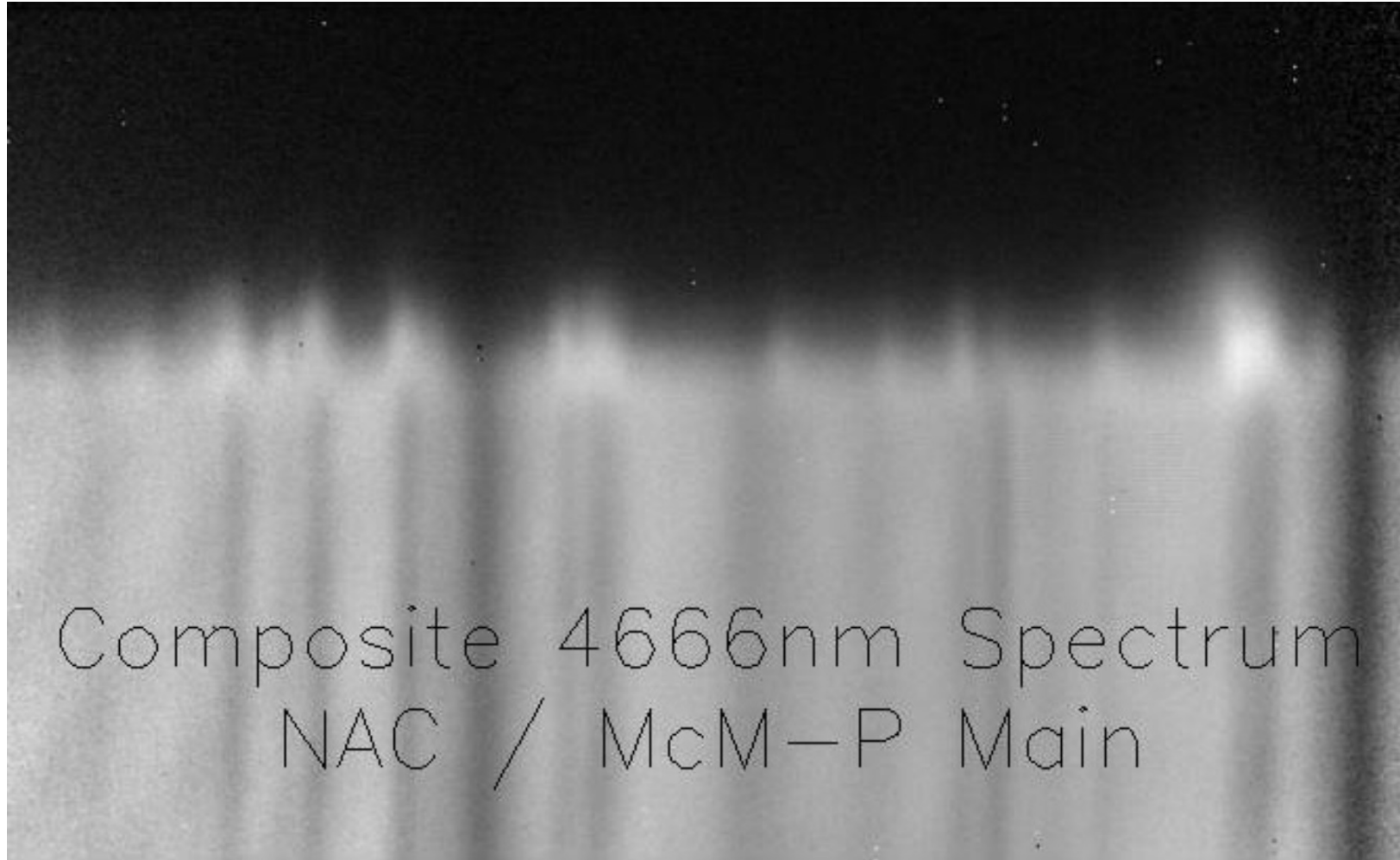
COmosphere – Atmospheric Bifurcation



Courtesy Johnathan Stauffer

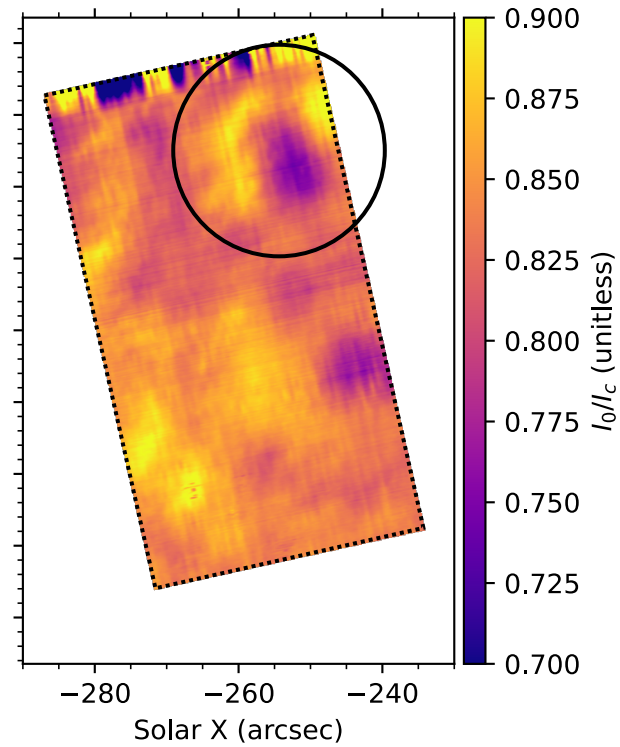
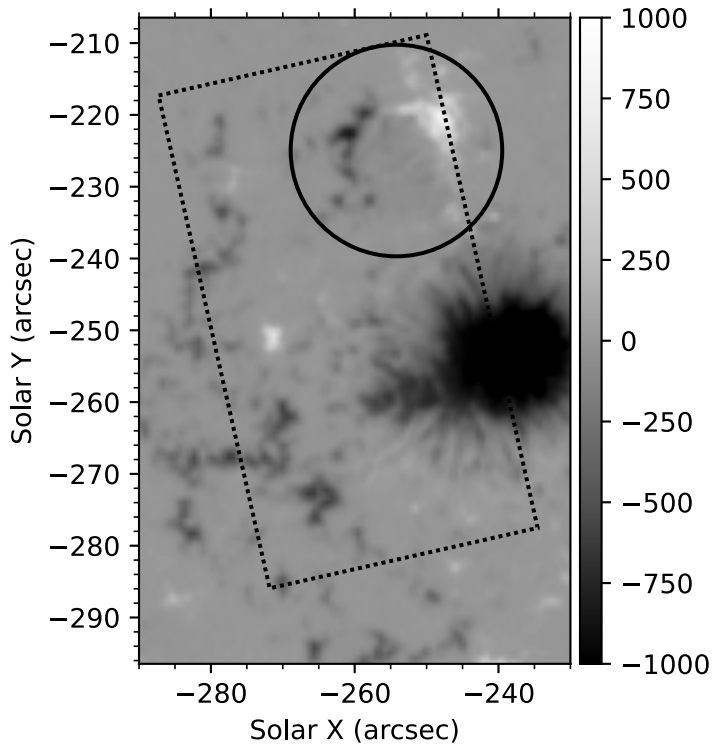
COmosphere – Atmospheric Bifurcation

solar limb →

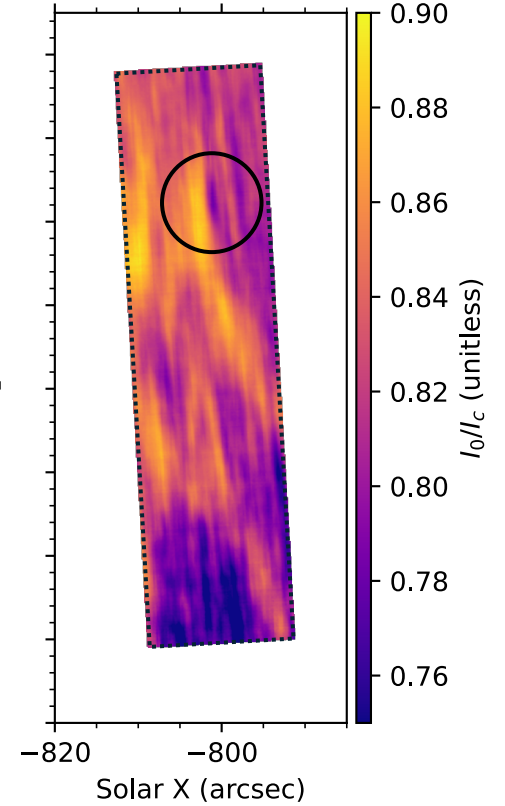
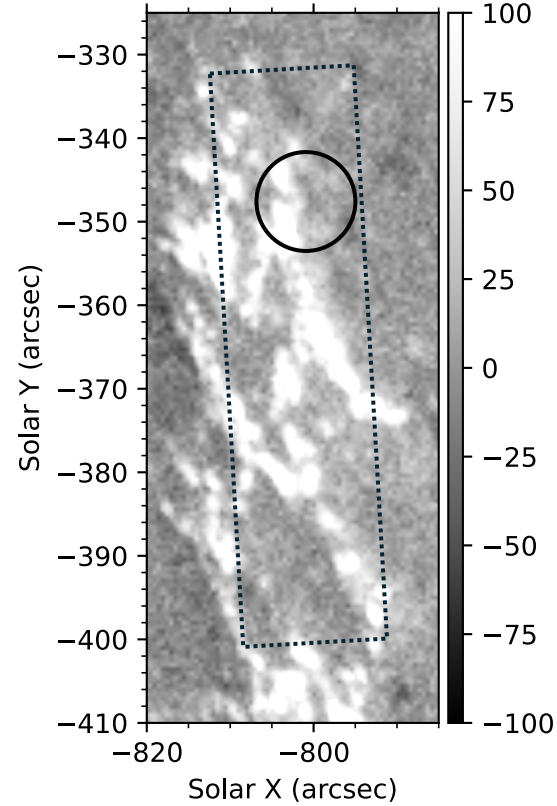


CYRA Observations of CO Dynamics

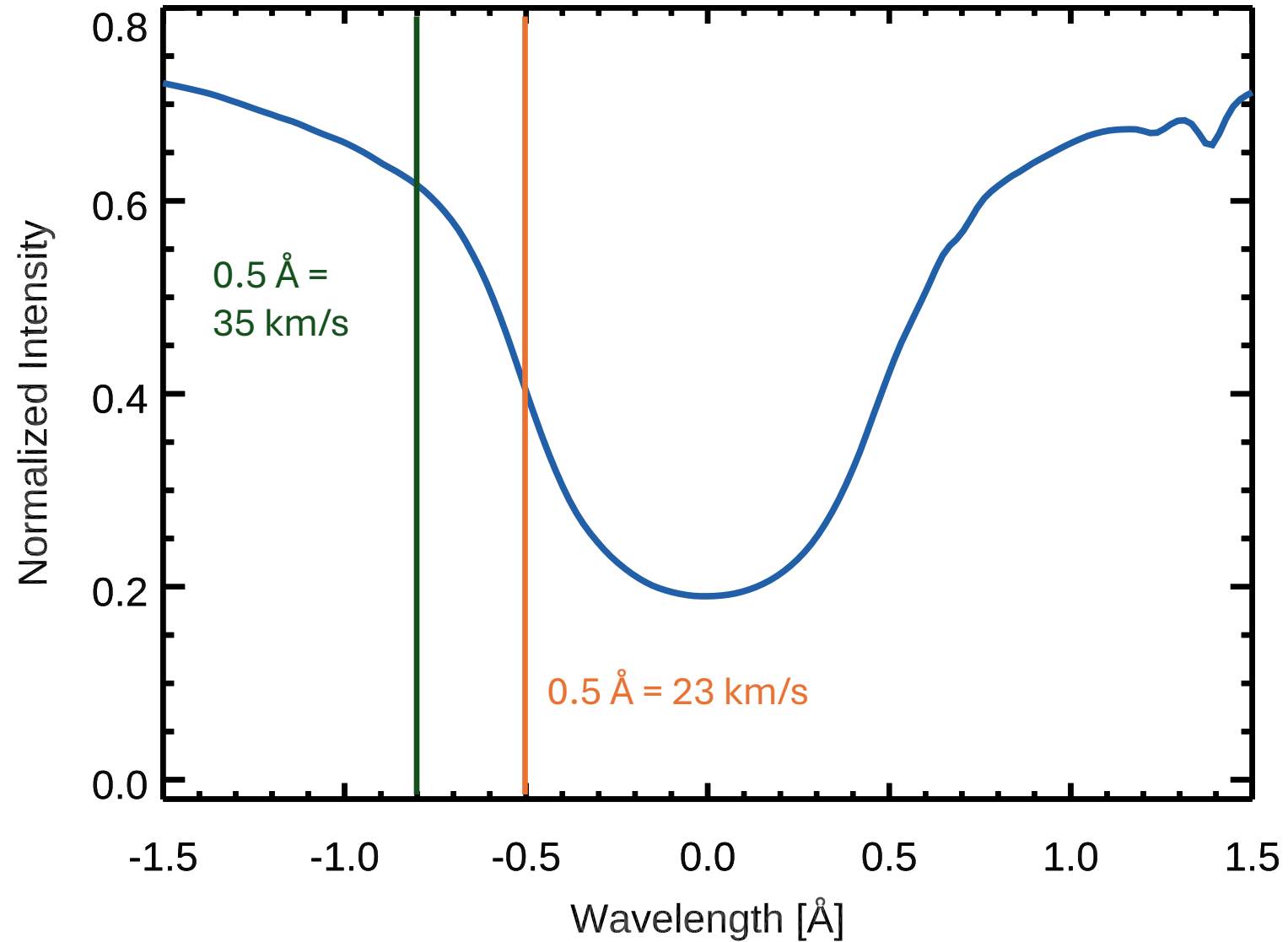
Emerging bipole: observed 4/28/2022



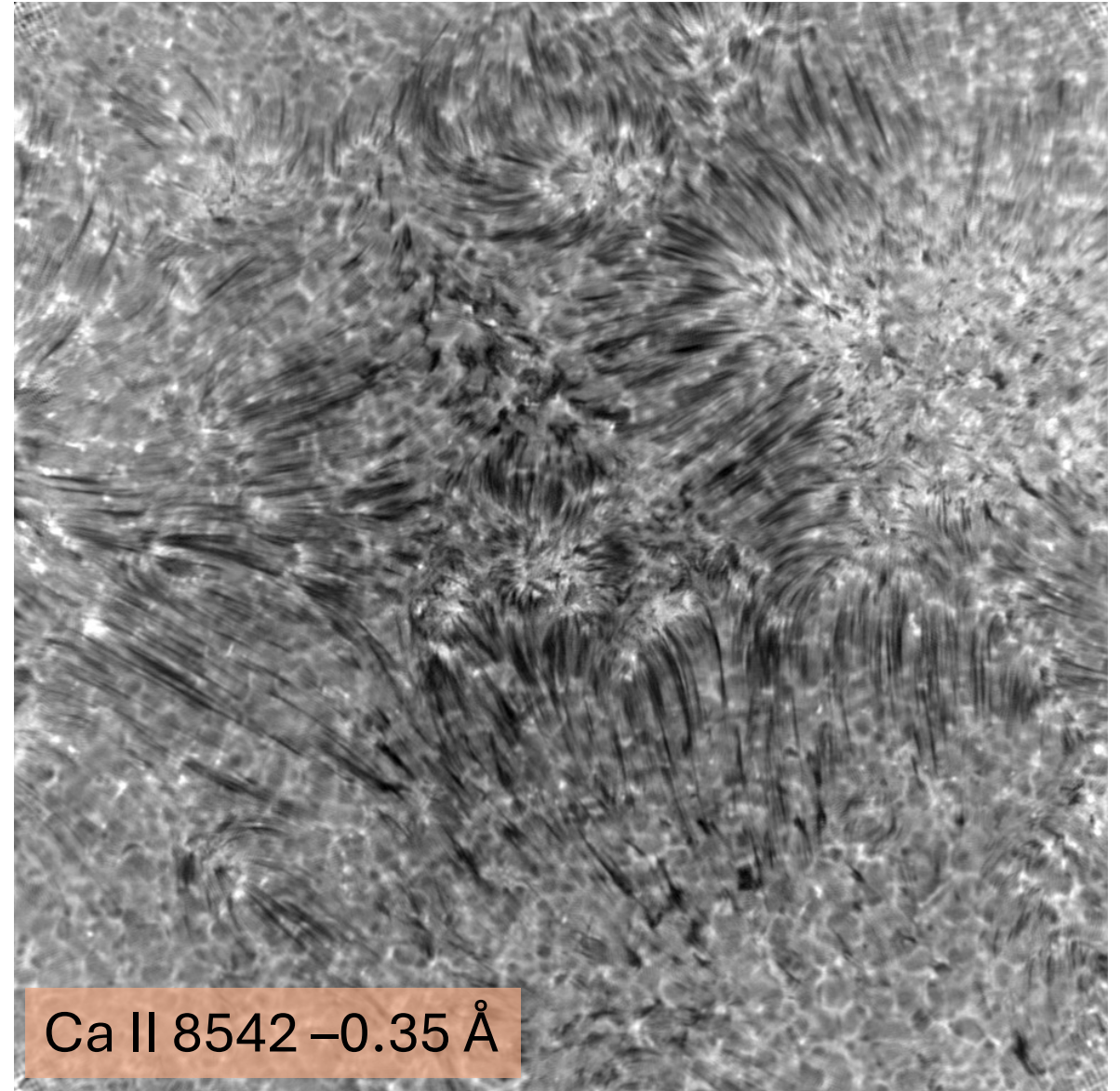
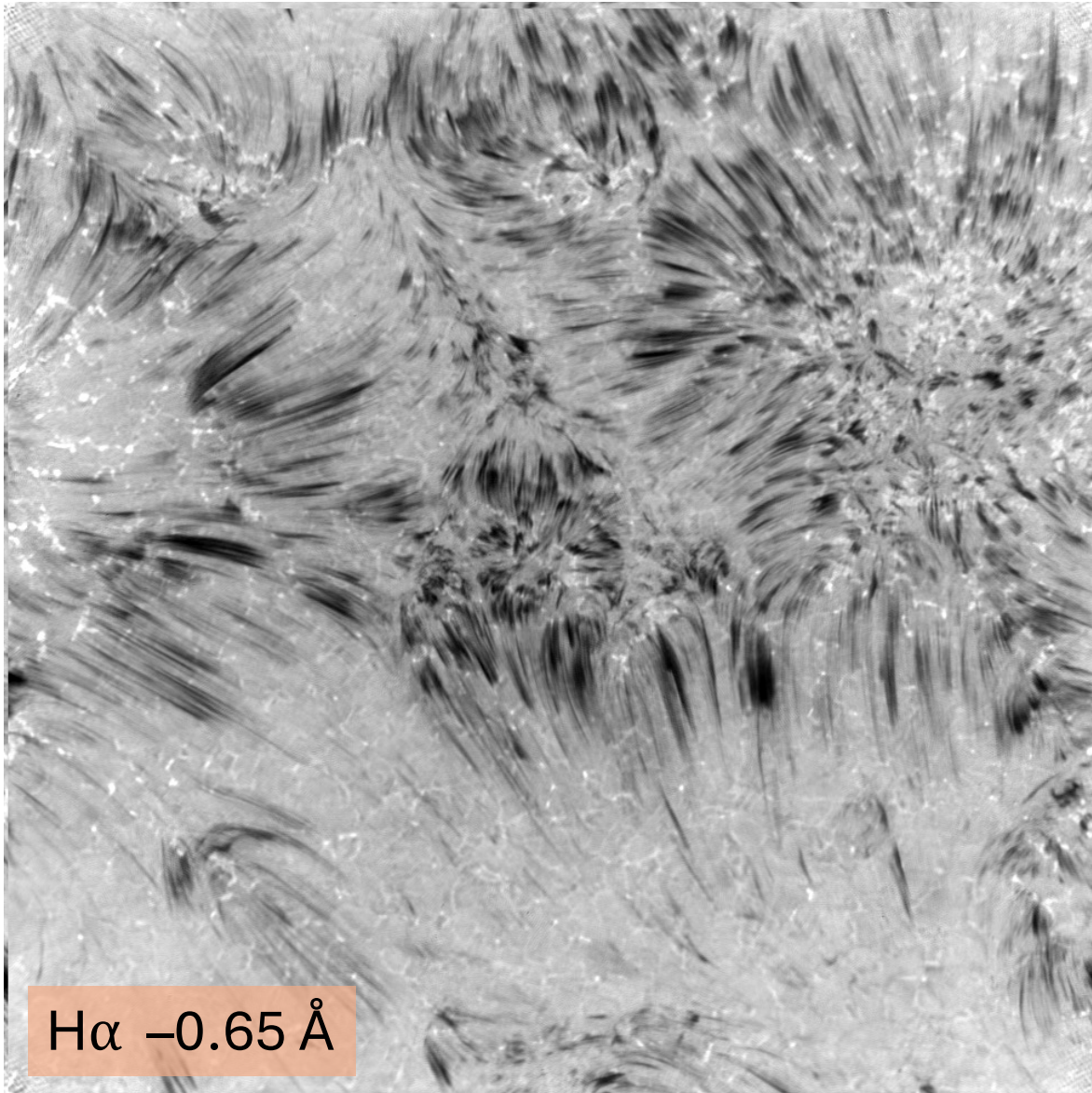
Plage canopy: observed 10/19/2021



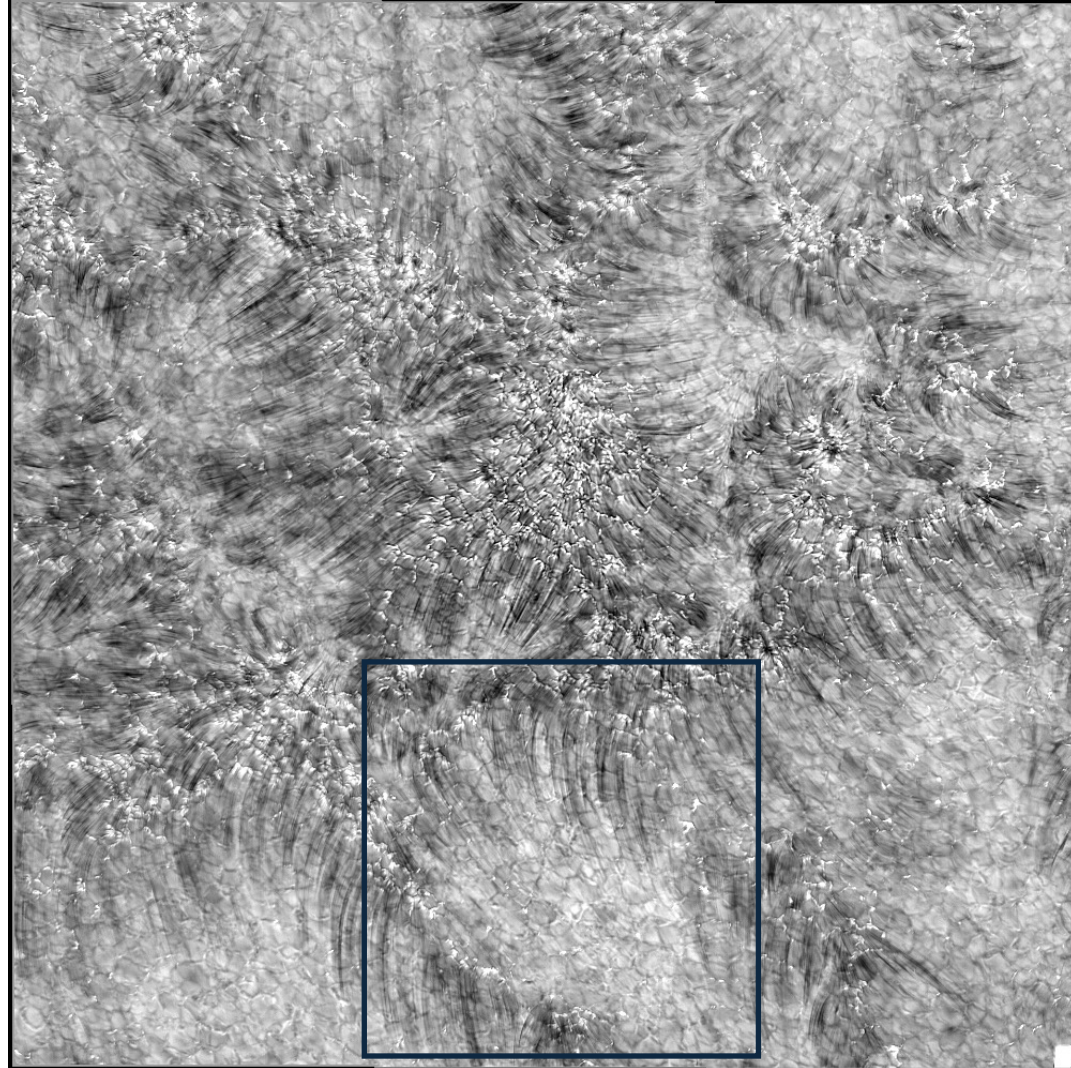
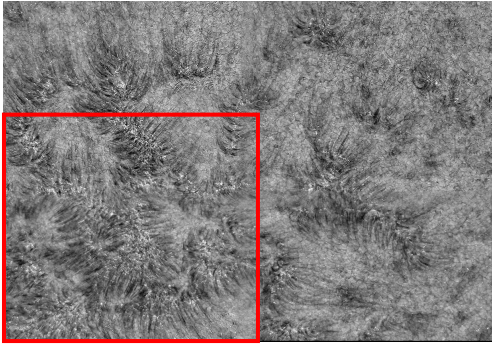
Line Wings and Doppler Shifts



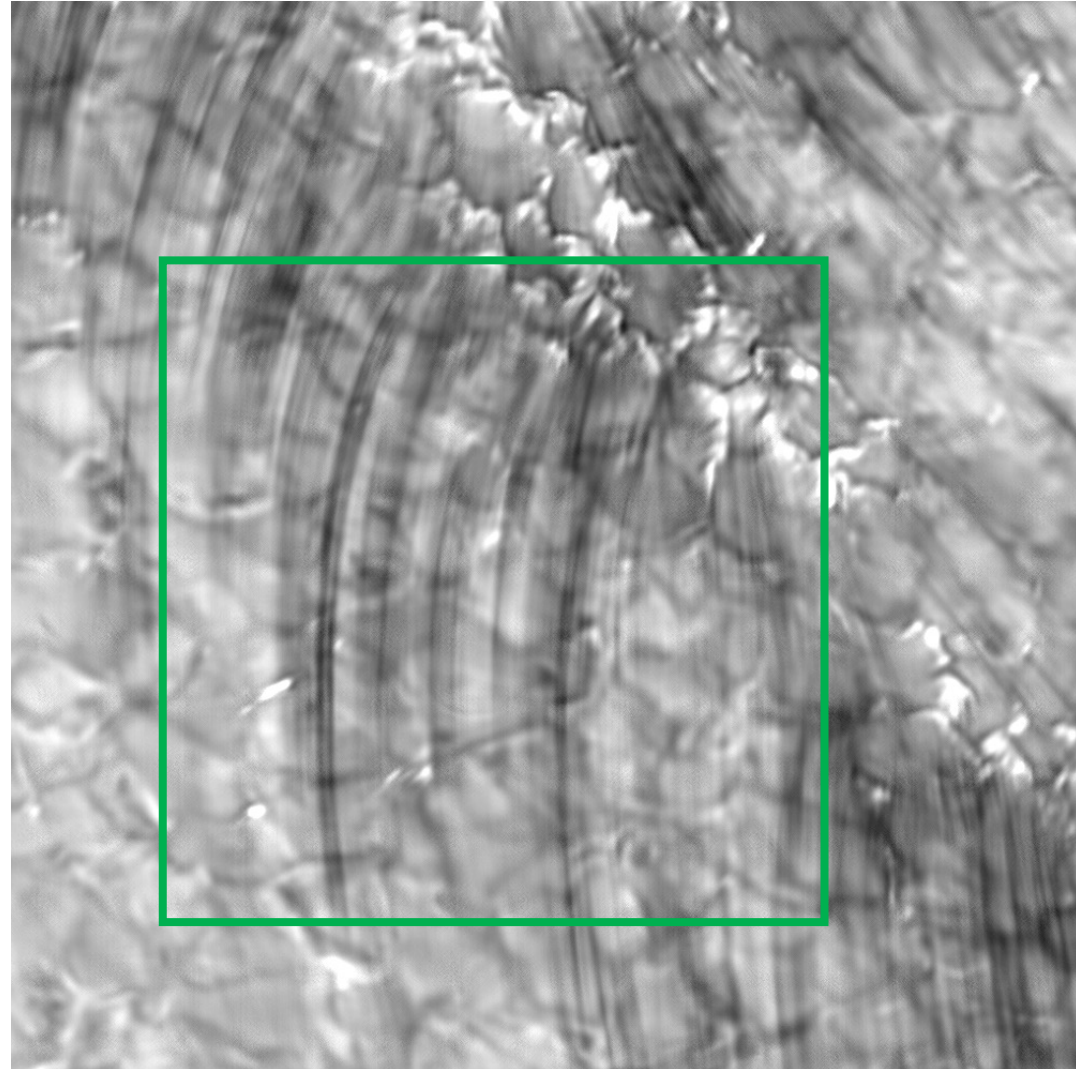
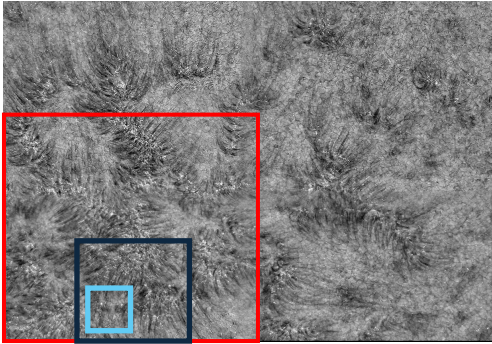
Line Wings and Doppler Shifts



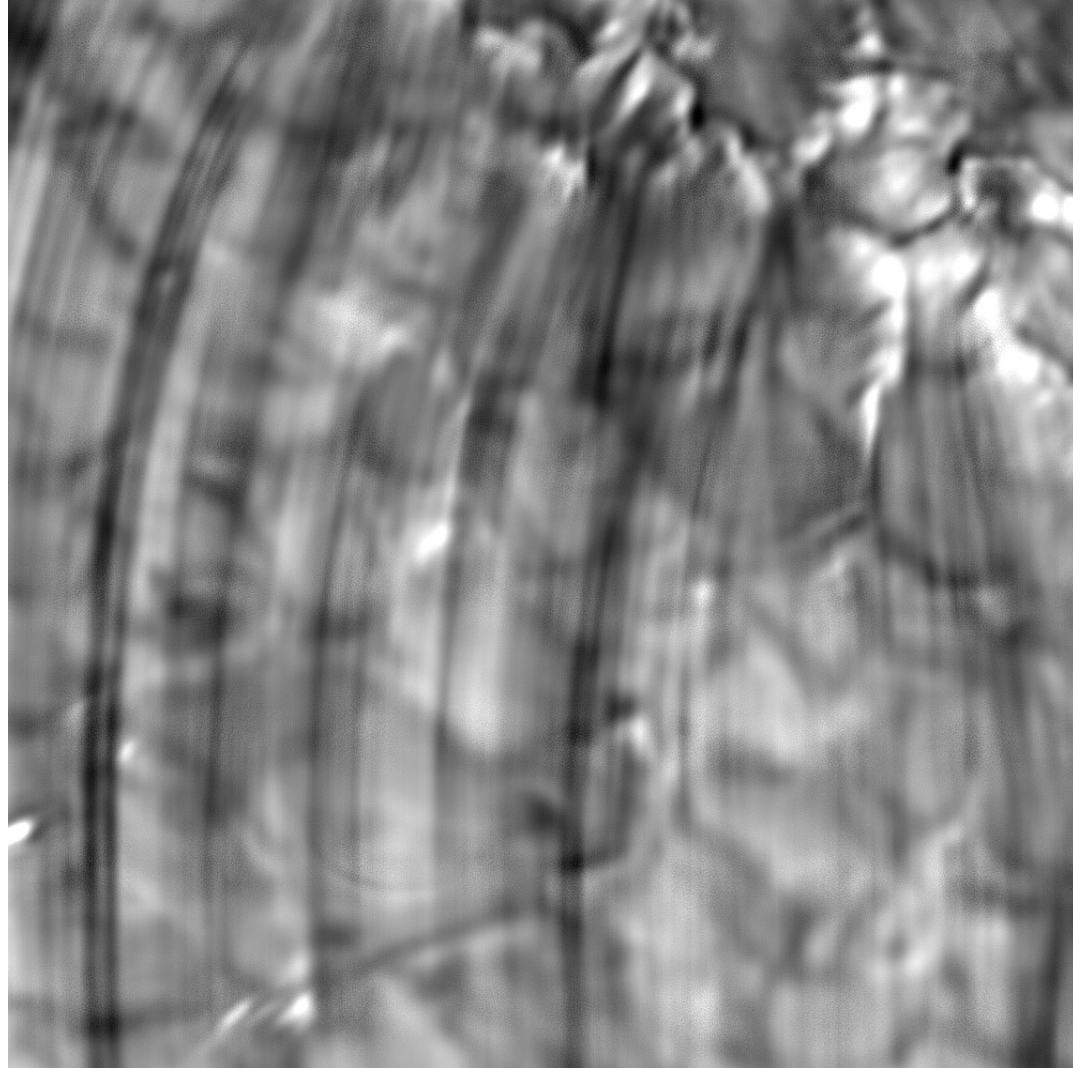
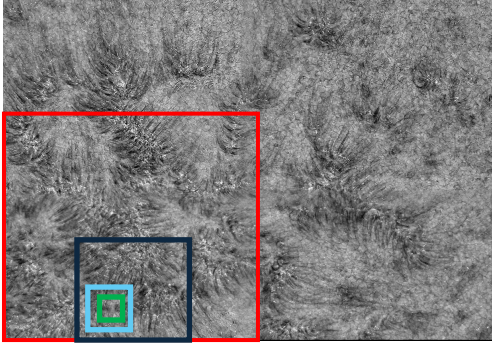
DKIST/VBI Meta-mosaic



DKIST/VBI Meta-mosaic

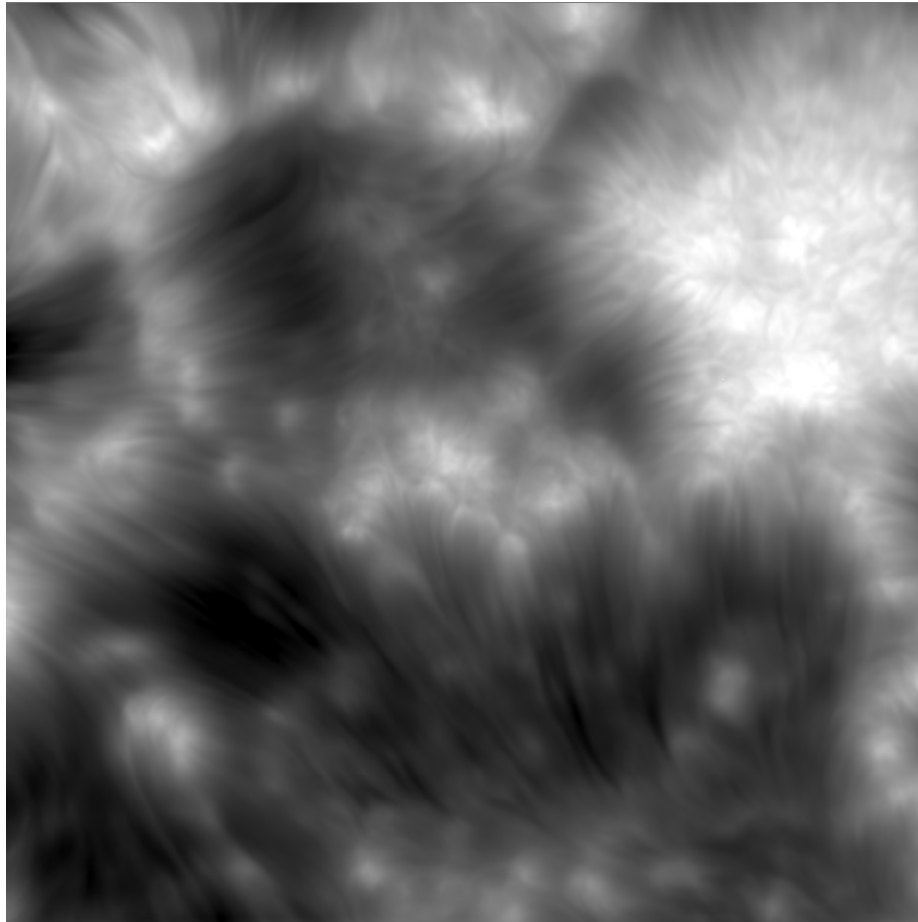


DKIST/VBI Meta-mosaic

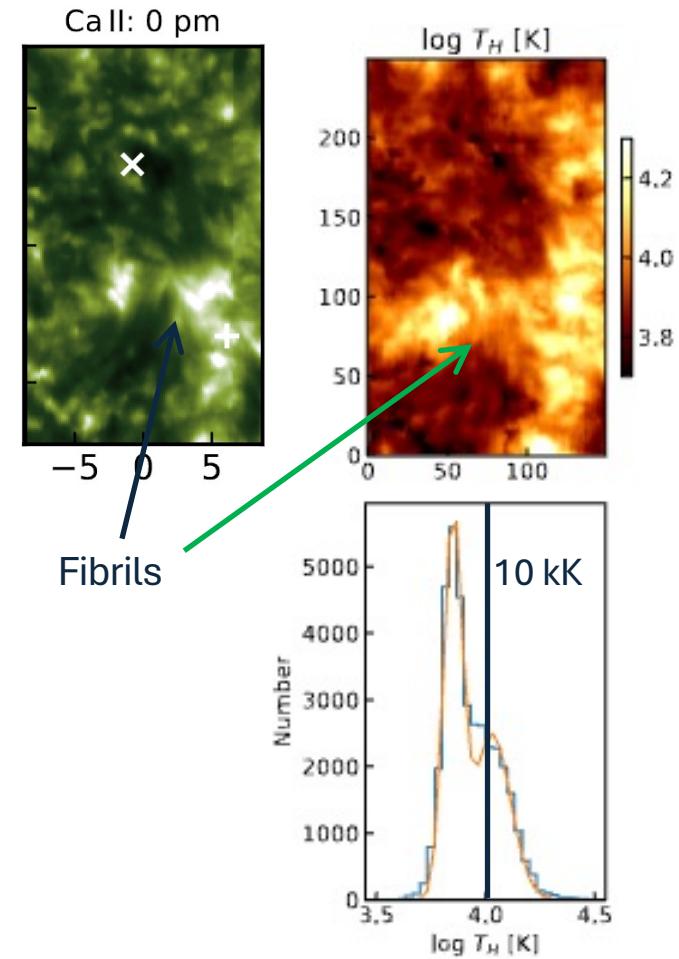


Base of fibrils are hot(ter)

IBIS Ca II 8542 Å Core Intensity



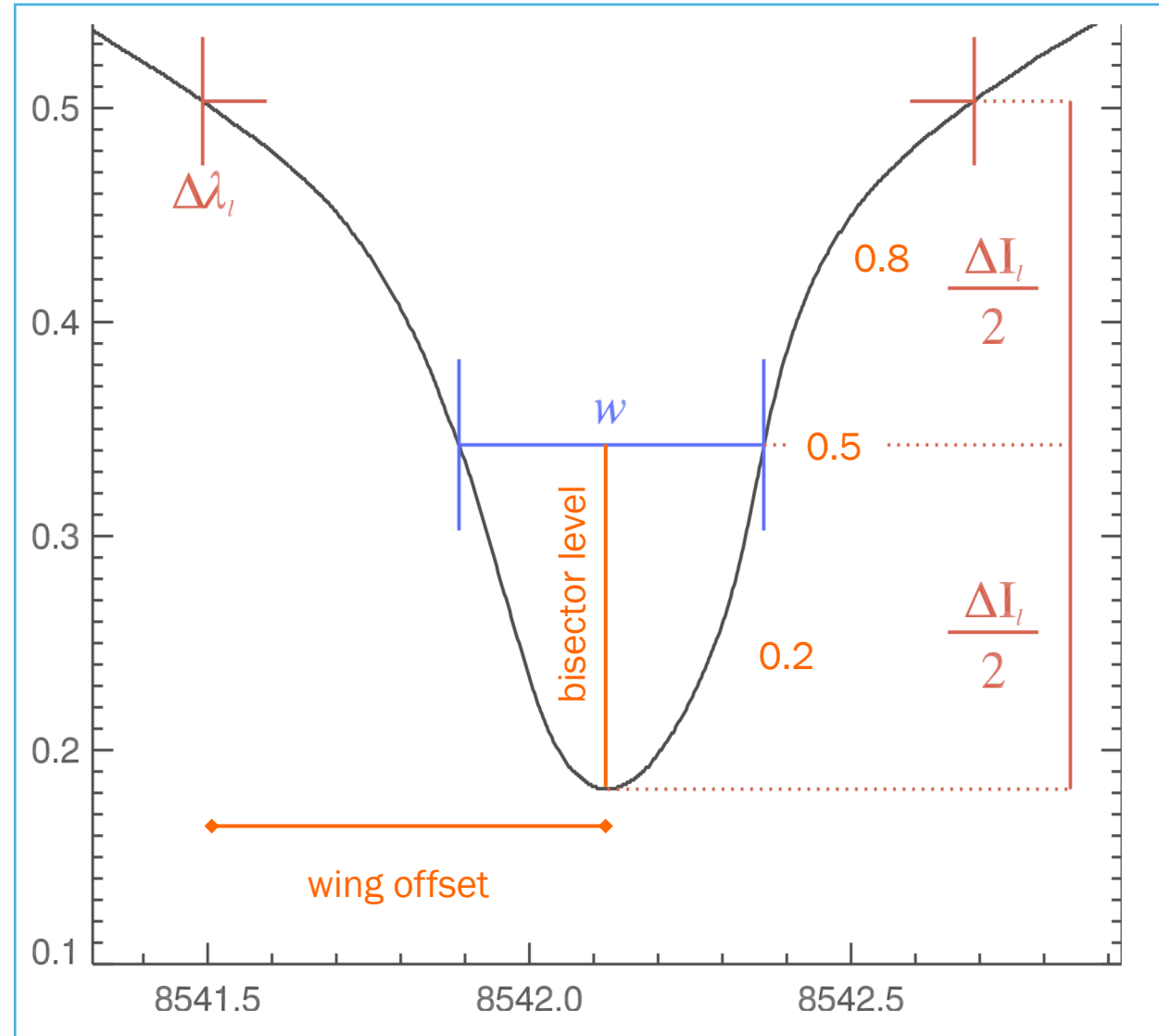
Brighter Ca II 8542 \sim hotter



Chae *et al.*, 2020, A&A

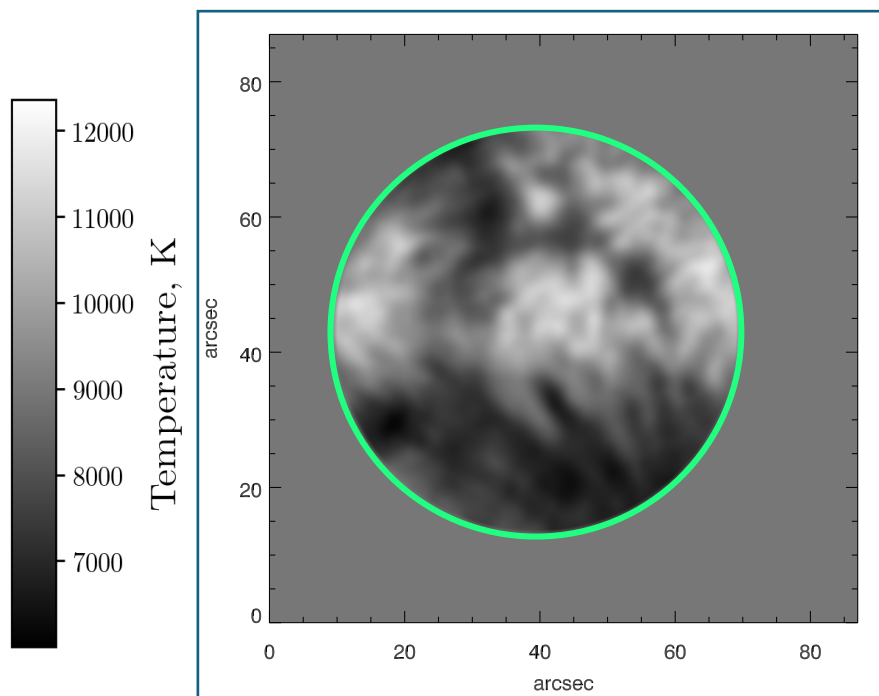
See also Kriginisky *et al.*, 2023, A&A

Line-Width Calculation



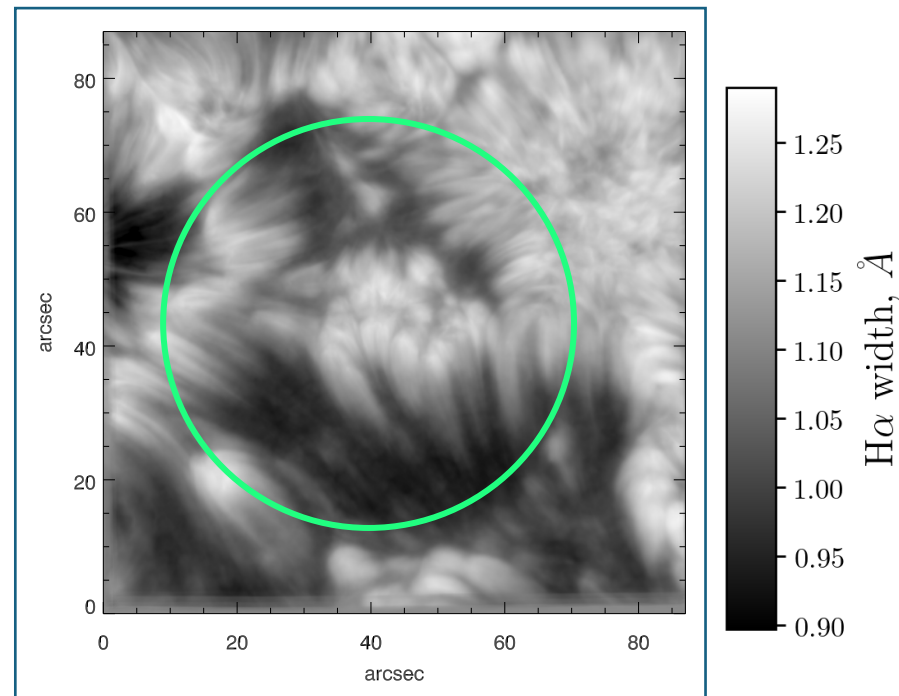
H α line-width as the key

ALMA – 3.1 mm



2 arcsec Gaussian beam

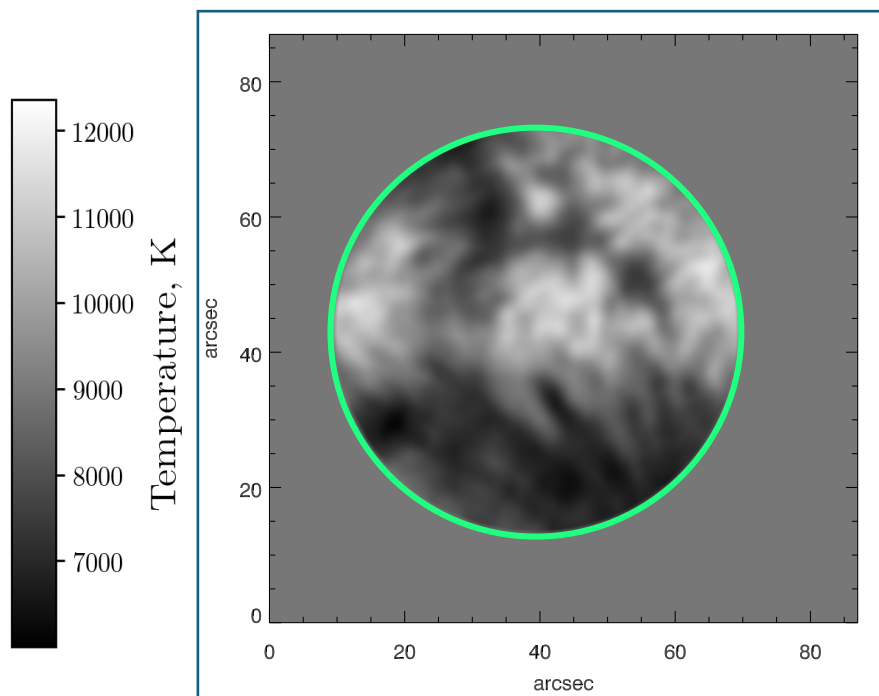
NSO/DST/IBIS –
H α line-profile width



0.2 arcsec resolution

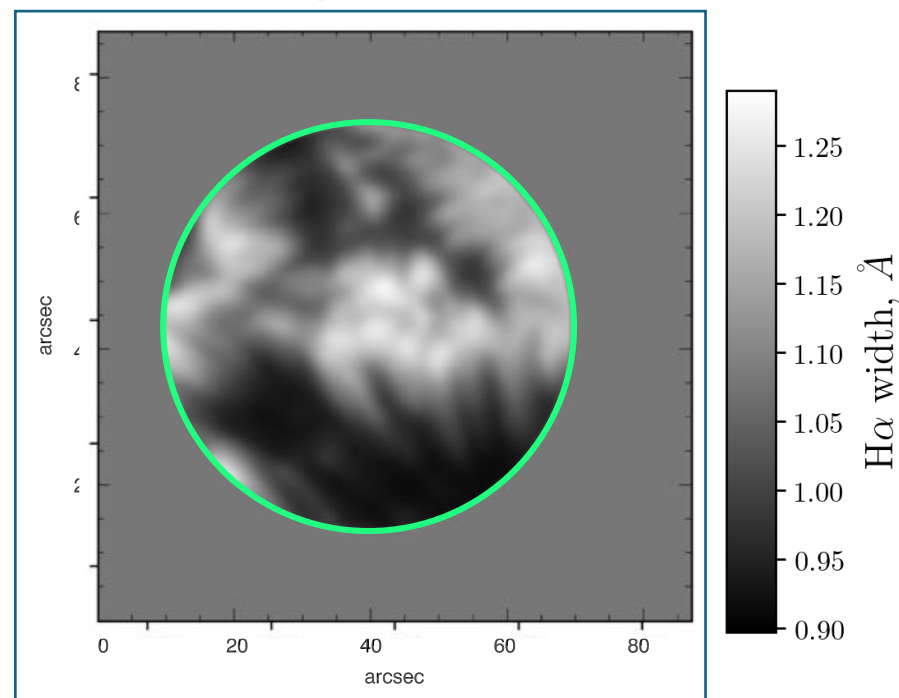
H α line-width as the key

ALMA – 3.1 mm

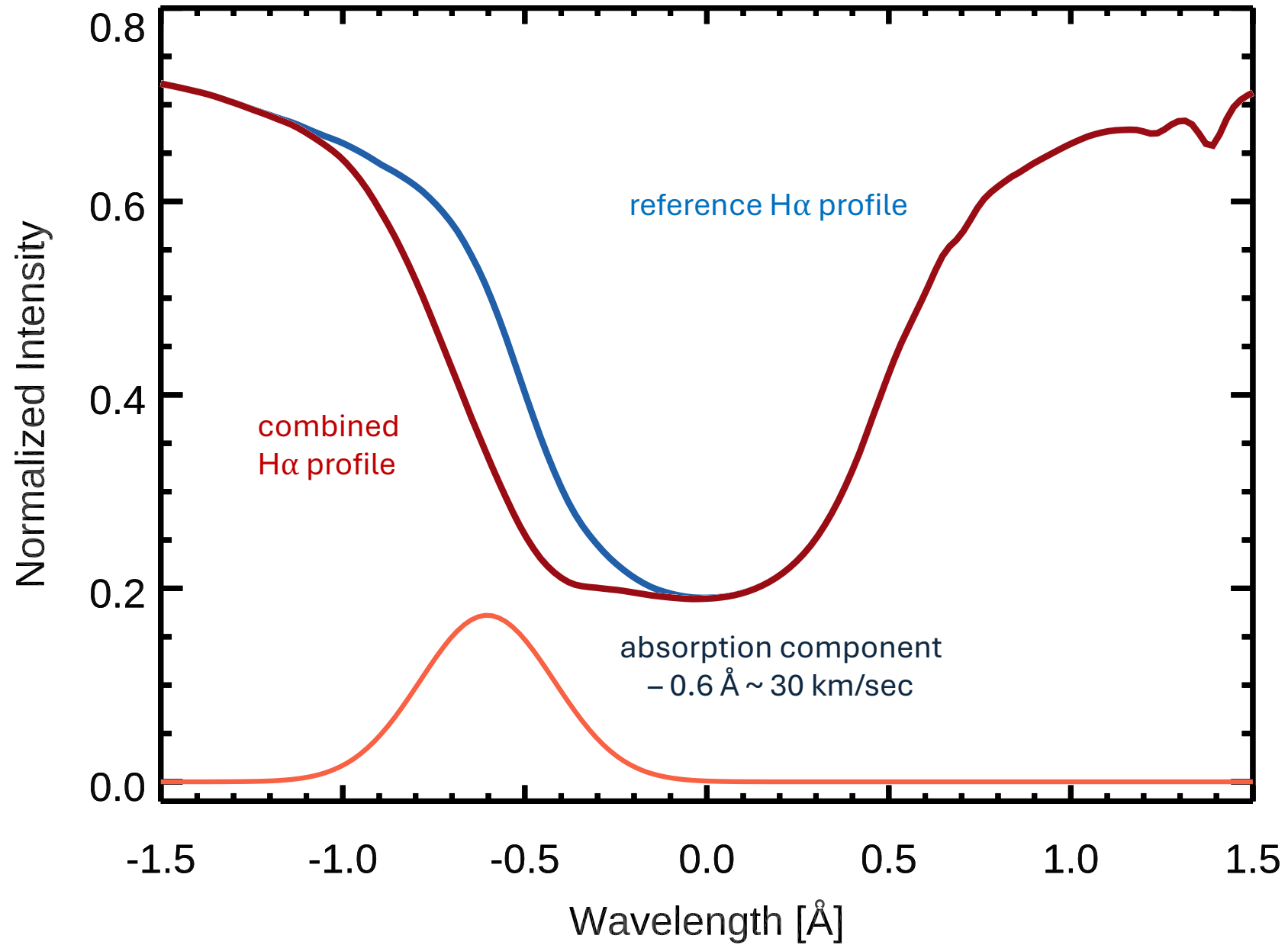


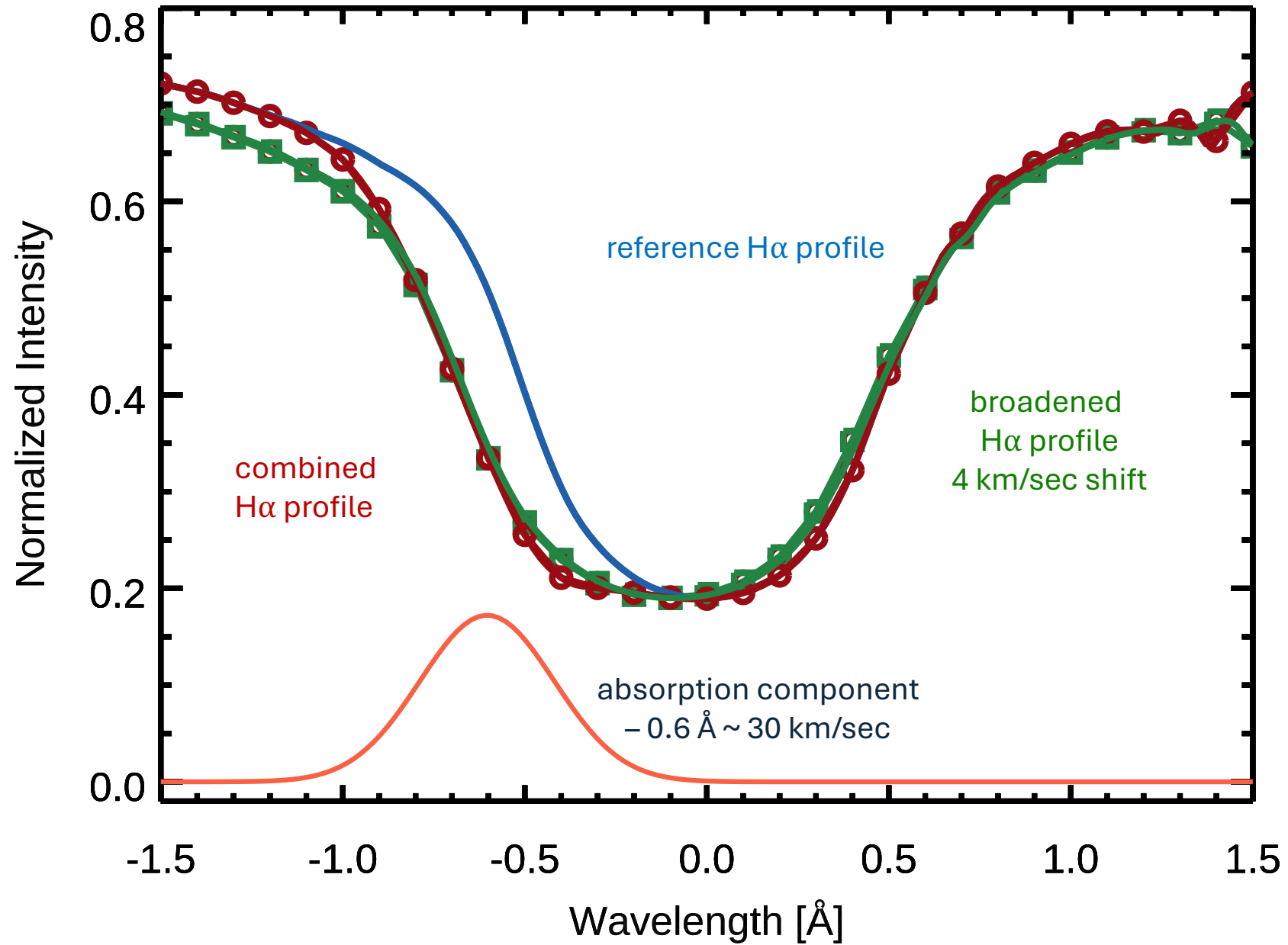
2 arcsec Gaussian beam

NSO/DST/IBIS –
H α line-profile width



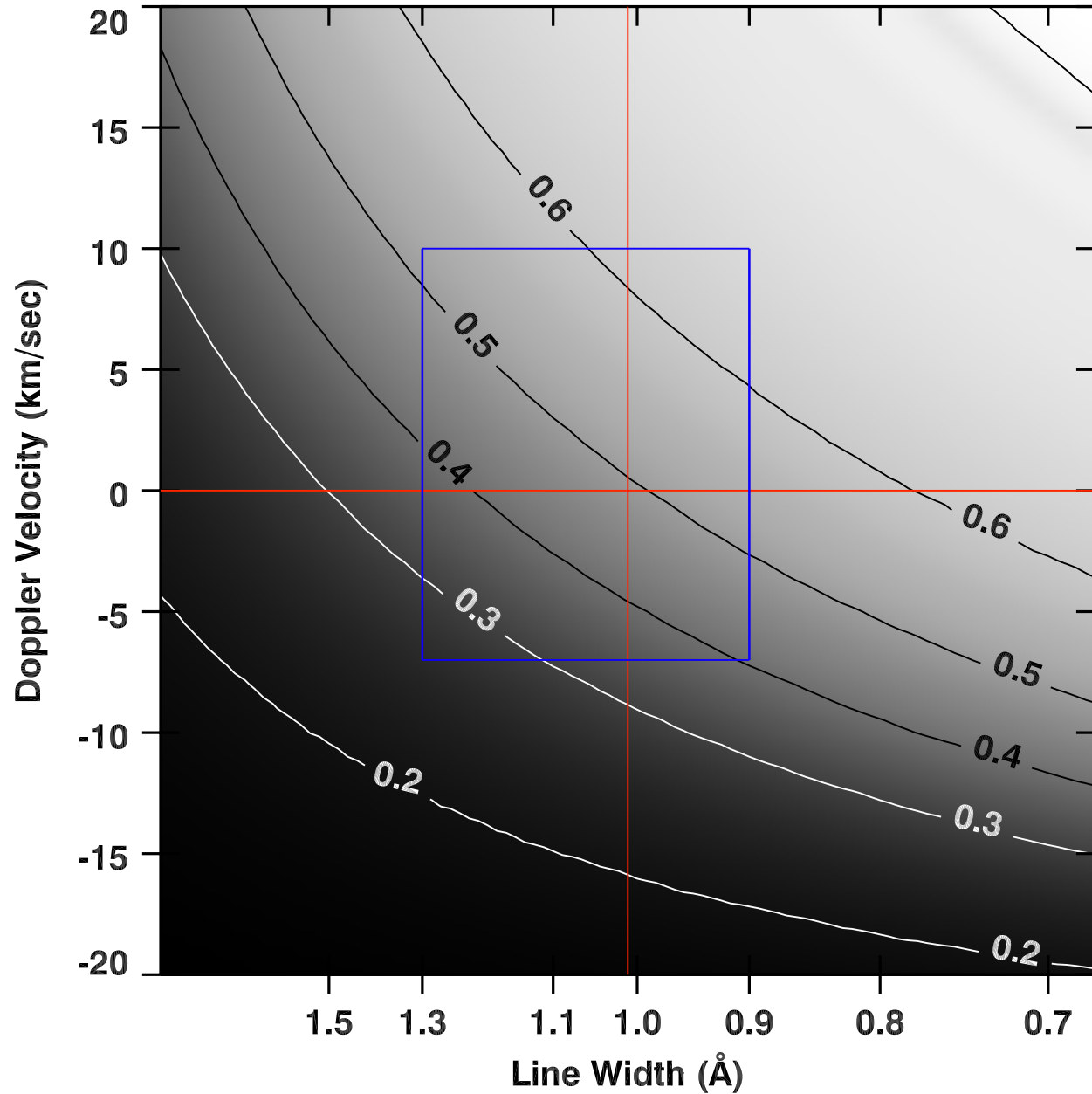
2 arcsec Gaussian convolution



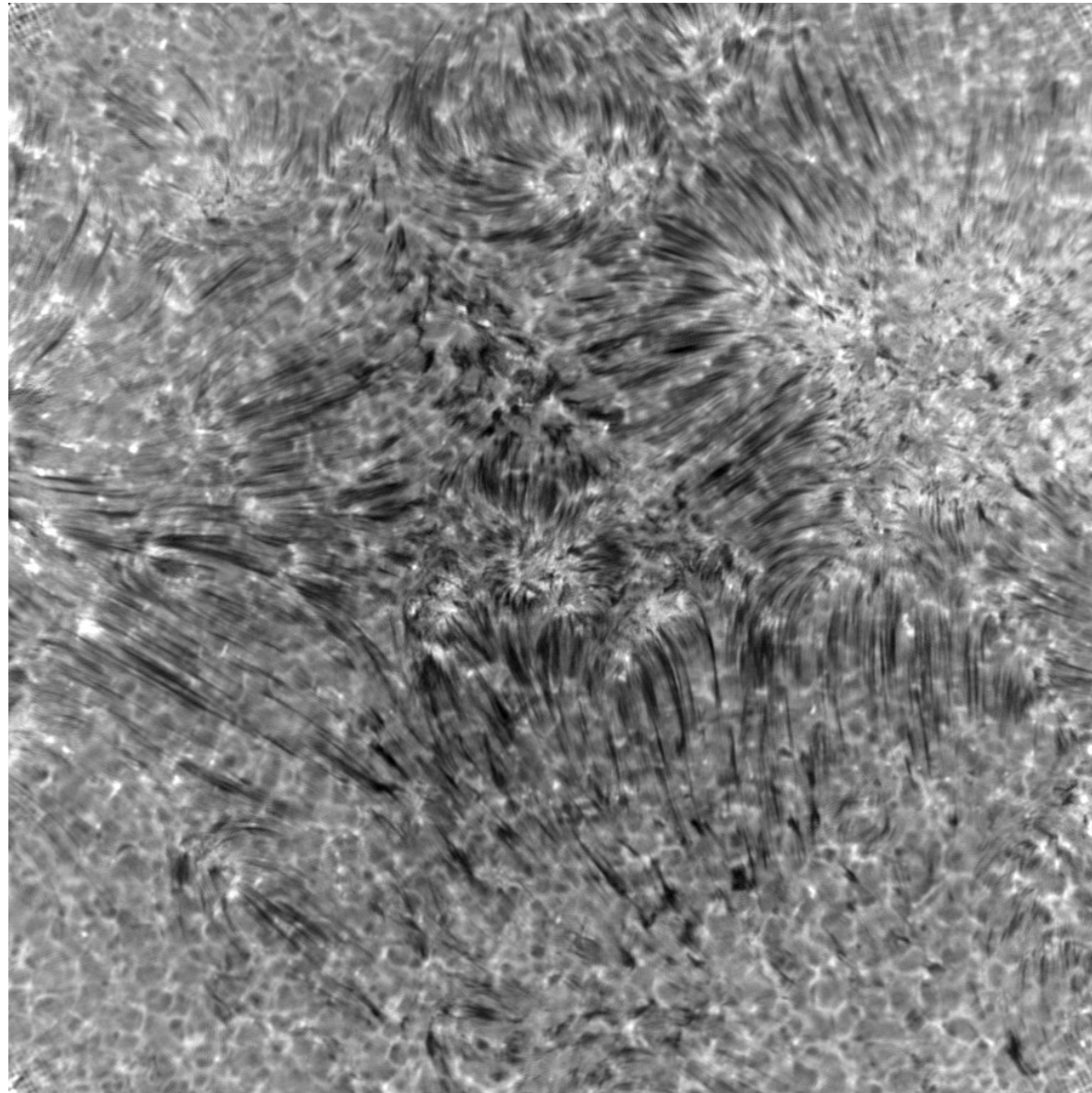
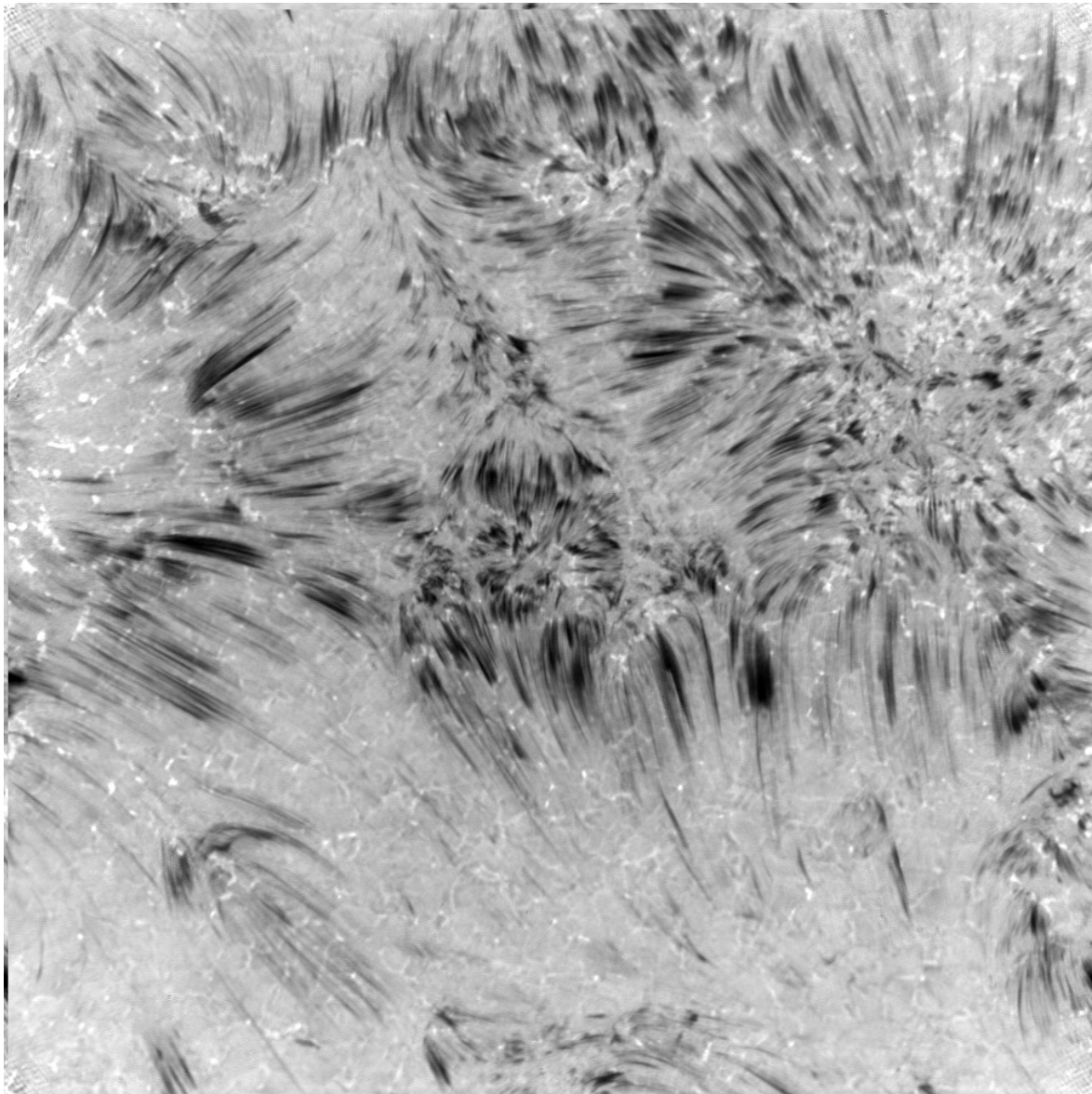


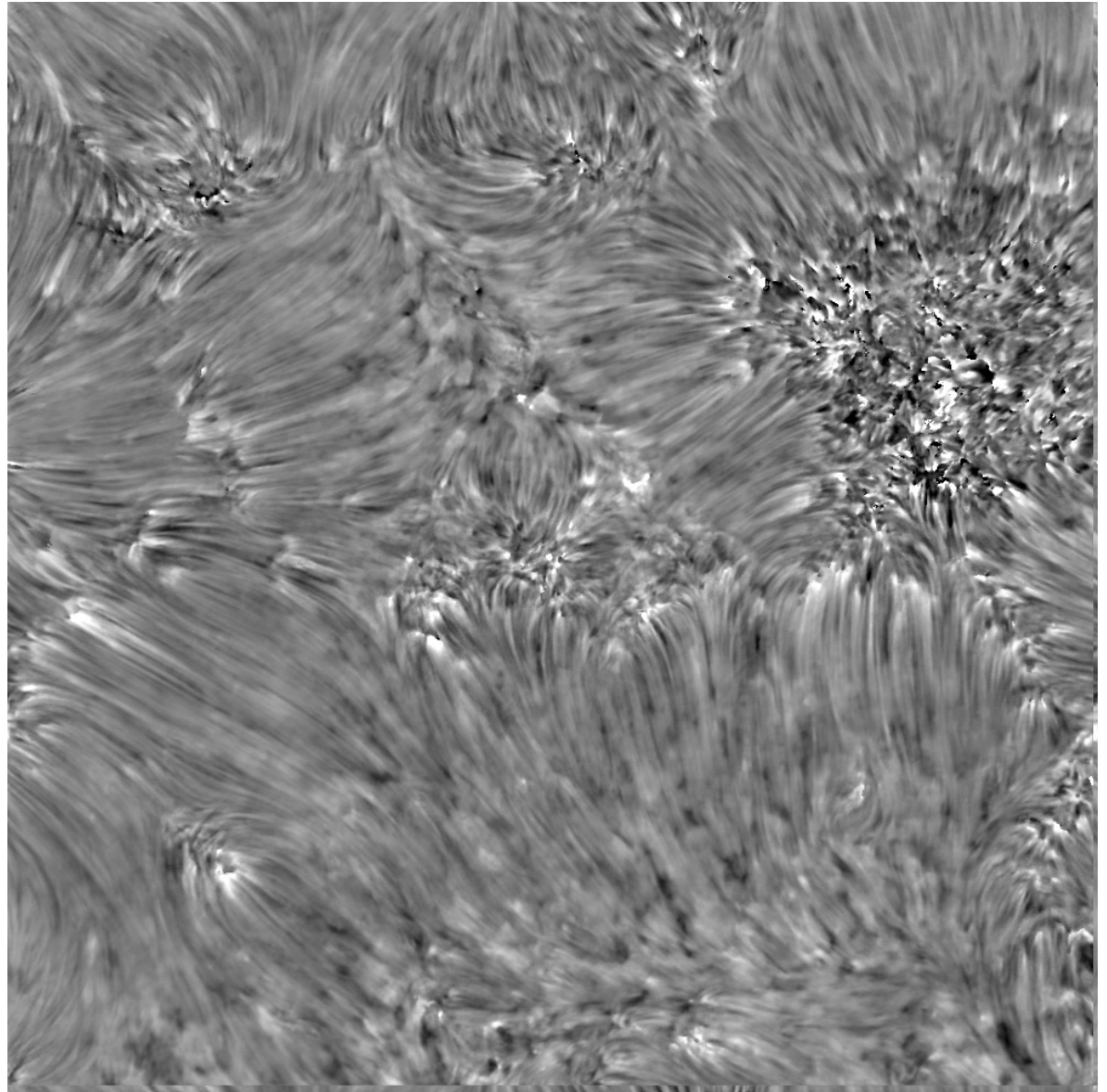
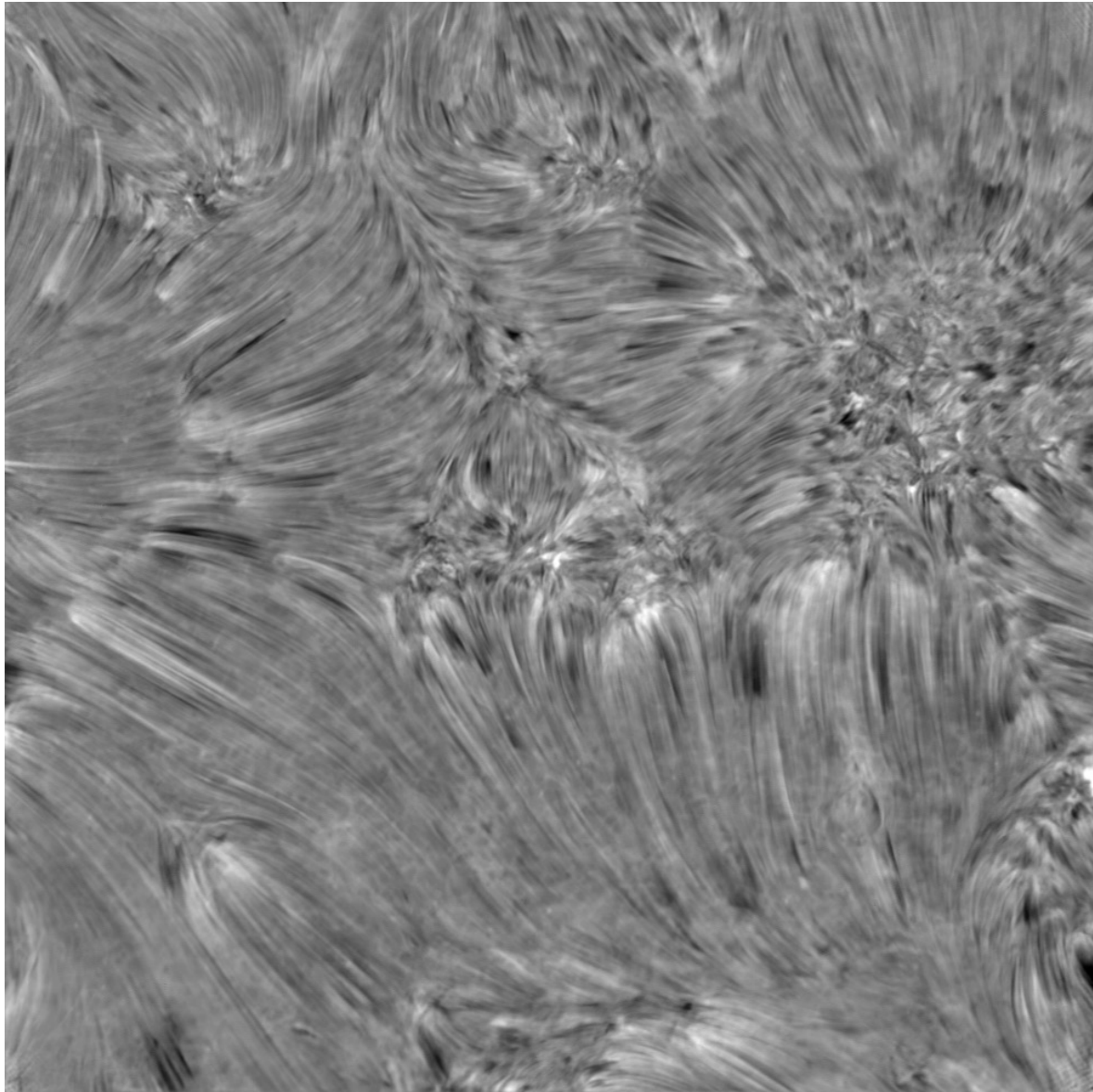
Width vs. Velocity Contrast

Multiple combinations of broadening and (small) doppler shifts, can lead to same intensity reduction in wings



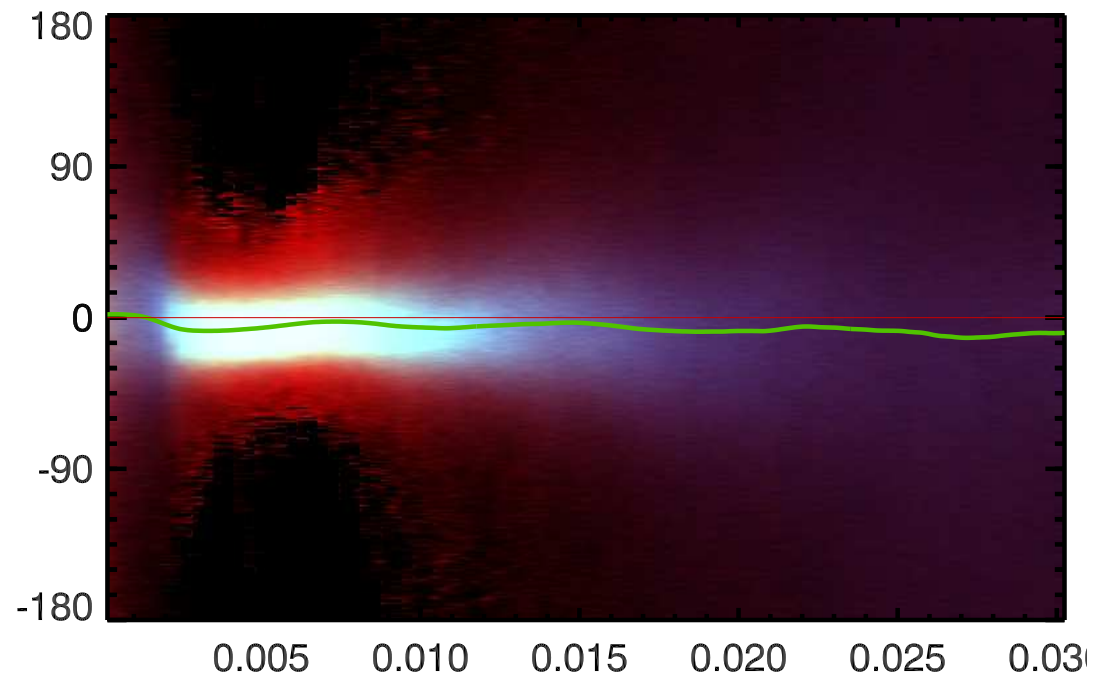
Wings and Shifts



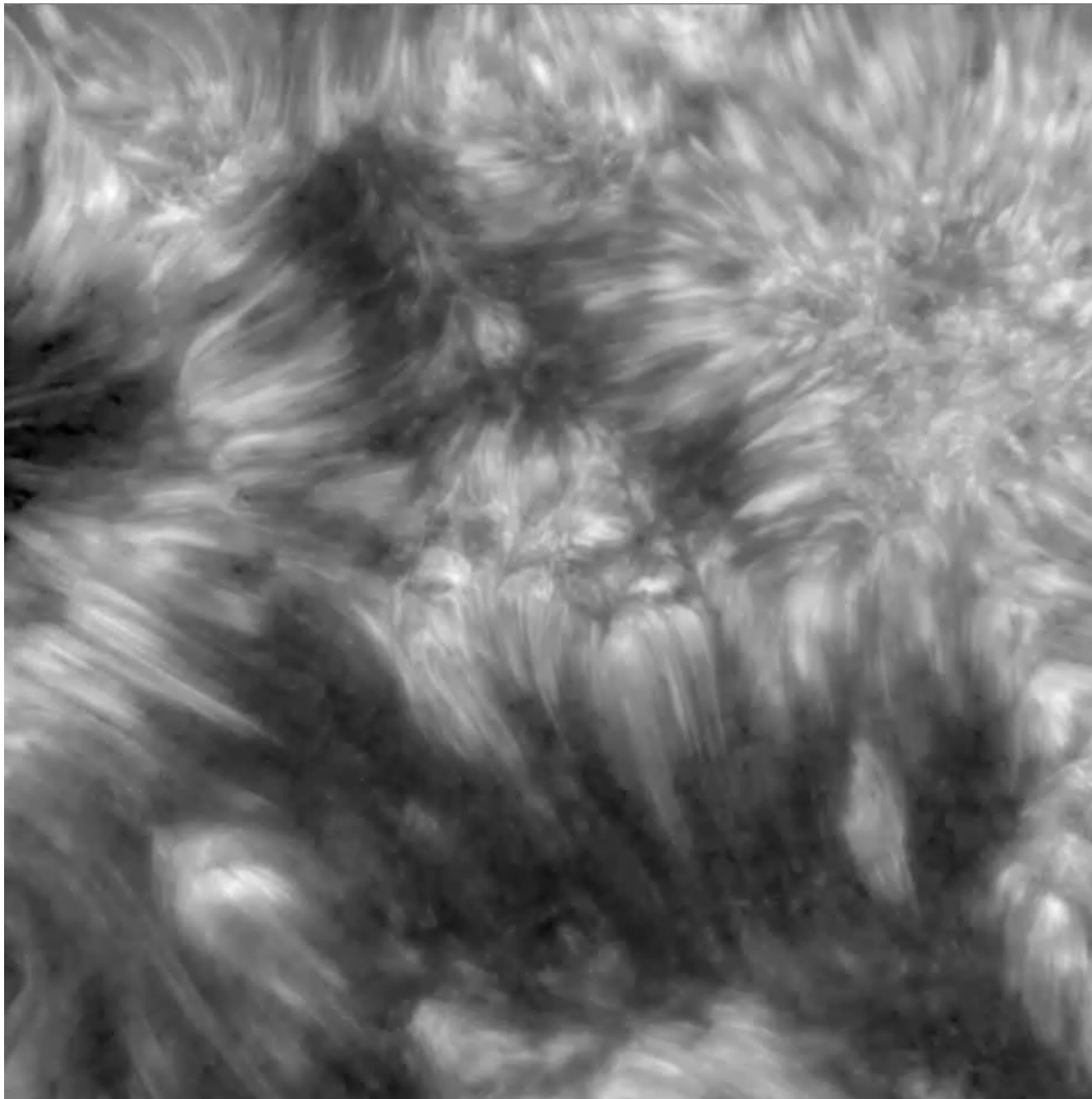


Chromospheric Confounding

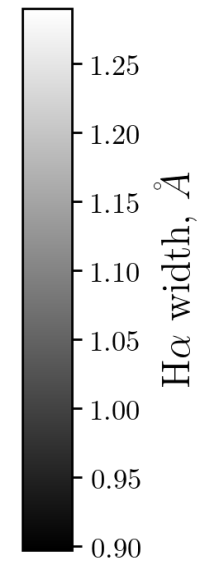
- "Chromospheric" bisectors



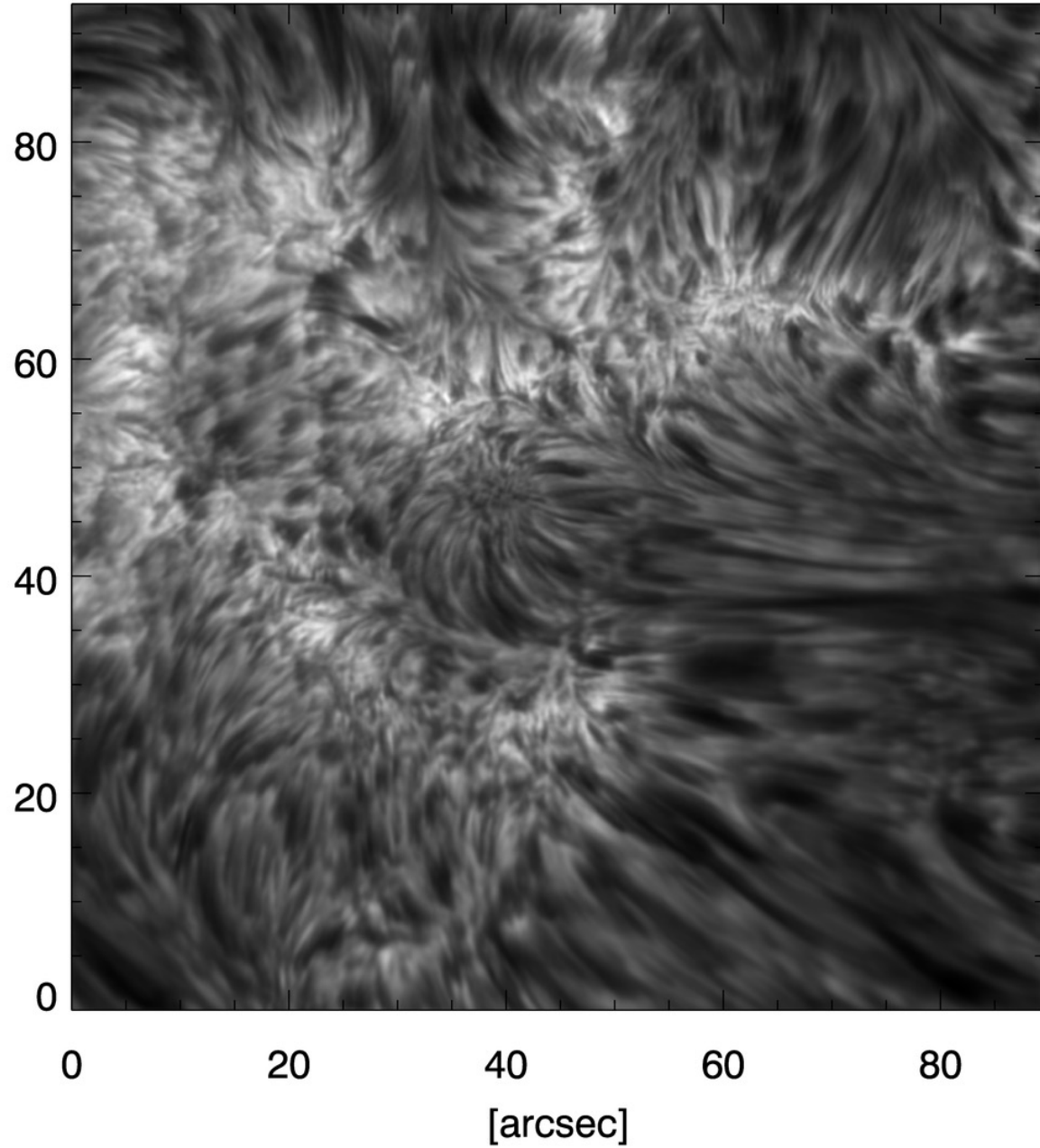
H-alpha core vs. bisector velocity



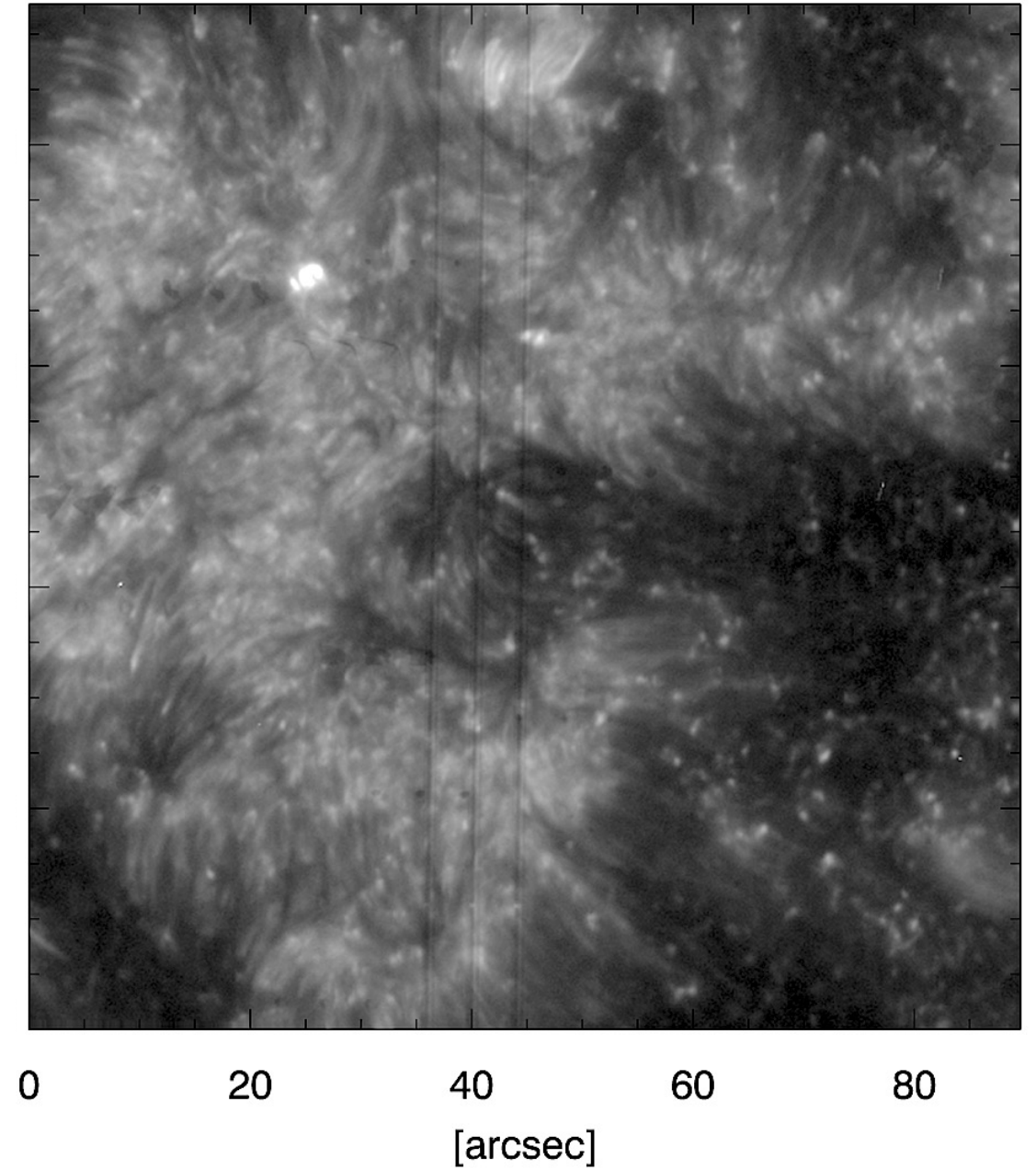
IBIS H α
Line Width
 $\Delta t = 3.6$ sec
T = 7.5 minutes



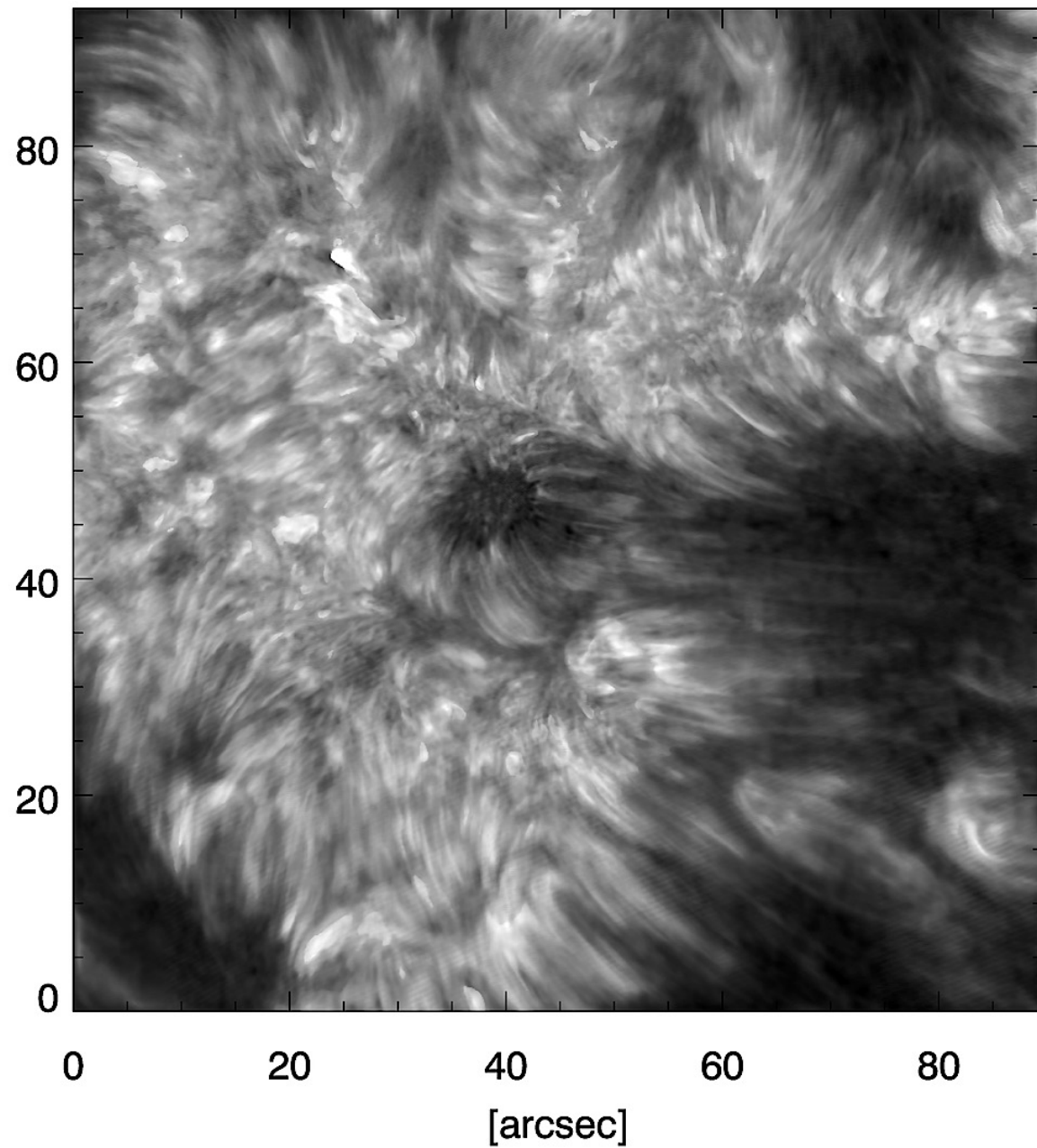
H α Line Core



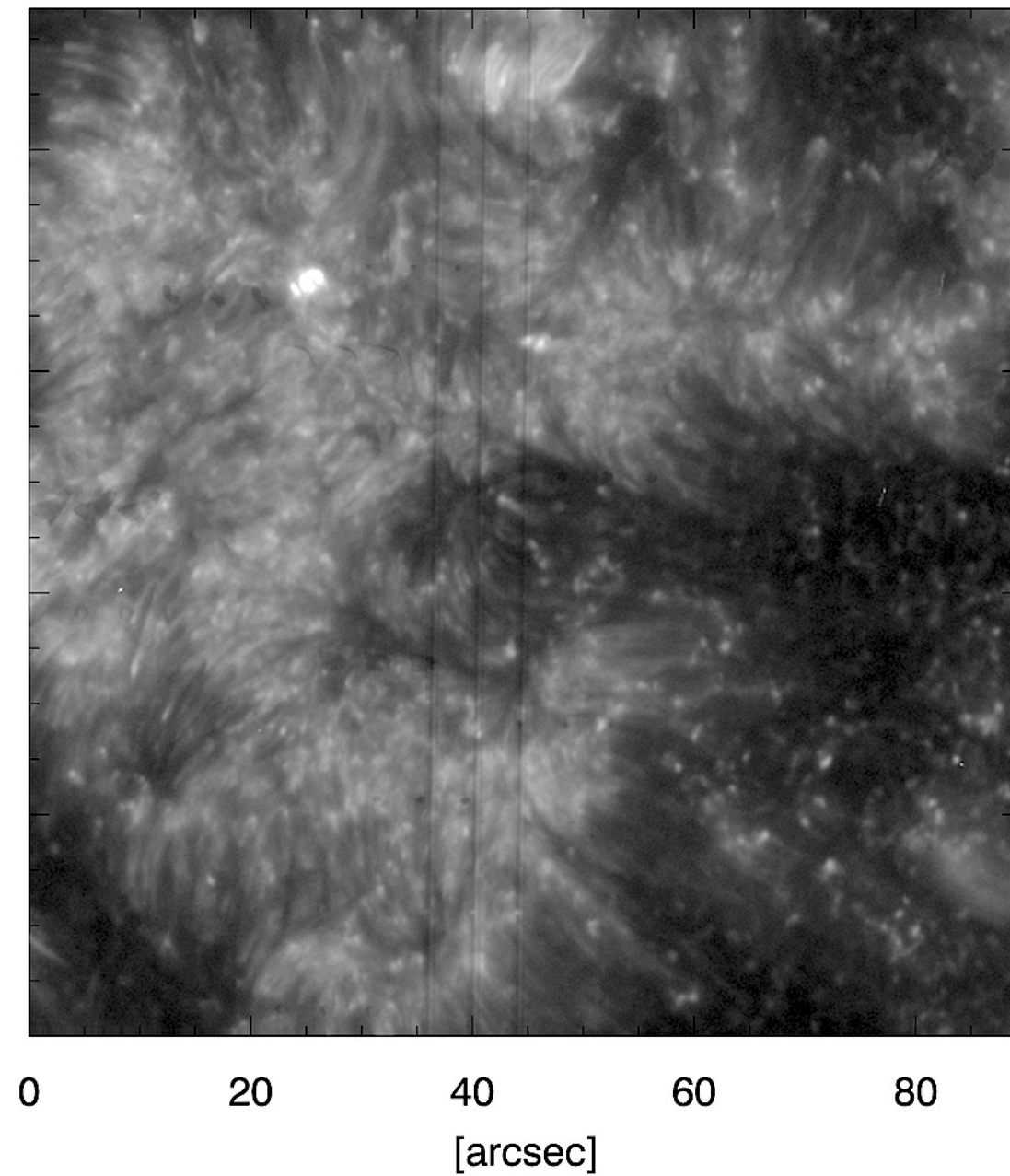
IRIS Slit Jaw - 1330 Å



H α Line Width

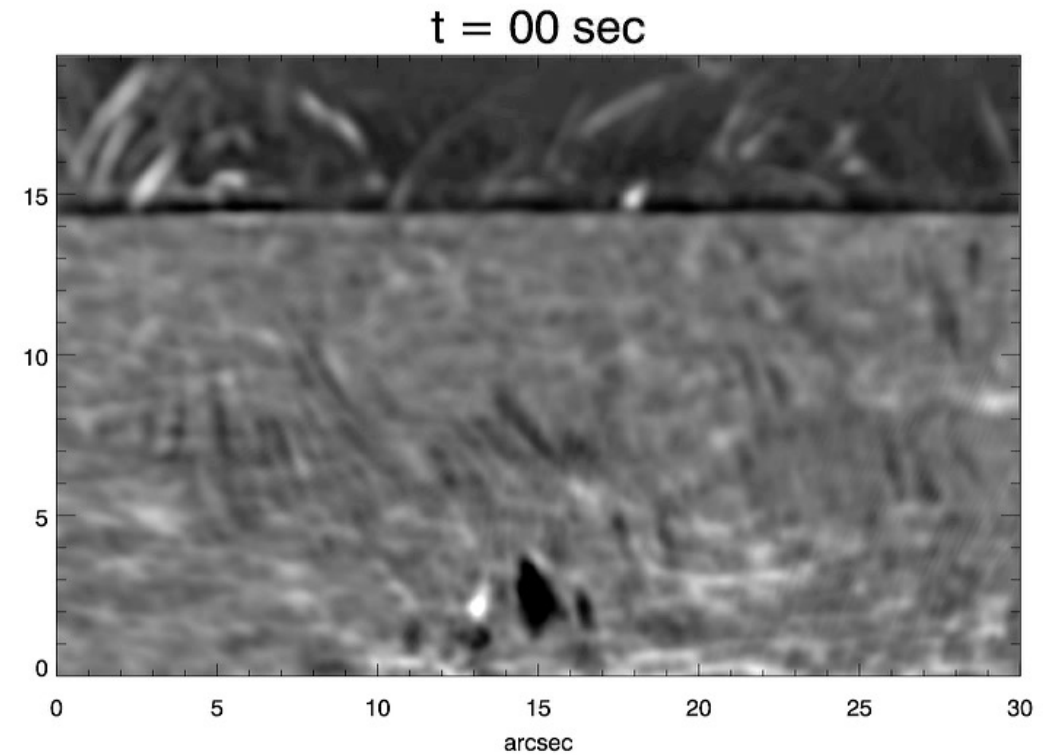
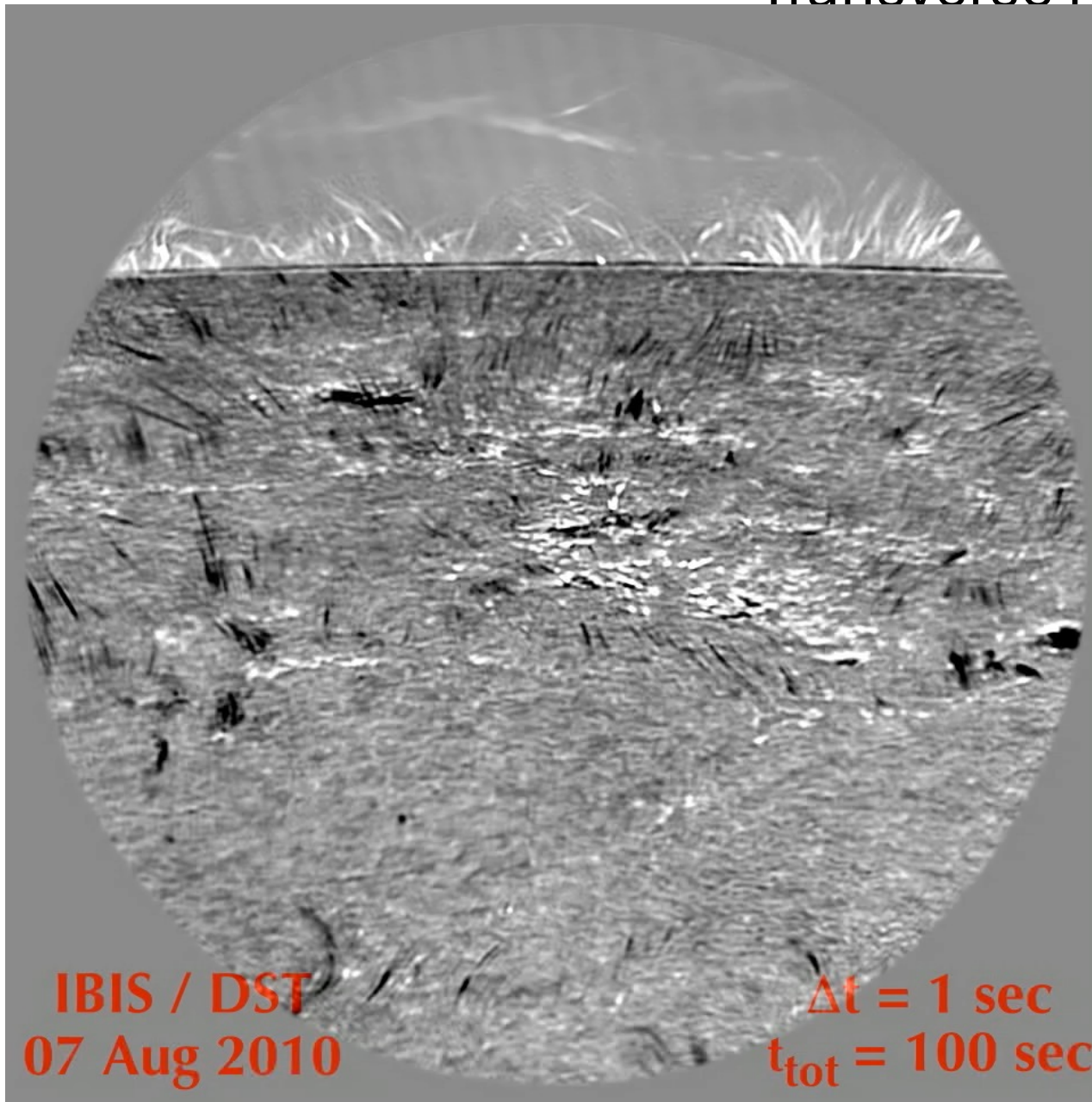


IRIS Slit Jaw - 1330 Å



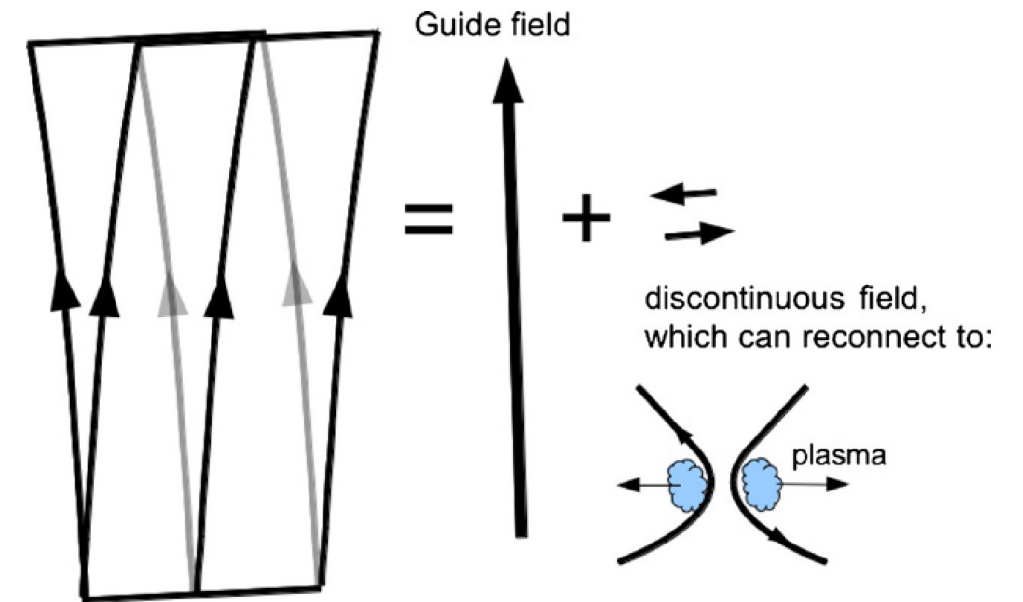
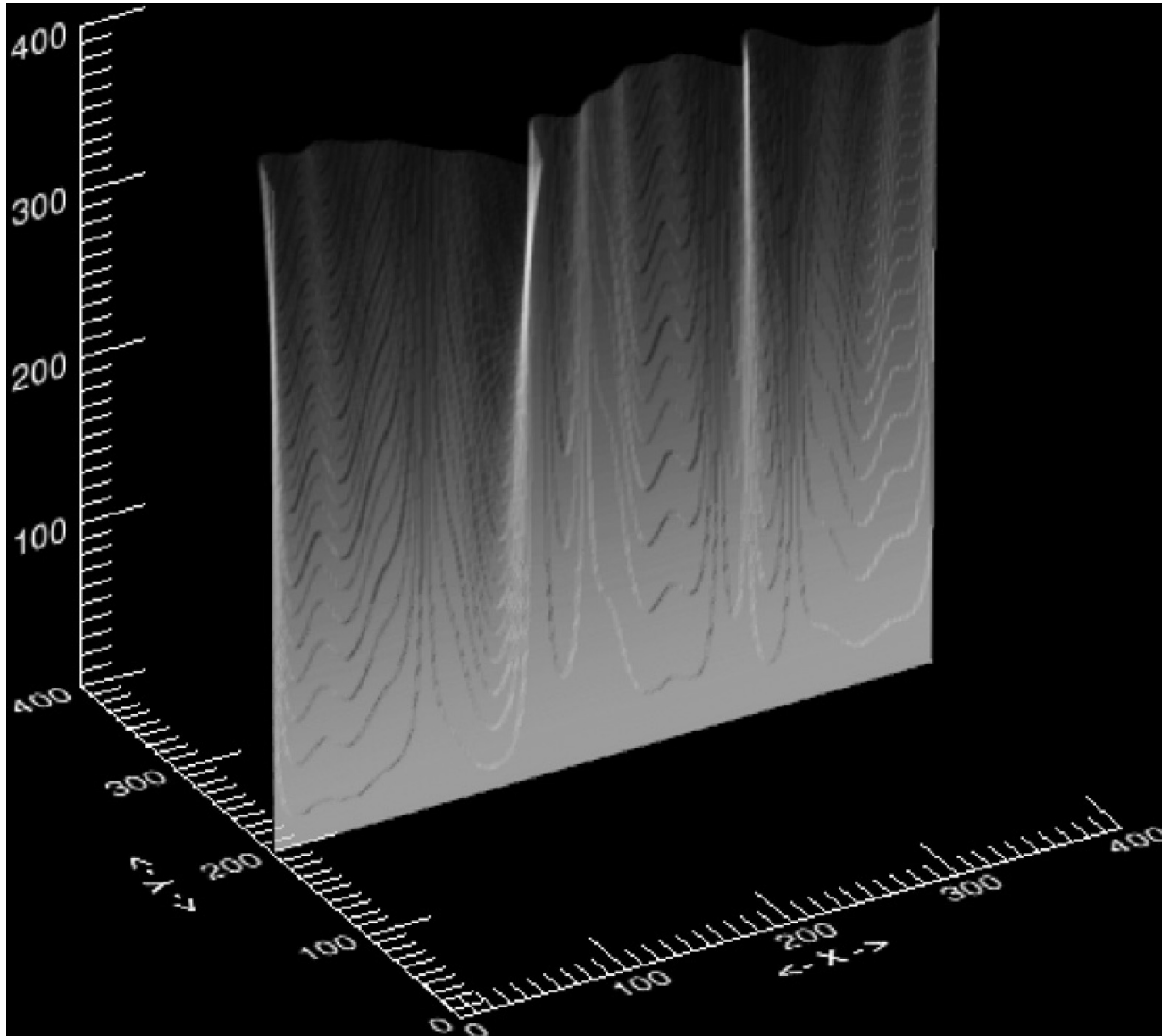
- Transverse motions – curtains?

ng



Judge et al., 2012

Chromospheric Curtains



Judge et al., 2011