Spectropolarimetry of the Solar Chromosphere

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Polarization in the Sun, the Solar System and Beyond
Granada
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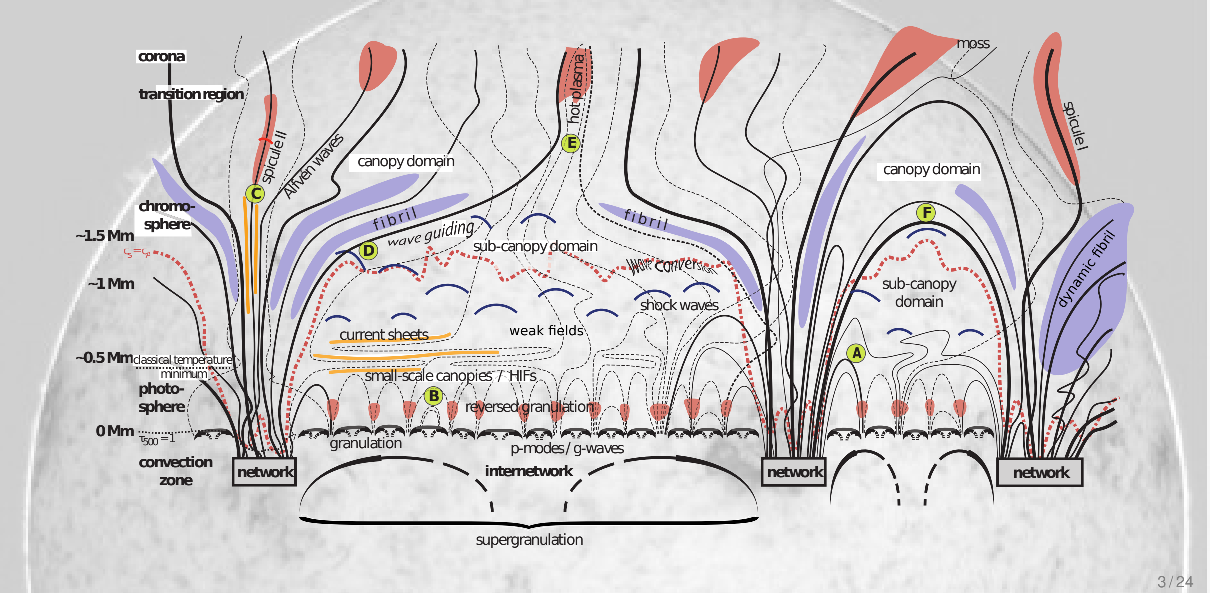
MAX-PLANCK-GESELLSCHAFT

MPS

The Problem...


corona
transition region
chromo-
sphere
~1.5 Mm
~1 Mm
~0.5 Mm
classical temperature
minimum
photo-
sphere
0 Mm
$\tau_{500}=1$
convection
zone
network
spicule II
Alfvén waves
canopy domain
fibril
wave guiding
sub-canopy domain
hot plasma
wave conversion
shock waves
current sheets
weak fields
small-scale canopies / HIFs
reversed granulation
granulation
p-modes / g-waves
internetwork
supergranulation
network
moss
spicule I
canopy domain
sub-canopy
domain
dynamic fibril
network
A
B
C
D
E
F

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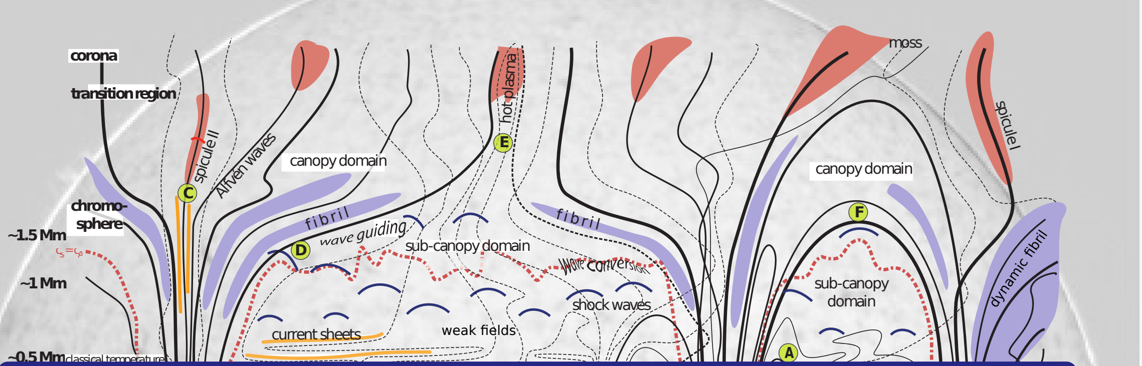
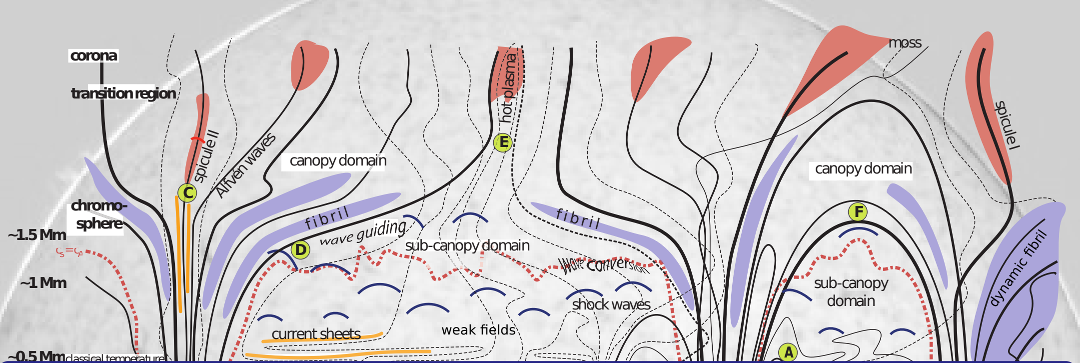


Summary: measuring chromospheric field is difficult!

- Processes are very fast ($v_A \approx 100\,\mathrm{km/s}$)
- occur on small scales (e.g. Hα-fibrilar structure).
- Densities are low.
- Fields are weak $\rightarrow$ weak signals
- Complex physics $\rightarrow$ loss of simplifying assumptions

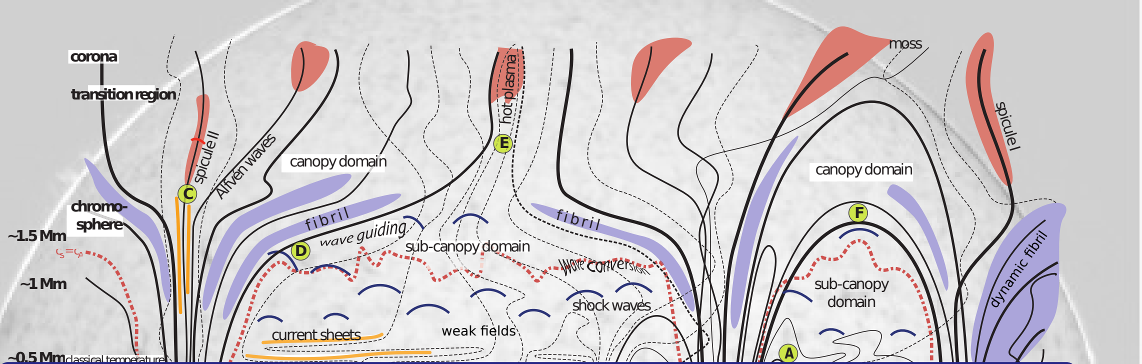
The Problem...



Loss of simplifying assumptions

- non-LTE
- 3D radiative transfer
- anisotropy of radiation field
- atomic polarization
- additional ambiguities (Hanle)
- many scale-heights
- highly corrugated layers

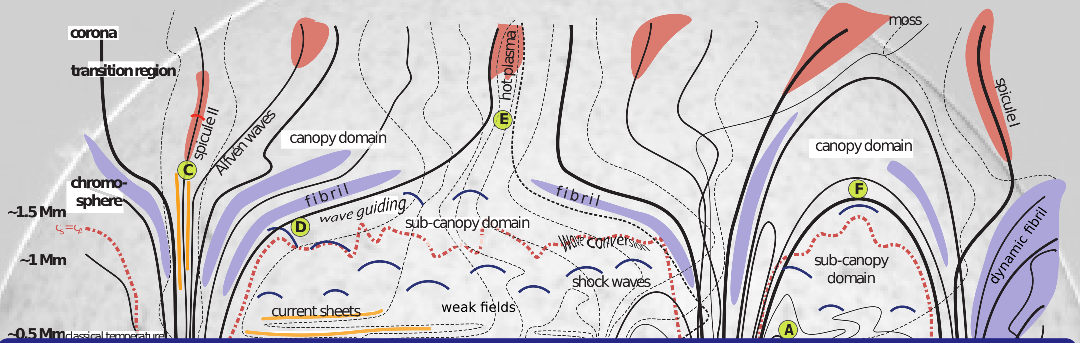
The Problem...



Requirements for reliable magnetic field information:

- sophisticated analysis techniques (inversions)
  → Jaime de la Cruz Rodriguez
- Hanle effect →Jiří Štěpán, Javier Trujillo Bueno
- high-quality measurments → this talk

The Problem...



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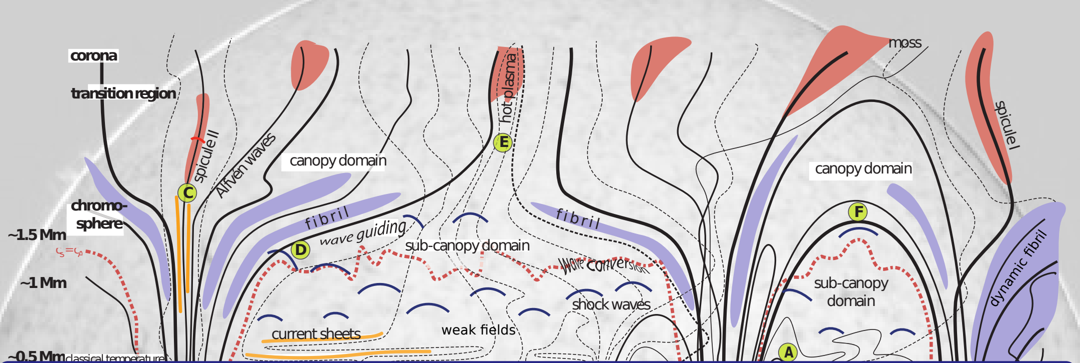

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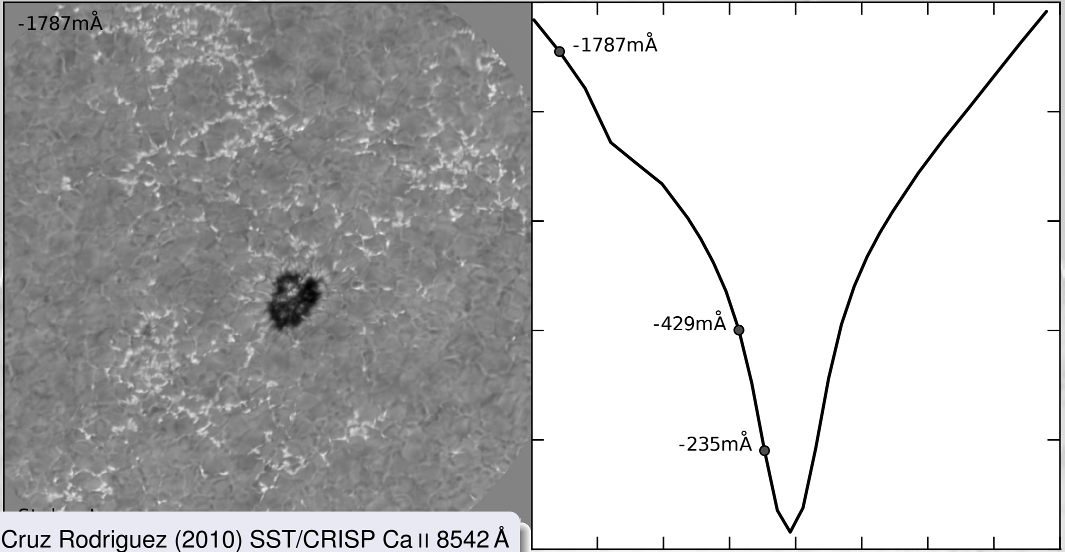
Low counts, weak signals



de la Cruz Rodriguez (2010) SST/CRISP Ca II 8542 Å

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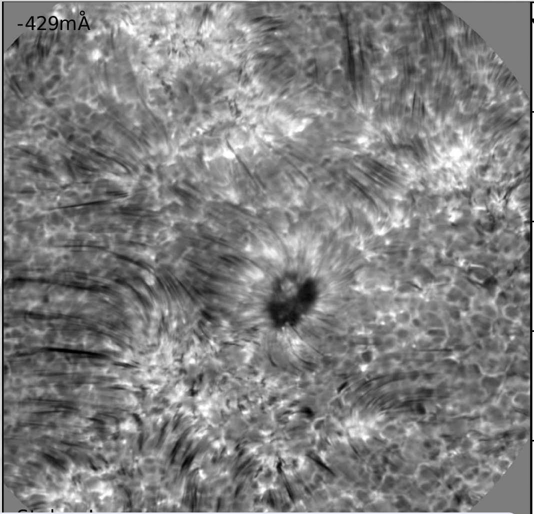

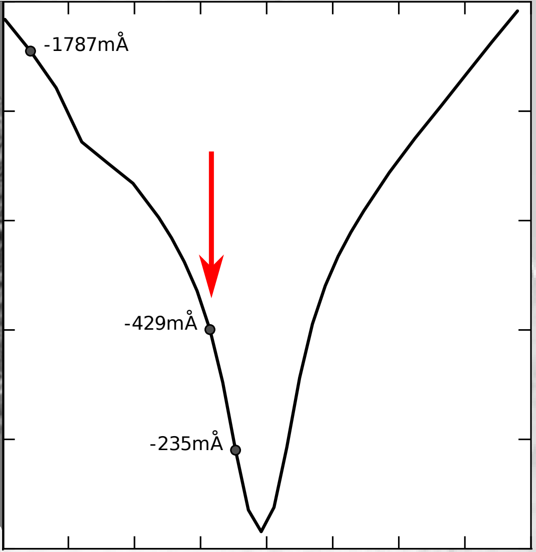

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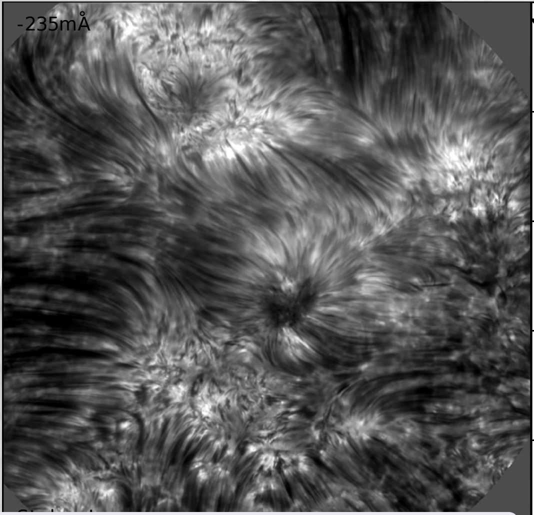

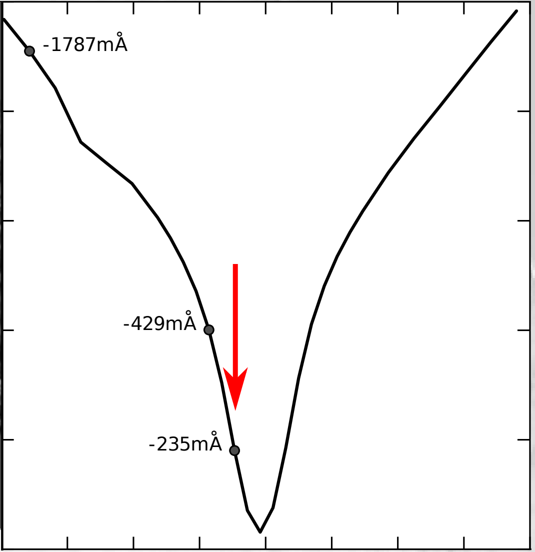

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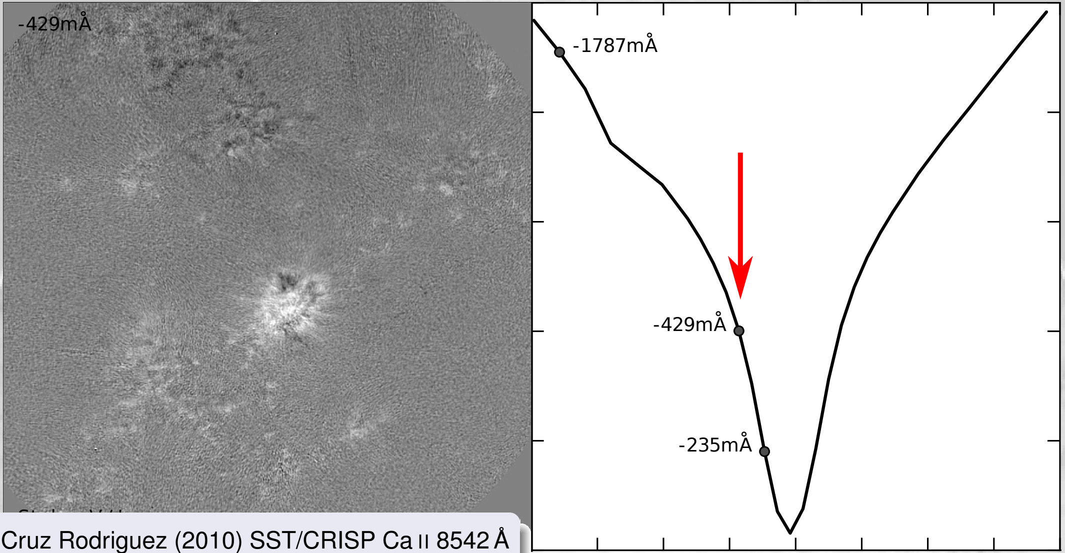

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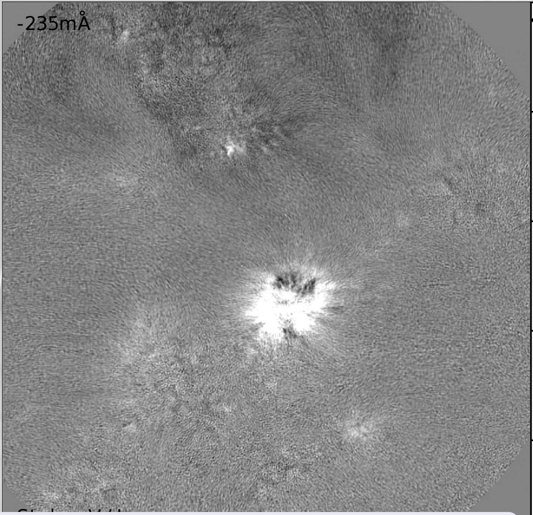

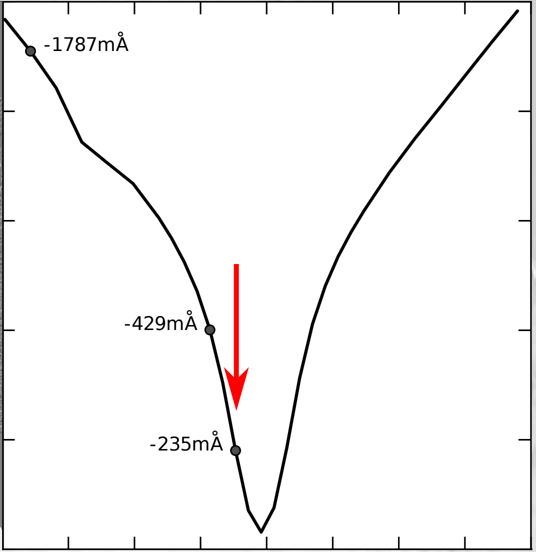

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Photon budget and solar evolution

Tradeoff: solar evolution vs. noise:

- Maximum integration time Δt_e allowed by solar evolution:

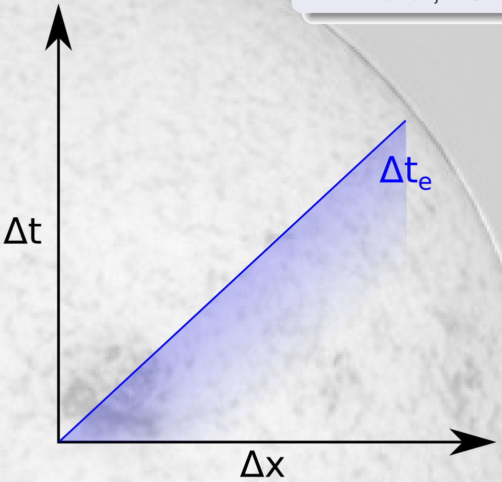
$$\Delta t_e = \frac{2\,\Delta x}{v}$$

- Minimum integration time to reach a given required rms noise level σ:

$$\Delta t_s = \frac{1}{F\sigma^2 \Delta x^2}$$

Δx: spatial sampling,
v: evolution speed,
F: Flux [phot / (s · arcsec^2)]

A. Feller, FSP



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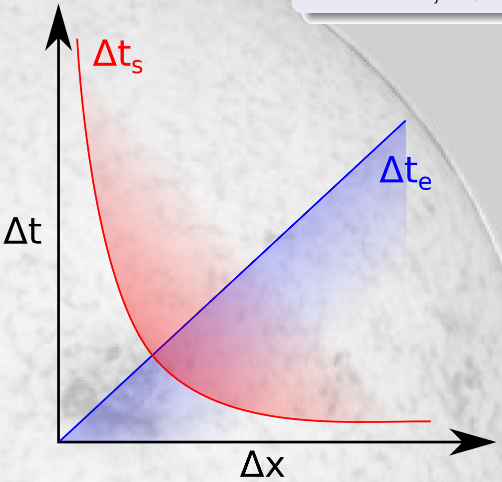

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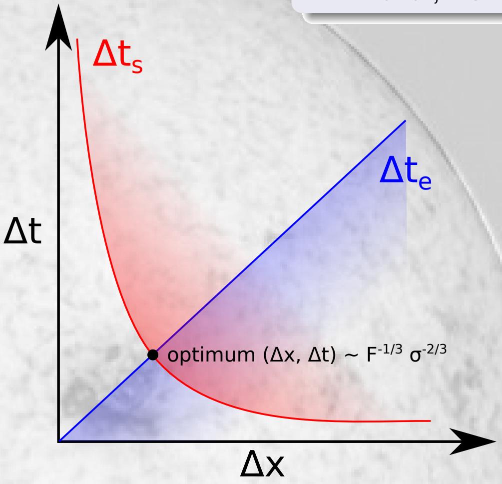


Photon budget and solar evolution

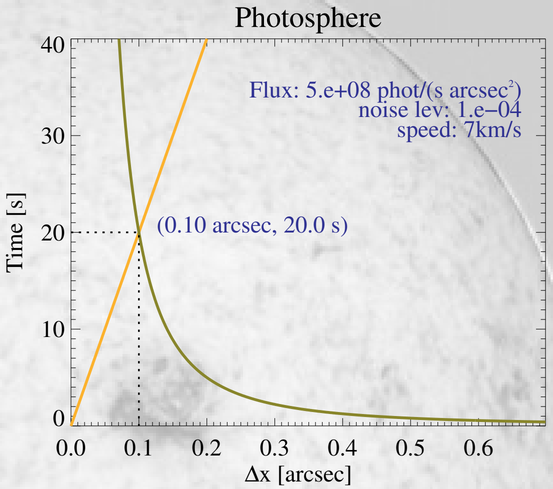
time scales vs. spatial resolution

- photosphere: $7\,\mathrm{km\,s^{-1}}$
- chromosphere: $35\,\mathrm{km\,s^{-1}}$
  (v_A(B=100 G, z=1 Mm) $= 100\,\mathrm{km\,s^{-1}}$)

Solutions

1. stay away from diffraction limit
   → collect photons
2. very fast measurements
   → “feature averaging”

(Note: solar evolution & seeing intrduce crosstalk in polarimetry → modulation much faster → FSP)



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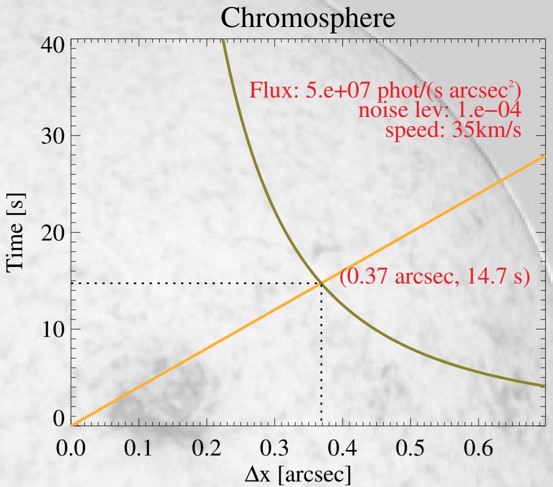

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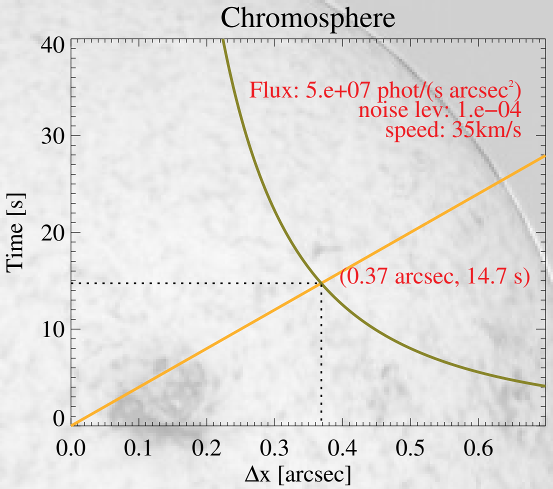

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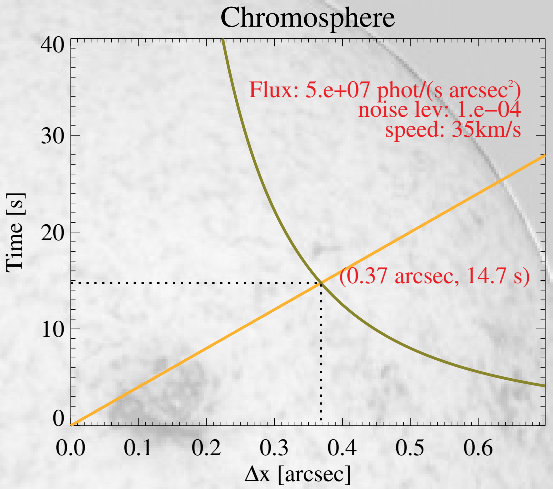
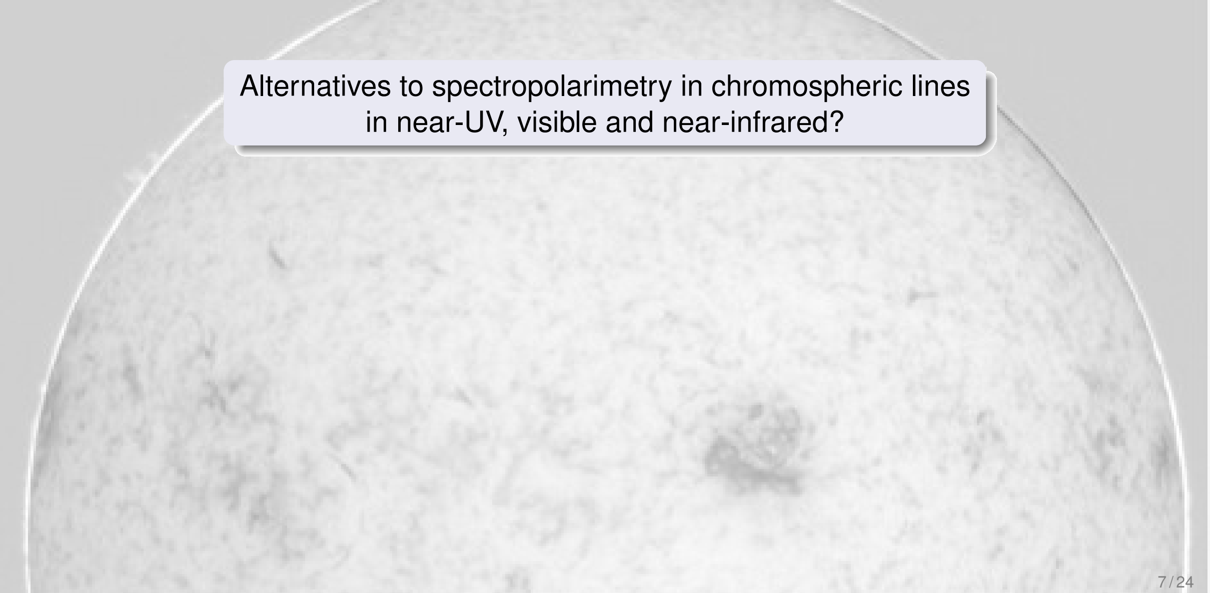


A. Feller, FSP

Aternatives



Alternatives to spectropolarimetry in chromospheric lines in near-UV, visible and near-infrared?

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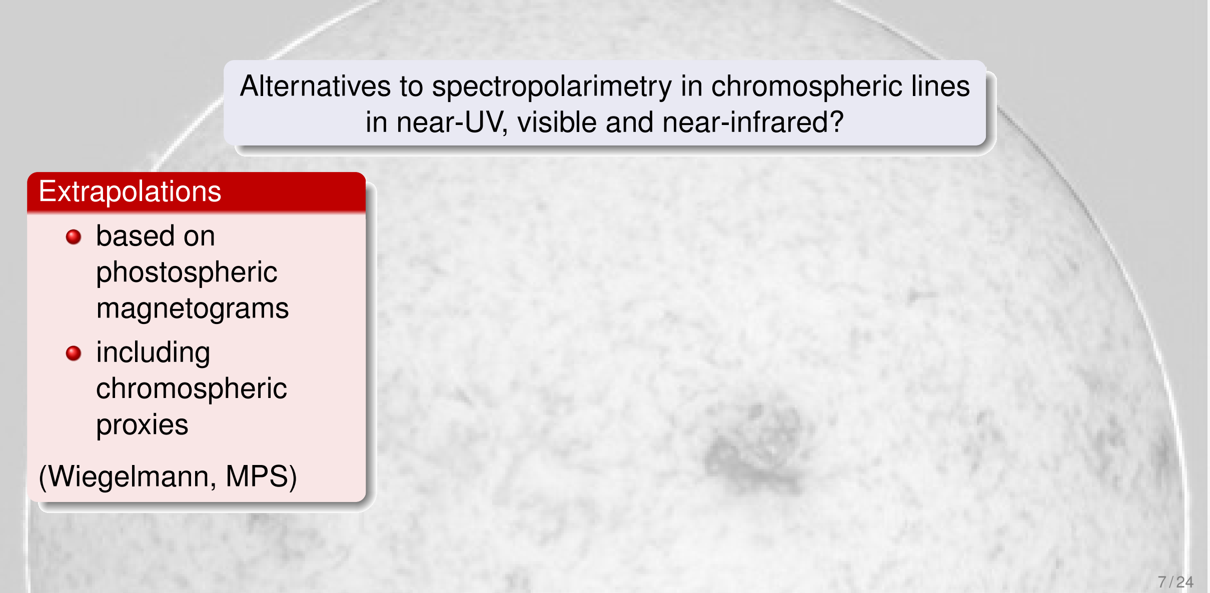

Alternatives to spectropolarimetry in chromospheric lines in near-UV, visible and near-infrared?

Extrapolations

- based on phostospheric magnetograms
- including chromospheric proxies

(Wiegelmann, MPS)

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Lyman-α

Chromospheric Lyman-Alpha SpectroPolarimeter (CLASP)

- 1211–1221 Å
- Stokes *IQU*
- $550'' \times 550''$
- $2\overset{''}{.}2$ resolution
- launch: Aug 2015

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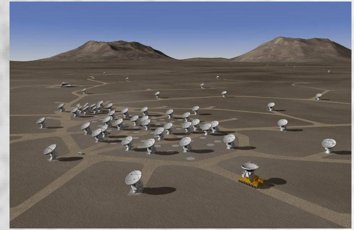
mm and sub-mm regime

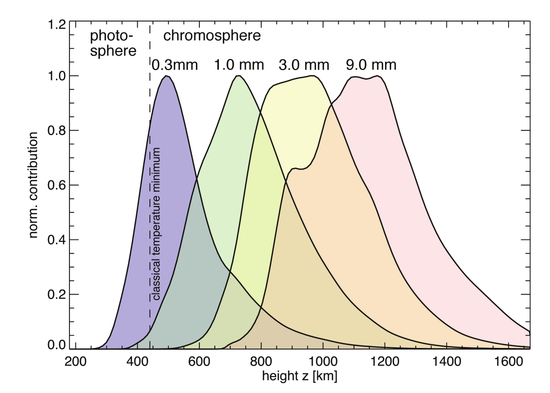
Radio measurements with the Atacama Large Millimeter/Submillimeter Array ALMA

ALMA - Atacama Large Millimeter/Submillimeter Array

ALMA basics

- ≈50 operational antennas, moveable to ≈185 different pads
- spatial resolution:
  point source: 0.″01 @850 μm
  for extended objects: ≈0.″20



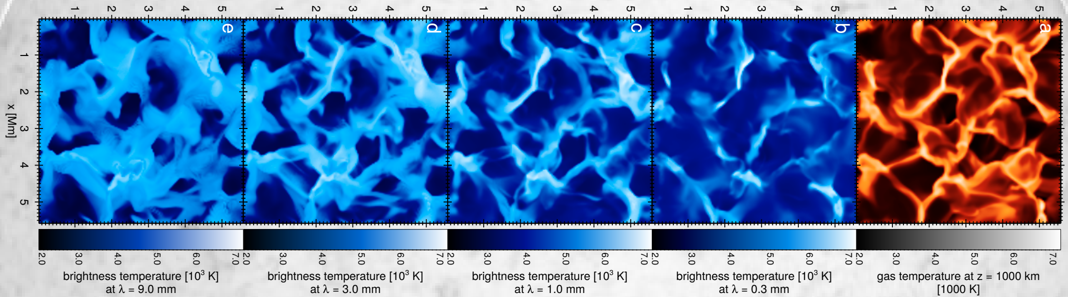


Wedemeyer et al. (2015); Bastian (2002); Shibasaki et al. (2011); Loukitcheva et al. (2014)

ALMA - Atacama Large Millimeter/Submillimeter Array

ALMA for chromospheric B?

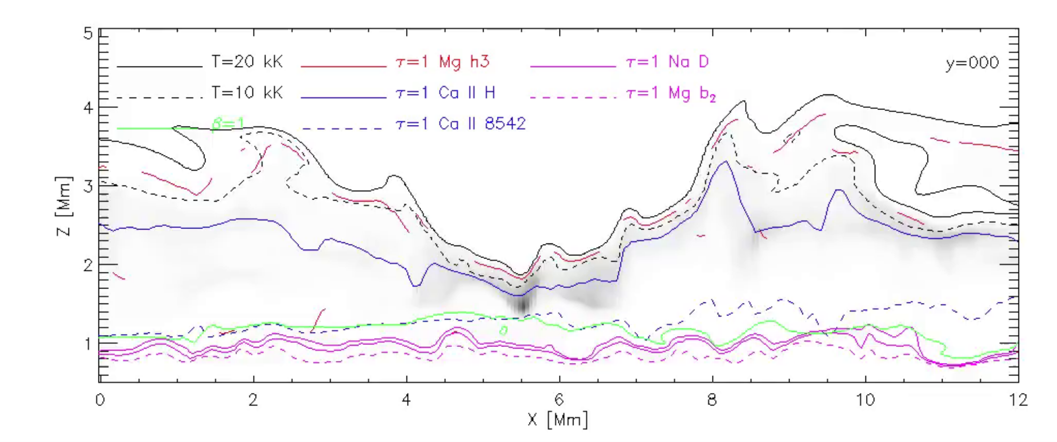
- B influences T distrib. by suppressing power of prop. waves
- Zeeman polarimetry:
  - high-n recombination lines of H
  - molecules (CH, CN, CO, NaH)



Wedemeyer-Böhm et al. (2007)

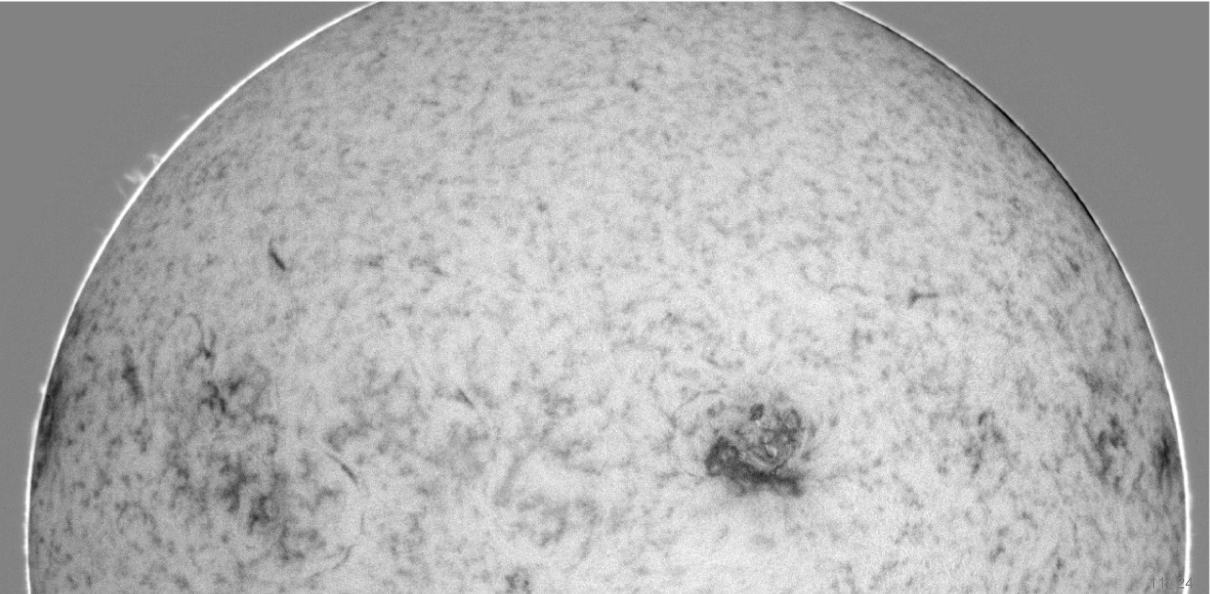
Chromospheric Lines

- Mg II h
- He I 10830
- Ca II H
- Ca II IR
- Mg I b
- Na D

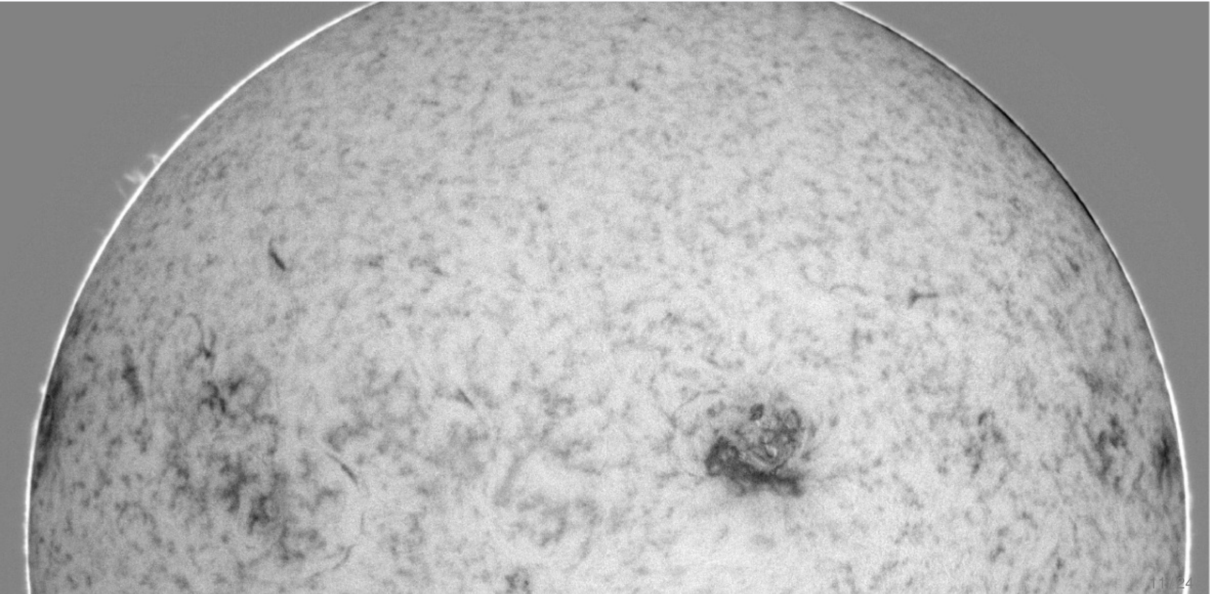


Mats Carlsson, Oslo

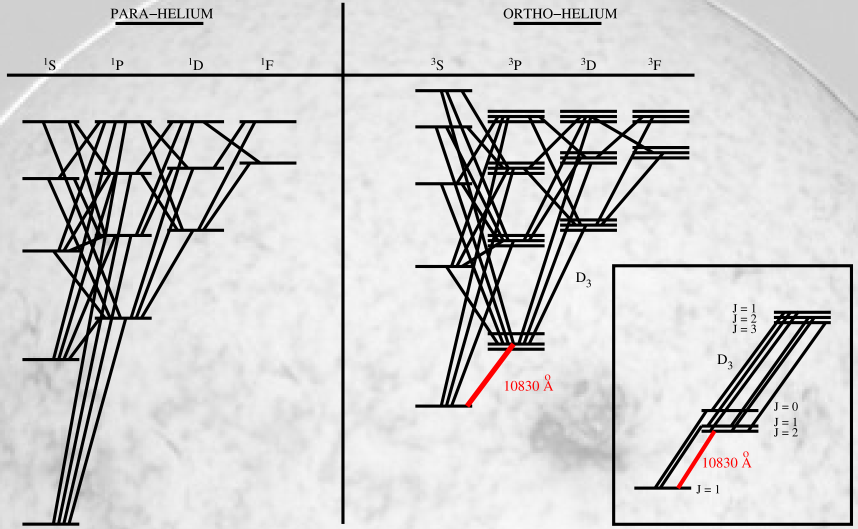
He I – What can be observed?



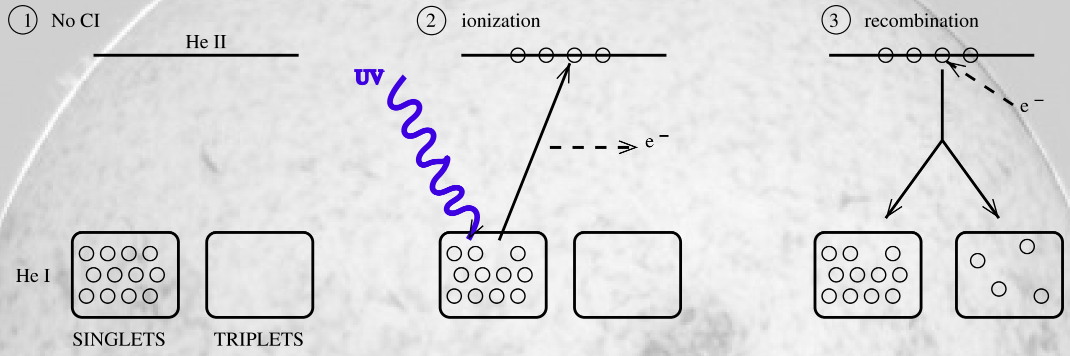
He I – Formation Height



The He I atom (Centeno et al., 2008)



Coronal Illumination - Ionization - Recombination (Centeno et al., 2008)



Recent He I 10830 Å Hi-Res Spectropolarimeters

SPINOR @ DST (Sac Peak)
Socas-Navarro et al. (2006)

- full Stokes simultaneous obs. of several VIS + IR regions
- virtually any combination of spectral lines possible

FIRS @ DST (Sac Peak)
Jaeggli et al. (2010); Schad (2013)

- 4-slit, dual-beam spectropol.
- Fe I 6302 & He I 10830
- simultaneous with IBIS

NIRIS @ 1.6m NST (Big Bear)
Cao et al. (2012)

- attached to 1.6 m NST at Big Bear
- dual Fabry-Pérot Interferometers
- imaging polarimetry @ 0.″25

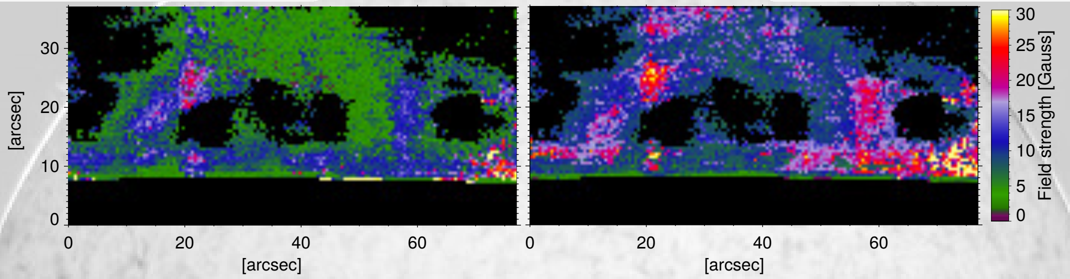
GRIS @ 1.5m GREGOR (Tenerife)
Collados et al. (2012)

- attached to 1.5 m GREGOR telescope (Tenerife)
- standard Czerny-Turner config.
- spectro-polarimetry @ 0.″25

The magnetic field configuration of a solar prominence inferred from spectropolarimetric observations in the He I 10830 Å triplet (Orozco Suárez et al., 2014)

quasi-horizontal solution

quasi-vertical solution



HAZEL inversions (Asensio Ramos et al., 2008)

70 s/slit pos

Ambiguities (unresolved, plausibility argument: use quasi-horizontal solution):

- Zeeman effect: 180° ambiguity
- Hanle effect: 90° and 180° ambiguity

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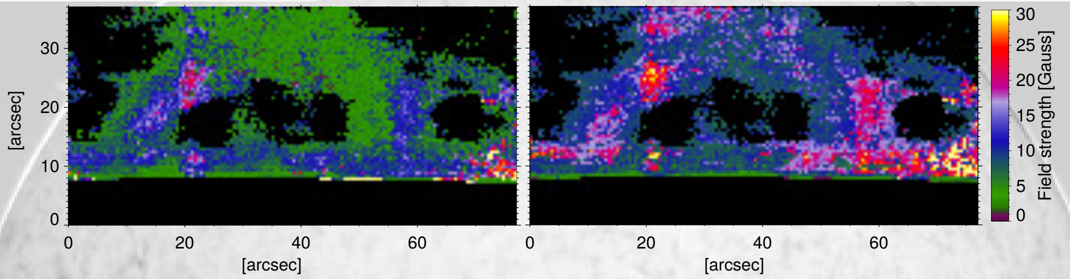

Magnetic field strength

- quiescent prominence, on average 7 G
- up to 30 G at prominence feet (coinciding with high opacity)

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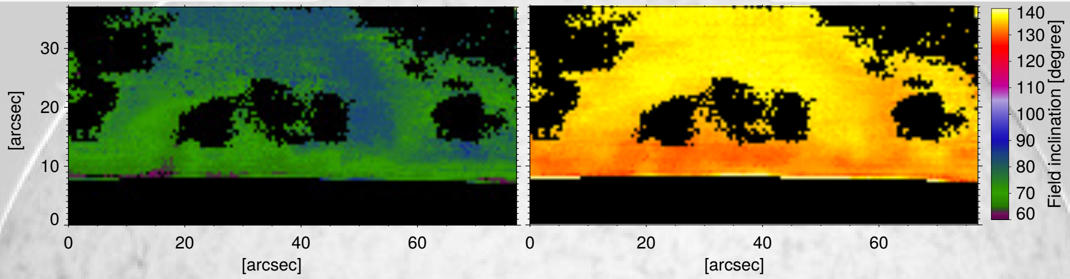

Magnetic field inclination

- inclined ≈77° to solar vertical;
  in between previous results: 60° (e.g., Bommier et al., 1994) and horizontal (Casini et al., 2003)

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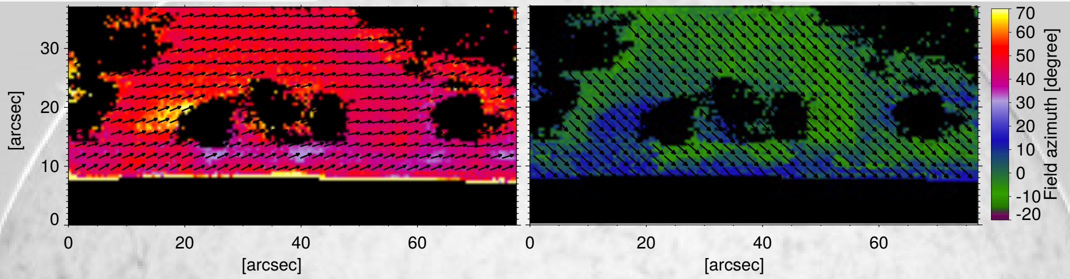
quasi-horizontal solution

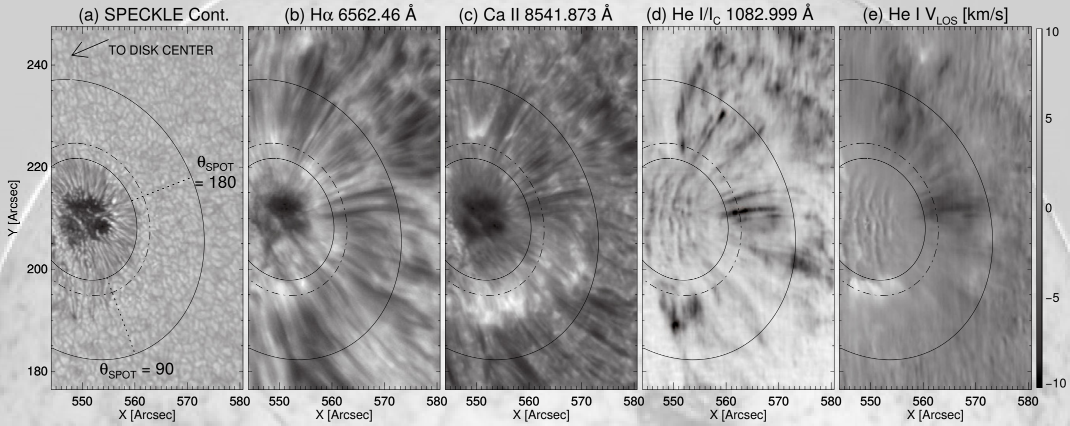
quasi-vertical solution



Magnetic field orientation wrt. prominence axis

- inclined ≈58° / ≈156° to prominence long axis (unresolved ambiguity), both solutions: inverse polarity prominence

He I Vector Magnetometry of Field-aligned Superpenumbral Fibrils (Schad et al., 2013)



IBIS & FIRS Observations, NOAA AR 11408, Jan 29 2012, $\mu = 0.8$

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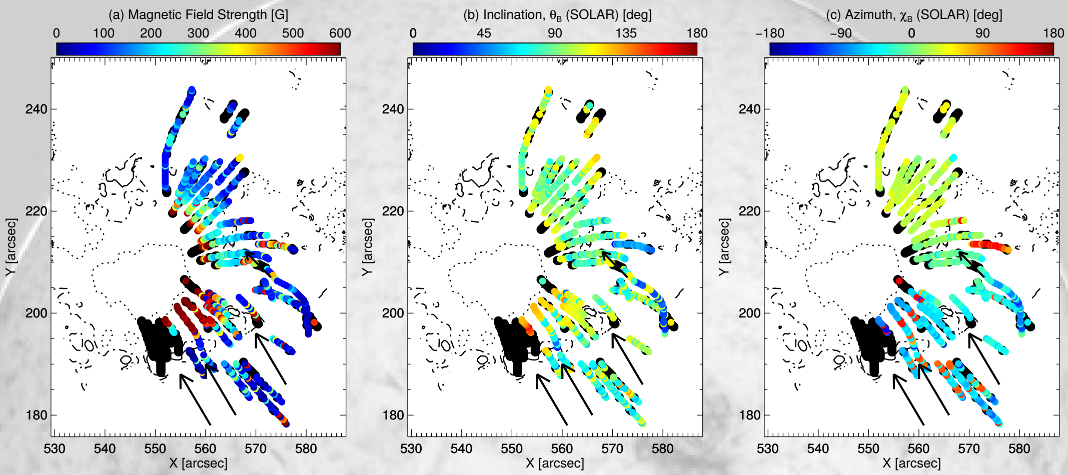

Fibril tracing (CRISPEX, Vissers & Rouppe van der Voort, 2012), careful disambiguation (Hanle & Zeeman), assumption on fibril height (1.75 Mm)

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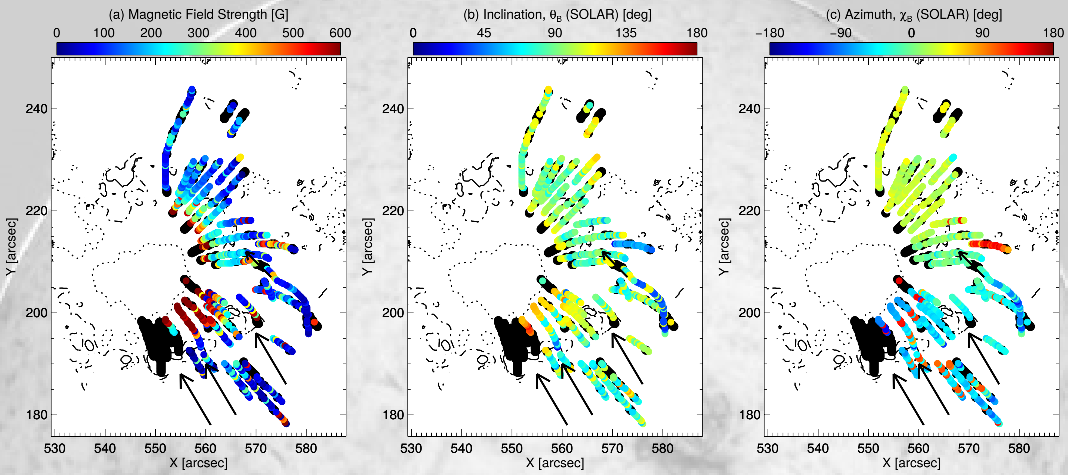
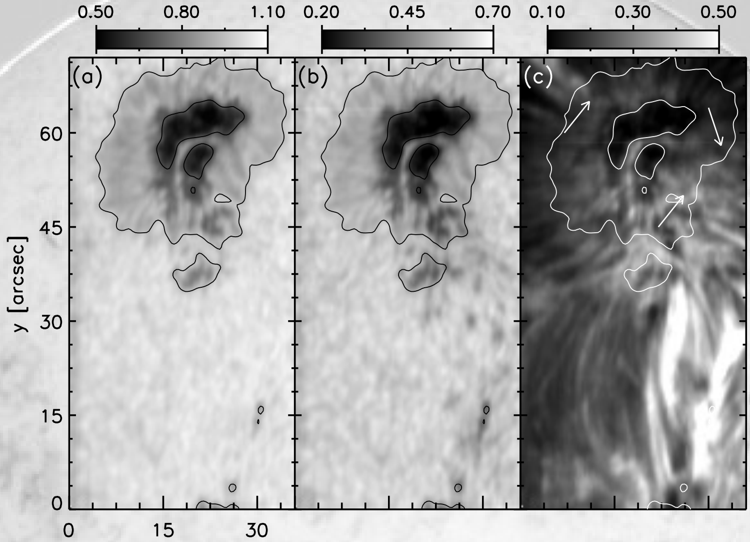
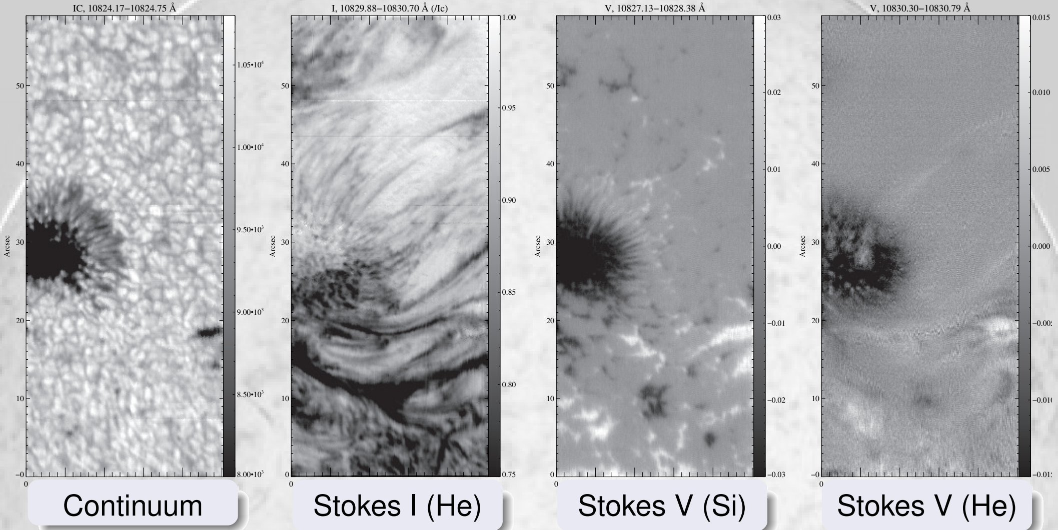


B-azimuth: aligned $\pm 10^\circ$ with fibrils
fibrils carry inverse Evershed flow

Comparison: High-res until 2013 (PhD thesis: Joshi, 2014)



GREGOR/GRIS Data & First Results (June 2014)



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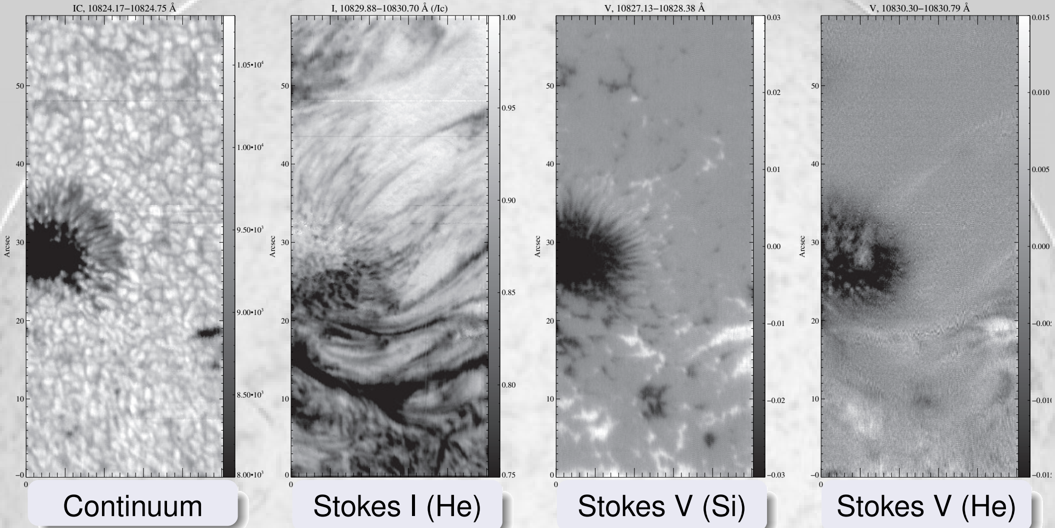

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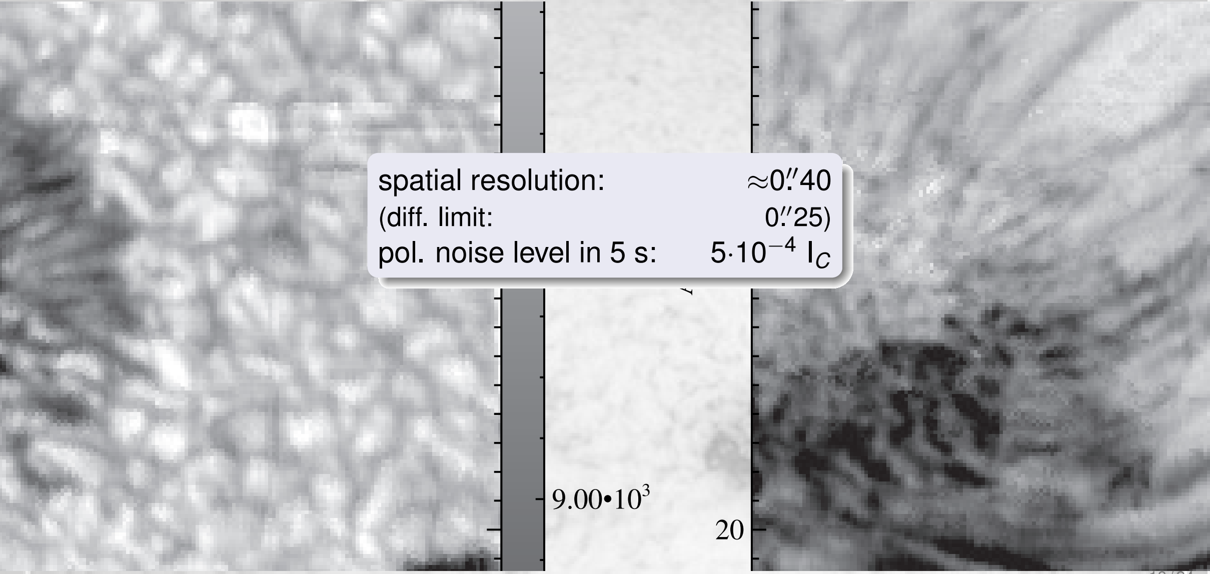

spatial resolution:	≈0.″40
(diff. limit:	0.″25)
pol. noise level in 5 s:	$5{\cdot}10^{-4}\ I_C$

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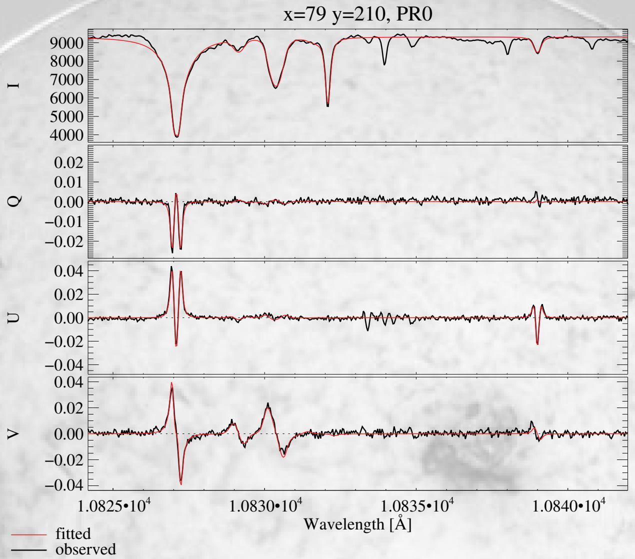

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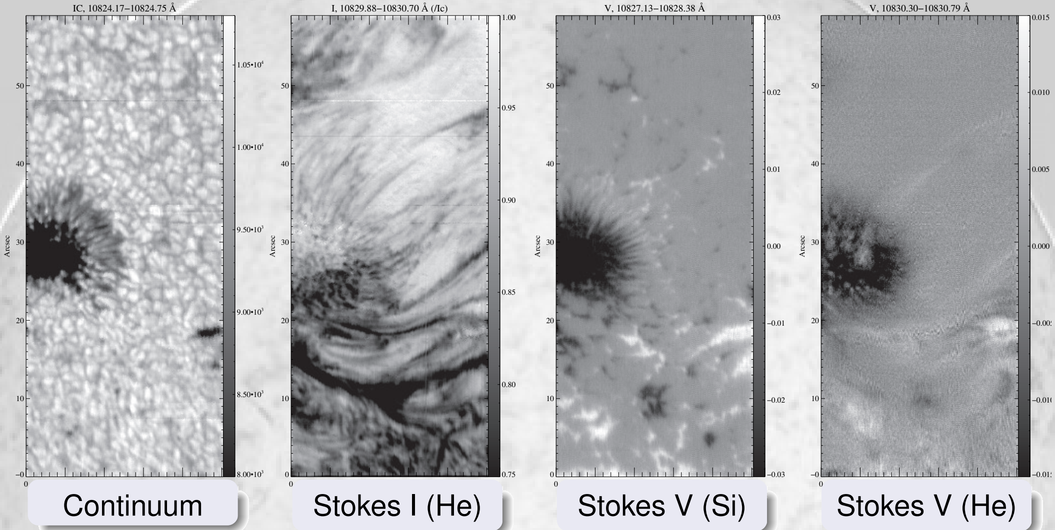
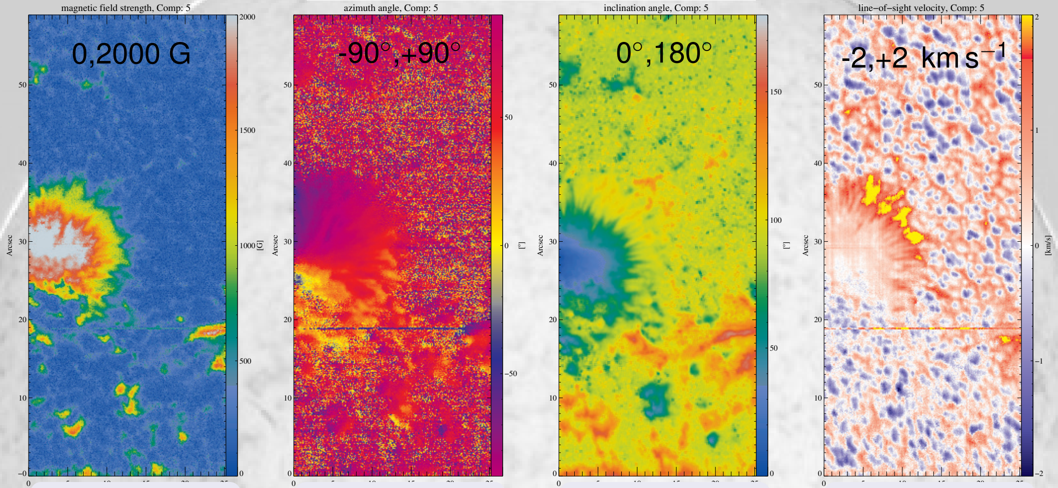


GREGOR/GRIS Data & First Results (June 2014)

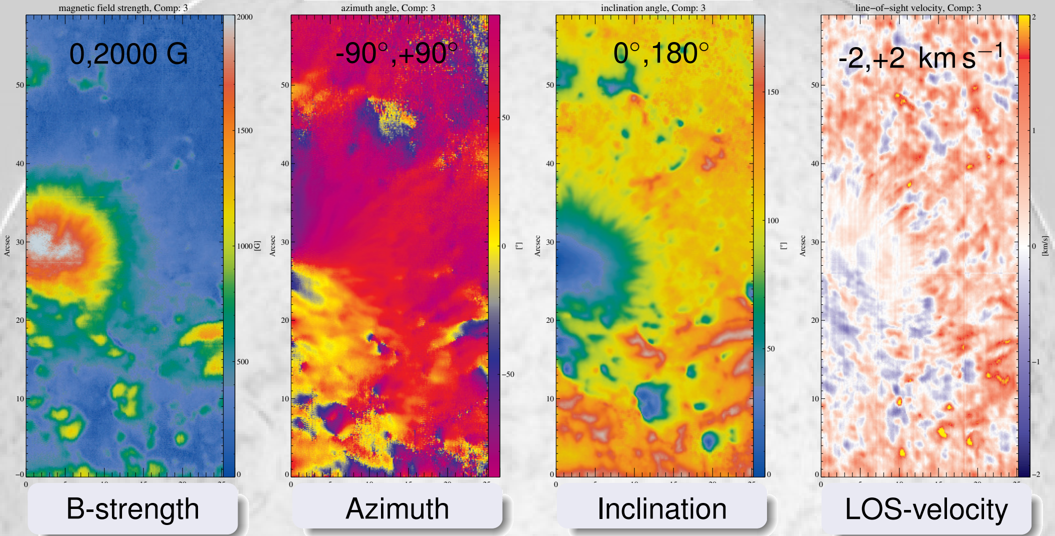
Ca I – deep photosphere



B-strength | Azimuth | Inclination | LOS-velocity

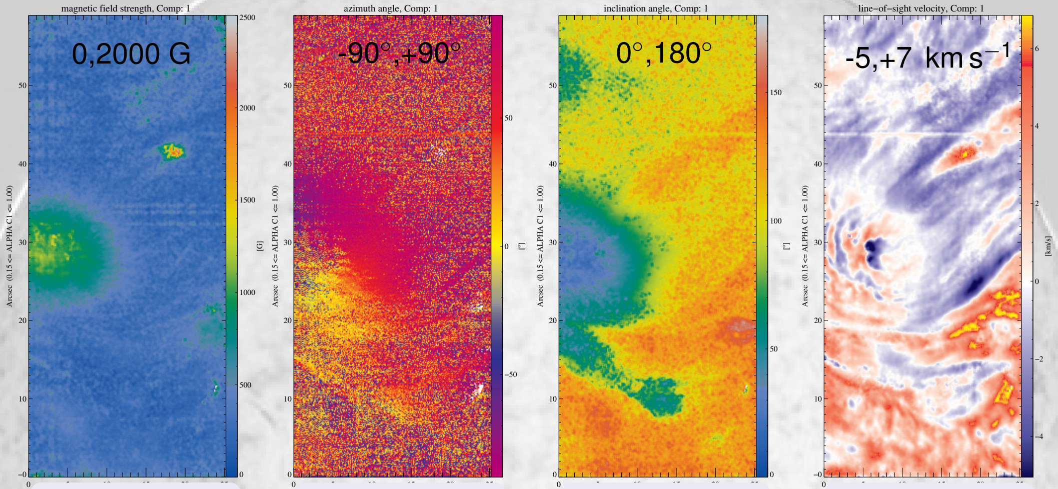
GREGOR/GRIS Data & First Results (June 2014)

Si I – mid/upper photosphere



GREGOR/GRIS Data & First Results (June 2014)

He I – upper chromosphere



B-strength | Azimuth | Inclination | LOS-velocity

GREGOR/GRIS Data & First Results (June 2014)

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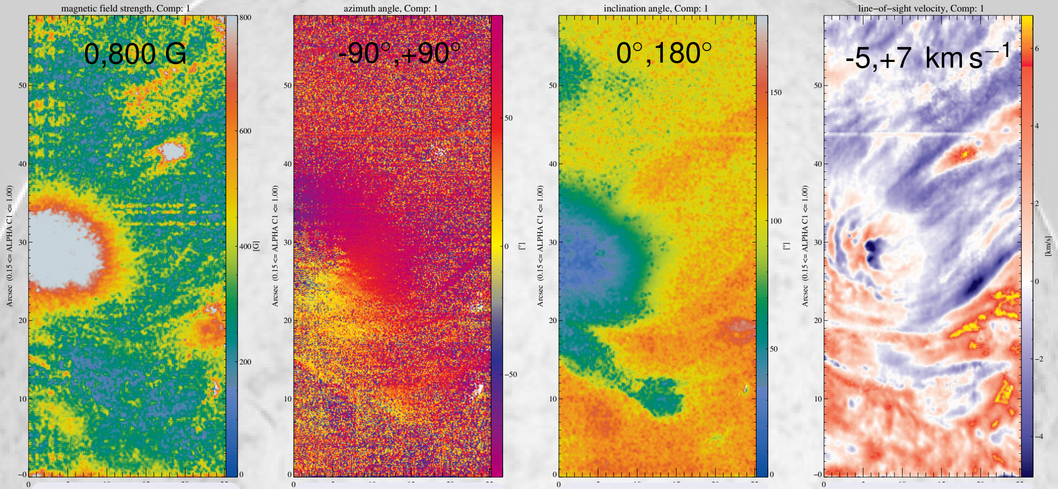

B-strength | Azimuth | Inclination | LOS-velocity

Chromospheric Fine Structure: Summary

Fine structure in the He I spectral region

- fine structure mainly He I intensity - almost absent in Stokes *QUV* images / B-vector
- continuous decrease of fine structure in B with height:
  - Ca I (deep photosphere): 0.″40
  - Si I (mid/upper photosphere): 0.″70
  - He I (chromosphere): 1.″00

→ Does the magnetic field loose the fine structure?

→ Does the Stokes *I* fine structure only outline velocity and density/temp. fluctuations?

→ Is the sensitivity of the measurement too low to detect the fine structure?

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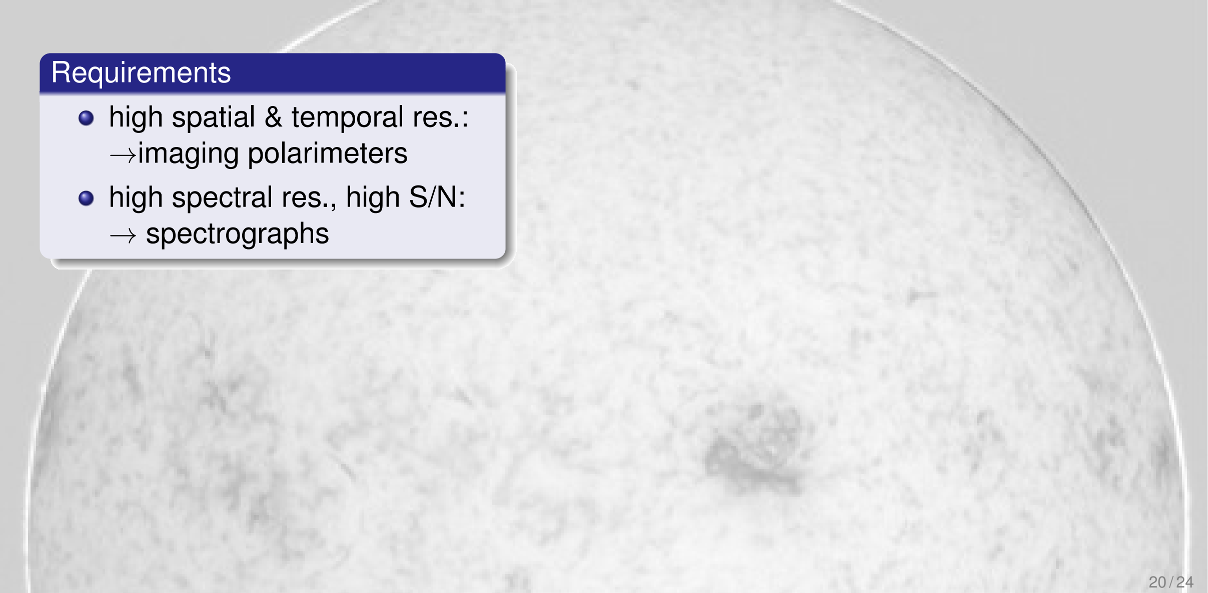
He I 10830 Observations: The next steps...

Requirements

- high spatial & temporal res.: →imaging polarimeters
- high spectral res., high S/N: → spectrographs



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- image slicer: EST (Manolo Collados)
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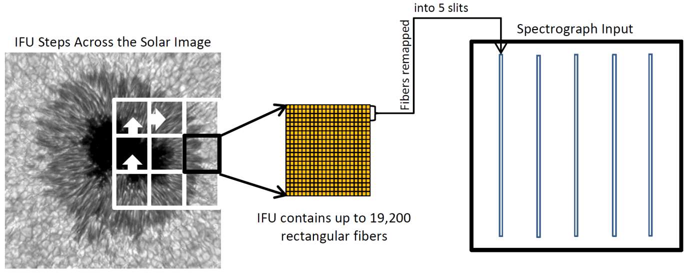

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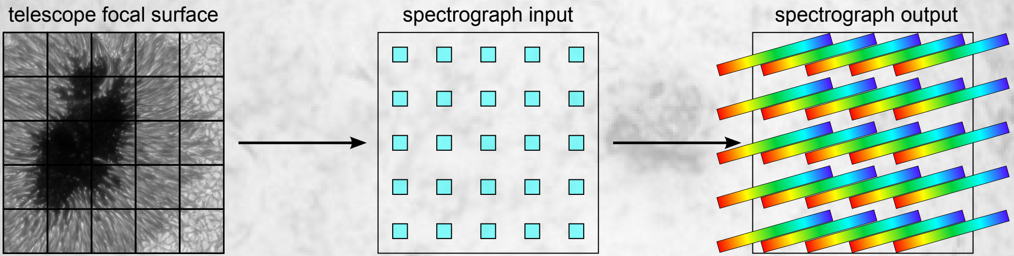
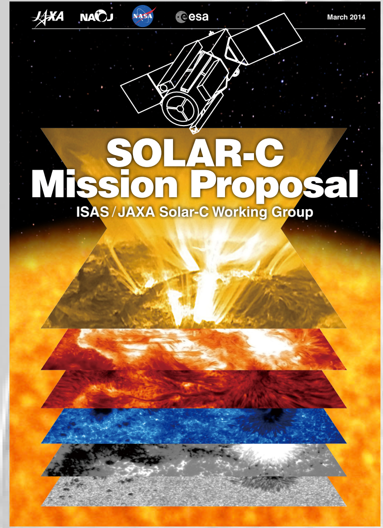


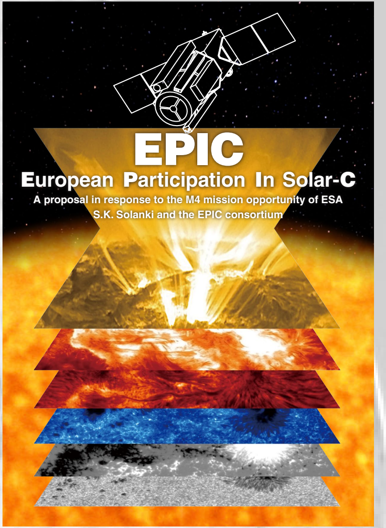
Future He I 10830 Å observatory



Solar-C / EPIC

1.4 m solar telescope in GSO

- spectropolarimetry in He I 10830, Ca II IR, Mg II h&k, Fe I 525
- *IQUV* @ 0.07″–0.14″
- target: 10^{-4}
- EPIC (ESA): Jan 15 2015
- Solar-C (JAXA): Feb 2015
- launch 2022–2025

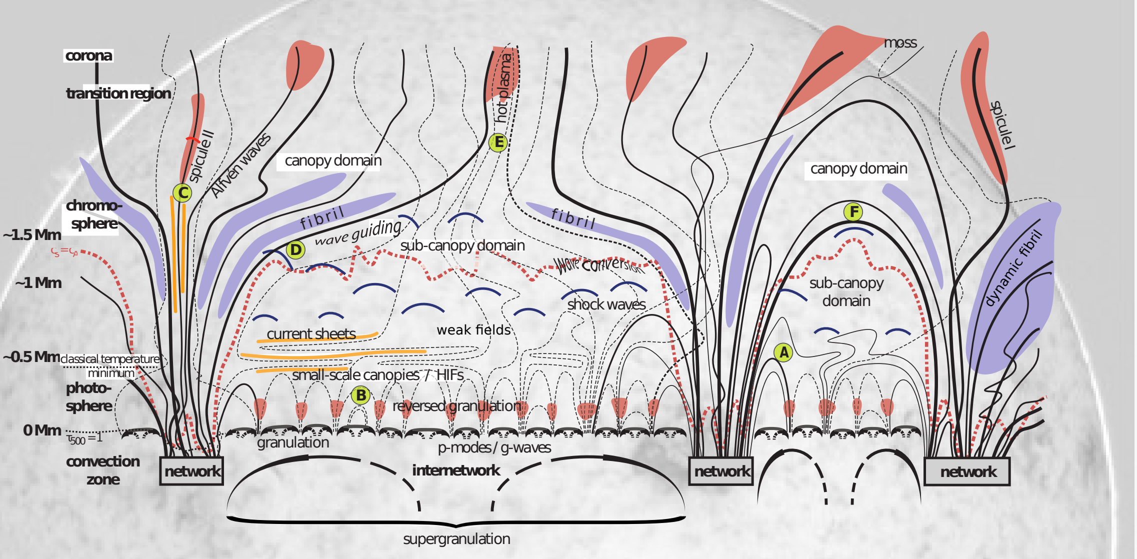


He I 10830 analysis: The next steps ...

To-Do list for He I 10830 Analysis

- 2D-spectropolarimetry:
  →improve deconvolution / 2D-inversions methods
- reliable disambiguation methods (Van Vleck ambiguity, 180° Hanle & Zeeman ambiguity):
  → combination with other chromospheric line?
- reliable anisotropy determination (take into account coronal illumination, symmetry breaking due to, e.g., sunspots):
  → determine population imbalances
- reliable height determination: → stereoscopy

Chromospheric Fields: The missing link...



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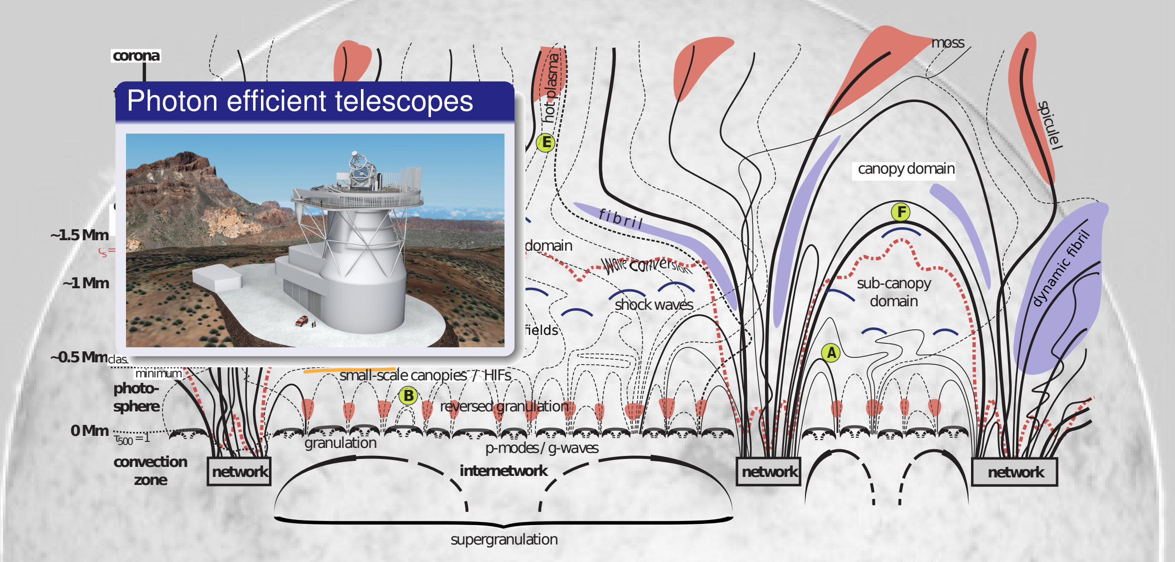
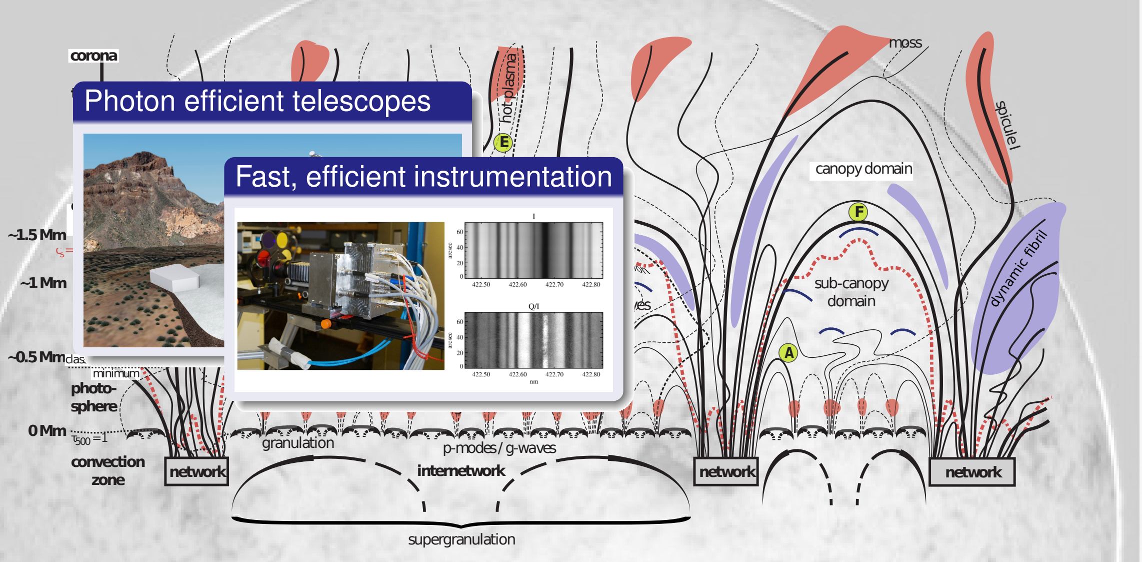


Photon efficient telescopes

Chromospheric Fields: The missing link...

Photon efficient telescopes

Fast, efficient instrumentation



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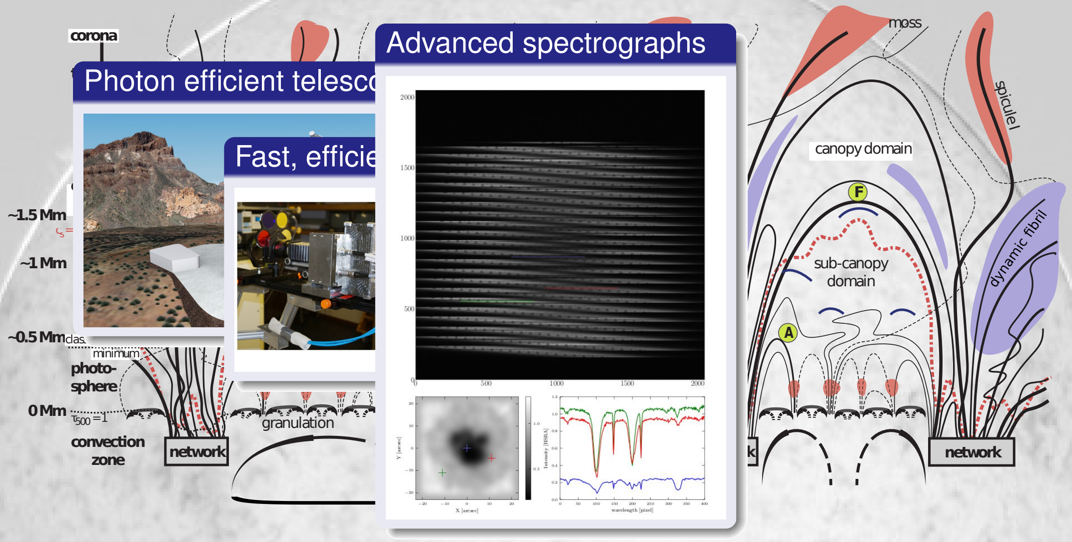

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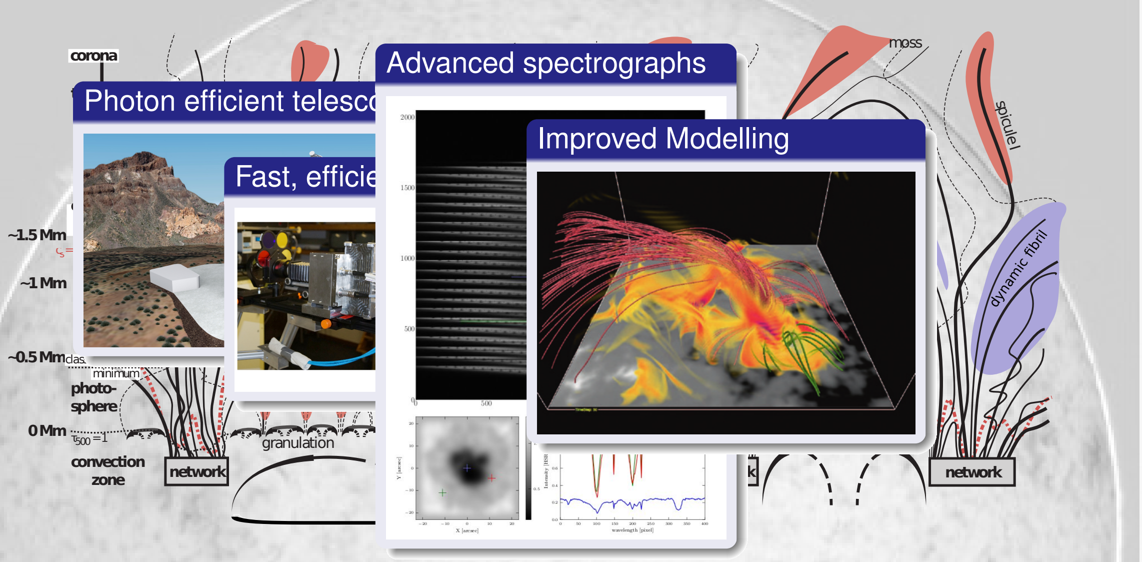

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