Chromospheric Magnetic Field Measurements

Challenges & Recent Developments

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ISSI Workshop on Solar Magnetic Fields:
From Measurements towards Understanding
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MAX-PLANCK-GESELLSCHAFT

The Problem...

Summary: measuring chromospheric field is difficult!

- Processes are very fast ($v_A \approx 100\,\mathrm{km/s}$, flares, reconnection, ...),
- and 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

Chromospheric Difficulties

Loss of simplifying assumptions

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

Requirements for reliable magnetic field information:

- sophisticated analysis techniques (inversions) → Jaime de la Cruz Rodriguez
- sophisticated treatment of RTE → Han Uitenbroek
- Hanle effect → Javier Trujillo Bueno
- high-quality measurments → this talk

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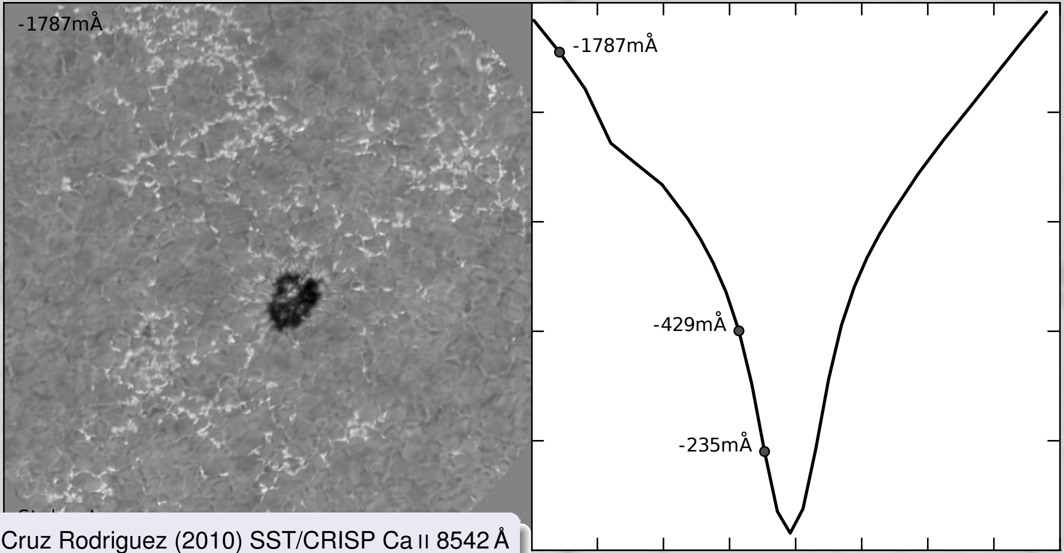
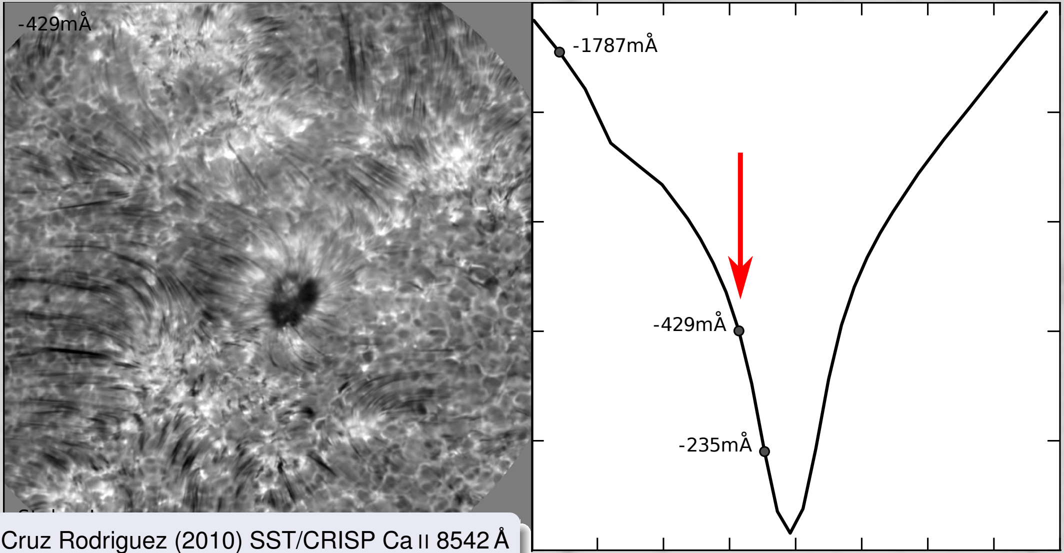
Low counts, weak signals



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

Low counts, weak signals



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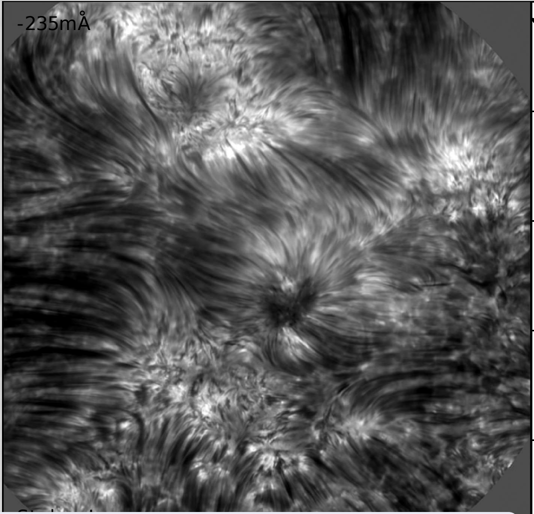

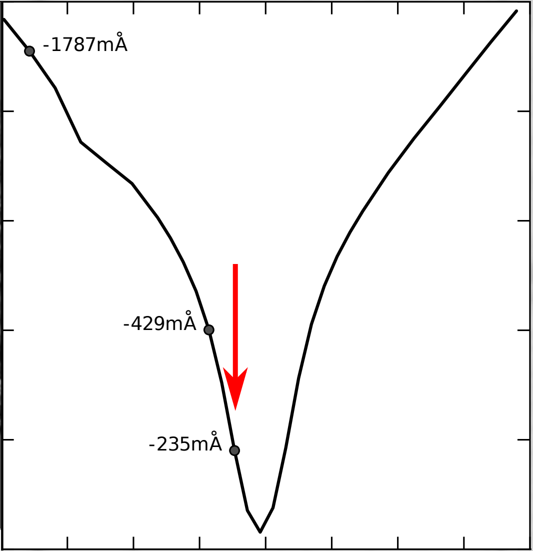

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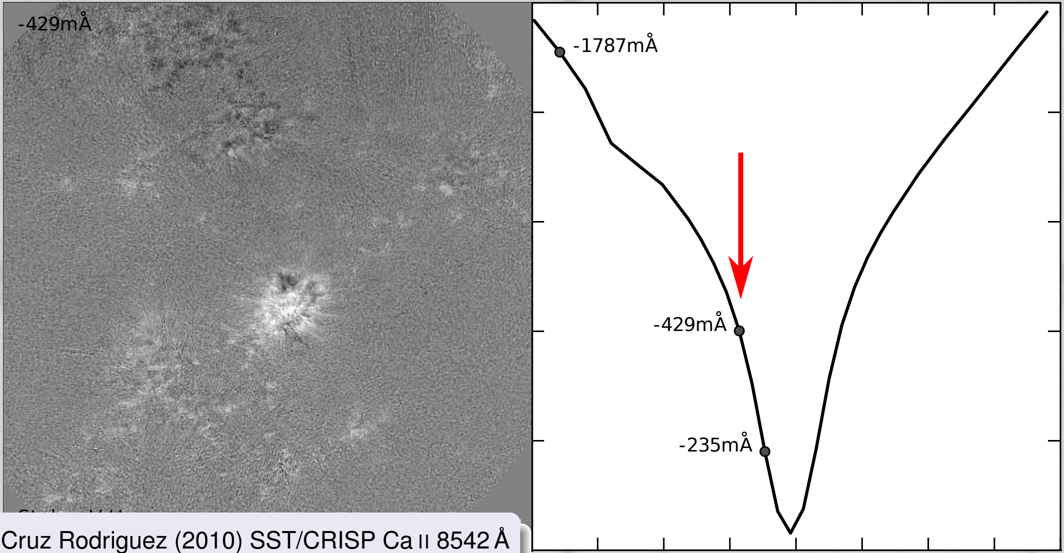

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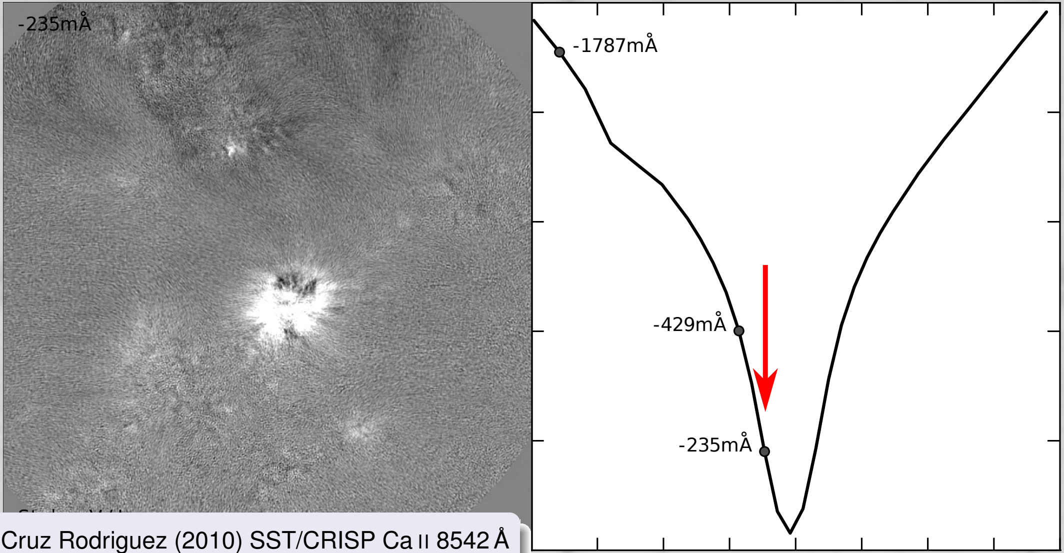

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Photon budget and solar evolution

Tradeoff: solar evolution vs. noise:

- Maximum integration time Δt_e allowed by solar evolution:

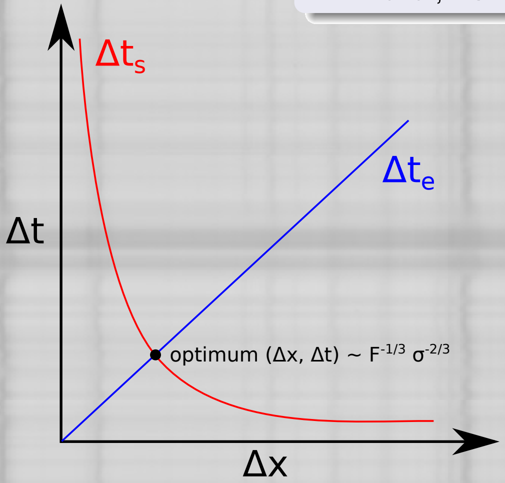
$$\Delta t_e = \frac{2\,\Delta x}{v}$$

- 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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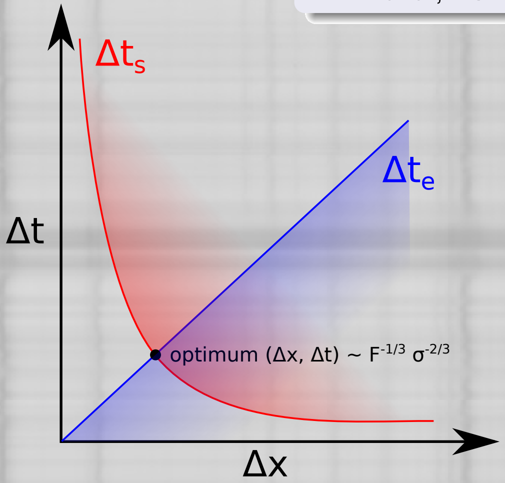

Photon budget and solar evolution

time scales vs. spatial resolution

- photosphere (blue): $7\,\mathrm{km\,s^{-1}}$
- chromosphere (red): $35\,\mathrm{km\,s^{-1}}$

(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 intrduces crosstalk in polarimetry → modulation much faster → FSP)

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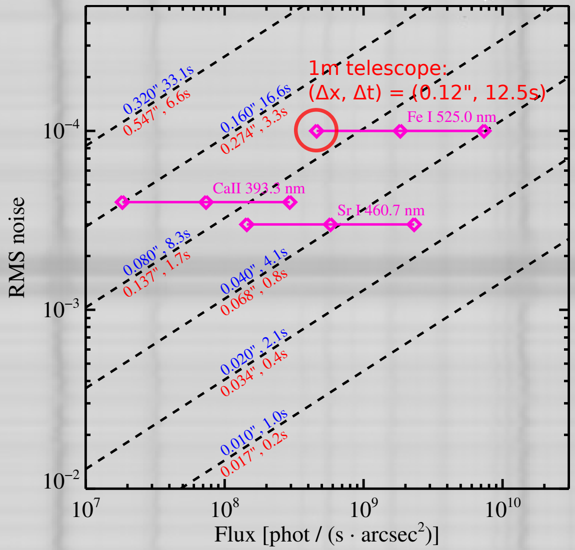

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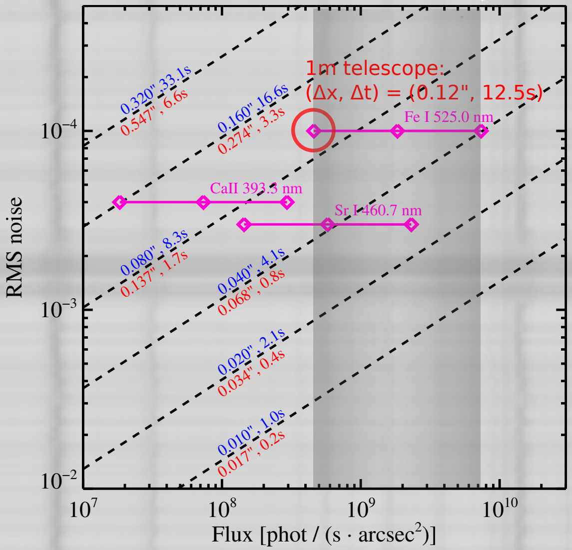

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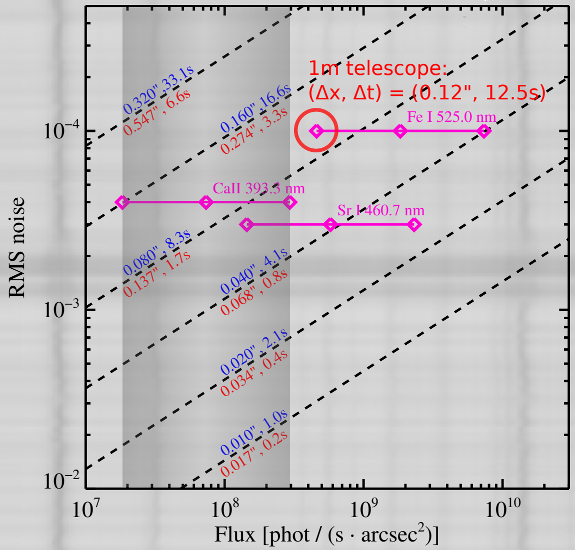

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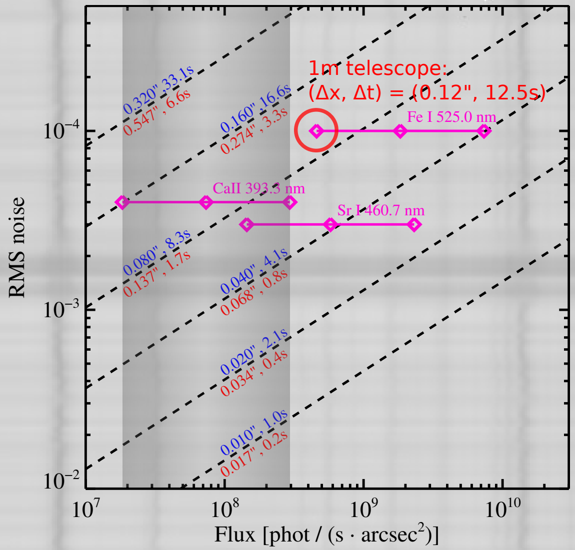

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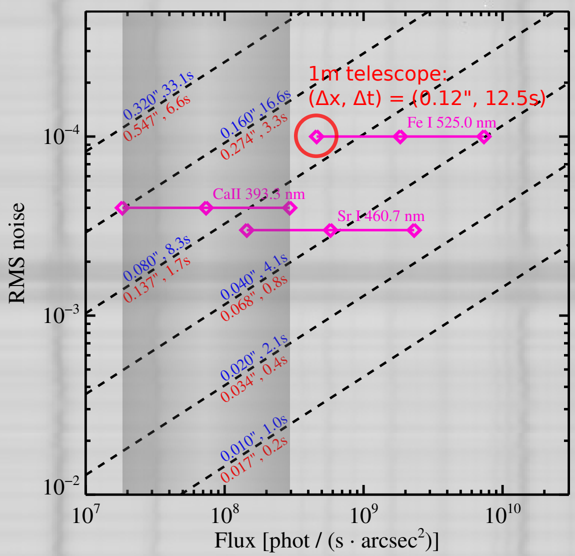

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Aternatives

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

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Extrapolations

- based on phostospheric magnetograms
- including chromospheric proxies

→ Thomas Wiegelmann (Tuesday afternoon)

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Lyman-α

Chromospheric Lyman-Alpha SpectroPolarimeter (CLASP)

- 1211–1221 Å
- Stokes *IQU*
- $550'' \times 550''$
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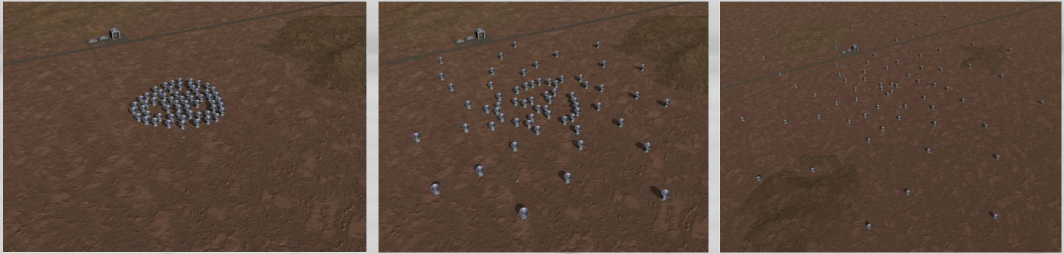
mm and sub-mm regime

Radio measurements with the Atacama Large Millimeter/Submillimeter Array ALMA

ALMA - Atacama Large Millimeter/Submillimeter Array

ALMA basics

- $\approx$50 operational antennas, moveable to $\approx$185 different pads
- spatial res.: $\leq 0\farcs01$ @850 μm



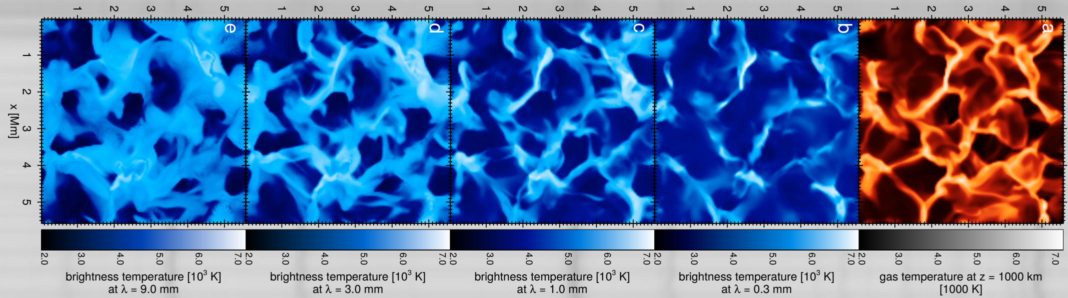
Bastian (2002); Loukitcheva et al. (2008); Shibasaki et al. (2011); Loukitcheva et al. (2014)

ALMA - Atacama Large Millimeter/Submillimeter Array

ALMA measurement

- bremsstrahlung from e^- interacting with ions / H
  (thermal free-free / H^- opacity)
- e^- in LTE $\rightarrow$ Planck source function
- Rayleigh-Jeans approx. highly accurate

$\rightarrow$ “thermometer” to probe the solar atmosphere

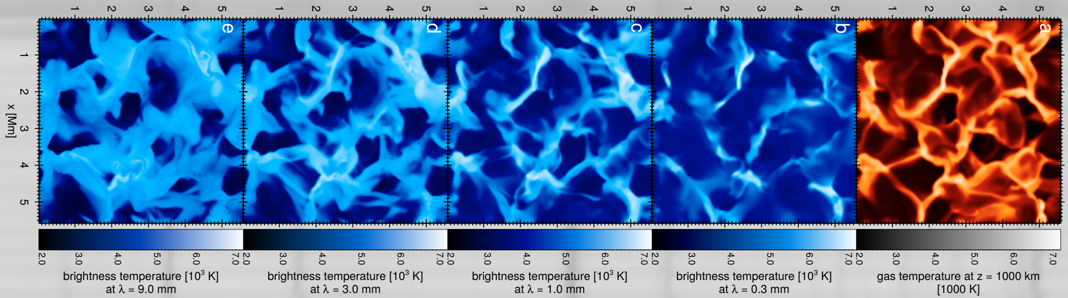


Wedemeyer-Böhm et al. (2007)

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)



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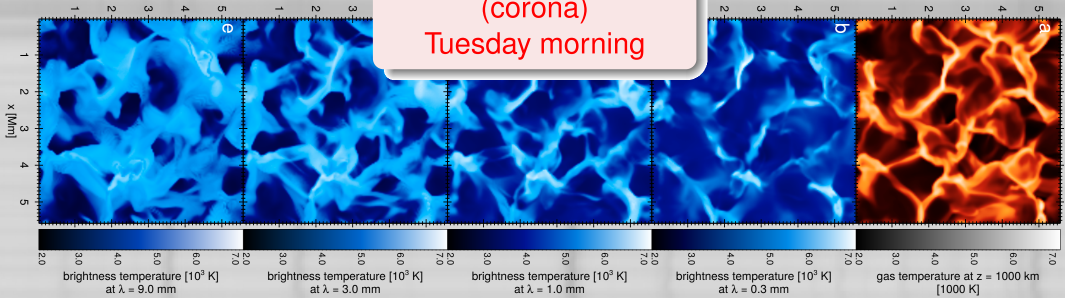
Stephen White
(corona)
Tuesday morning



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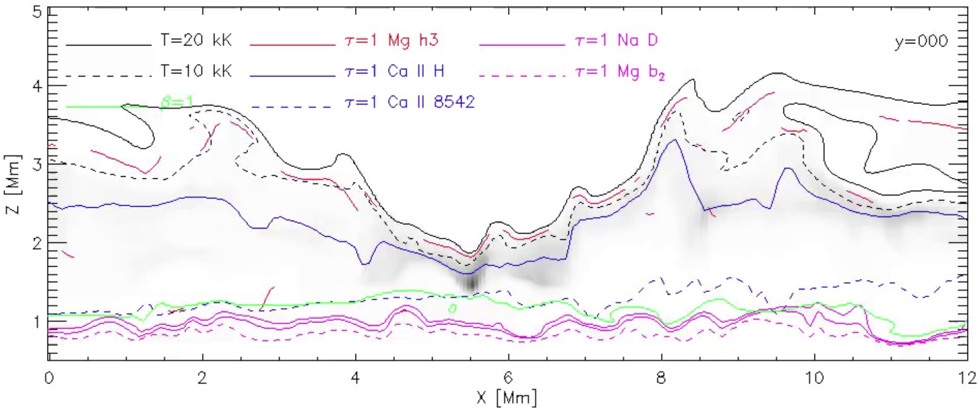
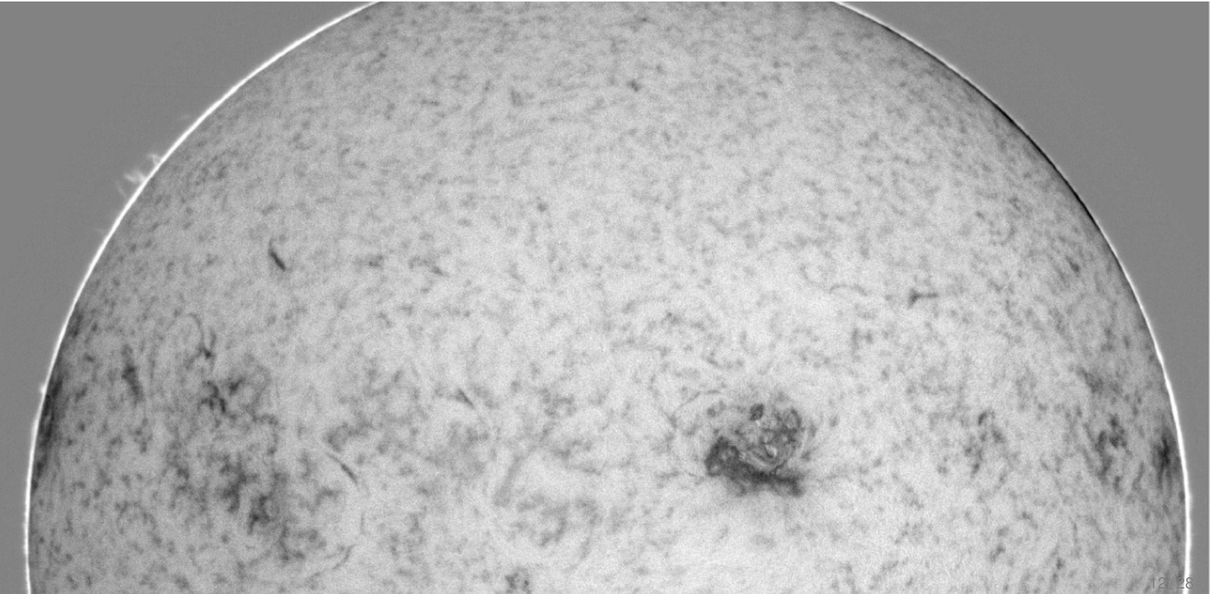
Chromospheric Lines

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

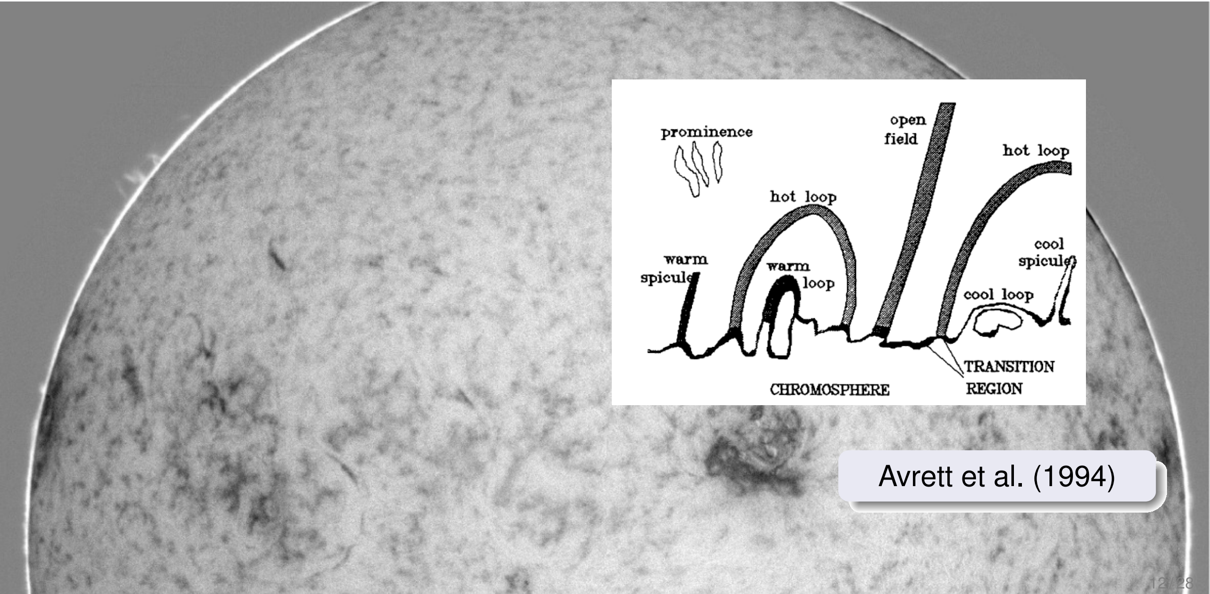


Mats Carlsson, Oslo

He I – What can be observed?

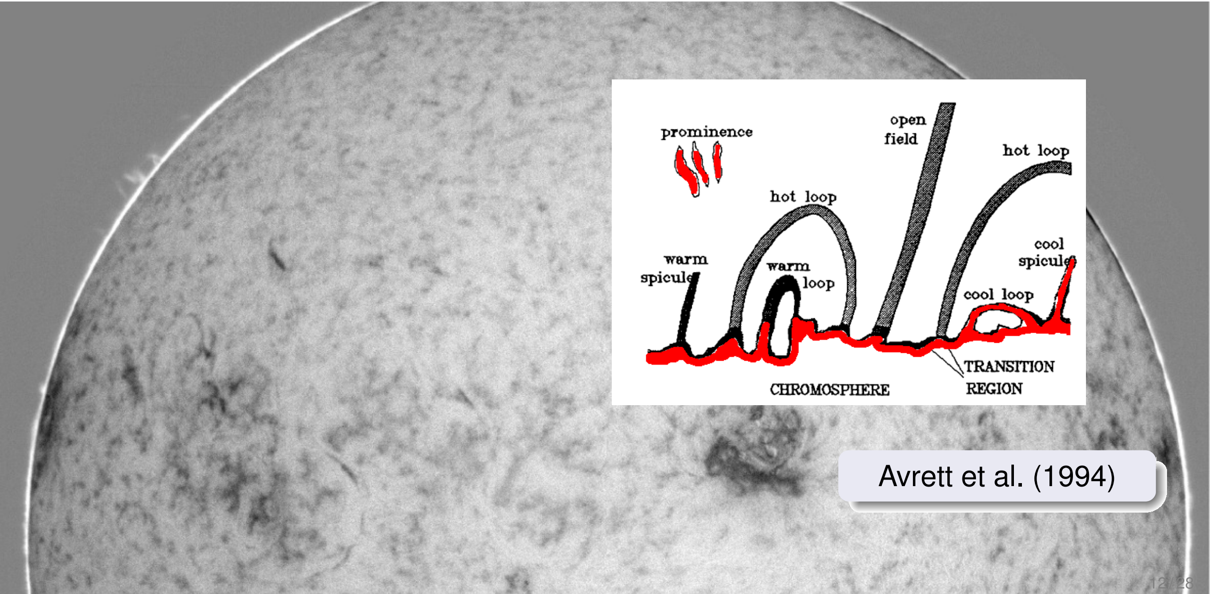


He I – Formation Height



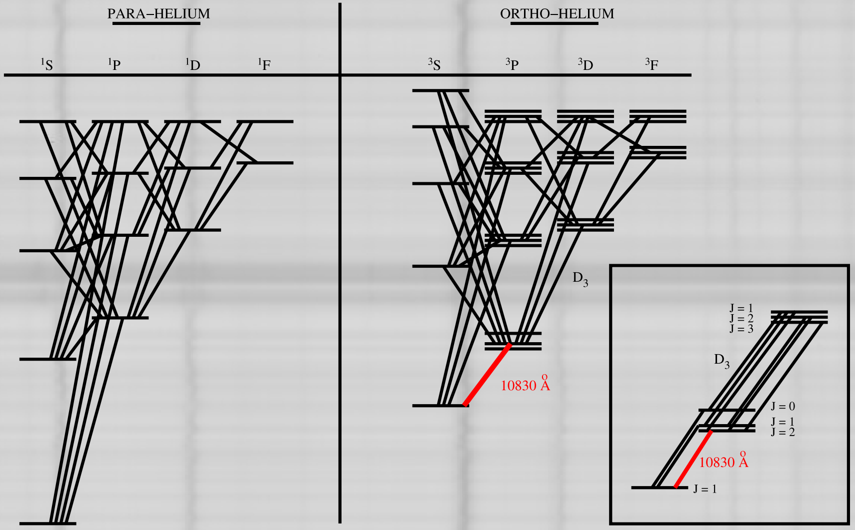
Avrett et al. (1994)

He I – Formation Height

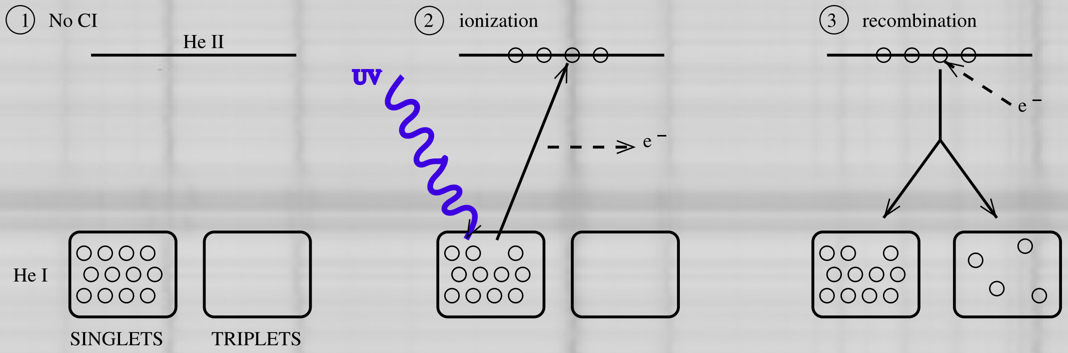


Avrett et al. (1994)

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 @ $0\farcs25$

GRIS @ 1.5m GREGOR (Tenerife)

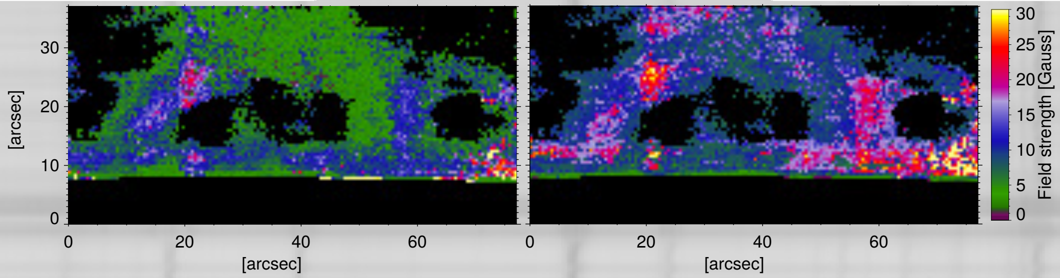
Collados et al. (2012)

- attached to 1.5 m GREGOR telescope (Tenerife)
- standard Czerny-Turner config.
- spectro-polarimetry @ $0\farcs25$

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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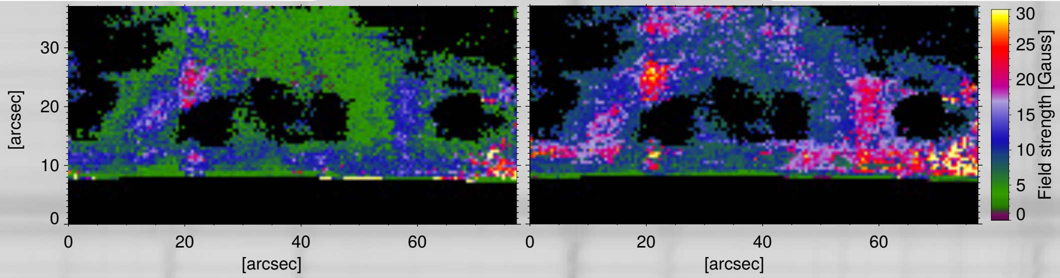

Magnetic field strength

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

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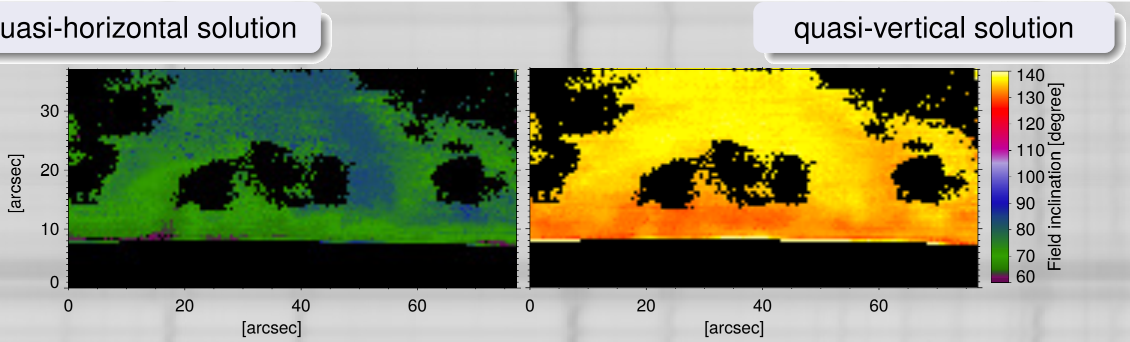

Magnetic field inclination

- 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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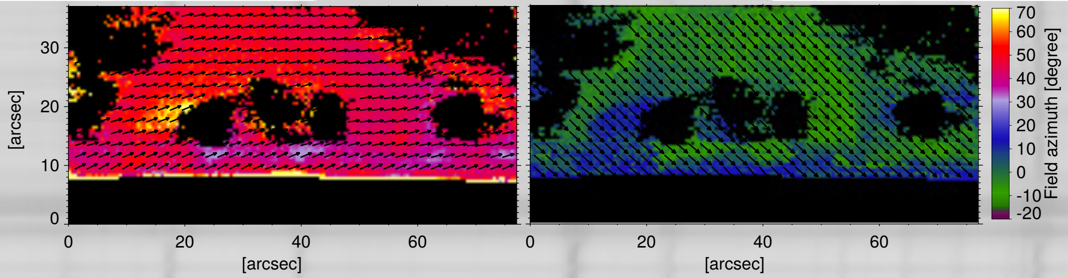
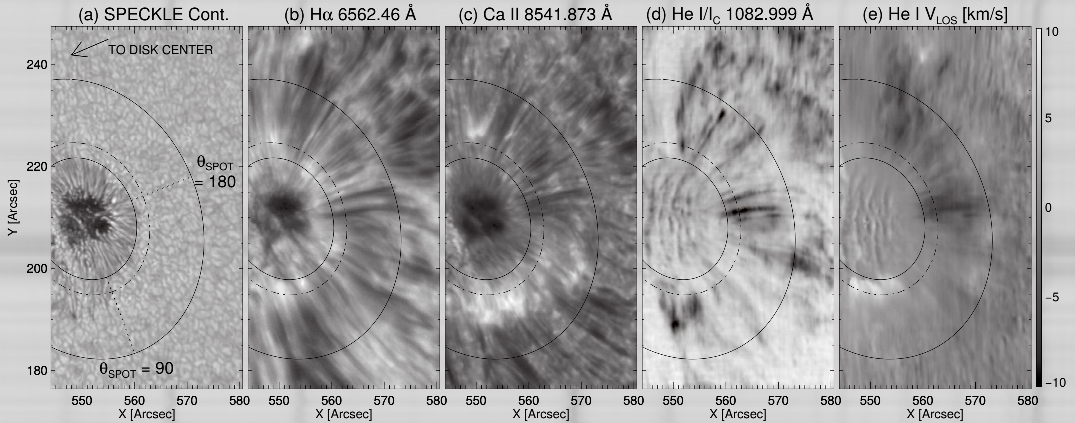


Magnetic field orientation wrt. prominence axis

- 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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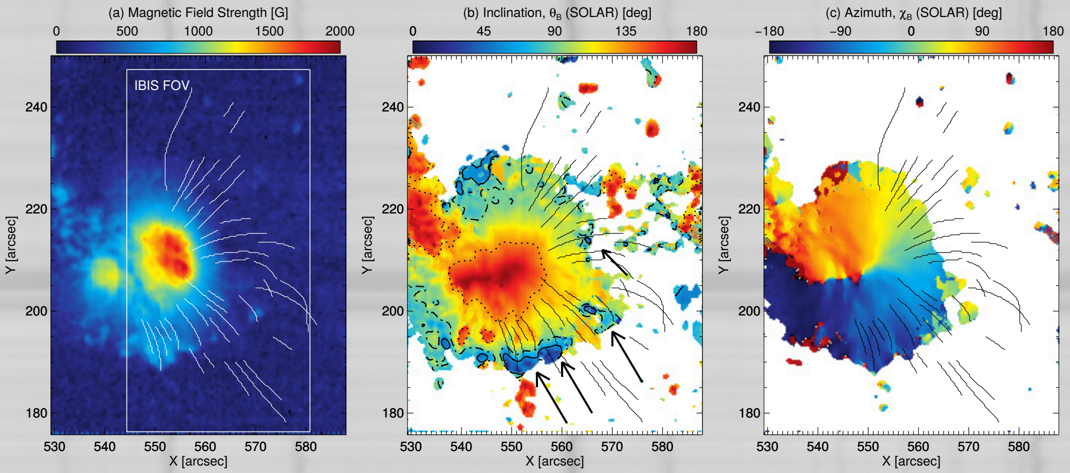

Photospheric field from Si I ME-inversions (HELIX$^+$ Lagg et al., 2009)

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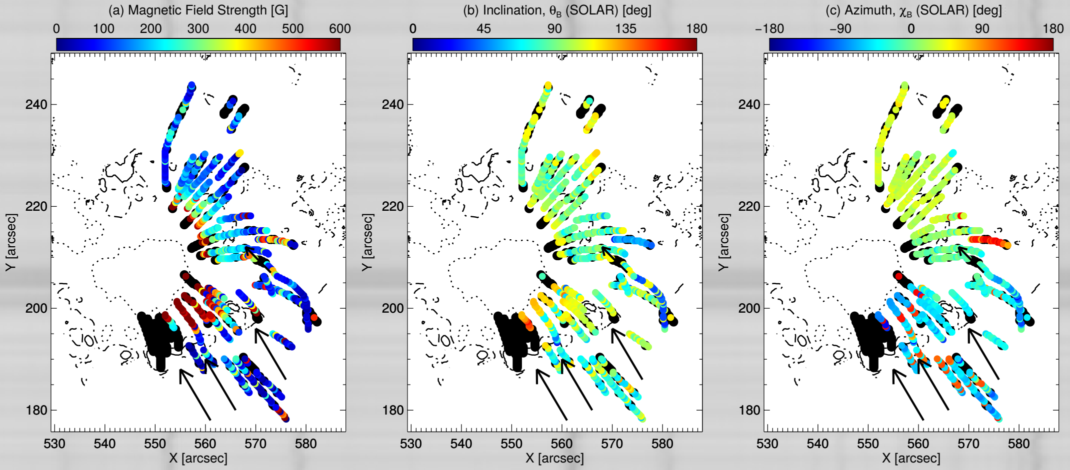

Fibril tracing (CRISPEX, Vissers & Rouppe van der Voort, 2012), careful disambiguation (Hanle & Zeeman), assumption on fibril height (1.75 Mm)

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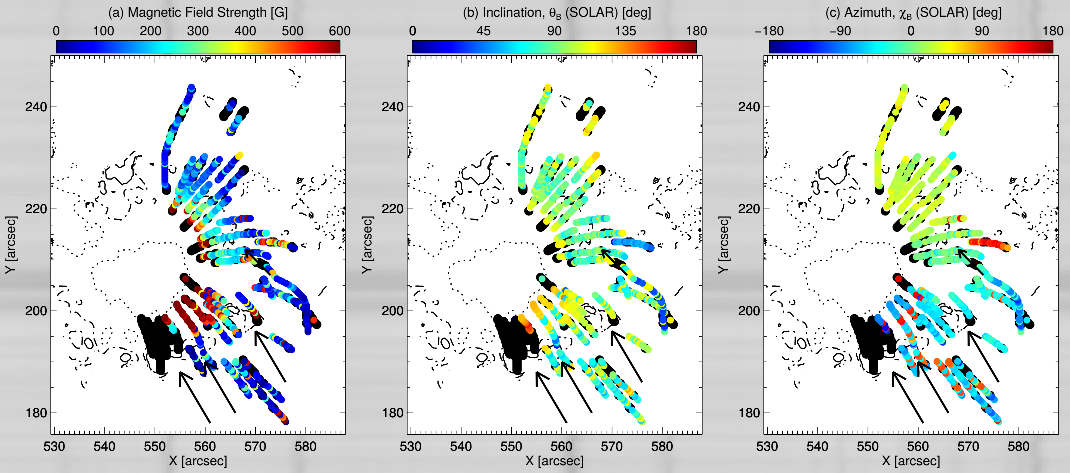

B-strength: rise in strength towards inner endpoints

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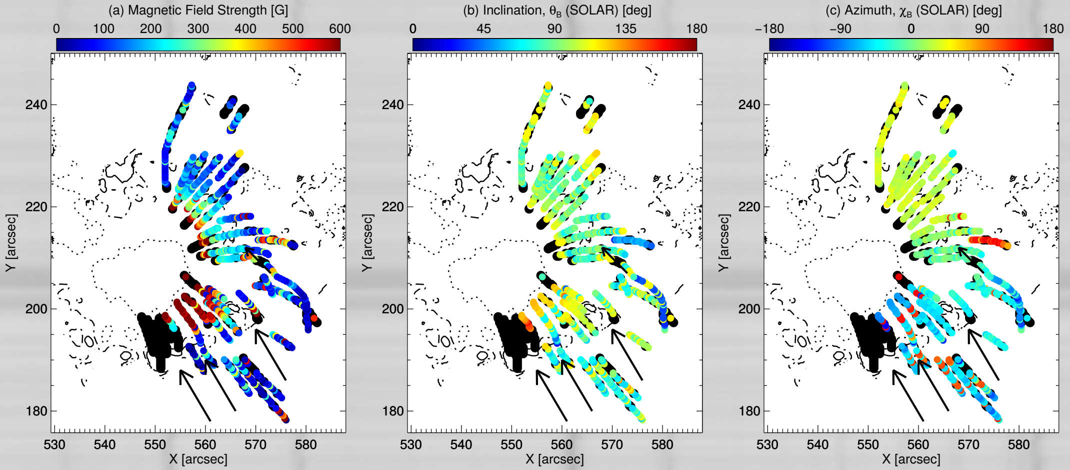

B-inclination: change at inner endpoint towards sunspot

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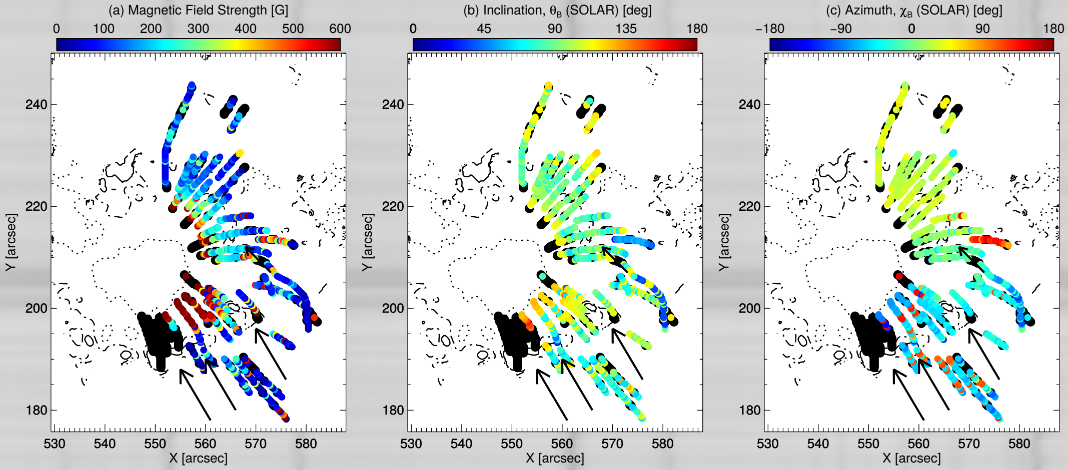
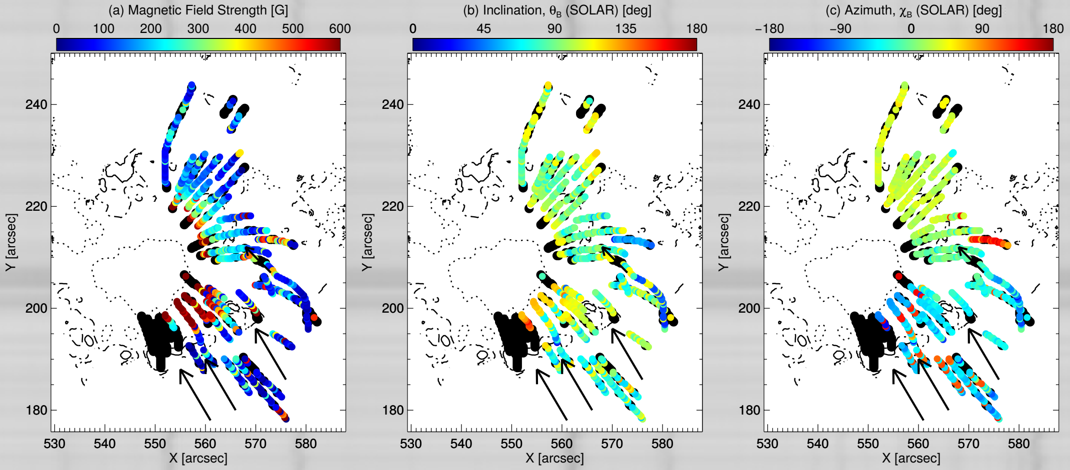


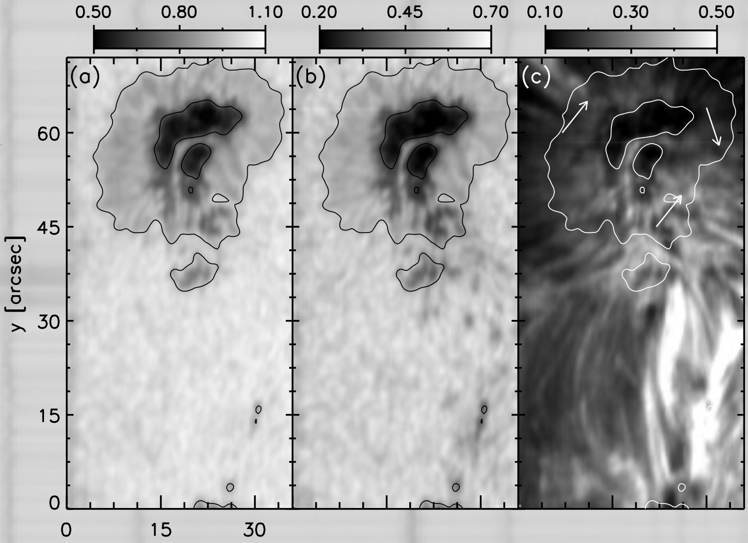
B-inclination: remain horizontal until outer endpoint
few fibrils: turn over again, connect in regions of opposite polarity photosphere

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

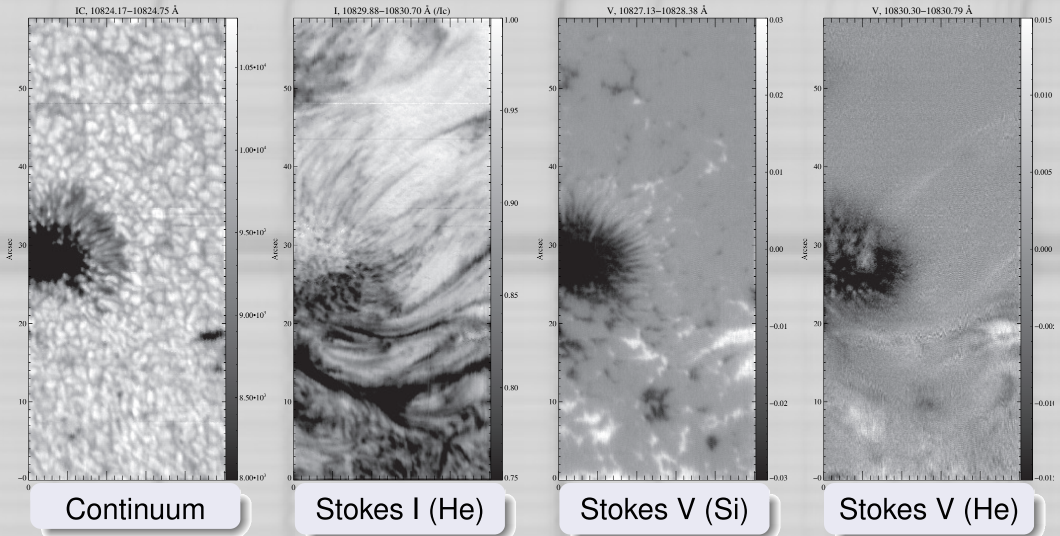


B-azimuth: aligned $\pm 10^\circ$ with fibrils
fibrils carry inverse Evershed flow

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



GREGOR/GRIS Data & First Results (June 2014)



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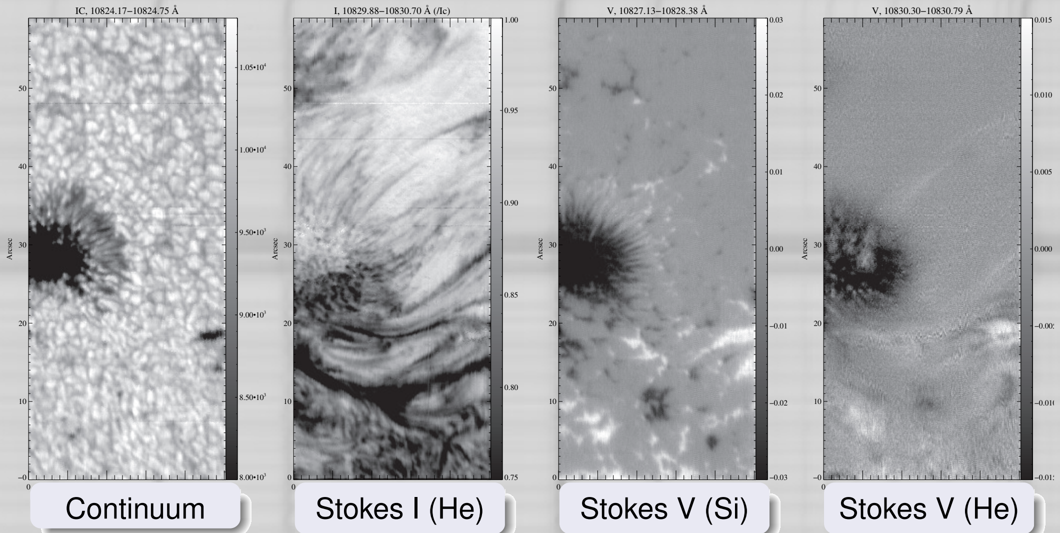

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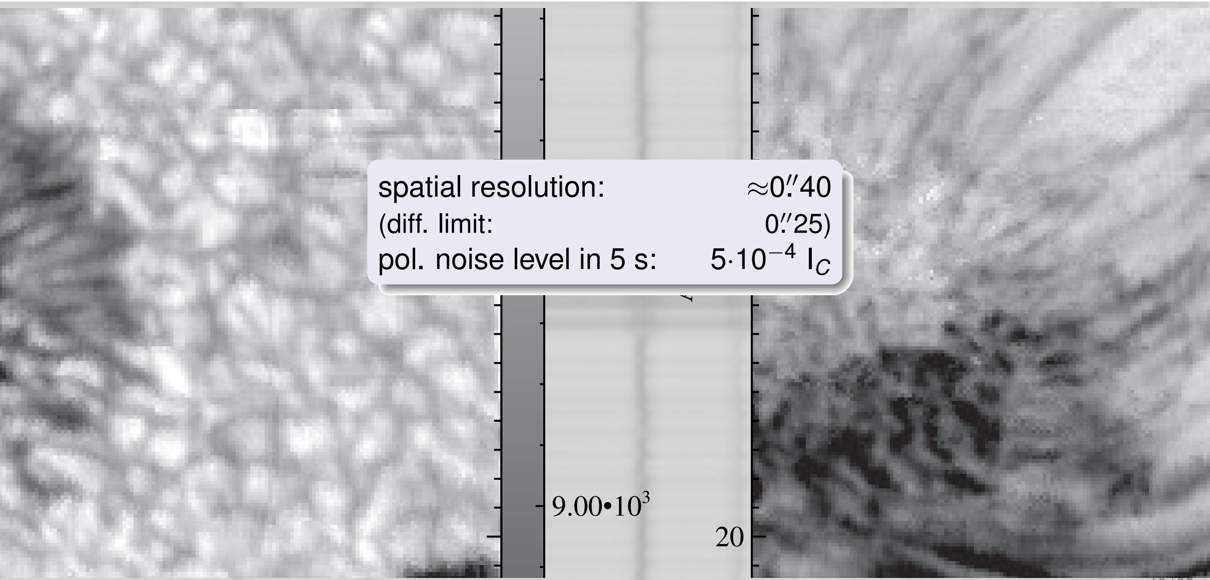

spatial resolution:	$\approx 0\overset{\prime\prime}{.}40$
(diff. limit:	$0\overset{\prime\prime}{.}25$)
pol. noise level in 5 s:	$5 \cdot 10^{-4}\ I_C$

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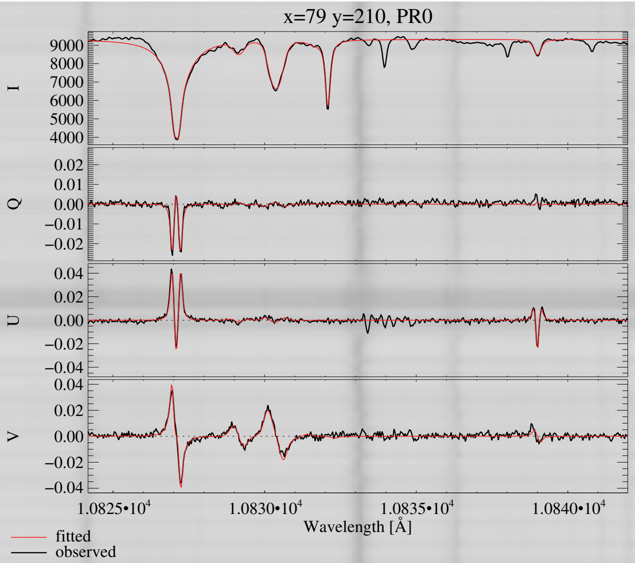
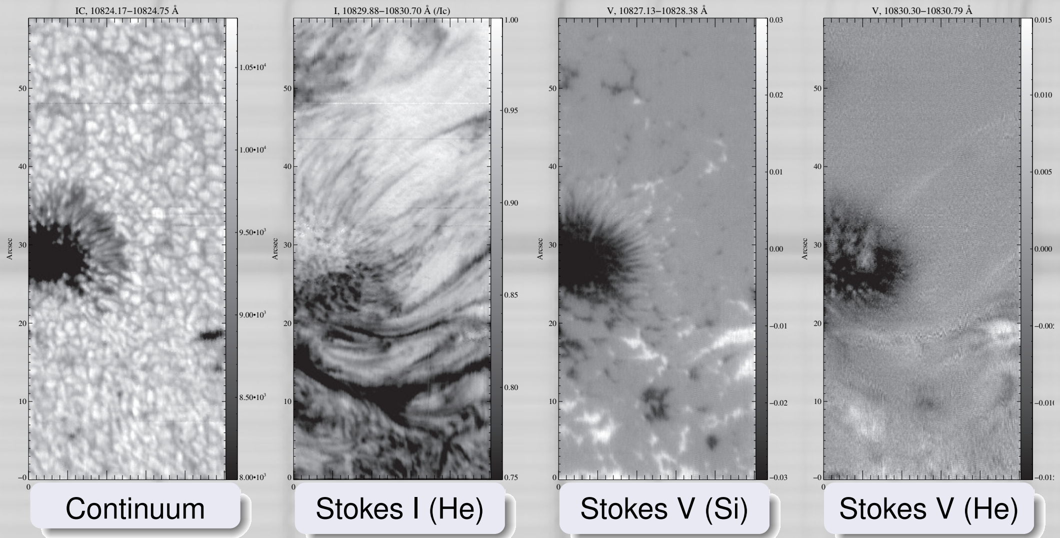
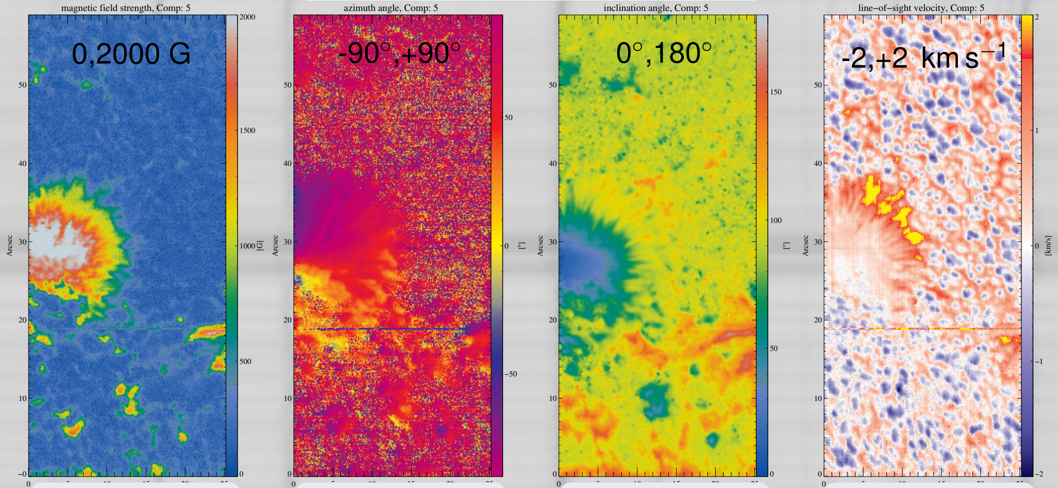


GREGOR/GRIS Data & First Results (June 2014)



GREGOR/GRIS Data & First Results (June 2014)

Ca I – deep photosphere



B-strength

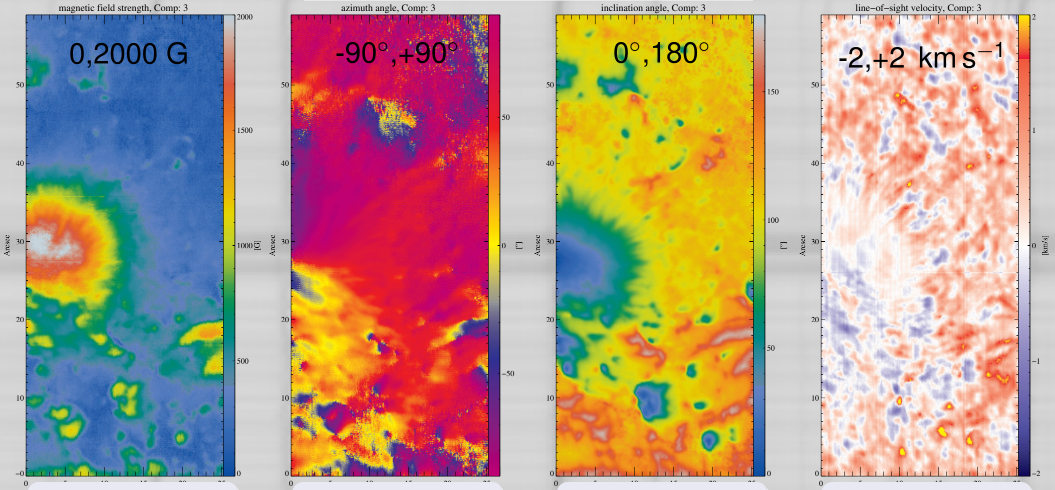
Azimuth

Inclination

LOS-velocity

GREGOR/GRIS Data & First Results (June 2014)

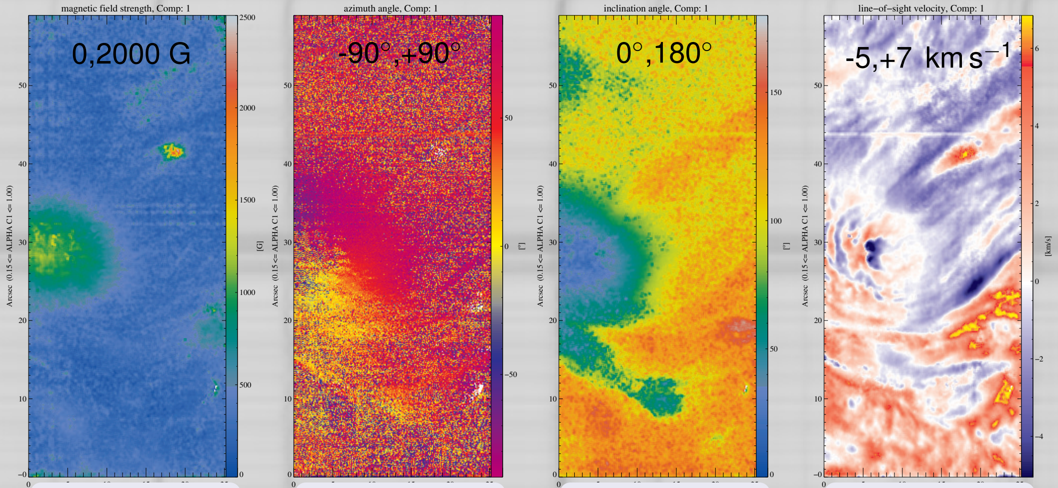
Si I – mid/upper photosphere



B-strength | Azimuth | Inclination | LOS-velocity

GREGOR/GRIS Data & First Results (June 2014)

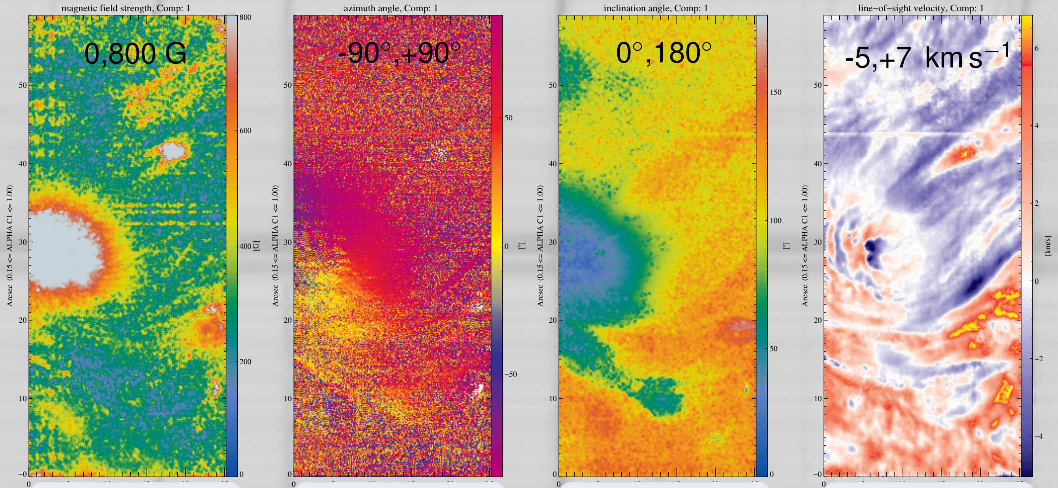
He I – upper chromosphere



B-strength | Azimuth | Inclination | LOS-velocity

GREGOR/GRIS Data & First Results (June 2014)

He I – upper chromosphere



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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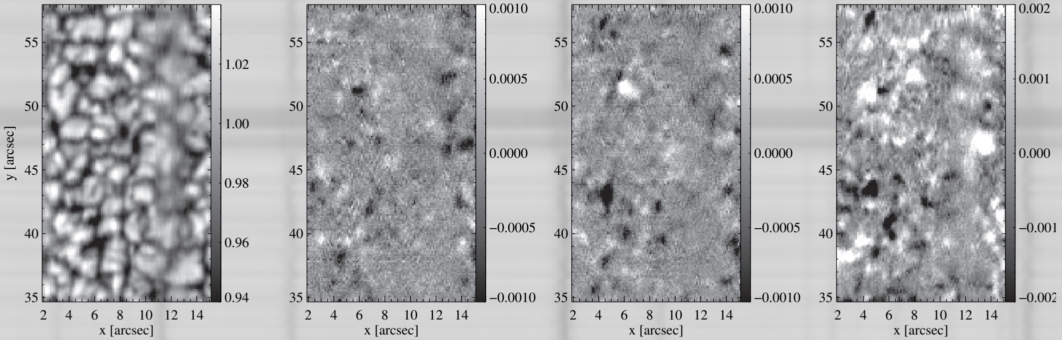
GREGOR/GRIS: Higher quality He I observation soon...

GREGOR/GRIS data at Fe I 1.56 μm (sep 2014):
0.35″ (≈ diff. limit) @ 3–5·10^{-4} I_C

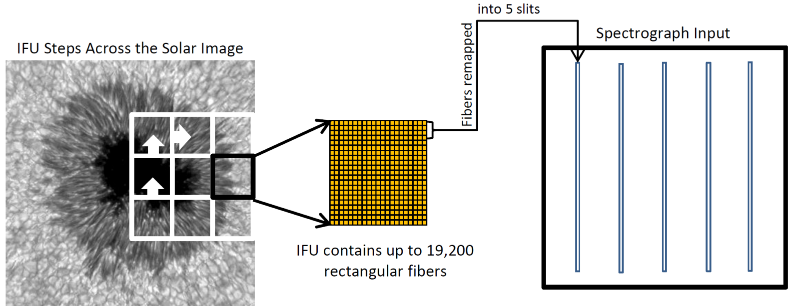


Ground-based: DKIST

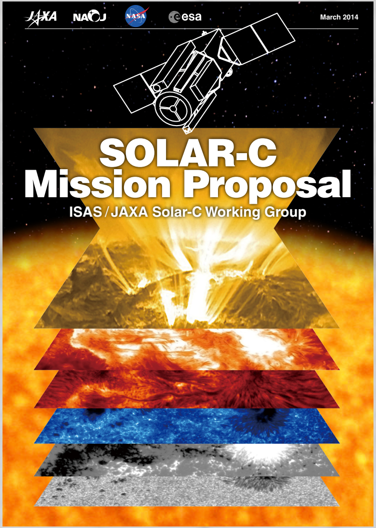
DL-NIRSP @ DKIST

The Diffraction Limited Near-Infrared Spectropolarimeter; Haosheng Lin

Spectral Range:	5000 Å – 18000 AA
Spectral resolution:	up to 250000
Spatial resolution:	0.07″ @10830Å
Target polarimetric accuracy:	$> 5 \cdot 10^{-4}$ Ic



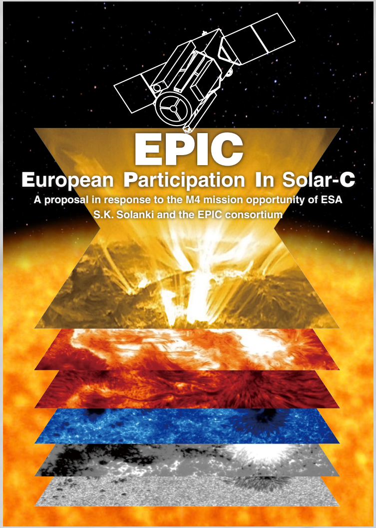
Future He I 10830 Å observatory



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



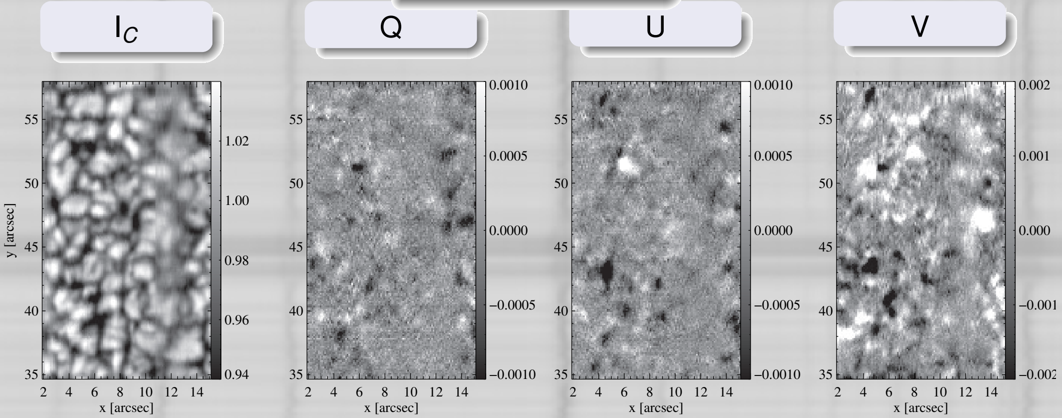
Scientific future of He I 10830

To-Do list for He I 10830 Science

- obtain measurements at highest possible spatial resolution, S/N in the low 10^{-4} range (ideal: 2D FOV)
- reliable disambiguation methods (Van Vleck ambiguity, 180° Hanle & Zeeman ambiguity):
  $\rightarrow$ combination with other chromospheric line?
- reliable anisotropy determination (take into account coronal illumination, symmetry breaking due to, e.g., sunspots):
  $\rightarrow$ determine population imbalances
- reliable height determination: $\rightarrow$ high S/N, stereoscopy

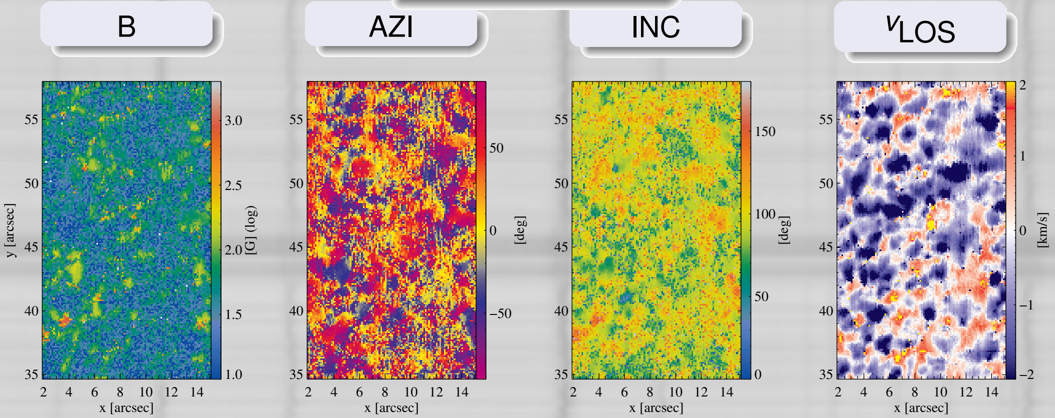
Very quiet sun region (2014-Sep-08)

All pixels



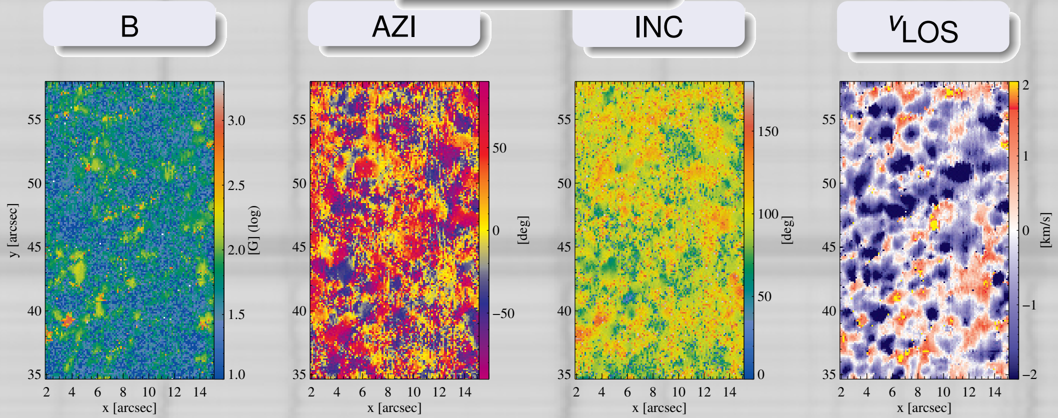
Very quiet sun region (2014-Sep-08)

All pixels



Very quiet sun region (2014-Sep-08)

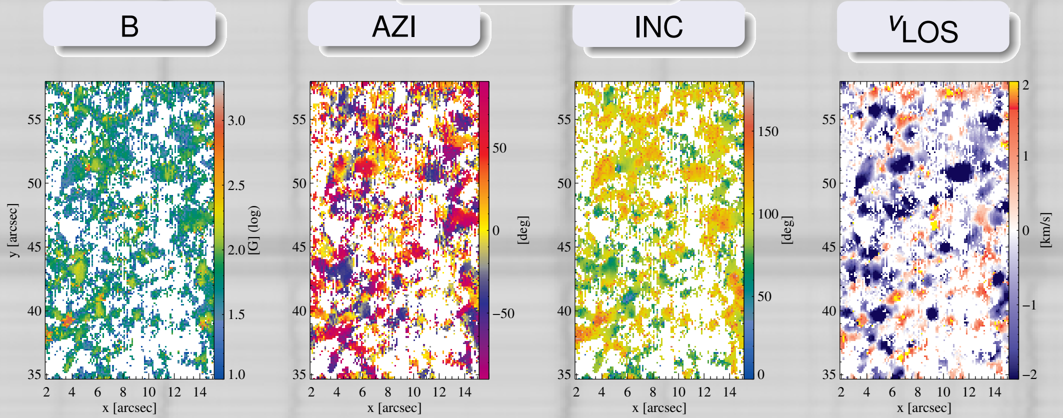
All pixels



remove all pixels with tot. pol $\leq 3\sigma$
Survival of IG lanes or granules?

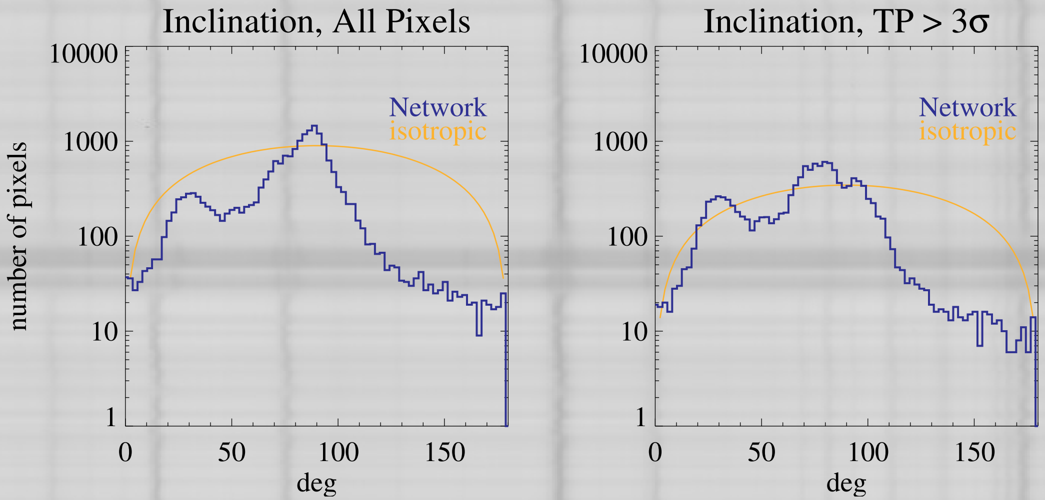
Very quiet sun region (2014-Sep-08)

Tot. Pol $> 3\sigma$

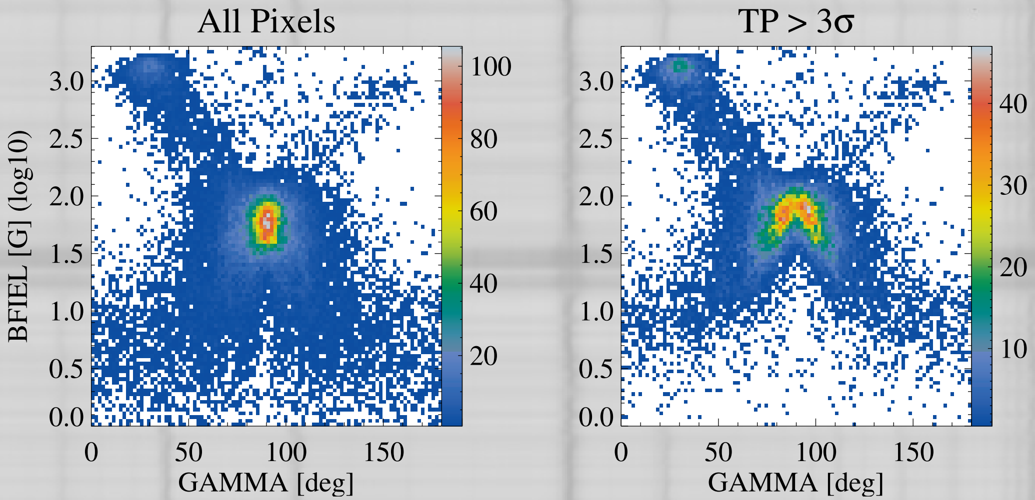


Mainly granules!
... and some IG lanes

Distribution: Inclination



Distribution: B & Inclination



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