Chromospheric and Coronal Diagnostics with DKIST

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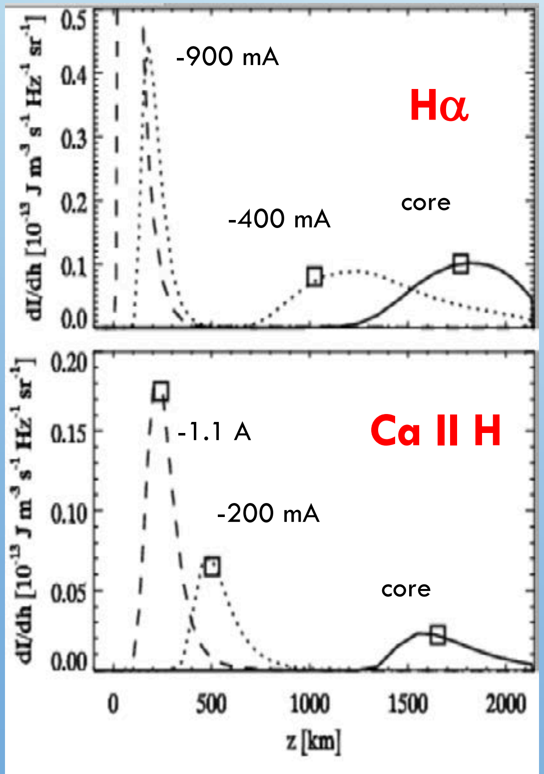
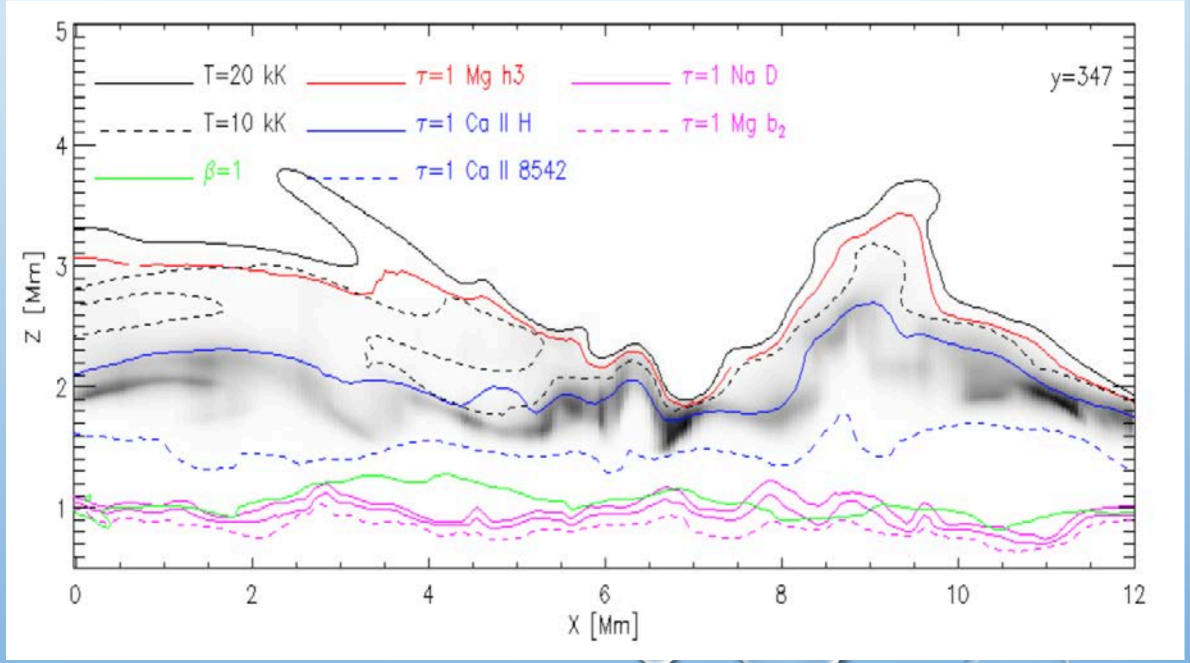
CHROMOSPHERE

2. Chromospheric lines

- Chromosphere is optically thin in most of the visible/near IR, apart from few strong lines: Balmer and Paschen series, CaII resonance (H&K) and subordinate triplet (849.8, 854.2, 866.2 nm), HeI triplet (1083 nm), subordinate HeI D_3 (587.6 nm)

- "Height of formation" is an over-simplification. Lines form over a large span, and heavily depend on local spatio-temporal conditions. HeI also strongly depends on local UV irradiation.

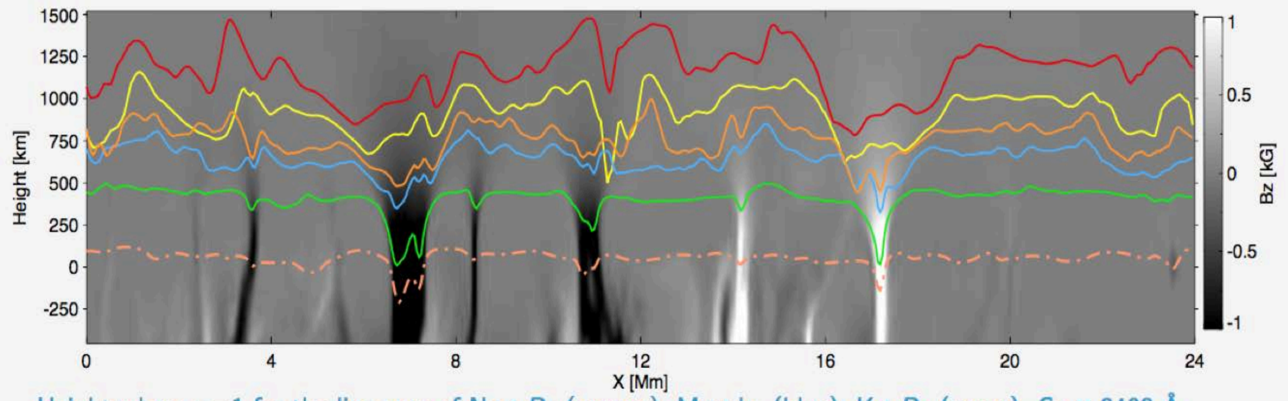




2. Chromospheric lines

- Resonance lines of alkali – e.g. Na I D_1, D_2; K I D_1 (small g_L but sensitive to velocitiy)

Scattering polarization; magnetism at T_{min} , flares

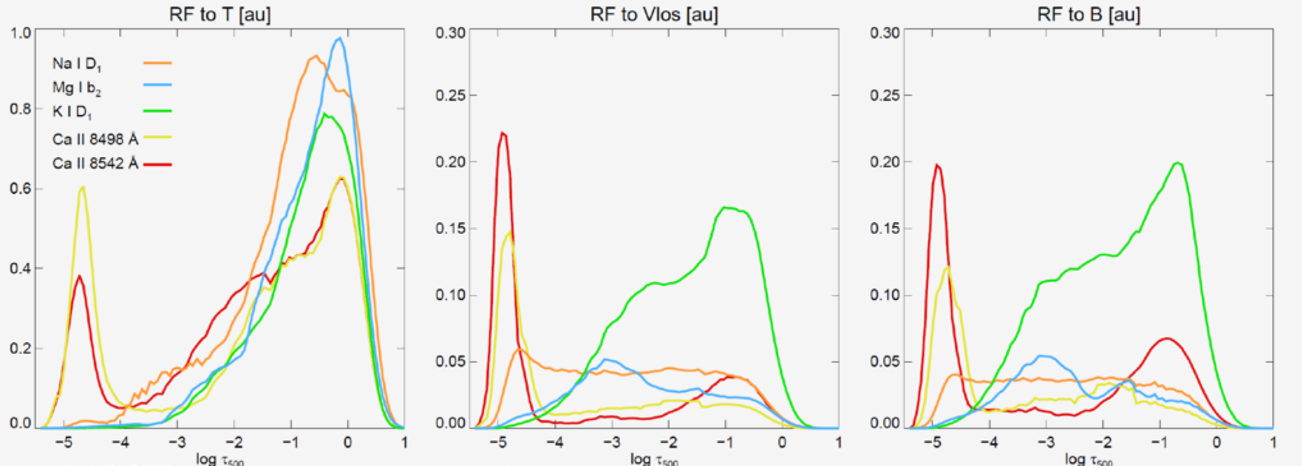


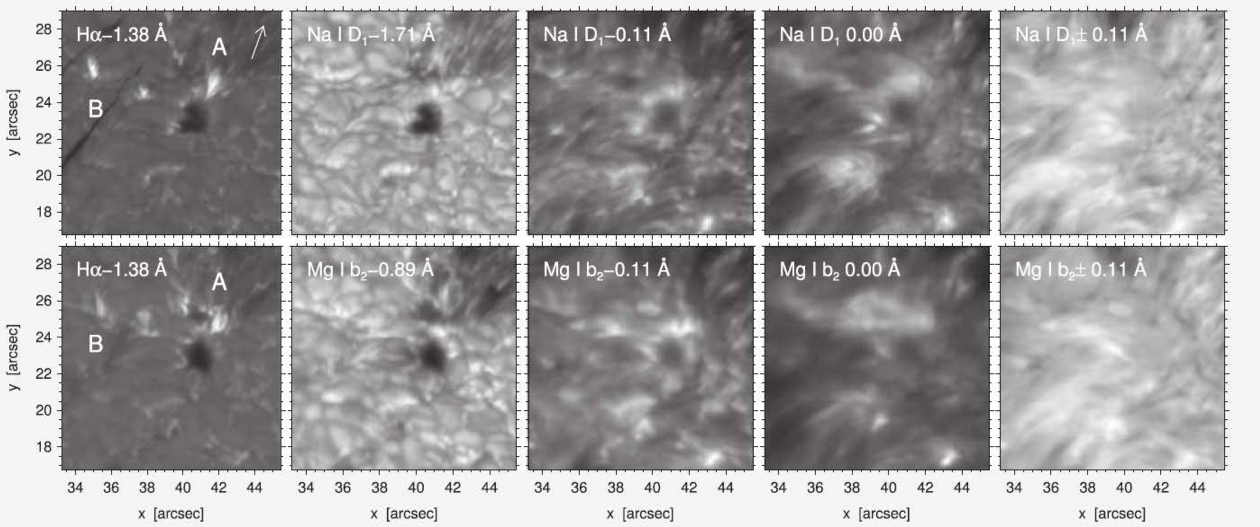
Height where τ=1 for the line core of Na I D_1 (orange), Mg I b_2 (blue), K I D_1 (green), Ca II 8498 Å (yellow), and 8542 Å (red). Dashed orange to τ=1 at continuum wavelengths.

Na I D2/1	589/589.6nm
Mg I b2	517.2 nm
K I D1	769.9 nm
Ca II	849 nm
Ca II	854 nm

Quintero Noda 2018

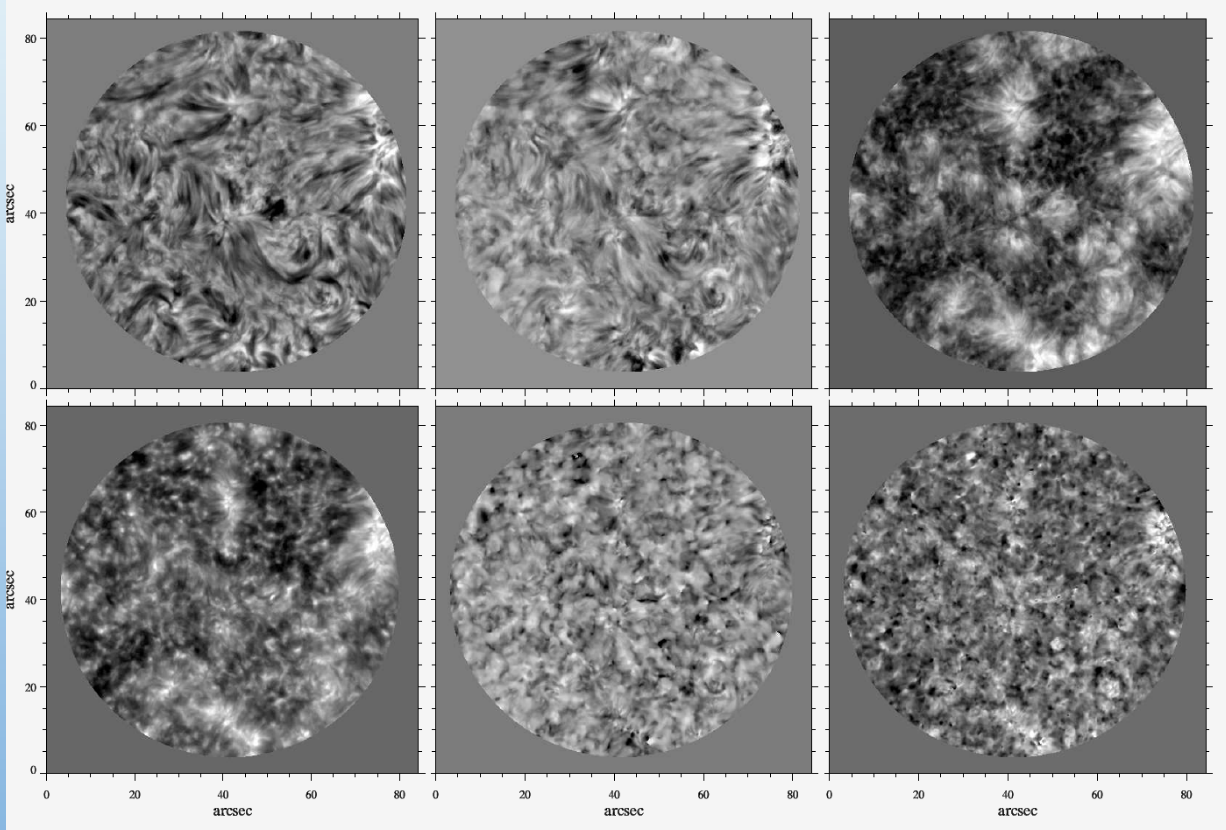
1D Response Functions using the FALC model and $B = 1000$ G, $\gamma = 45°$, $\phi = 45°$





- Rutten et al. (2010, 2015) compare the Na I and Mg I lines
- They seem to form at similar heights
- Maybe observing just one is enough

- Fibrils are more conspicuous on H_α
- However, we can infer $\vec{B}$ with Ca II
  - See H_α Response Function to $\vec{B}$ in Socas Navarro & Uitenbroek (2004)



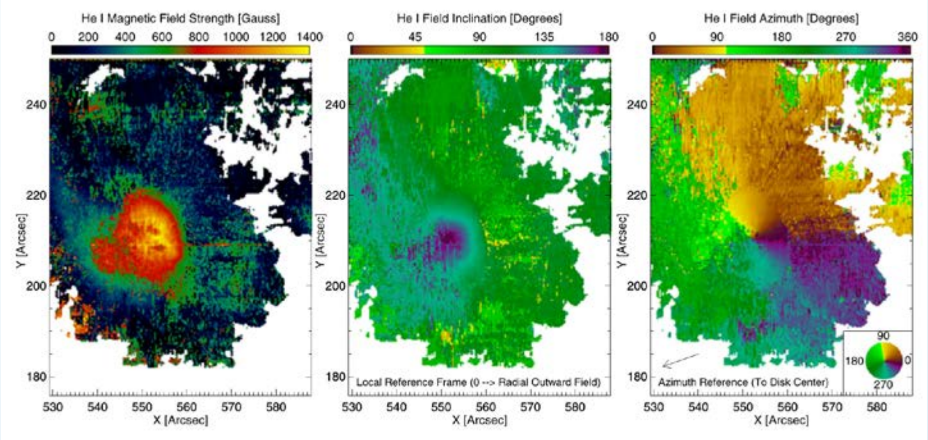
Cauzzi et al. 2009

- The **He I Triplet** system has well-known advantages for chromospheric polarimetry. Sensitive to *both* chromosphere and coronal conditions.

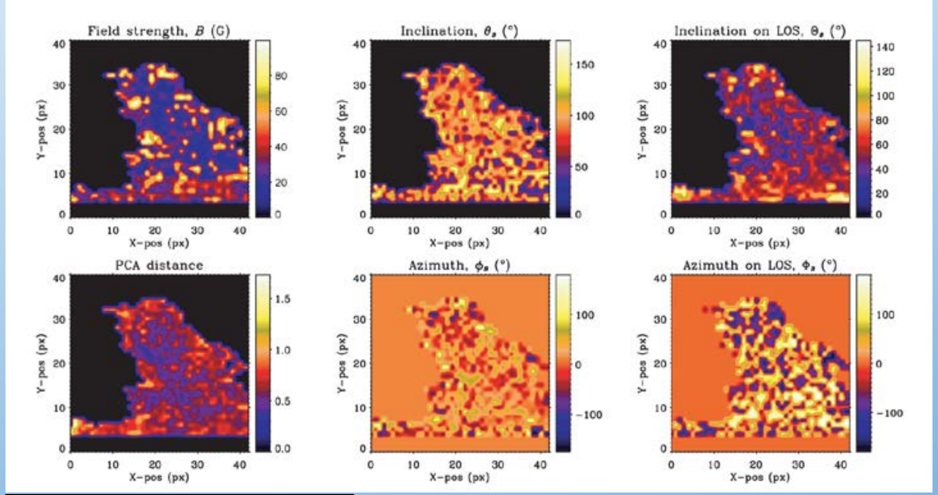
- Formed in a (relatively) thin and localized range of heights -> slab model.

- Strongest transitions at 1083 nm and 587.6 nm (D3) have Hanle sensitivity up to 10 and 50 Gauss respectively.

- Useful for active region magnetic field mapping in the chromosphere as well as cool material in the corona!



Schad et al. (2015)



Casini and Lopez-Ariste (2002)

3. Chromospheric lines: DKIST instruments

Hydrogen Lines

Spectral Window	Observing Mode	Spatial Resolution	DKIST Instrument
656.3 nm	spectral scan	0.033” ; 25 km	VTF
656,3 nm	filtergram	0.034” ; 25 km	VBI
486.1 nm	filtergram	0.024” ; 18 km	VBI
656.3, 486.1, 434.0, 410.1, 397.0 nm	spectrograph	0.04” x 0.06” ; 30 x 40 km	ViSP
P_{11} and higher, 820.4 (Paschen limit)	spectrograph	0.04” x 0.06” ; 30 x 40 km	ViSP

5. Chromospheric lines: DKIST instruments

Calcium Lines

Spectral Window	Observing Mode	Spatial Resolution	DKIST Instrument
393.3 nm	filtergram	0.022" ; 16km	VBI
393.3, 396.8 nm	spectrograph	0.04" x 0.06" ; 30 x 40 km	ViSP
854.2 nm	spectral scan	0.043" ; 30 km	VTF
854.2 nm	imaging spectrograph	0.06", 0.15" ; 43, 108 km	DL-NIRSP
854.2, 849.8, 866.2 nm	spectrograph	0.04" x 0.06" ; 30 x 40 km	ViSP

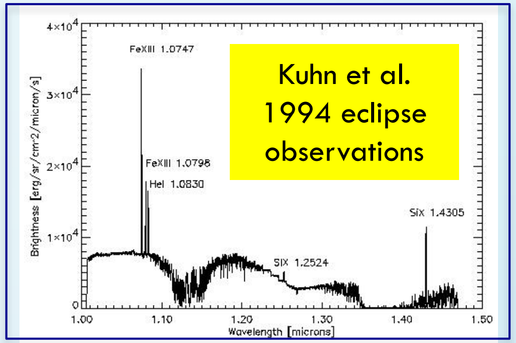
Helium Lines

Spectral Window	Observing Mode	Spatial Resolution	DKIST Instrument
1083.0 nm	imaging spectrograph	0.06", 0.15" ; 43, 108 km	DL-NIRSP
1083.0 nm	spectrograph	0.24 x 0.30" ; 175 x 215 km	Cryo-NIRSP
587.6 nm	spectrograph	0.04" x 0.06" ; 30 x 40 km	ViSP

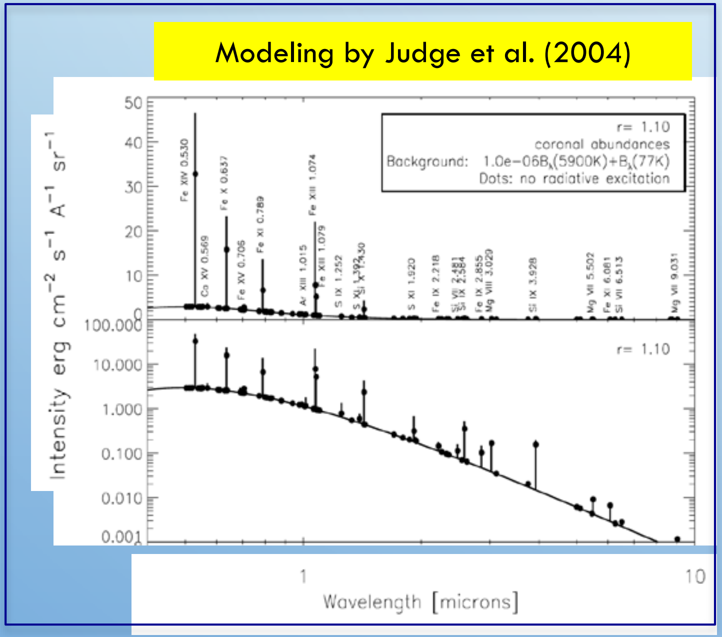
CORONA

The challenge of O/IR coronal spectral lines

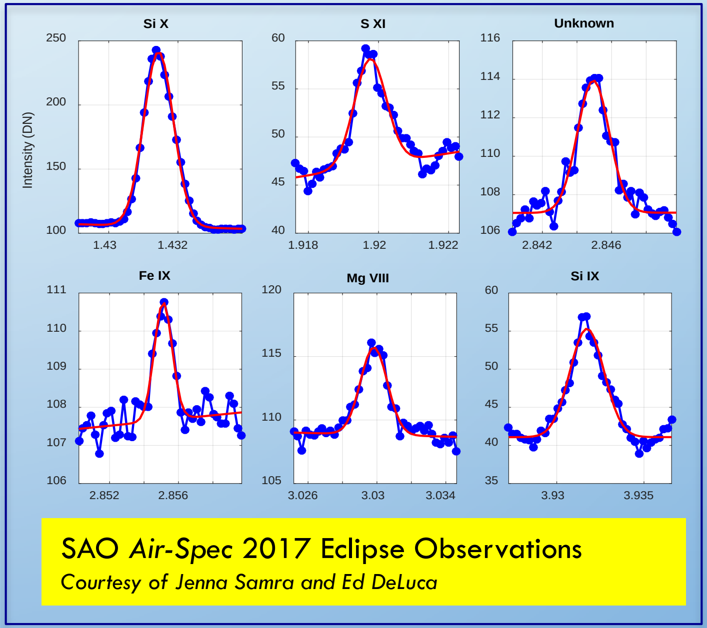
- ***Very weak*** compared to solar disk continuum intensity ~(1-100) : 10^6 ----- > *limited to off-limb measurements*.
- Atmospheric and telescopic scattering of disk light challenging.
- Incomplete exploration and atomic data make IR lines a big discovery space. See recent del Zanna & DeLuca (2017) review.



Kuhn et al. 1994 eclipse observations



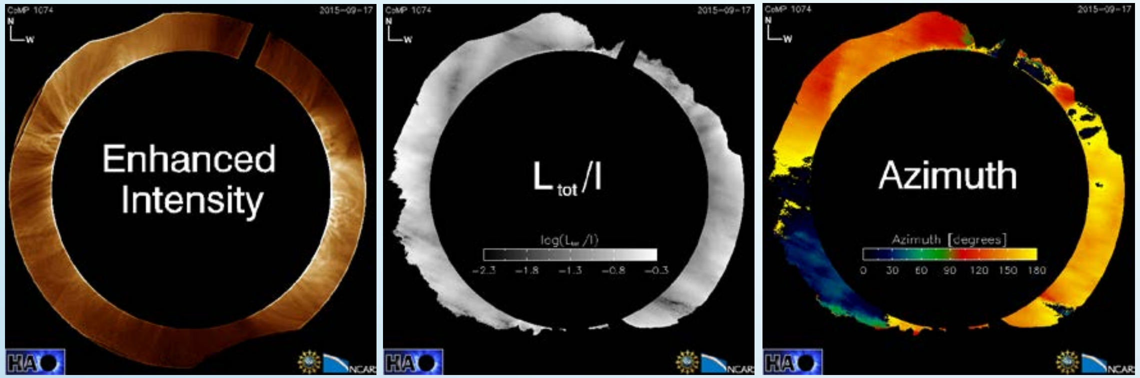
Modeling by Judge et al. (2004)



SAO *Air-Spec* 2017 Eclipse Observations

Courtesy of Jenna Samra and Ed DeLuca

Linear polarization is much easier to measure

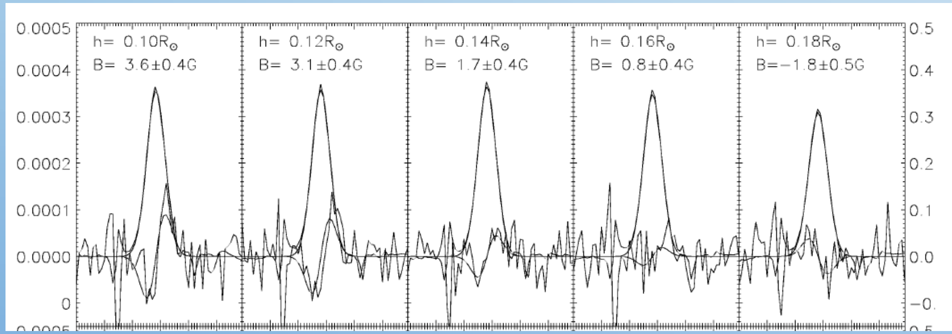


IR because Zeeman & Hanle available.
Zeeman prop. to λ^2

Linear polarization direction only sensitive to *magnetic azimuth in plane-of-sky.*

Amplitude depends on atomic orientation and requires detailed modeling to interpret.

Longitudinal polarization is difficult



Lin, Kuhn, Coulter 2004: 70 min. integration! Pixel=20 arcsec. D=50 cm

Requires careful calibrations
(flat, cross talk)

Reason why Cryo-NIRSP is not diffraction limited

DKIST: Opening a new era in coronal diagnostics!

Revolutionary Coronal Features:

4 meter aperture → More photons!!

Access to the infrared:

All-reflective design (transmission out to 28 μm)

First light instruments to 5 μm

Minimizes scattered light by:

Off-axis design (no beam obscuration)

High-grade M1 polish

Cleaning procedures (CO_2 + washing)

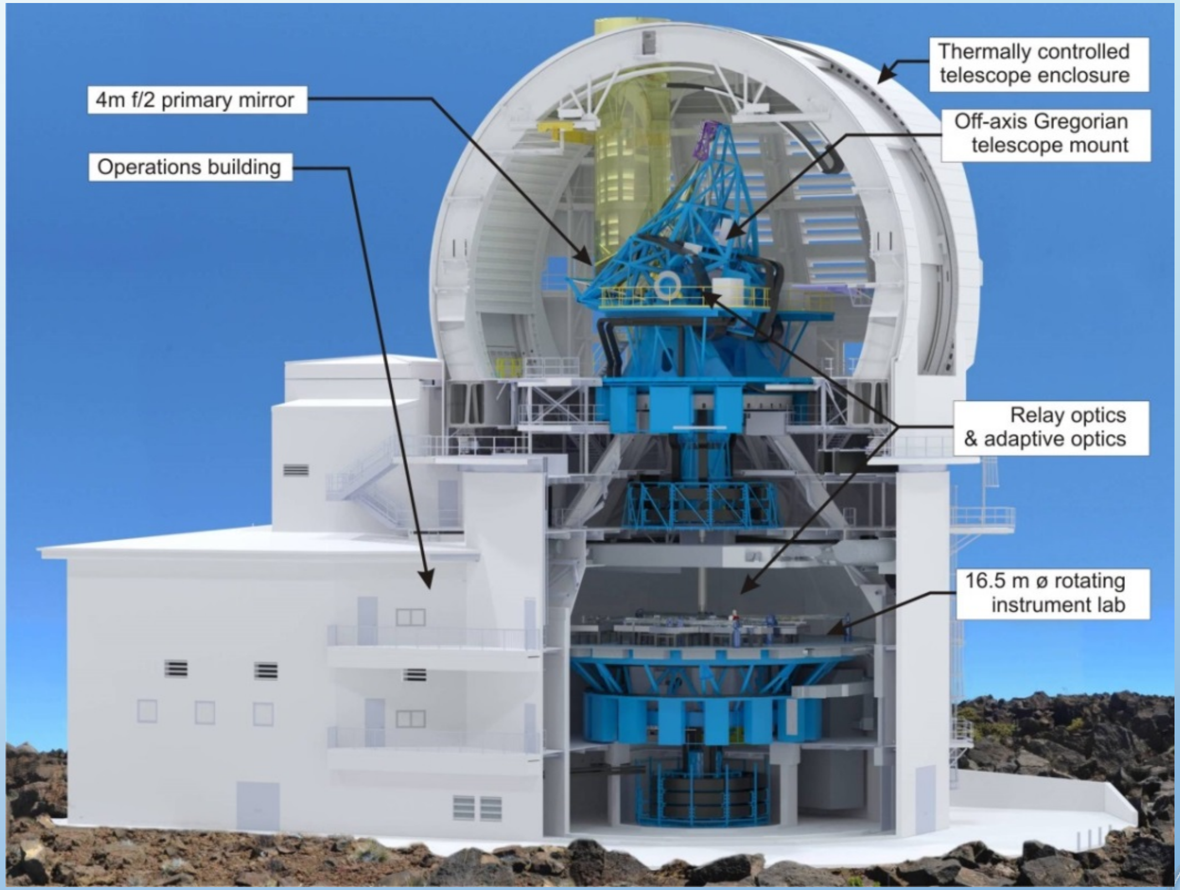
Access to the lower scatter infrared.

Occulters and stops:

Inverse occulter at prime focus (large 5' FOV)

Lyot stop at intermediary pupil

Limb occulting at Gregorian focus



DKIST coronal diagnostics during early operations

- Emphasis on bright line observations with greatest magnetic field sensitivity.
- Corresponding peak temperature coverage: 1 to 1.6 MK
- Filter availability can be expanded in the future.

Maximum FOV: 2.8 arcmin -- Coordinated Operations

DL-NIRSP Spectropolarimetry

Fe XI λ7892 ; Log(T) ~ 6.13
Fe XIII λ10747 ; Log(T) ~ 6.22
Fe XIII λ10797 ; Log(T) ~ 6.22
He I λ10830 ; Log(T) ~ 4*
Si X λ14300 ; Log(T) ~ 6.13

VBI Imaging

Fe XI λ7892 ; Log(T) ~ 6.13

VISP Spectropolarimetry

Various lines: 380 to 900 nm
Including FeXIV 5303, FeX 6375,
(green + yellow lines)

Maximum FOV: 5 arcmin

Cryo-NIRSP Spectropolar.

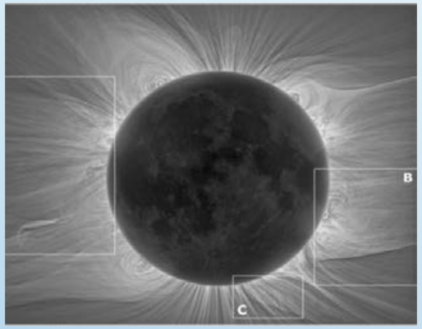
Fe XIII λ10747 ; Log(T) ~ 6.22
Fe XIII λ10797 ; Log(T) ~ 6.22
He I λ10830 ; Log(T) ~ 4*
Si X λ14300 ; Log(T) ~ 6.13
Si IX λ39350 ; Log(T) ~ 6.04

Cryo-NIRSP Context Imager

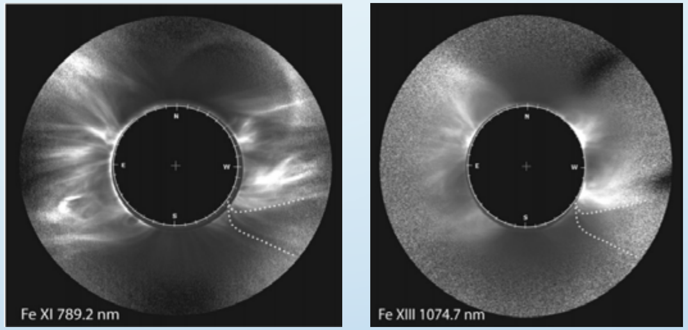
Fe XIII λ10747 ; Log(T) ~ 6.22
He I λ10830 ; Log(T) ~ 4*
Si IX λ39340 ; Log(T) ~ 6.04

Consequences of the line excitation mechanisms

- I_{coll} strong function of n_e^2
  I_{rad} depends on n_e (similar to Thompson scattered K-continuum).
- *Extended morphological structures seen in white-light eclipse photos also expected in VIS/IR spectral intensity maps.*

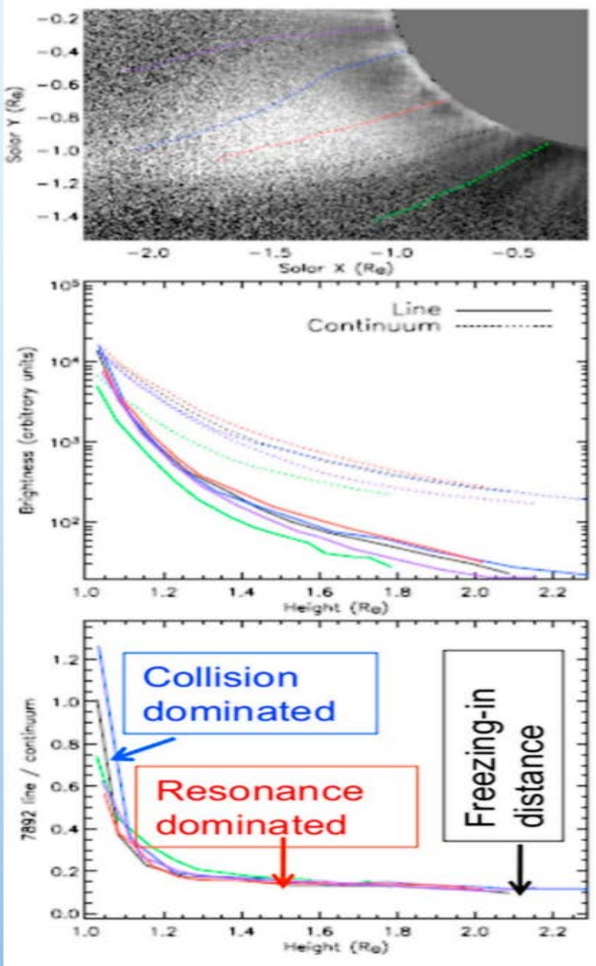


Druckmüller et al. 2014



Habbal et al. 2011

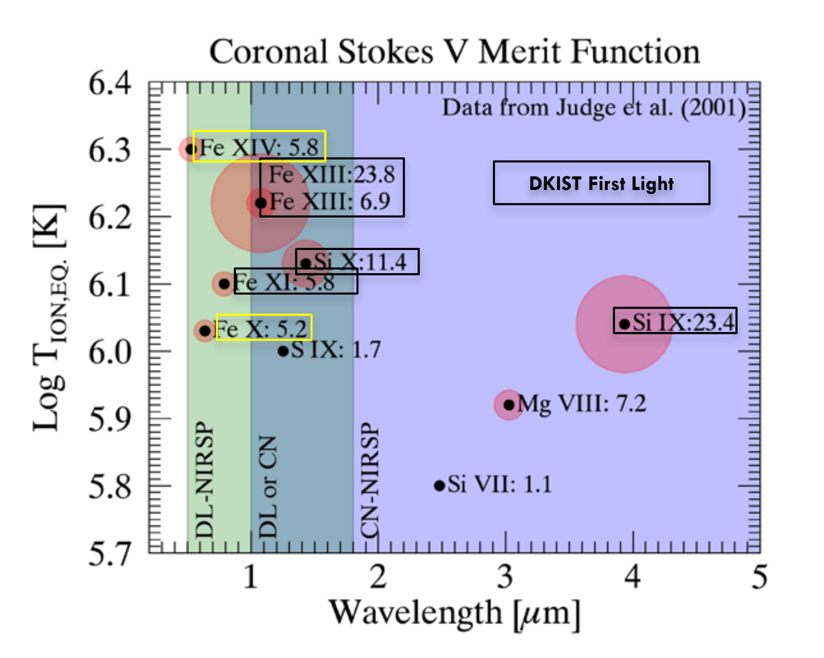
- Analysis must include radiative correction unless collisionally dominated (this is not needed for EUV).
- Mechanisms can be diagnosed using line to continuum (-polarized) ratios. Also helpful to pair with EUV observations.

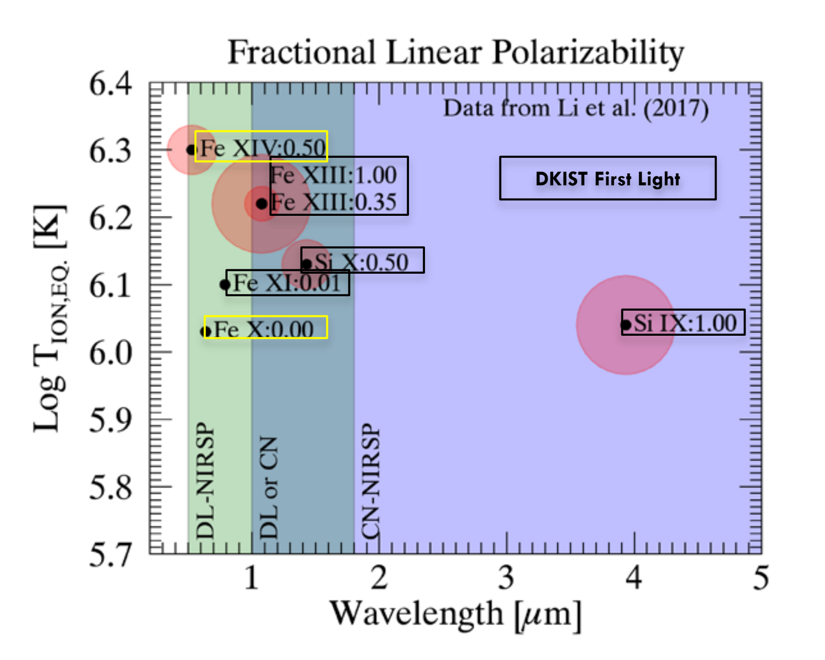


Habbal et al. 2007

Relative detectability of coronal polarization

- Stokes V sensitivity: line brightness + λ^2 Zeeman Effect [*geff=1.5*] (Judge et al. 2001).
- Linear polarizability depends on atomic parameters, i.e. $W_2(J_l,J_u)$ from Landi Degl'Innocenti & Landolfi 2004 Table 10.1.



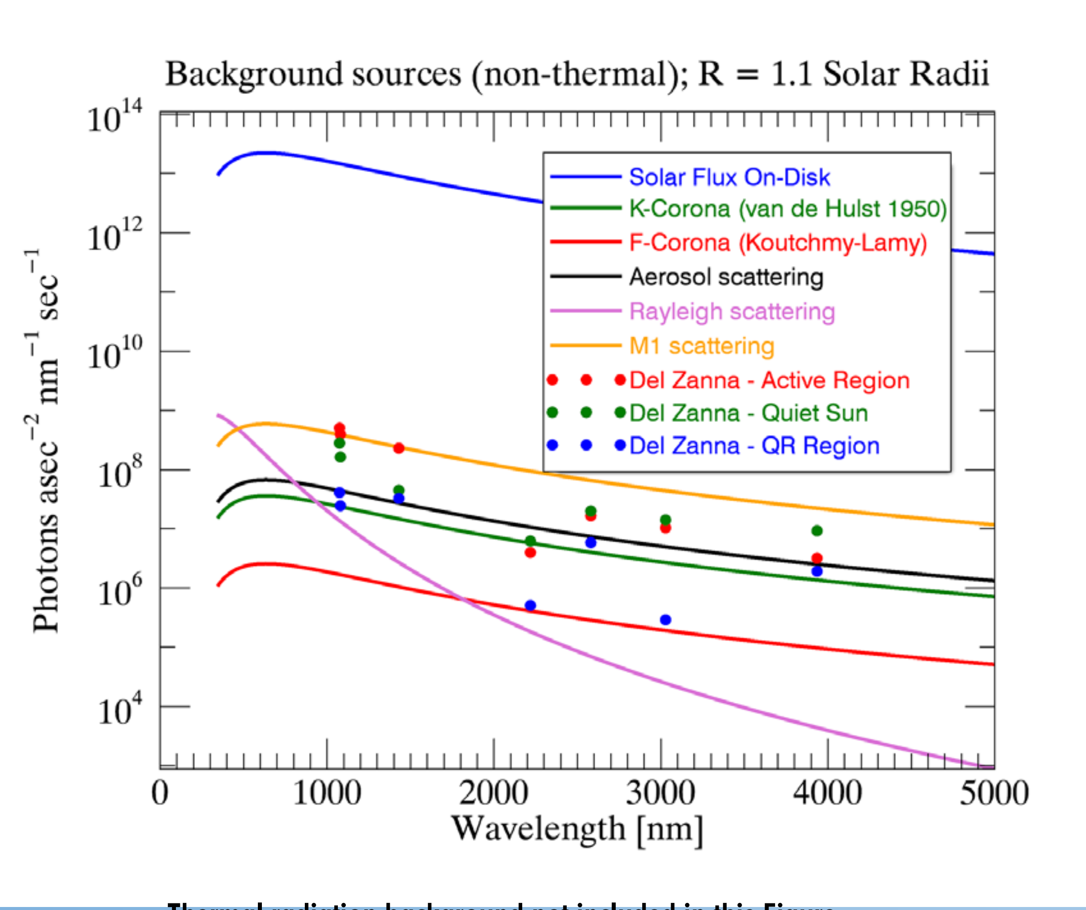


Background-limited measurements at DKIST.

$$\sigma = \sqrt{I_{tot}} = \sqrt{I_{Kcor} + I_{Fcor} + I_{Ecor} + I_{bg}}$$

- Emissive-corona (I_{Ecor}) of first-light lines typically > I_{kcor} > I_{Fcor}
  → Line intensities $\lesssim 10^{-5}$ of the disk intensity
  → QU & V polarization of a few-10% and ~ 10^{-4} of line signal, respectively.
  → *Circular polarization is $\lesssim 10^{-9}$ of disk intensity!*
- Background, I_{bg}, originates from (1) scattering in the Earth's atmosphere, (2) telescope/instrument scattering, and (3) the thermal sky/instrument background.
- Haleakala coronal conditions excellent but variable.
- Telescope scattering due to microroughness and cleanliness of M1 with a requirement of 2.5 x 10^{-5} of the disk intensity at 1.1 solar radii and 1 micron *after washing*.
- Thermal background must be controlled by cryogenic cooling for Cryo-NIRSP.

Modeled contributions to coronal measurements



Thermal radiation background not included in this Figure.

- Modeled line radiances of ***select lines*** from Del Zanna & DeLuca (2017).
- Atmospheric scattering for excellent coronal skies.
- Primary mirror (M1) scattering *cleaned/washed* within 1 day of observation.
- *Occulters* at prime focus and gregorian focus limit illumination of downstream optics. *Lyot stop* rejects diffraction ring of primary.

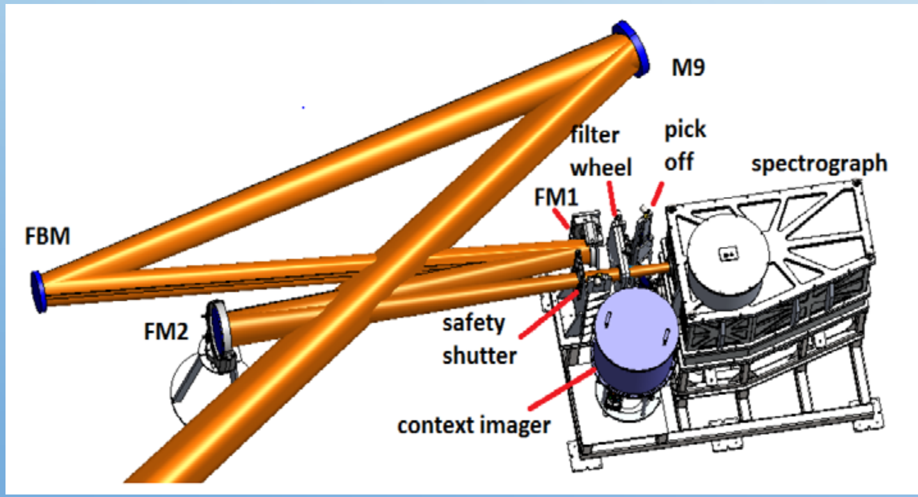
The thermal background is non-negligible beyond ~2.5 microns

Cryo-NIRSP's spectrograph, cryogenically cooled, nearly eliminates out-of-band thermal flux.

In-band thermal background is 10/20 % of signal at $\lambda > 3.8\ \mu m$

Context imager has higher out-of-band thermal background, but relevant only for $\lambda > 3.0\ \mu m$

Thermal background negligible for on disk observations

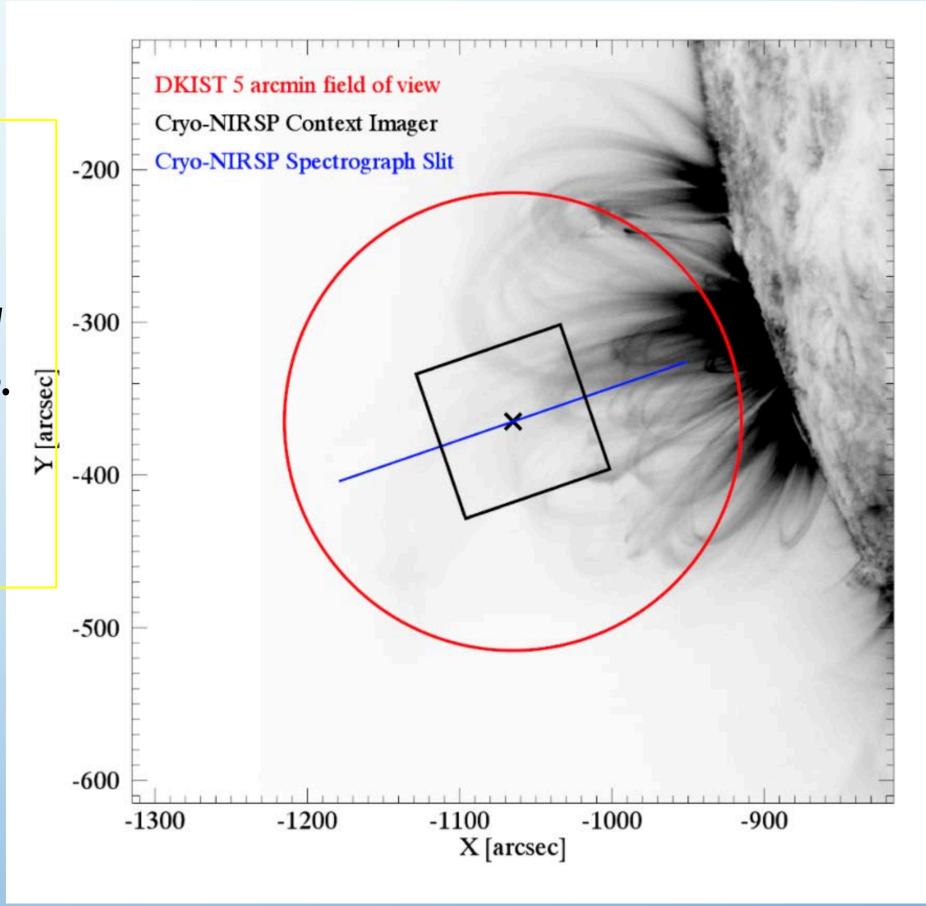


Coronal measurements with Cryo-NIRSP

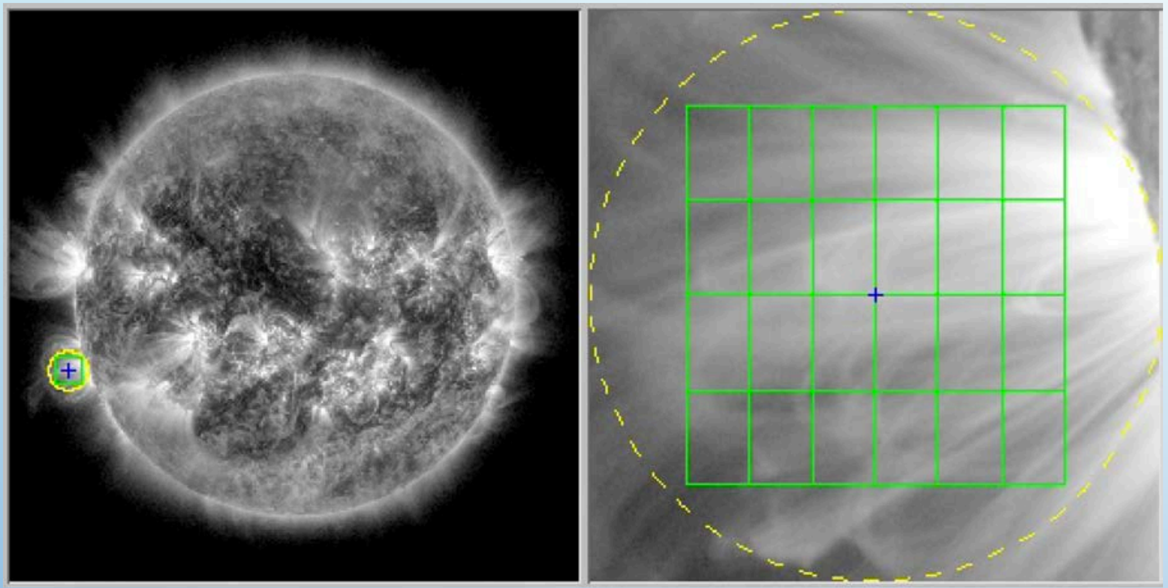
Sit-and-stare observations and limited field-of-view rastering is available for temporal diagnostics of, e.g., oscillations.

4 x 3 arcmin Cryo-NIRSP scan ***with 1" step size will require between 1 and 3 hours for a magnetic field sensitivity of a few Gauss in a single wavelength.***

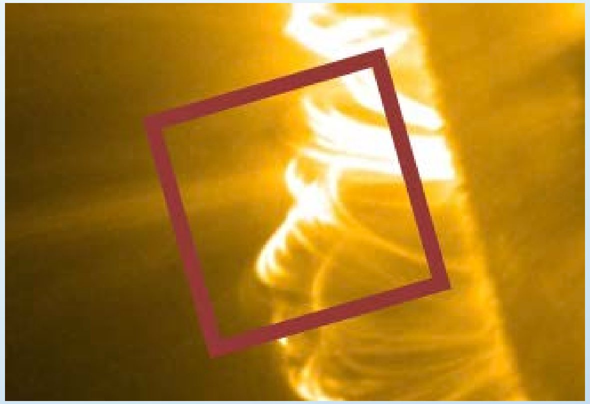
Must have a good understanding of what your use case demands.

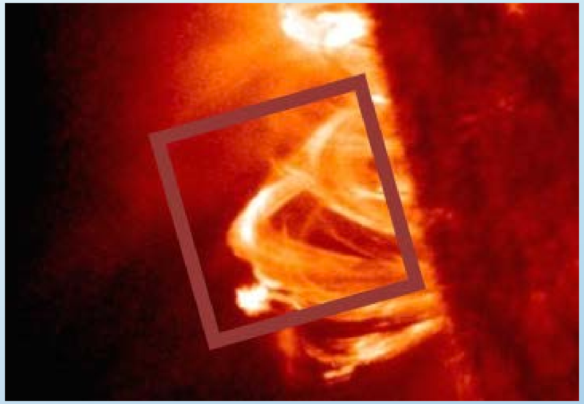


Coronal measurements with VISP, DL-NIRSP, and VBI

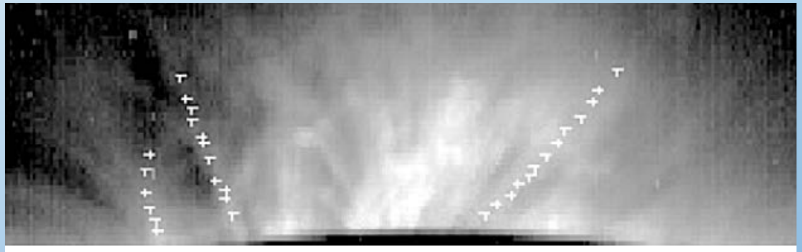


DL-NIRSP has a coarse sampling mode for coronal observations.
18” x 28” arcsec IFU coverage with multi-line coverage!





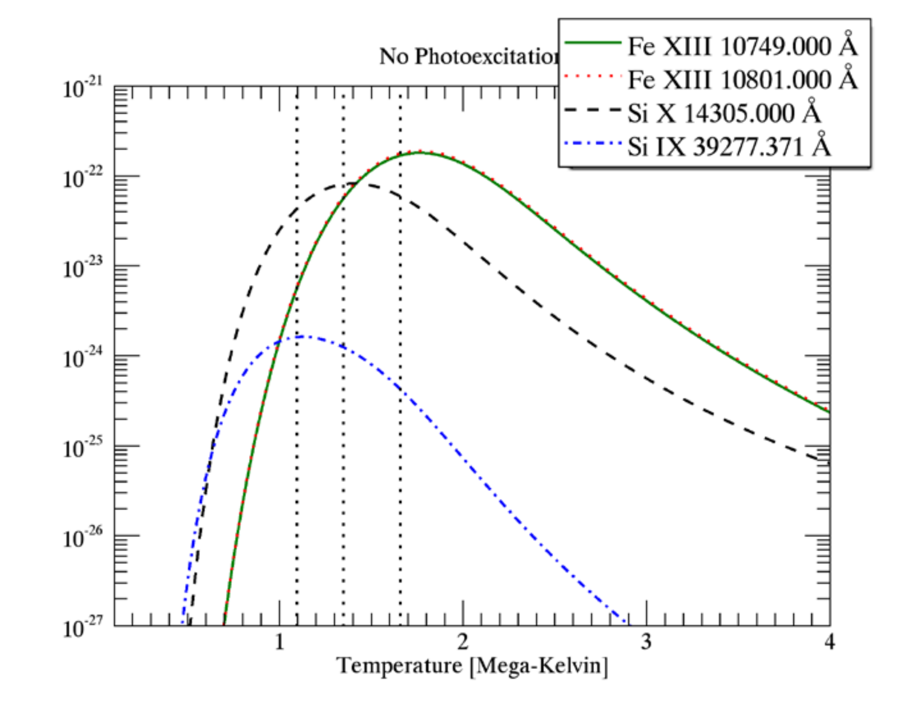
VBI imaging at
Fe XI 789.2 nm
and cool lines.

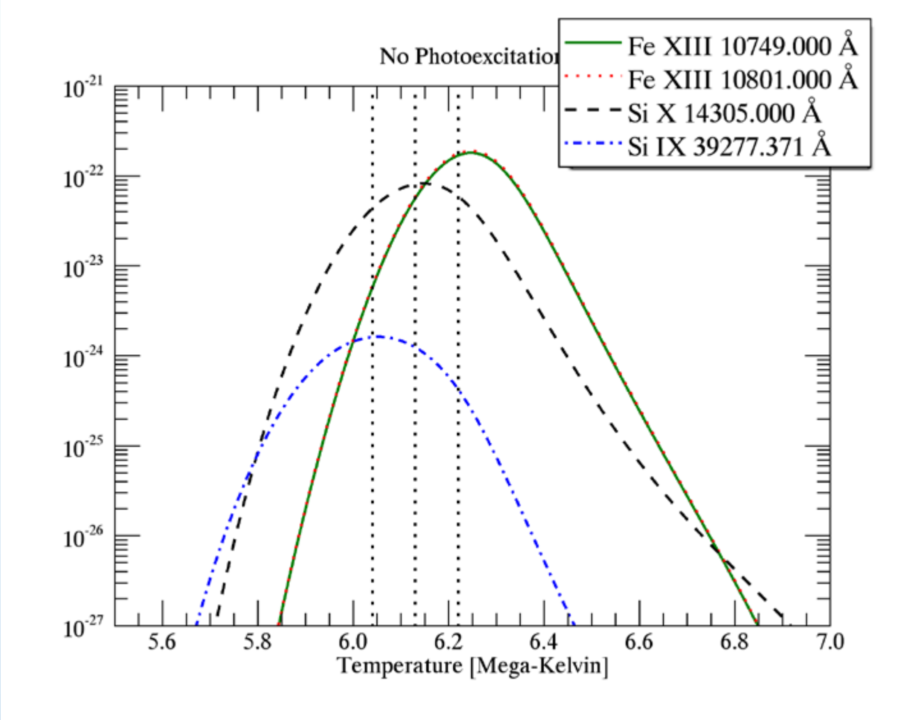


Singh, et al., 2006, *J. Astron Astr*, **27**, 115-124

+VISP rasters or sit-and-stare observations of visible coronal lines.

Contribution functions for Cryo-NIRSP first light spectral lines





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