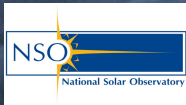




# DKIST Coronal Diagnostics + *Chromospheric Diagnostics II*

DKIST CSP Workshop  
Nagoya, Japan  
26 February 2018  
Tom Schad



# Why ground-based optical/IR observations of the corona?

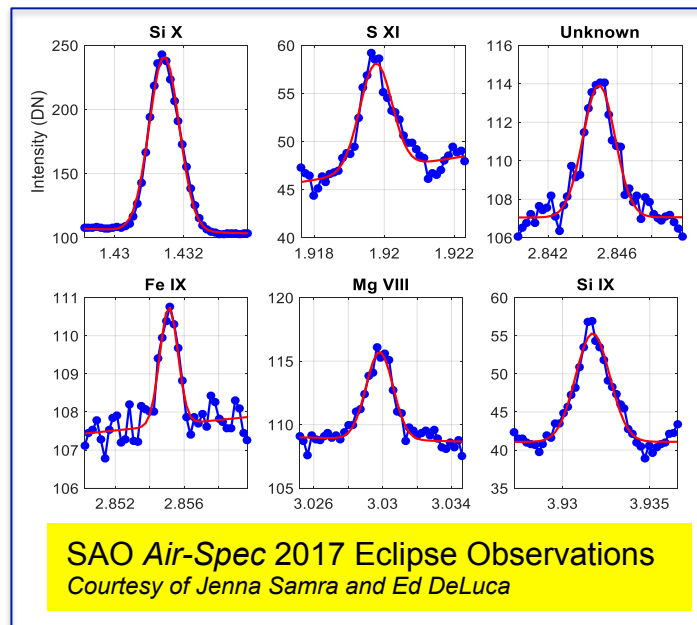
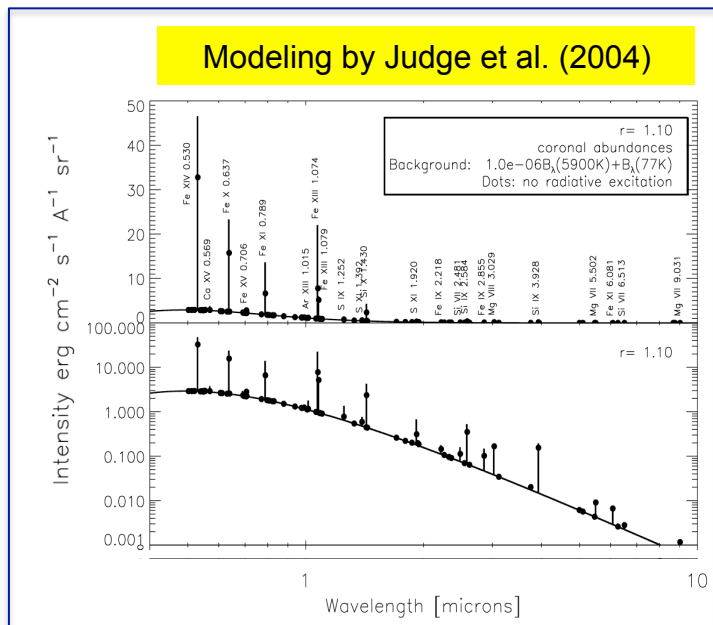
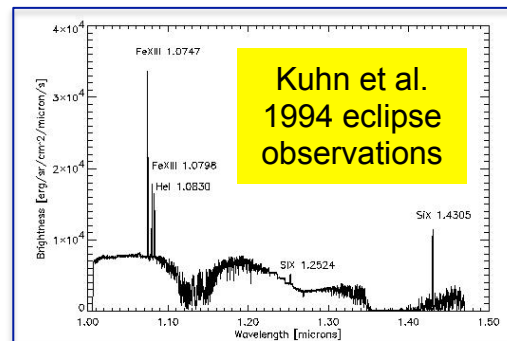
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*Following Landi, Habbal, & Tomczyk (2016) J. Geophys. Res. Space Physics, 121, 8237:*

1. **CRITICAL(!) measurements of magnetic field through Hanle AND Zeeman effects.**  
*X-ray and EUV lines do not provide this!  $B$  is small & Zeeman Effect prop. to  $\lambda^2$*
2. **Single line temperature discriminants + multi-line thermal structure diagnostics**  
*Comparable and complementary to EUV diagnostics.*
3. **High spatial/spectral resolution instruments with extended field coverage.**  
*The benefits of an EUV spectrometer combined with narrowband imaging (dynamics).*
4. **Diagnostic potential out to several solar radii due to radiative excitation.**  
*EUV diagnostics limited to  $<1.5 R_s$ . Note: DKIST pointing limited to  $<1.5 R_s$ .*

# The challenge of O/IR coronal spectral lines

- **Very weak** compared to solar disk continuum intensity  
 $\sim (1-100) : 10^6$  ----- > *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.



# 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  $\mu\text{m}$ )*

*First light instruments to 5  $\mu\text{m}$*

Minimizes scattered light by:

*Off-axis design (no beam obsuration)*

*High-grade M1 polish*

*Cleaning procedures ( $\text{CO}_2$  + washing)*

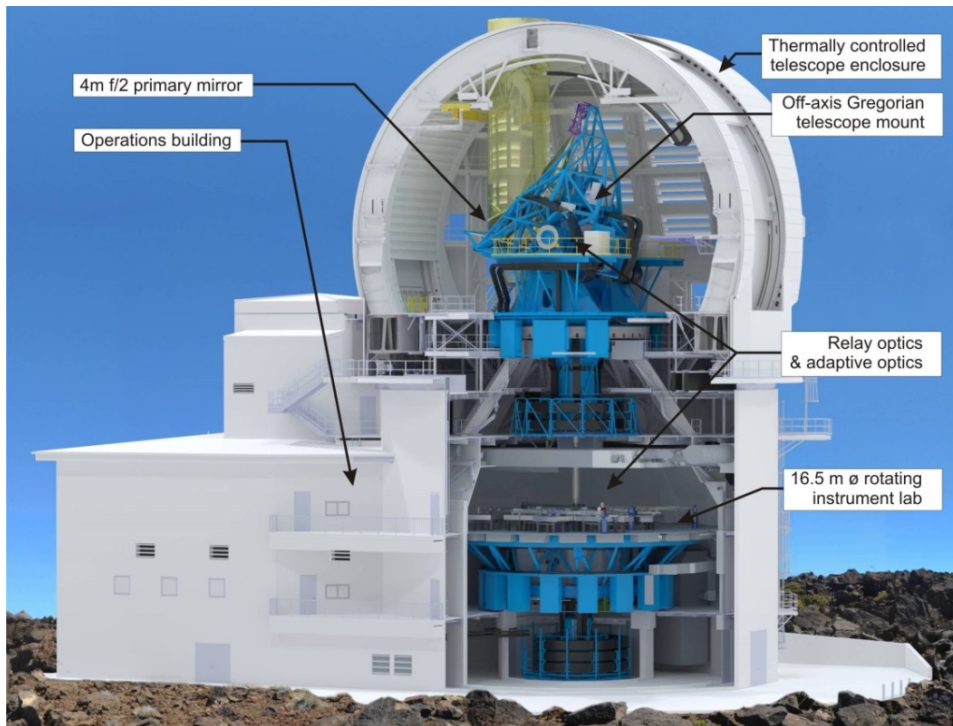
*Access to the lower scatter infrared.*

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  $\lambda 7892$  ; Log(T)  $\sim 6.13$   
Fe XIII  $\lambda 10747$  ; Log(T)  $\sim 6.22$   
Fe XIII  $\lambda 10797$  ; Log(T)  $\sim 6.22$   
He I  $\lambda 10830$  ; Log(T)  $\sim 4^*$   
Si X  $\lambda 14300$  ; Log(T)  $\sim 6.13$

### *VBI Imaging*

Fe XI  $\lambda 7892$  ; Log(T)  $\sim 6.13$

### *VISP Spectropolarimetry*

Various lines: 380 to 900 nm

## Maximum FOV: 5 arcmin

### *Cryo-NIRSP Spectropolar.*

Fe XIII  $\lambda 10747$  ; Log(T)  $\sim 6.22$   
Fe XIII  $\lambda 10797$  ; Log(T)  $\sim 6.22$   
He I  $\lambda 10830$  ; Log(T)  $\sim 4^*$   
Si X  $\lambda 14300$  ; Log(T)  $\sim 6.13$   
Si IX  $\lambda 39350$  ; Log(T)  $\sim 6.04$

### *Cryo-NIRSP Context Imager*

Fe XIII  $\lambda 10747$  ; Log(T)  $\sim 6.22$   
He I  $\lambda 10830$  ; Log(T)  $\sim 4^*$   
Si IX  $\lambda 39340$  ; Log(T)  $\sim 6.04$

# An introduction to DKIST coronal diagnostics

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1. Polarized visible/IR line formation in the corona
2. Sensitivity estimates of background-limited measurements at DKIST
3. Techniques for extracting useful diagnostics

# An introduction to DKIST coronal diagnostics

---

- 1. Polarized visible/IR line formation in the corona**
2. Sensitivity estimates of background-limited measurements at DKIST
3. Techniques for extracting useful diagnostics

# Line excitation mechanisms

- VIS/IR coronal spectral lines (unlike EUV lines) are both collisionally and radiatively excited. Using notation from Landi, Habbal, & Tomczyk (2016):

$$I_{\text{line}} = I_{\text{coll}} + I_{\text{rad}}$$

$$I_{\text{coll}} = \frac{1}{4\pi} \int_{-\infty}^{\infty} G(T, n_e) \varphi(T) dT$$

$$I_{\text{rad}} = \frac{B}{4\pi} \frac{A_{ij}}{A_{\text{tot}}} \int_{-\infty}^{\infty} N_{\text{abs}} p(\phi) F_{\text{inc}} D(v) dx$$

$$G_{ji}(T, n_e) = \frac{n_j(X^{+q})}{n(X^{+q})} \frac{n(X^{+q})}{n(X)} \frac{n(X)}{n(H)} \frac{n(H)}{n_e} \frac{A_{ji}}{n_e}$$

$$\varphi(T) = n_e^2 \frac{dx}{dT}$$

$$N_{\text{abs}} = \frac{n(X^{+q})}{n(X)} \frac{n(X)}{n(H)} \frac{n(H)}{n_e} n_e$$

Contribution function

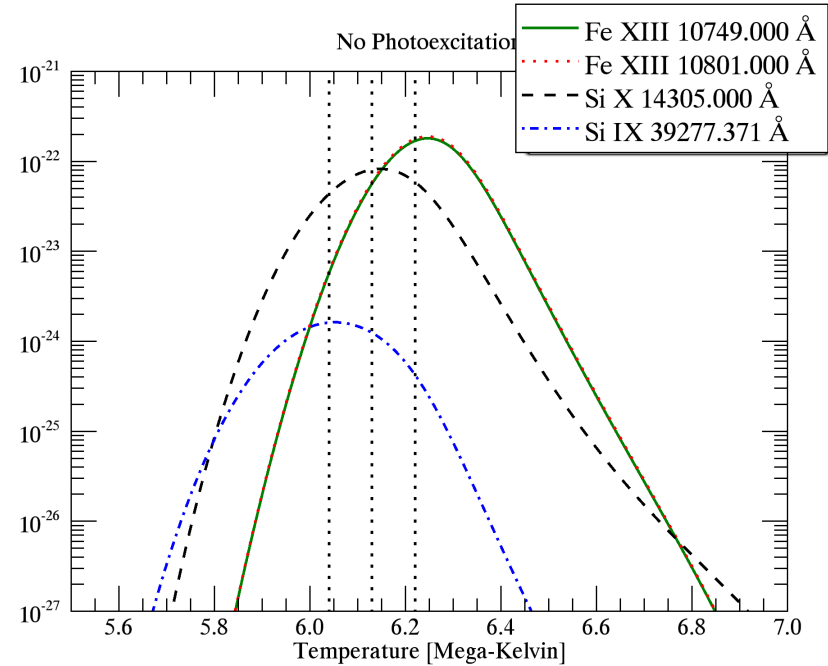
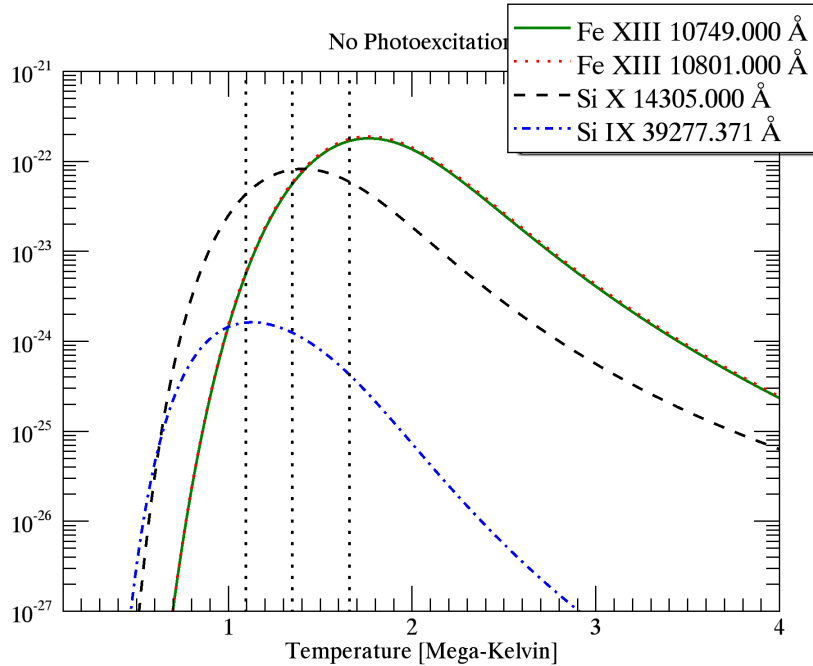
Differential Emission Measure (DEM)

Number of Absorbers

Incident radiation

- The contribution function, with corresponding level populations, can be calculated using CHIANTI, and is strongly peaked in temperature with a smaller dependence on source density.

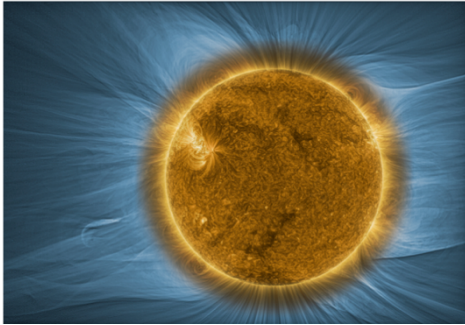
# Contribution functions for Cryo-NIRSP first light spectral lines



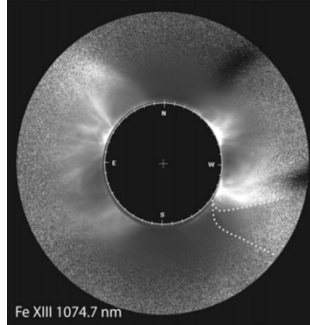
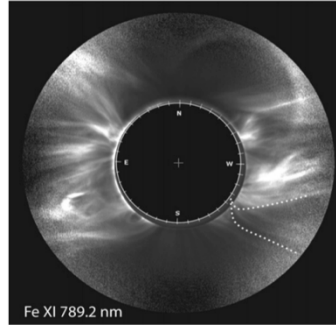
\*Generated using CHIANTI v6 using default ionization equilibrium and coronal densities.

# Consequences of the line excitation mechanisms

- $I_{\text{coll}}$  strong function of  $n_e^2$   
 $I_{\text{rad}}$  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.

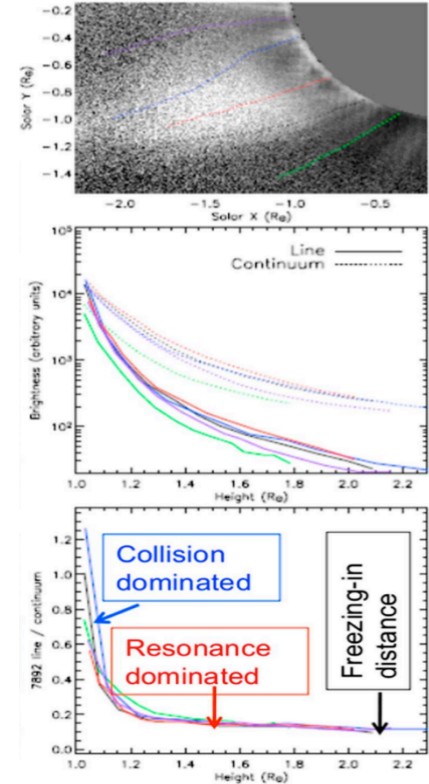


Landi, Habbal, Tomczyk (2016);  
Image credit: Karen Teramura



Habbal et al. 2011

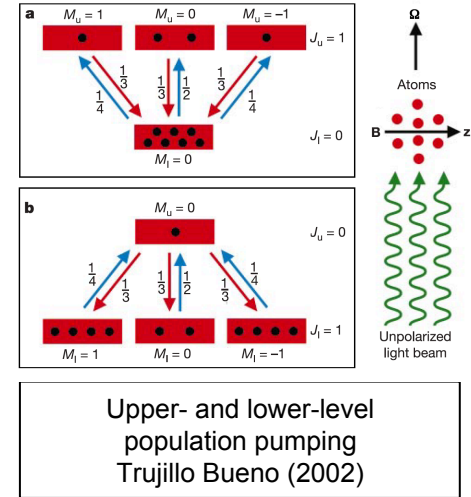
- Analysis must include radiative correction unless collisionally dominated.
- Mechanisms can be diagnosed using line to (polarized-) continuum ratios. Also helpful to pair with EUV observations.



Habbal et al. 2007

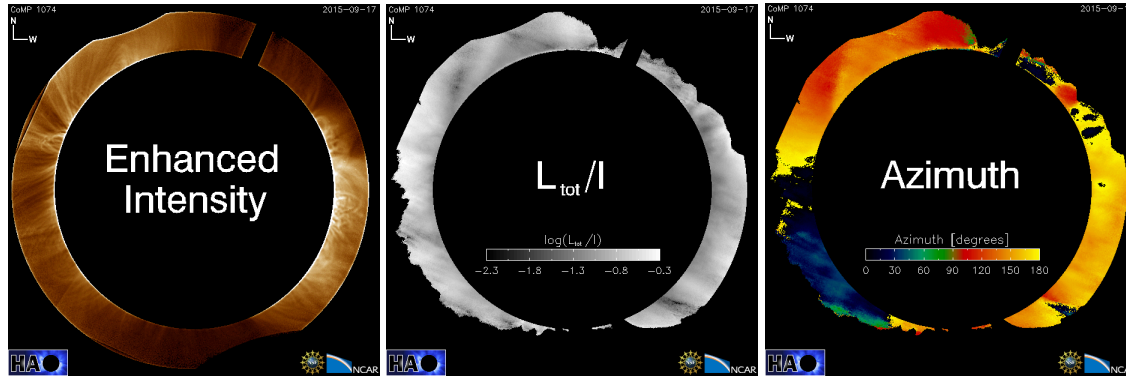
# Formation of polarized signals in coronal lines

- VIS/IR coronal lines are typically magnetic-dipole (M1) transitions with polarization generated off-limb via:
  - *Anisotropic radiative excitation leads to optical pumping effect (i.e. scattering/atomic-level polarization)*
  - *The Zeeman Effect.*
- Atomic-level population balances/coherences are modified by both the **Hanle Effect** and **Collisional Depolarization**.
- Long M1 radiative lifetimes means Hanle effect saturates (i.e. no field strength dependence) and collisions can be treated in CRD (complete redistribution -- no angular dependence).
- Zeeman splitting increases as  $\lambda^2 \rightarrow$  *major driver of infrared coronal observations!*
  - *Low field strengths of corona make transverse Zeeman signals in Q,U too weak.*
  - *Stokes V signals typically 100x weaker than atomic level polarization.*



For a complete treatment of polarized formation see  
Casini & Judge (1999)  
ApJ, 522

# Linear polarization is much easier to measure



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

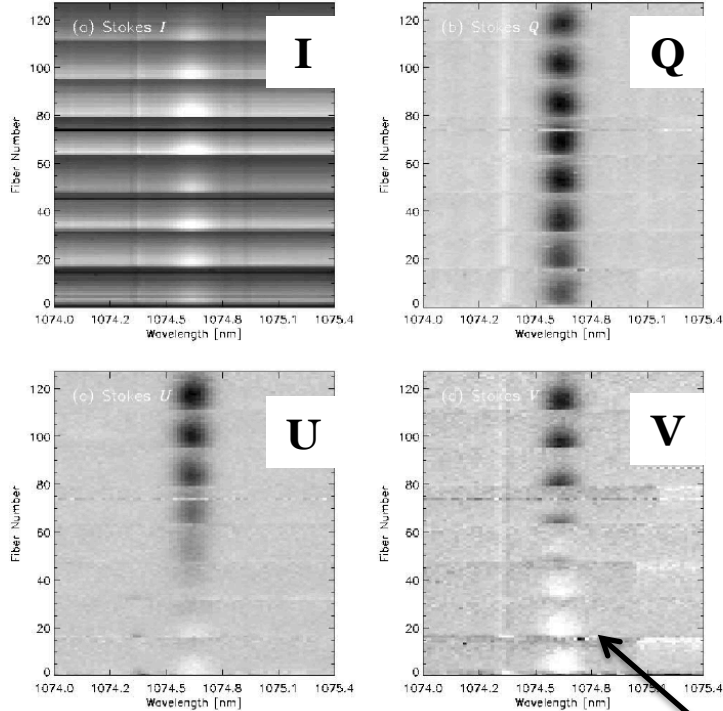
Amplitude depends on atomic orientation and requires detailed modeling to interpret.

Gibson (2017) and colleagues have shown linear polarization observations can discriminate models of coronal cavities.

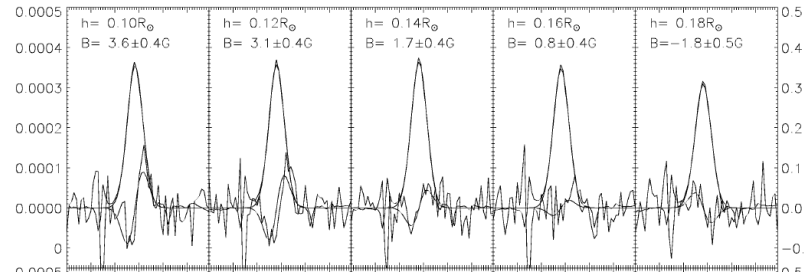
Polarization nulls and directional change in polarization azimuth relate to Van Vleck ambiguities.

# Measuring Stokes V is difficult and requires careful calibration

Fe XIII 1074.7 nm – Stokes Spectrum



Lin, Kuhn, and Coulter (2004) recover Stokes V through least squares fitting of  $I \pm V$  measurements with crosstalk.

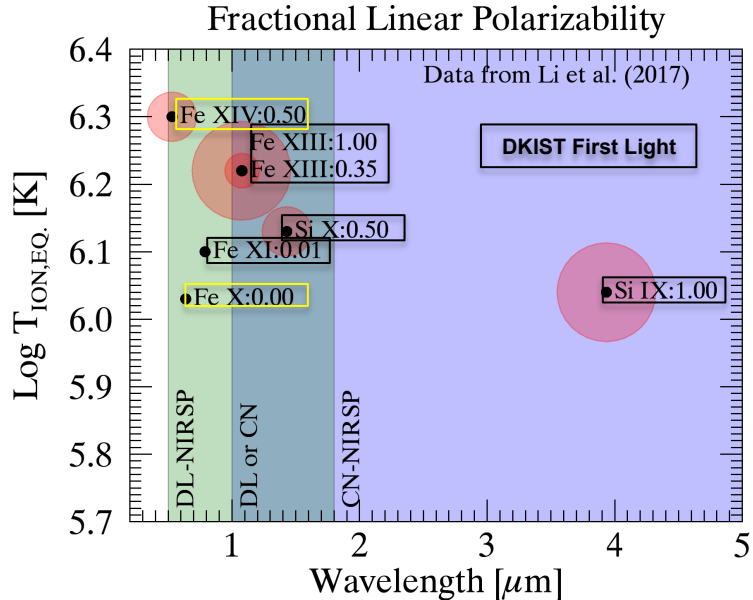
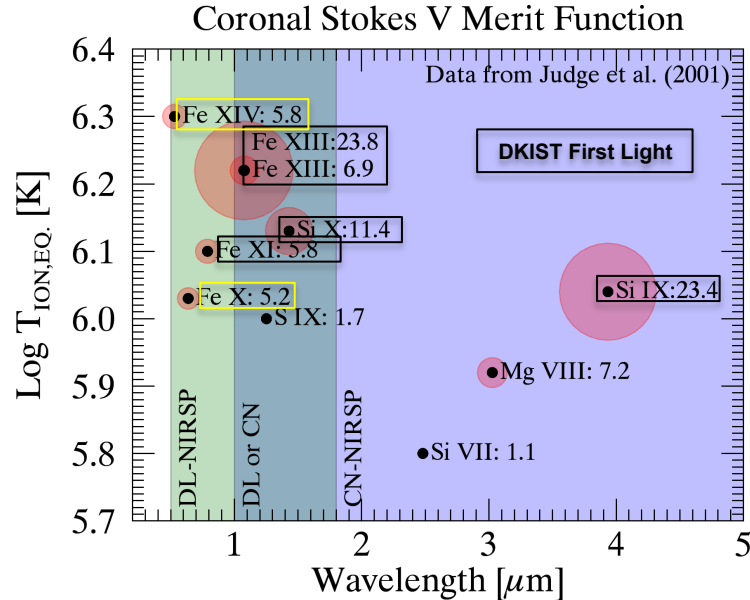


Circular polarization of spectral lines is sensitive to *longitudinal magnetic flux* ( $B \cos \Theta_B$ ).

Amplitudes of both circular polarization also depends on atomic alignment, which needs multiple lines to constrain or atomic polarization modeling.

# Relative detectability of coronal polarization

- Stokes V sensitivity: line brightness +  $\lambda^2$  Zeeman Effect [ $g_{eff}=1.5$ ] (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.
- Large differences in  $W_2(J_l, J_u)$  may provide better multi-line constraints on atomic level polarization.



# An introduction to DKIST coronal diagnostics

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1. Polarized visible/IR line formation in the corona
2. **Sensitivity estimates of background-limited measurements at DKIST**
3. Techniques for extracting useful diagnostics

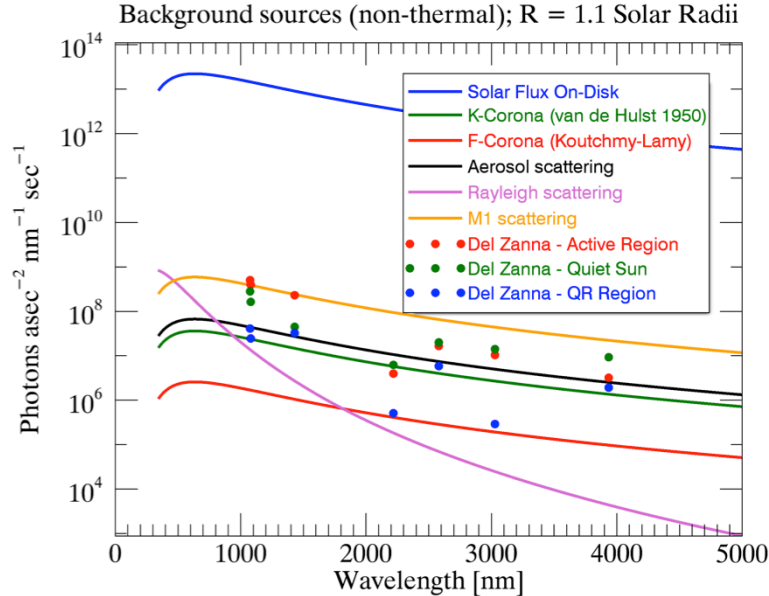
# Background-limited measurements at DKIST.

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

- Emissive-corona ( $I_{Ecor}$ ) of first-light lines typically  $> I_{Kcor} > I_{Fcor}$ 
  - Line intensities  $\approx 10^{-5}$  of the disk intensity
  - QU & V polarization of a few-10% and  $\sim 10^{-4}$  of line signal, respectively.
  - *Circular polarization is  $\approx 10^{-9}$  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  $2.5 \times 10^{-5}$  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.

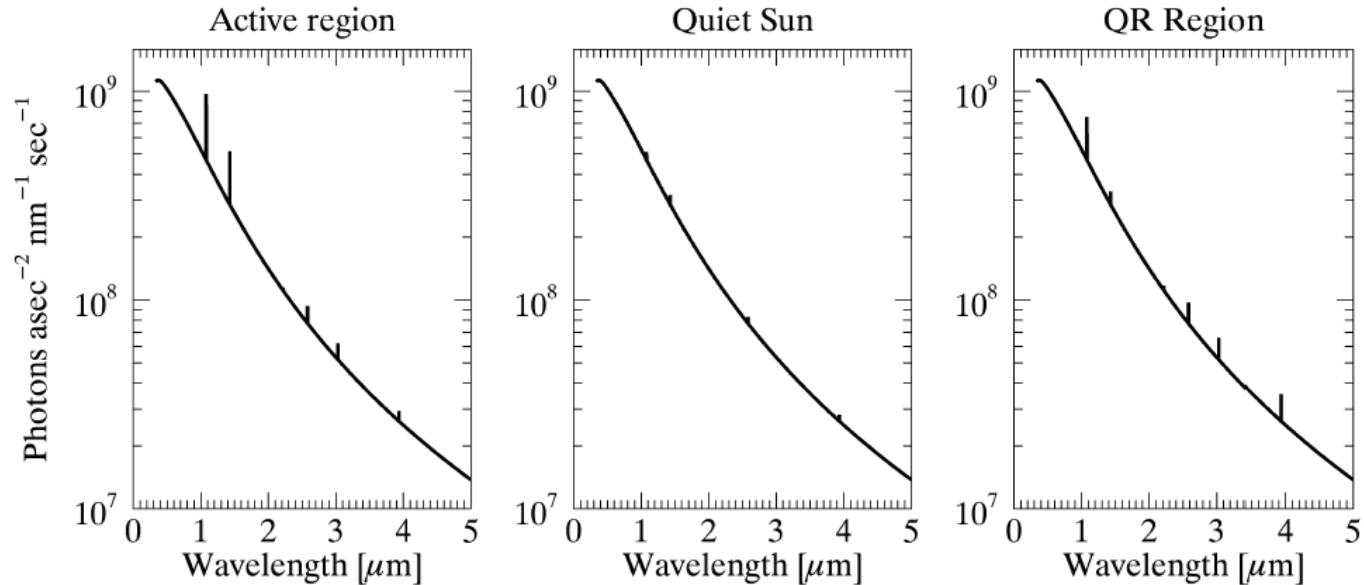
# Modeled contributions to coronal measurements



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.

# Cumulative coronal spectrum (no thermal background included)



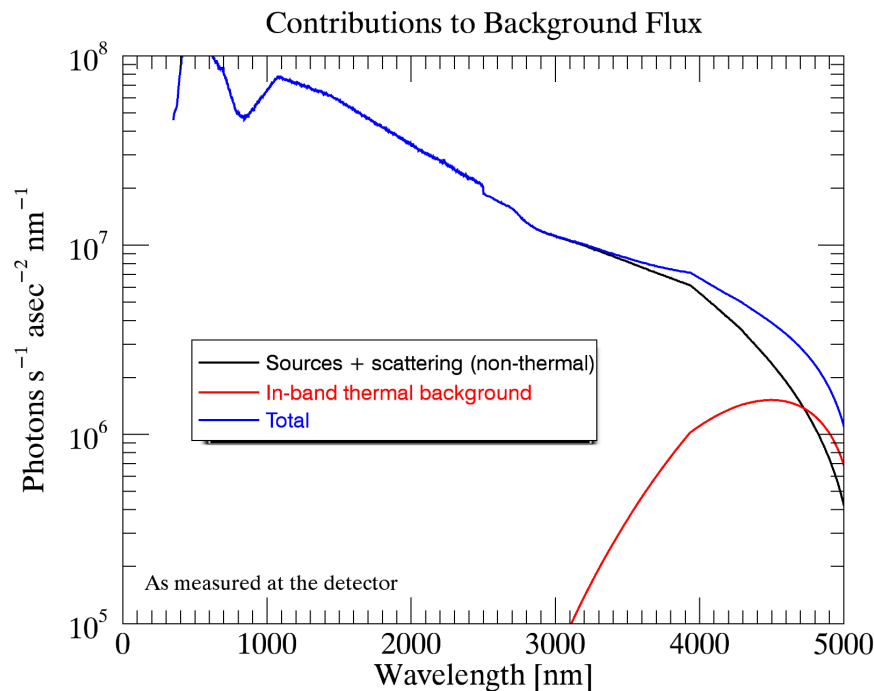
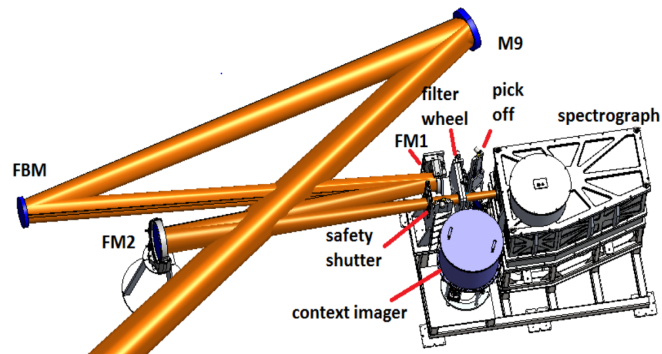
**R = 1.1 Solar Radii**

# The thermal background is non-negligible beyond ~2.5 microns

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

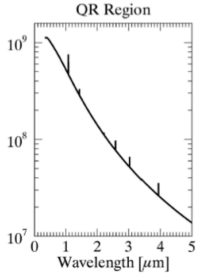
In-band thermal background is a few factors below other radiative sources at the important 3.935  $\mu\text{m}$  line.

Context imager has higher out-of-band thermal background.



# Monte-Carlo Determination of Measurement Sensitivities (Cryo-NIRSP)

Cryo-NIRSP Coronal Performance Estimates based on the <b>QUIET REGION (QR)</b> Model of Del Zanna & DeLuca (2017)								
R = 1.1 solar radii								
Background signals as specified in Figure 4 with read noise of 50 electrons per pixel.								
Spatial integration assumes 0.5" slit width and co-addition of 1" along the slit.								
Error values given for integration times of 1, 10, and 60 seconds as derived from a Monte Carlo simulation.								
Errors represent photon noise only. Calibration limitations not included.								
	Line radiance [photons cm <sup>-2</sup> sec <sup>-1</sup> asec <sup>-2</sup> ]	Inte- gration time [sec]	Integrated Intensity Error (dl/l) [percent]	Deg. of Linear Polarization Error [percent]	Line Width Error [percent]	Azimuthal Angle Error [degrees]	Doppler velocity error [m/sec]	Long. Mag. Field Error [Gauss]
<b>Fe XIII 1074.7</b>	240	1	0.09	0.19	0.13	1.05	11.8	10
		10	0.03	0.05	0.03	0.31	3.3	3
		60	0.01	0.02	0.01	0.12	1.3	2
<b>Fe XIII 1079.7</b>	140	1	0.16	0.31	0.21	1.79	19.7	16
		10	0.05	0.09	0.06	0.5	5.6	5
		60	0.02	0.03	0.02	0.2	2.2	2
<b>Si X 1430</b>	51	1	0.33	0.72	0.46	3.9	41.6	25
		10	0.09	0.19	0.13	1.07	11.7	7
		60	0.04	0.08	0.05	0.43	4.4	3
<b>Fe IX 2218</b>	11	1	1.13	3.81	1.59	59.53	146.9	57
		10	0.3	0.62	0.4	3.39	37.8	15
		60	0.12	0.24	0.16	1.34	15.2	6
<b>Si IX 2580</b>	41	1	0.32	0.7	0.46	3.85	41.8	14
		10	0.08	0.16	0.1	0.92	9.7	4
		60	0.03	0.06	0.04	0.37	4	2
<b>Mg VIII 3028</b>	34	1	0.42	1.19	0.56	15.32	51.4	14
		10	0.09	0.18	0.12	1.08	11.1	4
		60	0.04	0.07	0.05	0.42	4.5	2
<b>Si IX 3935</b>	29	1	0.38	0.74	0.5	4.2	47.6	11
		10	0.08	0.17	0.12	0.96	11.1	3
		60	0.03	0.07	0.04	0.38	4.6	1



*Photon-noise only.*

Long. Magnetic Field Error assumes weak-field approximation from single point.

Fe XIII and Si IX provides best B sensitivity.

See also Penn et al. (2004) for analytical error estimates.

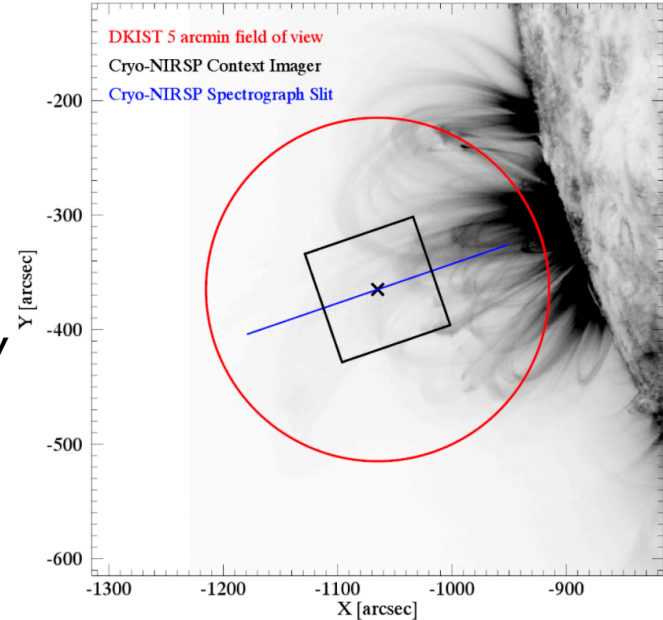
# Coronal measurements with Cryo-NIRSP

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

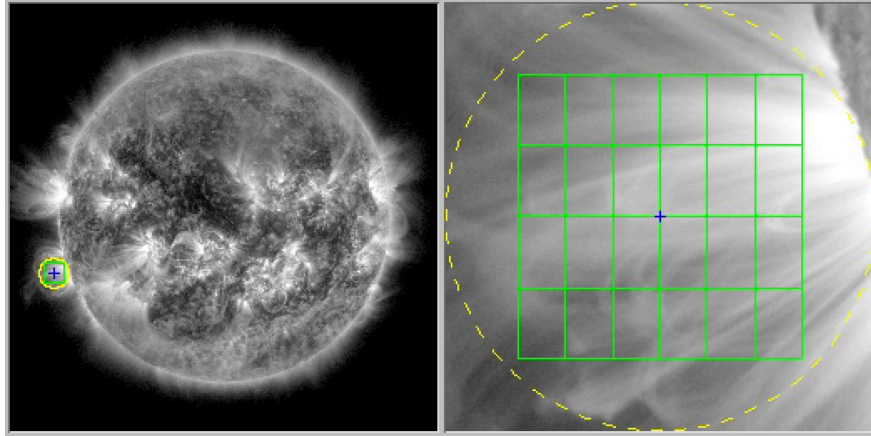
Errors will be dependent on distance from solar limb.

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.

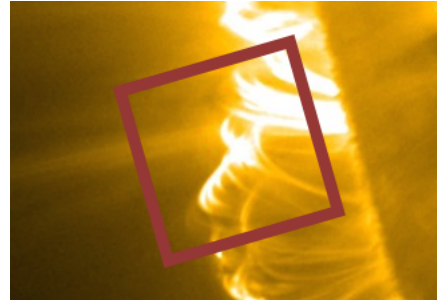


# Coronal measurements with VISP, DL-NIRSP, and VBI

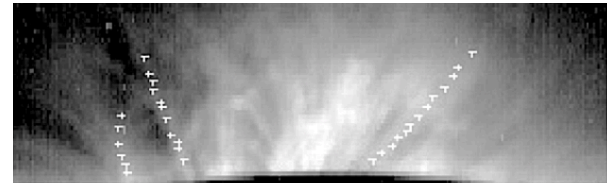
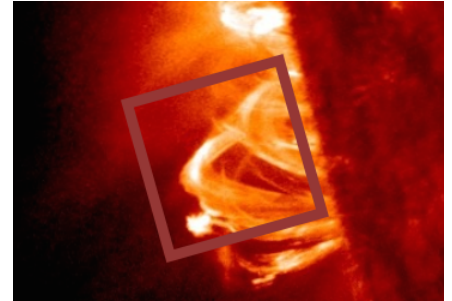


DL-NIRSP has a coarse sampling mode for coronal observations. 18" x 28" arcsec IFU coverage with multi-line coverage! Throughput less than CN.

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

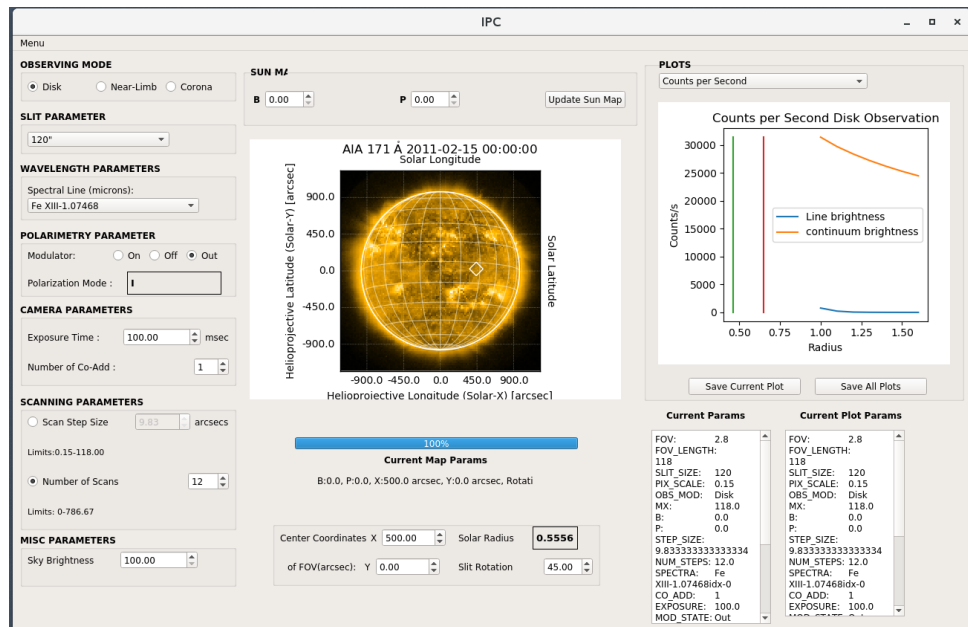


VBI imaging at Fe XI 789.2 nm and cool lines.

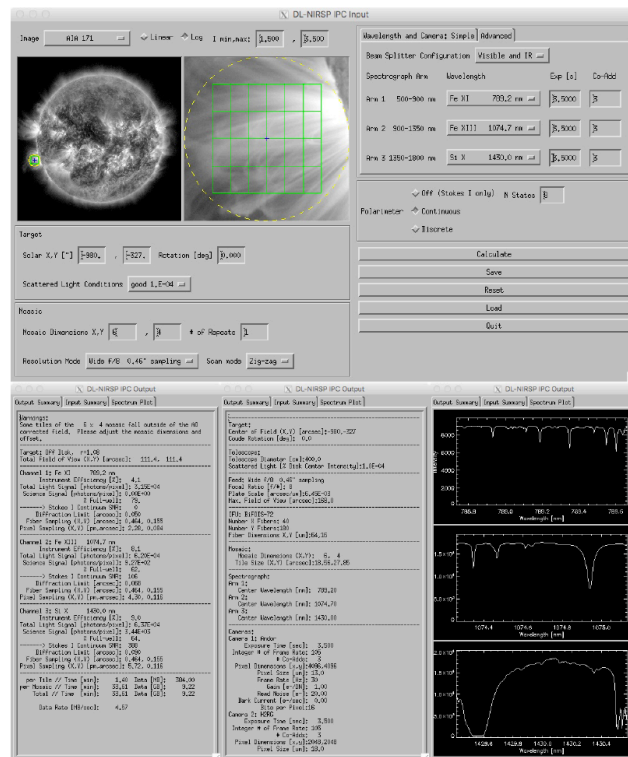


Singh, et al., 2006, *J. Astron Astr*, **27**, 115-124

# Estimates of signal-to-noise (and observable errors) by IPCs



*Cryo-NIRSP IPC – Draft Version  
Yet to be released.*



*DL-NIRSP IPC – Coronal Example*

# Understanding how to use DKIST coronal diagnostics

---

1. Polarized visible/IR line formation in the corona
2. Sensitivity estimates of background-limited measurements at DKIST
3. **Techniques for extracting useful diagnostics**

# Techniques for extracting useful diagnostics – Part 1

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## *Integrated quantities and radial dependencies:*

[see Landi, Habbal, & Tomczyk 2016; Del Zanna & DeLuca 2017]

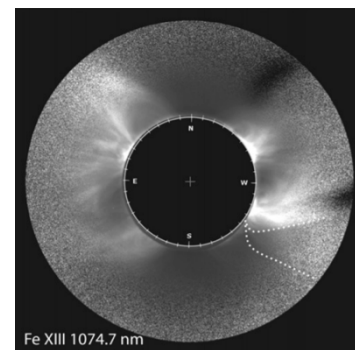
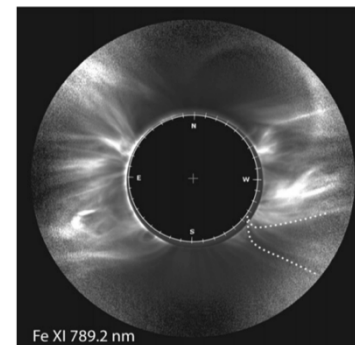
- a) **Electron density**: as function of radii distance can be related to continuum-polarized brightness
  - i) **DKIST Data** → CN or DL full Stokes spectra with source separation.
- b) **Plasma DEM,  $\Phi(T)$** : constrained by VIS/IR lines using EUV analysis techniques when collisionally dominated and coordinated with EUV diagnostics.
  - i) **DKIST Data** → VISP and DL, or CN intensity (or full Stokes) spectra.
- c) **Elemental abundances** can be derived from line ratio of two charge states from same ion in radiatively dominated regime. Good for FIP analysis, for example of the solar wind source region.
  - i) **DKIST Data** → Candidate first-light observation: Si IX 1430 nm and Si X 3935 nm. Future opportunities using only line pairs (see Del Zanna & DeLuca 2017).
- d) **Electron density**: derived from line ratio of different transition of same ion with same charge state.
  - i) **DKIST Data** → Sequential maps in Fe XIII line pair at 1074 nm and 1080 nm.
- e) **Integrated longitudinal magnetic flux**: Stokes V observation in M1 line proportional to longitudinal magnetic flux.
  - i) **DKIST Data** → CN or DL-NIRSP full Stokes spectra
- f) **Non-thermal line broadening**: Turbulence diagnostic and/or discriminant for optically thin line-of-sight integration effects.
  - i) **DKIST Data** → VISP and DL, or CN intensity (or full Stokes) spectra.

# Techniques for extracting useful diagnostics – Part 2

## *Local structure morphology, dynamics, and single-point inversions*

[see, e.g., Habbal et al. 2011; Judge, Habbal,& Landi 2013; Tomczyk et al. 2007]

- a) **Temperature distribution/morphology**: Maps of spectral line intensity in different diagnostics provide thermal tomographic imaging.
  - i) **DKIST Data** → CN or DL-NIRSP Stokes I spectral maps, CN context images, VBI 789.2 nm images.
- b) **Doppler and translational velocities of eruptions**: Simultaneous imaging with spectral scans (or fast narrow FOV scans) give 3D velocity of eruptive events.
  - i) **DKIST Data** → CN or DL-NIRSP Stokes I data cubes with CN or VBI imaging.
- c) **Doppler shift oscillations and wave propagation**: Alfvénic/MHD wave propagation previously observed in VIS/IR lines; coronal seismology diagnostic).
  - i) **DKIST Data** → CN slit or DL-NIRSP IFU Stokes I spectral data time series.
- d) **Single-point inversion of coronal magnetic field**: Isolated structures identified in Stokes I maps suggest use of single-point magnetic field inversions [see Judge, Habbal,& Landi 2013 and Plowman 2014]
  - i) **DKIST Data** → CN or DL-NIRSP Full Stokes mapped data cubes



Habbal et al. 2011

# Techniques for extracting useful diagnostics – Part 3

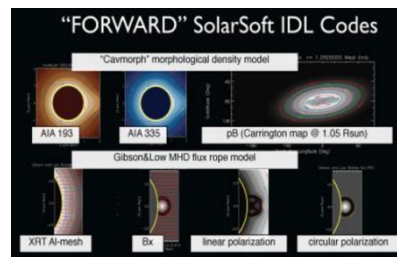
## ***FORWARD** model comparisons using synthesized observables.*

[see, e.g., Gibson et al. Frontiers, 2016; Gibson et al. 2017; Dalmasse et al. 2016]

Data/model comparison of VIS/IR polarization diagnostics offer new constraints for numerical models of the 3D magnetic field including:

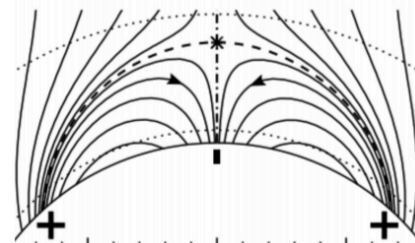
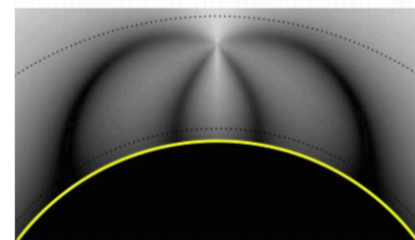
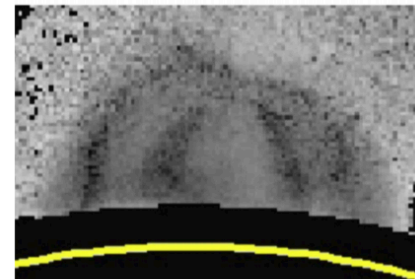
- a) **Integrated linear polarization amplitude**
- b) **Linear polarization direction in plane-of-sky**
- c) **Integrated circular polarization amplitude**

DKIST Data → CN or DL Full Stokes spectral data cubes in multiple spectral lines.



It's critical to include DKIST spectropolarimetric data as the primary magnetic model constraint within a range of coordinated EUV and VIS/IR observations.

Model-data fitting (i.e. inversions) techniques are in their infancy for coronal magnetometry. (see Dalmasse et al. 2016).



# Techniques for extracting useful diagnostics – Part 4

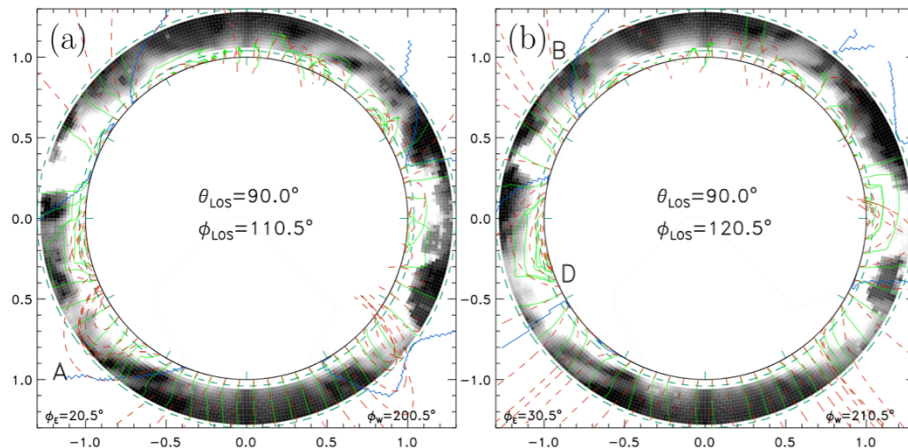
## *Tomographic inversions of coronal polarimetric data*

[see, e.g., Kramer et al. , 2006, 2013, 2016.]

Multiple polarimetric observations of the same coronal volume along multiple line-of-sights can be used to perform tomographic inversions of the full 3D coronal magnetic field.

For stable regions, time separated tomography may have some applications using DKIST data. Using COMP data, this has been done by Kramer et al. 2016 for the global corona for one spectral line.

Kramer et al. 2016



# An introduction to DKIST coronal diagnostics - summarized

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## 1. Polarized visible/IR line formation in the corona

- Collisional and radiatively excited M1 transitions.
- Polarization generated by the Zeeman Effect and resonance scattering in saturated regime.
- DKIST first light spectral lines target high Stokes V sensitivity for magnetic field measurements.

## 2. Sensitivity estimates of background-limited measurements at DKIST

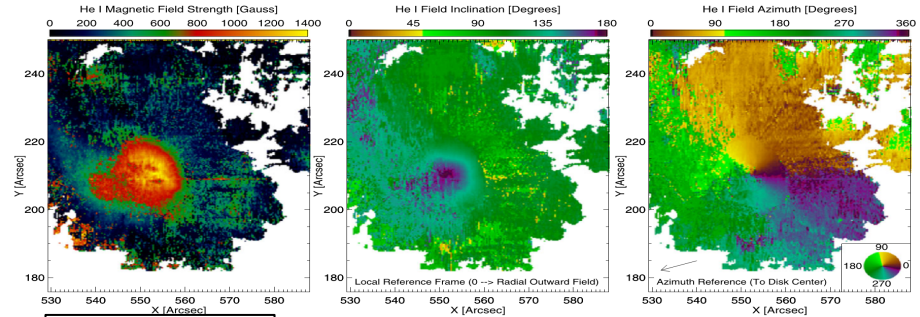
- Coronal measurements from the ground are background-limited, which is variable.
- Sensitivities based on models for background contributors and line radiances.
- Cryo-NIRSP offers brand new capabilities for coronal spectroscopy of Si IX 3.9  $\mu\text{m}$  line.

## 3. Techniques for extracting useful diagnostics

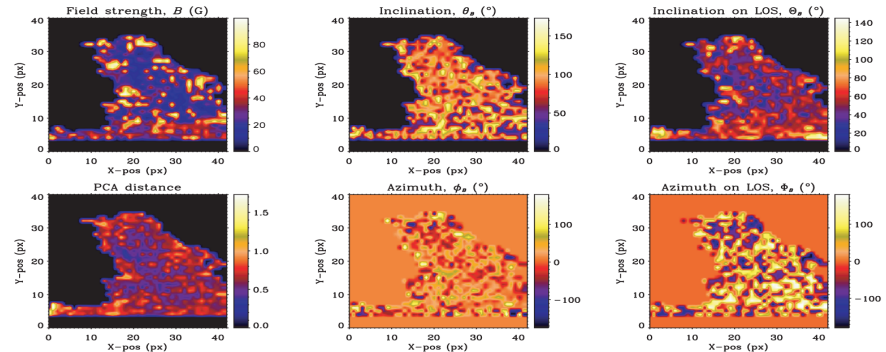
- Large range of diagnostics available.
- Need community involvement to take full advantage of this new capability!

# Chromospheric diagnostics II...towards the corona

- The He I Triplet system has well-known advantages for chromospheric polarimetry.
- Strongest transitions at 1083 nm and 587.6 nm (D3) have Hanle sensitivity up to 10 and 50 Gauss respectively.
- DKIST provides boost in sensitivity at non-diffraction limited scales.
- Useful for active region magnetic field mapping in the chromosphere as well as cool material in the corona!

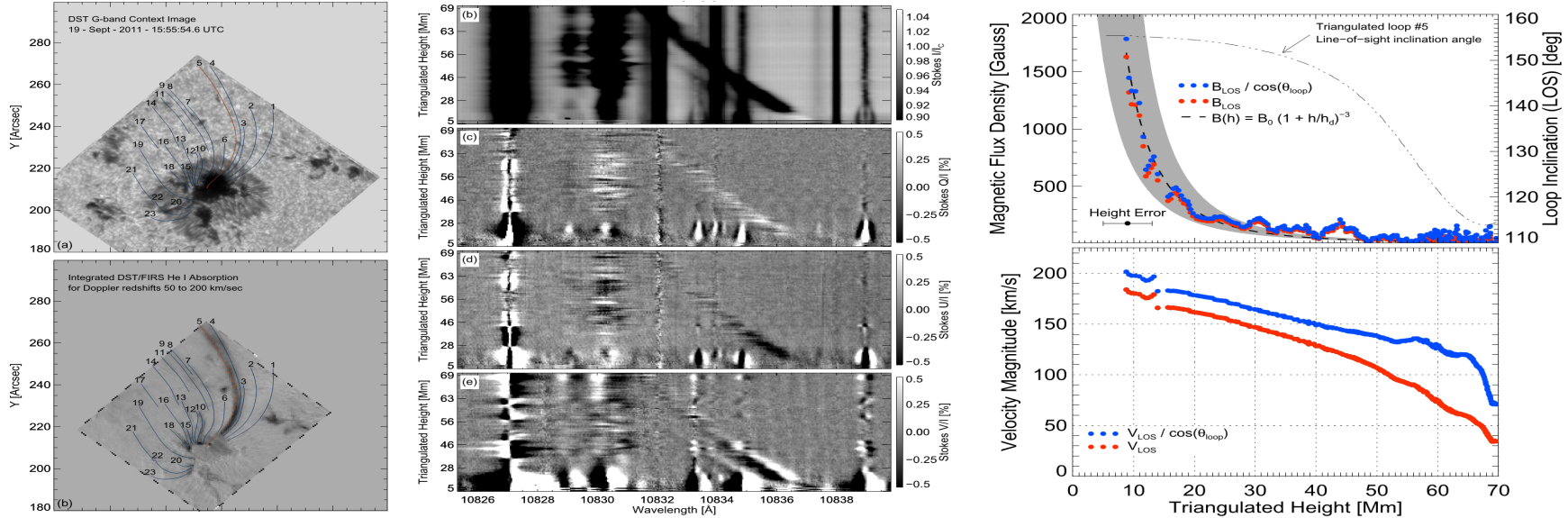


Schad et al. (2015)



Casini and Lopez-Ariste (2007)

# Chromospheric diagnostics II....towards the corona

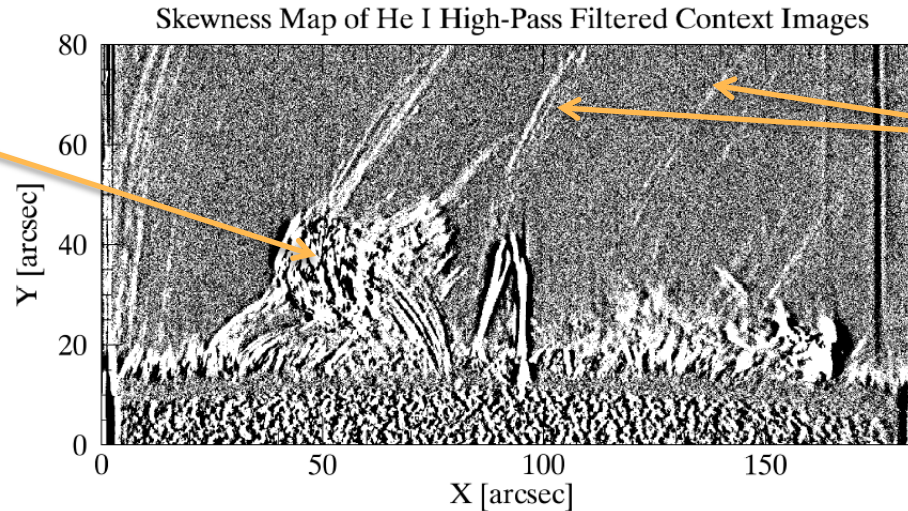


He I polarimetry of down-flowing material on disk provides vector coronal magnetic field measurements (Schad et al. 2016)

# Chromospheric diagnostics II...towards corona rain

Prominence

Exciting prospects to perform He I triplet polarimetry of coronal rain. See **CSP Use Case #50**.



He I 10830 coronal rain

# Looking forward to DKIST coronal science

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- DKIST coronal diagnostics have broad applicability and provide critical capabilities to diagnose the coronal magnetic field.
- Both measurement and interpretation is challenging. We rely on the wealth of tools already available and those to come. For example, CHIANTI and FORWARD.
- Cryo-NIRSP IPC to be available later this spring. A CSP workshop dedicated to coronal science scheduled for June 2018.
- Community involved is critical to advance these diagnostics further.

# Useful Resources on Optical/IR Coronal Diagnostics

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## References:

- Casini, R., White, S.M., Judge, P.G. (2017) *Magnetic Diagnostics of the Solar Corona: Synthesizing Optical and Radio Techniques*. Space Sci Rev, 210, 145
- Del Zanna, G., & DeLuca, E. (2017) *Solar coronal lines in the visible and infrared. A rough guide*. ARXIV.
- Gibson, S. E., Rachmeler, L. A., White, S. M., eds. (2017). *Coronal Magnetometry*. Lausanne: Frontiers Media. doi: 10.3389/978-2-88945-220-0
- Judge, P.G., Habbal, S., Landi, E. (2013) *From Forbidden Coronal Lines to Meaningful Coronal Magnetic Fields*. Solar Physics, 288, 267.
- Landi, E., Habbal, S.R., Tomczyk, S. (2016) *Coronal Plasma Diagnostics from Ground-Based Observations*. J. Geophys. Res. Space Physics, 121, 8237

## Spectral line synthesis:

- Chianti v8 (<http://www.chiantidatabase.org/>)

## Multiwavelength Coronal Forward Synthesis

- FORWARD (<https://www2.hao.ucar.edu/modeling/FORWARD-home>)  
[Gibson et al. 2016]