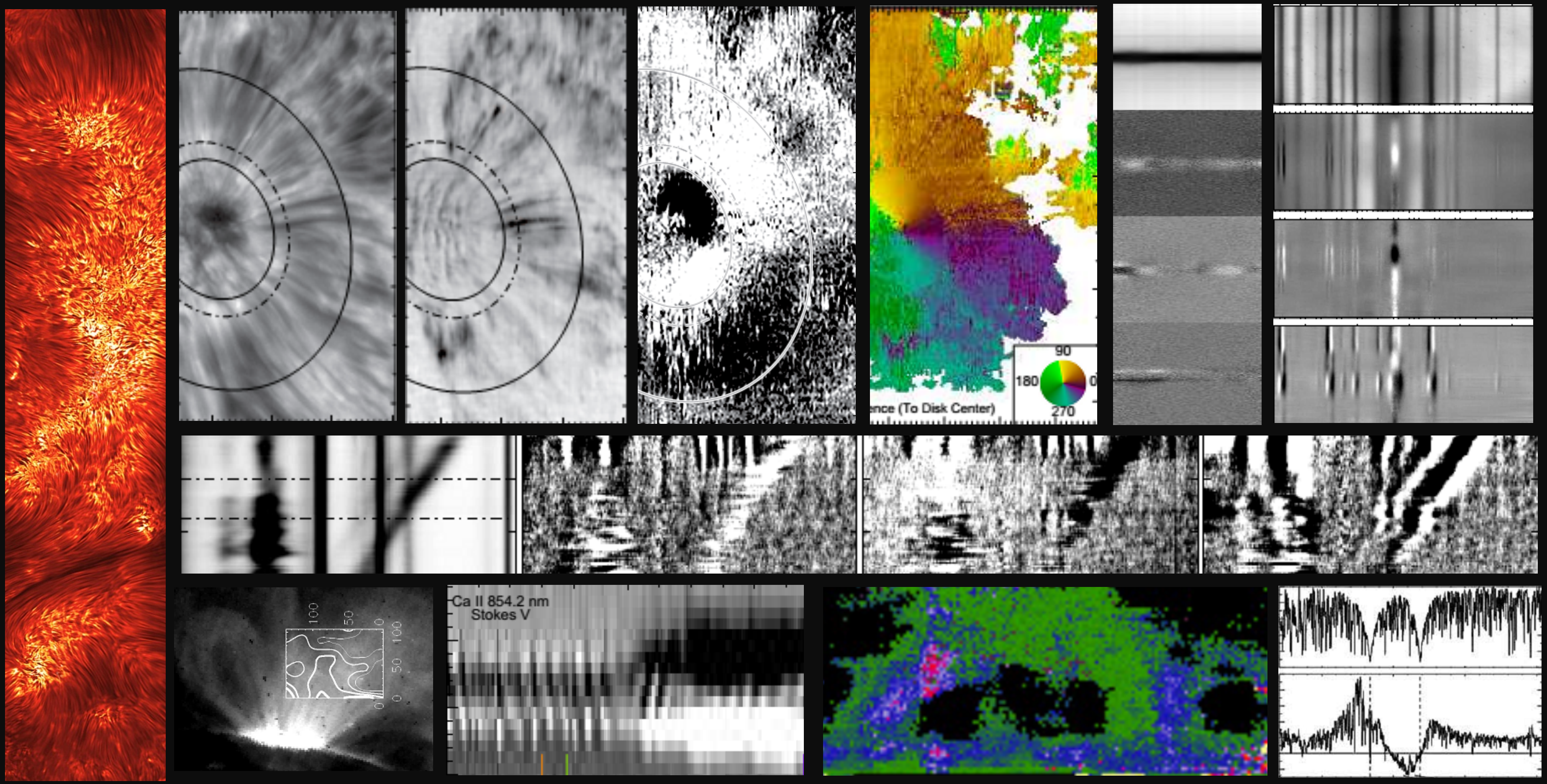


Spectropolarimetric Capabilities of DKIST: Looking Ahead to ALMA Cycle 6 and Beyond

Tom Schad
National Solar Observatory

ALMAIRISDKIST - 16 March 2016

Multi-scaled polarimetry with DKIST

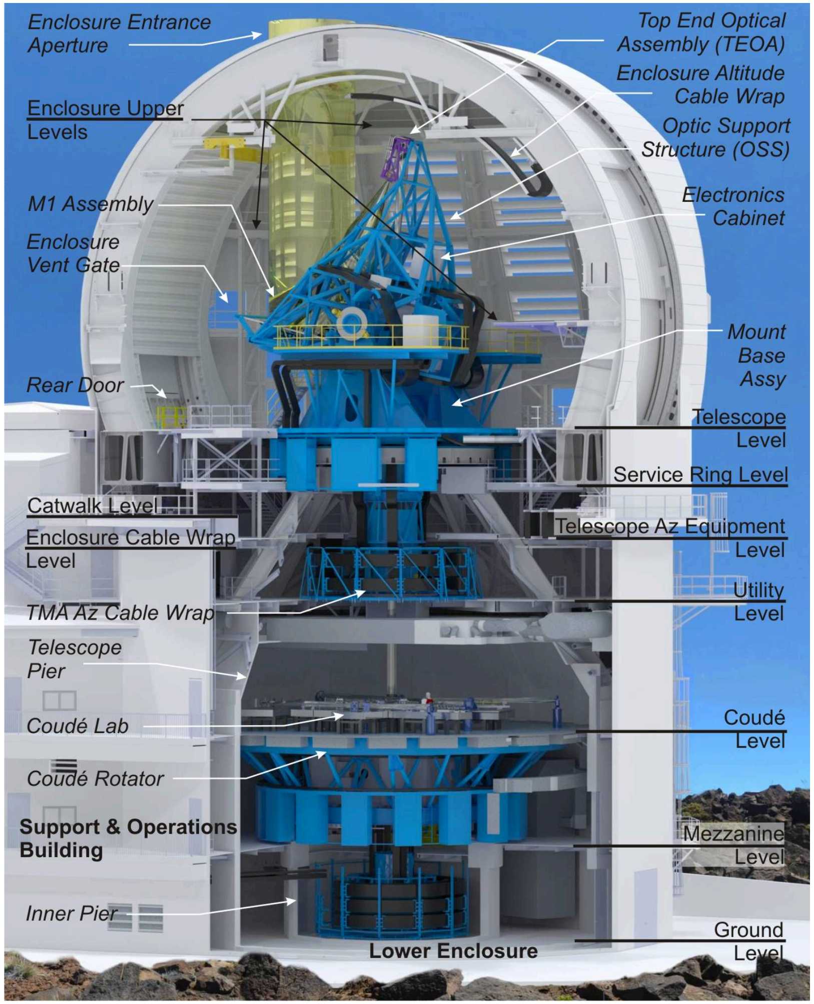
- ☐ **The Sun is a multi-scaled, dynamic object, organized in its outer layers by its magnetic field.**
  - Magnetic field intensity scales of 1000s of Gauss to ~ 1 Gauss magnitudes between the photosphere and the corona.

- ☐ **Polarization in UV/O/IR spectral lines is DKIST's primary means for the remote quantization of solar magnetic fields.**
  - Zeeman/PB effect:
    - Stokes V linearly scales with longitudinal field intensity.
    - Q/U scales with the square of transverse field intensity.
    - Zeeman sensitivity scales linearly with the wavelength (IR) and Lande factor (IR)
  - Scattering polarization and Hanle mechanism
    - Hanle sensitivity depends on ratio of level lifetime and magnetic splitting (UV).
    - Scattering polarization amplitudes depend scattering angle, the degree of local anisotropy (typically <1%) and the Hanle modification.

- ☐ **DKIST must measure magnetic fields via high precision spectropolarimetry with signals < 1% from the photosphere to the dark IR (10^{-6} B_{sun}) corona!**

DKIST High-Level Performance Requirements

Requirement	Value
Aperture	**4 meters**
Photon Flux	**Minimum collecting area > 12 m^2**
Polarization sensitivity	**10^{-5} Ic**
Polarization calibration accuracy	**5 x 10^{-4} Ic**
Scatter light (5 -50 arcsec above limb)	**< 10^{-4}**
Scattered light (1.1 Rsun; 1 micron)	**<25x10^{-6} Bsun**



Meeting the polarimetric requirements

☐ **Polychromatic crystal wave-plate polarization modulators**

- Most facility instruments equipped with polychromatic high-efficiency modulators in custom, precision rotation stages.
- Tight modulation tolerances plus high duty-cycle.

☐ **High frame rate / dual-beam polarimetry**

- Polarimeter cameras operate, in most cases, at > 30 fps to reduce the impact residual seeing uncorrected by AO.

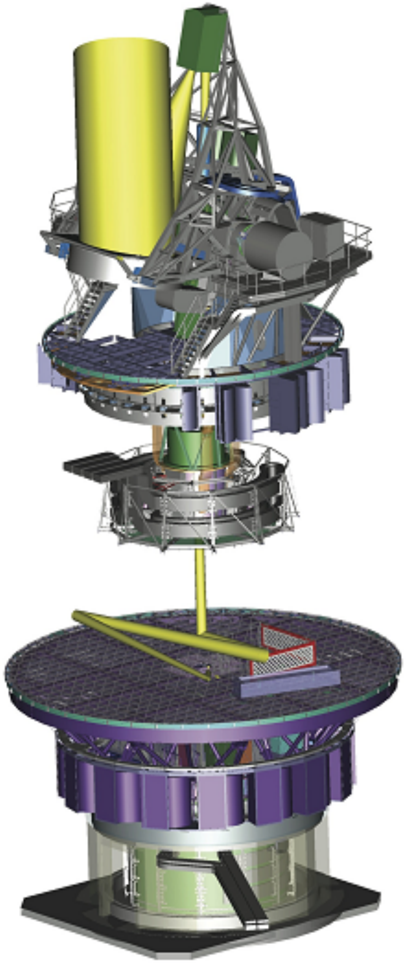
☐ **Facility polarization calibration optics and procedures**

- Large crystal optics at Gregorian focus provide polarization states for calibrating all time-dependent optics downstream.
- M1/M2 calibration baseline is to use "correlation method" based on as measured Zeeman signals in high field regions.

The O/IR chromospheric polarimetry toolbox

Spectral Lines	Formation	Tools/references
Ca II H & K	**Non-LTE; partial redistribution; Zeeman and scattering polarization diagnostic.**	[Martinez Pillet et al. 1990; Holzreuter et al. 2006]
Ca I 422.67 nm	**Non-LTE; partial redistribution**	
Hα (656.3 nm)	**Non-LTE; Large photospheric contributions in Stokes V**	[Socas-Navarro & Uitenbroek 2004; Stepan & Trujillo Bueno 2010[
He I D_3 (587.6 nm)	**Non-LTE; Very weak on disk; good prominence and filament diagnostic**	Inversions: Hazel [Asensio Ramos et al.]; Helix+ [Lagg et al.]
Ca II IRT (849.8, 854.2, 866.2 nm)	**Non-LTE; 1D inversions show promise.**	Inversions with Nicole [Socas-Navarro et al.]
He I (1083 nm)	**Non-LTE; Promising upper chromosphere diagnostic. Weak outside of active regions**	Inversions: Hazel [Asensio Ramos et al.]; Helix+ [Lagg et al.]
Ca I 3697.4 nm	**g_{eff} = 1.1**	
Mg I 3681.6 nm	**g_{eff} = 1.17**	
IR molecular lines? CO?		

DKIST – The User Perspective



☐ **Flexible and controlled operation for optimized study of diverse science**

- 5 permanently-installed facility instruments ranging 350 nm to 5 µm
- Diverse technologies: narrowband imaging (Visible to 5 um!) , Slit-based spectropolarimetry; Fabry-Perot 2D-spectropolarimetry; IFU spectropolarimetry
- Manually configurable distribution of light to AO-instruments (350 nm to 1800 nm)
- Simultaneously multi-instrument experiments

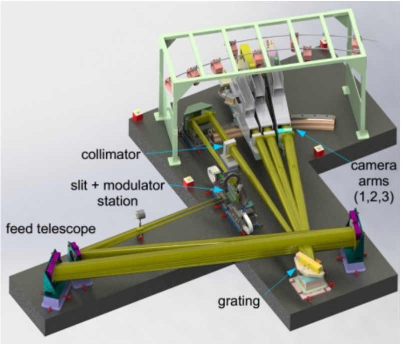
☐ **Operational model to boost ground-based efficiency**

- Majority in PI based service mode
  - Merit **and** condition-based mode.
- Data will be public domain (embargo available for graduate student data)
- Calibrated data sets will be the primary data product of the NSO Data Center.

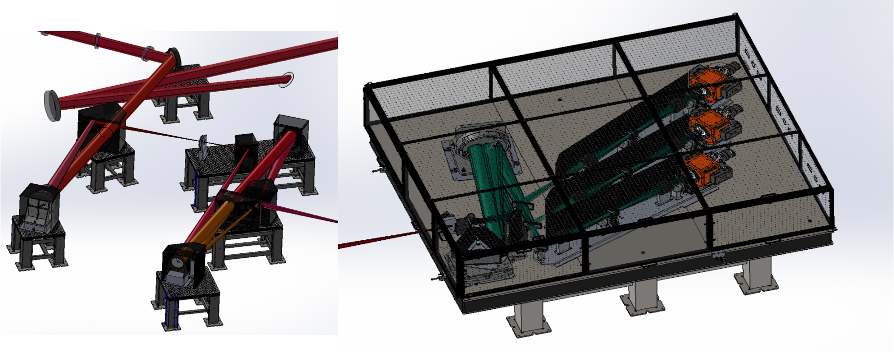
☐ **Early Science operations start in 2019!**

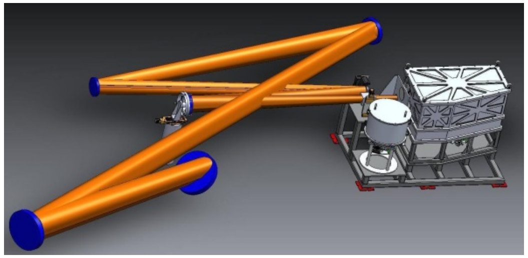
DKIST Instrumentation

VISP: 500 – 900 nm
Three channel
Slit-based
Spectropolarimeter



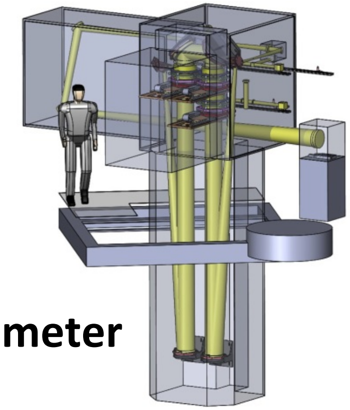
DL-NIRSP: 500 – 1800 nm
Three Channel IFU Spectropolarimeter



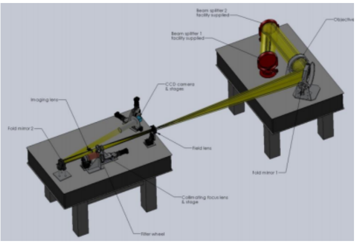


CRYO-NIRSP:
1000 – 5000 nm
Filter Imager + Slit-Based
Spectropolarimeter

VTF:
520-870 nm
Dual-Fabry
Perot 2D
Spectropolarimeter



VBI: 390 – 860 nm
Two-channel
Narrowband
(Speckle) Imager



More detailed specifications at **dkist.nso.edu/science/**

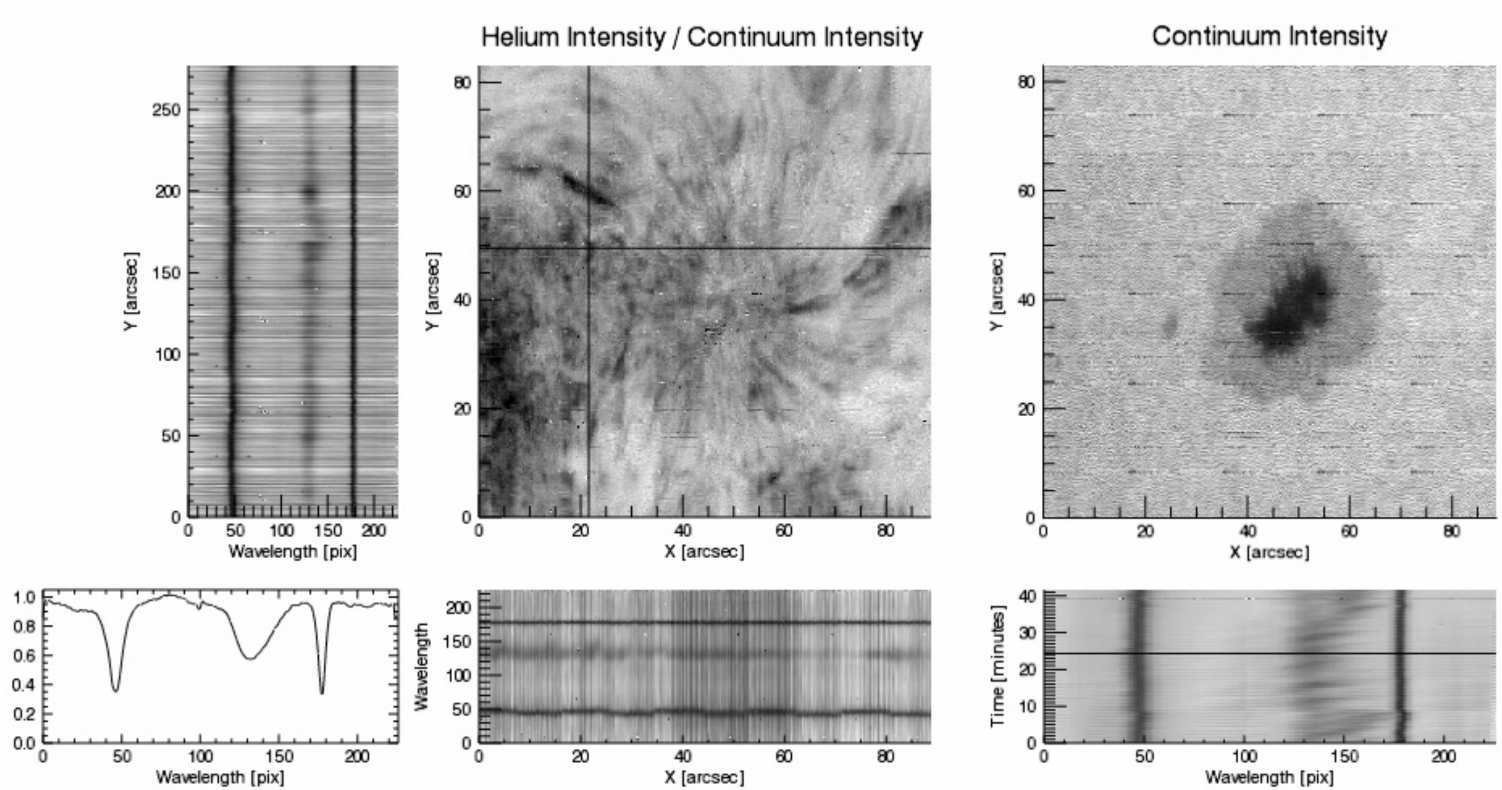
DL-NIRSP

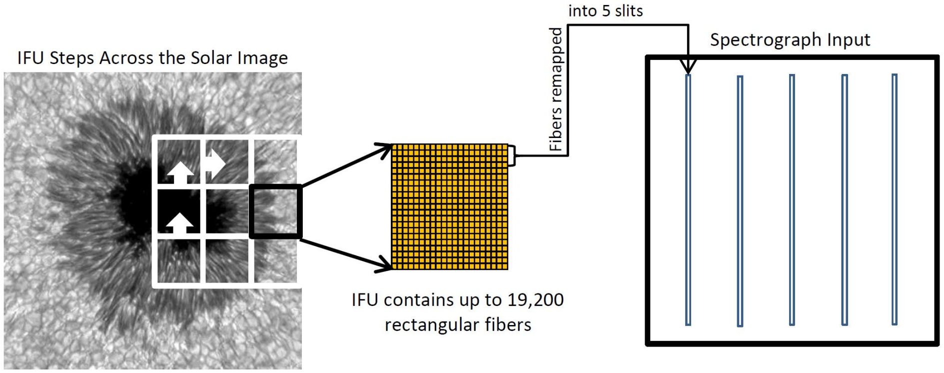
An IFU-based Spectropolarimeter for Solar Physics.

Two IFUs of different physical pixel sizes.

60 x 80 format
60 x 40 format

0.03'', 0.077'', 0.46''



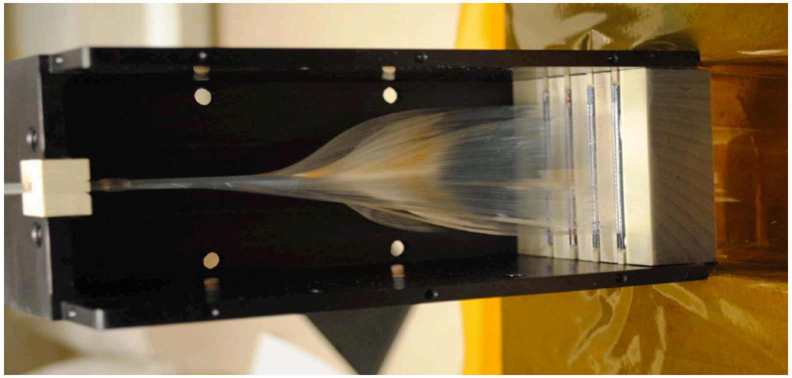

IFU Steps Across the Solar Image

Fibers remapped

into 5 slits

Spectrograph Input

IFU contains up to 19,200 rectangular fibers



One tile at a time, DL-NIRSP builds spectropolarimetric full data cubes: [X ; Y ; λ ; S [=I,Q,U,V] ; t]

Assessing polarimetric performance in the chromosphere

- ☐ The photon flux at the diffraction-limit is independent of aperture size. A bigger telescope doesn’t alleviate being photon starved at the diffraction limit.
- ☐ Balance evolution time-scale with required signal to noise to arrive at physical scale over which the observation can be considered static…

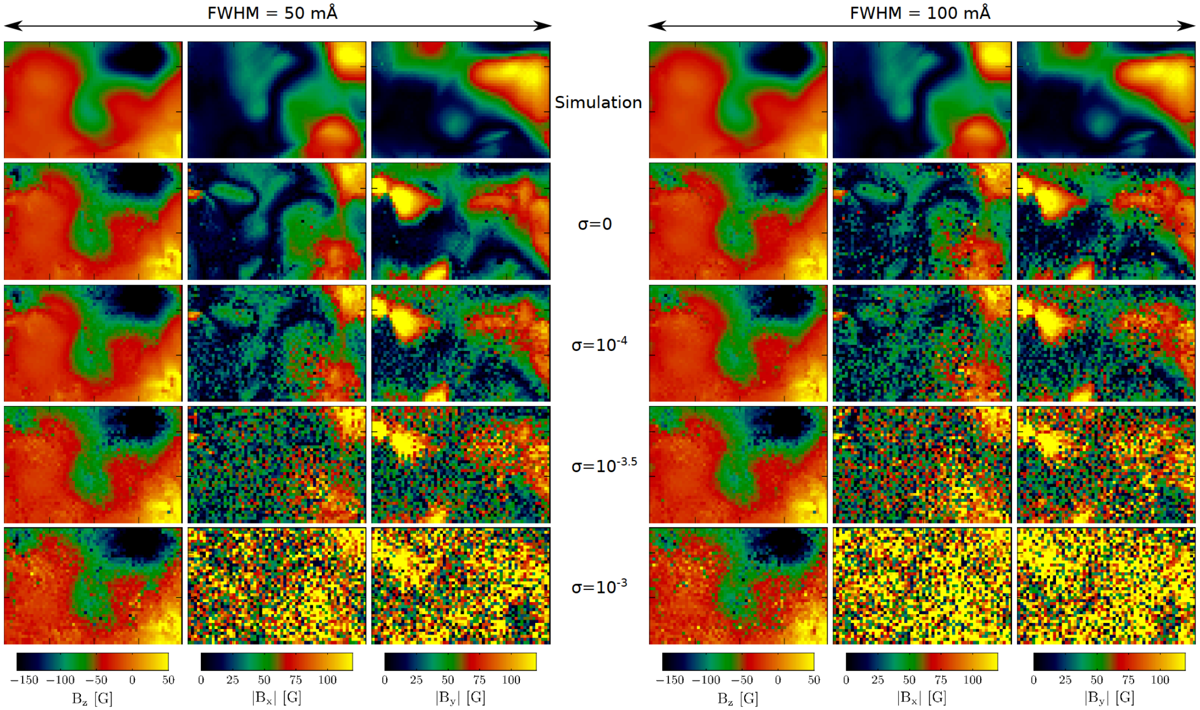
$$\Delta t_s = \frac{n}{0.577 * F(\lambda, \delta\lambda, \delta t, \delta x)\sigma^2(\delta x)^2}$$

$$\Delta t_e = \frac{2(\delta x)}{v} \qquad \delta x = \frac{(nv)^{1/3}}{2(0.577 * F(\lambda, \delta\lambda, \delta t, \delta x))^{1/3}\sigma^{2/3}}$$

- ☐ How to determine values for v and \sigma ?

Forward modeling by de la Cruz Rodriguez et al. (2012):

Quiet Sun magnetism returned via an inversion of Ca II 854.2 nm



Example DKIST parameters:

n = 1
$\sigma = 10^{-4}$
v ~ 50 km/s
50 mA FWHM
F ~ 3.7e9 photons/asec^2/sec

$$\delta x = \frac{(nv)^{1/3}}{2(0.577 * F(\lambda, \delta\lambda, \delta t, \delta x))^{1/3}\sigma^{2/3}}$$

(δx) ~ 0.074 arcsec
(δt) ~ 2.13 seconds
Diffraction limit: 0.054

→ ***effective resolution for DL-NIRSP /or ViSP***

Linear polarization outside of sunspots is very weak in Ca II 854.2 nm

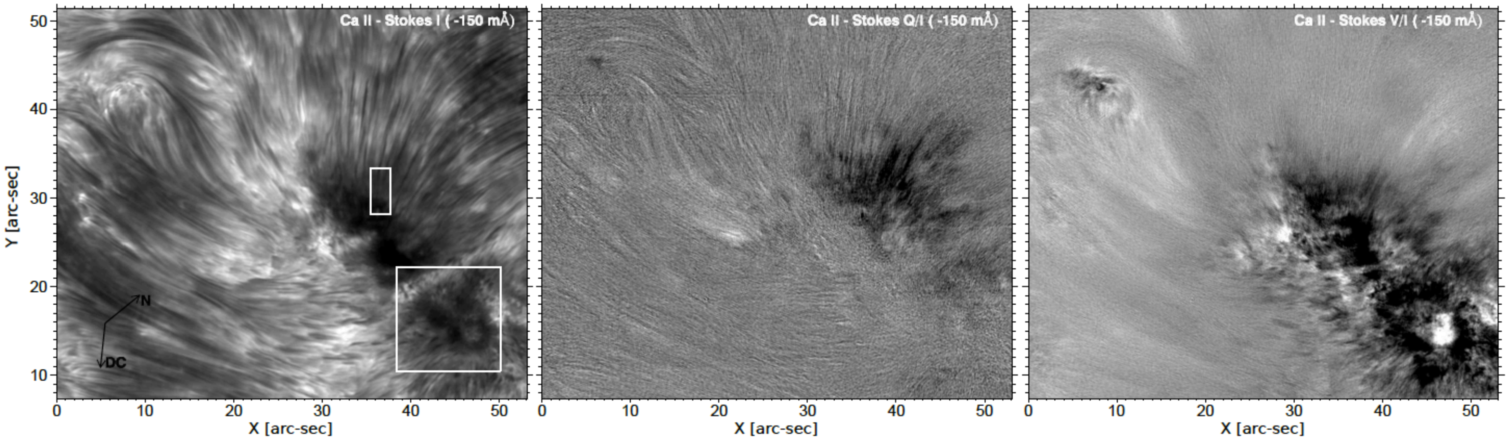
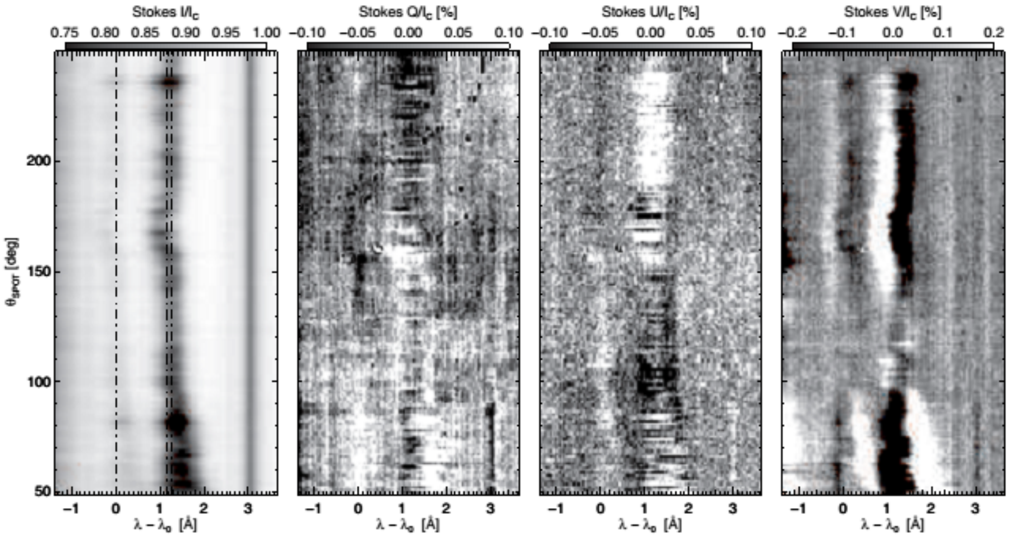
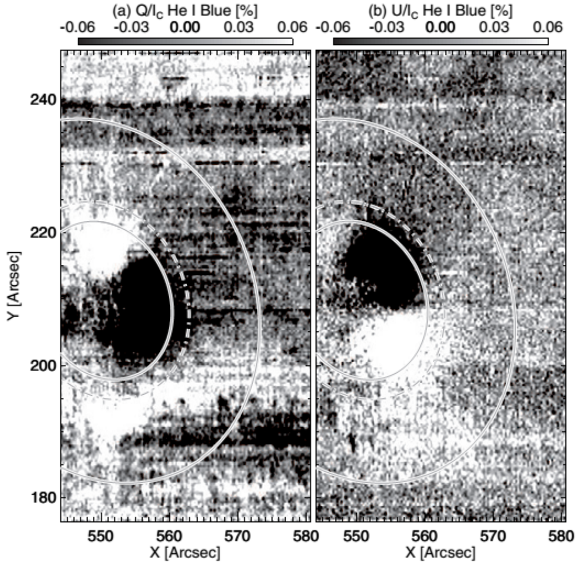


Fig. 15 CRISP Stokes I, Q/I, and V/I filtergrams at $\Delta\lambda = -150$ mÅ from the core of the Ca II 854.2 nm line (adapted from de la Cruz Rodríguez et al. 2013). The boxes mark the regions for which a detailed analysis of umbral flashes and running penumbral waves was performed.

He I 1083 has strong scattering polarizations profiles in superpenumbra

Schad et al. (2013)





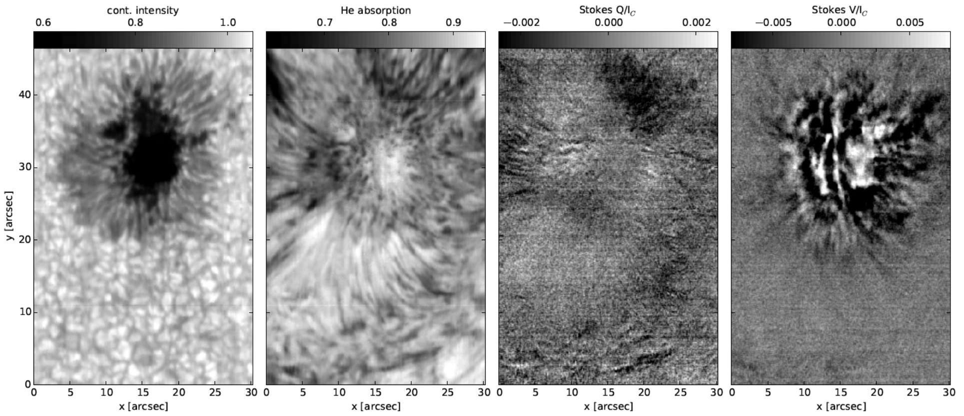
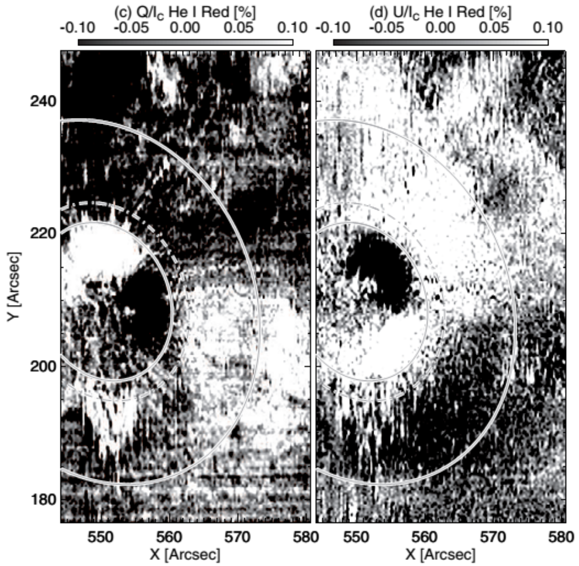
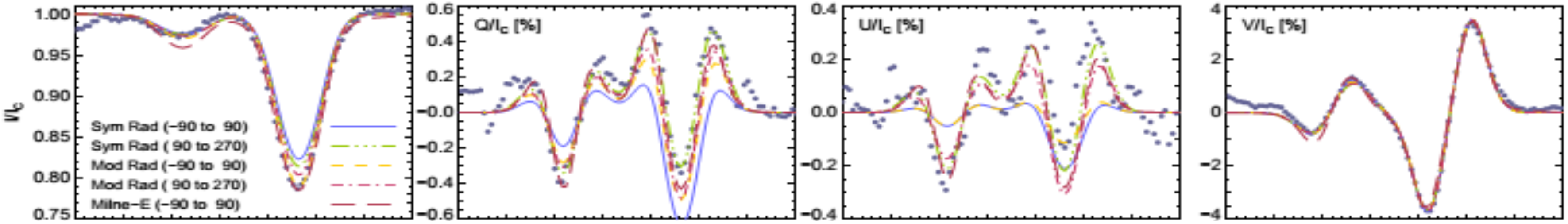
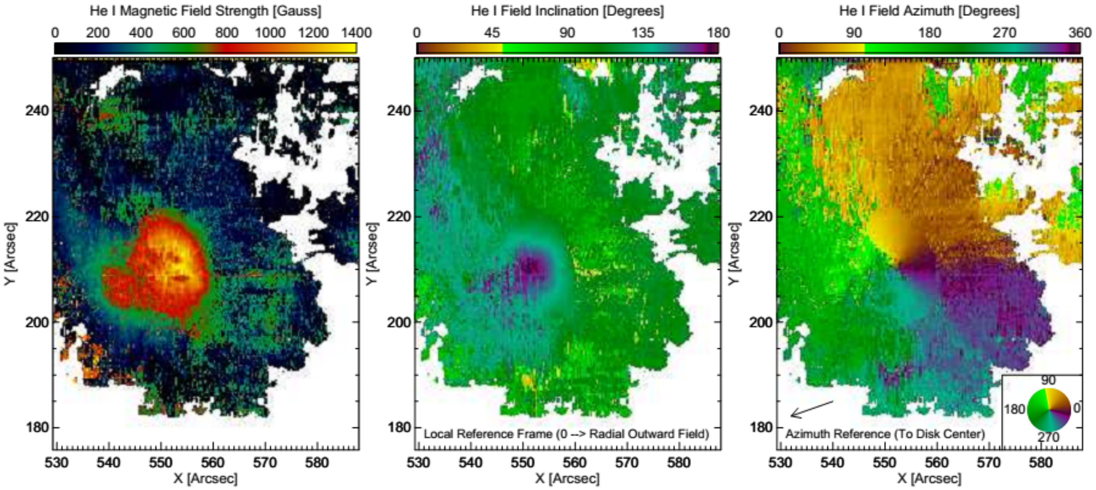
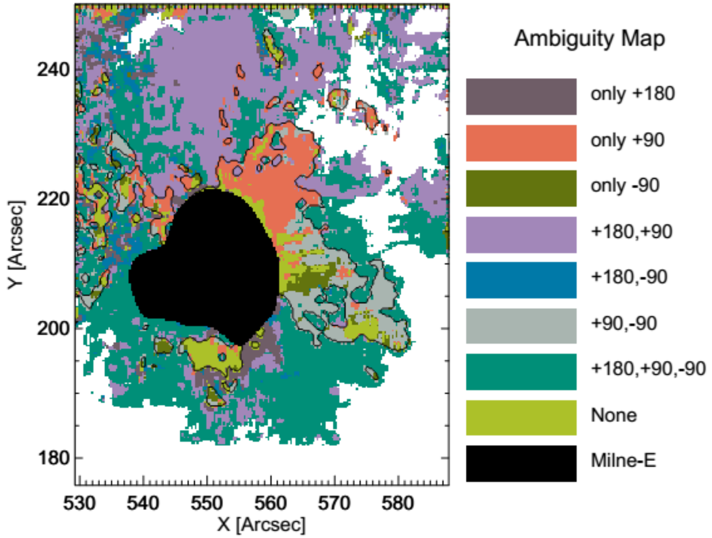


Fig. 14 Continuum image and He I 1083 nm Stokes I, Q, and V maps of AR 12096 obtained with GREGOR/GRIS on June 27 2014 close to disk center ($\mu = 0.98$). The achieved spatial resolution is 0.44″ at a spectral resolution of 200 000. The total exposure time of 1.6 s per slit position for the full Stokes vector (without readout and processing time) resulted in a noise level of 7–10×10^{-4} of the continuum intensity.





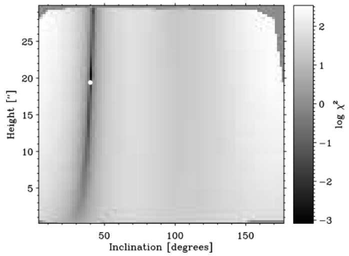




He I 1083 can be inverted with simple cloud models (non-LTE polarization)

Challenges include presence of ambiguities, lack of height information, height vs inclination degenerencies.

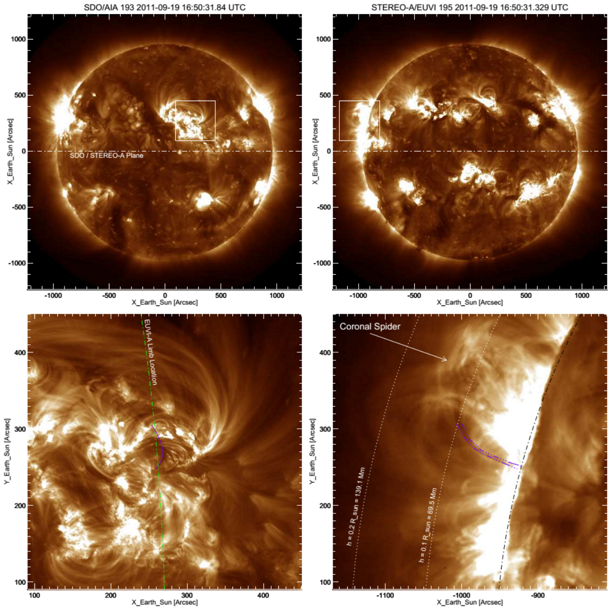
Umbral profiles are not well modeled.

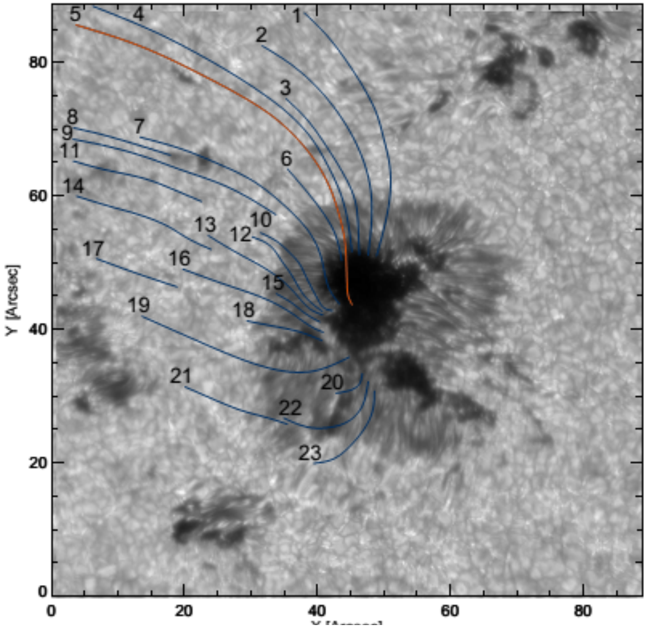


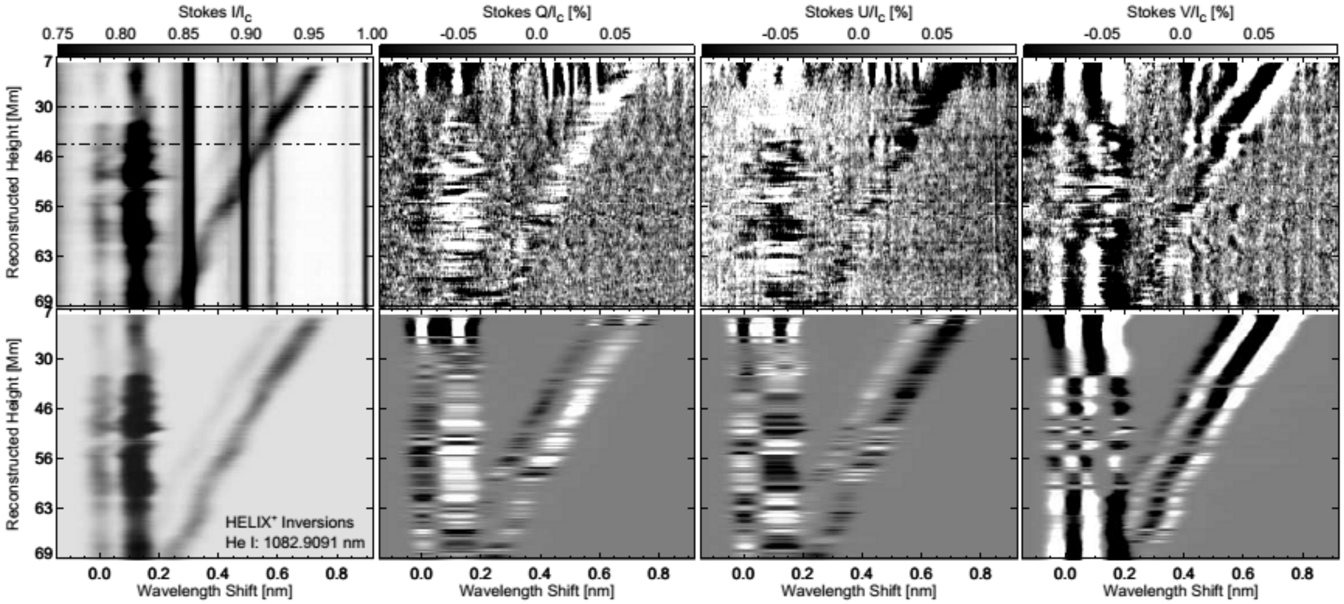
DST/FIRS
He I 1083 nm

(Like D3, used for prominences and filaments: e.g., Kuckein et al. 2012)

This example is of on disk coronal rain polarimetry + Stereoscopic reconstruction







ALMA/DKIST Joint Observing Strategies

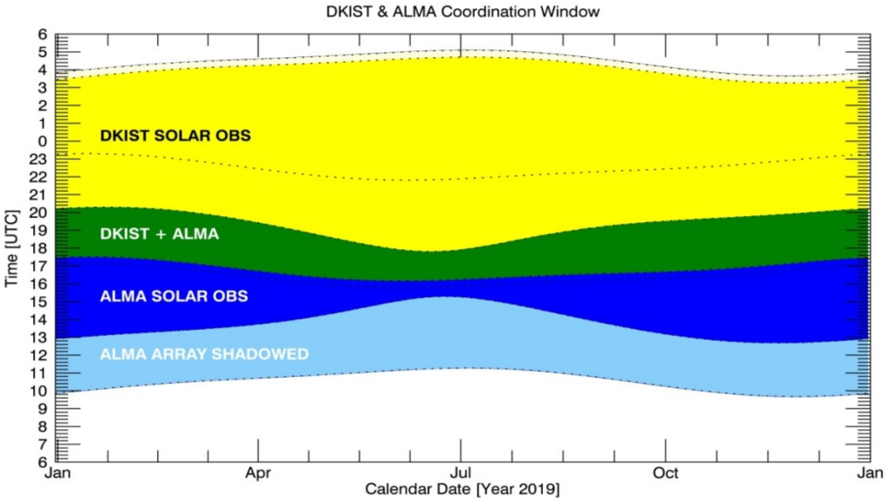
ALMA configurations (C40-1,-2,-3) [**SSALMON CYCLE 4 Document**]:

C40-1: Longest baseline (160.7 m)
C40-2: Longest baseline (376.9 m)
C40-3: Longest baseline (538.9 m)

Tight configurations require Sun at elevations > 40 degrees to avoid shadowing.

DKIST opening procedures and light level will limit observation ~ > 7 deg

1 to 2 hours of coordinated observing time is possible



Wedemeyer et al. (2015) SSRv

DKIST/ALMA coordination – an example

ID	**INT-1**
Name	**FAST**
Description	**high-cadence single-point sit-and-stare**
Pointings	1
Temporal resolution/ cadence	**2 s** *per map*
Duration	**60 min (default)** *Many science cases request shorter sequences but could use INT-1 data, too.*
Receiver band *(as requested for the science cases)*	• **only 3:** H2, J1 • **only 6:** G3, G6, G7, G8 • **first 3, then 6:** default.
Target	Versatile *(see comments in table below)*.
Science cases	G1-G8, H2, J1, J2, L4
Number	12

ID	**INT-1**
Name	**FAST**
0:00	Array + receiver setup **Band 3**
0:05	Initial calibration **Band 3**
0:30	Calibration Band 3
0:35	**Science Band 3** cadence 2 s 180 maps
0:40	Calibration Band 3
0:45	**Science Band 3** cadence 2 s 180 maps
0:50	Calibration Band 3
0:55	**Science Band 3** cadence 2 s 180 maps
1:00	Calibration Band 3
1:05	**Science Band 3** cadence 2 s 180 maps
1:10	Calibration Band 3
1:15	**Science Band 3** cadence 2 s 180 maps
1:20	…

Switch to Band 6 and repeat

What is a complementary polarimetry-focused DKIST **Experiment?**

Step #1: Define science objectives….

Step #2: Identify candidate spectral lines and data types...

Step #3: Assess feasibility

1) Light distribution (beam-splitter) tool
2) Aggregate data rates *(using standard modes)*
3) Instrument performance calculators (*define observing parameters…FOV, slit size, etc.)*

… once successful

Step #4: Prepare and submit proposal

DKIST/ALMA coordination – an example

ID	**INT-1**
Name	**FAST**
Description	**high-cadence single-point sit-and-stare**
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Temporal resolution/ cadence	**2 s** *per map*
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Target	Versatile *(see comments in table below).*
Science cases	G1-G8, H2, J1, J2, L4
Number	12

Beam-splitters: [BS_555,WI_002,BS_680,MI_002]

Data Type	Instrument	Line	FOV	Spatial Res	Cadence	SNR	Data rates
2D spectroscopic imaging	**VTF**	Hα 656.3 nm	58″ x 58″	0.028″ x 0.028″	3.6	> 850	1920 MB/sec
Slit scanning full-Stokes polarimetry	**VISP**	Ca II K 393 nm	21″ x 60″	0.21″ x 0.06″	35 minutes	> 300 (**)	27 MB/sec
		Ca I 422.67 nm	21″ x 60″	0.21″ x 0.06″	35 minutes	> 700 (**)	27 MB/sec
		Fe I 525 nm	21″ x 60″	0.21″ x 0.06″	35 minutes	> 1400 (**)	27 MB/sec
IFU Full-Stokes spectropolarimetry	**DL-NIRSP**	Ca II 854.2 nm	23″ x 25″	0.15″	23 sec	>2000 (5 x 10^-4)	55 MB/sec
		Si 1082.7 nm / He I 1083 nm	23″ x 25″	0.15″	23 sec	>2000 (5 x 10^-4)	55 MB/sec
		Fe I 1565 nm	23″ x 25″	0.15″	23 sec	>2000 5 x 10^-4	55 MB/sec

**** Lower bound on performance? (TBD)**

Aggregate data rate: 2166 MB/sec

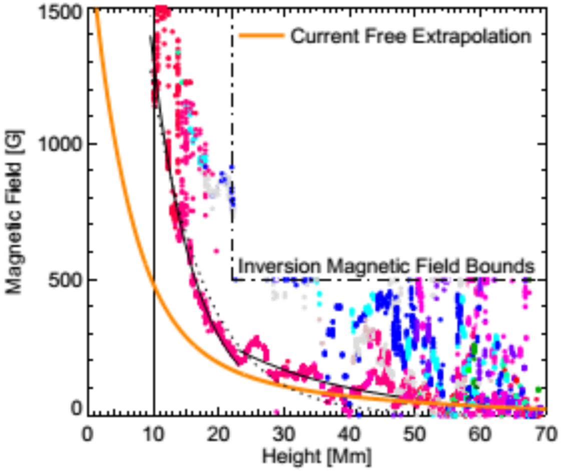
Closing remarks

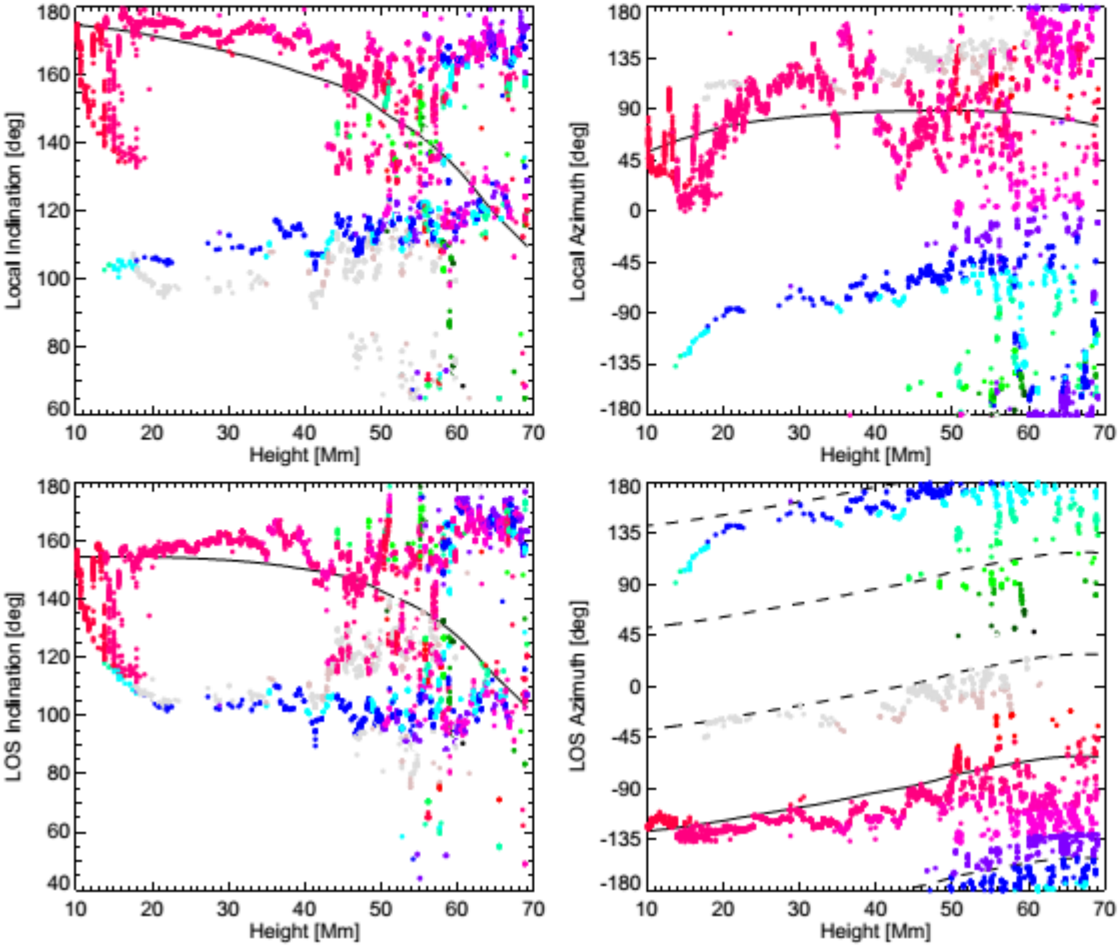
- ☐ DKIST will be the world's most powerful optical/IR solar telescope, and a precision polarimeter designed for multi-scale experiments.
- ☐ Its fleet of five facility instruments offers a highly customizable experiment platform that may be optimized for any number of problems.
- ☐ Optimizing the DKIST experiment for chromospheric polarimetric application should take advantage of the aperture's size more than its diffraction limit.
- ☐ A 1-2 coordination is available for ALMA and DKIST, and such observations are certain to provide important constraints on the magnetically coupled solar atmosphere.

dkist.nso.edu/science **dkist.nso.edu/CSP**

Extra slides

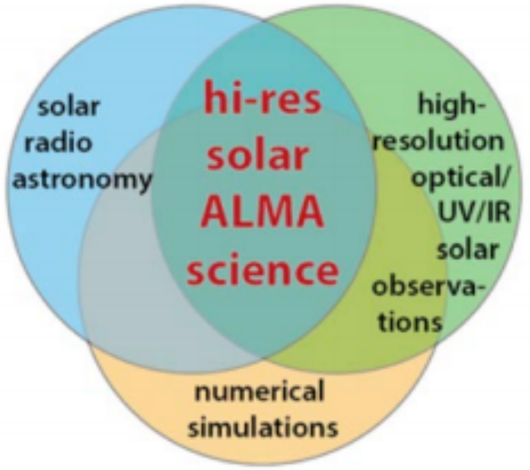
DST/FIRS
He I 1083 nm
Coronal rain inversions





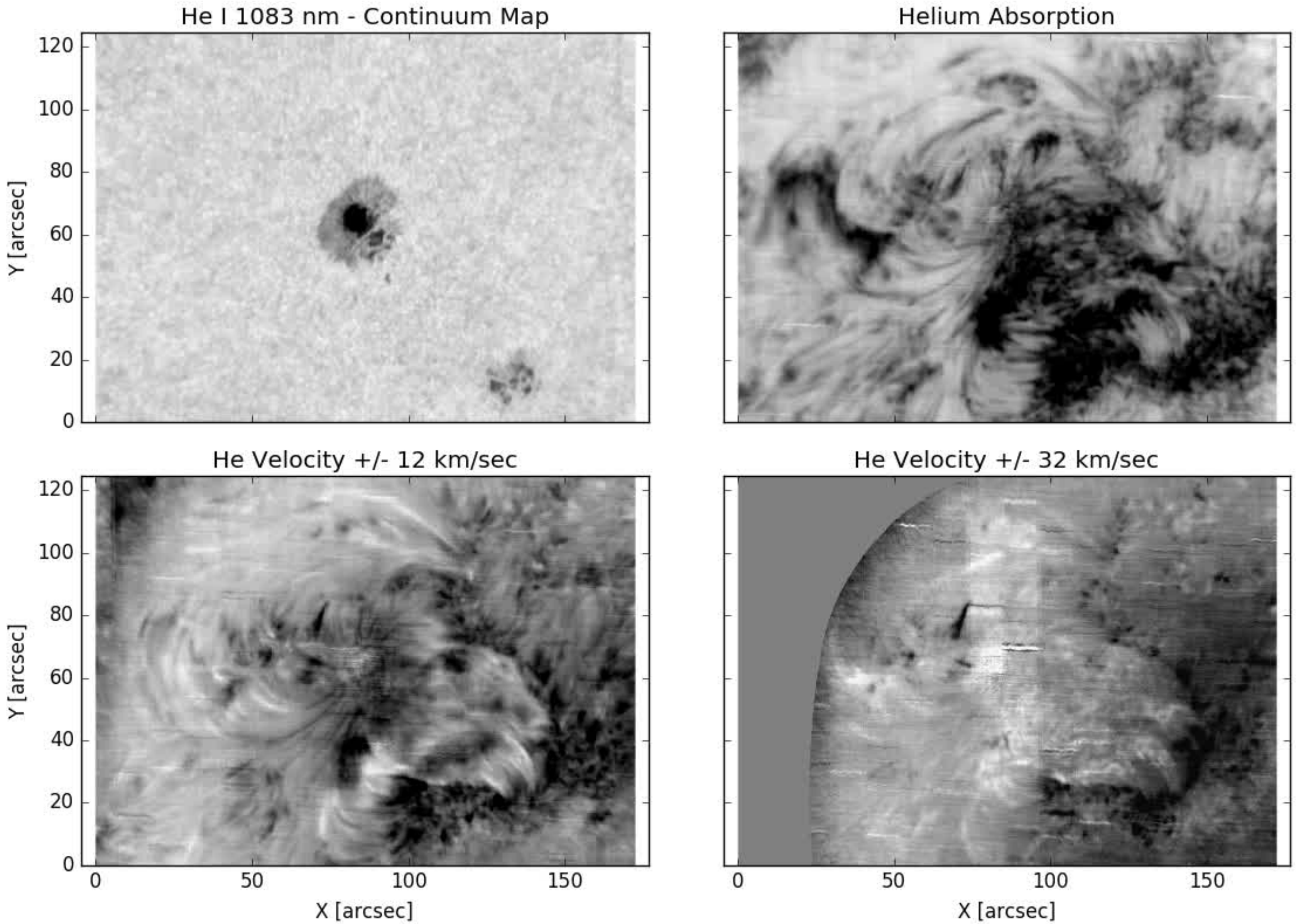
DKIST and ALMA Synergies

ALMA Strengths	DKIST Strengths
Continuum radiation at millimeter wavelengths acts as a linear thermometer in narrow layer in the solar atmosphere.	Host of deep NLTE optical lines provide polarimetric probe of chromospheric layers, but DKIST probes photospheric layers very well.
The polarization provides a measure of the longitudinal magnetic field component in the same layer in the solar atmosphere.	
The height of the probed atmospheric layers increases with the selected wavelength, enabling height scans through the solar atmosphere and tomographic techniques.	DKIST can access photospheric and coronal magnetic fields.



Wedemeyer et al. (2015) SSRv

High-res MxSPEC Experiment at the Dunn Solar Telescope (Preliminary Data)



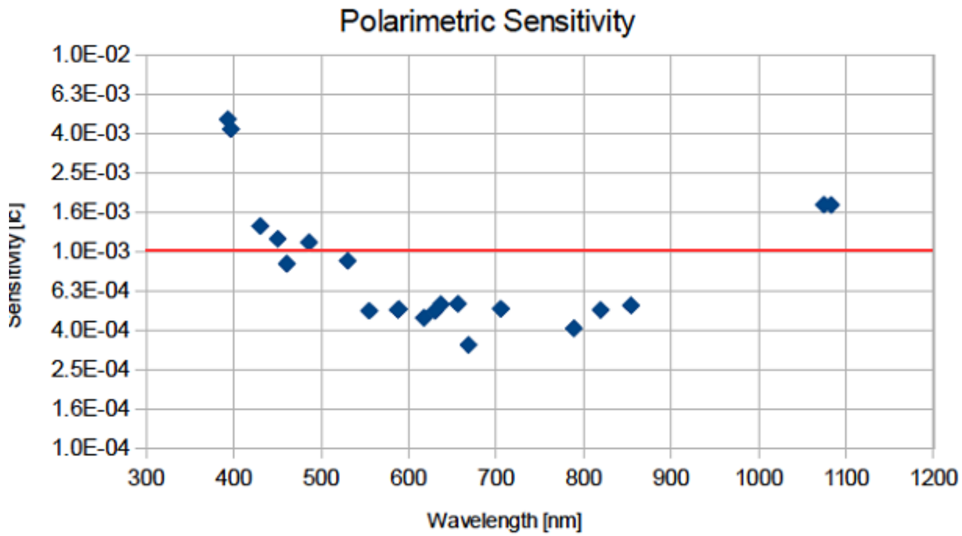
(Slide courtesy of Roberto Casini)

ViSP Flux Budget

(based on DKIST/ViSP flux estimates)

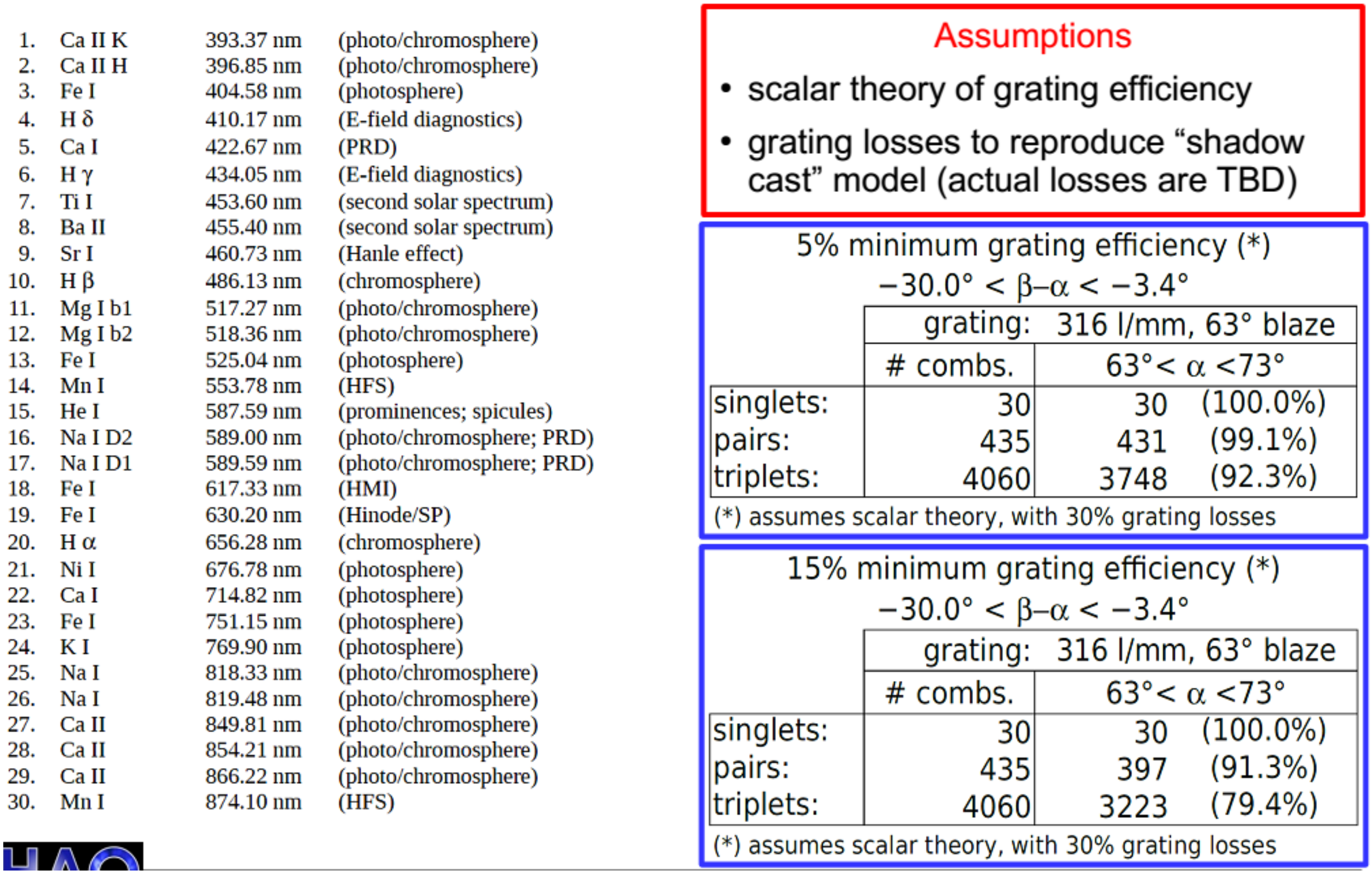
Andor Zyla 5.5
40 fps, 27000 e$^-$ max accumulation
10 s integration time
Wavelength scaled slit width

Shadow-cast grating



Ion / Line	Wavelength nm	N/S Integ. / resol.
Ca II K-line	393.33	4.7E-03
Ca II H-line	396.80	4.2E-03
CH G-band	430.50	1.4E-03
Blue continuum	450.40	1.2E-03
Sr I	460.73	8.7E-04
H-beta	486.13	1.1E-03
Fe XIV	530.30	9.0E-04
Green continuum	555.00	5.0E-04
He I D3	587.60	5.1E-04
Na I D2	589.00	5.1E-04
Fe I	617.33	4.6E-04
Fe I	630.20	5.0E-04
Fe X	637.00	5.4E-04
H-alpha	656.30	5.4E-04
Red continuum	668.40	3.4E-04
TiO band	705.40	5.1E-04
Fe XI	789.00	4.1E-04
Na I	819.48	5.1E-04
Ca II IR2	854.20	5.3E-04
Fe XIII	1074.60	1.7E-03
He I	1083.00	1.7E-03

(Slide courtesy of Roberto Casini)



1.	Ca II K	393.37 nm	(photo/chromosphere)
2.	Ca II H	396.85 nm	(photo/chromosphere)
3.	Fe I	404.58 nm	(photosphere)
4.	H δ	410.17 nm	(E-field diagnostics)
5.	Ca I	422.67 nm	(PRD)
6.	H γ	434.05 nm	(E-field diagnostics)
7.	Ti I	453.60 nm	(second solar spectrum)
8.	Ba II	455.40 nm	(second solar spectrum)
9.	Sr I	460.73 nm	(Hanle effect)
10.	H β	486.13 nm	(chromosphere)
11.	Mg I b1	517.27 nm	(photo/chromosphere)
12.	Mg I b2	518.36 nm	(photo/chromosphere)
13.	Fe I	525.04 nm	(photosphere)
14.	Mn I	553.78 nm	(HFS)
15.	He I	587.59 nm	(prominences; spicules)
16.	Na I D2	589.00 nm	(photo/chromosphere; PRD)
17.	Na I D1	589.59 nm	(photo/chromosphere; PRD)
18.	Fe I	617.33 nm	(HMI)
19.	Fe I	630.20 nm	(Hinode/SP)
20.	H α	656.28 nm	(chromosphere)
21.	Ni I	676.78 nm	(photosphere)
22.	Ca I	714.82 nm	(photosphere)
23.	Fe I	751.15 nm	(photosphere)
24.	K I	769.90 nm	(photosphere)
25.	Na I	818.33 nm	(photo/chromosphere)
26.	Na I	819.48 nm	(photo/chromosphere)
27.	Ca II	849.81 nm	(photo/chromosphere)
28.	Ca II	854.21 nm	(photo/chromosphere)
29.	Ca II	866.22 nm	(photo/chromosphere)
30.	Mn I	874.10 nm	(HFS)

Assumptions

- scalar theory of grating efficiency
- grating losses to reproduce "shadow cast" model (actual losses are TBD)

5% minimum grating efficiency (*)

$-30.0^\circ < \beta-\alpha < -3.4^\circ$

	grating:	316 l/mm, 63° blaze	
	# combs.	$63^\circ < \alpha < 73^\circ$	
singlets:	30	30	(100.0%)
pairs:	435	431	(99.1%)
triplets:	4060	3748	(92.3%)

(*) assumes scalar theory, with 30% grating losses

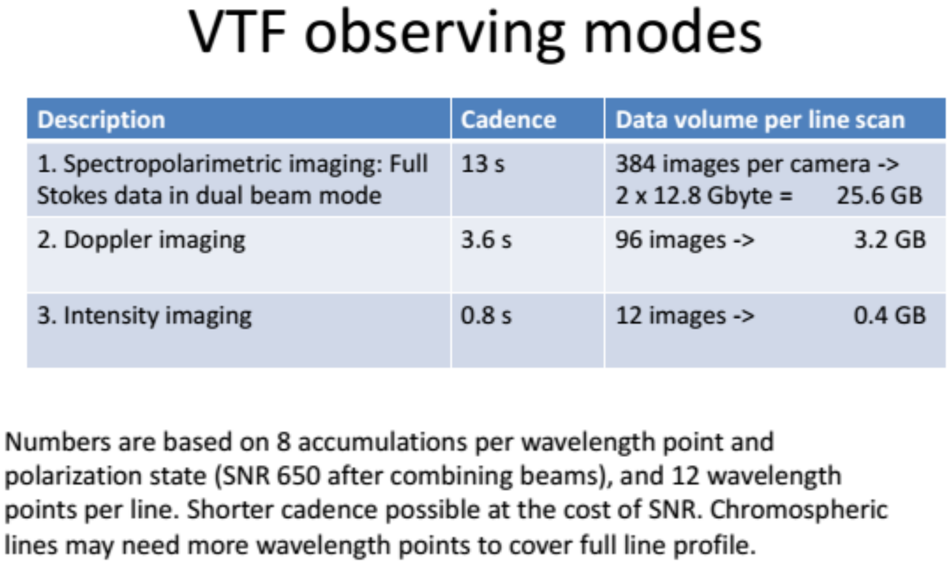
15% minimum grating efficiency (*)

$-30.0^\circ < \beta-\alpha < -3.4^\circ$

	grating:	316 l/mm, 63° blaze	
	# combs.	$63^\circ < \alpha < 73^\circ$	
singlets:	30	30	(100.0%)
pairs:	435	397	(91.3%)
triplets:	4060	3223	(79.4%)

(*) assumes scalar theory, with 30% grating losses

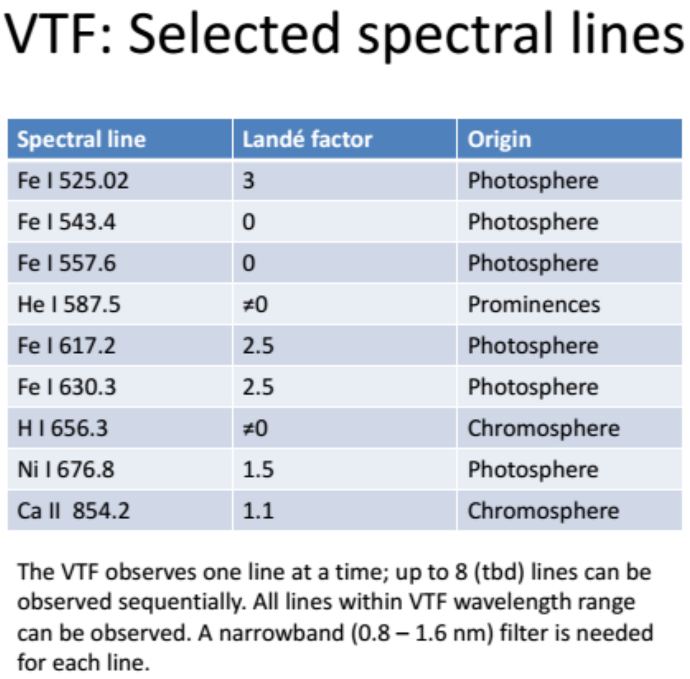
VTF Performance (Courtesy of Wolfgang Schmidt)



VTF observing modes

Description	Cadence	Data volume per line scan
1. Spectropolarimetric imaging: Full Stokes data in dual beam mode	13 s	384 images per camera -> 2 x 12.8 Gbyte = 25.6 GB
2. Doppler imaging	3.6 s	96 images -> 3.2 GB
3. Intensity imaging	0.8 s	12 images -> 0.4 GB

Numbers are based on 8 accumulations per wavelength point and polarization state (SNR 650 after combining beams), and 12 wavelength points per line. Shorter cadence possible at the cost of SNR. Chromospheric lines may need more wavelength points to cover full line profile.



VTF: Selected spectral lines

Spectral line	Landé factor	Origin
Fe I 525.02	3	Photosphere
Fe I 543.4	0	Photosphere
Fe I 557.6	0	Photosphere
He I 587.5	≠0	Prominences
Fe I 617.2	2.5	Photosphere
Fe I 630.3	2.5	Photosphere
H I 656.3	≠0	Chromosphere
Ni I 676.8	1.5	Photosphere
Ca II 854.2	1.1	Chromosphere

The VTF observes one line at a time; up to 8 (tbd) lines can be observed sequentially. All lines within VTF wavelength range can be observed. A narrowband (0.8 – 1.6 nm) filter is needed for each line.

DL-NIRSP Expected Exposure Times (T.Schad)

		Expected Exposure Time [milliseconds]		
Ion/Line	Wavelength [nm]	High Resolution Use Case (full well at disk center)	Coronal Use Case (15% of full well for 50 millionths I_{dc} bright corona)	Middle Resolution Use Case (full well at disk center)
Fe XIV	530.30	110	1798	16
Green cont.	555.00	94	1545	14
He I D3	587.60	89	1454	13
Na I D2	589.00	90	1474	13
Fe I	617.33	87	1418	13
Fe I	630.20	86	1409	13
Fe X	637.00	84	1374	13
H-alpha	656.30	99	1617	15
Fe XI	789.00	118	1914	17
Na I	819.48	151	2444	22
Ca II IR2	854.20	237	3810	35
Fe XIII	1074.70	76	1226	11
He I	1083.00	79	1275	12
Si X	1430.00	121	1978	18
Fe I	1565.00	83	1354	12
S XI	1920.00	605	9813	89
CO bands	2326.00	1180	18862	172