

# **A new window to the Sun: The Daniel K Inouye Solar Telescope**

The DKIST team



# Outline

1. The team & timeline
2. DKIST: a transformational facility
3. DKIST as a multiwavelength observatory
4. DKIST as a coronagraph
5. DKIST as a polarimeter
6. Instruments



# Daniel K Inouye Solar Telescope: The Team

## First light instruments

### DKIST PI:

NSO/AURA

DKIST Director: T. Rimmele

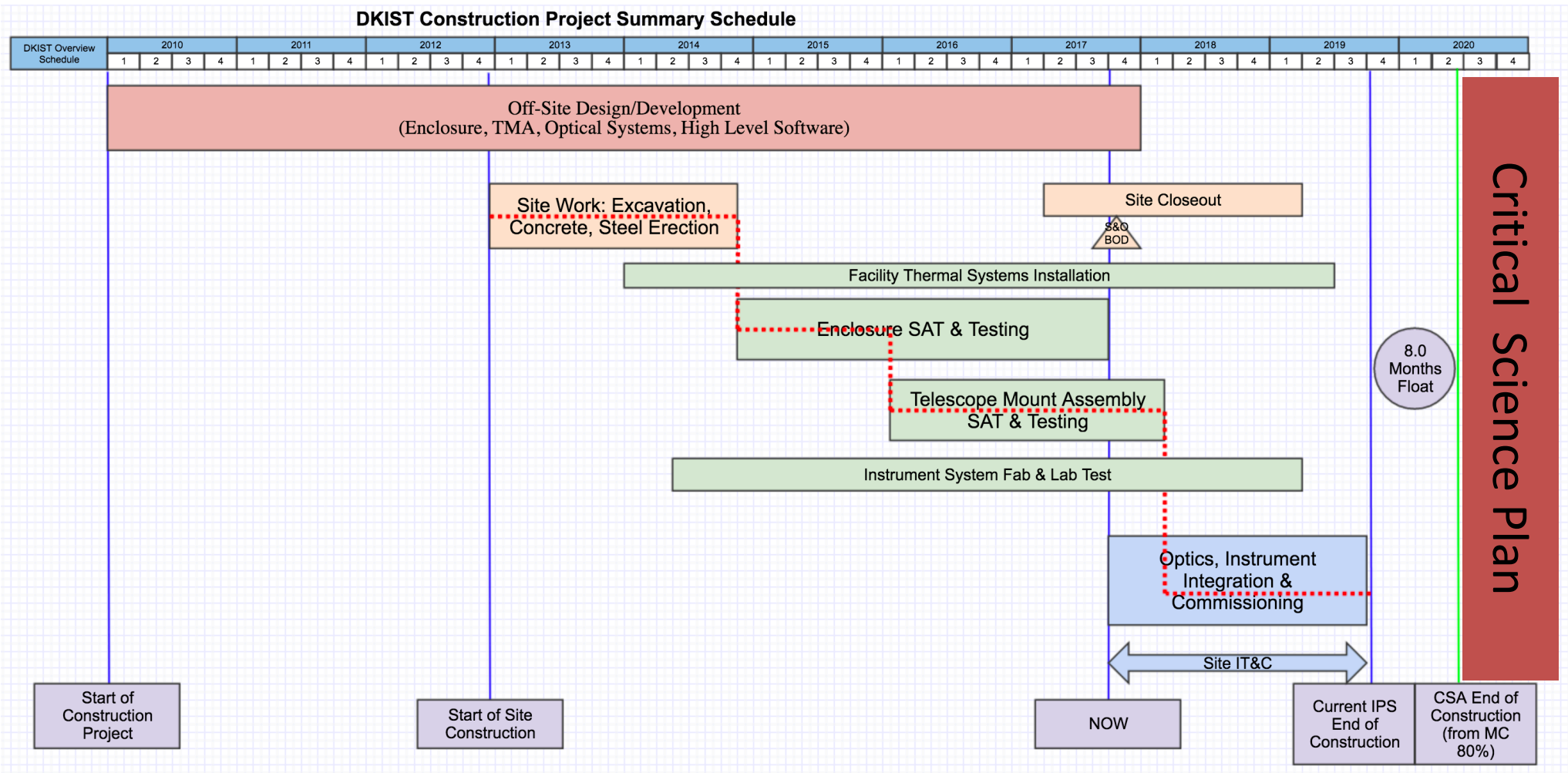
### DKIST co-Is:

P. Goode, M. Knoelker,  
J. Kuhn, R. Rosner

- NSO
  - VBI PI: F. Woeger
- University of Hawaii, IfA
  - CRYO-NIRSP PI: J. Kuhn
  - DL-NIRSP PI: H. Lin
- High Altitude Observatory
  - ViSP PI: R. Casini
- KIS, Germany,
  - VTF PI: O. vd Luehe
- UK DKIST Consortium
  - Visible Detectors, PI: M. Mathioudakis, QUB



# The DKIST: status and timeline



8 years of construction; 80% complete





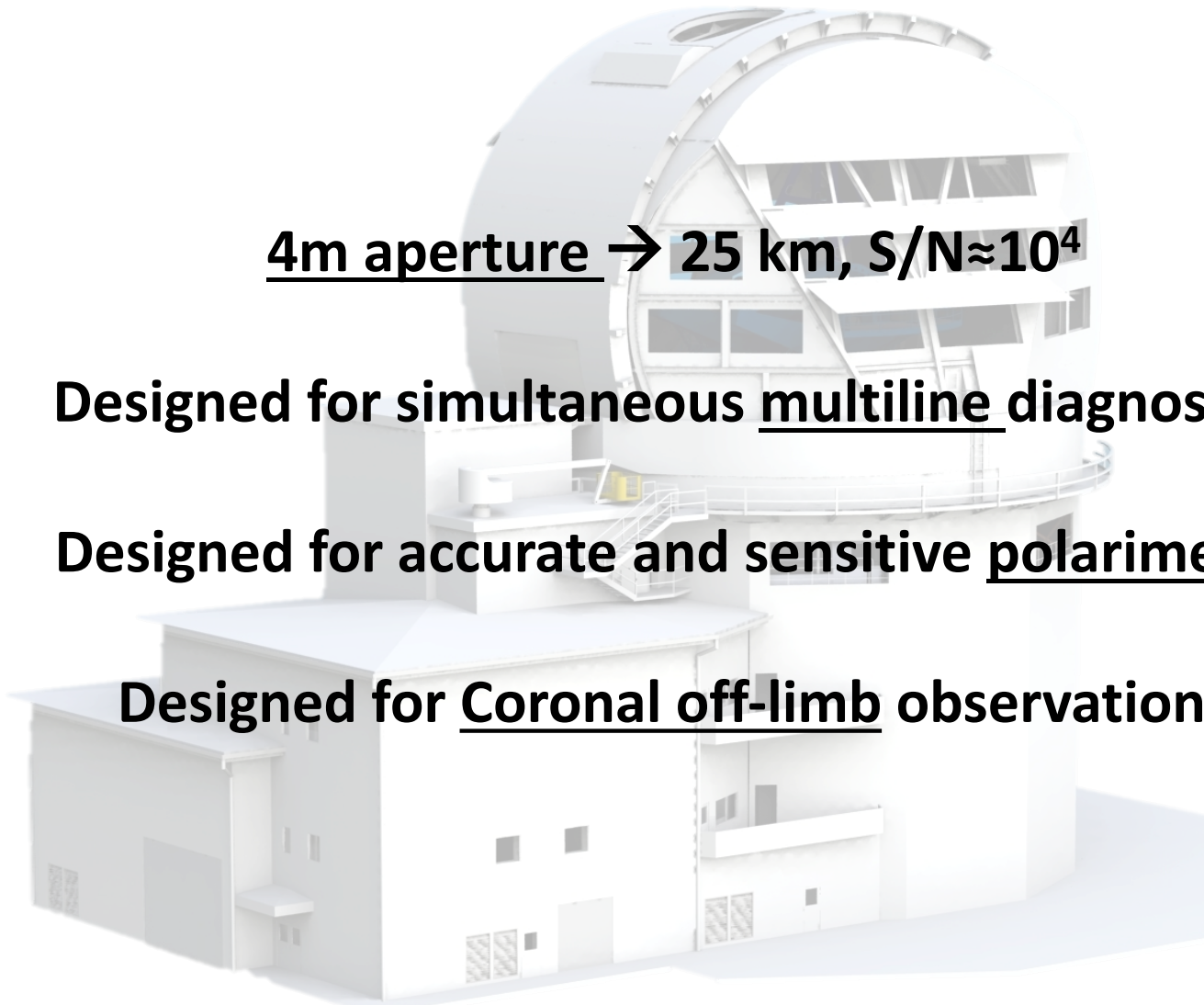
# DKIST: a transformational facility

4m aperture → 25 km,  $S/N \approx 10^4$

Designed for simultaneous multiline diagnostics

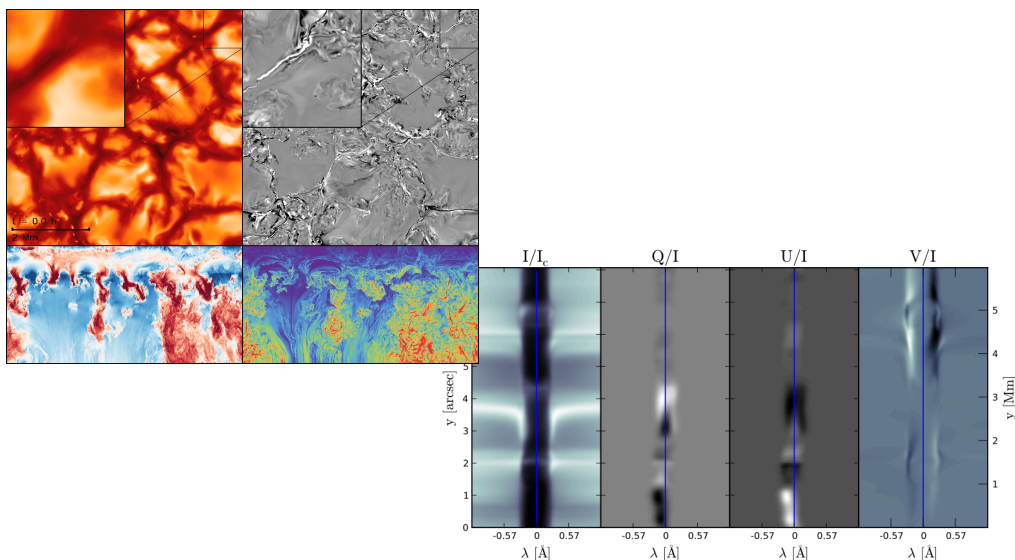
Designed for accurate and sensitive polarimetry

Designed for Coronal off-limb observations





# DKIST: a transformational facility



$$\begin{aligned} SNR &\sim 10^4 \\ \phi_{px} &\sim 0.1 \text{ arcsec} \\ t_{\text{exp}} &\sim 10 \text{ s} \end{aligned}$$

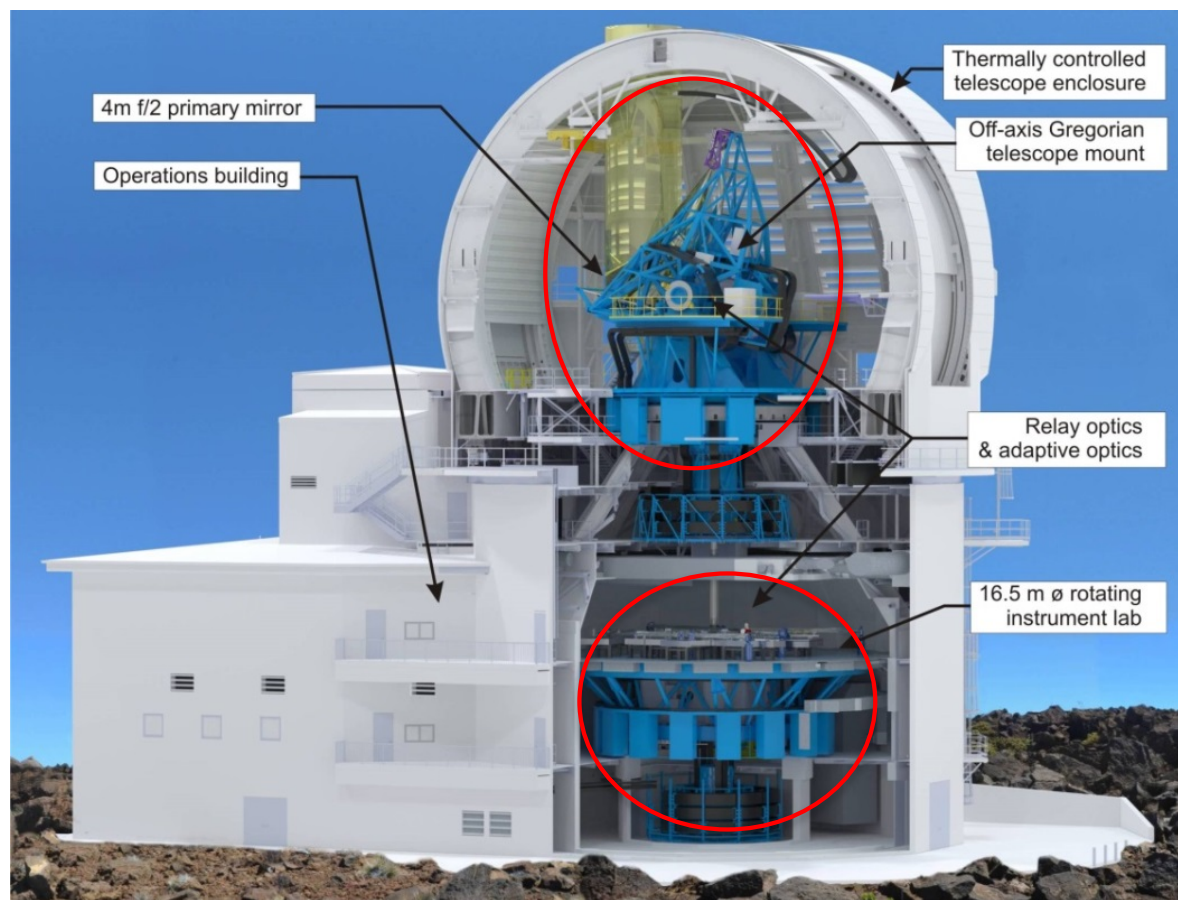


$$D = \frac{SNR}{\sqrt{0.7 N 10^{-0.4 m_0} \tau \Delta \lambda Q \phi_{px}^2 t_{\text{exp}}}}$$

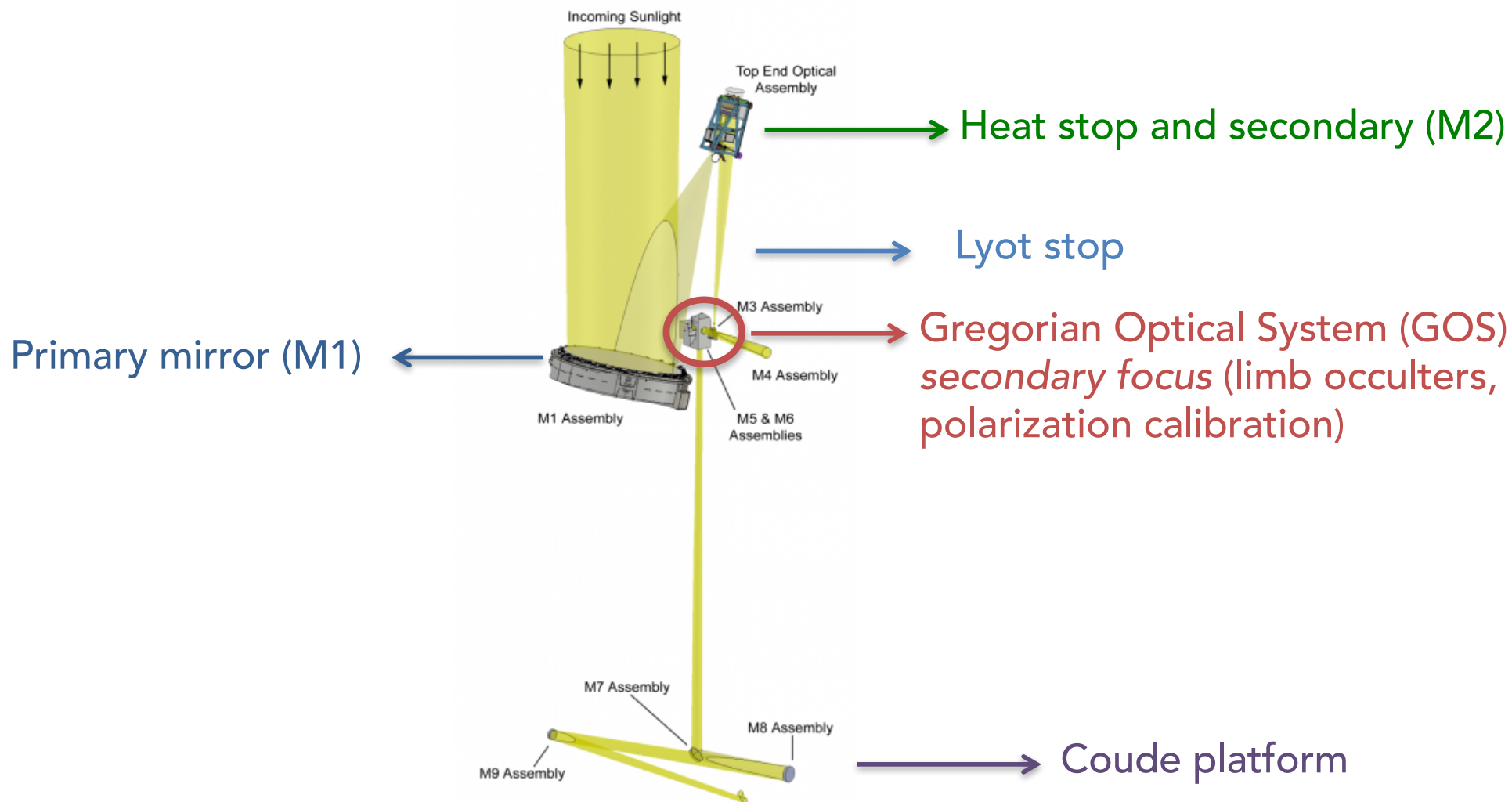


# DKIST: a transformational facility

- Four-meter aperture, f/2
- Alt/azimuth mount
- All reflecting optics
- Off-axis design (no spider, no central obscuration)
- Heat stop at prime focus: hard limit of 5' FOV
- Low-scattered light
  - Coronagraph
  - Lyot stop & limb occulter
  - In situ clean & wash of M1
- Integrated adaptive optics (on-disk)
- High-precision polarimetry
- Clean room conditions
- Service Mode: PI not present.
- Data available on-line: Boulder DC

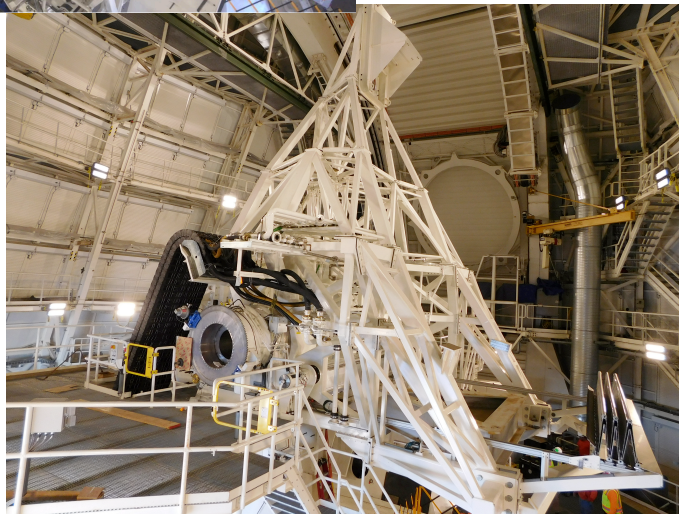


# Light Feed



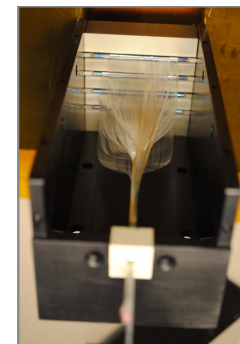
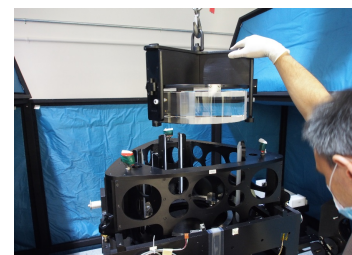
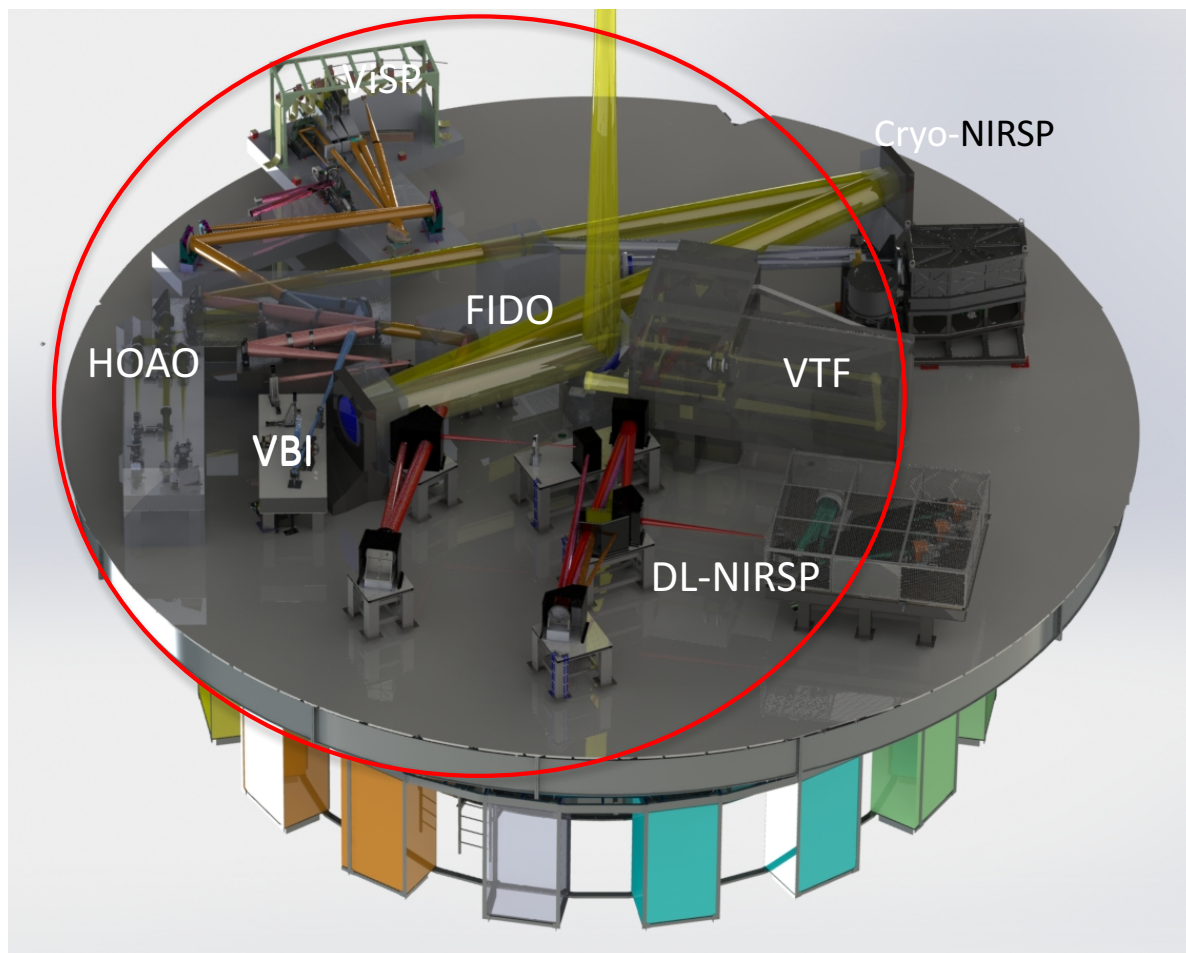
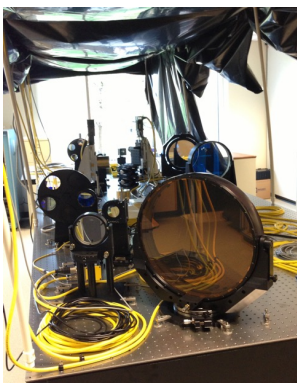
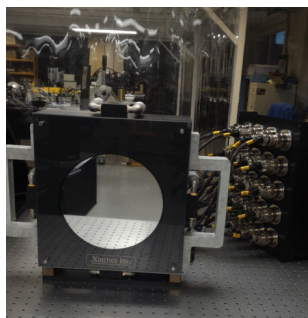
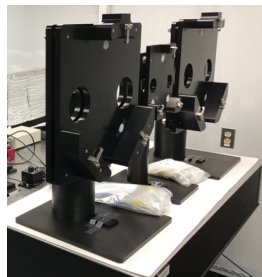


# DKIST: a transformational facility



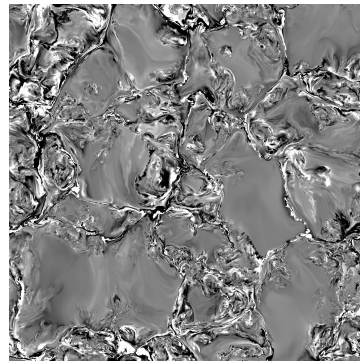
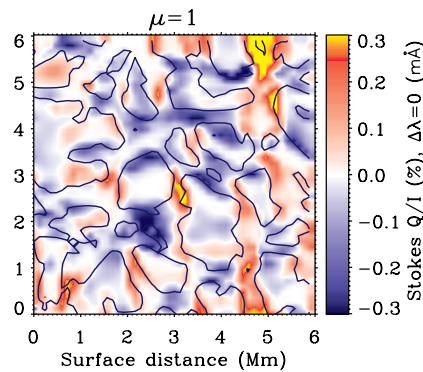
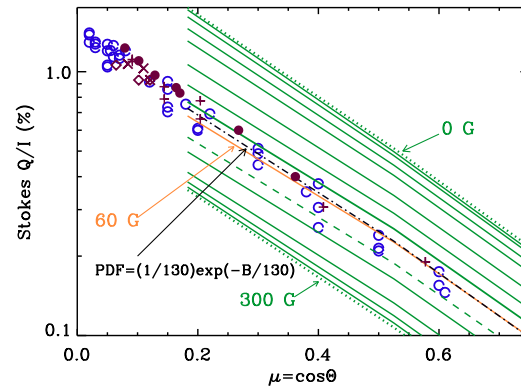
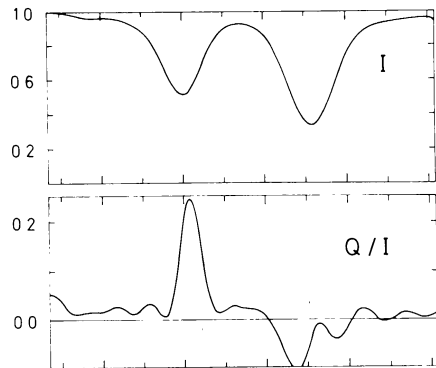


# DKIST as a Multiwavelength Observatory (nominal: 0.38 – 28 $\mu\text{m}$ )

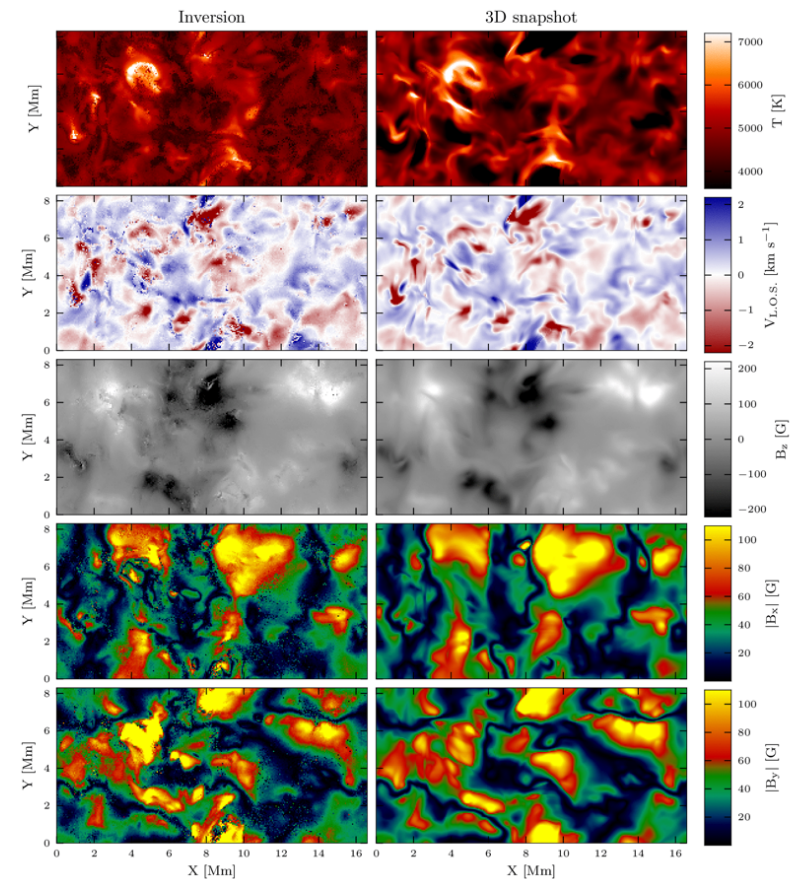


# DKIST as a Multiwavelength Observatory

- Sr I 4607 Å: ViSP
- SNR  $10^4$ , short cadence, Zeeman lines



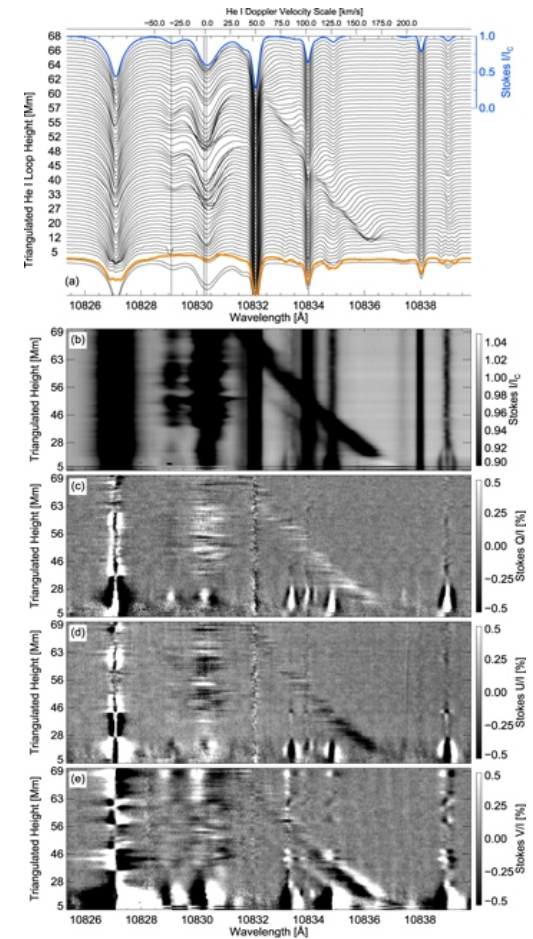
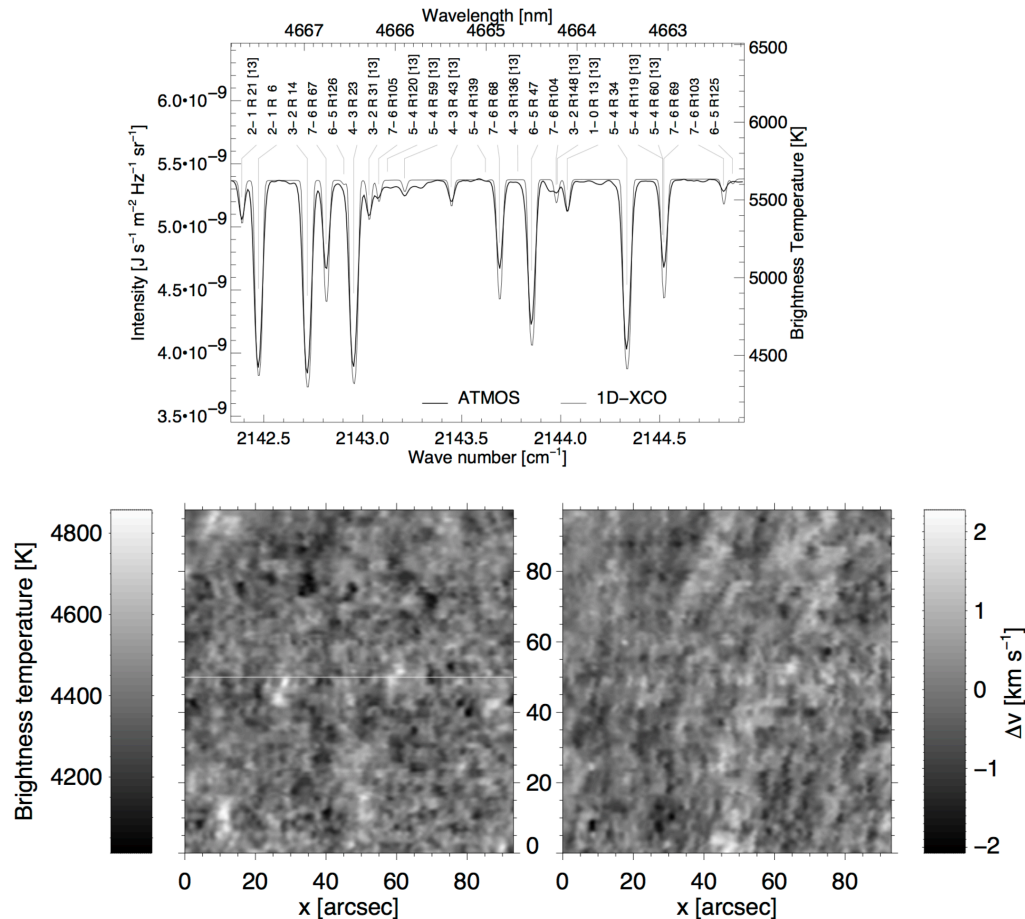
- Ca II IR 8542 Å: ViSP, VTF
- SNR  $10^4$ , short cadence, multi-height





# DKIST as a Multiwavelength Observatory

- CO vibration-rotation band 4.6  $\mu\text{m}$  : Cryo
- Both disk + limb obs.
- He I 10830  $\text{\AA}$ : DL-NIRSP, Cryo
- SNR  $10^4$  , short cadence, Hanle + Zeeman effect



# DKIST as a coronagraph

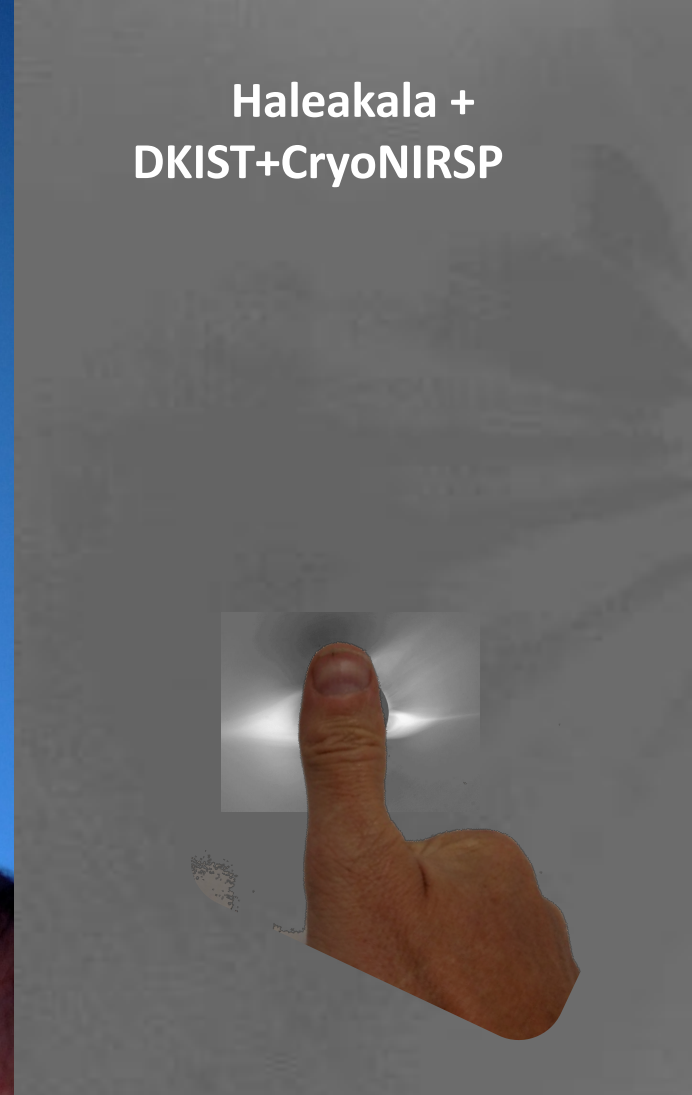
Wailea



Haleakala



Haleakala +  
DKIST+CryoNIRSP





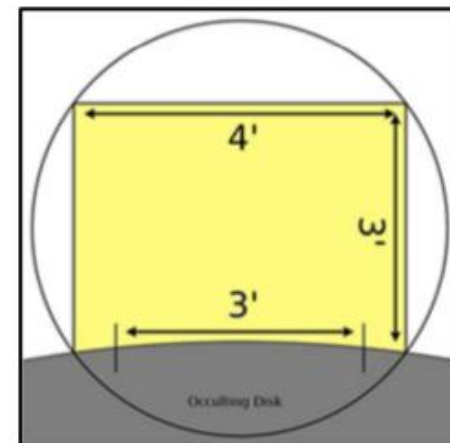
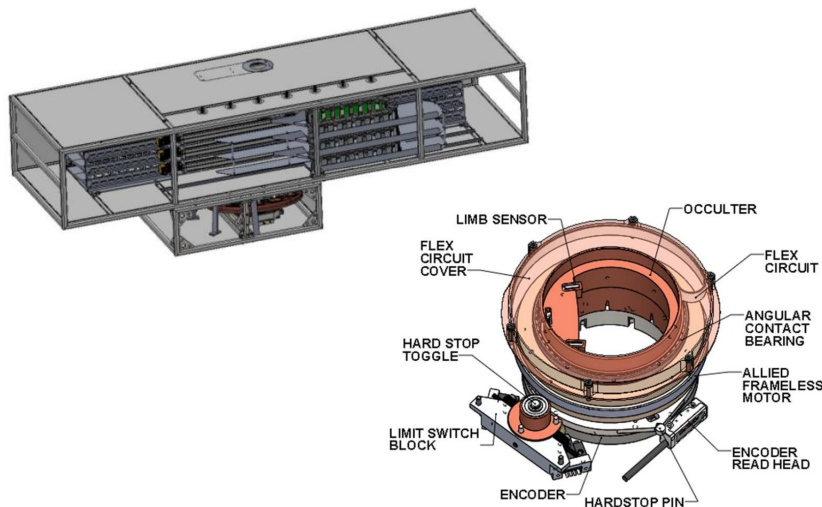
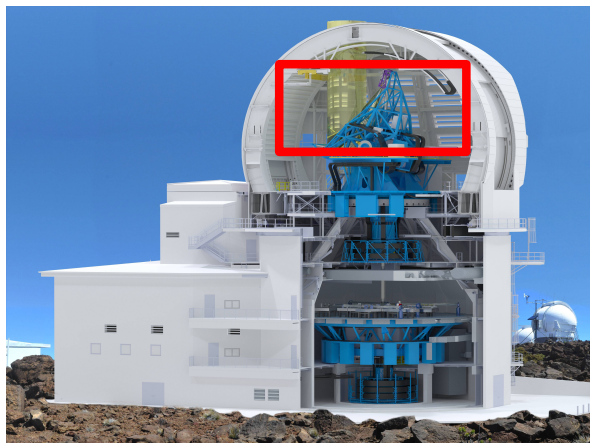
# DKIST as a coronagraph



High-grade polished M1 ( $\sim 1$  nm)



# DKIST as a coronagraph

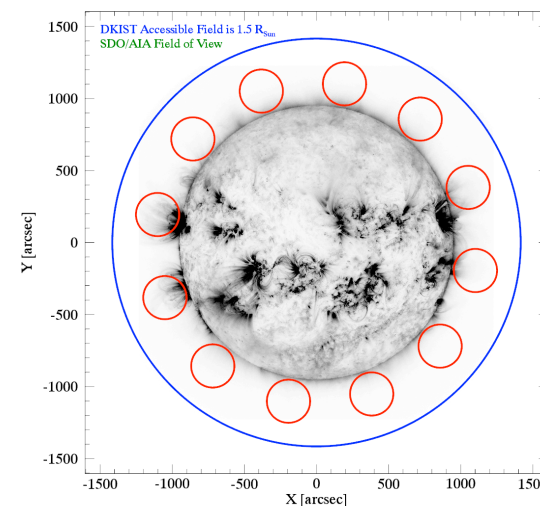


## Lyot and limb occulters (5' or 2.8'; round)

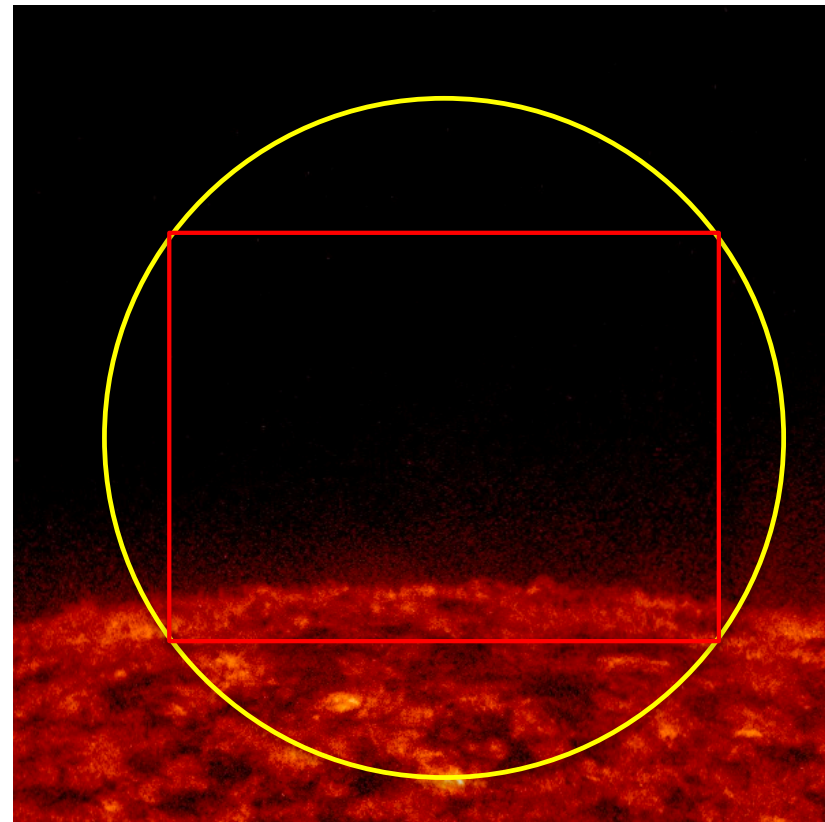
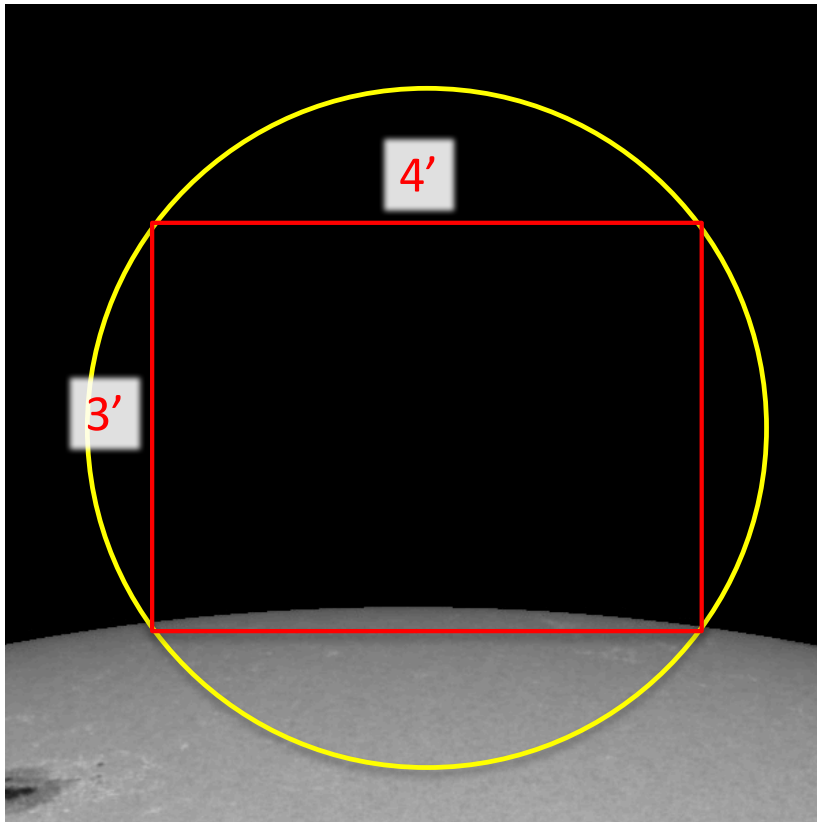
- How close?: 1 arcsec.
- How far from the limb?  $0.5 R_{\odot}$  max

## The Gregorian Optical System (GOS)

- Limb occulter: Disc(s) to block the solar disc near the limb
- Limb over/under-occulting of  $\pm 5$  arcsec possible
- Comes with a “limb sensor” that measure limb motions
- Drives M2 for image stabilization



# 5' Limb Occulter

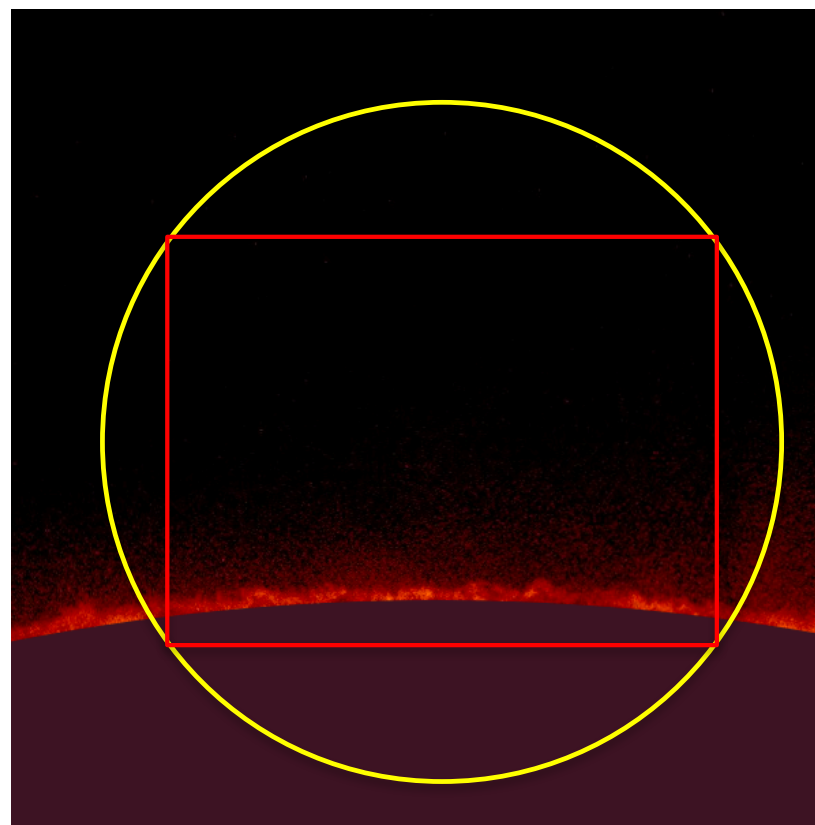
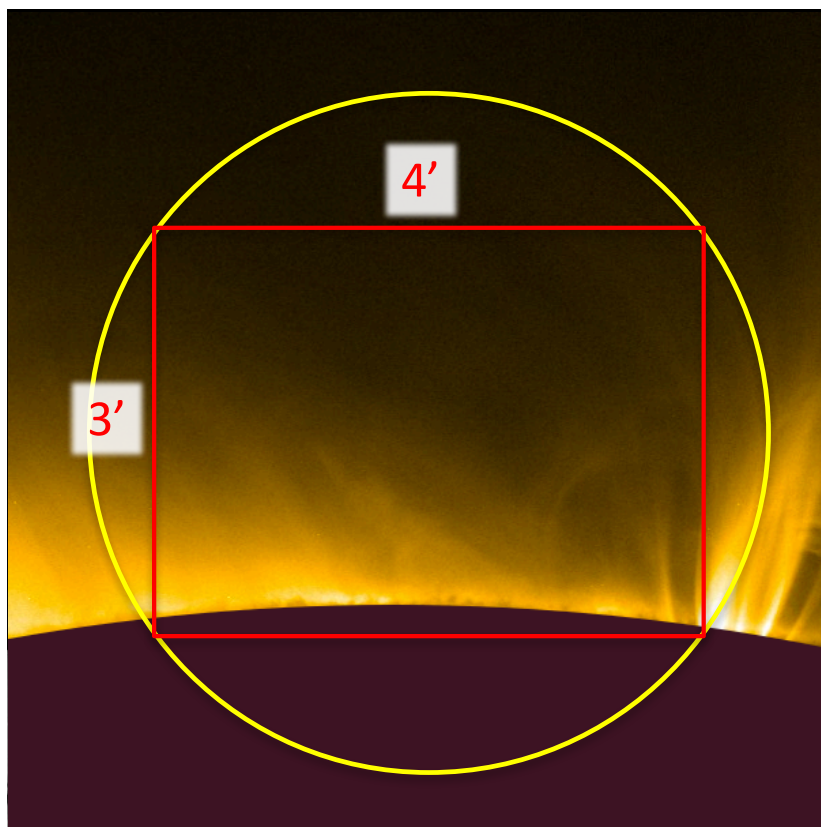


$\pm 5''$   
over/under  
occultation

Limb sensor tracks image motion perpendicular to limb (only), corrected by M2 fast tip



# 5' Limb Occulter



$\pm 5''$   
over/under  
occultation

Limb sensor tracks image motion perpendicular to limb (only), corrected by M2 fast tip



# DKIST as a coronagraph

## Cryo-NIRSP (UH/IfA)

4' slit x 3' scan

1-5  $\mu\text{m}$

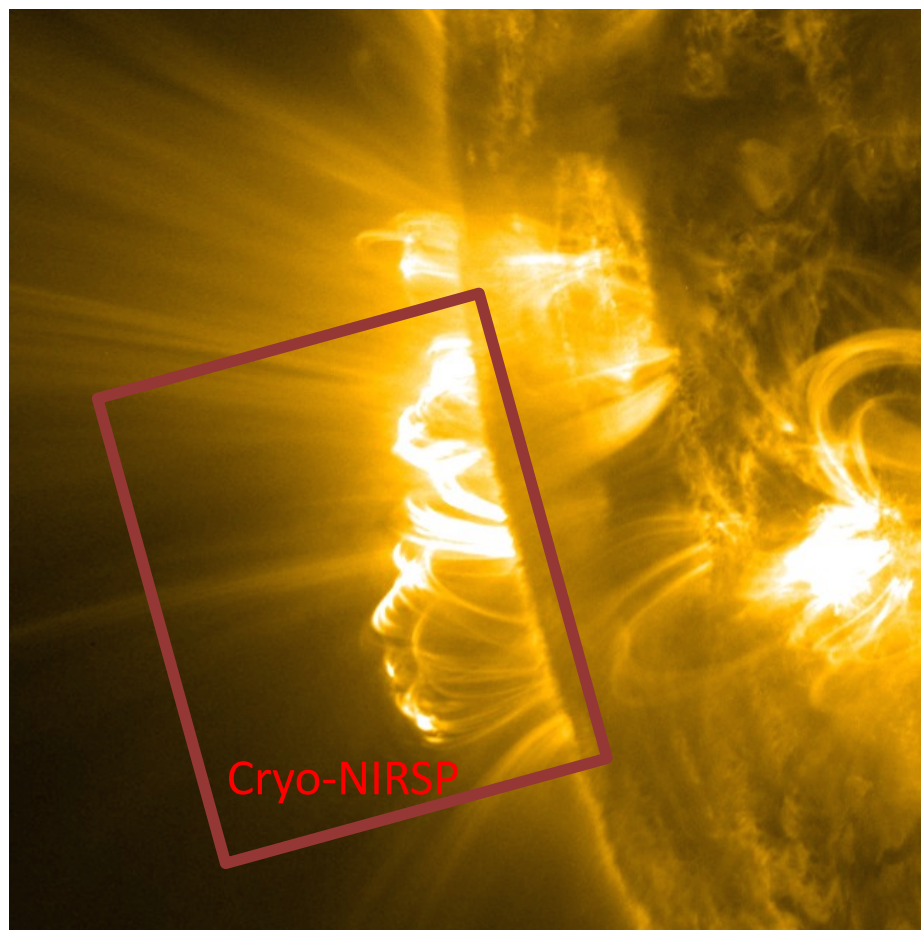
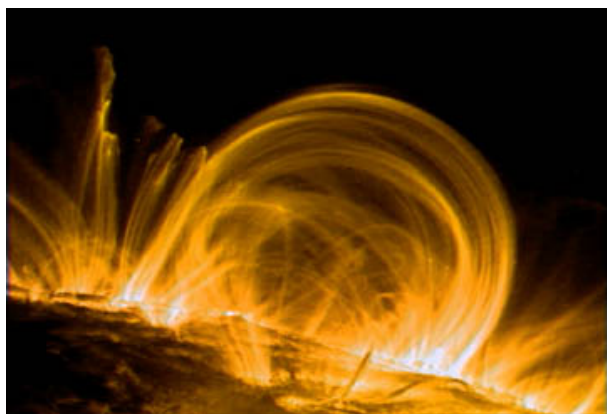
Off-point up to  $1.5 R_{\odot}$

1 arcsec resolution

Full Stokes-Dual Beam

~60 minutes cadence

(faster for smaller FOVs)  
(I-only available; faster)

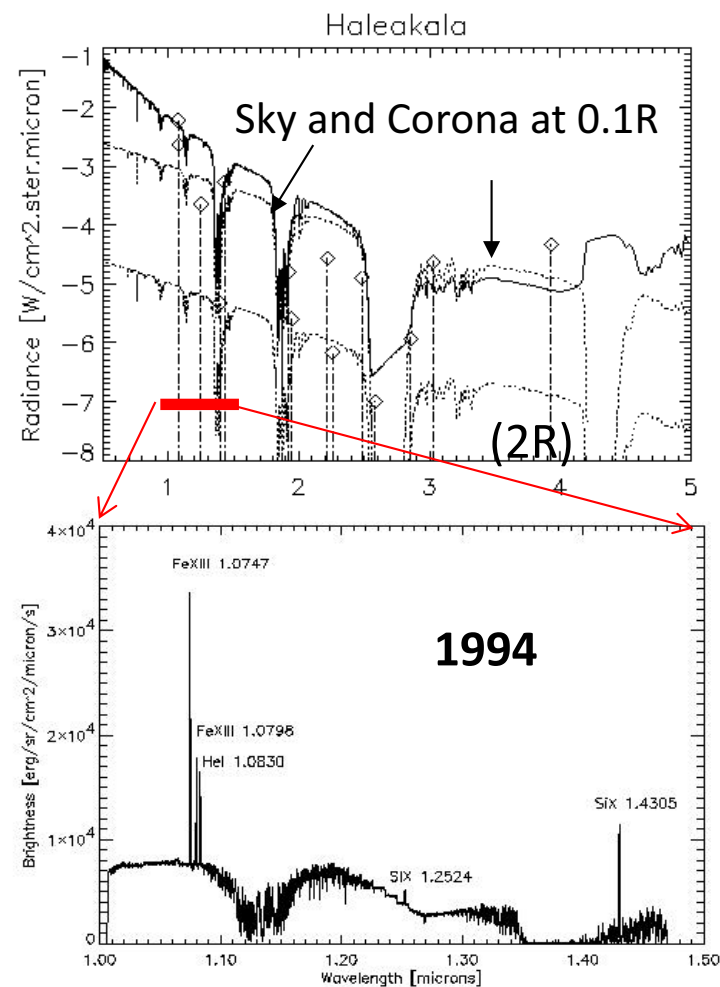


# DKIST as a coronagraph

Temperature sensitivity from 3000K to 2MK

Zeeman and  
saturated  
Hanle effect  
in forbidden  
lines

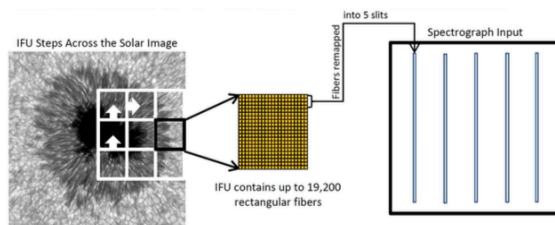
Wavelength (nm)	Line
1074.7, 1079.7	Fe XIII
1083	He I triplet
1430	Si X
2218	Fe IX
2326	CO
2580	Si IX
3028	Mg VIII
3935	Si IX
4651	CO



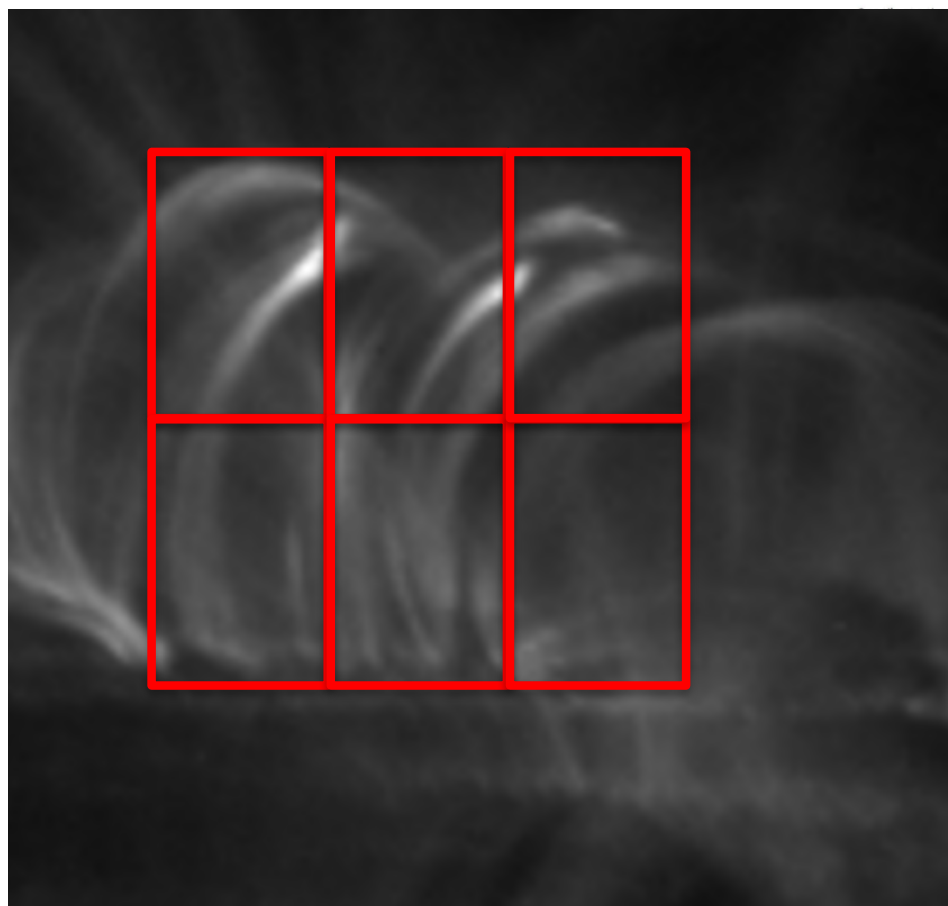
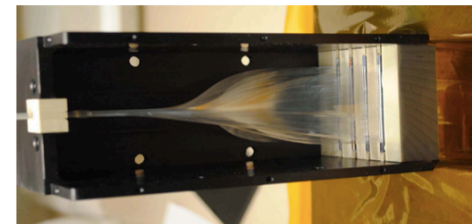
Discovery Space: MHD waves, Coronal magnetic fields, Coronal densities etc.

# DKIST as a coronagraph

But also...  
DL-NIRSP



DL-NIRSP builds spectropolarimetric full data cubes: [ X ; Y ;  $\lambda$  ; S [ =I,Q,U,V ] ; t ]



55"x55" (6 tiles)  
Near-limb (occulted)  
0.464" sampling  
15x6 seconds  
Full Stokes-Dual Beam  
Pol. sensitivity  $10^{-3}$

*FeXI 789.2, FeXIII 1074.7, SiX 1430  
at once*

# DKIST as a coronagraph

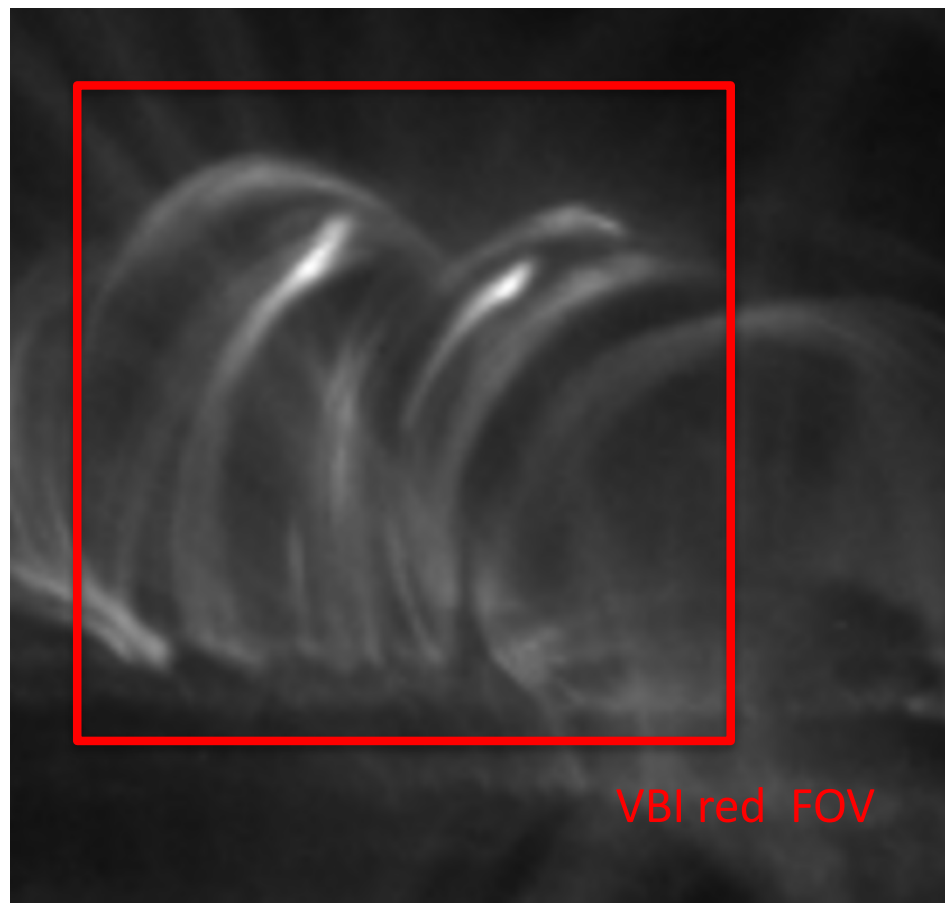
**But also...**  
**VBI**  
**(and other instruments)**

Fe XI 789.2 nm

FOV: 69" x 69"

0.03" resolution (no binning)

Few s cadence (depending on line  
brightness)



SDO/AIA 171 – 900 km resolution



# DKIST as a coronagraph

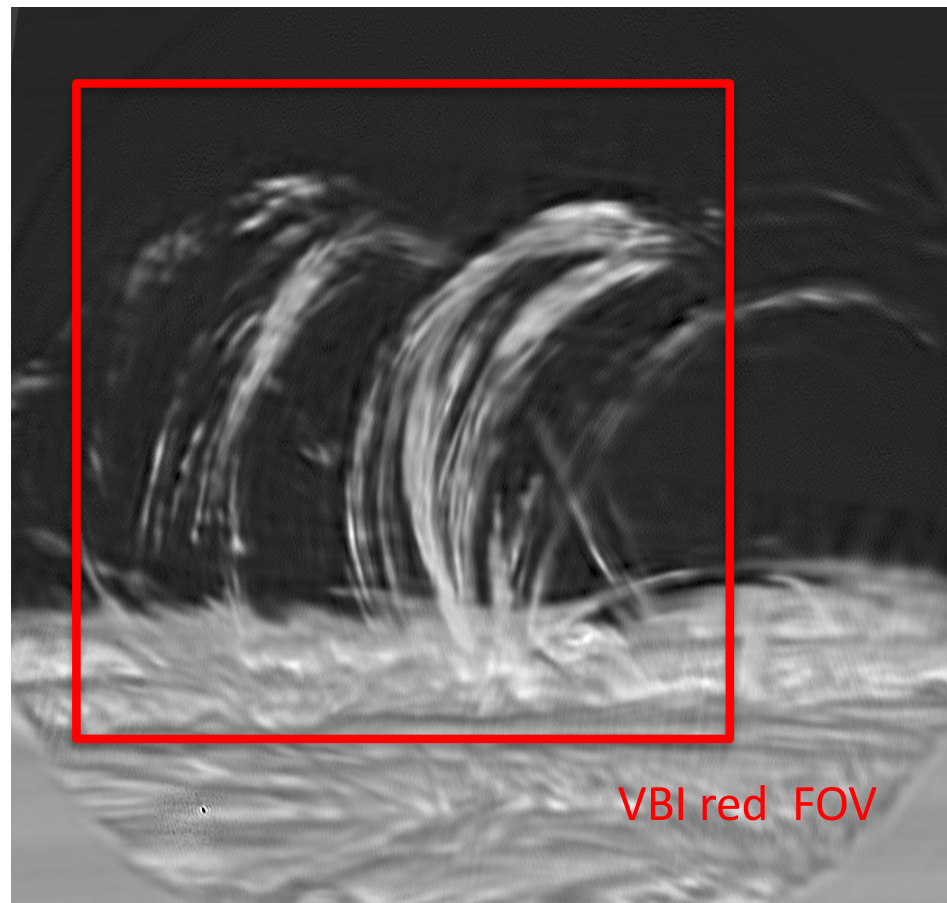
**But also...**  
**VBI**  
**(and other instruments)**

Fe XI 789.2 nm

FOV: 69" x 69"

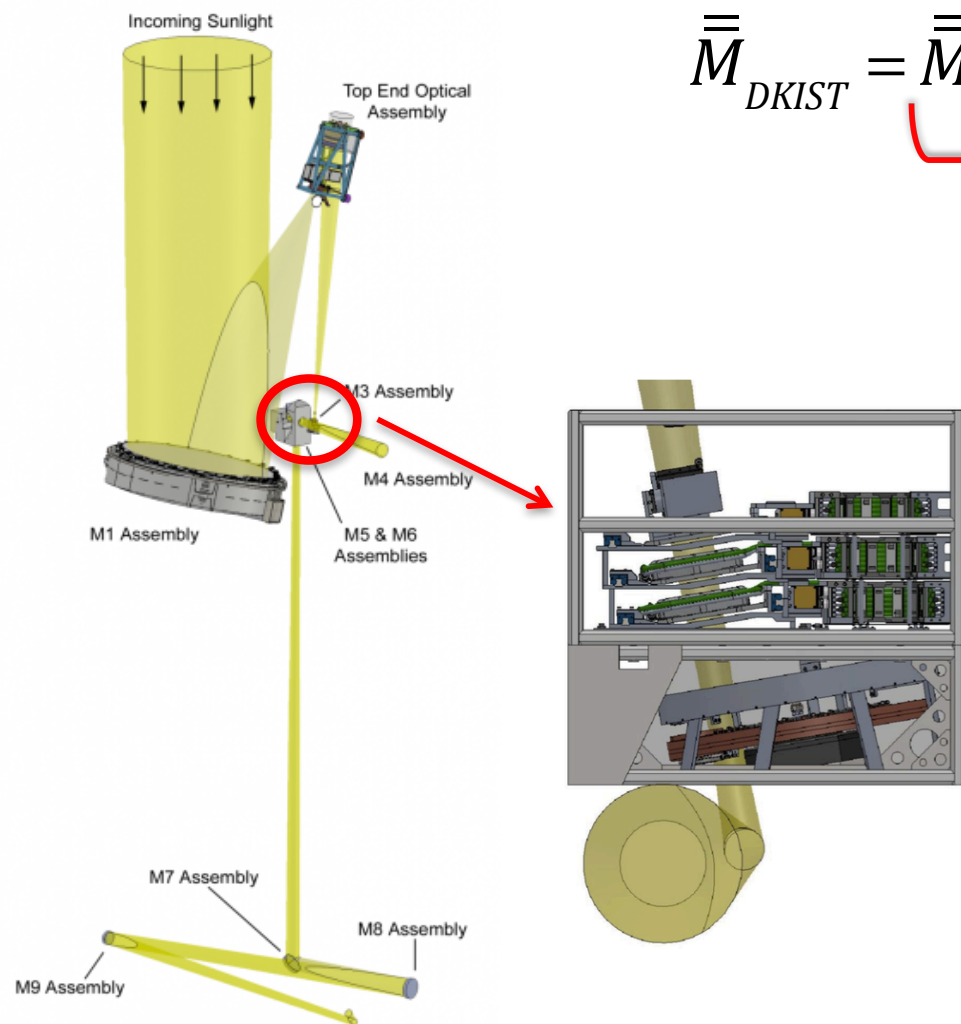
0.03" resolution (no binning)

Few s cadence (depending on line  
brightness)



IBIS H $\alpha$  – 130 km resolution

# DKIST as a Polarimeter

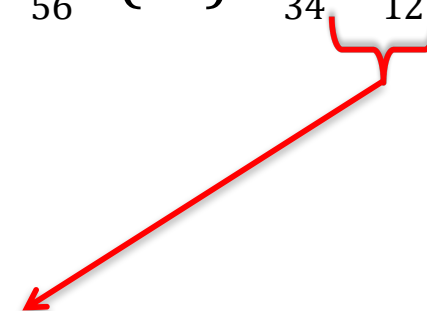


$$\bar{\bar{M}}_{DKIST} = \bar{\bar{M}}_7 \bar{\bar{R}}(Az - Table) \bar{\bar{M}}_{56} \bar{\bar{R}}(El) \bar{\bar{M}}_{34} \bar{\bar{M}}_{12}$$

- PA&C unit at Gregorian Focus
- Calibrates all optics downstream
- Similar to Gregor
- Polarization sensitivity  $10^{-5}$
- Exposure time dependent
- Polarization accuracy  $5 \times 10^{-4}$
- Cal optics after  $M_{12}$

# DKIST as a Polarimeter

$$\bar{\bar{M}}_{DKIST} = \bar{\bar{M}}_7 \bar{\bar{R}}(Az - Table) \bar{\bar{M}}_{56} \bar{\bar{R}}(El) \bar{\bar{M}}_{34} \underbrace{\bar{\bar{M}}_{12}}$$



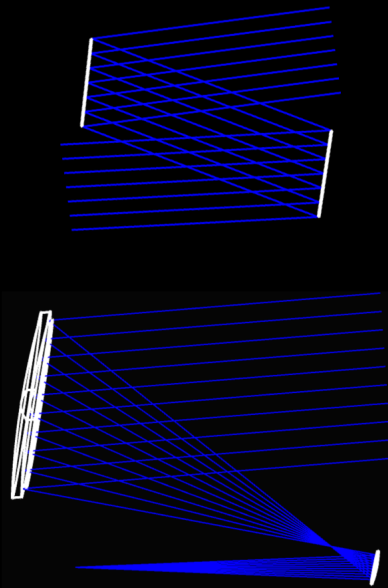
## Powered Optics & Aperture Averaging

1.00000	0.00461	0.00000	0.00000
0.00461	1.00000	0.00000	0.00000
0.00000	0.00000	0.99626	-0.08624
0.00000	0.00000	0.08624	0.99626

1.00000	0.00449	0.00000	0.00000
0.00449	0.99905	0.00000	0.00000
0.00000	0.00000	0.99552	-0.08471
0.00000	0.00000	0.08477	0.99457

0	0.00012	0	0
0.00012	0.00095	0	0
0	0	0.00074	0.00153
0	0	0.00147	0.00169

Diattenuation & retardance differ  
Diagonal terms lower than expected  
400nm, Al+Al2O3 on M1, 3-layer Ag on M2

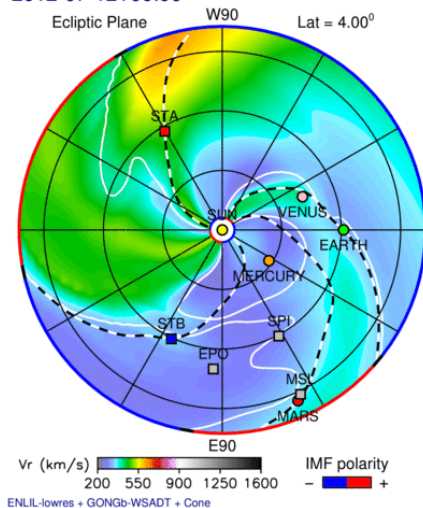


- $M_{12}$  independent of pointing
- Zeemax modeling including coatings
- Expected  $V \rightarrow U$  larger than  $V \rightarrow Q$
- Sky polarization
- Lines with no Q & U: Sun pointing
- Mirror samples
- **PolCal is a facility task**

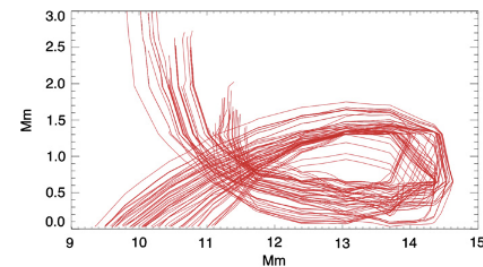
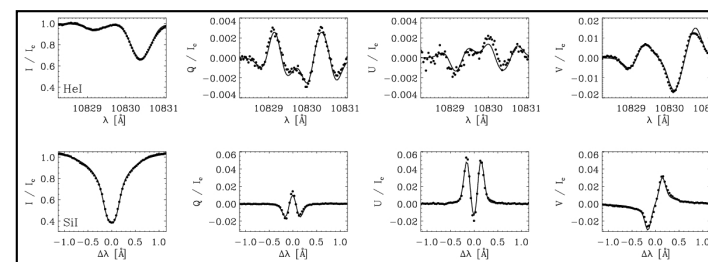
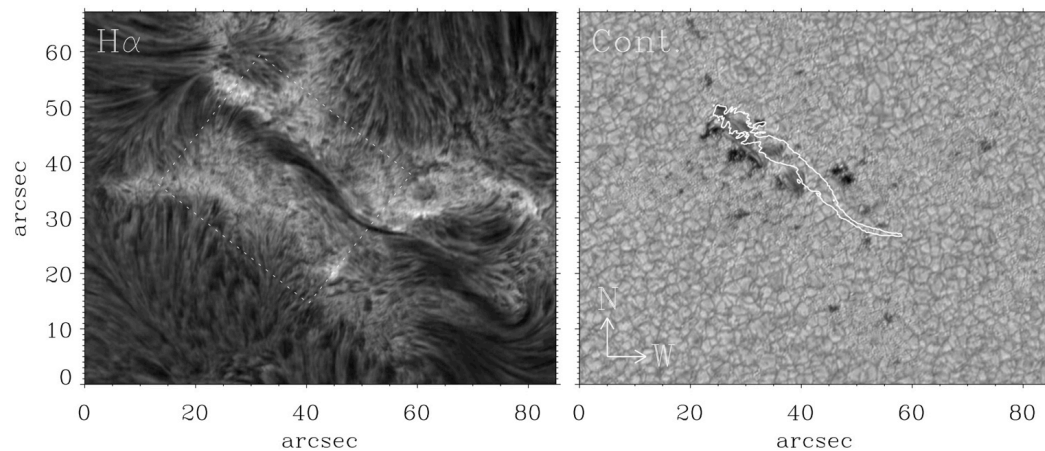
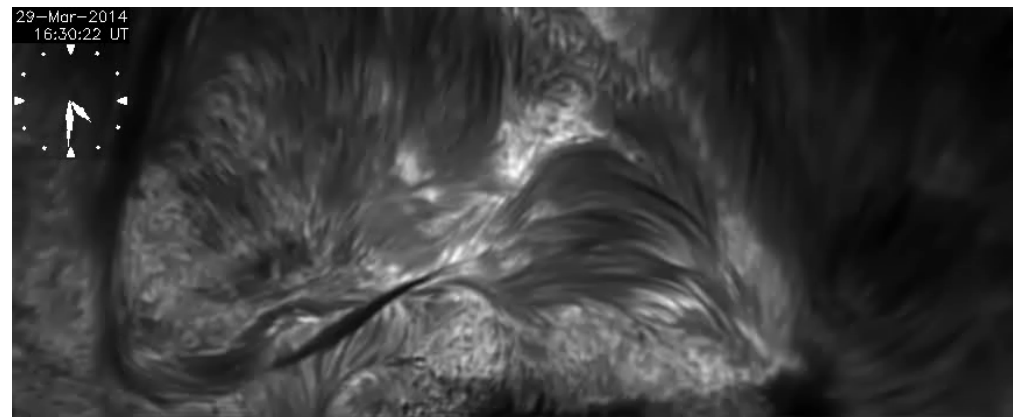
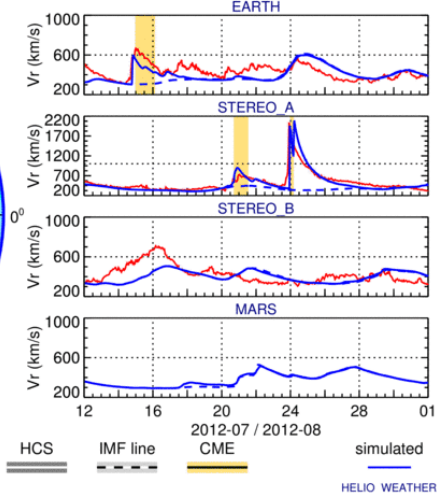


# DKIST as a Polarimeter

2012-07-12T00:00



2012-07-12T00 + 0.00 days







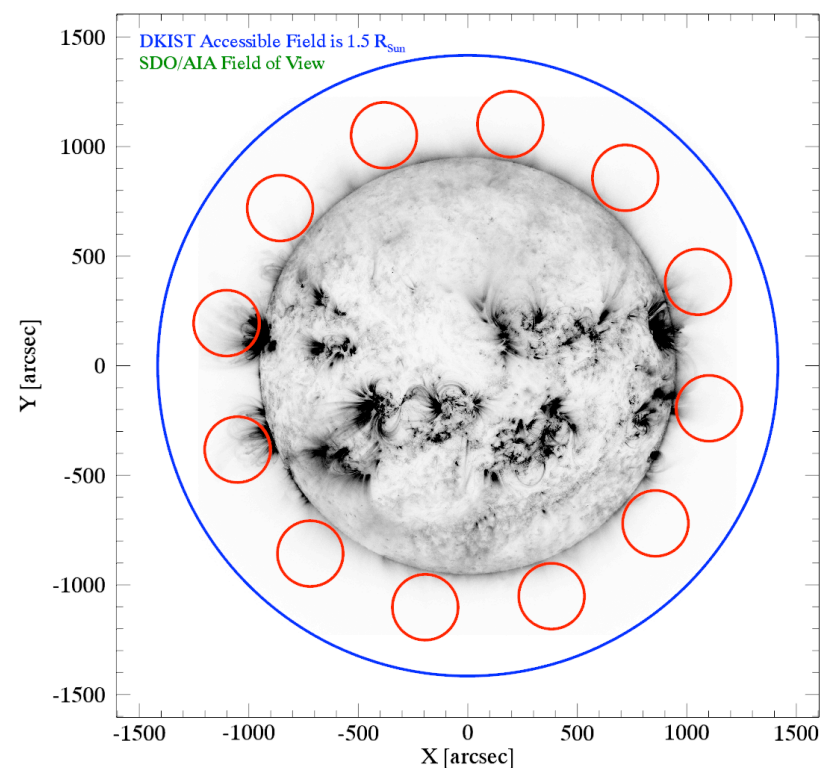
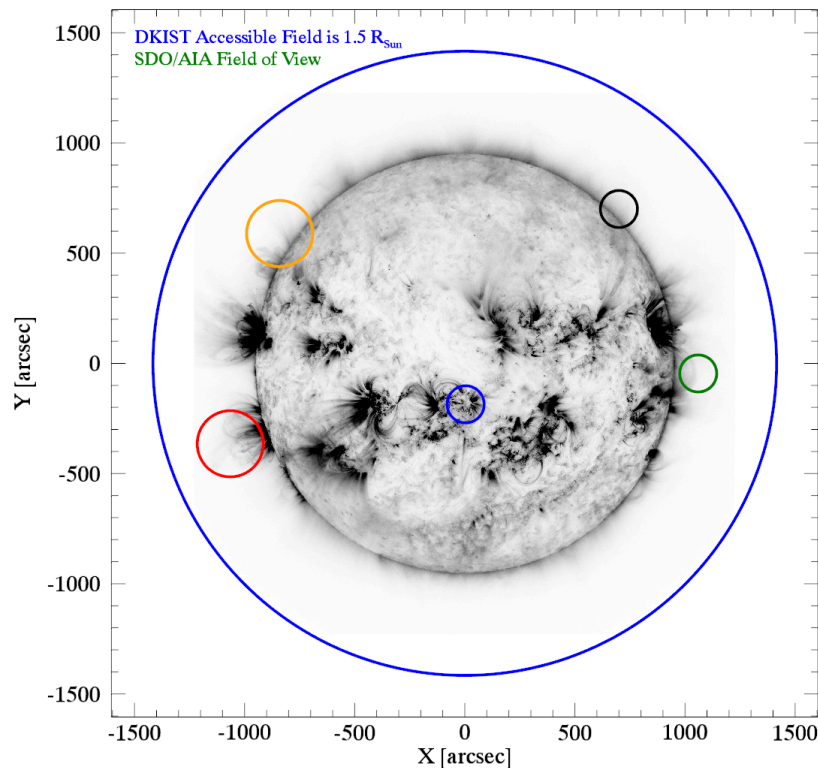
# Instruments

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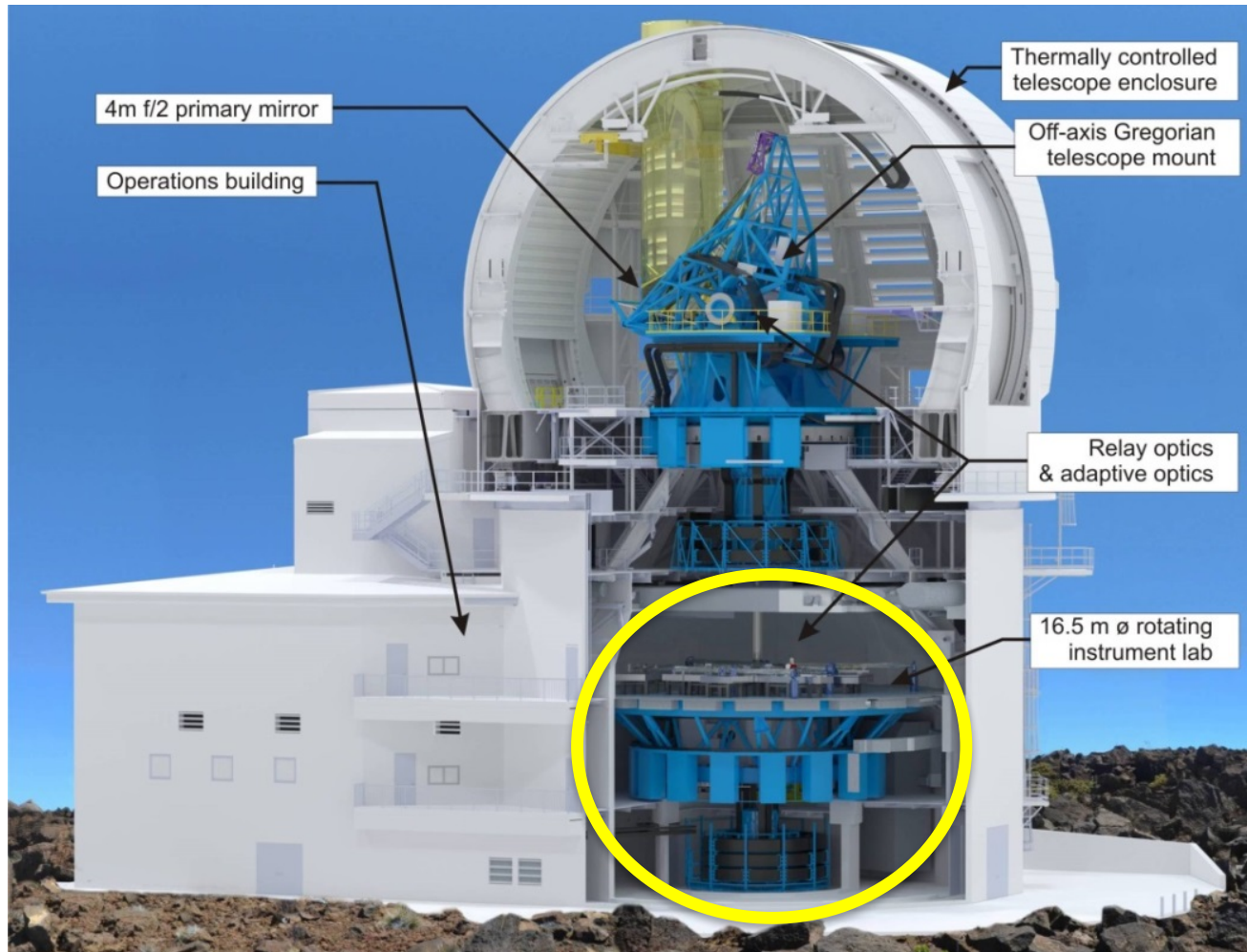
- DKIST instruments are complex, diverse, and rapidly\* flexible to support a very broad science portfolio.
- Users must understand and/or make decisions about:
  1. *Telescope field-of-view, pointing sequences, mosaics, coronagraphy, etc.*
  2. *Instrument lab rotation angle (solar image rotation)*
  3. *(Manually-changed) spectral distribution of light to instruments.*
  4. *Spectral/imaging/polarimetric capabilities of facility instruments*
  5. *Instrument parameters including domain coverage and SNR.*
  6. *Data rate/volume limits.*

# 1. Telescope field-of-view, pointing sequences, mosaics, and coronagraphy.

- Telescope prime field stop: 5' diameter.
- Solar pointing limitations:  $< 1.5$  solar radii
- Gregorian focus field stops: 5' and 2.8', each with a limb-occulting mode.
- 5' for Cryo-NIRSP (offlimb corona). 2.8' for all other instruments.
- Instruments each have separate instantaneous and scanning accessed field of view.
- The telescope can perform an automated pointing sequence of discrete targets, and mosaics (stitching together of a large FOV, adjacent tiles)



## 2. The instrument Coudé lab and the field rotation angle



All instruments live in the Coudé instrument Lab and have fixed mountings.

The target's angular orientation with respect to instruments is controlled by the Coudé platform rotation.





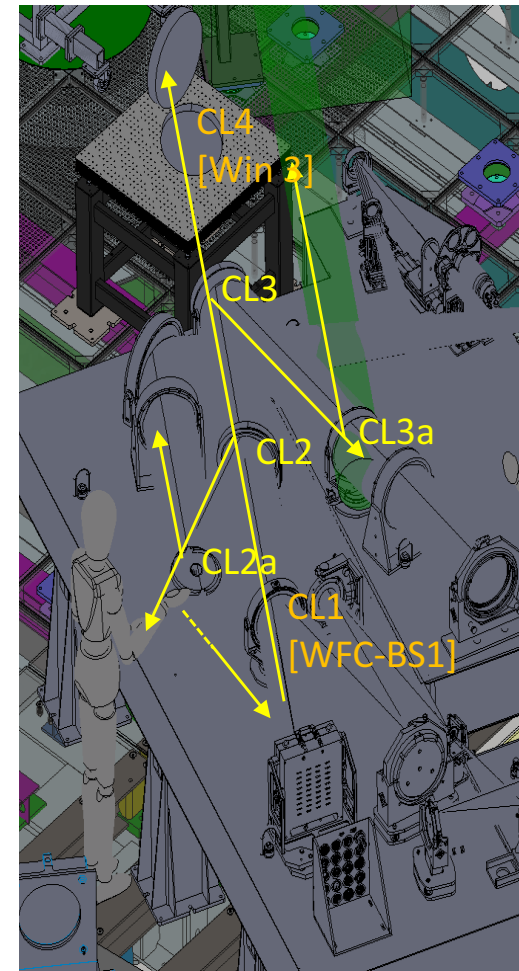
# Coudé Instrument Lab

- 16.5m rotating instrumental platform
- Clean, environment controlled, externally operated, laboratory.
- Constant rotation compensates mount-induced solar image rotation.
- Can be rotated to orient solar image based on science need, e.g.
  - Slits aligned N/S or E/W
  - Slits parallel/perpendicular to limb.
  - Slits freely aligned parallel to filament axis, polarity inversion line, etc.

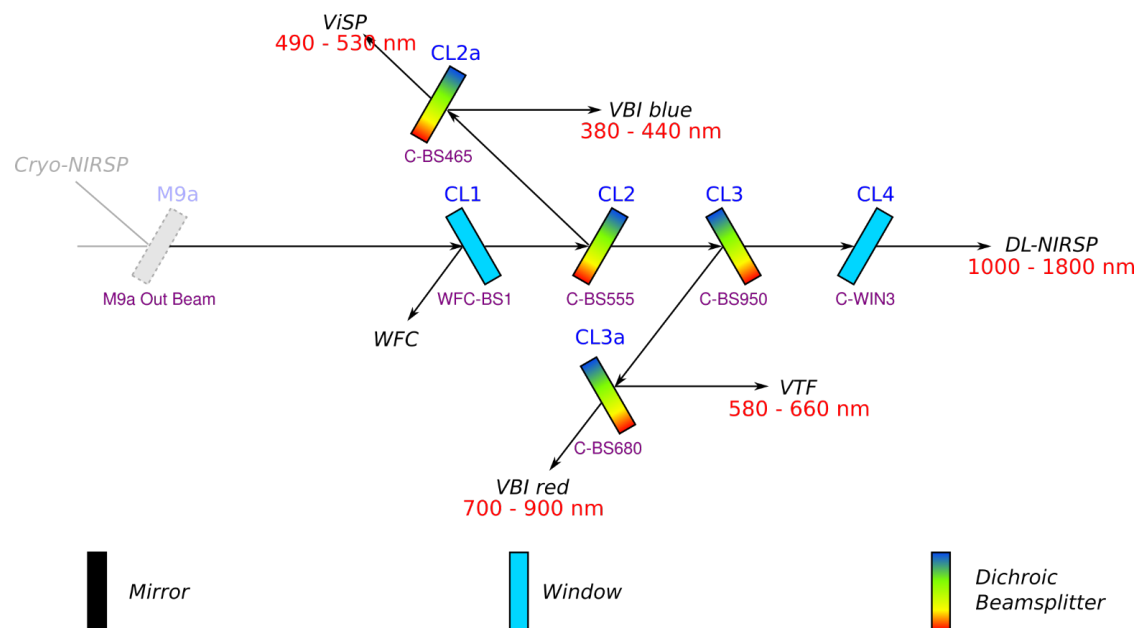
### 3. (Manually-changed) spectral distribution of light to instruments.

## Facility Instrument Distribution Optics (FIDO)

- FIDO consists of dichroic beamsplitters downstream of the adaptive optics deformable mirror.
- A mirror feeding the Cryo-NIRSP can be inserted ahead of AO within some *20-30 minutes* for fast switch-over
- “All or No Light in a wavelength band”
- The dichroics are *interchangeable* for maximum flexibility
- Each individual instrument can also be fed *all* of the light using a mirror and windows
- Changing a dichroic configuration can take up to *one day*
  - Changing of configurations will likely be minimized during DKIST operations
  - Aim is to establish a list of configurations that are often requested



### 3. Flexible (manually-changed) spectral distribution of light to instruments.



Light entering Coudé is spectrally distributed to instruments with user-configurable (manually-changed) distribution optics (FIDO).

Concept: “All or no light in a wavelength band.”

All instruments except one (Cryo-NIRSP) can be operated at same time and with AO.

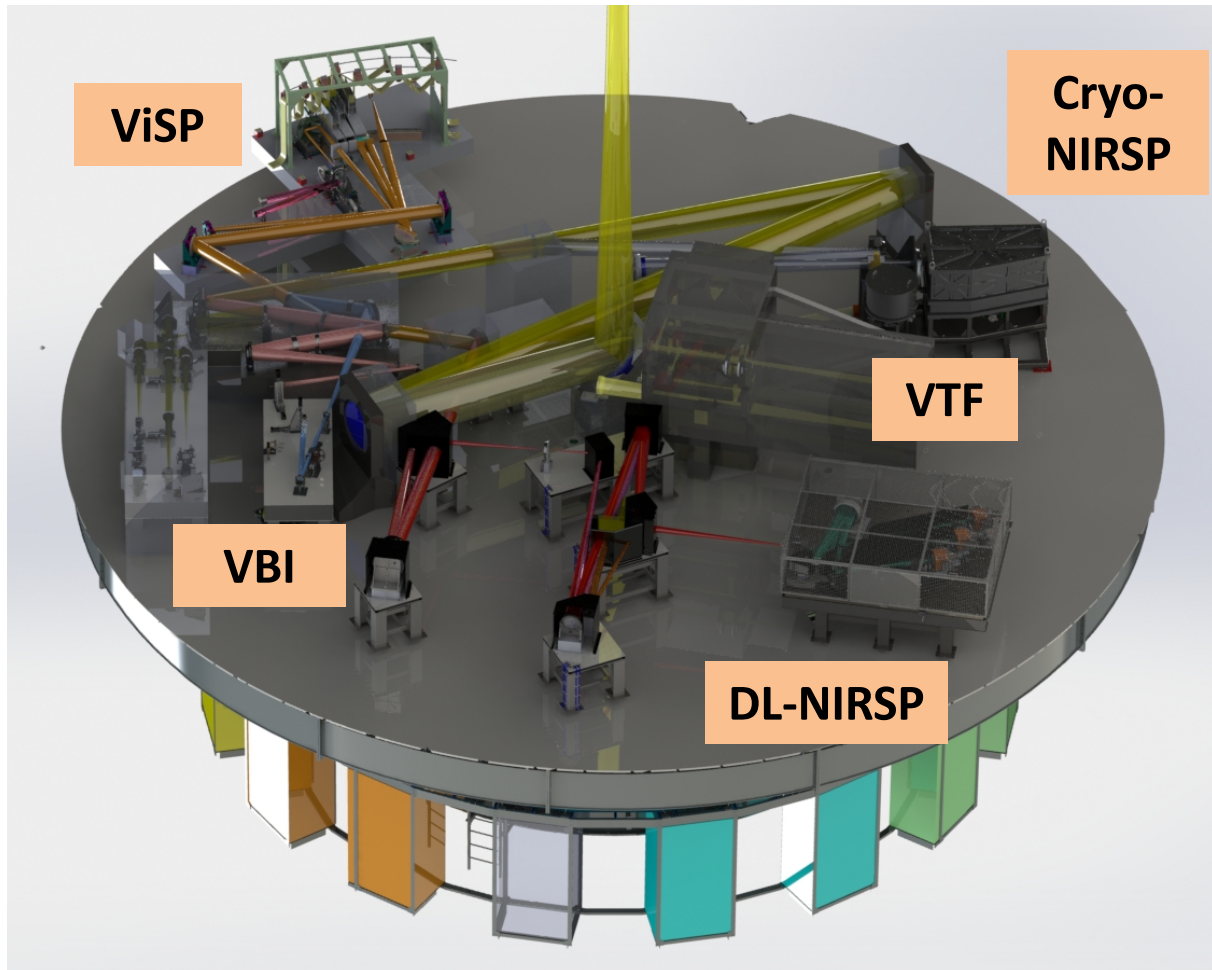
Detailed discussion to follow.

# Available beamsplitters/windows

Name	Reflected Band	Transmitted Band	Comment
C-BS465	380 – 440 nm	490 – 1800 nm	Standard Location: CL2A
C-BS555	380 – 530 nm	580 – 1800 nm	Standard Location: CL2
C-BS680	380 – 660 nm	700 – 1800 nm	Standard Location: CL3A
<i>C-BS643</i>	<i>380 – 630 nm</i>	<i>656 – 1800 nm</i>	<i>Procurement is a GOAL</i>
C-BS950	380 – 900 nm	1000 – 1800 nm	Standard Location: CL3
C-WIN1		380 – 900 nm	Transmission band AR coat
C-WIN2		380 – 1800 nm	Uncoated front surface
C-WIN3		500 – 1800 nm	Transmission band AR coat Standard Location: CL4
C-MIR1	380 – 1800 nm		Protected Silver coat



## 4. Spectral/imaging/polarimetric capabilities of facility instruments



### First-Light Instrument Suite

Five complementary image-, slit-, and IFU-based instruments.

Diverse spectral coverage with considerable overlap.

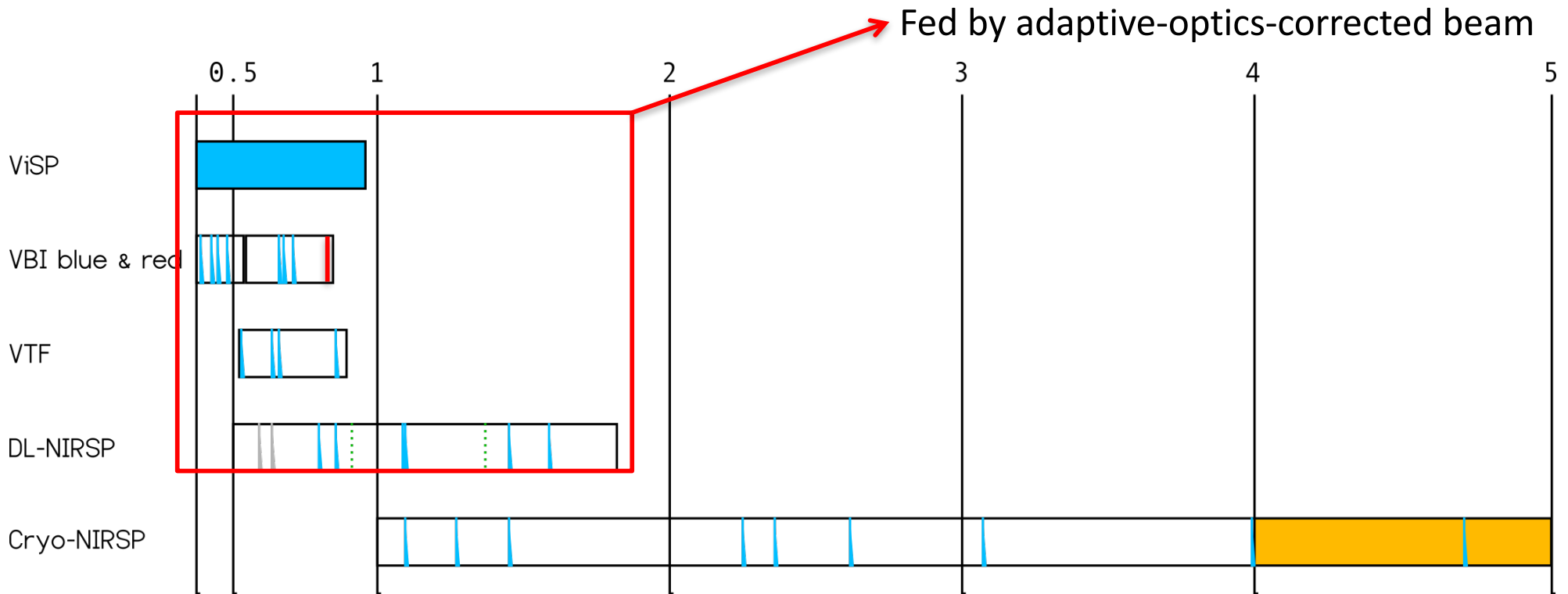
Diagnostics across the entire solar atmosphere.

Spectropolarimetric focus.

# DKIST Instrument Suite Overview

Instrument Name	Acronym	Wavelength Range	Analogs
Visible Broadband Imager	VBI (blue, red)	390 – 550 nm 600 – 860 nm	Hinode/BFI; ROSA <i>High cadence, high spatial res.</i>
Visible Spectro-Polarimeter	ViSP	380 – 900 nm	SPINOR, Hinode/SP, IRIS <i>Scanning spectrograph, high spectral fidelity</i>
Diffraction-Limited Near IR Spectro-Polarimeter	DL-NIRSP	500 – 900 nm 900 – 1350 nm 1350 – 1800 nm	SPIES <i>True IFU, variable spatial resolution / FOV</i>
Visible Tunable Filter	VTF	520 – 870 nm <b>(590 – 870 nm)</b>	IBIS, CRISP, GFPI, HMI <i>Imaging spectro-polarimeter</i>
Cryogenic Near IR Spectro-Polarimeter (with context imager)	Cryo-NIRSP	1000 – 5000 nm	CYRA (BBSO) <i>Cryogenic, scanning spectrograph, novel IR diagnostics</i>

# Spectral coverage summary

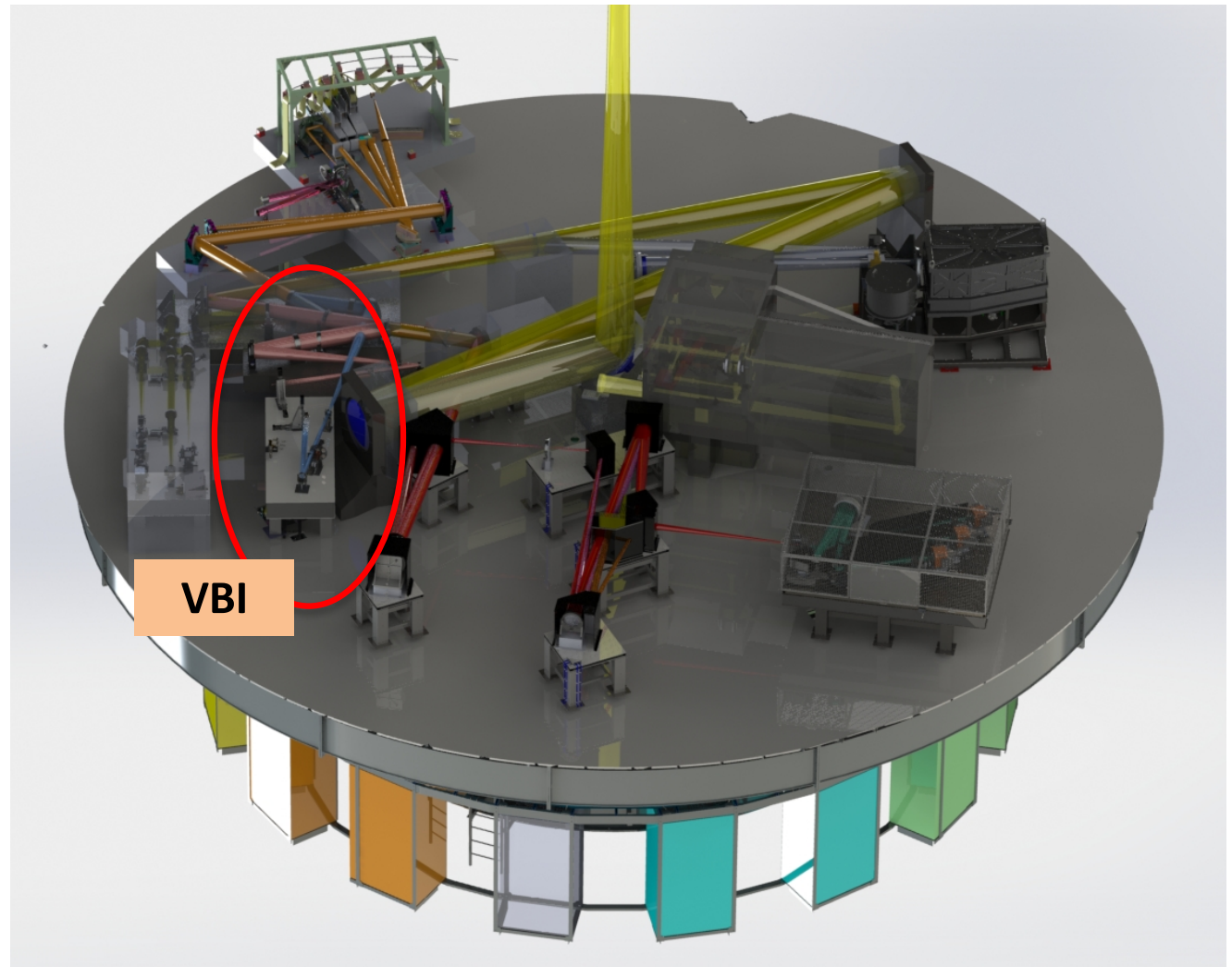
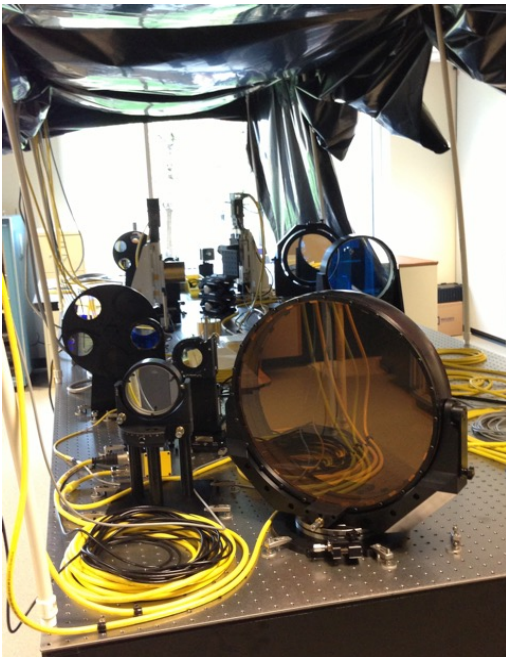


- Instruments – *with the notable exception of the ViSP* – operate at discrete wavelengths, because of the required pre-filters for the instruments.
- Instruments can work alone, or together (Cryo-NIRSP can only work alone)

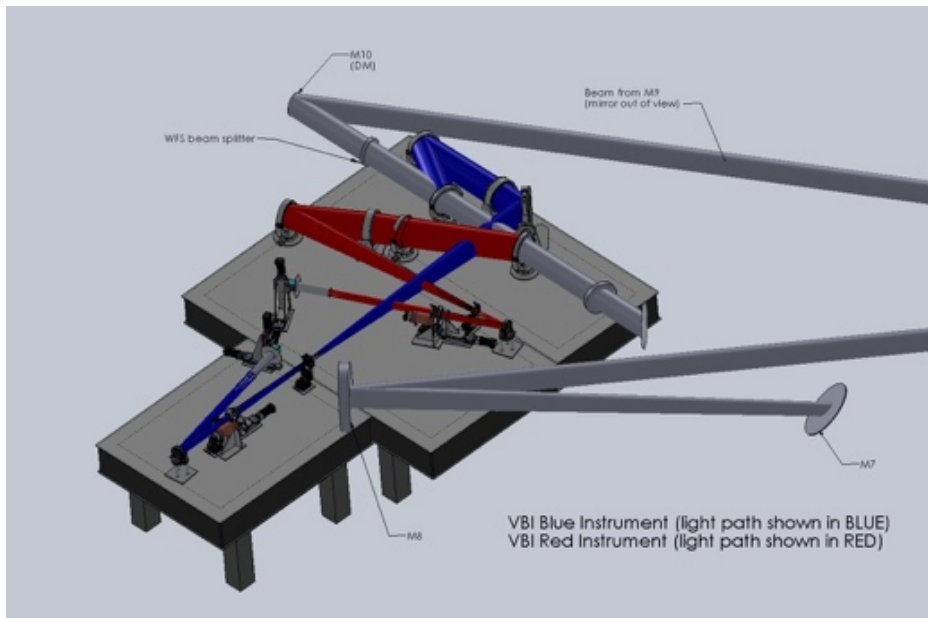
# Visible Broadband Imager (VBI)

*High cadence, high  
spatial resolution  
imaging w/ Speckle  
reconstruction*

NSO



# Visible Broadband Imager (VBI)

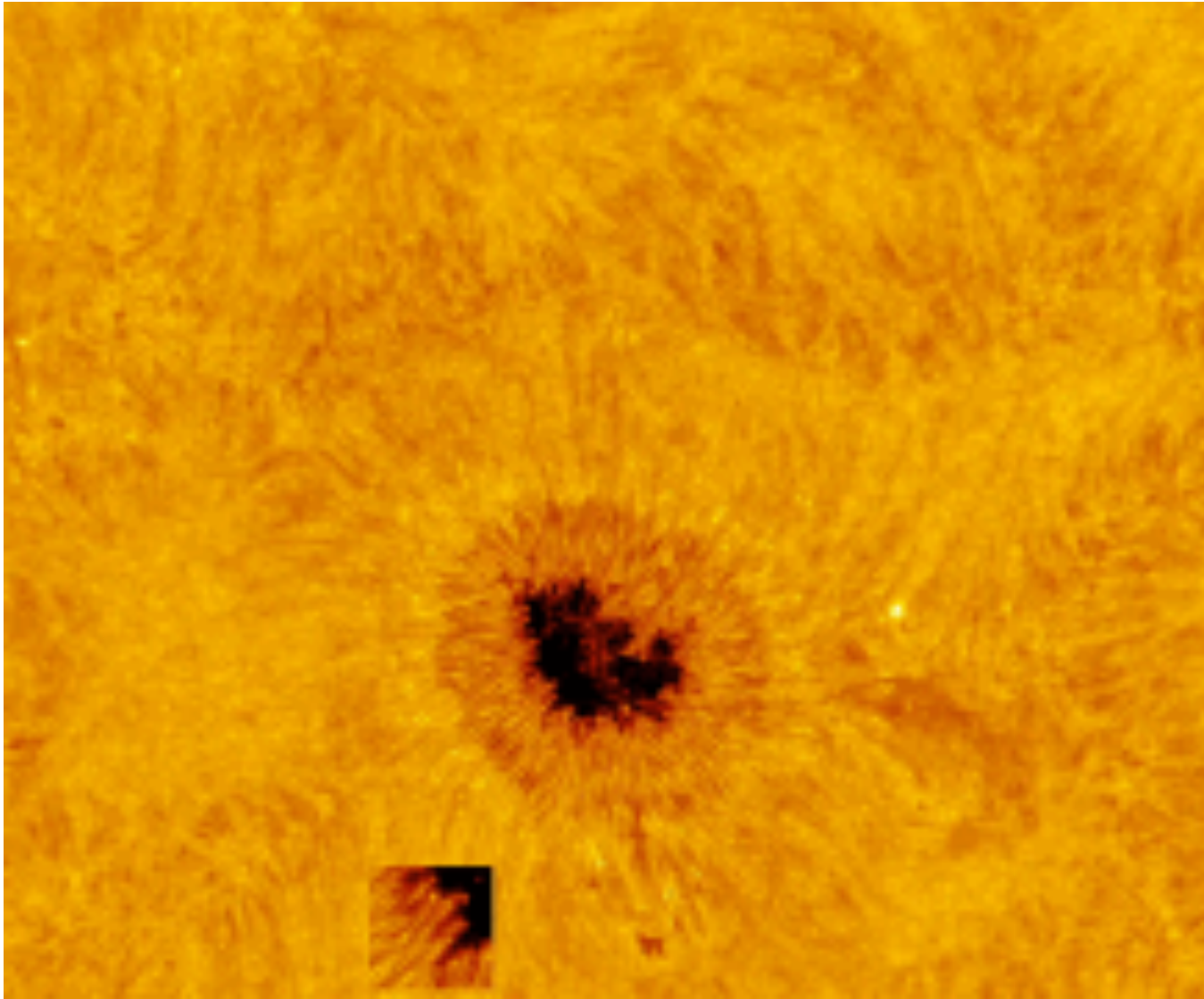


- 2 detectors (channels)  
4 filters available in each channel  
(0.05 – 0.5 nm FWHM)
- Sequential selection of filters  
(within each channel)
- Channels fully independent; can work together or alone
- BLUE (390-550 nm):  
CaII K, G-band,  
continuum, H-beta
- RED (600-860 nm):  
H-alpha, continuum,  
TiO, Fe XI 789.2 nm (corona)
- NO polarimetry



# Visible Broadband Imager (VBI)

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Demonstration  
of the VBI  
H-beta filter

486.139 nm  
FWHM: 0.0464 nm

# Visible Broadband Imager (VBI)

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## Instantaneous Field of View:

45 x 45 arcsec<sup>2</sup> (blue channel)

69 x 69 arcsec<sup>2</sup> (red channel)

## Full optical field:

2 x 2 arcmin<sup>2</sup> – by field sampling:

3 x 3 tiles in blue channel.

2 x 2 tiles in red channel

## Spatial sampling:

0.011 arcsec (blue)

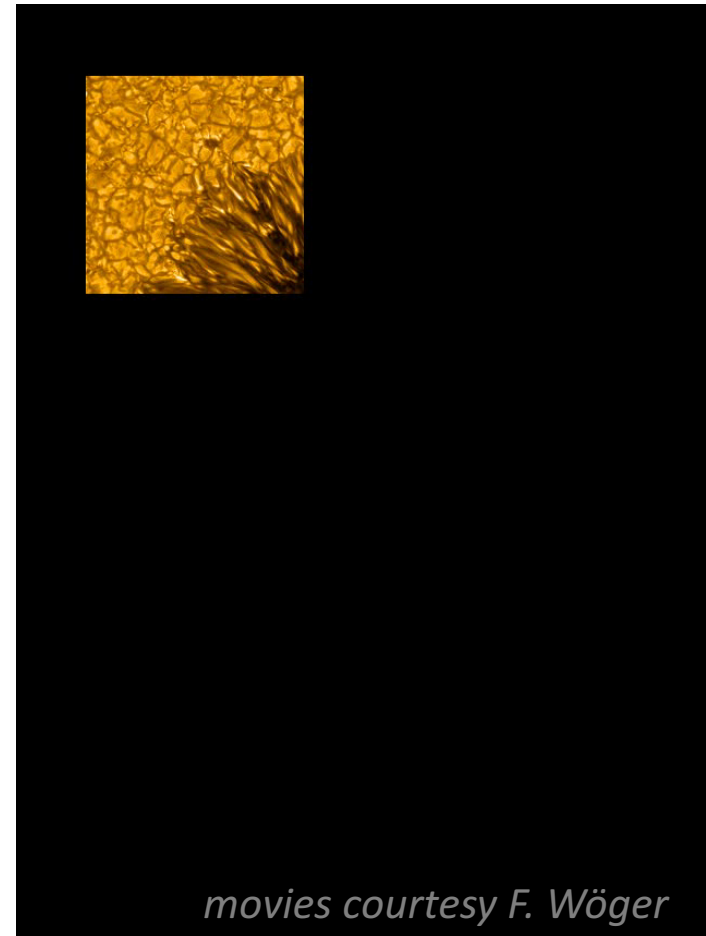
0.017 arcsec (red)

## Temporal Sampling:

3.2 s for speckle reconstructed images

0.033 s raw images

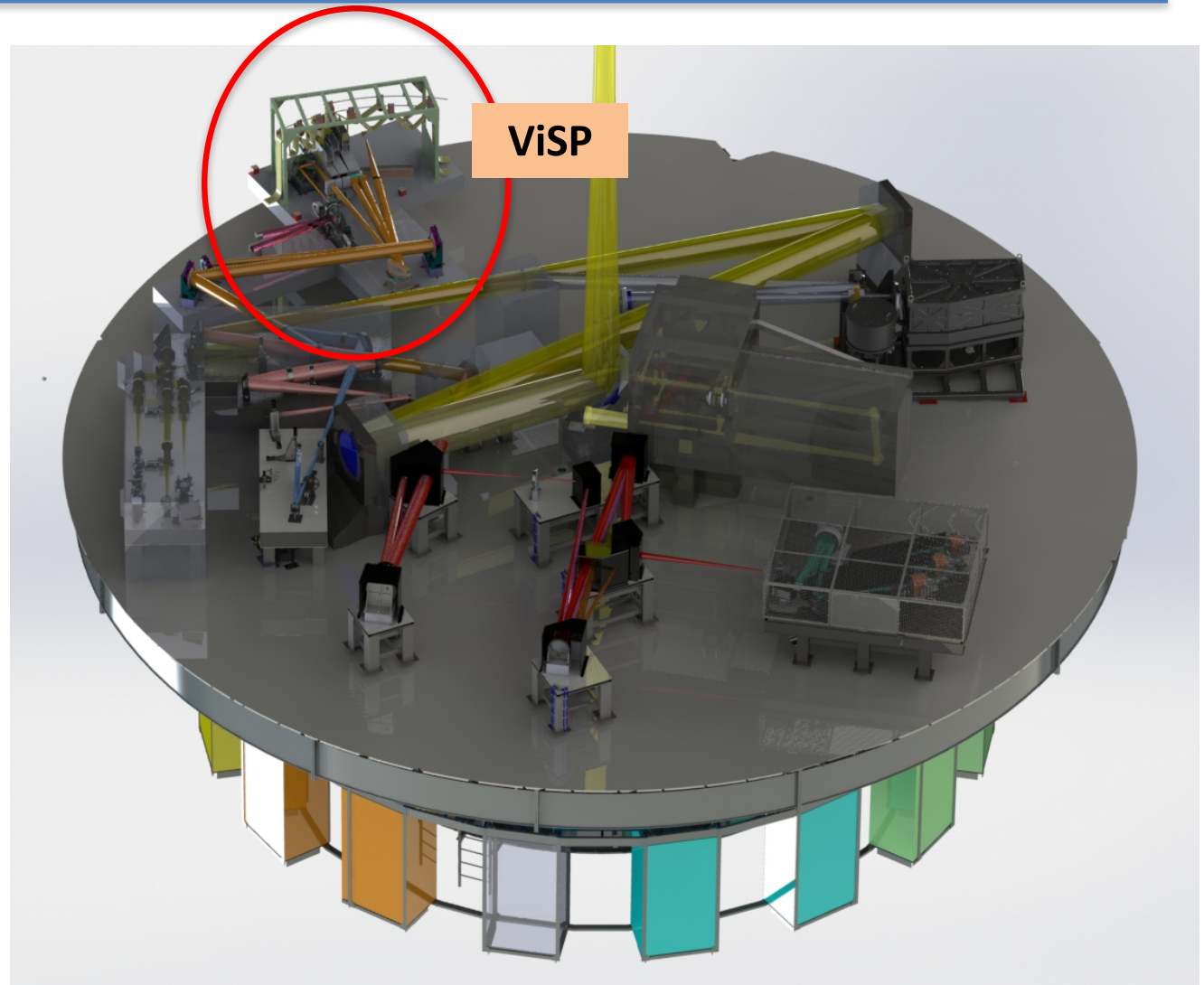
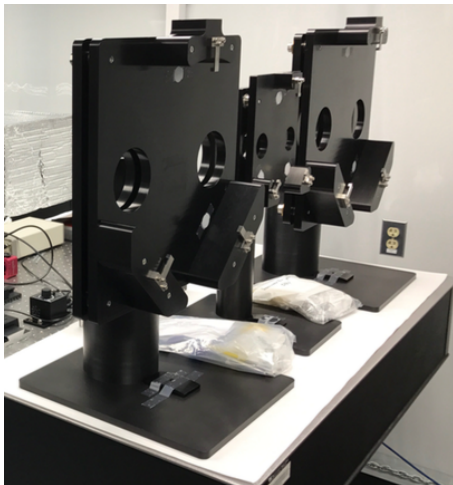
0.5 s change of FOV



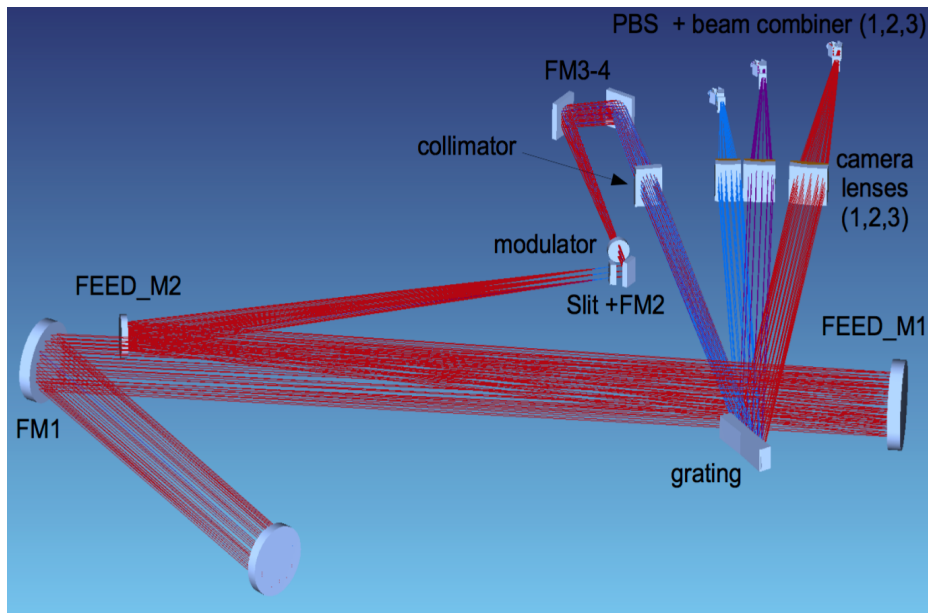
VBI stresses high cadence and high spatial resolution –  
will deliver images at the diffraction limit of the telescope

# Visible Spectro-Polarimeter (ViSP)

*Scanning slit  
spectropolarimeter,  
high spectral fidelity,  
broad access to well-  
established and new  
spectral diagnostics*



# Visible Spectro-Polarimeter (ViSP)



- Diffraction-grating based spectrograph. Access to full visible spectrum: 380 – 900 nm
- 3 distinct “arms”: up to 3 separate spectral bands ( $\sim 1$  nm wide) can be observed simultaneously
- ANY portion of the spectrum can be imaged on ANY spectral arm – depending on combination of desired ranges
- 5 possible slit widths: from 0.028” to 0.214”
- Dual beam full Stokes polarimetry
- Uses VBI blue-channel images for context

# Visible Spectro-Polarimeter (ViSP)

## Instantaneous Field of View:

slit width x (75", 60", 50")

## Full optical field:

Slit length x 2 arcmin – by slit scanning

## Spatial sampling:

0.03", 0.0236", 0.0198" (along slit, arms 1-2-3)

## Spectral Resolution:

$\leq 3.5$  pm @ 630 nm or  $R \gtrsim 180,000$

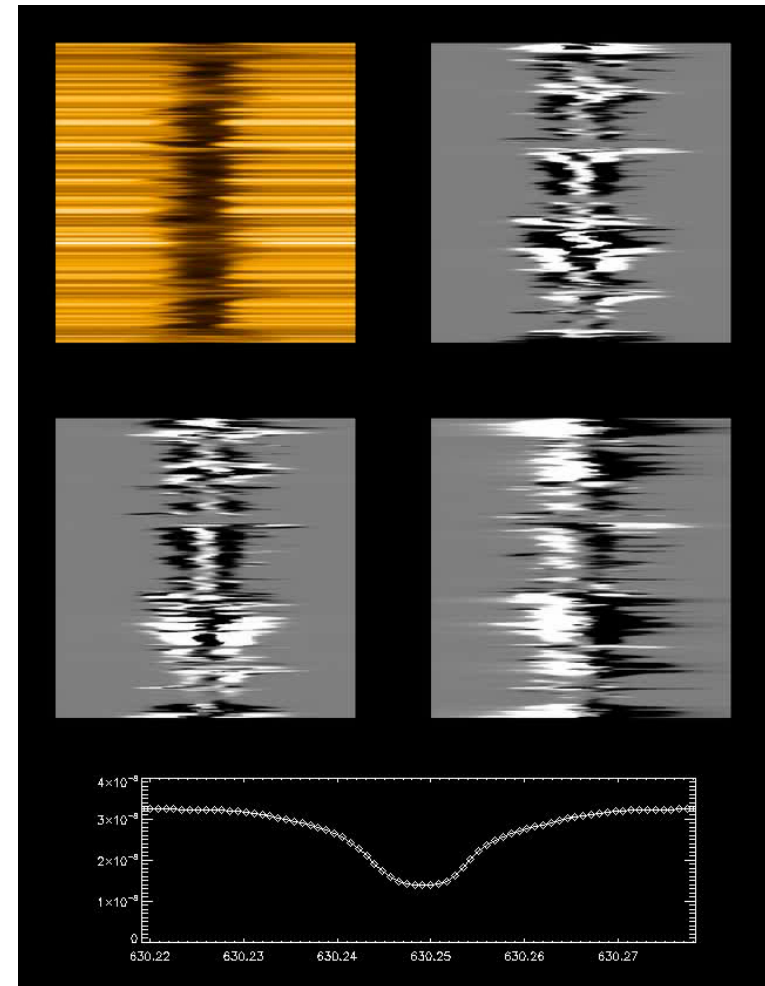
## Temporal Sampling:

0.5-10 sec per slit position (polarimetry);

0.02-0.2 sec per slit position (spectroscopy)

## Polarimetric Capability:

Target Accuracy:  $10^{-3}$  P/I<sub>cont</sub> in 10 sec



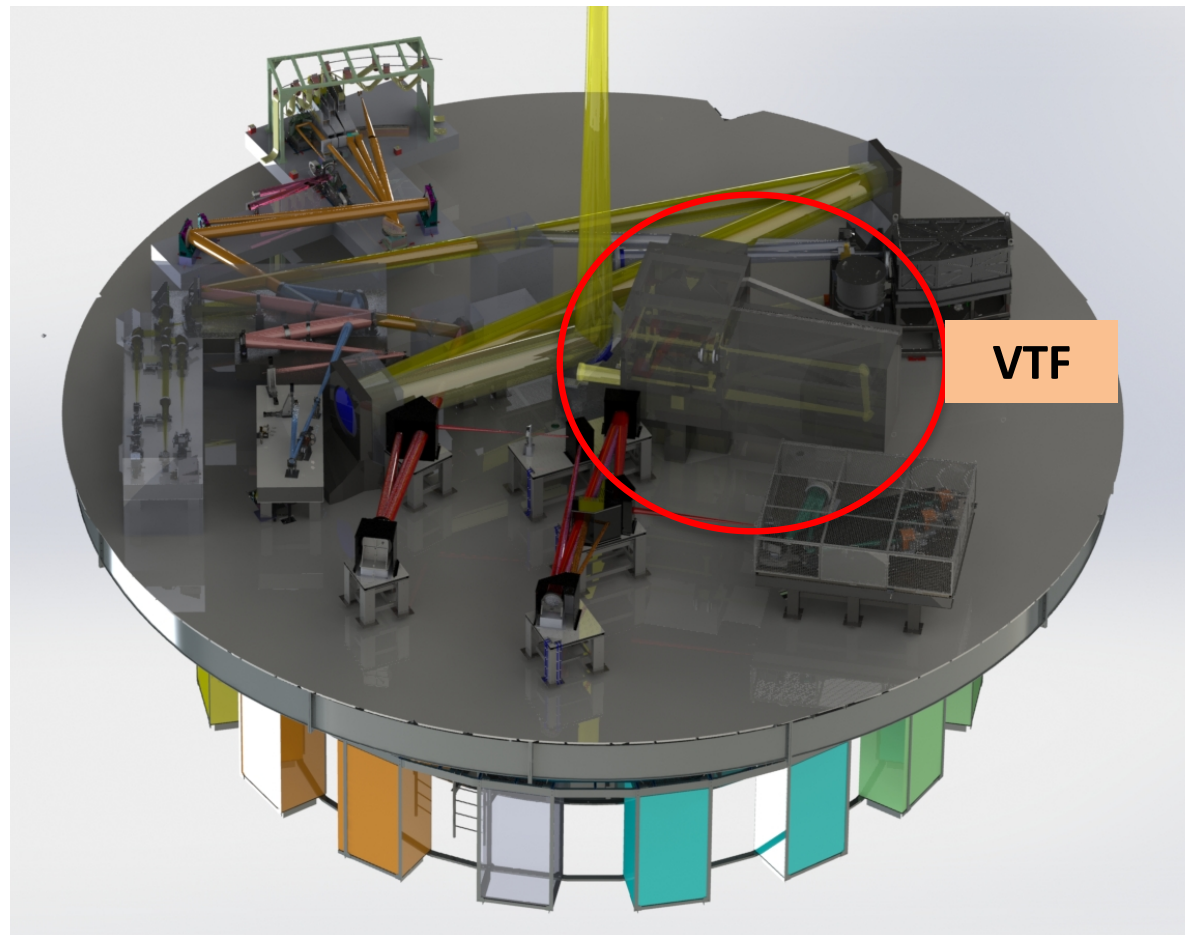
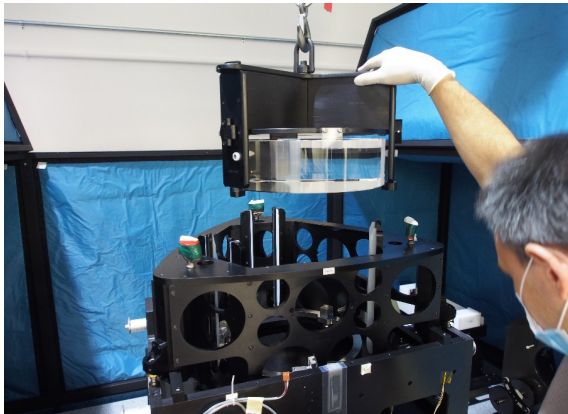
ViSP stresses high spectral fidelity and flexibility–  
will deliver high precision spectro-polarimetry



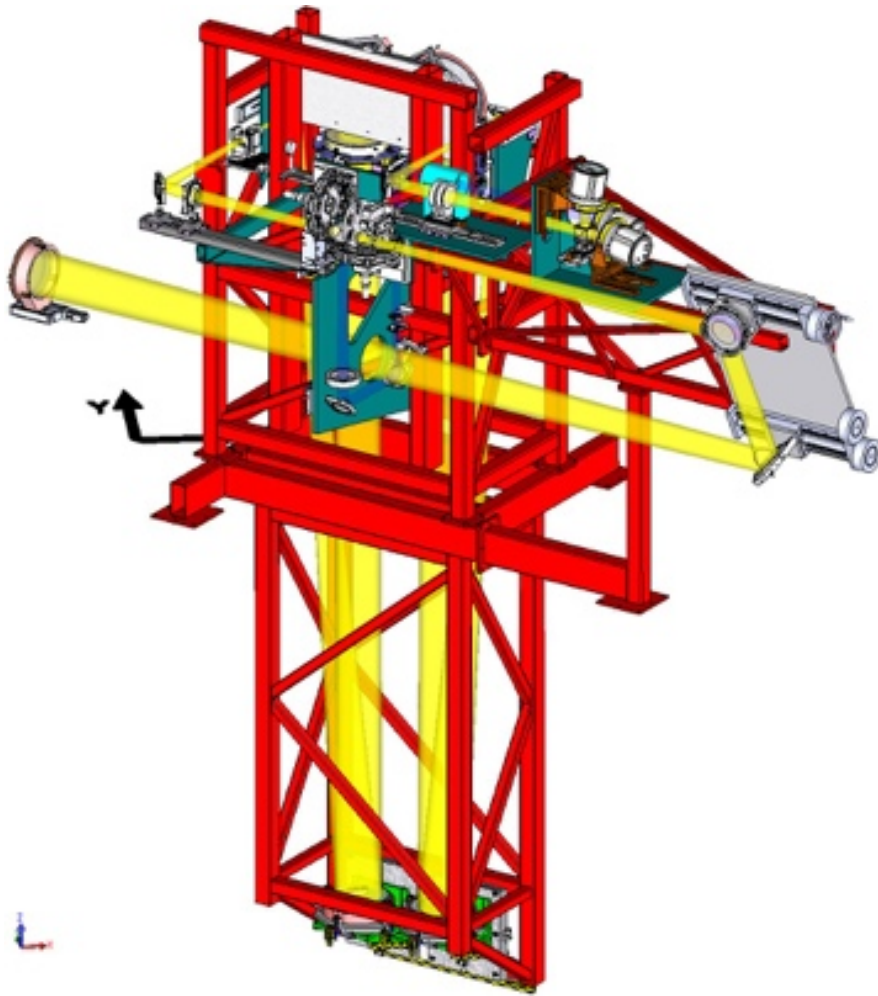
# Visible Tunable Filter (VTF)

*Fast-tuning, narrowband  
imaging spectro-  
polarimeter, high fidelity  
spectro- imaging with  
great coverage of  
temporal dynamics.*

KIS



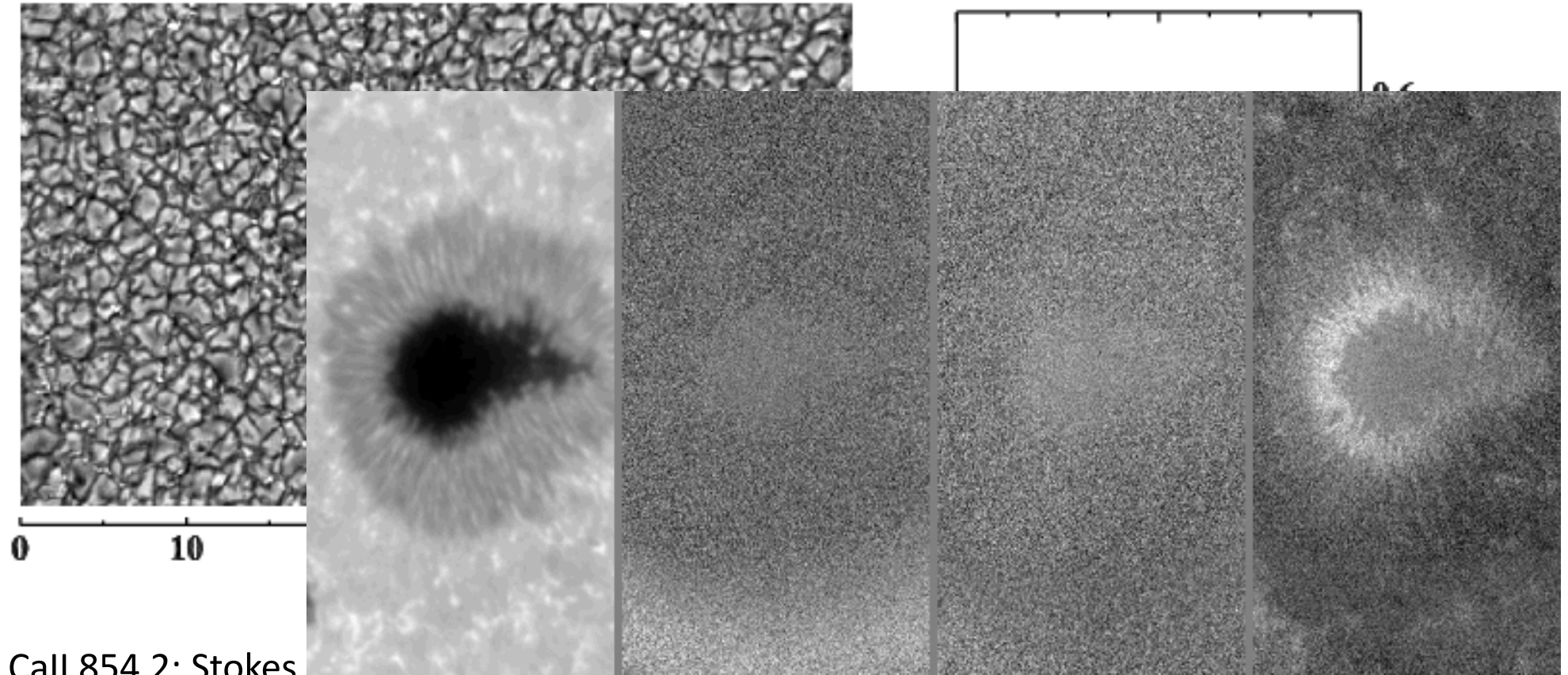
# Visible Tunable Filter (VTF)



- Dual Fabry-Perot system for imaging spectro-polarimetry (300 mm FP)
- Spectral range: 520 – 870 nm. First light filters: NaD1, FeI 630.2nm, H-alpha, CaII 854.2 nm ( ~ 1 nm wide)
- Sequential selection of filters/sampling wavelengths
- Simultaneous broad-band images
- Orthogonal polarization states are imaged on two separate detectors
- At first light, only one etalon will be available: limited sampling for broad (chromospheric) lines

# VTF Predecessor Example: IBIS

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Call 854.2: Stokes I only

Call 854.2: I, Q, U, V



# Visible Tunable Filter (VTF)

## Instantaneous Field of View:

60 x 60 arcsec<sup>2</sup>

## Spatial sampling:

0.014 arcsec/pixel

## Spectral Resolution:

6 pm FWHM (@600 nm),  $R \sim 100000$

## Temporal Sampling:

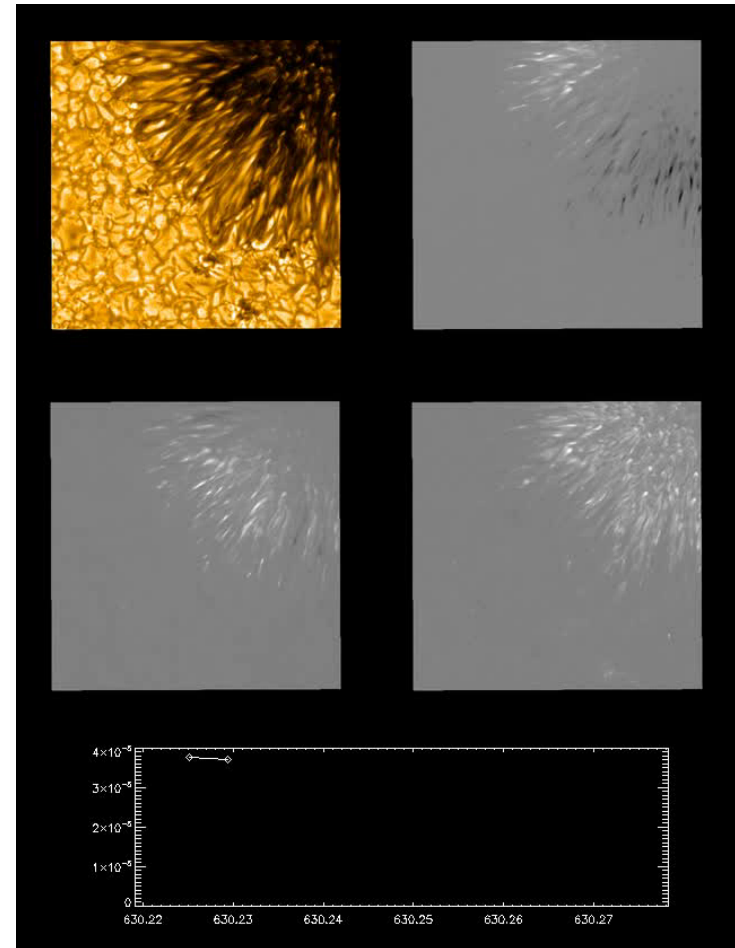
1-2 s per line scan (spectroscopy)

5-10 s per line scan (polarimetry)

## Polarimetric Capability:

Full Stokes vector polarimetry

Target Accuracy:  $3 \times 10^{-3} P/I_{\text{cont}}$

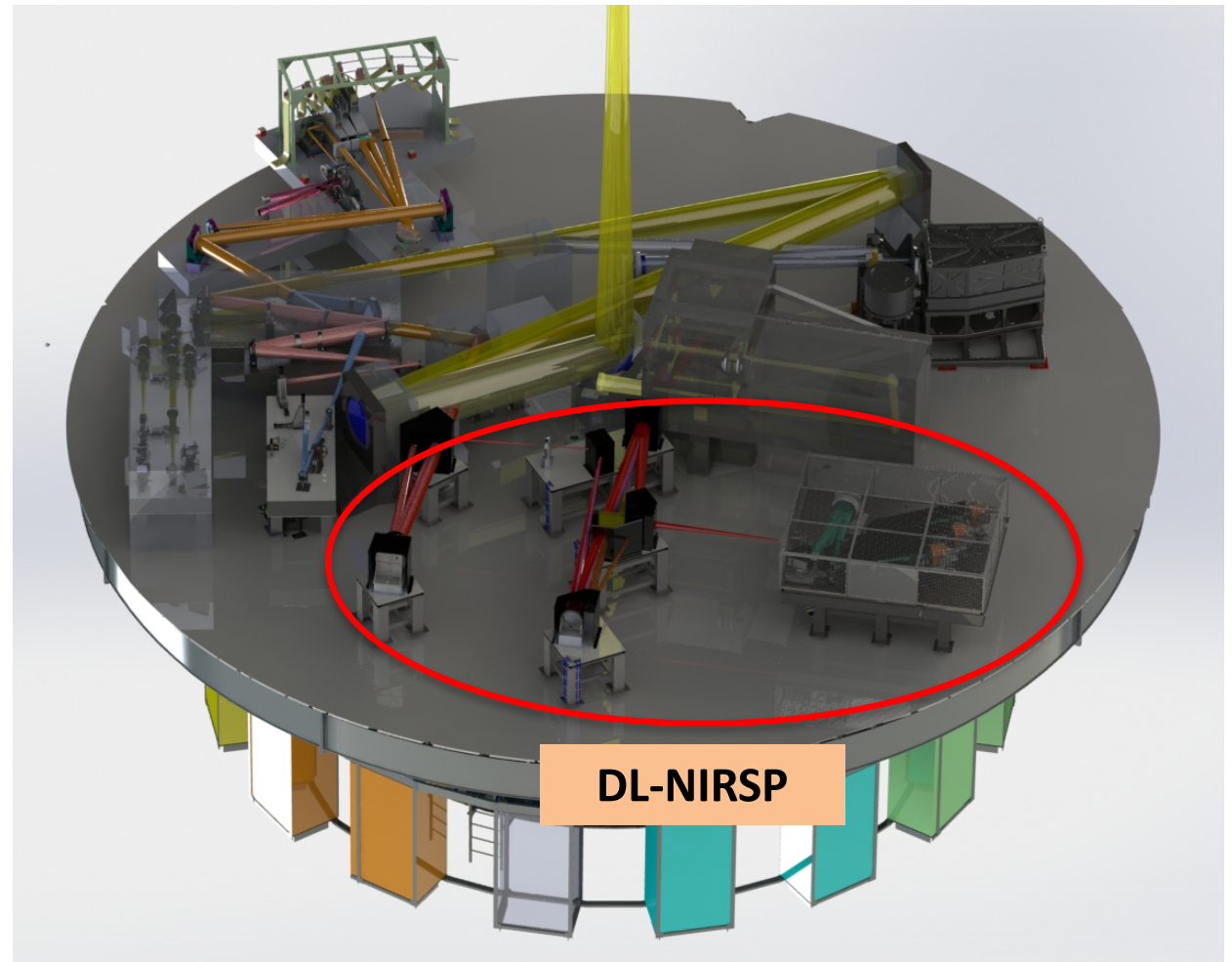
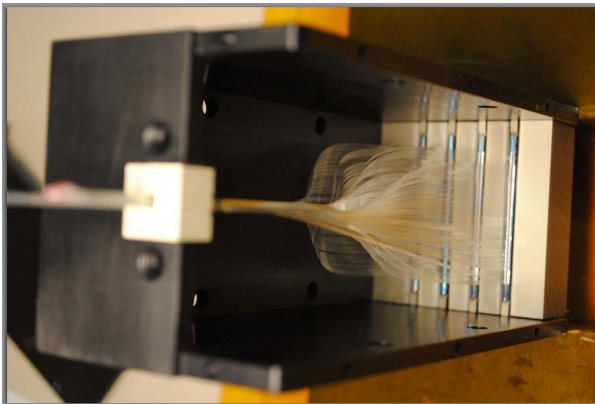


VTF will have very high spatial resolution, and allow rapid imaging spectrometry, Stokes imaging polarimetry, and accurate surface photometry.

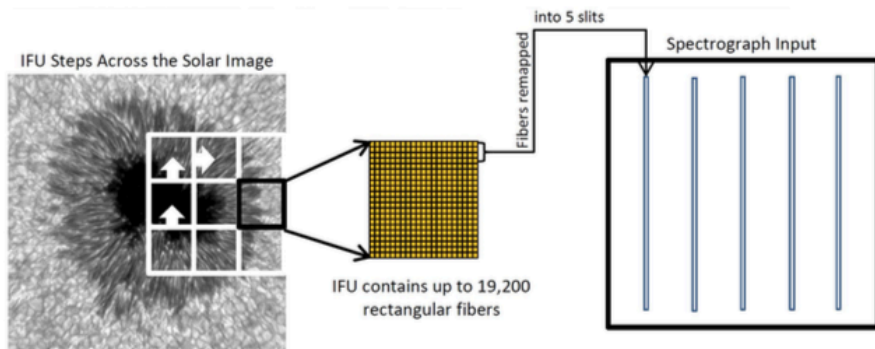
# Diffraction Limited Near-IR Spectropolarimeter (DL-NIRSP)

*First facility class  
integral field  
spectropolarimeter for  
solar physics.  
Simultaneous spectral  
and 2d spatial  
coverage.*

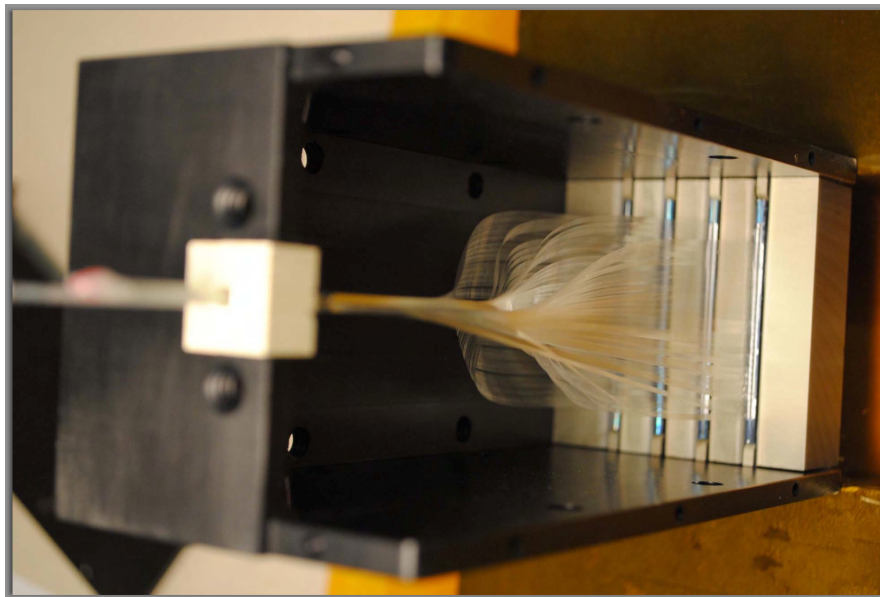
*UH/IfA*



# Diffraction Limited Near-IR Spectropolarimeter (DL-NIRSP)



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

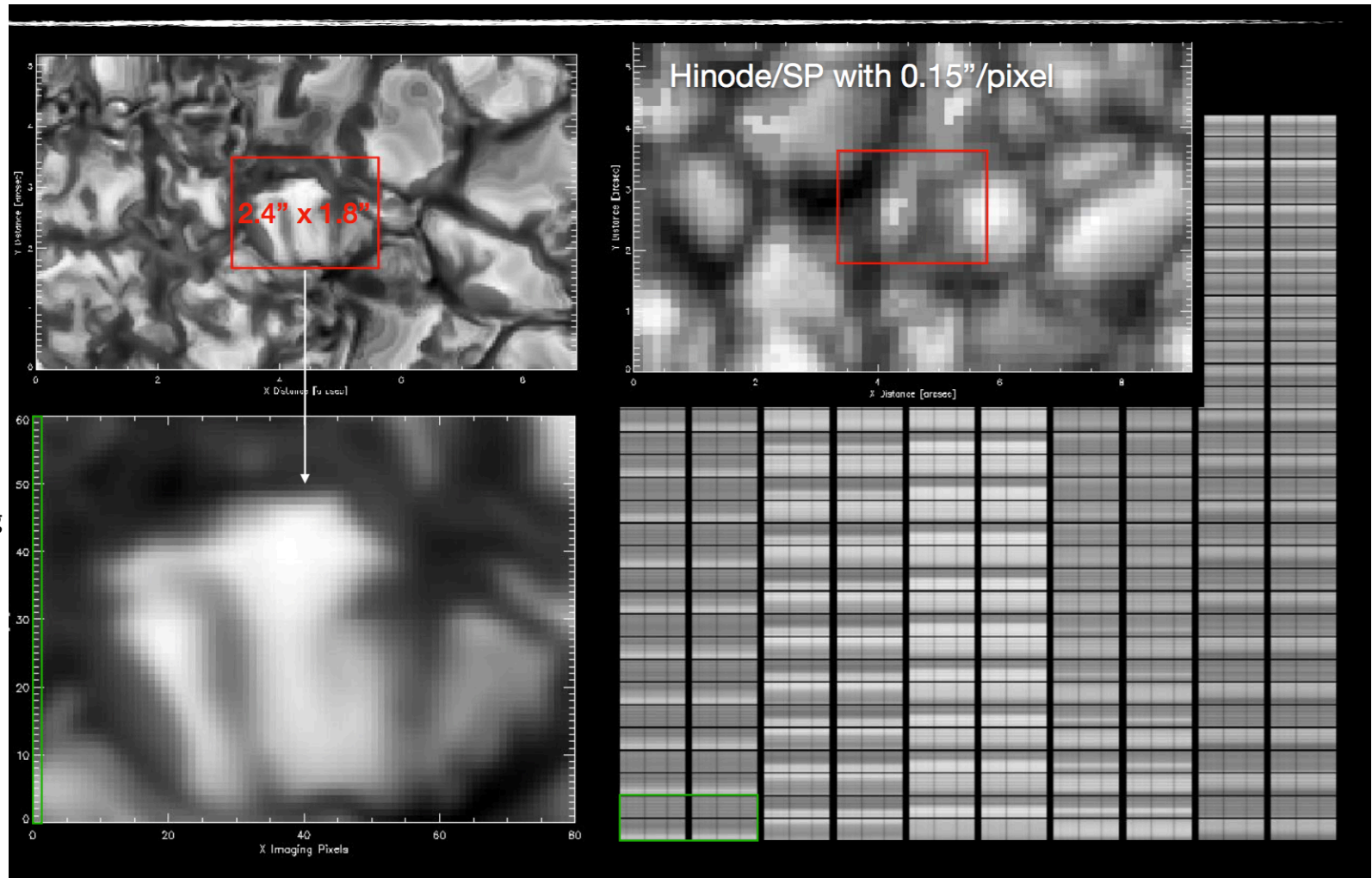


- Diffraction grating based Integral Field Spectrograph
- Spectral range: 500 -1800 nm
- 3 synchronized co-operating channels:  
500-900 nm  
900-1350 nm  
1350-1800 nm
- Only one spectral band ( $\sim 1-2$  nm) per channel can be observed. First light filters:  
Fe XI 789.2 ; Ca II 854.2;  
Fe XIII 1074.7 ; He I 1083.0;  
Si X 1430 ; Fe I 1565 nm
- Dual beam polarimetry



# DL-NIRSP : what do the data look like?

1D radiative transfer  
calculation @ 500 nm;  
simulation with 32 km  
resolution (Rempel, 2012)



Dual-beam spectra from each "pixel" in the FOV

# Diffraction Limited Near-IR Spectropolarimeter (DL-NIRSP)

## Instantaneous Field of View:

2.4 x 1.8 arcsec<sup>2</sup> (high-res.)

6.16 x 4.62 arcsec<sup>2</sup> (med-res.)

27.84 x 18.56 arcsec<sup>2</sup> (wide field)

## Full optical field:

2 x 2 arcmin – by field sampling

## Spatial sampling:

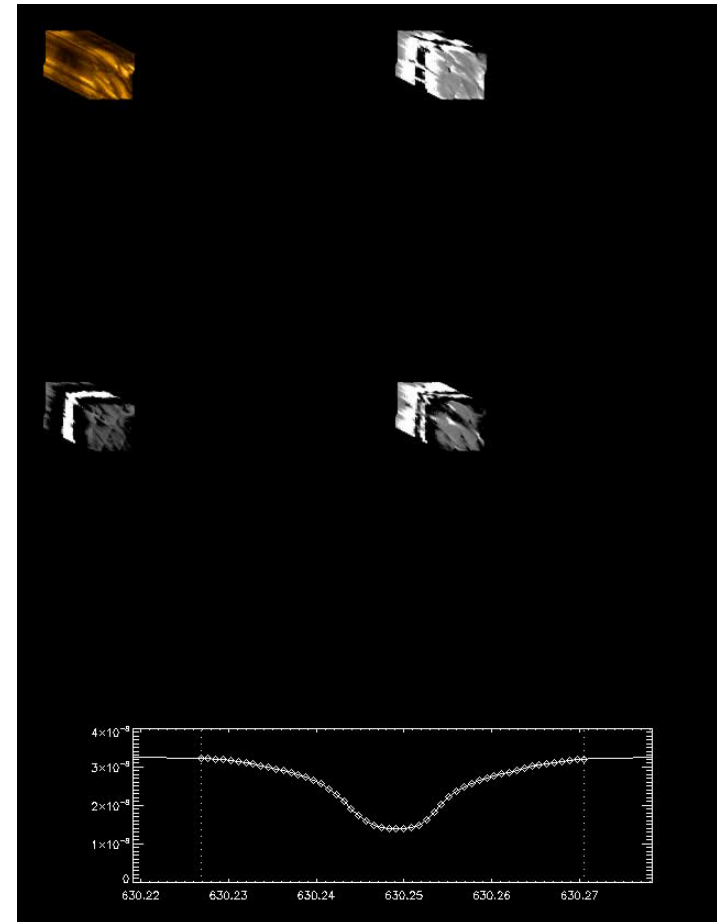
0.03, 0.077, 0.464 arcsec

## Spectral Resolution:

R = 125000

## Temporal Sampling:

0.03 – 10 seconds / tile

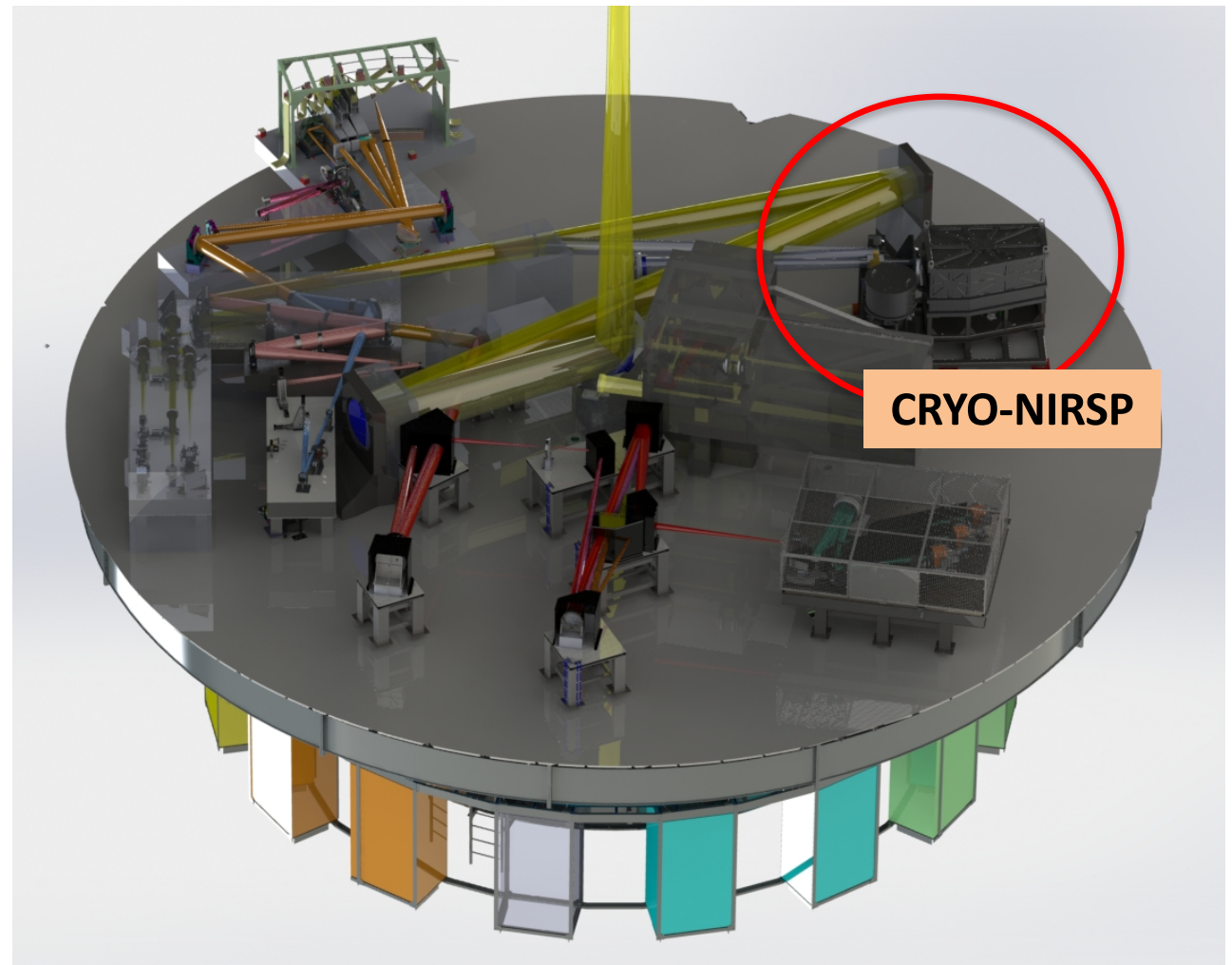


DL-NIRSP provides *simultaneous* spatial and spectral coverage over small-moderate FOVs, while maintaining high spatial resolution, spectral resolution, and polarimetric accuracy

# Cryogenic Near-IR Spectropolarimeter (Cryo-NIRSP)

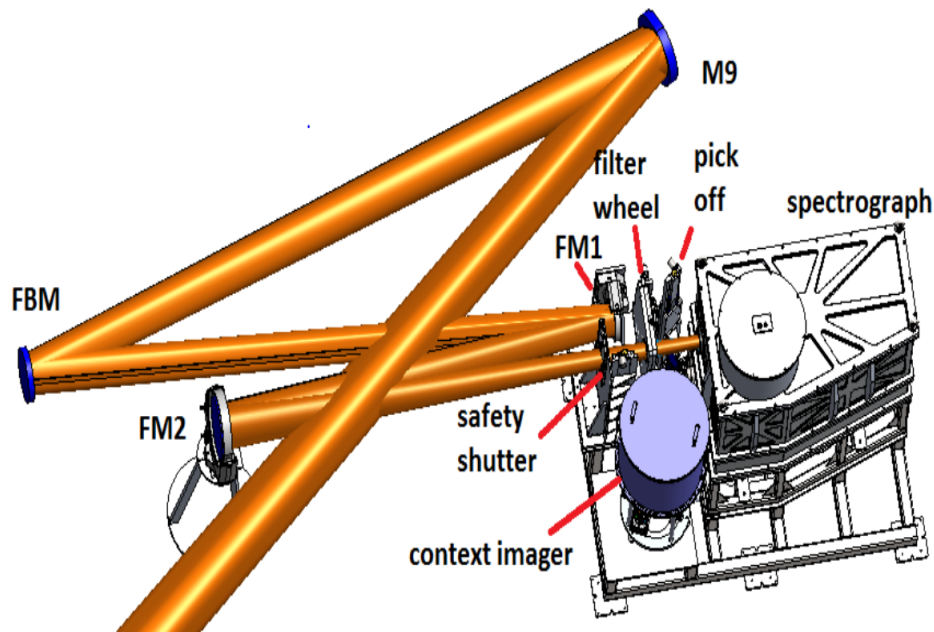
*Facility-class near-IR cryogenic slit-based spectrograph optimized for background-limited coronal and near-IR observations.*

*UH/IfA*





# Cryogenic Near-IR Spectropolarimeter (Cryo-NIRSP)



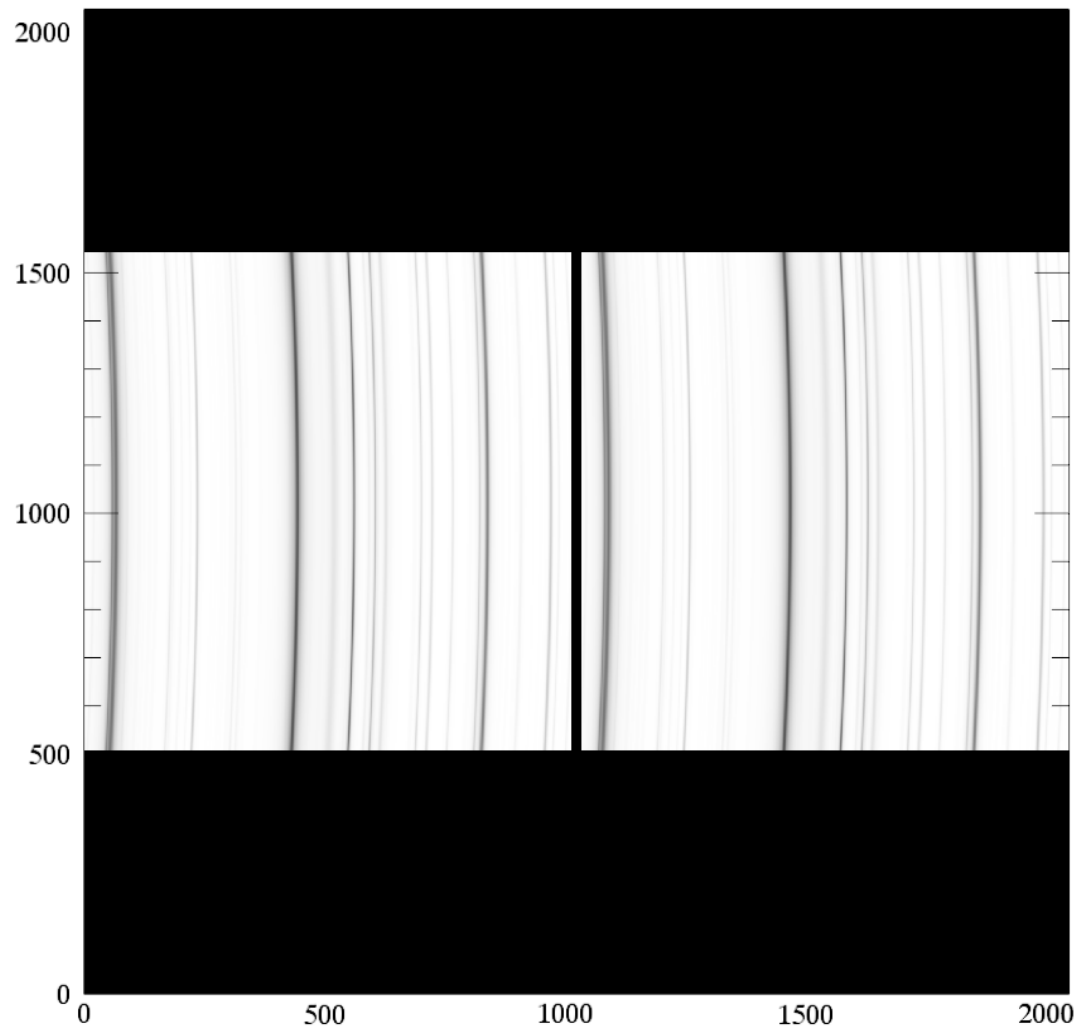
- Cryogenic: optimized for coronal observations (low background)
- Diffraction grating based spectrograph. Near IR range: 1000 – 5000 nm.
- Need order sorting filters (20-100 nm wide,  $\lambda$ -dependent). Six are currently available: diagnostics from 5,000 to 2MK
- 2 slit widths: 0.15" and 0.5" (nominal: on disk and off-limb)
- Dual beam polarimetry
- Context imager (100"x100")

# Cryo-NIRSP: dual beam polarimetry

Synthetic HeI 1083 spectra  
On-disk 2' Mode  
2' slit length

Coronal mode has 4' long slit  
and covers full array.

Context imager is 2k x 2k  
detector covering 100" x 100".



# Cryogenic Near-IR Spectropolarimeter (Cryo-NIRSP)

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## Instantaneous Field of View:

0.15" x 2' (on-disk)

0.5" x 4' (corona)

## Full optical field (by slit scanning):

2 x 2 arcmin<sup>2</sup> – on disk

4 x 3 arcmin<sup>2</sup> – coronal mode

## Spatial sampling:

0.12" along slit; 0.052" Context imager

*(No AO: stability better than 1")*

## Spectral Resolution:

R = 100,000 (Disk);

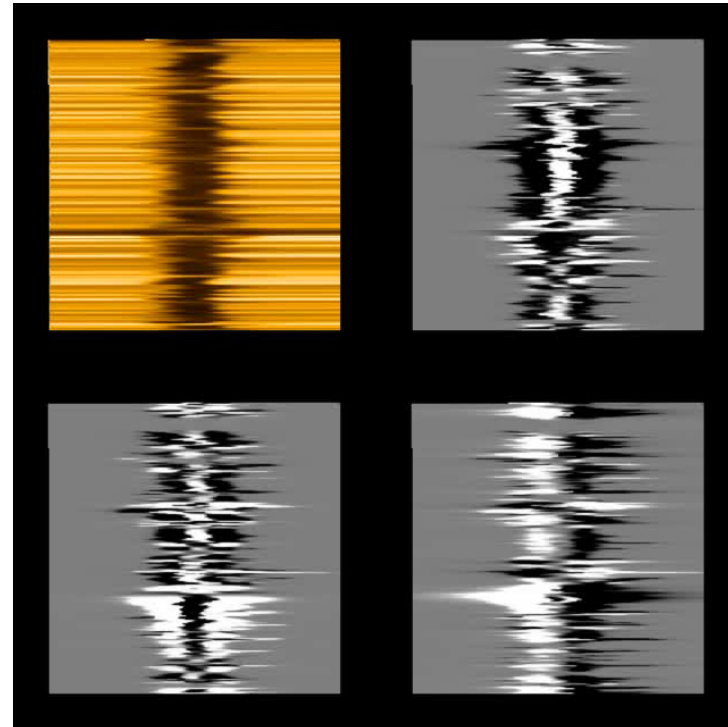
R = 30,000 Coronal Mode:

## Polarimetric Capabilities:

Full Stokes Polarimetry (Dual Beam)

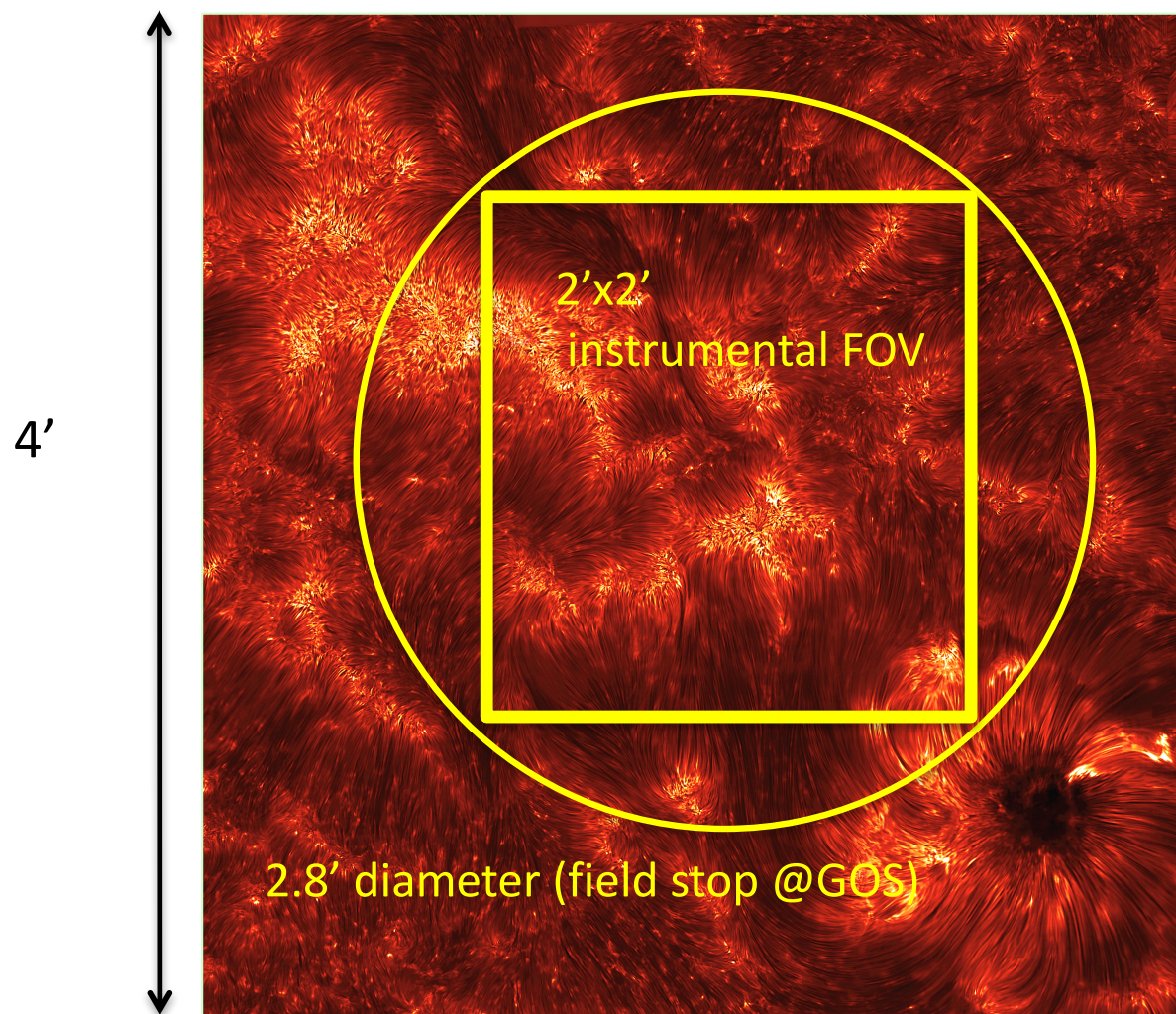
Target Accuracy:  $5 \times 10^{-4}$  P/I<sub>cont</sub>)

Context imager (100" x 100") centered on slit.



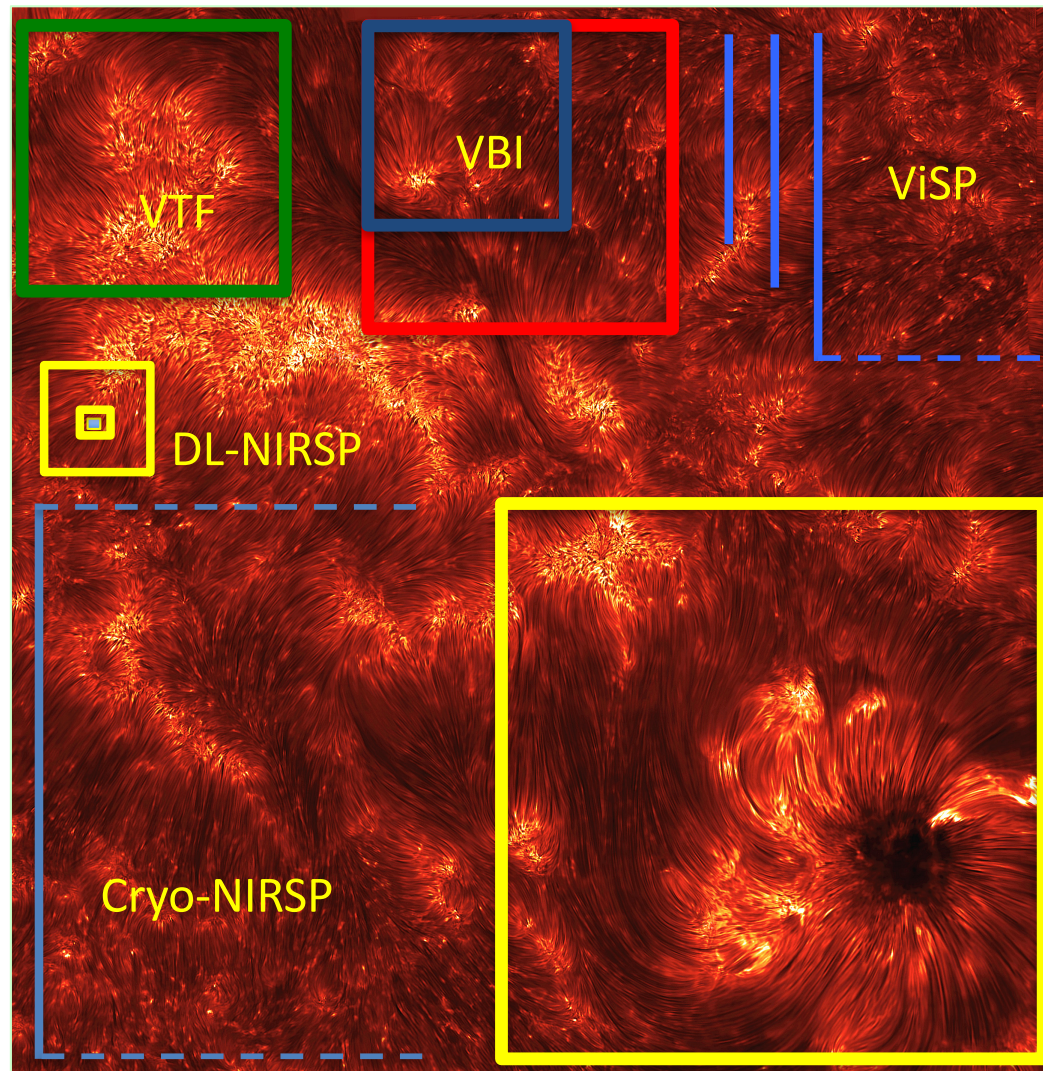
Cryo-NIRSP is optimized for coronal observations in novel, IR diagnostics. Operation flexibility serves wide range of exploratory science

# Instruments' FOV - on disk example





# Instruments' FOV comparison

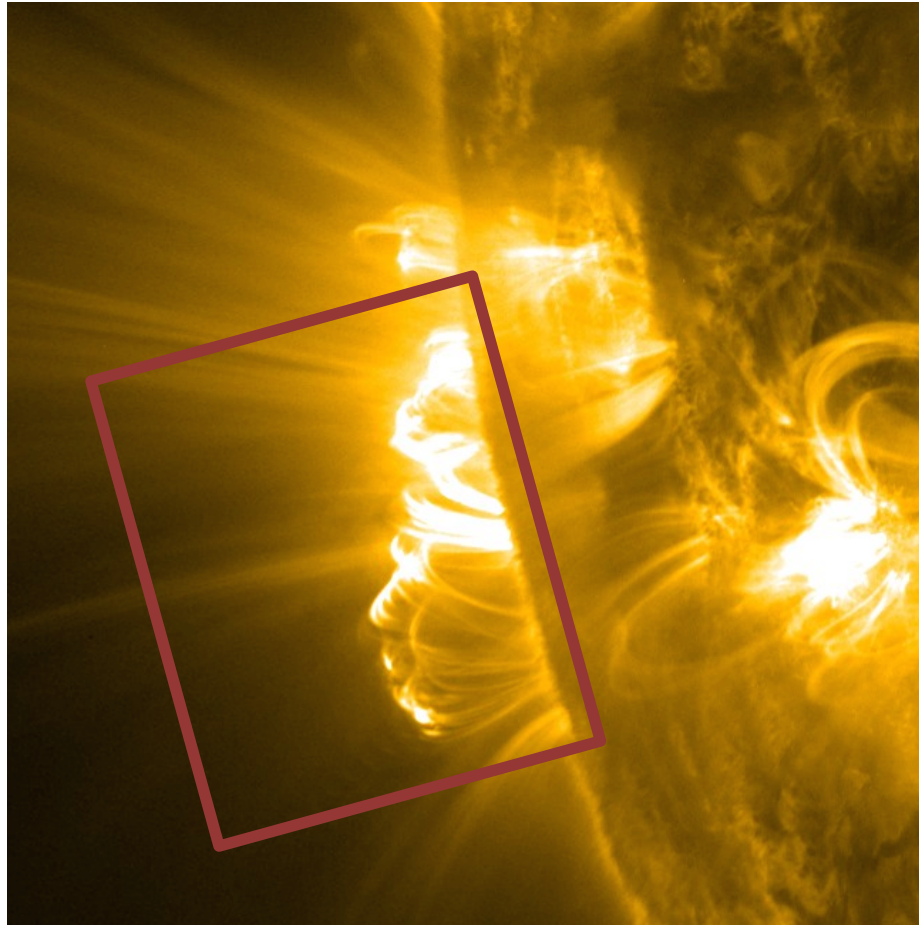


*Note: Cryo is a standalone instrument*

*Note: when working together, instruments co-point on Sun !*

# Cryo-NIRSP 5' FOV – off limb

Cryo-NIRSP





# Thanks !



<http://dkist.nso.edu/>

