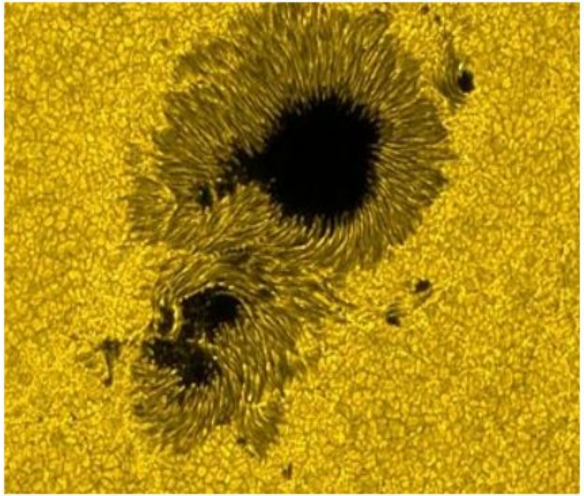
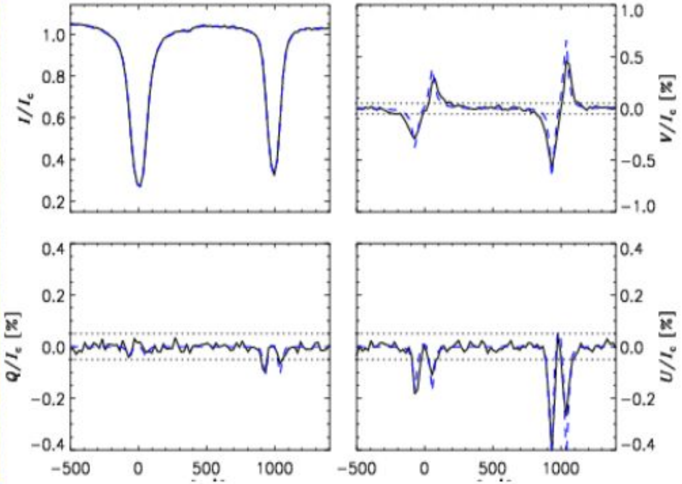
The Daniel K Inouye Solar Telescope (DKIST)

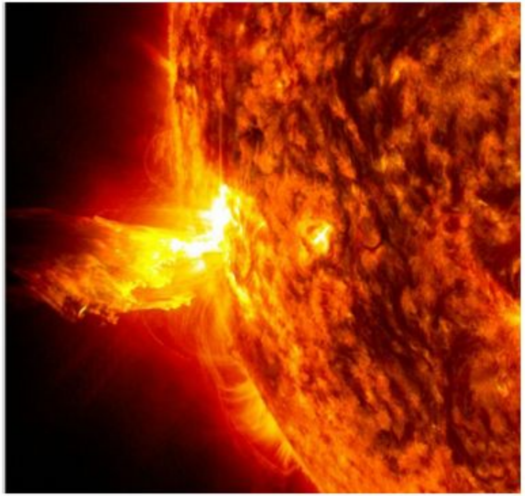
Tom Schad and the DKIST team
COLLAGE 2019 - Lecture 25
Tuesday - 23 April 2019

https://www.nso.edu/students/collage/collage-2019/

Image from the first lecture...







Key topics: solar magnetohydrodynamics, spectroscopic and spectropolarimetric plasma diagnostics, and modeling of solar activity and space weather

The solar atmosphere is

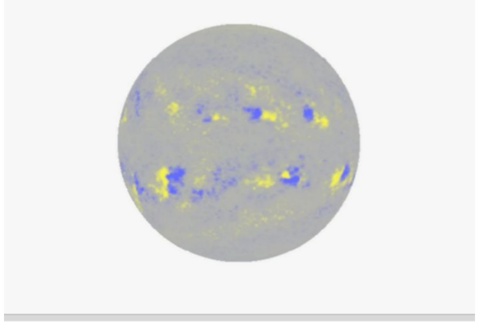
...multi-scaled and dynamic -- a complexity interplay of plasma motions and solar magnetism.

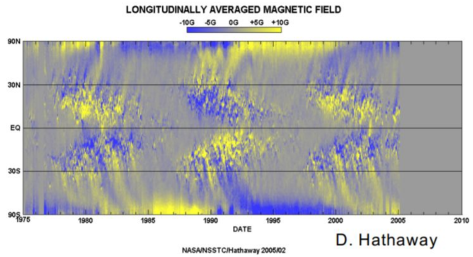
...the link between solar convective energy and energization/thermalization of the outer atmosphere

...where we study solar activity and space weather

...remotely sensed ***by developing*** imaging, spectral, and spectropolarimetric techniques.

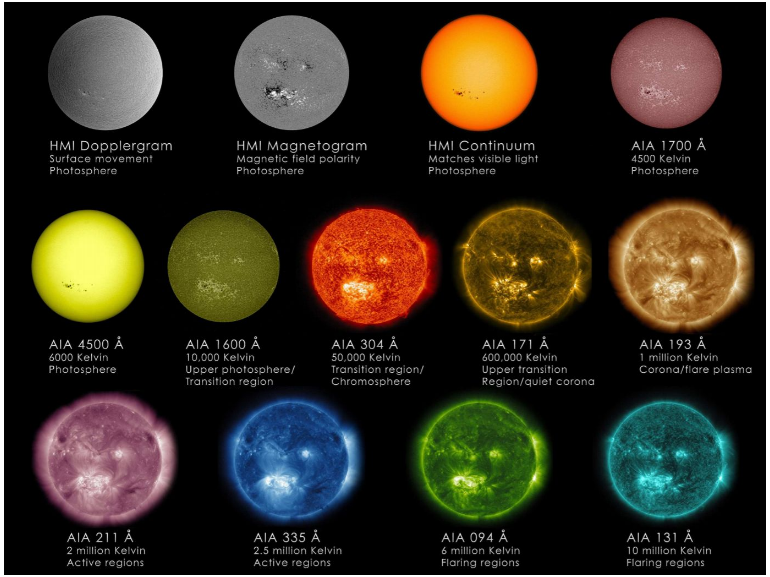
Multi-scaled atmosphere requires broad + deep observing coverage





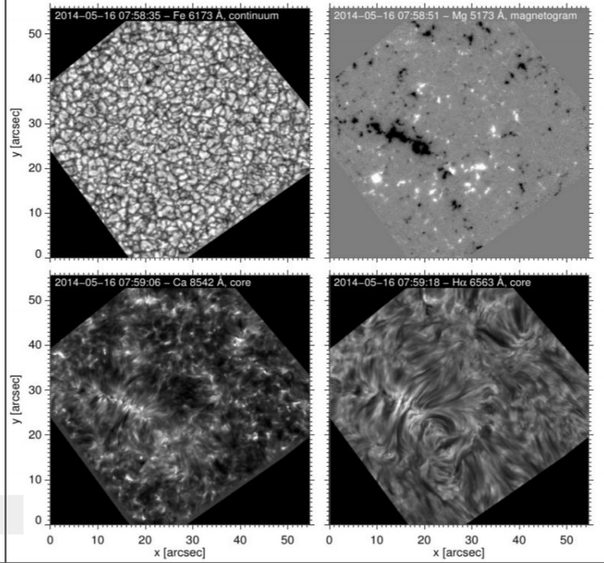
See Lecture 5

Full-disk synoptic magnetograms since mid 19th century. Sunspot record back to before 1650



See Lecture 19

Full-disk visible imaging, photospheric vector polarimetry, EUV imaging (relative high cadence ~ AIA: all channels every 12 seconds).



From Gosic et al., 2018 (see Lecture 1)

High spatial, *spectral*, temporal, *polarimetric* resolution probing multiple regimes over *limited field-of-view*.

The Daniel K Inouye Solar Telescope (DKIST)

DKIST is a ‘**microscope’** for the Sun nearing commissioning on Haleakala.

First major US solar ground-based facility built in more than a generation.

Early operations start next year (2020)!

Open access public facility build by the **US National Science Foundation**

Suite of diverse five first-light instruments (380 nm to 5 microns) covering wide array of use cases.

Design lifetime of 2 magnetic solar cycles (~50 years)

The DKIST Team

Results from a collaboration of 22 institutions reflecting broad segment of solar community.

Principal Investigator:
National Solar Observatory/DKIST

Co-Investigators:
Univ of Hawaii
High Altitude Observatory
New Jersey Institute of Technology
University of Chicago

Instrument teams:
National Solar Observatory
University of Hawaii
High Altitude Observatory
Leibniz Institute for Solar Physics
United Kingdom Consortium

DKIST Science:

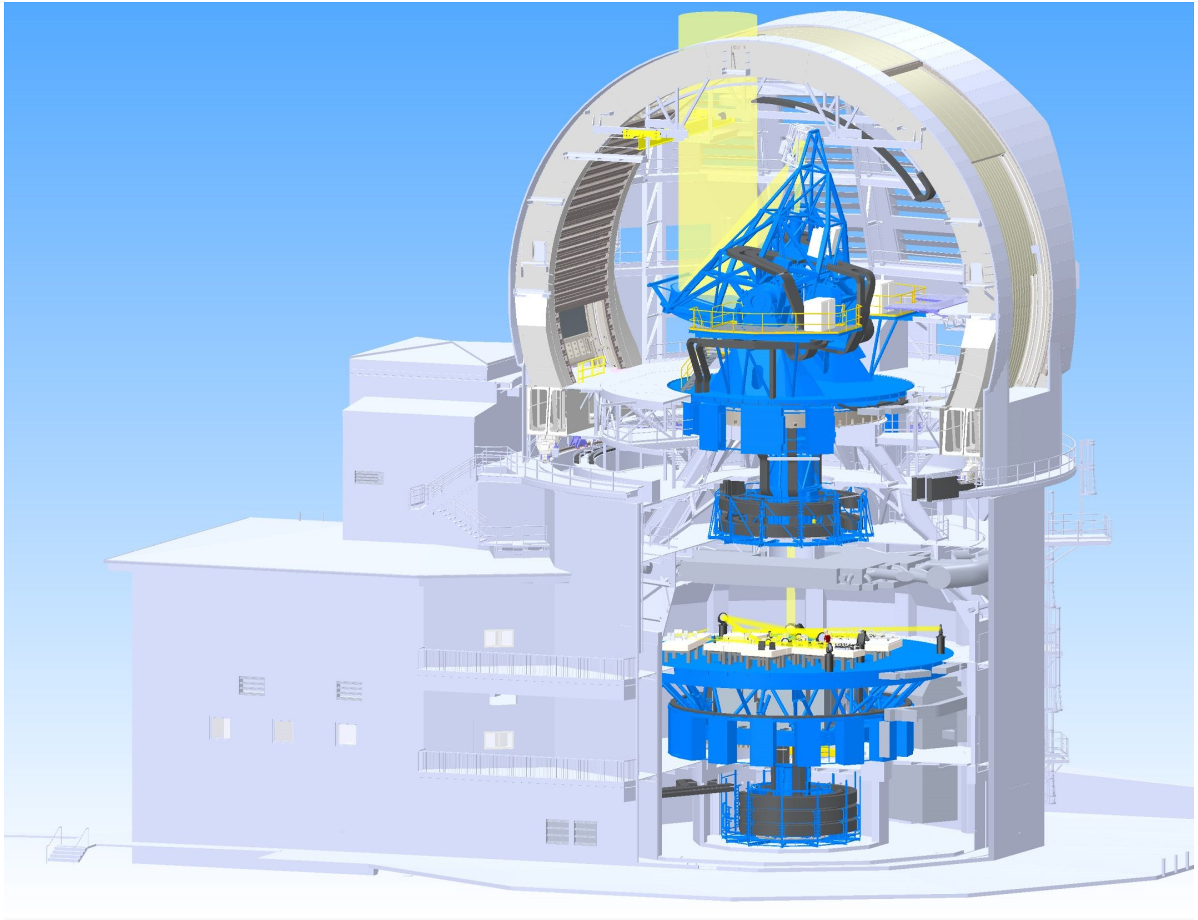
Today we will highlight four key capabilities:

High spatial resolution

High sensitivity polarimetry

Multi-wavelength diagnostics

Coronagraphic polarimetry



DKIST Science:

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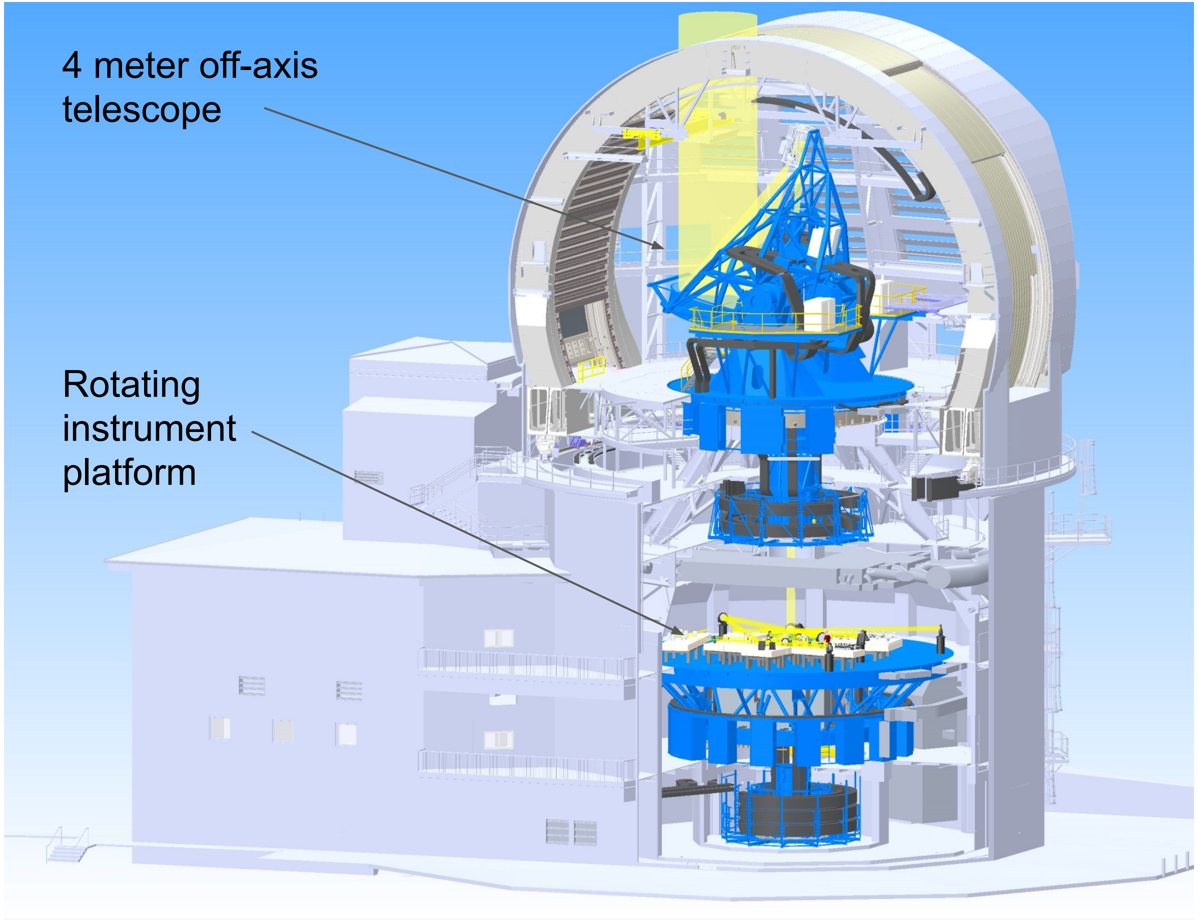
- High spatial resolution
- High sensitivity polarimetry
- Multi-wavelength diagnostics
- Coronagraphic polarimetry



Drivers of high resolution solar science

Need to understand fundamental scales, structure and dynamics of solar magnetic fields

Interactions between small-scale turbulence and flux concentrations (and role of SSD) are important but not currently resolved.

Key spatial scale of 10s of kilometers.

Lecture 6: At ~25 km res (i.e. DKIST) more than 90% of photospheric spectral energy distribution is measurable.

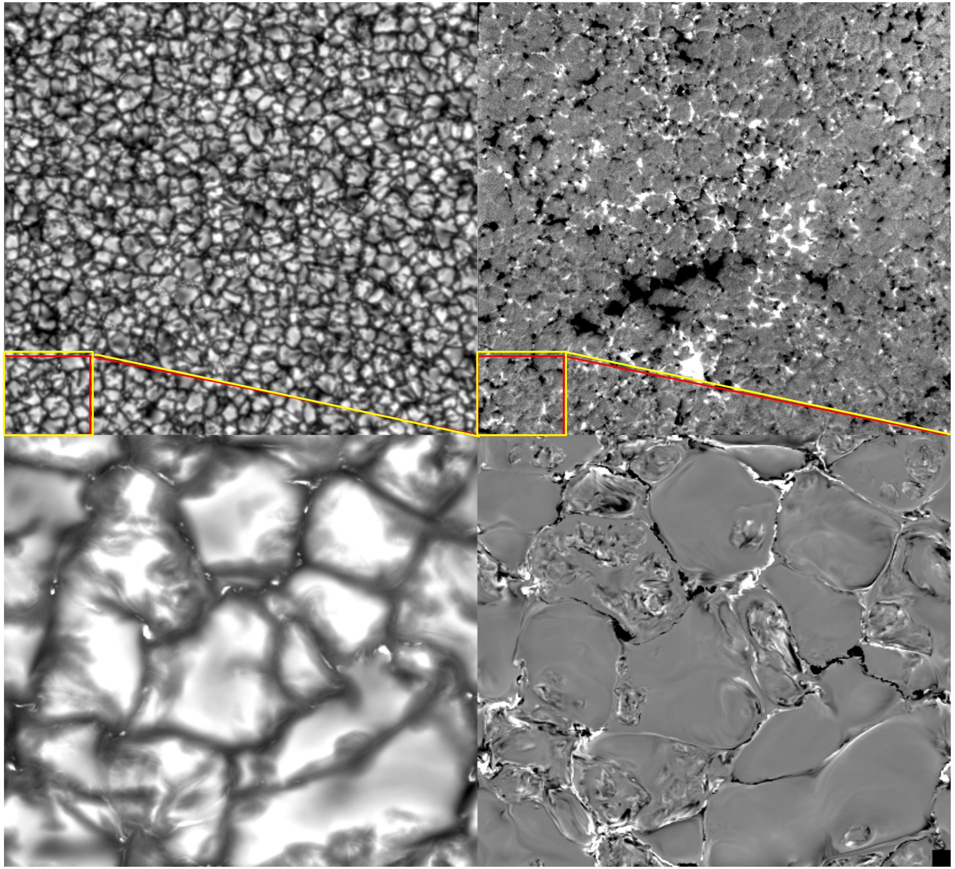


Image courtesy of M. Rempel.

Current 1 meter aperture observation limit:

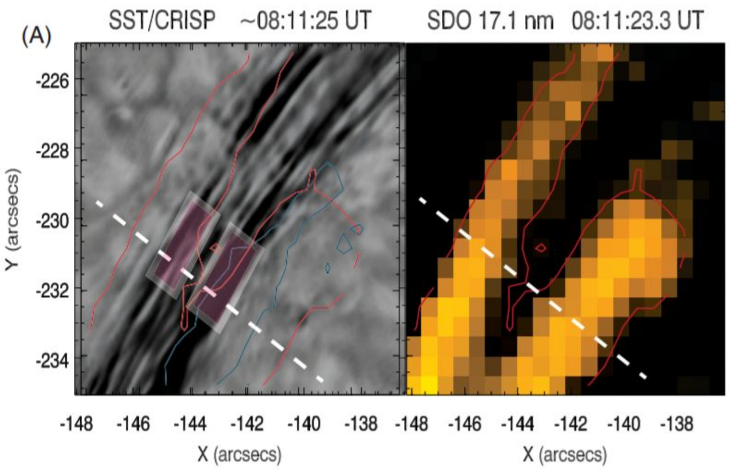
Swedish Solar Telescope

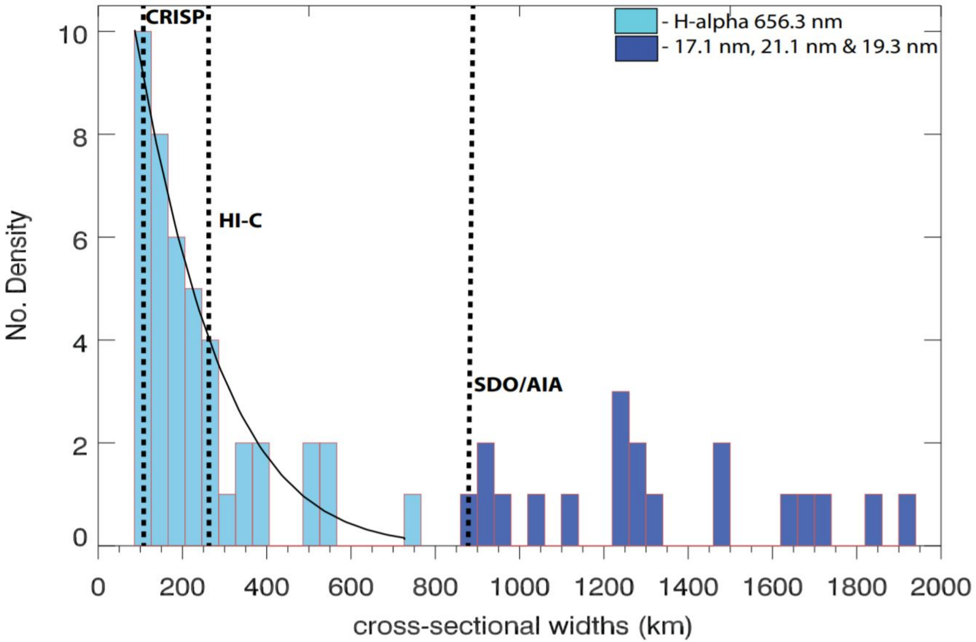
~100 km resolution

Advanced MHD simulation

4 km grid size

Drivers of high resolution solar science





Fundamental scales of chromospheric/coronal structure also not yet resolved [Scullion et al. (2014) ApJ 797,36]. Relation to chromospheric / coronal heating mechanisms?

Achieving high spatial resolution: the diffraction limit

Current observational limit ~100 km. Current numerical resolution <4 km. Key scales identified: 10s of kilometers.

Diffraction limit of angular resolution for a circular aperture (Rayleigh criterion at right): <u>θ = 1.22 λ/D</u>

1´´ is ~ 725 km at Sun as observed from Earth

To achieve ~30 km resolution at 630 nm (where magnetically sensitive Fe I lines exist), the required aperture is 4 meters.

DKIST has a **4 meter clear aperture.**

@ 380 nm, 1.22 λ/D → 0.0239´´ → 17 km
@ 500 nm, 1.22 λ/D → 0.0314´´ → 22 km
@ 630 nm, 1.22 λ/D → 0.0396´´ → 30 km

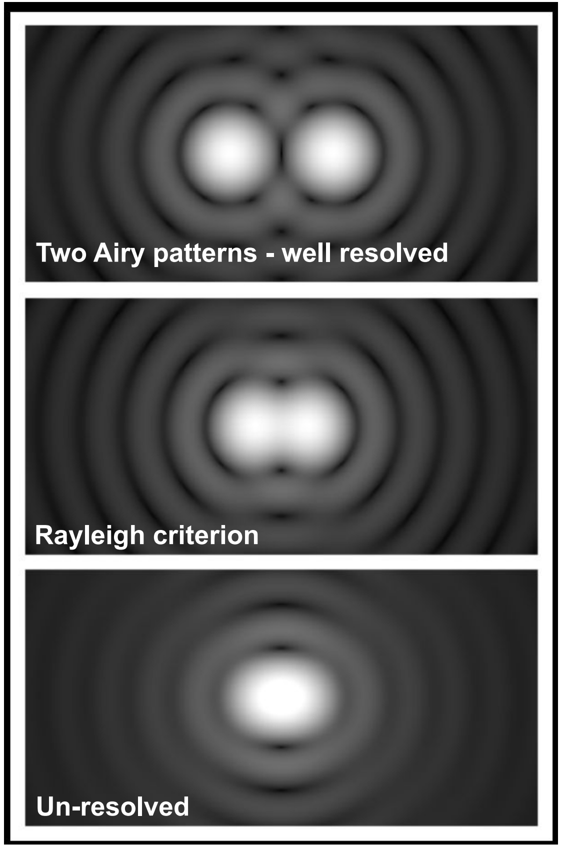
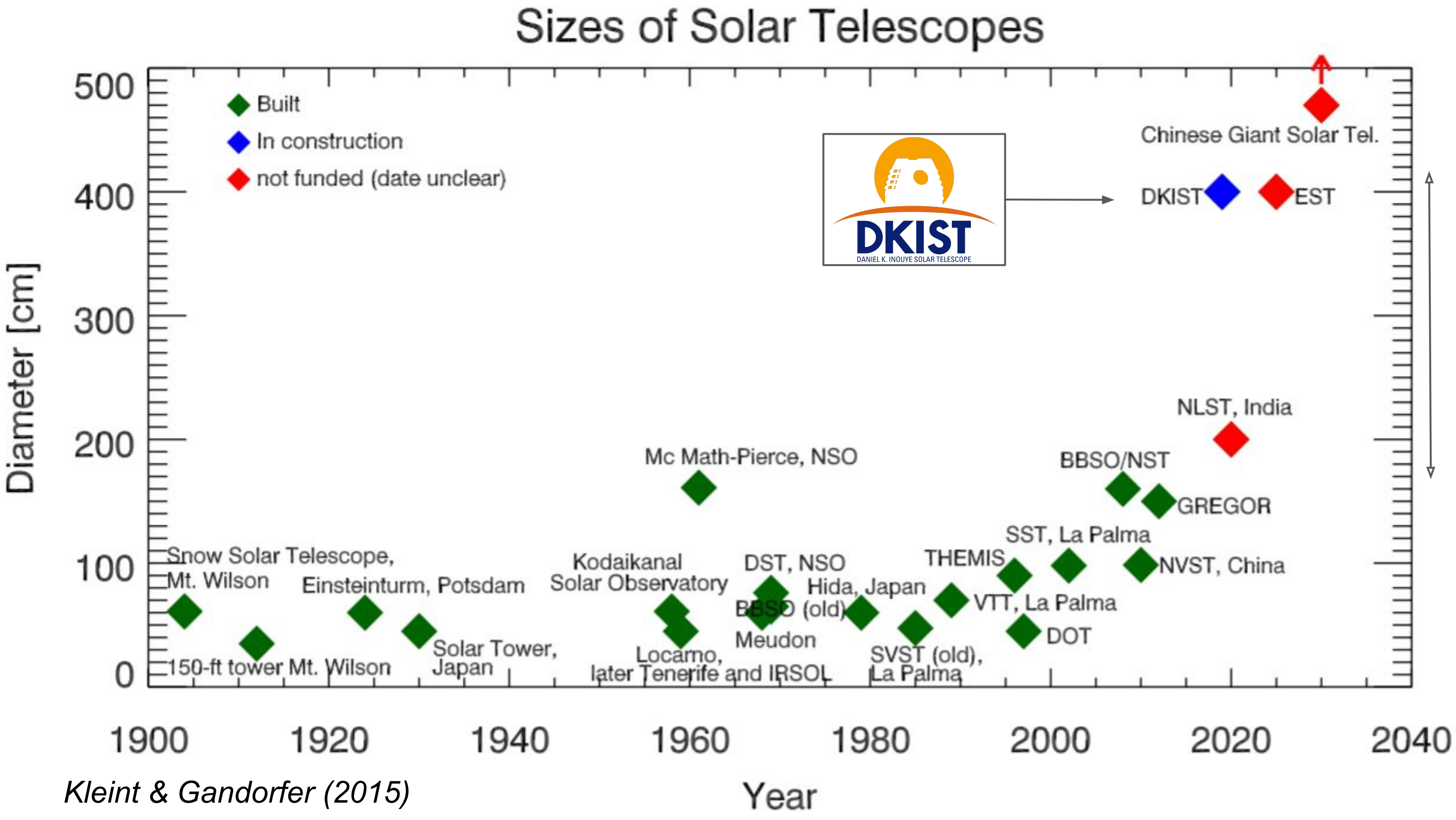


Image credit (S. Bliven / Wikimedia / public domain)

4 meter aperture is a great advance for solar telescope construction!



Kleint & Gandorfer (2015)

~2.7x larger diameter

~7x larger collecting area

Achieving high spatial resolution*:* other factors

Large telescopes traditionally must get heavy to yield needed strength. To lighten, other techniques are needed to control the wavefront → ***Active Optics (aO)***.

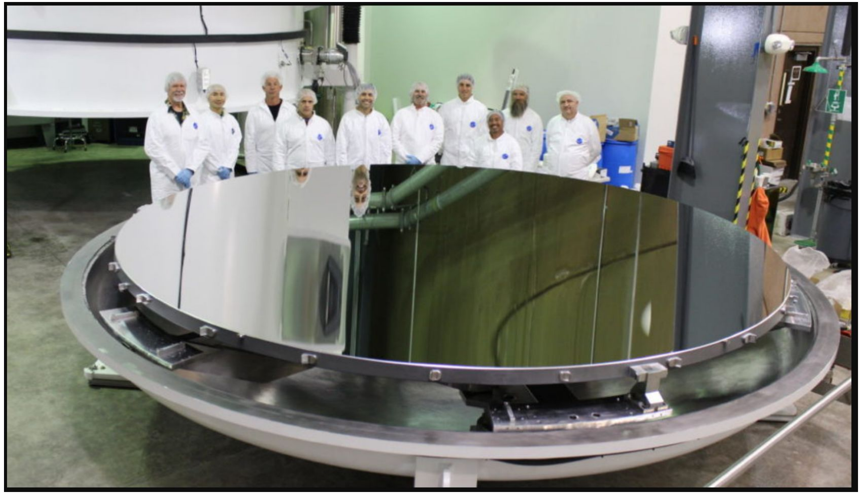
Seeing limitations (daytime Fried parameter @ 500 nm of ~7 to 15 cm) → High resolution requires ***Adaptive Optics (AO).***

Daytime observations must also contend with daytime heating!!

Solar insolation ~ 1 kW/m^2 at 10000 m elevation
1 meter telescope: <1 kW (local seeing partially managed using evacuated designs)
4 meter telescope: ~13 kW → ***Thermal control*** is critical.

Convention AO usually bandwidth limited and limited to small ***isoplanatic*** field-of-view ~< 5´´ to 10´´. Diffraction limit reached with post-facto deconvolution techniques → Using fast camera, short exposures (<5 ms) and image stacks.

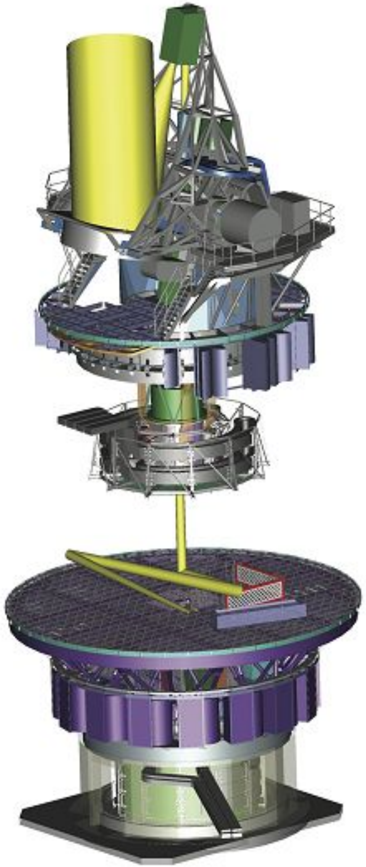
DKIST Wavefront Control: ‘Active’ optics



4 meter primary mirror is 75 mm thick (Aspect ratio ~ 53)

118 hydraulic actuators on backside provide active surface control.

<u>Other active components:</u>
M2 secondary (hexapod)
M3 pupil steering
M6 image positioning

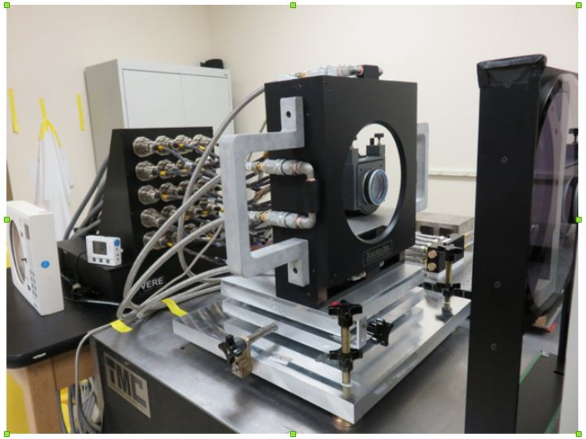


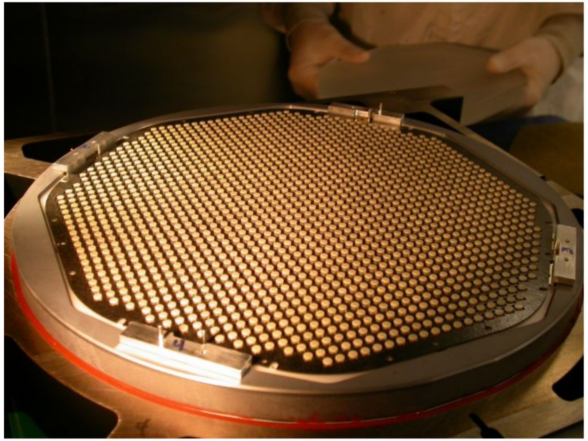
DKIST Wavefront Control: Adaptive optics

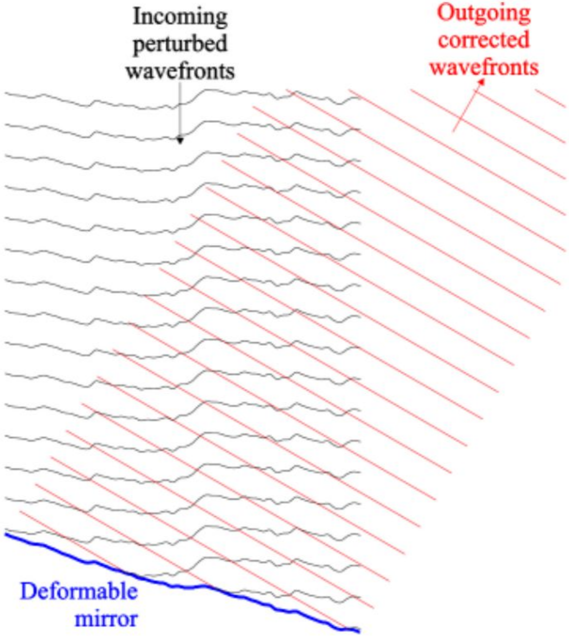
DKIST AO provides fast (i.e > 1 kHz update) adaptive control of M2, M5, and M10.

M10 is a deformable mirror with 1600 piezo-electric actuators.

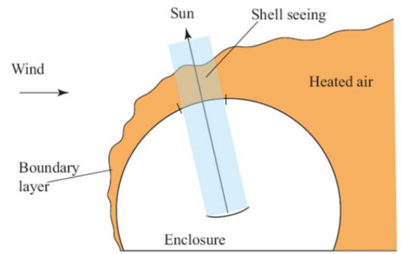
Two Shack-Hartman wavefront sensors

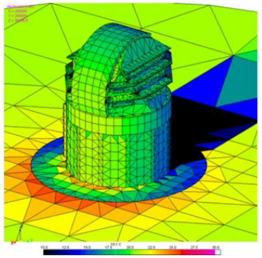


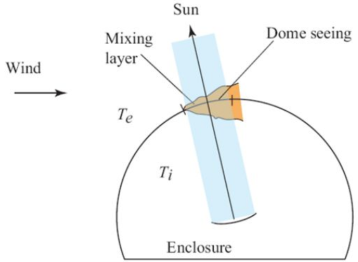


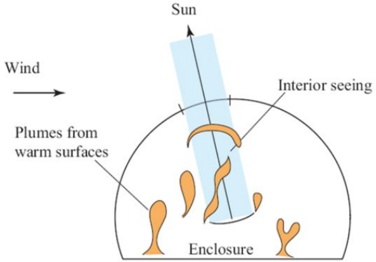


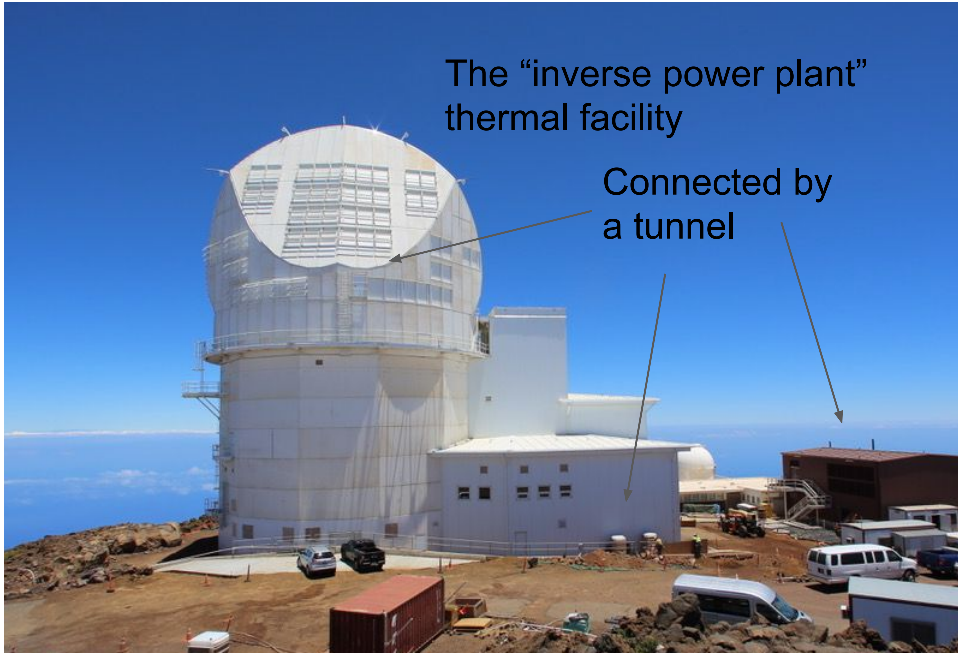
DKIST Facility Thermal Control: Enclosure









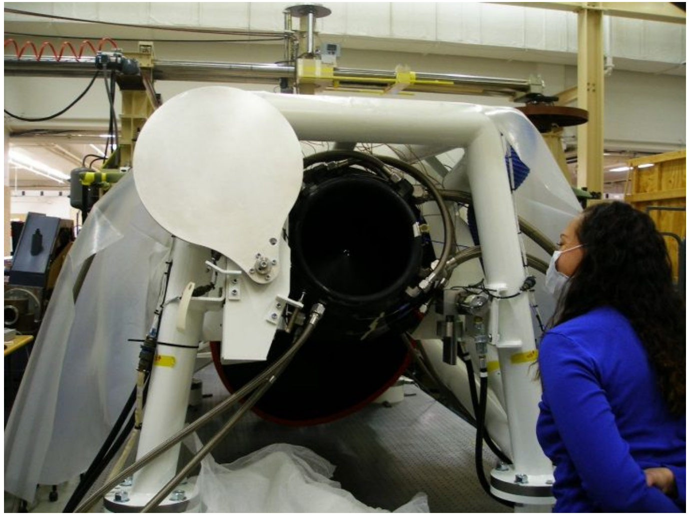


The "inverse power plant" thermal facility

Connected by a tunnel

Enclosure induced local seeing managed by active cooling of external structure and passive cooling (i.e. vent gates)

DKIST Facility Thermal Control: The prime heat stop

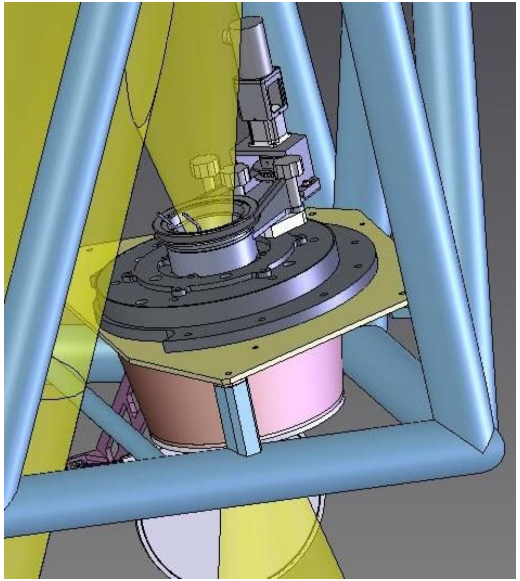


Prime focus field stop:

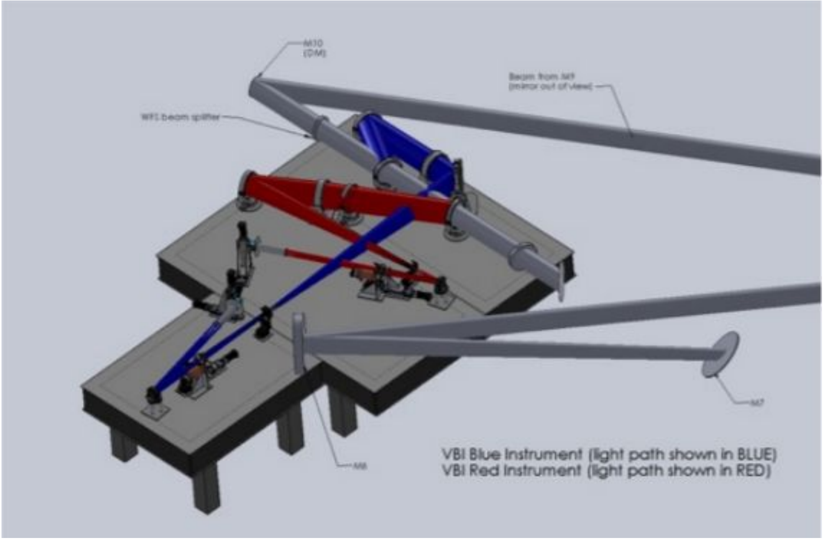
5 arcminute field of view (a few% of solar disk)

Removes ~12 kW heat using new porous metal technology

Safety shutter seen at left.



Highest resolution imaging --> Visible Broadband Imager (VBI)



VBI in thermally controlled Coude lab

Two channels: Blue (390-550 nm) / Red (600-860)
each with a 4096 x 4096 detector

4 filters for each channel (FWHM: 0.05 to 0.5 nm).

FOV: 45´´x45´´ (blue) / 69´´ x 69´´ (red)

Nyquist spatial sampling: 0.011´´ (blue)
0.017´´ (red)

Diffraction limit: @ 380 nm is 0.0239´´
@ 630 nm is 0.0396´´

Frame rates: 30 Hz
Disk exposure times: < ~5 ms (~10ms for Ca II K)
Default: 80 images used for reconstruction
3.2 temporal cadence

A quick photon flux estimate at 450 nm as an exercise...

Solar flux @ DKIST: ~ 2.0×10^{11} photons Å^{-1} arcsec^{-2} m^{-2} s^{-1}

DKIST collecting area: 12.56 m^{2}

Telescope/instrument throughput: ~10%

Spatial sampling: (0.011^{2}) arcsec^{2}

Filter FWHM: 4.1 Å ($\lambda/\delta\lambda$ ~ 1000)

Flux at instrument sampling: 1.25×10^{8} photons s^{-1}

Exposure time: 0.2 msec

Number of photons per frame: 25000 (detector full well ~ 30K)

Number of frames per temporal sample: 80

Poisson noise (also SNR): SQRT(80.*25000.) = 1414

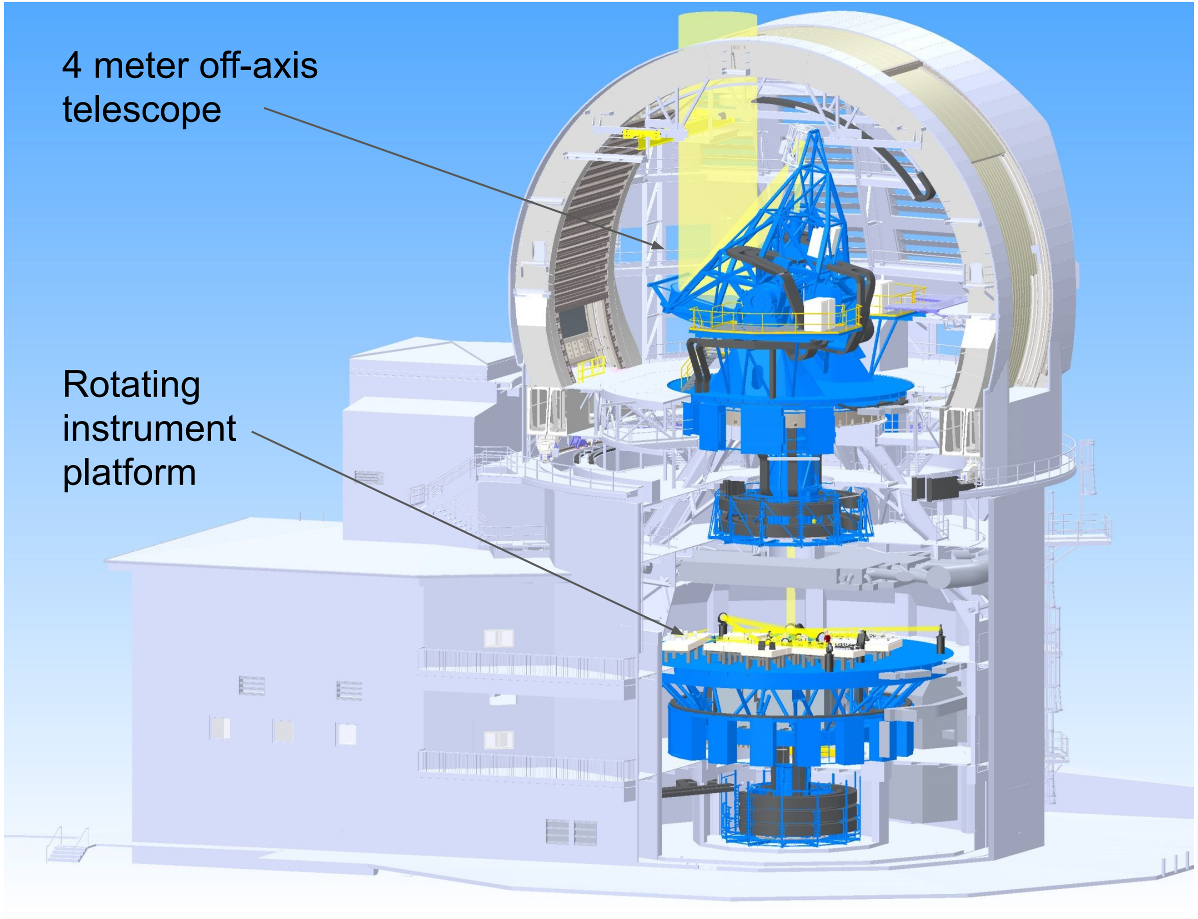
Relative error (1./SNR): 7.e-4

*450 nm is in the blue continuum. In a line core, the flux is lower and FWHM needs to be narrower.

DKIST Science:

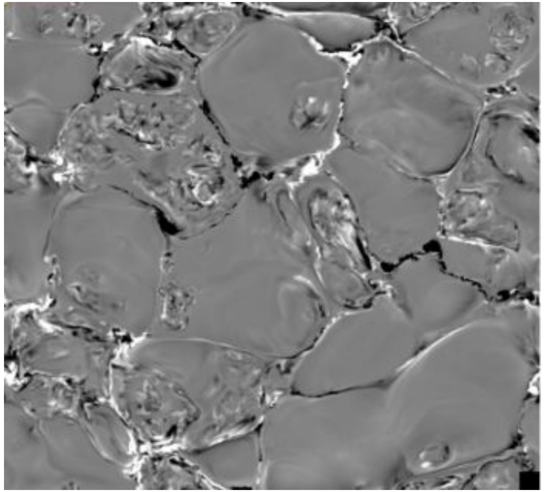
Today we will highlight four key capabilities:

- High spatial resolution
- High sensitivity polarimetry
- Multi-wavelength diagnostics
- Coronagraphic polarimetry

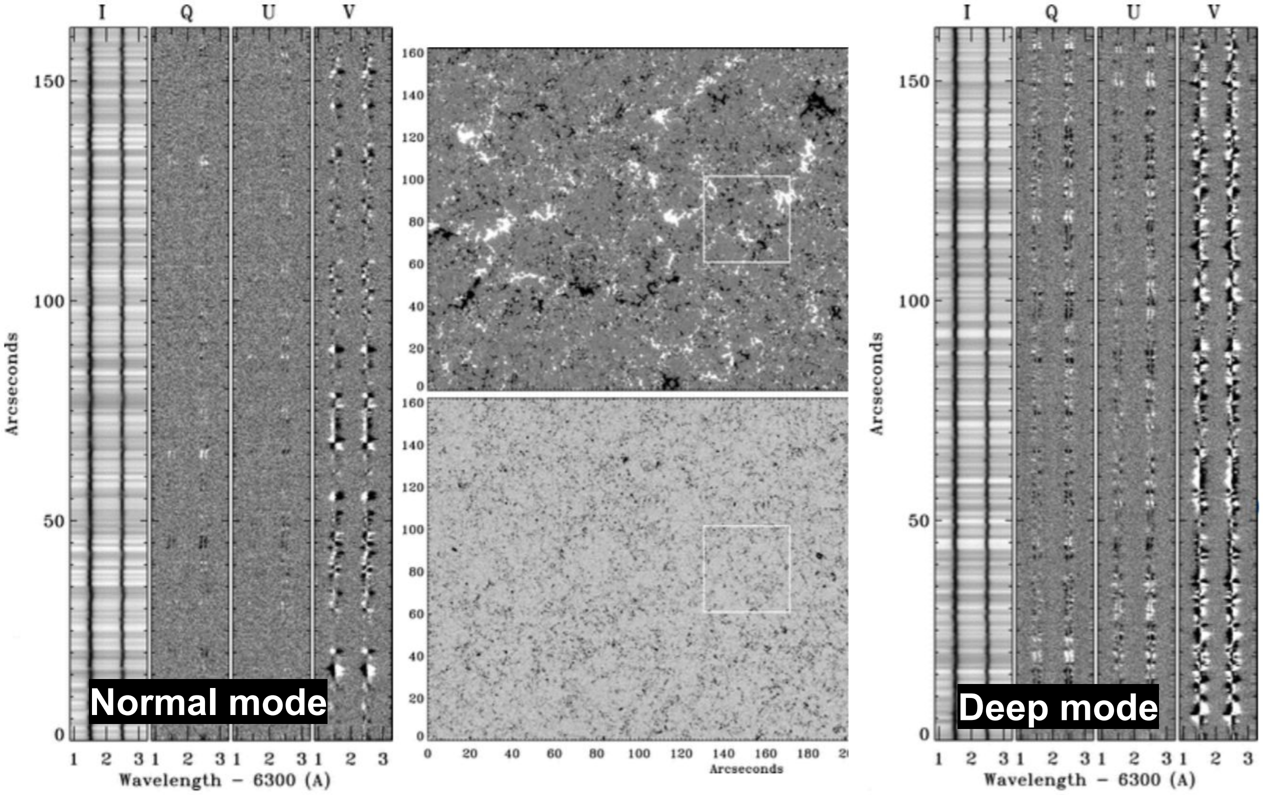


Drivers of high polarimetric sensitivity - photosphere

Quiet sun magnetism



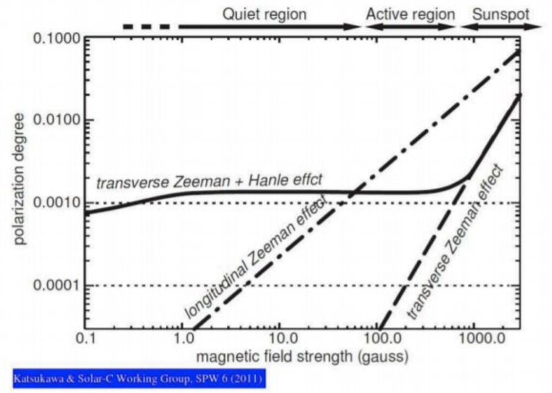
MHD simulation (4km grid size)



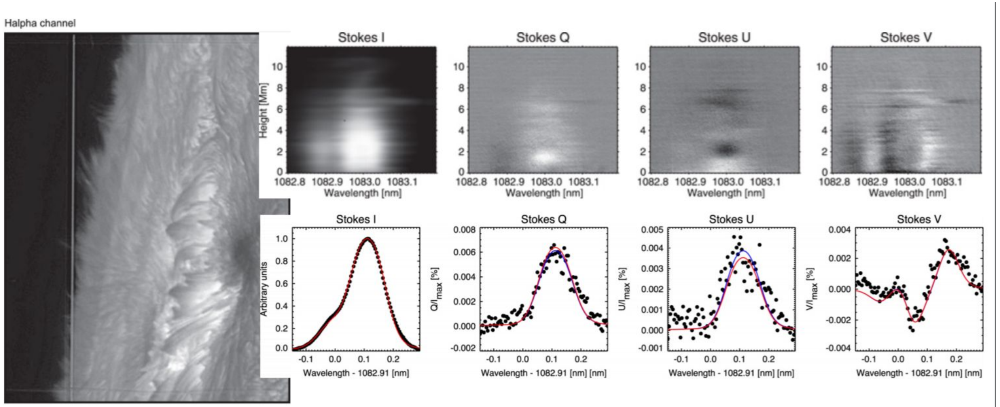
Lites et al. 2008 -> Nearly ubiquitious quiet sun signals using 70 second integration (at right: SNR ~ 10^4) with the Hinode Spectropolarimeter.

Drivers of high polarimetric sensitivity - chromosphere

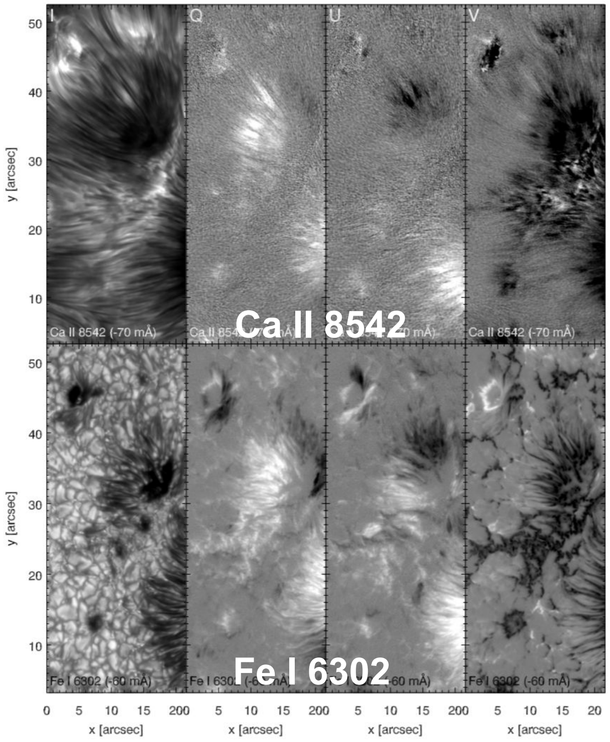
Chromospheric fields weaker and more horizontal → challenging to measure with Zeeman effect alone.



Katsukawa & Solar-C Working Group, SPW 6 (2011)



Spicules in He I 1083 nm; Orozco Suarez et al. 2015



Courtesy de la Cruz Rodriguez in Kleint & Gandorfer (2015)

Polarimetry at DKIST

- The great majority of DKIST science use cases employ spectropolarimetry.
- Used throughout photosphere, chromosphere, corona, flares, filaments, etc.
- Exploits Zeeman, Hanle, saturated Hanle effects + continuum polarization
- Spectral profiles observed at high resolution can be complex. Often need high spectral resolution: $\lambda/\delta\lambda > \sim 80{,}000$, and up to ~ 300,000.
- Signal-to-noise requirements often very high: > ~5000 and as high as 10^5.
- Errors in derived physical parameters are target, technique, and model dependent.

Back to our photon flux estimates, this time in **line core** of 854 nm..

Solar flux @ DKIST:	~ 3.4 x 10^{10} photons Å^{-1} arcsec^{-2} m^{-2} s^{-1}
DKIST collecting area:	12.56 m^{2}
Telescope/instrument throughput:	~1% (instrument dependent)
Spatial sampling:	**(0.1^2)** arcsec^{2} [2 x diffraction limit]
Filter FWHM / spectral sample:	85 mÅ (λ/δλ ~ 100,000)
Flux at instrument sampling:	1.81 x 10^{8} photons s^{-1}
Exposure time:	10 msec
Number of photons per modulated frame:	~35,000
Number of frames in total:	**1000 (i.e. 10 seconds of integration)**
Poisson noise (also SNR):	~ 0.57 * SQRT(1000.*35000.) ~ 3370
Relative error (1./SNR):	3.e-4

0.57 is general estimate of modulation efficiency. In summary, achieving high SNR at high resolution needs a large aperture!!! DKIST→ 0.1'' , 10 sec, SNR of ~10^4 is achievable!

Polarimetric error budget. Keep in mind:

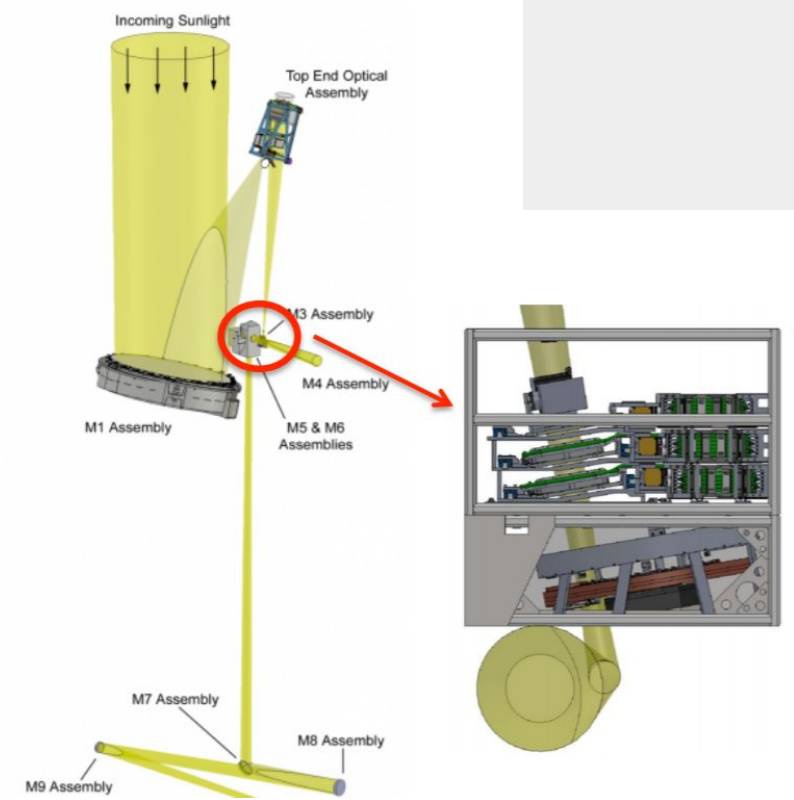
The measured flux at the diffraction limit is conserved.

- Collected light scales with telescope area, i.e the radius squared, (D/2)^2
- Diffraction limit scales with D^-1. Diffraction limited spatial sample scales as D^-2.

Based on SNR needs and the time required to achieve it, DKIST polarimetry is generally not diffraction-limited!!

Note, we have not discussed time to SNR requirements. Must take into account temporal time scales of the targeted phenomena.

Achieving polarimetric accuracy: calibrating instrument response



Optics modify the polarimetric characteristics of the incident light (crosstalk / depolarization).

$$\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}_{meas} = \begin{pmatrix} II & QI & UI & VI \\ IQ & QQ & UQ & VQ \\ IU & QU & UU & VU \\ IV & QV & UV & VV \end{pmatrix} \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}_{in}$$

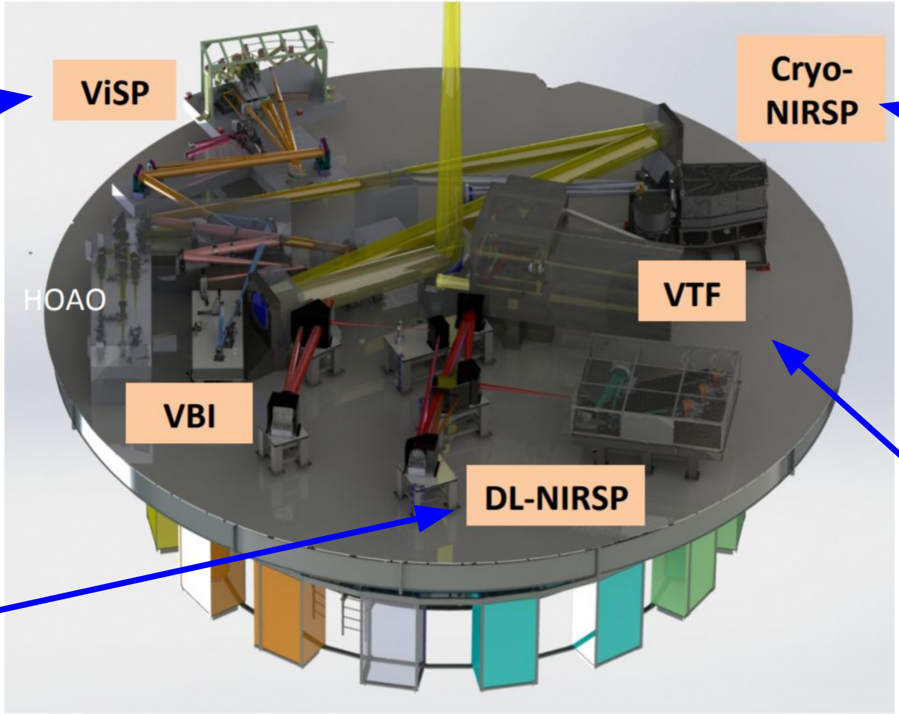
Describable with Mueller calculated, and must be calibrated using known (calibrated) sources.

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

DKIST introduces large crystal optics near 300 W georgian focus to calibrate downstream optical train.

M1/M2 is calibrated with other methods.

The DKIST Spectropolarimeters



Visible Spectropolarimeter
- Slit-based
- 380 to 900 nm)

Cryogenic Near-IR Spectropolarimeter
- Slit-based
- 1 to 5 microns

Visible Tunable Filter
- fabry-perot imaging spectropolarimeter
- 520 to 870 nm

Diffraction-Limited Near-IR Spectropolarimeter
- Fiber-optic-based integral field spectropolarimeter
- 500 to 1800 nm

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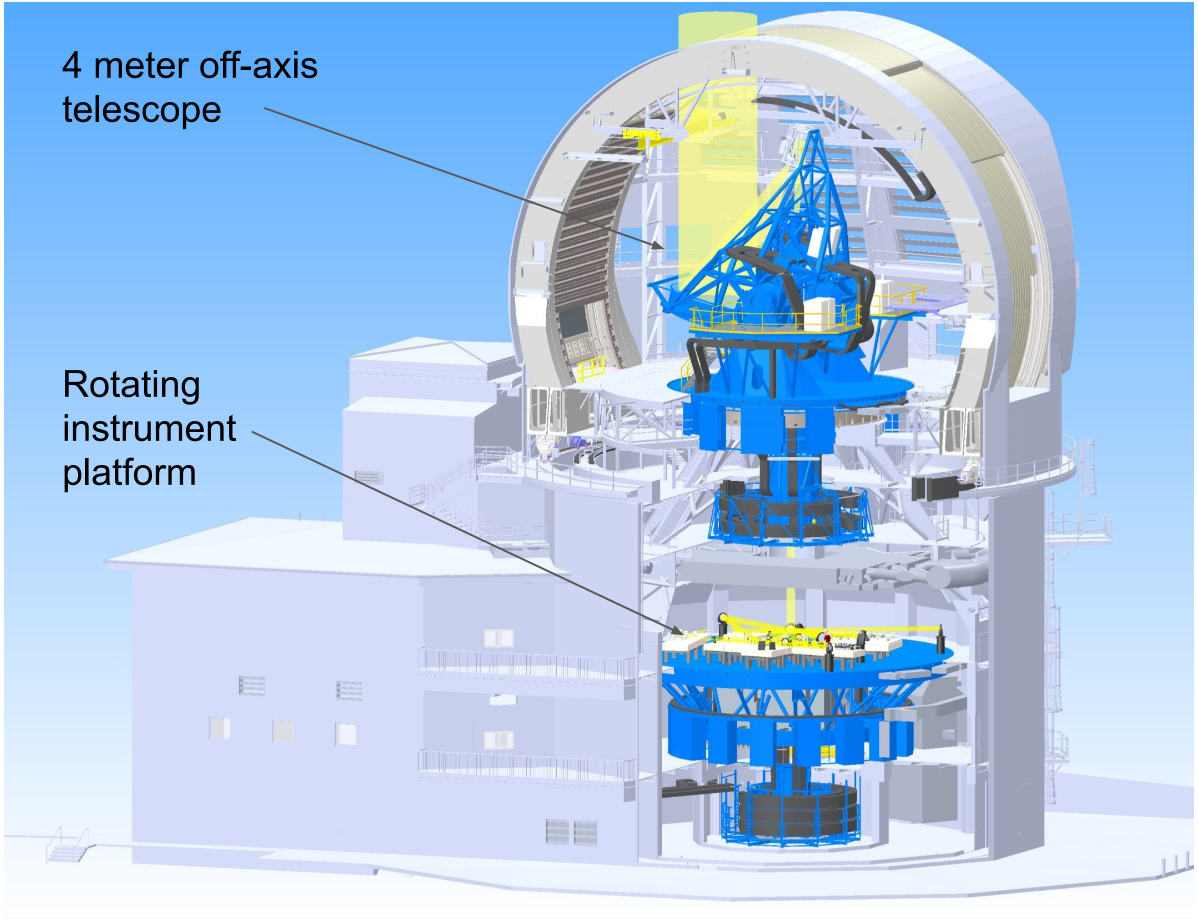
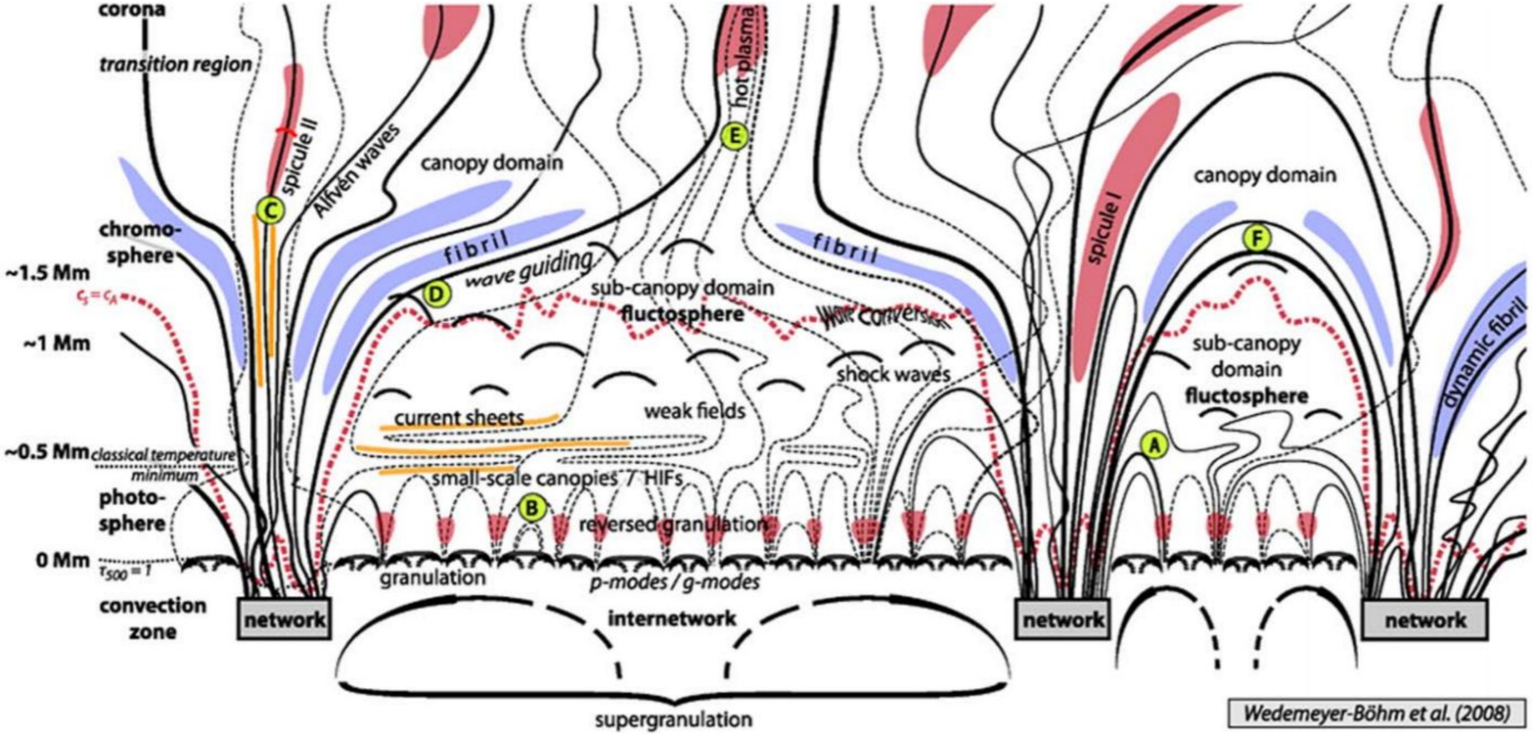
- Coronagraphic polarimetry

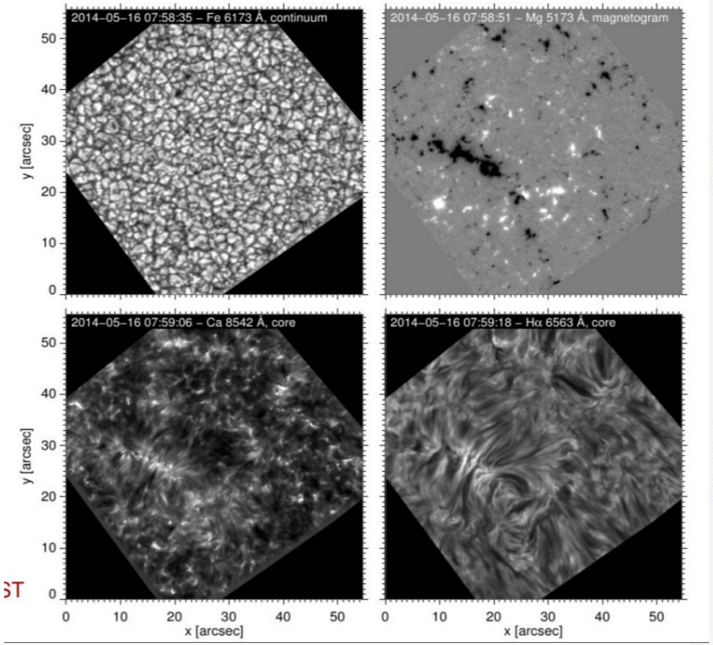


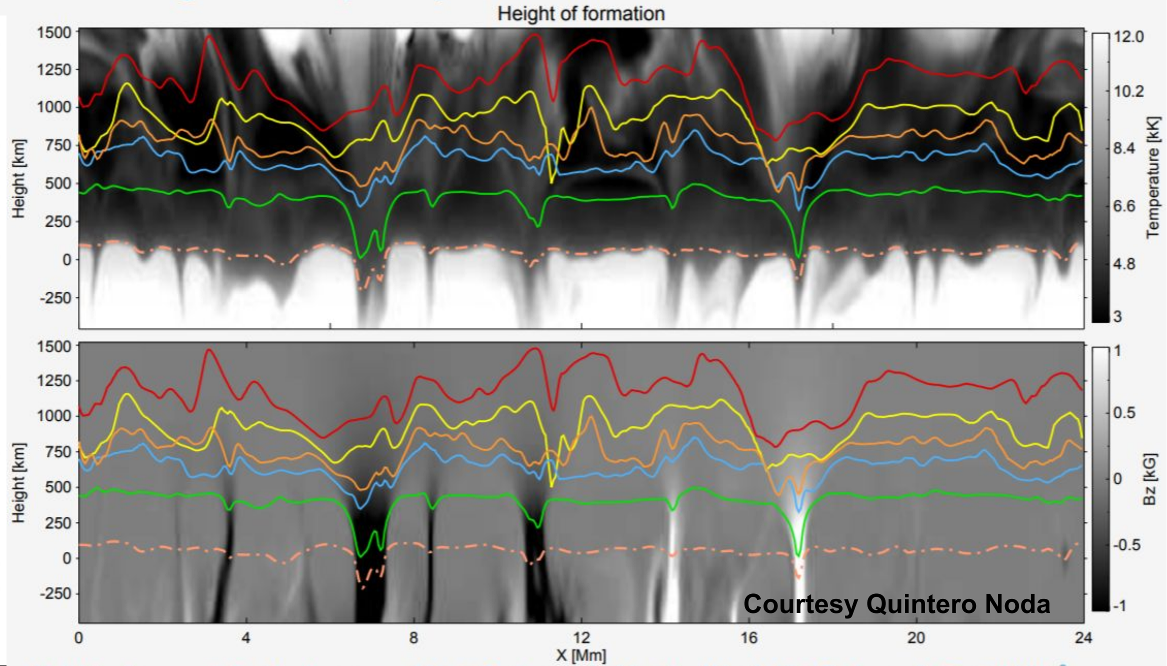
Key driver of multi-wavelength science



Wedemeyer-Böhm et al. (2008)

Magnetic connectivity throughout atmosphere, both in quiet and active regions. Understanding extension of field in different Beta regimes. [Discussed in Lecture 19]





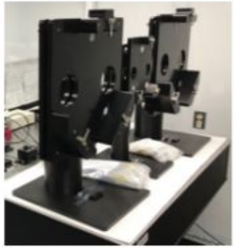
Courtesy Quintero Noda

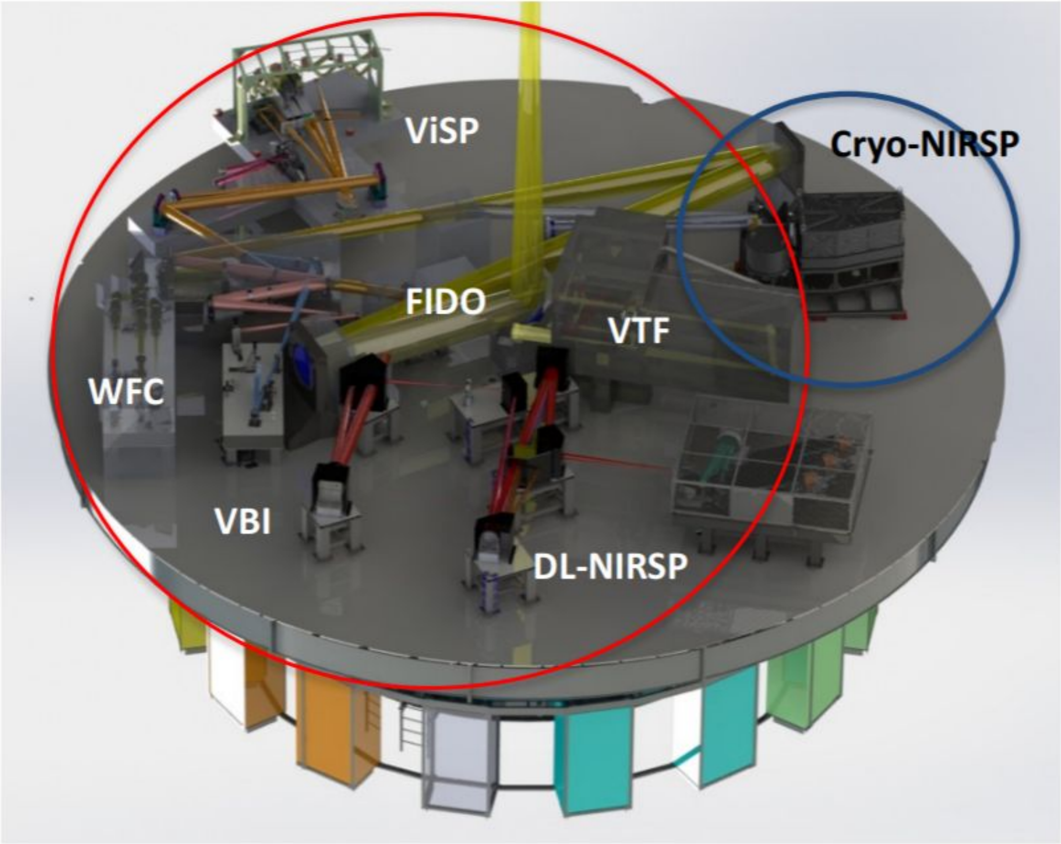
Height where $\tau=1$ for the line core of Na I D_1 (orange), Mg I b_2 (blue), K I D_1 (green), Ca II 8498 Å (yellow), and 8542 Å (red). Dashed orange to $\tau=1$ at continuum wavelengths.

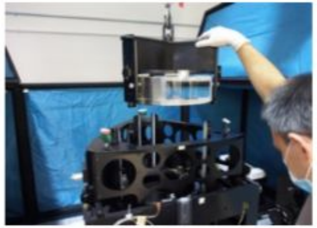
Simultaneous multi-wavelength science is essential to understand structure of solar atmosphere.

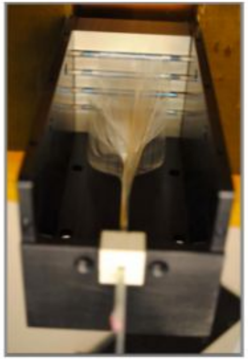
Peak response of spectral lines occur in different locations in atmosphere. See lectures 15 and 19 >

DKIST is an efficient multi-wavelength observatory - Up to 4 instrument simultaneously operated with AO

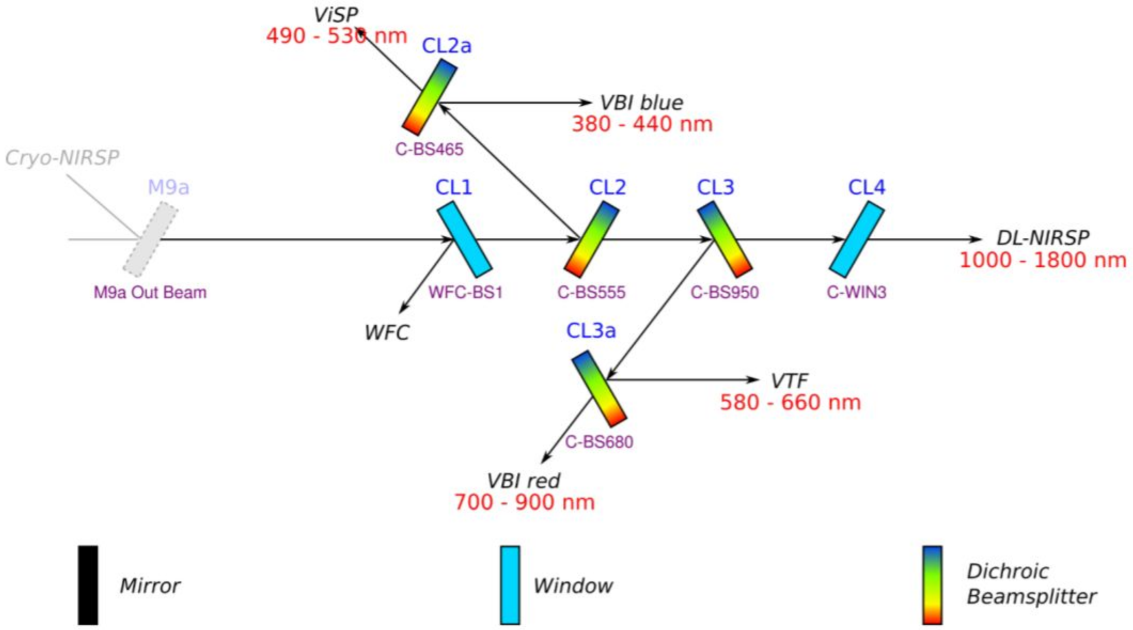


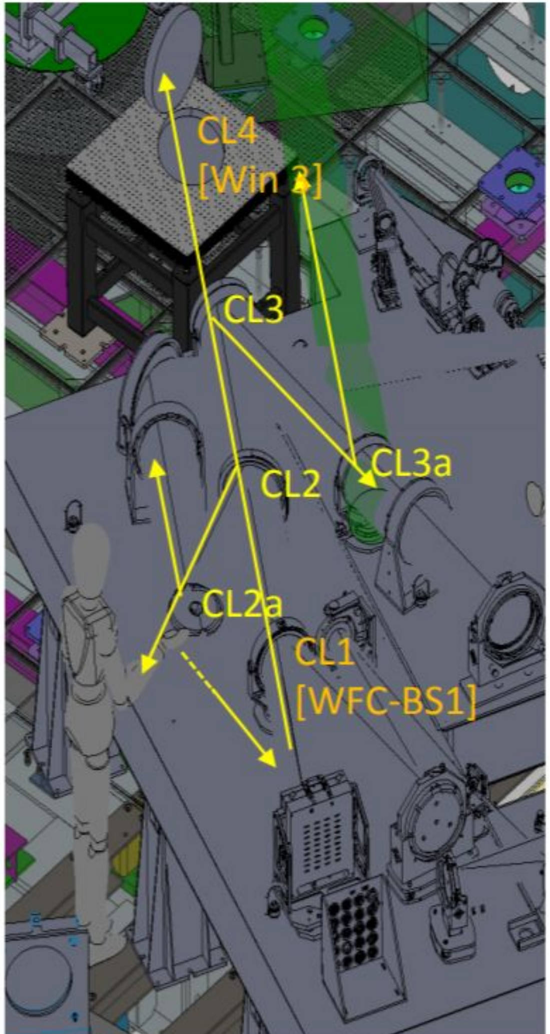






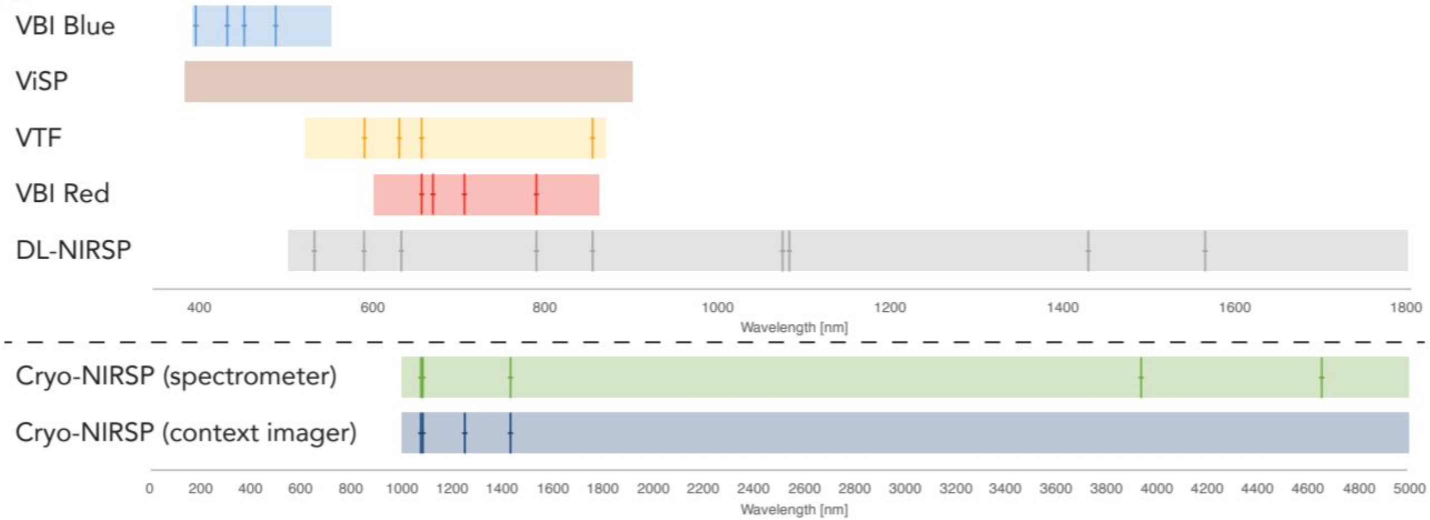
Key enabling technology - Large dichroic beamsplitters





A set of interchangeable beamsplitters that selected reflect/transmission portions of the spectrum also diversified science.

DKIST First Light Instrument Filters



VBI Blue

Ca II K	393.327nm
G-band	430.52nm
Continuum	450.287nm
H-beta	486.1nm

ViSP

Access to entire spectral range between 380-900 nm

VTF

Na D	589.6nm
Fe I	630.25nm
H-alpha	656.3nm
Ca II	854.2nm

VBI Red

H-alpha	656.282nm
Continuum	668.423nm
Ti O	705.839nm
Fe XI	789.186nm

DL-NIRSP

Fe XIV	530.3 nm
He I	587.6 nm
Fe I	630.2 nm
Fe XI	789nm
Ca II	854.2nm
Fe XIII	1074.7nm
He I	1083nm
Si X	1430nm
Fe I	1565nm

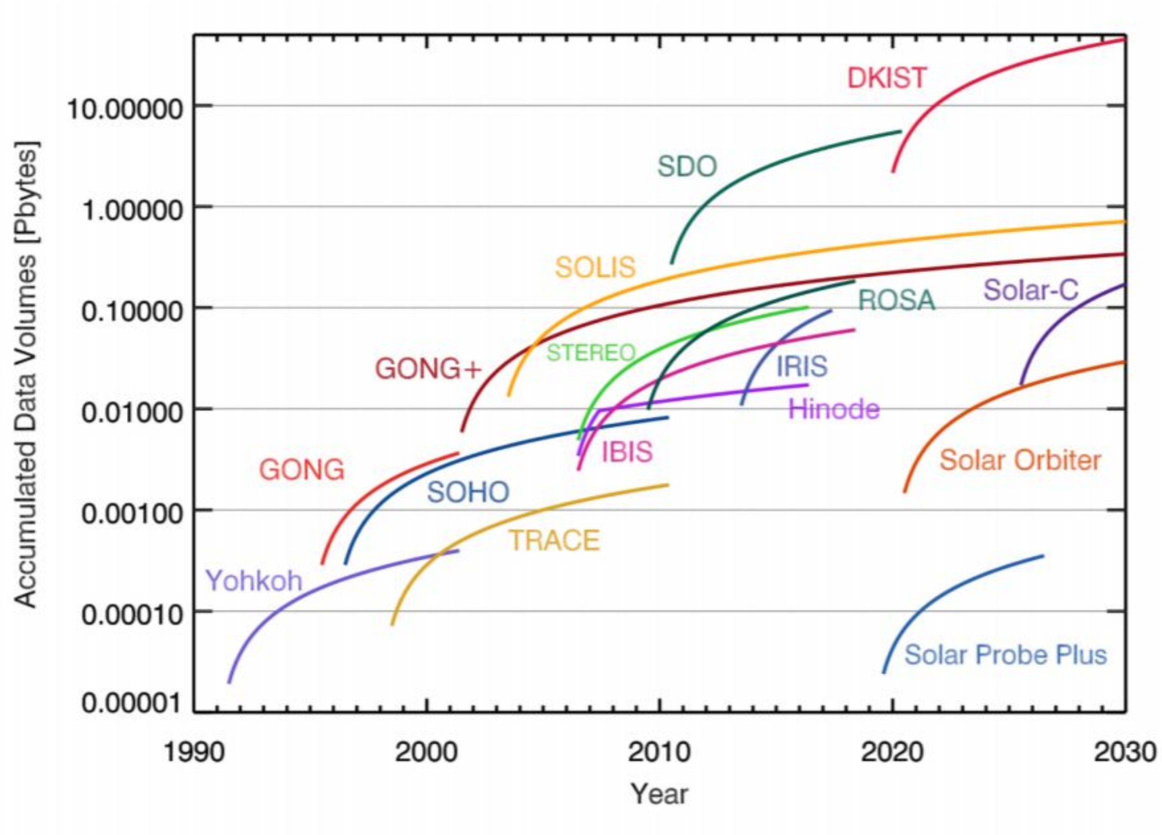
Cryo-NIRSP

Fe XIII	1074.7nm
Fe XIII	1079.7nm
He I	1083 nm
Si X	1430nm
Si IX	3935 nm
CO	4651nm

Cryo Context

Fe XIII	1074.7nm
He I	1083nm
J Band	1250nm
Si IX	1430nm

Multi-wavelength high cadence science → High data rates



DKIST will produce:

3 petabytes raw data / year
~ 1.5 x 10^8 images
~ 3.7 x 10^{10} metadata items

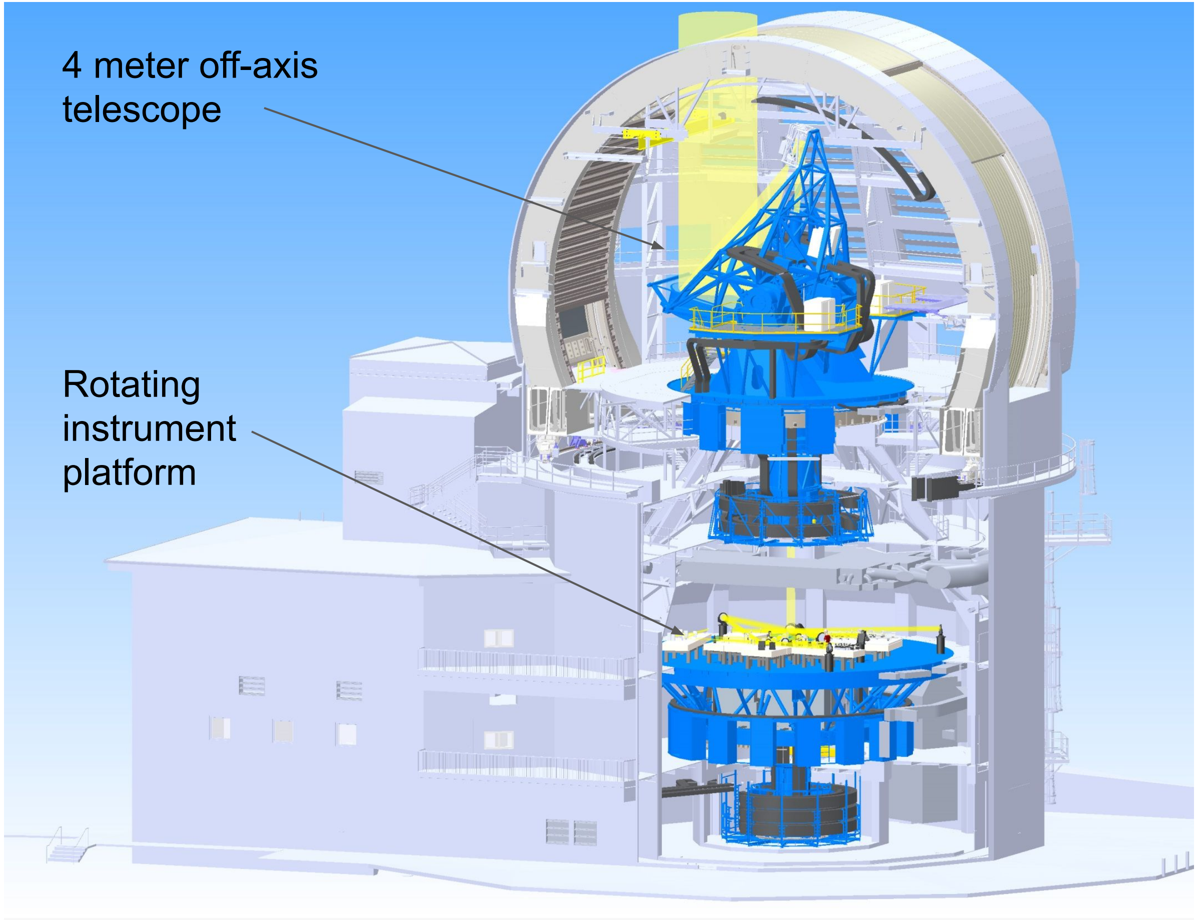
Mean of 8.25 TB/day

Peak of ~65 TB/day

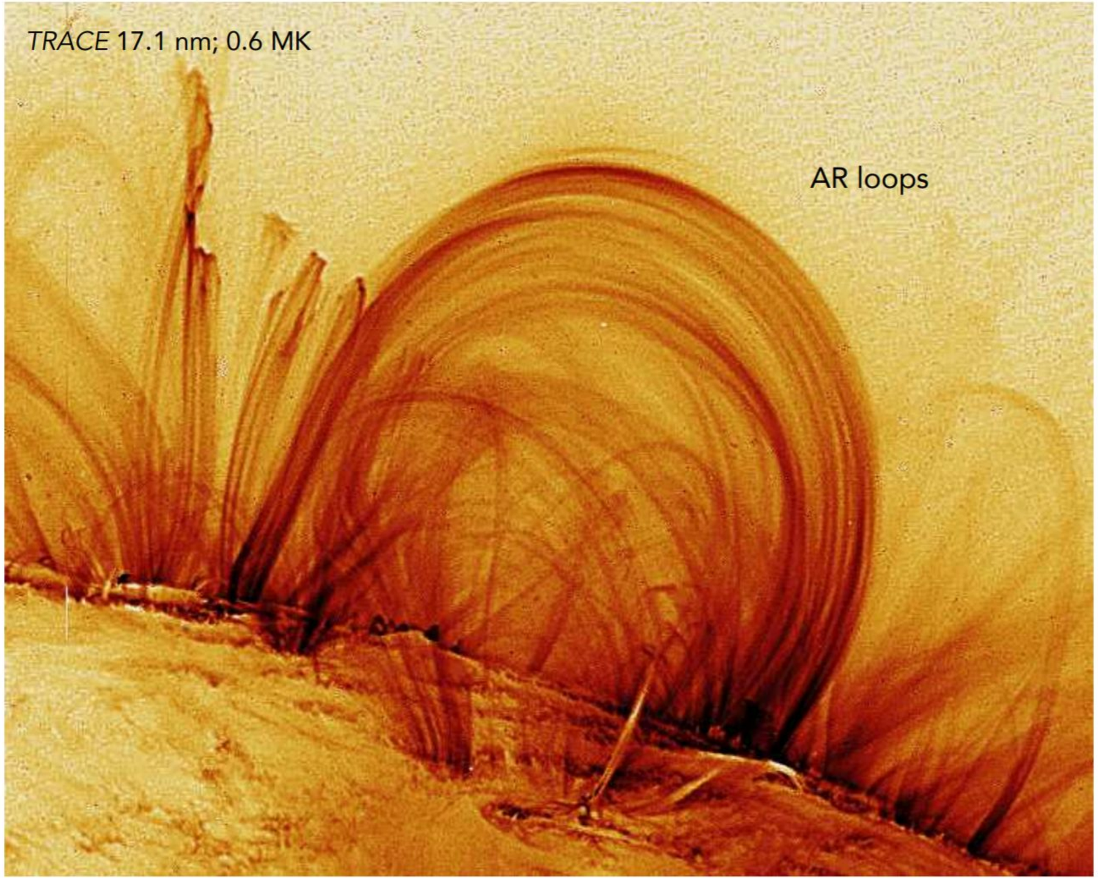
DKIST Science:

Today we will highlight four key capabilities:

- High spatial resolution
- High sensitivity polarimetry
- Multi-wavelength diagnostics
- Coronagraphic polarimetry



Drivers of coronal science...



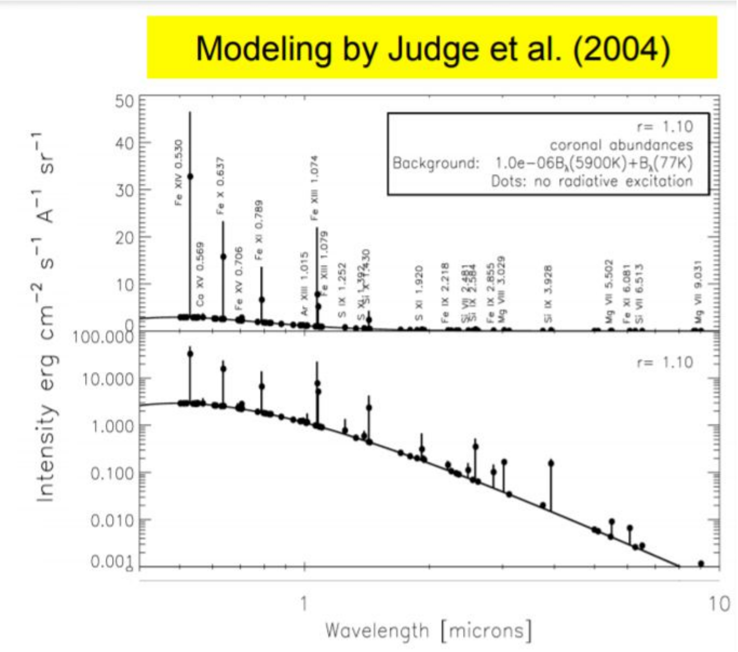
The solar corona is dominated by the magnetic field, but we do not measure it.

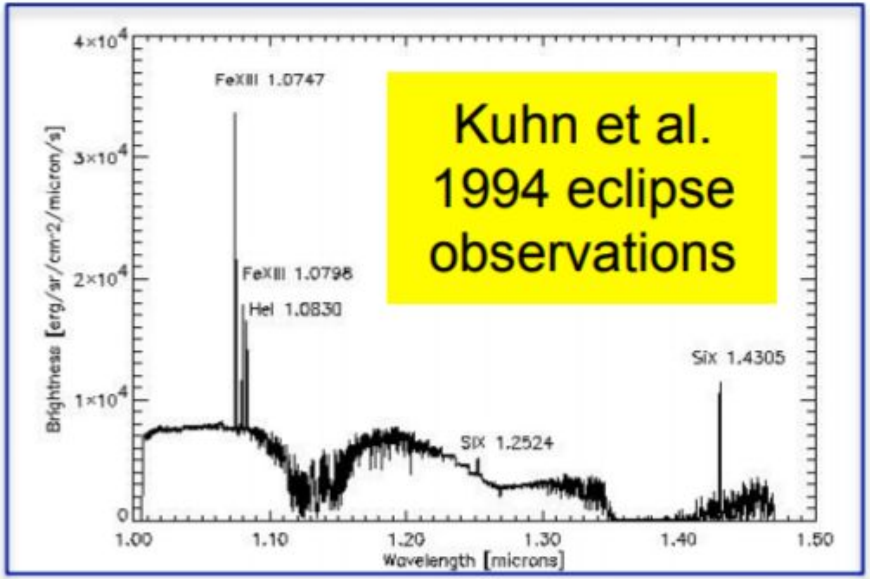
PFSS models and others inherently limited by ill-posed boundary conditions.

As discussed in last lecture: Infrared (and optical) coronal forbidden spectral lines offer magnetic sensitivity through Zeeman effect and saturated Hanle effect.

Zeeman splitting $\propto \lambda^2$
Thermal width $\propto \lambda$
Zeeman sensitivity $\propto \lambda^2 / \lambda \sim \lambda$

The visible and infrared coronal spectrum

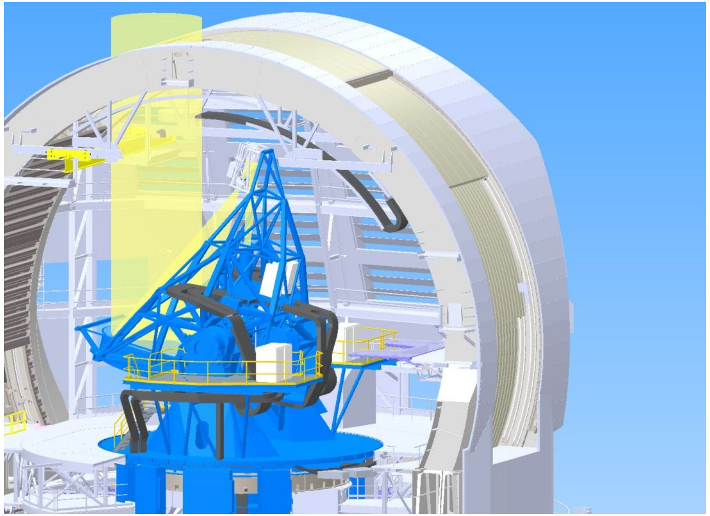

Modeling by Judge et al. (2004)


Kuhn et al. 1994 eclipse observations

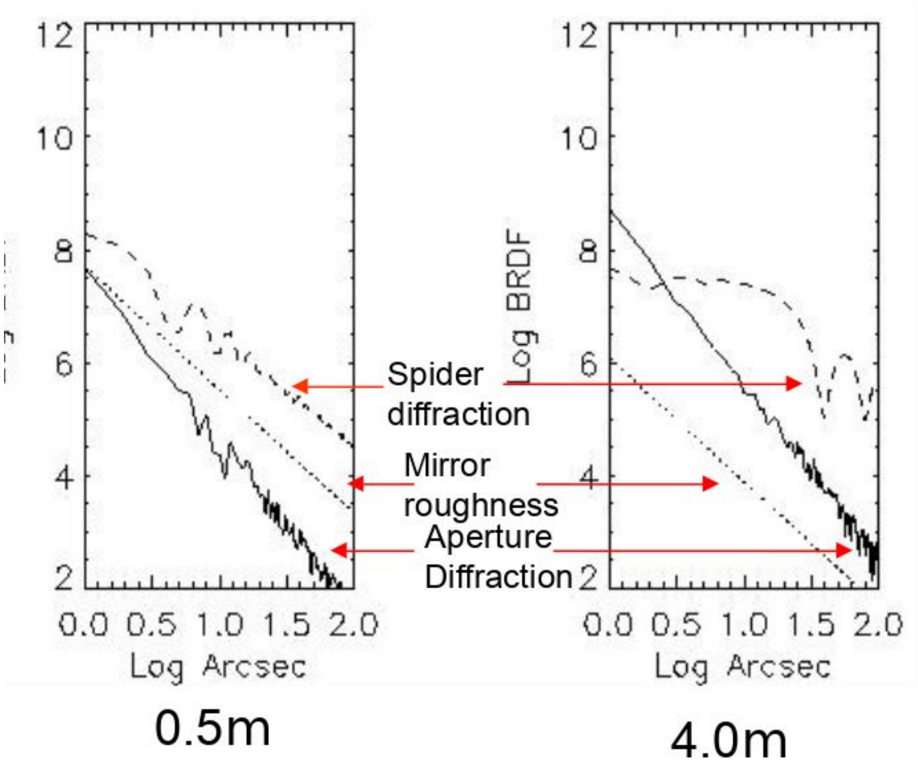
Lines are very weak in comparison to solar disk continuum intensity: ~ (1 to 100) :: 10^6
→ Zeeman signals ~ 0.1% of line intensity, i.e. 10^{-9} of the disk intensity (akin to exoplanets)
→ Limited to off-disk coronagraphic measurements
→ Must mitigate and/or control atmospheric and telescopic scattering of disk light!

One mitigation → finding good coronal skies

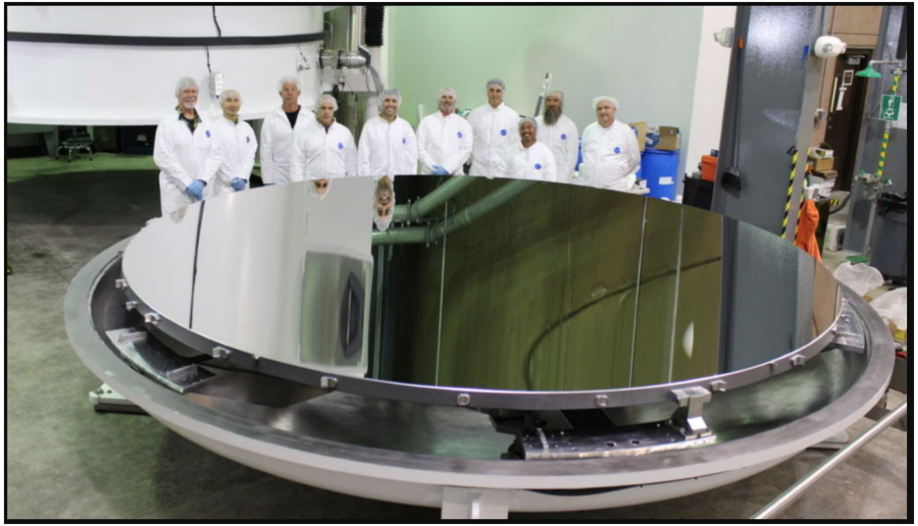
Minimizing scattered light -- off-axis telescope design

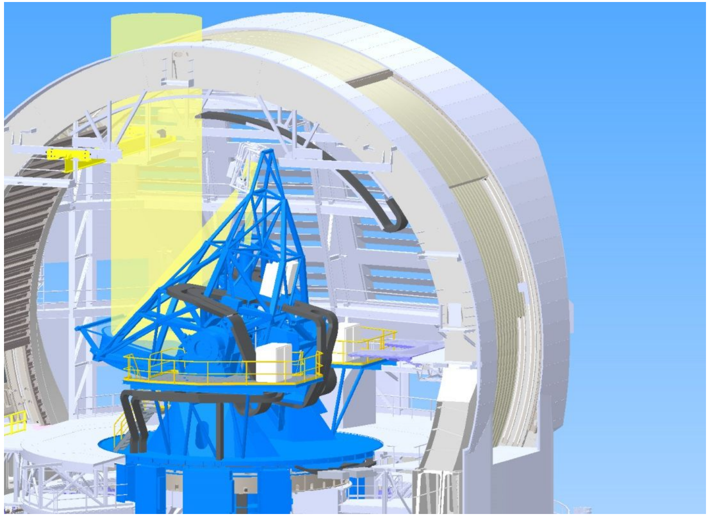


DKIST is off-axis and obscuration free! No secondary “spider” support structure.



Minimizing scattered light - mirror polishing and in-situ cleaning





Mirror roughness minimized. Final polish of 10.5 =/- 1.1 Angstrom rms.

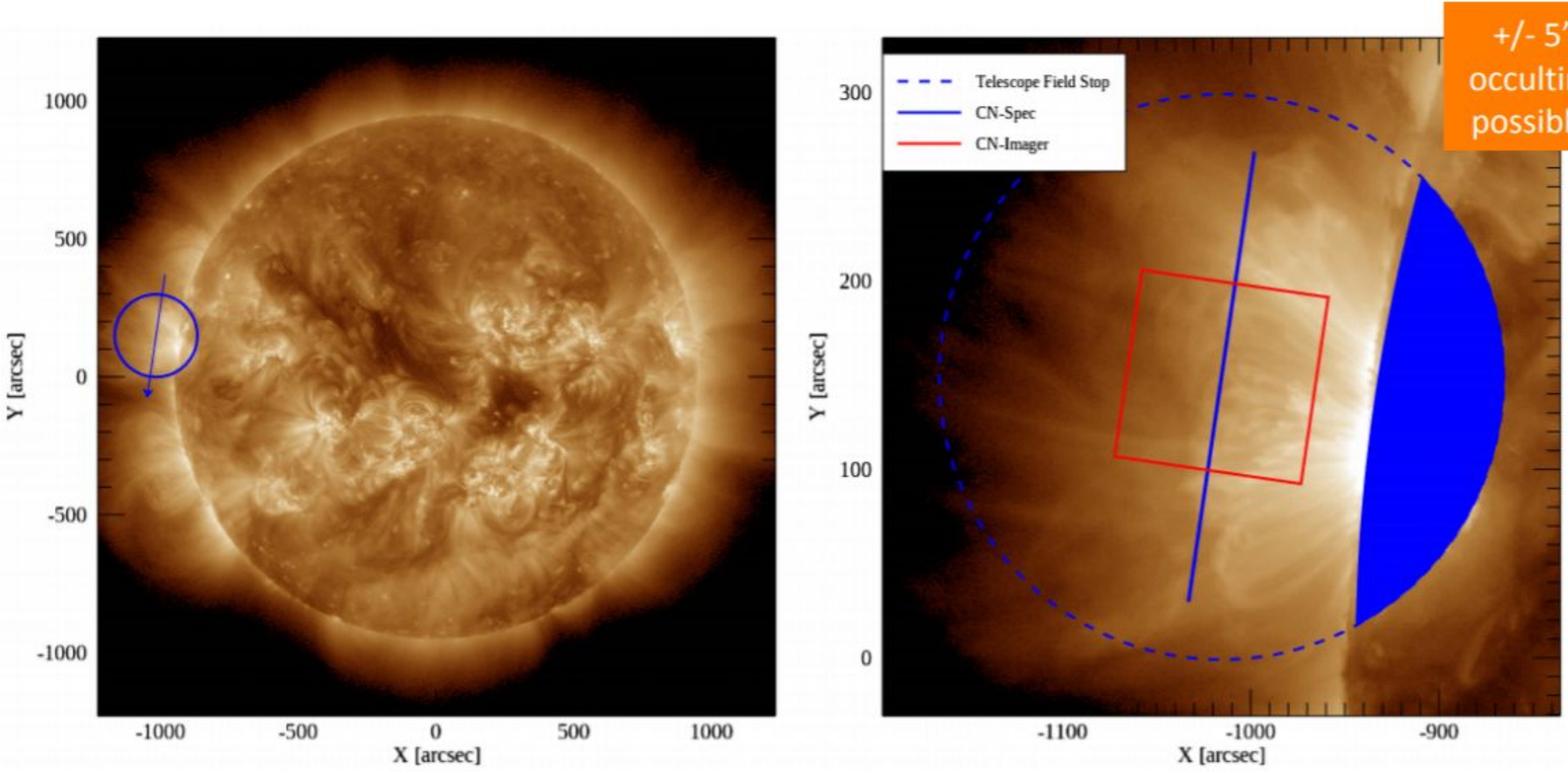
In-situ washing and/or CO2 snow cleaning of mirror

Estimating coronal performance expectations

We could go through a photon error estimate as before by including the influence of the scattered background. See Penn et al. (2004) Solar Physics 222, 61 for information for estimating background-limited observations of the coronal magnetic field.

For DKIST, we expect measurement errors of ~ 30 Gauss assuming the weak field approximation using Fe XIII 1074 nm at a height of 1.1 solar radii for a 1 arcsec^2 pixel, integration time of 1 second, and assuming the target has a brightness of 40 millionths.

Cryo-NIRSP Example: 5 arcmin field-of-view with limb occulter (blue)



+/- 5" occulting possible.

DKIST Science:

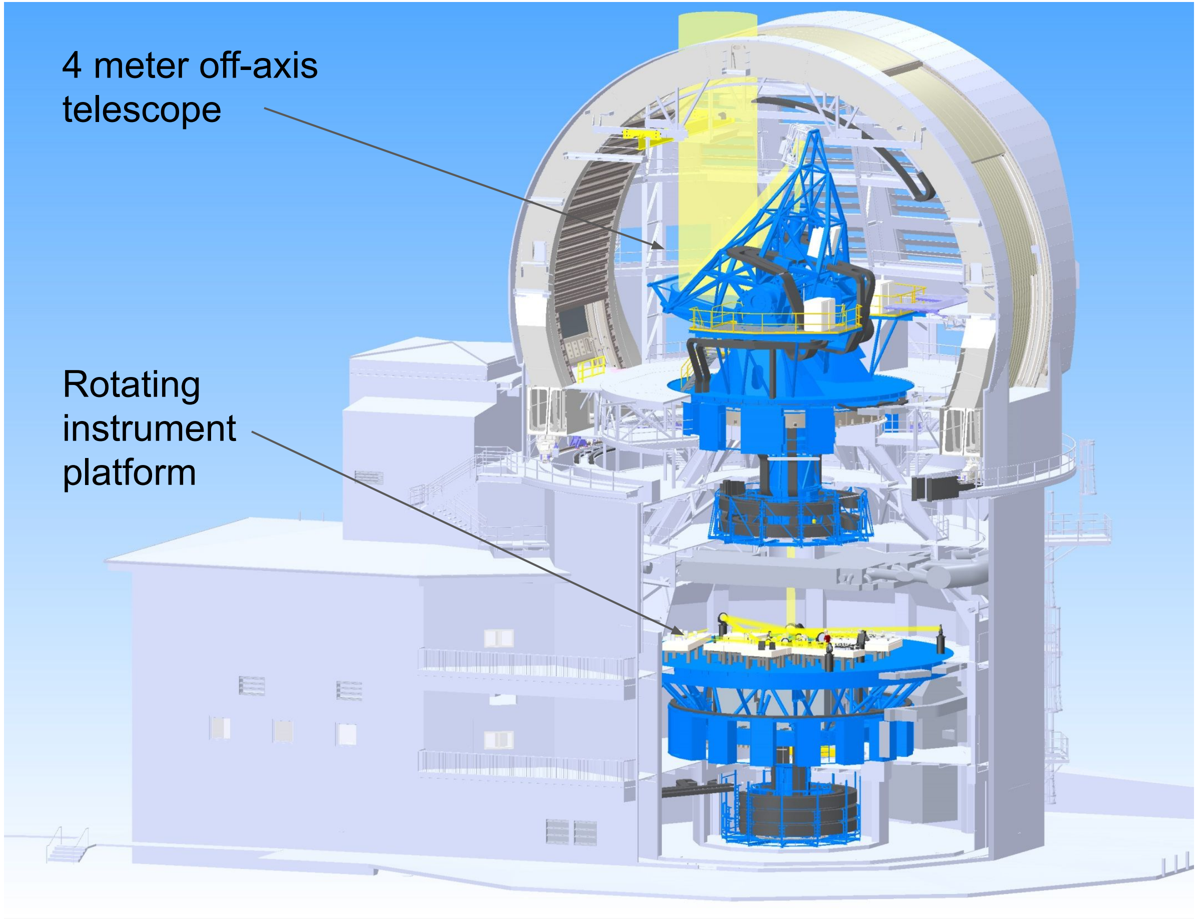
Today we highlight
four key capabilities:

High spatial resolution

High sensitivity polarimetry

Multi-wavelength diagnostics

Coronagraphic polarimetry



Recommended reading

More detailed information about DKIST and instruments at

https://www.nso.edu/telescopes/dkist/csp/

Cauzzi, Tritschler, & Deng.“Science with Large Solar Telescopes: Overview of SpS 6” (2015) Highlights of Astronomy, 16, 439

Kleint & Gandorfer “Prospects of solar magnetometry - from ground and in space” (2015) Space Science Reviews, 210, 397

Judge, Habbal, & Landi “From Forbidden Coronal Lines to Meaningful Coronal Magnetic Fields” (2013) Solar Physics, 288,467