How to plan (some of) your observations with DKIST

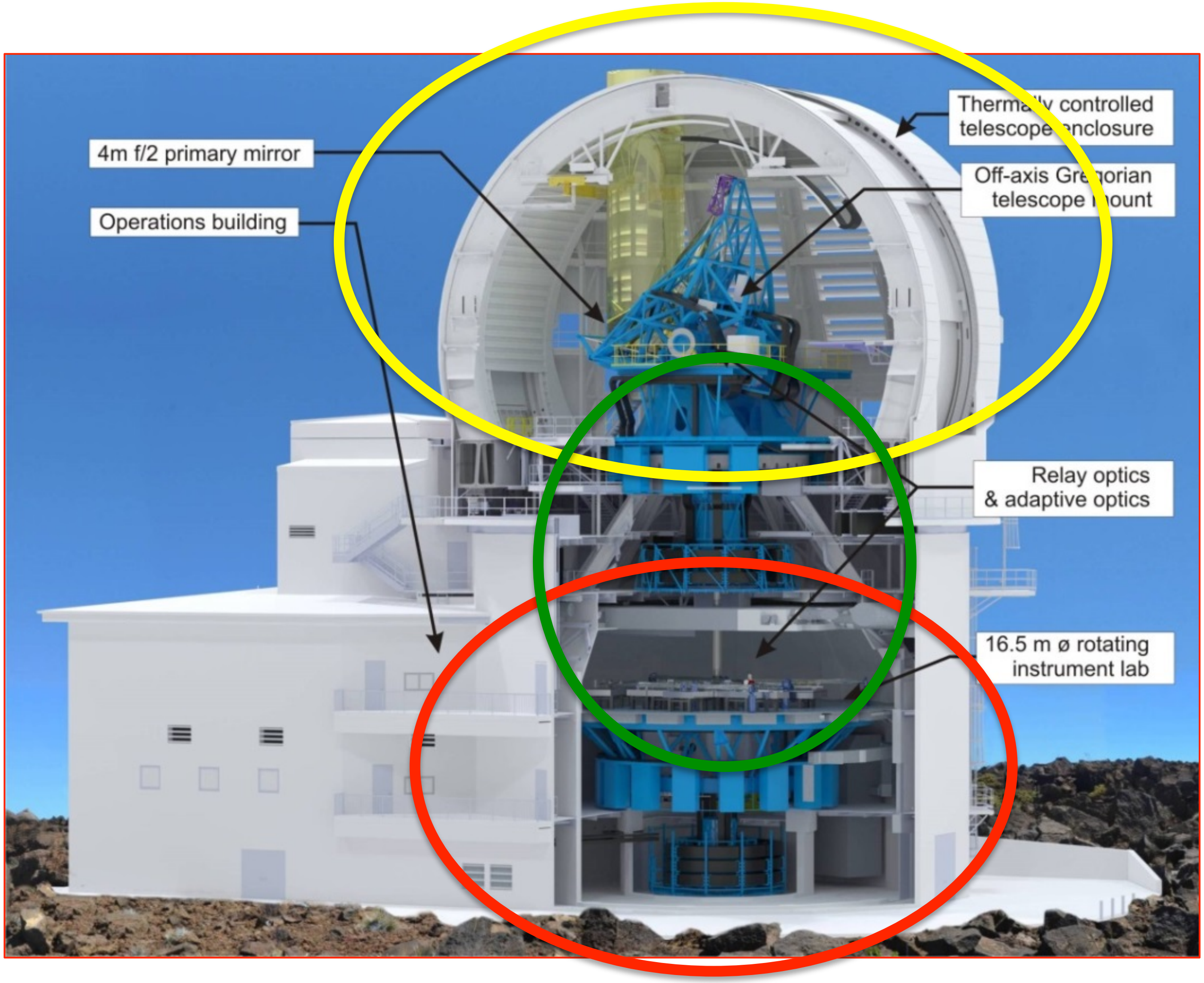
Gianna Cauzzi

National Solar Observatory

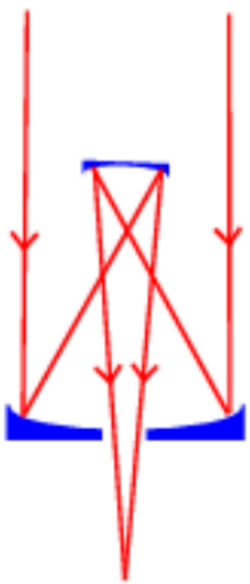
COLLAGE; 25 Feb 2020

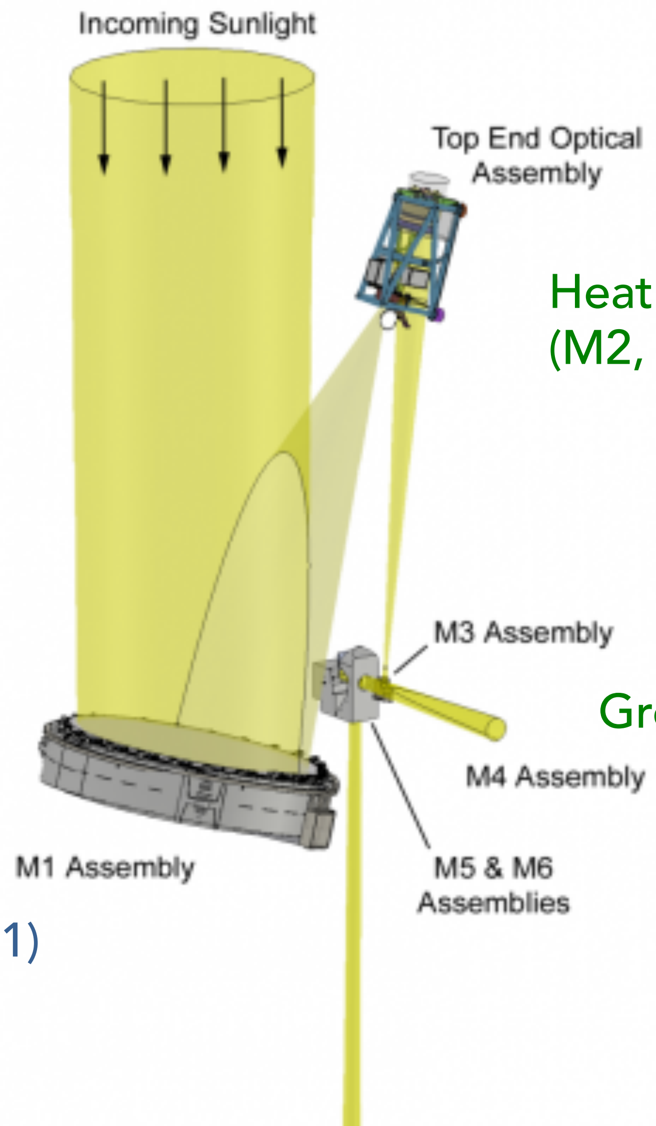
Daniel K. Inouye Solar Telescope
DKIST

DKIST cutaway



Off-axis Gregorian Telescope



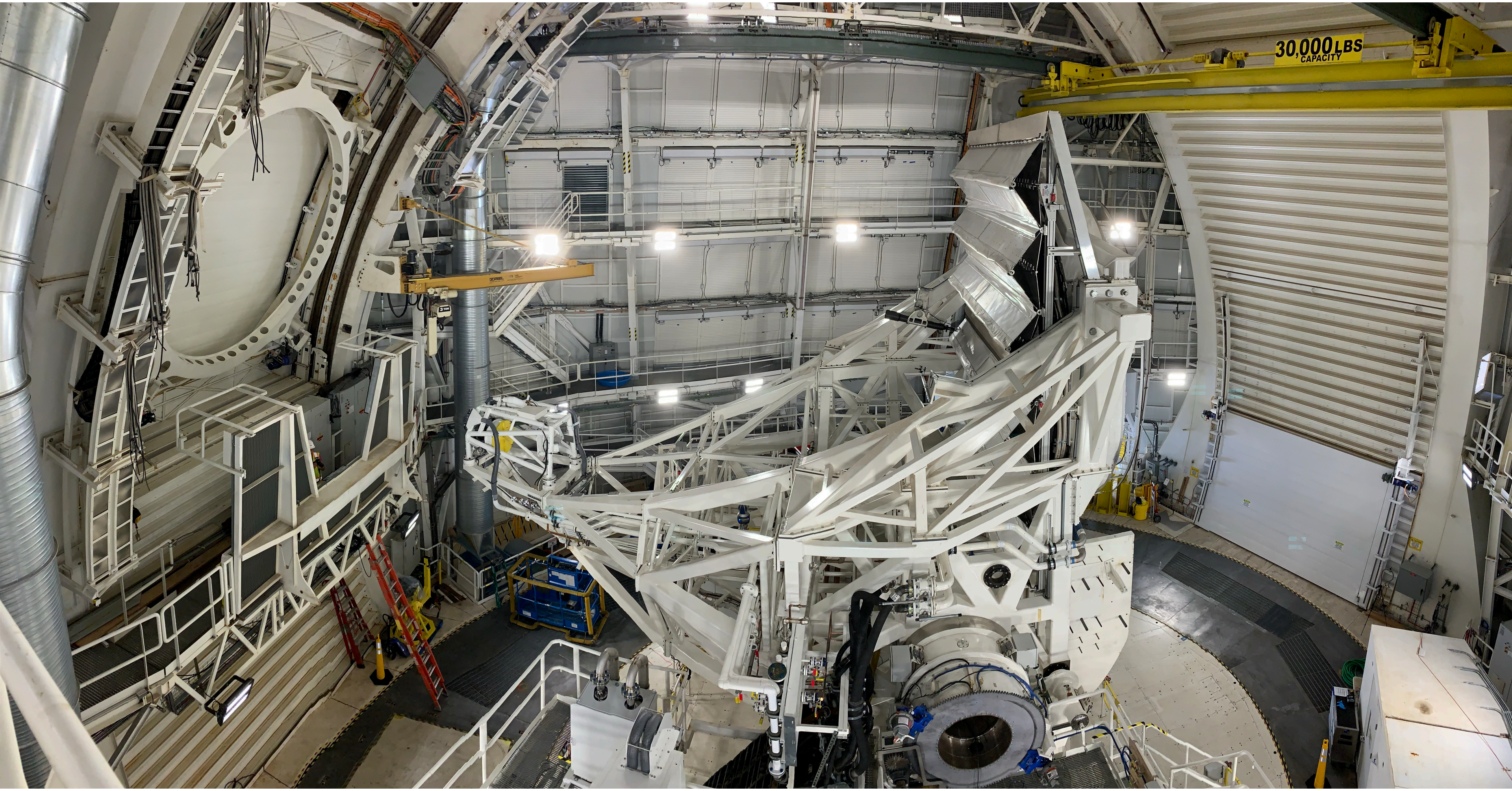


Heat stop and secondary (M2, 0.9 m diameter)

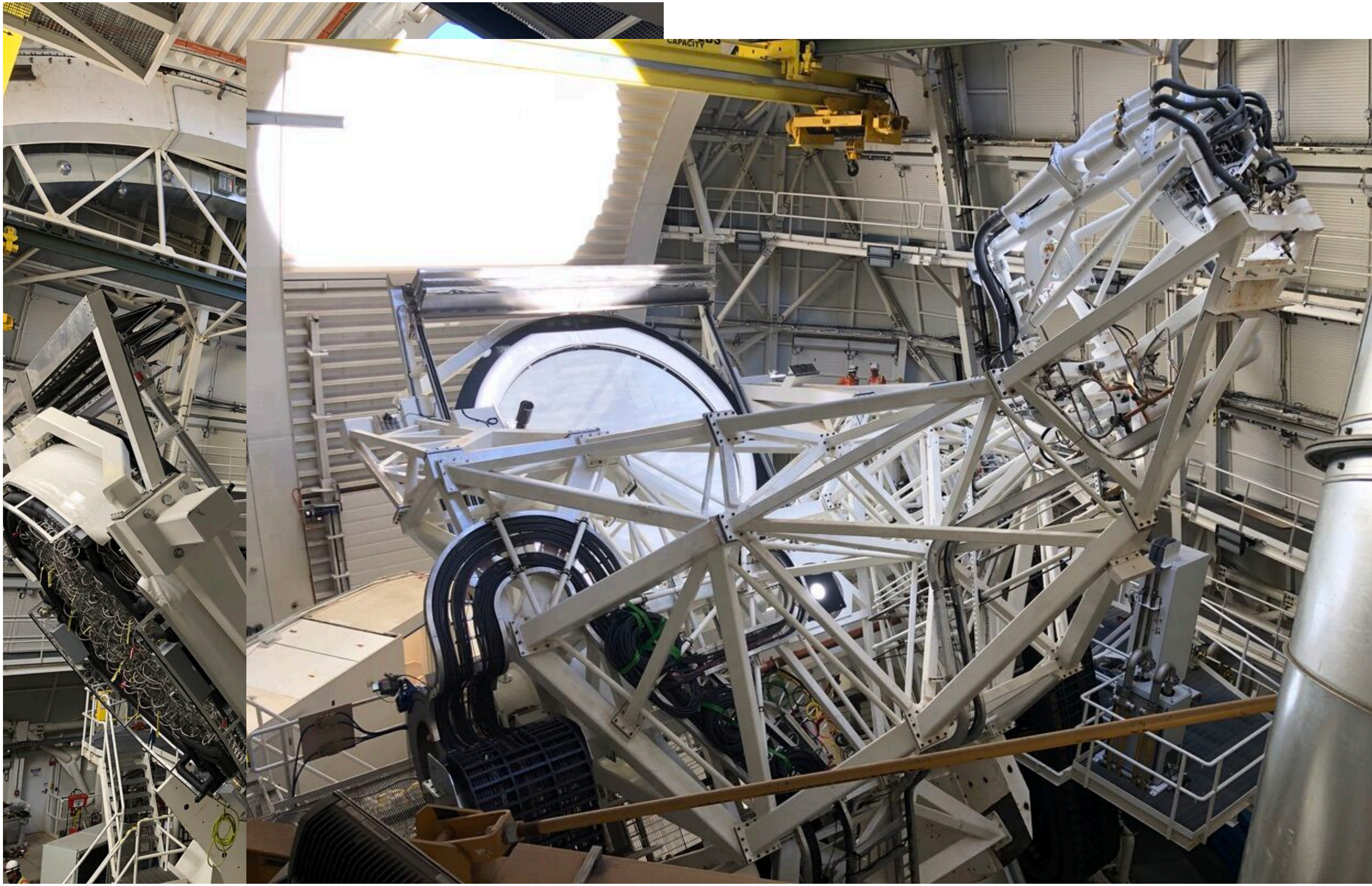
Gregorian Optical Station

Primary mirror (M1)
4 m diameter
f/2

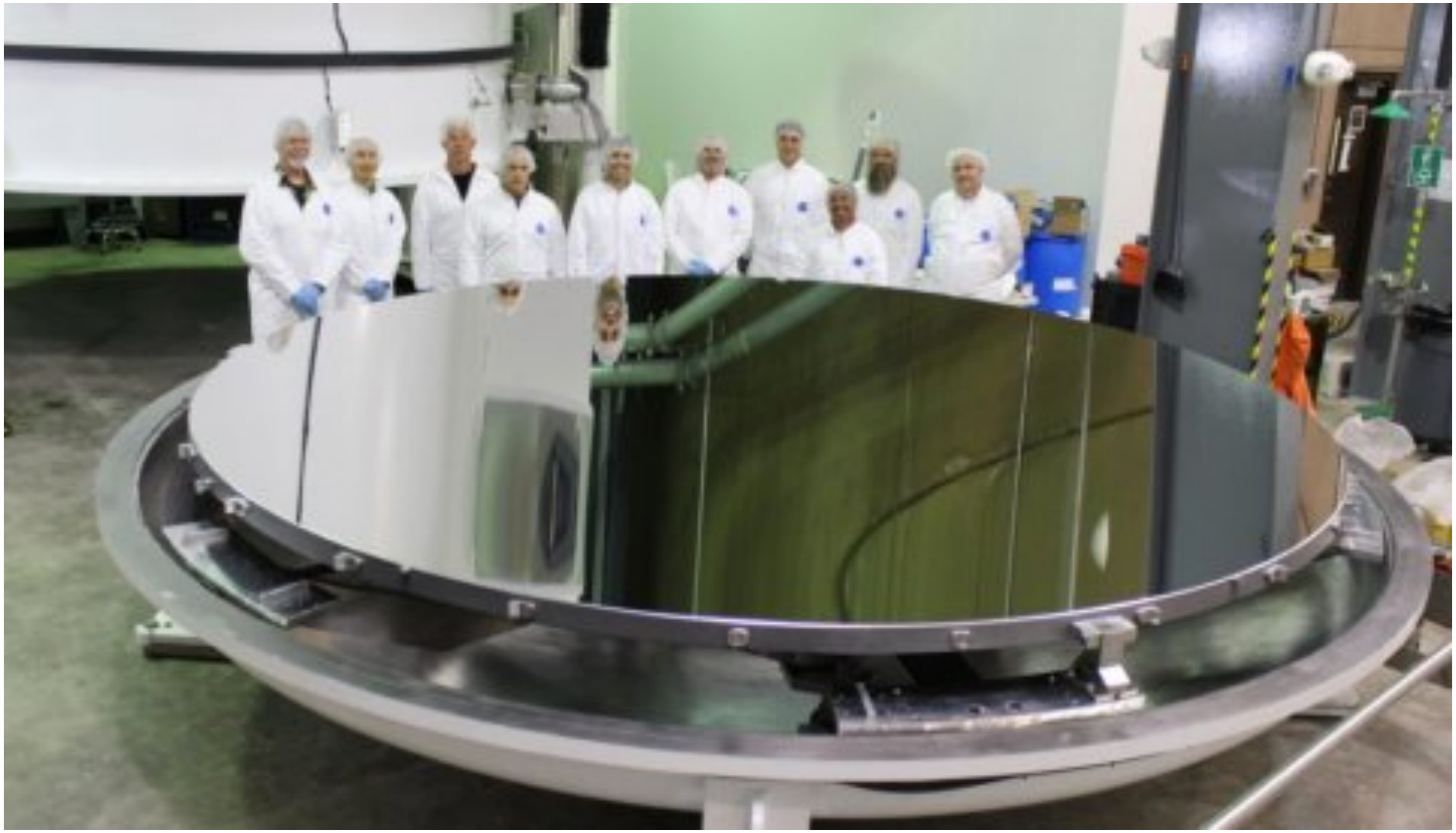
Telescope + enclosure



Sunlight!



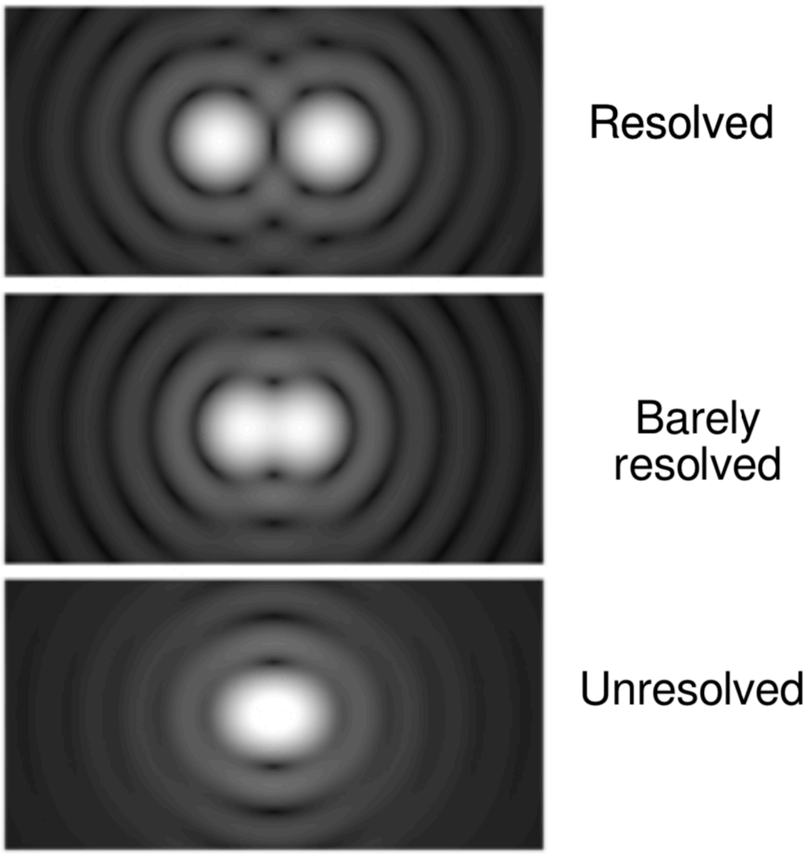
A transformational facility: 4 m primary

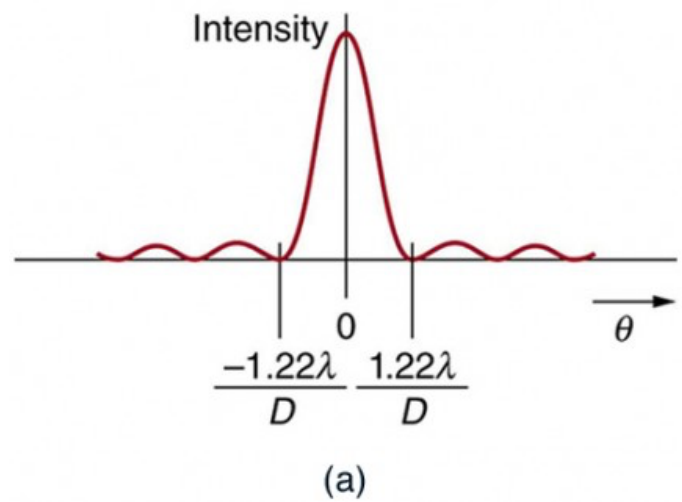


Current largest solar telescope=GST, 1.6 m

A transformational facility: 4 m primary

Rayleigh criterion





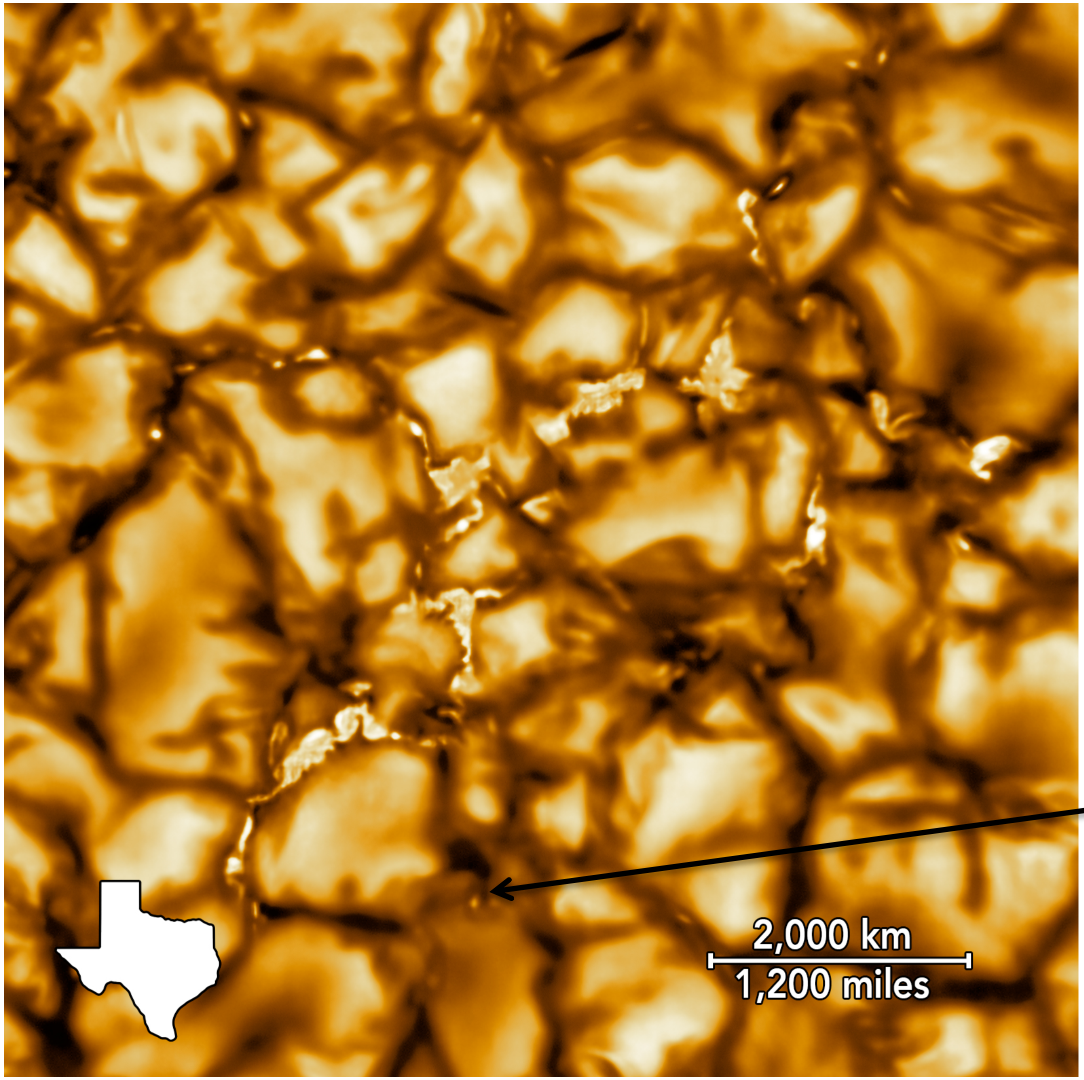
For DKIST (D= 4 m):

1.22 λ/D @ 400 nm =

10^{-7} rad =

0.02” = 15 km @ the SUN!

A transformational facility: 4 m primary



< 40 km resolution!!

@ 790 nm

But remember: photon flux per spatial resolution element is constant

DKIST focal ratio & heat load:

Solar image size at prime focus =

solar angular size x focal length

DKIST: 30’ x 8 m ~ 7 cm

(DST: 30’ x 53 m ~ 50 cm)

(McMath: 30’ x 90 m ~ 85 cm)

DKIST focal ratio & heat load:

Power collected =

Solar irradiance ('constant') at sea level x mirror area

DKIST: 1 kW/m^2 x (π x $4^2/4$) ≅ 12.5 kW

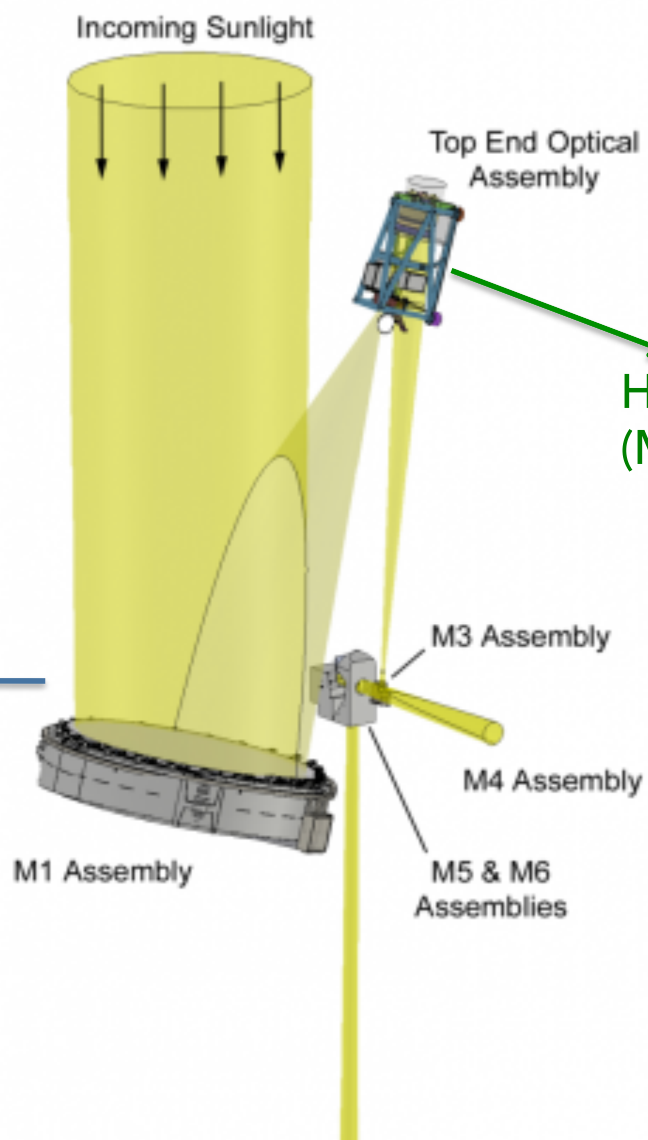
Heat load at prime focus =

power collected / image surface

DKIST: 12.5 kW /0.004 m^2 ~ 3200 kW/m^2 =

3000 Solar Irradiance !!

Telescope Optical Light Path



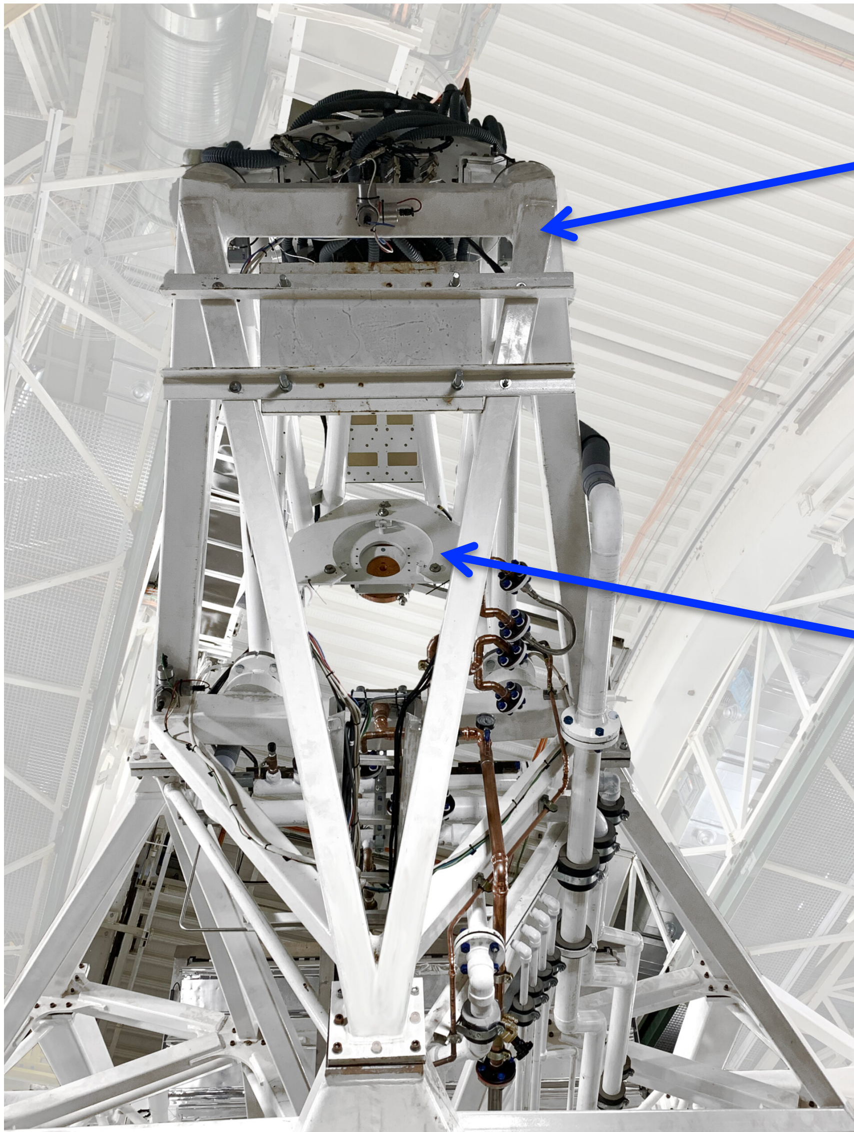
Heat stop and secondary
(M2, 0.9 m diameter)

Primary mirror (M1)
4 m diameter

OFF AXIS

Gregorian Optical Station

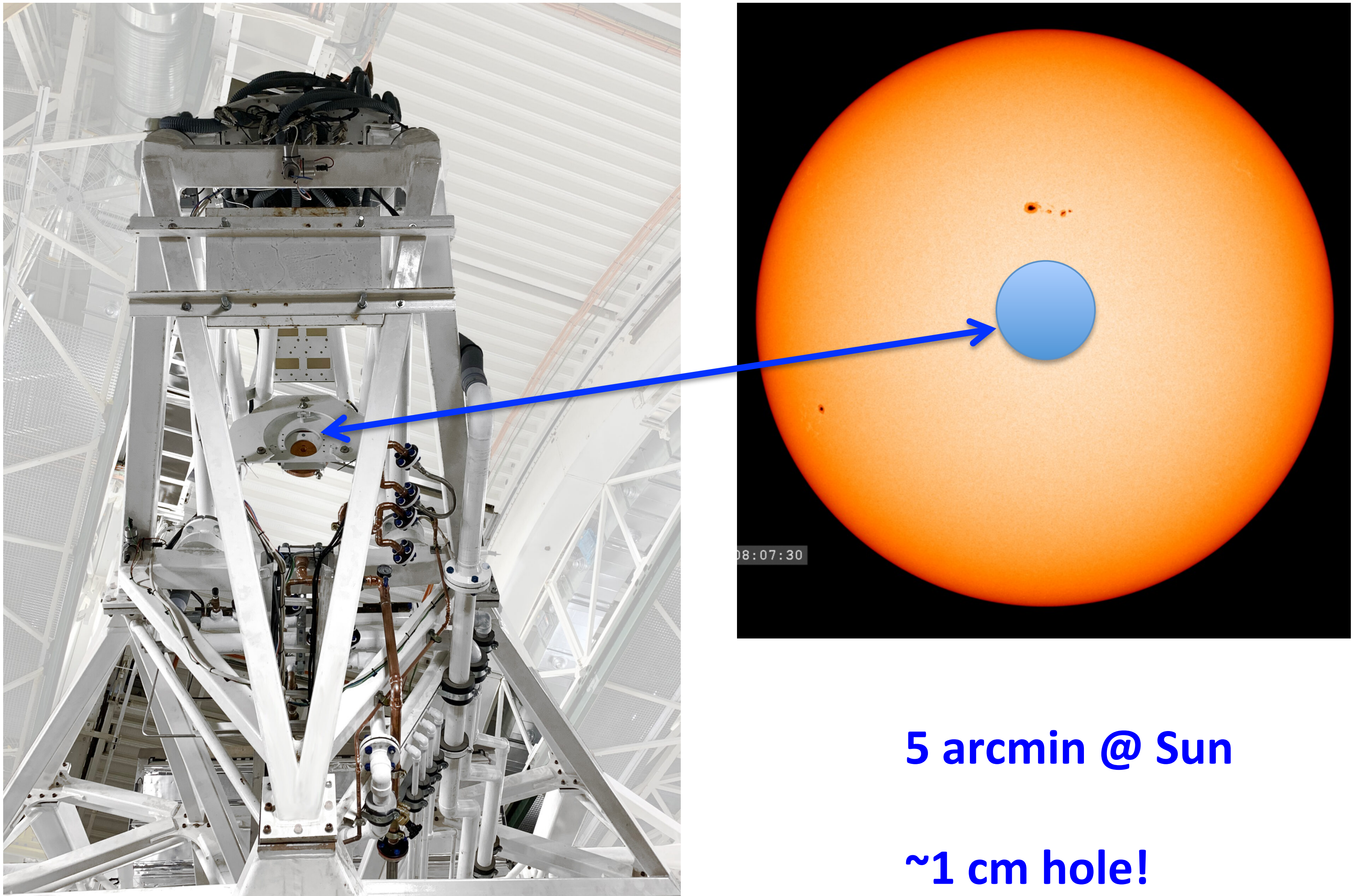
Top End Optical Assembly



M2

Heat stop

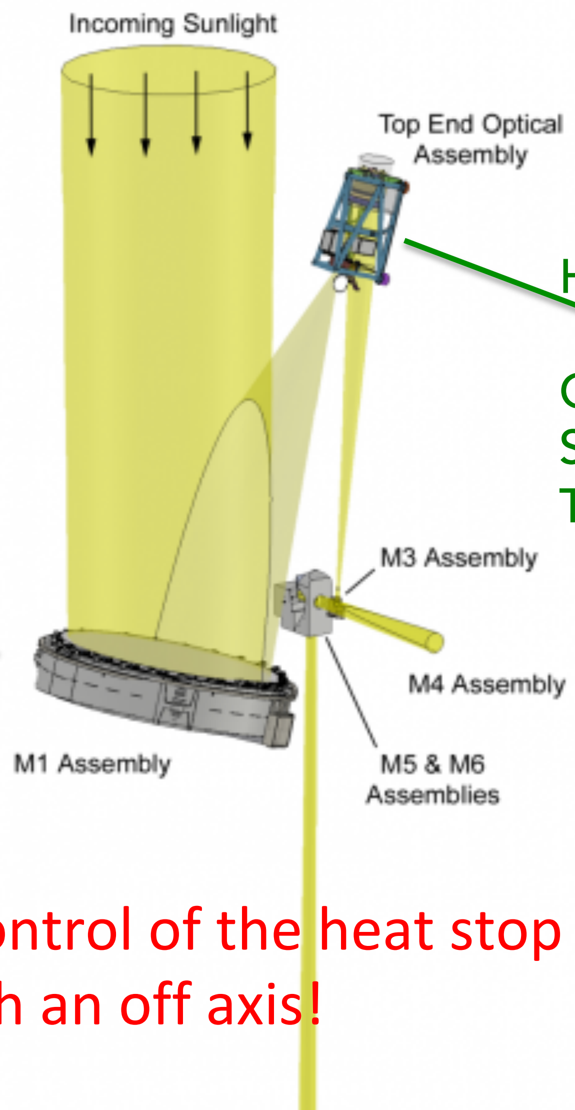
Top End Optical Assembly



5 arcmin @ Sun

~1 cm hole!

Telescope Optical Light Path



Heat stop and secondary (M2)

ONLY 5′ (~ 1cm) OF THE
SOLAR IMAGE IS TRANSMITTE
TO M2 AND BEYOND

Primary mirror (M1)

OFF AXIS

The assembly and control of the heat stop mechanism is much simpler, & safer, with an off axis!

Image quality: on-axis vs. off-axis

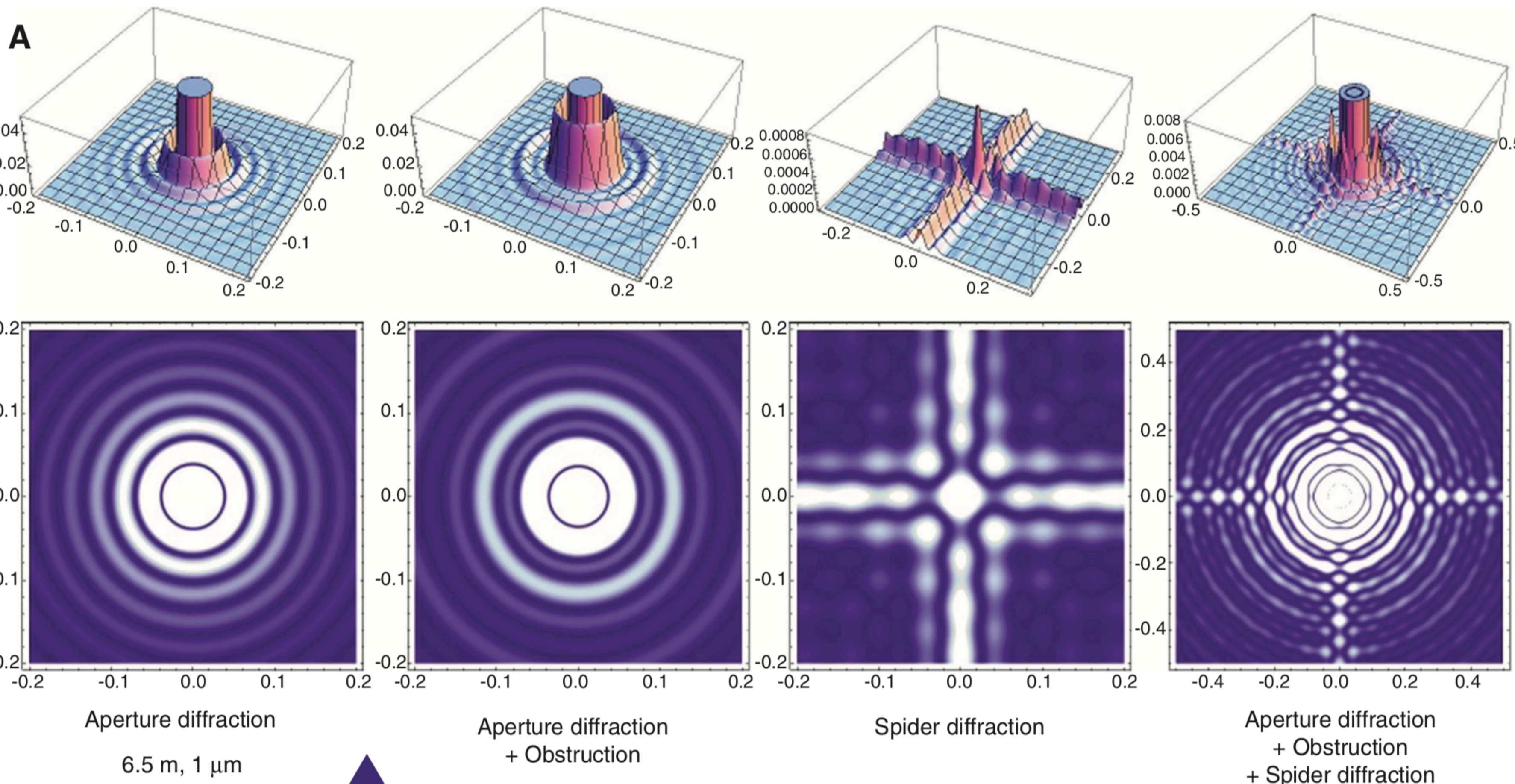
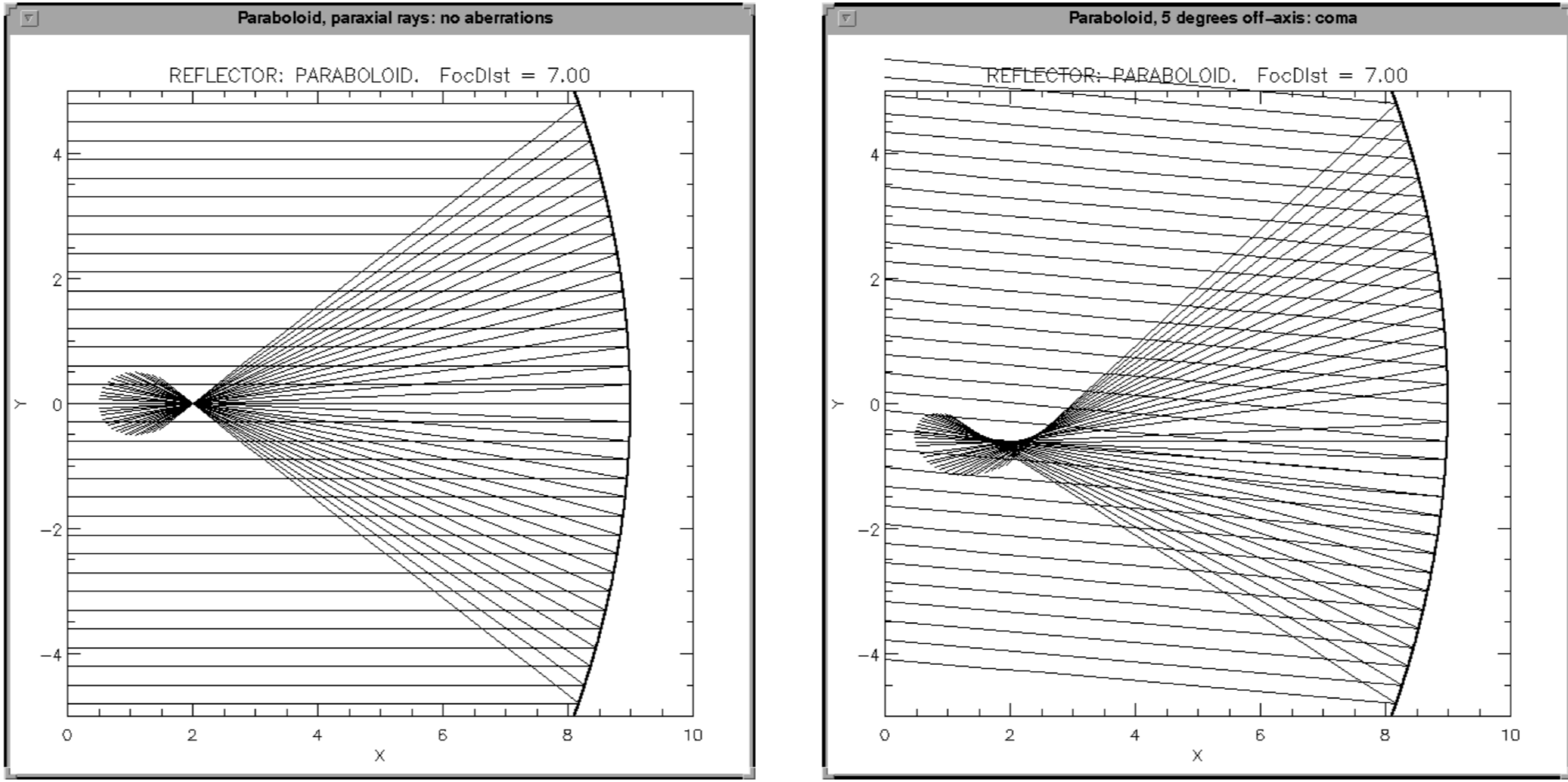


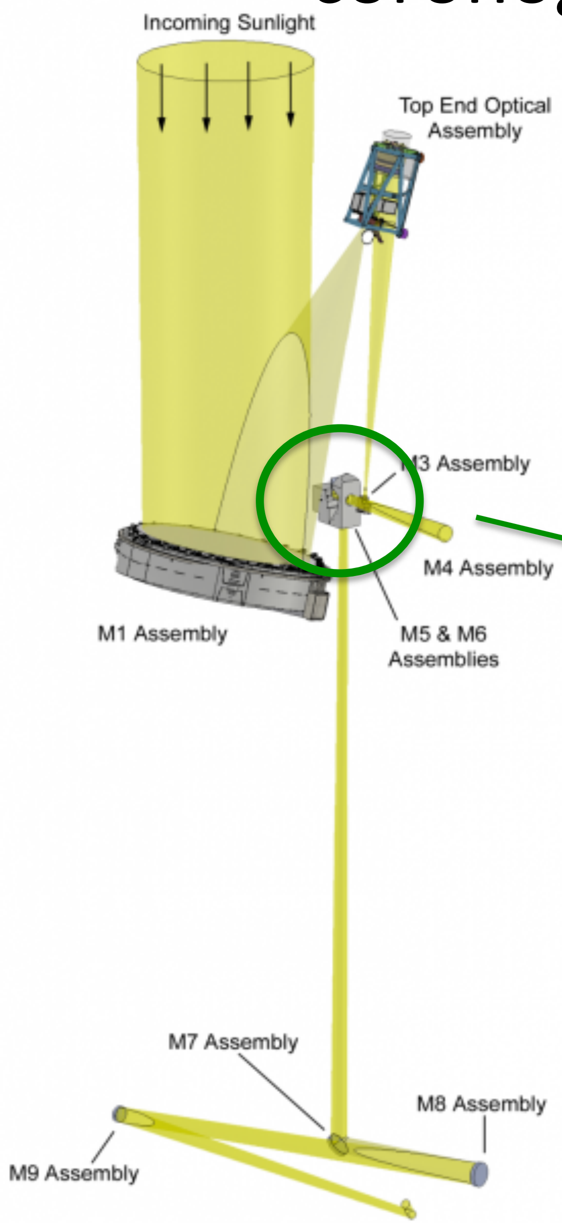
Image quality (in principle) and scattered light (especially) are much improved with an off-axis

Image aberration: coma



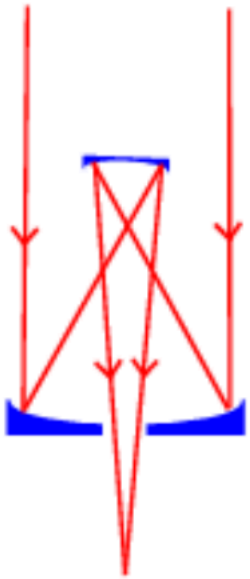
Can be compensated by chosing small FOV and long focal ratios

A transformational facility: polarimeter, coronograph, IR-telescope



Gregorian Optical Station:

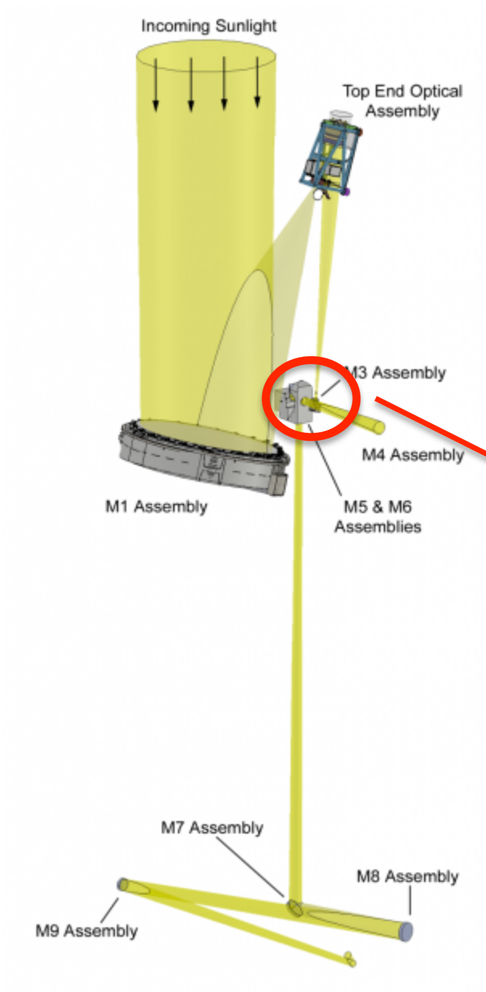
Polarization Calibration
More field Stops
Occulters

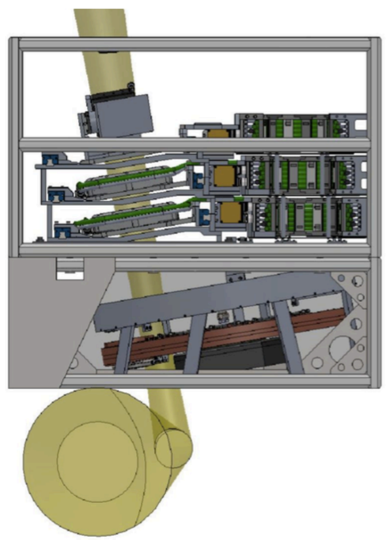


Gregorian focus

DKIST as a Polarimeter

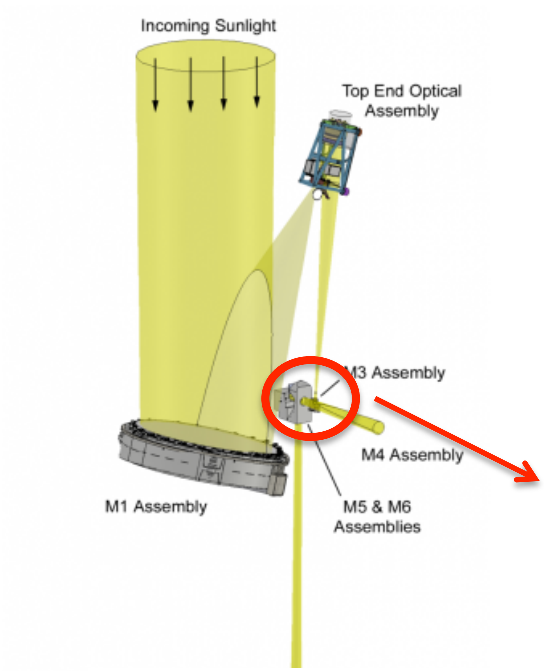
$$\bar{\bar{M}}_{DKIST} = \bar{\bar{M}}_7 \bar{\bar{R}}(Az-Table)\bar{\bar{M}}_{56}\bar{\bar{R}}(El)\bar{\bar{M}}_{34}\bar{\bar{M}}_{12}$$

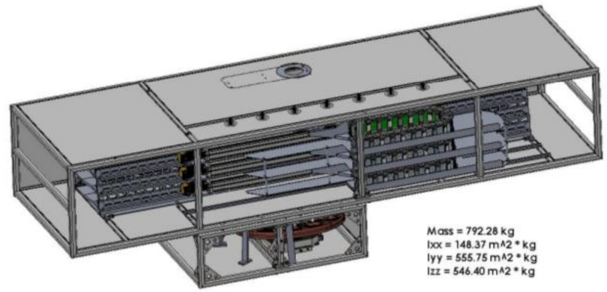


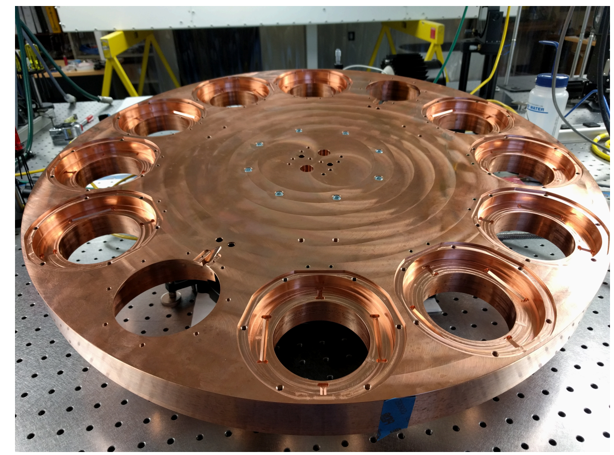


- <u>Polarization sensitivity 10^{-5}</u>
- <u>Polarization accuracy $5\ 10^{-4}$</u>
- Cal optics after M_{12} close to Gregorian Focus.
- Calibrates all optics downstream.
- Similar to Gregor.
- Exposure time dependent.

DKIST as coronograph



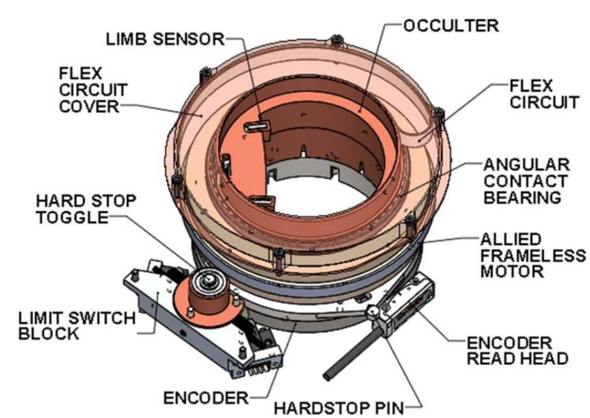




The Gregorian Optical System (GOS)

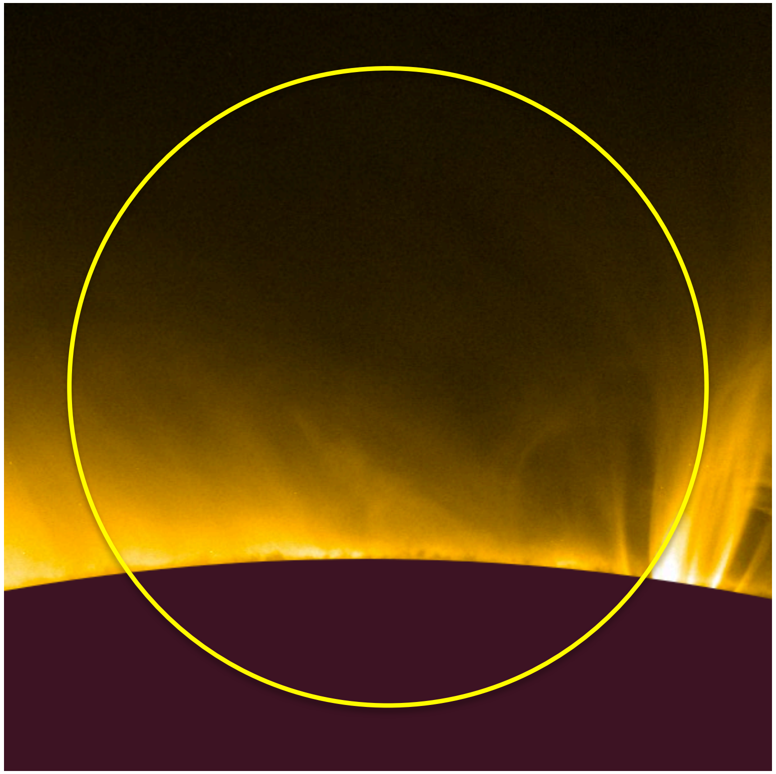
- Limb occulter: Disc(s) to block the solar disc near the limb.
- Limb over/under-occulting of ±5 arcsec possible.
- Comes with a “limb sensor” that measure limb motions.

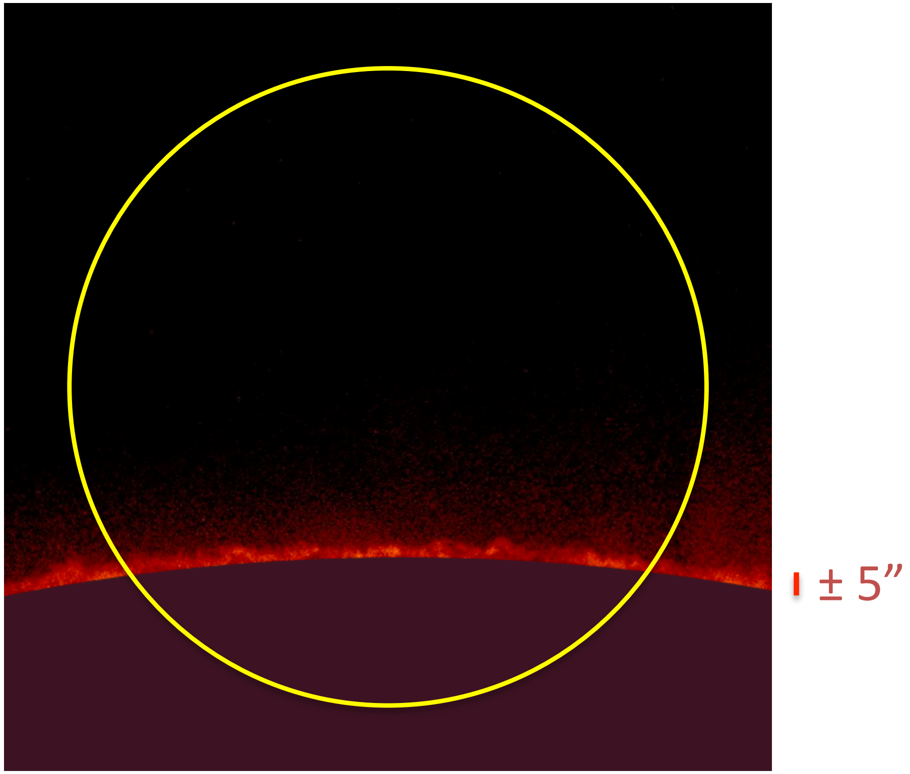
- PLUS, another Field Stop: 2.8’



Occulting the Limb

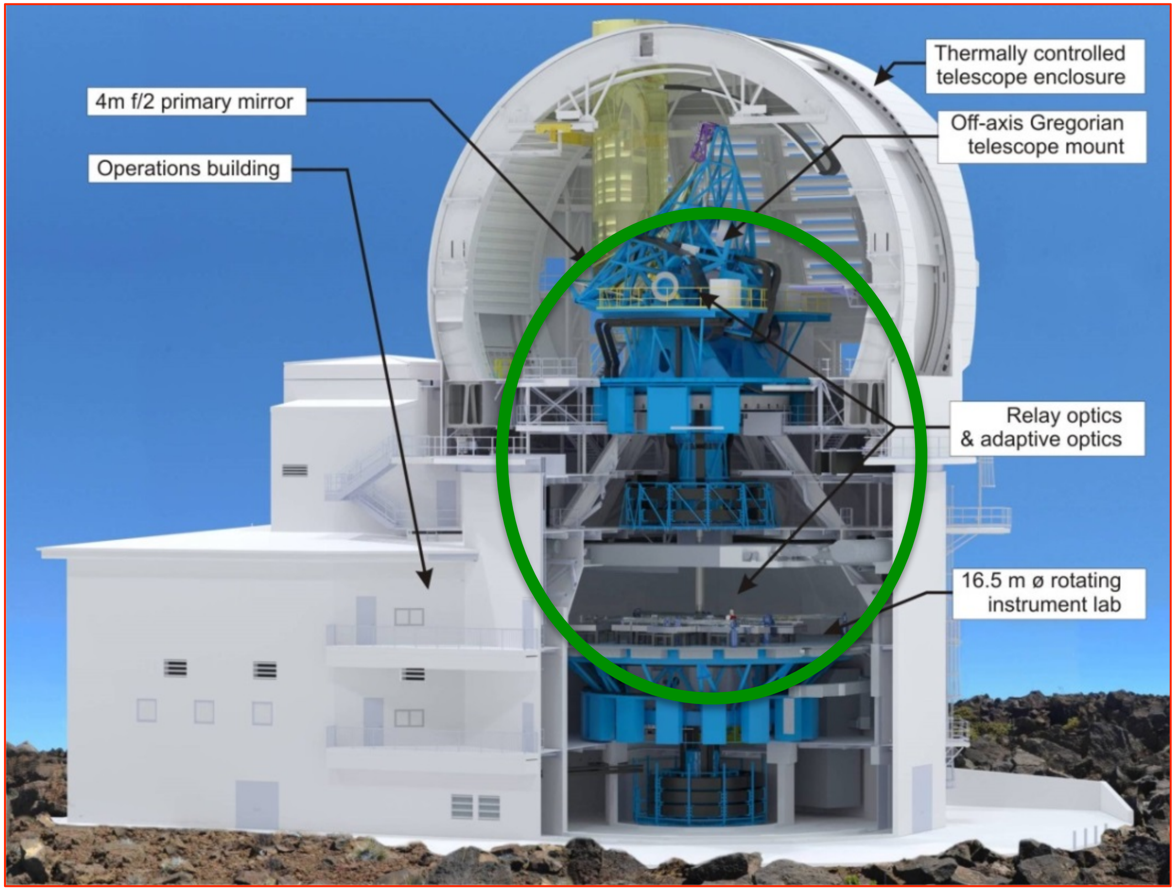
5 arcmin occulter





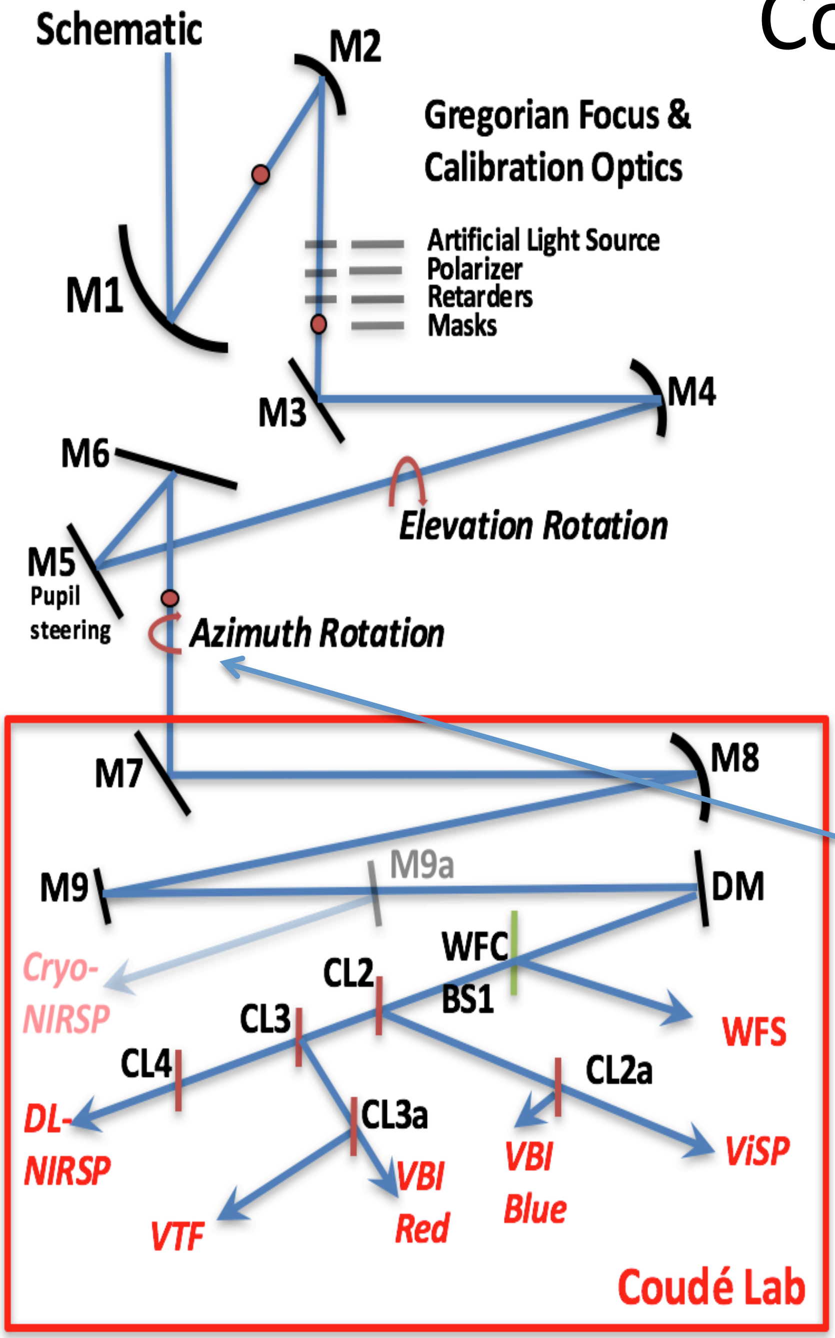
- Limb sensor tracks image motion in both axes, corrected by M2 fast tip/tilt.
- Over/under occultation possible by +/- 5 arcsec.

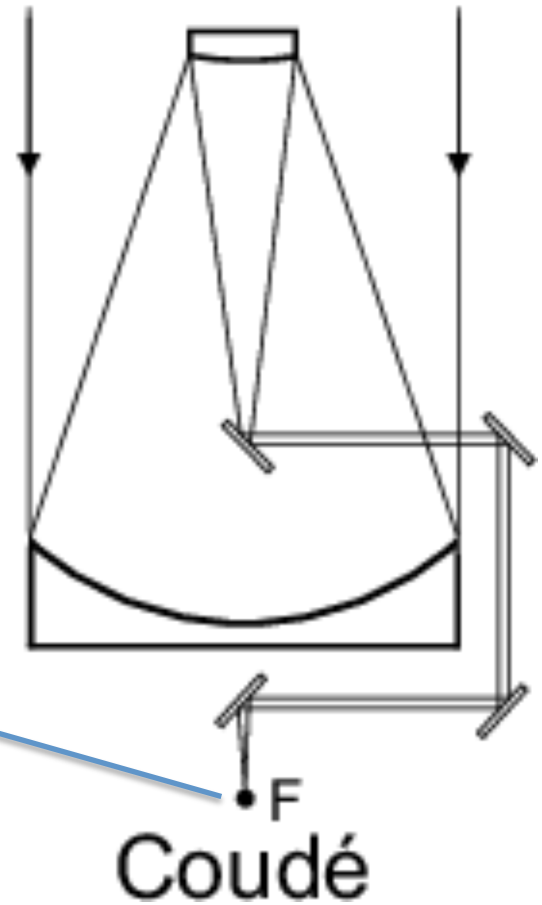
Relay optics: all reflective!



- All mirrors: ACHROMATIC !
- No lenses: can access up to thermal infrared (~ 28 μm)
- Current instruments designed for up to 5 μm)

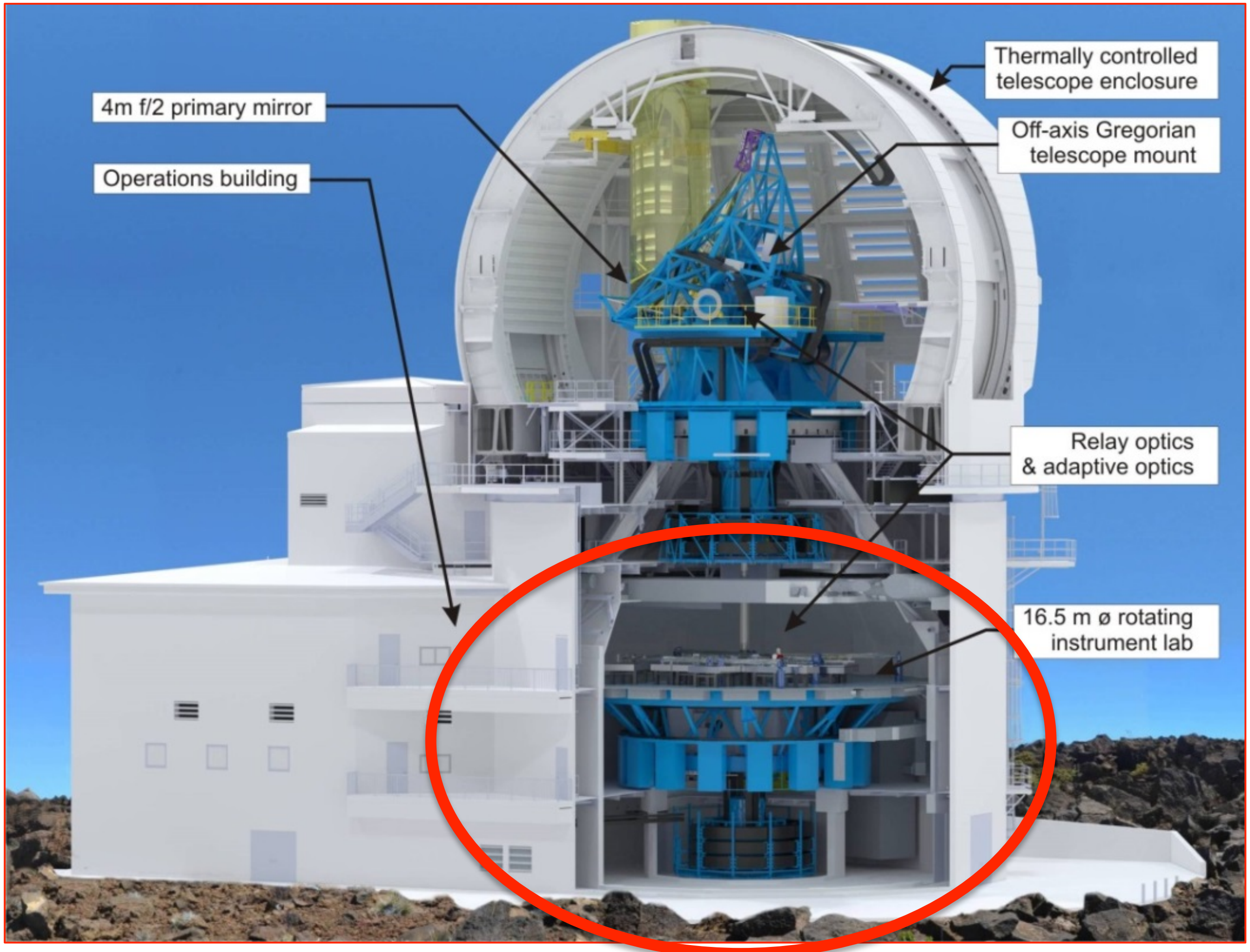
Coude' focus





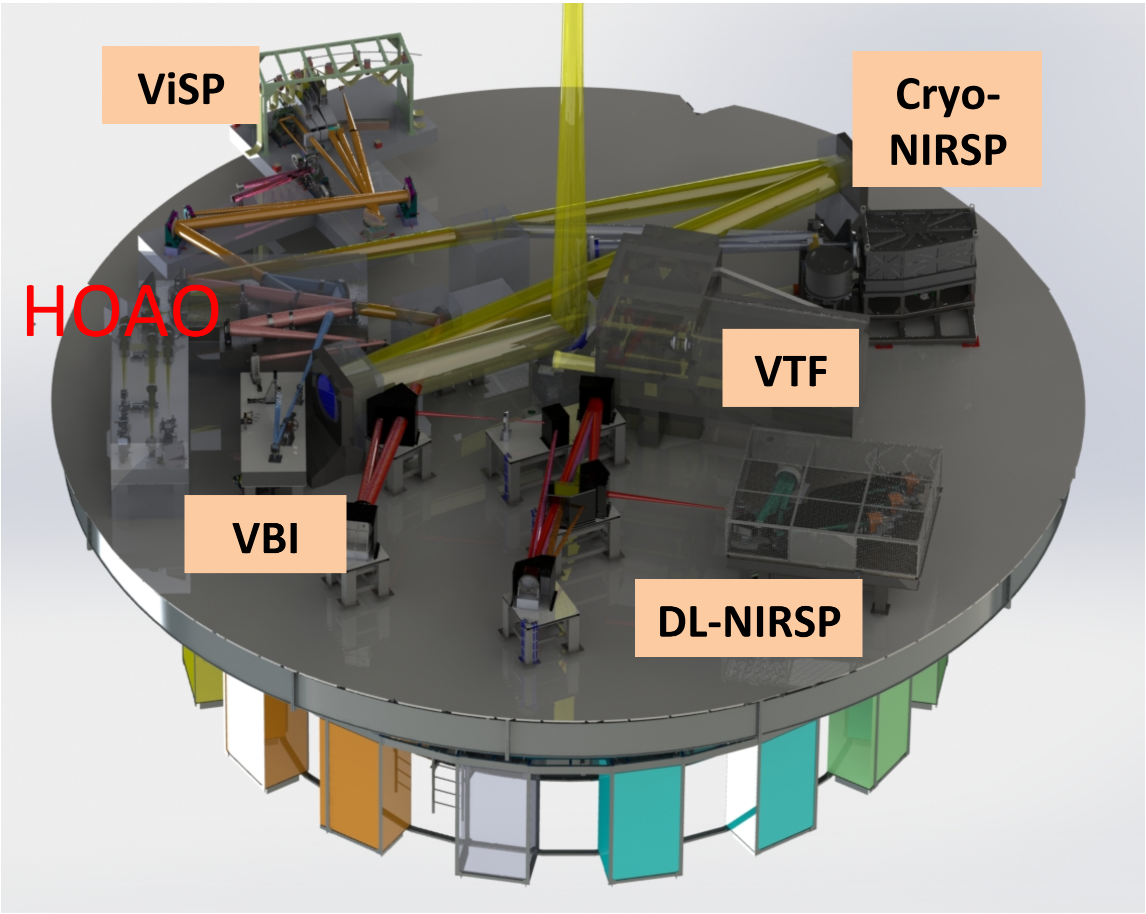
Coude' Focus does NOT move as the telescope is re-oriented: useful for large instruments, with long (effective) focal lengths. Used in all major solar telescopes

Coude' lab: where instruments live



The Coude' lab ROTATES during the day to keep constant the solar image orientation on the scientific instruments

A transformational facility: multi-instrument, multi-height diagnostics!



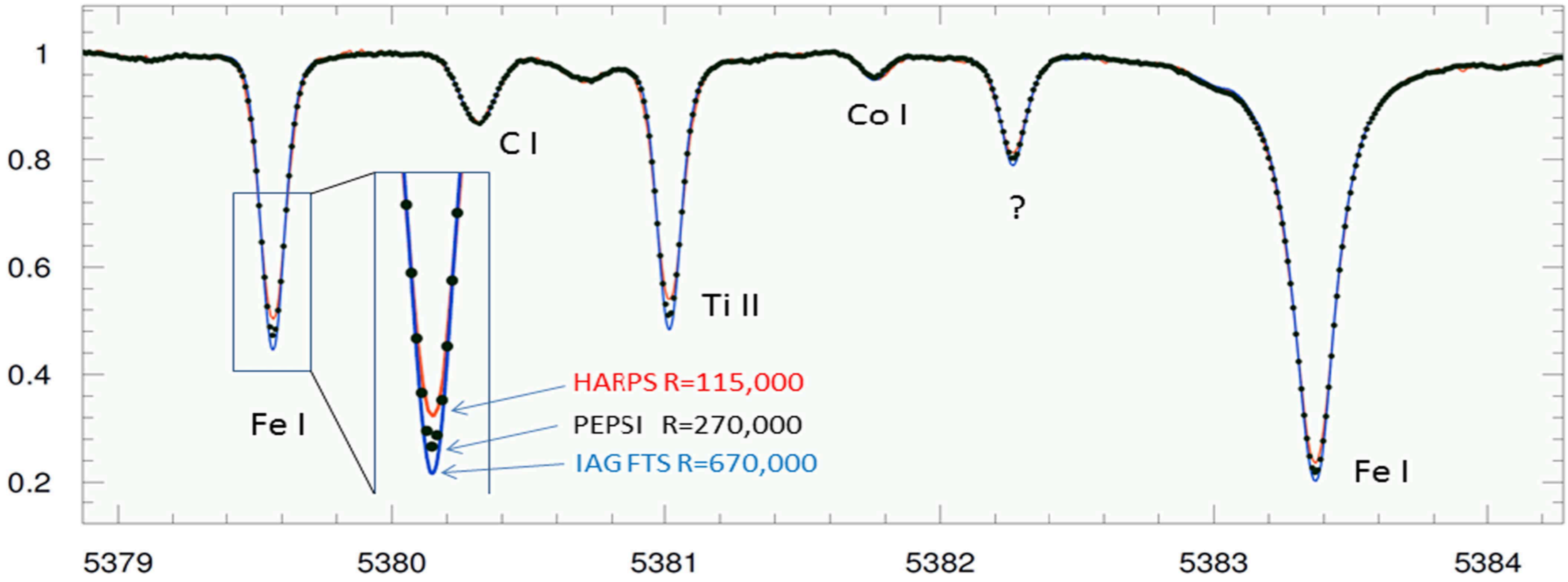
Five *complementary* image-, slit-, and IFU-based instruments.

Spectropolarimetric emphasis.

All instruments are fed with a wavefront corrected beam (with exception of Cryo-NIRSP).

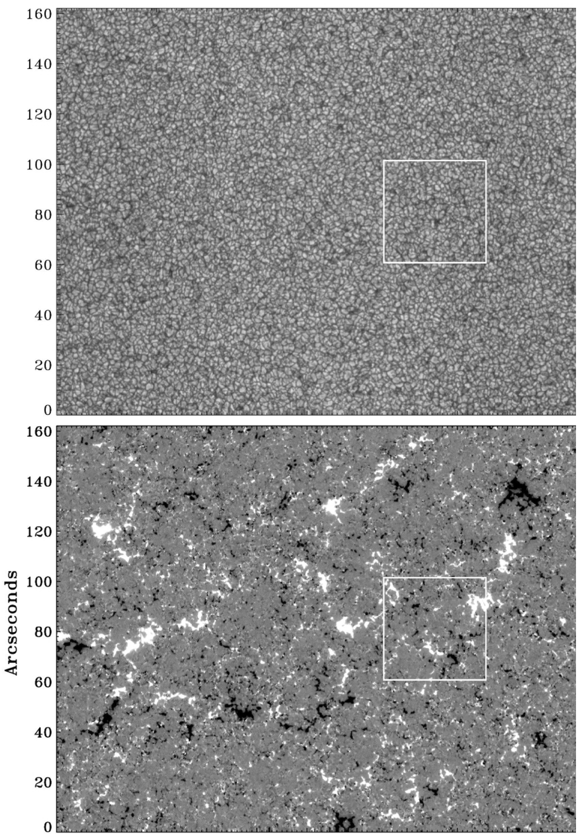
www.nso.edu/telescopes/dki-solar-telescopes/instruments

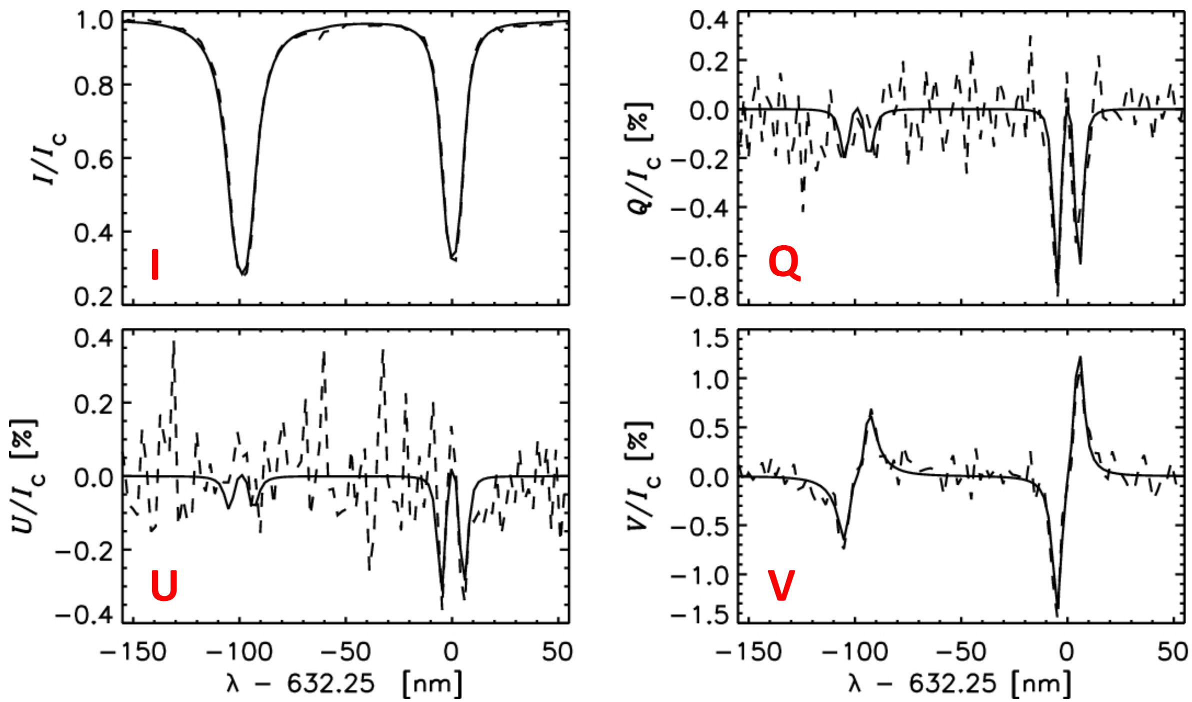
Analyze spectral intensity….



The presence of lines, and their shape, strength, position, polarization state, etc. give us the **physical state of the emitting plasma**: abundances, T, ρ, v, ioniz. state, magnetic field, and their temporal evolution.

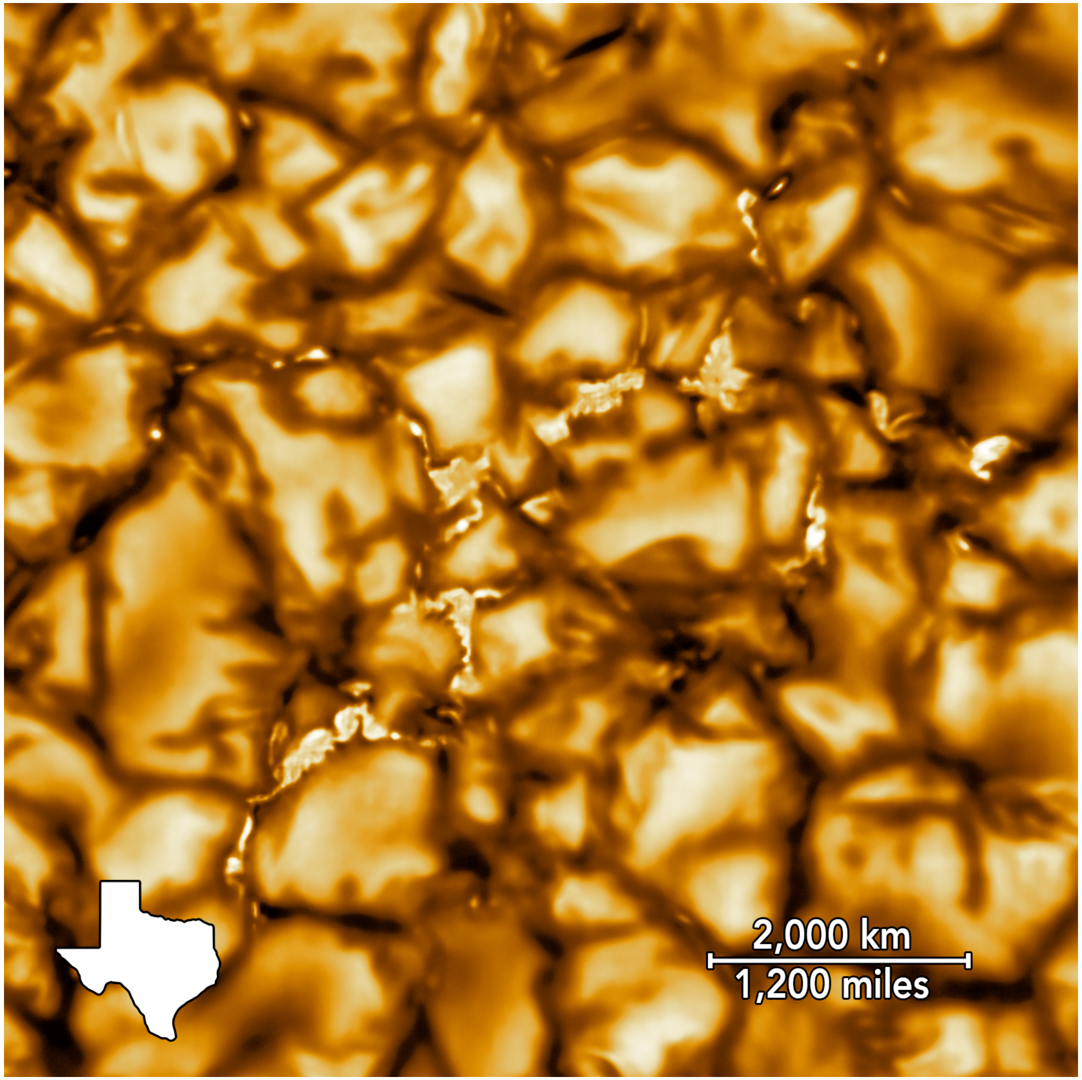
And polarization ….



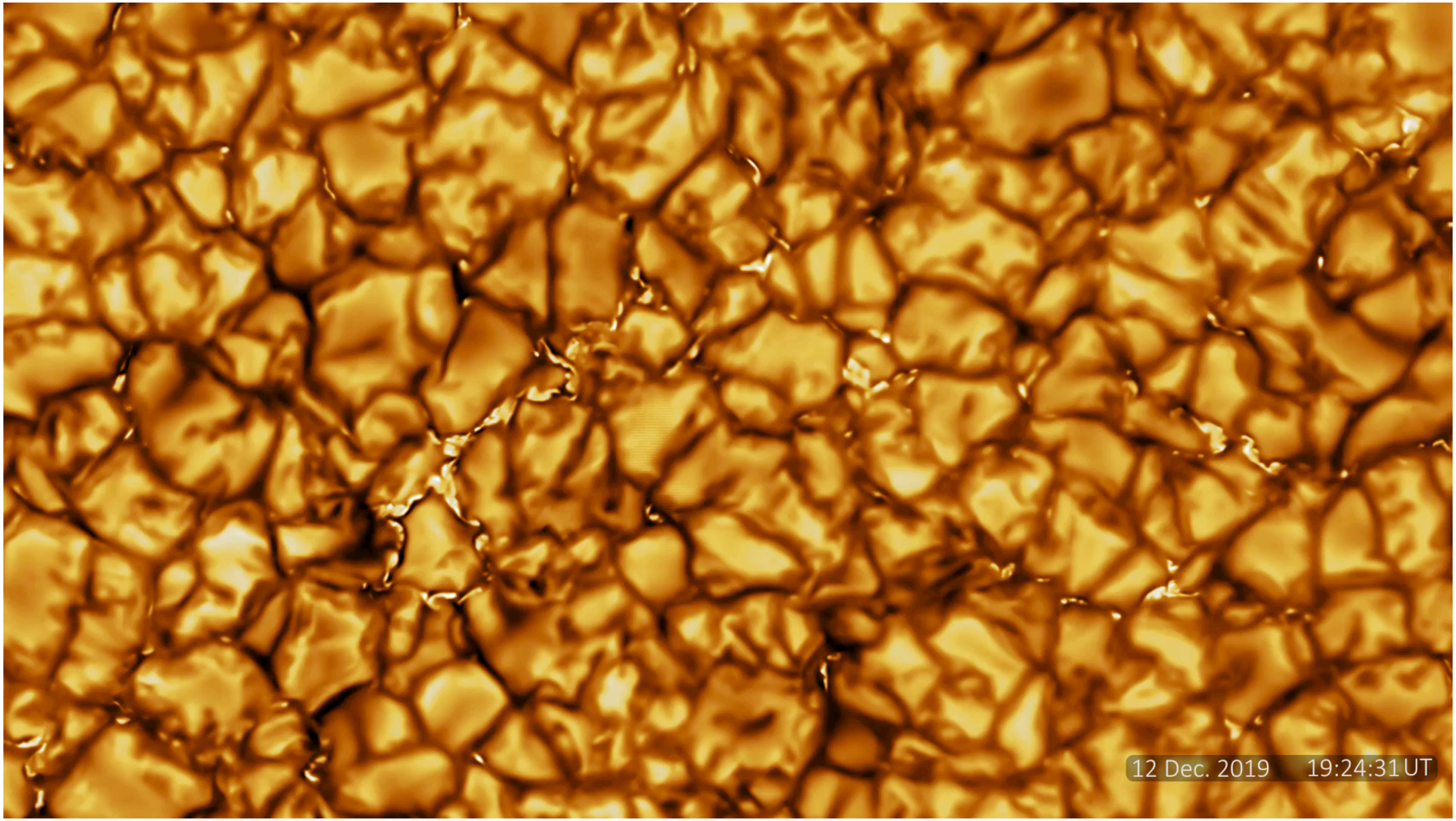


30,000 km

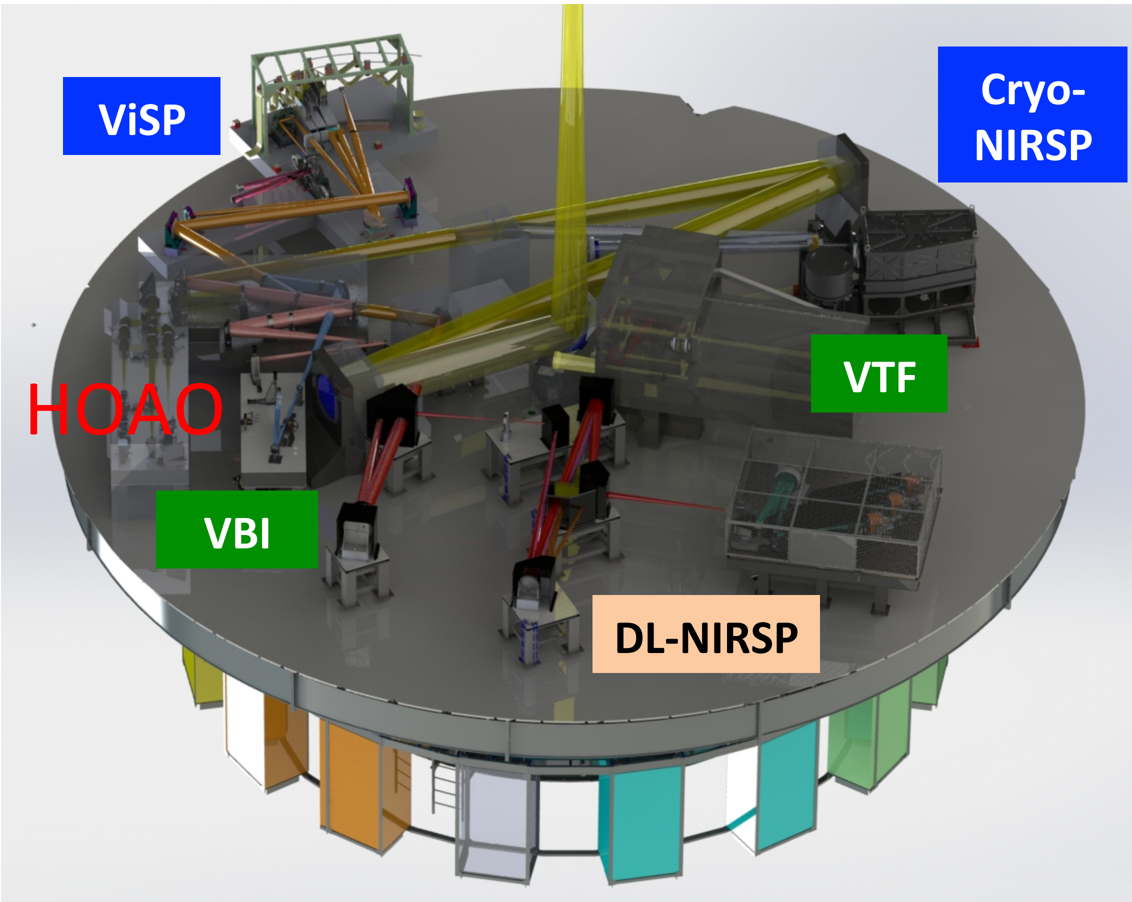
And spatial distribution ….



And temporal evolution !



First-Light Instrument Suite



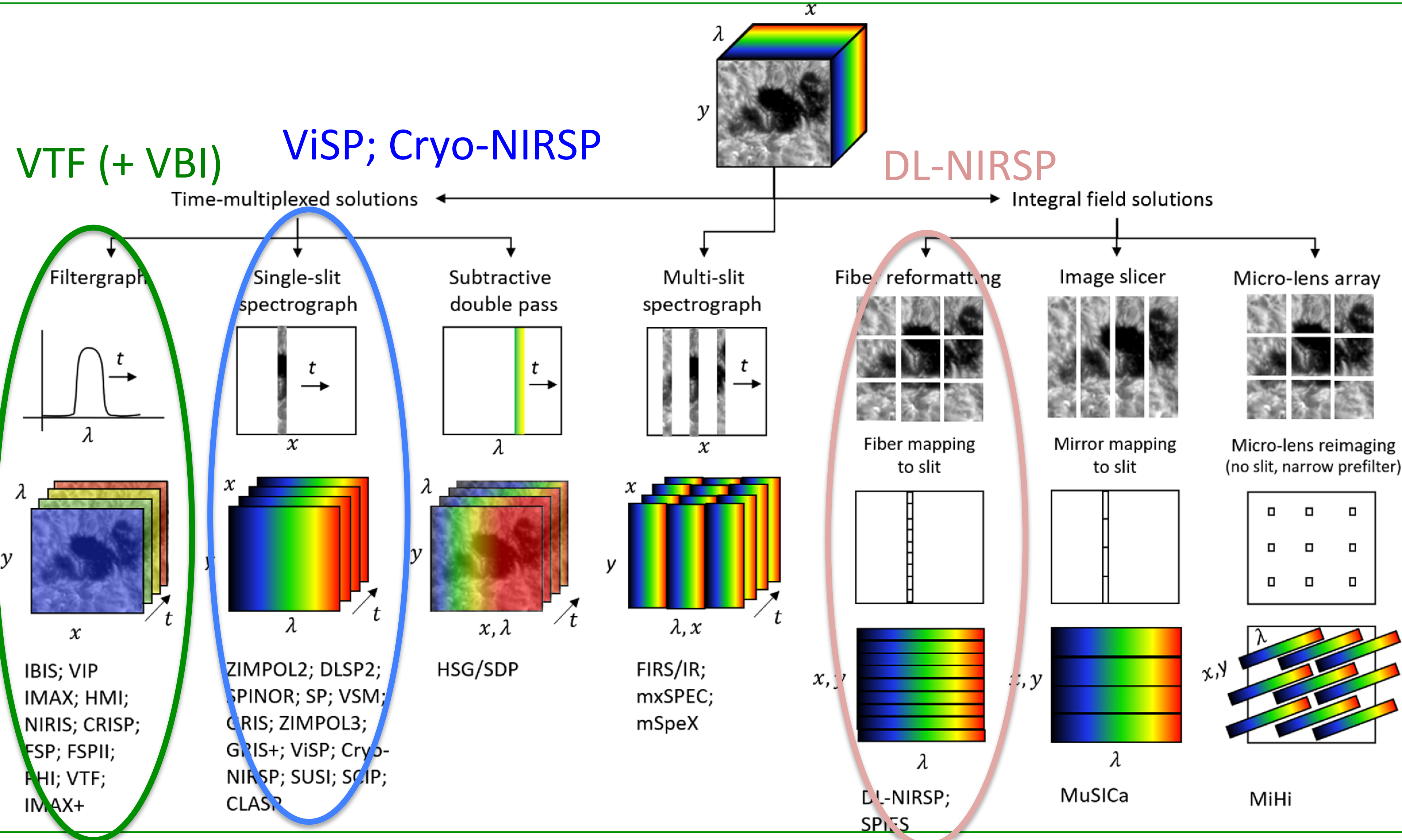
Two main "philosophies" of instruments:

Emphasis on imaging, large Field of view

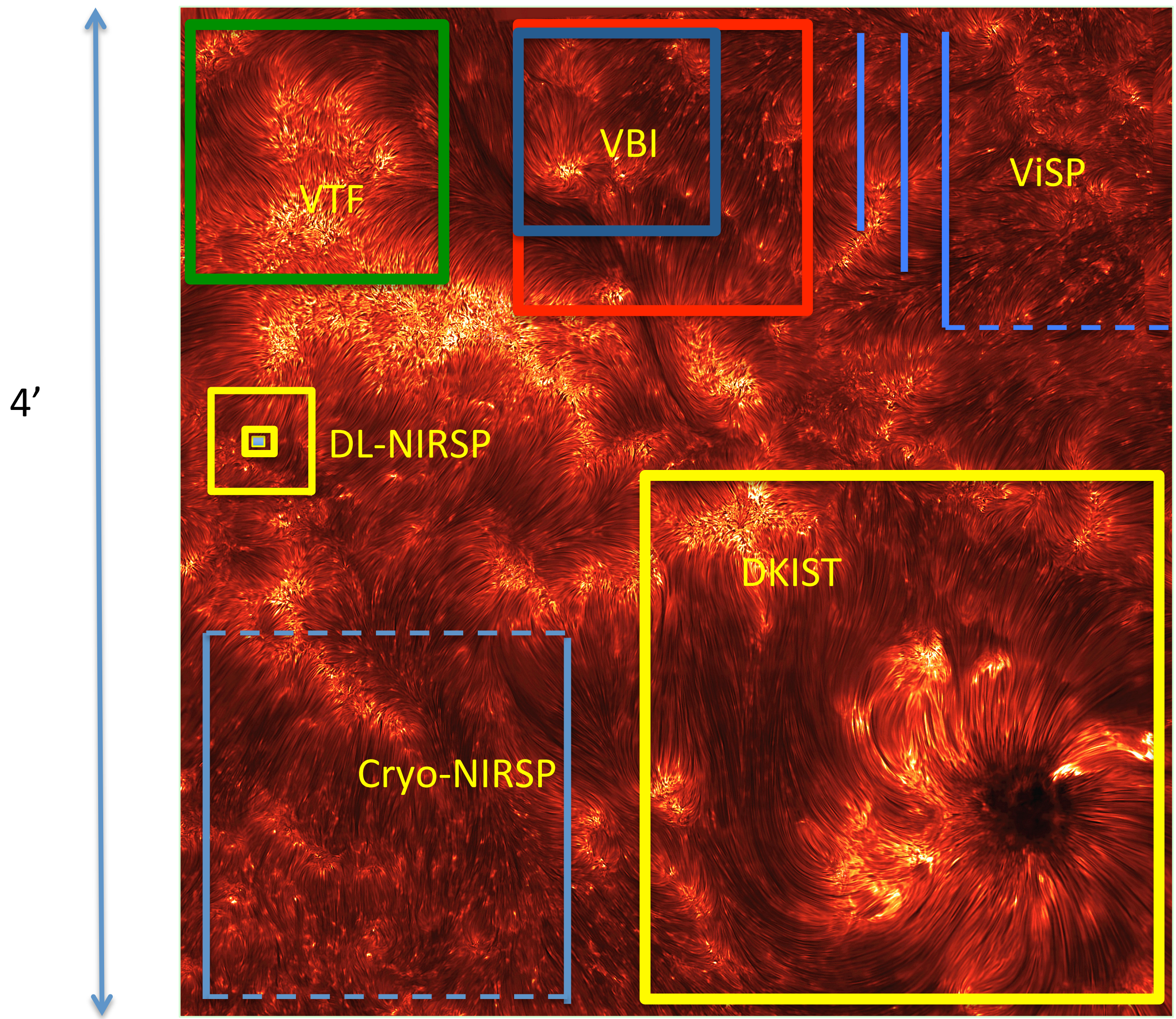
Emphasis on spectral fidelity

Both! (but you pay with small FOV)

Slicing your (x,y,λ) "hypercube"

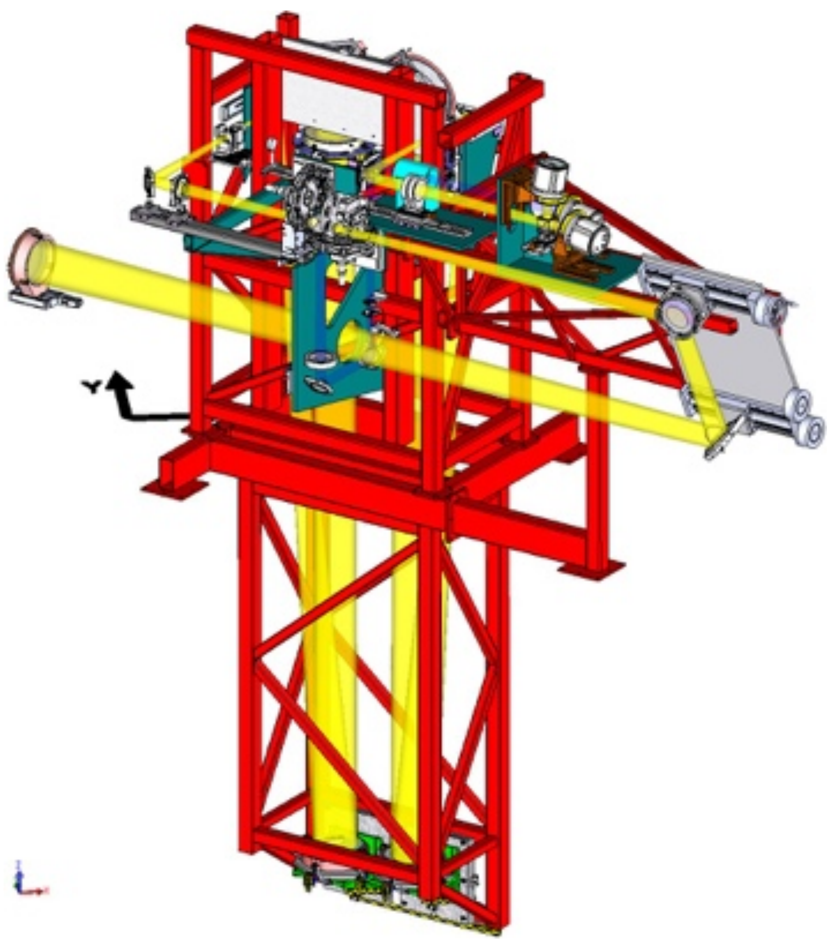


Instruments’ FOV



Note:
ALL instruments co-point !

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
- Sequential selection of filters/sampling wavelengths.
- Simultaneous broad-band images.
- Dual beam spectropolarimeter; orthogonal polarization states are imaged on two separate detectors.
- At first light, only one etalon will be available: limited sampling for broad (chromospheric) lines.

Visible Tunable Filter (VTF)

Instantaneous Field of View:

60 x 60 arcsec^2

Spatial sampling:

0.014 arcsec/pixel

Spectral Resolution:

6 pm FWHM (@600 nm), R ~ 100000

Temporal Sampling:

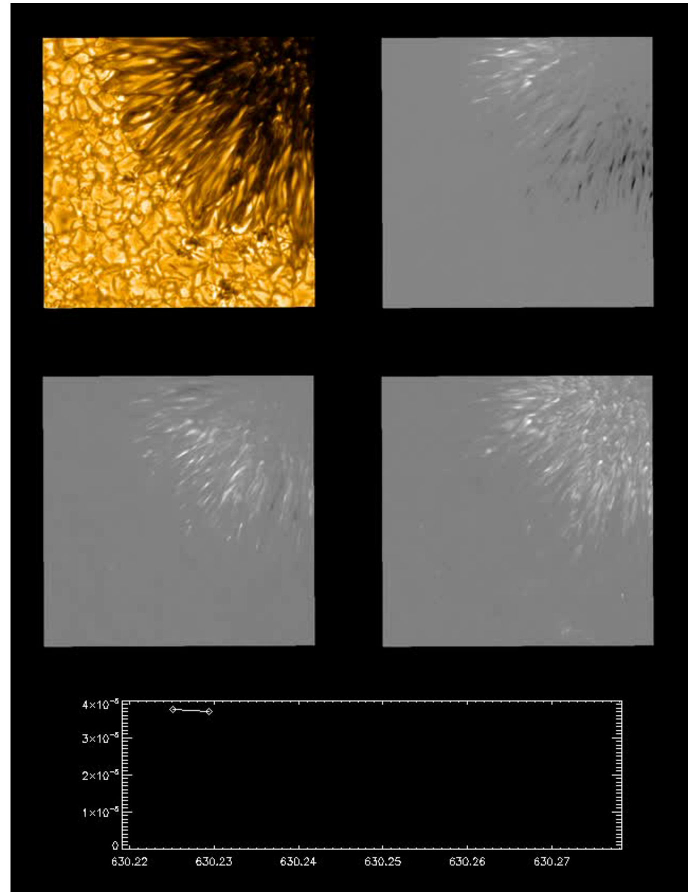
1-2 s per line scan (spectroscopy)

5-10 s per line scan (polarimetry)

Polarimetric Capability:

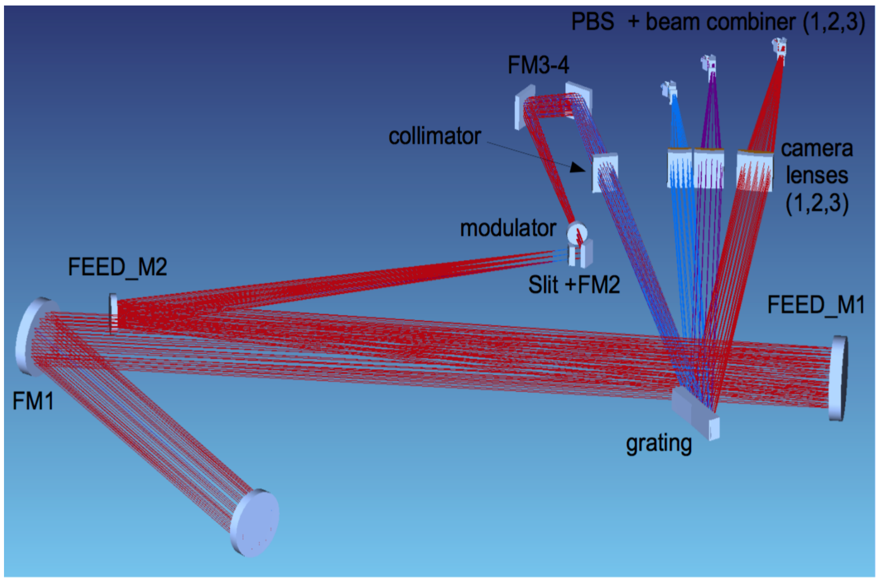
Full Stokes vector polarimetry

Target Sensitivity: 3×10^{-3} P/I_{cont}



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

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 (~ 1 nm wide) can be observed simultaneously; different spatial and spectral scales.
- ANY portion of the spectrum can be imaged on ANY spectral arm – depending on combination of desired ranges.
- 5 possible slit widths (motorized): 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 (slit is moved across solar image).

Spatial sampling:

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

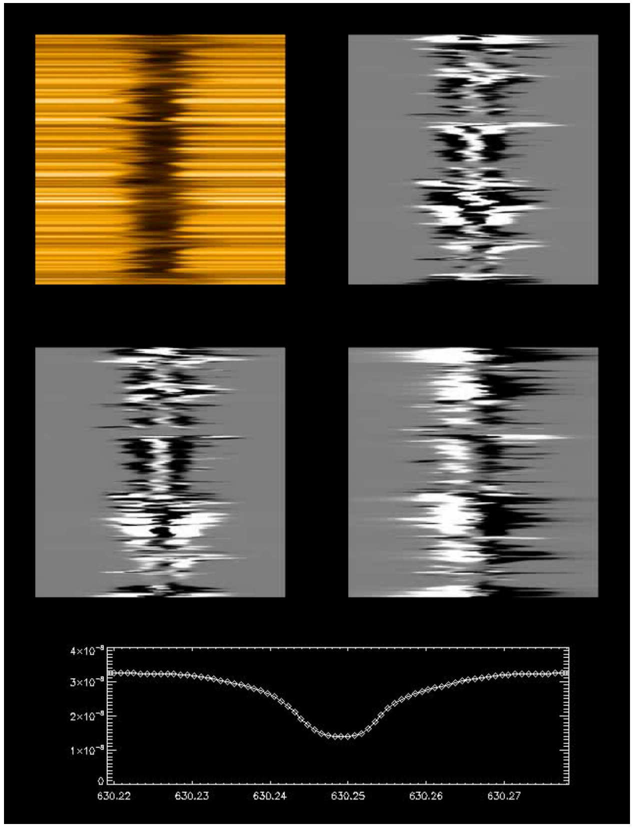
Spectral Resolution:

≤ 3.5 pm @ 630 nm or **R ≳ 180,000**

Temporal Sampling:

0.5-10 sec per slit position (polarimetry);

0.02-0.2 sec per slit position (spectroscopy)



Polarimetric Capability:

Target Sensitivity: 10^{-3} P/I_{cont} in 10 sec

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

So, how do we plan the observations?? (single instrument case)

1. Pick a physical problem
2. Think whether you value more the large FOV, the spectral fidelity, whether you want a certain line, etc -> Pick an instrument
3. Let's eyeball how long it will take to get the data we want, with the characteristics we need ("requirements": SNR=10E4, resolution = 0.1"; t=20 s; etc)
4. Tweak 3, and repeat
5. *Let's use some more sophisticated tools!!*

Use case: XXX @ 630 nm

From Ivan (lesson 2):

I_sun (630nm) ~ 2.2 E13 (SI units)
Number of photons $N_\gamma = E/E_\gamma = (I \times \Delta\sigma \times \Delta\Omega \times \Delta\lambda \times \Delta t) / E_\gamma$

For $\Delta\sigma$ = 100 km x 100 km; $\Delta\lambda$ = 0.01 A; = Δt 1s => N_γ ~4 E8

From Kevin (lesson 5):

SNR ~ sqrt (N_γ) ~ 2 E4 (assuming read-out noise is negligible)
Very nice.

maybe too optimistic ….

Use case: VTF @ 630 nm

Issue 1: telescope is not 100% transparent!!
e.g., 9 mirrors before getting to instruments : (0.9)^9 ~ 0.5

Issue 2: instrument is not 100% transparent!!
e.g., for VTF T ~ 0.38 (0.19 in polarimetry)

Issue 3: cameras are not 100% efficient!!
Balor/Andor (4k x 4k) QED @600 nm ~ 0.61

So now, true(N_γ) ~ 0.1 x N_γ = 4 E7, SNR ~ 6E3
Still very good.

BUT……

Use case: VTF @ 630 nm

Number of photons $N_\gamma = E/E_\gamma = (I \times \Delta\sigma \times \Delta\Omega \times \Delta\lambda \times \Delta t) / E_\gamma$

For VTF, $\Delta\sigma$ = 10 km x 10 km !!!
$\Delta\lambda$ ~ 0.03 A
Δt ~ 25 ms (max) !!!!
(plus, transparency issues of before)

=> true(true(N_γ)) ~ 3 E4 !!!

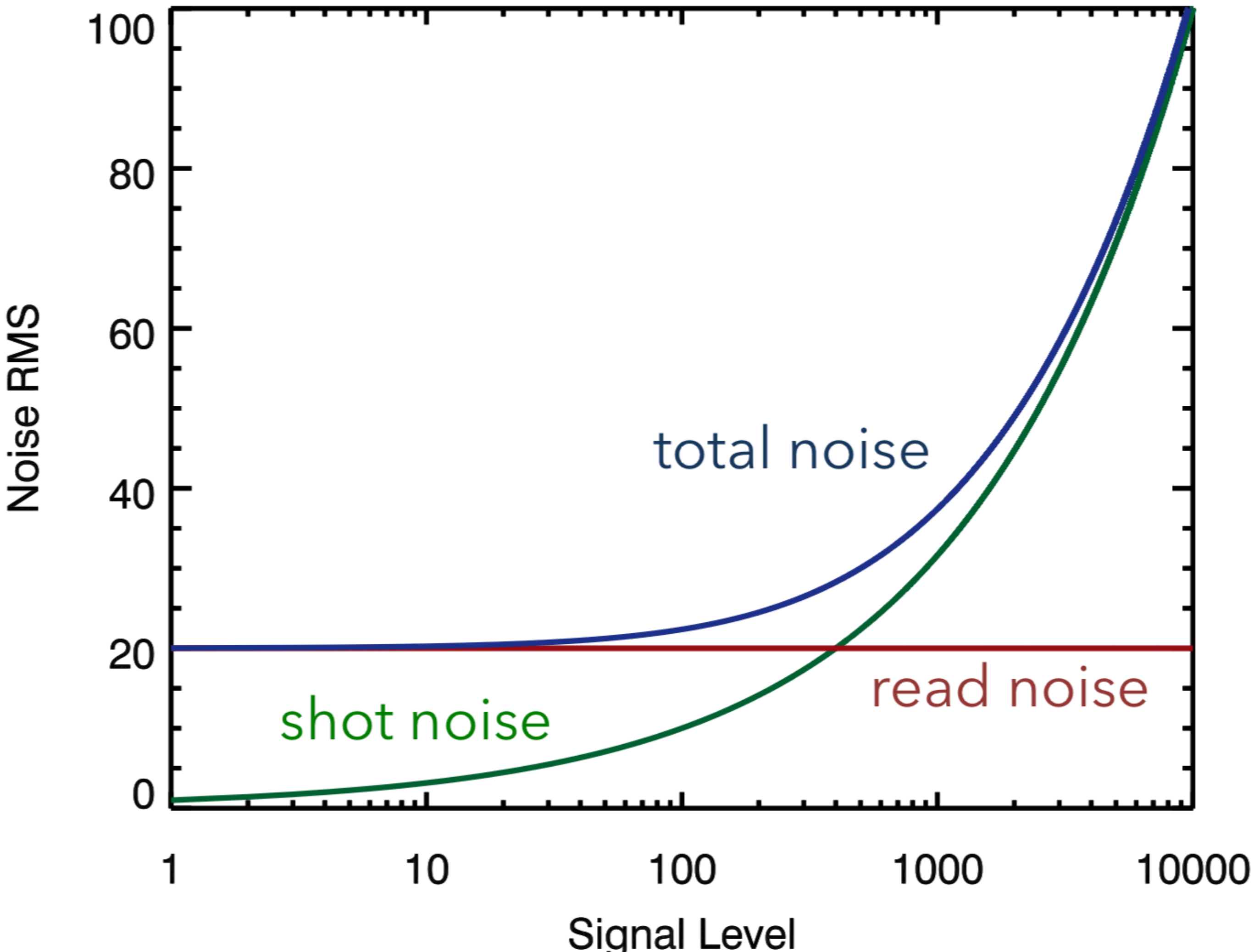
SNR ~ sqrt (N_γ) ~ 200 .... (albeit very fast)

Note, that an upper limit is given also by the camera saturation level: we cannot just keep exposing ....

Andor Balor-X Cameras (VBI, VTF, DL-NIRSP vis)

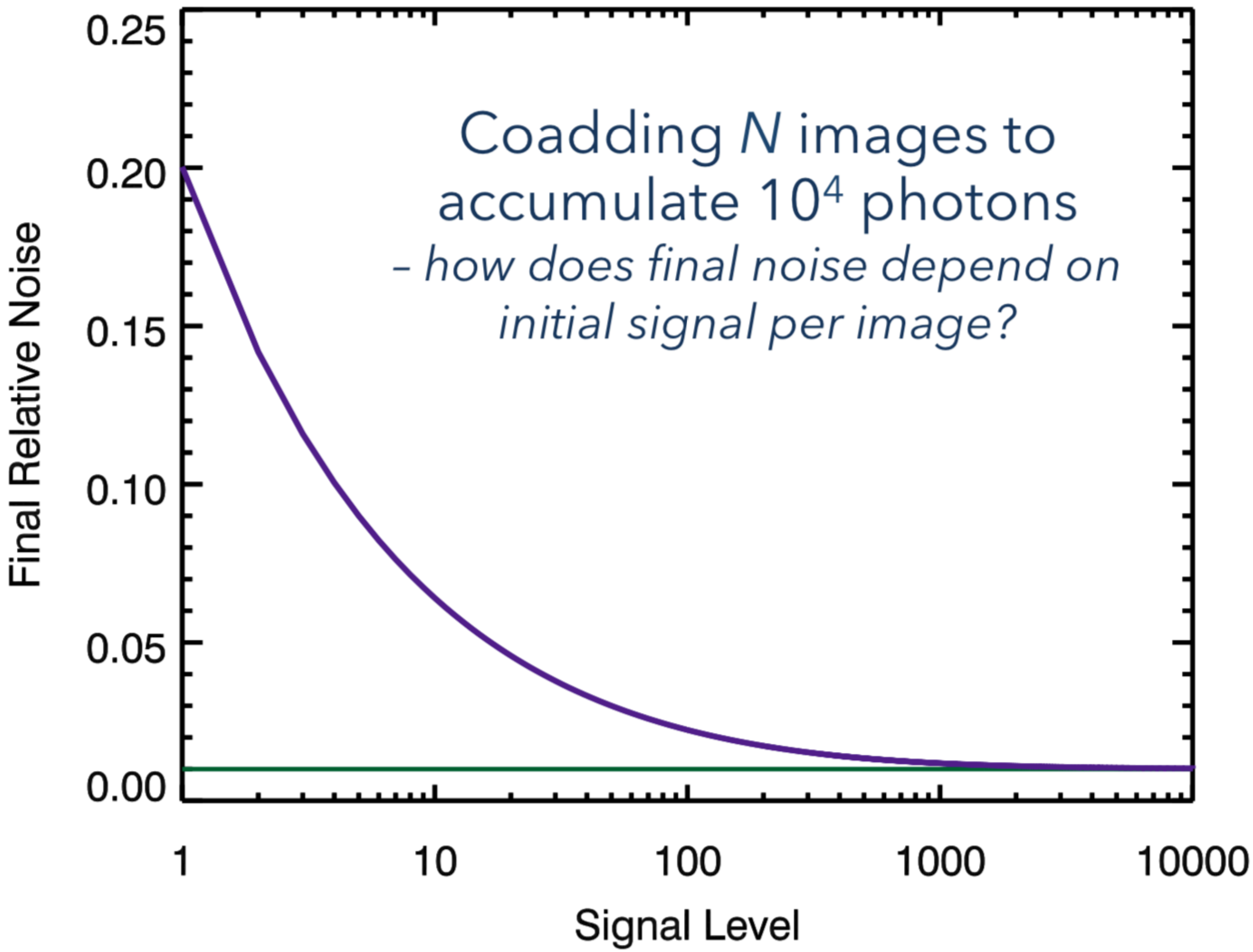
Feature	Benefit
49.5 x 49.2 mm sensor	Very large field of view from 16.9 Megapixel, 12 µm pixel pitch sensor.
18.5 millisecond readout	Readout a 4k x 4k sensor 2,500x faster than a CCD. More data throughput less downtime!!
Up to 54 fps	Unique solution for a range of high time-resolution observing challenges, without compromising noise or FOV.
Extended Dynamic Range and > 99.7% Linearity	Superb quantitative accuracy across a wide range of magnitudes within a single image.
Readout noise ~ 2.9 e-	Exceptionally low noise, even at max frame rate, suited to short exposure, low light observational challenges.
No inter-pixel "dead area"	No discontinuities in images that could contribute to loss of information.
80 000 e- well depth	Deep well depth, provides high dynamic range (high contrast) images thanks to sCMOS low noise floor. Enables the acquisition of long images without oversaturation of the pixels to record even the weakest signals.
UltraVac™ •1	SNR of single exposure: < 3-400 ain unequalled cooling and QE performance, year after year.
CoaXPress as standard	4 Lane CXP-6 interface enabling the highest frame rates over distances up to 30 m.
Rolling and Global shutter supported	Maximum exposure and readout flexibility across all applications. Global Shutter for snapshot capture of fast moving/changing events.

Noise Regimes



Kevin; lecture 5

Noise Reduction with coadding



1000 images

1 image

So many things to consider….

- Good example of “flux budget explained”. VMP for IMaX case (see, lectures & videos of 1st workshop, https://www.nso.edu/ncsp/ncsp-workshop/intro-to-dkist/

- All Instrument Performance Calculators can be found at: https://www.nso.edu/telescopes/dki-solar-telescope/csp/docs/ (Software Download)

- Let’s play with VTF a bit more

DKIST as a Multiwavelength Observatory

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 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

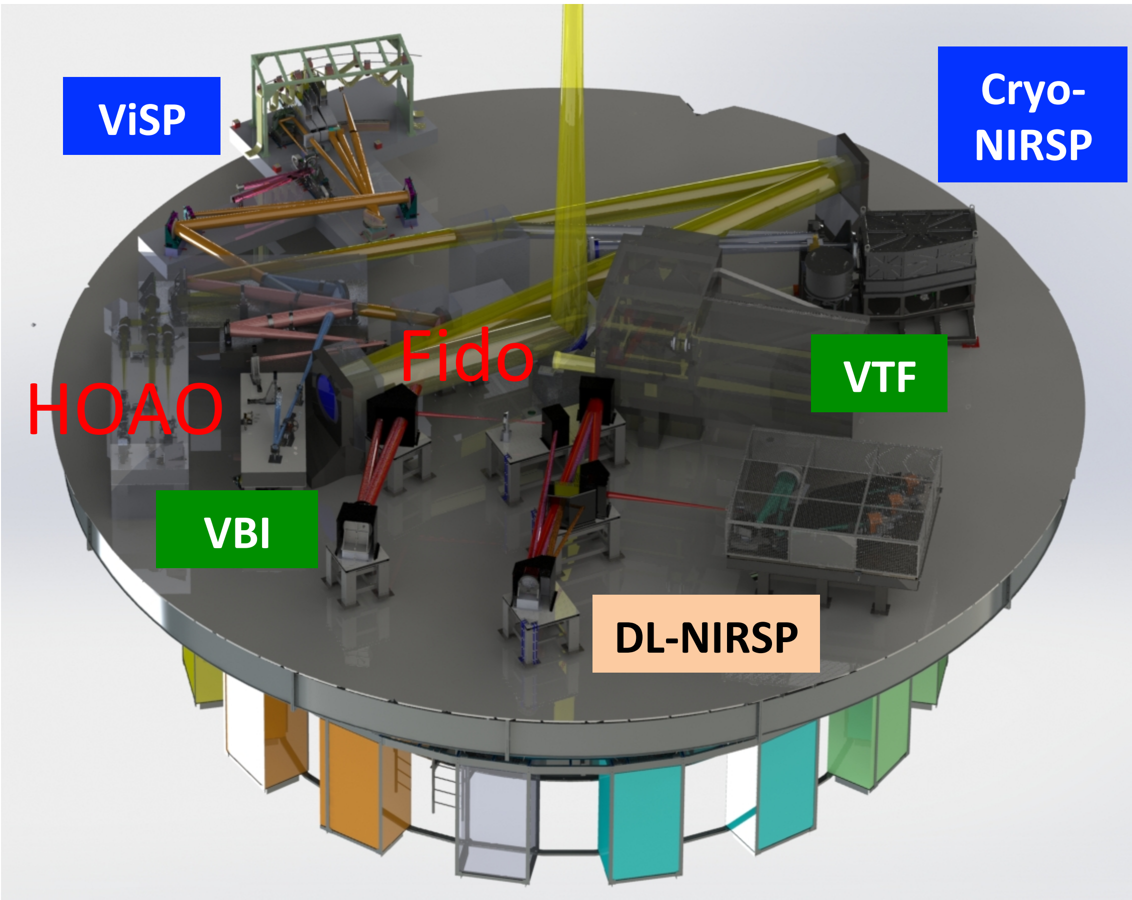
Fe XIII	1074.7nm
He I	1083nm
J Band	1250nm
Si IX	1430nm

This table is meant to give an idea of the capabilities of the DKIST first light instrument suite. It cannot capture the large trade space that is provided by the flexibility of the instruments. For more information, visit http://dkist.nso.edu/CSP/instruments

Visible light cameras for instruments are provided by a UK consortium.

- Instruments – *with the notable exception of the ViSP* – require pre-filters for specific spectral lines.
- Instruments can work alone, or together (<u>Cryo-NIRSP can only work alone</u>)

First-Light Instrument Suite



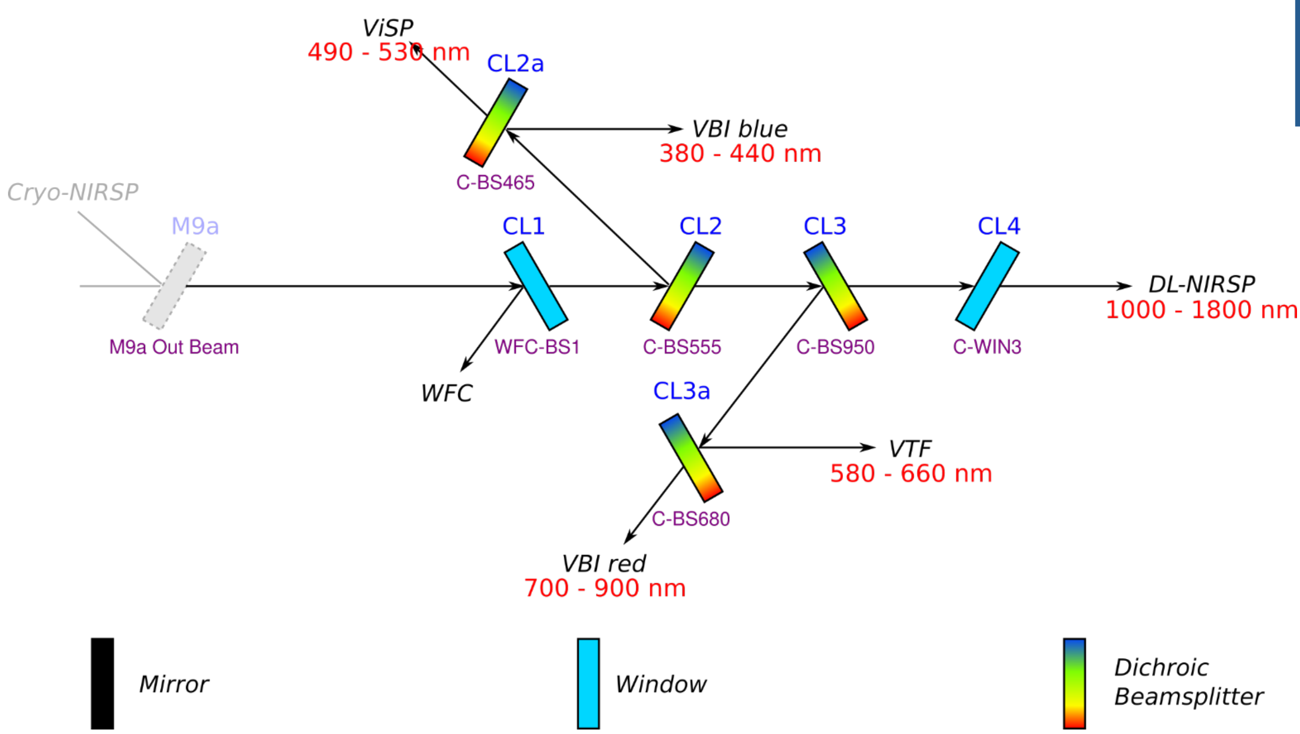
Two main "philosophies" of instruments:

Emphasis on imaging, large Field of view

Emphasis on spectral fidelity

DKIST as a Multiwavelength Observatory

FIDO TOOL



Shorter wavelengths reflected, longer wavelengths transmitted.

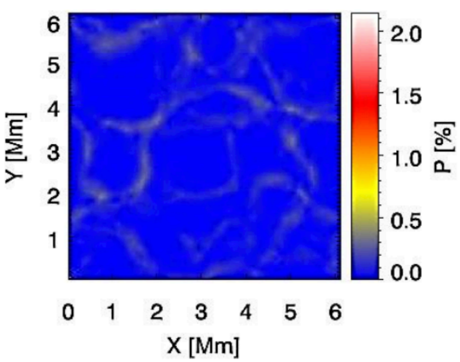
And, HOMEWORK!

Studying the QS: Hanle diagnosis

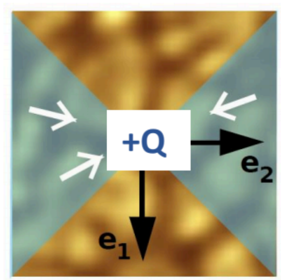
Francisco's requirements:
(0.03% -> SNR=3E3)

\+ No signal cancelation
- We are missing spatially resolved measurements of scattering pol.
- Goal: **~0.1 arcsec ; 0.03% ; 20 mA ; Sr I 460.7 nm ; < 10 s !!!**
- Better with aperture >1.5 m and integral field spectrometer

Linear pol. @ Disc center



Radiation Anisotropy



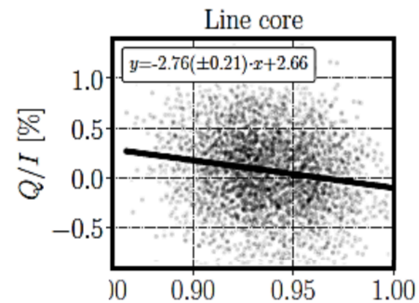
- Negative correlation

Del Pino Aleman et. al. 2018, ApJ

- Positive correlation (ZIMPOL)

Dahra et. al. 2019, A&A

- Negative correlation (FSP)



Zeuner et. al. 2018, A&A

Note that the best results to date (0.03%) have been obtained with 0.4"; 60 mA, and 210 s!!!

And, HOMEWORK!

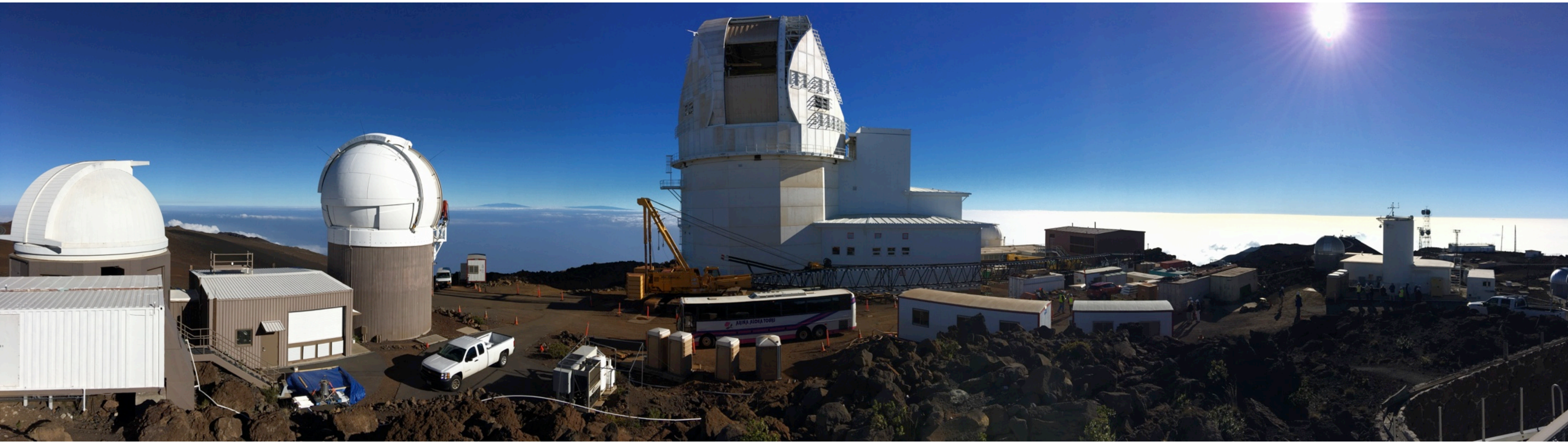
So, Neeraj asked: could you achieve those performances with DKIST ?

Can we???? To you the arduous judgement.

ViSP @ 4607 A:

- Detector QE =0.46
- Inst. Transmission = 0.1
- Modulation efficiency = 0.5
- Camera duty cycle = 0.95
- Pixel size (spatial, arm 1) = 0.03”
- Pixel size (spectral, arm1) = 0.016 Ang
- Slit size (chose 1) = [0.0284; 0.041; 0.0536; 0.1071;0.2142]”
- (and remember, you can bin…)

Thanks !



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