



NSF's National Solar Observatory

# DKIST instrumentation system – an overview

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# Overview

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- The DK1 Solar Telescope Introduction
  - Overview, incl. static and active optics
  - Operations
    - From proposal to experiment to data (cycle based, 1y cycle, service mode vs pi mode, where to find data)
- DKIST instrument suite
  - Differences between instruments
  - Trade-off space between different instrument types
- atmosphere, VBI, image reconstruction & issues

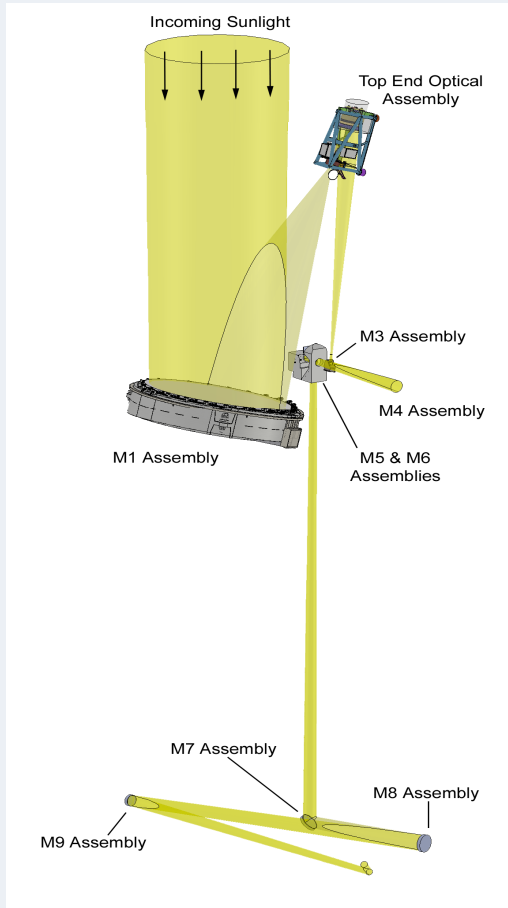


# DKIST overview

- World's largest telescope for observations of the Sun
  - Aperture diameter:  
*4 meter*
  - Design wavelength range:  
*320 nm – 25 μm (current instrumentation: 380 nm - 5 μm)*
  - Off-axis Gregorian design  
*no central obscuration!*
- Sensitivity
  - High spatial resolution:  
*approx. 25 mas*
  - Polarimetric precision:  
*approx.  $5 \times 10^{-4} I_{disk}$*
  - Polarimetric observations of the solar corona:  
*detect signals  $\leq 10^{-8} I_{disk}$*
- Flexible
  - Unique instrumentation can be combined in a vast number of ways



# DKIST overview



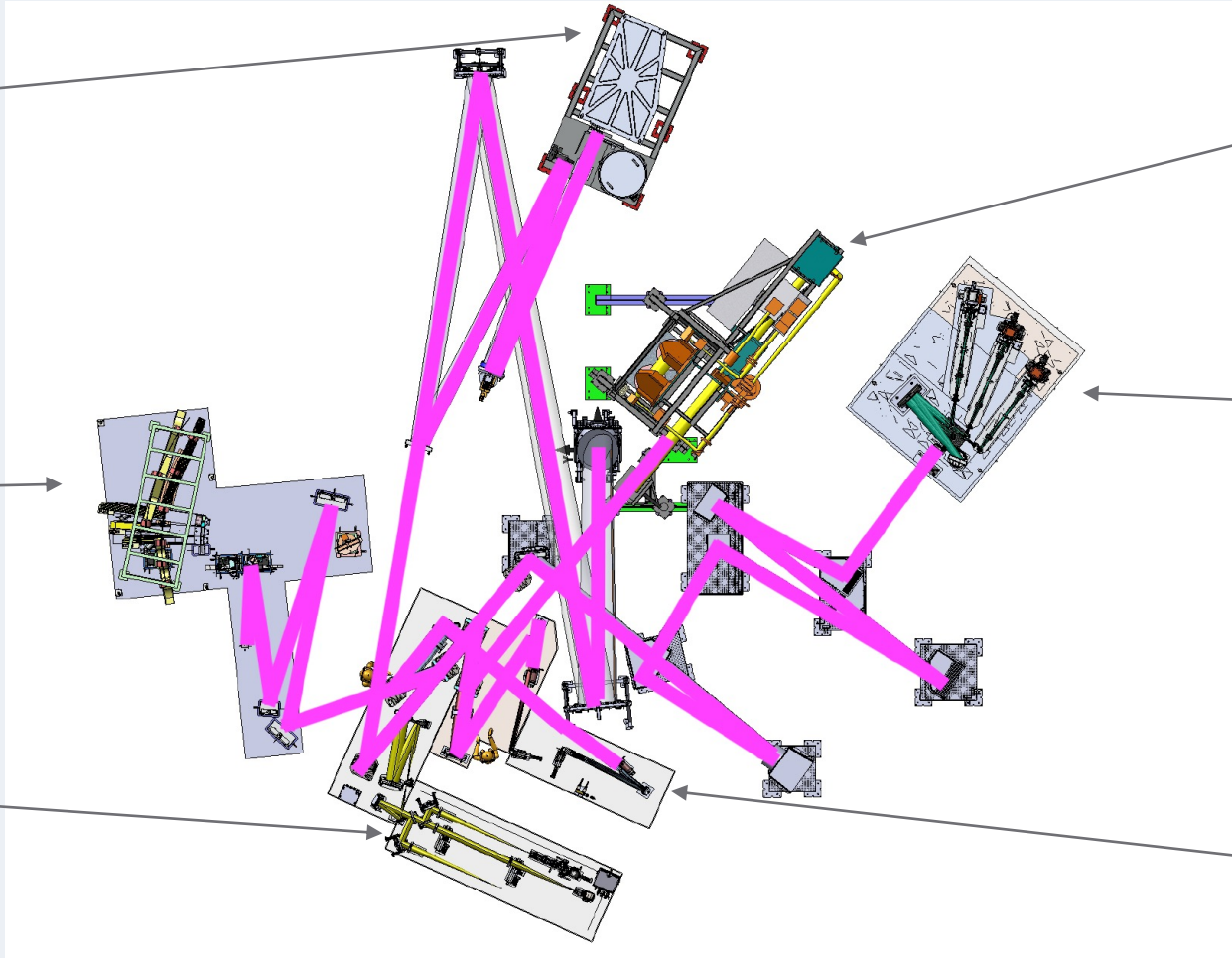
- Active M1/M2 to adjust quasi static alignment
- Heat stop reject about 12 kW of power in the prime focus
- Active M3/M6 to stabilize boresight and pupil positions
- Fast Tip/Tilt M5, adaptive M10 for adaptive optics system
- Field stops, occulters and calibration optics in the Gregorian Optical Station (GOS)
- Air knife between M6 and M7 to separate 'dirty' telescope level from coudé clean room environment
  - Access to the coudé clean room requires gearing up
- Many elements in the optical path are actively cooled

# DKIST Instrumentation

Cryogenic Near Infrared Spectro-Polarimeter (Cryo-NIRSP)

Visible Spectro-Polarimeter (ViSP)

Wavefront Correction System (WFC)

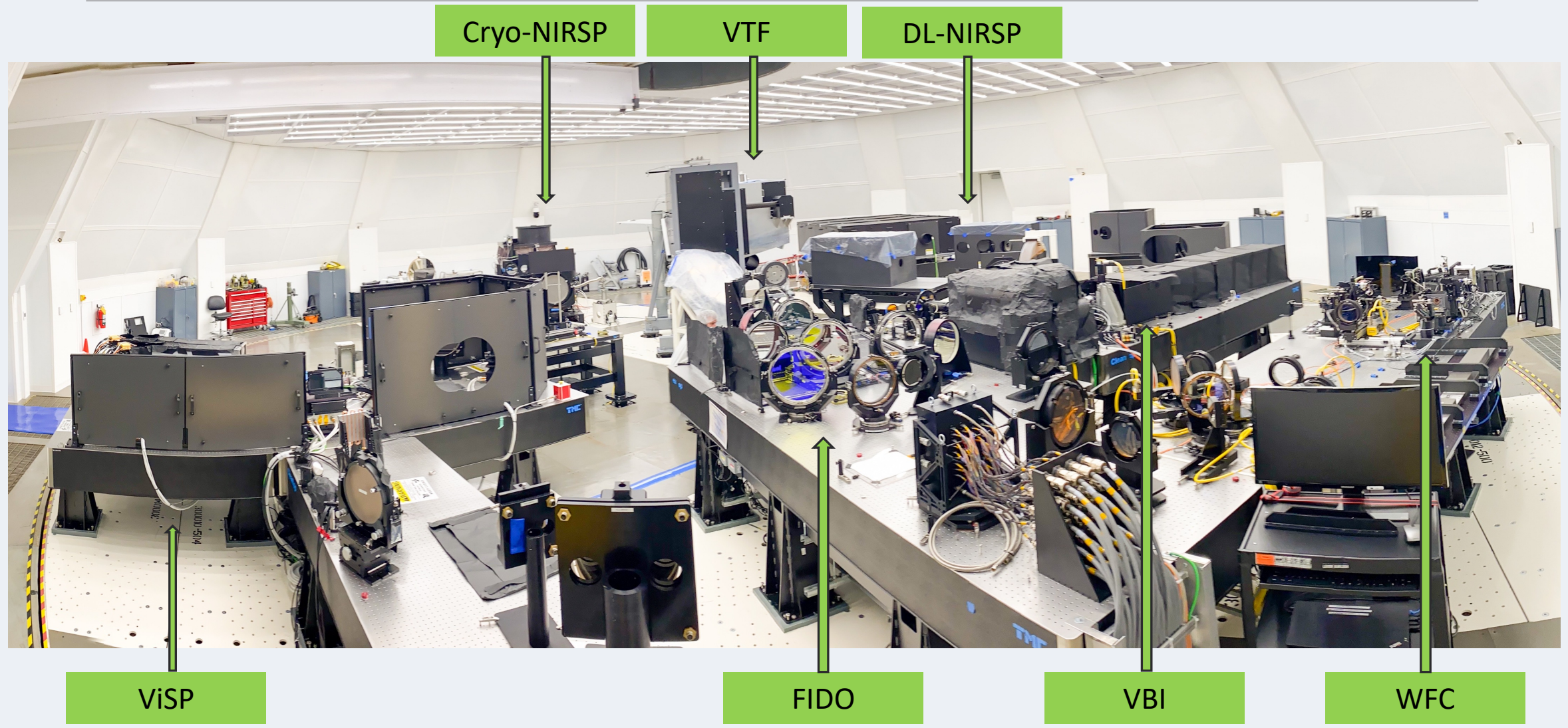


Visible Tunable Filter (VTF)

Diffraction Limited Near Infrared Spectro-Polarimeter (DL-NIRSP)

Visible Broadband Imager (VBI)

# DKIST Instrumentation





# What are we trying to achieve?

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*Measure scientific parameters of interest...*

- Vector field measurements of
  - Plasma velocity
  - Magnetic field
- Photometric properties of the solar atmosphere
- Oscillations in the solar atmosphere
- ...

*...ideally in all solar atmospheric layers at the same time...*

- Photosphere / Chromosphere / Corona

*... to infer / derive parameters of the prevailing 3D solar atmosphere*

- Temperature, pressure, density, etc

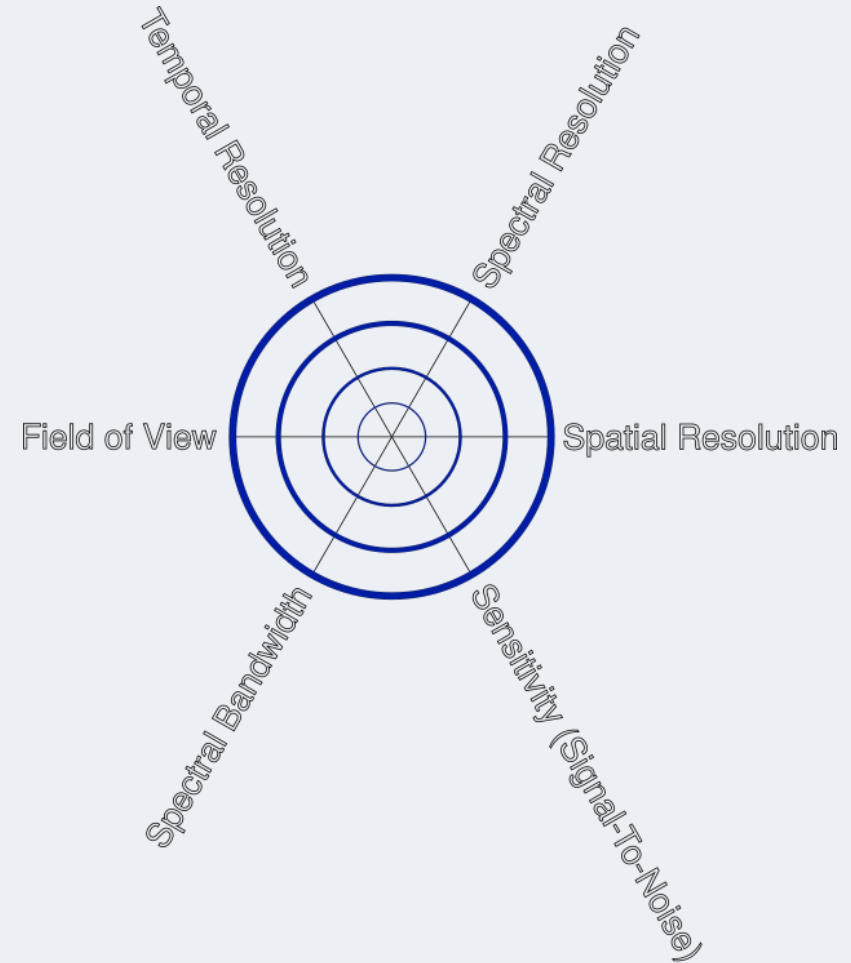
Remote sensing

- Electromagnetic waves and its properties
  - Wavelength/Frequency
  - Intensity
  - Polarization
  - (Phase, Coherence, ...)
- In-situ observations
  - Would allow for direct measurements of many desired diagnostics
  - Are (obviously) very difficult



# DKIST Instrumentation – General Comments

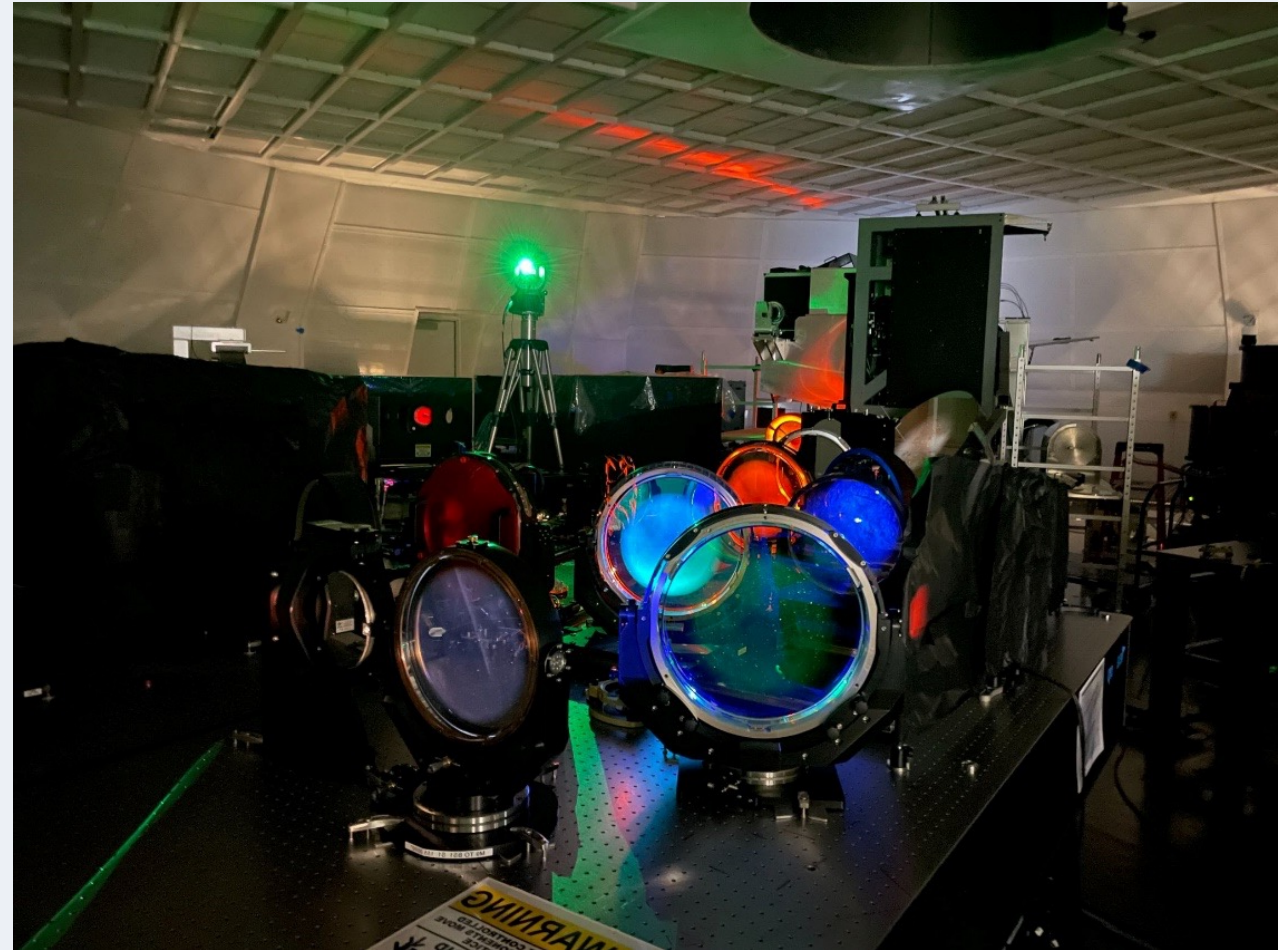
- **Any** instrument design
  - Addresses *specific science use cases*
  - Prioritizes certain performance criteria, and ...
  - ... de-prioritizing others
  
- **Trade-offs** in acquisition of ‘atomic’ DataSets are common and unavoidable
  - For example: camera number of pixels and frame rate will impact the trade between field of view and spatial and temporal resolution
  
- DKIST covers as much ‘discovery space’ as possible with its first light instrumentation
  - Unique measurement techniques
  - Multiple instrument ‘modes’
  - Operate instruments simultaneously





# Combining instruments

- Facility Instrument Distribution Optics (FIDO)
  - Suite of dichroic beamsplitters
  - Interchangeable at various locations feeding the instruments
  - Initial set is already being expanded to address additional use cases
- Combine instruments to utilize their strengths to address a specific science use cases
- However:  
Changing the configuration is not trivial, and takes one day of ensuring system performance
  - Optics weigh 10 kg each, and ...
  - ... need to be aligned to **arcsecond** optical tilt accuracy





# What it takes to observe at DKIST ...

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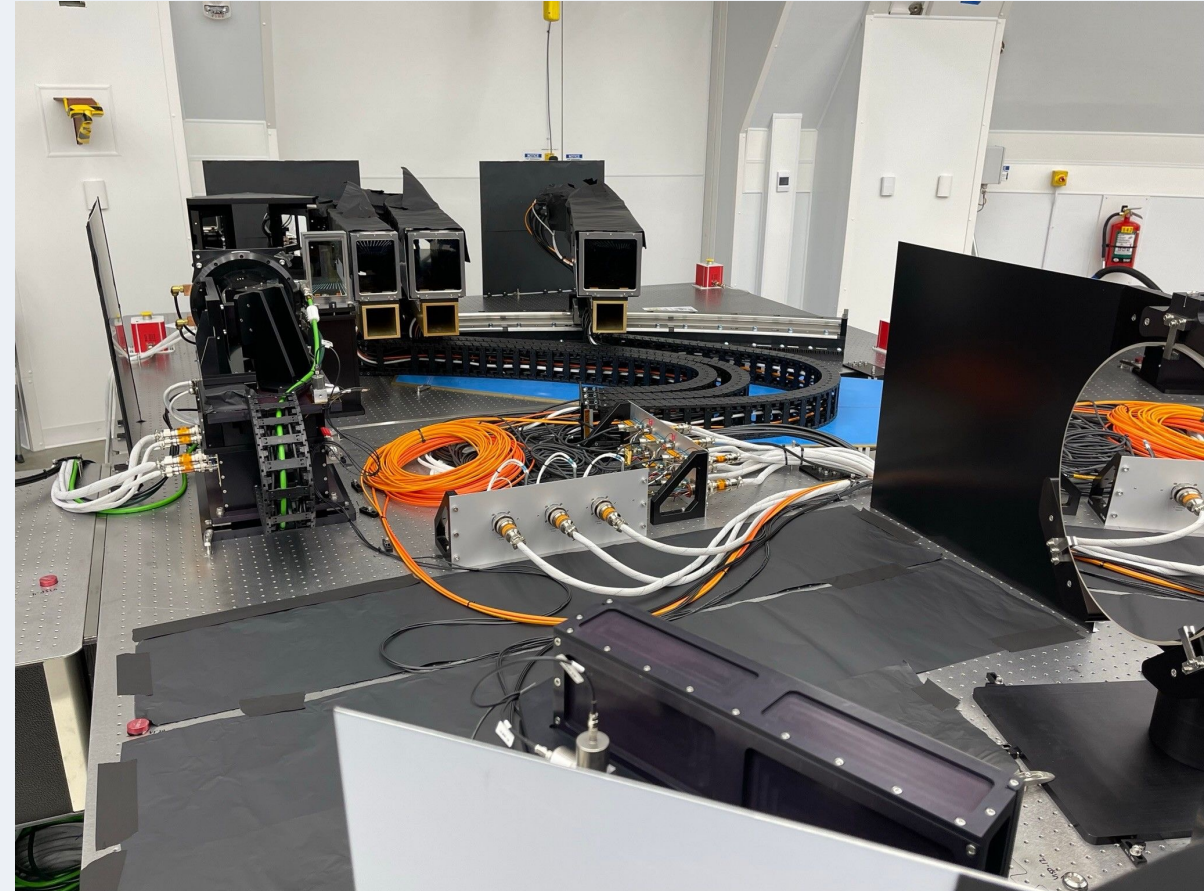
- DKIST is currently operated by NSO Scientists, Engineers, and Operators in ‘service mode’
  - Most efficient use of telescope time while still commissioning certain functionality
  - Visits to the telescope by non-NSO scientists are rare
- ‘Service mode’ operation of DKIST requires a significant amount of planning and preparation
  1. Submission of science proposal
  2. Review (scientific and technical) of science proposal
  3. Accepted proposals are finalized, and converted into executable Experiments
    - Experiments consist of multiple Observing Programs that contain telescope settings & Instrument Programs
    - Instrument Programs are ultimately the generators of Data Sets by each instrument
  4. Generated Experiments are verified for Quality Assurance
  5. Within the execution window, the Experiments are uploaded to DKIST and queued for execution, while *telescope (FIDO) and instrument configuration and performance, weather and target availability* are monitored and assured
  6. Once the Experiment has been executed successfully (i.e. data meets criteria), generated Data Sets are transferred to the DKIST Data Center
  7. At the Data Center the Data Sets are calibrated and published for download



# Visible Spectro-Polarimeter

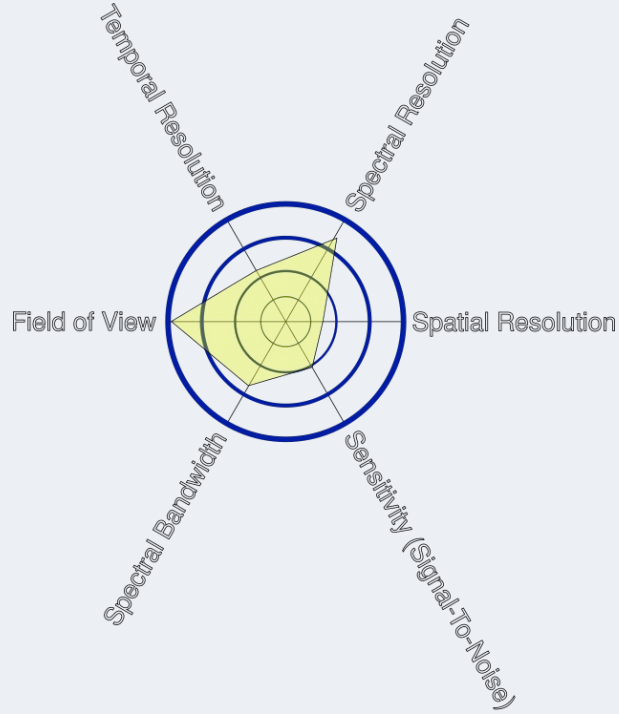
Science case: magnetic field vector and line-of-sight velocity simultaneously in multiple atmospheric layers

- Focus: wavelength diverse spectro-polarimetry, diagnostic discovery space
- Grating-based, (scanning) single slit spectrograph
- 3 wavelength channels
  - Spectral range: **380-900 nm**
  - Max field-of-view:  $\sim 1$  arcmin slit length,  $\sim 2 \times 1$  arcmin (scanning)
  - *Almost any* combination of 3 spectral windows accessible simultaneously
    - Currently, this functionality is limited for increased efficiency
  - Dual beam polarimeter

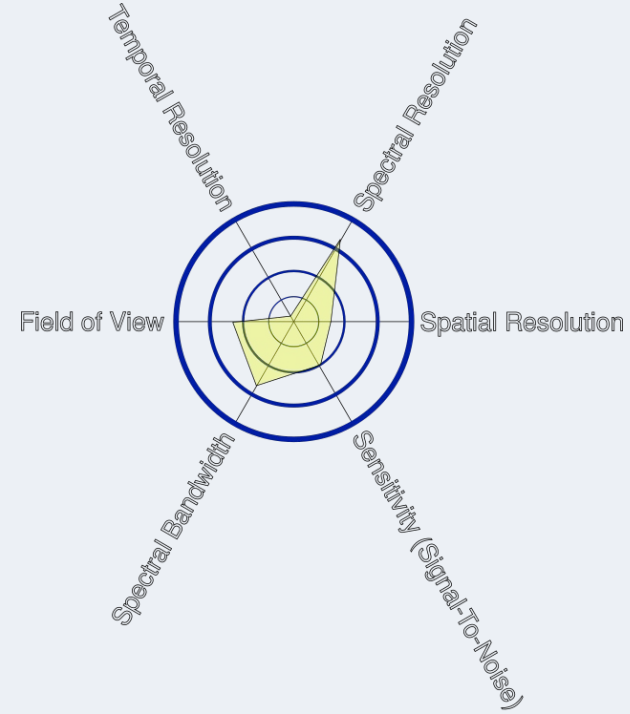


# Visible Spectro-Polarimeter

VISP INTENSTY MODE



VISP POLARIMETRY MODE



# Cryogenic Near-Infrared Spectro-Polarimeter

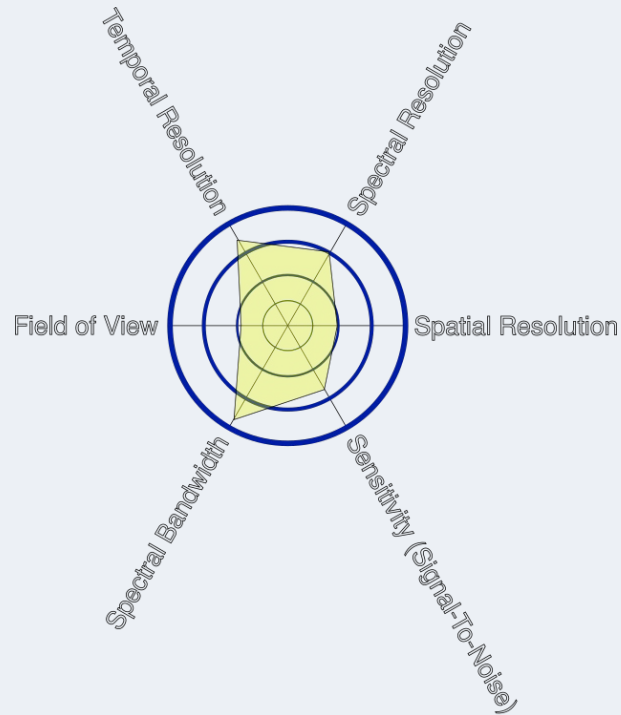
Science case: magnetic field vector and line-of-sight velocity (primarily) in the solar corona

- Focus: infrared spectro-polarimetry
- Grating-based, (scanning) single slit spectrograph
- single wavelength channel for spectrograph
  - Spectral range: **1 - 5  $\mu\text{m}$**
  - Max field-of-view: 2 & 3.75 arcmin slit lengths, up to 5 arcmin (scanning)
  - Dual beam polarimeter
- single wavelength channel for context imager
  - Spectral range: **1 - 5  $\mu\text{m}$**
  - Max field-of-view: 1.5x1.5 arcmin (square)

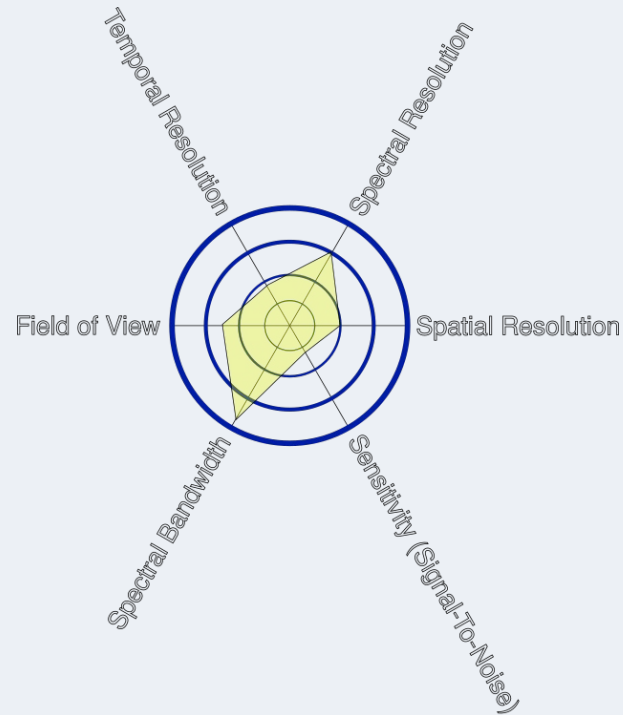


# Cryogenic Near-Infrared Spectro-Polarimeter

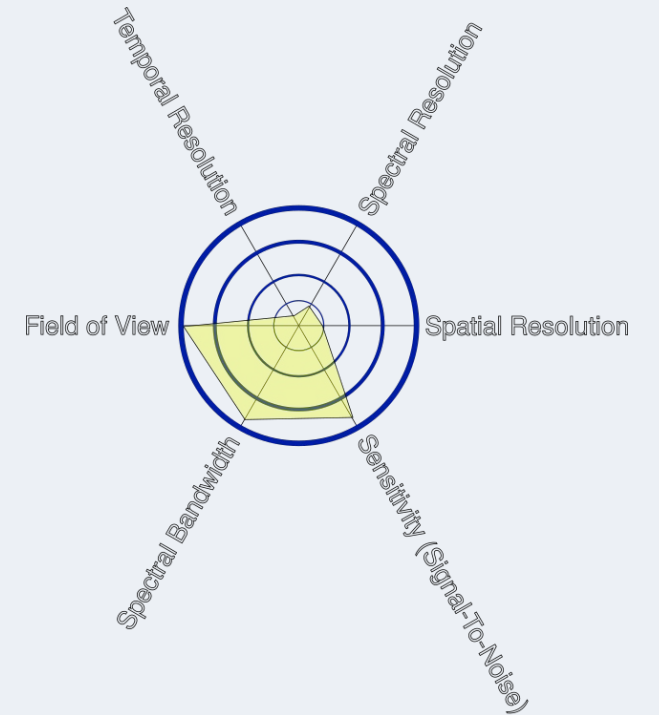
CN INTENSTY MODE  
(ON-DISK)



CN POLARIMETRY MODE  
(ON-DISK)



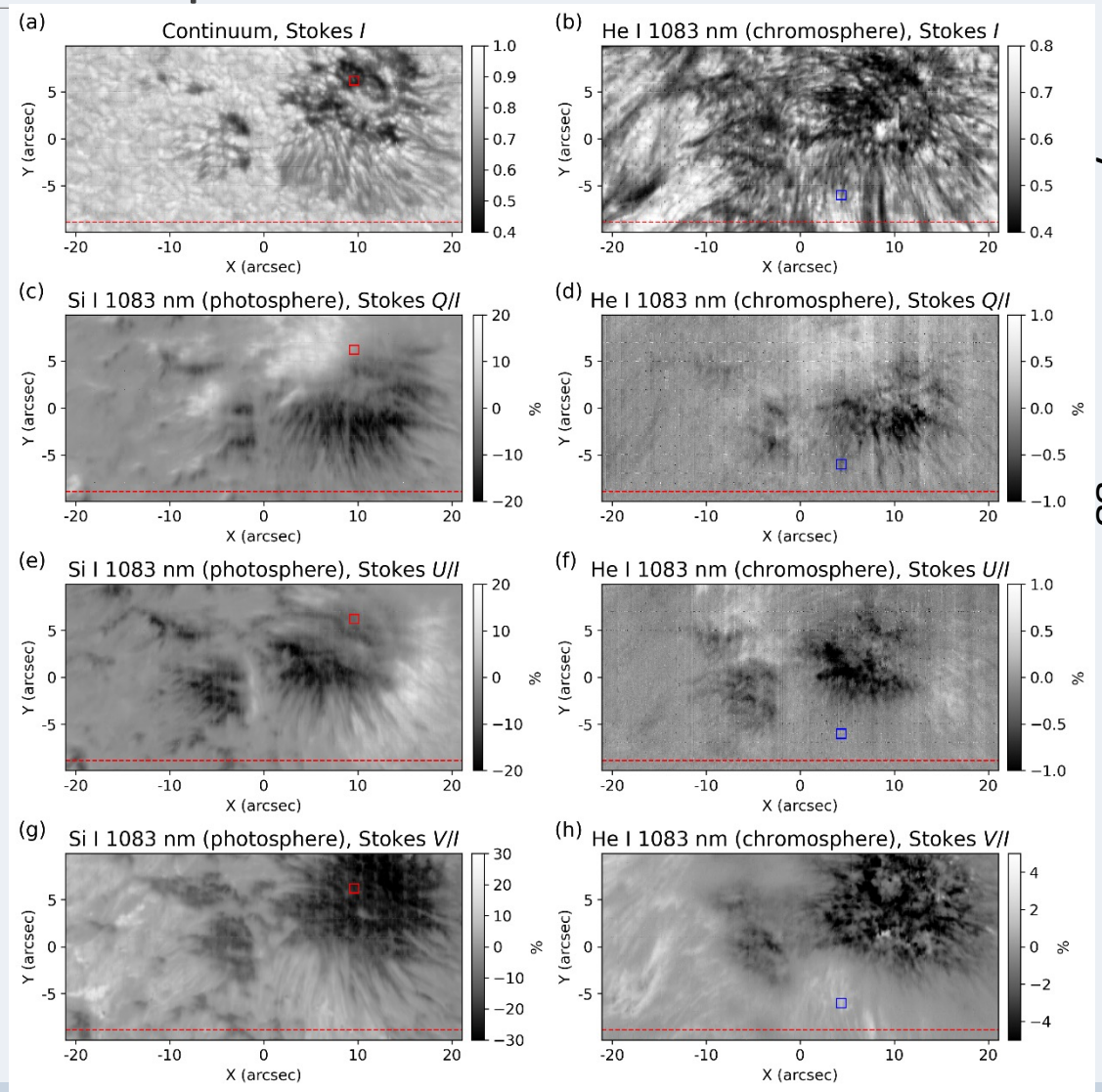
CN POLARIMETRY MODE  
(CORONA)



# Diffraction limited Near-Infrared Spectro-Polarimeter

Science cases: magnetic field and velocity vectors in various solar atmospheric layers

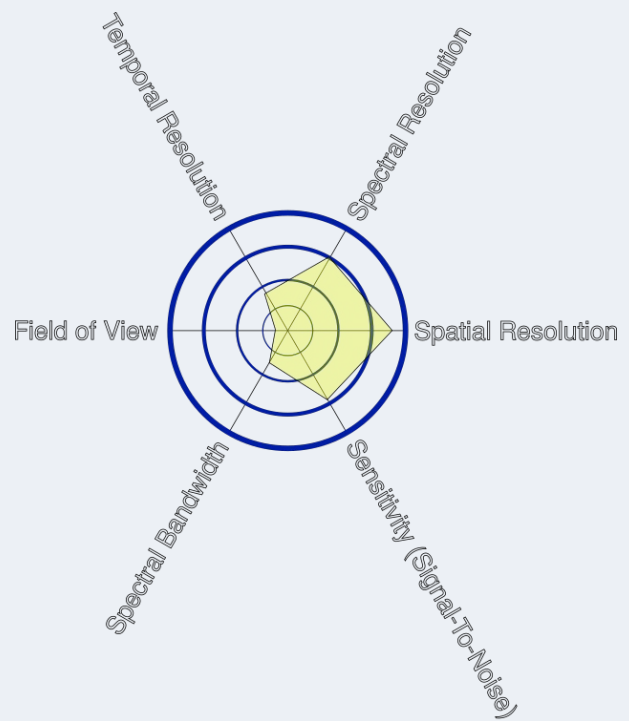
- Focus: *true* 2d imaging spectro-polarimetry
- [Grating-based, \(mosaicking\) image slicer spectrograph](#)
- 3 wavelength channels
  - Spectral ranges: **500-900 nm, 900-1200 nm, 1200-1600 nm**
  - Fixed (but upgradable) wavelength diagnostics in each channel
  - Max field-of-view: approx. 2x2, 4.5x4.5 arcsec (on disk), 27x10 arcsec (corona), 2 arcmin (round, mosaicking)
  - Dual beam polarimetry



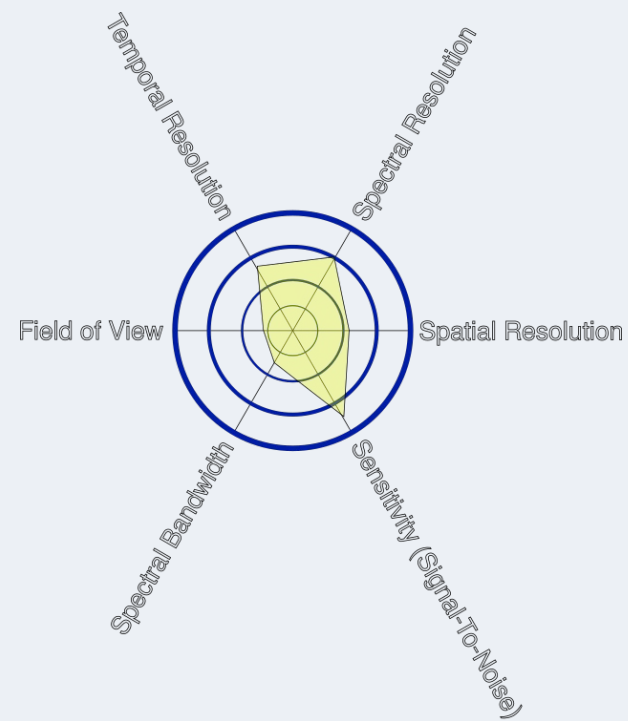
Courtesy T. Anan & S. Jaeggli

# Diffraction limited Near-Infrared Spectro-Polarimeter

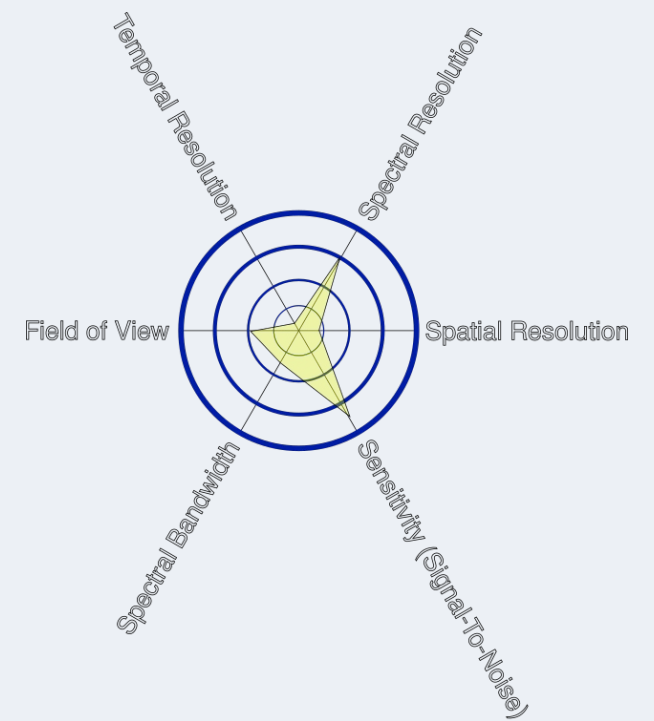
DL HI-RES MODE  
(ON-DISK)



DL MID-RES MODE  
(ON-DISK)



DL CORONAL MODE





# Visible Tunable Filter

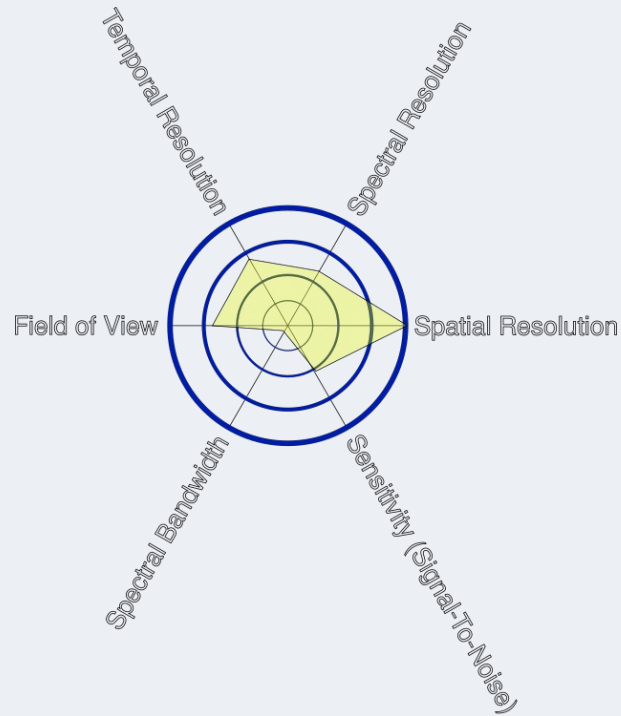
Science cases: magnetic field and velocity vectors in various solar atmospheric layers

- Focus: large FOV, high spatial resolution imaging spectro-polarimetry
- [Tunable Fabry-Perot Interferometer with polarimetric capability](#)
- 3 channels
  - 2 narrowband & 1 broadband cameras
  - Spectral range: **520-860 nm**
    - Fixed (but upgradable) wavelength diagnostics
  - Dual beam polarimetry
    - 2 synchronized narrowband cameras
  - Data post-facto processed to increase spatial resolution

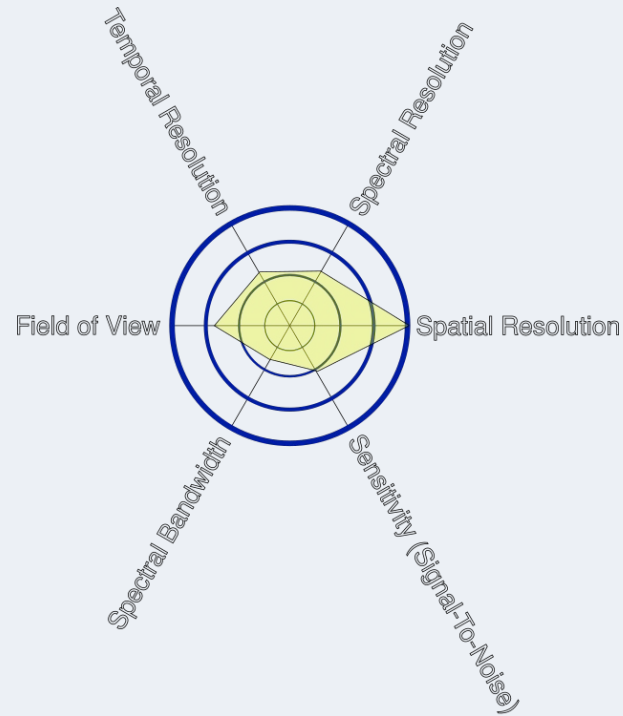


# Visible Tunable Filter

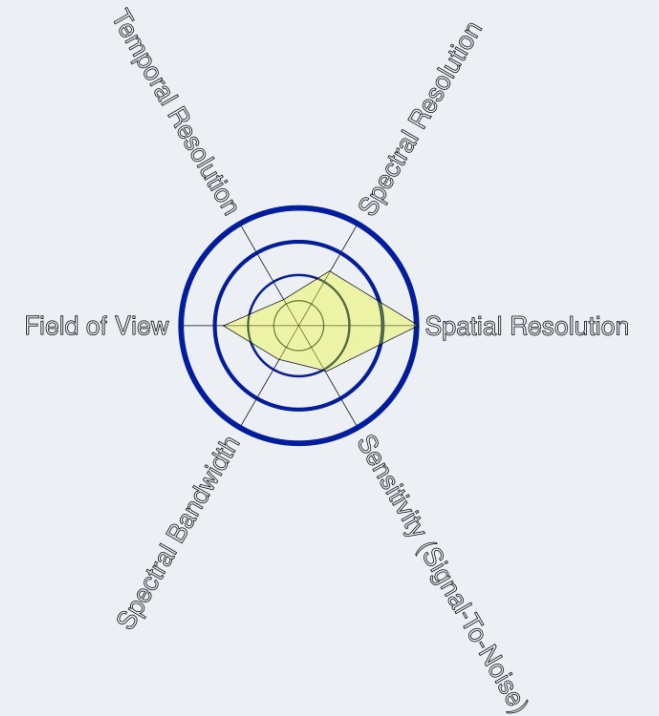
## VTF IMAGING MODE



## VTF DOPPLER MODE



## VTF POLARIMETRIC MODE



# Visible Broadband Imager

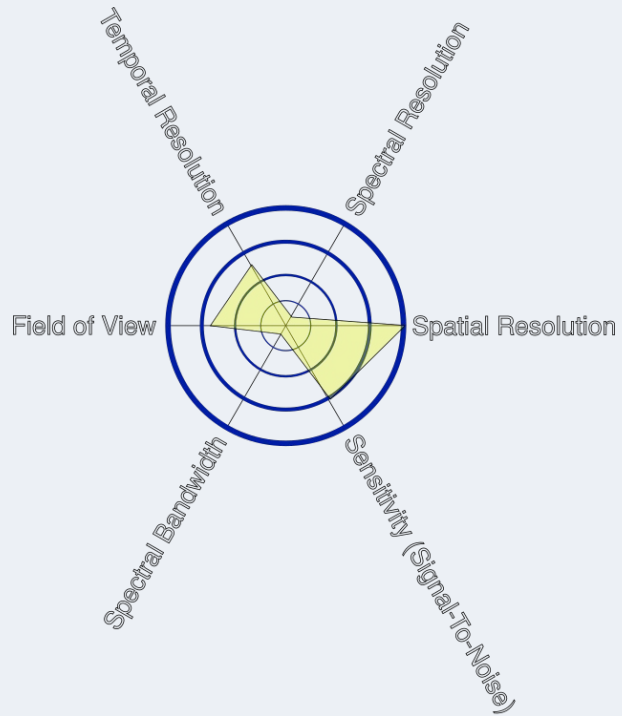
Science case: horizontal flow fields, oscillations

- Focus: high spatial and temporal resolution
- Fixed wavelength imager
- 2 wavelength channels:
  - Spectral ranges: **390 – 550 nm, 550 – 850 nm**
    - Total of 8 interference filters, w/ central wavelength centered at scientific diagnostics that image photosphere, chromosphere or corona
    - typical passbands:  $\leq 0.5$  nm (or much less)
  - Max field-of-view: approx. 1 arcmin square (single field), 2 arcmin square (mosicking)
  - Data post-facto processed to increase spatial resolution

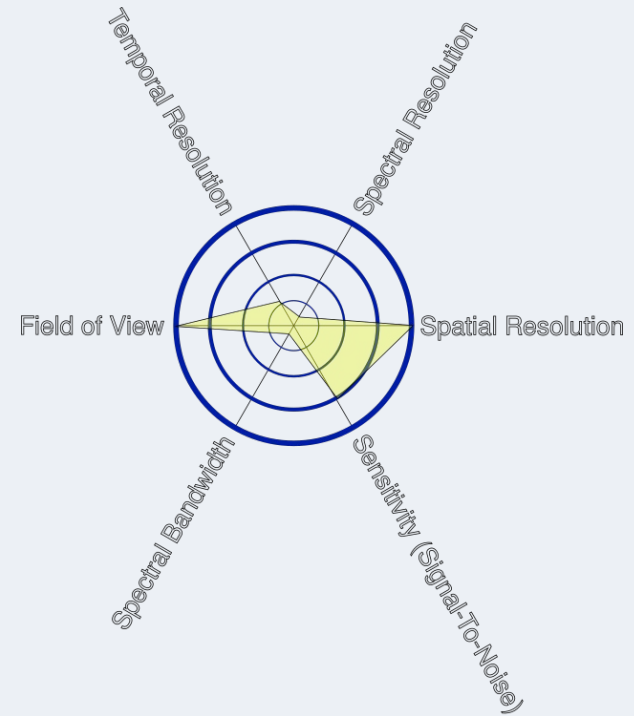


# Visible Broadband Imager

VBI SINGLE FIELD MODE

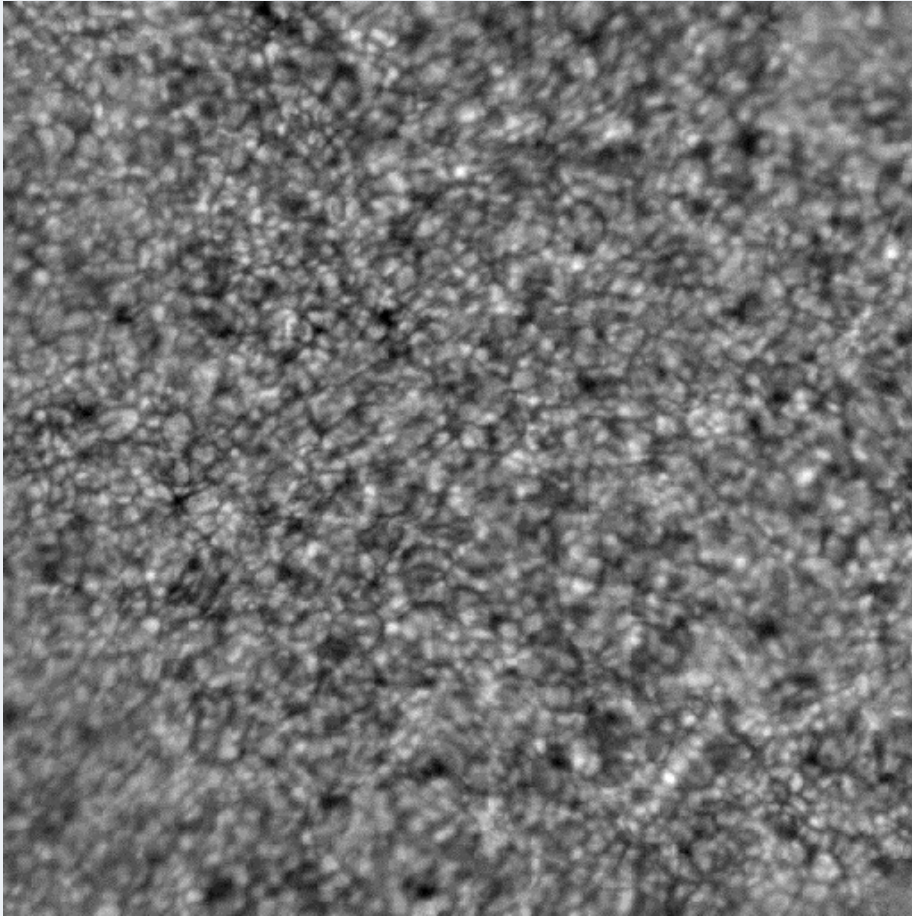


VBI FIELD SCANNING MODE

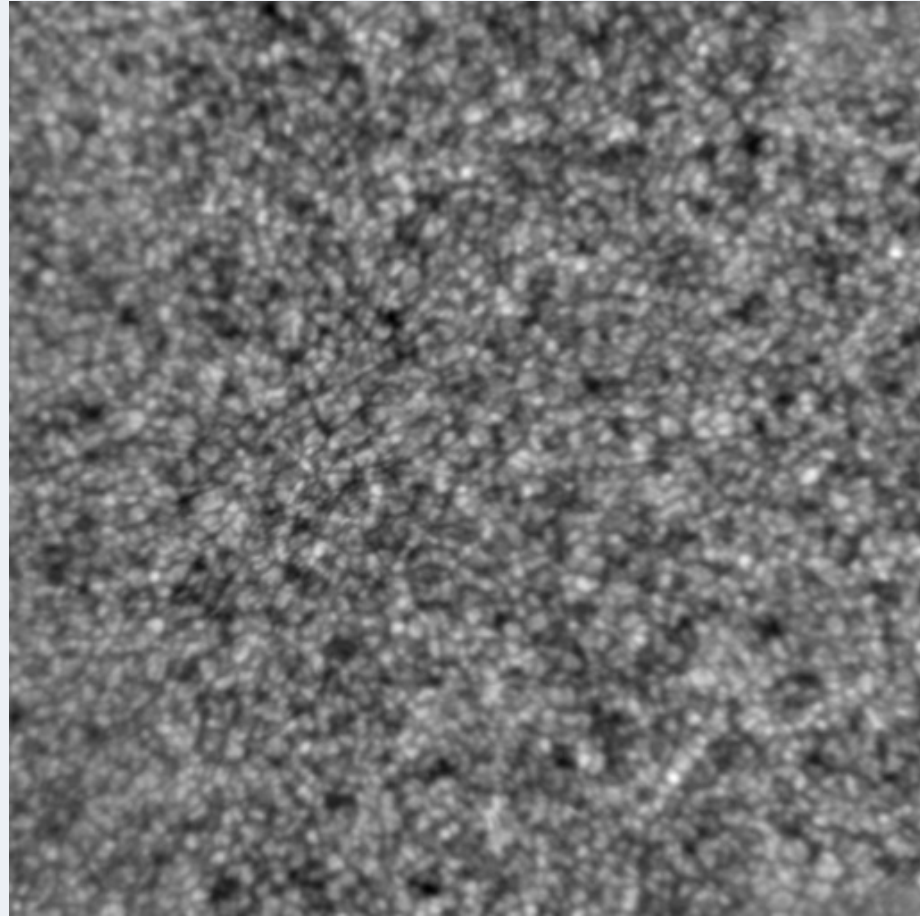


# Speckle Image Reconstruction

N short exposed image

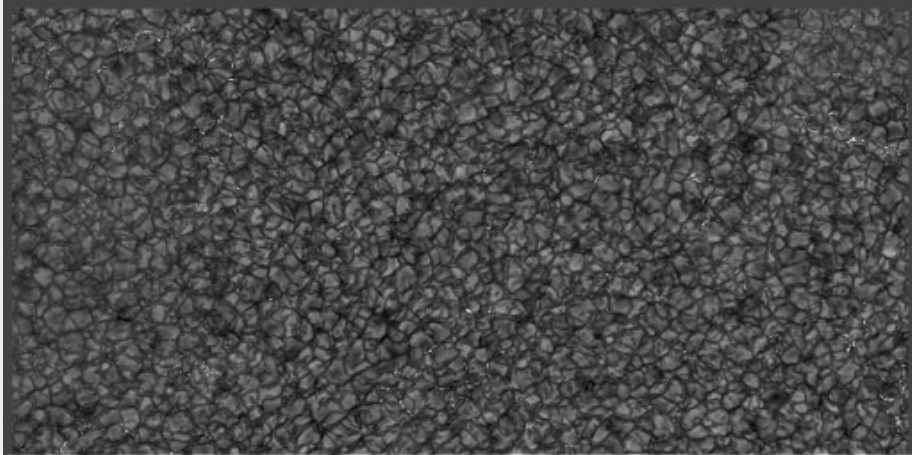


Average image

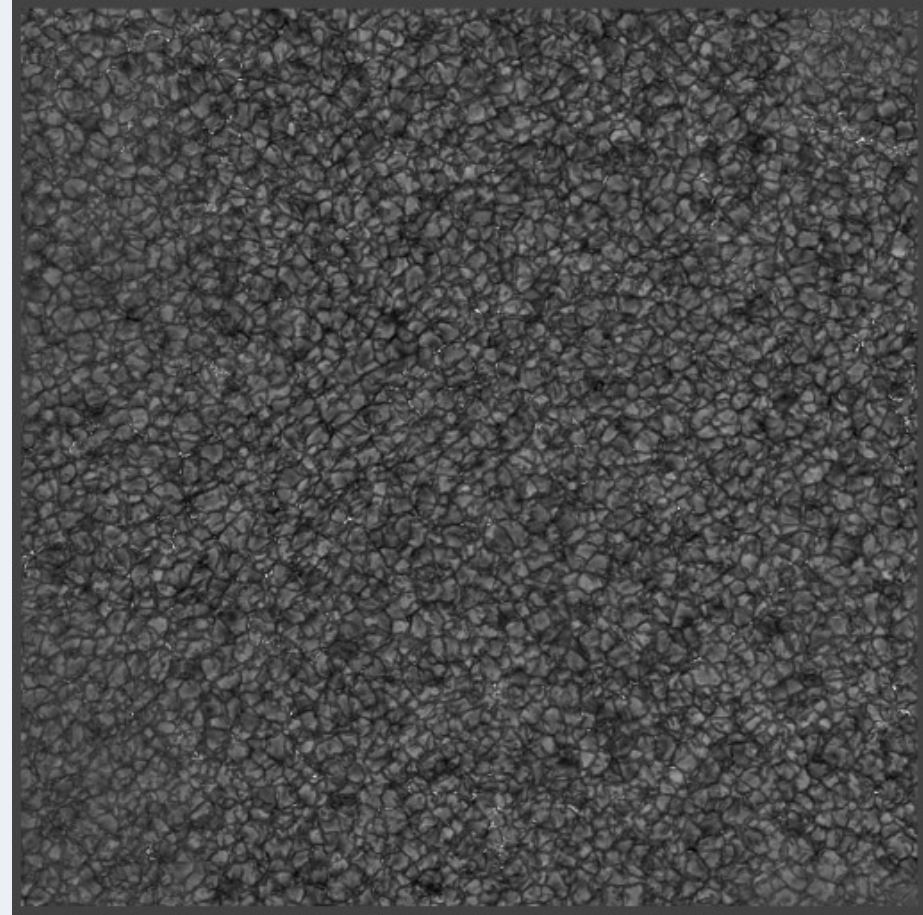
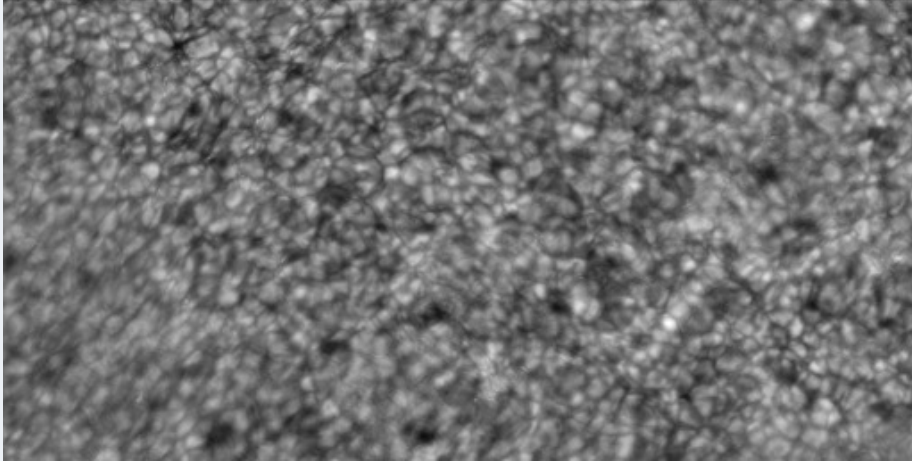


# Speckle Image Reconstruction

Reconstructed image



Best image





# Speckle Image Reconstruction

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Two independent, separate steps:

## Object **Fourier phase** recovery

- Robust: bi-spectrum analysis (aka triple correlation)
  - Somewhat time consuming
- Statistical averaging process that keeps the constant phase
  - Cannot remove fixed aberrations in the optical system
- Requires many, statistically independent realizations of the atmosphere

## Object **Fourier amplitude** recovery

Straight forward mathematically

**Critical** to achieve 'correct' photometry in the reconstruction

Highly non-trivial in reality:

- Need an estimate of the atmospheric conditions (and adaptive optics system, when used)
- **Noise filtering and amplification!**



# Fourier phase recovery

---

- For an incoherent source, formation of the n-th image

$$I_n(\vec{x}) = O(\vec{x}) * PSF_n(\vec{x}) \stackrel{FT}{\leftrightarrow} i_n(\vec{q}) = o(\vec{q}) \cdot otfn(\vec{q})$$

- Additionally, we can describe the complex  $i_n(\vec{q})$  as

$$i_n(\vec{q}) = A_n(\vec{q}) \cdot e^{i\theta_n(\vec{q})}$$

- Consider the normalized  $i_n(\vec{q})$  – they carry only the Fourier phase information

$$\hat{i}_n(\vec{q}) = \frac{i_n(\vec{q})}{\|i_n(\vec{q})\|}$$

and note the object and OTF contribution to the phase separately

$$\hat{i}_n(\vec{q}) = e^{i(\omega(\vec{q}) + \varphi_n(\vec{q}))}$$



# Fourier phase recovery

- Compute the average bispectrum of the normalized phase

$$C(\vec{u}, \vec{v}) = \langle \hat{i}_n(\vec{u}) \cdot \hat{i}_n(\vec{v}) \cdot \hat{i}_n^*(\vec{u} + \vec{v}) \rangle_{n=1 \dots N} = \left\langle e^{i(\theta_n(\vec{u}) + \theta_n(\vec{v}) - \theta_n(\vec{u} + \vec{v}))} \right\rangle_{n=1 \dots N}$$

$$= e^{i(\omega(\vec{u}) + \omega(\vec{v}) - \omega(\vec{u} + \vec{v}))} \cdot \left\langle e^{i(\varphi_n(\vec{u}) + \varphi_n(\vec{v}) - \varphi_n(\vec{u} + \vec{v}))} \right\rangle_{n=1 \dots N}$$

- *Lohmann, Weigelt and Wirnitzer (1983); v.d. Lühe (1985) showed that the second factor is **real (non-complex)**, and, thus, is just a scalar factor to  $C(\vec{u}, \vec{v})$ !*
- For given locations in the Fourier domain  $(\vec{u}, \vec{v})$ , one can then estimate the Fourier phase of the object, e.g.

$$\hat{o}(\vec{u} + \vec{v}) = e^{i\omega(\vec{u} + \vec{v})} = \left( \frac{\hat{C}(\vec{u}, \vec{v})}{\hat{i}_n(\vec{u}) \cdot \hat{i}_n(\vec{v})} \right)^*$$

- The `secret sauce` is in the selection of good combinations  $(\vec{u}, \vec{v})$

# Fourier phase recovery

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- Assumptions:
  - Dynamic (atmospherically induced) phase aberrations have a normal distribution with zero mean
  - There are no fixed aberrations  
(although: if those were known due to independent measurements, they could be removed, as well)
- The PSF is ***not estimated*** as part of the process!  
Speckle interferometry is a ‘clever averaging process’ that removes statistically zero-mean phase aberrations  
[however, PSF recovery can be done separately, e.g. Waldmann & v.d. Lühe, 2010]
- The result of the phase recovery is unique

# Fourier amplitude recovery

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- For an incoherent source, formation of the n-th image

$$I_n(\vec{x}) = O(\vec{x}) * PSF_n(\vec{x}) \stackrel{FT}{\leftrightarrow} i_n(\vec{q}) = o(\vec{q}) \cdot otf_n(\vec{q})$$

- So, theoretically speaking

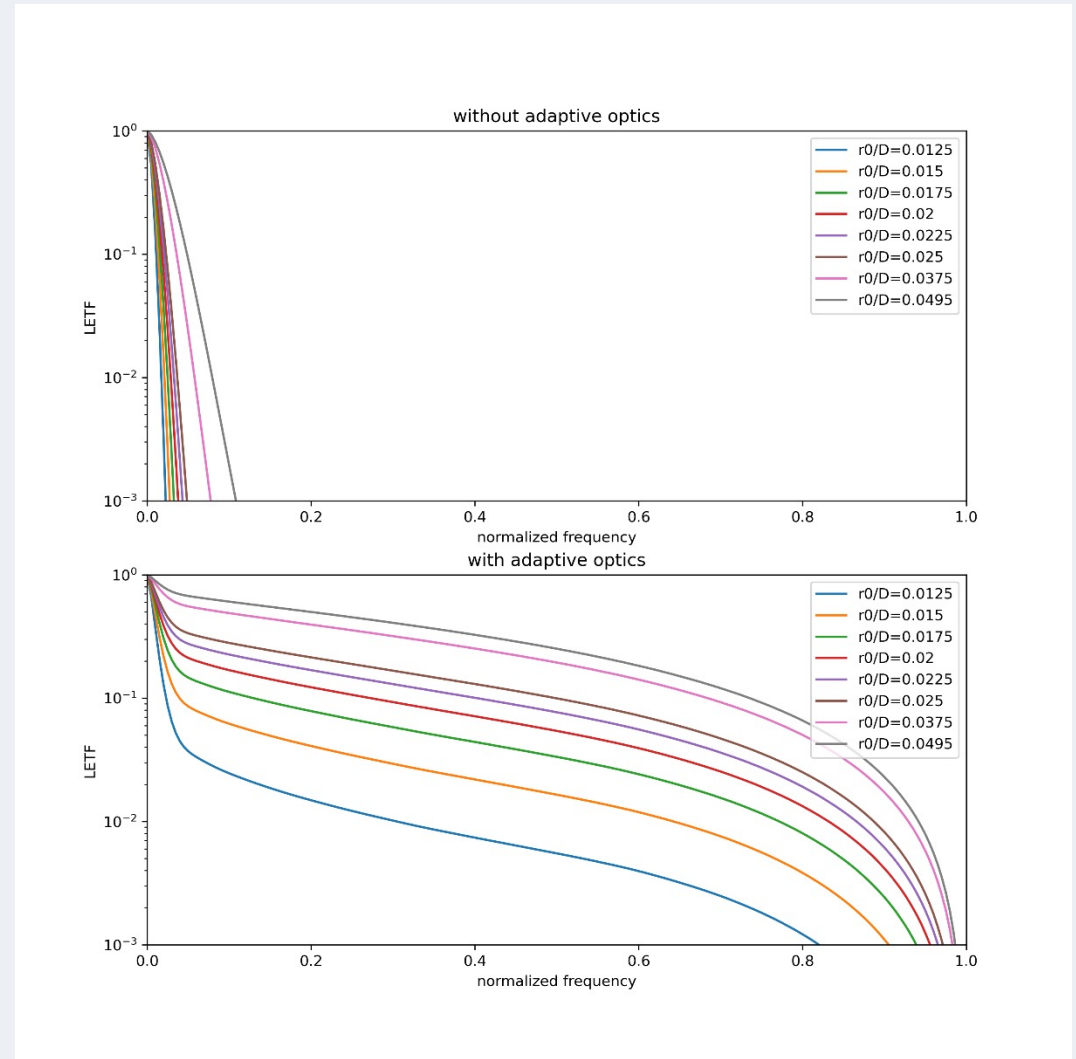
$$|o(\vec{q})|^2 = \frac{\langle |i_n(\vec{q})|^2 \rangle_n}{\langle |otf_n(\vec{q})|^2 \rangle_n}$$

- The term  $STF(\vec{q}) = \langle |otf(\vec{q})|^2 \rangle$  is often called “Speckle Transfer Function” and can be modeled with and without assumption of a correcting adaptive optics system. Aside from frequency  $\vec{q}$ , it depends on
  - Telescope aperture
  - Seeing conditions
  - If applicable, performance of the adaptive optics system



# Fourier amplitude recovery

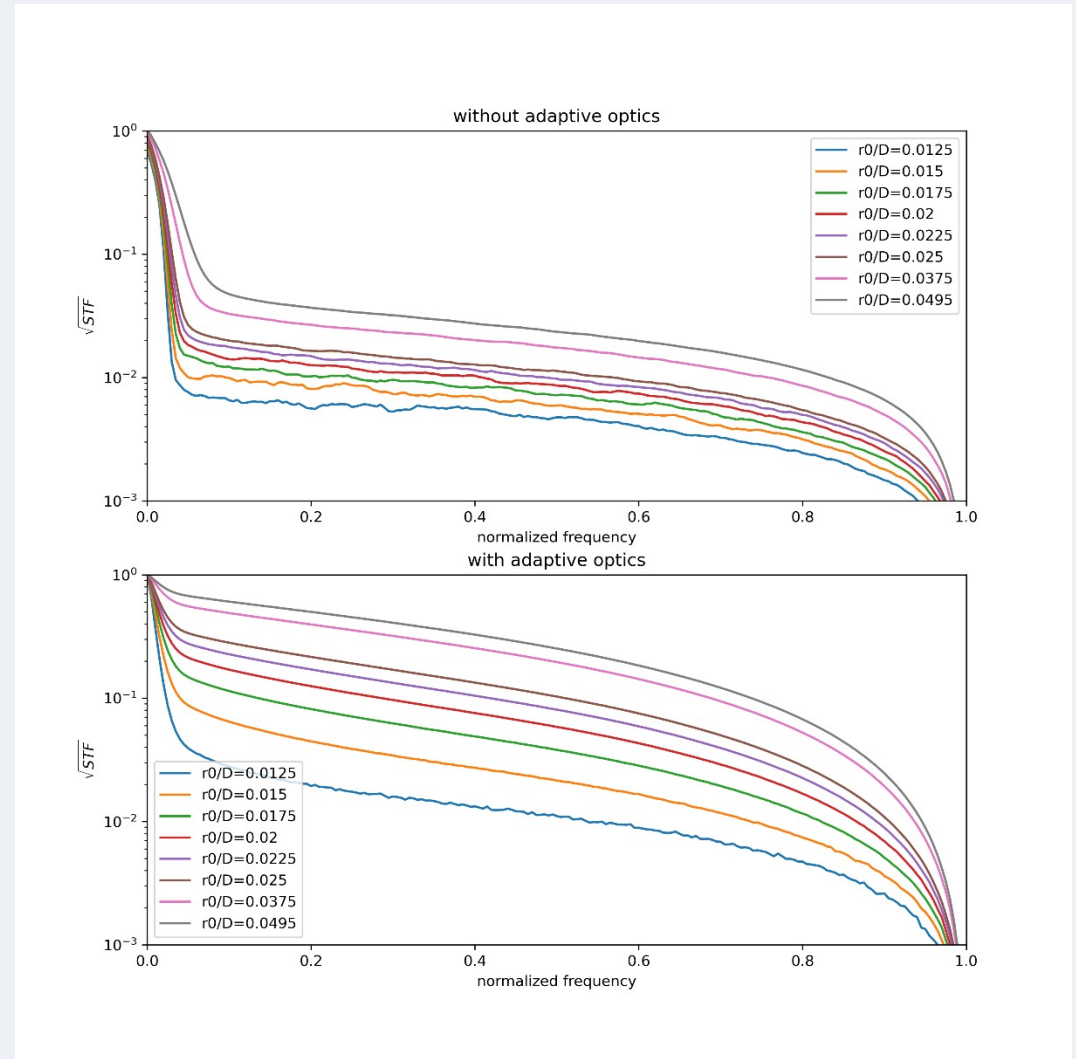
- Pure atmospheric turbulence:
  - Fried (1966) - LETF
  - Korff (1973) - STF
- Modifications for adaptive optics correction:
  - Wang & Markey (1978) - LETF
  - Woeger & v. d. Luehe (2007) – STF
    - Verified to a degree with simulations by Peck et al. (2017)





# Fourier amplitude recovery

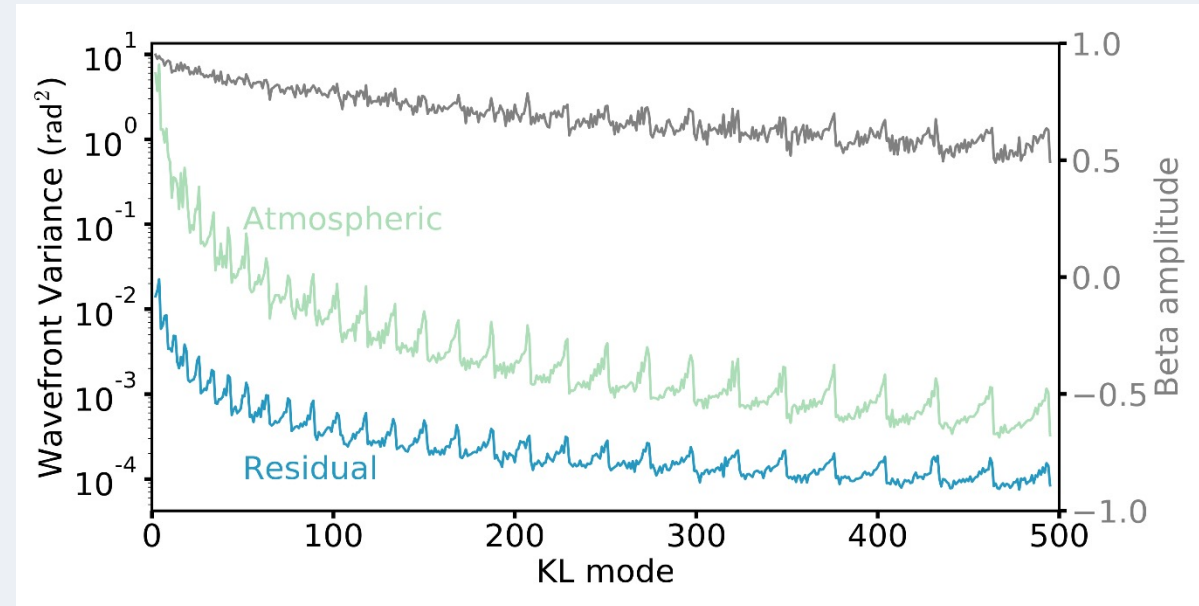
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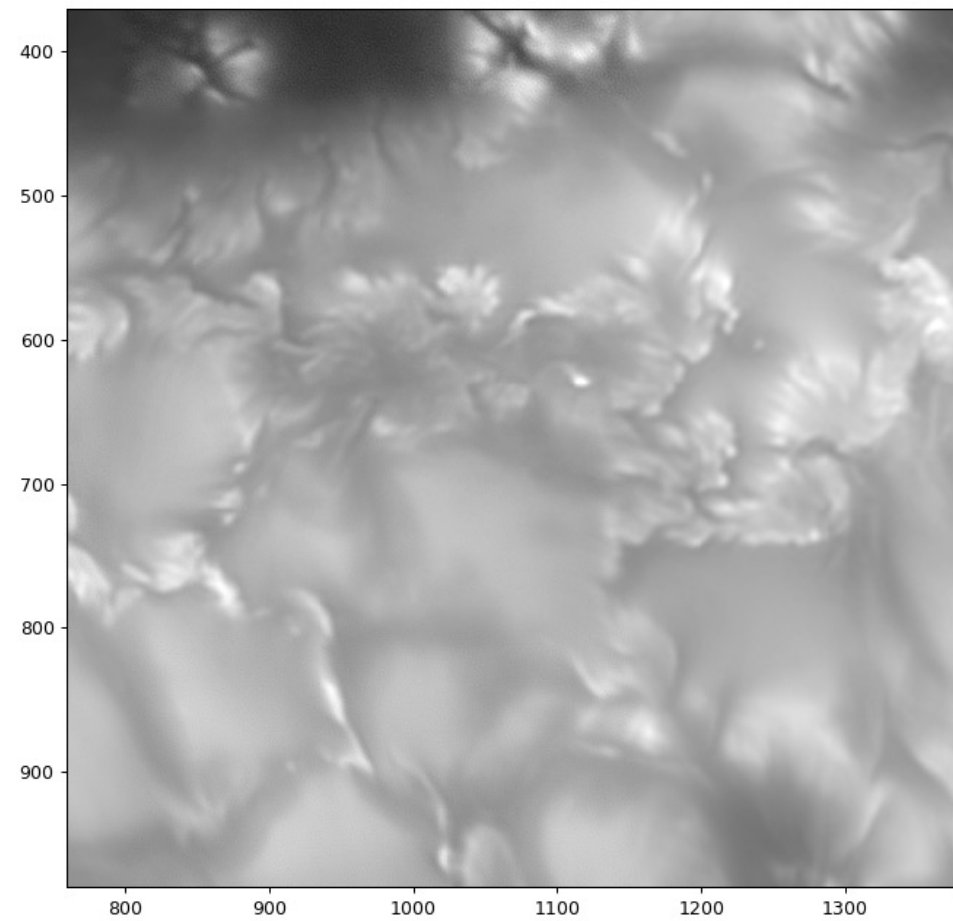
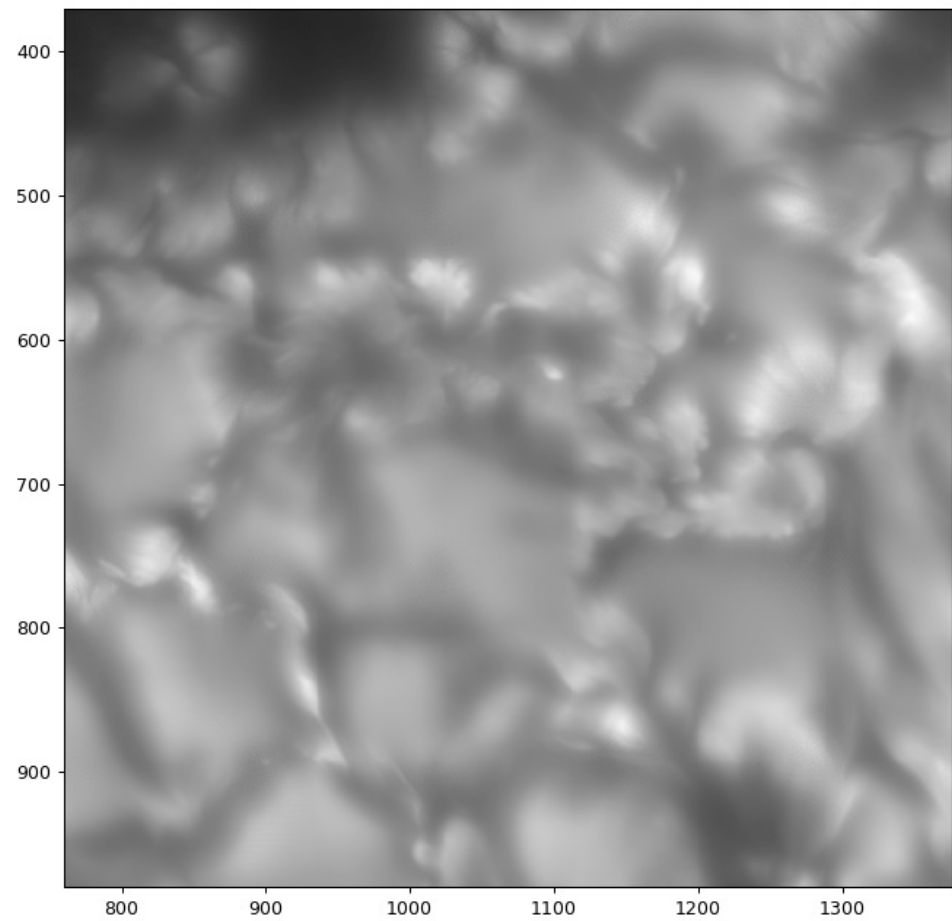


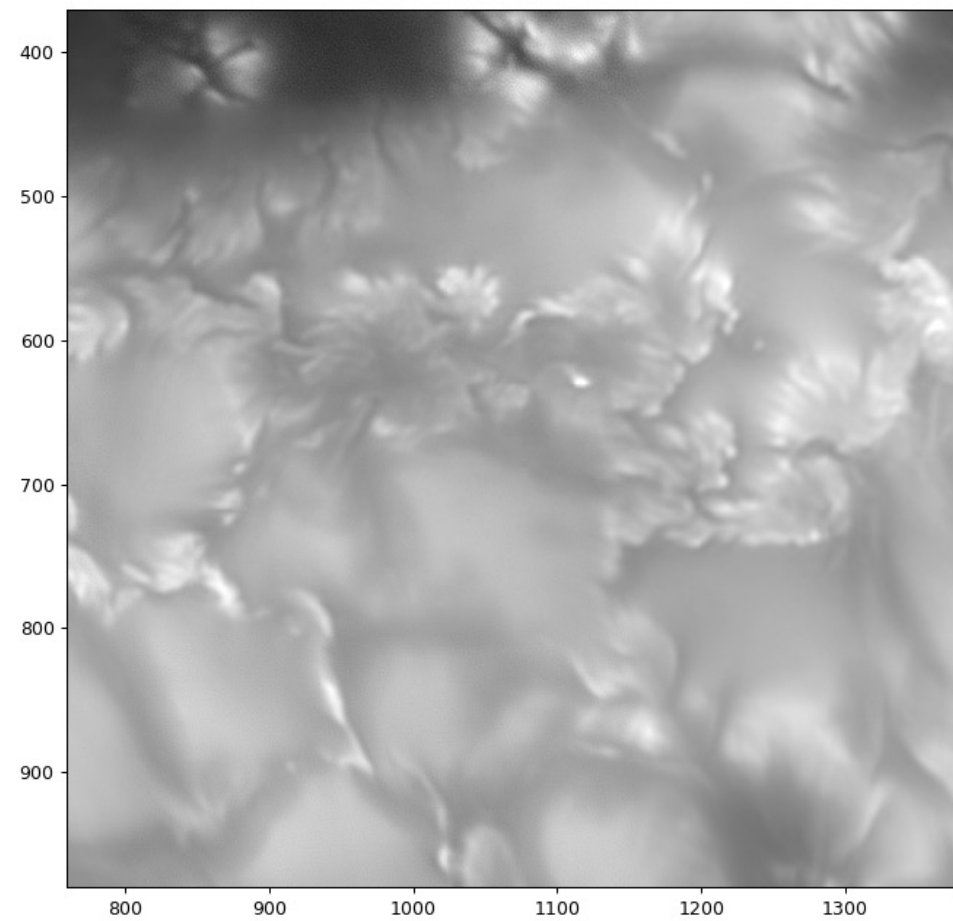
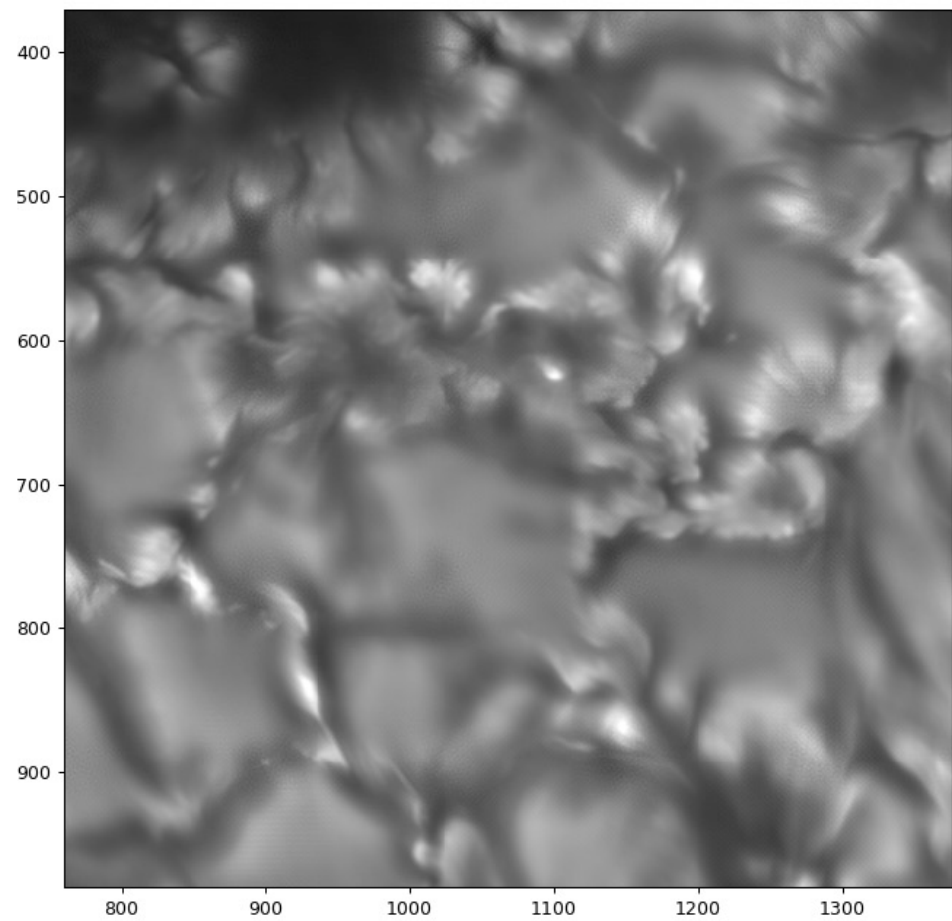


# Fourier amplitude recovery

- The photometry in a reconstruction critically depends on the 'correct' STF
  - Depends on Fried parameter  $r_0$
  - Modal correction efficiency  $\beta$
- The applied STF is chosen *per subfield* based on
  - Input AO control data/ $r_0$
  - Spectral ratio, to estimate correction efficiency (see explanation in later session)







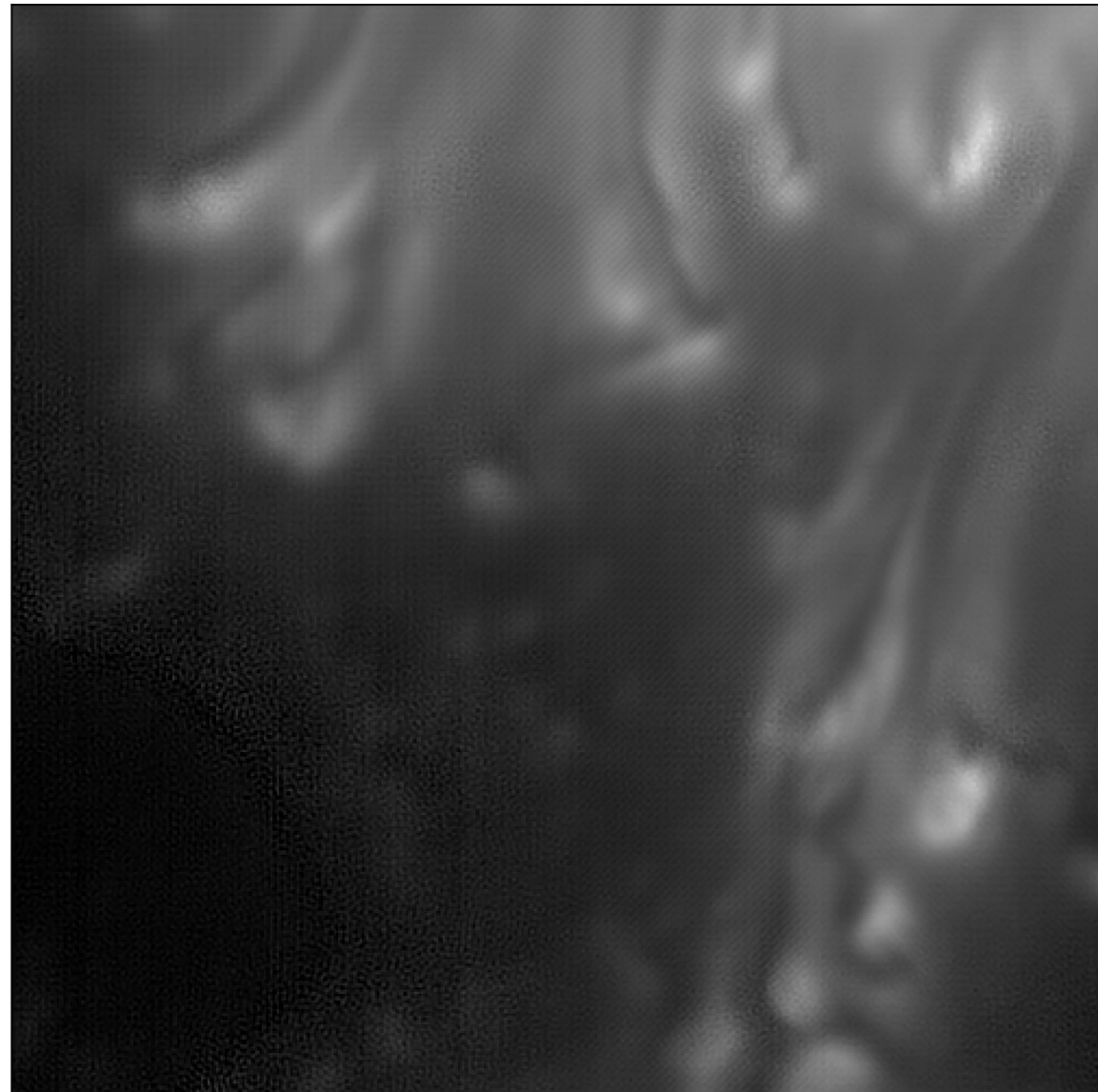
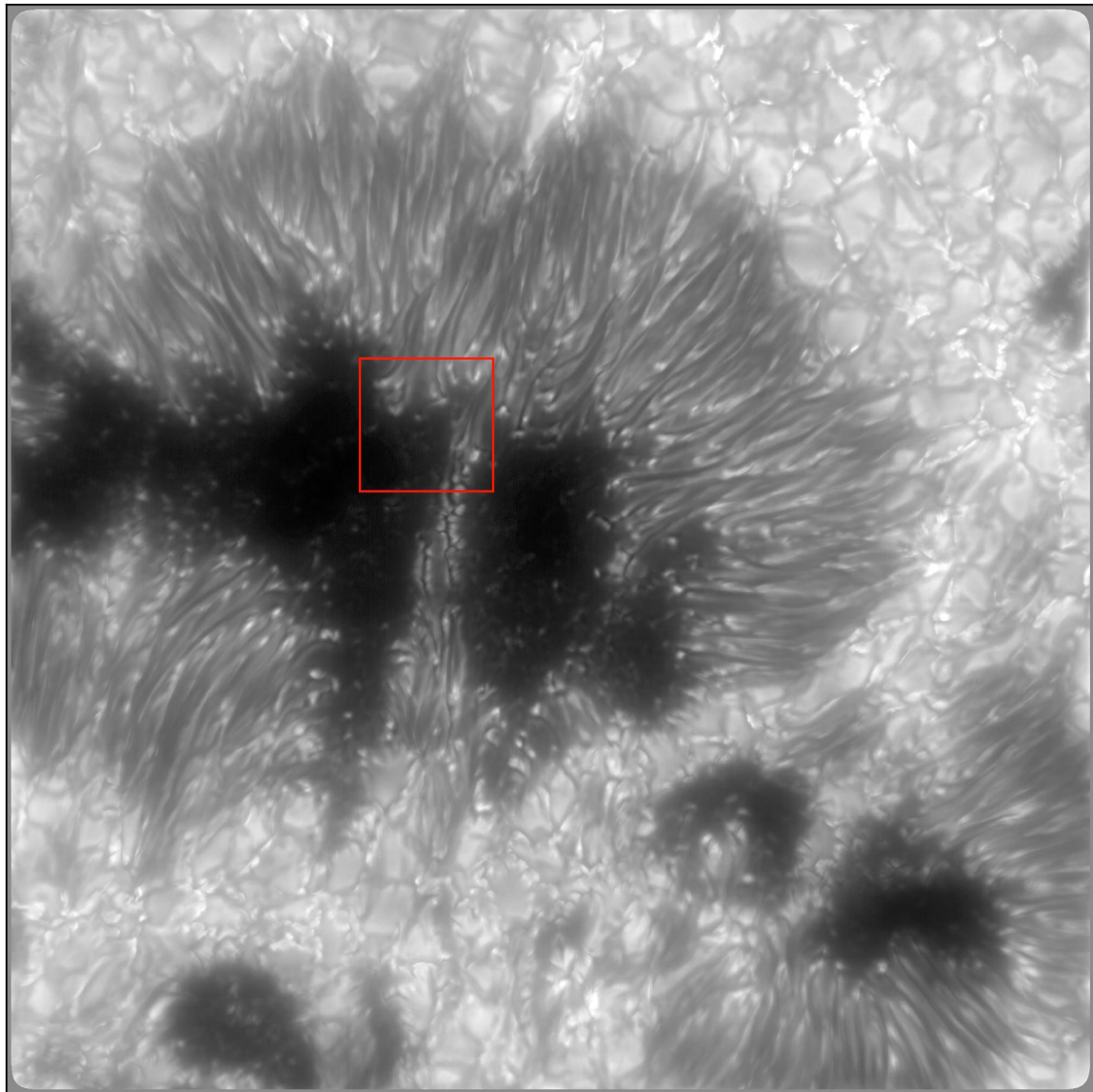




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This is cool ... but what about time series?





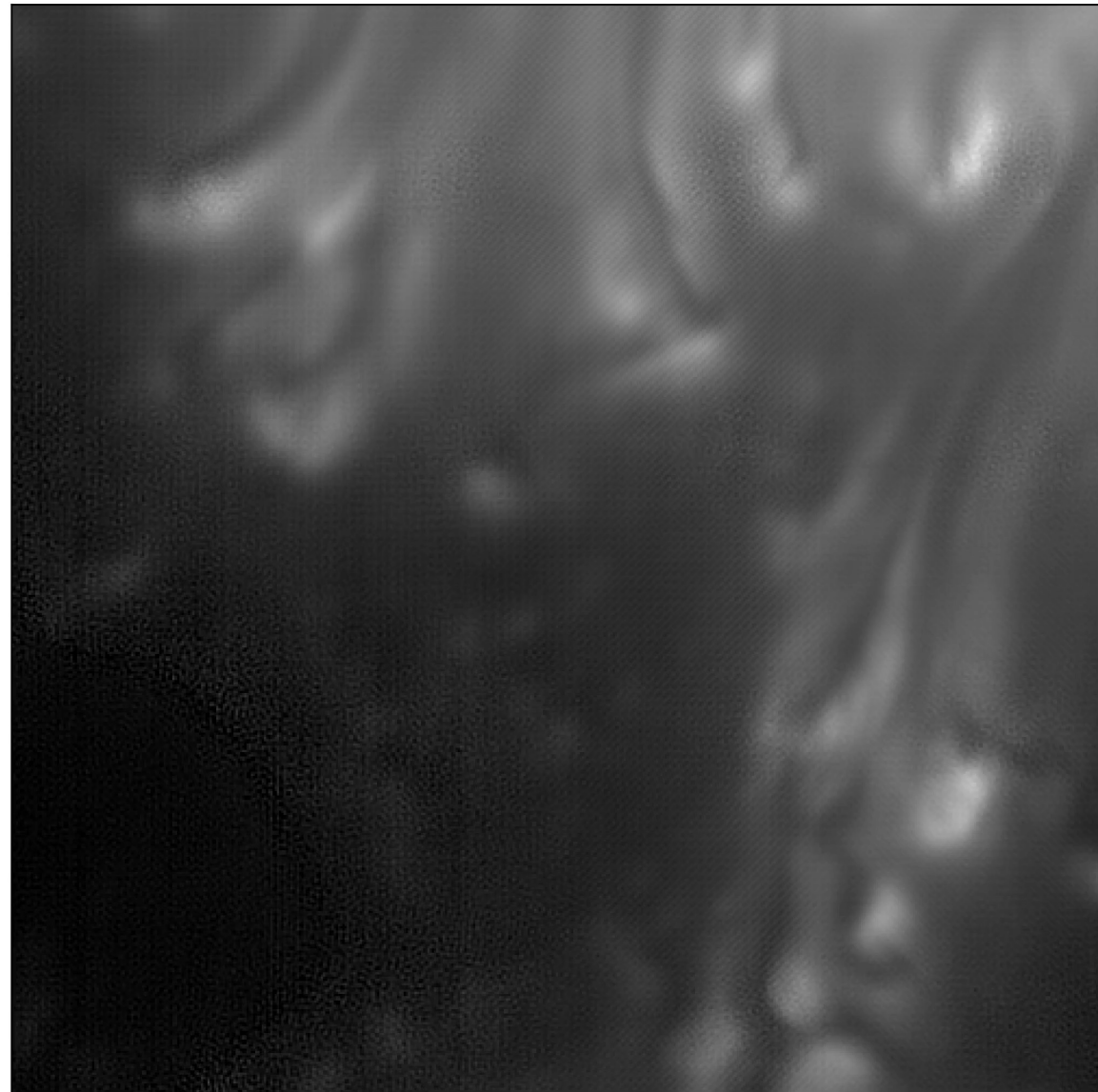
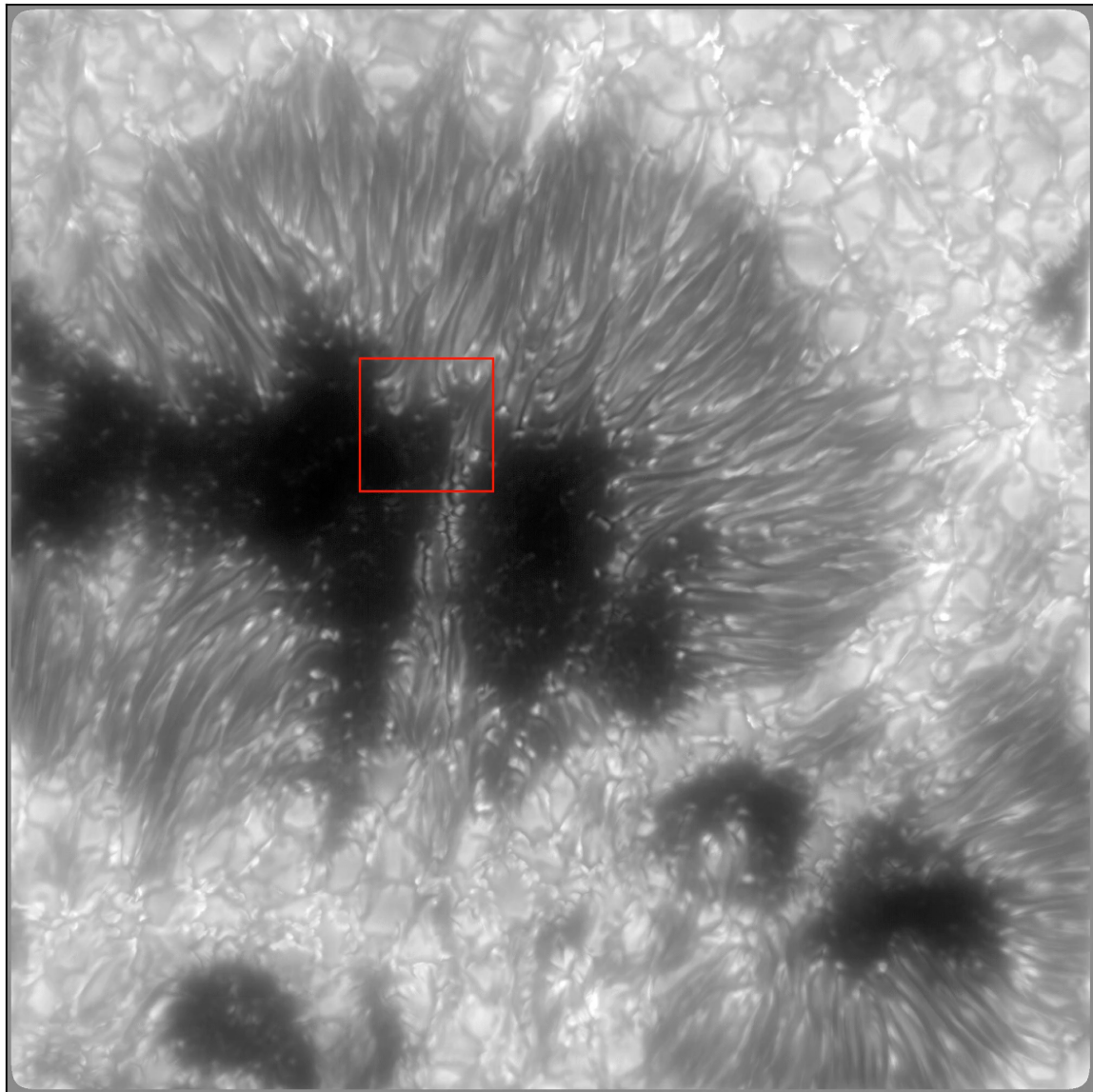


# Destretching time series

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- Time dependent distortion introduced by the random motion of Earth's atmosphere
- Each image burst is reconstructed independently from each other, so the 'position' of the structure depends on the 'mean' location within each burst
  - [remember: speckle interferometry is a statistical method!]
- Solution:
  - Create small sub-tiles and use a cross-correlation algorithm to *shift* (with subpixel accuracy) the sub-tiles' locations onto that of the common **reference**
    - This **reference** needs to be chosen carefully
- HOWEVER:
  - The destretch process is tricky, because it *\*can\** remove solar horizontal motion!!
  - Results depend on:
    - Subfield size
    - Reference selection
    - Input data cadence
    - ...







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Questions?

