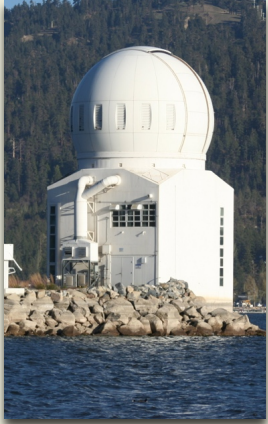
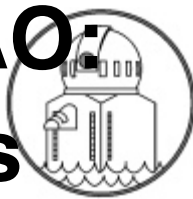


Major operational solar telescopes have AO: -AO routine for almost all observations



Goode Solar Telescope
Big Bear, USA
1.6 m
8 cm subap.
357 act.
2.2 kHz
highest order



GREGOR
Tenerife
1.5 m
9.6 cm subap.
256 act.
2.1 kHz



Swedish Solar Telescope
La Palma
1 m
10 cm subap.
85 act.
2 kHz



New Vacuum Solar Telescope
China
1 m
8.3 cm subap.
151 act.
3.5 kHz

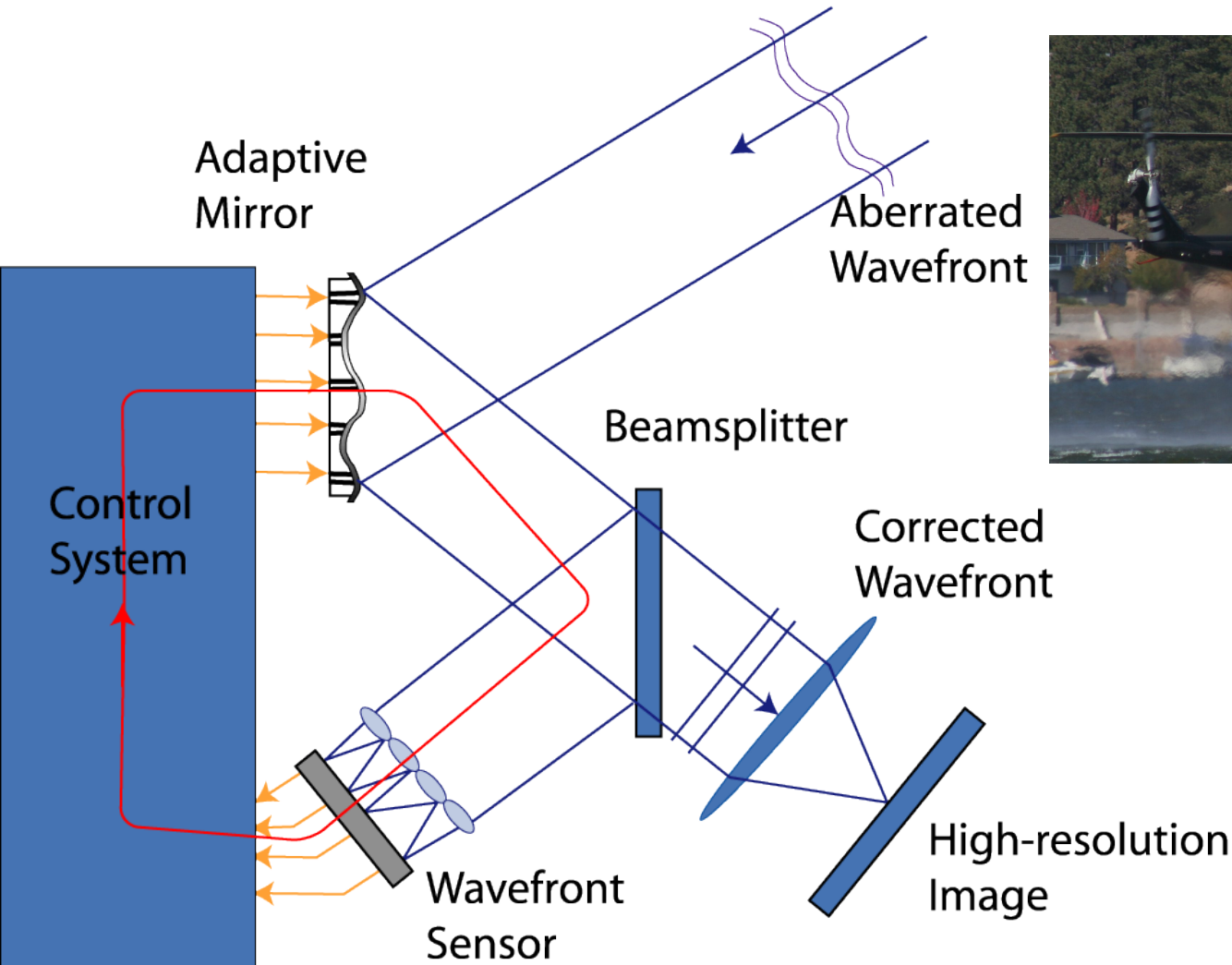


Dunn Solar Telescope
Sunspot, USA
0.76 m
7.6 cm subap.
97 act.
2.5 kHz
first solar AO

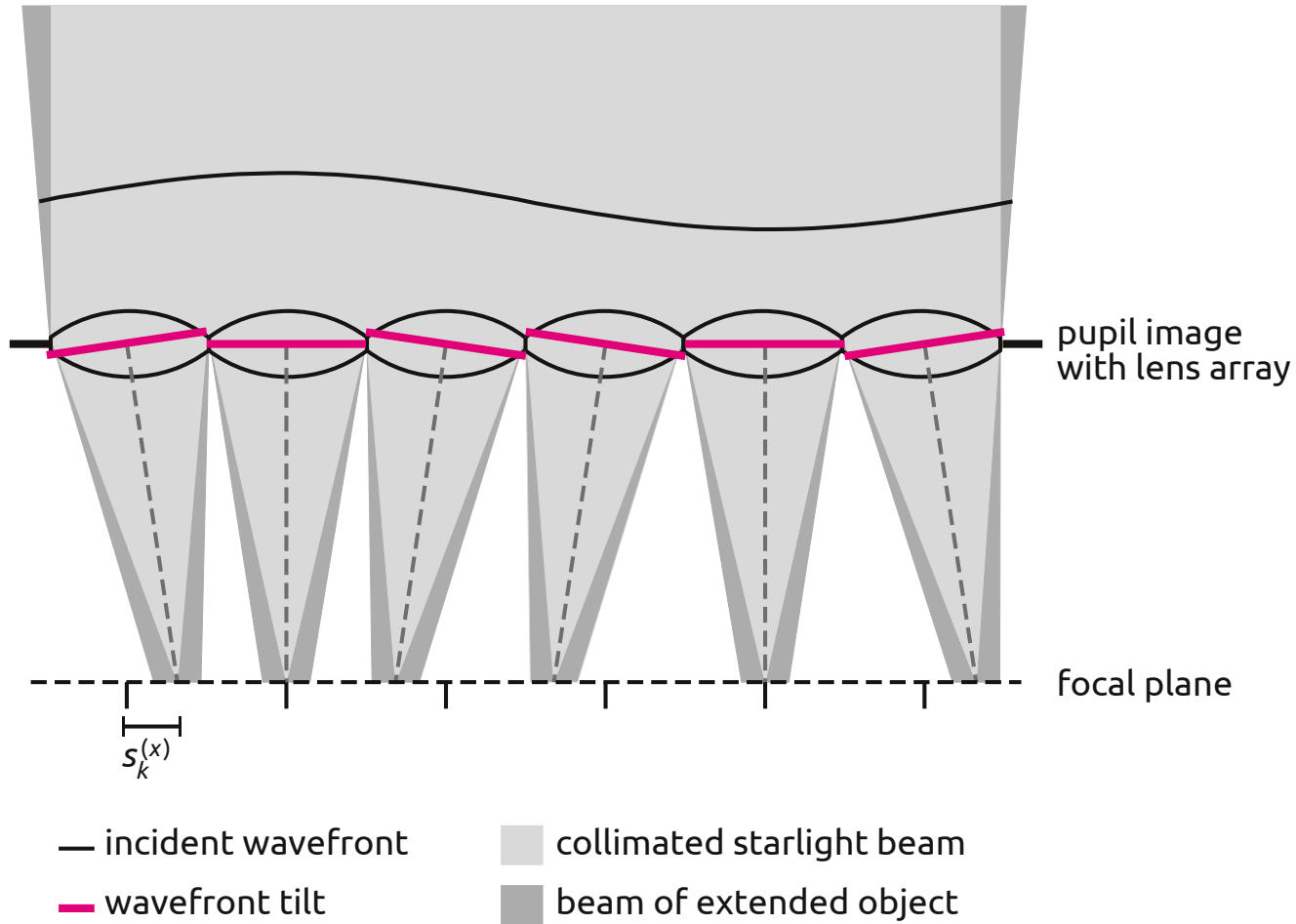


Vacuum Tower Solar Telescope
Tenerife
0.7 m
10 cm subap.
37 act.
2.1 kHz

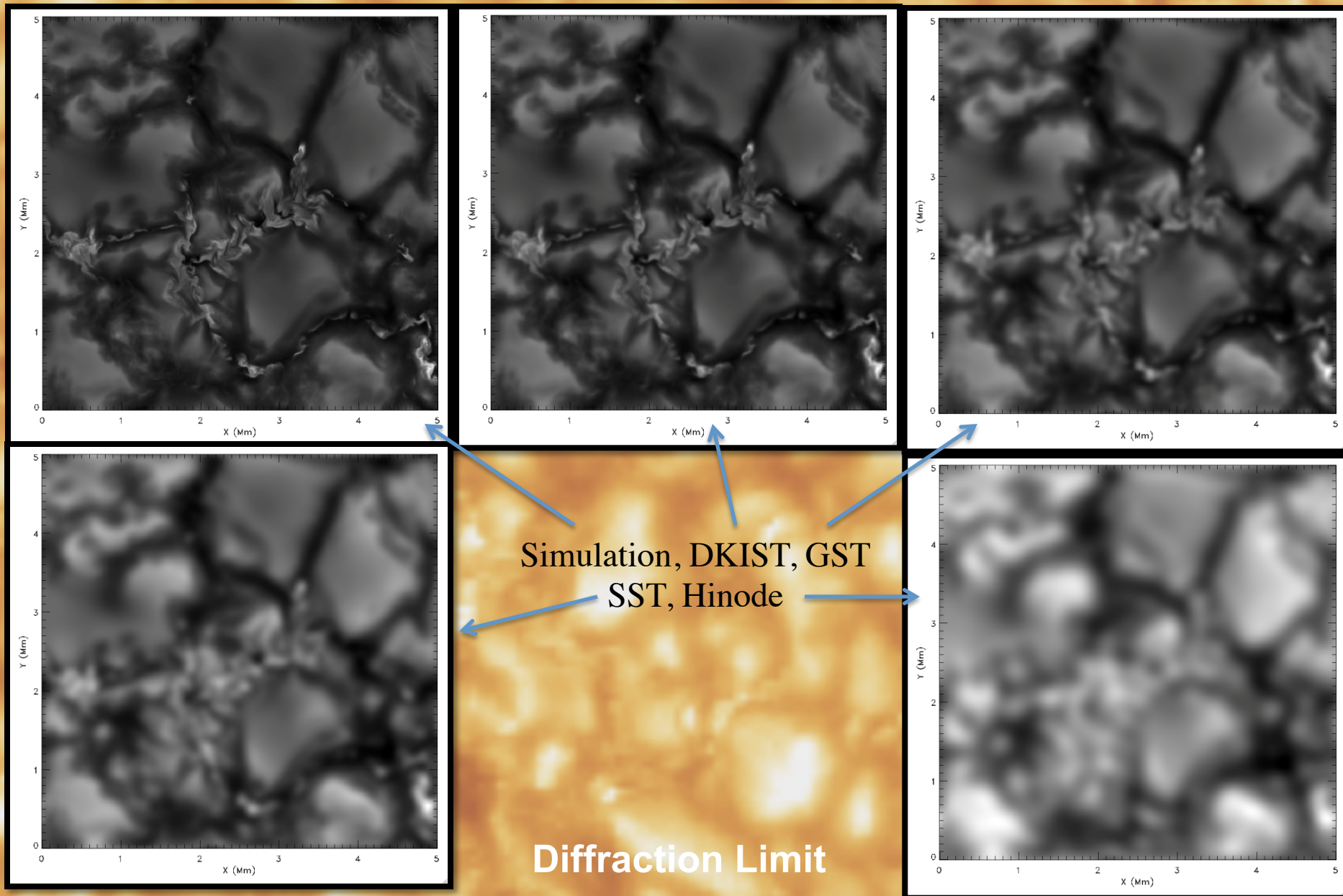
Schematic of Shack-Hartmann Adaptive Optics



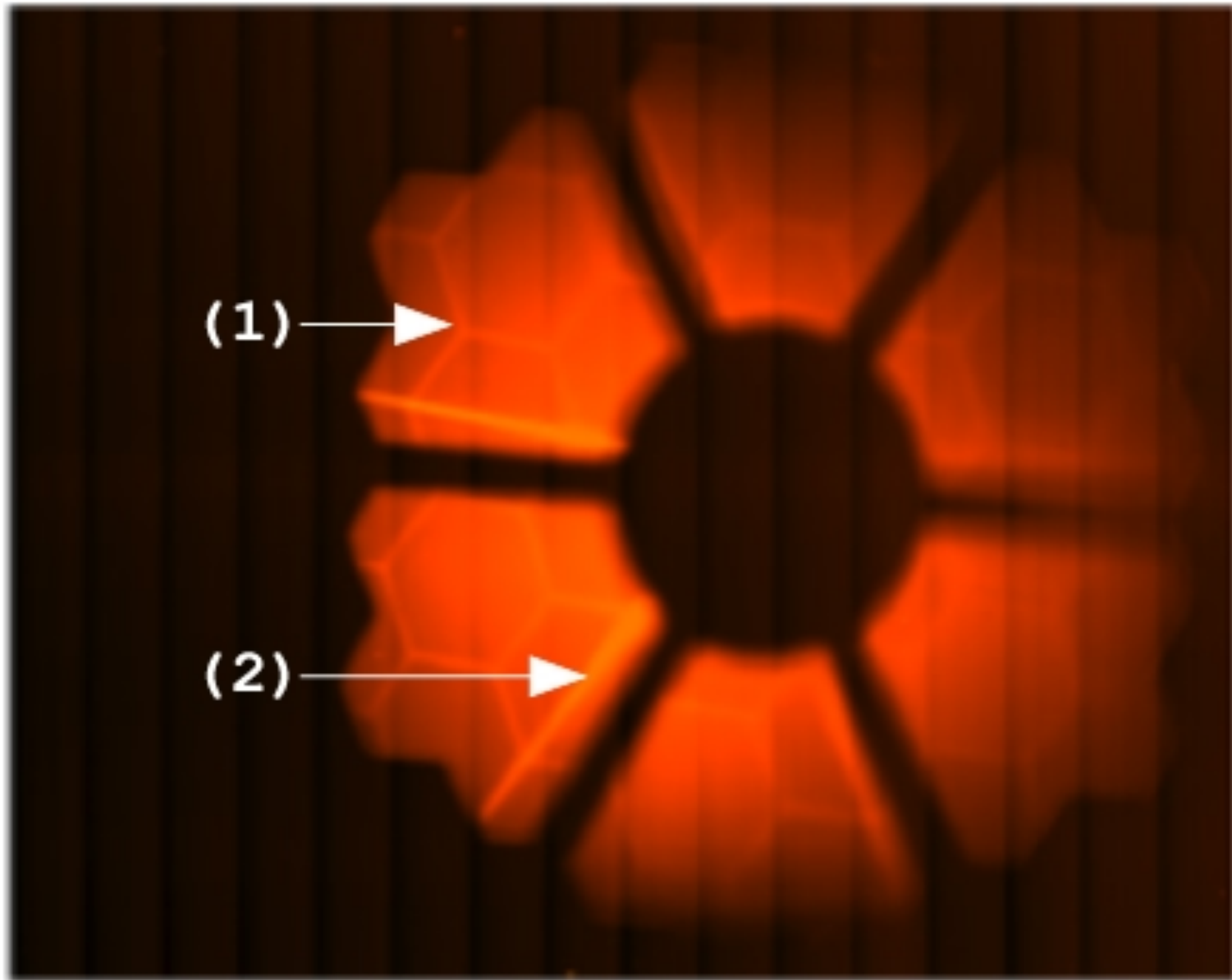
Pupil Wavefront into Subapertures



Effect of Telescope Resolution - Intensity



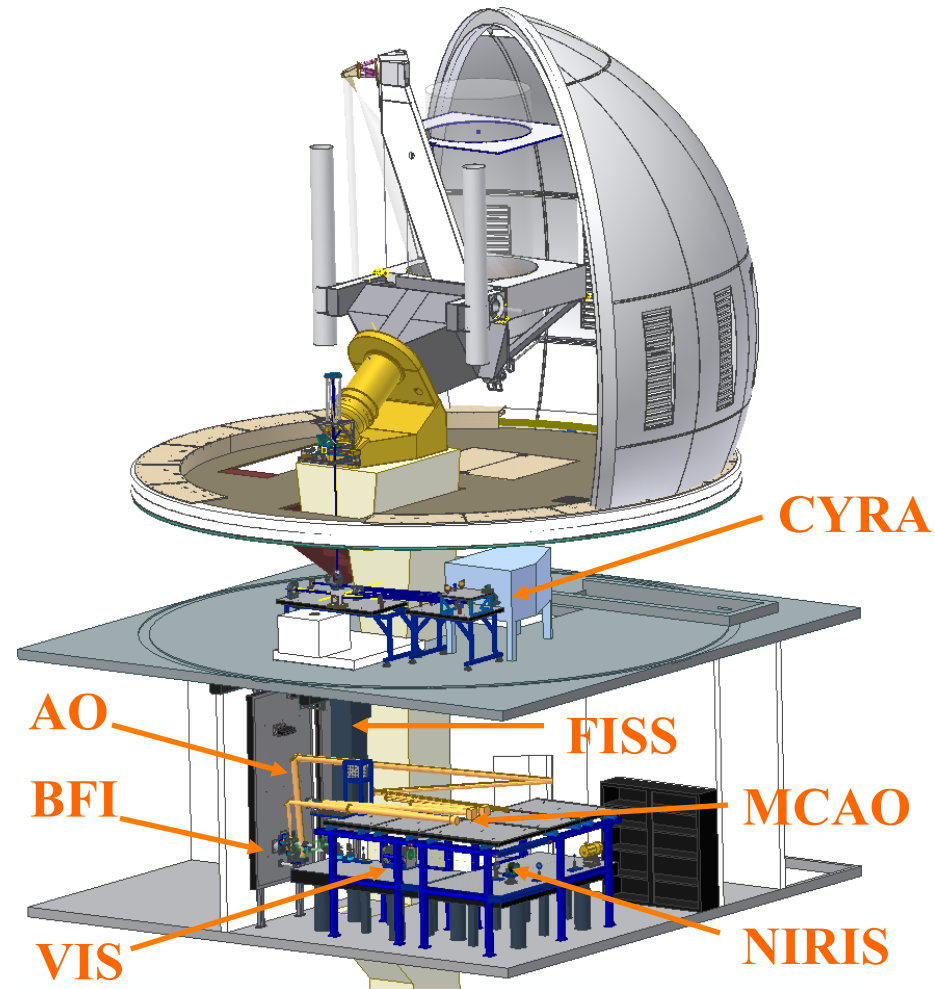
Why Off-Axis? 10.4 m Gran Telescopio Canarias in Thermal Emission (Goode, Kuhn & Moretto)



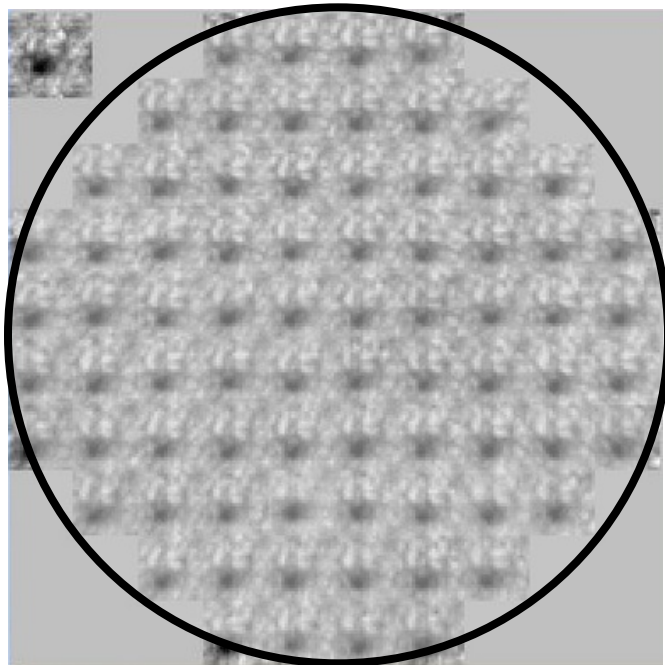
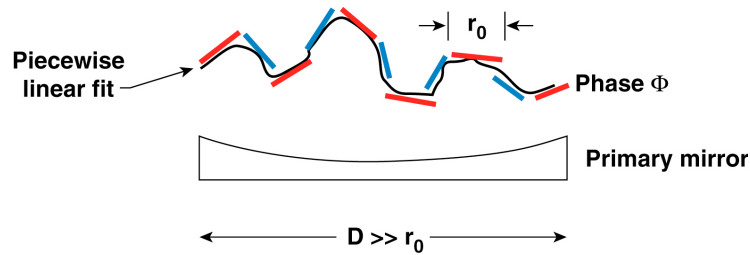
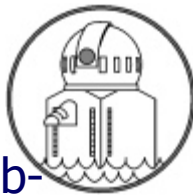


GST Scientific Instruments

- ❖ Adaptive Optics System (AO: **AO-76, AO-308, GLAO** & MCAO)
- ❖ Visible Imaging Spectrometer (**VIS, VISP**)
- ❖ Near InfraRed Imaging Spectropolarimeters (**IRIM, NIRIS**)
- ❖ Cryogenic Infrared Spectrograph (**CYRA**)
- ❖ Broad-band Filter Imager (**BFI**)
- ❖ Fast Imaging Solar Spectrograph (**FISS**)



1st Generation AO: AO-76



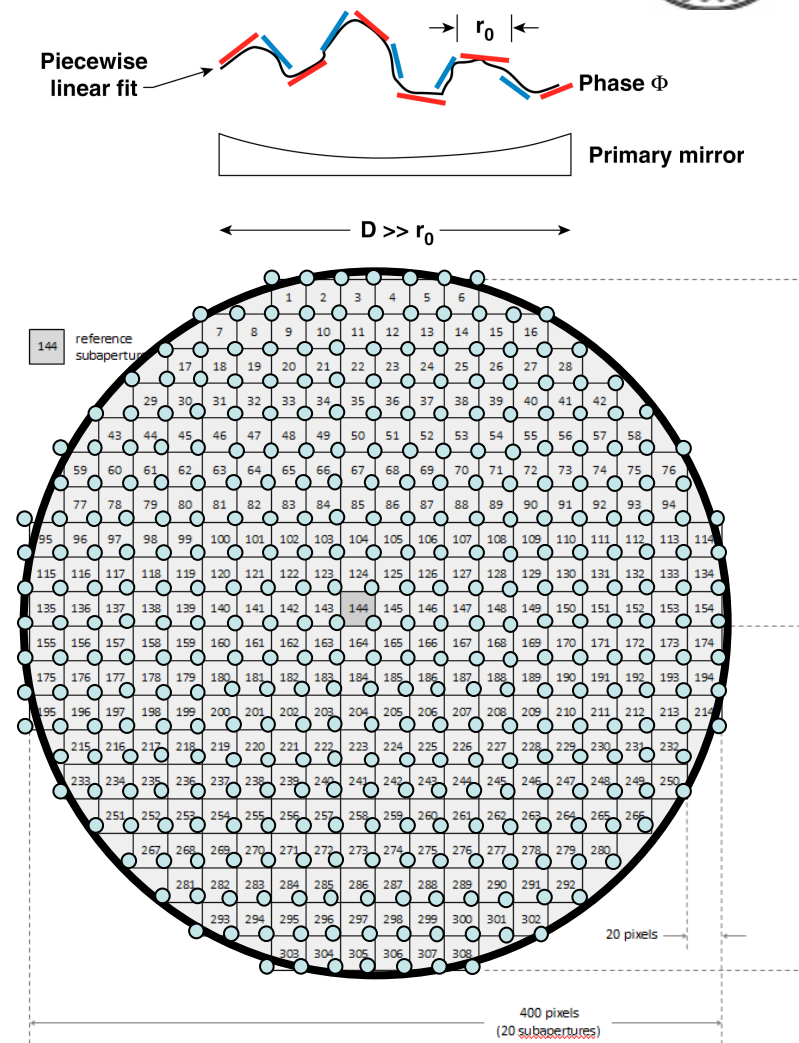
AO-76

- ❖ Shack Hartmann WFS with 76 sub-apertures (AO-76): 10 sub-apertures across the NST PM
- ❖ Xinetics Deformable Mirror with 97 actuators and 7 mm spacing
- ❖ Baja camera with a frame rate of 2500 Hz for **200 by 200** sub-array
- ❖ Bitware Hammerhead Boards with 40 digital signal processors (DSPs)
- ❖ Closed-loop Bandwidth: 120 Hz
- ❖ Strehl ratio: 0.7 in the NIR under median BBSO seeing
- ❖ BBSO $r_0 = 6 \sim 8$ cm @ 500 nm, GST requires 20 sub-apertures across pupil
- ❖ Note: @ 1000 nm $r_0 = 14 \sim 18$ cm, 10 sub-apertures across (r_0 varies as $\lambda^{6/5}$)

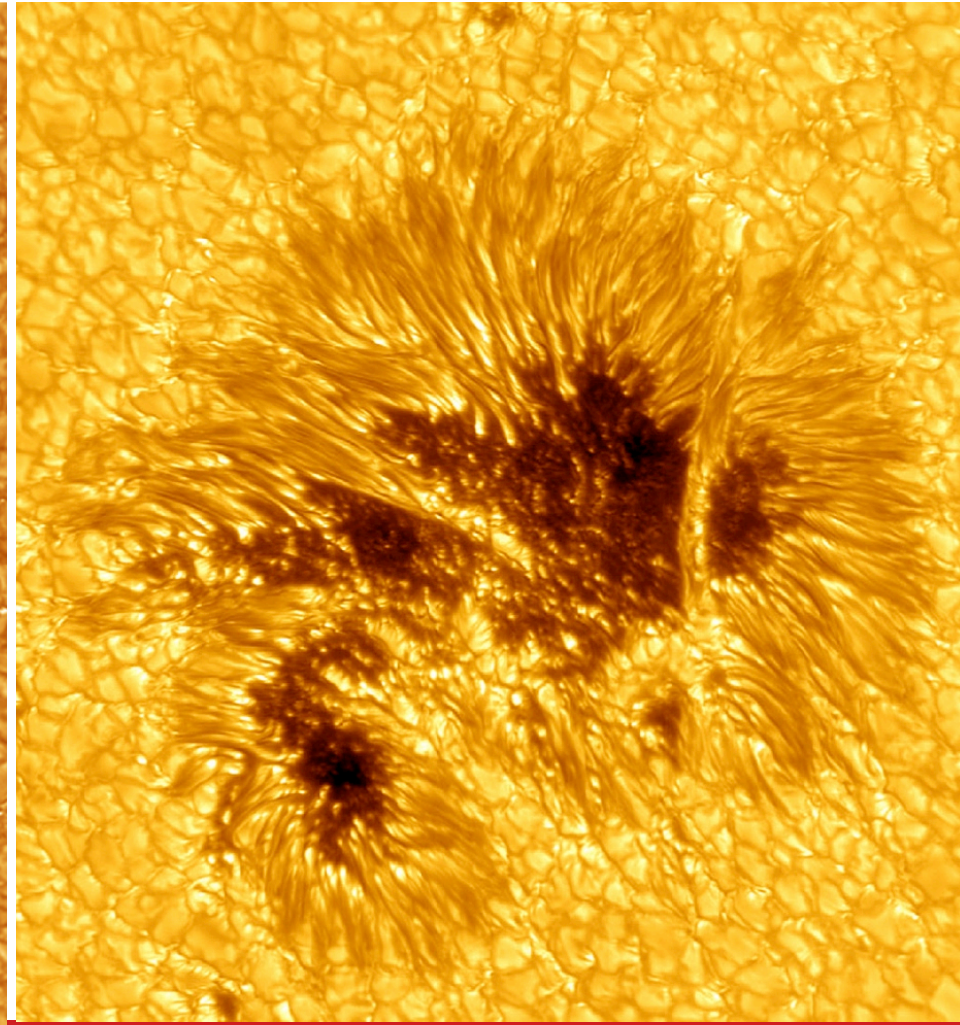
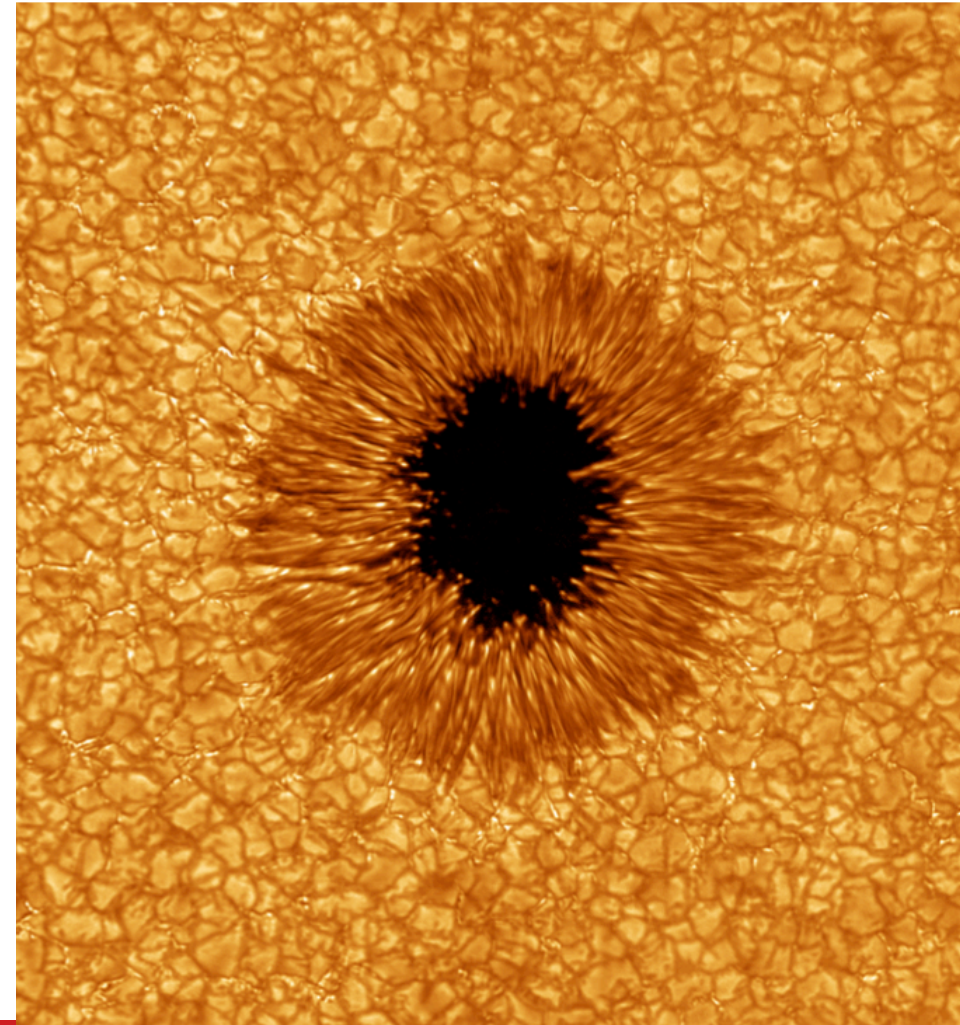
2nd Generation AO: AO-308



- ❖ AO-308 is operational, AO-308 is a collaboration between BBSO and NSO
- ❖ Shack Hartmann WFS with 308 sub-apertures (AO-308): 20 sub-apertures across the NST primary mirror
- ❖ Xinetics Deformable Mirror with 357 actuators and 5 mm spacing
- ❖ Phantom V.7.3 camera with a frame rate of 2000 Hz for 400 by 400 pixel sub-array
- ❖ Bitware TigerSHARC Boards with 16 digital signal processors (DSPs)
- ❖ Closed-loop Bandwidth: 120 Hz
- ❖ Acquire diffraction limited imaging over the telescope's full range of operation

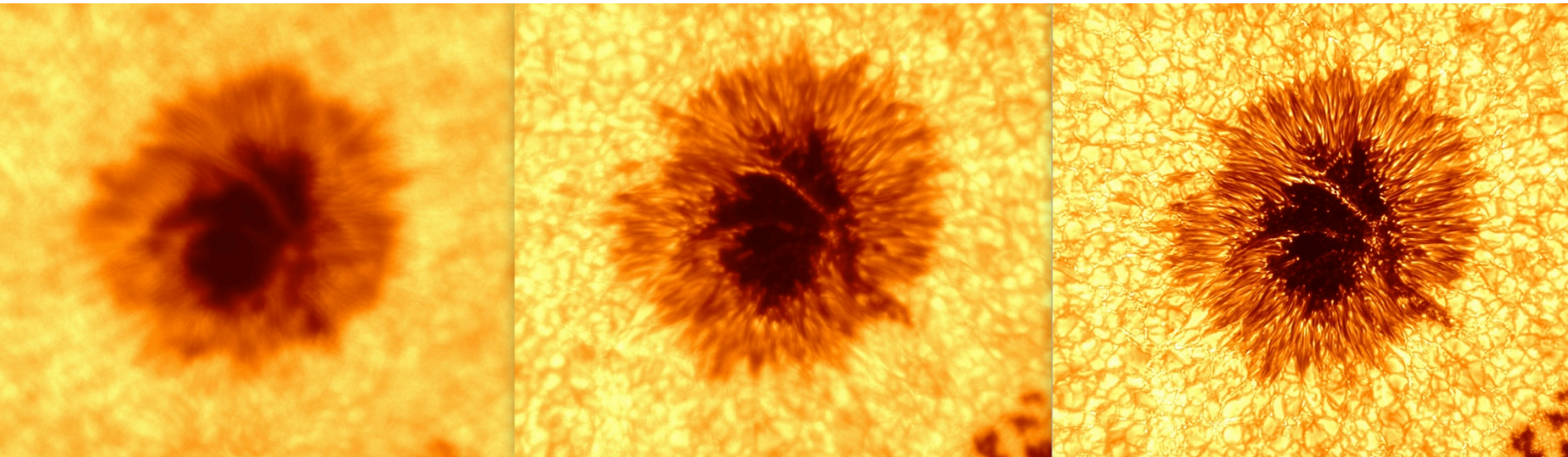


TiO (705 nm): 2010 (AO-76, 70''x70'') vs.
2013 (AO-308, 50''x45'')



CAO (Gen II, AO-308) – Off & On

CAO On + Speckle Image Reconstruction



Adaptive Optics Off

Adaptive Optics On

AO On with image post processing

2 September 2013 - TiO

18:39:17 UT

BBSO/NST

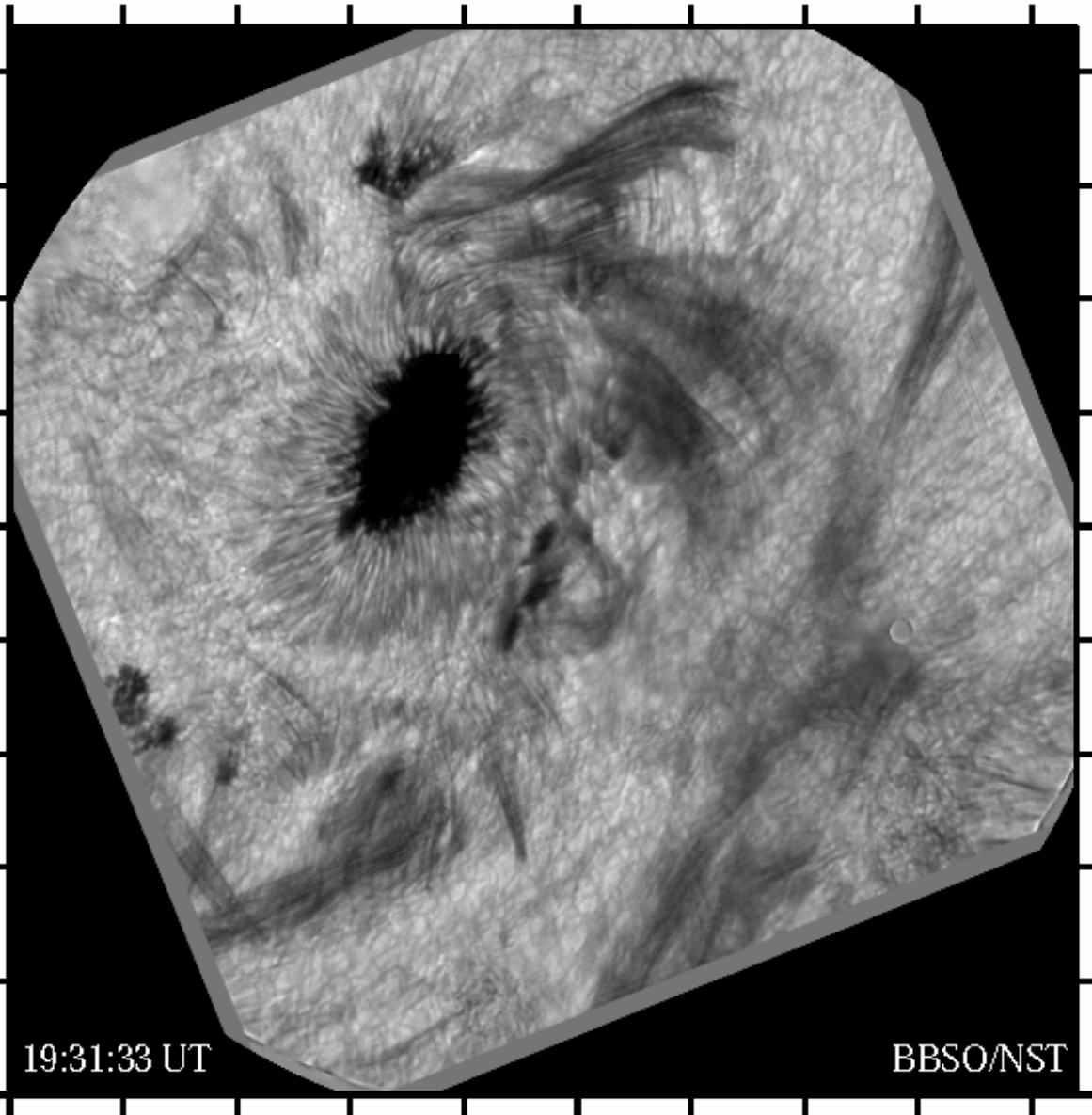


Classic AO Sunspot

- May 22, 2013
 - 43 mins
 - TiO (705 nm)
 - 50''x45'' FOV

Cao, W.

Flare 5 July 2012



- 1083.0 nm
- Nearly 3 hrs
- CAO & Speckle
- At 21:47 FOV Lit
- Need sub-second timestep over FOV
- 50000 km x 50000 km field
- Spot roughly the size of Earth

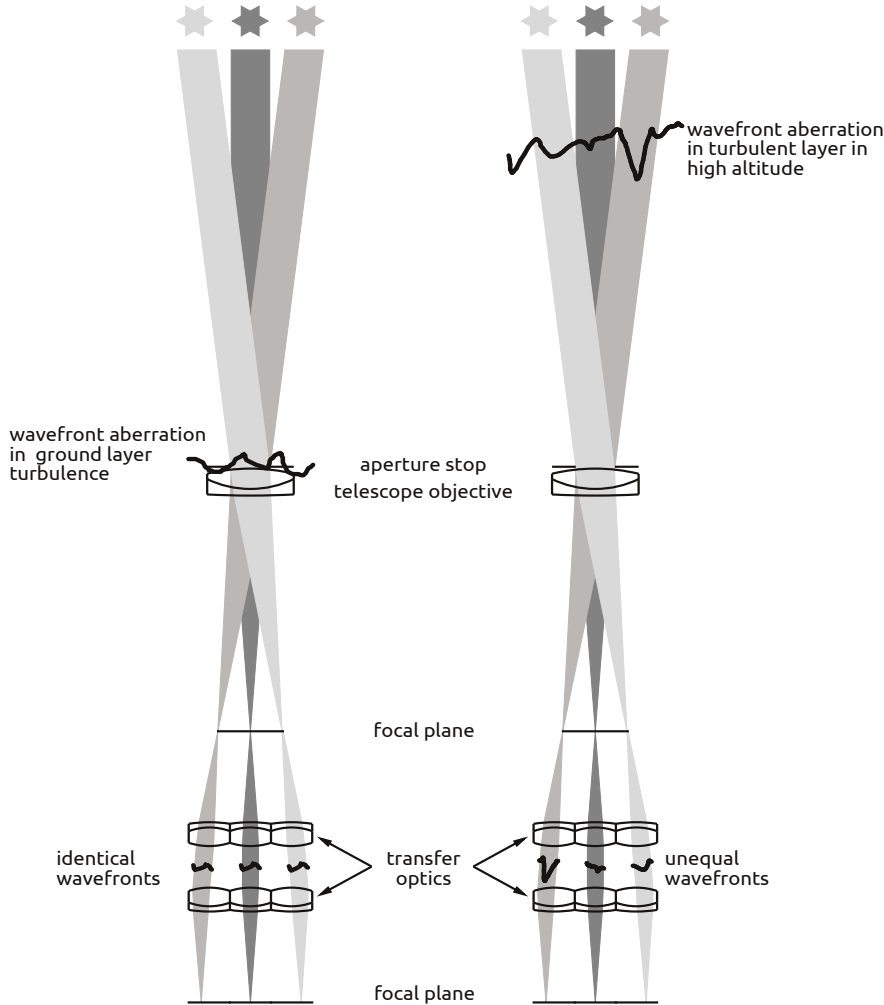
19:31:33 UT

BBSO/NST

atory

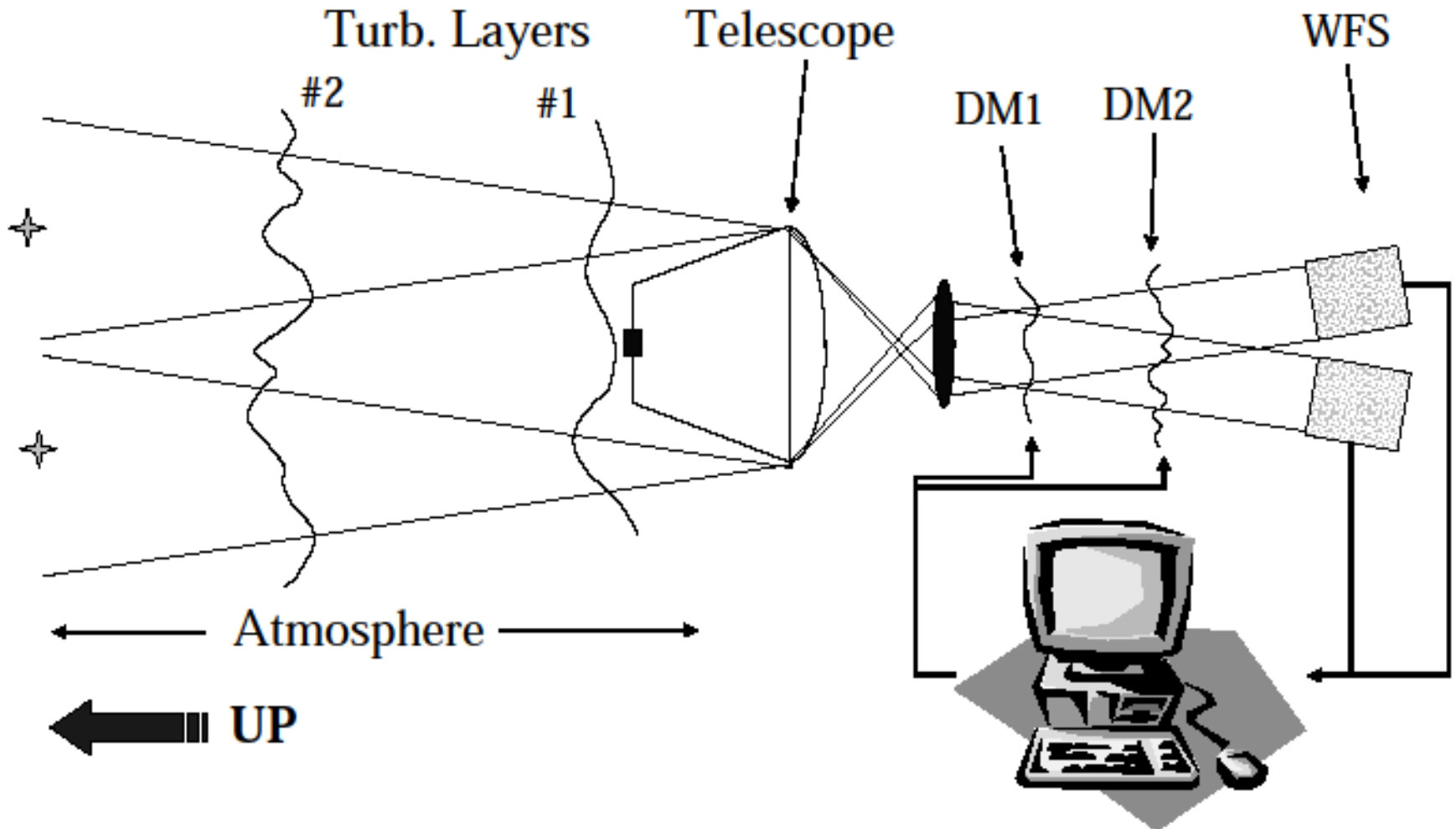


Why Isn't One Adaptive Mirror (DM) Enough?





MCAO Schematic

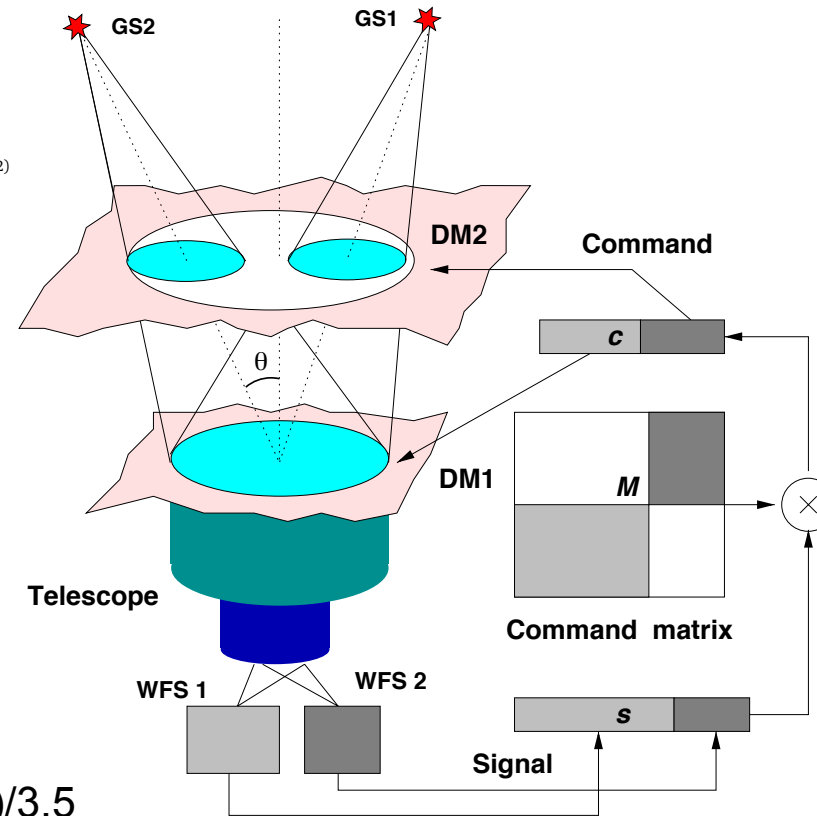
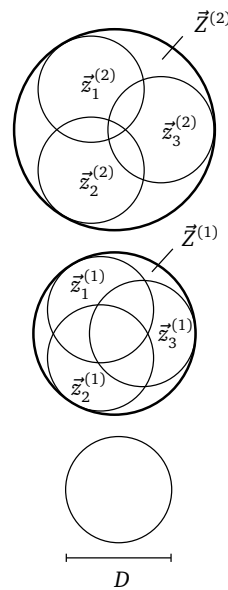
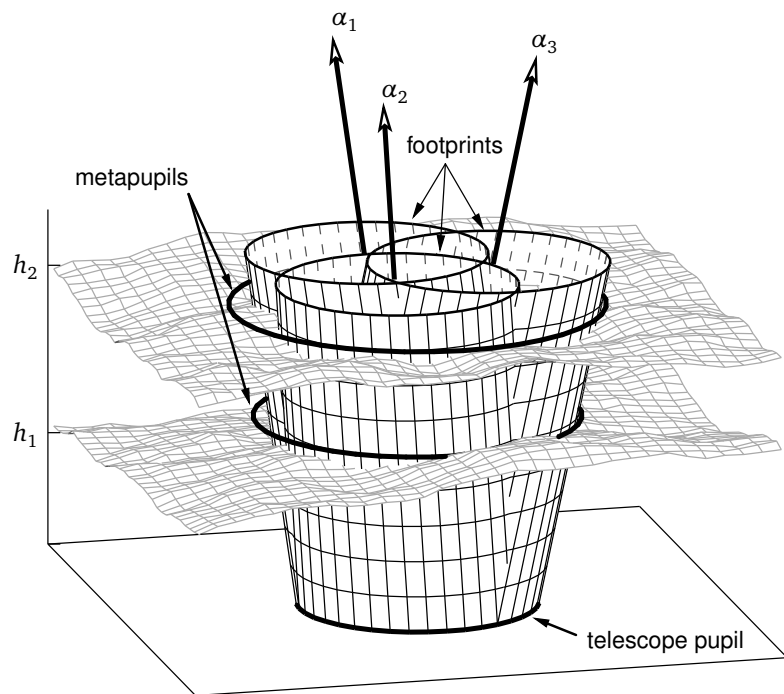




Generic Solar MCAO: WFS, DMs, & Guide Regions

- Why 3 DMs?
 - Rough expectation:
 - One for groundlayer
 - One for transition layer
 - One for jetstream?
- How Many Guide Regions are Required?
 - FOV & location of turbulent layers
 - # of Guide Regions & # of DMs Roughly Related
- WFSs
 - Two at first

How Many Guide Stars Do You Need?

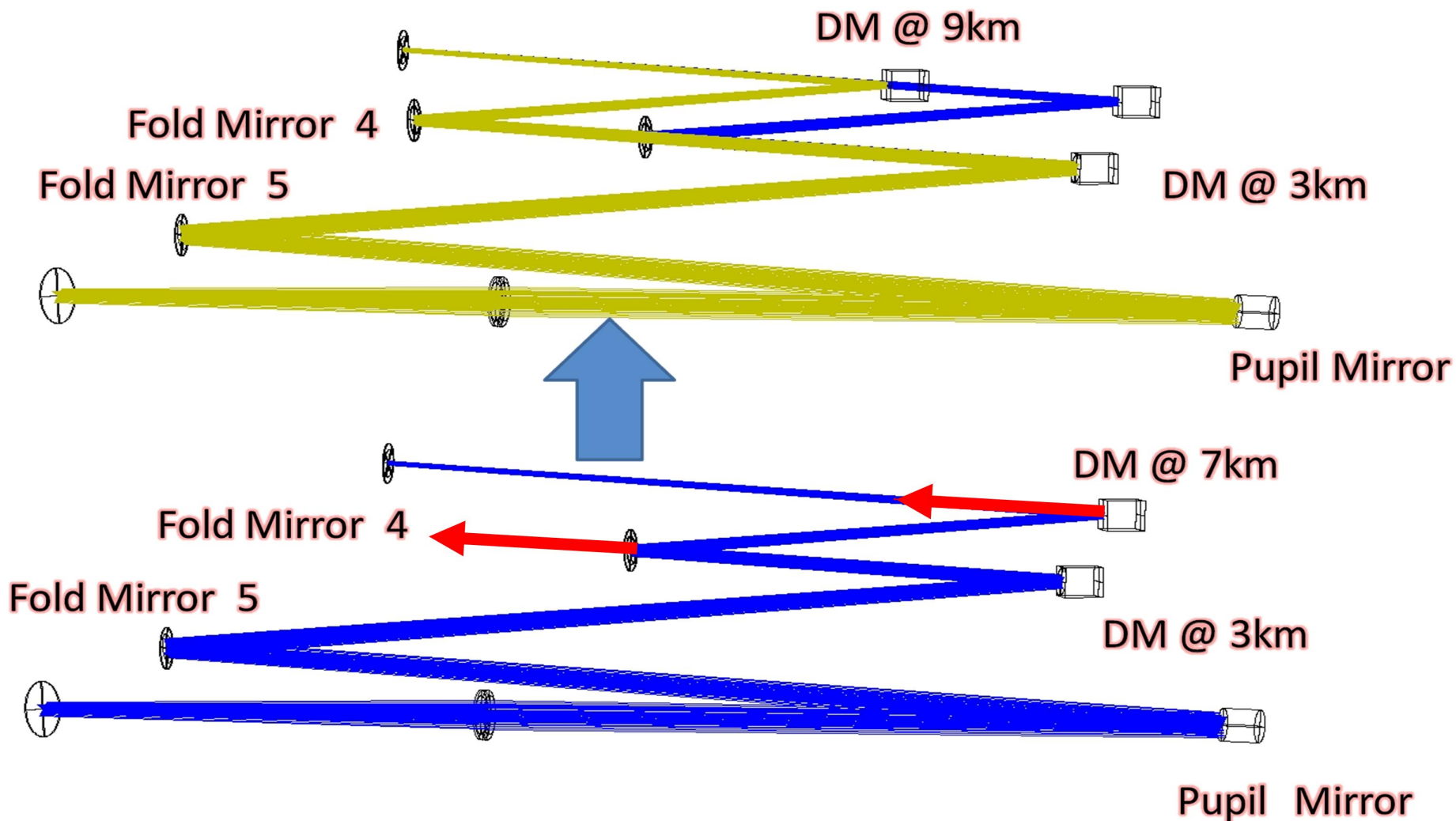


Meta-pupil Diameter = $D + 2\theta H = 1.6 + \theta \text{ (arcsec)}/60 H(\text{km})/3.5$

Setup with WFSs Downstream of DMs



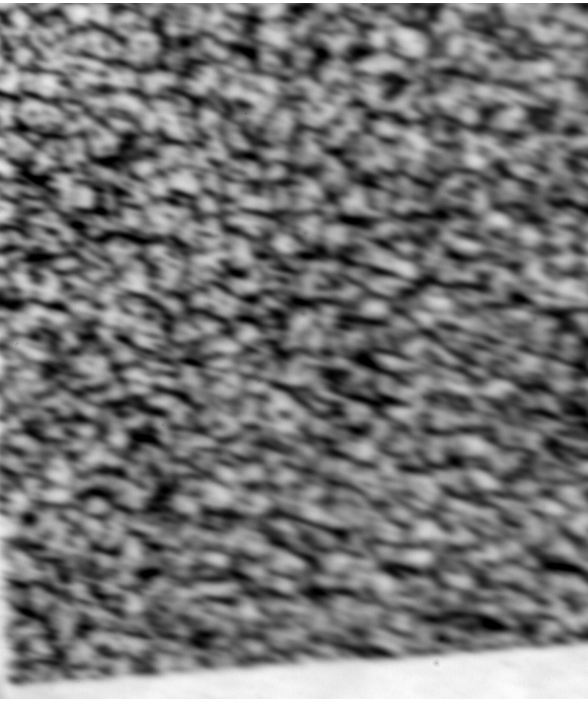
MCAO Design



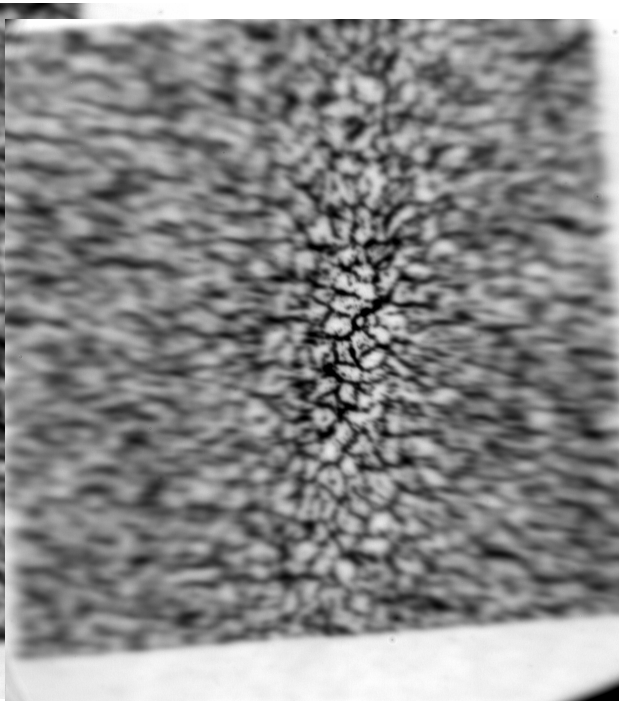
Three Cooktops Randomly Placed in Optical Path



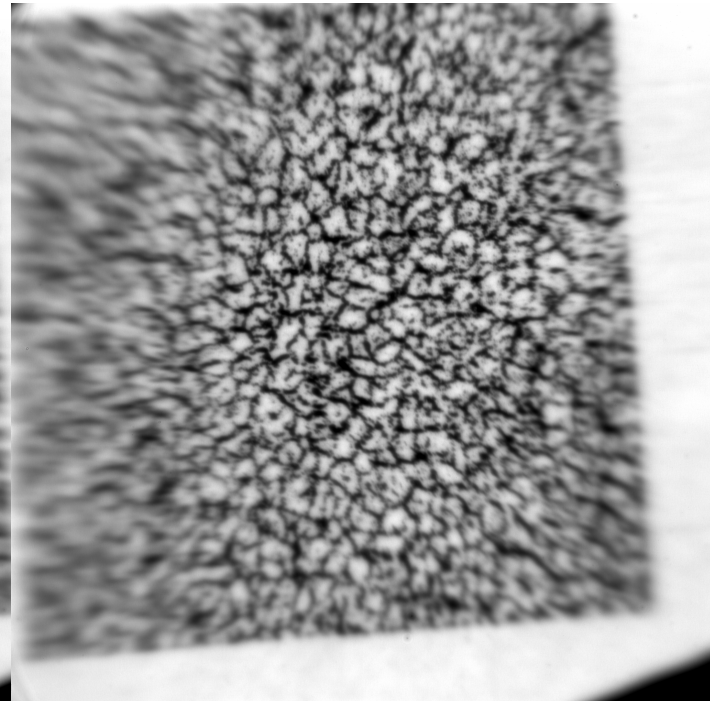
No AO



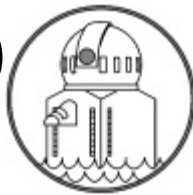
CAO (1DM)



MCAO (3DM)



Narrowing the FOV (Rigaut et al. 2000) from 70''x70'' to 35''x35''



Narrow FOV (θ) & Increase Depth of Field (Δh_{\max})

$$\Delta h_{\max} \text{ (in km)} = 3.6 d_{\text{act}} \text{ (in cm)} / \theta \text{ (in arcsec)}$$

- 35'' FOV, this is approximately $3.6 \times 9 \text{ cm} / 35'' \cong 1 \text{ km}$ for the DM conjugate to the pupil,
- approximately $\pm 2 \text{ km}$ for a DM when conjugate to 3 km,
- and about $\pm 3 \text{ km}$ for a DM in 8 km,
- **Thus, continuously cover the range from 0 to 11 km with the reduced wavefront sensing FOV**

Setup That Worked



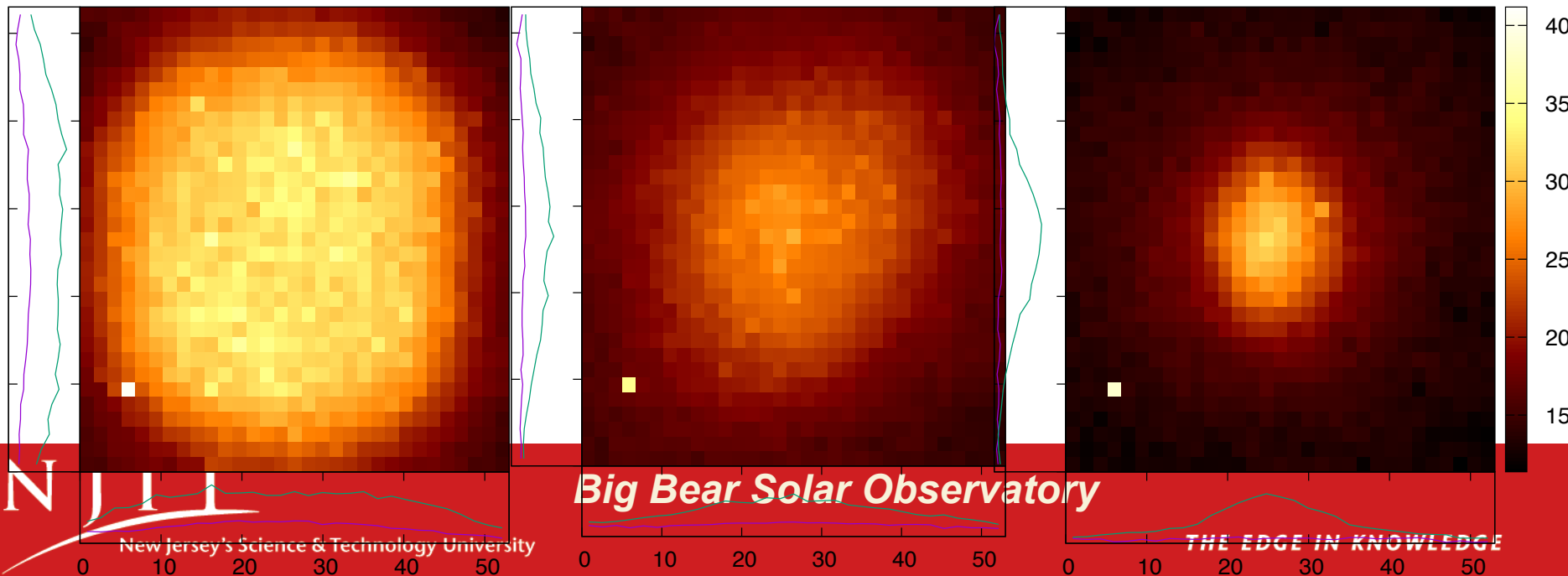
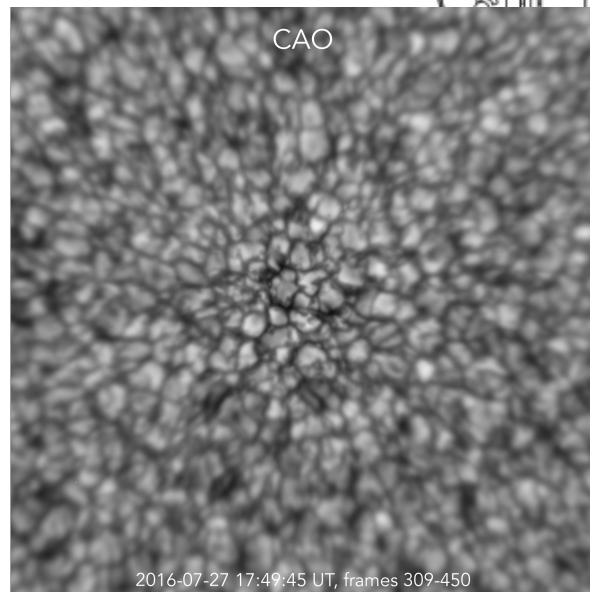
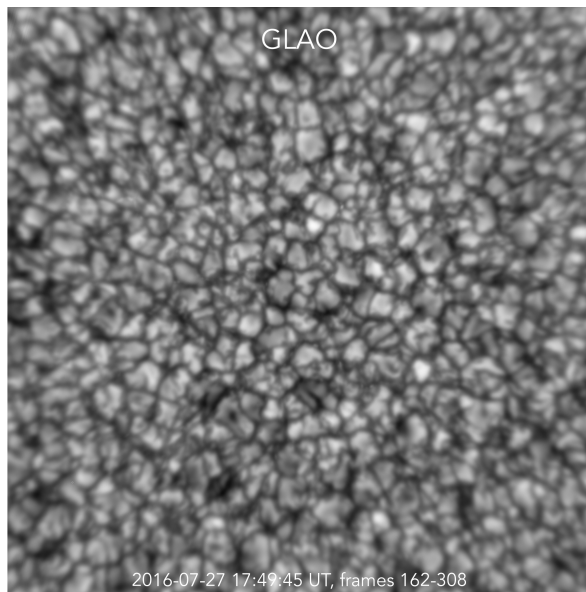
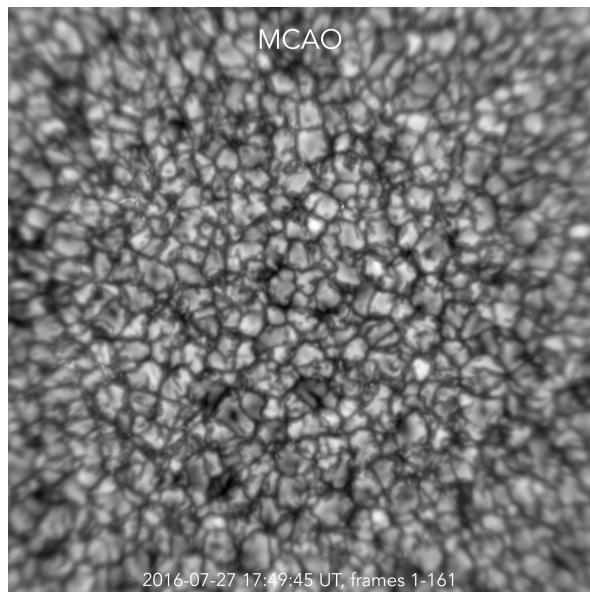
- *Clear Successful MCAO Demonstrator*

- Cut FOV from 70"x70" to 35"x35"
 - Narrow FOV to increase Depth of Field (Depth inverse to FOV)
 - Conjugated DMs to 0, 3 & 8 km – covers 0-11 km (0-1, 1-5, 5-11 km resp.)
 - 9(3x3 over field) Guide Regions (analogous to nighttime guide stars)
- New MD-WFS Camera
 - 208 (16 across diameter, 8.8 cm) subapertures, each with 3x3 guide regions
 - Camera 992x992 px able to read 208 @ 1600 fps (but limited to 1000 Hz by control computer)
- MCAO Light Feed
 - Highest conjugated DM to Mid-DM to Pupil DM to WFS
 - Same order as is Gemini South (two DMS & 3 Natural/5 Laser Guide Stars)
- “Science Camera”: PCO.2000 (2Kx2K) 15 frames/s
- 3DMs better than 2 DMs

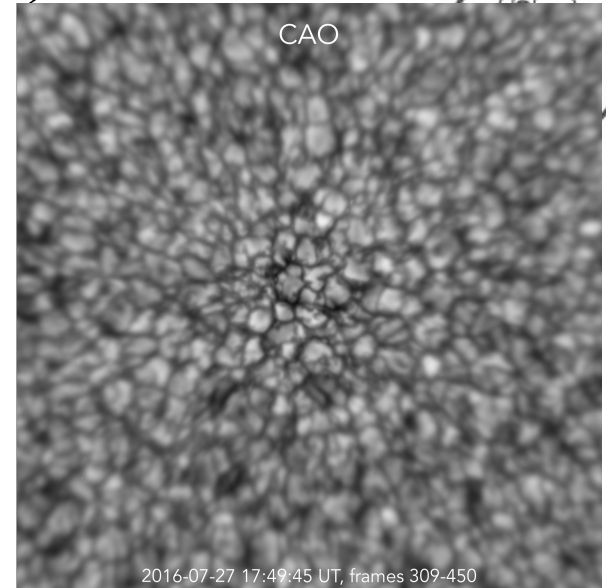
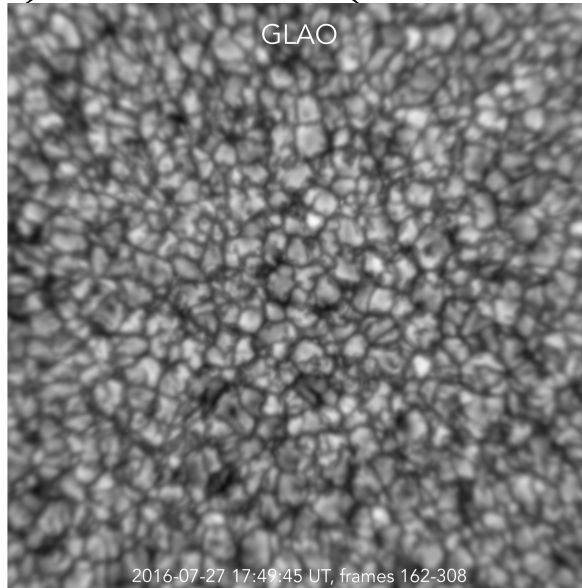
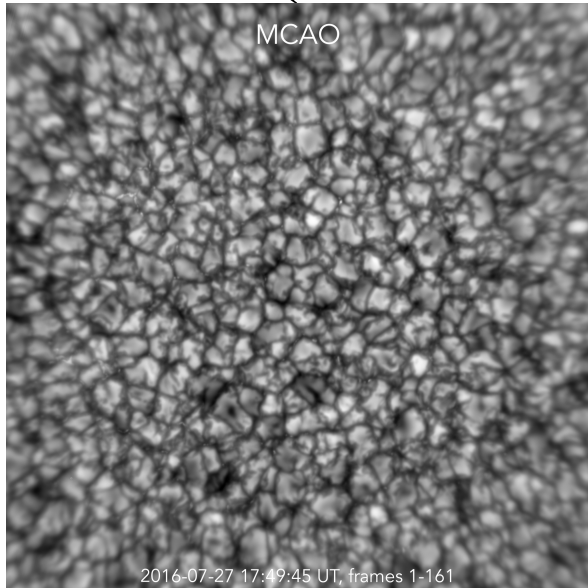
MCAO (53''x53'')

GLAO (7/27/16)

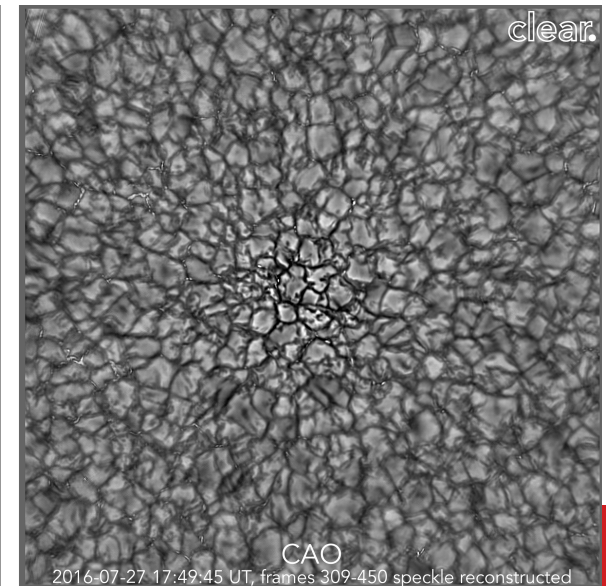
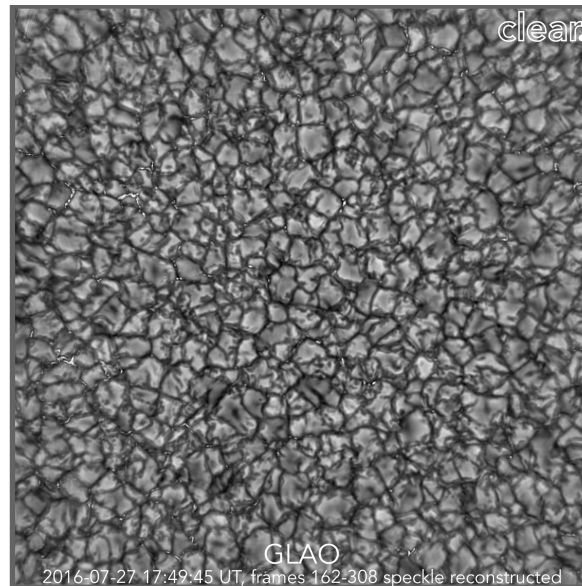
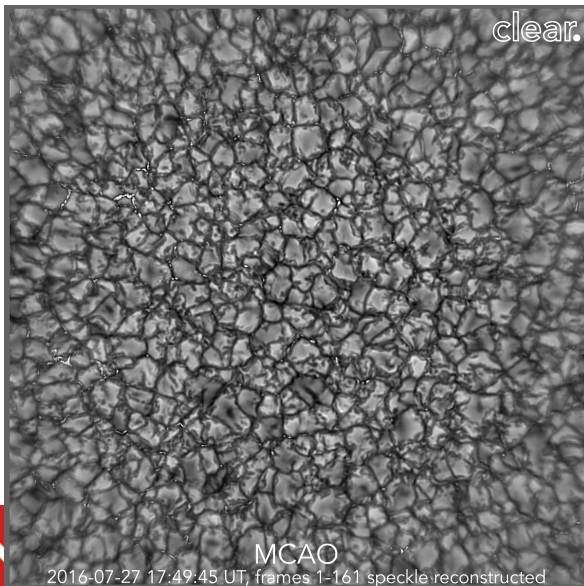
CAO

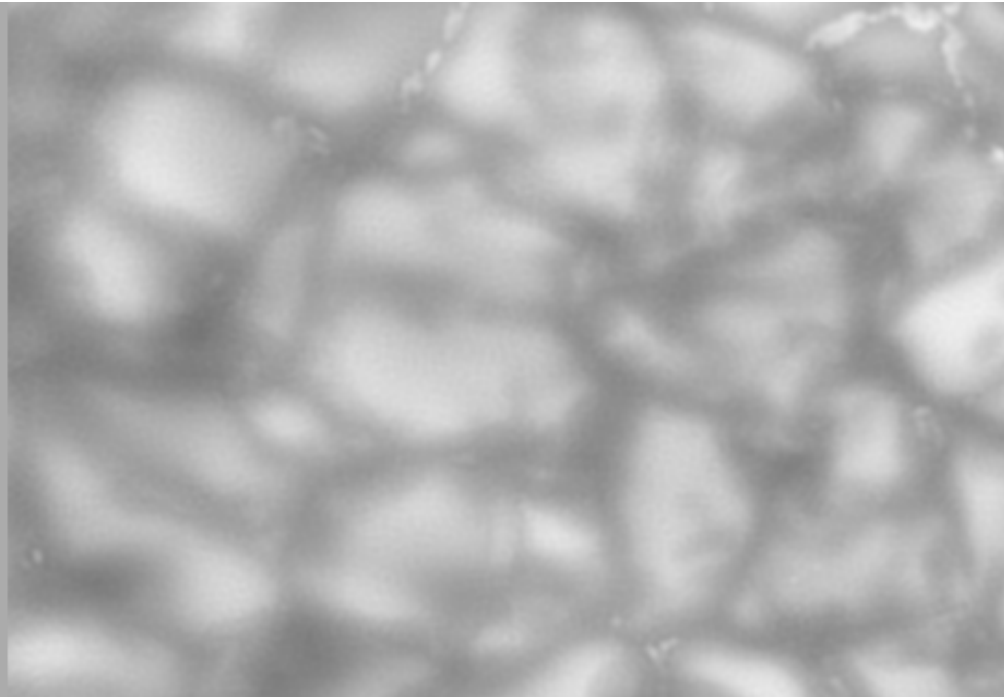


MCAO (53" x 53") GLAO (7/27/16) CAO



Above: Sum of from Images Burst; Below: Speckle Reconstructed Bursts





Upper Left
Corner of MCAO
Reconstructed



vs.

MCAO Summed

7/27/16 TiO
~15''x10''

G-Band (430.5 nm) 53''x53'' FOV



MCAO

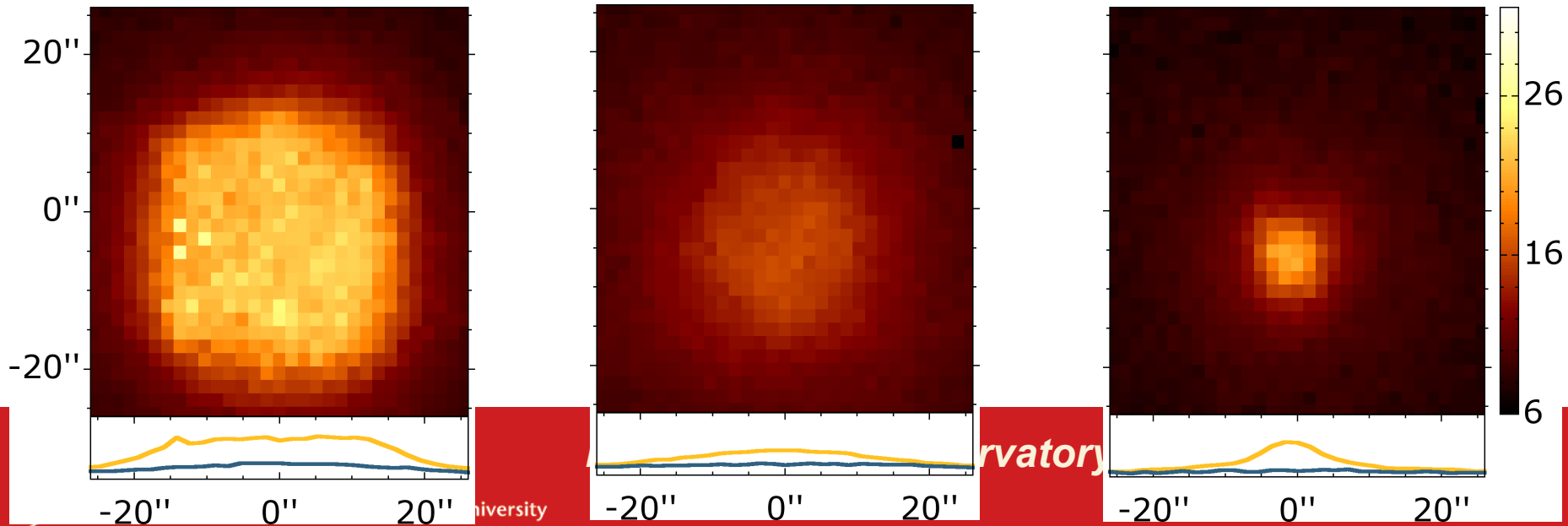
GLAO

CAO

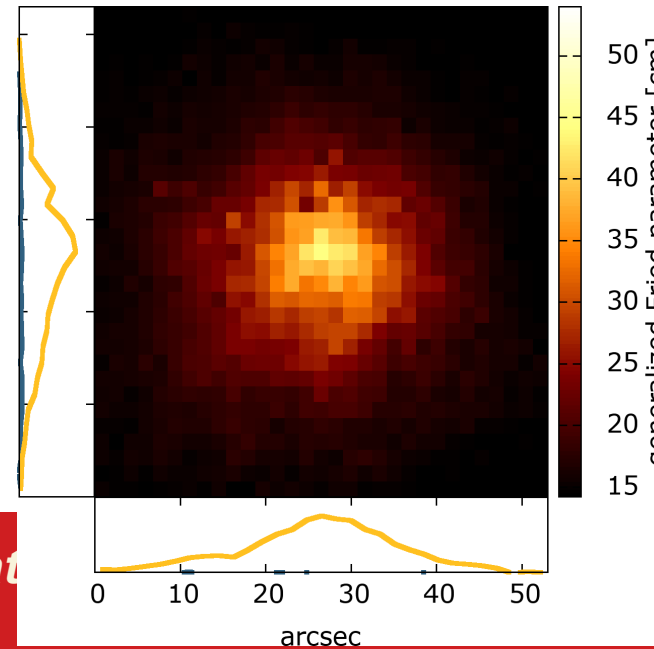
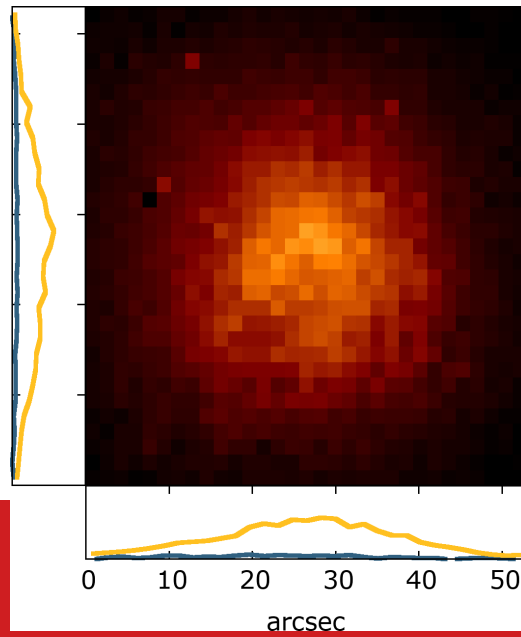
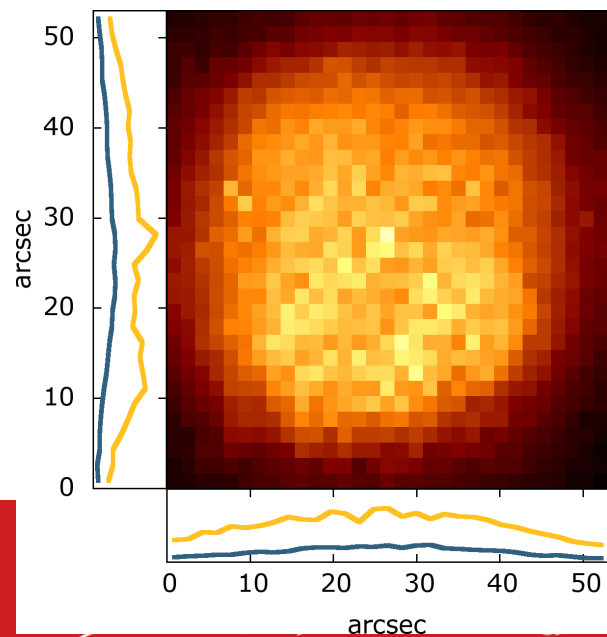
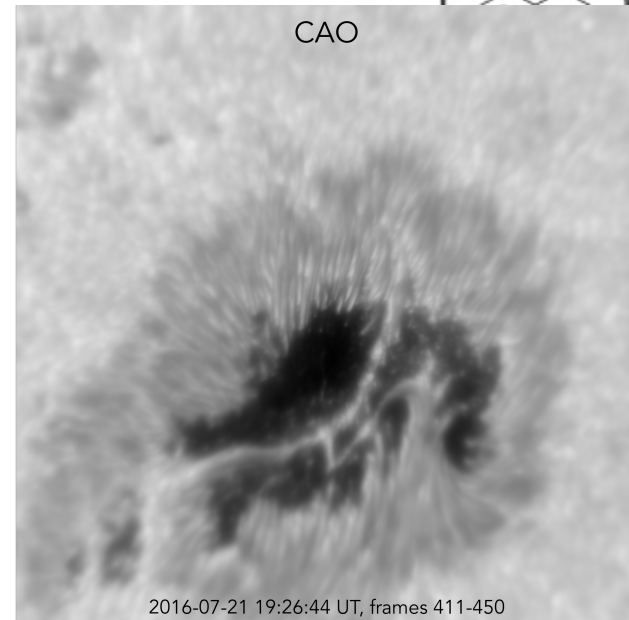
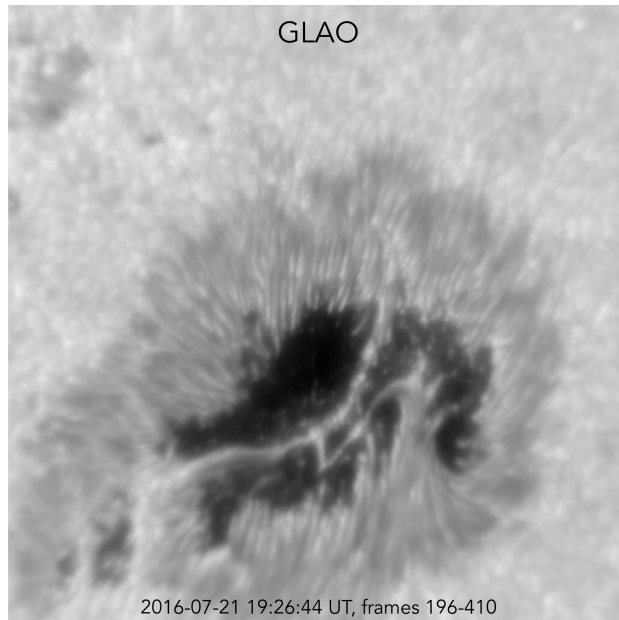
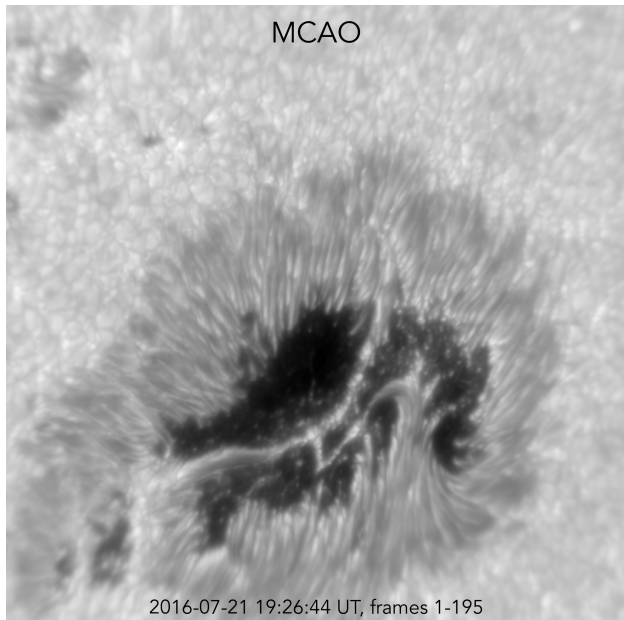
2016-07-25 19:47:05 UT, frames 1-162

2016-07-25 19:47:05 UT, frames 163-311

2016-07-25 19:47:05 UT, frames 312-450

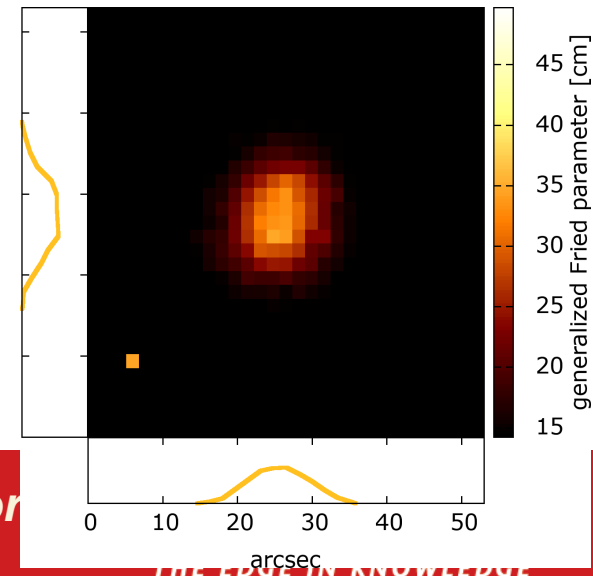
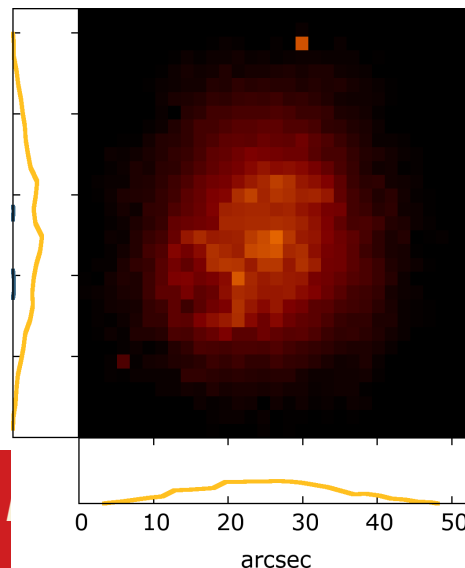
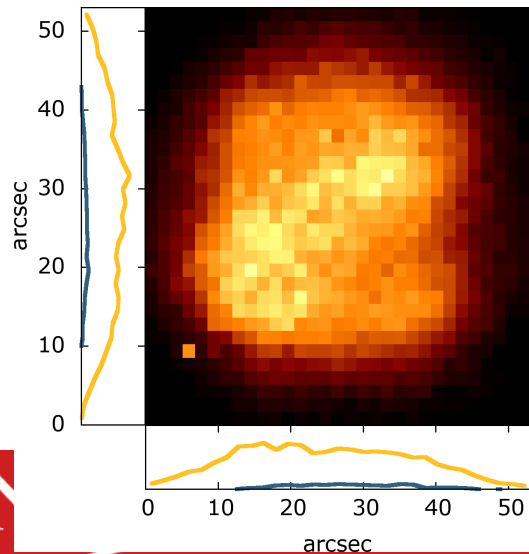
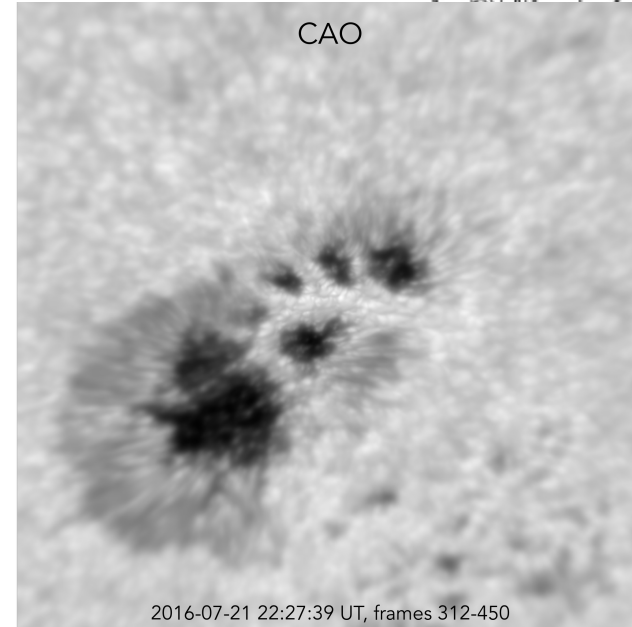
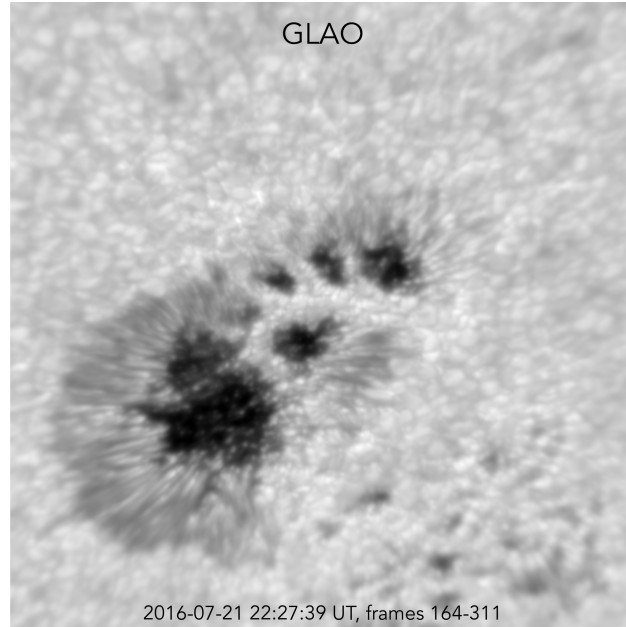
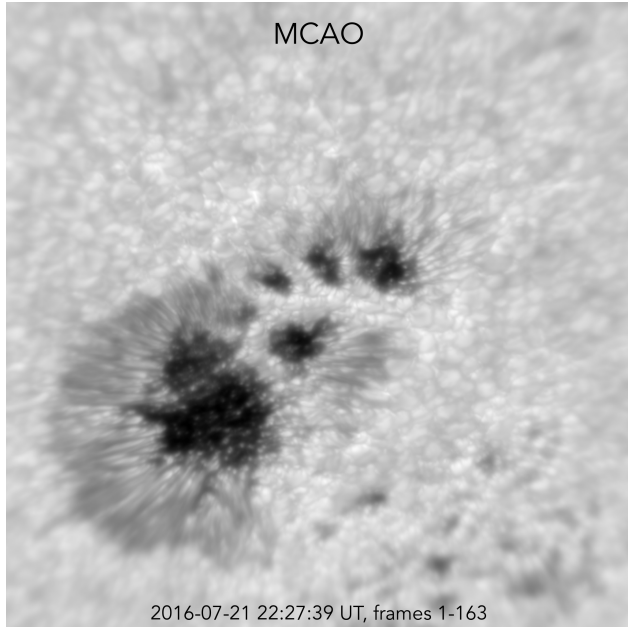


Sunspot 7/21 & Fried Parameter



vat

7/21 Another Sunspot 3 Hours Later



0.7 μm

Vs.

1.56 μm

-- Trial

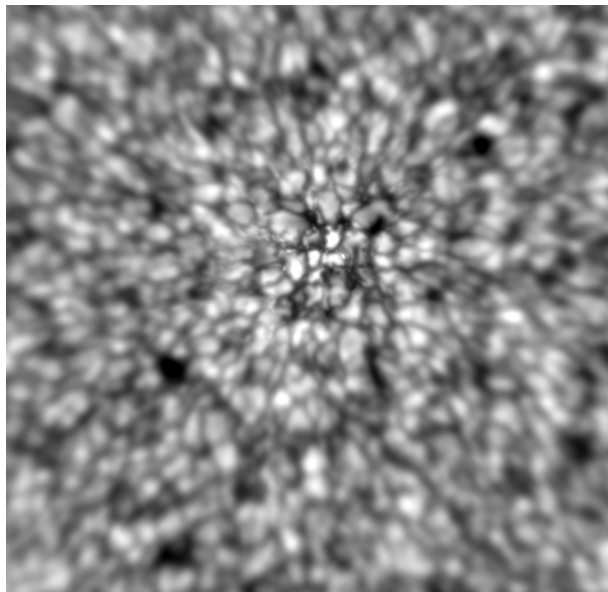
Run

Data

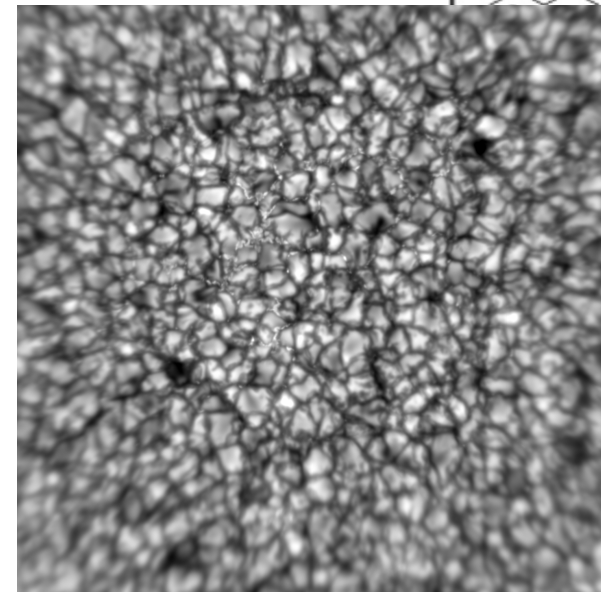
from

10/26/17

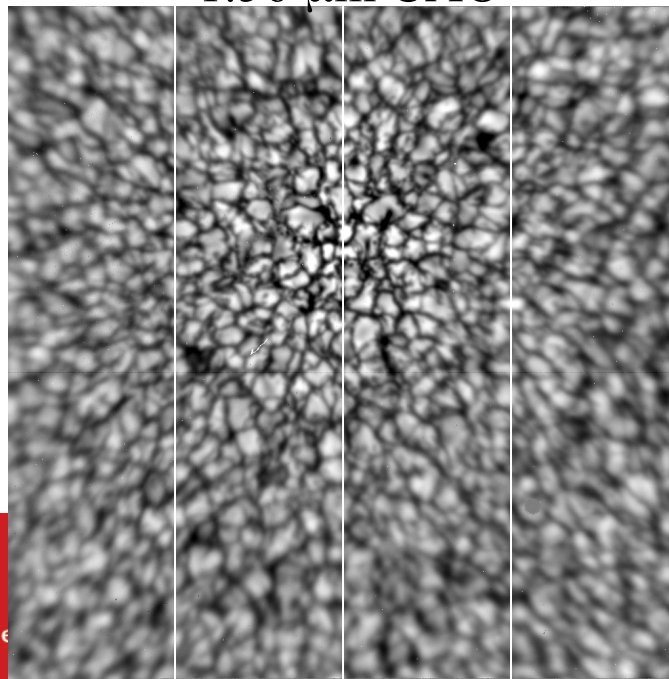
0.7 μm CAO



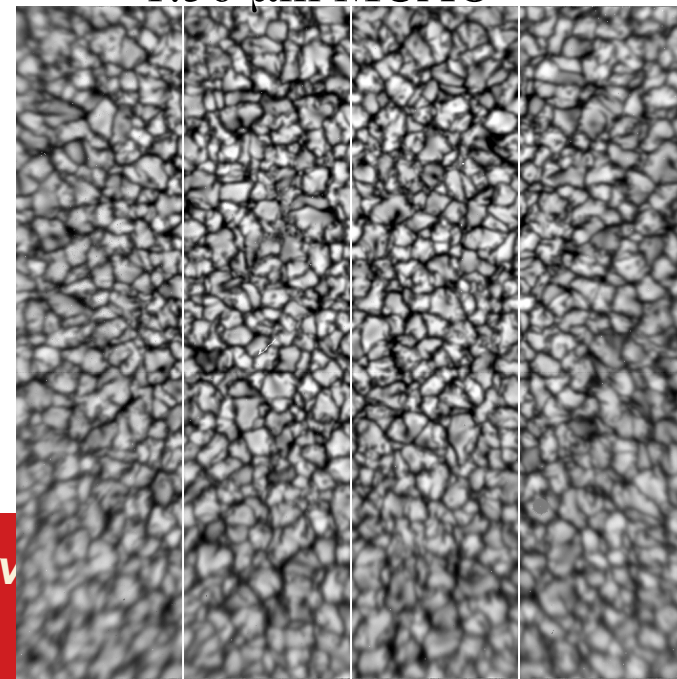
0.7 μm MCAO



1.56 μm CAO



1.56 μm MCAO



What Next?



- Feed current MCAO setup to BBSO spectro-polarimeters for origins of space weather studies
 - Lead in to Prof. Vasyl Yurchyshyn's Talk

! n i F



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