Advancements in Wide-field Adaptive Optics for Observations of the Sun

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clear.

1) National Solar Observatory / DKIST Daniel K. Inouye Solar Telescope

2) NJIT New Jersey's Science & Technology University

3) KIS Kiepenheuer-Institut für Sonnenphysik

supported by the National Science Foundation

Post-doc position

at NSO in Boulder, CO

Adaptive Optics

for

Solar Prominences

and wide-field AO topics

see me for details

image captured at
Dunn Solar Telescope,
speckle reconstructed
by F. Wöger, NSO

nso.edu/jobs

NSO
National Solar Observatory

DKIST
DANIEL K. INOUYE SOLAR TELESCOPE

Classical AO vs. MCAO

3 DMs
0, 3, 8 km

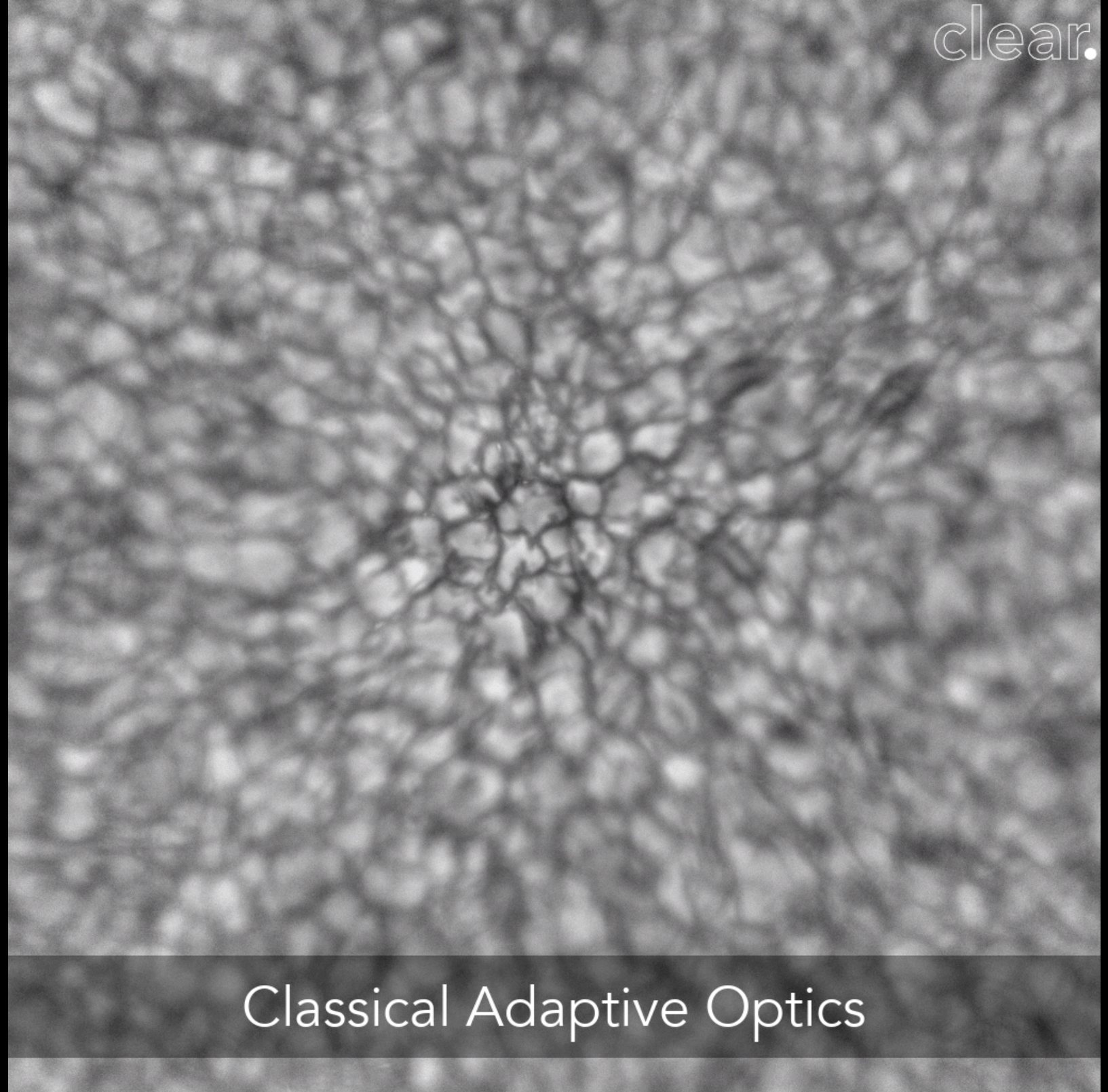
53 arcsec wide

real time movie

no image reconstruction

Titanium-oxide filter
(705.7 ± 5 nm)

Clear on the
New Solar Telescope at
Big Bear Solar Observatory
July 27, 2016



movie available at
http://tinyurl.com/yalx7hog

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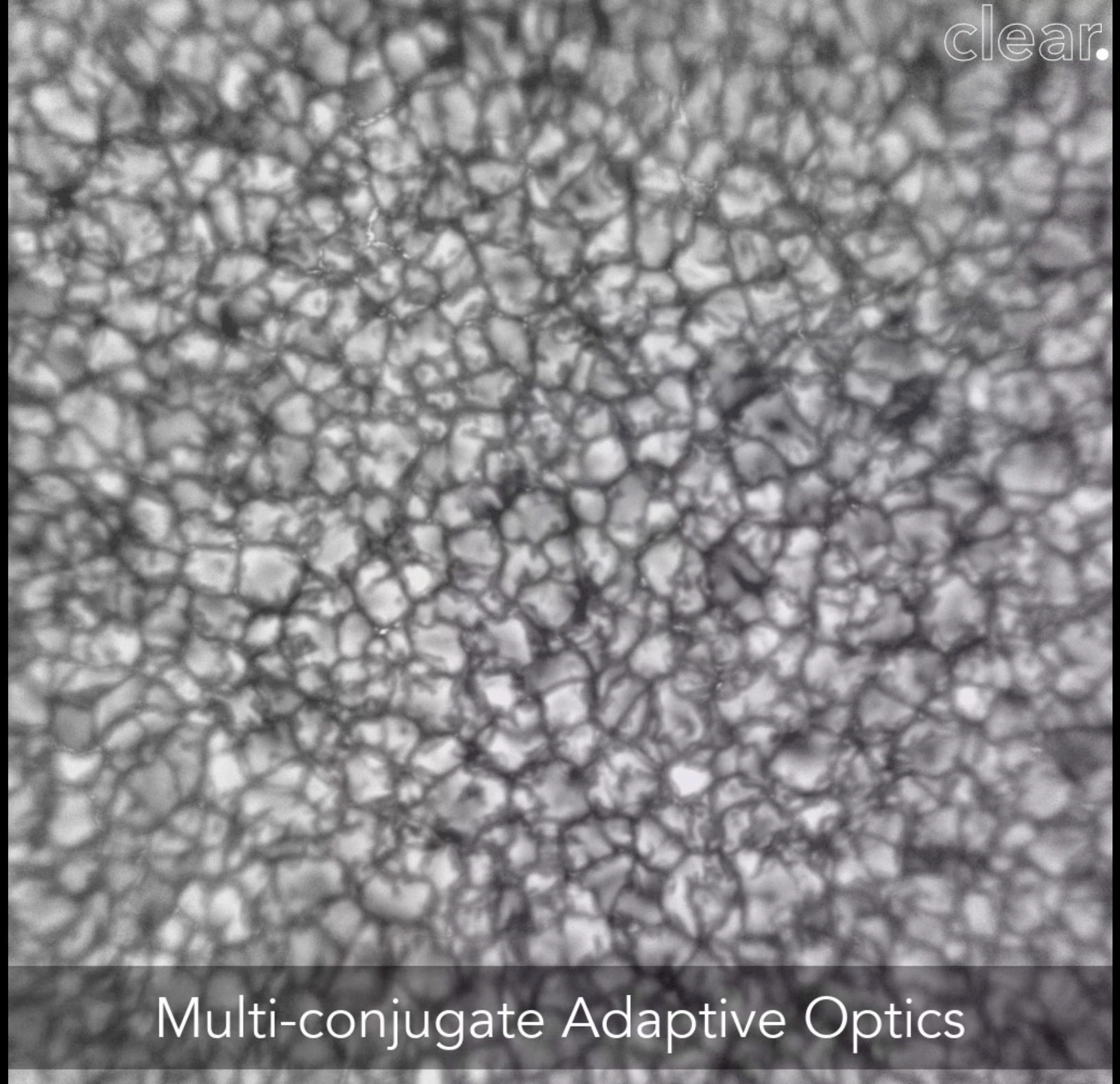

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Classical AO vs. GLAO

53 arcsec wide

real time movie

no image reconstruction

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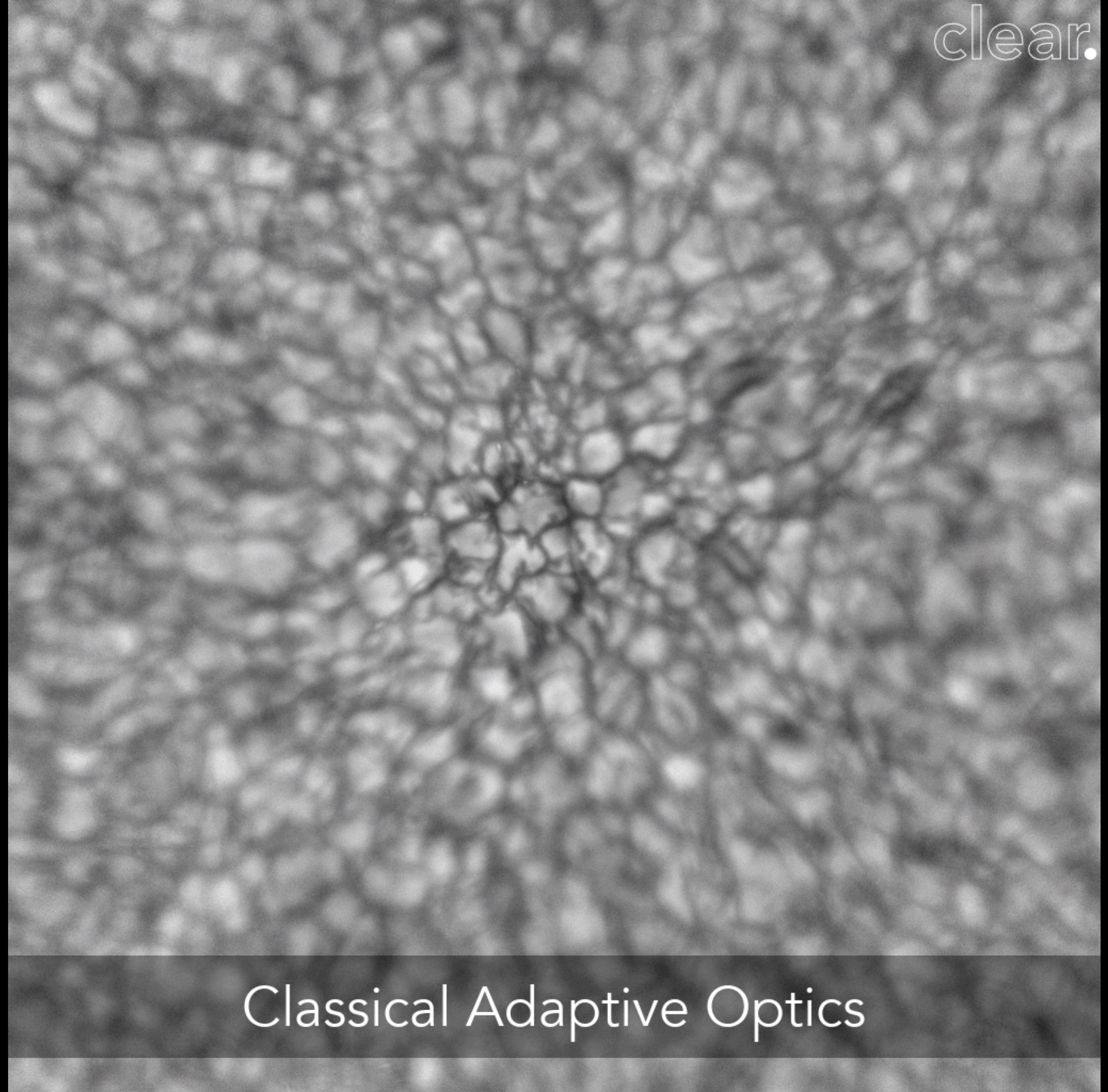

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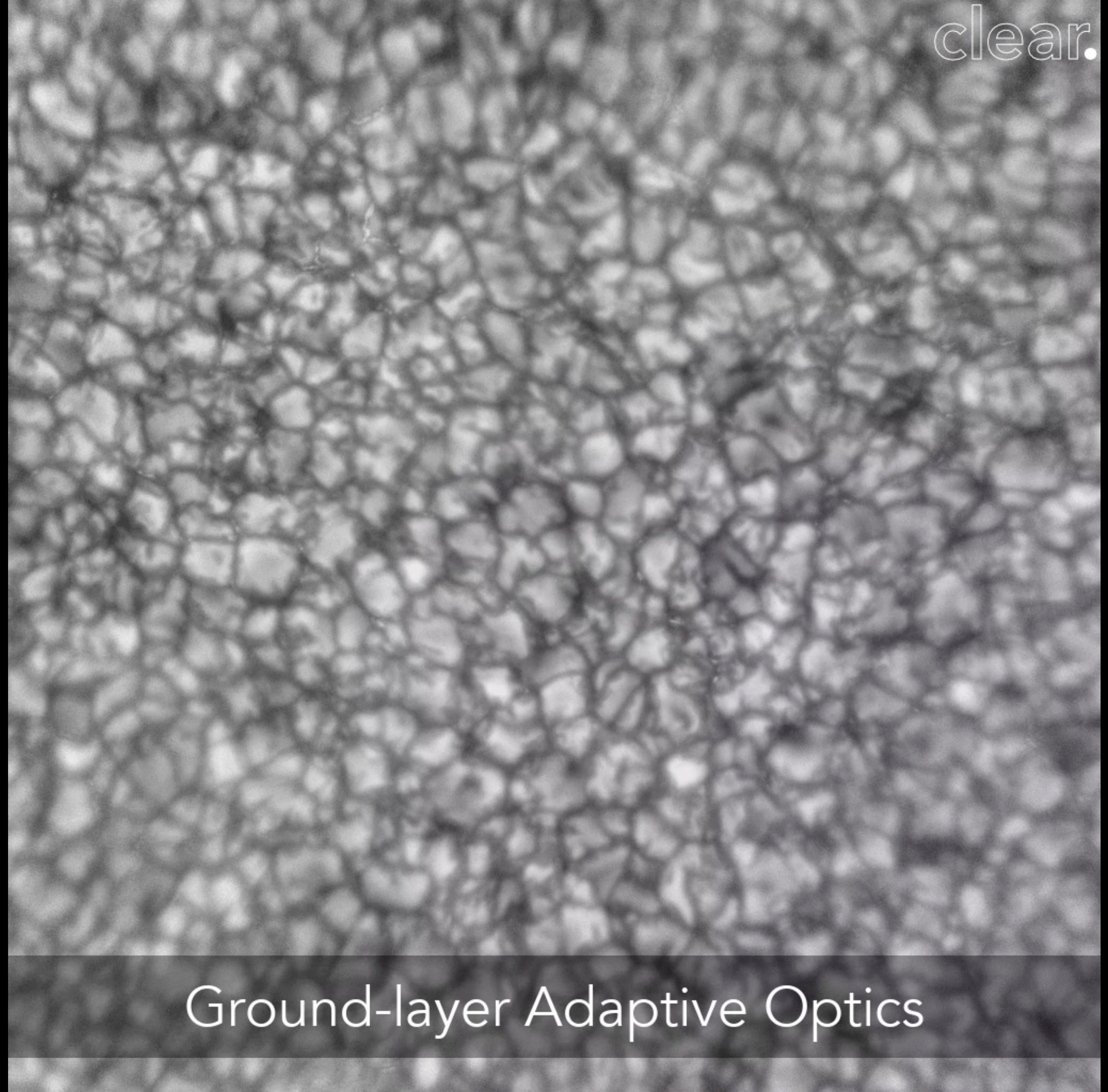

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MCAO at NST: How can we make MCAO for the Sun really work?

Clear: experimental wide-field AO pathfinder for DKIST

The New Solar Telescope of NJIT's Big Bear Solar Observatory

- 1.6 m clear aperture, off-axis primary mirror (DKIST's little brother)
- highest-resolving solar telescope today
- to be renamed **Goode Solar Telescope** in July during the next MCAO run

MCAO project

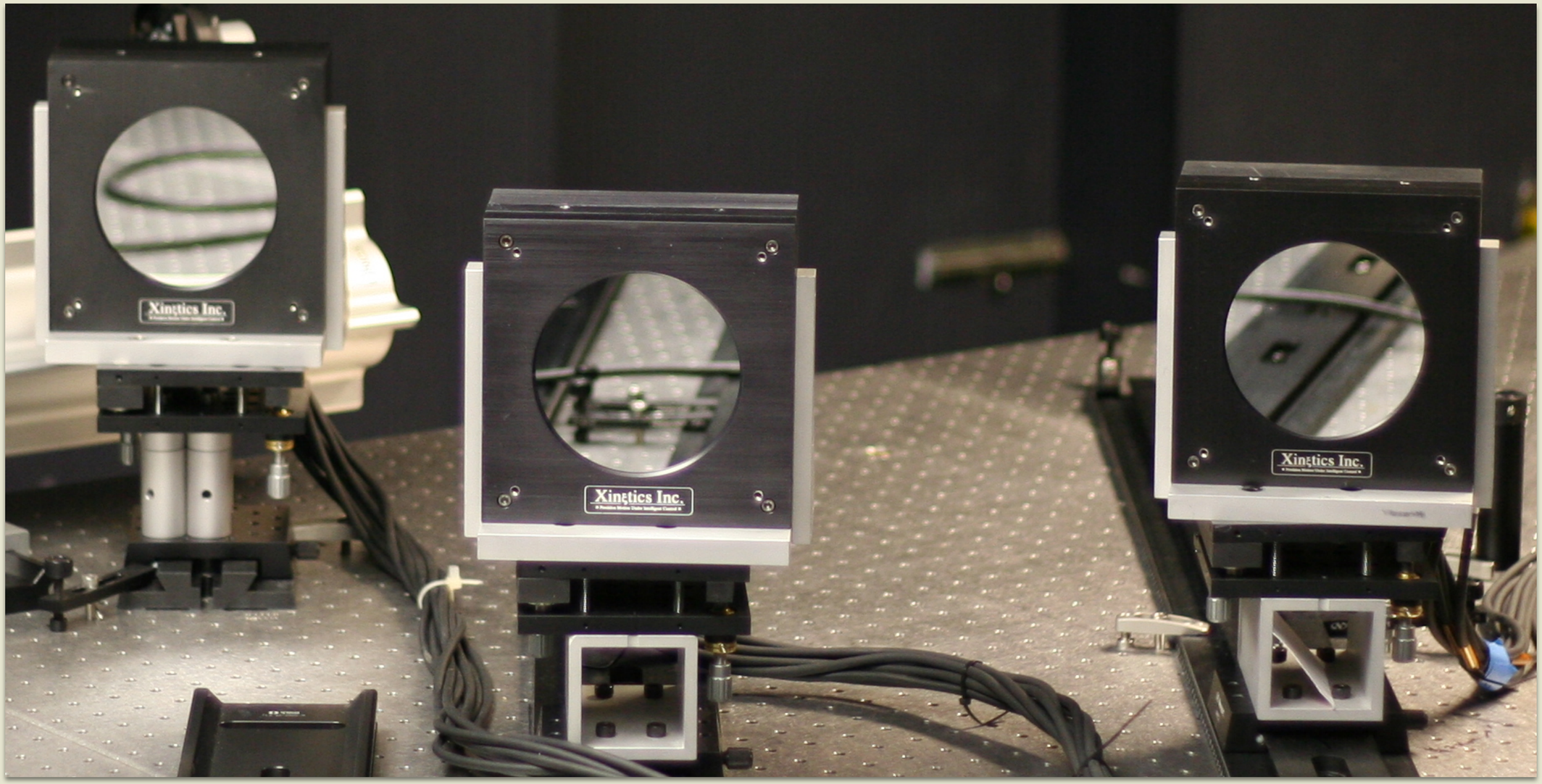
- following-up pioneering MCAO experiments at KIS's VTT and NSO's DST in mid 2000's
- 2011–2012: turbulence profiling
- 2013: from design to first MCAO lock
- since 2014: about 30 days each year operation as experimental pathfinder
- 2016: given the name **Clear** (not an acronym :-)

The *still* New Solar Telescope in Big Bear Lake, California (100 km north of Palomar)

clear.

The backbone of Clear

a highly motivated and well attuned team



The backbone of Clear

a highly motivated and well attuned team

NJIT New Jersey's Science & Technology University

P. Goode	N. Gorceix	J. Nenow	E. Norro	S. Shumko	C. Plymate	J. Varsik	W. Cao
PI	optical engineer	mech. engineer	admin	camera engineer	NST operator	NST operator	Co-Pi

NSO

KIS Kiepenheuer-Institut für Sonnenphysik

former members (NJIT)

D. Schmidt	J. Marino	T. Rimmele	T. Berkefeld	O. v.d. Lühe	X. Zhang	R. Coulter	A. Kellerer
AO / Co-PI	AO / Co-PI	AO / Co-PI	adaptive optics	project partner	opt. engineer	mech. engineer	turb. profiling

„How can we make MCAO for the Sun really work?“

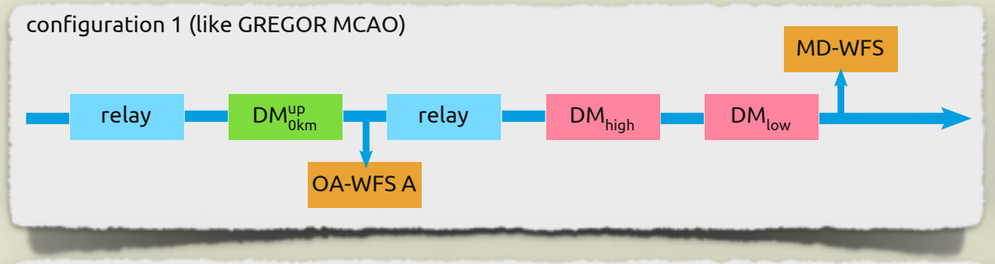
Let's find out…

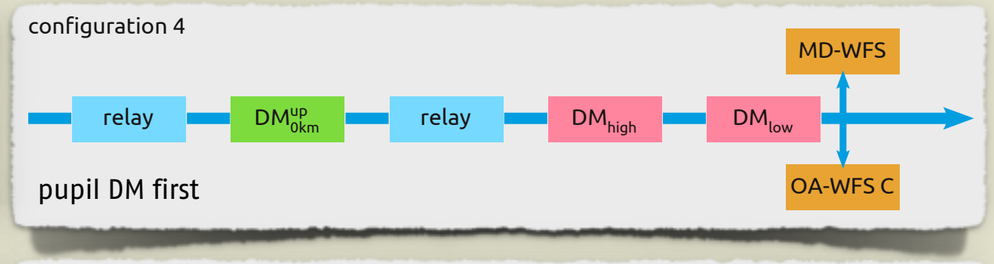
- Build the most **flexible** pathfinder system we possibly can
- **Test** and **compare any** previously implemented approach and feasible proposed **ideas**
- Be **prepared** to implement **new** ideas and **learn** as we go

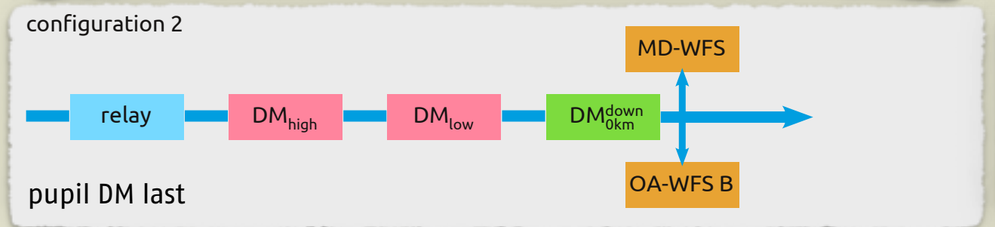
- **Genetic development**
  - **move on quickly** to the next approach if we don't see a *clear* effect
  - **no** premature local **micro-optimizations**
  - **make big**, fundamental **changes** in the setup

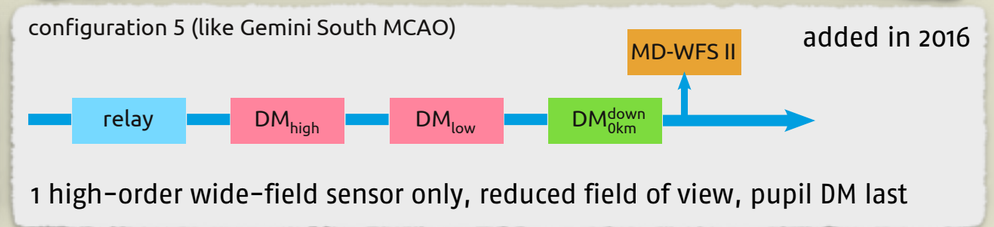
Clear

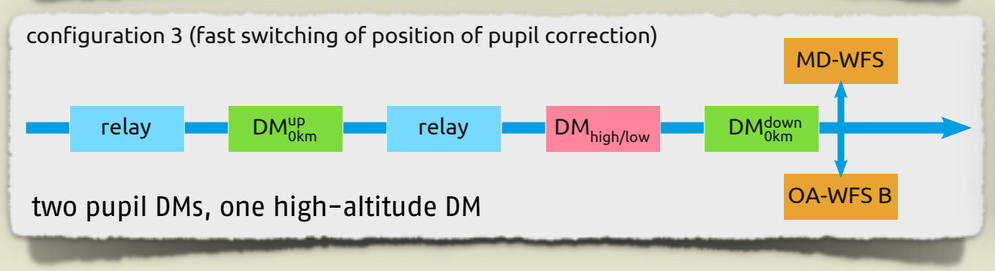
a multi-configuration multi-conjugate adaptive optics system with 3 DMs

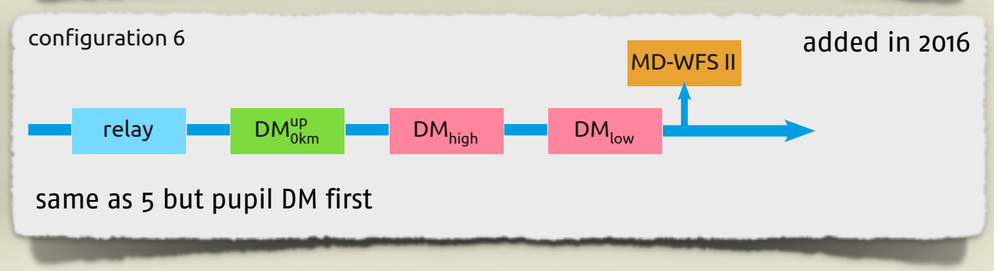












3 identical Xinetics DMs:
357 actuators each
(some not illuminated)
4 nm RMS best flat

- **3 different wavefront sensing schemes:** which works best? any which doesn't?
- **2 pupil images for deformable mirror:** before / after high-altitude DMs
  - relevance of correction sequence and dynamic misregistration?
- **adjustable conjugates of high-altitude DMs** between 2–8 km
- **flexible control software:** re-using and advancing KAOS (originally developed for GREGOR's AO/MCAO)

clear.

focus

pupil stop

OA-WFS A

OA-WFS B
(now SLODAR-WFS)

MD-WFS II

clear.

DM_{high}

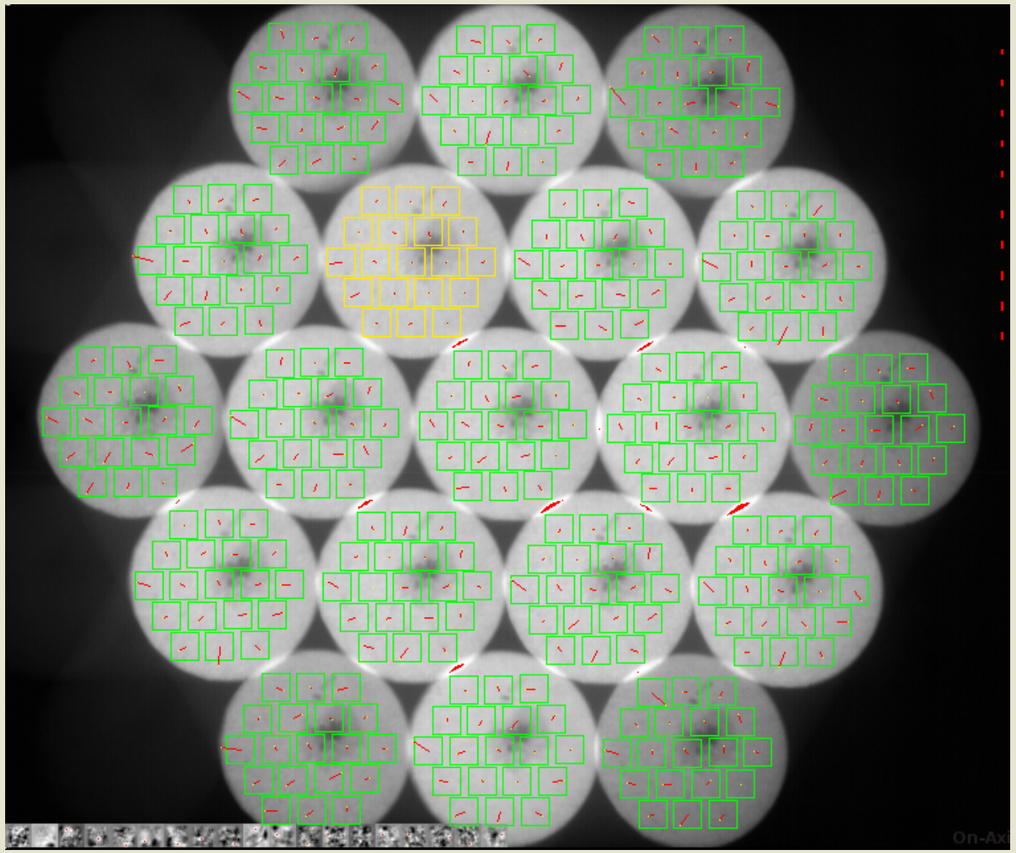
DM_{low}

$DM_{pup,\ after}$

Wavefront sensors in configurations 1-4 (2013-2015)

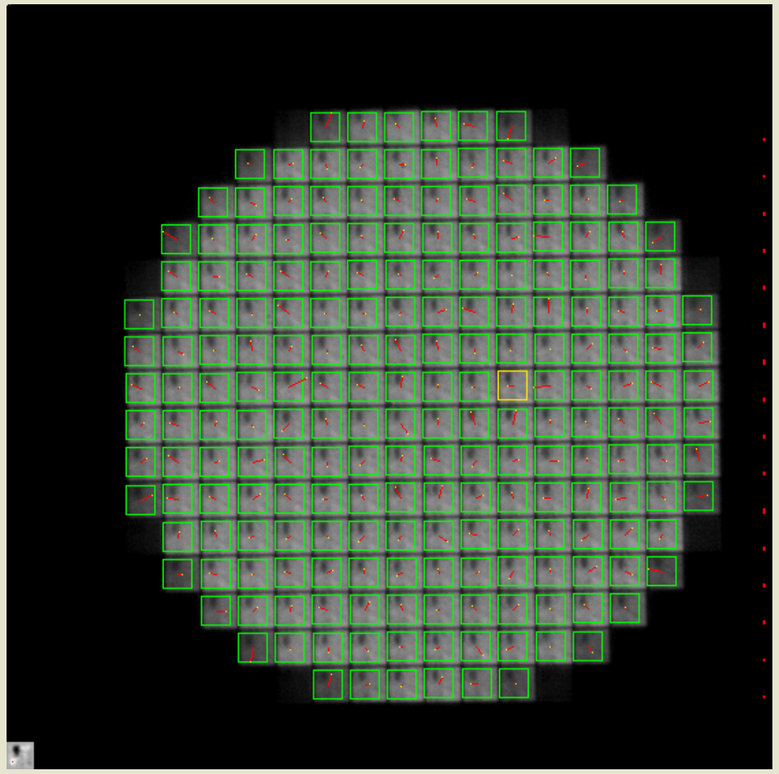
1 low-order multi-directional + 1 high-order on-axis sensor

Multi-Direction WFS



19 subapertures
70 arcsec
19 guide regions (10 arcsec each)

On-Axis WFS B



208 subapertures
10 arcsec
1 guide region

569 image correlations
1800 fps in this configuration

Advancement in camera interfacing

CoaXPress has brought 25 Gbit/sec to the market

CAMERA Link

up to 850 MB/sec

Mikrotron EoSens 3CL
used in MD-WFS
available since 2010
850 MB/sec link speed
760 × 640 Px: 1473 fps
(990 × 992 Px: 737 fps)

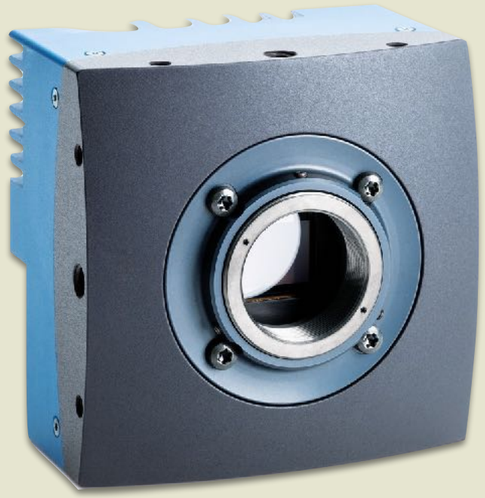
Mikrotron EoSens CL
used in On-Axis WFS
available since 2009
750 MB/sec link speed
440 × 440 Px: 2606 fps
(990 × 992 Px: 645 fps)

CoaXPress®

up to 3.125 GB/sec

Mikrotron EoSens 3CXP
received in Q2/2015
sensor of EoSens 3CL
2.5 GB/sec link speed
992 × 992 Px : 1567 fps

Intended use before A04ELT4:
more subapertures in MD-WFS,
maybe finer sampling, and/or
faster frame rate



source of max. frame rates: Mikrotron GmbH

Situation at AO4ELT4, Oct 2015

Significant is not significant enough, we need to do better

Where we were
- MCAO worked well for cooktop turbulence and lab target
- MCAO effect is „significant“ (statistically) on sky
- MCAO effect is not „significant“ (not *easily* visible) on sky
- only low-order GLAO mode capability

What we had
- the **new camera** with 1.5 GPx/sec
- **WFS redesign** in the budget plan
- advise: ***„correct in a smaller field of view!“*** (Rigaut and others)
  - less sensitive to spread-out turbulence

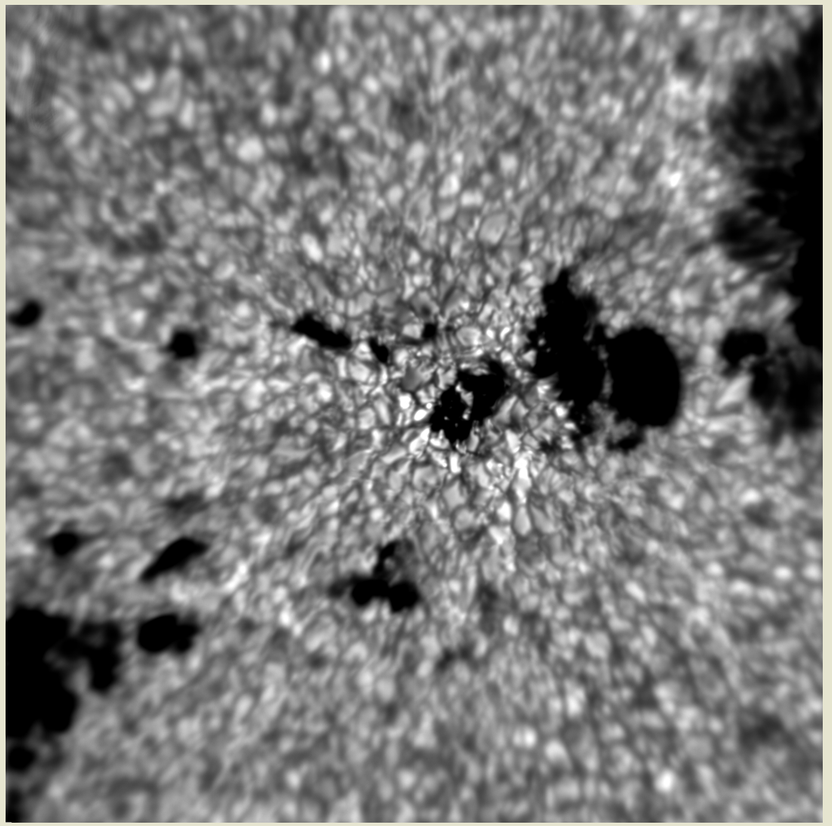
$$\text{DM range} = \pm 1.75 \times \frac{\text{actuator spacing}}{\text{field of view}}$$

[Rigaut et al., SPIE 2000]

- some discussions to surrender field of view

What we could do with a smaller field of view and the faster camera
- build a **high-order wide-field** wavefront sensor

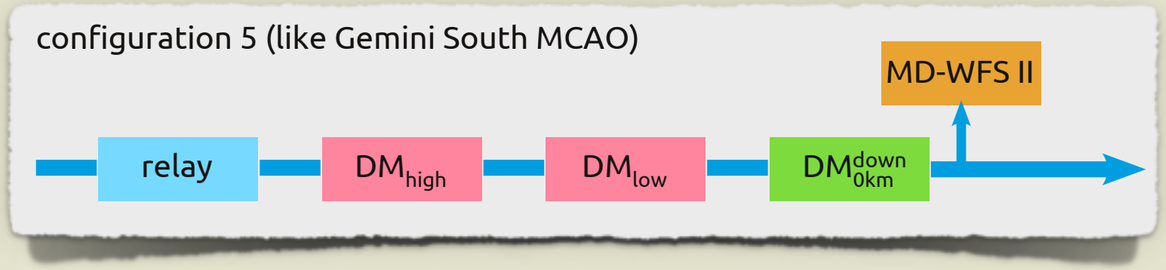
classical AO vs. multi-conjugate AO



averages of 400 frames each, 70 arcsec
DMs @ 0 km and 2.4 km
Sept 29, 2015 19:42:09

Wavefront sensors in configurations 5-6 (2016-...)

1 high-order multi-directional sensor only, no separate on-axis WFS anymore

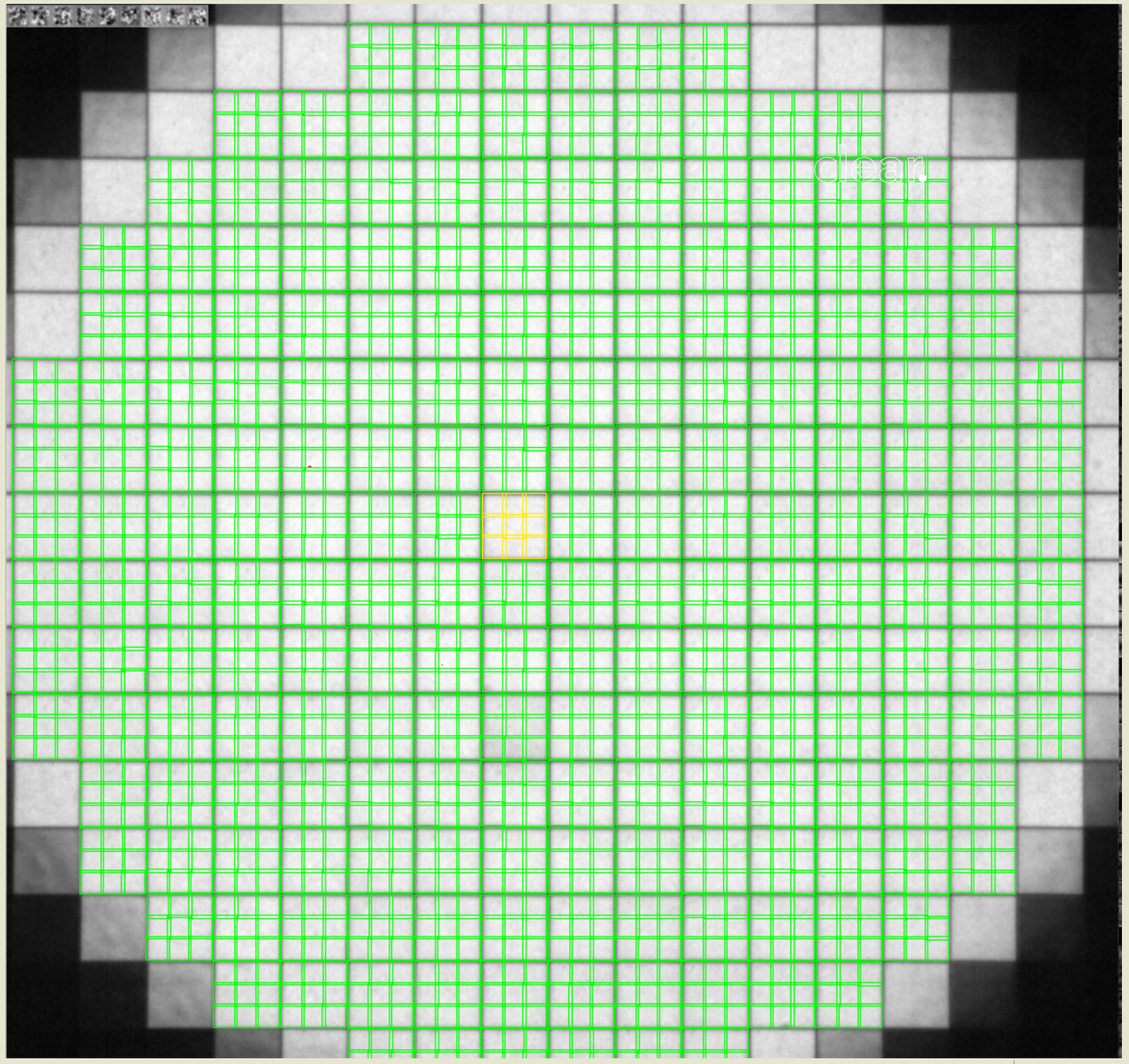


MD-WFS II

- 208 subapertures (8.8 cm)
- 35 arcsec field of view
- 3 × 3 guide regions
- 1872 image cross-correlations
- (DKIST CAO: 1457 correlations at 1975 fps)
- 1000 fps control loop frequency
  - limited by CPUs in RTC
  - camera could do ~1567 fps
  - built a back-up with 112 subapertures (~1500 fps)

fixed DM conjugates

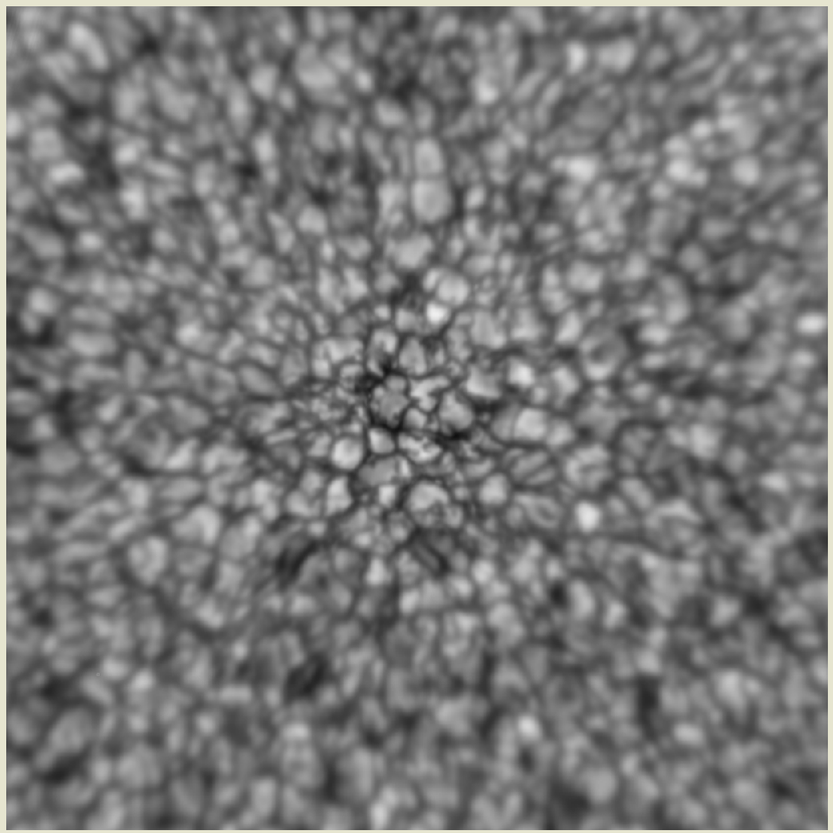
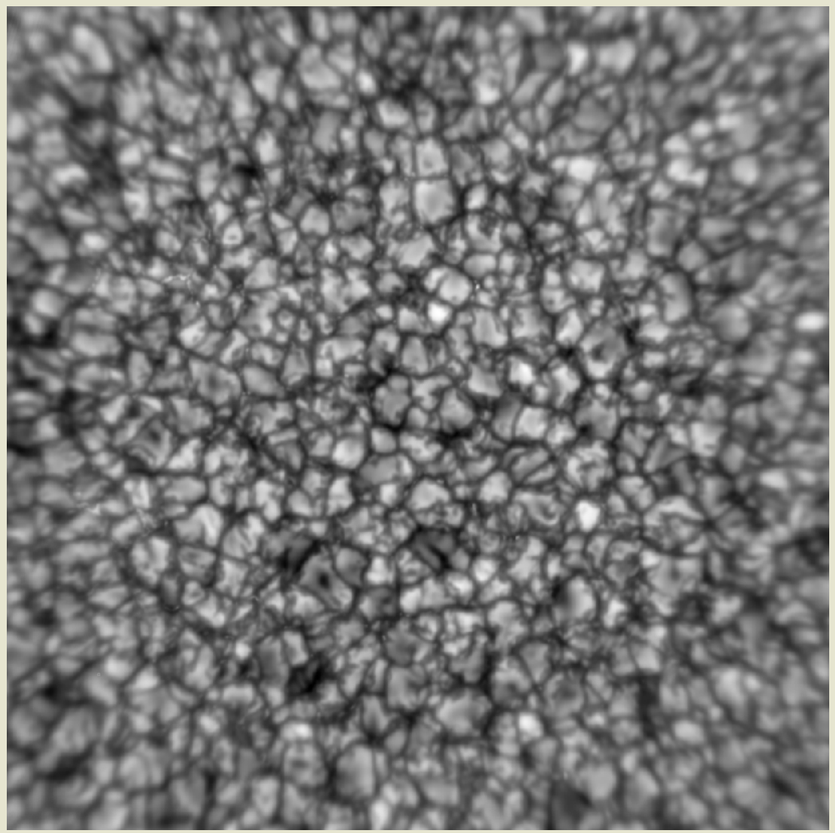
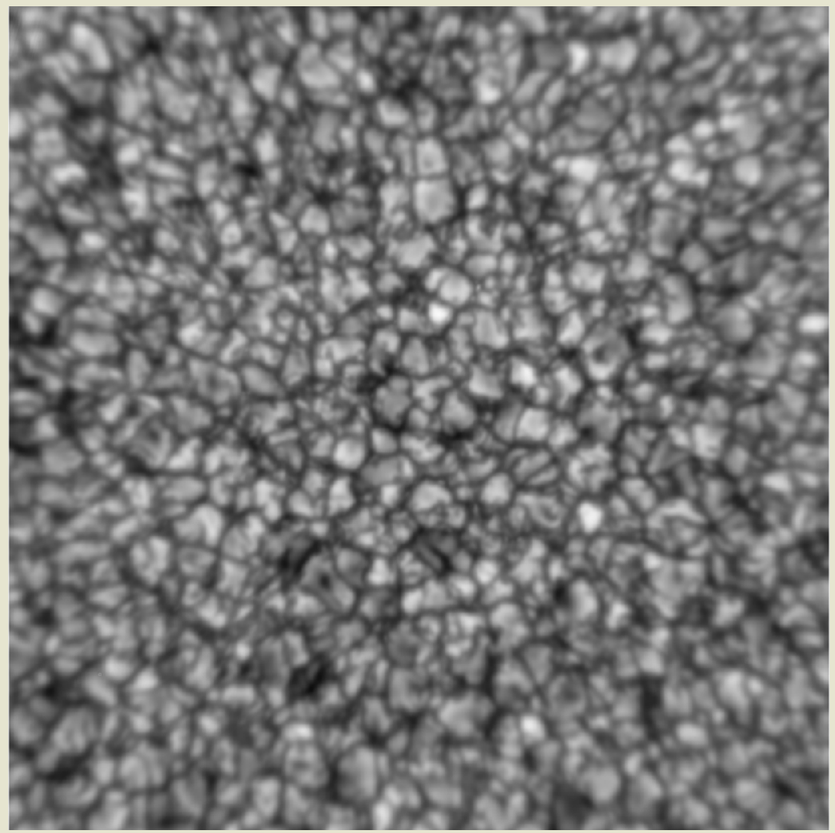
- 0, 3 and 8 km
- almost continuous coverage from 0 to 11 km



Classical, multi-conjugate and ground-layer AO

a side by side comparison of averages of ~150 frames (10 sec)

clear.

classical AO 1 DM in pupil	**multi-conjugate AO** 3 DMs	**ground-layer AO** 1 DM in pupil
		
very good correction in a small patch	good-very good correction in extended area	medium-good correction in extended area

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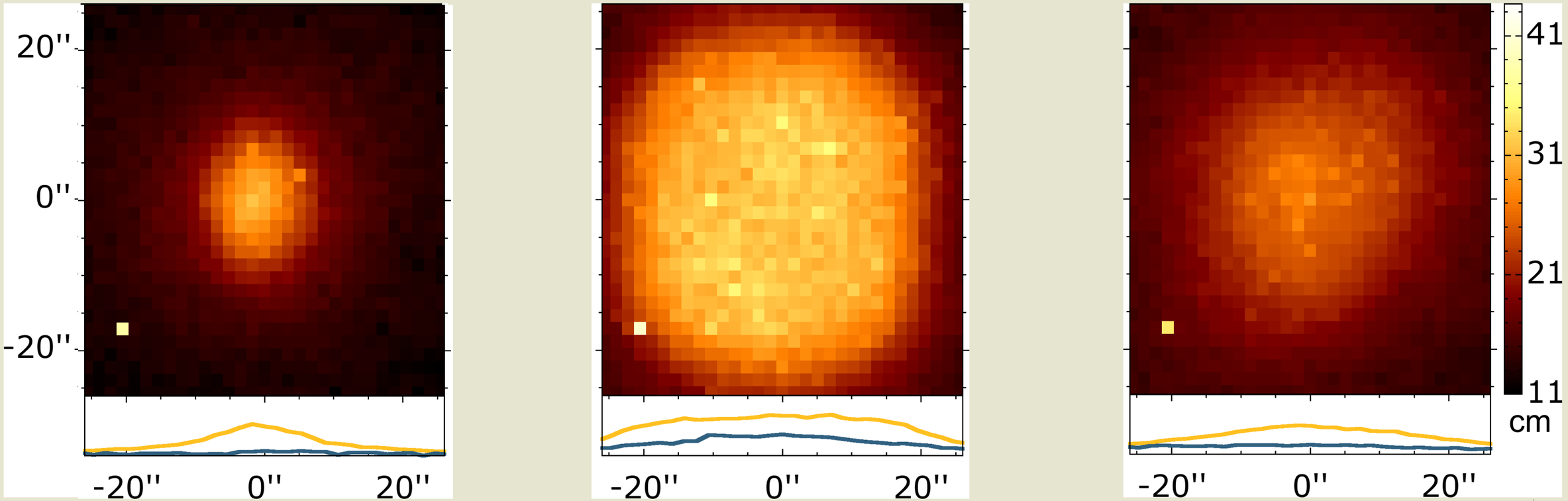
Classical, multi-conjugate and ground-layer AO

quantitative comparison of image qualities

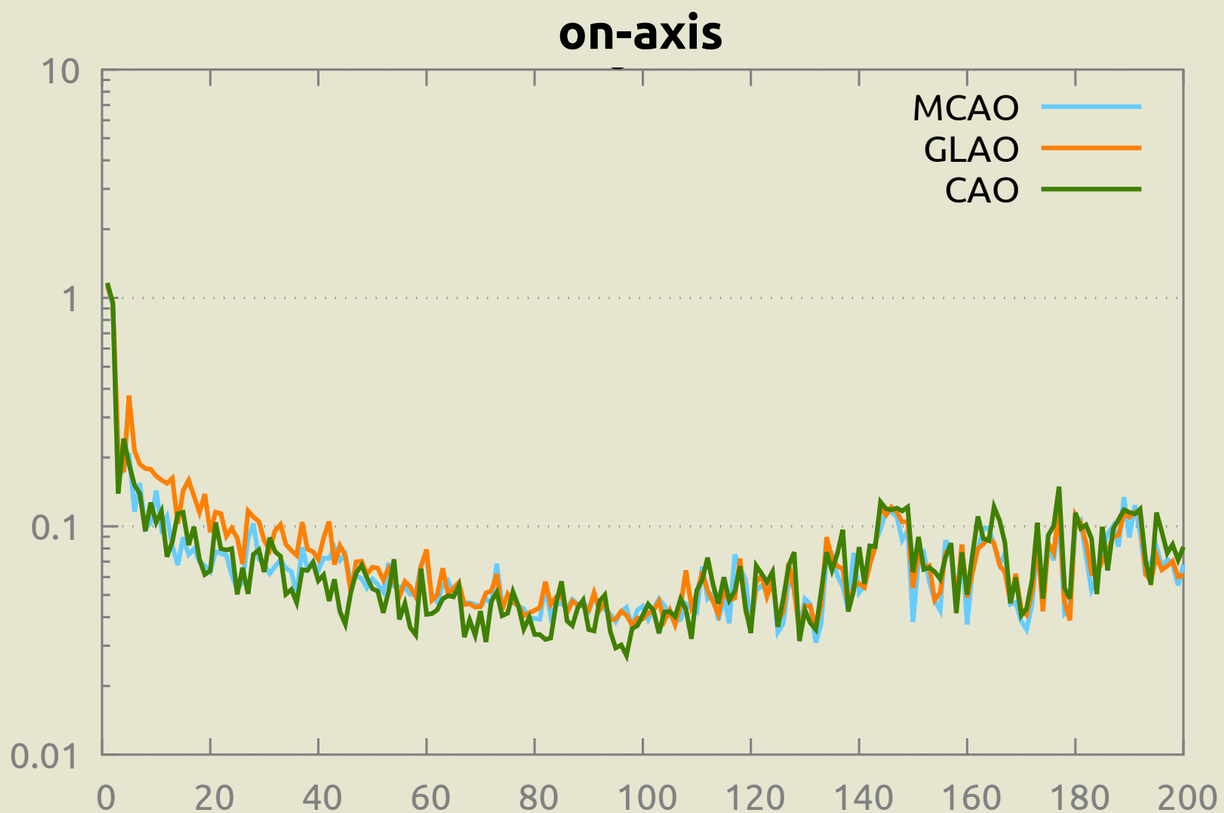
generalized Fried-parameter [Cagigal & Canales, 2000]
- estimates the apparent Fried parameter after AO correction
- computed from image bursts



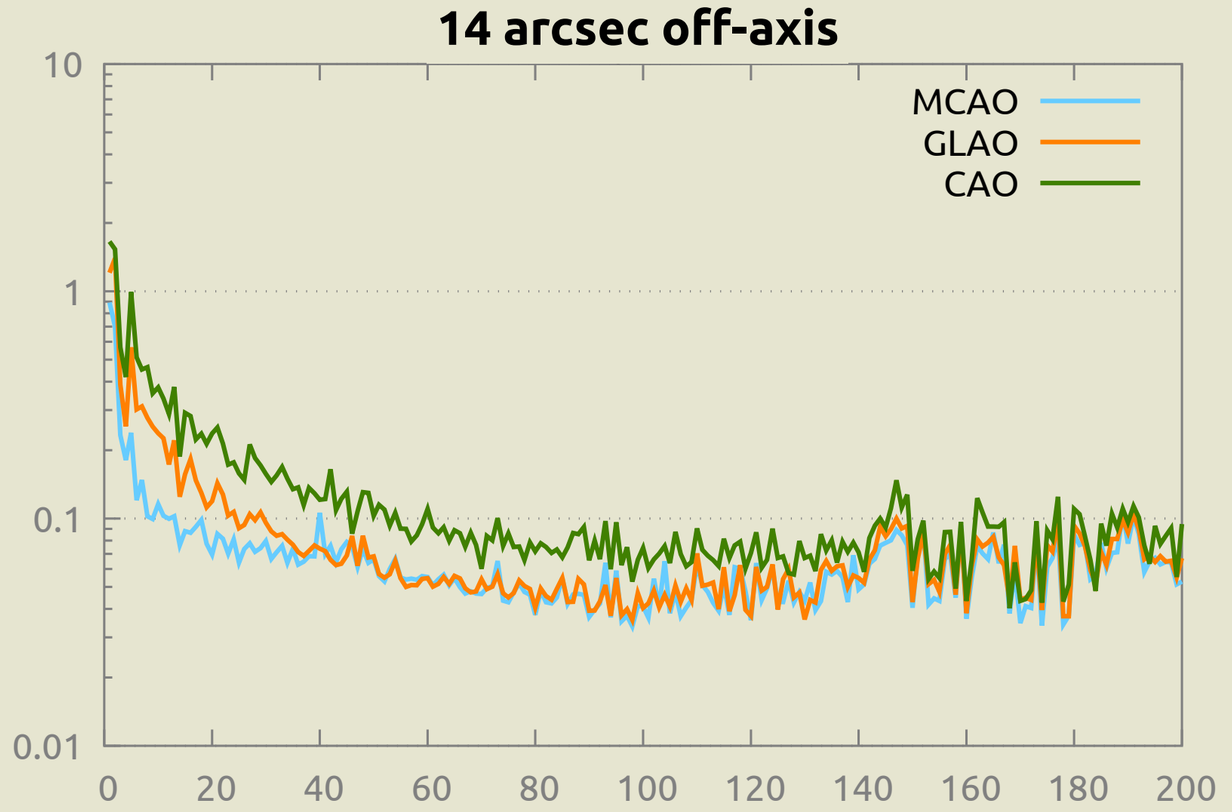
Classical, multi-conjugate and ground-layer AO

quantitative comparison of wavefront sensor data

variances of Karhunen-Loeve modes (reconstructed from WFS recordings)



MCAO: on par with CAO on-axis
GLAO: a bit worse



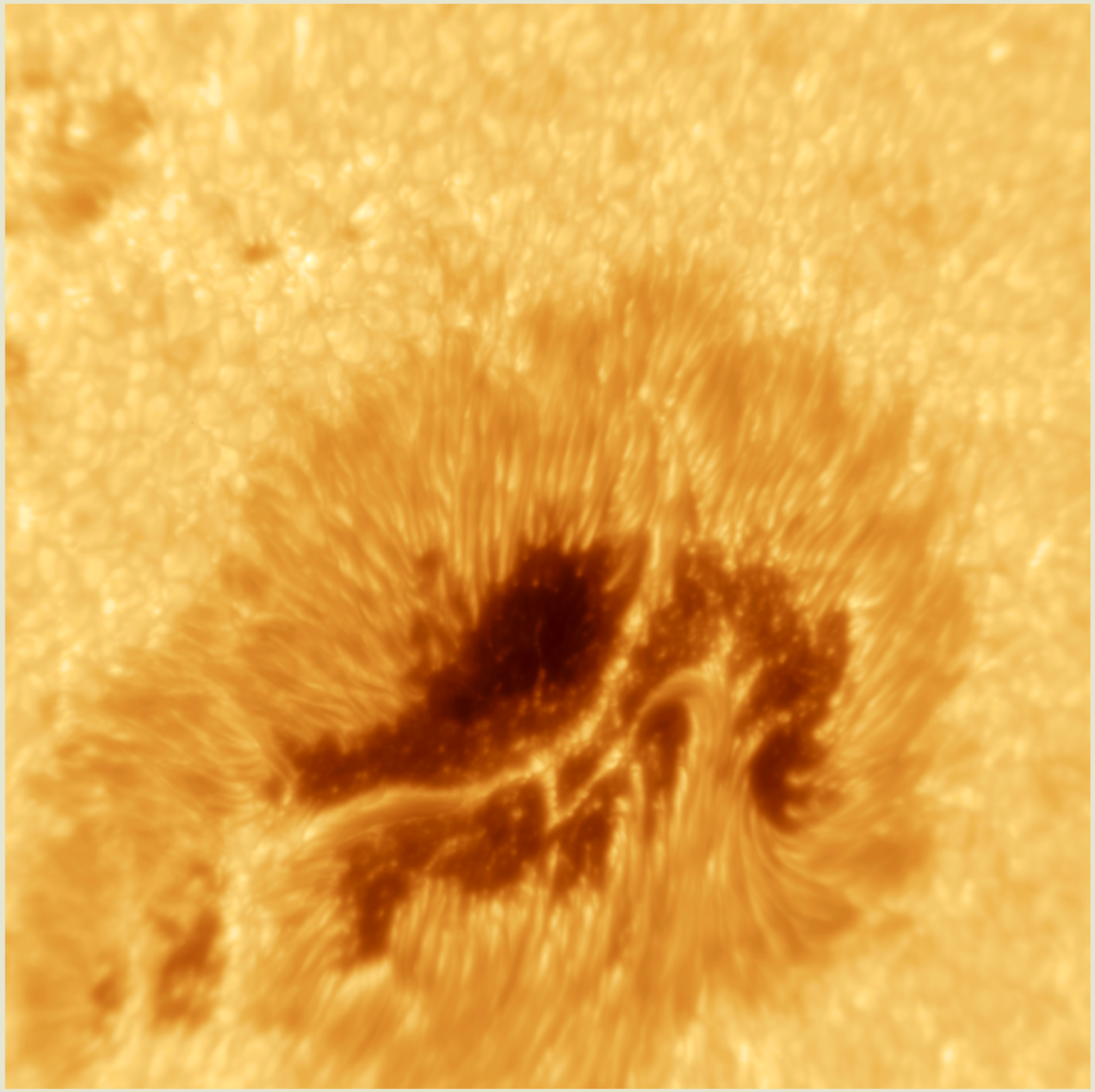
CAO: worst
GLAO: clearly better up to ~130 modes
MCAO: best of all, correction up to ~40 modes,
similar to on-axis wavefront error

Situation at AO4ELT5, June 2017

Benefit of MCAO easily visible by eye

clear.

- **MCAO can outperform high-order CAO correction** (science grade image quality demonstrated)
- single high-order MD-WFS with 35 arcsec works best
- no obvious impact of pupil DM location noticed
  - dynamic misregistration not critical
  - DM sequence not critical
  - *may still limit performance and impact systems with higher conjugates and shorter wavelengths...*
- GLAO is very attractive for non-MCAO solar telescopes
- **MCAO loop can be more stable than CAO loop in tough seeing**



MCAO vs. CAO, July 21, 2016

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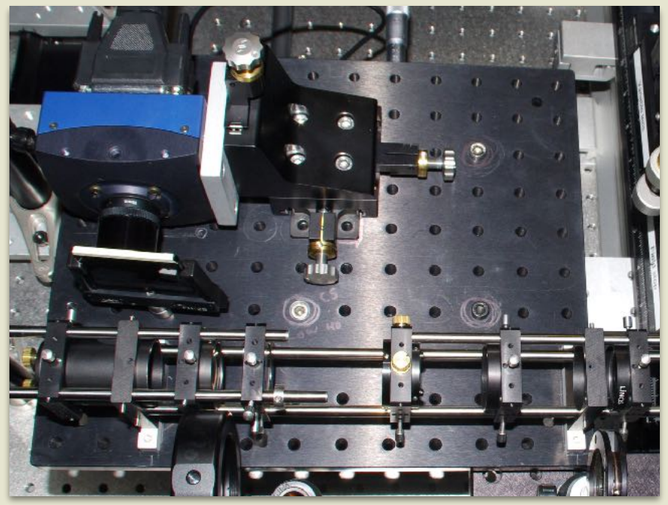
On the path to DKIST wide-field AO

next steps with Clear

MCAO still in pathfinder mode

- improve robustness of control loop
- optimize performance, more degrees of freedom
- get faster RTC to max out the camera frame rate
- test implication of DM sequence with 4 DMs (2 pupil, 2 high-altitude)
- re-increase the corrected field of view?



GLAO WFS

GLAO available for standard observations

dedicated GLAO WFS since May 2017

Turbulence profiling

dedicated SLODAR WFS prototype to be deployed to MCAO path

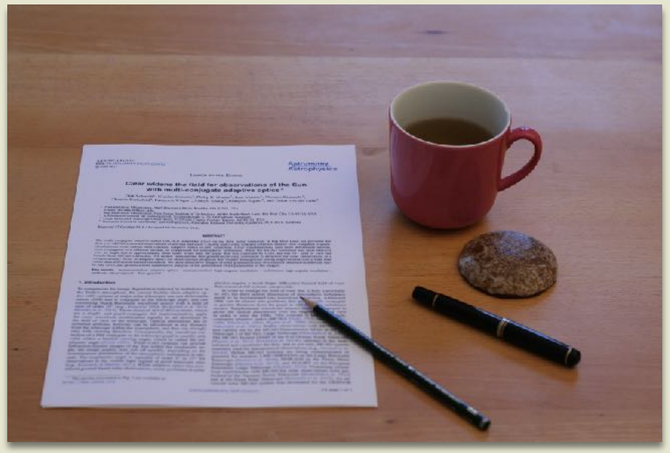
- camera: 1.6 Me^- well depth, superior SNR (closed-loop camera 27 ke^-)
- SLODAR algorithm by A. Guesalaga
- relocation to common light path, hardware upgrade, routine monitoring (2018)

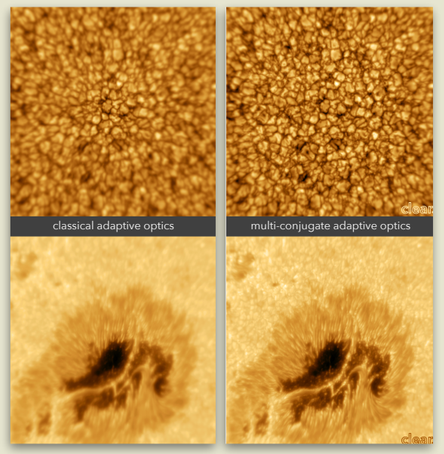
Publications

more details on-line

A&A letter 597 (2017) L8, January
D. Schmidt, N. Gorceix, P. Goode, J. Marino,
T. Rimmele, T. Berkefeld, F. Wöger,
X. Zhang, F. Rigaut, O. v. d. Lühe

tinyurl.com/zgvellu

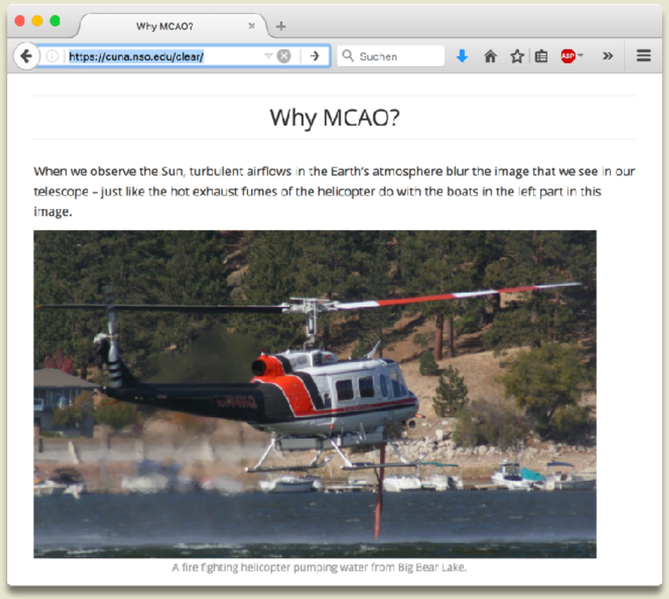




Clear blog
cuna.nso.edu/clear

Twitter
@Clear_AO

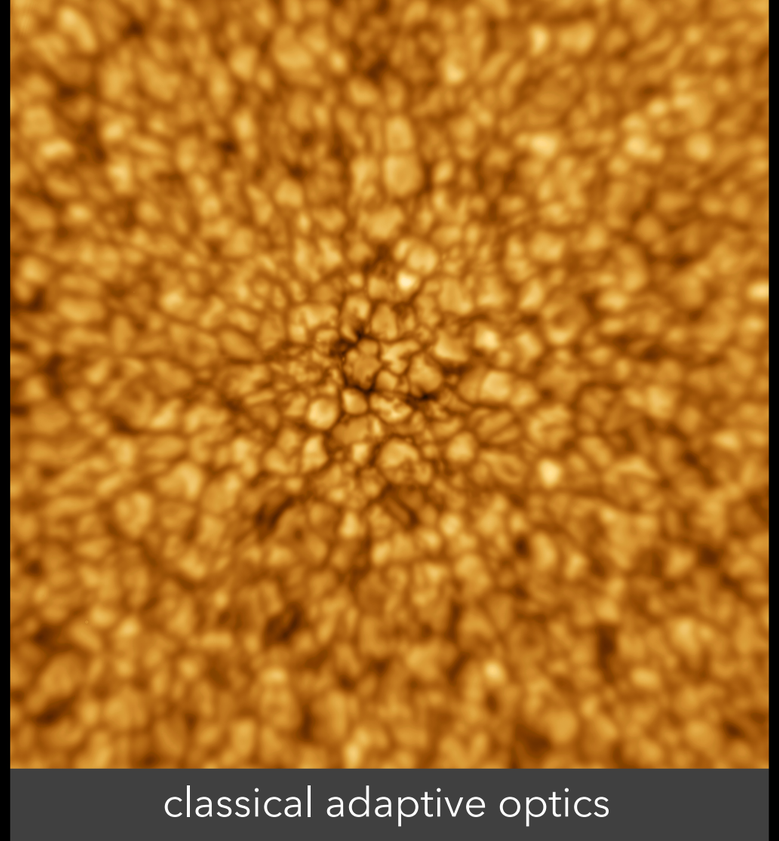
AO4ELT5
Closed loop simulations, J. Marino, yesterday
SLODAR simulations by E. Carlisle, Friday 9:00



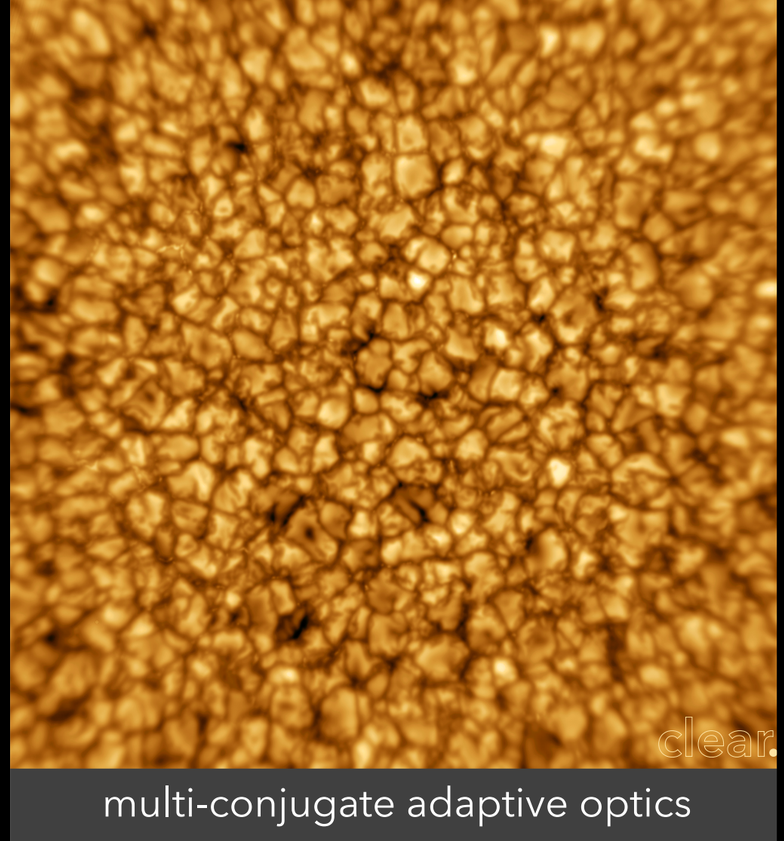
clear.

cuna.nso.edu/clear

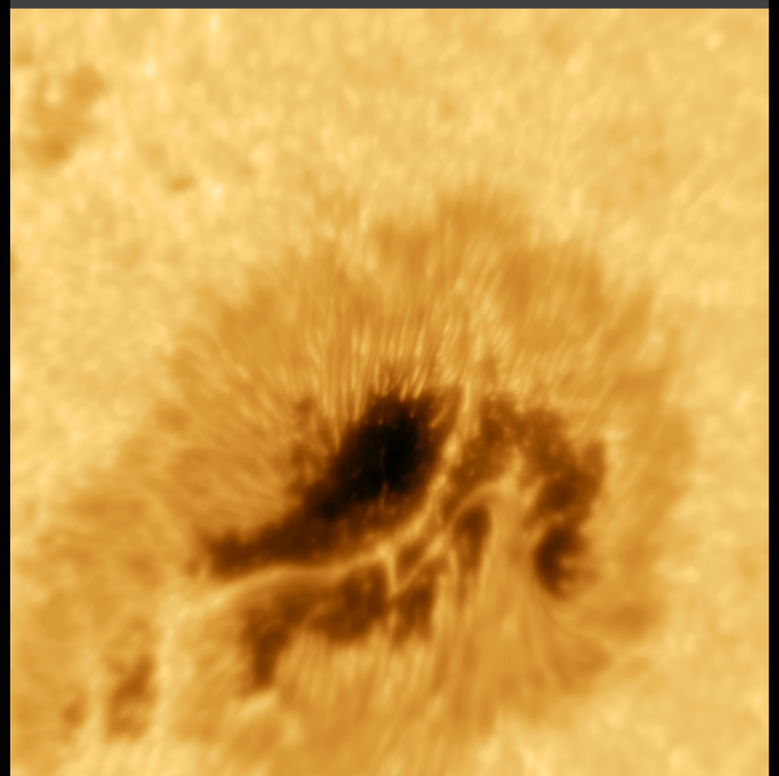
@Clear_AO

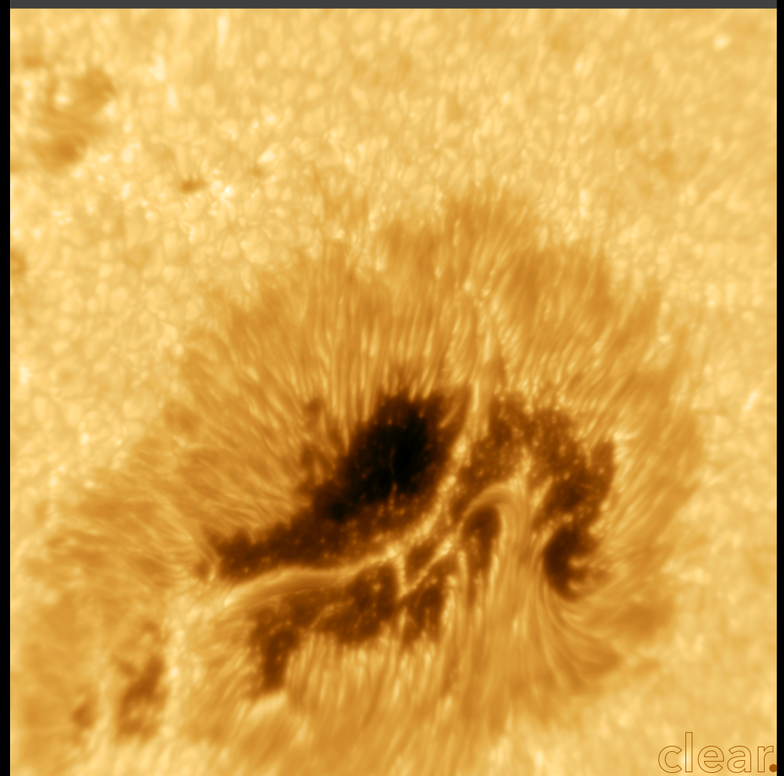


classical adaptive optics



multi-conjugate adaptive optics





A&A cover picture
Jan 2017

Adaptive Optics Internet Community

https://aoic.nso.edu