The Path to Direct Imaging and Spectroscopy of habitable Planets with Large Ground-Based Telescopes

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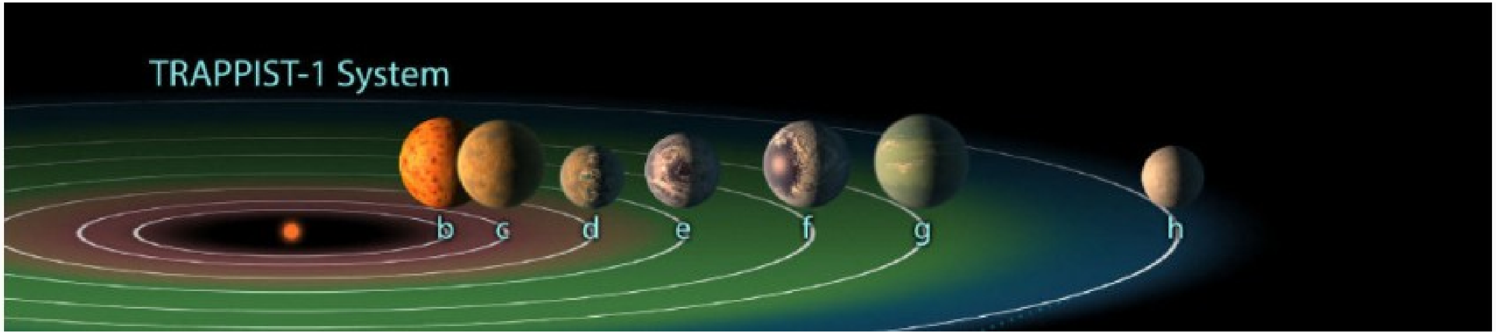
Subaru Telescope
NINS Astrobiology Center (Japan)

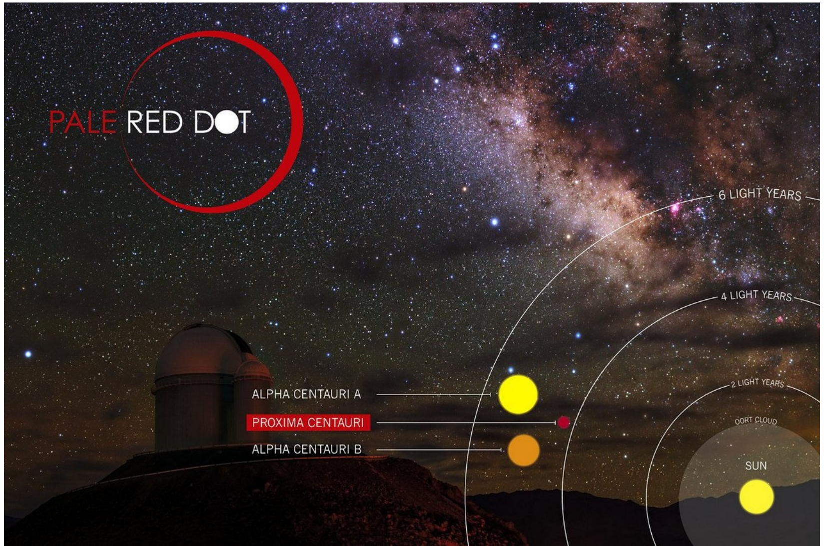
Spectacular discoveries around nearby stars

Trappist-1 system
7 planets
~3 in hab zone
likely rocky
40 ly away



Proxima Cen b planet
Possibly habitable

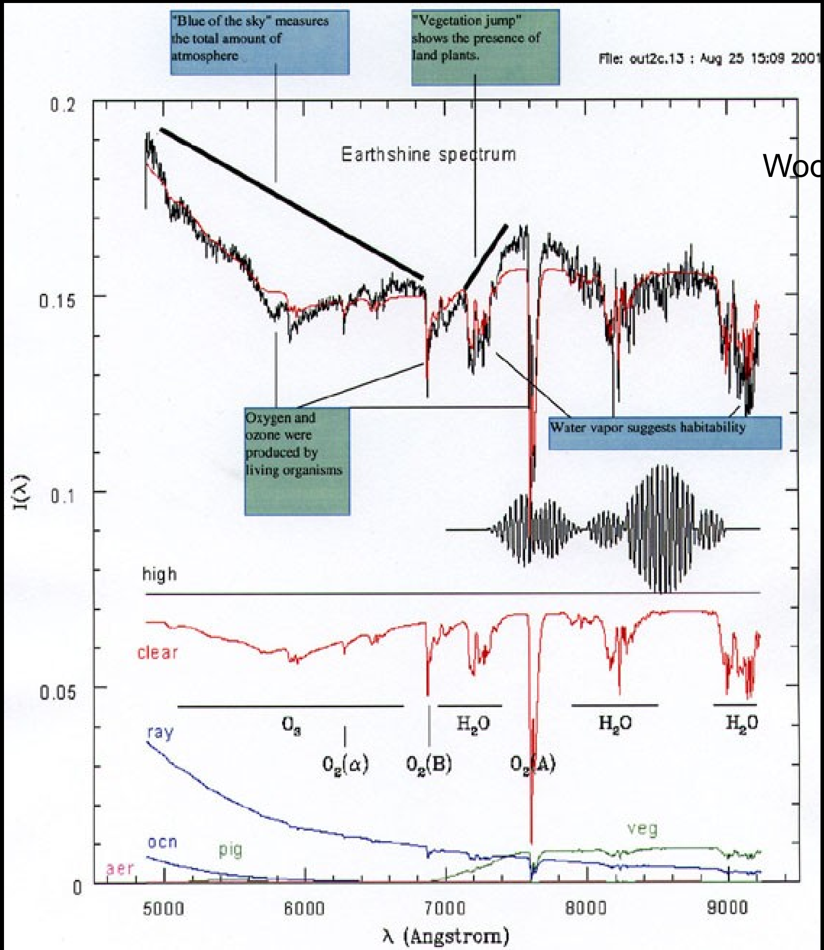
Closest star to our solar system (only 4.2 light years away)



Why should we image planets ?

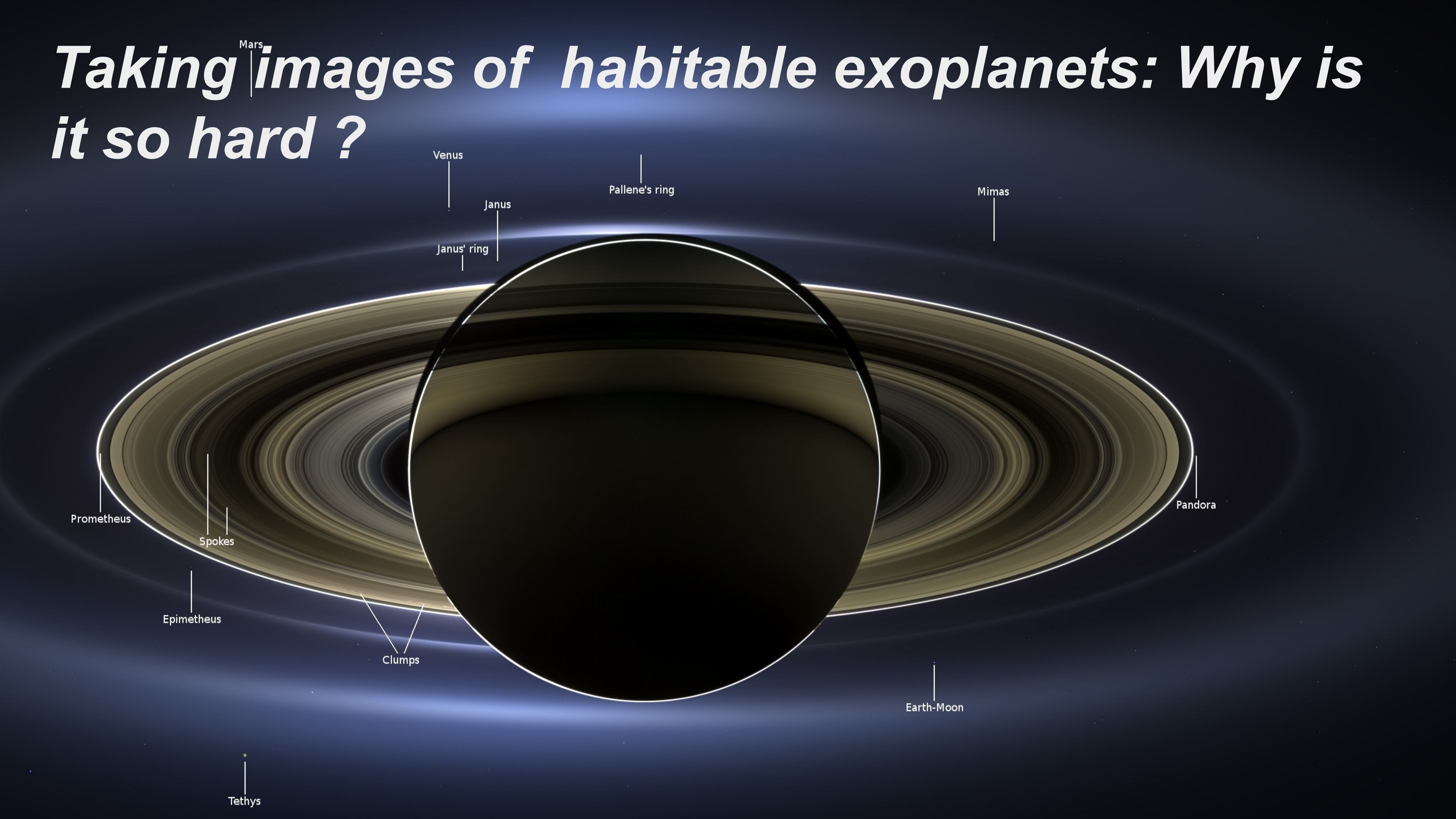
Imaging allows spectroscopy to measure atmosphere composition

Spectrum of Earth (taken by looking at Earthshine) shows evidence for life and plants

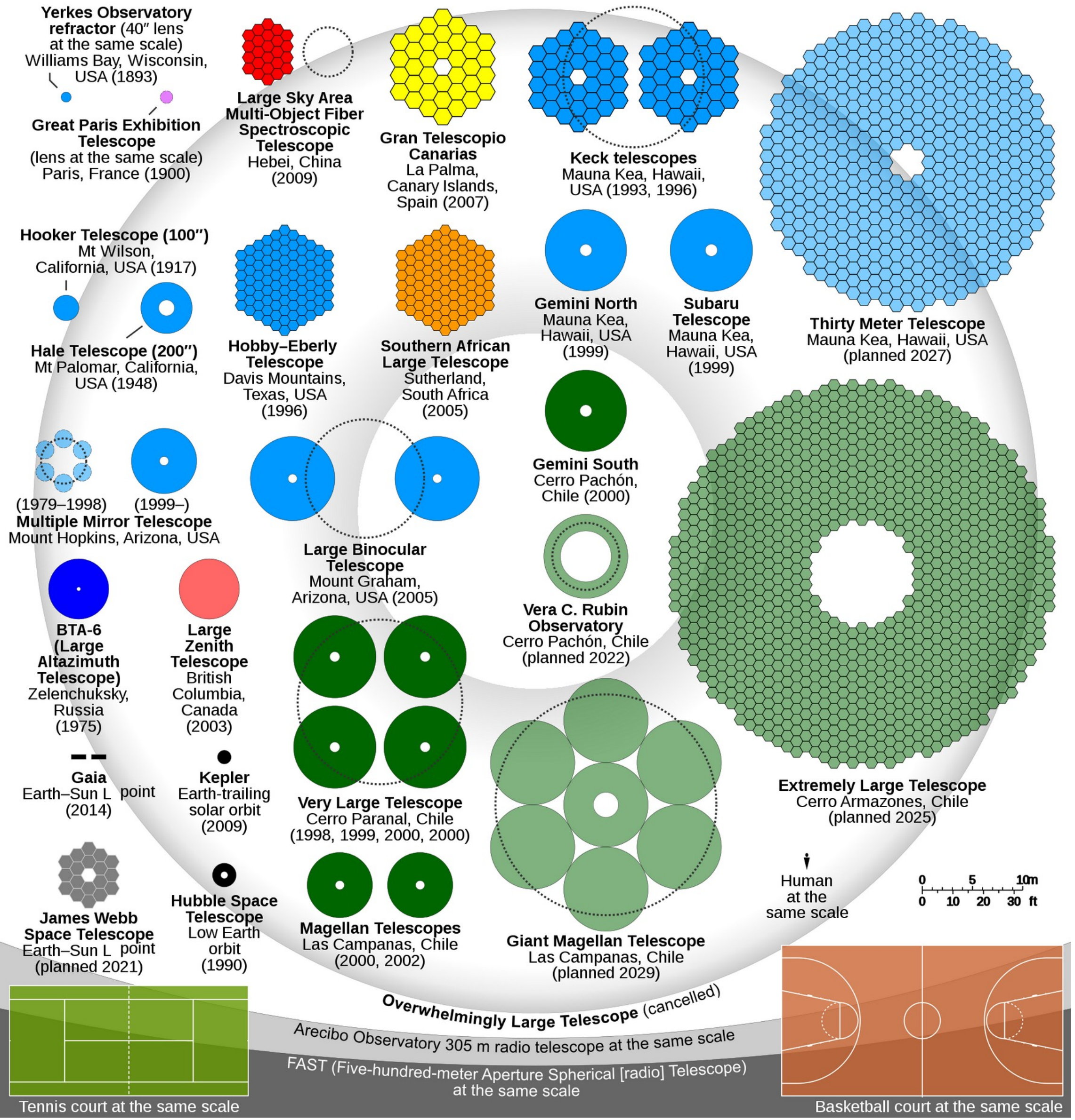


Woo

Taking images of habitable exoplanets: Why is it so hard ?




Saturn
Earth



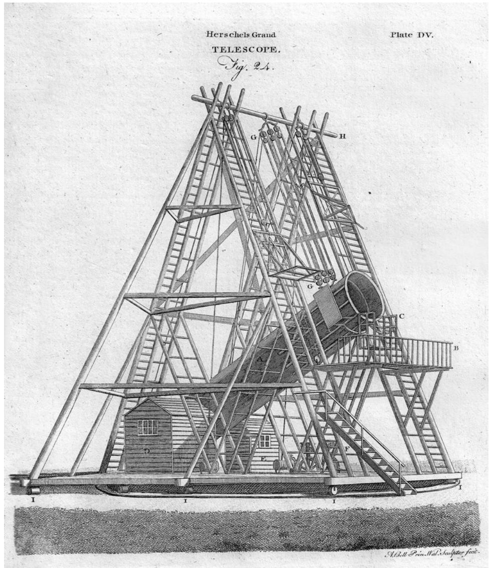
Why Build Bigger Telescopes ?

More light

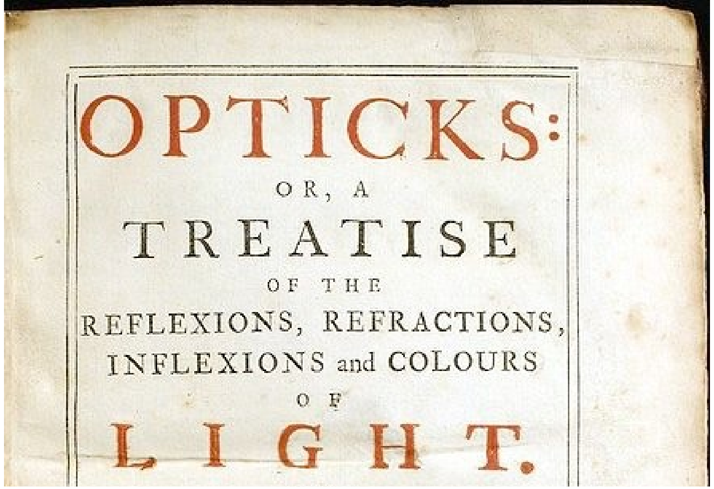
Collecting area goes as D^2

Sharper images

Angular resolution goes as 1/D

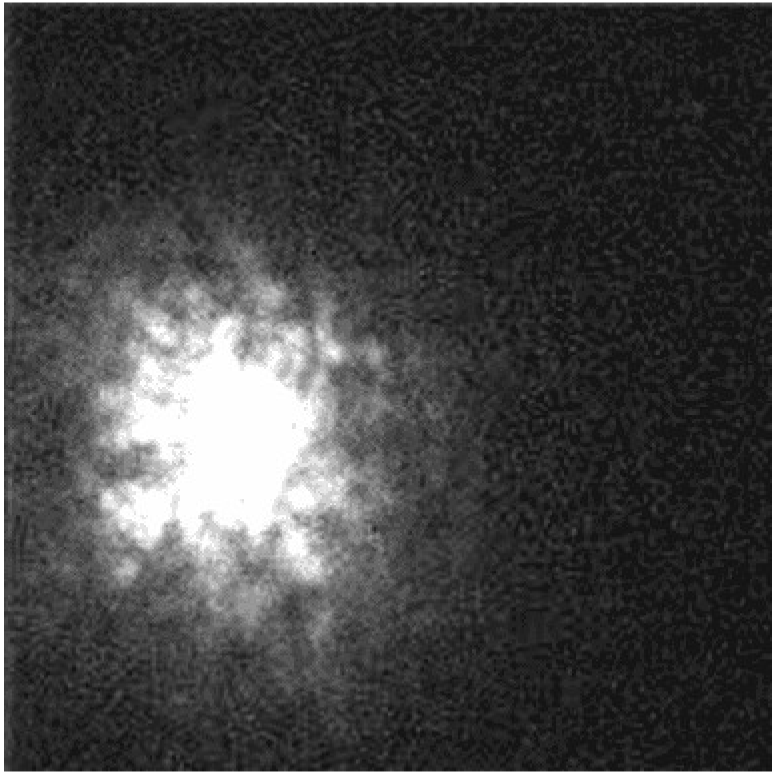


Atmospheric Turbulence

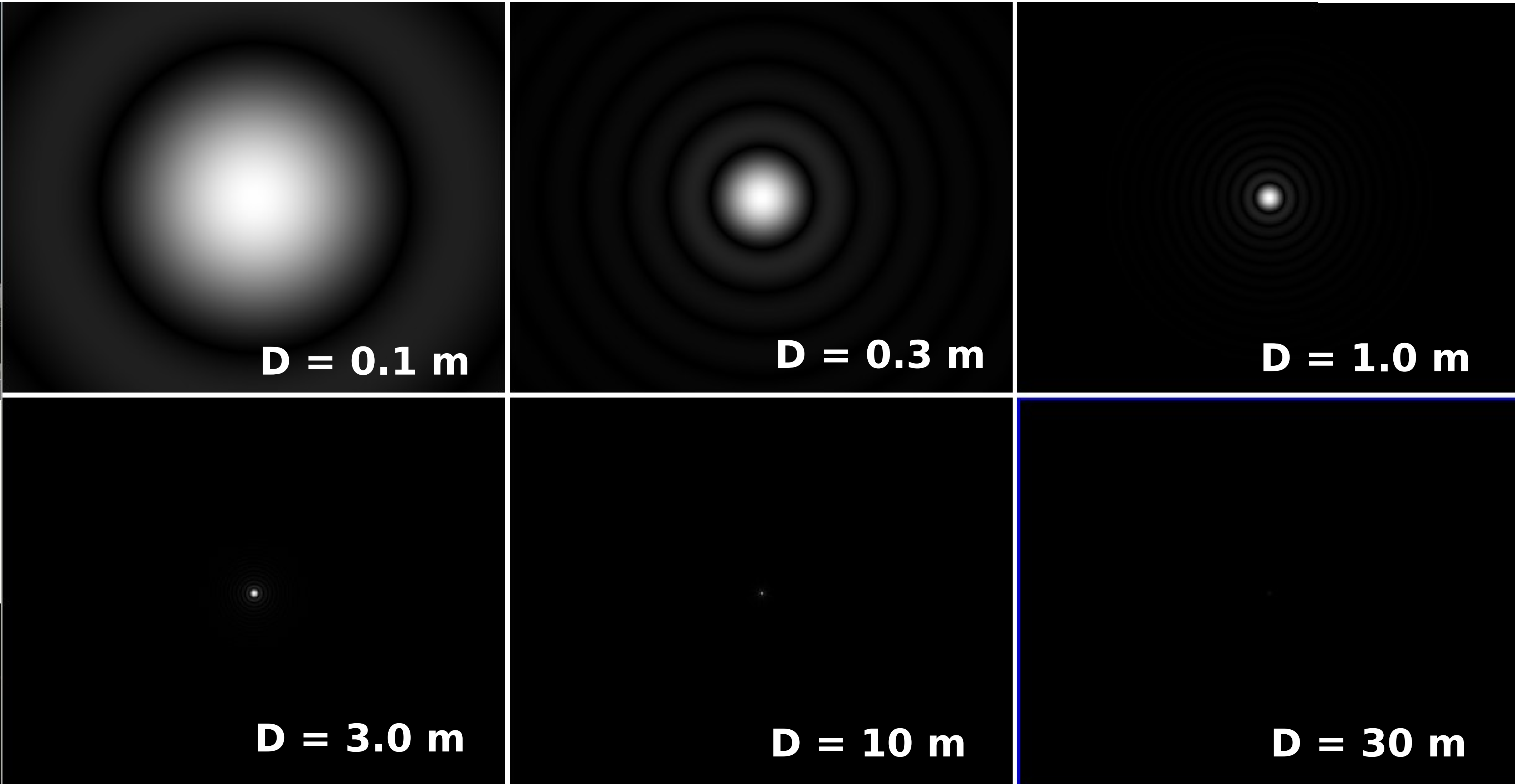

OPTICKS:
OR, A
TREATISE
OF THE
REFLEXIONS, REFRACTIONS,
INFLEXIONS and COLOURS
OF
LIGHT.

" . . . the Air through which we look upon the Stars, is in a perpetual Tremor . . . all these illuminated Points [in the focal plane] constitute one broad lucid Point, composed of these many trembling Points confusedly and insensibly mixed with one another by very short and swift Tremors **and thereby cause the Star to appear broader than it is**, and without any trembling of the whole. Long telescopes may cause Objects to appear brighter and larger than short ones can do, but they cannot be so formed as to take away the confusion of the Rays which arises from the Tremors of the Atmosphere. **The only remedy is a most serene and quiet Air, such as may perhaps be found on the tops of the highest Mountains above the grosser Clouds.**

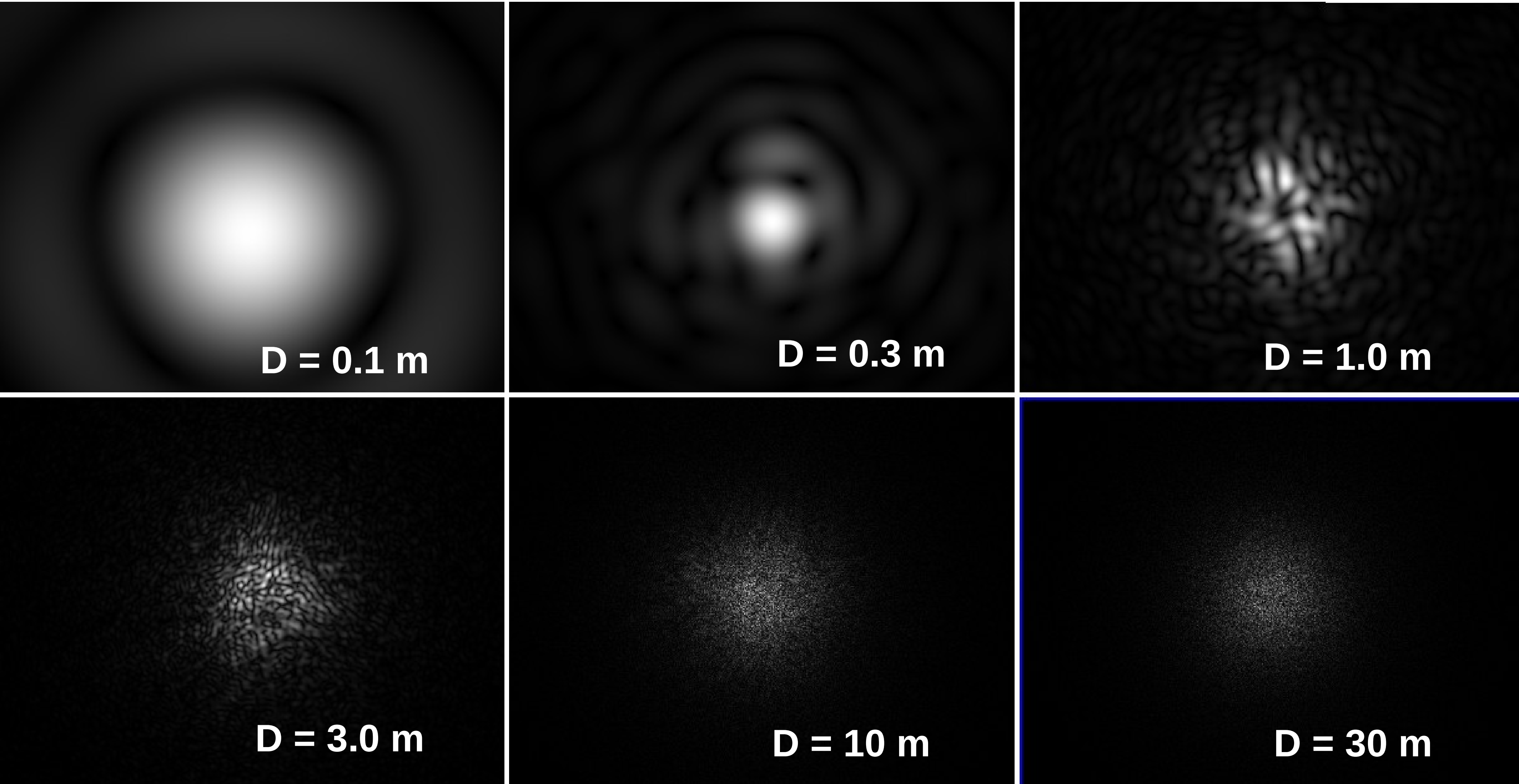
Newton, 1704



Star image at WHT (D=4.2m)

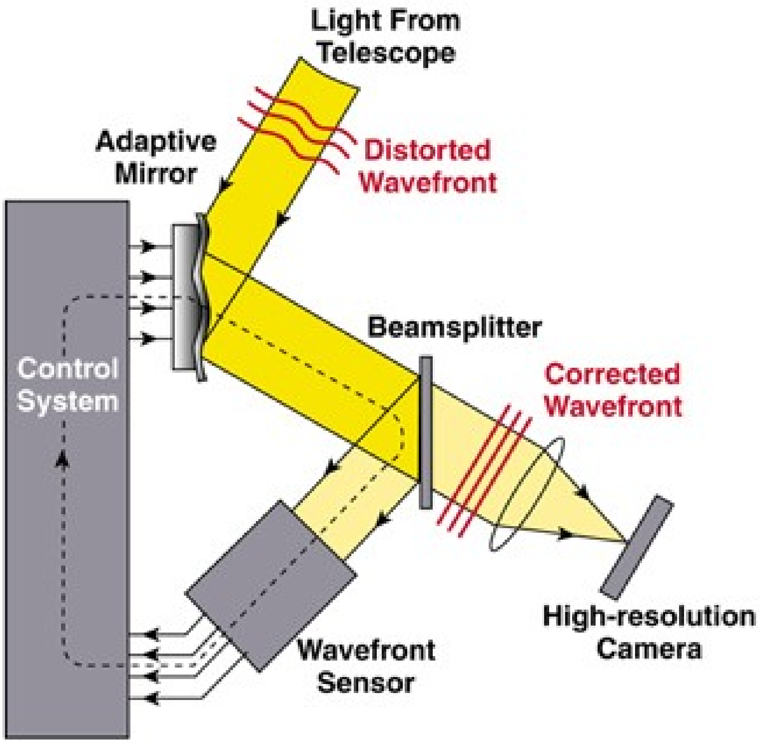

D = 0.1 m
D = 0.3 m
D = 1.0 m
D = 3.0 m
D = 10 m
D = 30 m

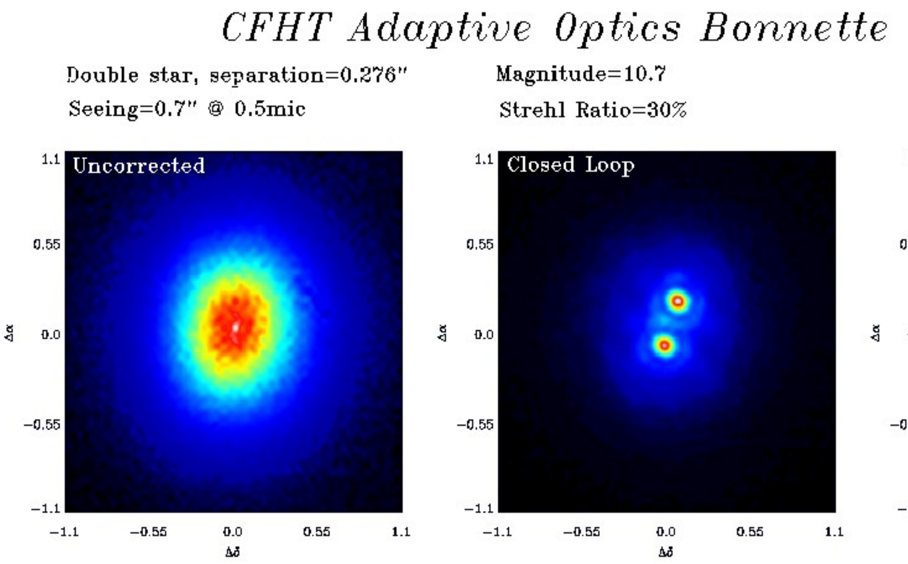
Imaging through Atmospheric turbulence



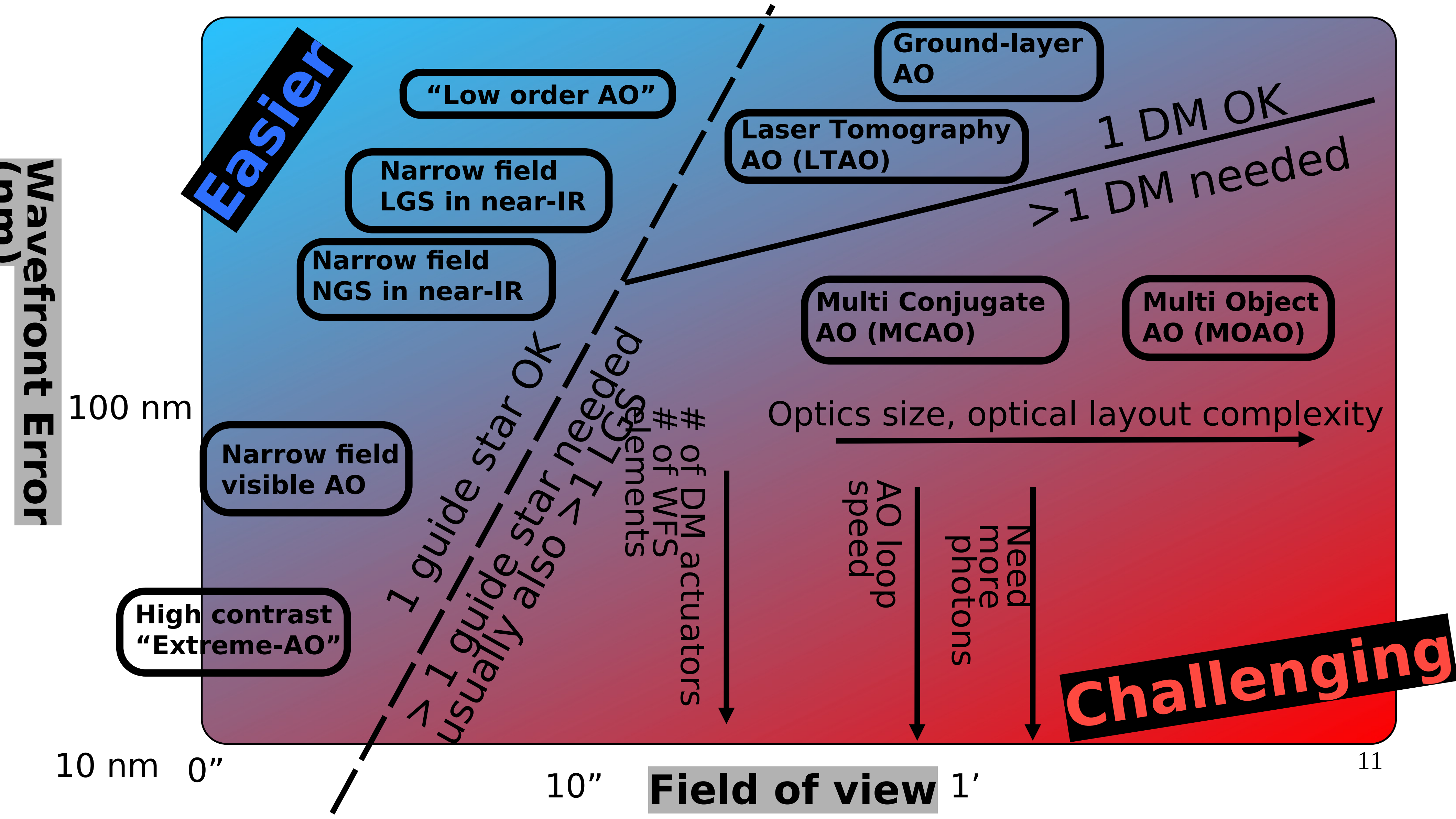
Adaptive Optics

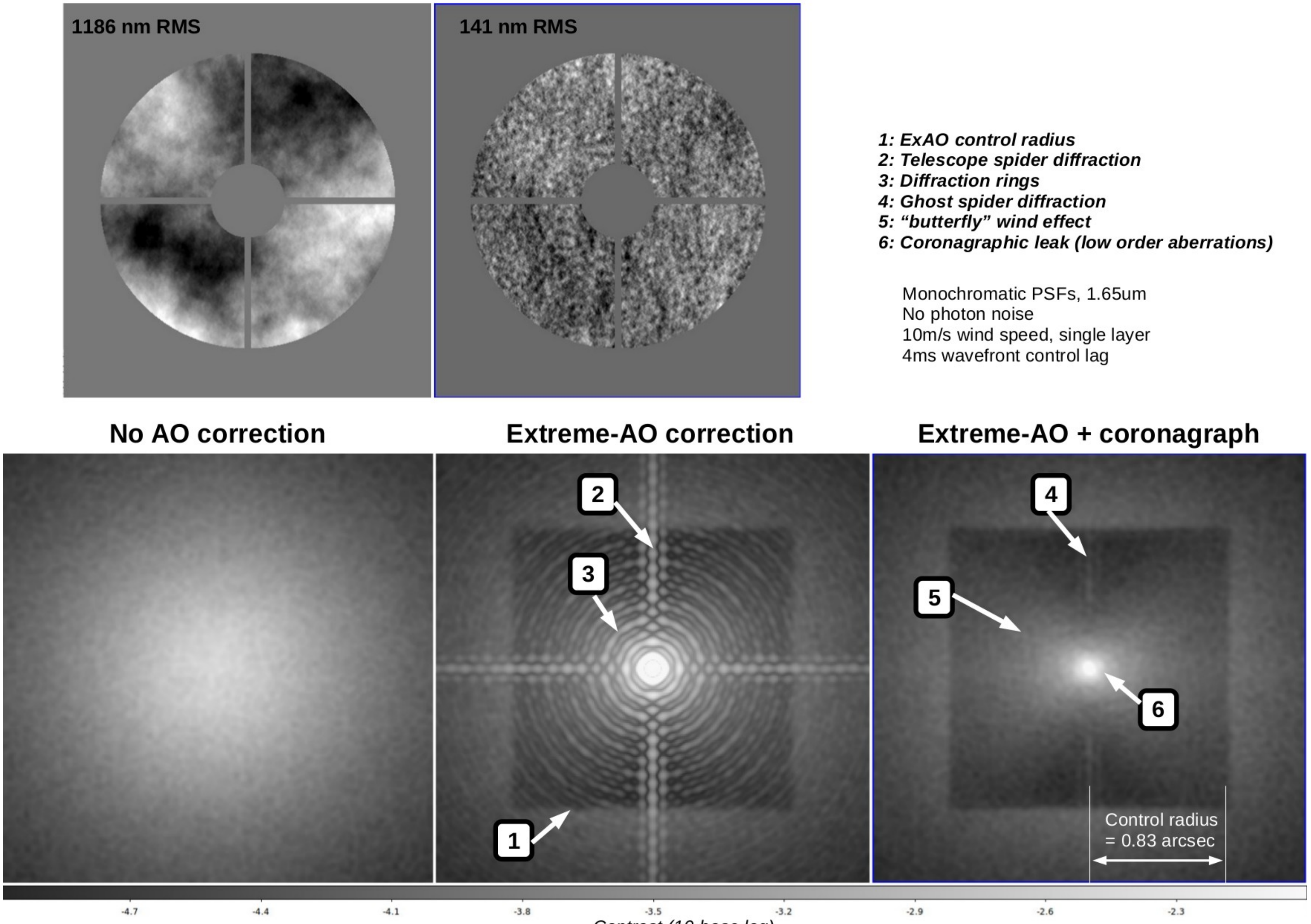
Feedback loop: next cycle corrects the (small) errors of the last cycle



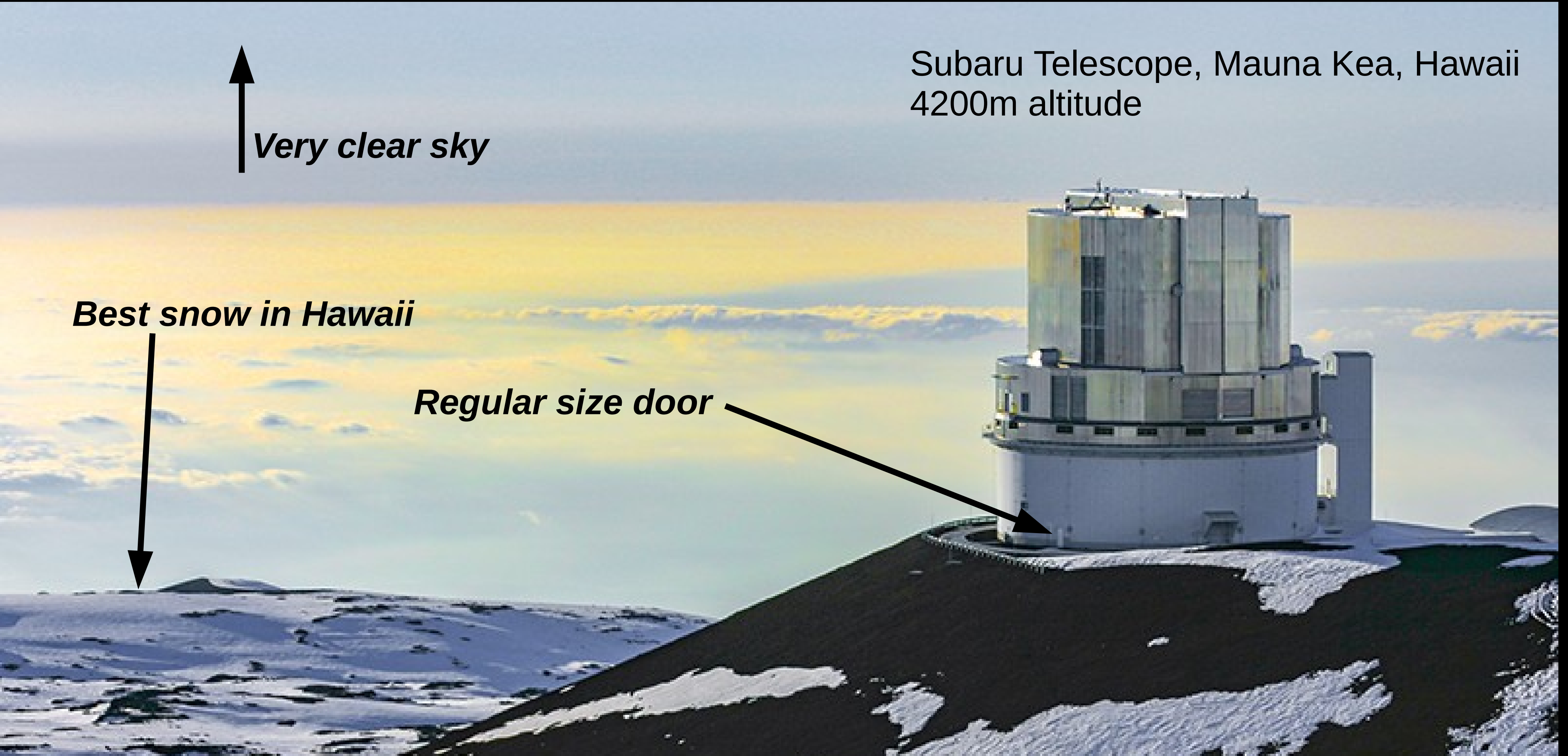


C. Max, Center for Adaptive Optics


Easier
"Low order AO"
Ground-layer AO
Laser Tomography AO (LTAO)
1 DM OK
>1 DM needed
Narrow field LGS in near-IR
Narrow field NGS in near-IR
Multi Conjugate AO (MCAO)
Multi Object AO (MOAO)
1 guide star OK
>1 guide star needed usually also >1 LGS
# of DM actuators
# of WFS elements
Optics size, optical layout complexity
AO loop speed
Need more photons
Narrow field visible AO
High contrast "Extreme-AO"
Challenging
Wavefront Error (nm)
100 nm
10 nm
0"
10"
Field of view
1'


1186 nm RMS
141 nm RMS
1: ExAO control radius
2: Telescope spider diffraction
3: Diffraction rings
4: Ghost spider diffraction
5: “butterfly” wind effect
6: Coronagraphic leak (low order aberrations)
Monochromatic PSFs, 1.65um
No photon noise
10m/s wind speed, single layer
4ms wavefront control lag
No AO correction
Extreme-AO correction
Extreme-AO + coronagraph
1
2
3
4
5
6
Control radius
= 0.83 arcsec
-4.7
-4.4
-4.1
-3.8
-3.5
-3.2
-2.9
-2.6
-2.3
Contrast (10 base log)

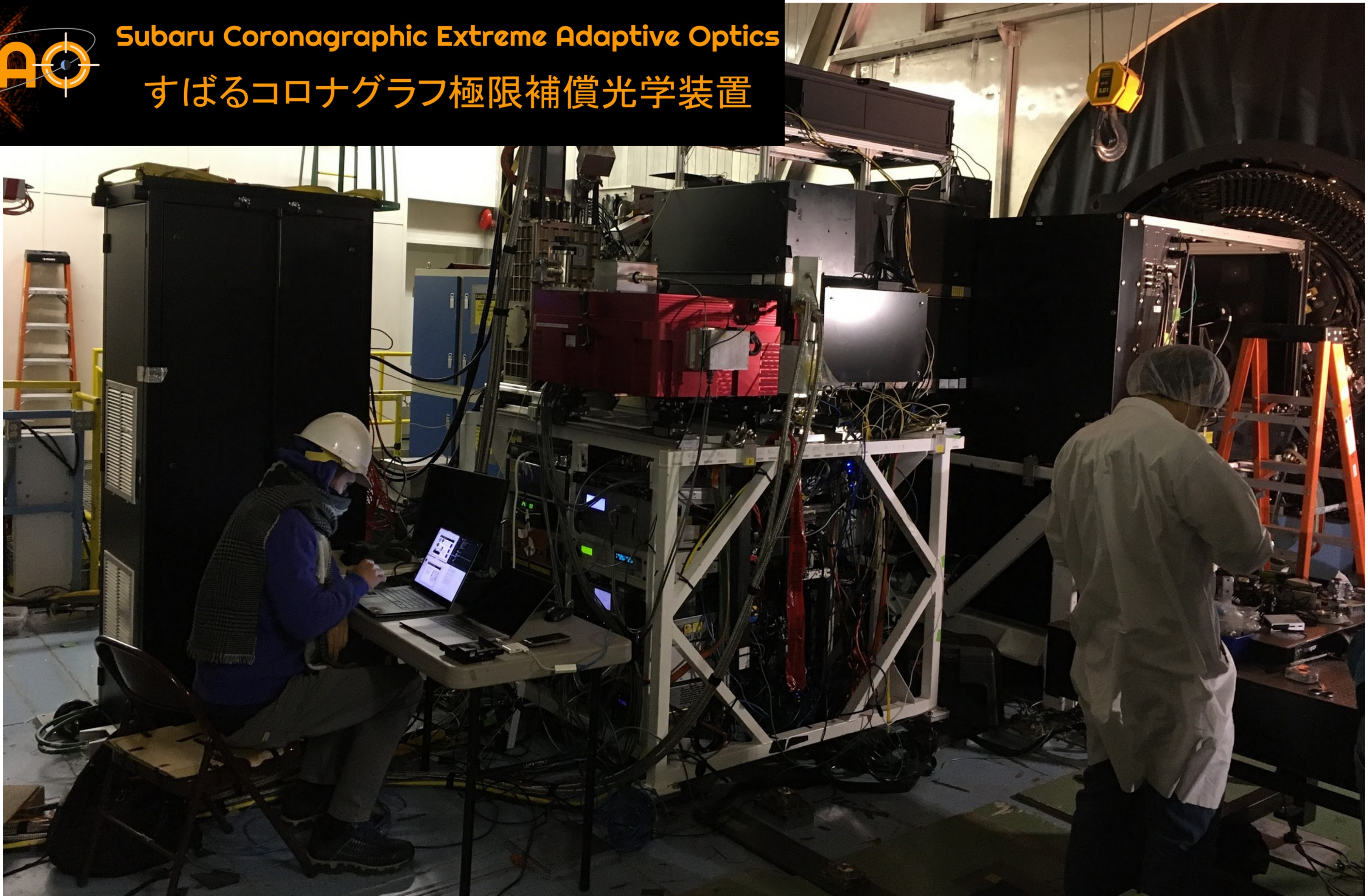
Subaru Telescope (8.2m diameter) has an exoplanet-imaging instrument (SCExAO)
The instrument team is developing advanced Extreme-AO techniques



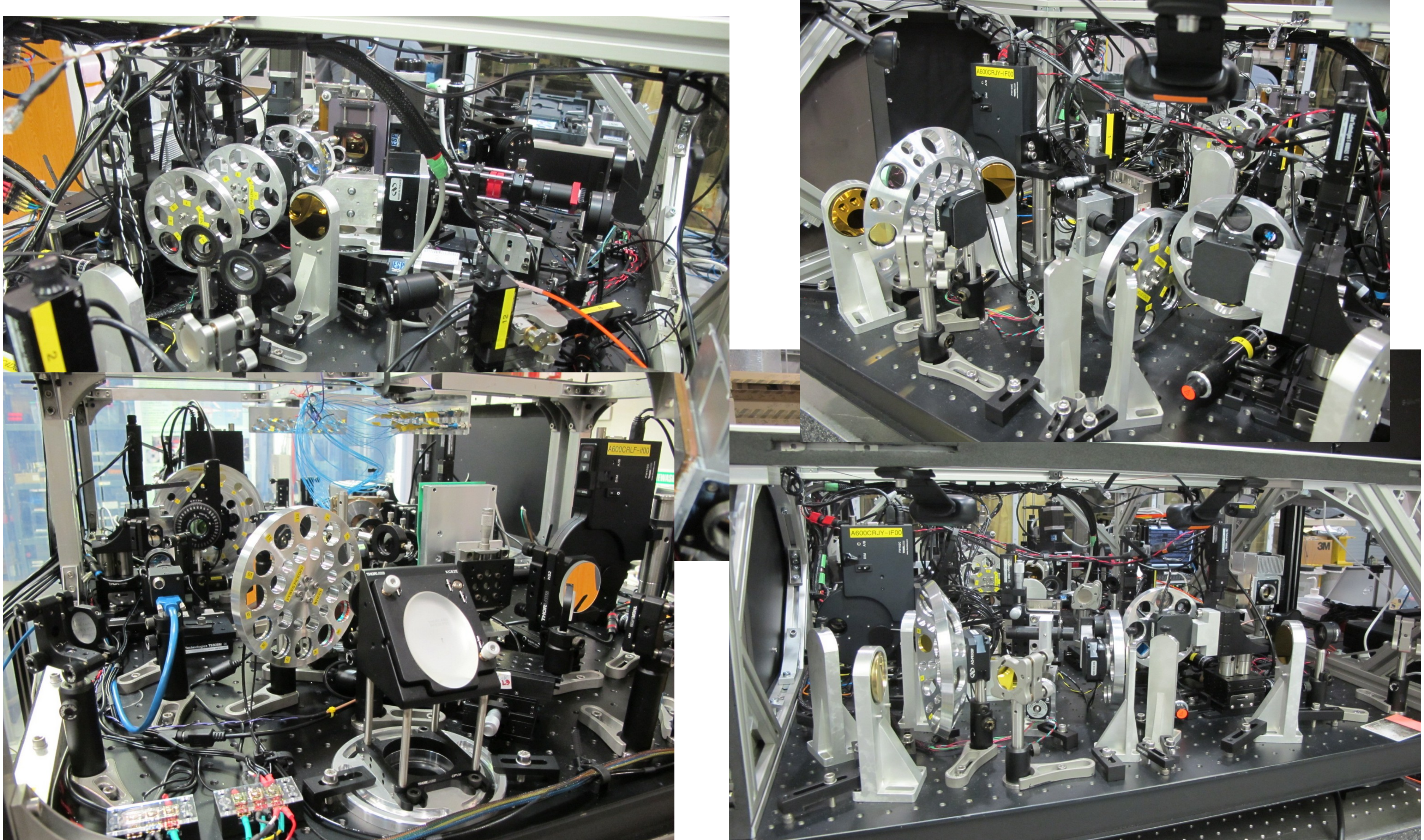
Subaru Telescope (view from inside dome) Photograph by Enrico Sachetti

Subaru Coronagraphic Extreme Adaptive Optics

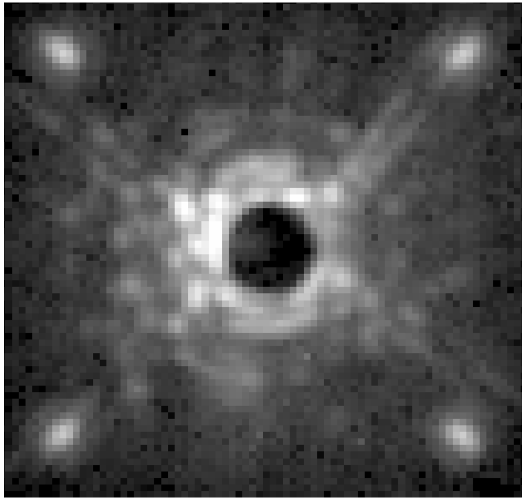
すばるコロナグラフ極限補償光学装置




Olivier Guyon
Summit (8893099)
Barnaby Norris


A600CRJY-IF00
A600CRLF-IF00
A600CRJY-IF00
THORLABS
3M

Imaging exoplanets requires 3 techniques to be combined:
(1) Extreme-AO corrects atmospheric turbulence
(2) A coronagraph masks the light of the bright star
(3) Smart image processing to recognize planets

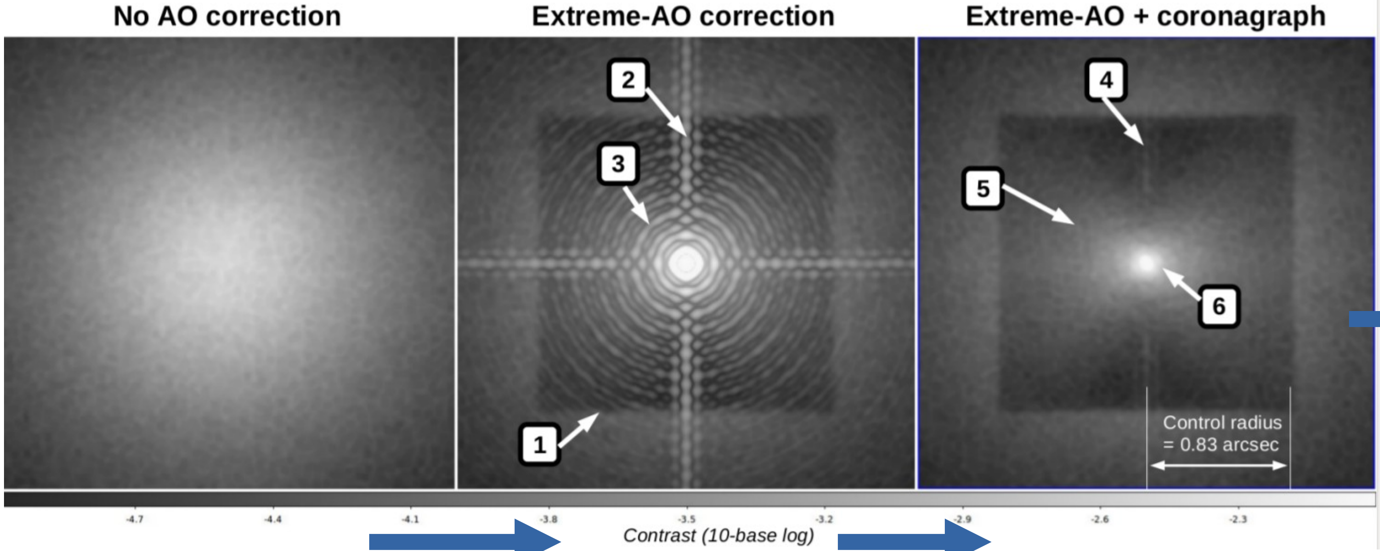


Raw on-sky image
Subaru Telescope/SCExAO

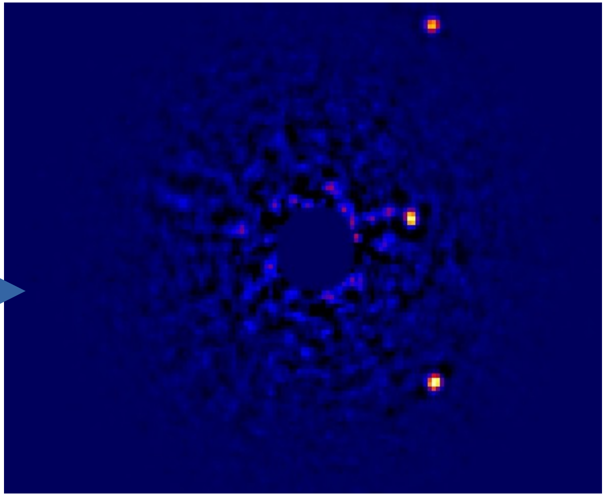
Simulated images below show how Extreme-AO and Coronagraphy deliver high contrast image of a star

1: ExAO control radius
2: Telescope spider diffraction
3: Diffraction rings
4: Ghost spider diffraction
5: "butterfly" wind effect
6: Coronagraphic leak (low order aberrations)

Monochromatic PSFs, 1.65um
No photon noise
10m/s wind speed, single layer
4ms wavefront control lag

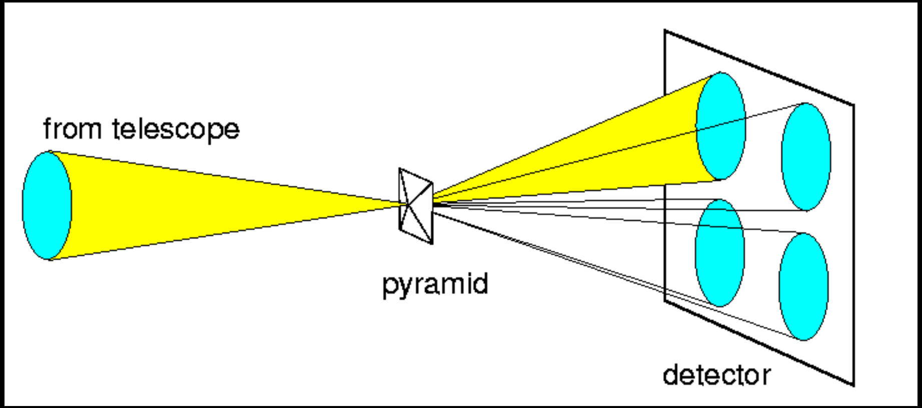


(1) (2) (3)

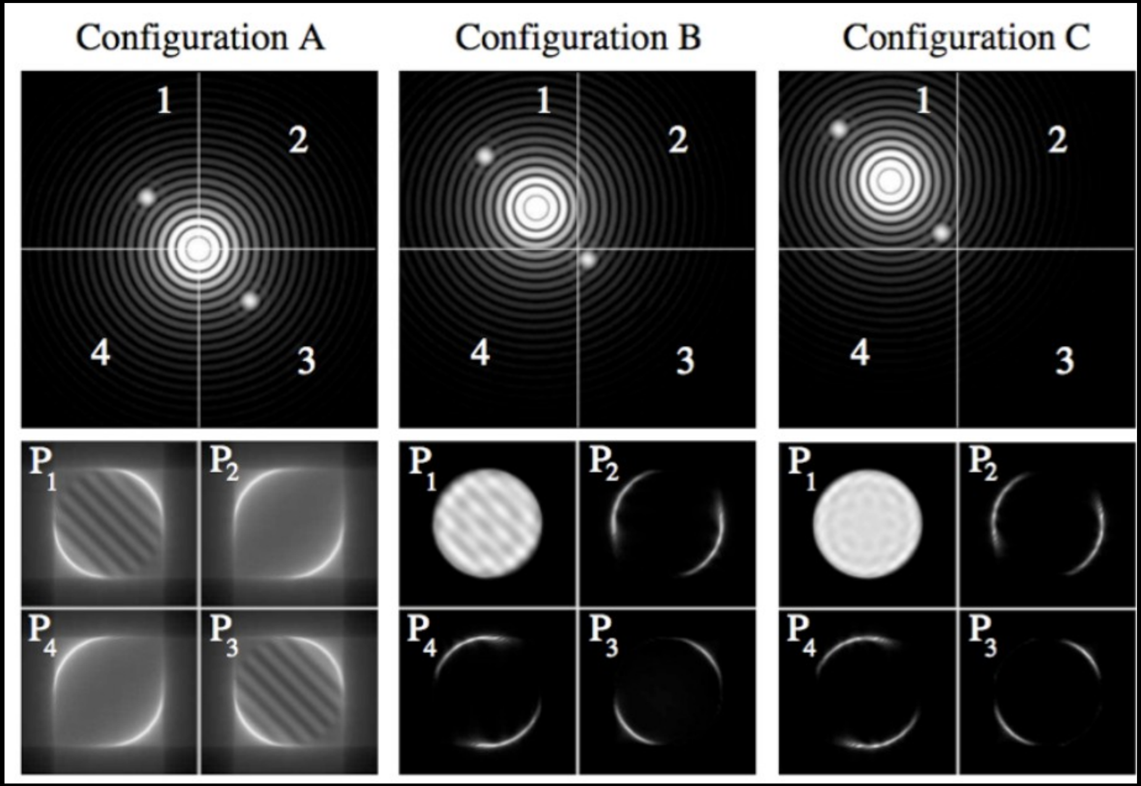


HR8799 system (b,c,d)
Subaru Telescope/SCExAO

Pyramid WFS



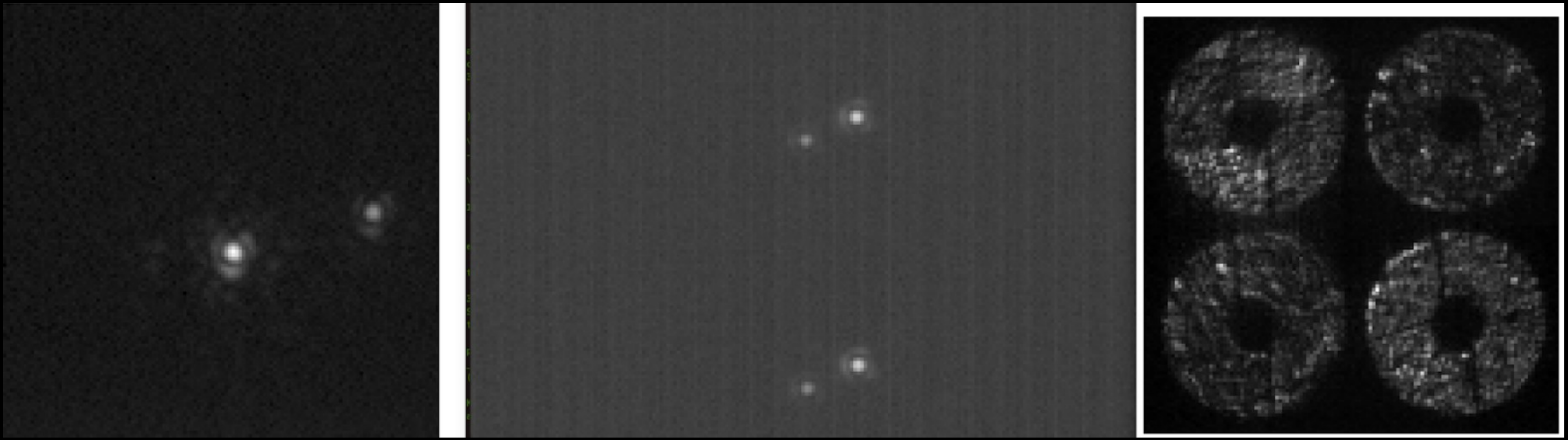
from telescope
pyramid
detector



Configuration A
Configuration B
Configuration C
1
2
3
4
P1
P2
P3
P4

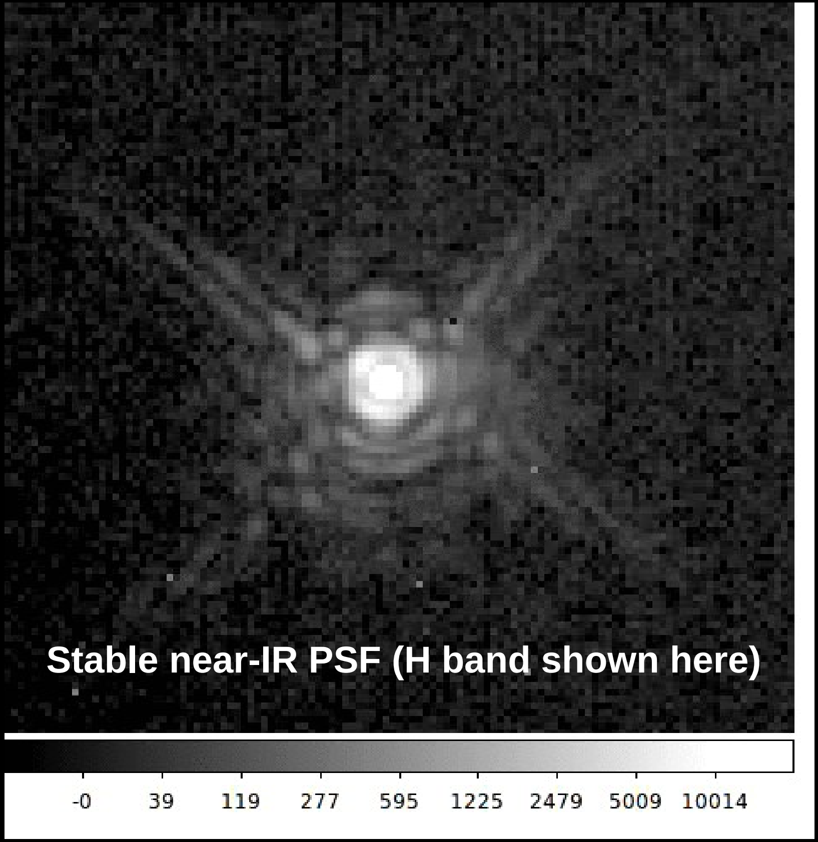
On-sky camera images (snapshot)

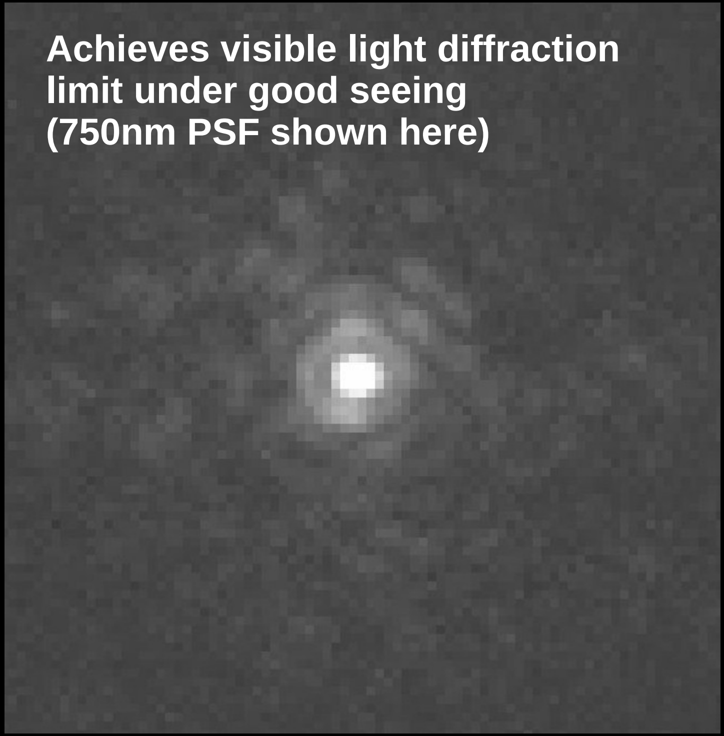
SCExAO example
Visible image (left), NearIR image (center), Visible pyramid WFS (right)

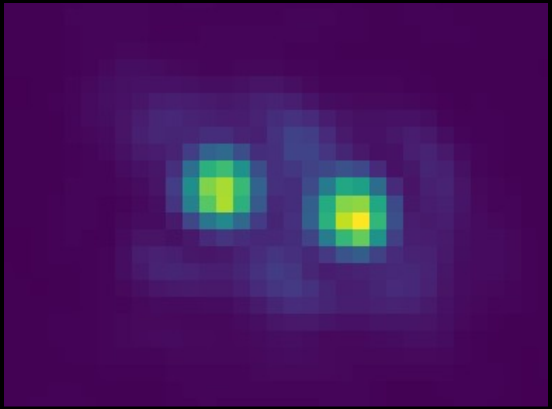


Star: Sigma Ori, 0.3" separation

AO loop runs at 0.5 kHz to 3.5 kHz
14,400 sensors → 2000 actuators





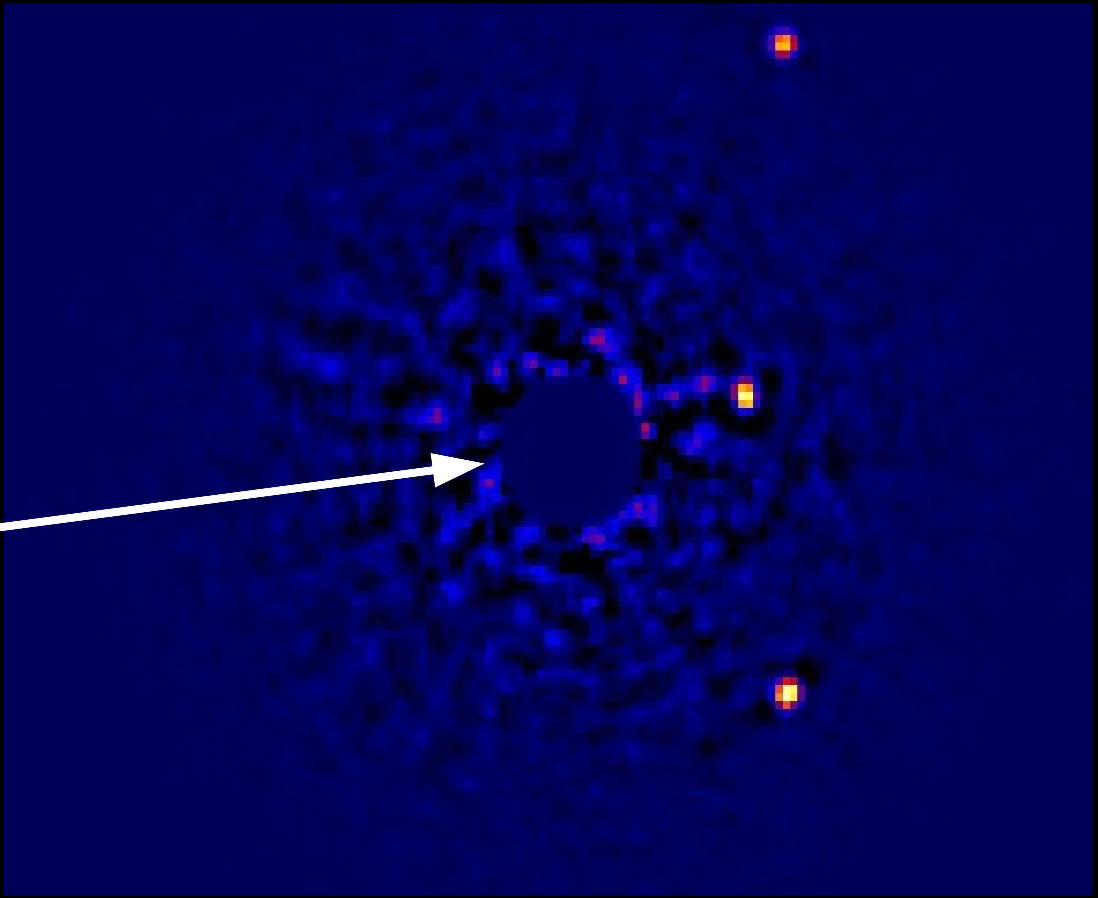


Capella
36mas separation

HR8799 system

Four planets, orbital periods on the order of 100yr
Each planet 5 to 7 Jupiter Mass

The central bright star is missing from the image: it has been successfully blocked by our optics, and removed by image processing

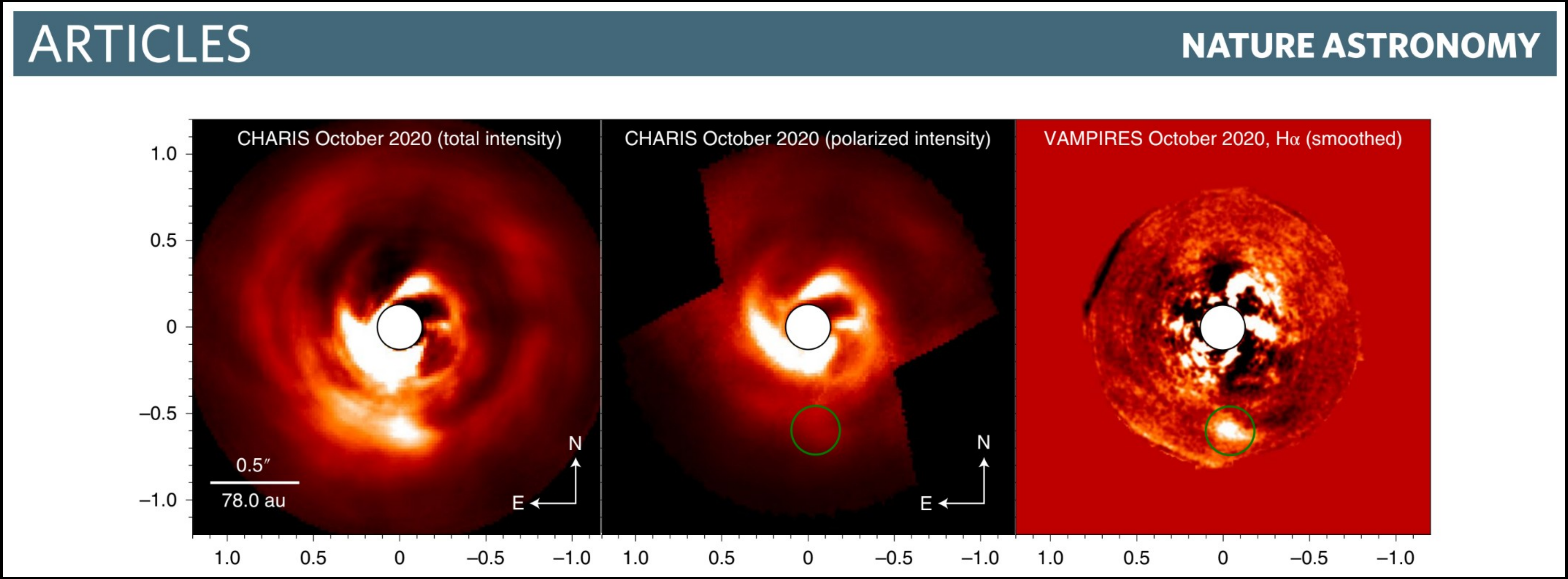


Subaru Telescope/ SCExAO (data reduction: T. Currie)

AB Aur b protoplanet

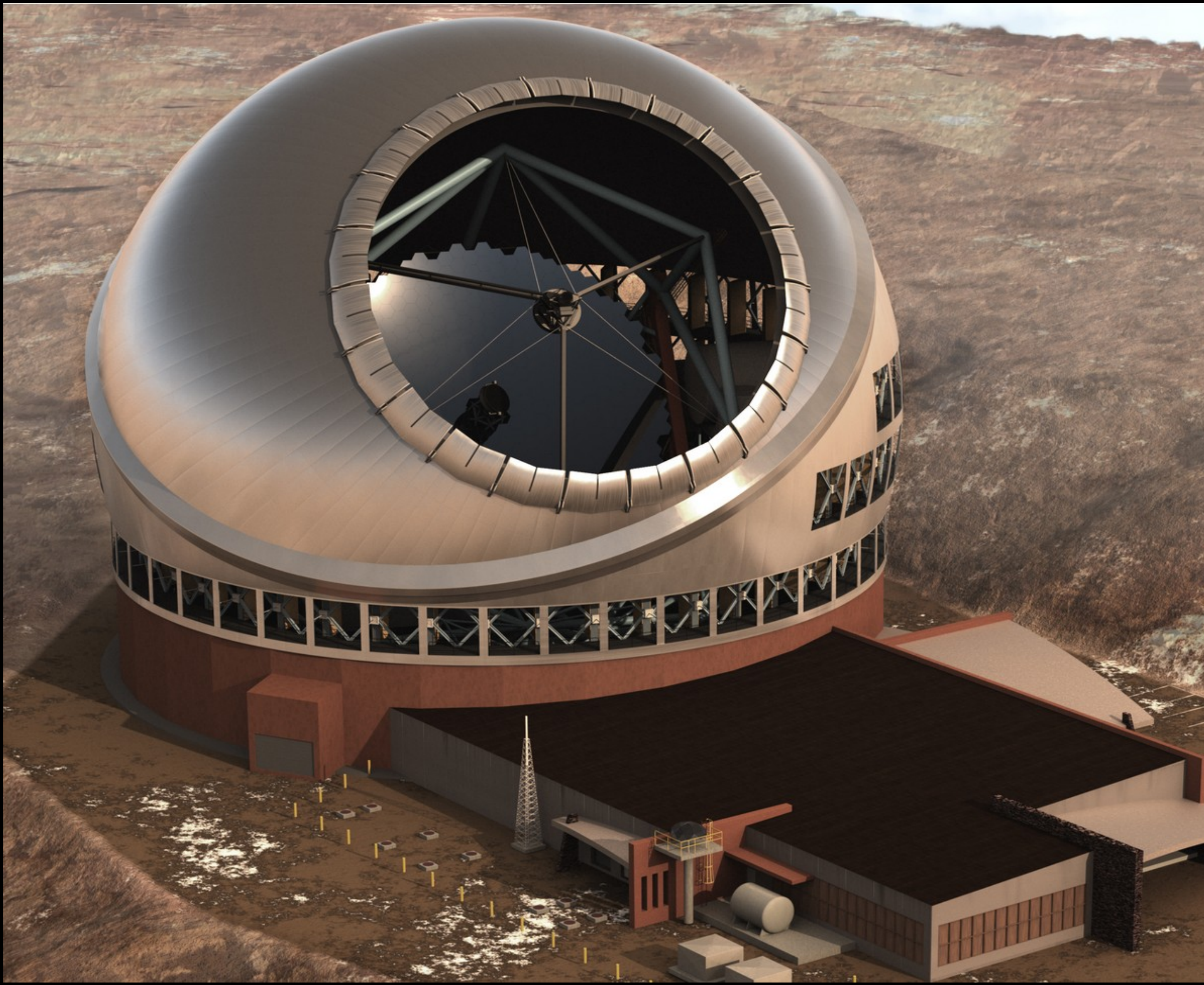
Planet is still forming from gravitational collapse of gas cloud

Mass ~ 9x Jupiter

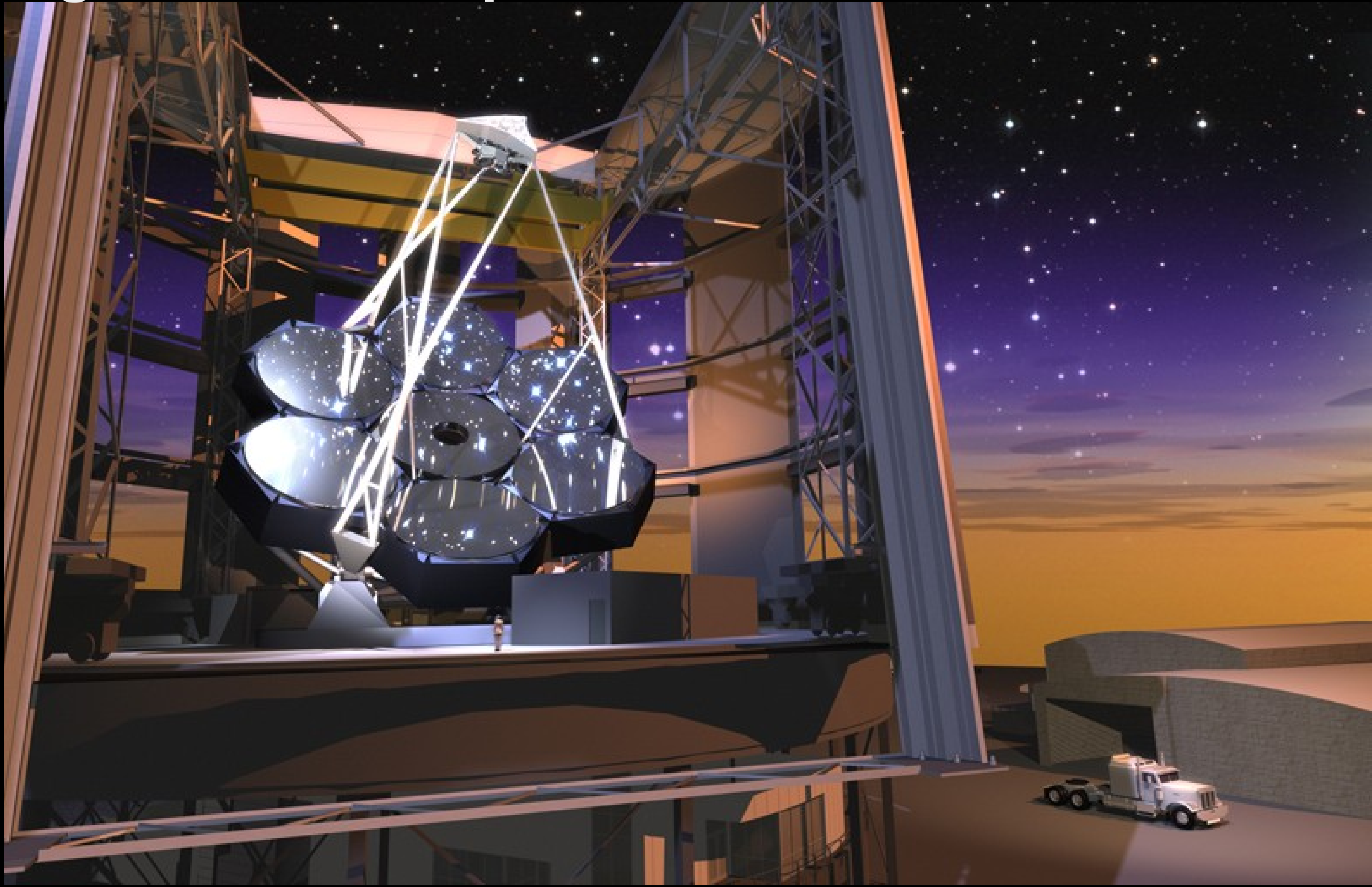


Subaru Telescope/ SCExAO (T. Currie et al. 2022)

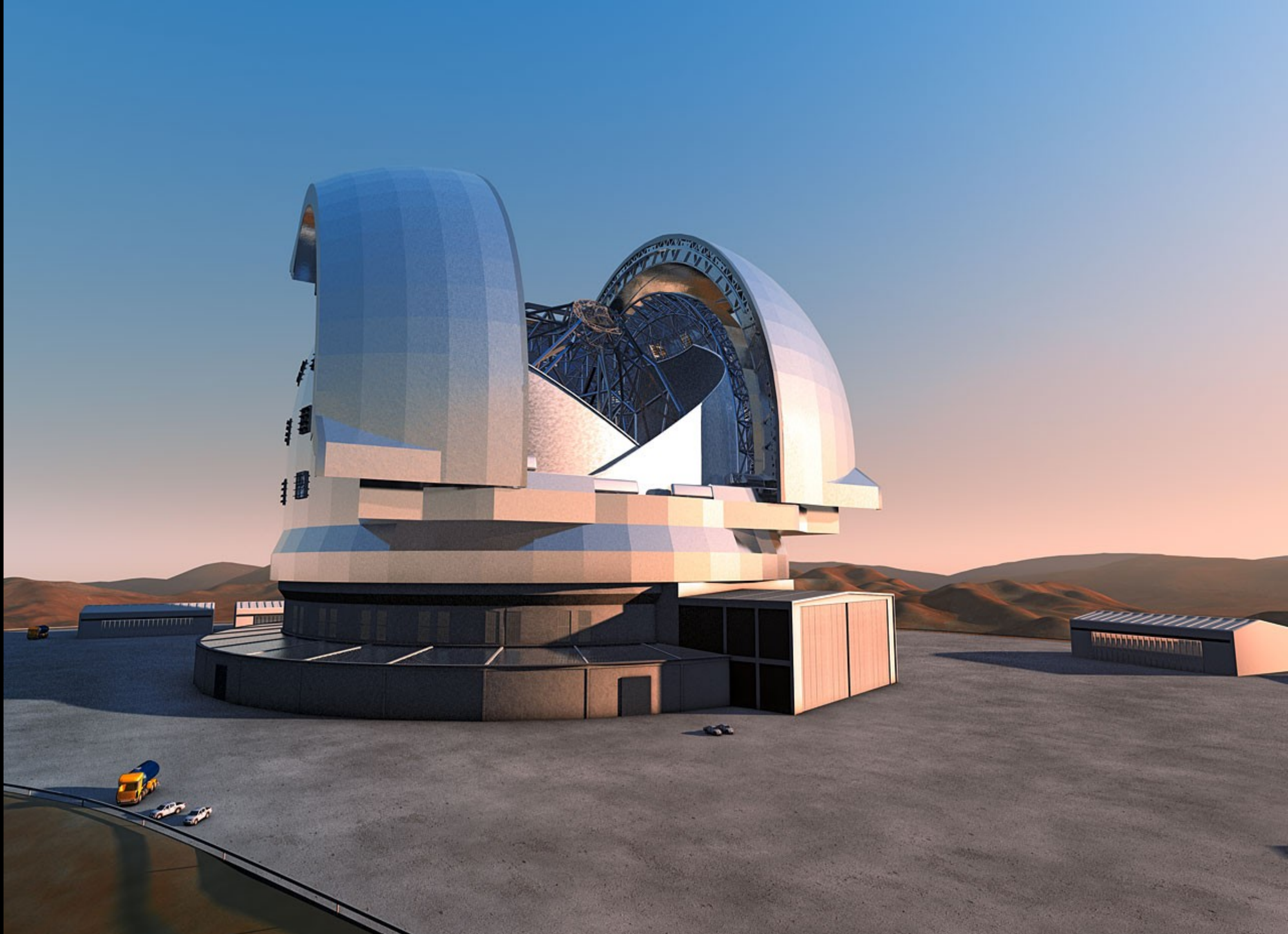
Thirty Meter Telescope



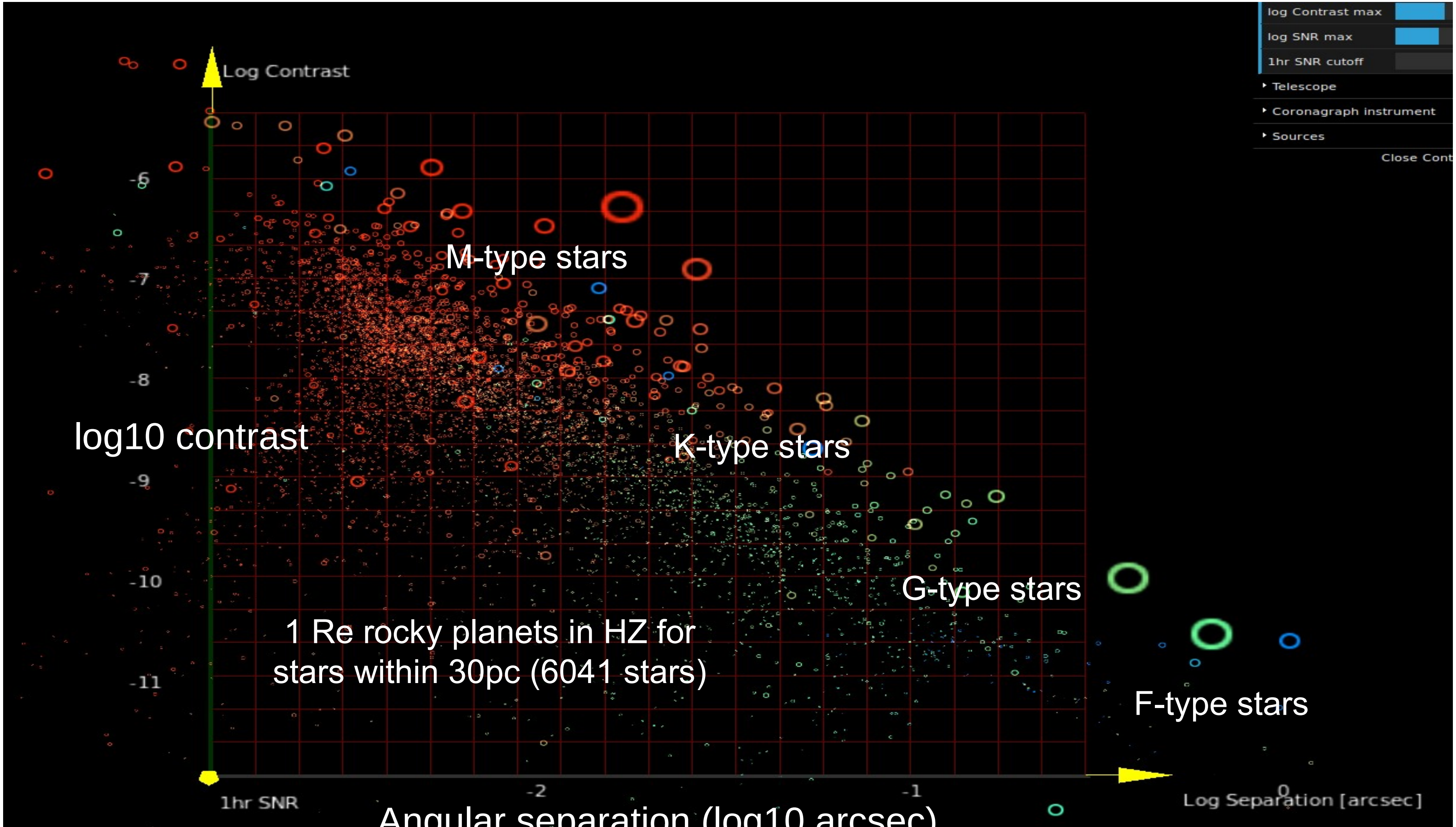
Giant Magellan Telescope



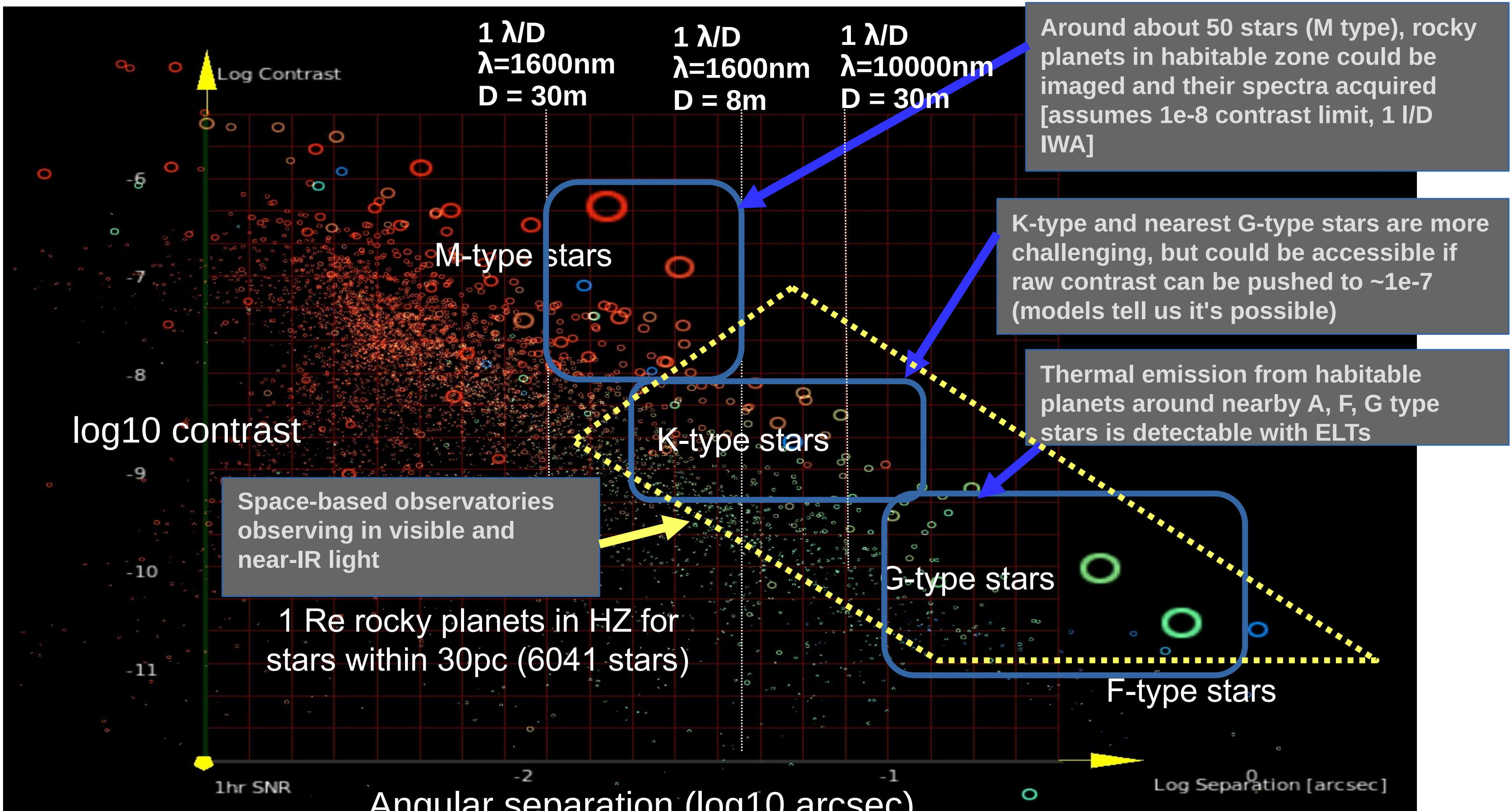
European Extremely Large Telescope



Contrast and Angular separation

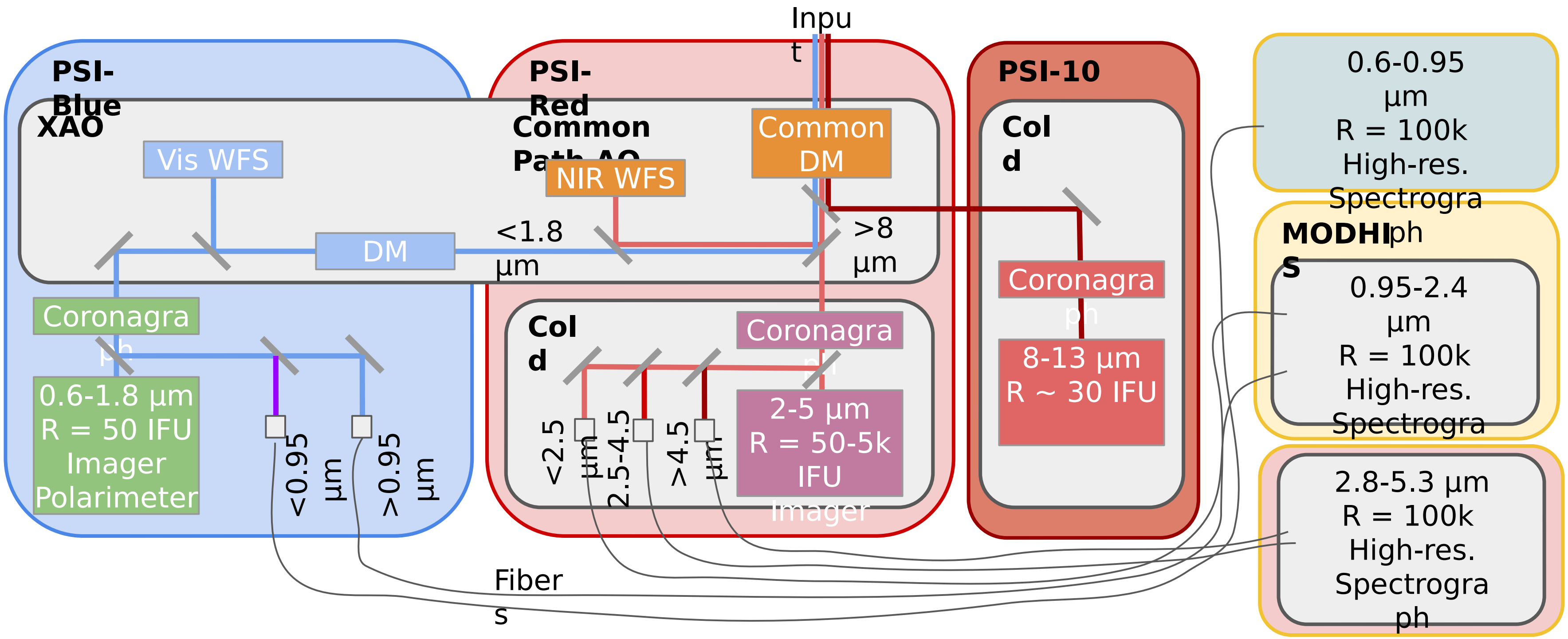


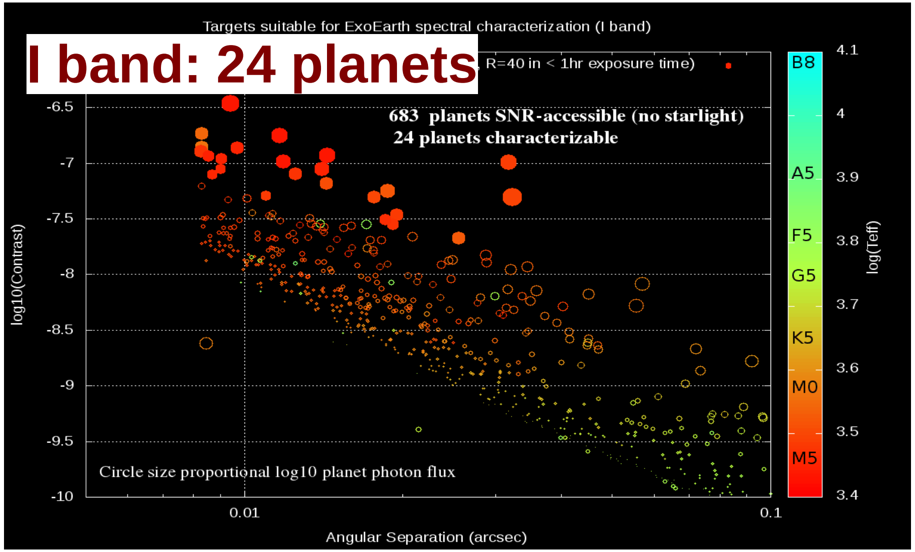
Contrast and Angular separation

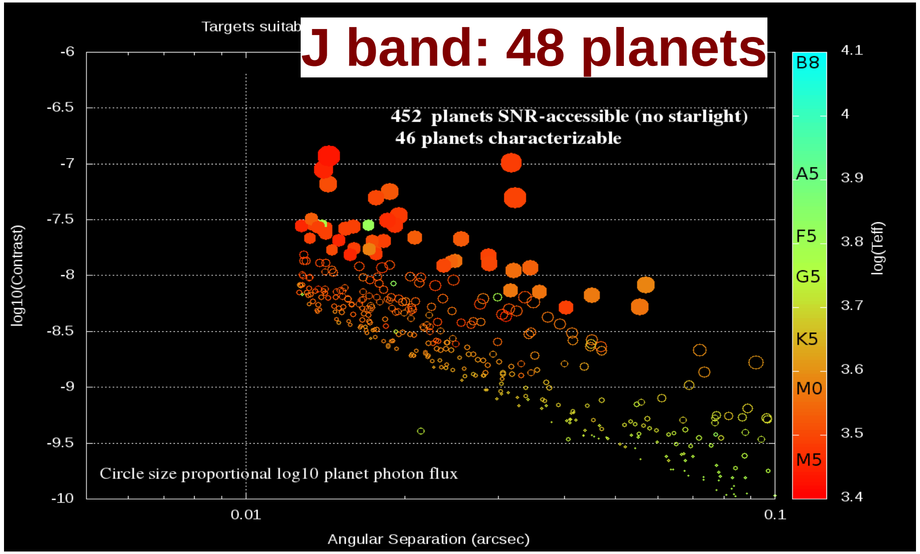


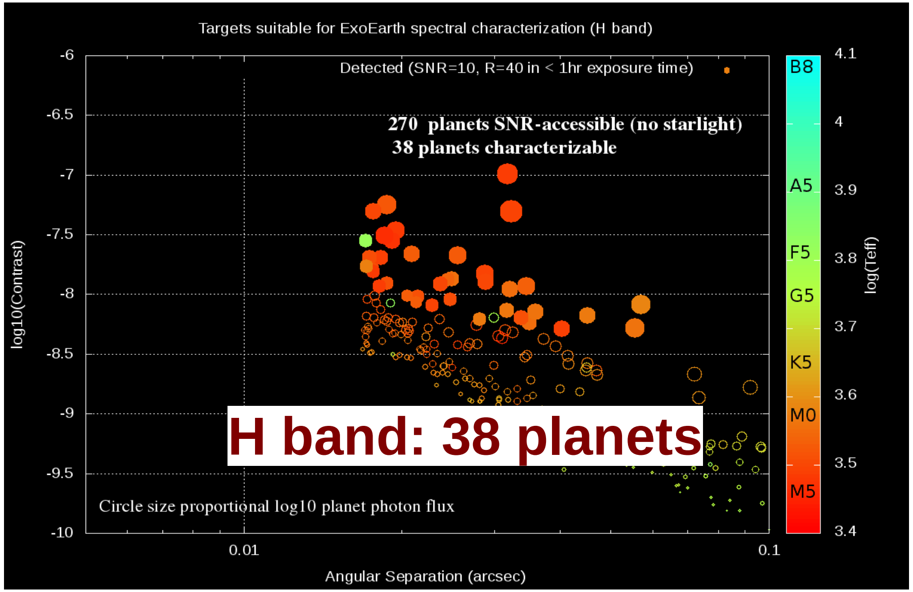
TMT Planetary Systems Imager (PSI)

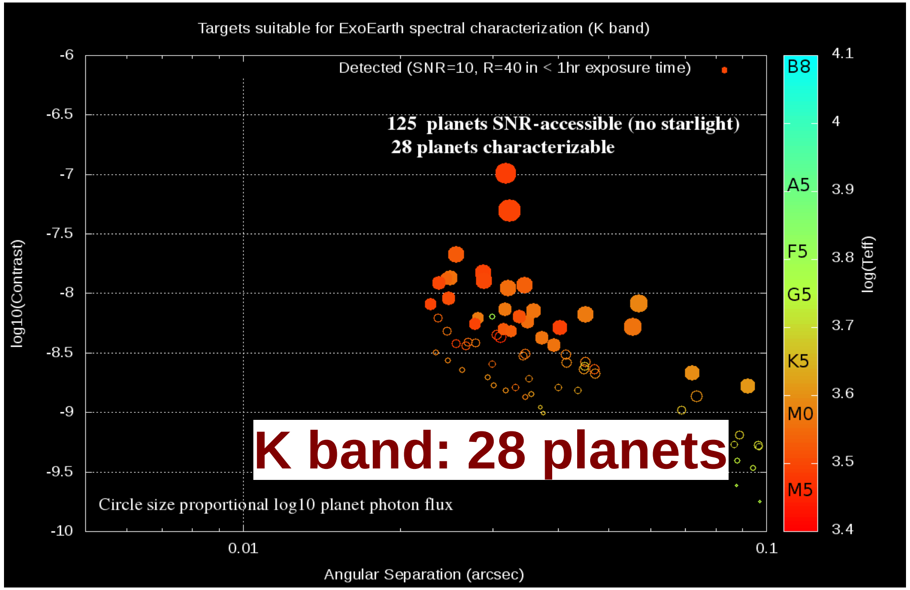
Northern Hemisphere
Broad wavelength coverage & spectroscopy

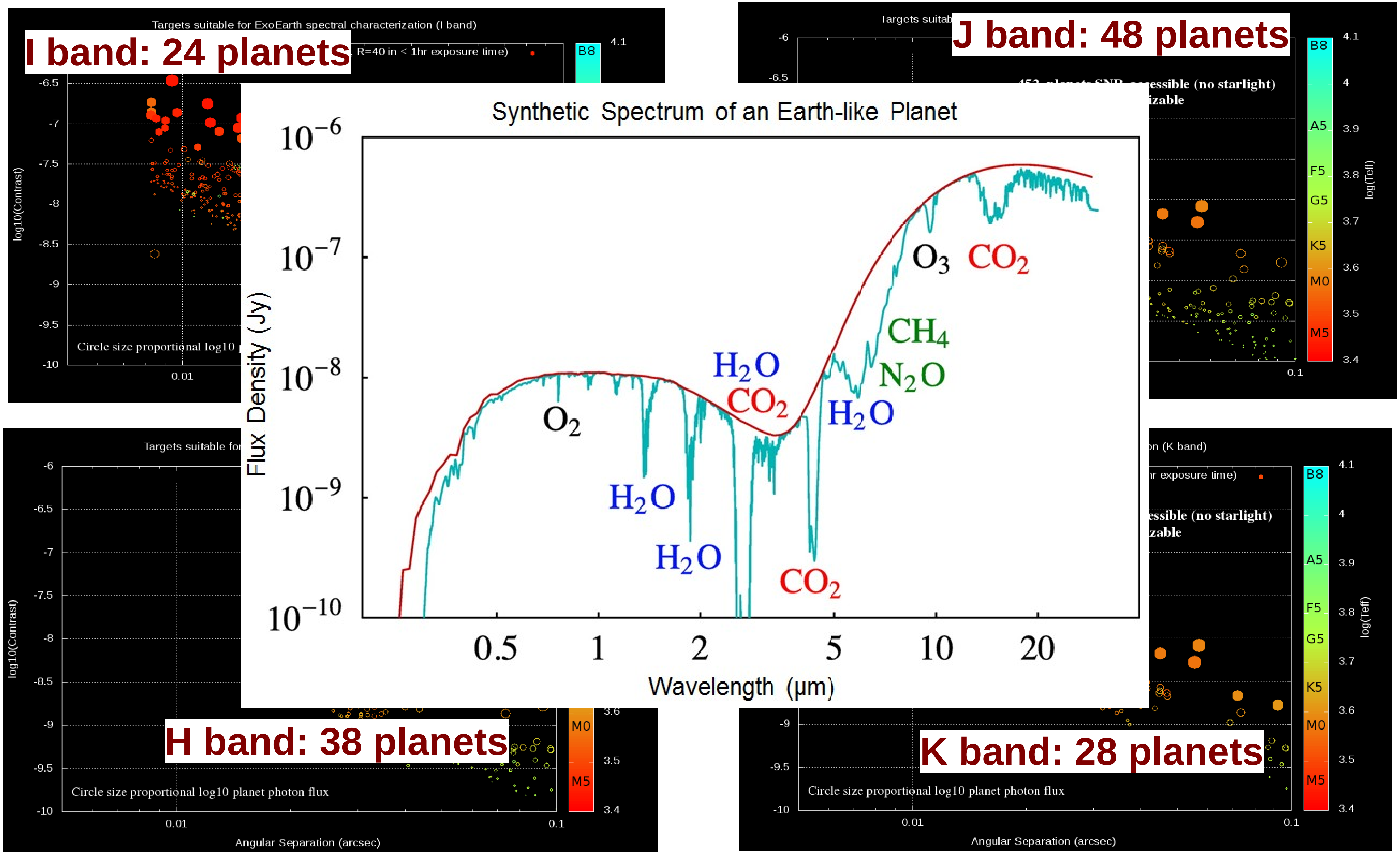



I band: 24 planets
Targets suitable for ExoEarth spectral characterization (I band)
R=40 in < 1hr exposure time)
683 planets SNR-accessible (no starlight)
24 planets characterizable
Circle size proportional log10 planet photon flux
log10(Contrast)
Angular Separation (arcsec)
log(Teff)
B8
A5
F5
G5
K5
M0
M5


J band: 48 planets
Targets suitab
452 planets SNR-accessible (no starlight)
46 planets characterizable
Circle size proportional log10 planet photon flux
log10(Contrast)
Angular Separation (arcsec)
log(Teff)
B8
A5
F5
G5
K5
M0
M5


Targets suitable for ExoEarth spectral characterization (H band)
Detected (SNR=10, R=40 in < 1hr exposure time)
270 planets SNR-accessible (no starlight)
38 planets characterizable
H band: 38 planets
Circle size proportional log10 planet photon flux
log10(Contrast)
Angular Separation (arcsec)
log(Teff)
B8
A5
F5
G5
K5
M0
M5


Targets suitable for ExoEarth spectral characterization (K band)
Detected (SNR=10, R=40 in < 1hr exposure time)
125 planets SNR-accessible (no starlight)
28 planets characterizable
K band: 28 planets
Circle size proportional log10 planet photon flux
log10(Contrast)
Angular Separation (arcsec)
log(Teff)
B8
A5
F5
G5
K5
M0
M5


I band: 24 planets
J band: 48 planets
H band: 38 planets
K band: 28 planets
Targets suitable for ExoEarth spectral characterization (I band)
R=40 in < 1hr exposure time)
Circle size proportional log10 planet photon flux
Angular Separation (arcsec)
log10(Contrast)
log(Teff)
B8
A5
F5
G5
K5
M0
M5
Synthetic Spectrum of an Earth-like Planet
Flux Density (Jy)
Wavelength (μm)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
0.5
1
2
5
10
20
O_2
H_2O
CO_2
O_3
CH_4
N_2O

AO & Infrastructure Upgrades at Subaru Telescope

Major upgrades are bringing SCExAO closer to TMT-PSI

Upgrades to 1st stage AO correction will boost performance:

[spring 2023] 1st stage Deformable Mirror: 188 elements → 3228 elements
Validating DM technology envisioned for TMT-PSI

[spring 2023] Adding high-order NearIR wavefront sensing

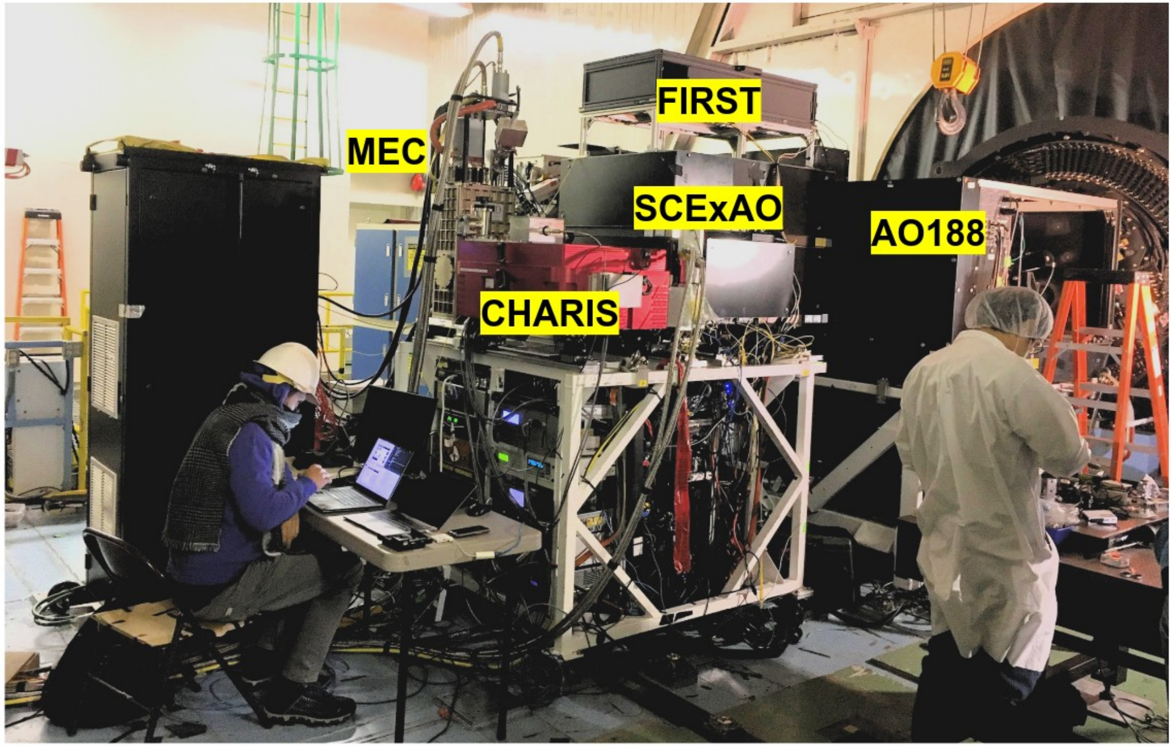
[late 2023] Adding 1st stage high order visible WFS

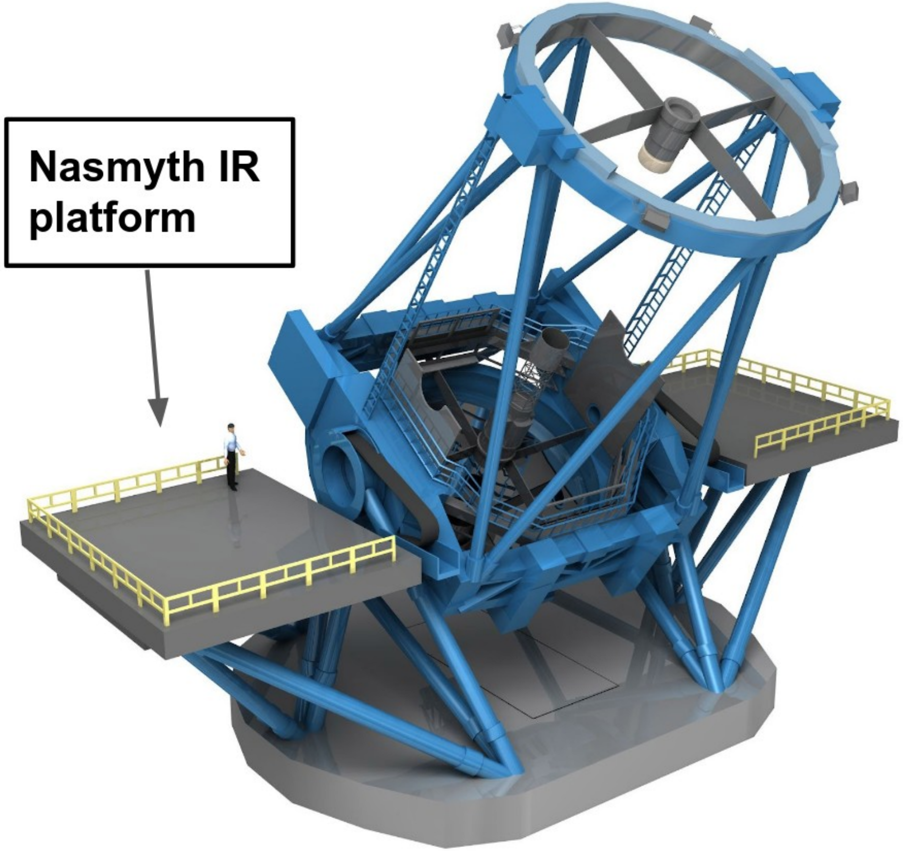
Infrastructure:

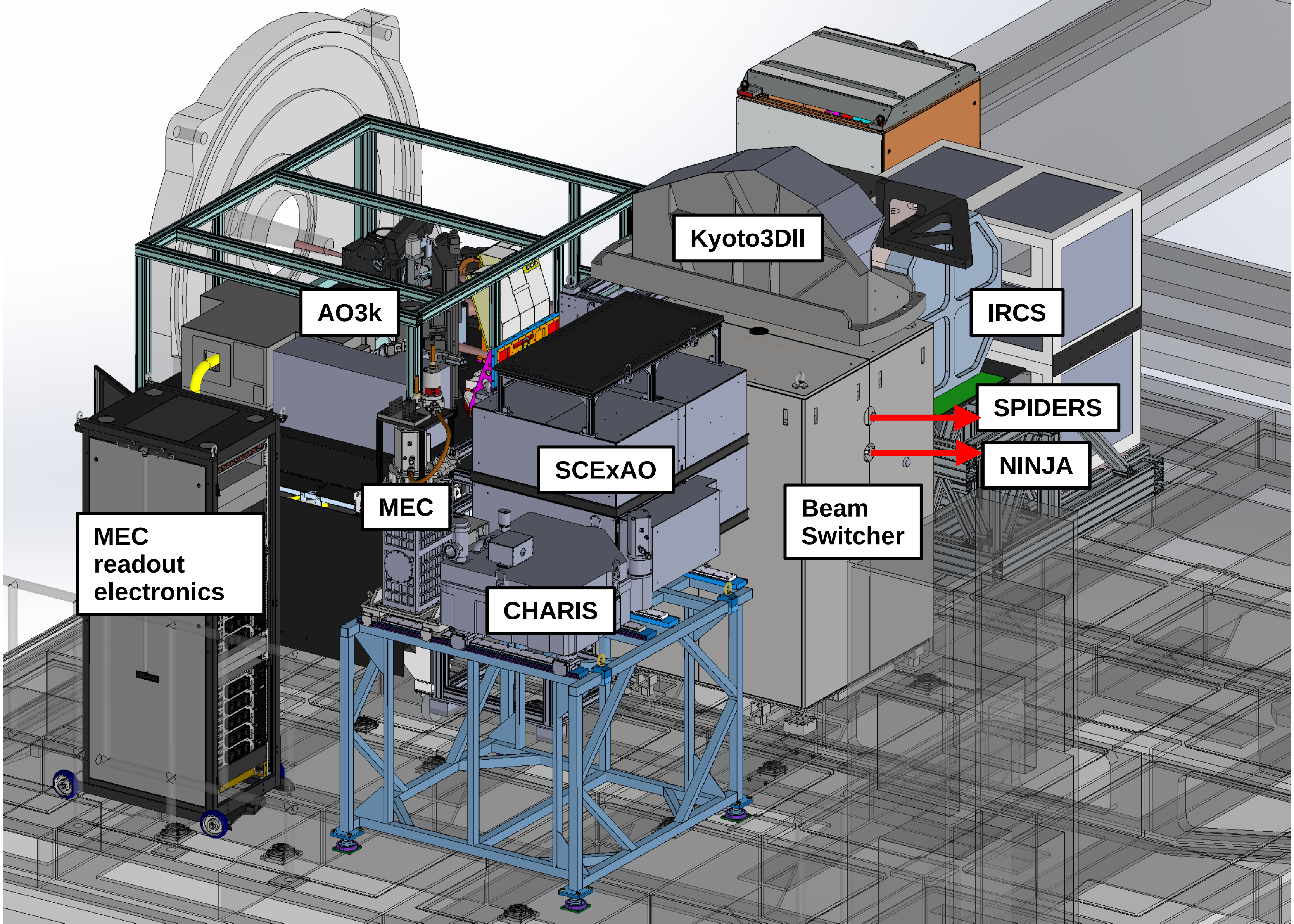
[2024] Beam switcher → easier operation + supports advanced modes

[2023+] Laser tomographic AO → access to fainter sources

[2026+] Adaptive Secondary Mirror


FIRST
MEC
SCExAO
AO188
CHARIS


Nasmyth IR
platform

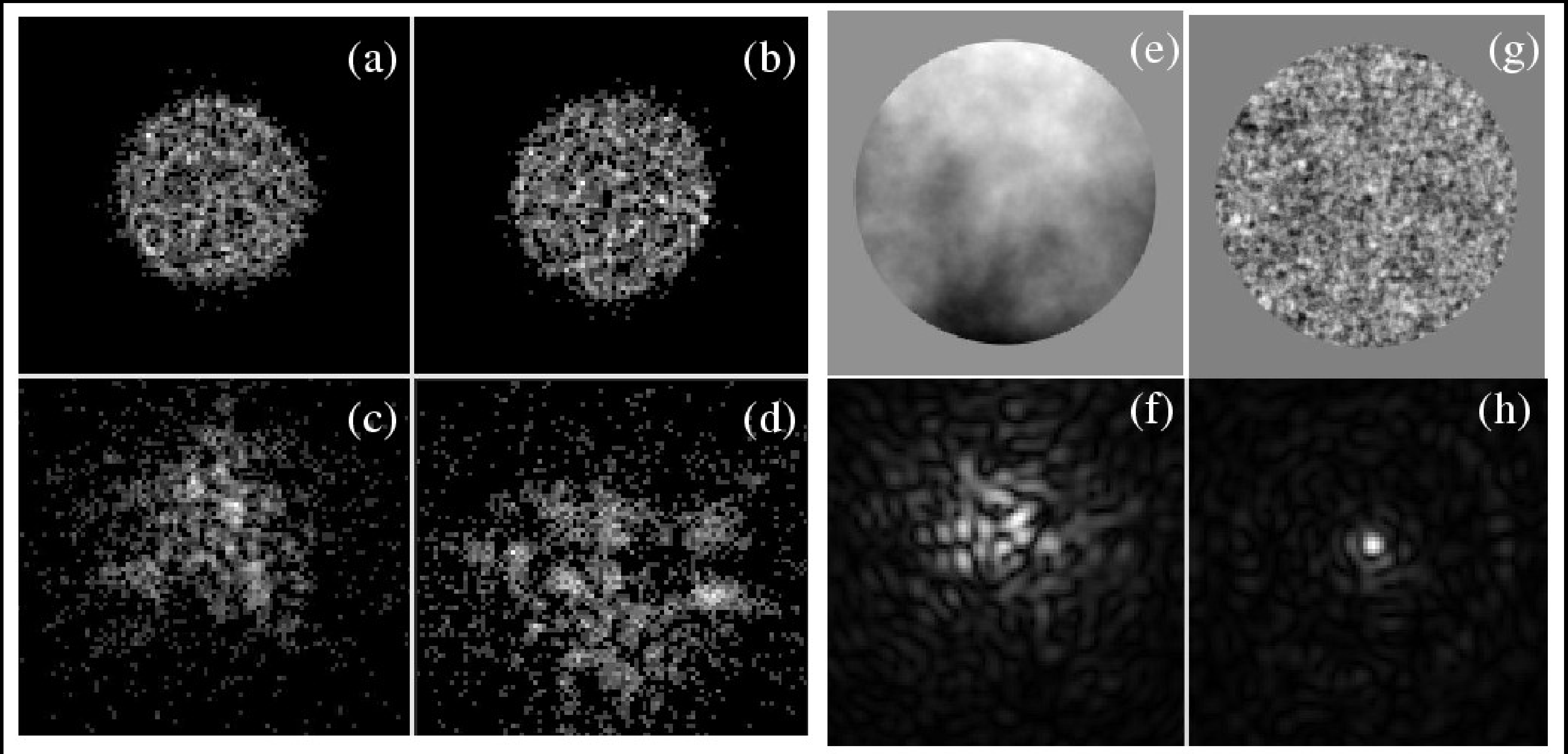


Kyoto3DII
AO3k
IRCS
SPIDERS
NINJA
SCExAO
MEC
Beam Switcher
MEC readout electronics
CHARIS

Advanced Control Techniques for Extreme AO

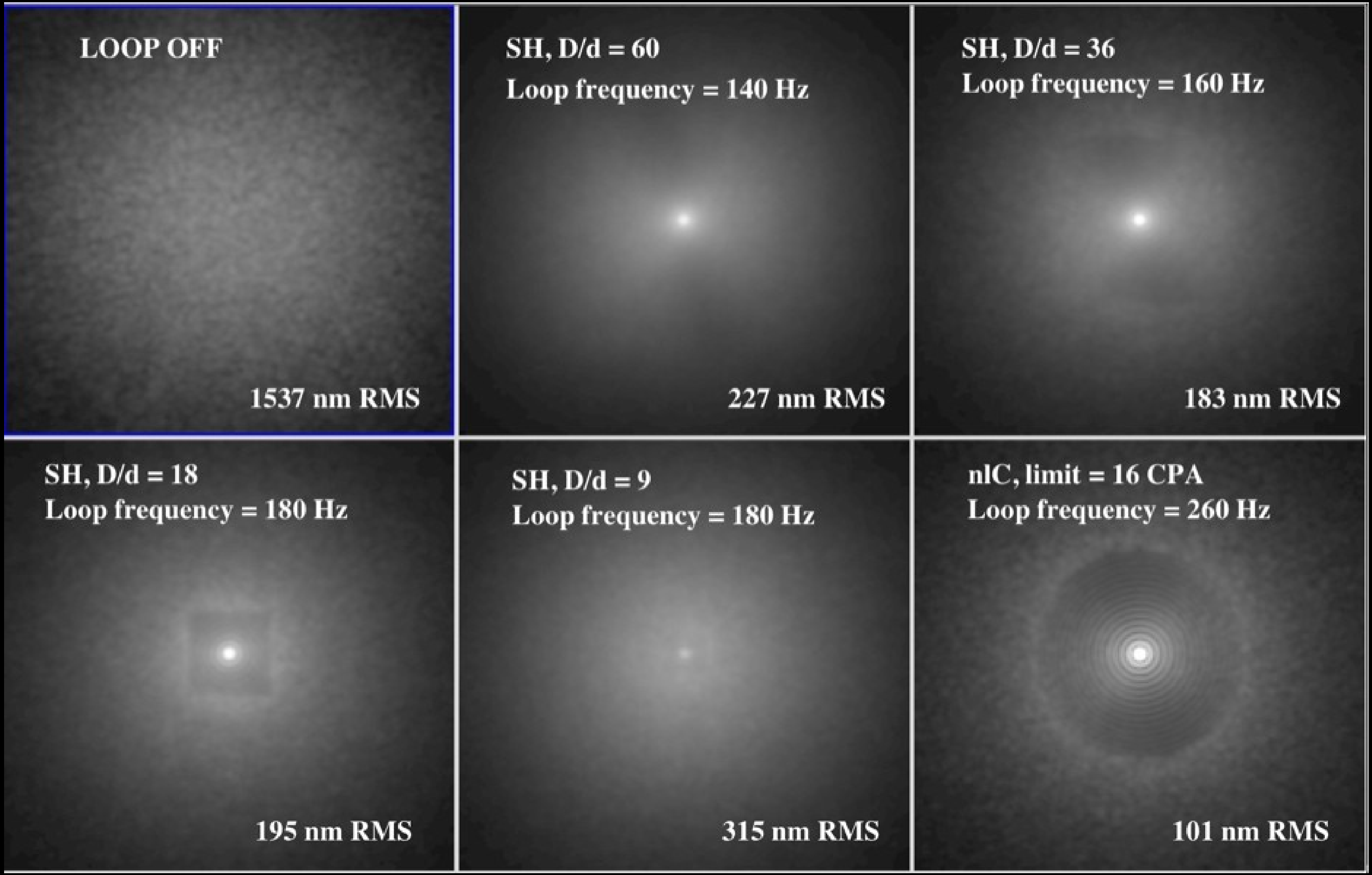
Phase Diversity / Curvature WFS: Reconstruction Simulation

20,000 ph total: 609nm → 34.4nm RMS



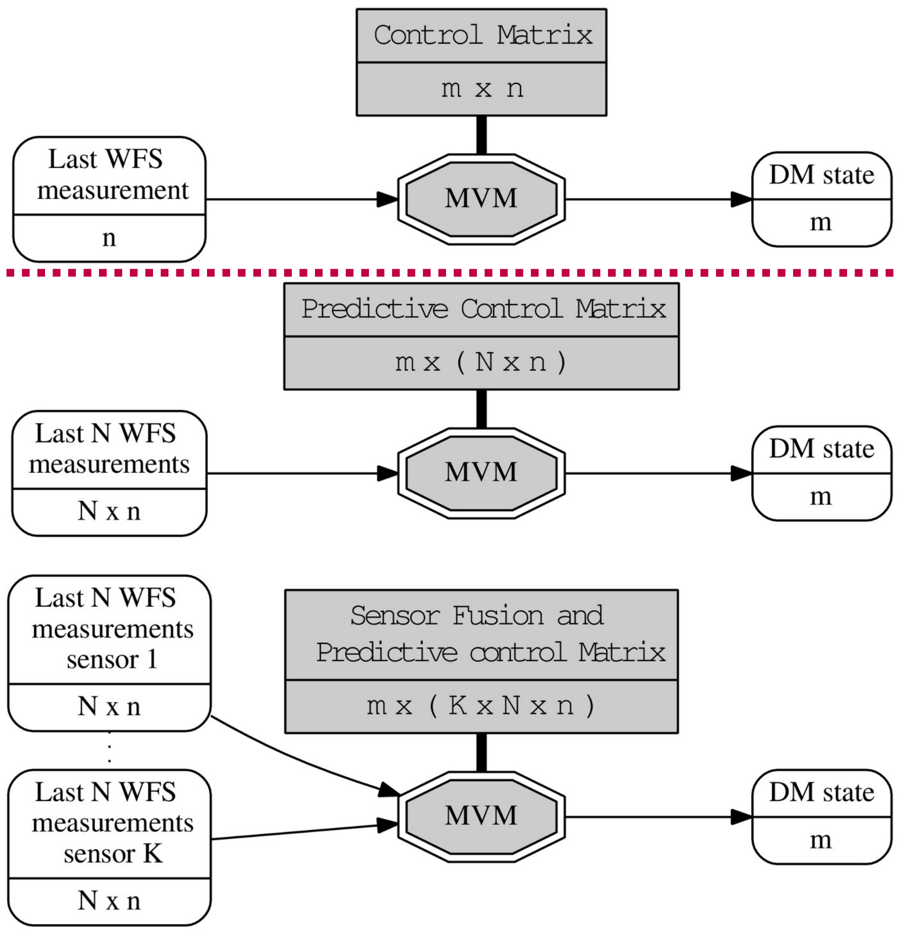
non-linear Curvature WFS: AO loop Simulation

Computer Simulations showing contrast gain with high sensitivity WFS (non-linear curvature)



Predictive Control and Sensor Fusion

Conventional AO:
<u>Measured</u> RM/CM

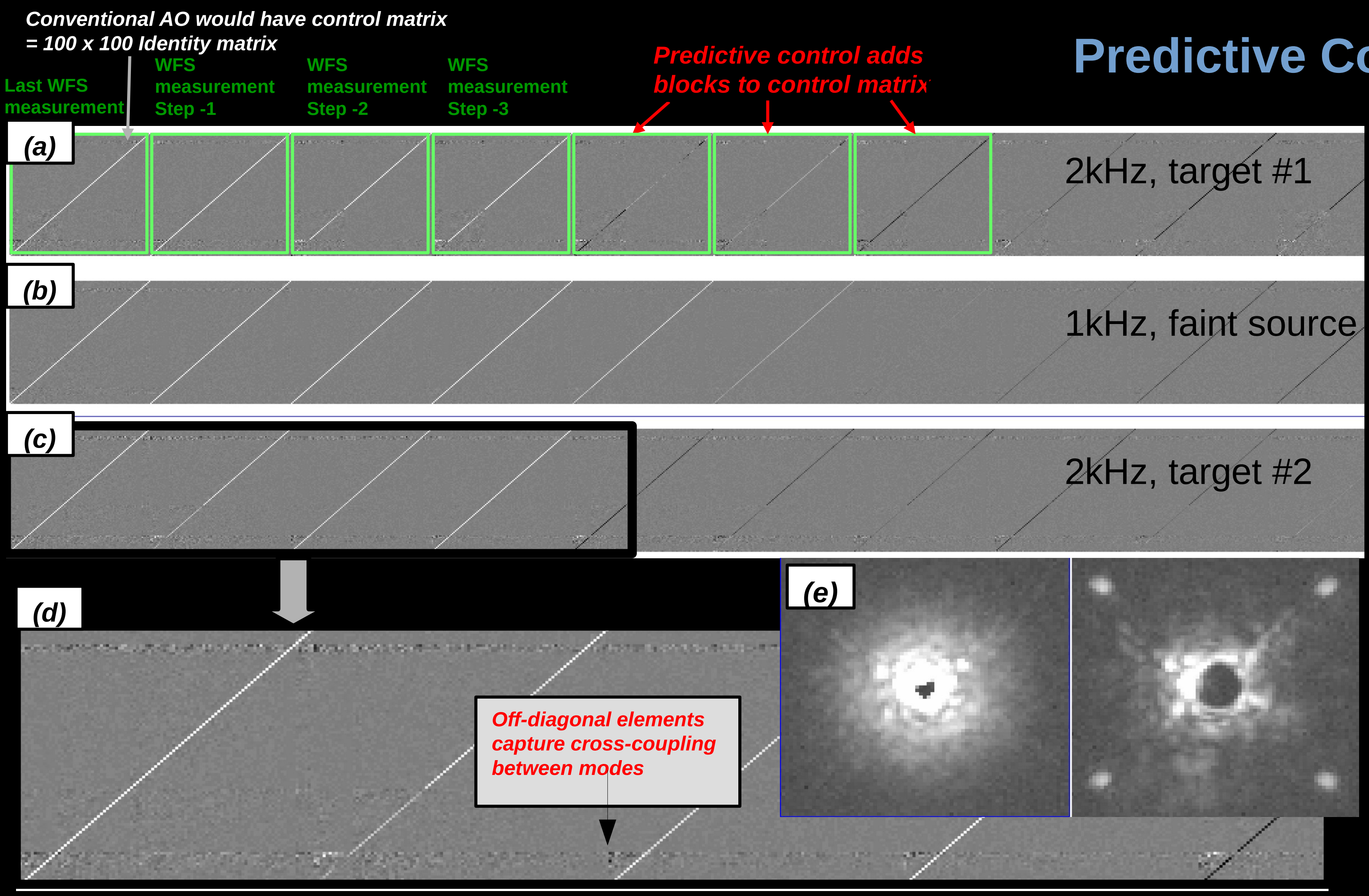


Advanced AO control:

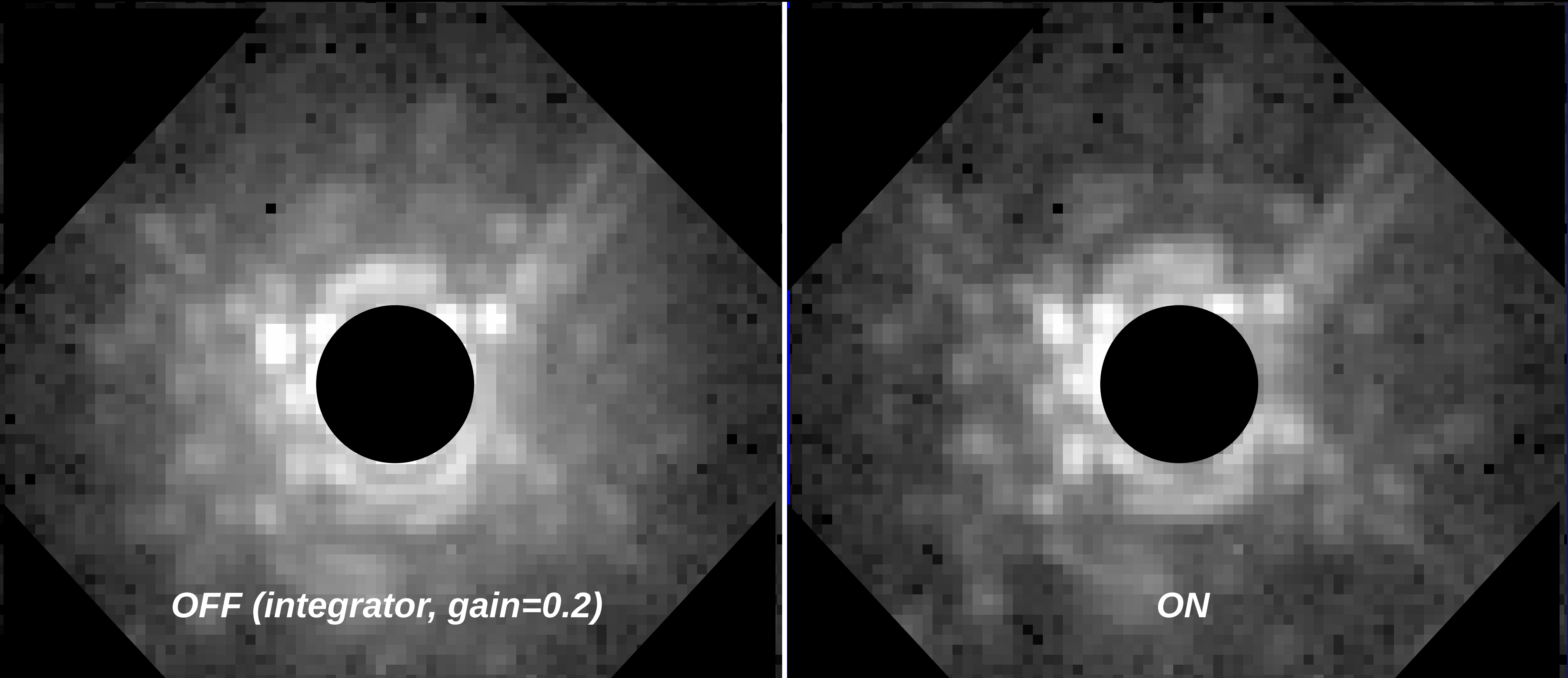
Using past measurements (predictive control) and other measurements (sensor fusion) → control matrix is very big, and usually impossible to measure

We **<u>derive</u>** CM from WFS(s) telemetry

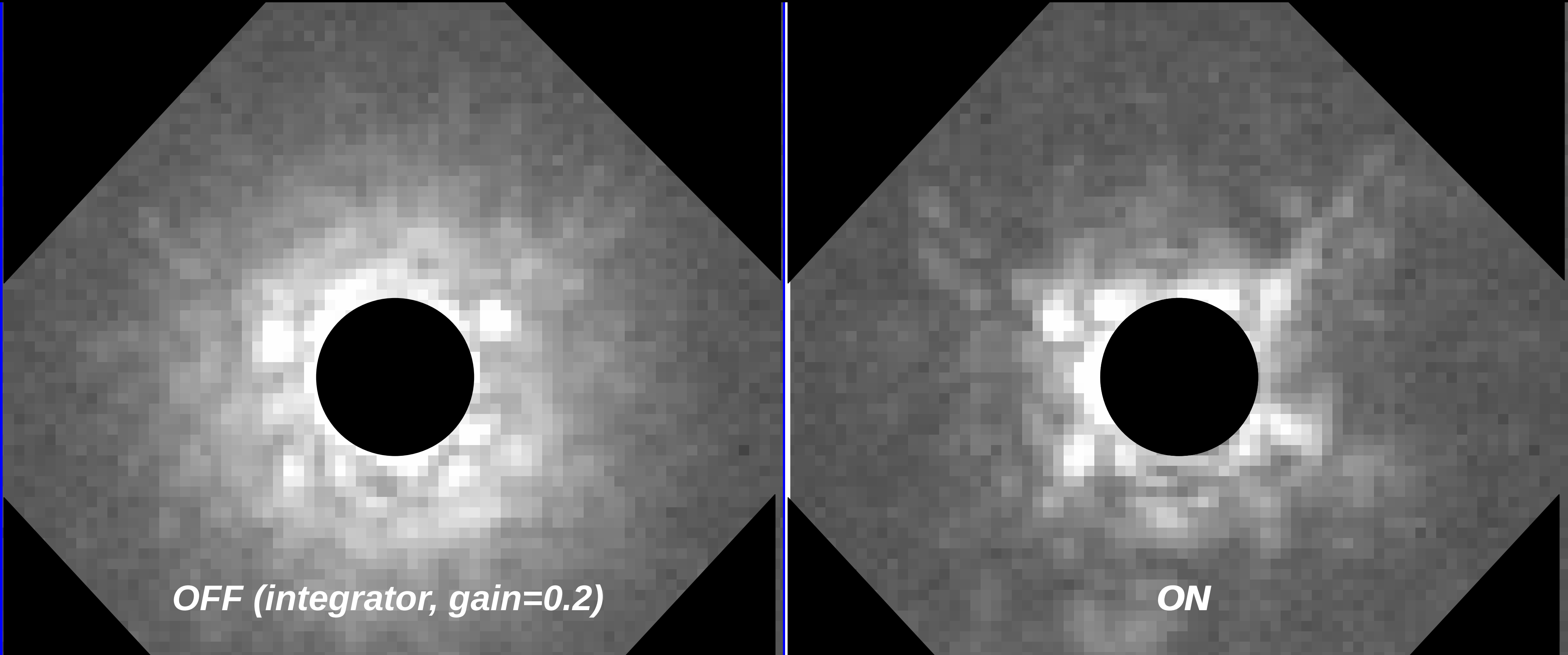
Predictive Control



Machine Learning based predictive control
First on-sky results (2 kHz, 50 sec update)
→ 2.5x raw contrast improvement

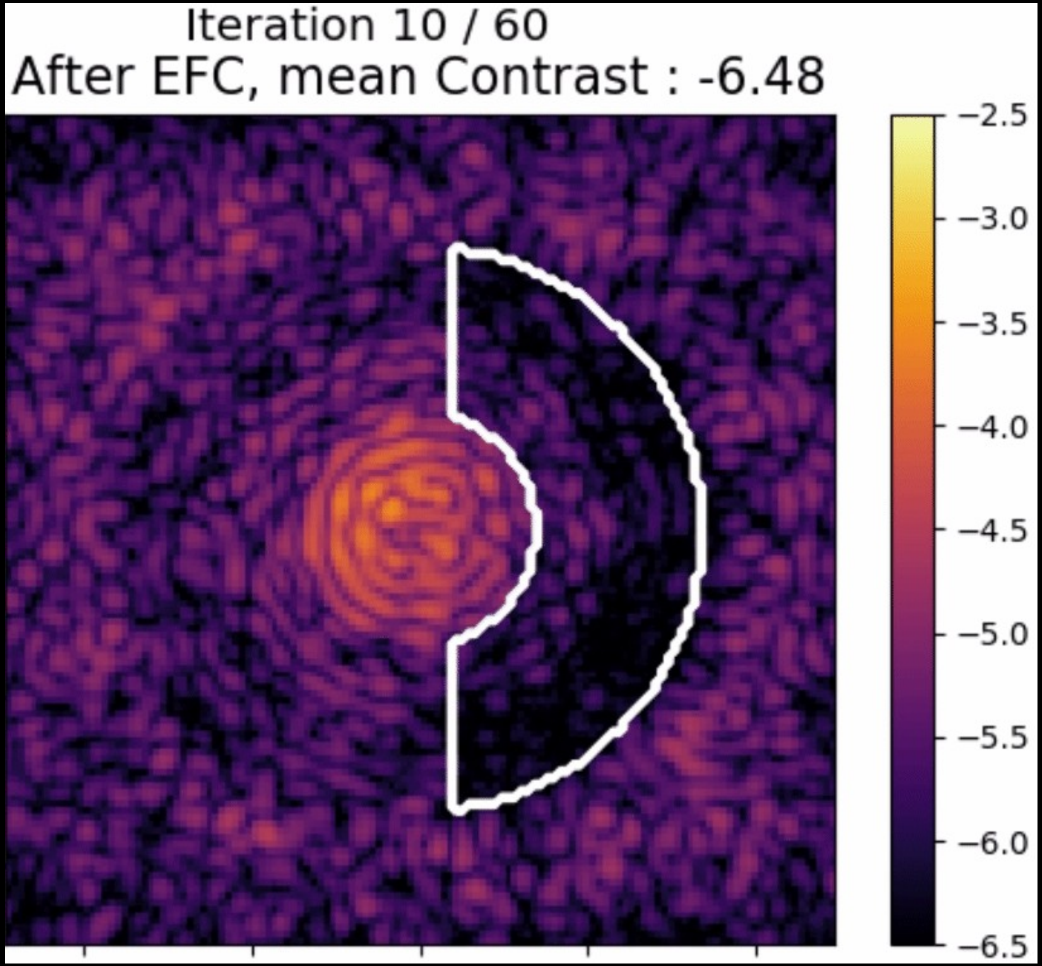


Improved Image Stability



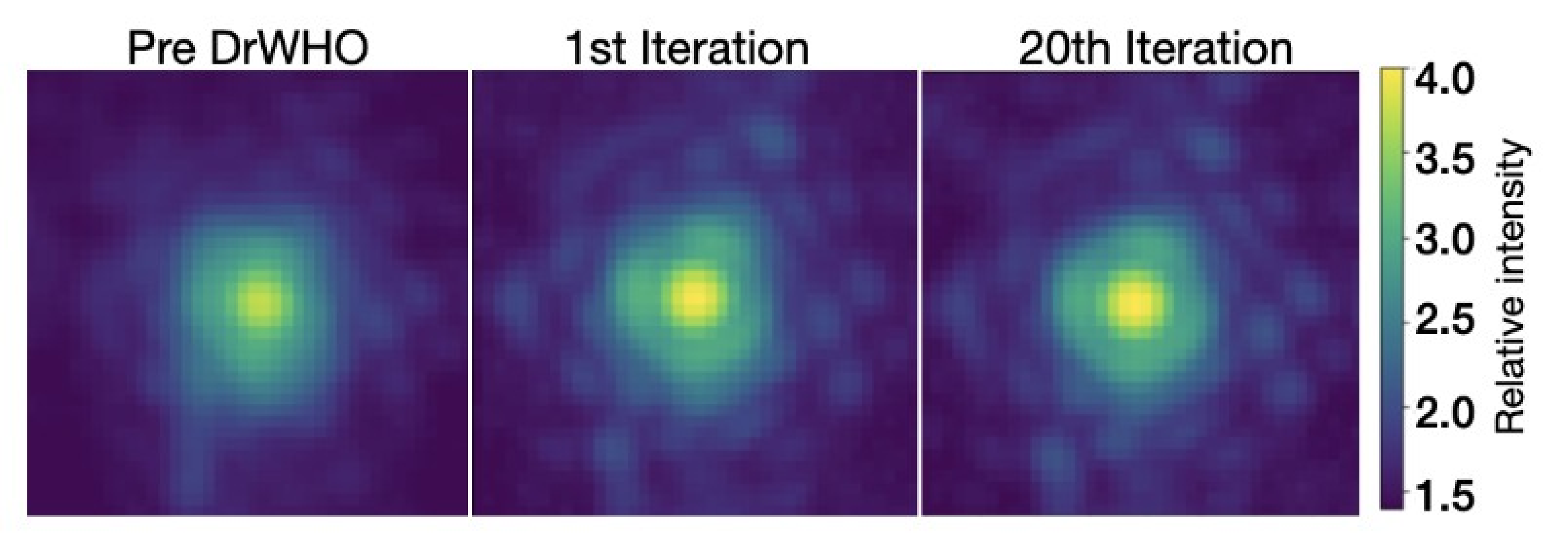
Standard deviation of 54 consecutives 0.5s images (26 sec exposure), 2 mn apart

Using Focal Plane Image for AO



Electric Field Conjugation
(K. Ahn, 2021)

Improving Image Quality by “Learning” from Focal Plane Image

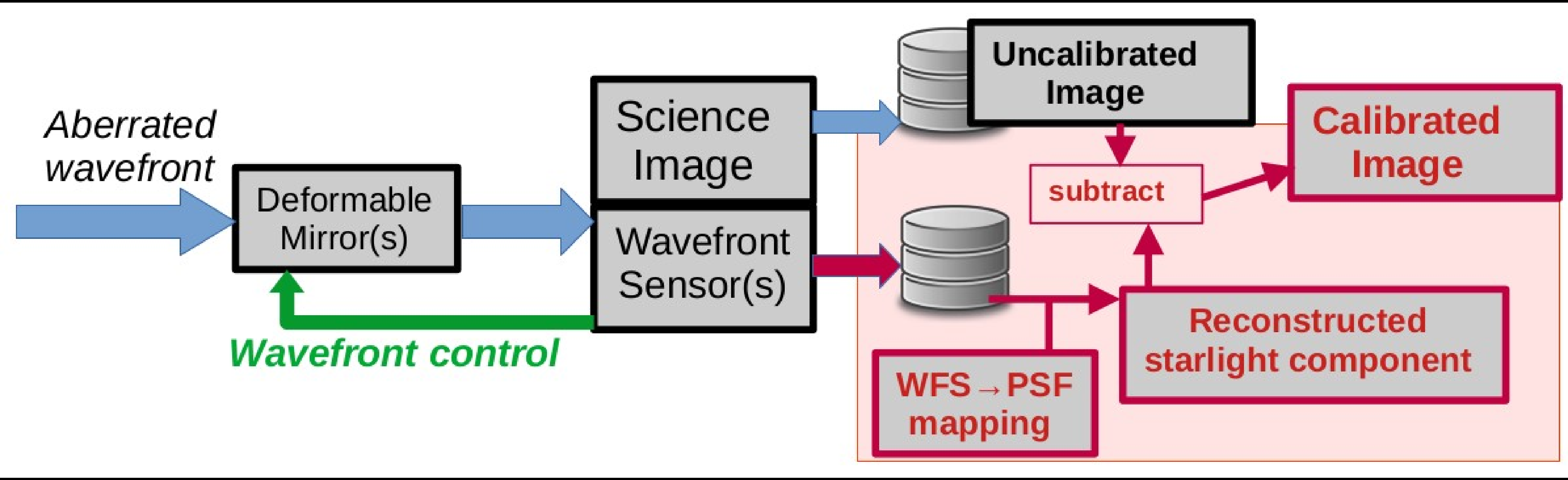


Evolution of the on-sky PSF before running the algorithm, after the first iteration, and the after last iteration. Each image is 0.25 arcsec (40x40 pixels) across, acquired at λ = 750 nm, 30 sec exposure time (computed by co-addition of 15,000 frames acquired at 500 Hz)

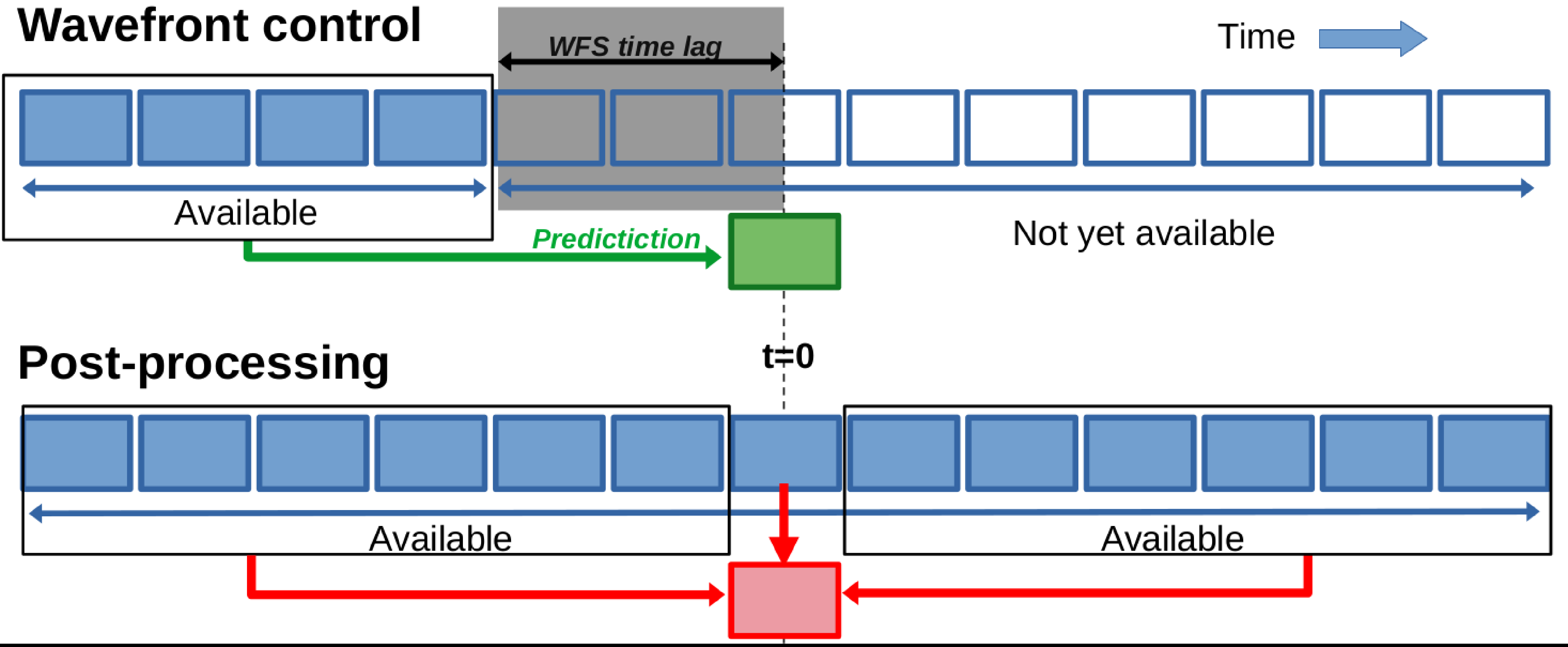
Skaf et al. 2022

Self-Calibrating
High Contrast Imaging

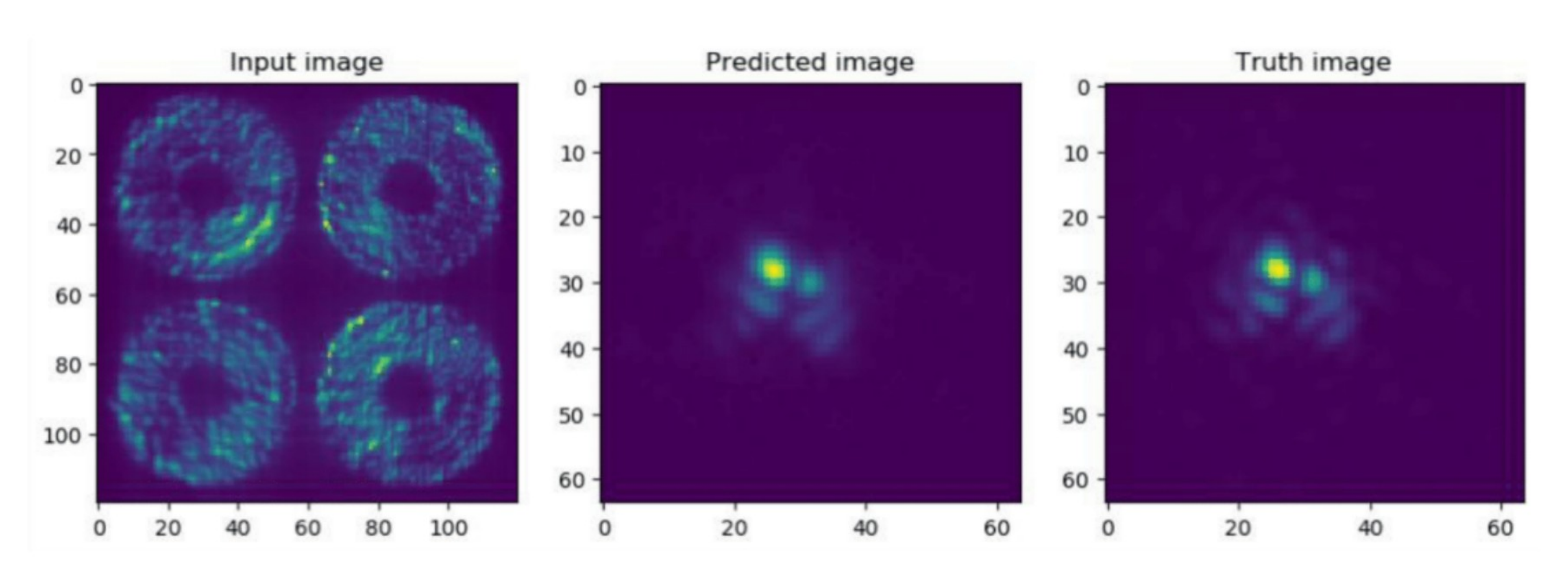
Principle


Aberrated wavefront
Deformable Mirror(s)
Science Image
Wavefront Sensor(s)
Wavefront control
Uncalibrated Image
subtract
Calibrated Image
Reconstructed starlight component
WFS → PSF mapping

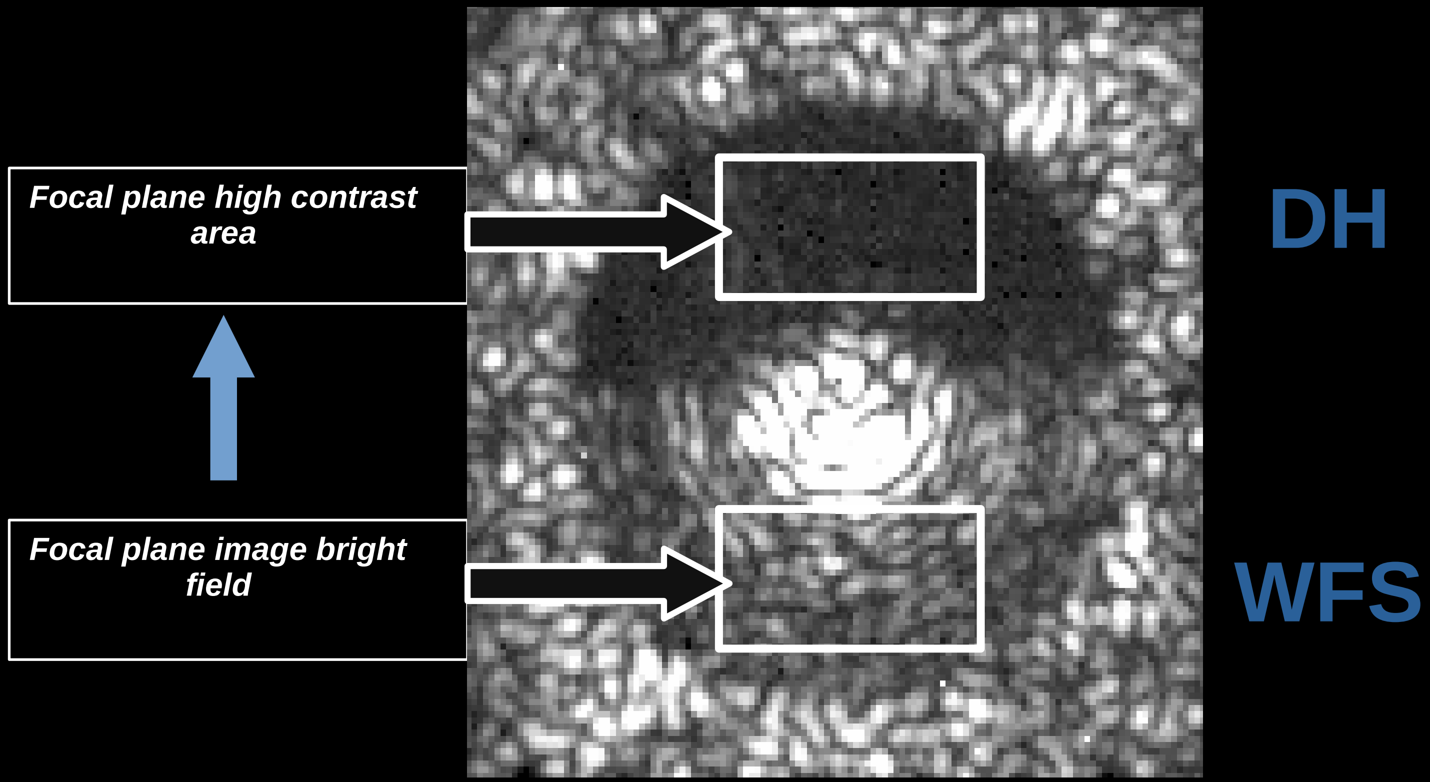
Why is Post-processing calibration better than AO control ?



Encouraging work: Neural Net PSF reconstruction



Credit: Barnaby Norris & Alison Wong

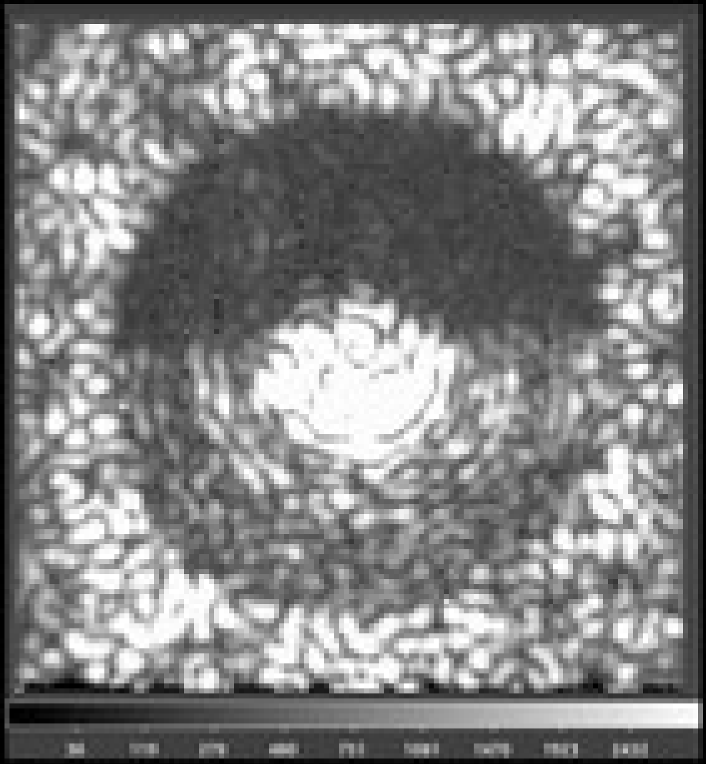


Focal plane high contrast area
Focal plane image bright field
DH
WFS

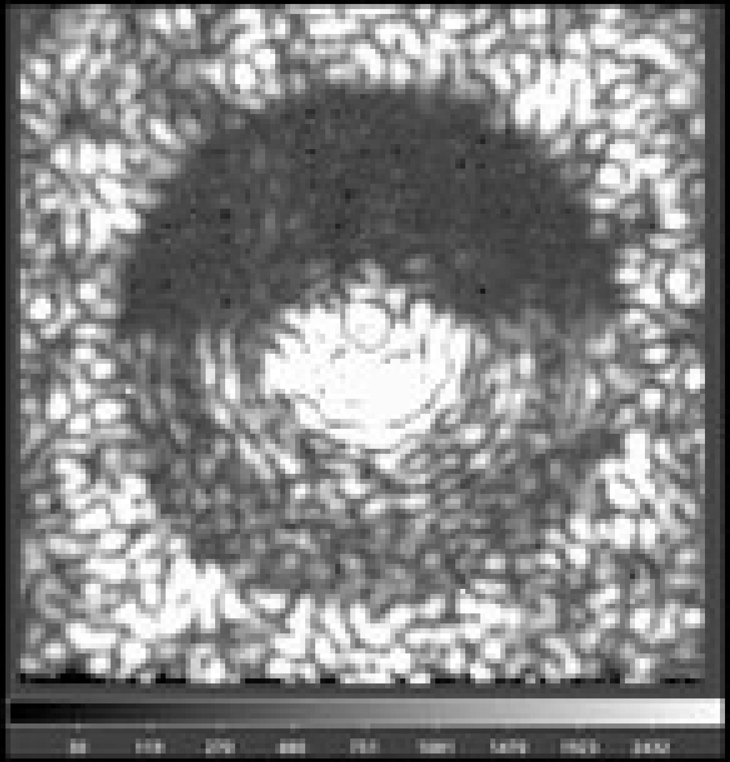
Experimental validation (lab)

1550nm, 25nm BW, Lyot Coronagraph, 7 kHz frame rate

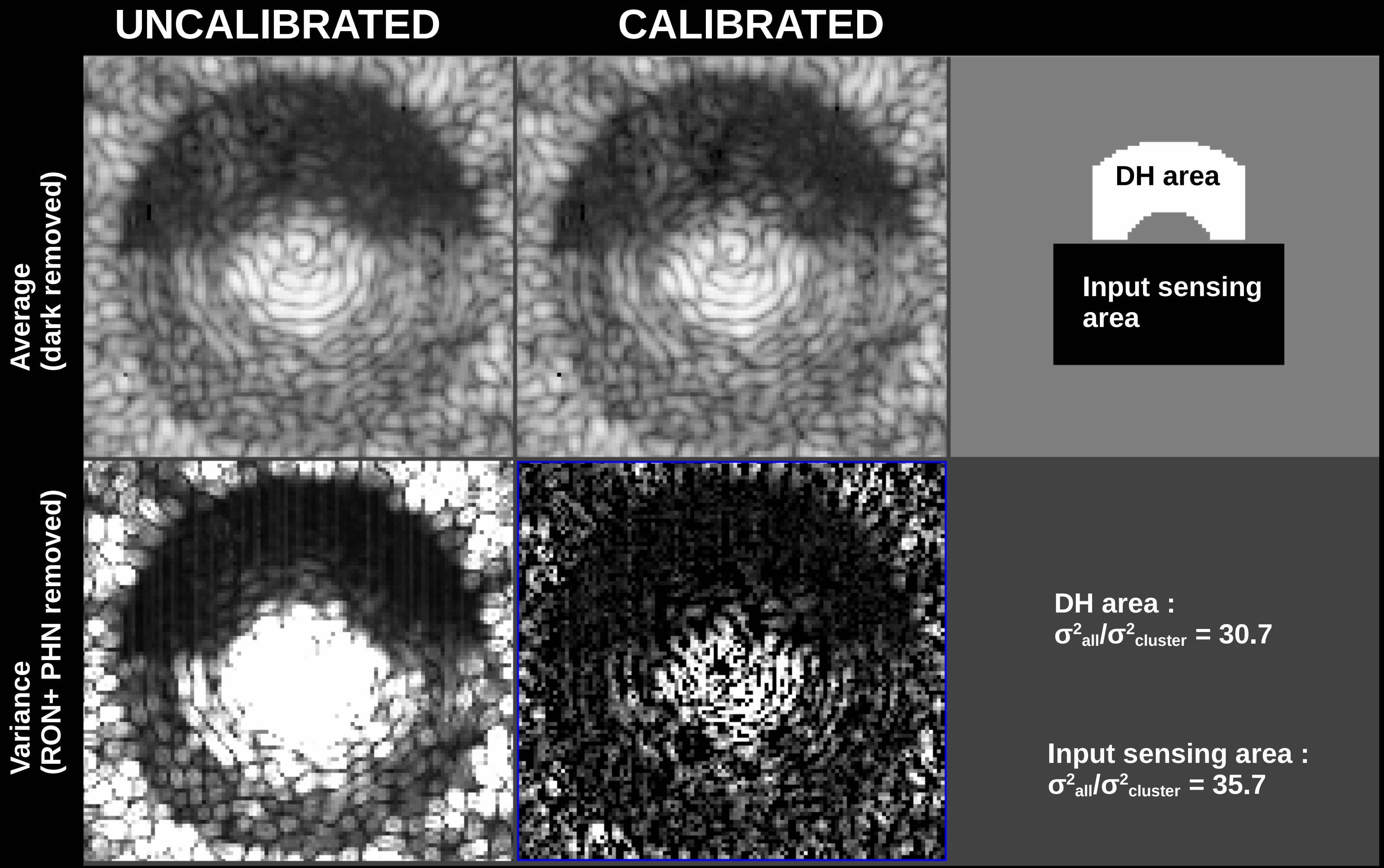
UNCALIBRATED



CALIBRATED

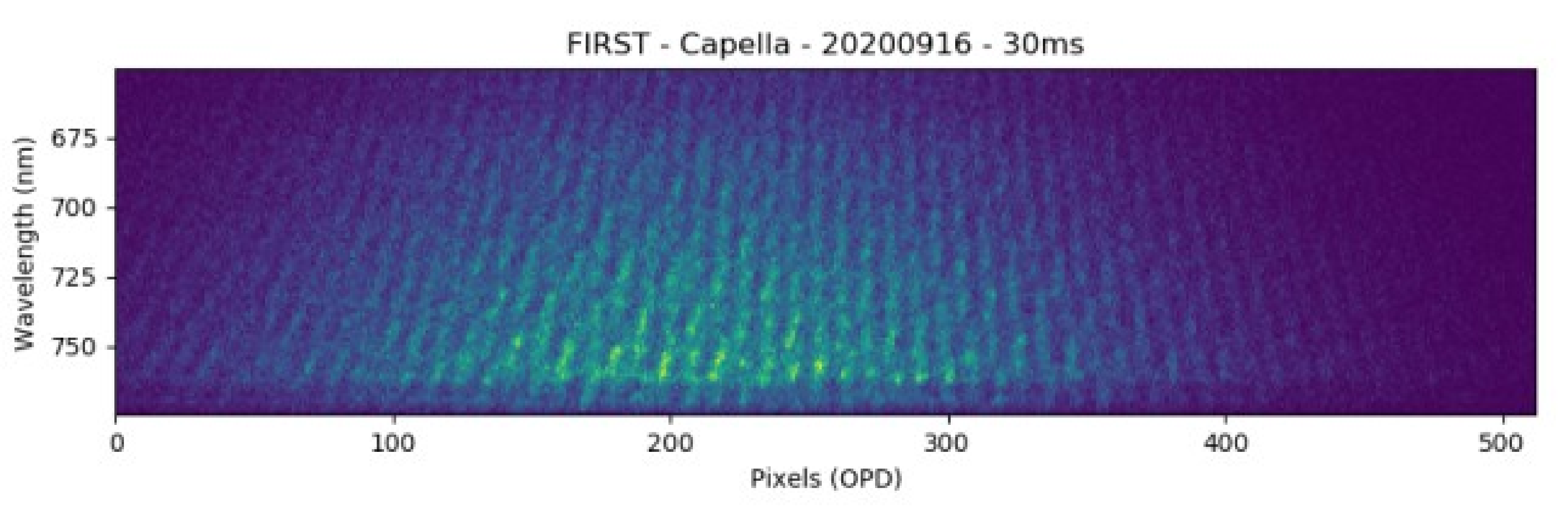


30x gain in speckle variance



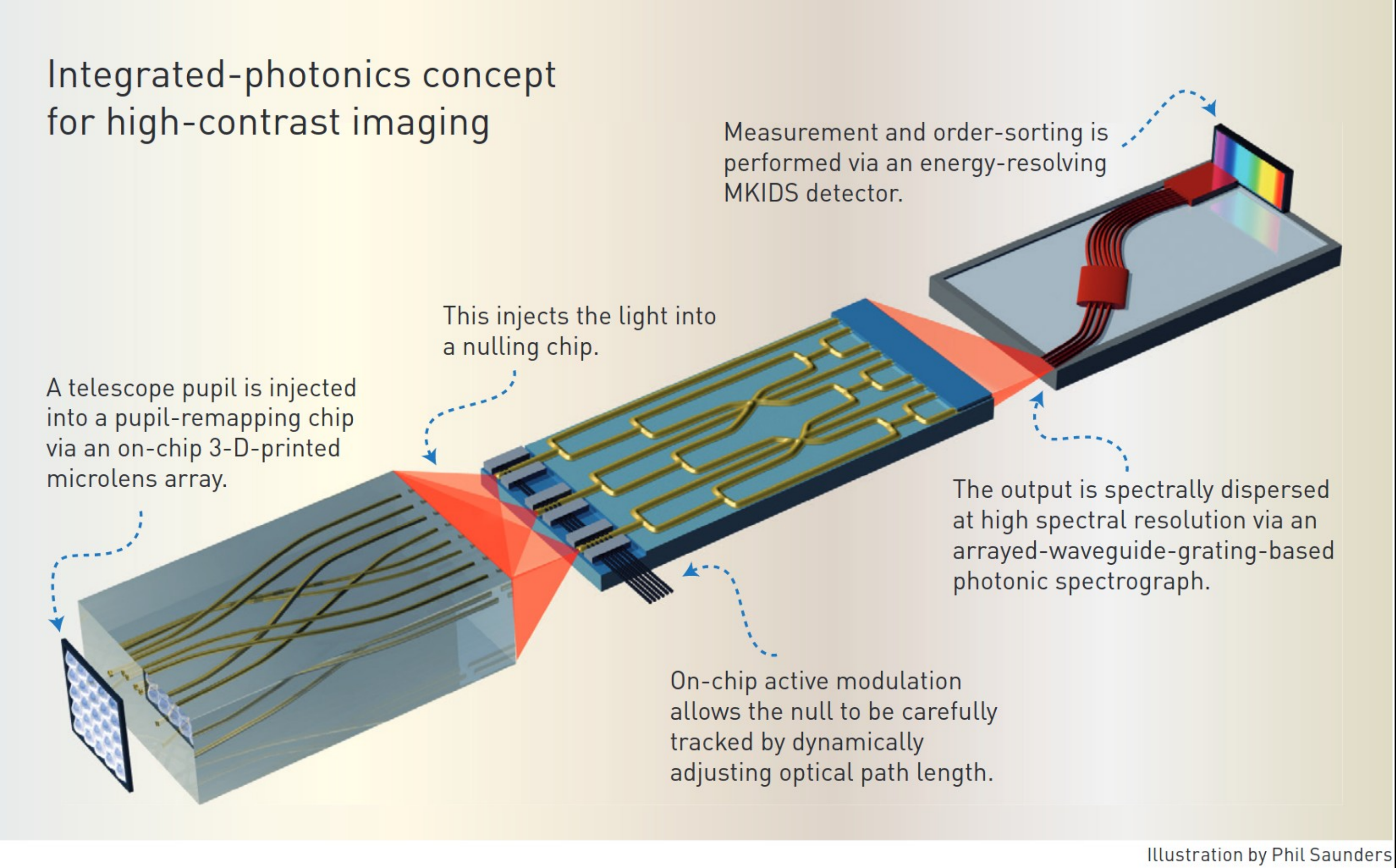
Photonic Nulling

Interferometric WFSs



Credit: S. Vievard and V. Deo

On-sky demonstration of interferometric WFS
→ provides path to high sensitivity chromatic WF measurement



Key advantages:

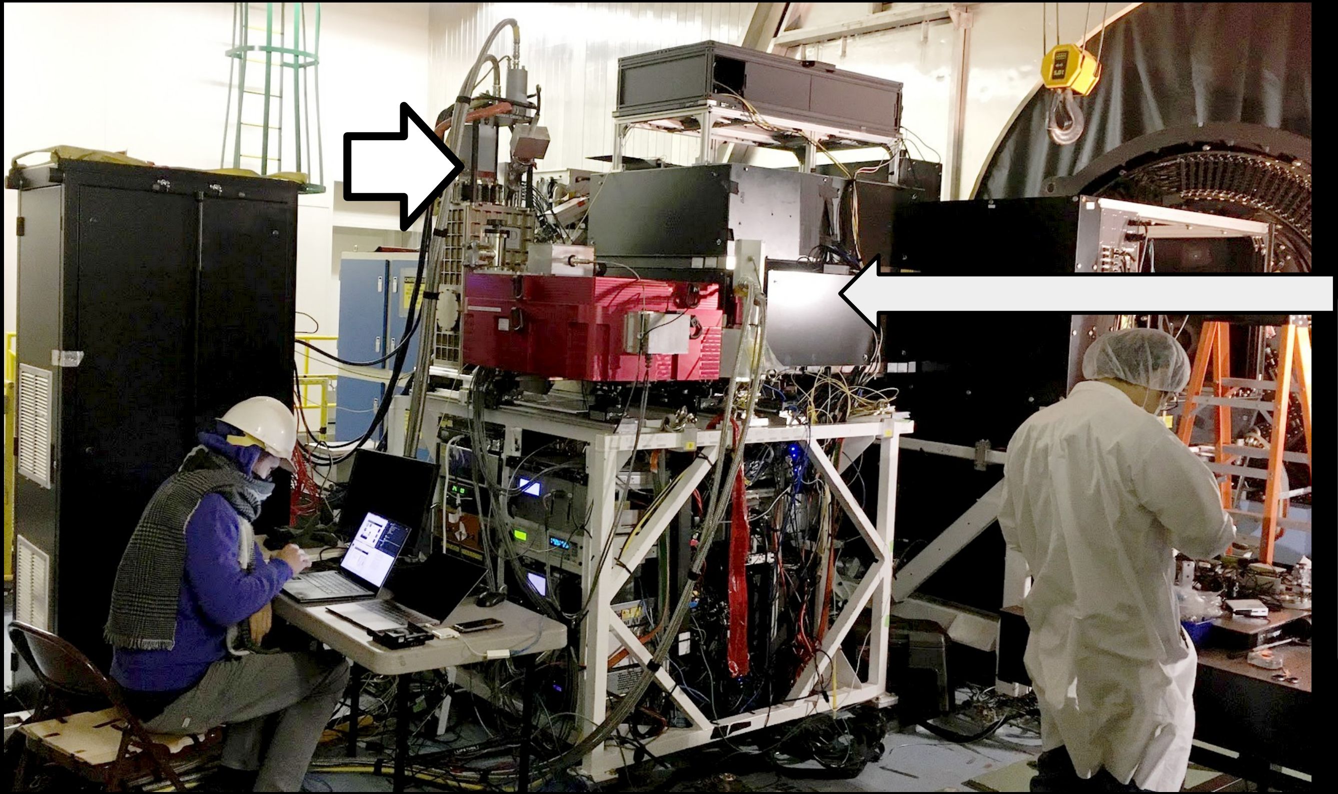
Access to very small separation (better than coronagraphy)

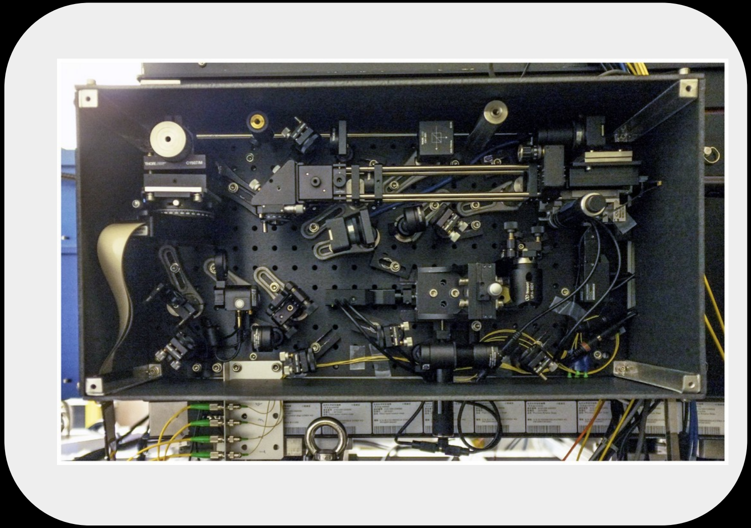
High sensitivity wavefront sensing integrated within chip

Spectroscopy at output

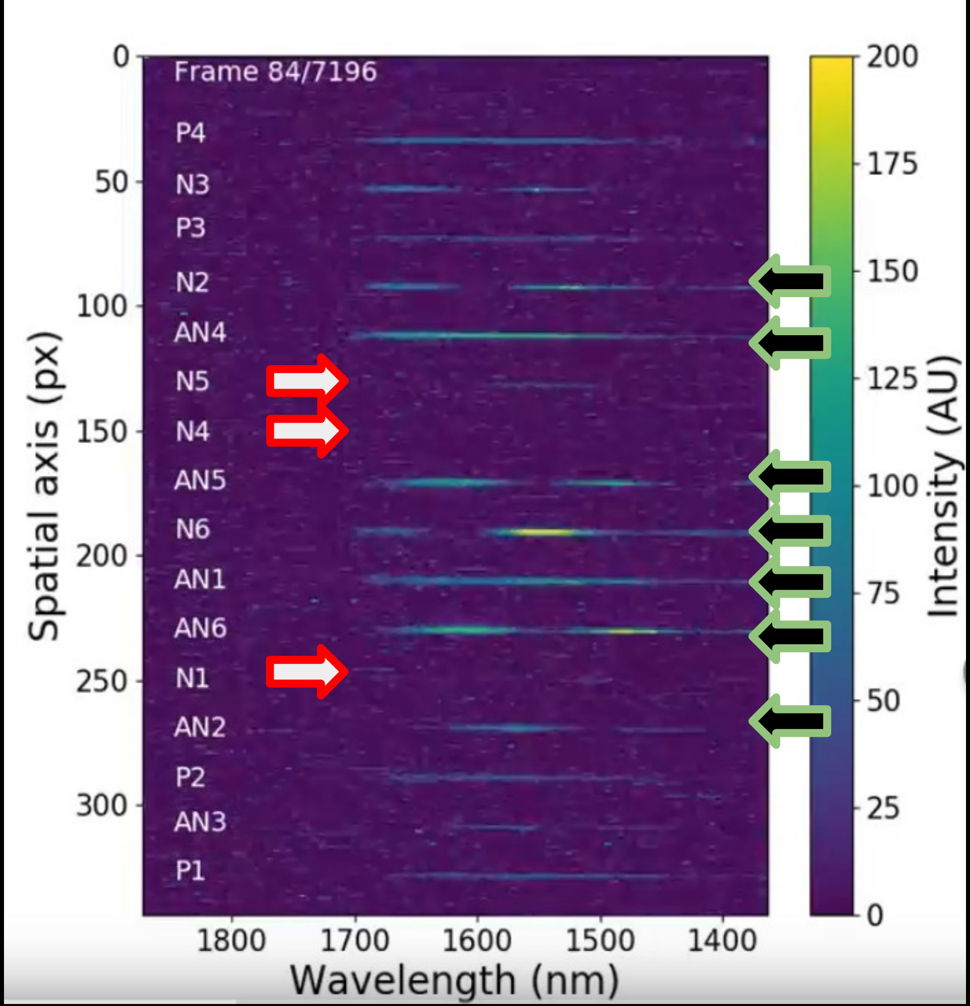
*“***Astrophotonics: The Rise of Integrated Photonics in Astronomy***”*
Norris & Bland-Hawthorn.
Optics and Photonics News (2019)
https://www.osa-opn.org/home/articles/volume_30/may_2019/features/astrophotonics_the_rise_of_integrated_photonics_in/

GLINT module @ Subaru/SCExAO





GLINT module @ Subaru/SCExAO



Null output: starlight is almost completely removed by destructive interference, providing deep contrast.

This is where planet light and spectra are extracted

Fringe tracking output: Bright starlight interference efficiently encode residual small (nm-level) optical aberration

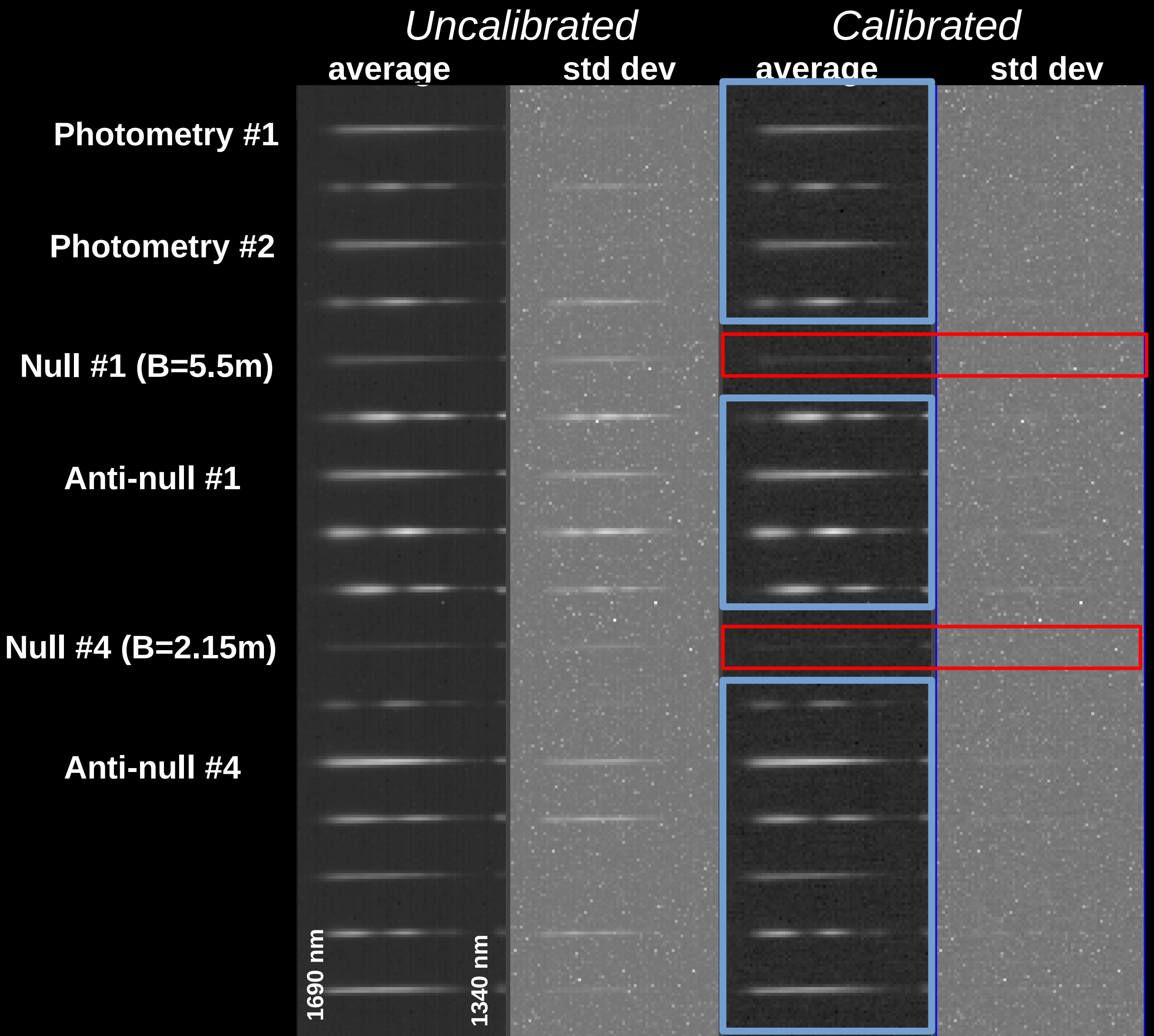
Feed this information in real-time to upstream deformable mirror for correction

Use this information to calibrate how much starlight is left in null outputs

Scalable photonic-based nulling interferometry with the dispersed multi-baseline GLINT instrument"
Martinod, Norris, Tuthill...Guyon et al.
Nature Communications (2021)
link: https://www.nature.com/articles/s41467-021-22769-x

GLINT – on-sky
Alpha Boo

1.4 kHz frame rate



Conclusions

We are already on the path to imaging habitable planets with 30m-class telescopes.
Habitable planets around nearby M and K type stars are most accessible for imaging and spectroscopy.
Spectra will be acquired in visible and NearIR.

SCExAO is leading the way in prototyping key technologies on this path – and enabling new science along the way.
Rapidly evolving technology landscape – important to keep up and validate on-sky.

SCExAO is an open platform → please consider joining the path
Email me at: guyon@naoj.org