The Search for Life around Nearby Stars: from Remote Sensing to Interstellar Travel

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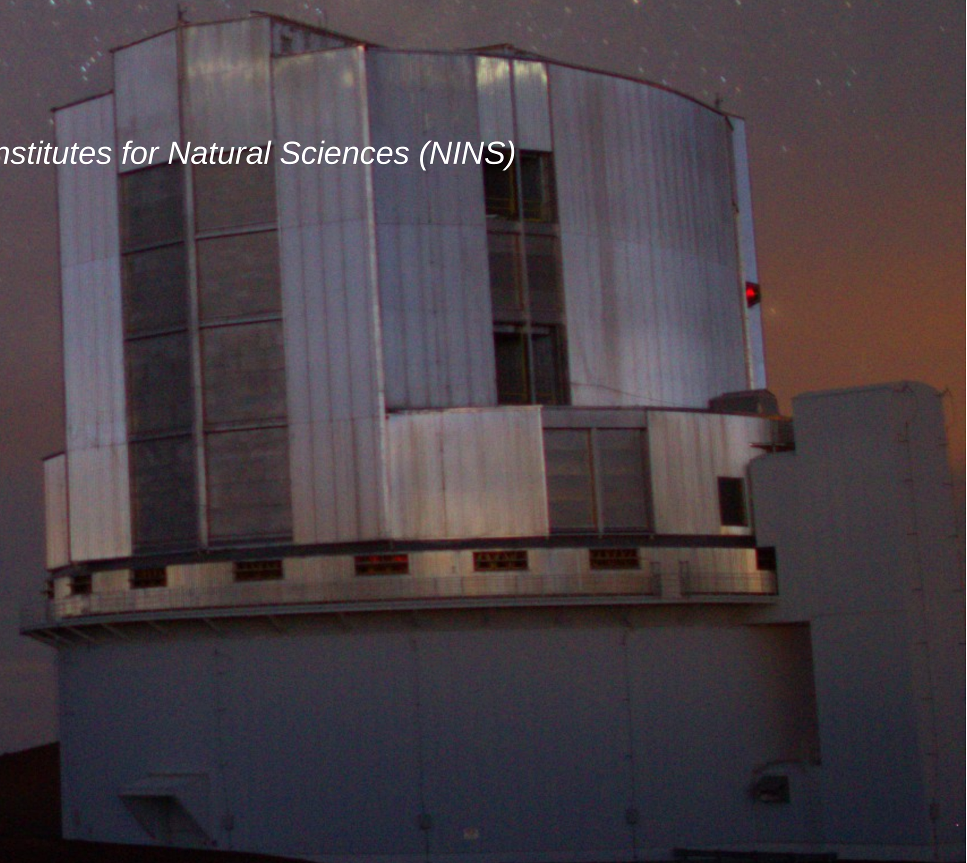
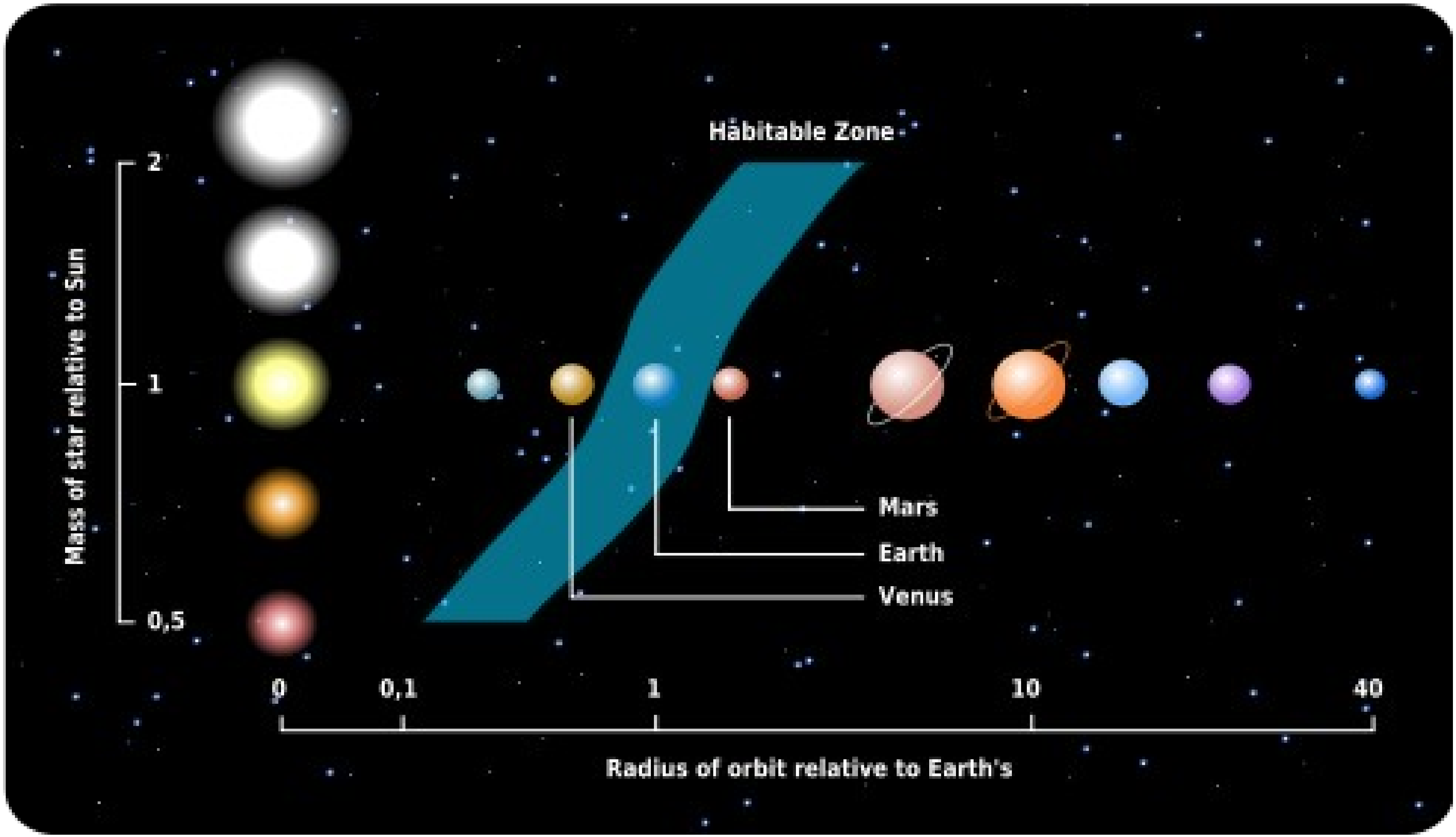
JAXA



Sept 29, 2016, University of Arizona

Habitable zone of a star



What makes planets habitable ?

The planet must be in the **habitable zone** of its star: not be too close or too far

Venera 13 lander, survived 127mn at 457 C, 89 atm

Venus: too close, too hot

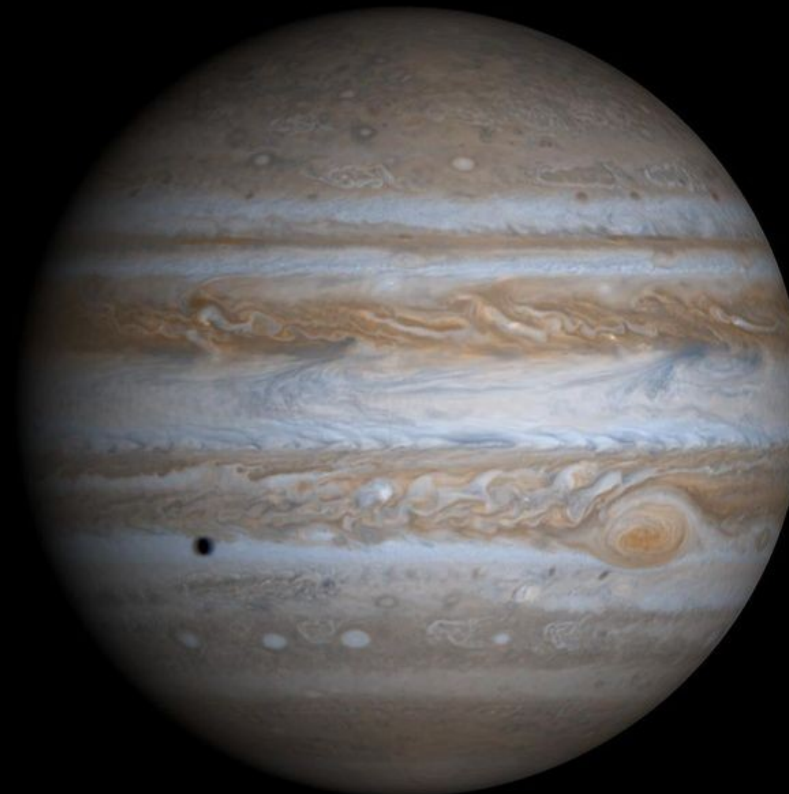
Mars: too far, too cold

What makes planets habitable ?

Size matters:
not too big, not too small

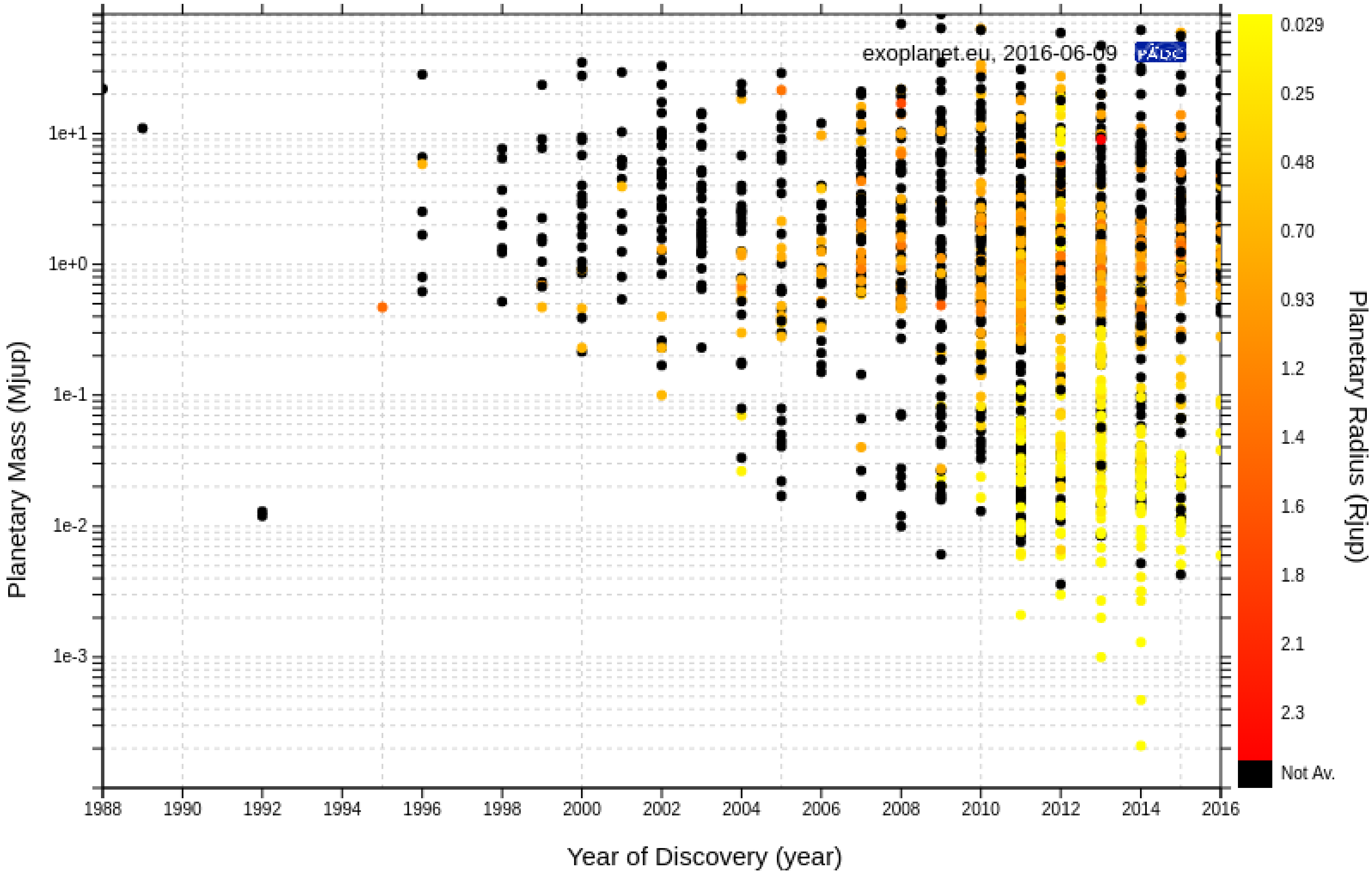
Moon: too small
No atmosphere

Earth



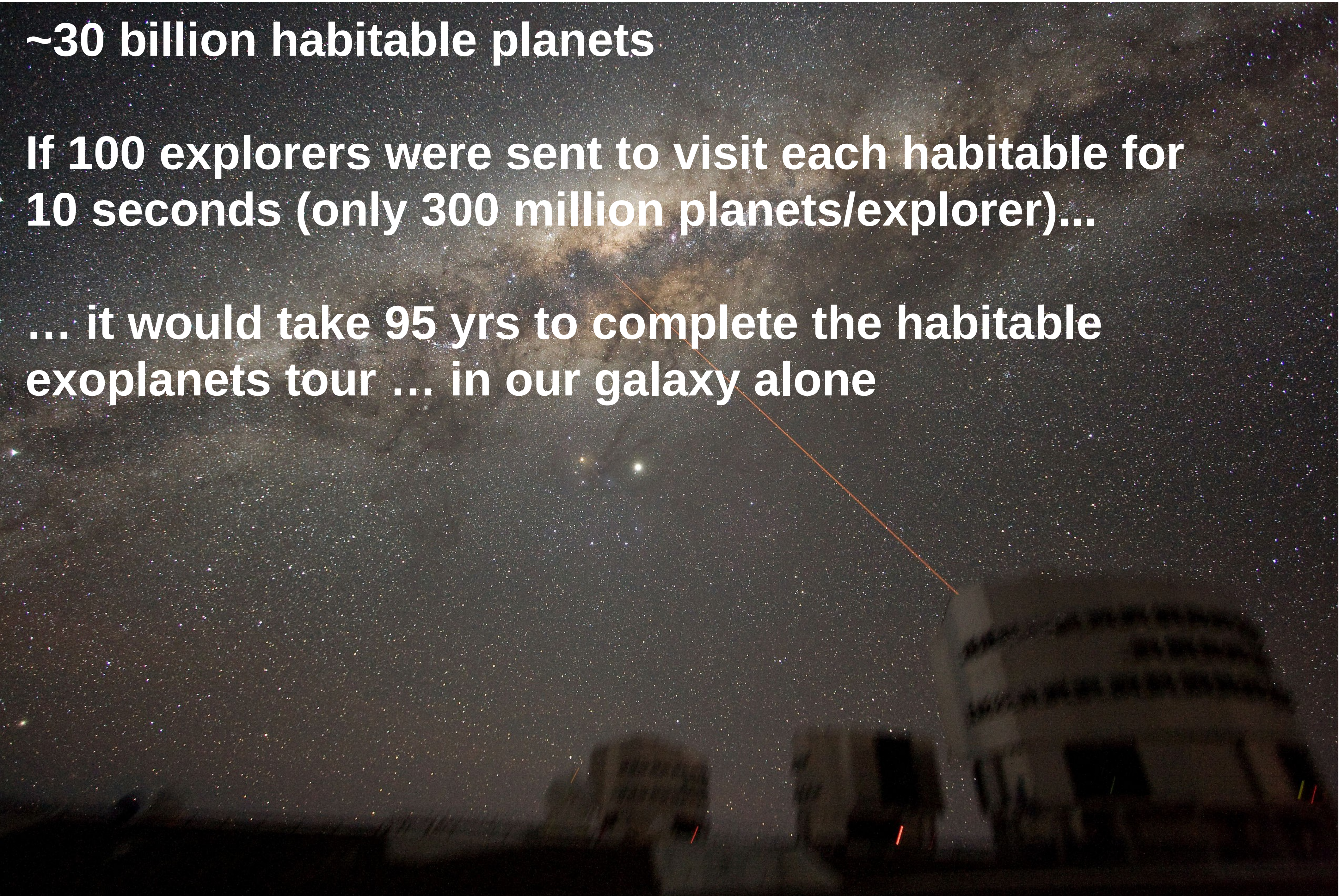
Jupiter: too big
Mostly gas

lots of planets, ~>10% of stars have potentially habitable planets



~300 billion stars in our galaxy

~300 billion stars in our galaxy



~30 billion habitable planets

If 100 explorers were sent to visit each habitable for 10 seconds (only 300 million planets/explorer)...

… it would take 95 yrs to complete the habitable exoplanets tour … in our galaxy alone

200 billion galaxies in the observable universe

How do astronomers identify exoplanets ?

HIGH PRECISION OPTICAL MEASUREMENTS OF STARLIGHT (indirect techniques)

Earth around Sun at ~30 light year

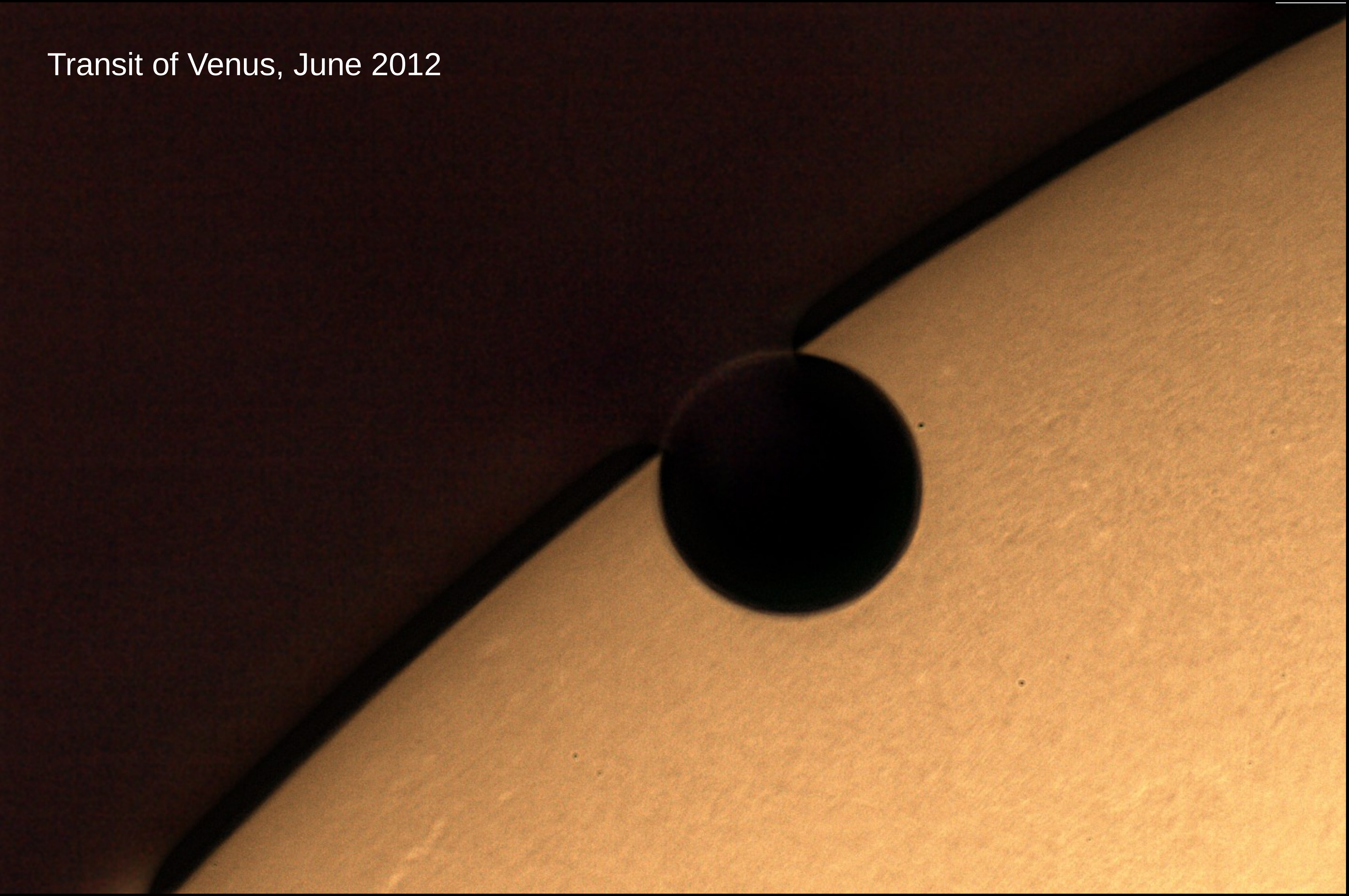
→ Star position moves by 0.3 micro arcsecond
(thickness of a human hair at 20,000 miles)

→ Star velocity is modulated by 10cm / sec
(changes light frequency by 1 part in 3,000,000,000)

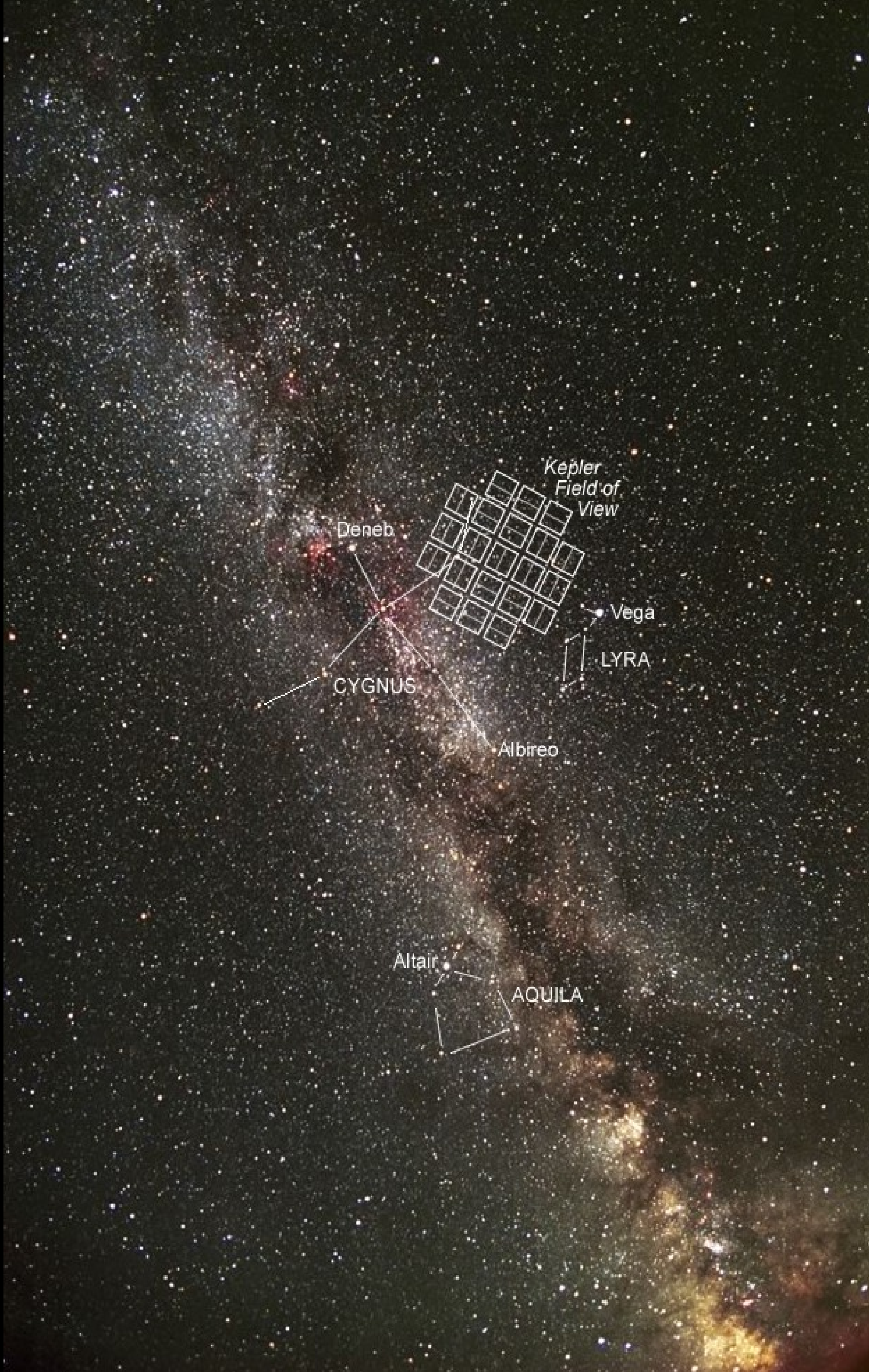
If Earth-like planet passes in front of Sun-like star, star dims by 70 parts per million
(12x12 pixel going dark on a HD TV screen 70 miles away)

Exoplanet transit

If the planet passes in front of its star, we see the star dimming slightly



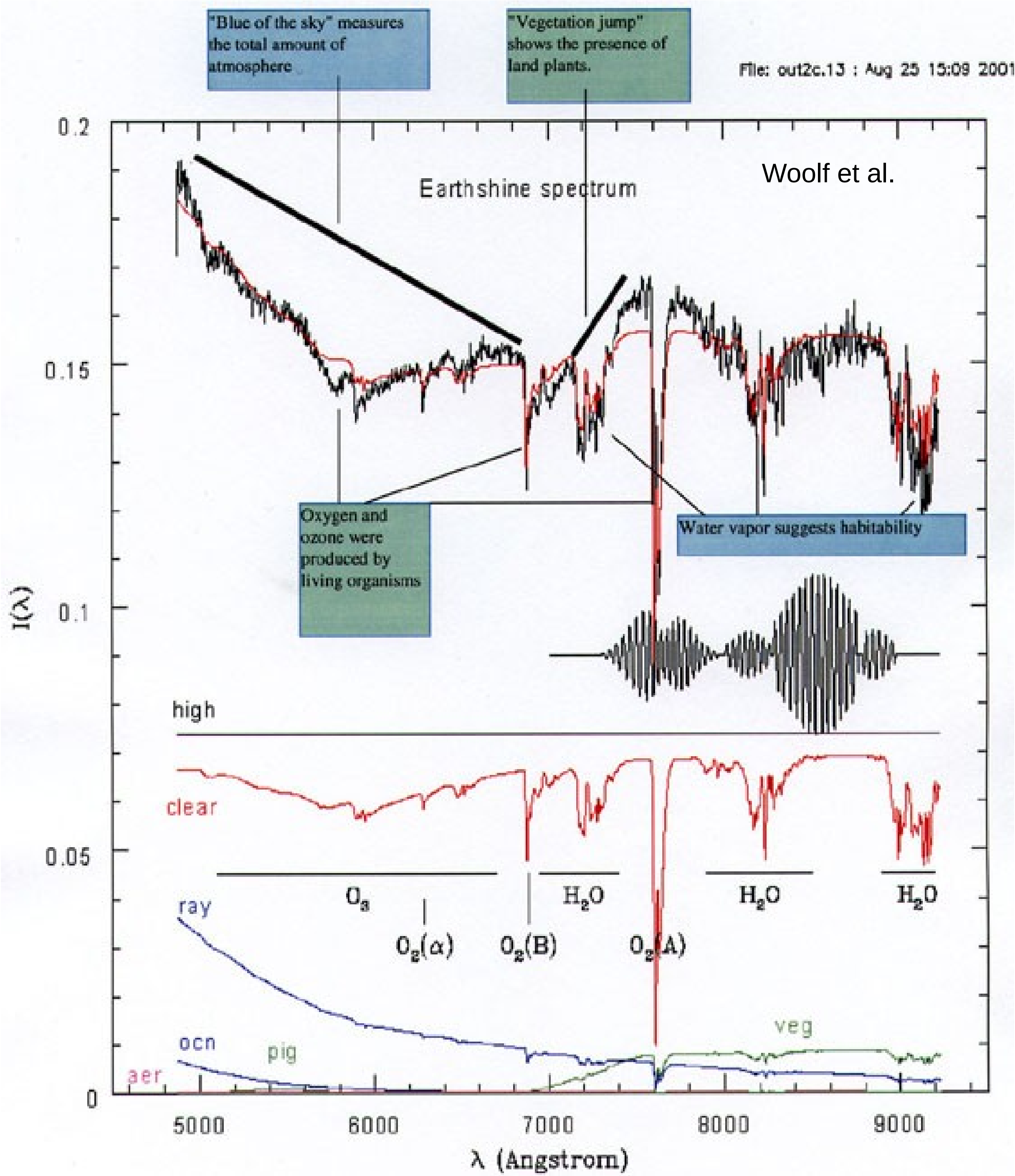
Kepler (NASA)


Kepler
Field of
View
Deneb
Vega
LYRA
CYGNUS
Albireo
Altair
AQUILA

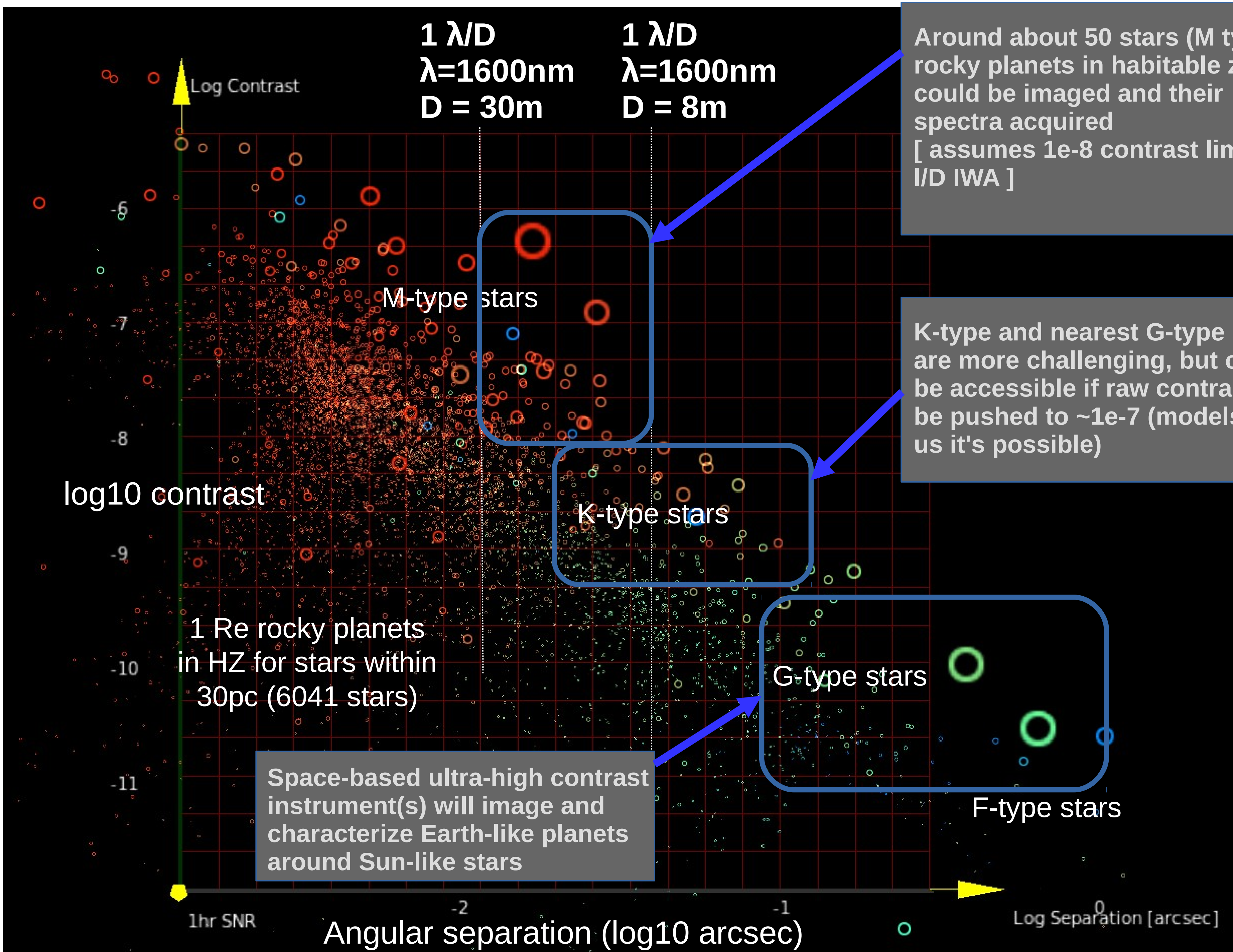
Directly imaging planet is necessary to find life

We need to take spectra of habitable planets

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



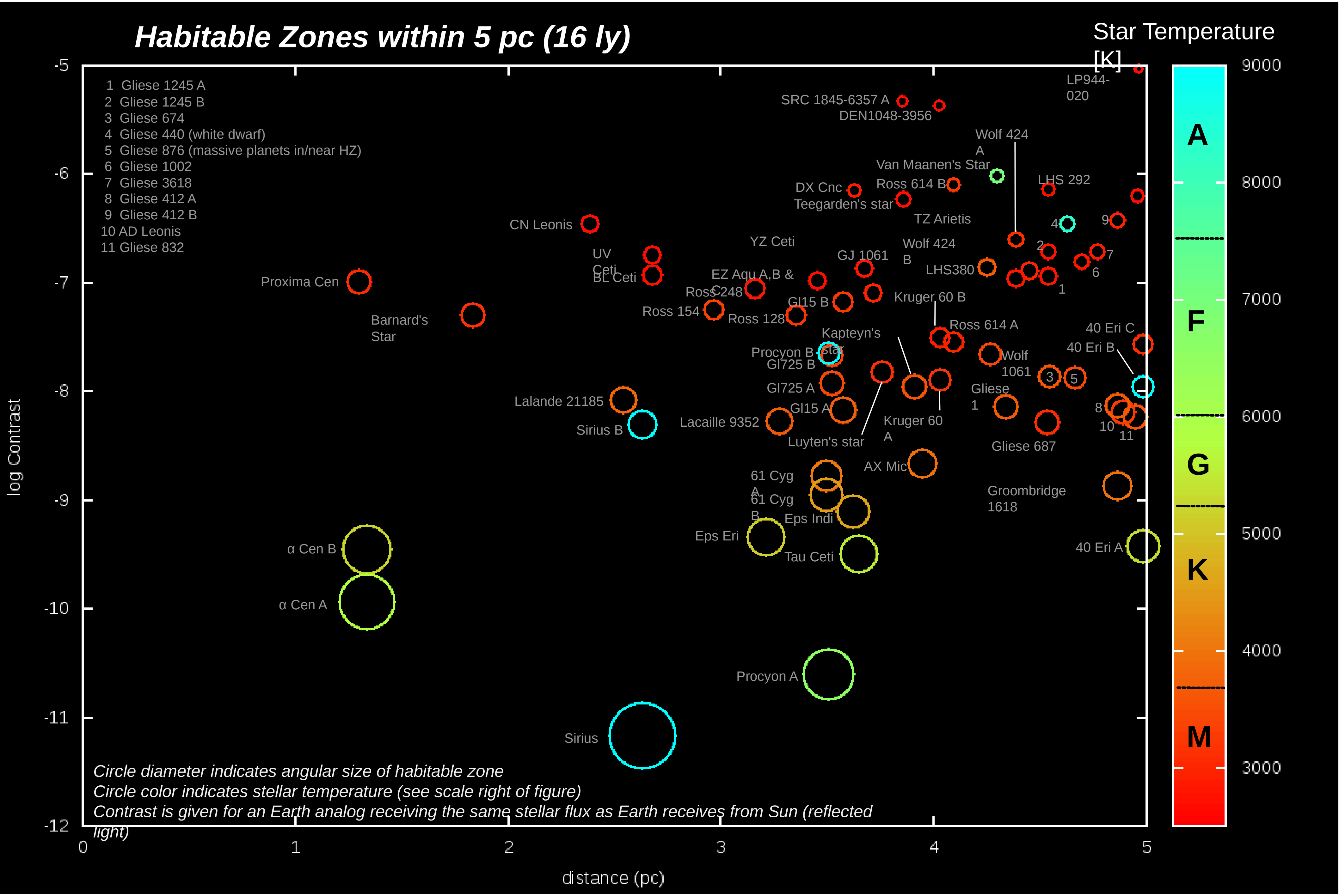
Spectroscopic characterization of Earth-sized planets with ELTs



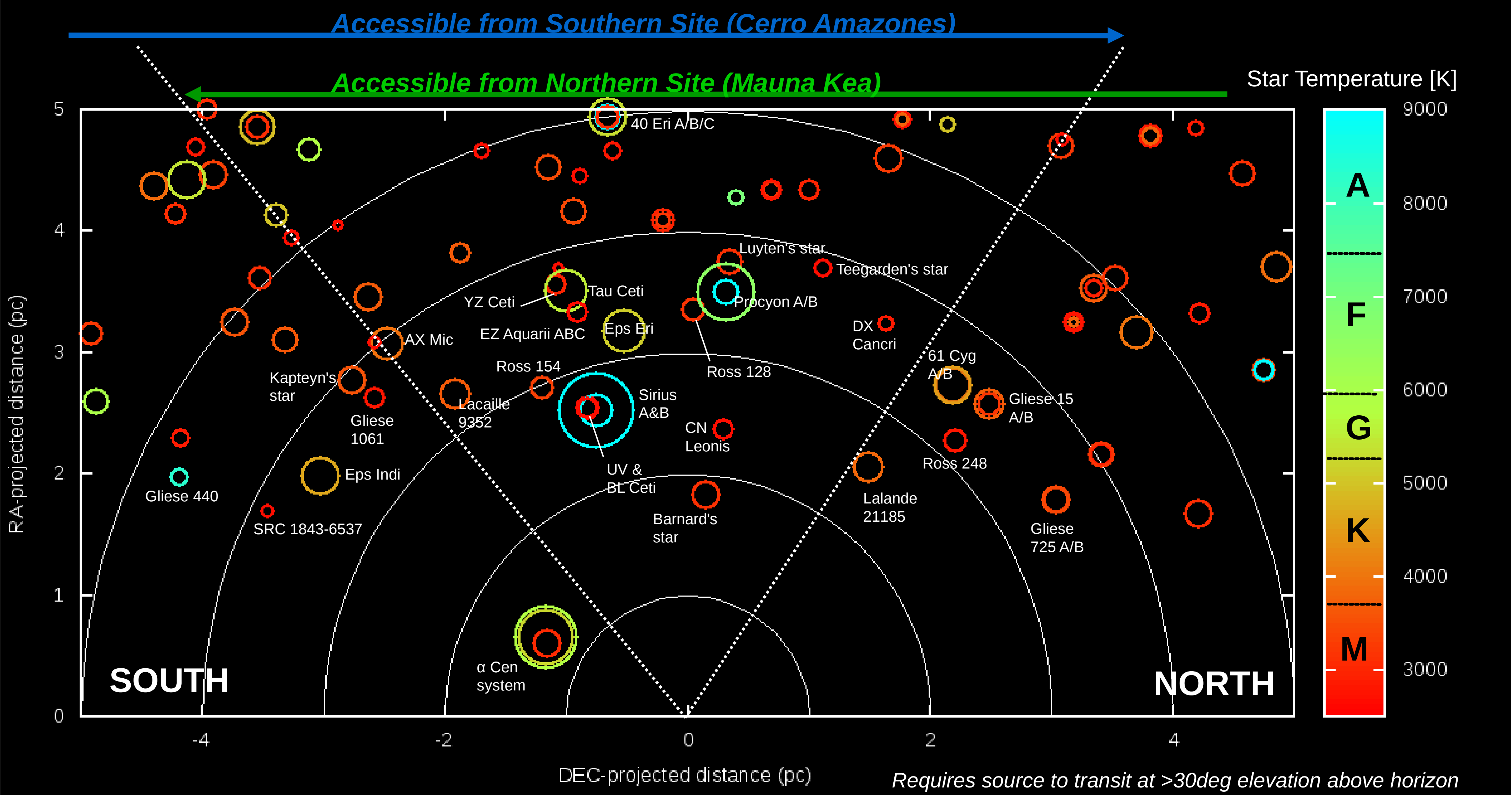
Around about 50 stars (M type), rocky planets in habitable zone could be imaged and their spectra acquired [assumes 1e-8 contrast limit, 1 l/D IWA]

K-type and nearest G-type stars are more challenging, but could be accessible if raw contrast can be pushed to ~1e-7 (models tell us it's possible)

Space-based ultra-high contrast instrument(s) will image and characterize Earth-like planets around Sun-like stars



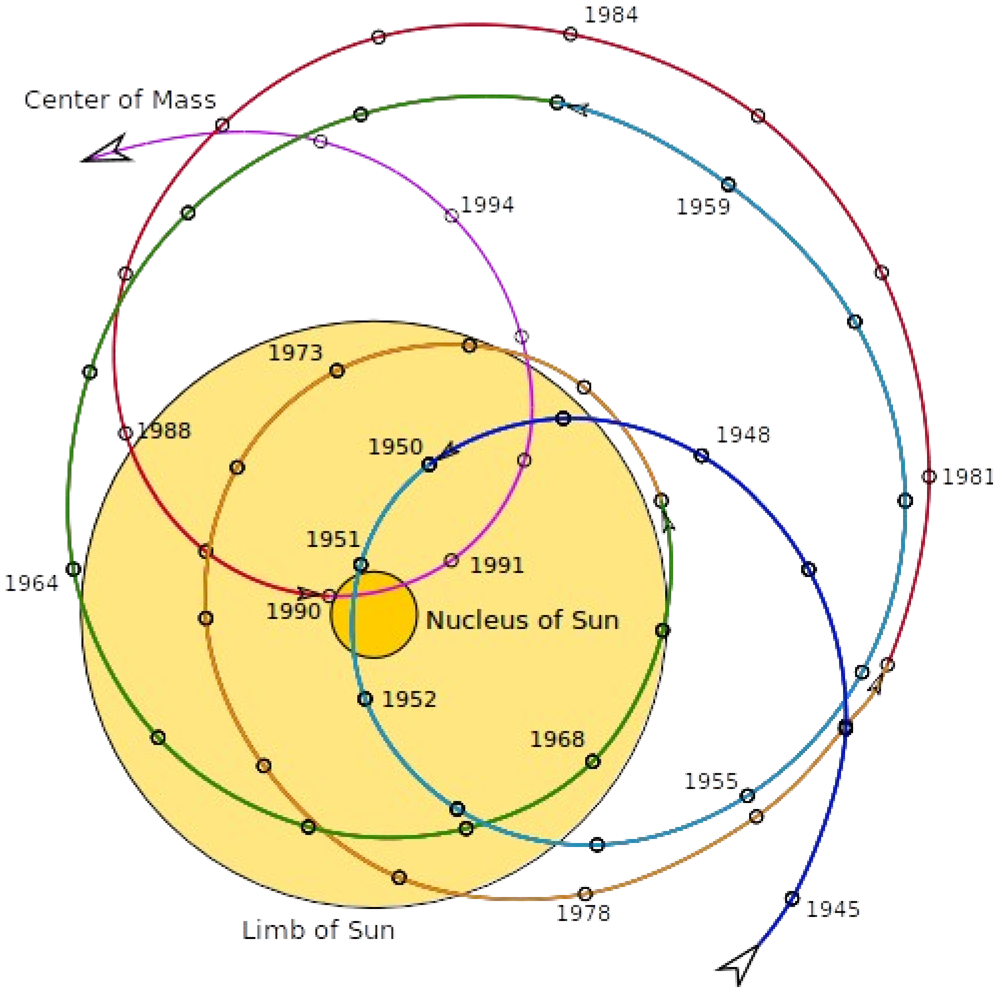
Habitable Zones within 5 pc (16 ly)
Star Temperature [K]
1 Gliese 1245 A
2 Gliese 1245 B
3 Gliese 674
4 Gliese 440 (white dwarf)
5 Gliese 876 (massive planets in/near HZ)
6 Gliese 1002
7 Gliese 3618
8 Gliese 412 A
9 Gliese 412 B
10 AD Leonis
11 Gliese 832
LP944-020
SRC 1845-6357 A
DEN1048-3956
Wolf 424 A
Van Maanen's Star
LHS 292
DX Cnc
Ross 614 B
Teegarden's star
TZ Arietis
CN Leonis
YZ Ceti
Wolf 424 B
GJ 1061
UV Ceti
BL Ceti
EZ Aqu A,B & C
LHS380
Proxima Cen
Ross 248
Gl15 B
Kruger 60 B
Ross 154
Ross 128
Ross 614 A
Barnard's Star
Kapteyn's star
40 Eri C
40 Eri B
Procyon B
Gl725 B
Wolf 1061
Gl725 A
Gliese 1
Lalande 21185
Gl15 A
Sirius B
Lacaille 9352
Kruger 60 A
Gliese 687
Luyten's star
AX Mic
61 Cyg A
61 Cyg B
Groombridge 1618
Eps Indi
Eps Eri
α Cen B
Tau Ceti
40 Eri A
α Cen A
Procyon A
Sirius
Circle diameter indicates angular size of habitable zone
Circle color indicates stellar temperature (see scale right of figure)
Contrast is given for an Earth analog receiving the same stellar flux as Earth receives from Sun (reflected light)
log Contrast
distance (pc)
-5
-6
-7
-8
-9
-10
-11
-12
0
1
2
3
4
5
9000
8000
7000
6000
5000
4000
3000
A
F
G
K
M



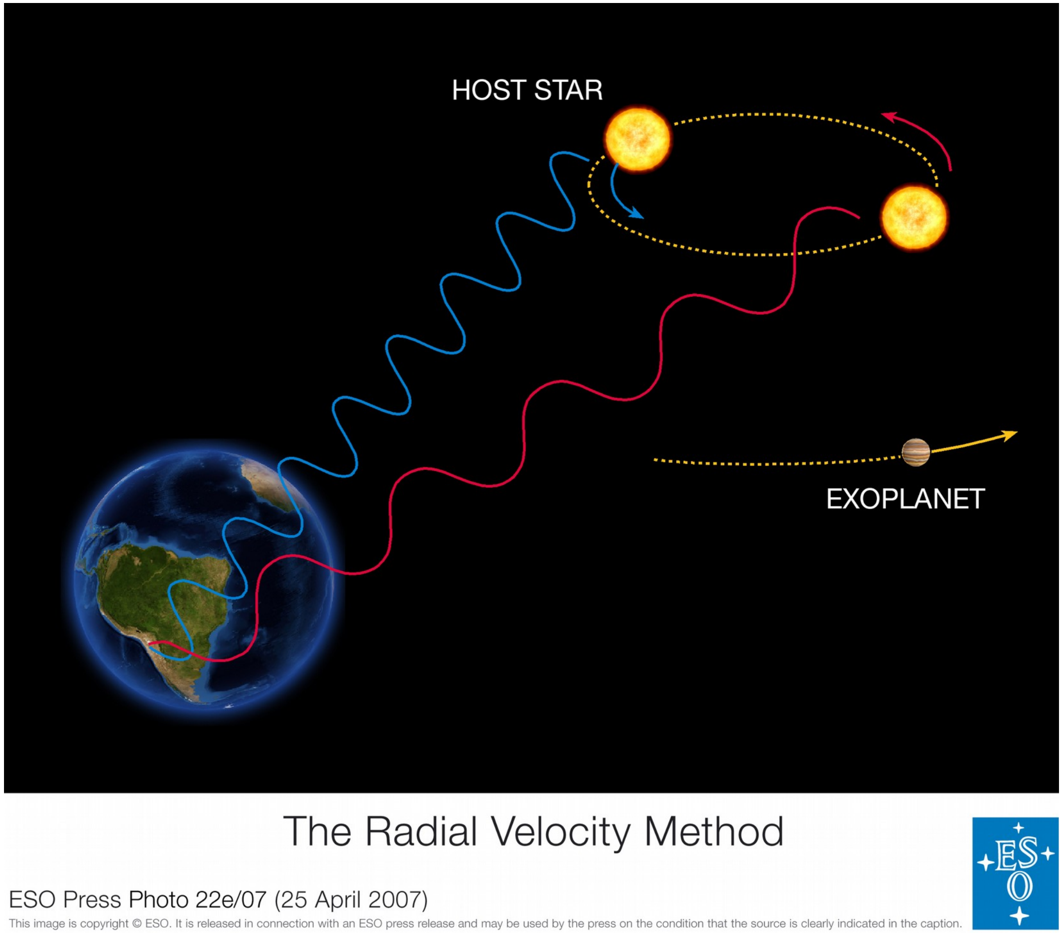
Accessible from Southern Site (Cerro Amazones)
Accessible from Northern Site (Mauna Kea)
Star Temperature [K]
9000
8000
7000
6000
5000
4000
3000
A
F
G
K
M
40 Eri A/B/C
Luyten's star
Teegarden's star
Tau Ceti
YZ Ceti
Procyon A/B
EZ Aquarii ABC
Eps Eri
AX Mic
DX Cancri
Ross 154
Ross 128
61 Cyg A/B
Kapteyn's star
Sirius A&B
Gliese 15 A/B
Lacaille 9352
Gliese 1061
CN Leonis
Eps Indi
UV & BL Ceti
Ross 248
Gliese 440
Lalande 21185
Barnard's star
Gliese 725 A/B
SRC 1843-6537
α Cen system
SOUTH
NORTH
RA-projected distance (pc)
DEC-projected distance (pc)
Requires source to transit at >30deg elevation above horizon

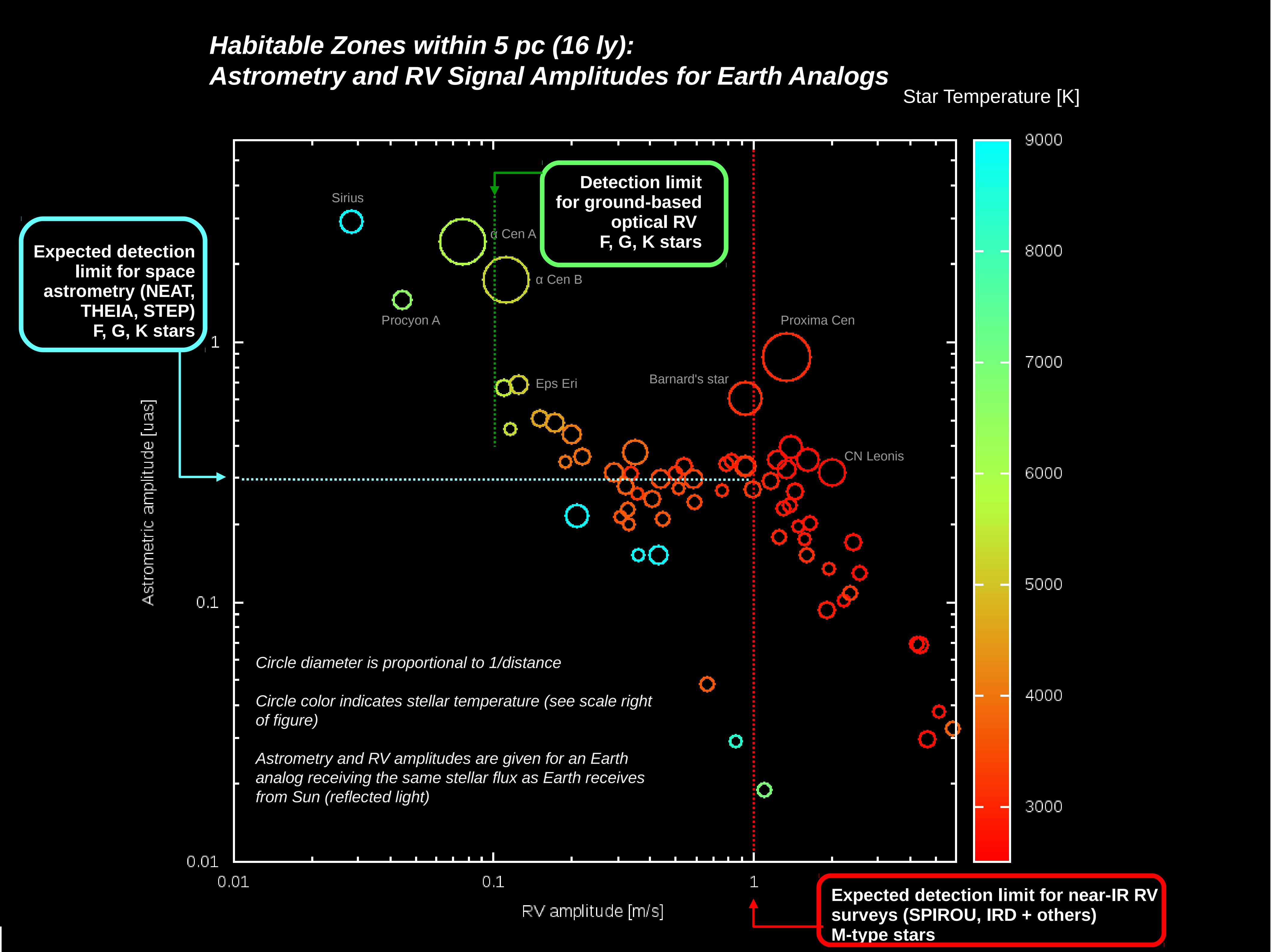
Indirect detection techniques → mass

Astrometry

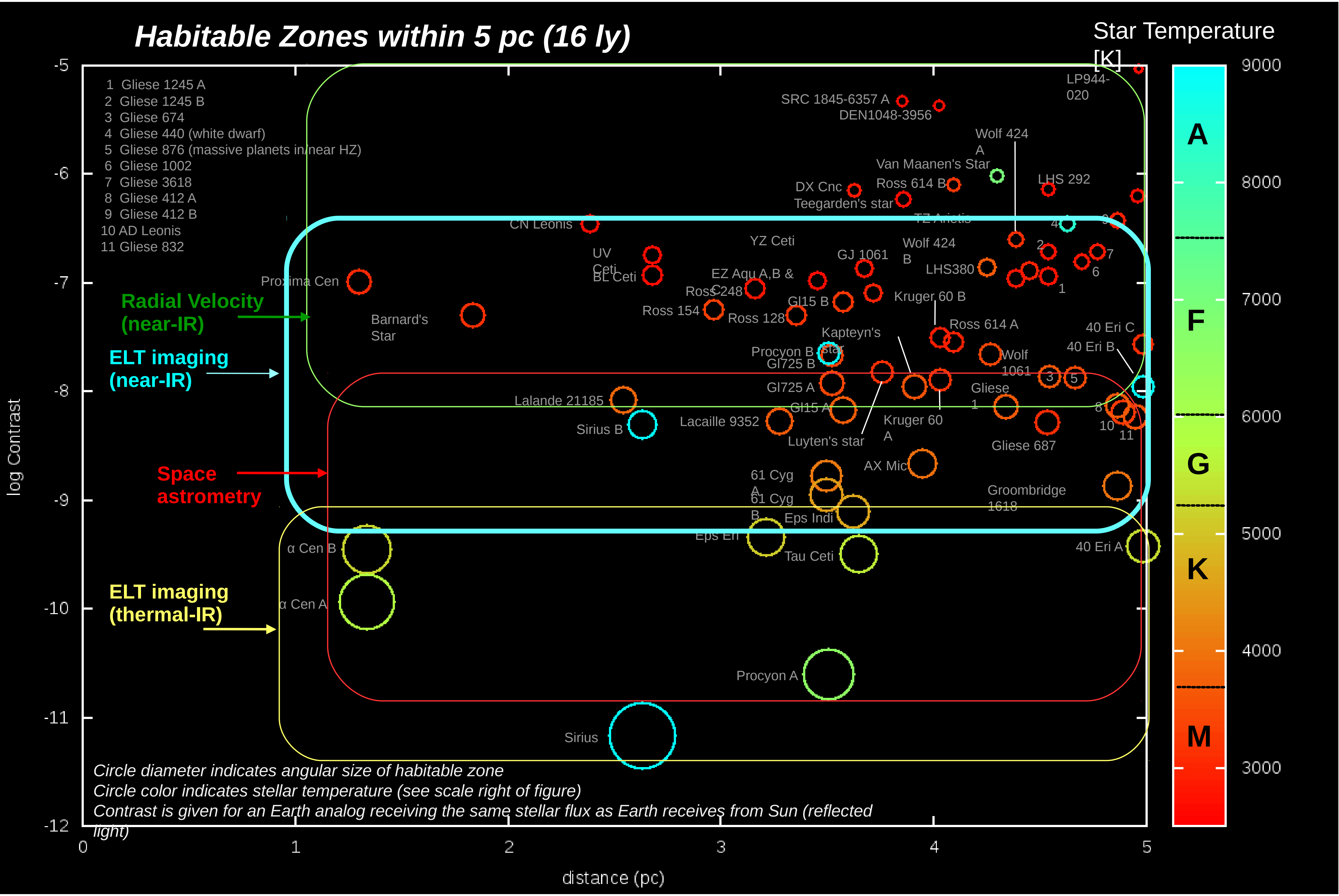


Radial Velocity





Habitable Zones within 5 pc (16 ly):
Astrometry and RV Signal Amplitudes for Earth Analogs
Star Temperature [K]
9000
8000
7000
6000
5000
4000
3000
Expected detection limit for space astrometry (NEAT, THEIA, STEP) F, G, K stars
Detection limit for ground-based optical RV F, G, K stars
Expected detection limit for near-IR RV surveys (SPIROU, IRD + others) M-type stars
Sirius
α Cen A
α Cen B
Procyon A
Eps Eri
Barnard's star
Proxima Cen
CN Leonis
Astrometric amplitude [uas]
RV amplitude [m/s]
0.01
0.1
1
Circle diameter is proportional to 1/distance
Circle color indicates stellar temperature (see scale right of figure)
Astrometry and RV amplitudes are given for an Earth analog receiving the same stellar flux as Earth receives from Sun (reflected light)



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6 Gliese 1002
7 Gliese 3618
8 Gliese 412 A
9 Gliese 412 B
10 AD Leonis
11 Gliese 832
Radial Velocity (near-IR)
ELT imaging (near-IR)
Space astrometry
ELT imaging (thermal-IR)
LP944-020
SRC 1845-6357 A
DEN1048-3956
Wolf 424 A
Van Maanen's Star
Ross 614 B
LHS 292
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Teegarden's star
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Kruger 60 B
Gl15 B
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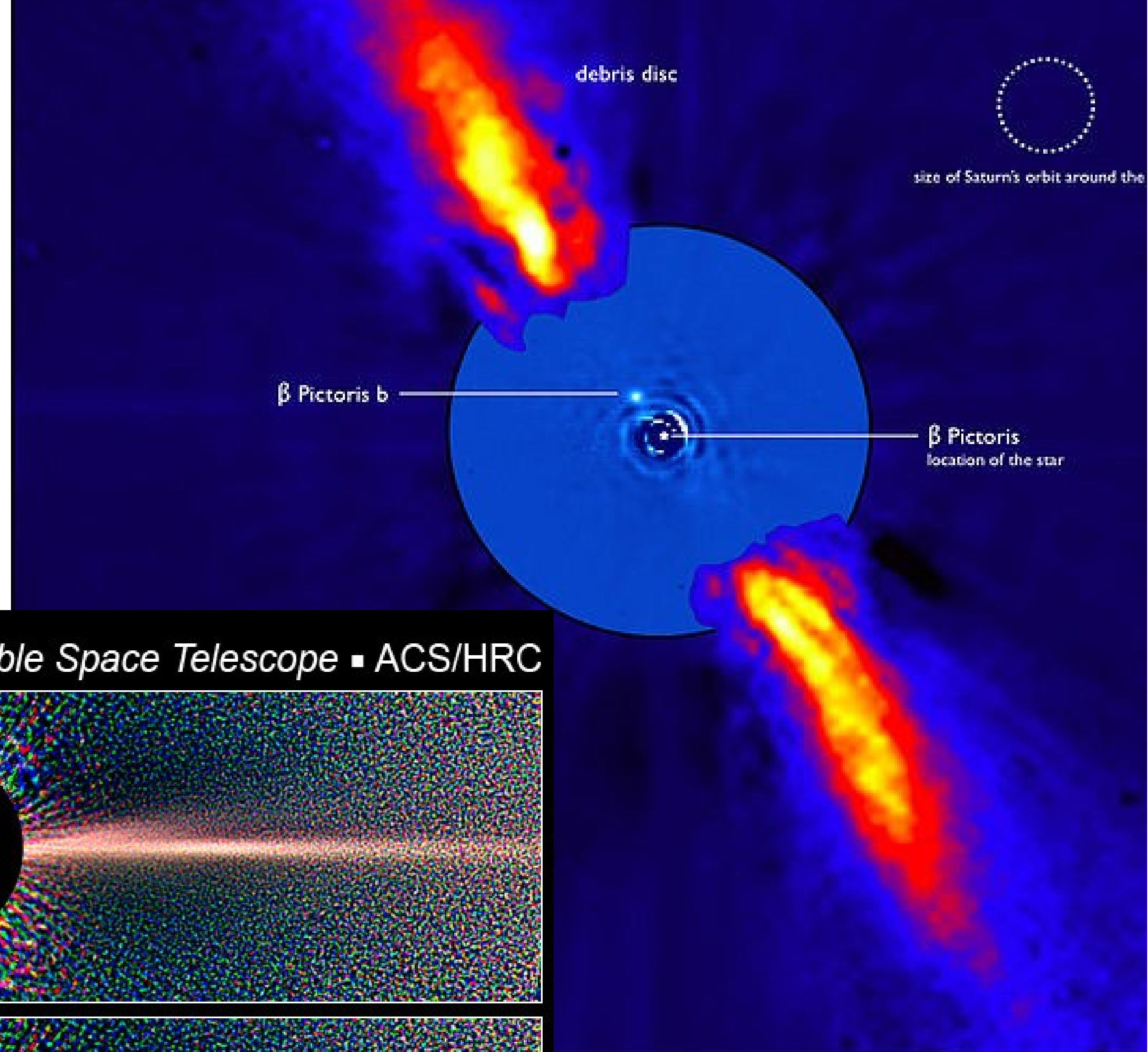
40 Eri A
α Cen A
Procyon A
Sirius
A
F
G
K
M
9000
8000
7000
6000
5000
4000
3000
-5
-6
-7
-8
-9
-10
-11
-12
log Contrast
0
1
2
3
4
5
distance (pc)
Circle diameter indicates angular size of habitable zone
Circle color indicates stellar temperature (see scale right of figure)
Contrast is given for an Earth analog receiving the same stellar flux as Earth receives from Sun (reflected light)

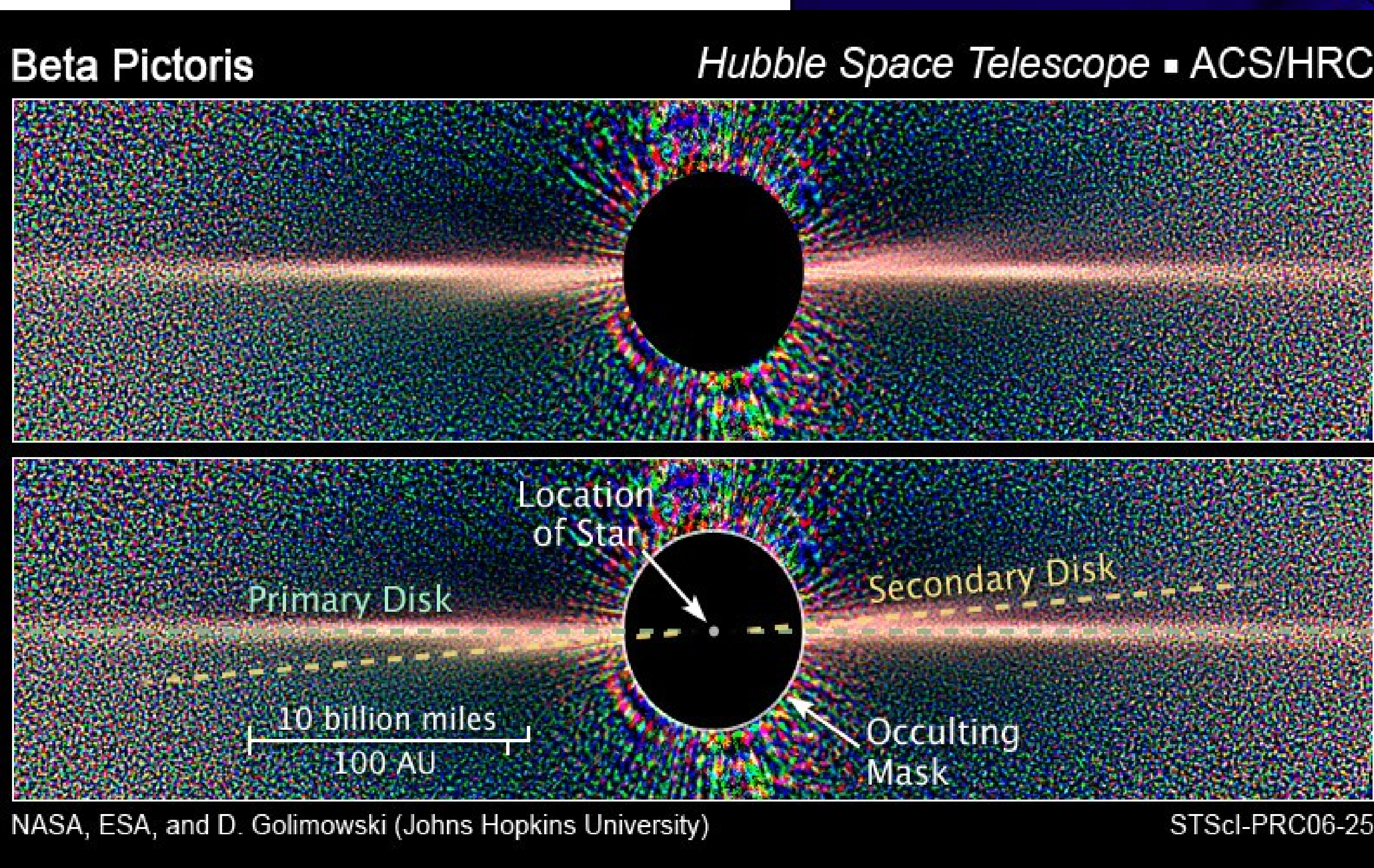
Beta Pictoris

8 Jupiter mass planet

Orbits young massive star in ~20yr

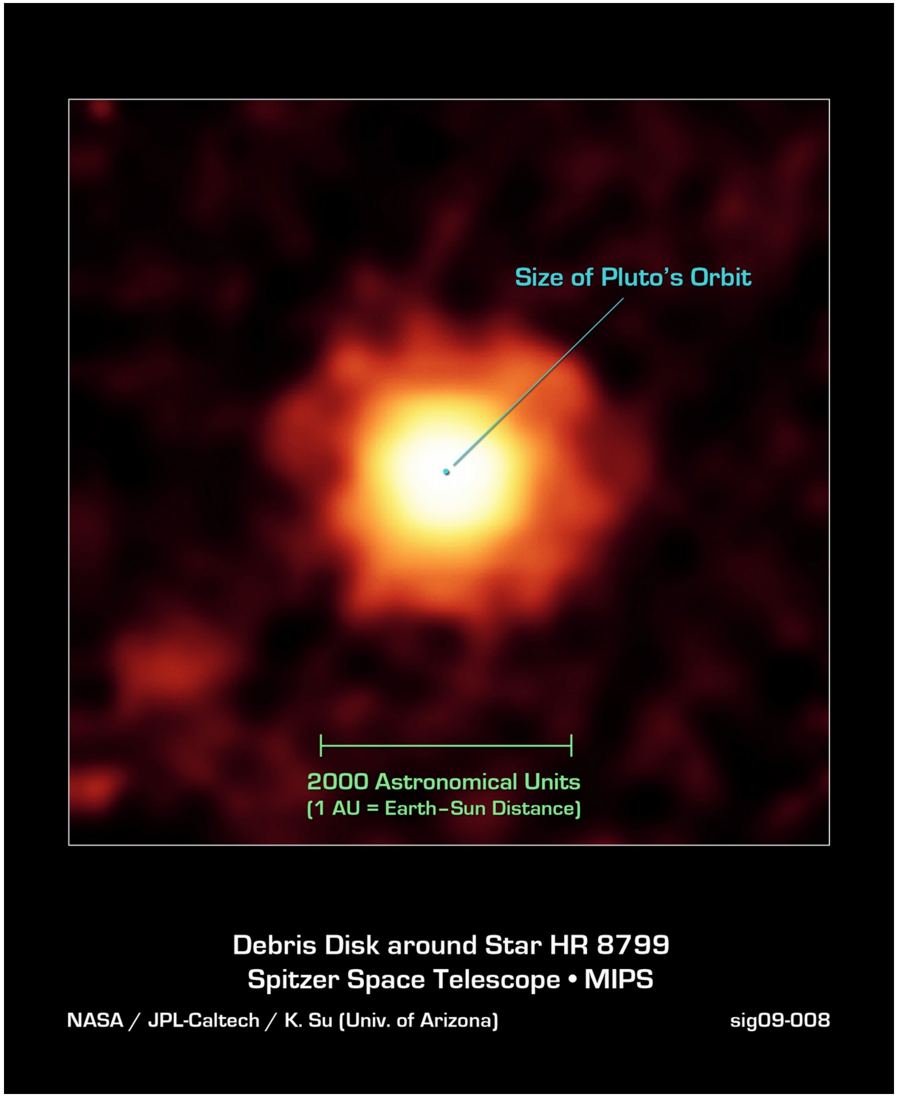


ESO VLT image (Lagrange et al.)

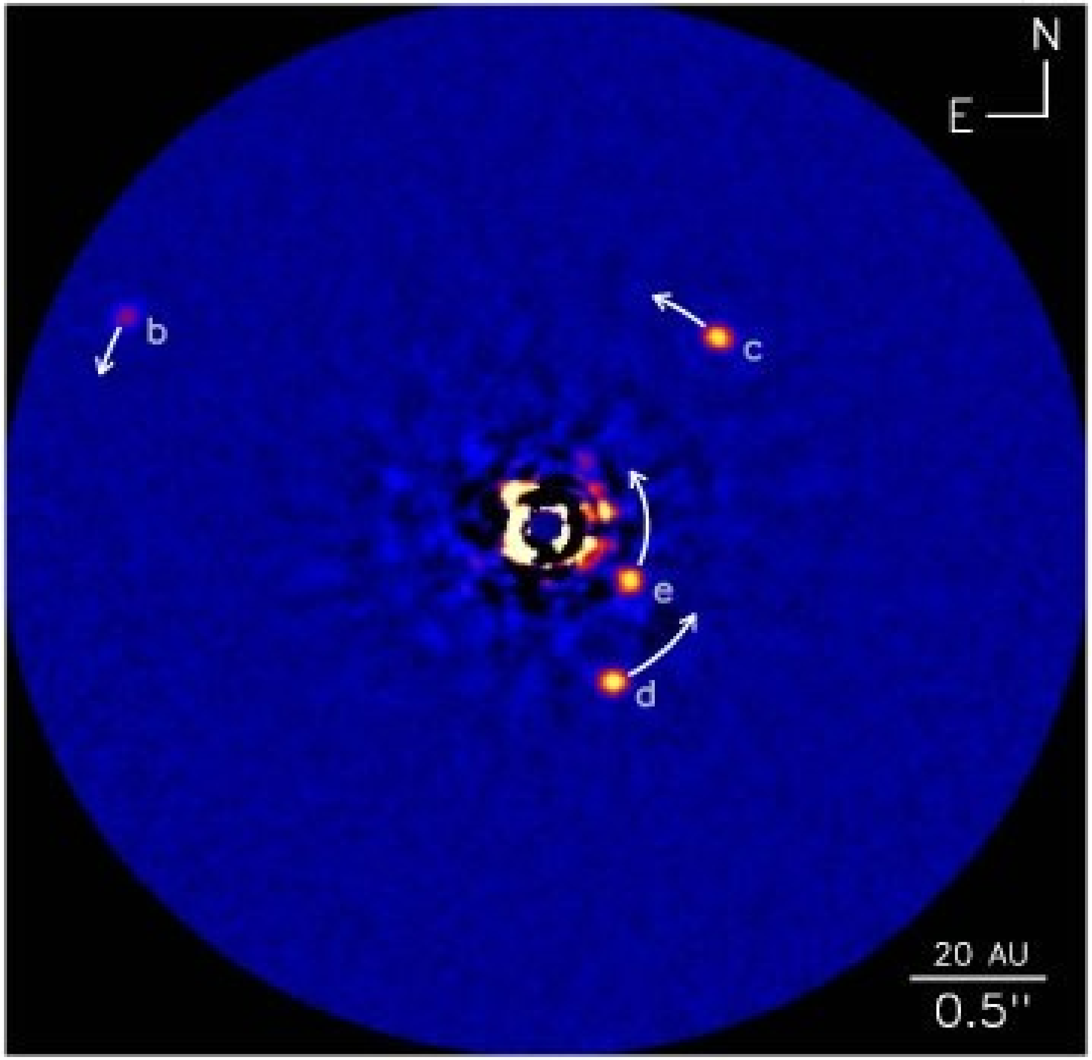


HR8799

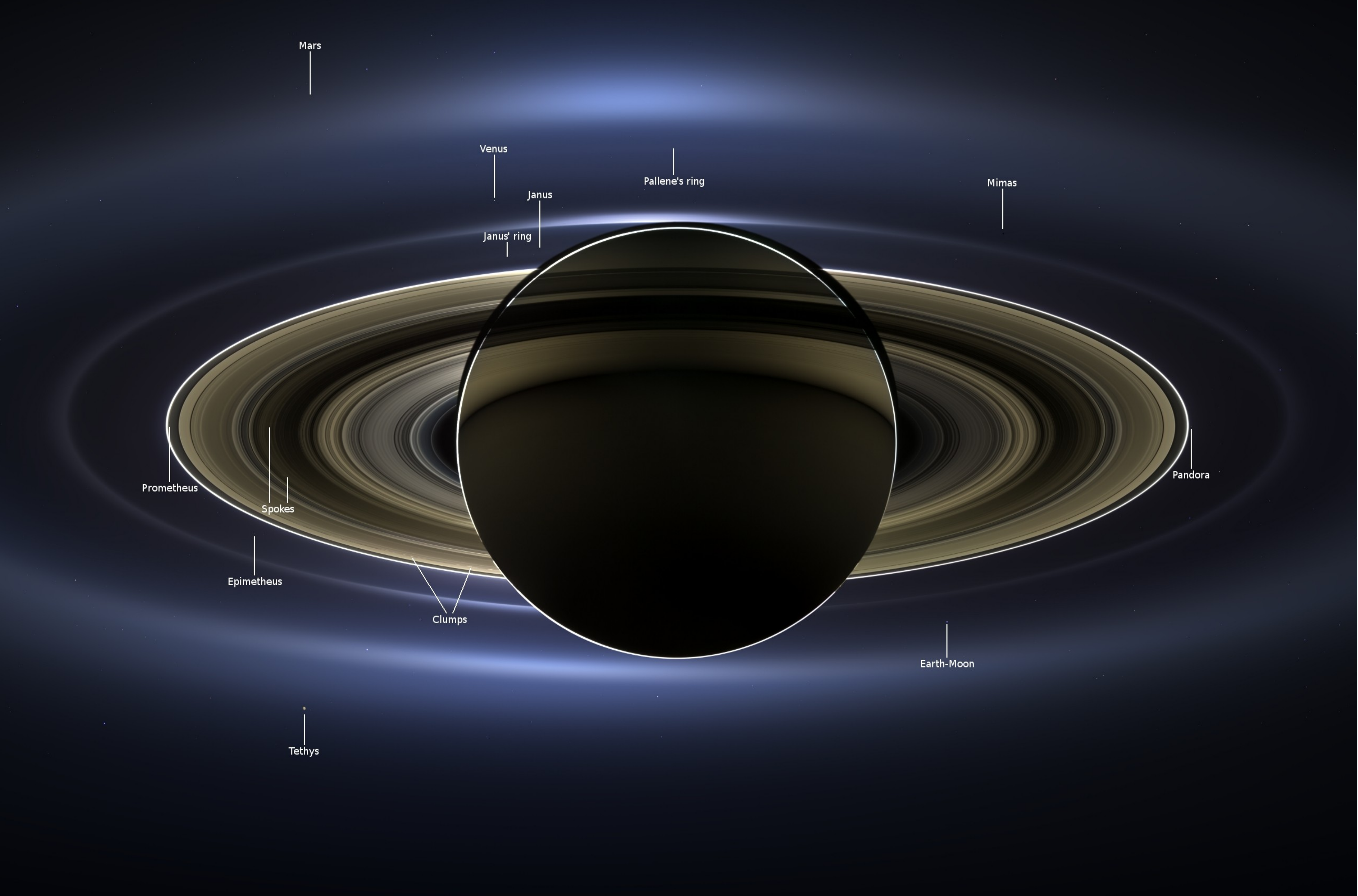
Four planets, orbital periods on the order of 100yr
Each planet 5 to 7 Jupiter Mass



Keck telescope image (Marois et. al)



Taking images of exoplanets: Why is it hard ?

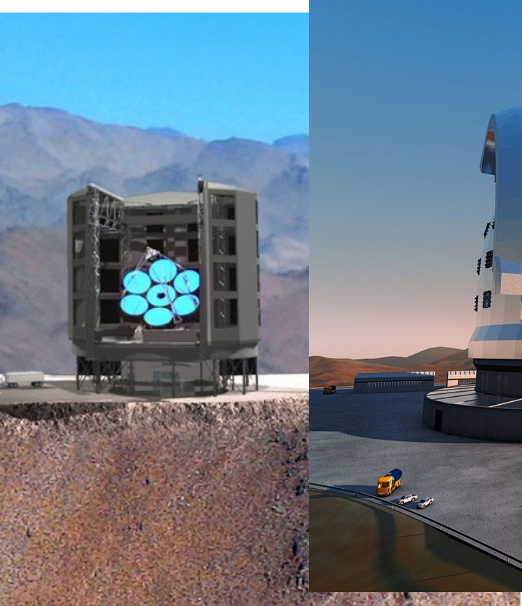
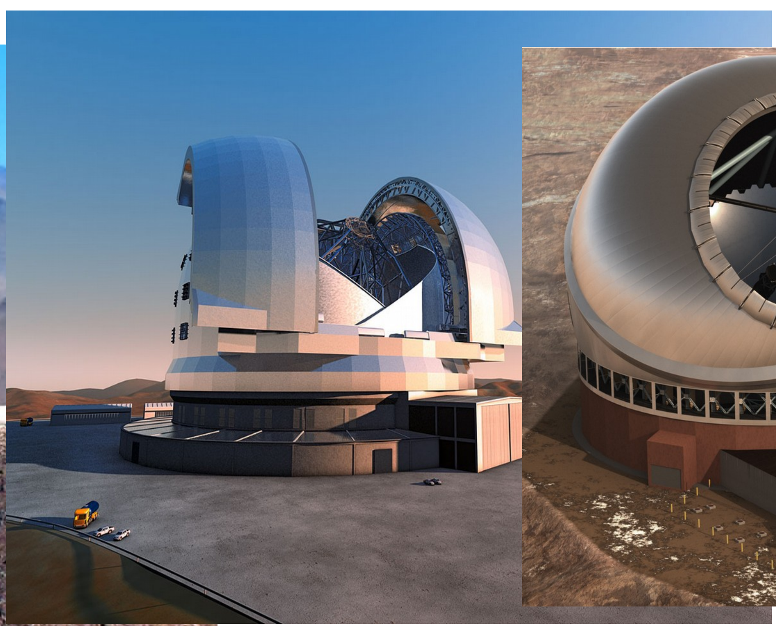


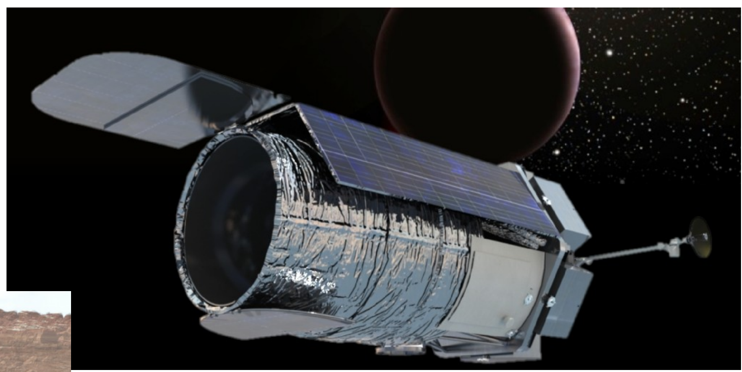
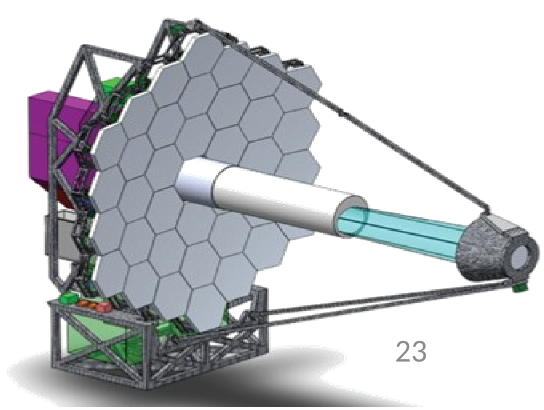

Saturn
Earth

Exciting future opportunities

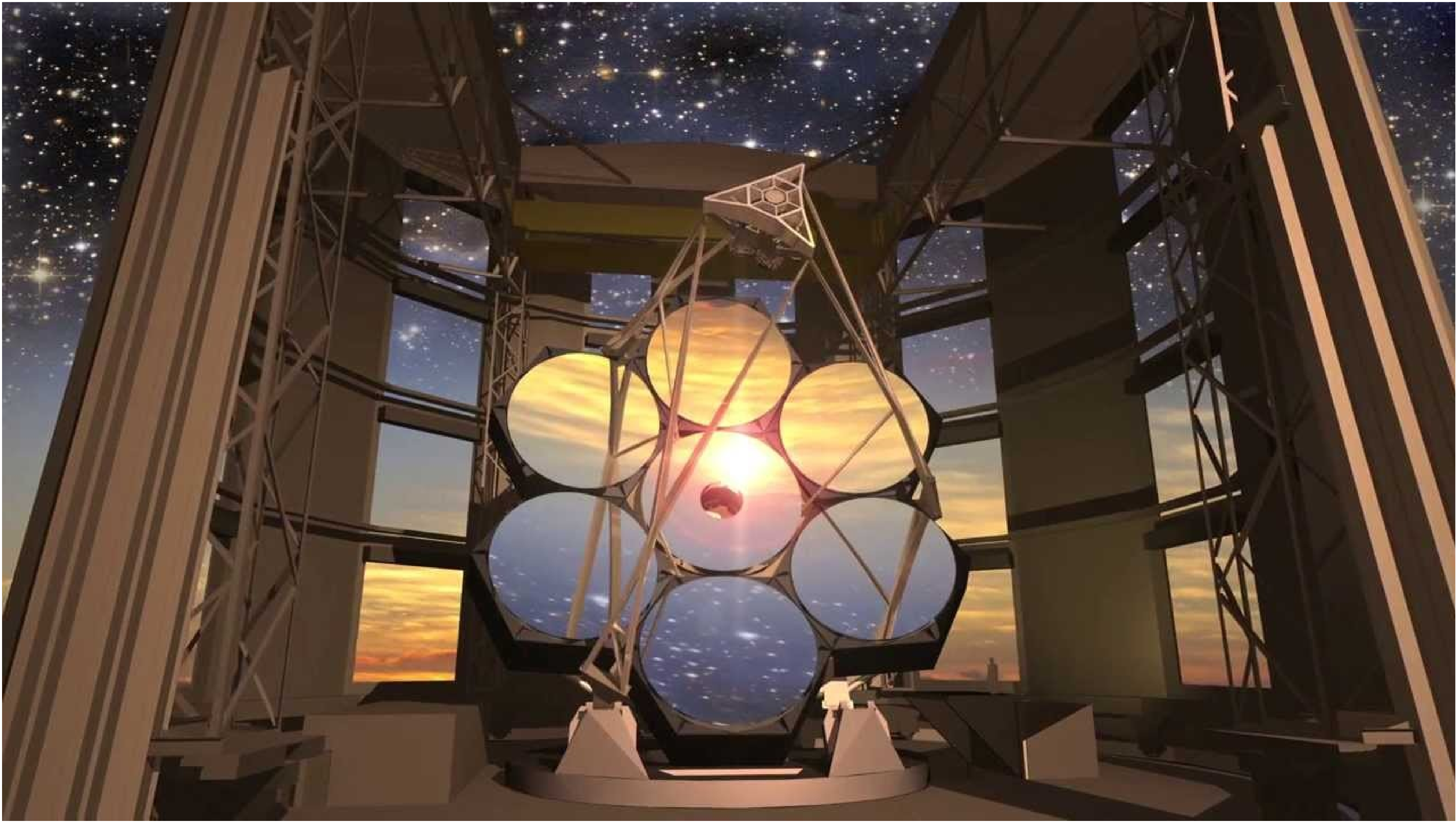
Next generation of large telescopes on the ground will be able to image habitable planets around nearby low mass red stars
3 projects, ~30m diameter

Space telescopes with coronagraphs will be able to image and study Earth-like planets around sun-like stars

Giant Magellan Telescope



Coronagraphy … Using optics tricks to remove starlight (without removing planet light)

← Olivier's thumb...
the easiest coronagraph
Doesn't work well enough to
see planets around other stars

We need a better coronagraph... and a larger eye (telescope)

Coronagraphy

Key coronagraph requirements :

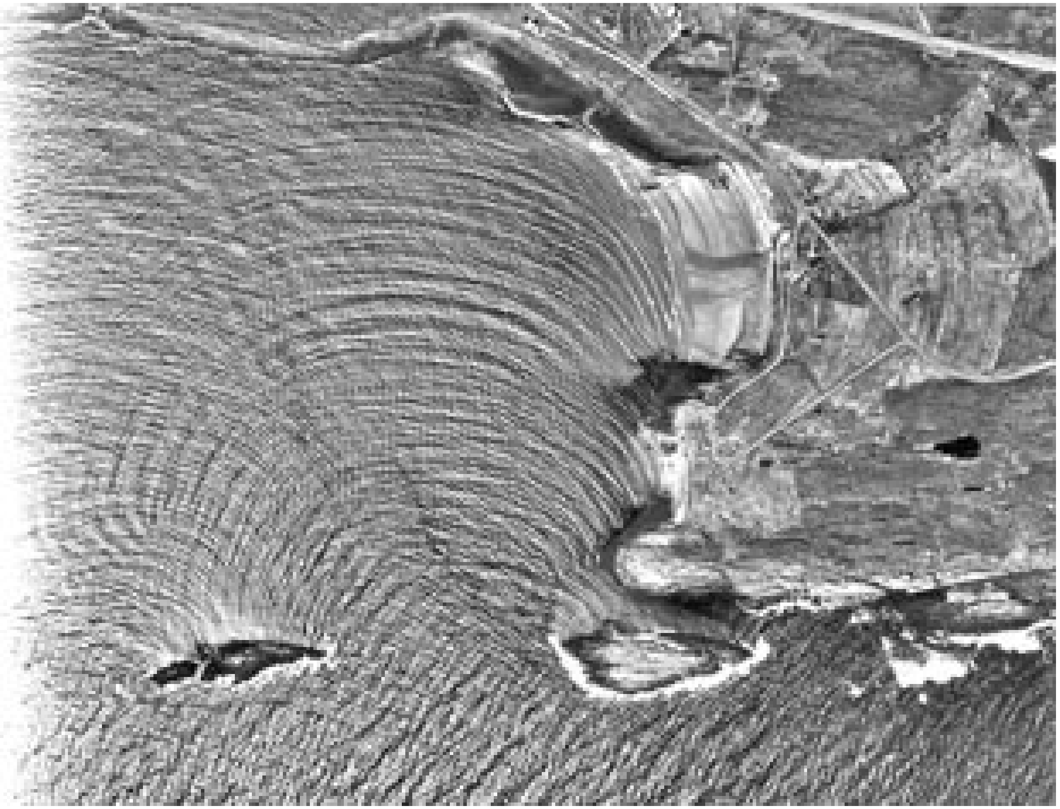
- IWA near 1 l/D

- high throughput

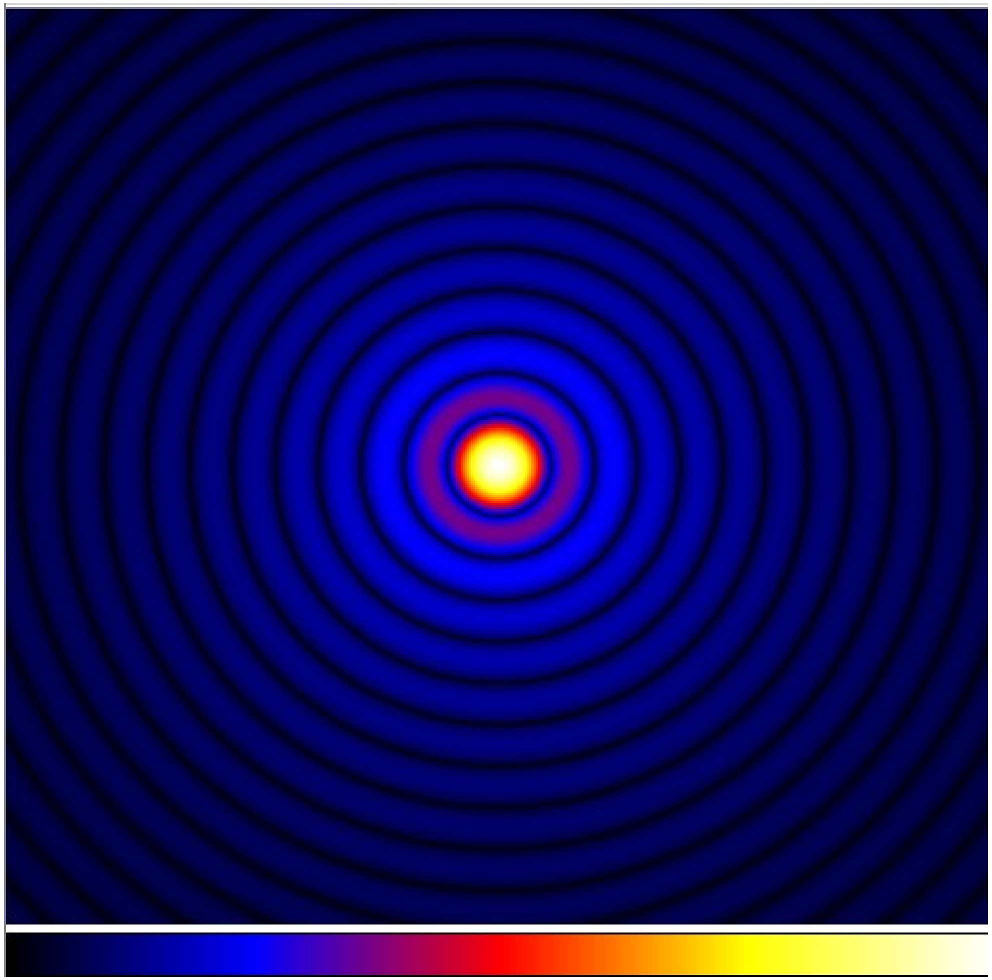
- ~1e-5 raw contrast

- resilient against stellar angular size (ELTs partially resolve stars)

Water waves diffract around obstacles, edges, and so does light



Waves diffracted by coastline and islands

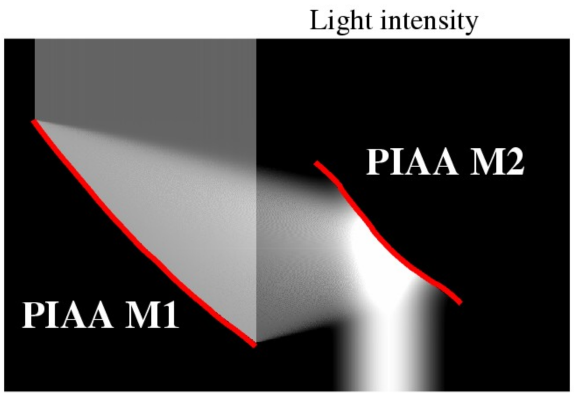


Ideal image of a distant star by a telescope
Diffraction rings around the image core

GMT coronagraph design

PIAACMC architecture:

- lossless apodization with aspheric mirrors
- multi-zone focal plane mask



60% throughput

IWA = 1.3 l/D

optimized for 10% wide band and stellar angular size

(largely) lossless apodization

Creates a PSF with weak Airy rings

Focal plane mask: -1<t<0

Induces destructive interference inside downstream pupil

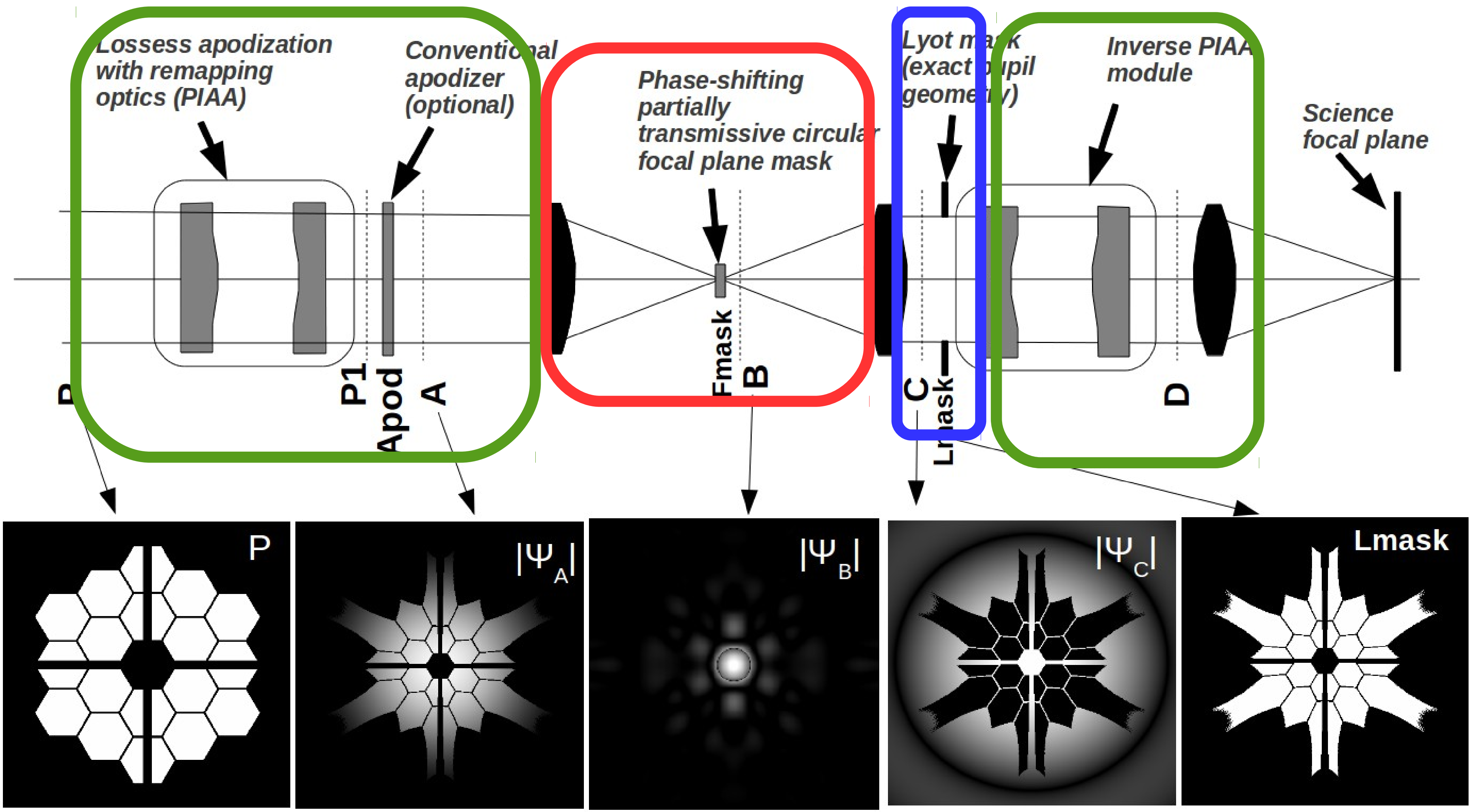
Lyot stop

Blocks starlight

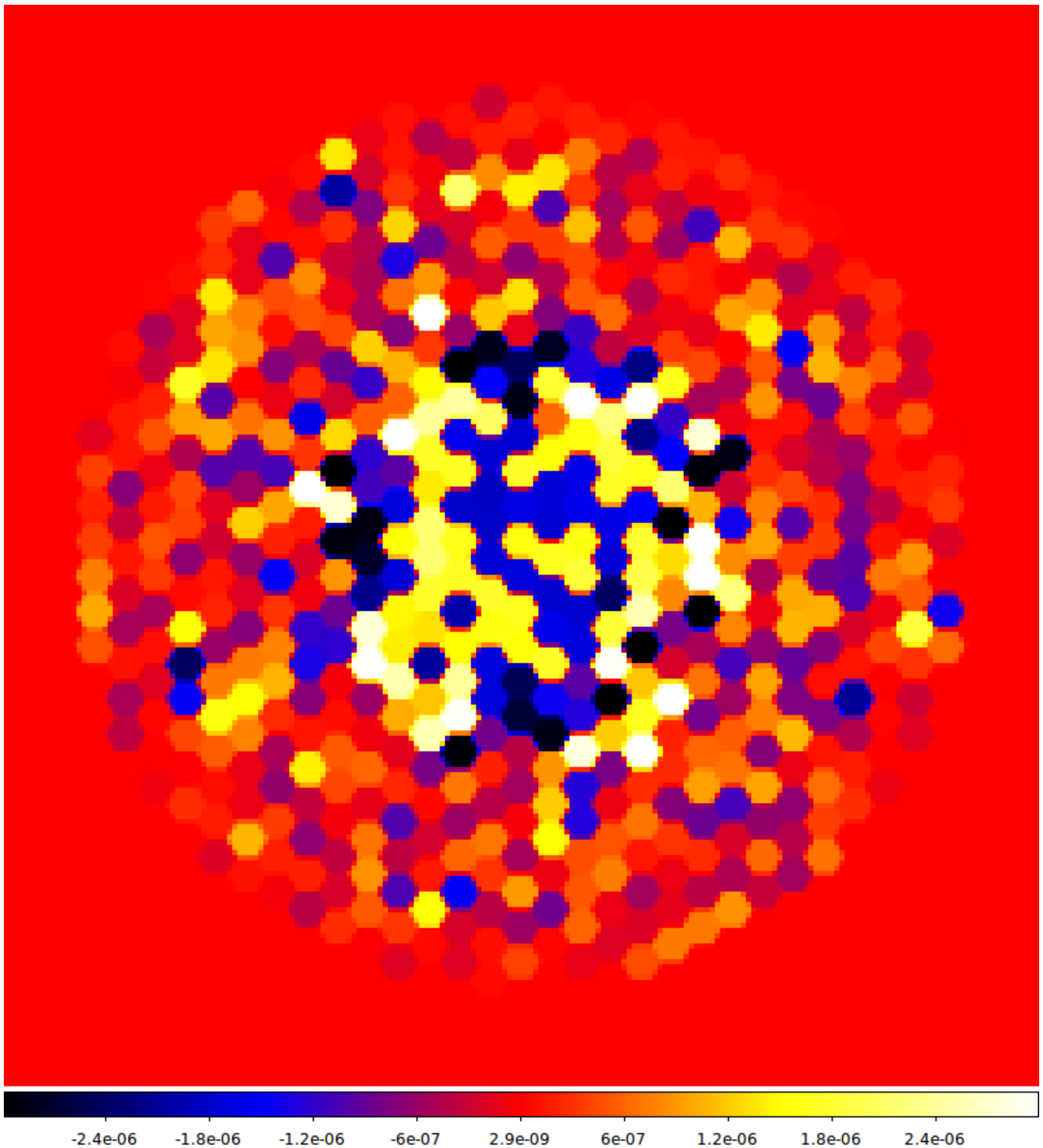
Inverse PIAA (optional)

Recovers Airy PSF over wide field

Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)



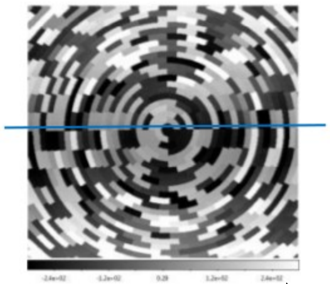
Focal plane mask

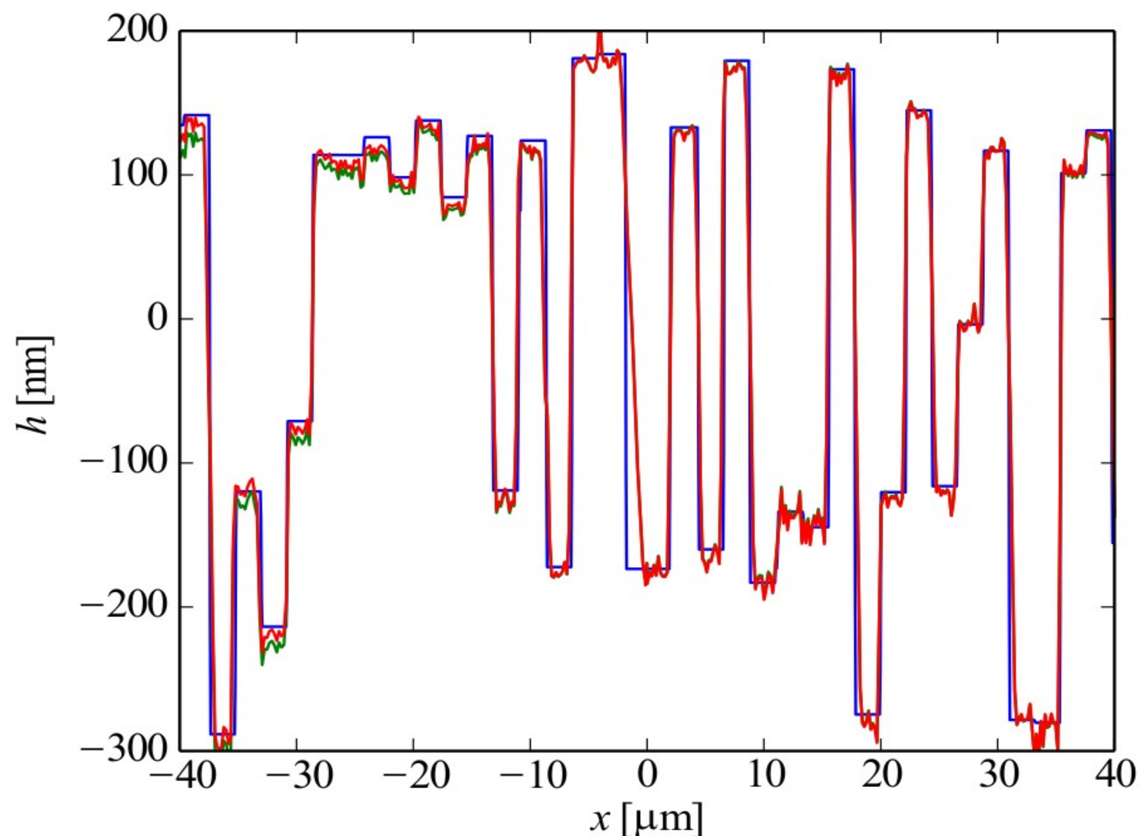


583 zones
SiO_2 (transmissive)
+/- 3 um sag

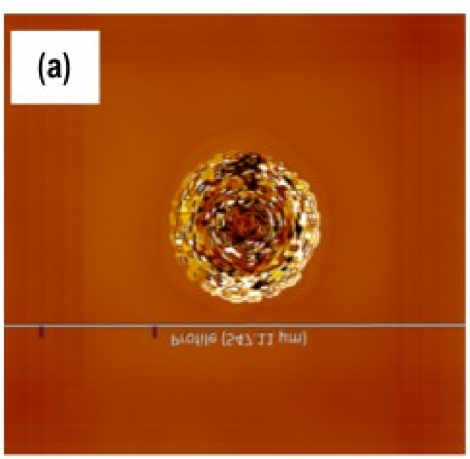
Optimized for 10% band,
partially resolved source

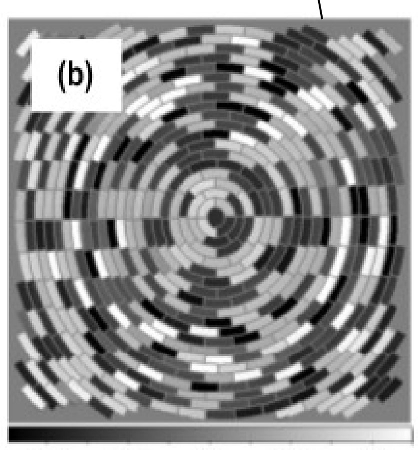
PIAACMC focal plane mask manufacturing

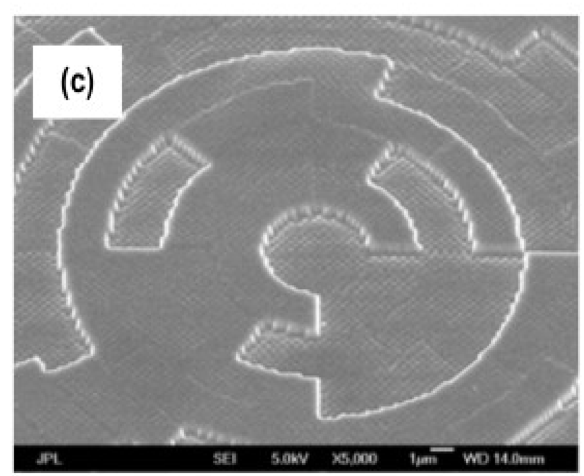


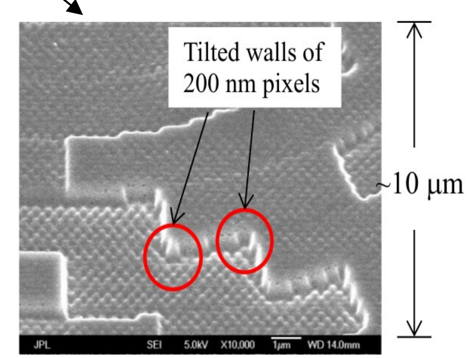


Focal plane mask manufactured at JPL's MDL
Meets performance requirements
(WFIRST PIAACMC Milestone report)





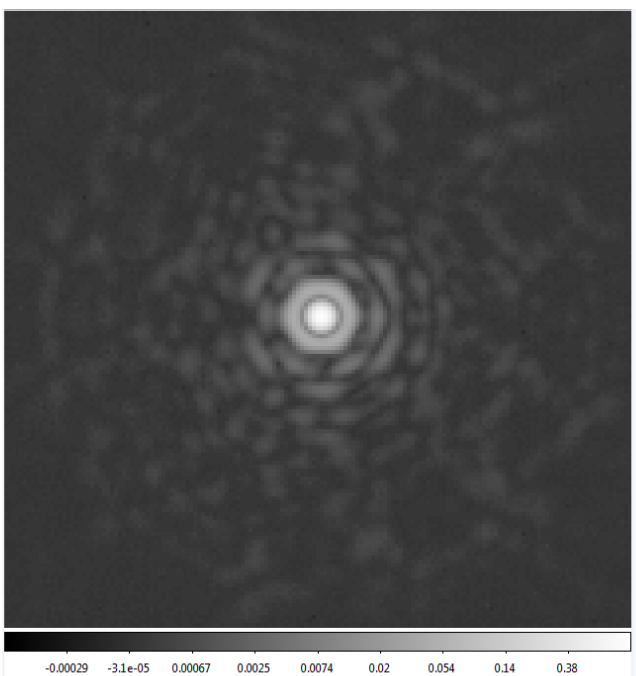




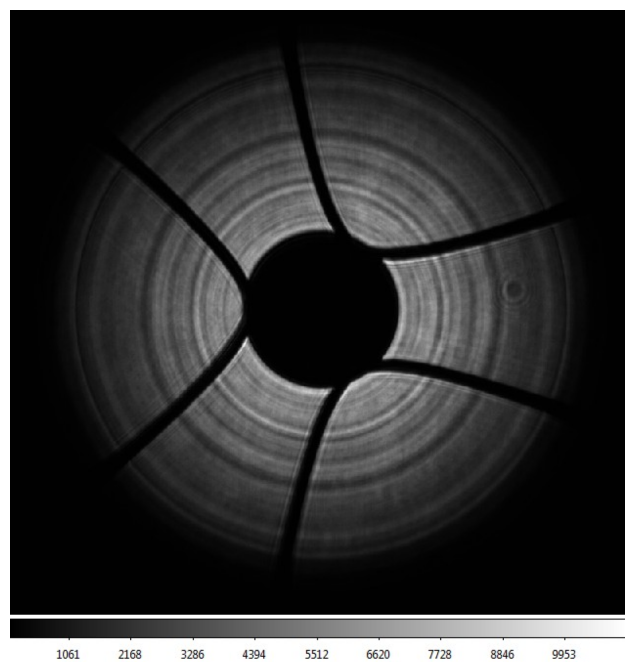
PIAACMC lab performance @ WFIRST (Kern et al. 2016)

Operates at 1e-7 contrast, 1.3 l/D IWA
Visible light

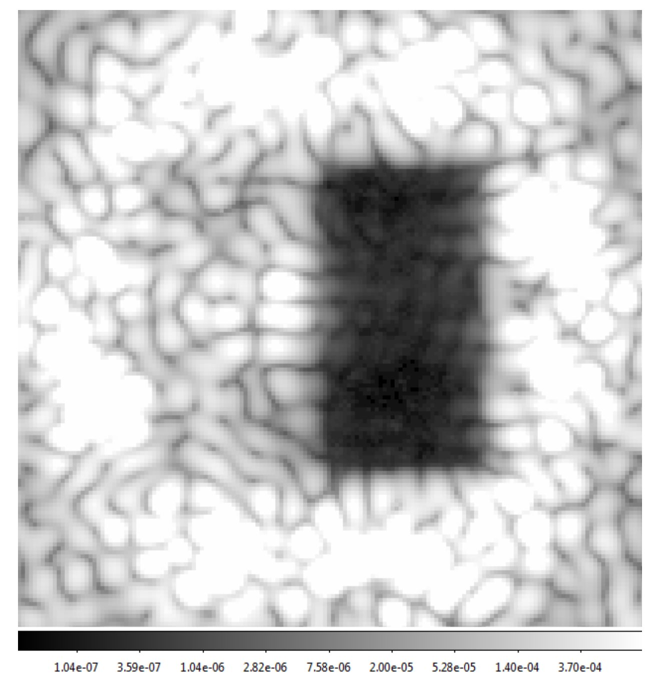
non-coronagraphic PSF

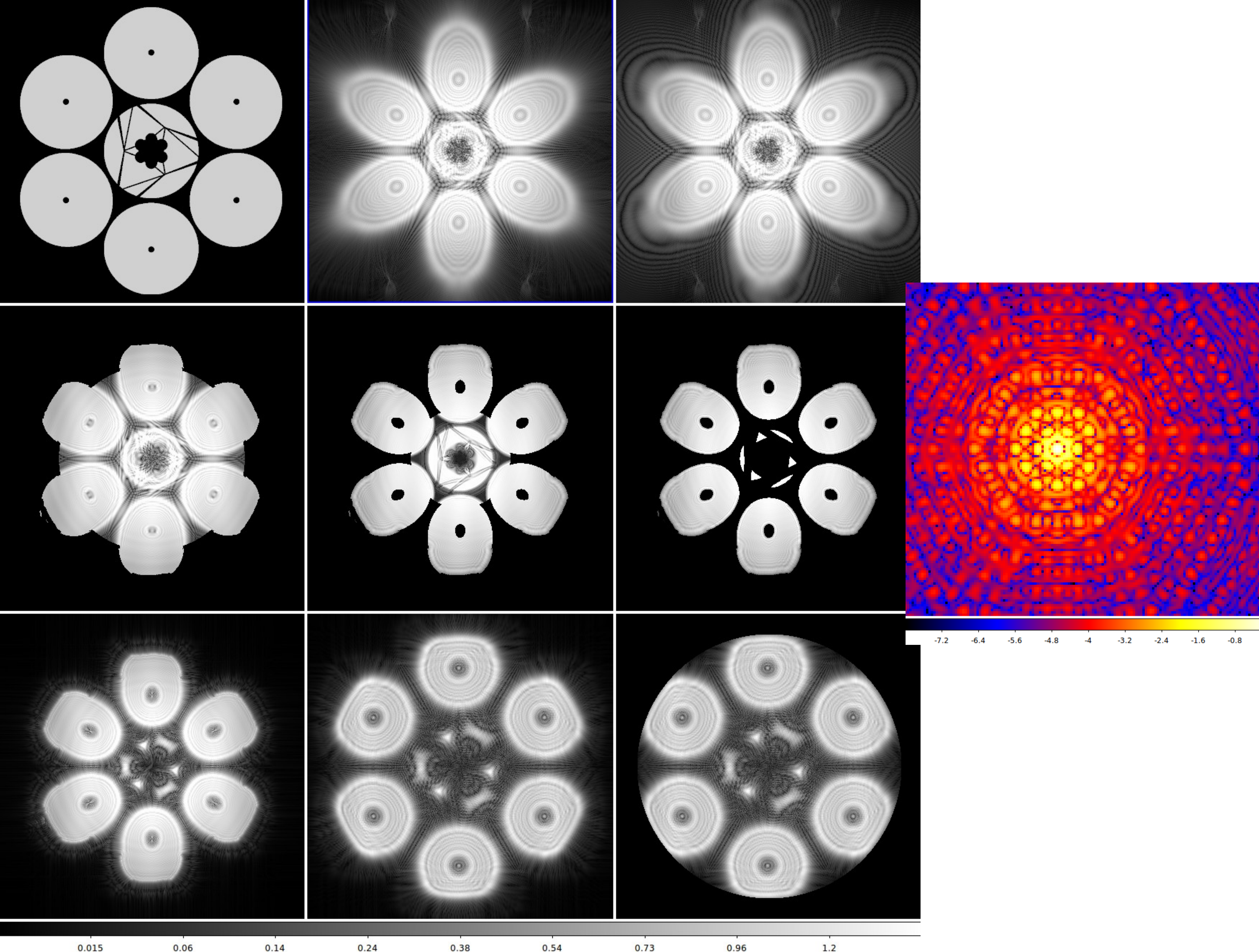


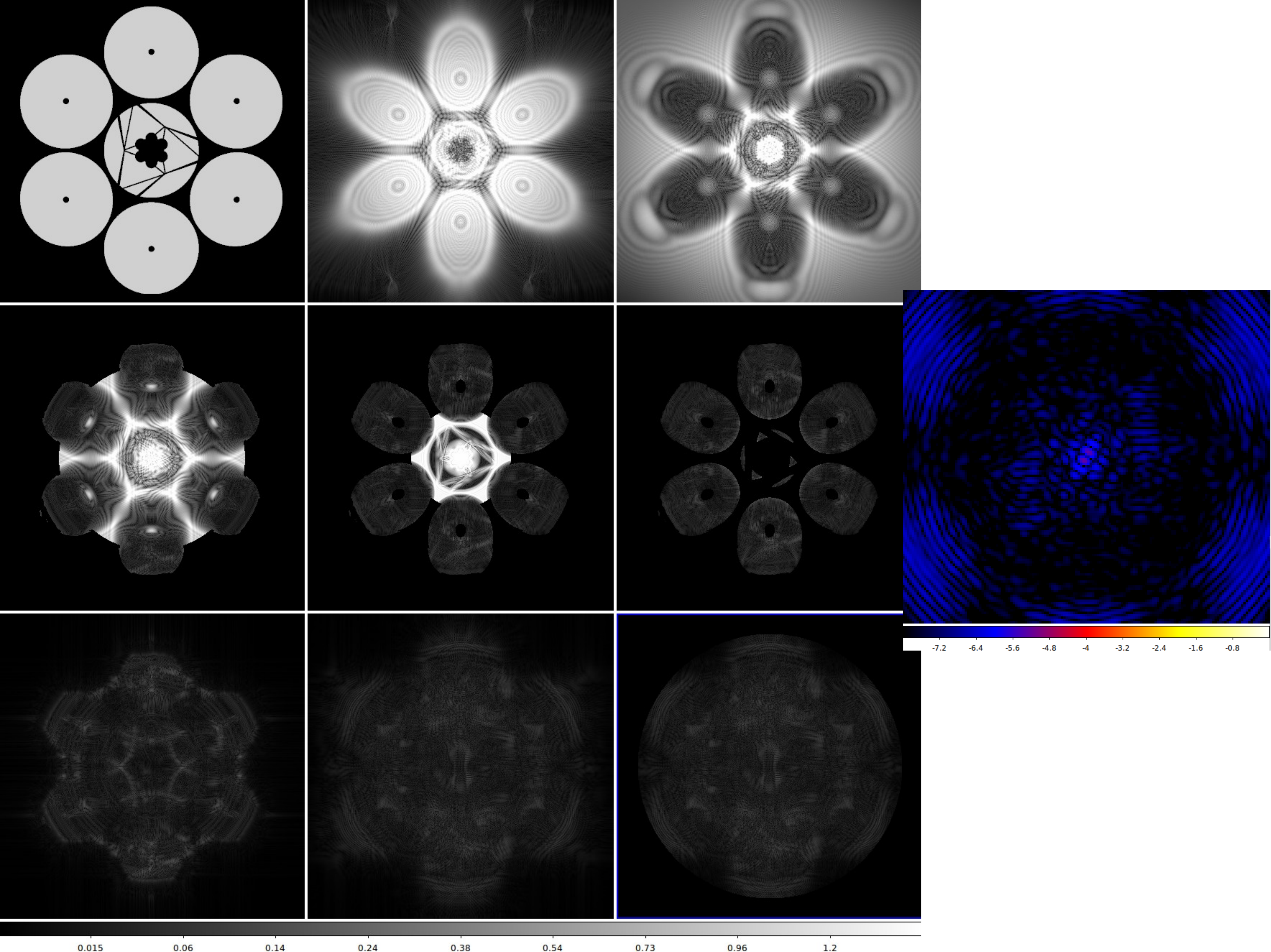
Remapped pupil



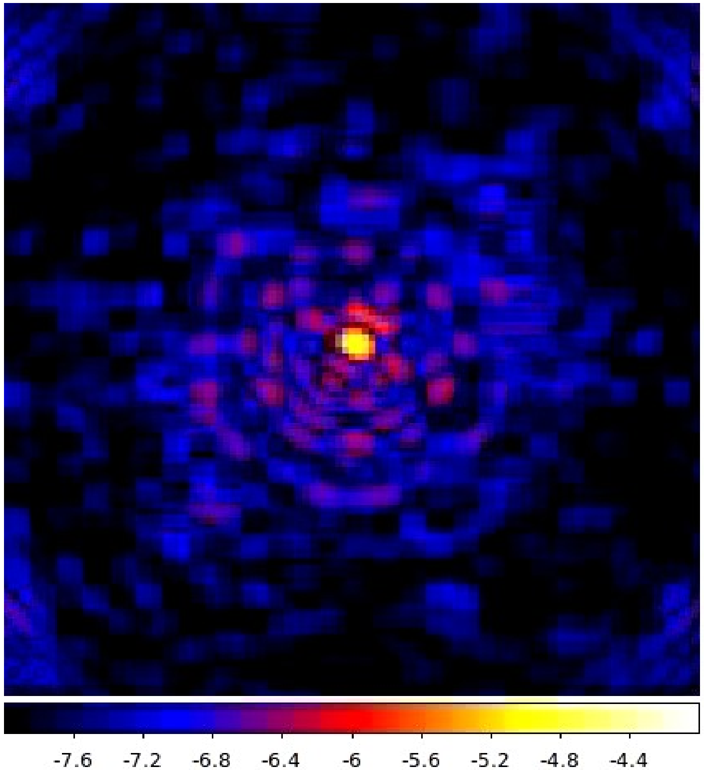
Coronagraphic image



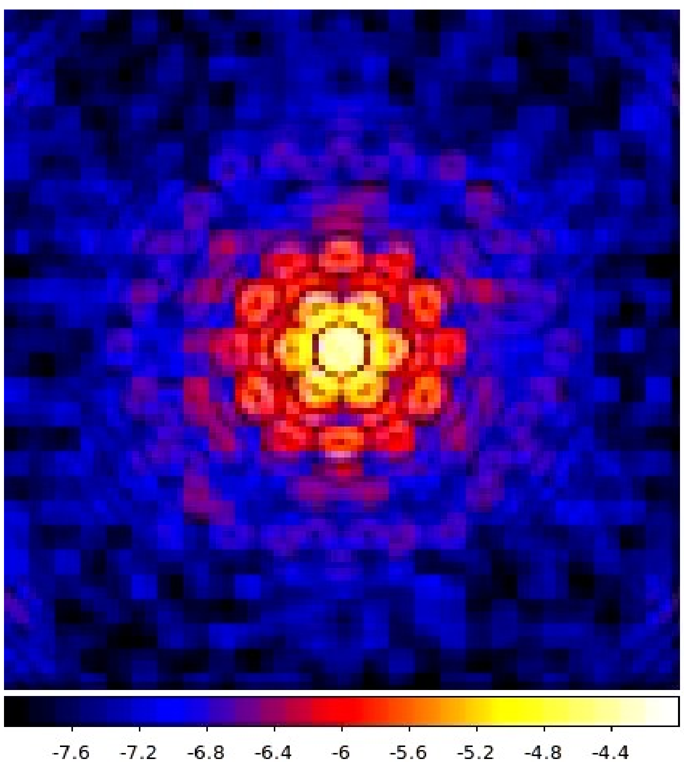

-7.2 -6.4 -5.6 -4.8 -4 -3.2 -2.4 -1.6 -0.8
0.015 0.06 0.14 0.24 0.38 0.54 0.73 0.96 1.2

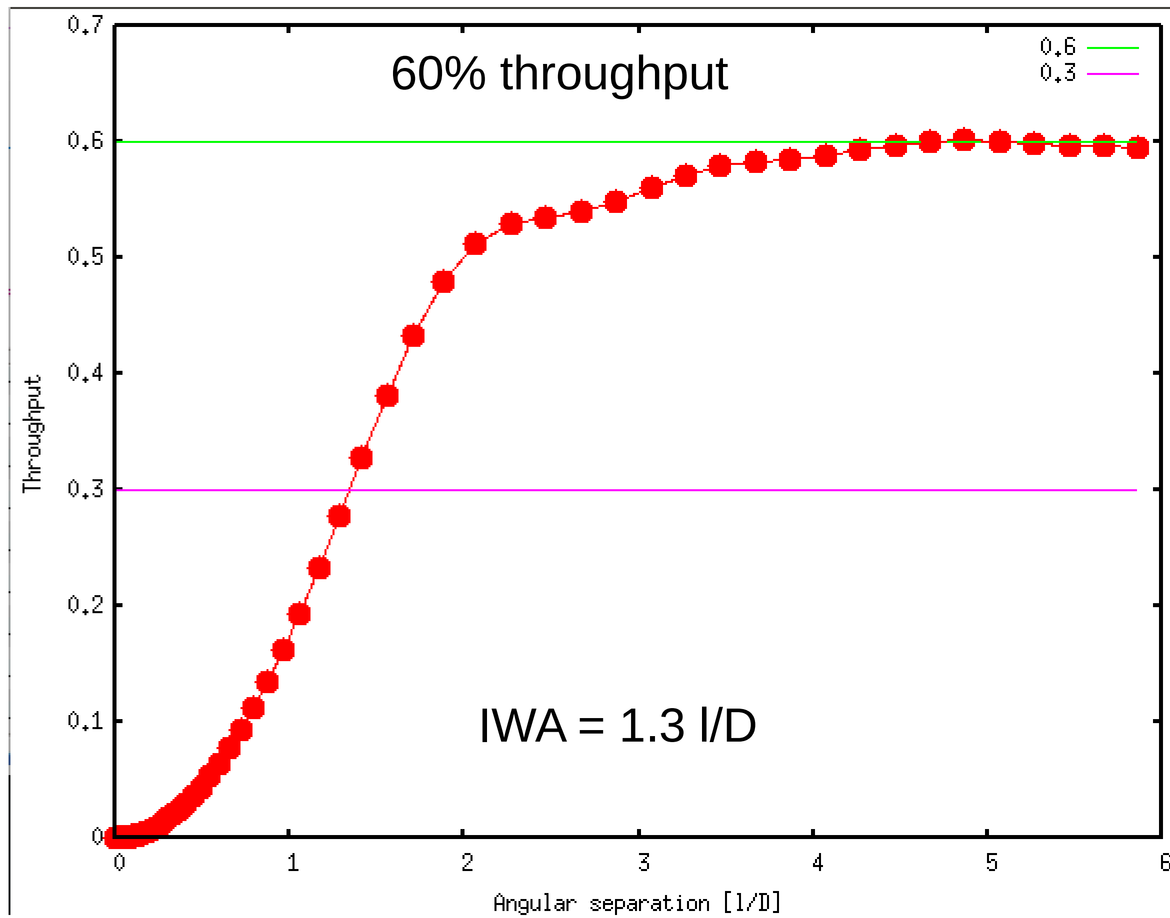

-7.2 -6.4 -5.6 -4.8 -4 -3.2 -2.4 -1.6 -0.8
0.015 0.06 0.14 0.24 0.38 0.54 0.73 0.96 1.2

Performance



1e-7 contrast (top: point source)
3e-6 contrast @ 3 l/D for 6% l/D disk (bottom)





WFC architecture game-changers

[1] High-efficiency WFS
M stars are not very bright for ExAO → need high efficiency WFS
For low-order modes (TT), seeing-limited (SHWFS) requires (D/r0)^2 times more light than diffraction-limited WFS (Pyramid)
This is a **40,000x gain for 30m telescope** (assuming r0=15cm) → 11.5 mag gain

[2] Low latency WFC (High-speed WFS + predictive control)
System lag is extremely problematic → creates "ghost" slow speckles that last crossing time
Need ~200us latency (10 kHz system, or slower system + lag compensation)
Predictive control is essential

[3] Managing chromaticity: Multi-wavelength WFC / LOWFS, closed loop ADC
Wavefront chromaticity is a serious concern when working at ~1e-8 contrast
Visible light (~0.6 – 0.8 um) photon carry most of the WF information, but science is in near-IR

[4] Fast speckle control, enabled by new detector technologies
Addresses non-common path errors
It doesn't take much to create a 1e-8 speckle !

[5] Real-time telemetry → PSF calibration
WFS telemetry tells us where speckles are → significant gain using telemetry into post-processing

WFC: Contrast limits

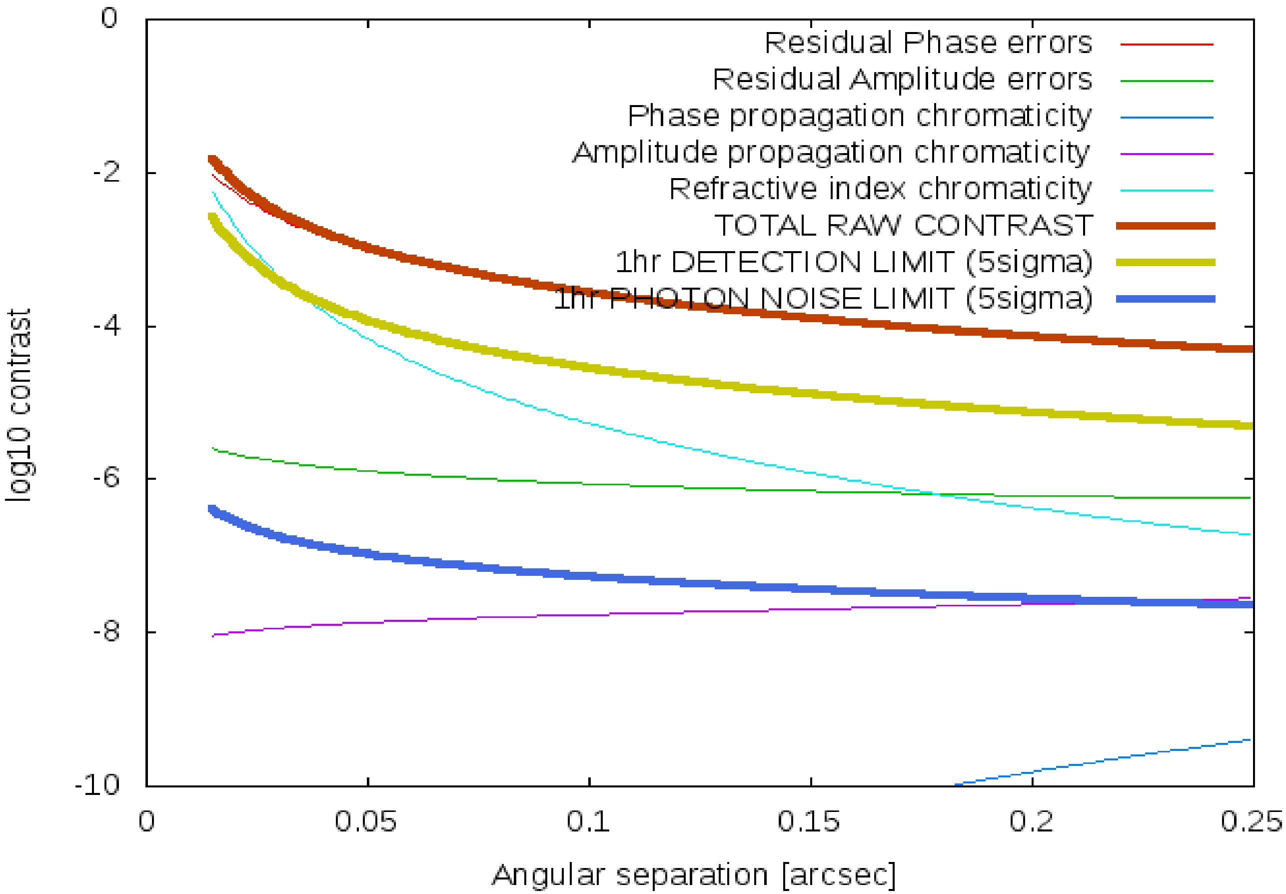
Assumptions:

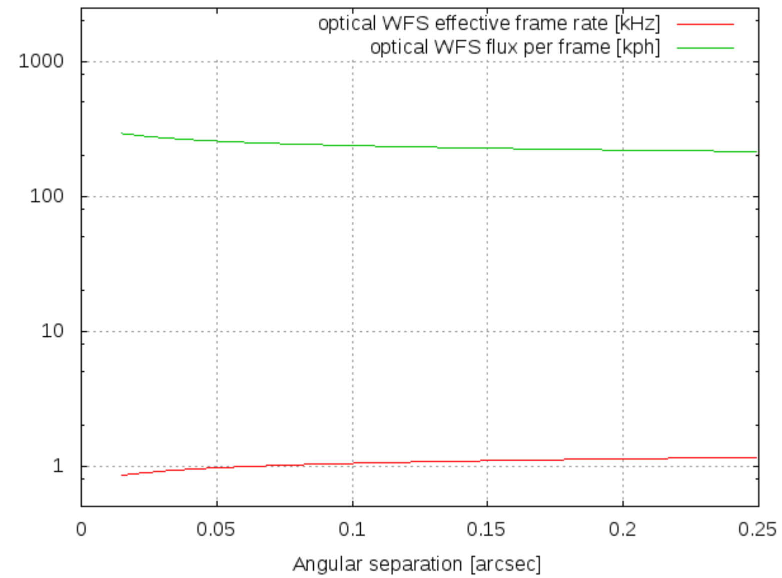
I mag = 8 (WFS – 100 targets)
H mag = 6 (Science)

Noiseless detectors
1.3 l/D IWA coronagraph
30% system efficiency
40% bandwidth in both WFS and science
Time lag = 1.5 WFS frames

Mauna Kea "median" atmosphere

30m: SH-based system, 15cm subapertures

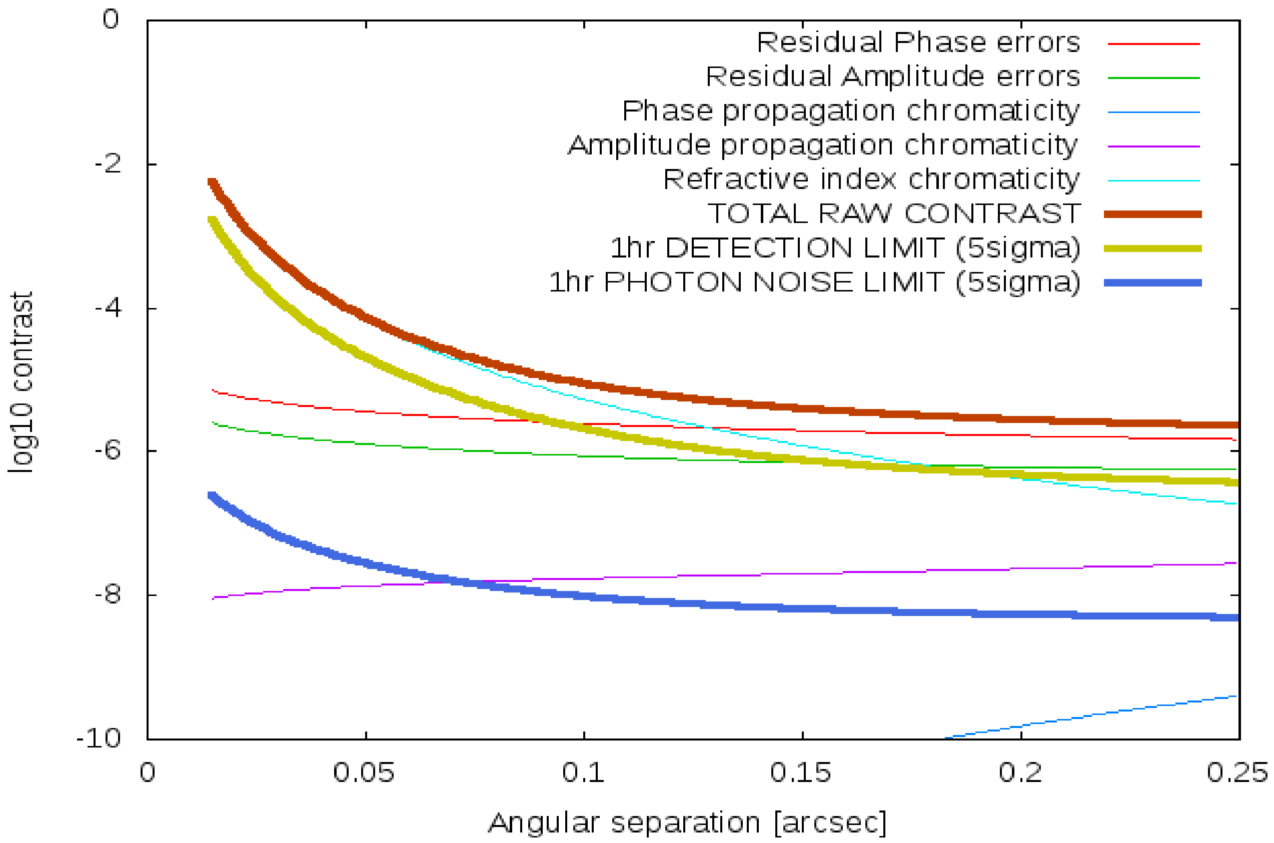


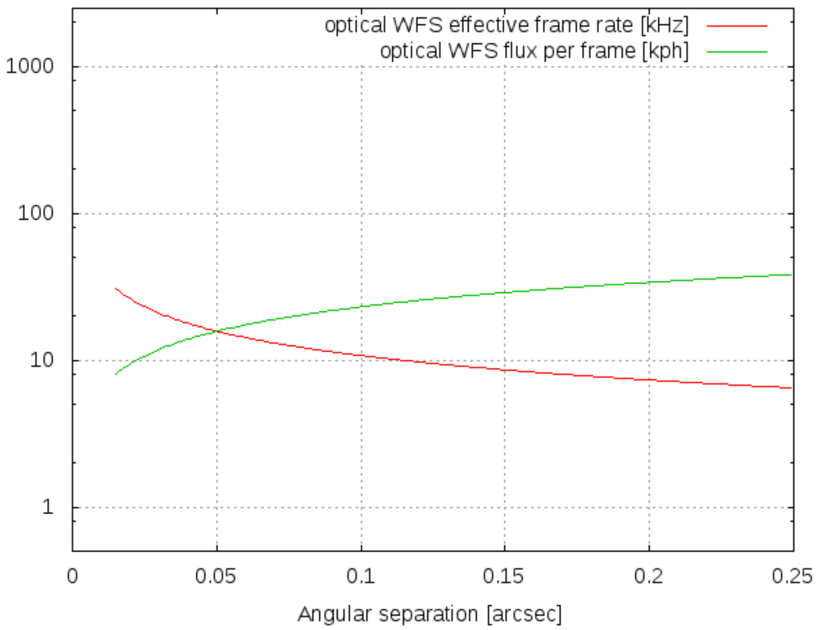


Limited by residual OPD errors: time lag + WFS noise
kHz loop (no benefit from running faster) – same speed as 8m telescope
>10kph per WFS required

Detection limit ~1e-3 at IWA, **POOR AVERAGING due to crossing time**

[1+2] 30m: Pyramid-based system

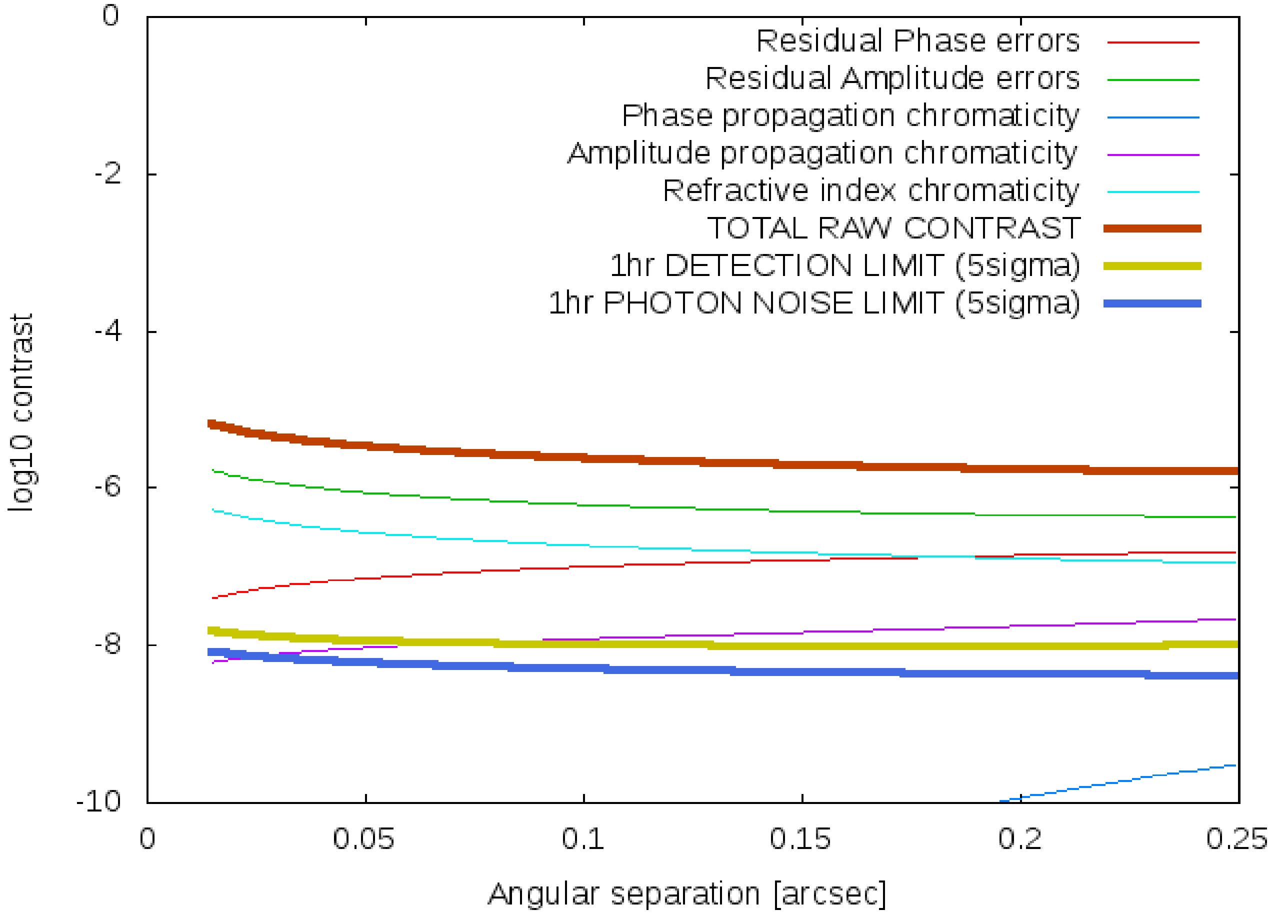


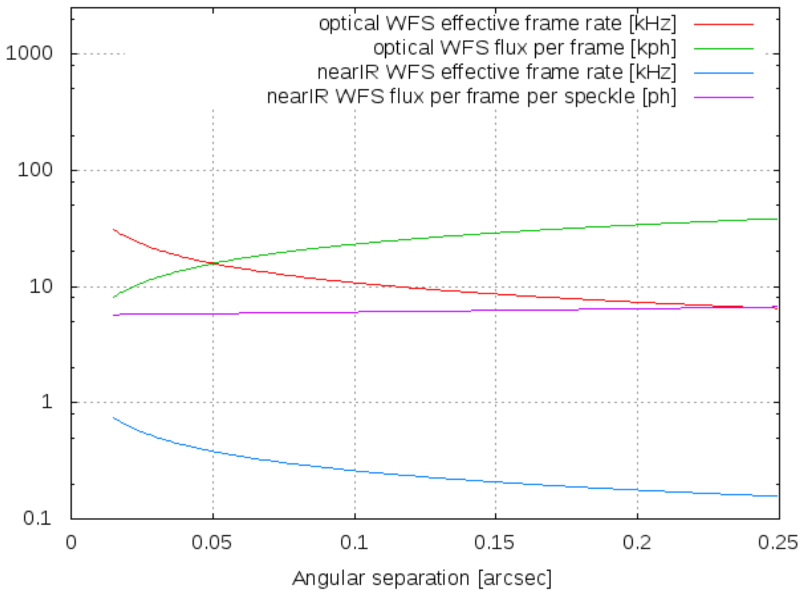


More sensitive WFS, can run faster (10kHz) with ~10 kph per WFS frame
Limited by atmosphere chromaticity

~((D/CPA)/r0)^2 flux gain: ~10,000x in flux = 10 mag near IWA
Sensitivity now equivalent to I mag = -2 with SHWFS

[1+2+3+4] 30m: Pyramid-based system + speckle control afterburner





300Hz speckle control loop (~1kHz frame rate) is optimal

Residual speckle at ~1e-6 contrast and fast → good averaging to detection limit at ~1e-8

Detection limit ultimately constrained by RAW contrast (photon noise)
→ predictive control can push performance deeper

Optimal linear predictive control
(model-free, uses Empirical Orthogonal Functions)

… what dumb people do with fast computers

Collect LOTS of data, and then find the multi-dimentional AR filter that best reproduce current measurement as a function of past measurements
(best = least square)

Computationally very intensive: need pseudo-inverse of data matrix

Data matrix size: # of time steps (60,000 for 1kHz system, 1mn telemetry) x # of AR filter coefficient (10,000 for 1000 modes, 10-step prediction)

Current WF (~1000 modes) = Prediction coefficients (10,000,000 coefficients) x past measurements (10,000 values)

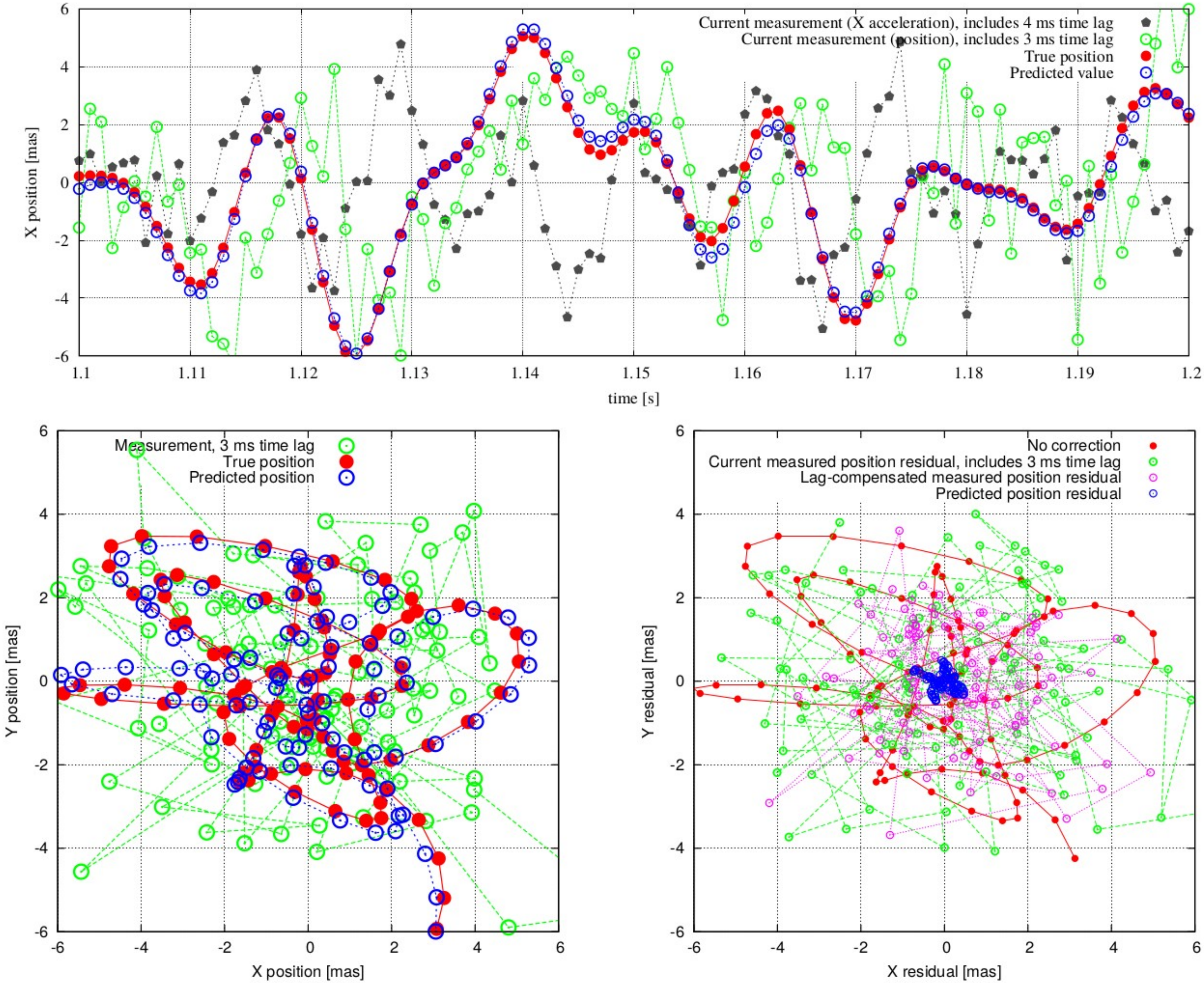


FIG. 3.— Top left: 2D-tracks for true pointing (red), predicted pointing (blue) and last measured position (green). Top right: Residual pointing error. Bottom: Single axis (x) values.

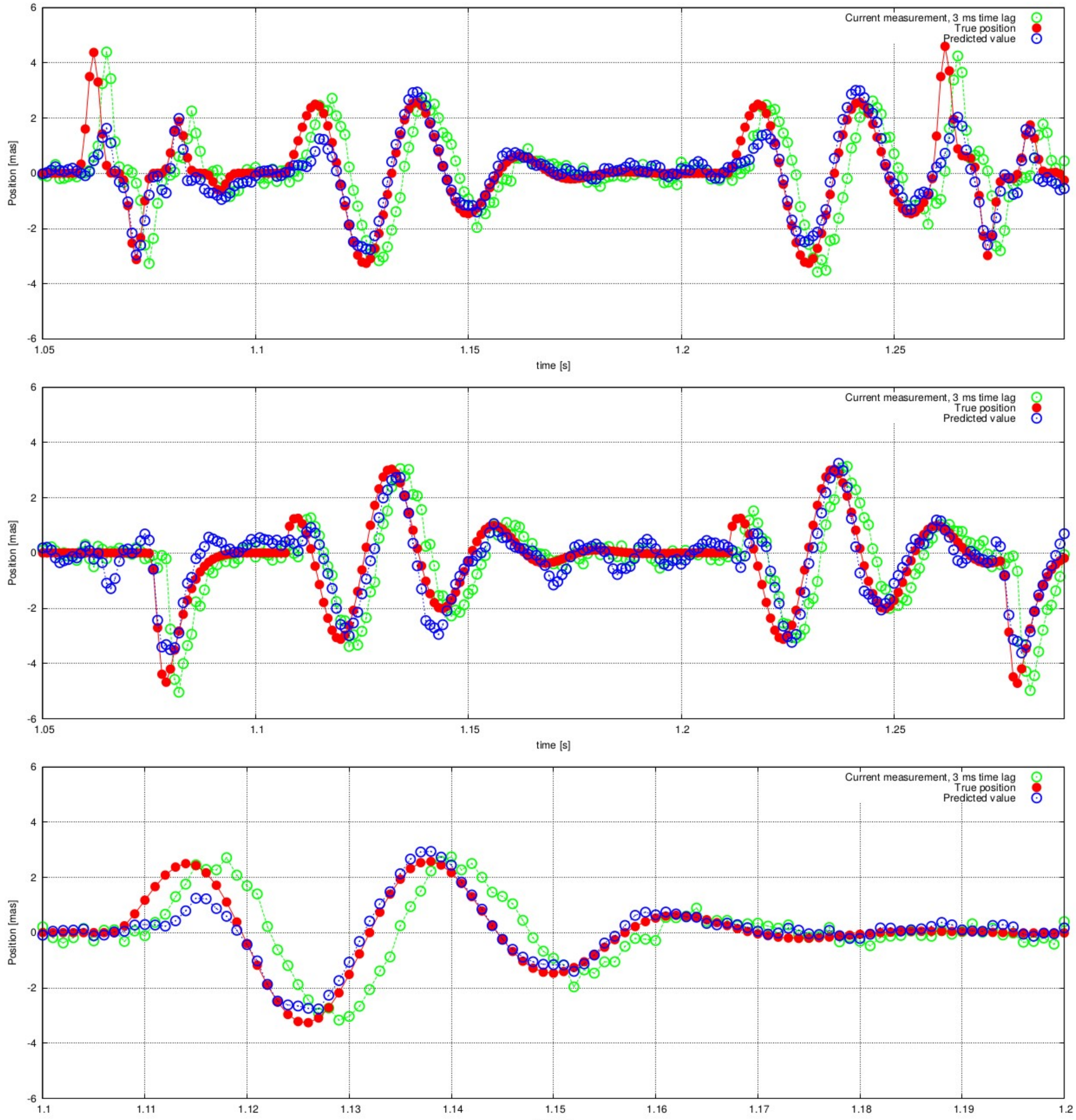


FIG. 4.— Top left: 2D-tracks for true pointing (red), predicted pointing (blue) and last measured position (green). Top right: Residual pointing error. Bottom: Single axis (x) values.

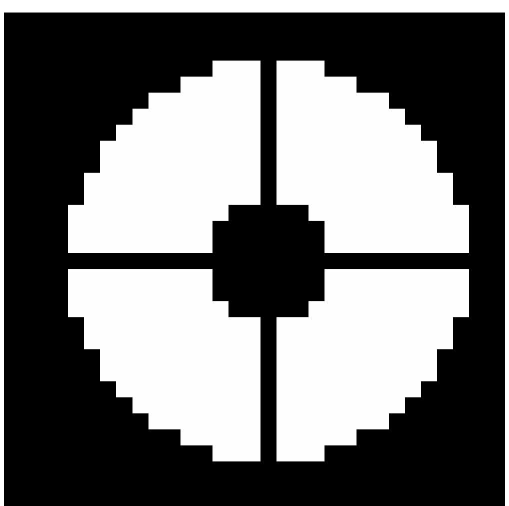
Optimal linear predictive control – 8m telescope (model-free, uses Empirical Orthogonal Functions)

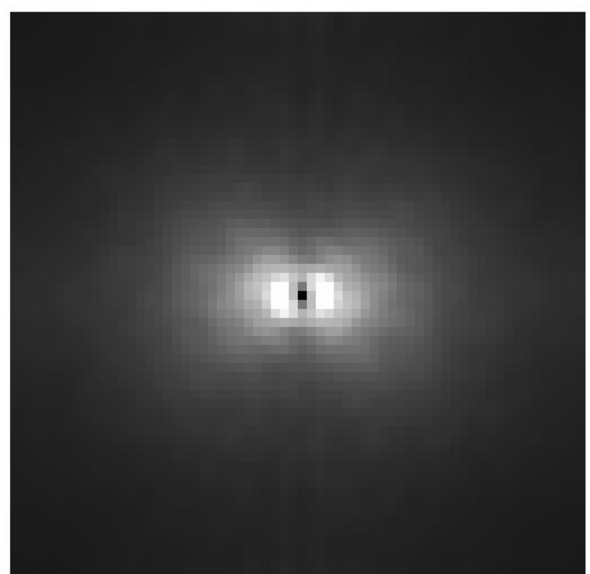
8m telescope
mag 8 source (R band)
1kHz sampling + 2ms lag
Photon-noise limited sensor
10% efficiency, 20% bandwidth
r0 = 20cm at 0.6um → 21 rad WFE RMS
7 layer turbulence, most power between 6 and 22 m/s

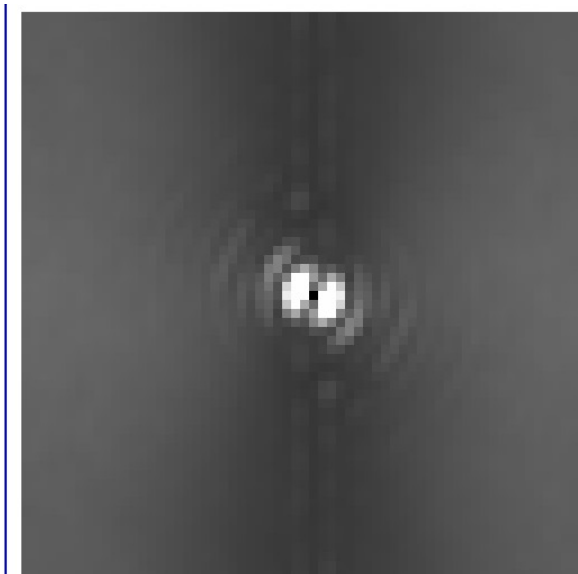
Optimal control of 400 zonal actuators
1mn training set → controller
(rolling average of 10 last controllers)

Integrator : RMS = 214 nm (gain = 1)
10-step prediction: RMS = 30.5 nm

System dominated by time lag (214nm error)
WFS noise small (9nm RMS over first 400 low-order modes)







Benefits & challenges

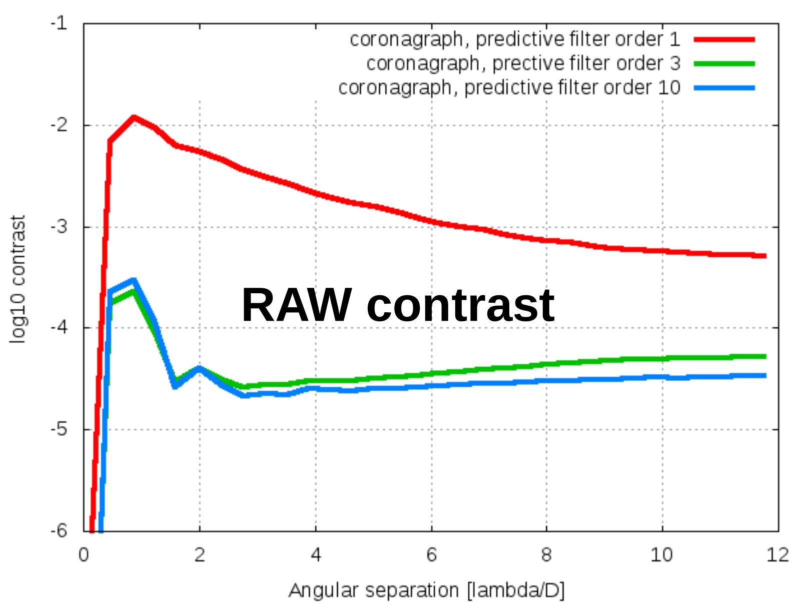
Lower wavefront error (30nm vs. >200nm)
Raw contrast improvement: ~100x gain

Relaxed speed requirement
contrast corresponds to 10 kHz WFS lag
→ 10x speed gain

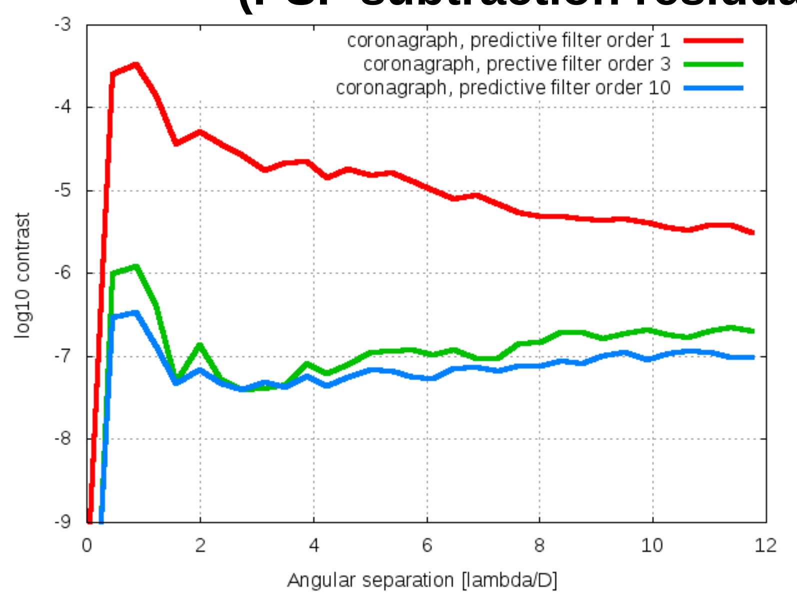
Smoother PSF halo
slow speckles are GONE

Computation requirements:
SVD of 60000x4000 dense matrix in <1mn
already met on single GTX980M GPU (laptop)

few 1000s modes @ few kHz can be done on
current hardware



1hr detection limit
(PSF subtraction residual)



Differential detection game-changers

[1] High spectral resolution template matching

100x – 1000x gain (photon-noise permitting)

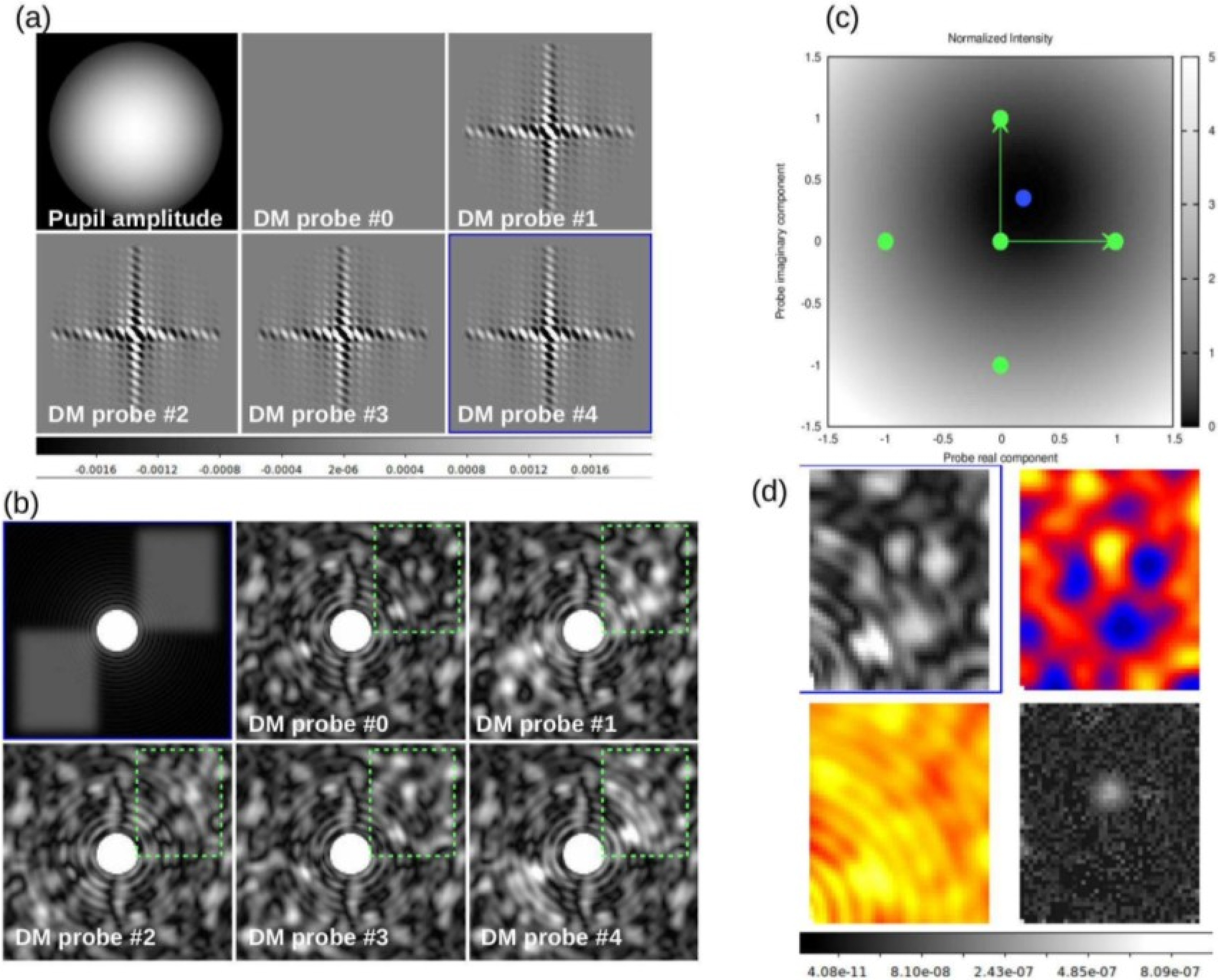
[2] Coherent differential imaging

10-100x gain ?

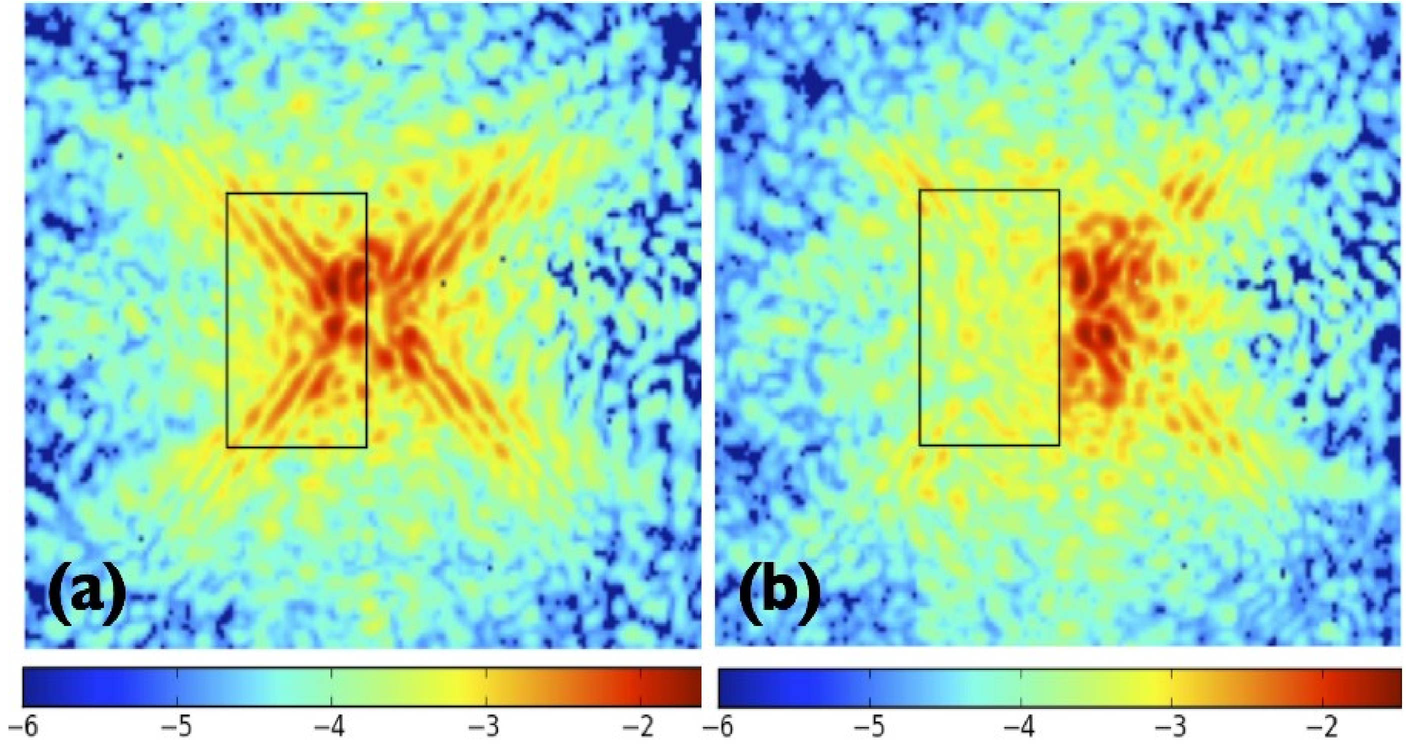
[3] Linear Dark field speckles control

10-100x gain ?

Coherent Speckle Differential Imaging



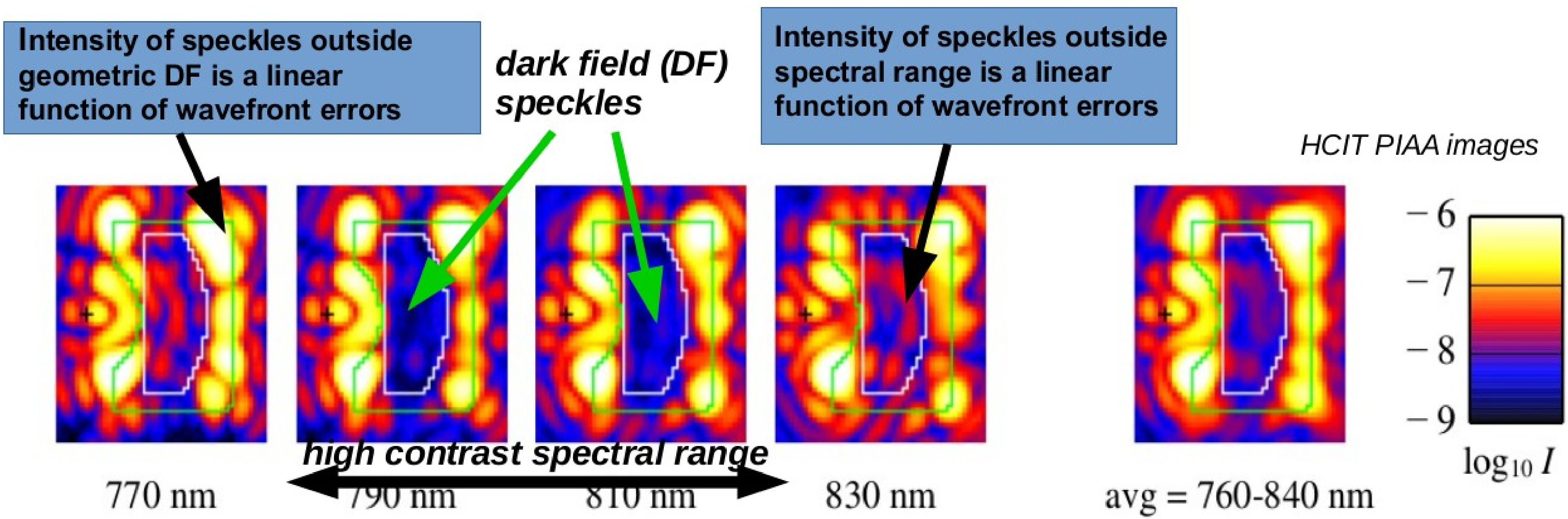
Bright field speckles in ½ field dark hole



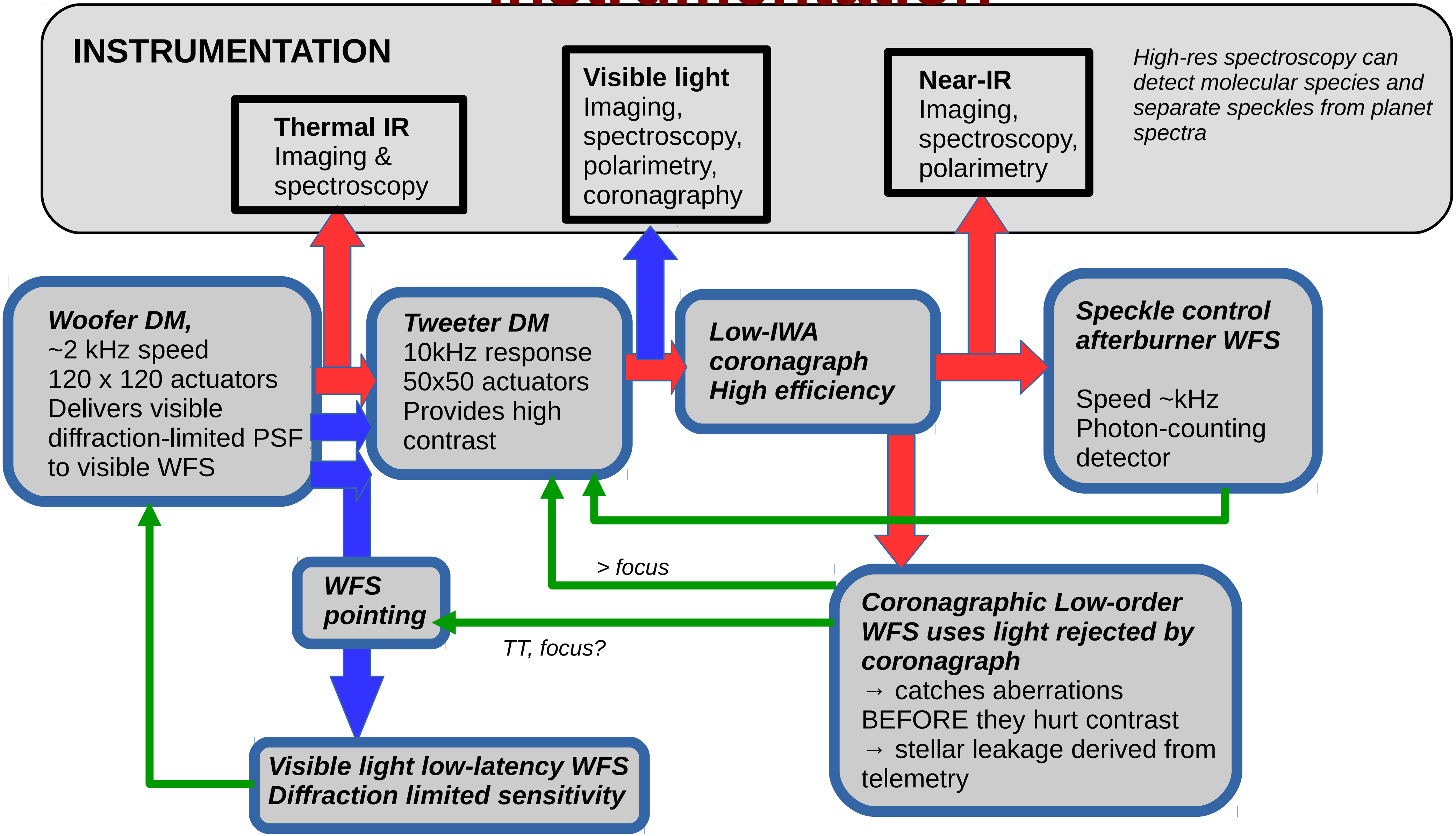
Linear Dark Field Control (LDFC)

Speckle intensity in the DF are a non-linear function of wavefront errors
→ current wavefront control technique uses several images (each obtained with a different DM shape) and a non-linear reconstruction algorithm (for example, Electric Field Conjugation – EFC)

Speckle intensity in the BF are linearly coupled to wavefront errors → we have developed a new control scheme using BF light to freeze the wavefront and therefore prevent light from appearing inside the DF



Example system architecture with instrumentation



Can we do it ?

GPI, SPHERE operate at ~1e-6 contrast at >0.3 arcsec separation, fall short of goal, but current technologies exist to meet requirements.

However, most of what we need has never been tested on sky and integrated into a system → this is what we need to do NOW on current large telescopes

It takes yrs of hard work to put all of this together, learn what works, and optimize algorithms / designs (including data reduction)

prototypes to ELT systems

SCExAO program on Subaru is technology development platform to mature techniques and system for ELTs

MagAO-X plays similar role on Magellan. Strong collaboration between the two projects (technology transfer, shared algorithms/software)

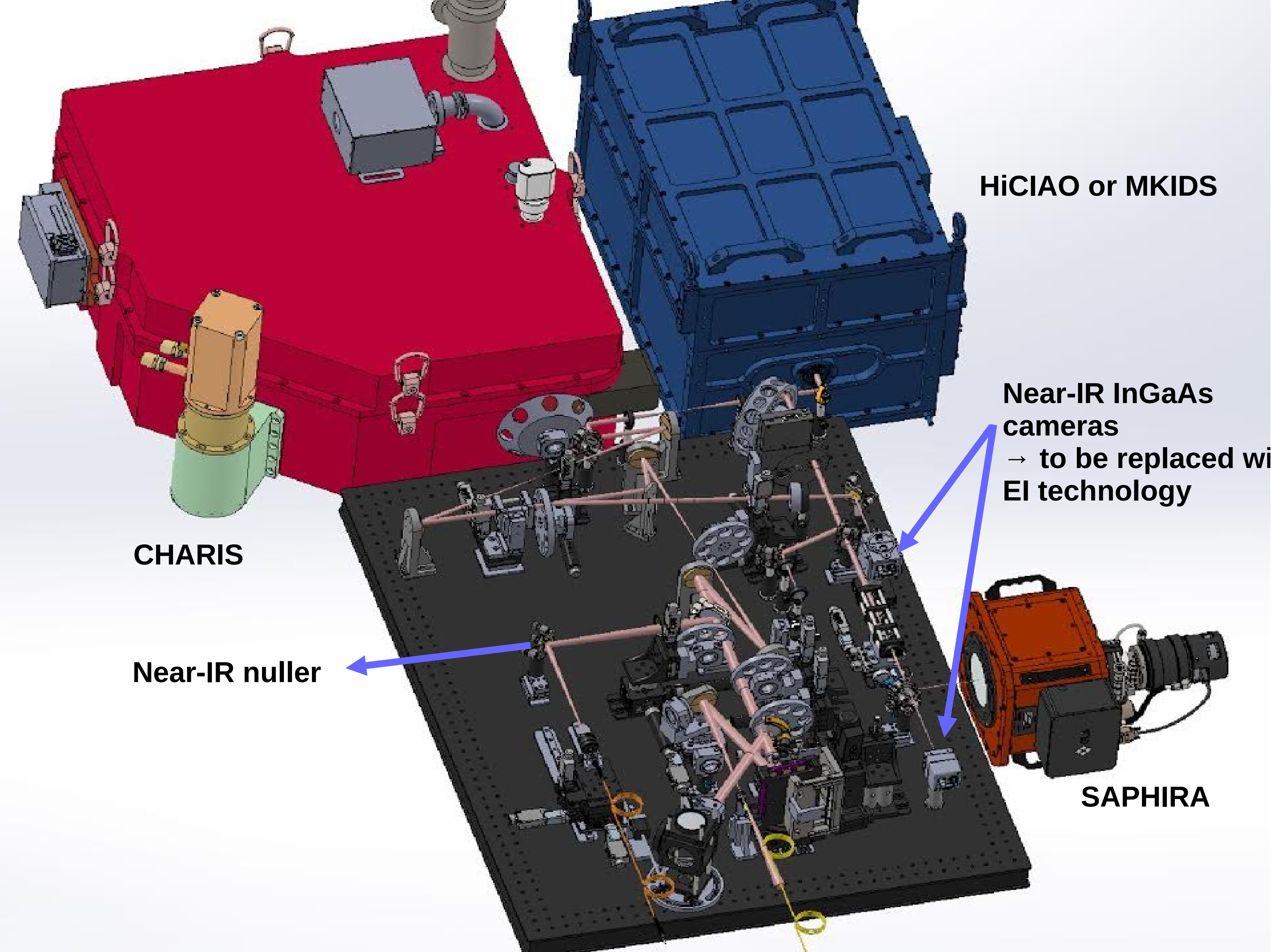
Focused efforts on Palomar & Keck validate key technologies (Vortex coronagraphy, LOWFS, HR template matching)

Lab efforts @ UofA, Caltech, JPL, Princeton, Stanford

SCExAO

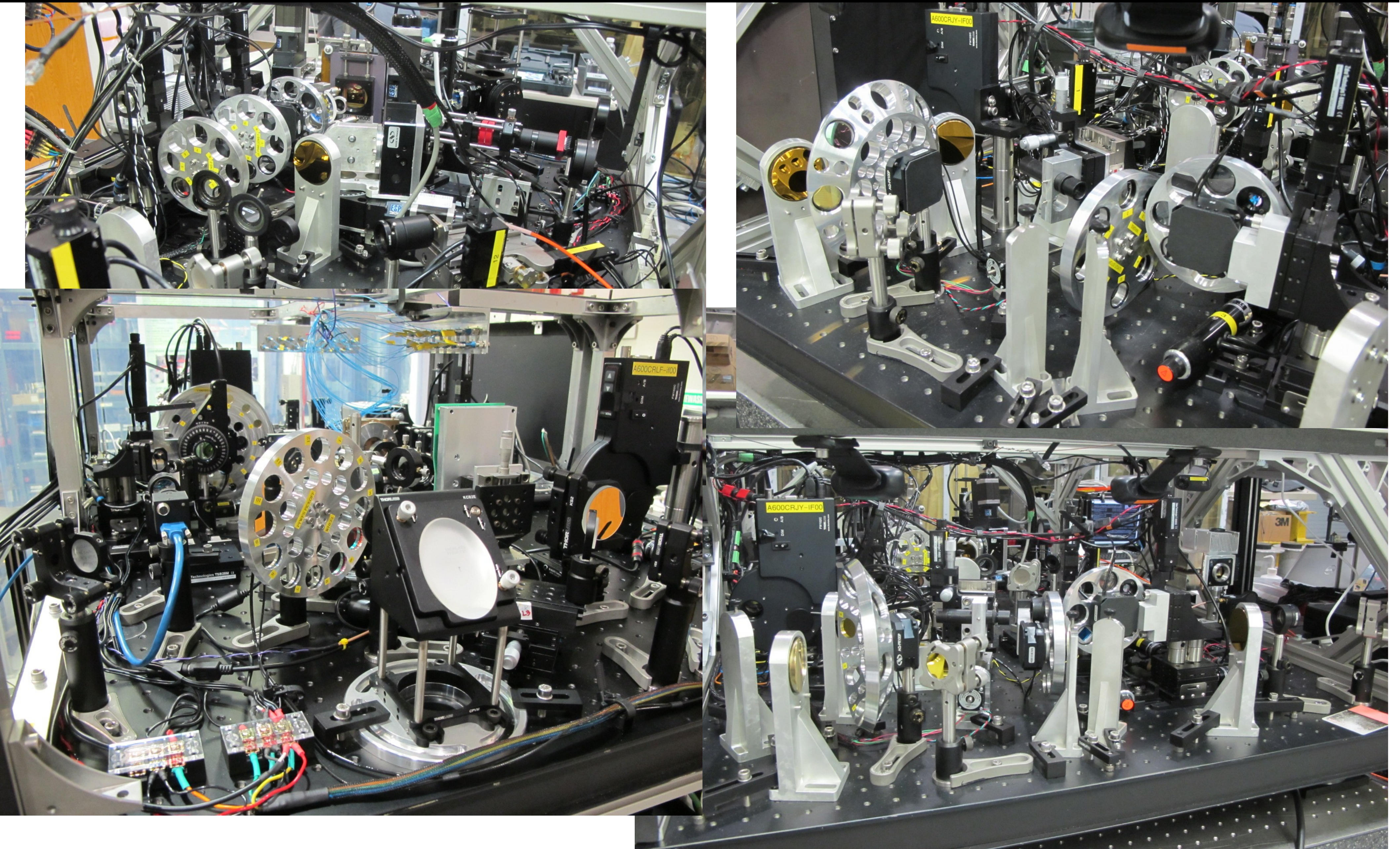
Subaru Coronagraphic Extreme Adaptive Optics

SCExAO/Subaru → TMT


HiCIAO or MKIDS
Near-IR InGaAs
cameras
→ to be replaced wi
EI technology
CHARIS
Near-IR nuller
SAPHIRA

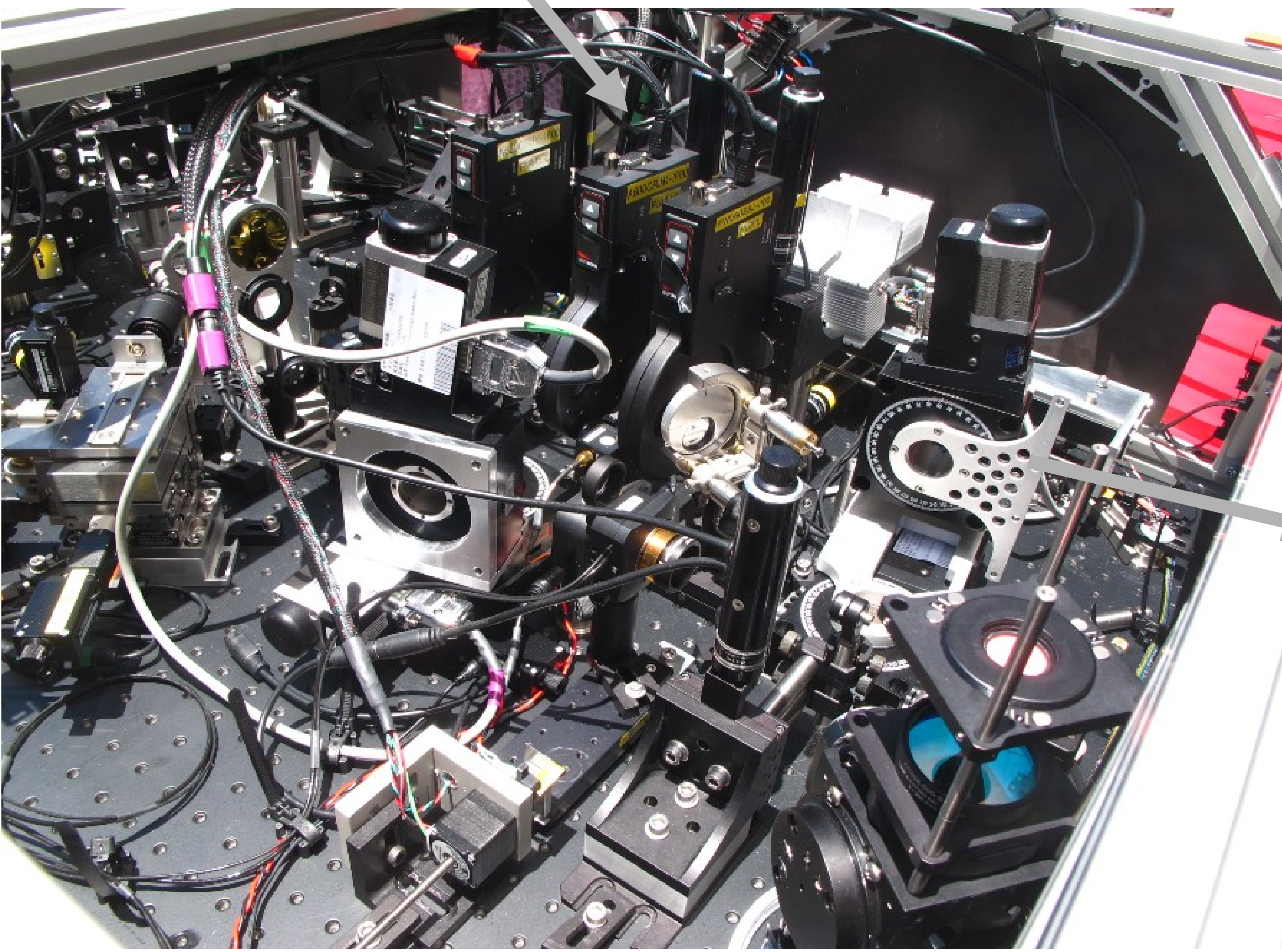
SCExAO

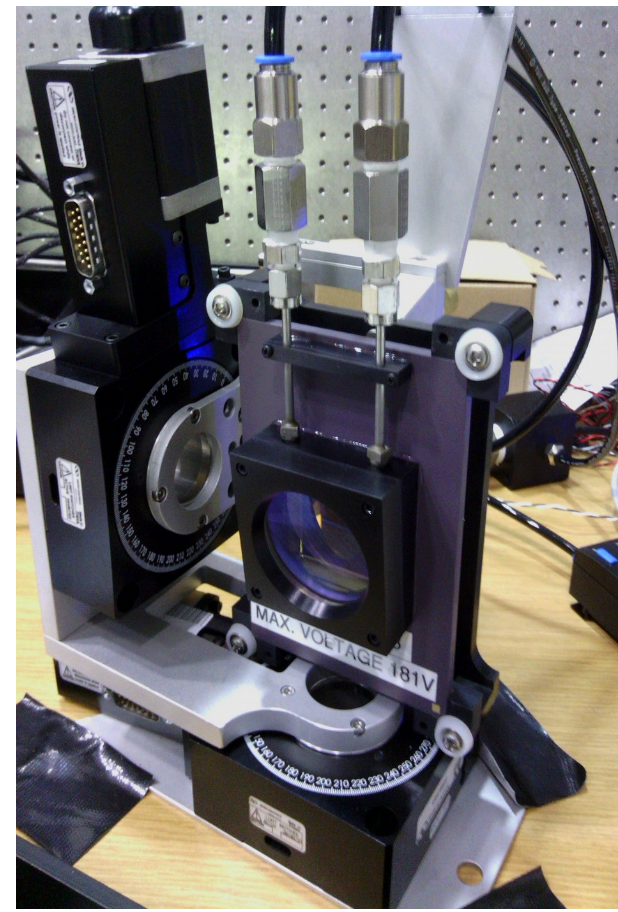
Subaru Coronagraphic Extreme Adaptive Optics



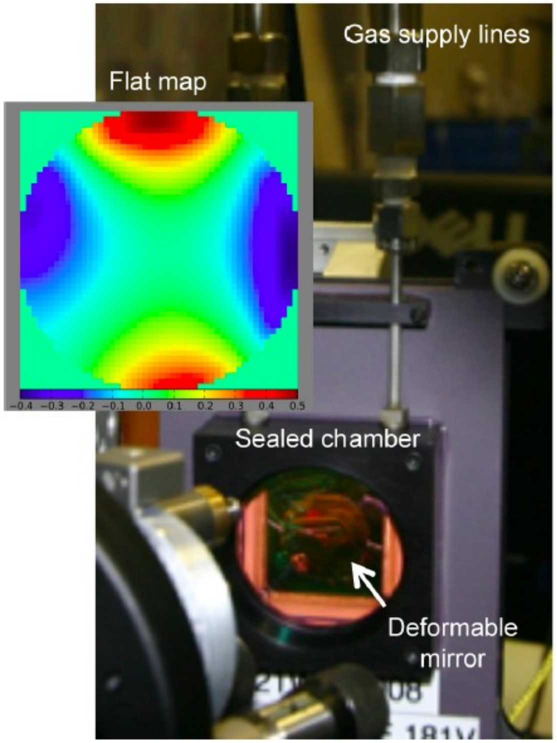
Deformable mirror

Coronagraphs





How SCExAO achieves high contrast



(1) Small IWA, high throughput Coronagraphy

→ removes diffraction (Airy rings), transmits r>1 l/D region

(2) Extreme-AO with fast diffraction-limited WFS

→ removes wavefront errors

(3) Near-IR LOWFS

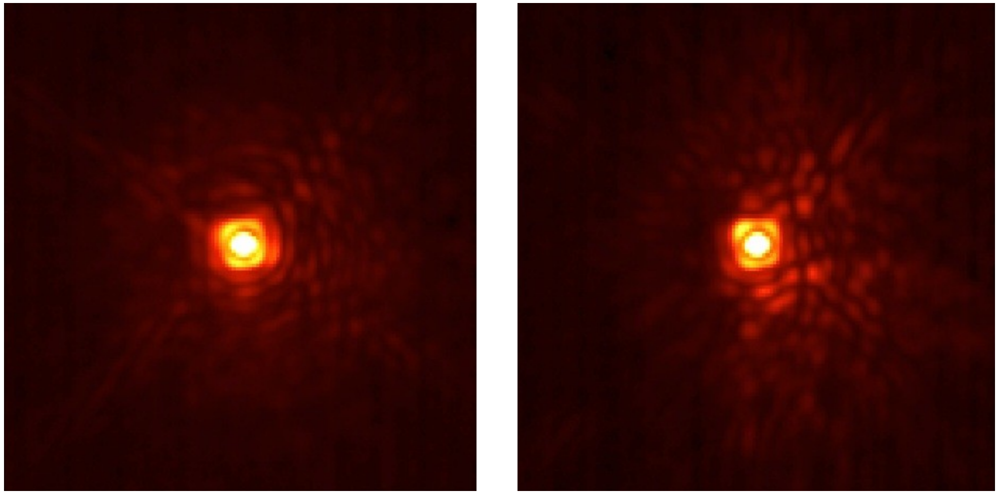
→ keeps star centered on coronagraph and controls Focus, Astig, etc..

→ records residual WF errors to help process data

(4) Fast Near-IR Speckle control

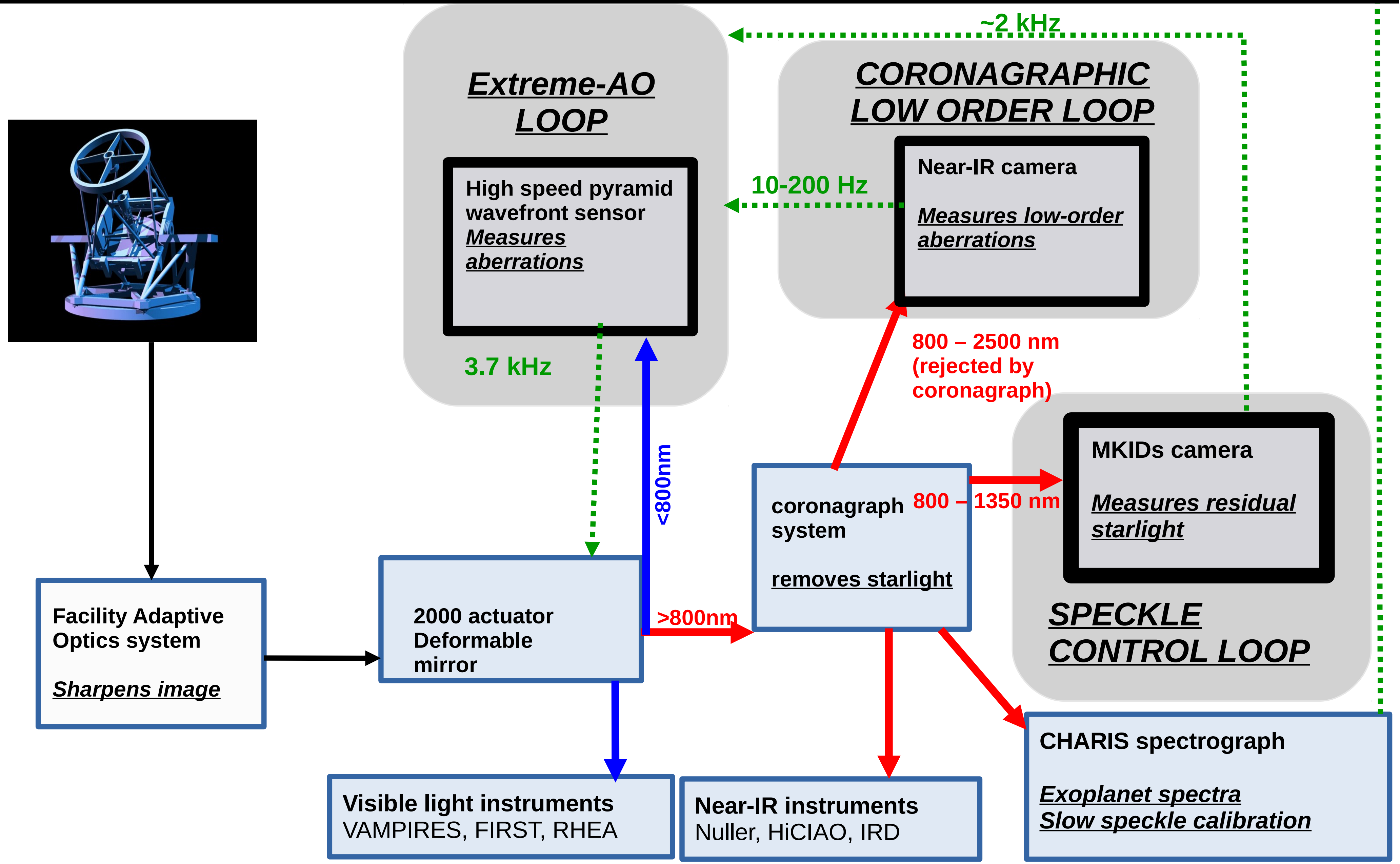
→ modulates, removes and calibrates residual speckles

Requires fast low-noise detectors



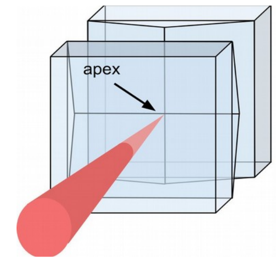
Speckle nulling on-sky

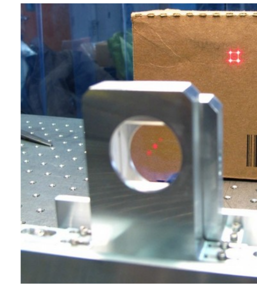
SCExAO Subaru Coronagraphic Extreme Adaptive Optics



SCExAO Subaru Coronagraphic Extreme Adaptive Optics

Low latency WFC in visible light at the diffraction limit sensitivity





2000 actuators MEMs DM running at 3.6 kHz
deep depletion EMCCD

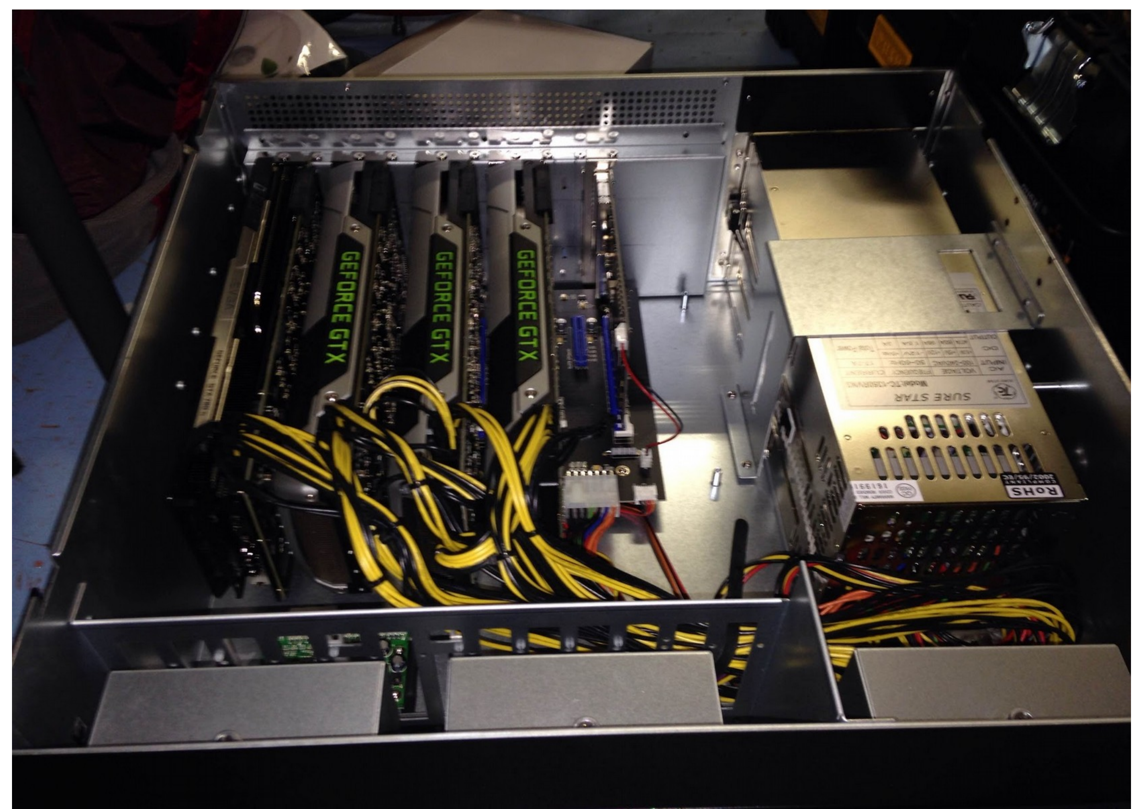
Non-modulated pyramid WFS cannot rely on slope computations
→ full WFS image is multiplied by control matrix

Now delivering 90% SR in H

Recent upgrade allows 3.6kHz loop operation with zonal and modal reconstruction
→ low-latency control
→ modal reconstruction for predictive / LQG control (under development)

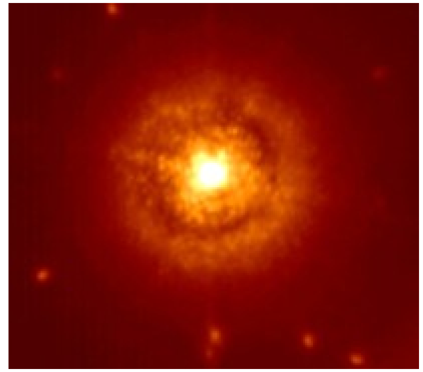
SCExAO uses 30,000 cores running @1.3GHz

One of two GPU chassis

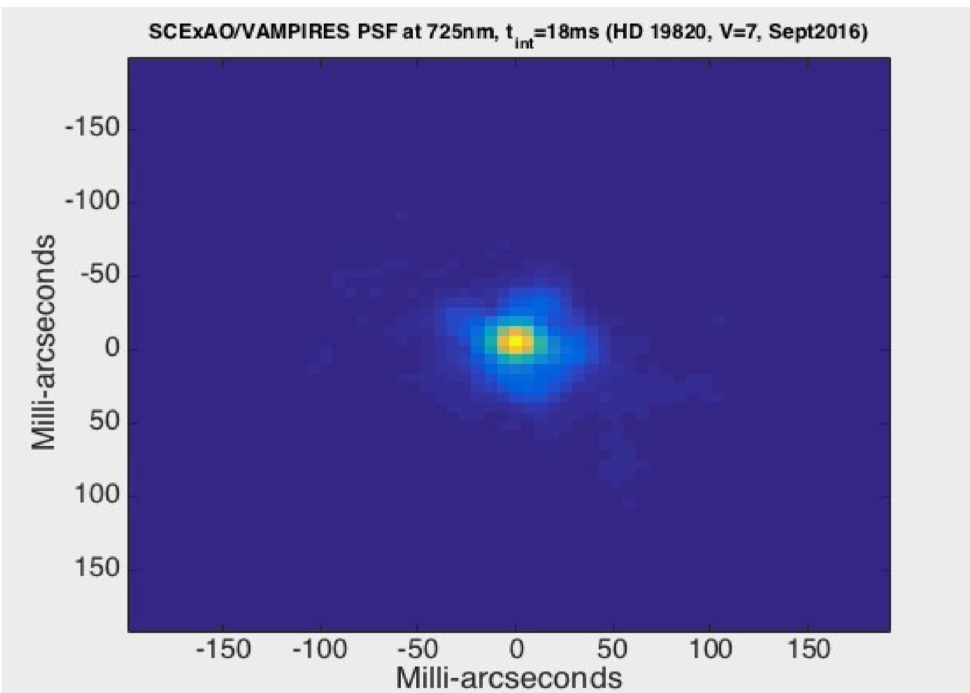


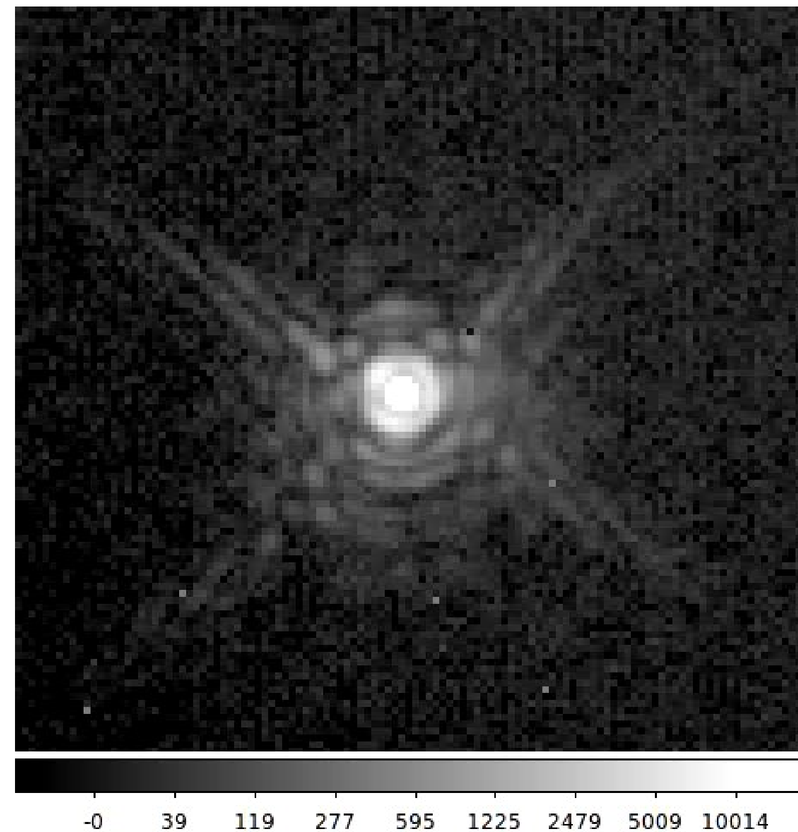
Current PSF stability @ SCExAO

725nm (VAMPIRES camera)
55 Hz sampling (bottom)
co-added (right)



1630nm (SCExAO internal camera)
3 Hz sampling





Current issues :
- residual vibration → dedicated TT loop, accelerometers on telescope
- occasional DM edge "flaring" → filtering in control loop

Preliminary VAMPIRES science

Circumstellar dust around Red Supergiant μ Cephei

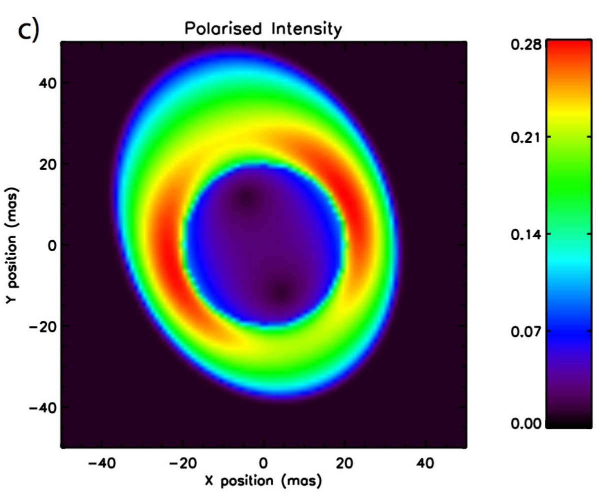
Model-fitting reveals extended, asymmetric dust shell, originating within the outer stellar atmosphere, without a visible cavity. Such low-altitude dust (likely Al_2O_3) important for unexplained extension of RSG atmospheres.

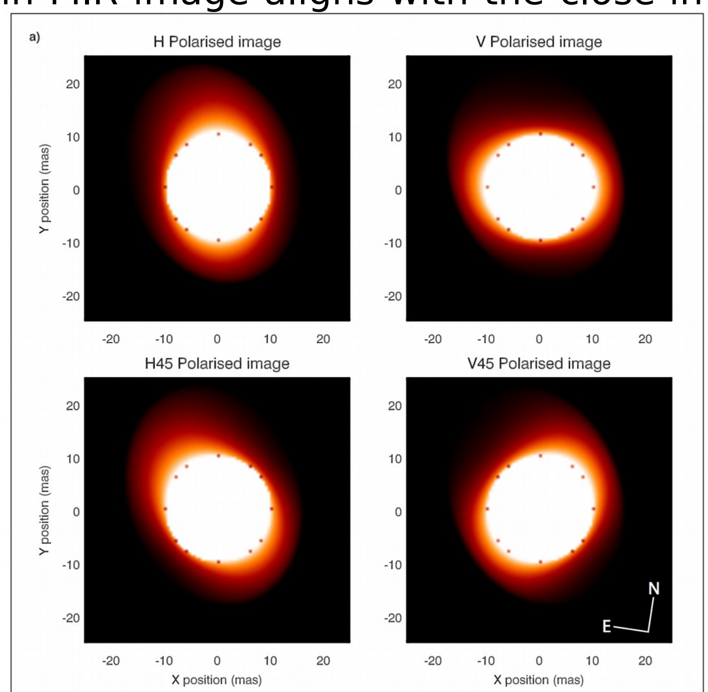
Inner radius: 9.3 ± 0.2 mas (which is roughly R_{star})

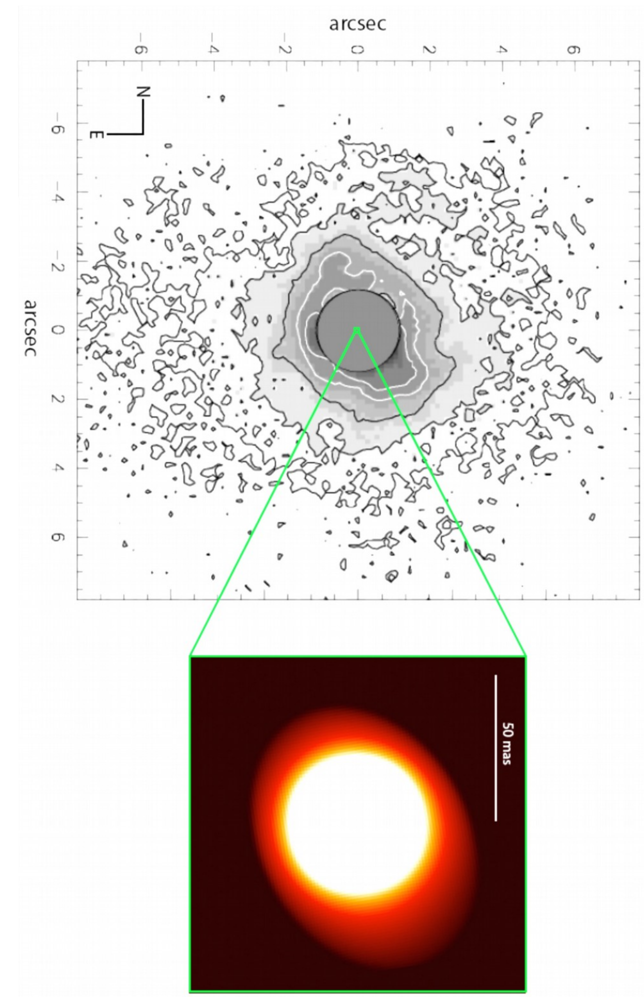
Scattered-light fraction: 0.081 ± 0.002

PA of major axis: 28 ± 3.7 ° • Aspect ratio: 1.24 ± 0.03

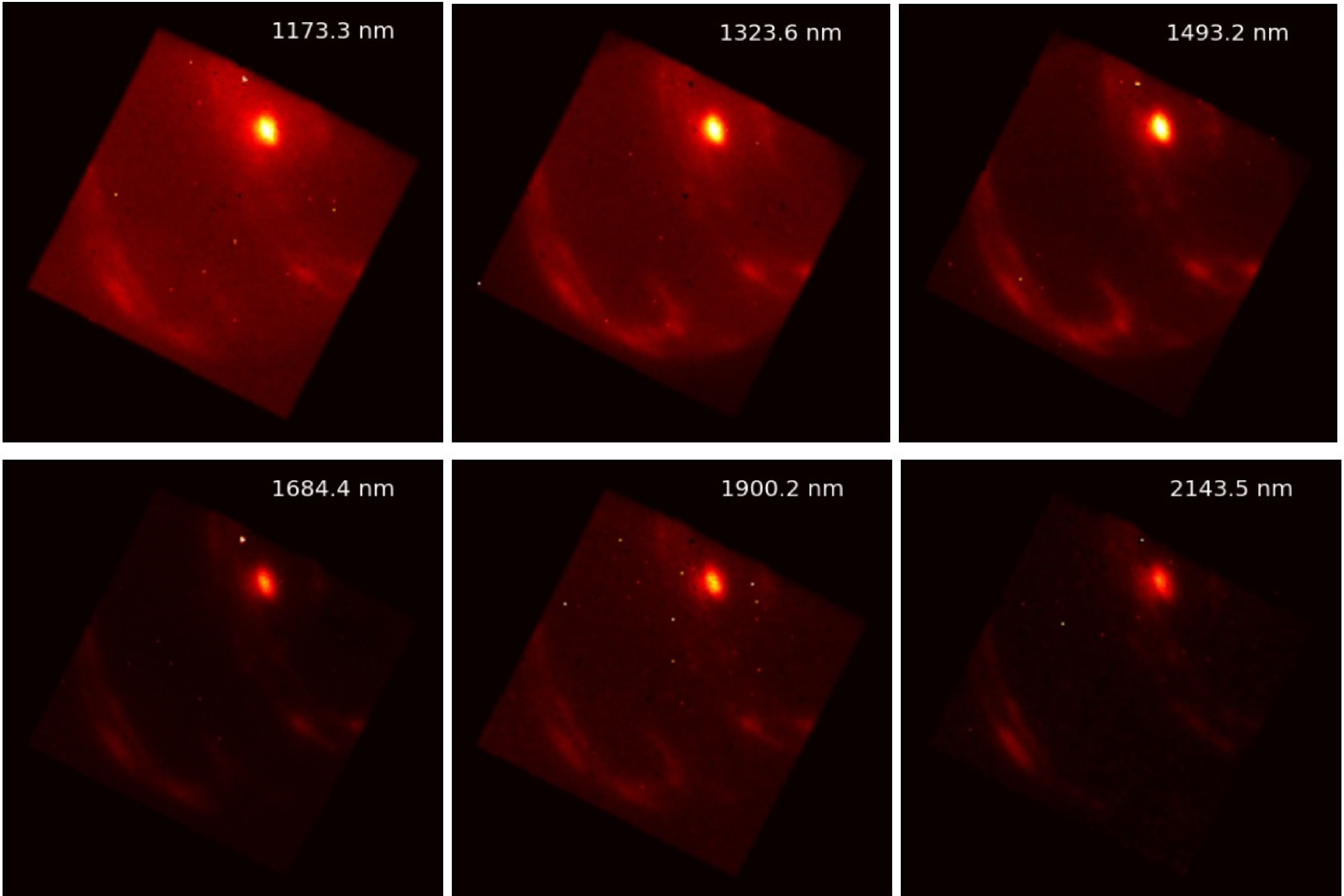
Left: model image, shown in polarized intensity. **Middle:** model image show in four polarisations. **Right:** Model image (intensity), shown with wide field MIR image (from de Wit et al. 2008 – green box shows relative scales. Axis of extension in MIR image aligns with the close-in VAMPIRES image.



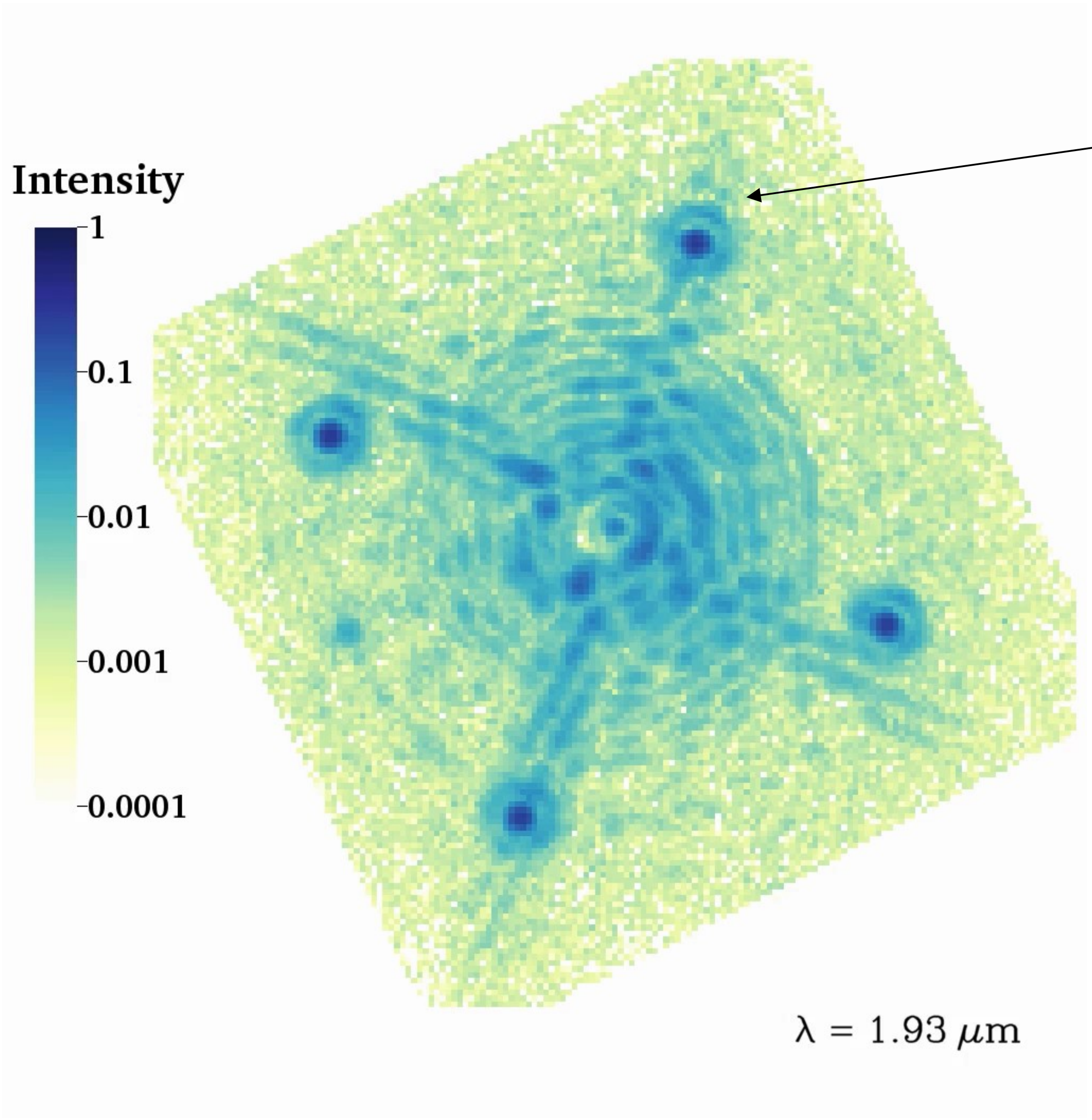




Neptune with CHARIS + SCExAO



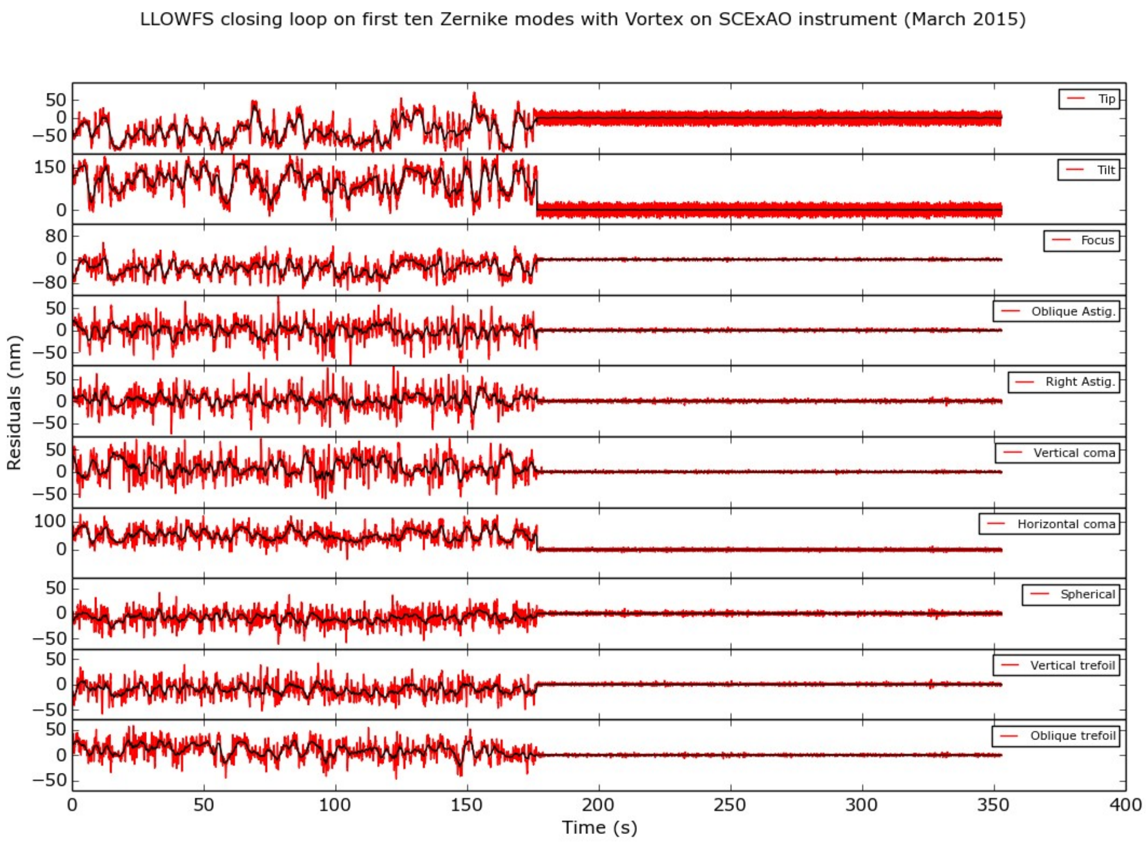
CHARIS data cube @ SCExAO

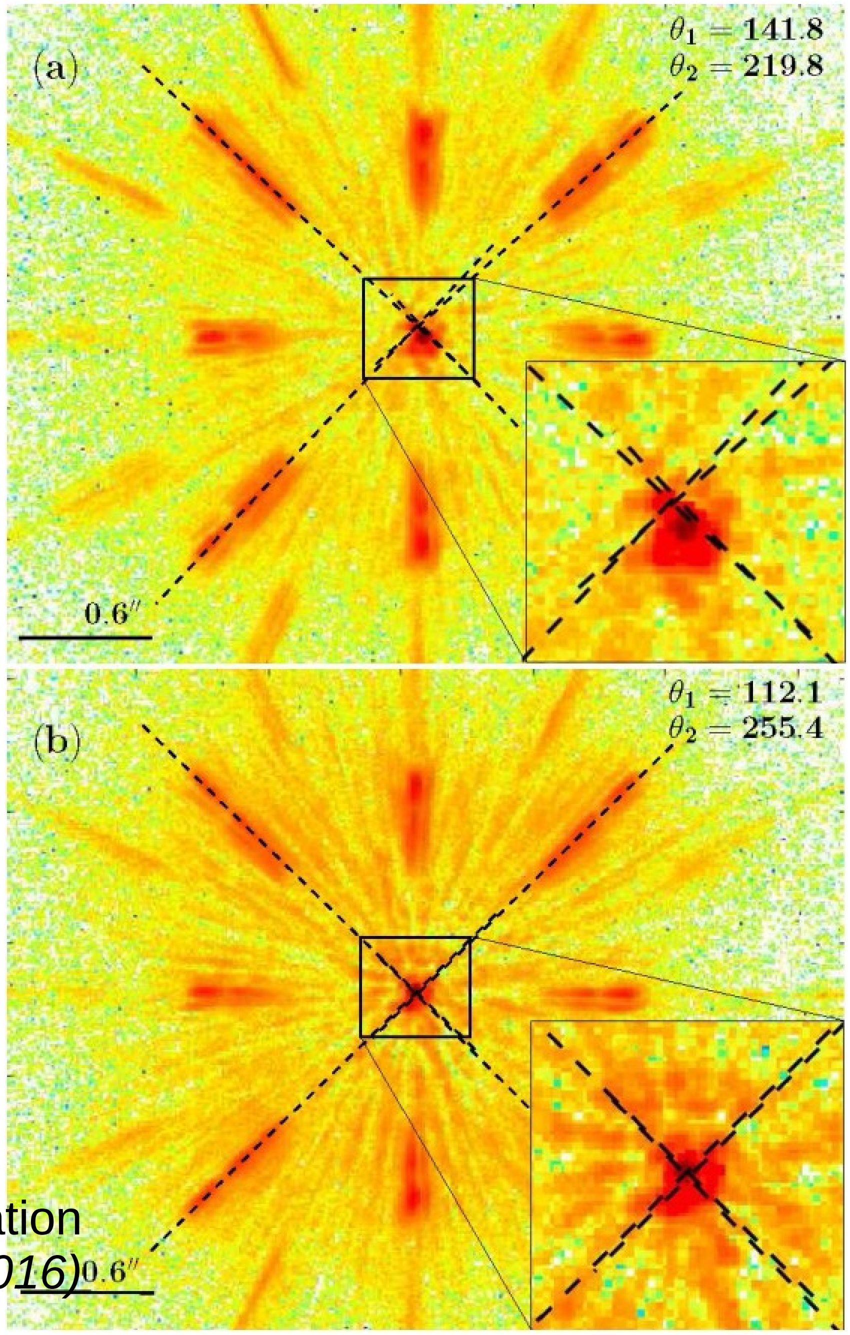


Calibration speckle

Modulated at 3.5kHz for decoherencing

Managing chromaticity





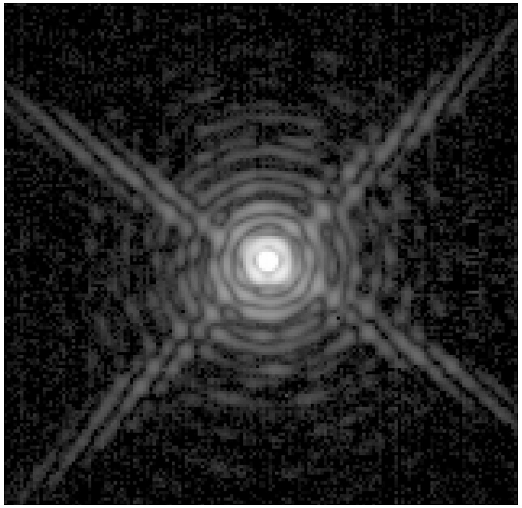
Near-IR low-order coronagraphic WFC
(Singh et al. 2015)

Closed loop atmospheric dispersion compensation
(Pathak et al. 2016)

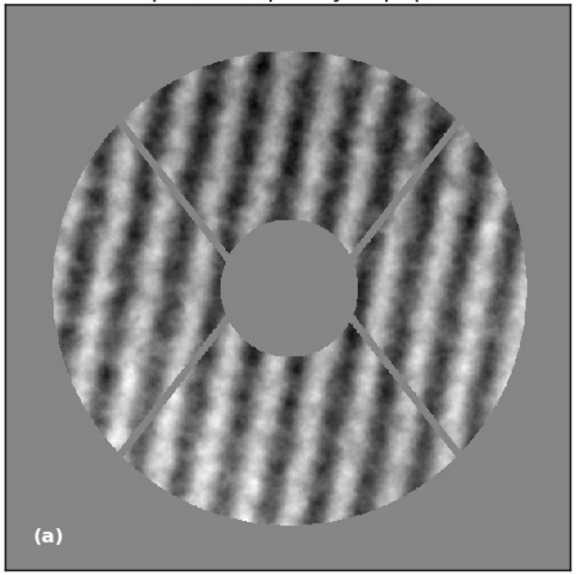
Systematically removing speckles

Presence of static & slow-varying aberrations in the path of science camera sets contrast limit at present

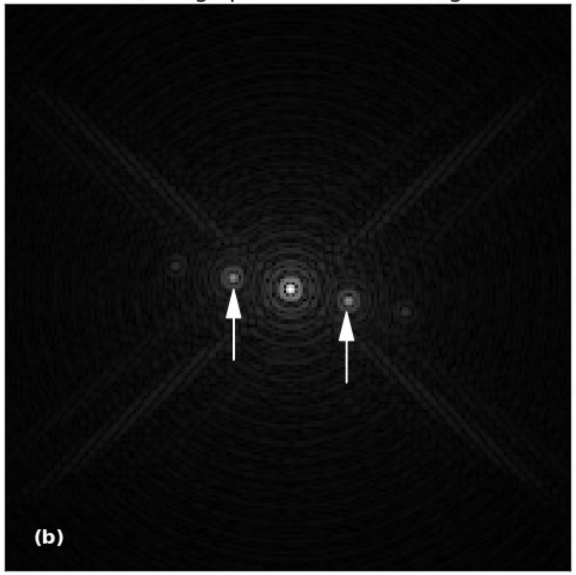
Typical SCExAO PSF



Spatial frequency in pupil

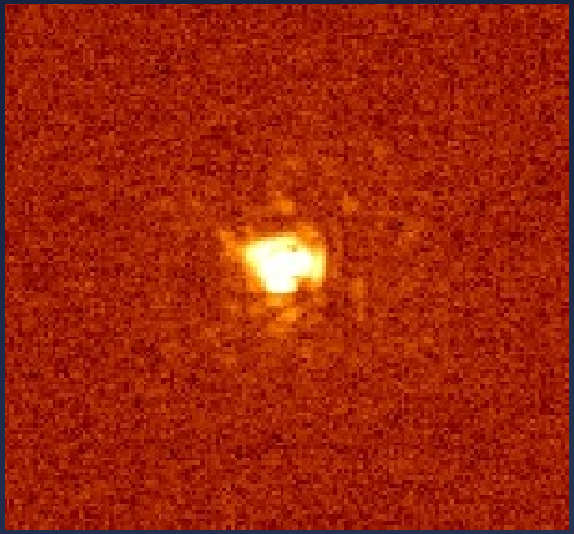


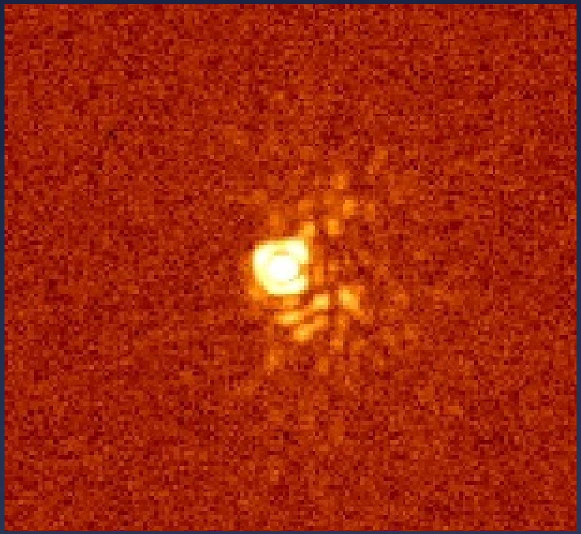
Matching speckles in the image

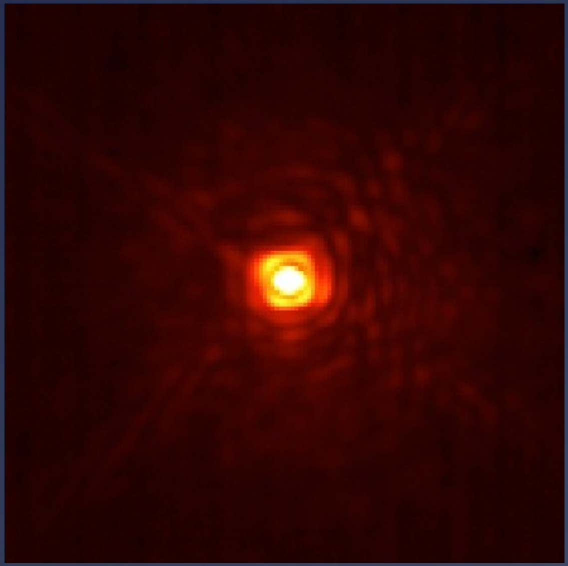


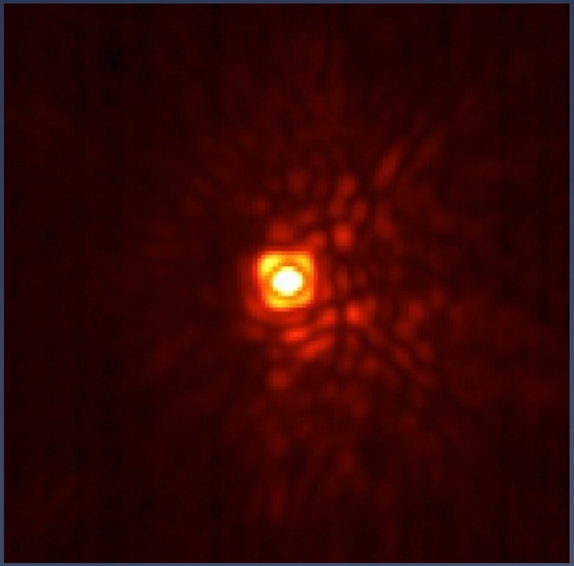
speckle nulling results on-sky (June 2014)

Single frames: 50 us









Sum of 5000 frames: shift and add

Meta data:

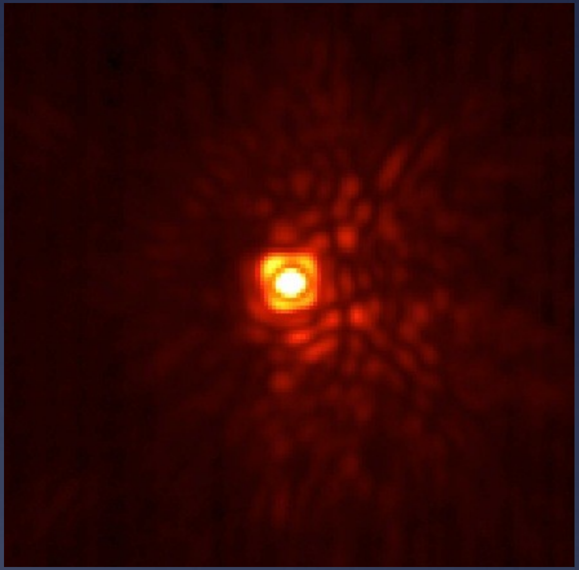
Date: 2nd or June

Target: RX Boo (also repeated on Vega)

Seeing: <0.6”

AO correction: 0.06” post-AO corrected in H- band (0.04” is diffraction-limit)

Coronagraph: None (used Vortex on Vega)

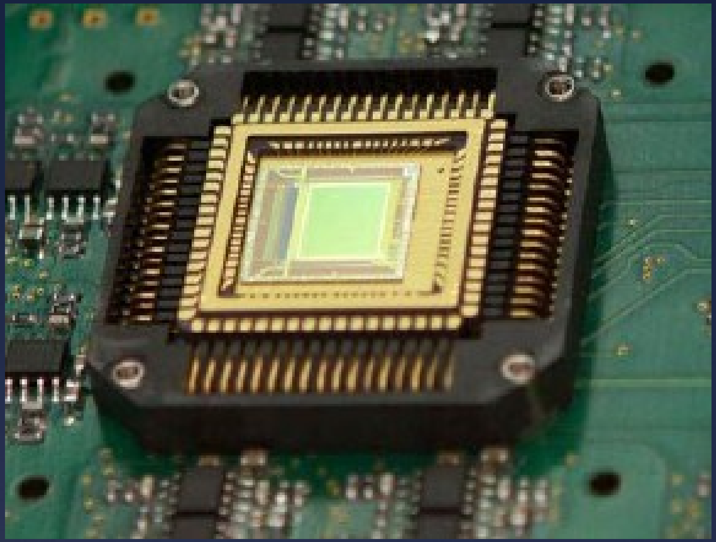


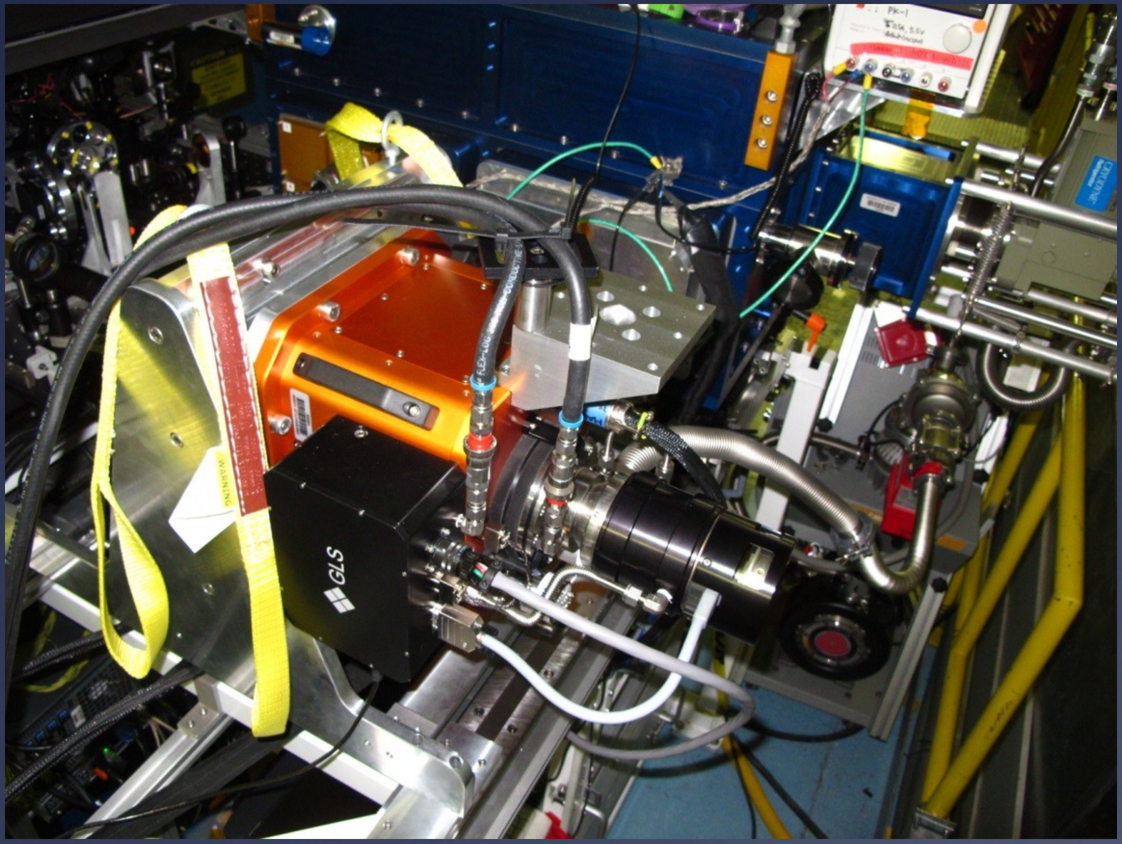
Martinache. et. al.

SAPHIRA Infrared APD array

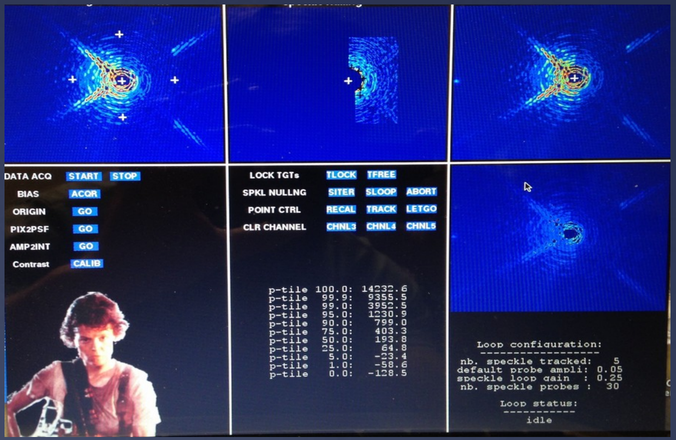
HgCdTe avalanche photodiode
manufactured by Selex

<u>Specifications</u>
320 x 256 x 24µm
32 outputs
5 MHz/Pix



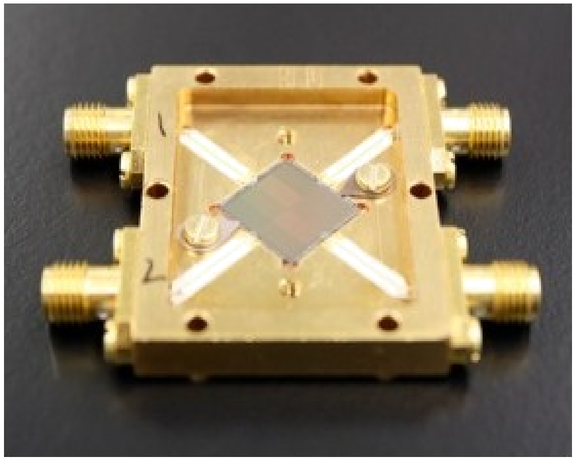


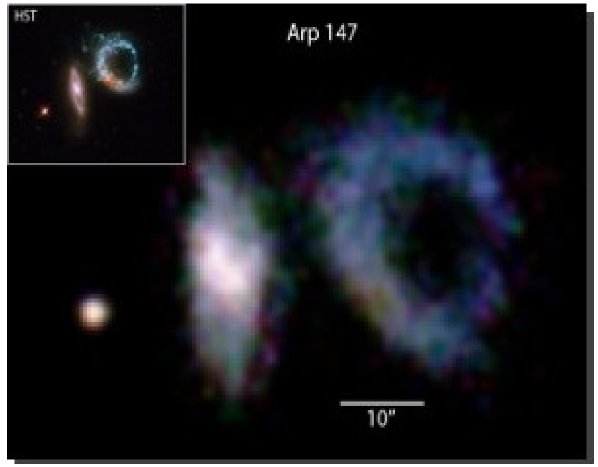
50 frame average

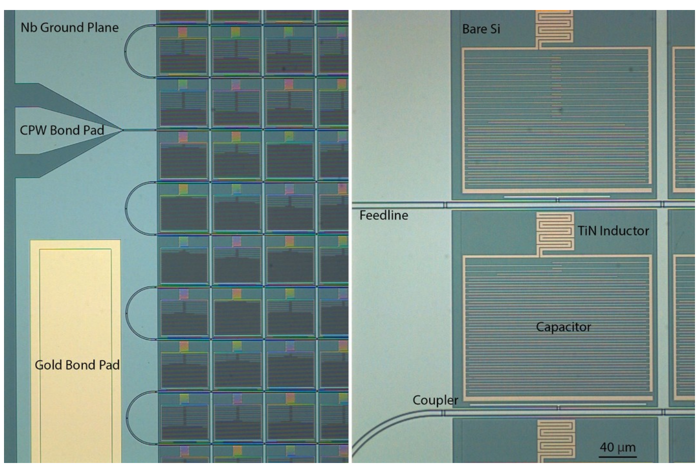


MKIDS camera (built by UCSB for SCExAO)

Photon-counting, wavelength resolving 100x200 pixel camera





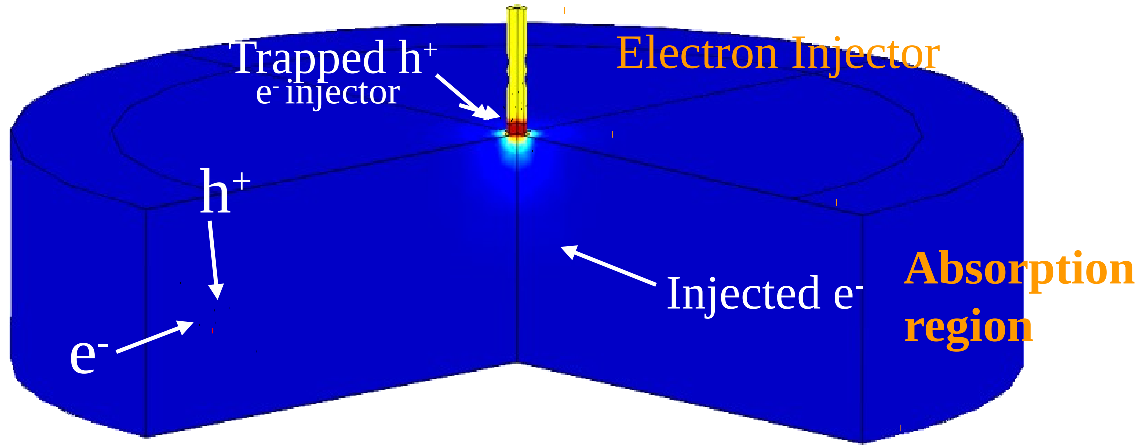


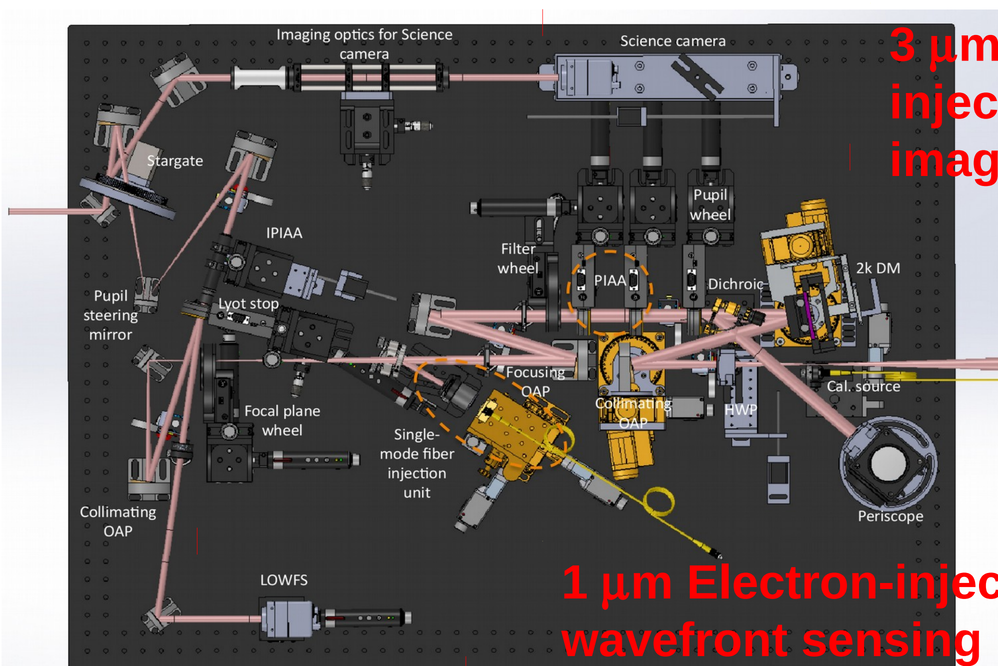
Pixels are microwave resonators at ~100mK
photon hits → resonator frequency changes

Photon-counting near-IR MKIDs camera for kHz speed speckle control under construction at UCSB

Delivery to SCExAO in CY2017

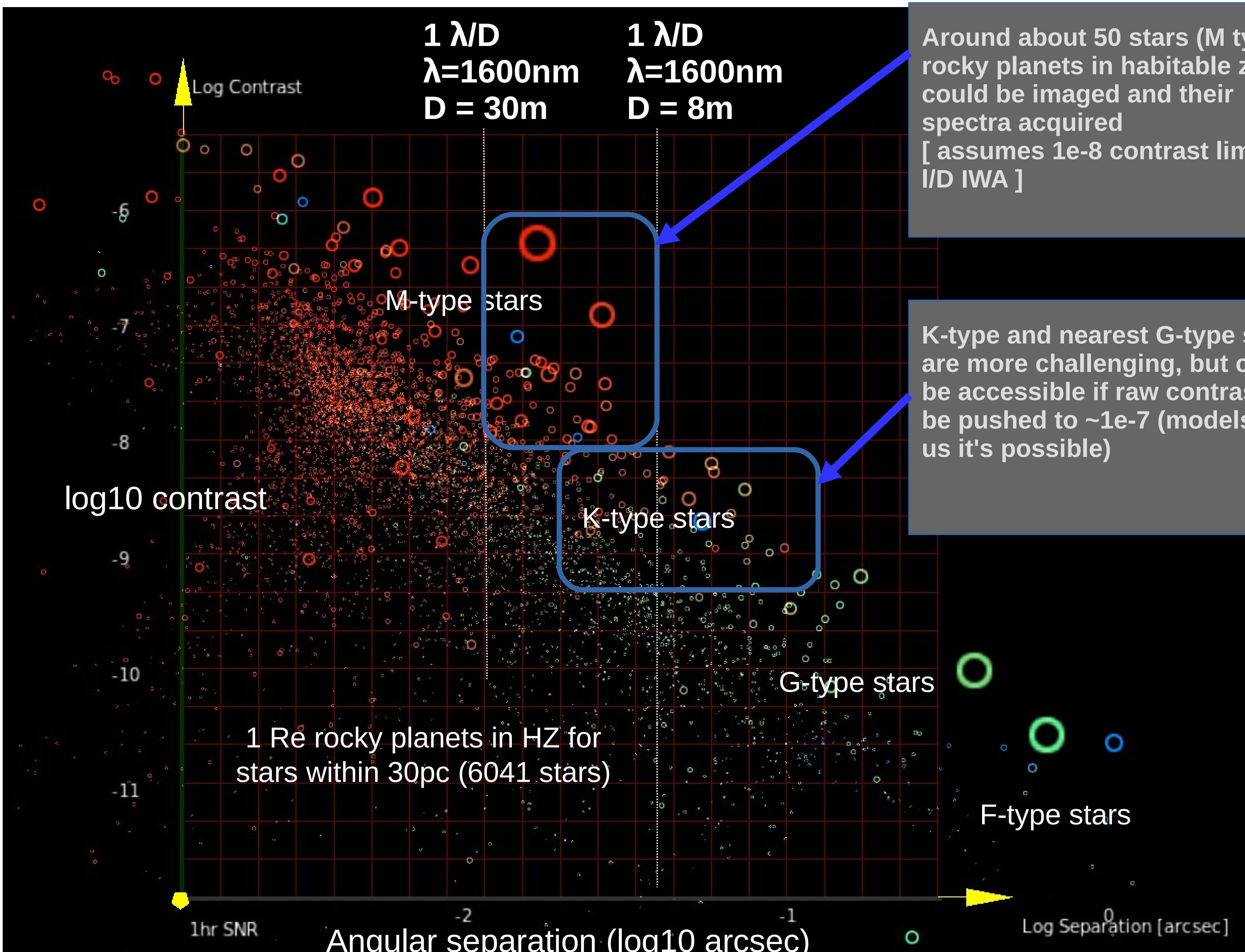
Electron-injector nearIR camera (Northwestern Univ / Keck foundation)





3 µm Electron-injection speckle imaging camera

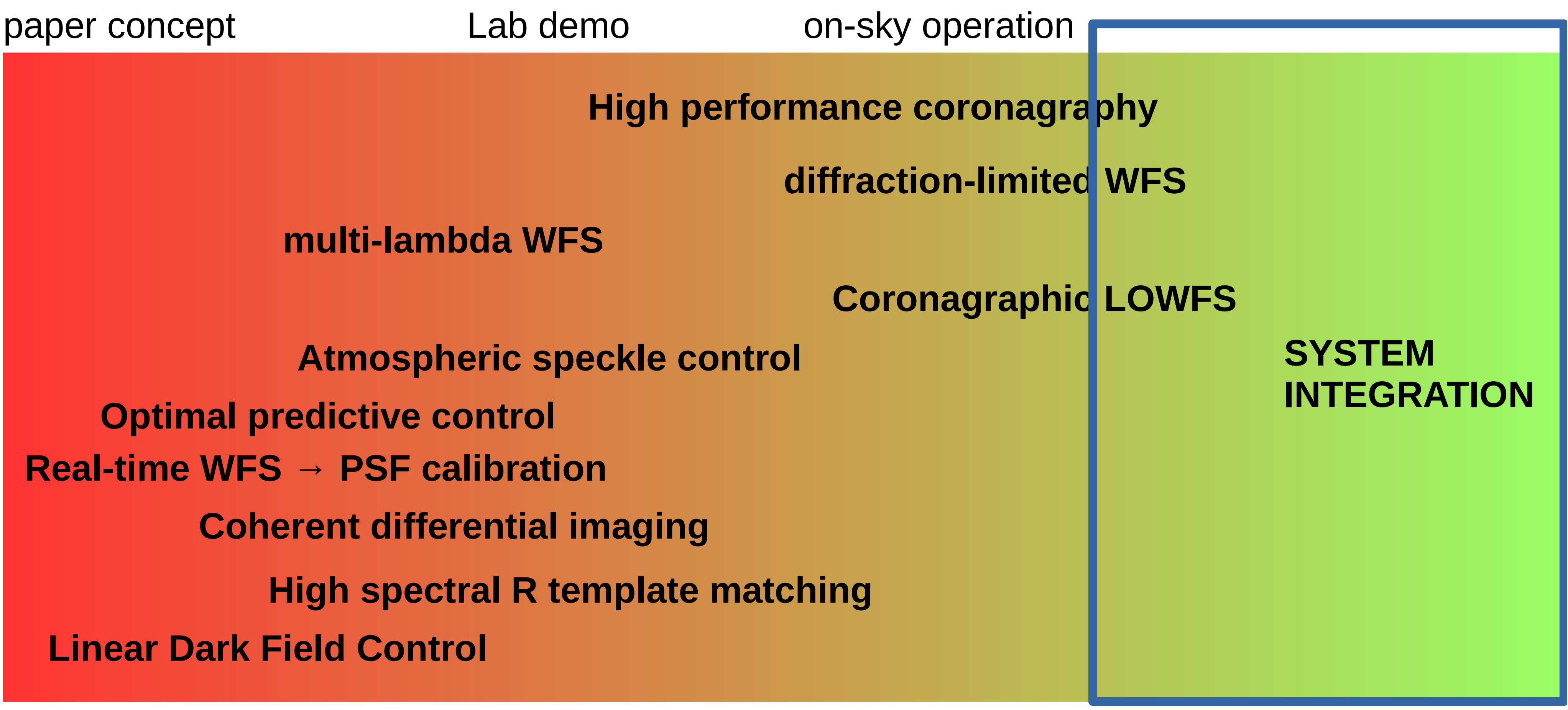
1 µm Electron-injection low-order wavefront sensing (pointing) camera



Around about 50 stars (M type), rocky planets in habitable zone could be imaged and their spectra acquired
[assumes 1e-8 contrast limit, 1 l/D IWA]

K-type and nearest G-type stars are more challenging, but could be accessible if raw contrast can be pushed to ~1e-7 (models tell us it's possible)

Key technologies are rapidly advancing from paper concepts to system integration



Direct imaging with ELTs - Conclusions

Low-hanging fruits (Prox Cen B) can be imaged on ELTs with current technology

ELTs can probably operate at ~1e-5/1e-6 raw contrast and photon-noise limited detection limit

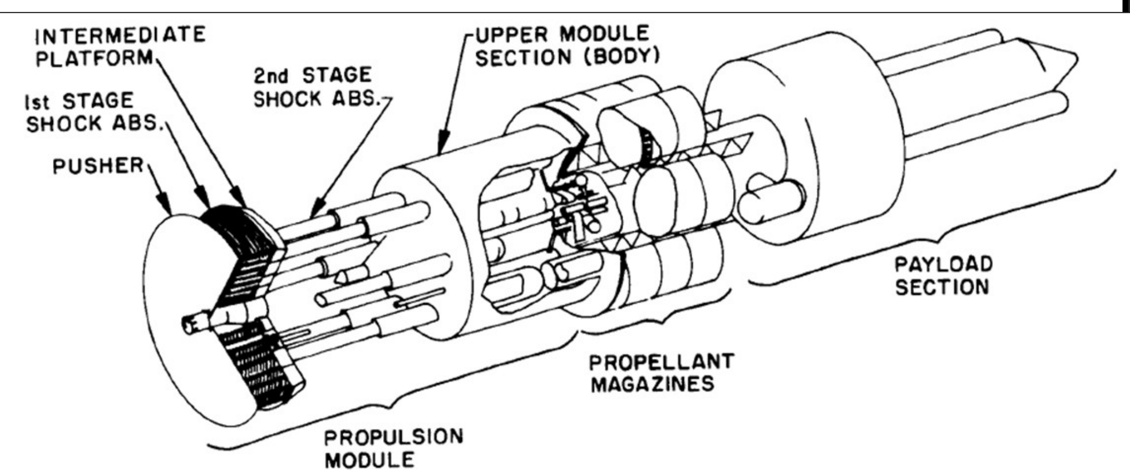
→ characterization (spectroscopy) of 1e-8 habitable planets accessible around >100 nearby stars, mainly near-IR/visible

Aggressive technology validation and system level testing is ongoing, aligned with (near-)first light deployment

Interstellar travel: pre-2000 studies

Several serious studies (Longshot, Orion, Deadalus)

Propulsion challenge is significant

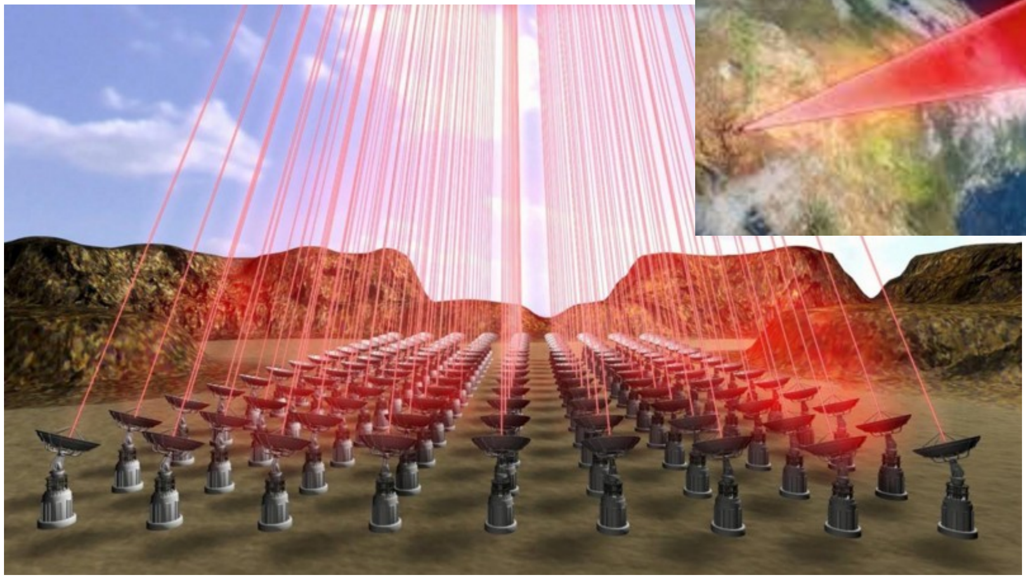


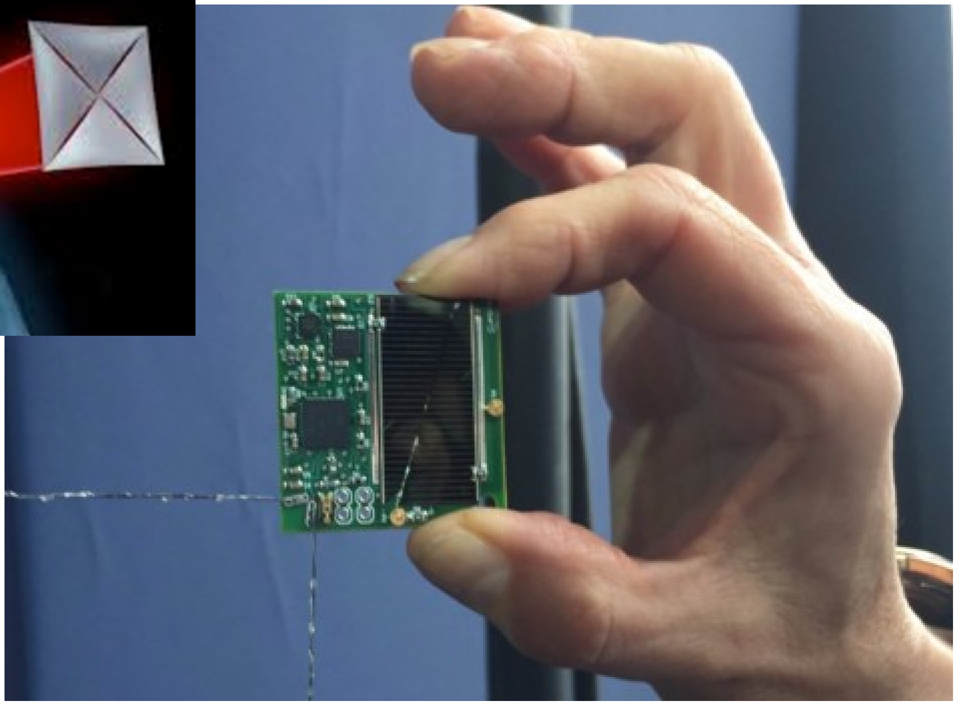
Project Orion – using nuclear propulsion, massive spacecraft

Starshot project

Leverages current/future technology developments:

- small spacecraft (~gram)
- Ground-based laser propulsion (“don't carry your fuel”)





Starshot project – overview

Goal speed: 20% speed of light. Acceleration phase: few minutes, >10,000 G. Travel time: few decades. Flyby, no deceleration phase.

Launch many nanocrafts ($$ is in launch facility and technology development, not in individual nanocrafts)

<u>Significant technology challenges</u> :

- Laser array power and cophasing
- Sail/nanocraft: reflectivity, stability (spinning sail ?), Interstellar medium abrasion, High-G low mass electronics, camera, battery
- Navigation (photon thrusters for course correction)
- Communication during flight (for course correction) and upon arrival (beaming back images)

Next steps: Sub-scale demonstration of sail laser propulsion reaching ~100km/s (in vacuum pipe) + concept studies for key challenging aspects of project

Breakthrough Initiatives Foundation will request proposals from industry/university teams to work on the hard problems… RFPs are under preparation – get ready !