Direct Imaging and Spectroscopy of nearby Habitable planets with ground-based ELTs

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Extreme AO systems (superAO+coronagraph) myths

Extreme AO myth #1

ExAO = "Extremely complicated/costly AO"

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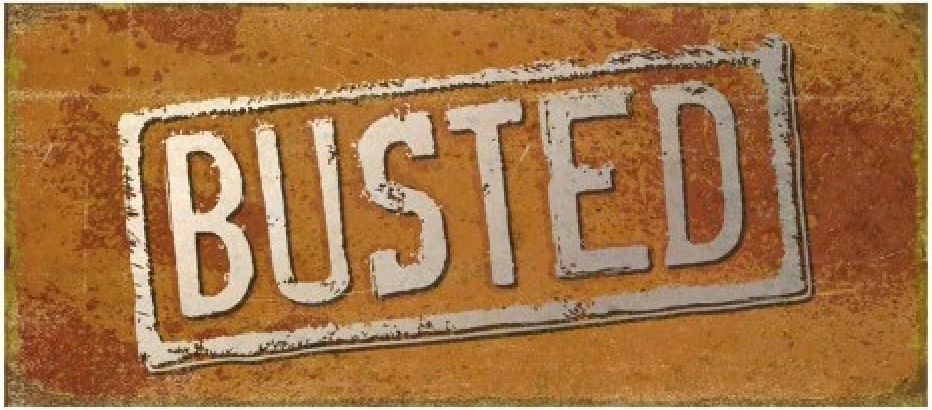
→ ExAO is in many respects simpler than other AO systems:

- bright on-axis natural guide star (no lasers, easiest configuration for cophasing segments)
- zero field of view system (small optics, single DM OK)



Extreme AO myth #2

High contrast imaging is all about achieving super low wavefront error
→ It's all about SR, more actuators, faster loops

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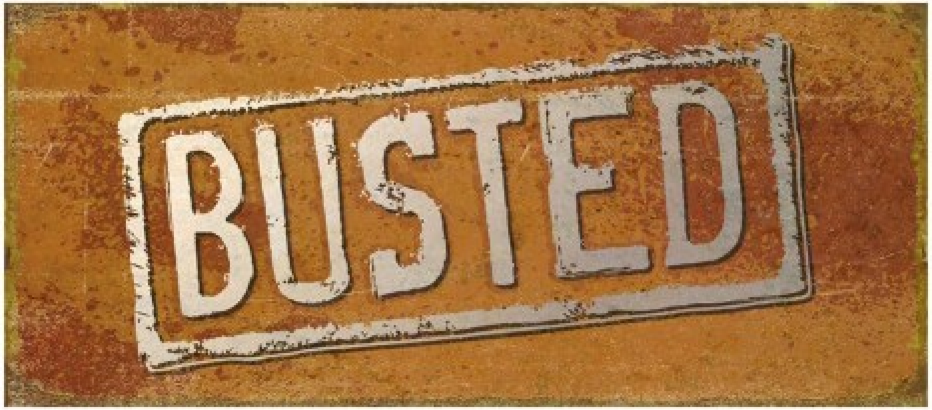
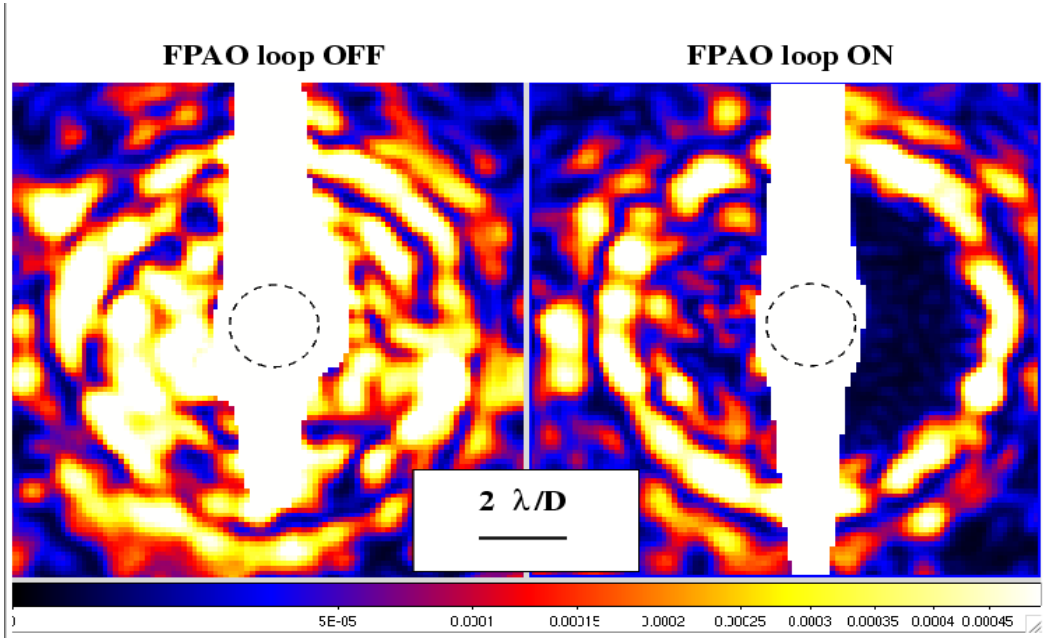
ExAO is not about making the star's image sharper.. it is about making sure no uncalibrated starlight falls on the exoplanet.

In ExAO, the number of actuators in the DM defines the field of view, not the contrast





Extreme AO myth #3

High performance coronagraphs don't work on segmented apertures… especially on GMT

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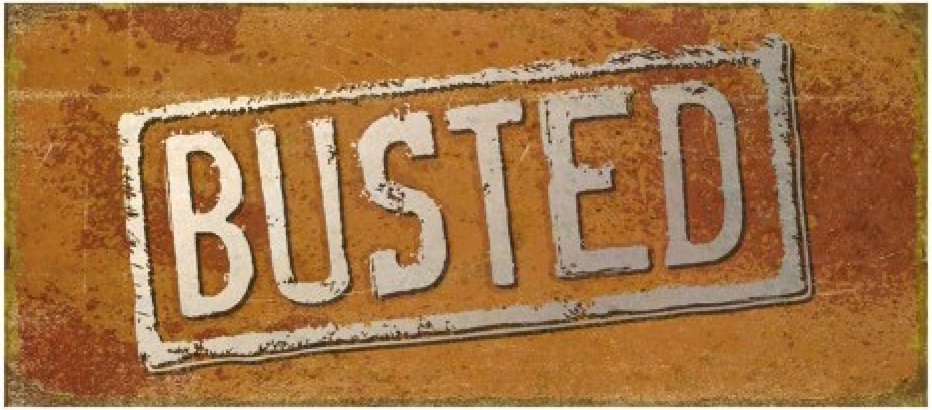
→ Nothing fundamental about segmented apertures: some high performance coronagraph option(s) don't care about pupil shape and are already working in the lab



Extreme AO myth #4

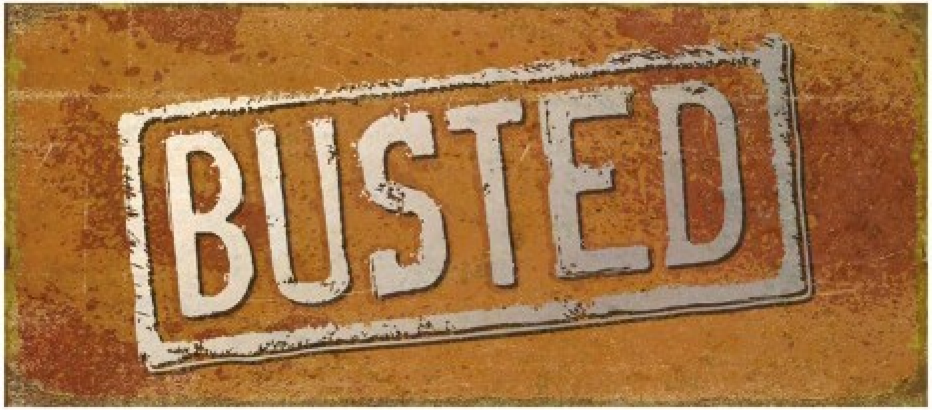
Ground-based telescopes will only ever image giant (Jupiter-like) planets.

Directly imaging habitable planets will require a space telescope.

Extreme AO myth #4

Ground-based telescopes will only ever image giant (Jupiter-like) planets.

Directly imaging habitable planets will require a space telescope.



New generation of Extremely Large Telescopes (ELTs) + key technologies will directly image Earth-size planets around nearby low-luminosity stars

Extreme AO myth #5

ExAO people have no clue what they are doing.
They change their mind about what coronagraph or wavefront sensor to use every two years.

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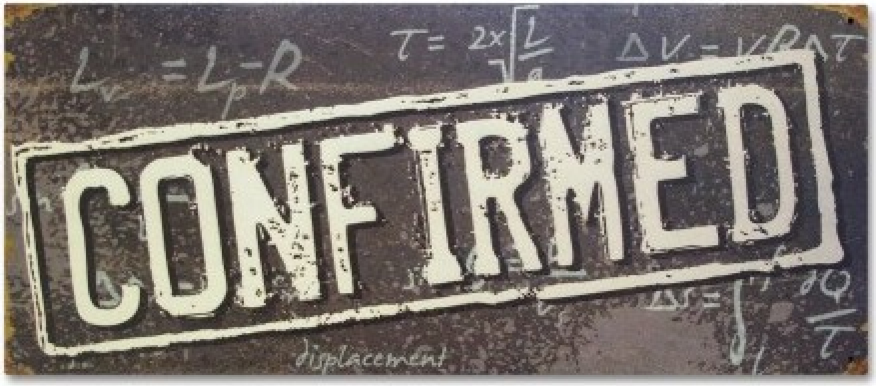
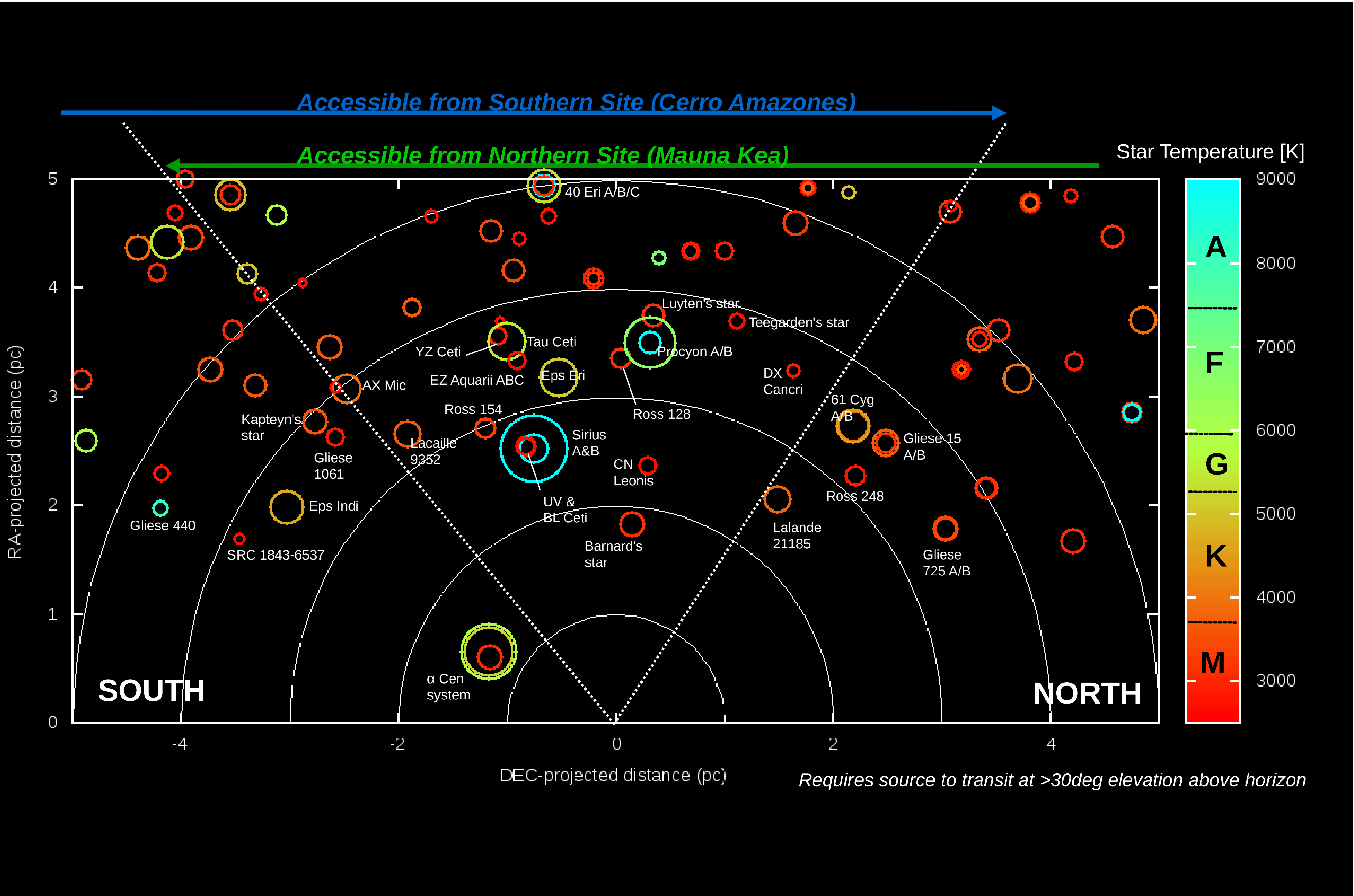
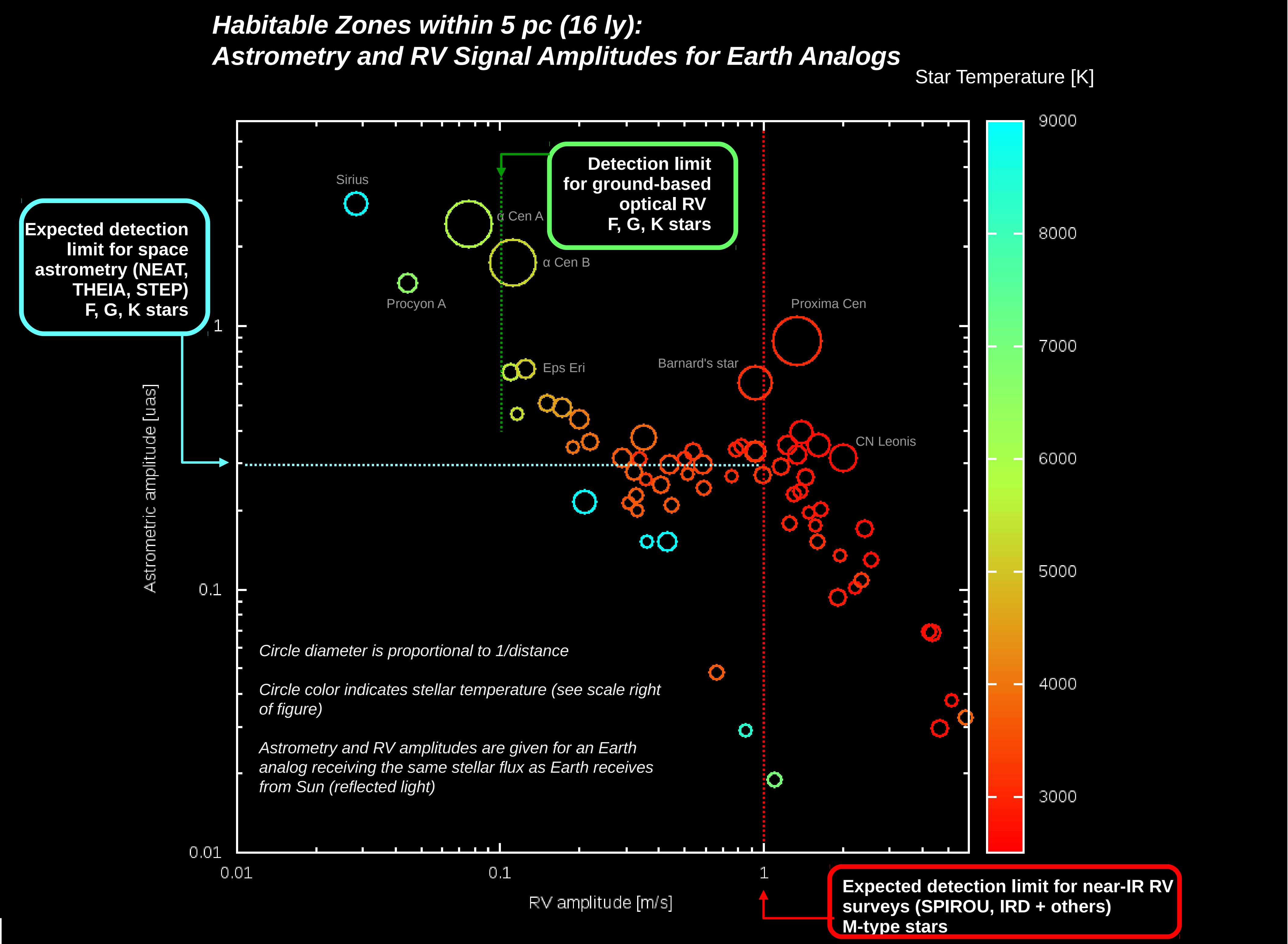


→ ExAO instrument with flexible evolutionary path has a lot of value

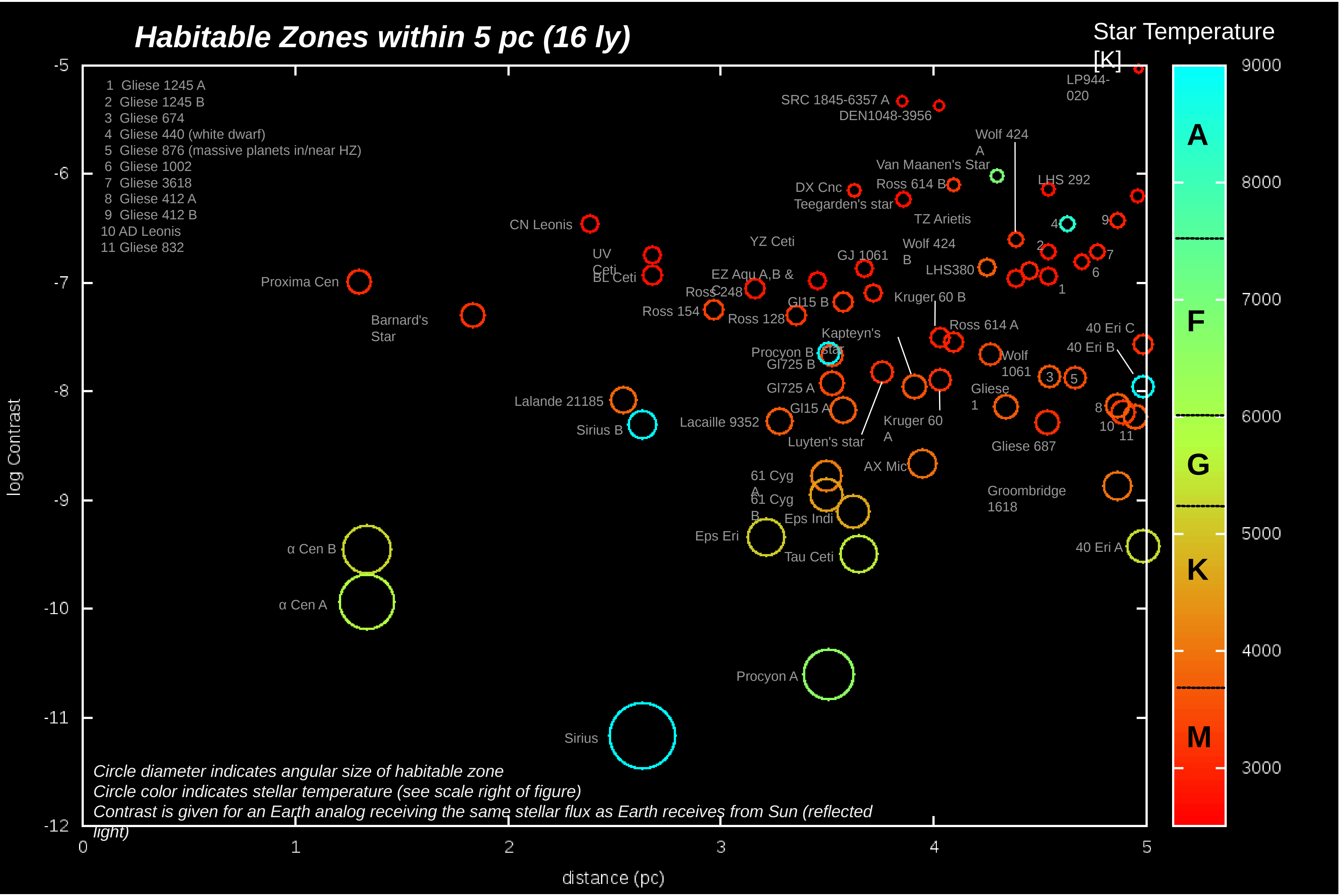
Develop, iterate & prototype on 5-10m, telescopes → quickly move to ELTs



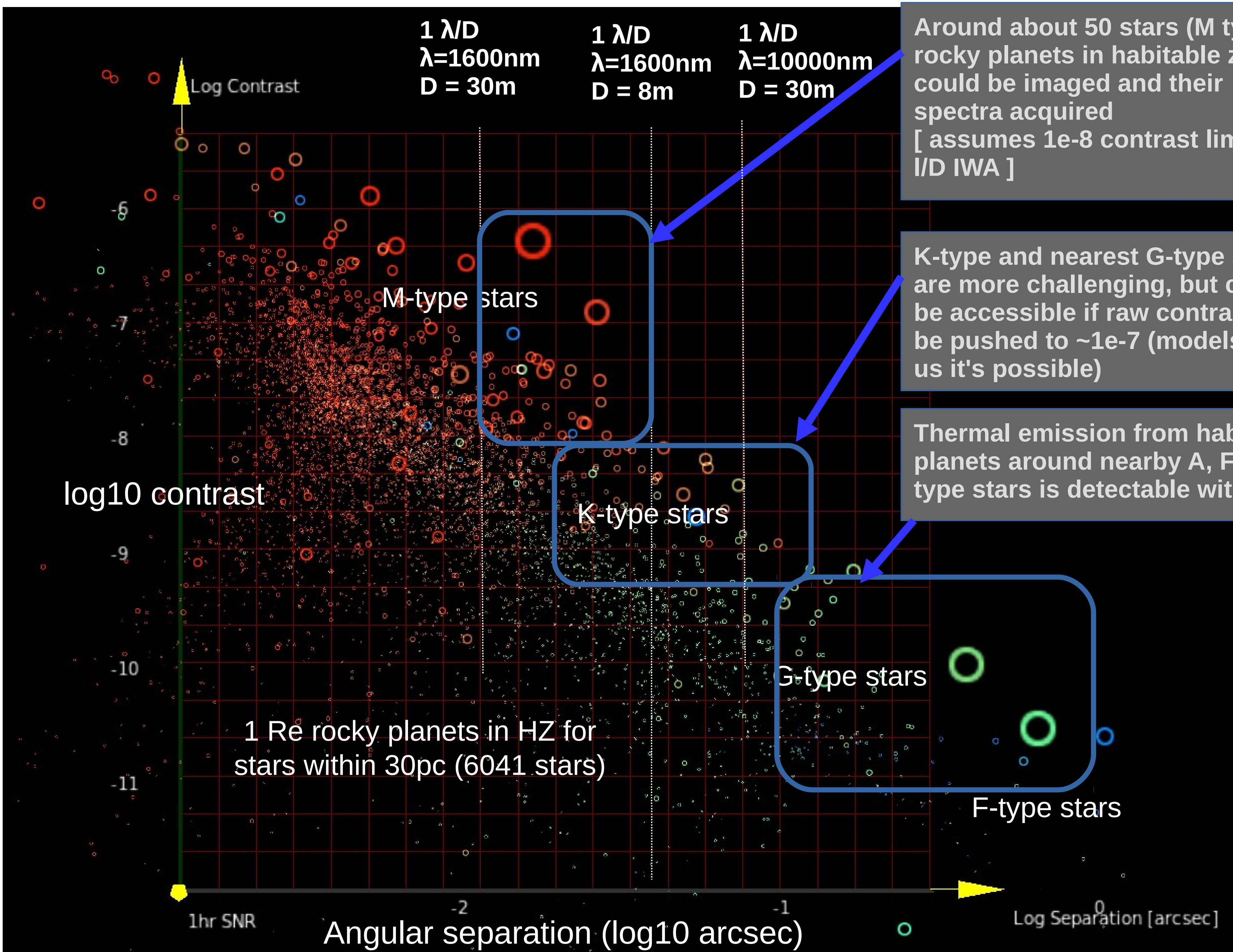
Accessible from Southern Site (Cerro Amazones)
Accessible from Northern Site (Mauna Kea)
Star Temperature [K]
9000
8000
7000
6000
5000
4000
3000
A
F
G
K
M
40 Eri A/B/C
Luyten's star
Teegarden's star
Procyon A/B
Tau Ceti
YZ Ceti
EZ Aquarii ABC
Eps Eri
AX Mic
DX Cancri
Ross 154
Ross 128
61 Cyg A/B
Kapteyn's star
Gliese 1061
Lacaille 9352
Sirius A&B
CN Leonis
Gliese 15 A/B
UV & BL Ceti
Ross 248
Eps Indi
Gliese 440
SRC 1843-6537
Barnard's star
Lalande 21185
Gliese 725 A/B
α Cen system
SOUTH
NORTH
RA-projected distance (pc)
DEC-projected distance (pc)
0
1
2
3
4
5
-4
-2
0
2
4
Requires source to transit at >30deg elevation above horizon



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
Proxima Cen
Eps Eri
Barnard's star
CN Leonis
Astrometric amplitude [uas]
RV amplitude [m/s]
1
0.1
0.01
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)


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
Proxima Cen
Barnard's Star
CN Leonis
UV Ceti
BL Ceti
Lalande 21185
Sirius B
Sirius
α Cen B
α Cen A
Procyon A
Procyon B
Ross 154
Ross 248
EZ Aqu A,B & C
YZ Ceti
Ross 128
Gl15 B
Gl15 A
Gl725 B
Gl725 A
Lacaille 9352
Luyten's star
Kapteyn's star
GJ 1061
SRC 1845-6357 A
DEN1048-3956
DX Cnc
Teegarden's star
Van Maanen's Star
Ross 614 B
Ross 614 A
TZ Arietis
Wolf 424 A
Wolf 424 B
LHS380
LHS 292
LP944-020
Kruger 60 B
Kruger 60 A
Wolf 1061
Gliese 1
Gliese 687
AX Mic
61 Cyg A
61 Cyg B
Eps Indi
Eps Eri
Tau Ceti
Groombridge 1618
40 Eri C
40 Eri B
40 Eri A
A
F
G
K
M
9000
8000
7000
6000
5000
4000
3000
log Contrast
-5
-6
-7
-8
-9
-10
-11
-12
distance (pc)
0
1
2
3
4
5
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)

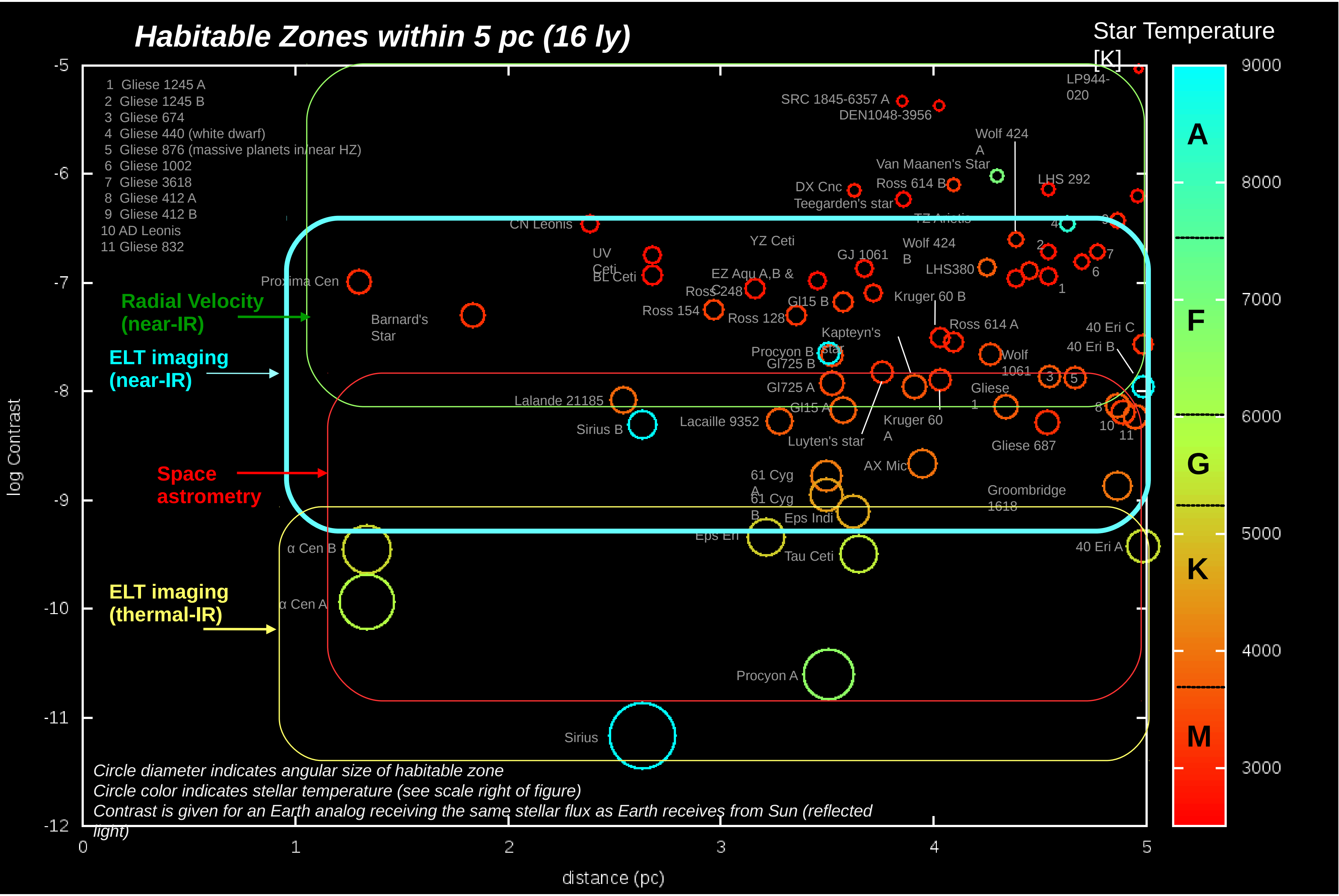
Spectroscopic characterization of Earth-sized planets with ELTs



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)

Thermal emission from habitable planets around nearby A, F, G type stars is detectable with ELTs



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Radial Velocity (near-IR)
ELT imaging (near-IR)
Space astrometry
ELT imaging (thermal-IR)
Proxima Cen
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log Contrast
distance (pc)
Circle diameter indicates angular size of habitable zone
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Contrast is given for an Earth analog receiving the same stellar flux as Earth receives from Sun (reflected light)

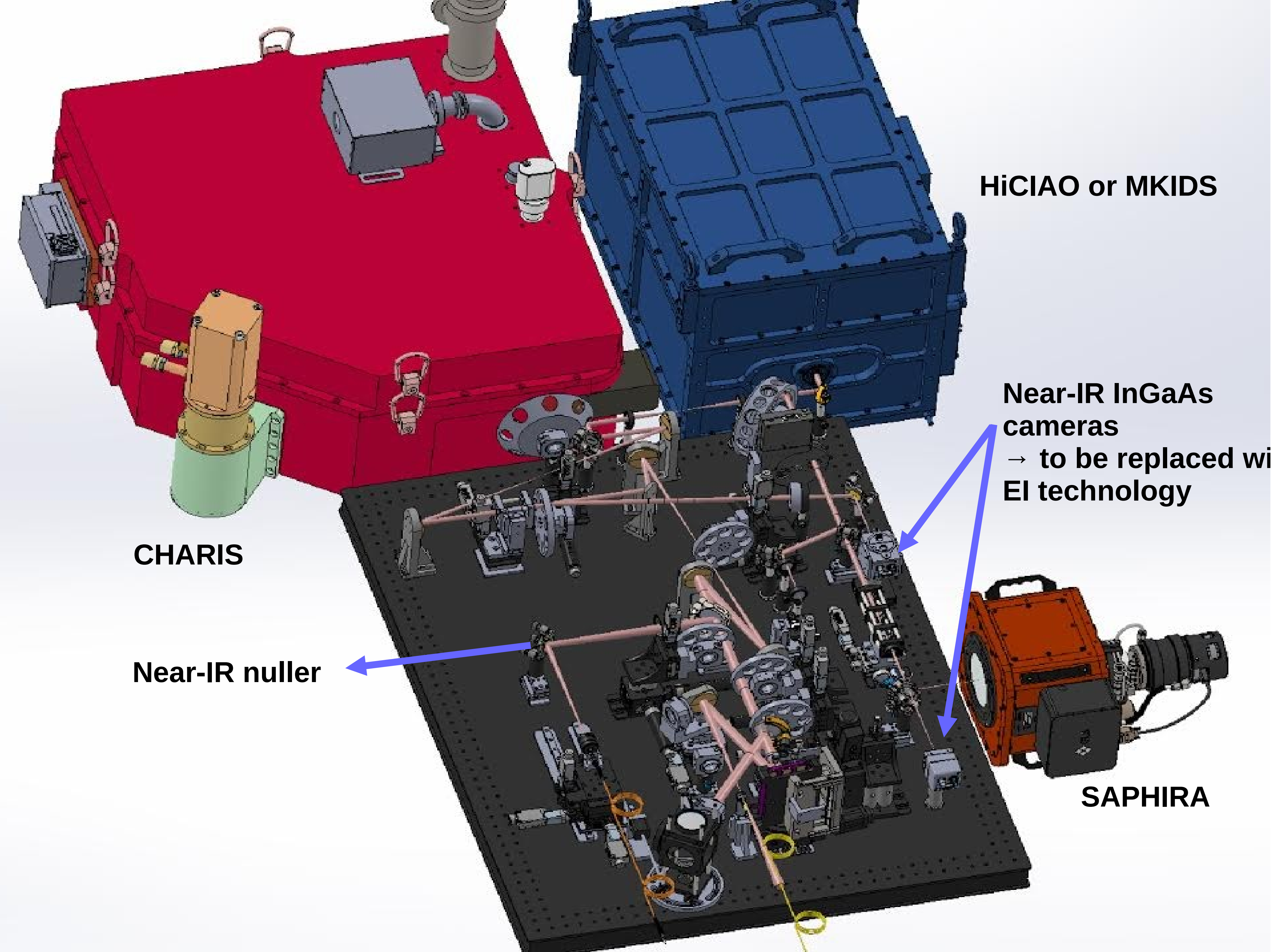
The Subaru Coronagraphic Extreme-AO (SCExAO) instrument

- **Flexible** high contrast imaging platform
- Meant to **evolve to TMT instrument** and validate key technologies required for direct imaging and spectroscopy of habitable exoplanets

Core system funded by Japan from multiple grants, current JSPS grant “Imaging Habitable zone Planets with Subaru Telescope and TMT” focused on wavefront control (includes MKIDs camera for speckle control + efficient WFS/C)

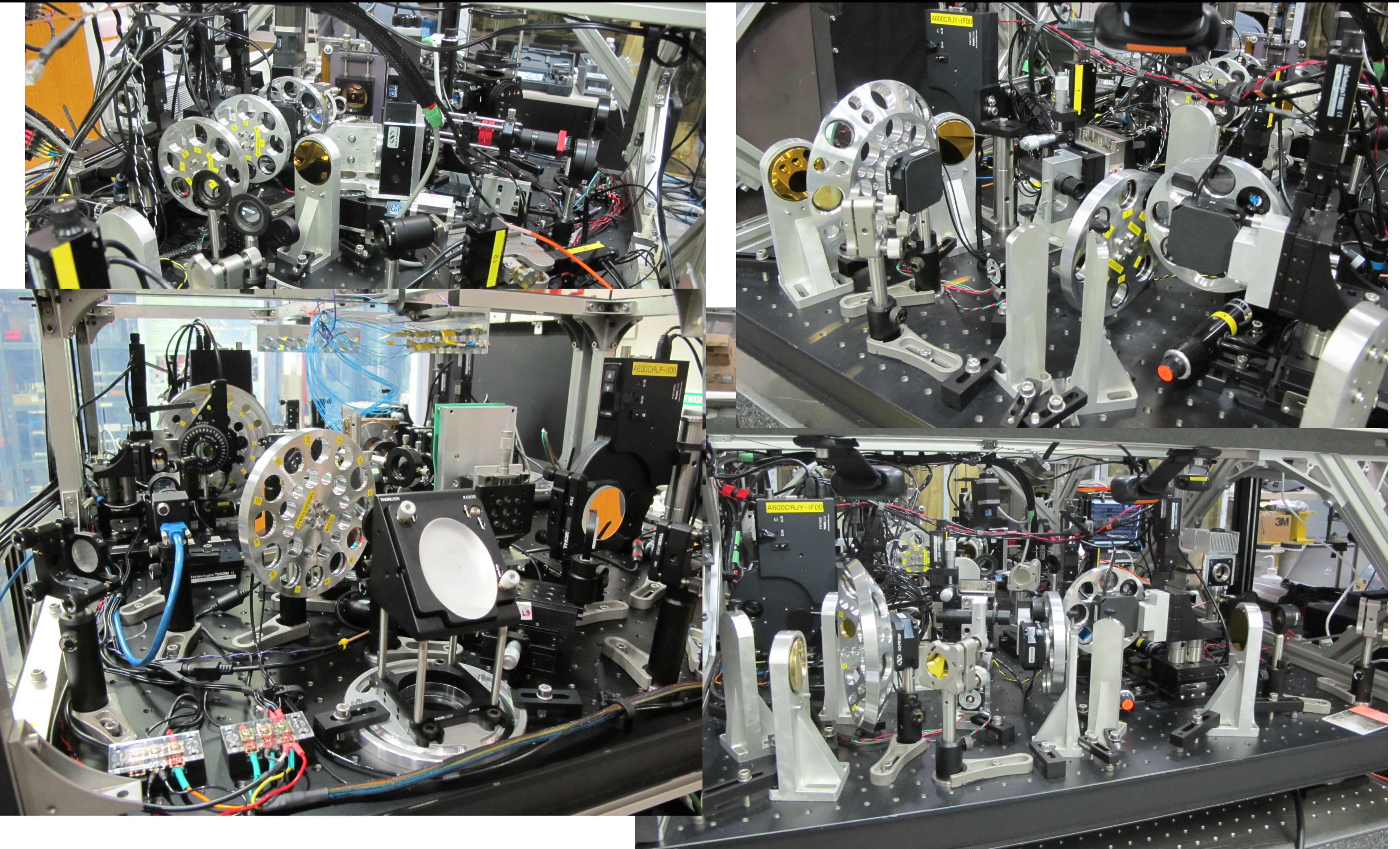
Modules/instruments funded by Japan + international partners:
- IFS funded by Japan, built by Princeton Univ
- MKIDs funded by Japan, built by UCSC
- SAPHIRA camera provided by UH
- VAMPIRES instrument funded and built by Australia
- FIRST instrument funded and built by Europe

Subaru Coronagraphic Extreme Adaptive Optics


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

SCExAO

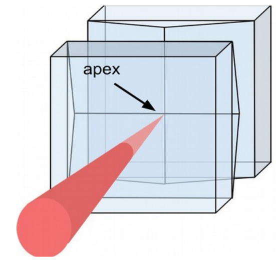
Subaru Coronagraphic Extreme Adaptive Optics

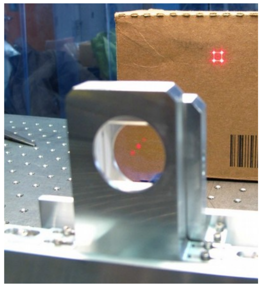


Low latency WFC in visible light at the diffraction limit sensitivity

Subaru Coronagraphic Extreme Adaptive Optics

2000 actuators MEMs DM running at 3.6 kHz
deep depletion EMCCD





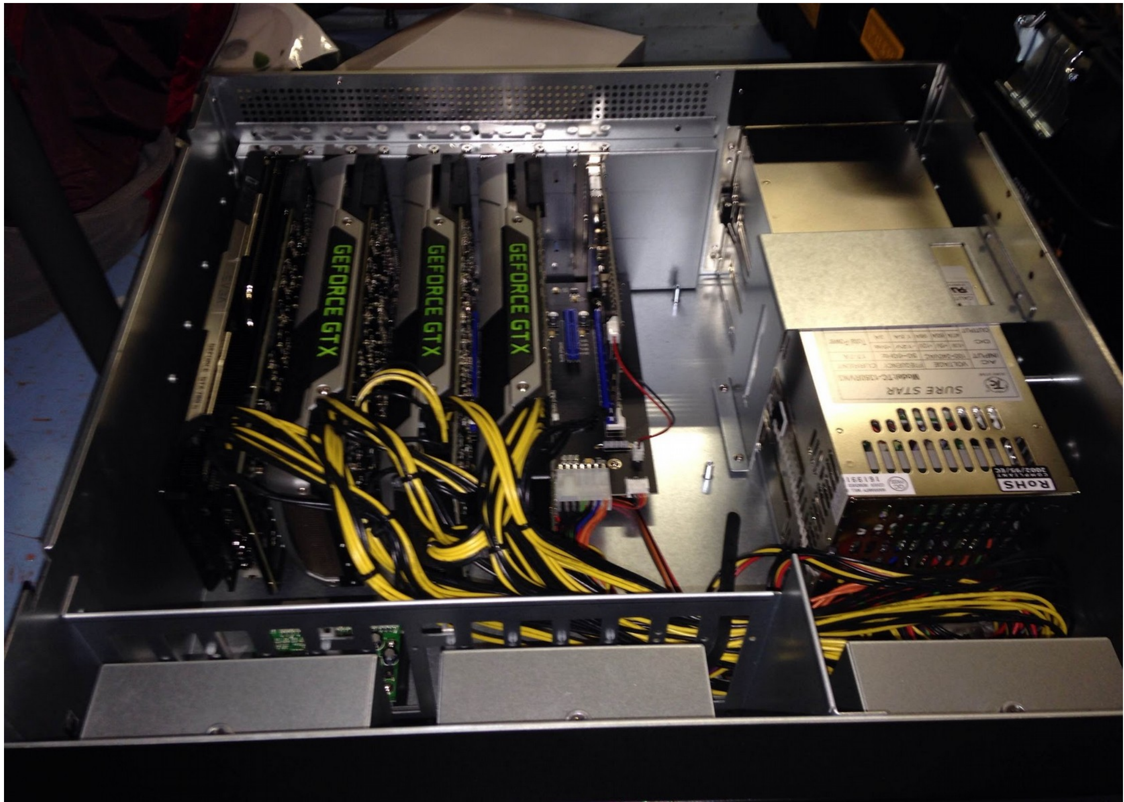
Non-modulated pyramid WFS cannot rely on slope computations
→ full WFS image is multiplied by control matrix

Now delivering 90% SR in H

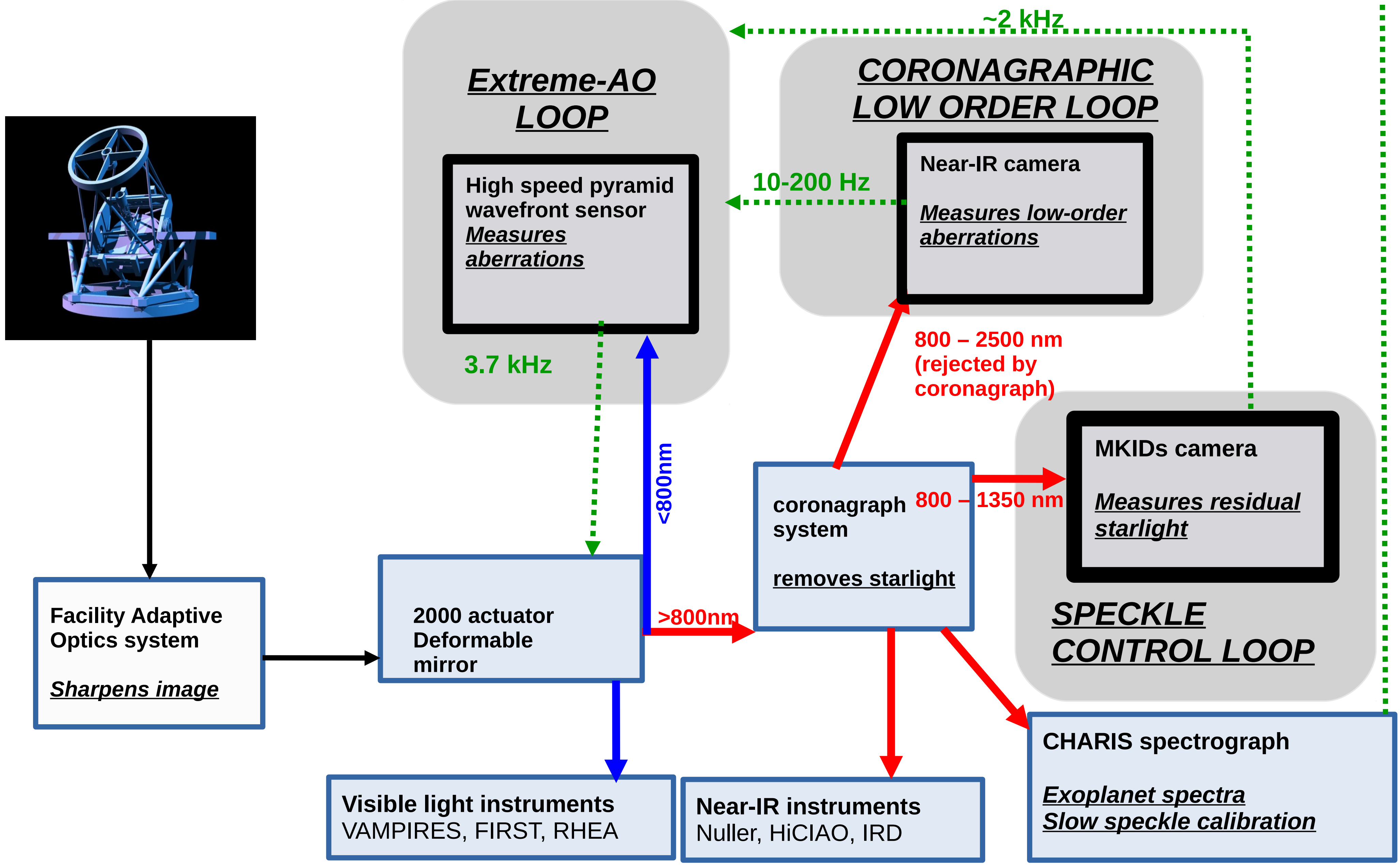
Recent upgrade allows 3.6kHz loop operation with zonal and modal reconstruction
→ low-latency control
→ modal reconstruction for predictive / LQG control (under development)

SCExAO uses 30,000 cores running @1.3GHz

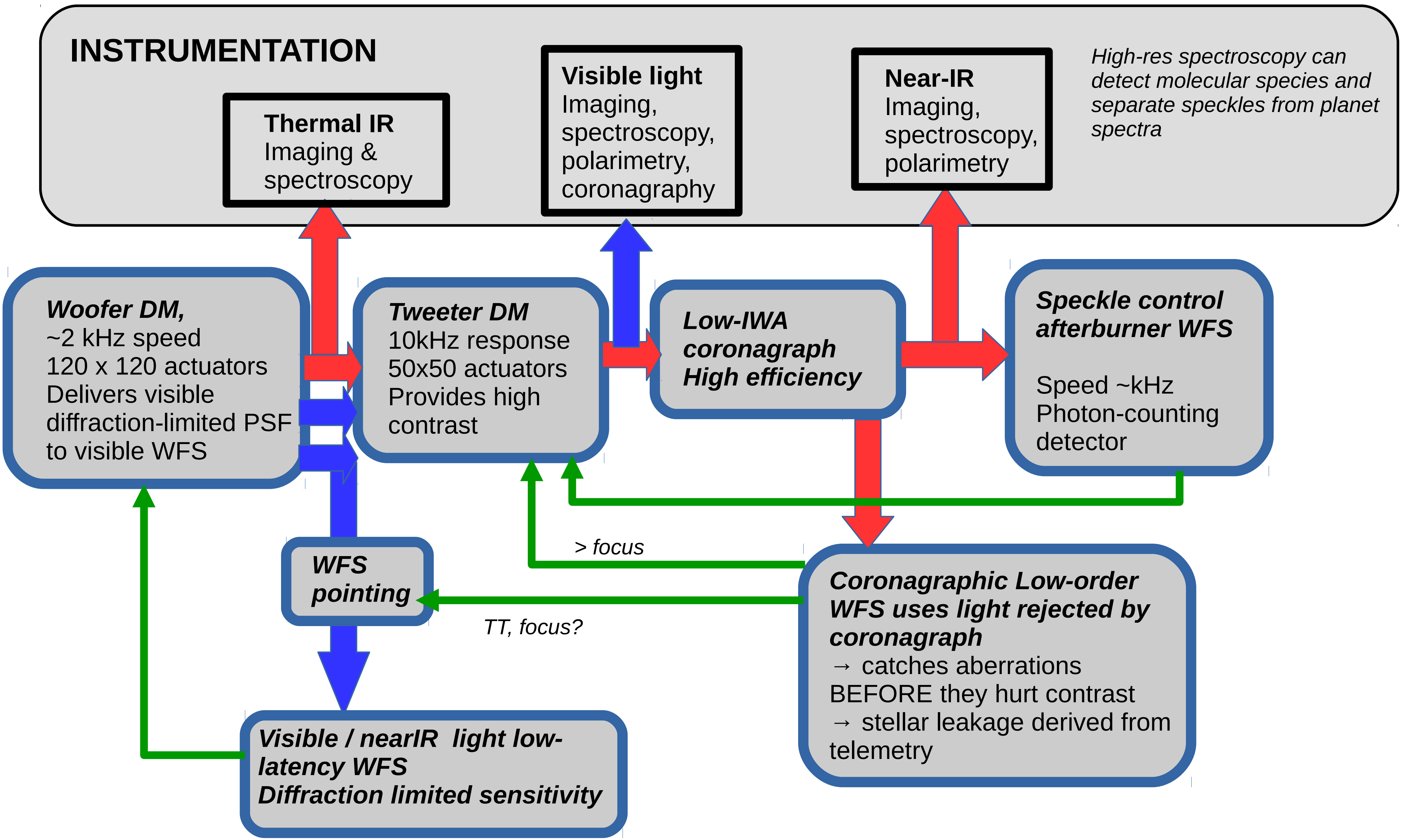
One of two GPU chassis



Subaru Coronagraphic Extreme Adaptive Optics



Nominal ELT ExAO system architecture



Coronagraph System

Requirements :
- IWA near 1 l/D
- high throughput (>~50% @ 2 l/D)
- ~1e-6 raw contrast
- resilient against stellar angular size (ELTs partially resolve stars)

Current status:

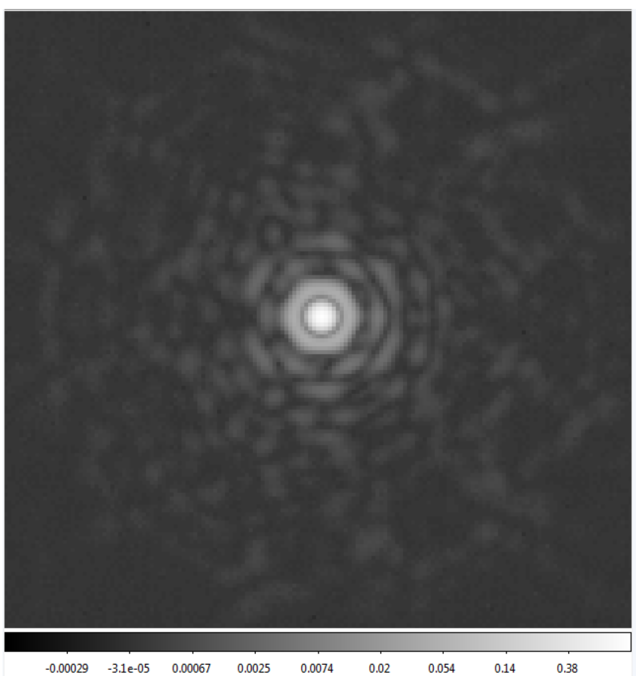
At least two approaches meet requirements: Vortex, PIAACMC
Performance demonstrated in lab on centrally obscured pupil (WFIRST) in visible light. Designs for segmented apertures have been produced (see next slides) but not tested.

No component-level significant challenge, but system-level performance has yet to be demonstrated on-sky

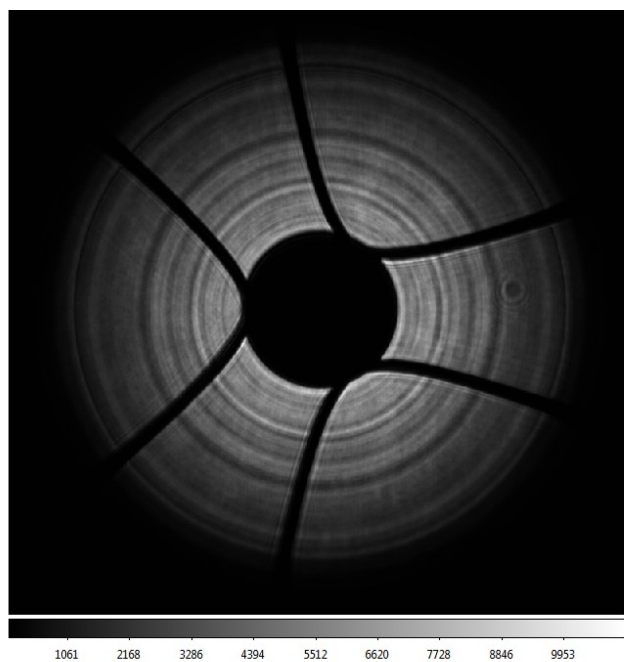
PIAACMC lab performance @ WFIRST (Kern et al. 2016)

Operates at 1e-7 contrast, 1.3 l/D IWA, 70% throughput
Visible light

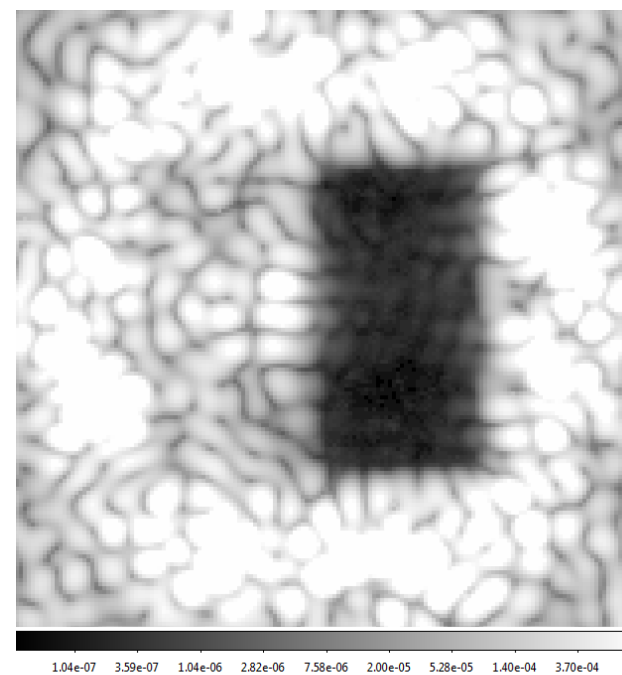
non-coronagraphic PSF



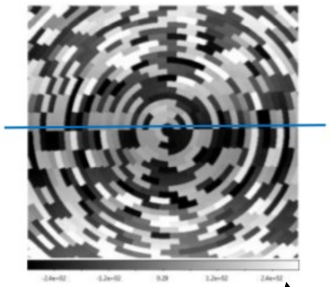
Remapped pupil

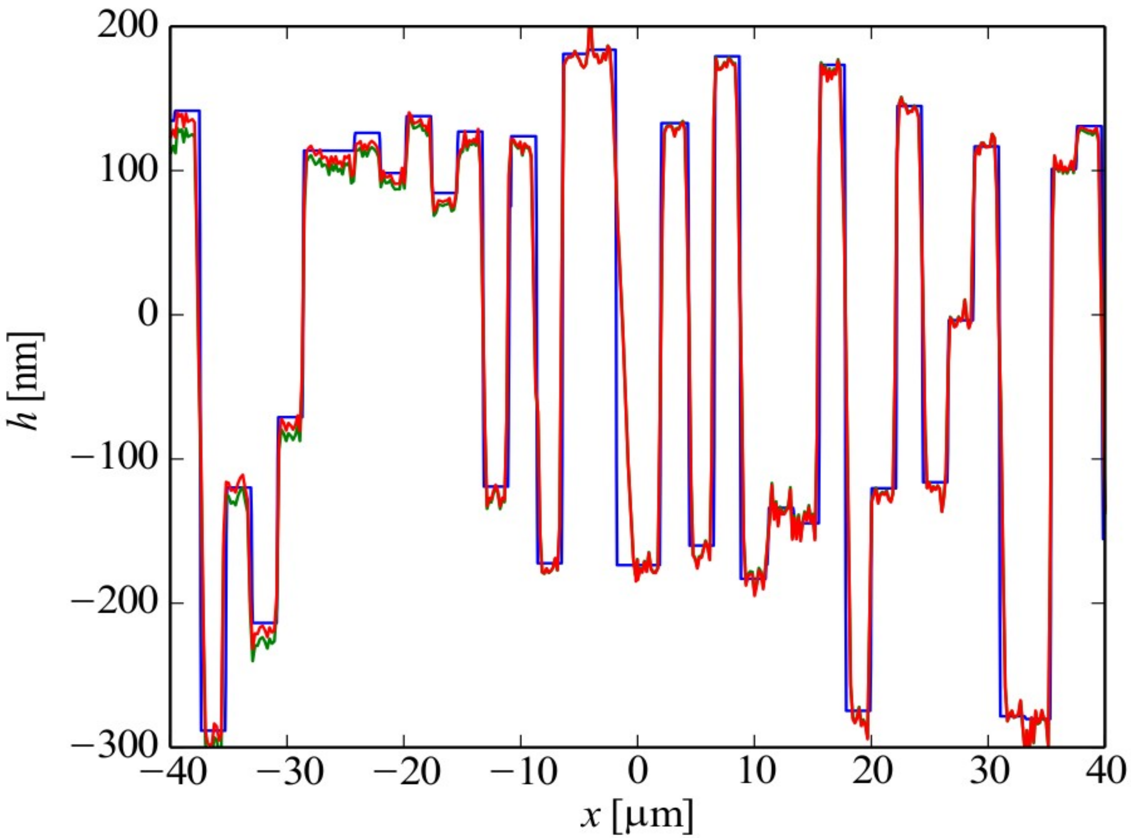


Coronagraphic image

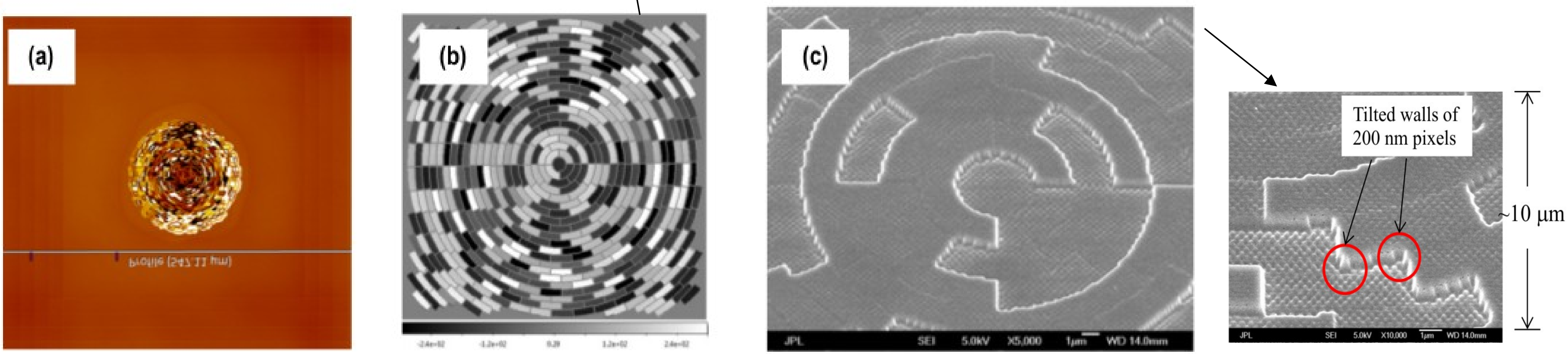


PIAACMC focal plane mask manufacturing





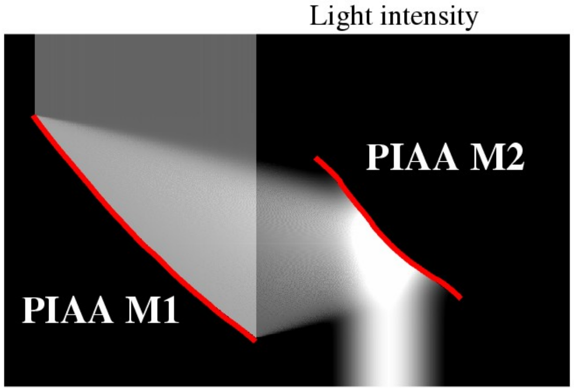
Focal plane mask manufactured at JPL's MDL
Meets performance requirements
(WFIRST PIAACMC Milestone report)



Example: GMT coronagraph design

PIAACMC architecture:

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



60% throughput

IWA = 1.3 l/D

co-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

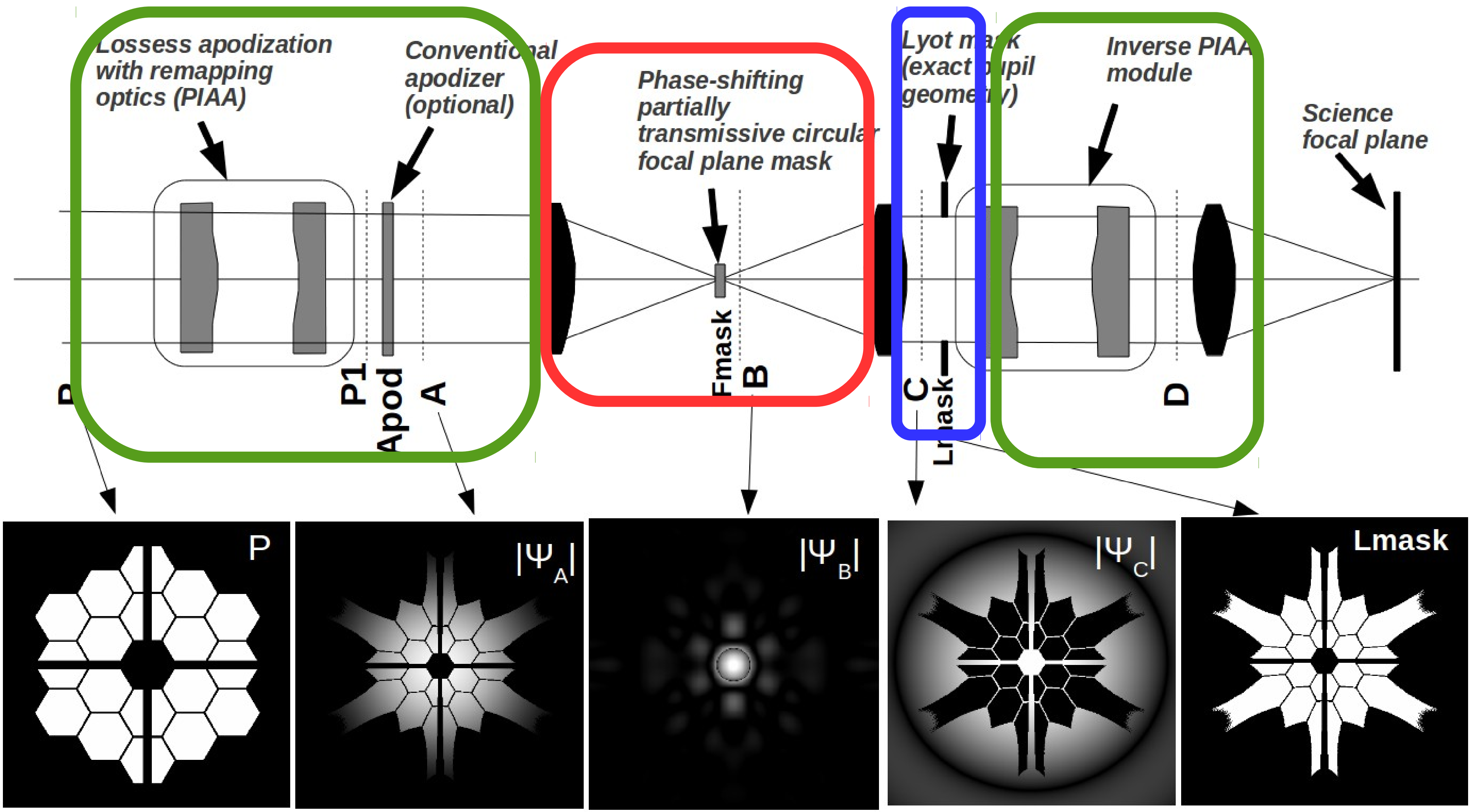
Lyot stop

Blocks starlight

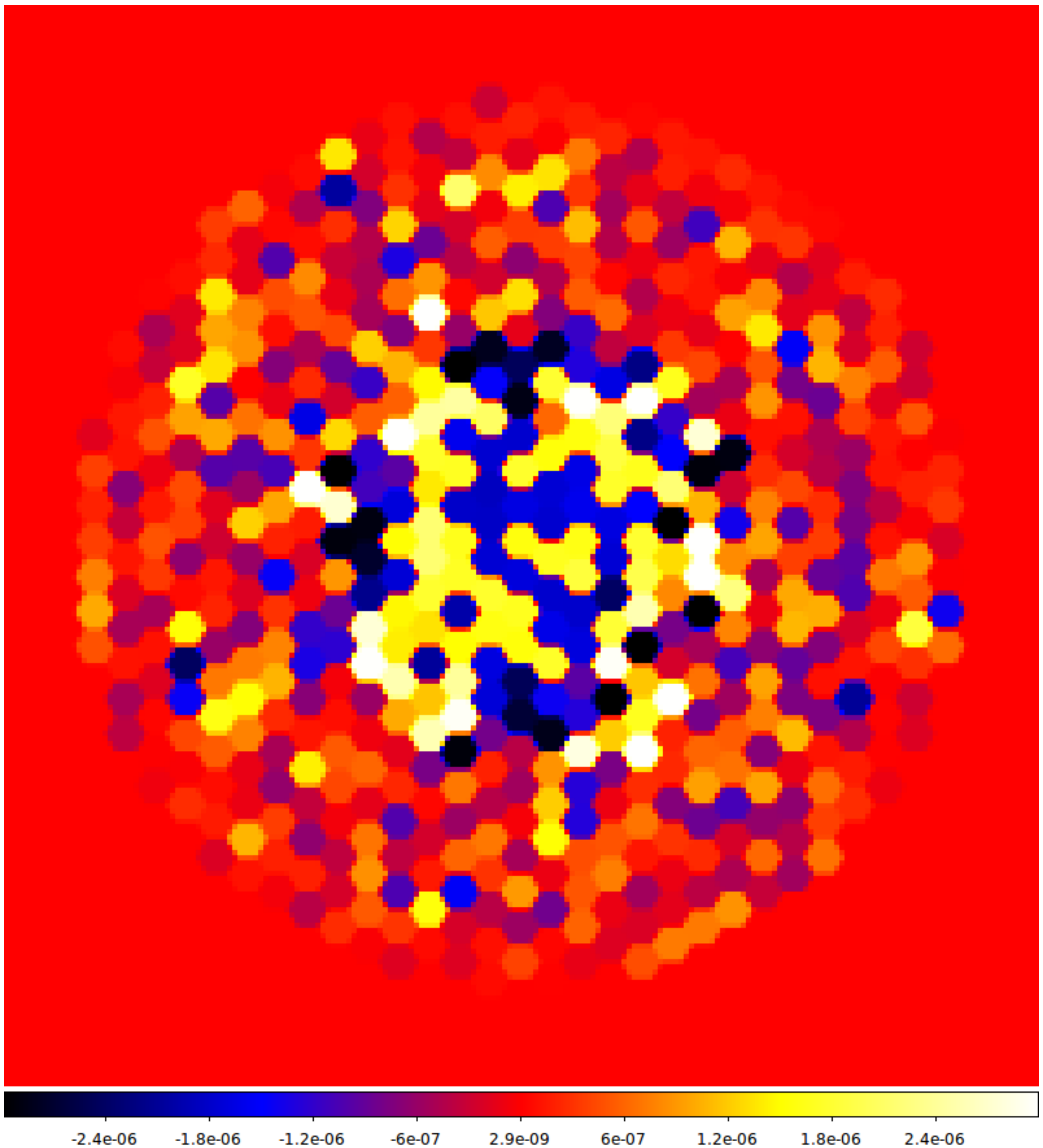
Inverse PIAA (optional)

Recovers Airy PSF over wide field

Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)

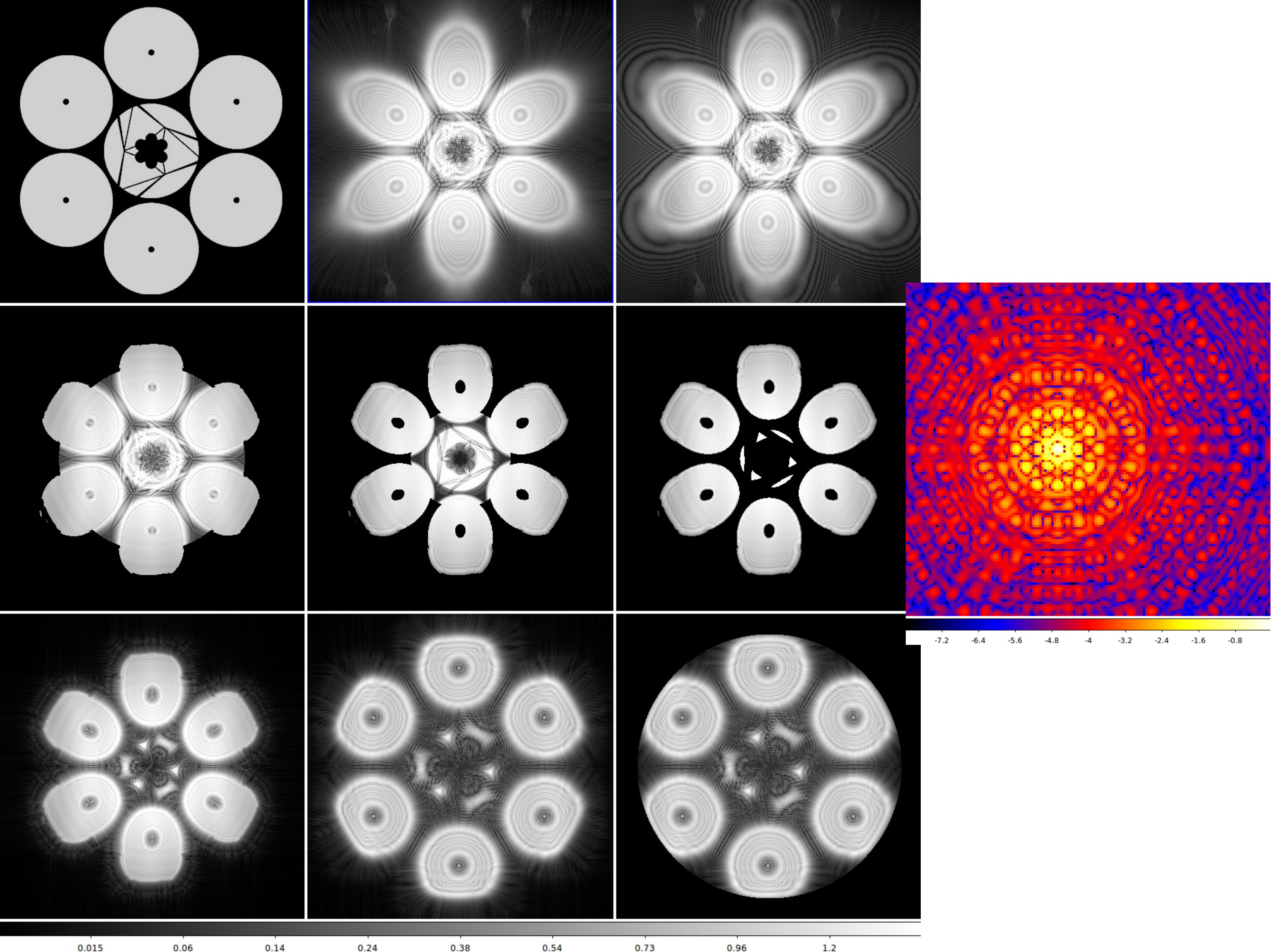


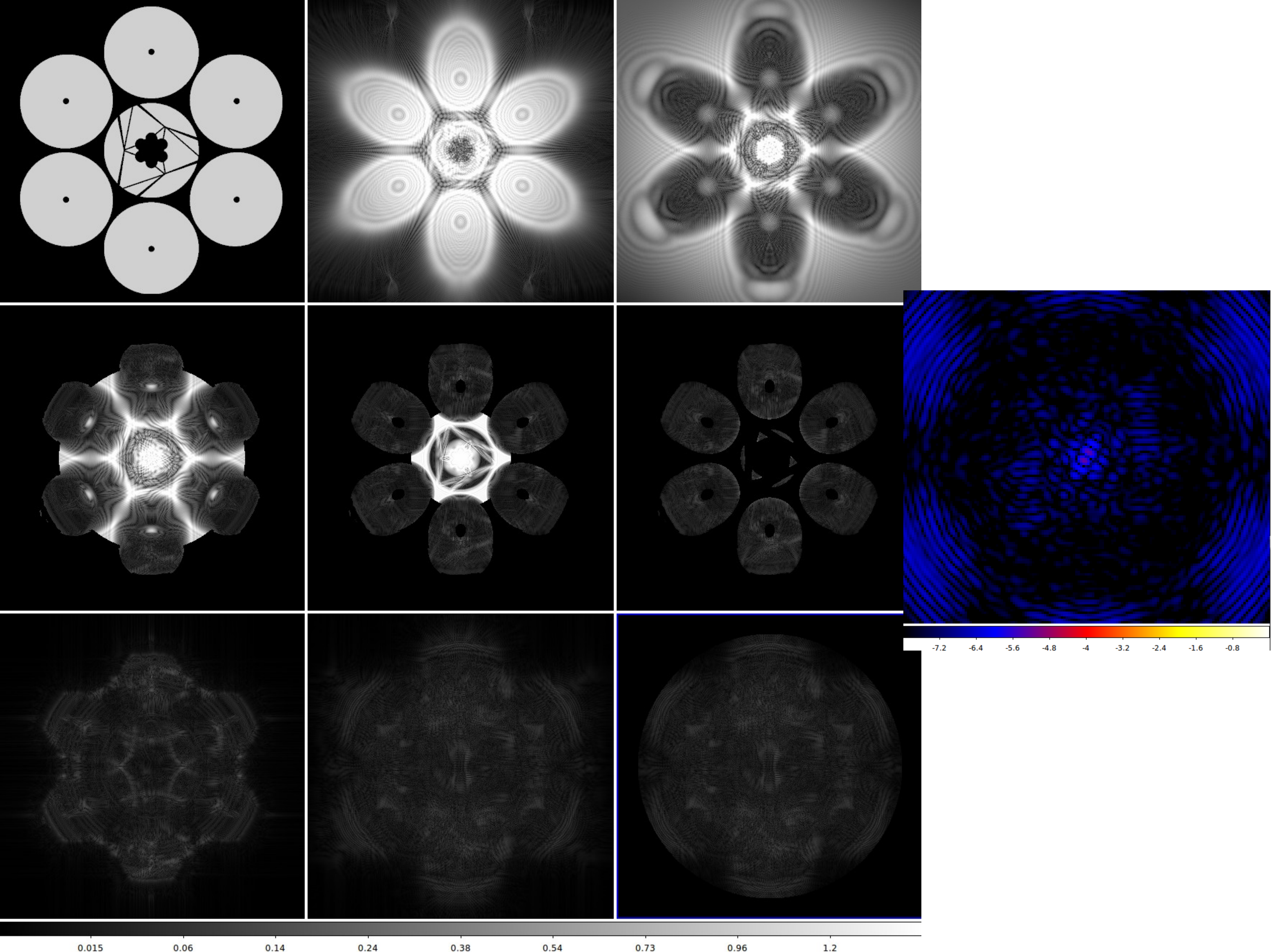
Focal plane mask



583 zones
SiO2 (transmissive)
+/- 3 um sag

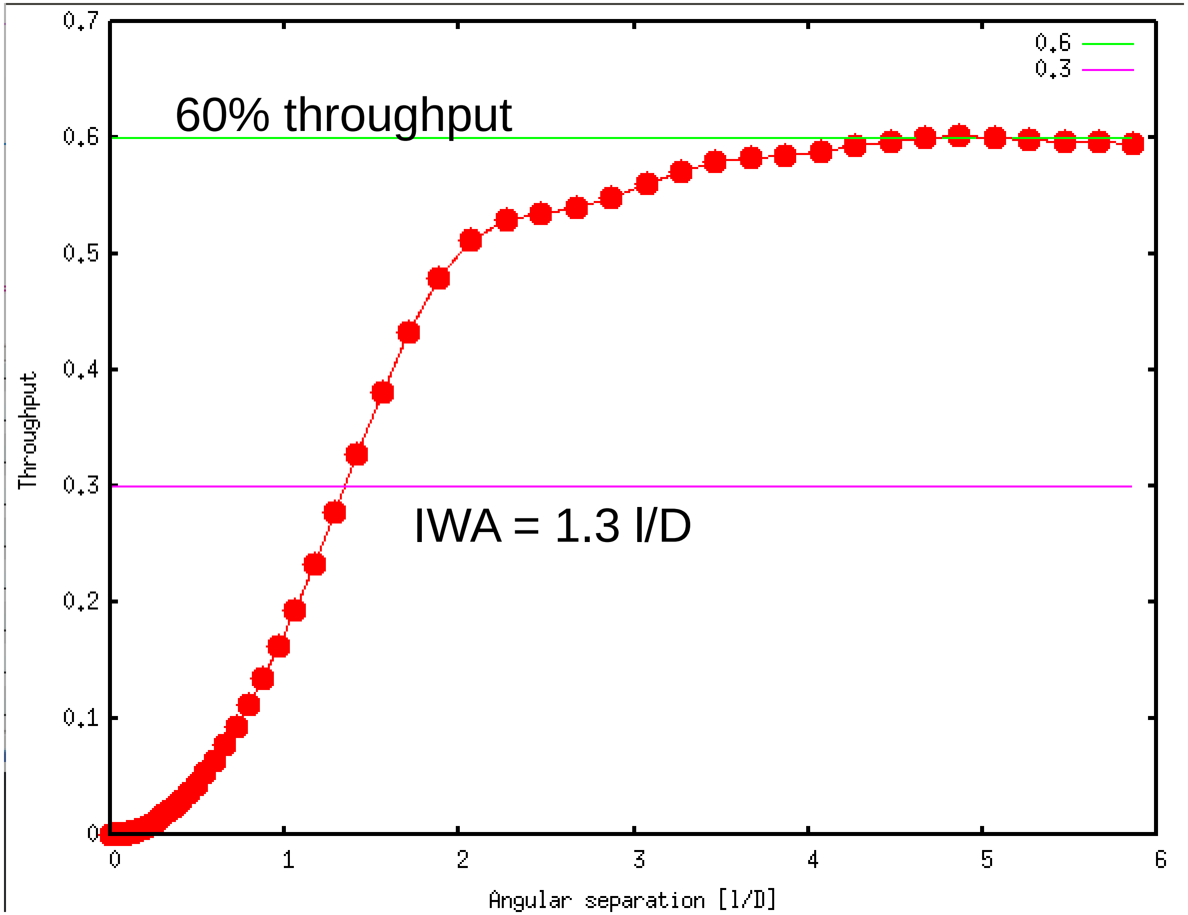
Optimized for 10% band,
partially resolved source


-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 solutions

[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

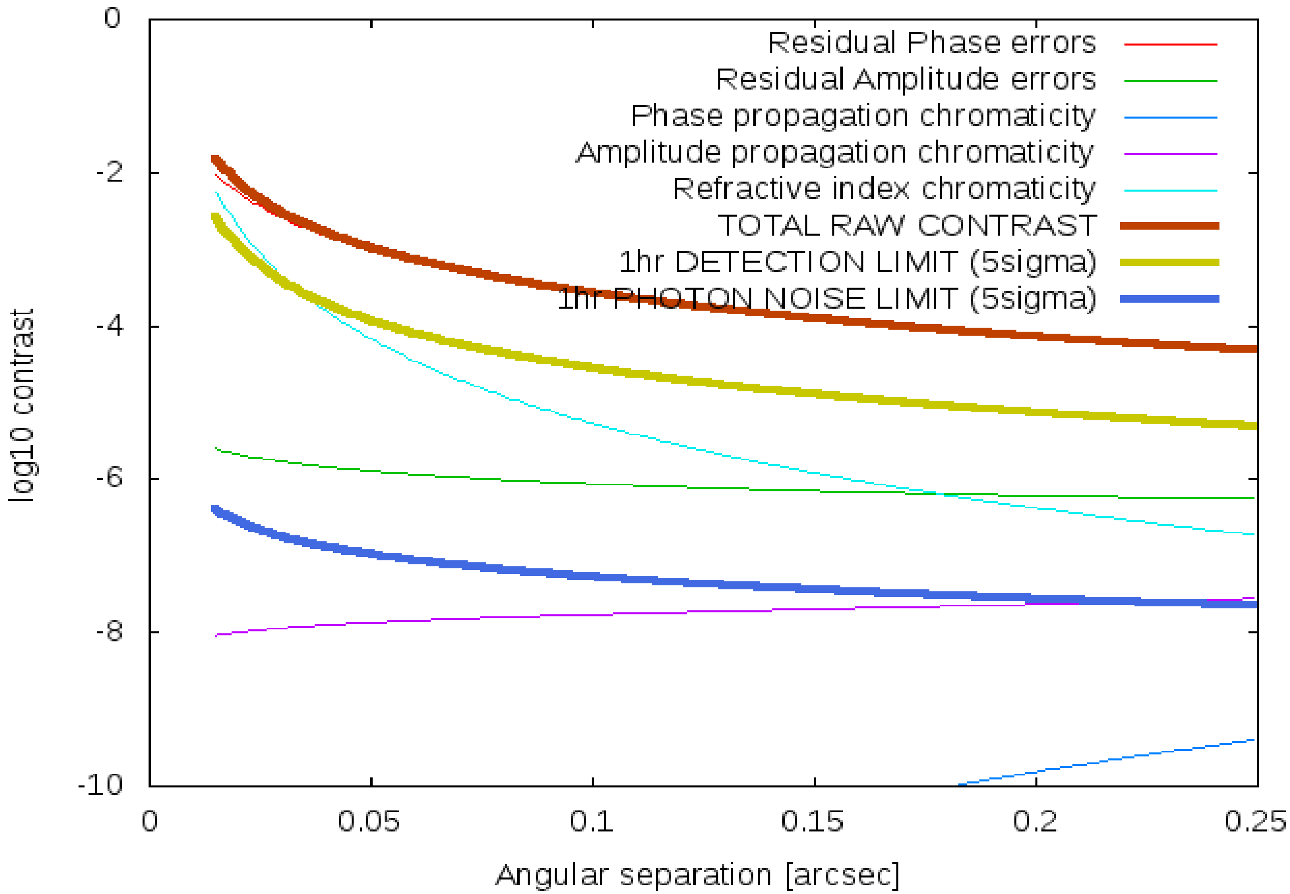
Assumptions:

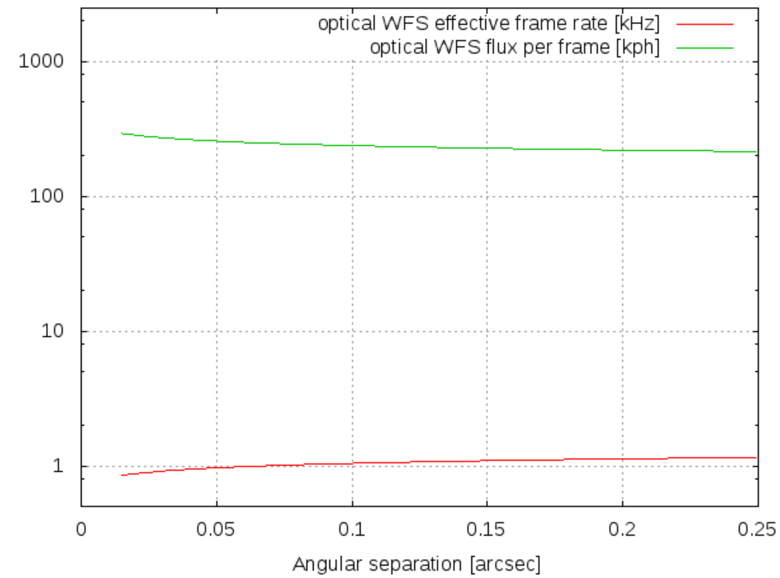
I mag = 8 (WFS – 100 targets)
H mag = 6 (Science)

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

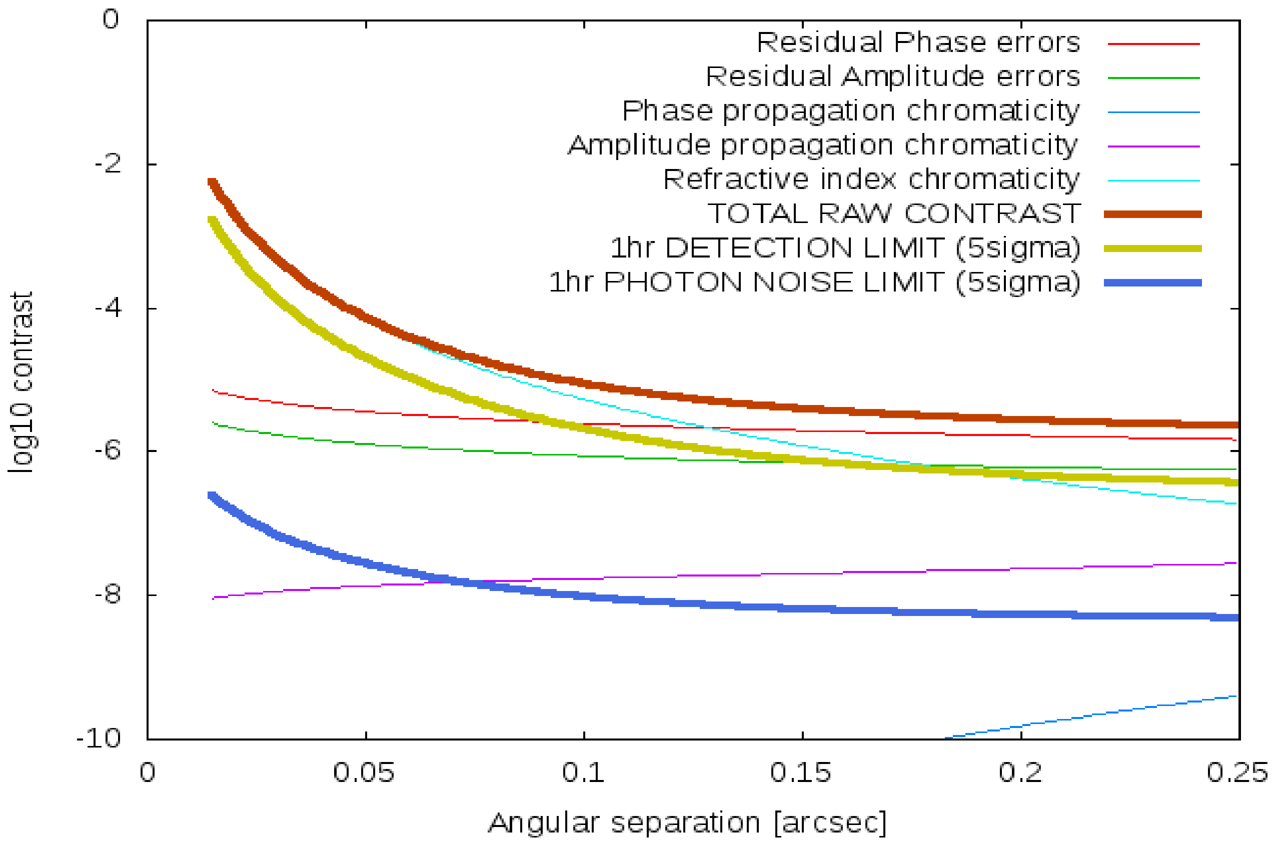


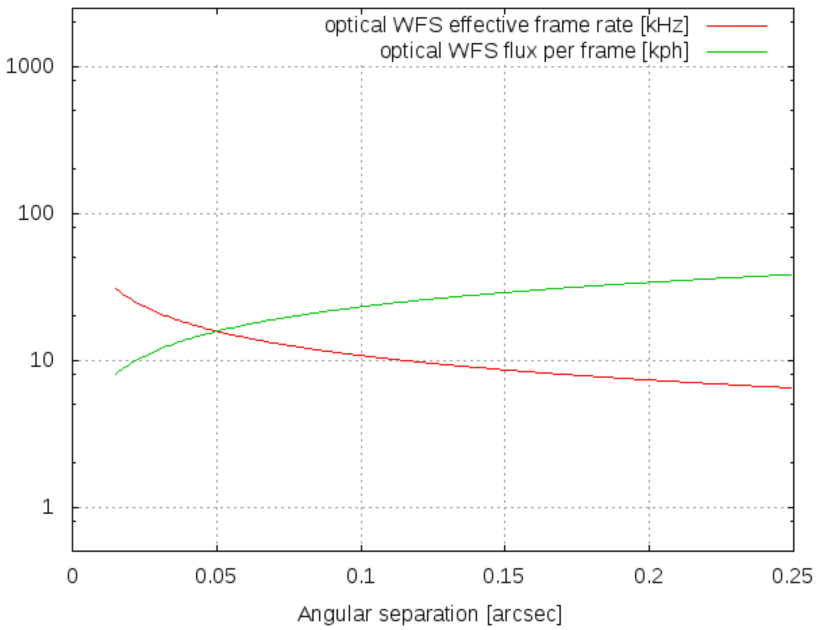


Limited by residual OPD errors: time lag + WFS noise
kHz loop (no benefit from running faster) – same speed as 8m telescope
>10kph per WFS required

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

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

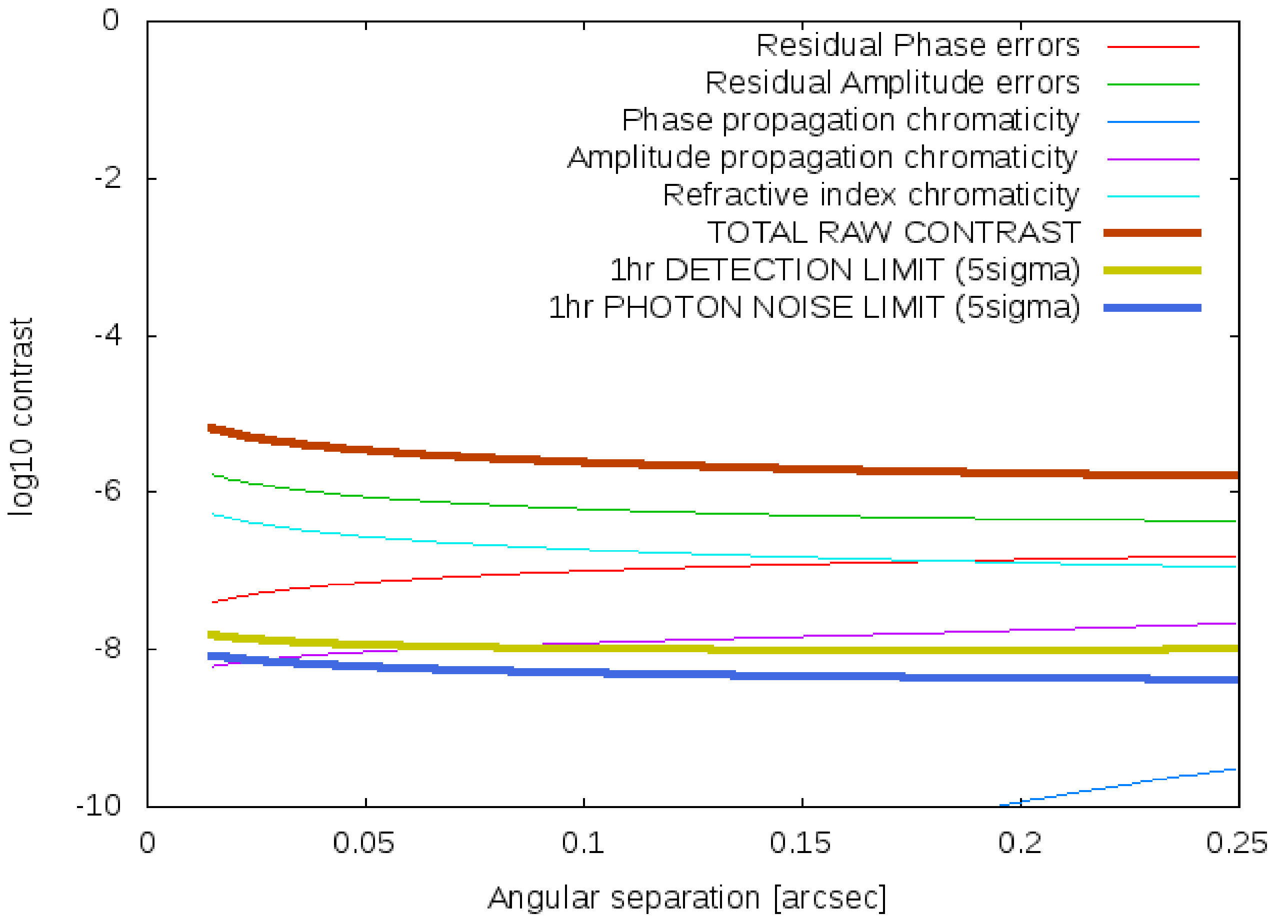


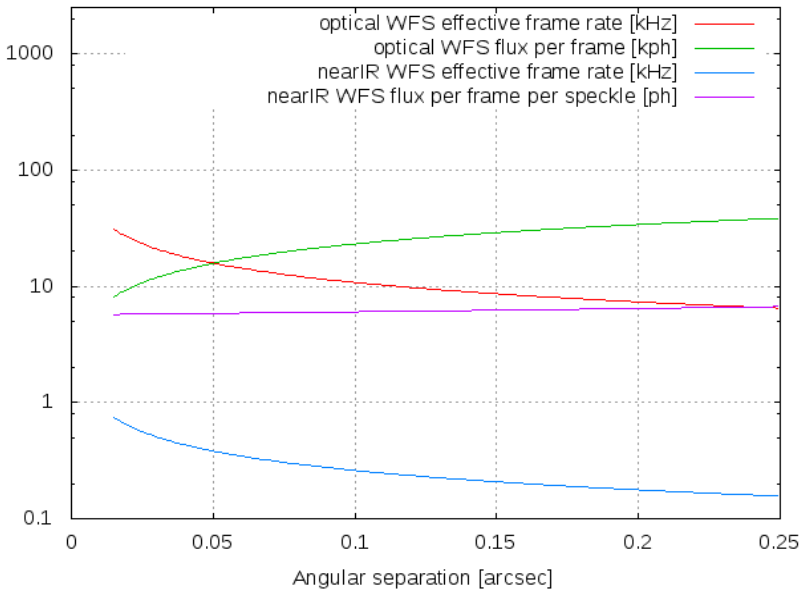


More sensitive WFS, can run faster (10kHz) with ~10 kph per WFS frame
Limited by atmosphere chromaticity

~((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

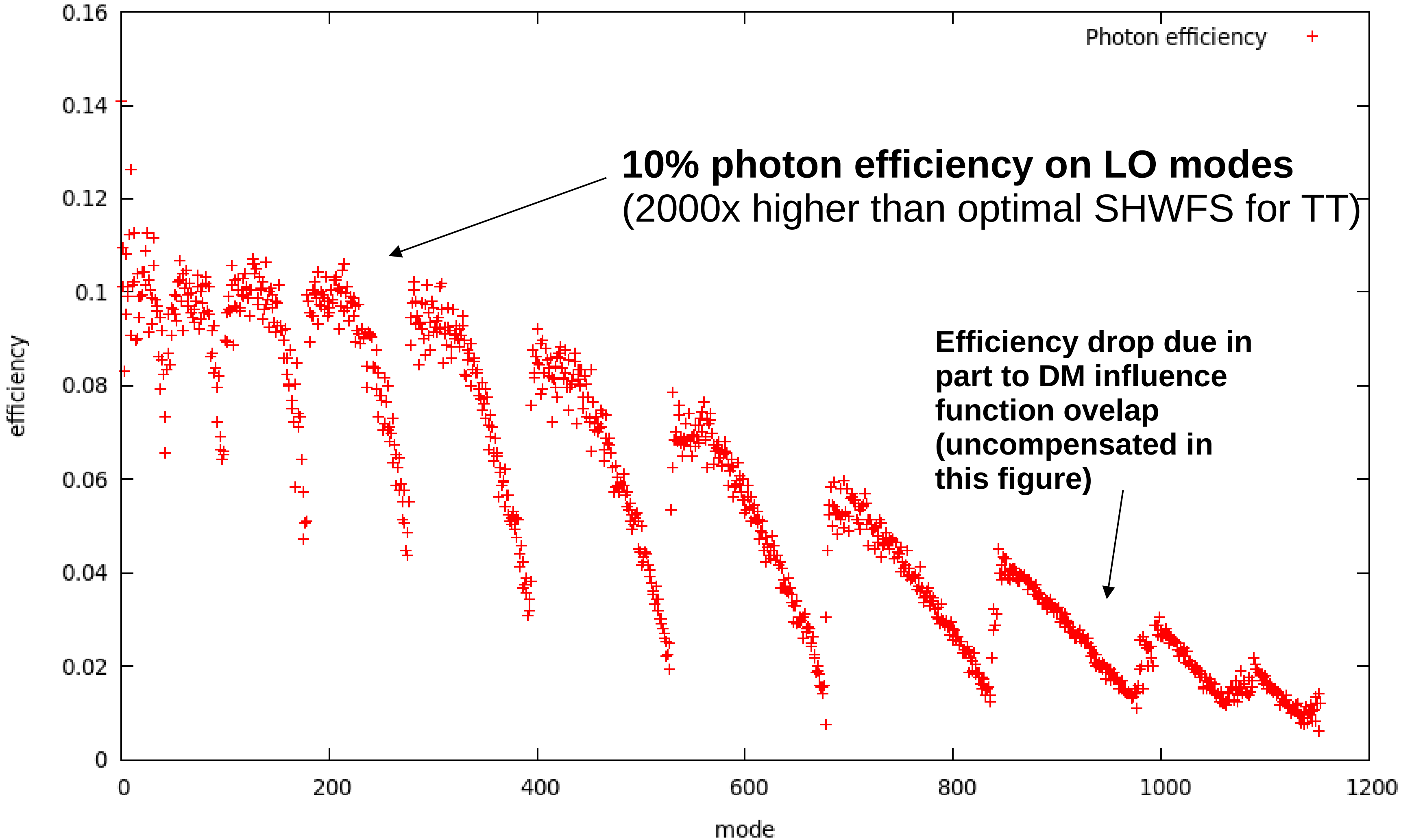




300Hz speckle control loop (~1kHz frame rate) is optimal

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

Measured photon efficiency (SCExAO, sub-l/D modulation pyramid)



Non-modulated PyWFS

Closed loop on SCExAO internal source in visible (EMCCD) and near-IR (SAPHIRA) demonstrated

Visible on-sky operation is challenging due to low (~50% or lower) and variable Strehl ratio + non-linearities

→ SCExAO usually operates at ~2 l/D modulation (more stable)

Low modulation PyWFS operation is still a research area

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)

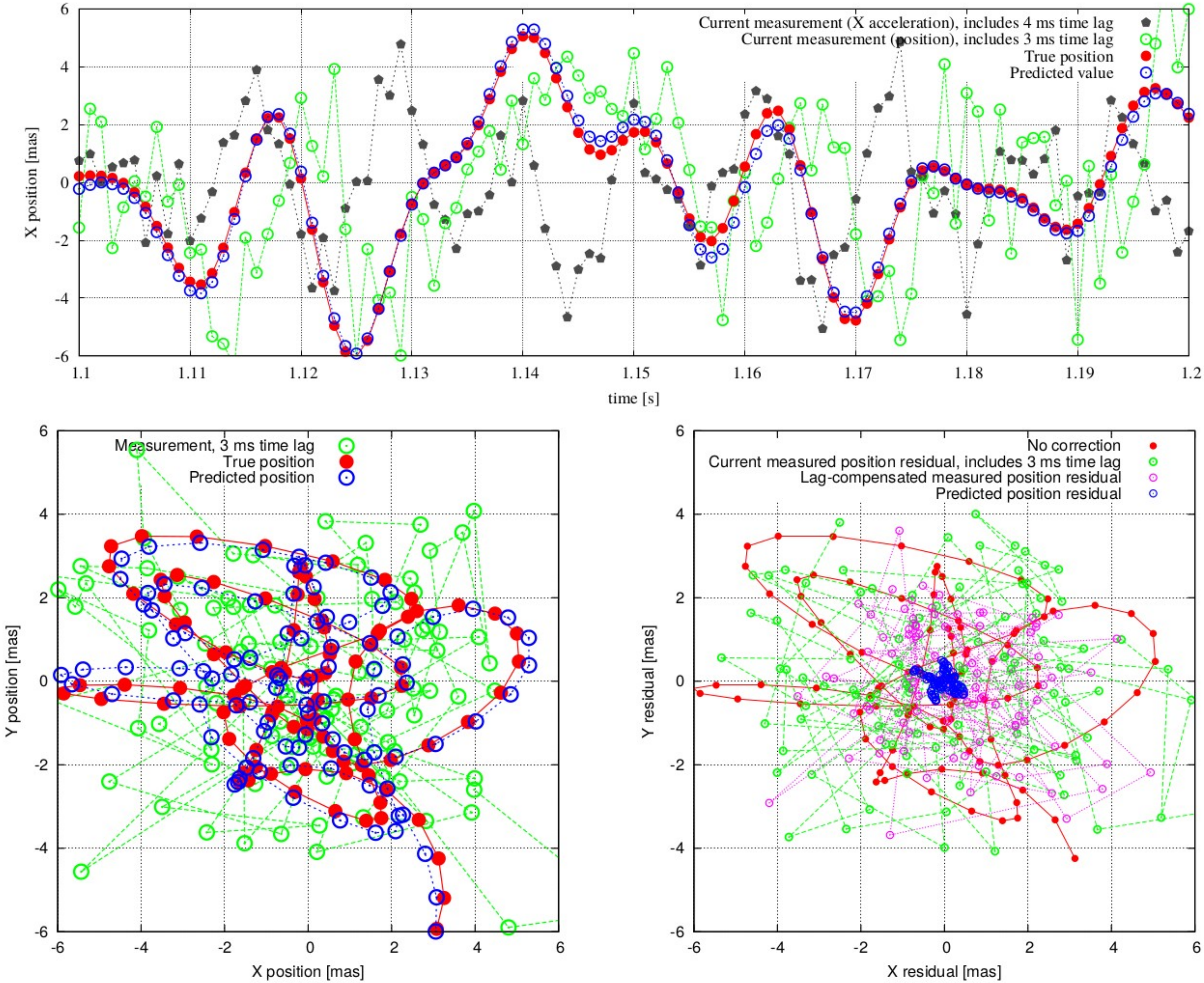


FIG. 3.— Top left: 2D-tracks for true pointing (red), predicted pointing (blue) and last measured position (green). Top right: Residual pointing error. Bottom: Single axis (x) values.

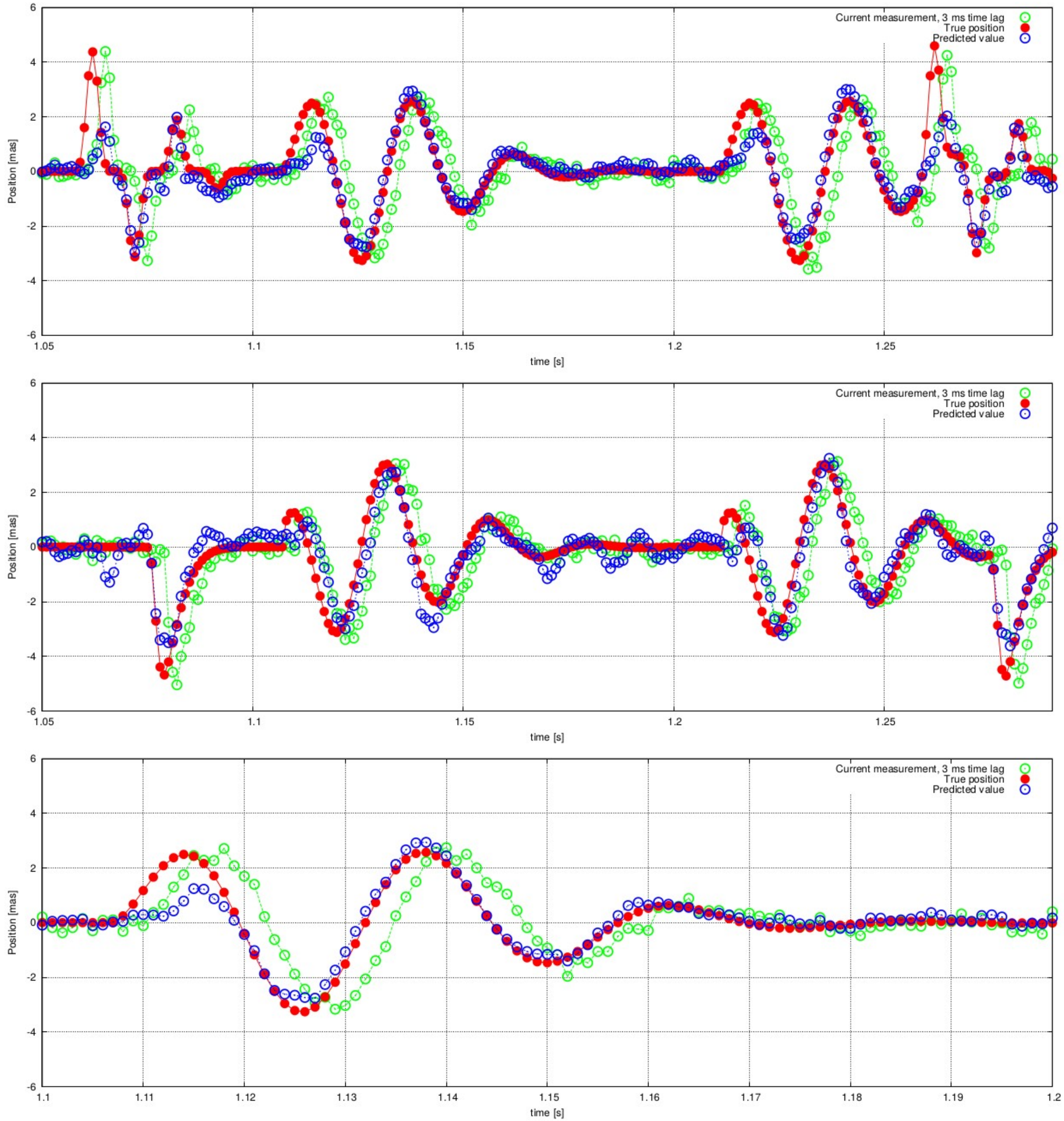


FIG. 4.— Top left: 2D-tracks for true pointing (red), predicted pointing (blue) and last measured position (green). Top right: Residual pointing error. Bottom: Single axis (x) values.

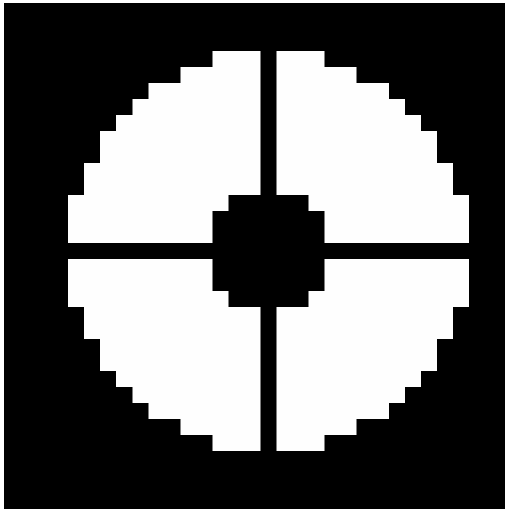
Optimal linear predictive control – 8m telescope (model-free, uses Empirical Orthogonal Functions)

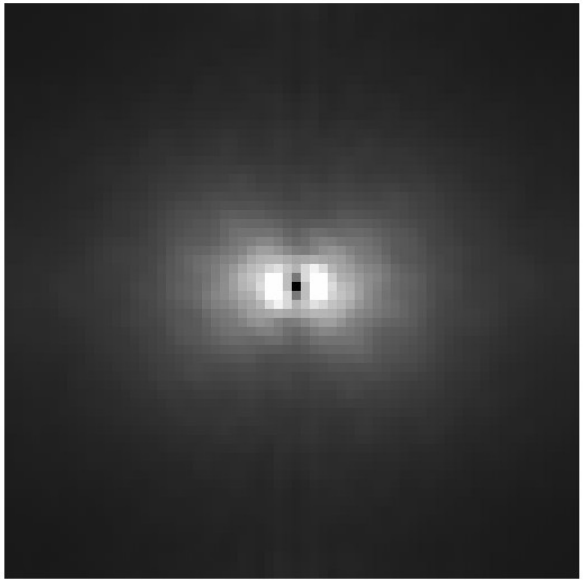
8m telescope
mag 8 source (R band)
1kHz sampling + 2ms lag
Photon-noise limited sensor
10% efficiency, 20% bandwidth
r0 = 20cm at 0.6um → 21 rad WFE RMS
7 layer turbulence, most power between 6 and 22 m/s

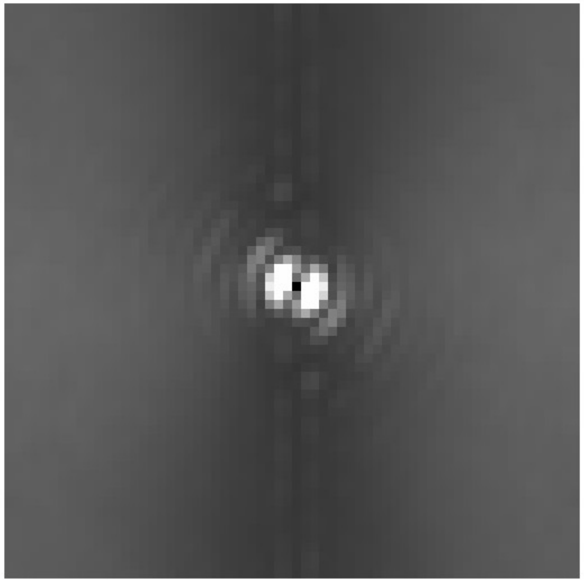
System dominated by time lag (214nm error)
WFS noise small (9nm RMS over first 400 low-order modes)

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







Benefits & challenges

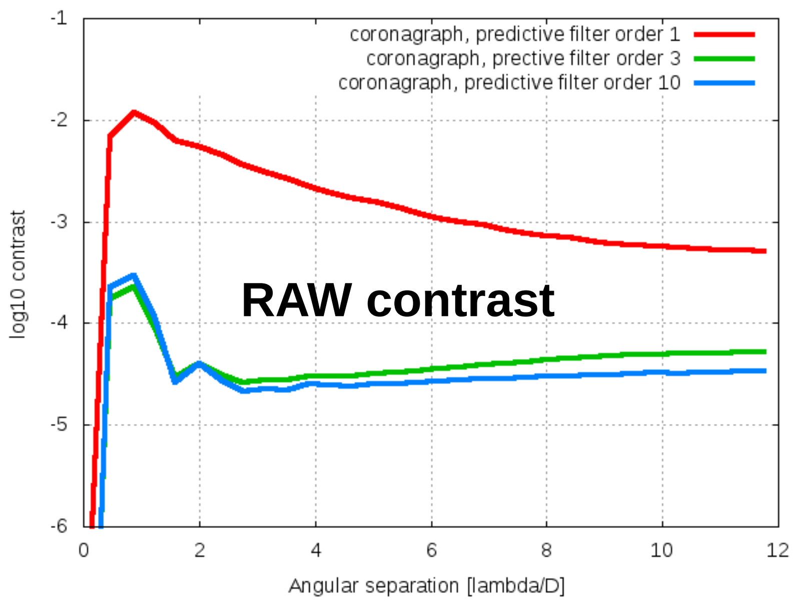
Lower wavefront error (30nm vs. >200nm)
Raw contrast improvement: ~100x gain

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

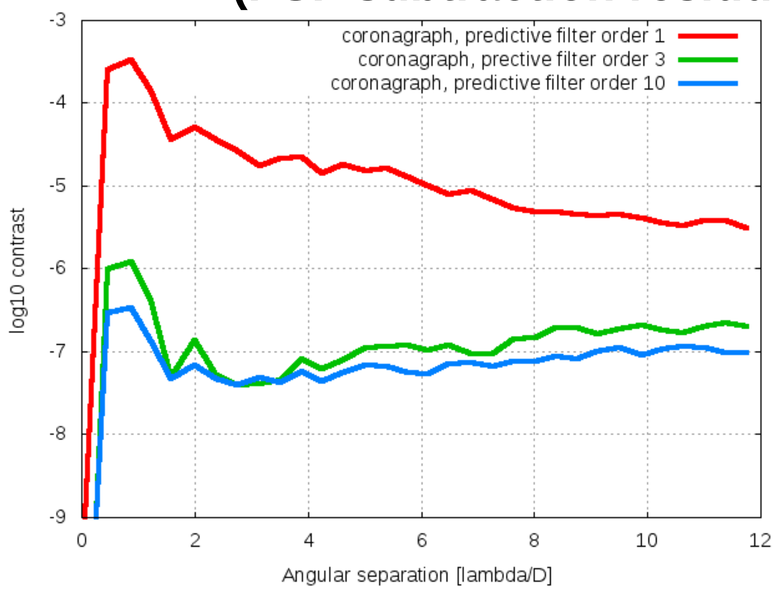
Smoother PSF halo
slow speckles are GONE

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)



Next steps

On-sky deployment in late 2016 (Nov or Dec runs)

Software currently supports mixing between classical and predictive modes for smooth transition

Current SCExAO computer supports 2kHz operation
Full speed (3.7kHz) operation will require additional GPU boards.

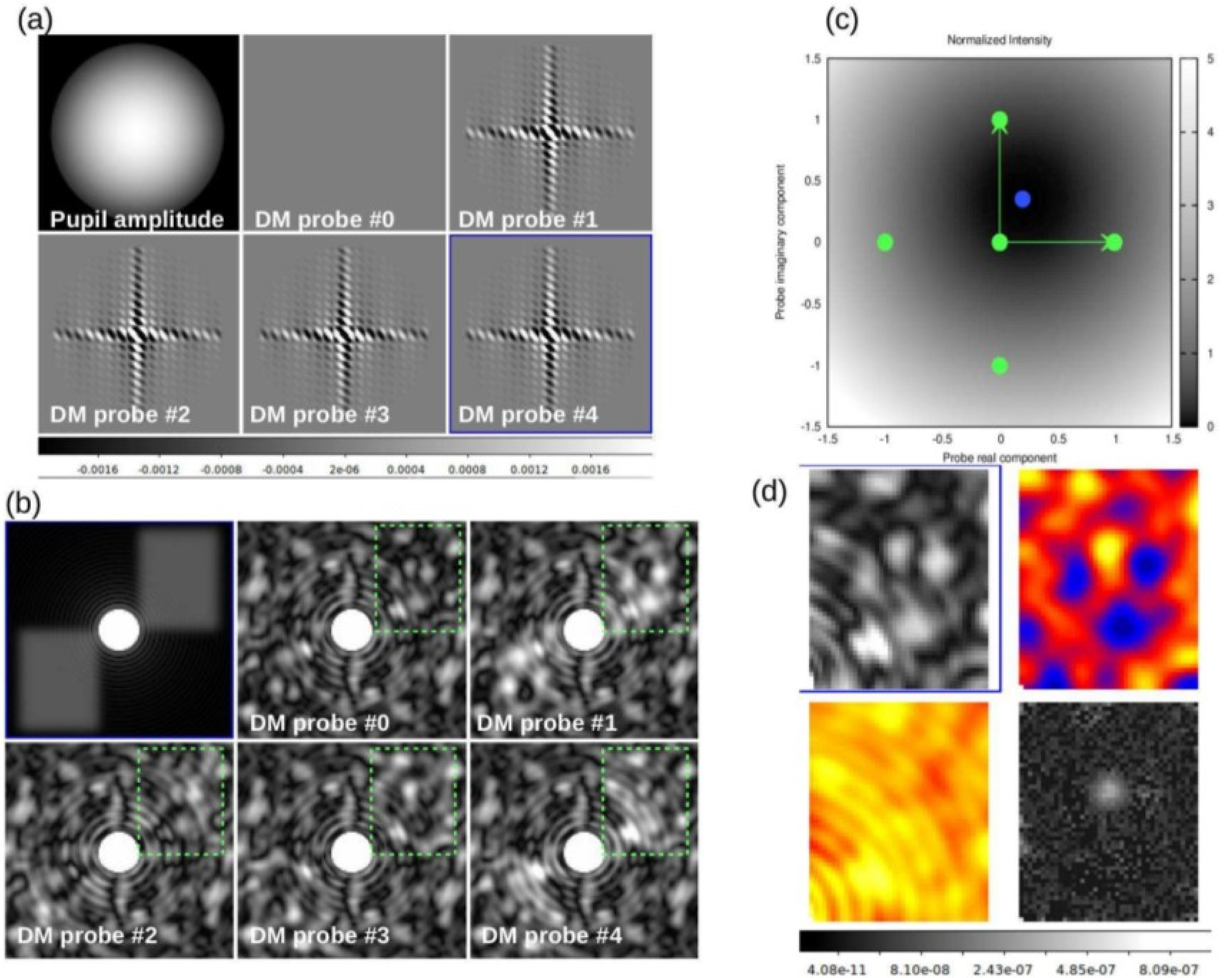
Research areas

[1] High spectral resolution template matching
100x – 1000x gain (photon-noise permitting)

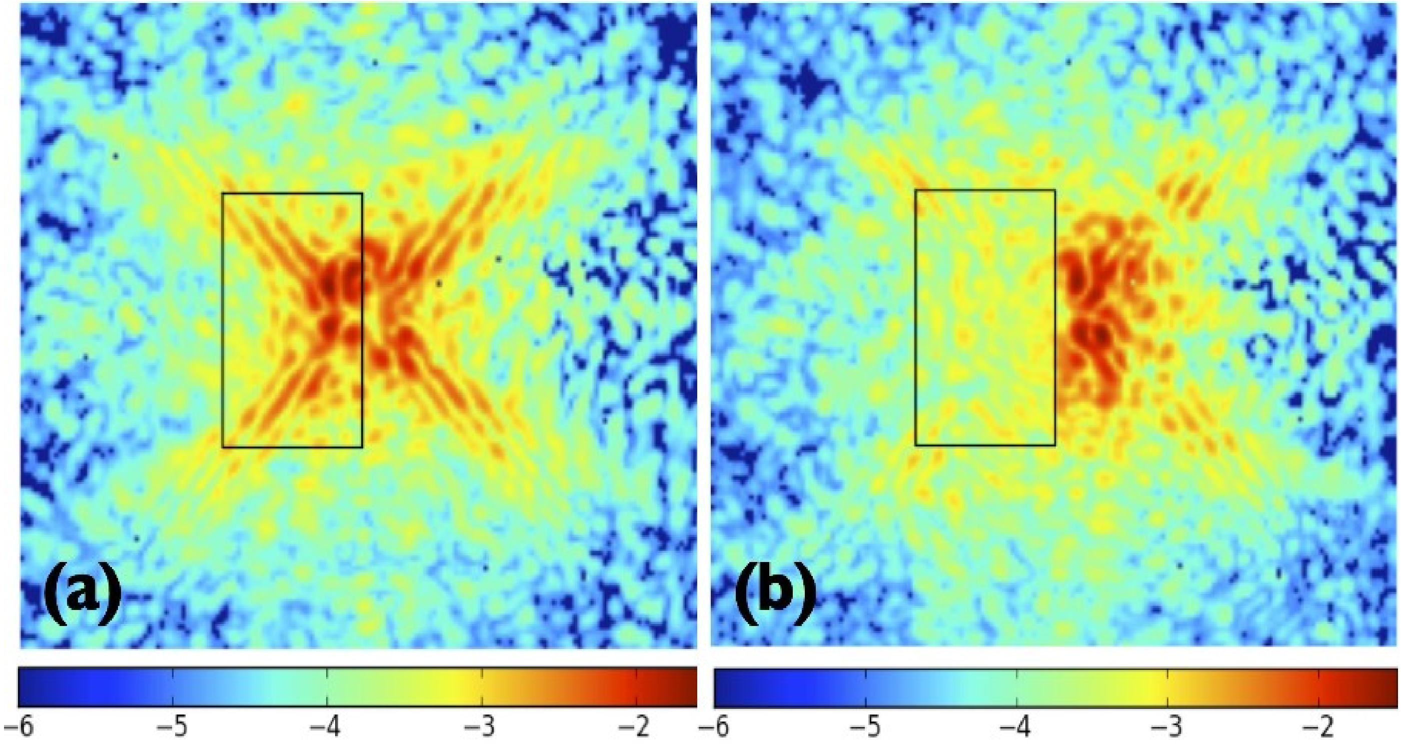
[2] Coherent differential imaging
10-100x gain ?

[3] Linear Dark field speckles control
10-100x gain ?

Coherent Speckle Differential Imaging



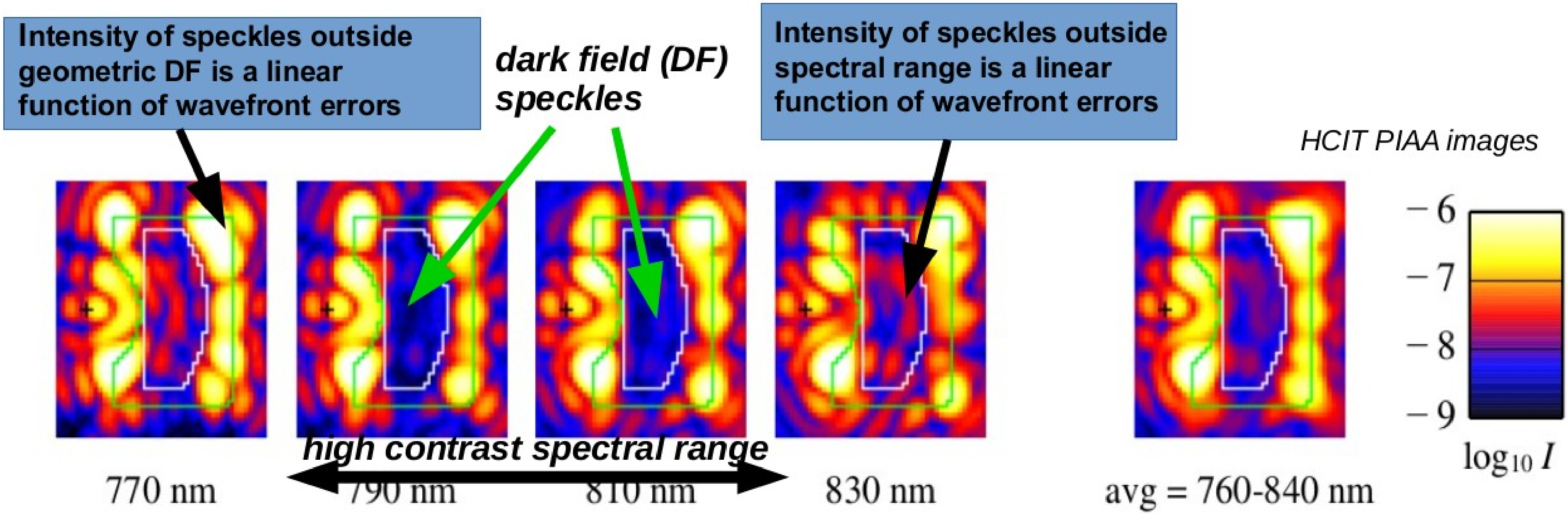
Bright field speckles in ½ field dark hole



Linear Dark Field Control (LDFC)

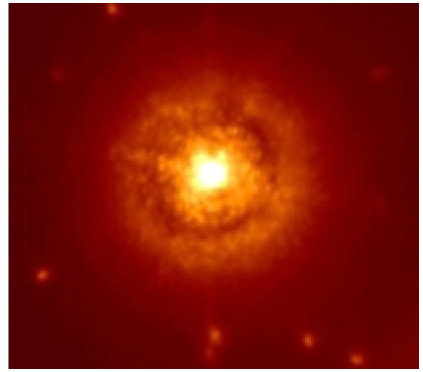
Speckle intensity in the DF are a non-linear function of wavefront errors
→ current wavefront control technique uses several images (each obtained with a different DM shape) and a non-linear reconstruction algorithm (for example, Electric Field Conjugation – EFC)

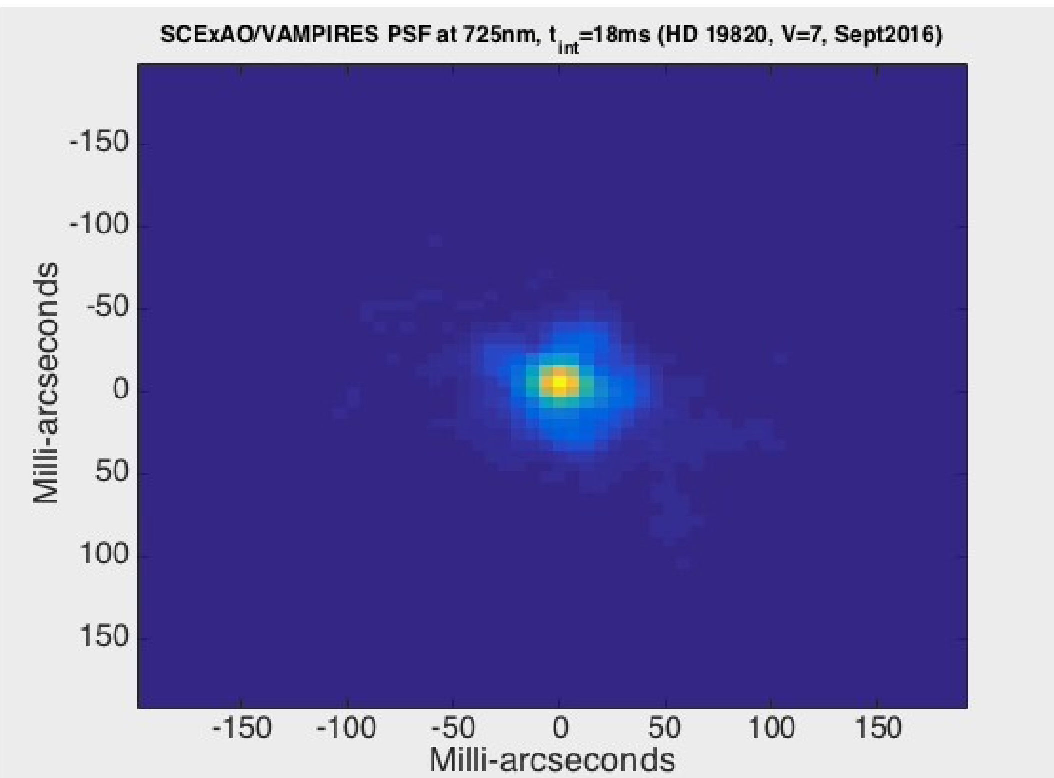
Speckle intensity in the BF are linearly coupled to wavefront errors → we have developed a new control scheme using BF light to freeze the wavefront and therefore prevent light from appearing inside the DF



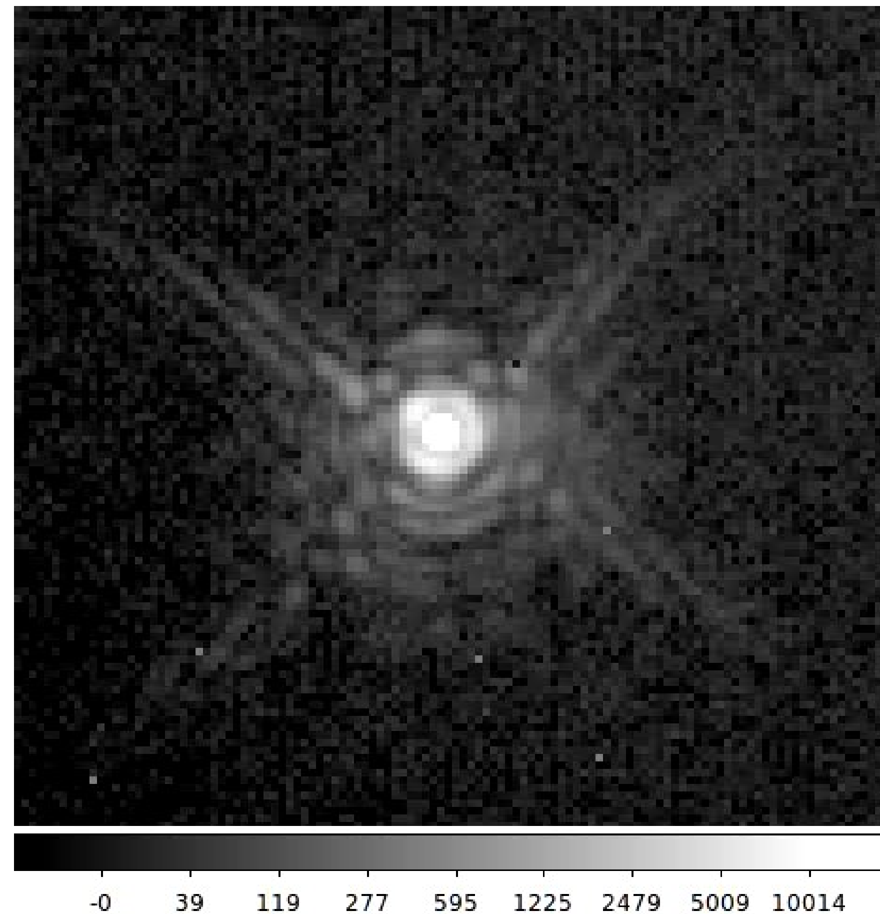
Current PSF stability @ SCExAO

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

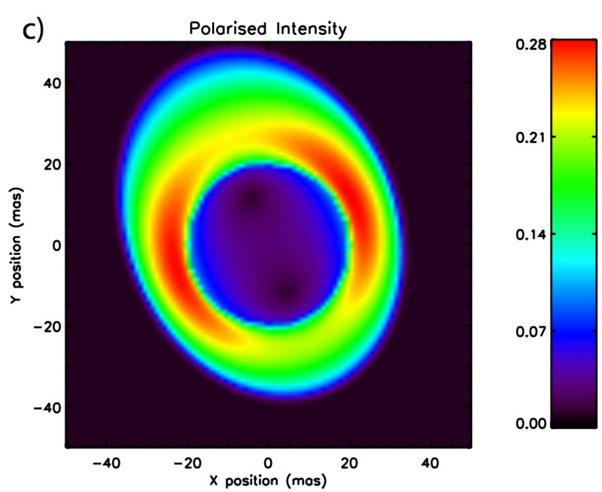
Model-fitting reveals extended, asymmetric dust shell, originating within the outer stellar atmosphere, without a visible cavity. Such low-altitude dust (likely Al_2O_3) important for unexplained extension of RSG atmospheres.

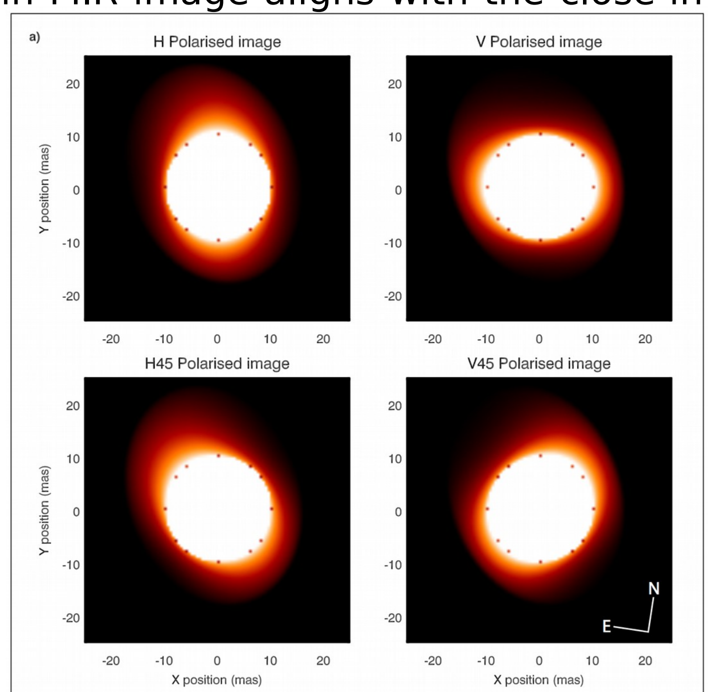
Inner radius: 9.3 ± 0.2 mas (which is roughly R_{star})

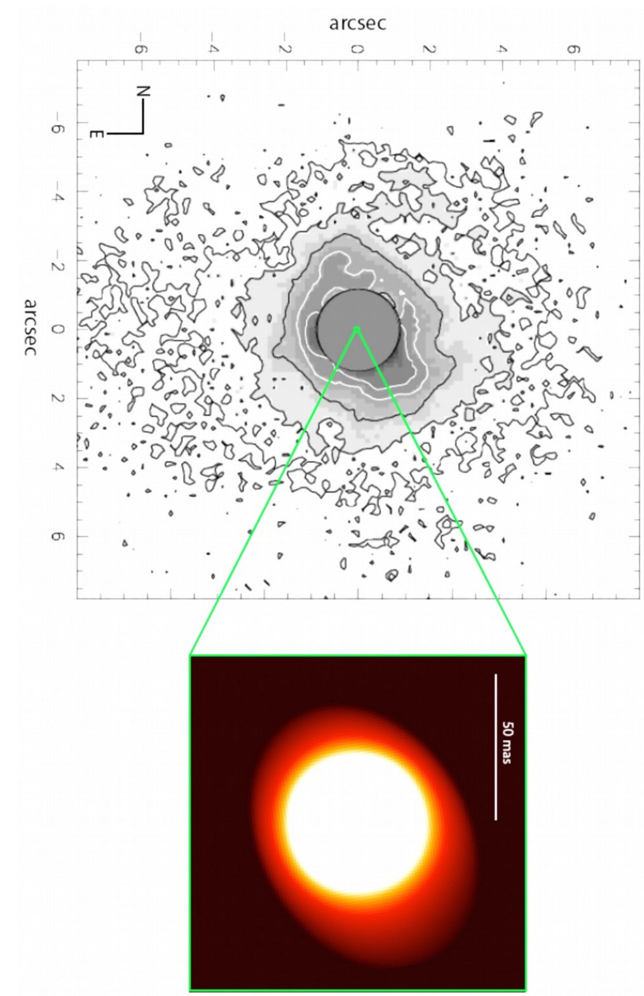
Scattered-light fraction: 0.081 ± 0.002

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

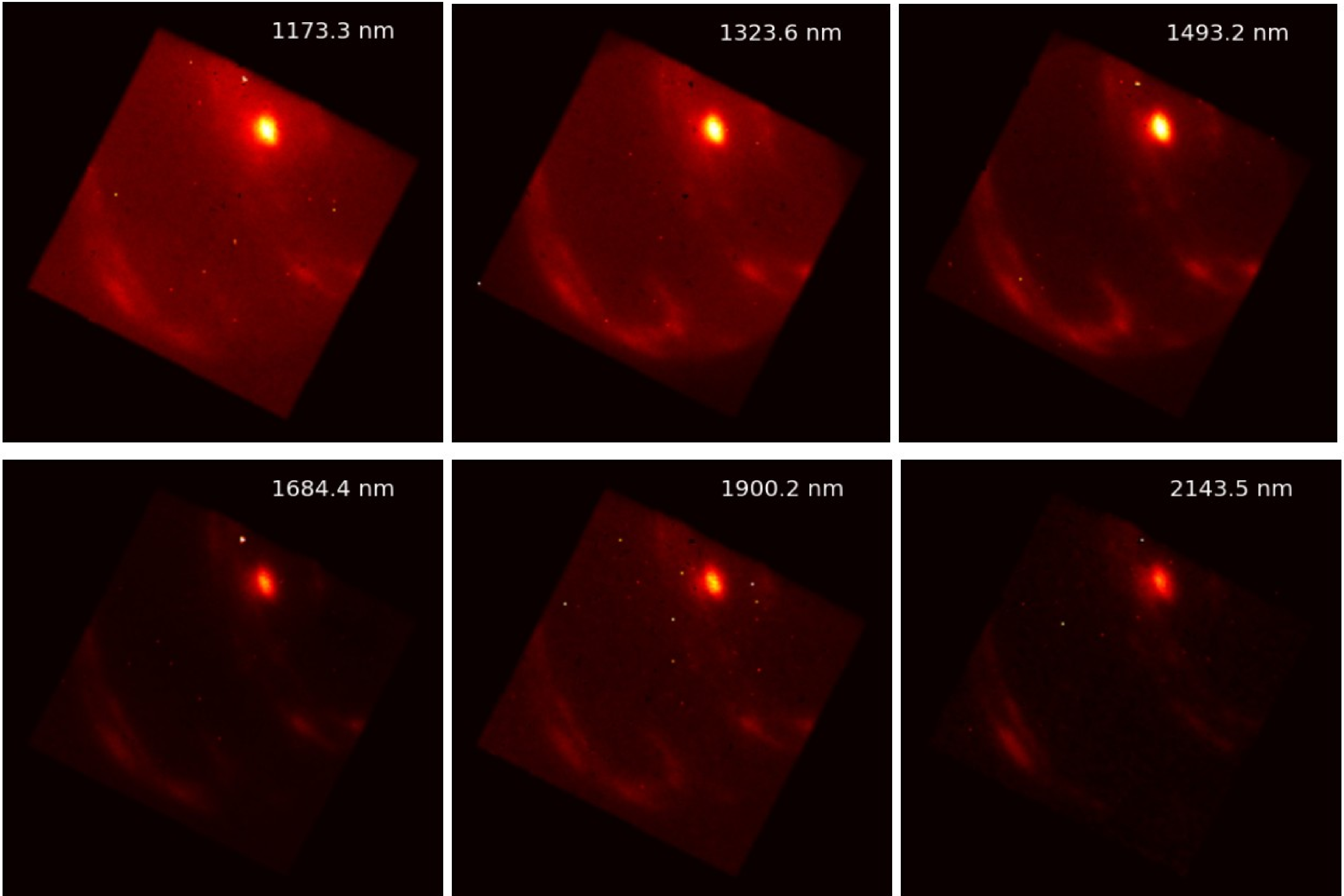
Left: model image, shown in polarized intensity. **Middle:** model image show in four polarisations. **Right:** Model image (intensity), shown with wide field MIR image (from de Wit et al. 2008 – green box shows relative scales. Axis of extension in MIR image aligns with the close-in VAMPIRES image.



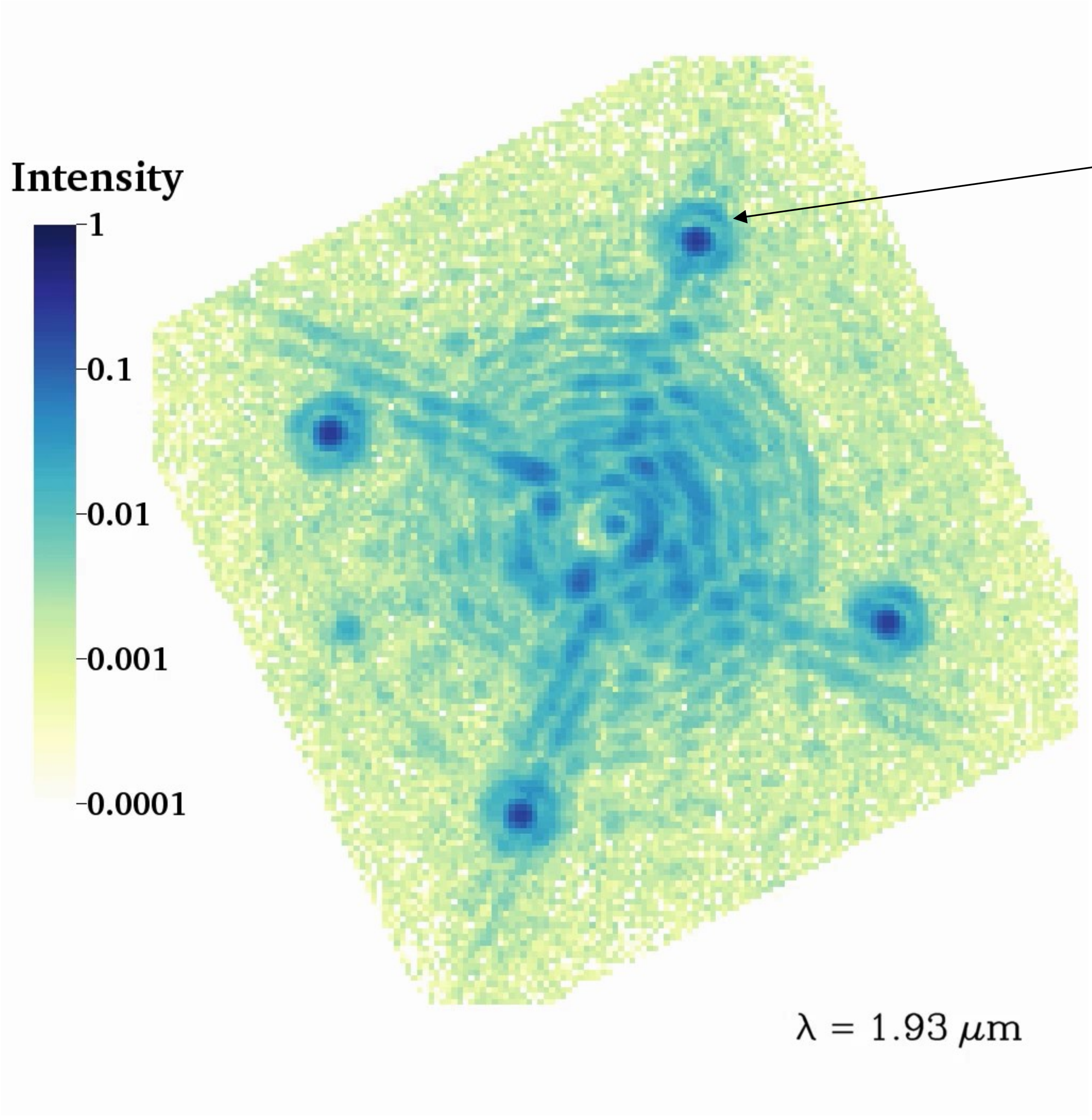




Neptune with CHARIS + SCExAO



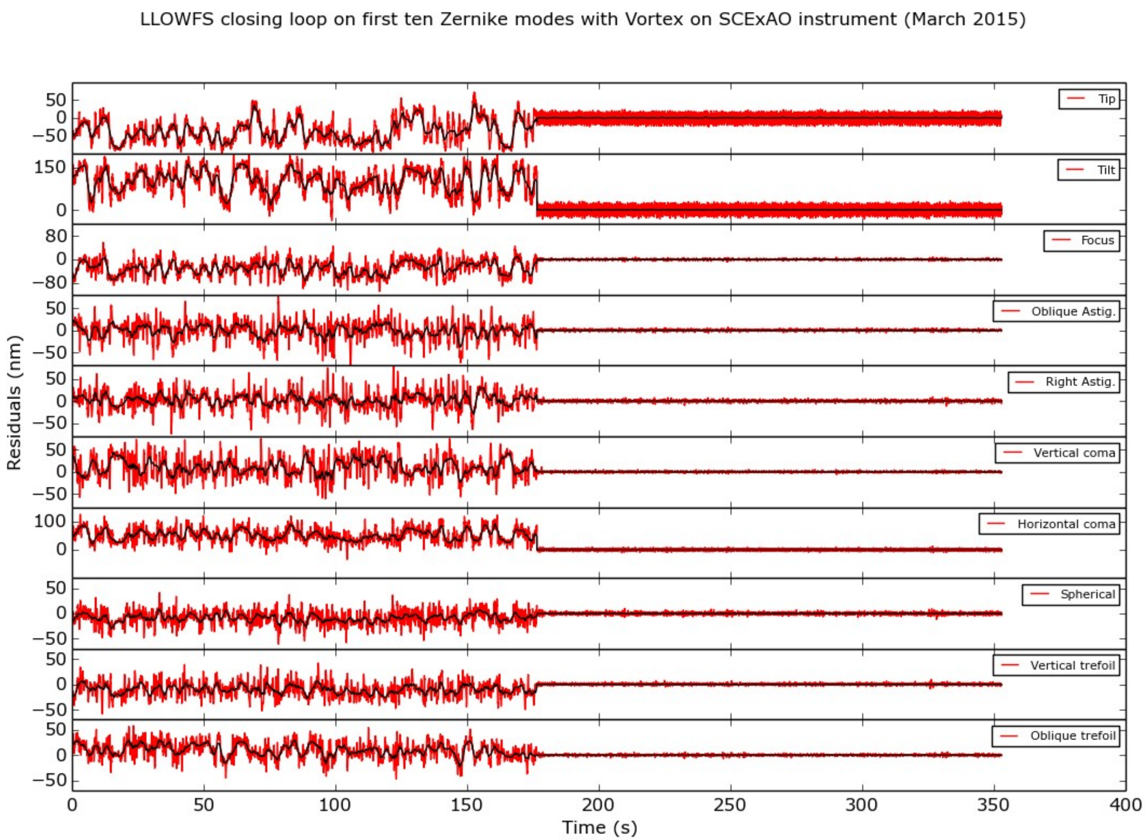
CHARIS data cube @ SCExAO



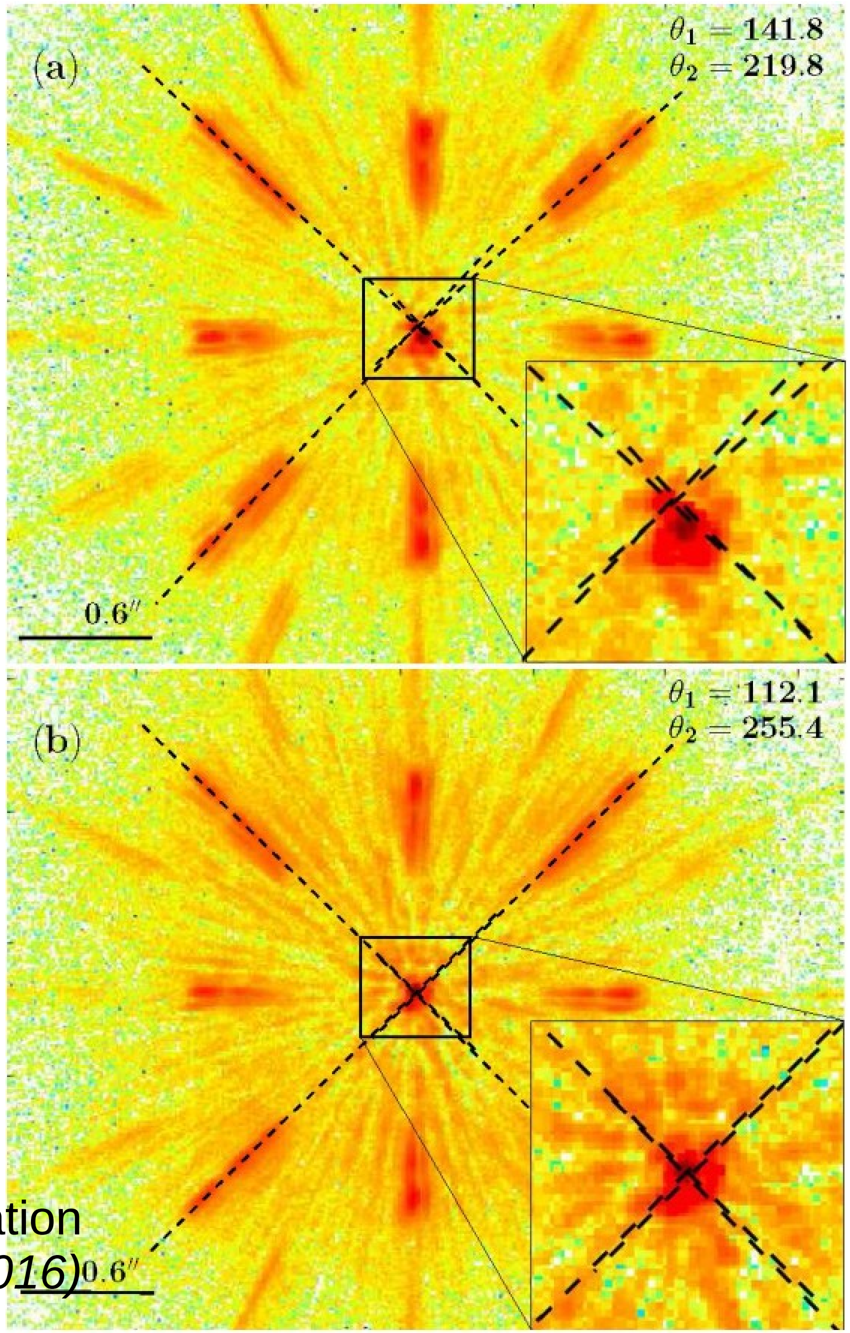
Calibration speckle

Modulated at 3.5kHz for decoherencing

Managing chromaticity



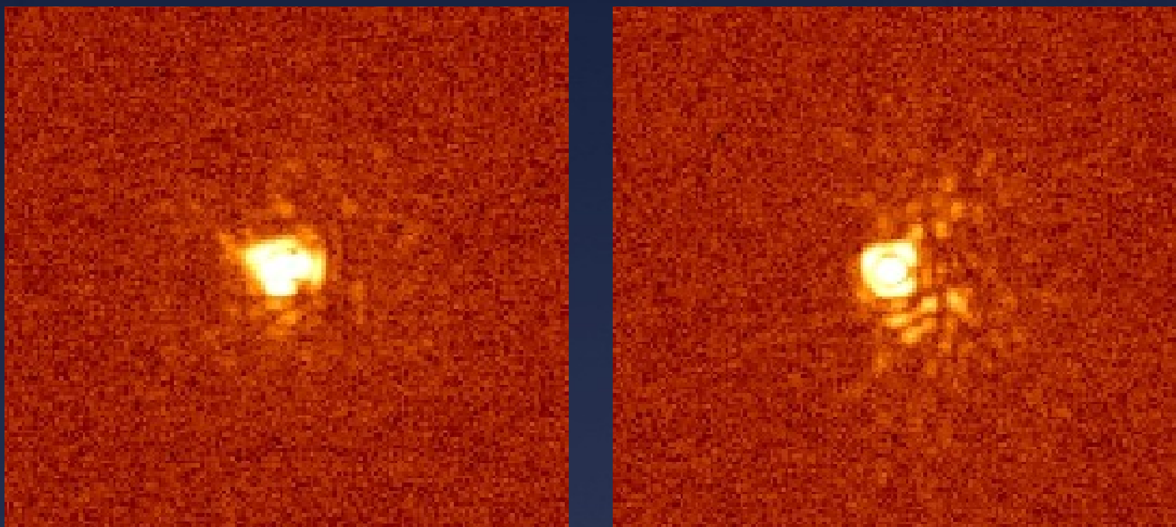
Near-IR low-order coronagraphic WFC
(Singh et al. 2015)

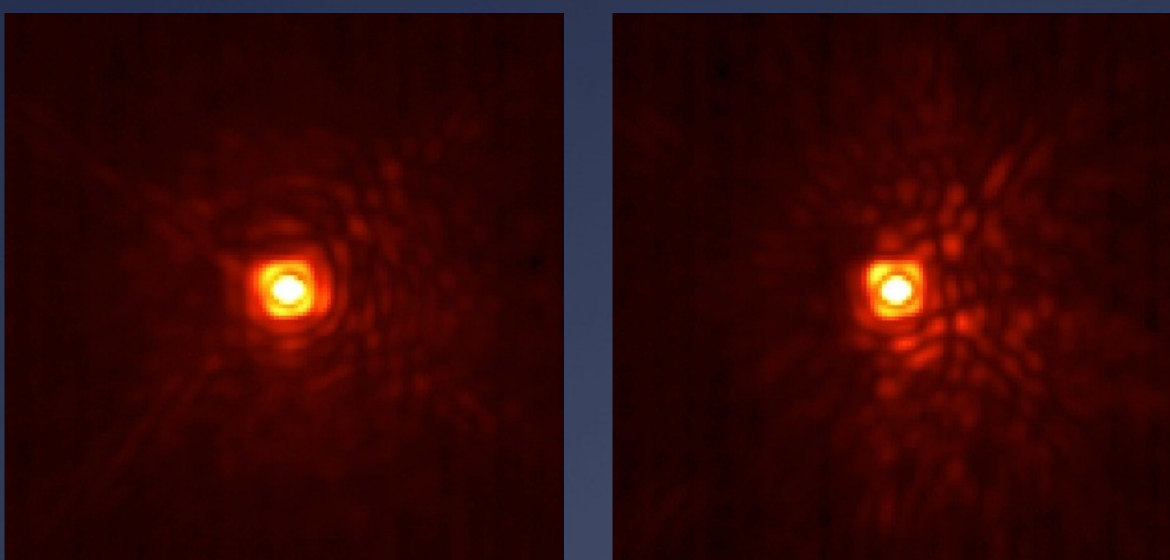


Closed loop atmospheric dispersion compensation
(Pathak et al. 2016)

speckle nulling results on-sky (June 2014)

Single frames: 50 us

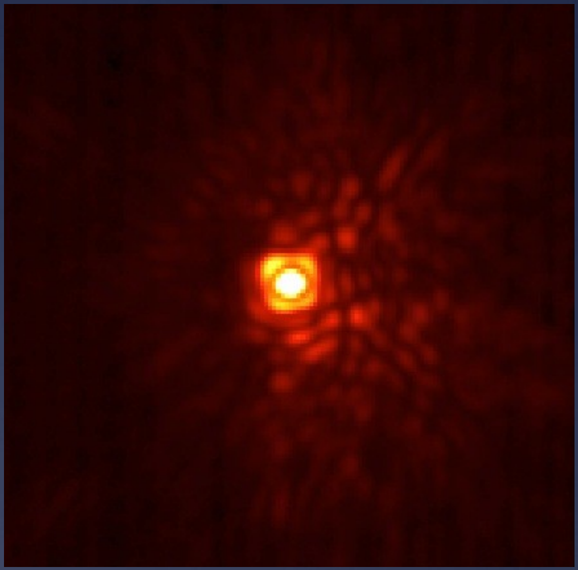




Sum of 5000 frames: shift and add

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)

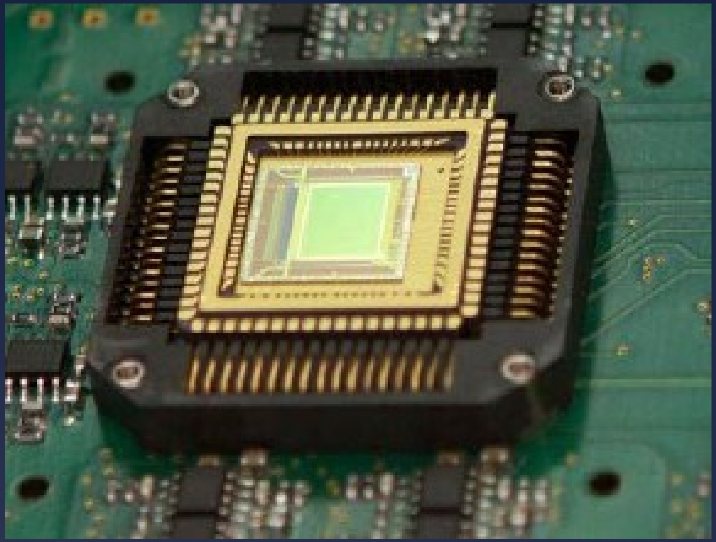


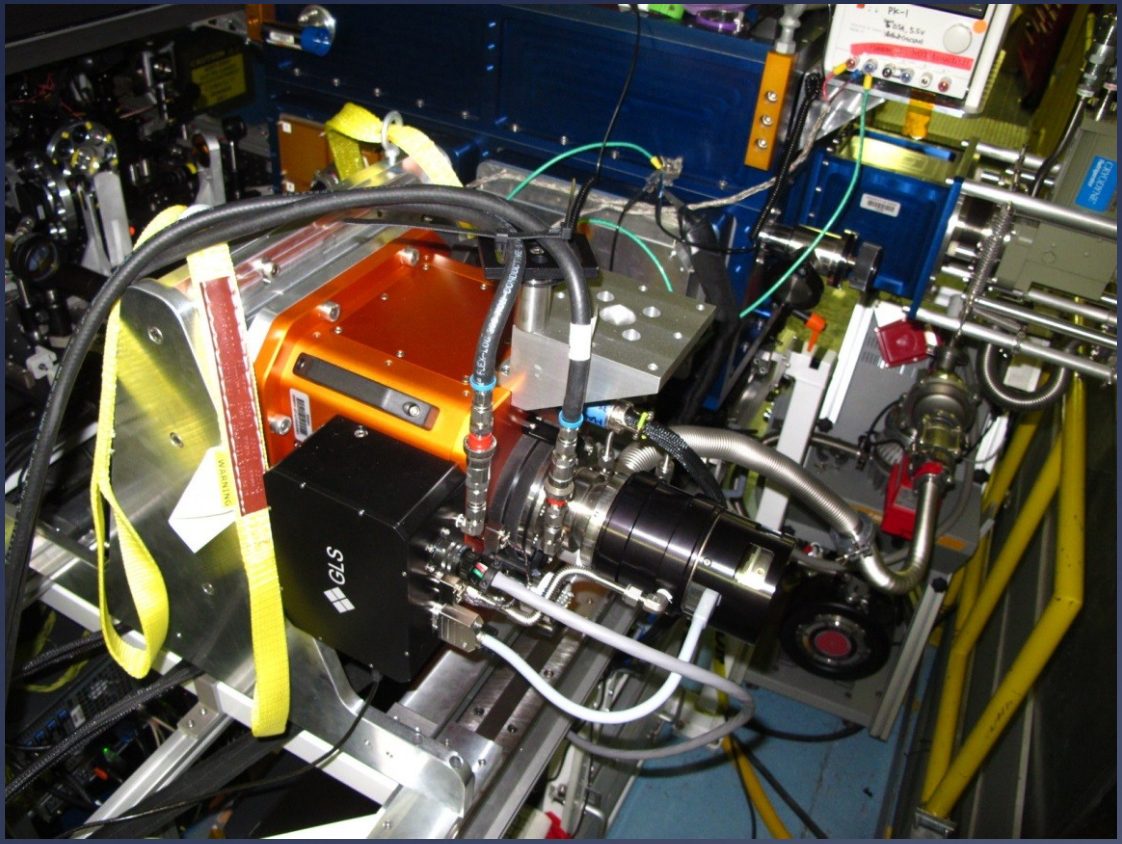
Martinache. et. al.

SAPHIRA Infrared APD array

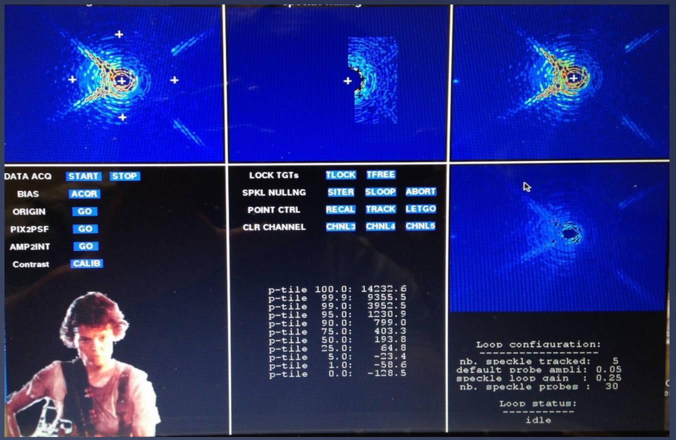
HgCdTe avalanche photodiode
manufactured by Selex

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



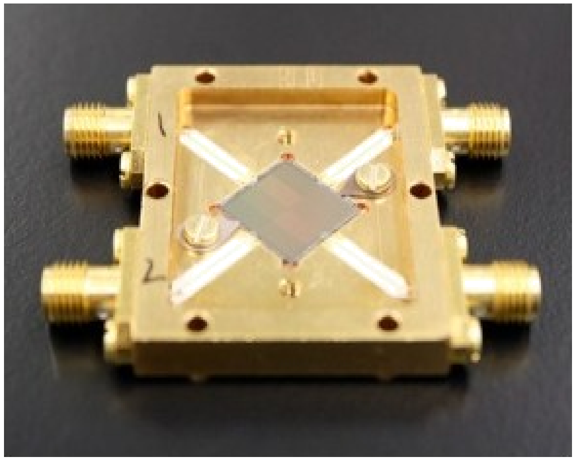


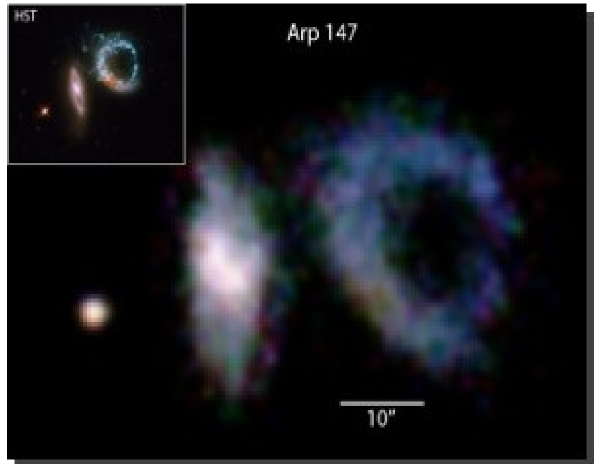
50 frame average

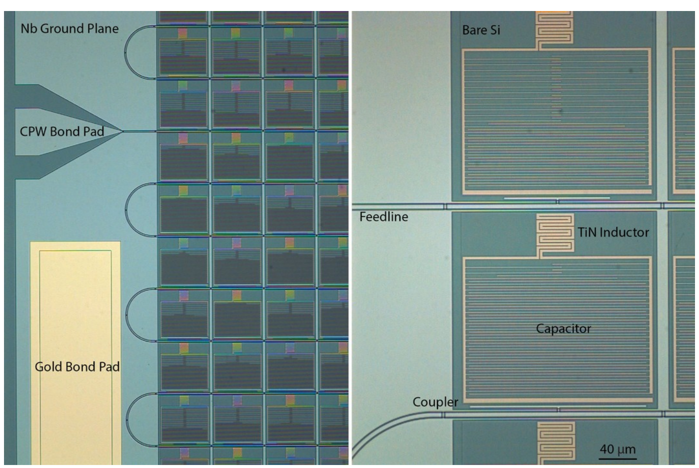


MKIDS camera (built by UCSB for SCExAO)

Photon-counting, wavelength resolving 100x200 pixel camera





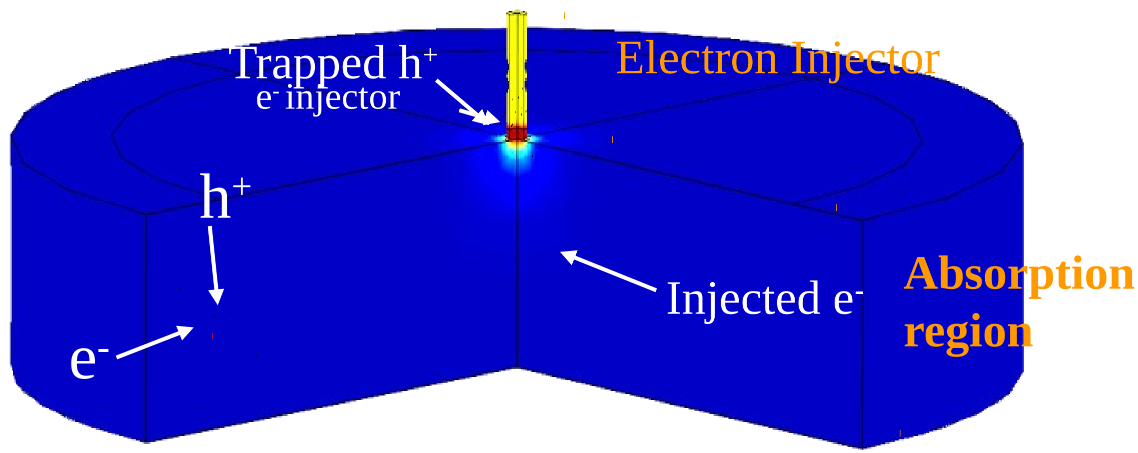


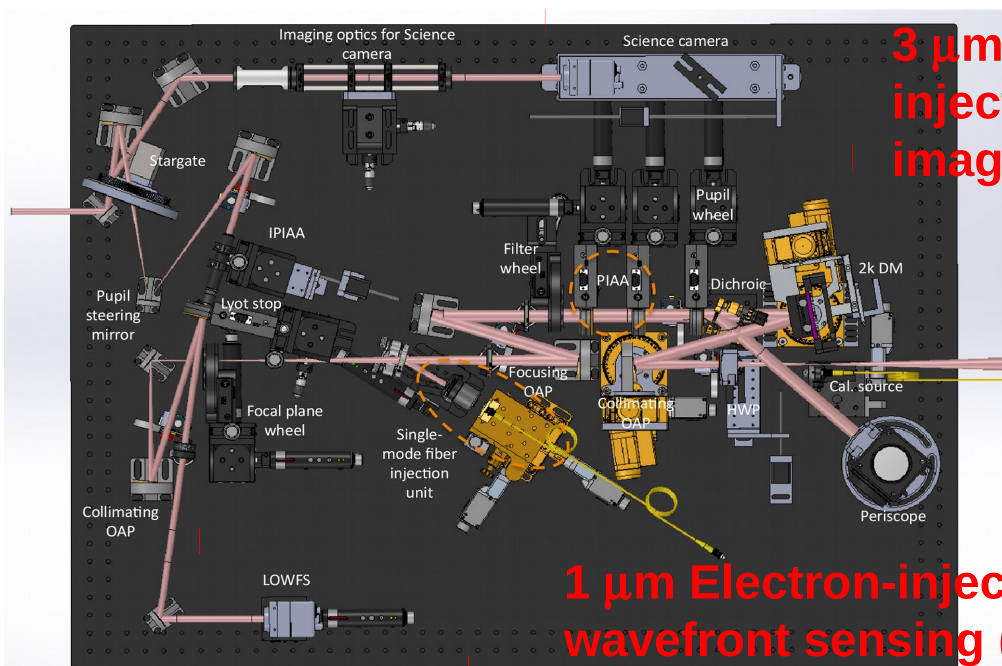
Pixels are microwave resonators at ~100mK
photon hits → resonator frequency changes

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)

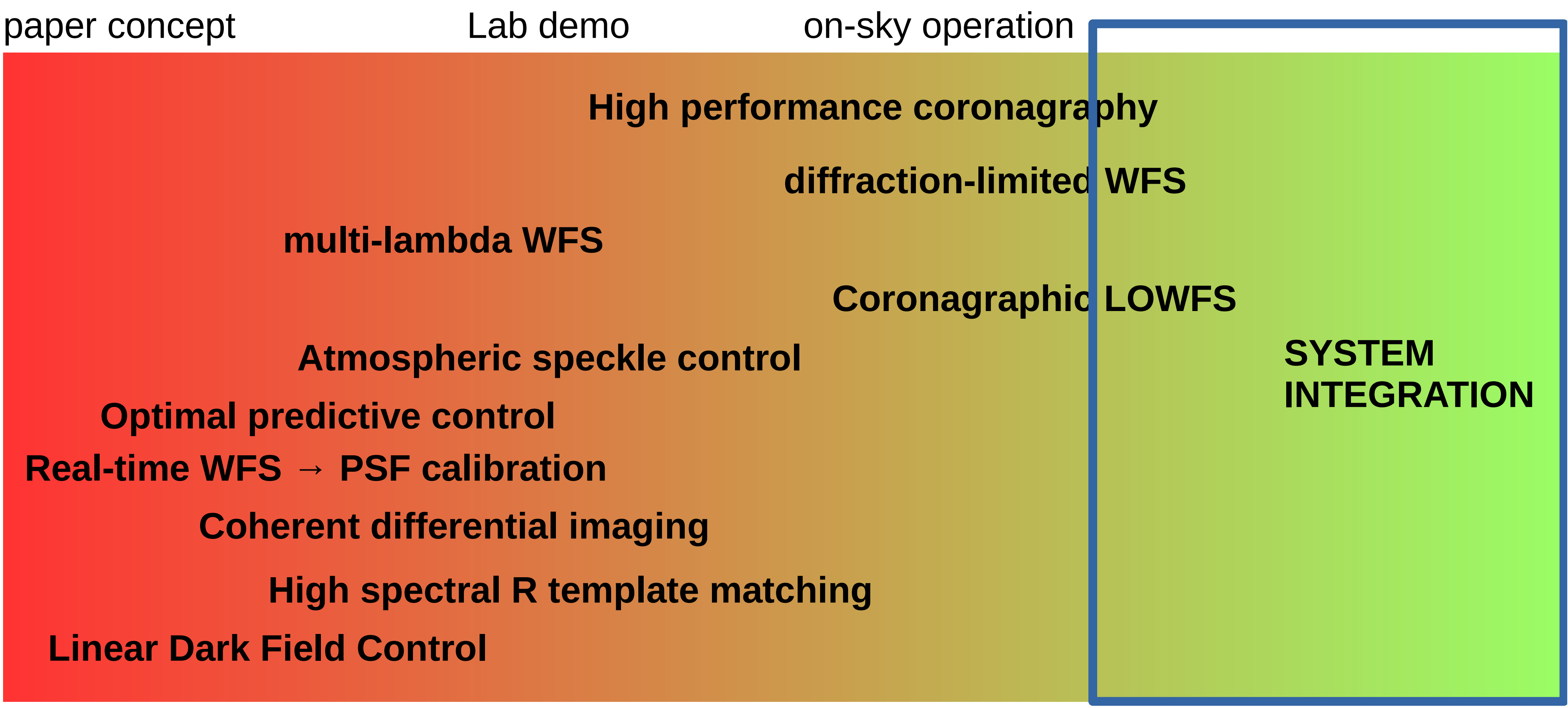




3 µm Electron-injection speckle imaging camera

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

Key technologies are rapidly advancing from paper concepts to system integration



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