Direct Imaging with Ground-Based Telescopes

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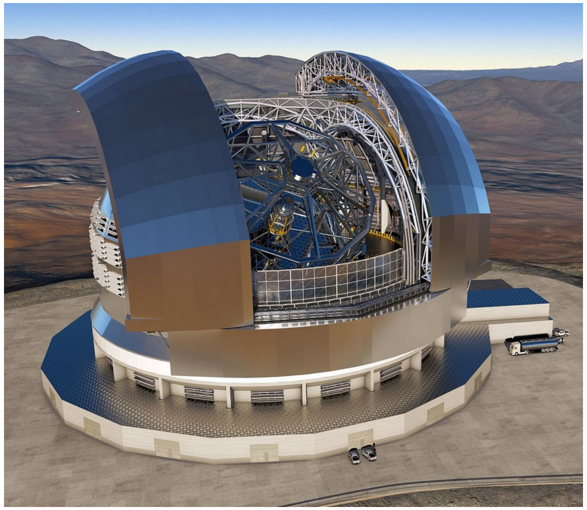
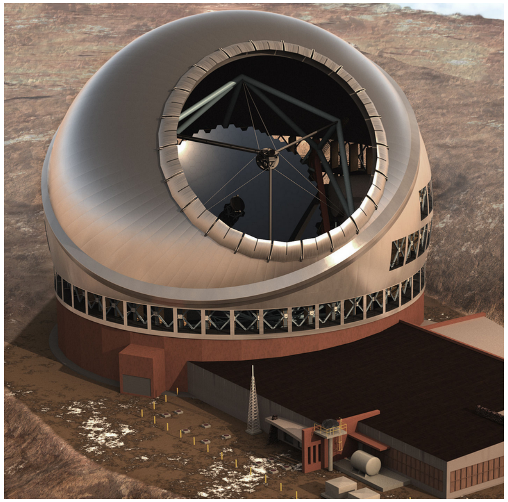
Breakthrough Watch committee chair





Mar 7, 2018

Outline

Direct imaging measurements fundamentals
- Brief introduction
- Planetary formation / disks
- Exoplanetary systems
- Exoplanet spectroscopy

Exoplanet Imaging / Detection with ELTs

Habitable planets imaging & biosignatures detection with ELTs
- Thermal emission
- Reflected light

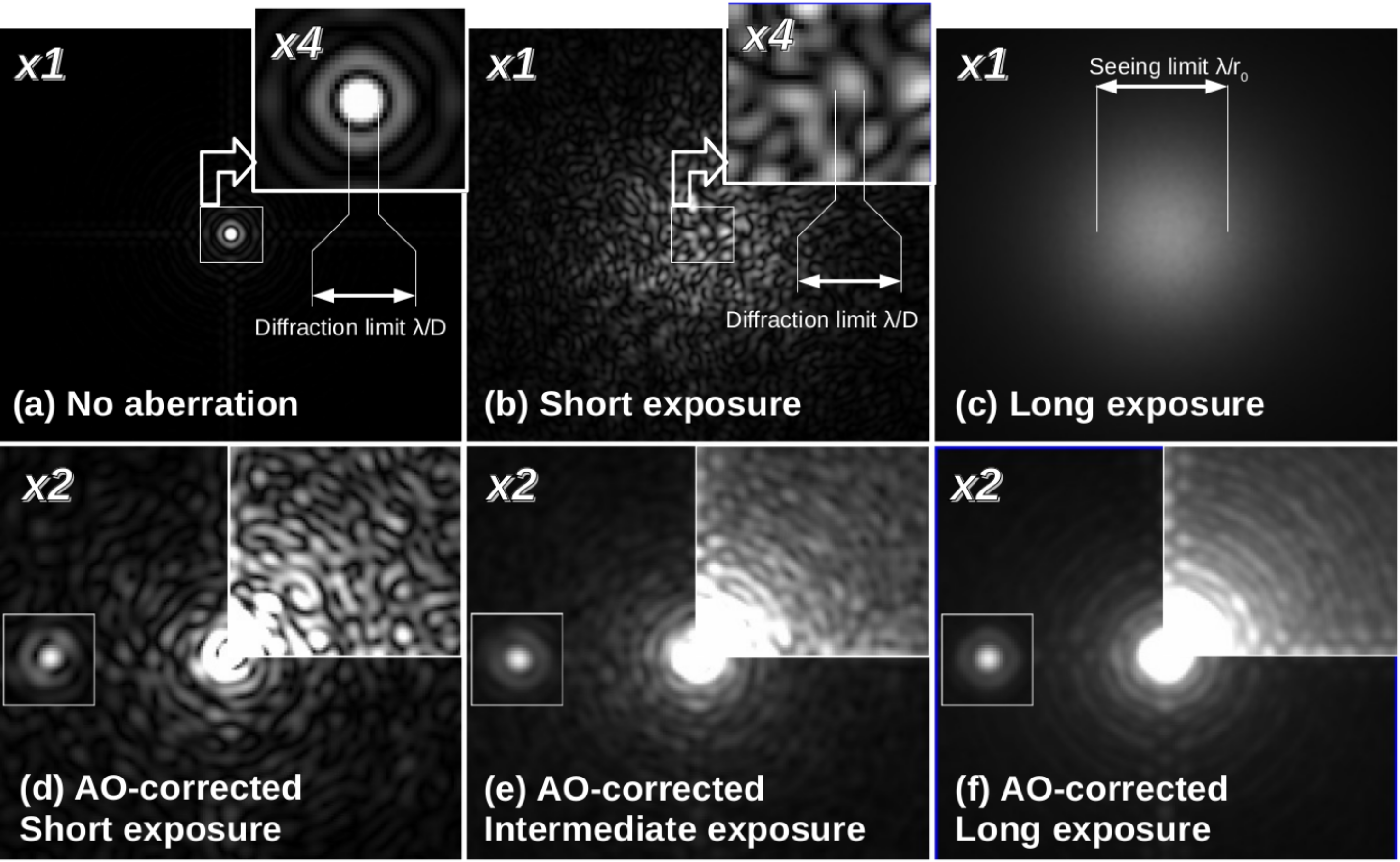
Technology & expected performance
- Coronagraphy
- Wavefront control

Planning future instruments
- From 10m-class telescopes to 30m-class telescopes
- ELT, TMT and GMT plans

Direct imaging measurements fundamentals

- **Brief introduction**
- **Planetary formation / disks**
- **Exoplanetary systems**
- **Exoplanet spectroscopy**

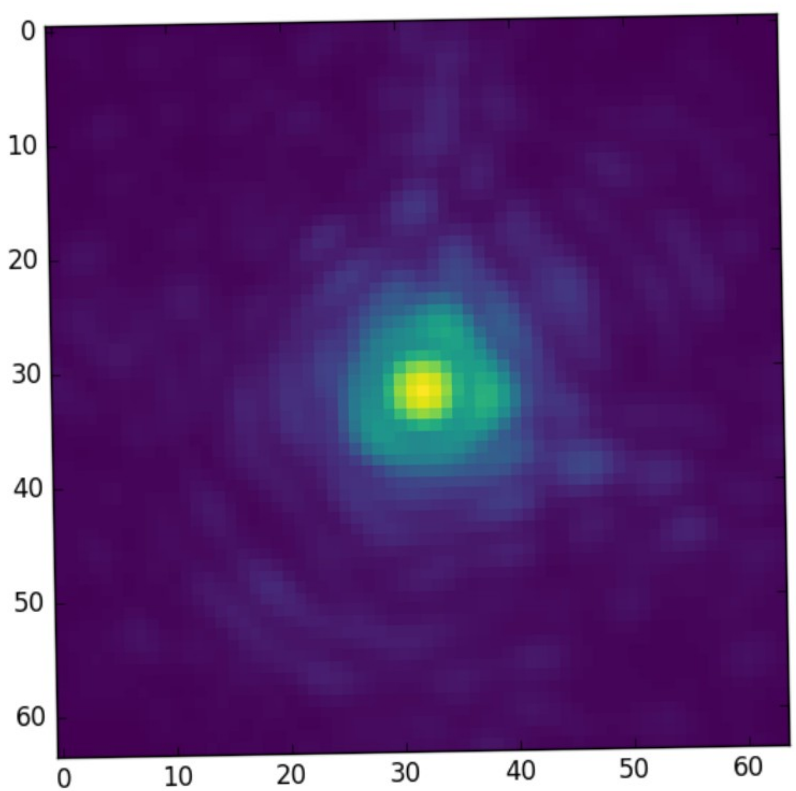
Adaptive Optics Correction of Atmospheric Turbulence



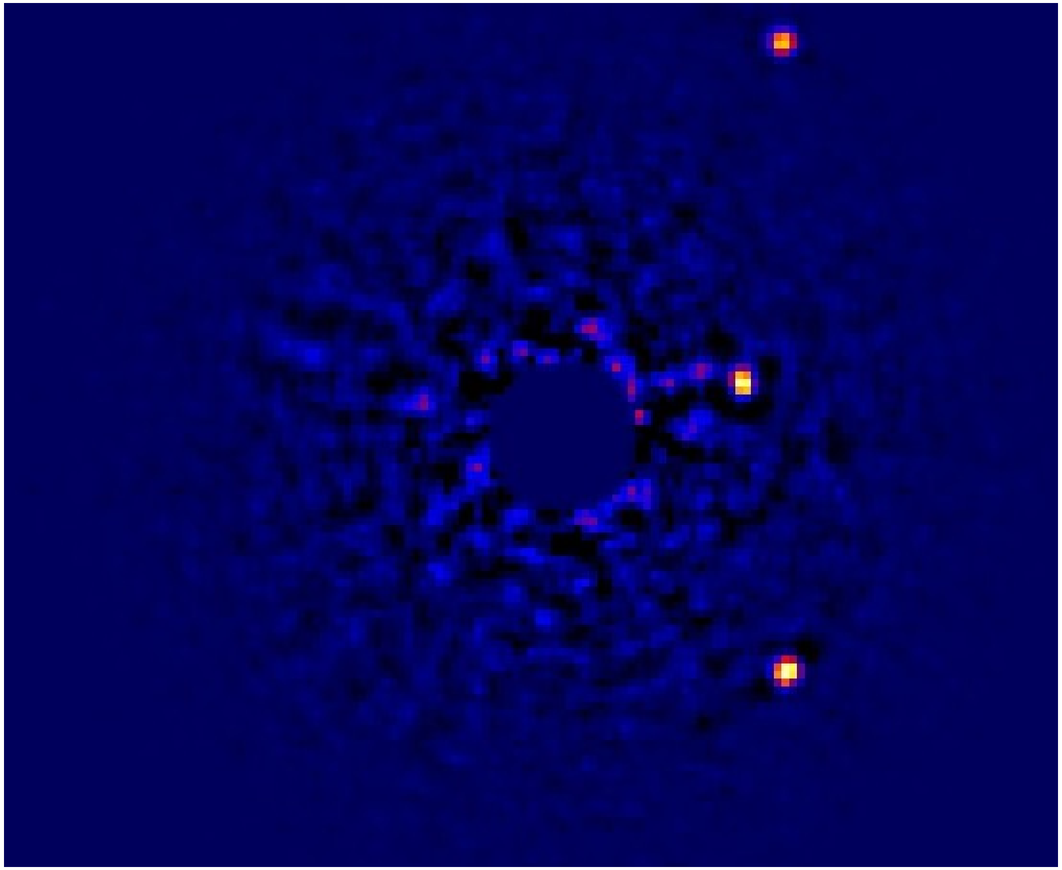
The REAL challenge: Wavefront error (speckles)

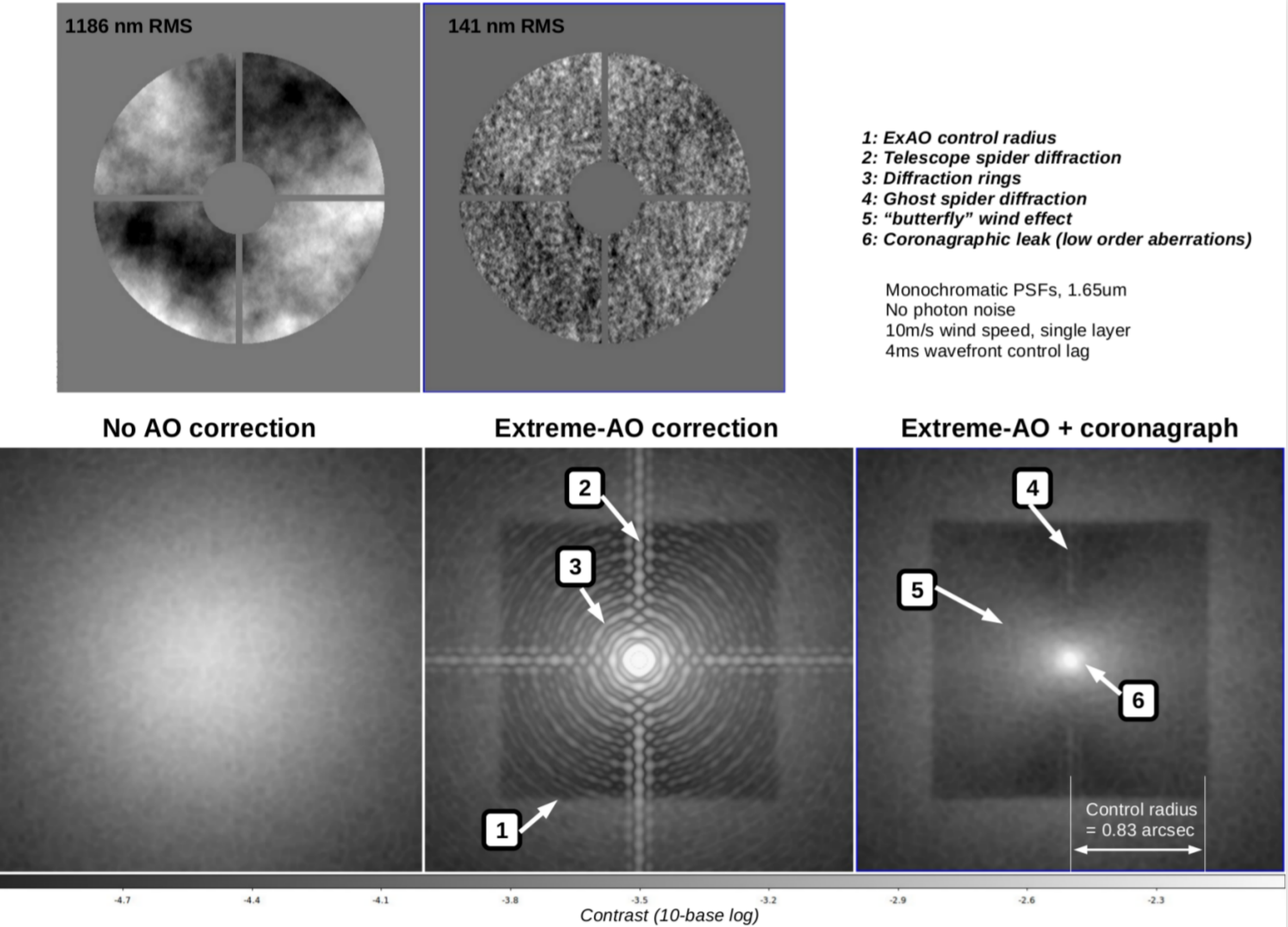
SCExAO: 1200 modes corrected at 3 kHz

Visible (750nm)
Subaru/SCExAO/VAMPIRES

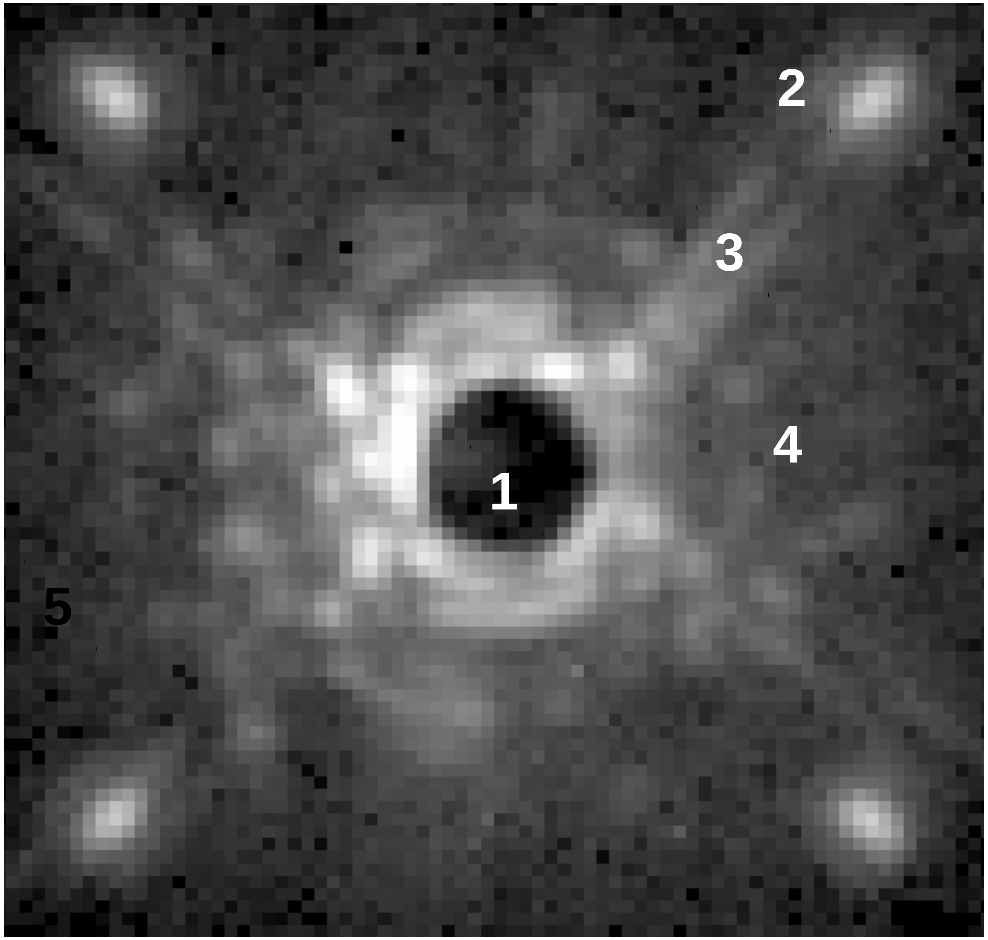


NearIR high contrast image
Subaru/AO188/HiCIAO

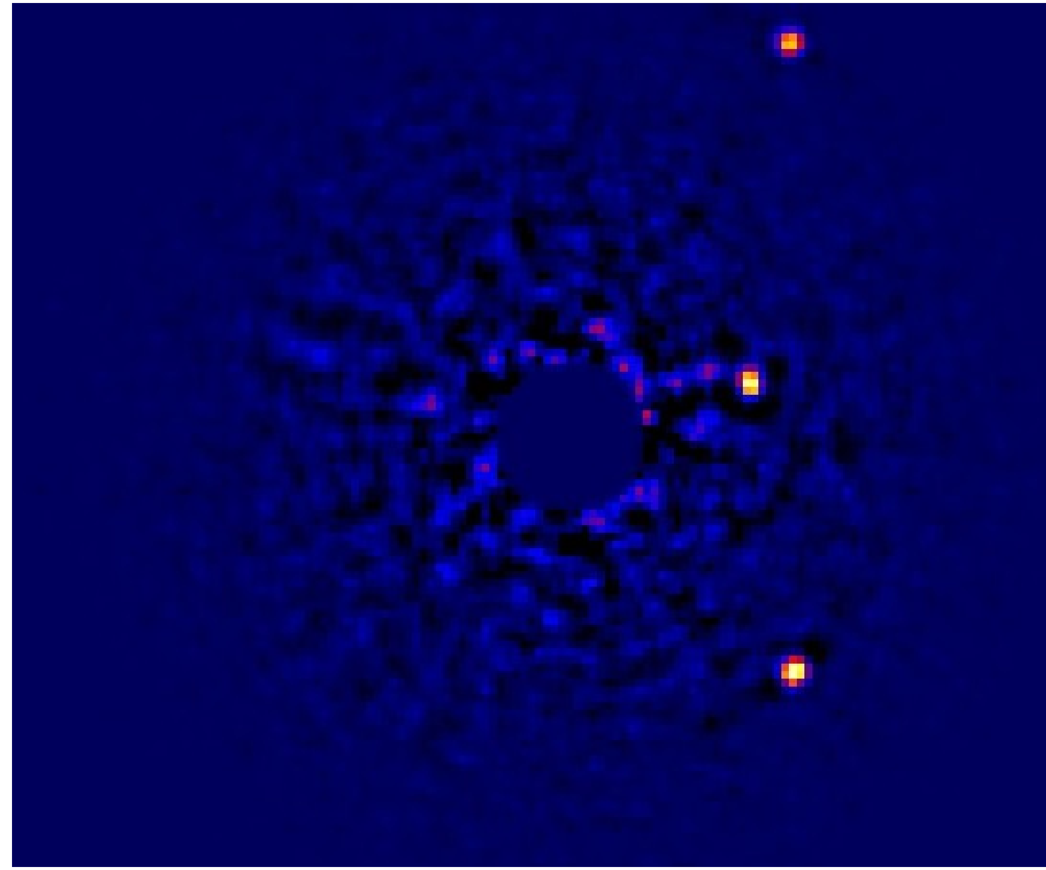



1186 nm RMS
141 nm RMS
1: ExAO control radius
2: Telescope spider diffraction
3: Diffraction rings
4: Ghost spider diffraction
5: "butterfly" wind effect
6: Coronagraphic leak (low order aberrations)
Monochromatic PSFs, 1.65um
No photon noise
10m/s wind speed, single layer
4ms wavefront control lag
No 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)

RAW image

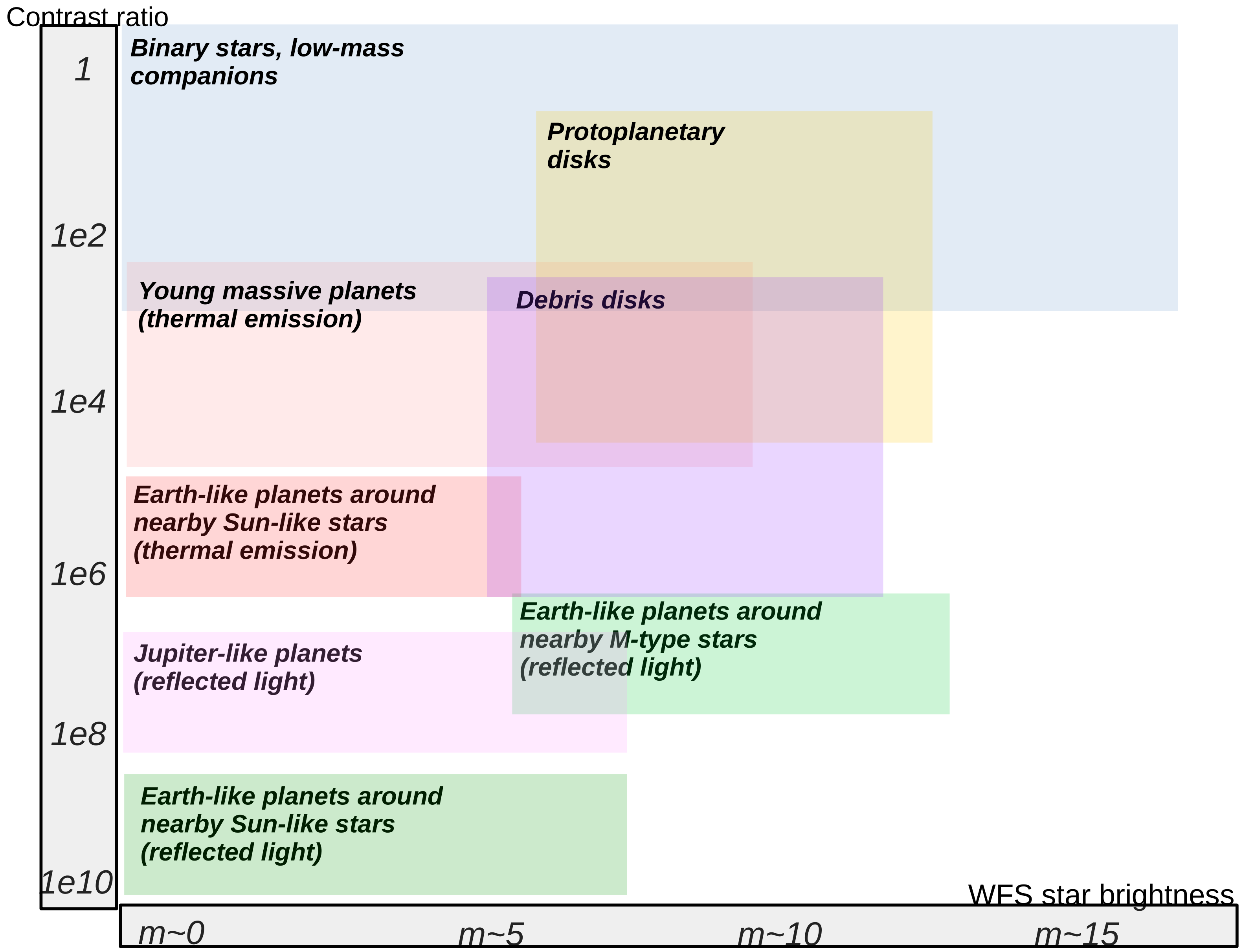


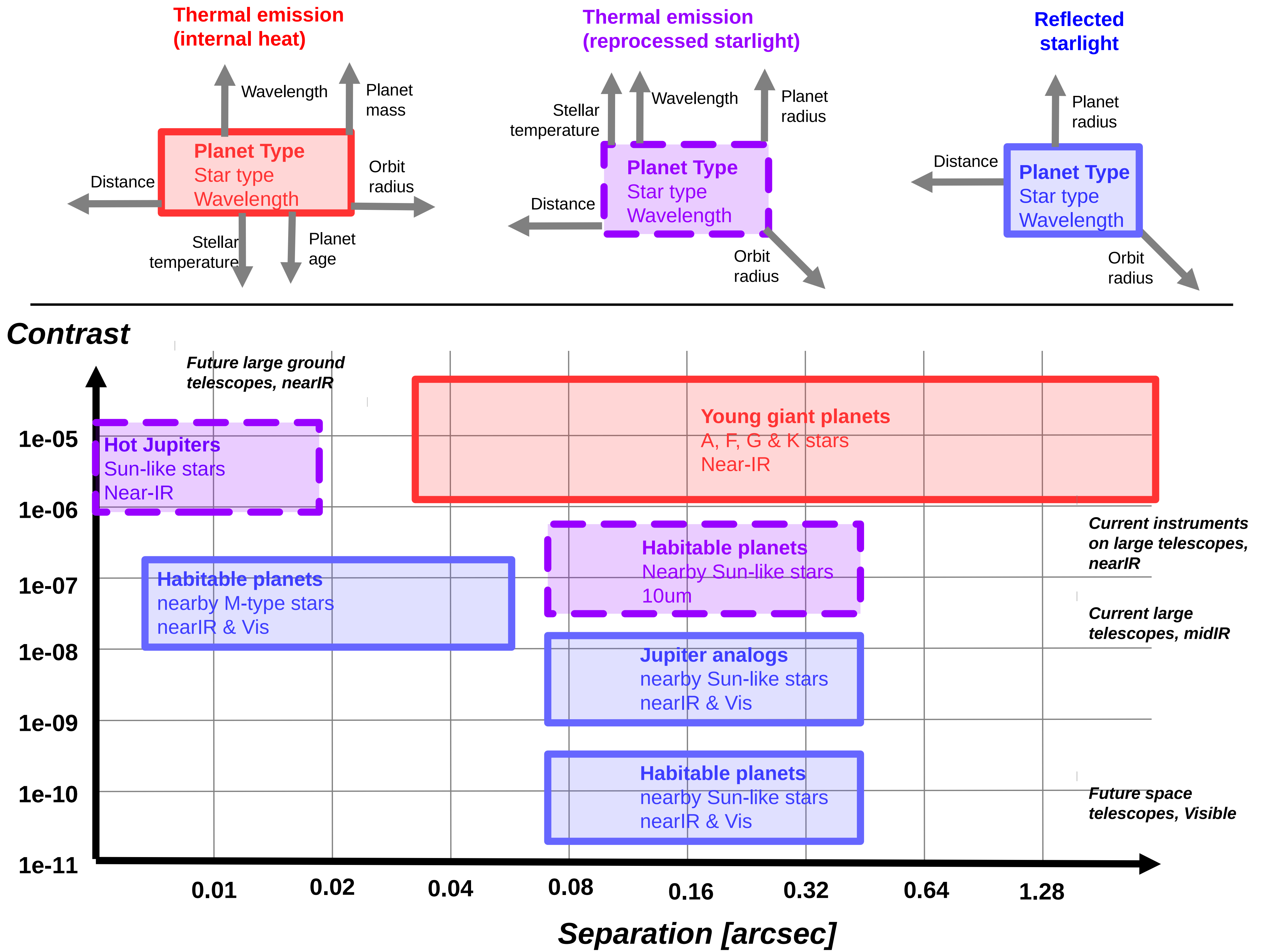
PROCESSED image



1: Coronagraph Focal plane mask
2: Calibration Speckles (astrometry and photometry)
3: Residual diffraction
4: Speckle Noise
5: Photon and Readout noise

Detection noise dominated by :
- residual speckle noise
- photon noise
- readout noise


Contrast ratio
1
1e2
1e4
1e6
1e8
1e10
Binary stars, low-mass companions
Protoplanetary disks
Young massive planets (thermal emission)
Debris disks
Earth-like planets around nearby Sun-like stars (thermal emission)
Earth-like planets around nearby M-type stars (reflected light)
Jupiter-like planets (reflected light)
Earth-like planets around nearby Sun-like stars (reflected light)
WFS star brightness
m~0
m~5
m~10
m~15



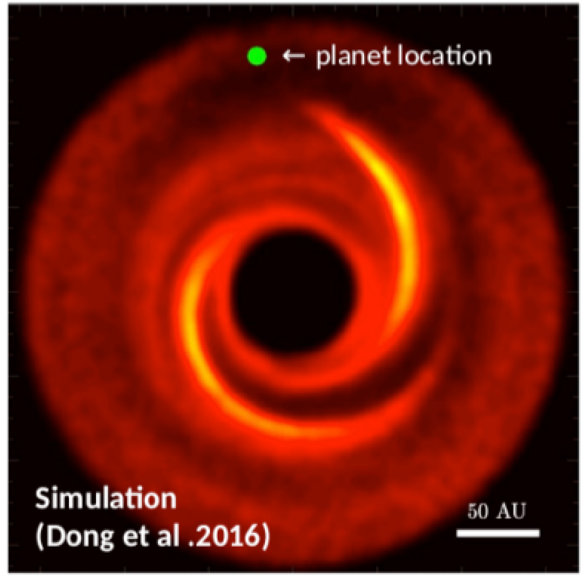
Thermal emission
(internal heat)
Wavelength
Planet mass
Planet Type
Star type
Wavelength
Distance
Orbit radius
Stellar temperature
Planet age
Thermal emission
(reprocessed starlight)
Stellar temperature
Wavelength
Planet radius
Planet Type
Star type
Wavelength
Distance
Orbit radius
Reflected starlight
Planet radius
Distance
Planet Type
Star type
Wavelength
Orbit radius
Contrast
Future large ground telescopes, nearIR
Young giant planets
A, F, G & K stars
Near-IR
Hot Jupiters
Sun-like stars
Near-IR
Current instruments on large telescopes, nearIR
Habitable planets
Nearby Sun-like stars
10um
Habitable planets
nearby M-type stars
nearIR & Vis
Current large telescopes, midIR
Jupiter analogs
nearby Sun-like stars
nearIR & Vis
Habitable planets
nearby Sun-like stars
nearIR & Vis
Future space telescopes, Visible
1e-05
1e-06
1e-07
1e-08
1e-09
1e-10
1e-11
0.01
0.02
0.04
0.08
0.16
0.32
0.64
1.28
Separation [arcsec]

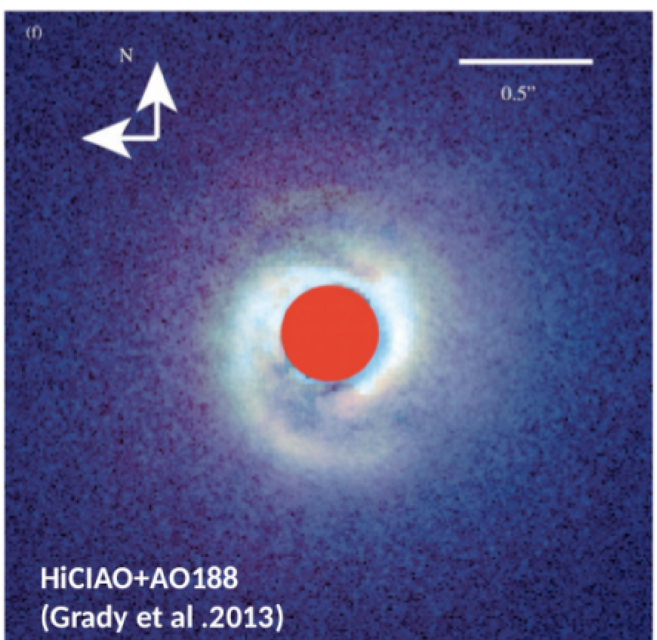
Disk Imaging

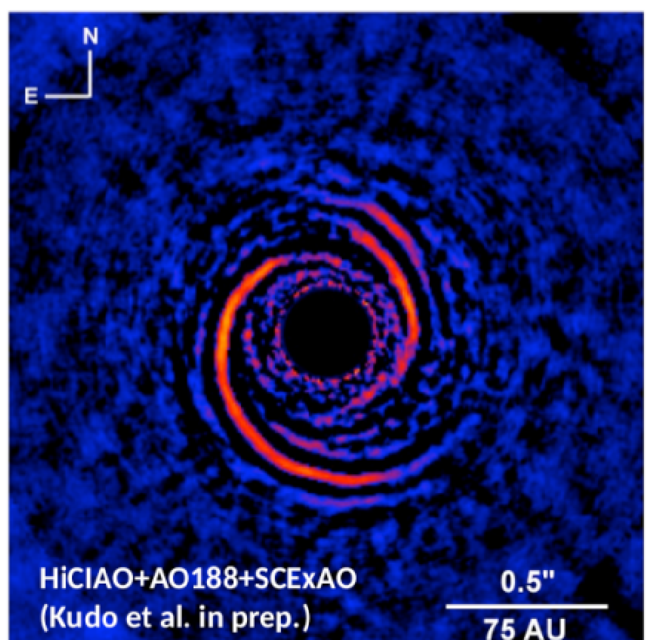
Figure 2: MWC 758 disk

Top right: Disk model and predicted planet position to produce spiral arms.
Bottom left: Near-IR image without exAO.
Bottom right: H-band image with SCExAO. The image quality is greatly improved.

High speed polarimetric imaging without coronagraph and saturation will map innermost disk and constrain location & mass of forming planets.





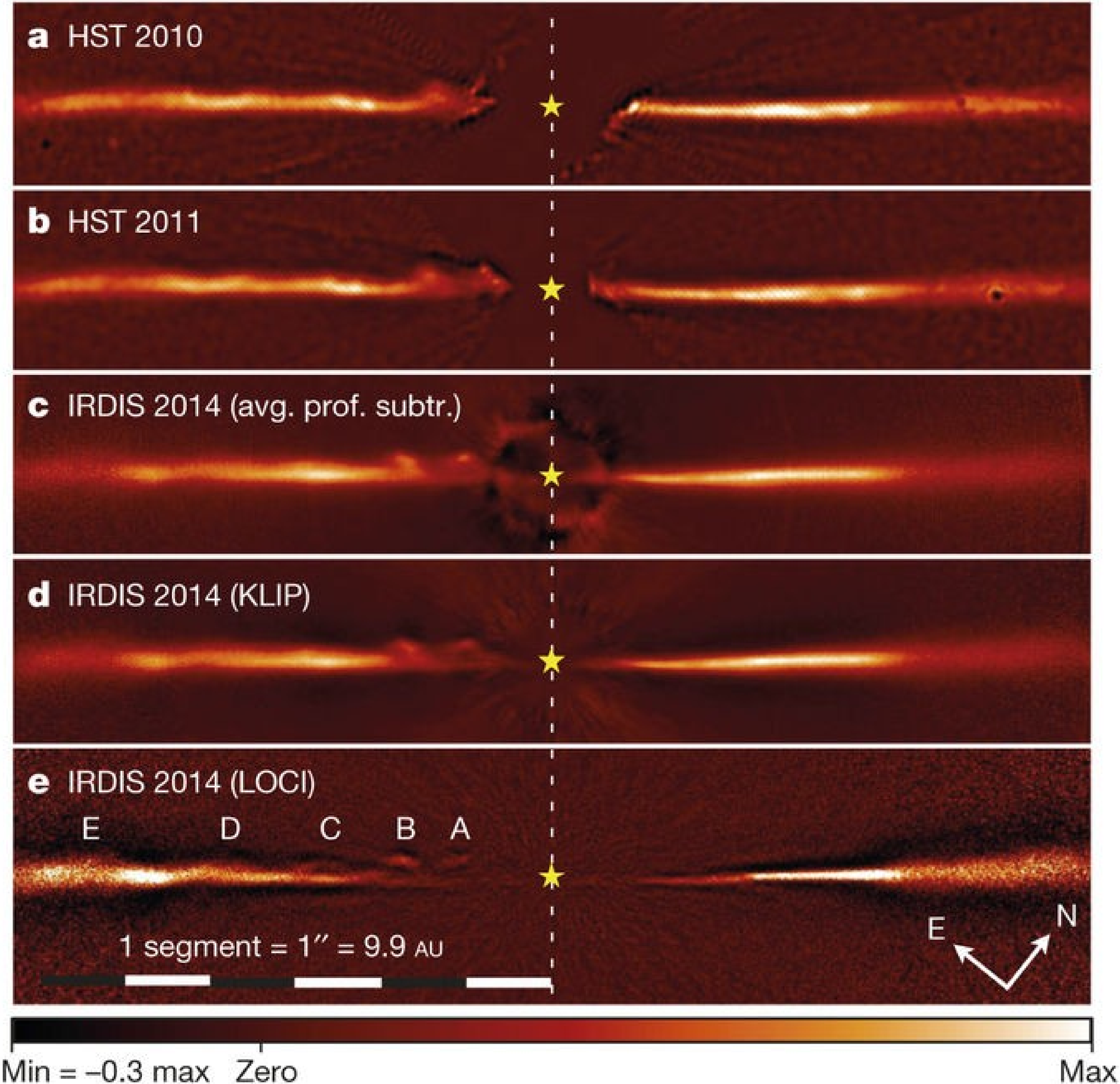


Planet formation and early evolution

Disks shaped by planets' gravity (gaps, spiral arms)

Debris disks composition

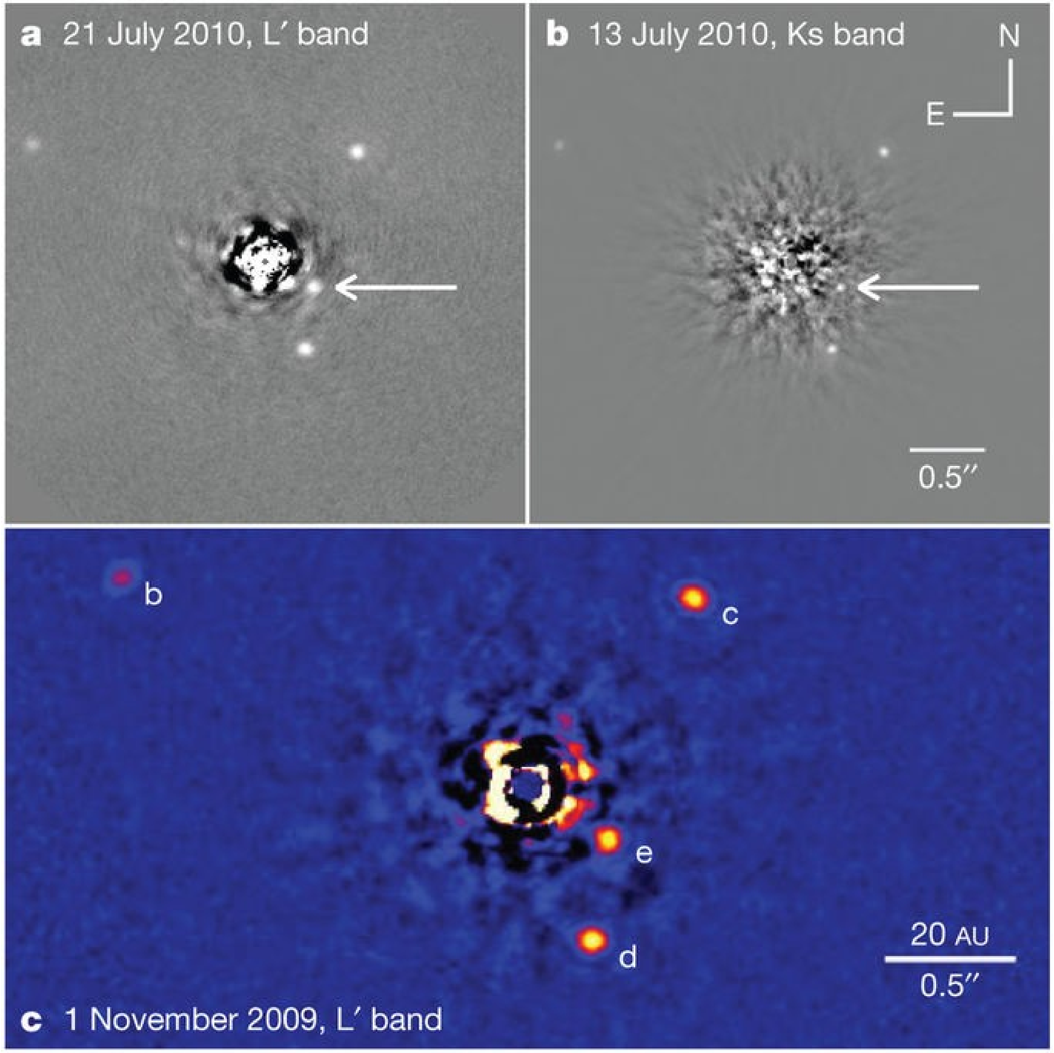
Debris disks replenished by asteroid collisions



Fast-moving disk features around AU Mic

(Boccaleti et al. 2015)

Measurements: Astrometry & Photometry



Astrometry

Multi-planet systems:
Orbits and masses constrained by dynamical stability requirements

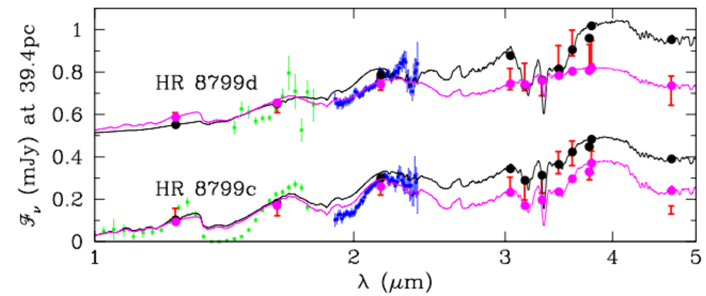
Spectro-astrometry: Moons

Photometry

Multi-band
→ bulk properties (temperature, size)

Variability
→ Clouds, rotation period
→ Moons (transit) & Rings

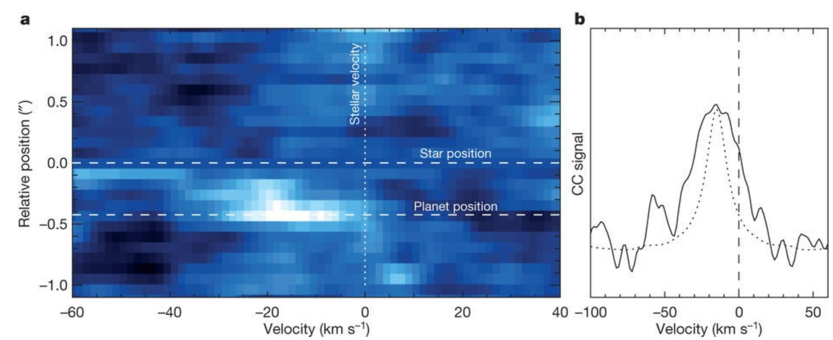
Measurements: Spectroscopy



Ingraham et al. 2014

Absorption lines → chemistry
Can be observed with Thermal emission / Reflected light / Transit spectroscopy

Model-fitting → temperature, composition, gravity

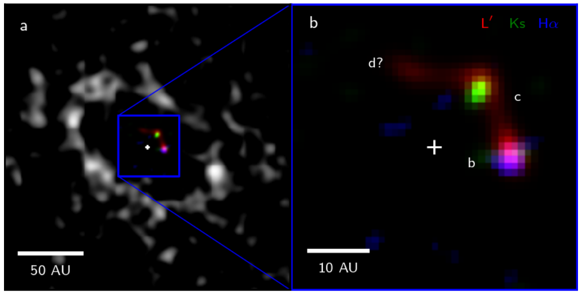


Snellen et al. 2014

Dynamics (High res)
Planet rotation (beta pic spin: Snellen et al 2014)
Orbits
Winds

Emission lines (Accretion Halpha, Aurorae)

- Halpha accretion (LkCa 15, Sallum et al. 2015)
- Prox Cen b Oxygen emission could be imaged with ELT in ~day exposure time (Luger et al. 2017)
- 819nm circular polarized emission on M8.5 star (Berdyugina et al. 2017)



Sallum et al. 2015

Measurements: Spectroscopy

Direct imaging spectroscopy complementarity with transit spectroscopy

- Transit spectroscopy samples higher atmosphere layers
- Different planets. **Direct imaging strongly favors nearest systems**
- **Direct imaging fundamentally more sensitive** IF exoplanet orbit resolved, and contrast >~ 1e4
- **Direct imaging performance scales strongly with telescope diameter**, transit spectroscopy performance scales slowly

Example: Earth-like planet around M-type star

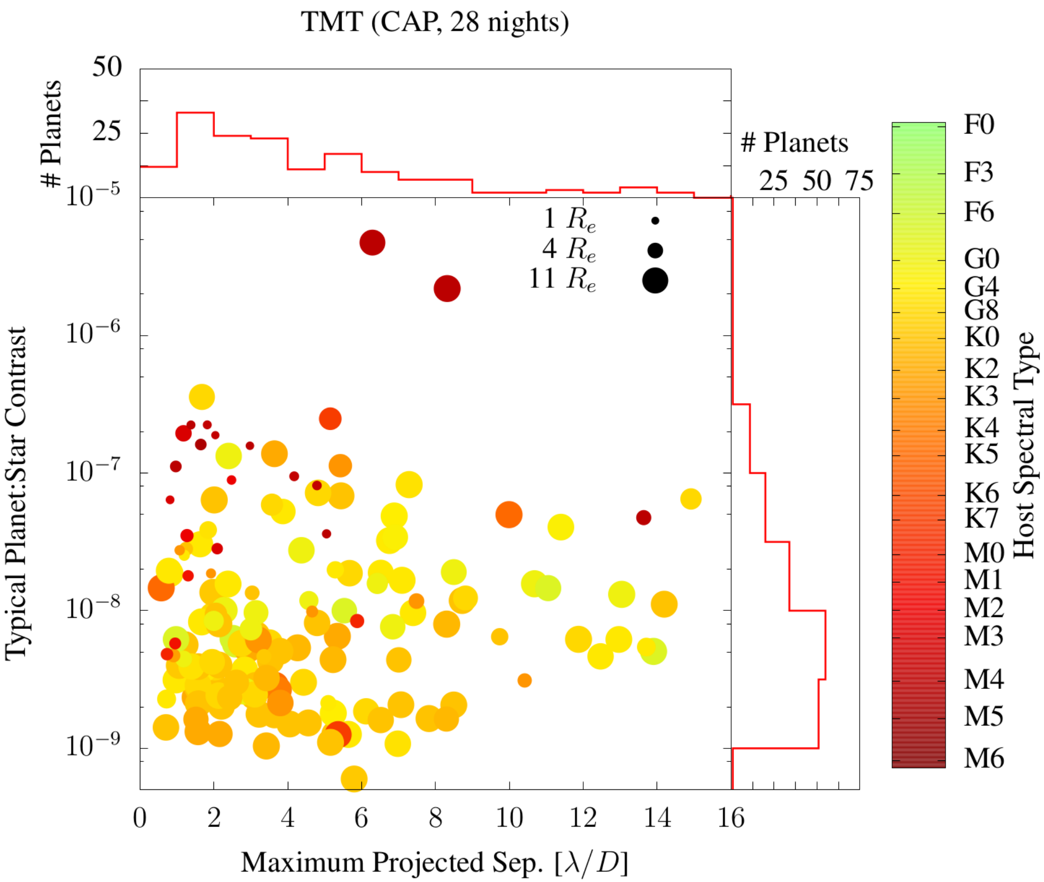
Transit spectroscopy signal is ~100x stronger than Reflected light spectroscopy, scales as D^2
… but photon noise is much higher (instrument contrast = 1), scales as D
→ SNR ~ D

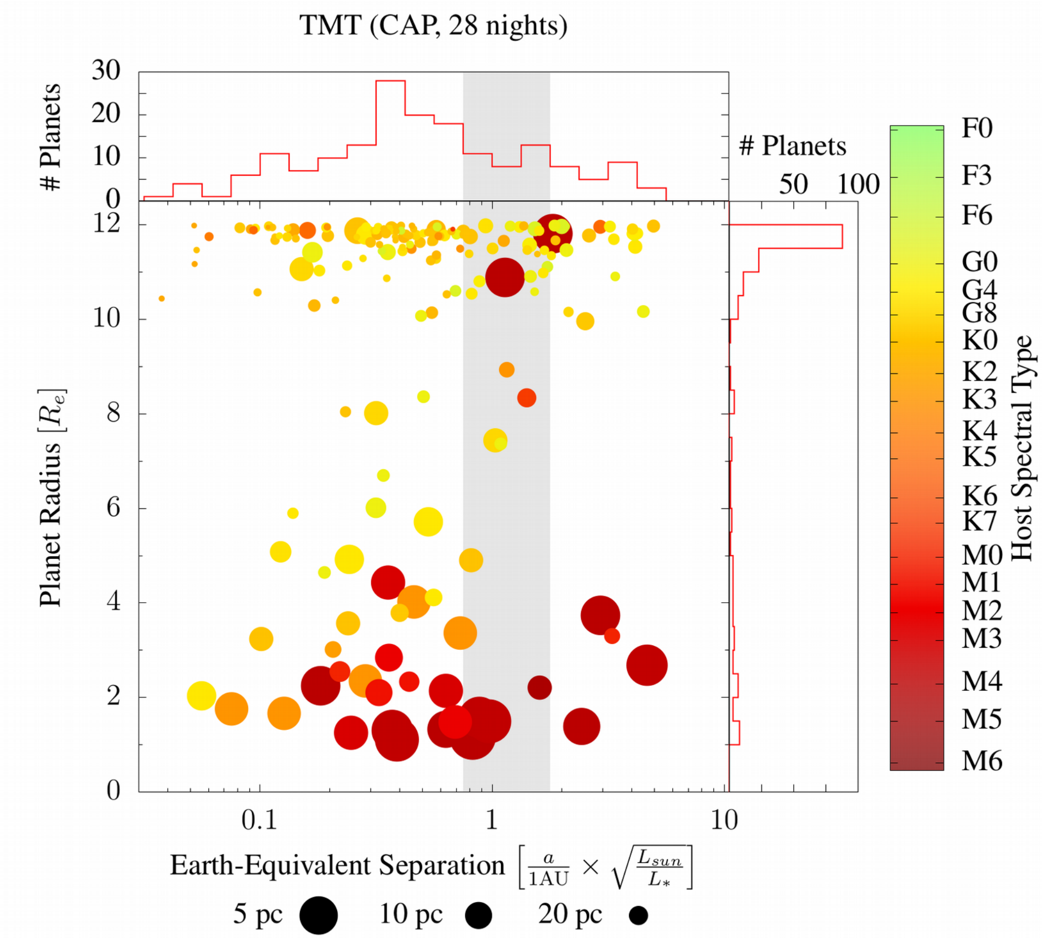
Exoplanet Imaging / Detection with GSMTs

Study performed by Jared Males, Univ. of Arizona

Direct Imaging of known RV planets - TMT

Assumptions:
1 l/D IWA coronagraph, SNR=5 in broadband (400nm) @ 800nm
Speckle-noise limited with predictive control
No chromatic effects (WFS and science at 800nm)

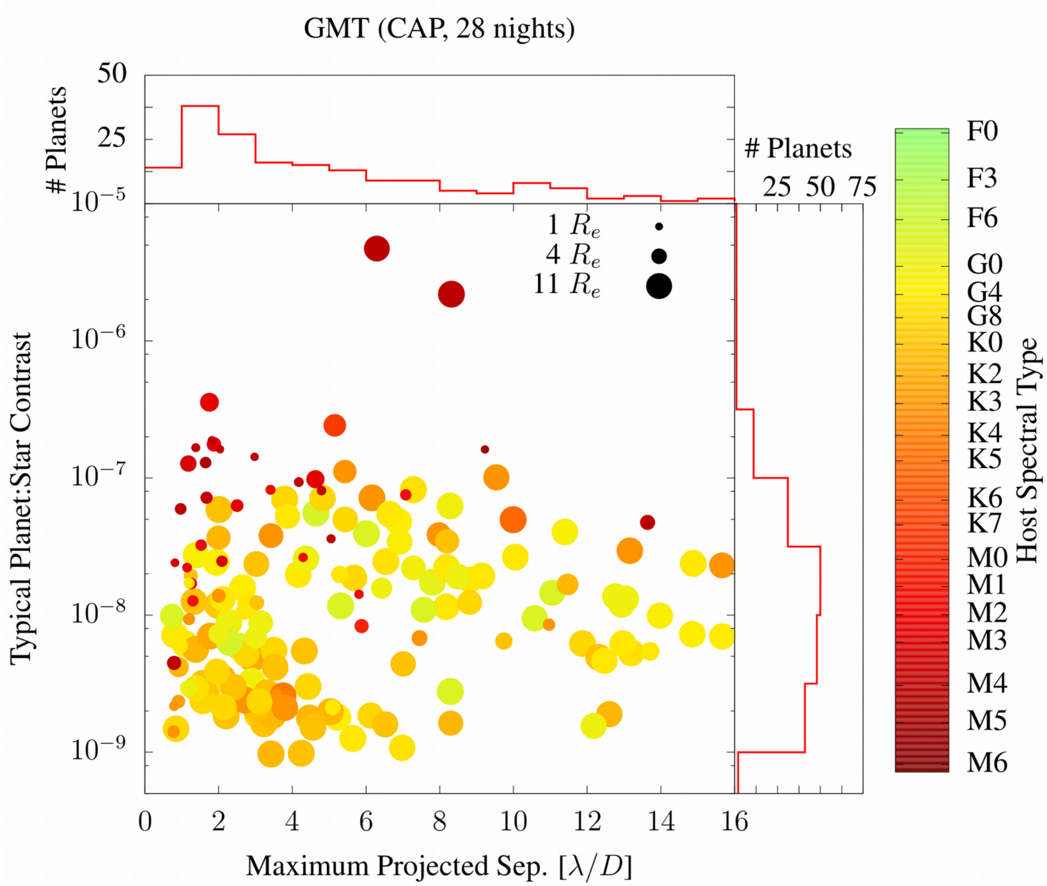


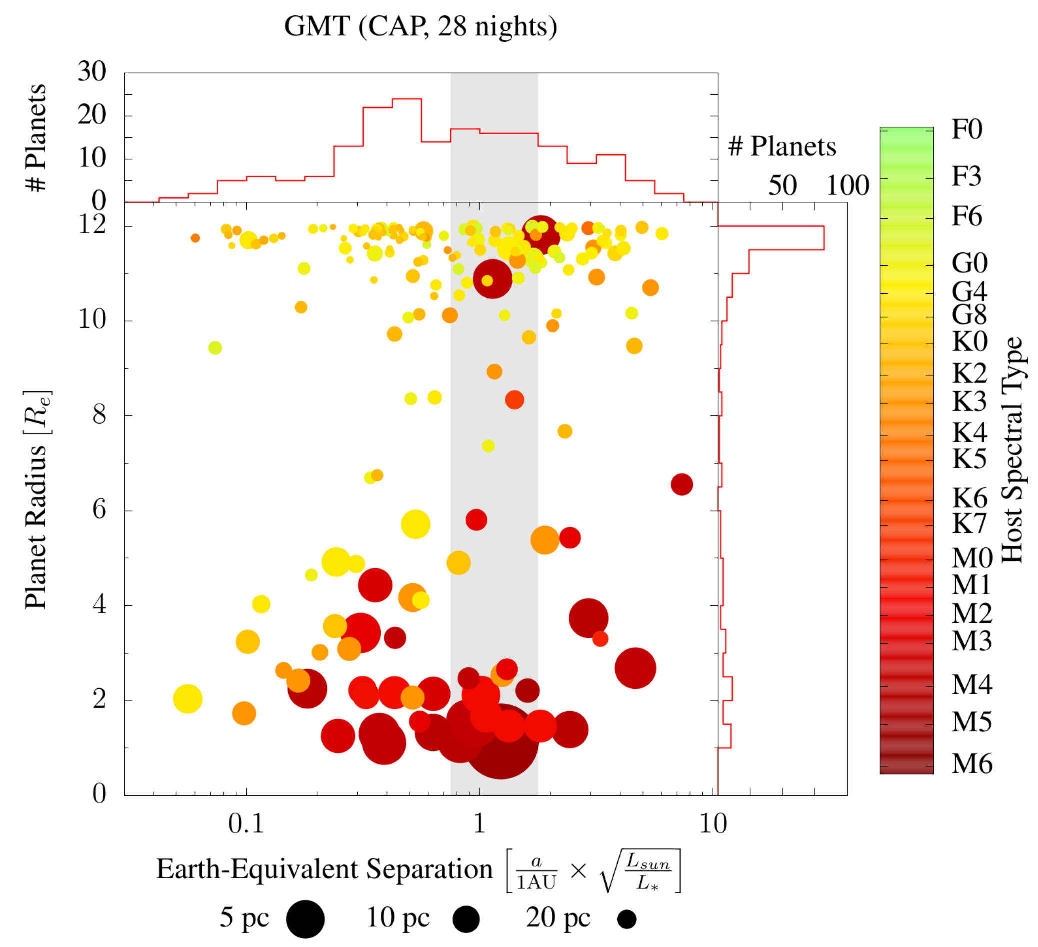


Jared Males, Univ. of Arizona

Direct Imaging of known RV planets - GMT

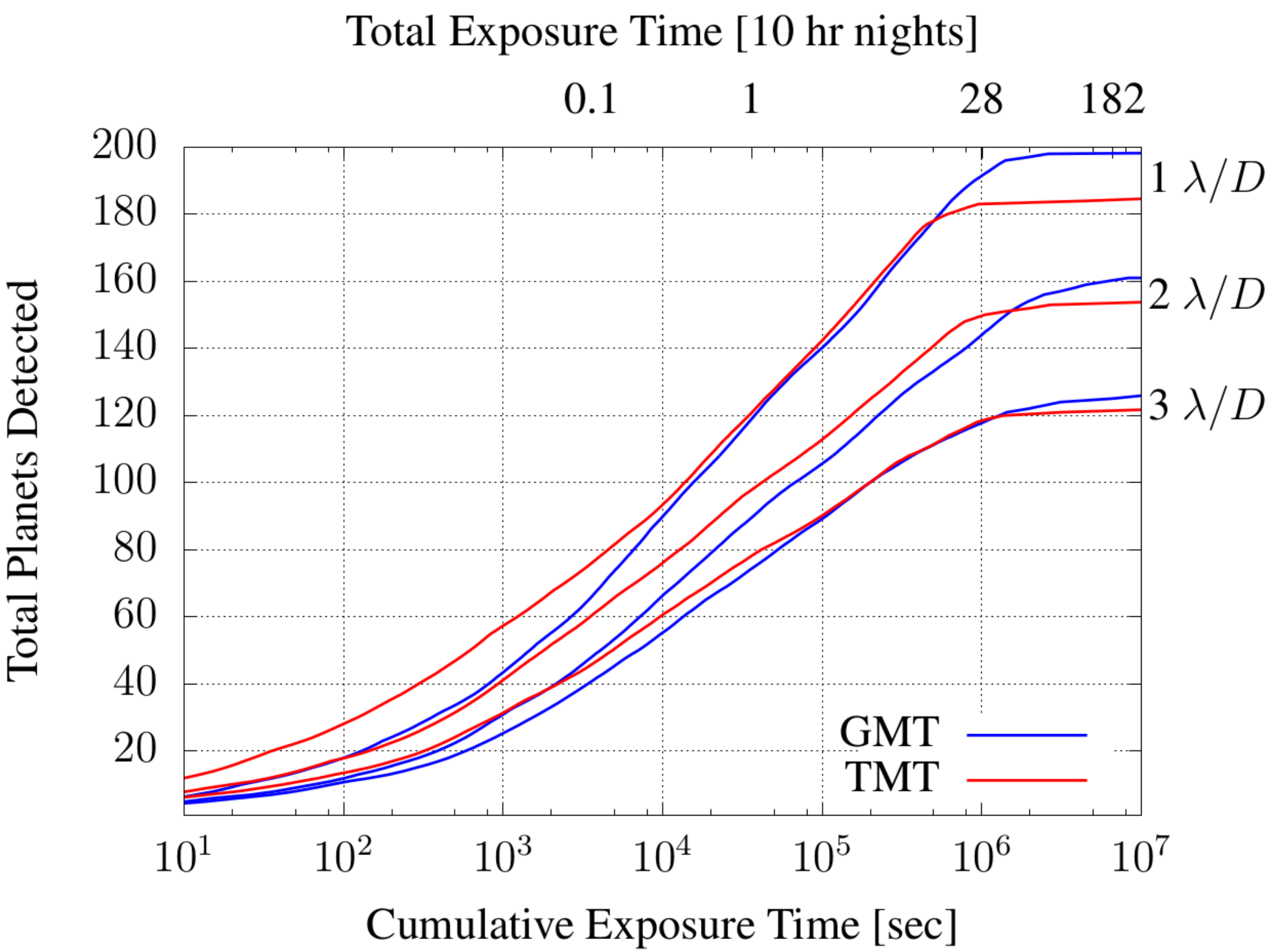
Assumptions:
1 l/D IWA coronagraph, SNR=5 in broadband (400nm) @ 800nm
Speckle-noise limited with predictive control
No chromatic effects (WFS and science at 800nm)





Jared Males, Univ. of Arizona

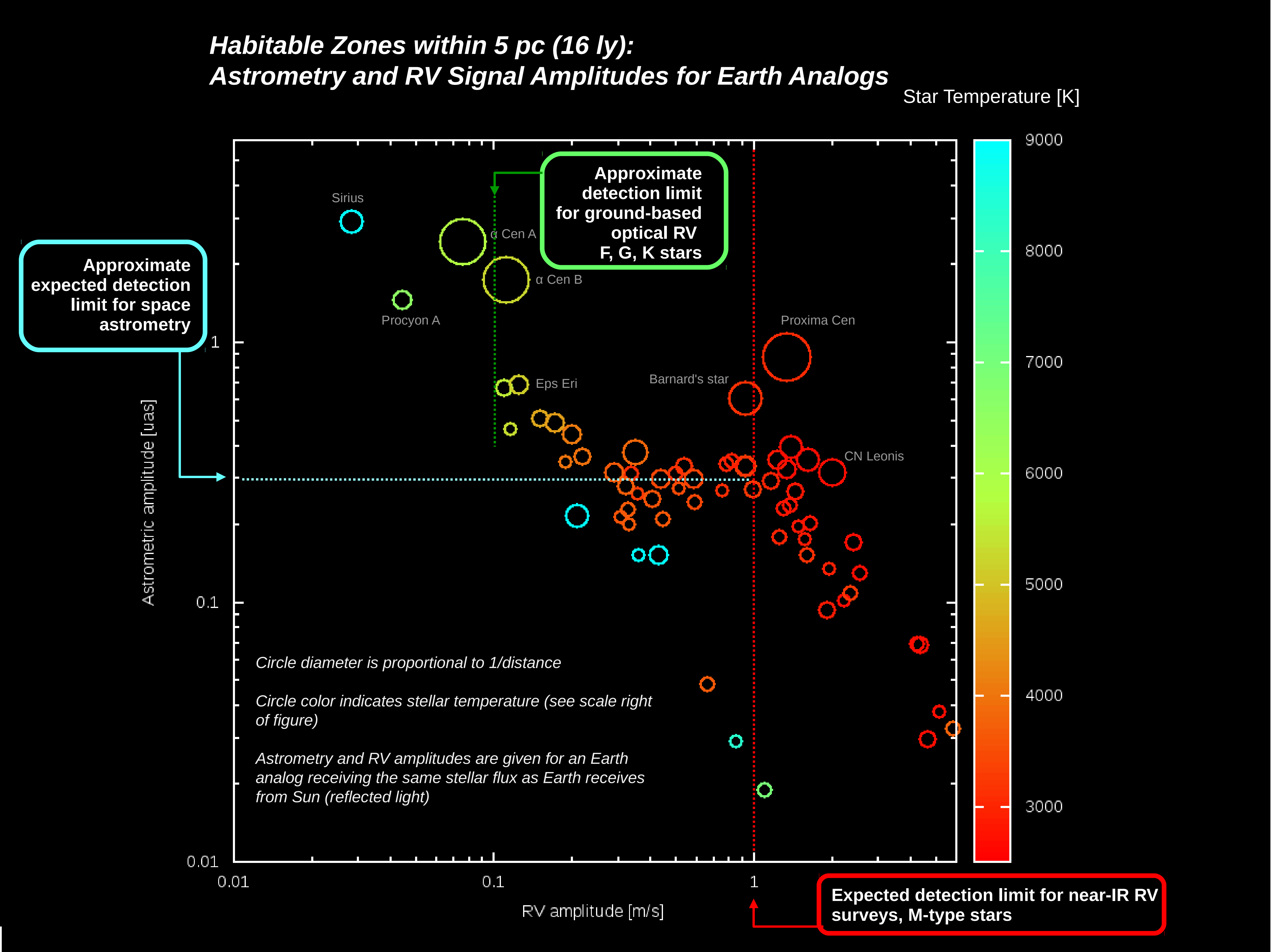
Direct Imaging of known RV planets – IWA / exposure time



Jared Males, Univ. of Arizona

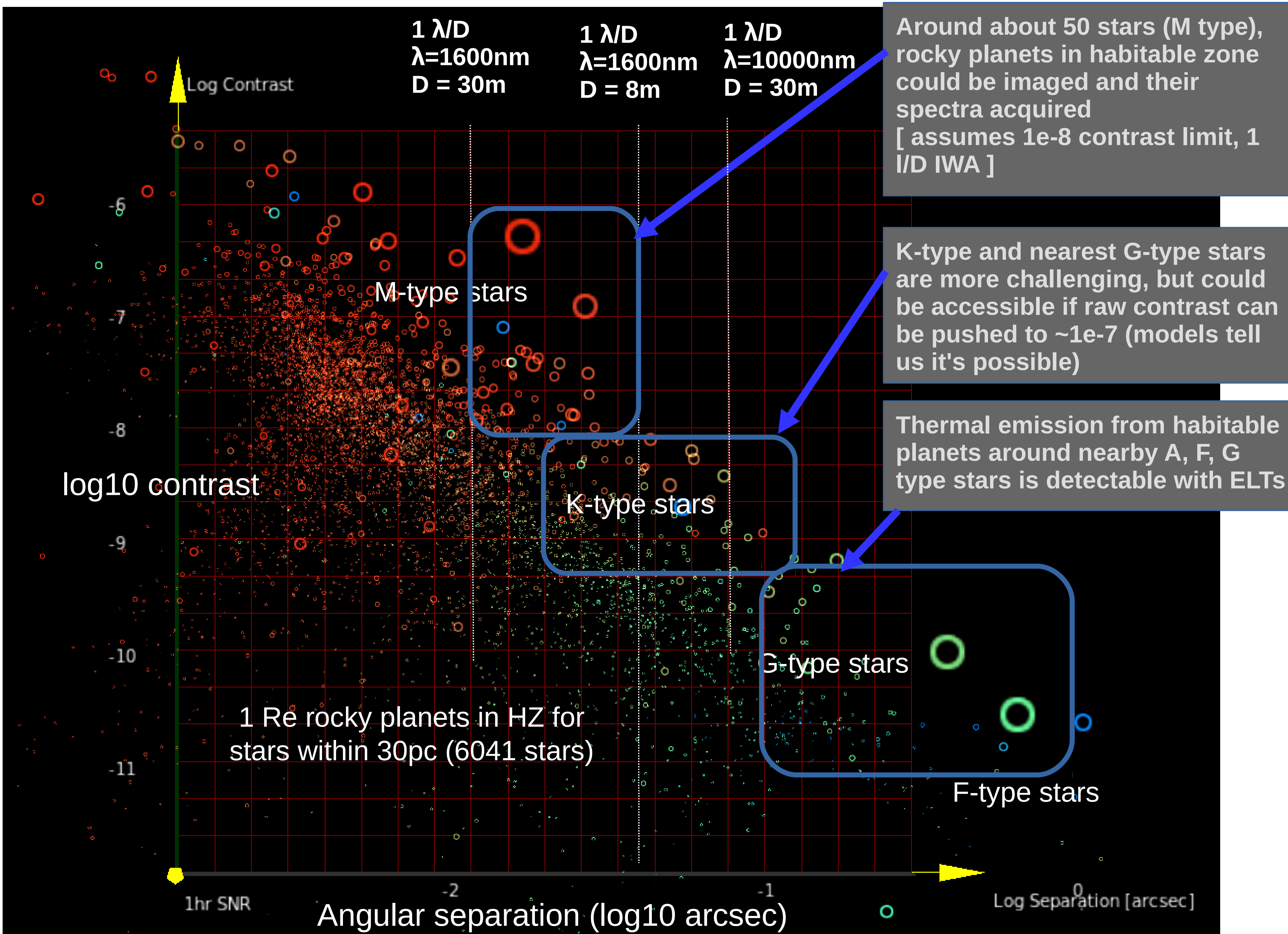
Habitable planets imaging & biosignatures detection with ELTs

- **Thermal emission**
- **Reflected light**



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
Approximate detection limit for ground-based optical RV F, G, K stars
Approximate expected detection limit for space astrometry
Expected detection limit for near-IR RV surveys, M-type stars
Sirius
α Cen A
α Cen B
Procyon A
Proxima Cen
Eps Eri
Barnard's star
CN Leonis
Astrometric amplitude [uas]
1
0.1
0.01
0.01
0.1
1
RV amplitude [m/s]
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 Planets: Contrast and Angular separation



10um imaging and spectroscopy

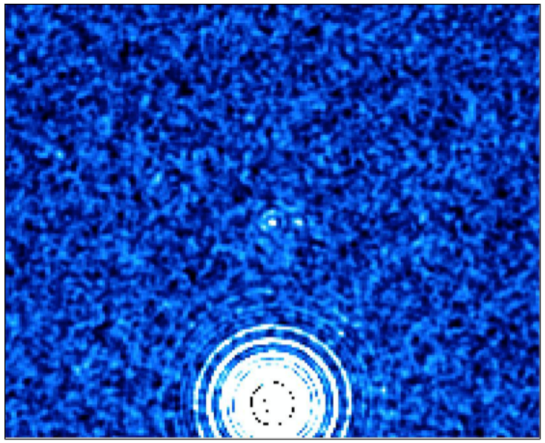


Fig. 1: A simulated 100h sequence of Alpha Cent at 10 microns for an 8m telescope. The target star (center) is hidden behind a coronagraph. A faint 4.5 sigma 1 Earth radius 288K planet is detected West of the star at 1 arcsec. The 2nd star of the system is visible South of the target star.

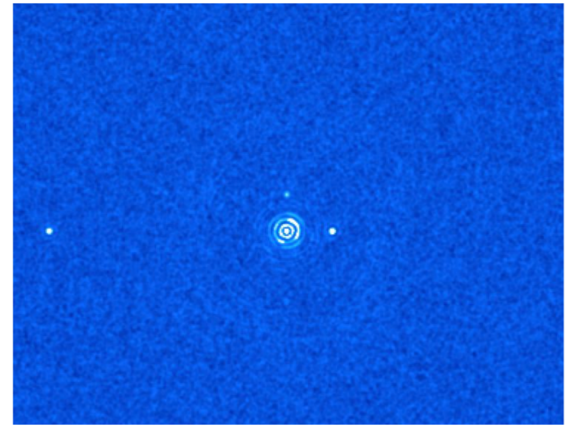


Fig. 2: Same as Fig.1, but for a 30m telescope. A bright 25 sigma 1 Earth radius 288K planet is detected West of the star at 1 arcsec. A Venus-like planet is detected North of the star, as a Jupiter-like planet is detected East.

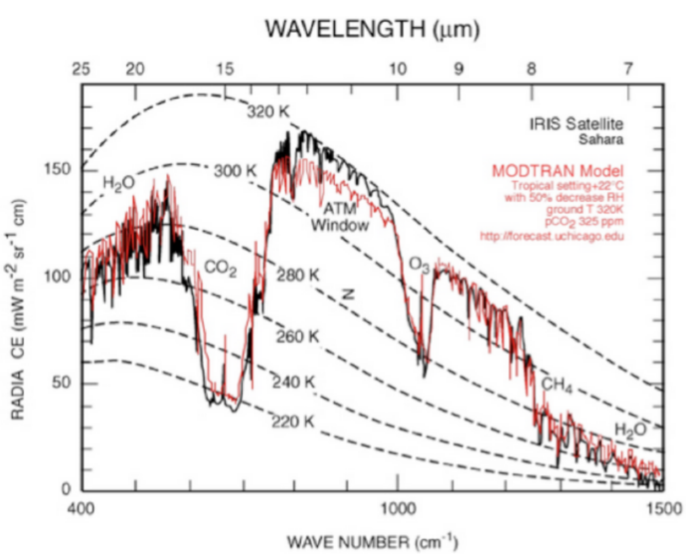
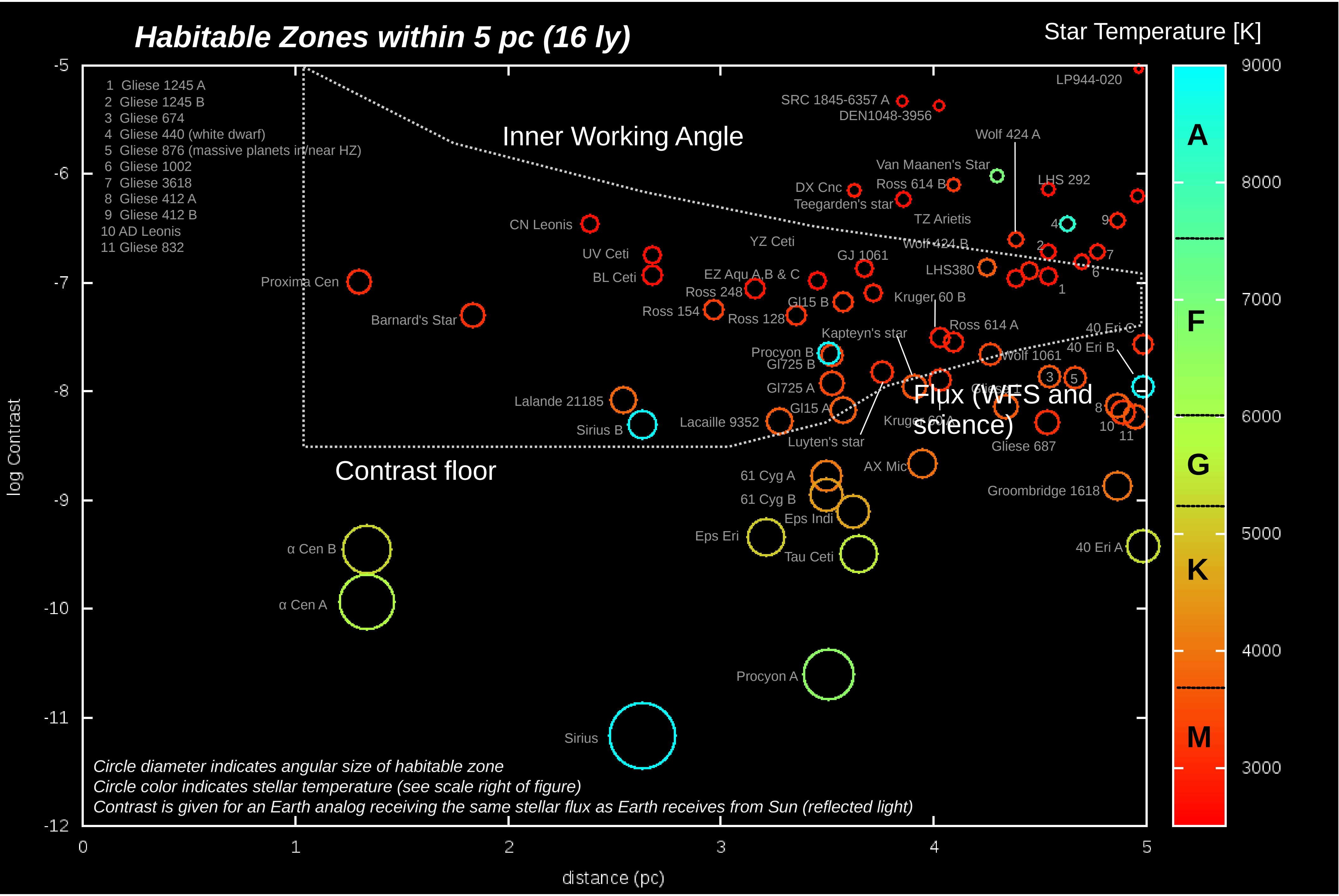


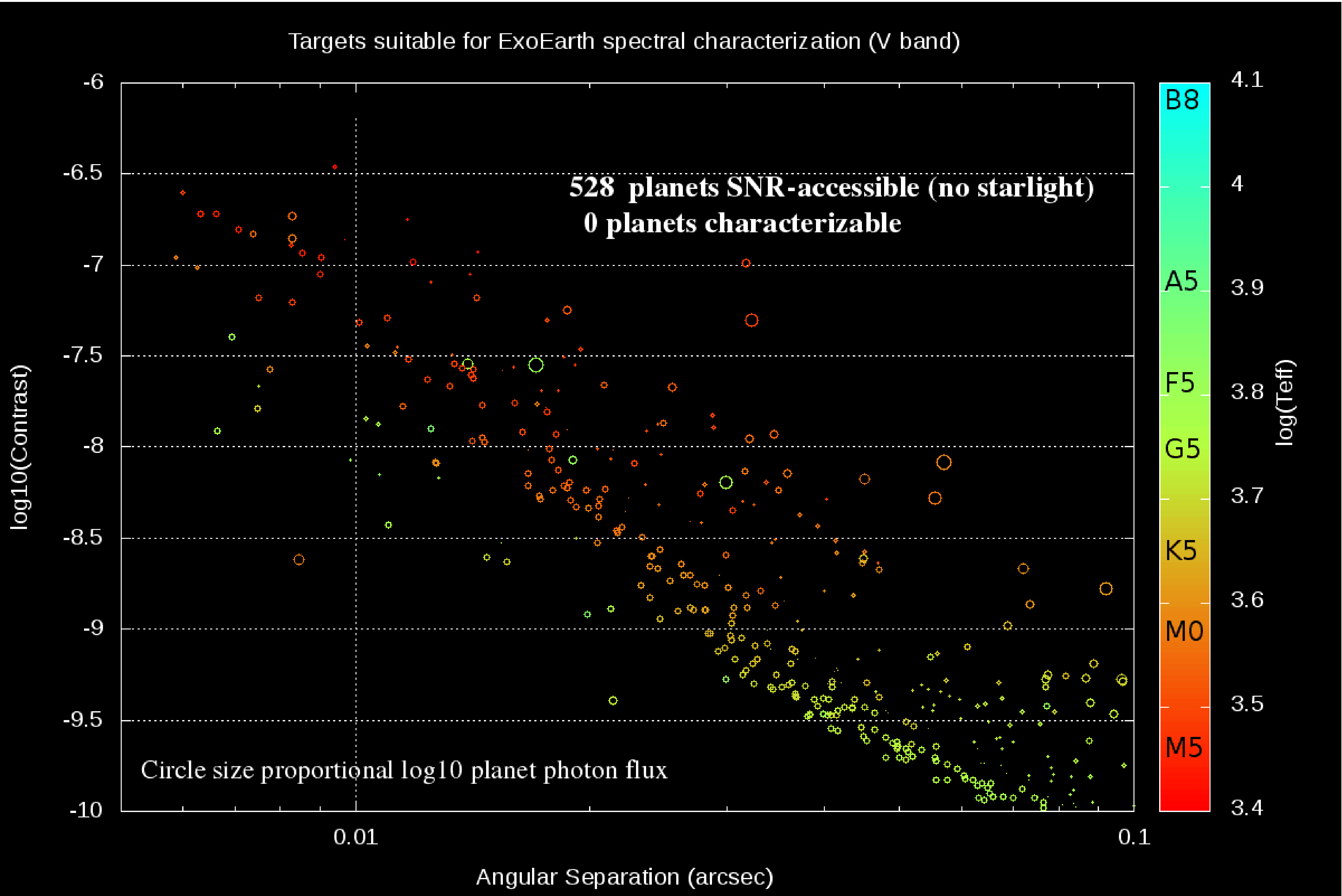
Fig. 3: Earth spectrum acquired from space for the Sahara. Note the peak emission between 10-13 microns. Biomarkers: CO2, O3, CH4 and water bands are visible in the N-band.

Credit: Christian Marois

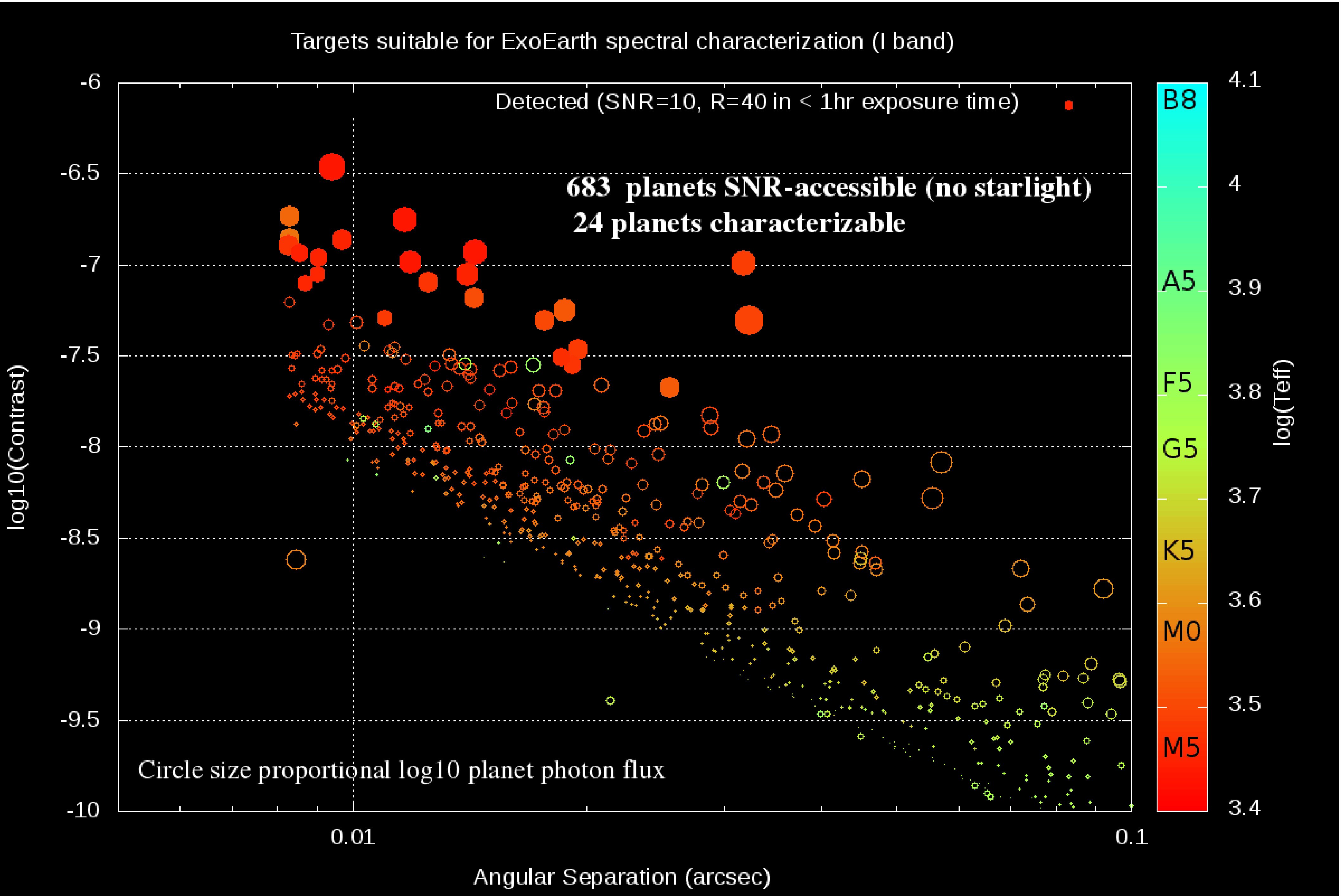


Habitable Zones within 5 pc (16 ly)
Star Temperature [K]
1 Gliese 1245 A
2 Gliese 1245 B
3 Gliese 674
4 Gliese 440 (white dwarf)
5 Gliese 876 (massive planets in/near HZ)
6 Gliese 1002
7 Gliese 3618
8 Gliese 412 A
9 Gliese 412 B
10 AD Leonis
11 Gliese 832
Inner Working Angle
Contrast floor
Flux (WFS and science)
Proxima Cen
Barnard's Star
CN Leonis
UV Ceti
BL Ceti
Lalande 21185
Sirius B
α Cen B
α Cen A
Sirius
Procyon A
Procyon B
Gl725 B
Gl725 A
Gl15 A
Gl15 B
Lacaille 9352
Luyten's star
61 Cyg A
61 Cyg B
Eps Indi
Eps Eri
Tau Ceti
AX Mic
Kruger 60 A
Kruger 60 B
Kapteyn's star
Ross 614 A
Ross 614 B
Wolf 1061
Gliese 687
Groombridge 1618
40 Eri A
40 Eri B
40 Eri C
Ross 154
Ross 128
Ross 248
EZ Aqu A,B & C
YZ Ceti
GJ 1061
LHS380
Wolf 424 A
Wolf 424 B
TZ Arietis
LHS 292
Van Maanen's Star
DX Cnc
Teegarden's star
SRC 1845-6357 A
DEN1048-3956
LP944-020
A
F
G
K
M
9000
8000
7000
6000
5000
4000
3000
log Contrast
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)

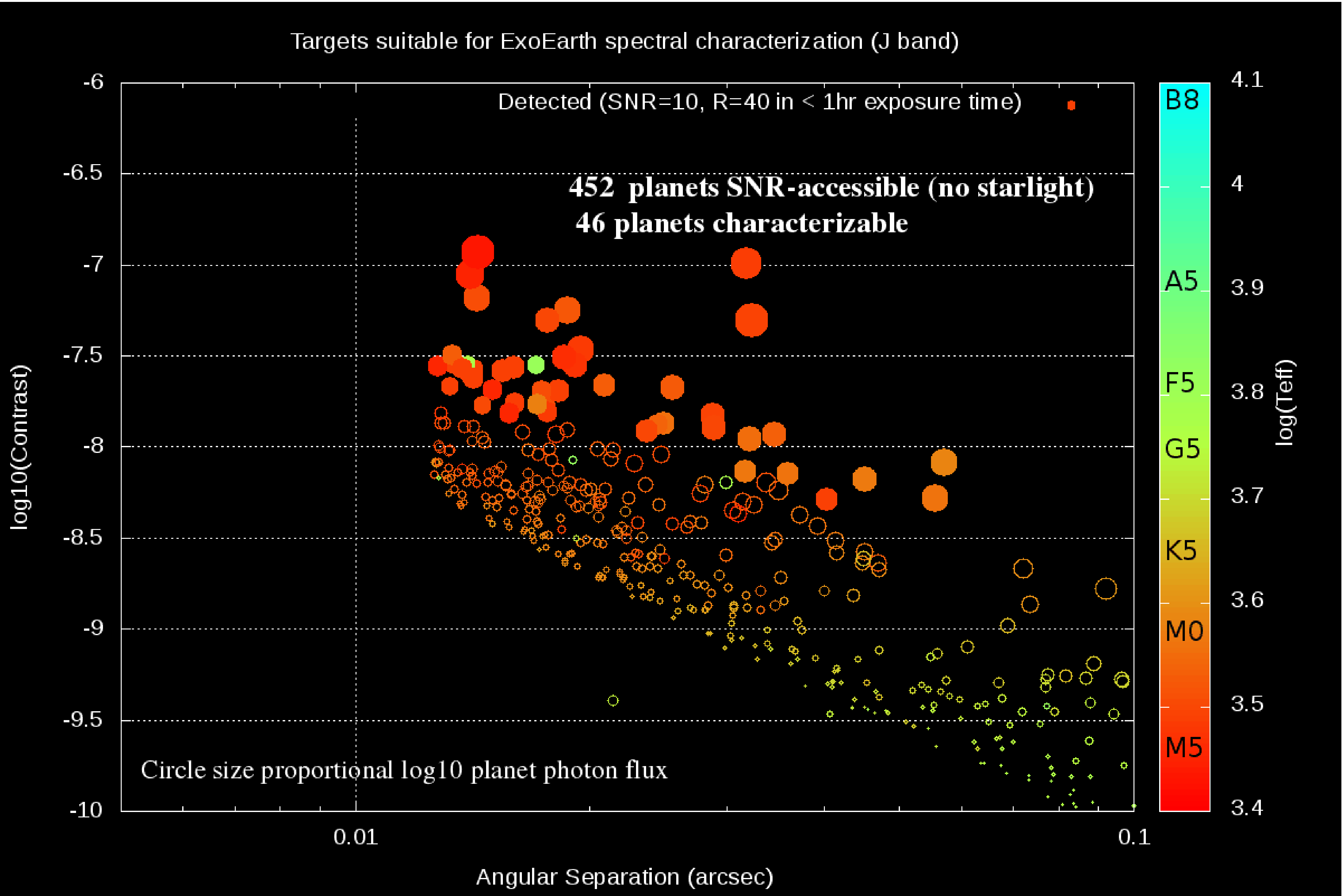
Photon-noise limited detections (1e-6 raw contrast at 1um)



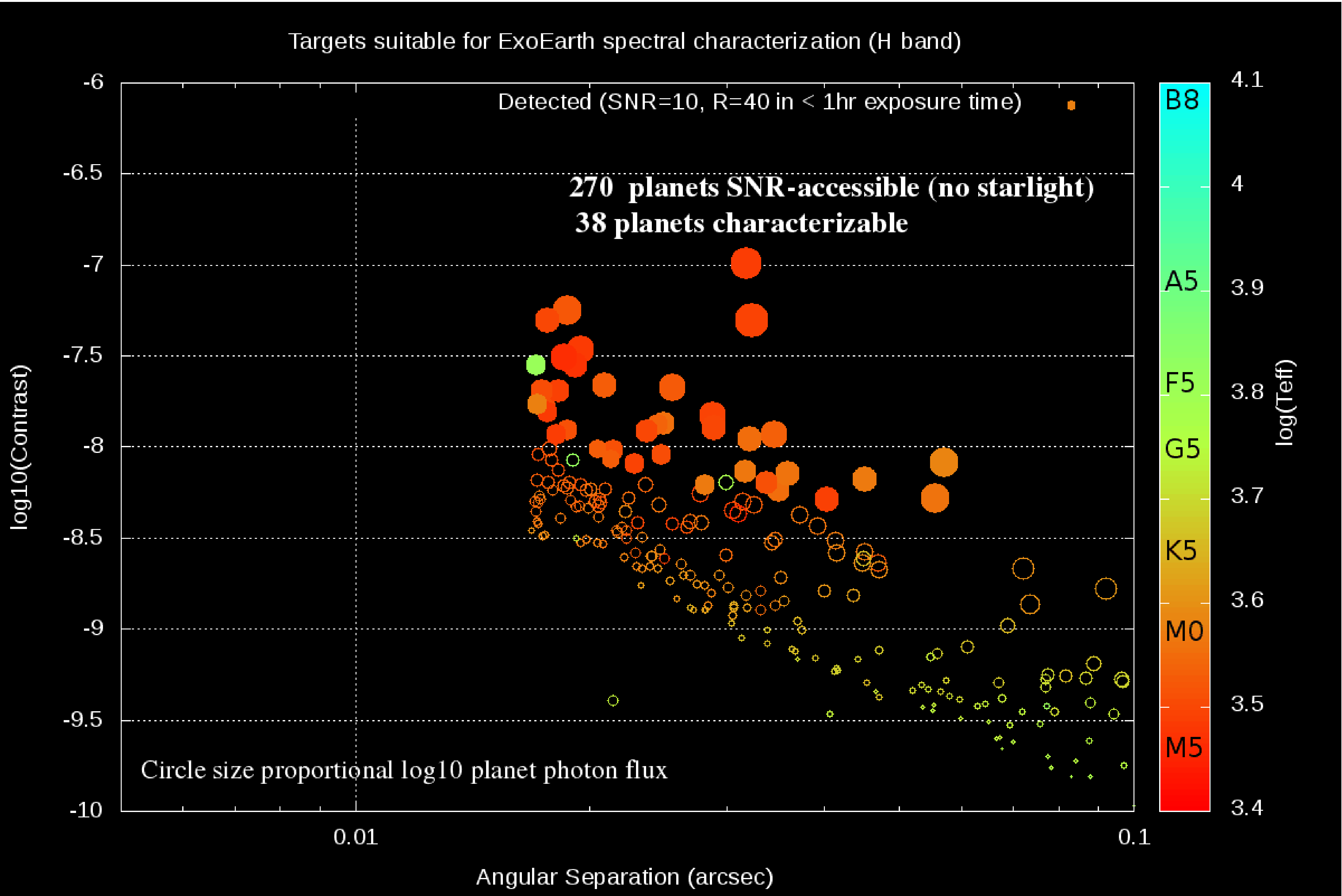
Photon-noise limited detections (1e-6 raw contrast at 1um)



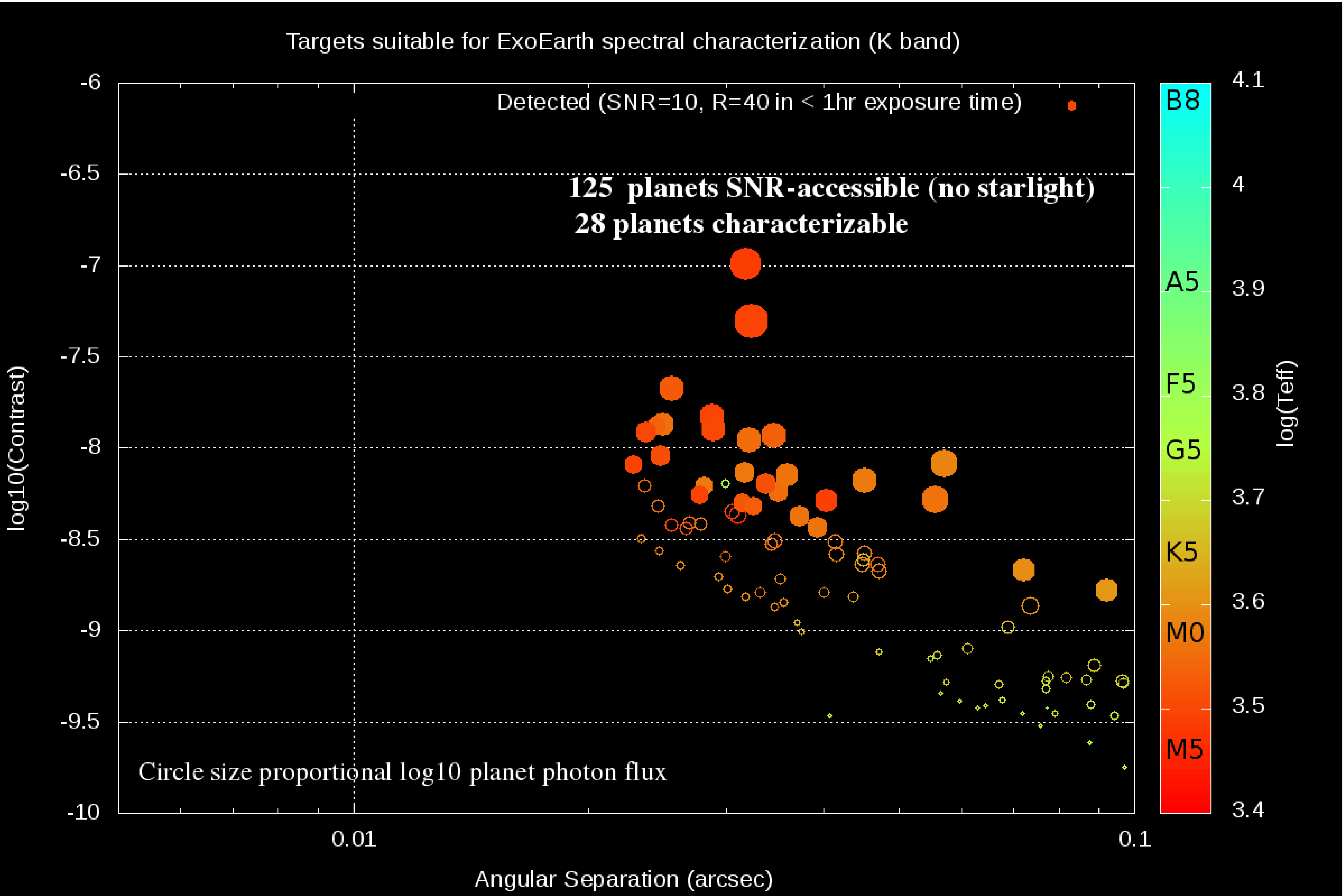
Photon-noise limited detections (1e-6 raw contrast at 1um)



Photon-noise limited detections (1e-6 raw contrast at 1um)



Photon-noise limited detections (1e-6 raw contrast at 1um)



Technology

Previous material assumes :

- Raw contrast ~1e-5 to 1e-6 (1e-5 on mI=8 target)
- Photon-noise limited residual noise
- ~1 l/D IWA coronagraphy

Current systems on ~8m telescopes have not yet demonstrated this level of performance

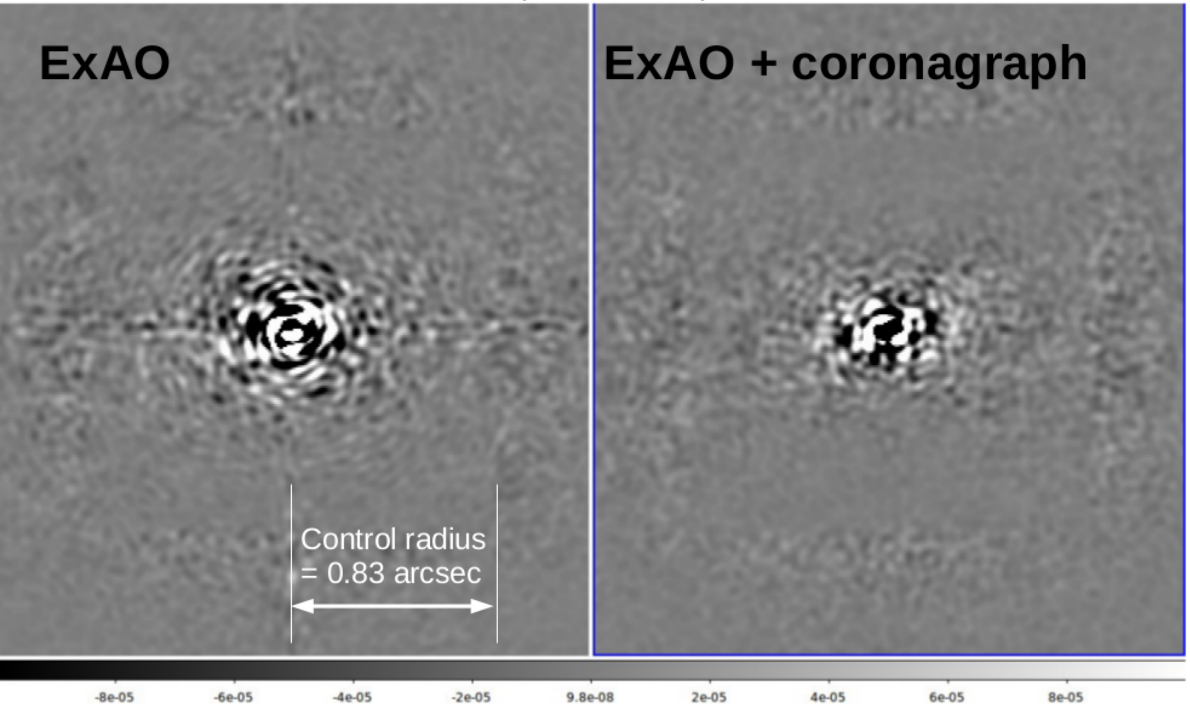
Is this realistic ?

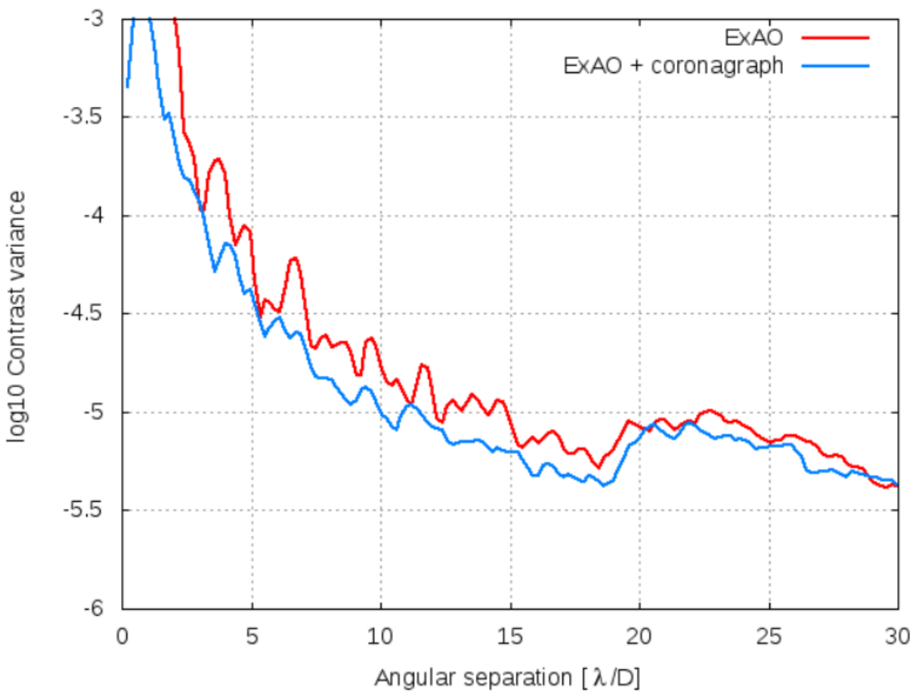
Coronagraphs reduce speckle noise

"speckle pinning" effect
See: Bloemhof et al. 2001, Aime & Soummer 2004, Soummer et al. 2007

PSF subtraction residual (no photon noise)

Difference between two PSFs, exposure time per PSF=100 coherence times





(largely) lossless apodization

Creates a PSF with weak Airy rings

Focal plane mask: -1<t<0

Induces destructive interference inside downstream pupil

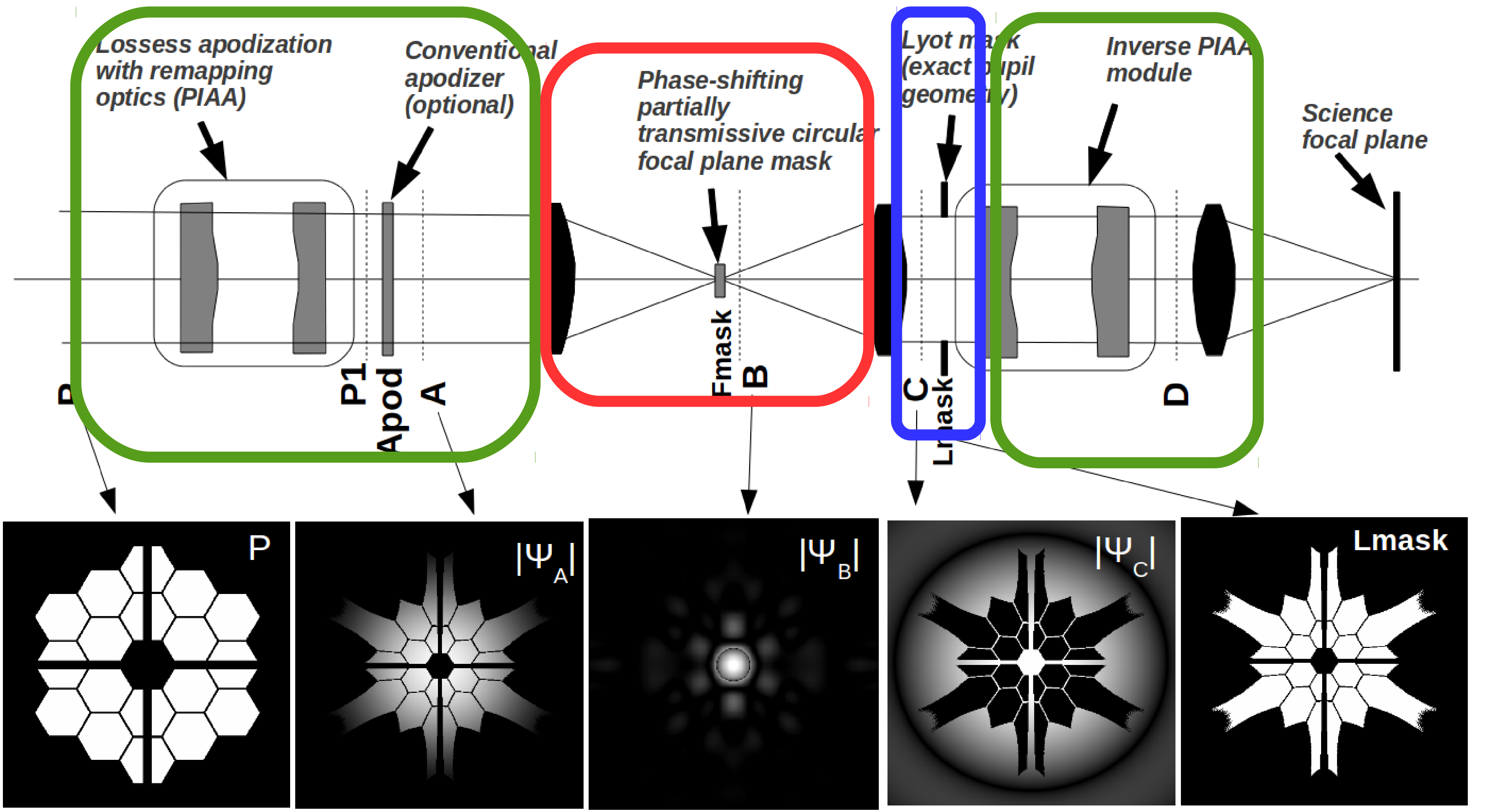
Lyot stop

Blocks starlight

Inverse PIAA (optional)

Recovers Airy PSF over wide field

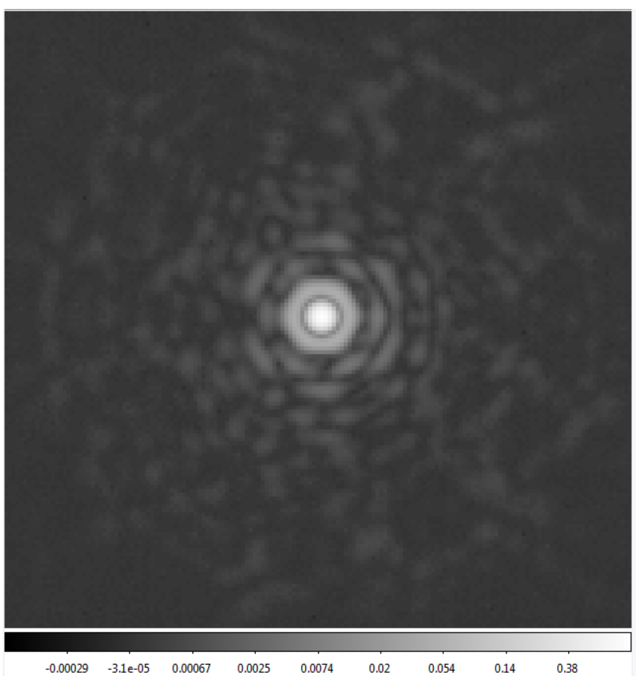
Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)



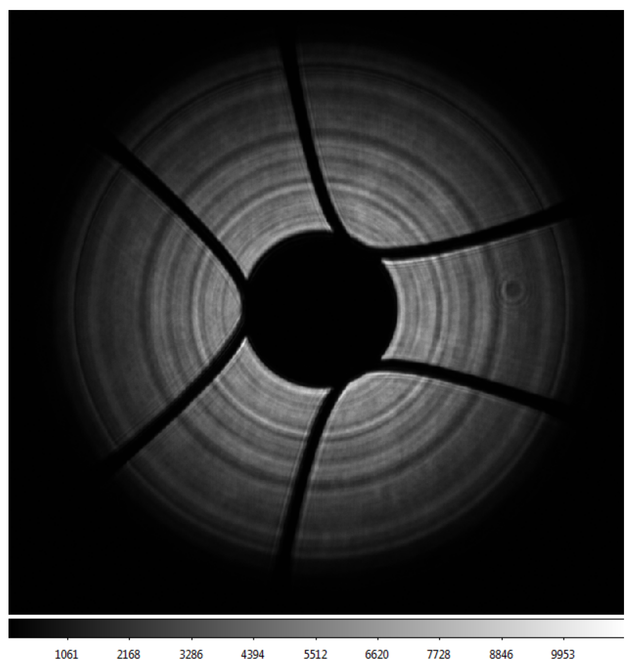
PIAACMC lab performance @ WFIRST (Kern et al. 2016)

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

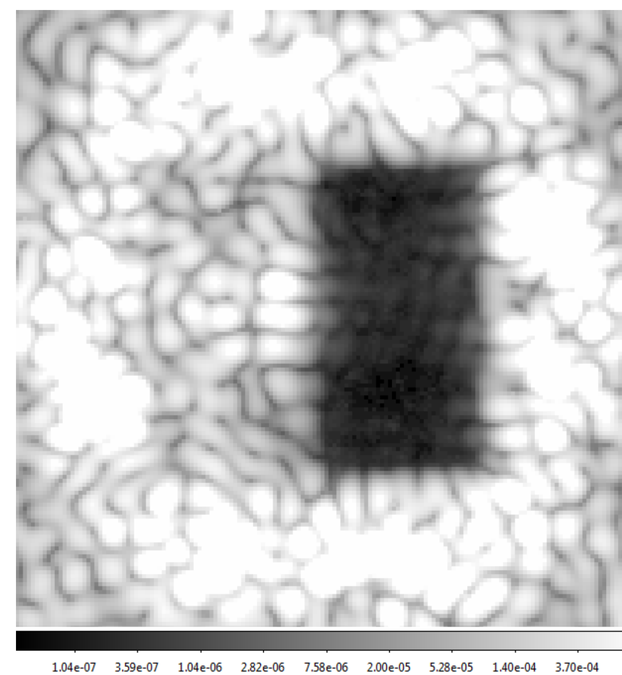
non-coronagraphic PSF



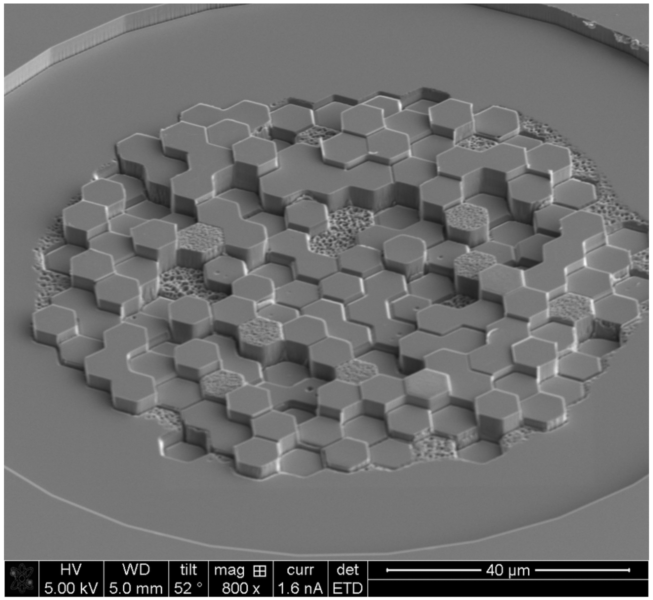
Remapped pupil



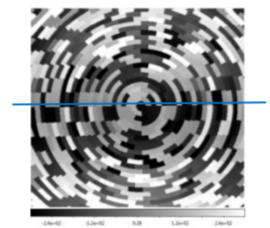
Coronagraphic image

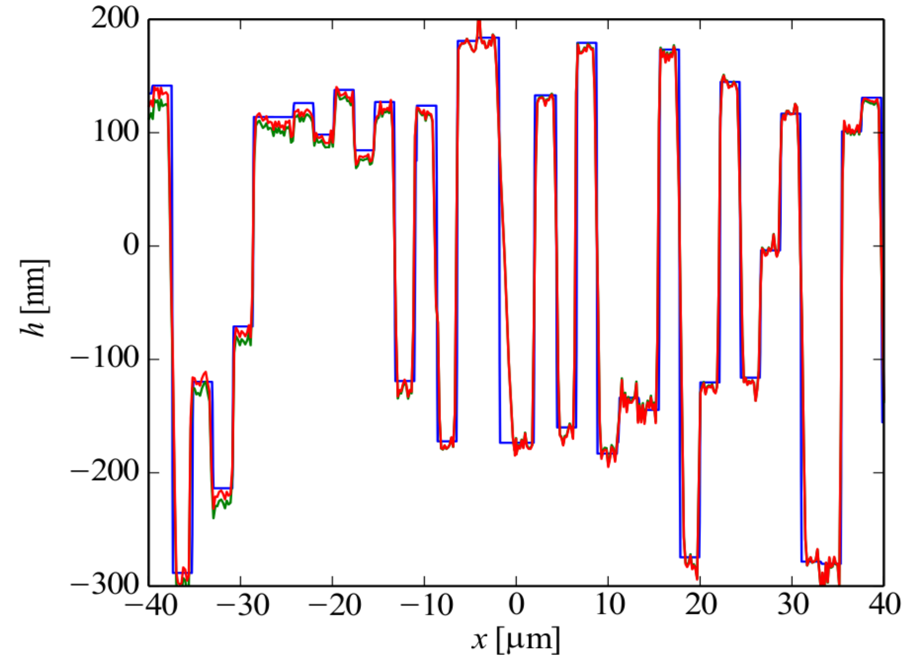


Multi-zone PIAACMC focal plane mask

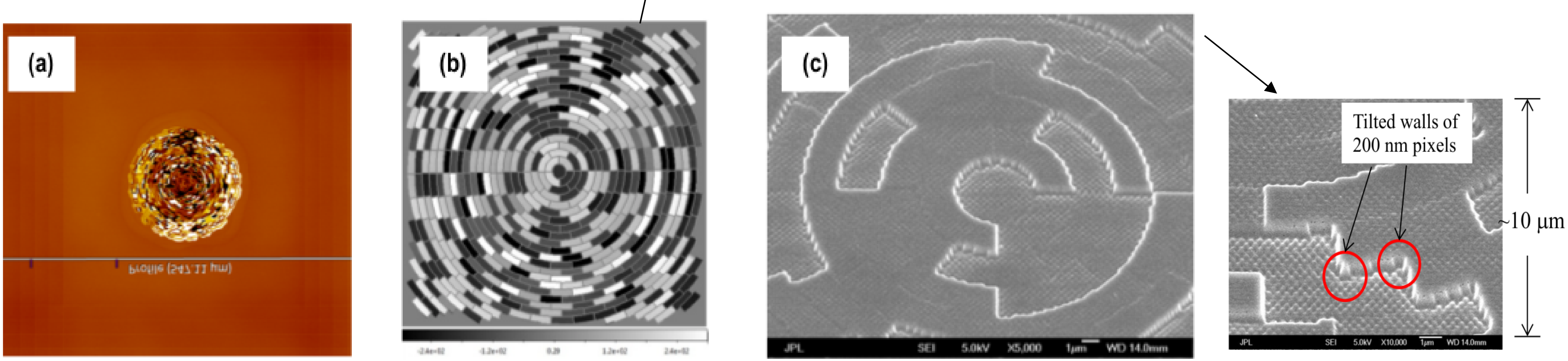


← SCExAO focal plane mask (2017)

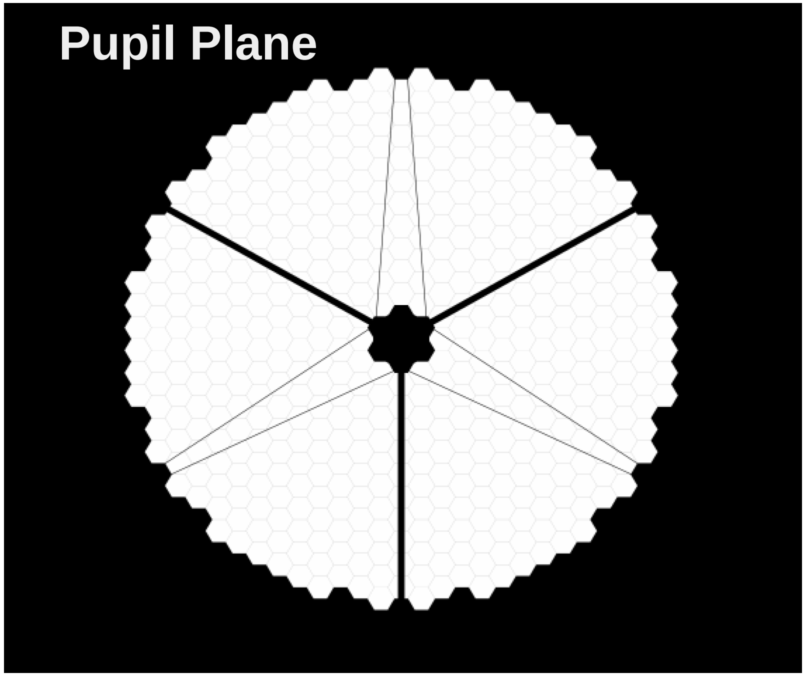


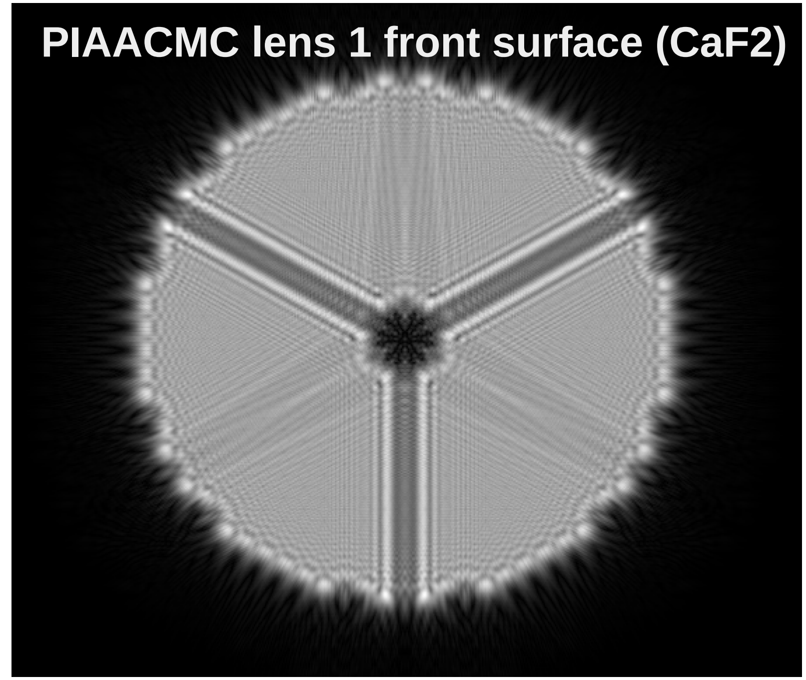


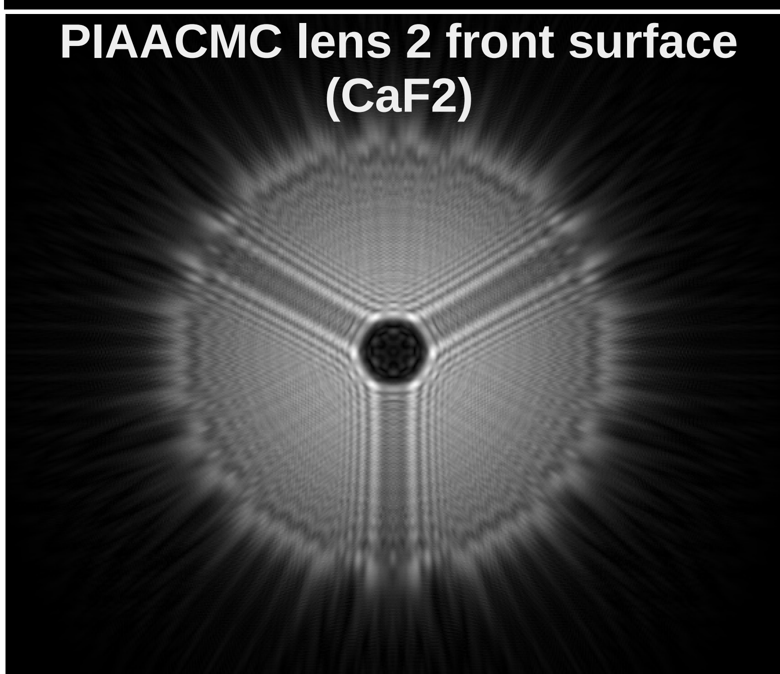
Focal plane mask manufactured at JPL's MDL
Meets performance requirements
(WFIRST PIAACMC Milestone report)

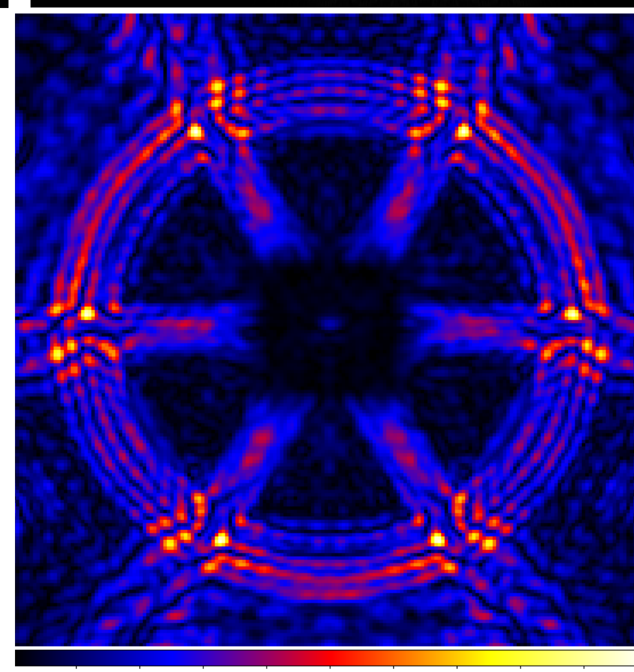


TMT coronagraph design for 1 l/D IWA









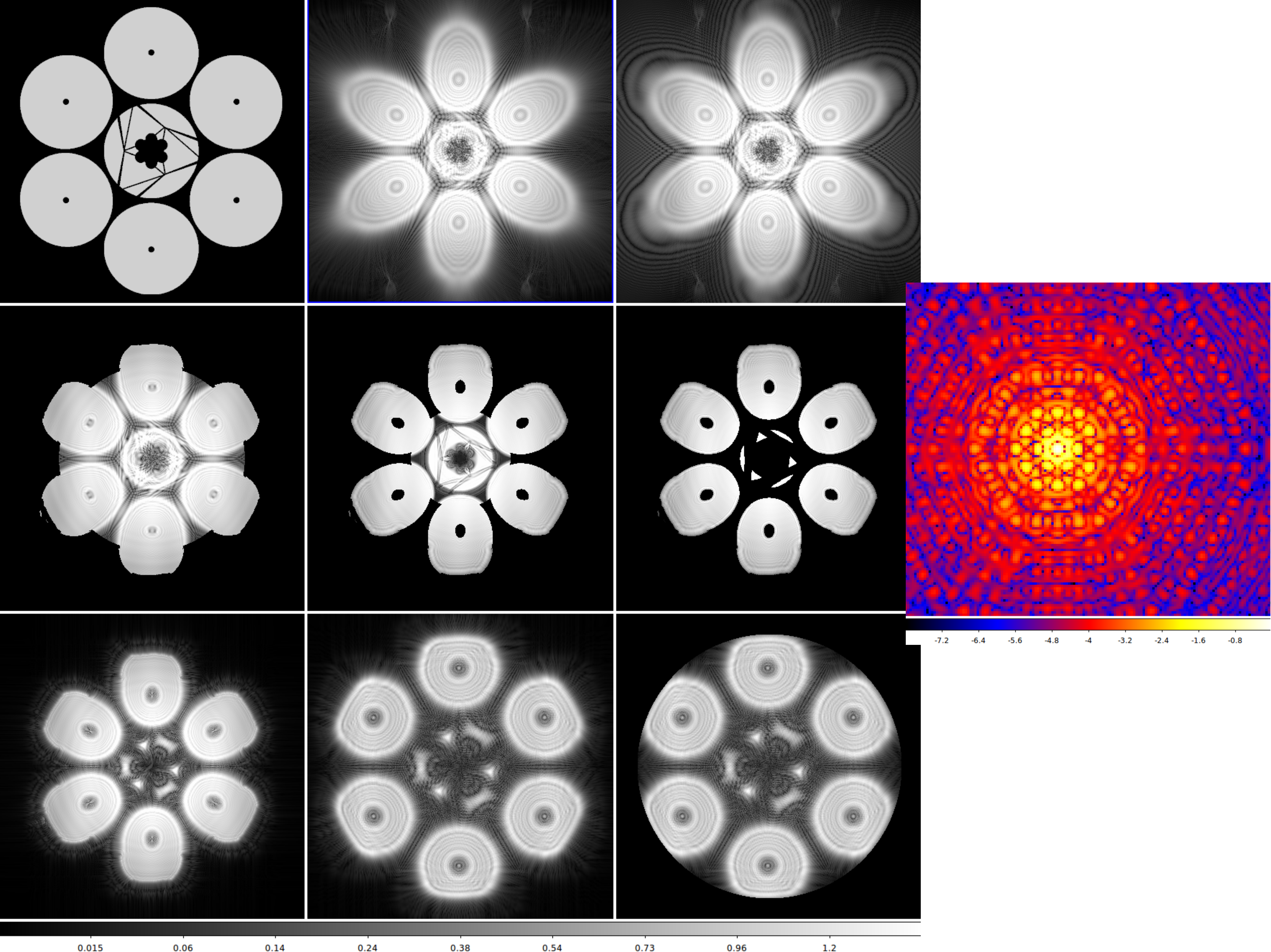
PSF at 1600nm

3e-9 contrast in 1.2 to 8 l/D

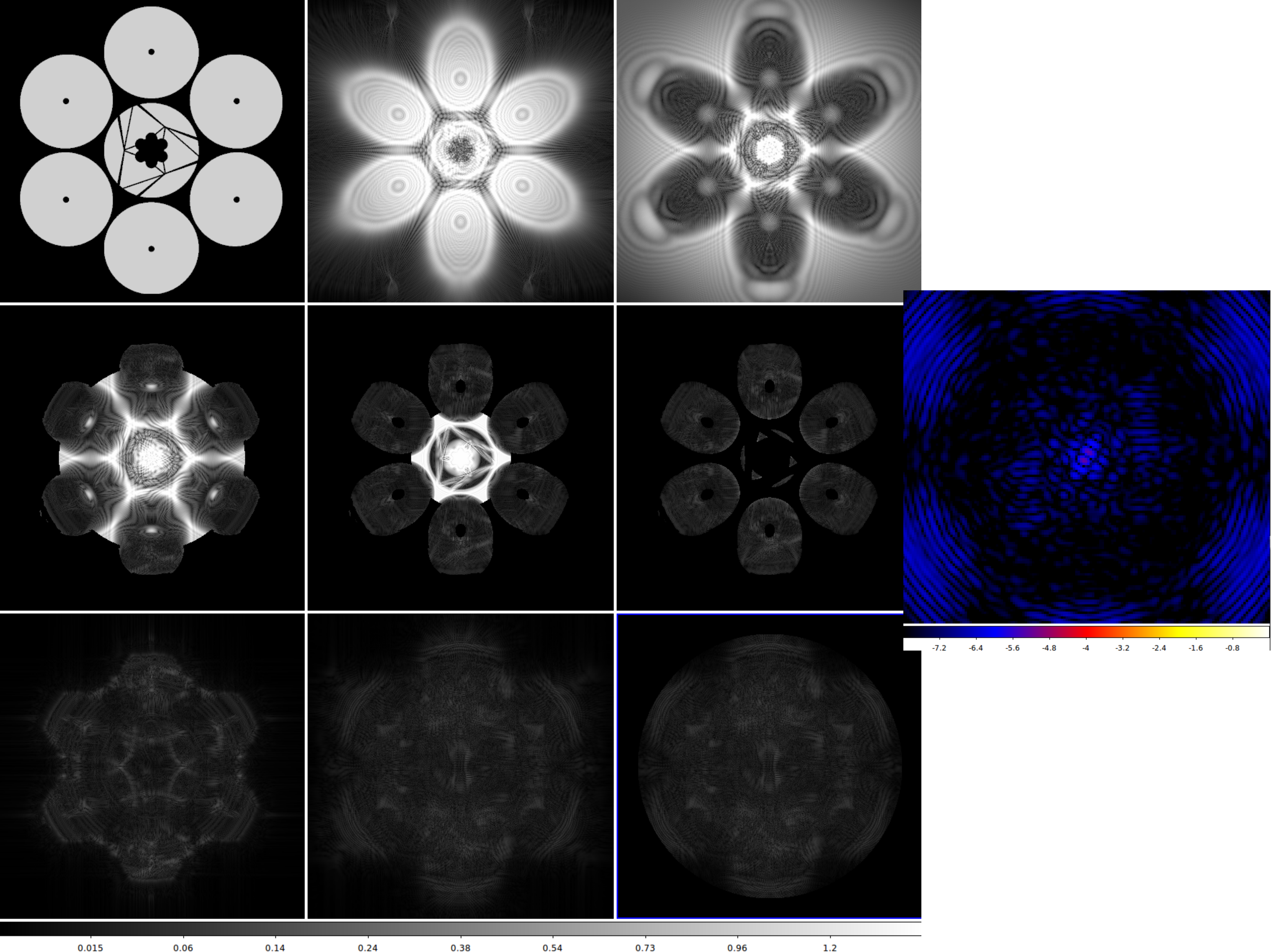
80% off-axis throughput

1.2 l/D IWA

CaF2 lenses
SiO2 mask

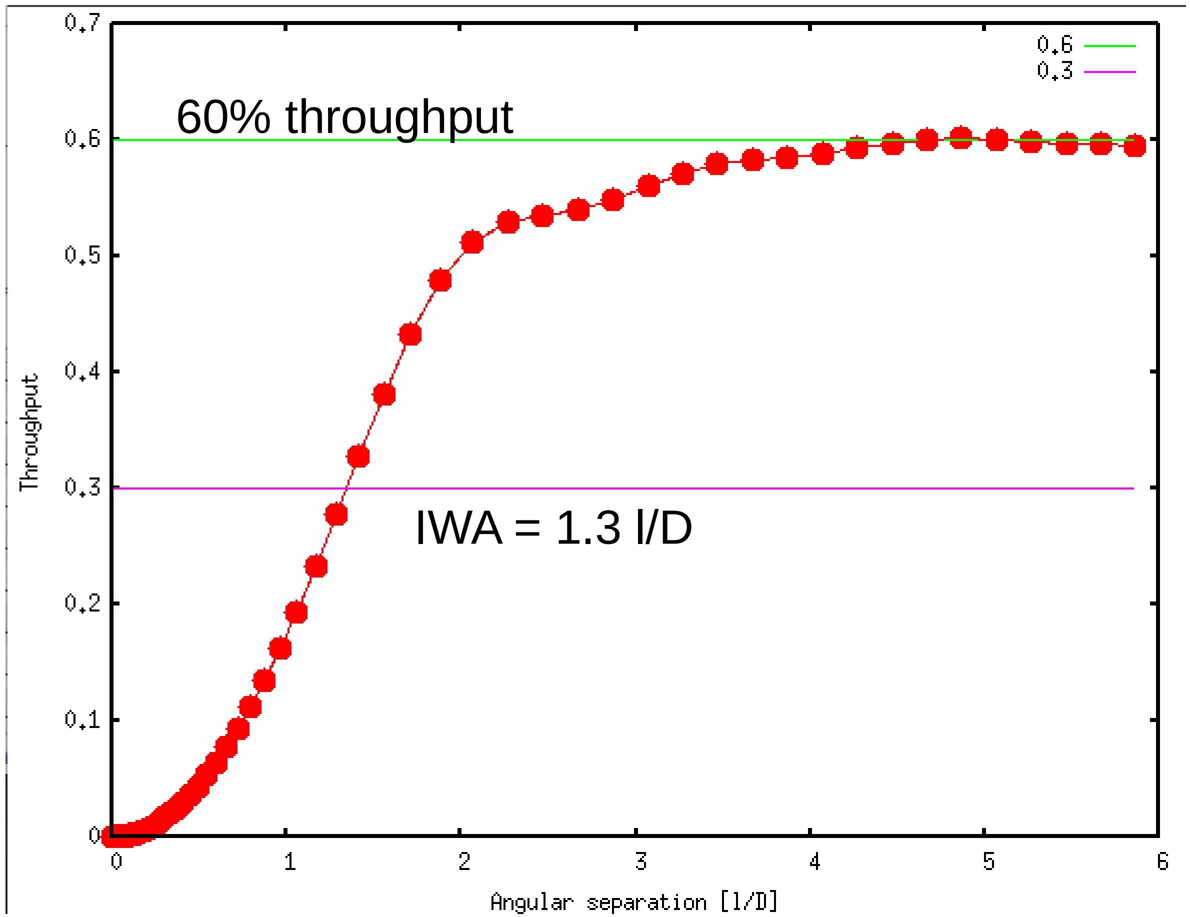


-7.2 -6.4 -5.6 -4.8 -4 -3.2 -2.4 -1.6 -0.8
0.015 0.06 0.14 0.24 0.38 0.54 0.73 0.96 1.2

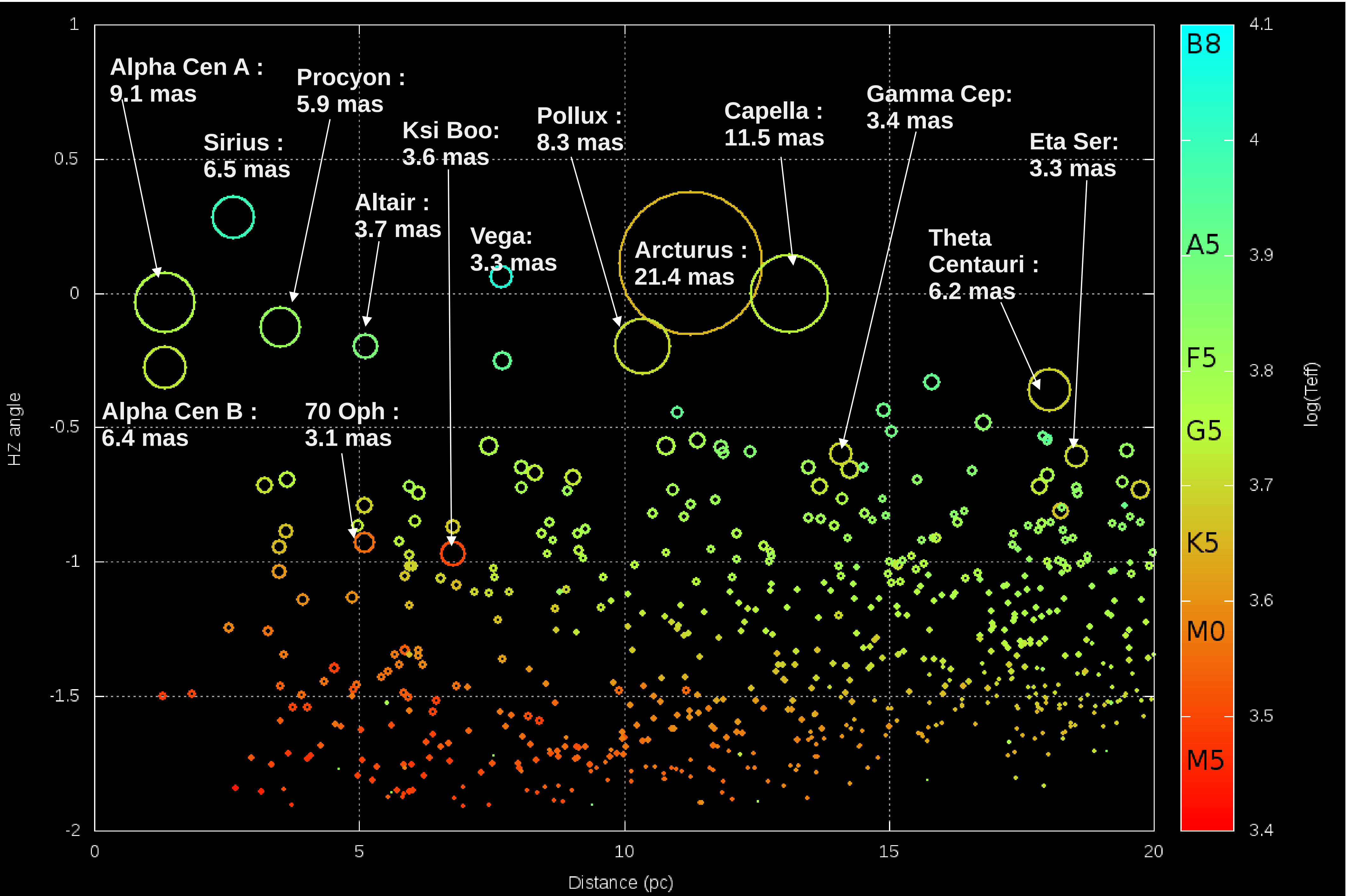

-7.2 -6.4 -5.6 -4.8 -4 -3.2 -2.4 -1.6 -0.8
0.015 0.06 0.14 0.24 0.38 0.54 0.73 0.96 1.2

Performance (GMT pupil)

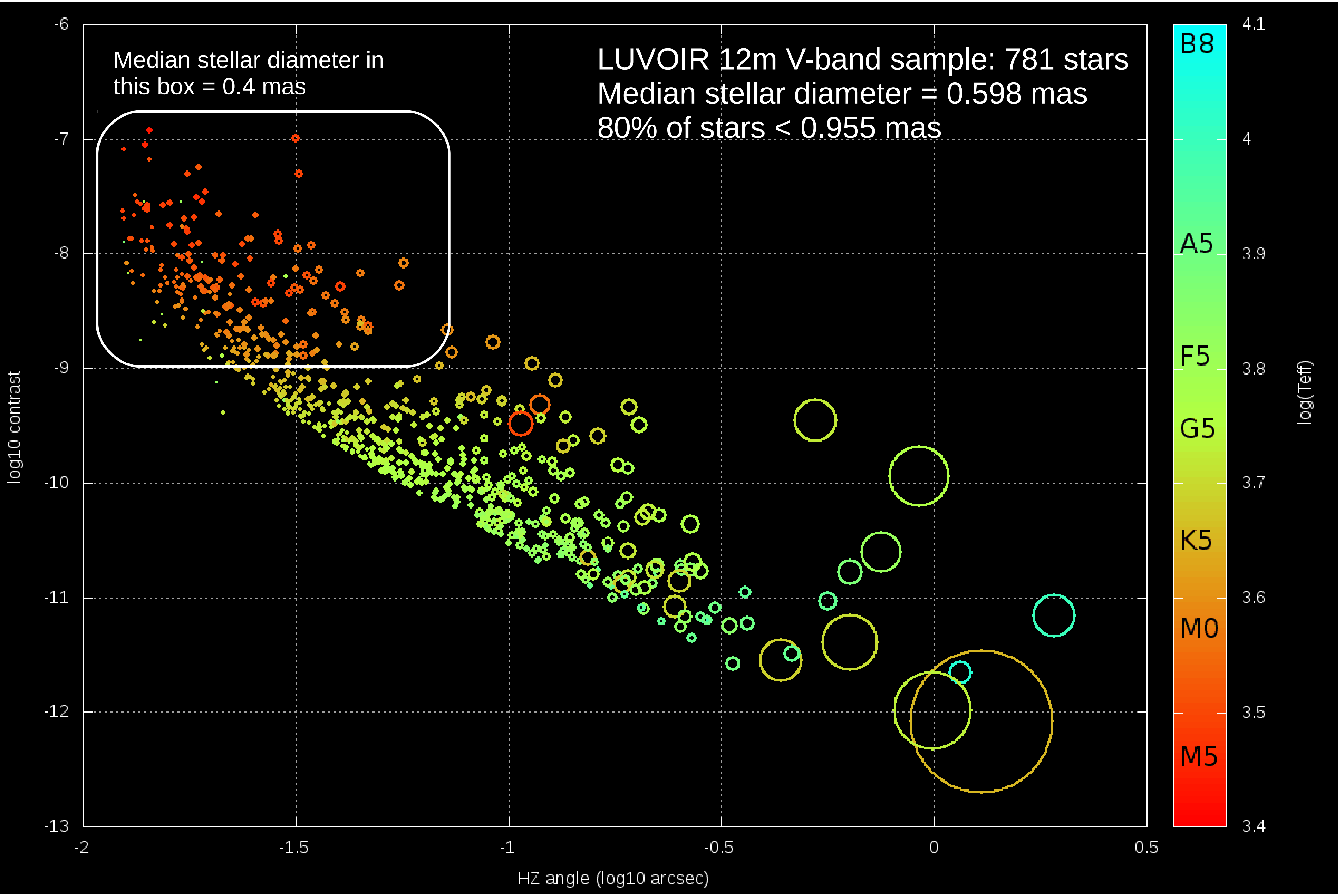
1e-7 contrast
3e-6 contrast @ 3 l/D for 6% l/D disk



Stellar angular sizes strongly correlate with HZ angle



… and contrast

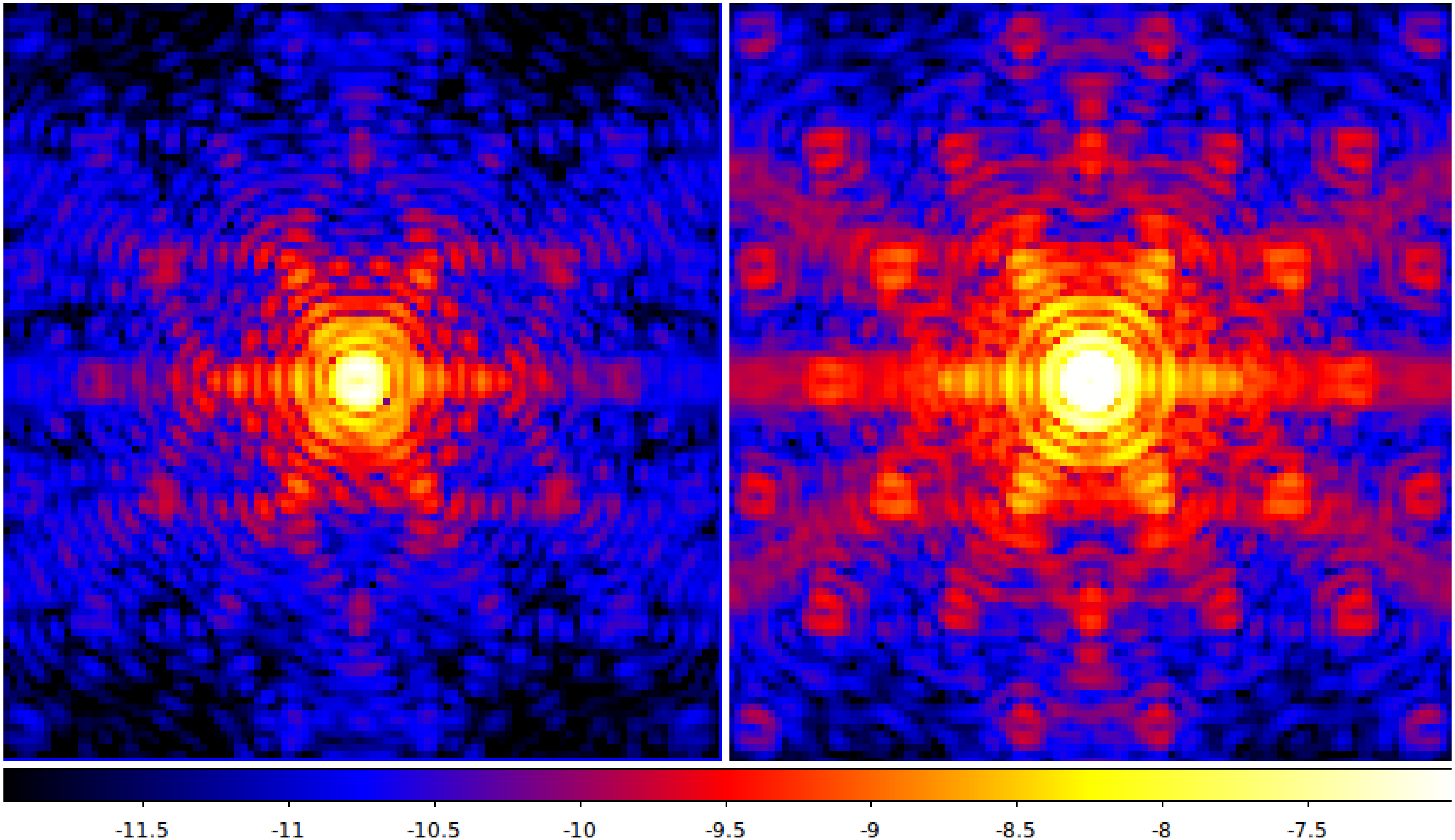


PSF is dominated by stellar angular size

PSF dominated by incoherent spots due to stellar angular size →contributes to photon noise, but does not interfere coherently with wavefront errors → can be removed in post-processing

Instead of radial average contrast, we use 50-percentile (search) and 20-percentile (spectroscopy) radial contrasts for performance evaluation: we avoid the bright spots

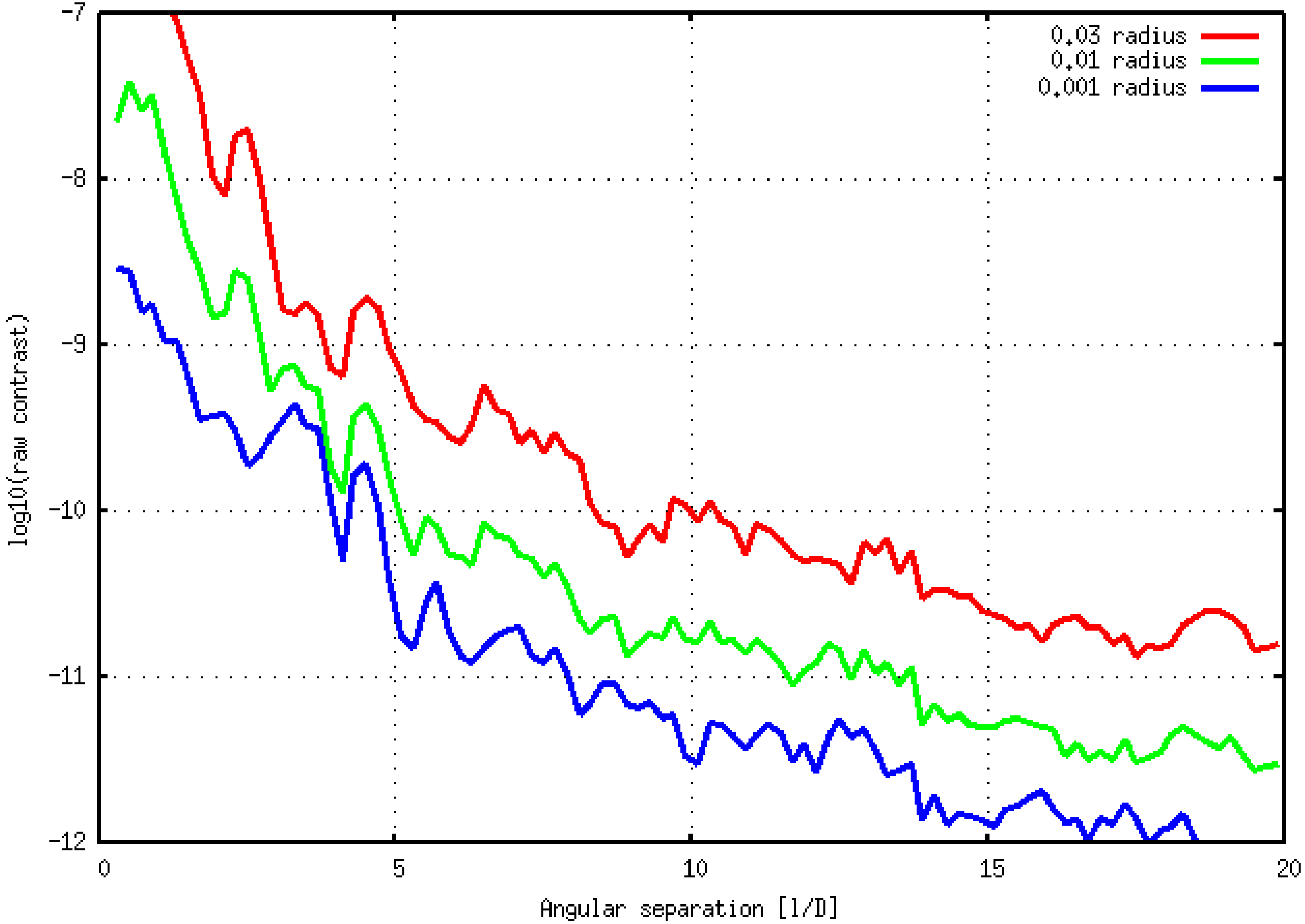
Source radius = 0.01 l/D **Source radius = 0.03 l/D**



10% bandwidth optimized

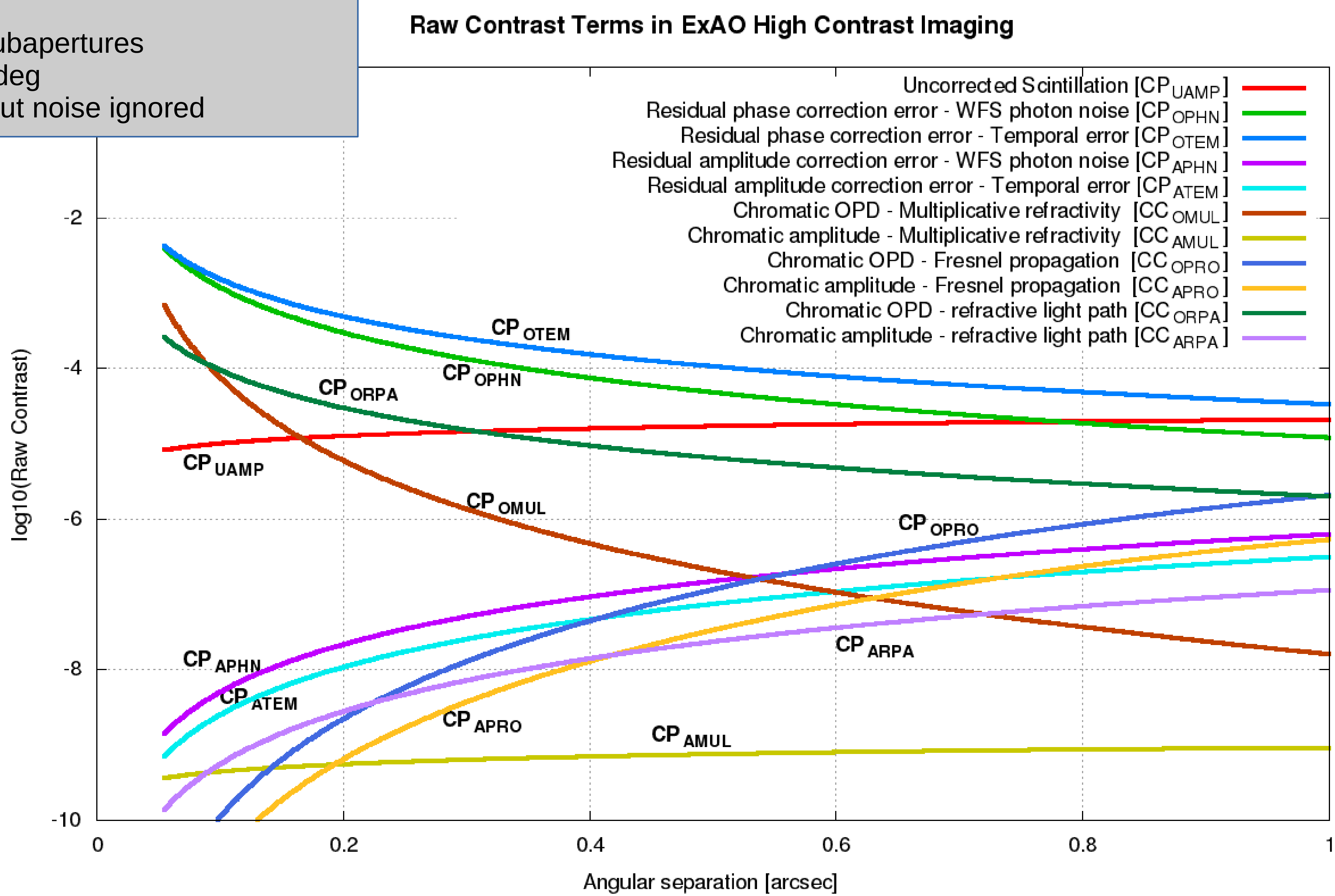
APLCMC design – Raw Contrast

(20 percentile along each radius)



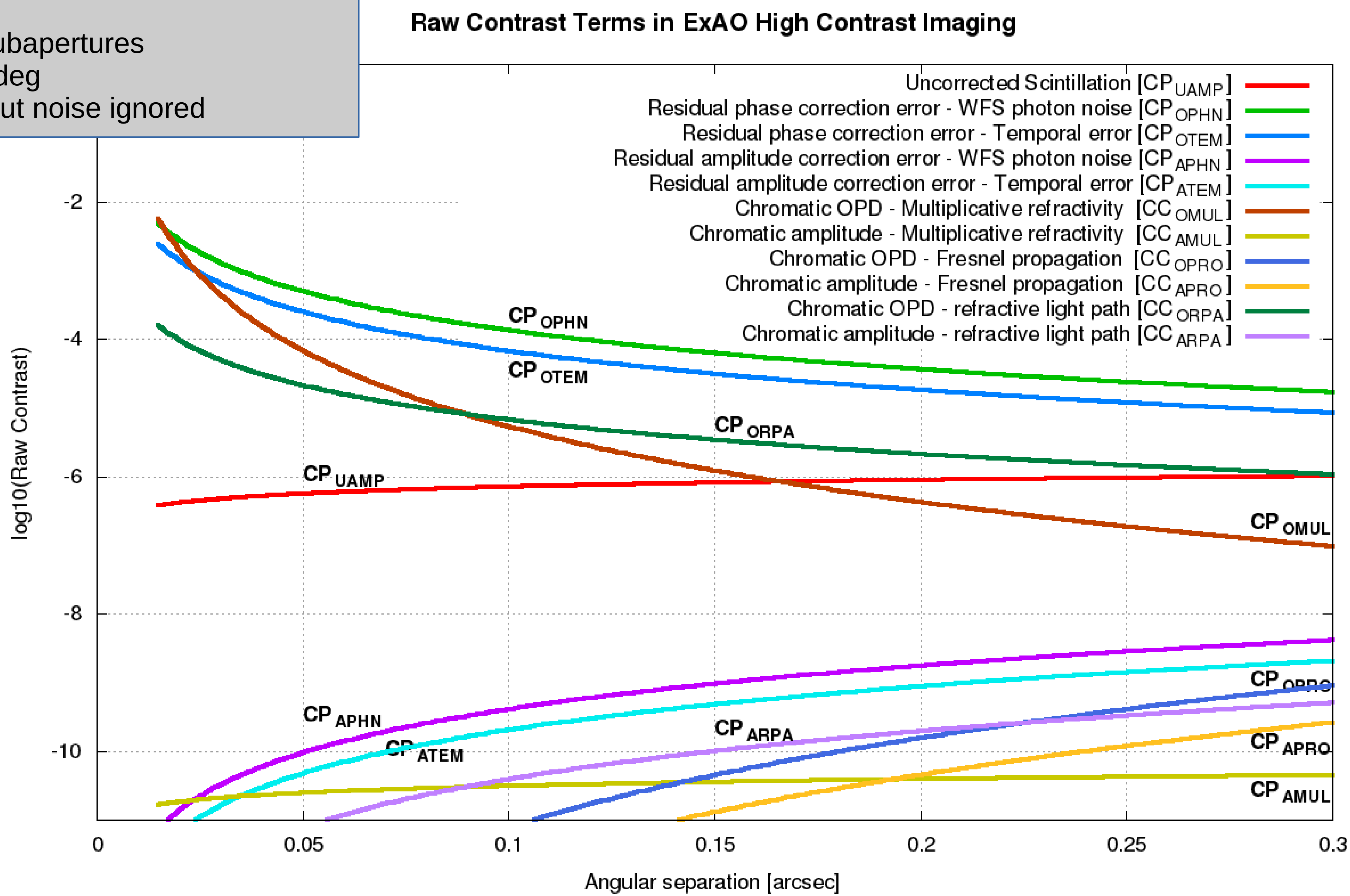
Contrast Error Budget (Primary WFC)

D=8m telescope
High contrast imaging at 1.6 um
Wavefront sensing at 0.8 um
30% efficiency WFS
40% wide WFS spectral band
1 kHz WFS frame rate
Integrator controller with optimal gain setting
Wind speed = 8 m/s
Fried parameter r_0 = 0.15 m at 0.5 um
m_I = 8 target
SHWFSm 15cm subapertures
Zenith angle = 40 deg
Aliasing and readout noise ignored



D=30m telescope
High contrast imaging at 1.6 um
Wavefront sensing at 0.8 um
30% efficiency WFS
40% wide WFS spectral band
5 kHz WFS frame rate
Integrator controller with optimal gain setting
Wind speed = 10 m/s
Fried parameter r_0 = 0.15 m at 0.5 um
m_I = 8 target
SHWFSm 15cm subapertures
Zenith angle = 40 deg
Aliasing and readout noise ignored

Contrast Error Budget (Primary WFC)



How ExAO@ GSMTs will differ from current "conventional" AO ?

Current AO systems (SPHERE, GPI) at ~<3 l/D : ~1e-3 raw contrast, ~1e-4 detection limit.
To image habitable planets, ExAO systems will require ~1000x gain in raw contrast (1e-6), and 10000x gain in detection limit (~1e-8)

Current limits, and how to overcome them:

Star is too faint for ExAO WFS

→ More efficient wavefront sensing (for example unmodulated pyramid) to provide >1000x gain in equivalent star brightness

→ Predictive Control

→ Sensor fusion between multiple sensors

Current systems are too slow → need low latency systems

→ Predictive control

→ Faster loop speed

Non-common path errors (including WF chromaticity) and slow speckles

→ Focal plane wavefront control + sensor fusion

Lyot Coronagraph doesn't provide required suppression at 2 l/D

→ Advanced coronagraphs (Vortex, PIAACMC etc…)

Planet image is still ~100x below starlight halo

→ High dispersion spectroscopy template matching

→ Coherent differential imaging (use coherence to separate starlight from planet light)

→ Use WF telemetry to subtract PSF

WFS/C : Game-changing advances

High-sensitivity WFS required to reduce WFS photon noise term

Focal plane "speckle control" addresses chromaticity and non-common path error terms

Predictive control and **sensor fusion** increase sensitivity and speed

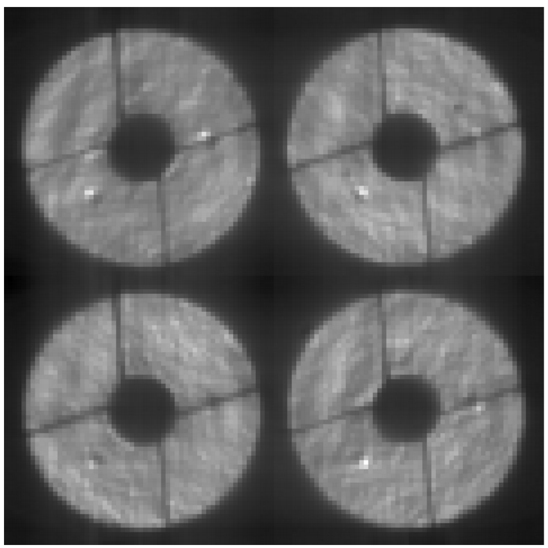
Machine learning based control loop self-calibrates system, and learns how to use WFS telemetry for PSF calibration

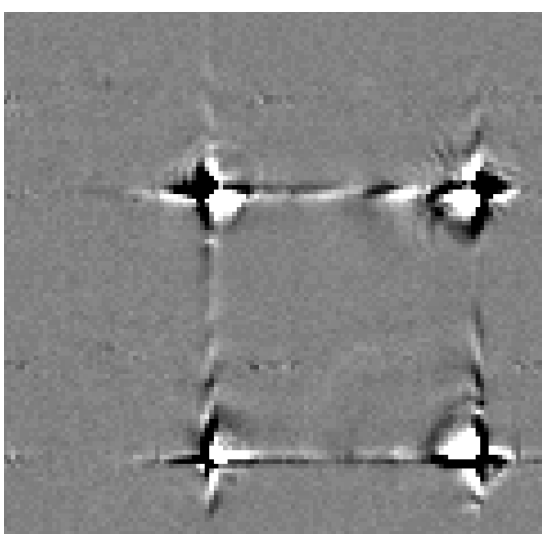
High-performance calibration approaches:

- **High dispersion coronagraphy**
- **Coherent differential imaging**

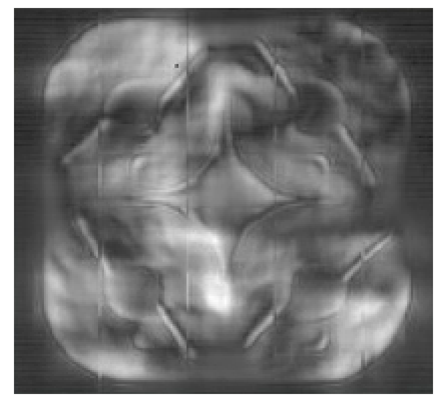
High performance WFS

Low-modulation PyWFS (600-900nm)
14400 sensors → 2000 actuators
loop runs at up to 3.5 kHz

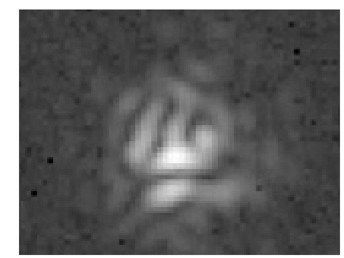


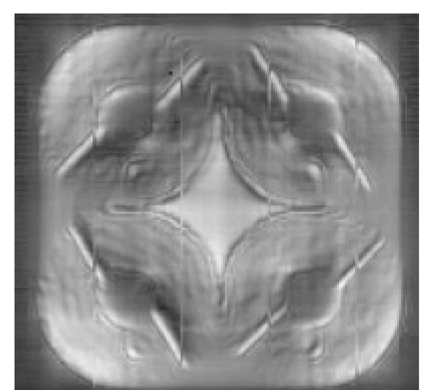


Unmodulated PyWFS demo (H band, SAPHIRA)
14400 sensors → 2000 actuators

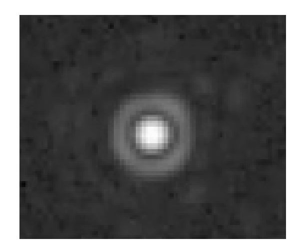


NearIR PyWFS correction OFF

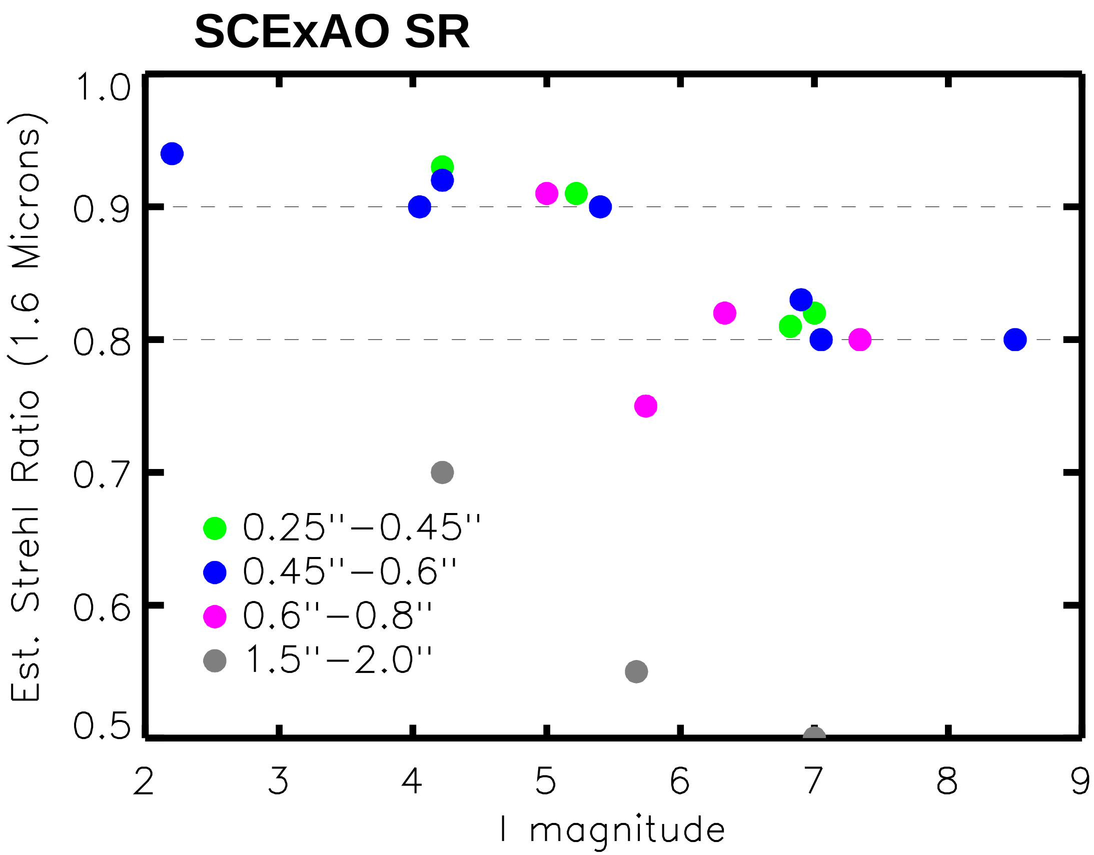


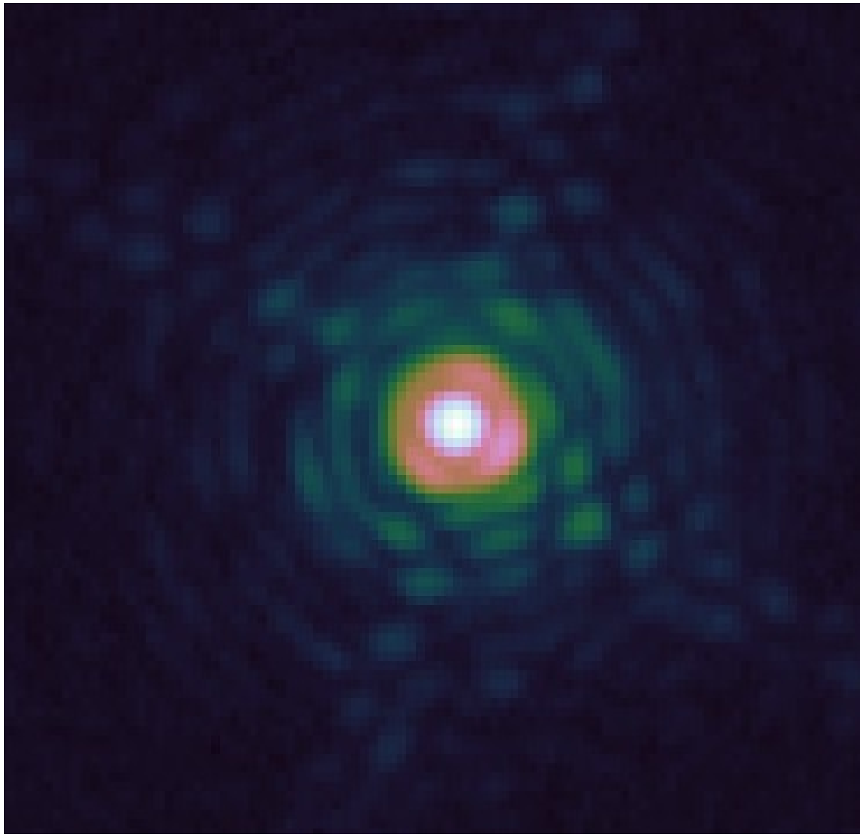


NearIR PyWFS correction ON



Faint Star Performance



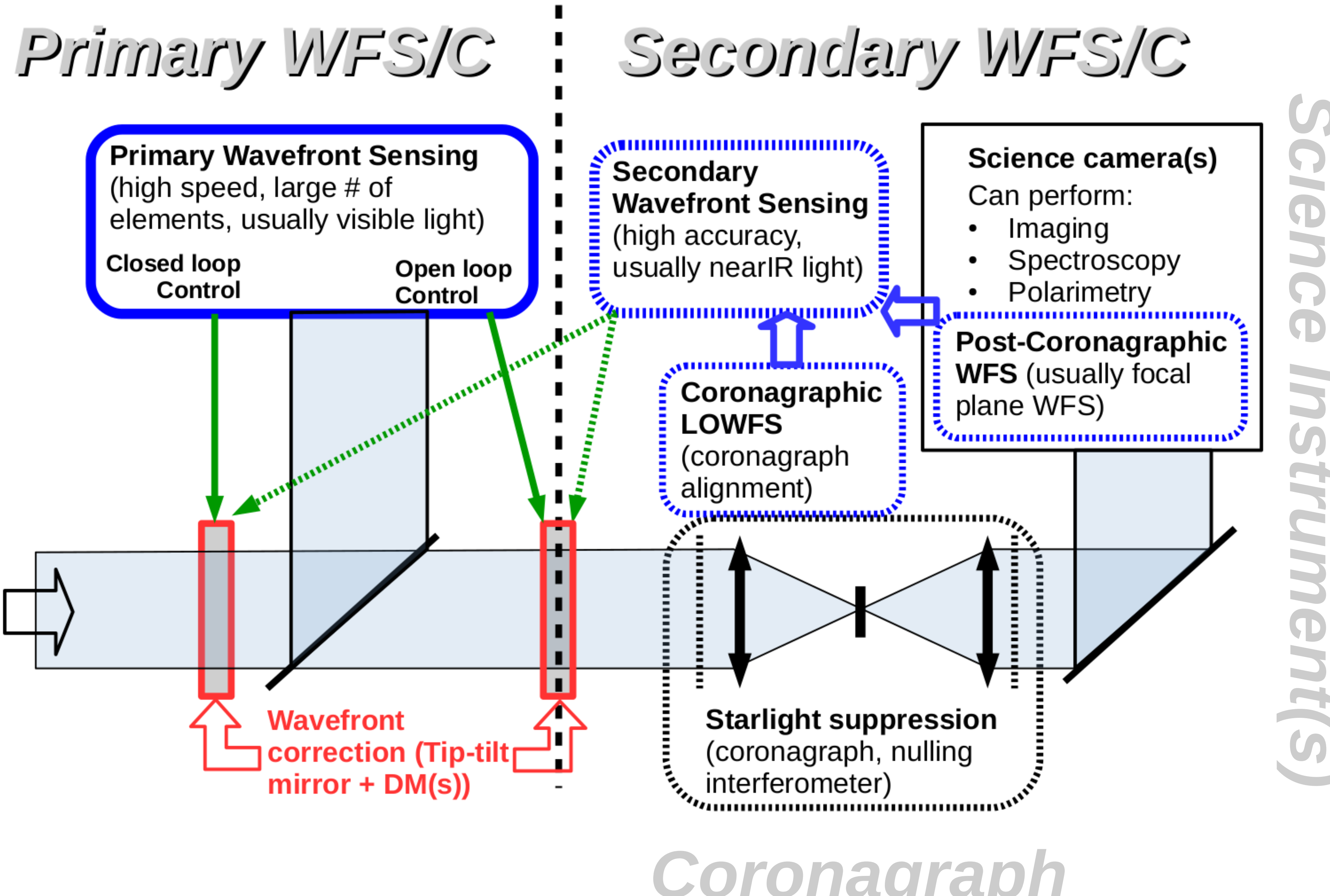


S.R. ~ 0.9 for bright stars under average to good conditions
x-AO correction demonstrated down to I ~ 9

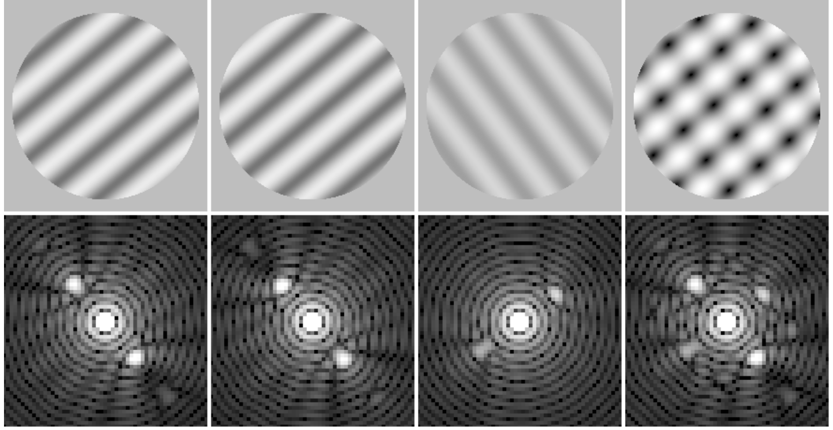
LkCa 15:
R ~ 11.6 star, K band

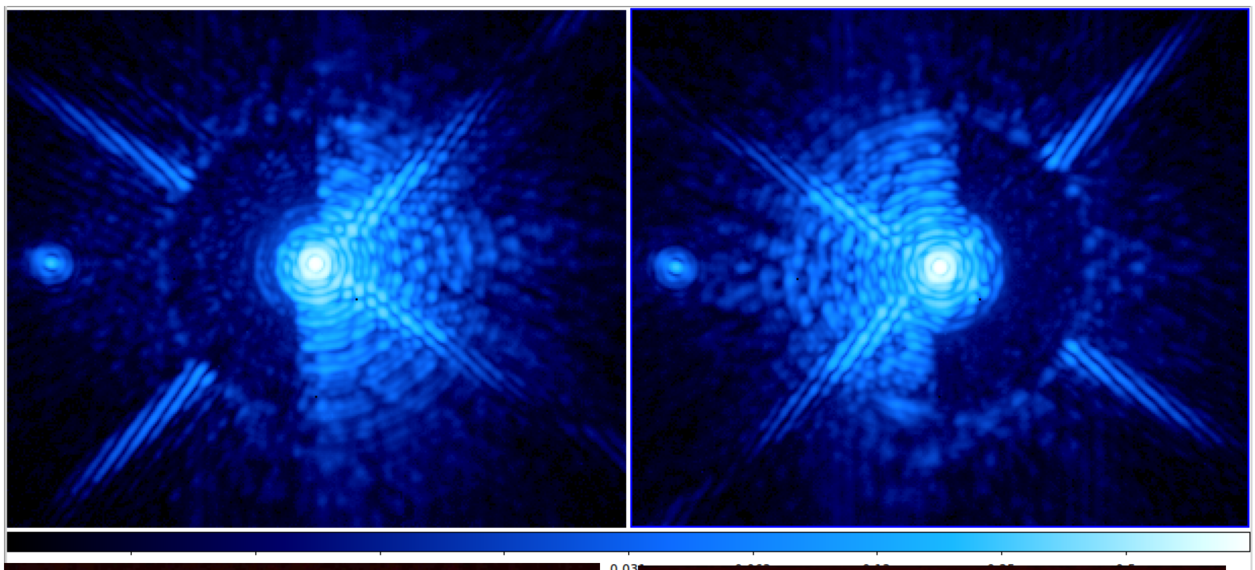
SR~0.65 @ H
Predictive control ON

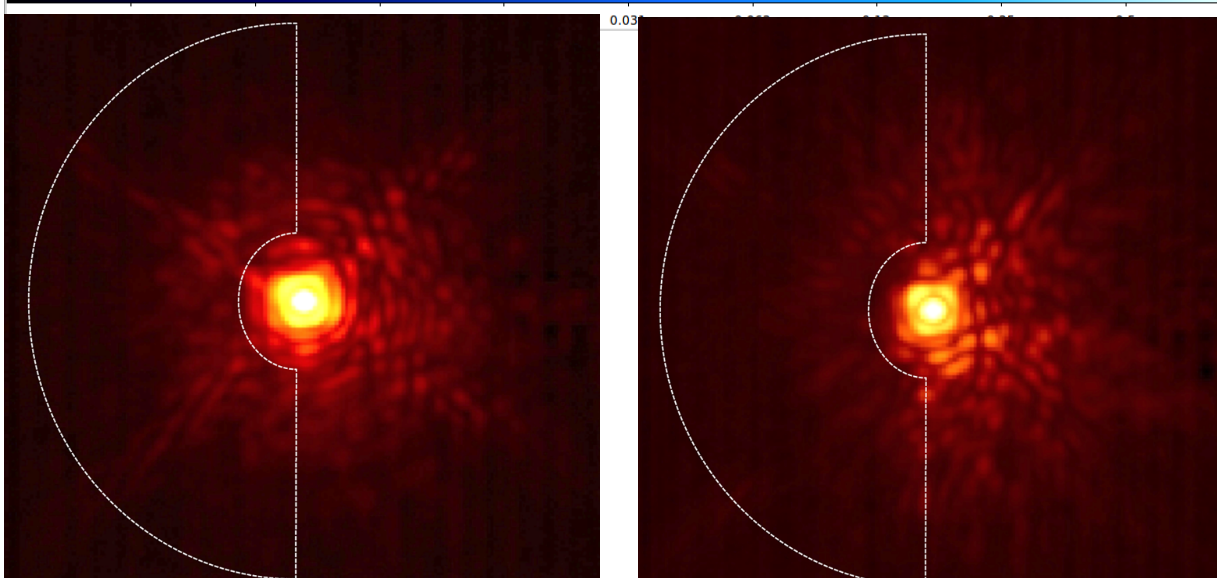
High Contrast Imaging System Architecture



Speckle Control







Speckle nulling, in the lab and on-sky (no XAO).

Experience limited by detector readout noise and speed.

KERNEL project: C-RED-ONE camera.

From:
- 114 e- RON
- 170 Hz frame rate

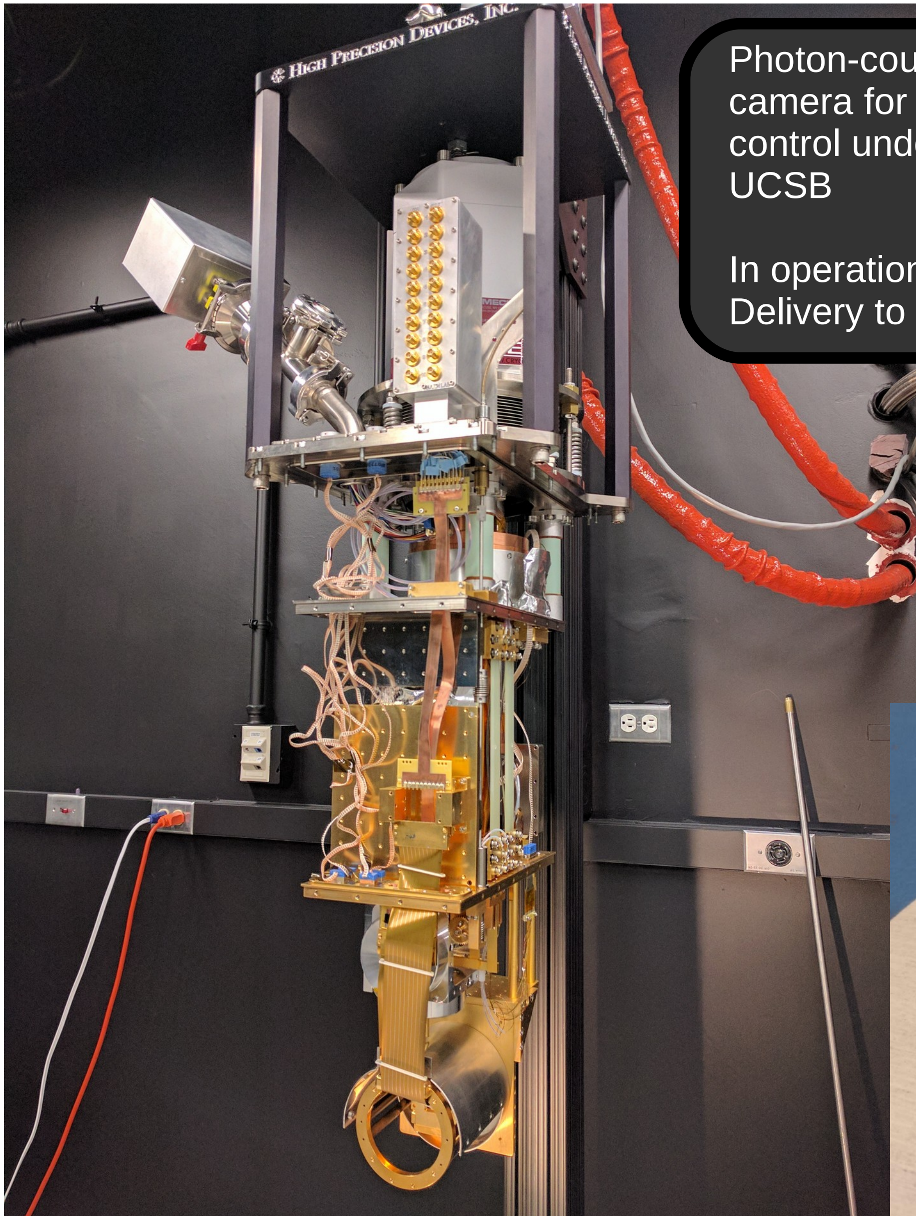
To:
- 0.8 e- RON
- 3500 Hz frame rate

Expect some updates

Observatoire de la CÔTE d'AZUR

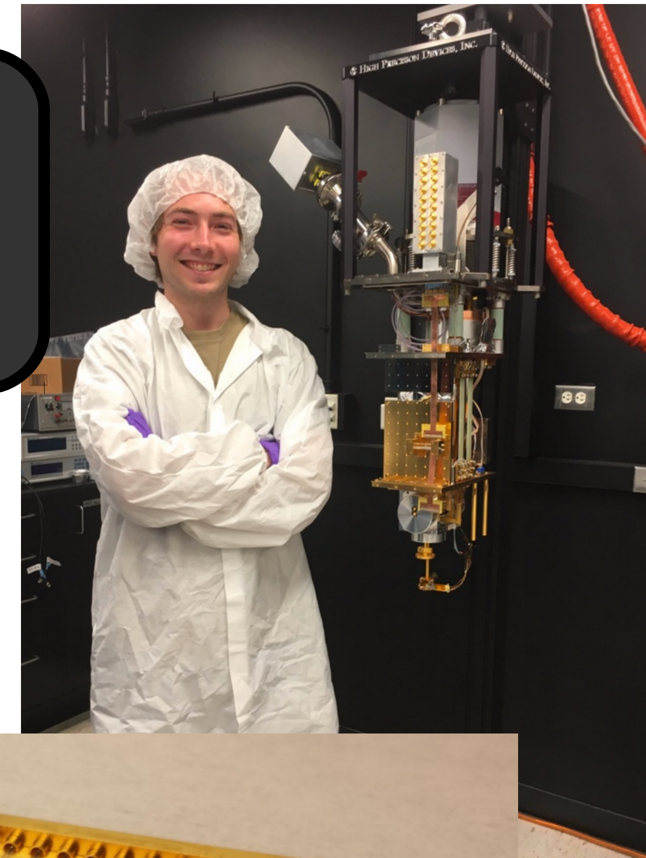
MKIDS camera (Ben Mazin, UCSB)

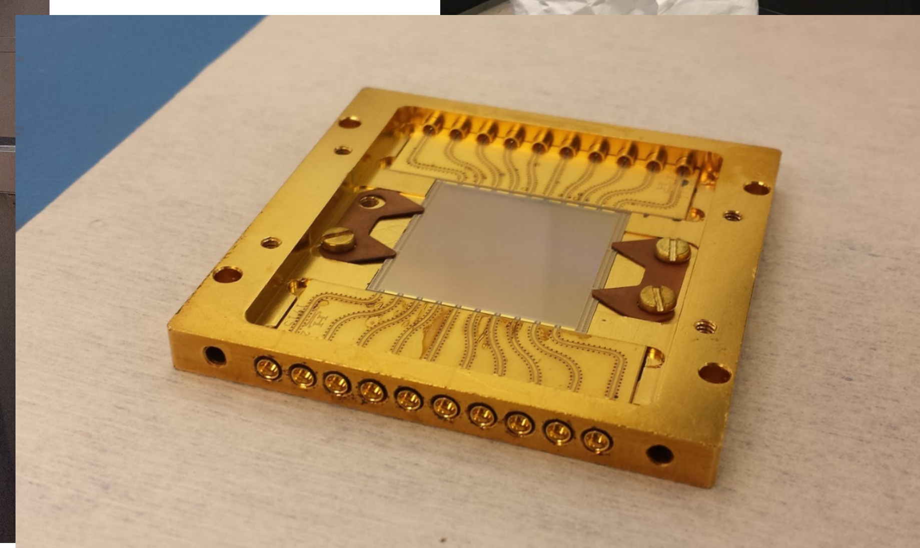
Photon-counting, wavelength resolving 140x140 pixel camera

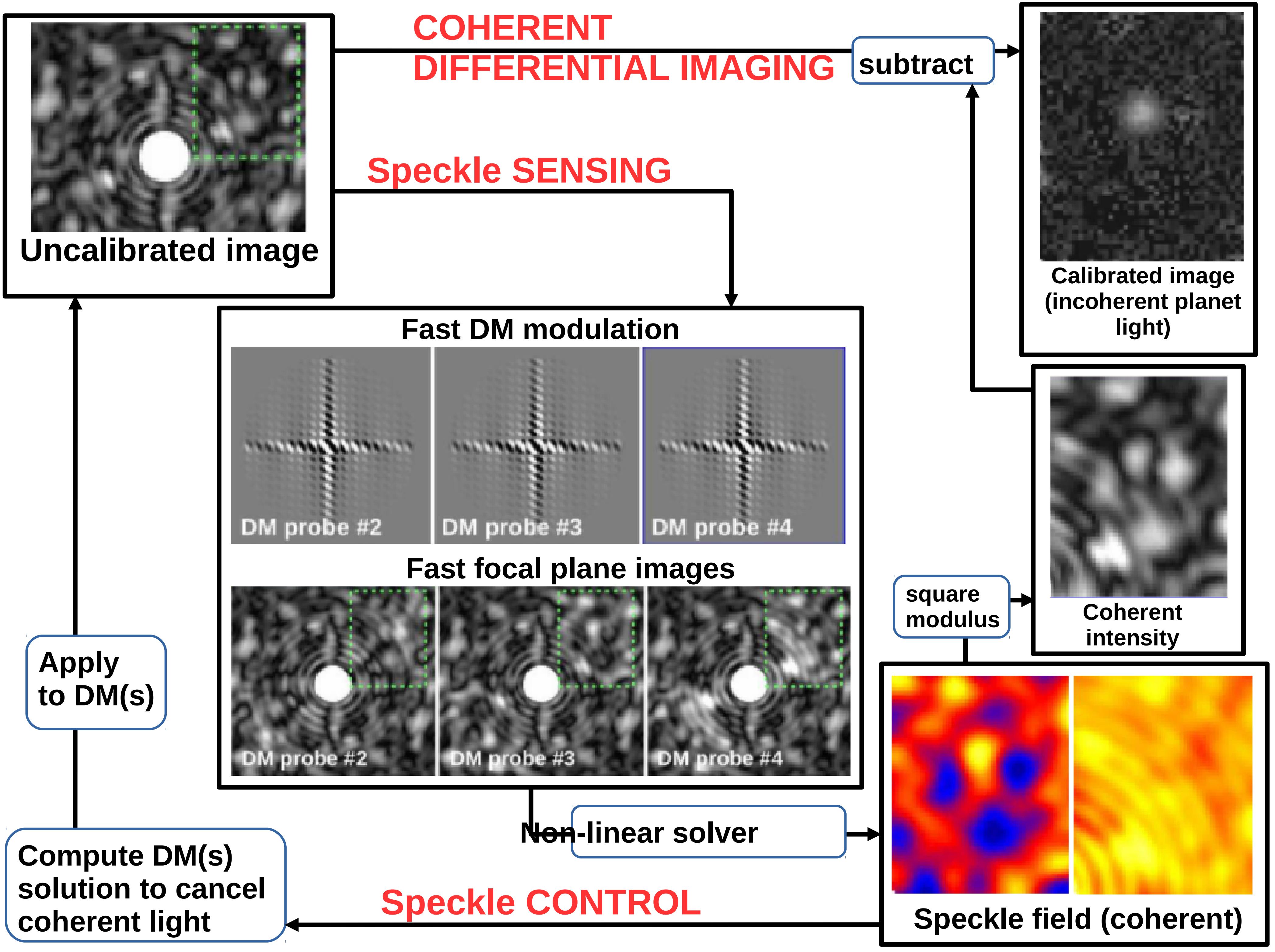


Photon-counting near-IR MKIDs camera for kHz speed speckle control under construction at UCSB

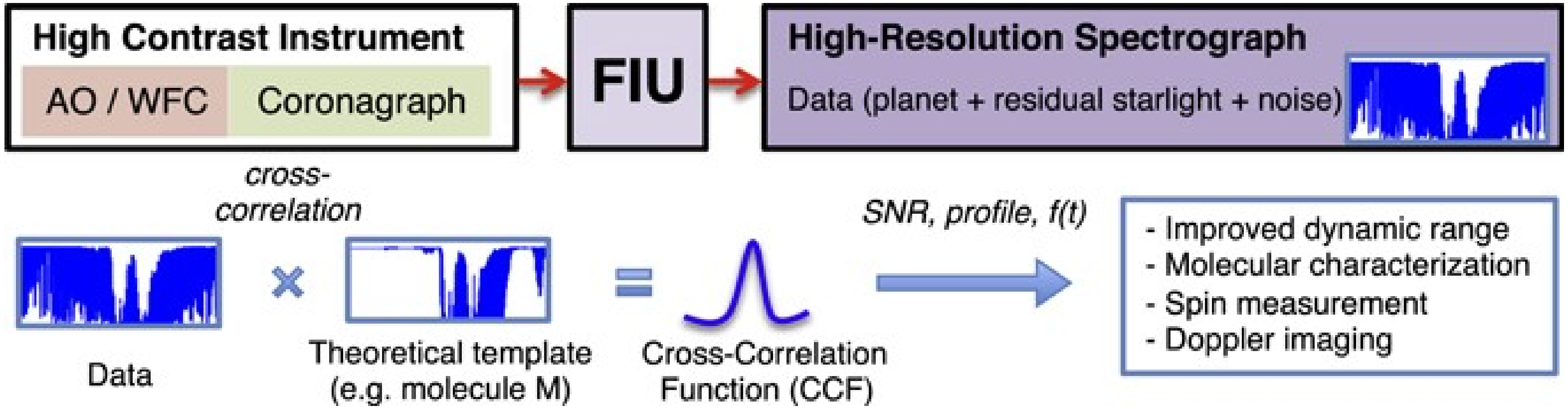
In operation @ Palomar
Delivery to SCExAO March 2018

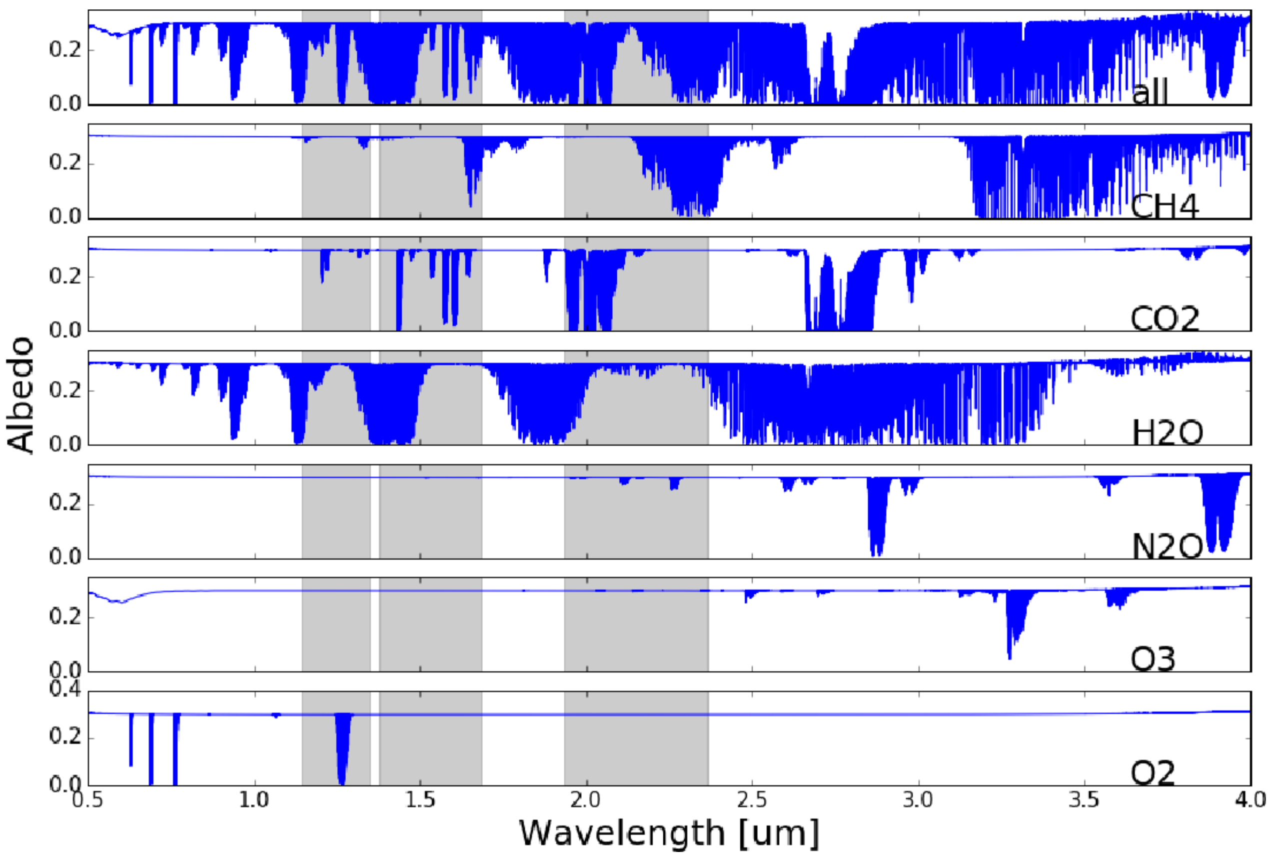





Uncalibrated image
COHERENT
DIFFERENTIAL IMAGING
subtract
Calibrated image
(incoherent planet
light)
Speckle SENSING
Fast DM modulation
DM probe #2
DM probe #3
DM probe #4
Fast focal plane images
DM probe #2
DM probe #3
DM probe #4
square
modulus
Coherent
intensity
Apply
to DM(s)
Non-linear solver
Speckle field (coherent)
Compute DM(s)
solution to cancel
coherent light
Speckle CONTROL

High Dispersion Coronagraphy





Very robust differential signature

First demonstrated on combined light (no coronagraph) – Snellen et al.

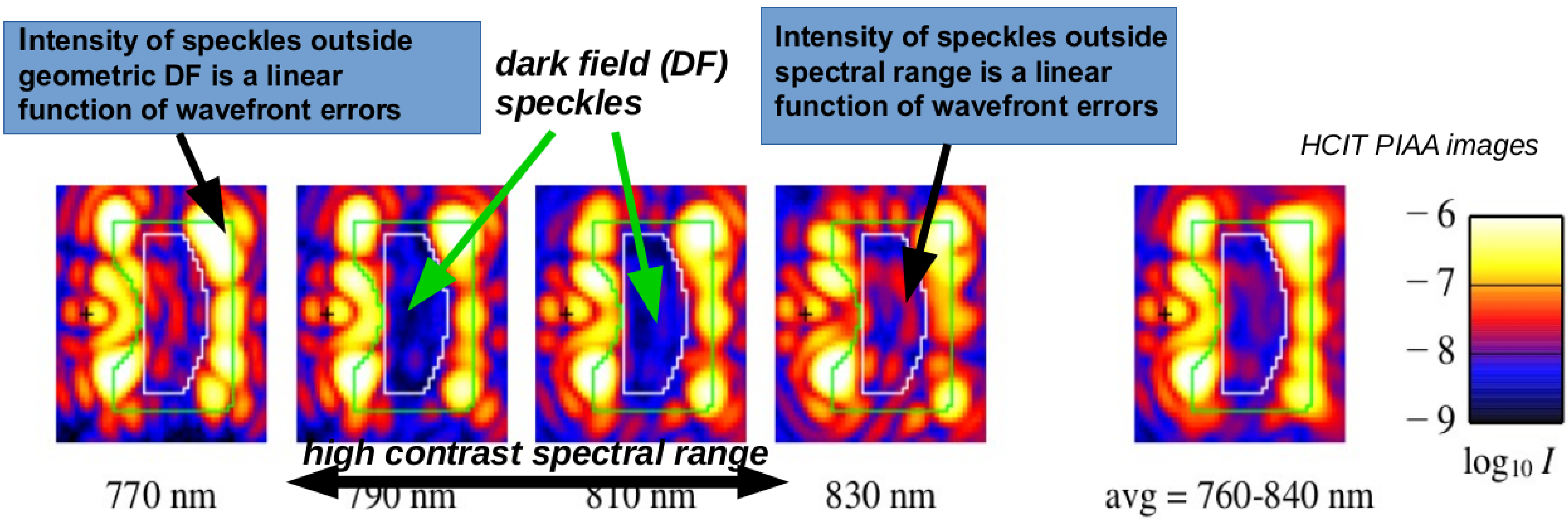
Mawet, Wang et al.

Linear Dark Field Control (LDFC)

See also: Miller et al. 2017, Guyon et al. 2017 (astro-ph)

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



Predictive Control and Sensor Fusion

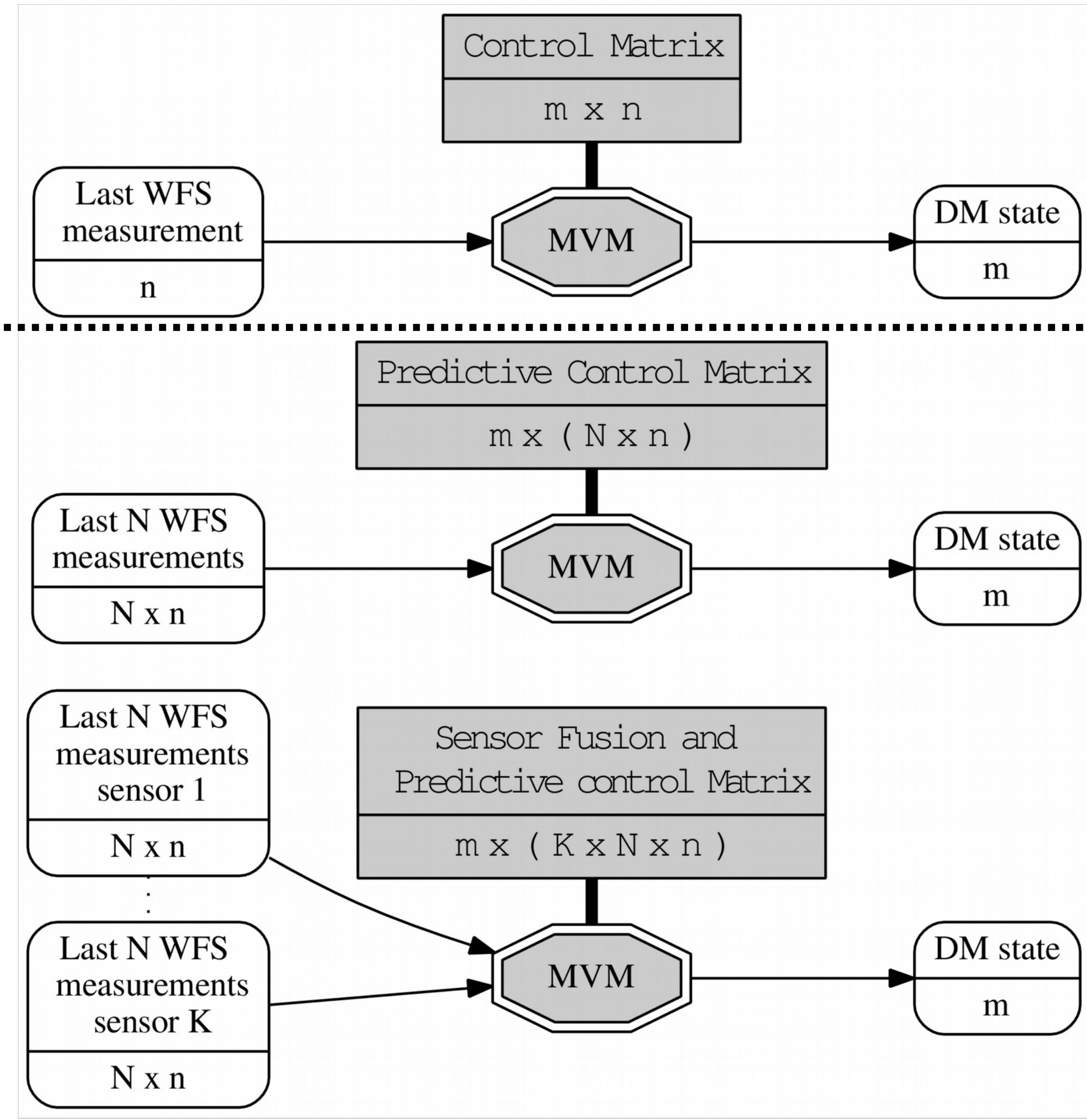
Conventional AO:

We **measure** RM/CM

Advanced AO control:

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

We **derive** CM from WFS(s) telemetry



Predictive control & sensor fusion→ 100x contrast gain ?

See also: Males & Guyon 2017 (astro-ph)

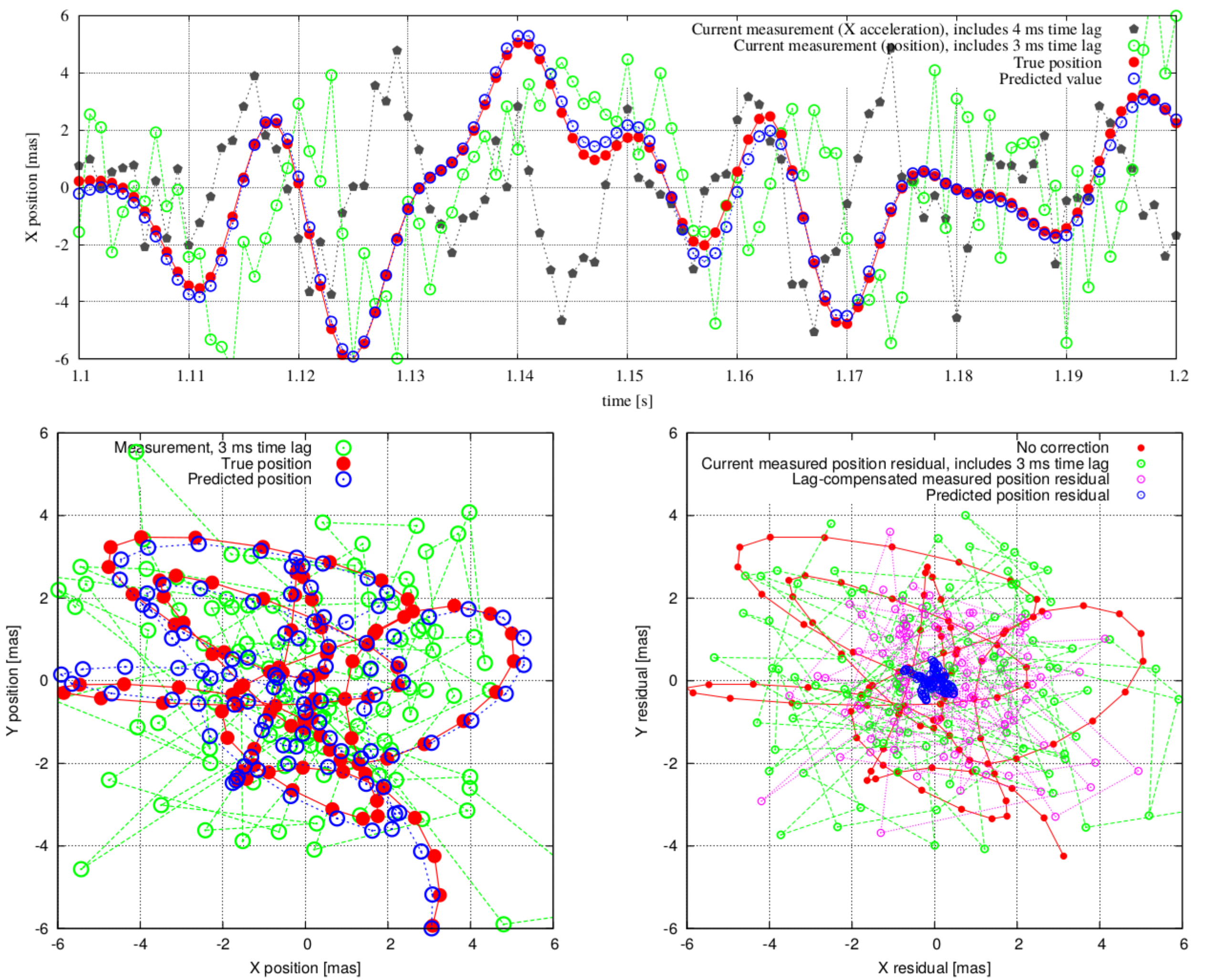
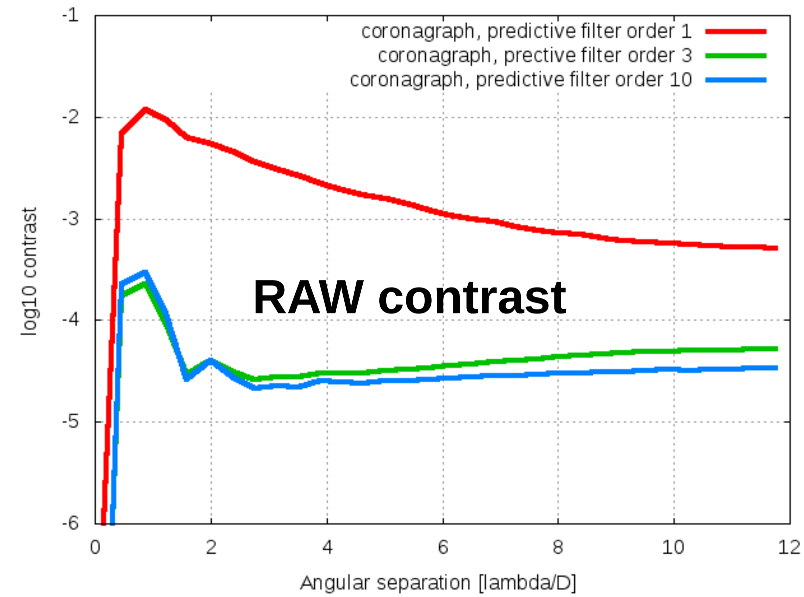
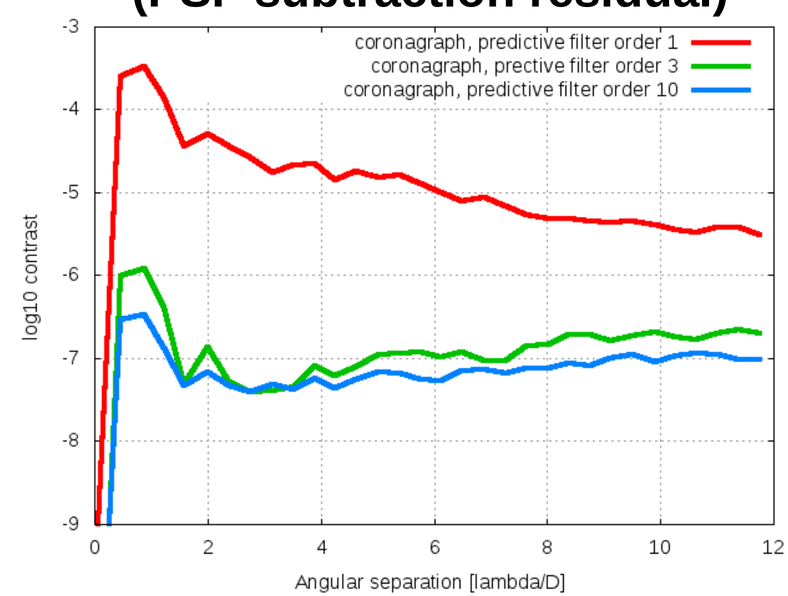


FIG. 3.— Top left: 2D-tracks for true pointing (red), predicted pointing (blue) and last measured position (green). Top right: Residual pointing error. Bottom: Single axis (x) values.



1hr detection limit (PSF subtraction residual)



The Machine Learning challenge

Need to derive 100s of millions of CM values within minutes, using billions of samples...

Example:
SCExAO, 3 kHz, 10-step predictive control, 100 sec training
Input: 14,400 x 3,000 x 100 = 4.32e9 measurements
Output: 14,400 x 2000 x 10 = 288e6 CM coefficients

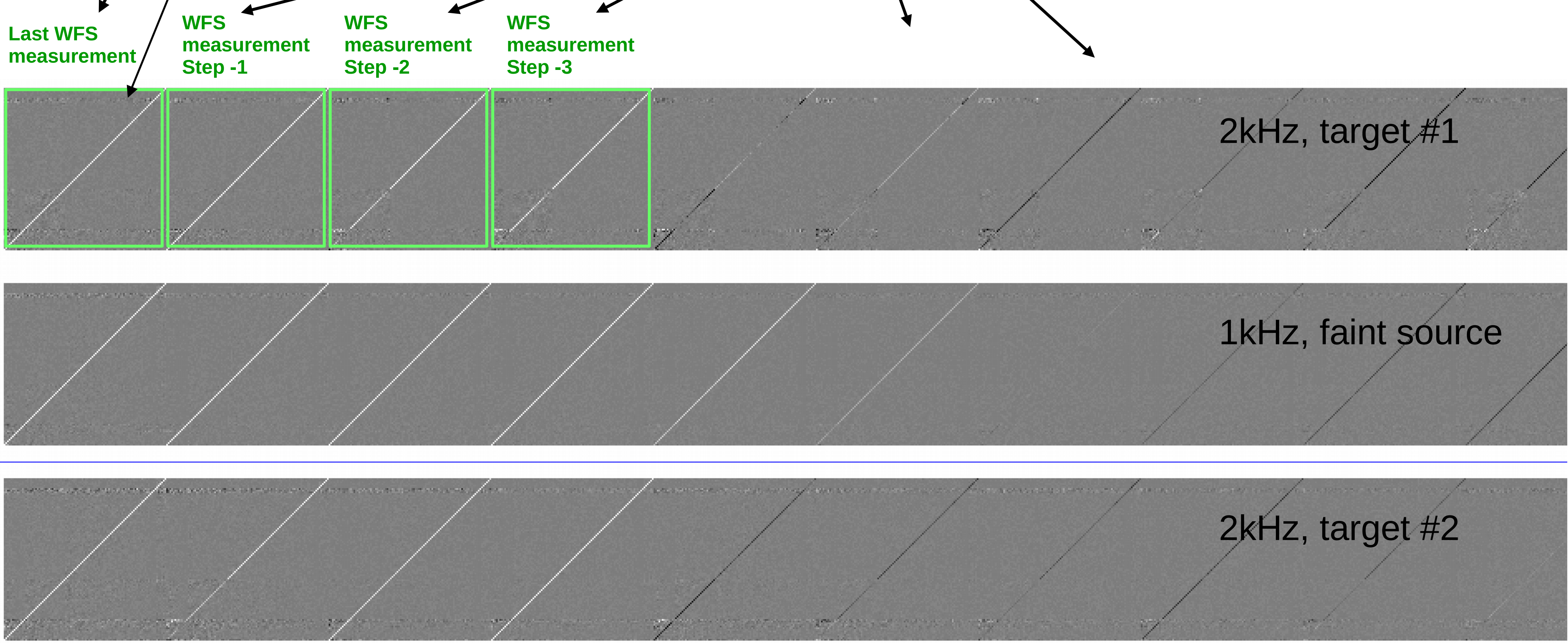
Solution:
We deploy linear ***Machine Learning*** technique on a modal control space (smaller # of dimensions).
We use GPU cores (35,000 cores @ 1.6 GHz in SCExAO main RTC).

Prediction control matrix (100 modes shown)

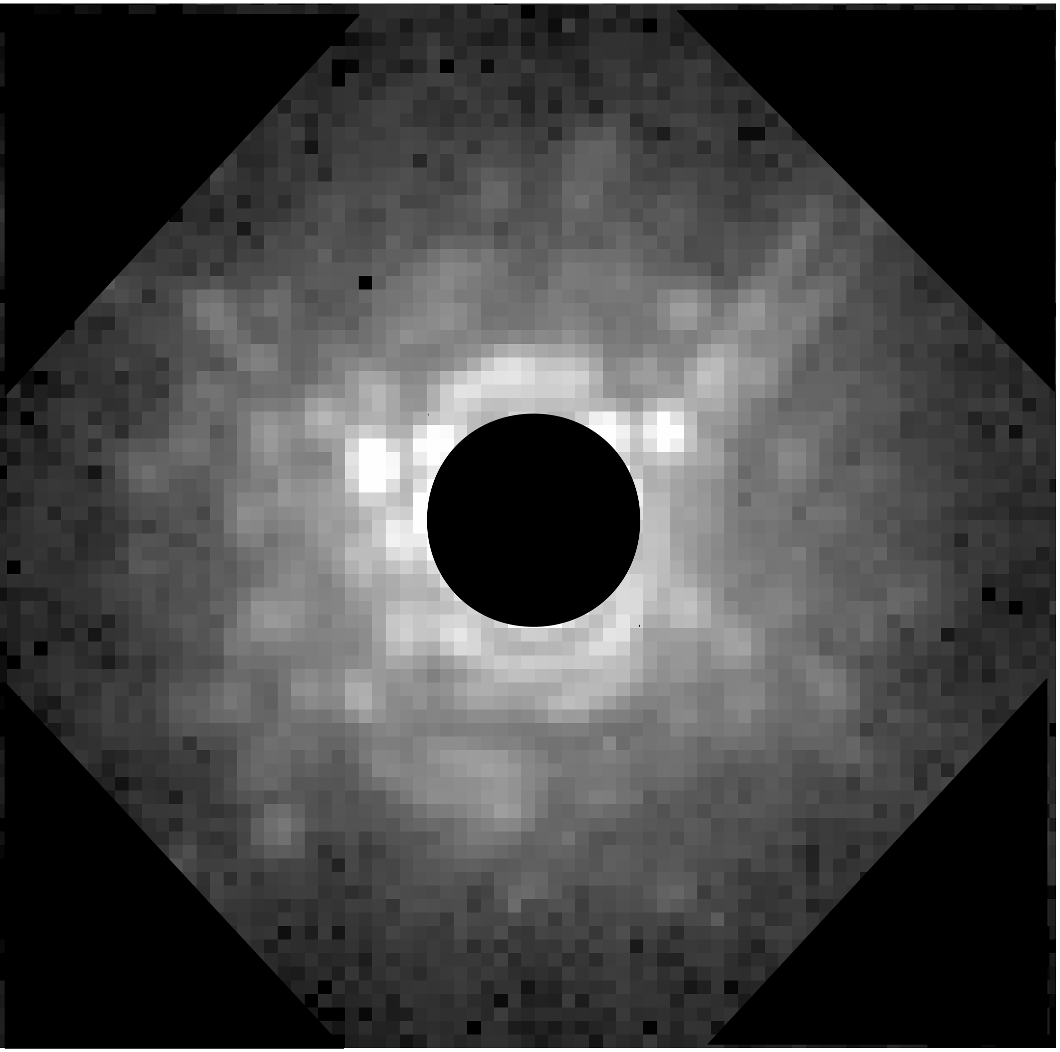
Conventional AO would have control matrix 100 x 100 elements Identity matrix

Optimal control adds elements outside of diagonal

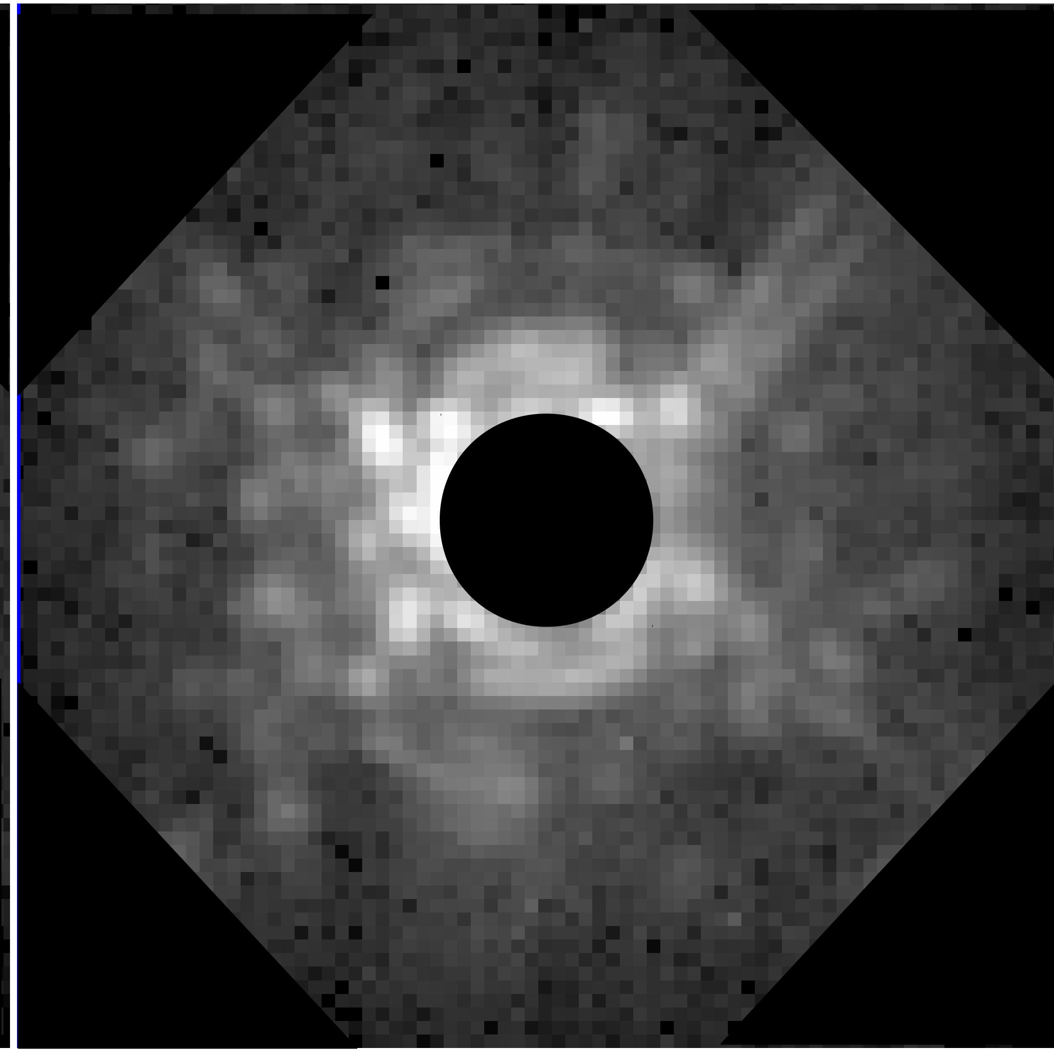
Predictive control adds these blocks to control matrix



First on-sky results (2 kHz, 50 sec update) → 2.5x raw contrast improvement



OFF (integrator, gain=0.2)



ON

Average of 54 consecutives 0.5s images (26 sec exposure), 3 mn apart
Same star, same exposure time, same intensity scale

Planning future instruments

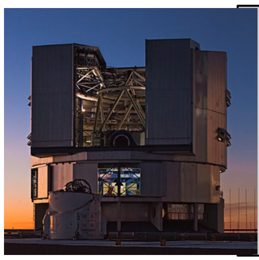
- **From 10m-class telescopes to 30m-class telescopes**
- **ELT, TMT and GMT plans**

BREAKTHROUGH
WATCH

10um Ground Based Imaging

Phase 1 (Alpha Cen, VLT/Gemini/Magellan) effort will enable Phase 2 (ELTs) imaging and characterization of habitable planets around a dozen nearby stars

Thermal IR imaging/spectroscopy detects habitable exoplanets, measures radius and temperature + some chemical species (CO_2, H_2O, O_3)
Overlap with space missions targets (reflected visible light) → Direct measurement of greenhouse effect and detailed characterization of atmospheres.



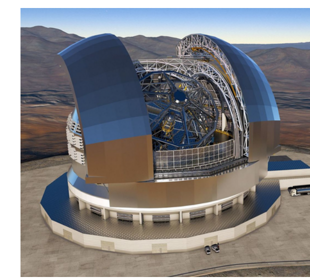
ESO VLT observation campaign

Gemini South observation campaign

Magellan Telescope Observation campaign

Detector development

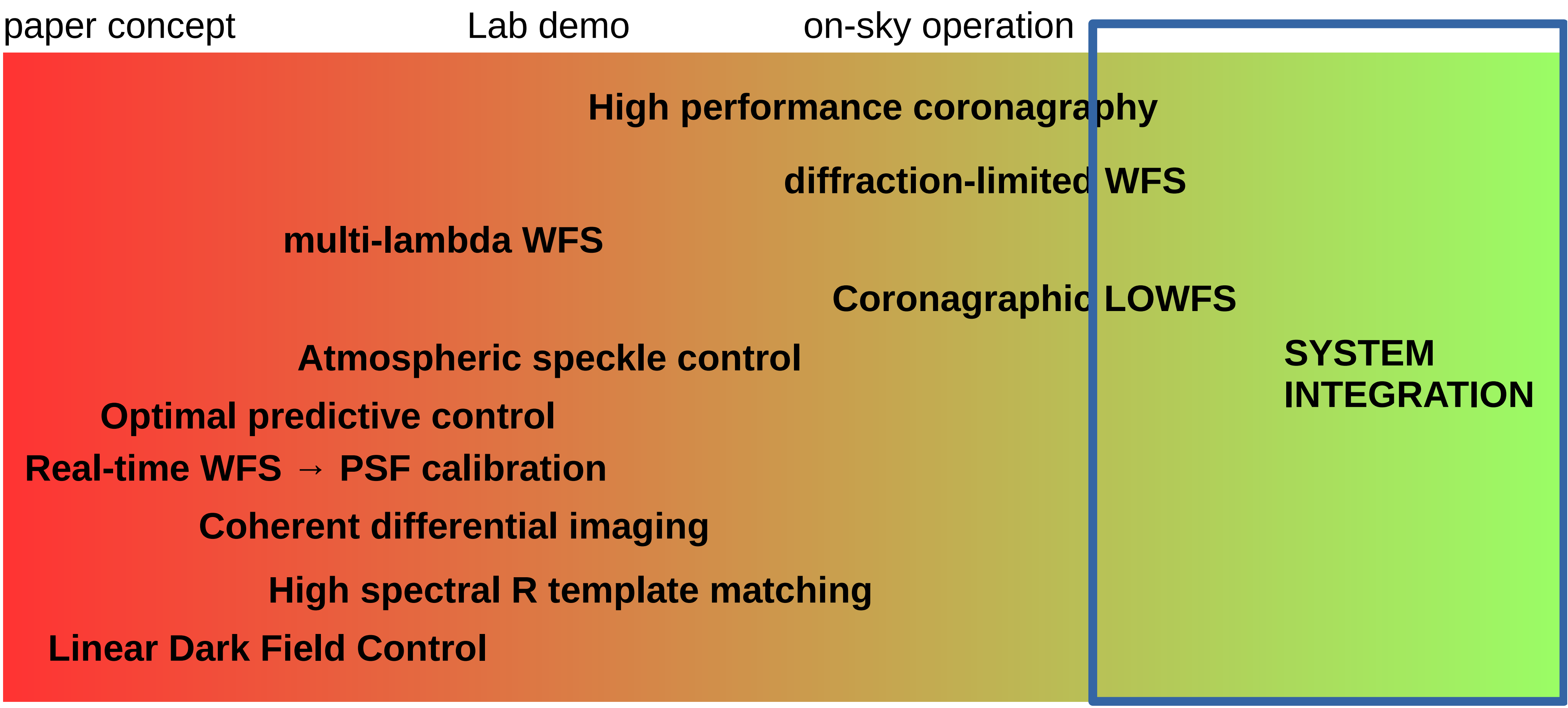
E-ELT: METIS instrument upgrade for exoplanet imaging (first generation instrument)



TMT: Considering MIR instrument
visitor instrument possible

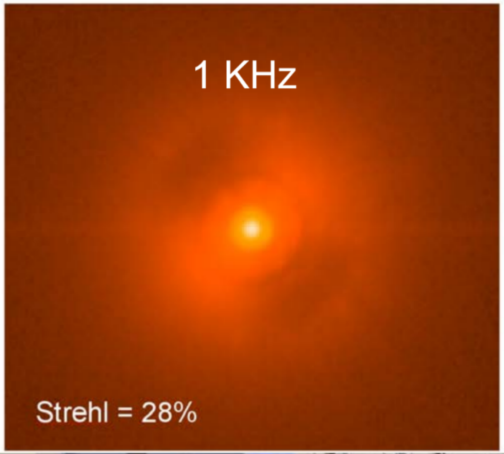
GMT: Considering MIR instrument (TIGER)
visitor instrument possible

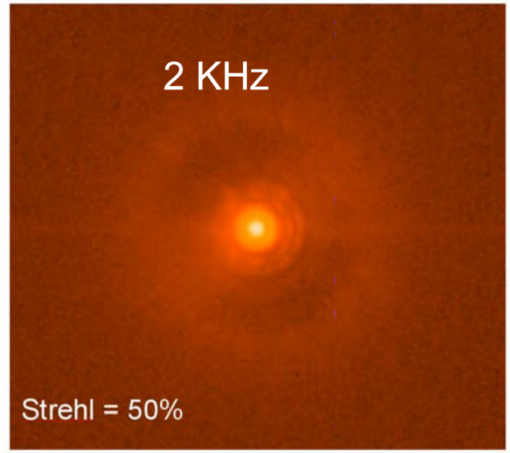
Key technologies need rapid maturation from paper concepts to system integration



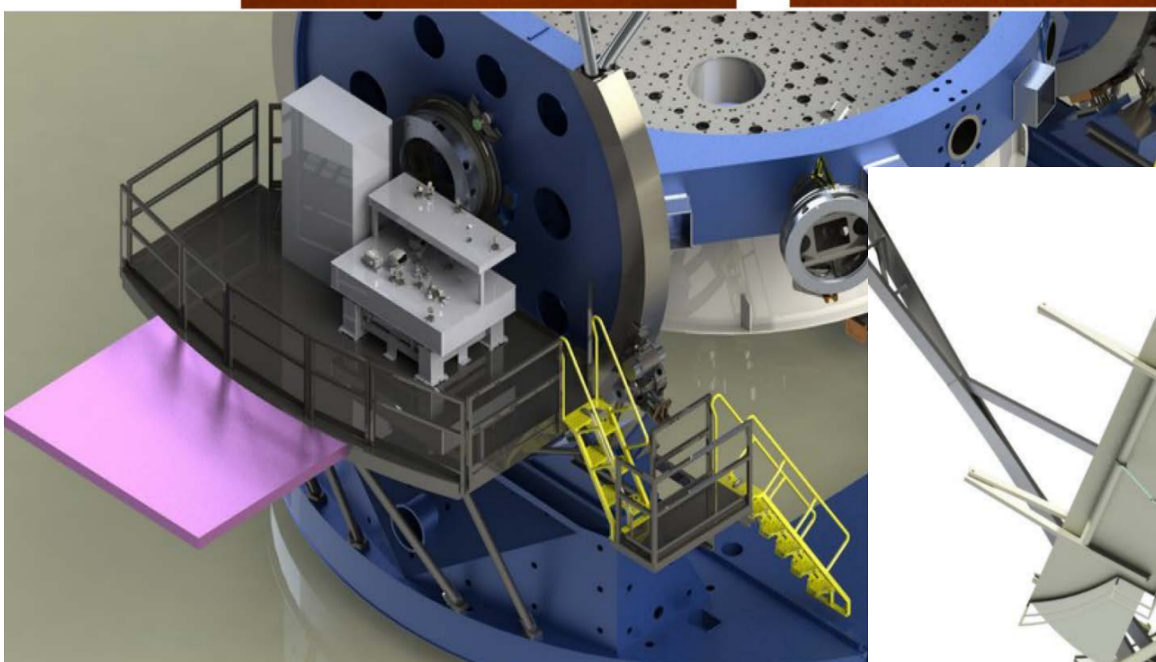
MagAO → MagAO-2k → MagAO-X → GMTAO-X

(Males, Close, Guyon et al.)



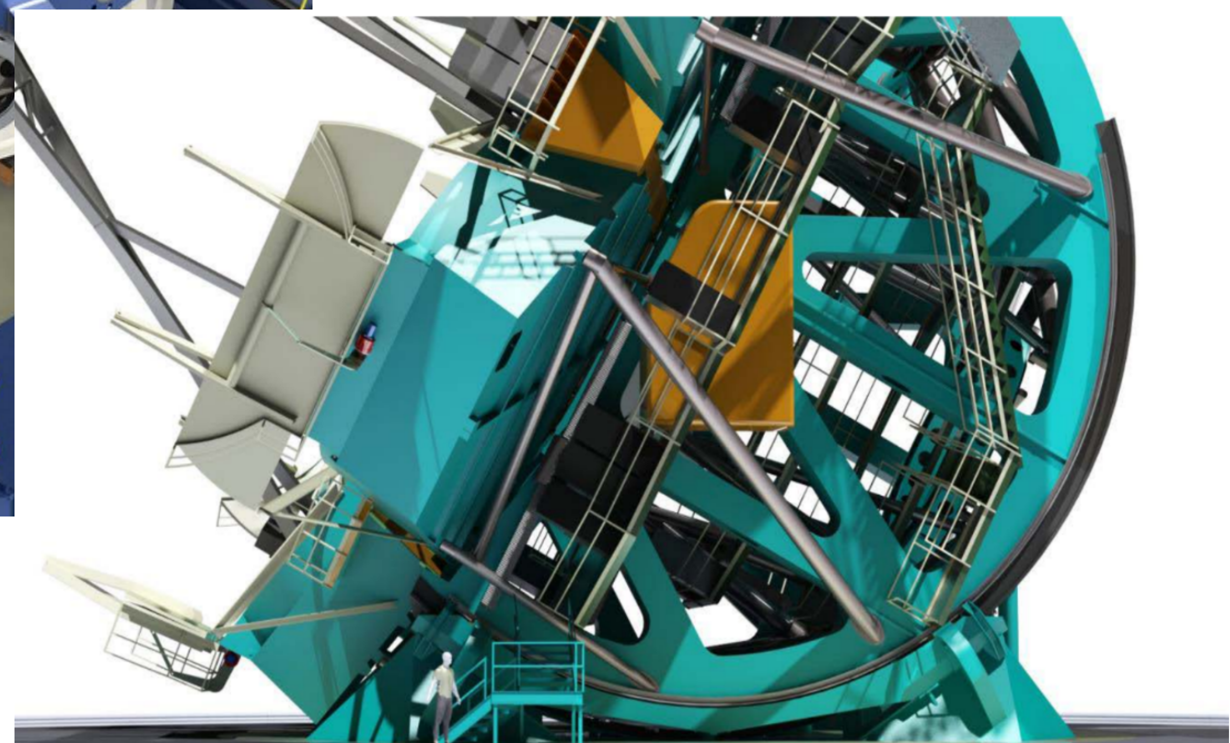


MagAO → MagAO-2k upgrade
High-perf AO in optical (0.9um)

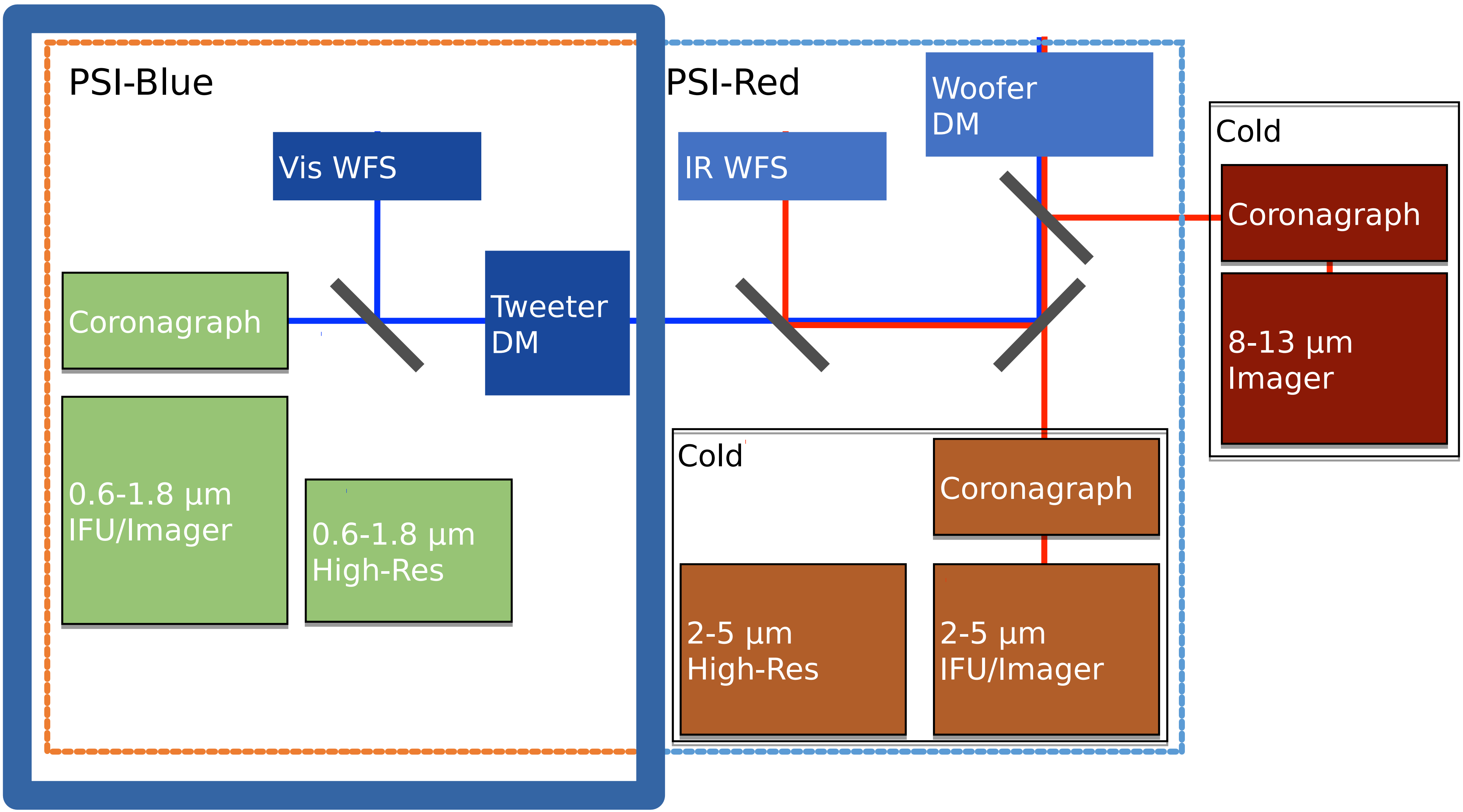


MagAO-X
Extreme-AO @ Magellan
Under construction, NSF-funded
(Males et al.)

GMTAO-X concept

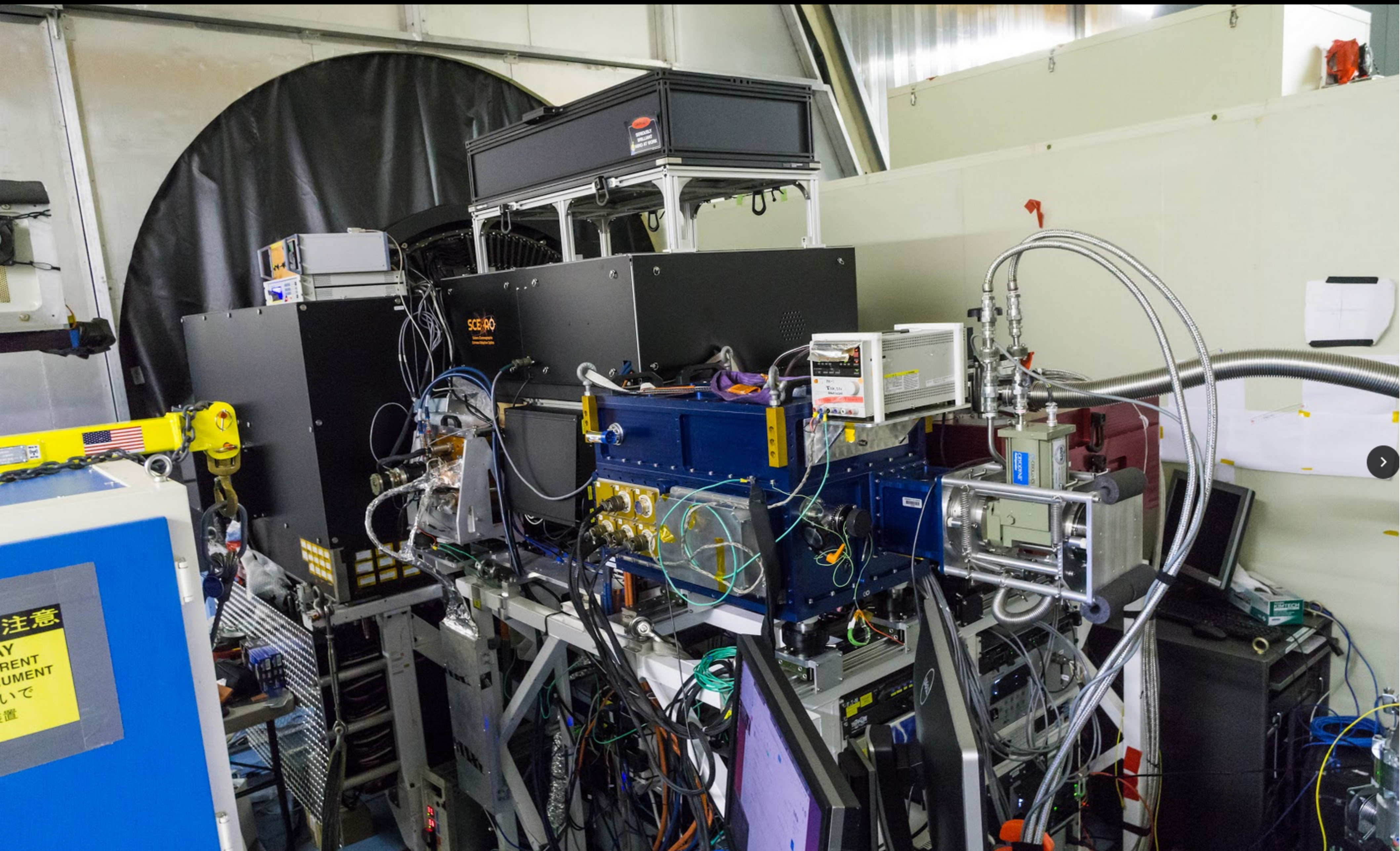


TMT PST concept

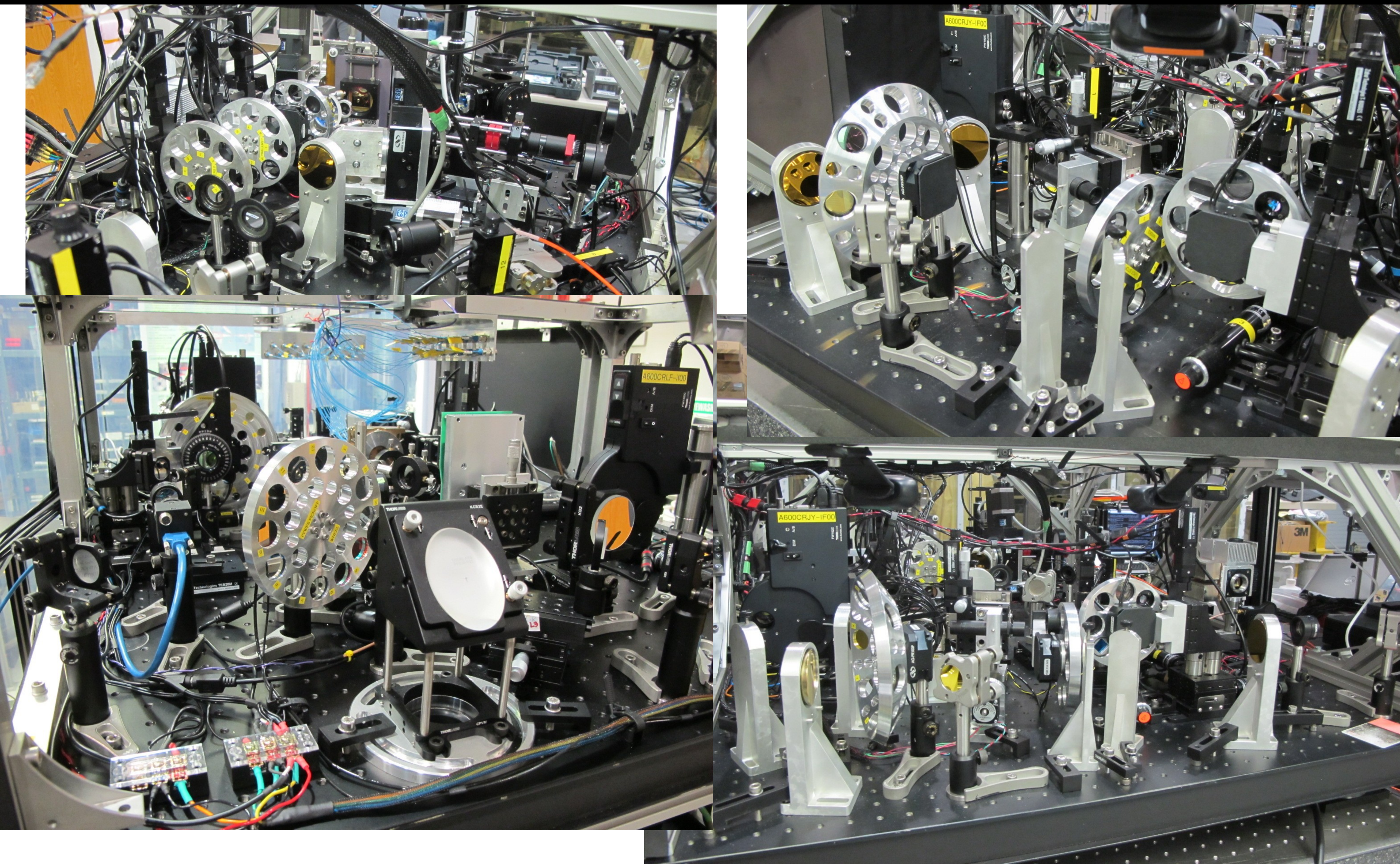


Flexible system / ongoing development

Subaru Coronagraphic Extreme Adaptive Optics



Subaru Coronagraphic Extreme Adaptive Optics



Conclusions, thoughts...

High contrast imaging instrument on GSMTs using current technology would be scientifically extremely rewarding → **should be deployed ASAP after first light**

Opportunity to detect biomarkers on nearest hab exoplanets in 10yr
Fundamental advantages: large aperture, near-IR access

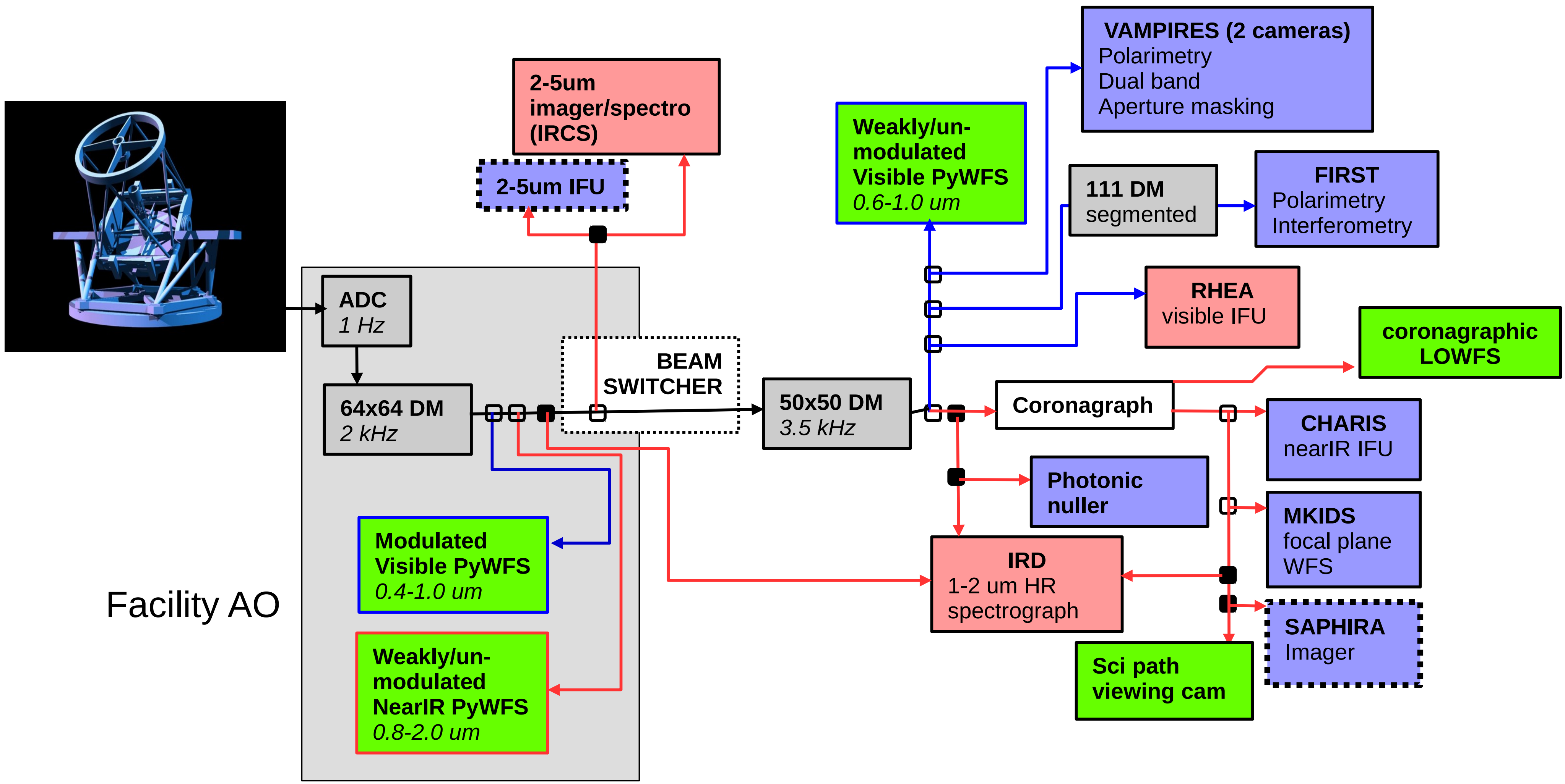
Search for biomarkers on habitable planets around M-type stars is within reach of GSMTs, but still requires technology maturation at intermediate TRL
→ currently difficult to estimate with certainty science yield of GSMTs for hab planet characterization, but easiest targets (Prox Cen b) appear very promising

We should aim for HCI instrument deployment in ~10yr timescale
→ need to start design NOW
→ must welcome new technologies to allow challenging science (most tech dev has small impact on instrument design: algorithms, detectors, coronagraph masks)

Must create / use ecosystem of lab+on-sky precursors to mature technologies, and develop/test hardware and **better integrate technology development for space and ground systems**

Subaru Coronagraphic Extreme Adaptive Optics

SCExAO Light path



Active WF correction
Dedicated science instrument
Mixed science/WFS
Dedicated WFS
Visitor port
dichroic
beam switch

11 wavefront sensors