Imaging Exoplanets

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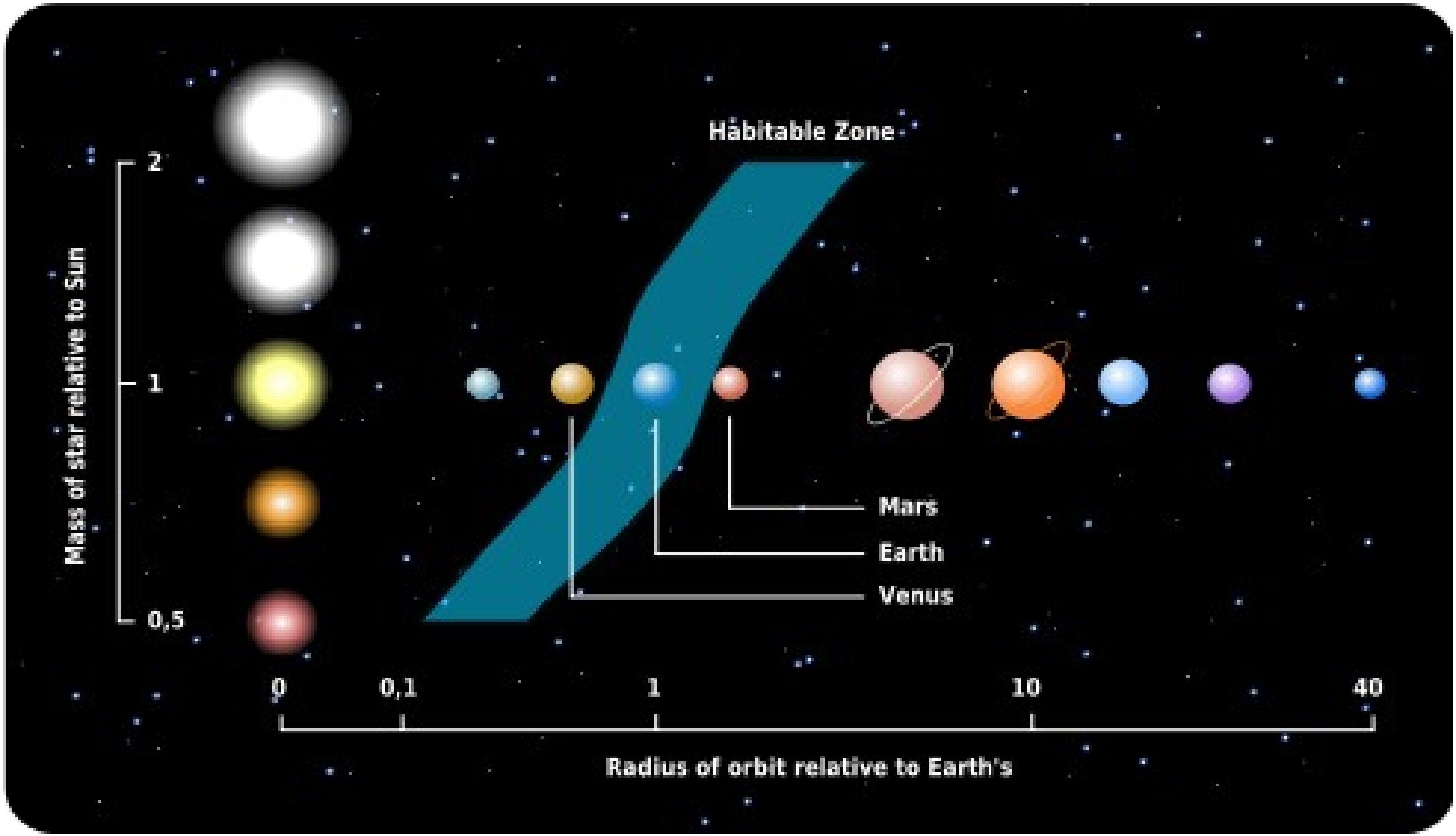
Habitable zone of a star



How do astronomers identify exoplanets ?

HIGH PRECISION OPTICAL MEASUREMENTS OF STARLIGHT (indirect techniques)

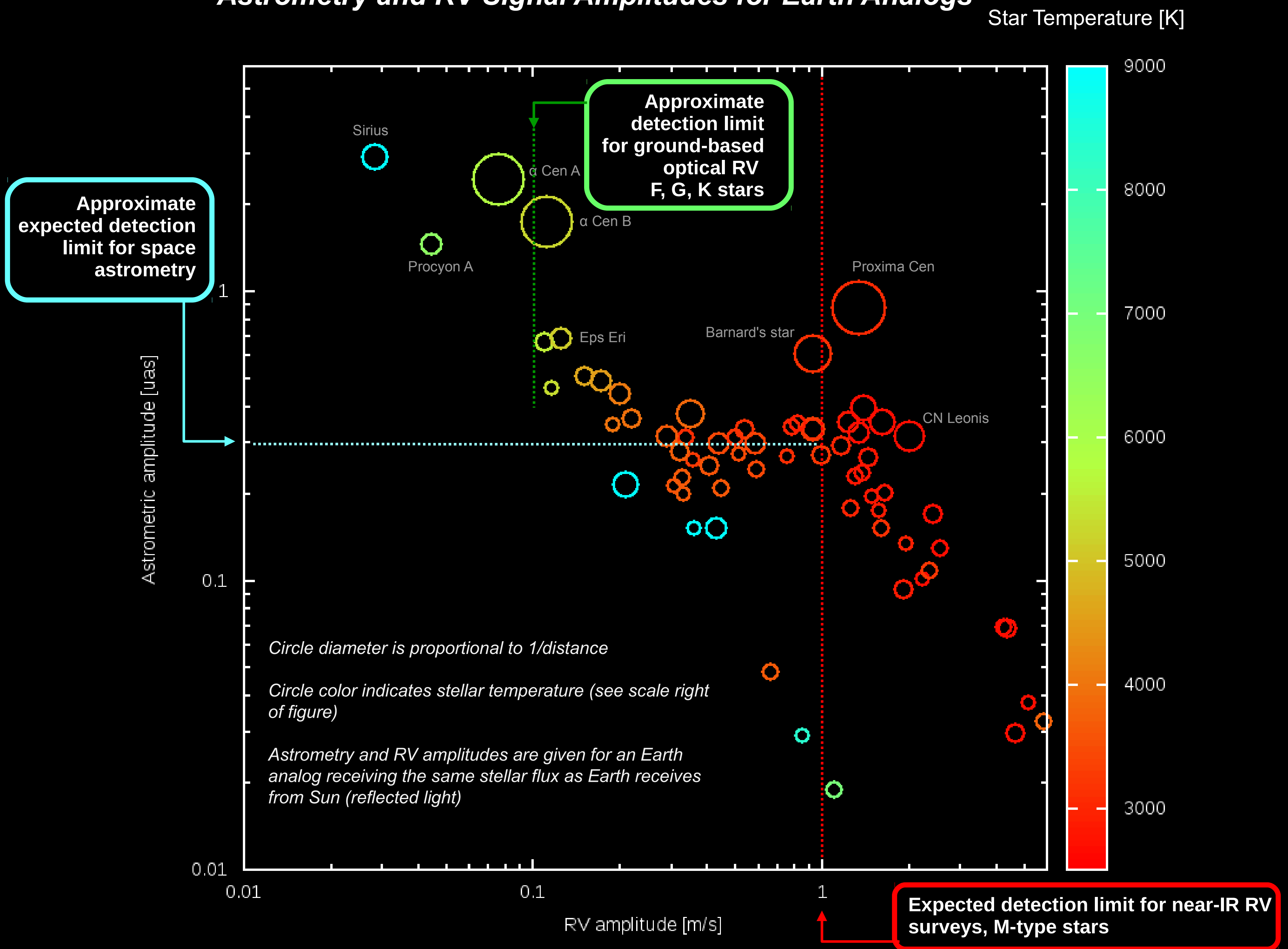
Earth around Sun at ~30 light year

→ Star position moves by 0.3 micro arcsecond
(thickness of a human hair at 30,000 km)

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

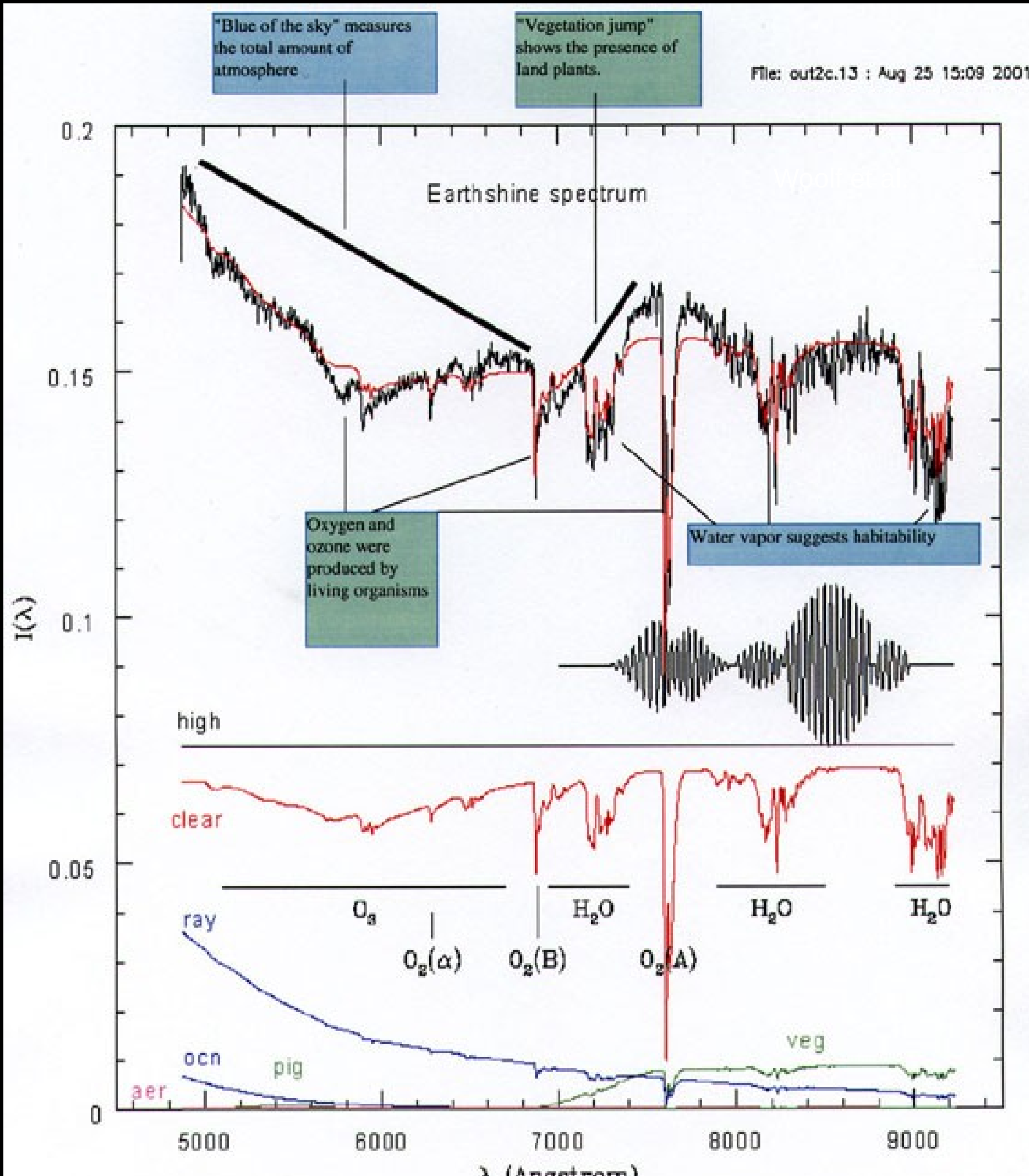
If Earth-like planet passes in front of Sun-like star, star dims by 70 parts per million
(12x12 pixel going dark on a HD TV screen 70 miles away)

Habitable Zones within 5 pc (16 ly): Astrometry and RV Signal Amplitudes for Earth Analogs



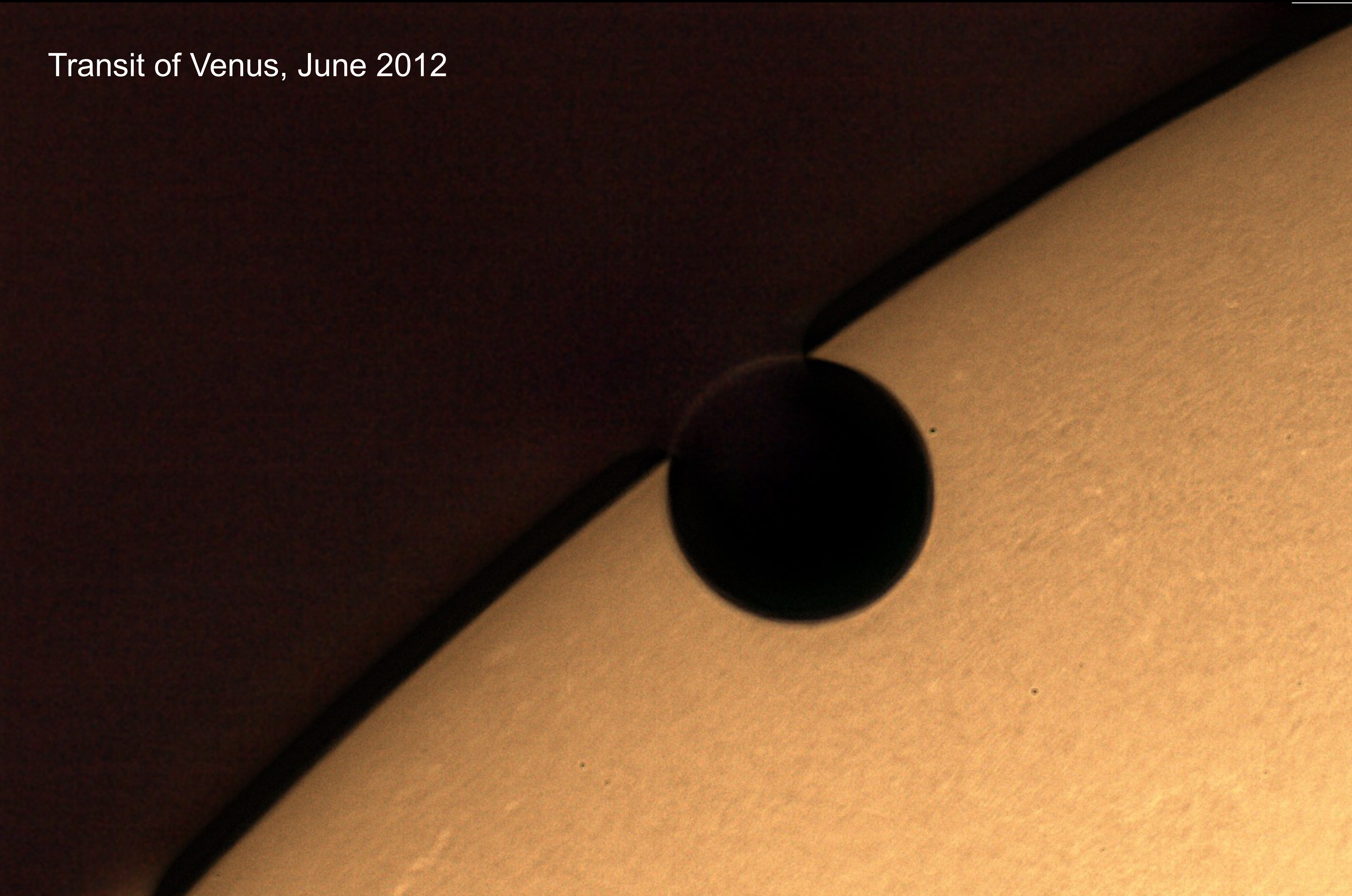
Why directly imaging ?

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

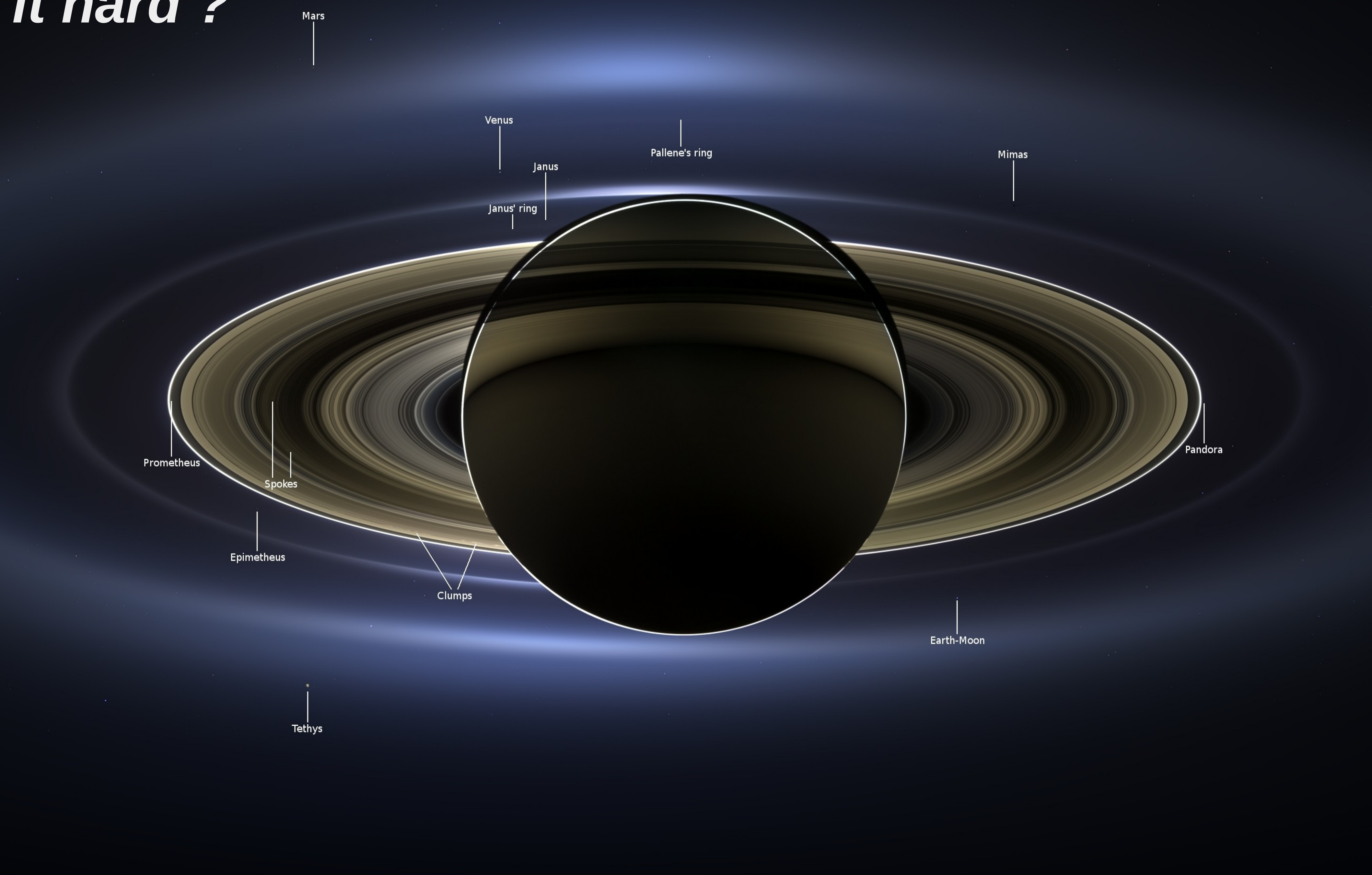


Exoplanet transit

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



Taking images of habitable exoplanets: Why is it hard ?



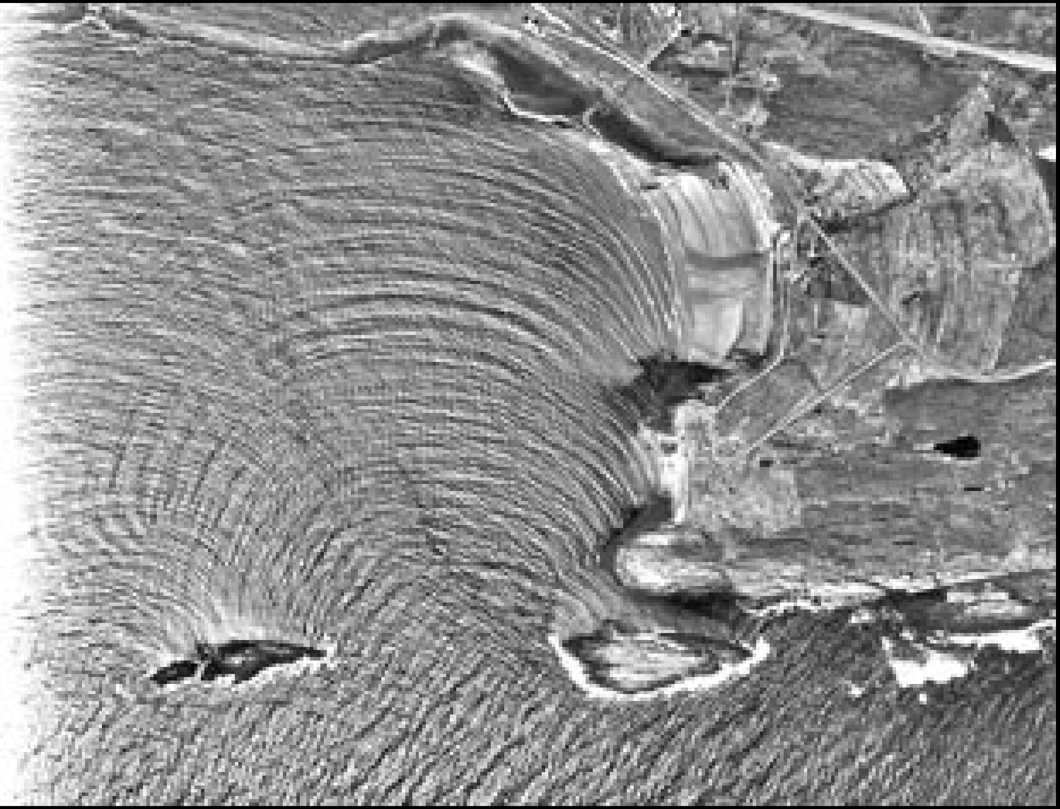

Saturn
Earth

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

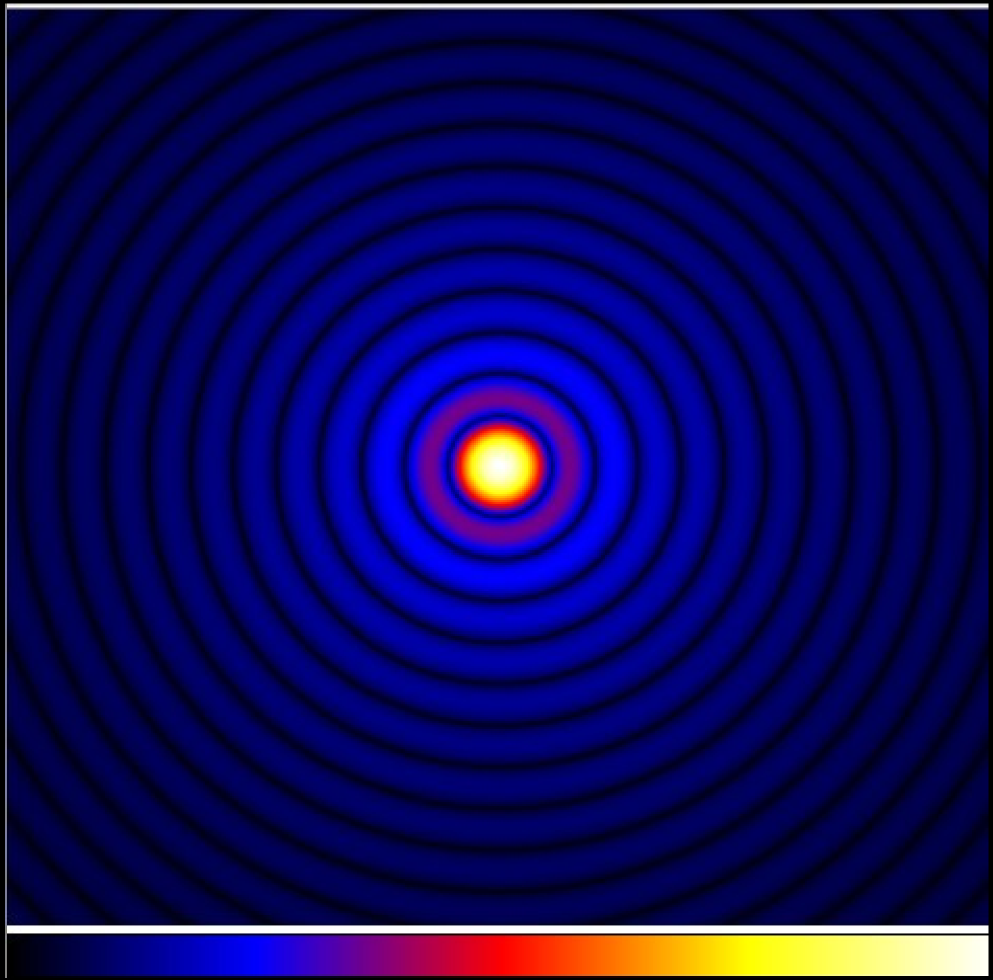
← Olivier's thumb...
the easiest coronagraph
Doesn't work well enough to
see planets around other stars

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

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

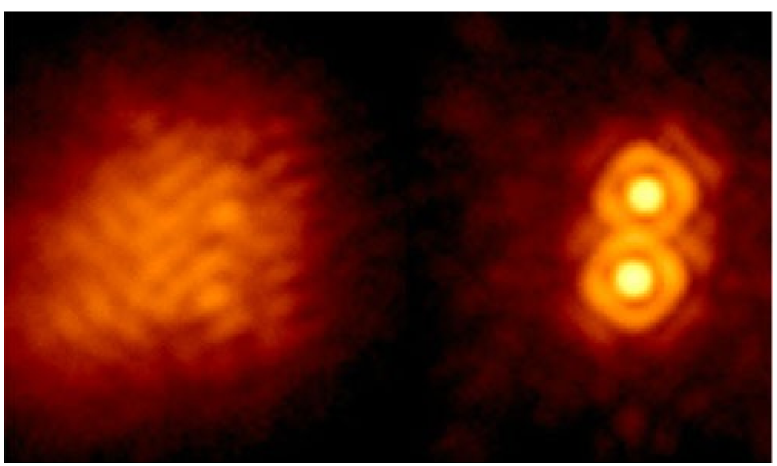
Adaptive Optics (AO)

Atmosphere Turbulence: Earth's atmosphere introduces strong and fast optical aberrations

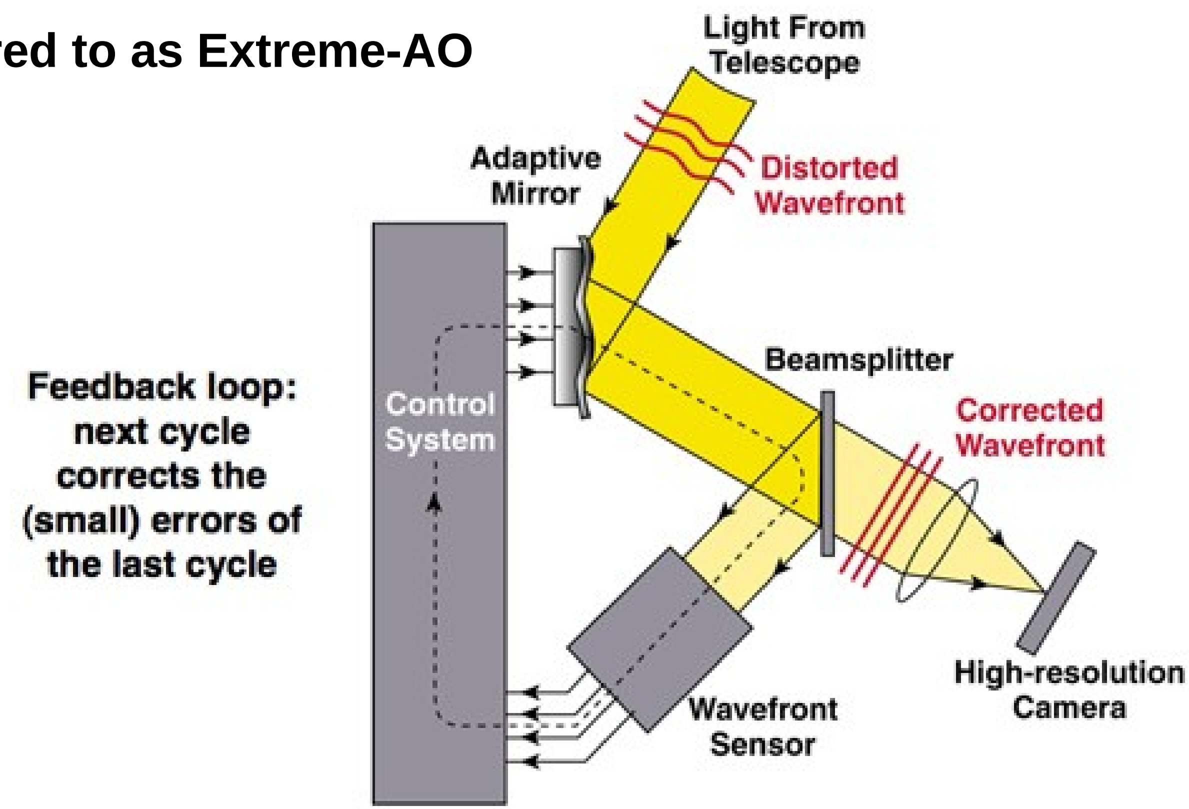
Aberrations must be continuously **measured** and **corrected** to provide sharp images.

Imaging exoplanets is particularly demanding, as the planet is much fainter that the star it orbits: very little room for error !
→ **AO for exoplanet imaging is referred to as Extreme-AO**

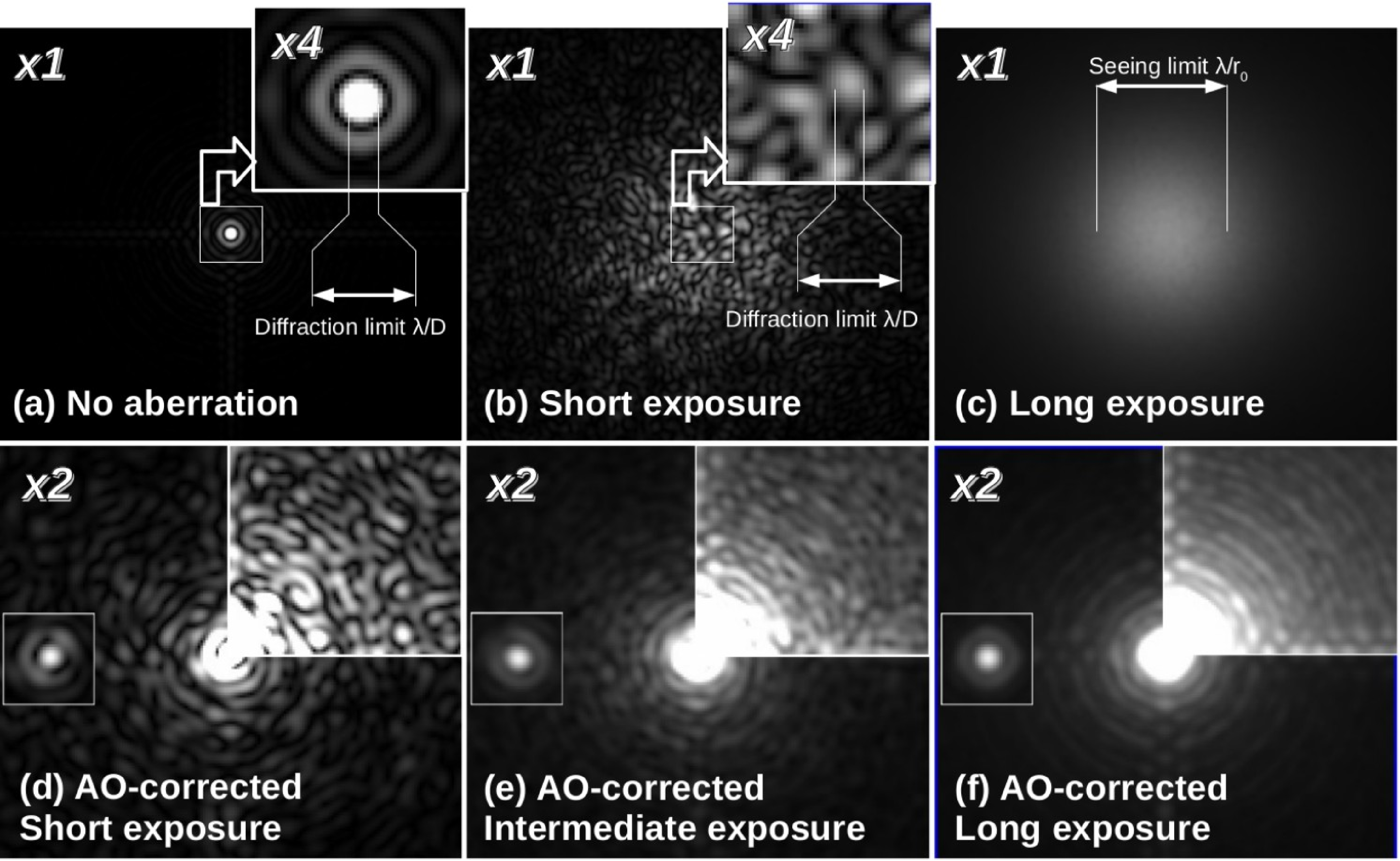
AO OFF AO ON



Palomar obs / NASA JPL



Adaptive Optics Correction of Atmospheric Turbulence



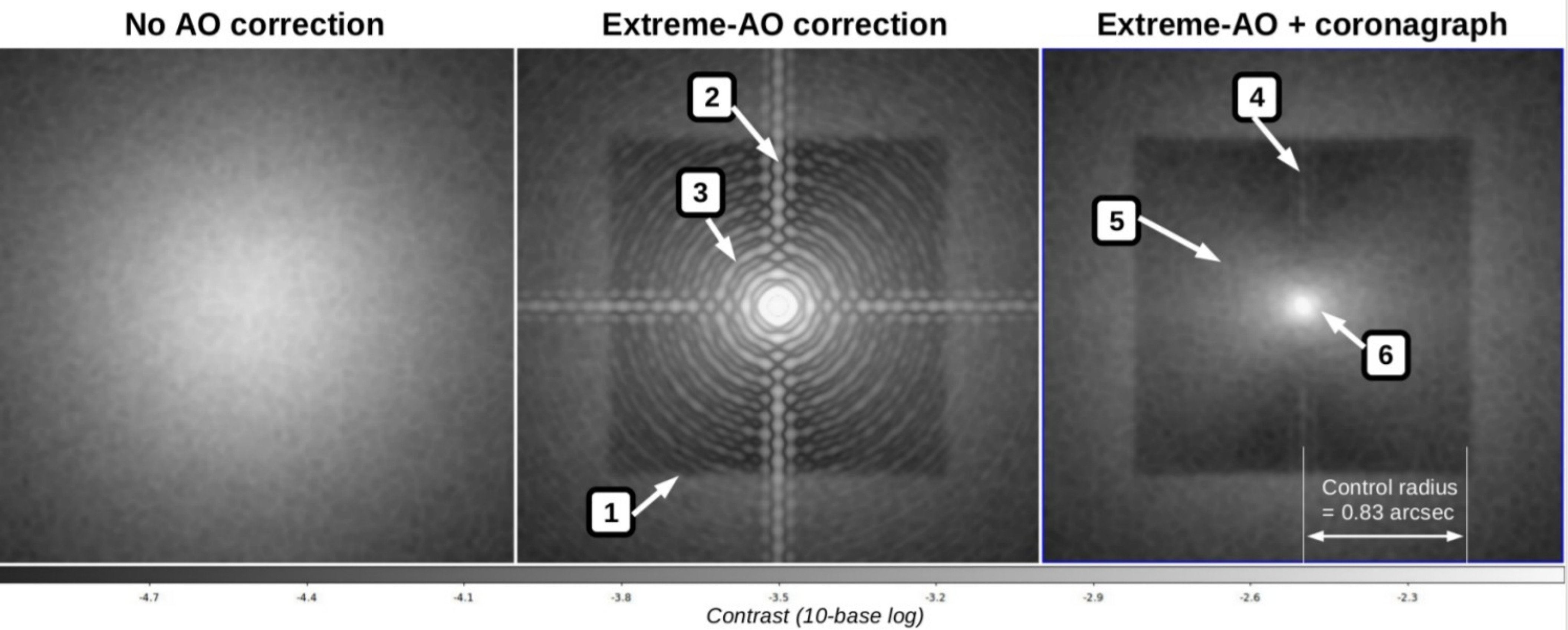
Imaging exoplanets requires two techniques to be combined:

- **Extreme-AO corrects atmospheric turbulence**
- **A coronagraph masks the light of the bright star**

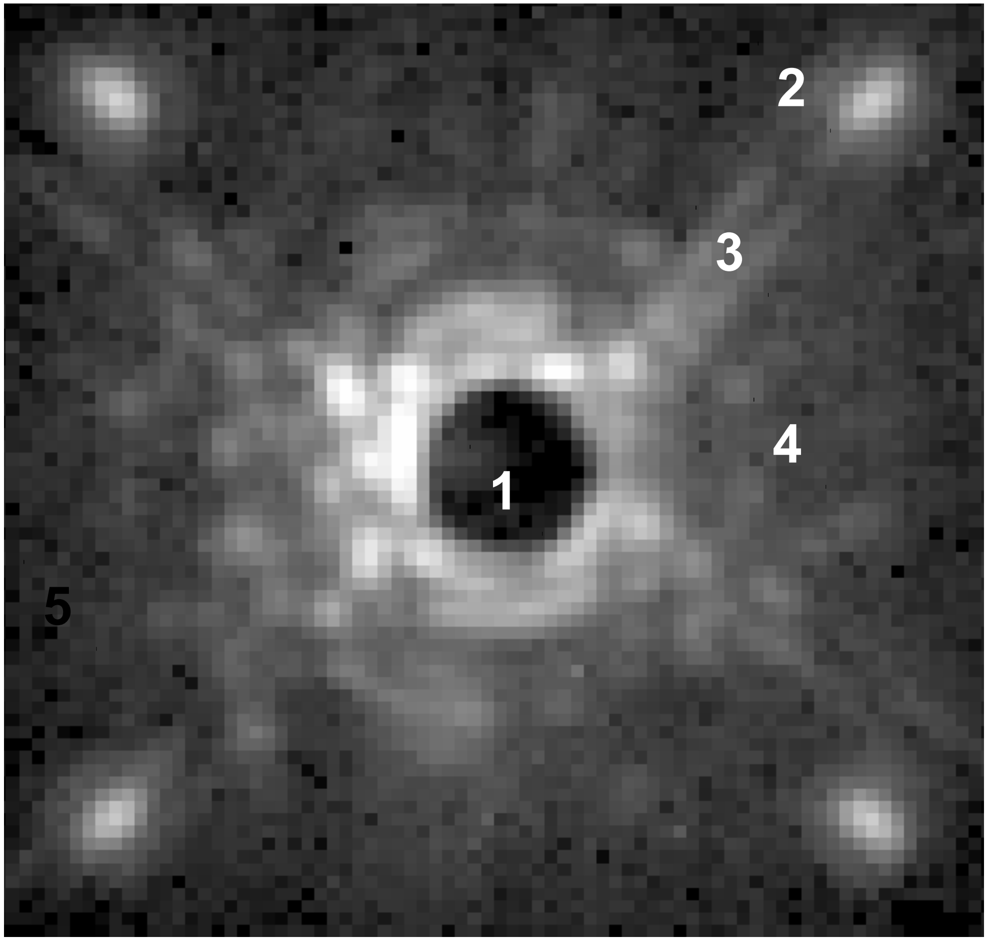
1: ExAO control radius
2: Telescope spider diffraction
3: Diffraction rings
4: Ghost spider diffraction
5: "butterfly" wind effect
6: Coronagraphic leak (low order aberrations)

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

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

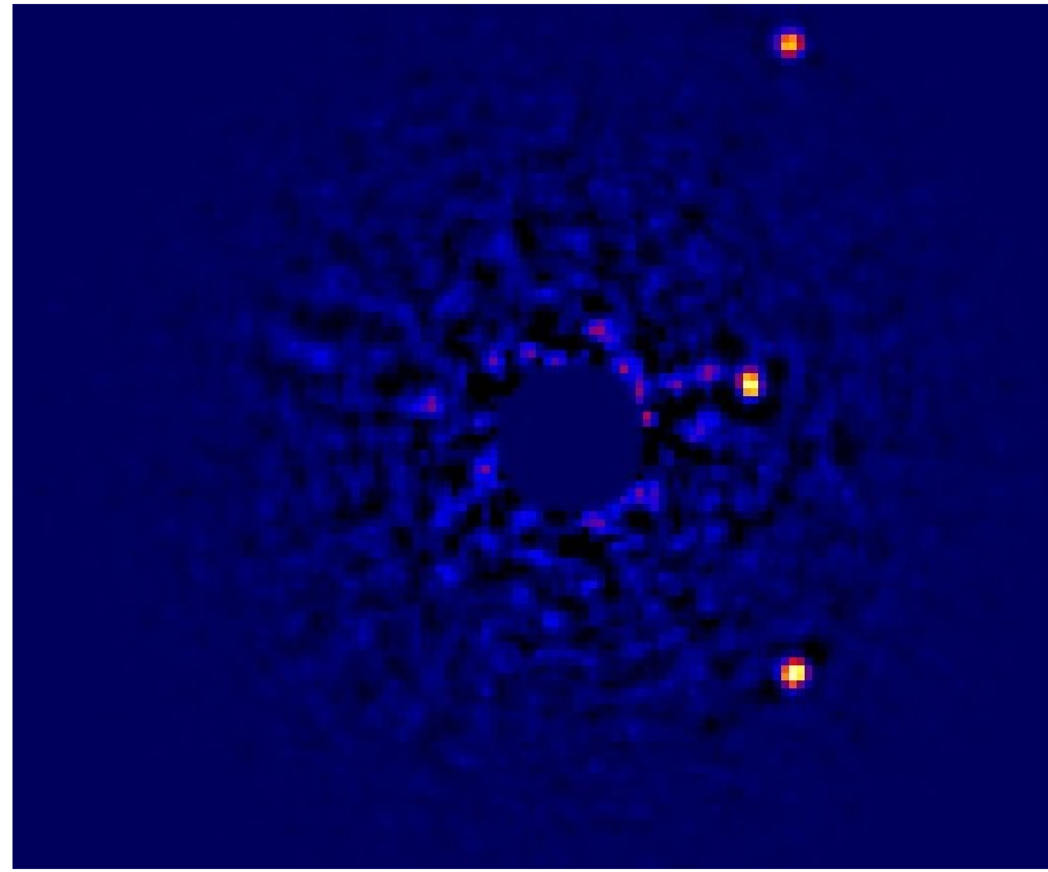


RAW image

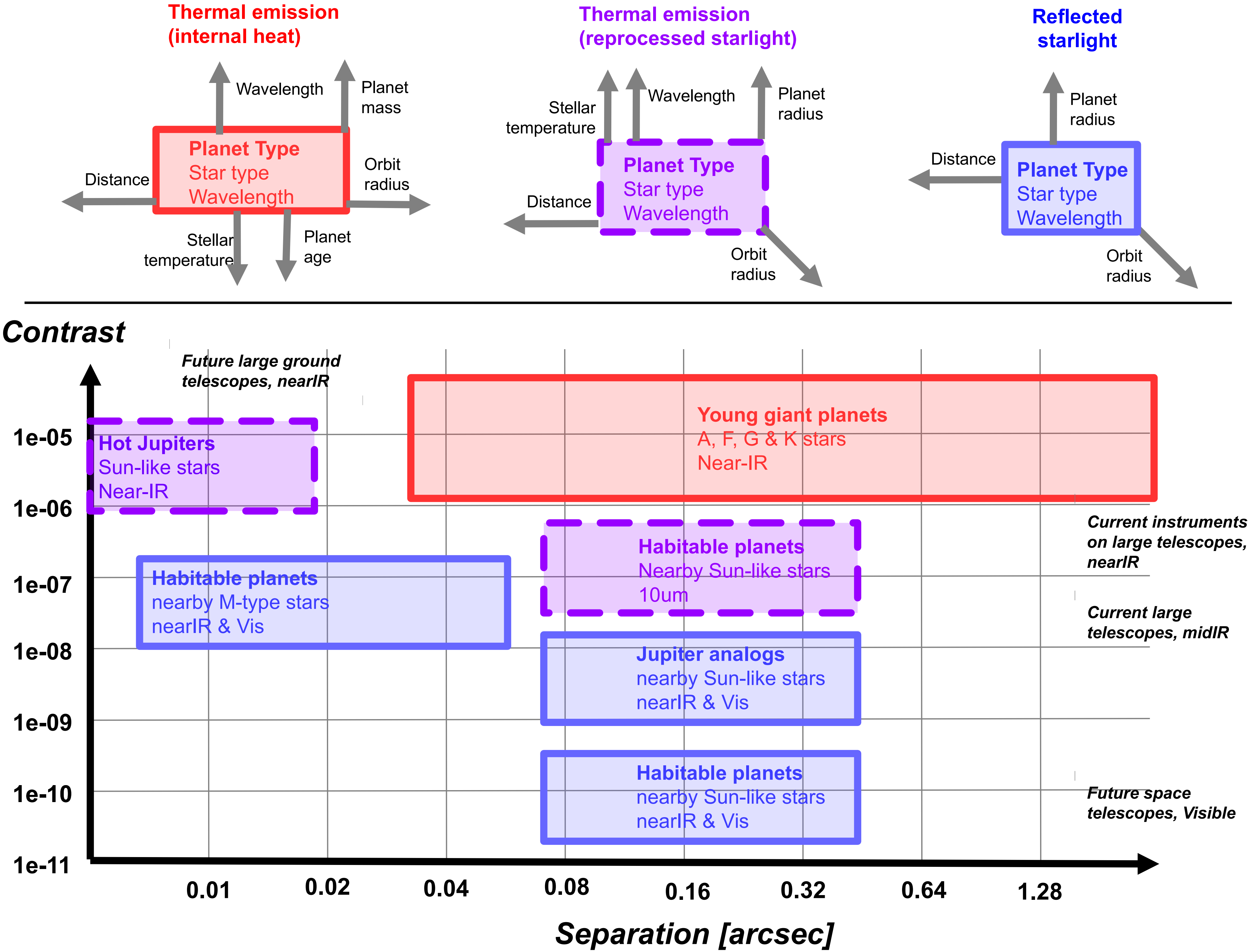


1: Coronagraph Focal plane mask
2: Calibration Speckles (astrometry and photometry)
3: Residual diffraction
4: Speckle Noise
5: Photon and Readout noise

PROCESSED image

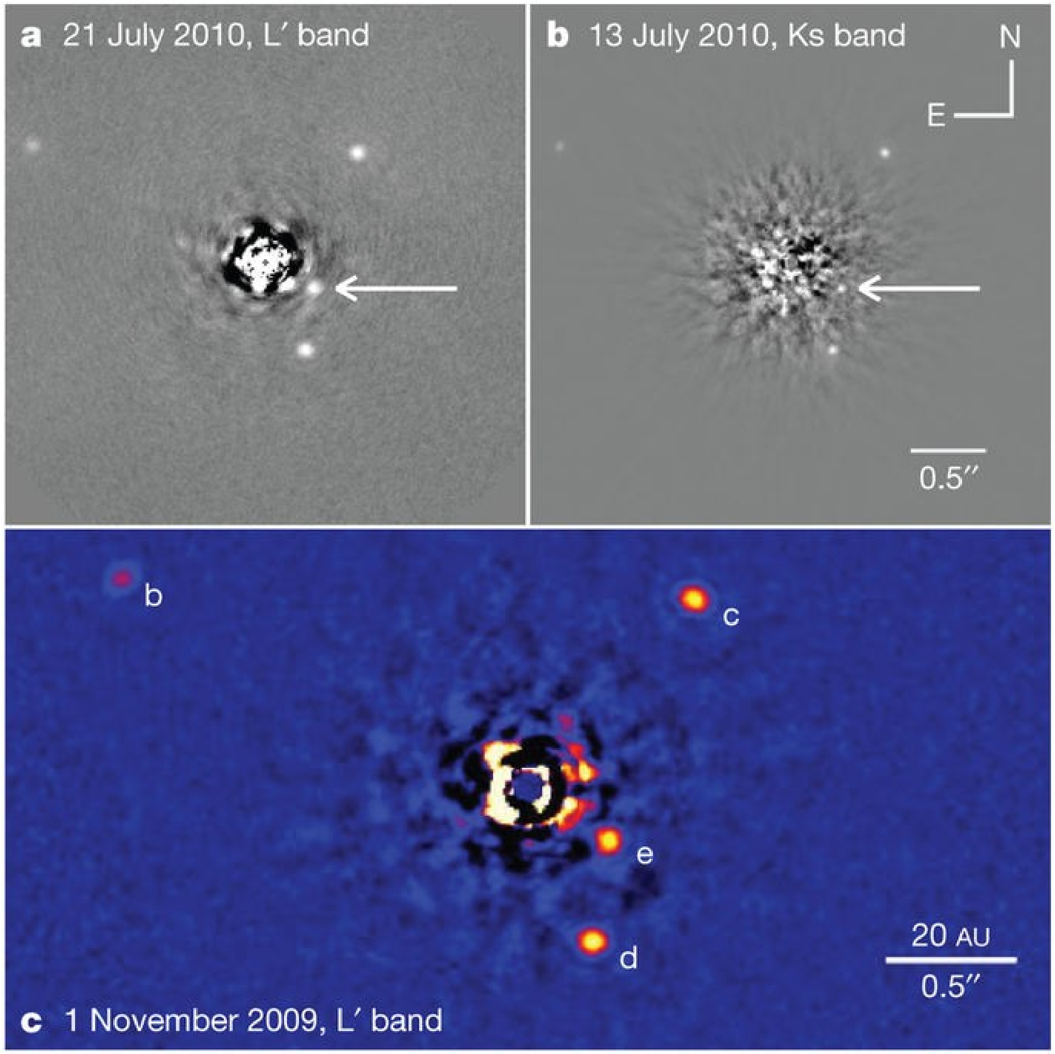


Detection noise dominated by :
- residual speckle noise
- photon noise
- readout noise



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
1e-05
1e-06
1e-07
1e-08
1e-09
1e-10
1e-11
Hot Jupiters
Sun-like stars
Near-IR
Young giant planets
A, F, G & K 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
0.01
0.02
0.04
0.08
0.16
0.32
0.64
1.28
Separation [arcsec]

Measurements: Astrometry & Photometry



Astrometry

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

Spectro-astrometry: Moons

Photometry

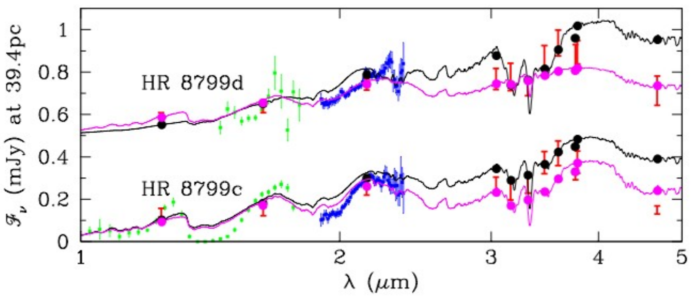
Multi-band
→ bulk properties (temperature, size)

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

Measurements: Spectroscopy

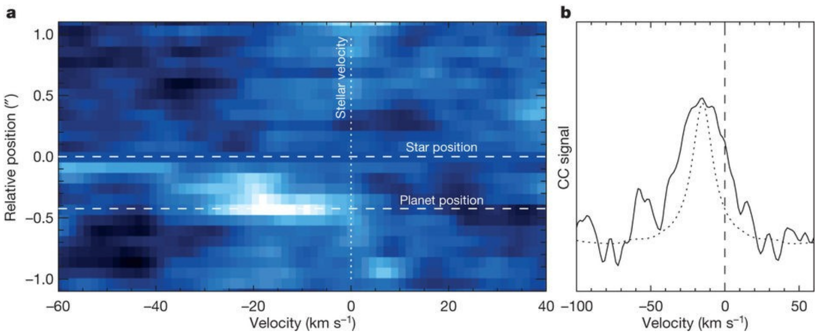
Absorption lines → chemistry
Can be observed with Thermal emission / Reflected light / Transit spectroscopy

Model-fitting → temperature, composition, gravity



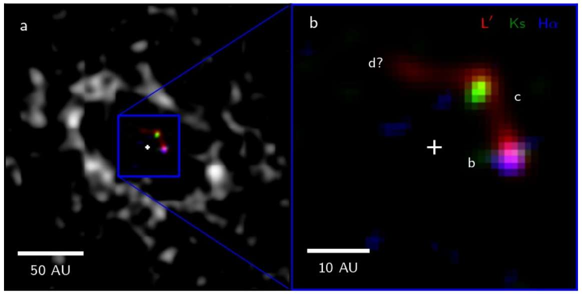
Ingraham et al. 2014

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



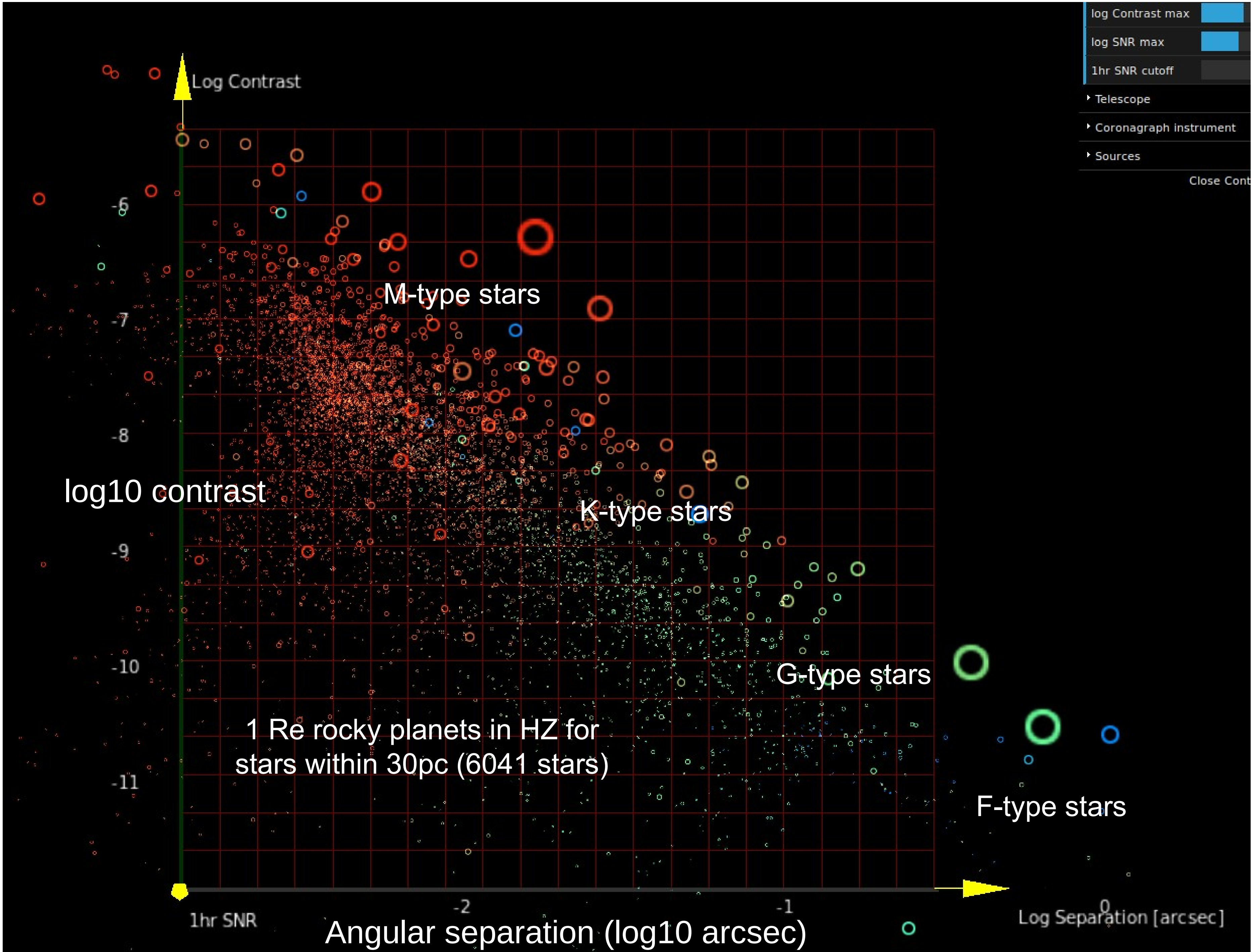
Snellen et al. 2014

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)

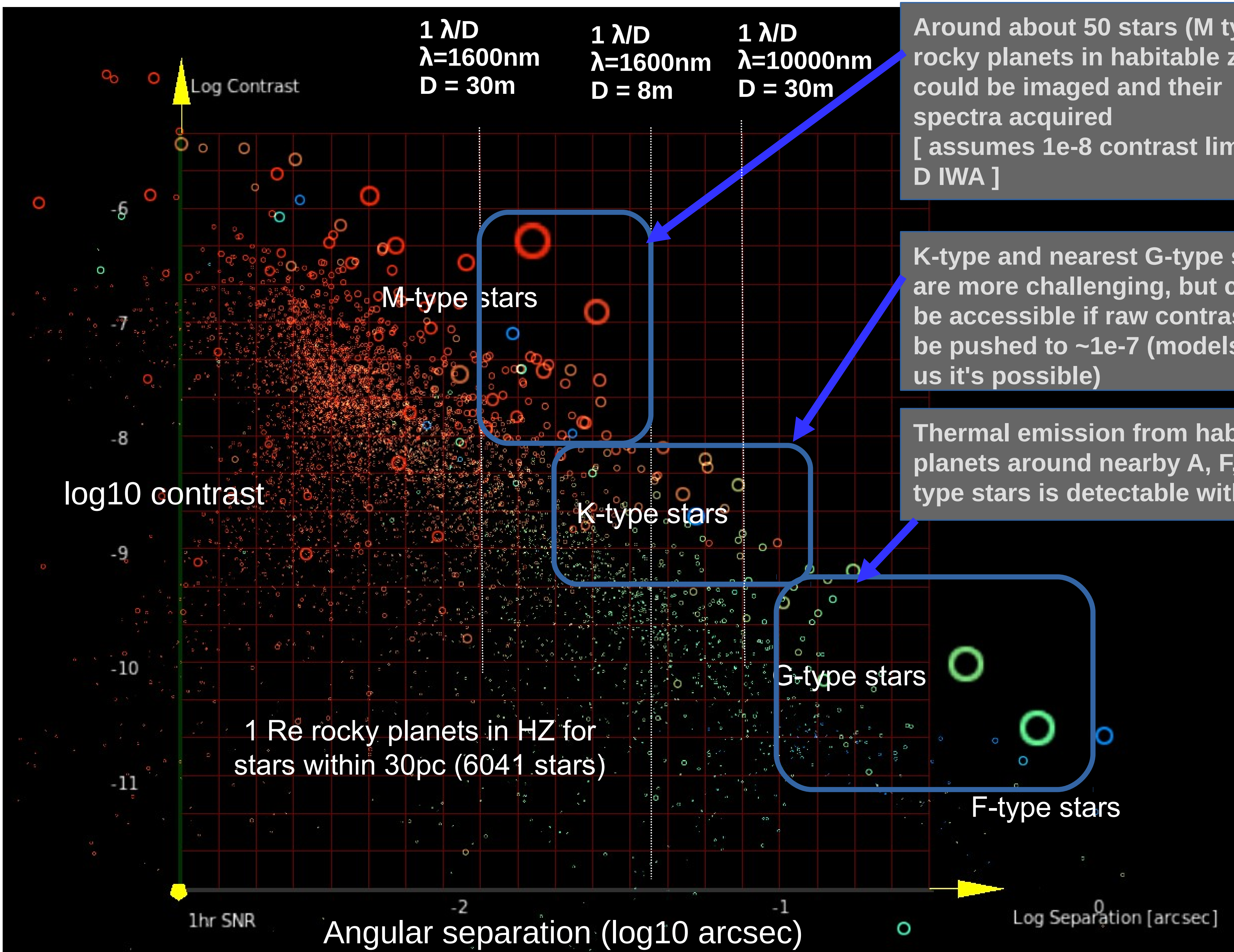


Sallum et al. 2015

Contrast and Angular separation (Reflected Light)



Habitable Planets: Contrast and Angular separation



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]

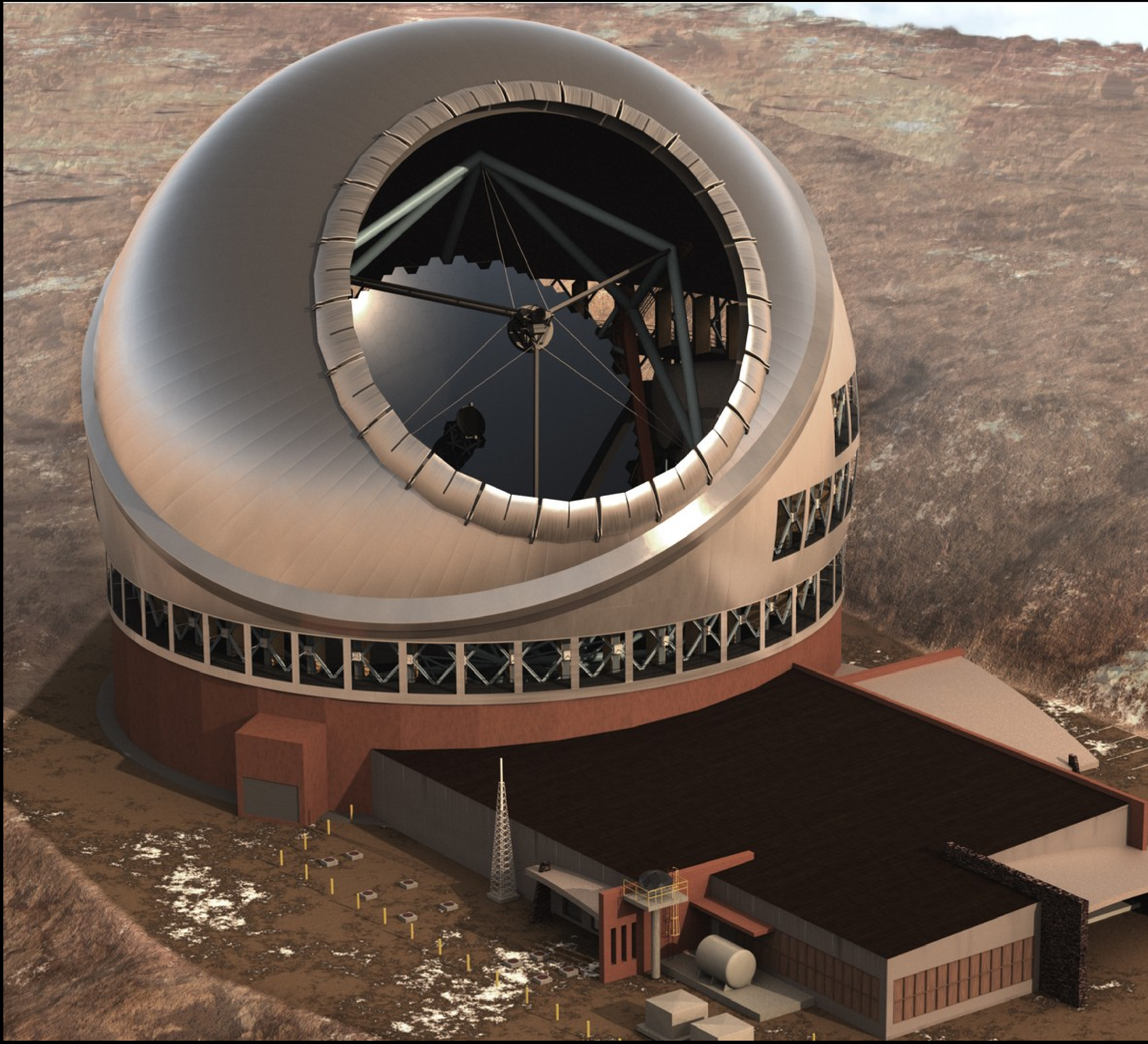
K-type and nearest G-type stars are more challenging, but could be accessible if raw contrast can be pushed to ~1e-7 (models tell us it's possible)

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

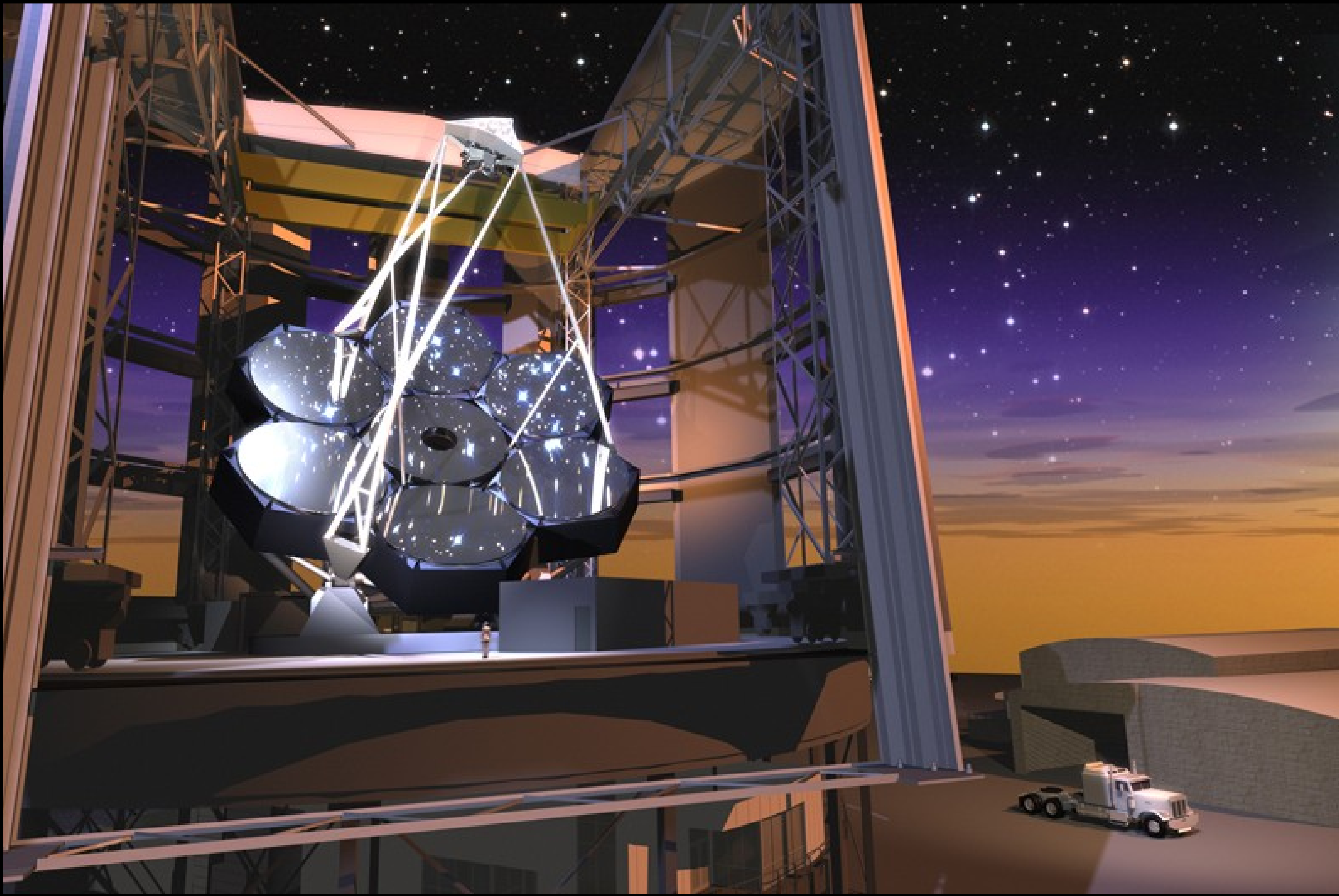
NASA's Large UV Optical Infrared Surveyor

(LUVOIR)

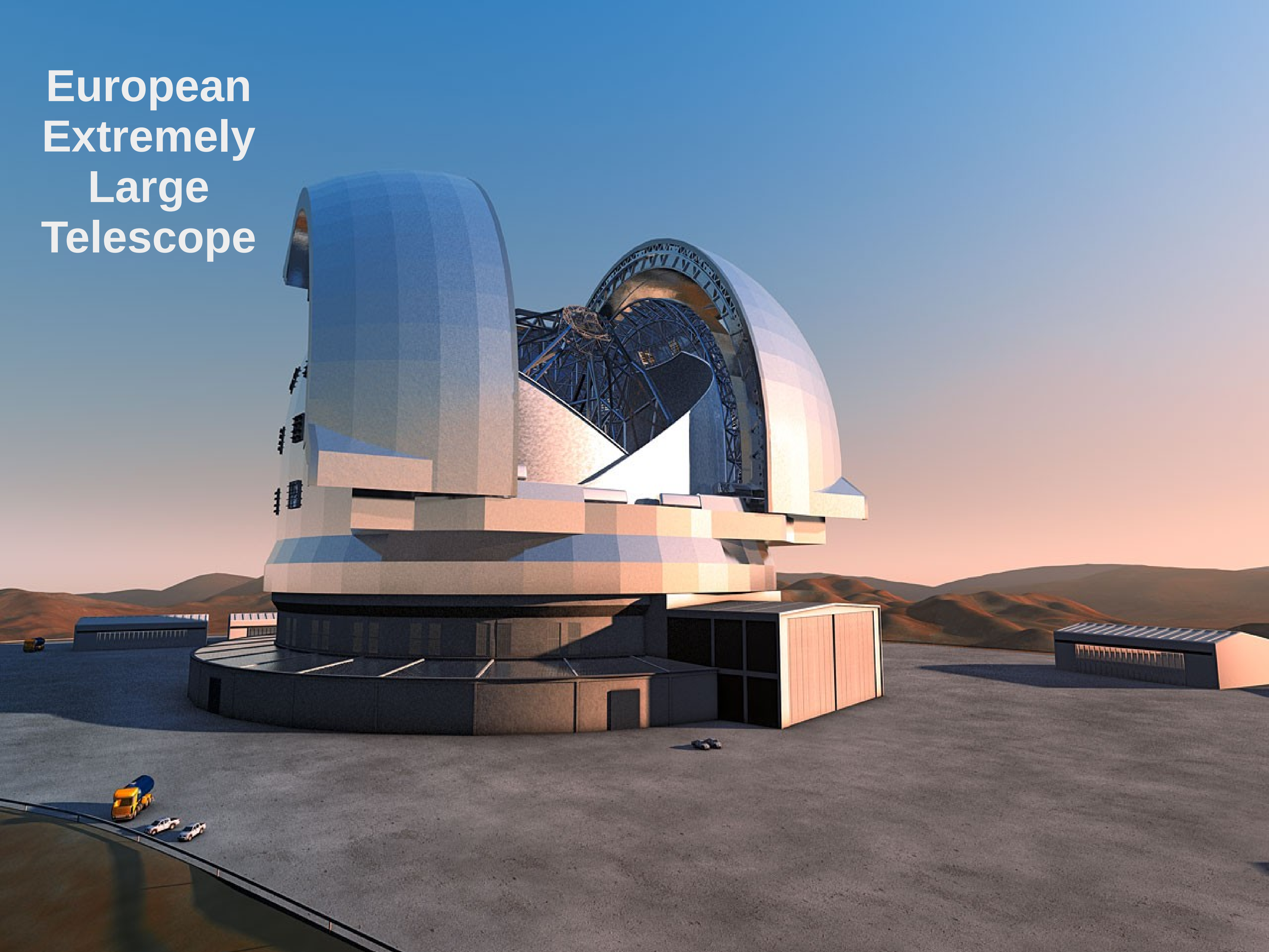
Thirty Meter Telescope



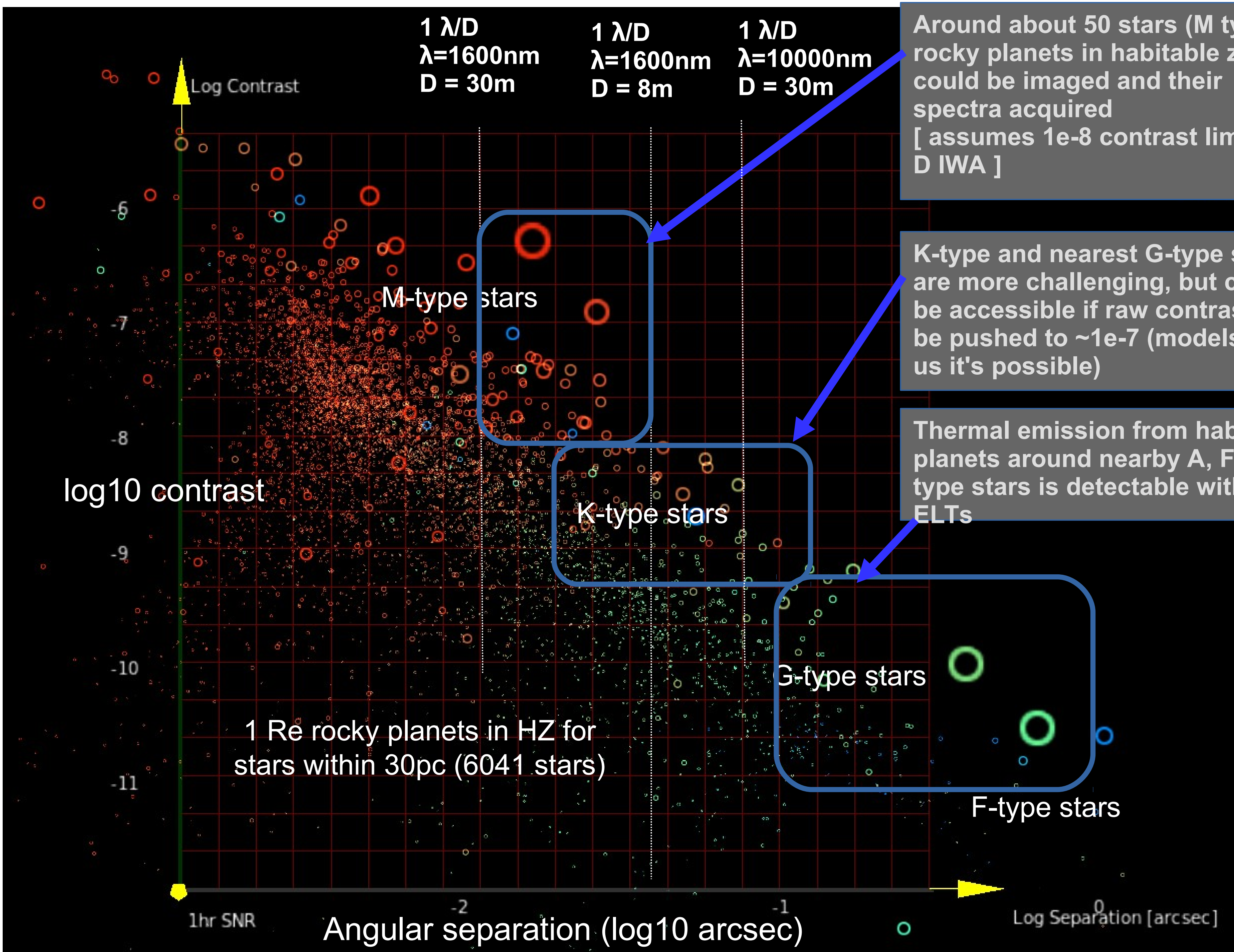
Giant Magellan Telescope



European Extremely Large Telescope



Habitable Planets: Contrast and Angular separation



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10um imaging and spectroscopy

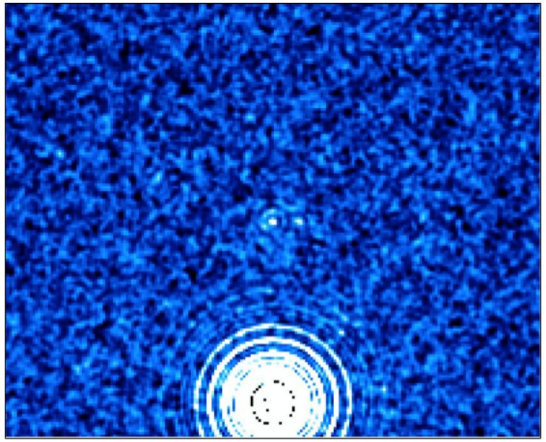


Fig. 1: A simulated 100h sequence of Alpha Cent at 10 microns for an 8m telescope. The target star (center) is hidden behind a coronagraph. A faint 4.5 sigma 1 Earth radius 288K planet is detected West of the star at 1 arcsec. The 2nd star of the system is visible South of the target star.

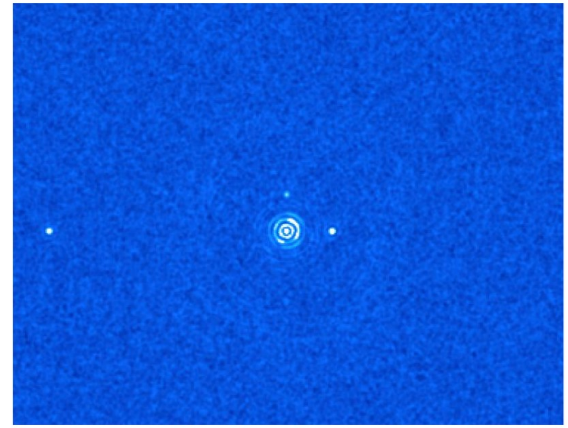


Fig. 2: Same as Fig.1, but for a 30m telescope. A bright 25 sigma 1 Earth radius 288K planet is detected West of the star at 1 arcsec. A Venus-like planet is detected North of the star, as a Jupiter-like planet is detected East.

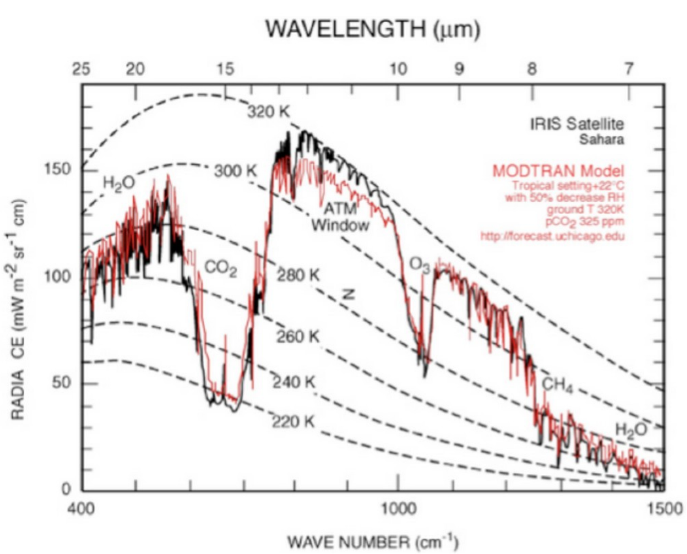


Fig. 3: Earth spectrum acquired from space for the Sahara. Note the peak emission between 10-13 microns. Biomarkers: CO2, O3, CH4 and water bands are visible in the N-band.

Credit: Christian Marois

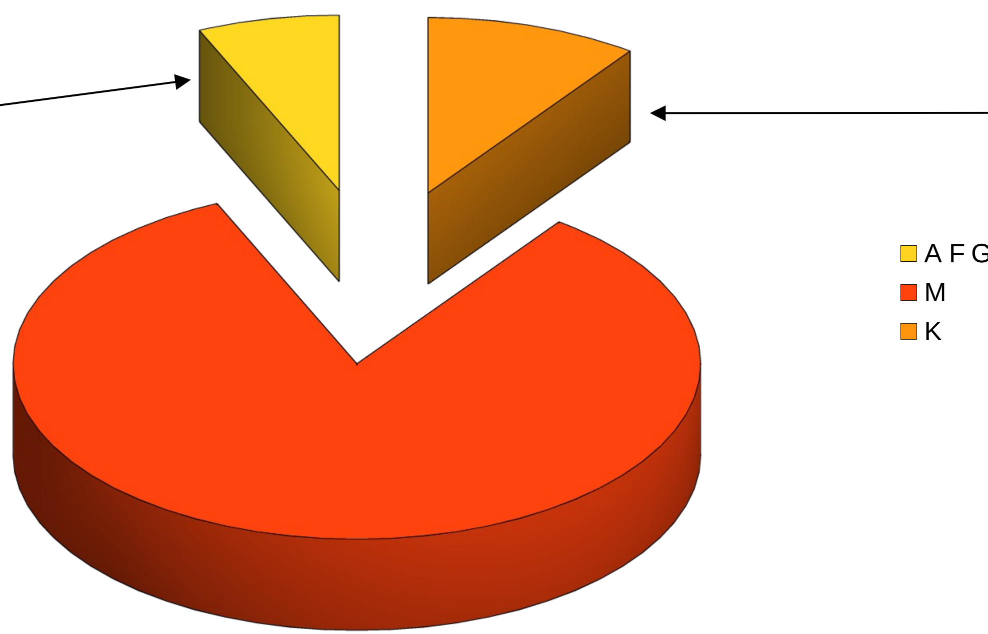
What is so special about M stars ?

They are **abundant**: >75% of main sequence stars are M type

Class	Effective temperature[1][2][3]	Vega-relative "color label"[4][nb 1]	Chromaticity[5][6][7][nb 2]	Main-sequence mass[1][8] (solar masses)	Main-sequence radius[1][8] (solar radii)	Main-sequence luminosity[1][8] (bolometric)	Hydrogen lines	Fraction of all main-sequence stars[9]
O	≥ 30,000 K	blue	blue	≥ 16 $M_\odot$	≥ 6.6 $R_\odot$	≥ 30,000 $L_\odot$	Weak	~0.00003%
B	10,000–30,000 K	blue white	deep blue white	2.1–16 $M_\odot$	1.8–6.6 $R_\odot$	25–30,000 $L_\odot$	Medium	0.13%
A	7,500–10,000 K	white	blue white	1.4–2.1 $M_\odot$	1.4–1.8 $R_\odot$	5–25 $L_\odot$	Strong	0.6%
F	6,000–7,500 K	yellow white	white	1.04–1.4 $M_\odot$	1.15–1.4 $R_\odot$	1.5–5 $L_\odot$	Medium	3%
G	5,200–6,000 K	yellow	yellowish white	0.8–1.04 $M_\odot$	0.96–1.15 $R_\odot$	0.6–1.5 $L_\odot$	Weak	7.6%
K	3,700–5,200 K	orange	pale yellow orange	0.45–0.8 $M_\odot$	0.7–0.96 $R_\odot$	0.08–0.6 $L_\odot$	Very weak	12.1%
M	2,400–3,700 K	red	light orange red	0.08–0.45 $M_\odot$	≤ 0.7 $R_\odot$	≤ 0.08 $L_\odot$	Very weak	76.45%

Within 5pc (15ly) : 60 hydrogen-burning stars, 50 are M type, 6 are K-type, 4 are A, F or G

4.36 Alpha Cen A
8.58 Sirius A
11.40 Procyon A
11.89 Tau Ceti



4.36 Alpha Cen B
10.52 Eps Eri
11.40 61 Cyg A
11.40 61 Cyg B
11.82 Eps Ind A
15.82 Gliese 380

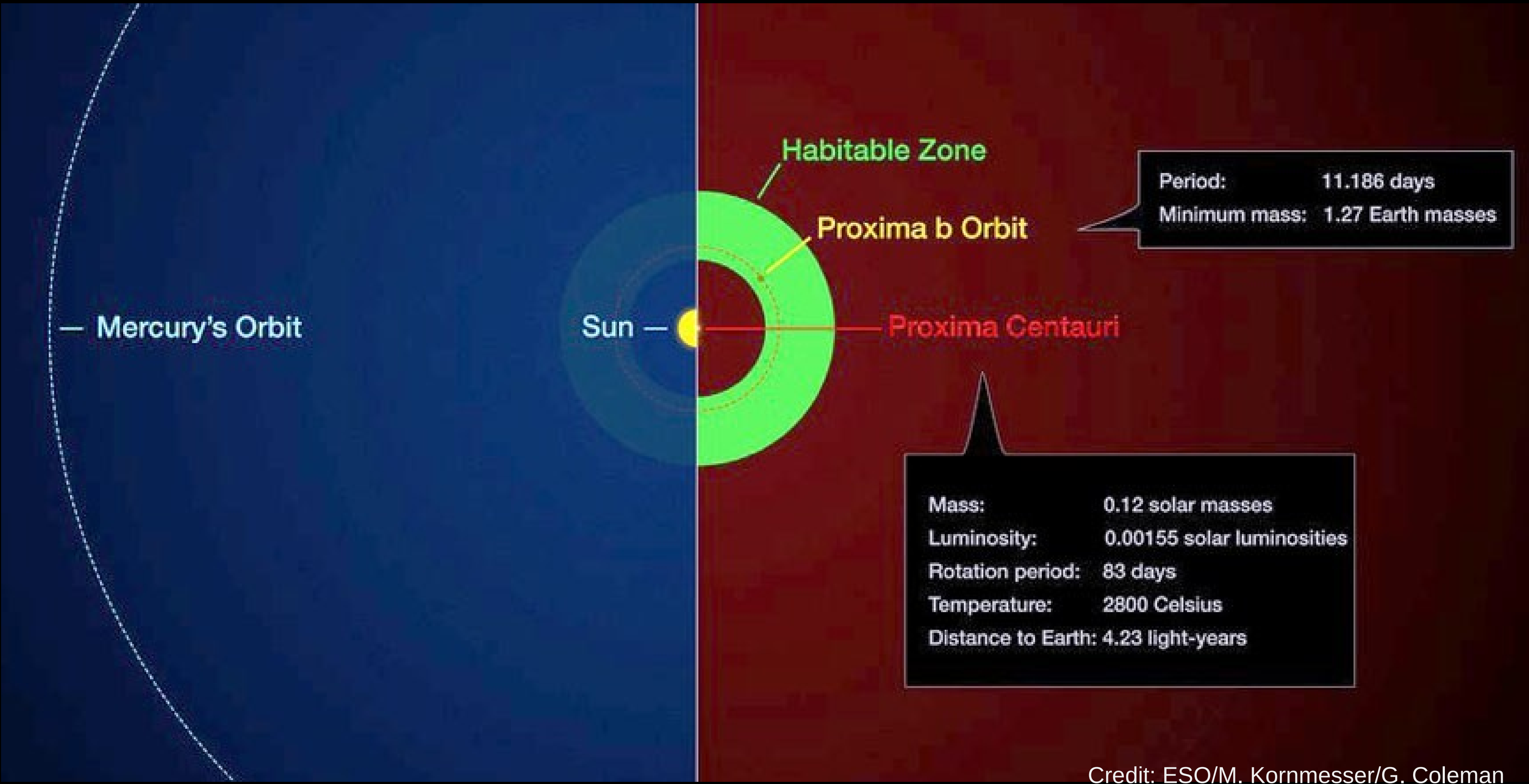
M-type stars (low mass)

Habitable zone is close to star

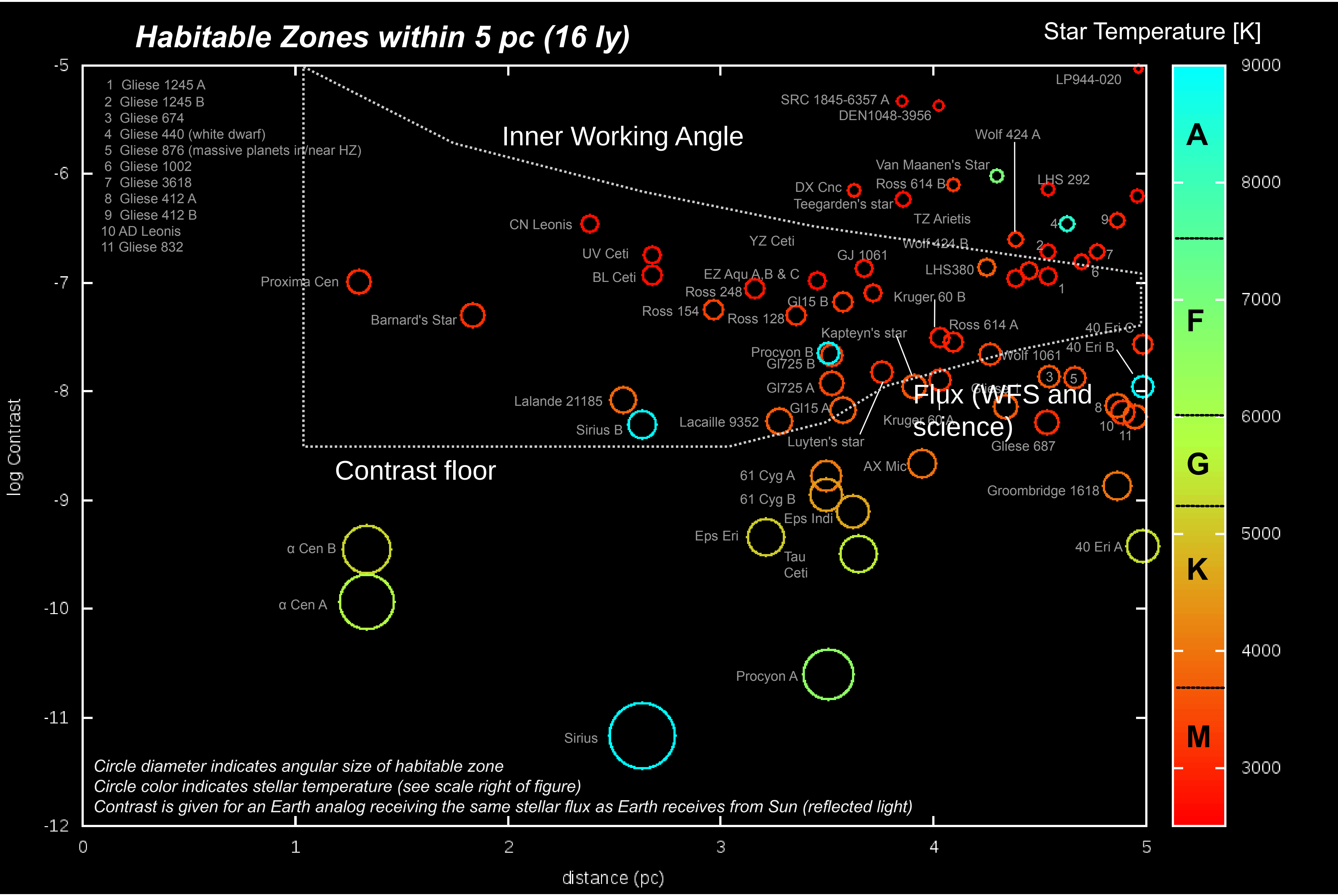
→ **big telescope needed to resolve it**

Star is fainter, so Star/Planet contrast is easier

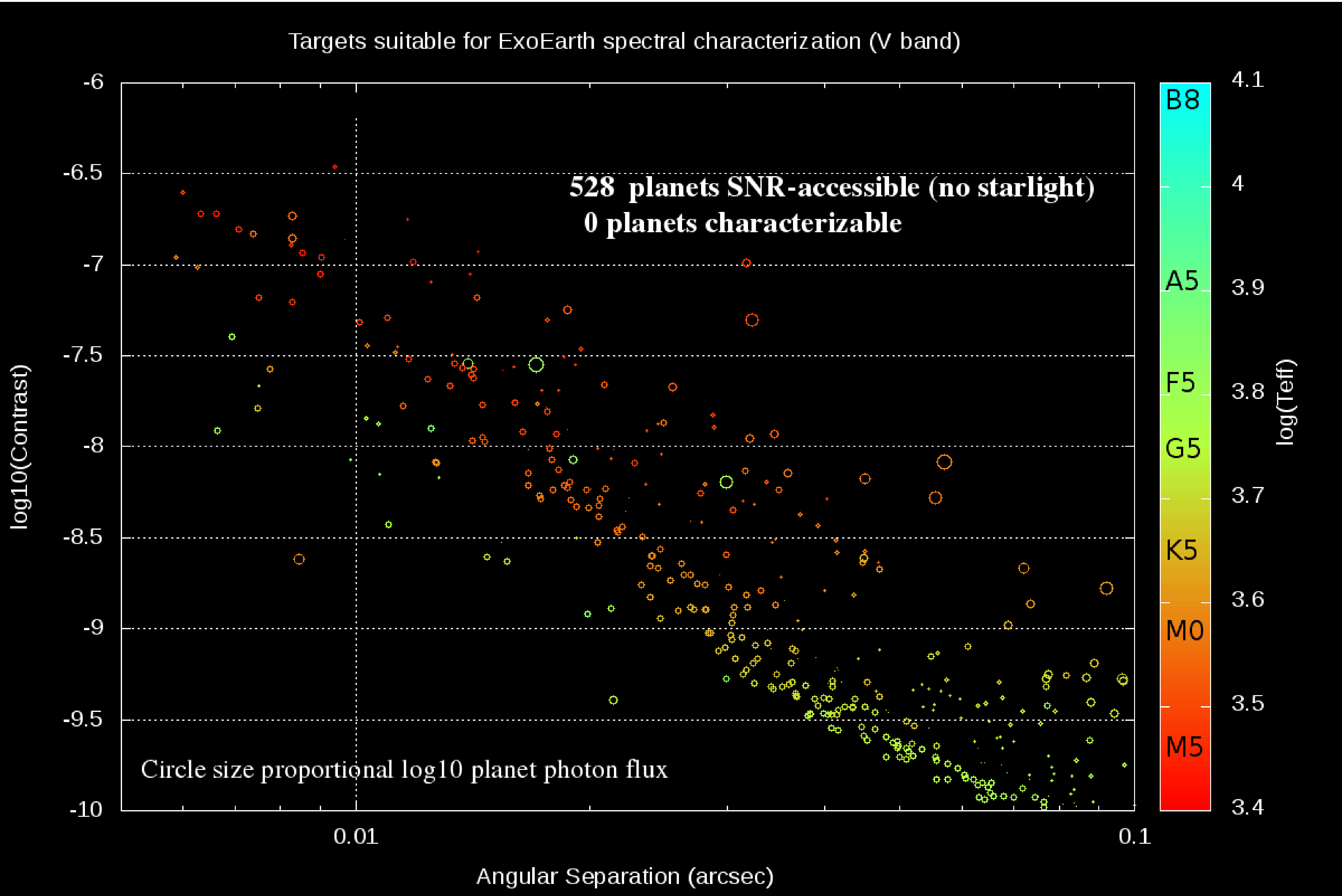
→ **can be done from ground** **(no need to be in space)**



Credit: ESO/M. Kornmesser/G. Coleman


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
Eps Eri
Tau Ceti
Eps Indi
61 Cyg A
61 Cyg B
AX Mic
Groombridge 1618
40 Eri A
40 Eri B
40 Eri C
Gliese 687
Kruger 60 A
Kruger 60 B
Luyten's star
Lacaille 9352
Gl15 A
Gl15 B
Gl725 A
Gl725 B
Kapteyn's star
Ross 614 A
Ross 614 B
Wolf 1061
Ross 128
Ross 154
Ross 248
EZ Aqu A,B & C
YZ Ceti
GJ 1061
LHS380
Wolf 424 A
Wolf 424 B
TZ Arietis
Teegarden's star
DX Cnc
Van Maanen's Star
LHS 292
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)



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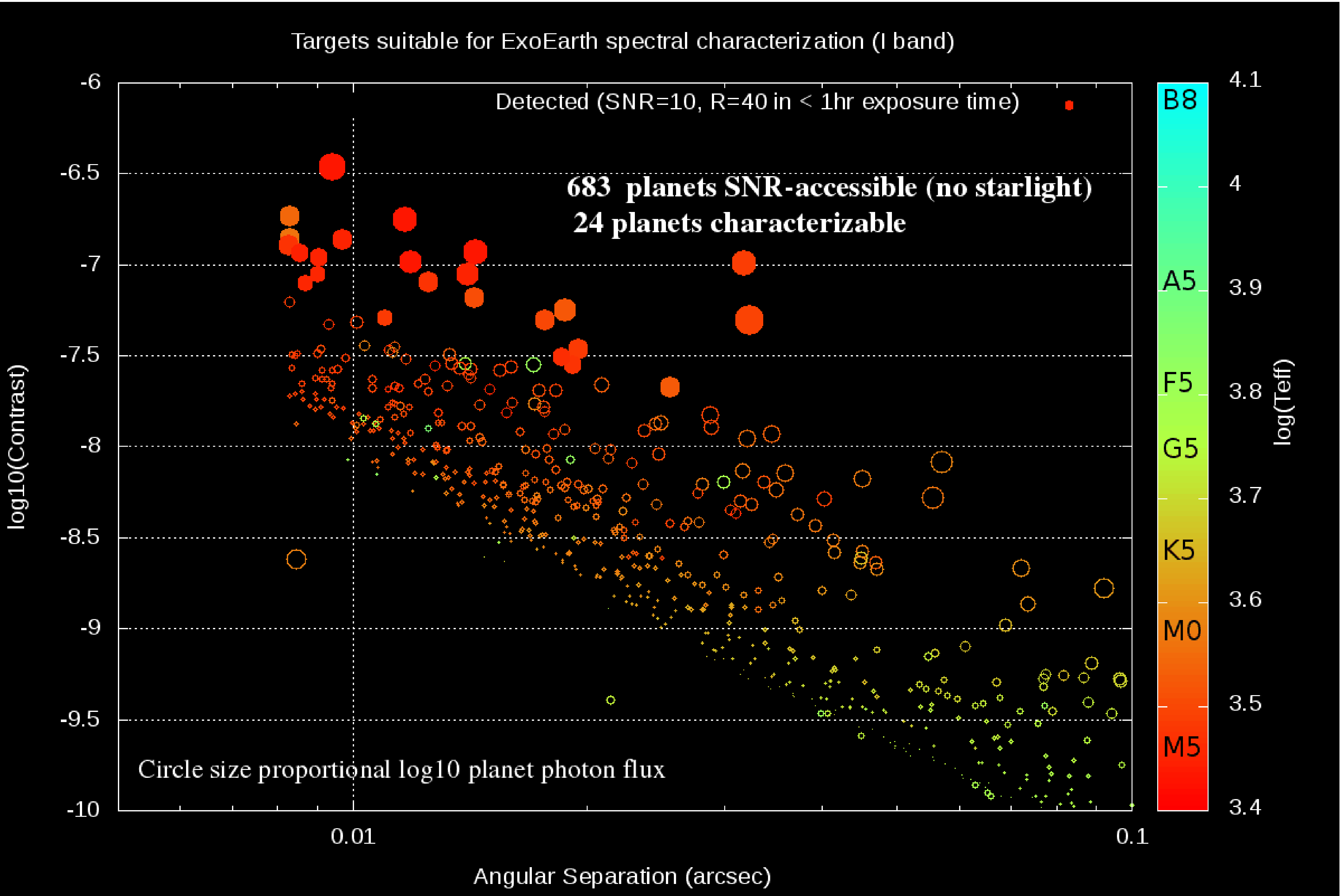

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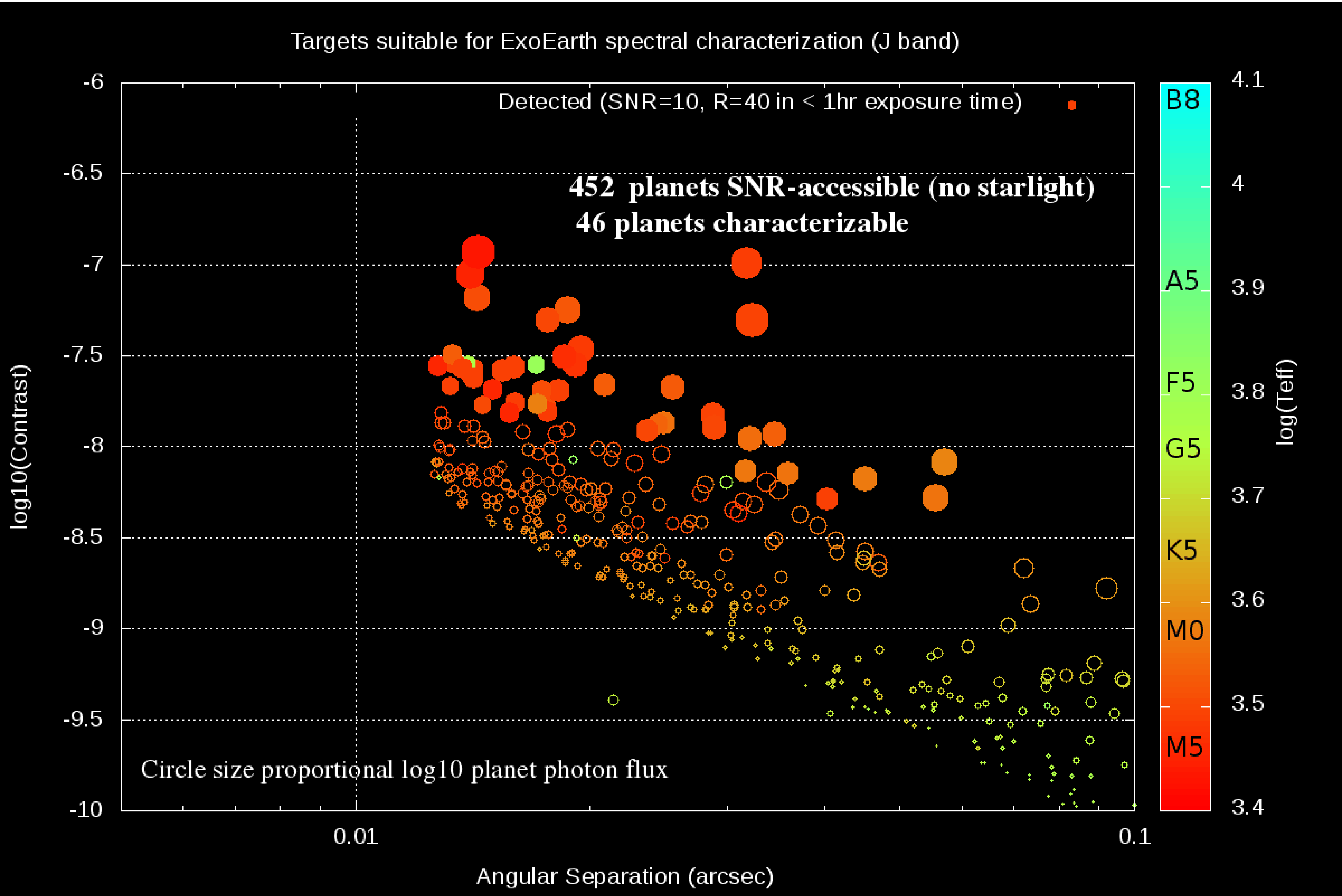
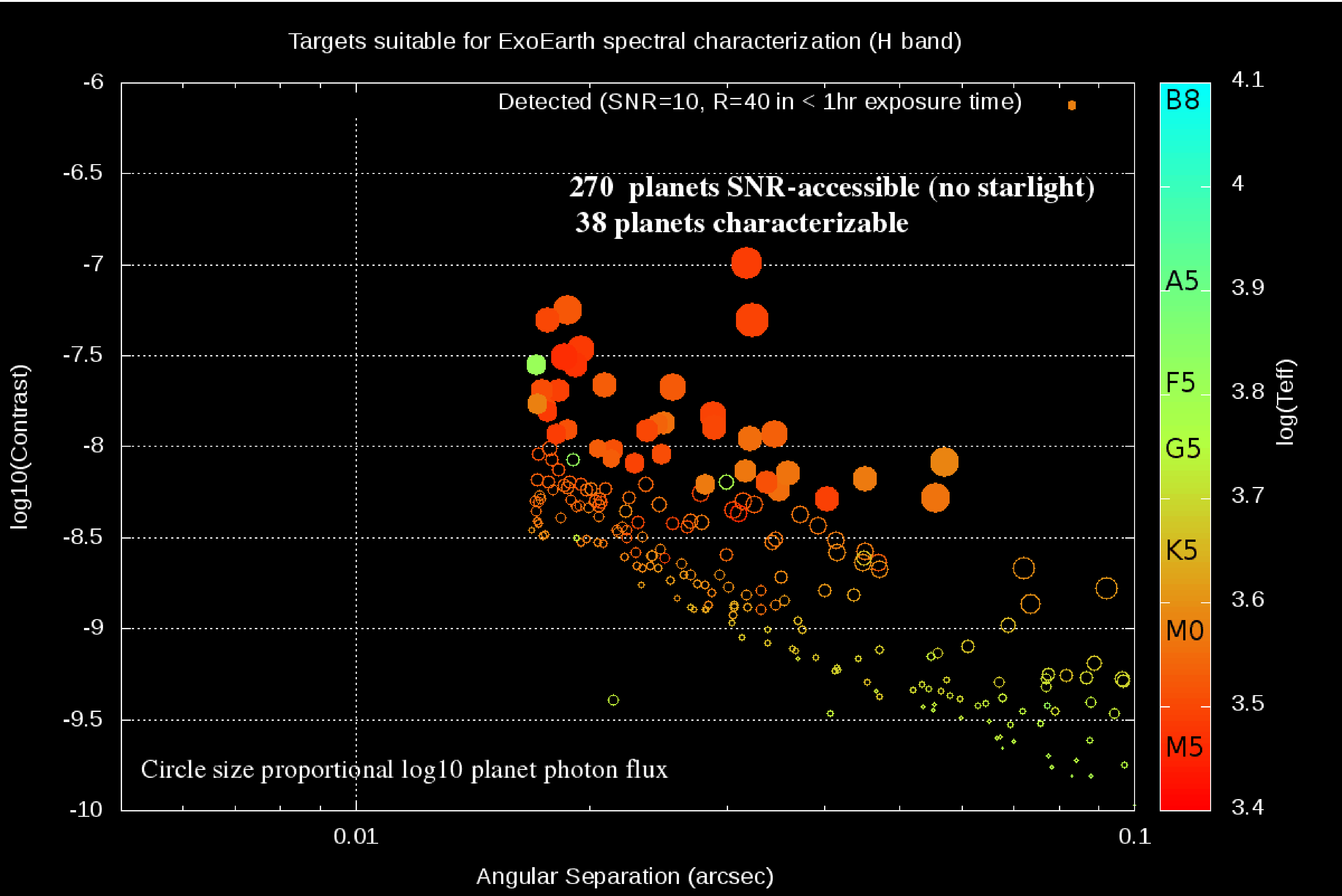
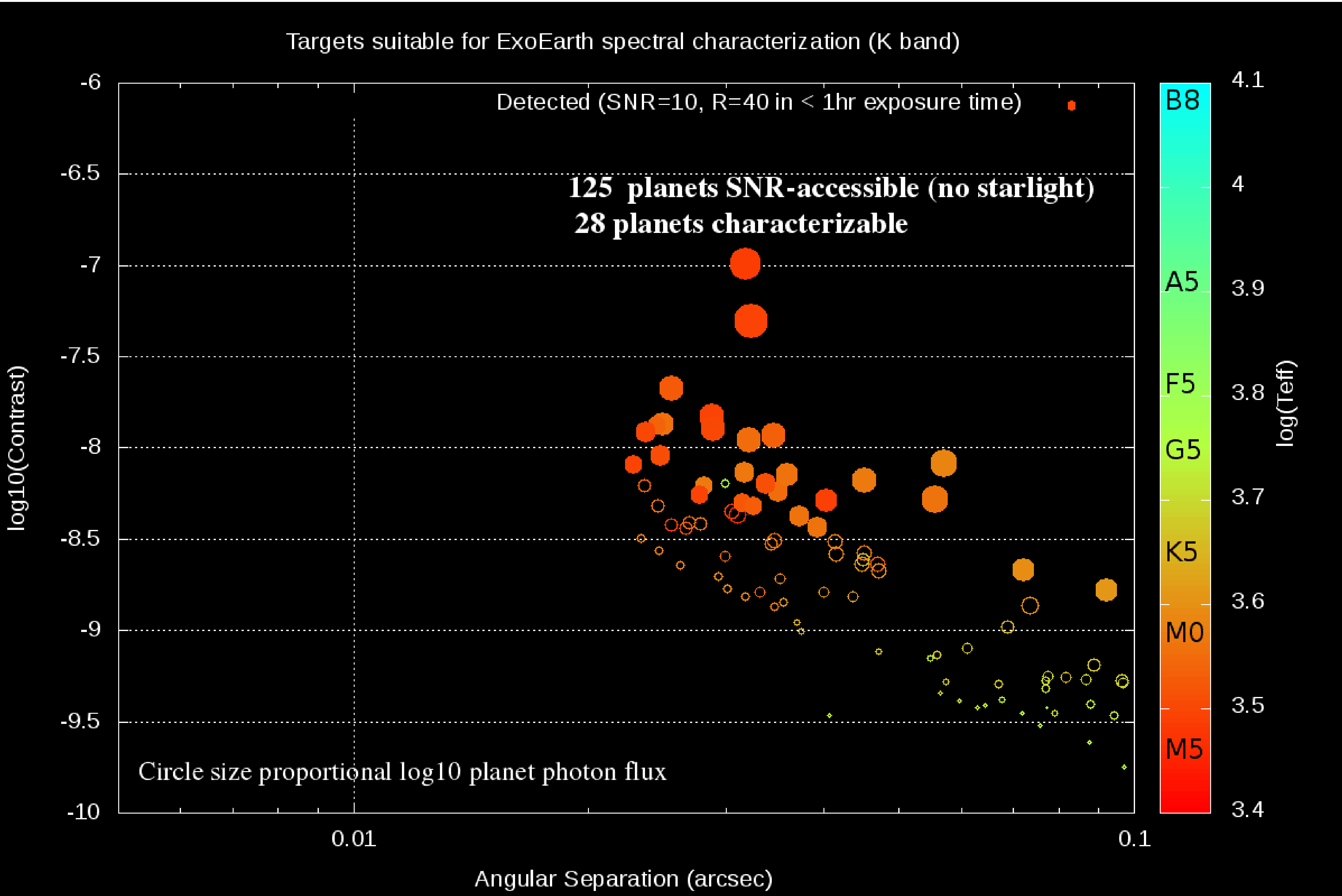


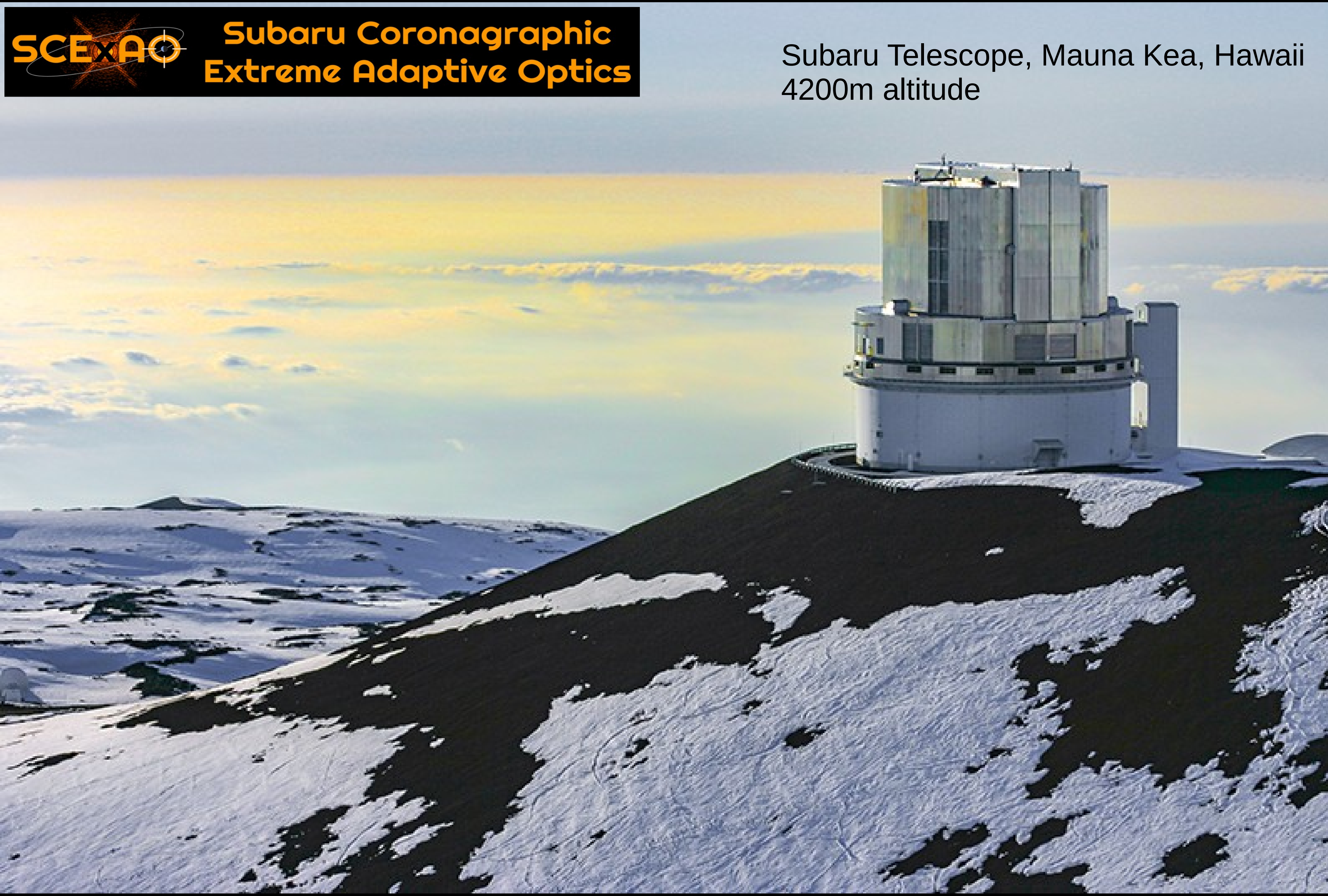
Photon-noise limited detections (1e-6 raw contrast at 1um)

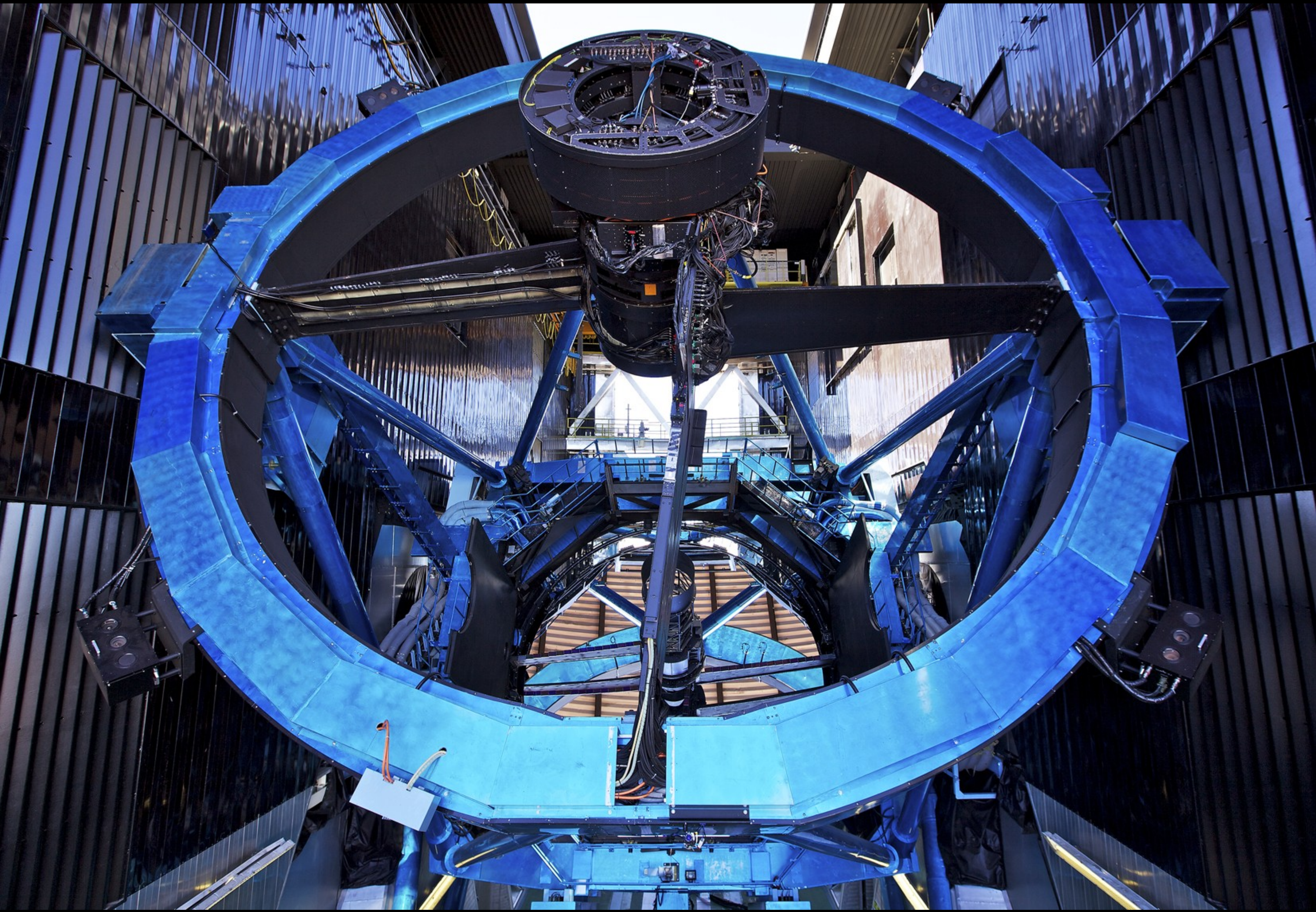


Photon-noise limited detections (1e-6 raw contrast at 1um)



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

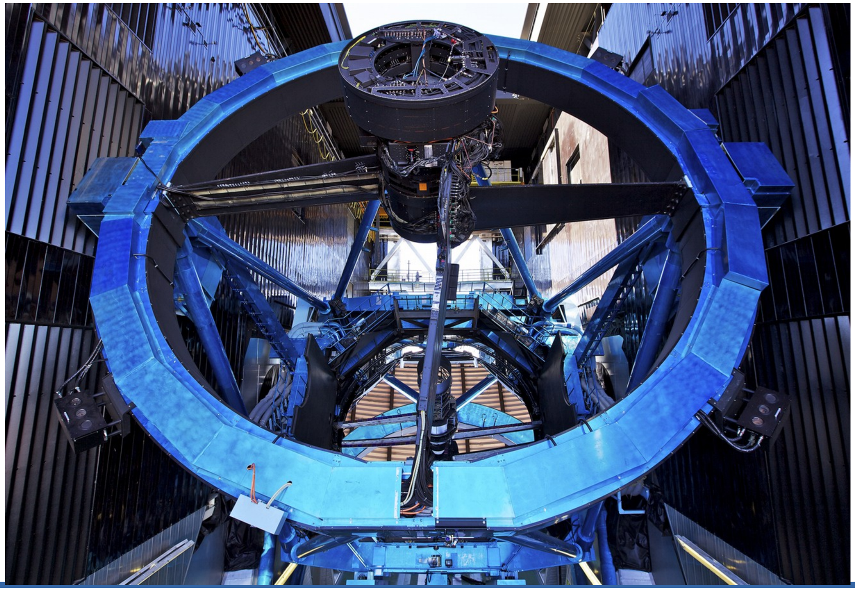




Subaru Telescope (view from inside dome)   Photograph by Enrico Sachetti


DANGER
SERIOUSLY BRILLIANT MIND AT WORK
SCExAO
Subaru Coronagraphic Extreme Adaptive Optics
P004
HIGH PRECISION DEVICES, INC.
HPD
DENALI Model 102 Cryostat
ExAO: lessons learned for a future TMT instrument
Pioneering high contrast science instruments for planet
characterization on ELTs

What is SCExAO ?



Science instrument in operation for high contrast imaging

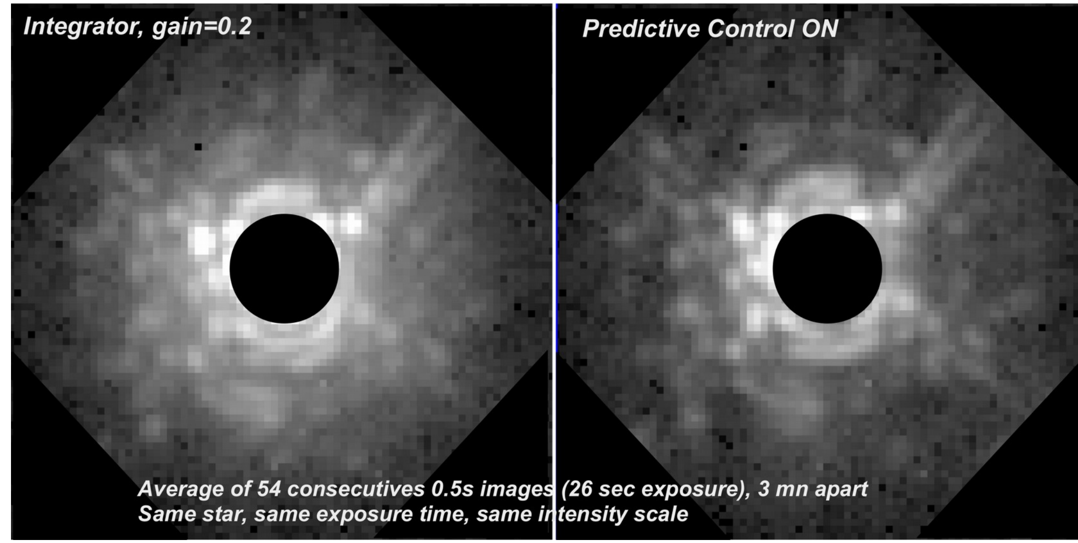
CHARIS (Near-IR)
Princeton, US

VAMPIRES (visible)
Univ. of Sydney, Australia

Development platform for on-sky validation of new technologies

→ prototyping for imaging habitable planets with upcoming large telescopes

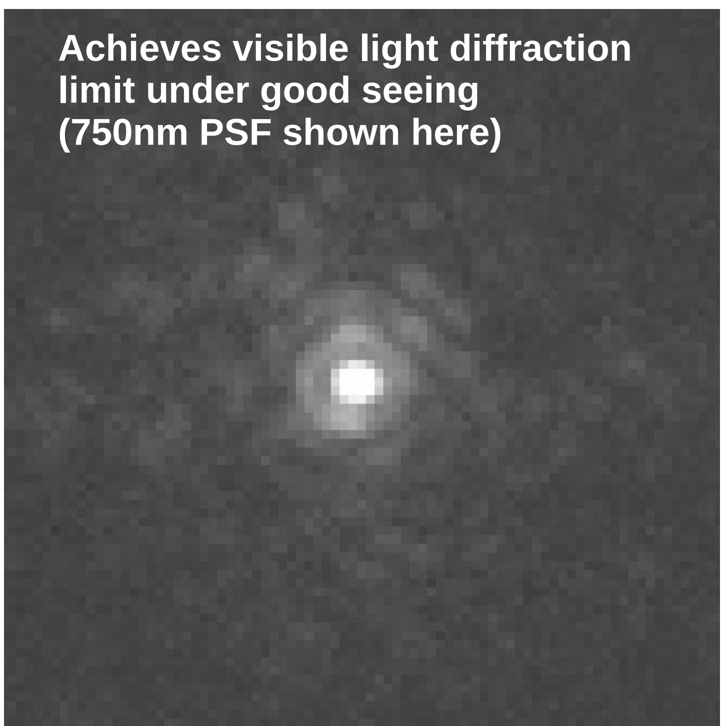
AO control loop

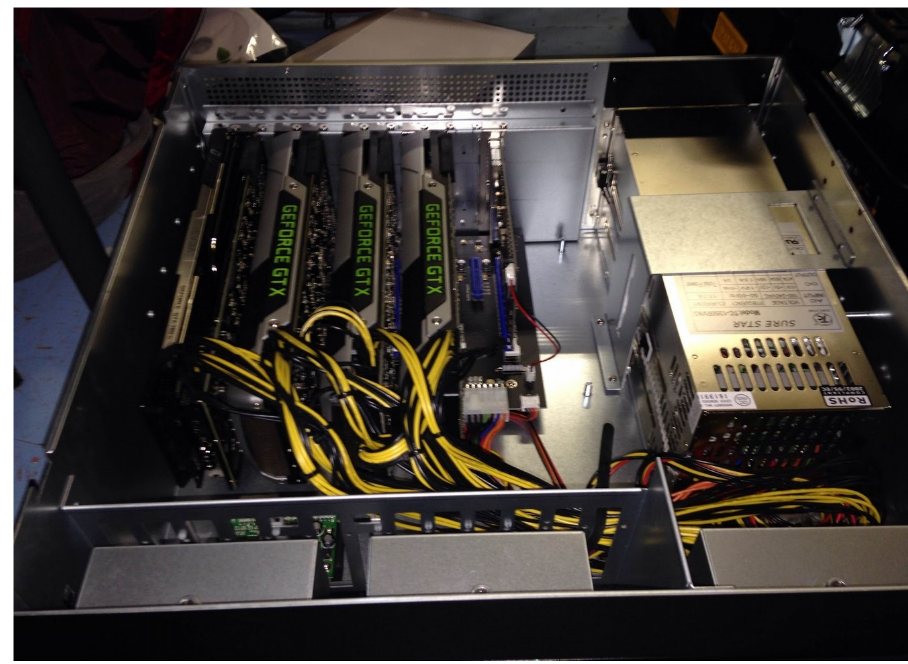


AO loop can run at 3.5 kHz (bright stars)
14,400 sensors → 2000 actuators

Includes predictive control

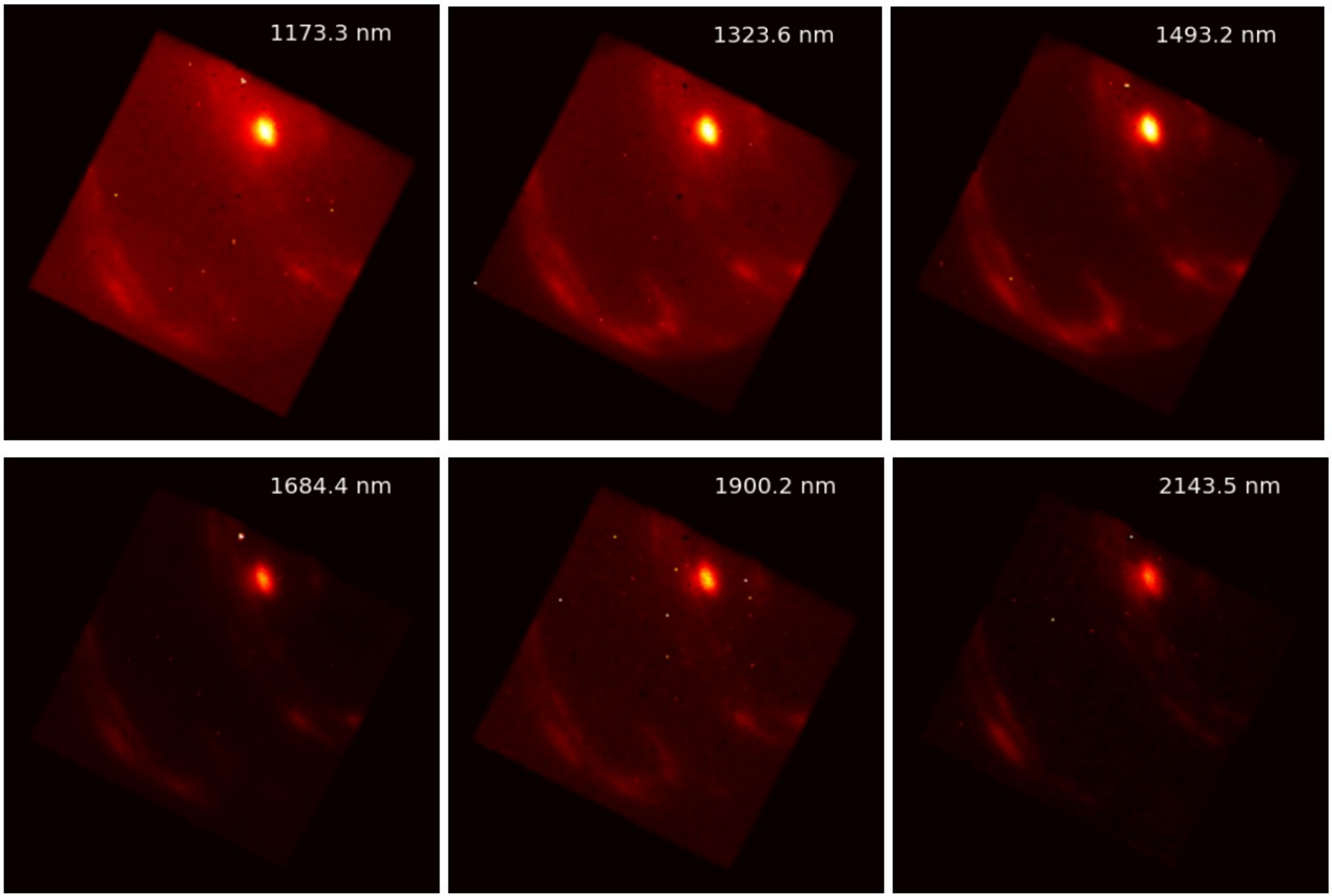
One of two GPU chassis





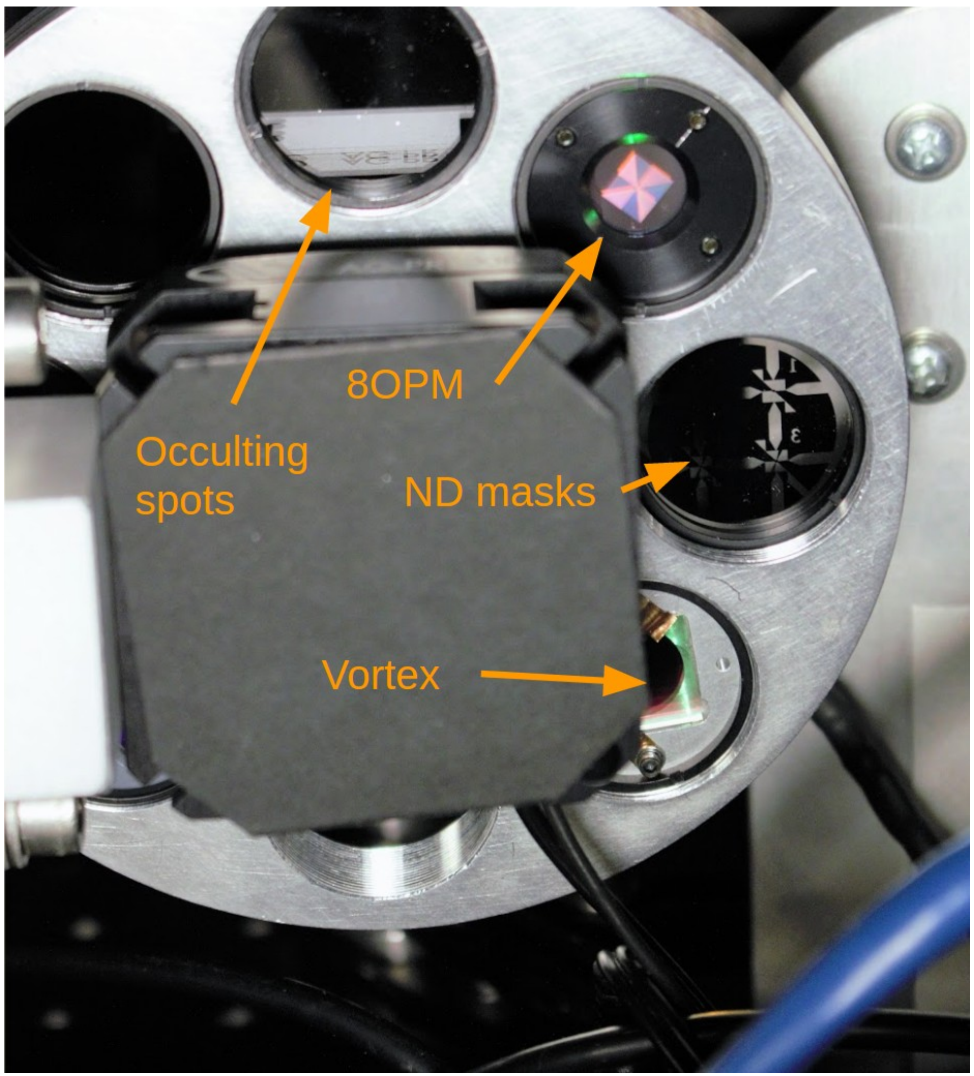
SCExAO uses >30,000 cores
Total RTC computing power several 100s TFLOPS

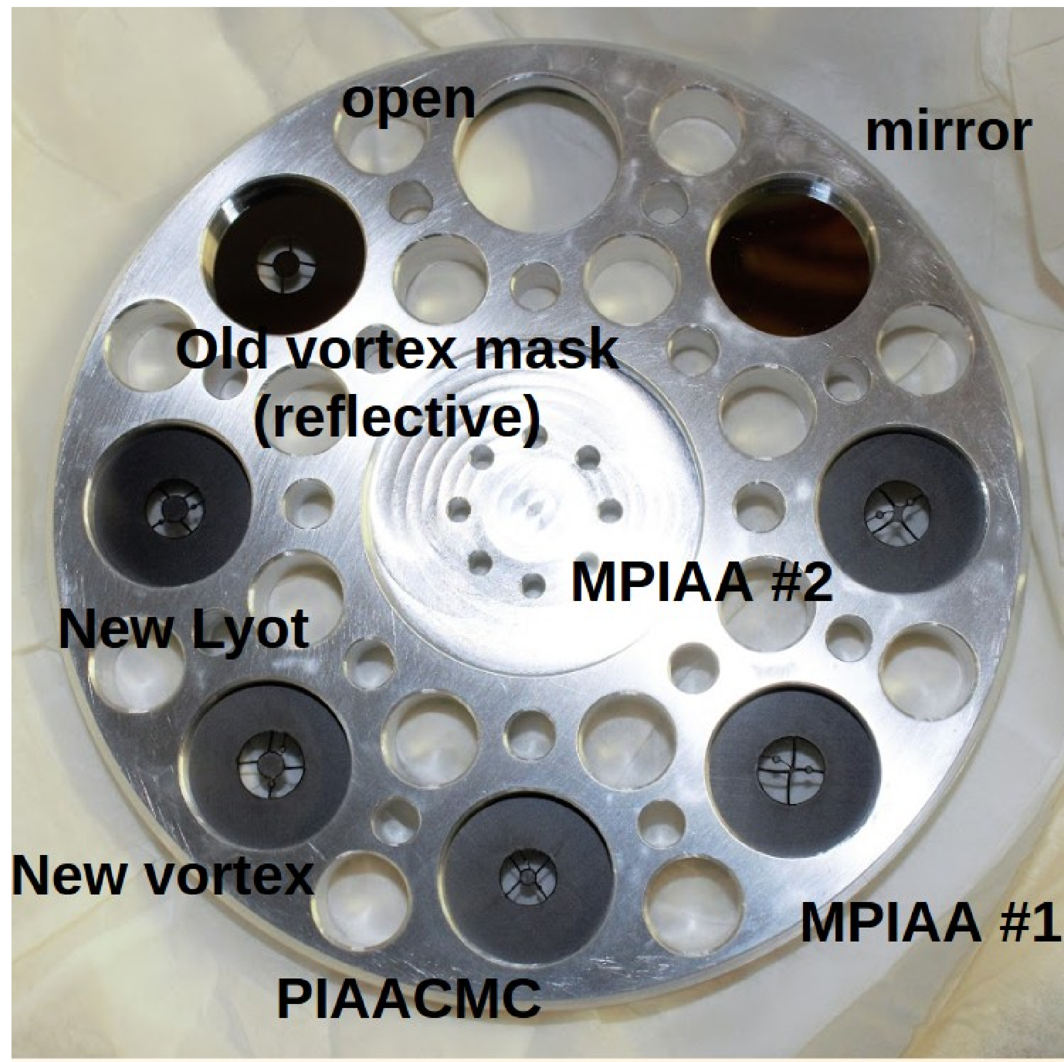
Neptune imaged with SCExAO doesn't fit in field of view ! (using CHARIS camera)

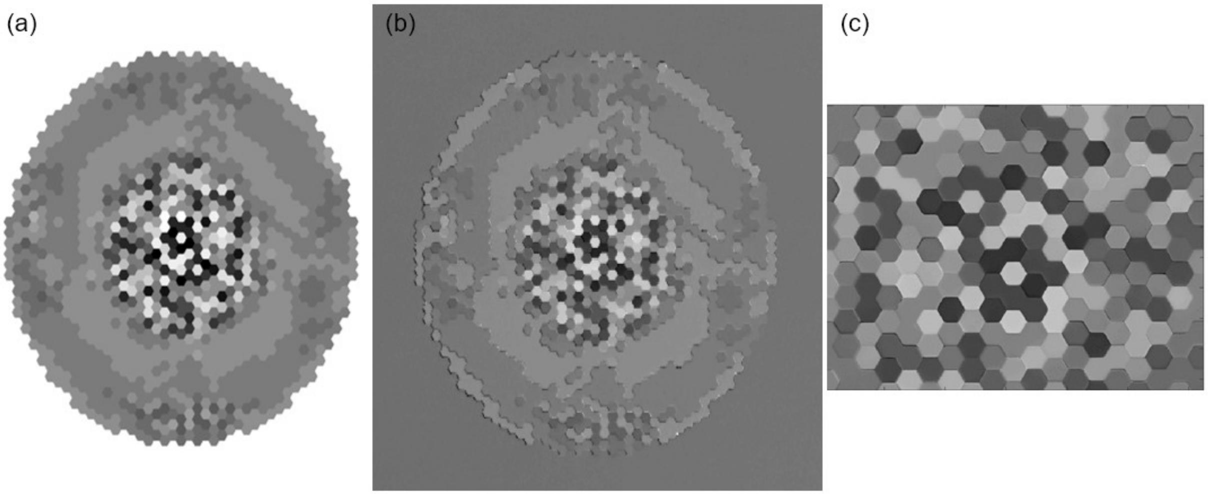


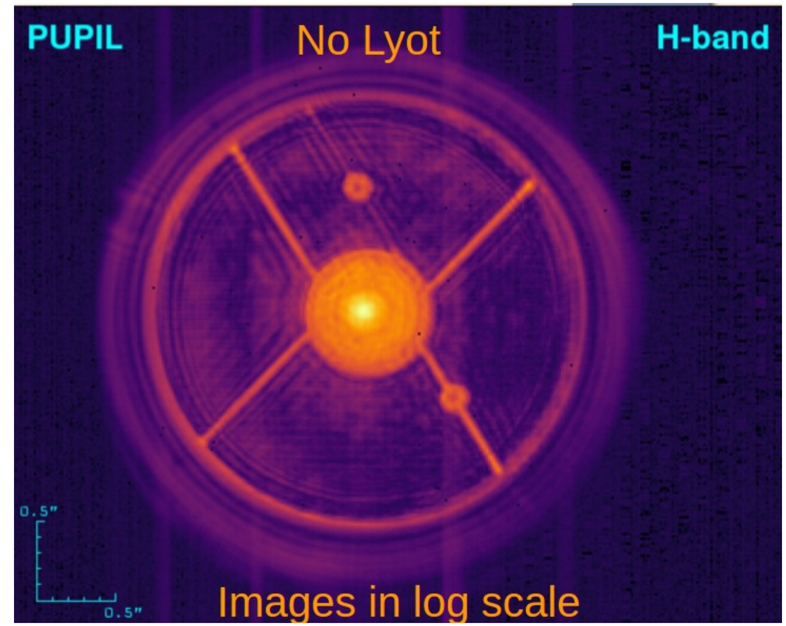
Coronagraphy

Coronagraphs:
- Vortex
- Lyot
- PIAACMC
- 8QPM
- Shaped Pupil
- vAPP

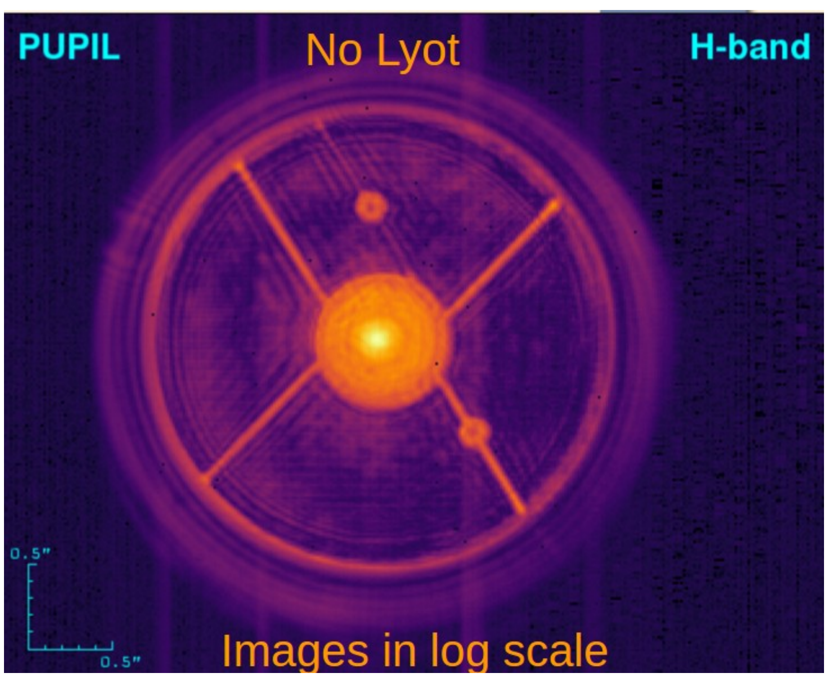




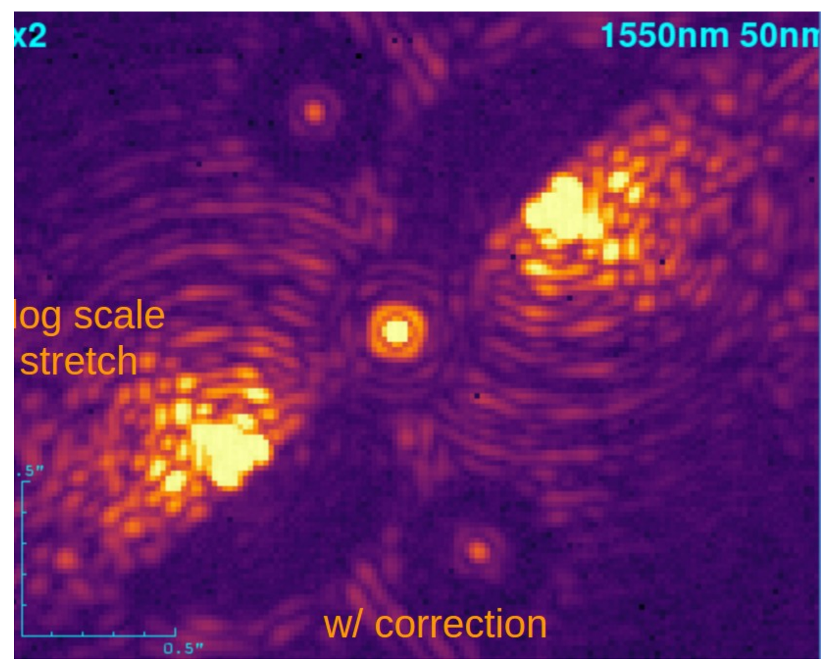




PIAACMC, Knight & Lozi, 2017



VVC, Lozi & JPL Vortex, 2017



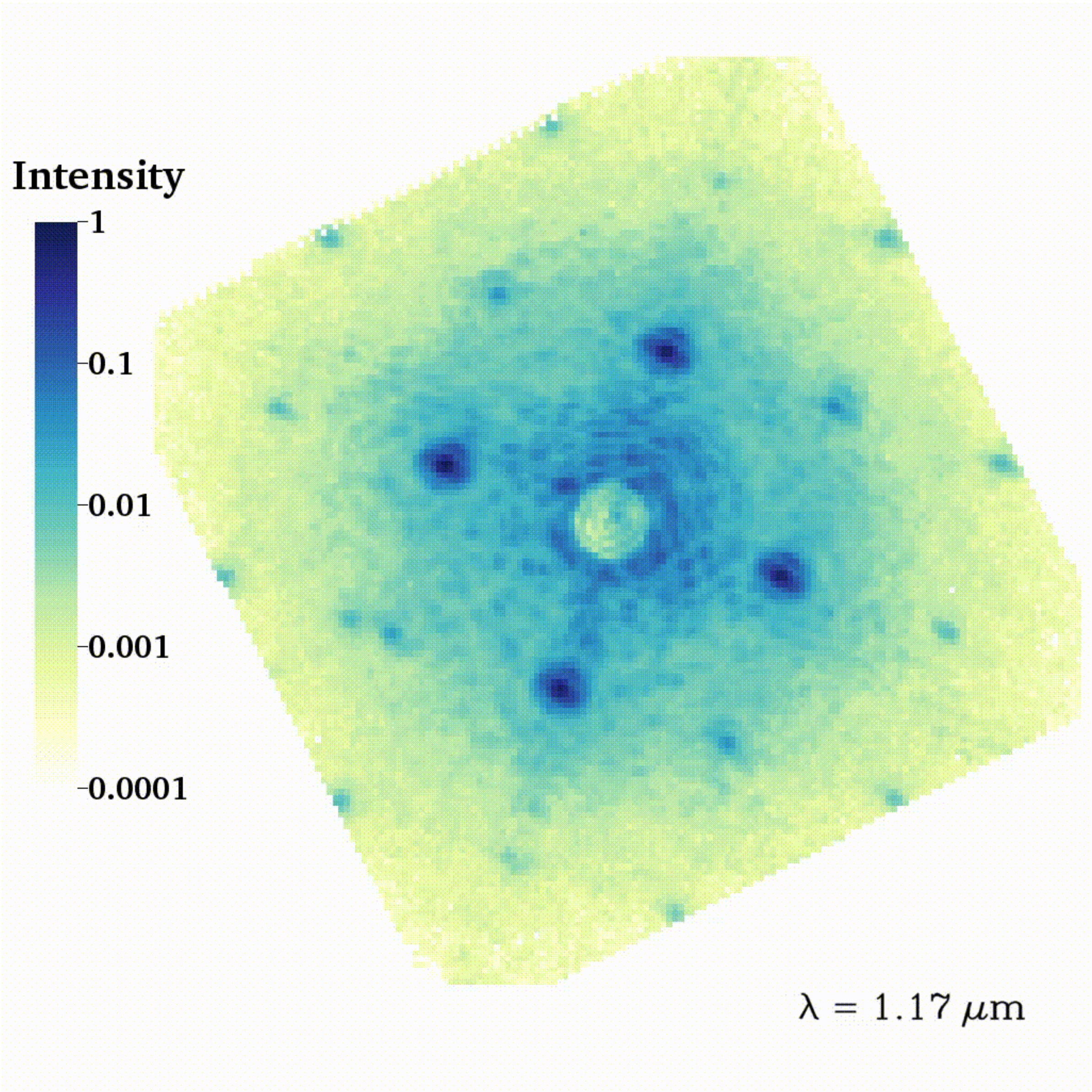
VAPP, Lozi & Leiden University, 2017

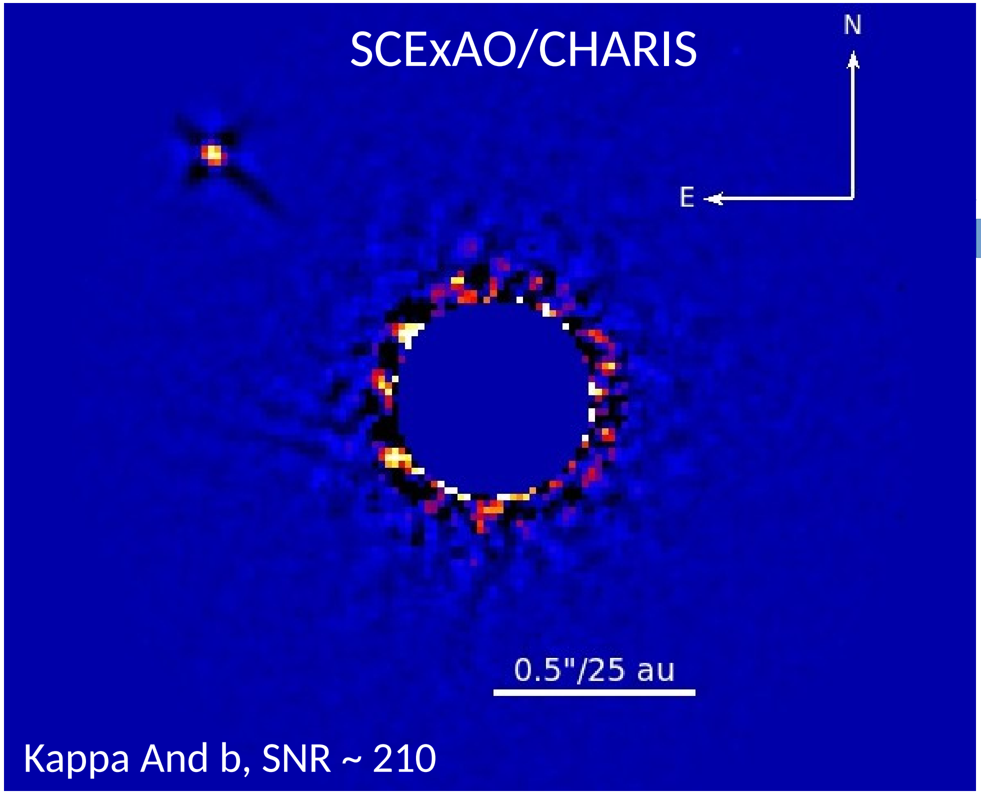
CHARIS

Near-IR IFU

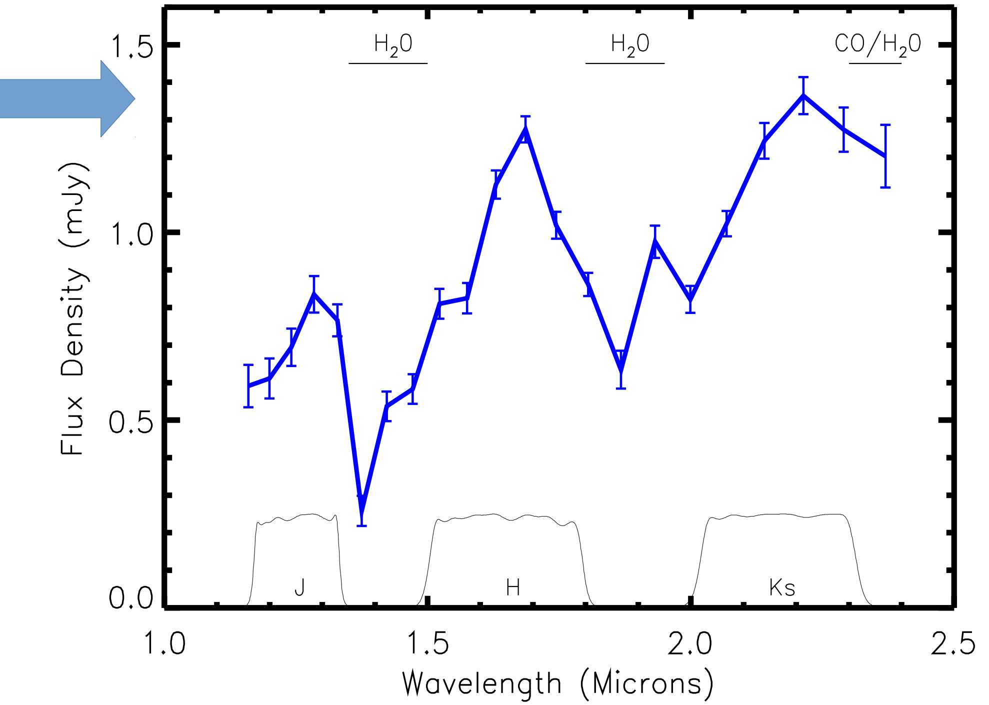
2" FOV
16.2mas / lenslet
J/H/K bands

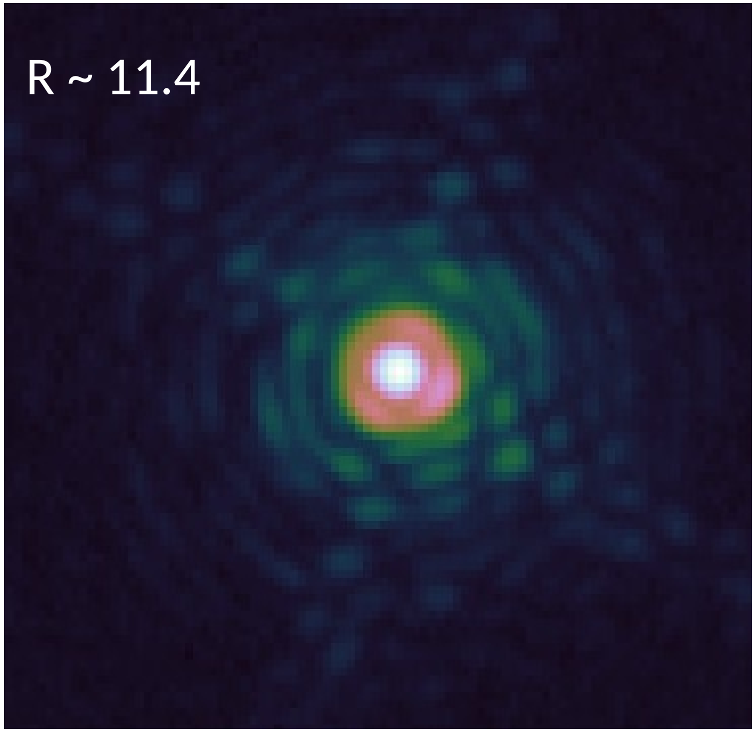
R=19 (low res, J+H+K)
R=70 (high res, J, H or K)

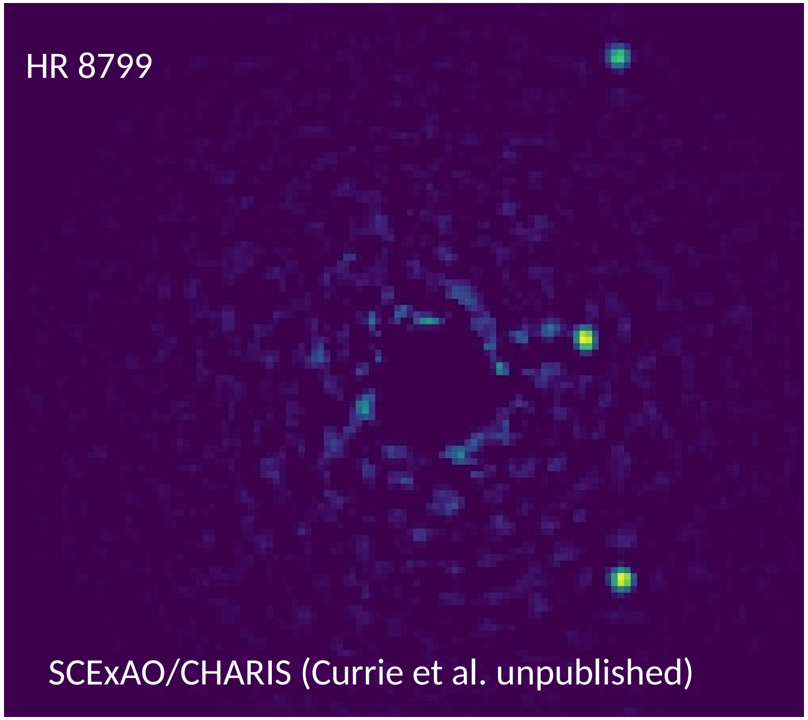


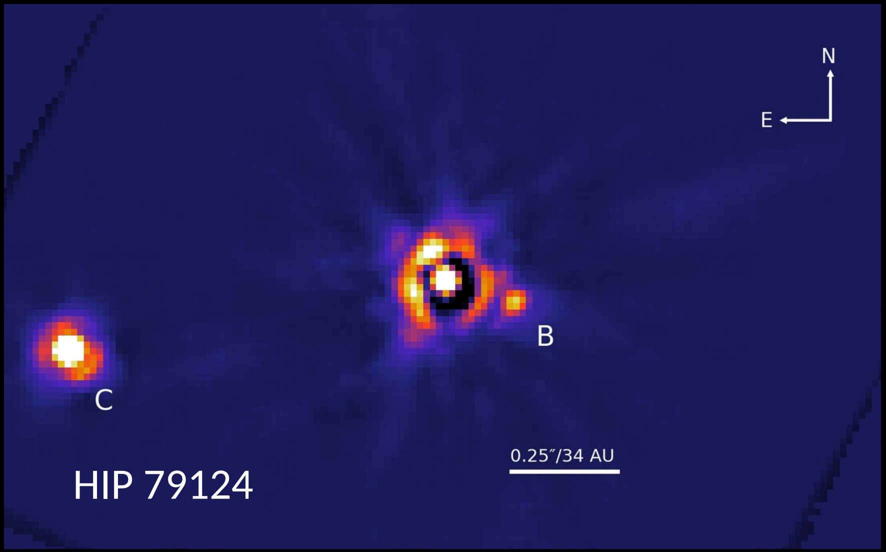


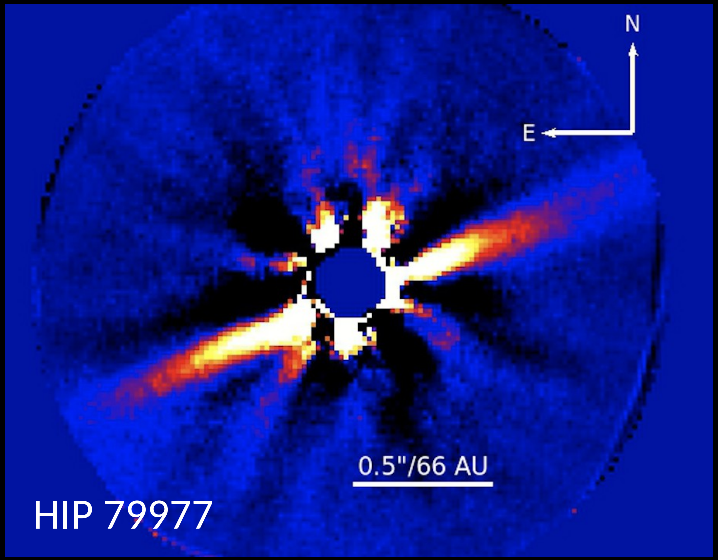
Sharply-peaked H band spectrum suggestive of low gravity ***(Currie et al. 2018, AJ, 156, 291)***

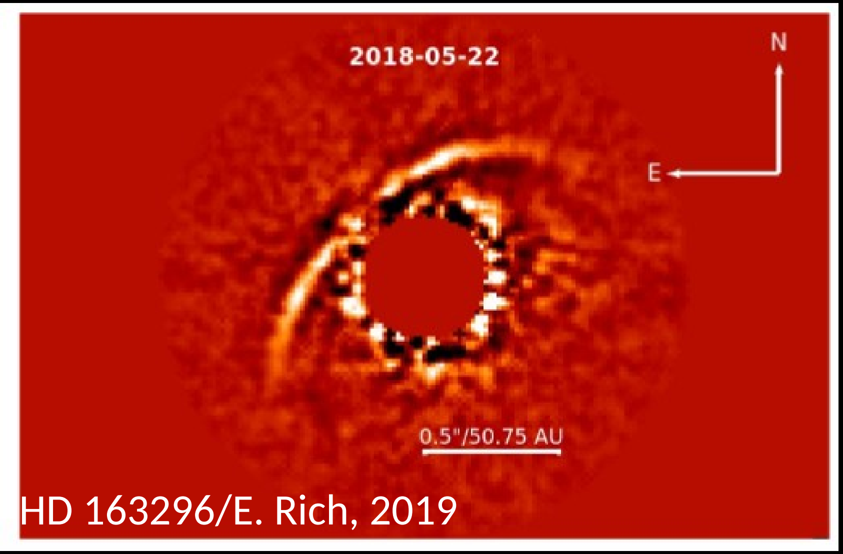


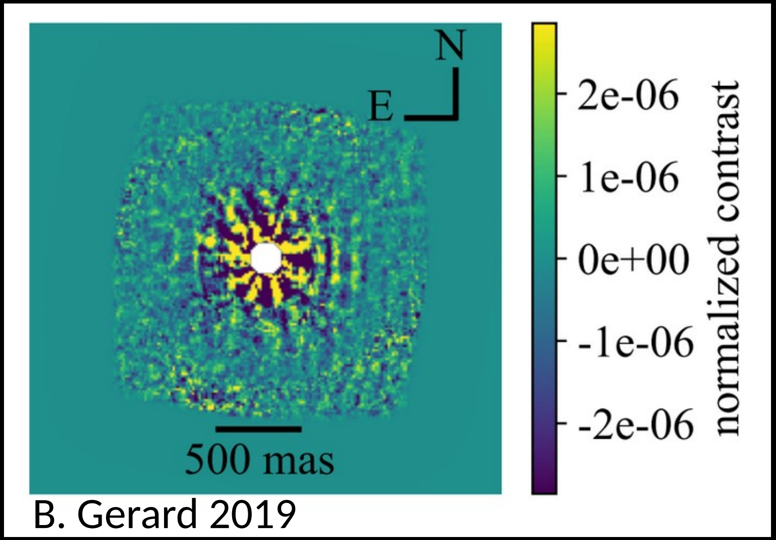





N
E
B
C
0.25″/34 AU
HIP 79124


N
E
0.5"/66 AU
HIP 79977


2018-05-22
N
E
0.5"/50.75 AU
HD 163296/E. Rich, 2019


N
E
500 mas
2e-06
1e-06
0e+00
-1e-06
-2e-06
normalized contrast
B. Gerard 2019

VAMPIRES

Visible Aperture Masking Polarimetric Interferometer for Resolving Exoplanetary Signatures

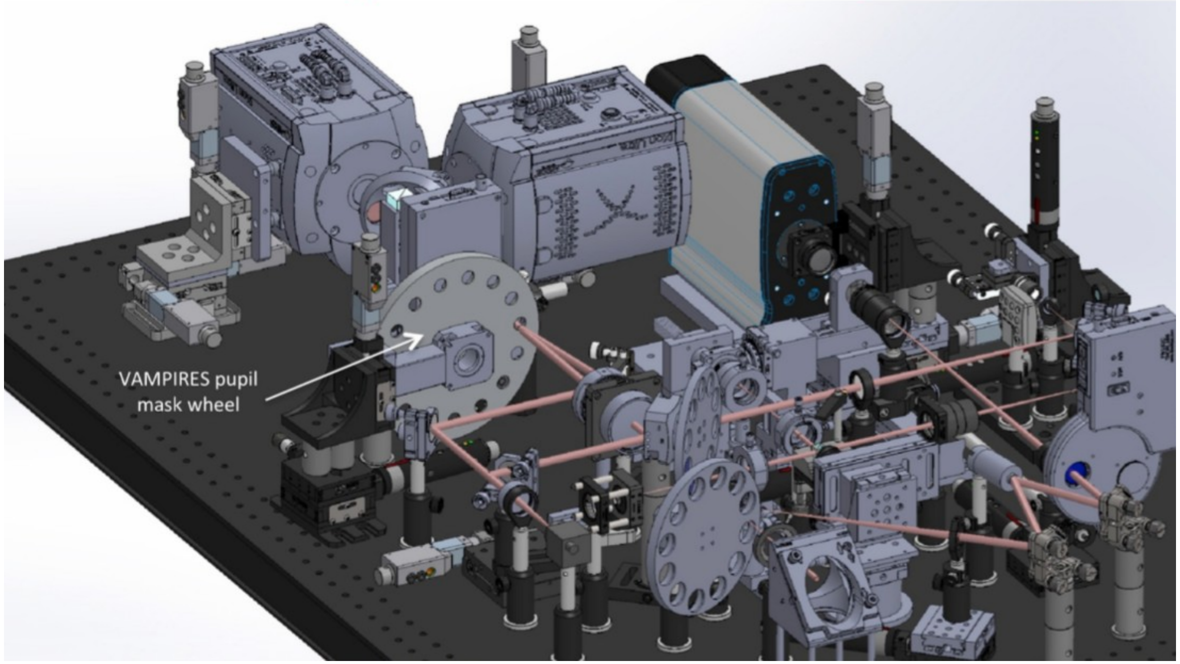
Dual EMCCD camera visible imaging.
512x512 pixel, 6mas/pix (3” FOV)

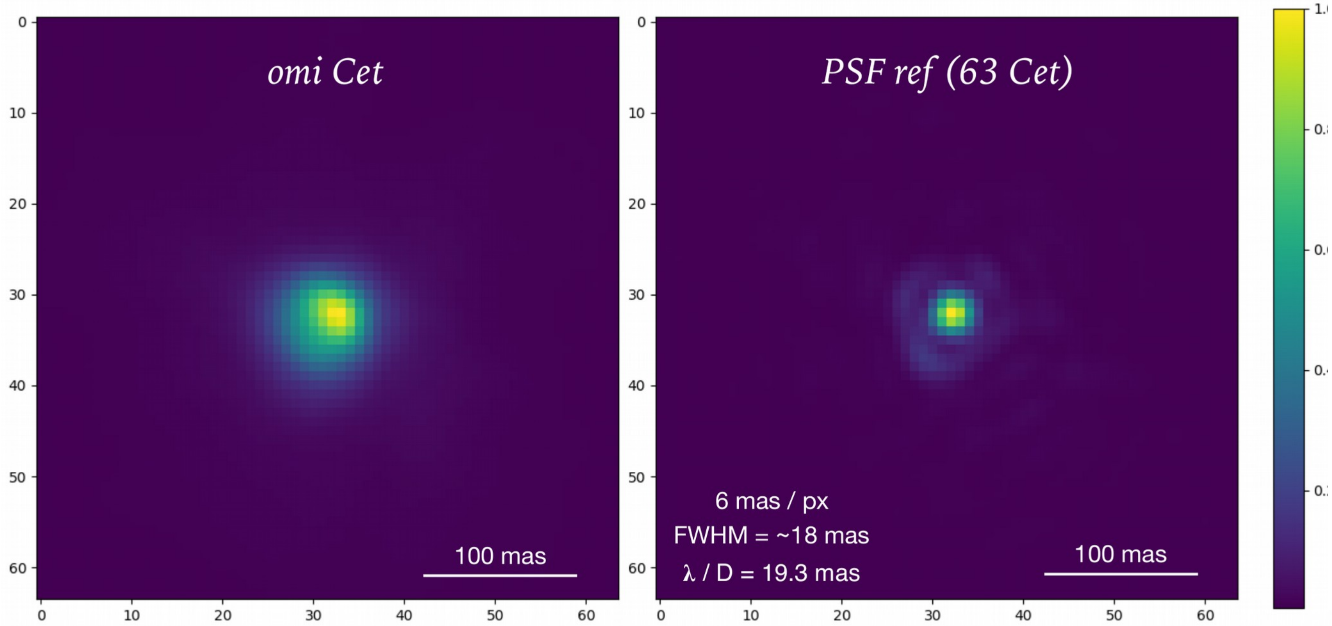
Fast frame imaging
35 Hz full frame, faster with small array

Simultaneous differential spectral imaging
Halpha emission

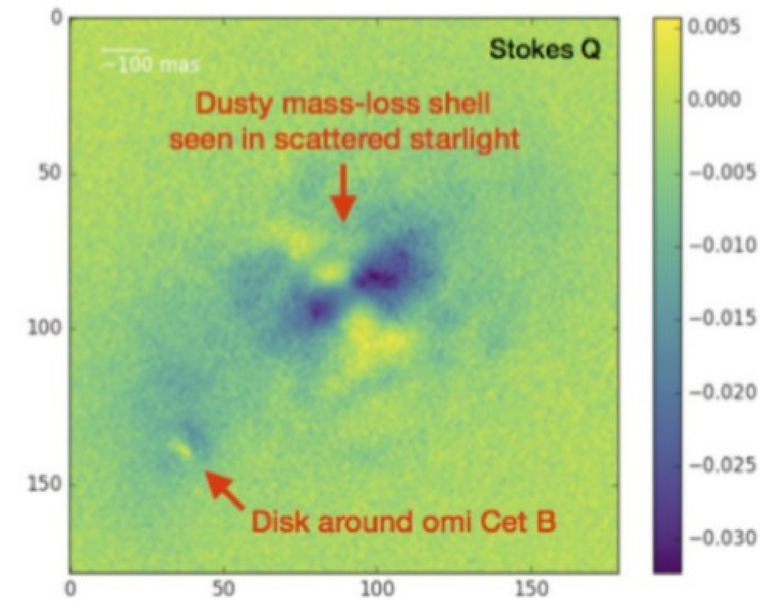
Simultaneous differential polarimetric imaging
Circumstellar disks

Aperture masking (+PDI)
High precision measurements beyond telescope diffraction limit





Observed 12/09/2017

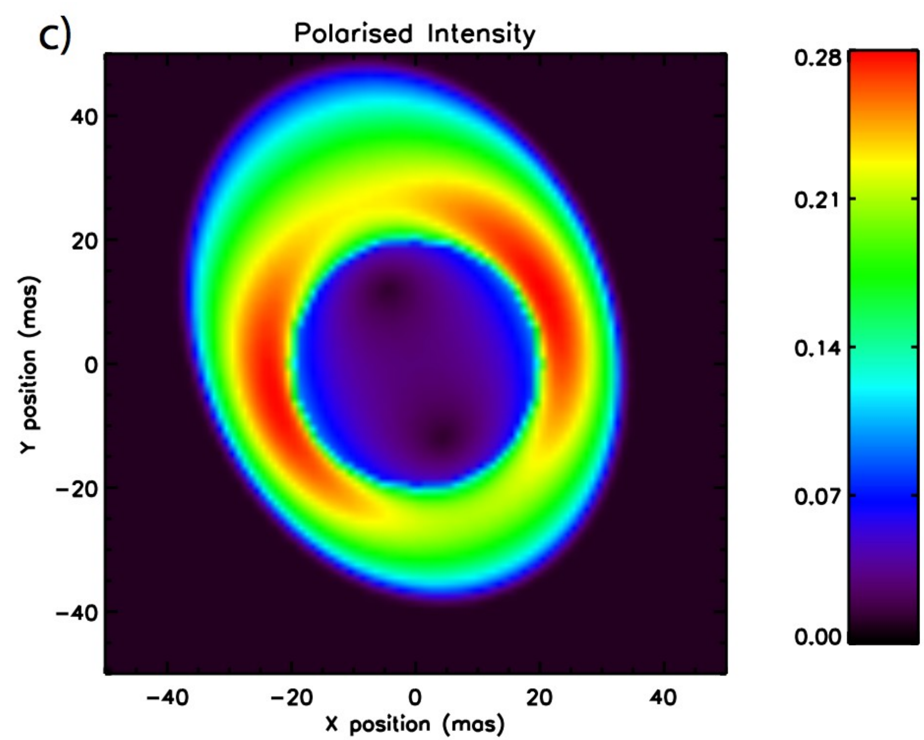


μ Cephei

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



New & upcoming capabilities

Observing modes / instruments :

Speckle control → higher contrast
NearIR Polarimetry → disks imaging/characterization
High-Res spectroscopy → Exoplanet atmospheres
Interferometric imaging → ultra-high angular resolution

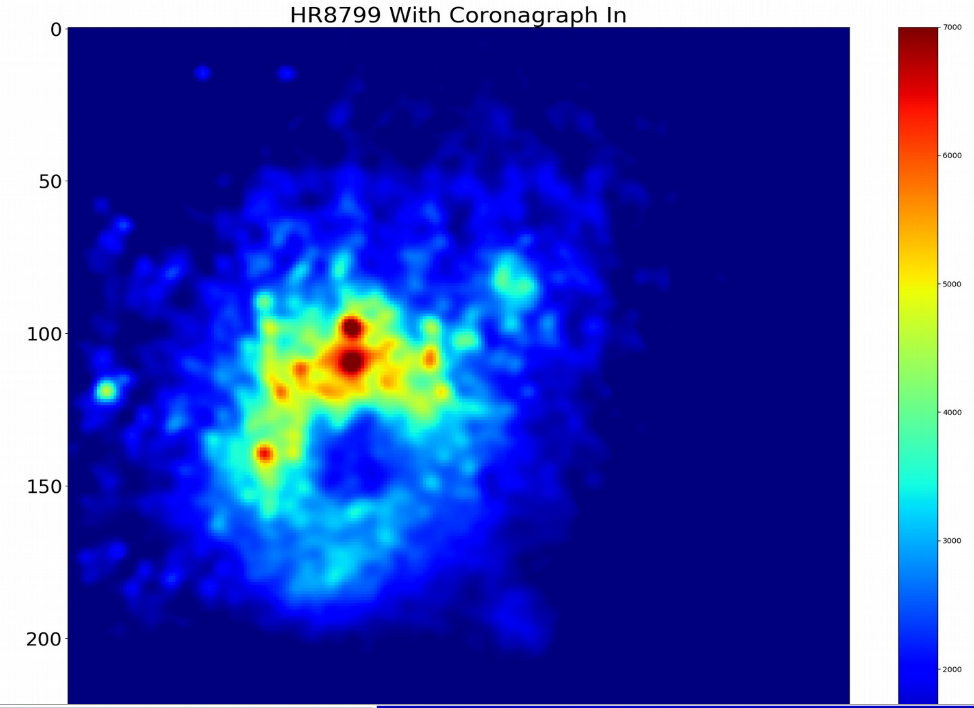
Software / data analysis:

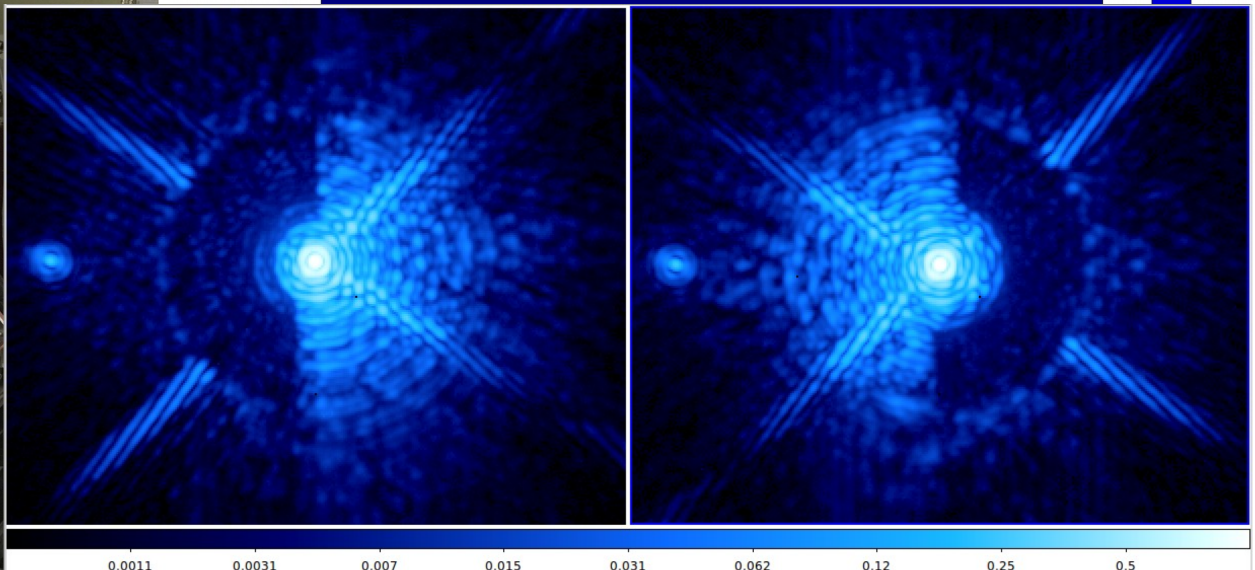
PSF calibration

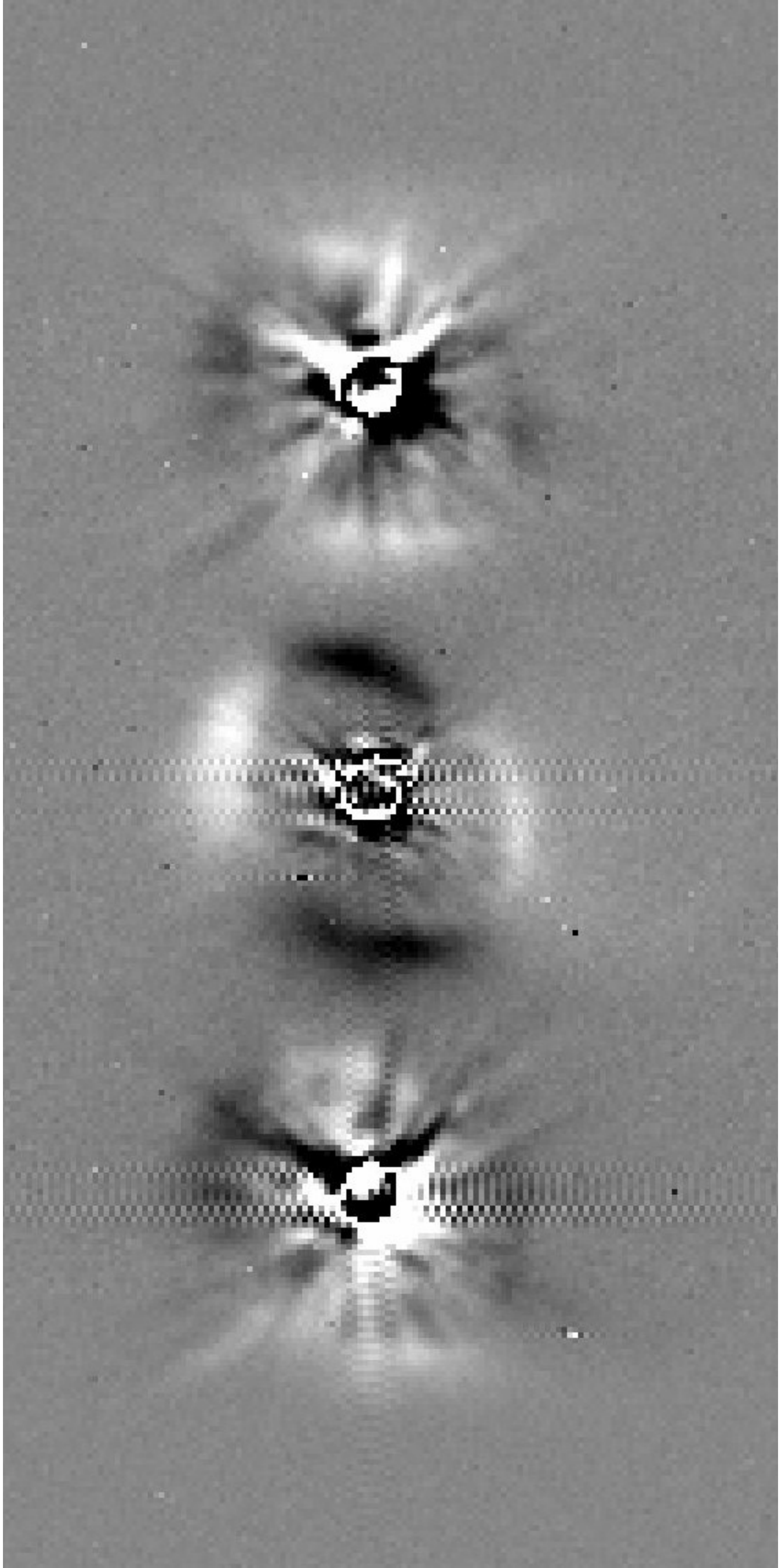
AO188 upgrades:

Beam switcher → easier operation
64x64 DM → higher performance overall
nearIR WFS → pushing limiting magnitude
Ultimate-START → LGS to push limiting magnitude

MKIDs camera [MEC, UCSB]
Optimized for fast speckle control







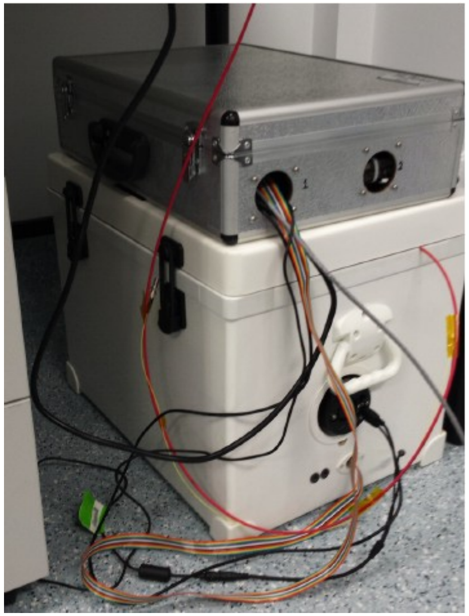
Near-IR polarimetry

Spectro-Polarimetry (CHARIS)
PDI mode feeding CHARIS

High speed PDI
Fast modulation with FLC

Both modes to be offered in S19B

Fiber-fed HR spectroscopy (R~70,000 to 100,000)



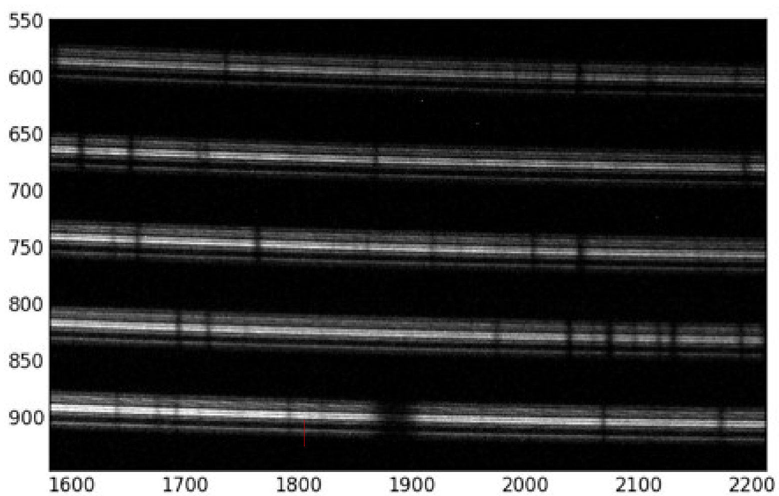
Visible

RHEA

Replicable High-resolution Exoplanet & Asteroseismology

(Michael Ireland, ANU
Christian Schwab, Macquarie Univ)

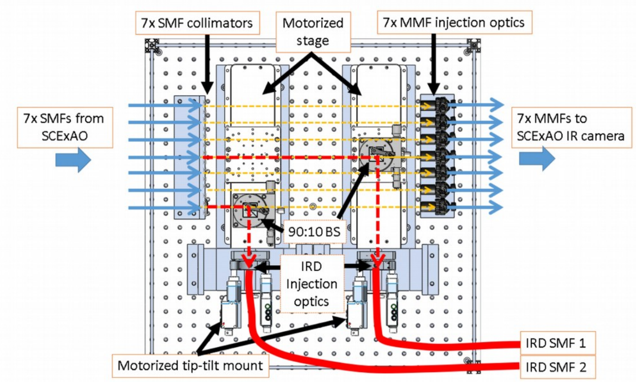
RHEA first light @ Subaru: Eps Vir (detail) Feb 2016

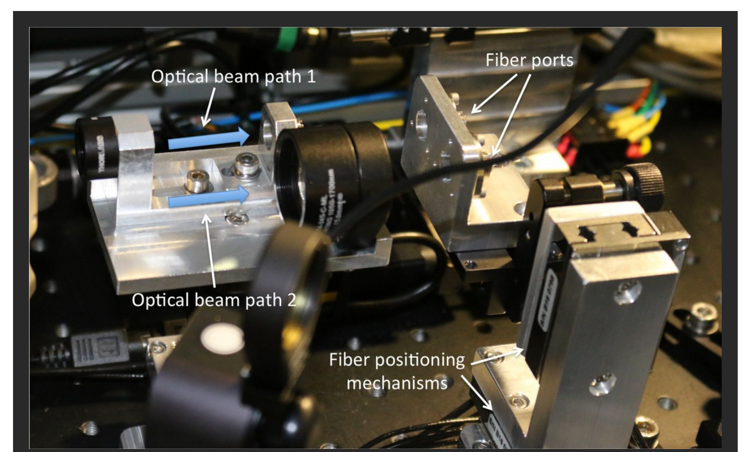


Near-IR

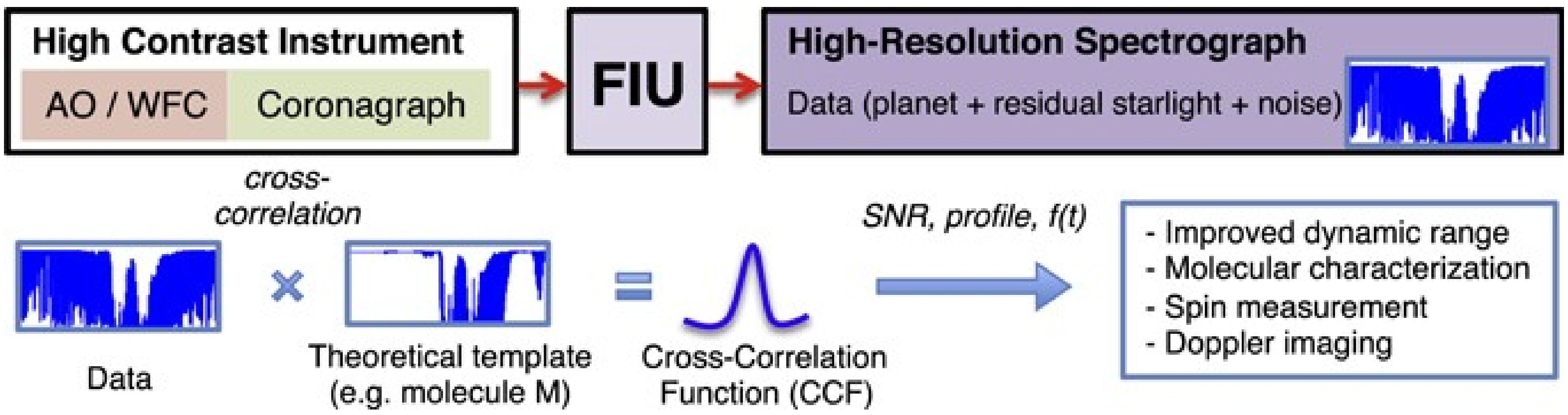
SCAHLET

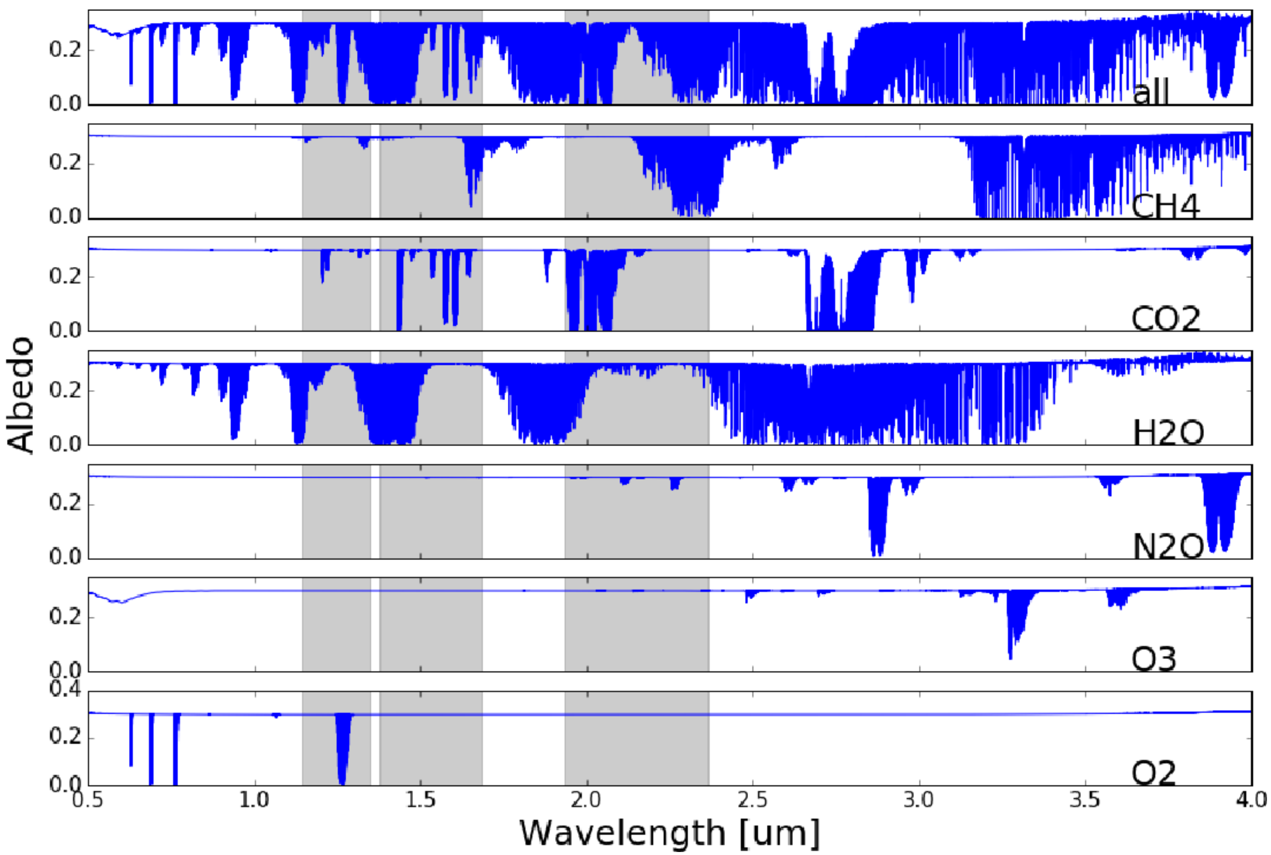
SCExAO → IRD feed
T. Kotani, H. Kawahara





High Dispersion Coronagraphy



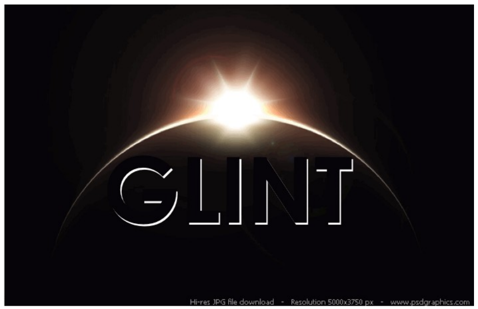


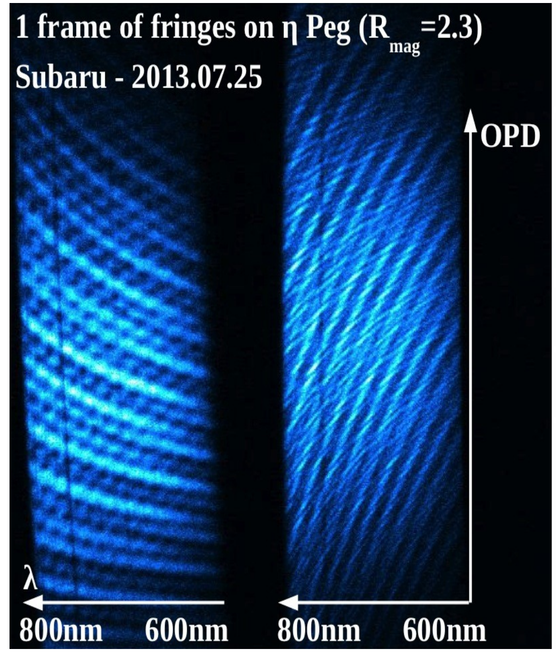
Very robust differential signature

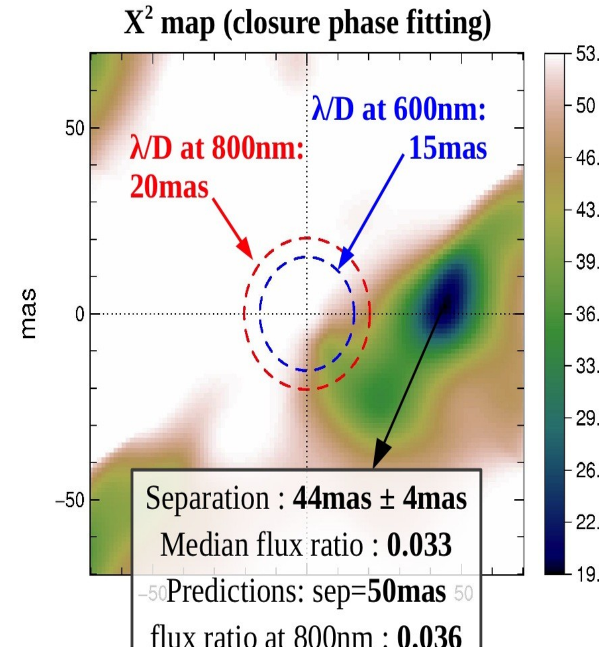
First demonstrated on combined light (no coronagraph) – Snellen et al.

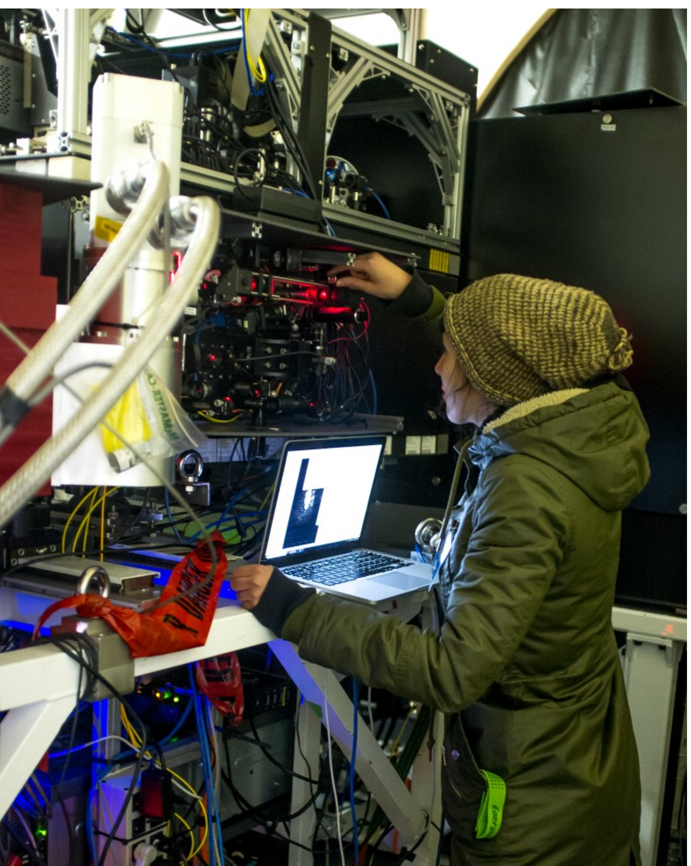
Mawet, Wang et al.

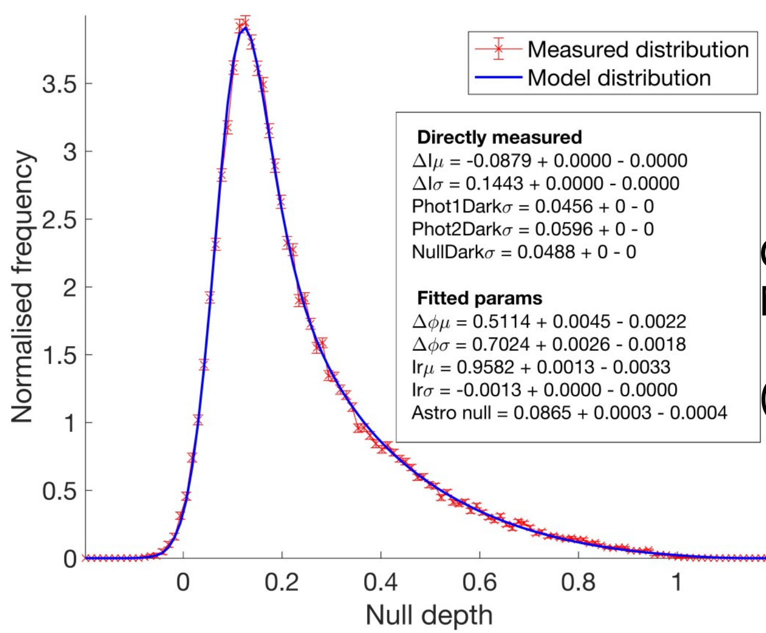
Interferometry: FIRST (vis) and GLINT (NIR)











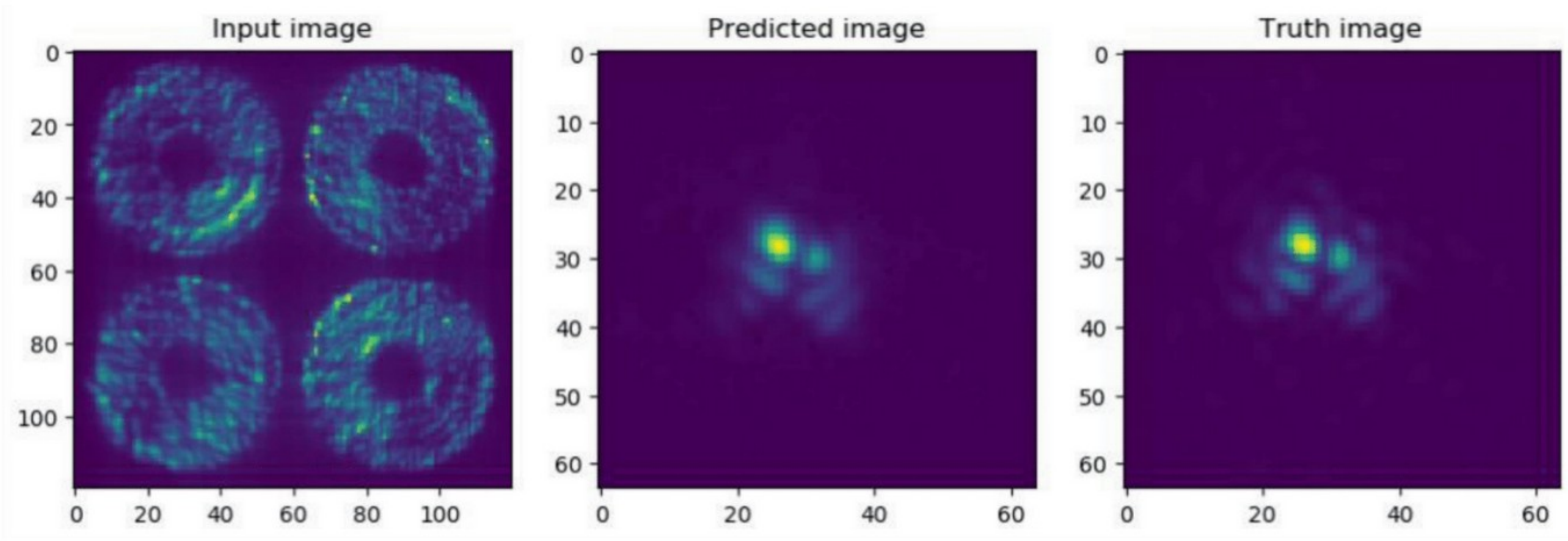
Chi Cyg observed June 2017
Null depth= 0.0865 +- 0.0004
→ **diameter = 21.6 mas**
(literature values: 20-25 mas)

PSF calibration from real-time telemetry
→ it should be nearly impossible for speckles to "hide"

Two goals:
#1 improve **Wavefront control** sensitivity and accuracy
#2 provide real-time stellar PSF estimate for **PSF subtraction**

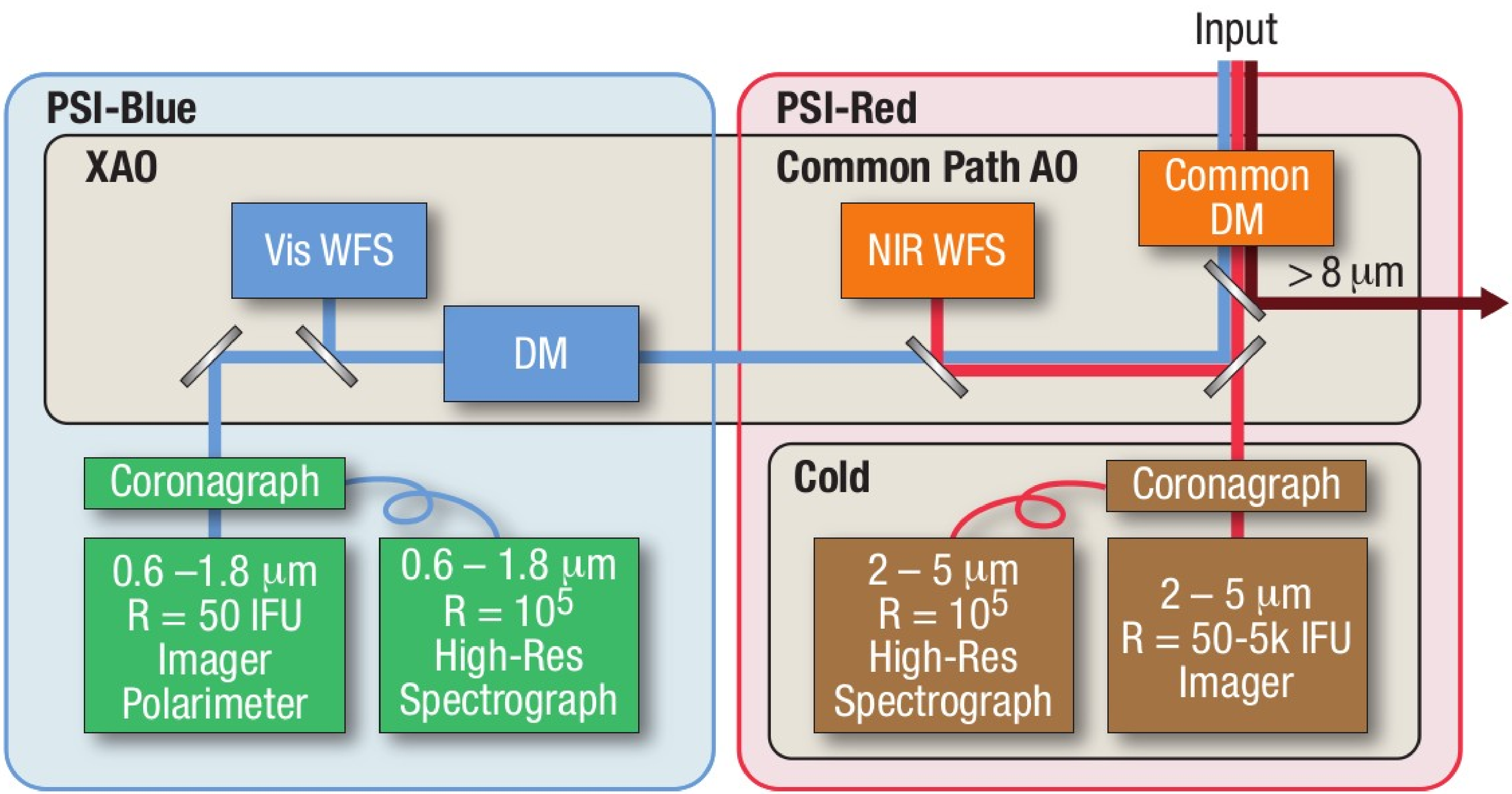
Promising… but realtime reconstruction of PSF from multiple WFSs is very challenging

Early work: PSF reconstruction using NN successfully estimates visible PSF (B. Norris, Univ. of Sydney)



Thirty Meter Telescope’s PSI Instrument

PSI Instrument Architecture (notional)



Wide wavelength coverage
3 science outputs for cameras/spectrographs:

- Thermal IR (> 8 um) could be feeding MICHI
- Near-IR (2-5 um)

Cold

Warm

- Optical (< 1.8 um)

Contrast / Separation requirements

PSI’s ultimate goal: habitable planet observations around nearby M-type stars:
Separation ~2 l/D, ~1e-8 contrast, mR~10

Small IWA
coronagraphy

ExAO +
Differential
imaging

Efficient WFS,
multi-band, multi-sensor,
predictive control

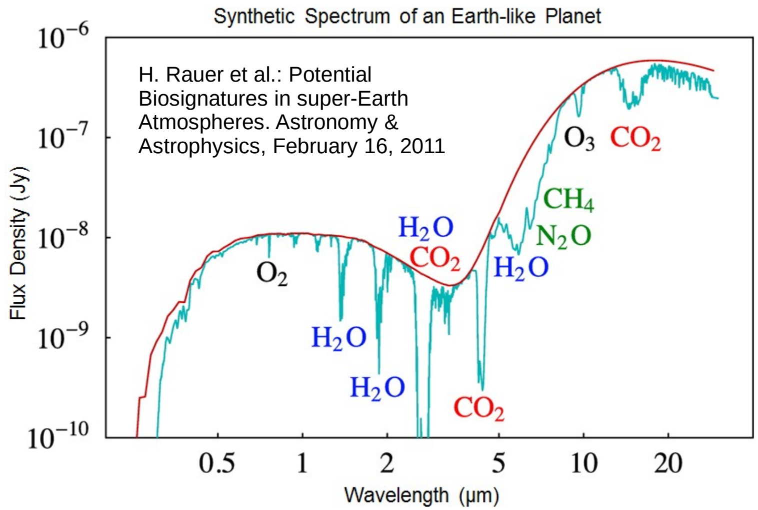
Optimal spectral range : ~1-2 um

Scientific Value

Blue/visible: Rayleigh scattering
760 nm Oxygen A band

NearIR rich in absorption bands:
Oxygen (1.27um), Water, Methane, Carbon Dioxyde

Thermal emission starts at ~3 um, rich in molecules



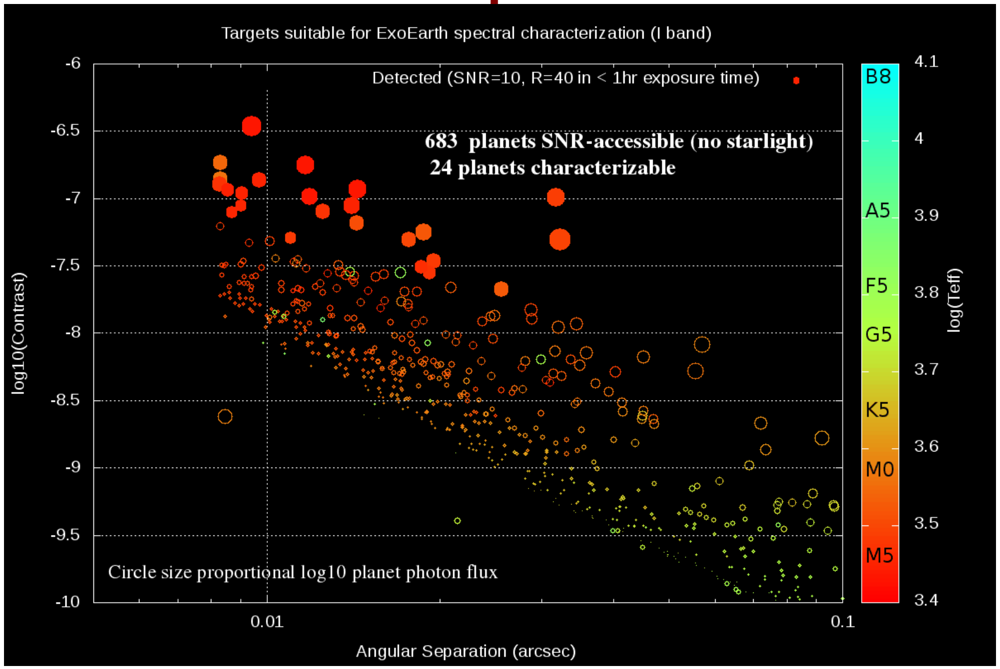
Expected Instrument Capabilities

Let us assume that :
(1) ExAO system can deliver 1e-6 raw contrast at 1um ← Initial guess for Q2
(2) Every star has one Earth analog
(3) Photon noise limit from both starlight and planet light

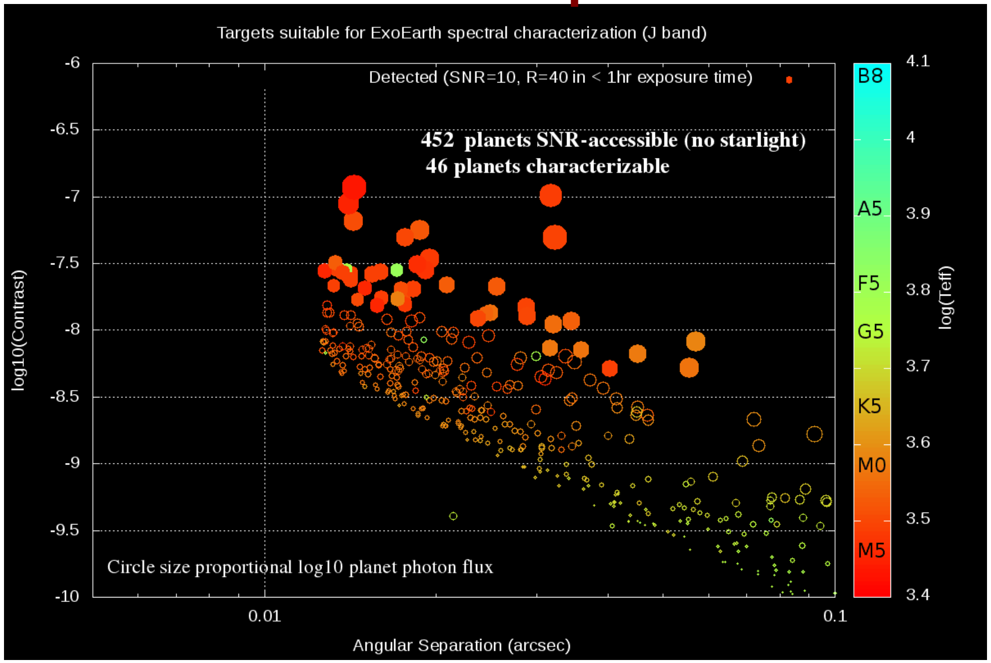
We can scale contrast according to wavelength (C ~ lambda^-2)
.. and scale coronagraph according to wavelength (IWA ~ lambda)

We count, for each spectral band (V, I, J, H, K), how many planets are characterizable:
R=40 spectra at SNR=10 can be acquired in < 1hr
(approximate requirement for spectroscopic detection of key molecular species)

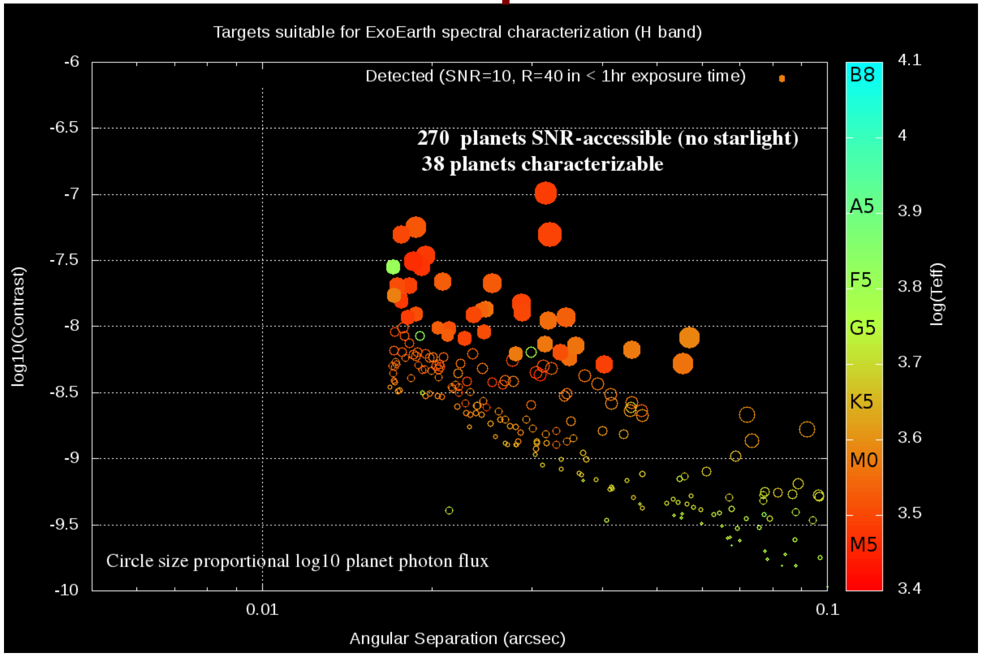
I band: 24 planets



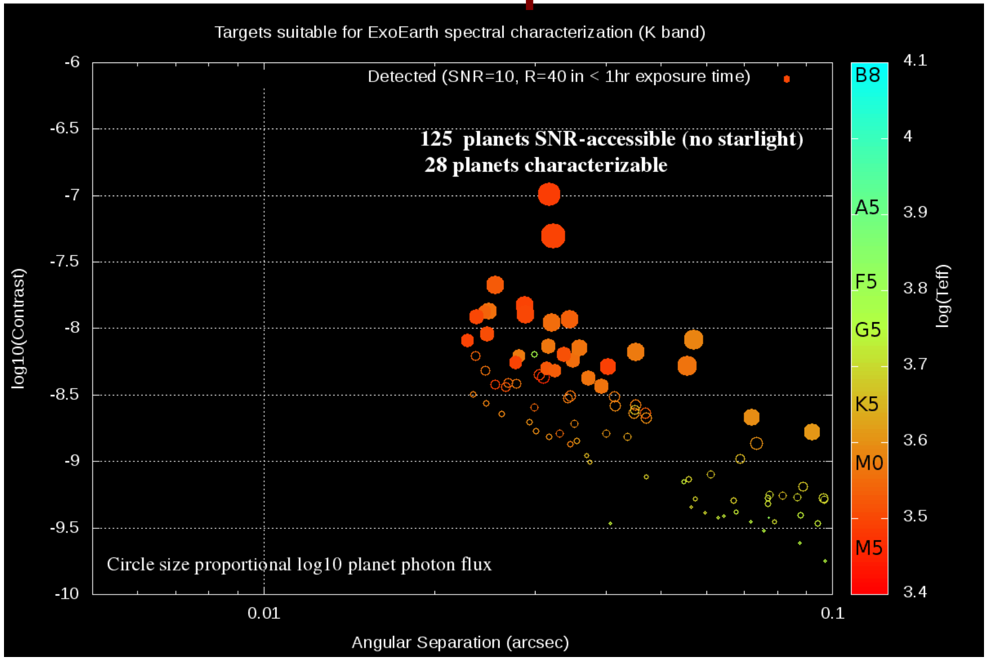
J band: 48 planets



H band: 38 planets



K band: 28 planets



Optimal wavelength range: J & H / Required raw contrast ~1e-5 / Best targets are M0-M6

Optimal wavefront sensing wavelength: red/visible

Blue light: Better information content per photon, but fewer photons
Red light: More photons, but less signal per photon

Table 6 Optimal Wavefront Sensing Wavelength - Linear Regime

Spectral Type	Teff [K]	Optimal Band[a]	Photon flux[b] $[m^{-1}.ms^{-1}]$	Flux gain relative to ... B	R	H
B0V	31500	U	1.08e10	2.14	12.06	1337.0
A0V	9700	B	5.01e7	1.00	4.25	204.7
F0V	7200	B	1.05e7	1.00	2.78	82.1
G0V	5920	B	1.34e6	1.00	1.80	33.7
K0V	5280	B	3.26e5	1.00	1.33	17.6
M0V	3850	R	3.53e4	2.03	1.00	3.93
M4V	3200	I	4.65e3	12.5	1.80	2.83
M8V	2500	J	6.00e2	150.0	11.6	1.98

[a]Optimal bandwidth selected among standard astronomical spectral bands (U, B, R, I, J, H). Assumes fixed relative spectral bandwidth $d\lambda/\lambda$. Central wavelength listed; [b]Assuming 10% effective spectral band at optimal sensing wavelength, main sequence star at 10pc.

Prime wavelength range: 600nm to 900nm

Rocky planets orbiting in the habitable zones of M-type stars will be the first targets suitable for imaging and spectroscopic characterization.

Are they habitable ?
(tidal locking, atmosphere loss ?)