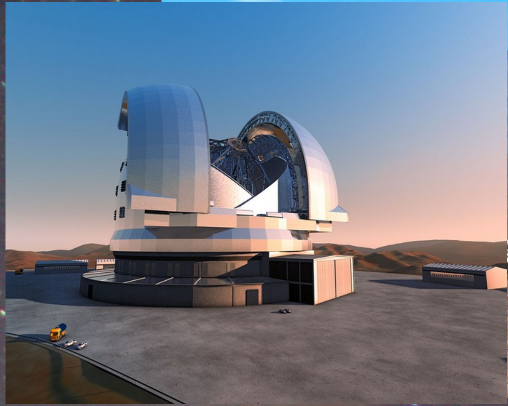

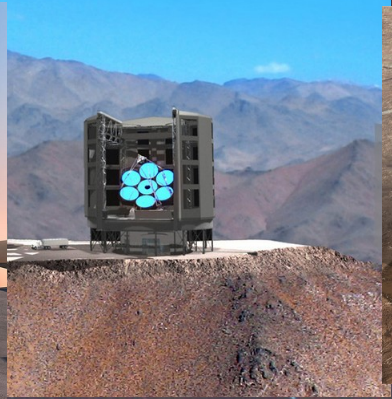

Imaging Habitable Exoplanets with Large Ground-based Telescopes: Challenges and Opportunities

Olivier Guyon

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Astrobiology Center, National Institutes for Natural Sciences (NINS)

Subaru Telescope, National Astronomical Observatory of Japan (NINS)

University of Washington, May 3, 2017

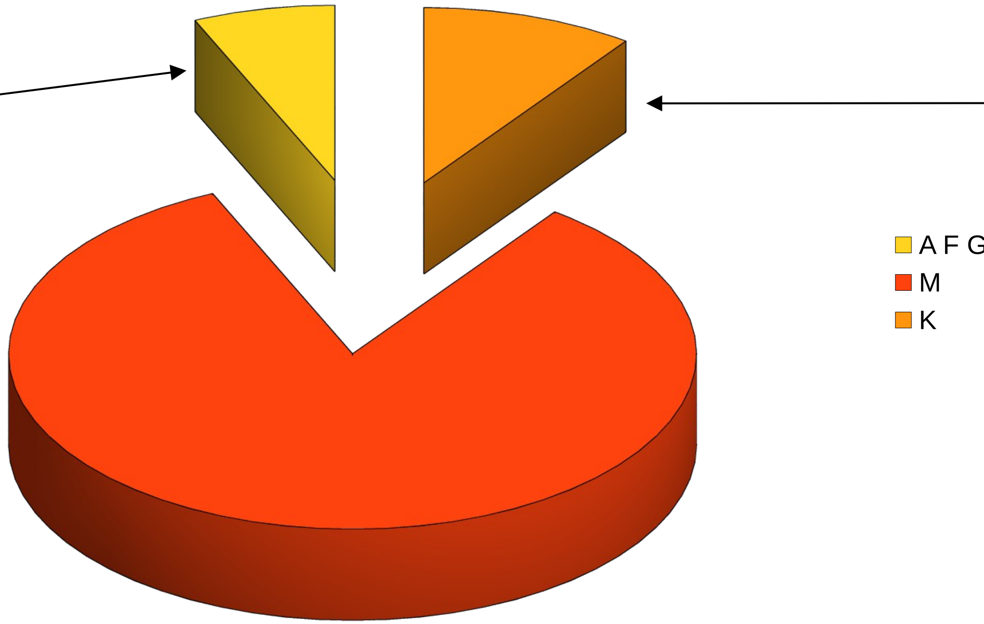
What is so special about M stars ?

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

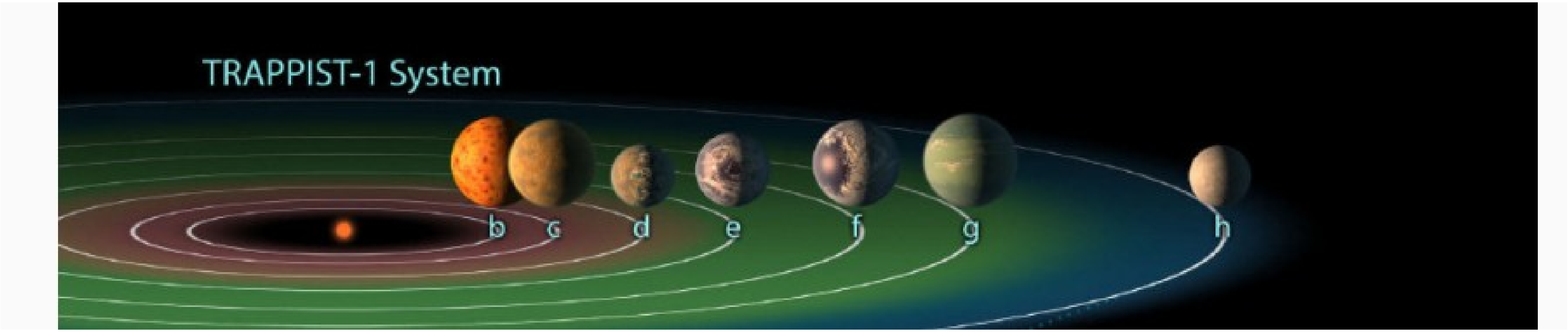


4.36 Alpha Cen B
10.52 Eps Eri
11.40 61 Cyg A
11.40 61 Cyg B
11.82 Eps Ind A
15.82 Gliese 380

What is so special about M stars ?

Strong evidence that their systems are **rich in terrestrial planets:**

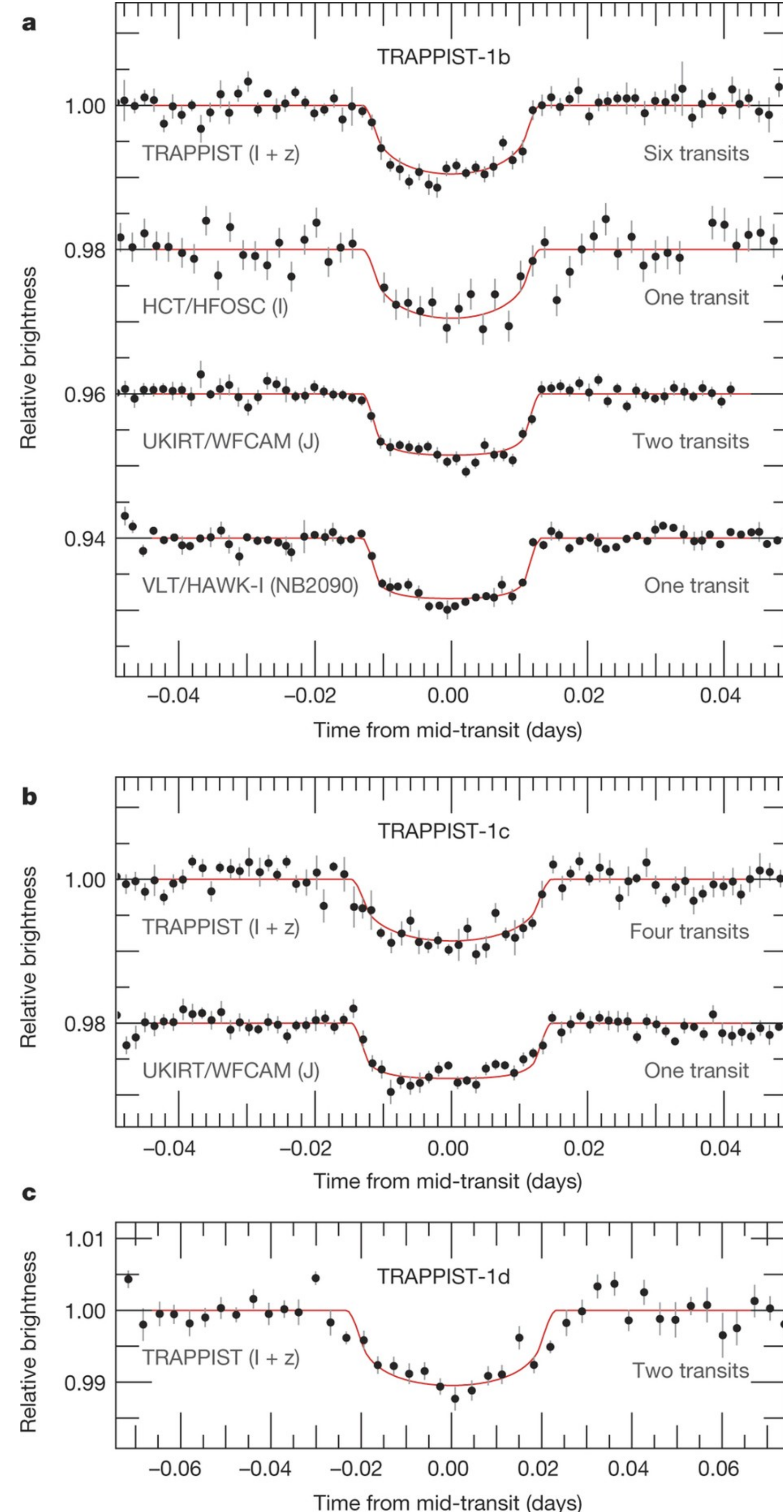
- Planet formation models evidence
- Lack of giant planets near HZ → good thing !
- Kepler data shows trend : more rocky planets around M-type stars
- Recent discoveries:
  Prox Cen b
  Trappist-1



What is so special about M stars ?

<u>“Easy” to observe</u>

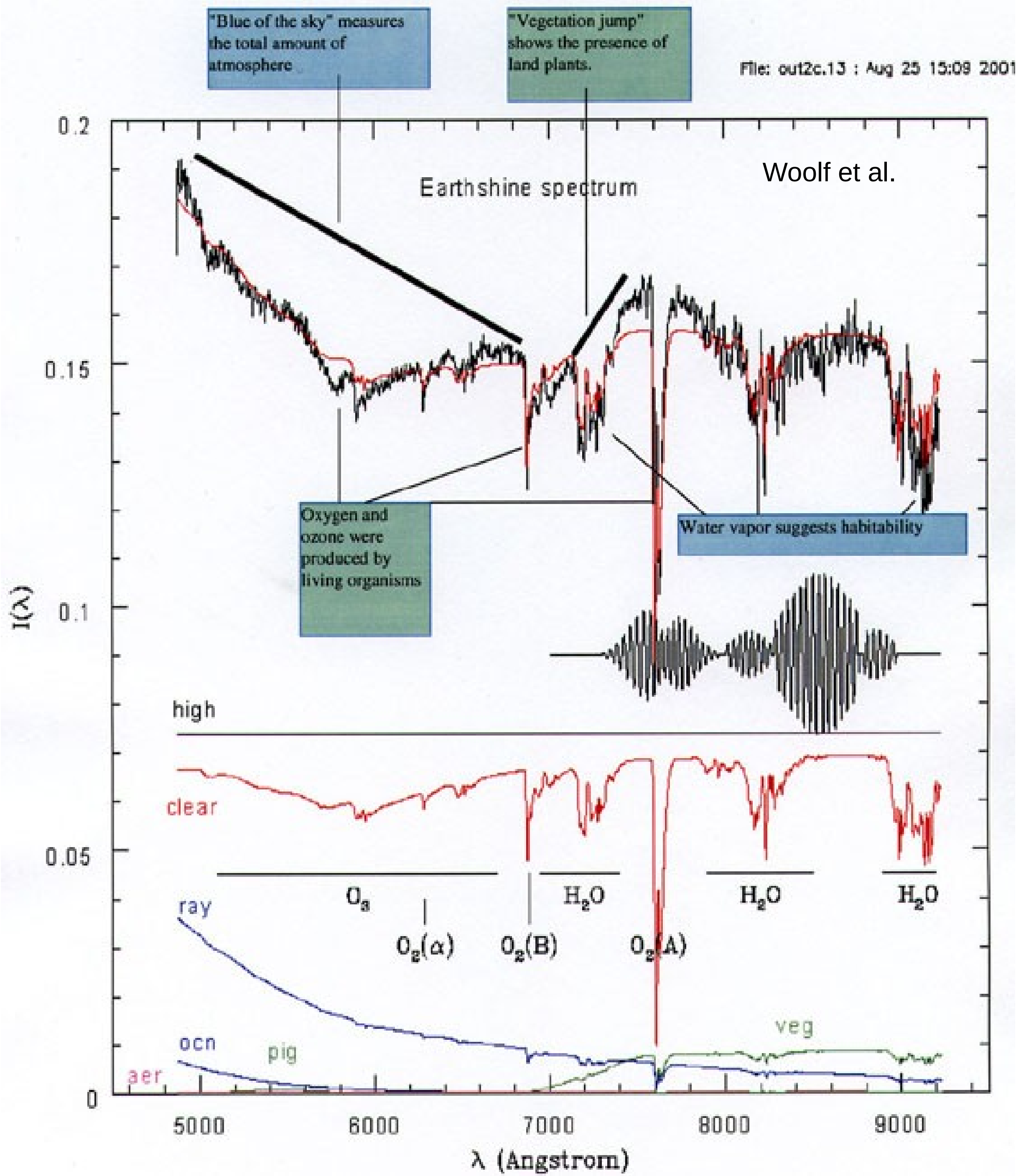
- Strong RV signal (near-IR RV instruments coming online)
- Moderate contrast (this talk): good for direct imaging
- Excellent transit targets:
  - Larg(er) probability of transit: some hope for transit+RV+direct imaging
  - Larger transit depth: JWST transit spectroscopy



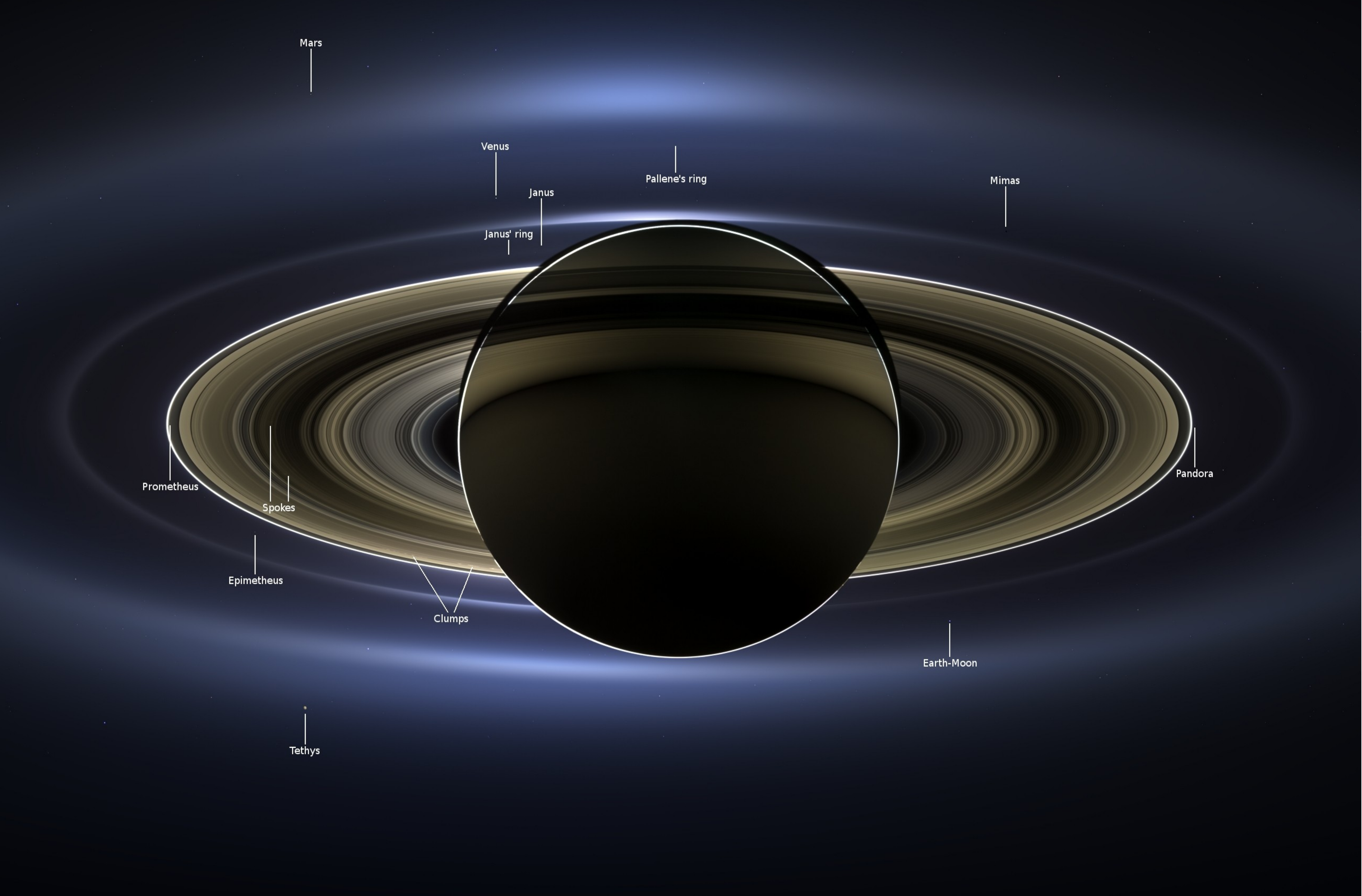
Why directly imaging ?

Spectra can also be obtained by transit, but :
- Low probability (few %)
- High atmosphere only

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

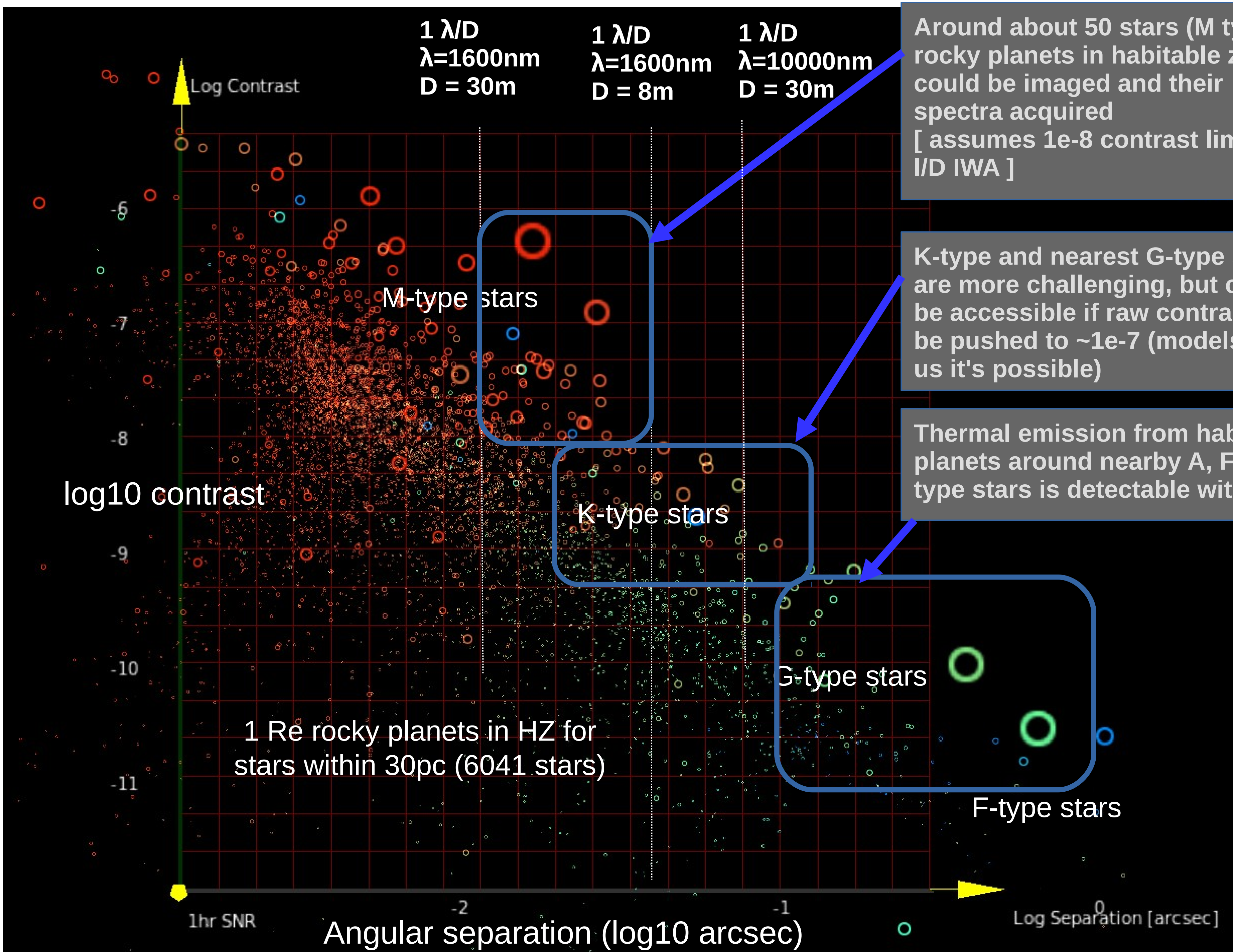


Taking images of exoplanets: Why is it hard ?




Saturn
Earth

Contrast and Angular separation

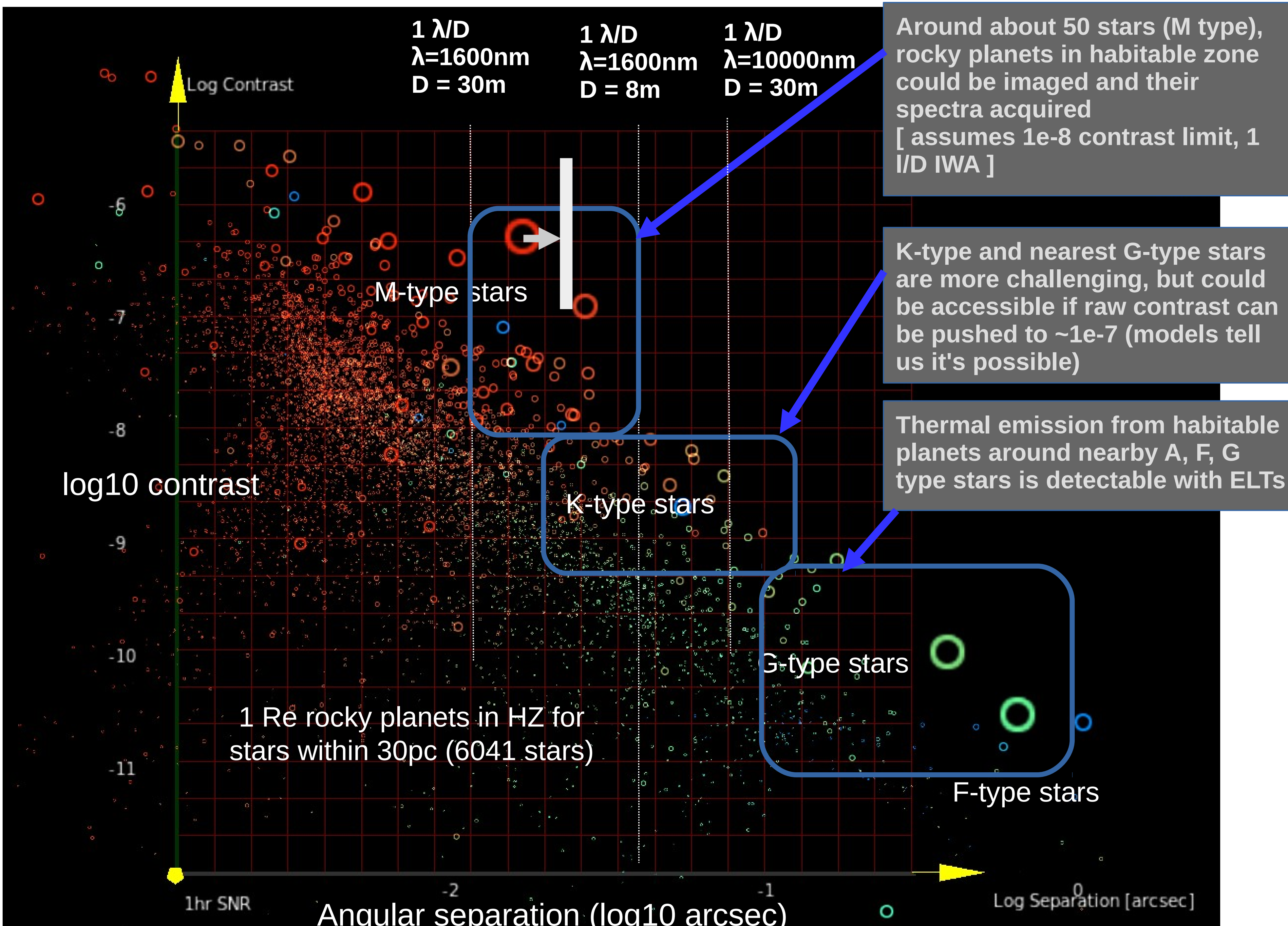


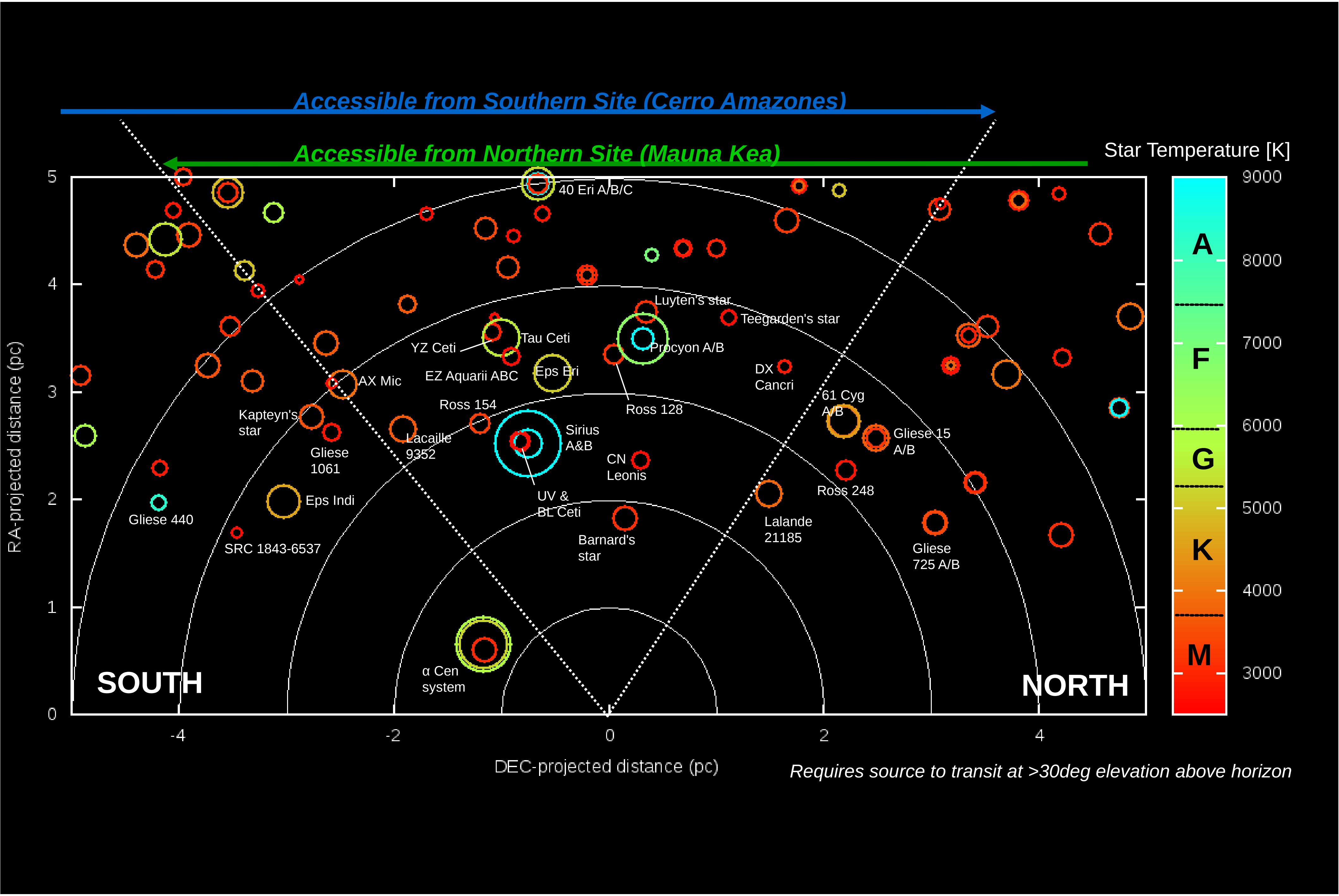
Around about 50 stars (M type), rocky planets in habitable zone could be imaged and their spectra acquired
[assumes 1e-8 contrast limit, 1 l/D IWA]

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)

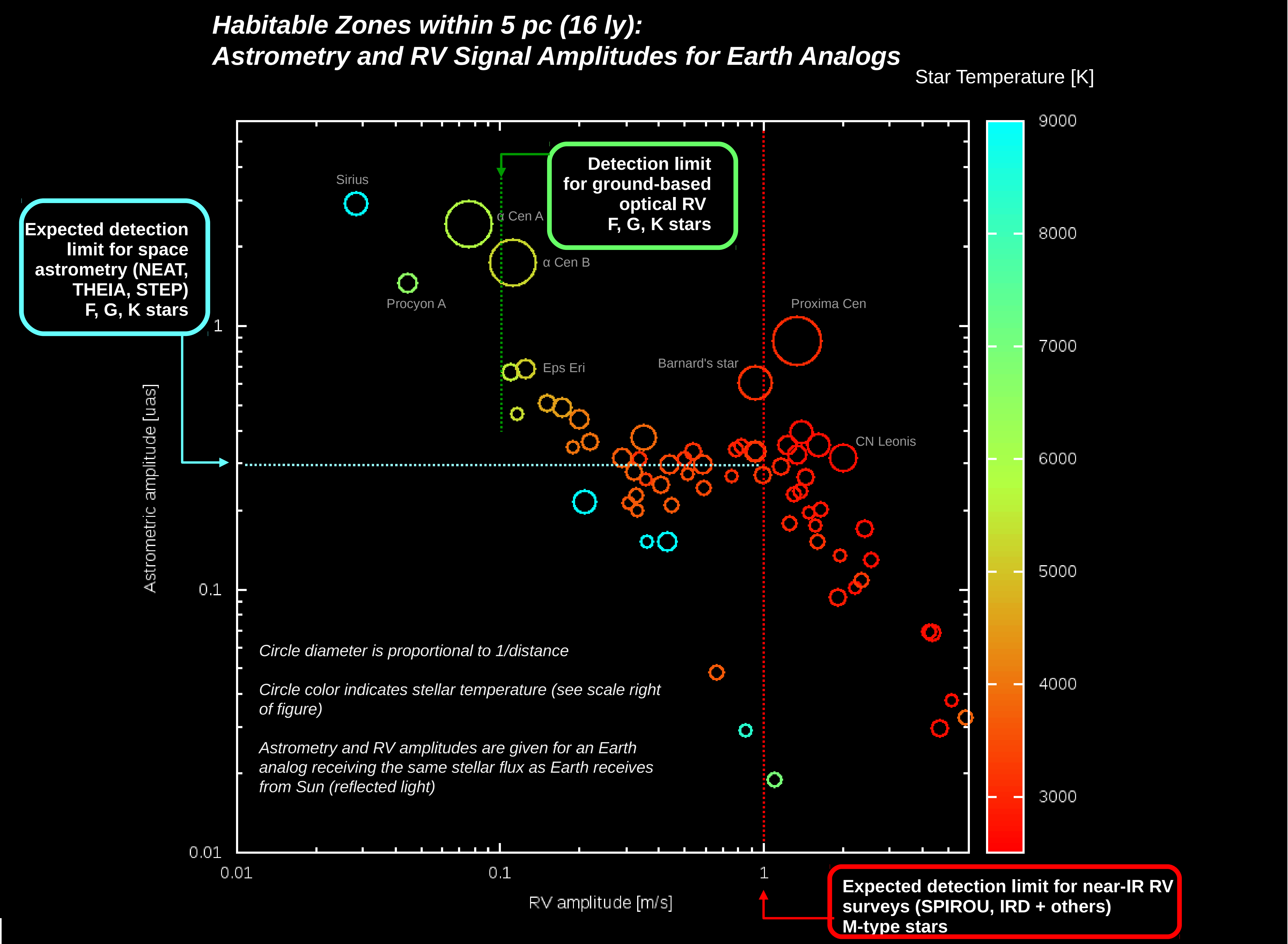
Thermal emission from habitable planets around nearby A, F, G type stars is detectable with ELTs

Contrast and Angular separation (updated)

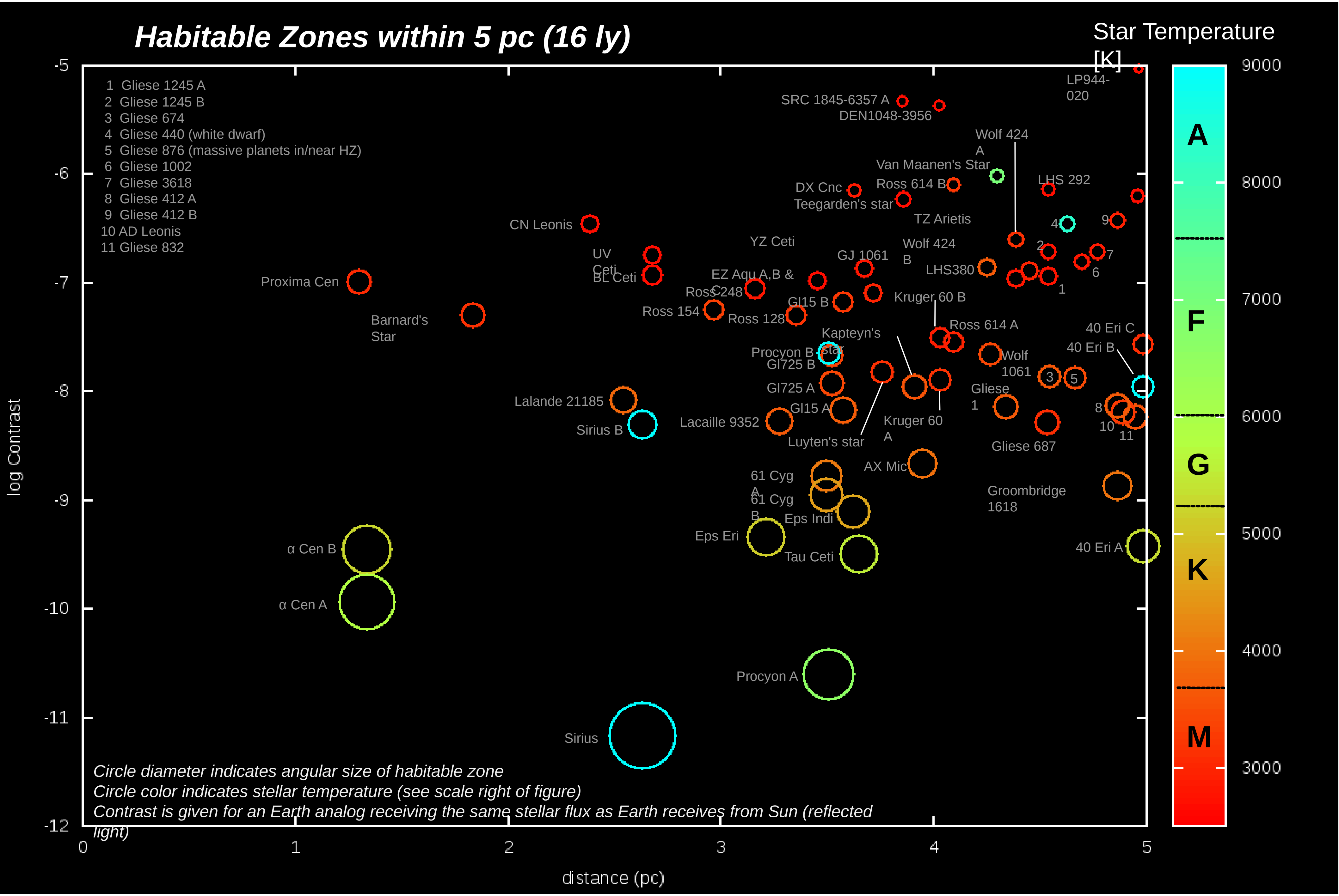




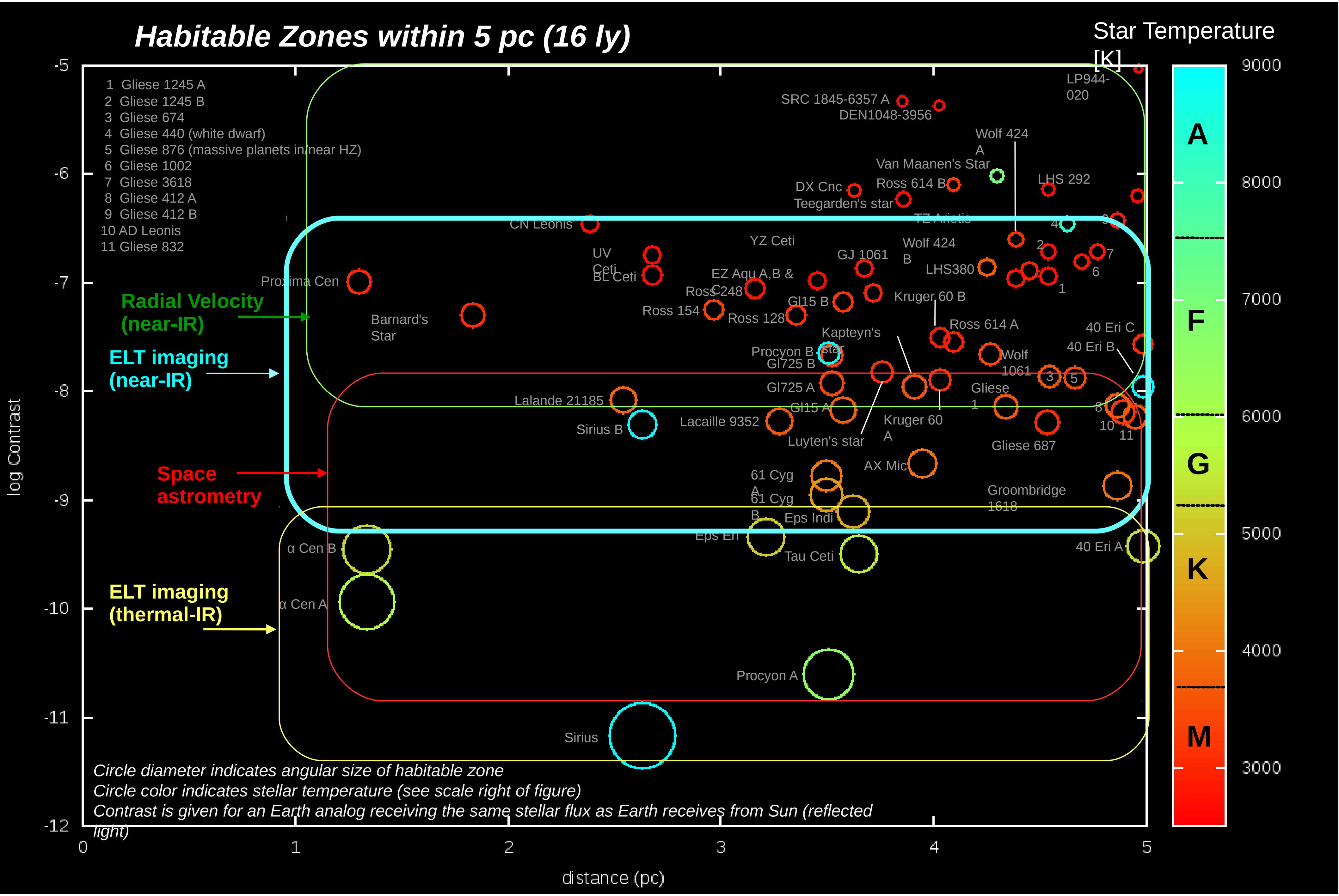
Accessible from Southern Site (Cerro Amazones)
Accessible from Northern Site (Mauna Kea)
Star Temperature [K]
9000
8000
7000
6000
5000
4000
3000
A
F
G
K
M
40 Eri A/B/C
Luyten's star
Teegarden's star
Tau Ceti
YZ Ceti
Procyon A/B
EZ Aquarii ABC
Eps Eri
AX Mic
DX Cancri
61 Cyg A/B
Ross 154
Ross 128
Kapteyn's star
Sirius A&B
Gliese 15 A/B
Lacaille 9352
Gliese 1061
CN Leonis
UV & BL Ceti
Ross 248
Eps Indi
Gliese 440
Lalande 21185
Barnard's star
SRC 1843-6537
Gliese 725 A/B
α Cen system
SOUTH
NORTH
RA-projected distance (pc)
DEC-projected distance (pc)
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
Eps Eri
Barnard's star
Proxima Cen
CN Leonis
Astrometric amplitude [uas]
RV amplitude [m/s]
0.01
0.1
1
Circle diameter is proportional to 1/distance
Circle color indicates stellar temperature (see scale right of figure)
Astrometry and RV amplitudes are given for an Earth analog receiving the same stellar flux as Earth receives from Sun (reflected light)



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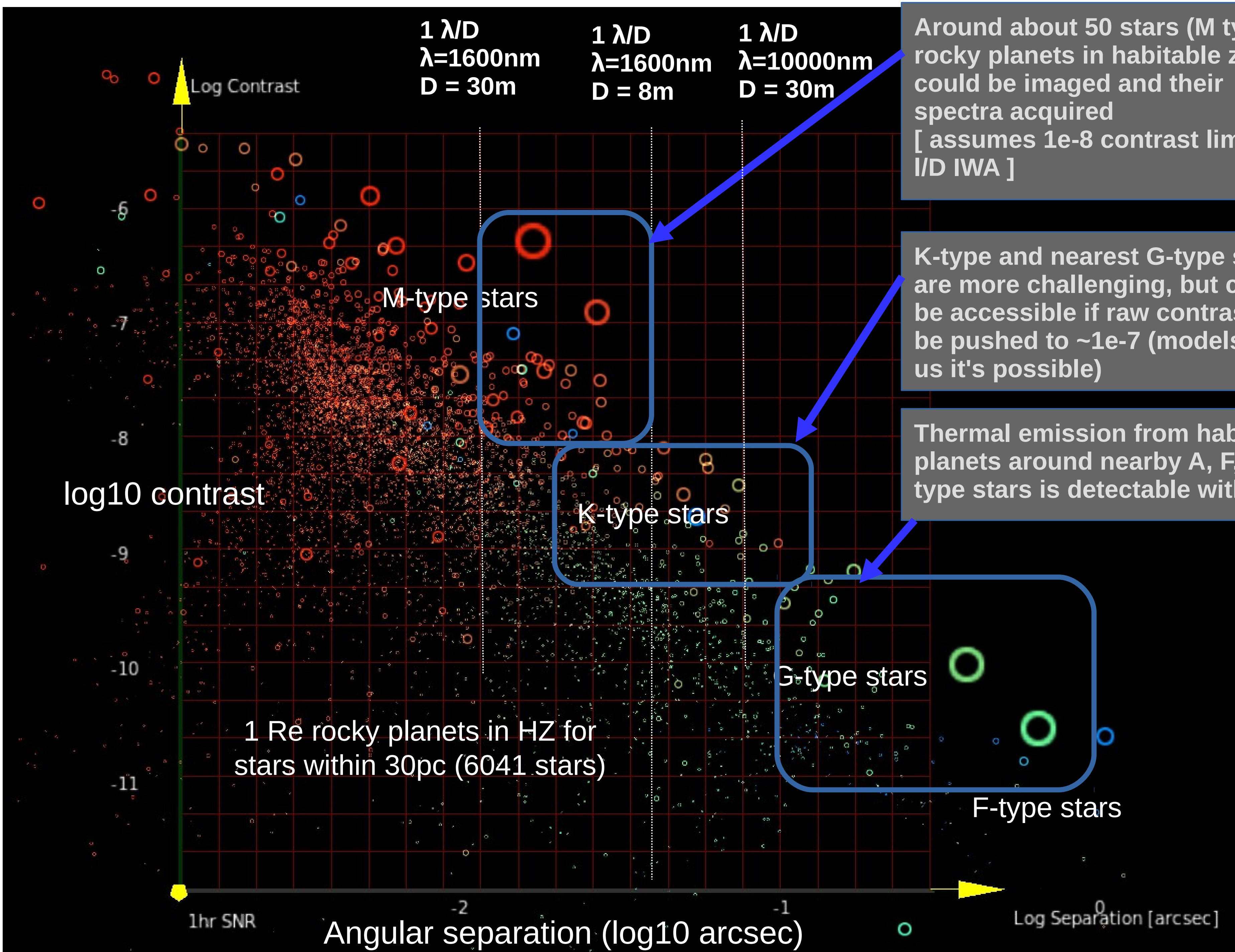
SRC 1845-6357 A
DEN1048-3956
LP944-020
A
F
G
K
M
9000
8000
7000
6000
5000
4000
3000
log Contrast
-5
-6
-7
-8
-9
-10
-11
-12
distance (pc)
0
1
2
3
4
5
Circle diameter indicates angular size of habitable zone
Circle color indicates stellar temperature (see scale right of figure)
Contrast is given for an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

Contrast and Angular separation



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[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

We need a Coronagraph ...

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)

… can be met now

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.

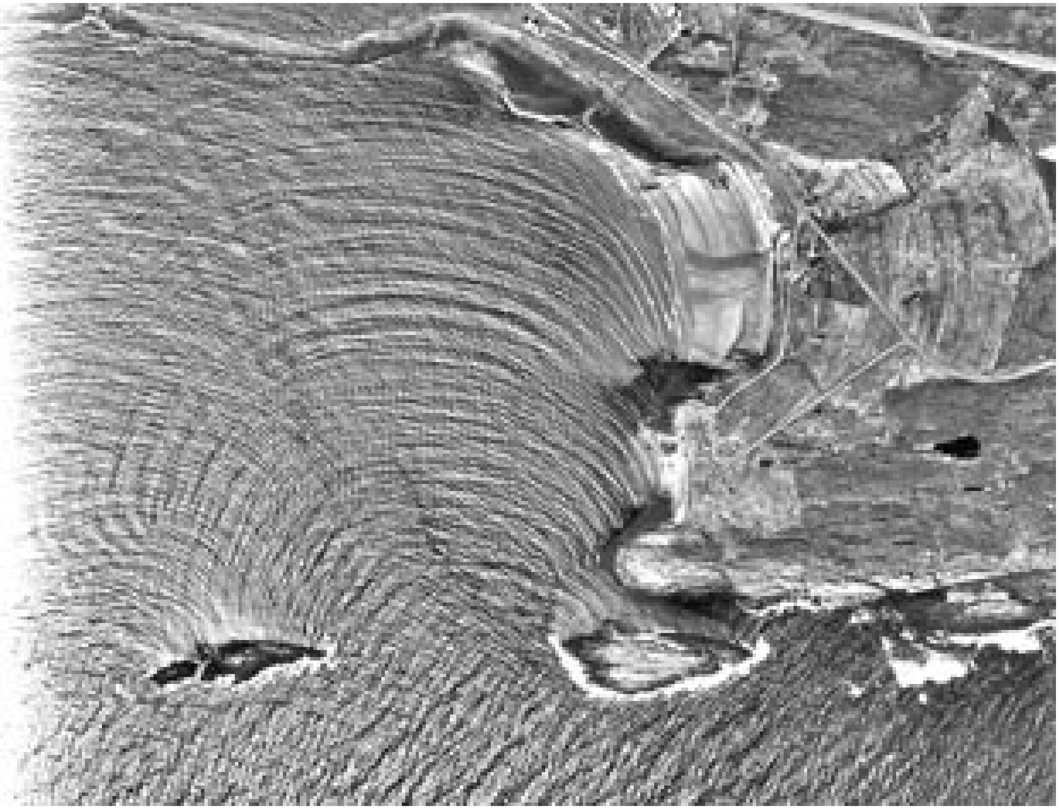
No component-level significant challenge, but system-level performance has yet to be demonstrated on-sky

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

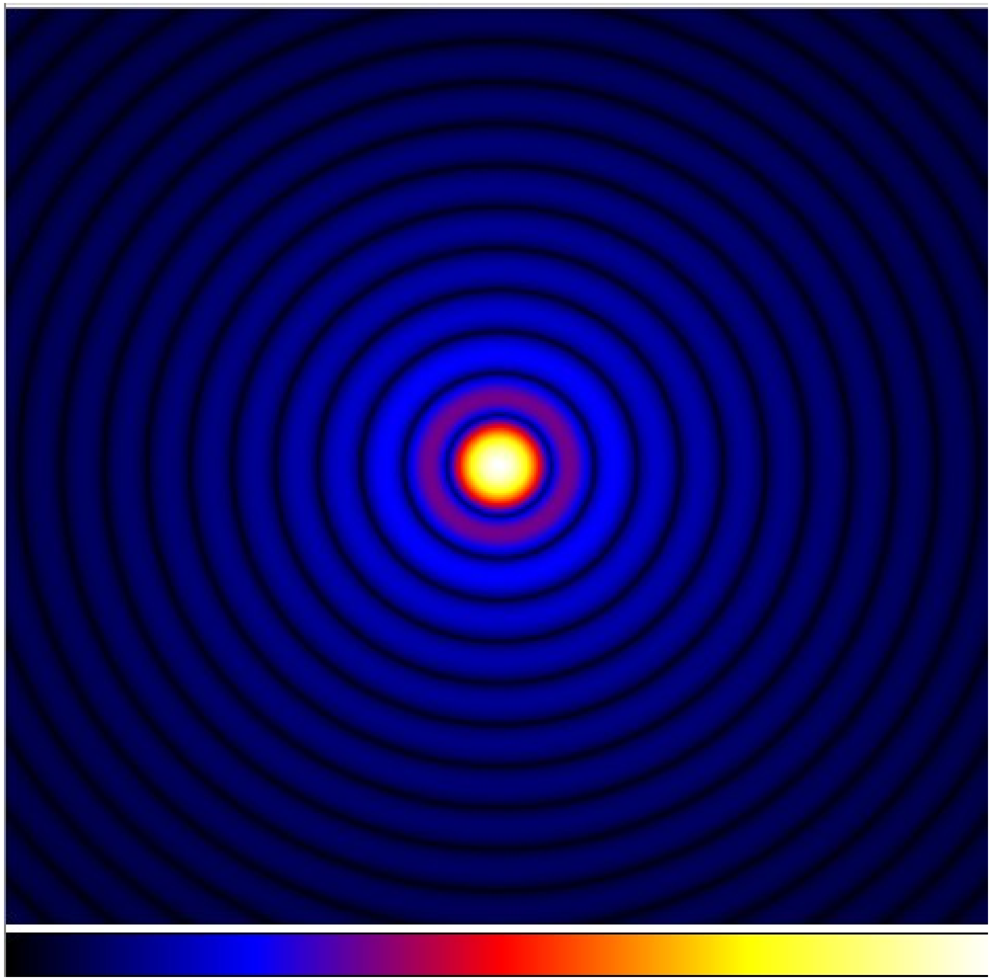
← Olivier's thumb...
the easiest coronagraph
Doesn't work well enough to
see planets around other stars

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

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

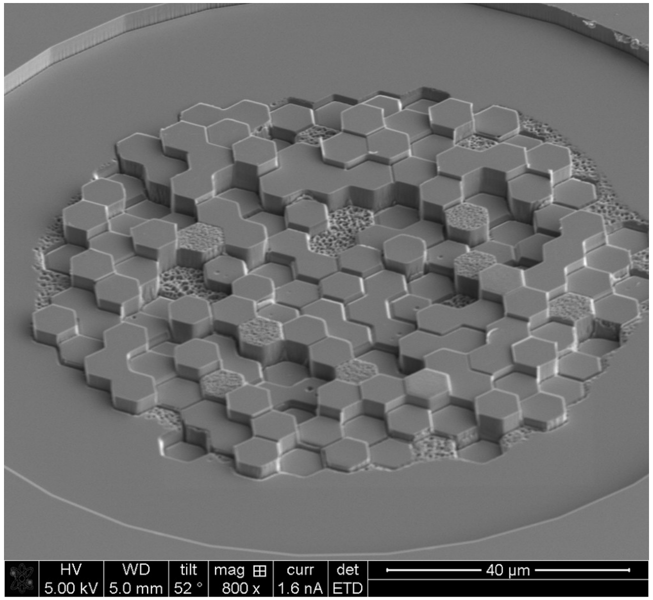


Waves diffracted by coastline and islands

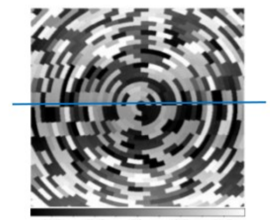


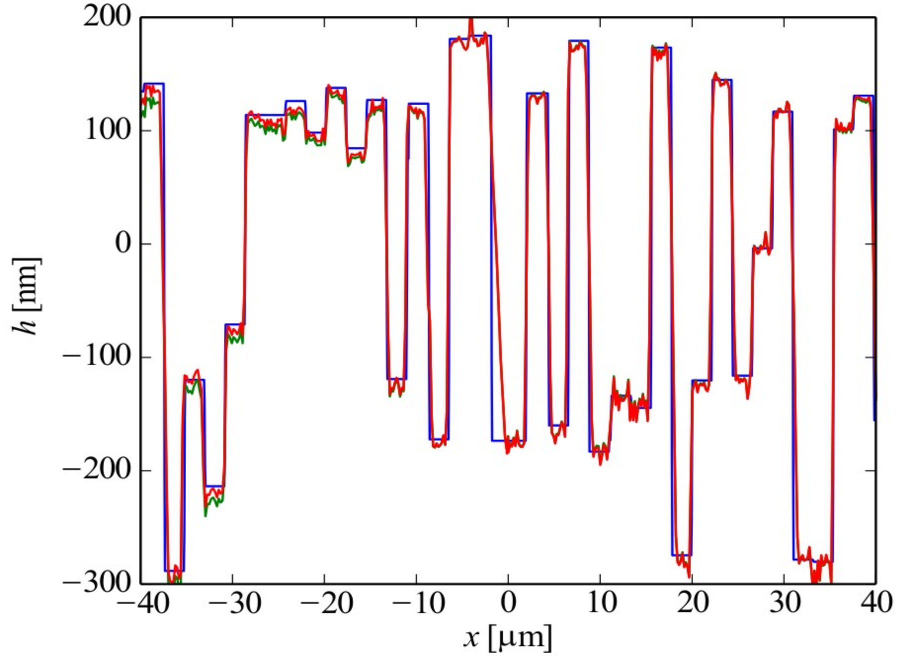
Ideal image of a distant star by a telescope
Diffraction rings around the image core

PIAACMC focal plane mask manufacturing

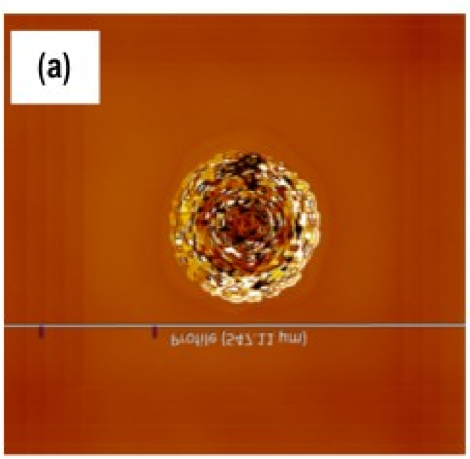


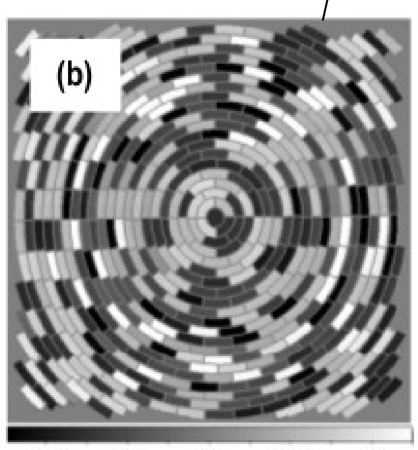
← SCExAO focal plane mask (Mar 2017)

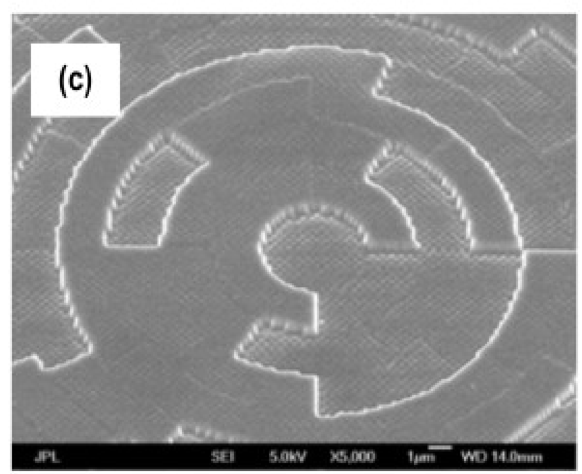


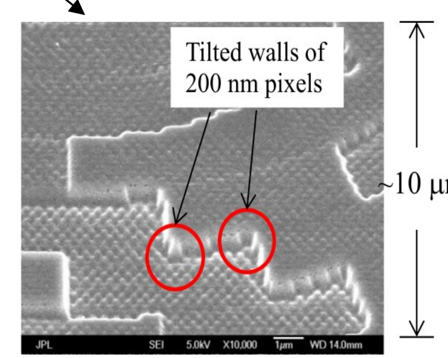


Focal plane mask manufactured at JPL's MDL
Meets performance requirements
(WFIRST PIAACMC Milestone report)





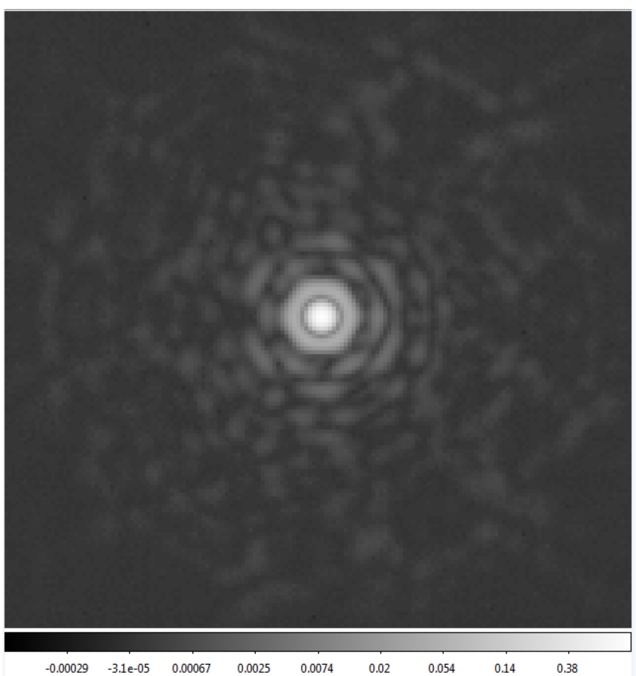




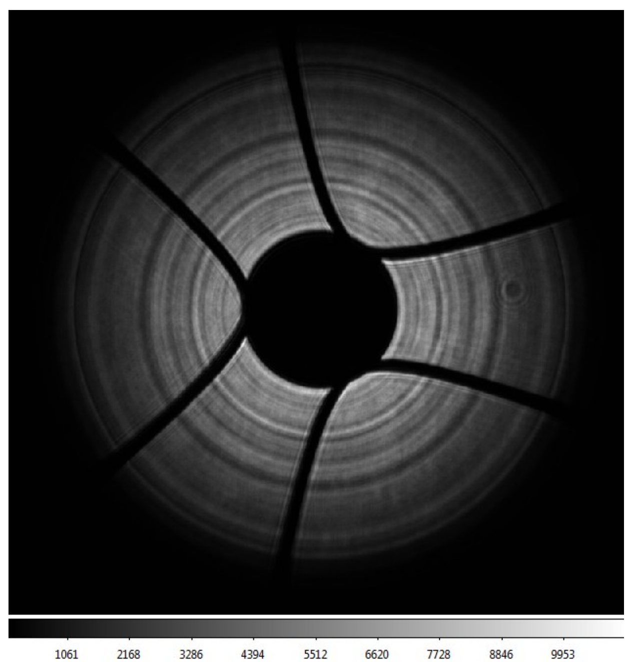
PIAACMC lab performance @ WFIRST (Kern et al. 2016)

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

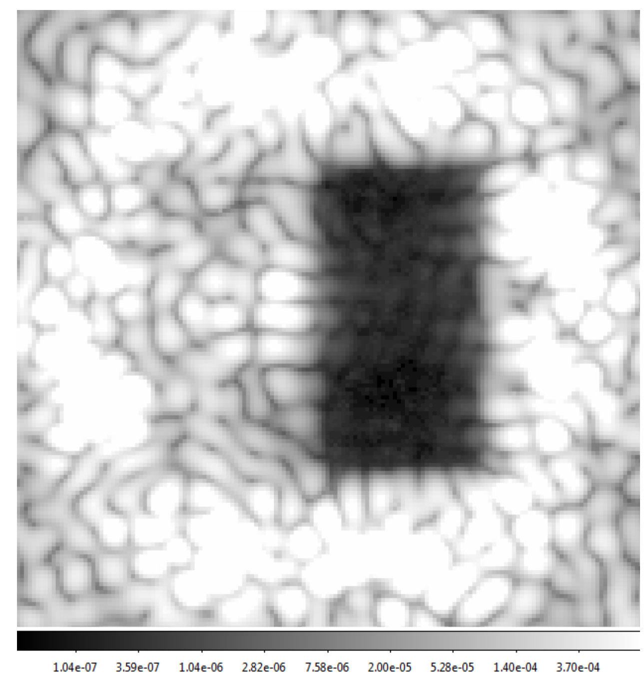
non-coronagraphic PSF



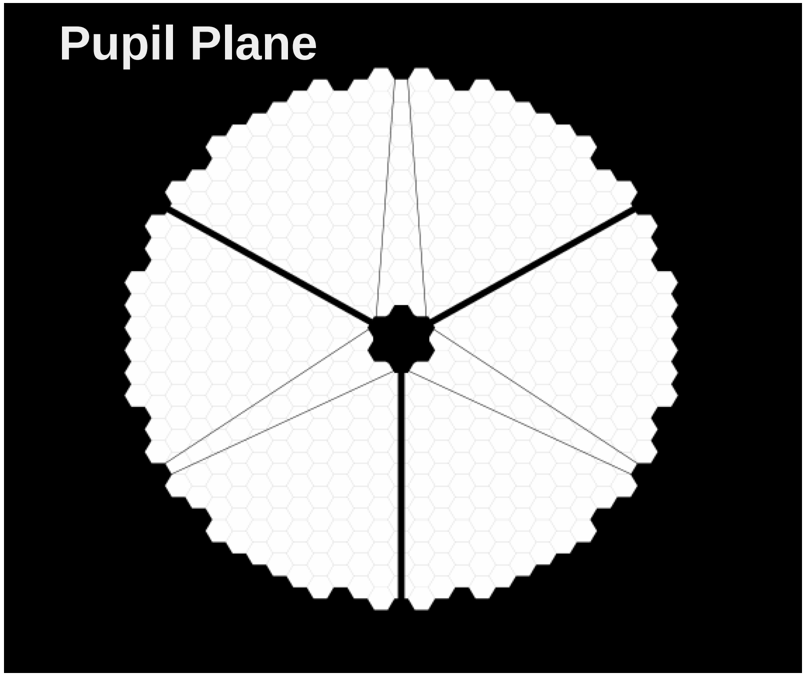
Remapped pupil

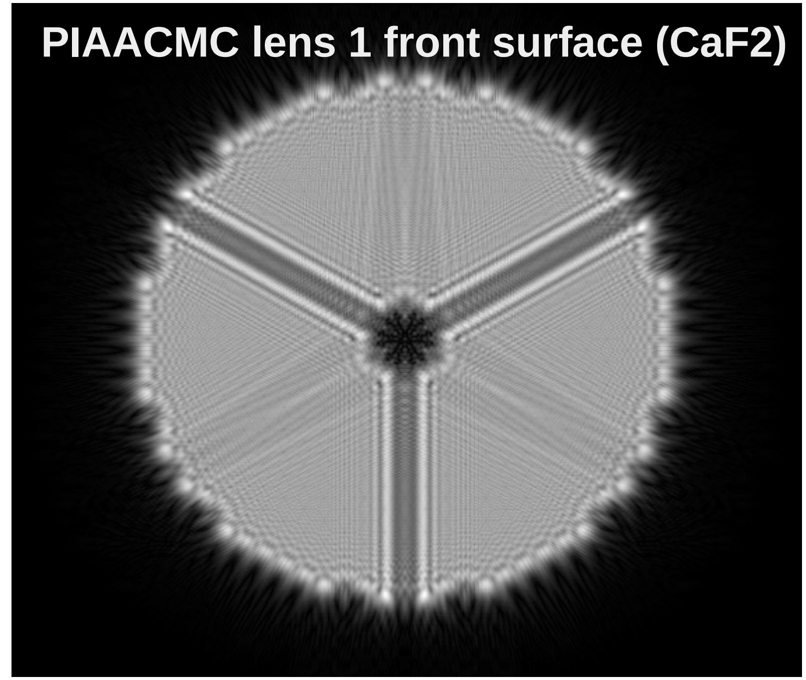


Coronagraphic image

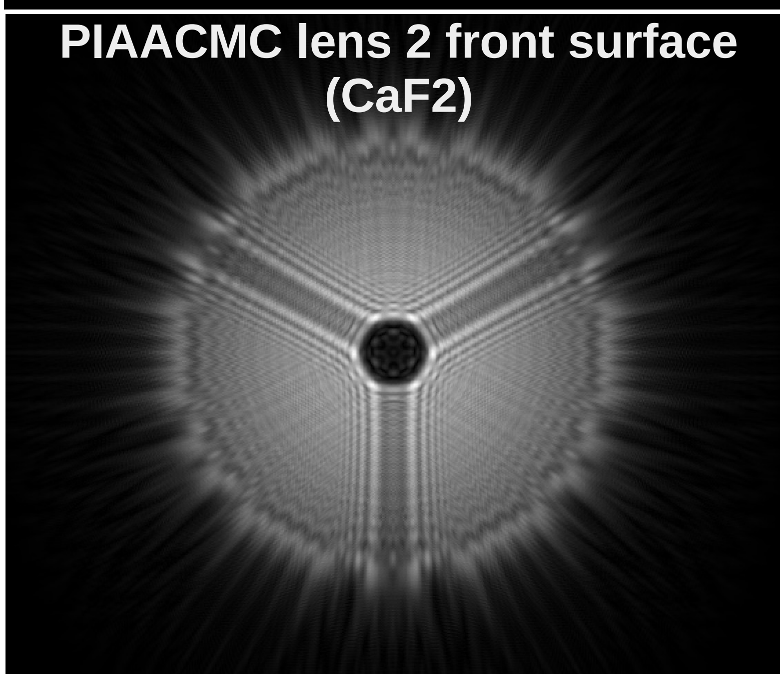


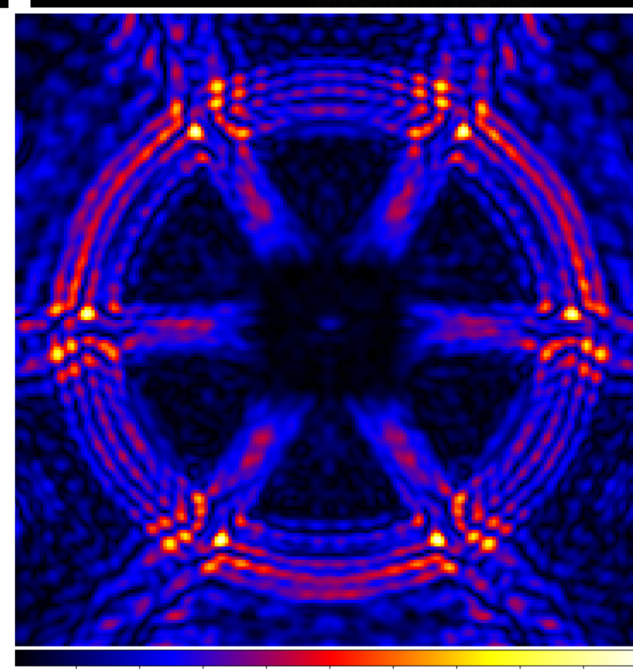
TMT coronagraph design for 1 l/D IWA





To be updated with new pupil shape





PSF at 1600nm

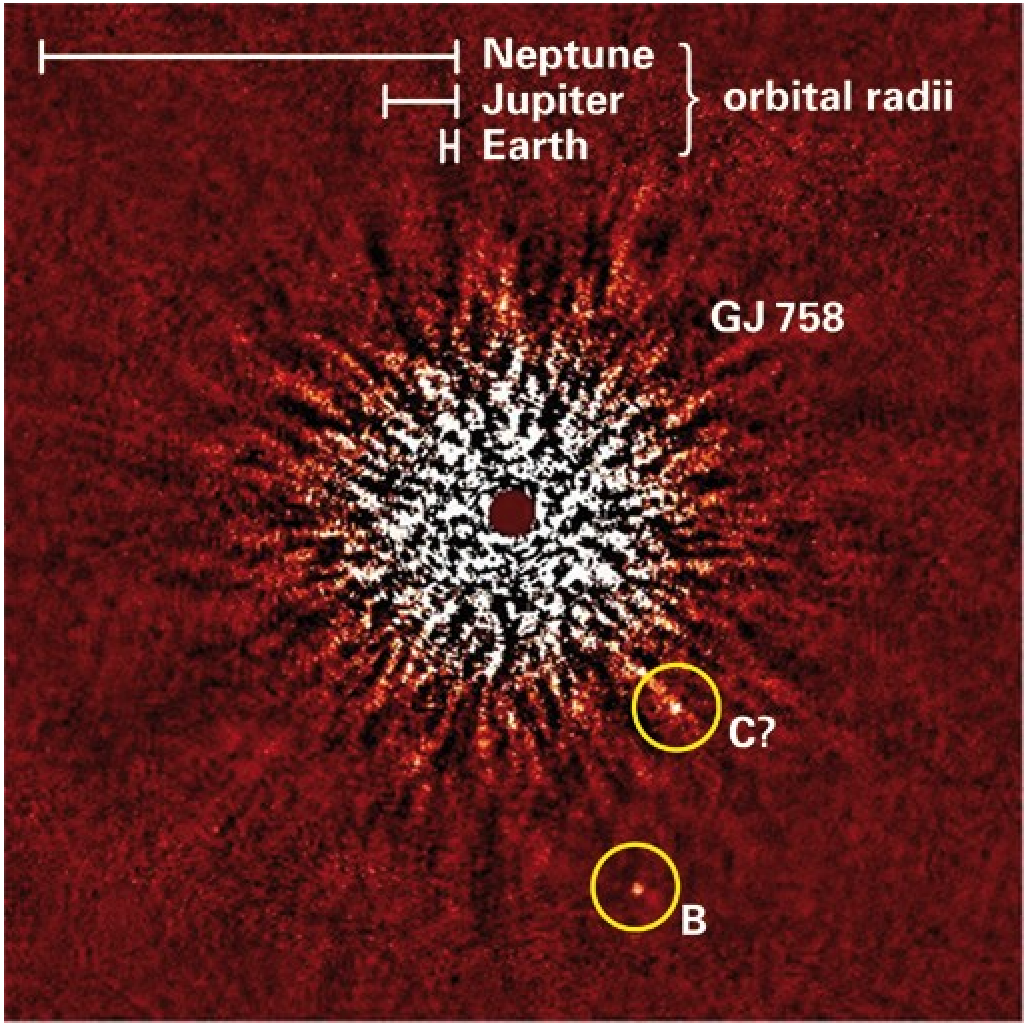
3e-9 contrast in 1.2 to 8 l/D

80% off-axis throughput

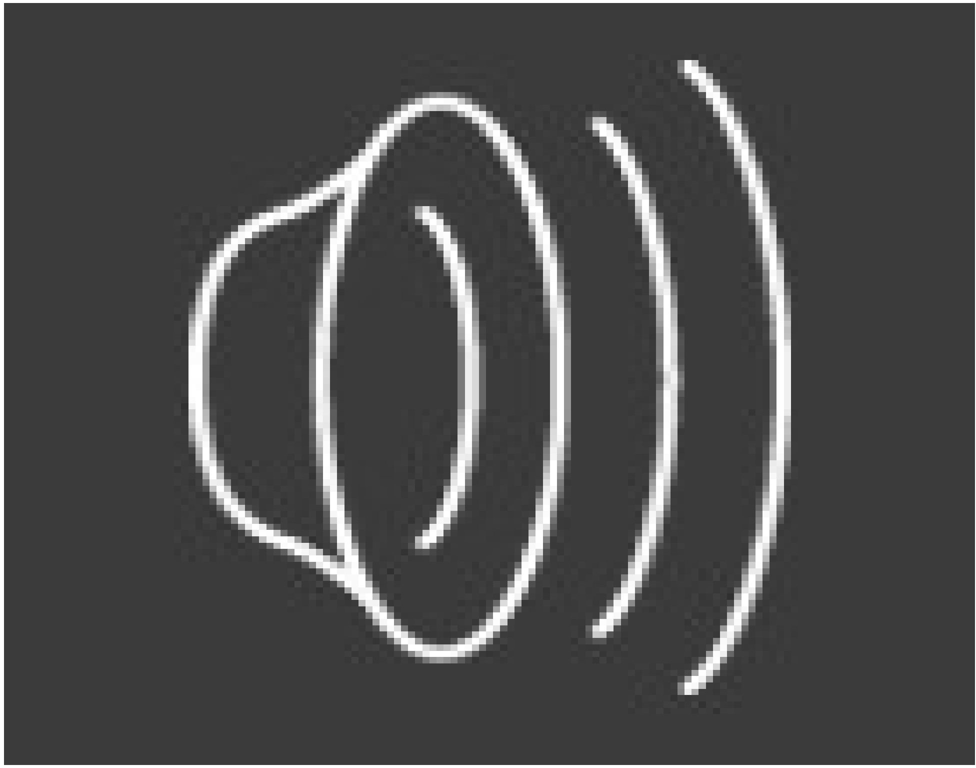
1.2 l/D IWA

CaF2 lenses
SiO2 mask

What about speckles ?

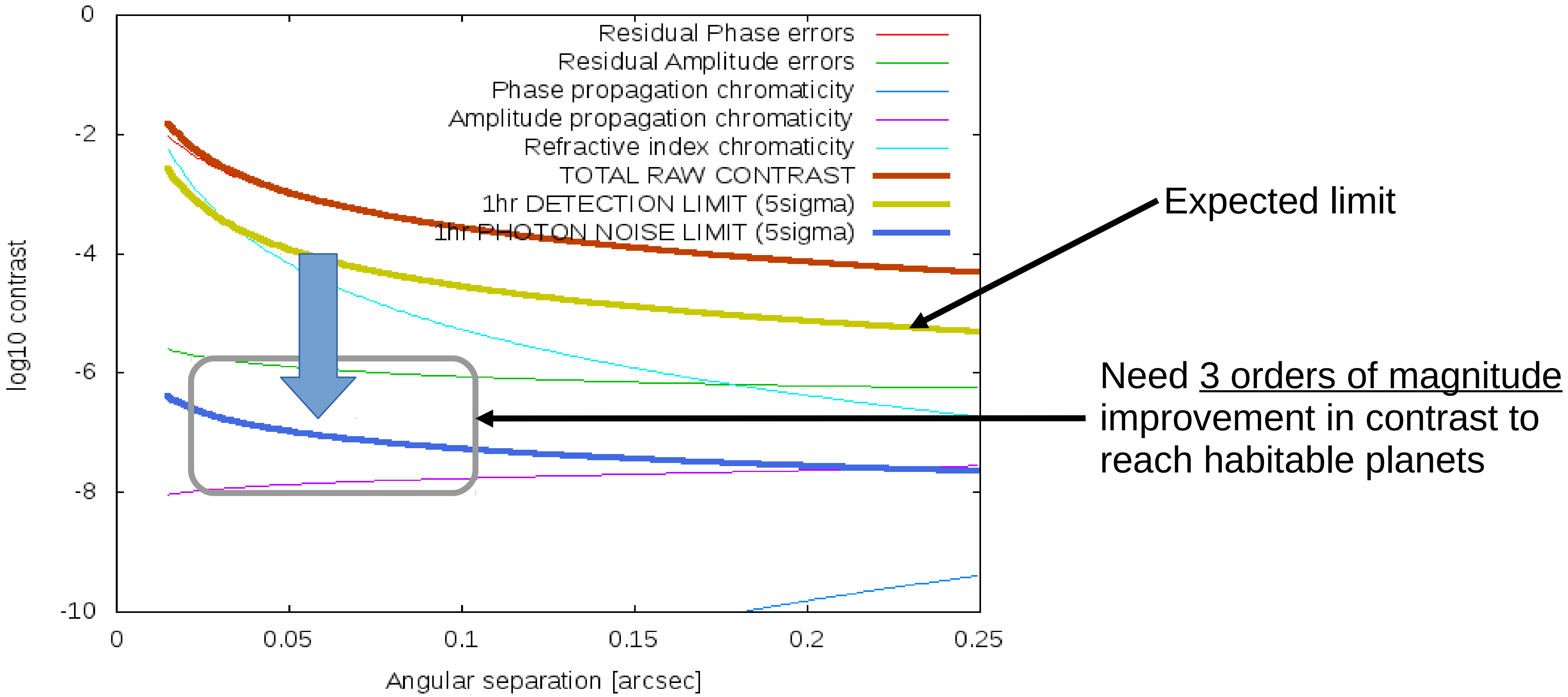


H-band fast frame imaging (1.6 kHz)



PREVIOUS technologies

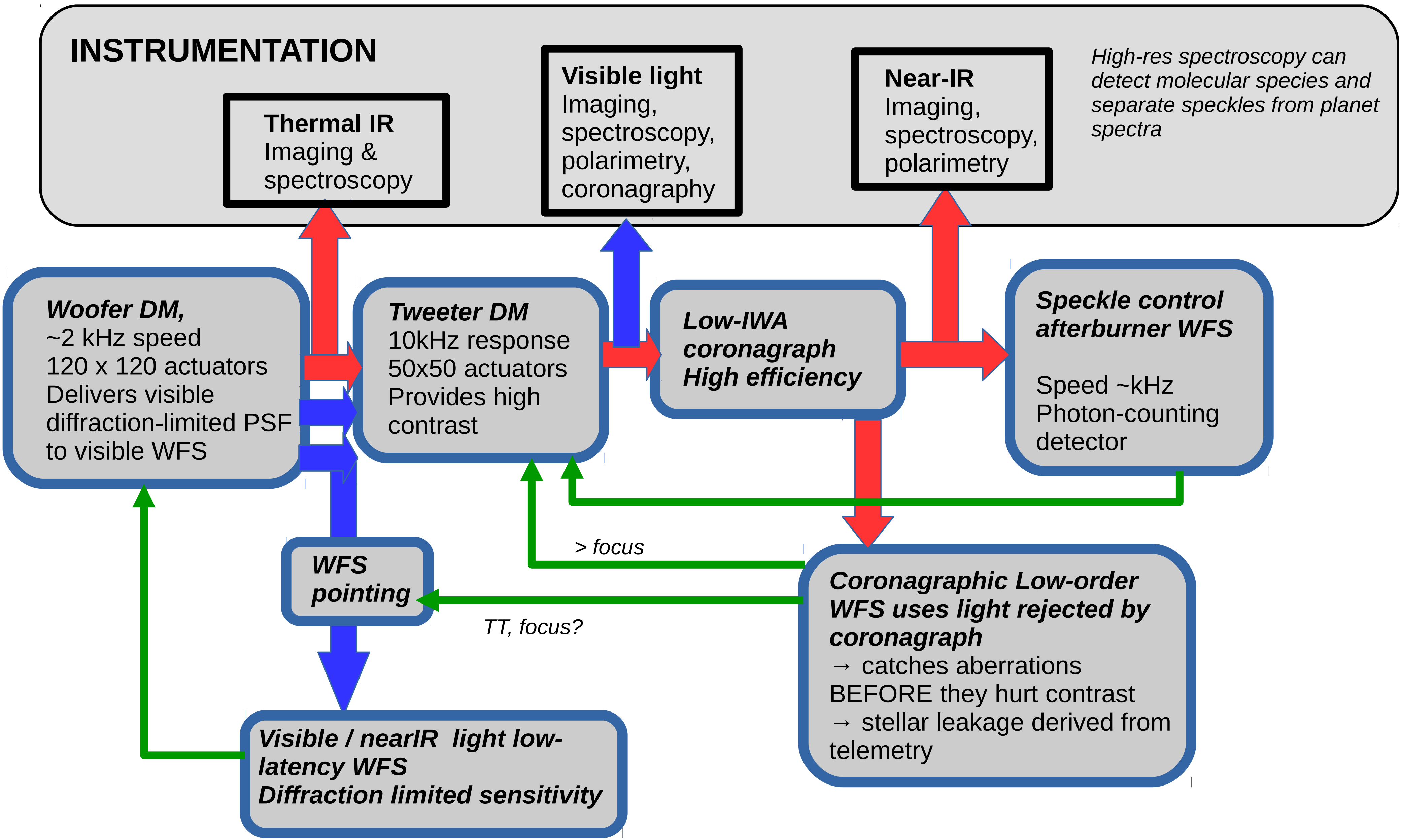
30m: SH-based system, 15cm subapertures



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**

Nominal ELT ExAO system architecture



Wavefront Control: challenges … and 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

Predictive control → 100x contrast gain

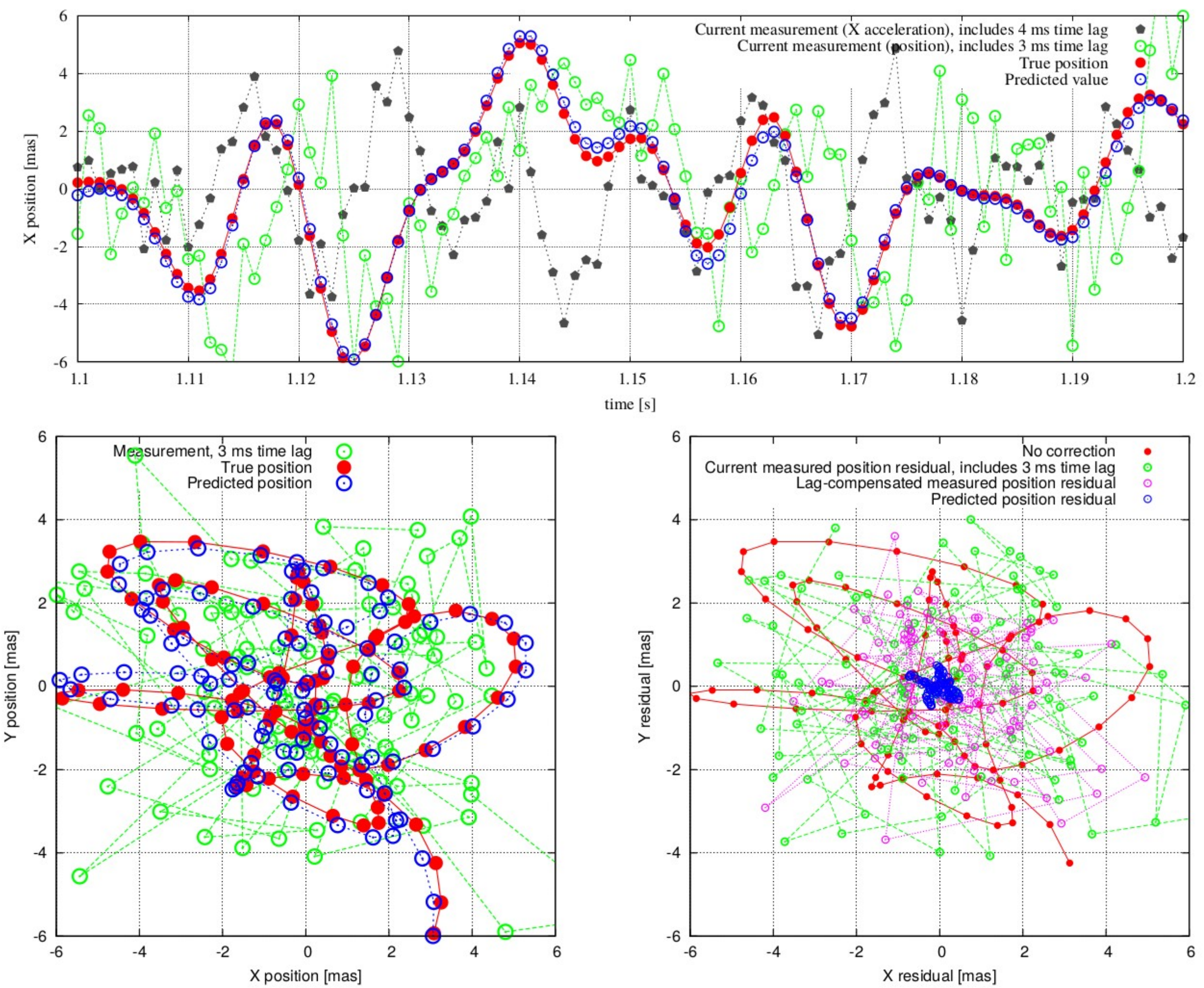
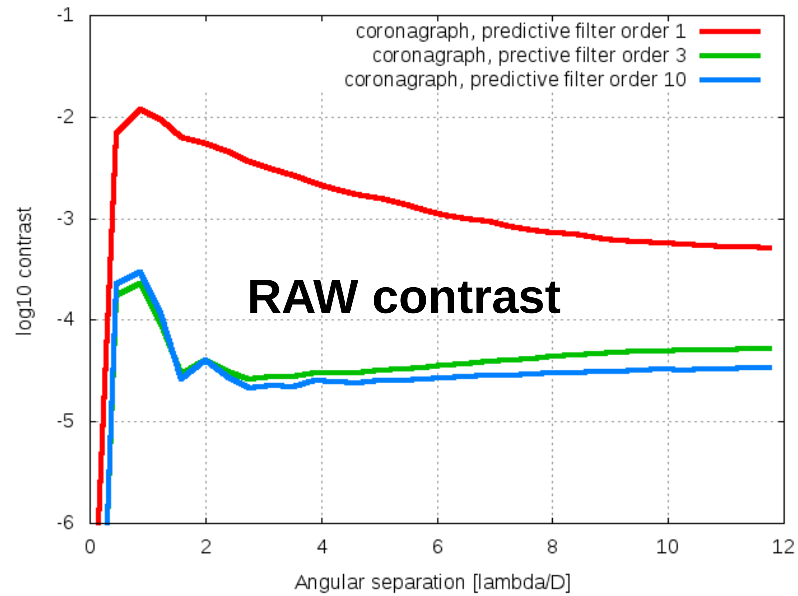
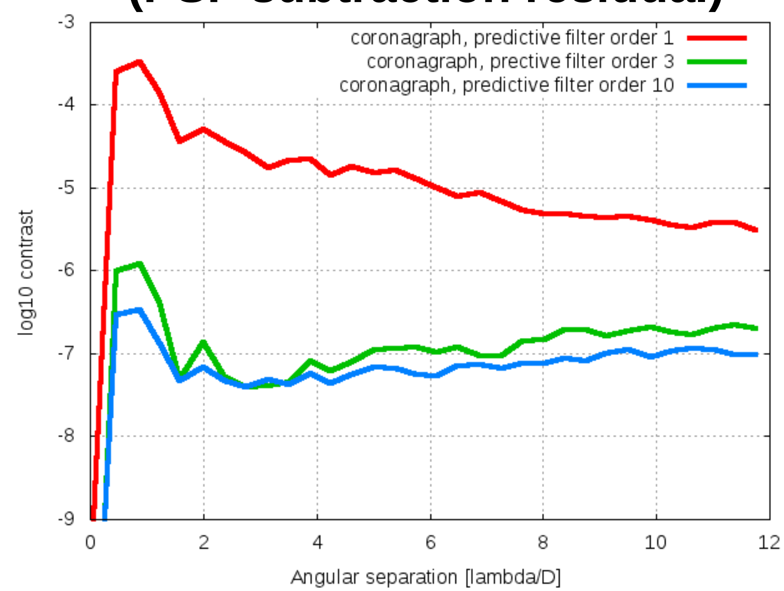


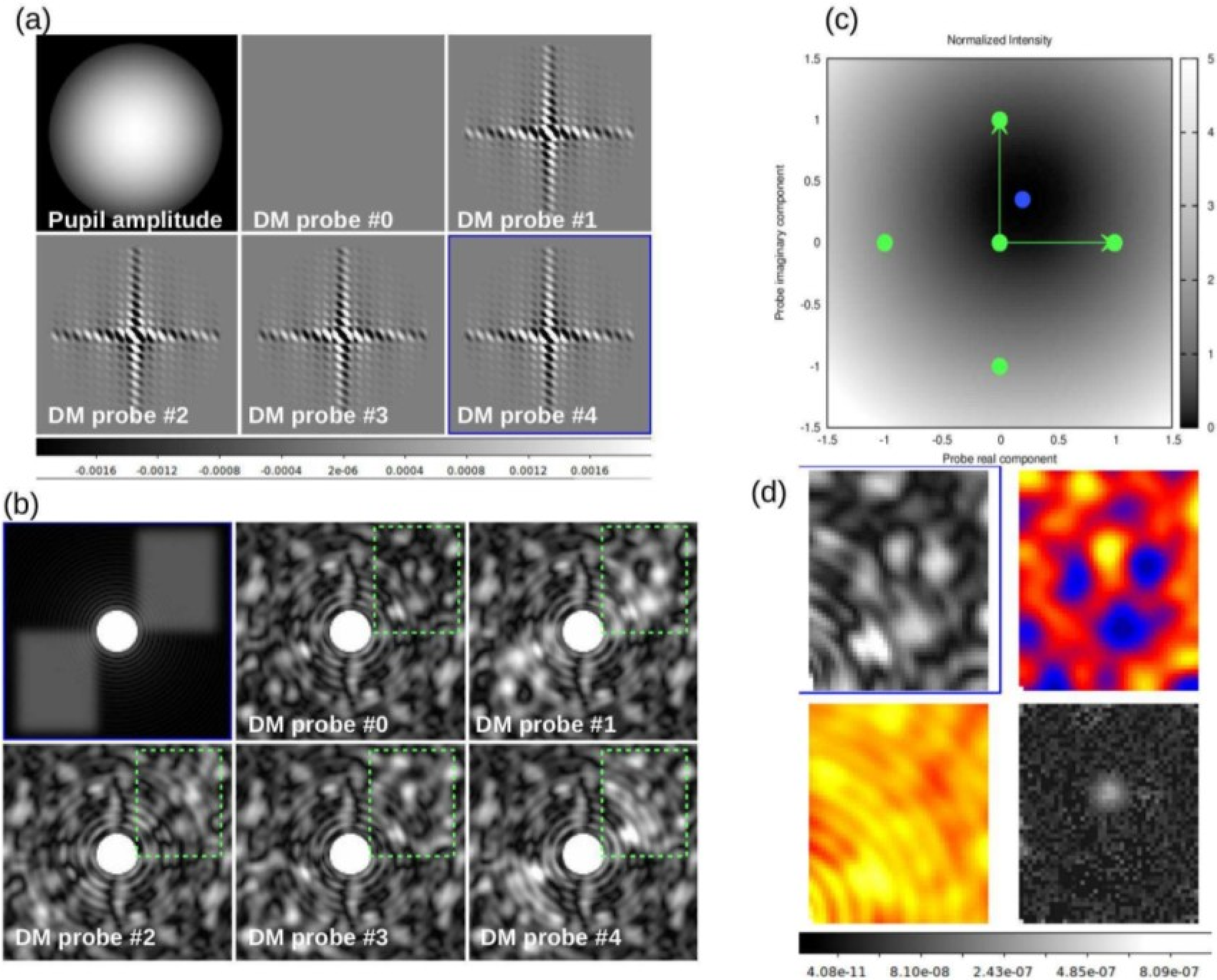
FIG. 3.— Top left: 2D-tracks for true pointing (red), predicted pointing (blue) and last measured position (green). Top right: Residual pointing error. Bottom: Single axis (x) values.



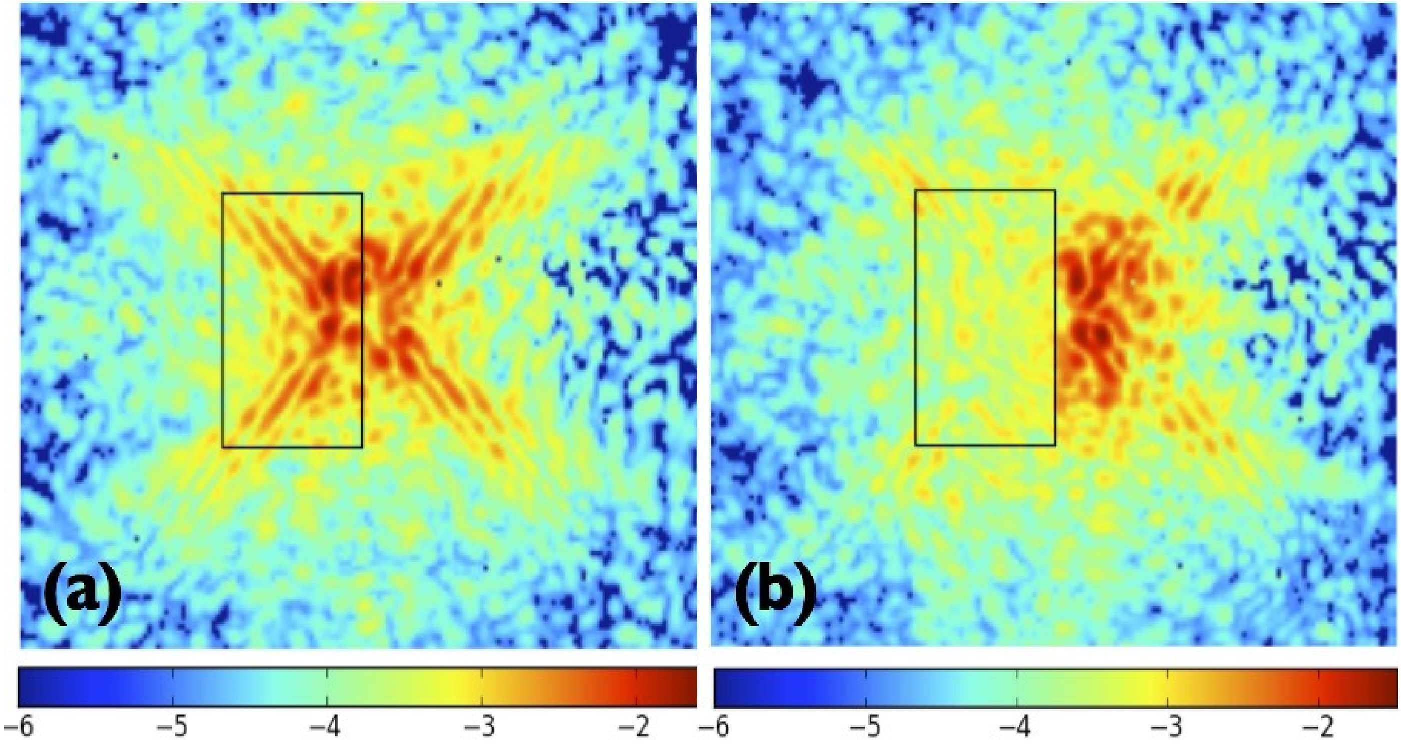
1hr detection limit (PSF subtraction residual)



Coherent Speckle Differential Imaging



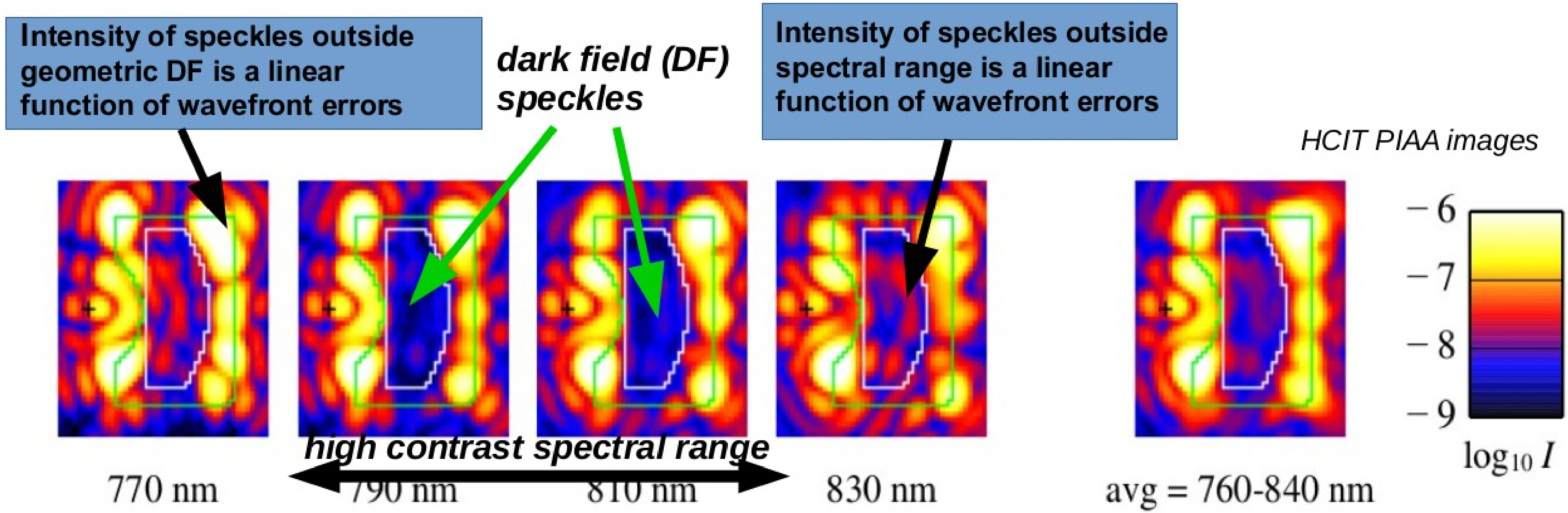
Speckle control
→ remove speckles in ½ field dark hole



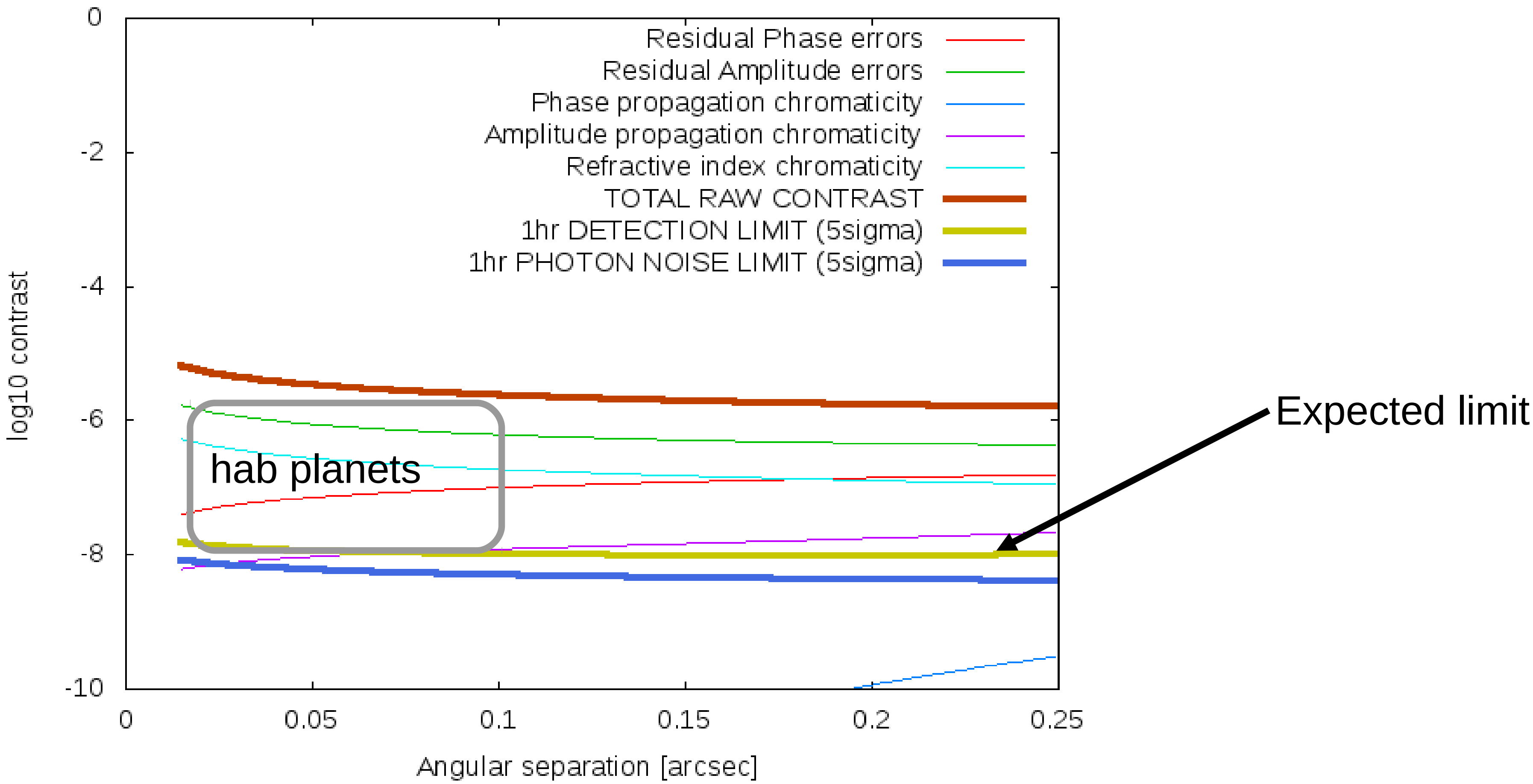
Linear Dark Field Control (LDFC)

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



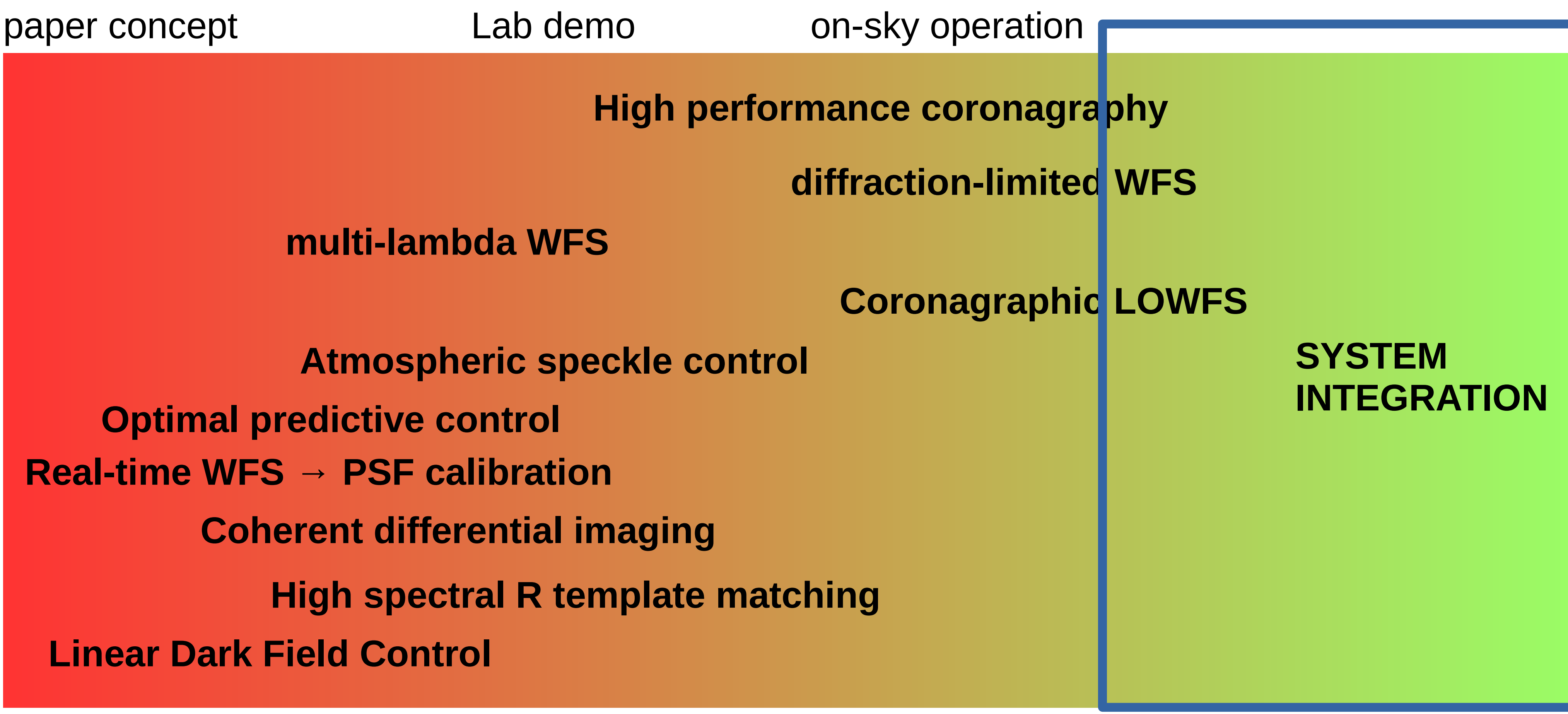
CURRENT technologies



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

Key technologies need rapid maturation from paper concepts to system integration



Subaru Coronagraphic Extreme Adaptive Optics

- **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
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

SCExAO is an international platform to prepare ELT imaging of habitable planets around M-type stars

Modules

SCExAO Subaru Coronagraphic Extreme Adaptive Optics

The wavefront control feeds a high Strehl PSF to various modules, from 600 nm to K band.

Visible (600 – 950 nm):

VAMPIRES, non-redundant masking, polarimetry, with spectral differential imaging capability (h-alpha, SII)

FIRST, non-redundant remapping interferometer, with spectroscopic analysis

RHEA, single mode fiber injection, high-res spectroscopy, high-spatial resolution on resolved stars

IR (950-2400 nm):

HiCIAO - high contrast image (y to K-band)

SAPHIRA - high-speed photon counting imager, (H-band for now)

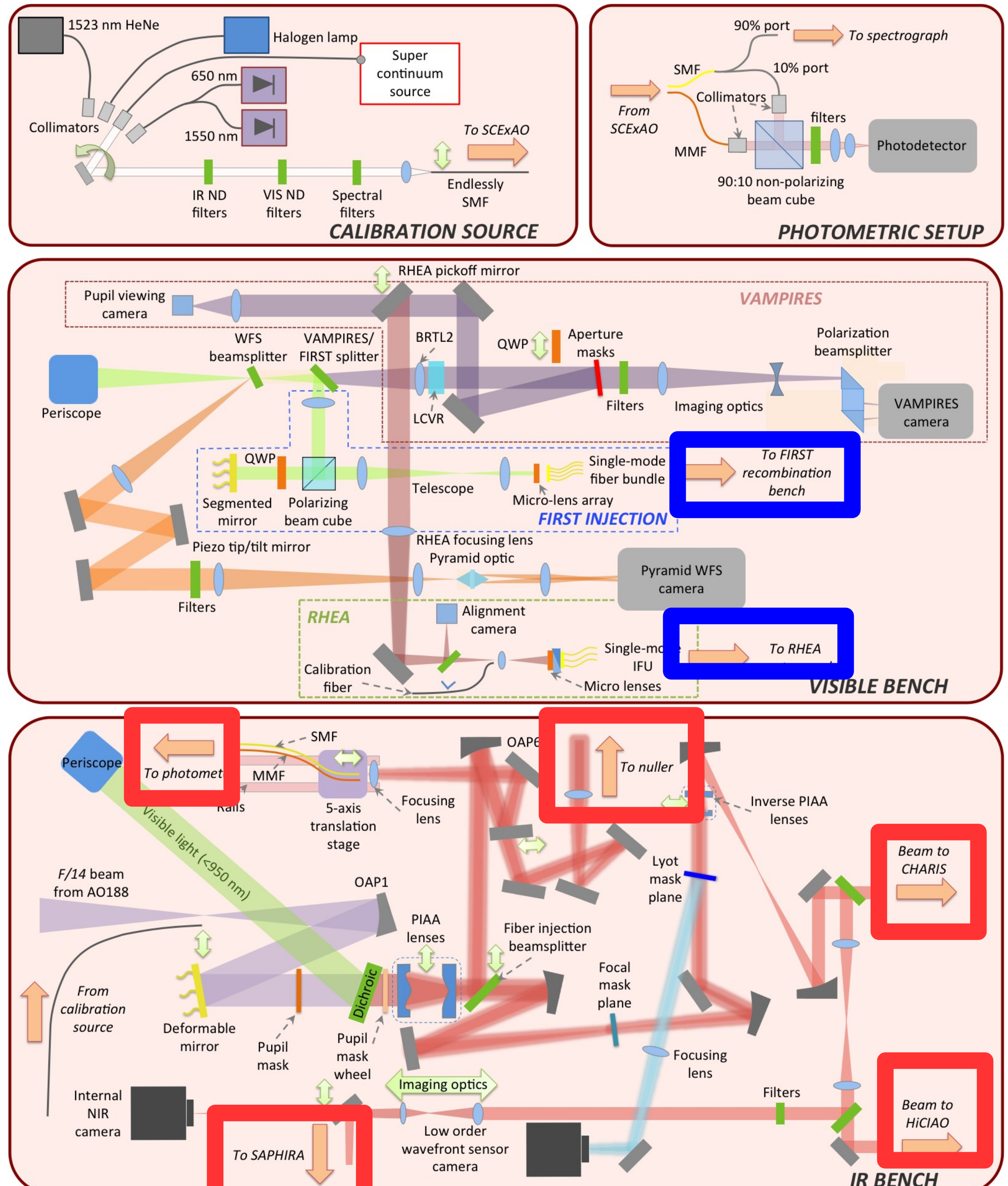
CHARIS - IFS (J to K-band)

MEC - MKIDs detector, high-speed, energy discriminating photon counting imager (y to J-band)

NIR single mode injection, high throughput high resolution spectroscopy. Soon will be connected to the new IRD

Various small IWA (1-3 l/D) coronagraphs for high contrast imaging – PIAA, vector vortex, 8OPM

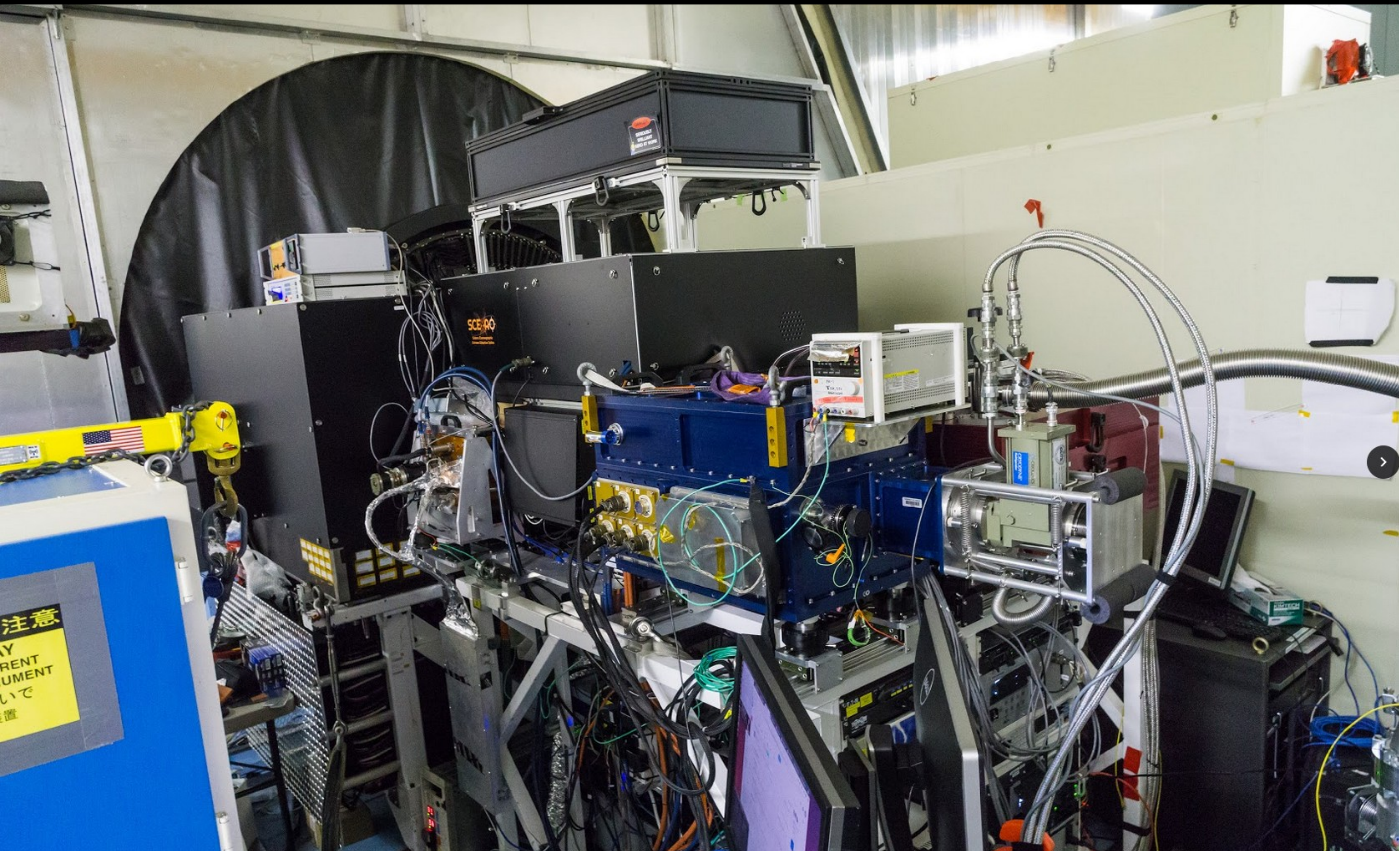
GLINT - NIR nulling interferometer based on photonics



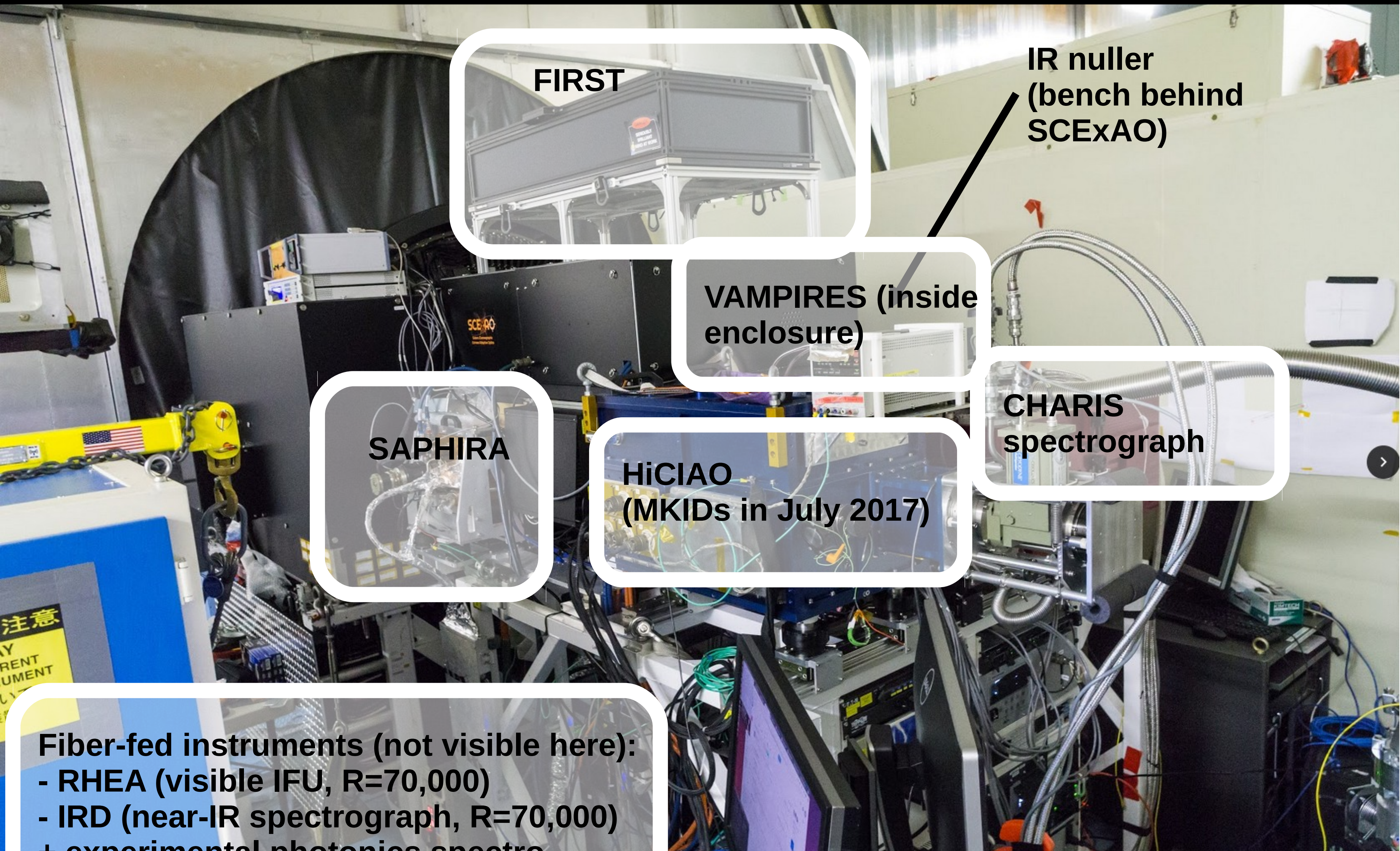
Jovanovic et al, PASP, 127, 890 (2015)

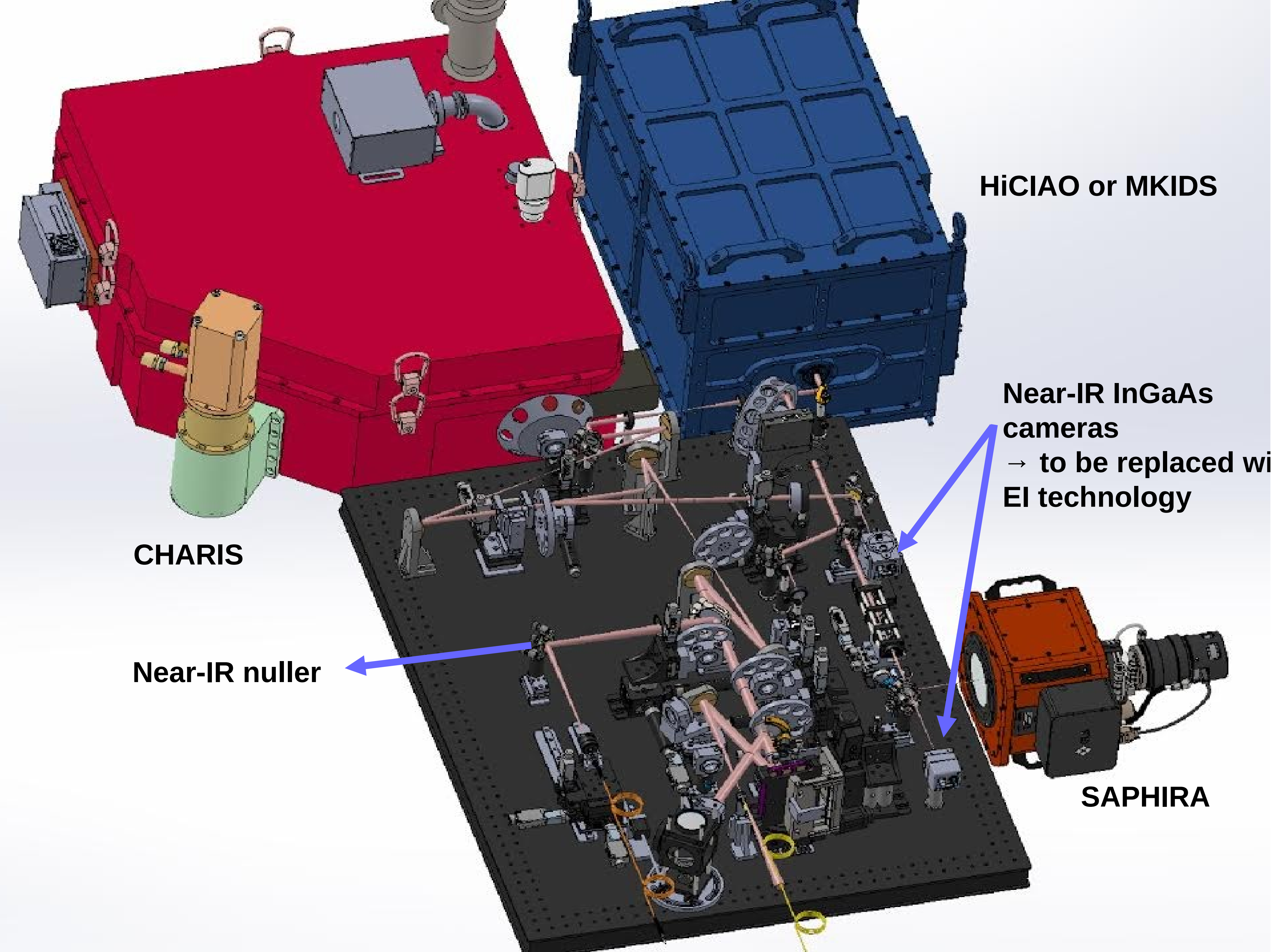
SCExAO

Subaru Coronagraphic Extreme Adaptive Optics



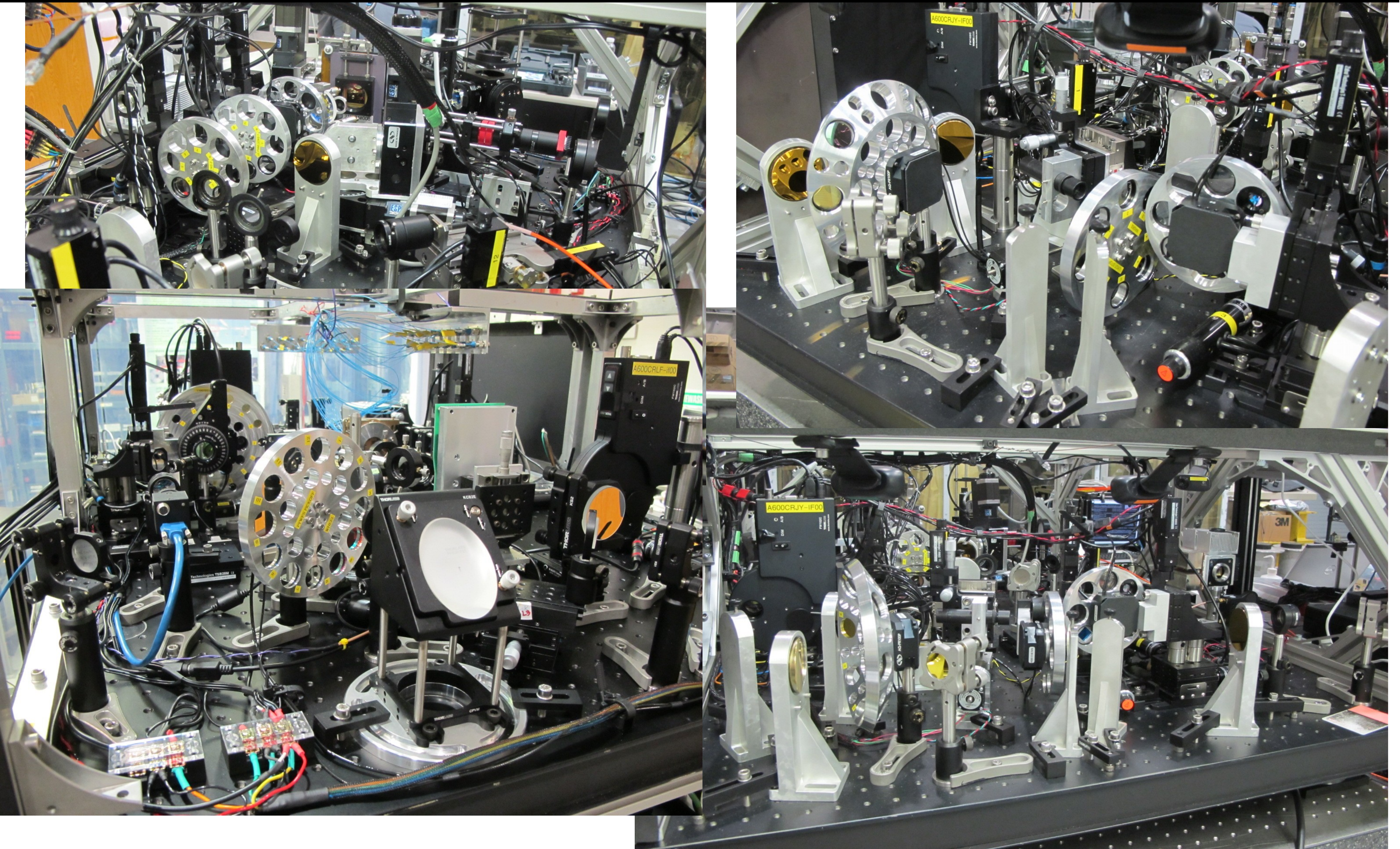
Subaru Coronagraphic Extreme Adaptive Optics



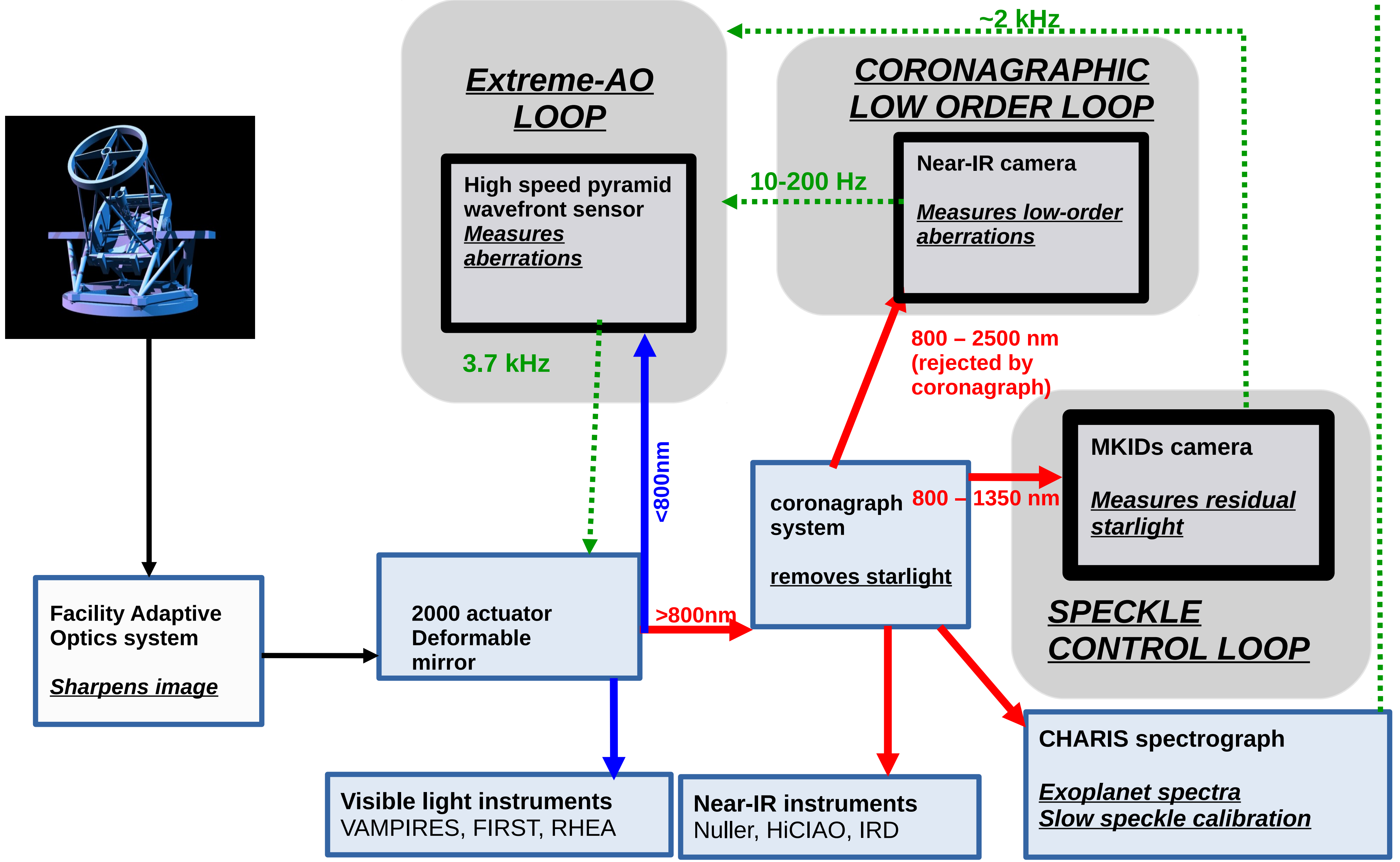

HiCIAO or MKIDS
Near-IR InGaAs
cameras
→ to be replaced wi
EI technology
CHARIS
Near-IR nuller
SAPHIRA

SCExAO

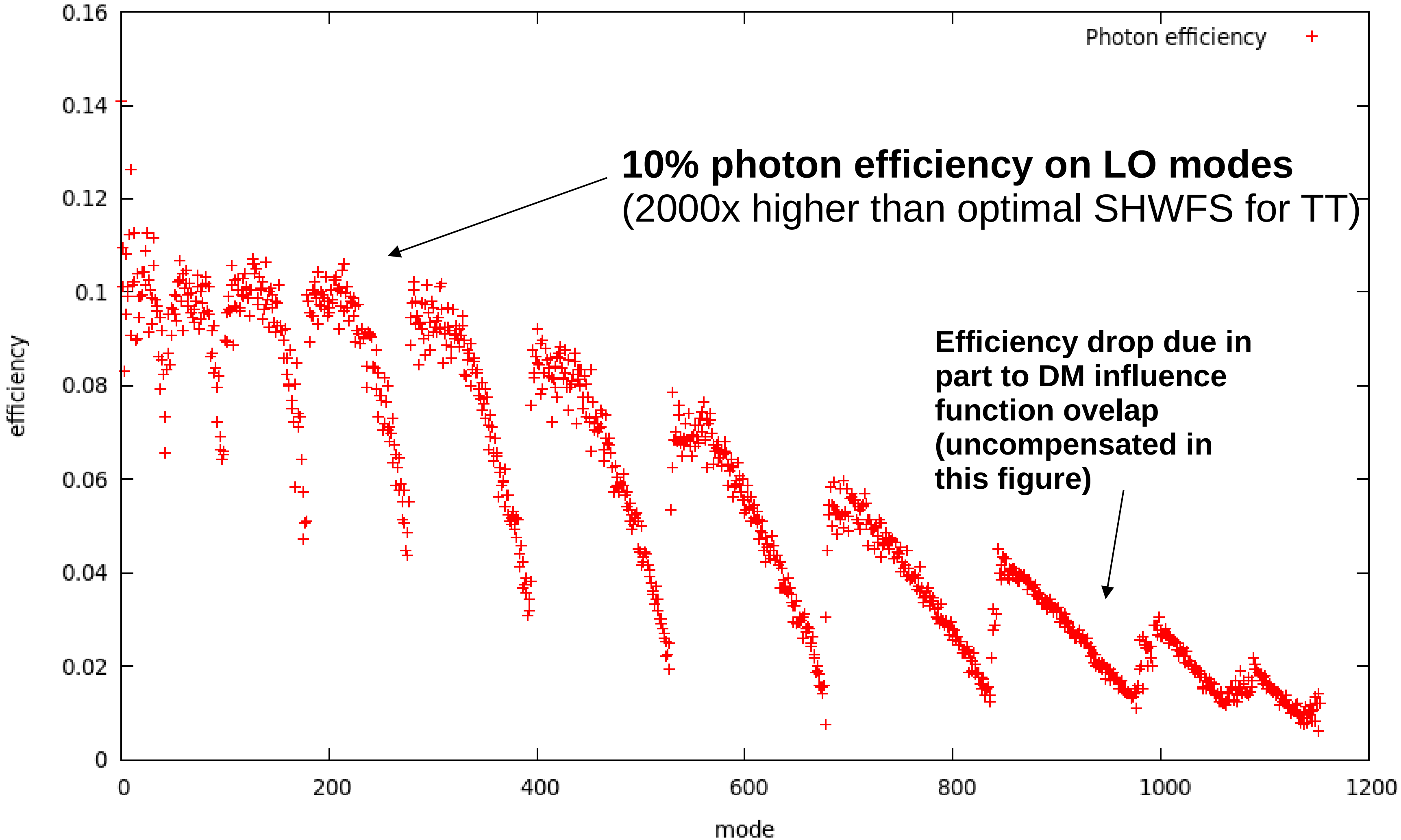
Subaru Coronagraphic Extreme Adaptive Optics



Subaru Coronagraphic Extreme Adaptive Optics

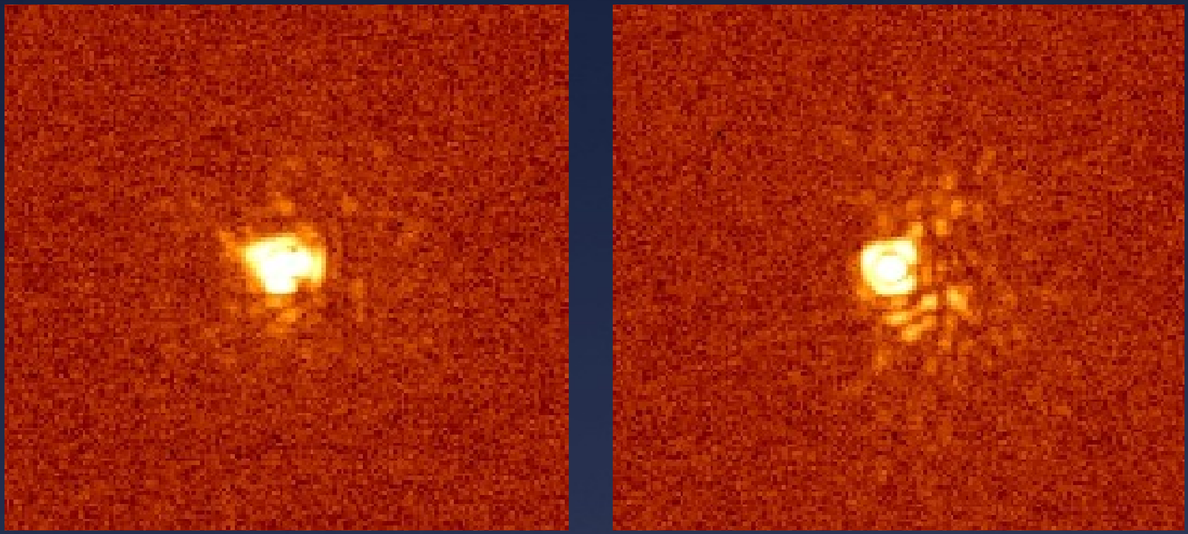


Measured photon efficiency (SCExAO, sub-l/D modulation pyramid)



speckle nulling results on-sky (June 2014)

Single frames: 50 us



Meta data:

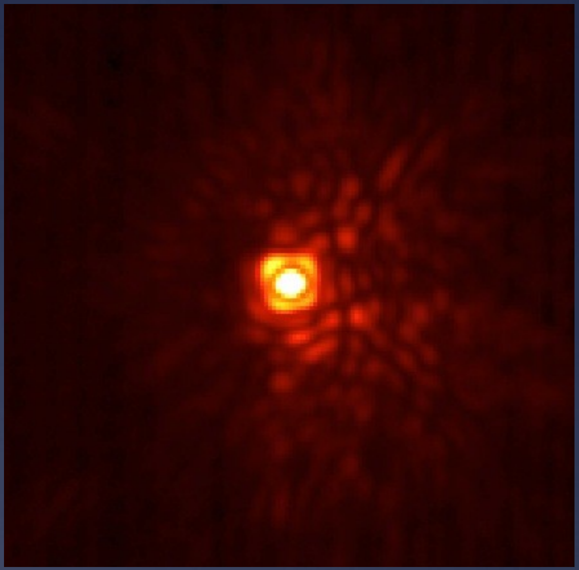
Date: 2nd or June

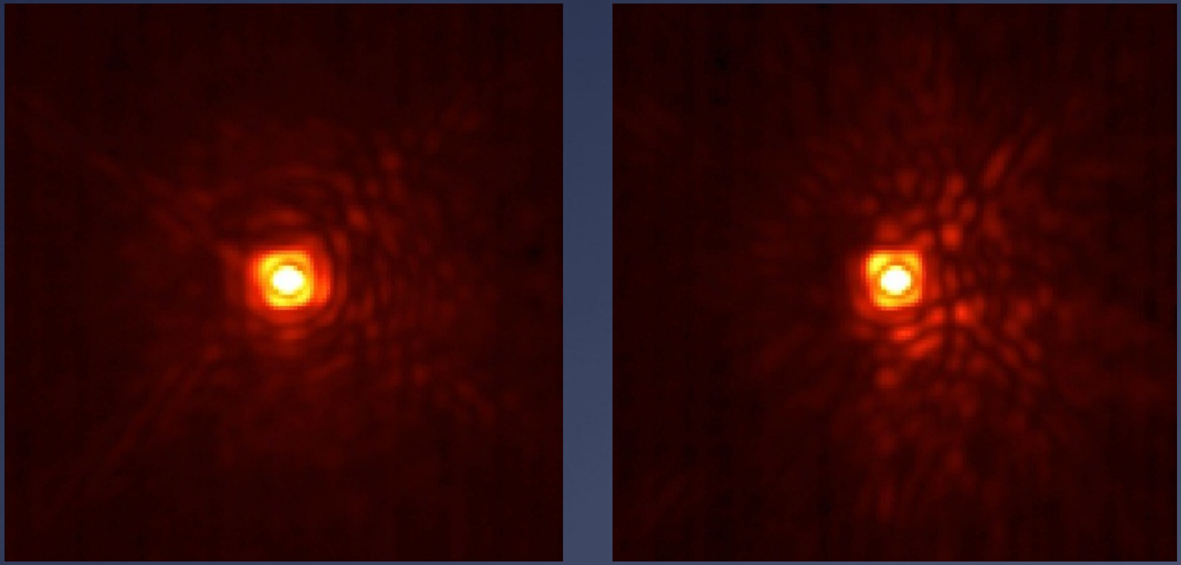
Target: RX Boo (also repeated on Vega)

Seeing: <0.6”

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

Coronagraph: None (used Vortex on Vega)





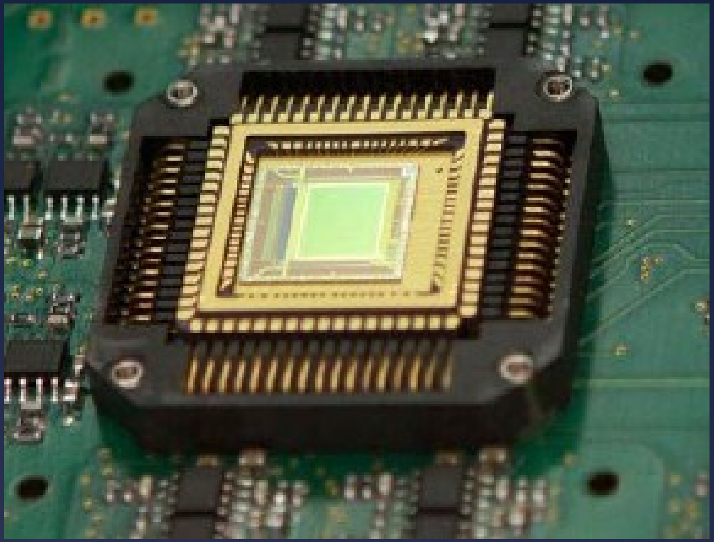
Sum of 5000 frames: shift and add

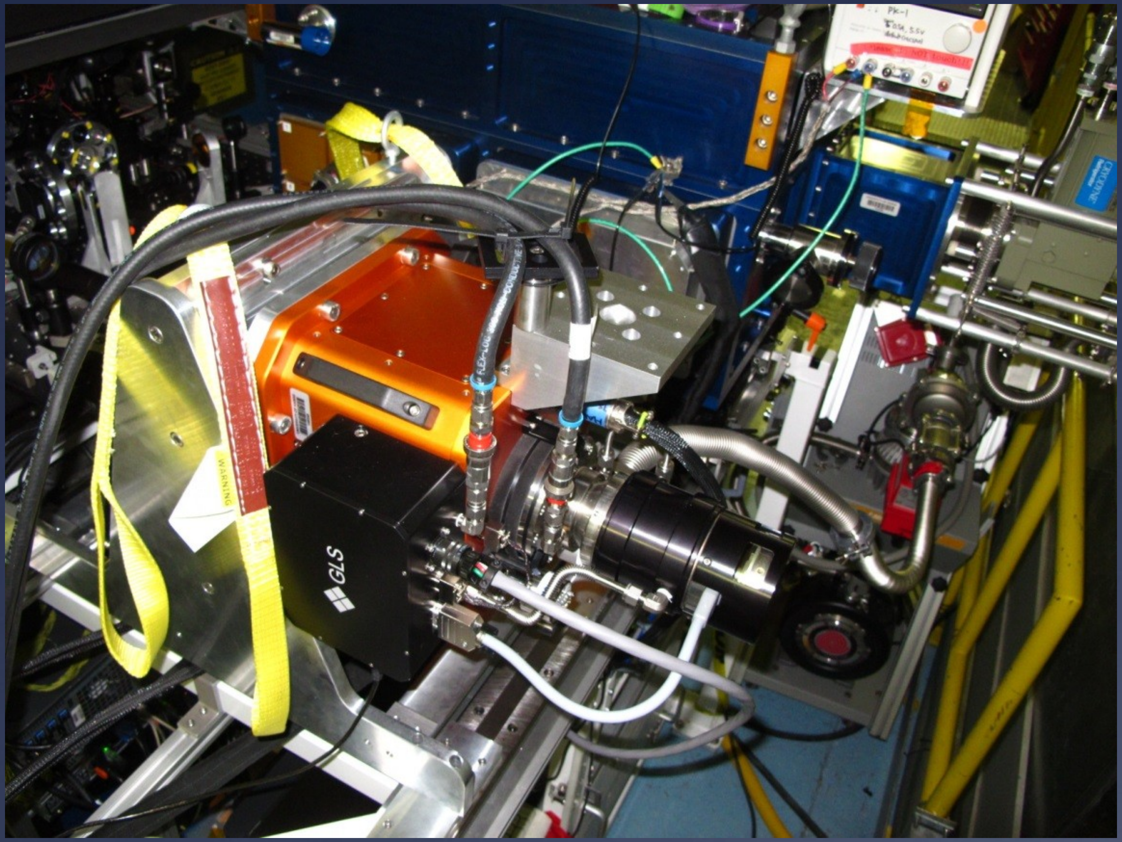
Martinache. et. al.

SAPHIRA Infrared APD array

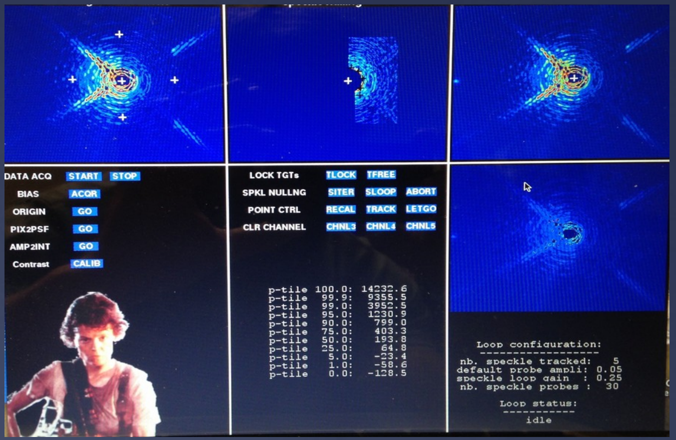
HgCdTe avalanche photodiode
manufactured by Selex

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



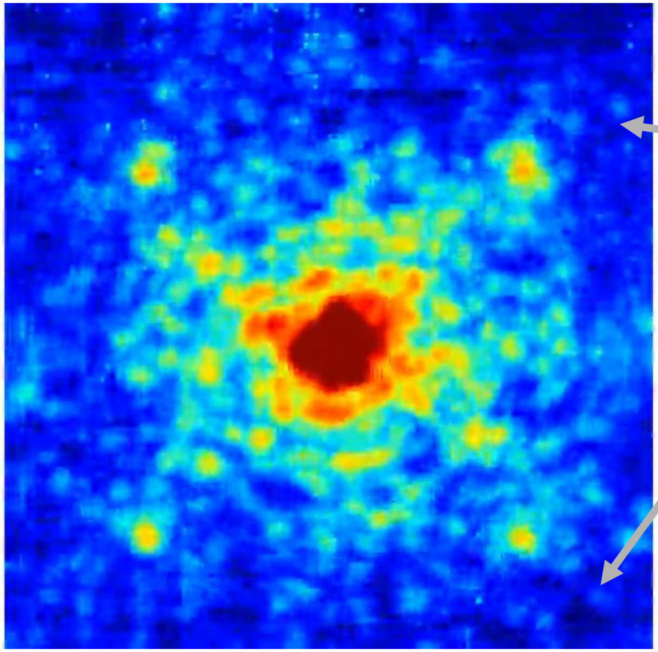


50 frame average



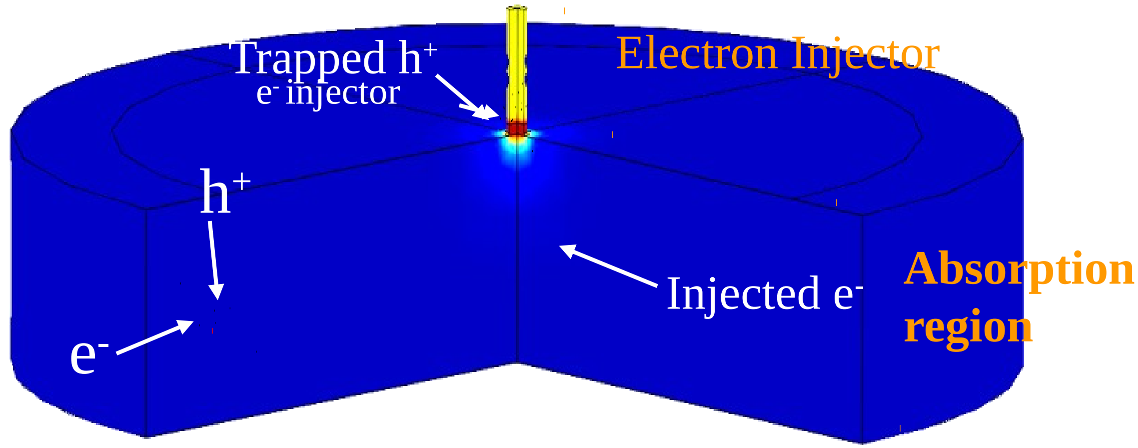
High speed speckle modulation

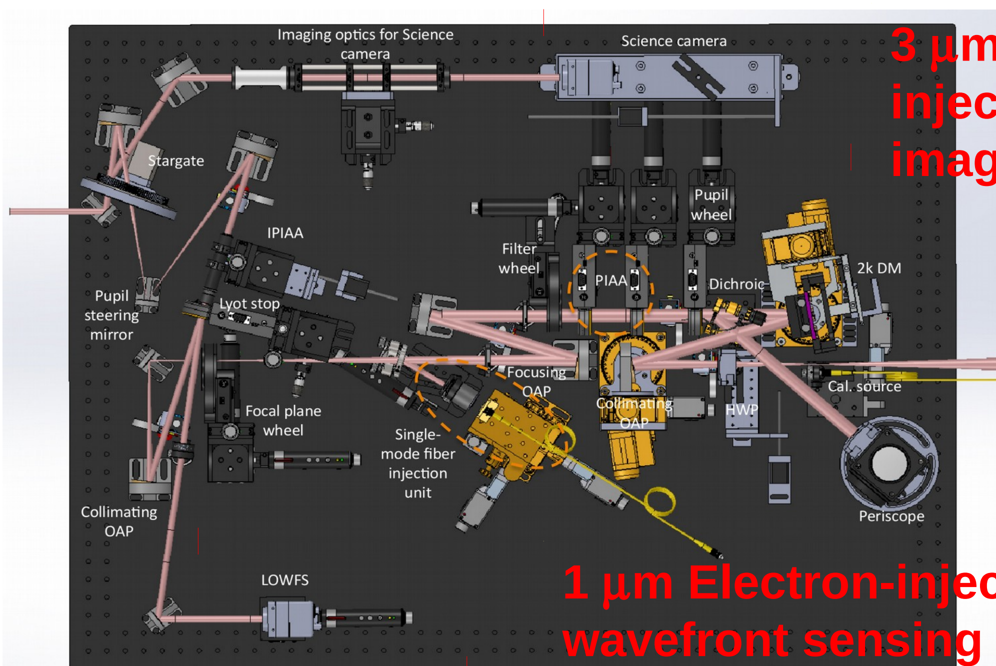
1.6 kHz frame rate, H-band
(played at 30 Hz)



Speckles modulated at 1 kHz

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



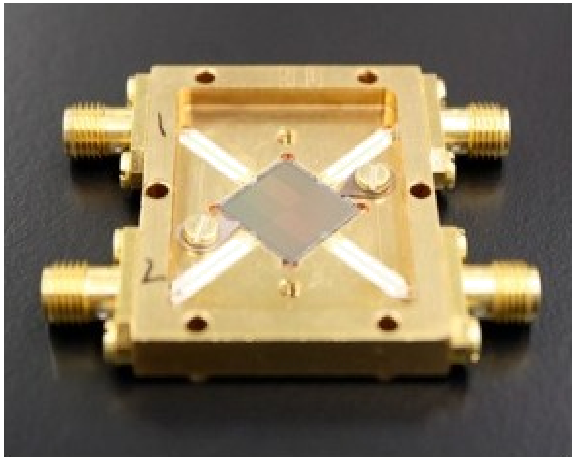


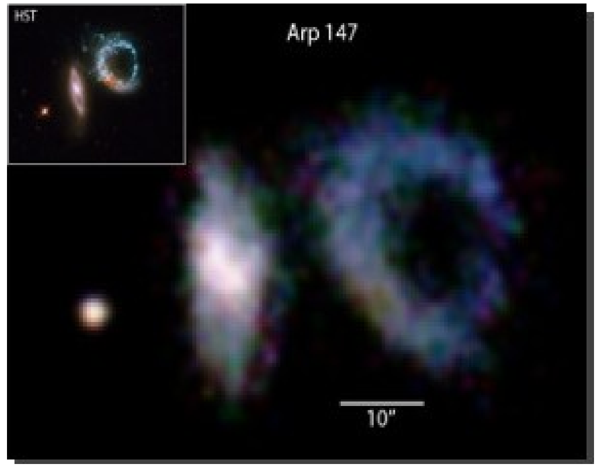
3 µm Electron-injection speckle imaging camera

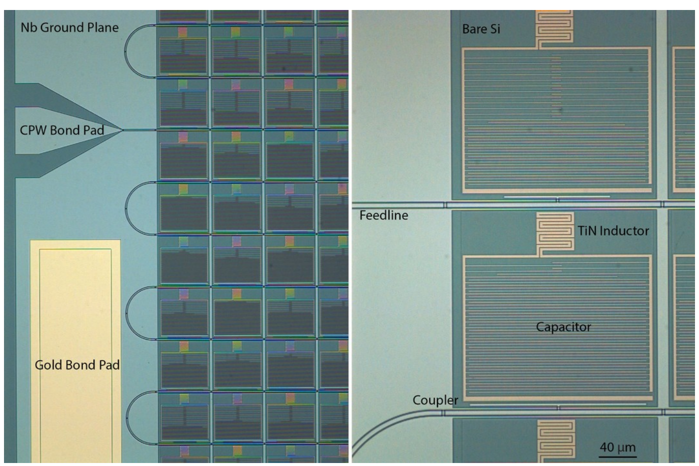
1 µm Electron-injection low-order wavefront sensing (pointing) camera

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

From Subaru to TMT

Demonstrate and validate performance on Subaru prior to deployment on TMT

→**ready to go as first light visitor instrument**, well understood

→**mitigates risks,** minimizes need for engineering time on TMT

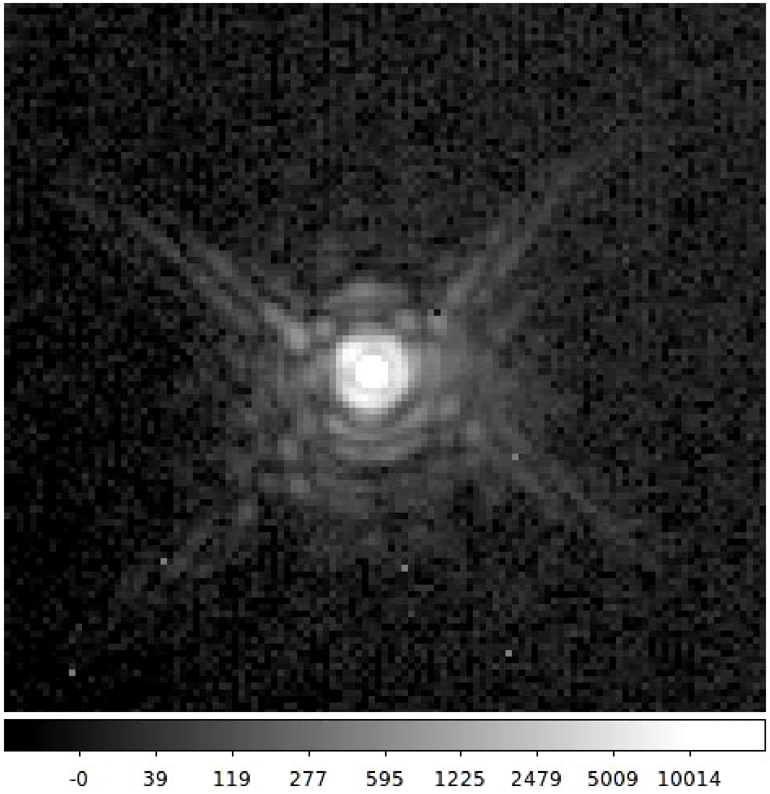
→ **benefits from yrs of experience** on Subaru (loop control, data reduction algorithms, observing strategy)

→ Subaru provides path to quickly and safely integrate/validate new technologies prior to instrument deployment on TMT

Open international effort engaging TMT partners. Expected overlap with development team of 2nd generation, more capable ExAO system. Re-use experience/technologies and possibly hardware to reduce schedule/cost/risk of 2nd generation instrument.

Current PSF stability @ SCExAO

Highly stable PSF for coronagraphy
SCExAO provides sensing and correction at 3.5 kHz



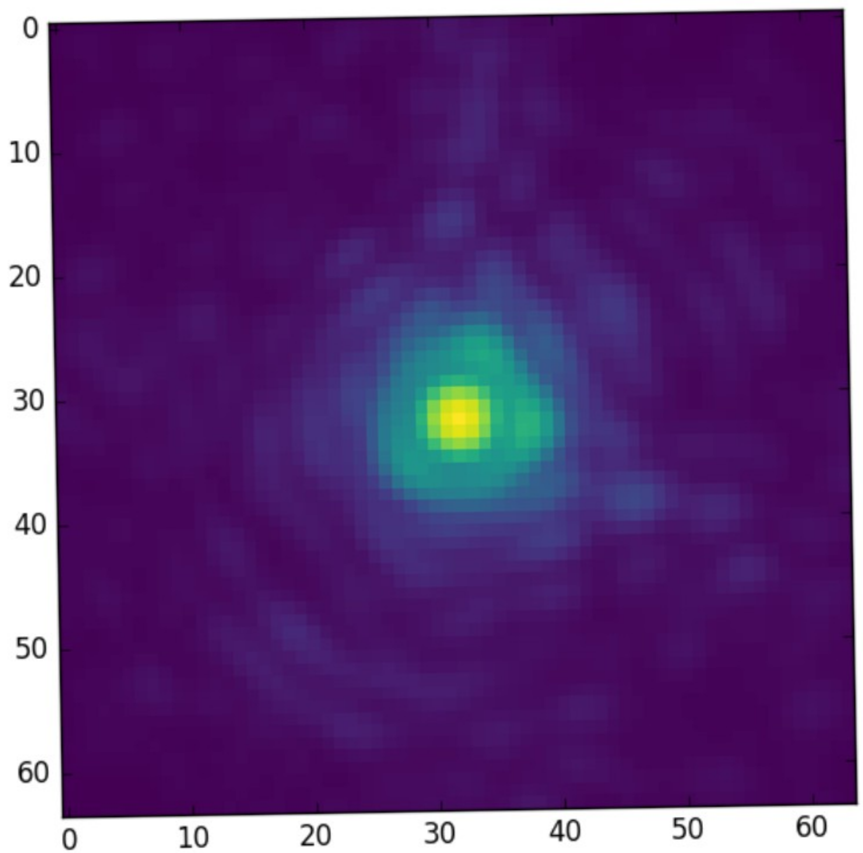
1630nm (SCExAO internal camera)
3 Hz sampling

Preliminary VAMPIRES science

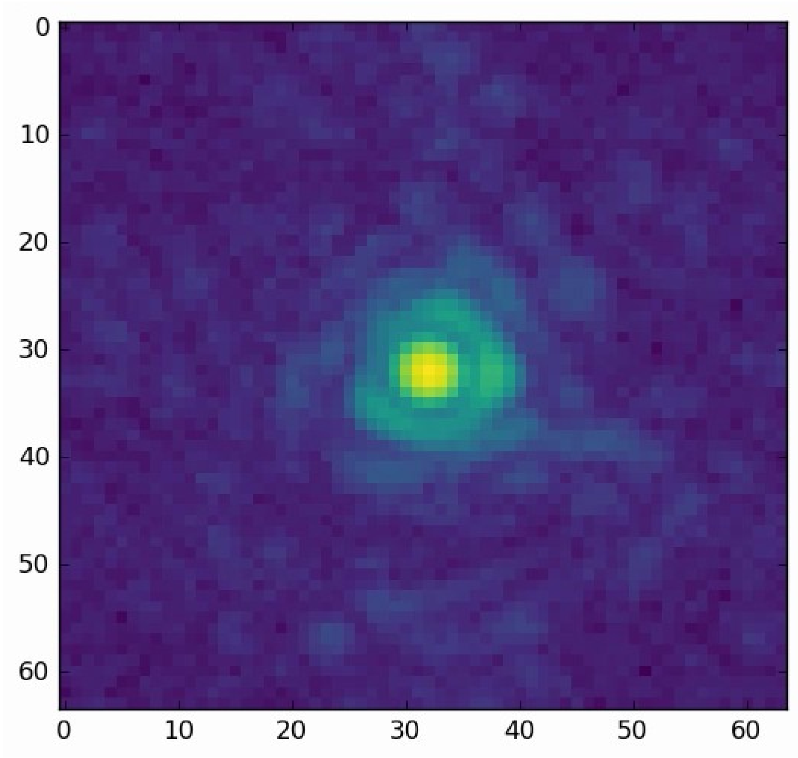
Diffraction-limited imaging in visible light

750nm, 1kHz imaging
log scale

Summed image



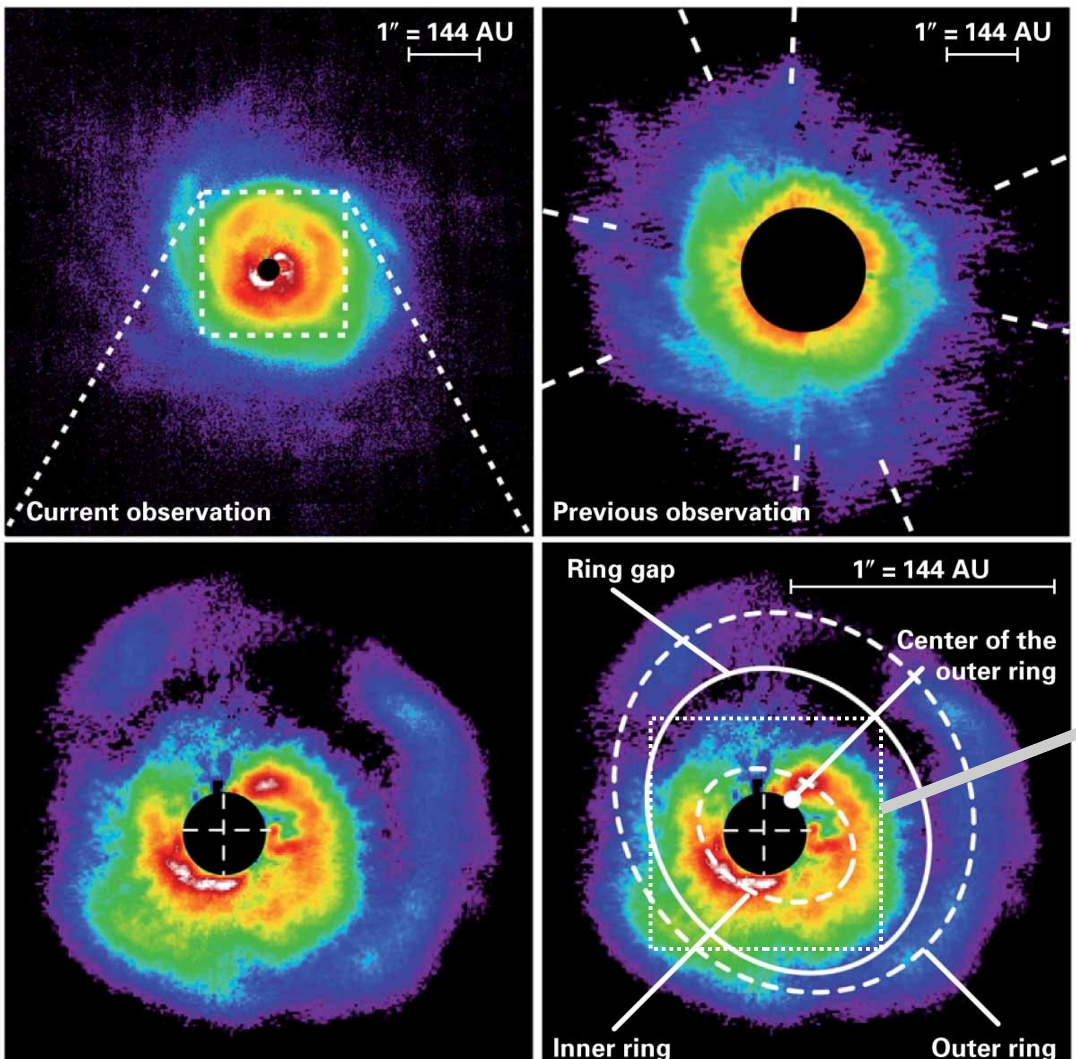
Video



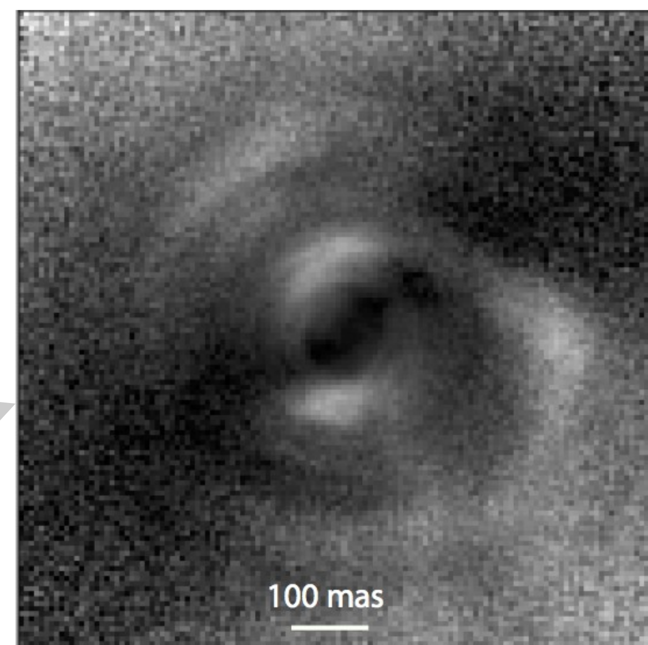
Preliminary VAMPIRES science

AB Aur star, polarimetric imaging mode

HiCIAO, near-IR



VAMPIRES
(preliminary data reduction)



Preliminary VAMPIRES science

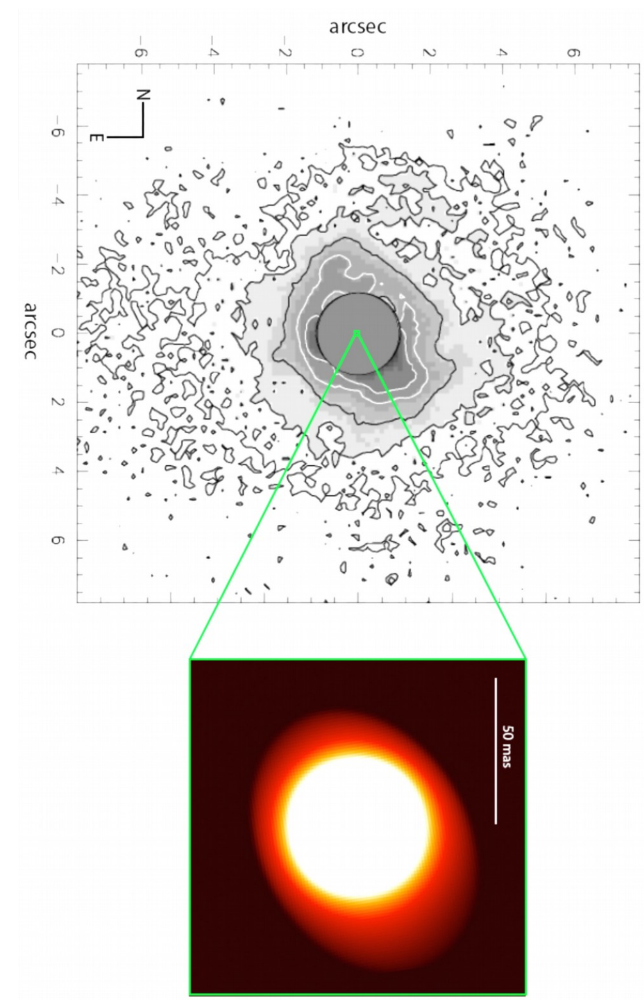
Circumstellar dust around Red Supergiant μ Cephei

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.

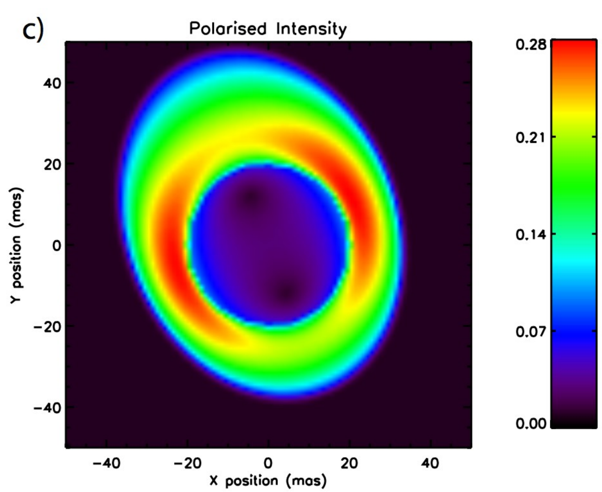
Inner radius: 9.3 ± 0.2 mas (which is roughly R_{star})

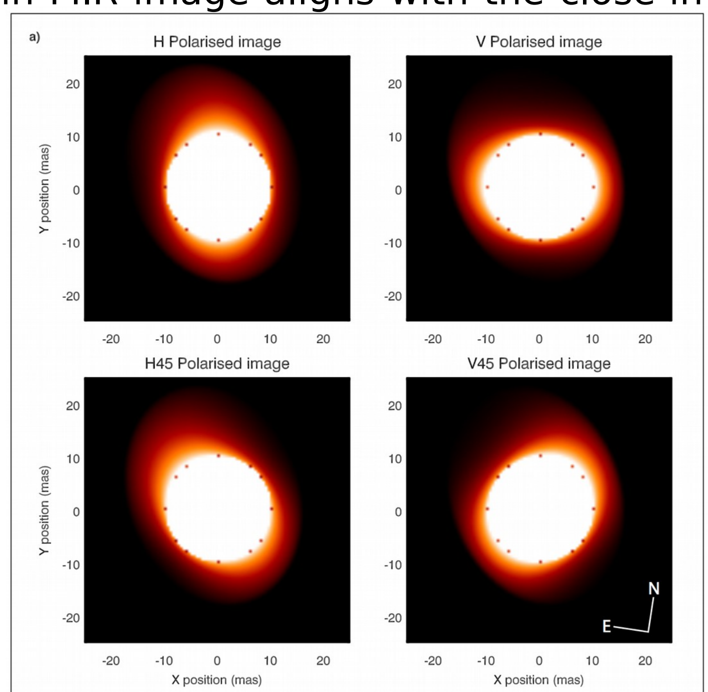
Scattered-light fraction: 0.081 ± 0.002

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

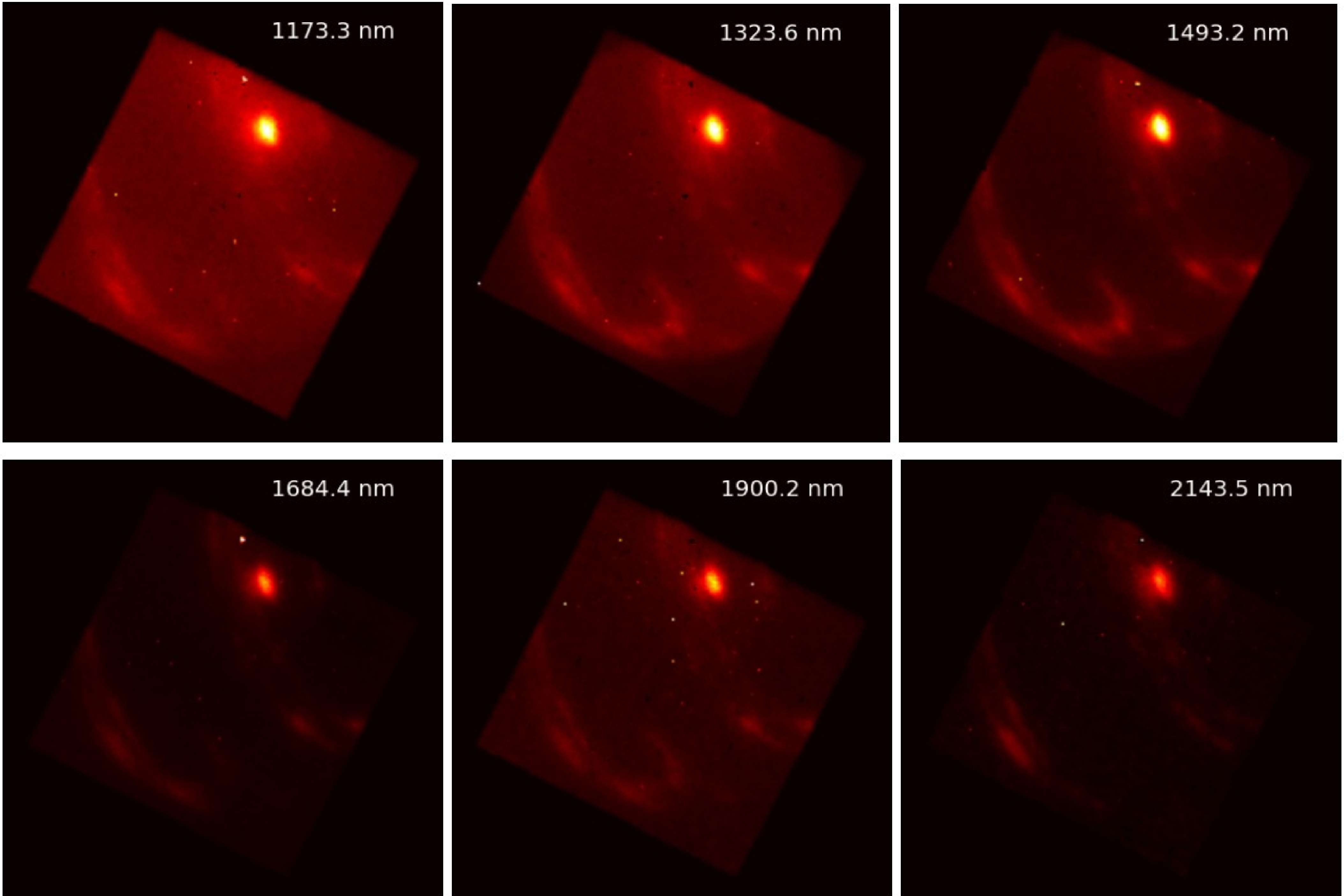


Left: model image, shown in polarized intensity. **Middle:** model image show in four polarisations. **Right:** Model image (intensity), shown with wide field MIR image (from de Wit et al. 2008 – green box shows relative scales. Axis of extension in MIR image aligns with the close-in VAMPIRES image.

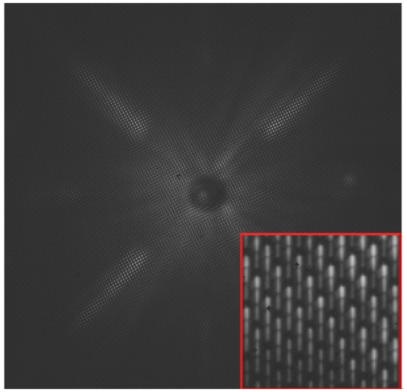


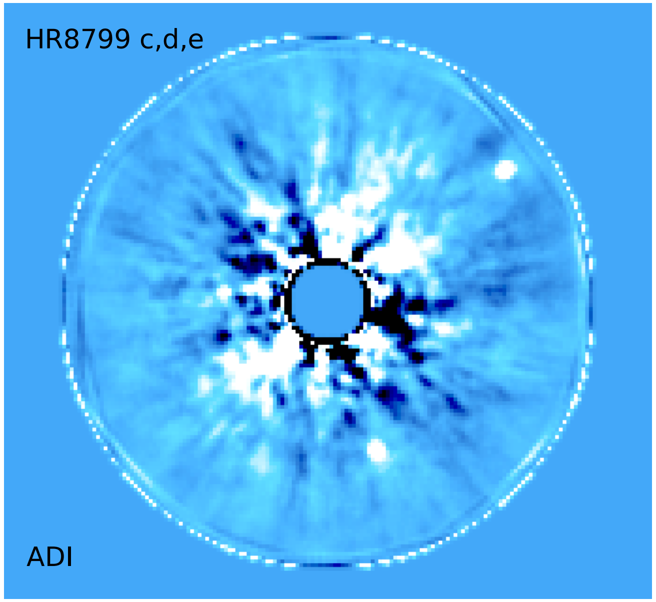


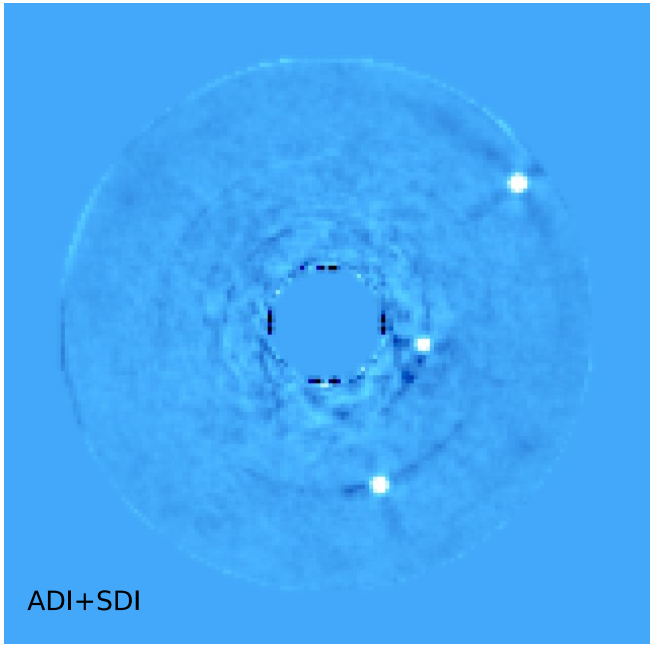
Neptune with CHARIS + SCExAO



CHARIS – early data on HD1160 and HR8799







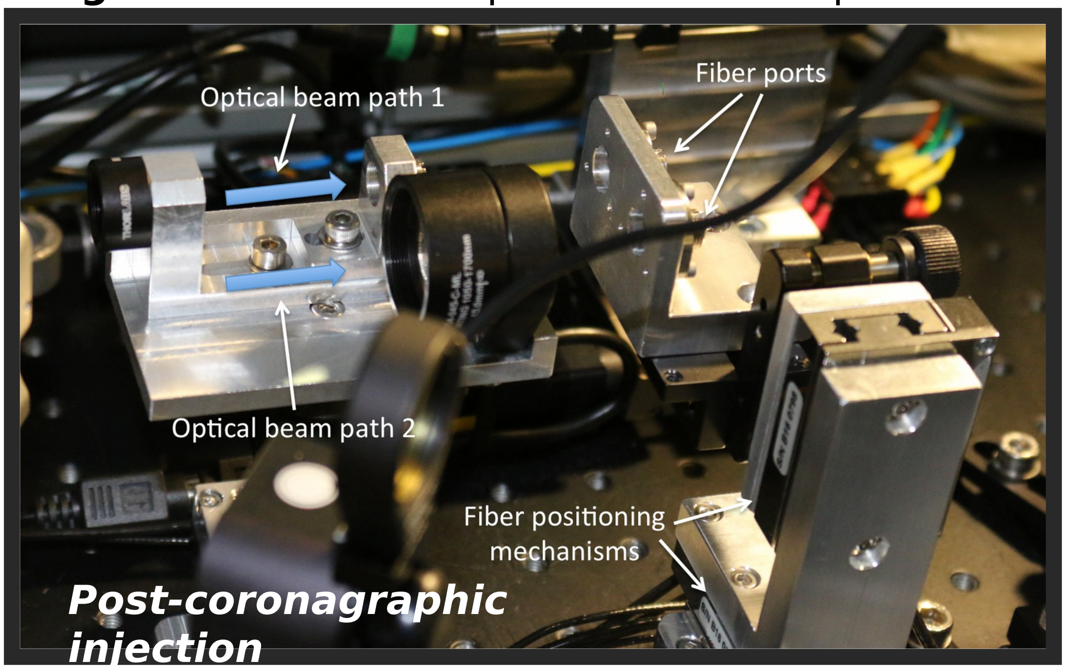
Images and movie courtesy of Tim Brandt

- HD1160 easily visible in the speckle halo with a basic data reduction thanks to large wavelength range
- HR8799 c,d,e easily extracted with ADI+SDI.
- SNR of 70, 35 and 15

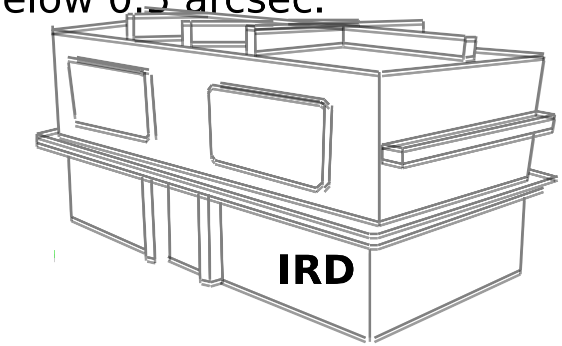
Post-Coronagraphic spectroscopy

Aim: Detection of atmospheric molecules and planetary radial velocity using post-coronagraphic high-dispersion spectroscopy

Targets: self-luminous planets whose separation are below 0.5 arcsec.

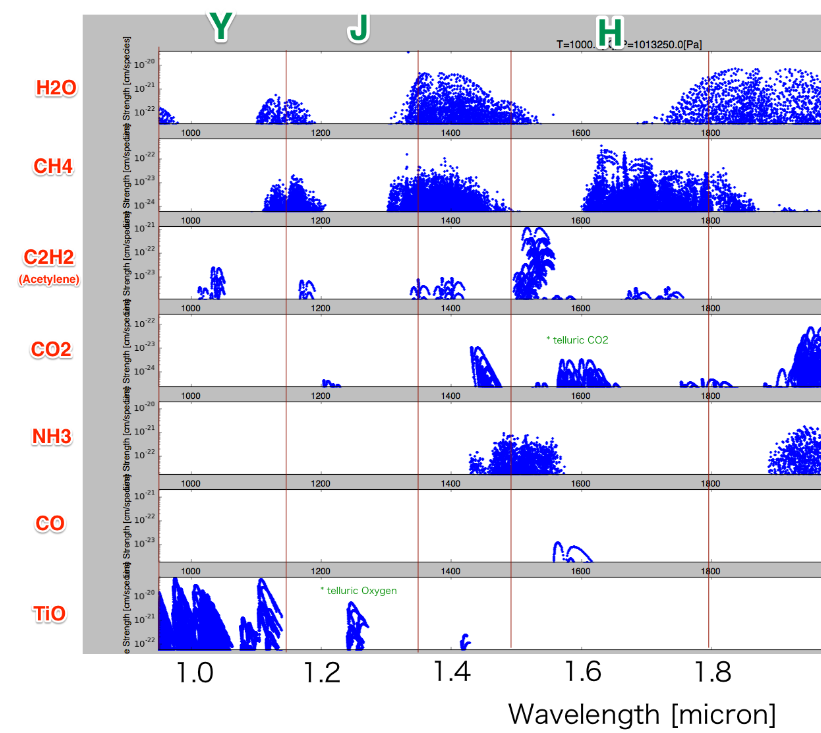


Jovanovic et al.

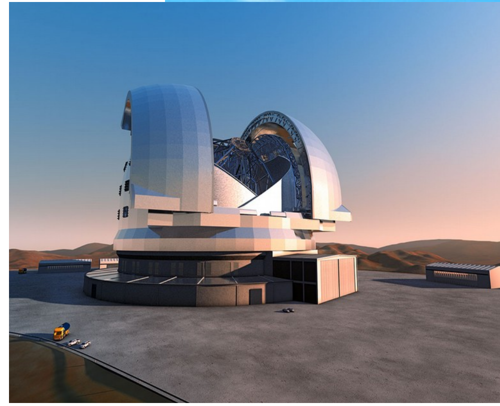
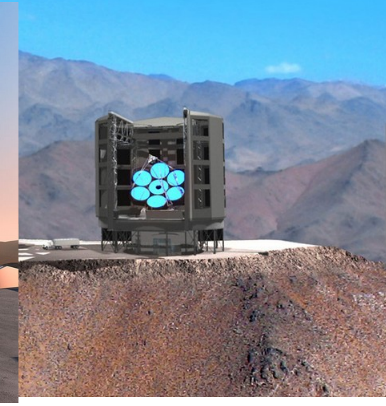


R~70,000,
Y, J, H
bands,
laser comb

Molecular lines in Y, J, and H band



Conclusions


Low-hanging fruits (Prox Cen B !) can be imaged on ELTs with current technology (… possible even with VLT with high resolution spectroscopy)

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

Near-complete sample of M0-M5 stars within 5pc

BUT: ELTs intrument development process is slow compared to the pace of science in technology progress in our field

→ Schedule for (near-)first light instrument on ELT is very challenging

(No “extreme-AO” currently planned as ELT 1^{st} generation instrument)