Planet Searching from Ground and Space

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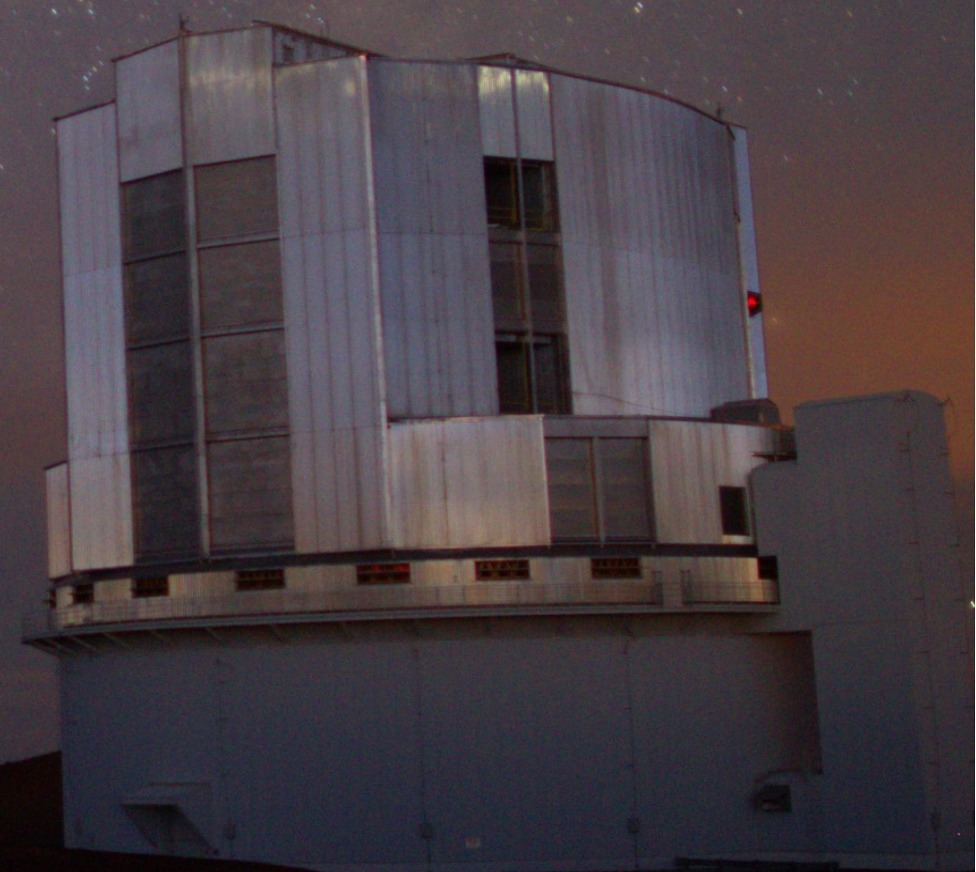


June 8, 2017

Perspectives on O/IR Astronomy in the Mid-2020s

Outline

1. Current status of exoplanet research
2. Finding the nearest habitable planets
3. Characterizing exoplanets
4. Breakthrough Watch and Starshot initiatives
5. Subaru Telescope instrumentation, Japan/US collaboration toward TMT
6. Recommendations

1. Current Status of Exoplanet Research

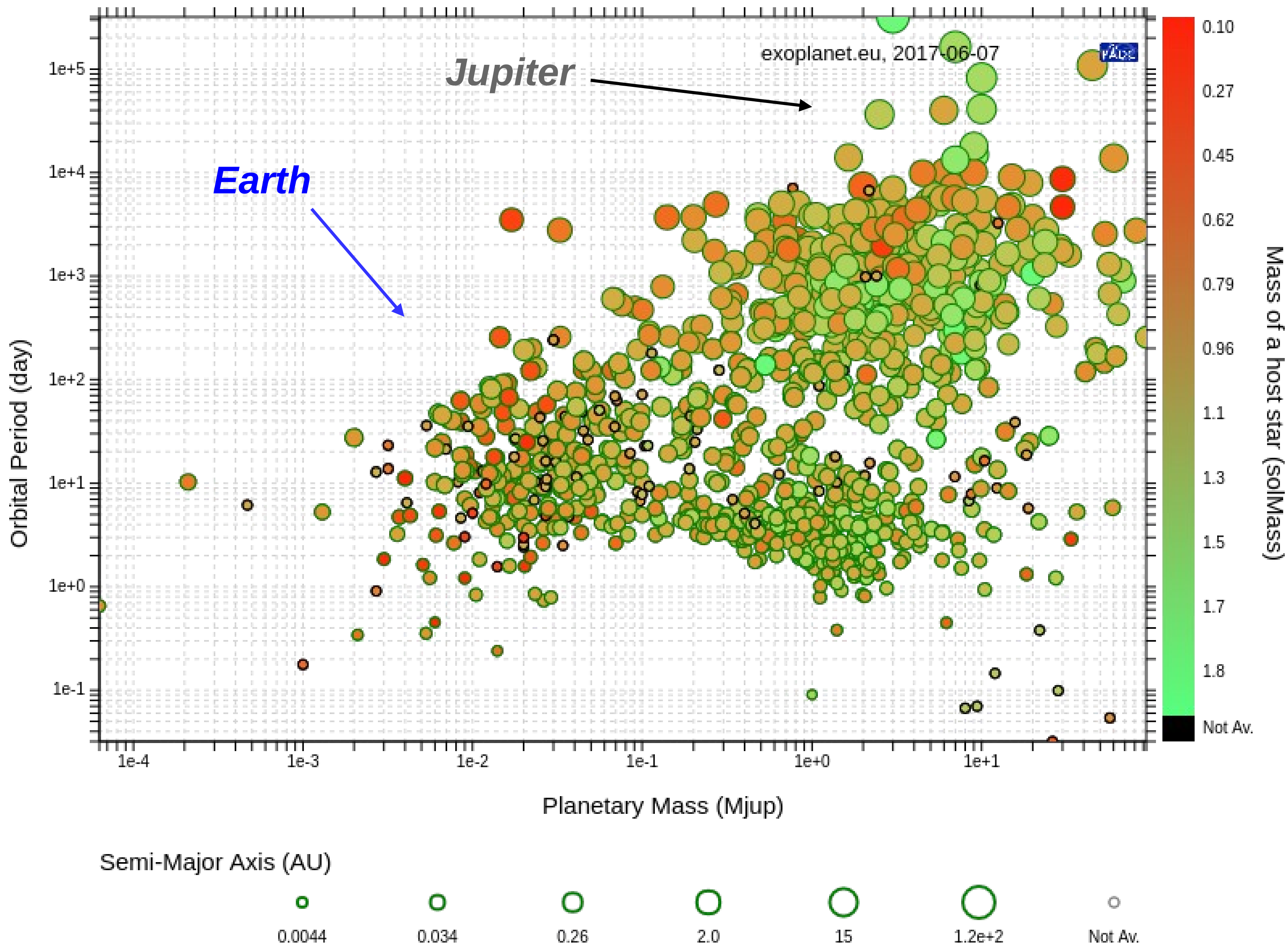
3,500 confirmed planets (as of June 2017)

Most identified by two techniques:

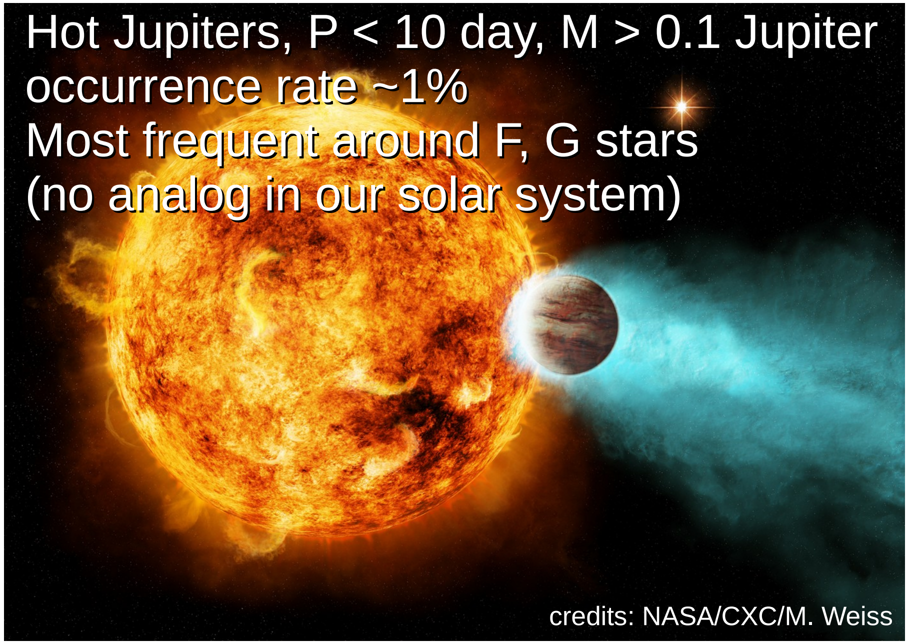
Radial Velocity with ground-based telescopes

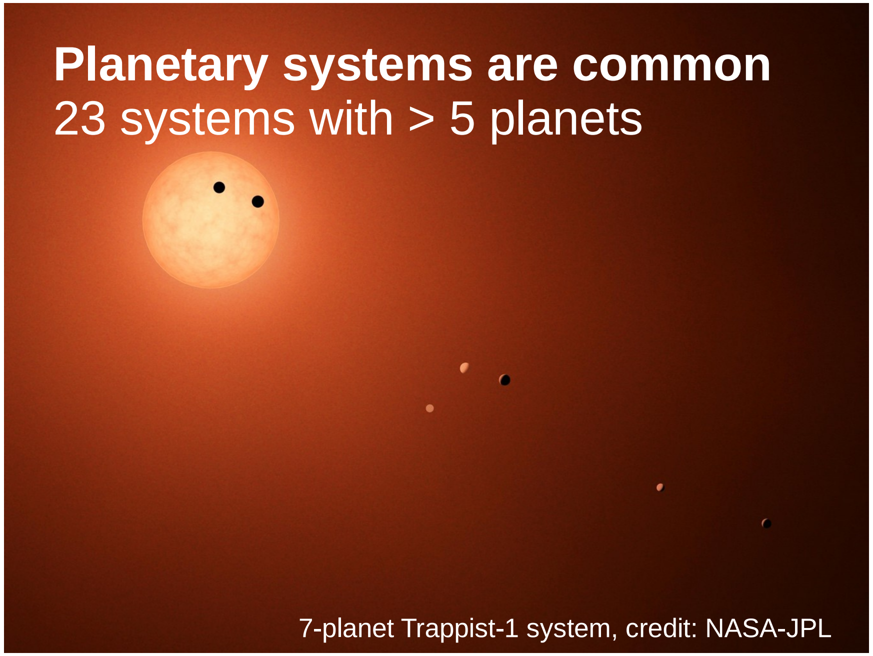
Transit (most with NASA Kepler mission)

Strong observational bias towards short period and high mass
(lower right corner)

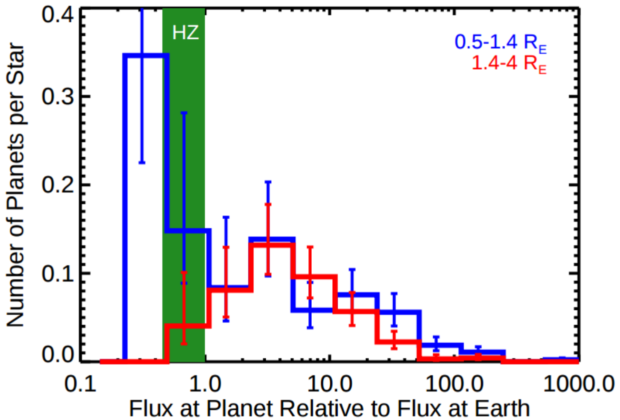


Key statistical findings





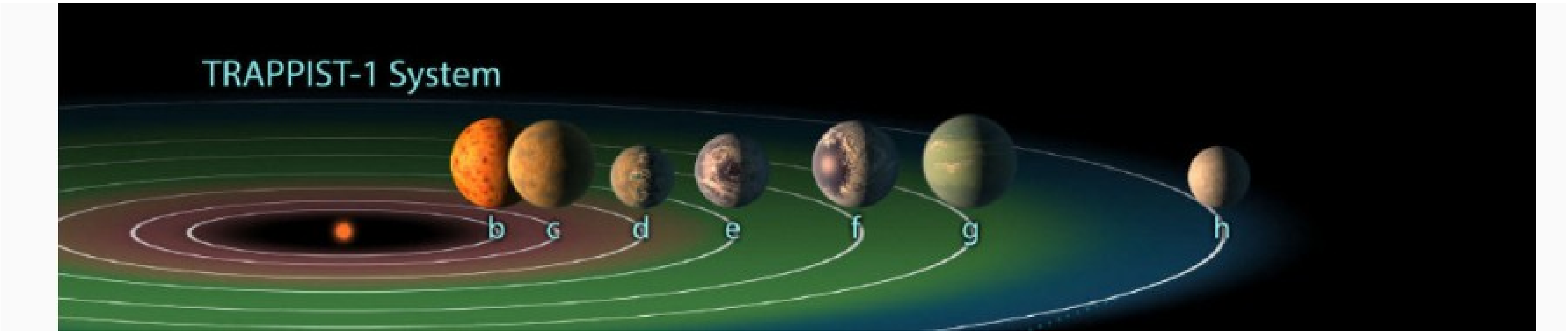
Earth-size rocky planets are abundant



Dressing & Charbonneau 2013

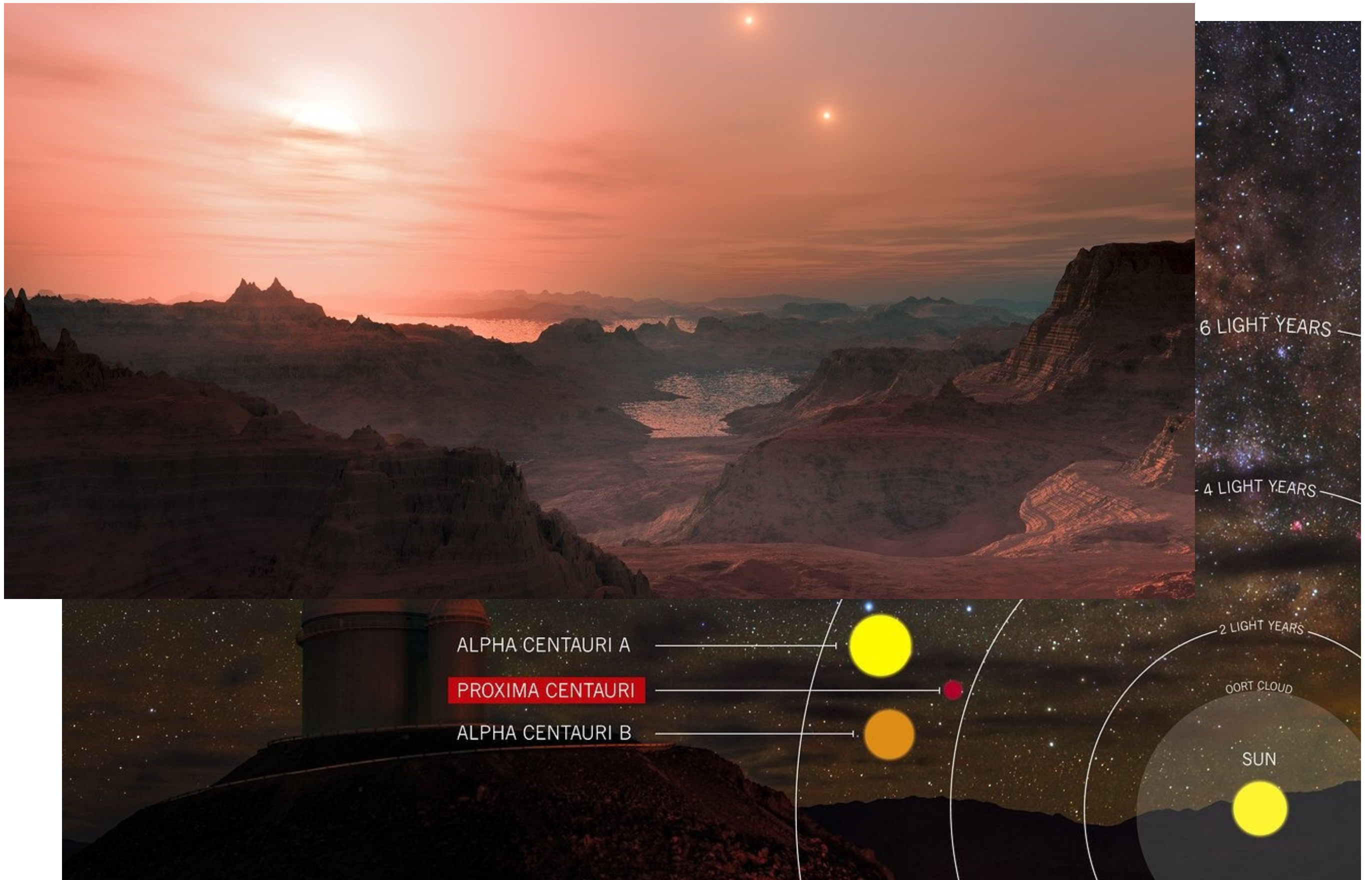
Spectacular discoveries around M stars

Trappist-1 system
7 planets
~3 in hab zone
likely rocky
40 ly away



Proxima Cen b
planet
Possibly habitable

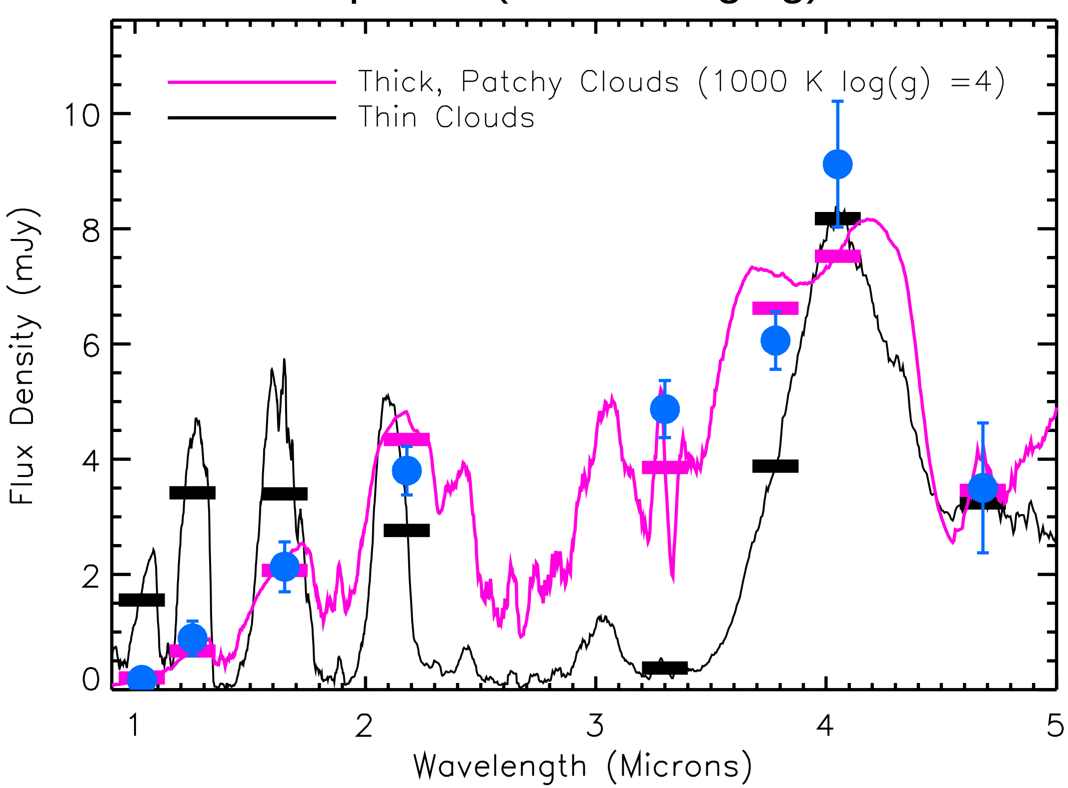
Closest star to our
solar system
Faint red M-type
star



Spectroscopic characterization limited to Giant young planets or close-in planets

For most planets, only Mass, radius and orbit are constrained

HR 8799 d planet (direct imaging)

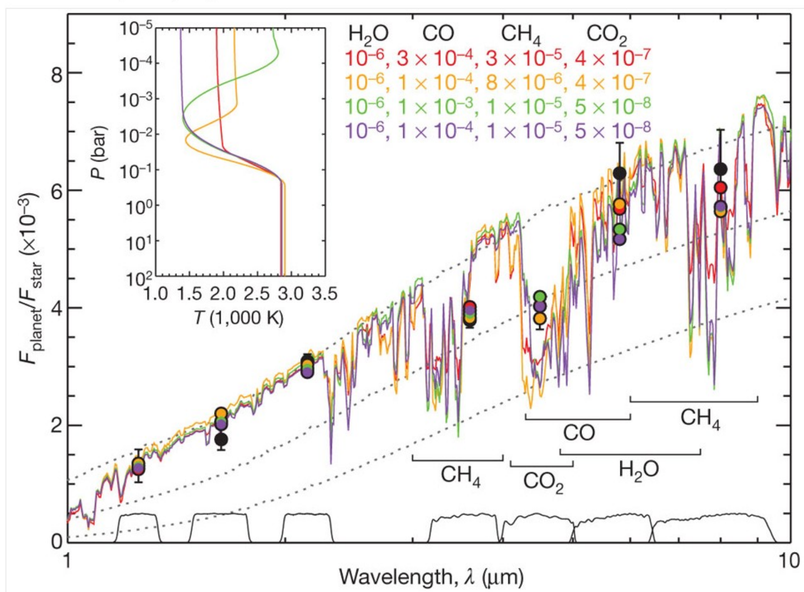


Currie, Burrows et al. 2011, ApJ, 729, 128

A high C/O ratio and weak thermal inversion in the atmosphere of exoplanet WASP-12b

Nikku Madhusudhan, Joseph Harrington, Kevin B. Stevenson, Sarah Nymeyer, Christopher J. Campo, Peter J. Wheatley, Drake Deming, Jasmina Blecic, Ryan A. Hardy, Nate B. Lust, David R. Anderson, Andrew Collier-Cameron, Christopher B. T. Britt, William C. Bowman, Leslie Hebb, Coel Hellier, Pierre F. L. Maxted, Don Pollacco & Richard G. West

Nature **469**, 64–67 (06 January 2011) | doi:10.1038/nature09602



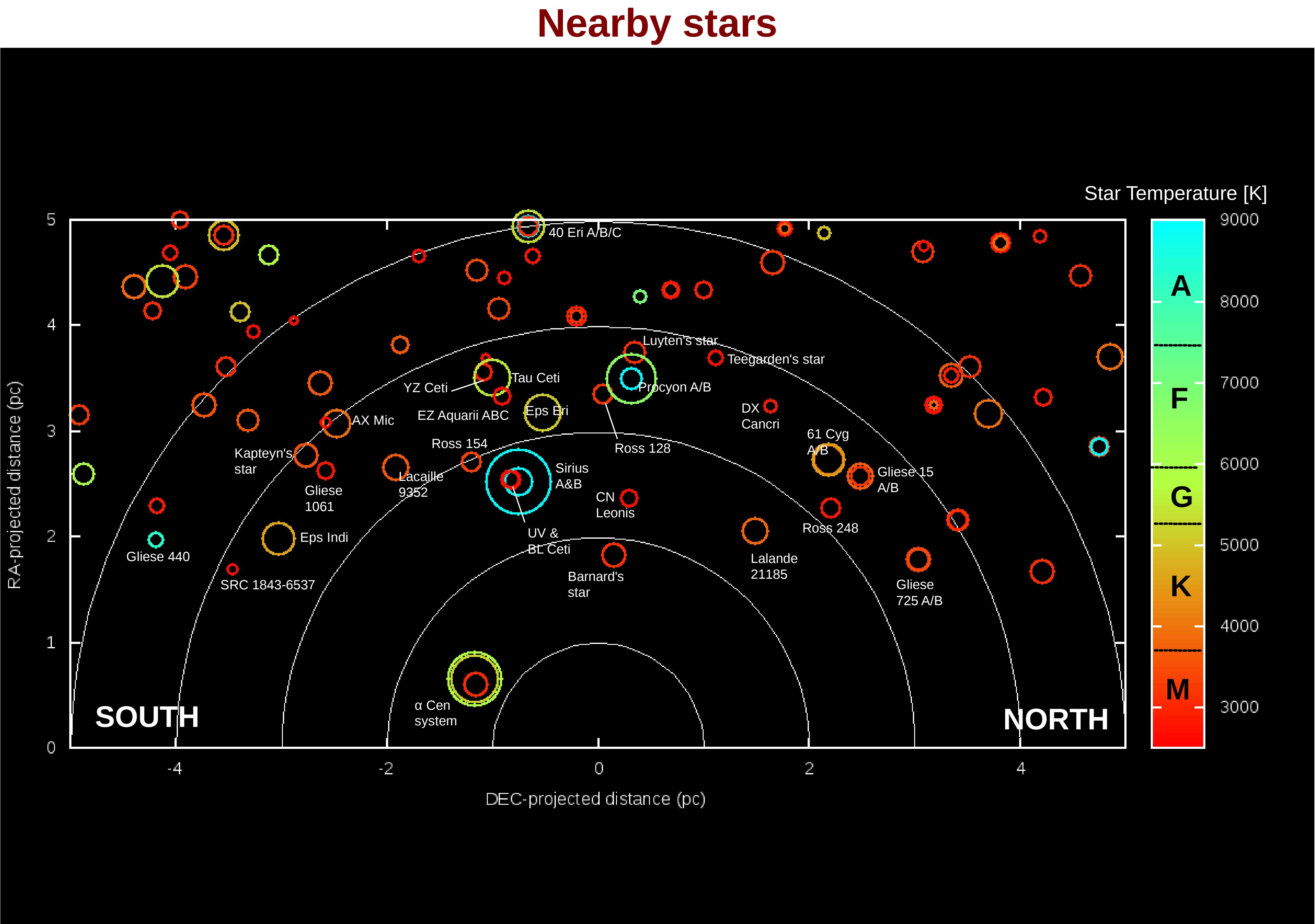
F is the flux. The black filled circles with error bars show the data with 1 s.d. errors: four Spitzer observations[4] (3.6 µm, 4.5 µm, 5.8 µm and 8 µm), and three ground-based observations in the J (1.2 µm), H (1.6 µm), and Ks (2.1 µm) bands[5]. Four models fitting the observations are shown in the coloured solid curves in the main panel, and the coloured circles are the channel-integrated model points. The corresponding temperature profiles are shown in the inset. The molecular compositions are shown as number ratio with respect to molecular hydrogen; all the models have C/O between 1 and 1.1. The thin grey dotted lines show the blackbody spectra of WASP-12b at 2,000 K (bottom), 2,500 K (middle) and 3,000 K (top). A Kurucz model[29] was used for the stellar spectrum, assuming uniform illumination over the planetary disk (that is, weighted by 0.5; ref. 7). The black solid lines at the bottom show the photometric band-passes in arbitrary units. The low fluxes at 3.6 µm and 4.5 µm are explained by methane and CO absorption, respectively, required for all the models that fit. The high flux in the 5.8-µm channel indicates less absorption due to H_2O. The observations can be explained to high precision by models without thermal inversions. Models with strong thermal inversions are ruled out by the data (see Fig. 3). The green model features a thermal inversion at low pressures ($P < 0.01$ bar), but the corresponding spectrum is almost indistinguishable from the purple model, which does not have a thermal inversion; both models have identical compositions and identical thermal profiles for $P > 0.01$ bar. Thus, any potential thermal inversion is too weak to be detectable by current instruments.

2. Finding the nearest habitable planets

Nearest =

Best opportunity for characterization (especially direct imaging) and possible flyby (BT Starshot)

2. Finding the nearest habitable Exoplanets



2. Finding the nearest habitable Exoplanets

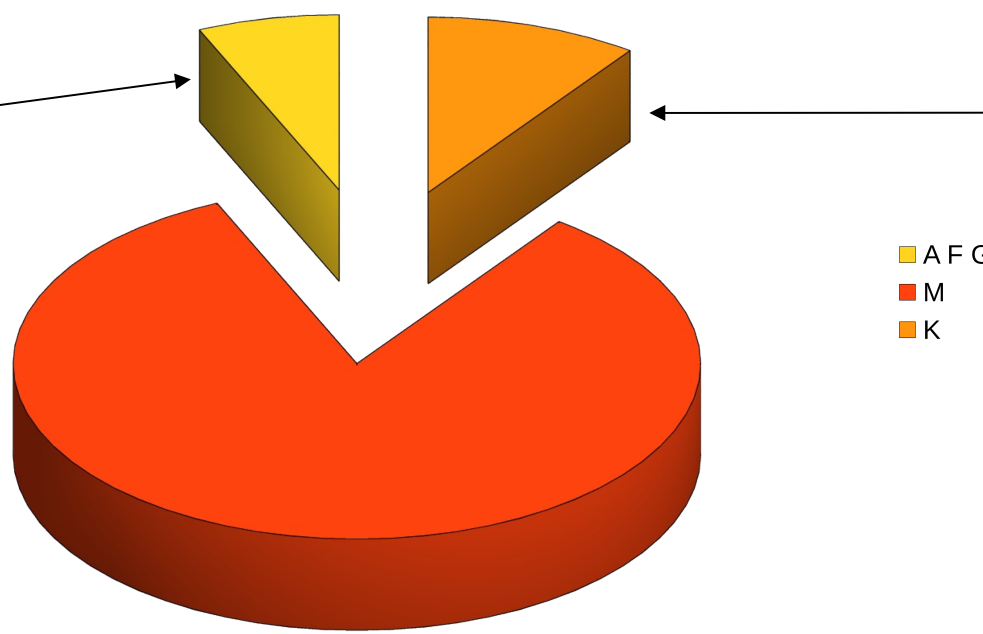
Nearby stars

>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



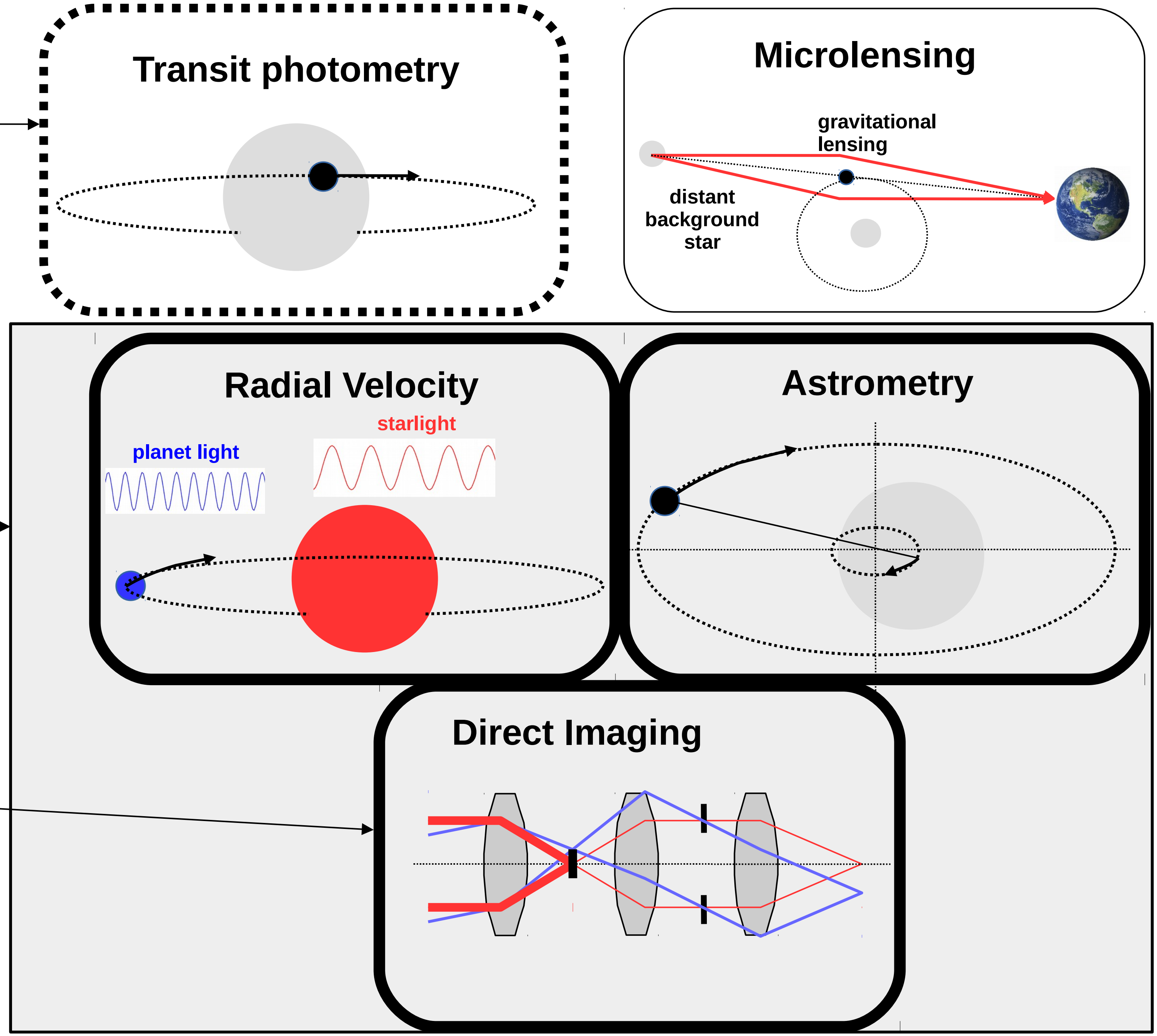
4.36 Alpha Cen B
10.52 Eps Eri
11.40 61 Cyg A
11.40 61 Cyg B
11.82 Eps Ind A
15.82 Gliese 380

Main Exoplanet Detection techniques

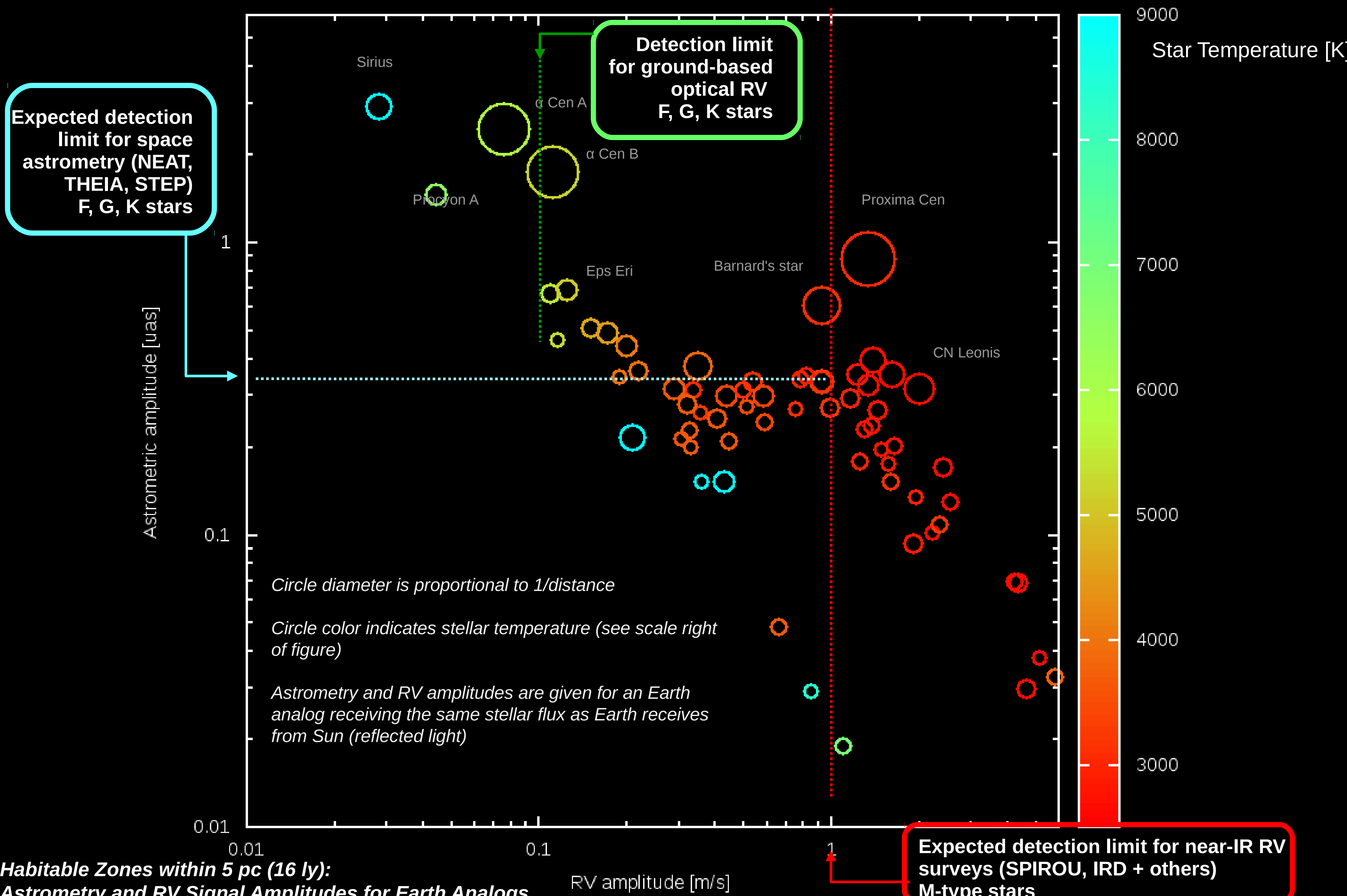
Requires orbit alignment

optimal for finding nearest exoplanets

optimal for characterization

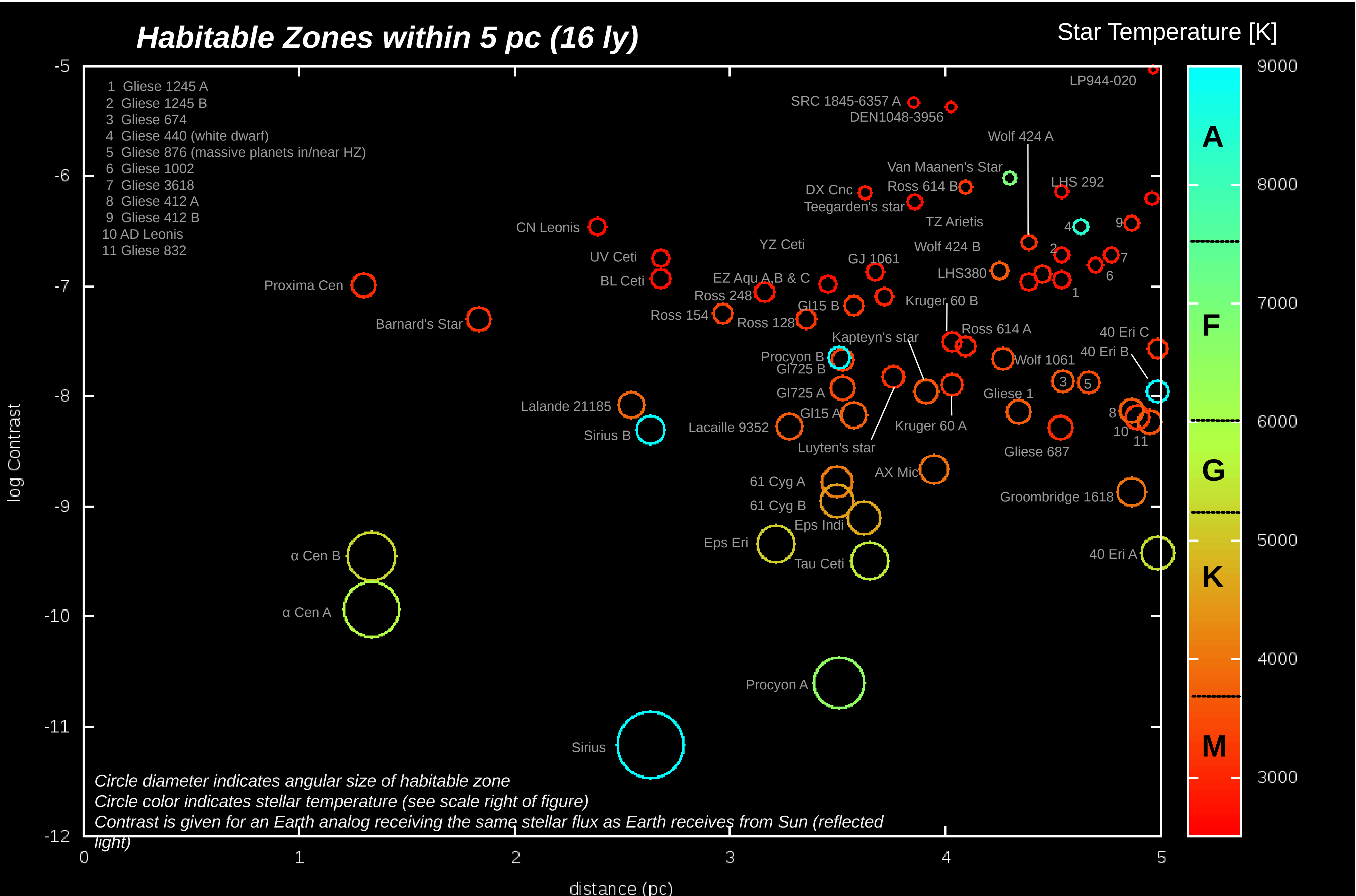


Radial Velocity extending to cool M-type stars



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

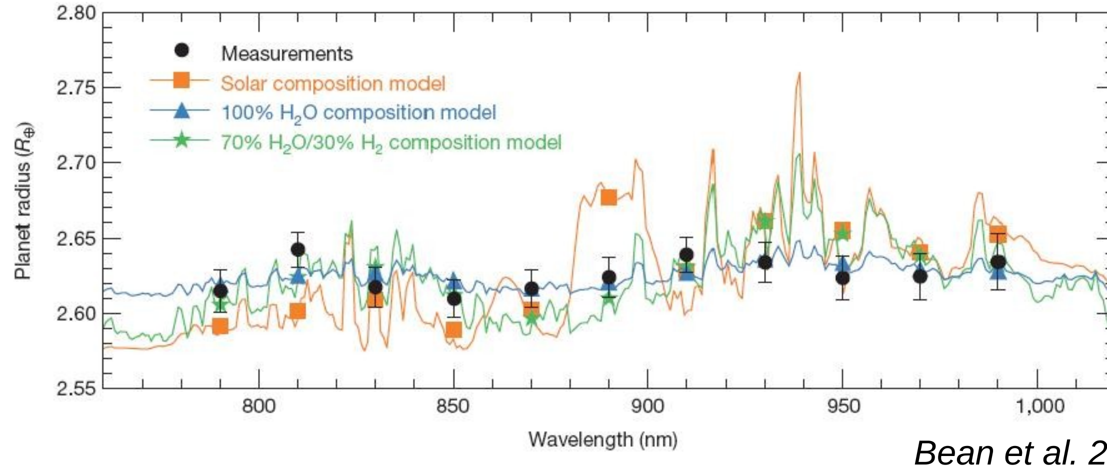
Direct imaging: Contrast challenge



3. Characterizing exoplanets

Transit Spectroscopy

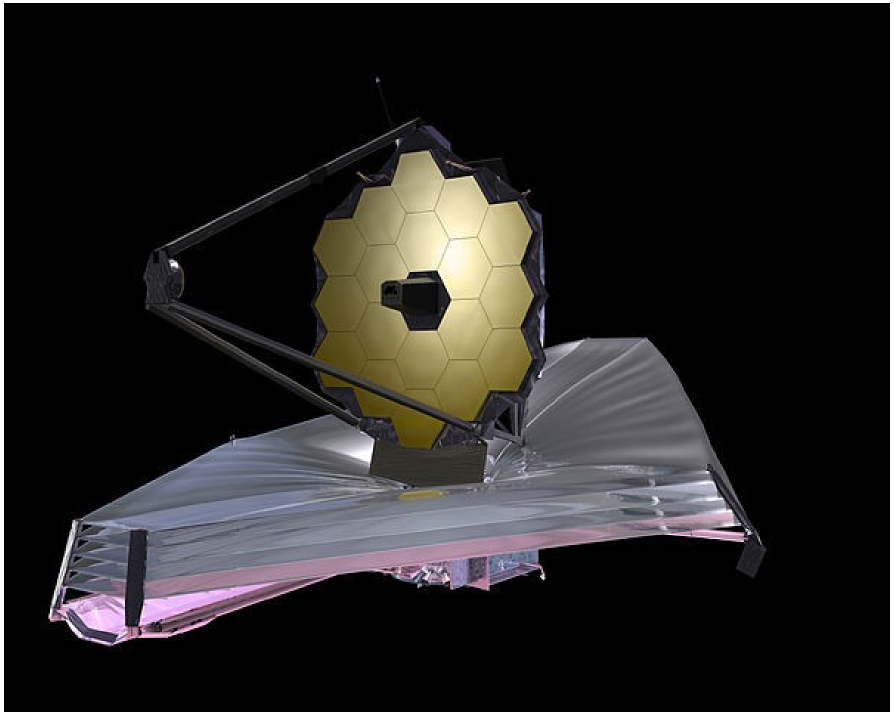
Starlight passing through planet atmosphere during transit reveals atmospheric composition



Bean et al. 2010

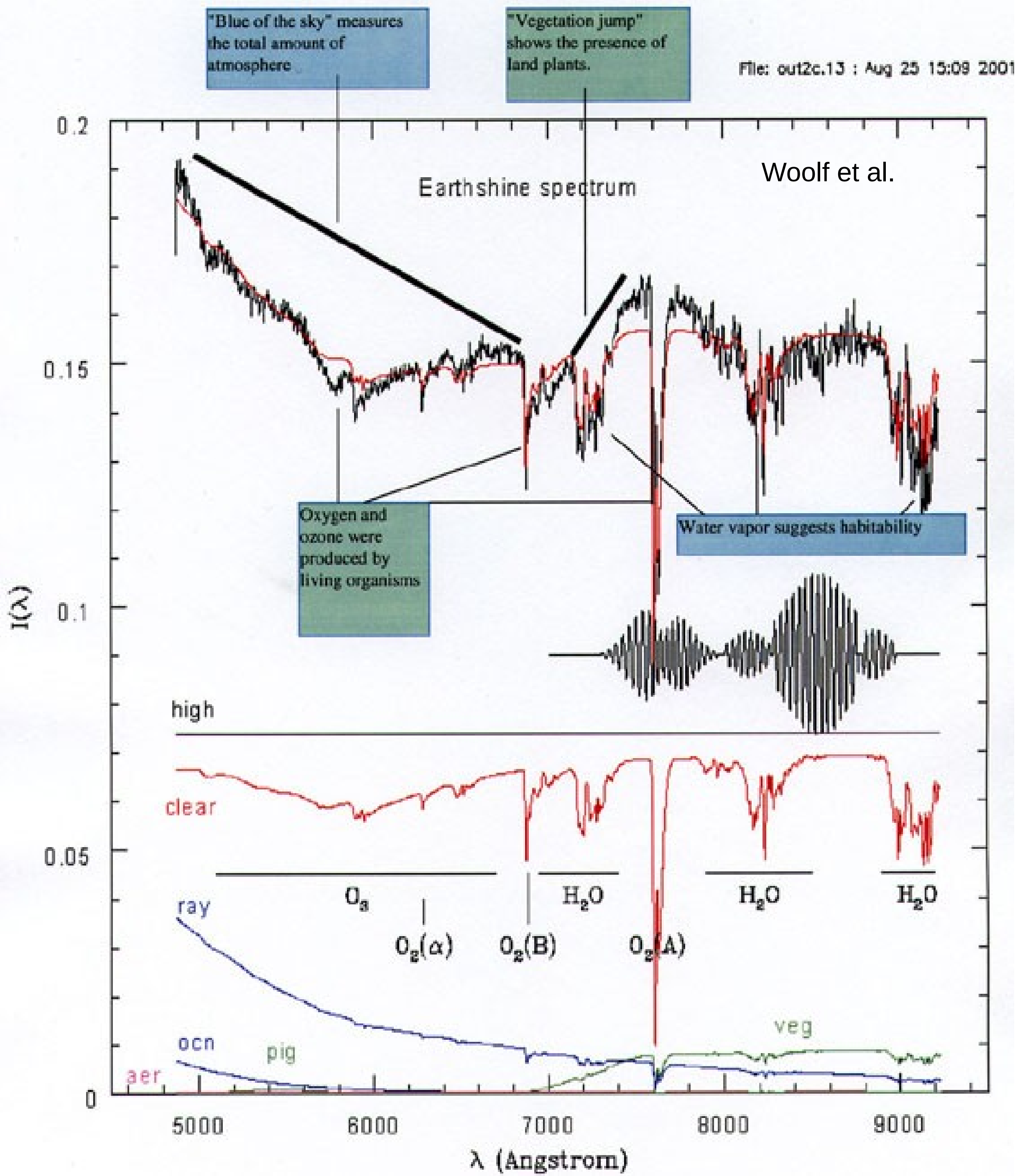
NASA TESS mission finds best transits

JWST transit spectroscopy

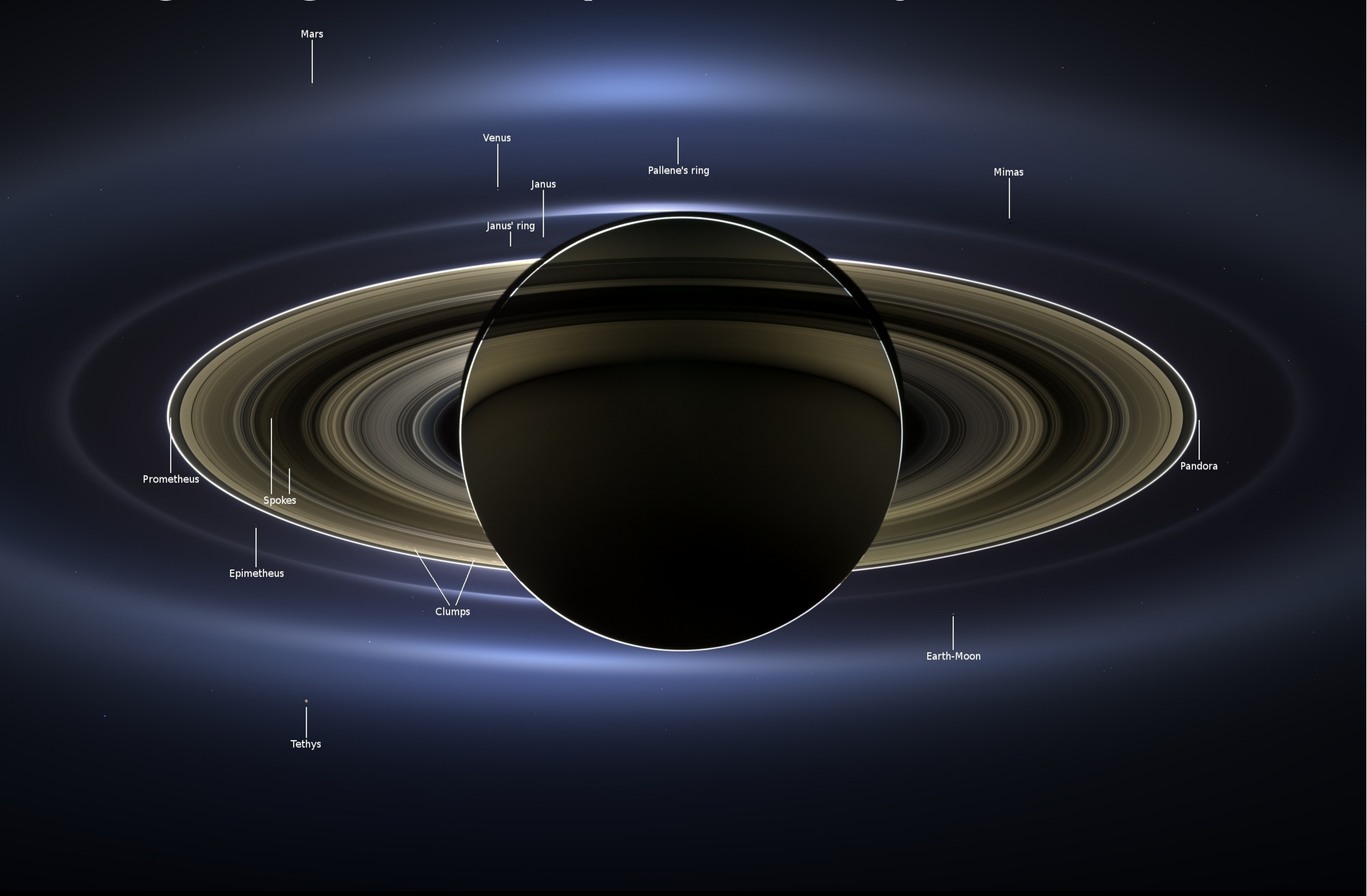


Why directly imaging ?

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

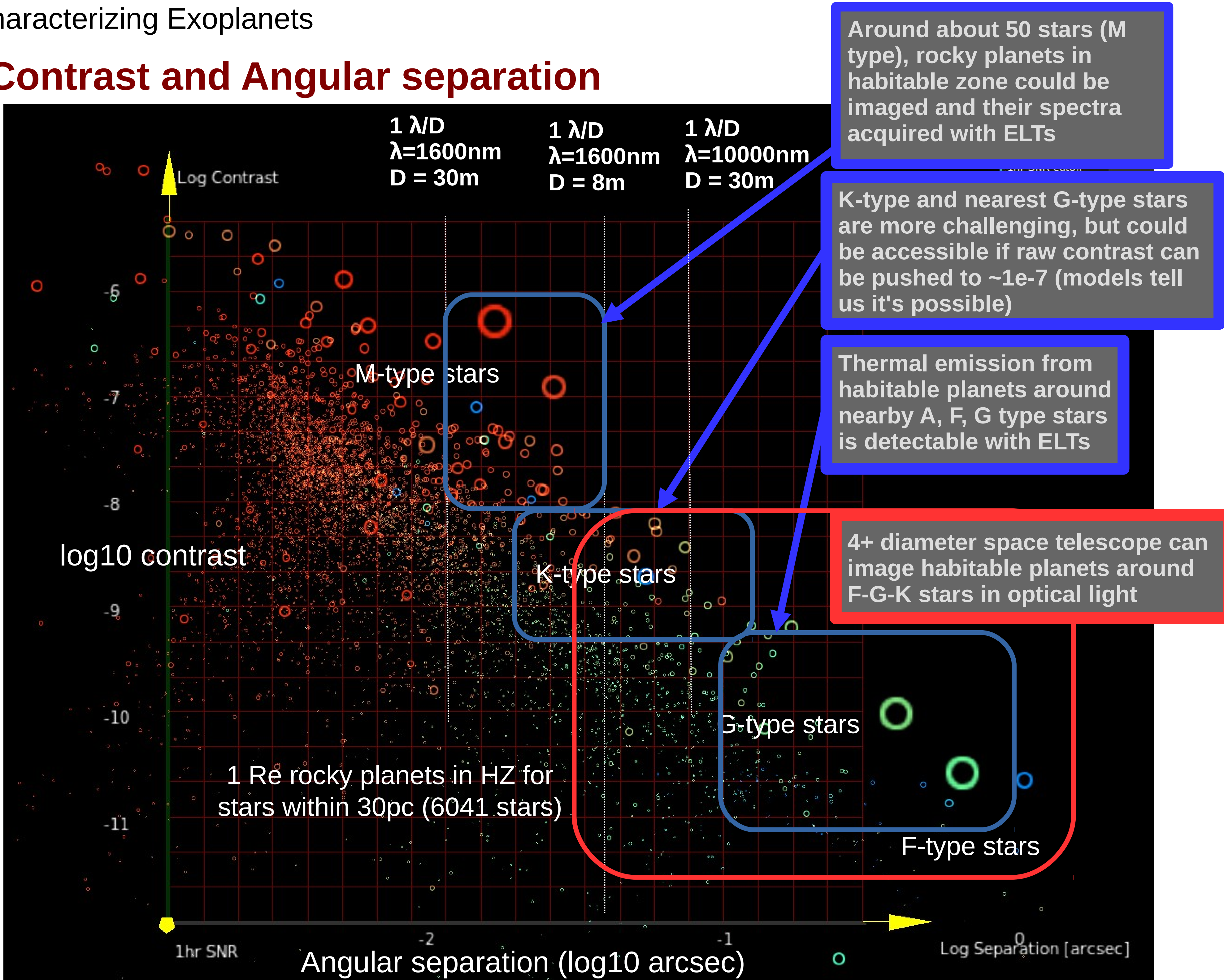


Taking images of exoplanets: Why is it hard ?

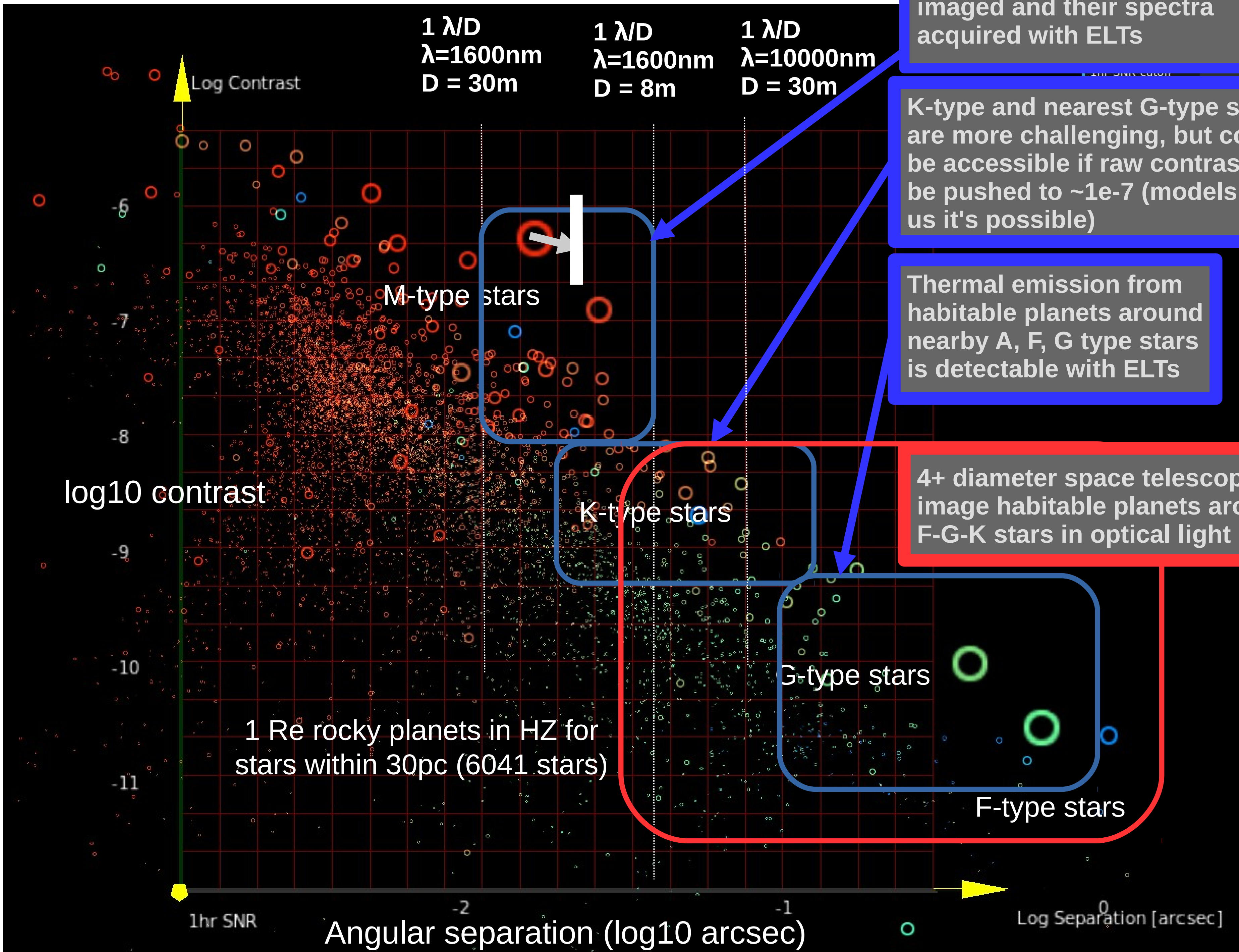



Saturn
Earth

Contrast and Angular separation



Contrast and Angular separation - updated



Around about 50 stars (M type), rocky planets in habitable zone could be imaged and their spectra acquired with ELTs

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

4+ diameter space telescope can image habitable planets around F-G-K stars in optical light

Approximate timeline

Direct imaging + spectroscopy is the more promising technique for exoplanet characterization, but is also very challenging.
Current systems can only detect thermal emission → limited to young giant planets

Near future (2020s):
- TESS + JWST transit spectroscopy
- WFIRST mission will measure reflected light of nearby giant planets at optical wavelengths
- Continuous progress from ground-based systems → will also reach reflected light (already some early results with high resolution spectroscopy)

End 2020s/early 2030s:
- Habitable exoplanets spectroscopy with ELTs in near-IR, mostly around M-type stars
- Thermal imaging with ELTs for hotter stars

2030s+:
- Space mission (HabEx or LUVOIR): visible light spectroscopy (+ some near-IR).
- Further advances with ELTs, reaching deeper contrast, more targets, shorter wavelength

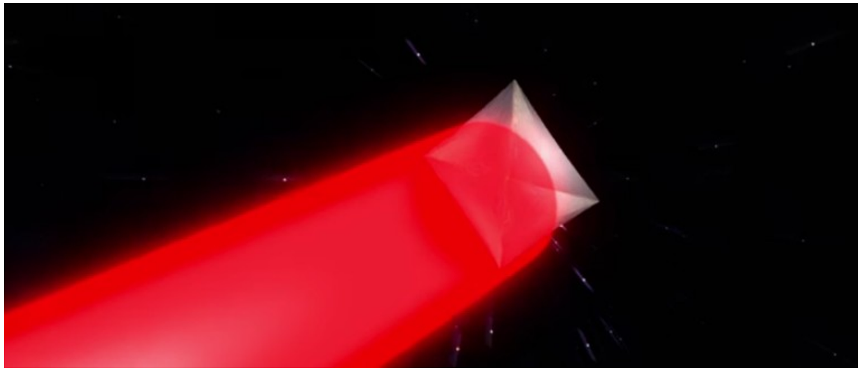
Both tracks are complementary

long term:
- Larger telescopes for better spectroscopy
- possible resolved imaging with interferometer
- fly-by (starshot)

Breakthrough Initiatives

Breakthrough Listen

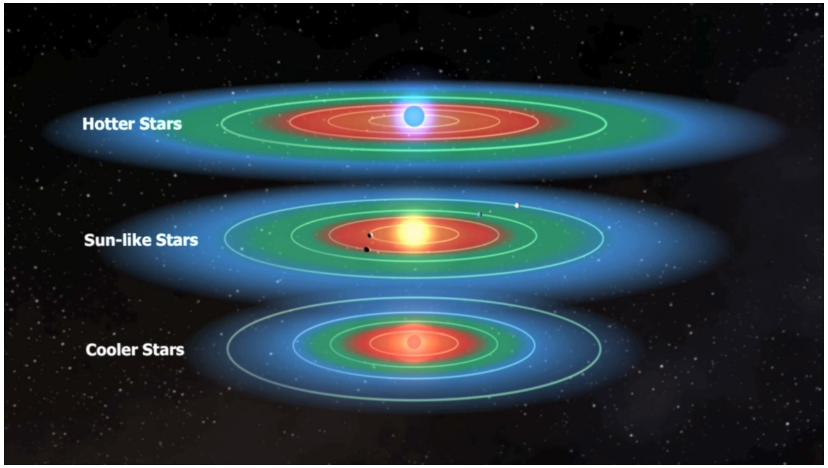
Radio and optical search for artificial signals from other civilizations.
Uses multiple radio telescopes + optical spectroscopy.



Breakthrough Starshot

Send lightweight unmanned starchips to nearby exoplanets (flyby) using laser propulsion.

Multi-GW ground-based laser coherent array focuses on meter-scale sail. Acceleration phase fow a few minutes, travel time ~20yr, flyby time ~1hr.
Images/spectra sent back to Earth by laser comm



Breakthrough Watch

Identify and characterize nearby (<5pc) habitable planets using Earth-based (ground and space) observations.

Breakthrough Watch will find targets for Breakthrough Starshot

BTW Report Top Recommendations

Phase 1 focused on Alpha Cen A & B

- Space-based astrometry (30cm telescope)
- 10 um ground-based imaging (ESO/VLT, Gemini, Magellan)

Phase 2 efforts expands effort to dozens of nearby stars, includes spectroscopic characterization

ELT instrumentation:

- 10 um imaging of Earth-like planets around Sun-like and hotter stars
- Near-IR/Visible imaging of Earth-like planets around nearby M stars (including Prox Cen b)

RV & Astrometry:

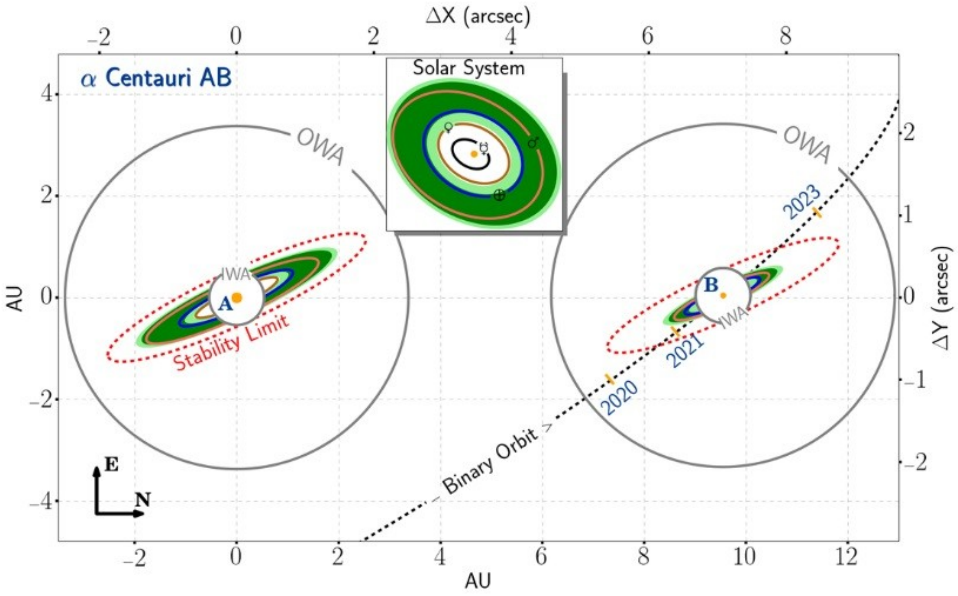
- Possible participation to RV / Astrometry mission(s)

BREAKTHROUGH
INITIATIVES

TOLIMAN Space Astrometry Mission

30cm telescope accurately measures the angular separation between Alpha Cen A and B (~4” apart).

Planet would orbiting one of the two stars will induce a periodic modulation of the angular separation.



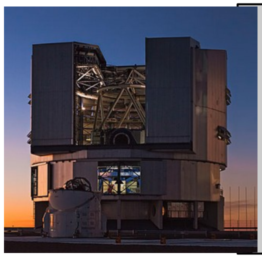
Now starting 6-month study, led by Peter Tuthill (Univ. of Sydney)
Scientific and technical participation from JPL, NASA Ames

Study establishes project technical feasibility, schedule/cost.
Study to engage international partners :
- Italian space agency
- Japan (JAXA) - could provide stable telescope

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.



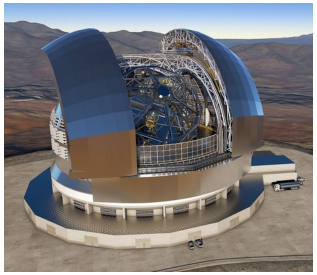
ESO VLT observation campaign

Gemini South observation campaign

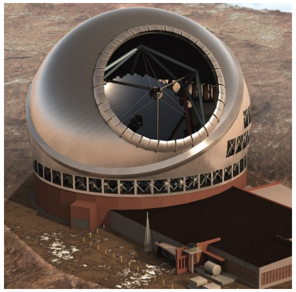
Magellan Telescope Observation campaign

Detector development

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



TMT: Considering MIR instrument
visitor instrument possible

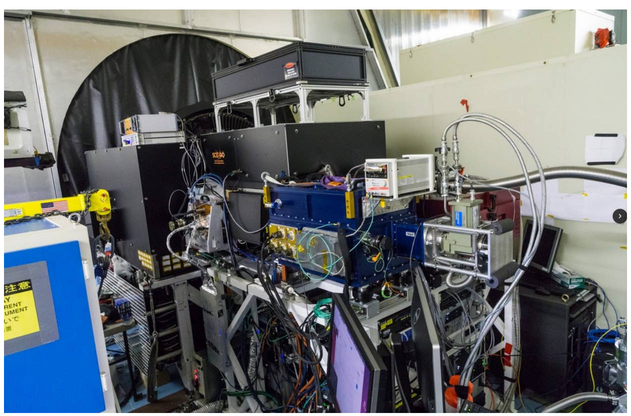


GMT: Considering MIR instrument (TIGER)
visitor instrument possible

5. Subaru Telescope instrumentation, Japan/US partnership → TMT

Subaru Telescope exoplanet instrumentation

IRD spectrograph will survey nearby low-mass stars.
IRD is key part of RV+transit effort (SPIROU, TESS, HPF etc..)
IRD is uniquely competitive for late M type stars (M4-M7, 0.1-0.3 M_{Sun})



SCExAO direct imaging system is leading development platform for high contrast imaging → pushes toward reflected light giant planets on Subaru, and key to imaging exoplanets with ELTs.
There is already a strong US involvement in SCExAO :

- Princeton (CHARIS)
- UCSB (MKIDs)
- UH (SAPHIRA)

Subaru exoplanet instrumentation is planning transition from Subaru to TMT with US partners:
Evolve SCExAO to a TMT high contrast imaging instrument
Validate exoplanet high spectral resolution with IRD to prepare for diffraction-limited spectrograph on TMT

Infrared Doppler (IRD) for the Subaru telescope

What is IRD?

- High-resolution, NIR spectrometer for the Subaru for planet detection by radial velocity method
- Instrument is ready!

Goal of IRD

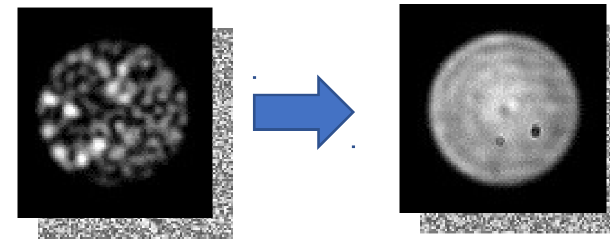
- Detection of ~ 50 planets around nearby M dwarfs, including ~10 Earth-like planets in their habitable zone
- Characterization of planet atmospheres

Uniqueness of IRD

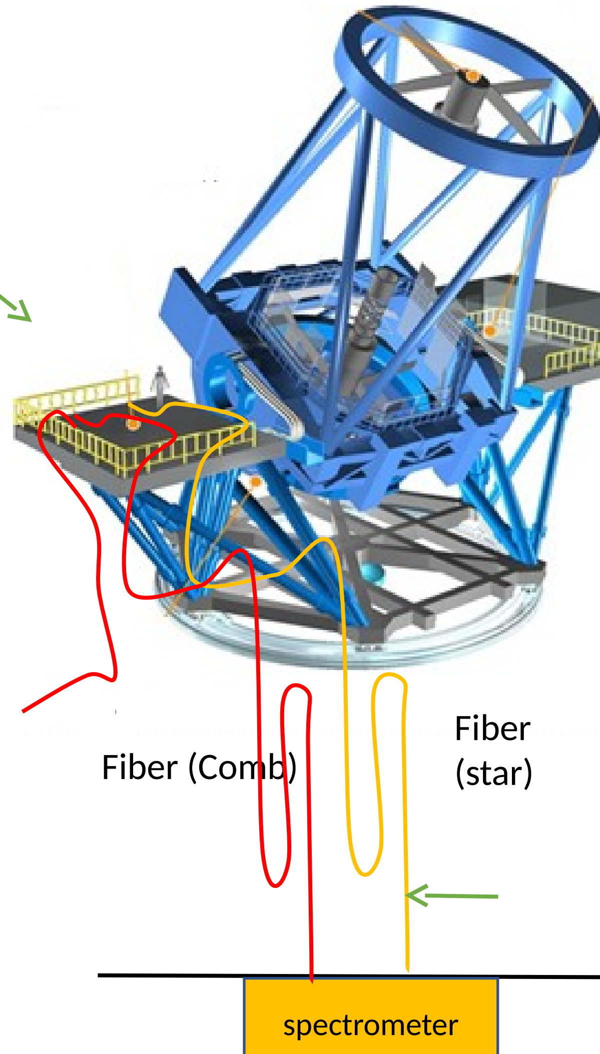
- One Earth-mass planet in HZ around a low-mass M dwarf (late-type M dwarf) can be detected
  - Late M dwarfs are too faint to observe with optical/3-meter class IR Doppler
  - Wide spectral coverage (J,H,K) Sp+Comb

Overview of the IRD instrument

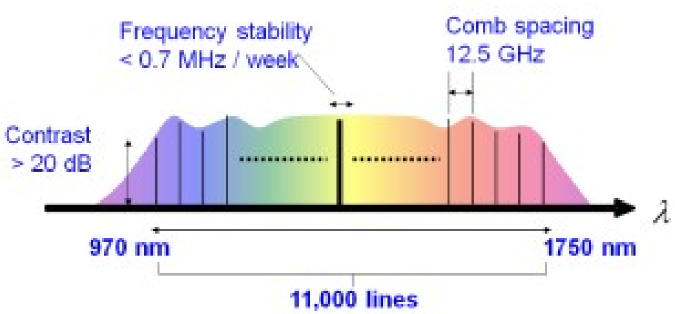
Fiber injection system
AO bench



Mode scrambler



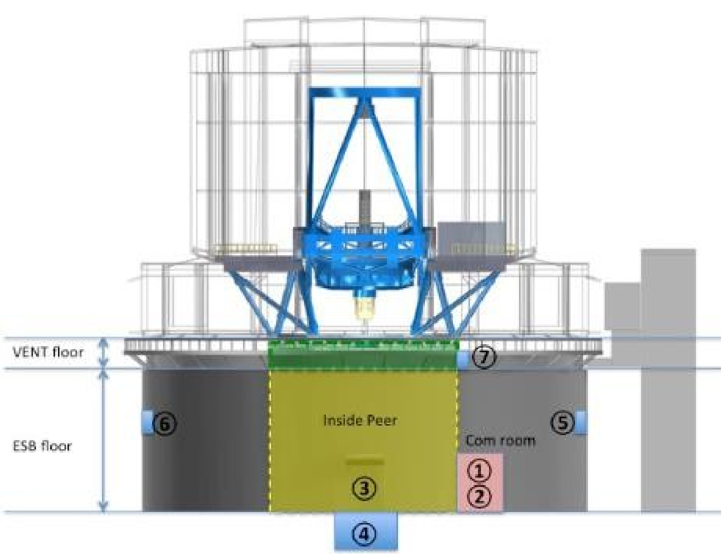
Spectrometer system
(Coudé room)



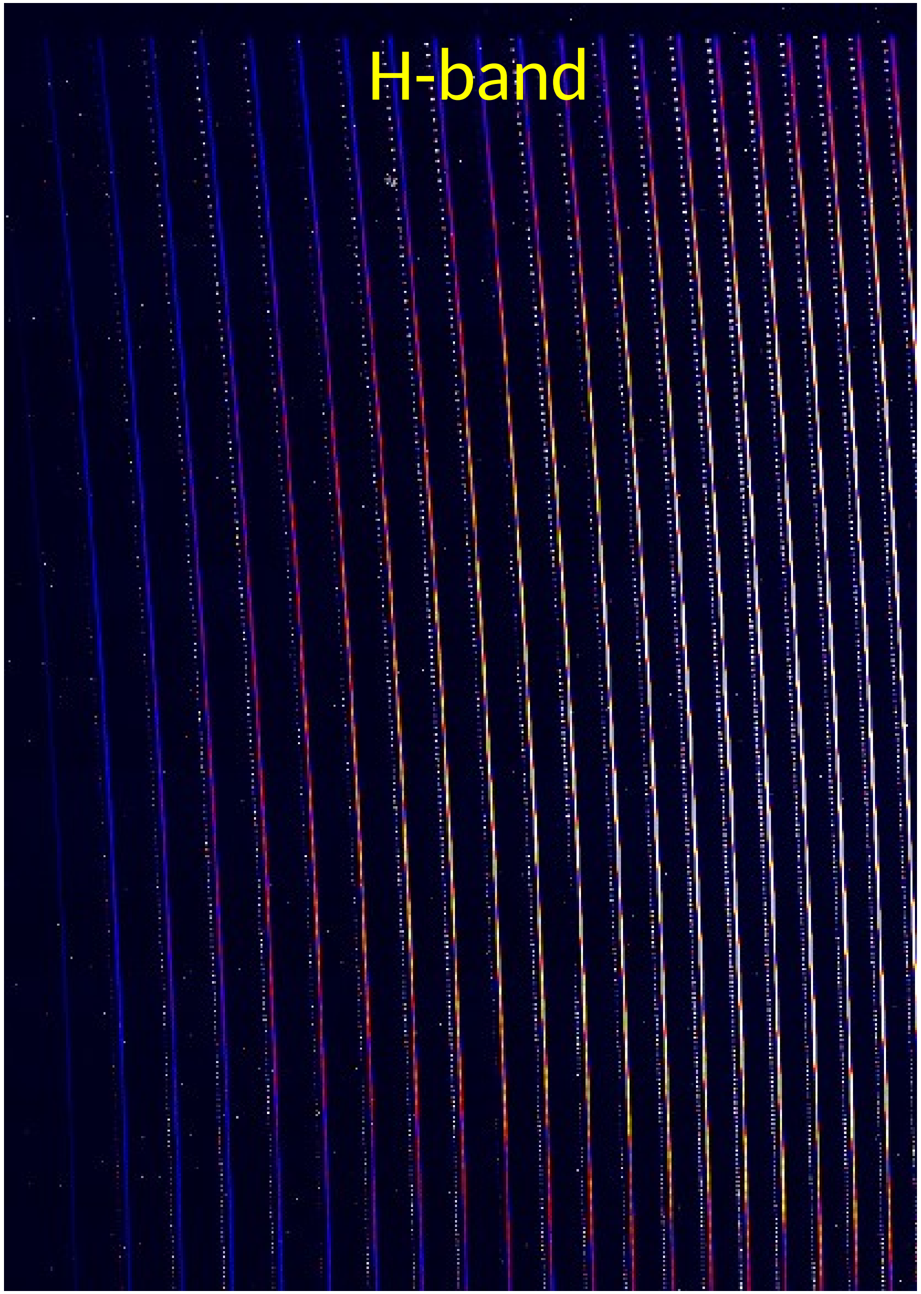
Laser frequency comb
ESB floor

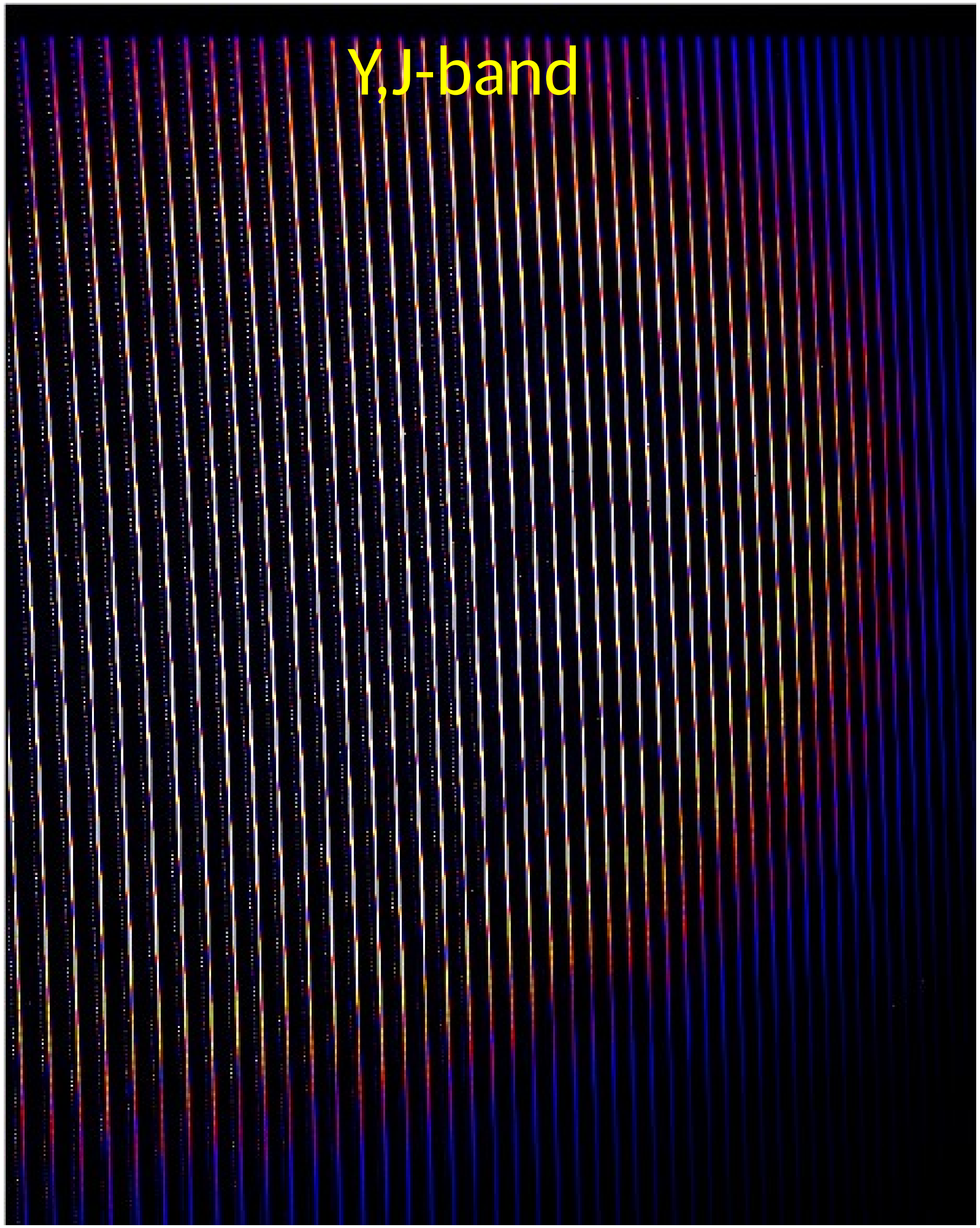
IRD Instrument specification

Spectral coverage	0.97-1.75 μm
Spectral resolution	70,000 @ 1480nm（3-pixel sampling）
Fiber	star + comb, a multi-mode or single-mode fiber
Grating	Echelle & VPH-Grating (order sorting)
RV precision	1 m/s w/ laser frequency comb
Detector	2 x HAWAII 2RG (2x 2048 x 2048 HgCdTe) arrays
Cryogenic system	Detector: 60K, Optics: 200K, 2 Pulse-tube coolers

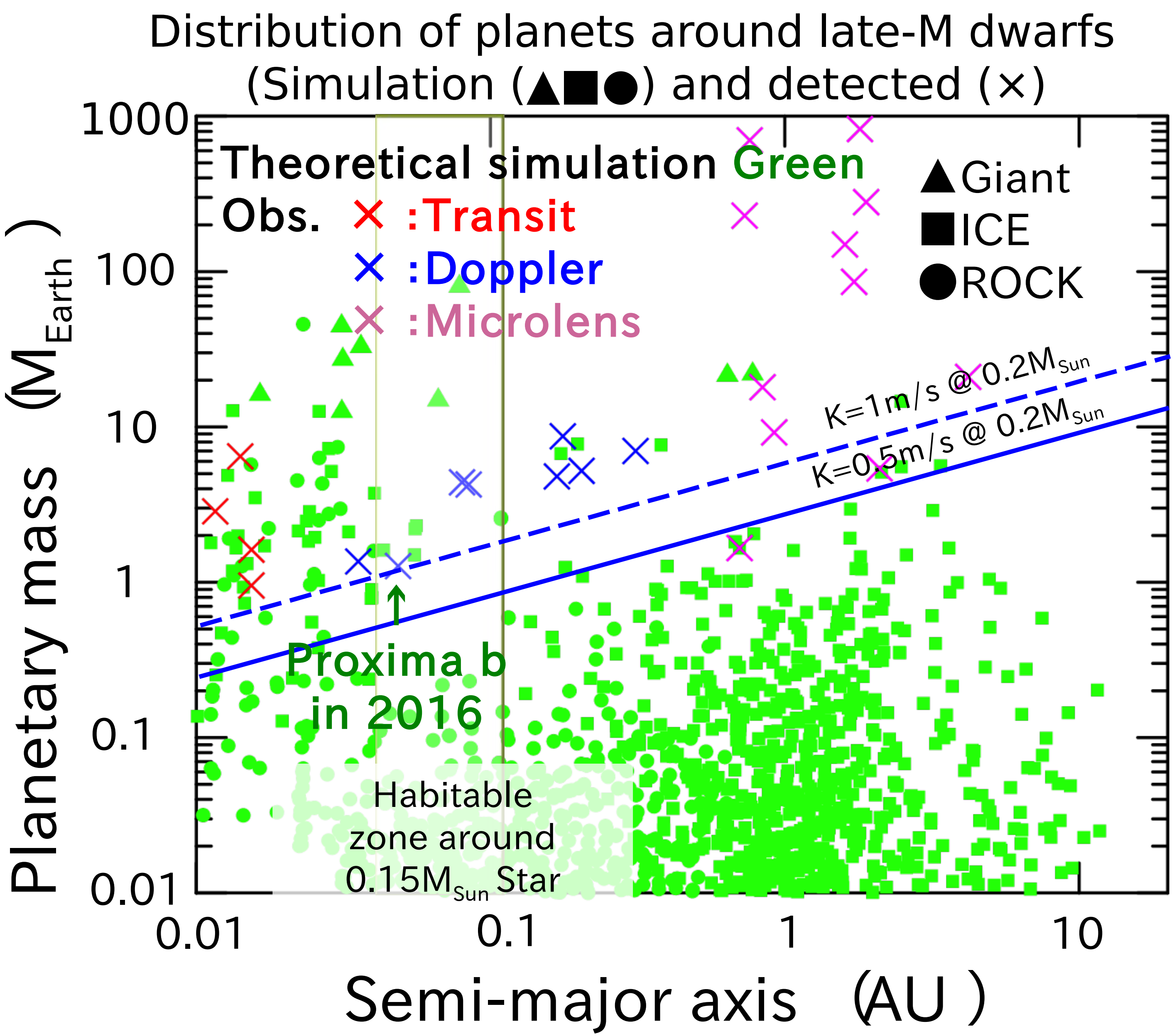


Real Stellar & Comb Spectra at YJH-bands





IRD survey: simulation results



Plan for IRD Survey

N of Night : 170 (SSP)

Targets : 100 stars (Late-M, M4-M8) (0.1-0.3M_{Sun})

N of obs. : 50~80

Precision : ~1m/s

Model : Standard (Pop. synthesis)

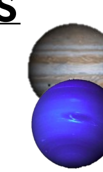
Expected number of detectable planets

Jupiter-mas: 4

Neptune : 7

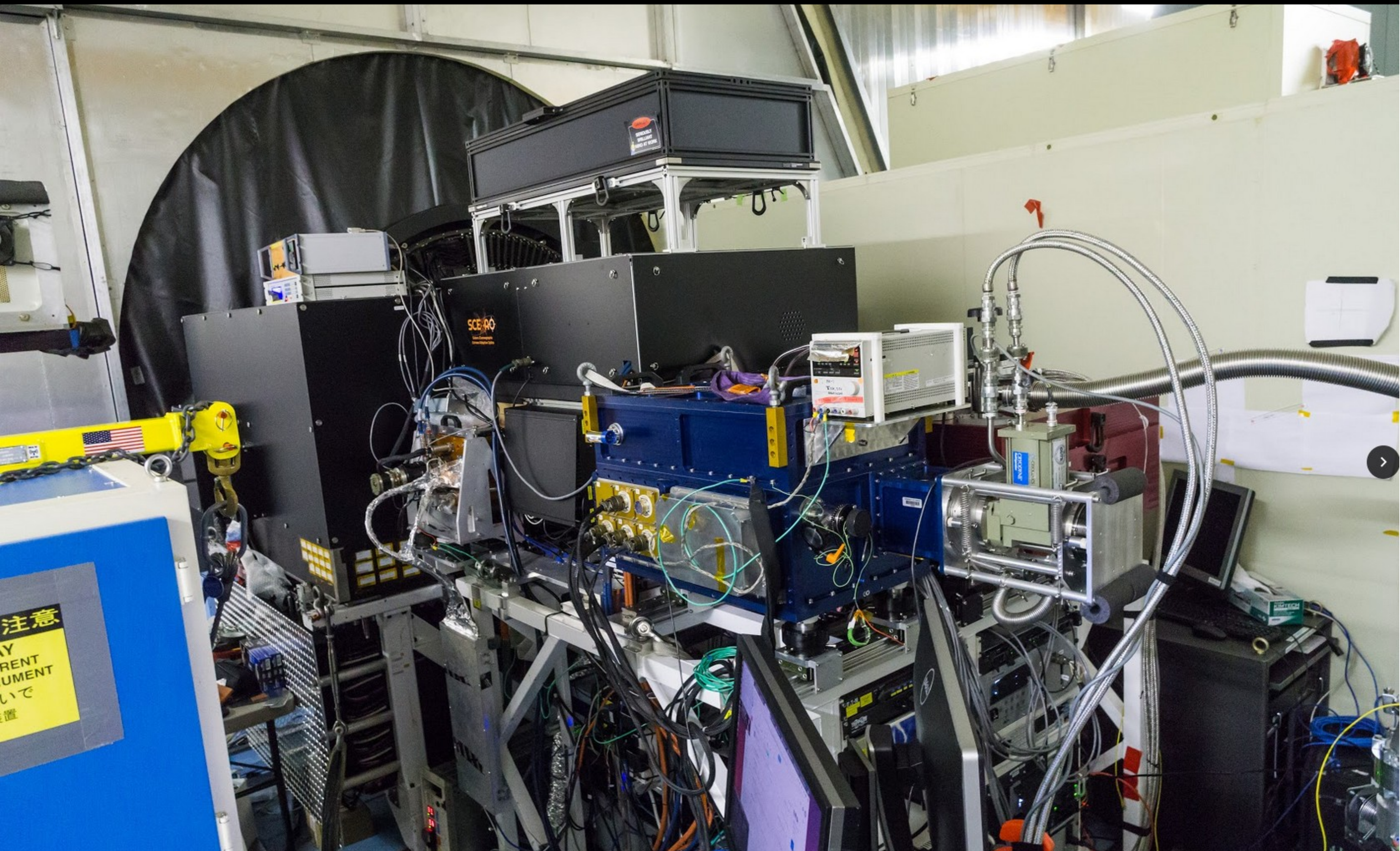
Super Earth: 13

Earth-mass: 28

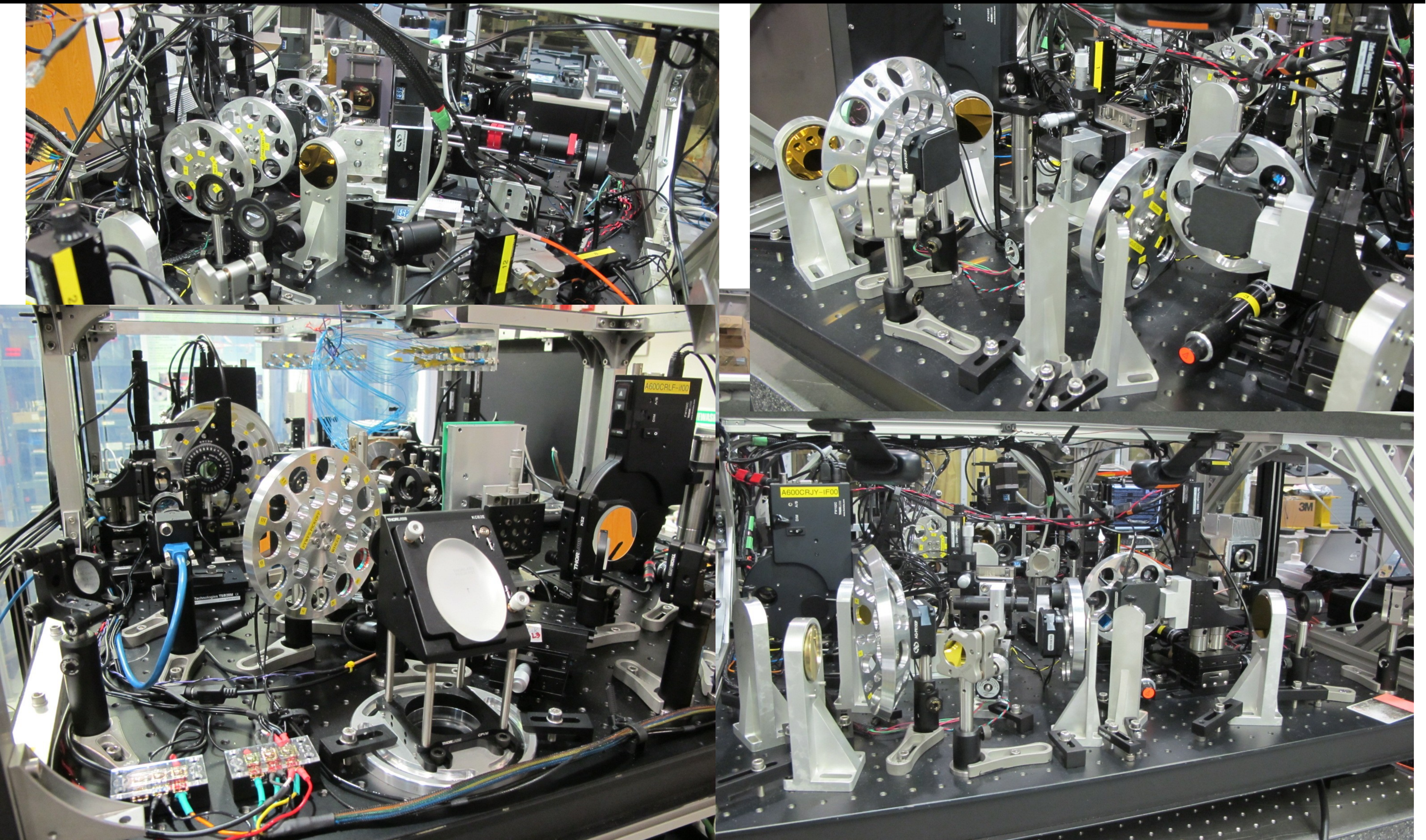


SCExAO

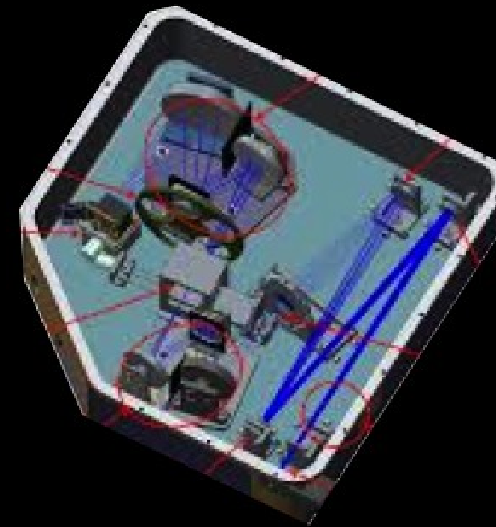
Subaru Coronagraphic Extreme Adaptive Optics

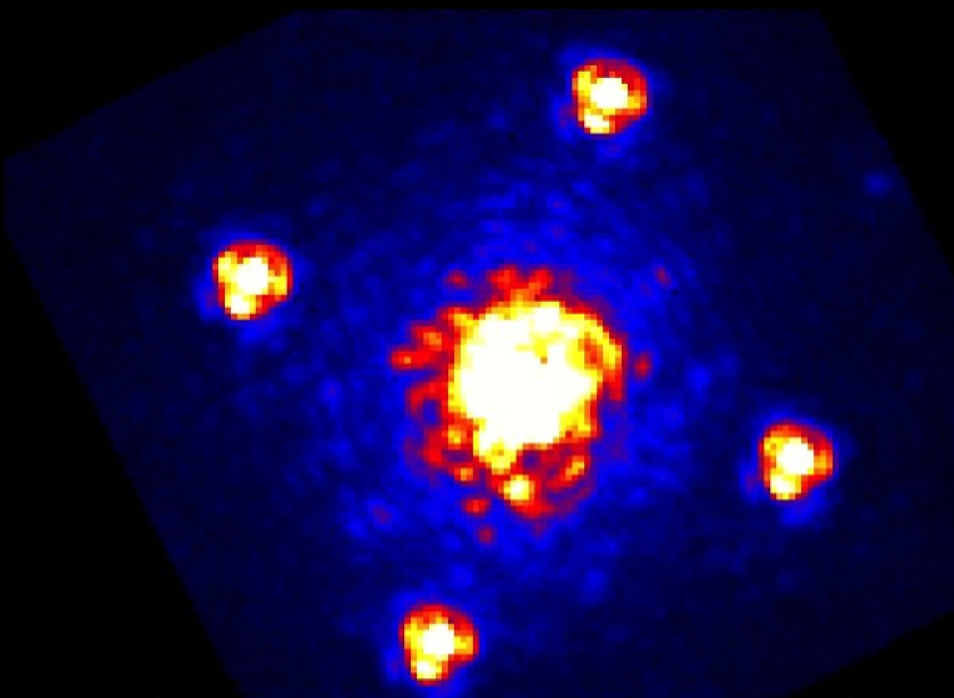


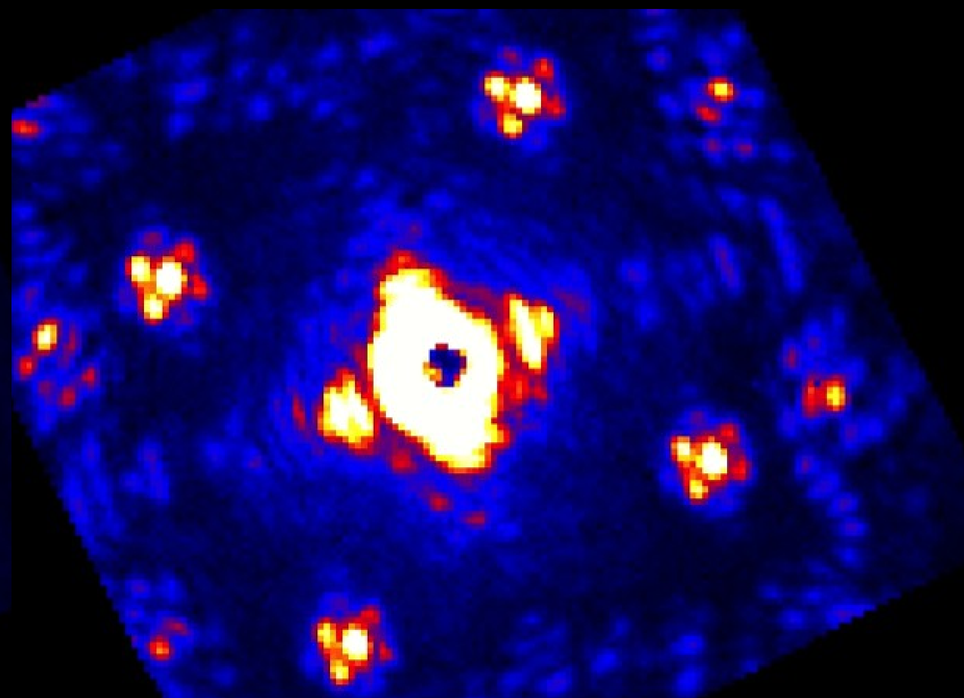
SCExAO Subaru Coronagraphic Extreme Adaptive Optics



CHARIS spectrograph, built by Princeton University under JSPS grant



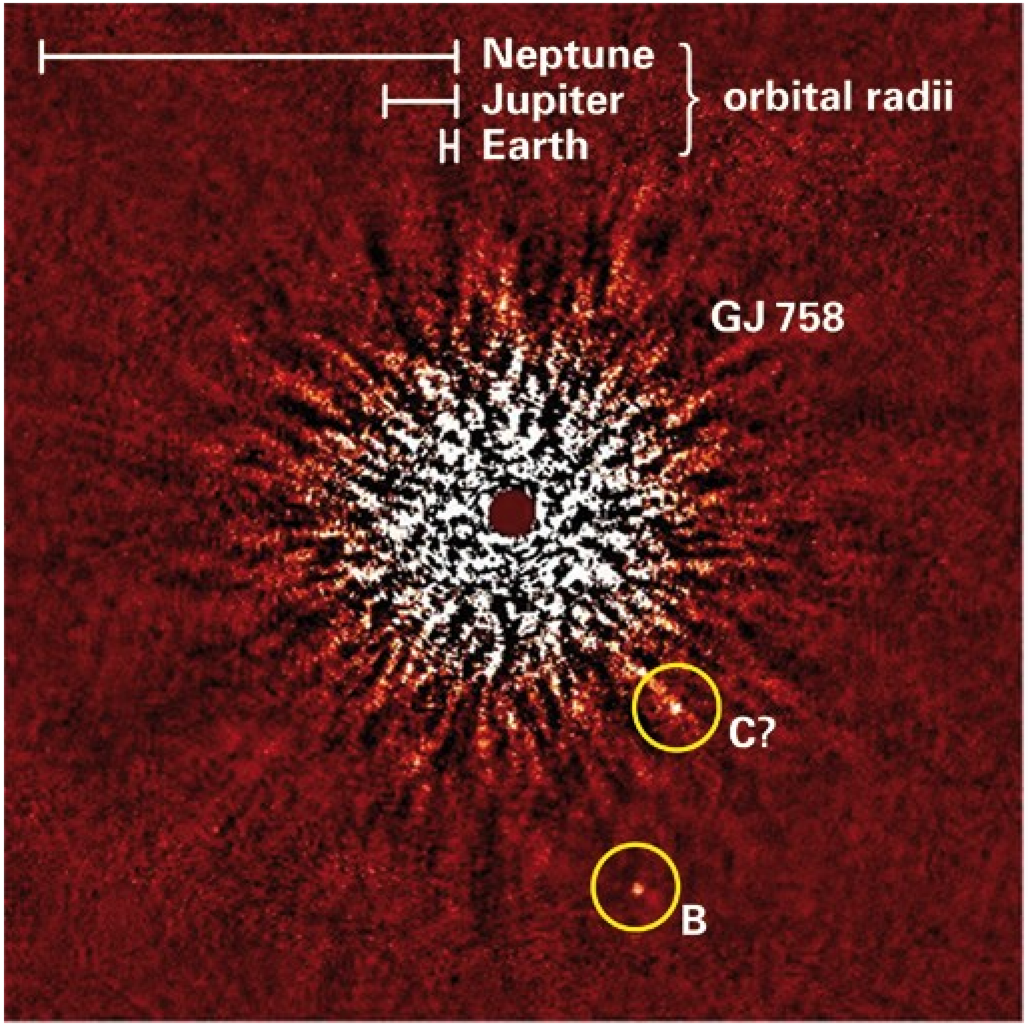




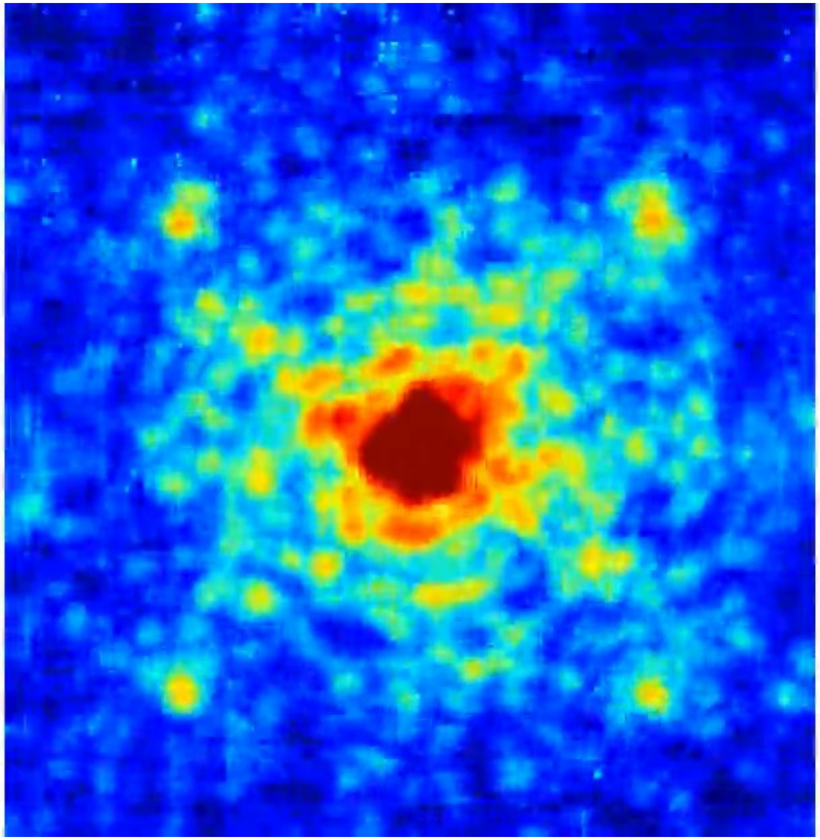
Lyot Coronagraph

Shaped Pupil Coronagraph

The REAL challenge: Wavefront error (speckles)

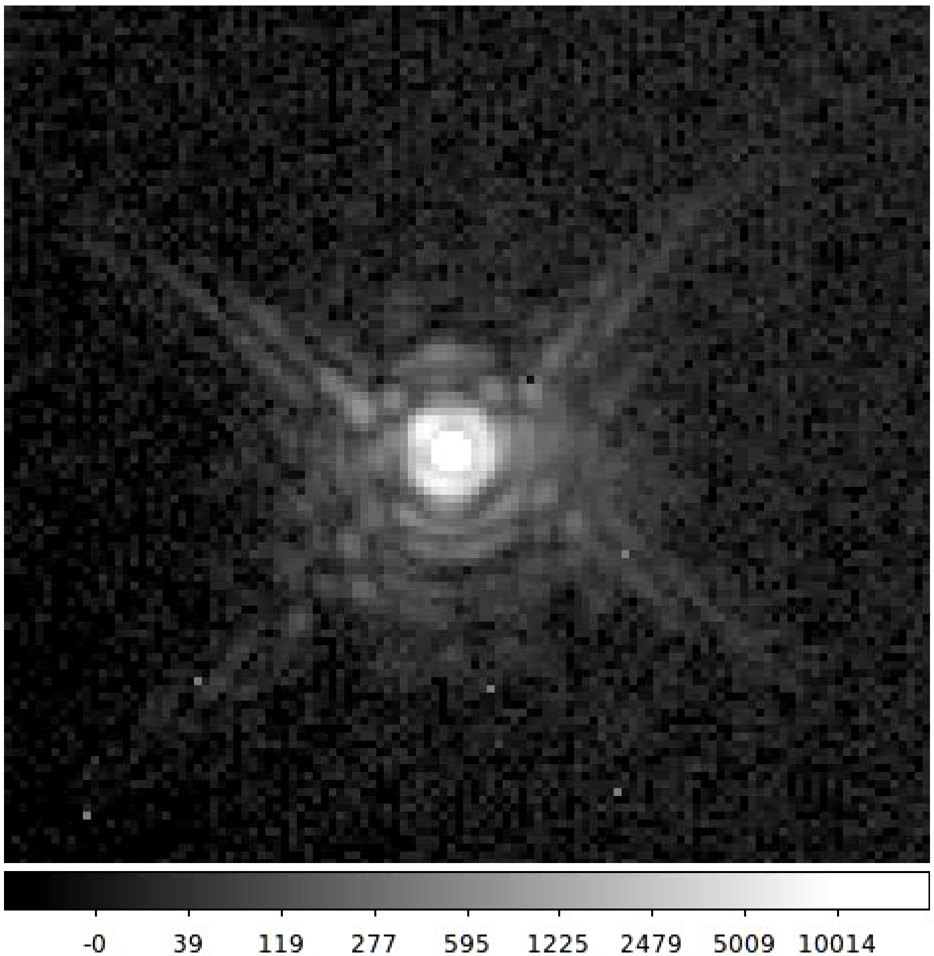


H-band fast frame imaging (1.6 kHz)



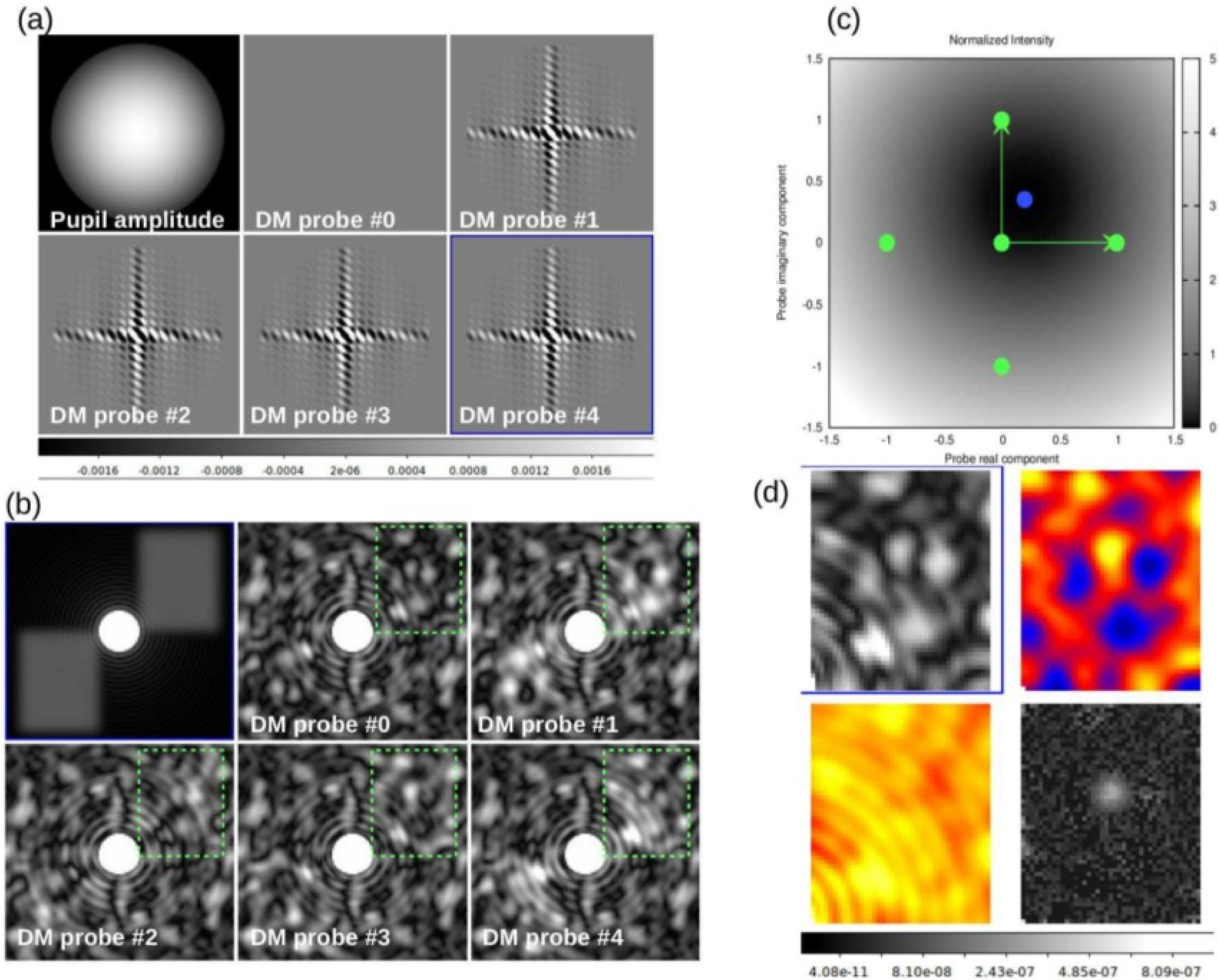
Current PSF stability @ SCExAO

Highly stable PSF for coronagraphy
SCExAO provides sensing and correction at 3.5 kHz
14,400 pixel WFS → 2000 actuators



1630nm (SCExAO internal camera)
3 Hz sampling

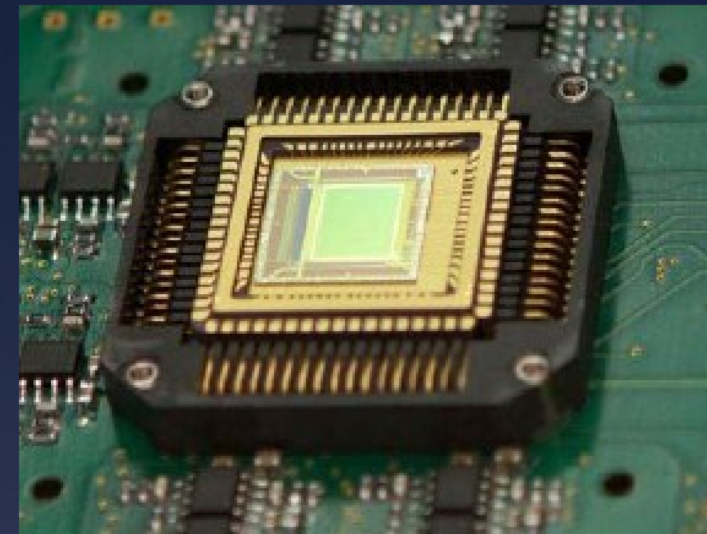
Coherent Speckle Differential Imaging

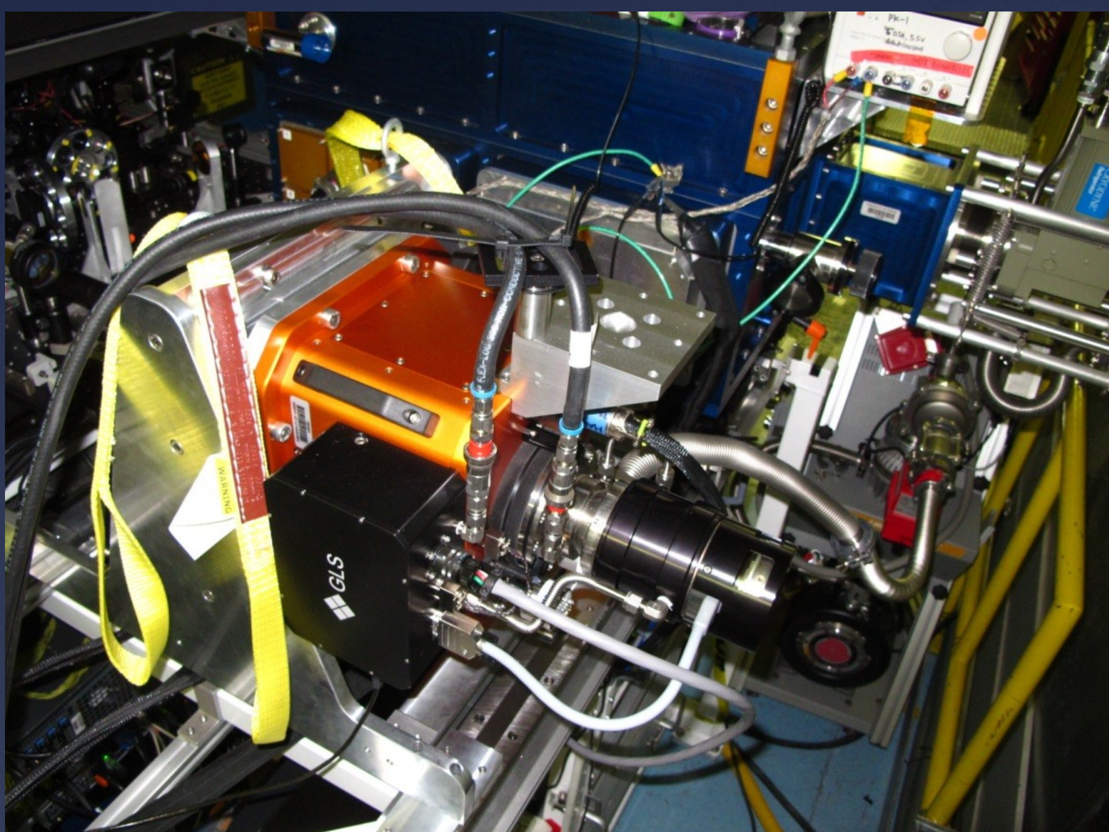


SAPHIRA Infrared APD array (U. of Hawaii)

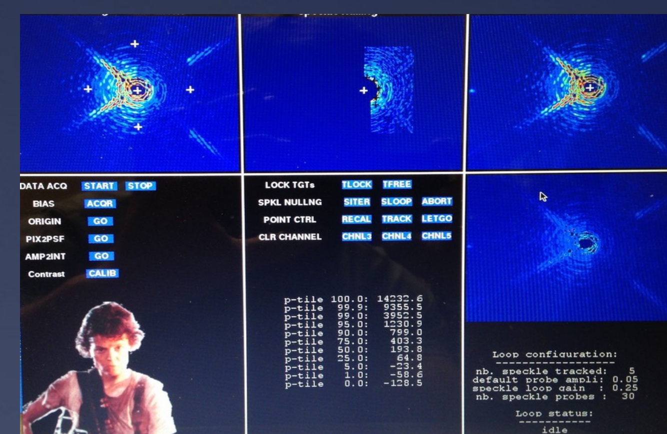
HgCdTe avalanche photodiode
manufactured by Selex

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





50 frame average



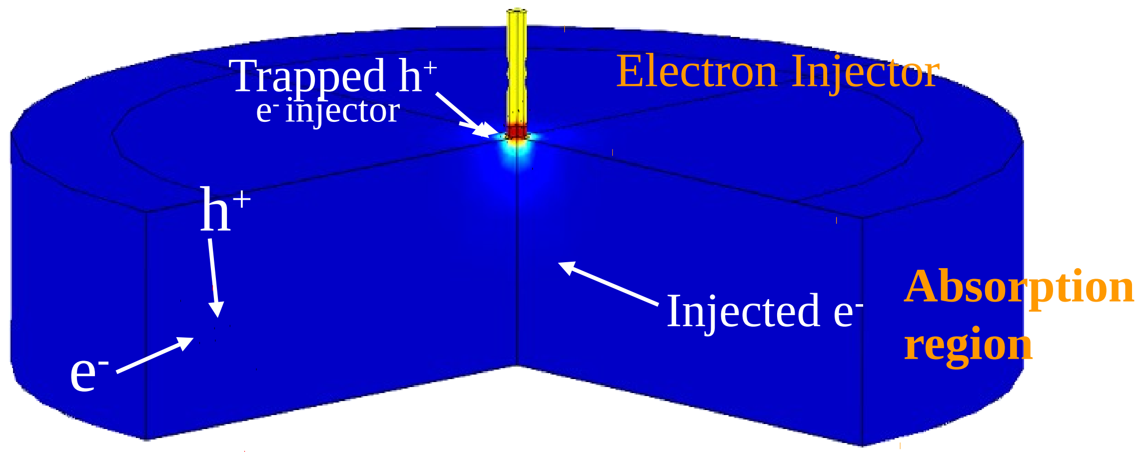
Electron-injector nearIR camera (Northwestern Univ / Keck foundation)

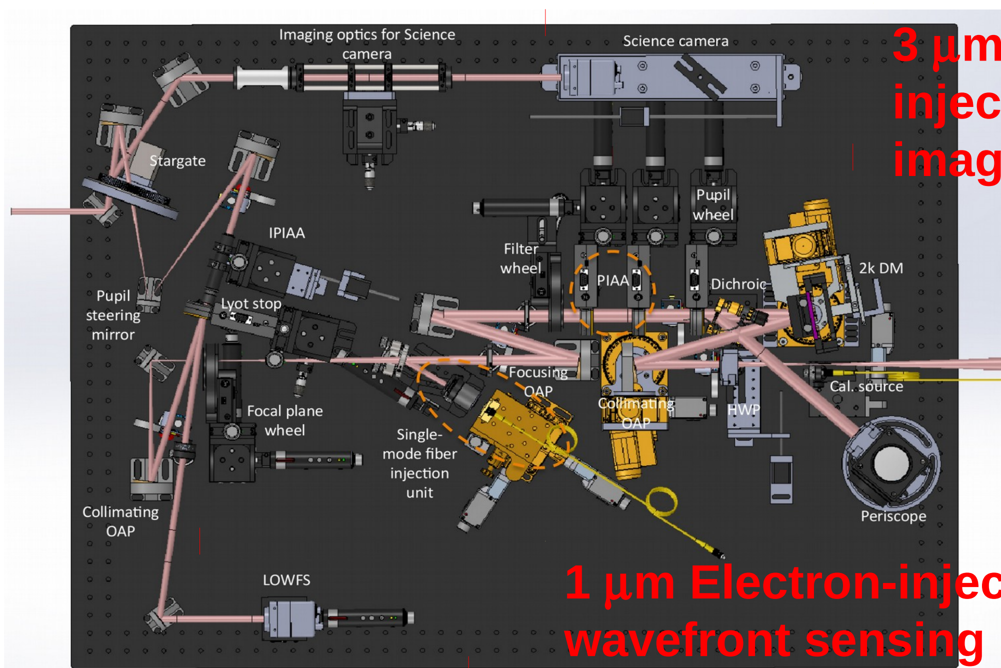
NORTHWESTERN UNIVERSITY

W.M. KECK FOUNDATION

SUBARU TELESCOPE

National Astronomical Observatory of Japan



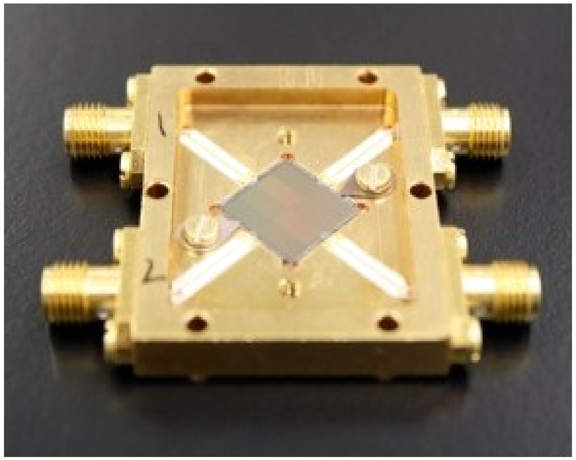


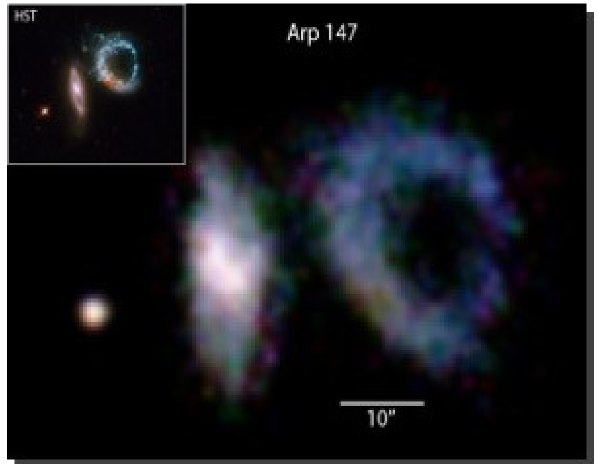
3 µm Electron-injection speckle imaging camera

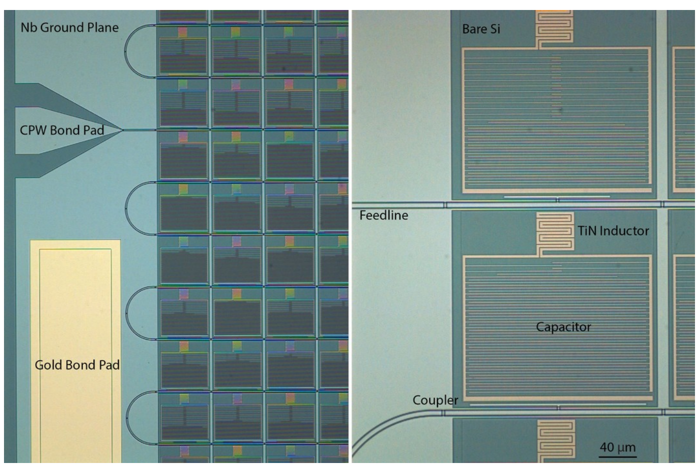
1 µm Electron-injection low-order wavefront sensing (pointing) camera

MKIDS camera (built by UCSB for SCExAO)

Photon-counting, wavelength resolving 140x140 pixel camera







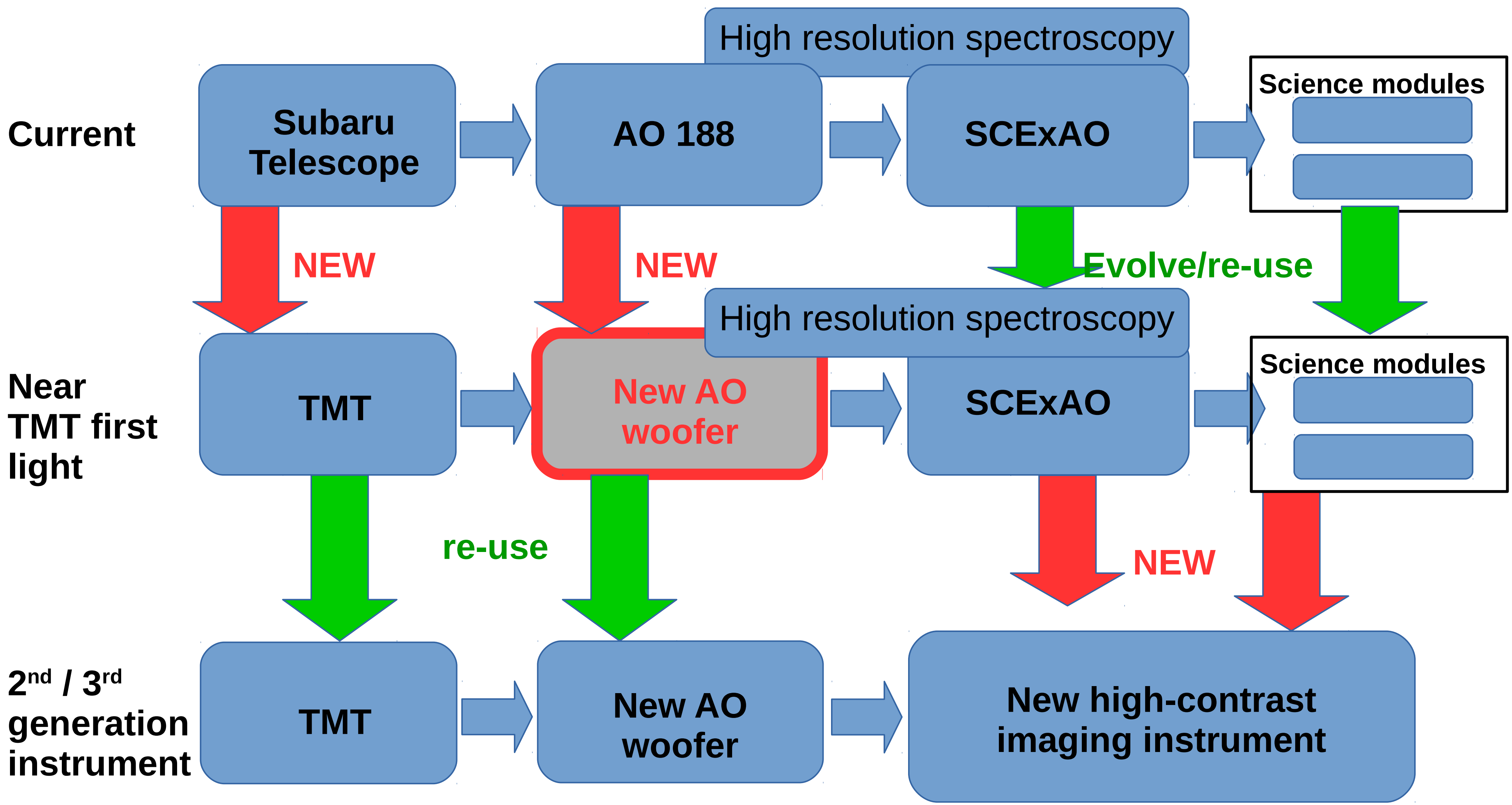
Pixels are microwave resonators at ~100mK
photon hits → resonator frequency changes

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

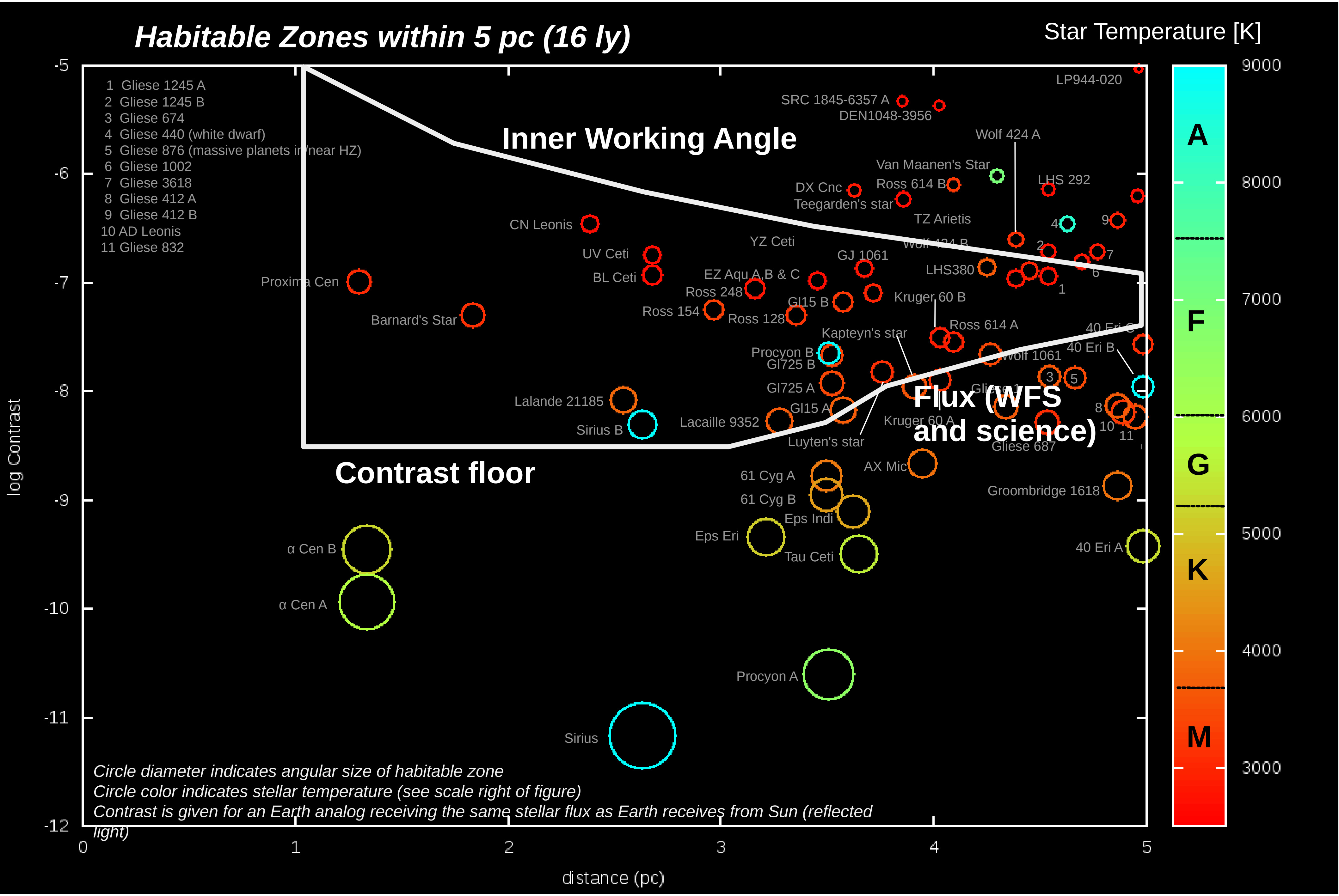
Delivery to SCExAO in CY2017

Notional plan toward TMT instrument

Path to TMT requires new AO woofer (~120x120 DM elements) to be built.
Likely US/Japan/Canada joint effort



5. Subaru Telescope instrumentation, Japan/US partnership → TMT



3 Key Recommendations & Goals for next 10yr

<u>Japan and US should grow collaboration to prepare TMT exoplanet imaging instrument</u>

ELT instrumentation will be first opportunity for habitable exoplanet spectroscopy of nearest exoplanets.
Japan and US are both major partners in the Thirty Meter Telescope.

- Subaru Telescope (SCExAO + modules, IRD) provides platform for TMT instrument development and R&D
- Japanese Astrobiology Center (ABC) can be a Japanese partner for designing and R&D phase
- Large instrument development funding will require international effort

Some institutional obstacles can be eased: Open telescope access for TMT partnership R&D ? Coordinated international proposals to agencies (NSF PIRE, etc)

Coordination / collaboration opportunities across ELTs (GMT, European ELT):

- Joint R&D
- Possible exoplanet imaging NSF center with access to Subaru Telescope for development ?
- Private/Public partnership (Breakthrough initiatives)

<u>Stronger science and technical coordination between Space and Ground needed</u>

Space and ground capabilities are highly complementary (wavelength coverage, targets) → coordinated observation program should be implemented: what is the mechanism for this ?

Examples: WFIRST/Subaru, ELTs/LUVOIR/HabEx survey

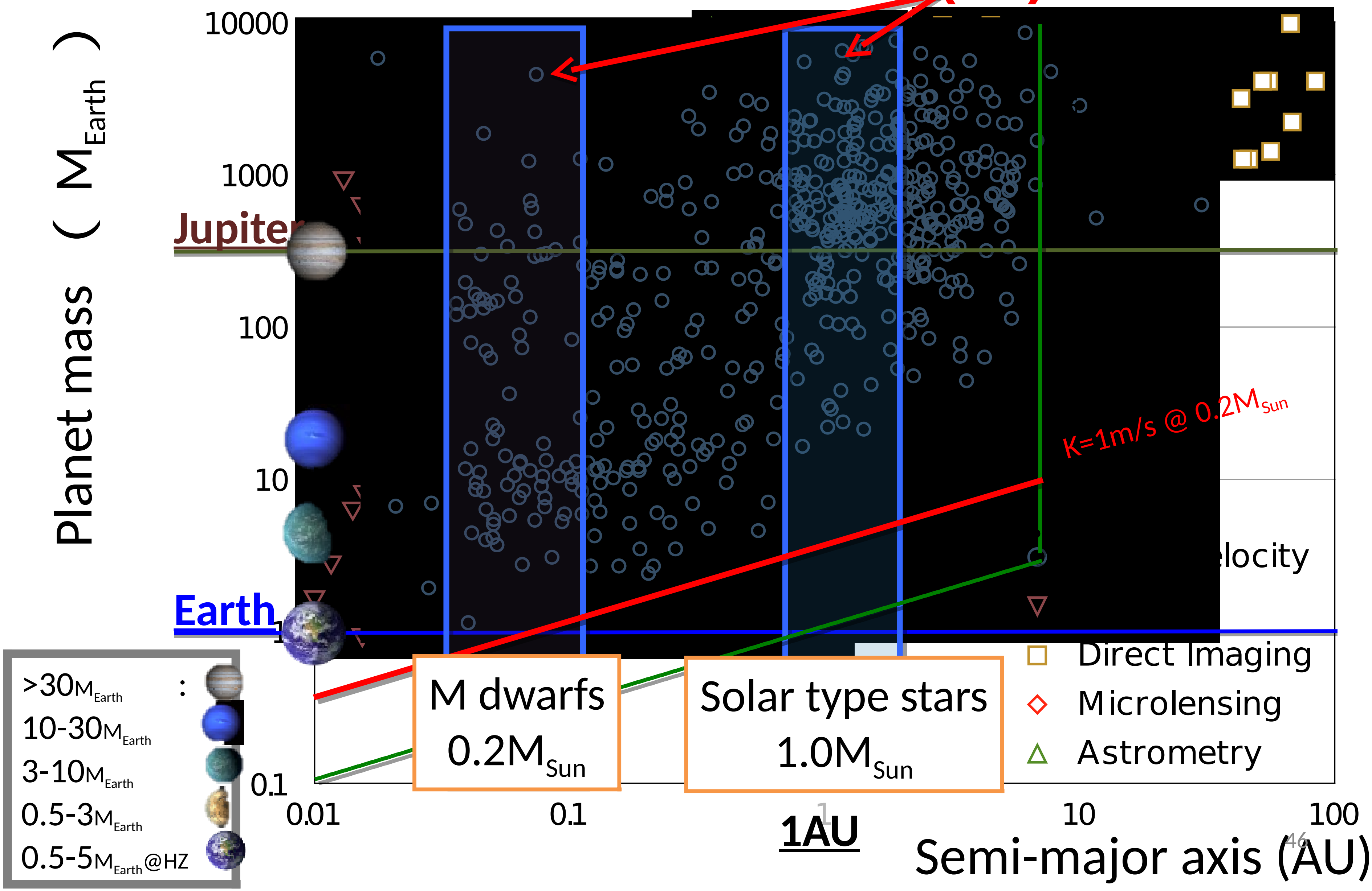
Common R&D challenges: NASA investment in ground-based validation of technologies pay off (detectors, coronagraphs, wavefront control)

<u>Stronger link between observation and theory needed</u>

Planetary atmosphere retrieval, evolution models
Encourage joint US/Japan science team membership to exoplanet projects, space and ground

Backup slides

Understanding of Earth-like planets in their habitable zone (HZ)



Current status of the spectrograph

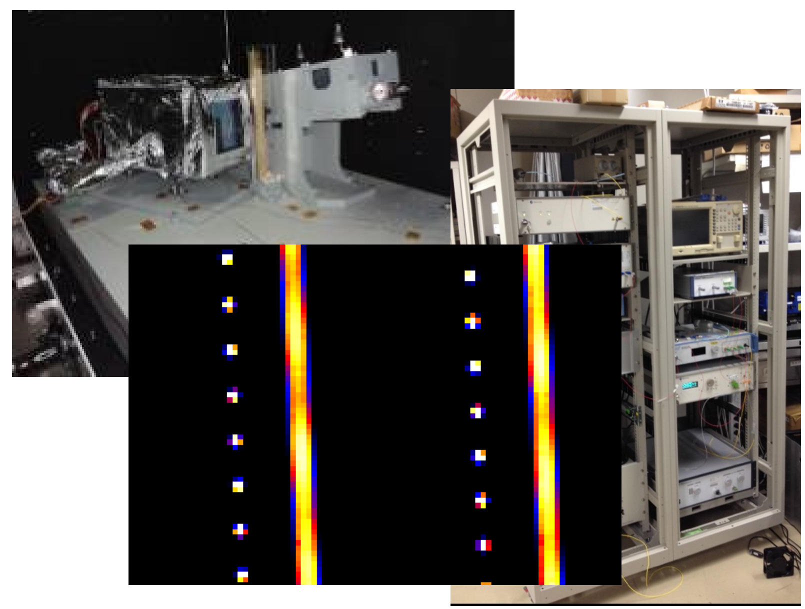
Optical performance ：OK
Spectral resolution 70,000max, 0.97-1.75mm
No stray light, ghost

Cryogenic system ：OK
Optical bench temperature 180K, detector 80K
Temperature stability: ±6.5mK/2Weeks

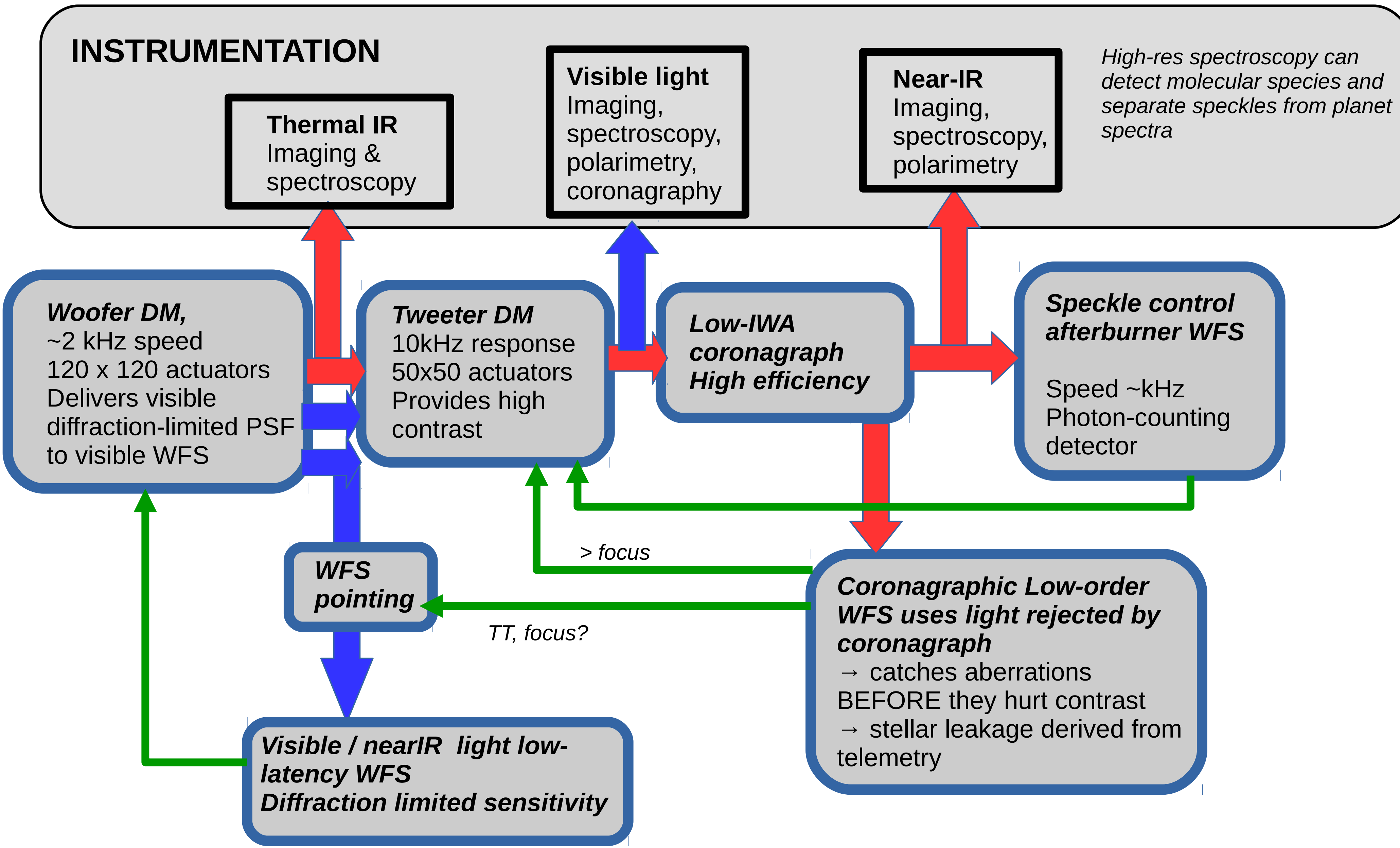
Detector H2RG ：OK
Read-out noise <10e- (10min exposure)
Dark ～ 0.01 e-/sec/pixel

Laser frequency comb ：OK
Covering 1050-1750nm with 12.5GHz span
Better than 0.3m/s stability

Radial velocity stability: Partially OK
Need for on-sky stability test

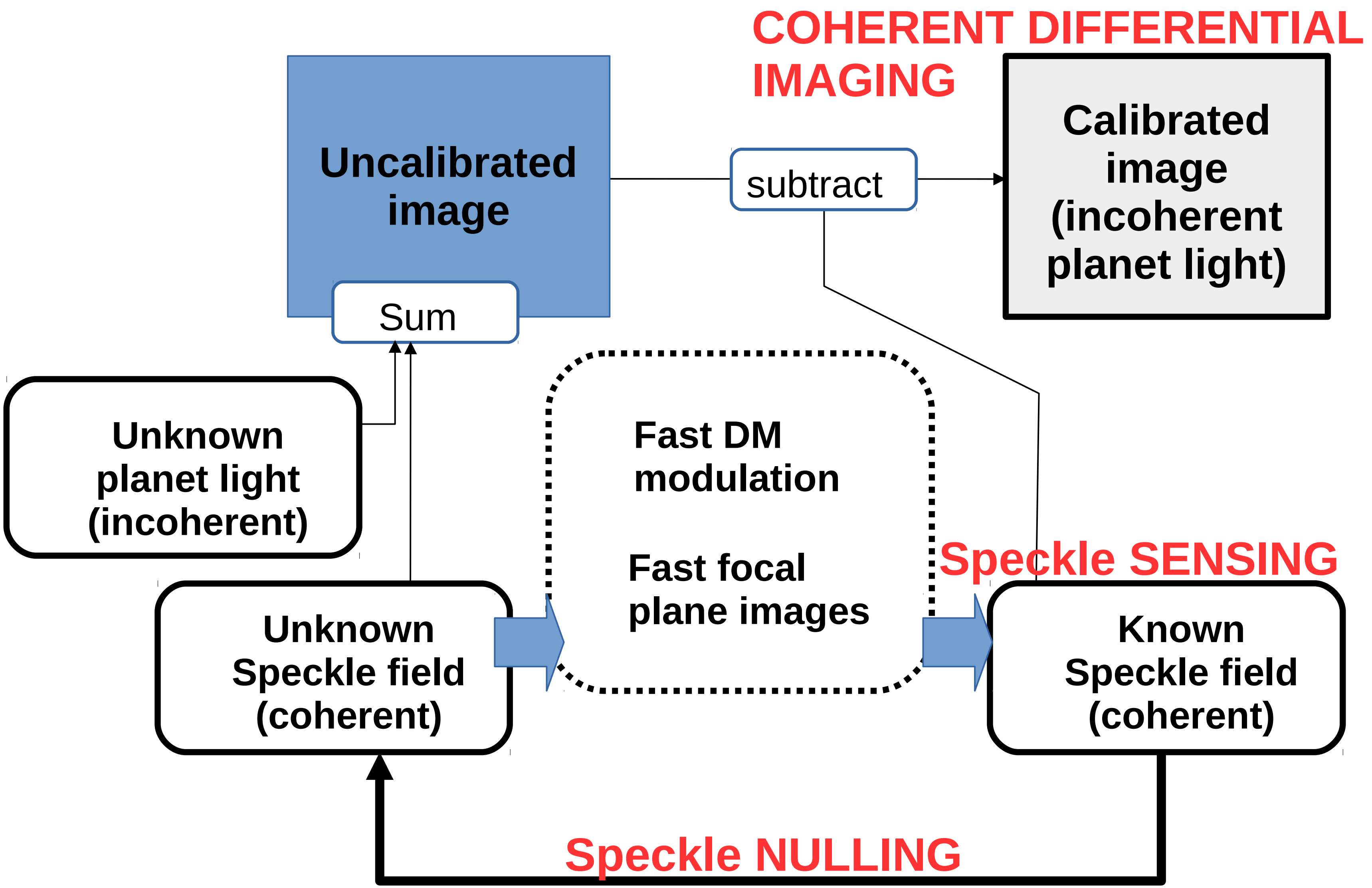


Nominal ELT ExAO system architecture

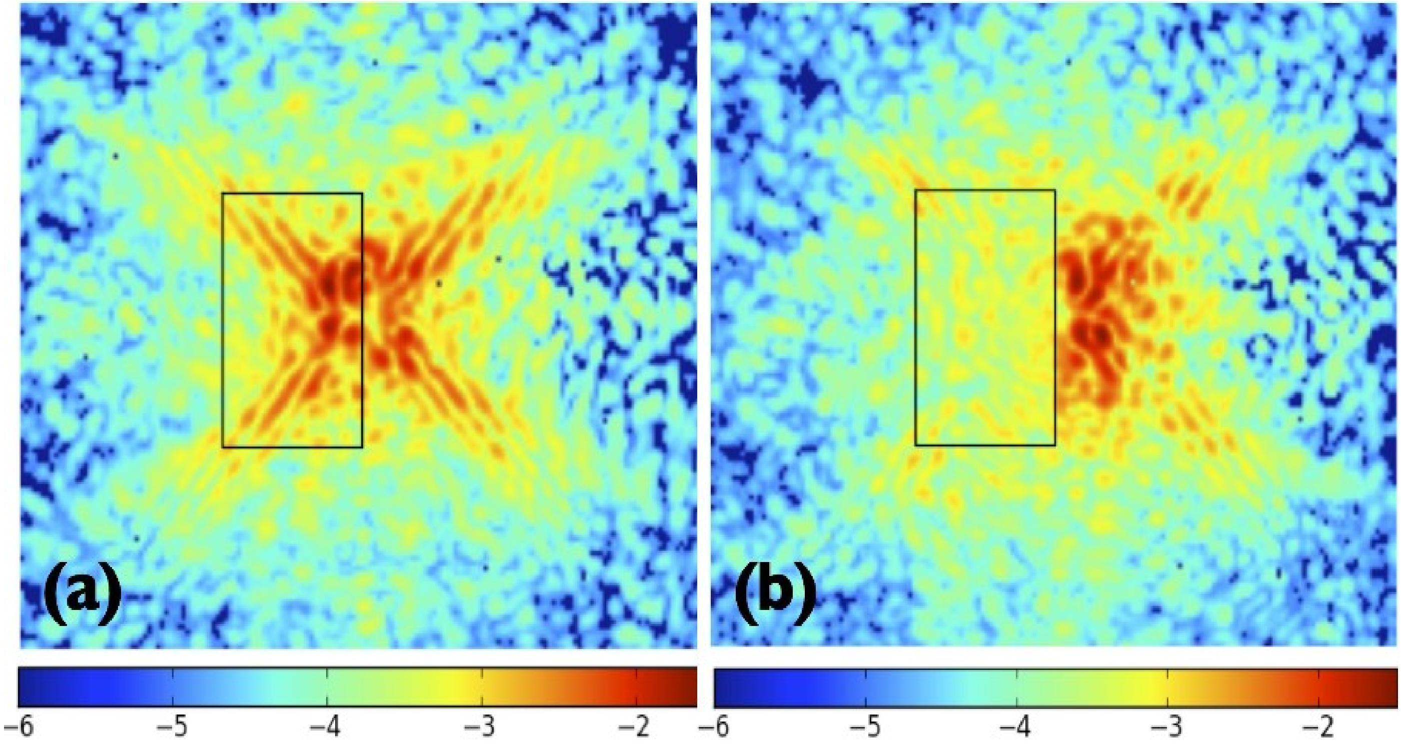


High Speed Speckle Control

Main SCExAO upgrade: High speed speckle control with MKIDs



Speckle control
→ remove speckles in ½ field dark hole



SCExAO Subaru Coronagraphic Extreme Adaptive Optics

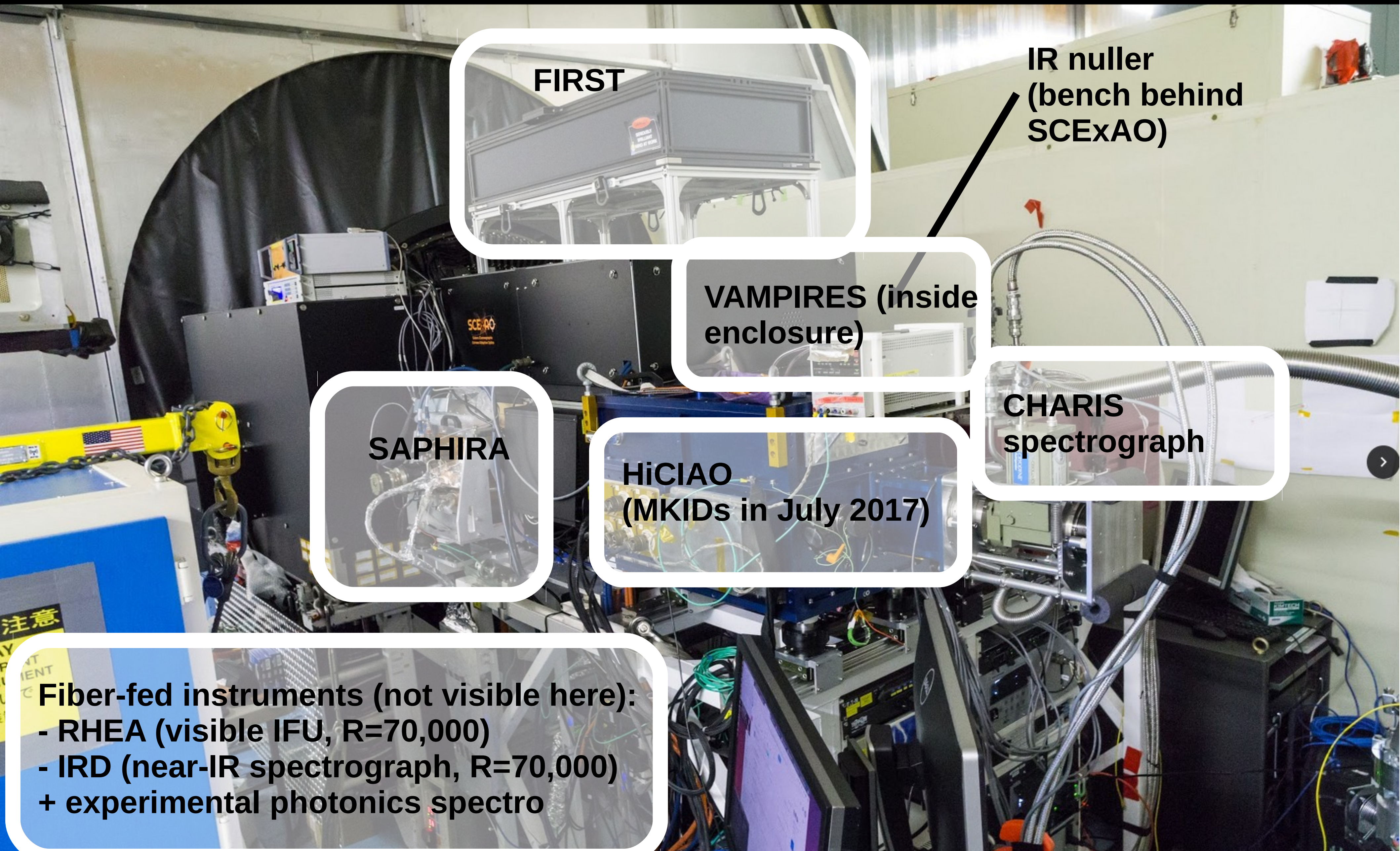
- **Flexible** high contrast imaging platform
- Meant to **evolve to TMT instrument** and validate key technologies required for direct imaging and spectroscopy of habitable exoplanets

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

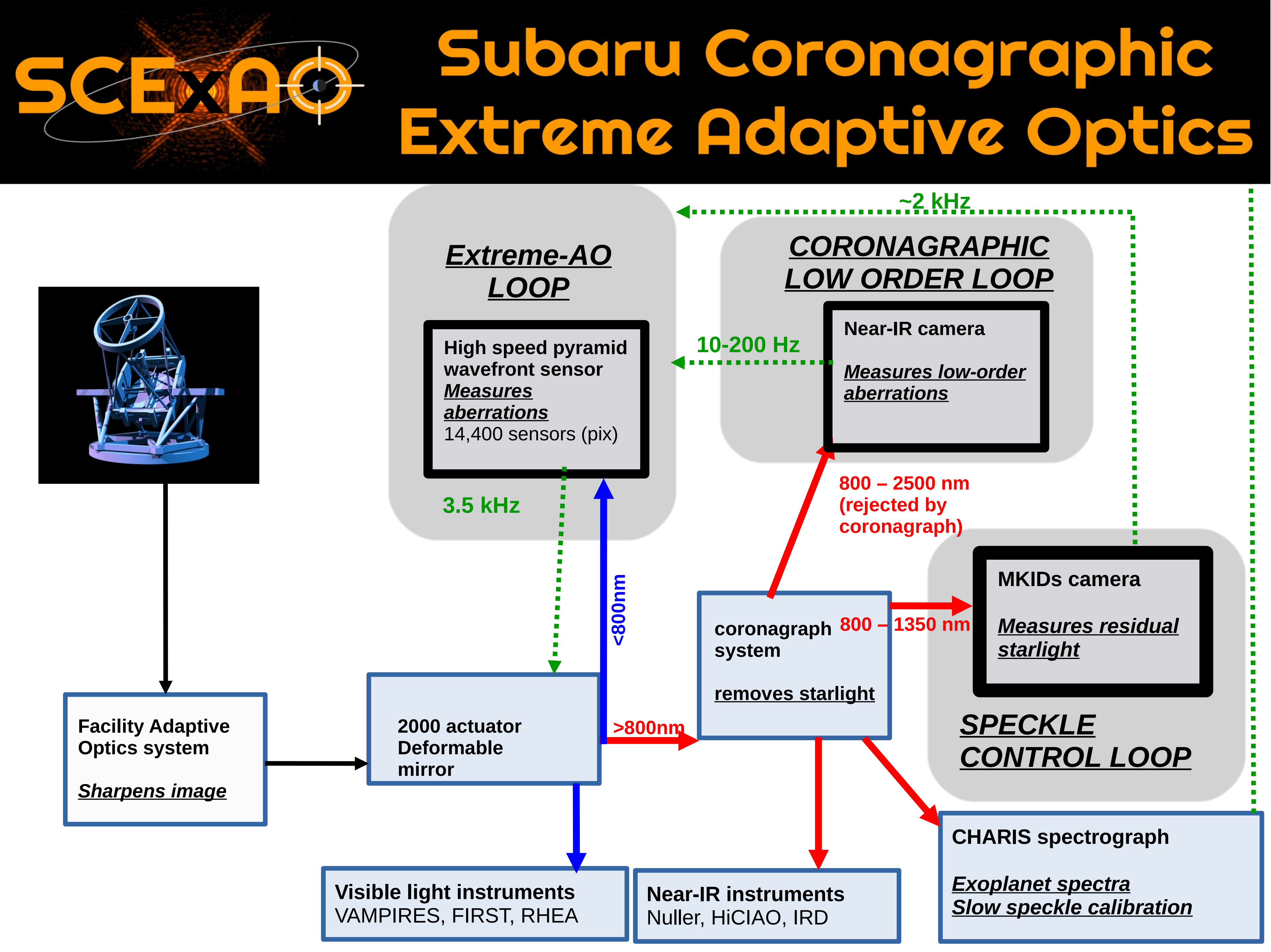
SCExAO is an international platform to prepare ELT imaging of habitable planets around M-type stars

SCExAO

Subaru Coronagraphic Extreme Adaptive Optics



Subaru Coronagraphic Extreme Adaptive Optics



Preliminary VAMPIRES science

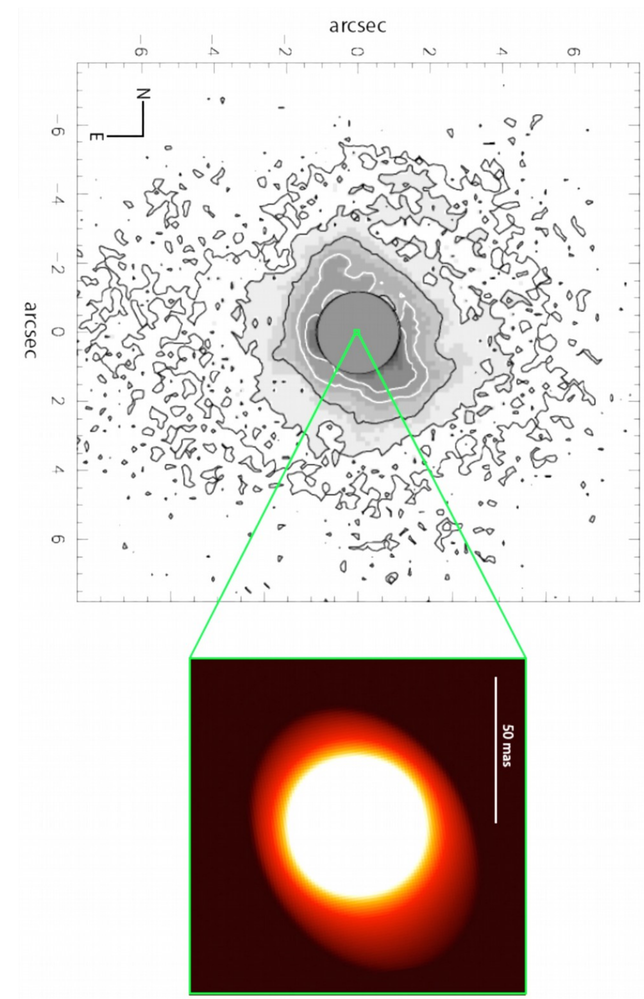
Circumstellar dust around Red Supergiant μ Cephei

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.

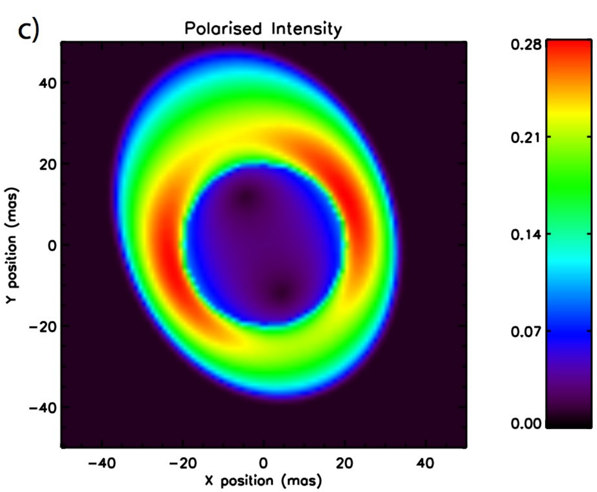
Inner radius: 9.3 ± 0.2 mas (which is roughly R_{star})

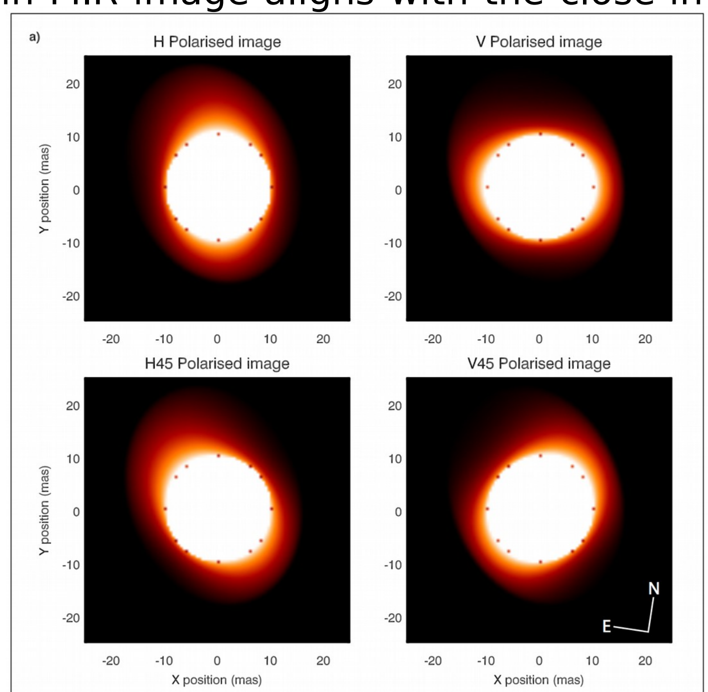
Scattered-light fraction: 0.081 ± 0.002

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.

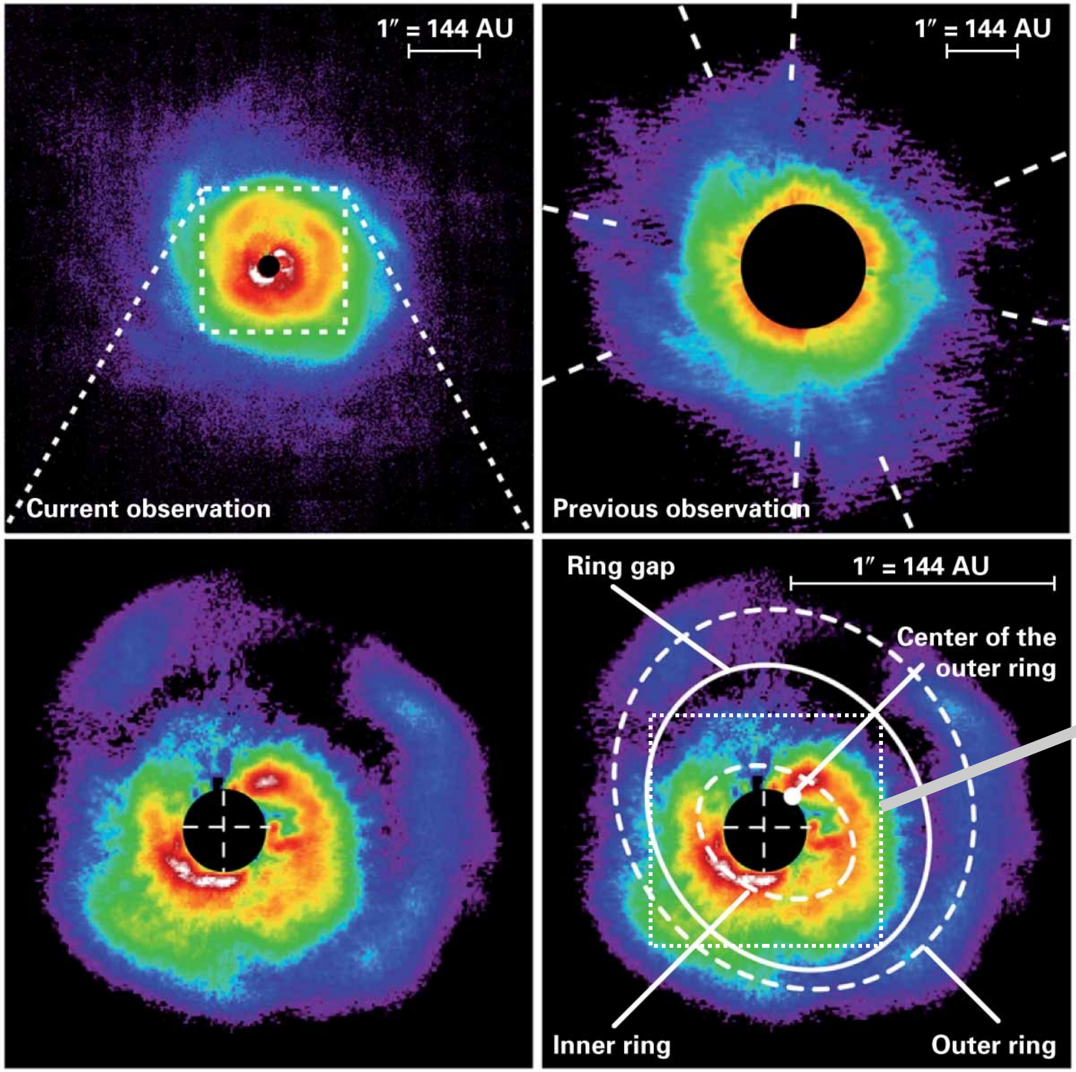




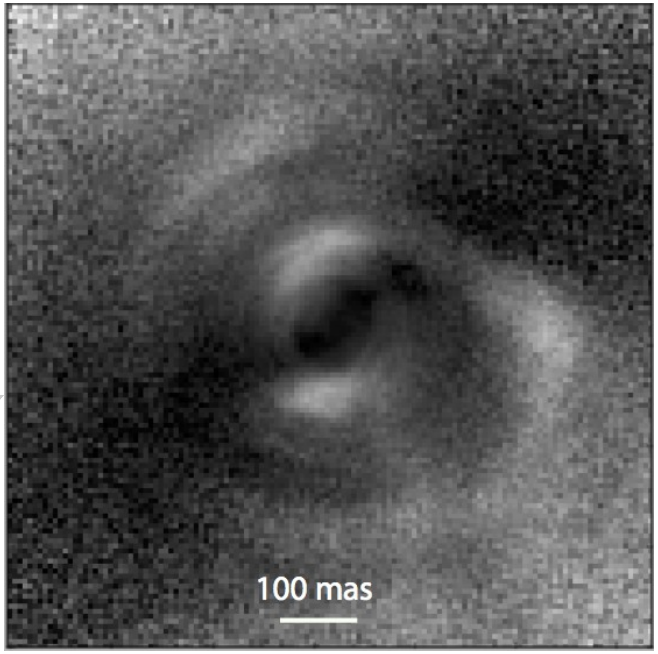
Preliminary VAMPIRES science

AB Aur star, polarimetric imaging mode

HiCIAO, near-IR

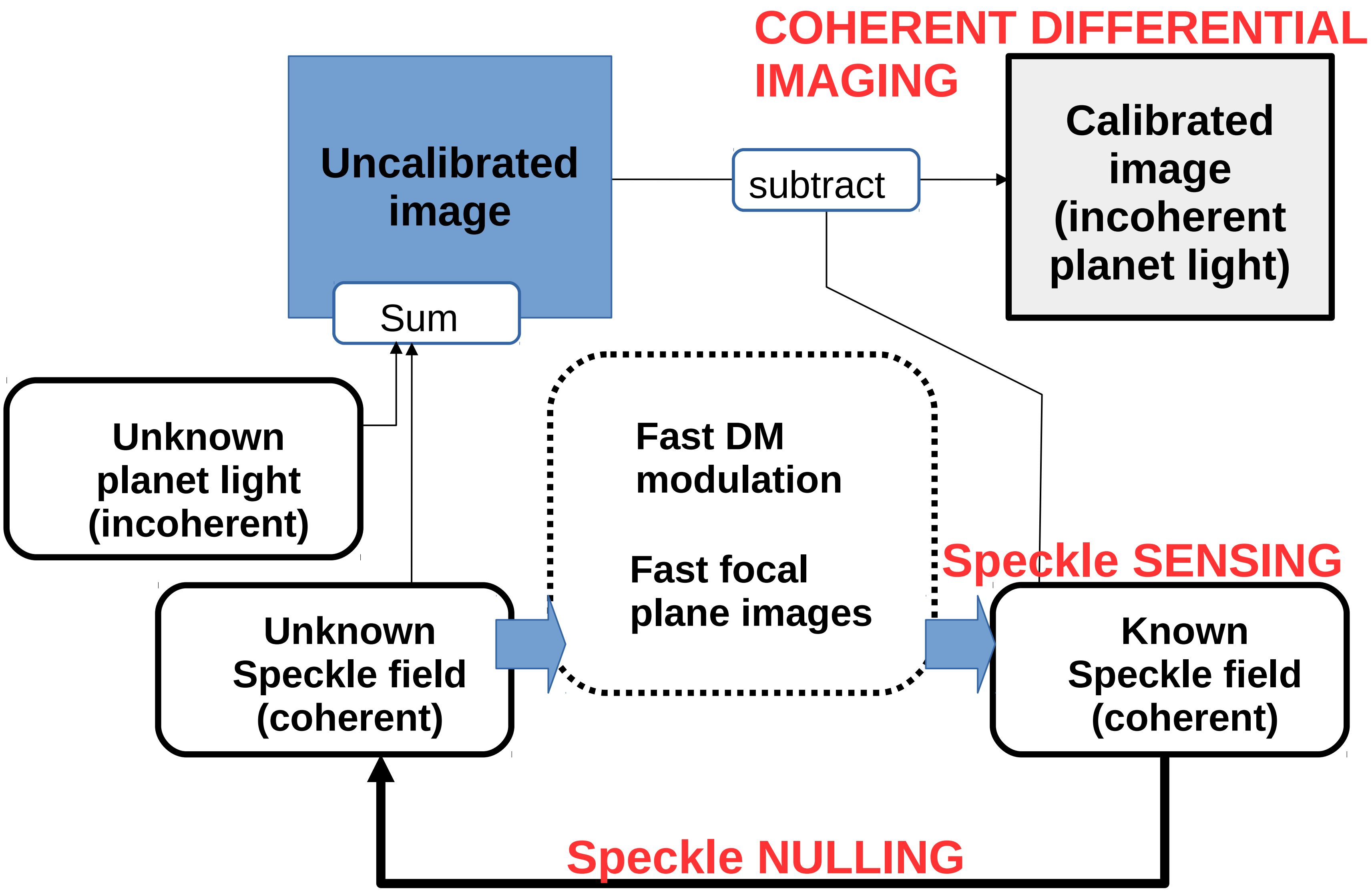


VAMPIRES
(preliminary data reduction)



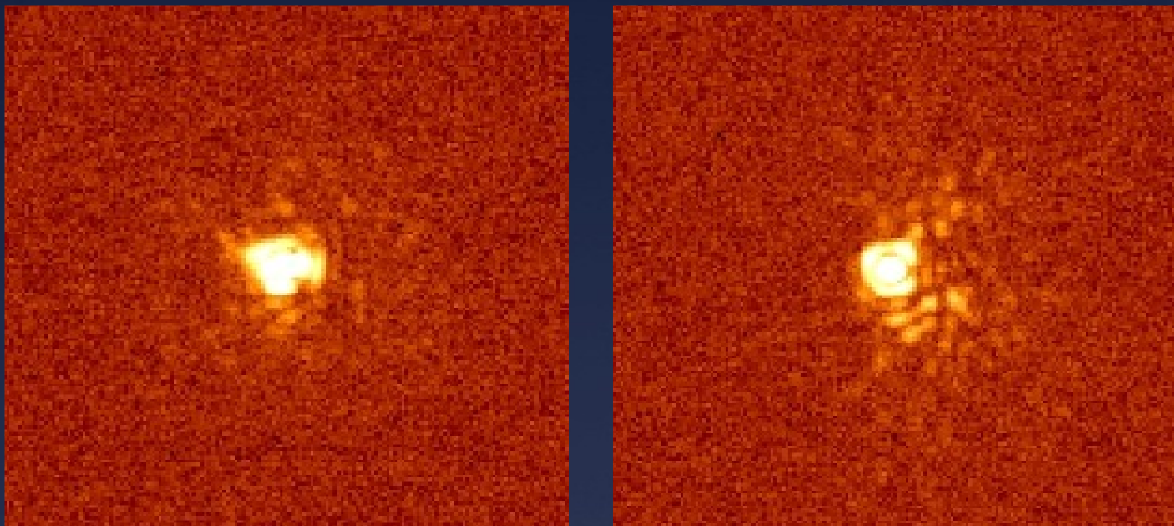
High Speed Speckle Control

Main SCExAO upgrade: High speed speckle control with MKIDs



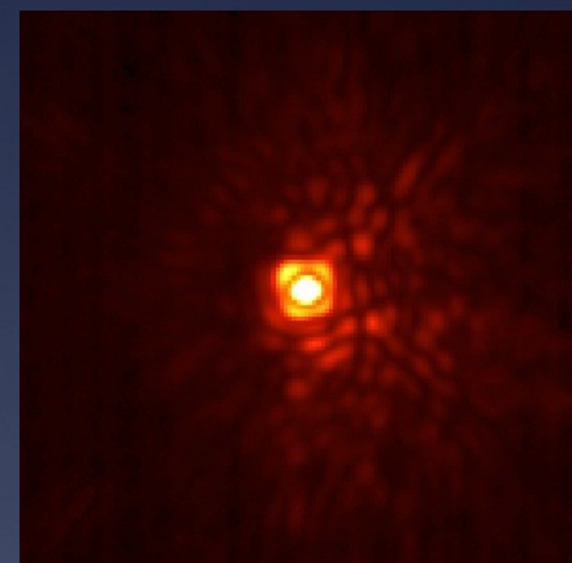
speckle nulling results on-sky (June 2014)

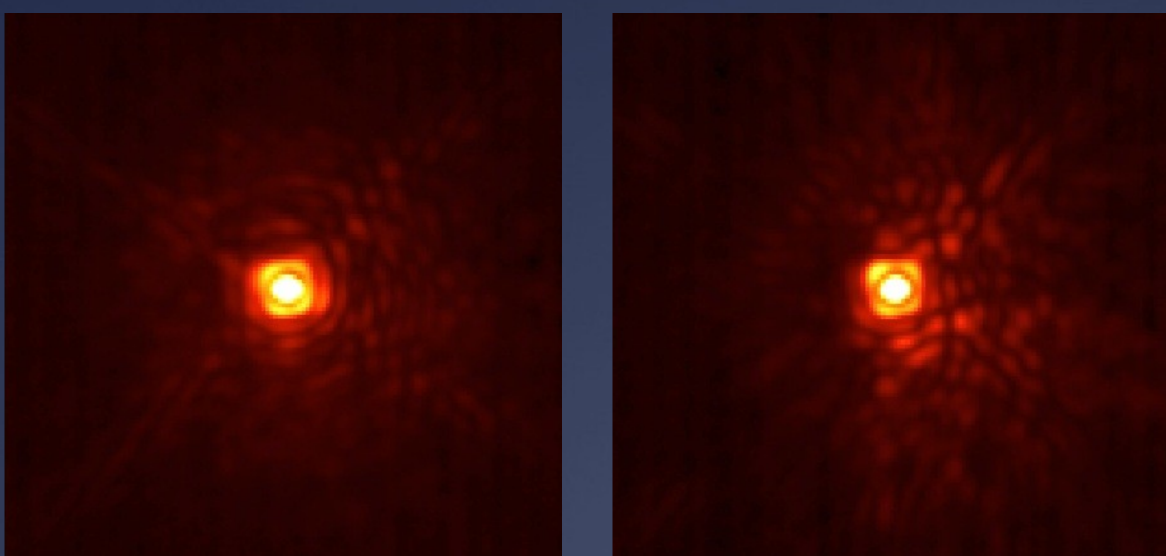
Single frames: 50 us



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.

SCExAO@Subaru → TMT

Demonstrate and validate performance on Subaru prior to deployment on TMT

→Goal: **be ready to go as soon as telescope ready (visitor instrument ?)**, with well understood instrument

→**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.

SCExAO→ TMT

Habitable planets can be imaged on ELTs (physics and nature are on our side)

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

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

Ideal targets are M0-M5 stars within 5pc

BUT: conventional instrument 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 <u>very challenging</u>… still lots of work to be done

→ We are exploring, and advocating for a fast path from 8-m telescope to TMT, to yield early science and mitigate risks for longer path 2nd/3rd generation instrument