Directly imaging of exoplanets and disks from ground and space-based observatories, and scientific potential of an Antartic-based facility

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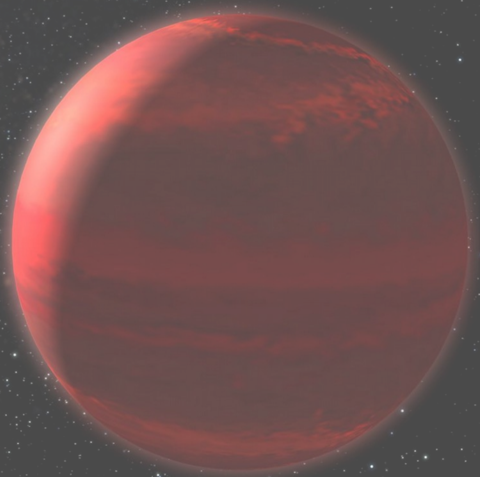

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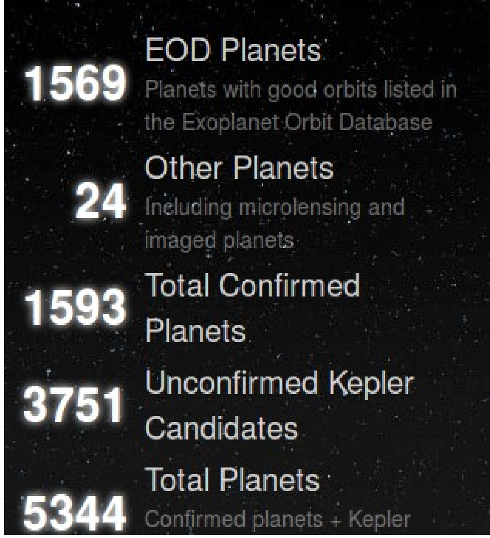
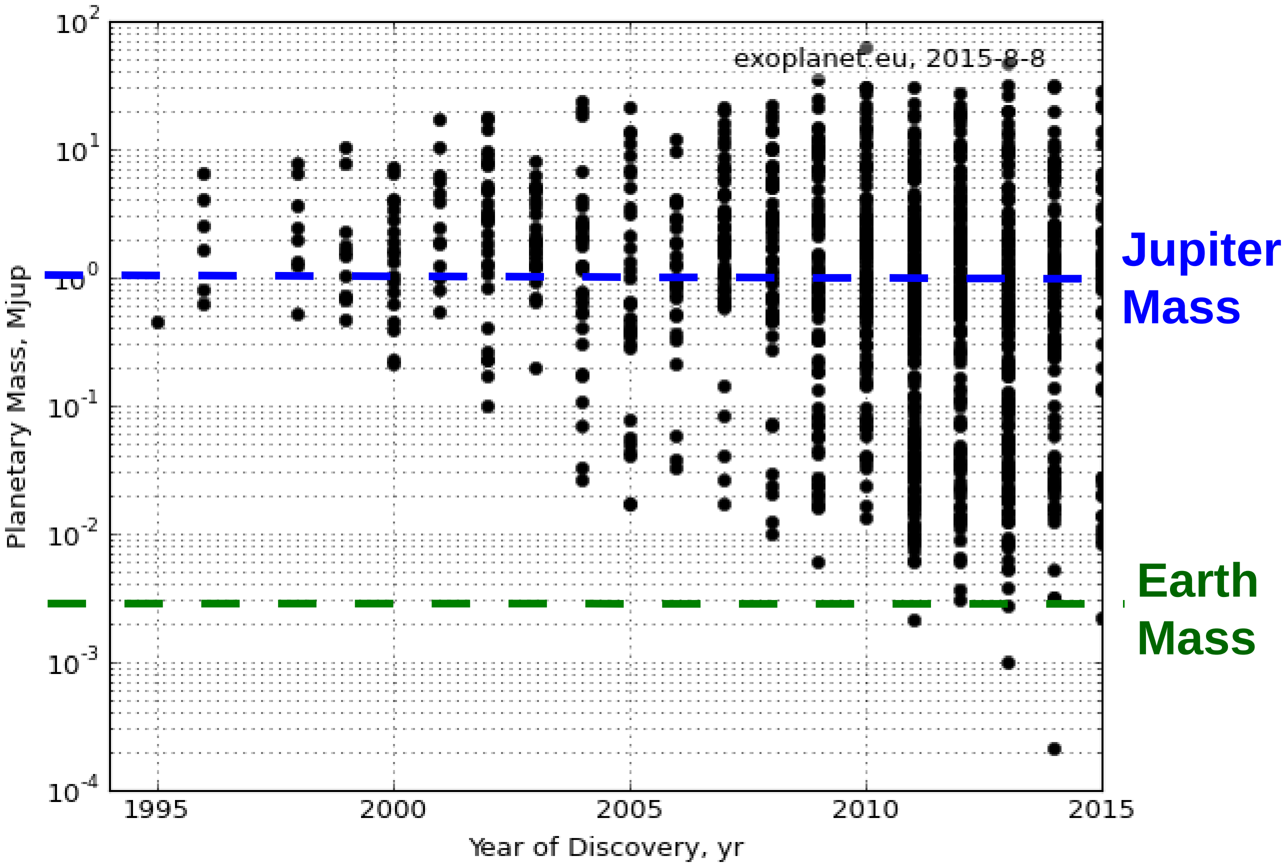
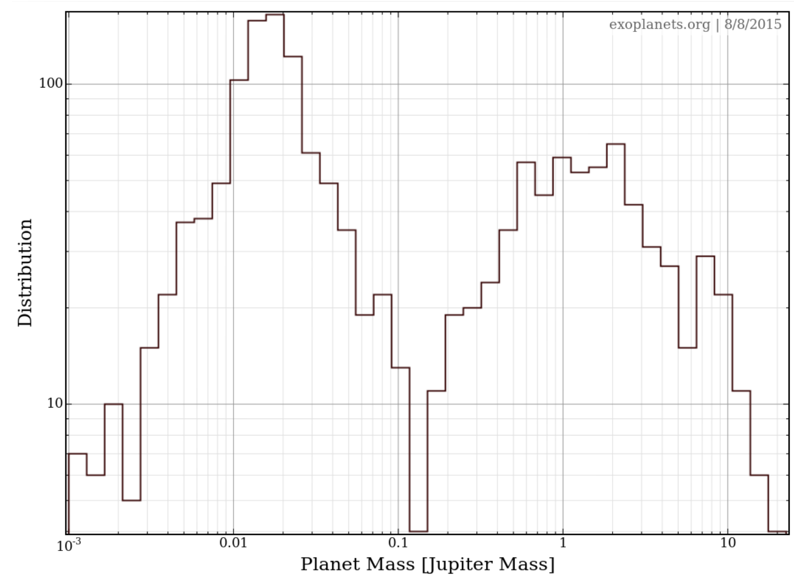
SCAR-AAA, Aug 8, 2015

Planets identified – we are now identifying Earth-size planets





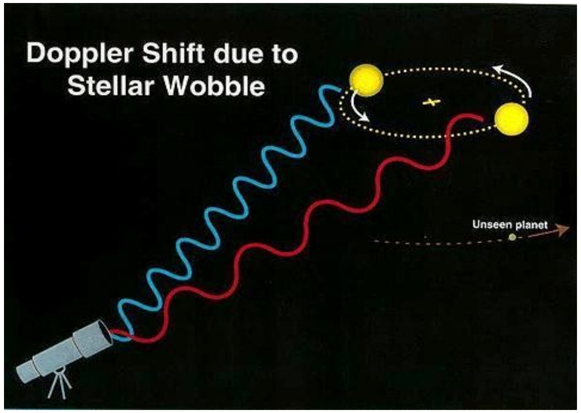
Small rocky planets are abundant



Observation techniques

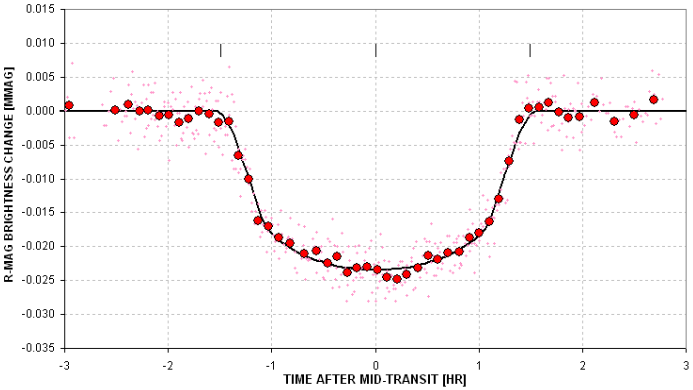
Techniques to detect exoplanets around main sequence stars (many of them covered in this course):

Radial velocity: measure small shift in star's spectra to compute its speed along line of sight.

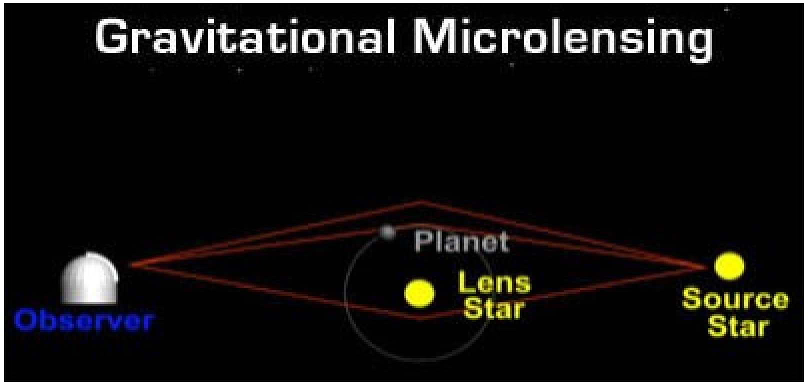


Astrometry: measure accurate position of star on sky to identify if a planet is pulling the star in a small periodic orbit around the center of mass

Transit photometry: if planet passes in front of its star, the star apparent luminosity is reduced



Microlensing: planet can bend light, and amplify background starlight through gravitational lensing



Direct imaging (with telescope or interferometer): capture high contrast image of the immediate surrounding of a star

Habitable planets

Potentially habitable planet :

- **Planet mass** sufficiently large to retain atmosphere, but sufficiently low to avoid becoming gaseous giant
- **Planet distance to star** allows surface temperature suitable for liquid water (habitable zone)

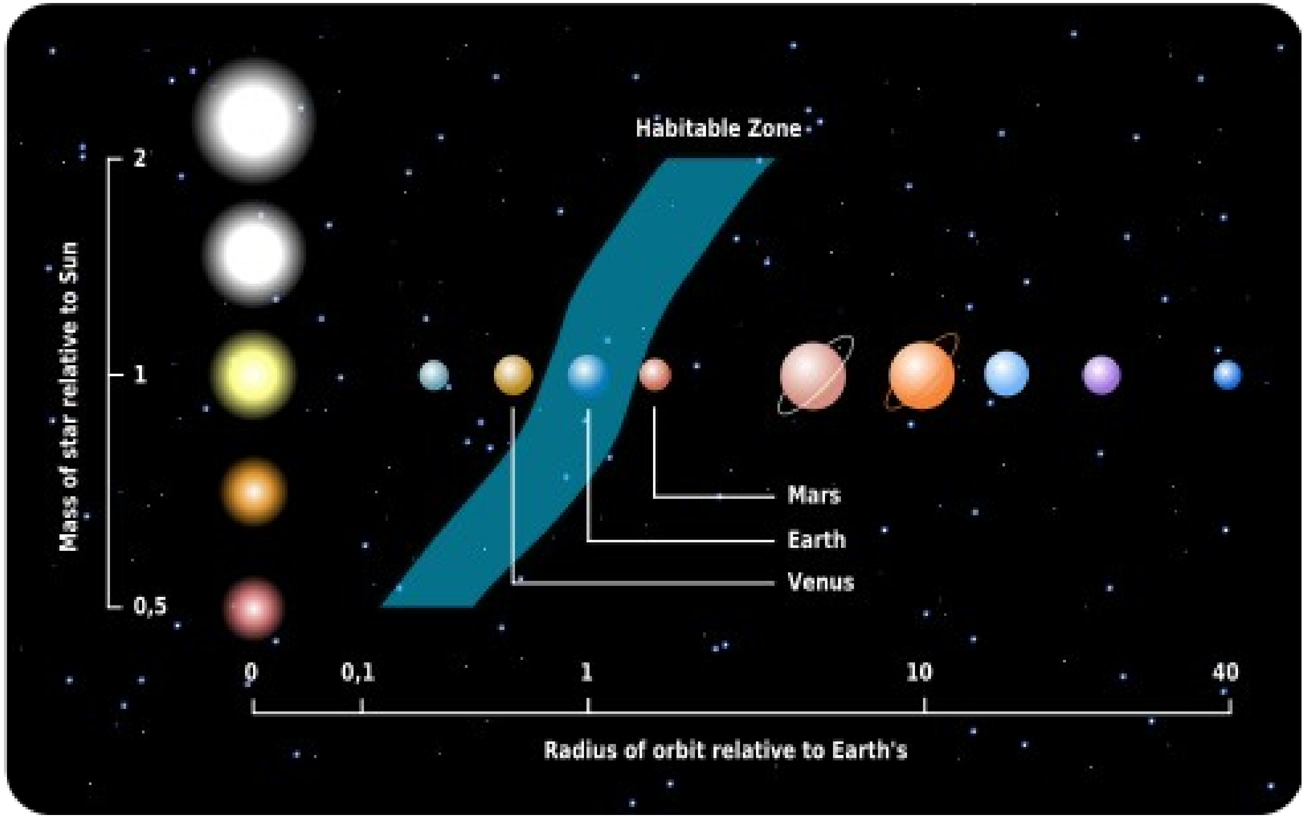
Habitable zone = zone within which Earth-like planet could harbor life
Location of habitable zone is function of star luminosity L. For constant stellar flux, distance to star scales as $L^{1/2}$

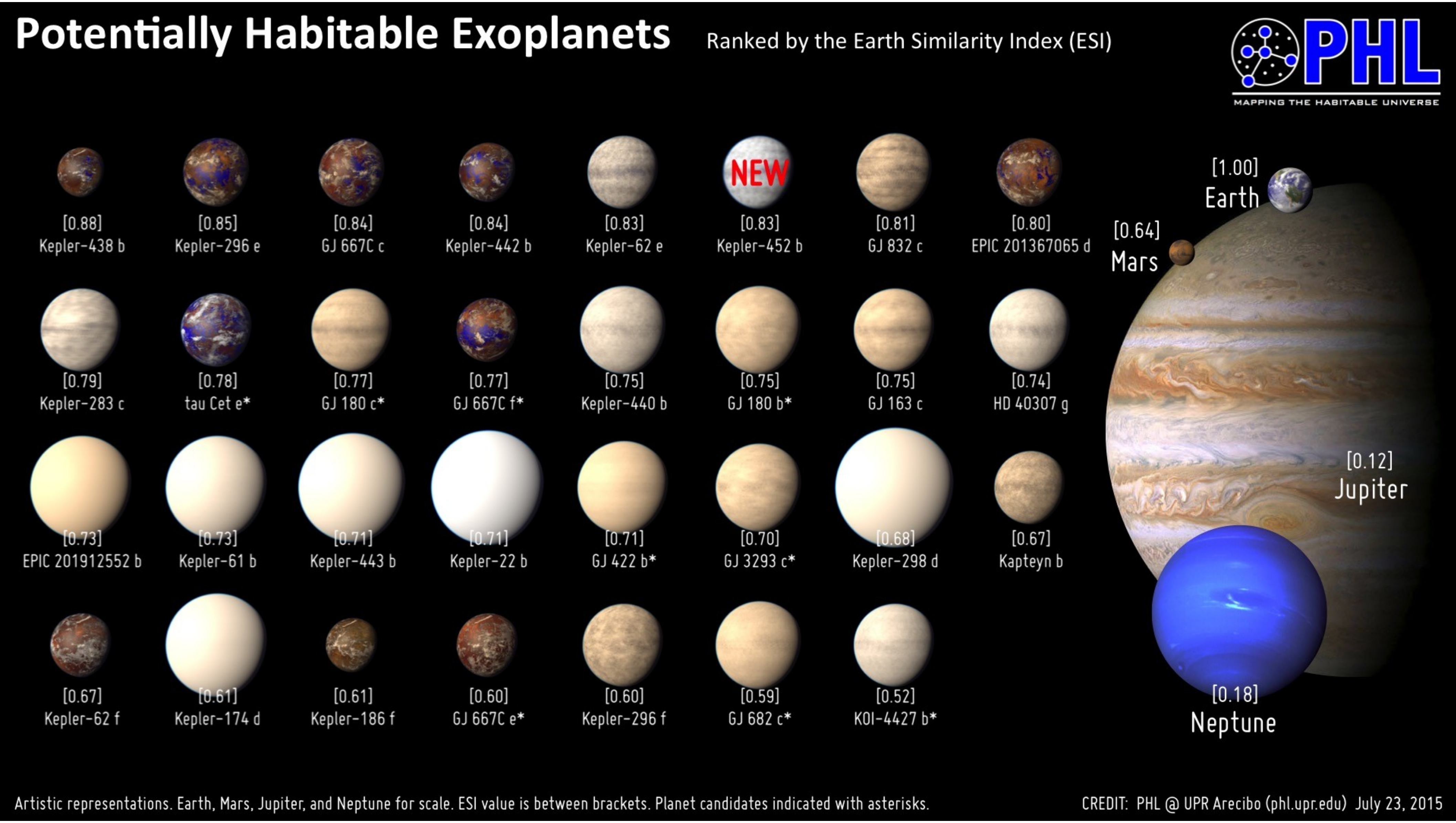
Examples:

Sun
→ habitable zone is at ~1 AU

Rigel (B type star):
18 solar mass
100000x Sun luminosity
→ habitable zone is at ~300 AU

Proxima Centauri (M type star):
0.123 solar mass
1/600 Sun luminosity
→ habitable zone is at ~0.04 AU




Potentially Habitable Exoplanets
Ranked by the Earth Similarity Index (ESI)
PHL
MAPPING THE HABITABLE UNIVERSE
NEW
[0.88] Kepler-438 b
[0.85] Kepler-296 e
[0.84] GJ 667C c
[0.84] Kepler-442 b
[0.83] Kepler-62 e
[0.83] Kepler-452 b
[0.81] GJ 832 c
[0.80] EPIC 201367065 d
[0.79] Kepler-283 c
[0.78] tau Cet e*
[0.77] GJ 180 c*
[0.77] GJ 667C f*
[0.75] Kepler-440 b
[0.75] GJ 180 b*
[0.75] GJ 163 c
[0.74] HD 40307 g
[0.73] EPIC 201912552 b
[0.73] Kepler-61 b
[0.71] Kepler-443 b
[0.71] Kepler-22 b
[0.71] GJ 422 b*
[0.70] GJ 3293 c*
[0.68] Kepler-298 d
[0.67] Kapteyn b
[0.67] Kepler-62 f
[0.61] Kepler-174 d
[0.61] Kepler-186 f
[0.60] GJ 667C e*
[0.60] Kepler-296 f
[0.59] GJ 682 c*
[0.52] KOI-4427 b*
[1.00] Earth
[0.64] Mars
[0.12] Jupiter
[0.18] Neptune
Artistic representations. Earth, Mars, Jupiter, and Neptune for scale. ESI value is between brackets. Planet candidates indicated with asterisks.
CREDIT: PHL @ UPR Arecibo (phl.upr.edu) July 23, 2015

Direct imaging of Exoplanets (incl. Habitable planets) allows …

Orbit

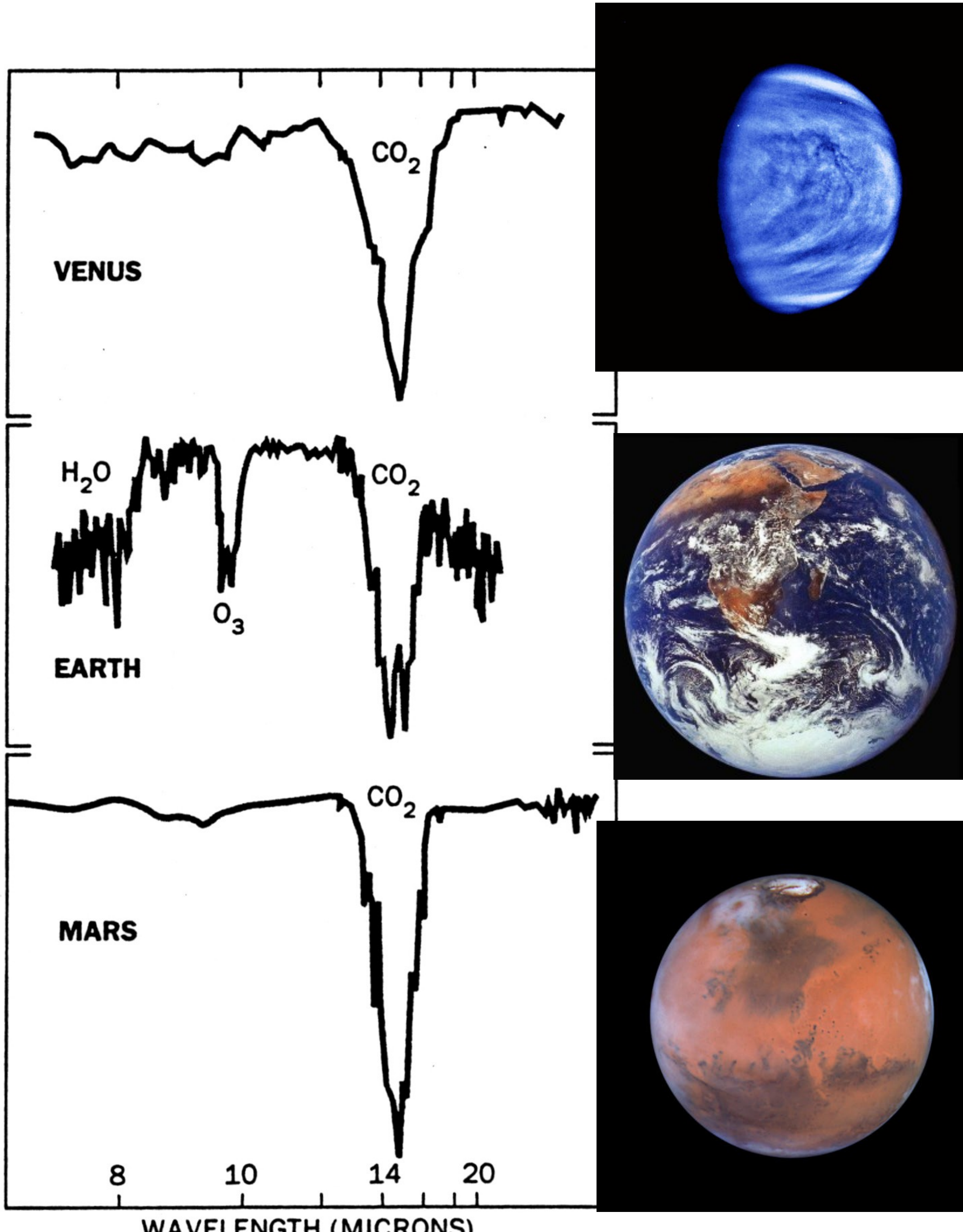
Atmosphere composition

Continents vs. Oceans ?

Rotation period

Weather patterns

Planetary environment :
Planets + dust



Spectroscopy of Earth-like planets
… may allow detection of life

Spectroscopy can identify biomarkers: molecular species, or combinations of species that can only be explained by biological activity

On Earth: water + O_2 + O_3 + CH_4

Spectra of Earth obtained through Earthshine observation also reveals vegetation's red edge !

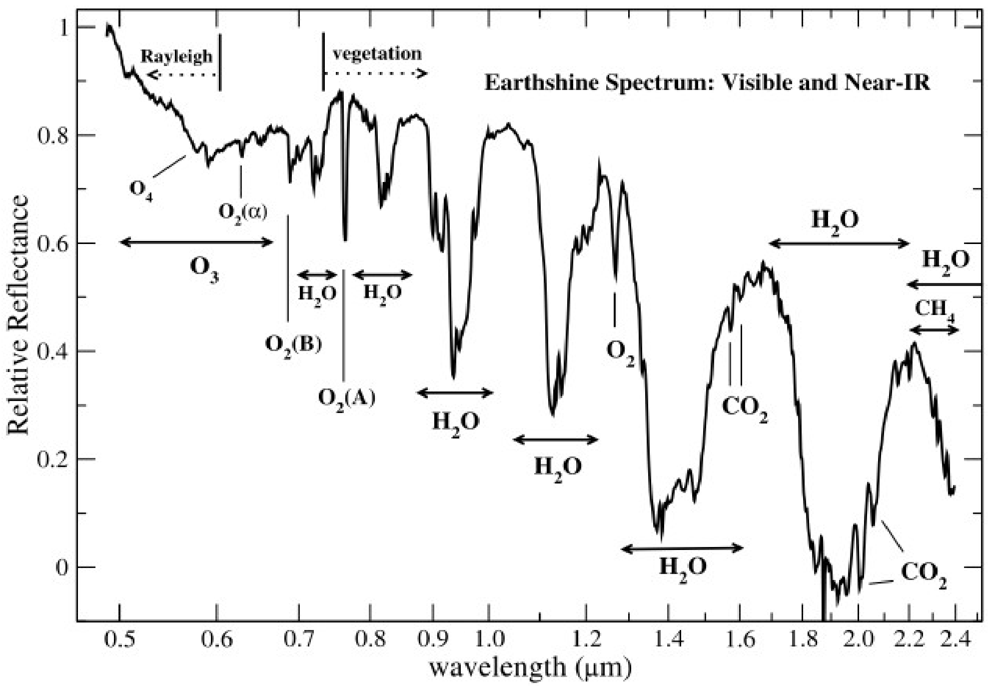
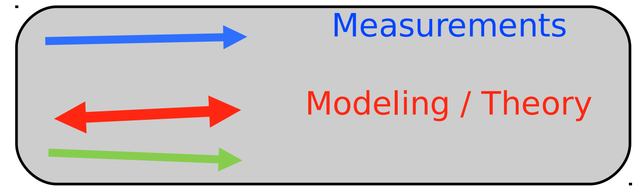
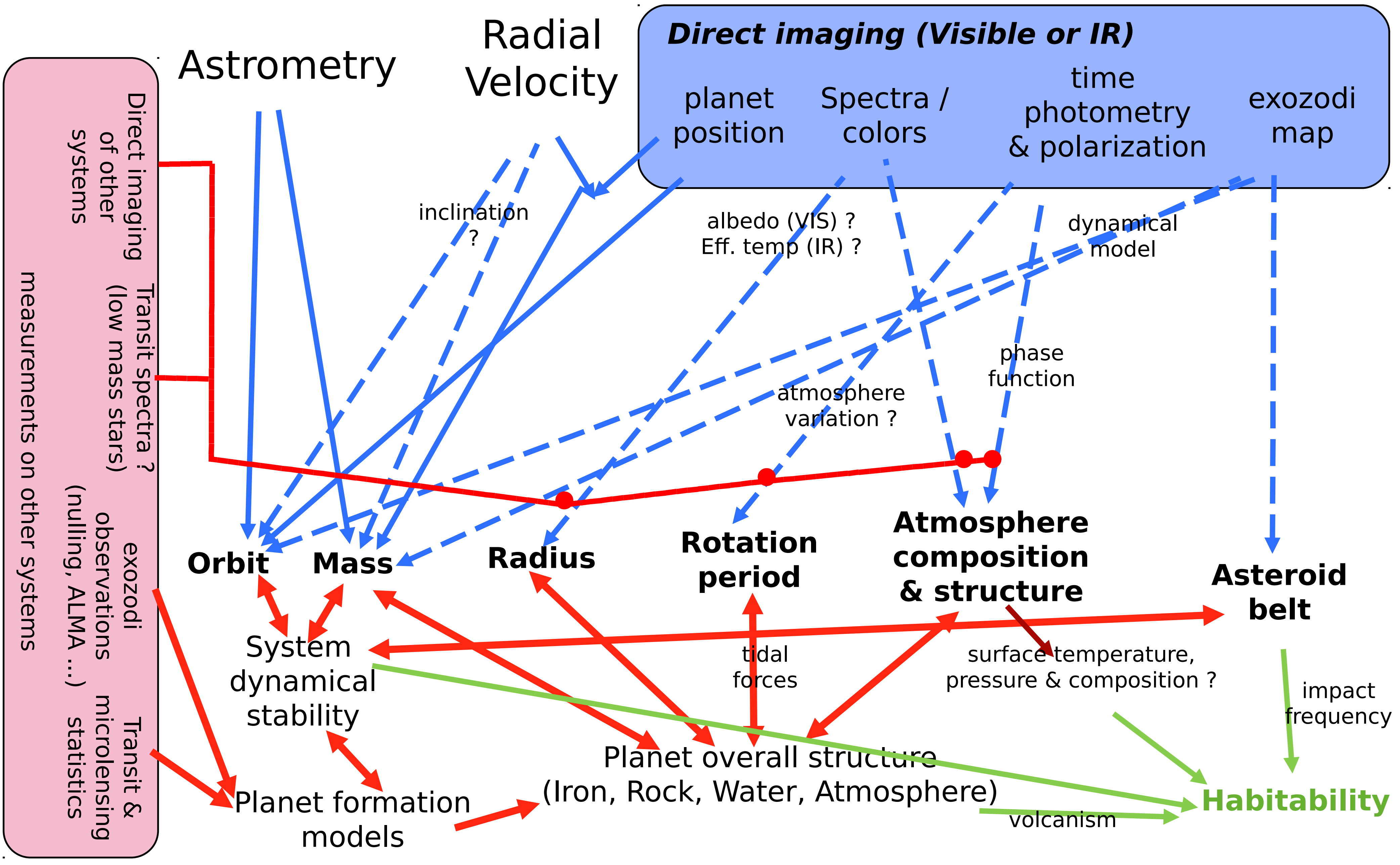


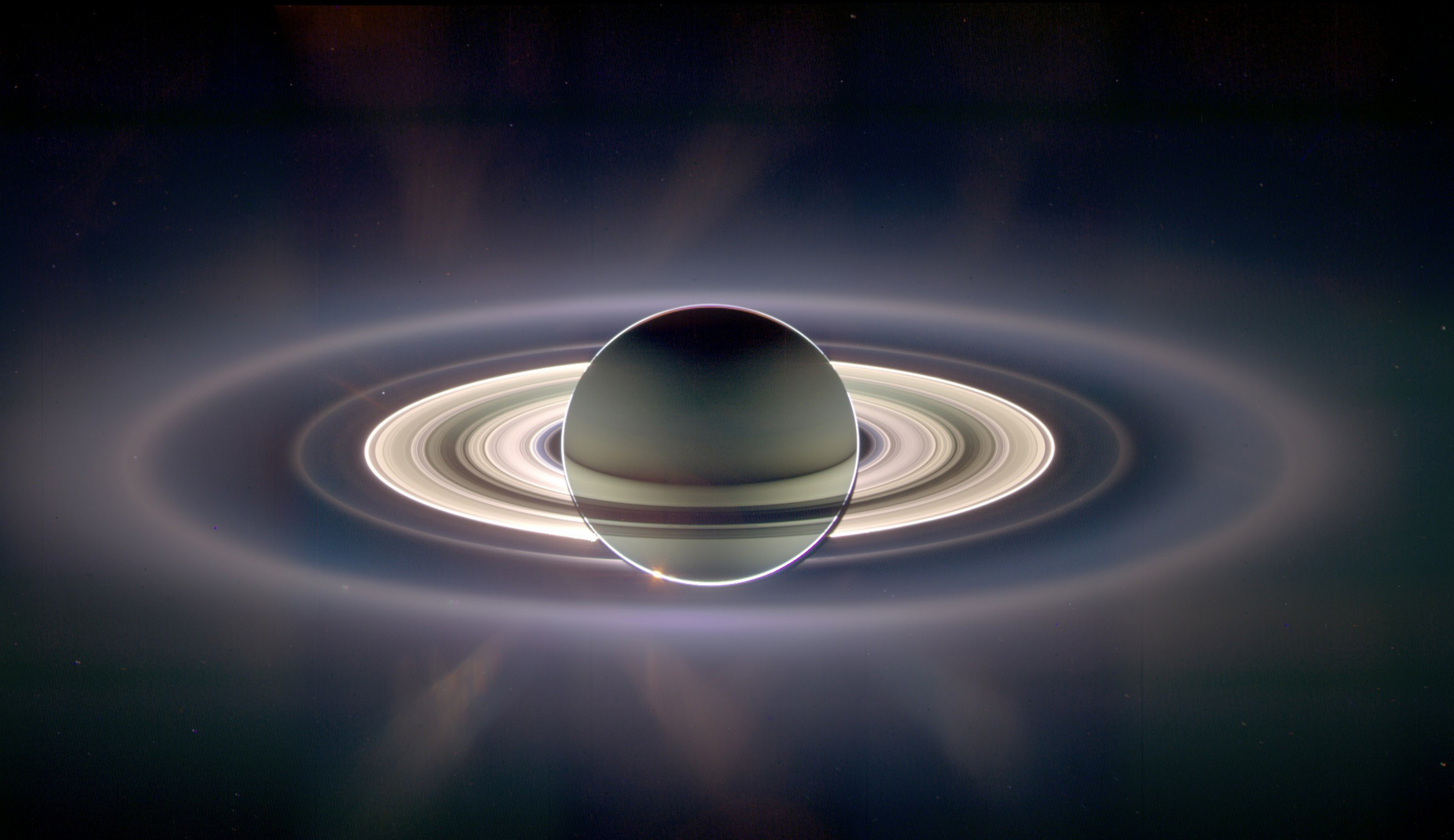
FIG. 7.—Earth's observed reflectance spectrum, at visible and near-infrared wavelengths, created from a composite of the data in this paper (0.8–2.4 μm) and the data presented in Paper I (0.5–0.8 μm). The strongest molecular signatures are indicated, as are the wavelengths where Rayleigh scattering and vegetation reflection are most significant.

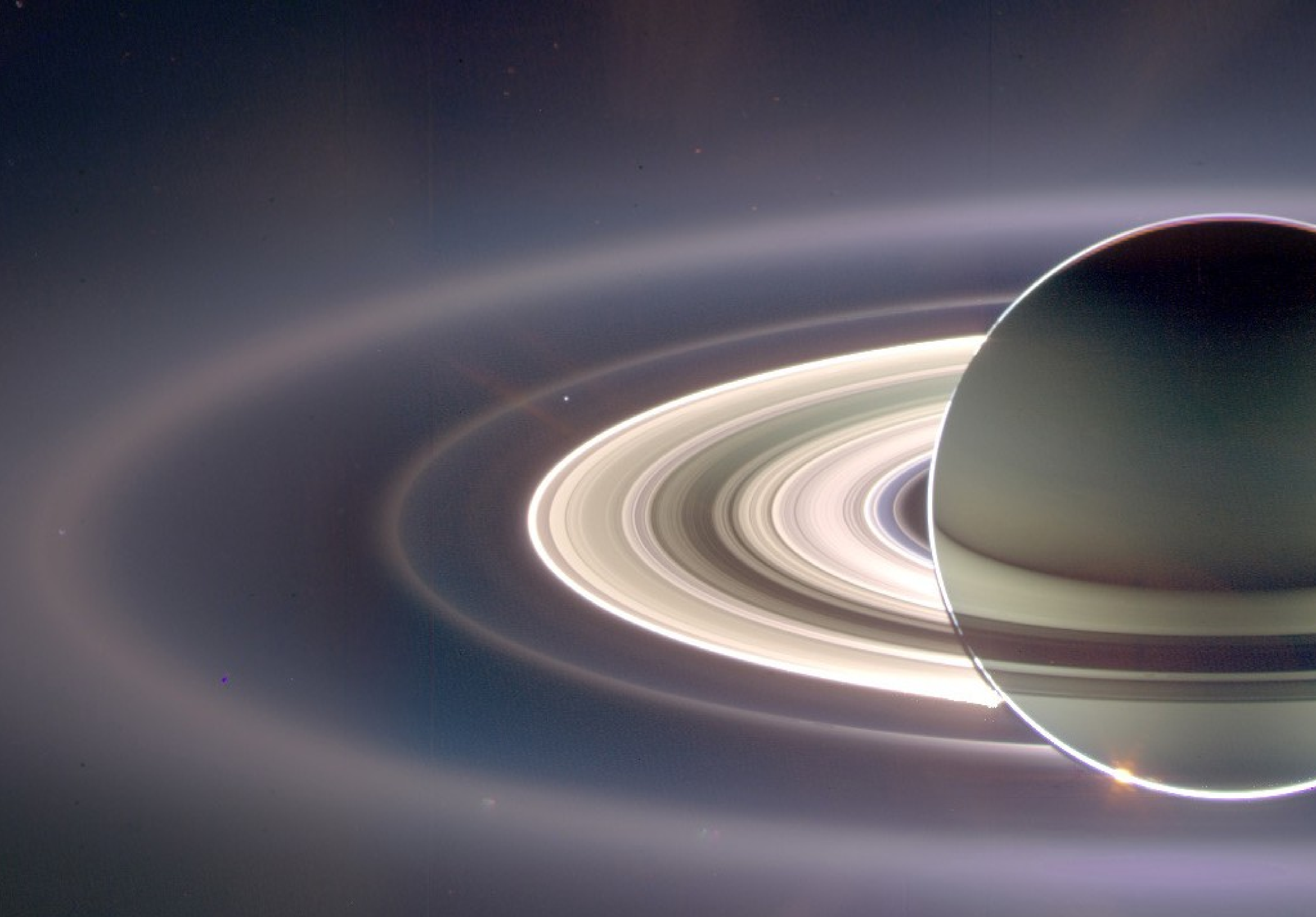
Turnbull et al. 2006

Habitable exoplanet characterization







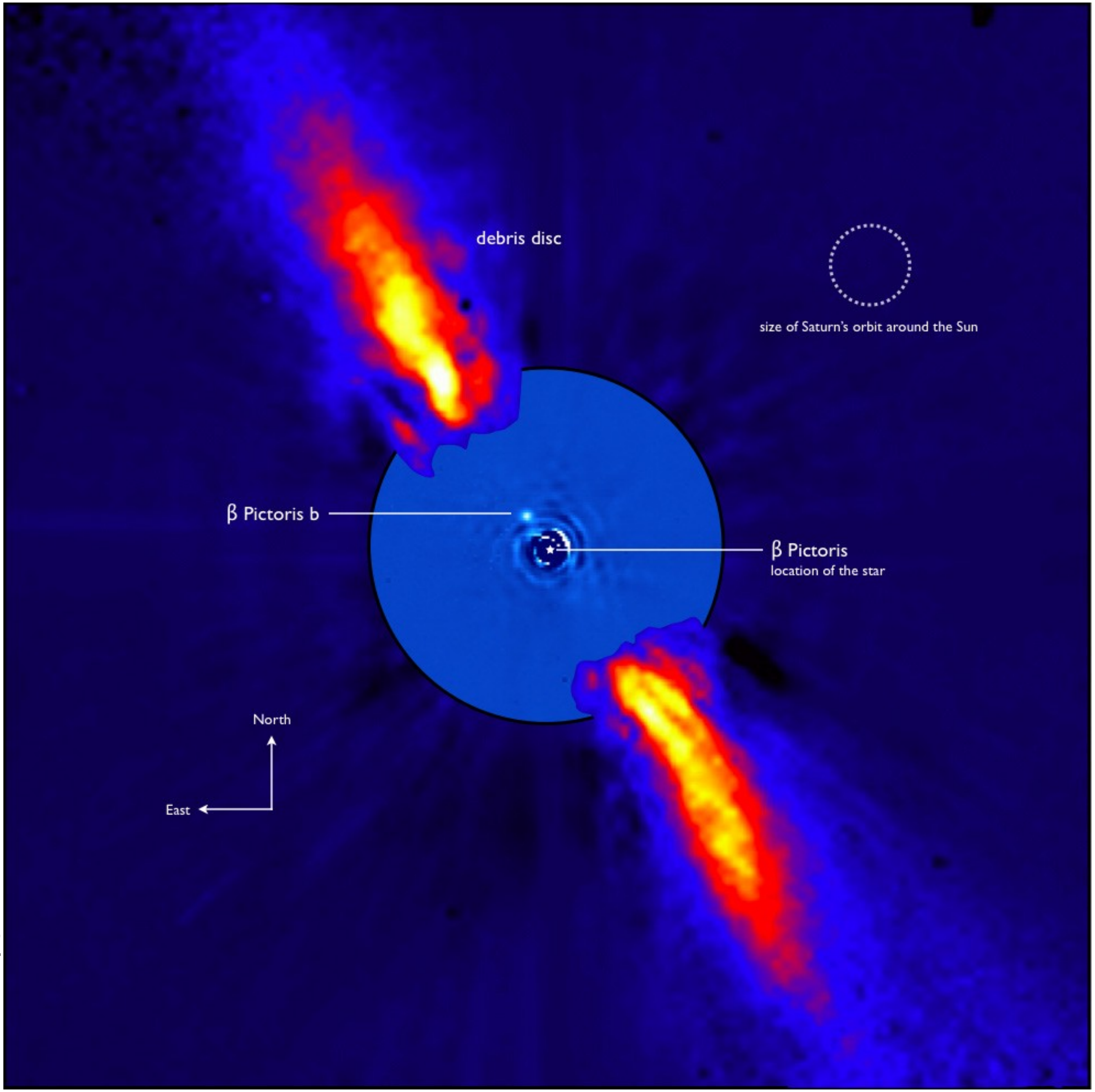


Exoplanets & dust disks

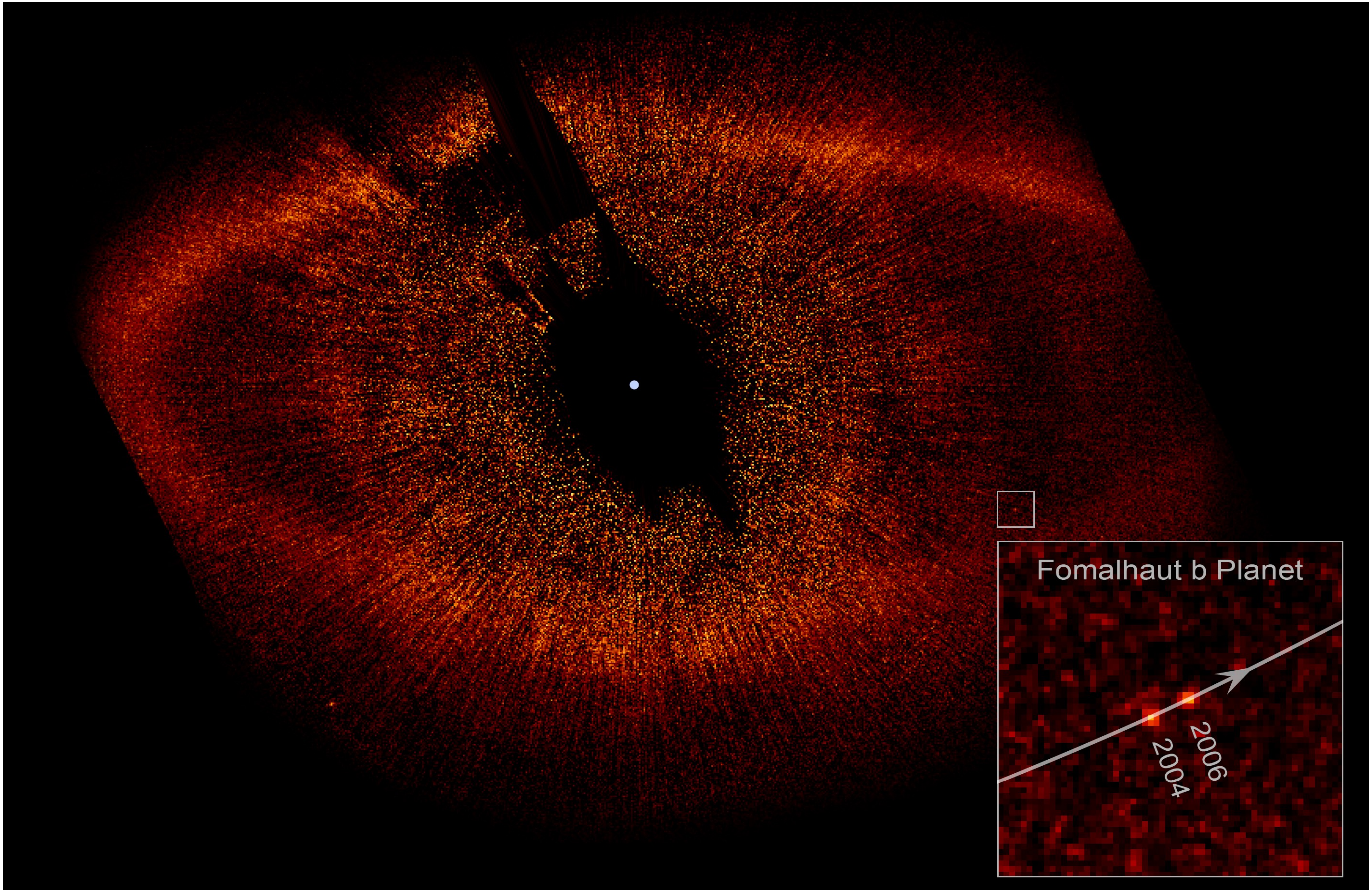
Protoplanetary disk:
Disk in the process of forming planets

Debris disk:
Disk generated by collision between small bodies

Ability to image planets and disks → study planetary formation and evolution of planetary systems



Beta Pic exoplanet and dust disk (Lagrange et al. 2009)



Kalas et al., HST image

What is a high contrast imaging system (ground or space) ?

Imaging system optimized to provide high contrast at small angular separation.

Key elements:

- **Coronagraph** or nulling interferometer to optically remove starlight and isolate planet light (overcomes diffraction)

- **Wavefront correction system** to reduce and calibrate residual wavefront errors
  For coronagraphs: Extreme-AO system to flatten wavefront
  For interferometers: Optical pathlength sensing / correction (+ AO on individual apertures of the interferometer)

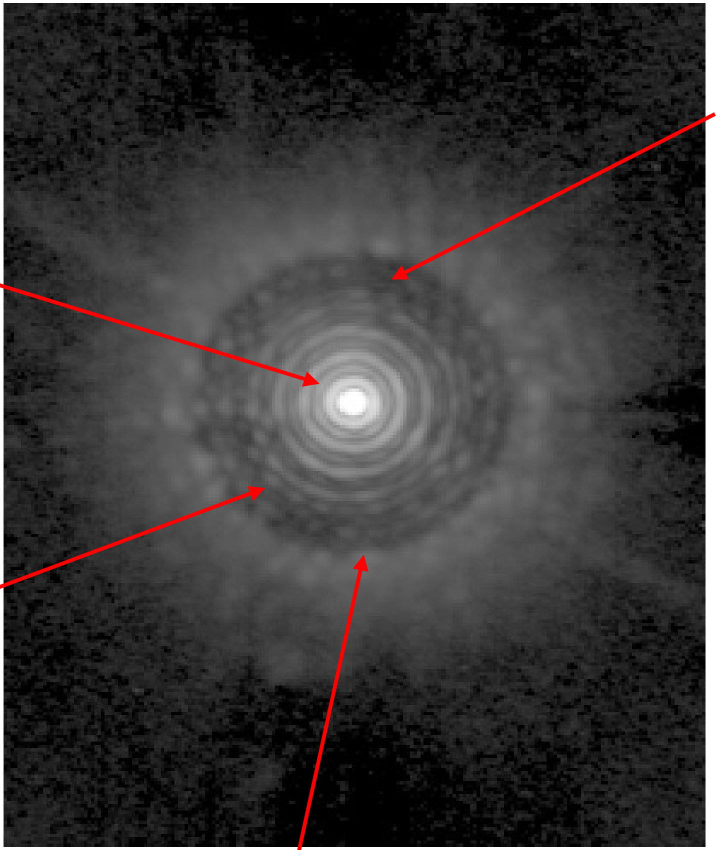
- **Science detector (+ differential detection technique)** for imaging, spectroscopy and polarimetry
  (note: the science detector can be part of the wavefront control system, and measure residual scattered light to be removed)

Olivier's thumb...
the simplest coronagraph

Doesn't work well enough to see planets around other stars

From conventional AO to Coronagraphic Extreme-AO

We use a non-extreme AO system image as starting point
Example of a very good PSF with a current AO system: LBT AO image



Residual atmospheric speckle halo

REDUCED BY FAST, ACCURATE AND EFFICIENT AO SYSTEM

PSF diffraction (Airy rings, spiders)

REMOVED BY CORONAGRAPH

Static and slow speckles

MUST BE REMOVED BY CALIBRATION SYSTEM OR DIFFERENTIAL IMAGING (actively or in post processing)

Control radius of AO

DEFINED BY NUMBER OF ACTUATORS IN DM: MAY BE INCREASED WITH MORE ACTUATORS IF REQUIRED

Current and future high contrast systems - ground

NICI on Gemini South telescope – ongoing, large survey completed
85-element curvature AO system + Lyot coronagraph
Differential imaging capability (methane absorption line)

HiCIAO on Subaru Telescope – ongoing survey
188-element curvature AO system + Lyot coronagraph
Differential imaging capability (methane absorption line)

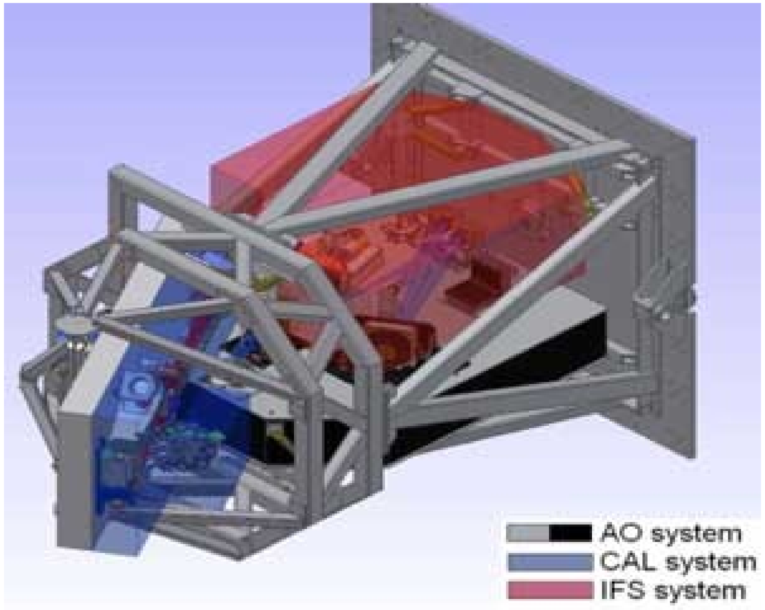
→ **Subaru Coronagraphic Extreme AO (upgrade of HiCIAO)** – on sky since 2012
Small inner working angle PIAA coronagraph
Pointing sensing and control with coronagraphic low order WFS
Speckle control using focal plane image as sensor
32x32 MEMS deformable mirror (upgraded 2013 to 2000 elements)
Includes Integral Field Spectrograph to help remove speckles and acquire spectra

P1640 + Palm300 on Palomar 5-m telescope – on sky since 2012
3000 element high order AO system + Lyot coronagraph
Includes Integral Field Spectrograph to help remove speckles and acquire spectra

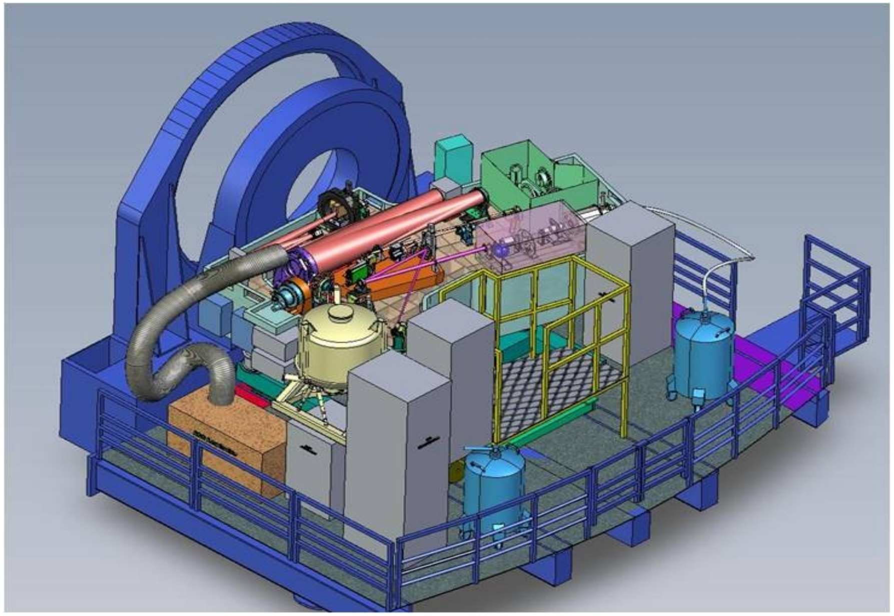
Gemini Planet Imager (GPI) – large survey started observations in 2014
ExAO system using 64x64 MEMS DM + coronagraph
Includes calibration interferometer to accurately measure residual speckles
Includes Integral Field Spectrograph to help remove speckles and acquire spectra

ESO's SPHERE on VLT – large survery started observations in 2014
ExAO system + coronagraph
Highly stable bench
Includes Integral Field Spectrograph to help remove speckles and acquire spectra
Includes differential polarimetric imager

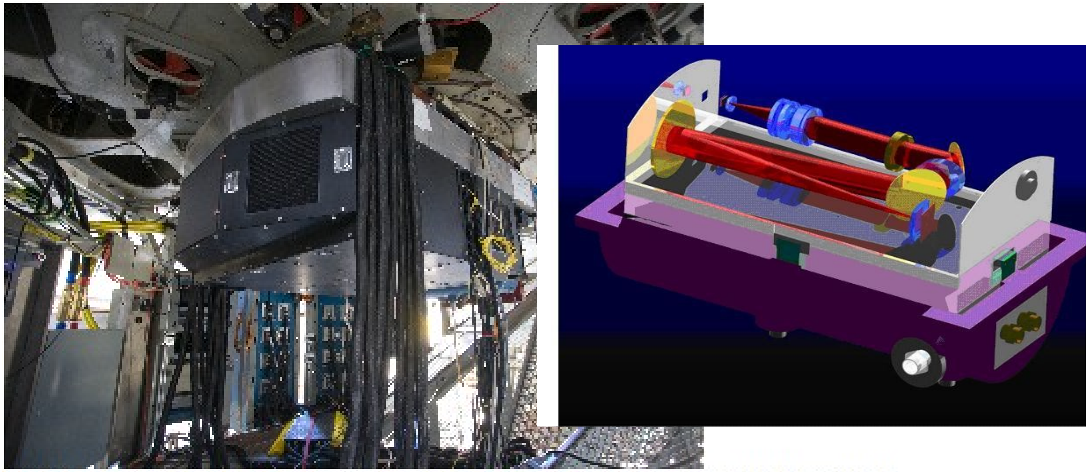
Current and future high contrast systems - ground



Gemini Planet Imager

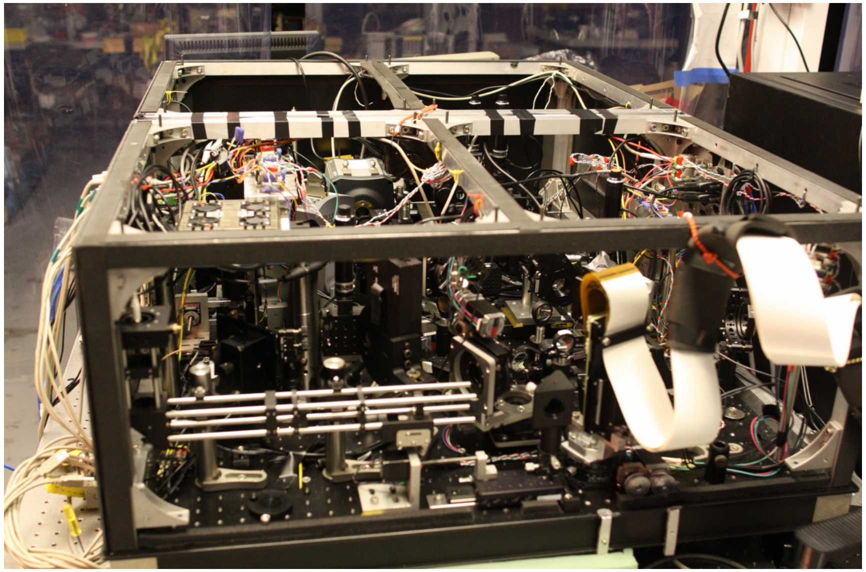


SPHERE (European Southern Observatory)



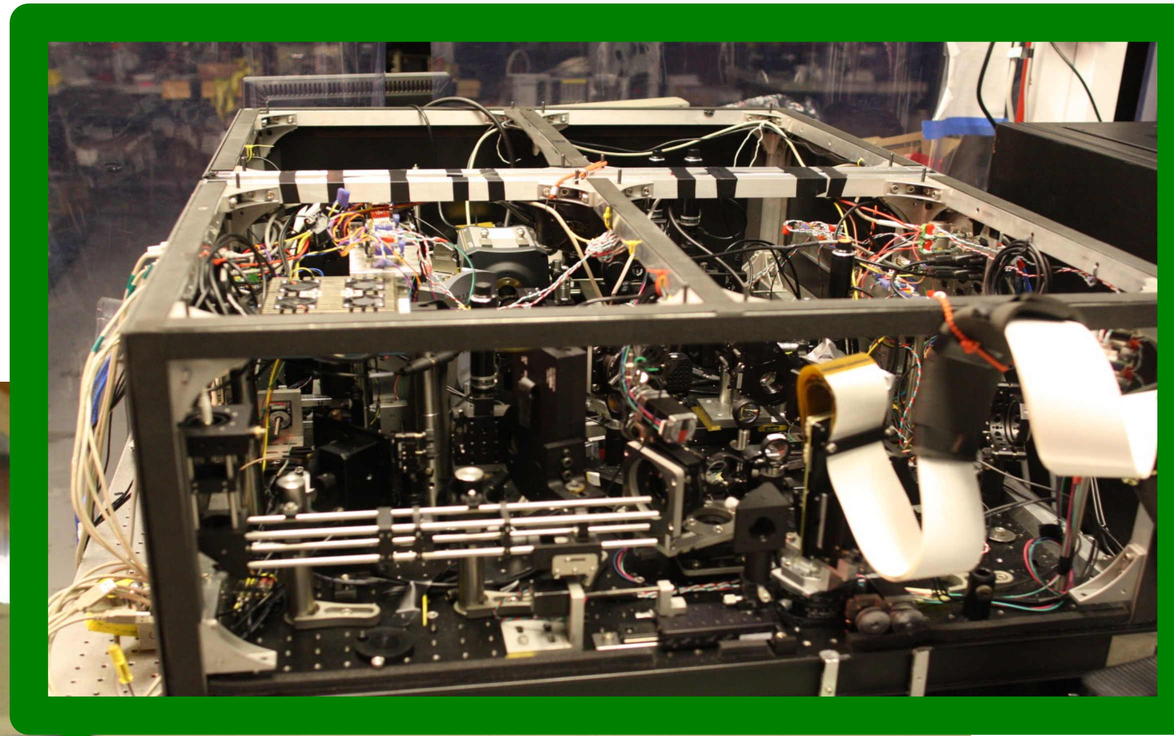
PALM-3000 installed at the Cass focus of the Hale Telescope at Palomar Mountain. Photo: Scott Kardel.

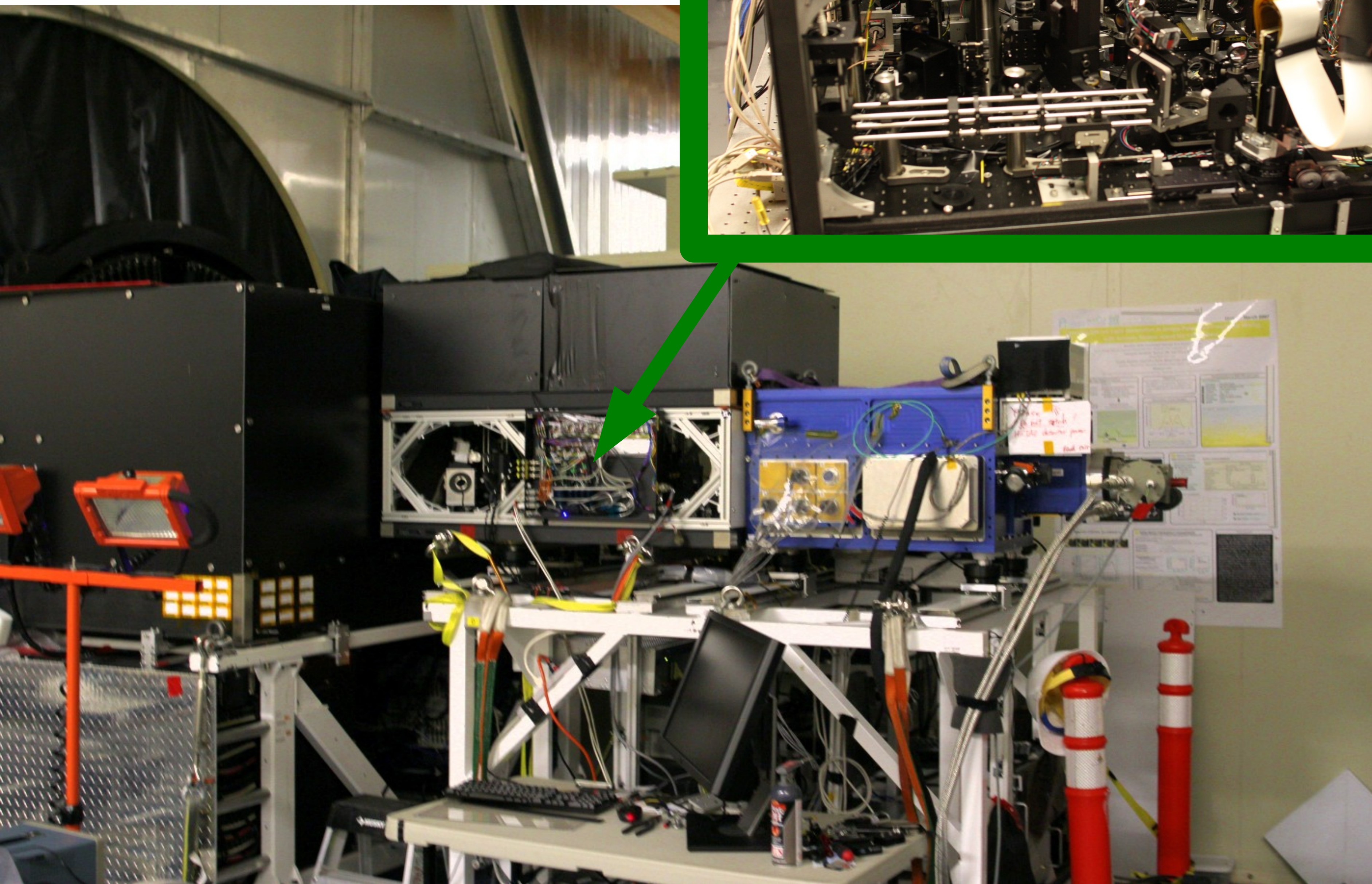
PALM3000/P1640 (Palomar 5-m Telescope)



Subaru Coronagraphic Extreme-AO

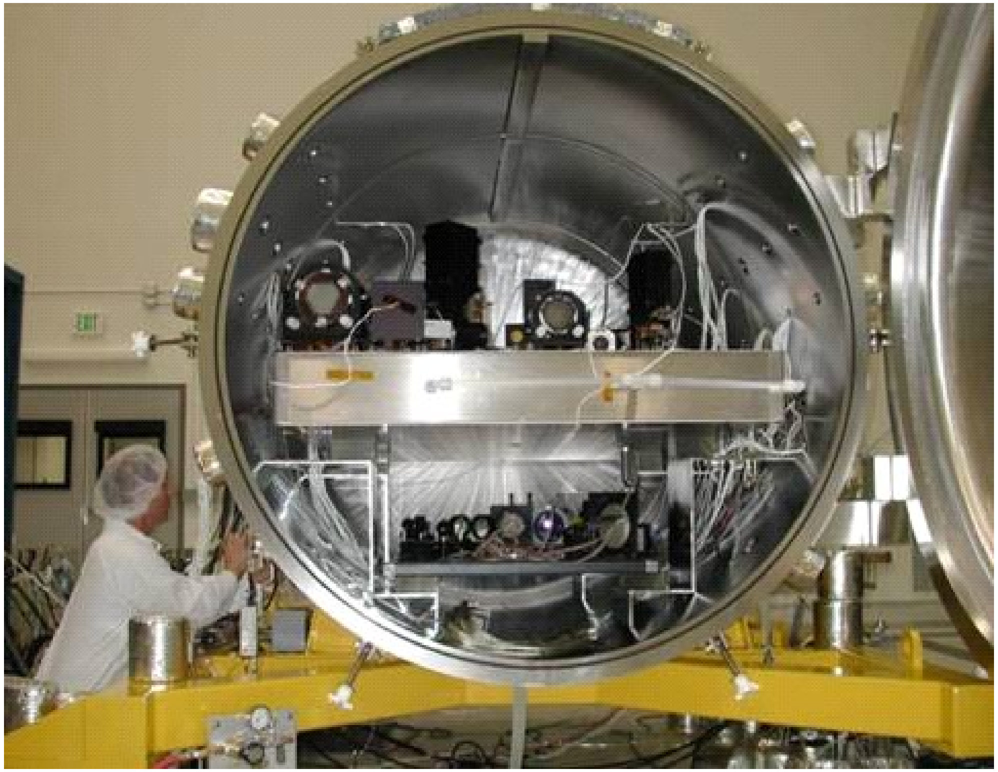
The Subaru Coronagraphic Extreme Adaptive Optics (SCExAO) system



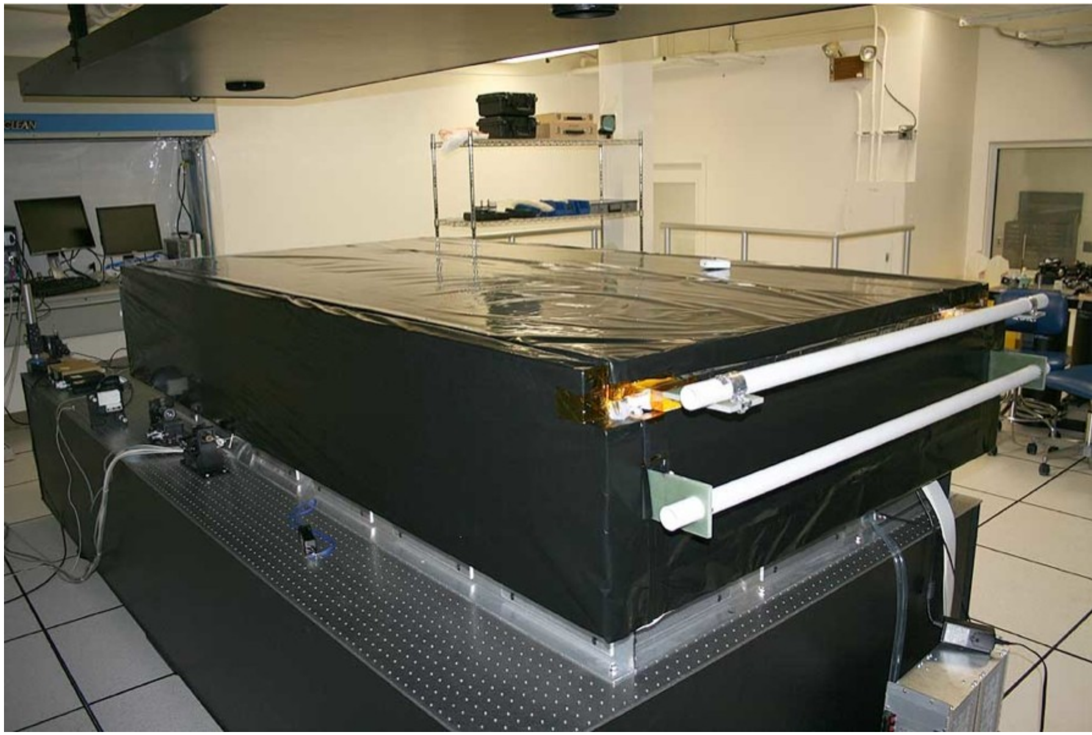


Coronagraphy testbeds for high contrast (< 1e-8) work need to achieve high stability

High Contrast Imaging Testbed (HCIT) is a vacuum facility at NASA JPL

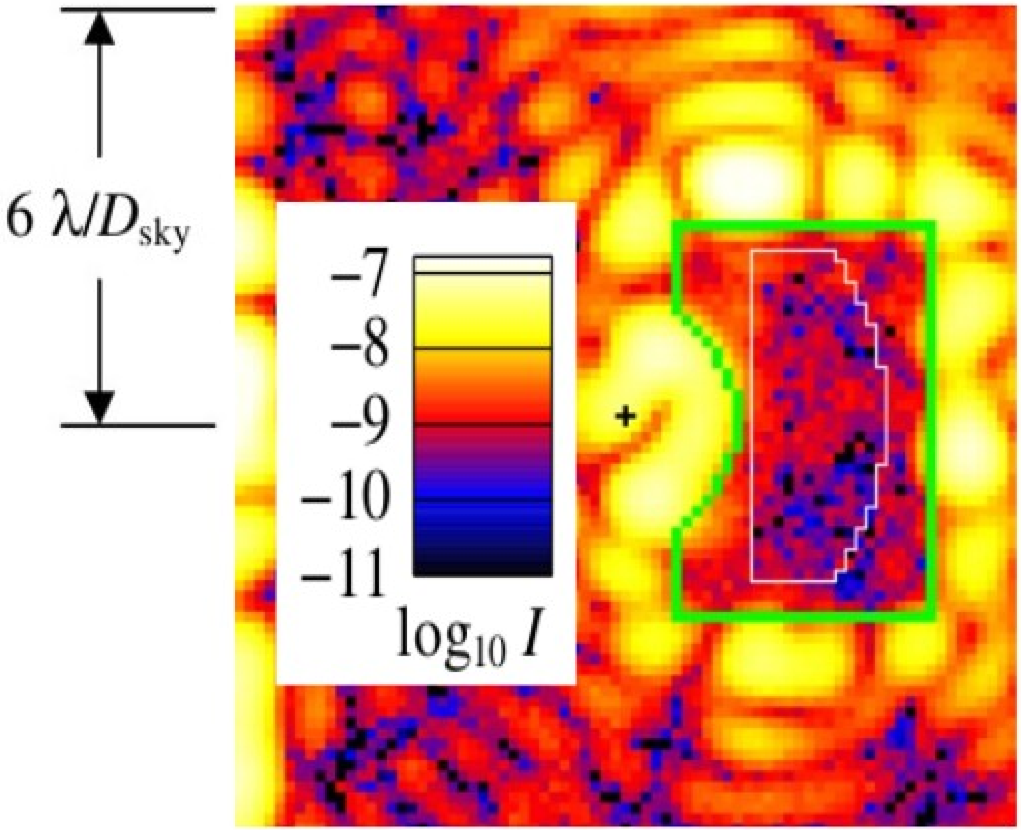


NASA Ames testing PIAA coronagraph / WFC architectures & MEMs DMs.



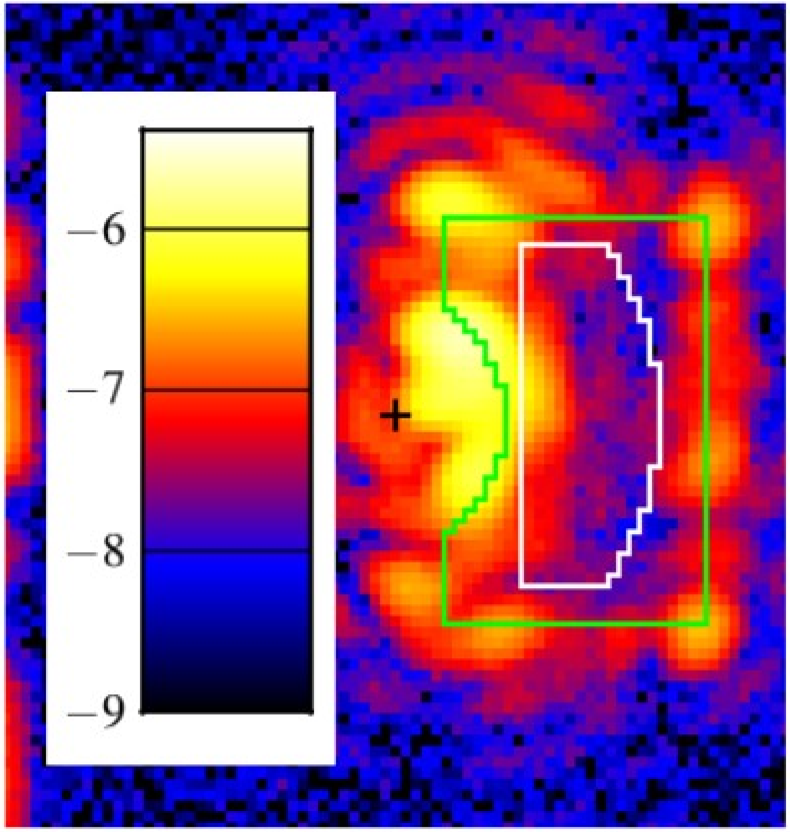
High contrast images obtained in NASA labs
Example: PIAA coronagraph lab results

Monochromatic light (800nm, vacuum)



3 runs, contrast values averaged from 2 to 4 λ/D between 5.10^{-10} to 9.10^{-10} (figure shows $7.3.10^{-10}$ result)

7.5% wide band (770 – 830 nm, in air)



5.10^{-8} contrast from 2 to 4 λ/D,
2.10^{-8} contrast from 3 to 4 λ/D
Contrast performance limited by wavefront instability (test in air)

WFIRST-AFTA 2.4m telescope

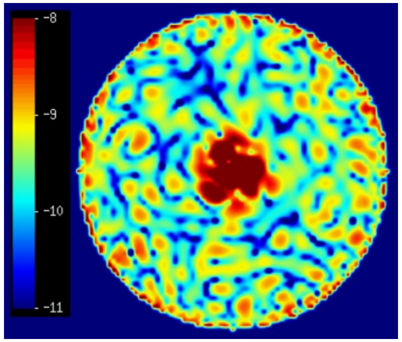
2.4m wide field space telescope (same size as Hubble)
Two instruments:
- wide field near-IR imager
- coronagraph

Will image Jupiter-size planets
… and possibly a few super-Earths

Telescope was originally made for military use, and was donated to NASA

launch < 2025

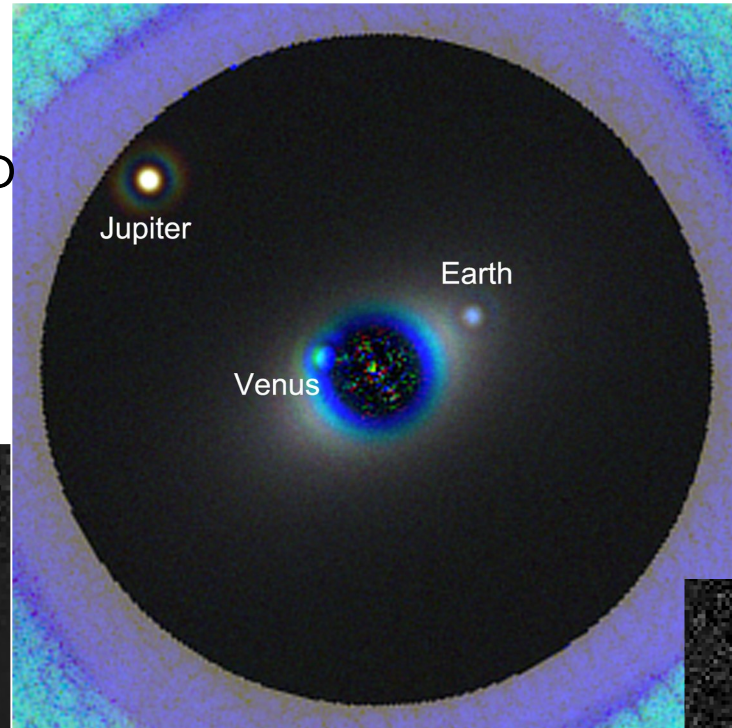
2.4-m telescope assembly



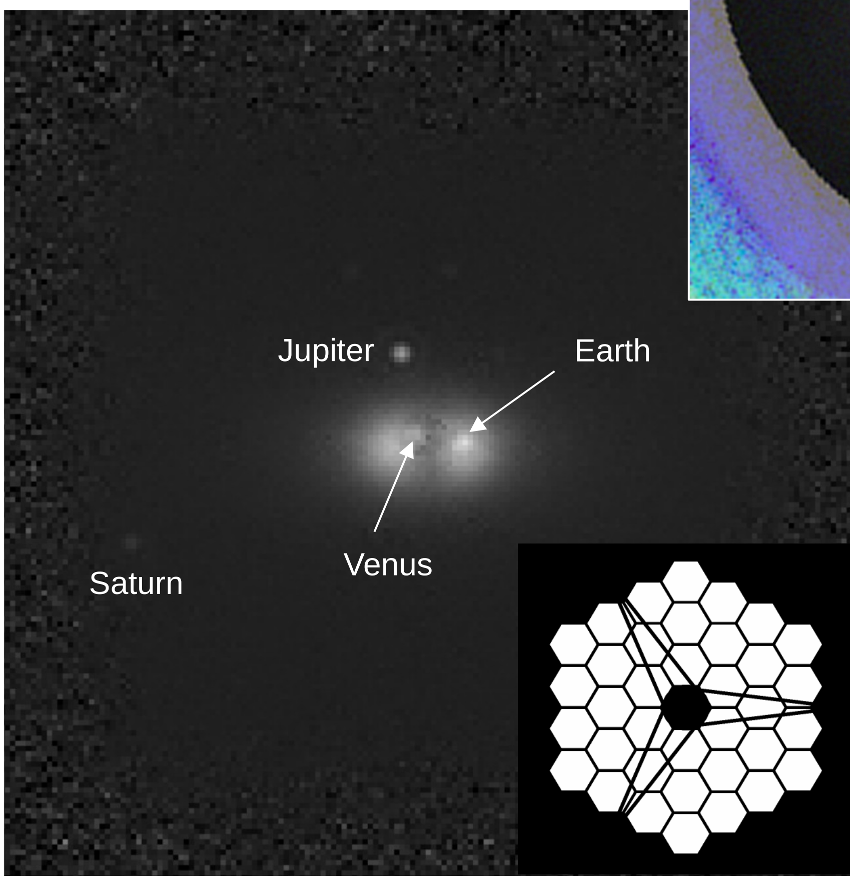
WFIRST-AFTA HLC simulated image (J. Krist, JPL)

Simulated images of solar system twin – 12m telescope, 2 day exposure

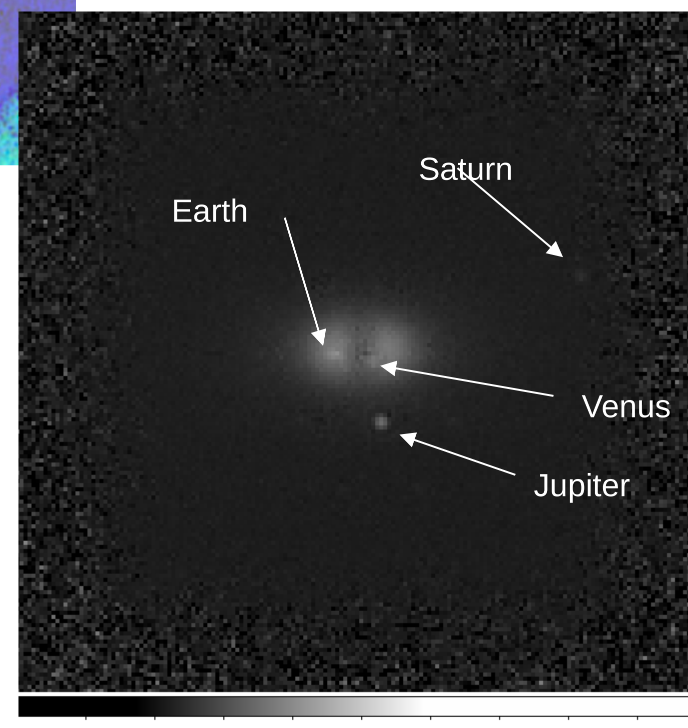
SS twin at 13pc
Visible light
APLC, IWA=3.6 l/D



SS twin at 13pc
near-IR (1600nm)
PIAACMC, IWA=1.2 l/D



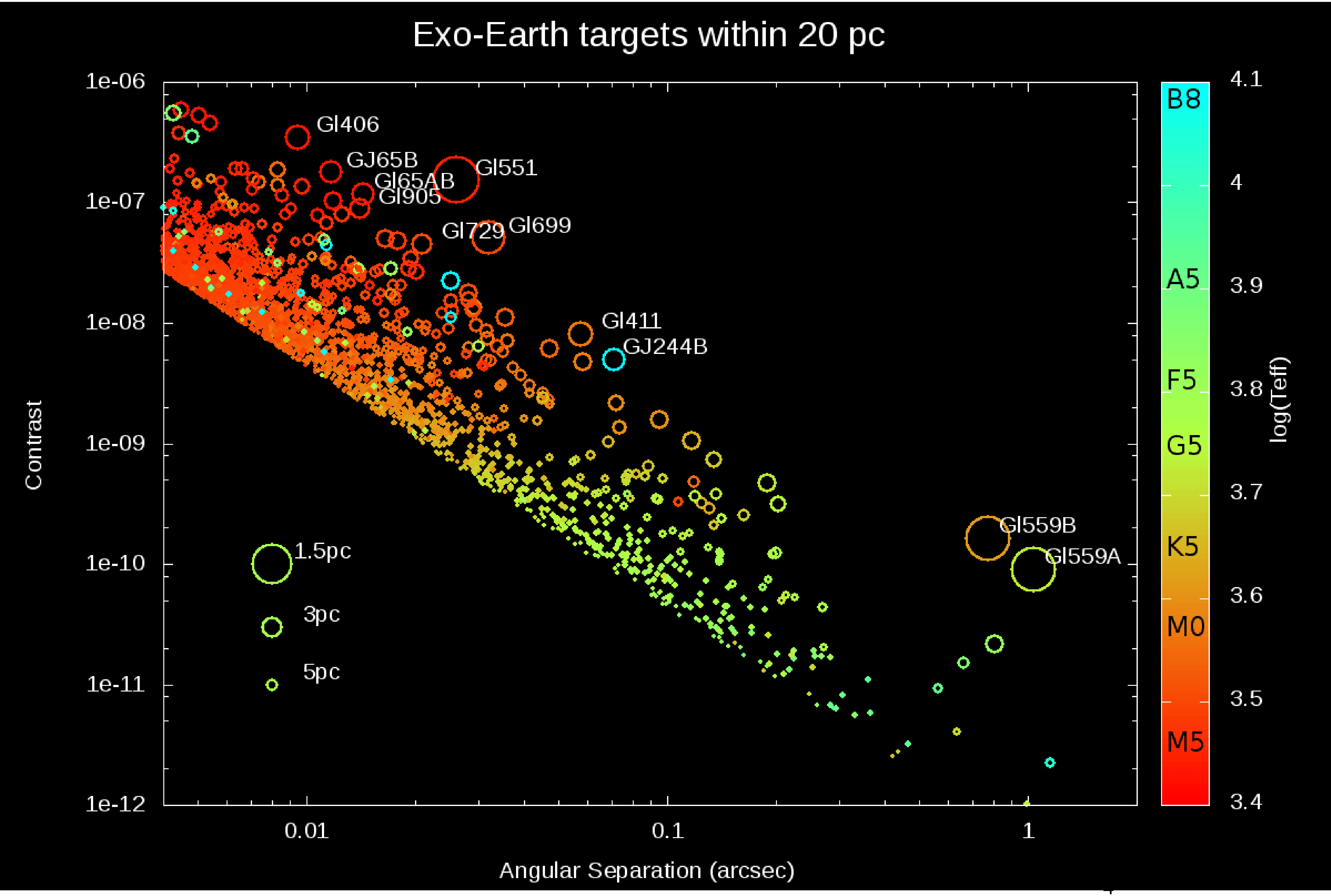
SS twin at 40pc
Visible (550nm)
PIAACMC, IWA=1.2 l/D



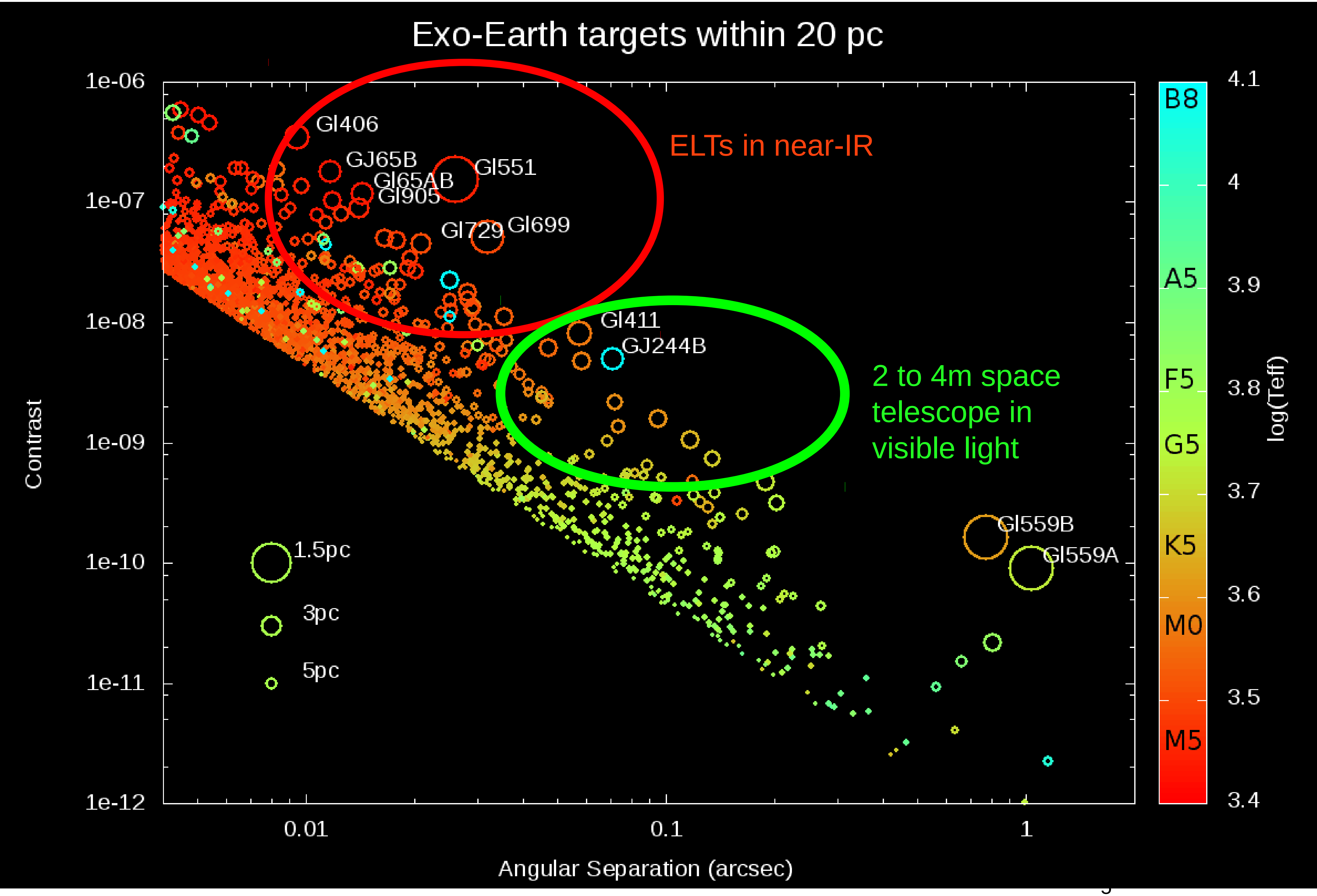
Habitable planet imaging: Scientific opportunities

Space allows access to very high contrast (no atmosphere), but aperture size is limited

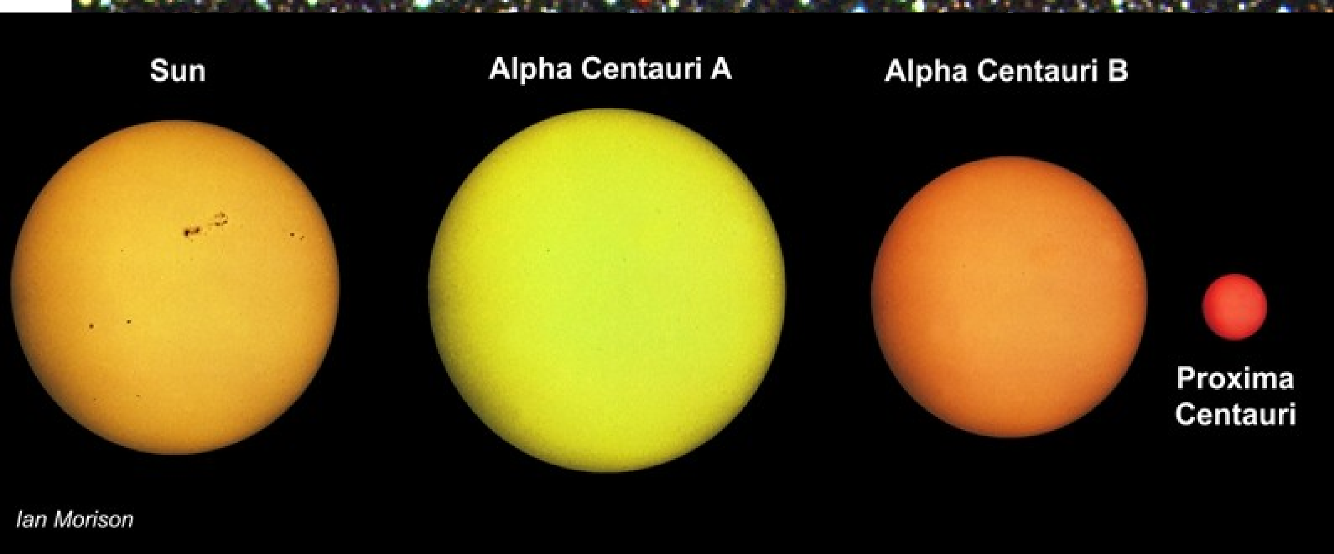
Ground-based telescopes can be very large (~30m), but the contrast is limited due to atmosphere



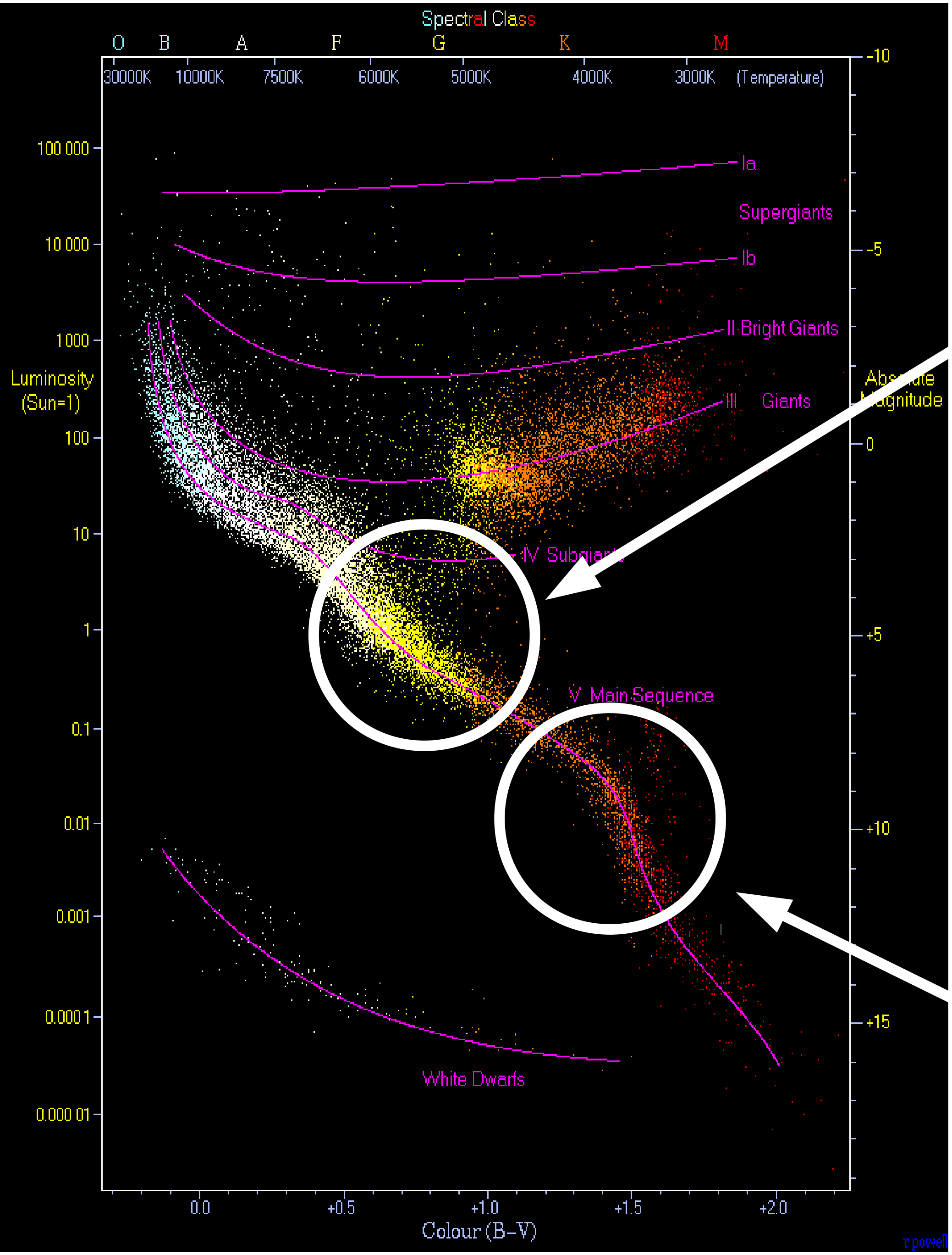
Exo-Earth targets within 20 pc
Contrast
Angular Separation (arcsec)
1e-06
1e-07
1e-08
1e-09
1e-10
1e-11
1e-12
0.01
0.1
1
Gl406
GJ65B
Gl551
Gl65AB
Gl905
Gl729
Gl699
Gl411
GJ244B
Gl559B
Gl559A
1.5pc
3pc
5pc
B8
A5
F5
G5
K5
M0
M5
4.1
4
3.9
3.8
3.7
3.6
3.5
3.4
log(Teff)


Exo-Earth targets within 20 pc
ELTs in near-IR
2 to 4m space telescope in visible light
Gl406
GJ65B
Gl65AB
Gl905
Gl551
Gl729
Gl699
Gl411
GJ244B
Gl559B
Gl559A
1.5pc
3pc
5pc
Contrast
1e-06
1e-07
1e-08
1e-09
1e-10
1e-11
1e-12
Angular Separation (arcsec)
0.01
0.1
1
B8
A5
F5
G5
K5
M0
M5
log(Teff)
4.1
4
3.9
3.8
3.7
3.6
3.5
3.4

Proxima Centauri



Imaging habitable planets from space and ground



------------- Space ---------------

Habitable planets can be imaged around nearby Sun-like stars with 2-4m telescope

--------- Ground --------------

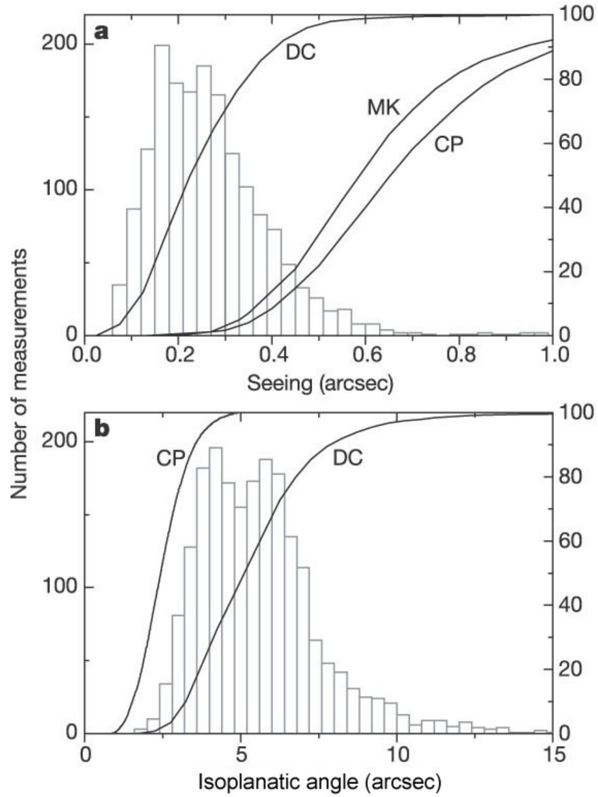
Next generation of 30-m telescopes will image habitable planets around nearby low-mass stars

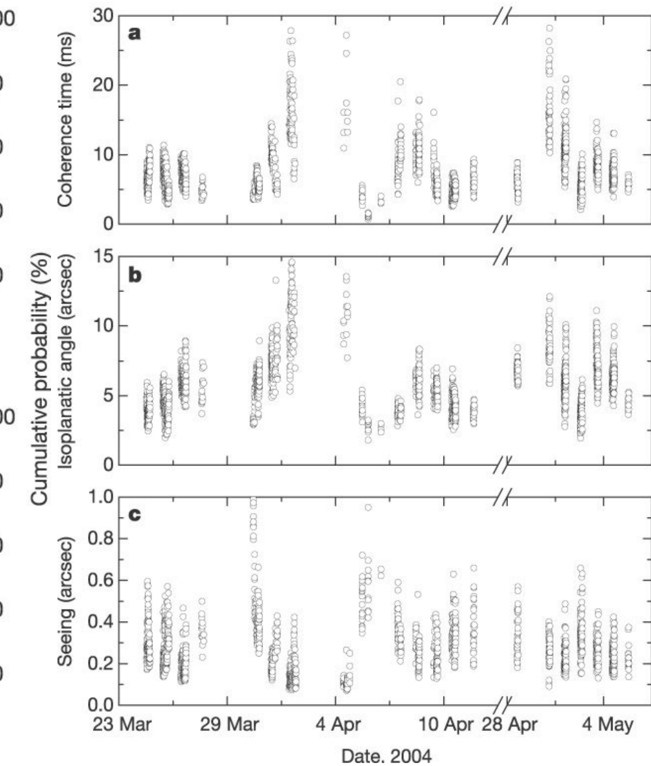
Benefits of an Antartica site for exoplanet imaging

Table 1 **Comparison of observatory site conditions**

Site	ϵ_0	θ_0	τ_0
Dome C	0.27	5.7	7.9
South Pole	1.8	3.2	1.6
Mauna Kea	0.5–0.7	1.9	2.7
San Pedro Martir	0.59	1.6	6.5
Cerro Paranal	0.80	2.6	3.3
La Palma	0.76	1.3	6.6

ϵ_0 is the seeing in arcseconds, θ_0 is the isoplanatic angle in arcseconds and τ_0 is the coherence time in milliseconds. All values are corrected to the zenith and at a wavelength of 500 nm. Seeing, isoplanatic angle and coherence time at South Pole are mean total atmosphere values (above ground-level) from 16 microthermal balloon launches in winter 1995 combined with microthermal tower measurements of the 0–30 m ground layer[7]. Seeing and isoplanatic angle values at Mauna Kea, Hawaii are based on 20 nights of SCIDAR observations in 1995 (seeing above ground level)[1], and FWHM measurements from the Auto Guider of the Subaru telescope during focus checks over a 12 month period from 2000 to 2001 (seeing above ~15 m)[4]. Seeing from San Pedro Martir, Mexico, is the median from 2 yr of DIMM measurements (seeing above 8 m)[3]. Isoplanatic angle and coherence time from San Pedro Martir are obtained with generalized SCIDAR (located 15 m above ground level) over 27 nights in 1997 and 2000[29]. Seeing and isoplanatic angle from Cerro Paranal, Chile, are average values from DIMM measurements (above 5 m) over 10 yr (1989–95 and 1998–2002)[2]. The coherence time at Cerro Paranal is derived (to an accuracy of 20%) from DIMM measurements combined with balloon-borne wind speed measurements[2]. Seeing from La Palma, Canary Islands, is from 9 months of DIMM measurements (seeing above 5 m)[5]. Isoplanatic angle and coherence time from La Palma are from six microthermal balloon launches[30] in 1990.





(Lawrence et al. 1994)

Small seeing size
Slow seeing

Very good seeing → high contrast imaging boost

Low IR background → better sensitivity to self-luminous planets (mid-IR "high contrast" interferometry ?)

Benefits of an Antartica site for exoplanet imaging

ExAO contrast

In a closed-loop AO system:
Raw contrast = C0 D^(-2) r0^(-5/9) v^(2/3) lambda^(-13/9)

DomeC vs Maunakea :

0.27" vs. 0.65" → r0 is 2.4x larger
7.9ms vs. 2.7ms → v is 3x slower

DomeC contrast is ~4x better than MK
The same contrast limit can be reached with a telescope 2x smaller: 15m telescope @ domeC = 30m telescope on MK

Technology:
- ExAO system on DomeC would run 4x slower than on MK (easier)
- Same # of actuators (defined by field of view)
- Easier linearity and calibration

Angular resolution, contrast, wavelength

A 15m domeC telescope would have the contrast but lack the angular resolution to access ExoEarths around M-type stars
Options:
→ larger telescope, slightly hotter stars
22m telescope, contrast gain over MK30m telescope = 2.15x corresponding angular resolution gain = 1.47 ~ 30m/20m

→ shorter wavelength (but loose near-IR spectroscopy)

Spectroscopy and water detection

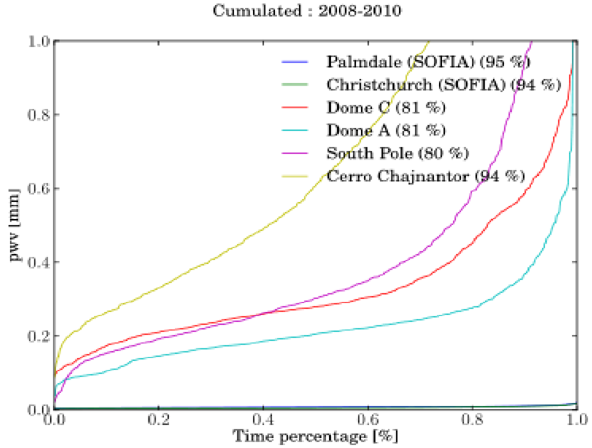
Water is an excellent biomarker, but extremely difficult to detect at low (<Earth) concentration.

Requires simultaneous spectroscopy of planet and star to calibrate atmospheric transmission.
Lower SNR in water absorption bands.

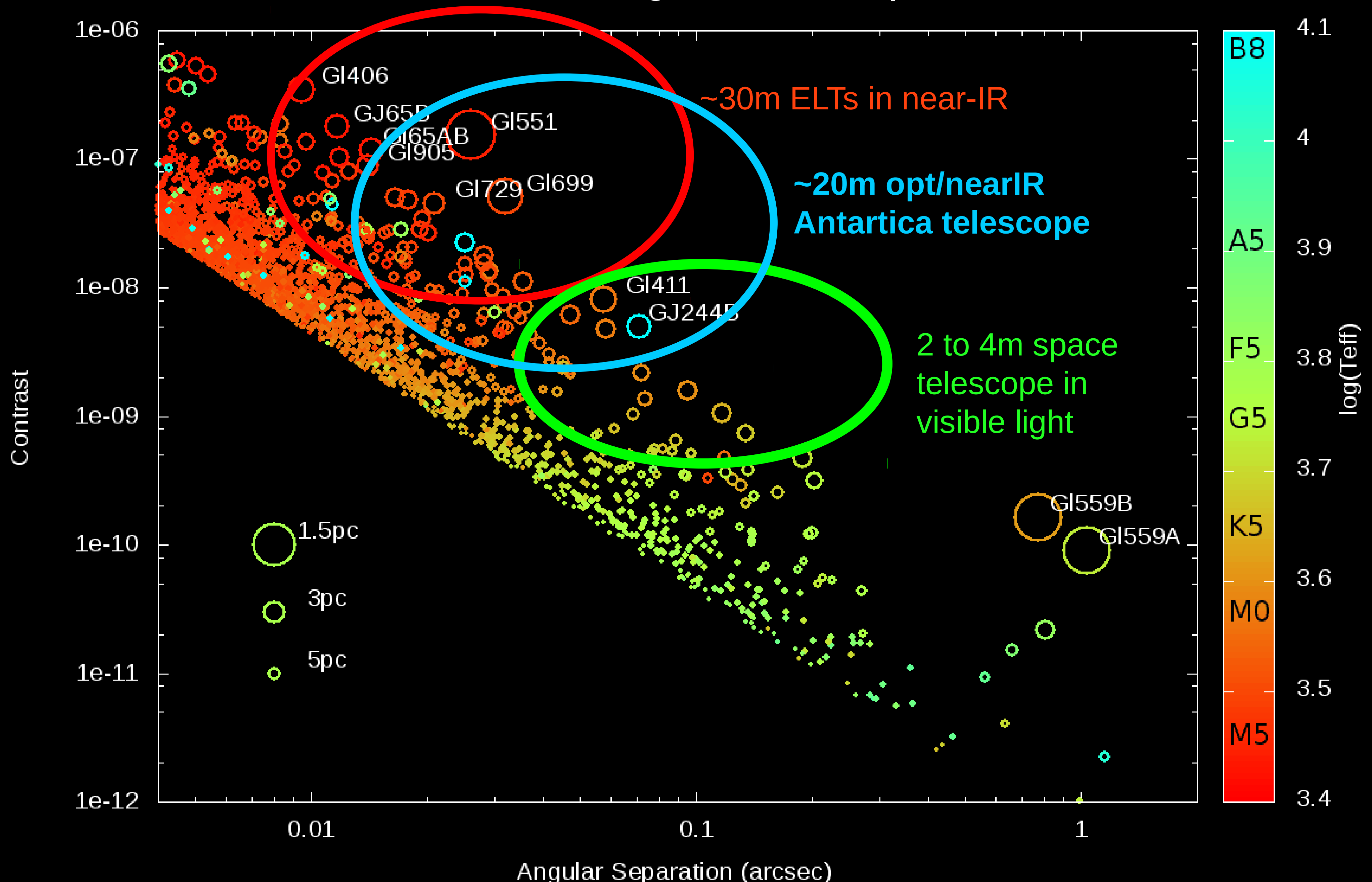
TPW (Tremblin et al. 2012)

Time fraction 2008-2010	SOFIA (Palm./Christ.)	Dome A	Dome C	South Pole	Cerro Chajnantor
0.10	0.006/0.004	0.11	0.17	0.15	0.27
0.25	0.006/0.005	0.16	0.22	0.21	0.37
0.50	0.007/0.006	0.21	0.28	0.30	0.61
0.75	0.009/0.007	0.26	0.39	0.49	1.11

Time fraction 2008-2010	Chajnantor Plateau	Summit	Cerro Macon	Mauna Kea	Yangbajing
0.10	0.39	0.36	0.47	0.62	1.21
0.25	0.53	0.51	0.66	0.91	2.47
0.50	0.86	0.94	1.02	1.44	inf
0.75	1.63	1.96	1.66	2.57	inf



Exo-Earth targets within 20 pc



Path forward – how SCAR can help

Other exciting things to do with a ~20m optical near-IR telescope in Antartica ?

- mid-IR imaging → planet formation, higher angular resolution compared to JWST
- high precision astrometry thanks to reduced high altitude turbulence
- precision photometry: transit photometry

Initiate working group / discussion to evaluate/gather interest in exoplanet + mid-IR large telescope