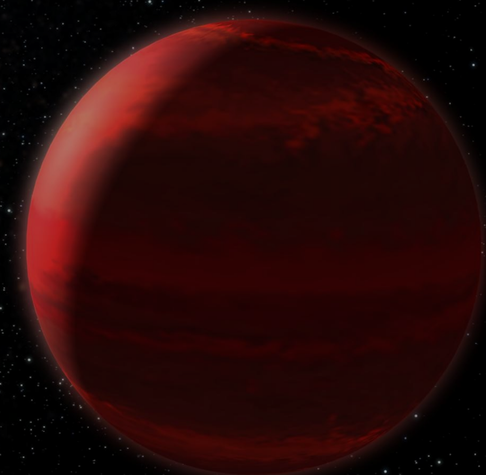
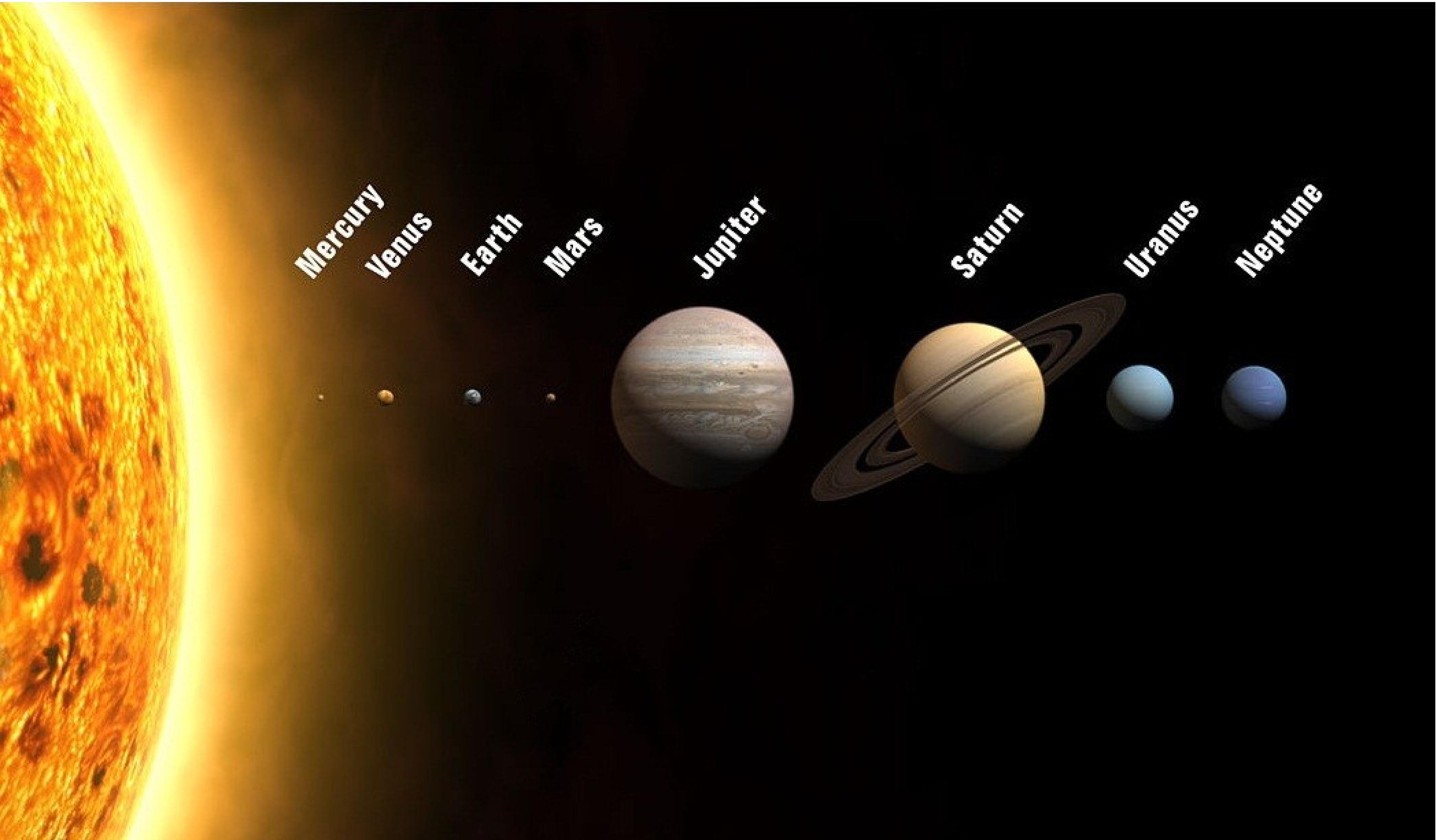
Anybody out there ?

Optical Tricks to Find and Study Exoplanets

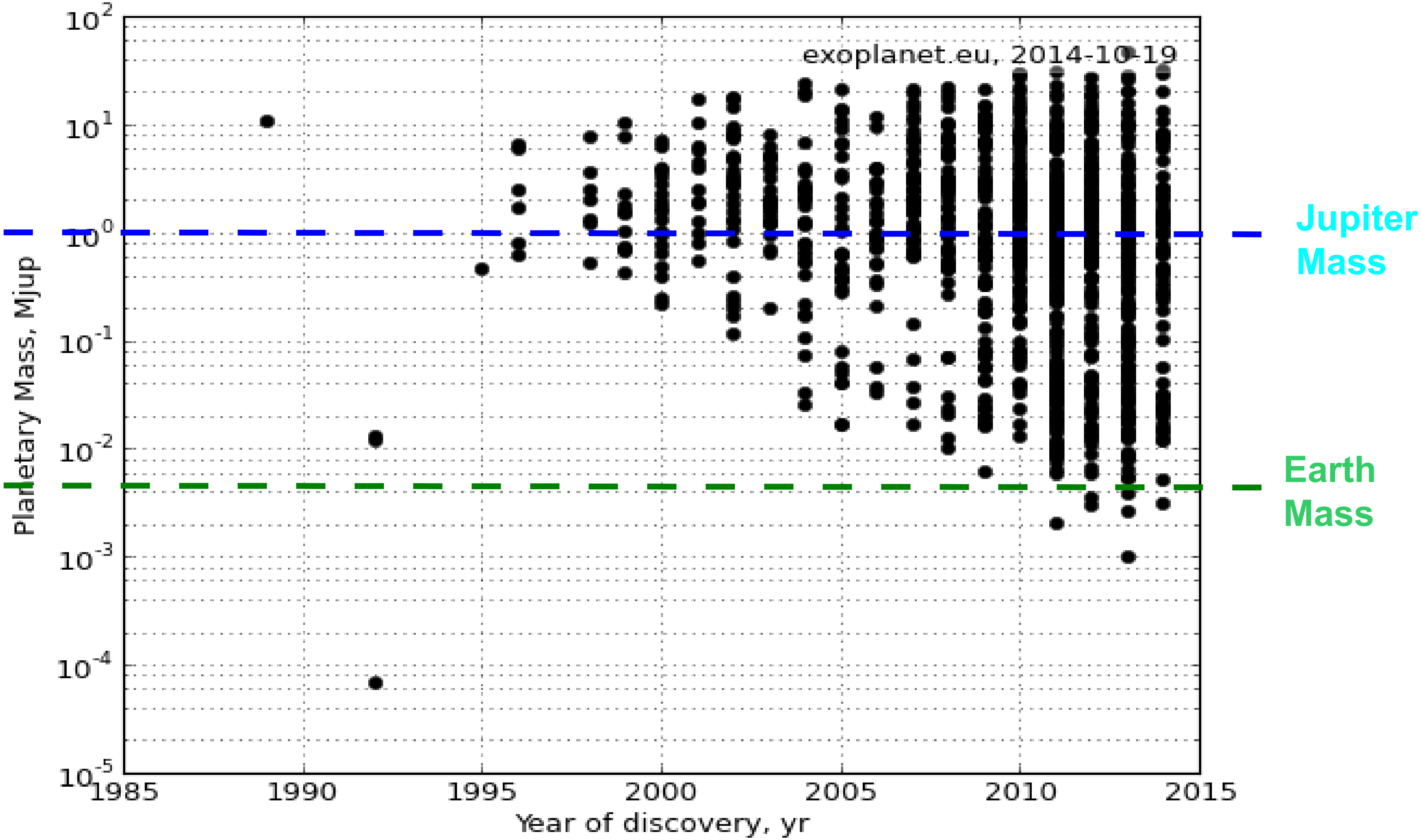


Contact: oliv.guyon@gmail.com

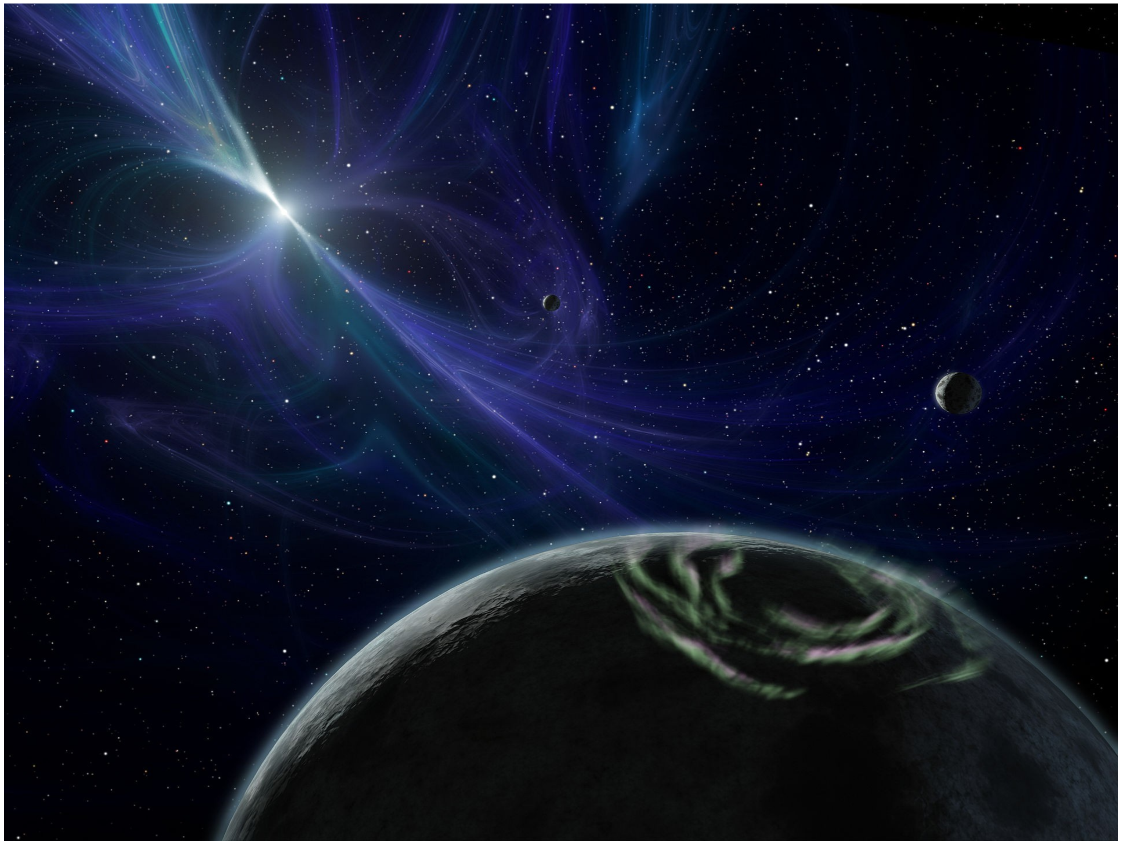
ALL known Planets from 1846 to 1989



Planets identified – we are now starting to identify Earth-size planets



Oddballs



PSR 1257+12 : 3 planets around a pulsar

How could planets survive a supernova ?
Planets may have formed from debris after the supernova explosion

51 Peg b : The first confirmed "Hot Jupiter"

A Jupiter-size planet at only 5.3% of the Sun-Earth distance from its host star, orbiting in 4.2 days

Exoplanet Detection Methods Visualized

PHL
MAPPING THE HABITABLE UNIVERSE

Simple Telescope

A twinkling star caused by atmospheric effects

Pulsar Timing
[5]

Pulsar Frequency by Radio
[orbit • mass]

Radial Velocity
[511]

Star Motion by Doppler Effect
[orbit • mass]

Transit
[1,137]

Star Brightness by Eclipse
[orbit • radius • atmosphere]

Stars appear to twinkle with many colors as observed by the naked eye or simple telescopes.

Precise instruments were required to remove this atmospheric effect and reveal planets.

Since 1992 we know of over 1,800 planets around other stars detected by six main methods.

Astrometry
[1]

Star Motion by Imaging
[orbit • mass]

Microlensing
[26]

Star Brightness by Lensing
[orbit • mass]

Direct Imaging
[35]

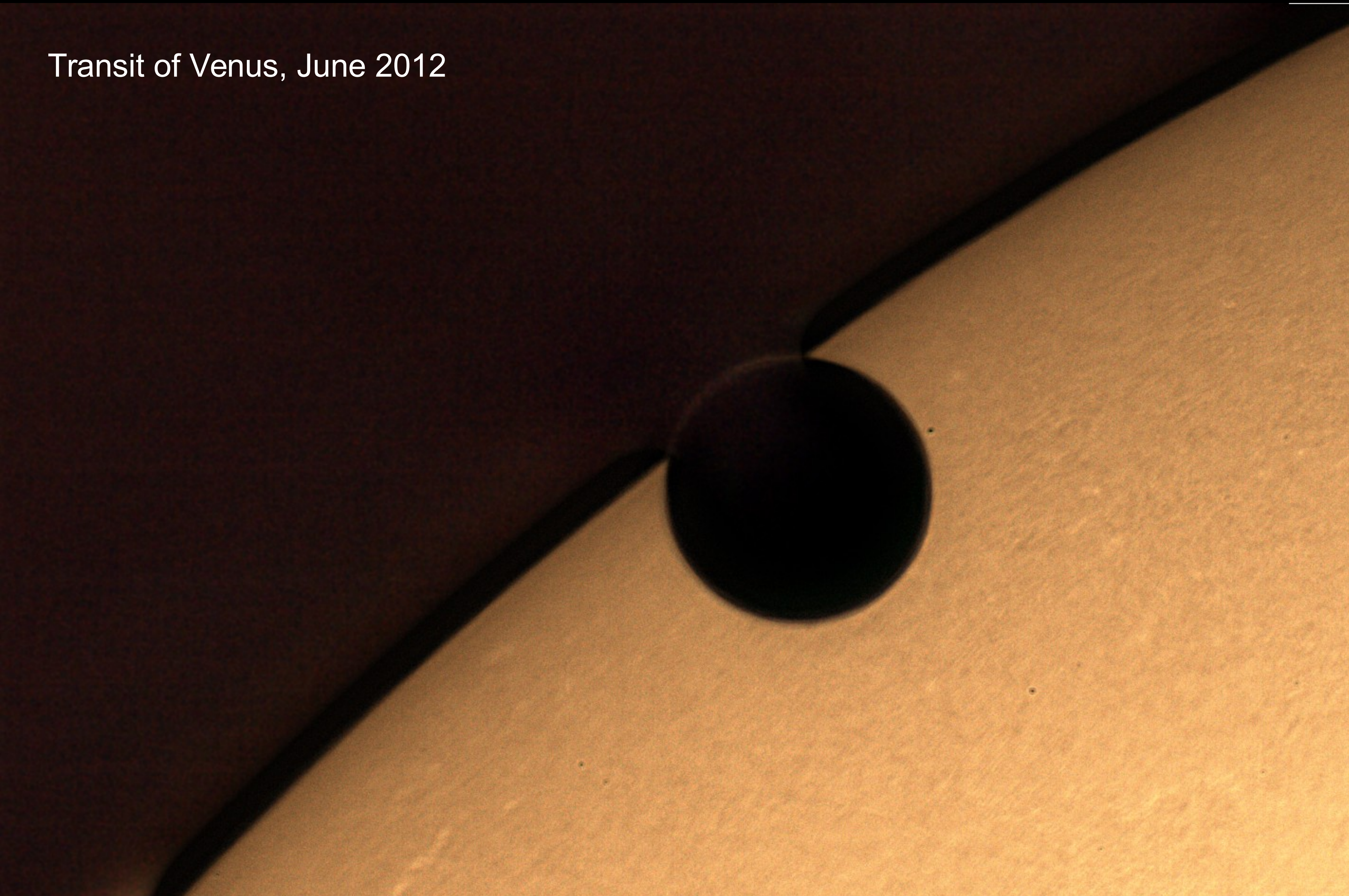
Planet Brightness by Imaging
[orbit • radius • atmosphere]

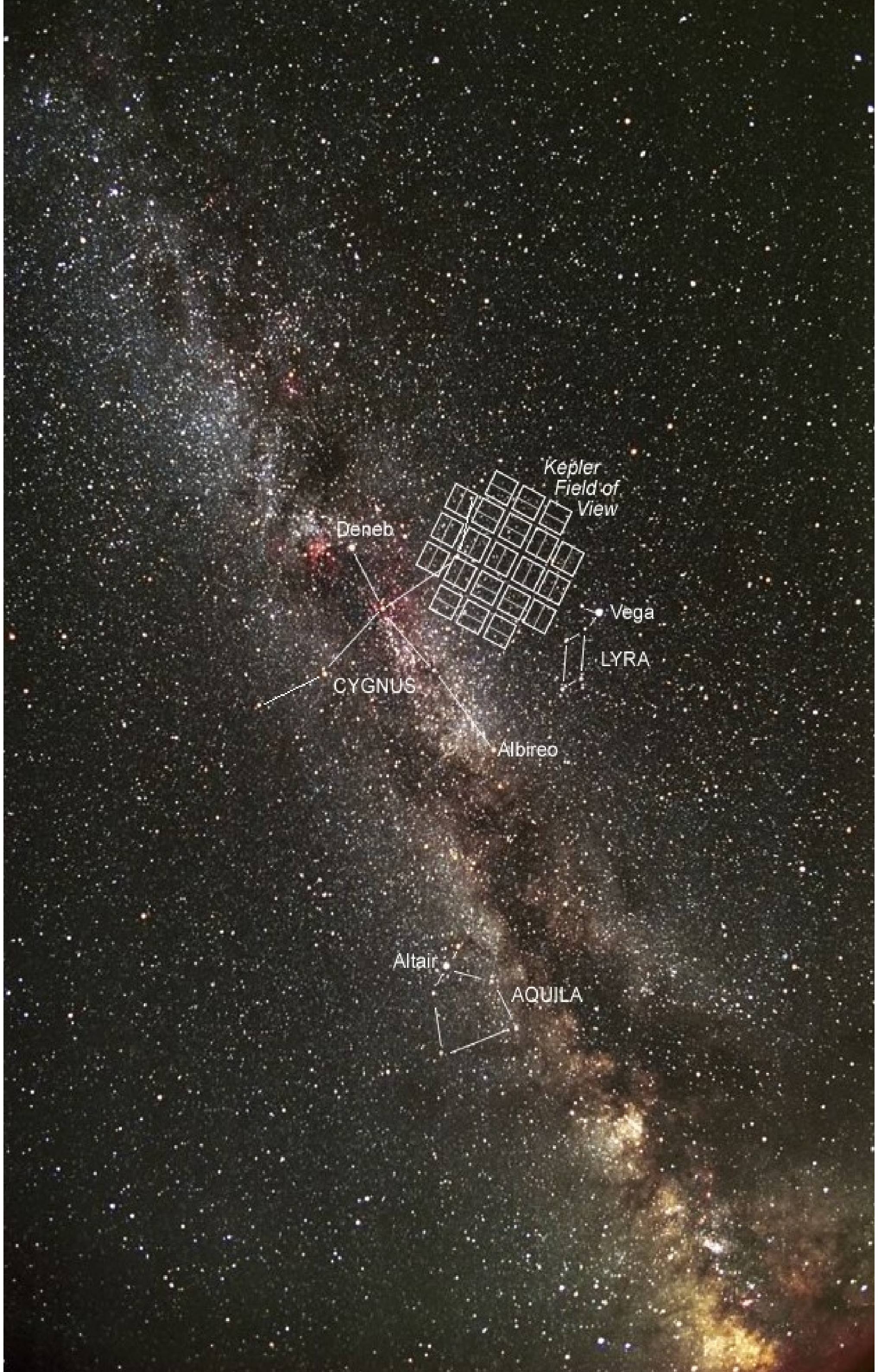
Planet effects on stars are exaggerated for clarity. Numbers correspond to the number of planets detected so far by each method.

CREDIT: PHL @ UPR Arecibo

Exoplanet transit

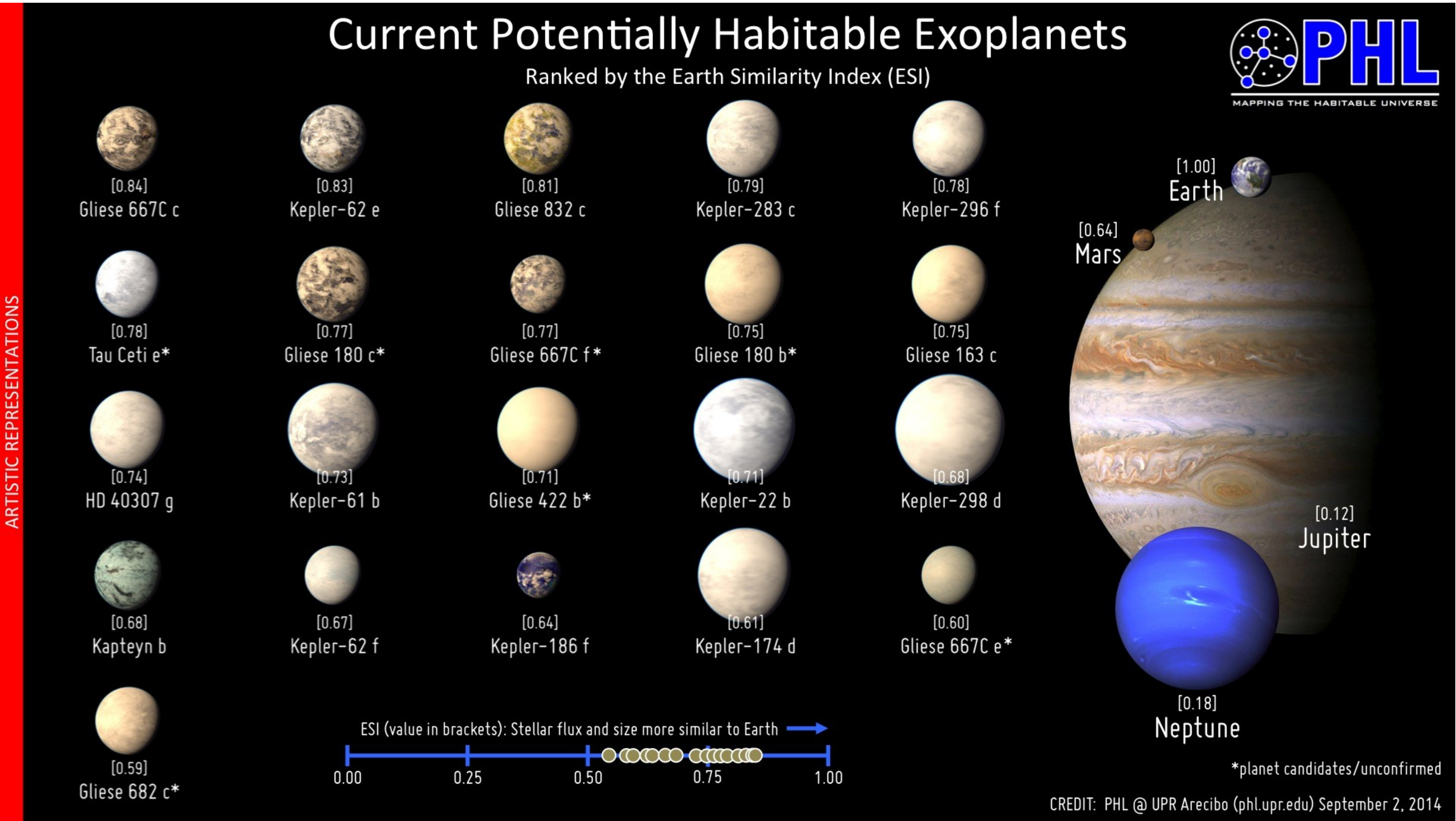
If the planet passes in front of its star, we see the star dimming slightly



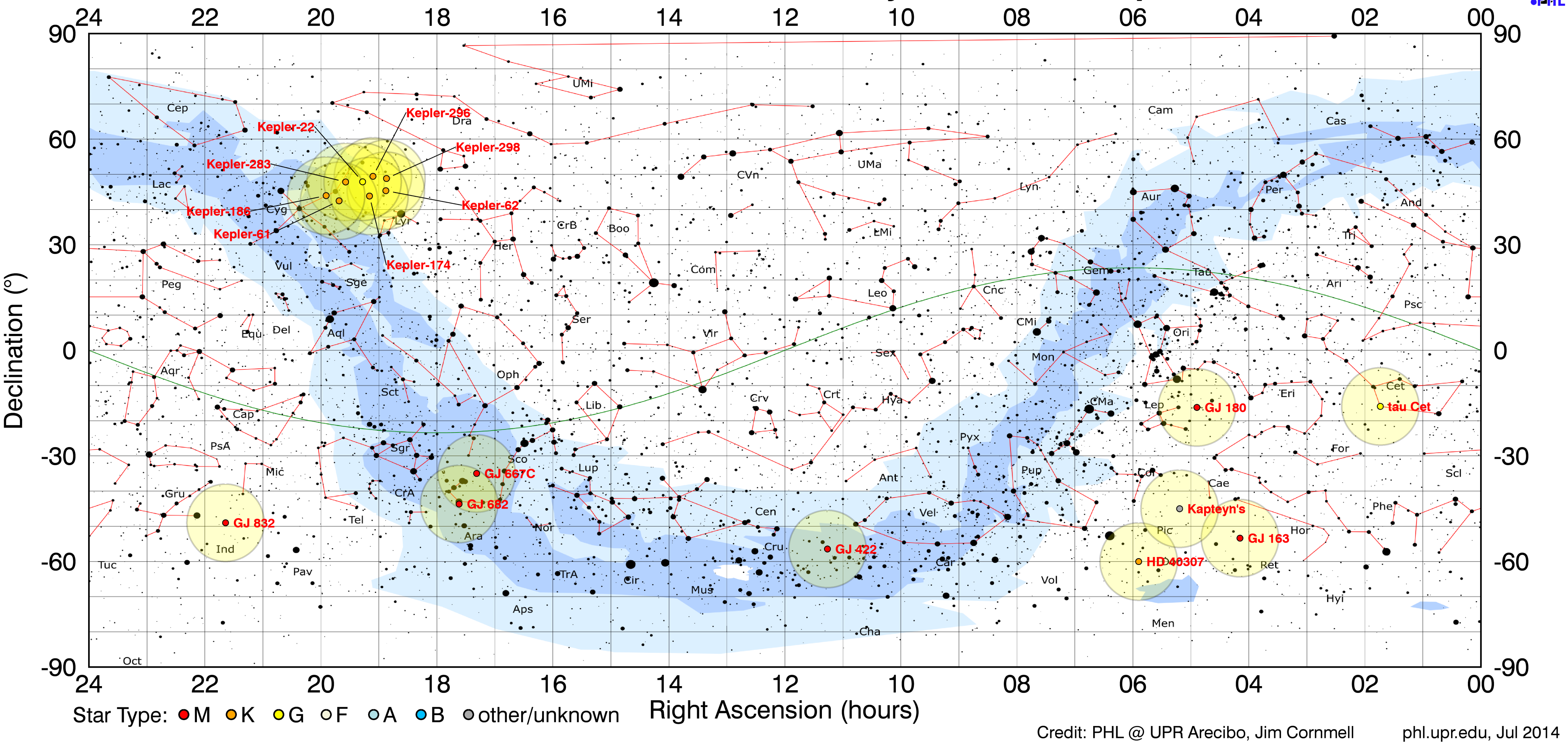

Kepler
Field of
View
Deneb
Vega
LYRA
CYGNUS
Albireo
Altair
AQUILA

Kepler (NASA)

>~10% of stars have potentially habitable planet
First potentially habitable planets now identified



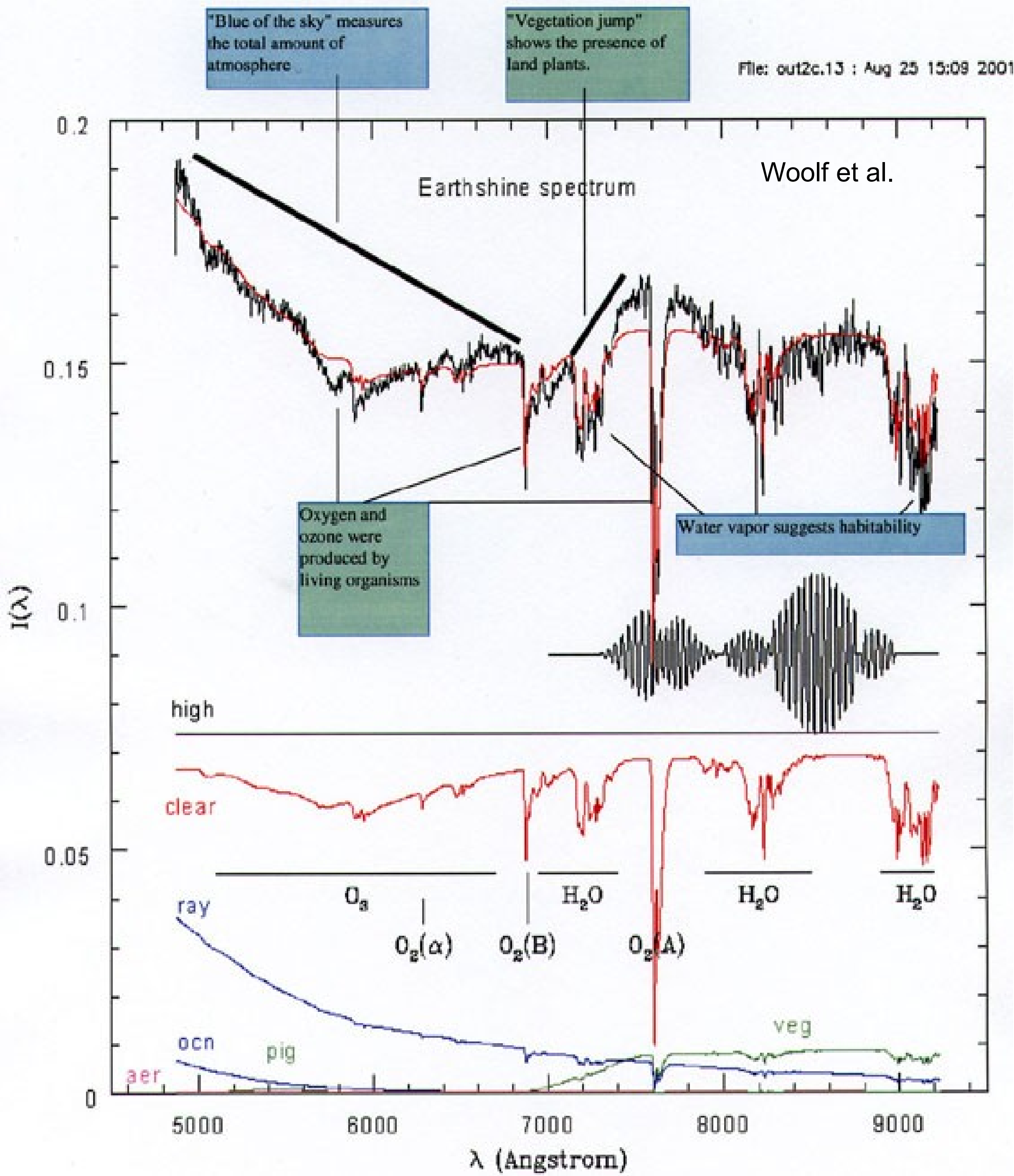
Location of the Stars with Potentially Habitable Exoplanets



Directly imaging planet is necessary to find life

We need to take spectra of habitable planets

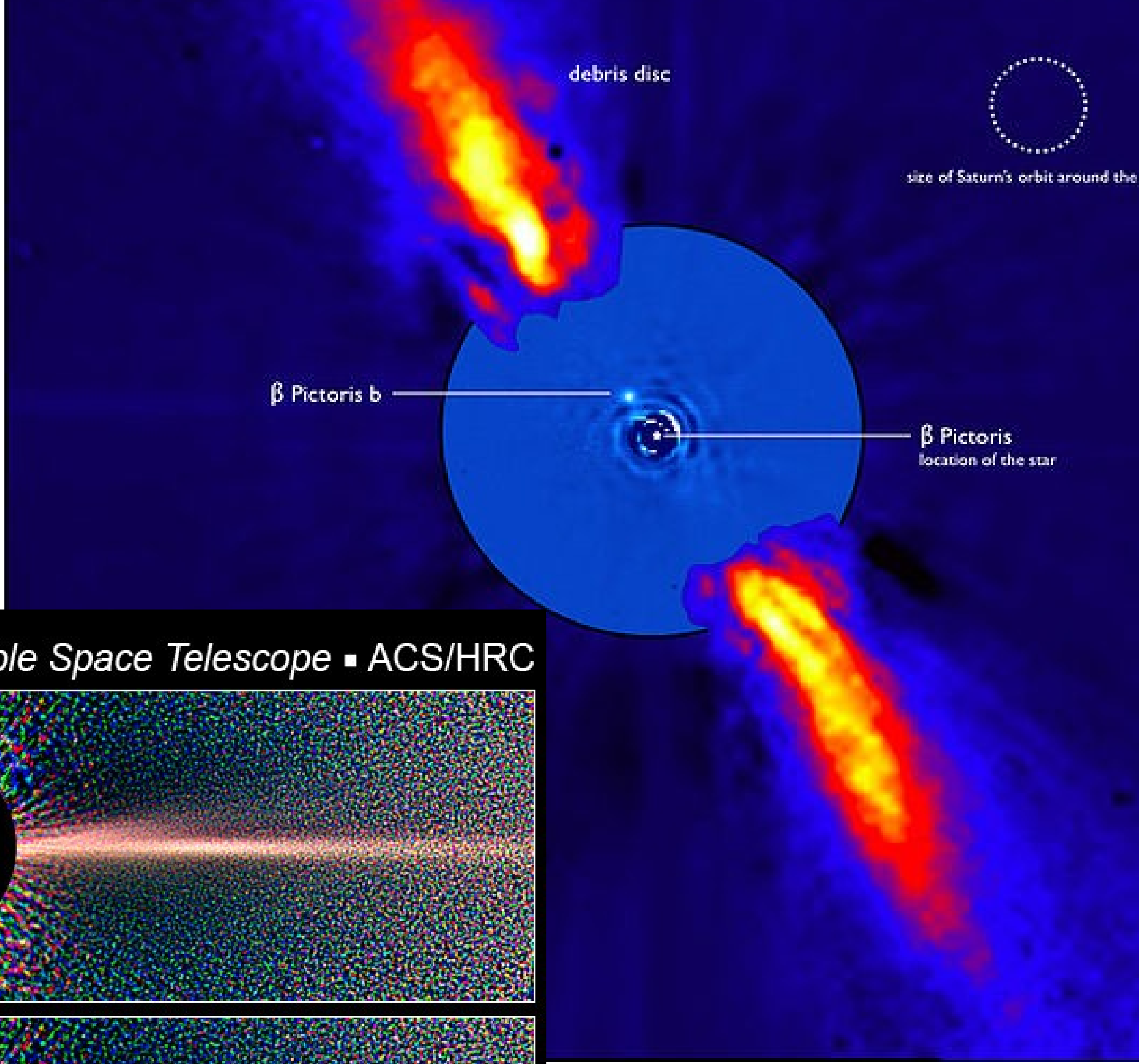
Spectra of Earth (taken by looking at Earthshine) shows evidence for life and plants



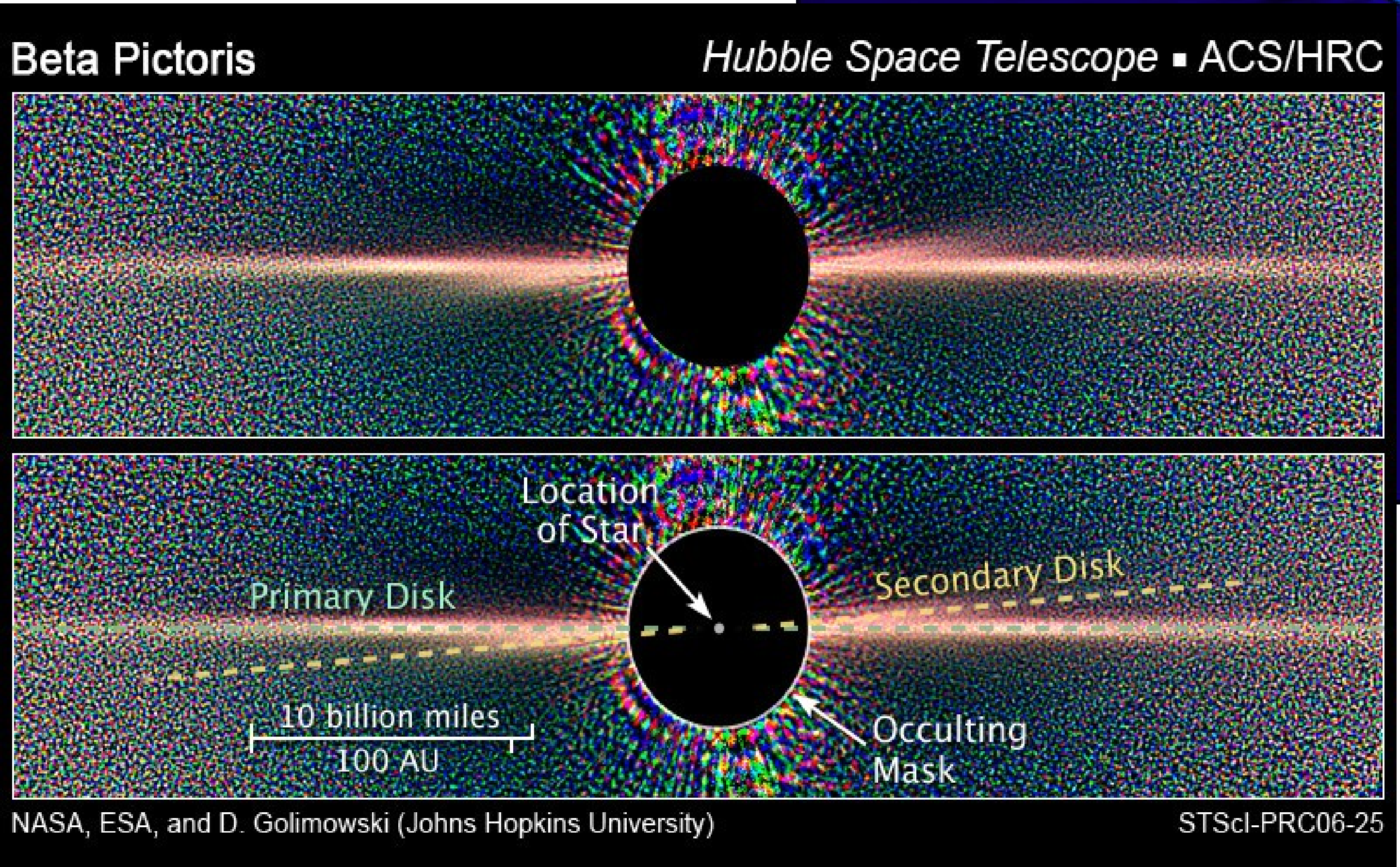
Beta Pictoris

8 Jupiter mass planet

Orbits young massive star in ~20yr

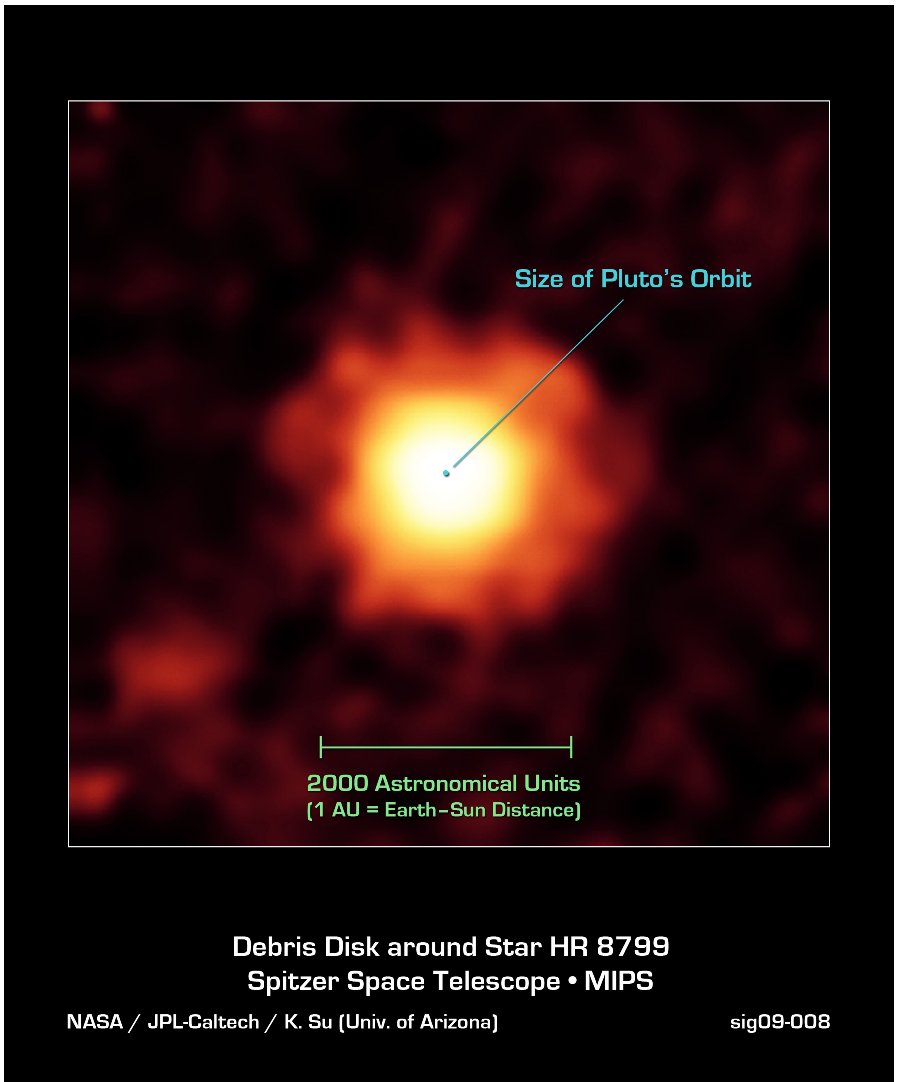


ESO VLT image (Lagrange et al.)

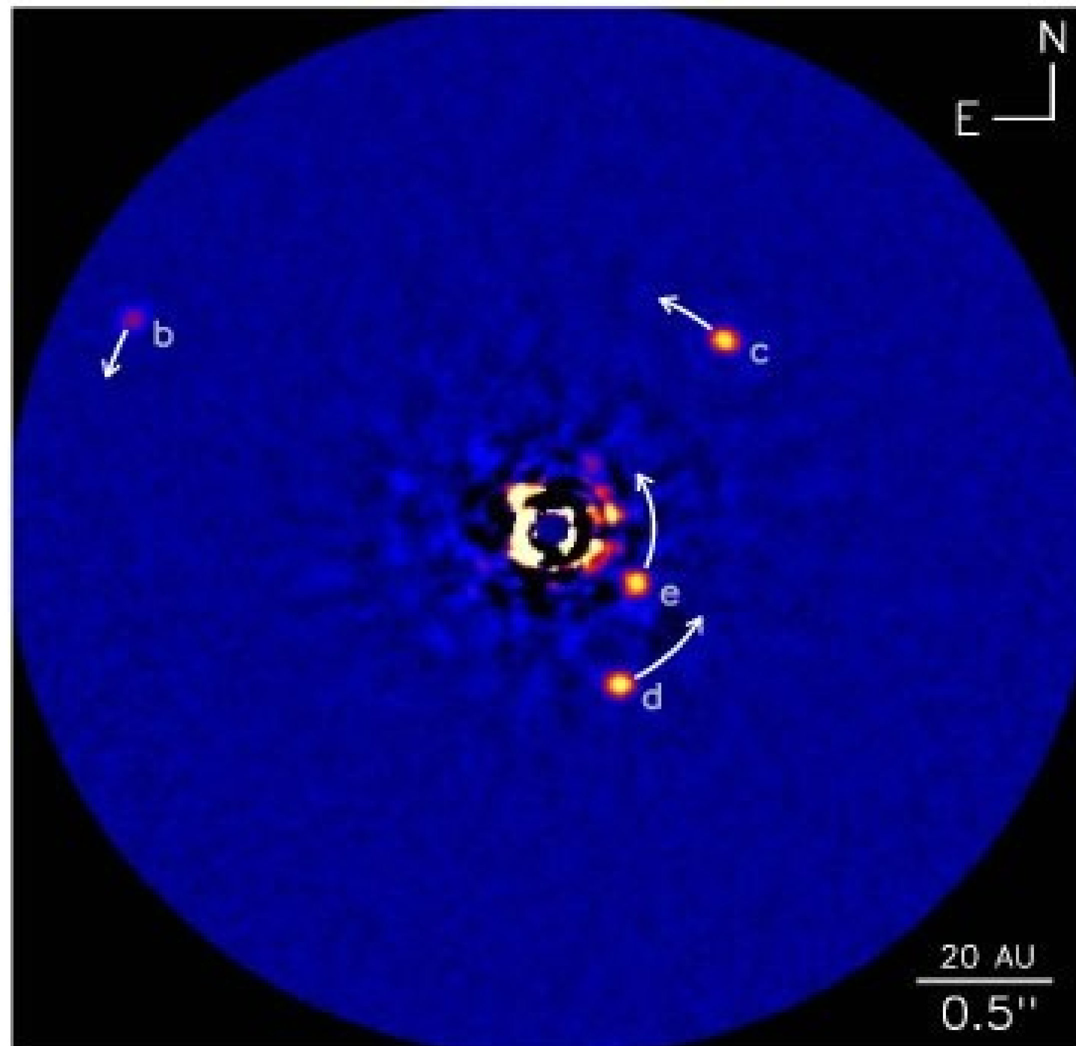


HR8799

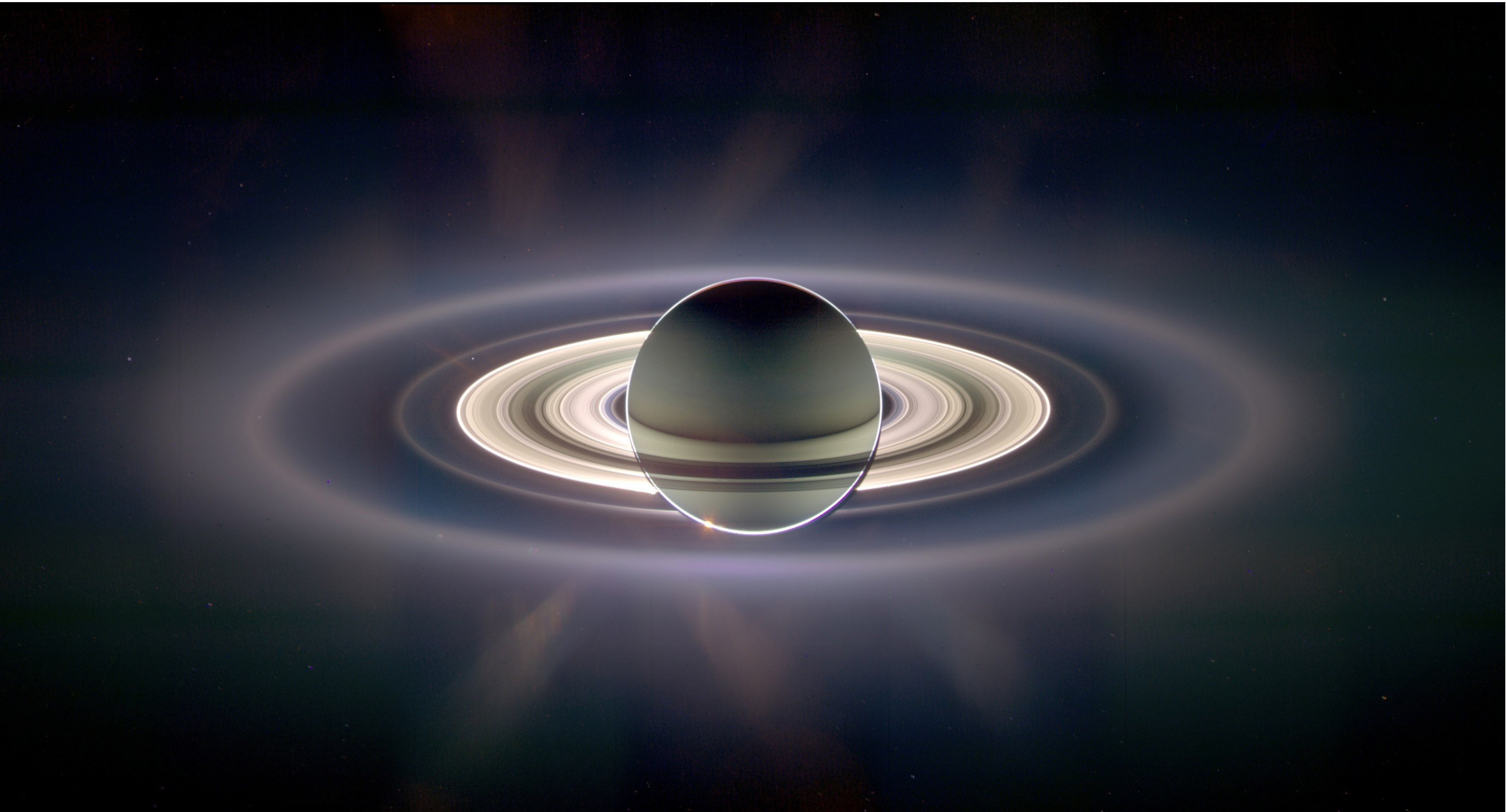
Four planets, orbital periods on the order of 100yr
Each planet 5 to 7 Jupiter Mass

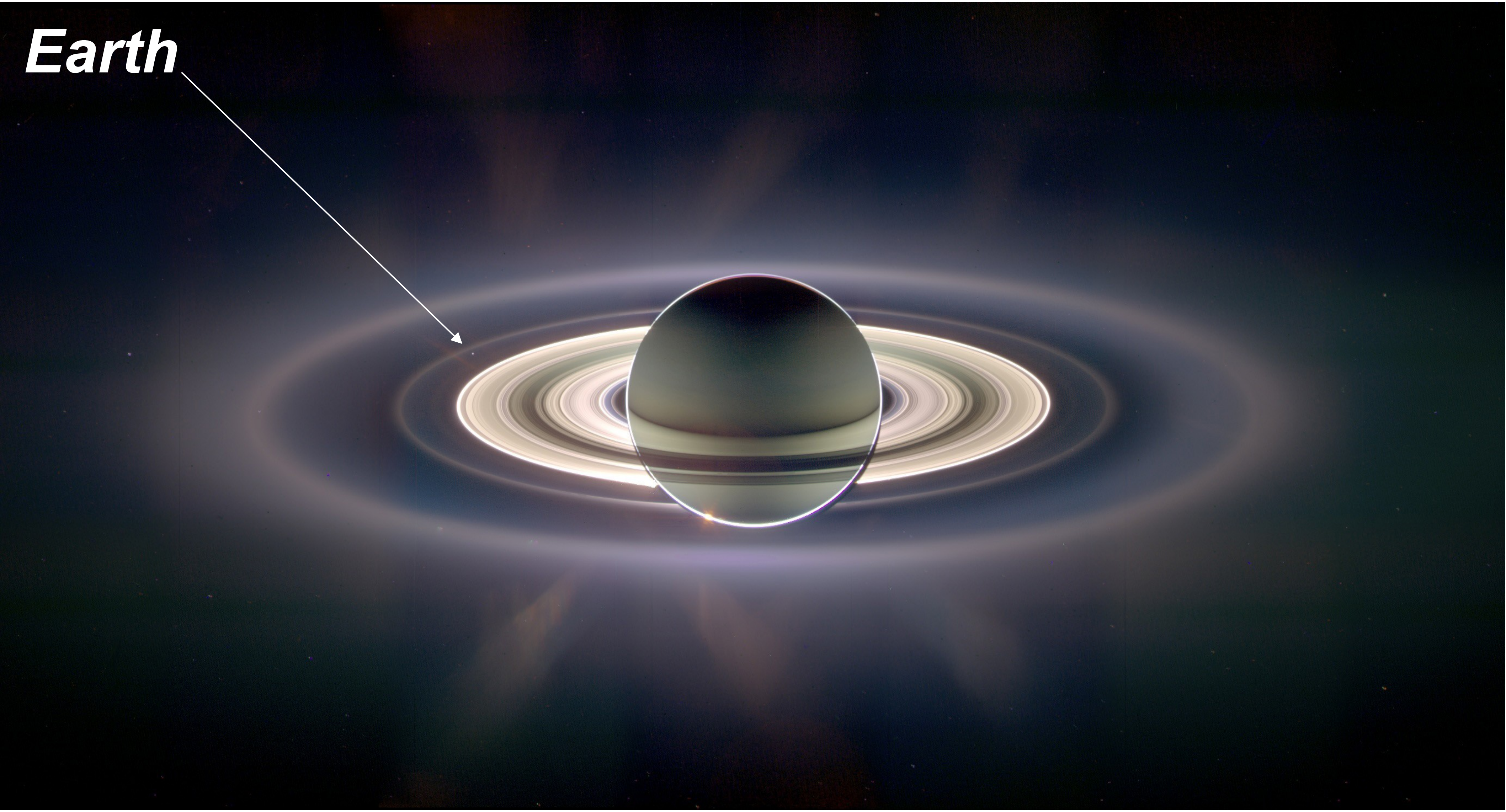


Keck telescope image (Marois et. al)



Taking images of exoplanets: Why is it hard ?




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)

What is light: particle or wave ?

1807: Thomas Young publishes his double-slit experiment result
… cannot be explained by Newton's corpuscular theory of light

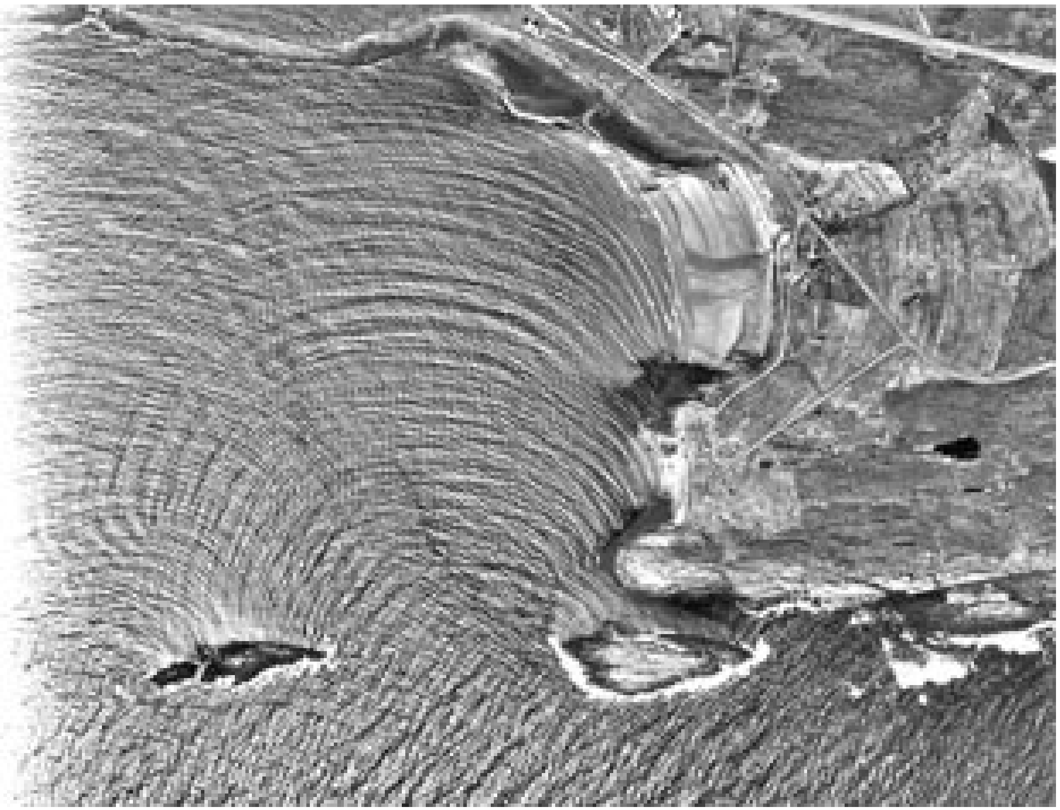
1818: French academy of science committee launches a competition
to explain nature of light

Augustin-Jean Fresnel
submits wave theory of light

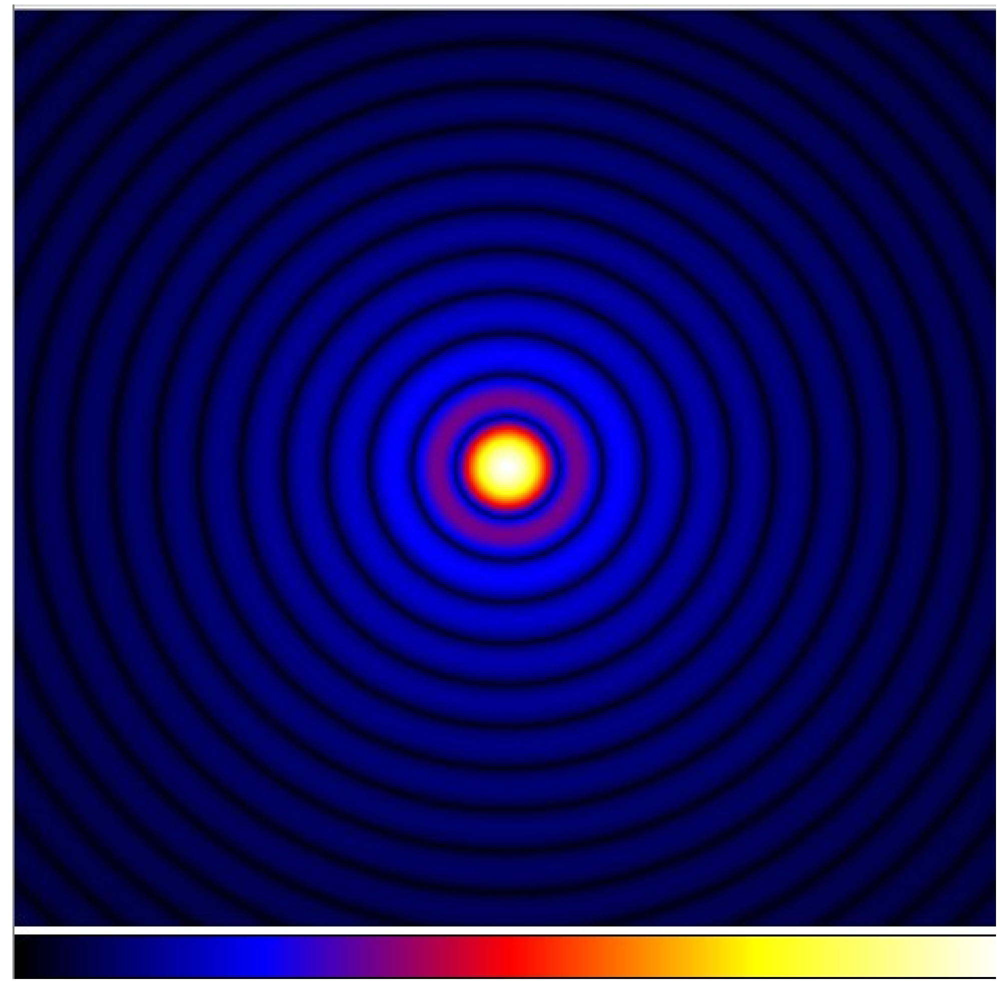
Simeon-Denis Poisson finds a flaw in Fresnel's theory:
According to Fresnel's equations, a bright spot should appear in
the shadow of a circular obstacle → this absurd result disproves Fresnel's theory

Dominique-Francois-Jean Arago, head of the committee, performs the experiment
He finds the predicted spot → Fresnel wins the competition

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



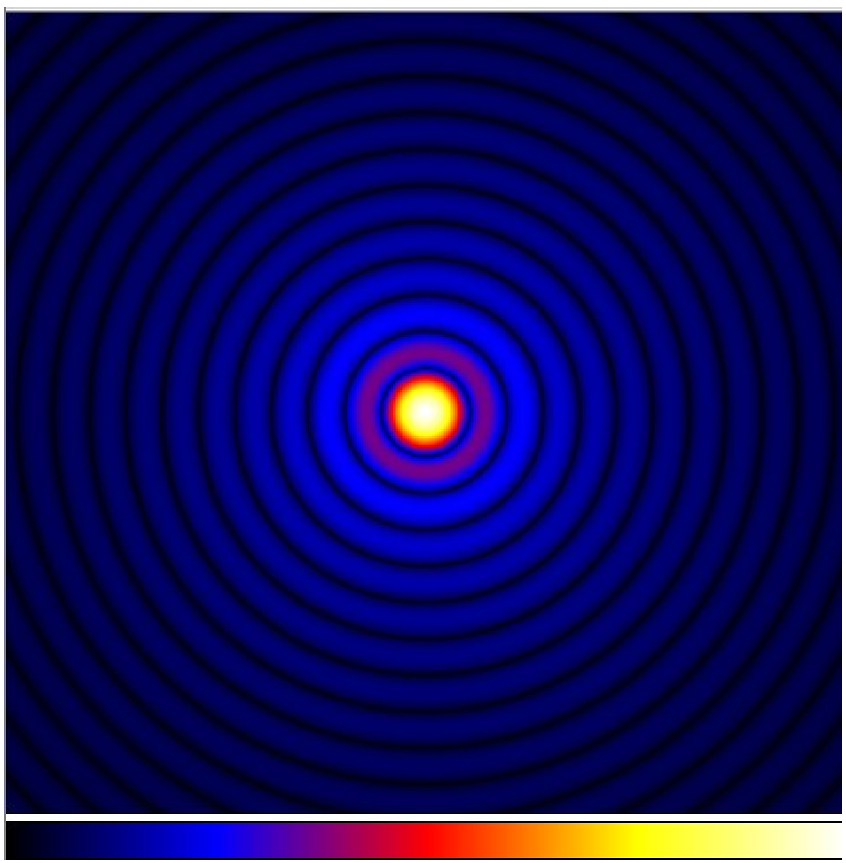
Waves diffracted by coastline and islands

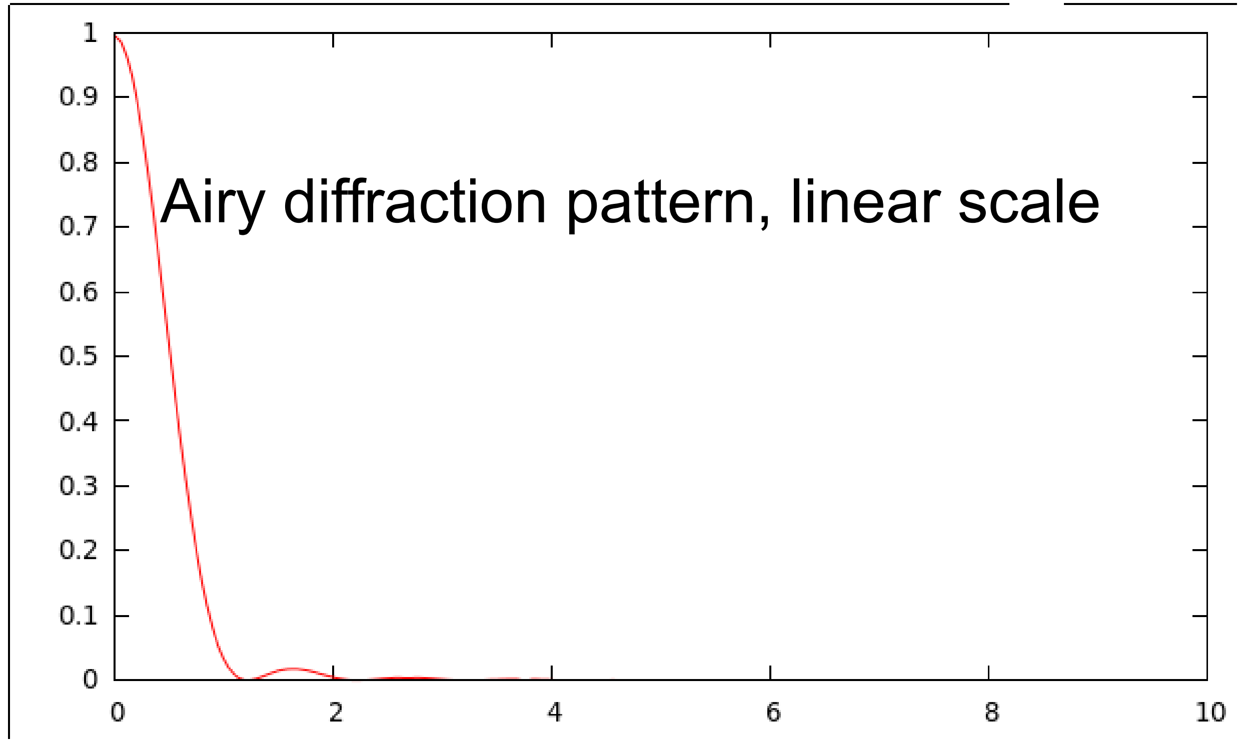


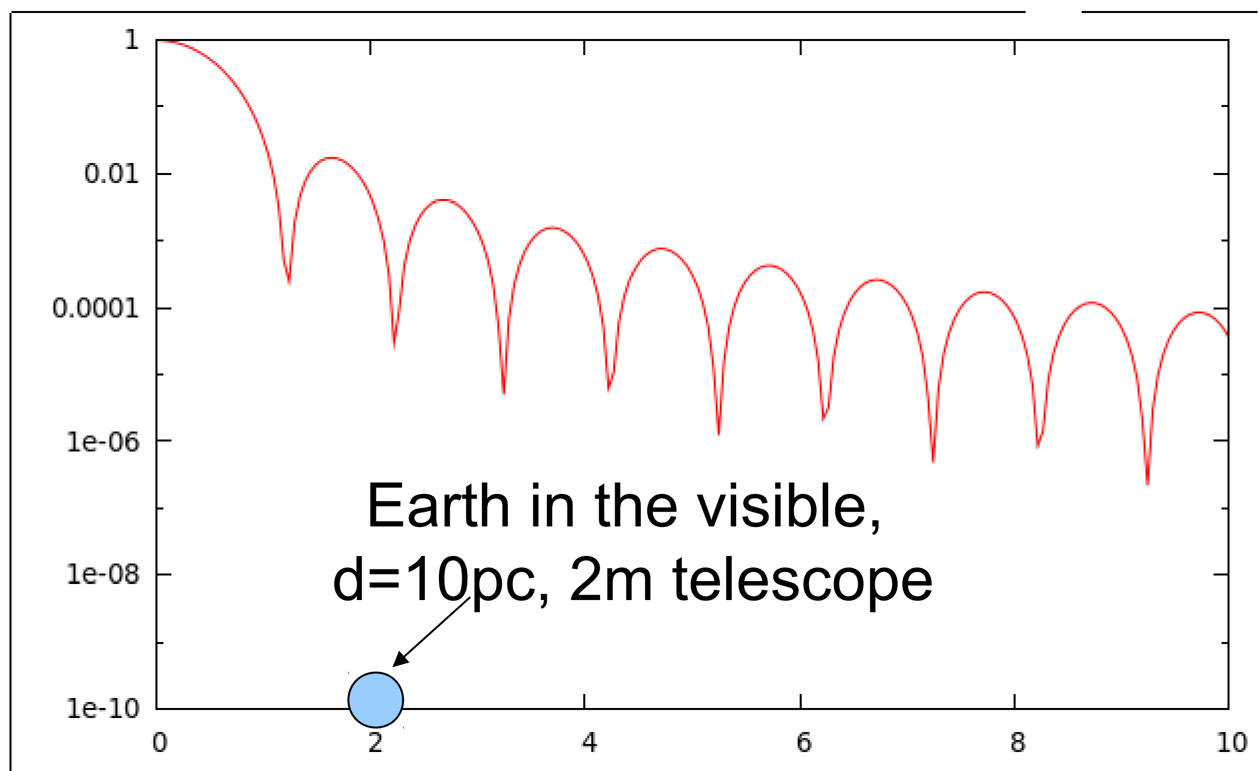
Ideal image of a distant star by a telescope
Diffraction rings around the image core

Why coronagraphy ?

Conventional imaging systems are not suitable for high contrast (even if perfect) due to diffraction





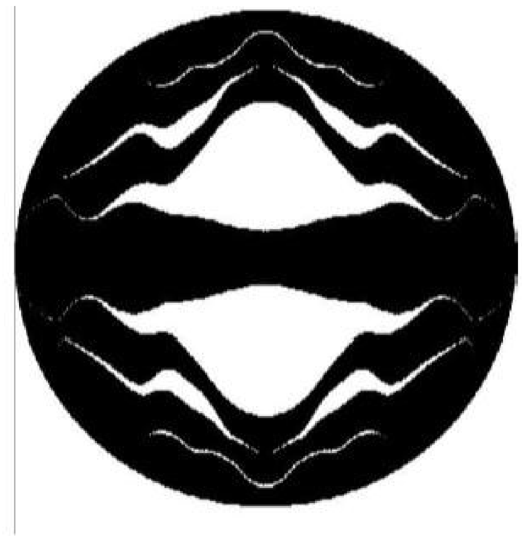


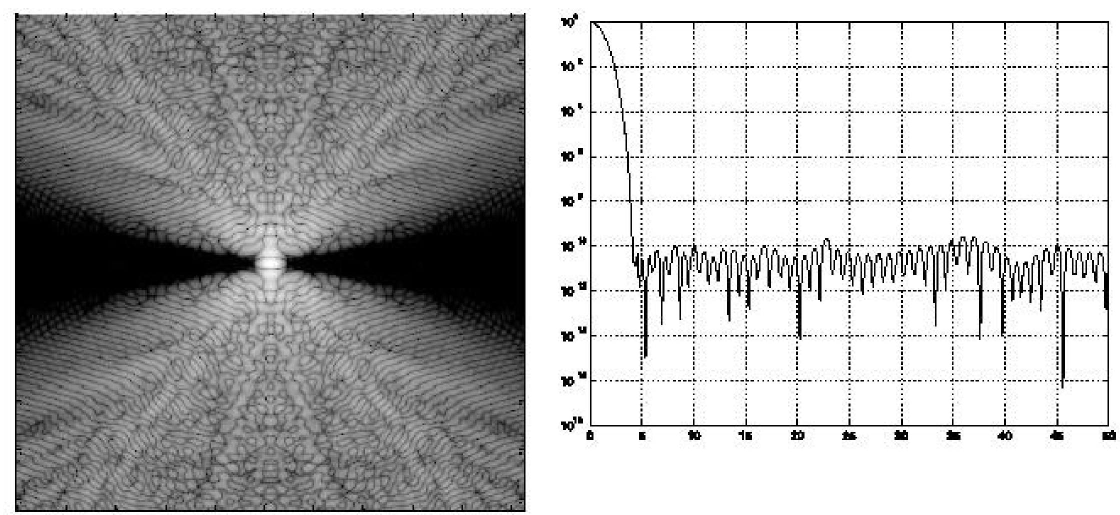
Conventional Pupil Apodization (CPA)

Many pupil apodizations
have been proposed.

Apodization can be
continuous or binary.

+ Simple, robust, achromatic
 - low efficiency for high contrast

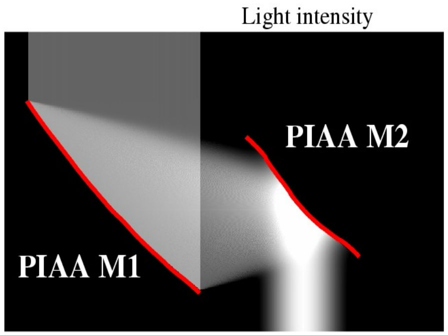




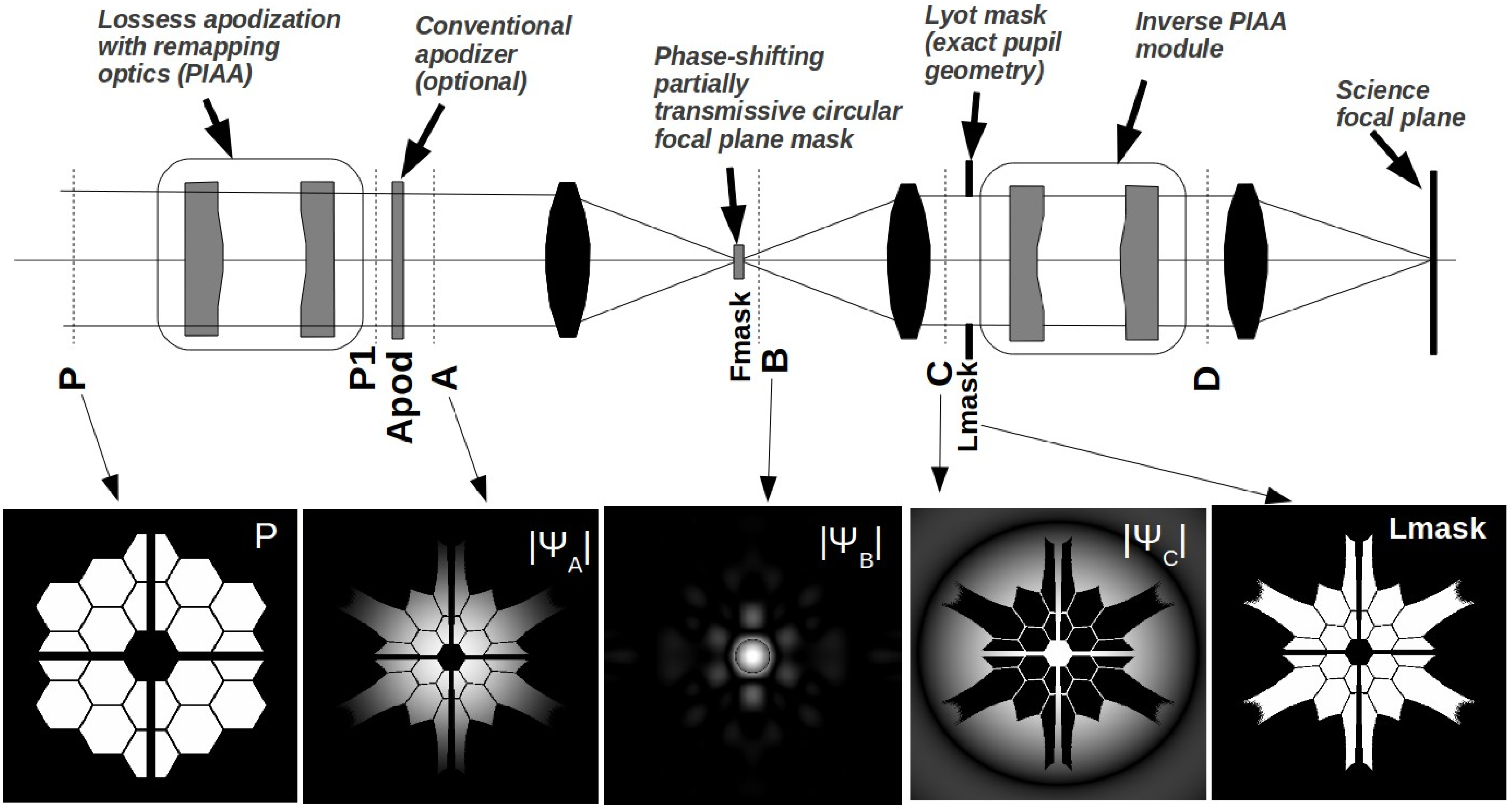
Jacquinot & Roisin-Dossier 1964
Kasdin et al. 2003, ApJ, 582, 1147
Vanderbei et al. 2003, ApJ, 590, 593
Vanderbei et al. 2003, ApJ, 599, 686
Vanderbei et al. 2004, ApJ, 615, 555

FIG. 9.—*Top*: Asymmetric multiopening mask designed to provide high-contrast, 10^{-10}, from $\lambda/D = 4$ to $\lambda/D = 100$ in two angular sectors centered on the x-axis. Ten integrations are required to cover all angles. Total throughput and pseudoarea are 24.4%. Airy throughput is 11.85%. *Bottom*: Associated PSF. (Note that this mask was originally designed for an elliptical mirror. It has been rescaled to fit a circular aperture.)

- PIAACMC gets to < 1 l/D with full efficiency, and no contrast limit

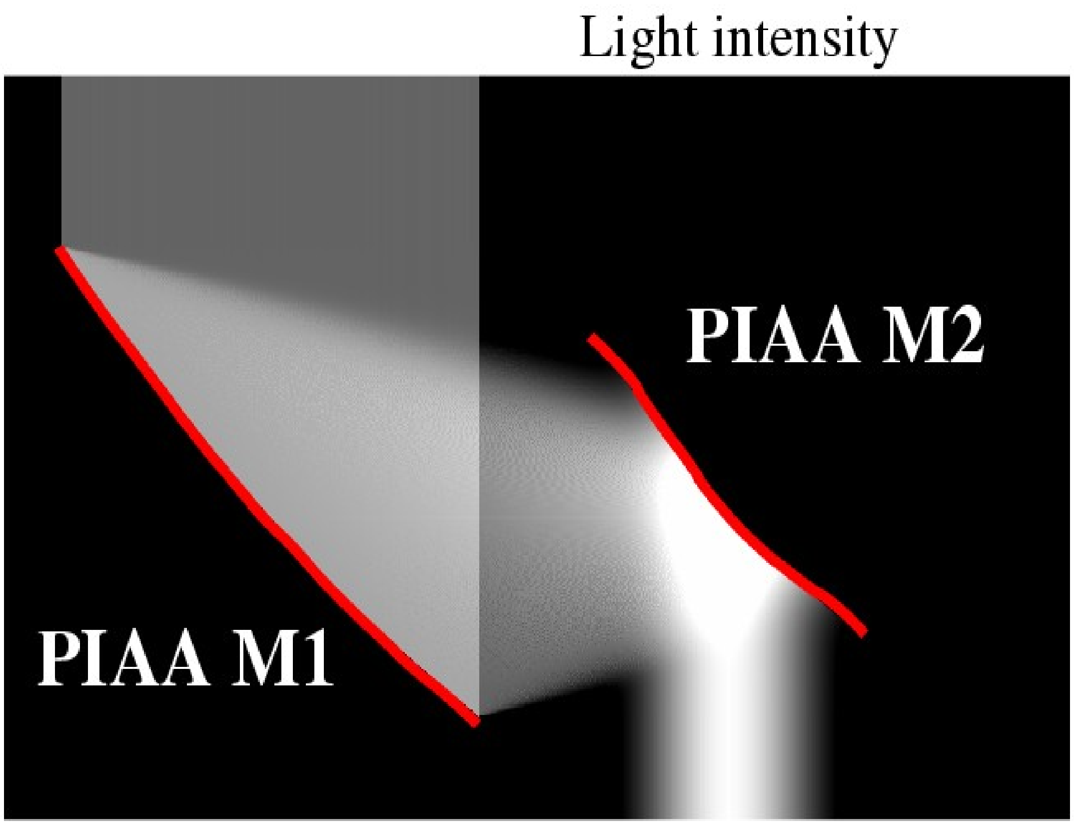


Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)



Phase-Induced Amplitude Apodization Coronagraph (PIAAC)

Lossless apodization by aspheric optics.

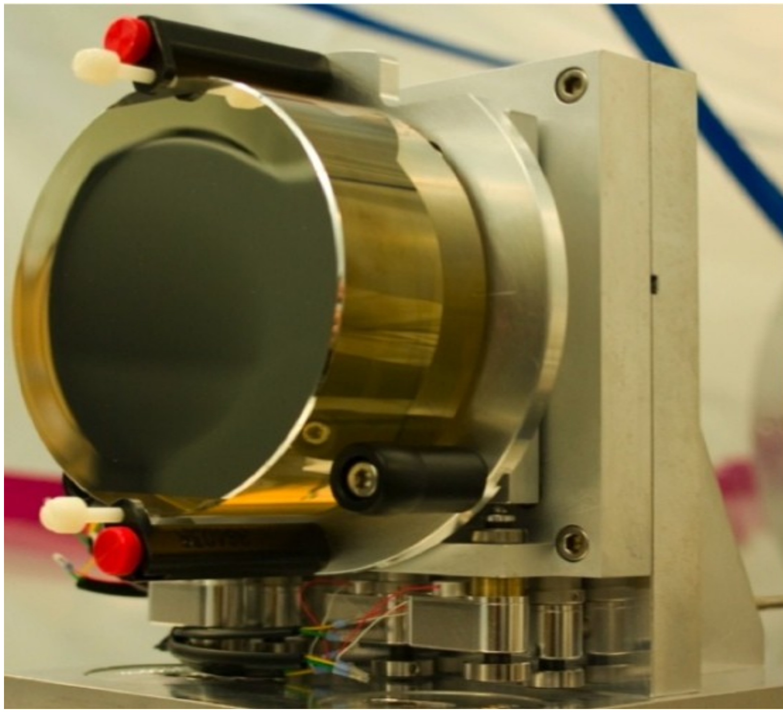


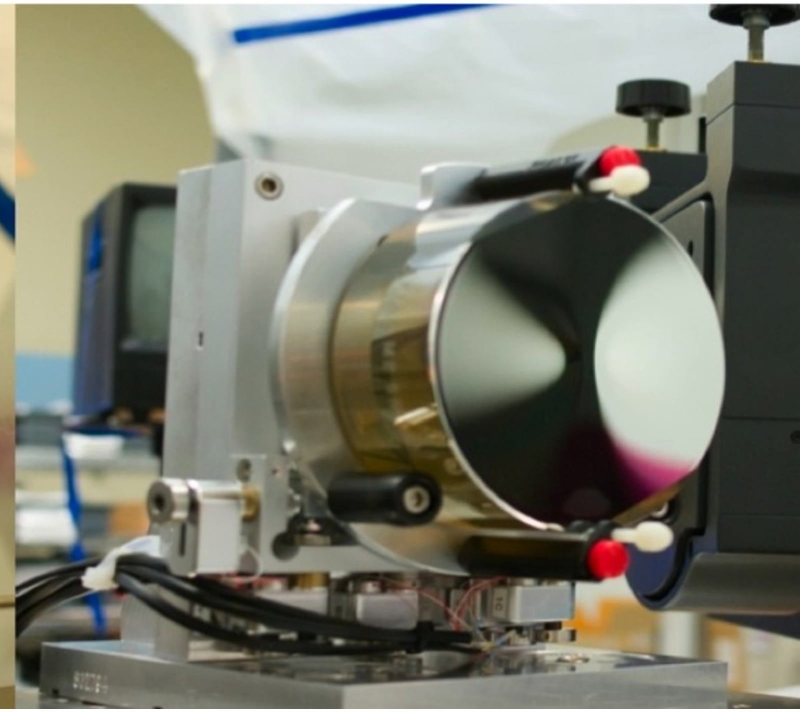
No loss in angular resolution or sensitivity
Achromatic (with mirrors)
Small inner working angle

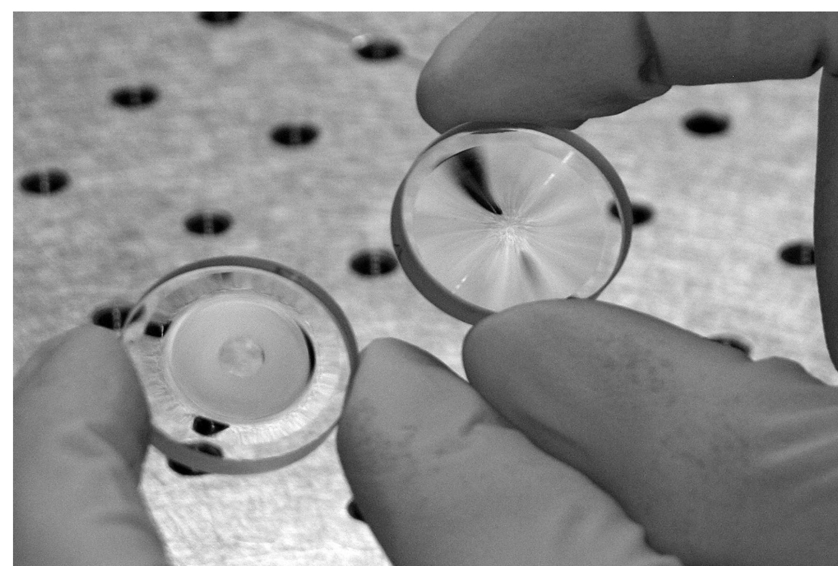
→ Gain ~x2 to x3 in telescope diameter over previous concepts

Guyon, Belikov, Pluzhnik, Vanderbei, Traub, Martinache ... 2003-present

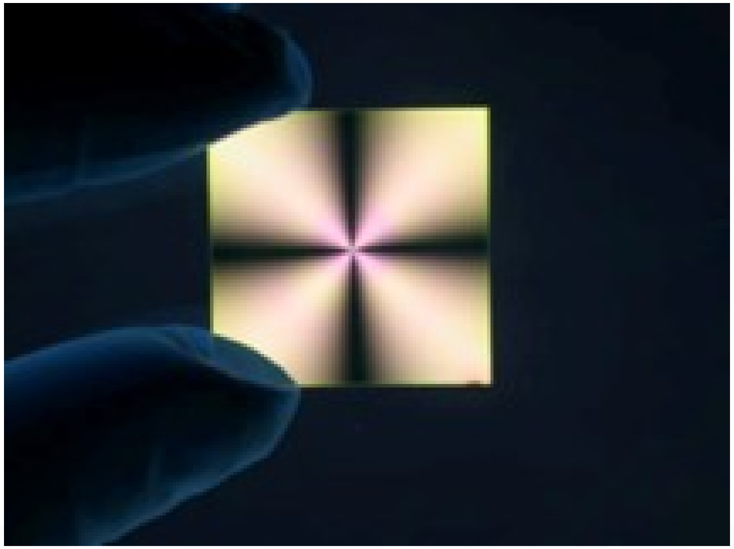
We use strangely shaped optics to reshape light

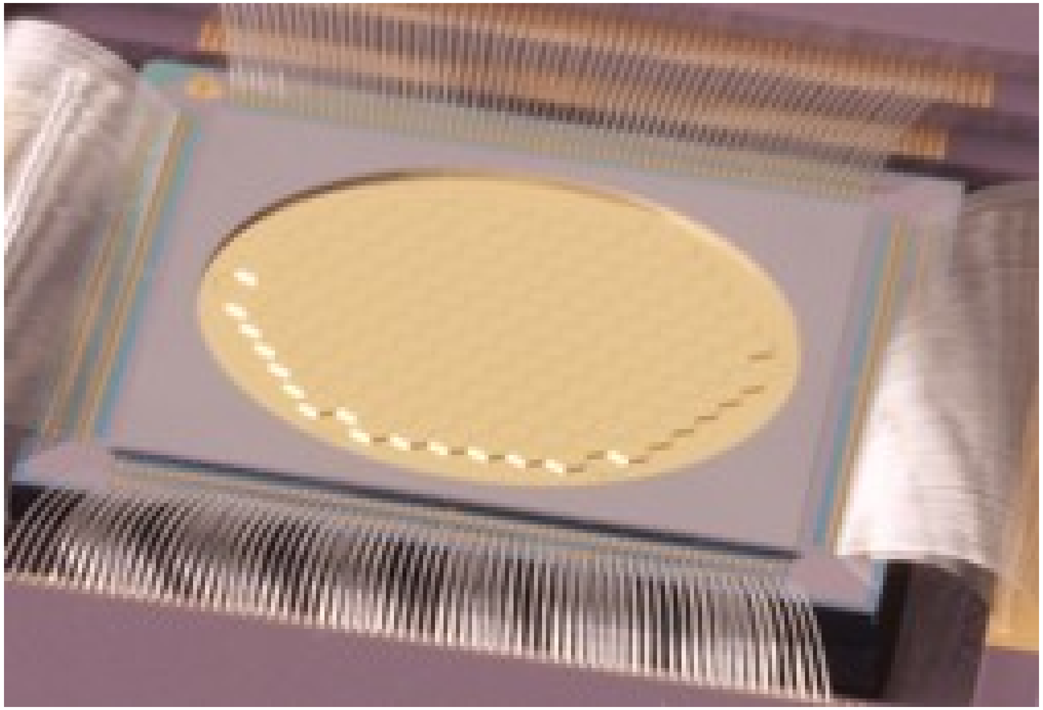


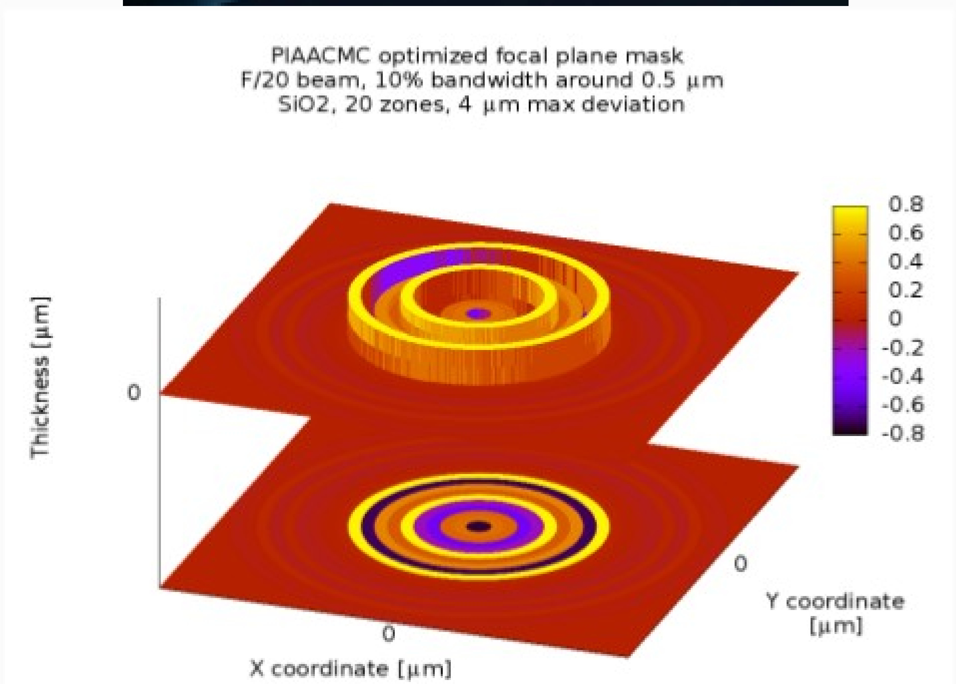




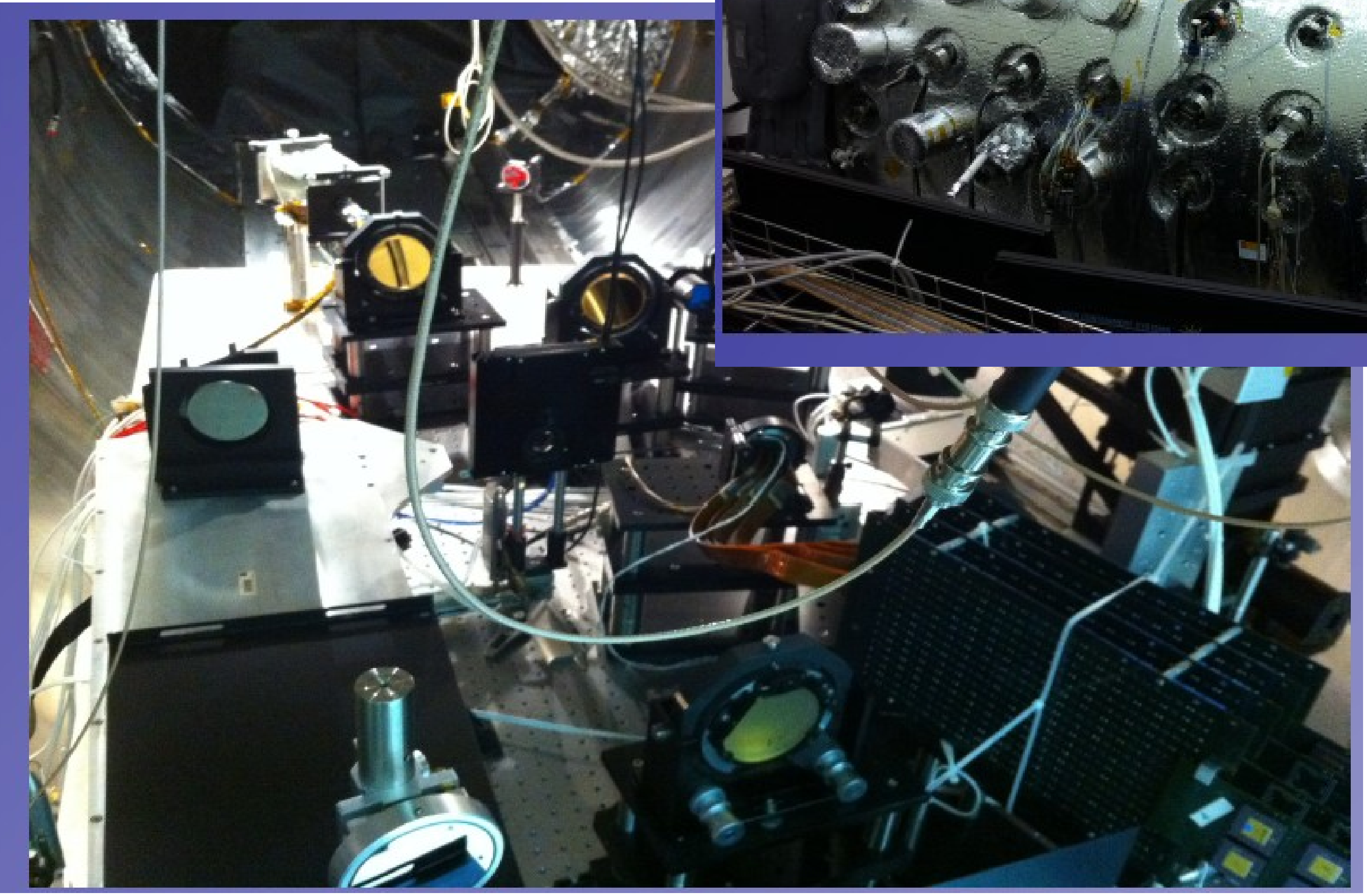
Technology: components





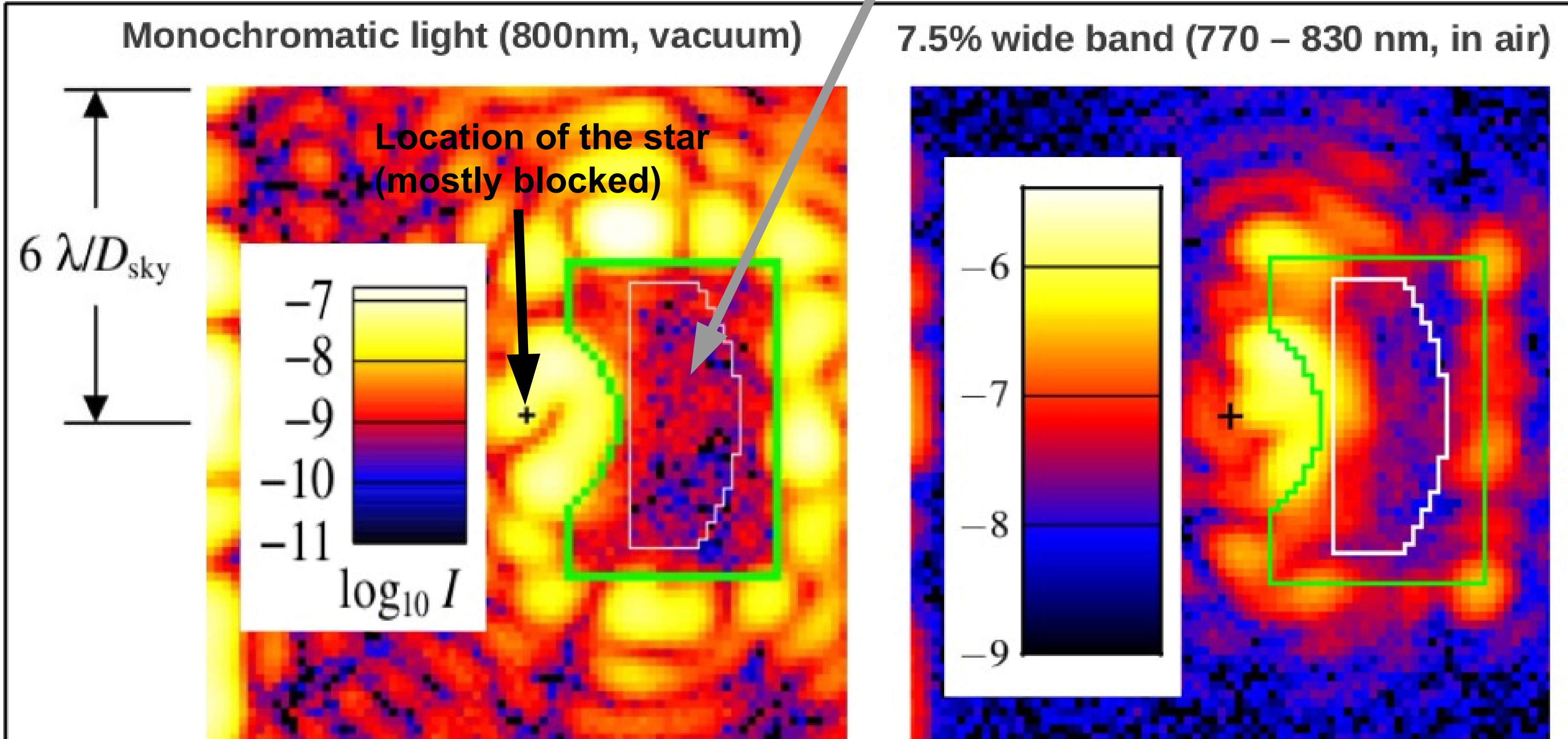


Vacuum testbeds at JPL



PIAA testbed at NASA JPL : lab results
(B. Kern, O. Guyon, A. Kuhnert et al.)

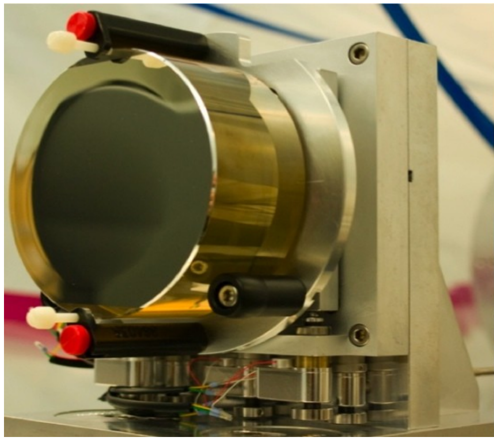
An Earth-like planets could be seen !

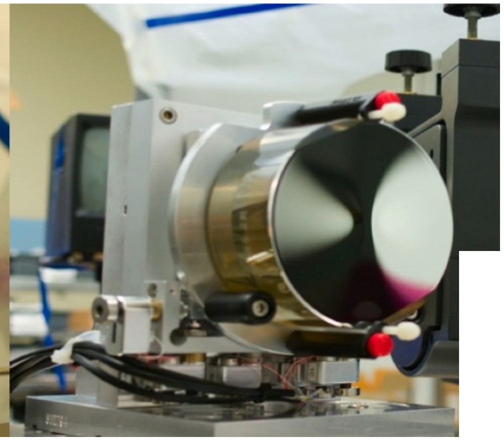


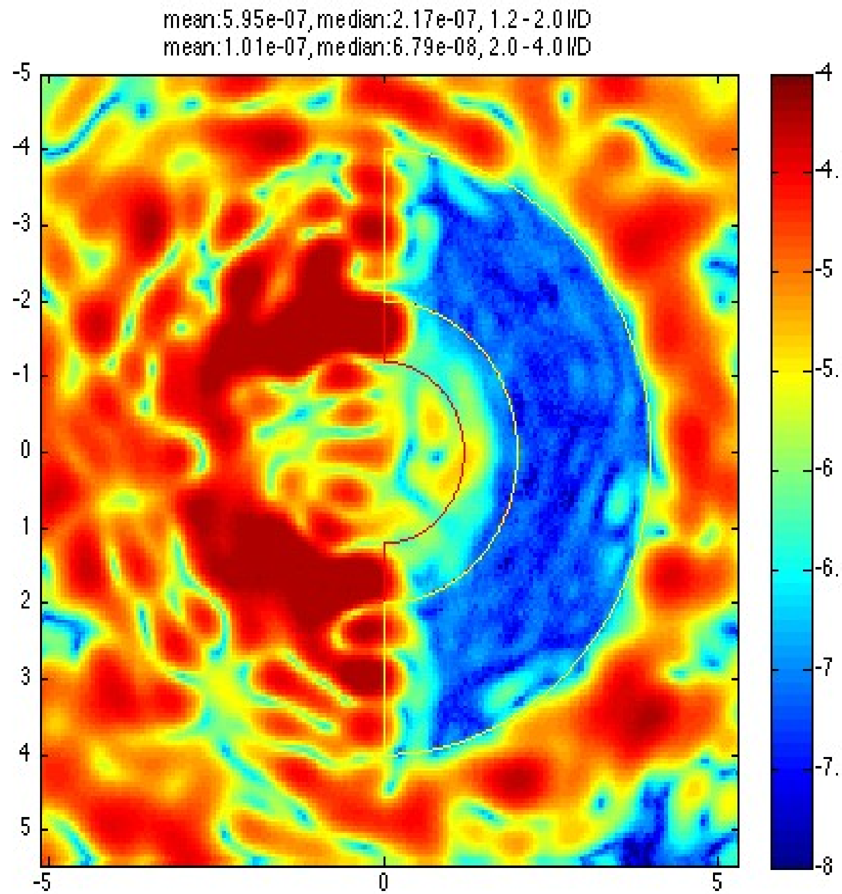
3 runs, contrast values averaged from 2 to 4 λ/D between 5.10^{-10} to 9.10^{-10} (figure shows $7.3.10^{-10}$ result)

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)

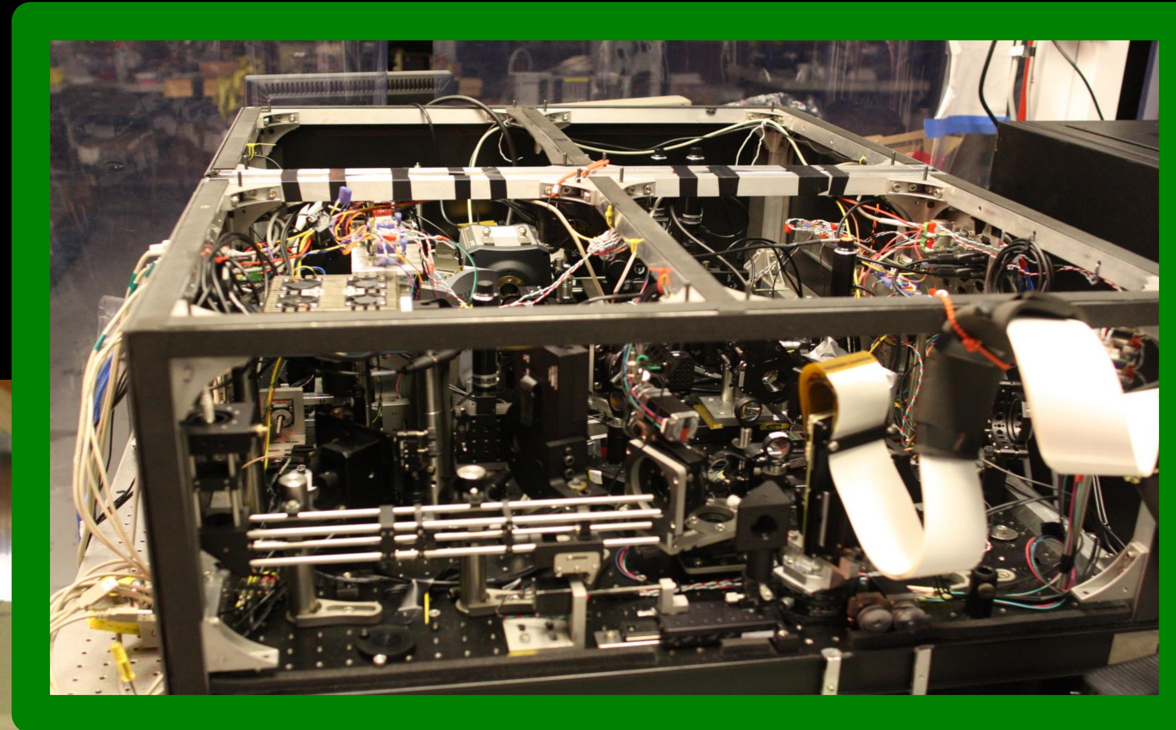
Testbed at NASA Ames

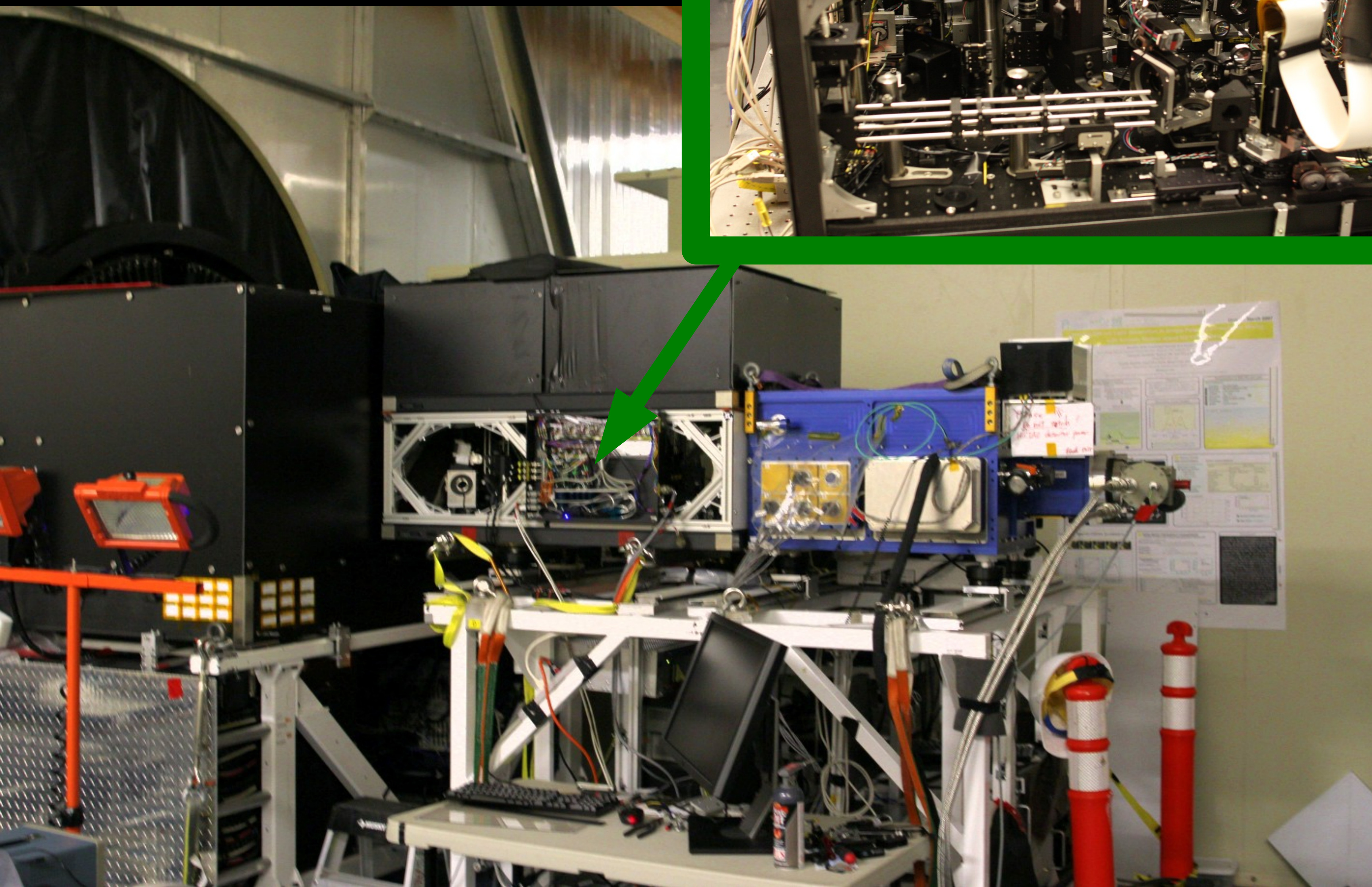






The Subaru Coronagraphic Extreme Adaptive Optics (SCExAO) system

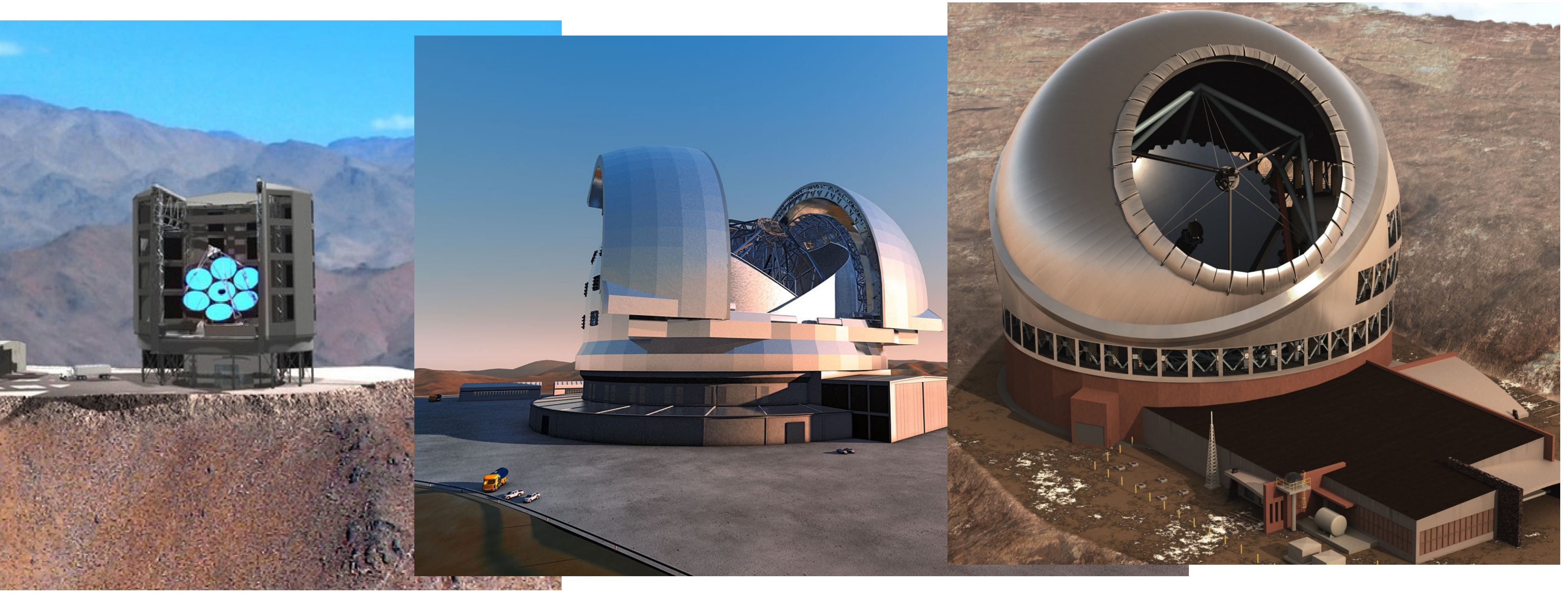


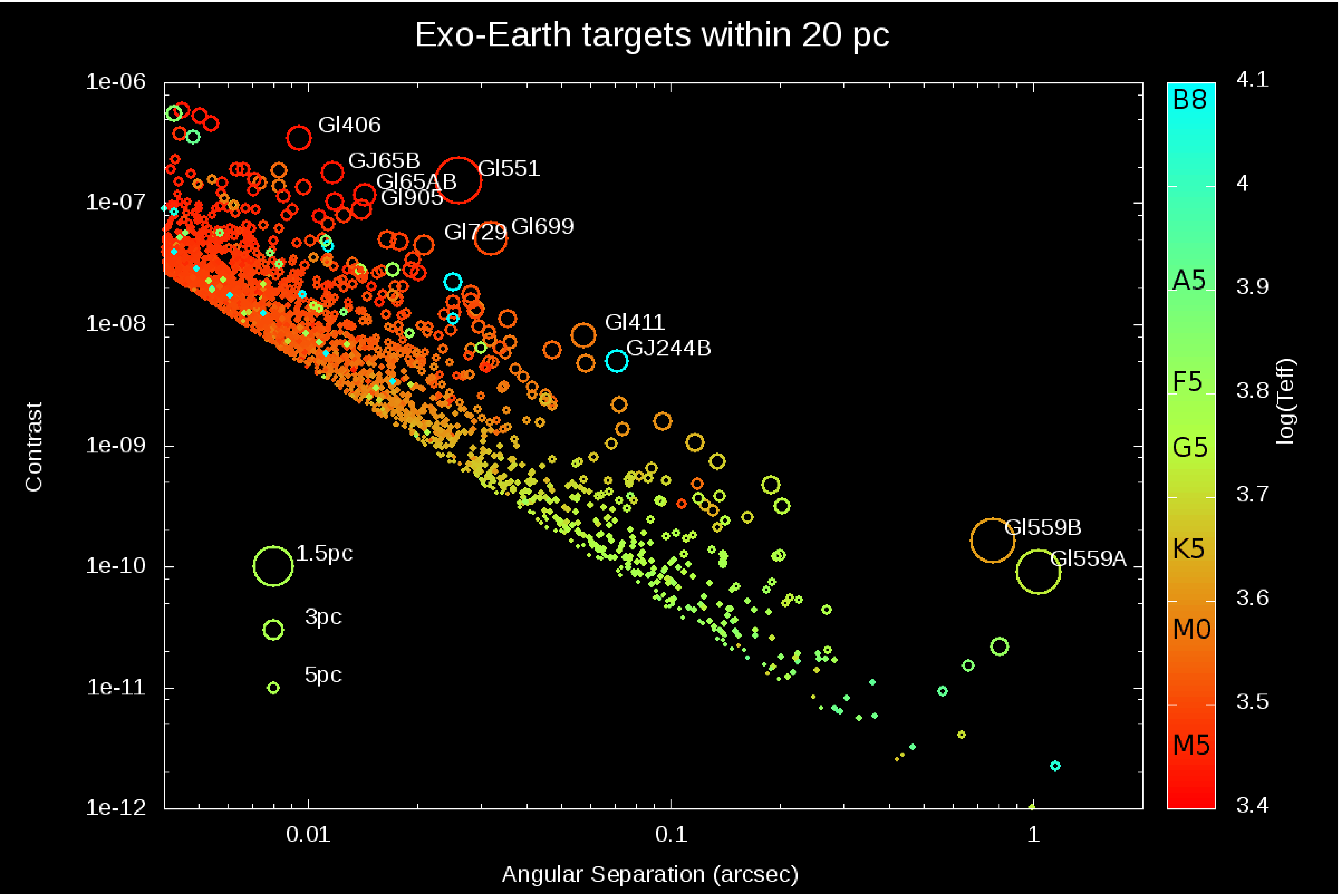


Exciting future opportunities

Next generation of large telescopes on the ground will be able to image habitable planets around nearby low mass red stars
3 projects, ~30m diameter

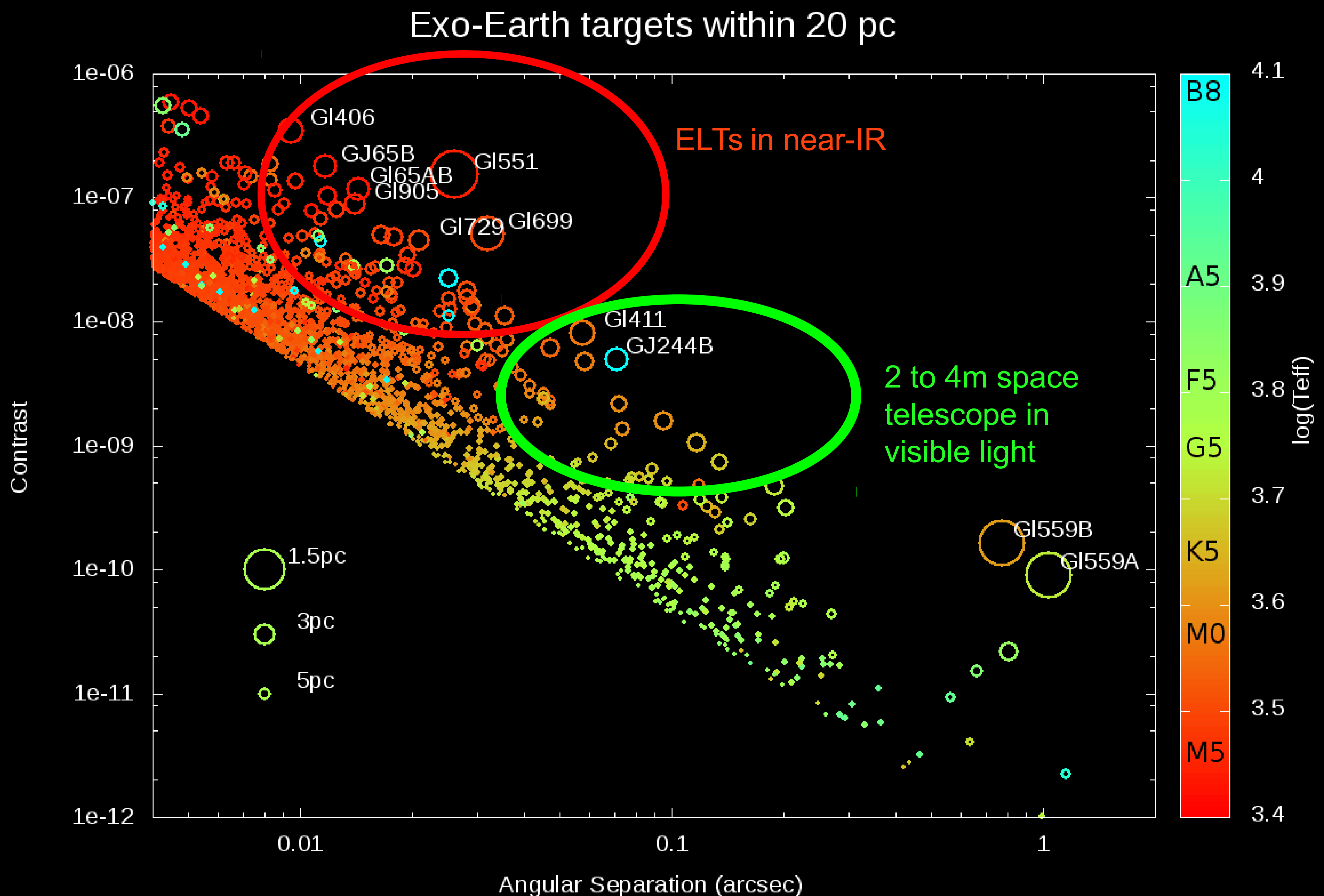
Space telescopes with coronagraphs will be able to image and study Earth-like planets around sun-like stars



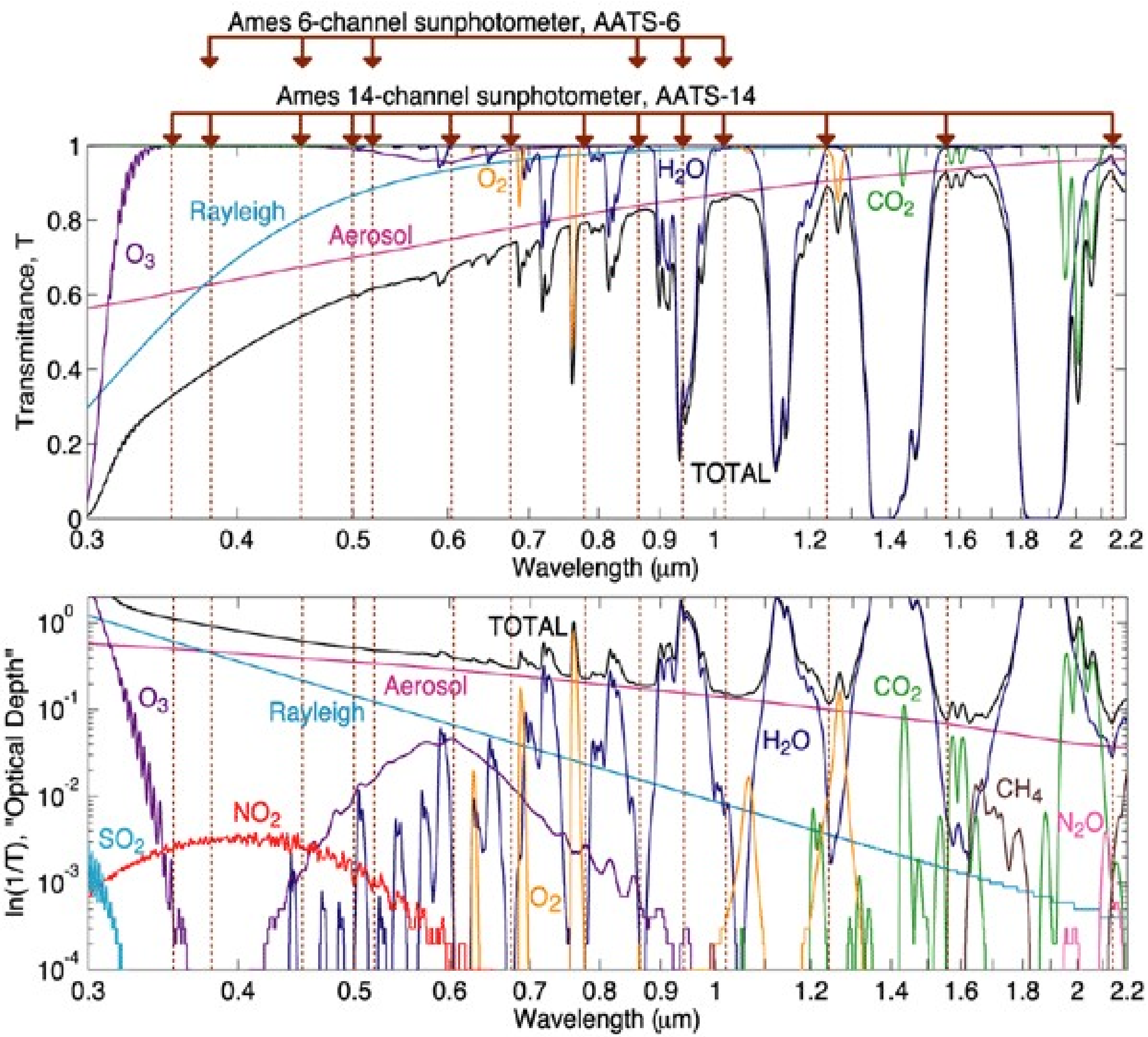


Exo-Earth targets within 20 pc
Contrast
Angular Separation (arcsec)
log(Teff)
1e-06
1e-07
1e-08
1e-09
1e-10
1e-11
1e-12
0.01
0.1
1
B8
A5
F5
G5
K5
M0
M5
4.1
4
3.9
3.8
3.7
3.6
3.5
3.4
Gl406
GJ65B
Gl551
Gl65AB
Gl905
Gl729
Gl699
Gl411
GJ244B
Gl559B
Gl559A
1.5pc
3pc
5pc

Detecting planets from space and ground



Habitable Planets Spectroscopy in near-IR



Credit: NASA/Ames Airborne Tracking Sunphotometer (AATS)

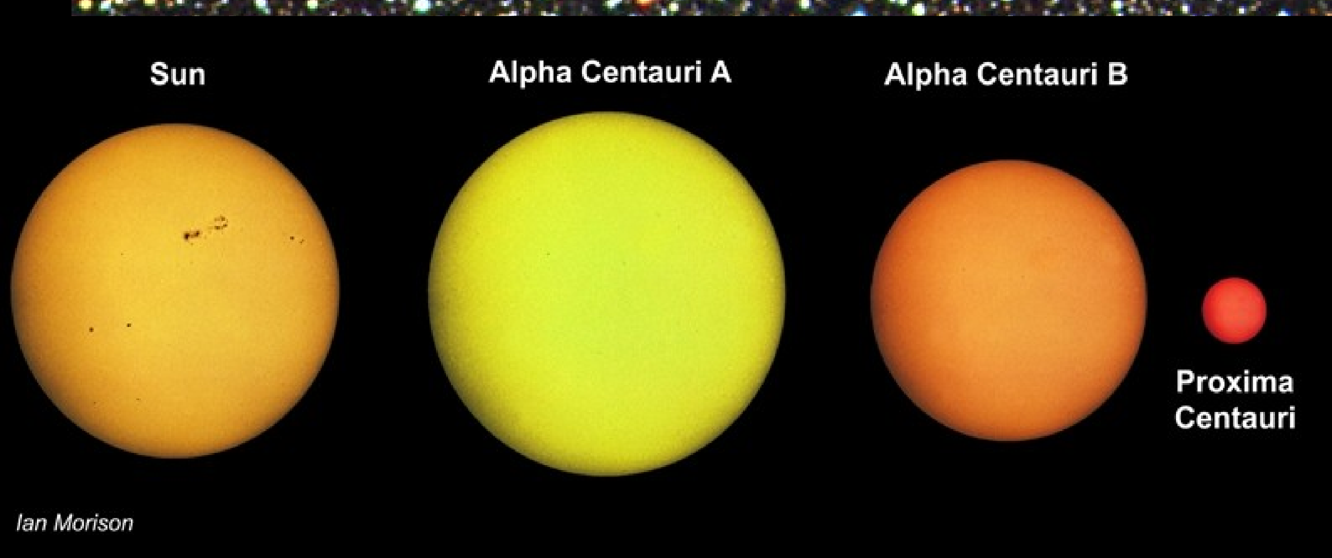
Atmosphere transmission:
O2 (see Kawara et al. 2012)
H2O
CO2
CH4

Polarimetry

Cloud cover, variability
Rotation period

Reflectivity from ground in atmosphere transparency bands (Ice cap, desert, ocean etc...)

Proxima Centauri



How citizen scientists, schools, amateur astronomers can help discover exoplanets using digital cameras

Project **PANOPTES**

Panoptic **A**stronomical **N**etworked **OP**tical observatory for **T**ransiting **E**xoplanets **S**urvey

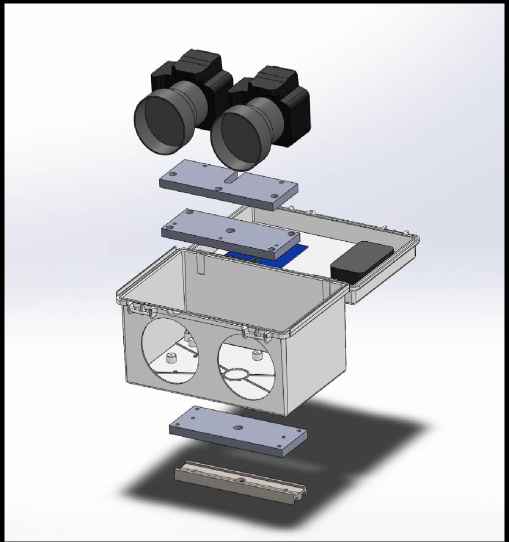
Check : **projectpanoptes.org**
Email: info**@projectpanoptes.org**

PANOPTES

Discovering transiting exoplanets requires monitoring large parts of the sky for long periods of time

Amateur astronomers, citizen scientists are very good at this, and schools can participate with student team projects

We are developing an easy to assemble, low cost system based on digital SLR cameras to do exoplanet transit survey work



projectpanoptes.org
info@**projectpanoptes.org**

PANOPTES prototype #3 unit at Mauna Loa observatory (May 19, 2013)

Example image (Cygnus field): >100,000 stars in a single image