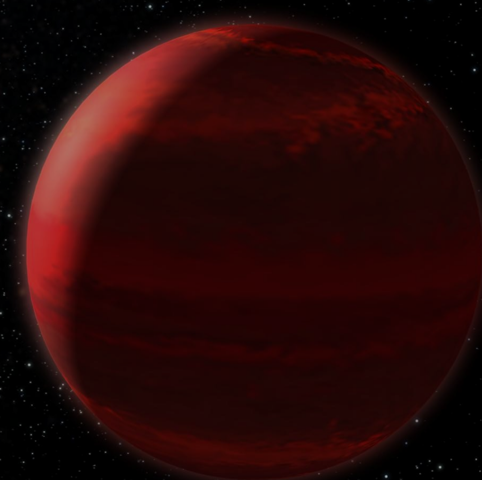
Searching for Habitable Worlds and Life in the Universe with Optics



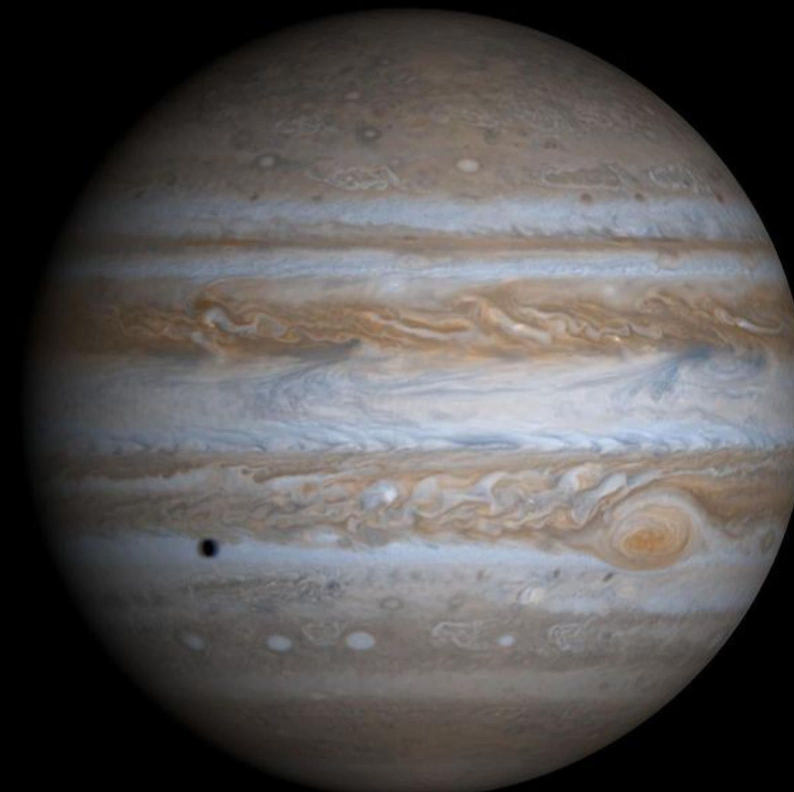
Contact: oliv.guyon@gmail.com

What makes planets habitable ?

Size matters:
not too big, not too small

Moon: too small
No atmosphere

Earth



Jupiter: too big
Mostly gas

What makes planets habitable ?

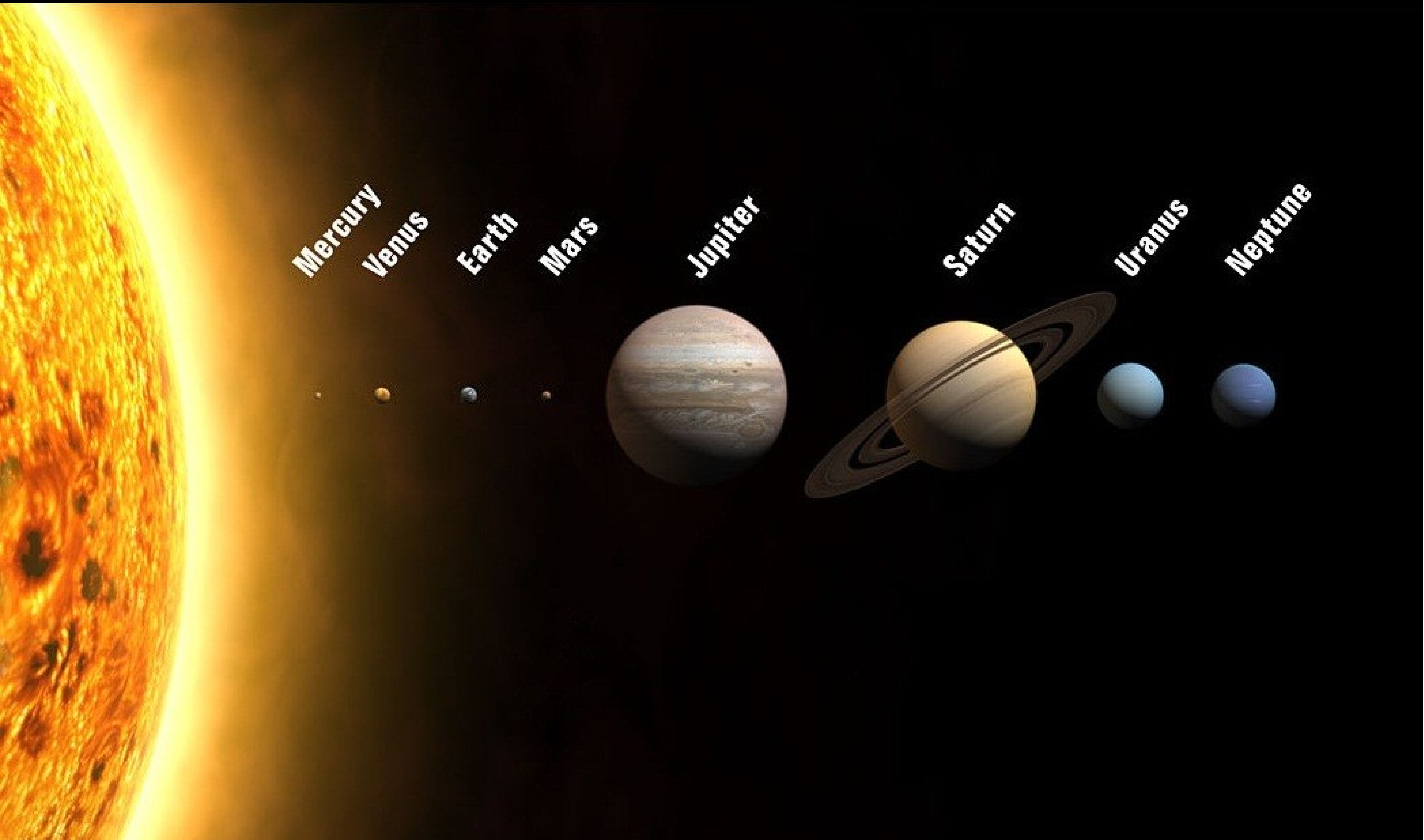
The planet must be in the **habitable zone** of its star: not be too close or too far

Venera 13 lander, survived 127mn at 457 C, 89 atm

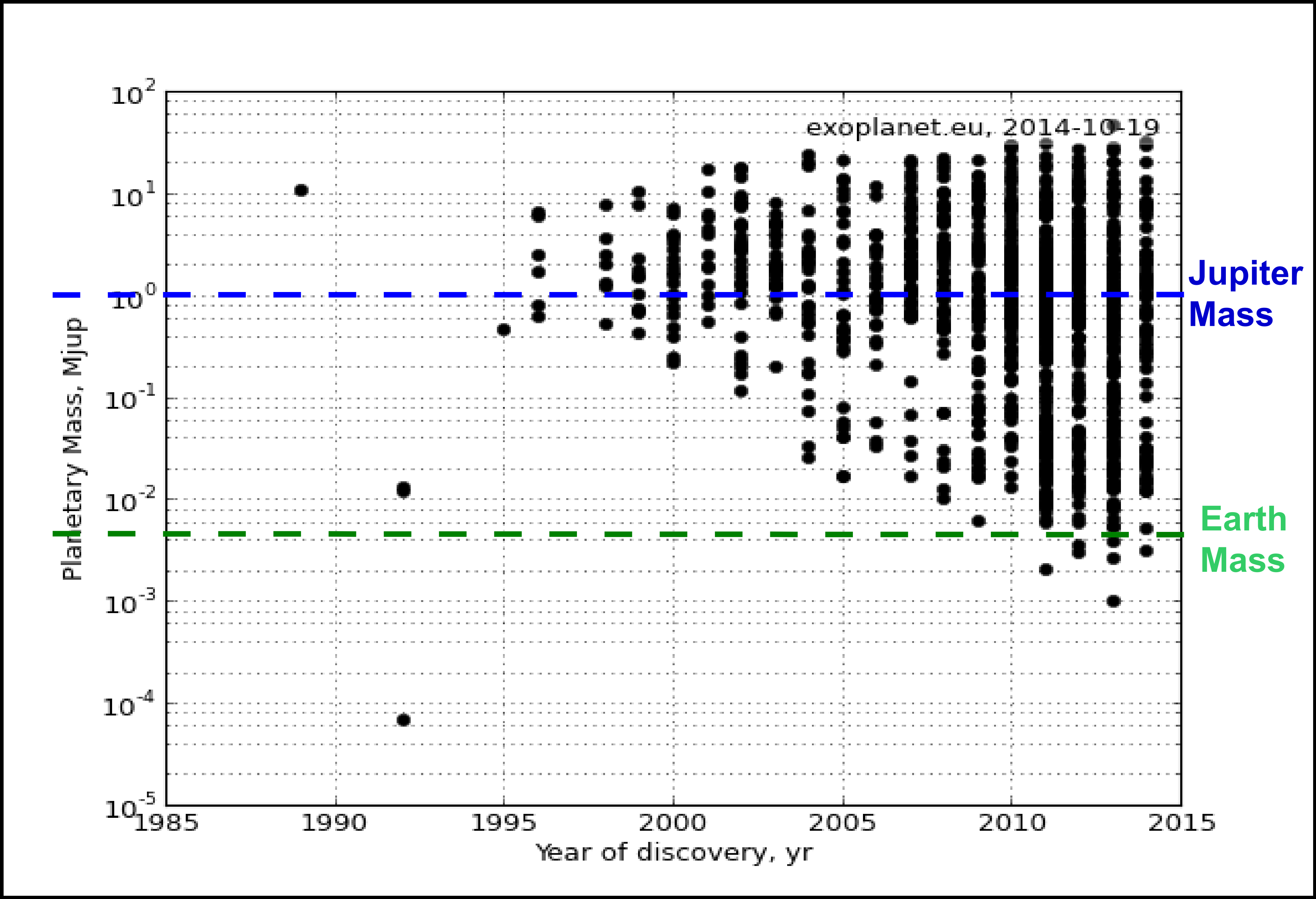
Venus: too close, too hot

Mars: too far, too cold

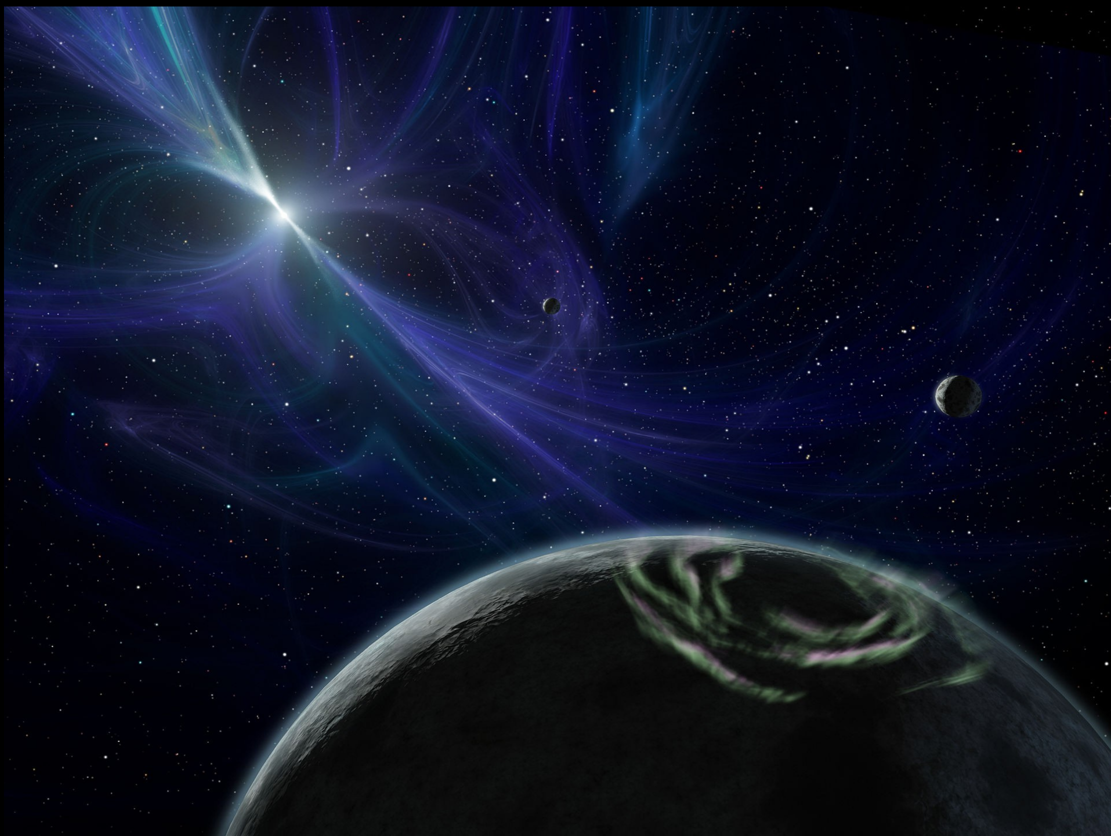
ALL known Planets until 1989



<u>*Exoplanets*</u> *identified – we are now starting to identify Earth-size planets*



First discoveries: 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

Approximately 10% of stars have a habitable planet

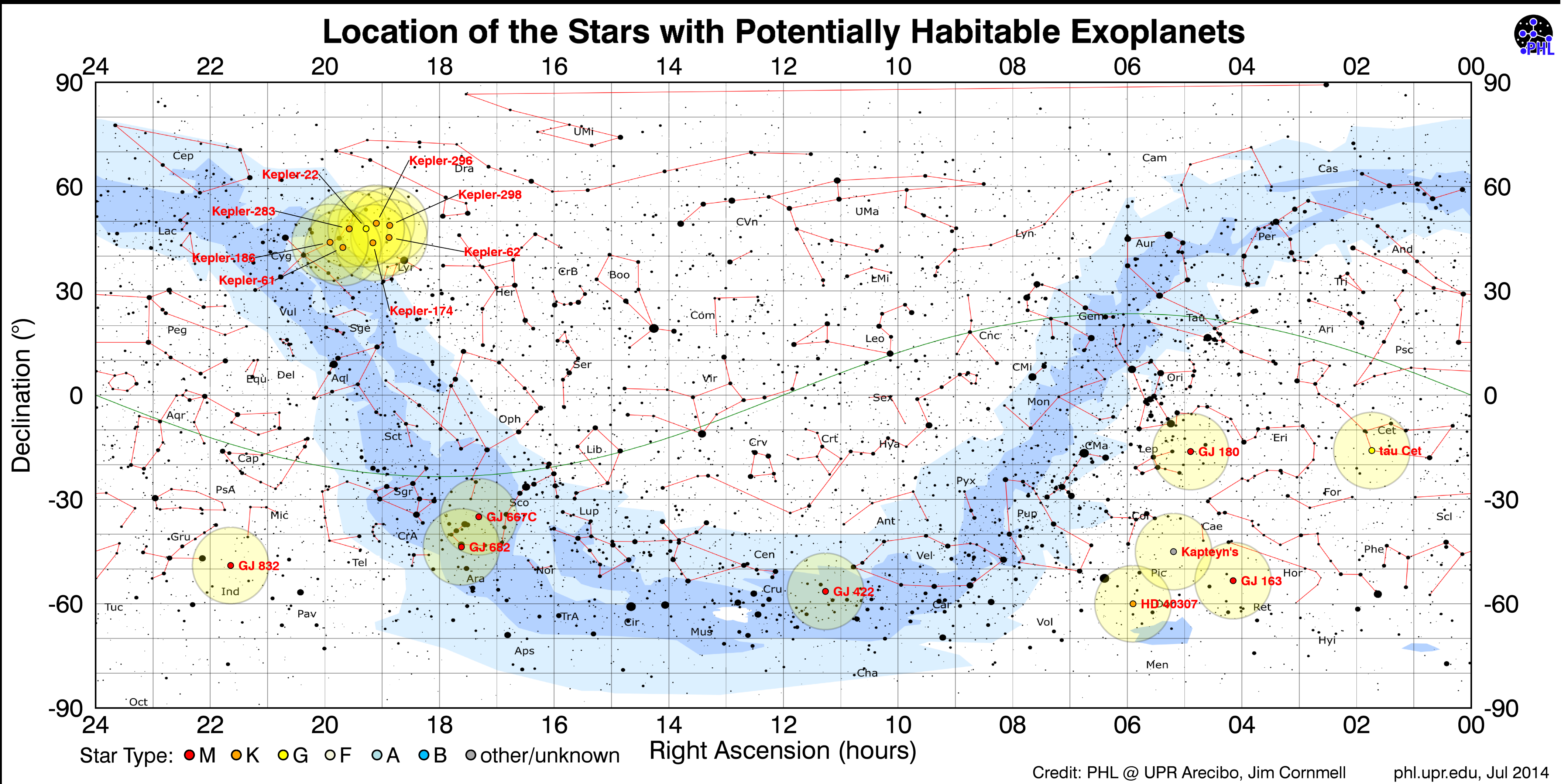
200 billion stars in our galaxy

→ approximately 20 billion habitable planets

Imagine 200 explorers, each spending 20s on each habitable planet, 24hr a day, 7 days a week.

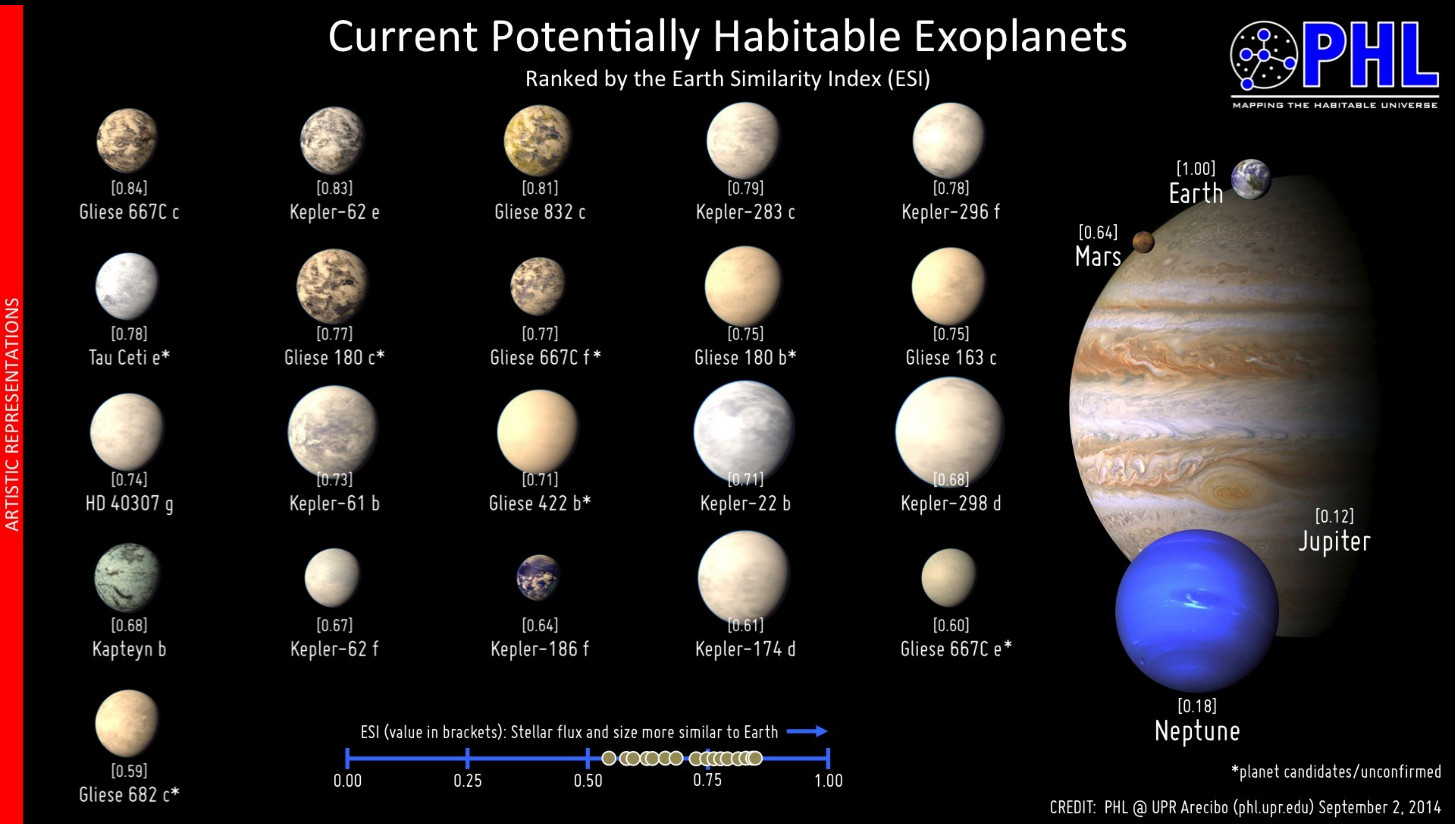
It would take >60yr to explore all habitable planets in our galaxy alone.

x 100,000,000,000 galaxies in the observable universe



Location of the Stars with Potentially Habitable Exoplanets
PHL
Kepler-296
Kepler-22
Kepler-298
Kepler-283
Kepler-62
Kepler-186
Kepler-61
Kepler-174
GJ 180
tau Cet
GJ 667C
GJ 682
GJ 832
GJ 422
Kapteyn's
GJ 163
HD 40307
Declination (°)
Right Ascension (hours)
Star Type: M K G F A B other/unknown
Credit: PHL @ UPR Arecibo, Jim Cornmell
phl.upr.edu, Jul 2014

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



How do astronomers identify exoplanets ?

HIGH PRECISION OPTICAL MEASUREMENTS OF STARLIGHT (indirect techniques)

Earth around Sun at ~30 light year

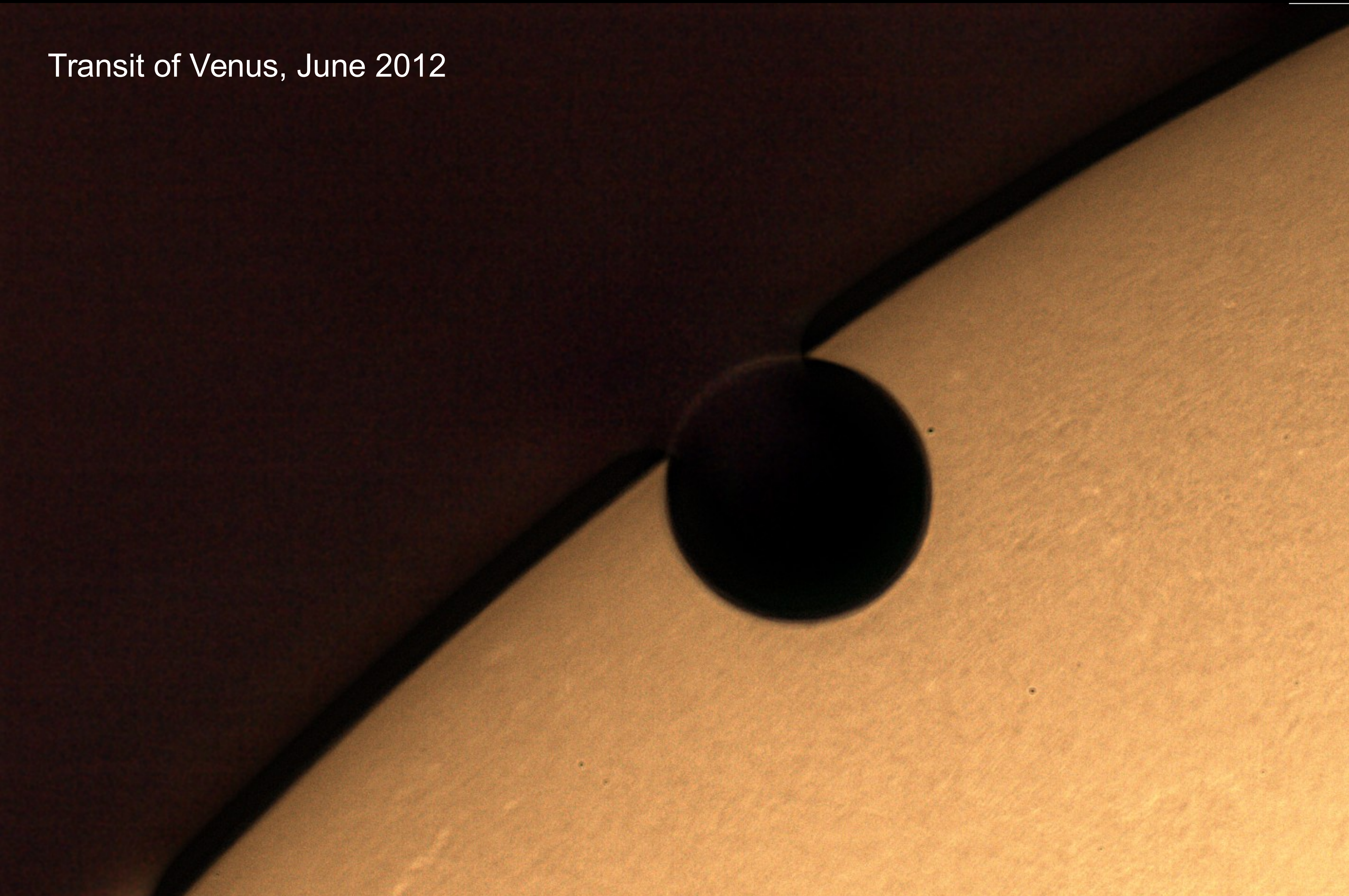
→ Star position moves by 0.3 micro arcsecond
(thickness of a human hair at 20,000 miles)

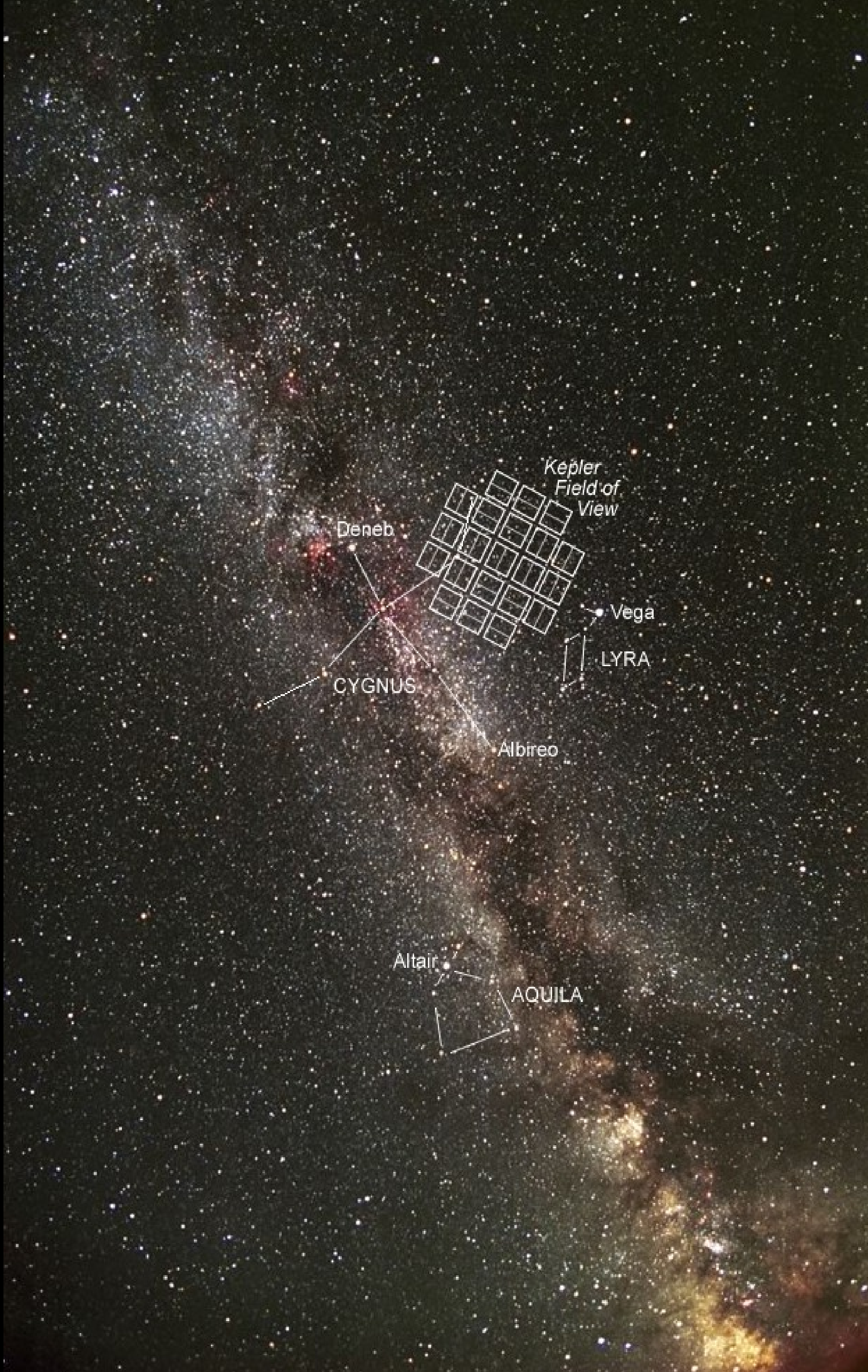
→ Star velocity is modulated by 10cm / sec
(changes light frequency by 1 part in 3,000,000,000)

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

Exoplanet transit

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



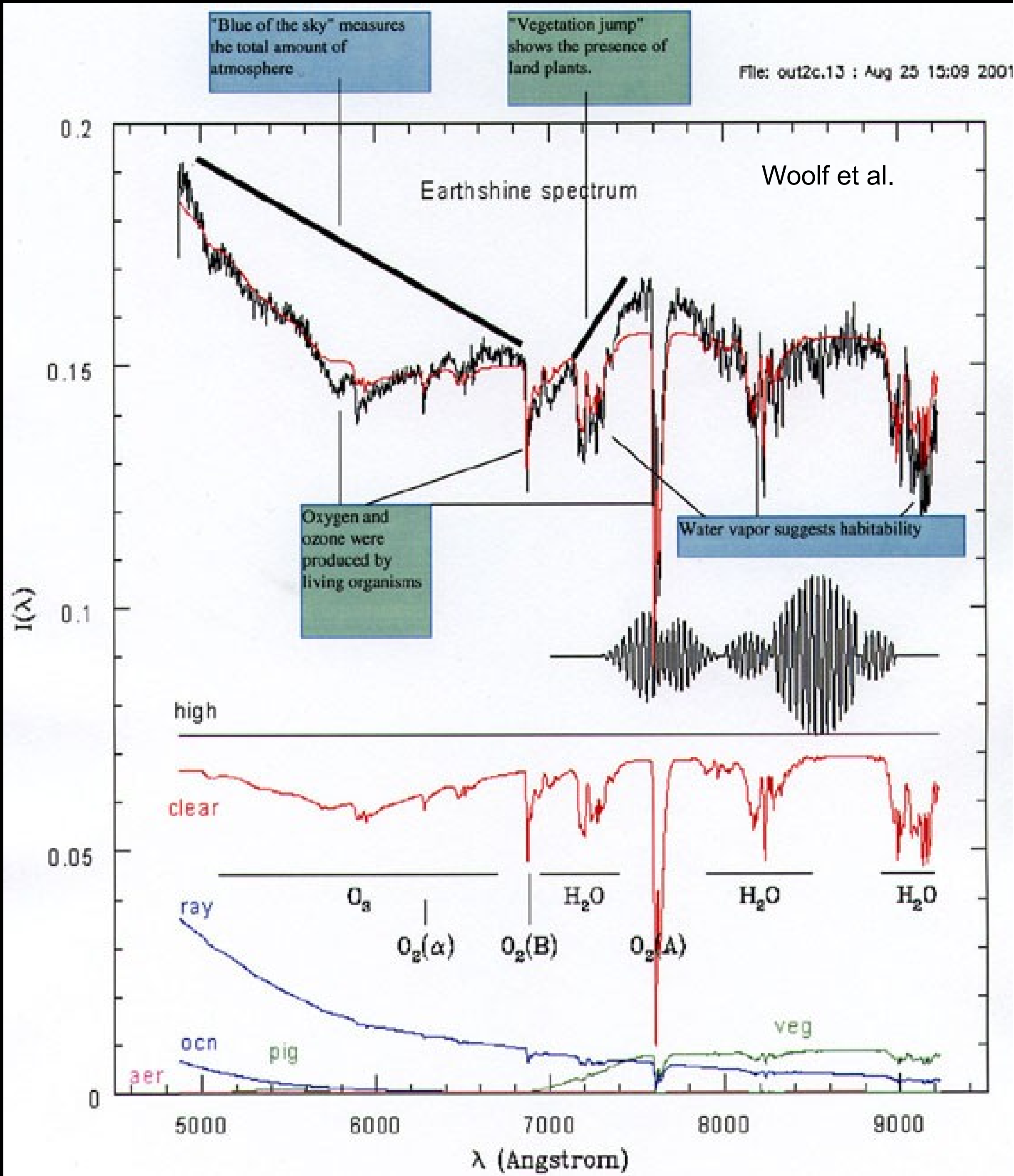

Kepler
Field of
View
Deneb
Vega
LYRA
CYGNUS
Albireo
Altair
AQUILA

Kepler (NASA)

Directly imaging planet is necessary to find life

We need to take spectra of habitable planets

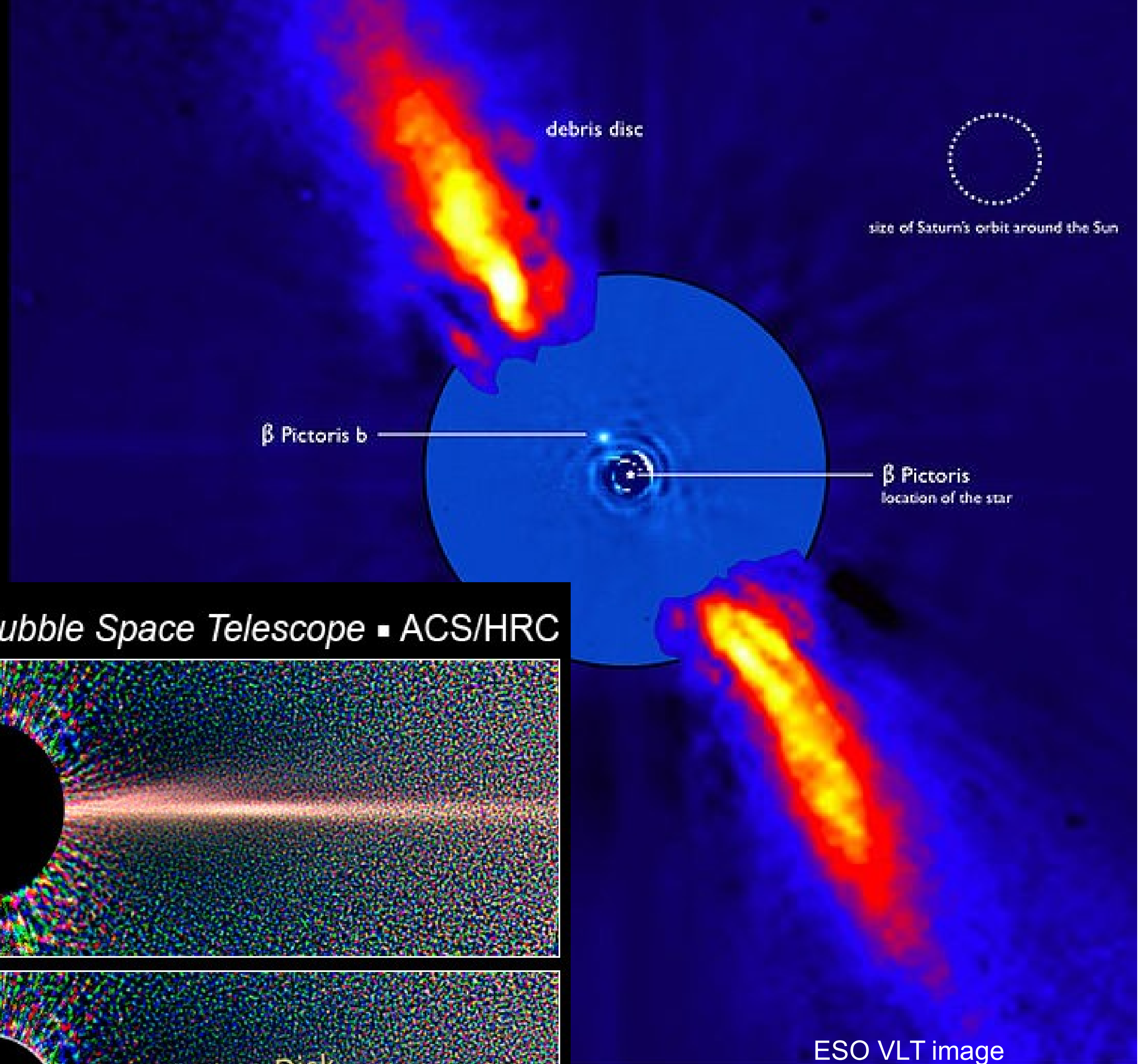
Spectra of Earth (taken by looking at Earthshine) shows evidence for life and plants



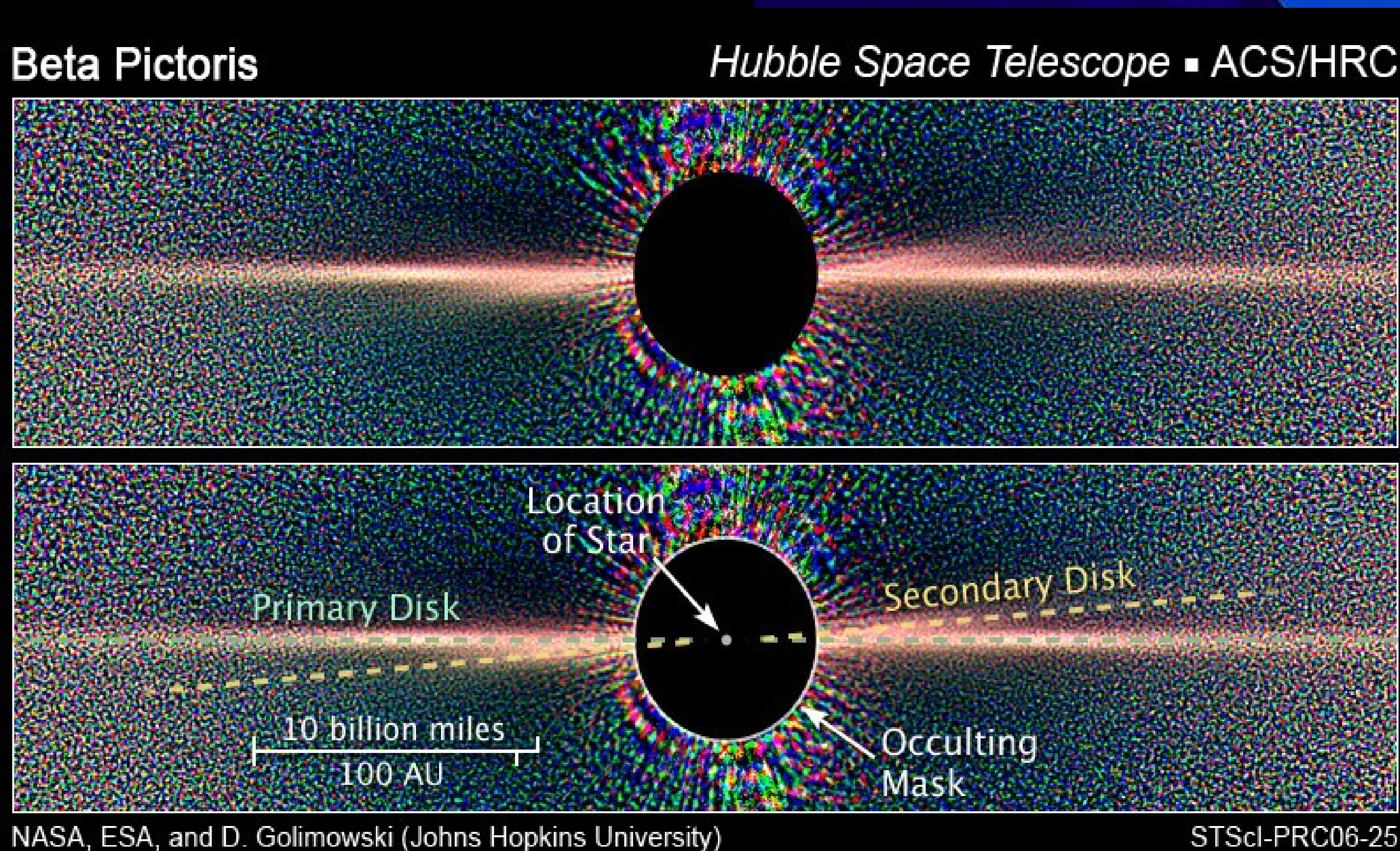
Beta Pictoris

8 Jupiter mass planet

Orbits young massive star in ~20yr



ESO VLT image
(Lagrange et al.)



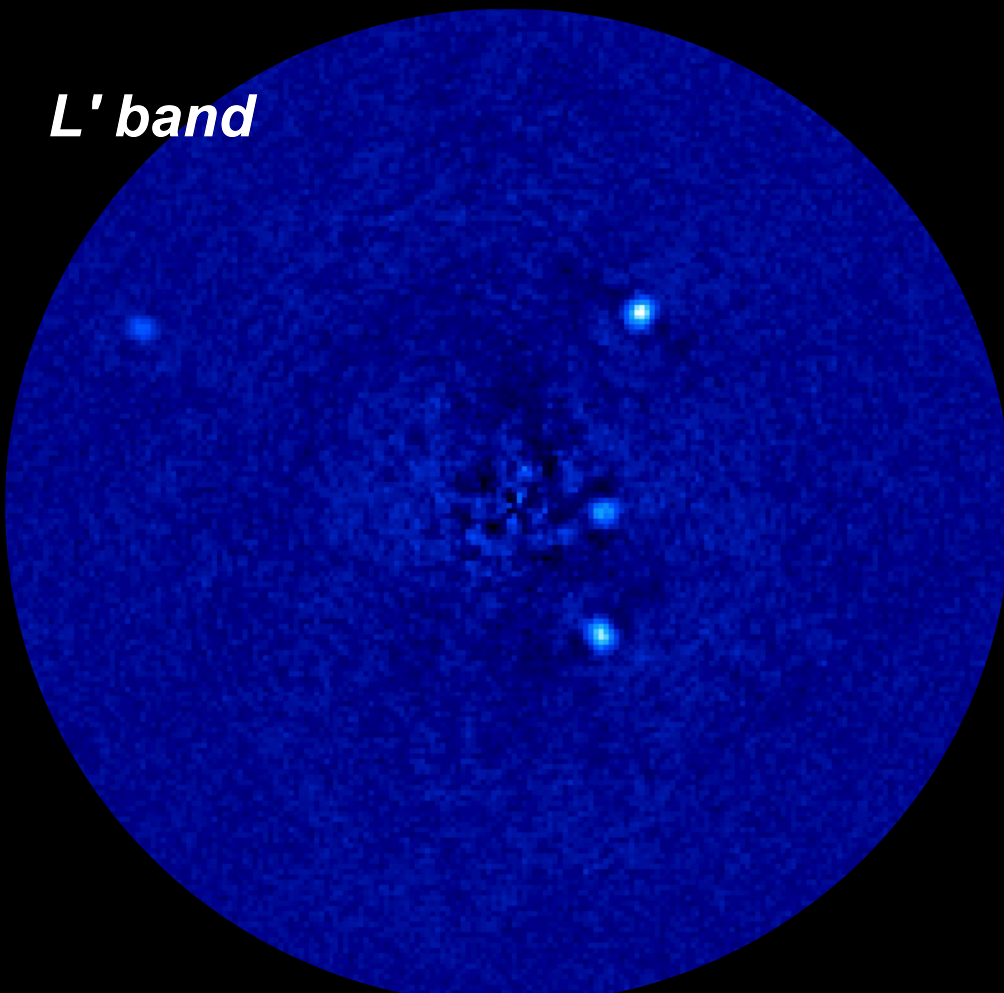
Large Binocular Telescope, AZ

Ground-based telescopes use adaptive optics to mitigate atmospheric turbulence

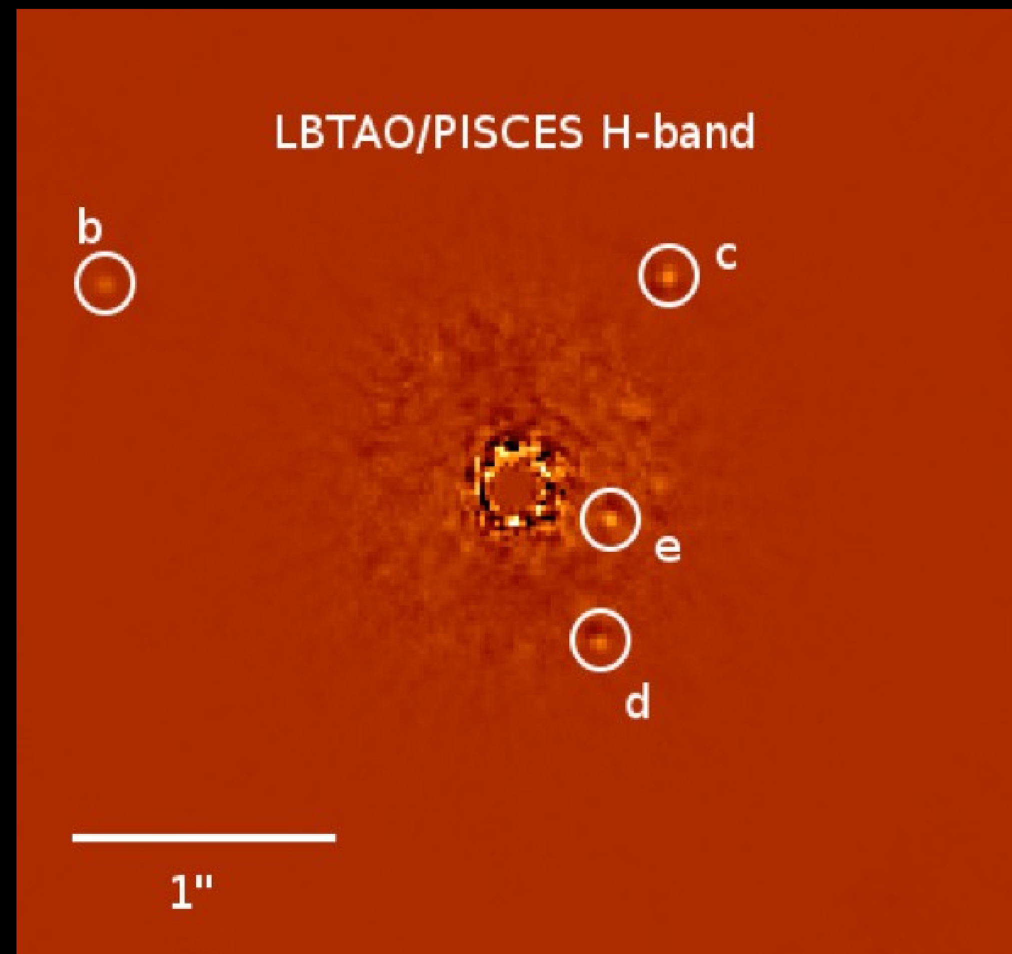
Large Binocular Telescope adaptive secondary mirror

HR8799 imaged with Large Binocular Telescope

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

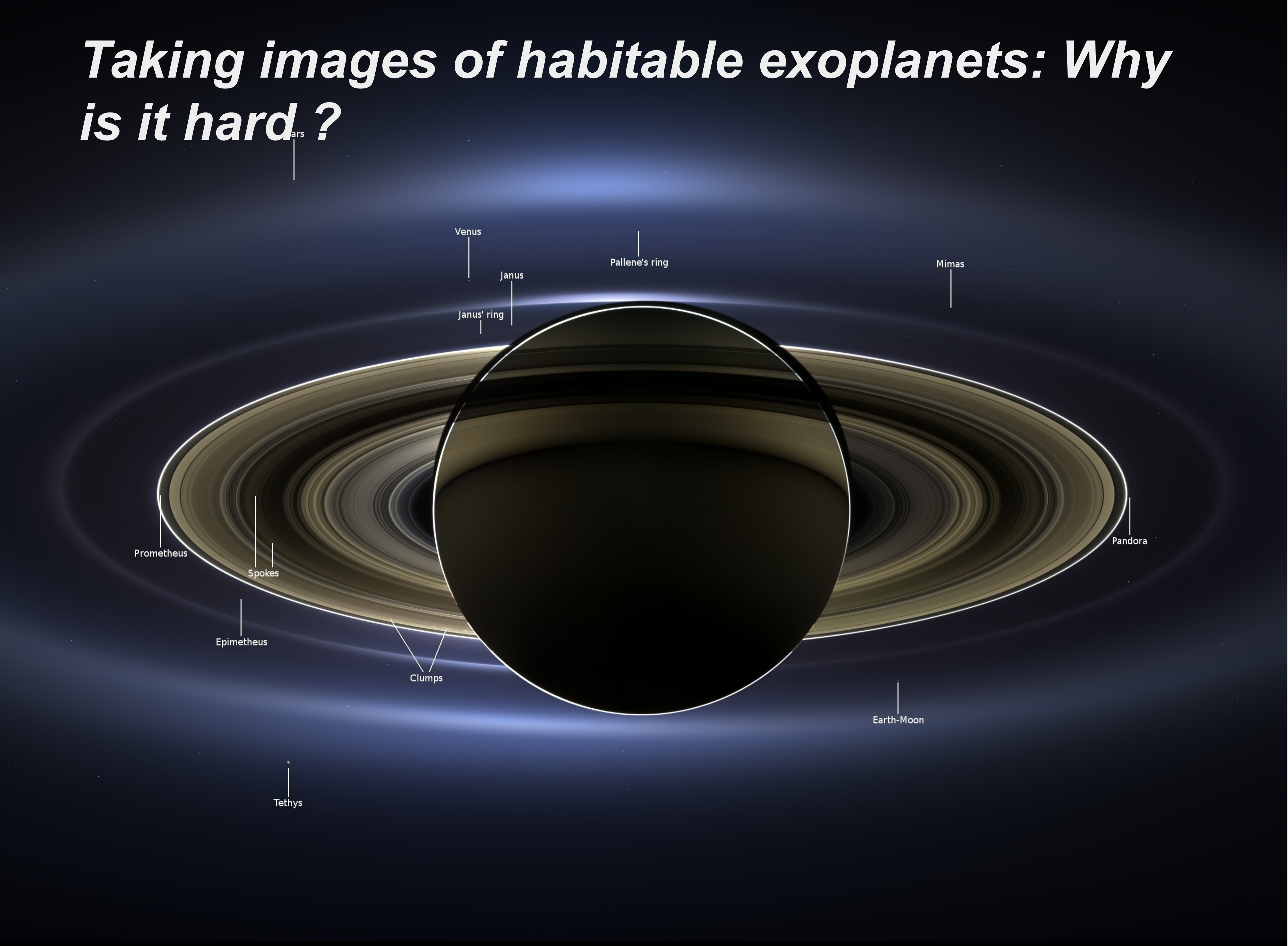


Defrere et al.



Skemer et al..

Taking images of habitable exoplanets: Why is it hard ?




Saturn
Earth

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

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

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

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

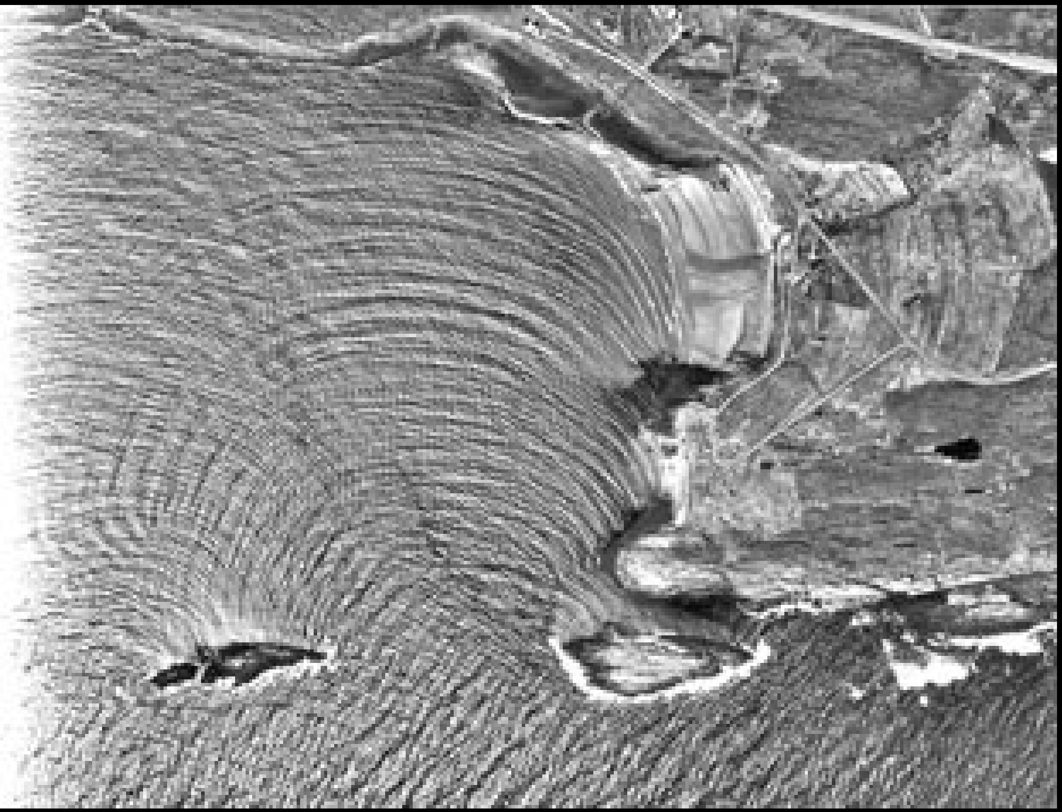
1818: French academy of science committee launches a competition
to explain nature of light

Augustin-Jean Fresnel
submits wave theory of light

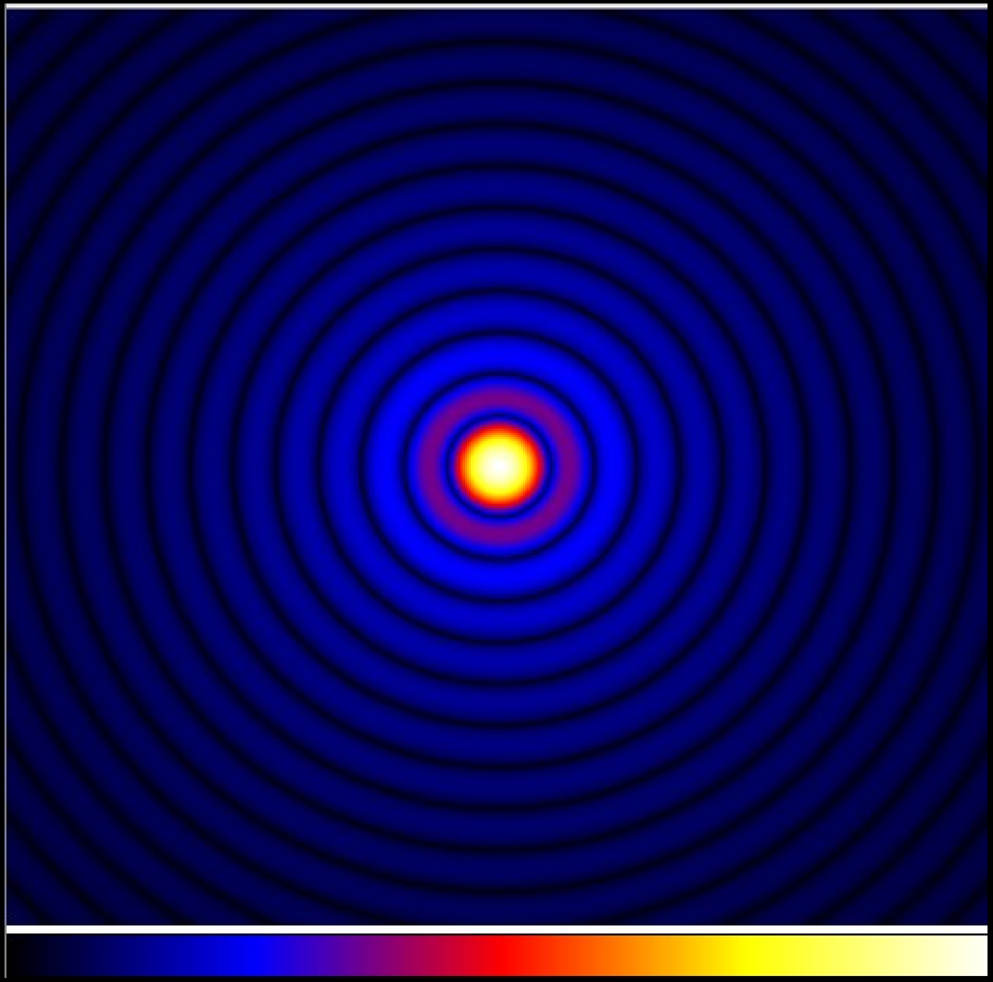
Simeon-Denis Poisson finds a flaw in Fresnel's theory:
According to Fresnel's equations, a bright spot should appear in
the shadow of a circular obstacle → this absurd result disproves Fresnel's theory

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



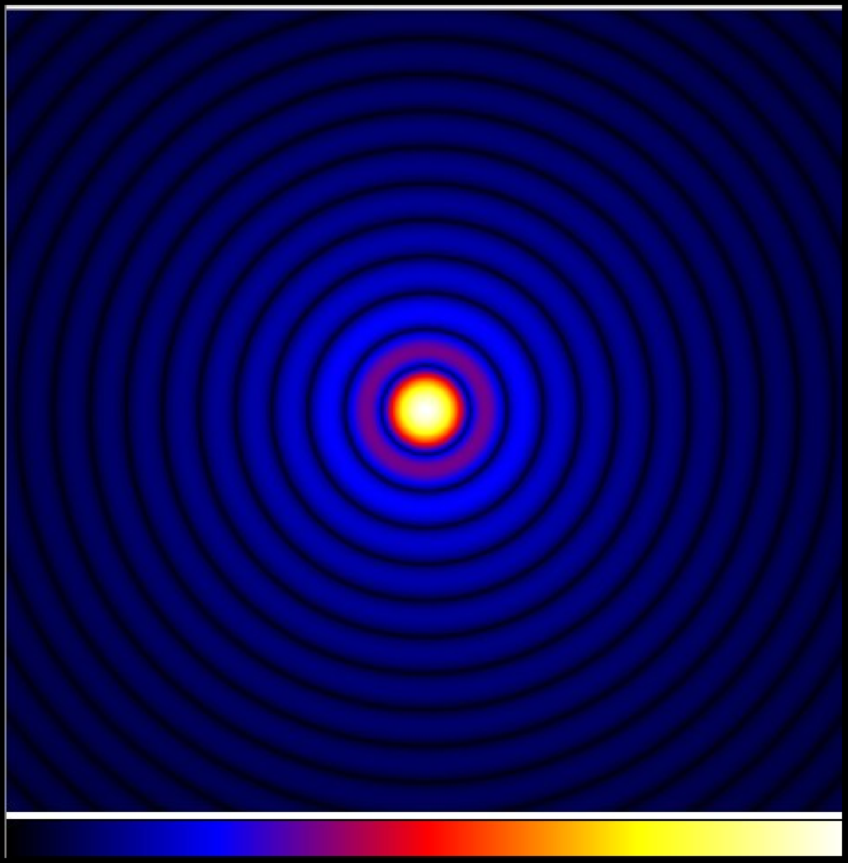
Waves diffracted by coastline and islands

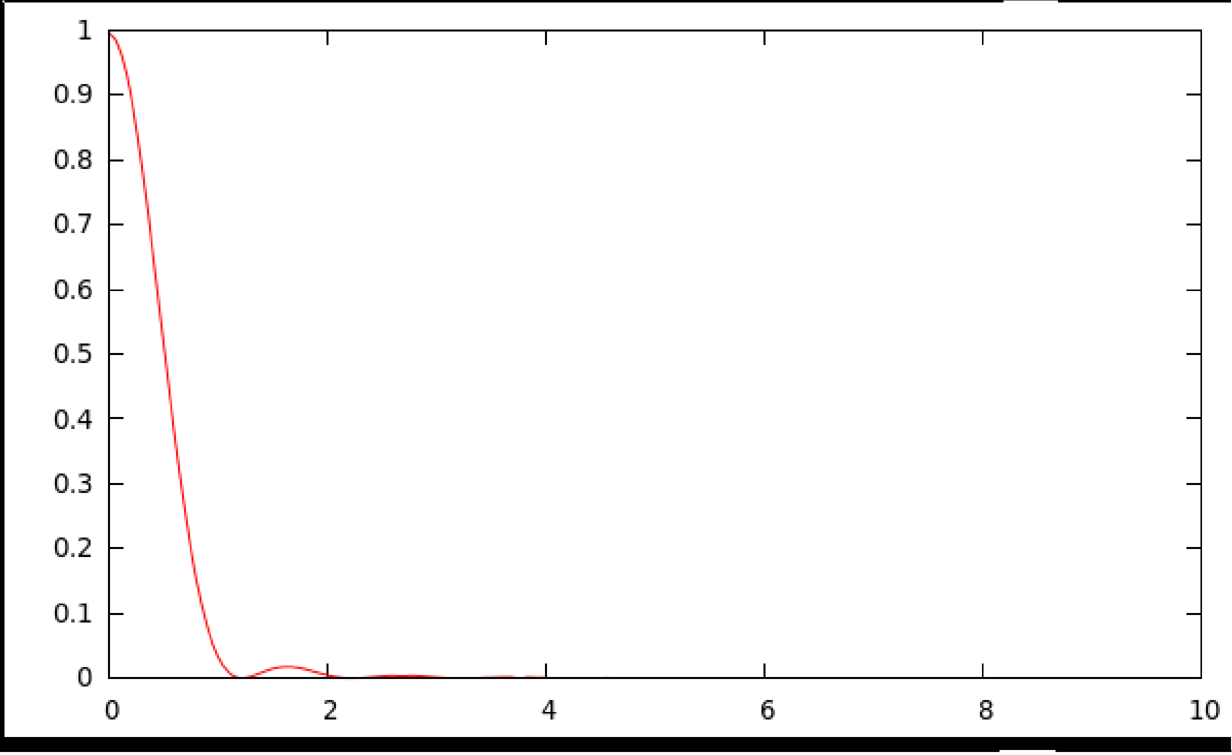


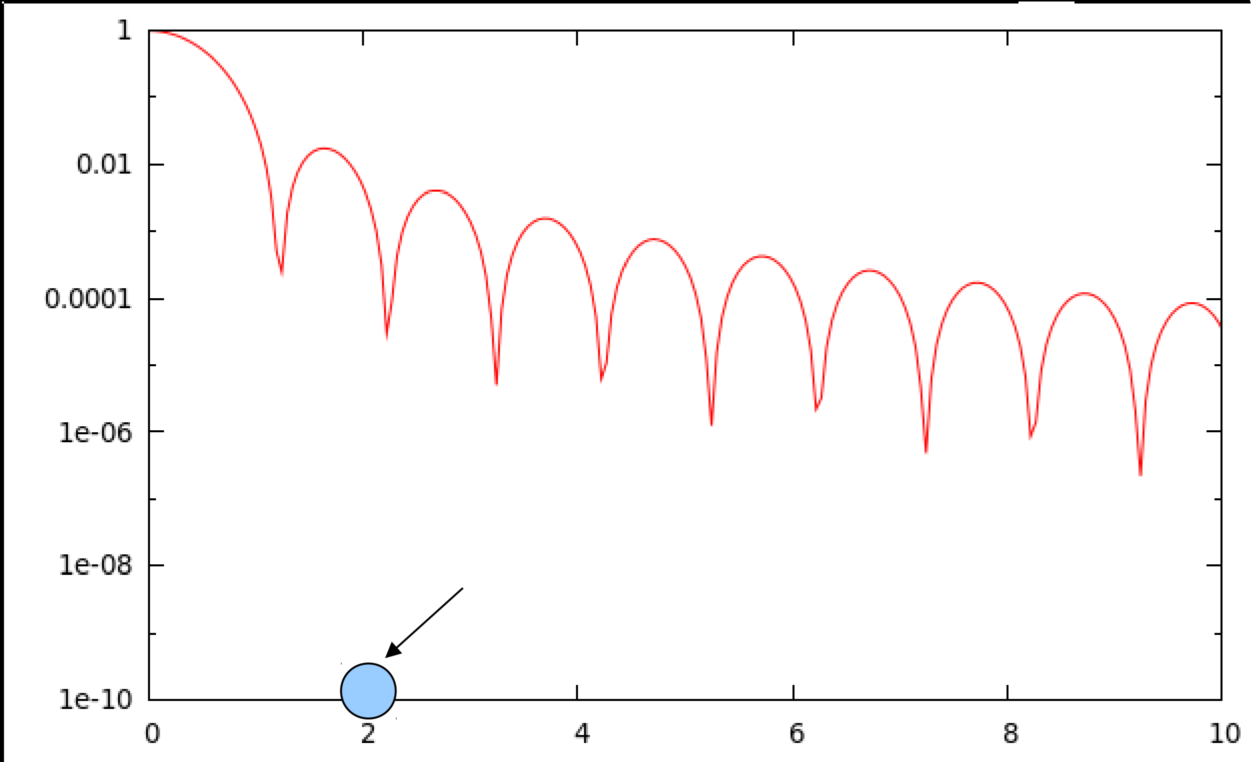
Ideal image of a distant star by a telescope
Diffraction rings around the image core

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

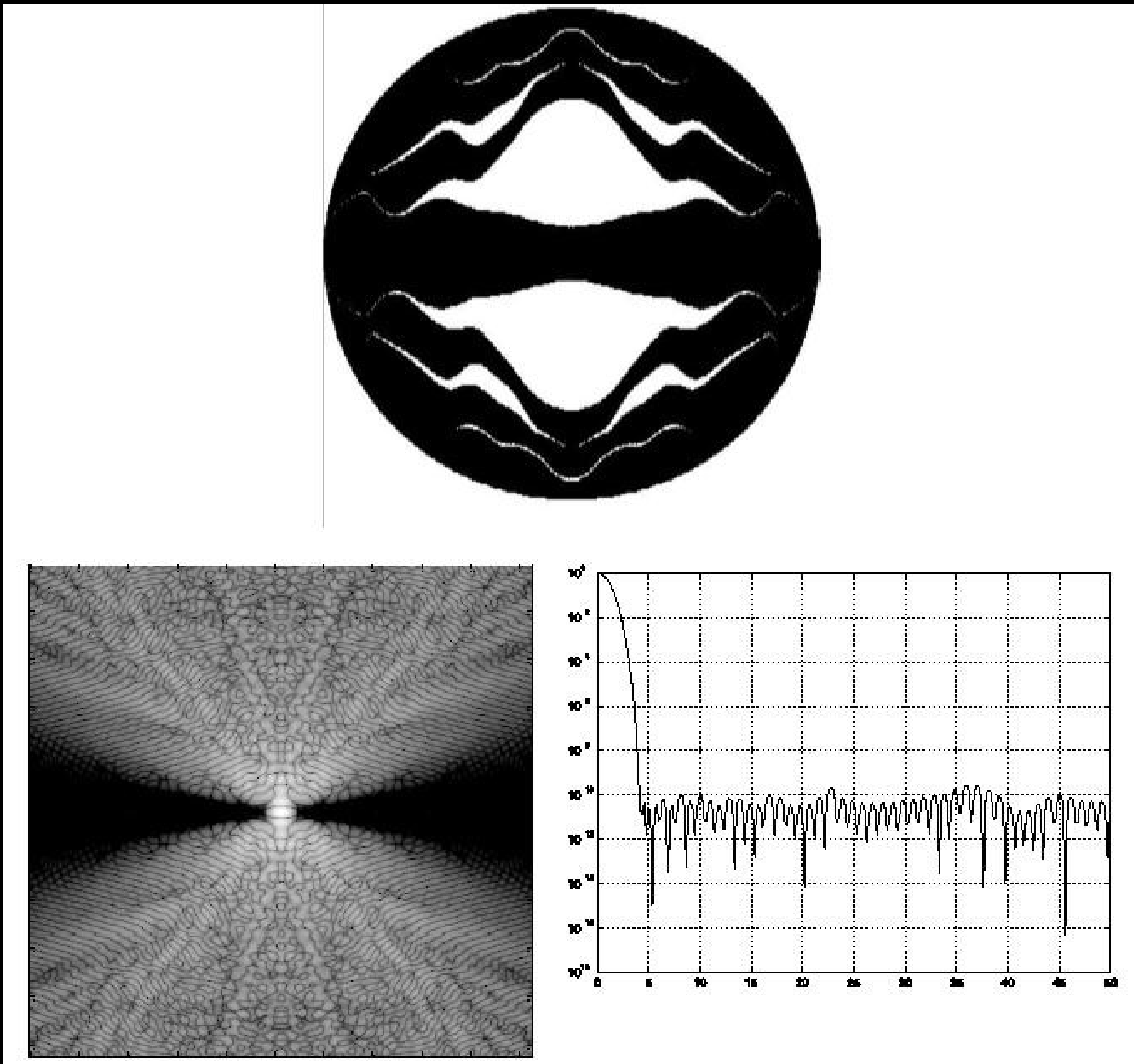
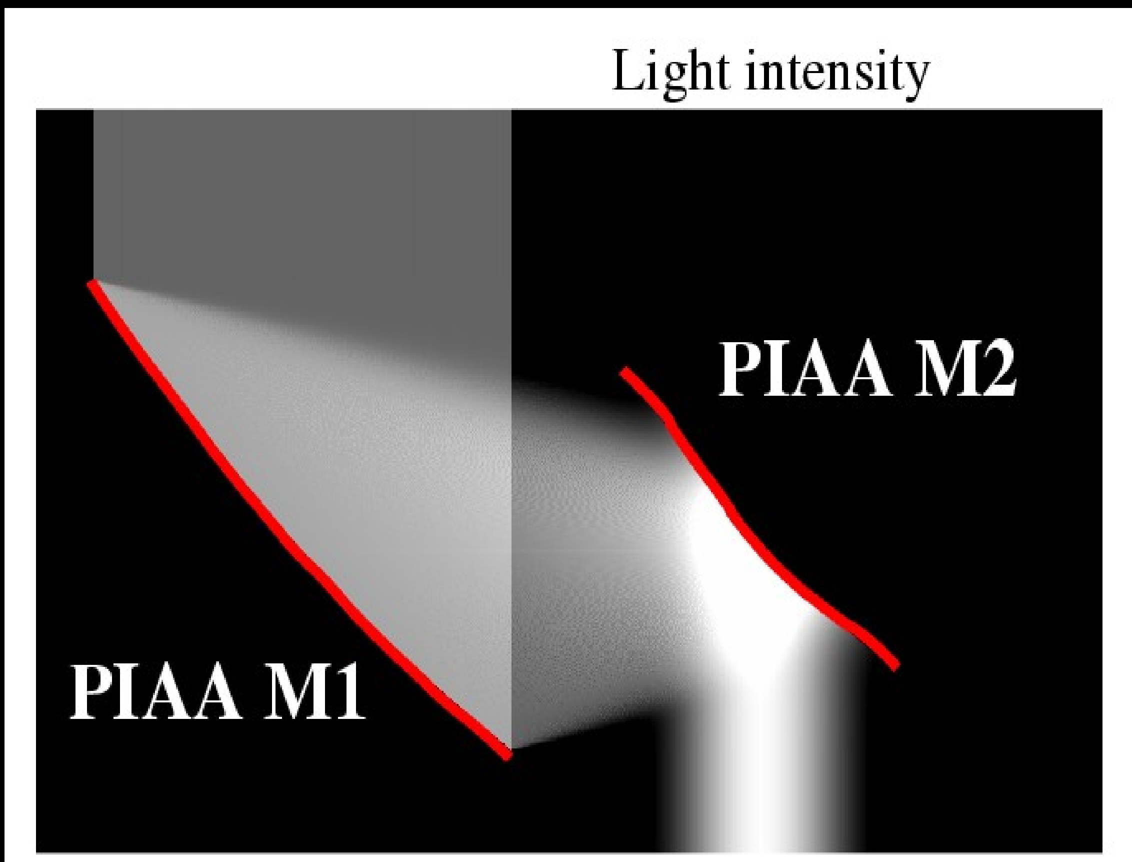


Fig. 9.—*Top*: Asymmetric multiopening mask designed to provide high-contrast, 10^{-10}, from $\lambda/D = 4$ to $\lambda/D = 100$ in two angular sectors centered on the x-axis. Ten integrations are required to cover all angles. Total throughput and pseudoarea are 24.4%. Airy throughput is 11.85%. *Bottom*: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

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

Phase-Induced Amplitude Apodization Coronagraph (PIAAC)

Lossless apodization by aspheric optics.

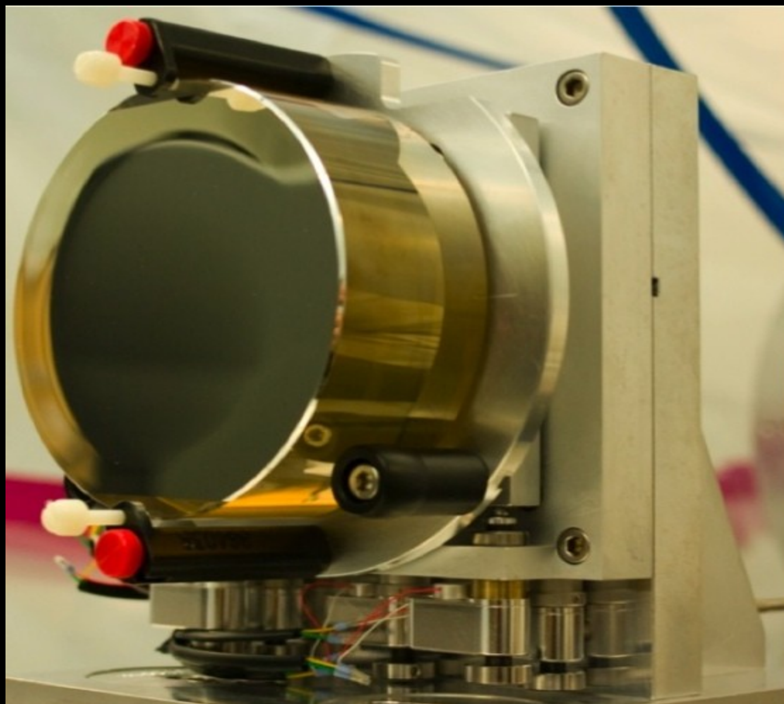


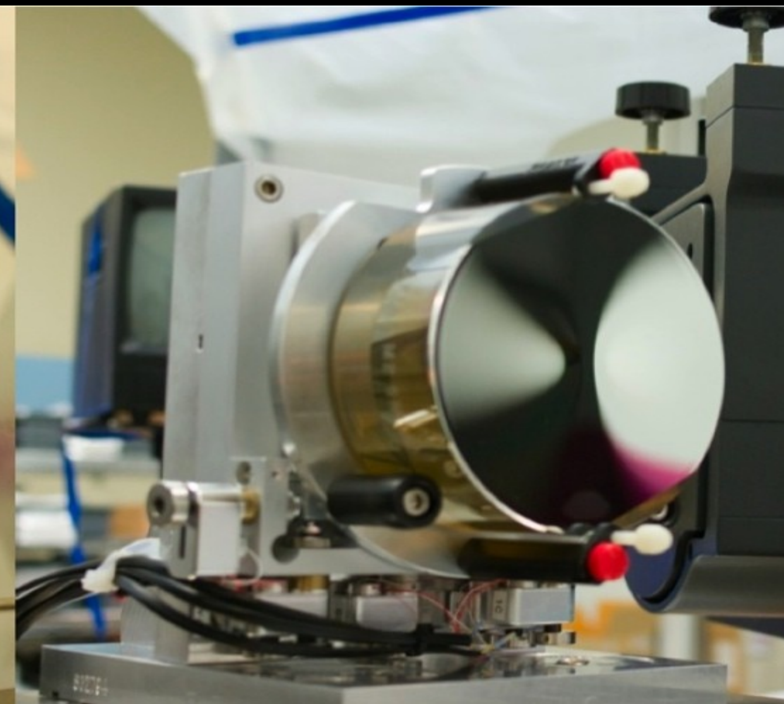
No loss in angular resolution or sensitivity
Achromatic (with mirrors)
Small inner working angle

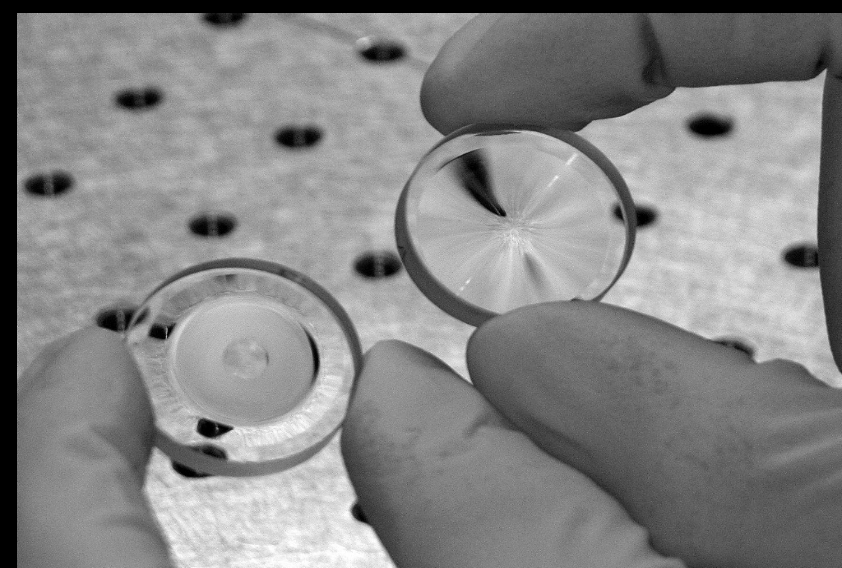
→ Gain ~x2 to x3 in telescope diameter over previous concepts

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

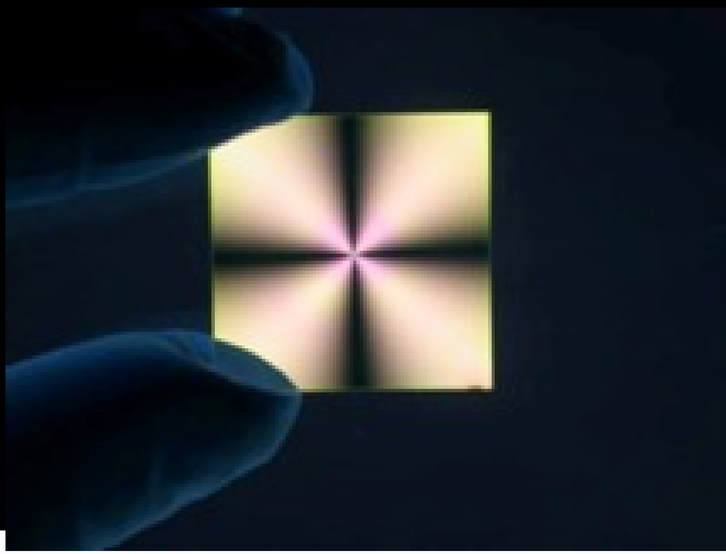
We use strangely shaped optics to reshape light

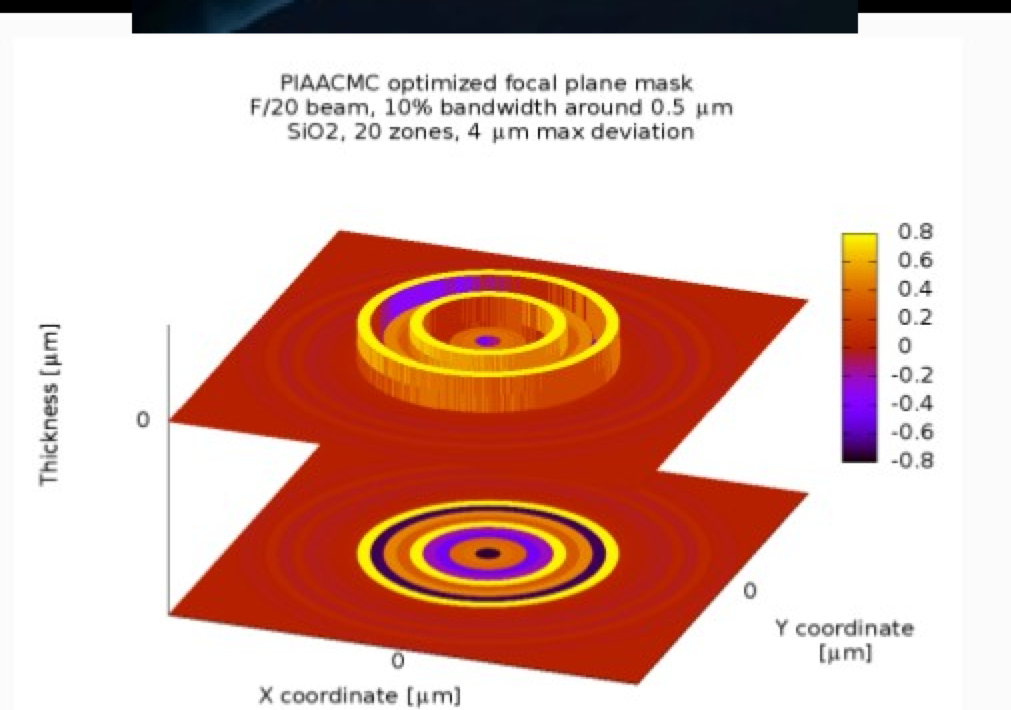


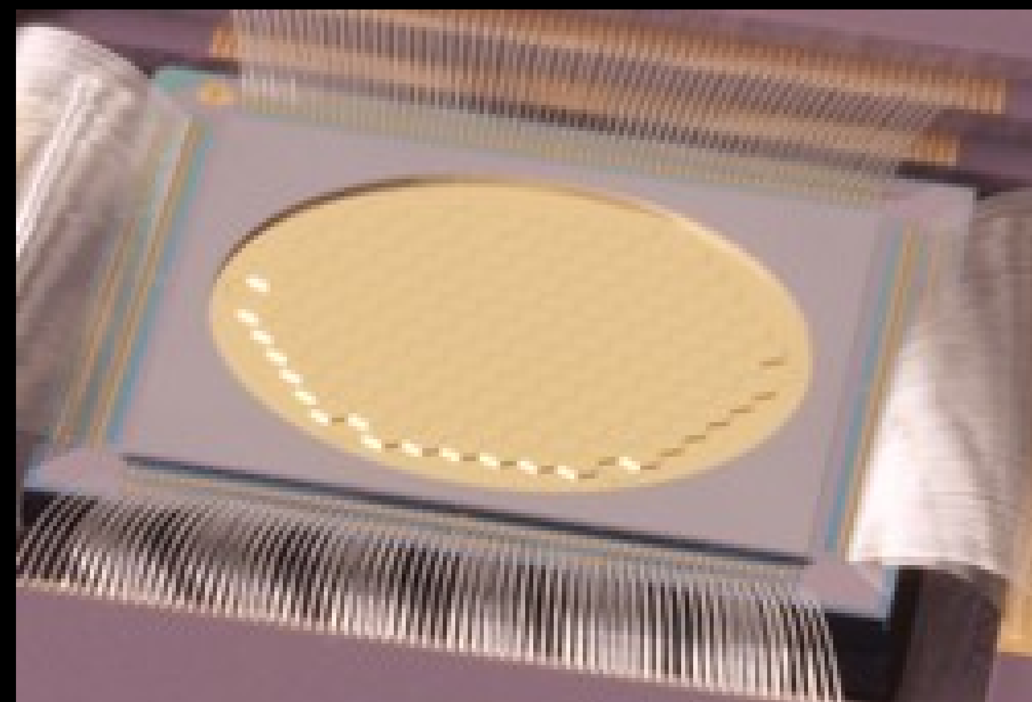




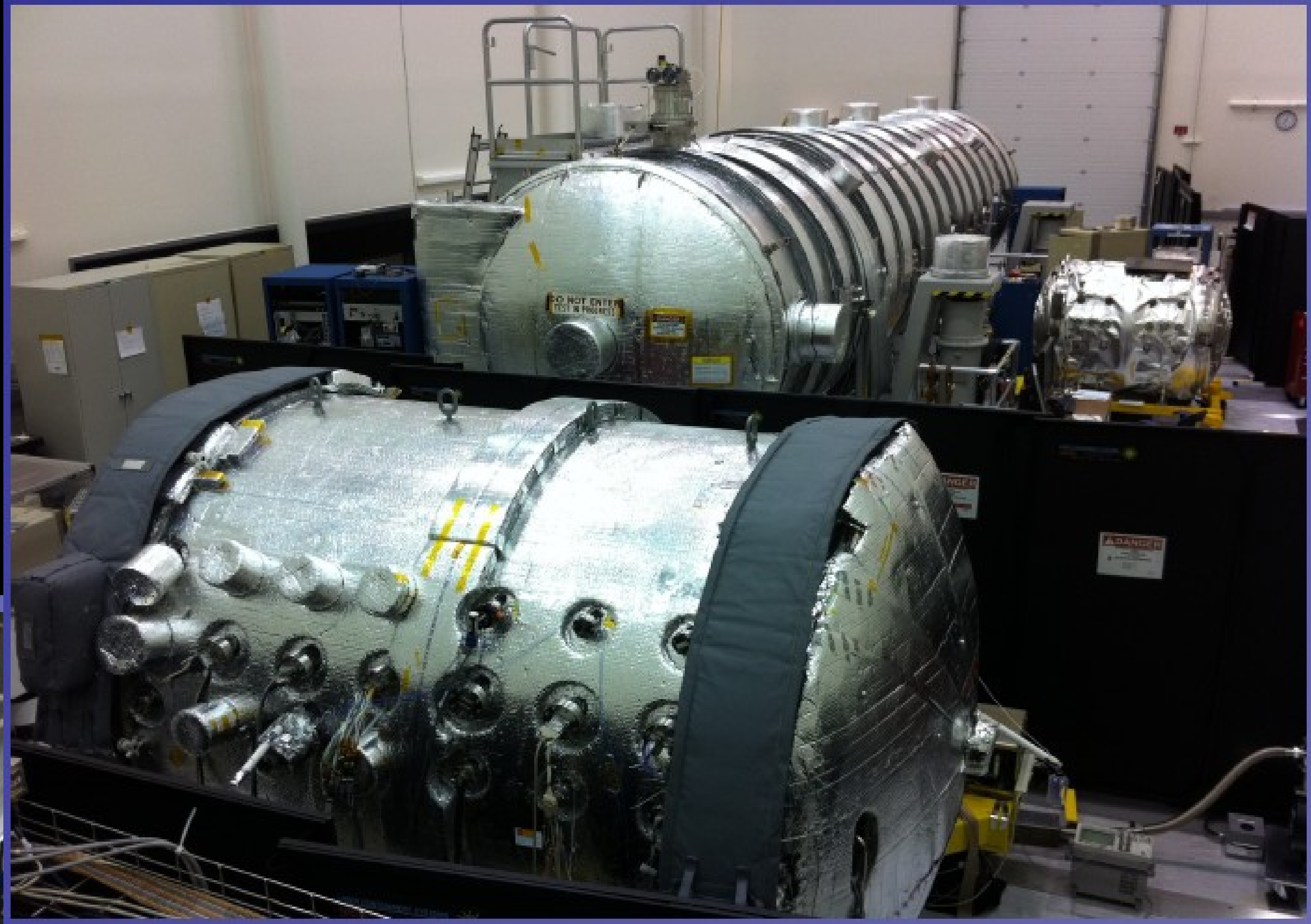
Technology: components

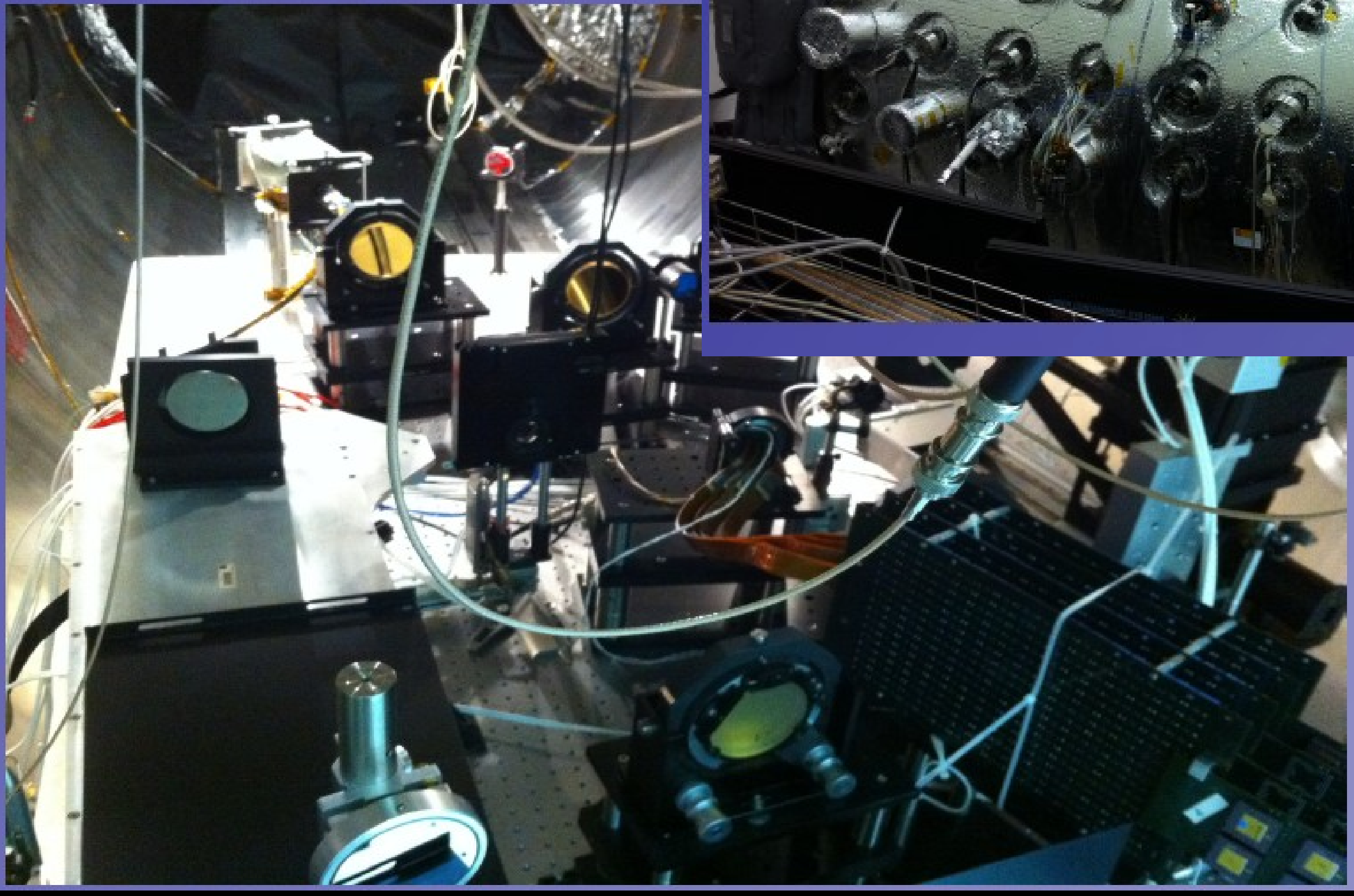






Vacuum testbeds at NASA JPL



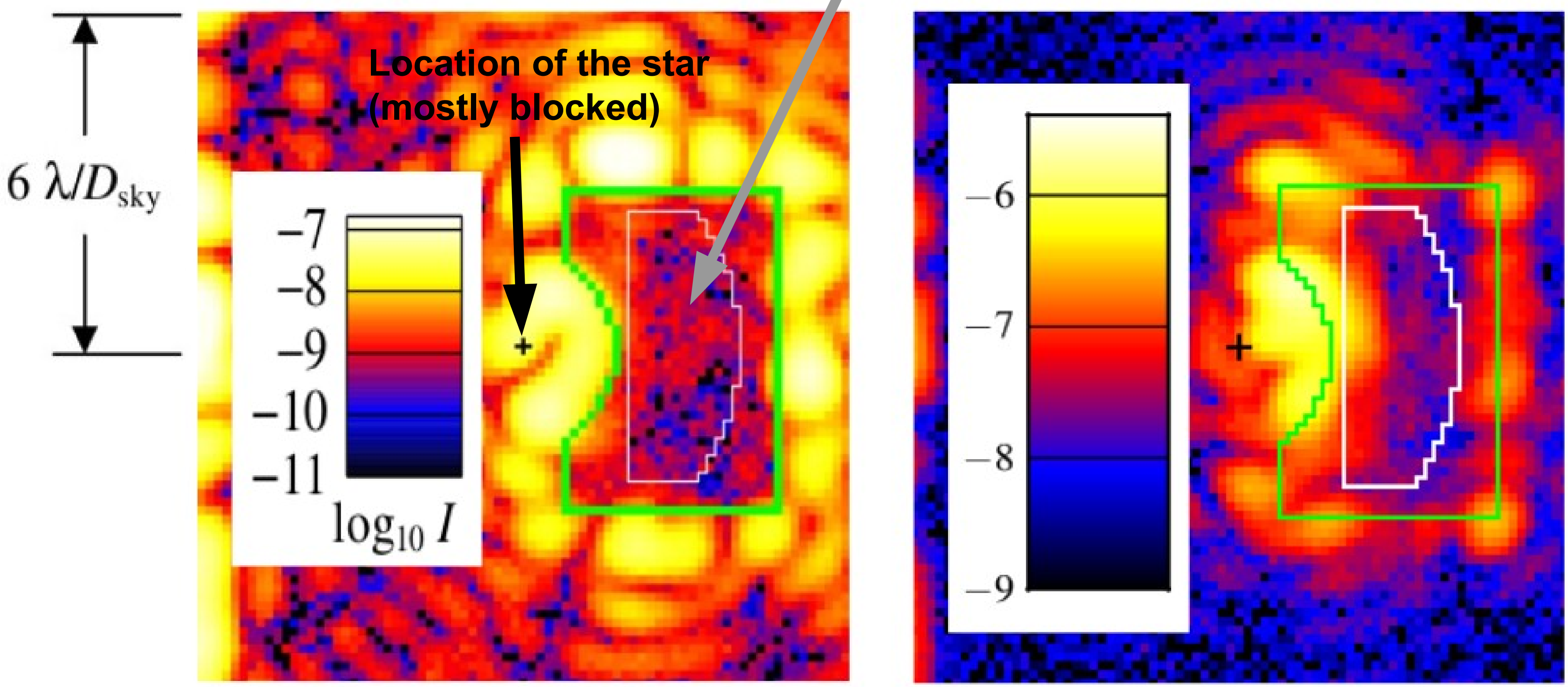


PIAA testbed at NASA JPL : lab results

An Earth-like planets could be seen !

Monochromatic light (800nm, vacuum)

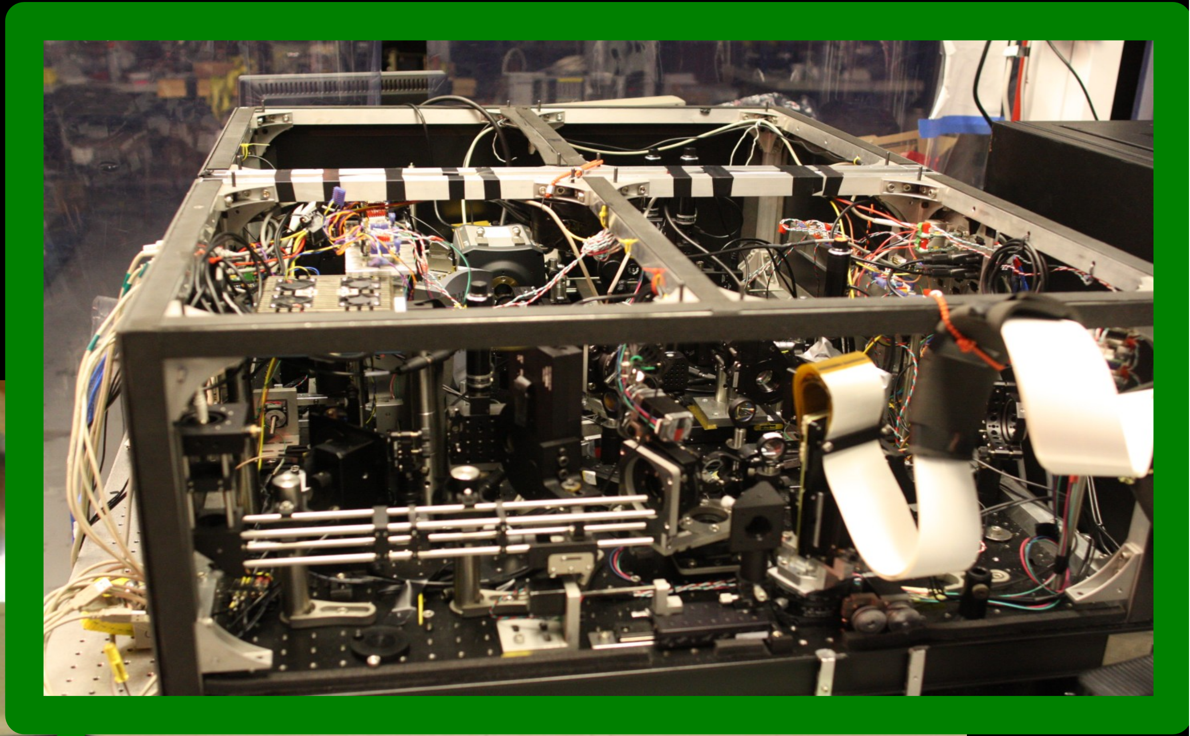
7.5% wide band (770 – 830 nm, in air)

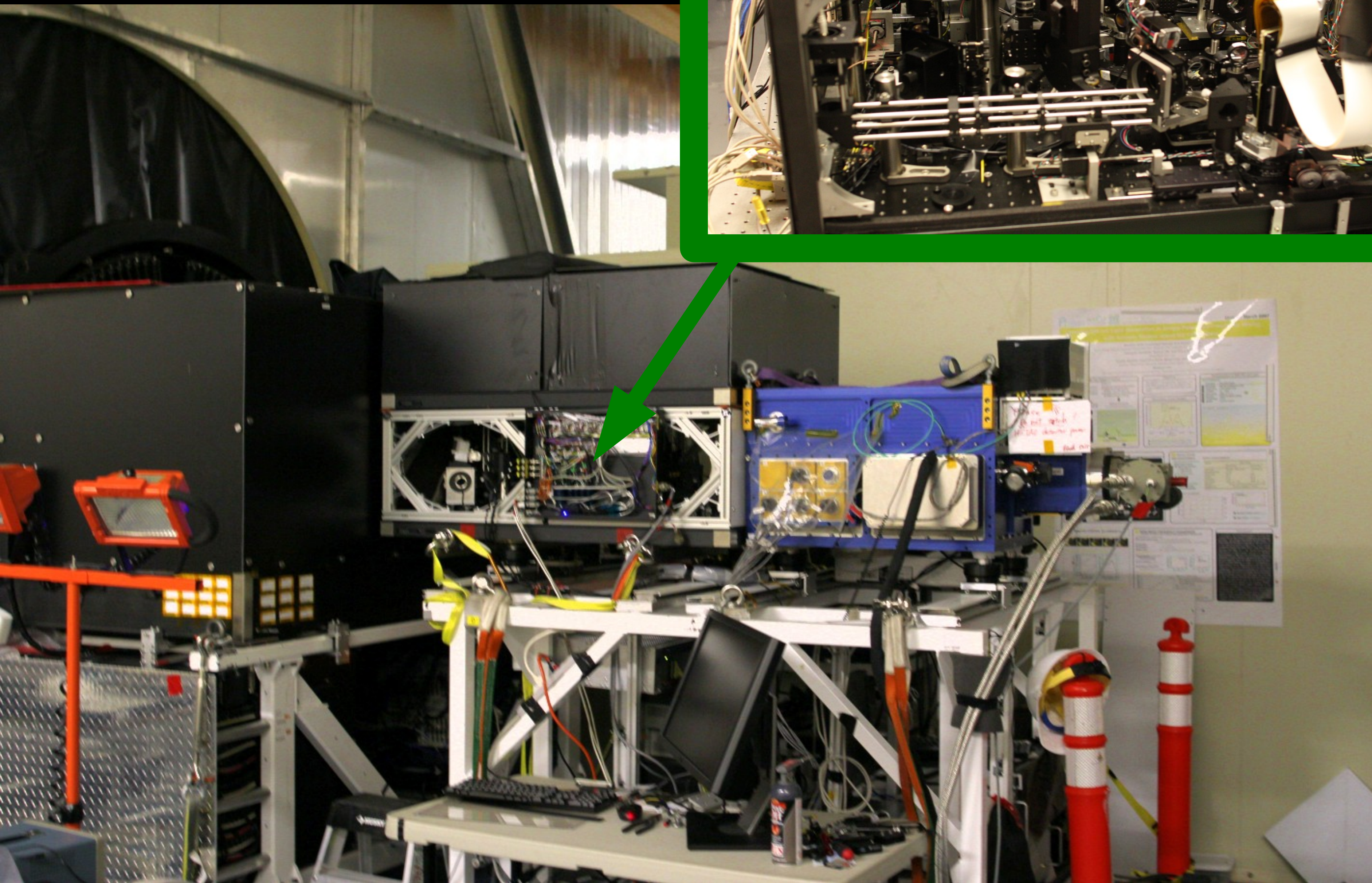


3 runs, contrast values averaged from 2 to 4 λ/D between 5.10^{-10} to 9.10^{-10} (figure shows $7.3.10^{-10}$ result)

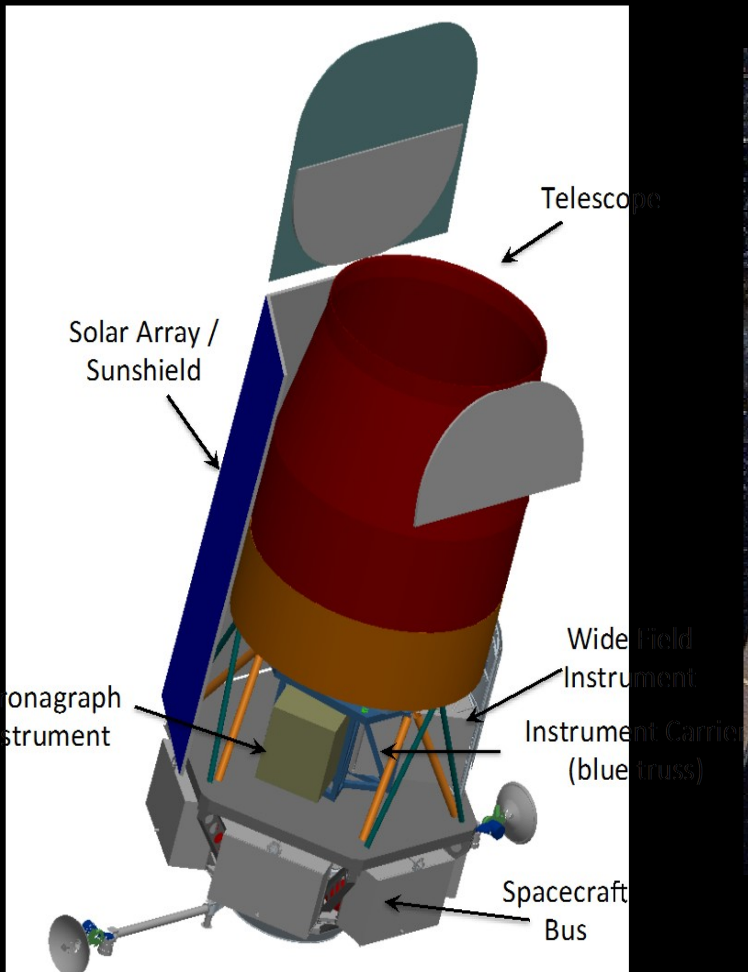
5.10^{-8} contrast from 2 to 4 λ/D,
2.10^{-8} contrast from 3 to 4 λ/D
Contrast performance limited by wavefront instability (test in air)

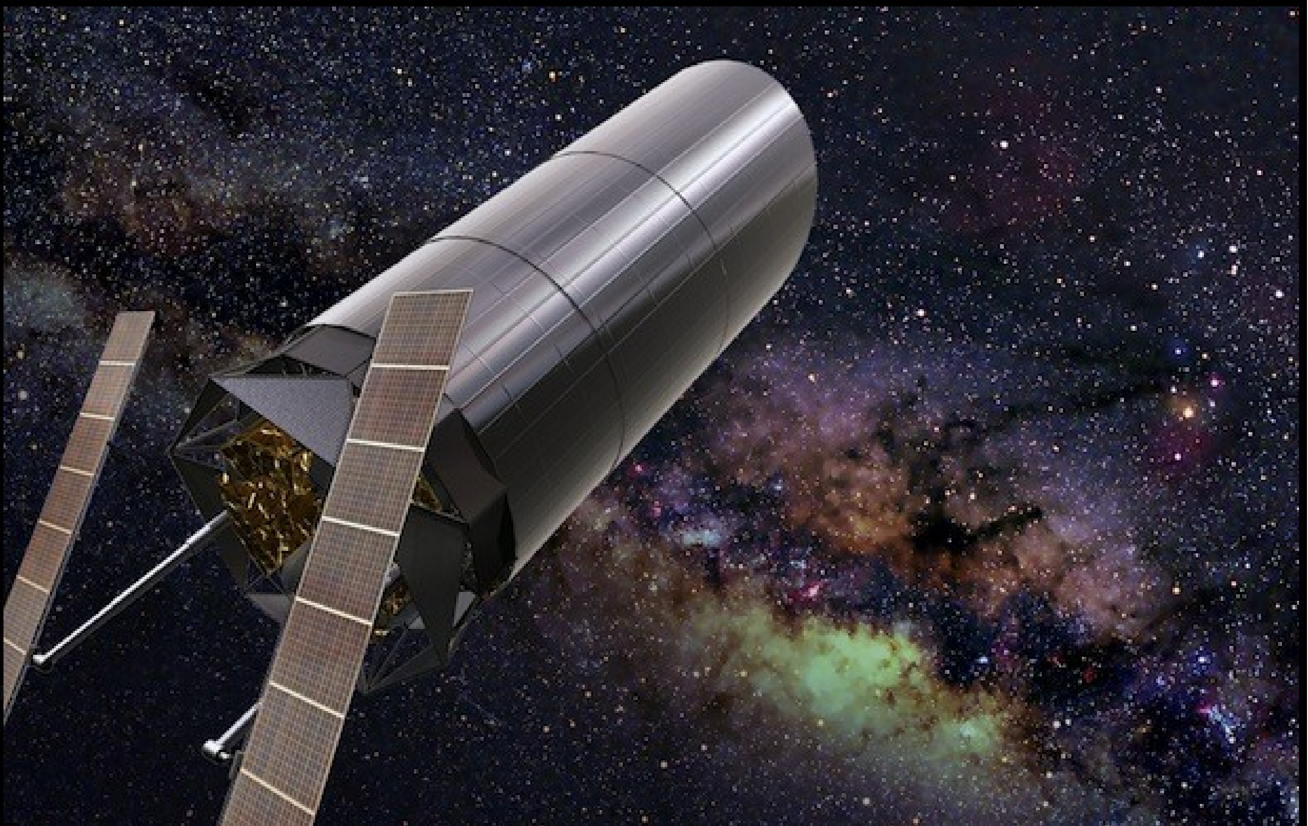
The Subaru Coronagraphic Extreme Adaptive Optics (SCExAO) system





Space telescopes





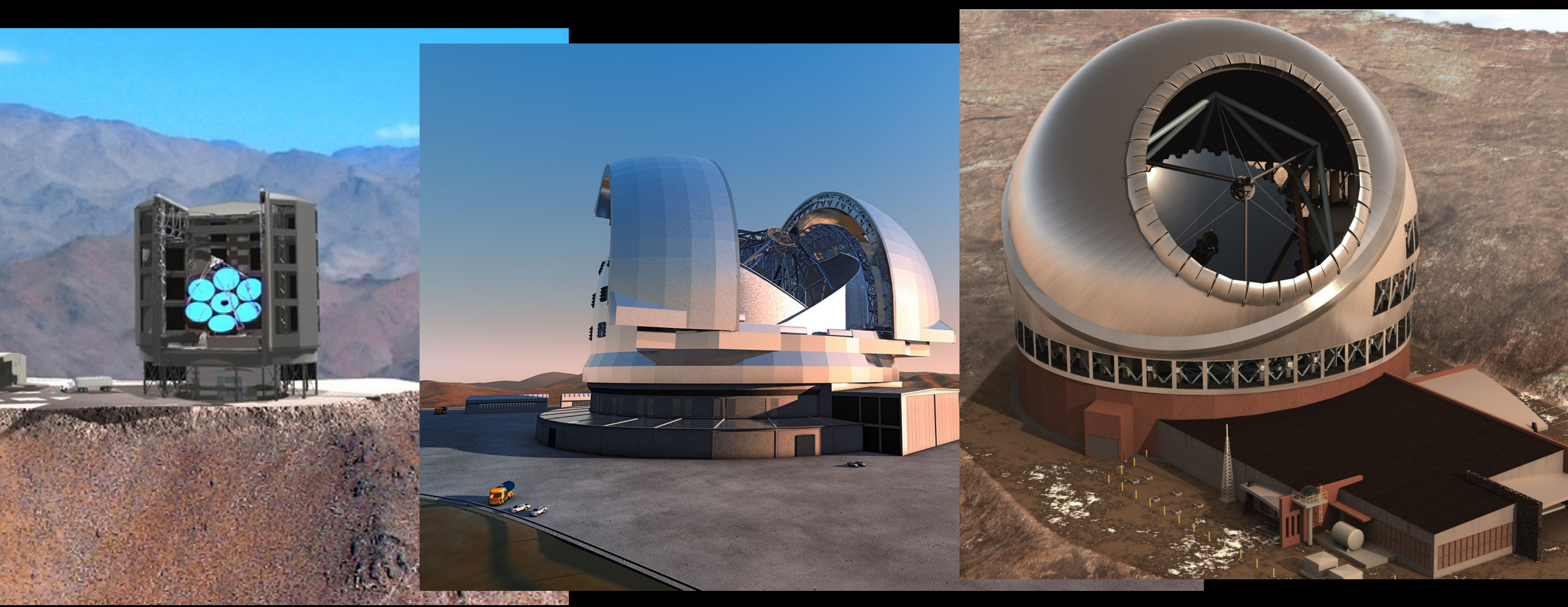
ATLAS 8m telescope project

WFIRST-AFTA telescope, 2.4m diameter

Exciting future opportunities

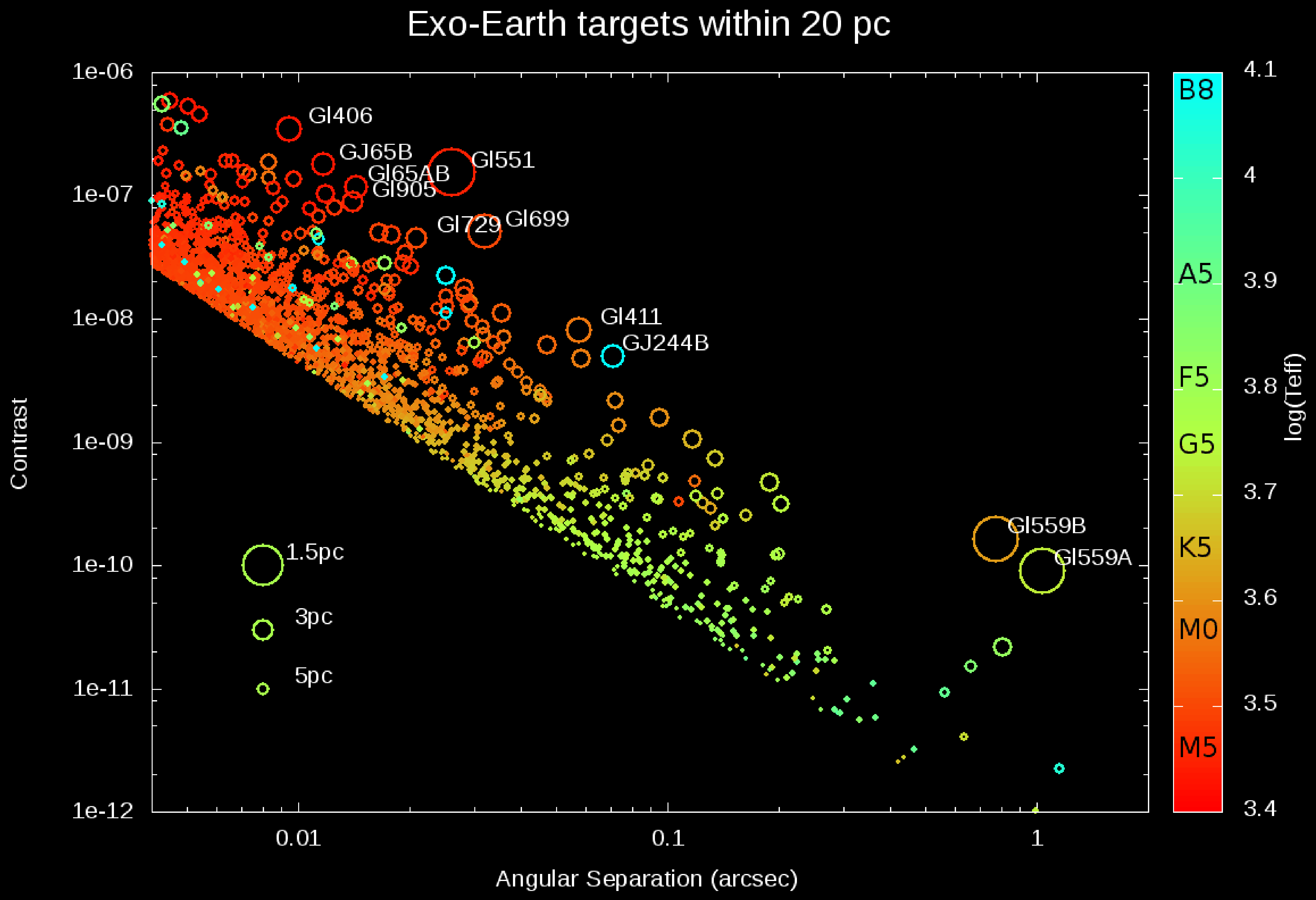
Next generation of large telescopes on the ground will be able to image habitable planets around nearby low mass red stars
3 projects, ~30m diameter

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

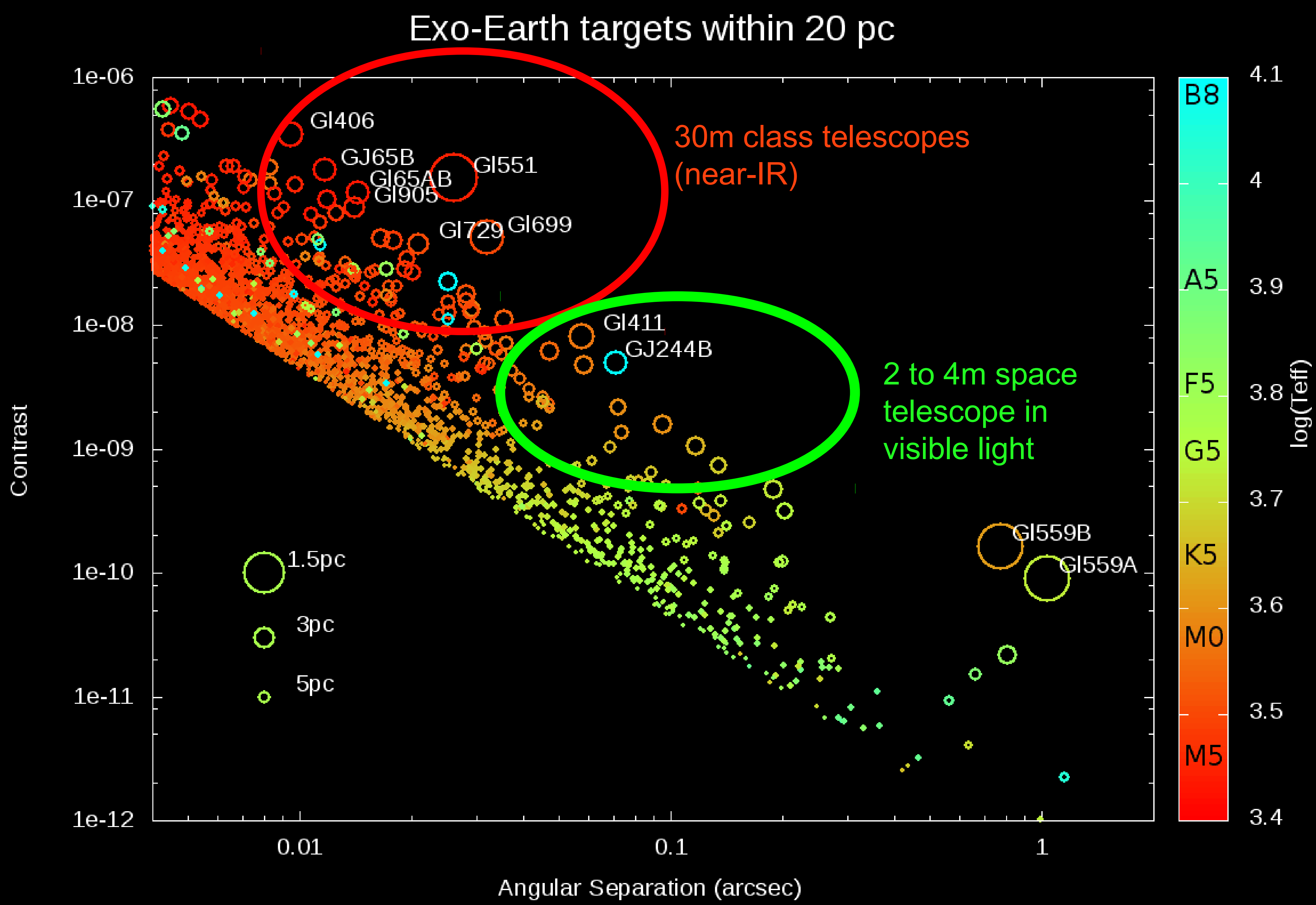


Giant Magellan Telescope

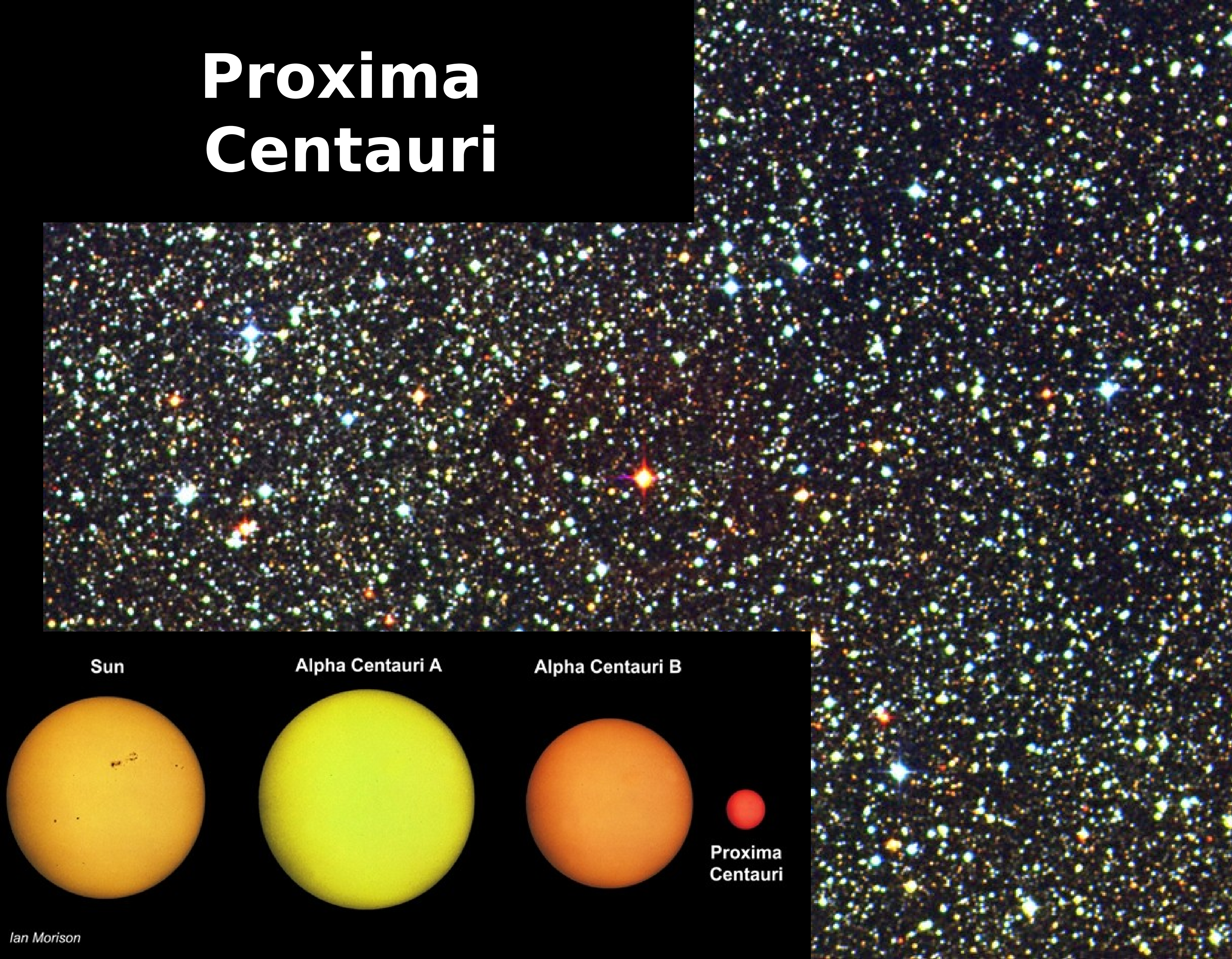
Detecting planets from space and ground



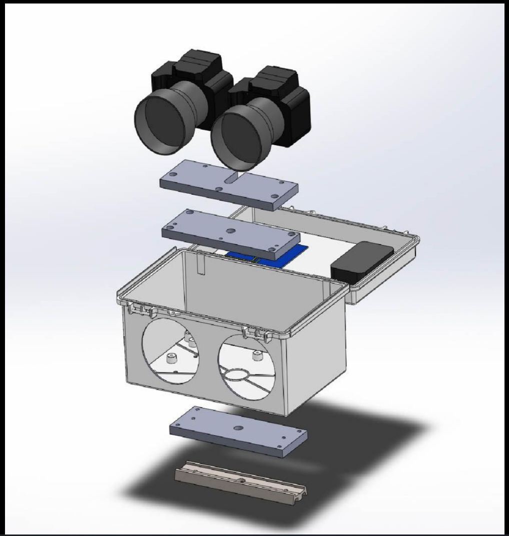
Detecting planets from space and ground



Proxima Centauri



PANOPTES **P**anoptic **A**stronomical **N**etworked **OP**tical observatory for **T**ransiting **E**xoplanets **S**urvey



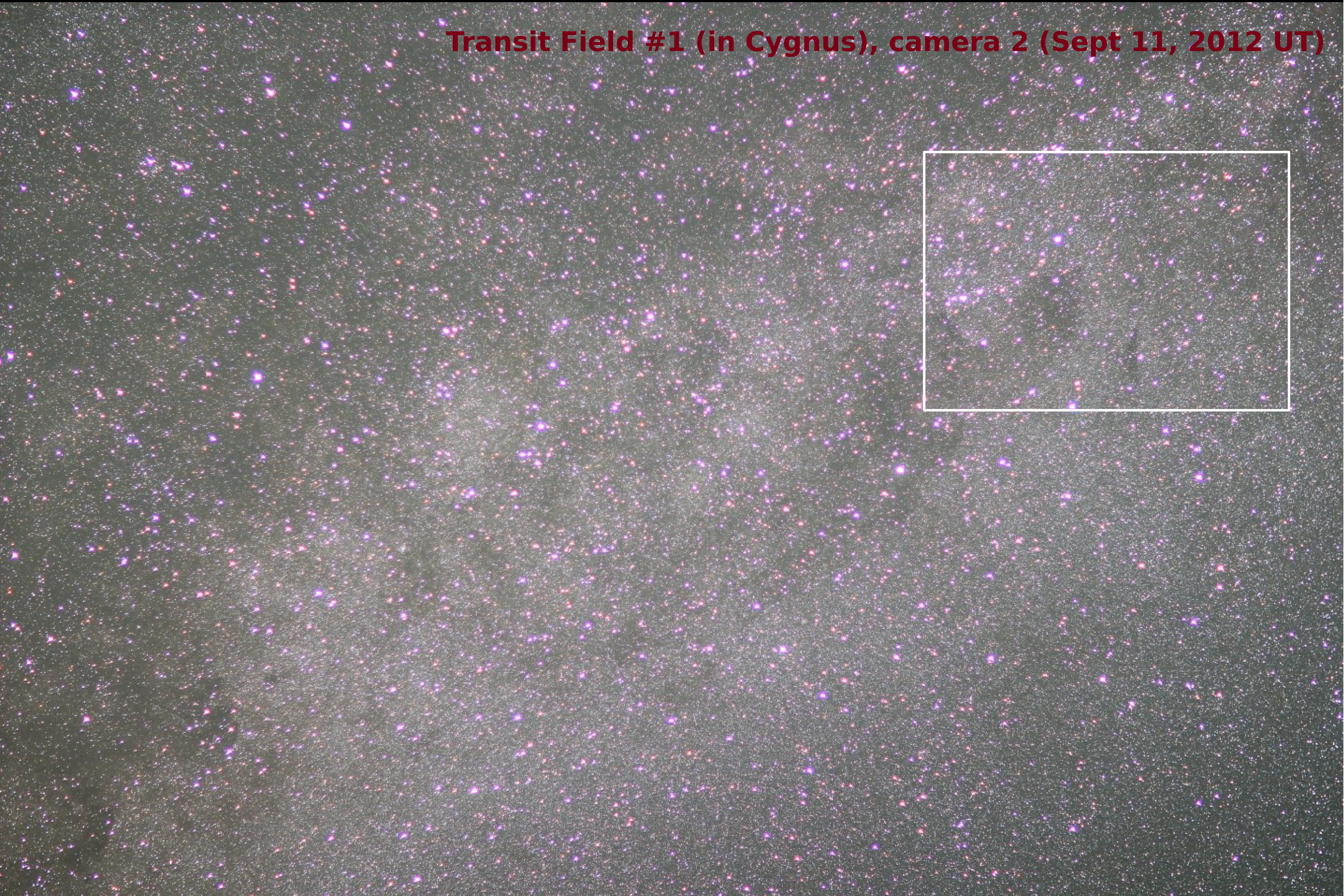
Discovering transiting exoplanets requires monitoring large parts of the sky for long periods of time

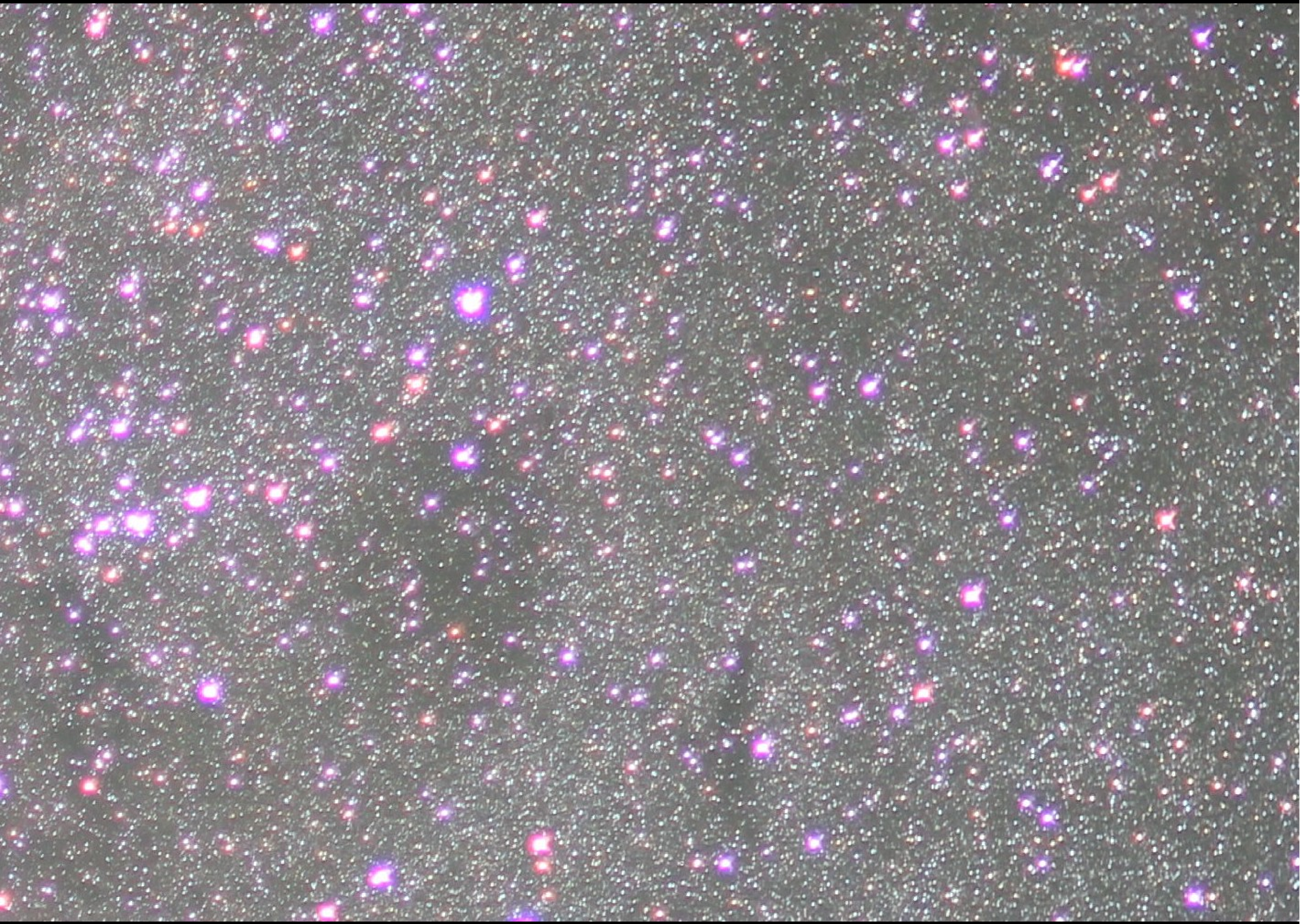
Amateur astronomers, citizen scientists are very good at this, and schools can participate with student team projects

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

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

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





More information, local resources

College of Optical Sciences/Steward Observatory/Lunar and Planetary Laboratory

Astrobiology at University of Arizona: http://astrobiology.arizona.edu/

Mirror laboratory: http://mirrorlab.as.arizona.edu/

Missions/Telescopes:

Large Binocular Telescope: http://www.lbto.org/
http://lbti.as.arizona.edu/LBTI

Giant Magellan Telescope: http://www.gmto.org/

OSIRIX-REX: http://www.asteroidmission.org/

NASA:
http://exep.jpl.nasa.gov/

Project PANOPTES: http://projectpanoptes.org