Anybody out there ?

Imaging exoplanets

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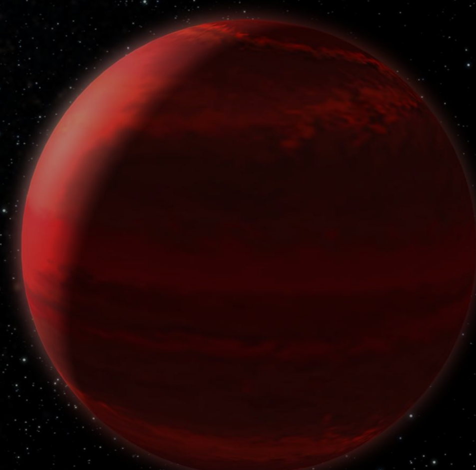
Subaru Telescope

NASA JPL



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Outline

Introduction

- What we know about exoplanets
- Why direct imaging ? Why is it difficult ?

Technology

- Coronagraphy
- Optics fabrication
- Re-thinking adaptive optics for high contrast imaging

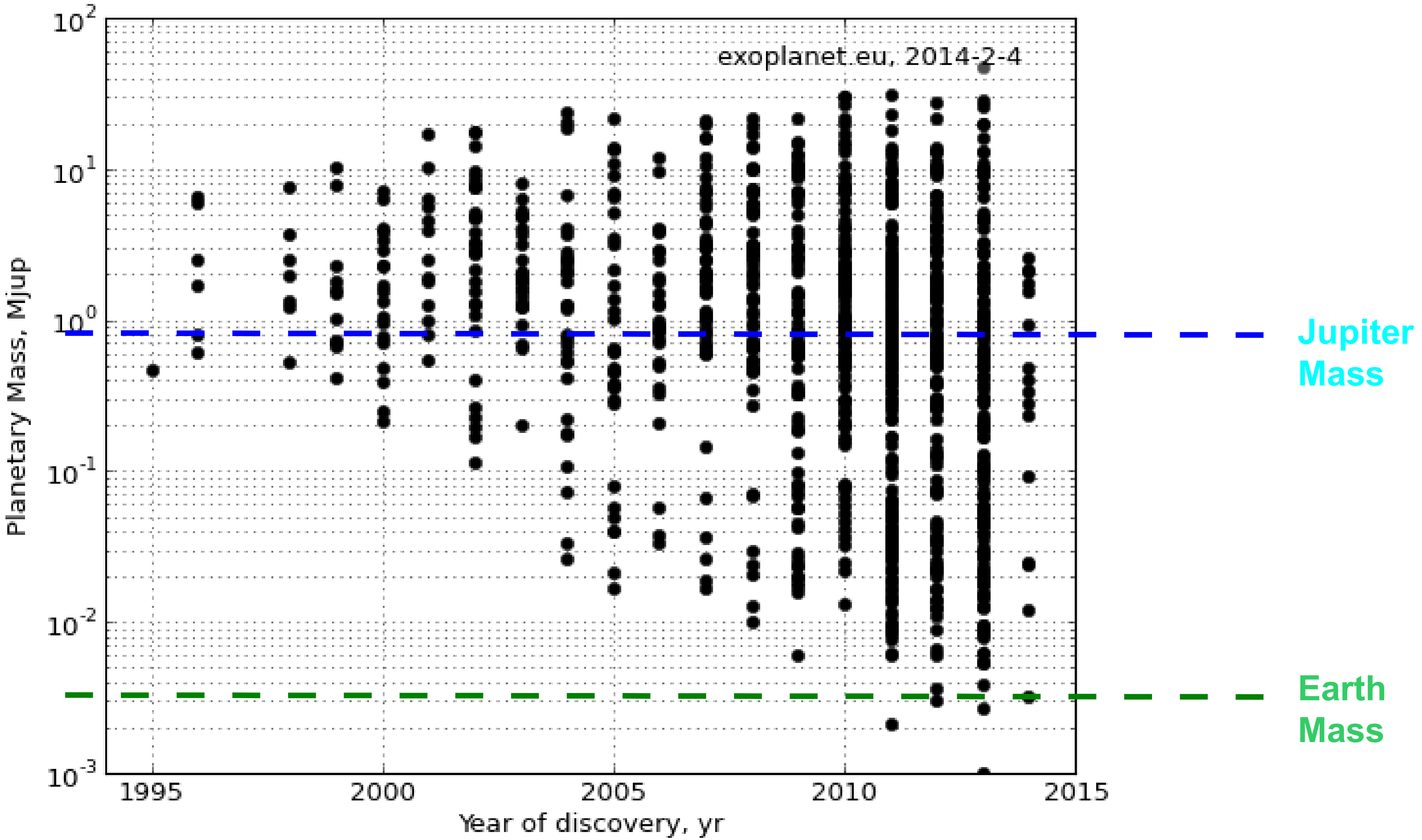
Scientific Opportunities

- SPACE: Direct imaging of Earth-like planets around Sun-like stars
- GROUND: Imaging habitable planets around M-type stars with ELTs

project PANOPTES

- Engaging citizen scientists, amateur astronomers and schools in the search for other worlds

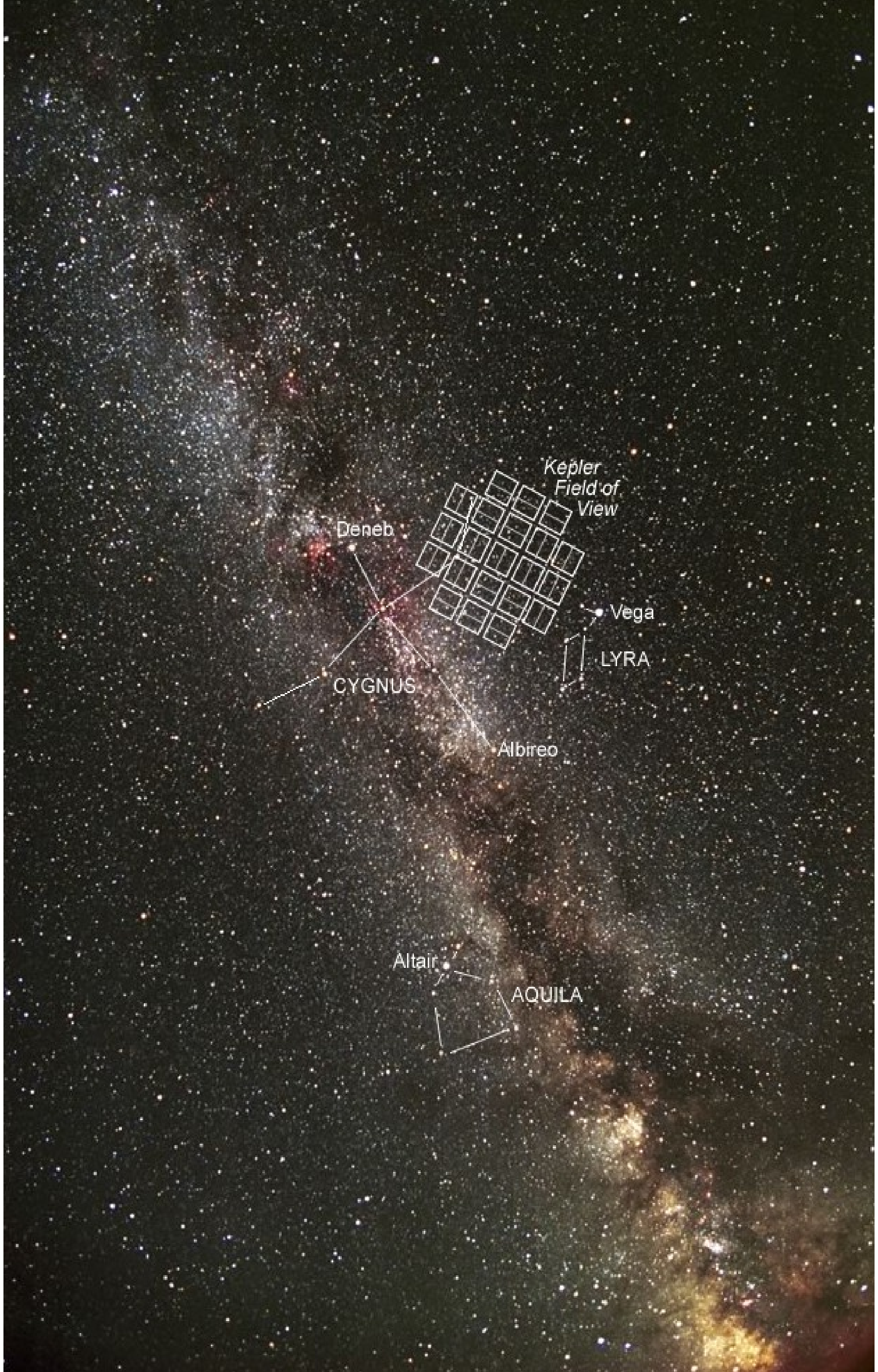
Planets identified – we are now starting to identify Earth-size planets



Exoplanet transit: An easier way to detect a planet

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

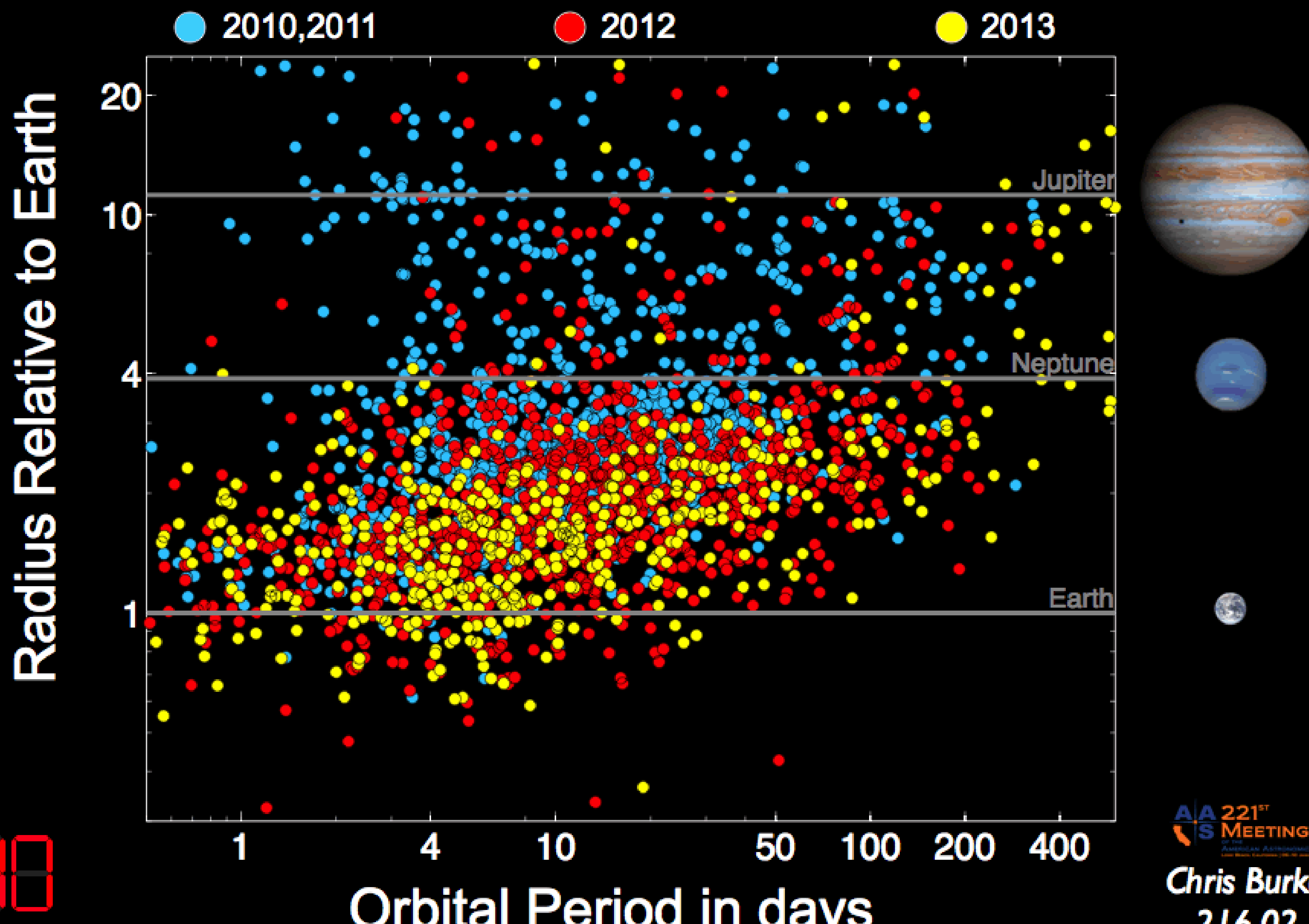
Kepler (NASA)



Kepler Field of View
Deneb
Vega
LYRA
CYGNUS
Albireo
Altair
AQUILA

Kepler's Planet Candidates

22 Months: May 2009 - Mar 2011

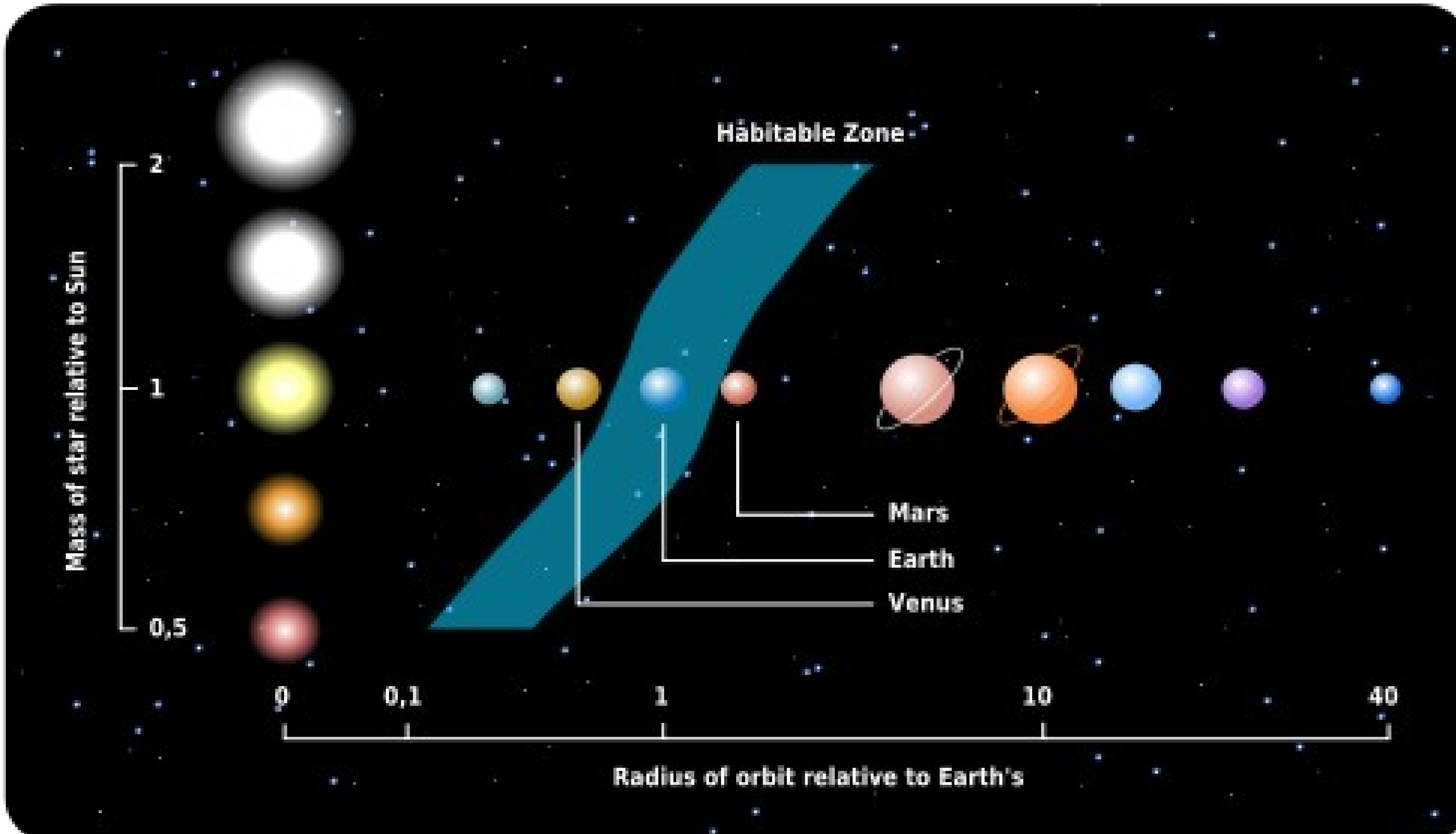


2740

AAS 221st Meeting of the American Astronomical Society

Chris Burke: 216.02

Habitable zone of a star



1,070 Confirmed Exoplanets

The Periodic Table of Exoplanets

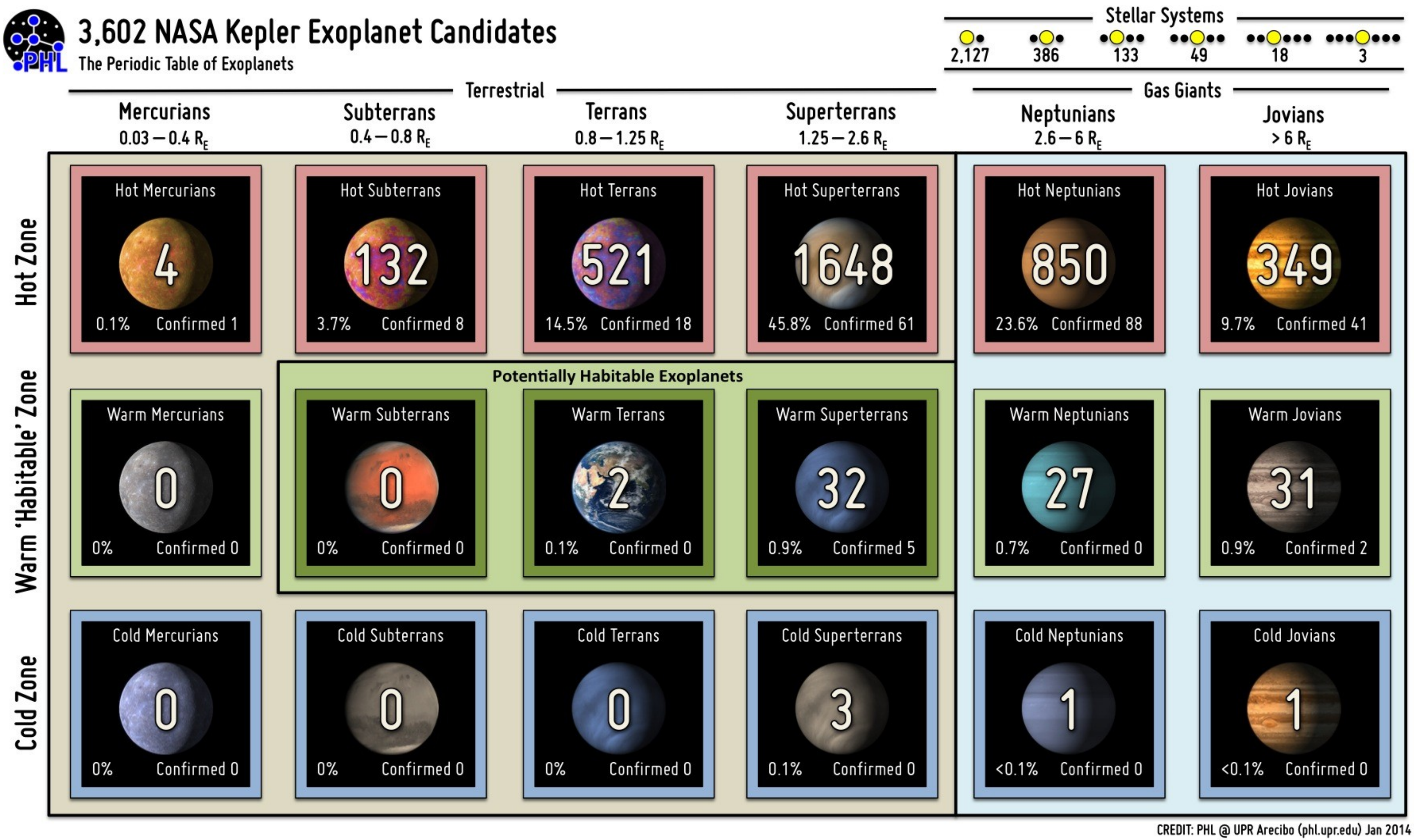
Stellar Systems

635	126	29	10	5	4	1

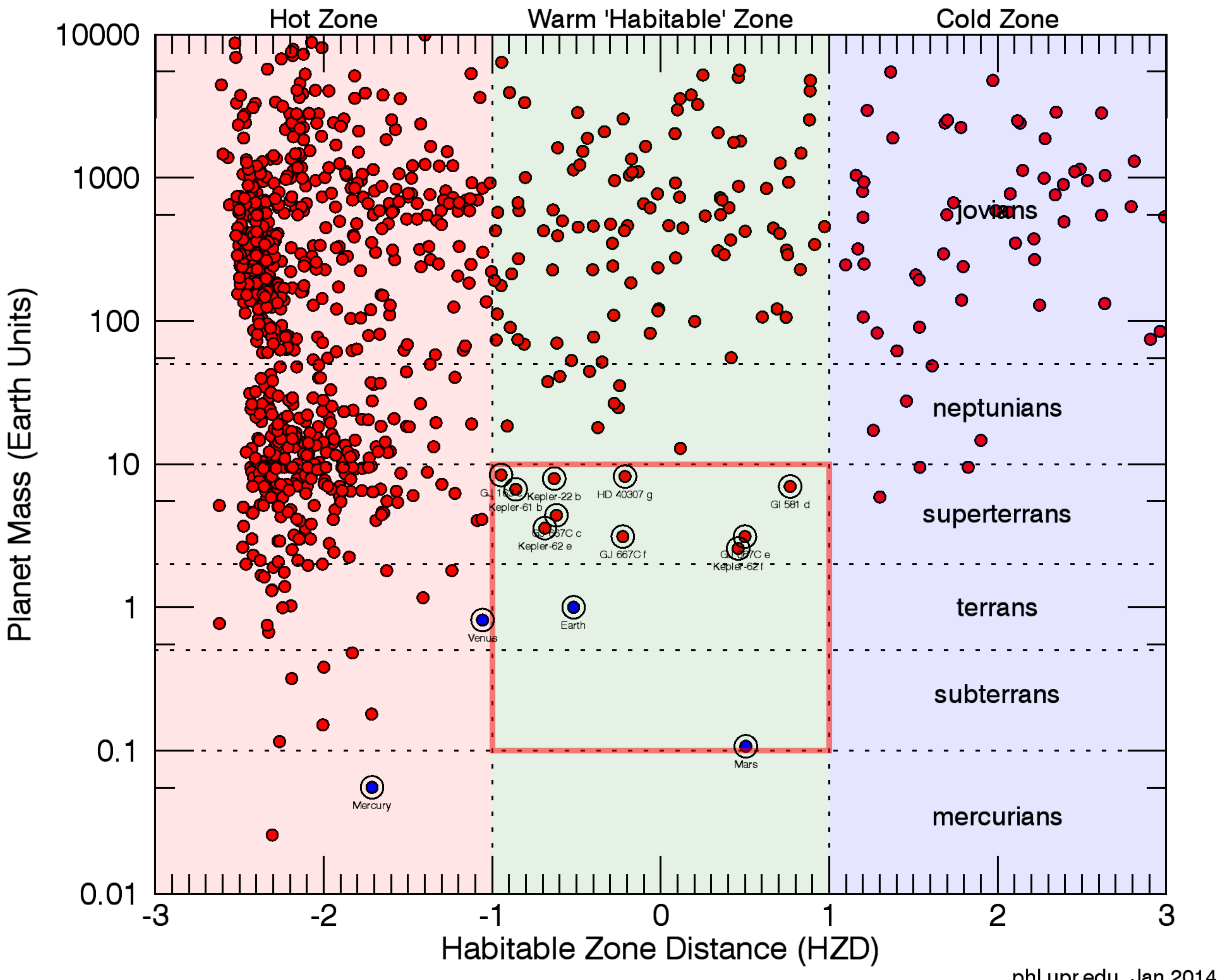
	Terrestrial				Gas Giants	
	Mercurians $10^{-5} - 0.1\ M_E$	**Subterrans** $0.1 - 0.5\ M_E$	**Terrans** $0.5 - 2\ M_E$	**Superterrans** $2 - 10\ M_E$	**Neptunians** $10 - 50\ M_E$	**Jovians** $> 50\ M_E$
Hot Zone	Hot Mercurians 1 (0.1%)	Hot Subterrans 6 (0.6%)	Hot Terrans 16 (1.5%)	Hot Superterrans 100 (9.3%)	Hot Neptunians 153 (14.3%)	Hot Jovians 462 (43.2%)
Warm 'Habitable' Zone	Warm Mercurians 0 (0%)	Warm Subterrans 0 (0%)	Warm Terrans 0 (0%)	Warm Superterrans 10 (0.9%)	Warm Neptunians 5 (0.5%)	Warm Jovians 106 (9.9%)
Cold Zone	Cold Mercurians 0 (0%)	Cold Subterrans 0 (0%)	Cold Terrans 0 (0%)	Cold Superterrans 4 (0.4%)	Cold Neptunians 10 (0.9%)	Cold Jovians 184 (17.2%)

Potentially Habitable Exoplanets: Warm Subterrans, Warm Terrans, Warm Superterrans

CREDIT: PHL @ UPR Arecibo (phl.upr.edu) Jan 2014

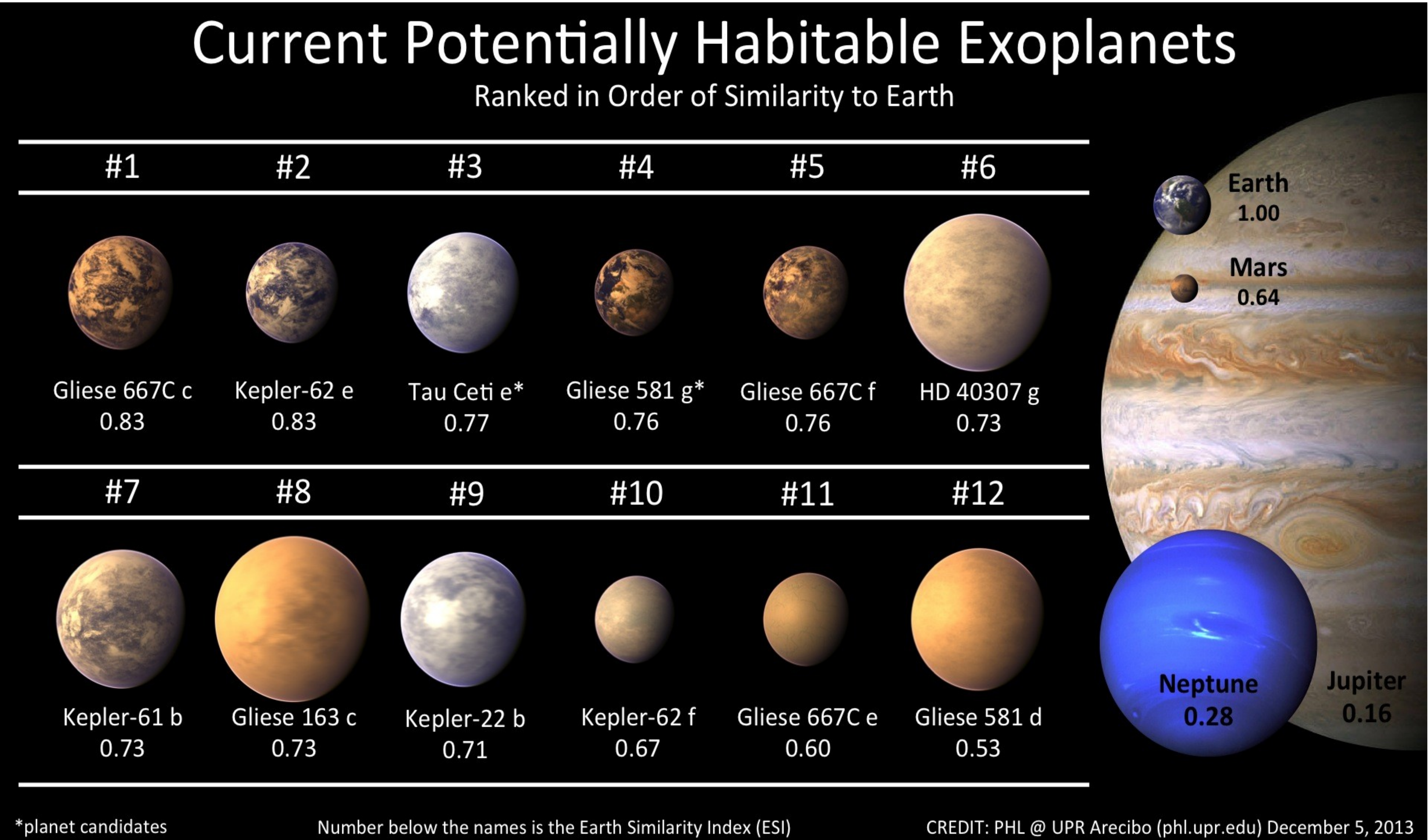


PHL
3,602 NASA Kepler Exoplanet Candidates
The Periodic Table of Exoplanets
Stellar Systems
2,127
386
133
49
18
3
Terrestrial
Gas Giants
Mercurians
0.03 — 0.4 R_E
Subterrans
0.4 — 0.8 R_E
Terrans
0.8 — 1.25 R_E
Superterrans
1.25 — 2.6 R_E
Neptunians
2.6 — 6 R_E
Jovians
> 6 R_E
Hot Zone
Warm 'Habitable' Zone
Cold Zone
Hot Mercurians 4 0.1% Confirmed 1
Hot Subterrans 132 3.7% Confirmed 8
Hot Terrans 521 14.5% Confirmed 18
Hot Superterrans 1648 45.8% Confirmed 61
Hot Neptunians 850 23.6% Confirmed 88
Hot Jovians 349 9.7% Confirmed 41
Potentially Habitable Exoplanets
Warm Mercurians 0 0% Confirmed 0
Warm Subterrans 0 0% Confirmed 0
Warm Terrans 2 0.1% Confirmed 0
Warm Superterrans 32 0.9% Confirmed 5
Warm Neptunians 27 0.7% Confirmed 0
Warm Jovians 31 0.9% Confirmed 2
Cold Mercurians 0 0% Confirmed 0
Cold Subterrans 0 0% Confirmed 0
Cold Terrans 0 0% Confirmed 0
Cold Superterrans 3 0.1% Confirmed 0
Cold Neptunians 1 <0.1% Confirmed 0
Cold Jovians 1 <0.1% Confirmed 0
CREDIT: PHL @ UPR Arecibo (phl.upr.edu) Jan 2014



Hot Zone
Warm 'Habitable' Zone
Cold Zone
10000
1000
100
10
1
0.1
0.01
-3
-2
-1
0
1
2
3
Planet Mass (Earth Units)
Habitable Zone Distance (HZD)
jovians
neptunians
superterrans
terrans
subterrans
mercurians
Kepler-22 b
Kepler-61 b
HD 40307 g
Gl 581 d
Kepler-62 e
GJ 667C f
Kepler-62 f
Venus
Earth
Mars
Mercury
phl.upr.edu, Jan 2014

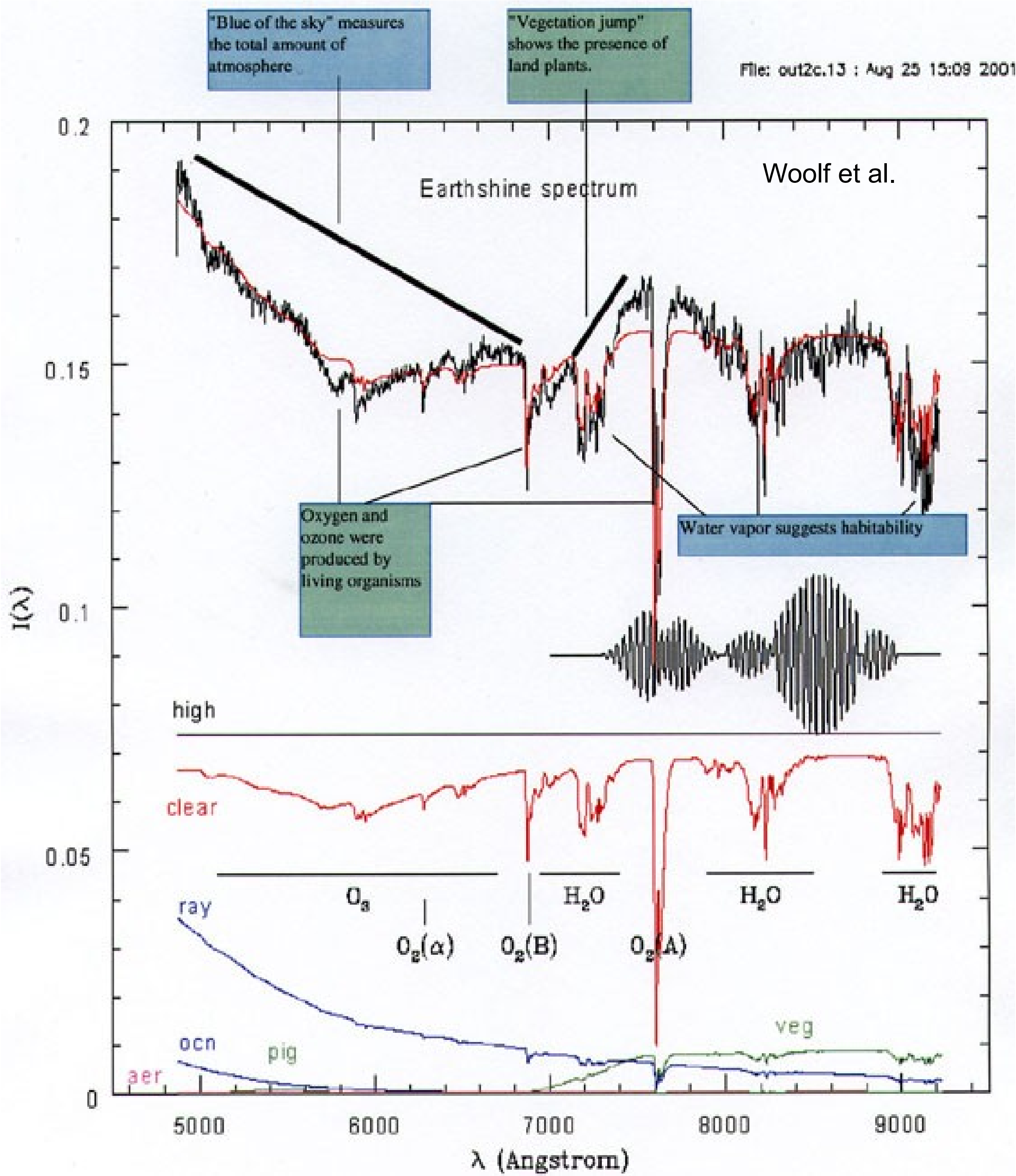
~10% of stars have potentially habitable planet
First potentially habitable planets now identified



Directly imaging planet is necessary to find life

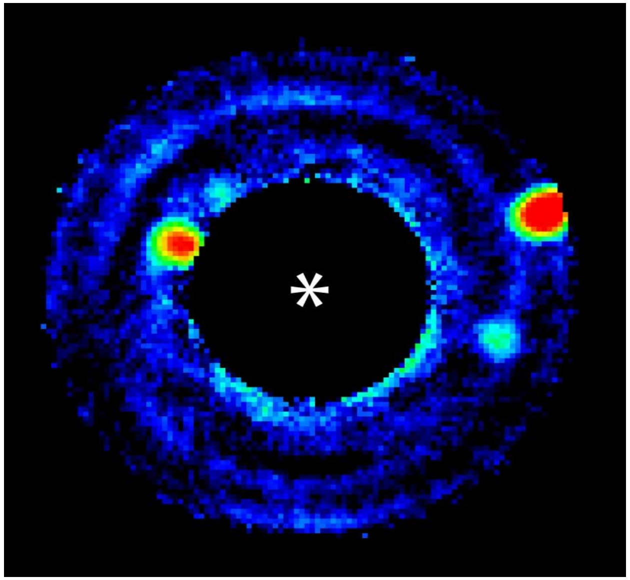
We need to take spectra of habitable planets

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



Terrestrial Planet Finder (TPF) study (NASA)

Technology validation
Demonstrated project feasibility

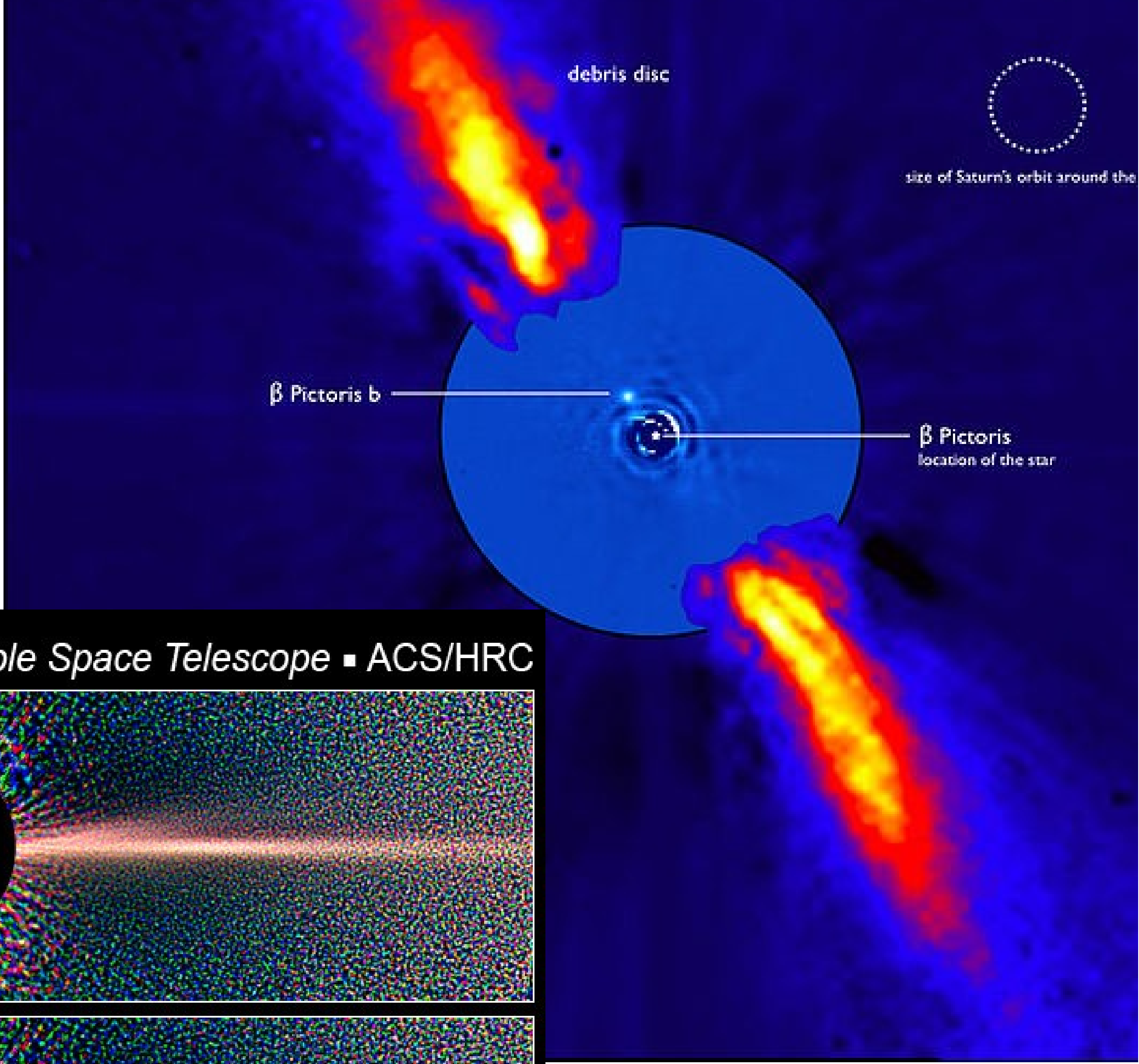


Identified two space-based approaches:
- Large telescope + coronagraph, visible light
- Nulling interferometer, mid-IR

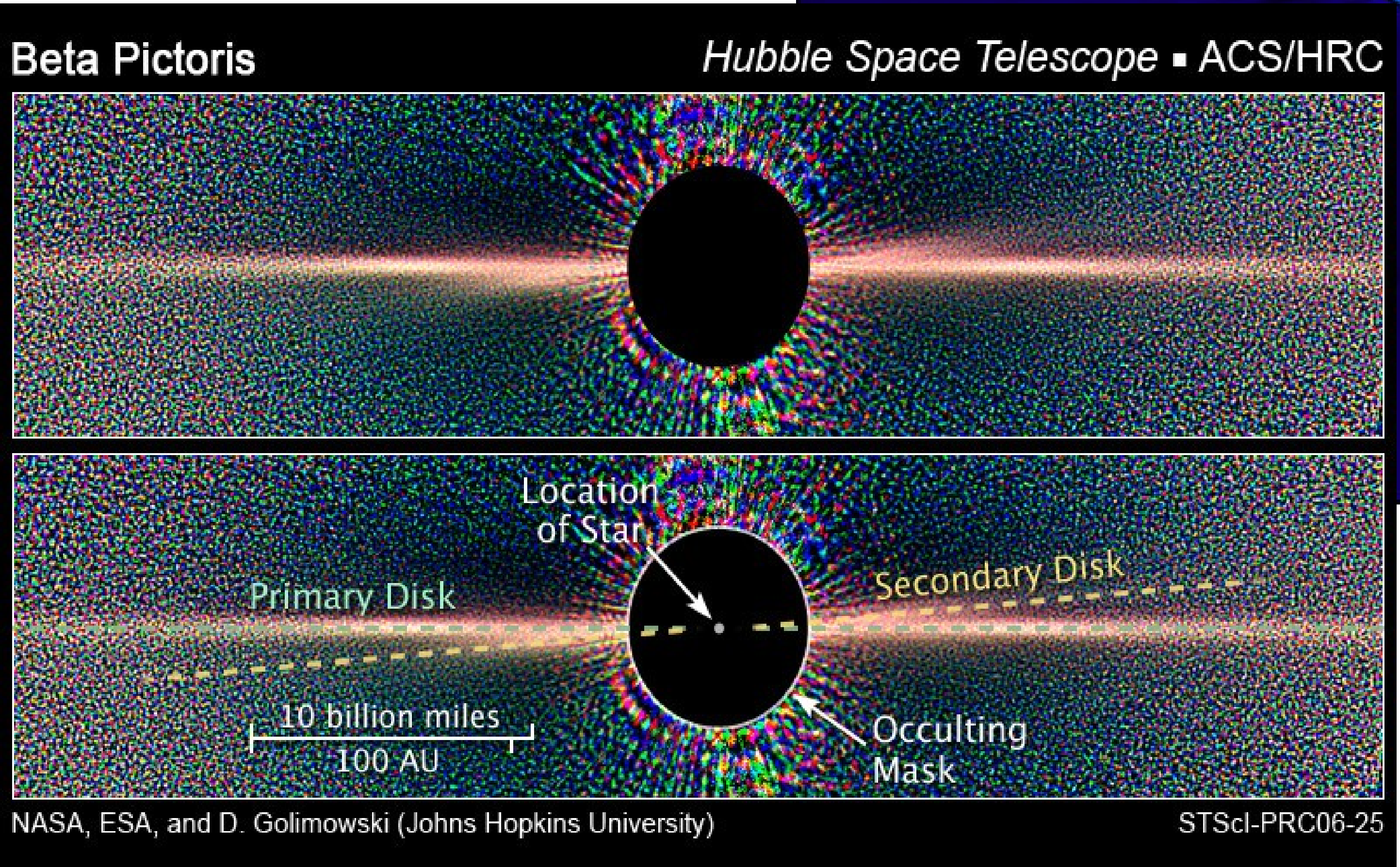
Beta Pictoris

8 Jupiter mass planet

Orbits young massive star in ~20yr

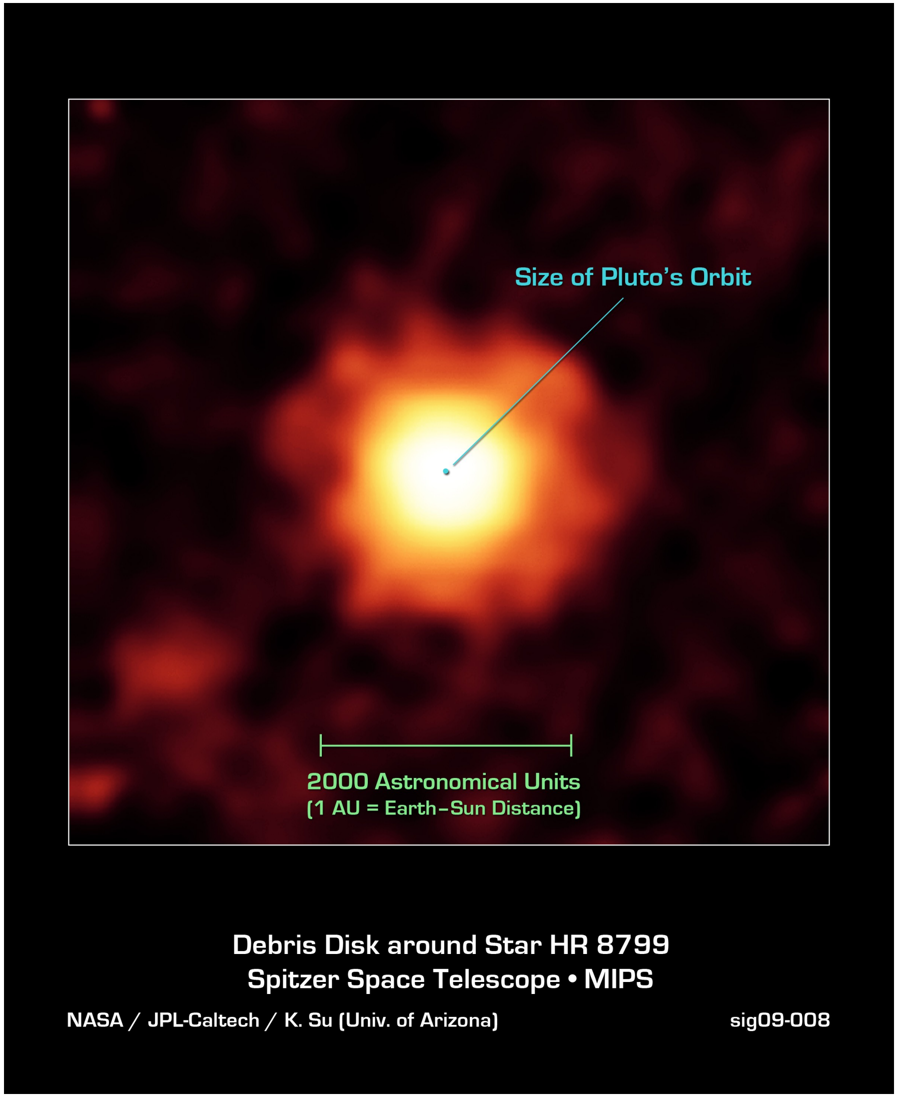


ESO VLT image (Lagrange et al.)

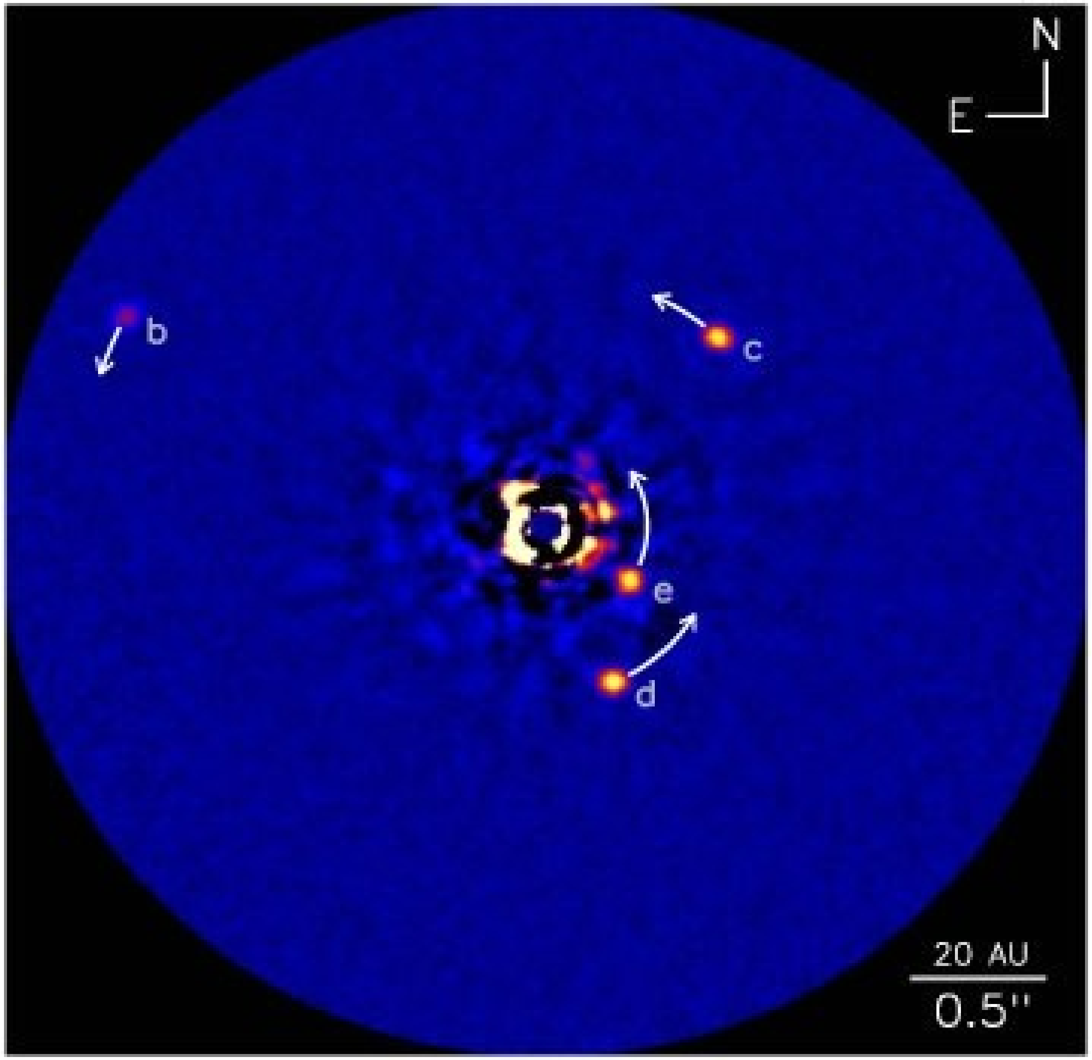


HR8799

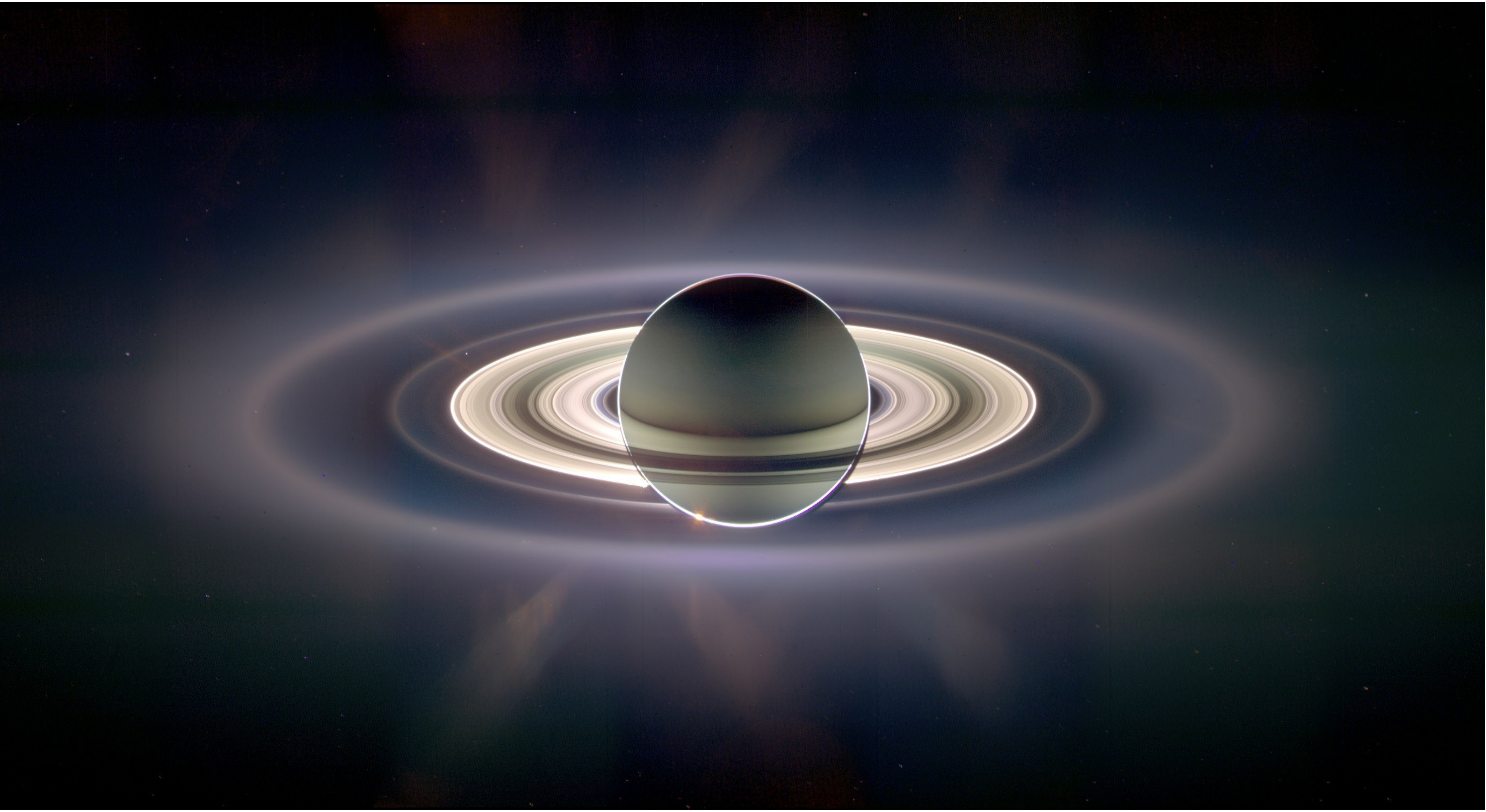
Four planets, orbital periods on the order of 100yr
Each planet 5 to 7 Jupiter Mass

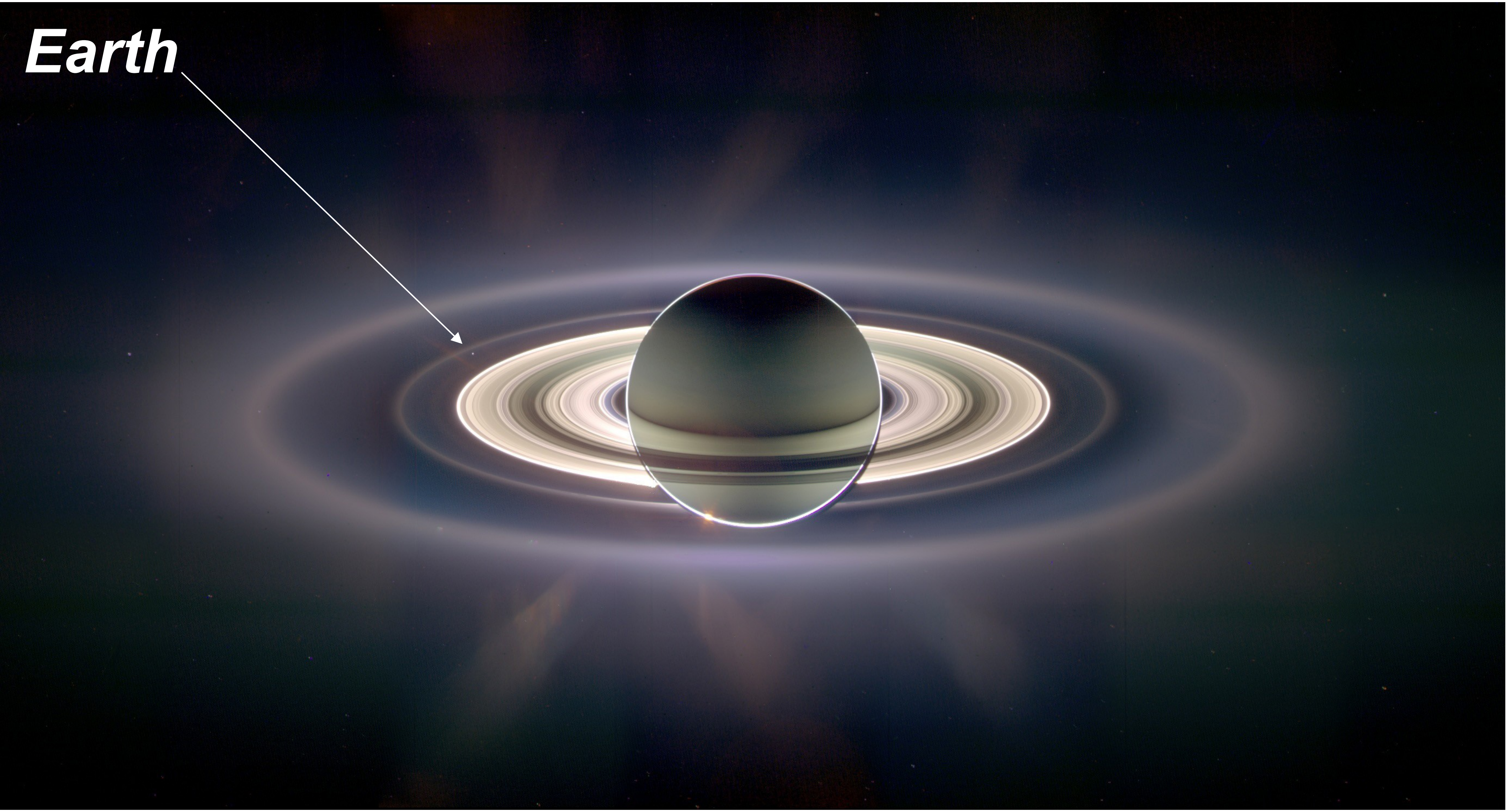


Keck telescope image (Marois et. al)



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

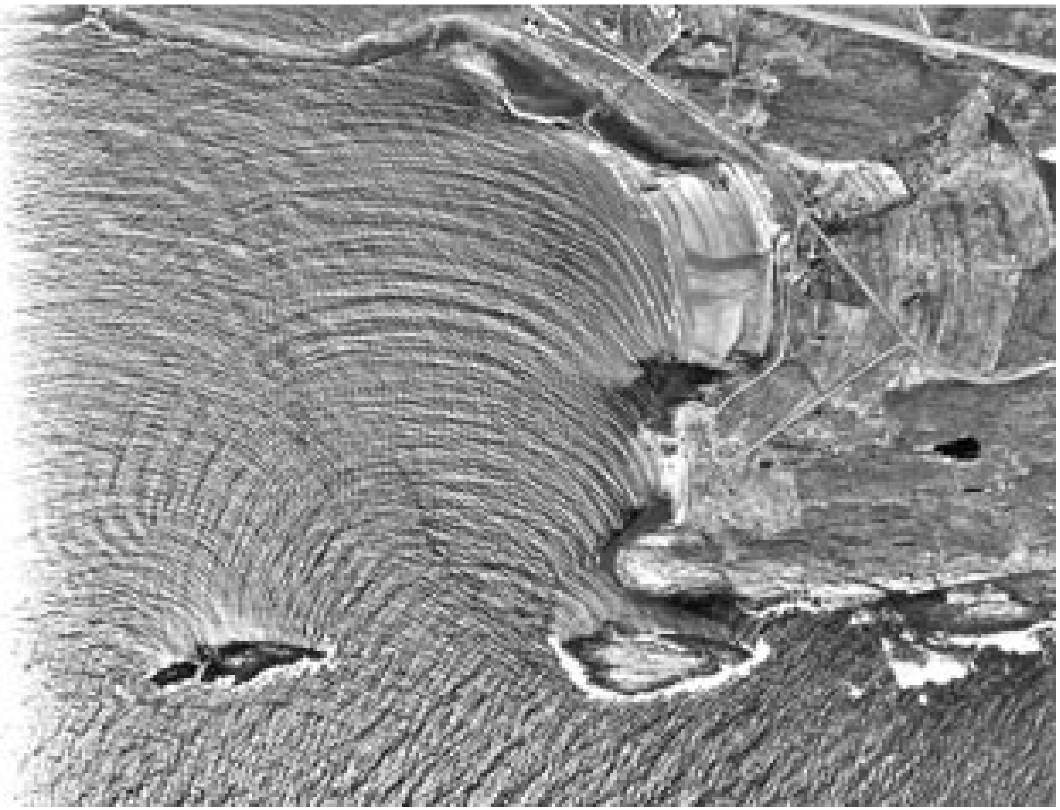
1818: French academy of science committee launches a competition
to explain nature of light

Augustin-Jean Fresnel
submits wave theory of light

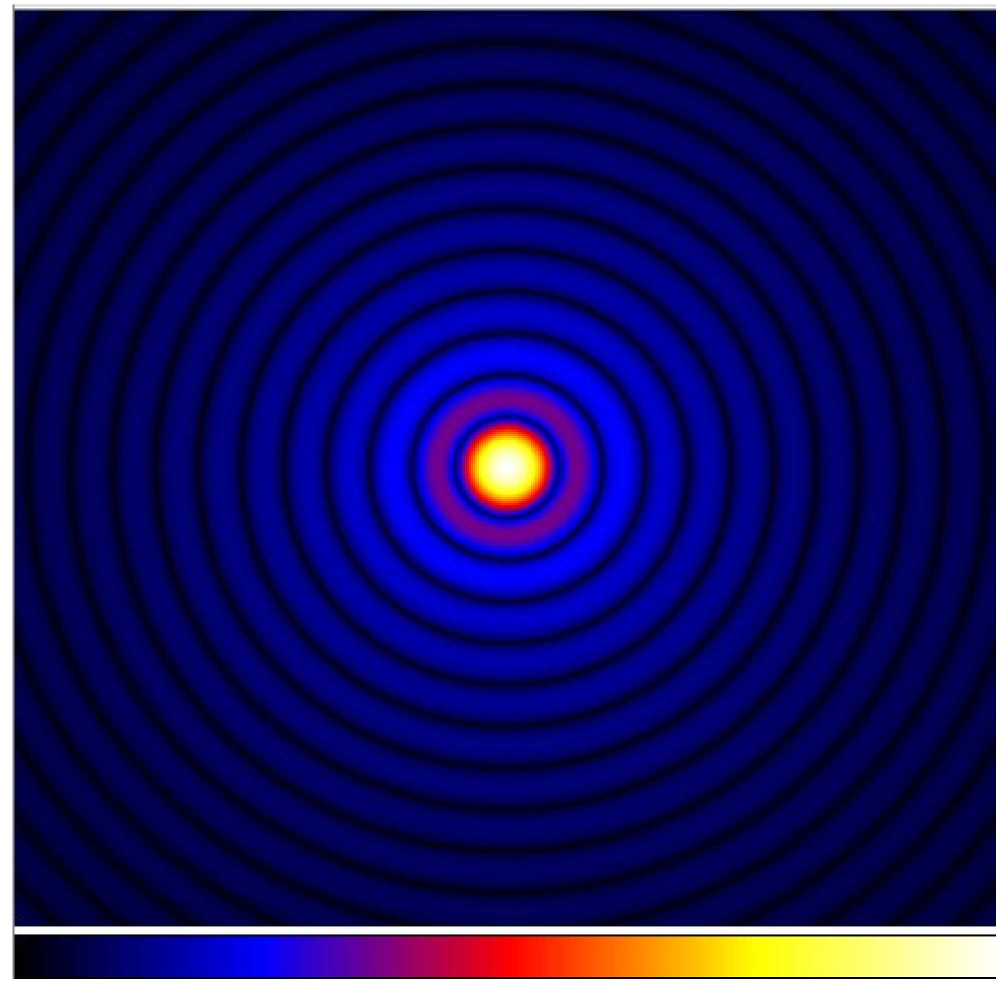
Simeon-Denis Poisson finds a flaw in Fresnel's theory:
According to Fresnel's equations, a bright spot should appear in
the shadow of a circular obstacle → this absurd result disproves Fresnel's theory

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



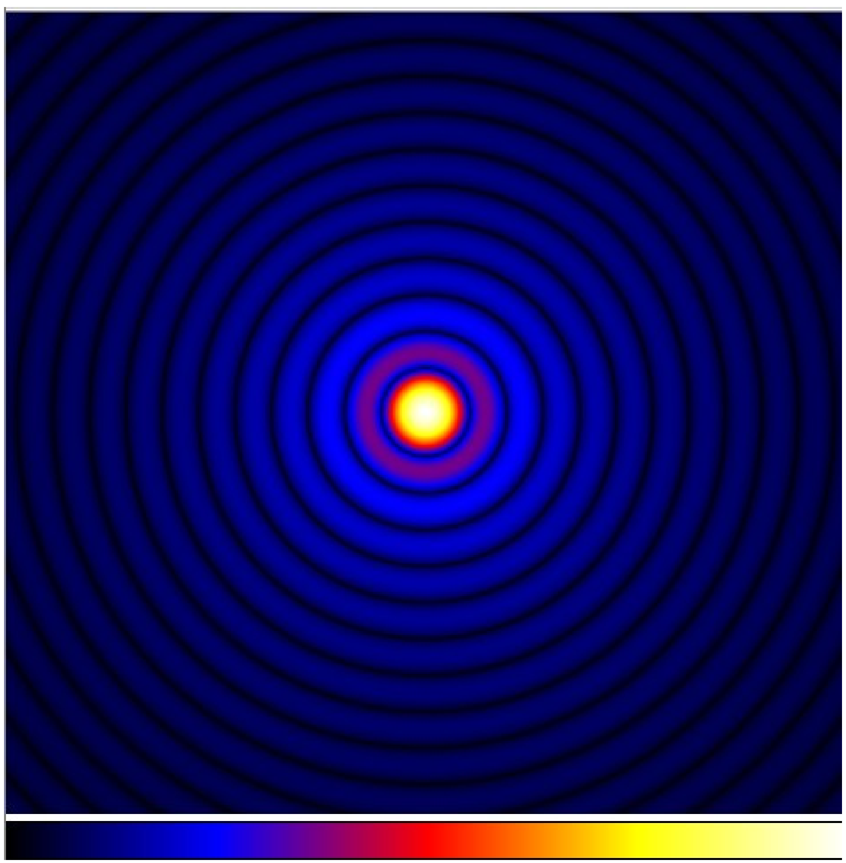
Waves diffracted by coastline and islands

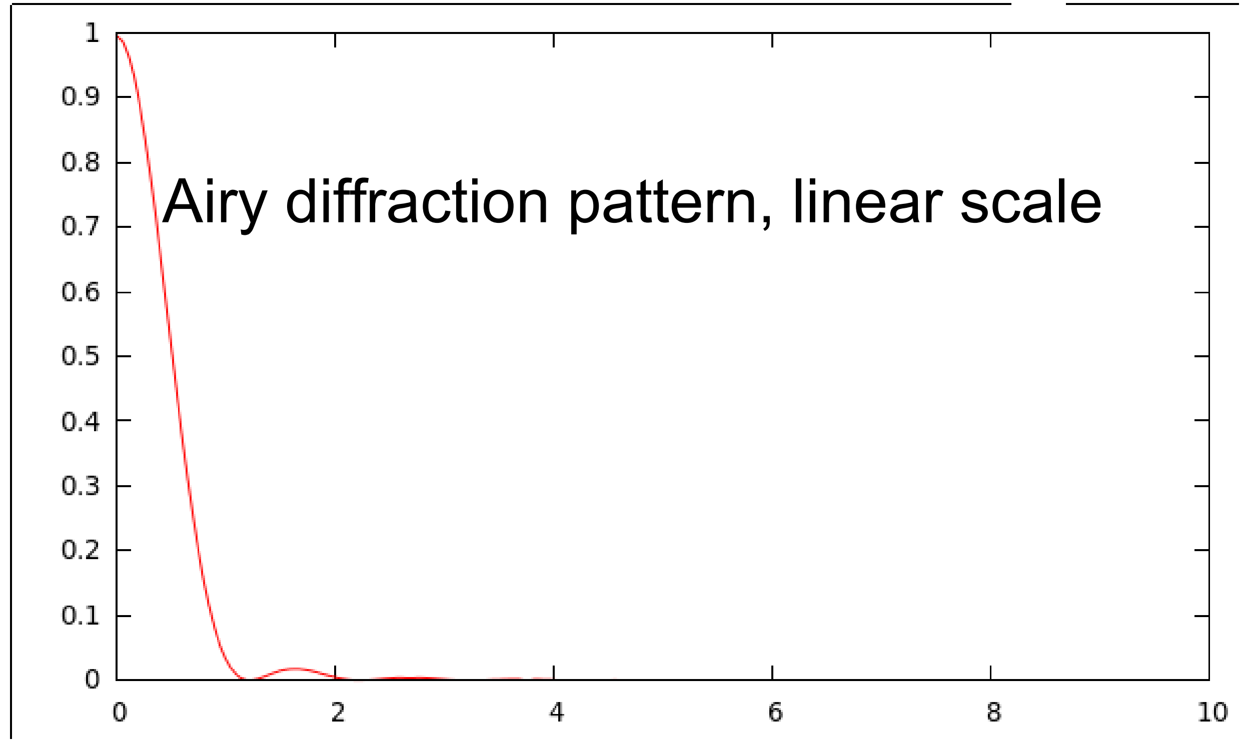


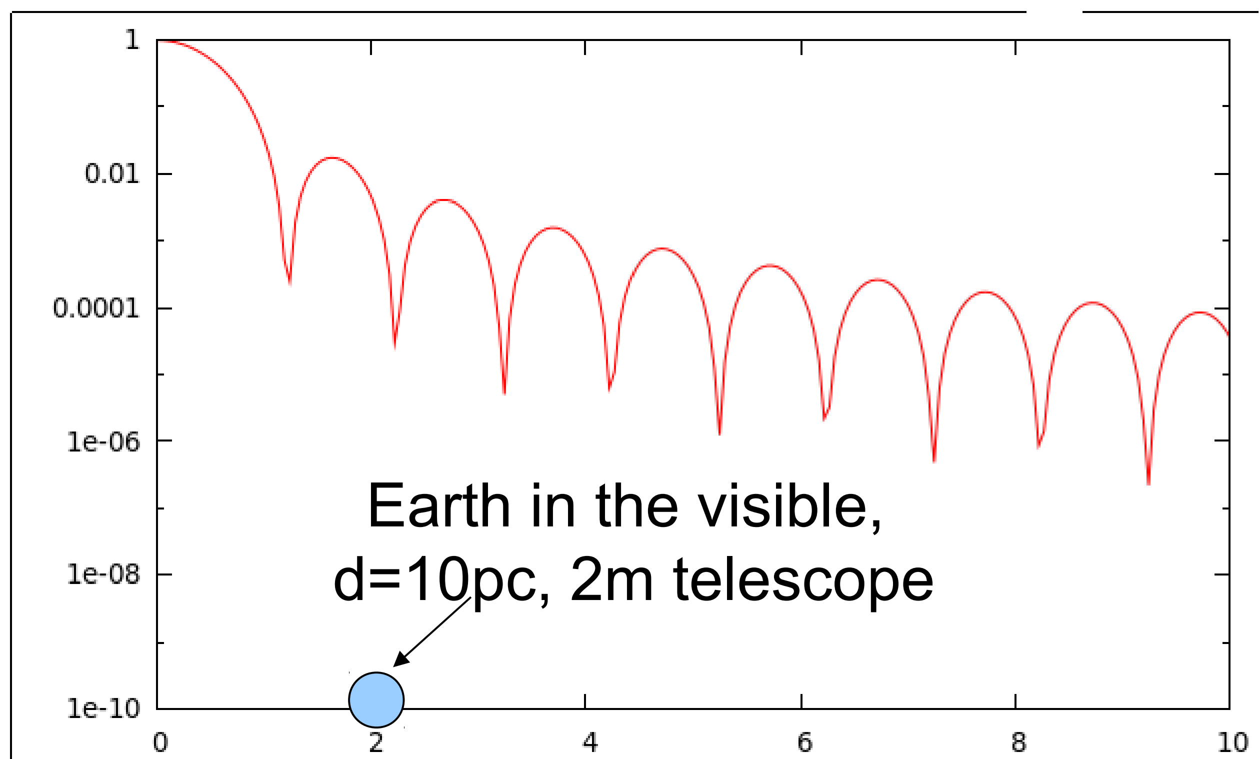
Ideal image of a distant star by a telescope
Diffraction rings around the image core

Why coronagraphy ?

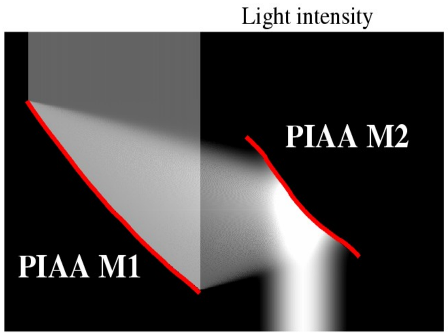
Conventional imaging systems are not suitable for high contrast (even if perfect) due to diffraction



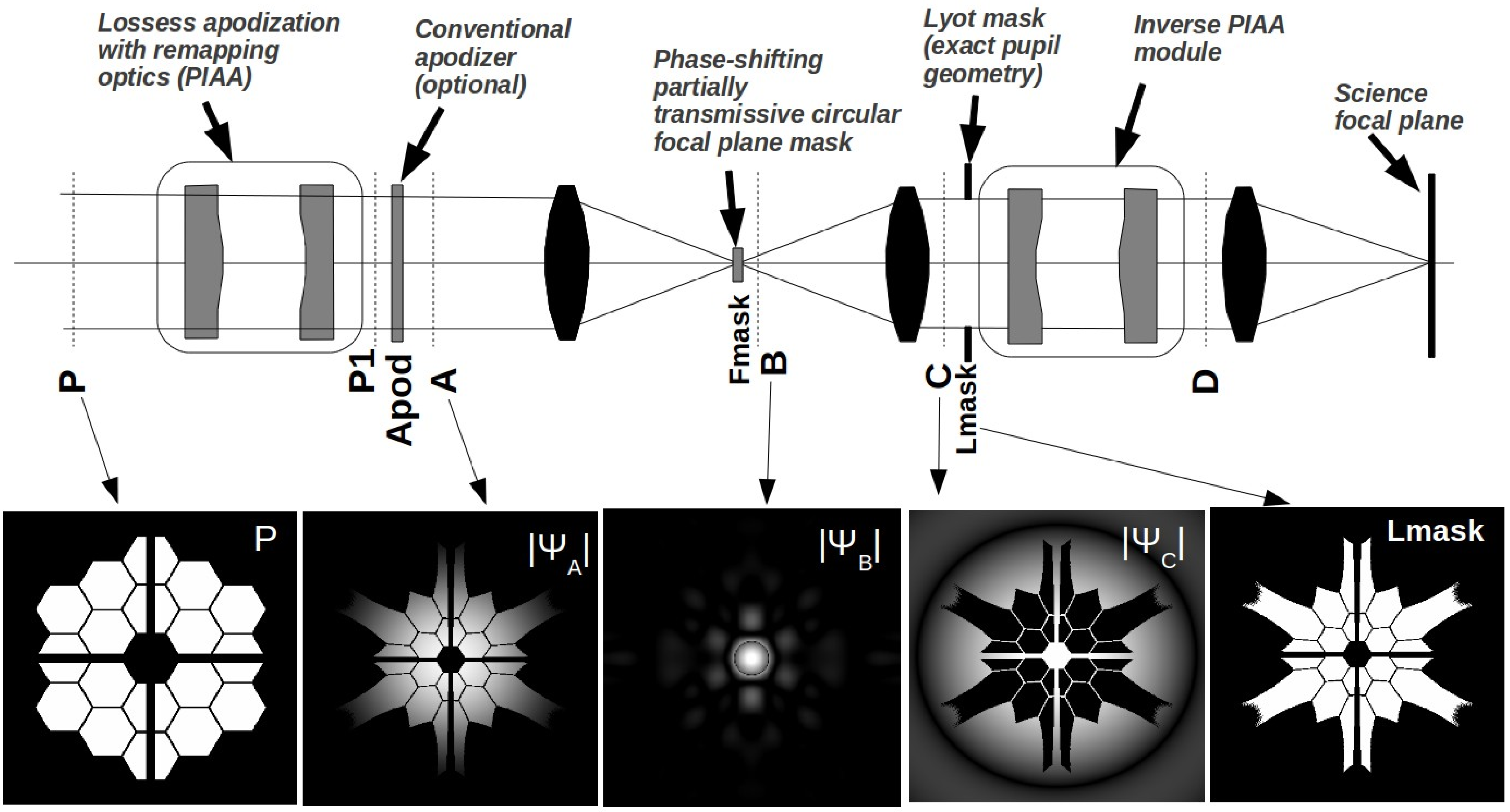




- PIAACMC gets to < 1 l/D with full efficiency, and no contrast limit



Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)

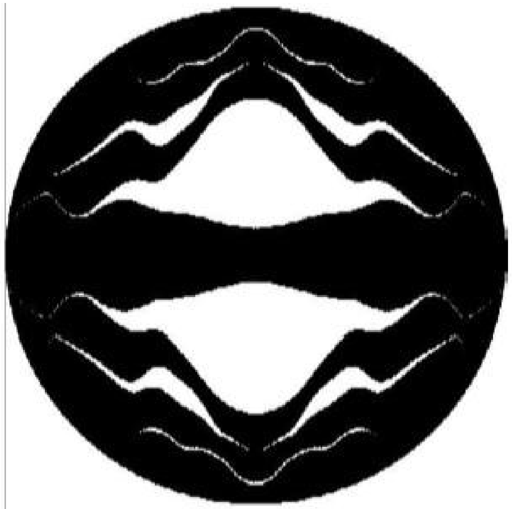


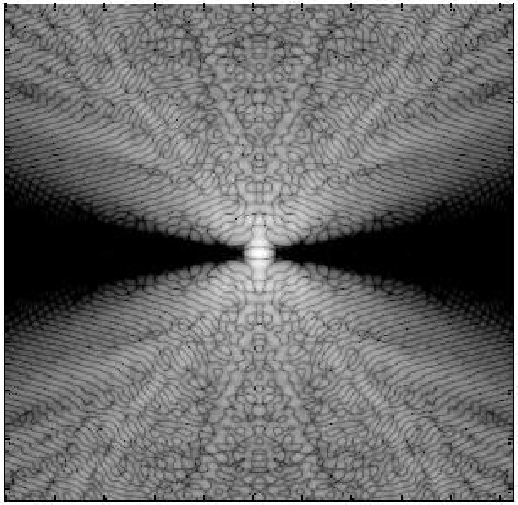
Conventional Pupil Apodization (CPA)

Many pupil apodizations have been proposed.

Apodization can be continuous or binary.

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





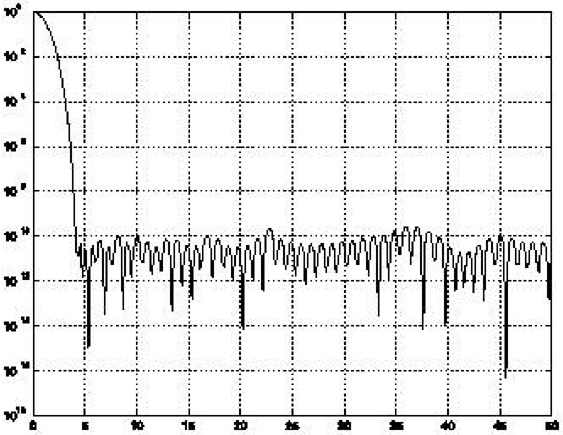
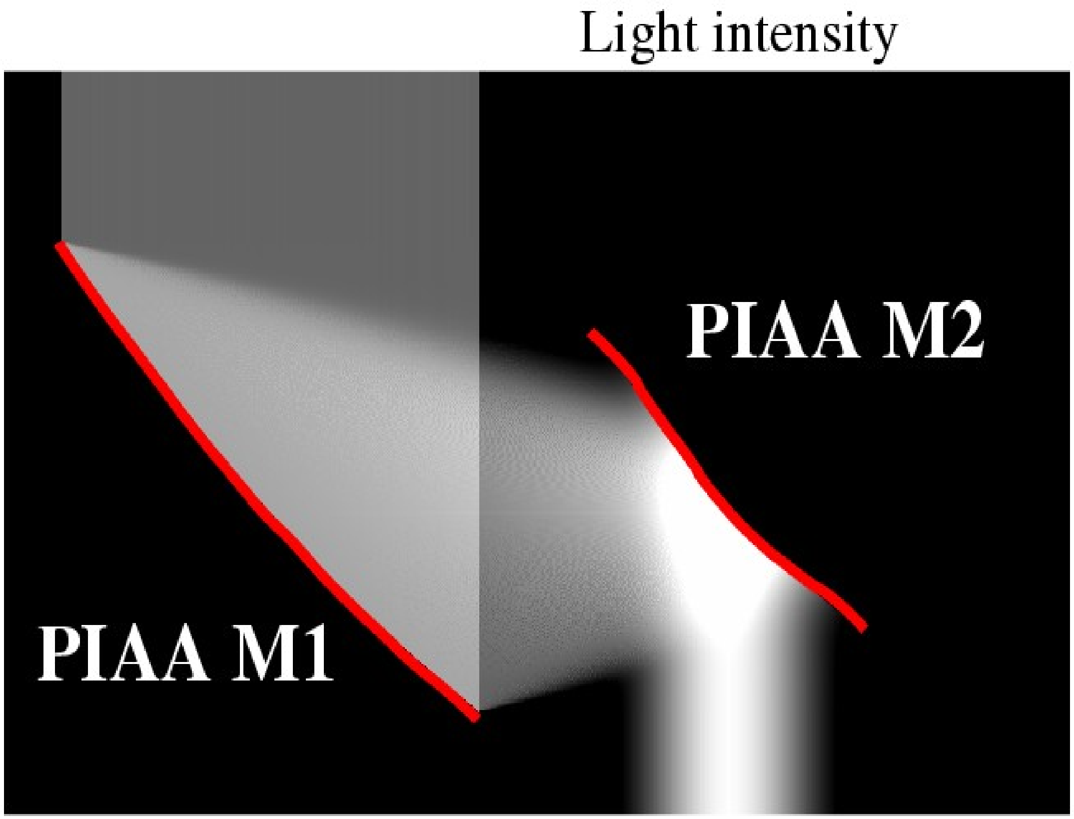


Fig. 9.—*Top*: Asymmetric multiopening mask designed to provide high-contrast, 10^{-10}, from $\lambda/D = 4$ to $\lambda/D = 100$ in two angular sectors centered on the x-axis. Ten integrations are required to cover all angles. Total throughput and pseudoarea are 24.4%. Airy throughput is 11.85%. *Bottom*: 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.

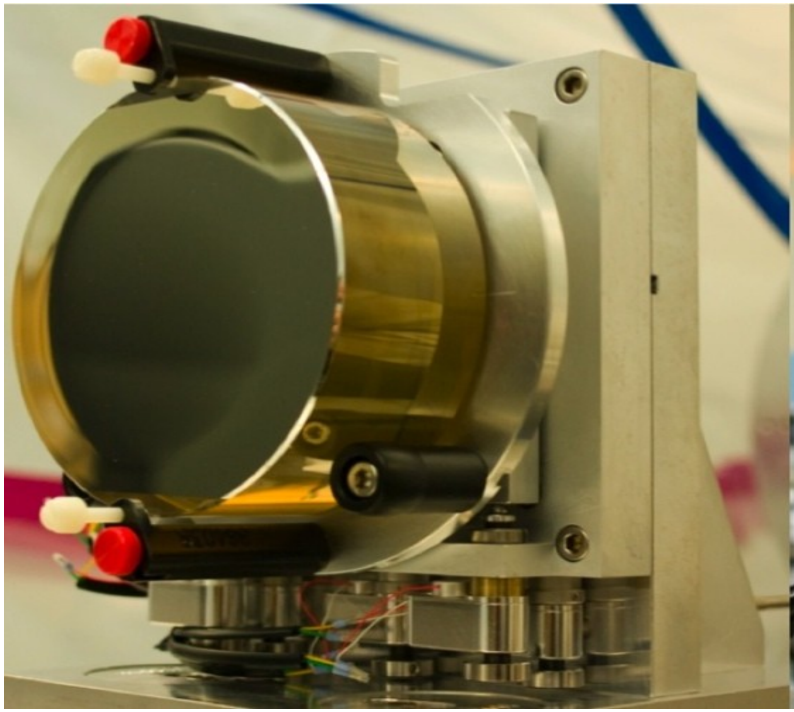
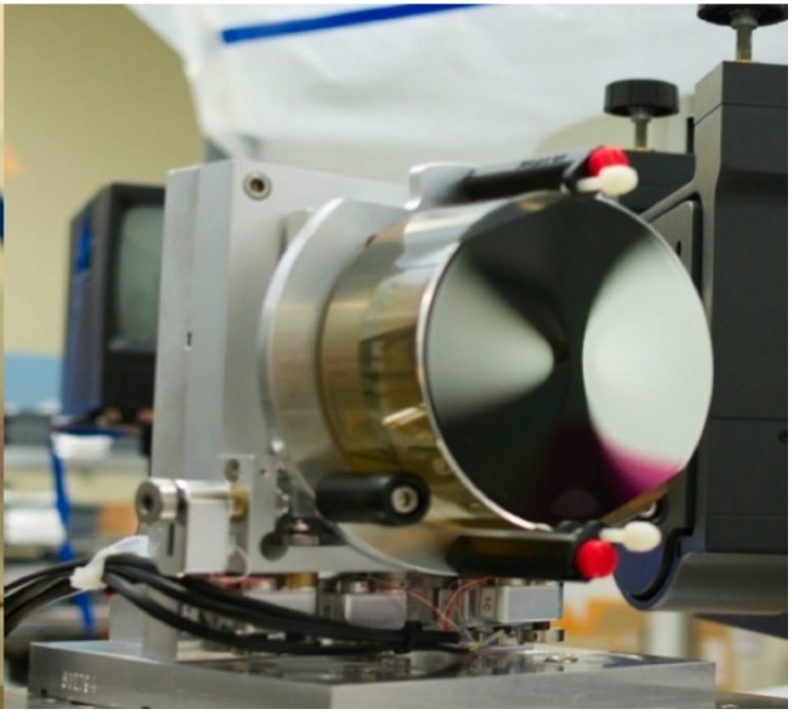
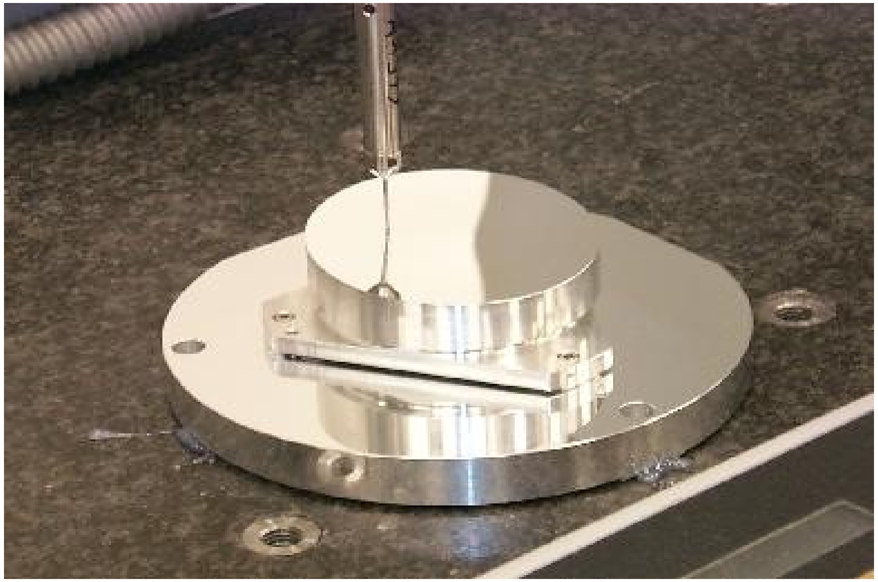
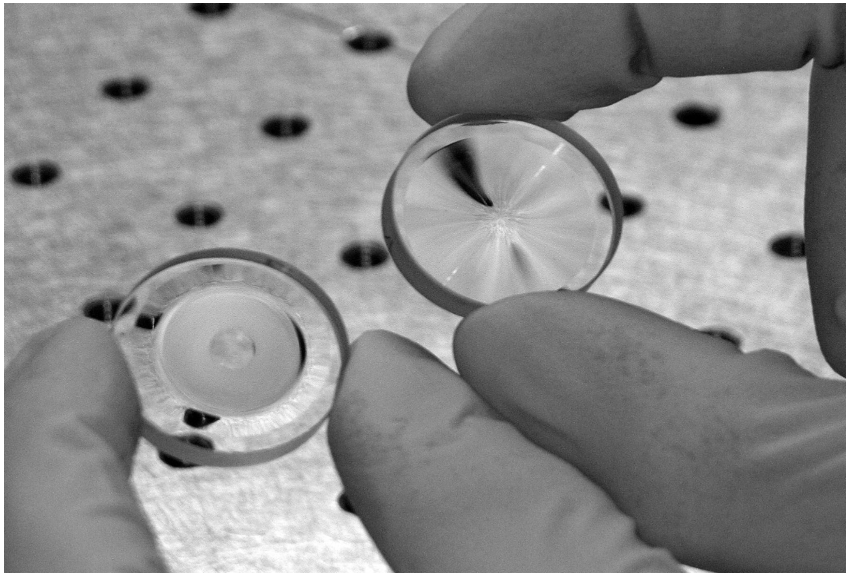


No loss in angular resolution or sensitivity
Achromatic (with mirrors)
Small inner working angle

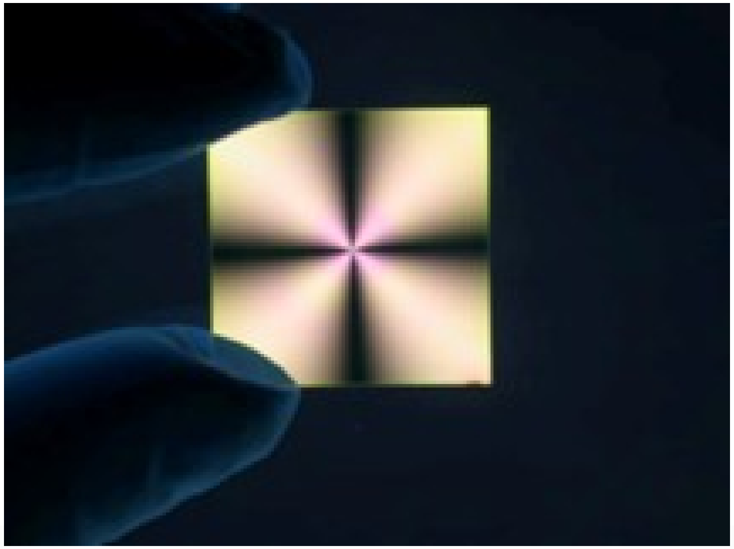
→ Gain ~x2 to x3 in telescope diameter over previous concepts

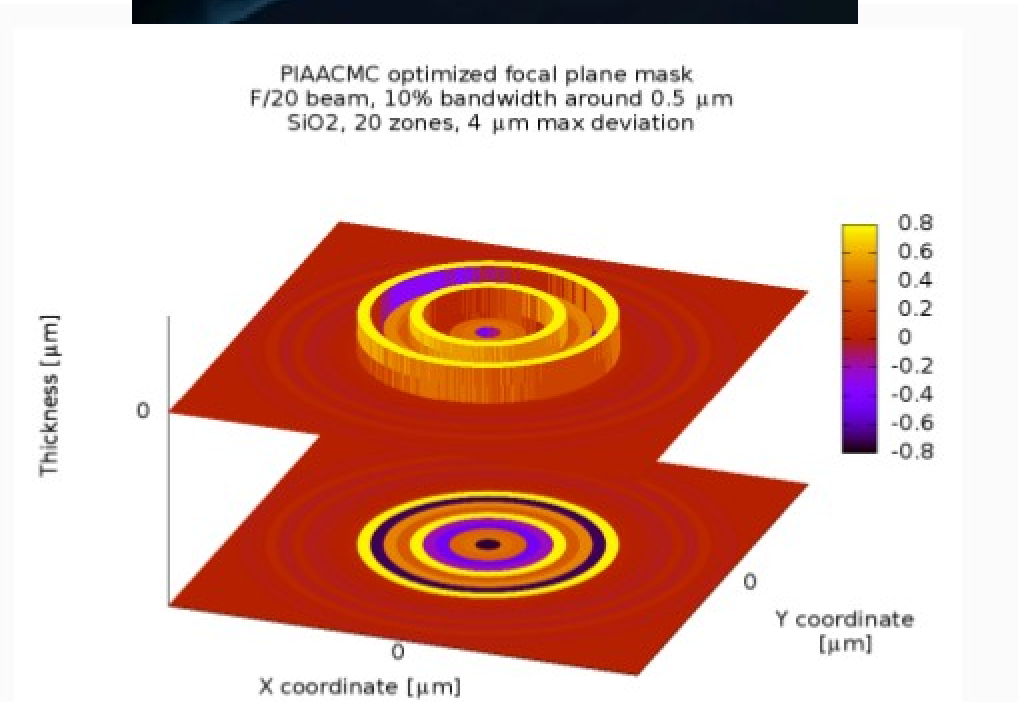
Guyon, Belikov, Pluzhnik, Vanderbei, Traub, Martinache ... 2003-present

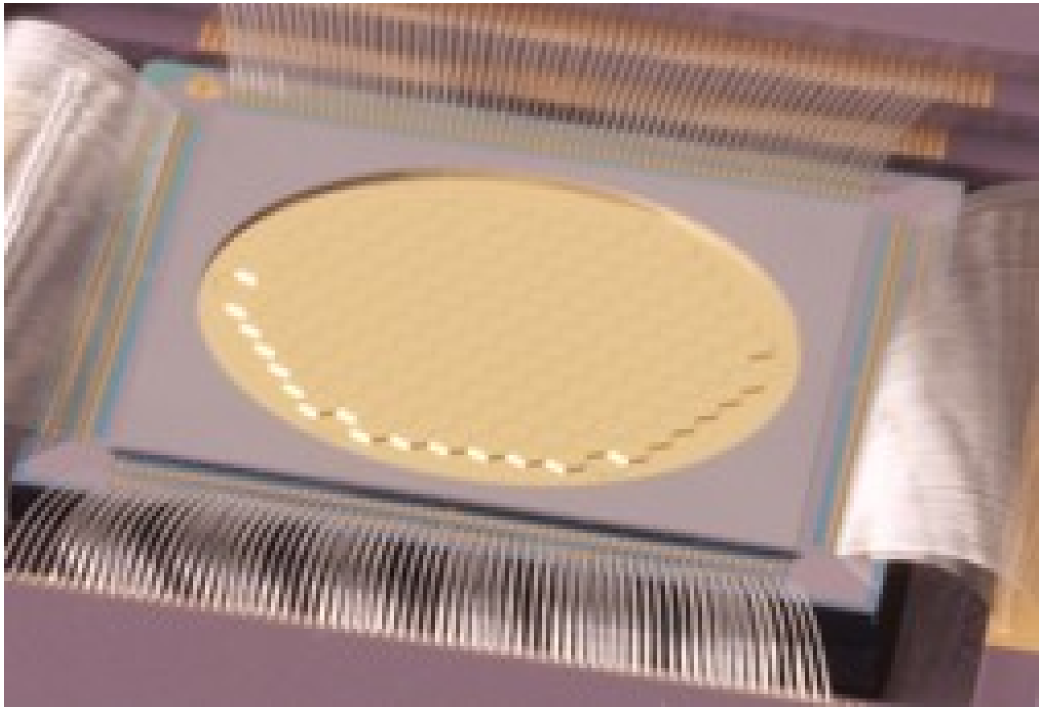
PIAA optics

Technology: components



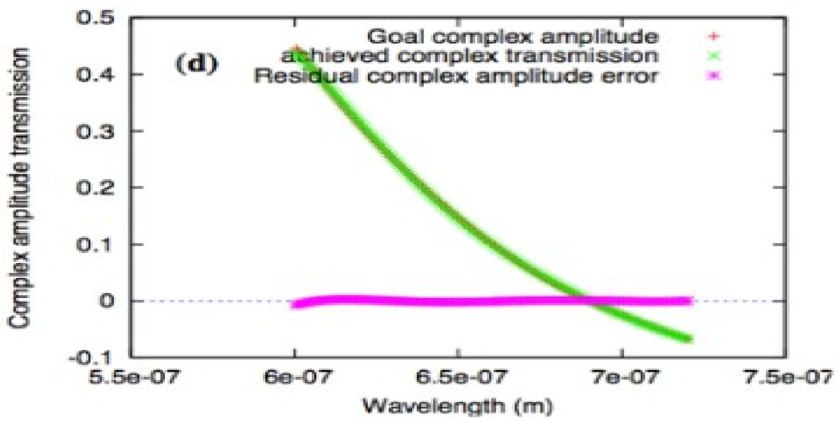


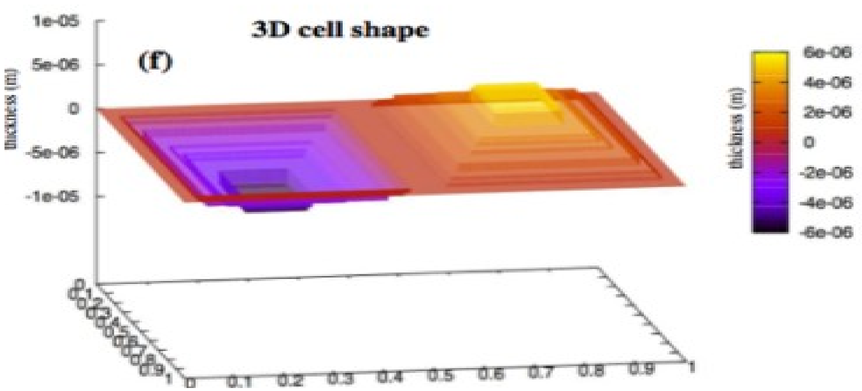


Coronagraphy: chromaticity

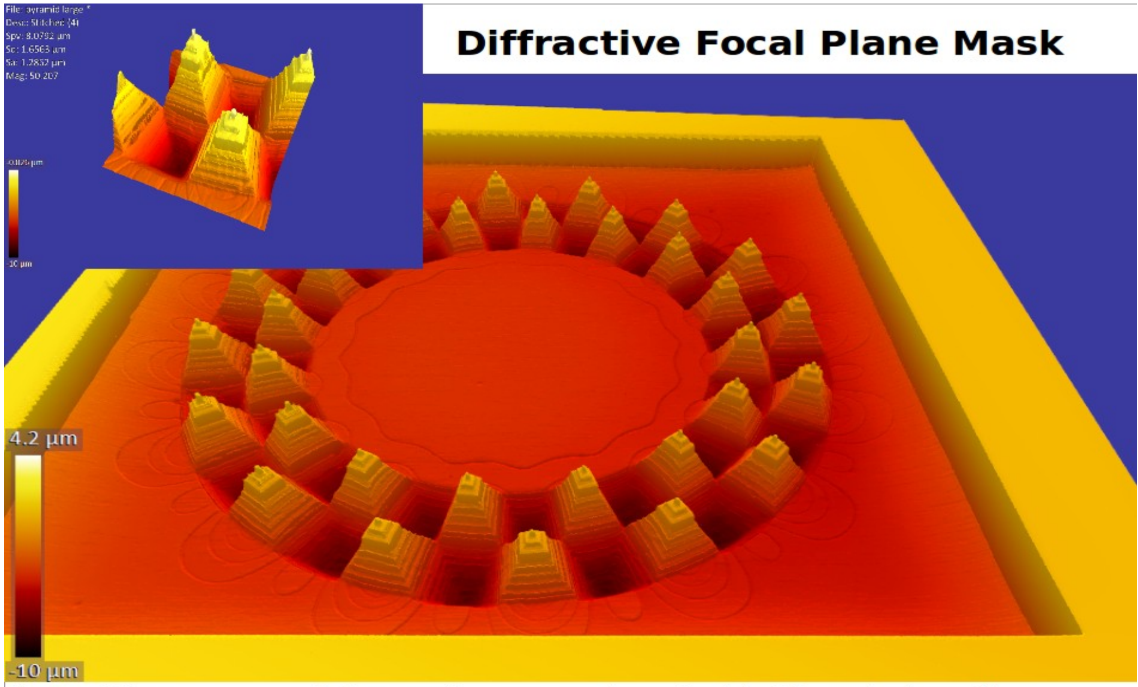
Diffractive focal plane mask for
high performance coronagraphy in broad band
(developped for ~1e-9 contrast, directly applicable to ELTs)
Work funded by NASA, PI: R. Belikov, NASA Ames

Design of a single diffractive cell

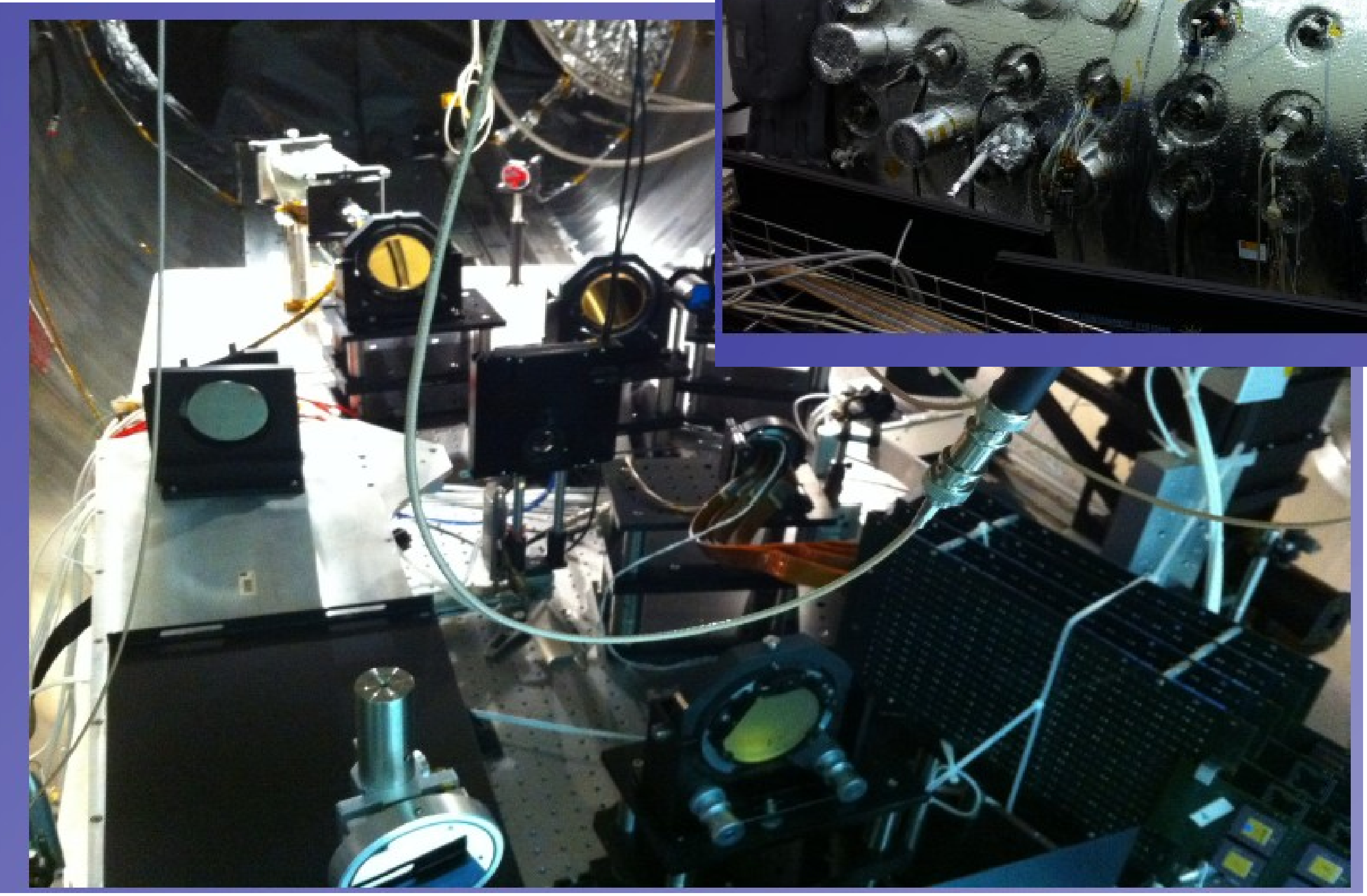




Prototype mask
(Manufactured by JPL MDL)

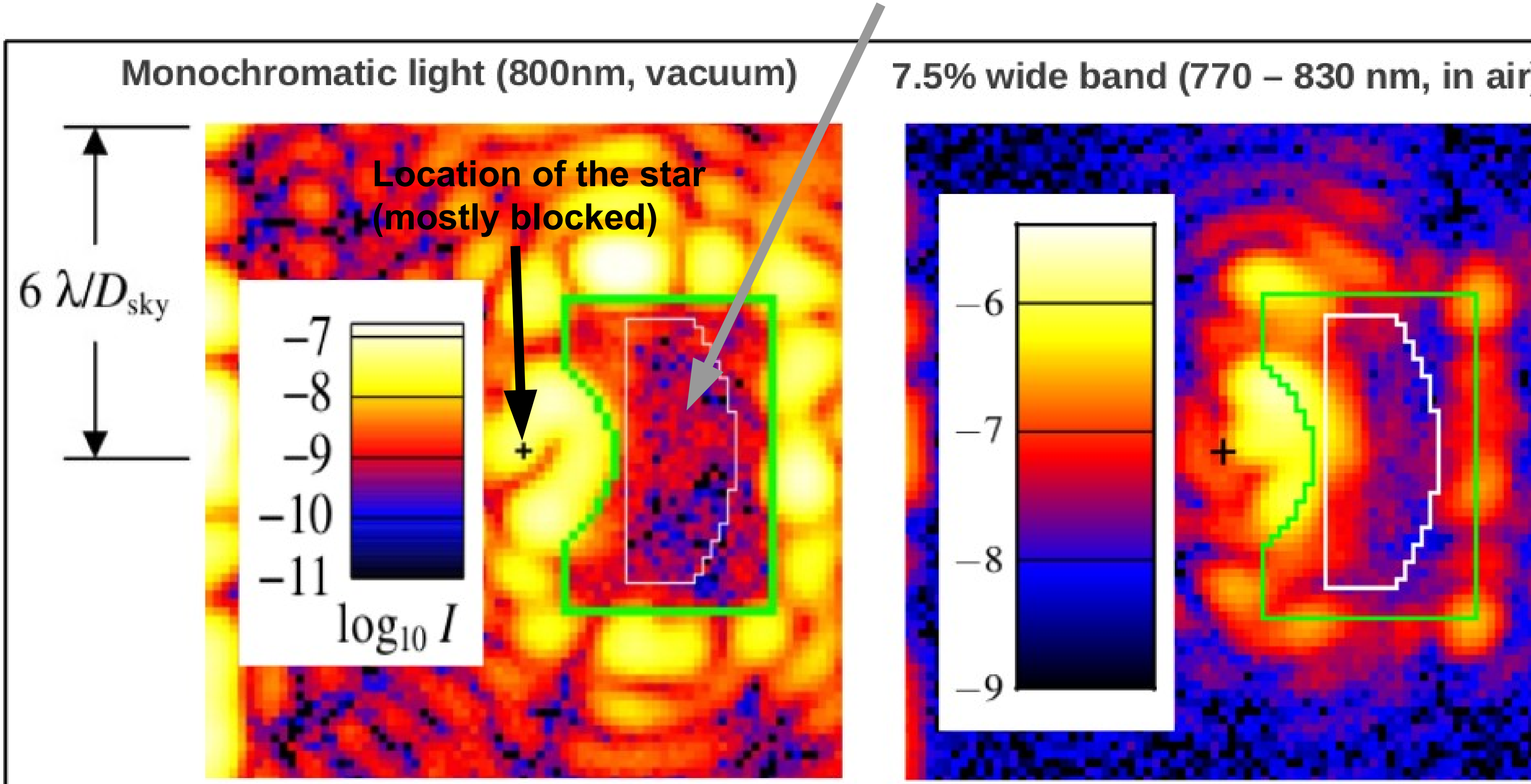


Vacuum testbeds at JPL



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

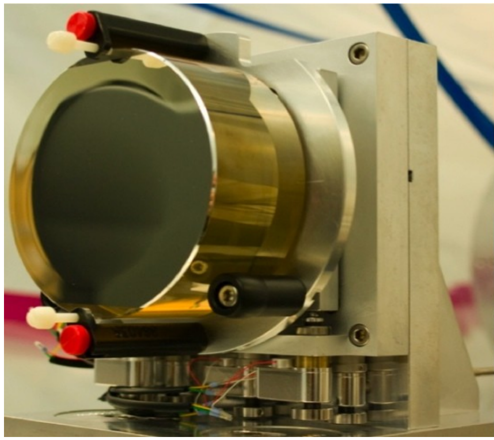
An Earth-like planets could be seen !

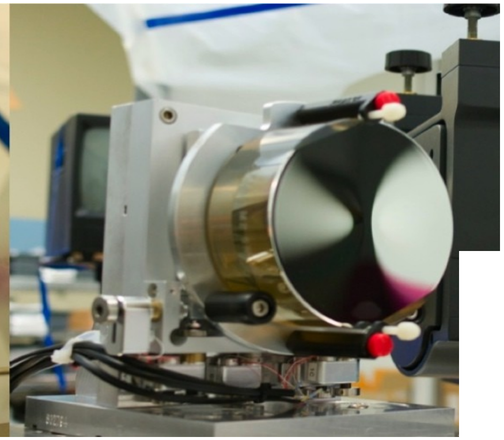


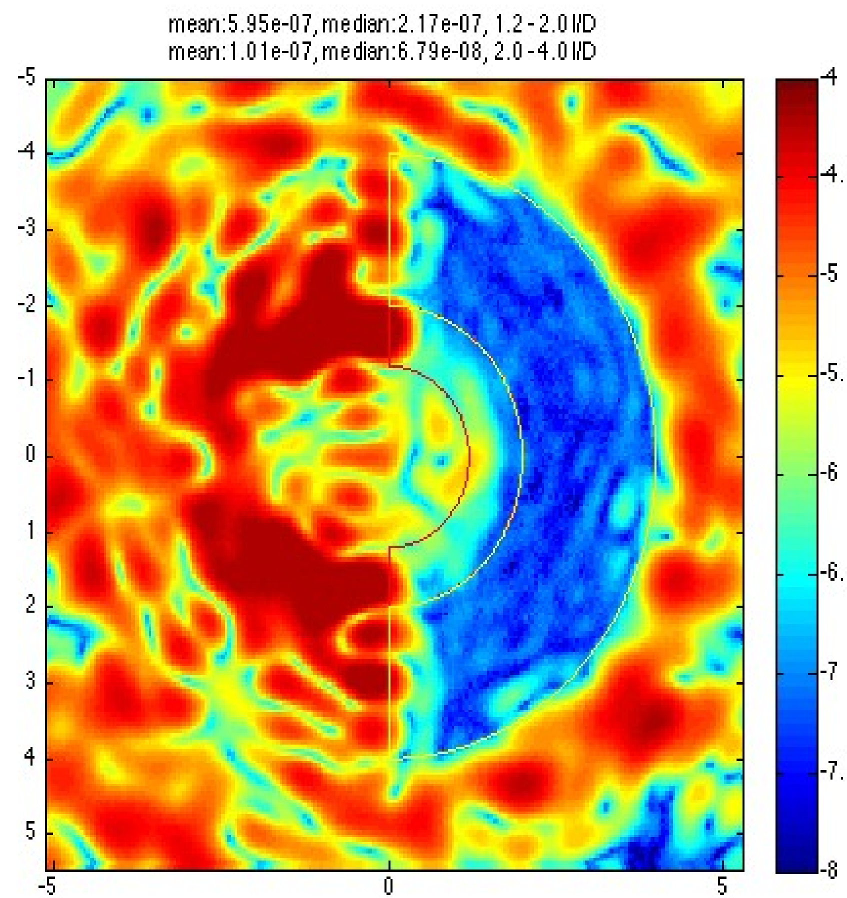
3 runs, contrast values averaged from 2 to 4 λ/D between 5.10^{-10} to 9.10^{-10} (figure shows $7.3.10^{-10}$ result)

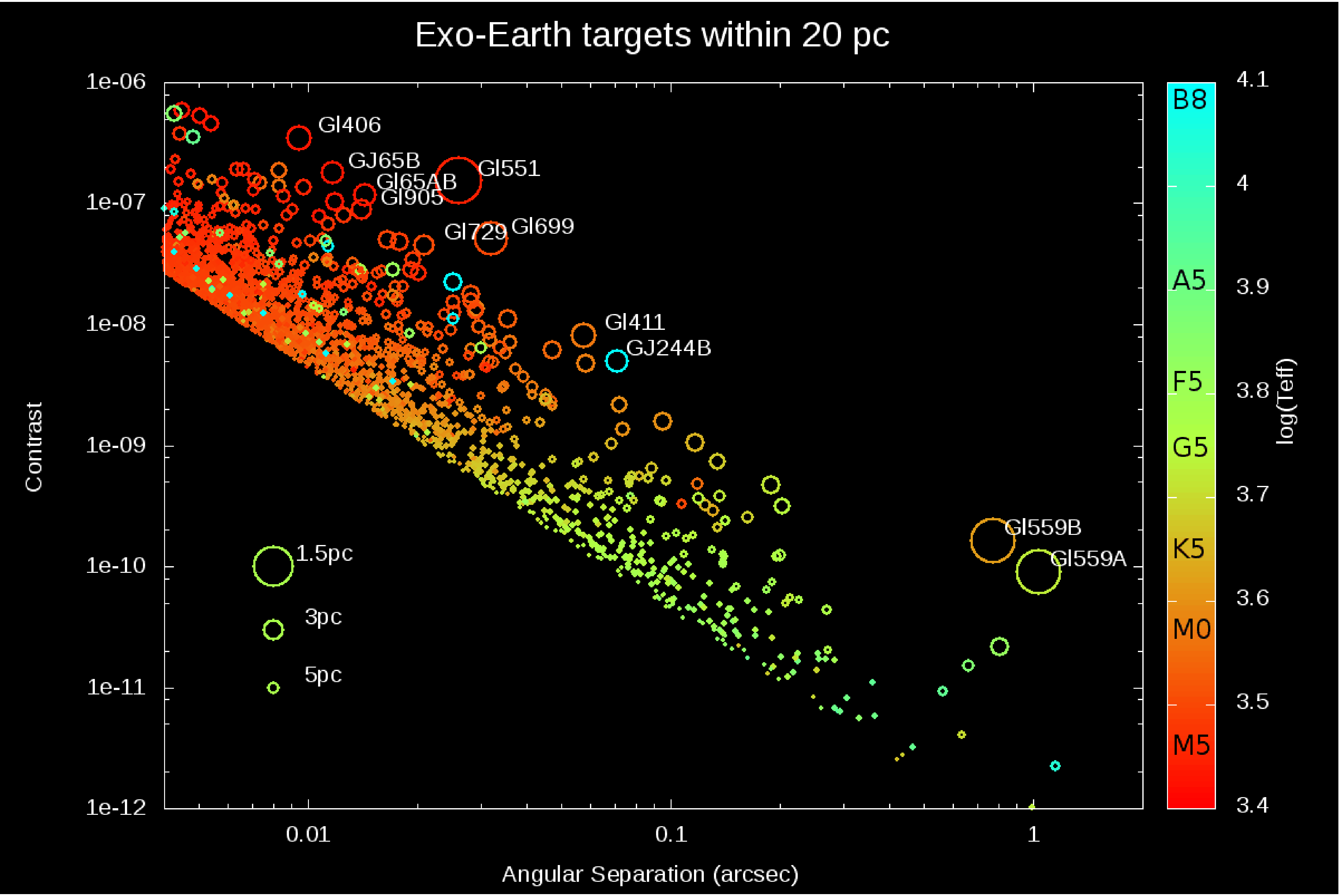
5.10^{-8} contrast from 2 to 4 λ/D,
2.10^{-8} contrast from 3 to 4 λ/D
Contrast performance limited by wavefront instability (test in air)

Testbed at NASA Ames

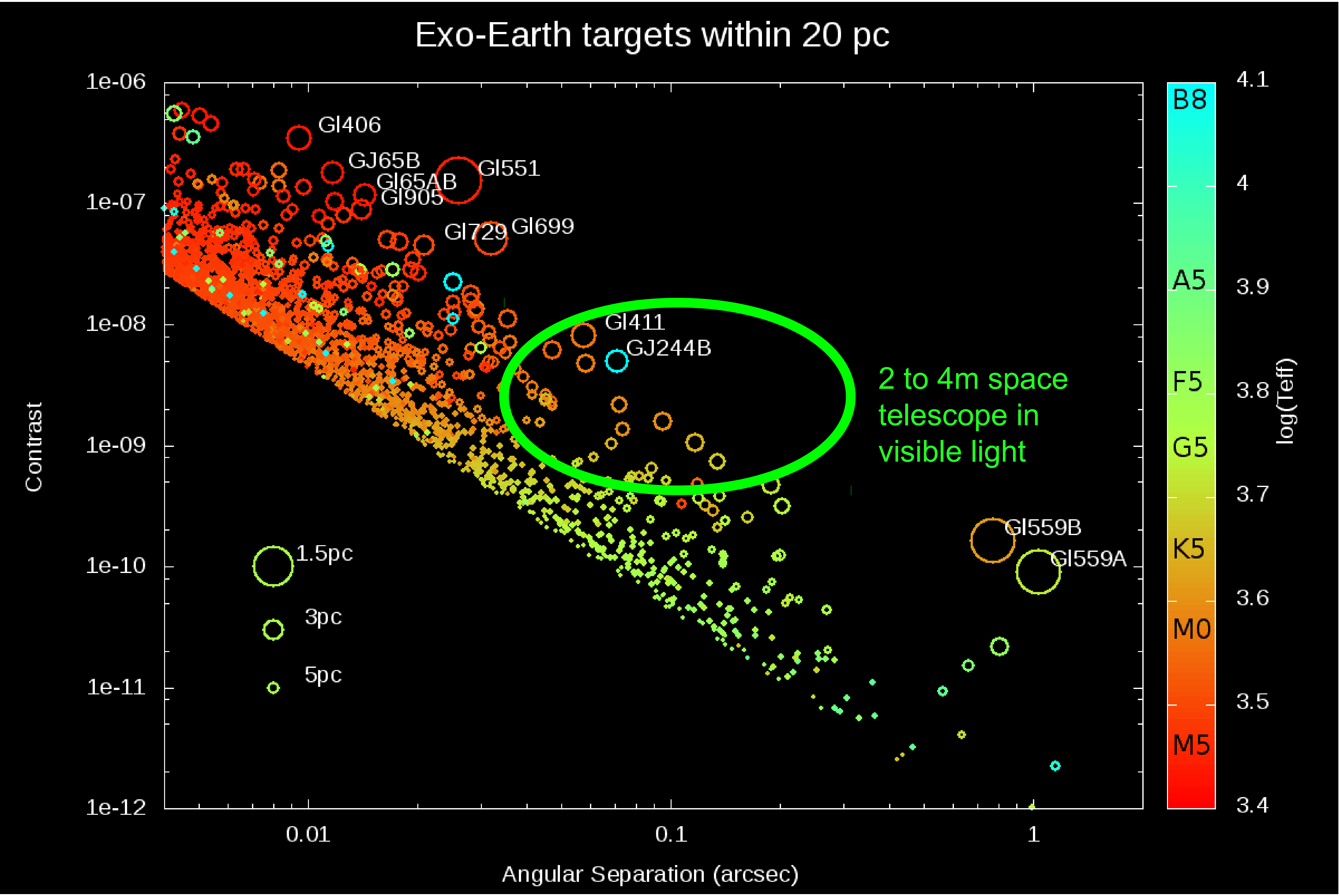








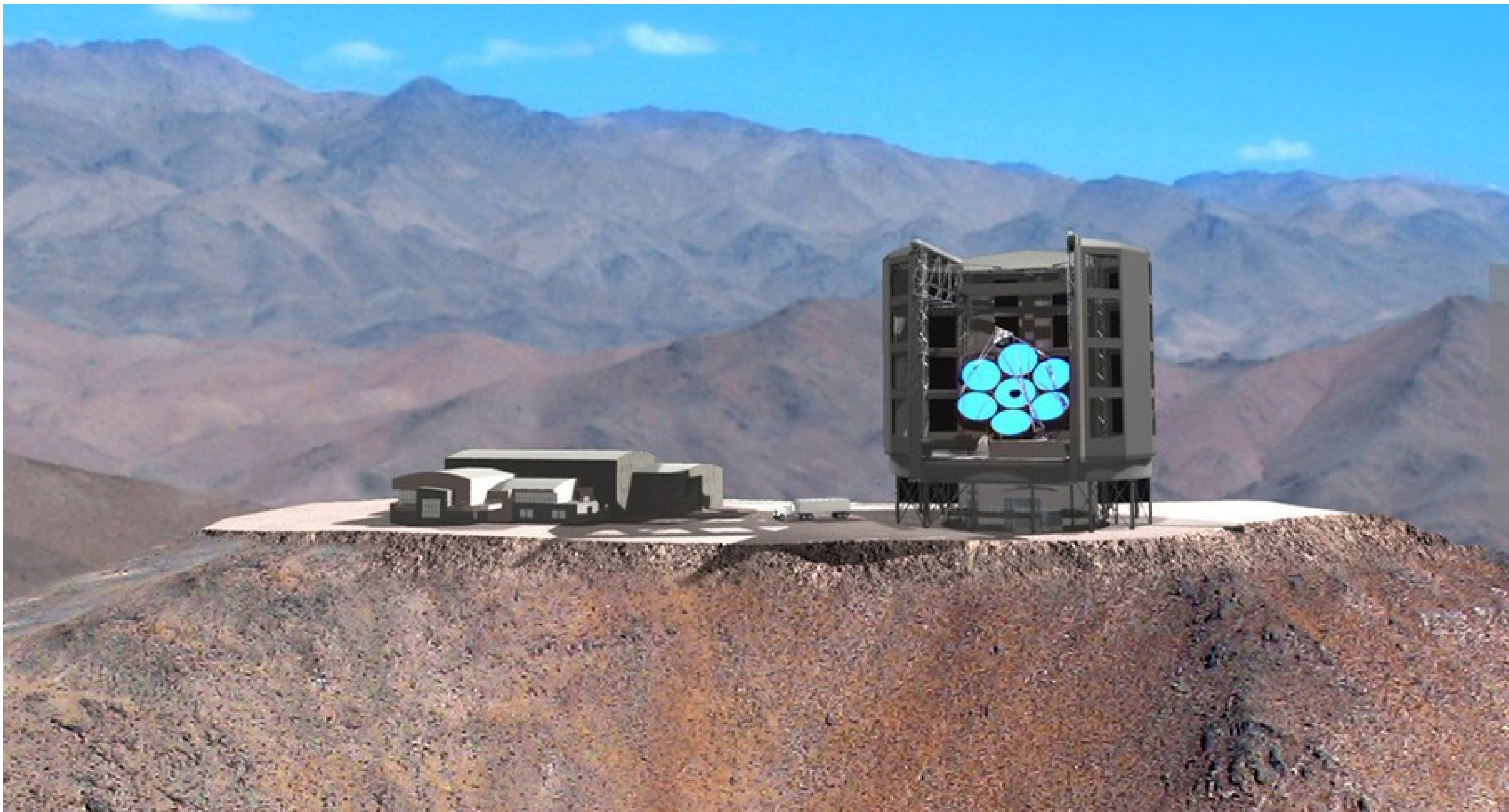
Exo-Earth targets within 20 pc
Contrast
1e-06
1e-07
1e-08
1e-09
1e-10
1e-11
1e-12
0.01
0.1
1
Angular Separation (arcsec)
Gl406
GJ65B
Gl551
Gl65AB
Gl905
Gl729
Gl699
Gl411
GJ244B
Gl559B
Gl559A
1.5pc
3pc
5pc
B8
A5
F5
G5
K5
M0
M5
4.1
4
3.9
3.8
3.7
3.6
3.5
3.4
log(Teff)



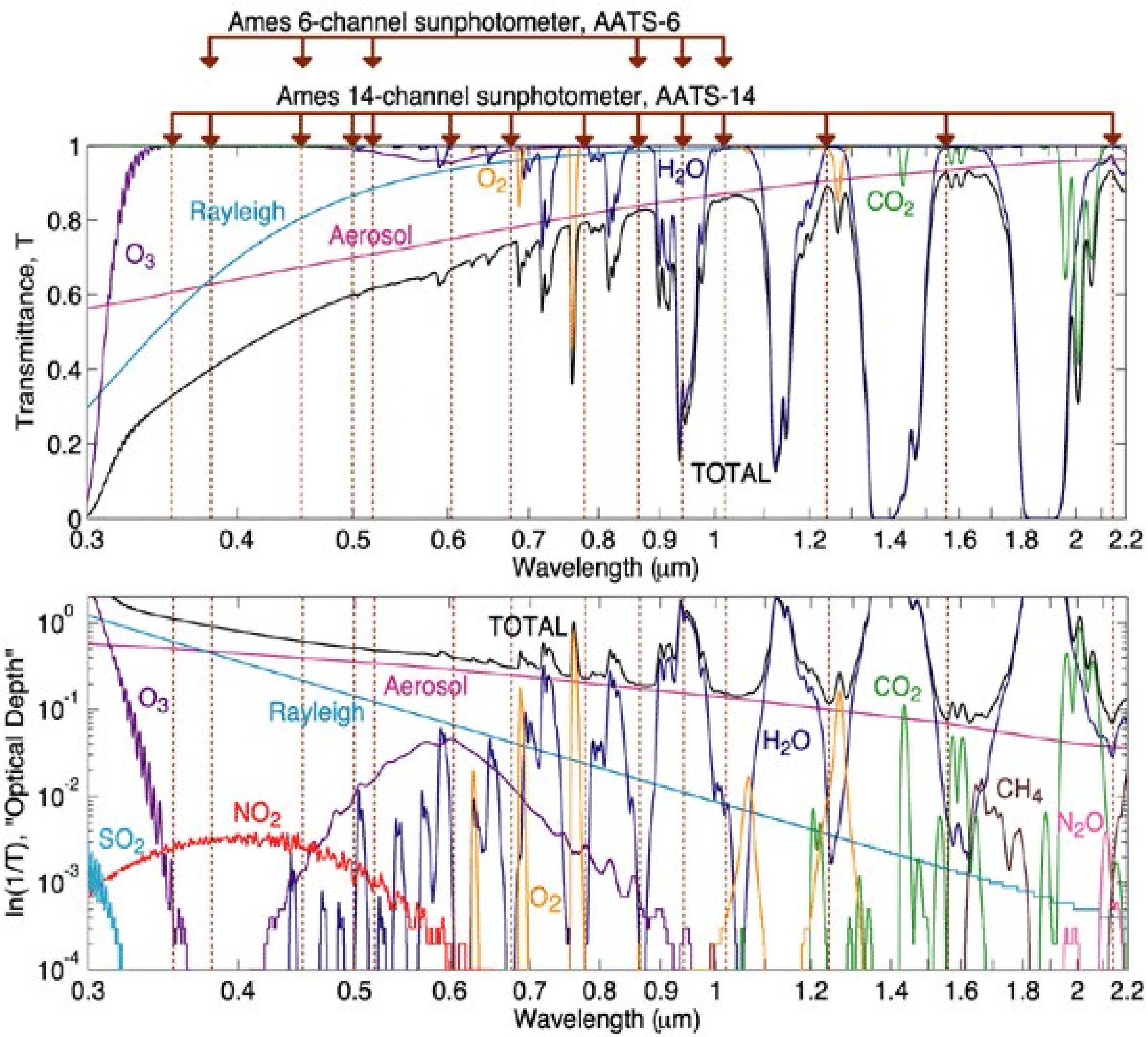
Exo-Earth targets within 20 pc
Contrast
Angular Separation (arcsec)
1e-06
1e-07
1e-08
1e-09
1e-10
1e-11
1e-12
0.01
0.1
1
Gl406
GJ65B
Gl551
Gl65AB
Gl905
Gl729
Gl699
Gl411
GJ244B
2 to 4m space telescope in visible light
Gl559B
Gl559A
1.5pc
3pc
5pc
B8
A5
F5
G5
K5
M0
M5
4.1
4
3.9
3.8
3.7
3.6
3.5
3.4
log(Teff)

Extremely Large Telescopes (ELTs)

3 projects, 25 to 40m diameter



Habitable Planets Spectroscopy in near-IR



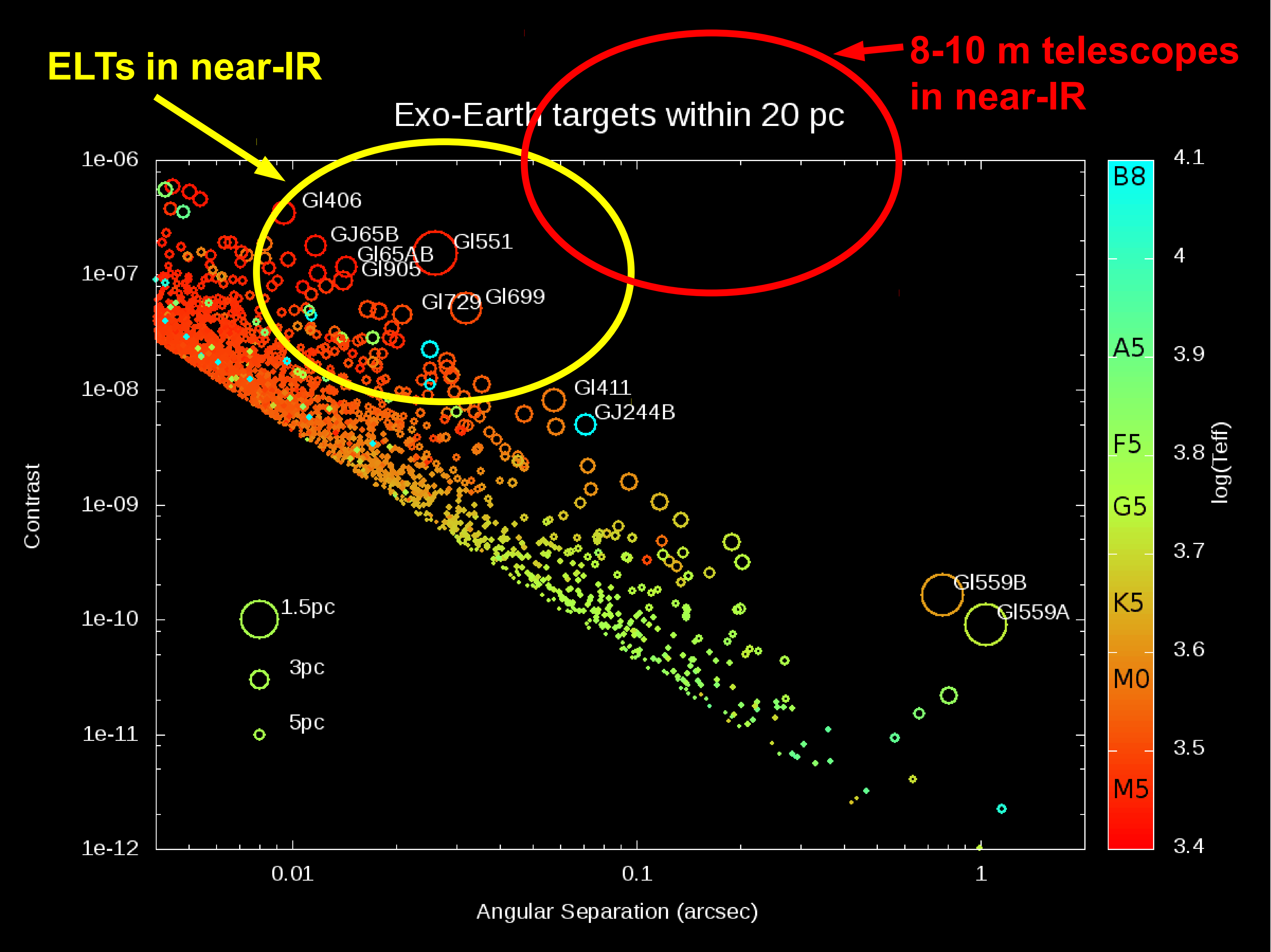
Credit: NASA/Ames Airborne Tracking Sunphotometer (AATS)

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...)



ELTs in near-IR
8-10 m telescopes
in near-IR
Exo-Earth targets within 20 pc
Contrast
1e-06
1e-07
1e-08
1e-09
1e-10
1e-11
1e-12
0.01
0.1
1
Angular Separation (arcsec)
Gl406
GJ65B
Gl65AB
Gl905
Gl551
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)

Reflected light planets

Assuming that each star has a SuperEarth (2x Earth diameter) at the 1AU equivalent HZ distance

(assumes Earth albedo, contrast and separation for max elongation)

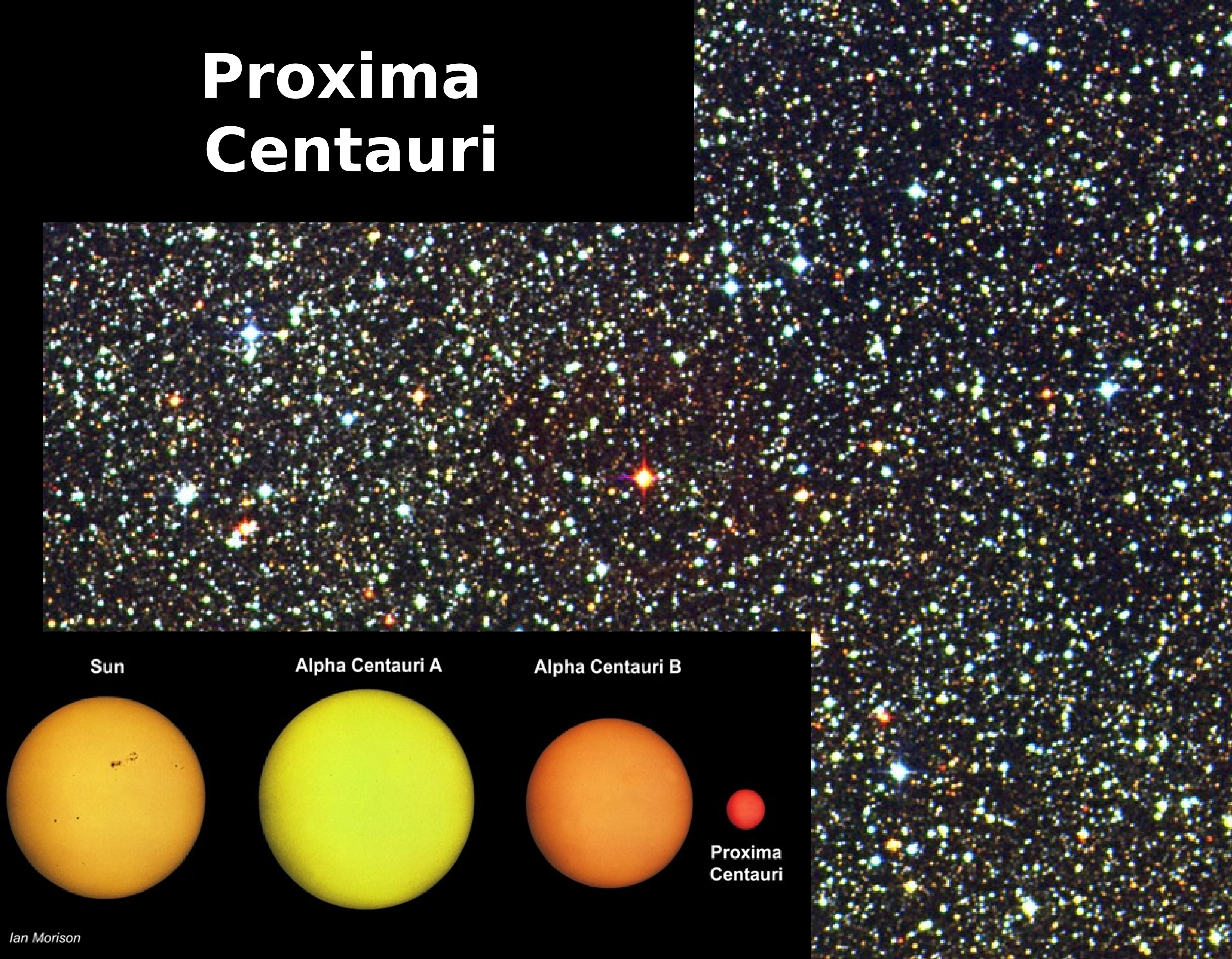
MOST FAVORABLE TARGETS

STAR							PLANET				
Name	**Type**	**Distance**	**Diameter**	**L_{bol}**	**m_V**	**m_R**	**m_H**	**Separation**	**Contrast**	**m_H**	**Notes, Multiplicity**
Proxima Centauri (Gl551)	M5.5	1.30 pc	0.138 R_{Sun} 0.990 +- 0.050 mas [1]	8.64e-04	11.00	9.56	4.83	22.69 mas	8.05e-07	20.07	RV measurement exclude planet above 3 Earth mass in HZ [Endl & Kurster 2008]
Barnard's Star (Gl699)	M4	1.83 pc	0.193 R_{Sun} 0.987 += 0.04 mas [2]	4.96e-03	9.50	8.18	4.83	38.41 mas	1.40e-07	21.97	-
Kruger 60 B (Gl860B)	M4	3.97 pc	0.2 R_{Sun}[3]	5.81e-03	11.30	9.90	5.04	19.20 mas	1.20e-07	22.35	-
Ross 154 (Gl729)	M4.5	2.93 pc	0.2 R_{Sun}[3]	5.09e-03	10.40	9.11	5.66	24.34 mas	1.37e-07	22.82	-
Ross 128 (Gl447)	M4.5	3.32 pc	0.2 R_{Sun}[3]	3.98e-03	11.10	9.77	5.95	18.99 mas	1.75e-07	22.84	-
Ross 614 A (Gl234A)	M4.5	4.13 pc	0.2 R_{Sun}[3]	5.23e-03	11.10	9.82	5.75	17.51 mas	1.33e-07	22.95	Double star (sep=3.8 AU)
Gl682	M3.5	4.73 pc	0.26 R_{Sun}[3]	6.41e-03	10.90	9.70	5.92	16.93 mas	1.09e-07	23.33	-
Groombridge 34 B (Gl15B)	M6	3.45 pc	0.18 R_{Sun}[3]	5.25e-03	11.00	9.61	6.19	20.98 mas	1.33e-07	23.39	150 AU from M2 primary
40 Eri C (Gl166C)	M4.5	4.83 pc	0.23 R_{Sun}[3]	5.92e-03	11.10	9.88	6.28	15.93 mas	1.18e-07	23.61	35AU from 40 Eri B (white dwarf), 420 AU from 40 Eri A (K1)
GJ 3379	M4	5.37 pc	0.24 R_{Sun}[3]	6.56e-03	11.30	10.06	6.31	15.09 mas	1.06e-07	23.75	-

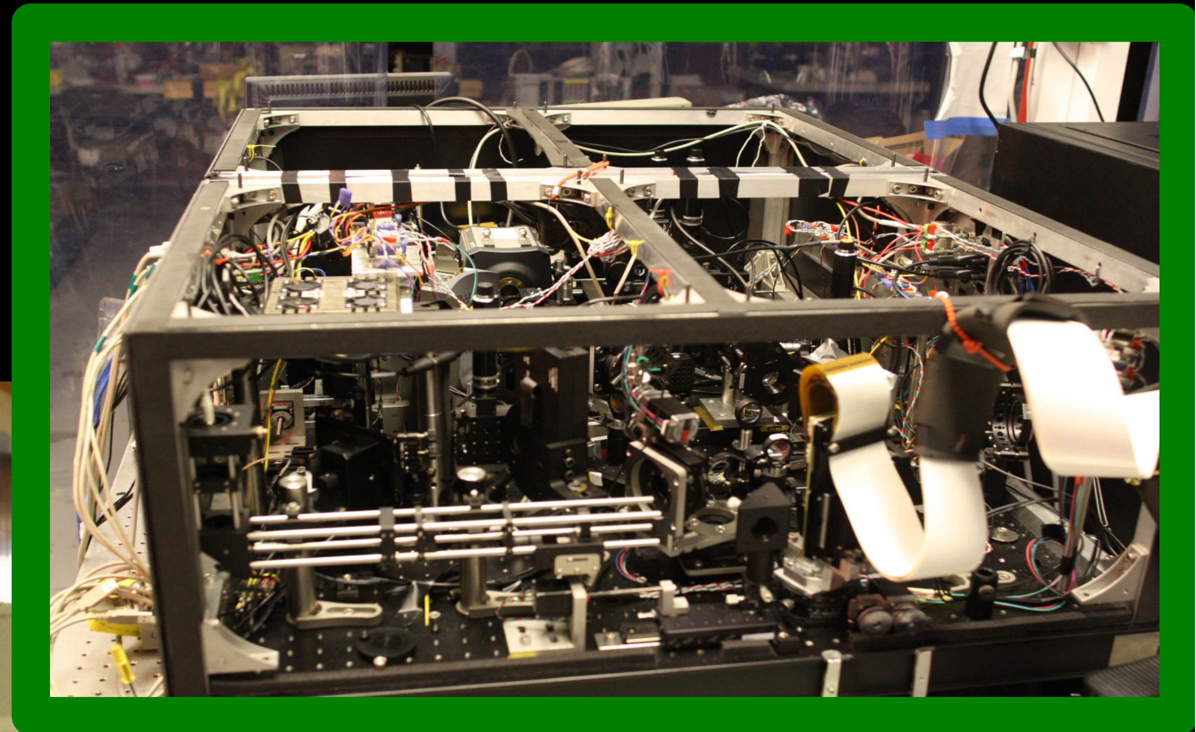
[1] Angular diameter (uniform disk, non limb-darkened value) measured by optical interferometry with VLTI Demory et al. 2009
[2] Uniform disk angular diameter from Lane et al. 2001
[3] No direct measurement. Approximate radius is given. If possible, radius is extrapolated from photometry using K magnitude and radius vs. absolute K magnitude relationship in Demory et al. 2009

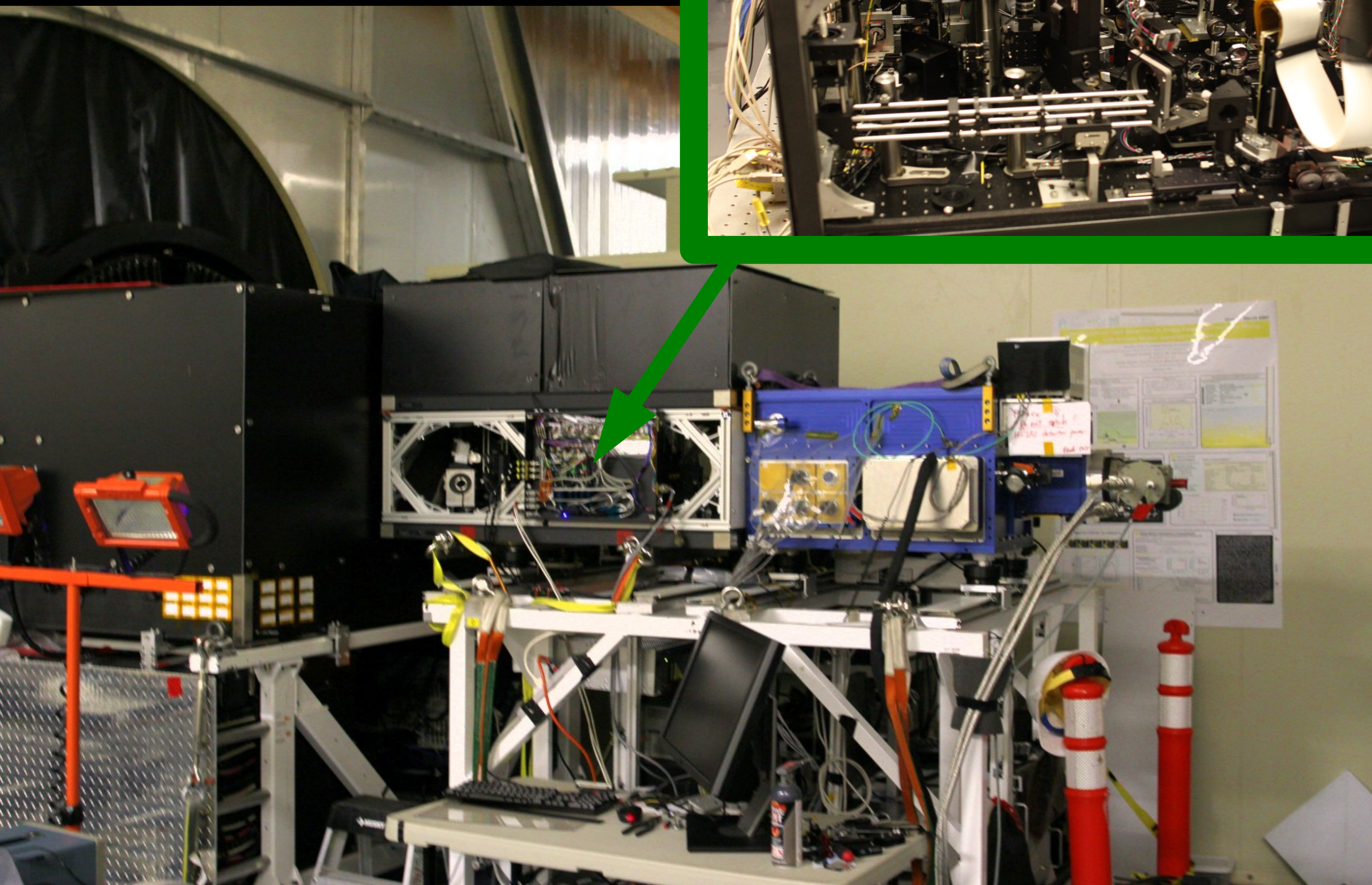
Requirement : ~1e-7 contrast, ~15mas, mR ~ 9.5 guide star

Proxima Centauri

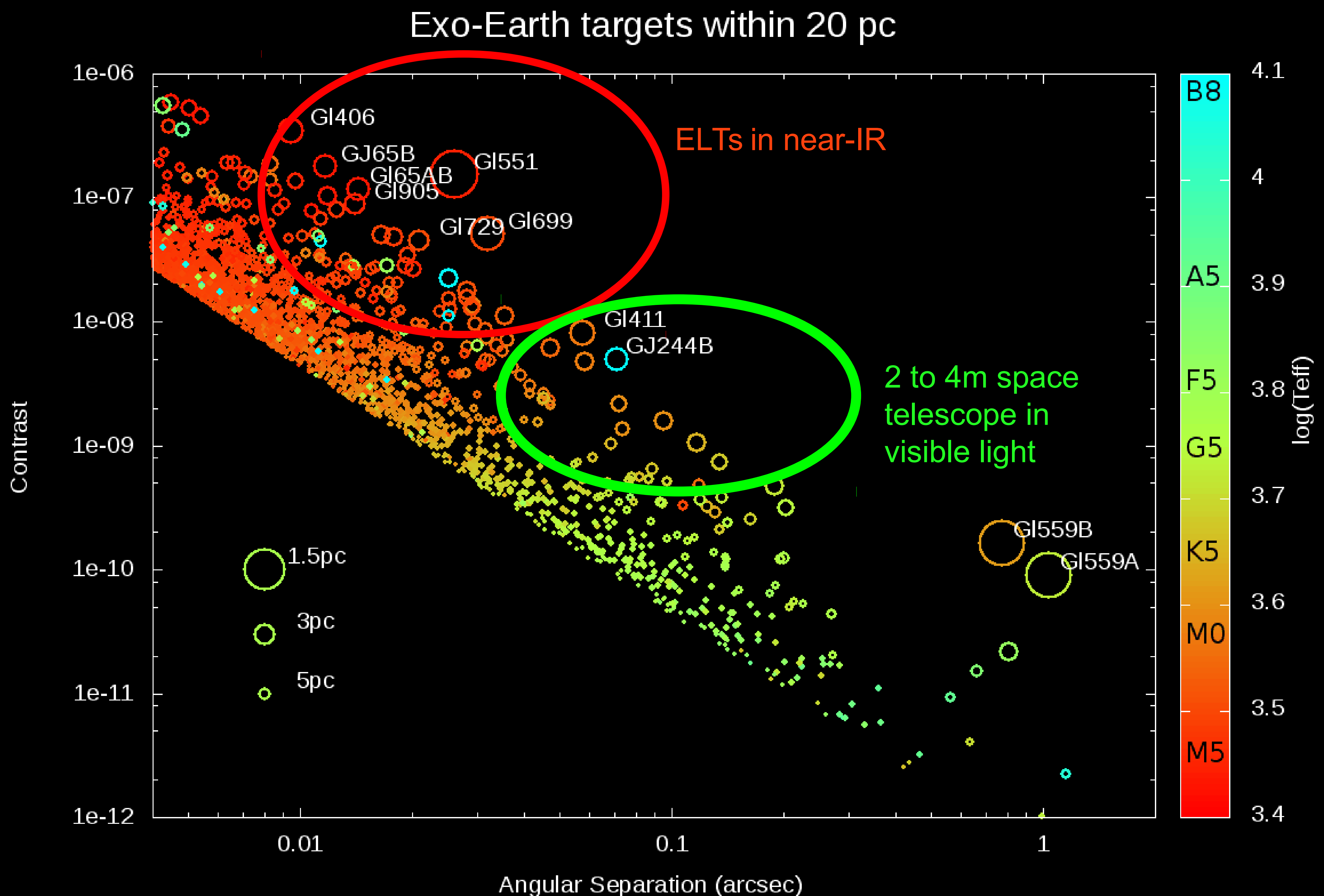


The Subaru Coronagraphic Extreme Adaptive Optics (SCExAO) system





Detecting planets from space and ground



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 goals

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

BUT:

- Cost must be small to get strong community participation
- Technical challenges: hardware, software
- Requires coordination (data must be combined between many observers)

→ project PANOPTES is aimed at solving these 3 problems to enable a world-wide network of low-cost imaging units for exoplanet transit discoveries
→ PANOPTES is aimed at enabling collaboration between citizen scientists, amateur astronomers, schools and “real”

Enabling technologies

Digital cameras are relatively cheap and high quality

~20 Mpix
<3e- readout noise
Outstanding cosmetic quality
Fast readout (<<`1sec)
Robust construction
Low dark current (<< sky background)

…. for a few $100s

Using many digital cameras + lenses is the most cost-effective way to cover large parts of the sky with good sensitivity
(Few $1000s per square degree square meter of etendue)

Feasibility study (completed)

GOALS:

Demonstrate low-cost reliable hardware solution

→ prototype systems #1 and #2 have been running for 2 yrs

Demonstrate that high precision photometry can be achieved with low-cost digital cameras

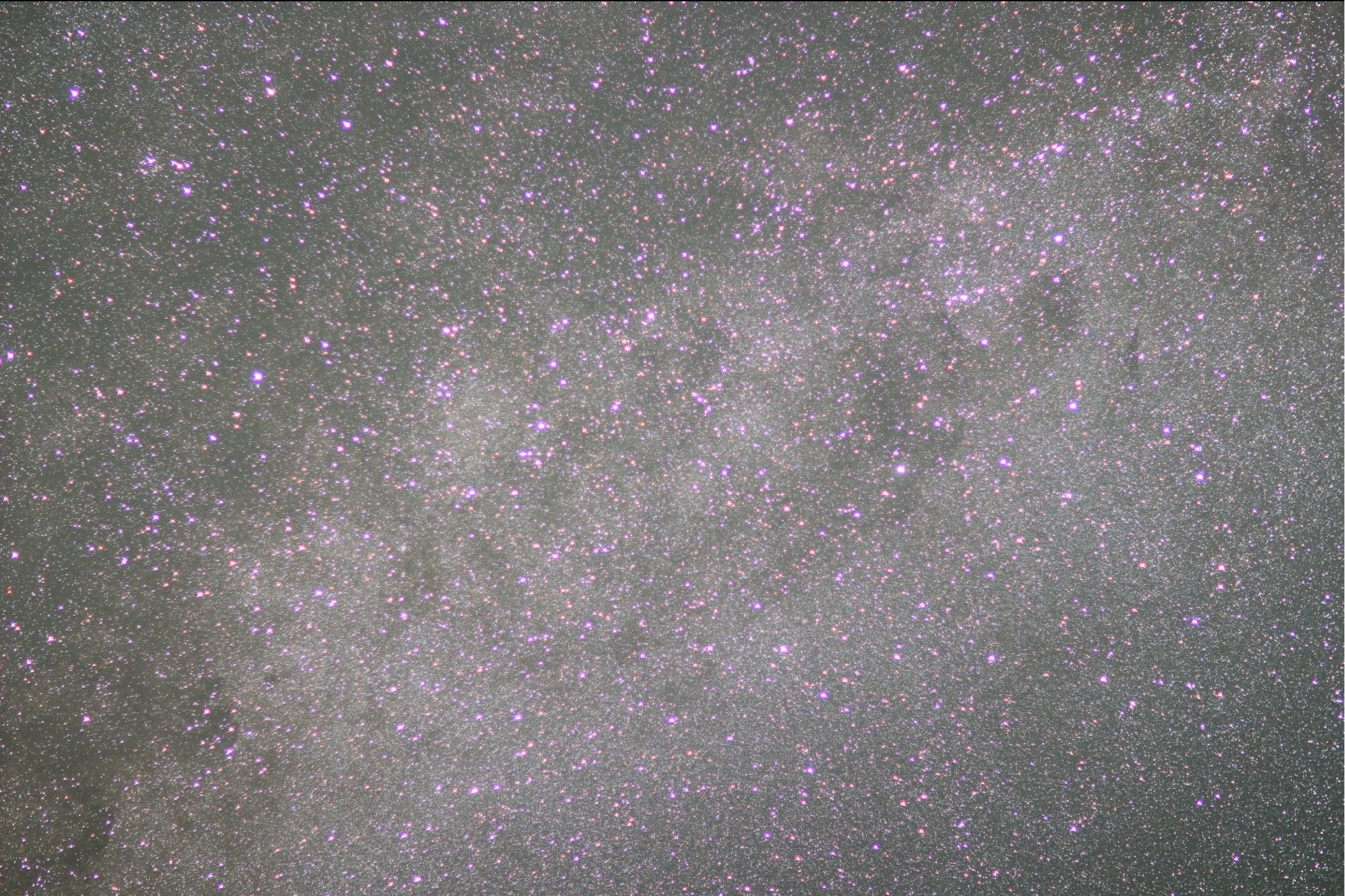
Color camera have complex pixel / star interaction

→ demonstrated % level photometry in 1mn exposure with a single camera

→ demonstrated that a single camera can detect a single transit

PANOPTES prototype #2 unit at Mauna Loa observatory

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



Example image – 315 sec exposure, ISO 100 (March 1, 2011)

Lower left corner of previous image

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

Ongoing activities

Building more units, deploying them around the globe

Partnering with schools, amateur astronomers, and existing exoplanet transit surveys

Setting up data storage and processing hub

Check:

Www.projectpanoptes.org