Anybody out there ?

Optical tricks to image and study habitable exoplanets

Olivier Guyon

University of Arizona
Astronomy & Optics

Subaru Telescope

NASA JPL

Contact: oliv.guyon@gmail.com

Outline

Introduction

Why direct imaging ? Why is it difficult ?

Technology

High performance PIAA coronagraphy, recent lab results, coronagraphy + WFC

Scientific Opportunities

SPACE: Direct imaging of Earth-like planets around Sun-like stars

GROUND: **Imaging habitable planets around M-type stars with ELTs**; SCExAO as a precursor

project PANOPTES

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

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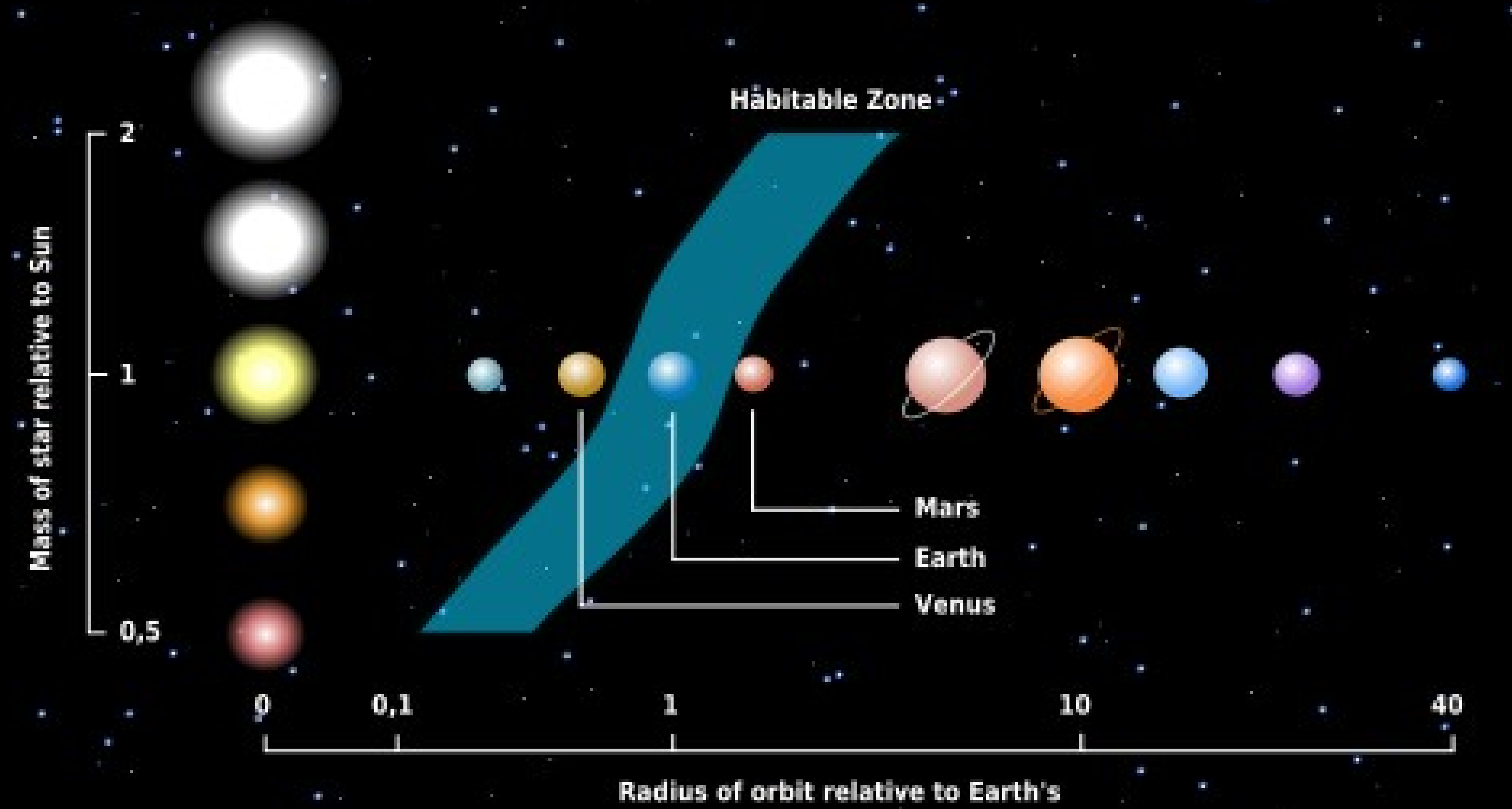
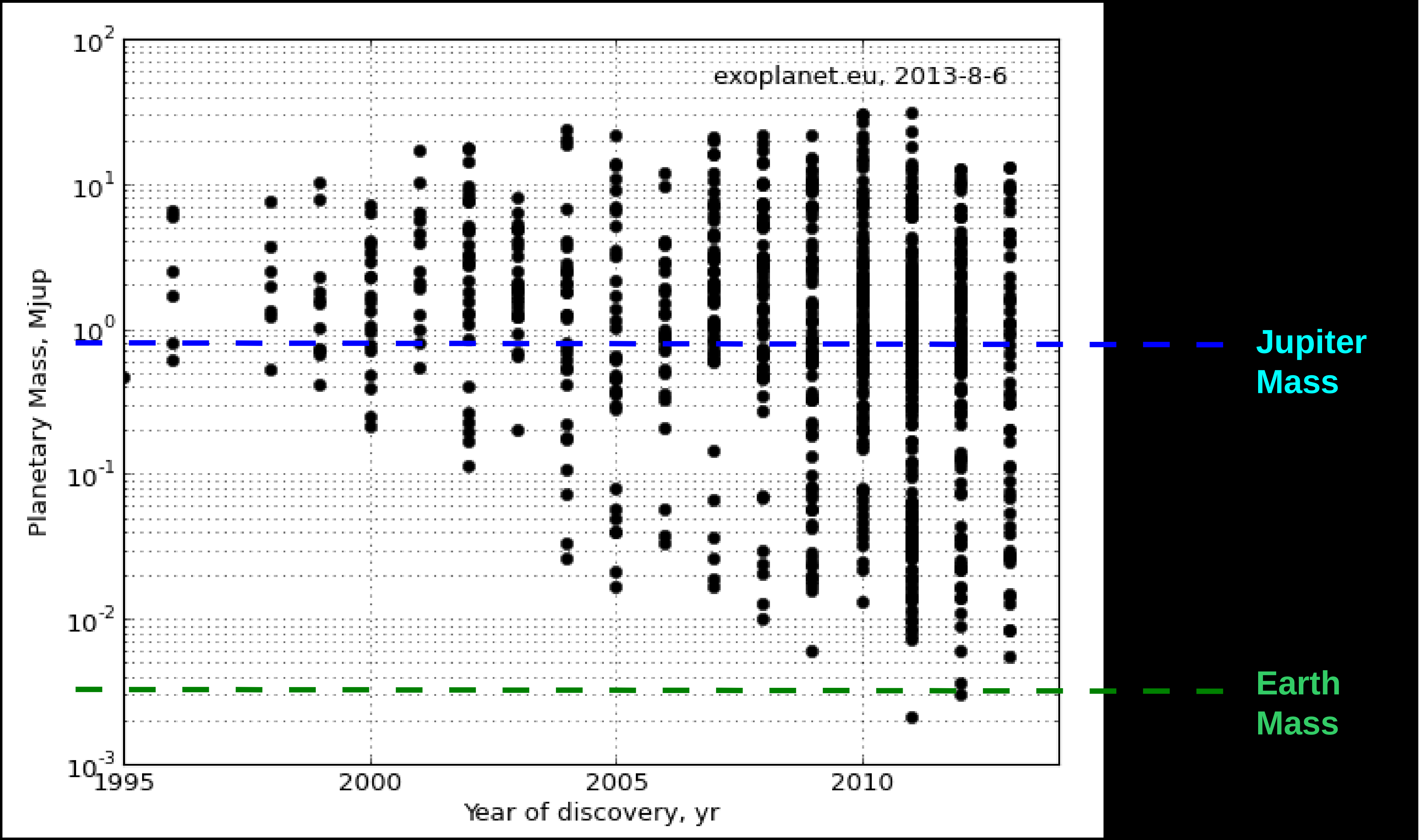
Habitable zone of a star



Every star has a habitable zone

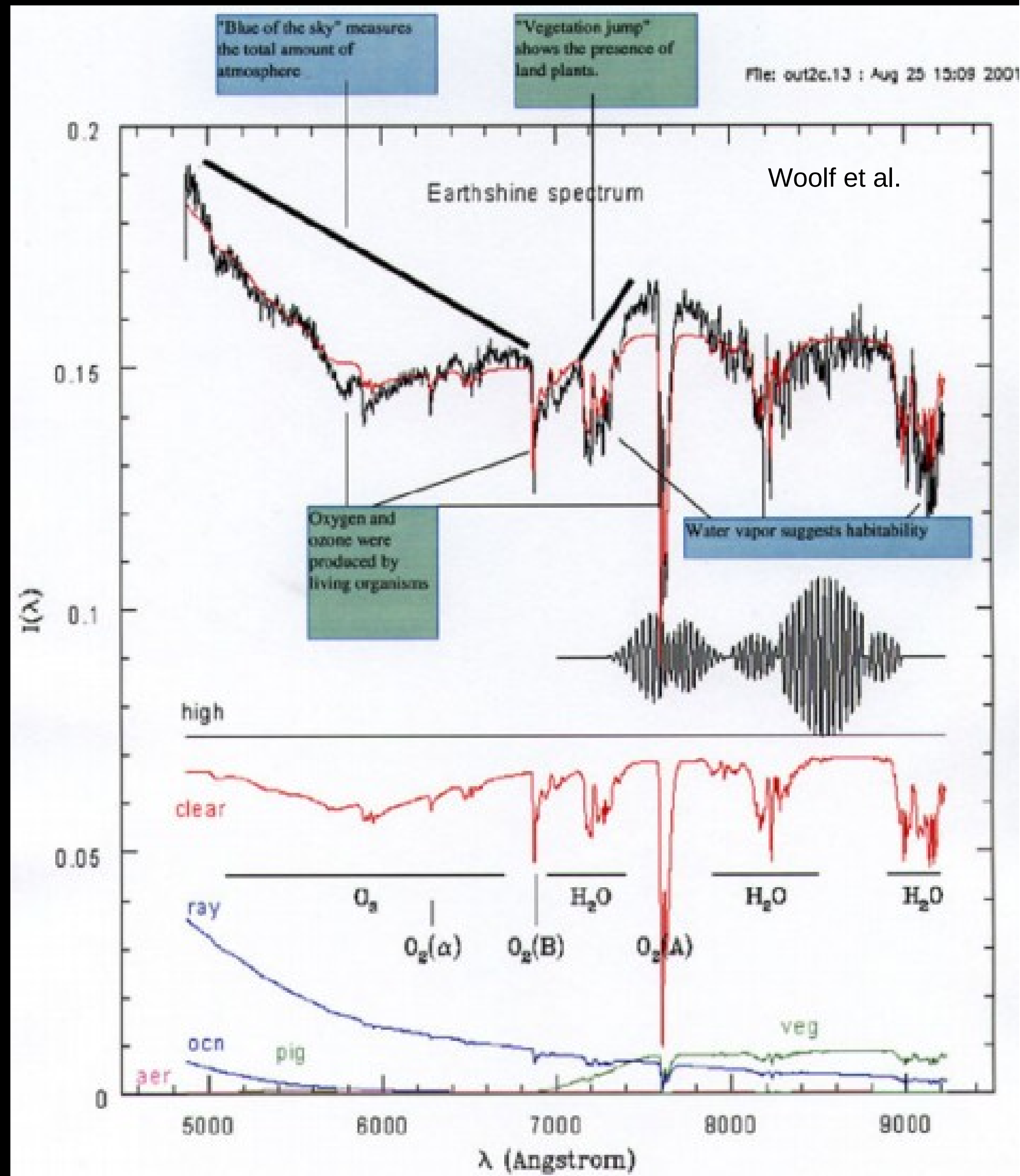
Planets identified – we are now starting to identify Earth-like planets



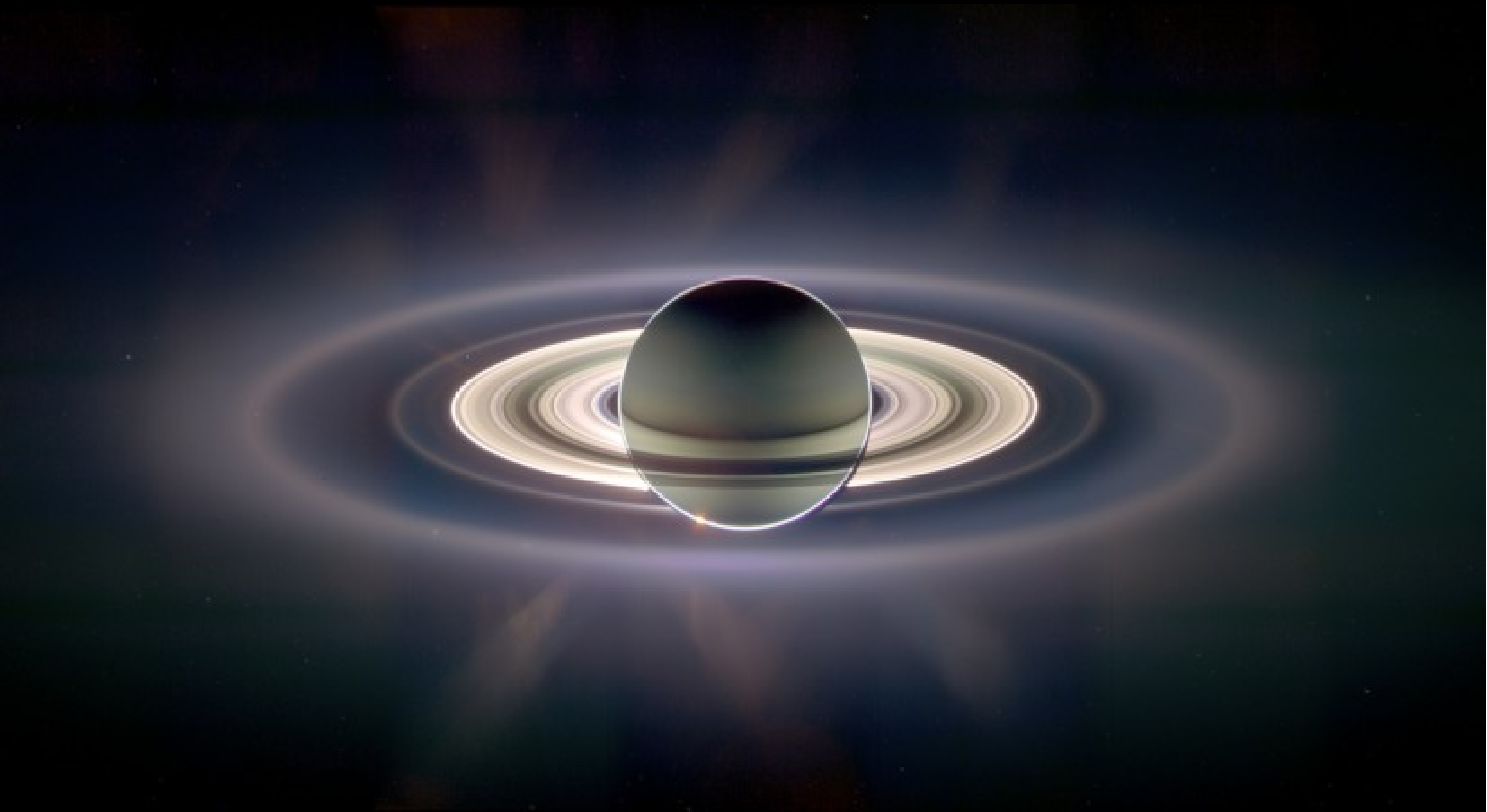
Directly imaging planet is necessary to find life

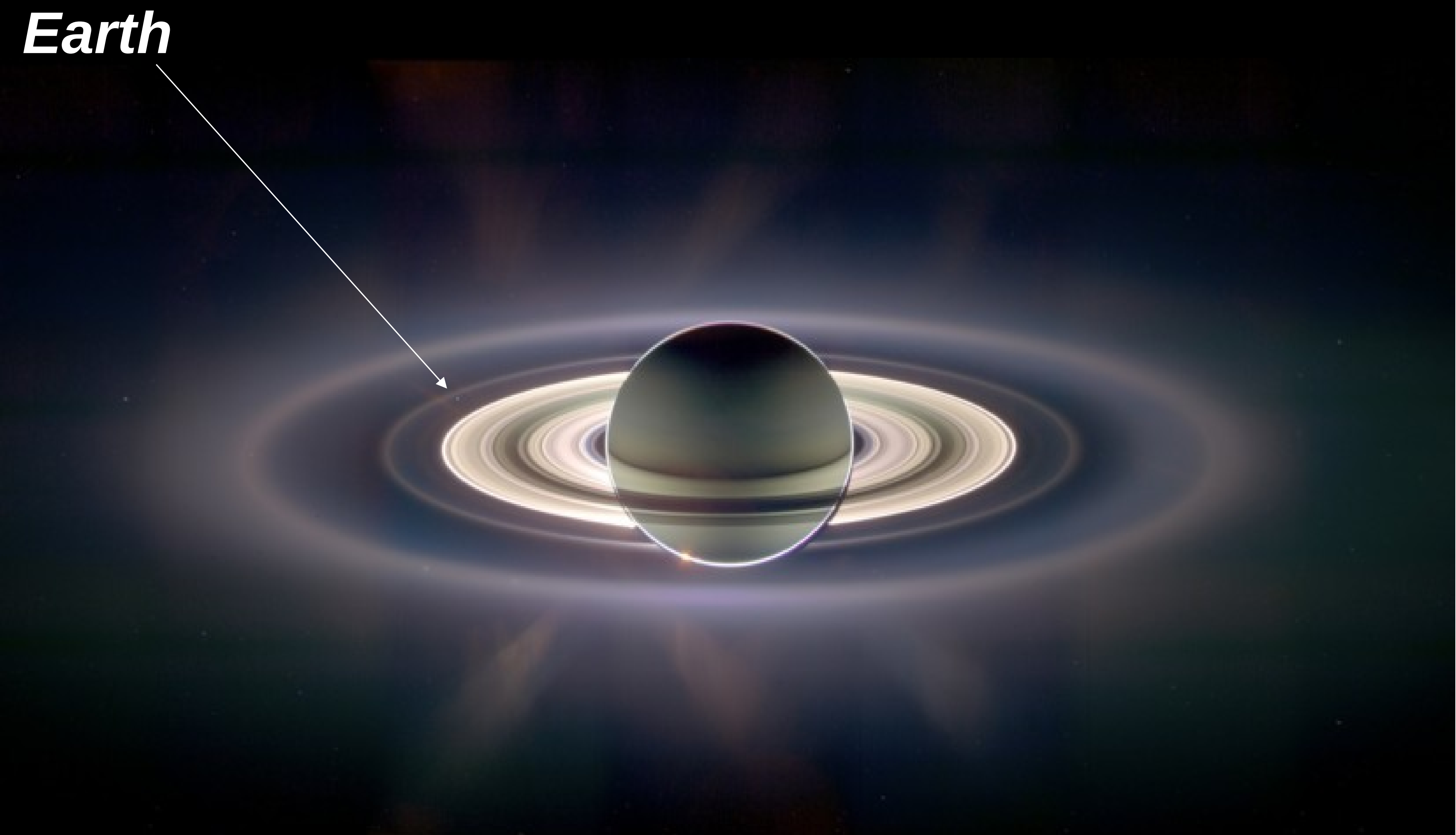
We need to take spectra of habitable planets

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



Taking images of exoplanets: Why is it hard ?




Earth

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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

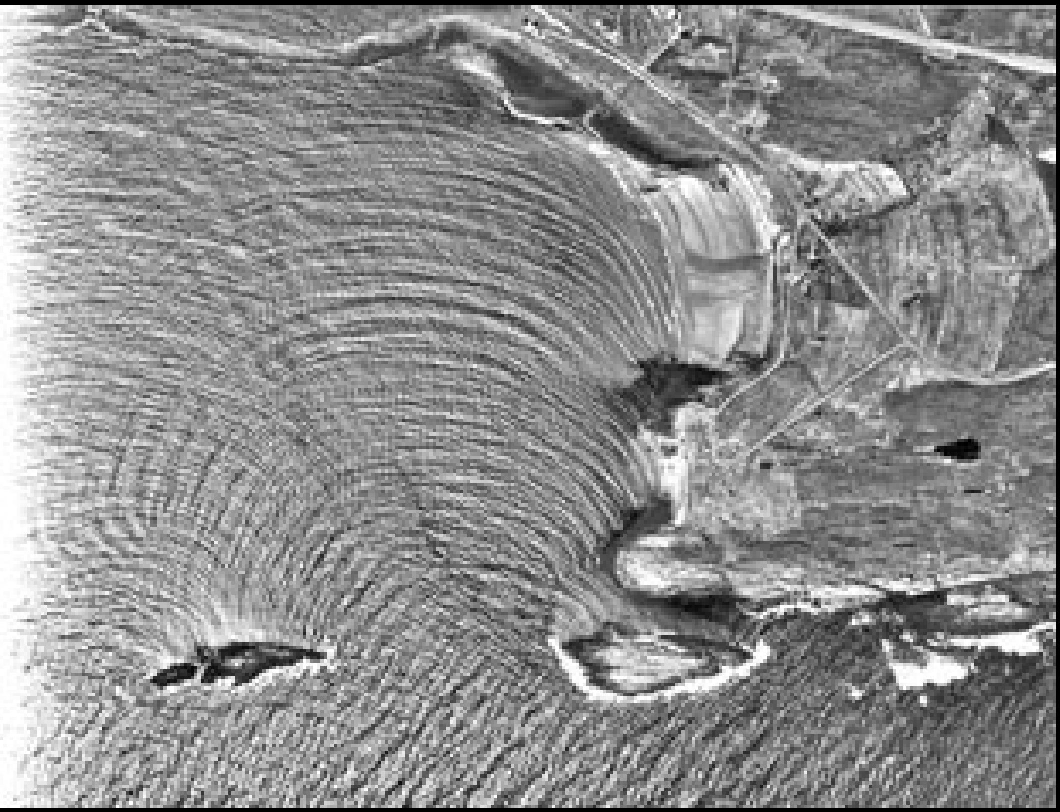
1818: French academy of science committee launches a competition
to explain nature of light

Augustin-Jean Fresnel
submits wave theory of light

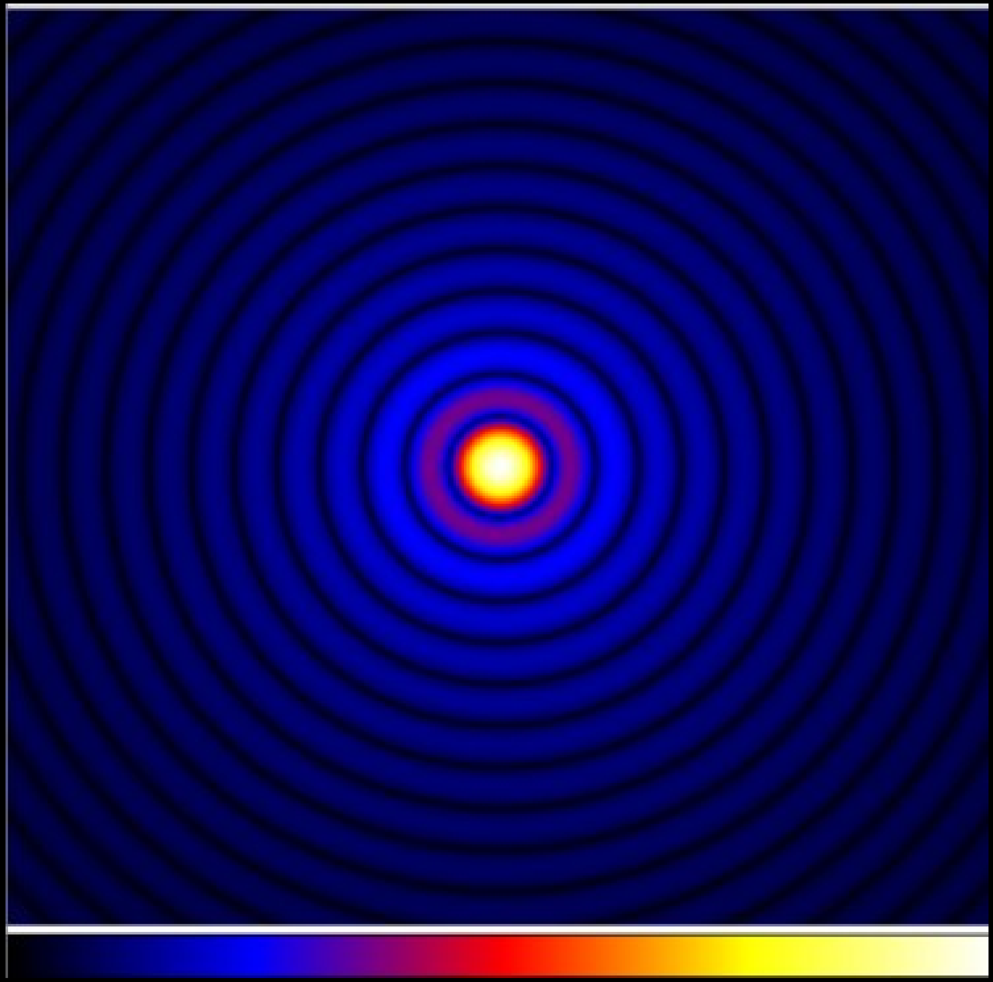
Simeon-Denis Poisson finds a flaw in Fresnel's theory:
According to Fresnel's equations, a bright spot should appear in
the shadow of a circular obstacle → this absurd result disproves Fresnel's theory

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



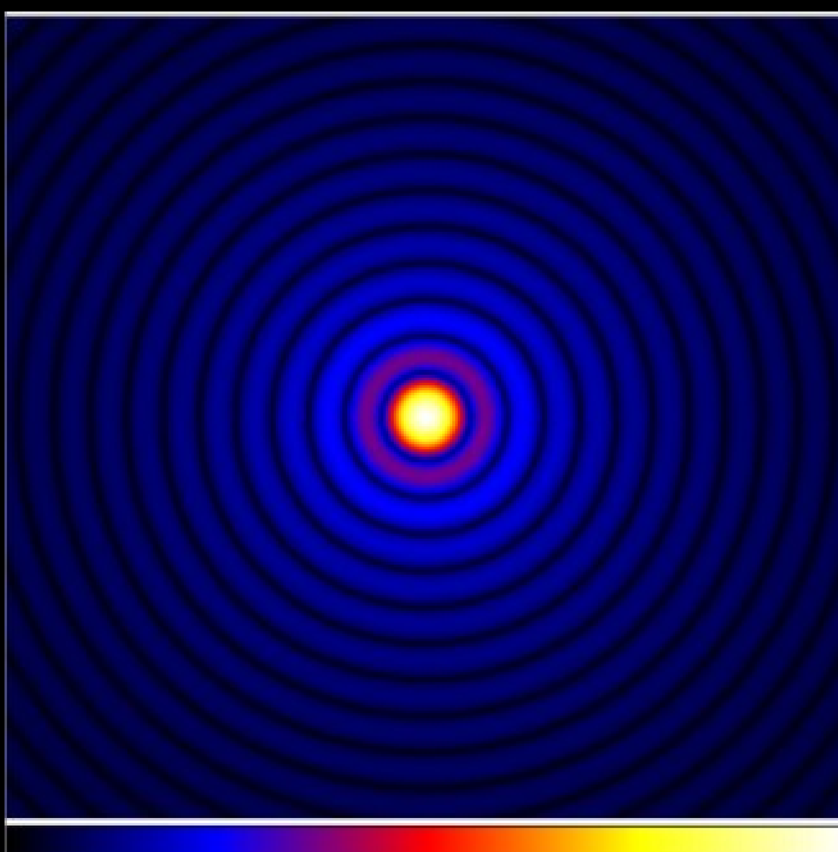
Waves diffracted by coastline and islands

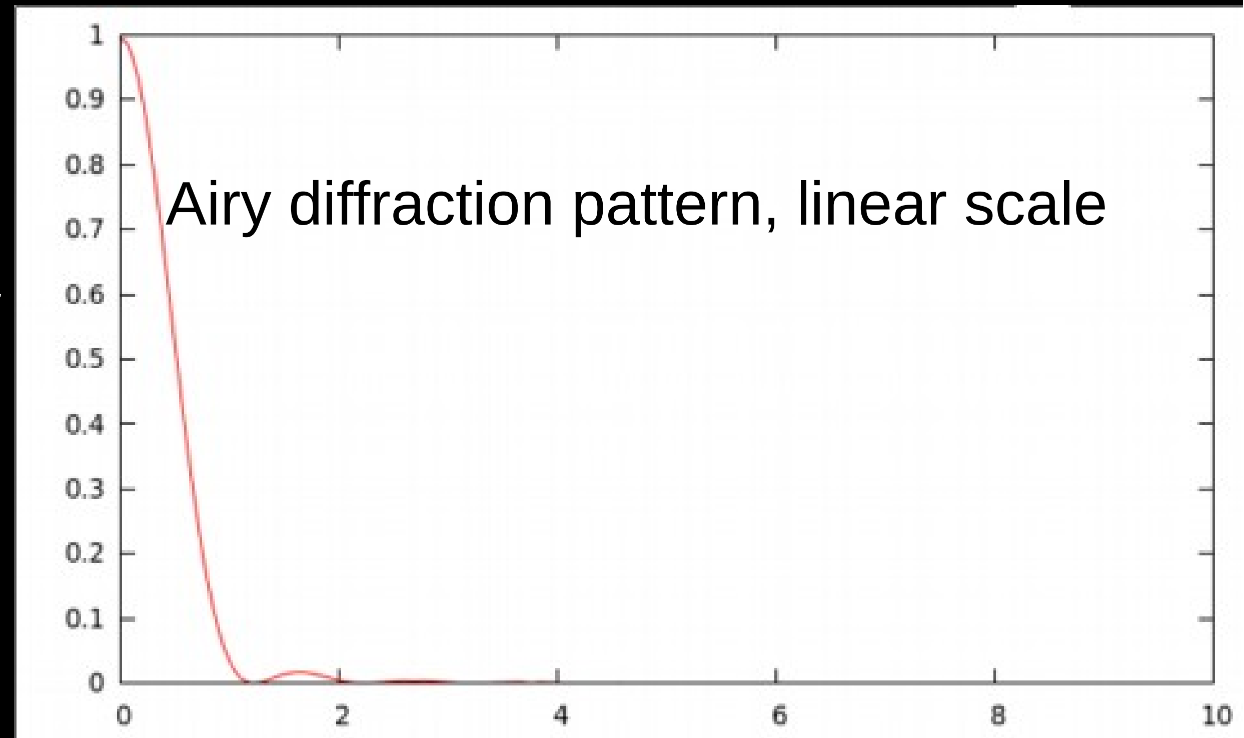


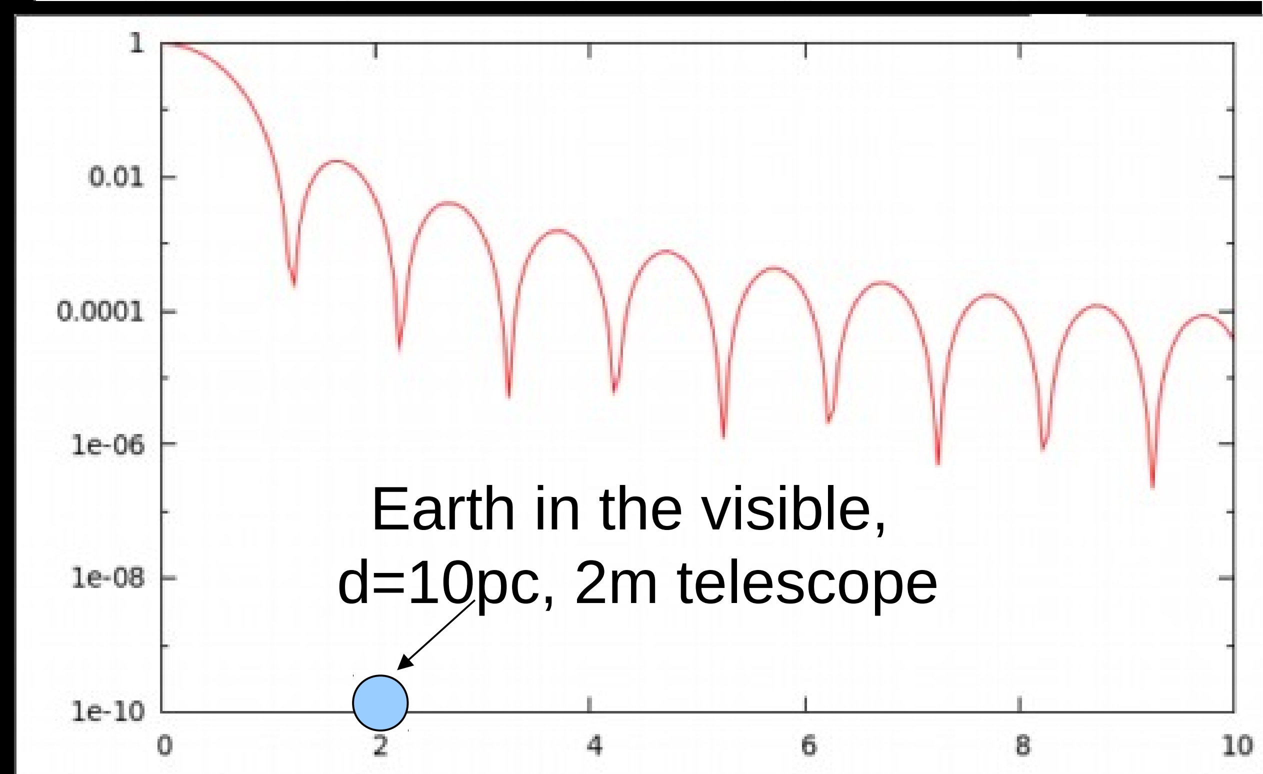
Ideal image of a distant star by a telescope
Diffraction rings around the image core

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

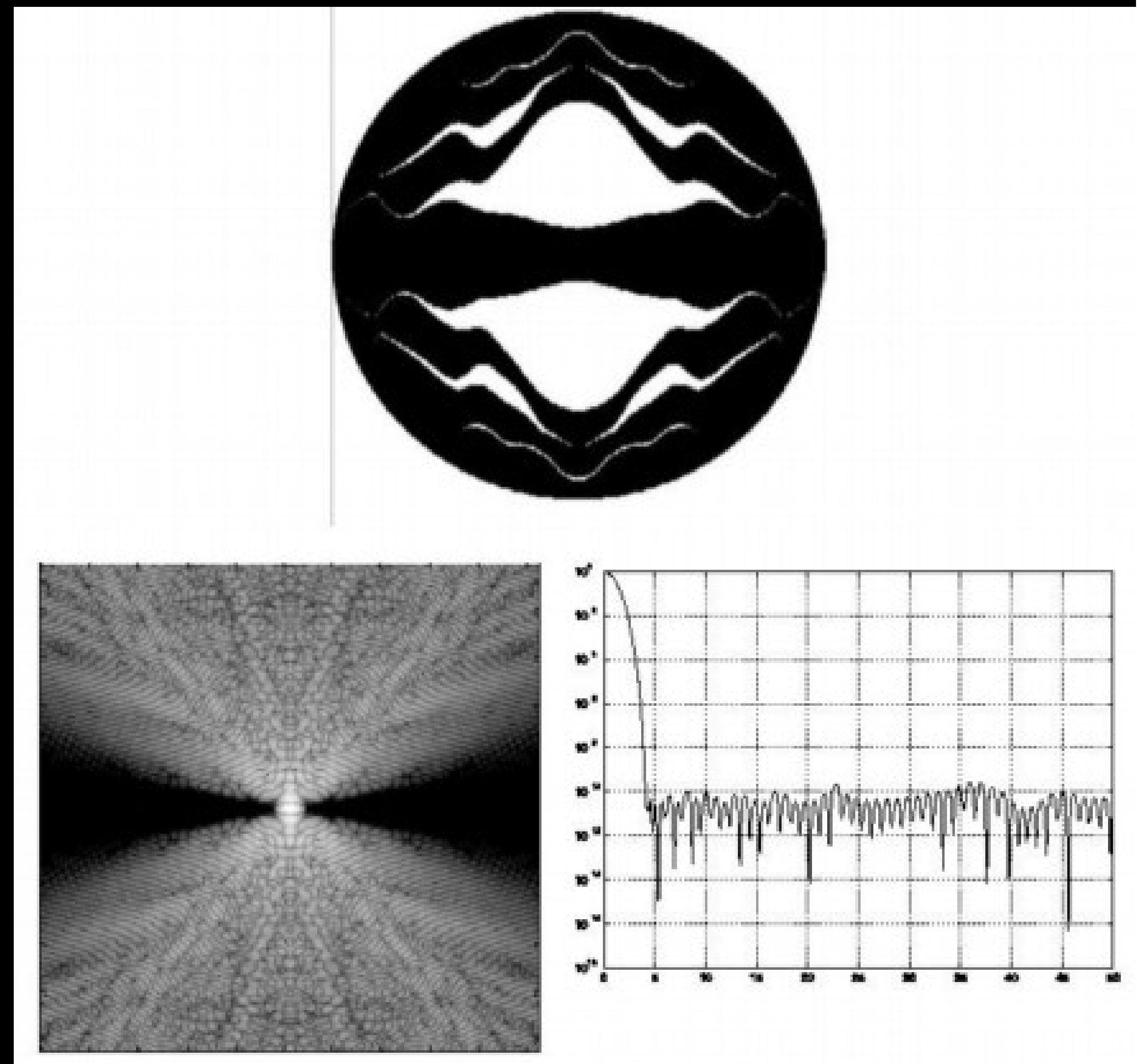
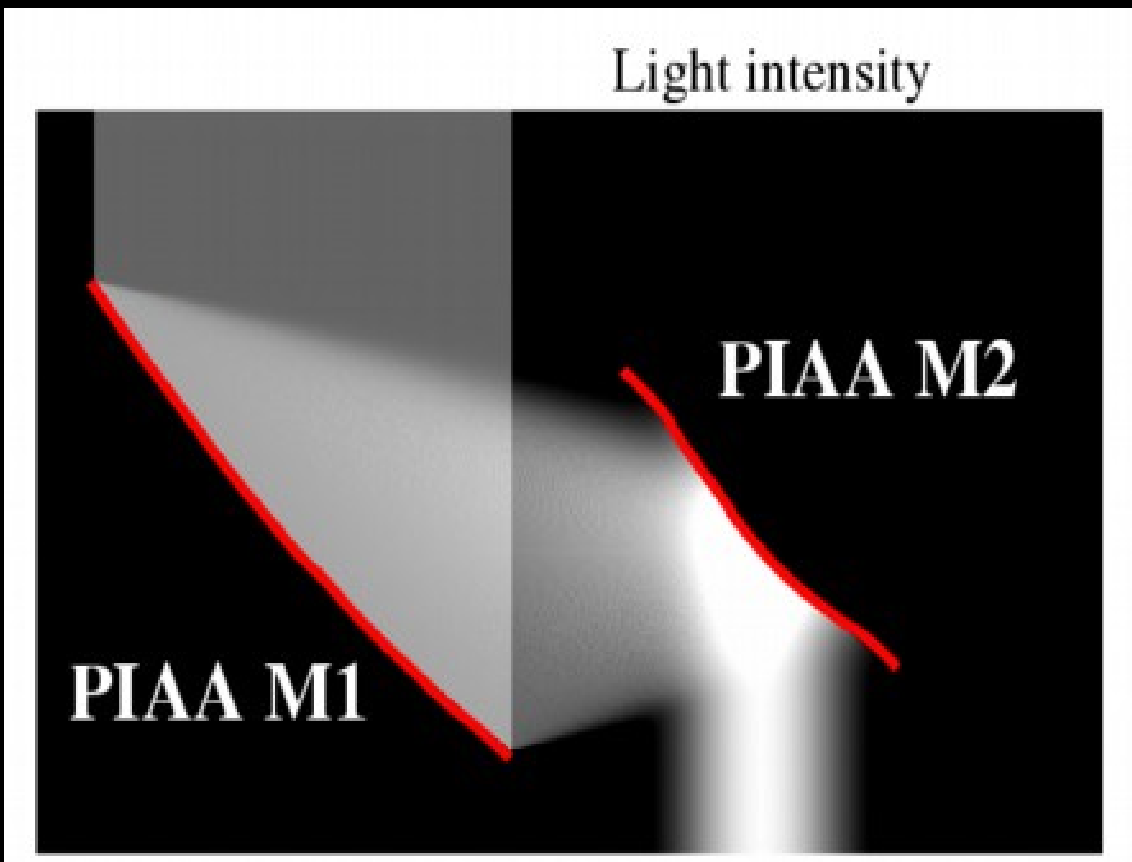


FIG. 9.—*Top*: Asymmetric multiopening mask designed to provide high-contrast, 10^{-10}, from $\lambda/D = 4$ to $\lambda/D = 100$ in two angular sectors centered on the x-axis. Ten integrations are required to cover all angles. Total throughput and pseudoarea are 24.4%. Airy throughput is 11.85%. *Bottom*: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

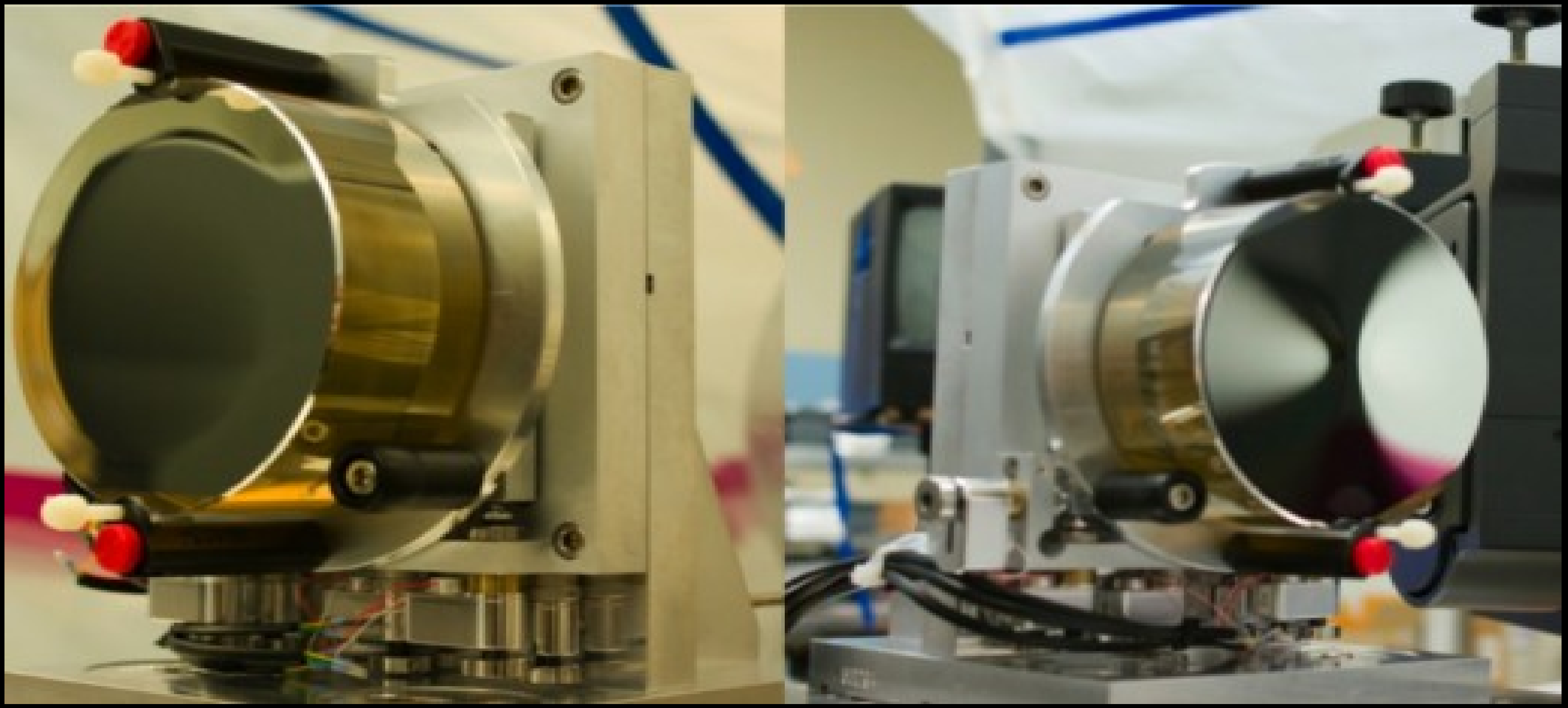


No loss in angular resolution or sensitivity
Achromatic (with mirrors)
Small inner working angle

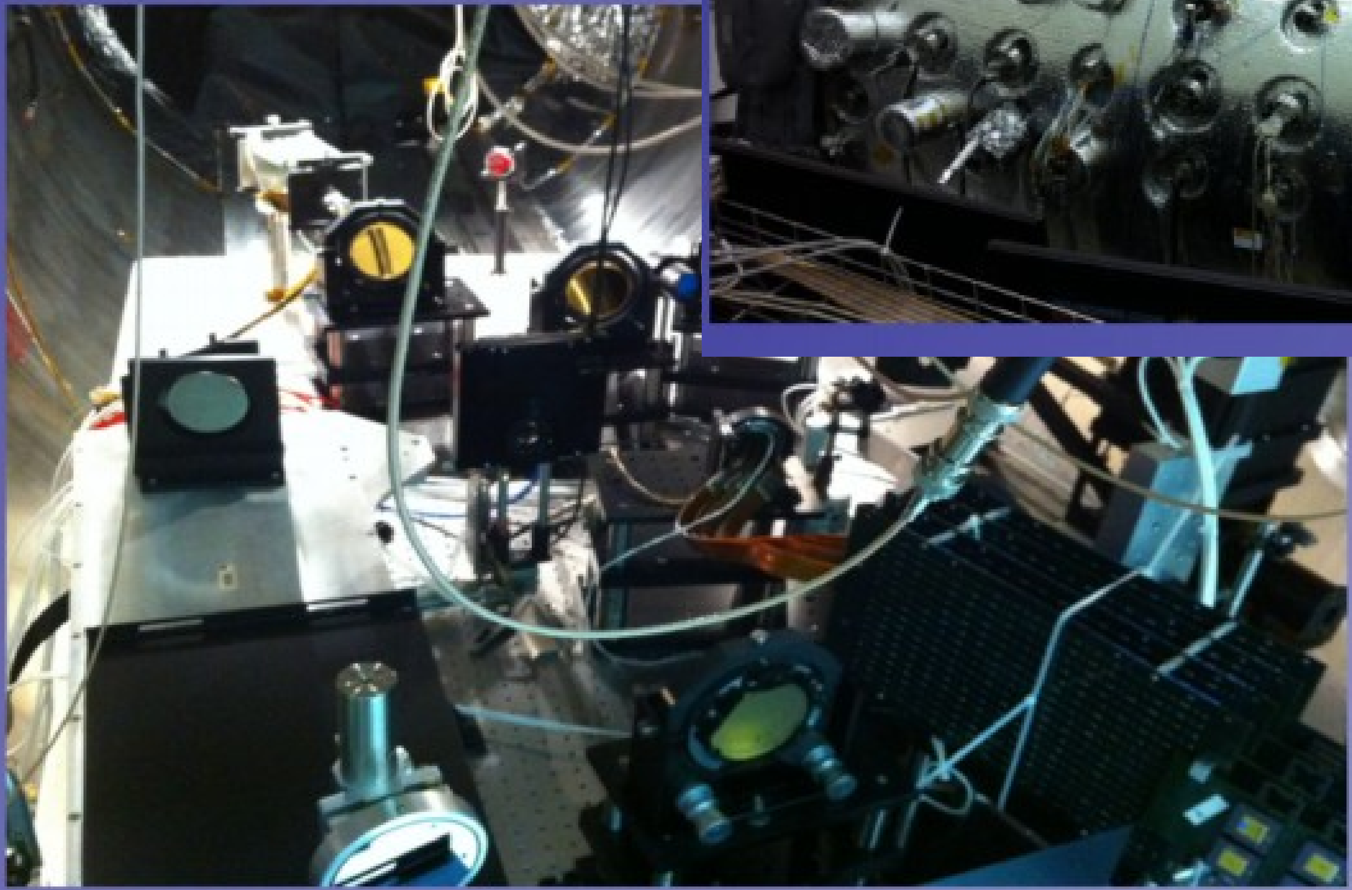
→ Gain ~x2 to x3 in telescope diameter over previous concepts

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

PIAA optics

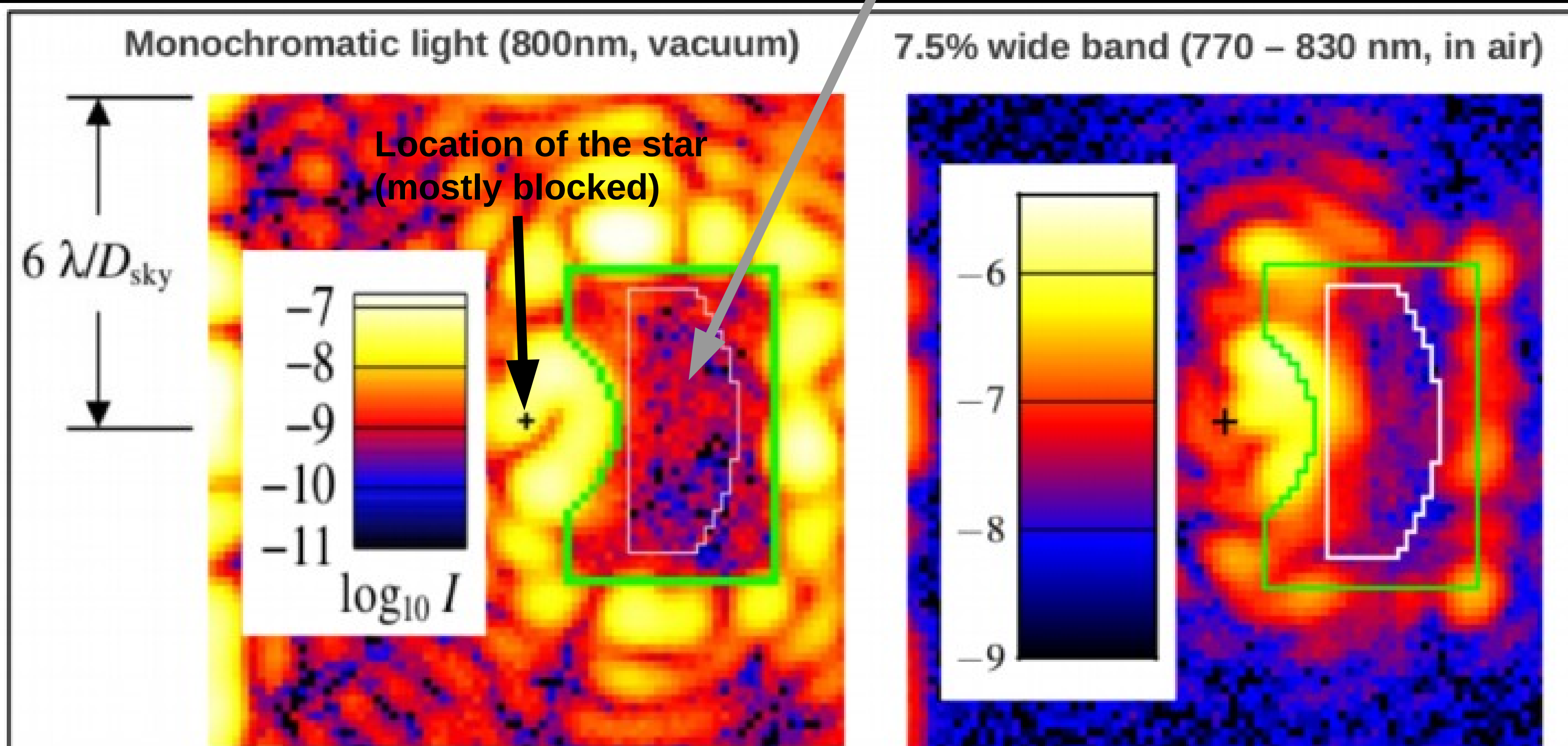


PIAA testbed at JPL



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

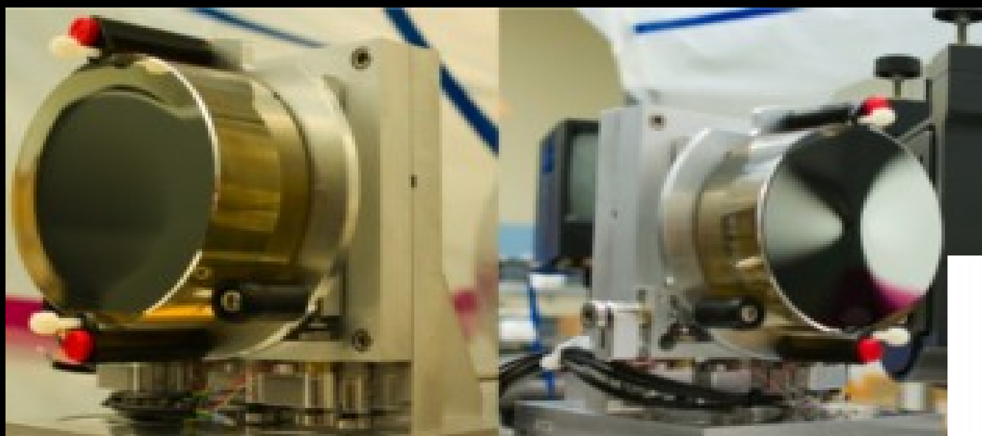
An Earth-like planets could be seen !

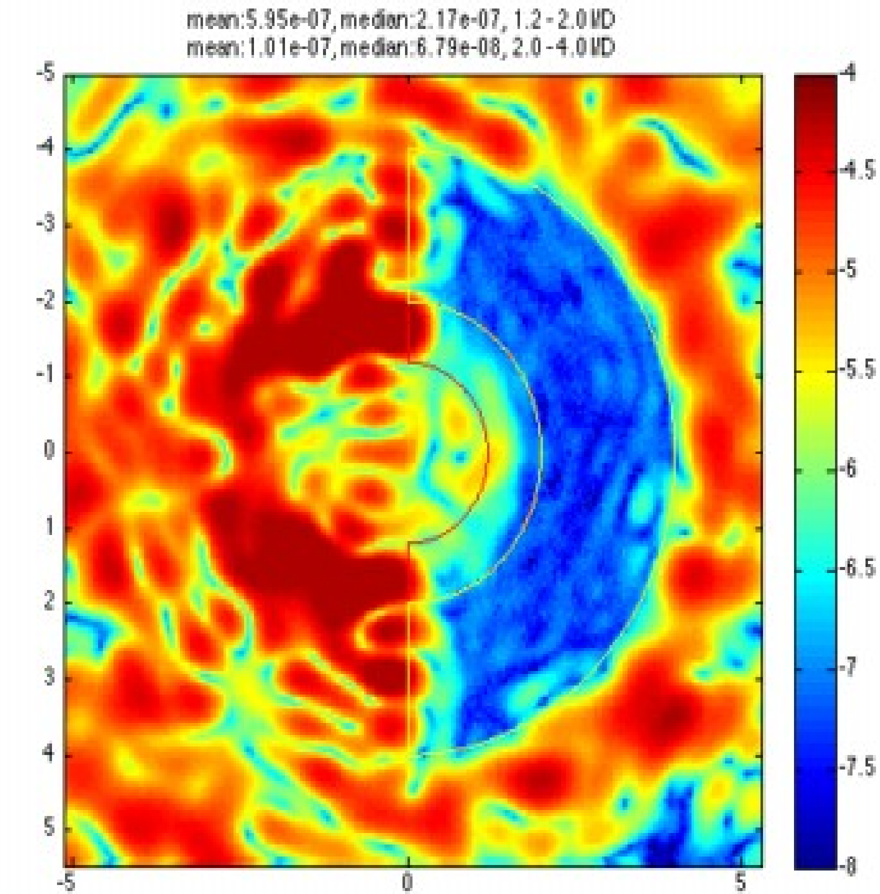


3 runs, contrast values averaged from 2 to 4 λ/D between 5.10^{-10} to 9.10^{-10} (figure shows $7.3.10^{-10}$ result)

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)

PIAA testbed at NASA Ames





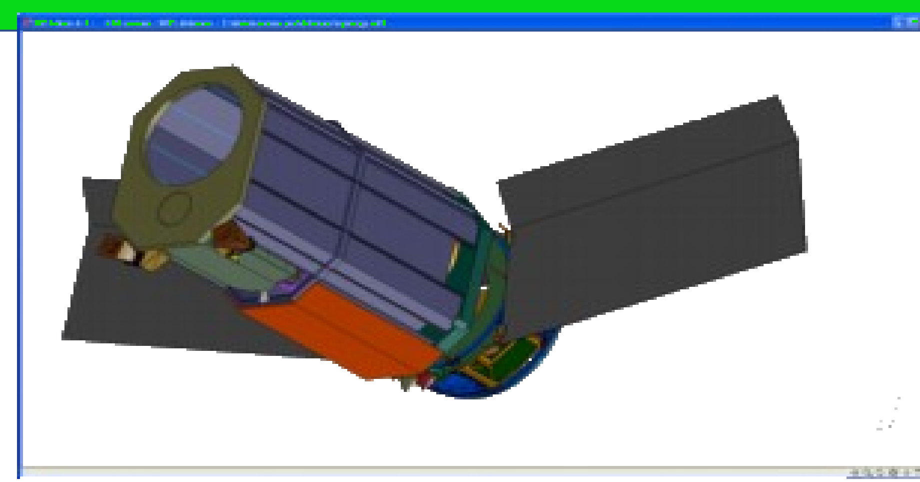
Mission Overview

EXCEDE

EXOPLANETARY CIRCUMSTELLAR ENVIRONMENTS and DISK EXPLORER

Dr. Glenn Schneider (PI)
Dr. Olivier Guyon (IS)
Steward Observatory, The University of Arizona
NASA Ames, Lockheed Martin

Studying the formation, evolution, and architectures of exoplanetary systems, and characterizing circumstellar environments in habitable zones.



- 0.7 meter off-axis visible-light telescope

- Active Starlight Suppression System:
  - PIAA Coronagraph (~1 l/D IWA)
  - 2000-Element MEMS Deformable Mirror
  - Low-Order Wavefront Sensor

- Two-band Imaging Polarimeter

- Three-year mission (2000-km LEO Sun-synchronous orbit)
  - Appx. 350 targets hosting Protoplanetary, Transitional, & Debris Disks, and high-priority EGPs

- Newly NASA-funded 2-year Tech. Dev program
  - Partnership contributions from UofA, Lockheed-Martin, NASA/AMES

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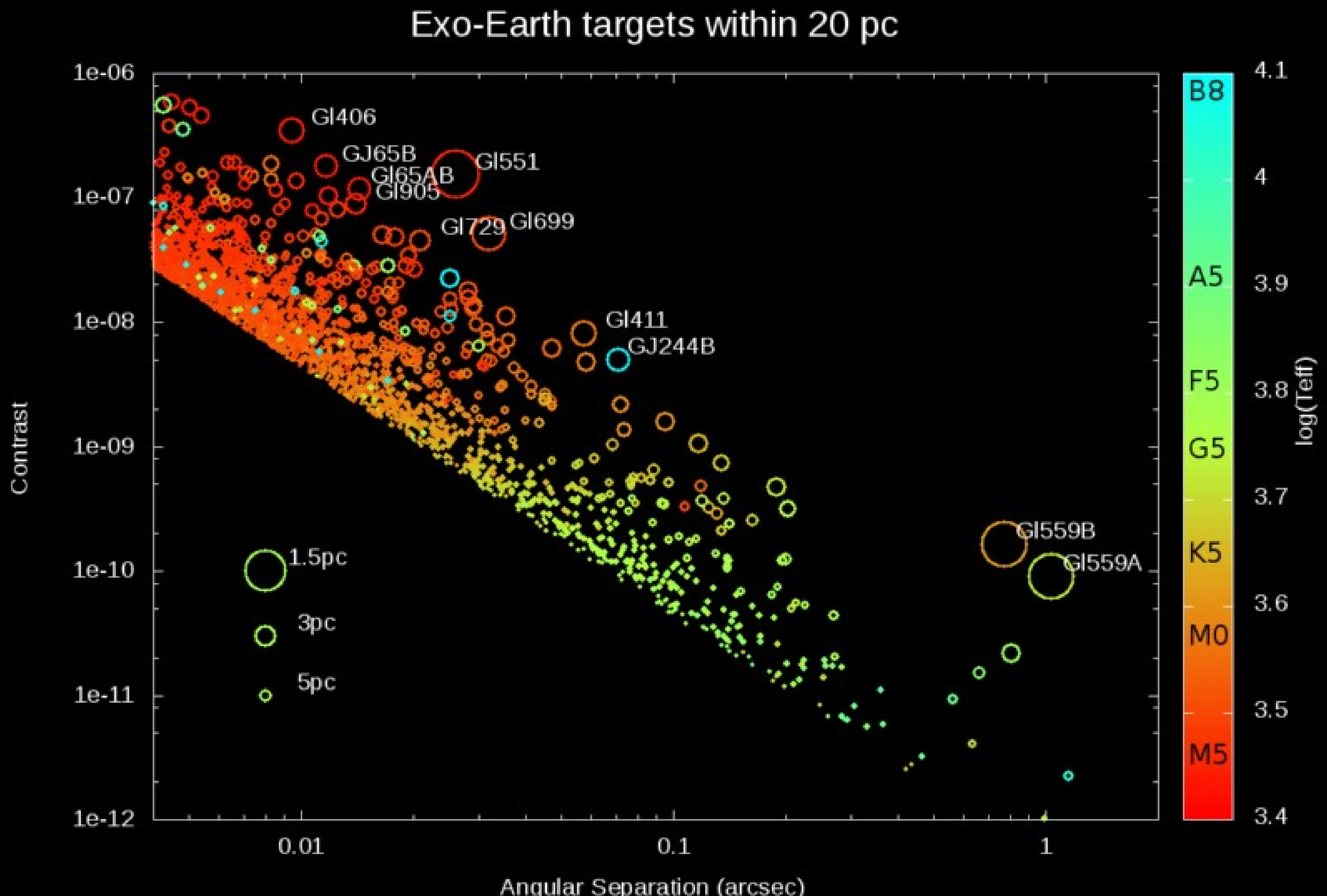
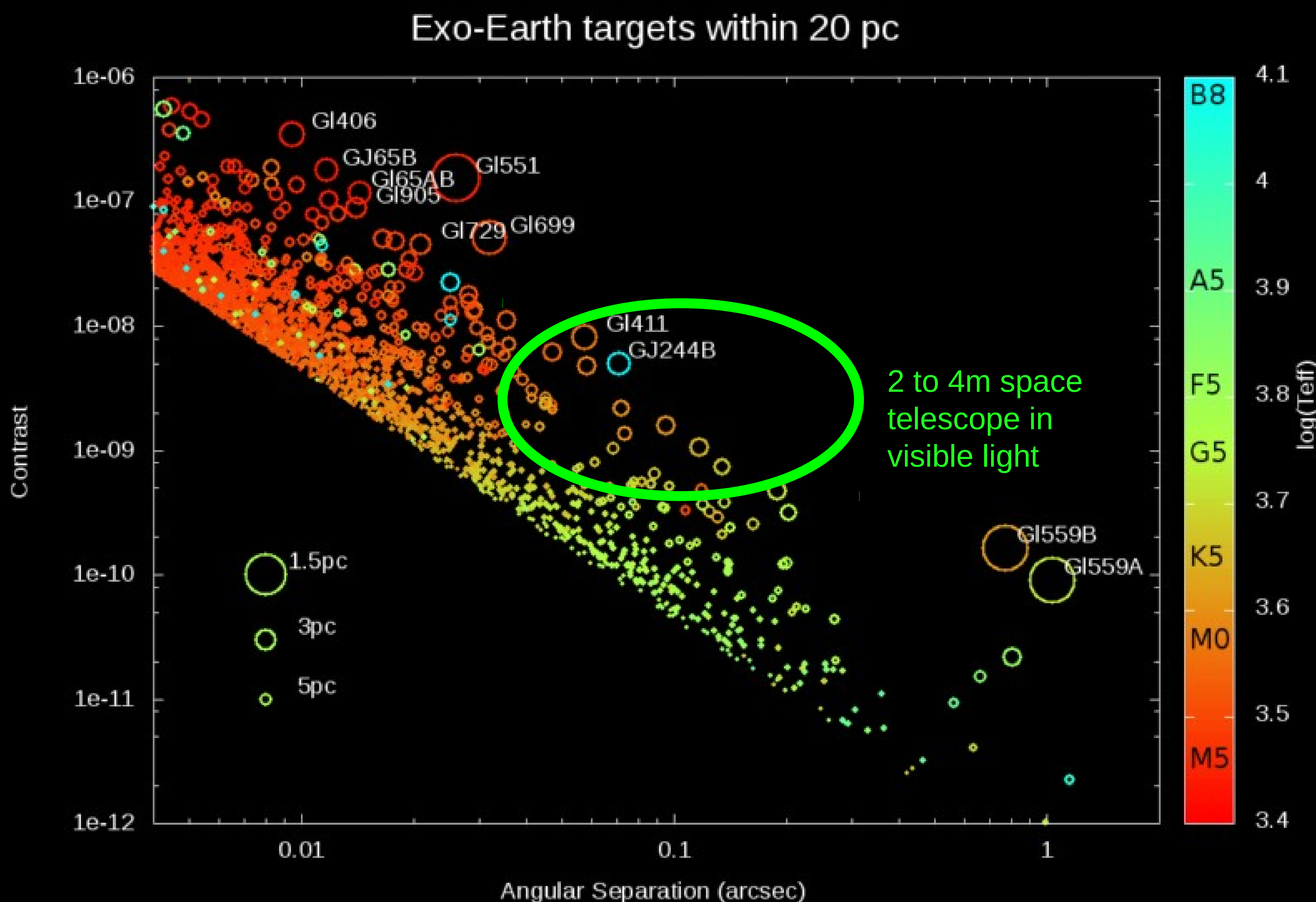
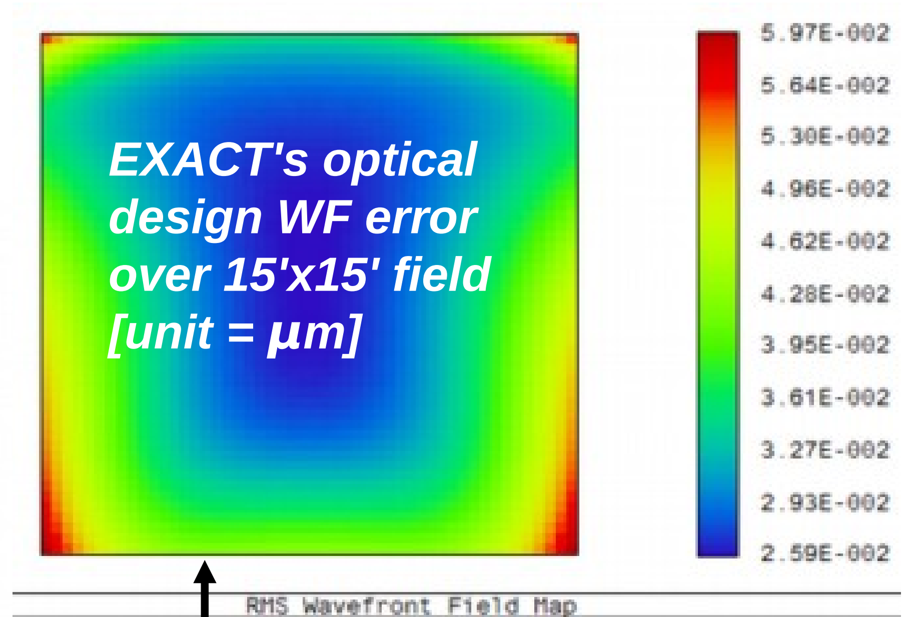


Exo-Earth targets within 20 pc
Contrast
Angular Separation (arcsec)
log(Teff)
1e-06
1e-07
1e-08
1e-09
1e-10
1e-11
1e-12
0.01
0.1
1
B8
A5
F5
G5
K5
M0
M5
4.1
4
3.9
3.8
3.7
3.6
3.5
3.4
Gl406
GJ65B
Gl65AB
Gl905
Gl551
Gl729
Gl699
Gl411
GJ244B
Gl559B
Gl559A
1.5pc
3pc
5pc

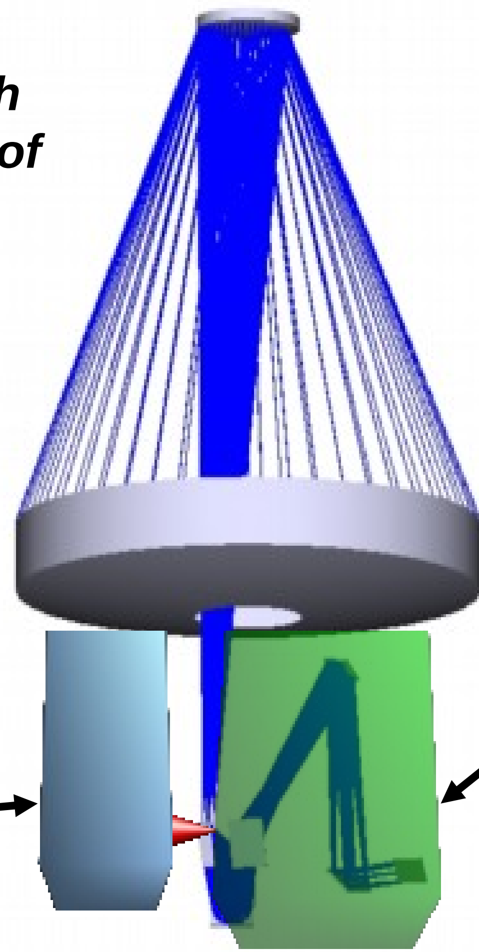


Exo-Earth targets within 20 pc
Gl406
GJ65B
Gl65AB
Gl905
Gl551
Gl729
Gl699
Gl411
GJ244B
Gl559B
Gl559A
1.5pc
3pc
5pc
2 to 4m space telescope in visible light
Contrast
Angular Separation (arcsec)
1e-06
1e-07
1e-08
1e-09
1e-10
1e-11
1e-12
0.01
0.1
1
B8
A5
F5
G5
K5
M0
M5
4.1
4
3.9
3.8
3.7
3.6
3.5
3.4
log(Teff)

Exoplanetary Astrometric Coronagraphic Telescope (EXACT) concept:
2.4-m Telescope, Two instruments
Custom coating on PM



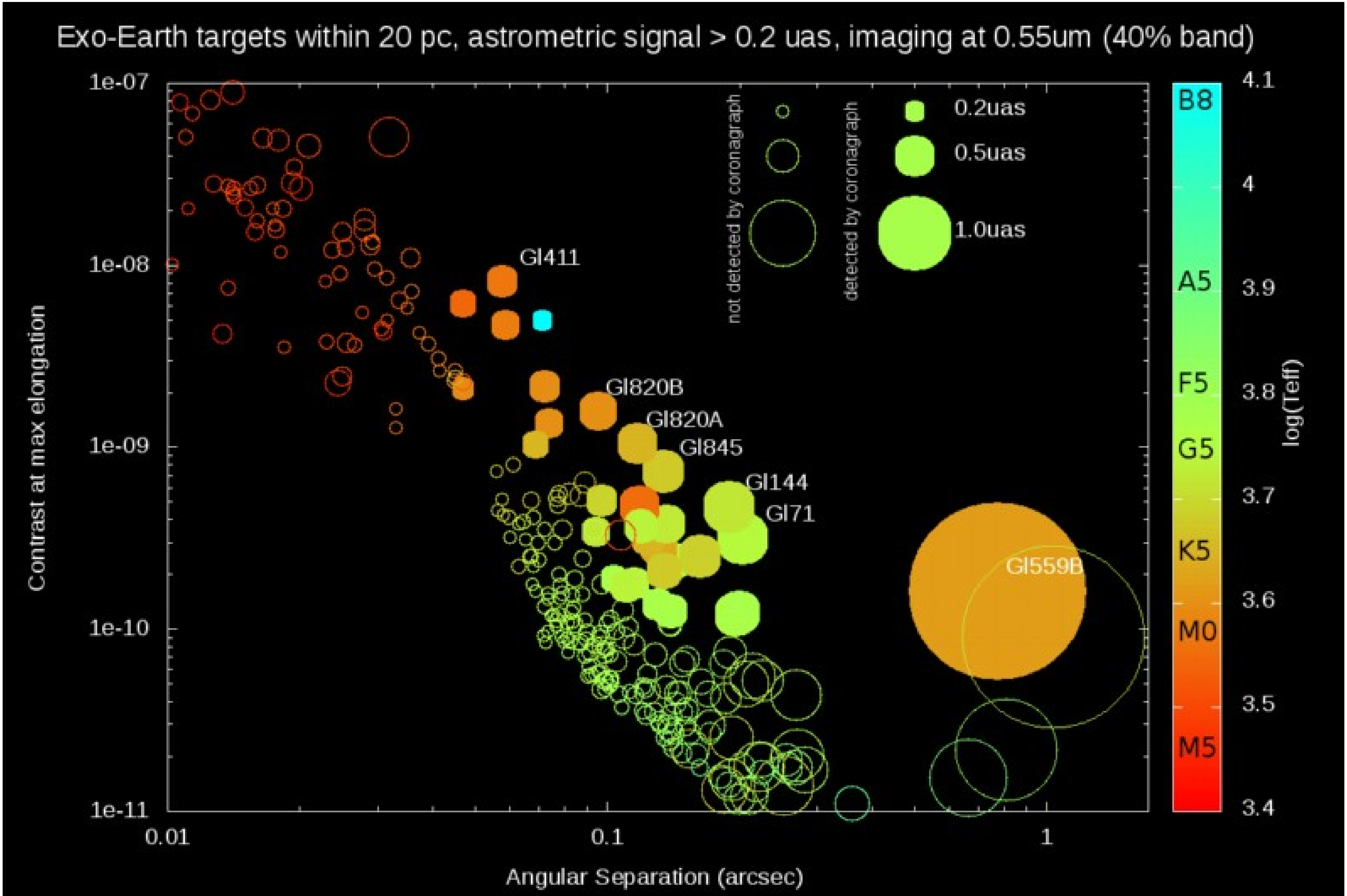
Primary mirror coated with micro-dots covering ~1% of surface area, used for astrometric calibration



EXACT's high contrast imaging camera extracts a narrow field of view in the center of the astrometric camera's intermediate focus

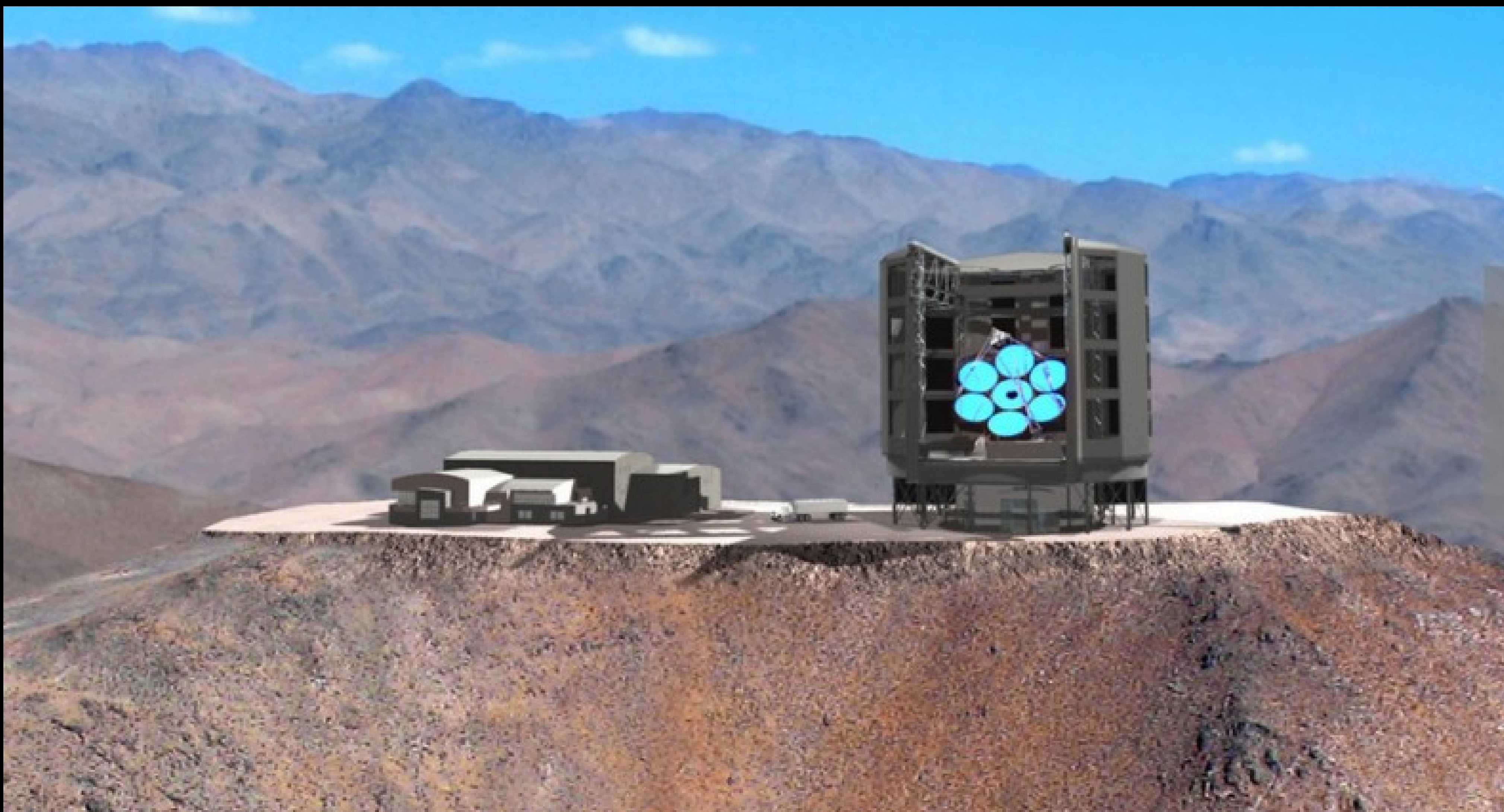
EXACT's astrometric wide field camera design offers <60 nm WF error over a 15'x15' field

EXACT can identify and characterize Earth-mass habitable planets around ~20 stars

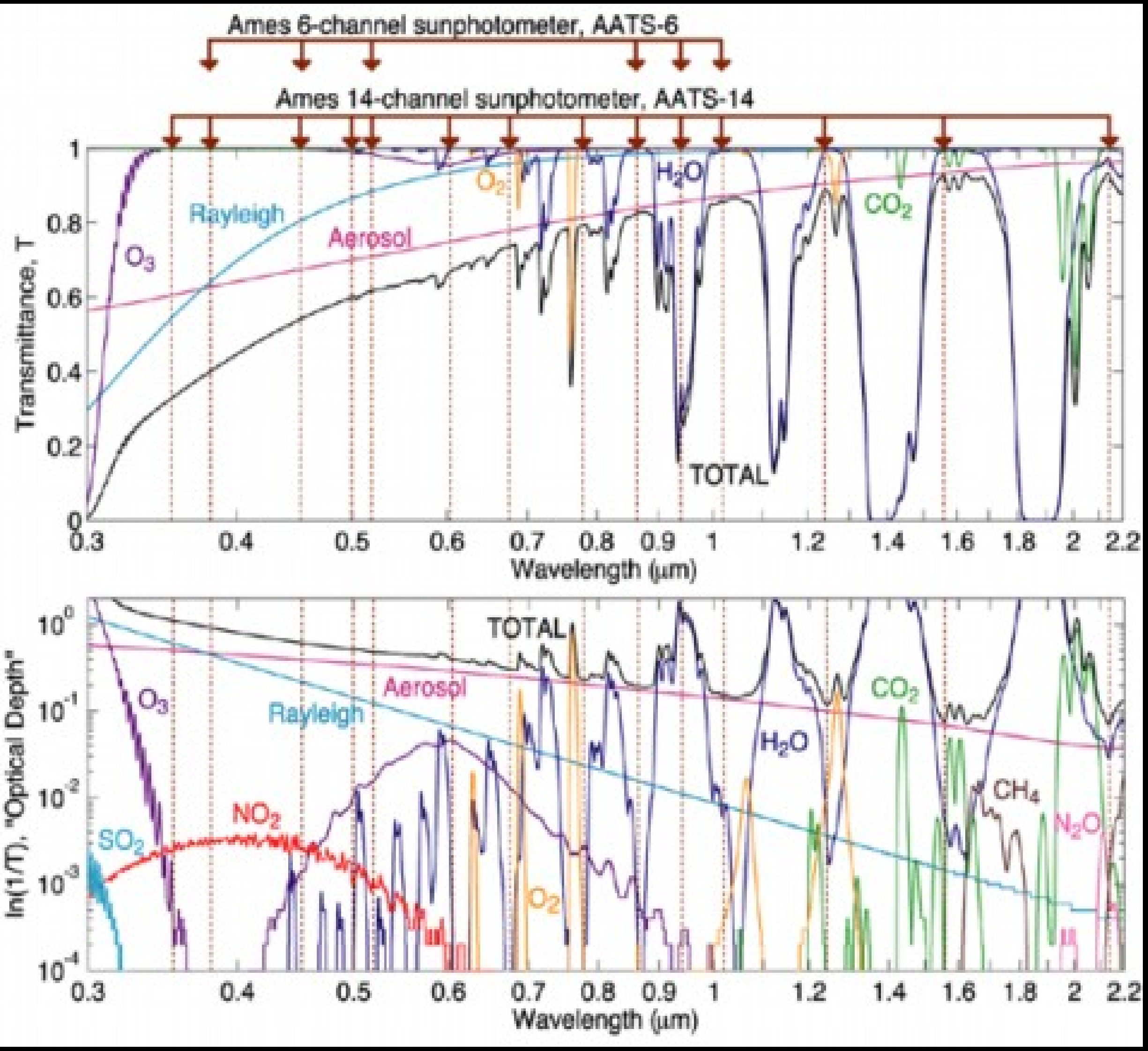


Extremely Large Telescopes (ELTs)

3 projects, 25 to 40m diameter



Habitable Planets Spectroscopy in near-IR



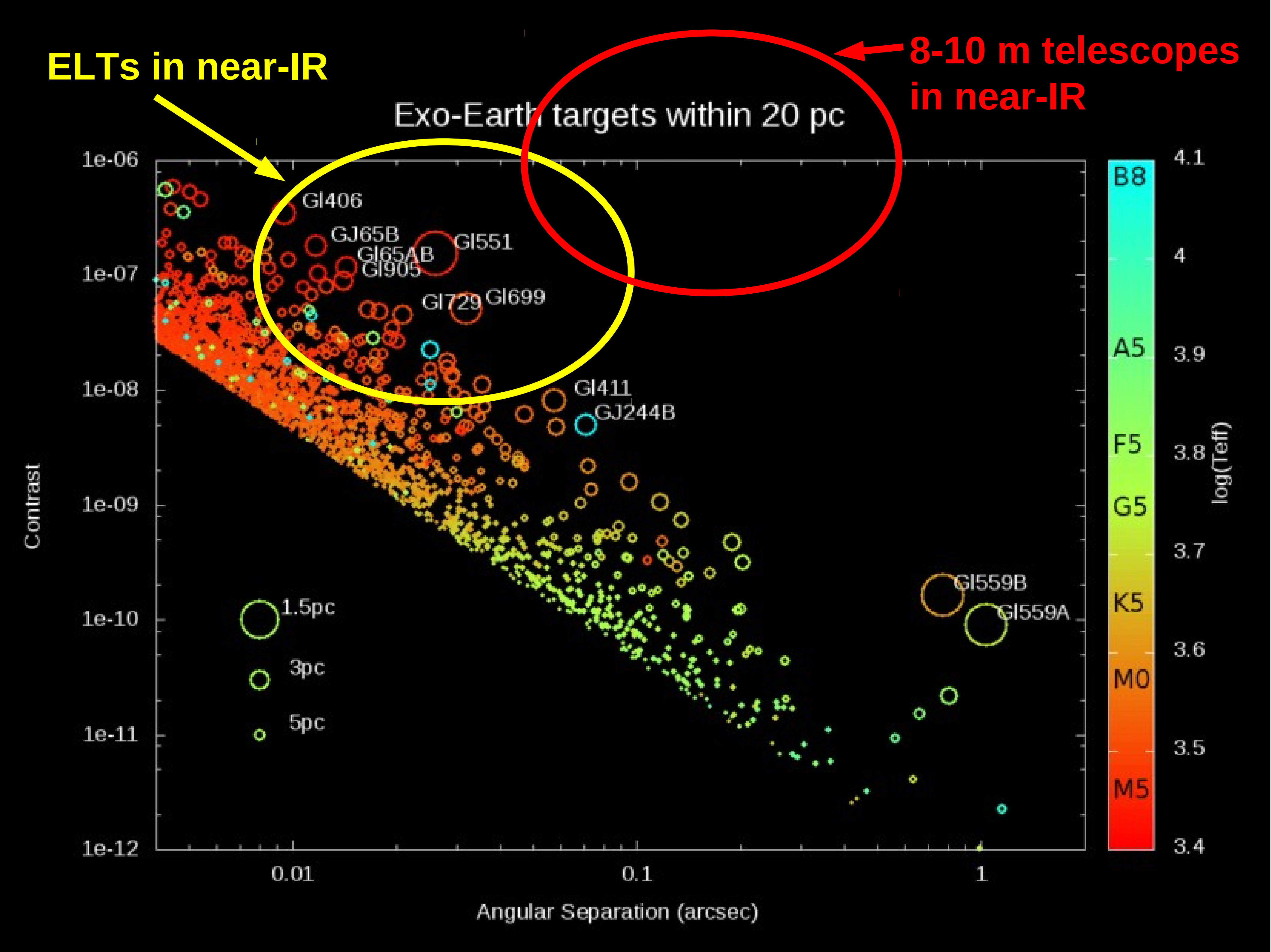
Credit: NASA/Ames Airborne Tracking Sunphotometer (AATS)

Atmosphere transmission:
O_2 (see Kawara et al. 2012)
H_2O
CO_2
CH_4

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
Gl406
GJ65B
Gl551
Gl65AB
Gl905
Gl729
Gl699
Gl411
GJ244B
Gl559B
Gl559A
1.5pc
3pc
5pc
Contrast
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4.1
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3.9
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3.7
3.6
3.5
3.4
log(Teff)

Reflected light planets

First cut limits meant to exclude clearly impossible targets
→ used to identify potential targets → instrument requirements

FIRST CUT LIMITS

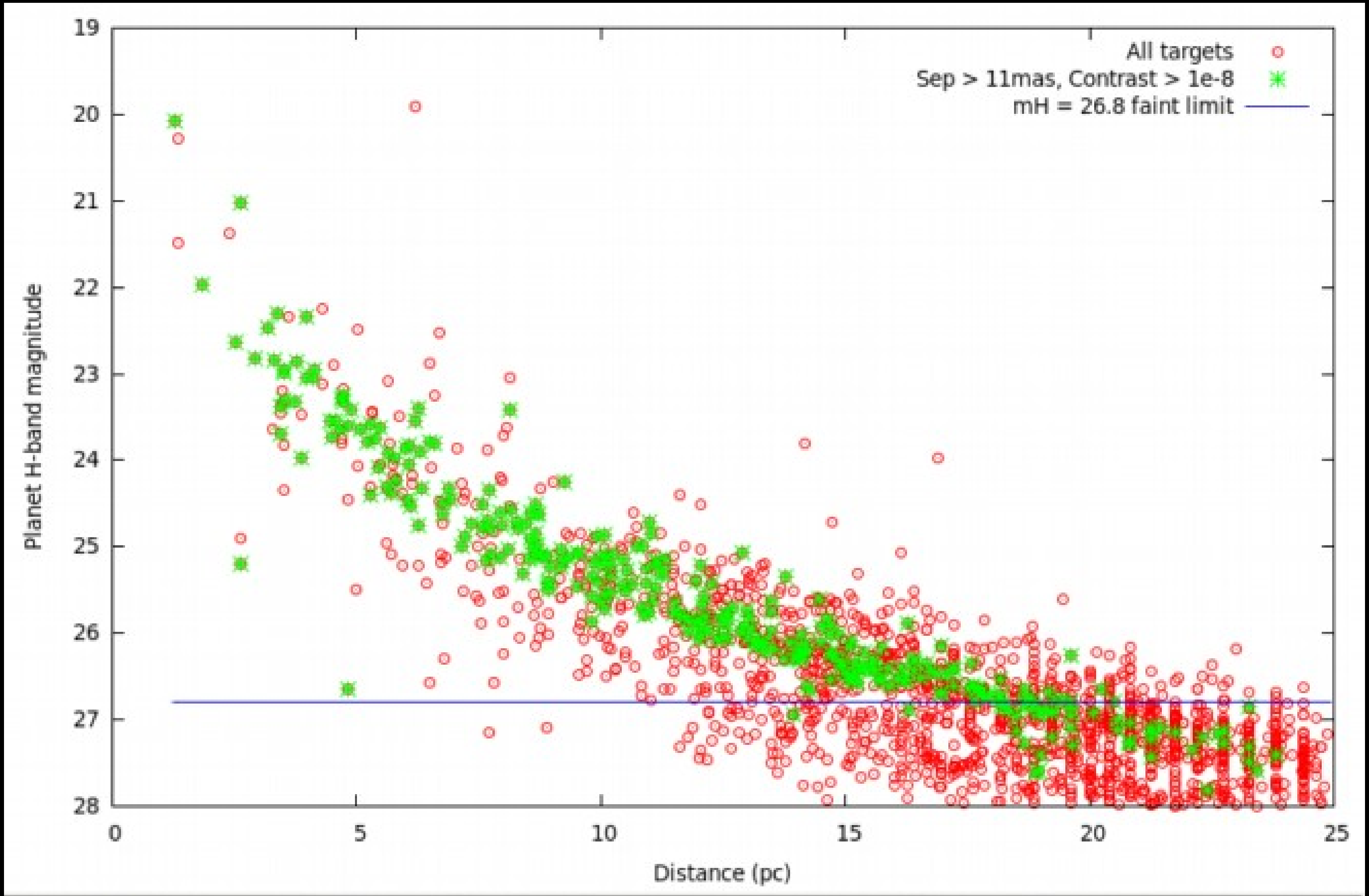
	Limit/constraints	**Comments**
Angular Separation	Must be > 1.0 λ/D	Limit imposed by coronagraph (see section 4). Corresponds to 11mas on a 30-m telescope in H band.
Contrast	Must be > 1e-8	High contrast imaging limit (see section 5)
Star brightness	Must be brighter than $m_R = 15$	Required for high efficiency wavefront correction (see section 5)
Planet Brightness	Must be brighter than $m_H = 26.8$	Faint detection limit

background-limited SNR > 10 in H band image in 1 hr on 30-m telescope (assuming 15% efficiency)

Reflected light planets

Assuming 2x Earth diameter planets, 274 targets survive the first cut

Strong correlation between planet apparent brightness and system distance

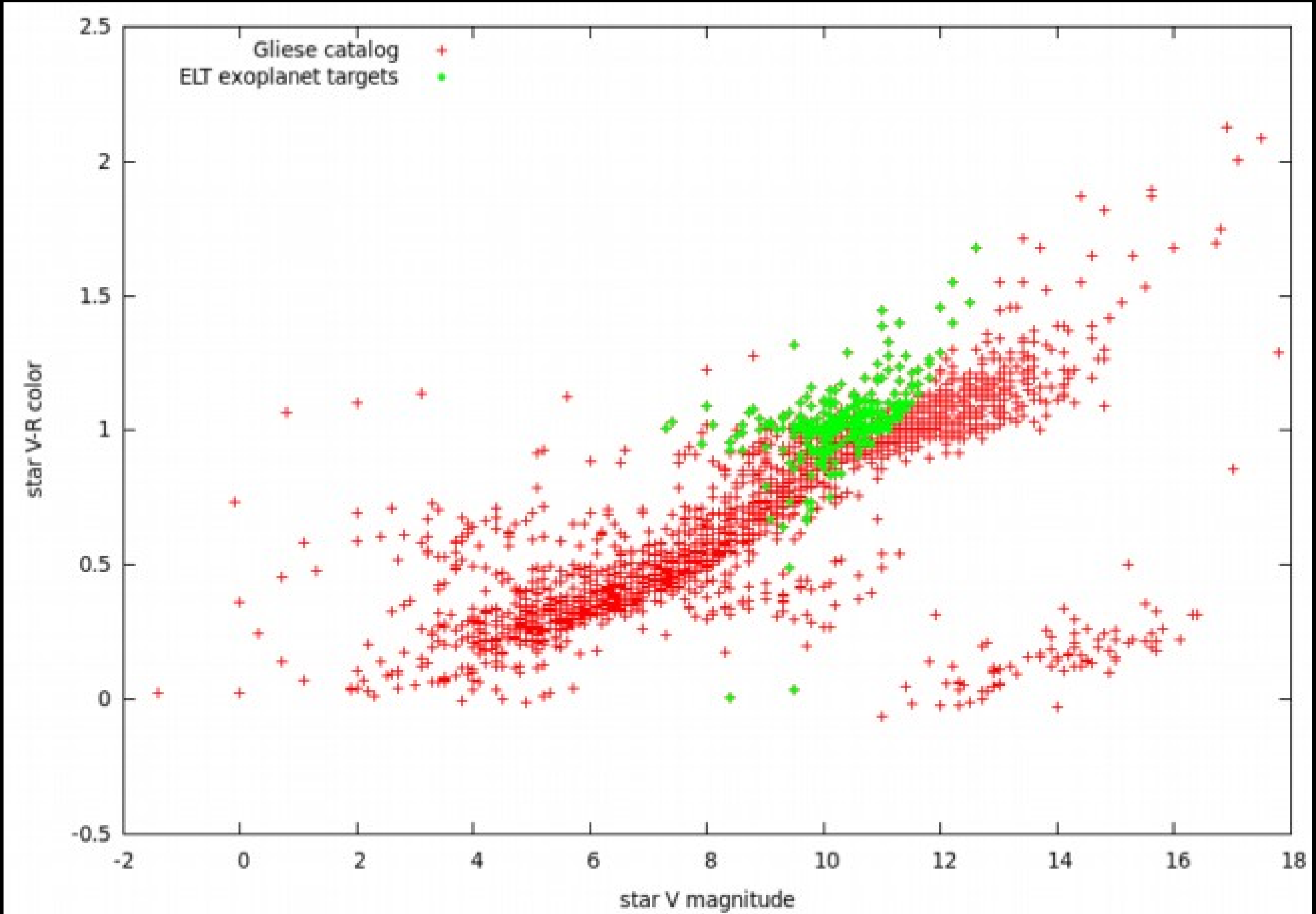


Reflected light planets

Most targets are red stars (M type), around V ~ 10, R ~ 9

2 white dwarfs : 40 Eri B and Sirius B

Early type stars → contrast too challenging



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	-

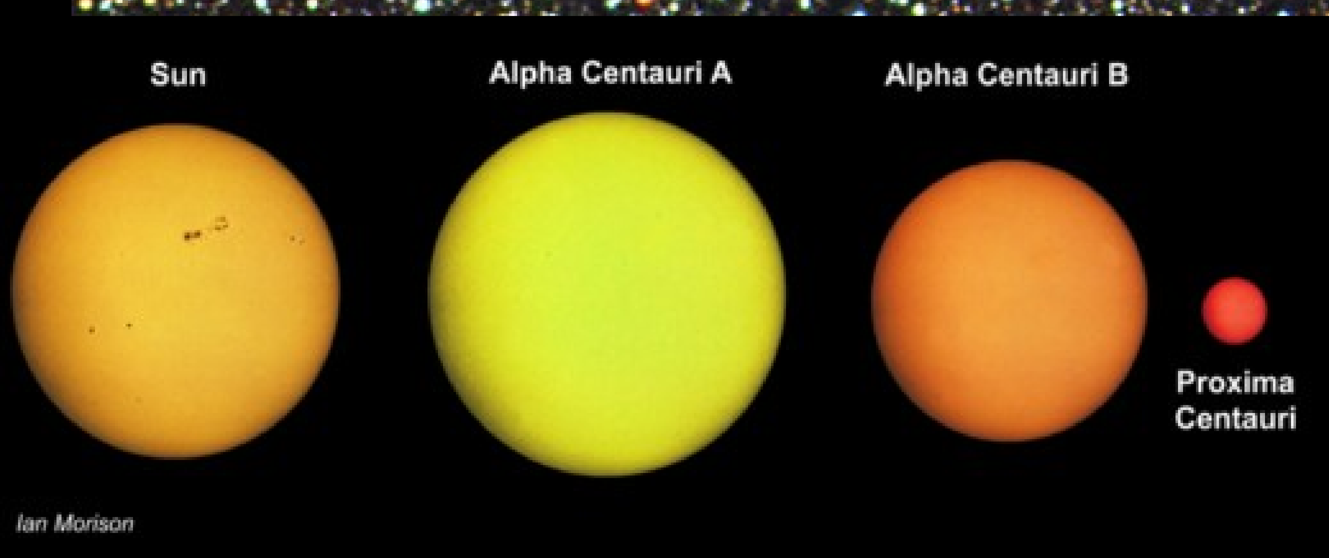
[1] Angular diameter (uniform disk, non limb-darkened value) measured by optical interferometry with VLTI Demory et al. 2009

[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



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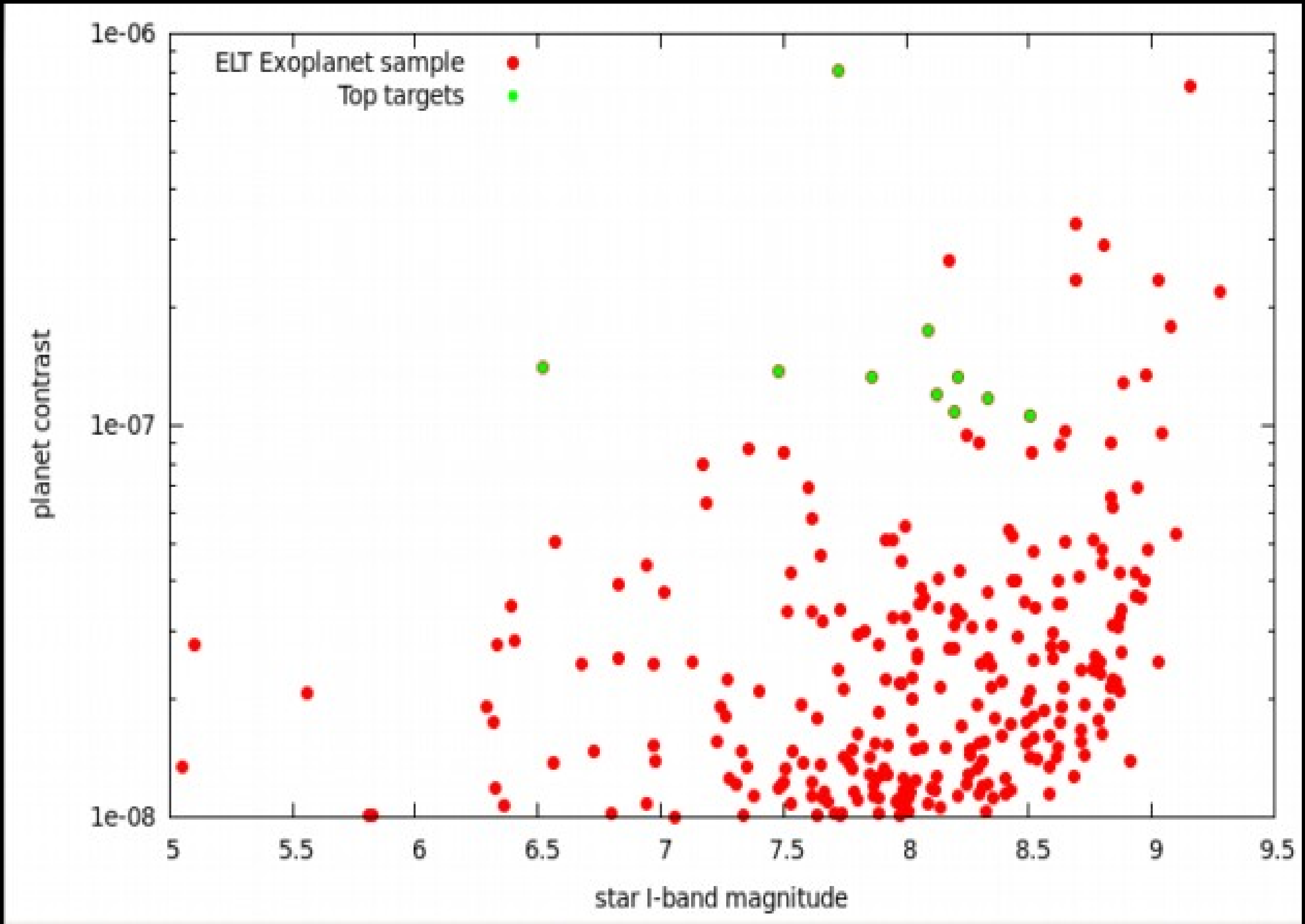


RAW contrast required

Photon-noise limited SNR limit in H band

Earth like planet around M type star at 5pc

Assumptions:

- D = 30m telescope, m_H=14.4 arcsec^{-2} background, 20mas aperture
- 15% efficiency (coatings, detector), 0.3 um bandpass (H band), 1 hr exposure
- planet mH = 25.2 (Earth at 5pc)

background = 230 ph/sec

Planet = 27.5 ph/sec

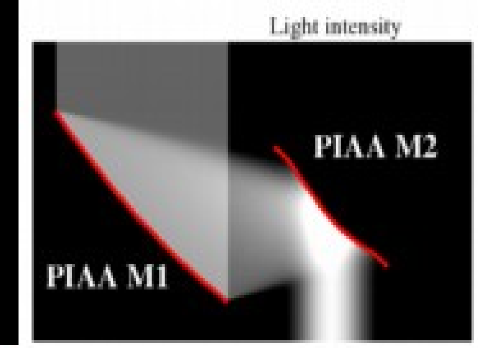
Star = 9.98e8 ph/sec (mH=6.3, M4 stellar type)

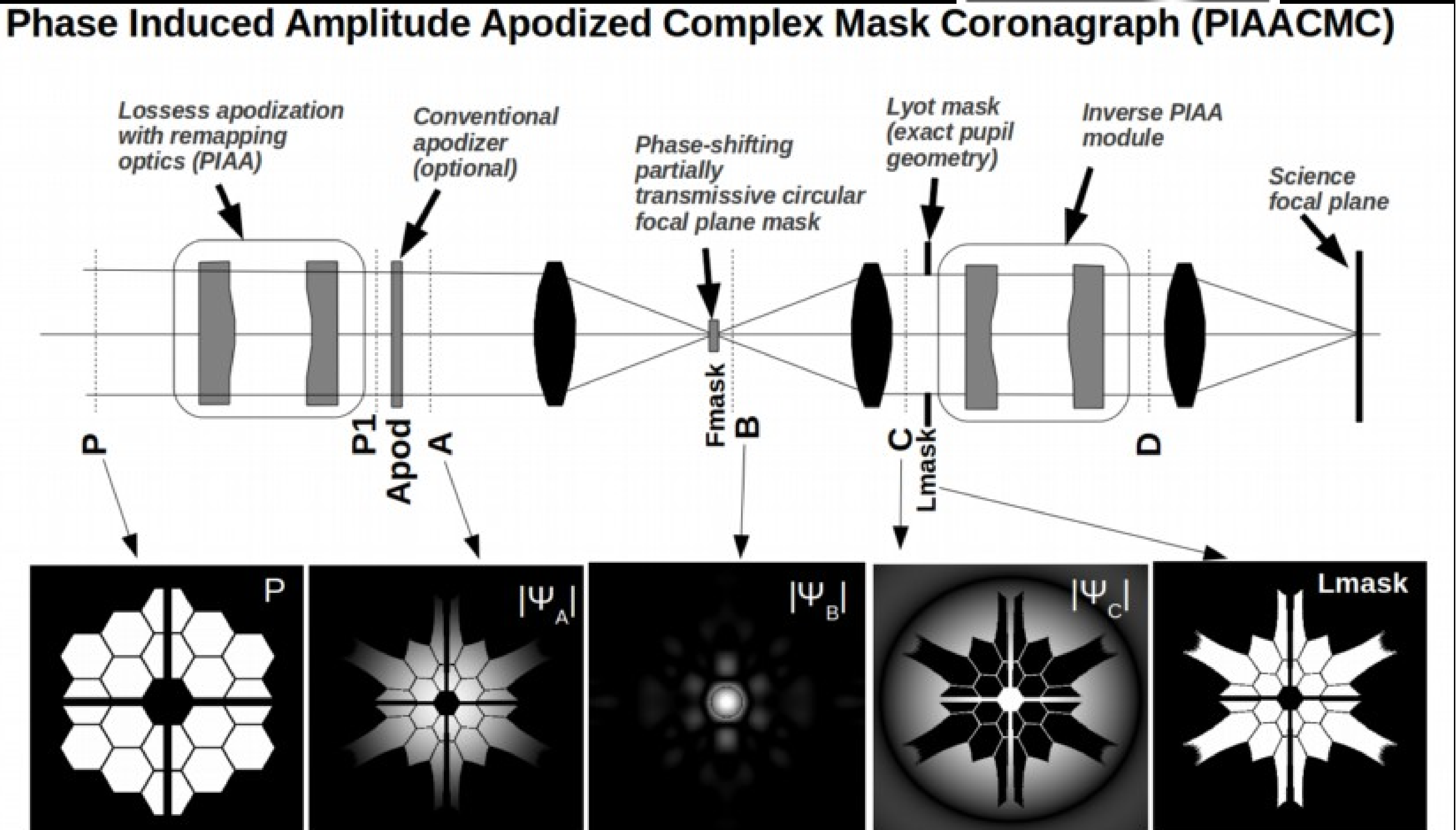
Star / Planet contrast = 3.6e7

SuperEarth at 5pc around M star (4x Earth flux, 2x diameter)

	Detection SNR H band (R~5)	Spectroscopy SNR R = 100
Imaging, no starlight	**102 [356]**	**23.5 [83]**
Imaging, 1e5 raw contrast	**16.31 [65]**	**3.8 [15]**
Imaging, 1e4 raw contrast	**5.16 [20.6]**	**1.2 [4.8]**
No nulling/coronagraphy, 100% efficiency	**0.05 [0.2]**	**hopeless...**

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





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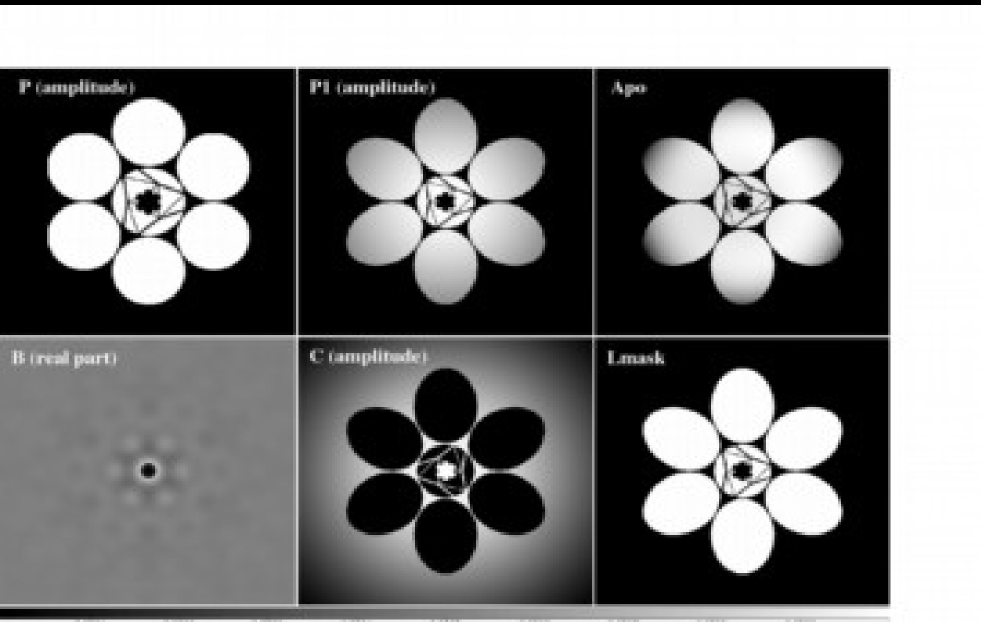
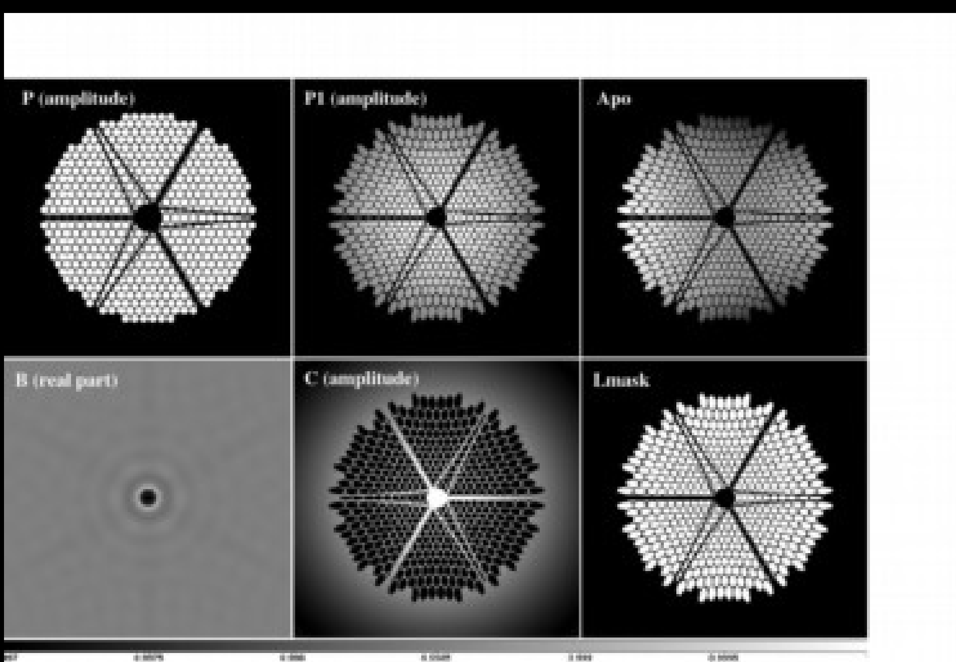
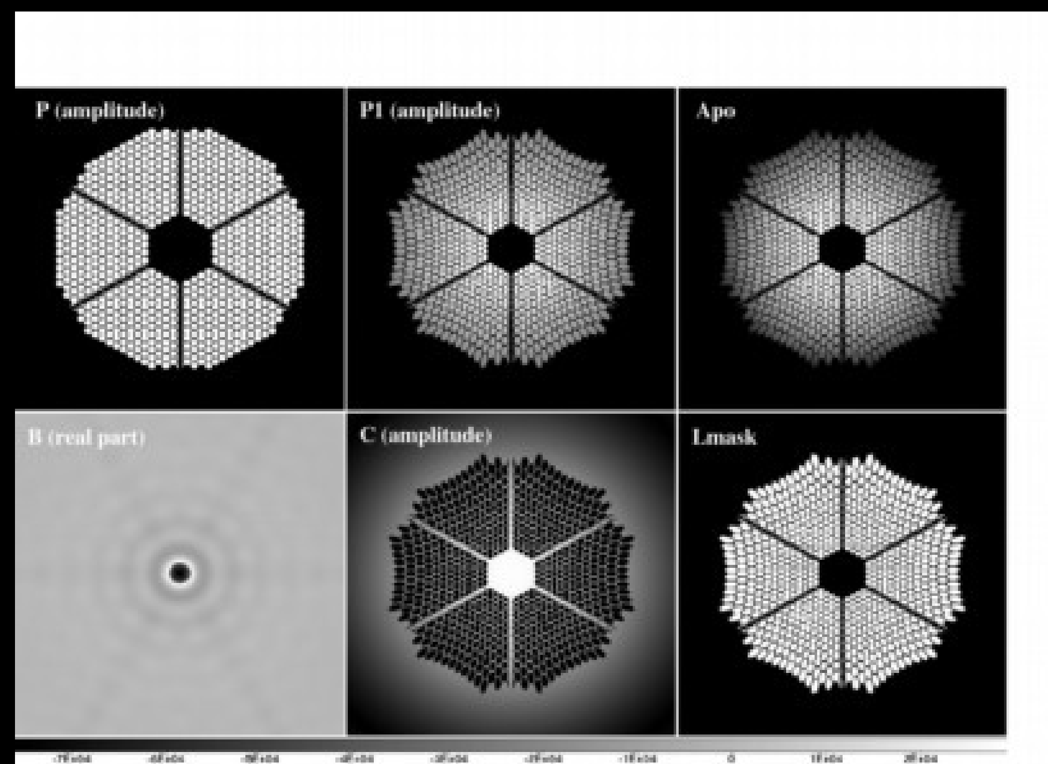


<u>Pupil shape does not matter !!!</u>





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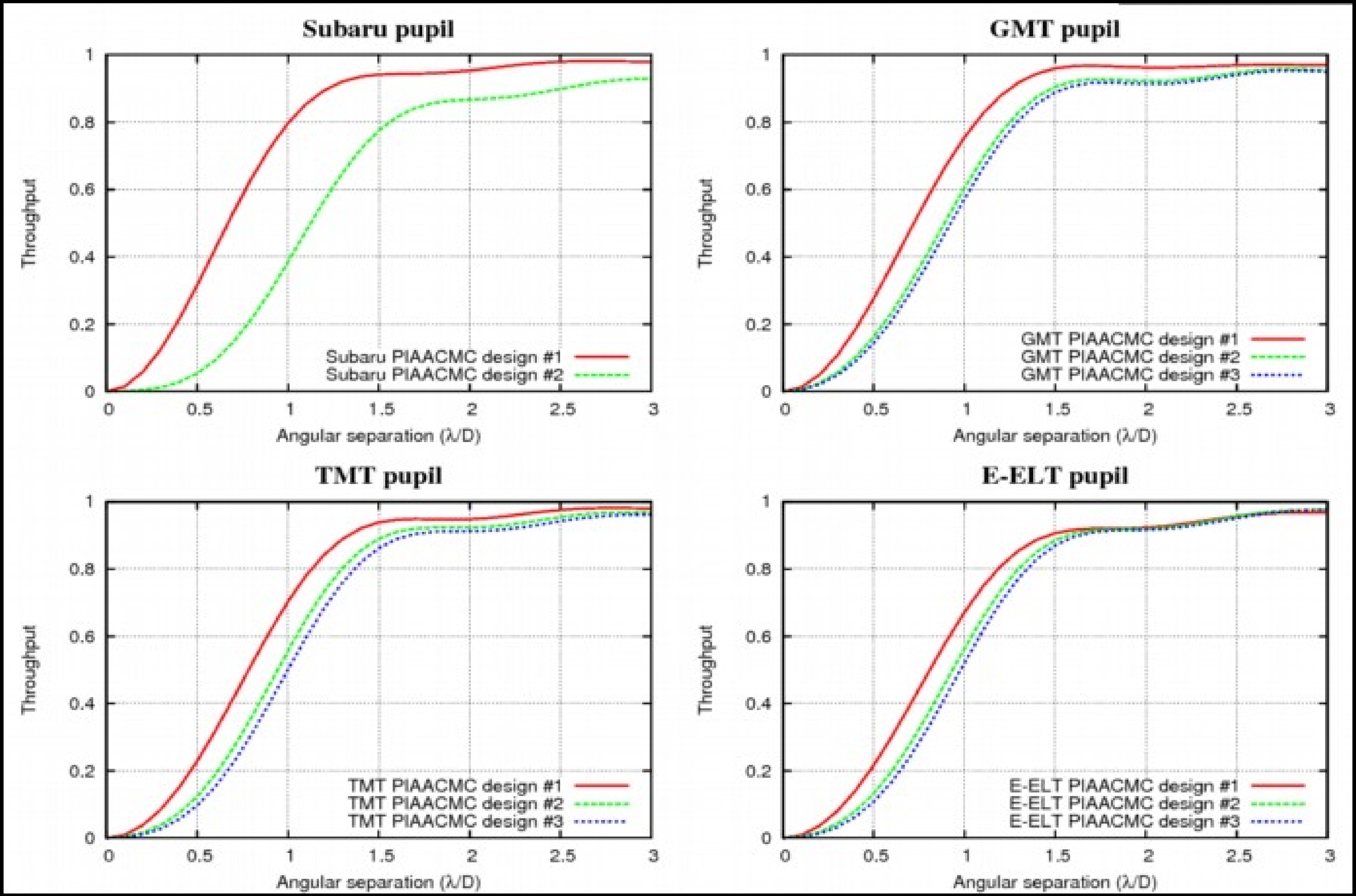
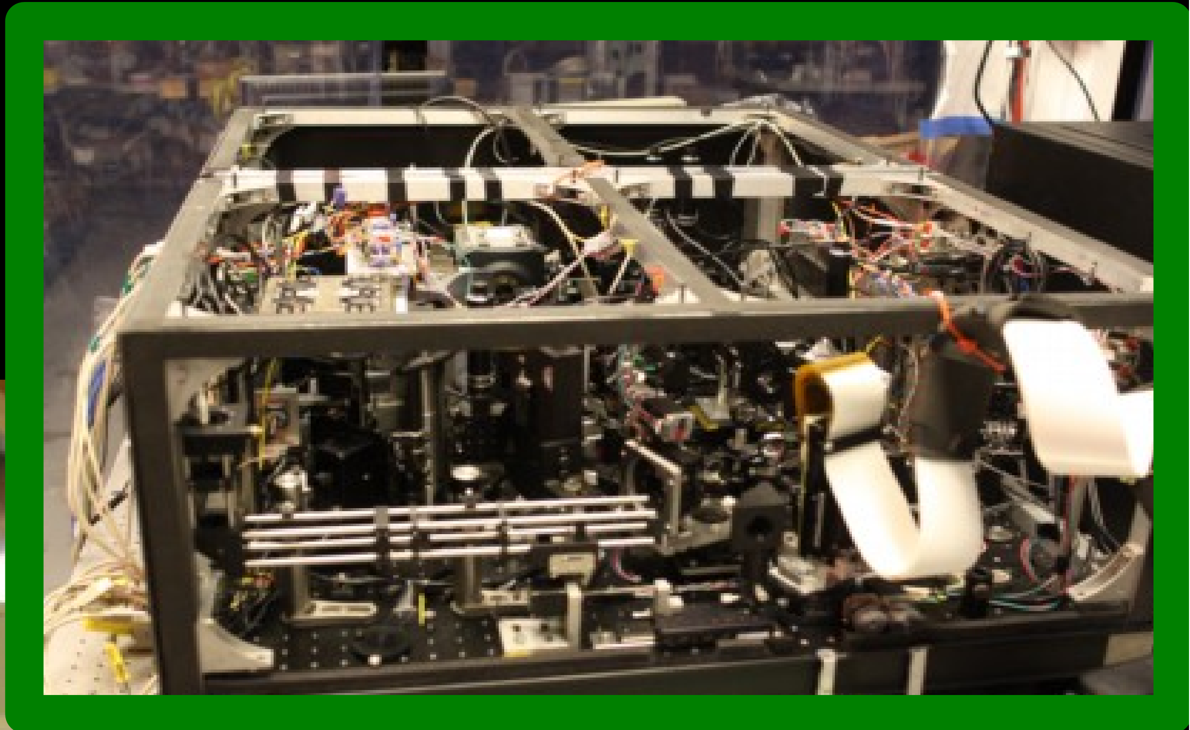
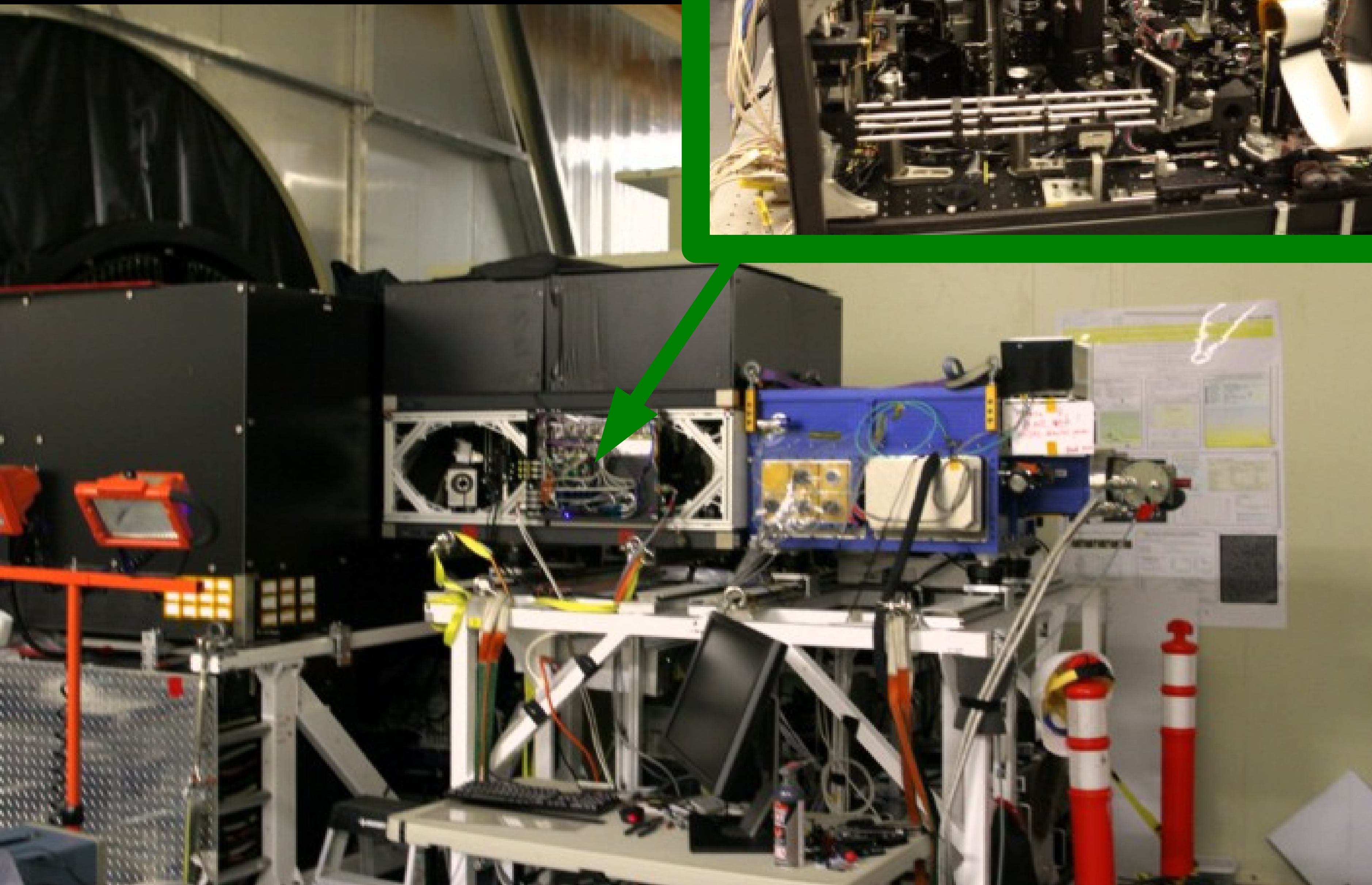
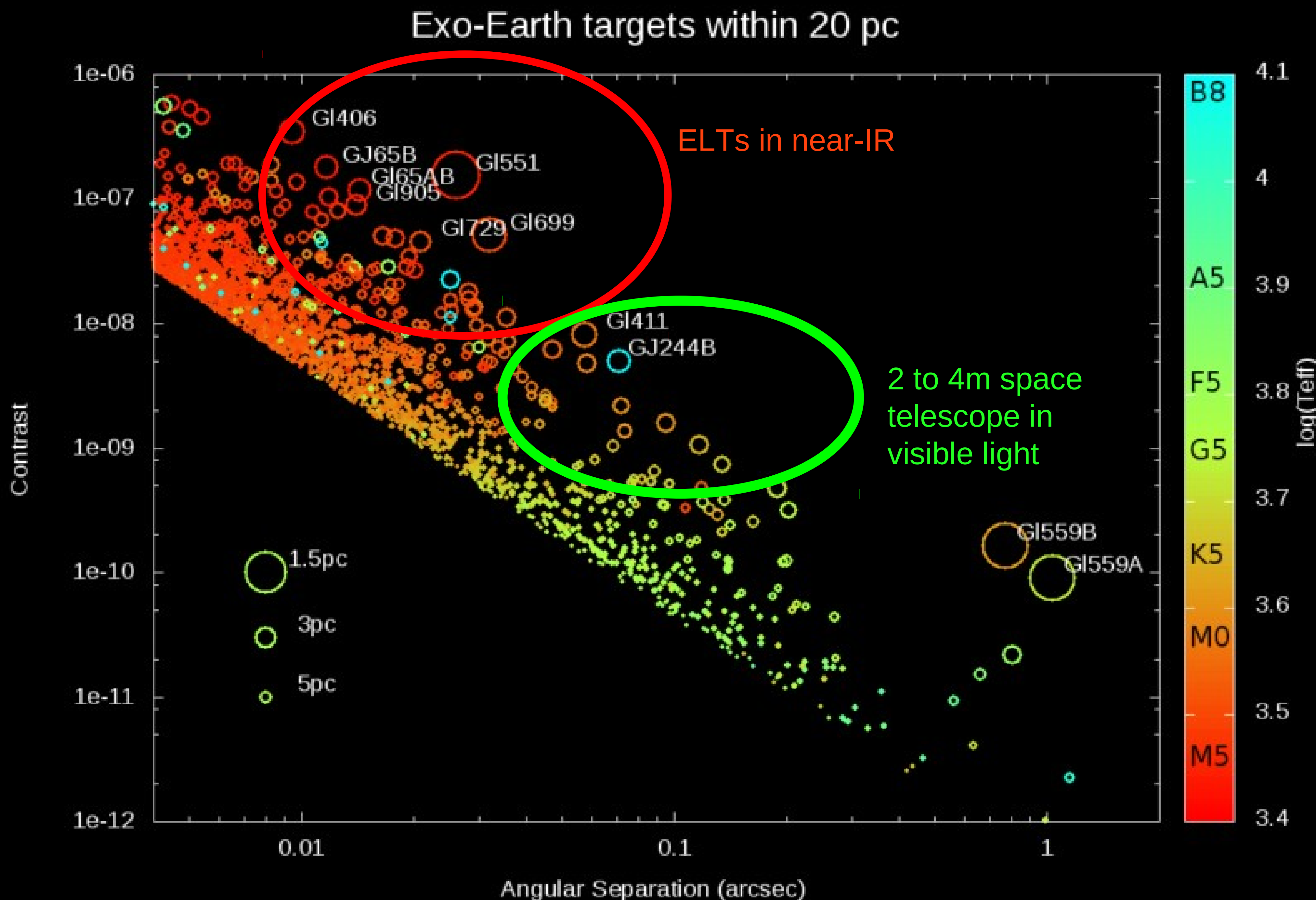


The Subaru Coronagraphic Extreme Adaptive Optics (SCExAO) system





Detecting planets from space and ground



Outline

Introduction

Why direct imaging ? Why is it difficult ?

Technology

High performance PIAA coronagraphy, recent lab results, coronagraphy + WFC

Scientific Opportunities

SPACE: Direct imaging of Earth-like planets around Sun-like stars

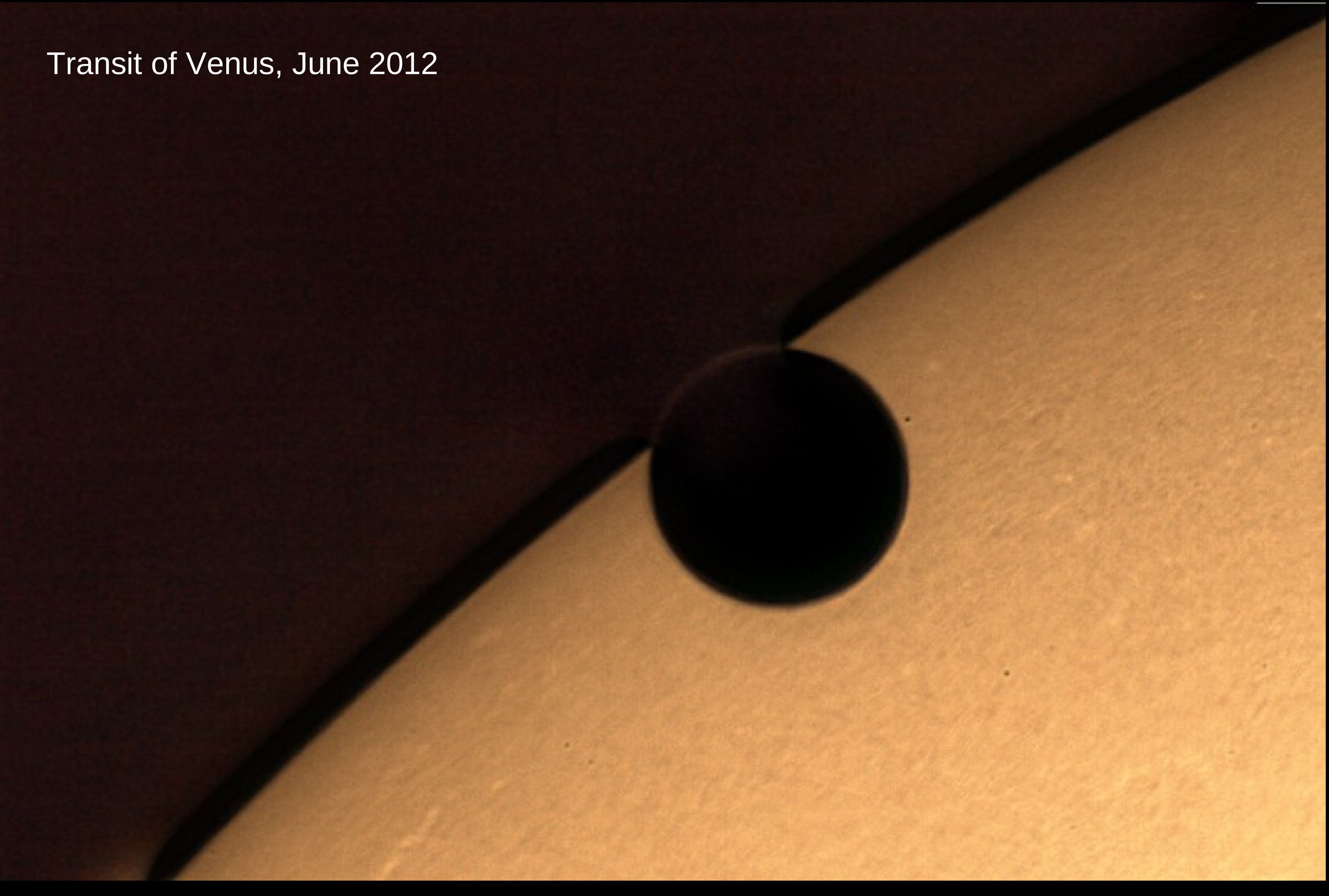
GROUND: Imaging habitable planets around M-type stars with ELTs; SCExAO as a precursor

project PANOPTES

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

Exoplanet transit: An easier way to detect a planet

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



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

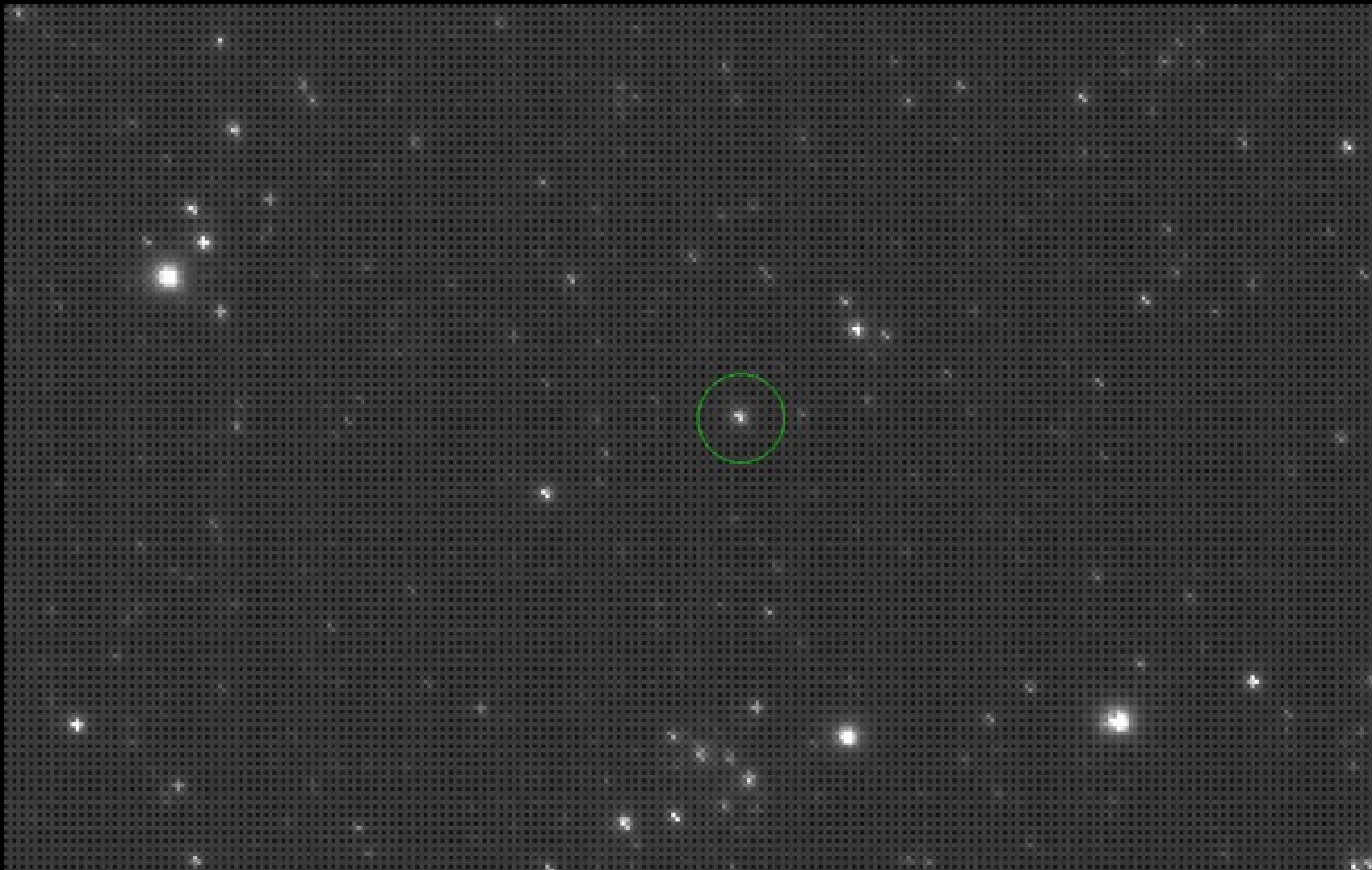
Example image (Cygnus field):
>100,000 stars in a single image

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

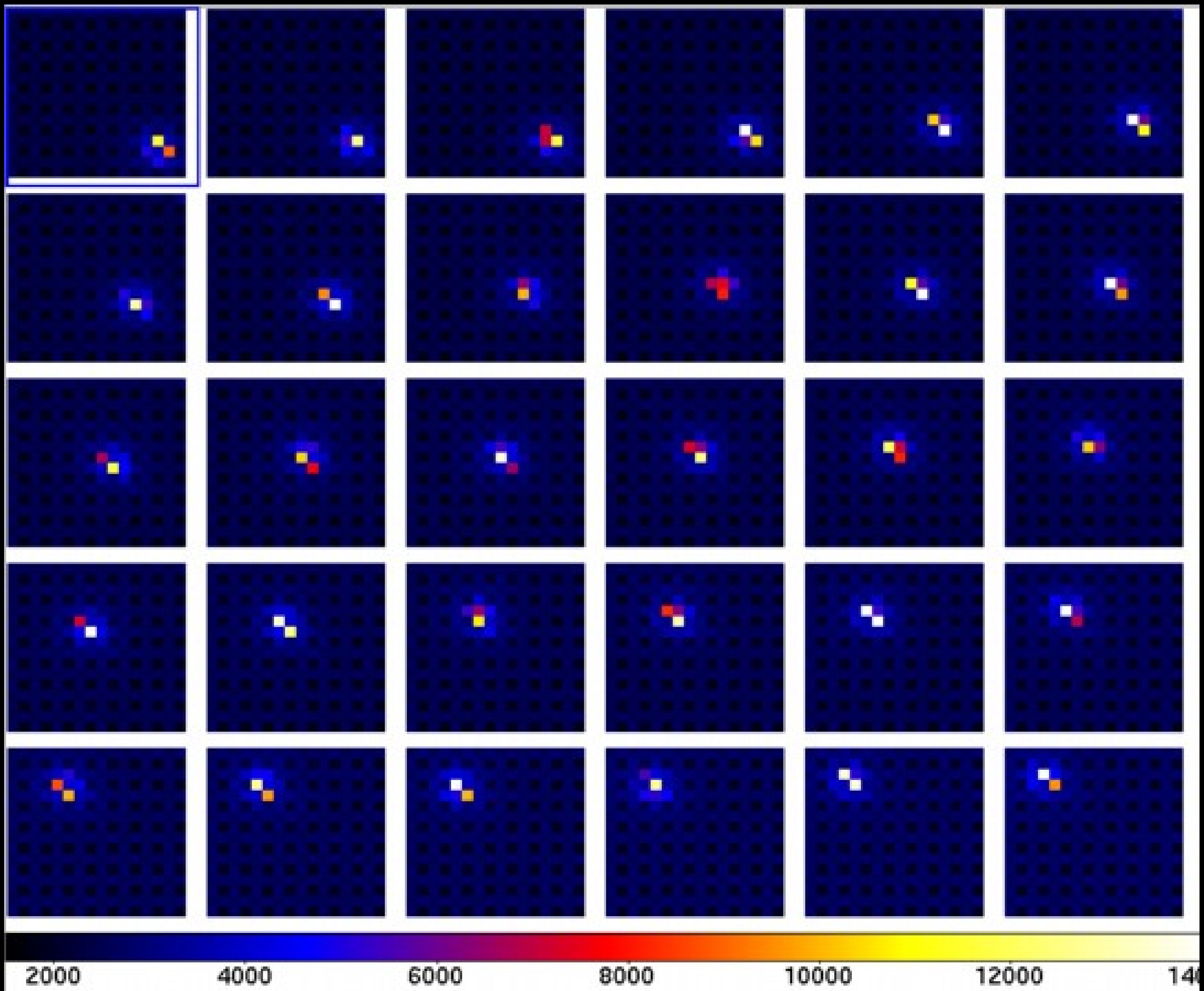
Lower left corner of previous image

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

Test on star HD54743 (V=9.35)
1 mn cadence

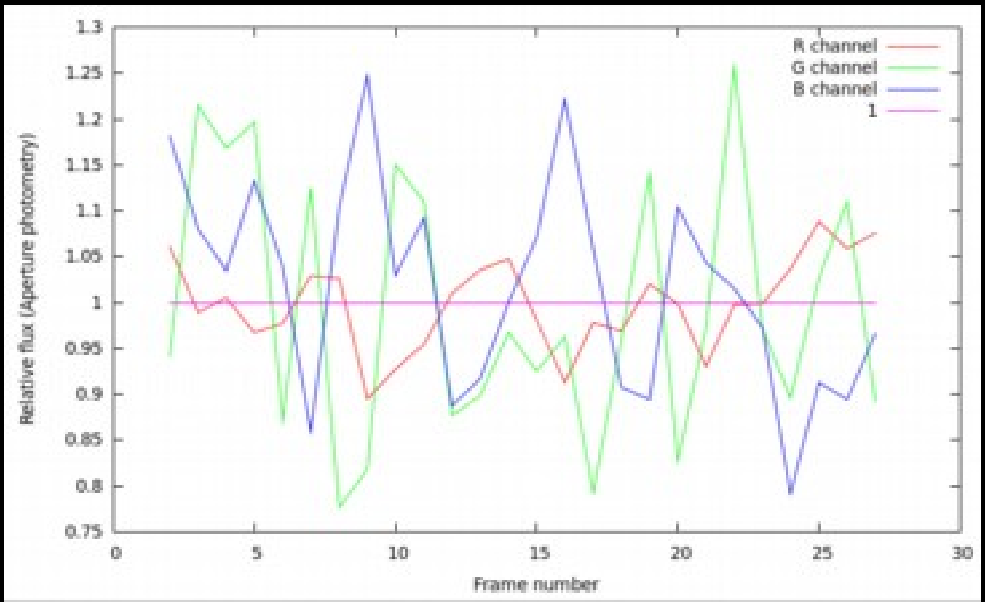


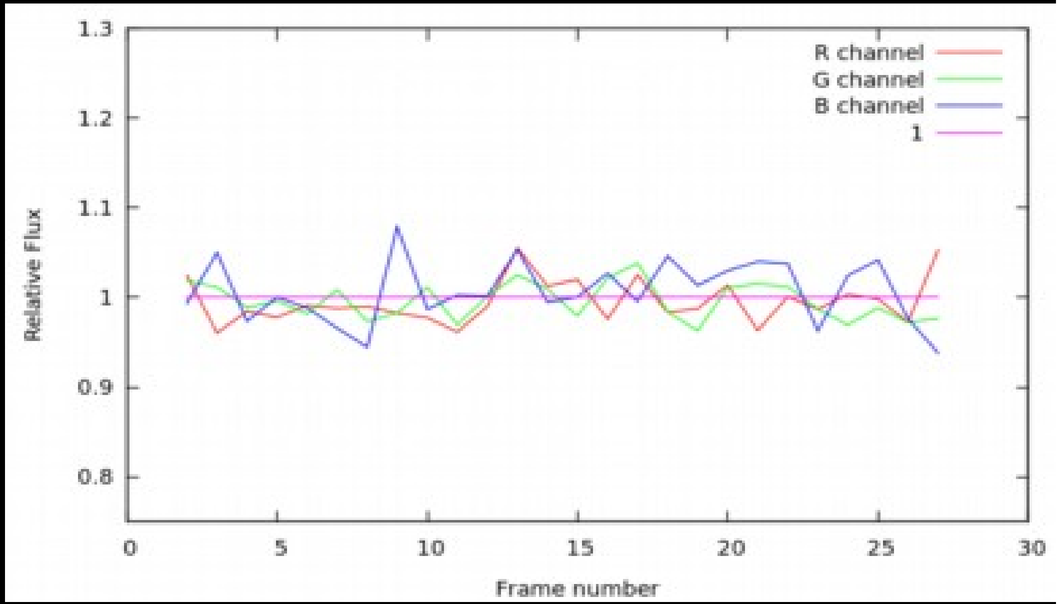
Test on star HD54743 (V=9.35)
1 mn cadence



Test on star HD54743 (V=9.35)
1 mn cadence

Error term	R channel	G channel	B channel	Notes
Atmospheric Scintillation	0.3%	0.3%	0.3%	
Photon Noise	2.79%	1.00%	2.24%	mV=9.35, includes background contribution (bright time, r=40arcsec mask)
Readout Noise	0.40%	0.23%	0.71%	
Flat field error	0.5%	0.4%	0.5%	Error term irrelevant with good tracking
Total (expected)	2.88%	1.14%	2.42%	
Achieved	**2.48%**	**2.04%**	**3.51%**	





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