Anybody out there ?

Optical tricks to look for life around nearby stars

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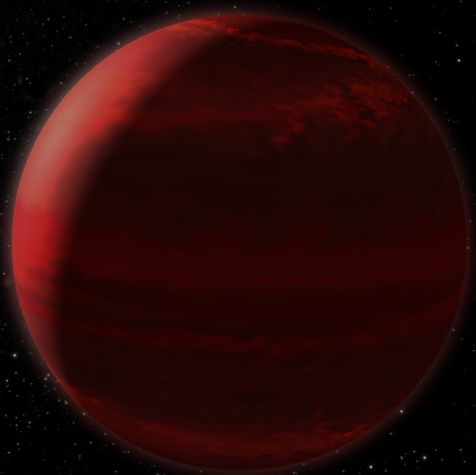

Caltech, Feb 25, 2013

Contact: oliv.guyon@gmail.com

See also: projectpanoptes.org

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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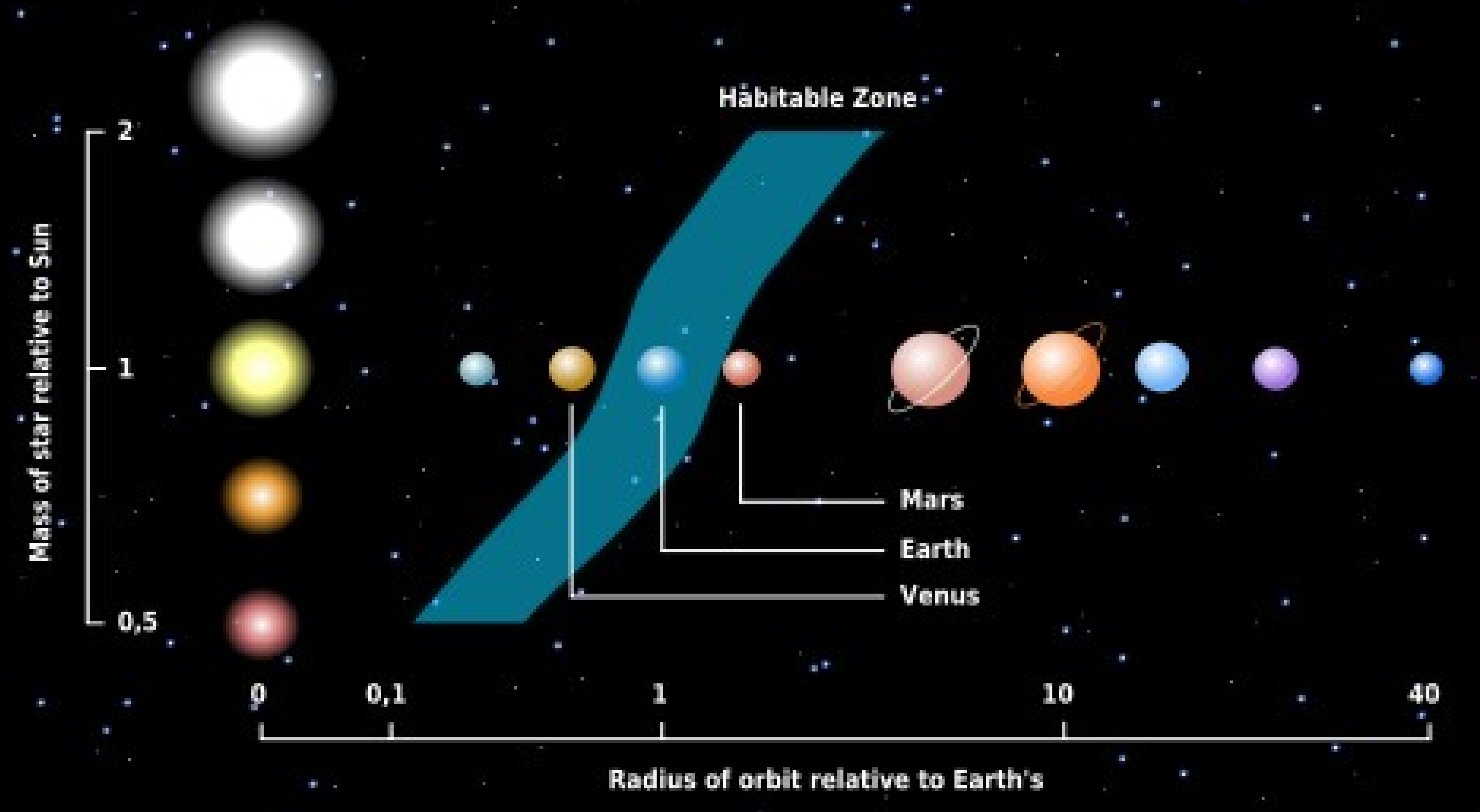
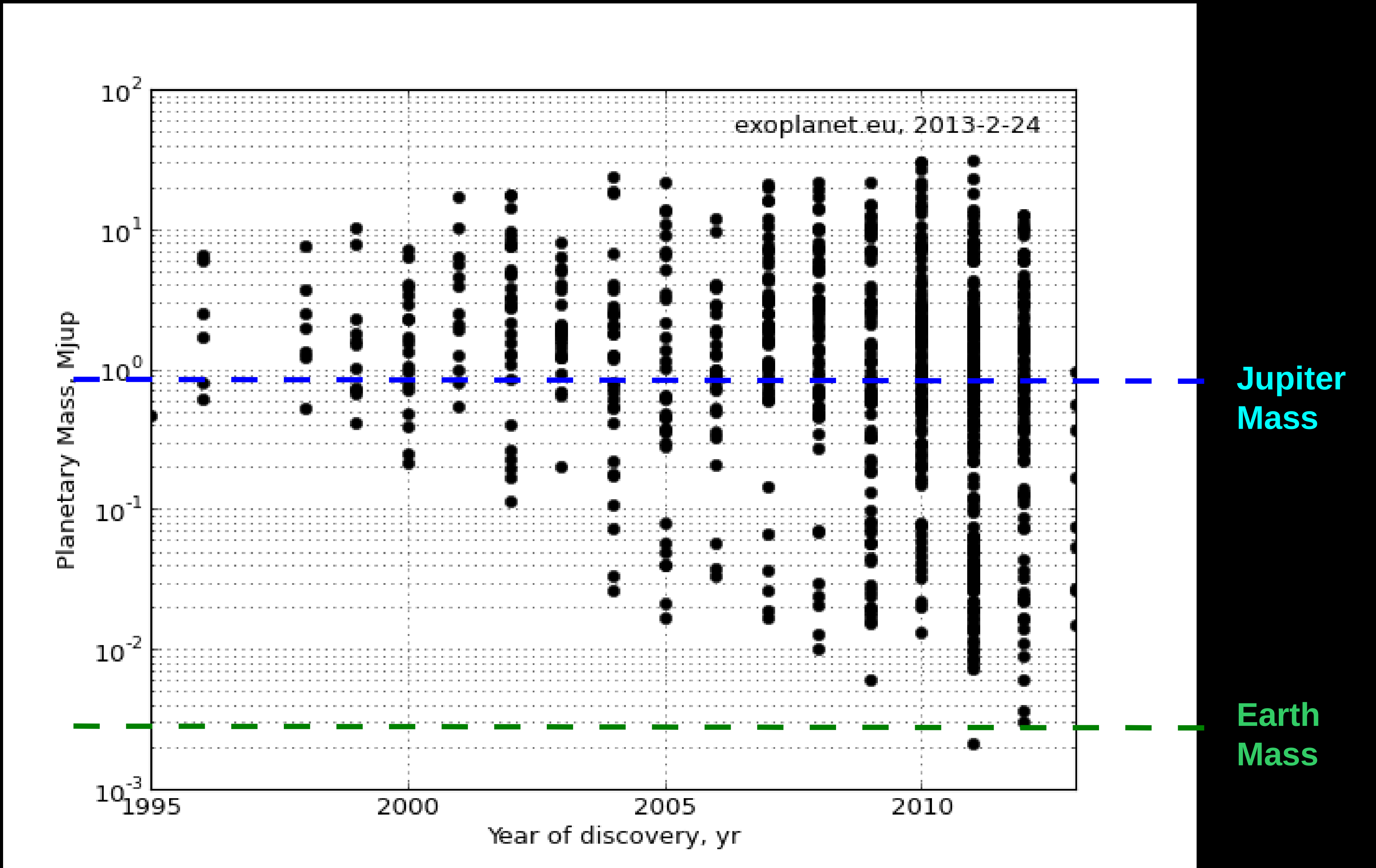
Habitable zone of a star



Every star has a habitable zone

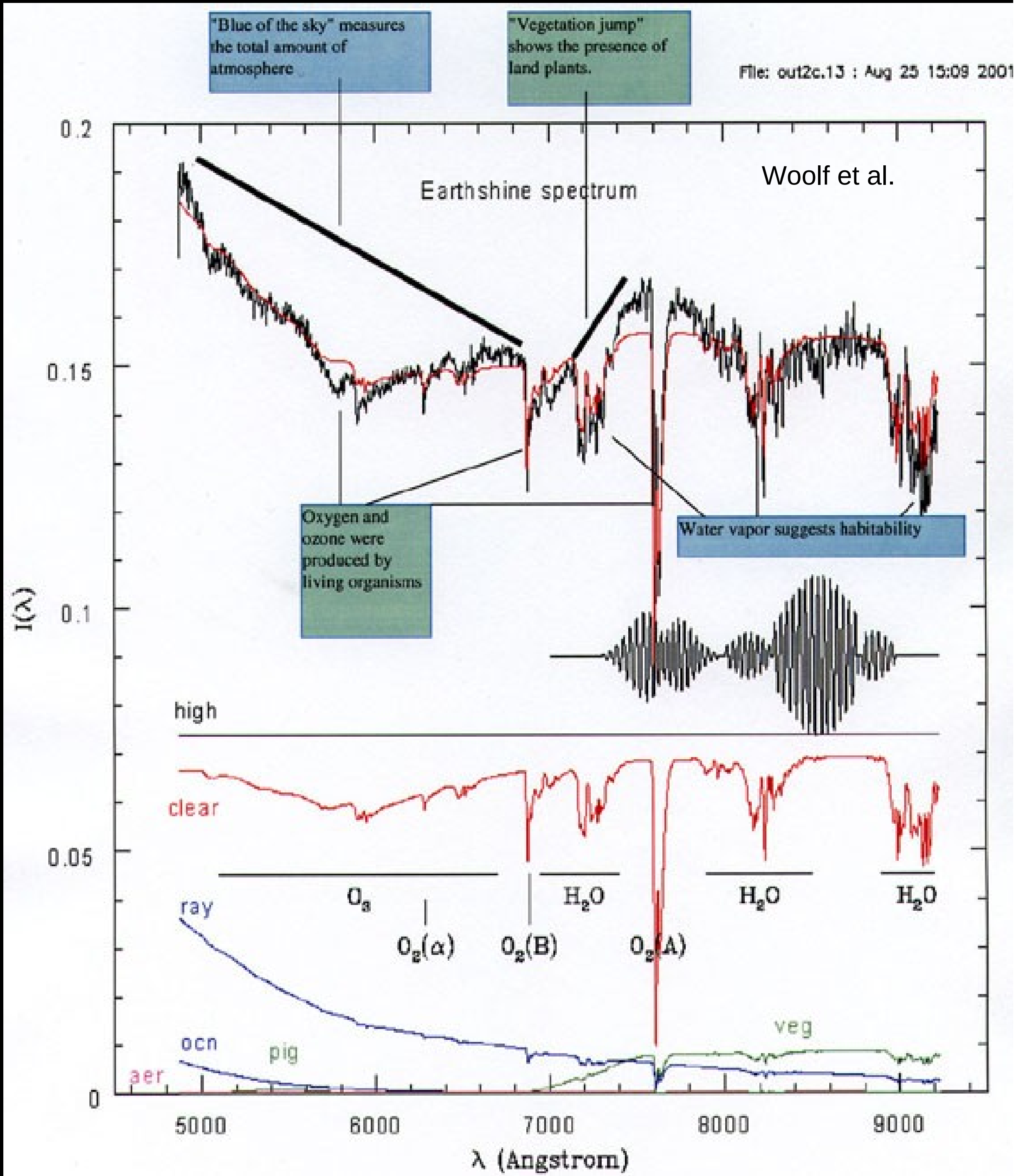
Planets identified – we are now starting to identify Earth-like planets



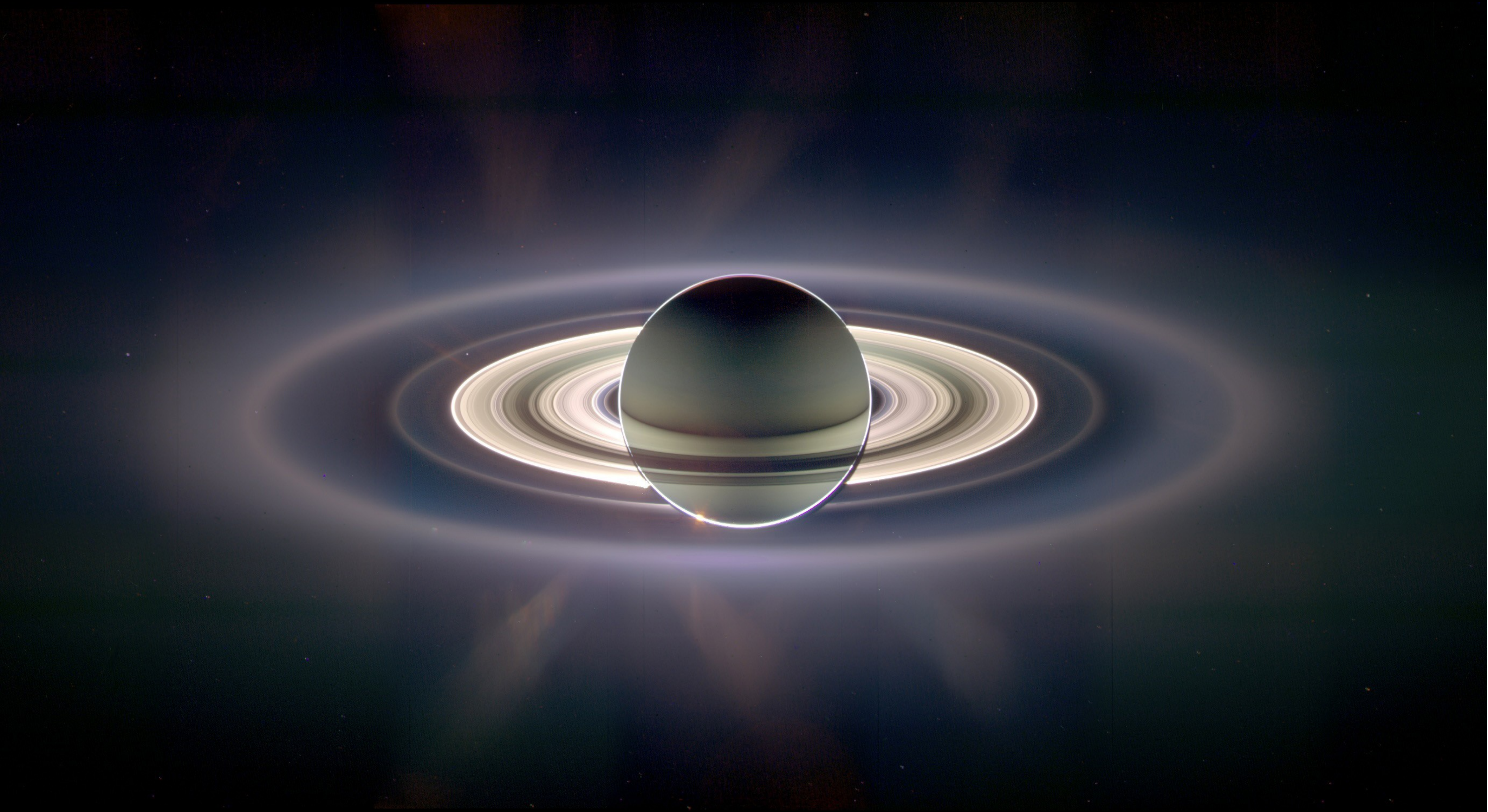
Directly imaging planet is necessary to find life

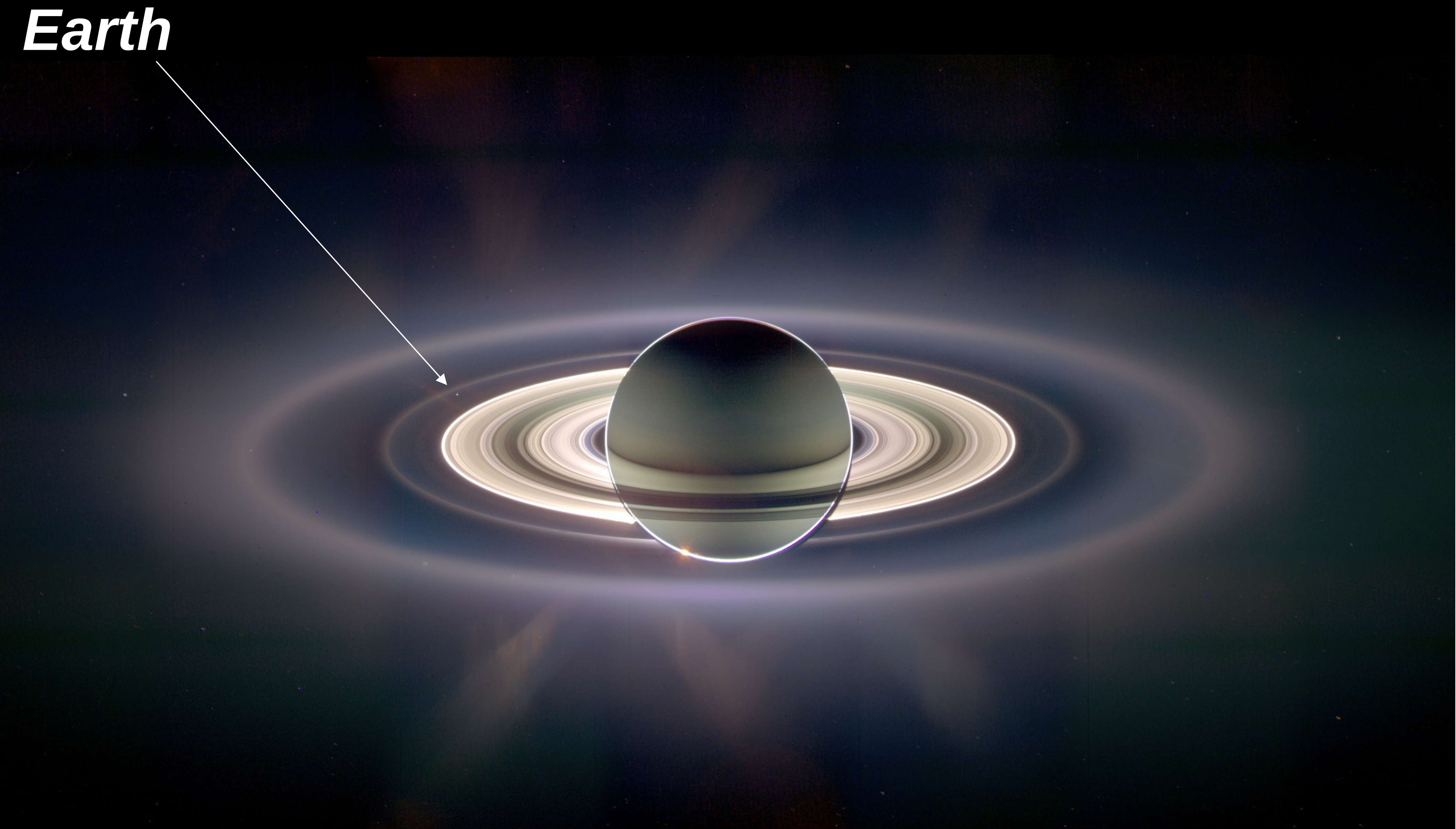
We need to take spectra of habitable planets

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 slimplest 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

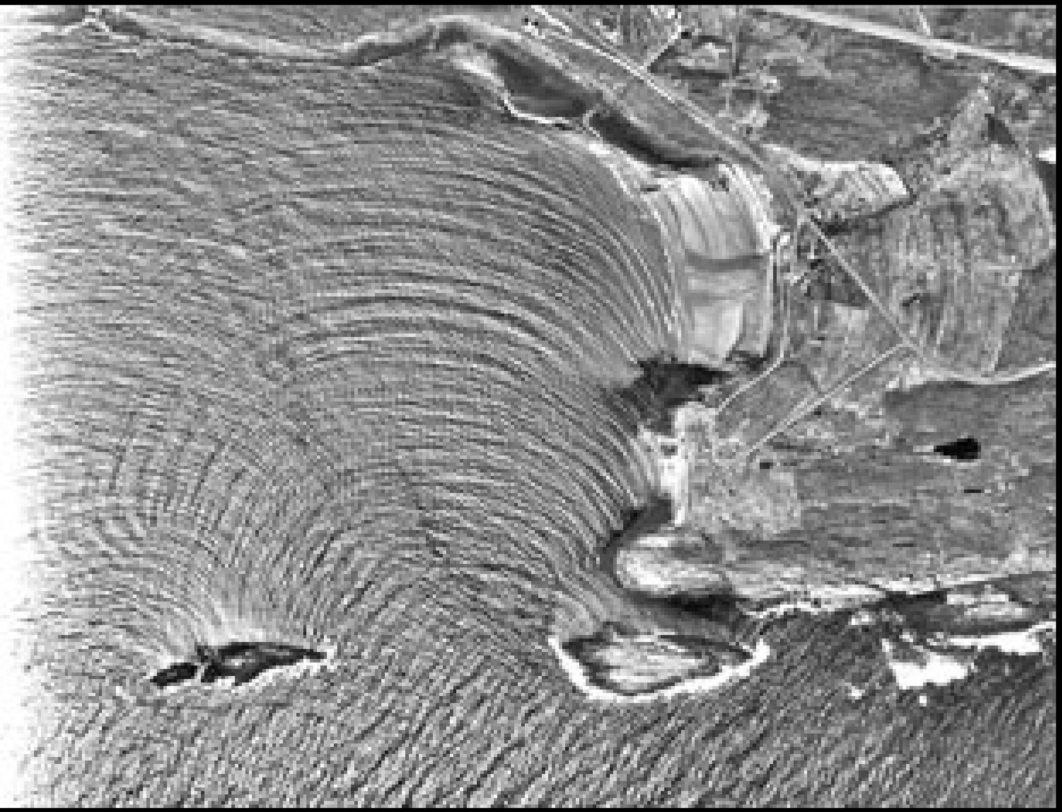
1818: French academy of science committee launches a competition
to explain nature of light

Augustin-Jean Fresnel
submits wave theory of light

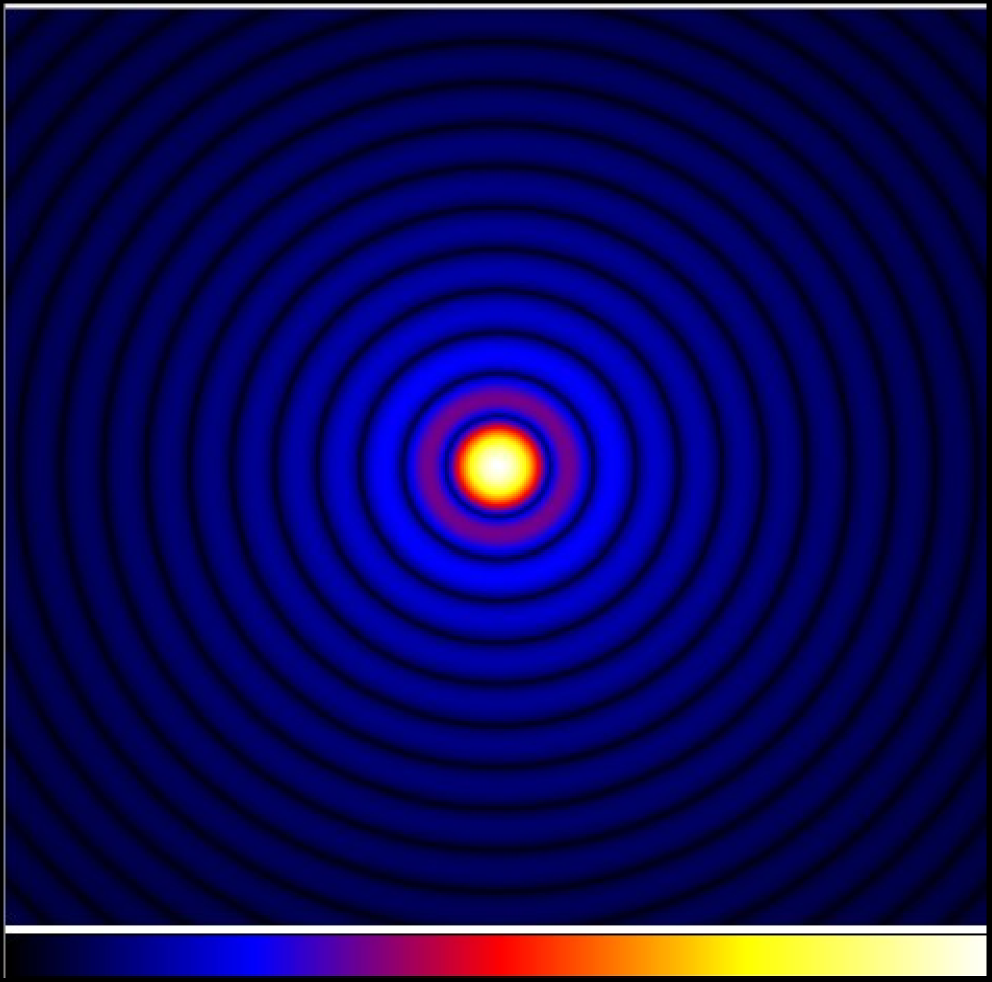
Simeon-Denis Poisson finds a flaw in Fresnel's theory:
According to Fresnel's equations, a bright spot should appear in
the shadow of a circular obstacle → this absurd result disproves Fresnel's theory

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



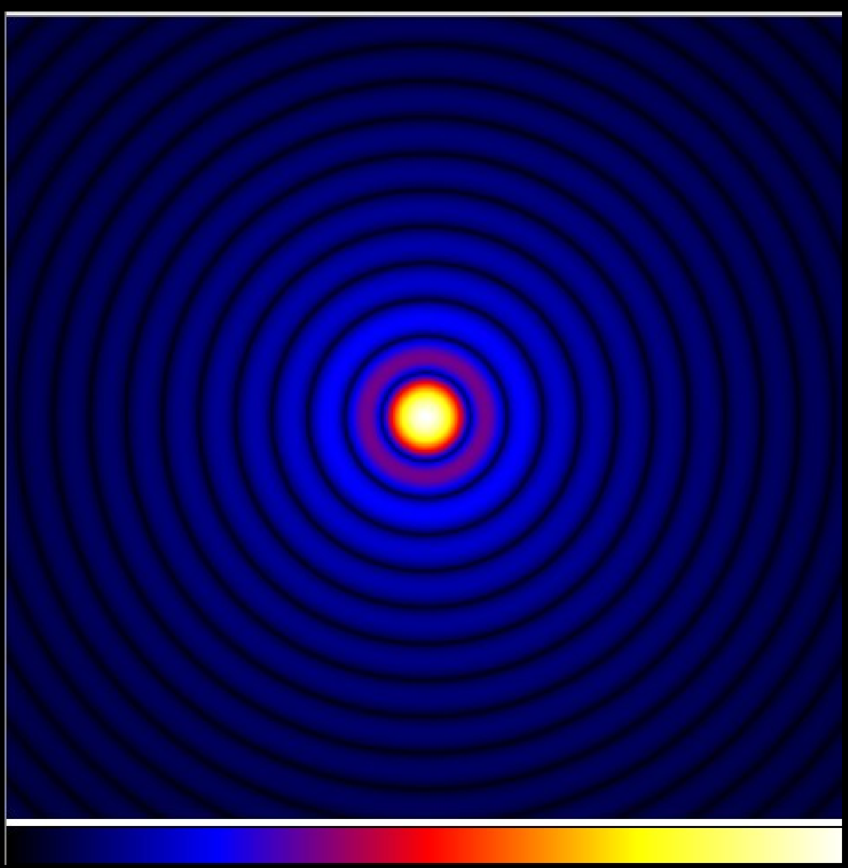
Waves diffracted by coastline and islands

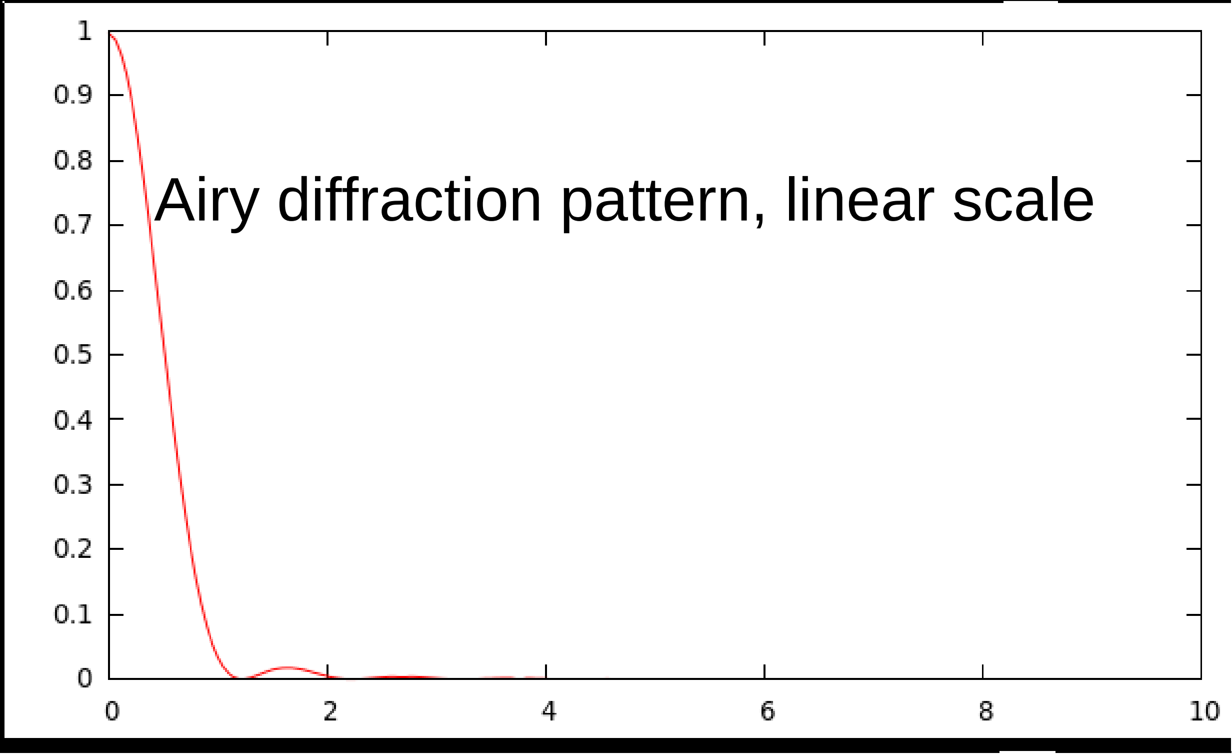


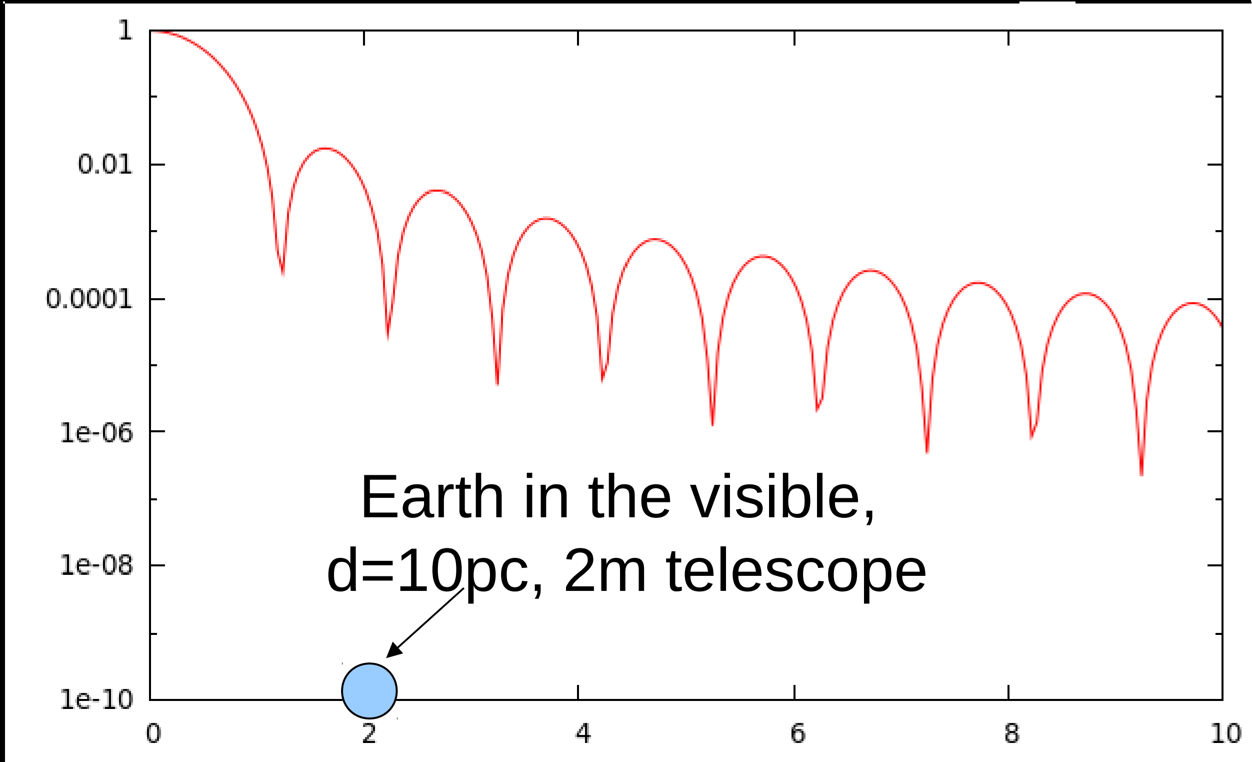
Ideal image of a distant star by a telescope
Diffraction rings around the image core

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

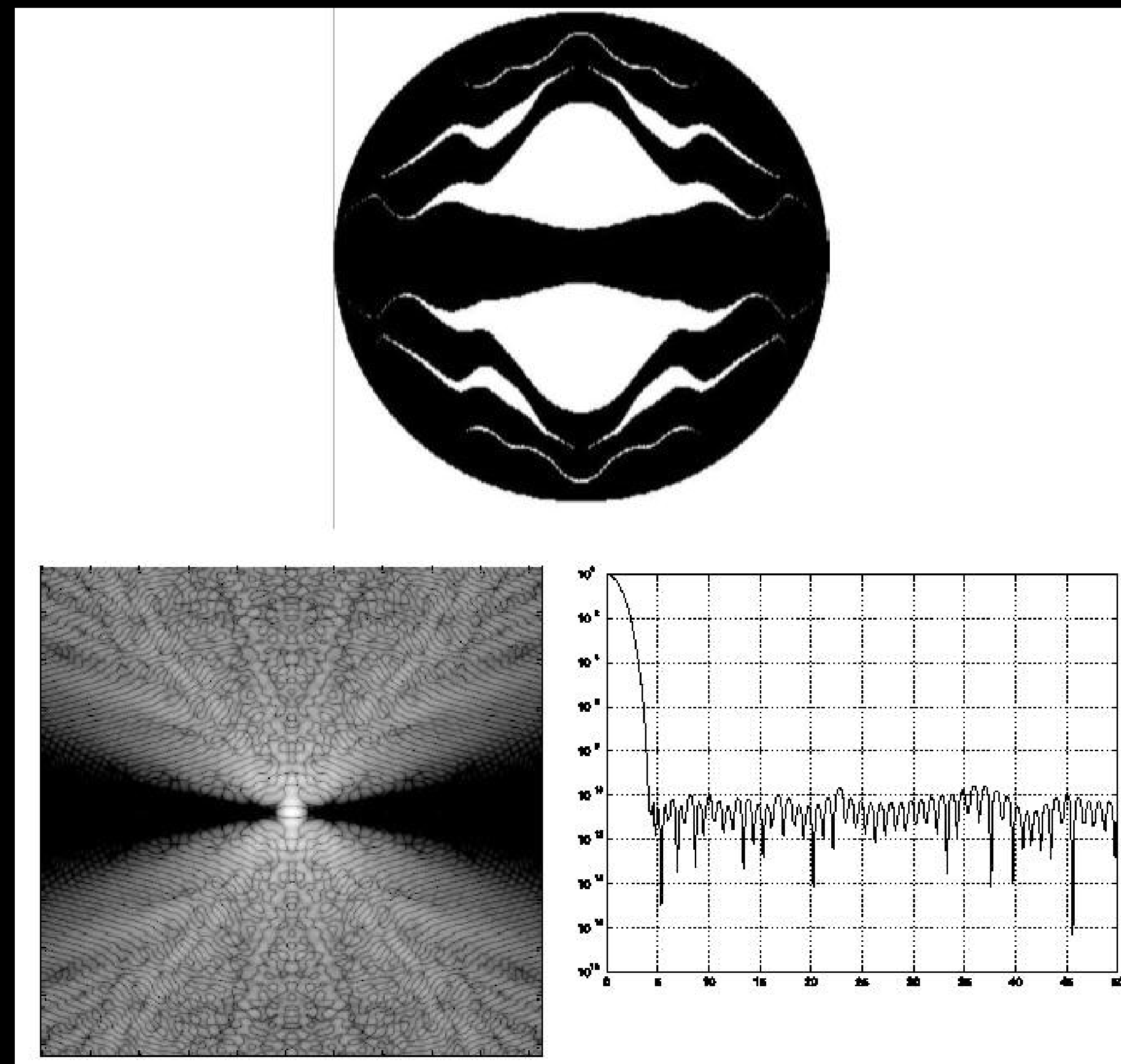
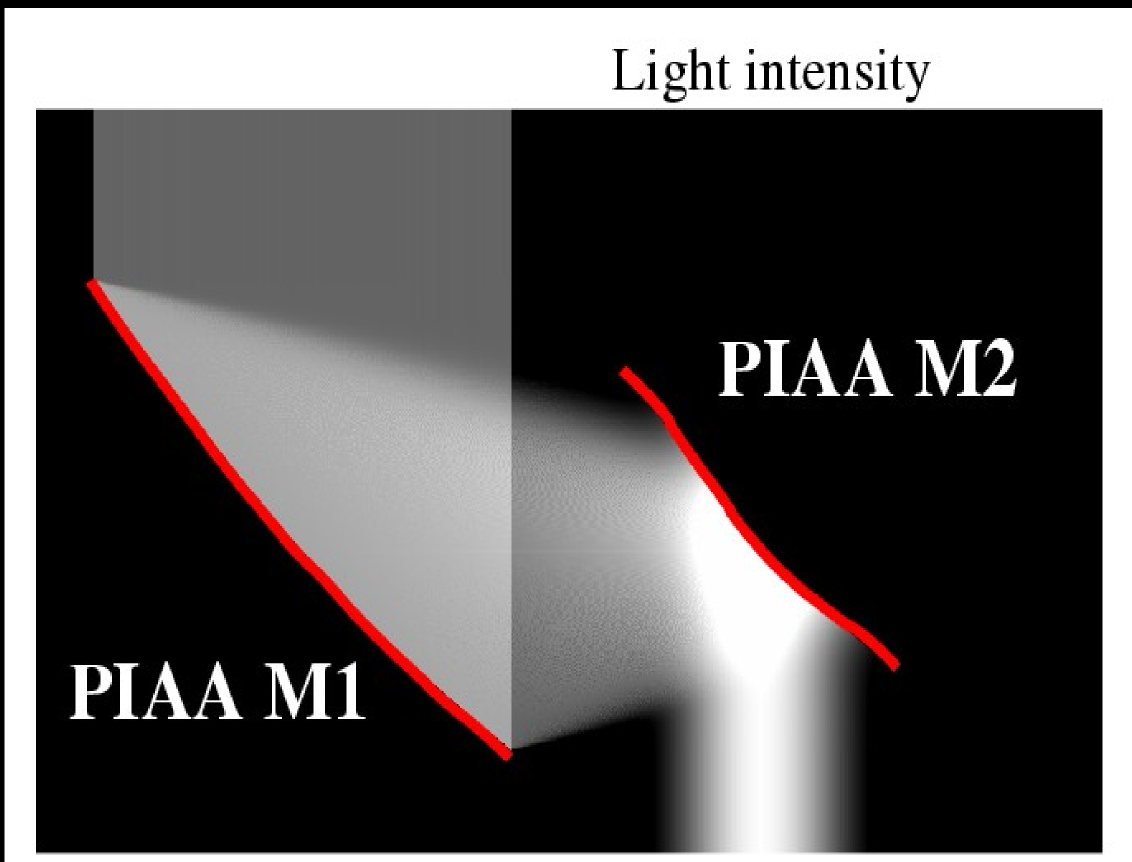


FIG. 9.—*Top*: Asymmetric multiopening mask designed to provide high-contrast, 10^{-10}, from $\lambda/D = 4$ to $\lambda/D = 100$ in two angular sectors centered on the x-axis. Ten integrations are required to cover all angles. Total throughput and pseudoarea are 24.4%. Airy throughput is 11.85%. *Bottom*: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

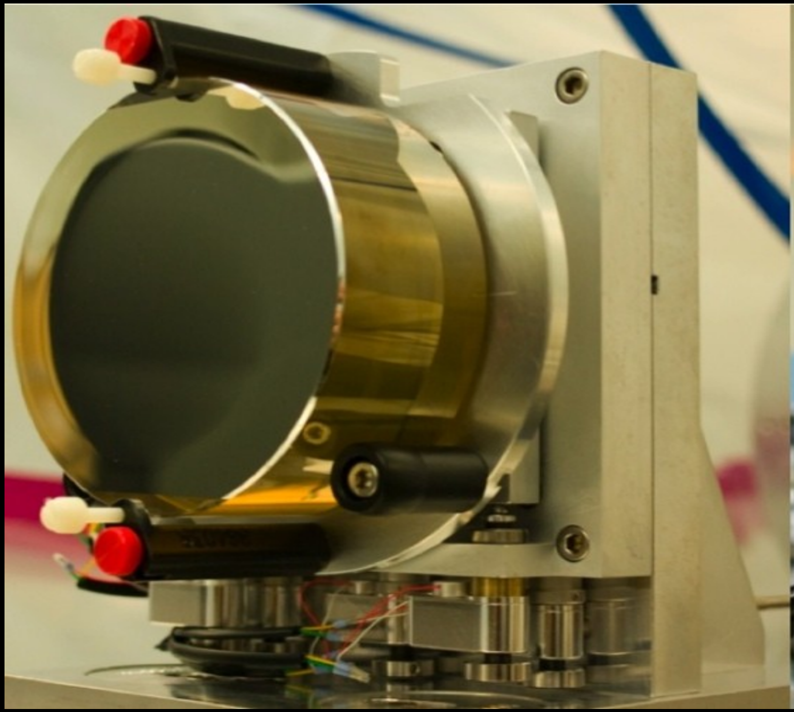


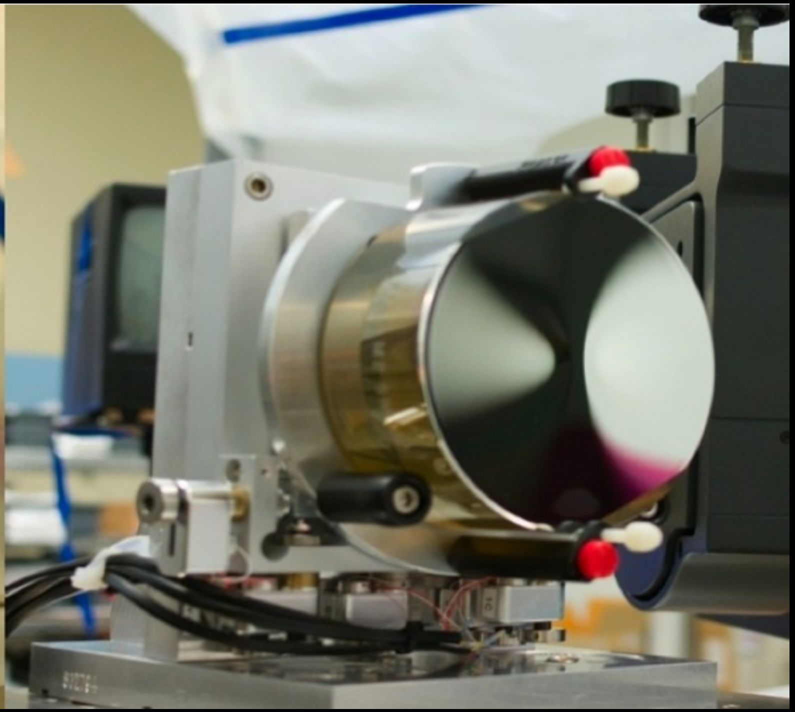
No loss in angular resolution or sensitivity
Achromatic (with mirrors)
Small inner working angle

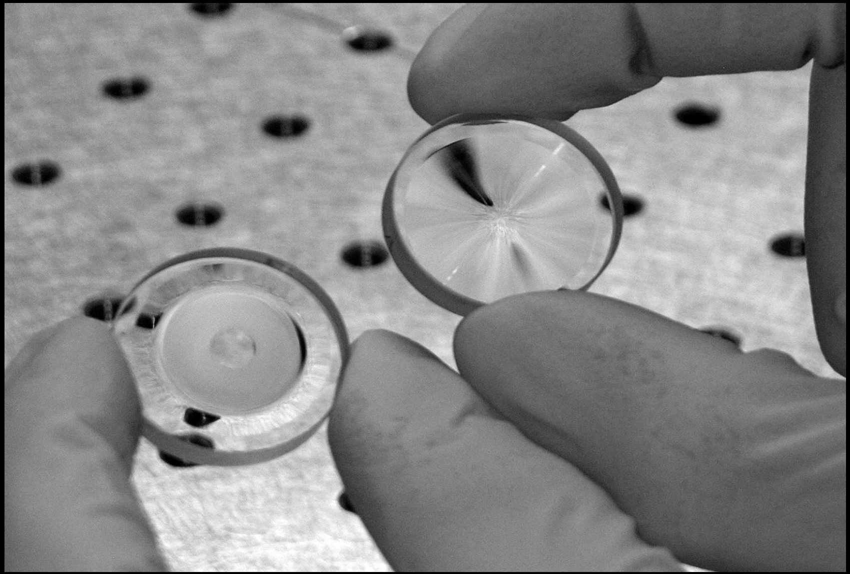
→ Gain ~x2 to x3 in telescope diameter over previous concepts

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

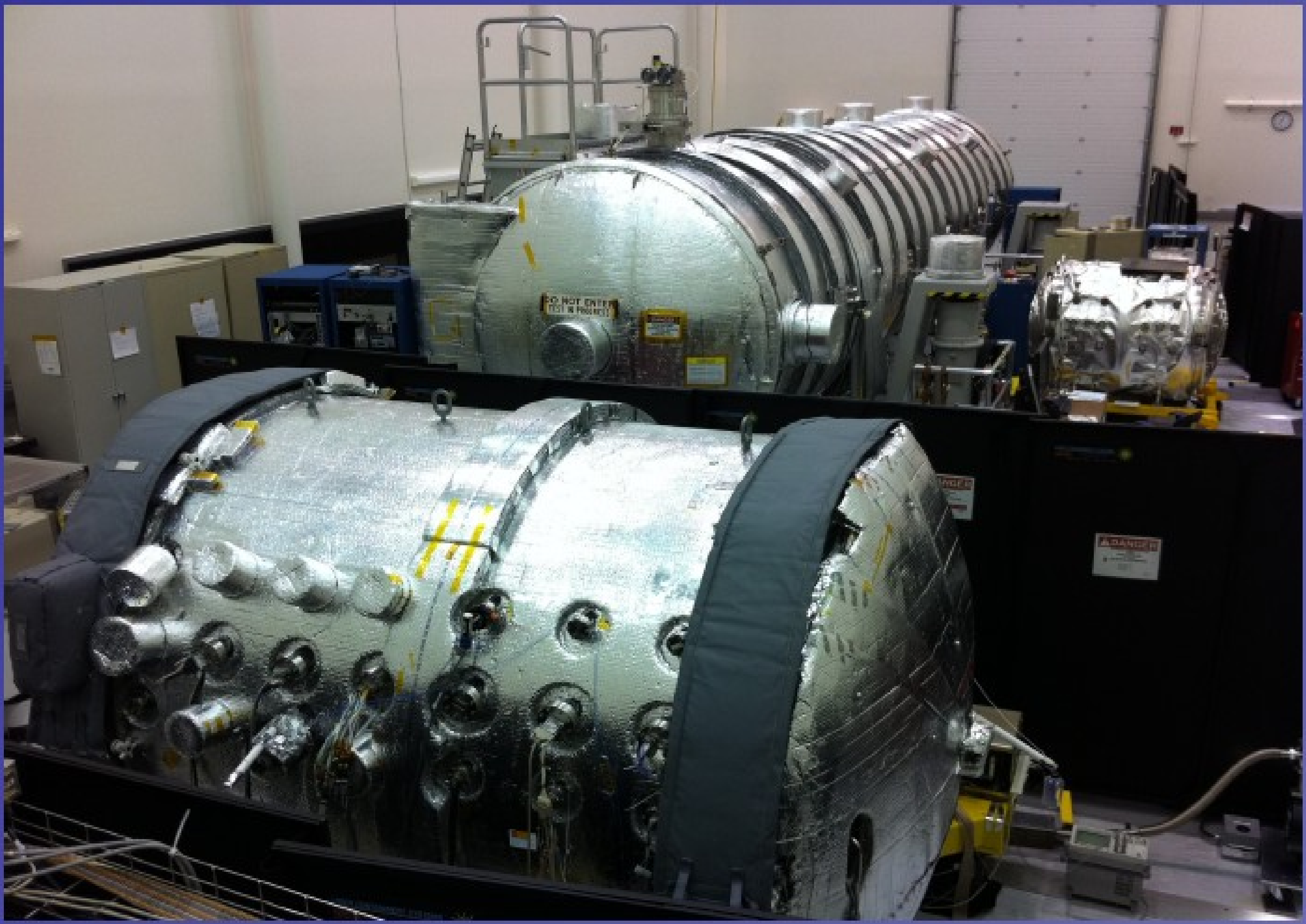
PIAA optics

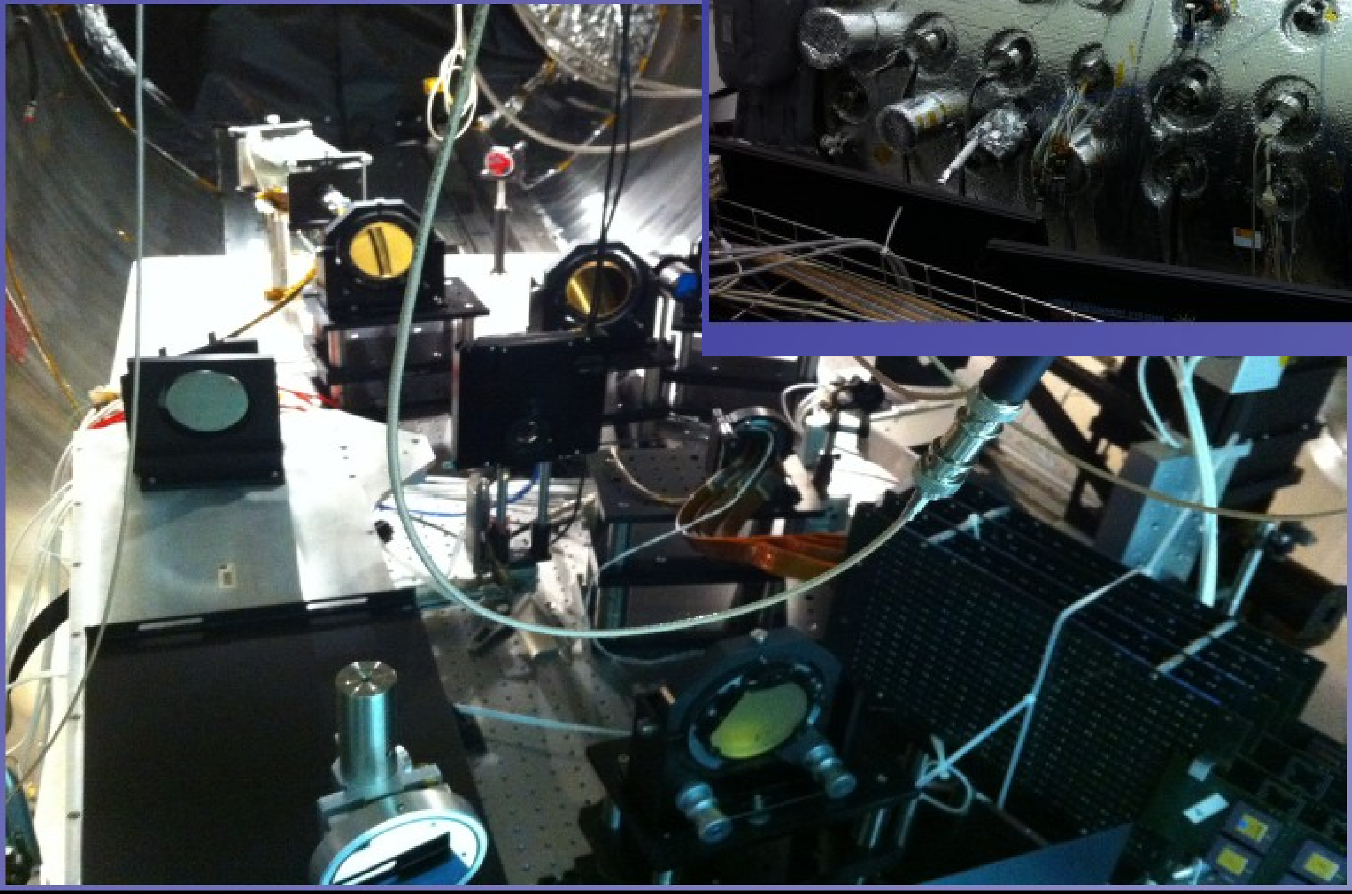




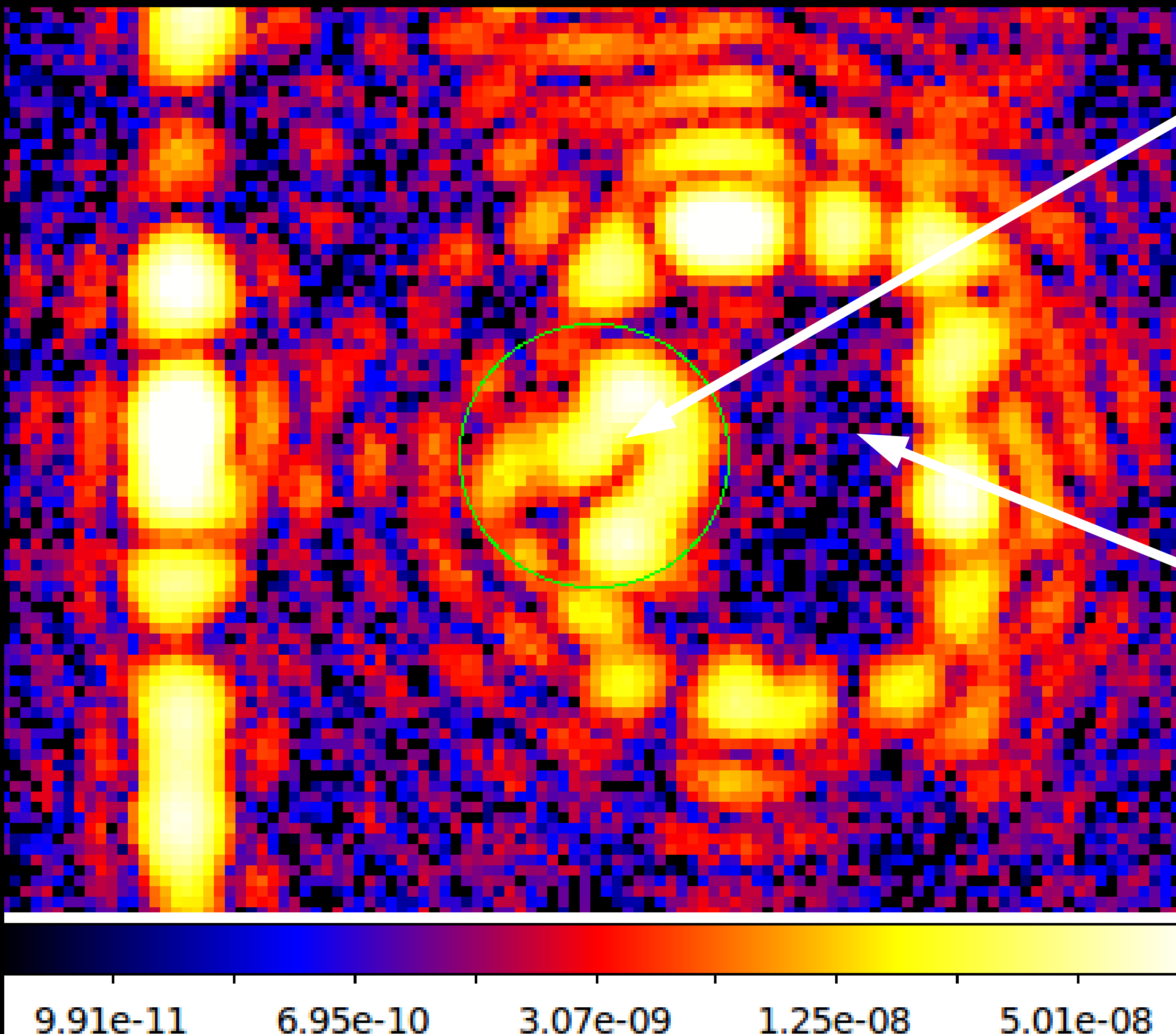


PIAA testbed at JPL





PIAA testbed at NASA JPL : lab results

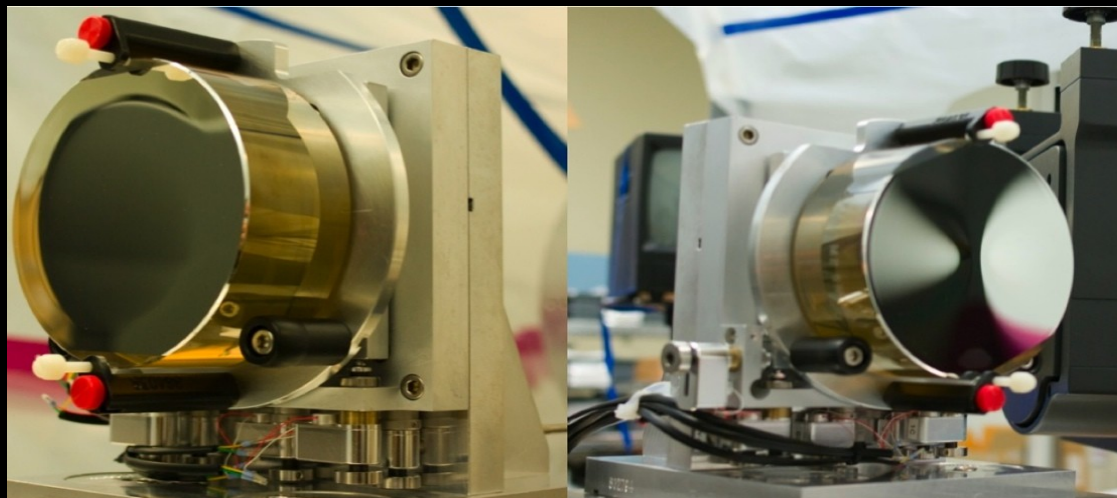


Location of the star (mostly blocked)

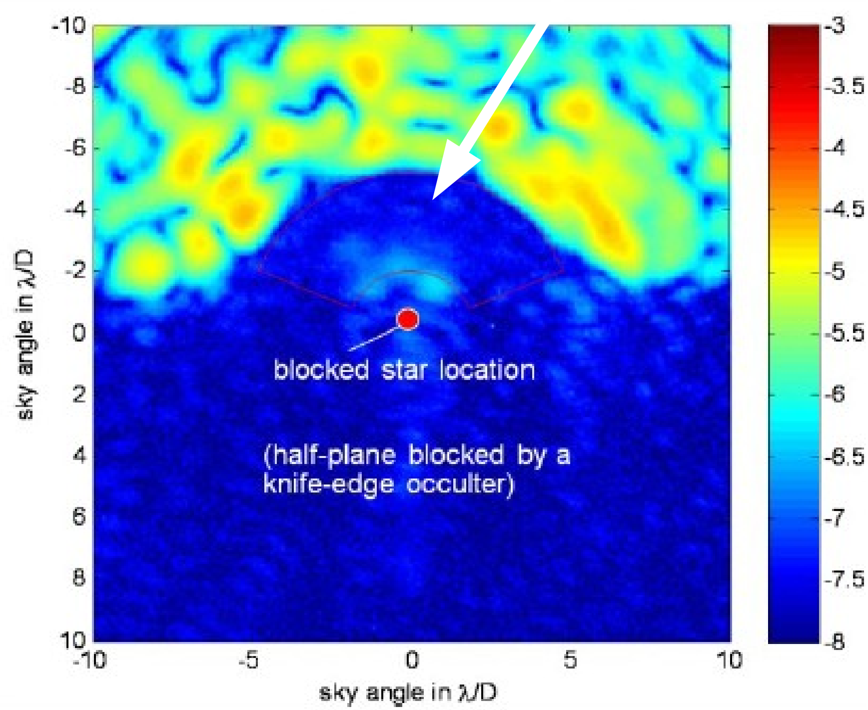
Contrast ~5e-10 between 2 and 4 l/D

An Earth-like planets could be seen !

PIAA testbed at NASA Ames



This area is more than one million times fainter than the star



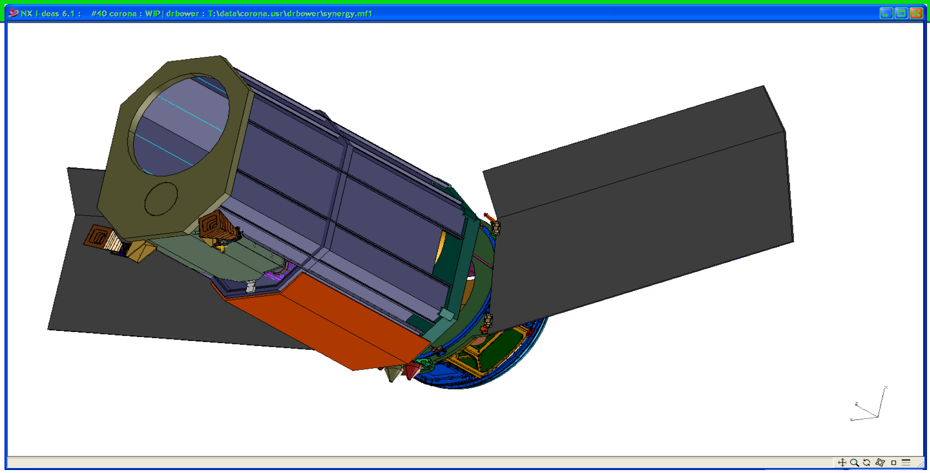
EXCEDE

Mission Overview

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

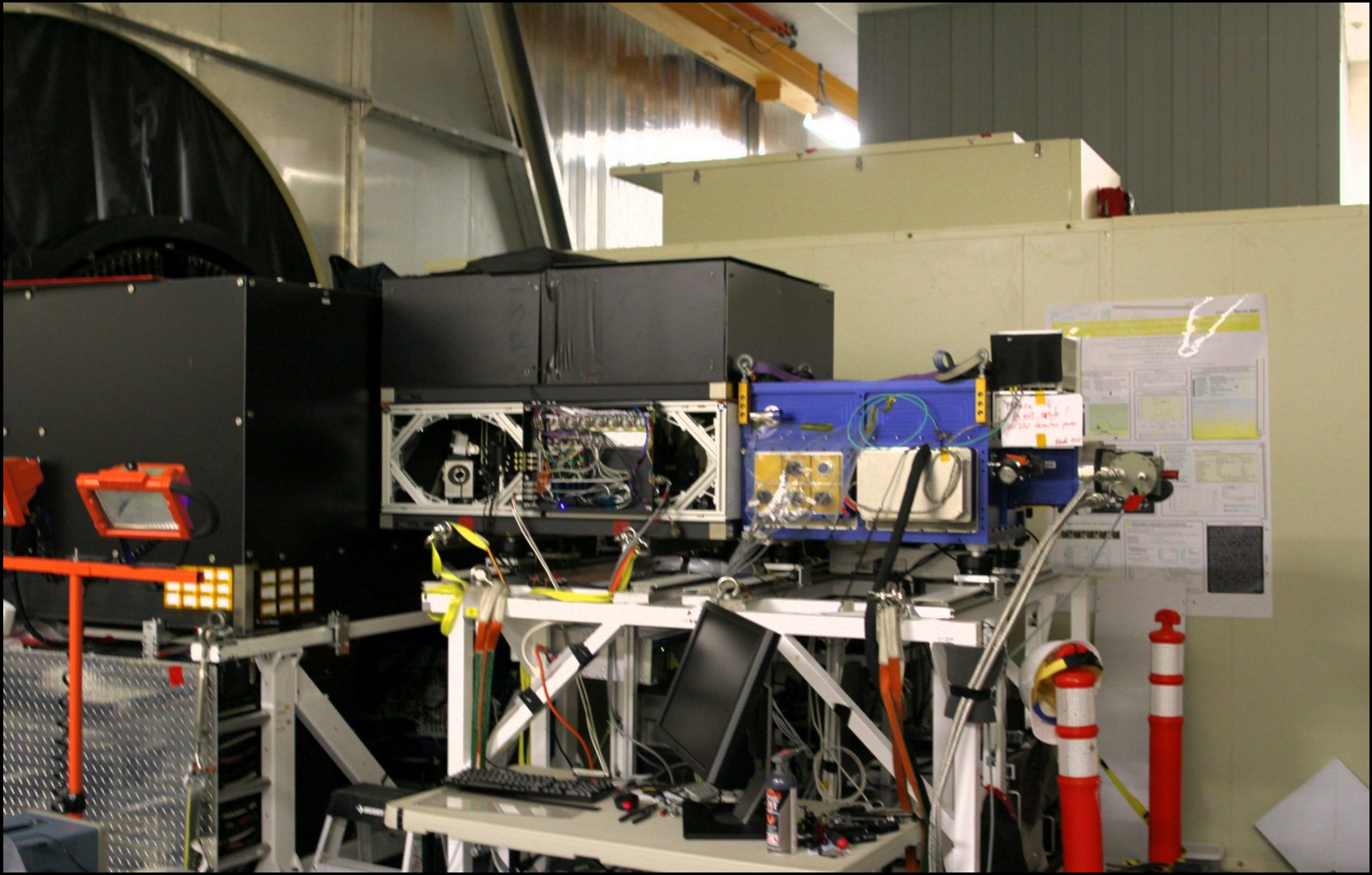
- Active Starlight Suppression System:
  - PIAA Coronagraph (~1 l/D IWA)
  - 2000-Element MEMS Deformable Mirror
  - Low-Order Wavefront Sensor

- 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

The Subaru Coronagraphic Extreme Adaptive Optics (SCExAO) system



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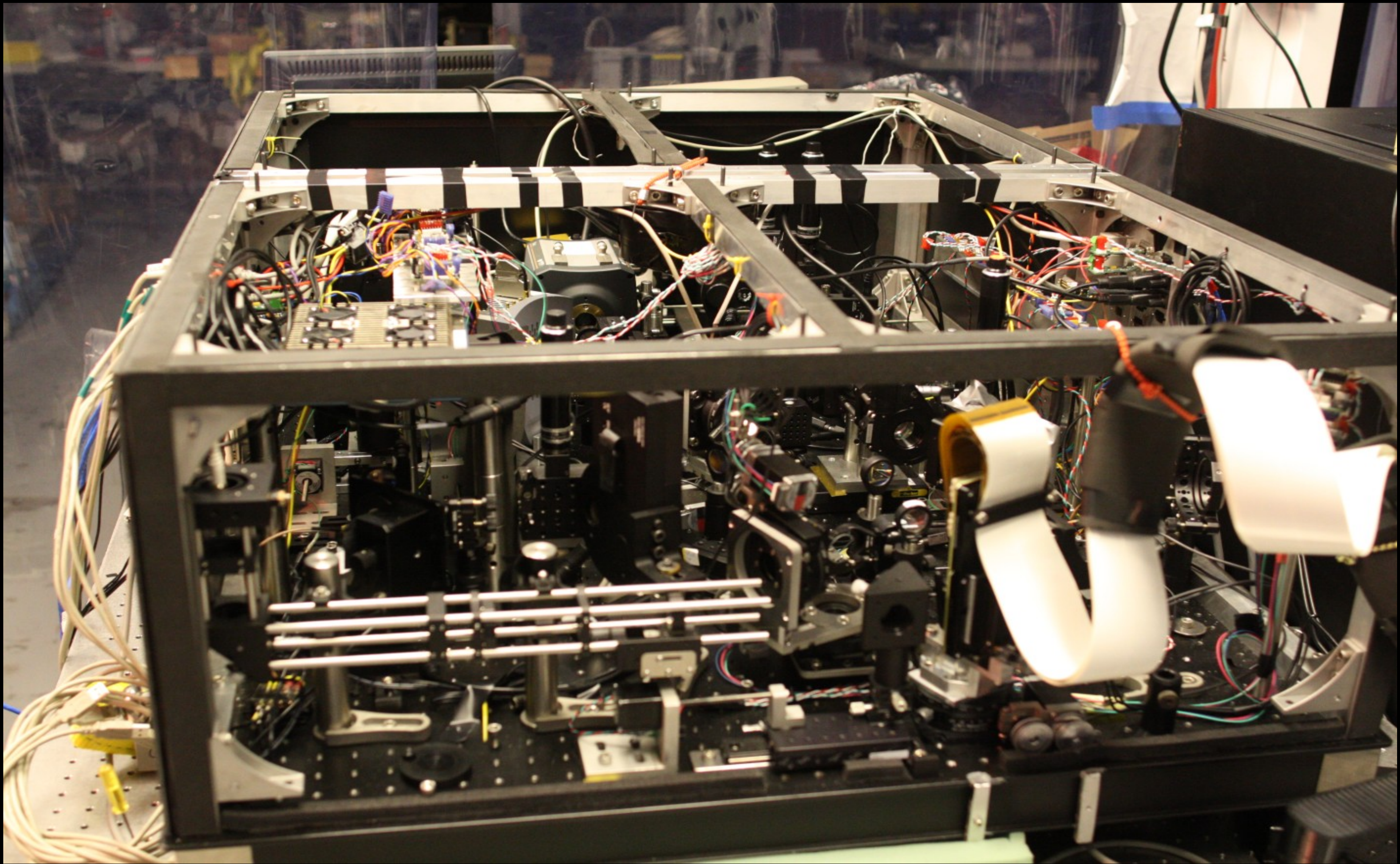

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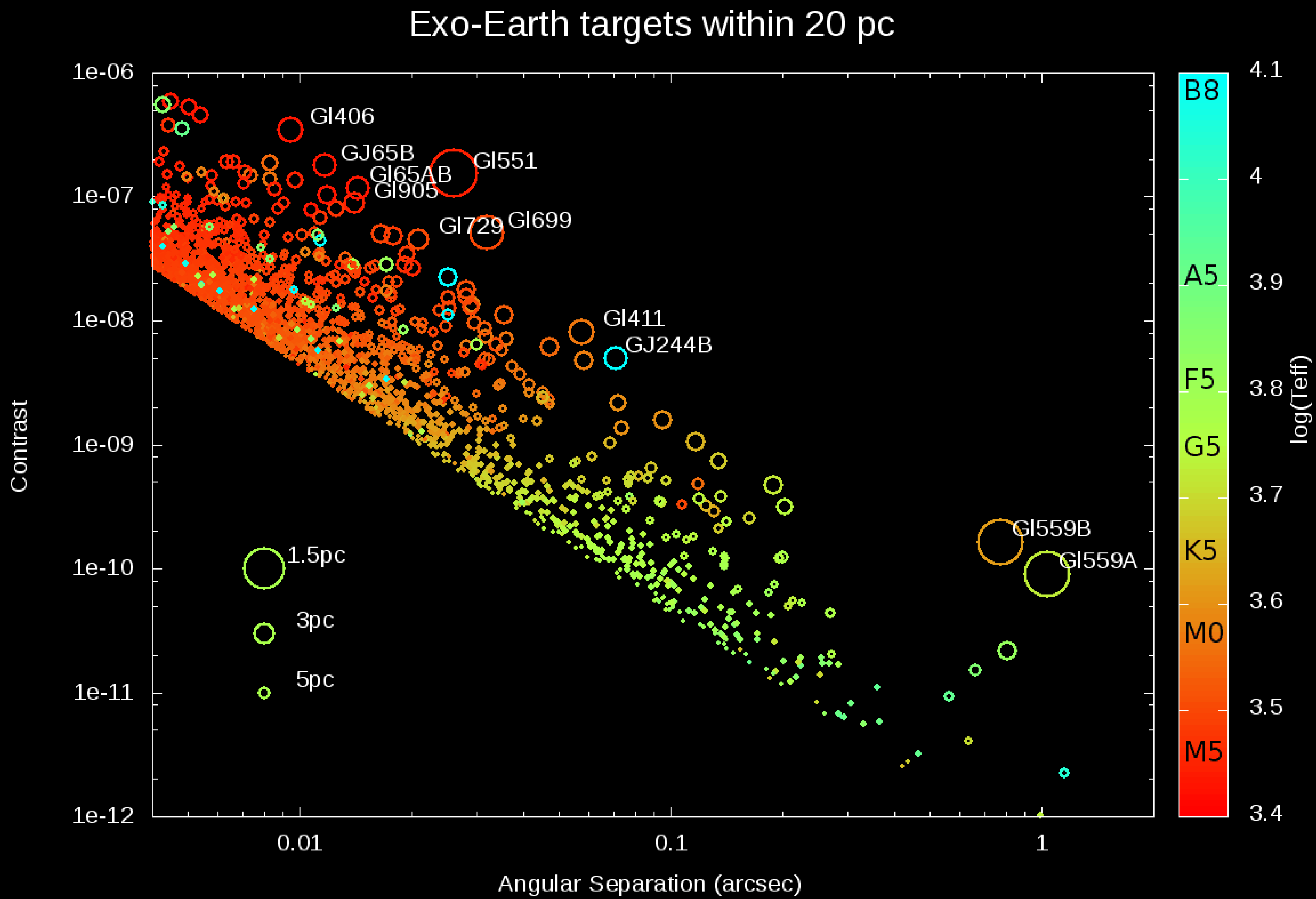
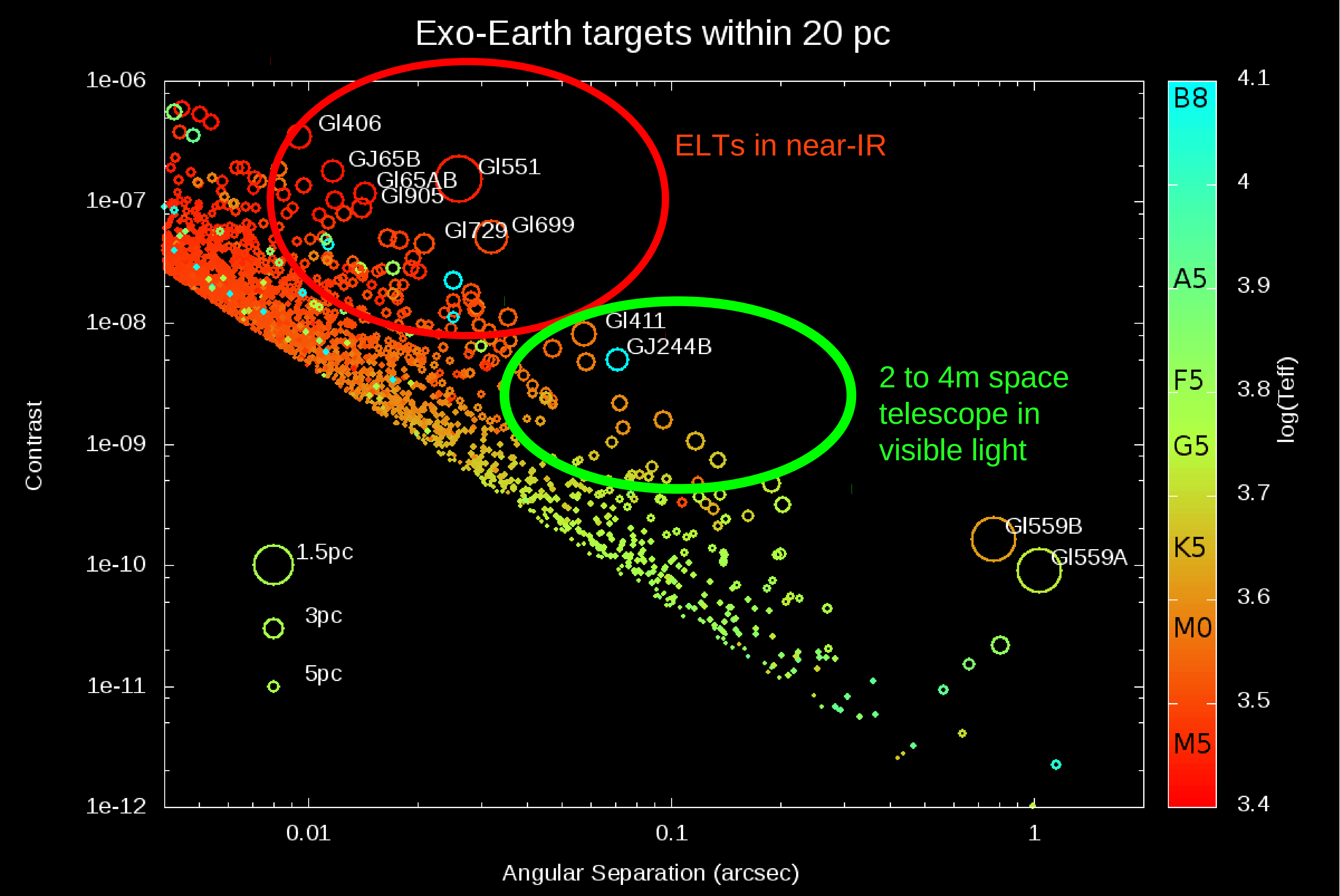


Exo-Earth targets within 20 pc
Contrast
Angular Separation (arcsec)
log(Teff)
1e-06
1e-07
1e-08
1e-09
1e-10
1e-11
1e-12
0.01
0.1
1
4.1
4
3.9
3.8
3.7
3.6
3.5
3.4
B8
A5
F5
G5
K5
M0
M5
Gl406
GJ65B
Gl551
Gl65AB
Gl905
Gl729
Gl699
Gl411
GJ244B
Gl559B
Gl559A
1.5pc
3pc
5pc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1e-06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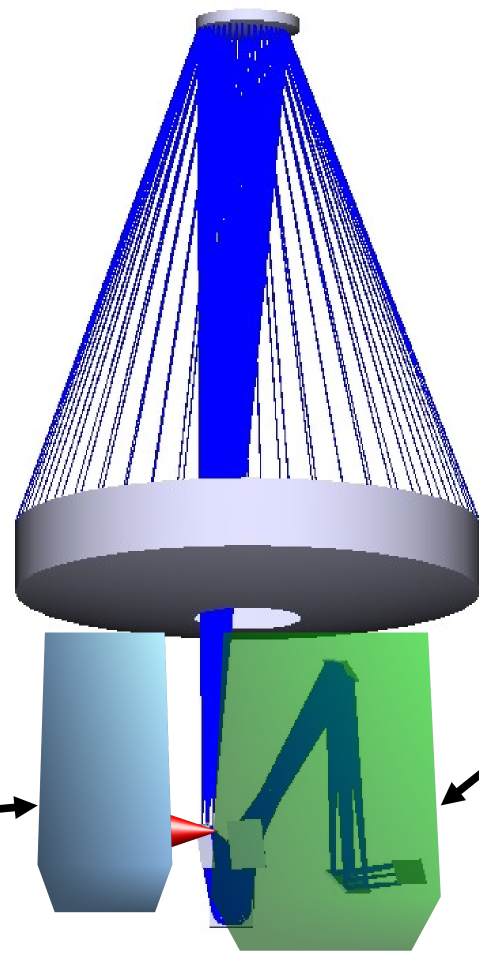
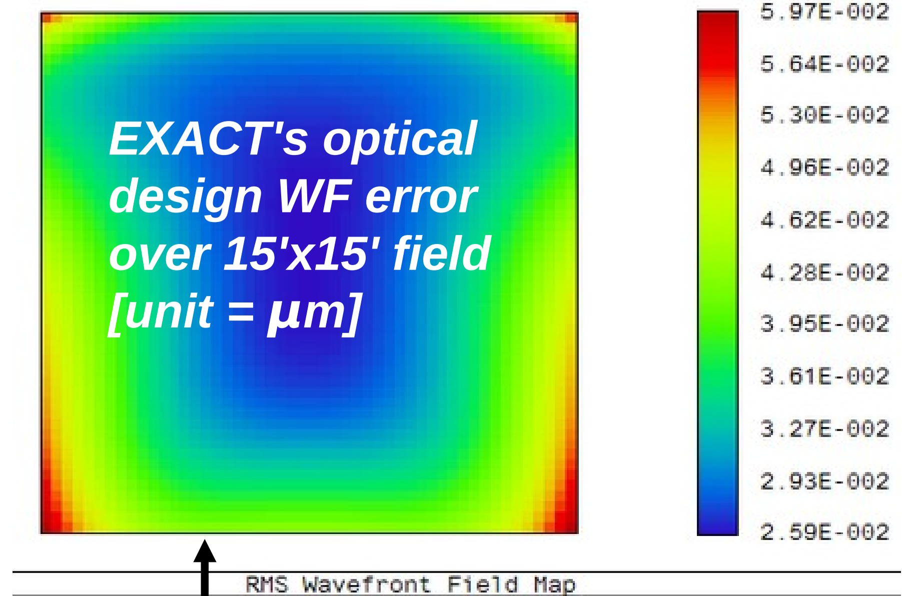
1e-09
1e-10
1e-11
1e-12
0.01
0.1
1
Gl406
GJ65B
Gl65AB
Gl905
Gl551
Gl729
Gl699
ELTs in near-IR
Gl411
GJ244B
2 to 4m space telescope in visible light
Gl559B
Gl559A
1.5pc
3pc
5pc
B8
A5
F5
G5
K5
M0
M5
4.1
4
3.9
3.8
3.7
3.6
3.5
3.4
log(Teff)

2.4-m ex-NRO Telescope, Two instruments
Custom coating on PM

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

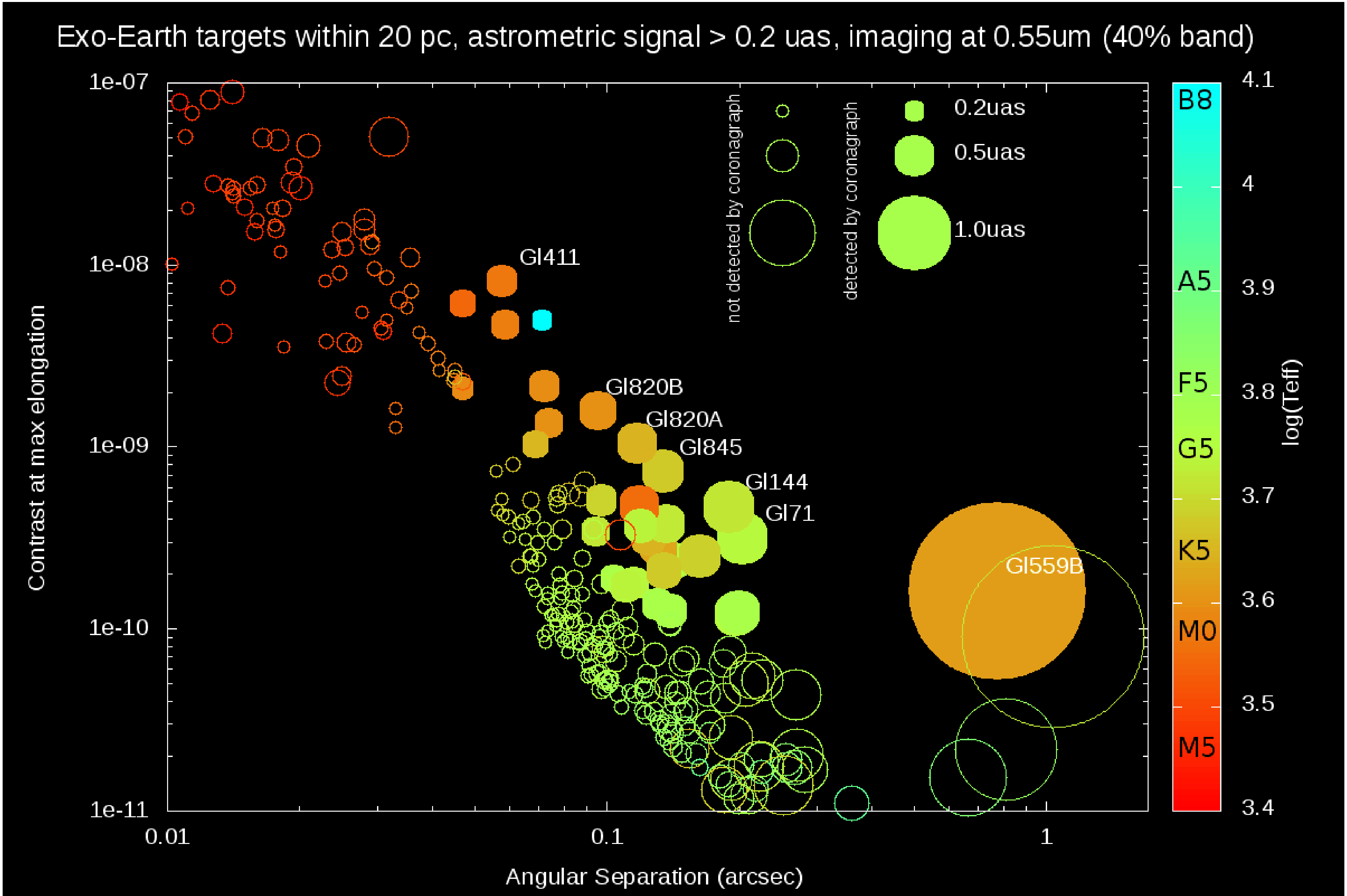




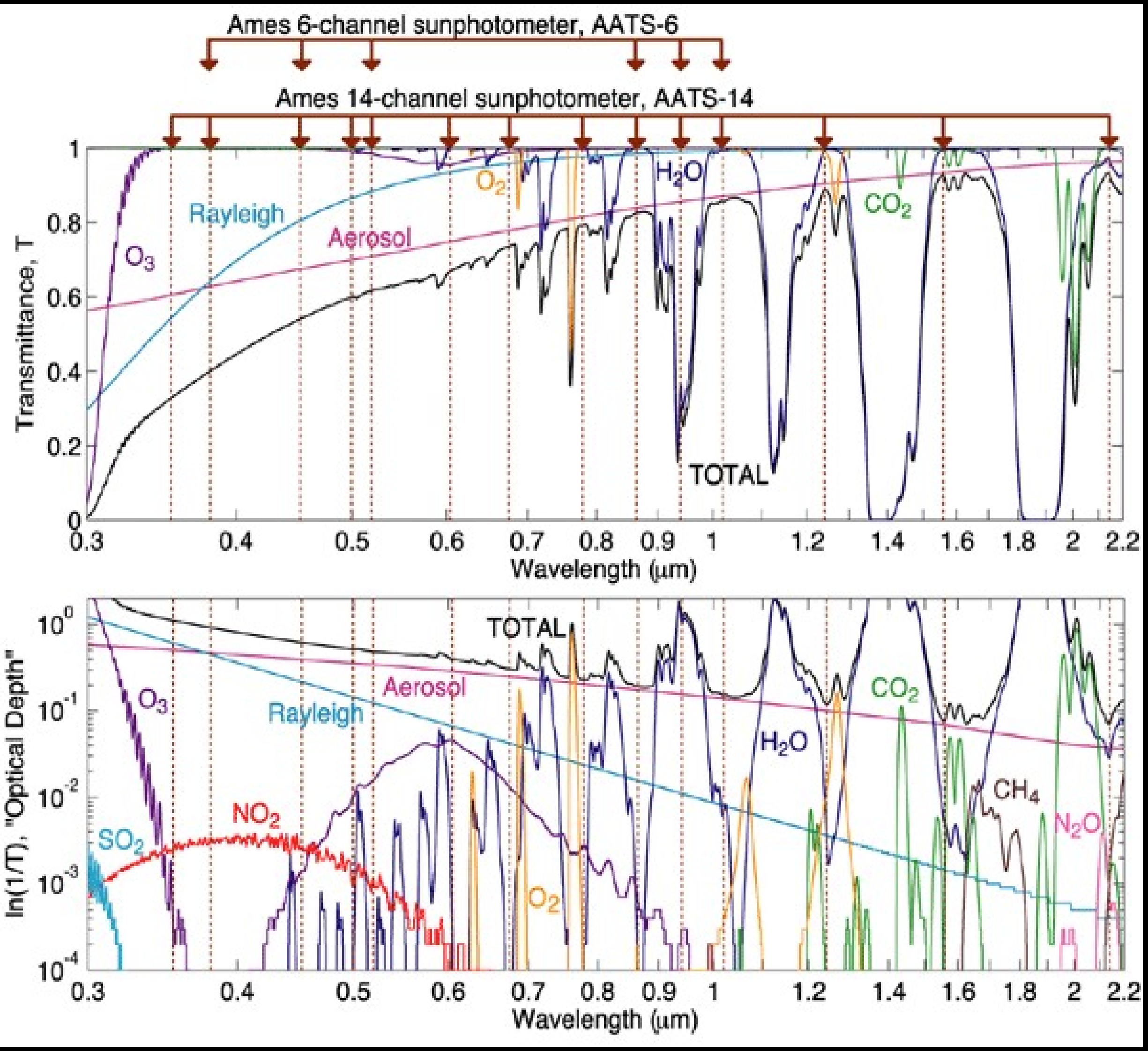
EXACT's high contrast imaging camera extracts a narrow field of view in the center of the astrometric camera's intermediate focus

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



Habitable Planets Spectroscopy in near-IR



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

Polarimetry

Cloud cover, variability
Rotation period

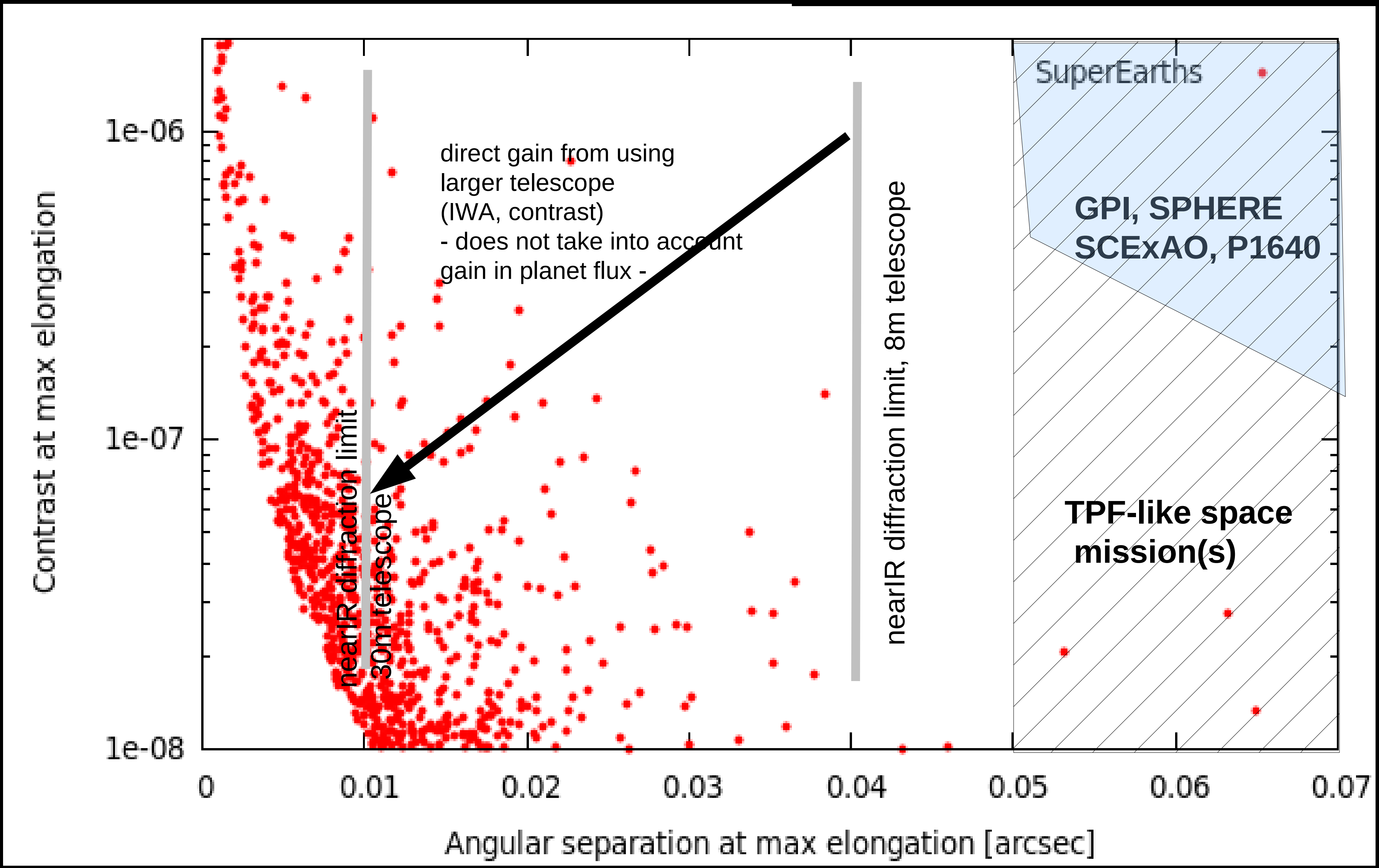
Reflectivity from ground in atmosphere transparency bands
(Ice cap, desert, ocean etc...)

Credit: NASA/Ames Airborne Tracking Sunphotometer (AATS)

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)



Reflected light planets

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

FIRST CUT LIMITS

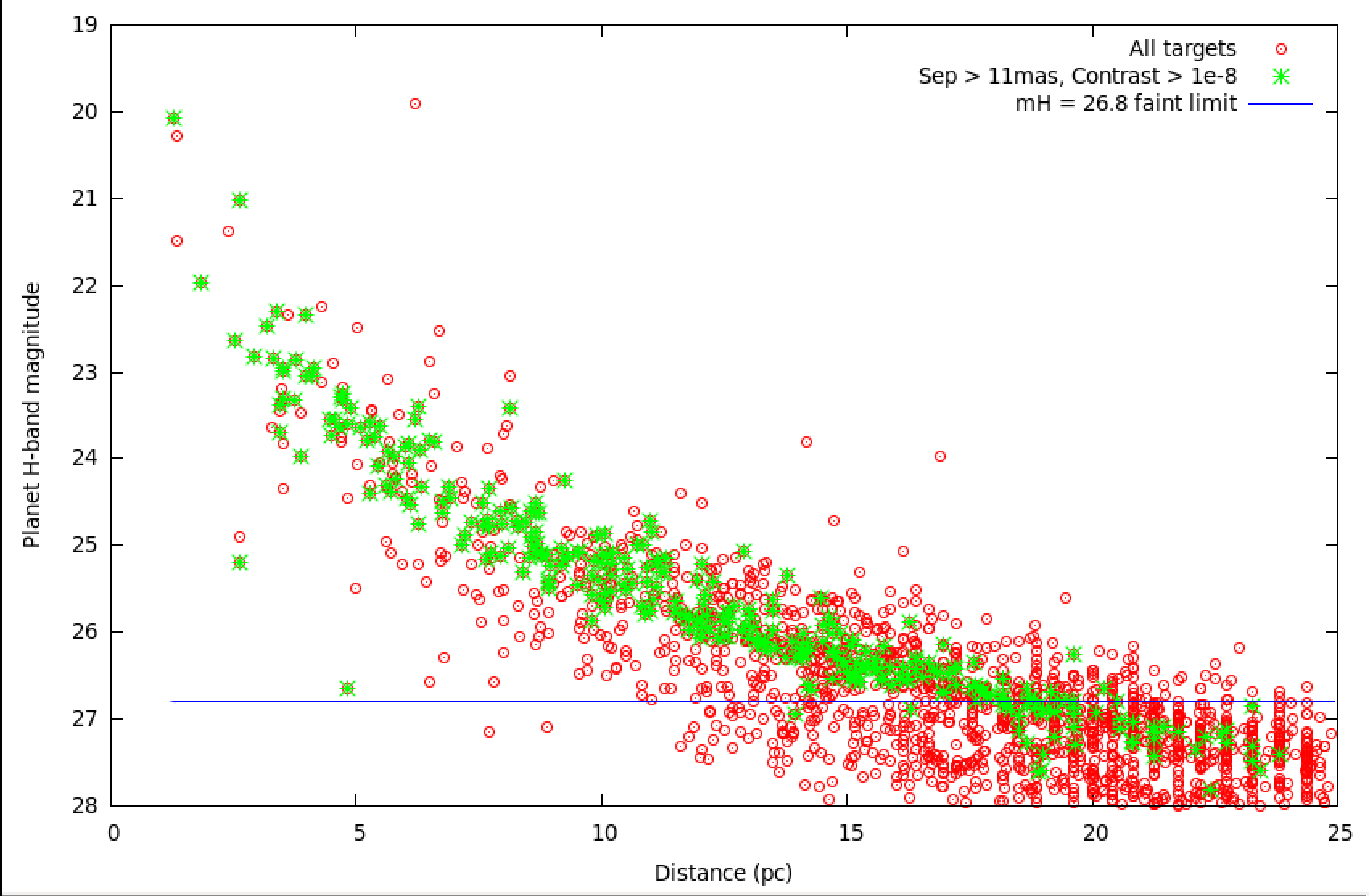
	Limit/constraints	Comments
Angular Separation	Must be > 1.0 λ/D	Limit imposed by coronagraph (see section 4). Corresponds to 11mas on a 30-m telescope in H band.
Contrast	Must be > 1e-8	High contrast imaging limit (see section 5)
Star brightness	Must be brighter than $m_R = 15$	Required for high efficiency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

274 targets survive the first cut

Strong correlation between planet apparent brightness and system distance

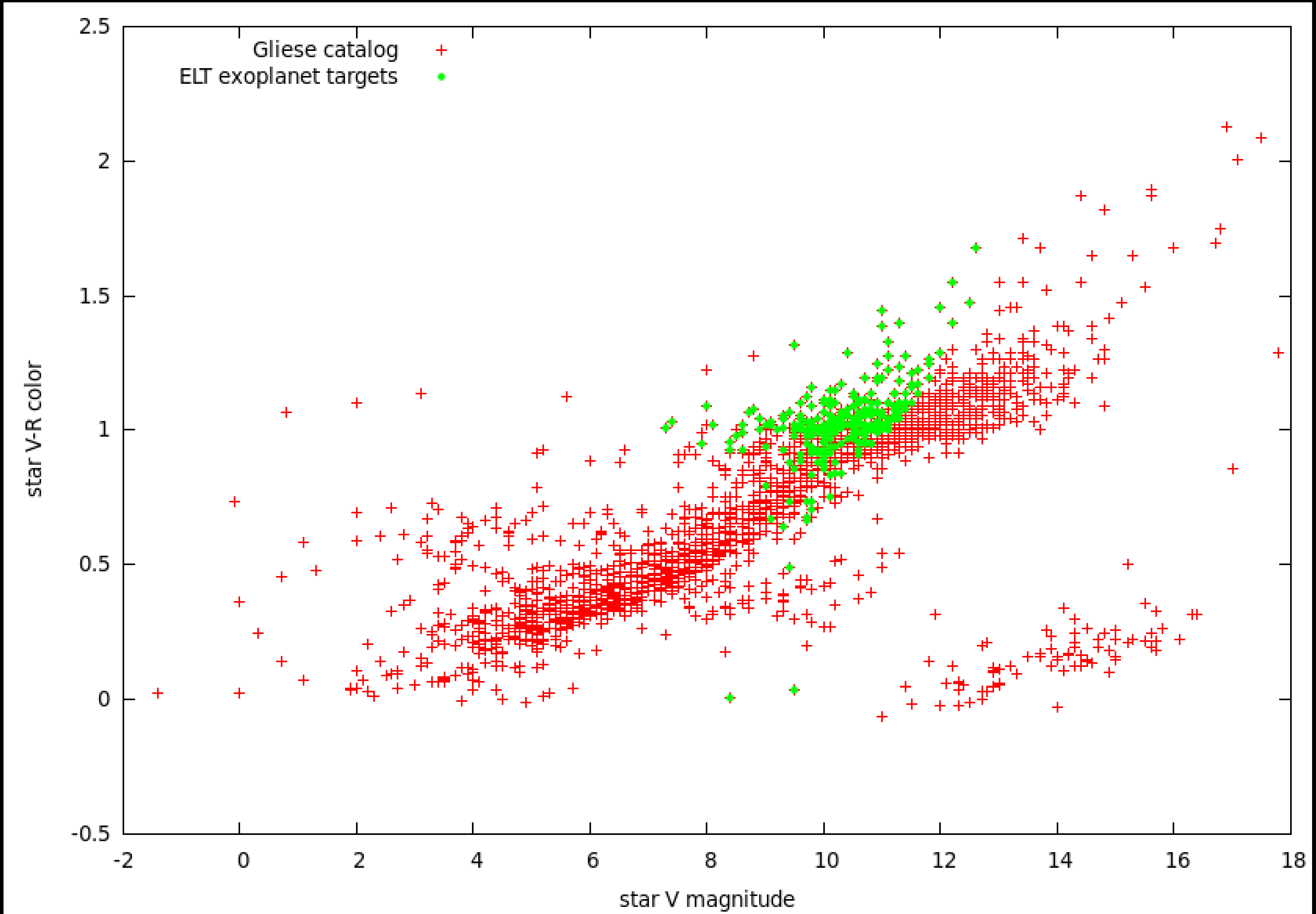


Reflected light planets

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

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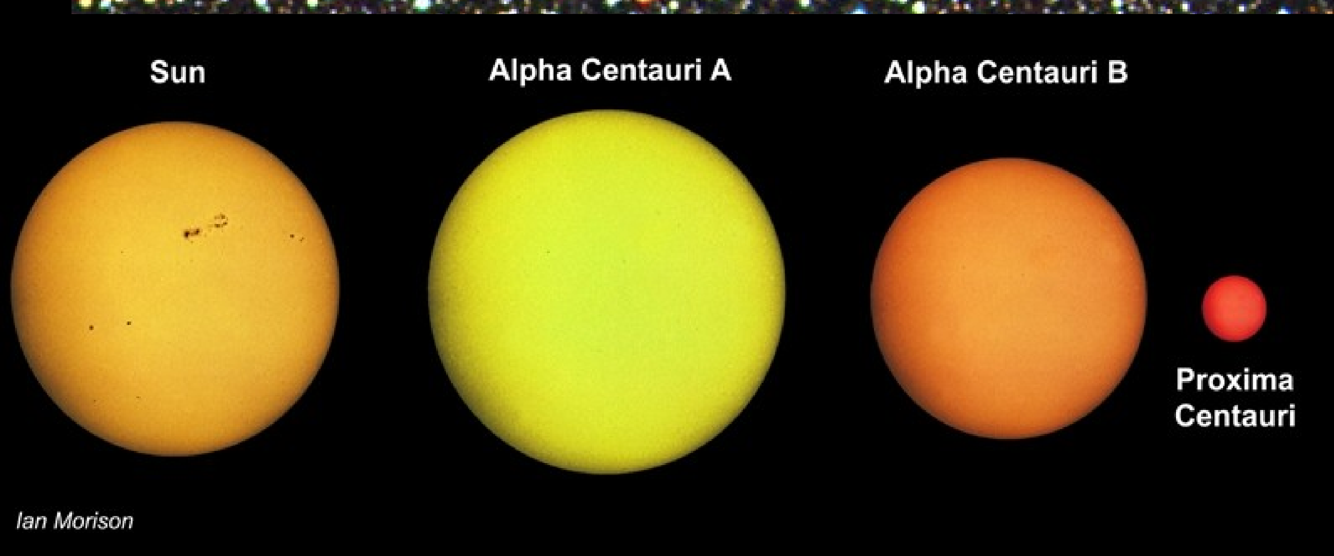
MOST FAVORABLE TARGETS

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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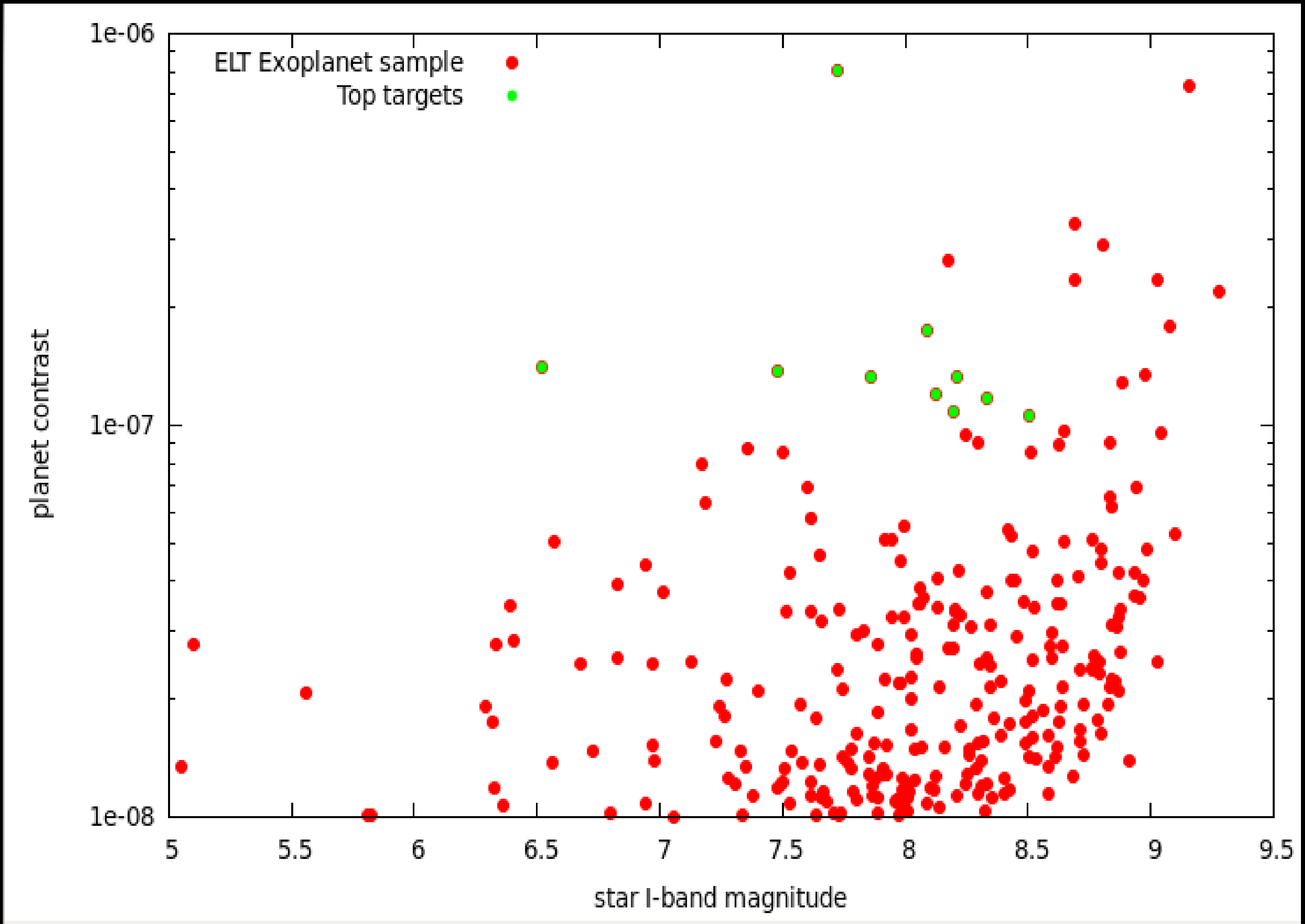


RAW contrast required

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]**
Aperture masking, 100% efficiency	**0.05 [0.2]**	**hopeless...**

Requirements, Top challenges

Efficient coronagraphy

… down to 1 l/D separation on segmented pupils

Coronagraph design

Chromaticity

Stellar angular size

Wavefront control

(getting raw contrast at or below 1e-4 at 1 l/D)

Efficient sensing of low order aberrations

Control and calibration of pointing errors

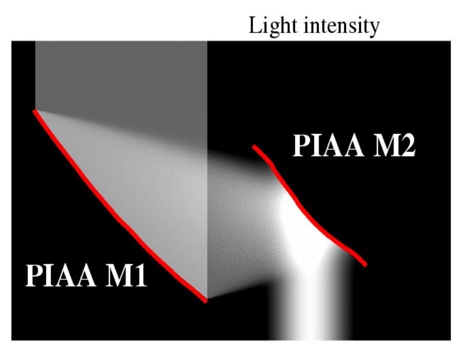
Wavefront calibration to 1e-7

(separating scattered light from planet light)

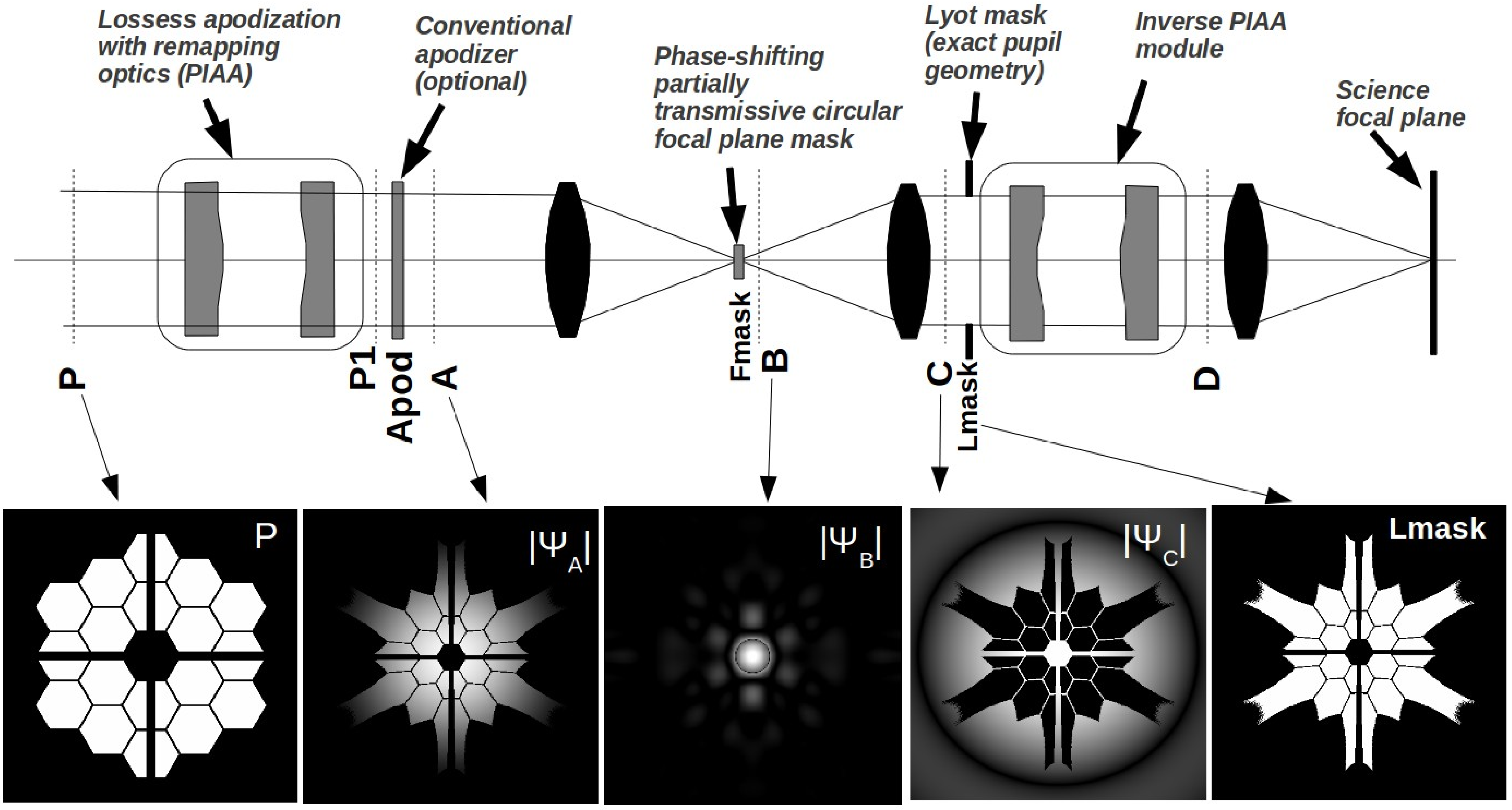
Main issues: time lag, chromatic effects, systematics

The need for nearIR wavefront modulation and correction

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



Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)



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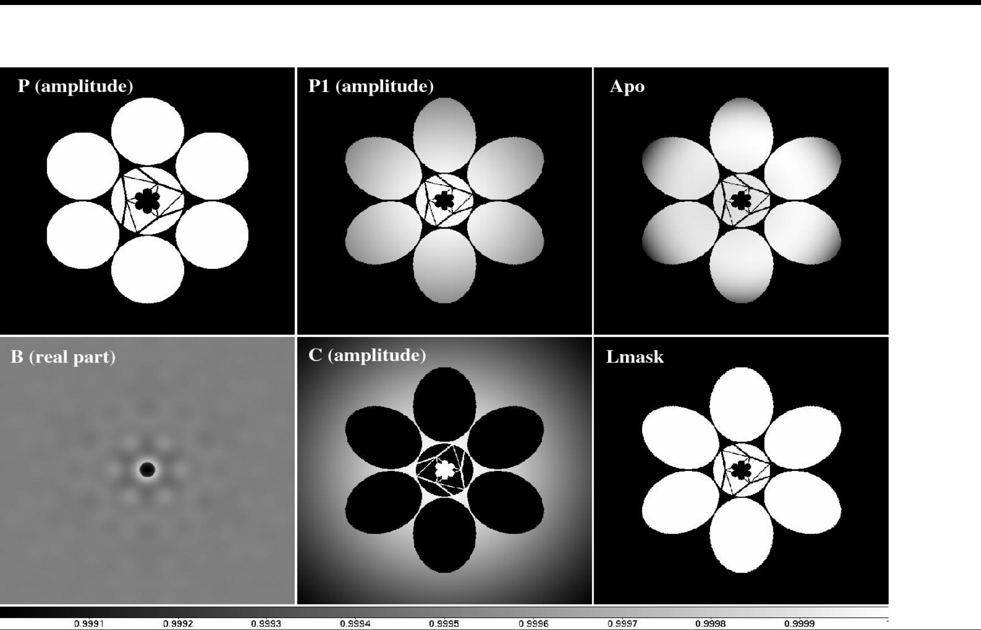
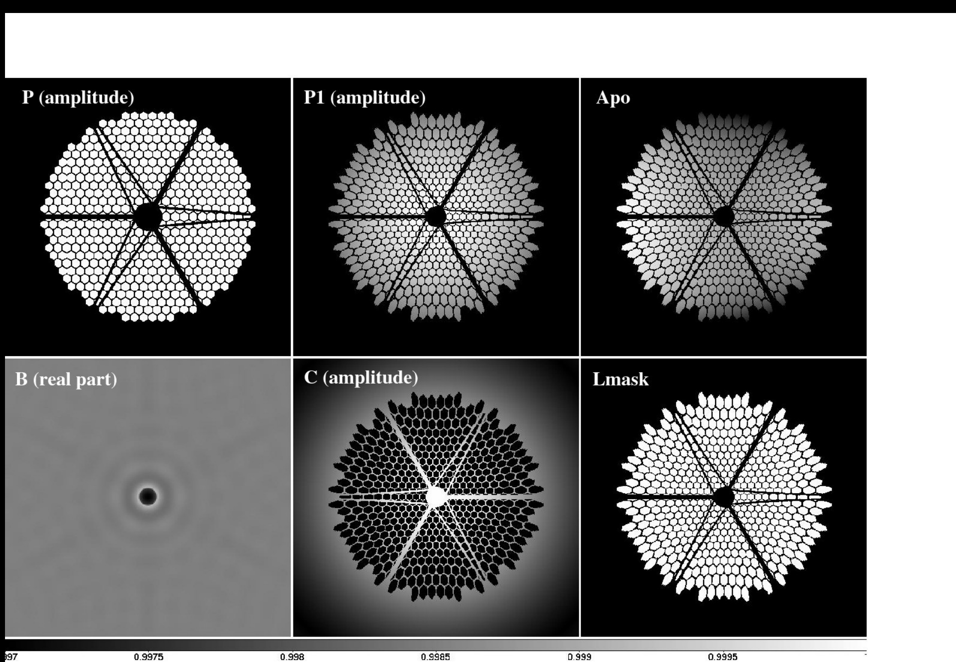
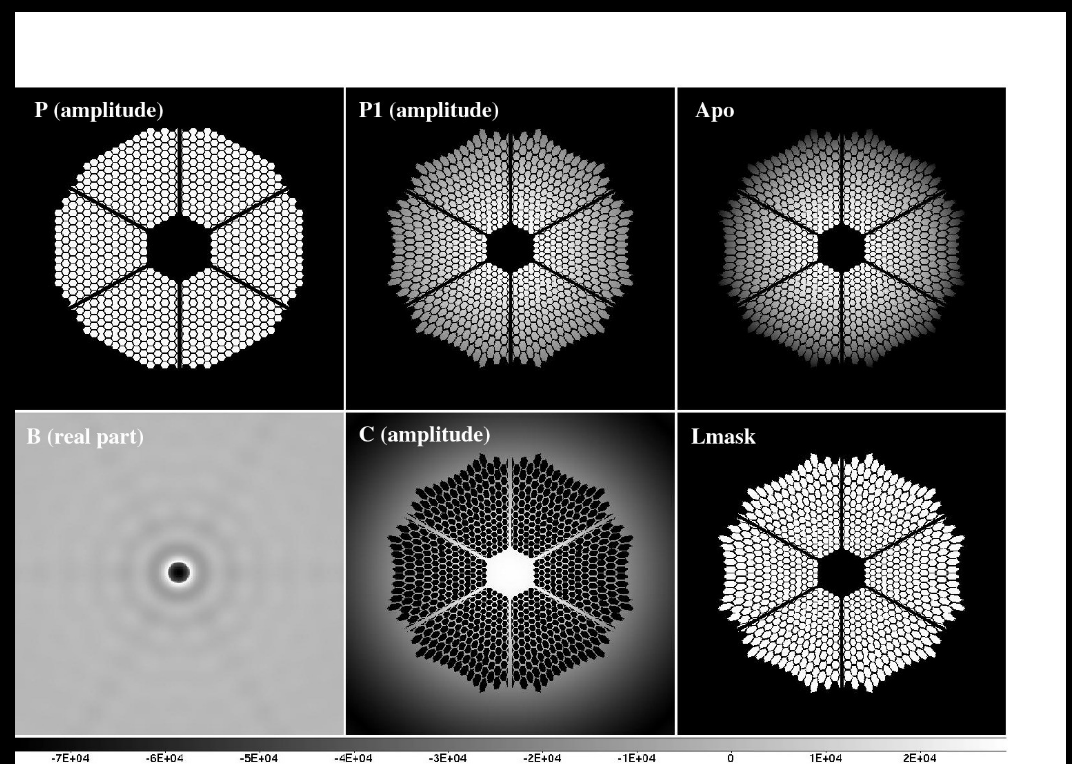
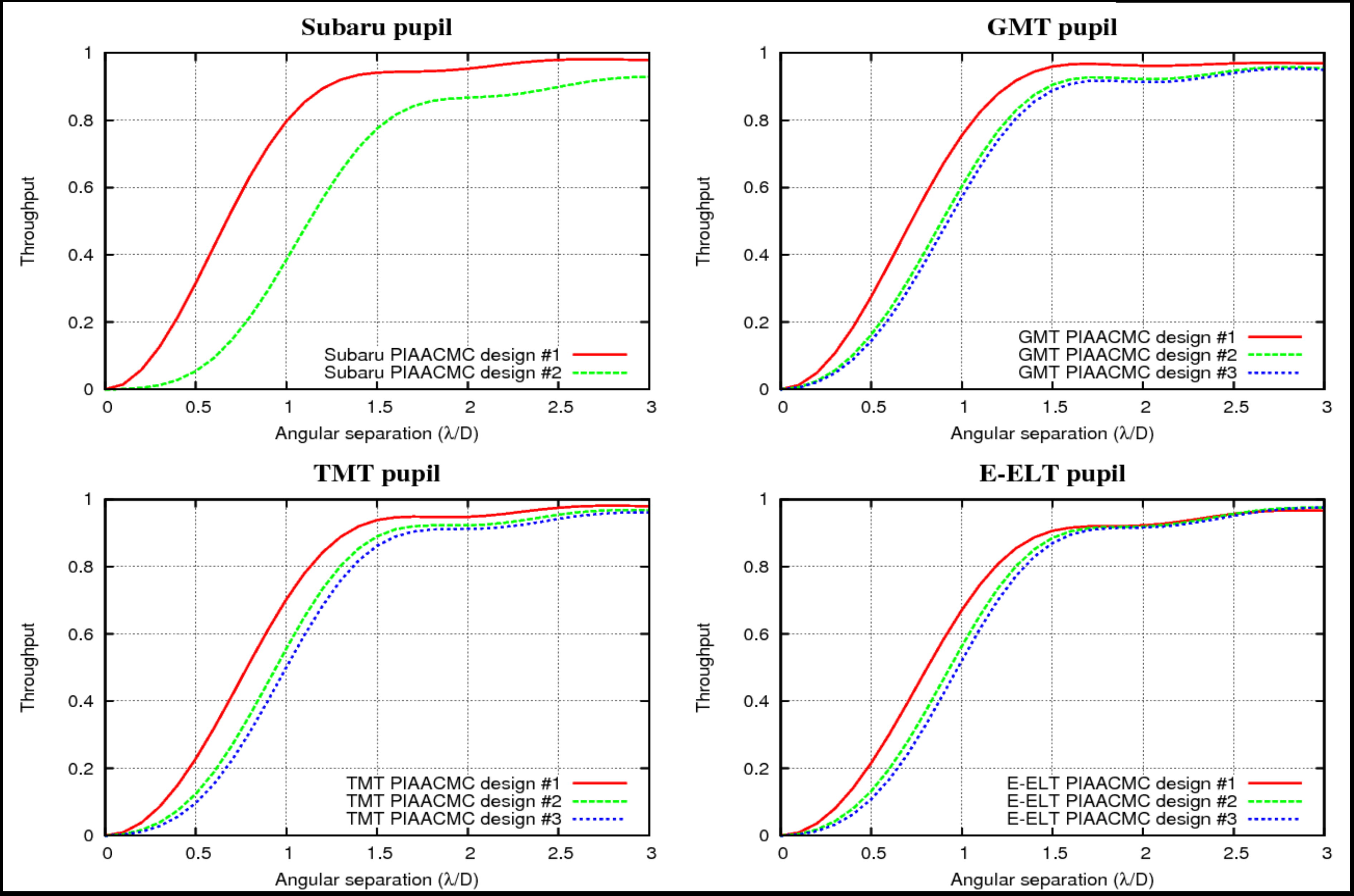


<u>Pupil shape does not matter !!!</u>





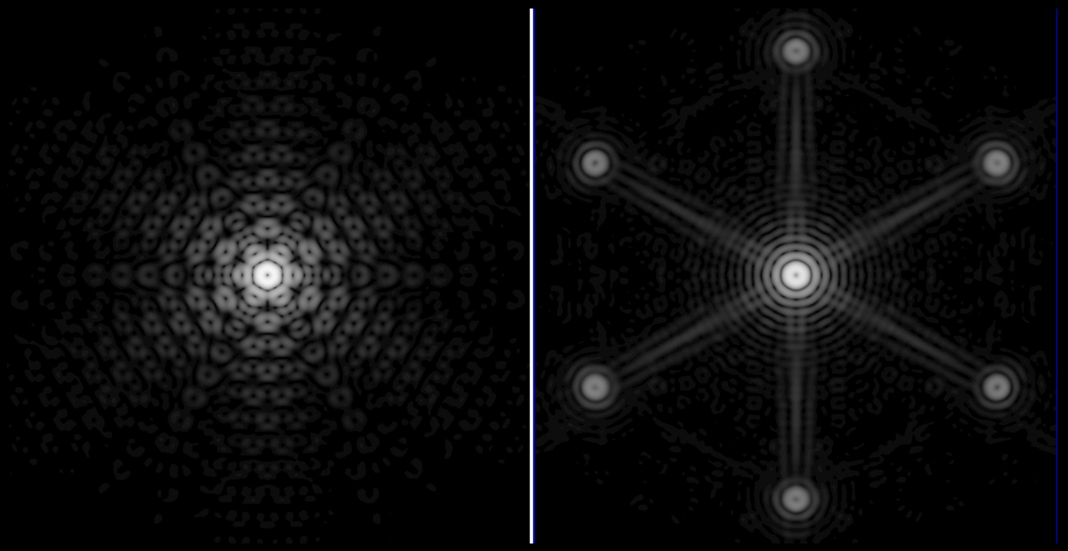
PIAACMC gets to < 1 l/D with full efficiency, and no contrast limit

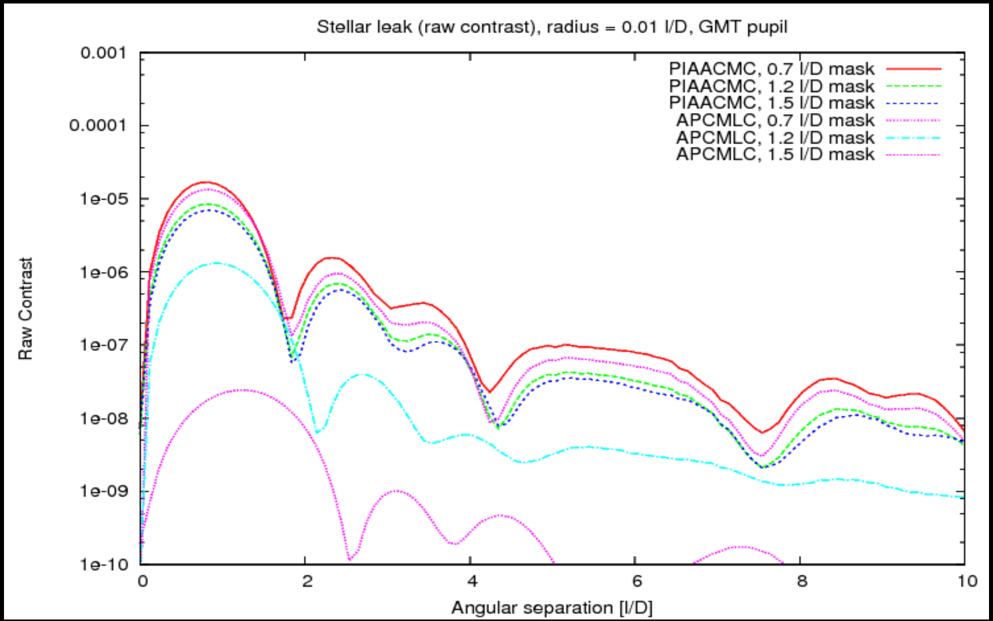


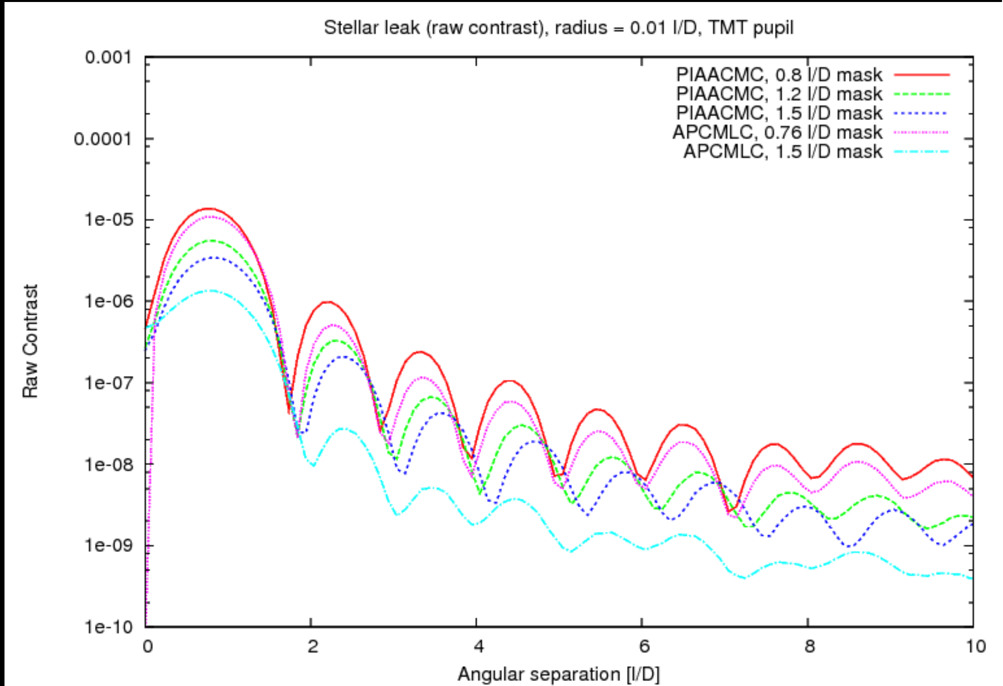
Coronagraphy: Stellar angular size

On ELT in near-IR, nearby M dwarf is about 0.1 to 0.5 mas radius = 0.01 to 0.05 l/D

→ for 1 l/D IWA coronagraph
RAW contrast limited to ~1e5







Wavefront control

Can we reach 1e-4 RAW contrast in the 1 to 2 l/D range ?

Goal: ~1e-5 contrast at 1 l/D

We are not that far from it with current technology...

Conventional high order ExAO on 8-m class telescope achieves ~1e-3 contrast in near-IR at few l/D

Moving to 3x larger telescope diameter will help (dilute speckle halo) – at equal SR, 10x gain in contrast → 1e-4

BUT **we can EASILY do much better** by :

(1) Using diffraction-limited WFS (Pyramid with little or no modulation, nlCWFS, Zernike etc...)

For Tip-tilt, gain in flux is $(D/r_0)^2$ = 90,000 on 30m telescope (12.8 mag)

(2) Making use of predictive control in the control loop (inner PSF flux dominated by time lag)

Wavefront calibration to ~1e7 contrast

SDI, ADI WILL NOT WORK AT 1 l/D !!!

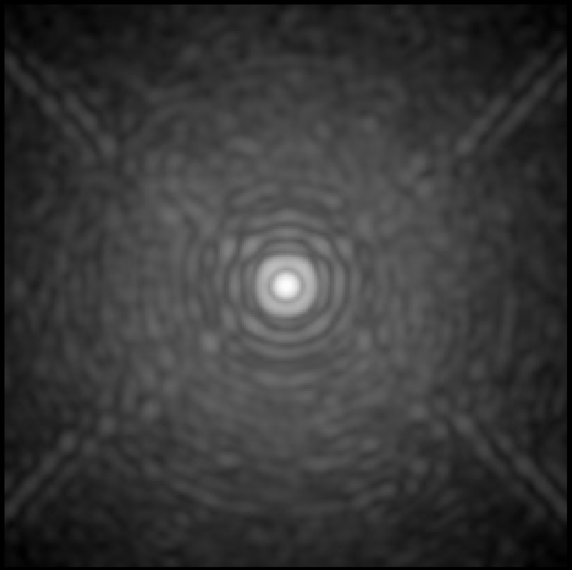
Focal plane speckle modulation appears to be very promising:

- no need for high optical quality
- non non-common path errors
- detectors now exist to do this efficiently

→ SCExAO (and others...) using this technique

Works well in the lab when things are stable... will it also work on sky with speckles moving around ?

Focal plane AO and speckle calibration



Use Deformable Mirror (DM) to add speckles

SENSING: Put “test speckles” to measure speckles in the image, watch how they interfere

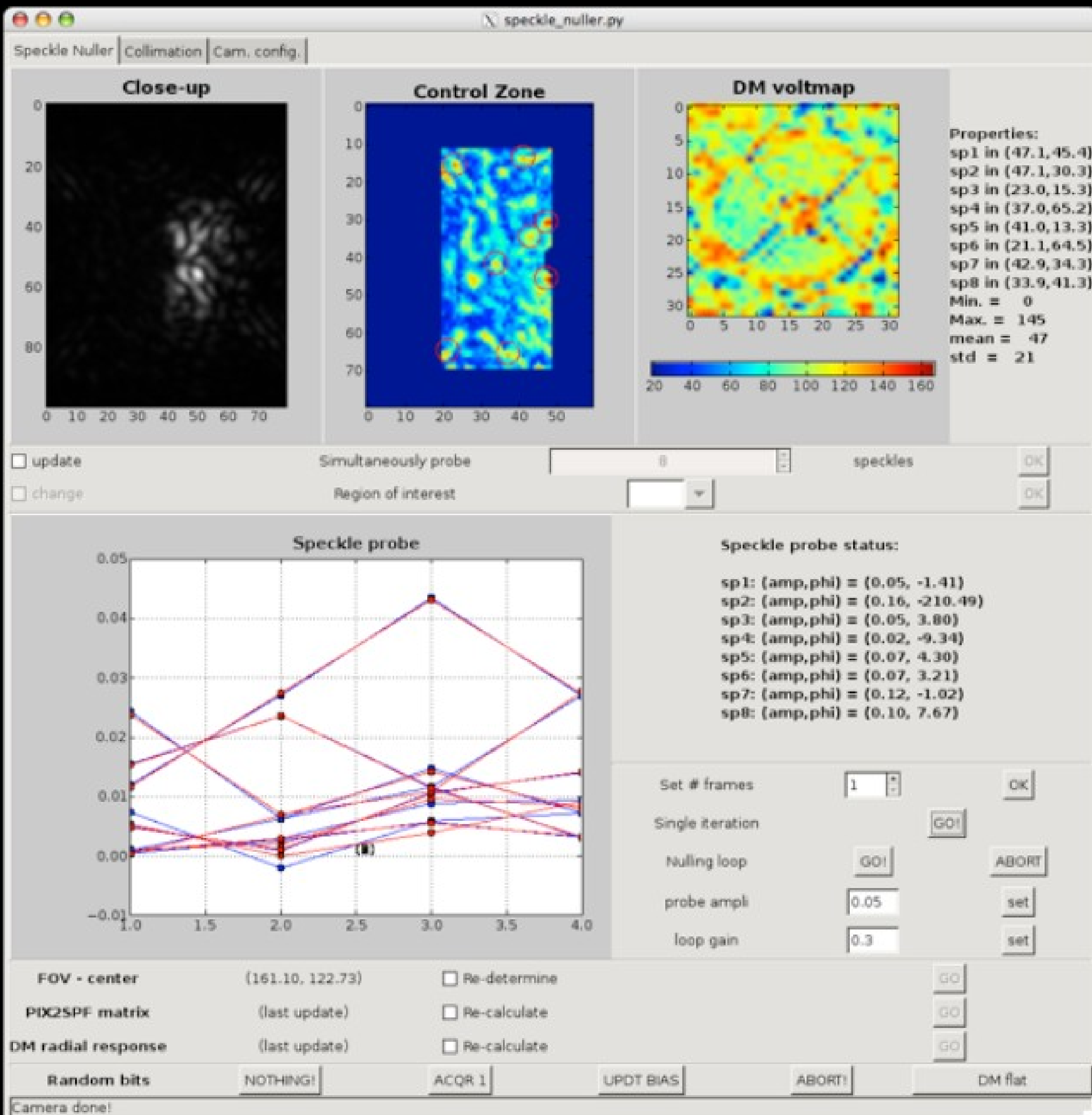
CORRECTION: Put “anti speckles” on top of “speckles” to have destructive interference between the two (Electric Field Conjugation, Give’on et al 2007)

CALIBRATION: If there is a real planet (and not a speckle) it will not interfere with the test speckles

Fundamental advantage:
Uses science detector for wavefront sensing:
“What you see is EXACTLY what needs to be removed / calibrated”

Speckle nulling control software

(Martinache et. al)



Readout overhead with HiCIAO ~ 10-15 seconds prevents from using it in an even remotely efficient close-loop.

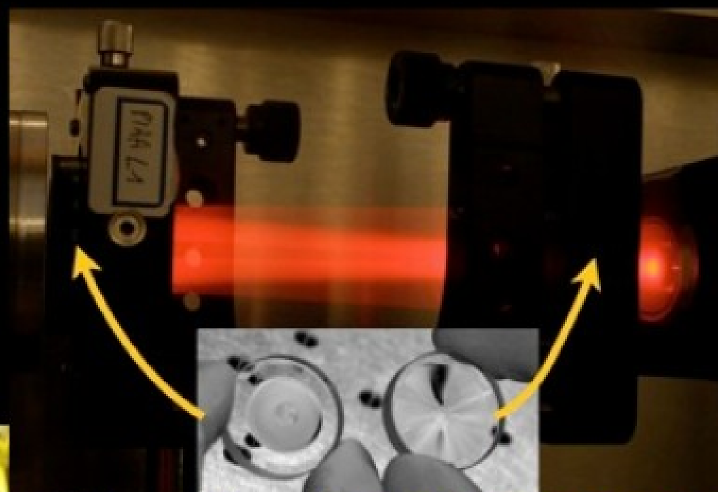
Speckle nulling relies on the analysis of images acquired with the internal "science" camera. Readout is faster than necessary (~50 Hz), however integration time is limited by the dark current to ~ 20 milli-seconds.

The software can track an arbitrary number of diffraction features, and iteratively drives them down with the DM by adding speckles that interfere destructively with the diffraction (in half the field of view).

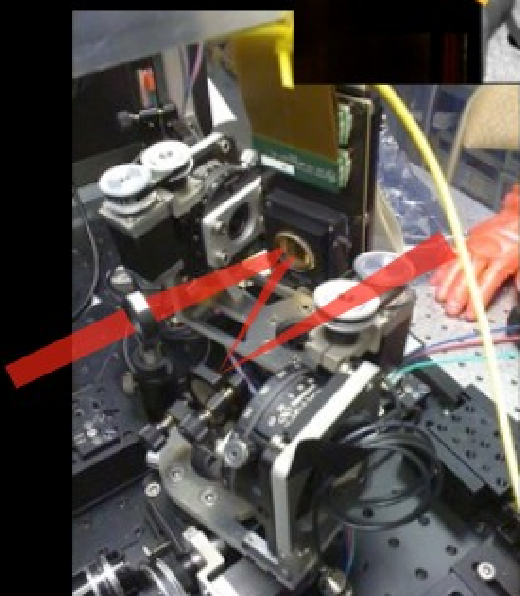
After several iterations of speckle nulling, long exposures with HiCIAO can be used for science purposes, benefiting from a cleaner image at small angular separation.

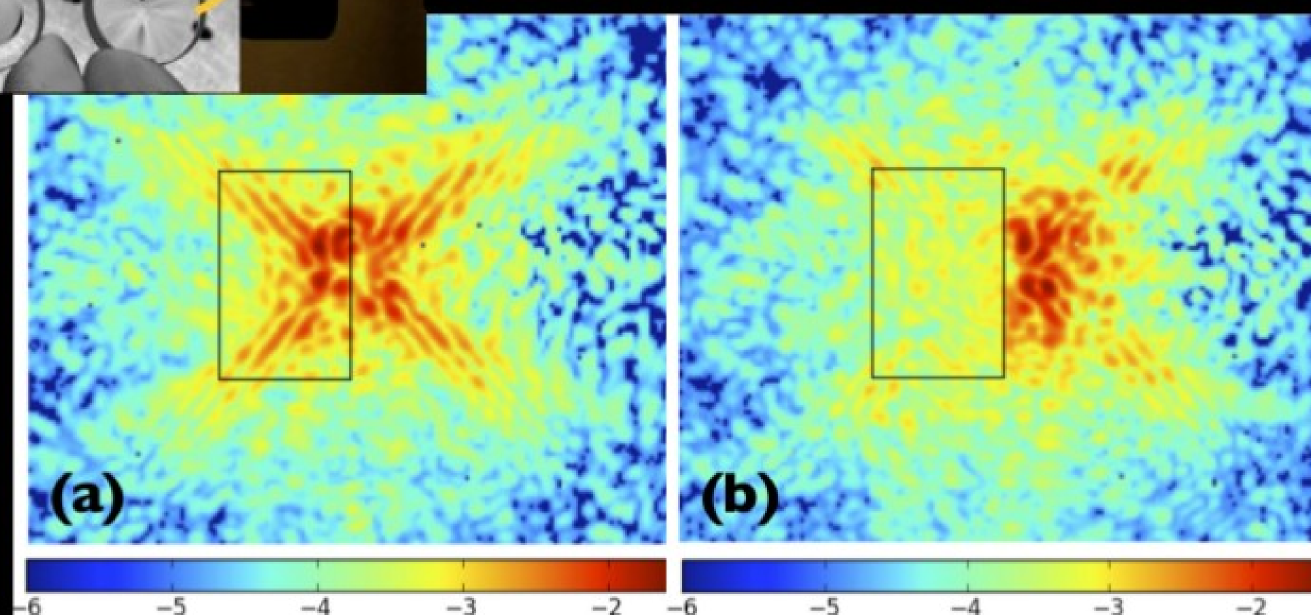
Active speckle control (Martinache et. al)

Active MEMS DM to replace a passive ADI approach at small angular separation



Taking advantage of the full PIAA - focal plane mask - $PIAA^{-1}$ optical configuration

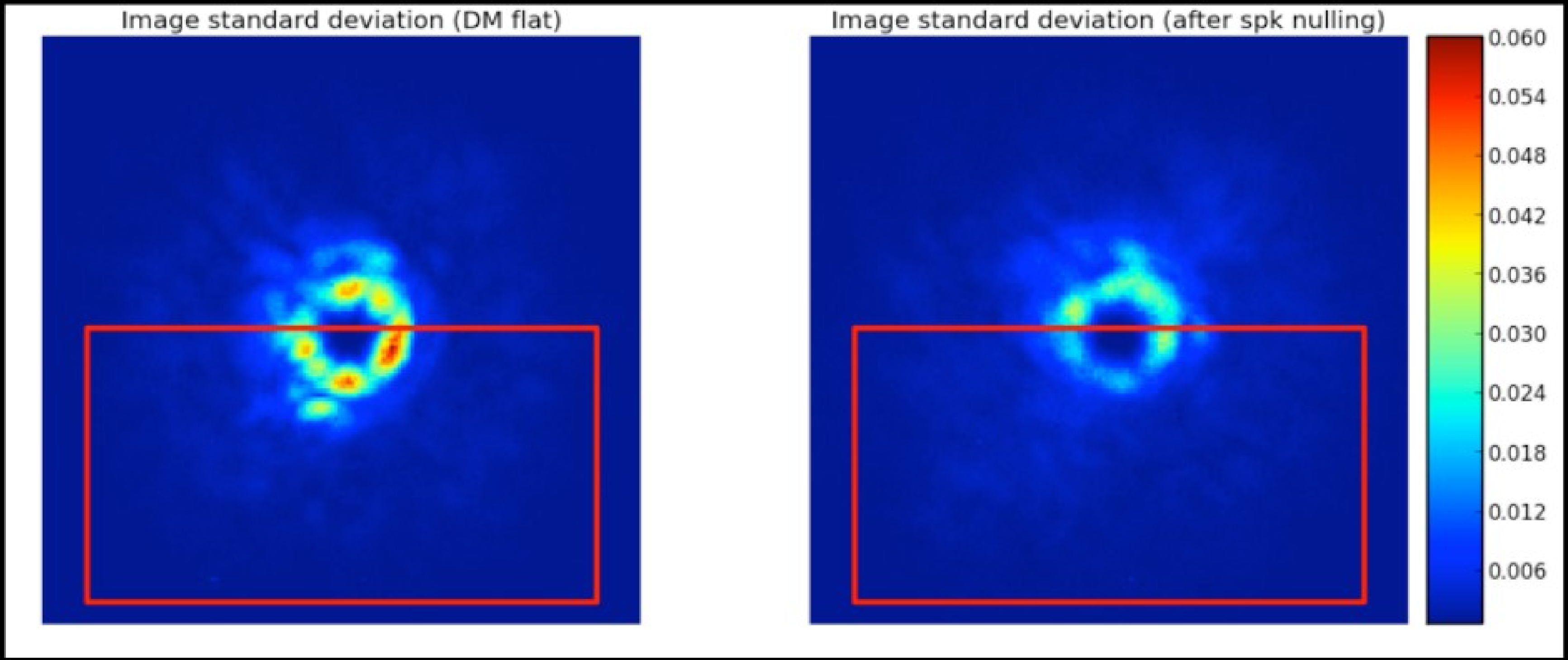




SCExAO's PIAA coronagraph permits speckle control from 1.5 to 14 λ/D
Raw contrast ~ 3e-4 inside the DM control region

Martinache et al, 2012, PASP, 124, 1288

Improved sensitivity (Martinache et. al)



Detection limits are fundamentally set by the local effect of temporal fluctuations in the diffraction.
The proper metric to estimate the benefit of the technique: standard deviation across the same data-cubes for the "flat" and the "optimized" DM volt-maps

Two observations:
- overall, the standard of the image after speckle nulling is reduced over the entire frame (x ~1/2)
- inside the control region, the sensitivity gain tops at a factor of ~7.

At the smallest angular separations (how many l/D?), the detection limit is improved by 1-2 magnitudes.

Martinache et al, 2013, in preparation

Imaging habitable planets with ELTs

Habitable planets can be imaged with ELTs around low-mass stars. Spectroscopy of several targets could also be done at a very useful R~100 → this is the easiest quickest way to characterize habitable planets

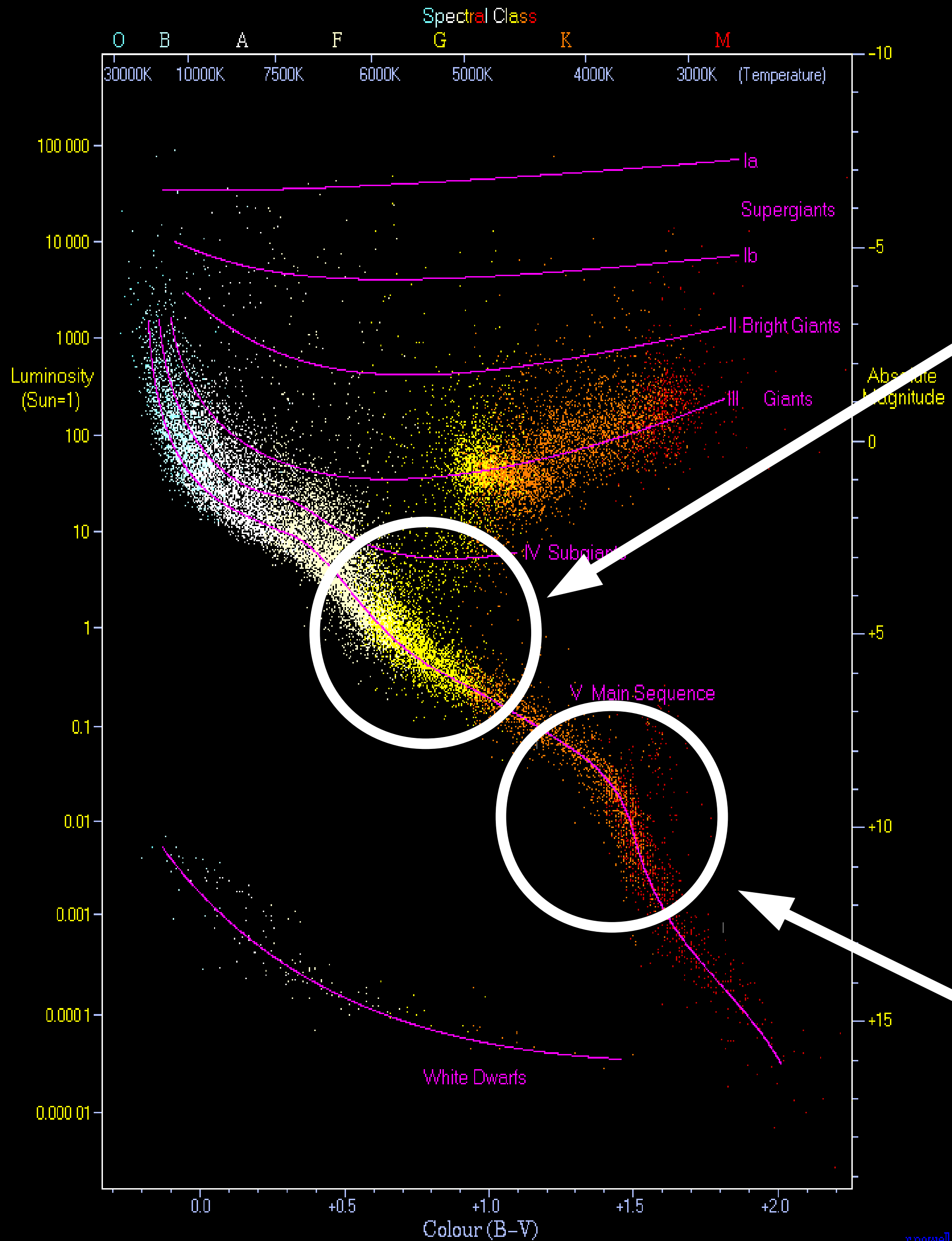
This requires aggressive IWA system able to work at 1 lambda/D and somewhat unusual (but not particularly challenging) technical choices

Technologies are being matured now, and should be ready in 10yrs **ASSUMING WE WORK ON IT**

This should be a focused experiment for <100 targets. Can be deployed quickly and cheap → great science per $!!!!

SCExAO is a precursor to such a system. A SCExAO-like system could be placed on an ELT in a short time, as optical interfaces for narrow FOV system are relatively easy

Detecting planets from space and ground



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

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

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

SCExAO on Subaru will image giant planets in the habitable zone of nearby stars

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

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

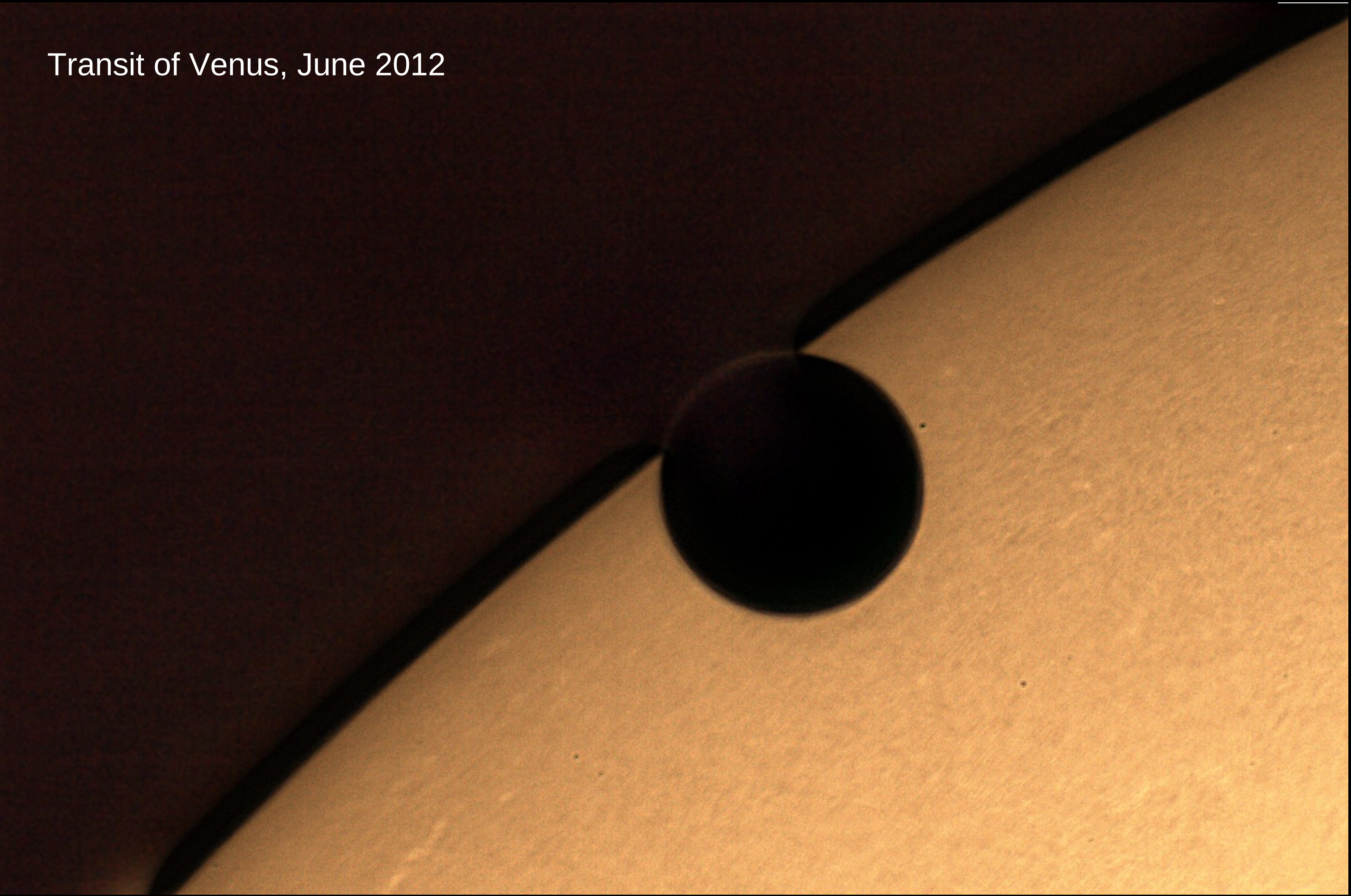
GROUND: Imaging habitable planets around M-type stars with ELTs; SCExAO as a precursor

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: **users@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)

Phase 1 (completed)

GOALS:

Demonstrate low-cost reliable hardware solution

→ prototype system has 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

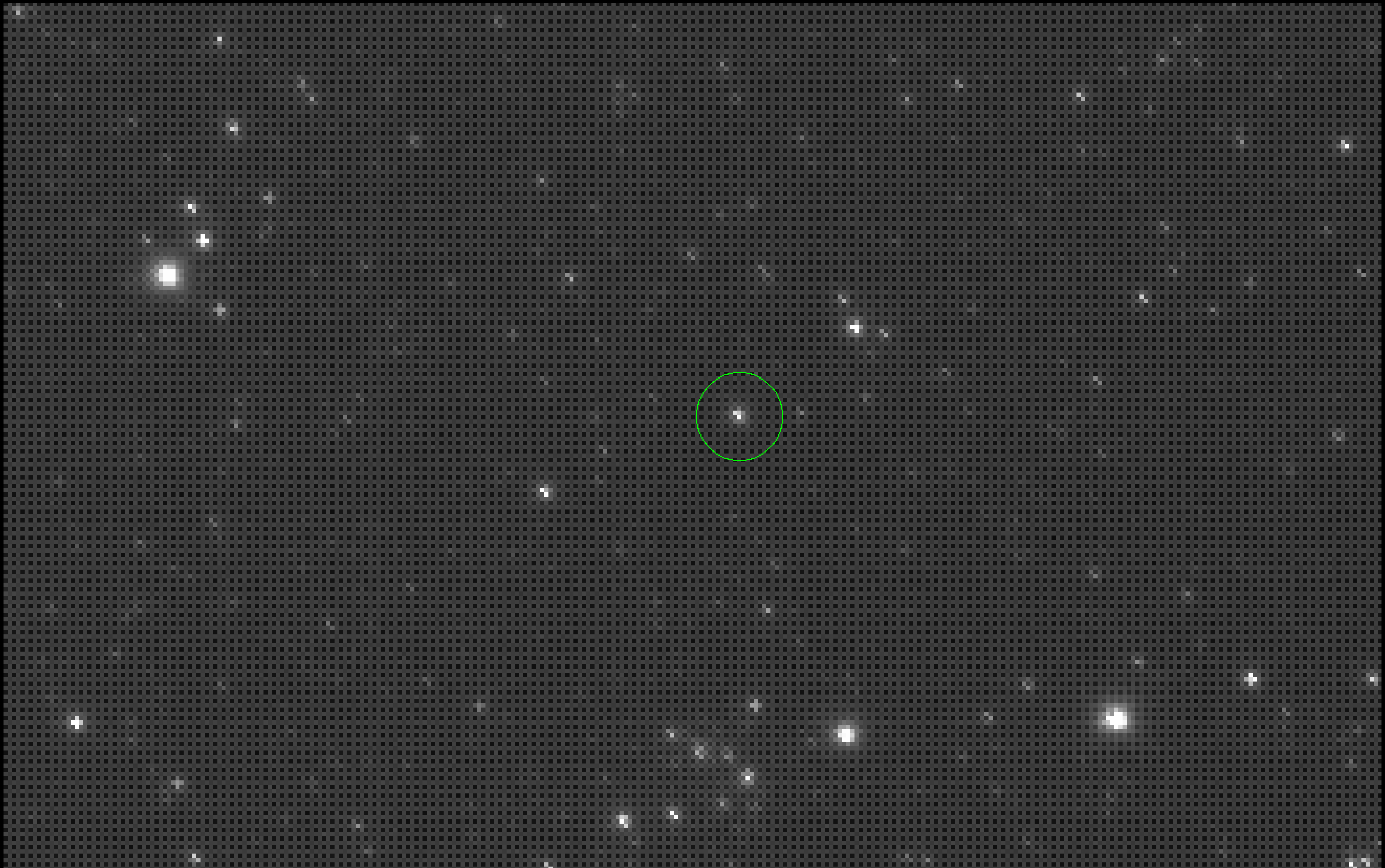
PANOPTES prototype unit at Mauna Loa observatory

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

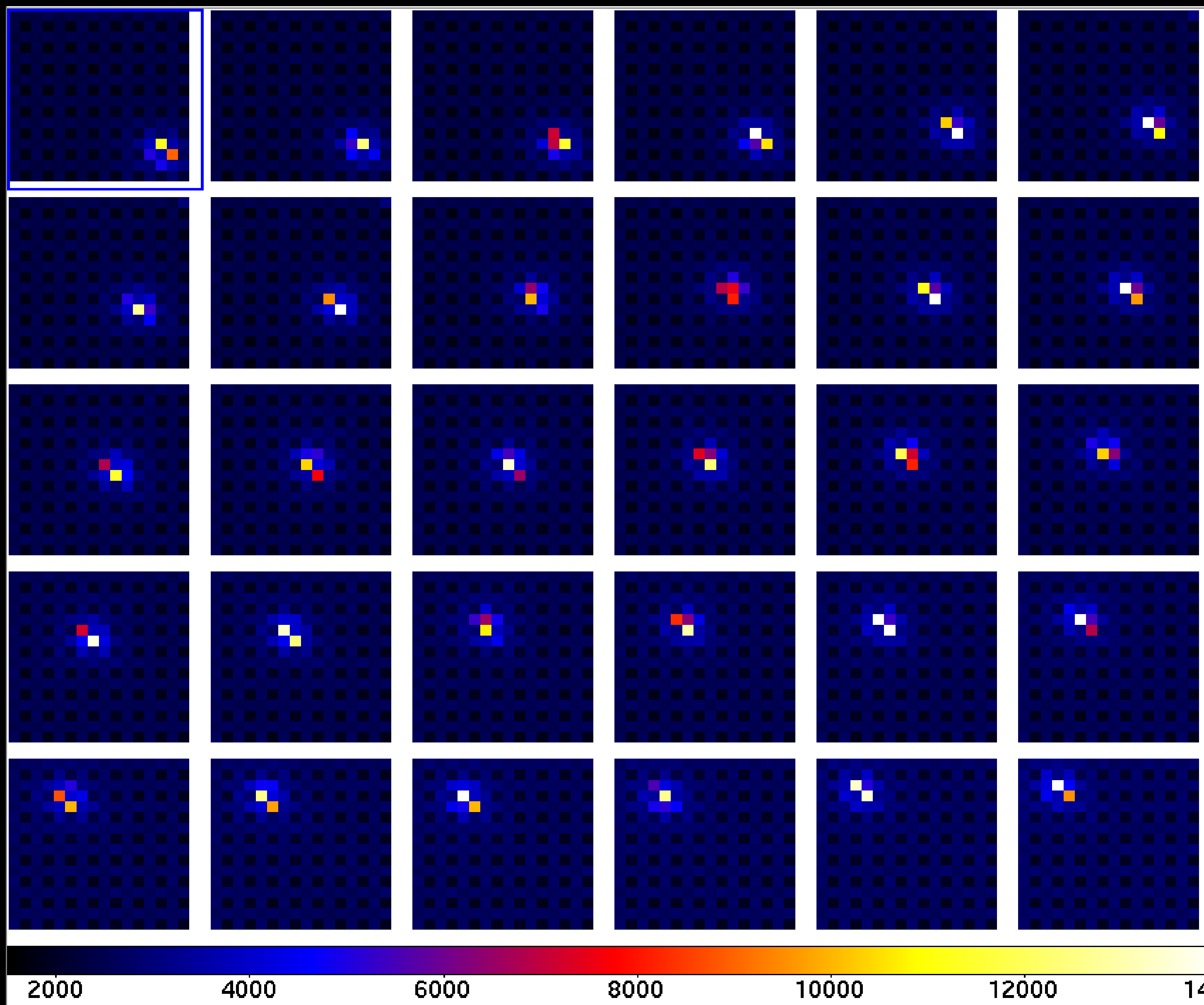
Example image – 315 sec exposure, ISO 100 (March 1, 2011)

Lower left corner of previous image

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

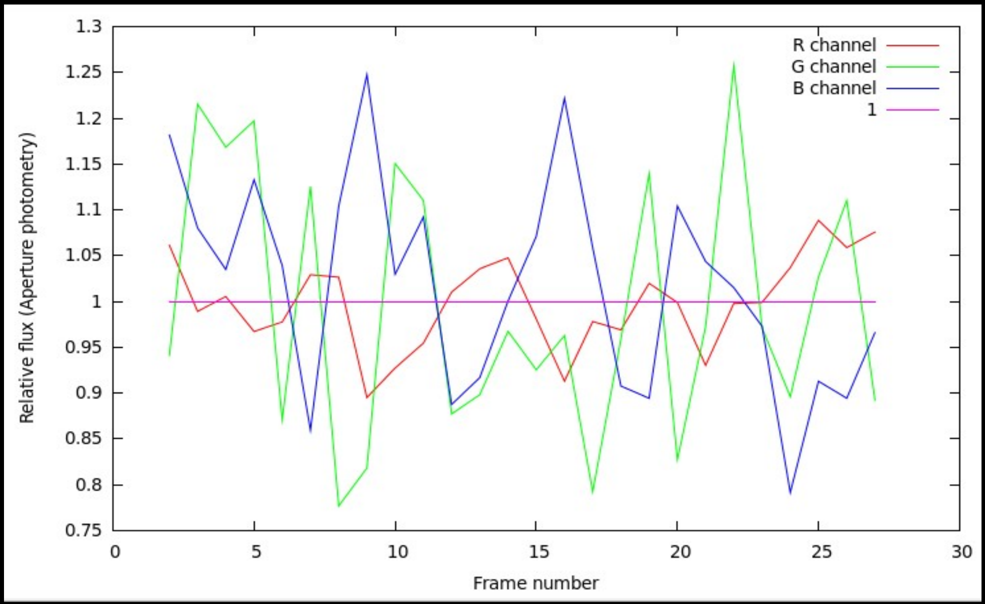


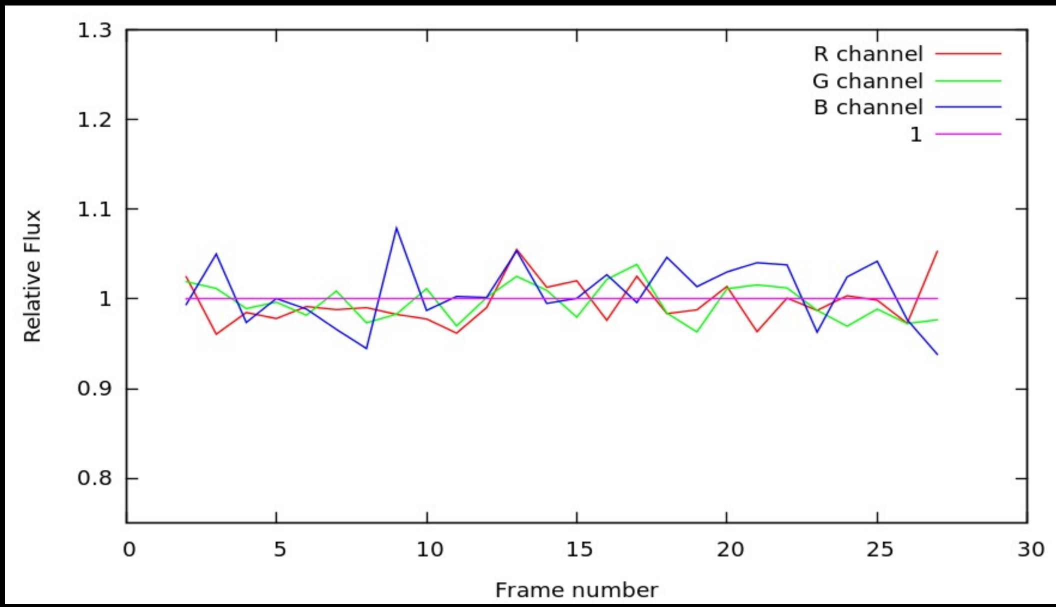
Test on star HD54743 (V=9.35)
1 mn cadence



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%**	





Next steps

Build more units, deploy them around the globe for 24hr coverage

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

Set up data storage and processing hub