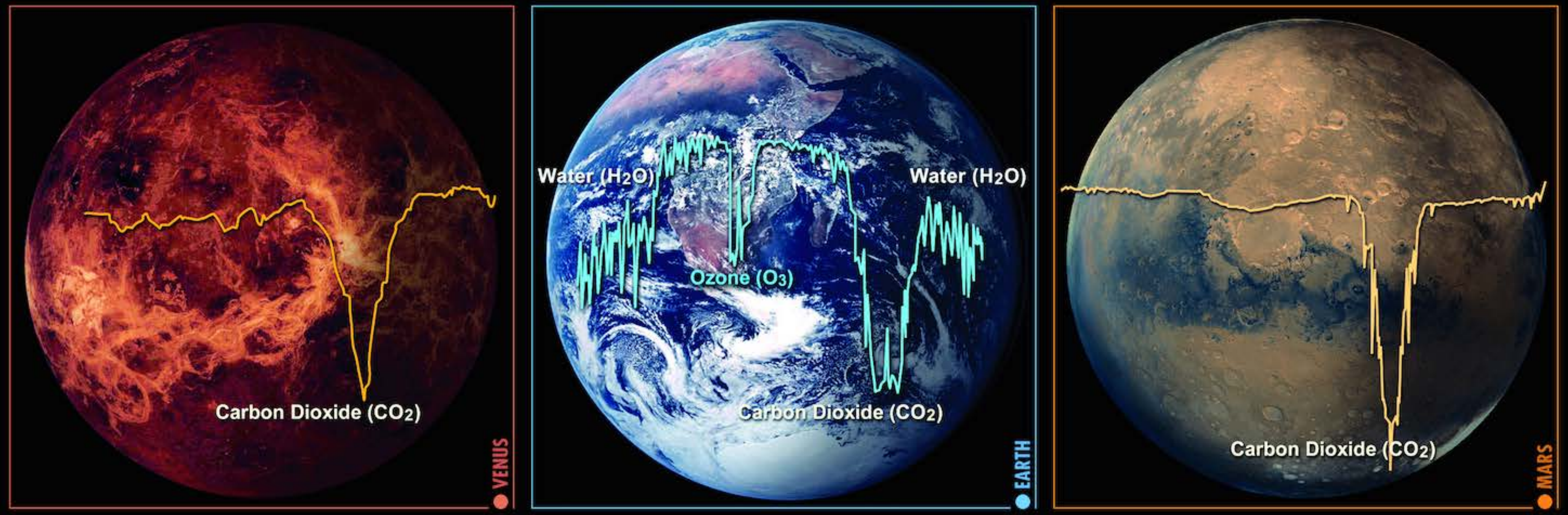
Towards the direct detection of terrestrial exoplanets

Sascha P. Quanz (ETH Zurich)

LTP/PSI Thursday Colloquium
Nov. 26, 2020



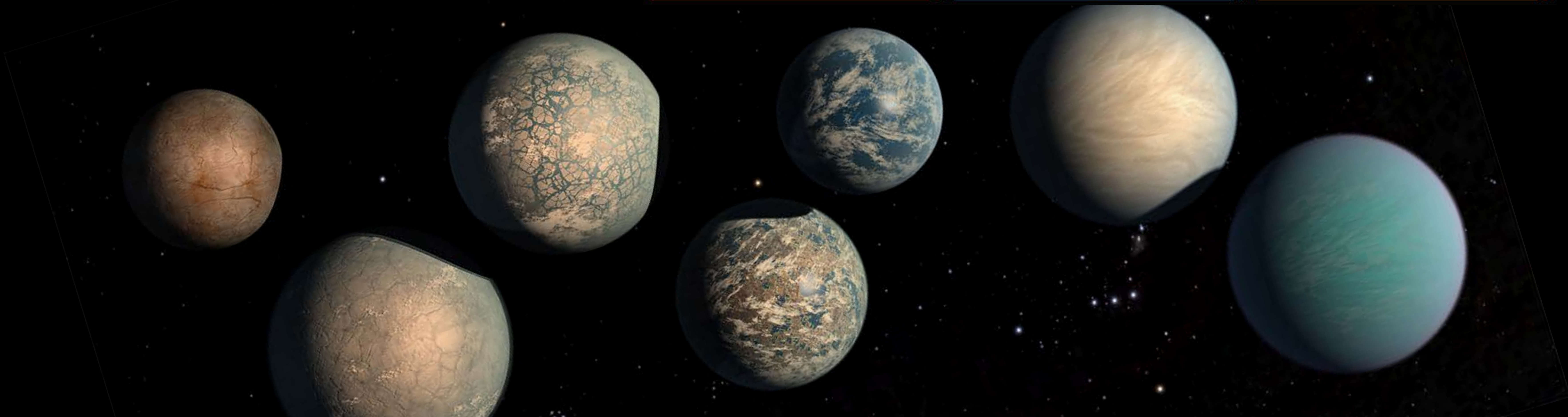
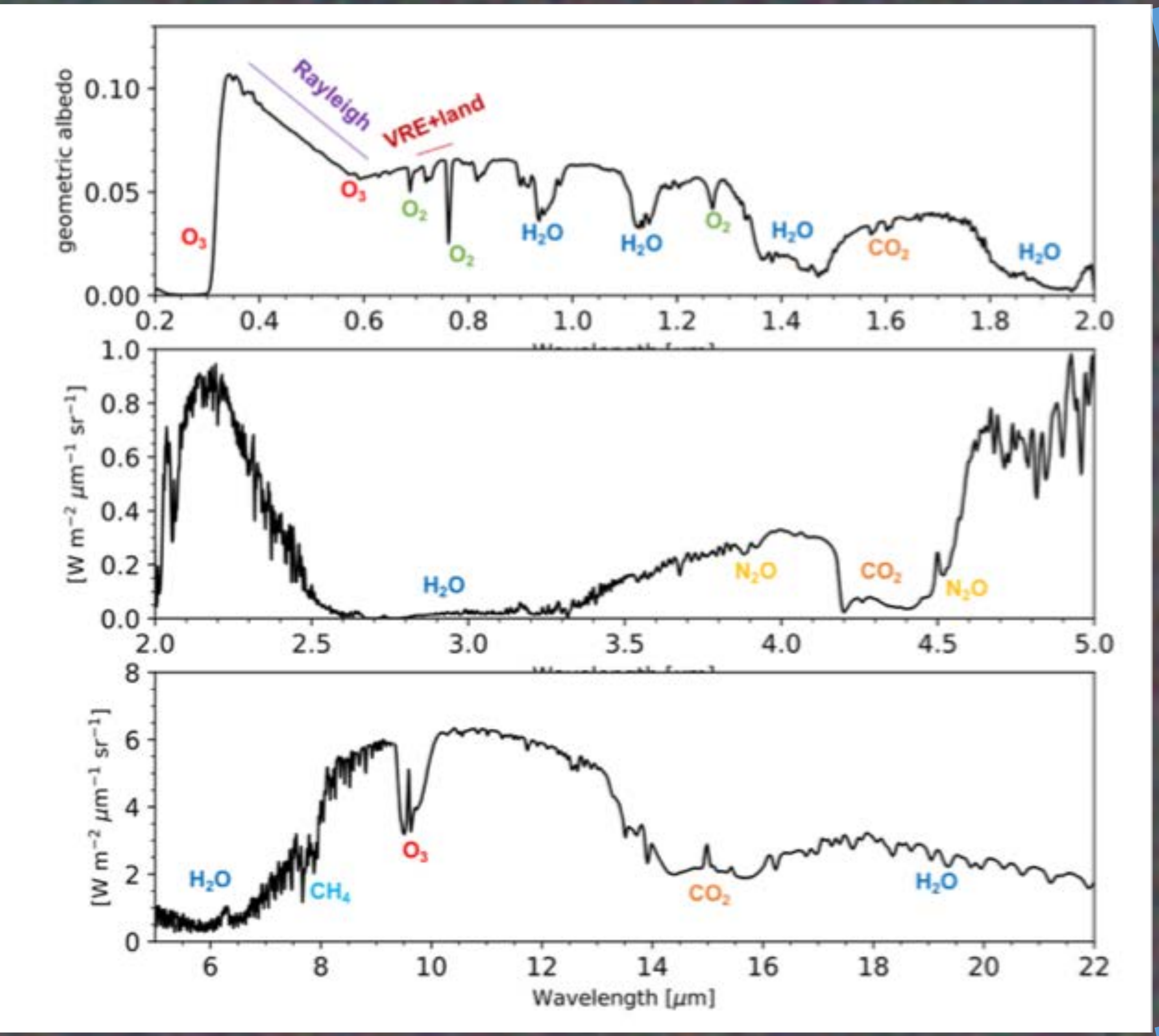


Image credit: NASA/JPL Caltech; ESA Medialab

ARE WE ALONE IN THE UNIVERSE



Schwieterman et al. 2017

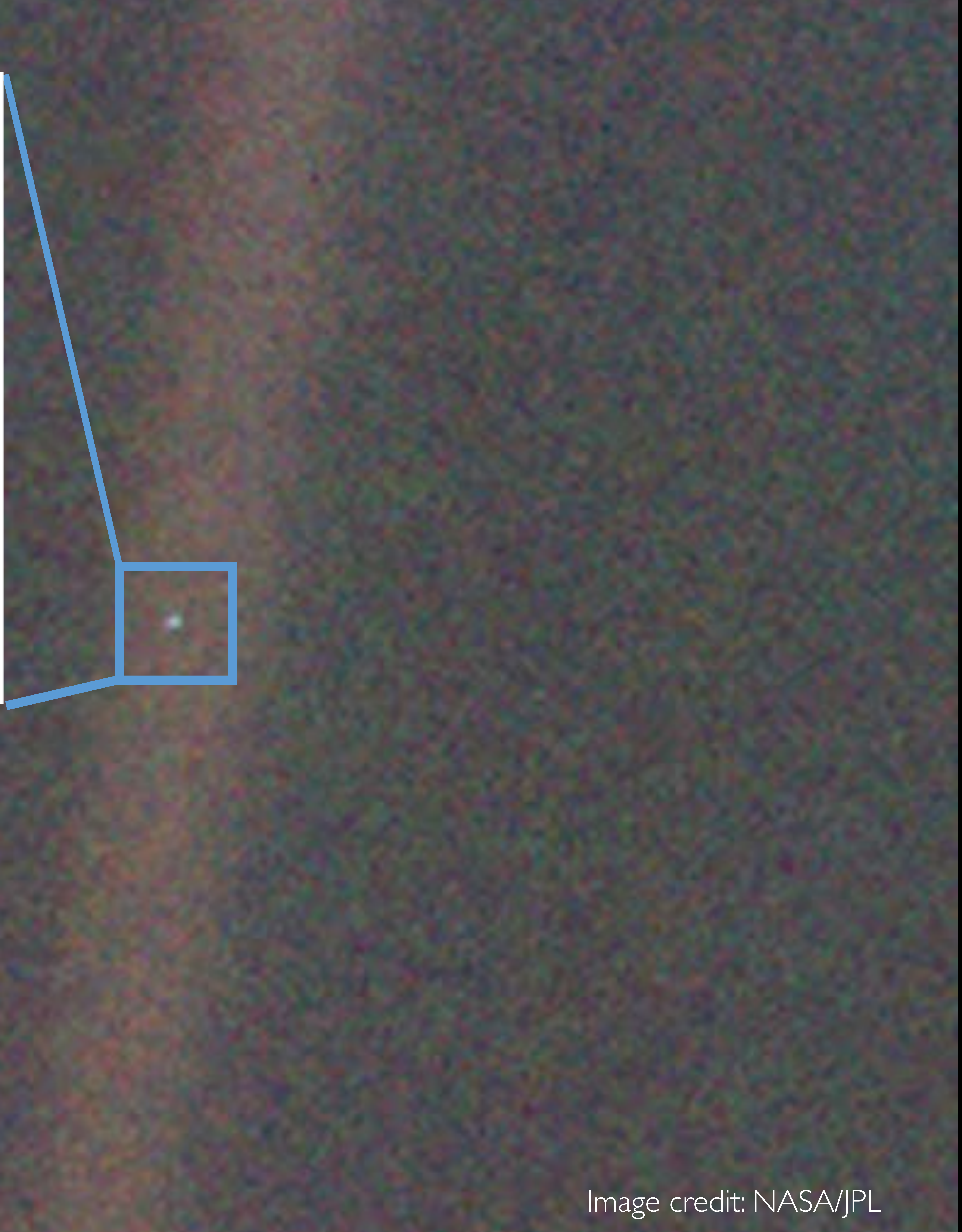
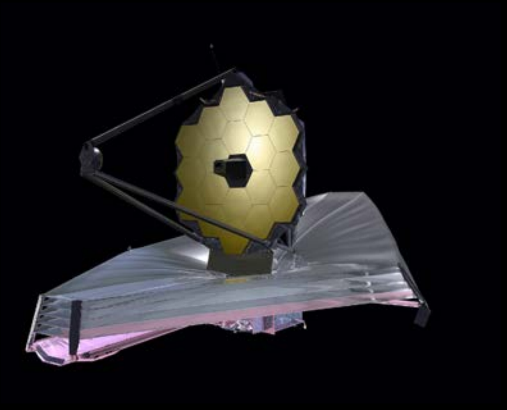
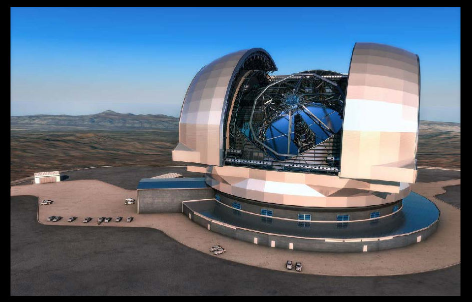
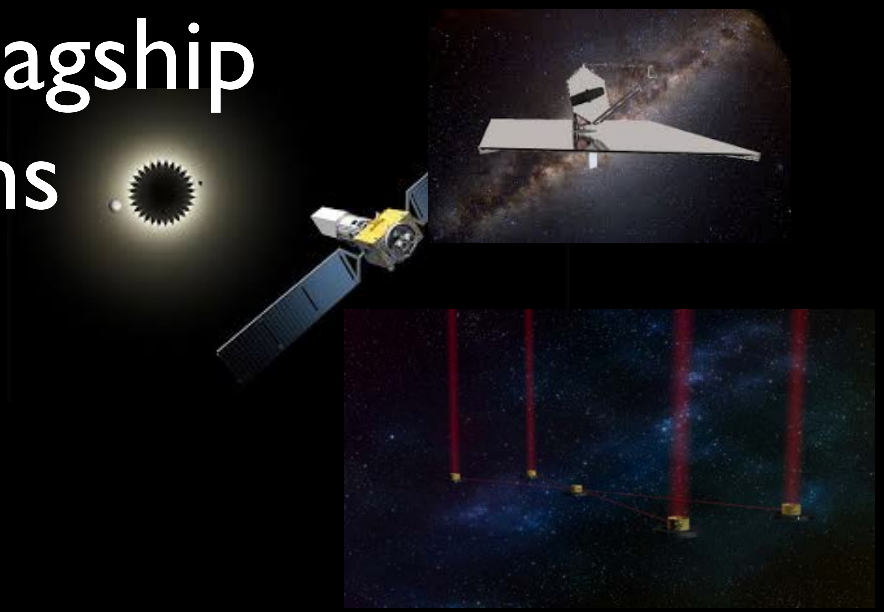
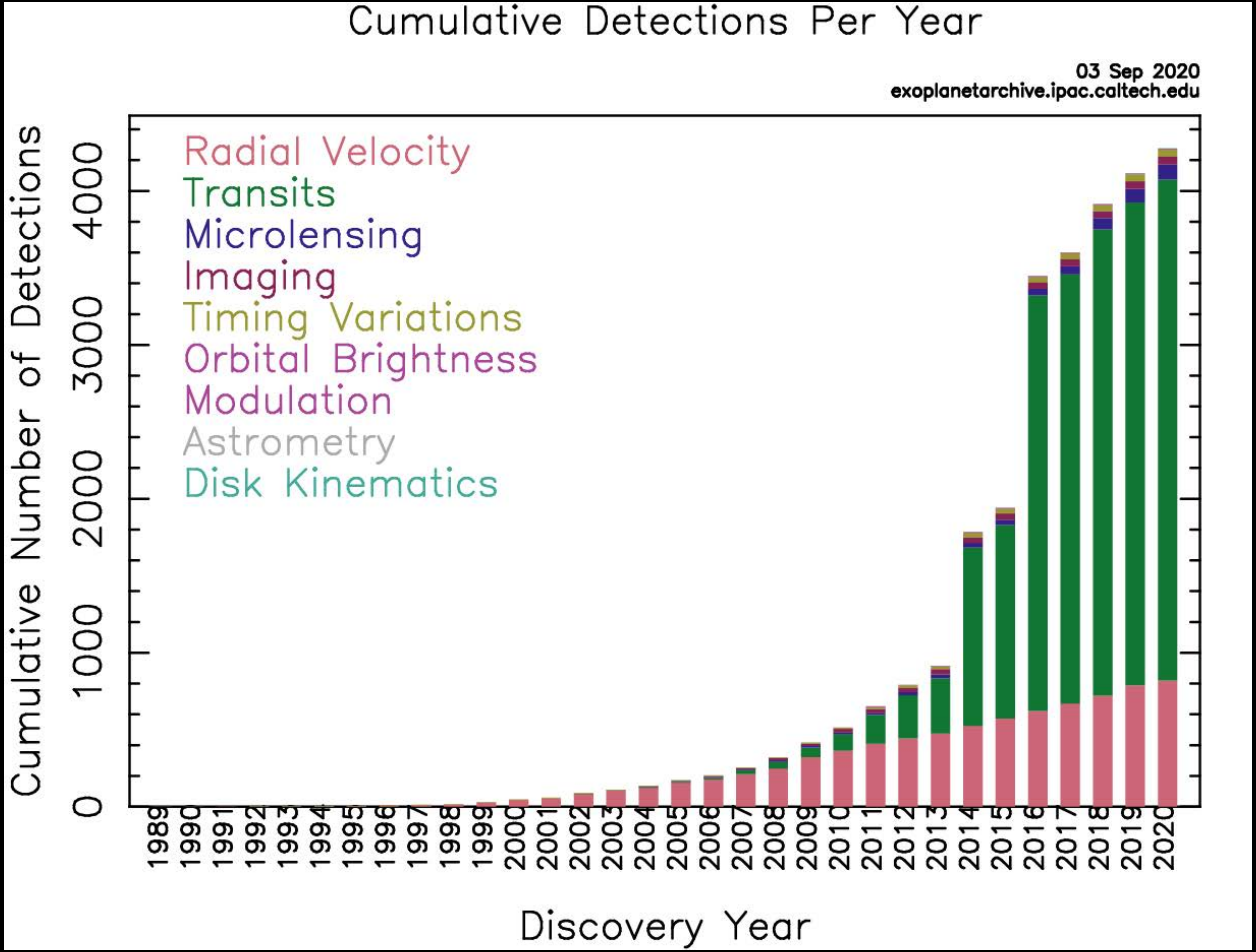


Image credit: NASA/JPL

What to expect in the coming 10-30 years?

			Direct detection & atmospheric characterization of Earth-like exoplanets	
Today	8-10 m telescopes		X	
	JWST		X	
10+ years	30-40 m telescopes		(✓)	A few Earth-like planets
20-30+ years	Next flagship missions		✓	Dozens of Earth-like planets + search for biosignatures

WHERE DO WE STAND TODAY


Cumulative Detections Per Year
03 Sep 2020
exoplanetarchive.ipac.caltech.edu
Radial Velocity
Transits
Microlensing
Imaging
Timing Variations
Orbital Brightness
Modulation
Astrometry
Disk Kinematics
Cumulative Number of Detections
0
1000
2000
3000
4000
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
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2002
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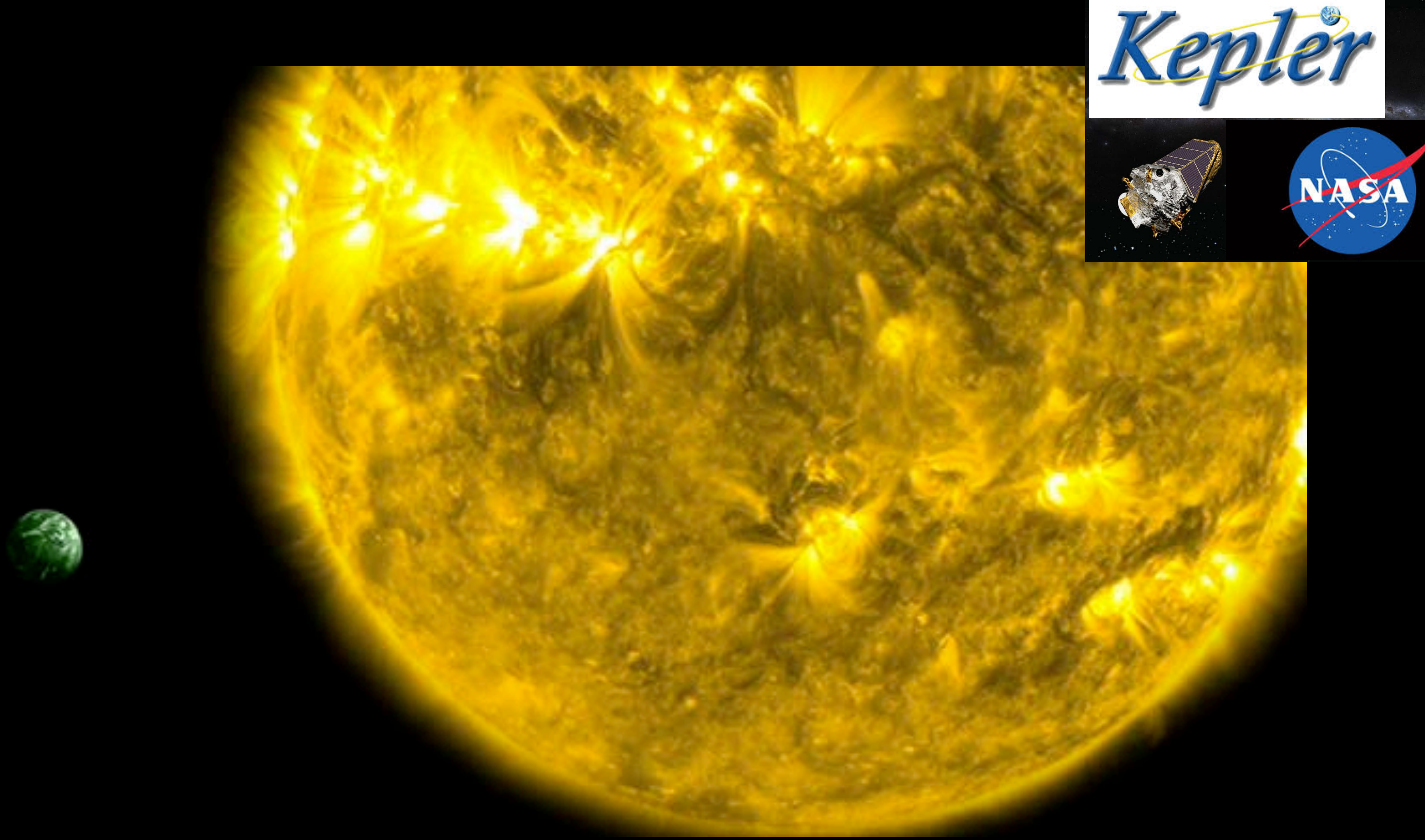
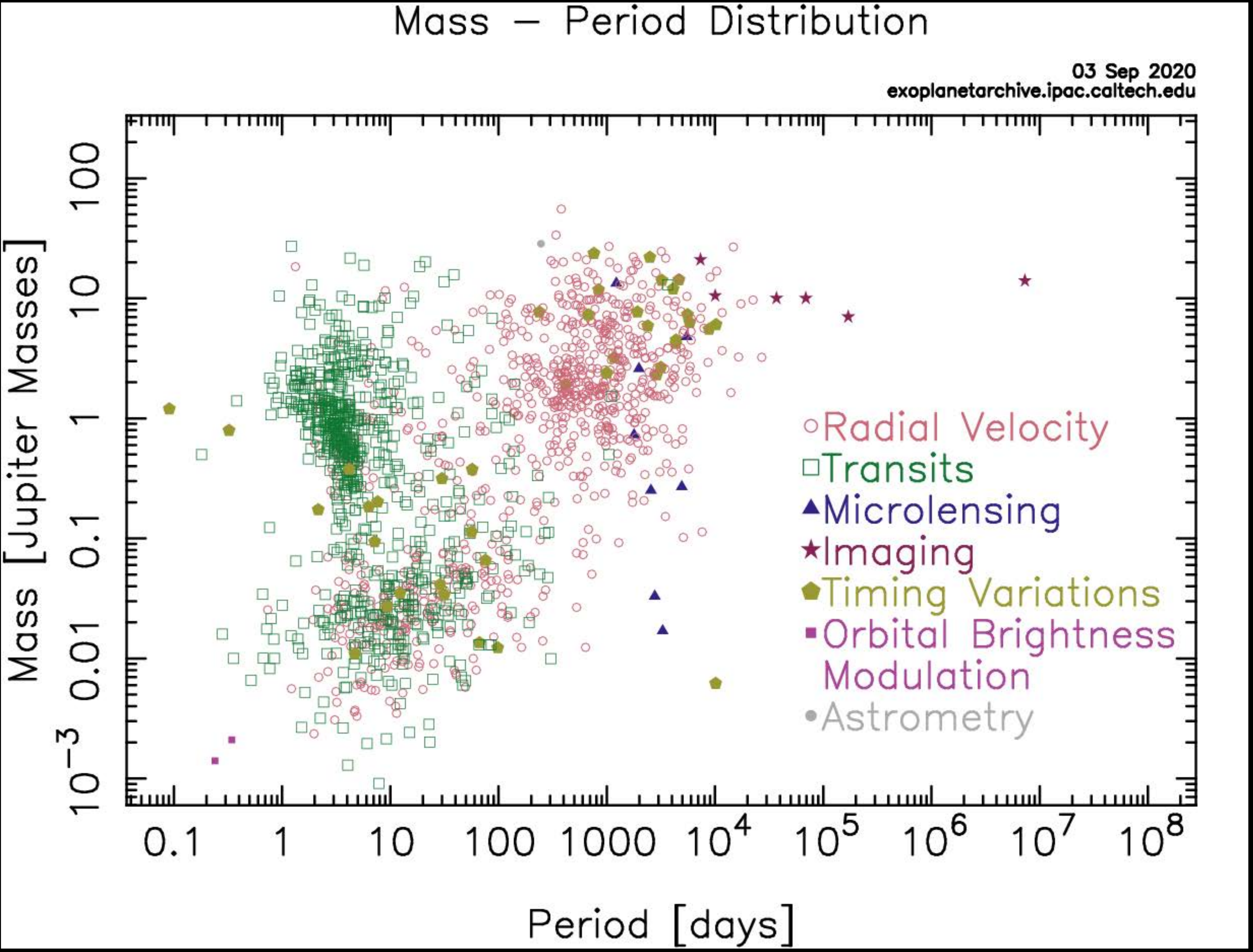
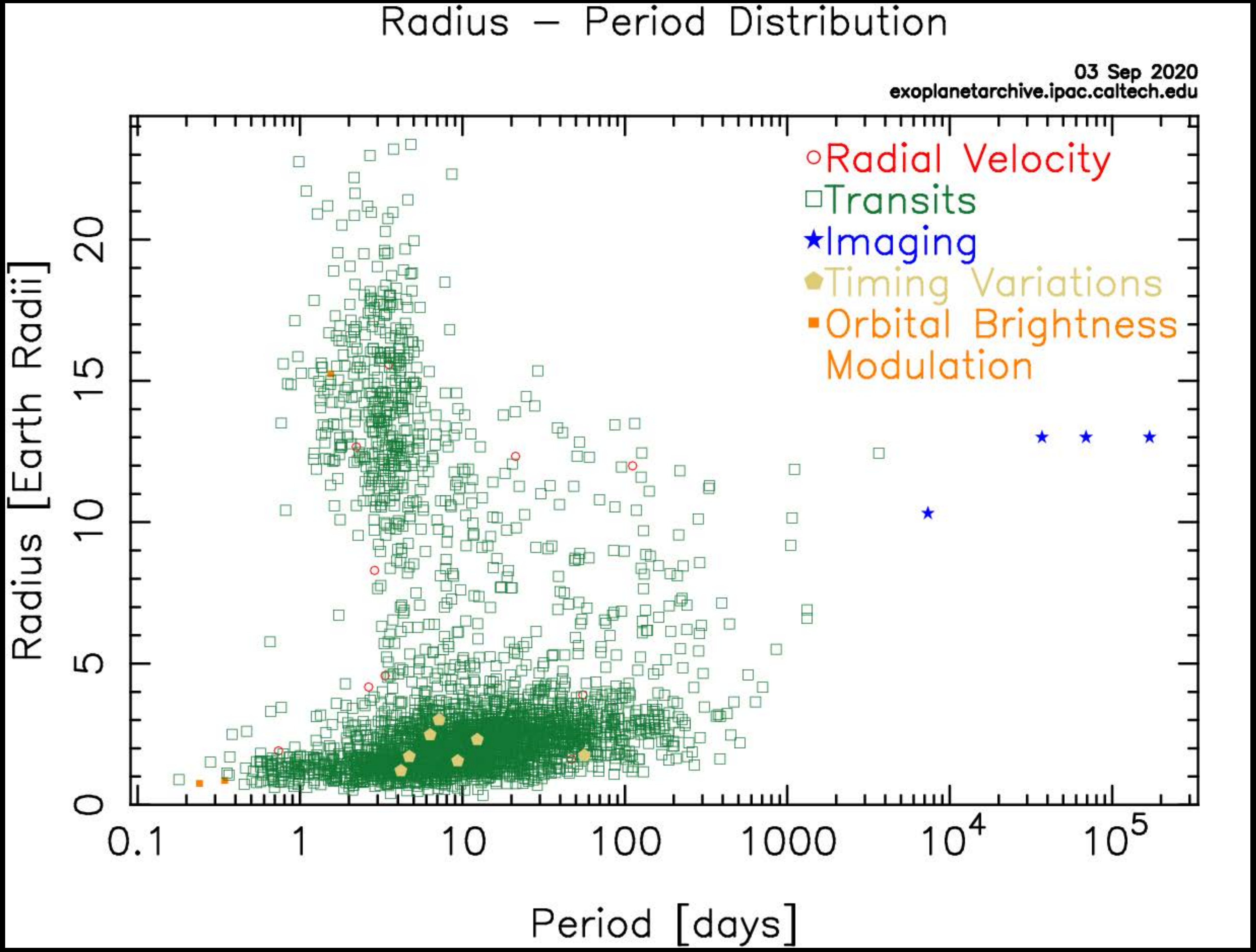
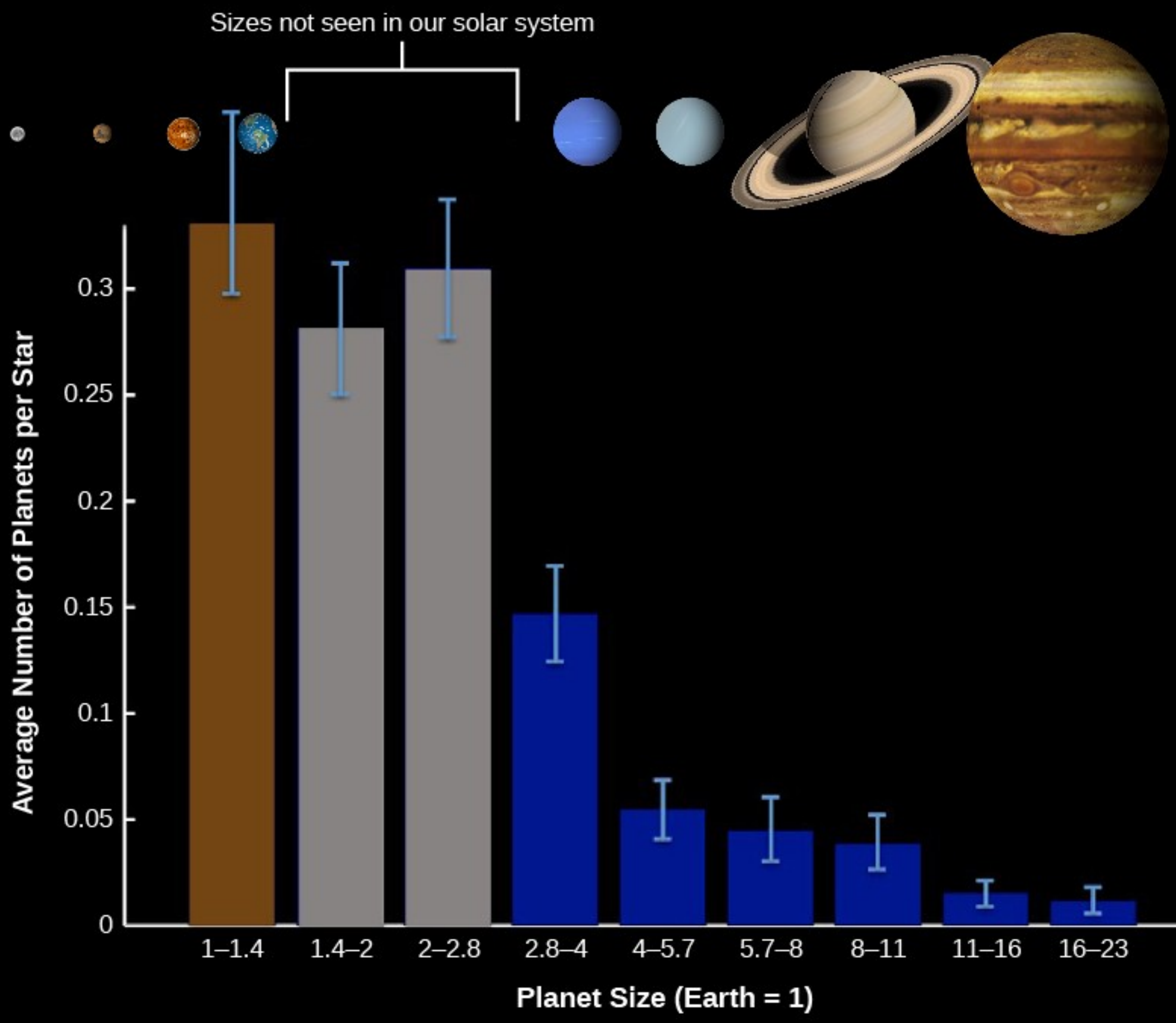
2017
2018
2019
2020
Discovery Year

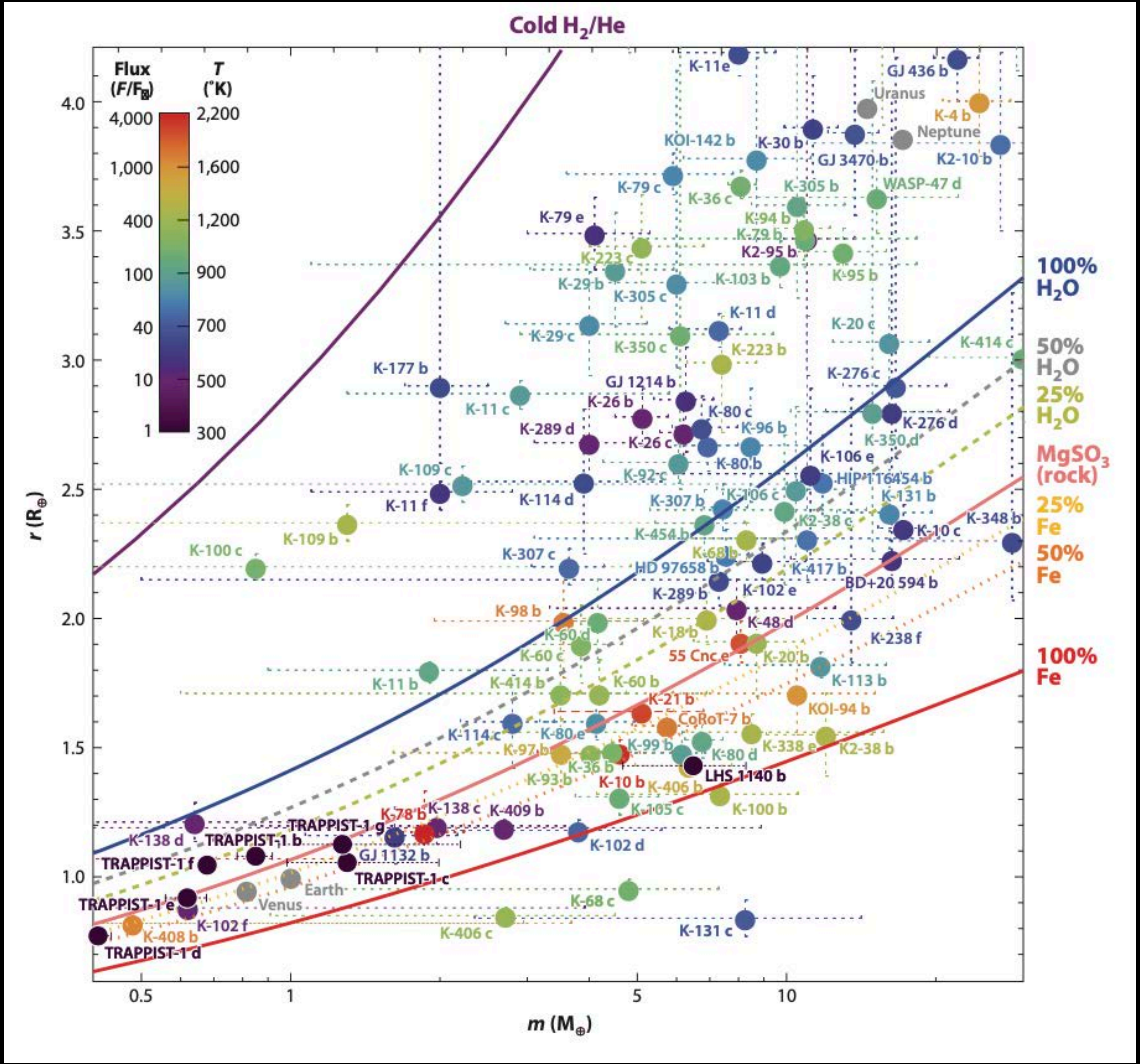
www.eso.org


Kepler
NASA


Mass – Period Distribution
03 Sep 2020
exoplanetarchive.ipac.caltech.edu
Mass [Jupiter Masses]
Period [days]
Radial Velocity
Transits
Microlensing
Imaging
Timing Variations
Orbital Brightness Modulation
Astrometry

Radius – Period Distribution
03 Sep 2020
exoplanetarchive.ipac.caltech.edu
Radius [Earth Radii]
Period [days]
Radial Velocity
Transits
Imaging
Timing Variations
Orbital Brightness Modulation



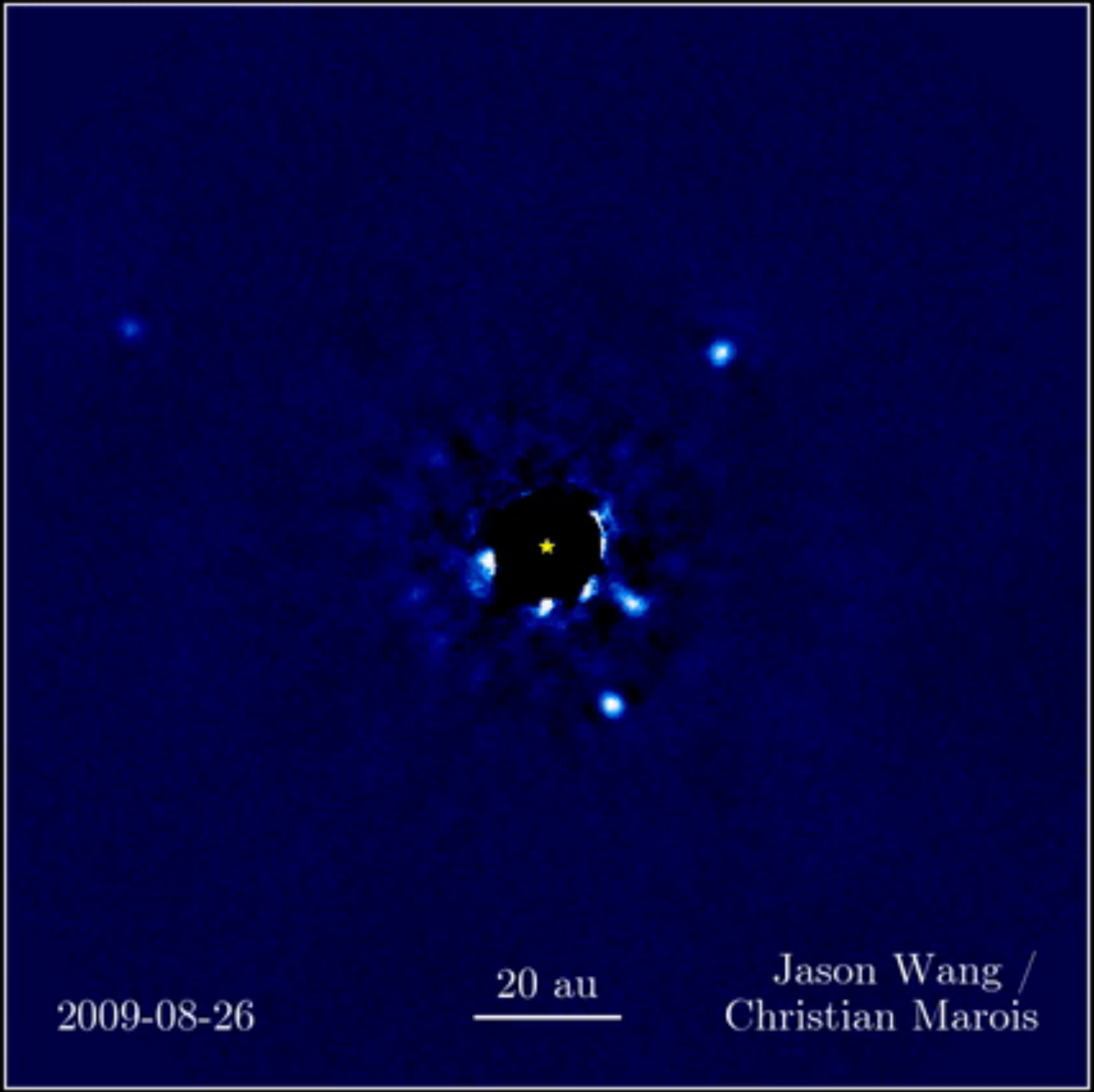
https://courses.lumenlearning.com/astronomy/chapter/exoplanets-everywhere-what-we-are-learning/; image credit: modification of work by NASA/Kepler



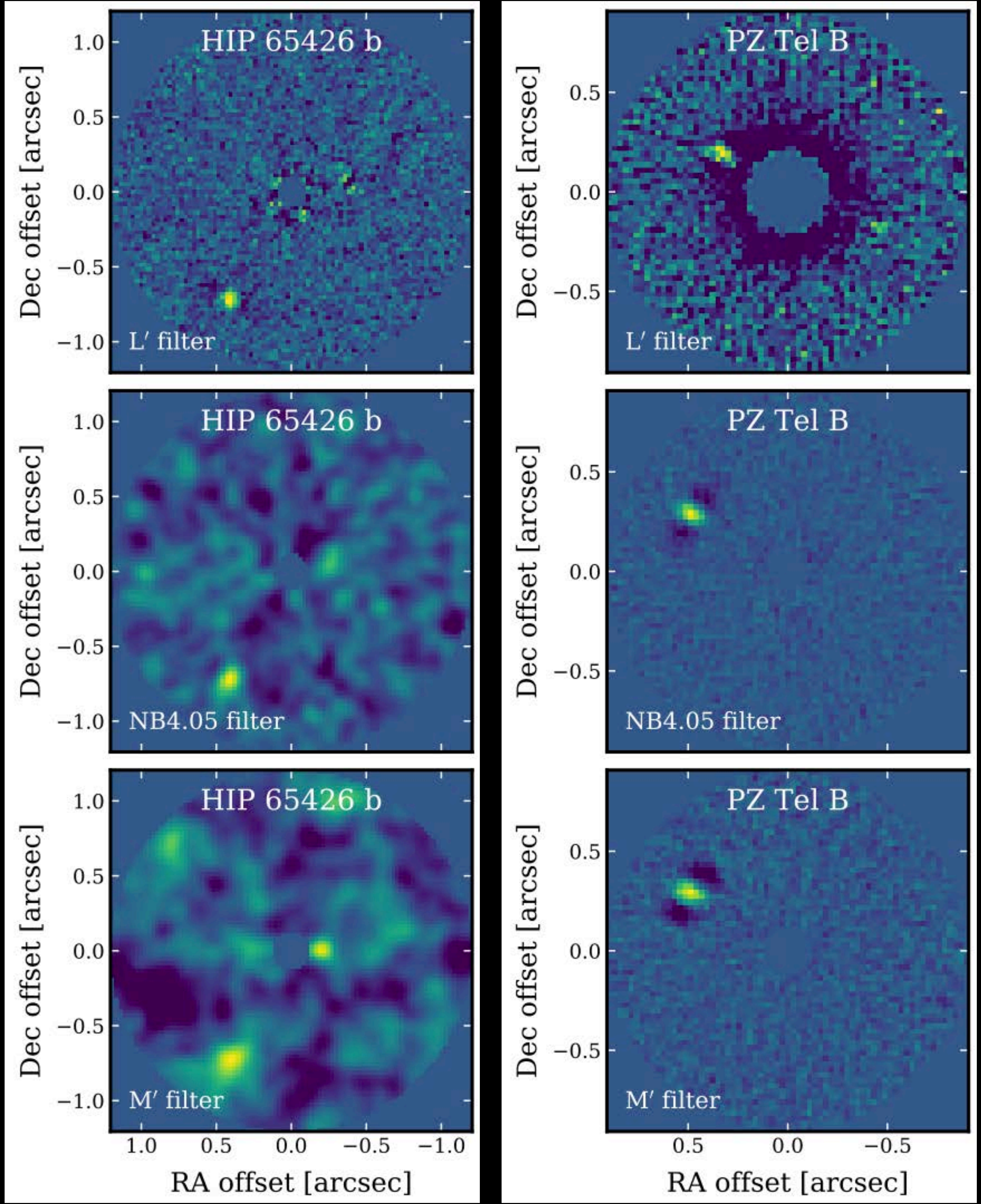
Kaltenegger 2017

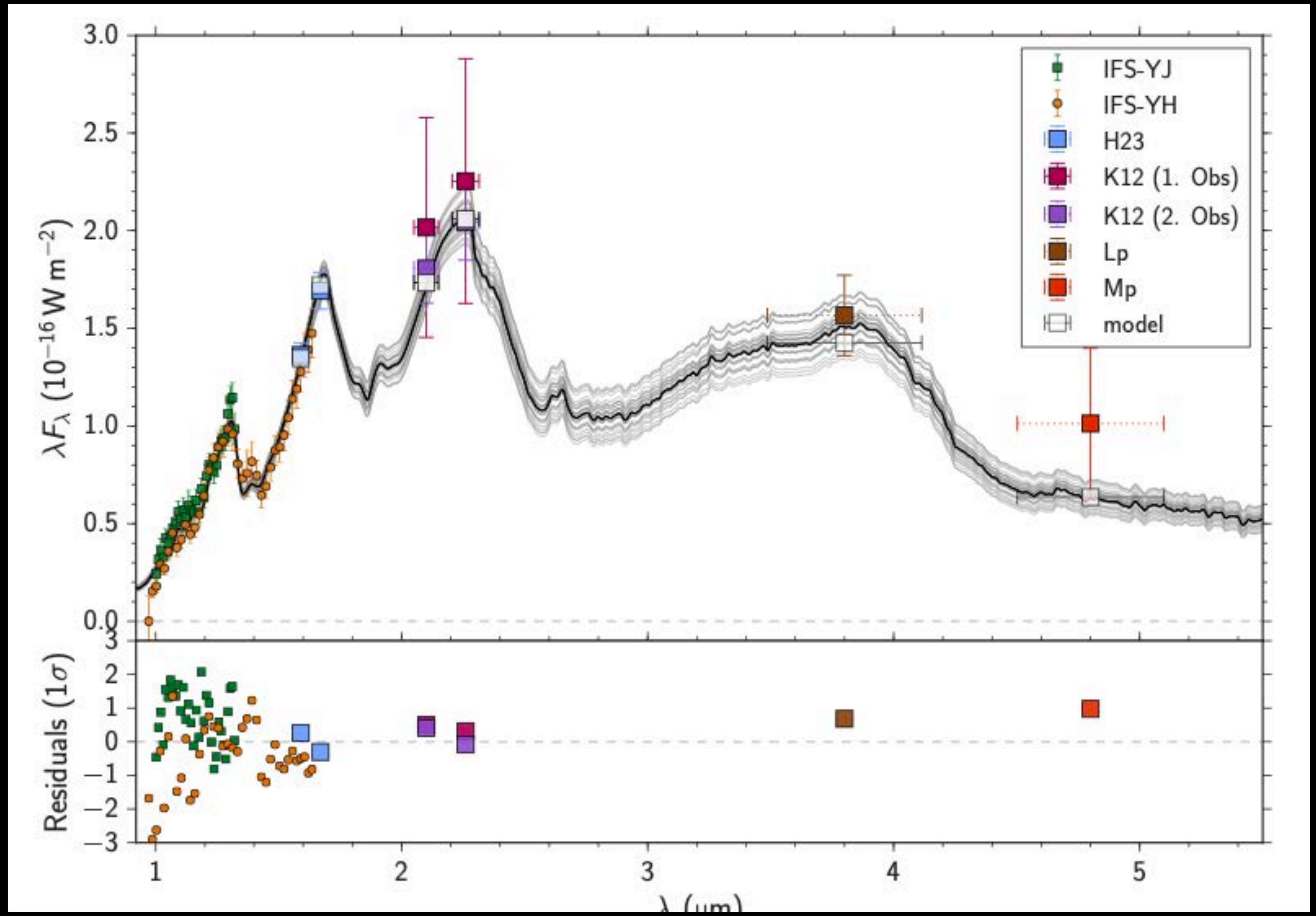
….but its difficult - well, impossible - to get information about atmospheric composition for Earth-analogs with these techniques…

We need to image (small) planets directly



Credit: Jason Wang





Stolker, Quanz et al. 2020
Cheetham et al. 2019

MAIN CHALLENGES

1 ...**high spatial resolution:** the planet-star separation is extremely small

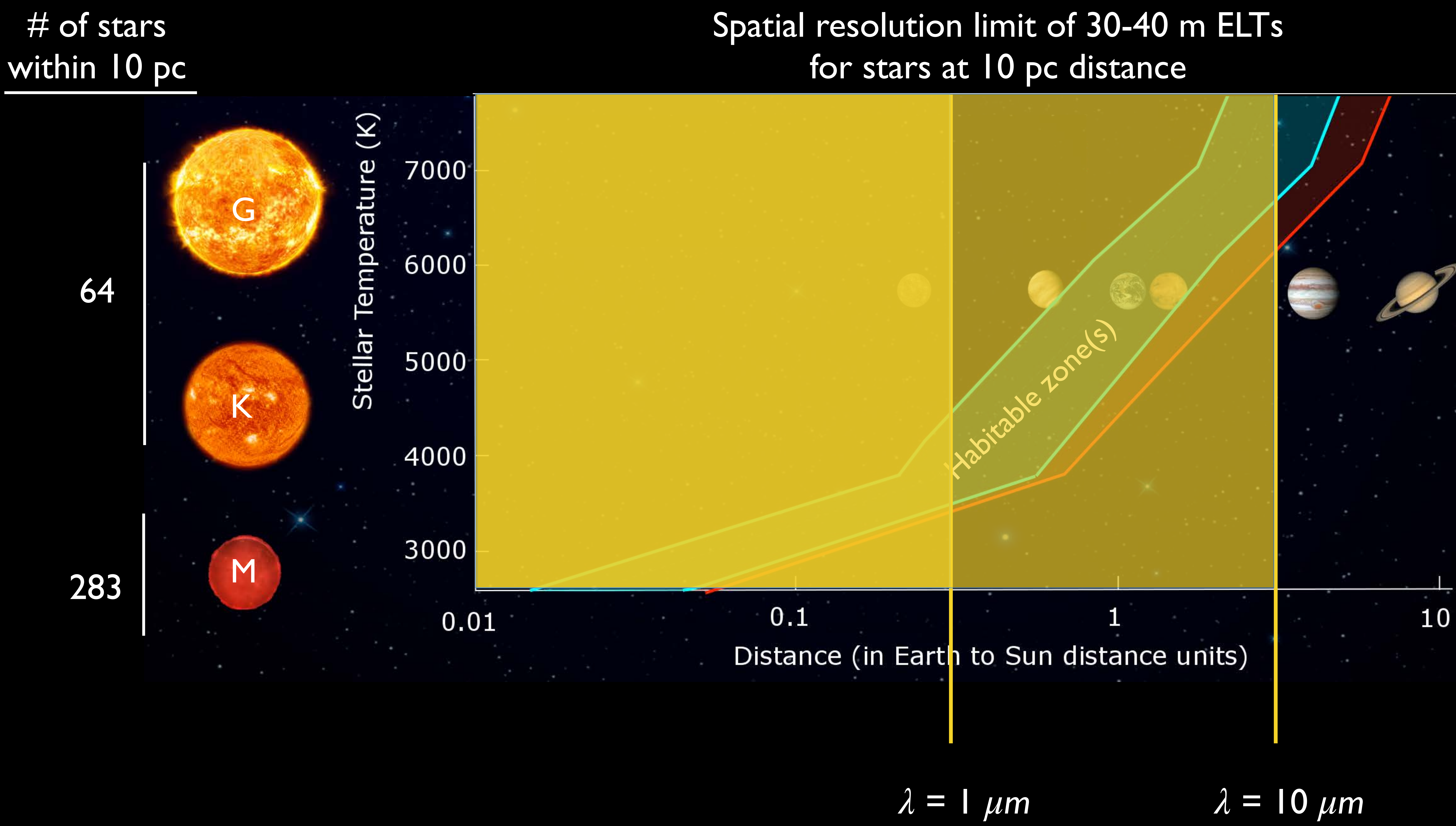
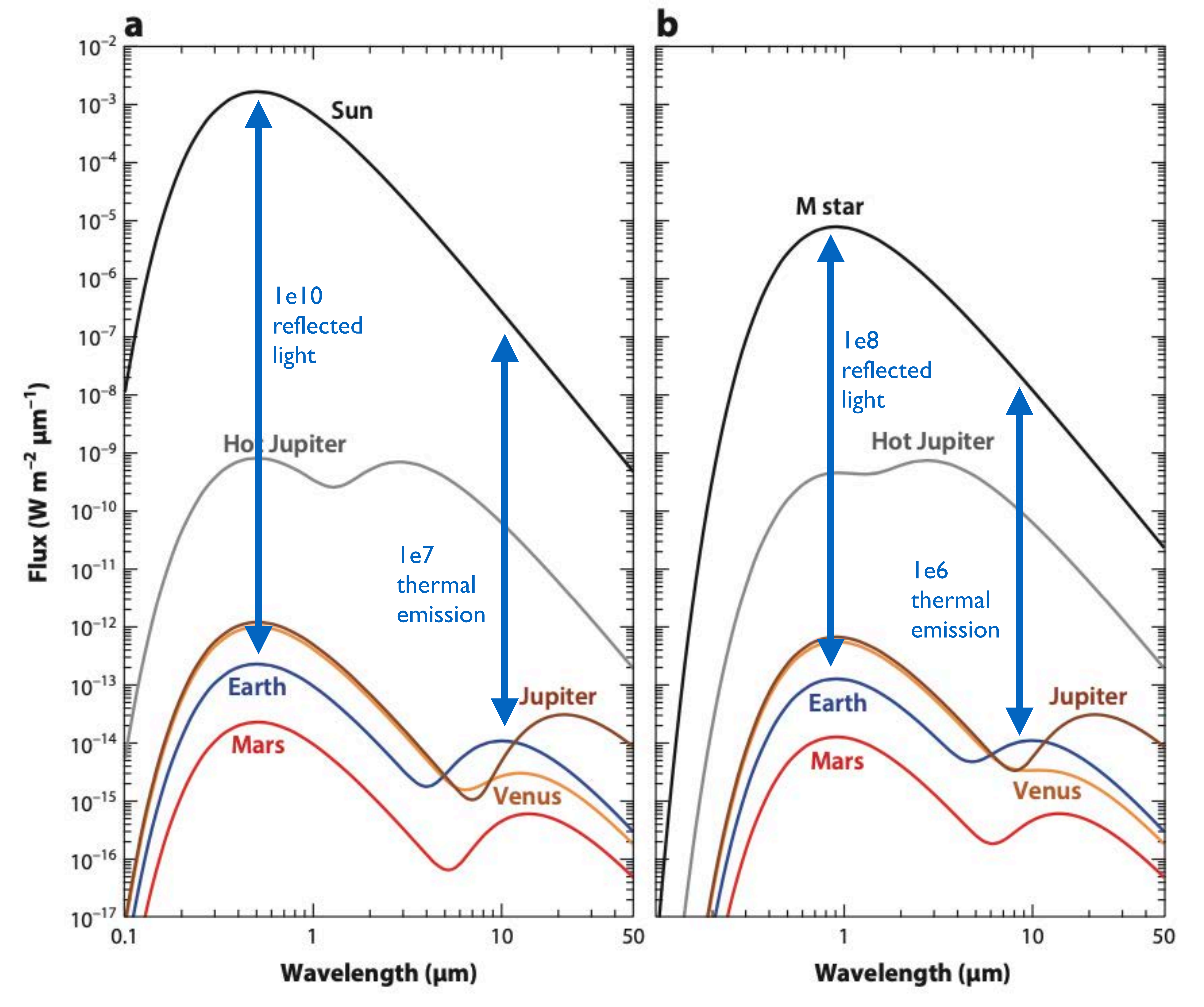


Image credits: R. Ramirez, Carl Sagan Institute, Cornell

1 …**high spatial resolution:** the planet-star separation is extremely small

2 …**high contrast performance:** the planet is orders of magni-tude fainter than the star



Kaltenegger 2017

THE EXTREMELY LARGE TELESCOPES

Image credit: ESO

The direct detection of terrestrial exoplanets from the ground

2nd gen. instrument:
PCS (~2035)

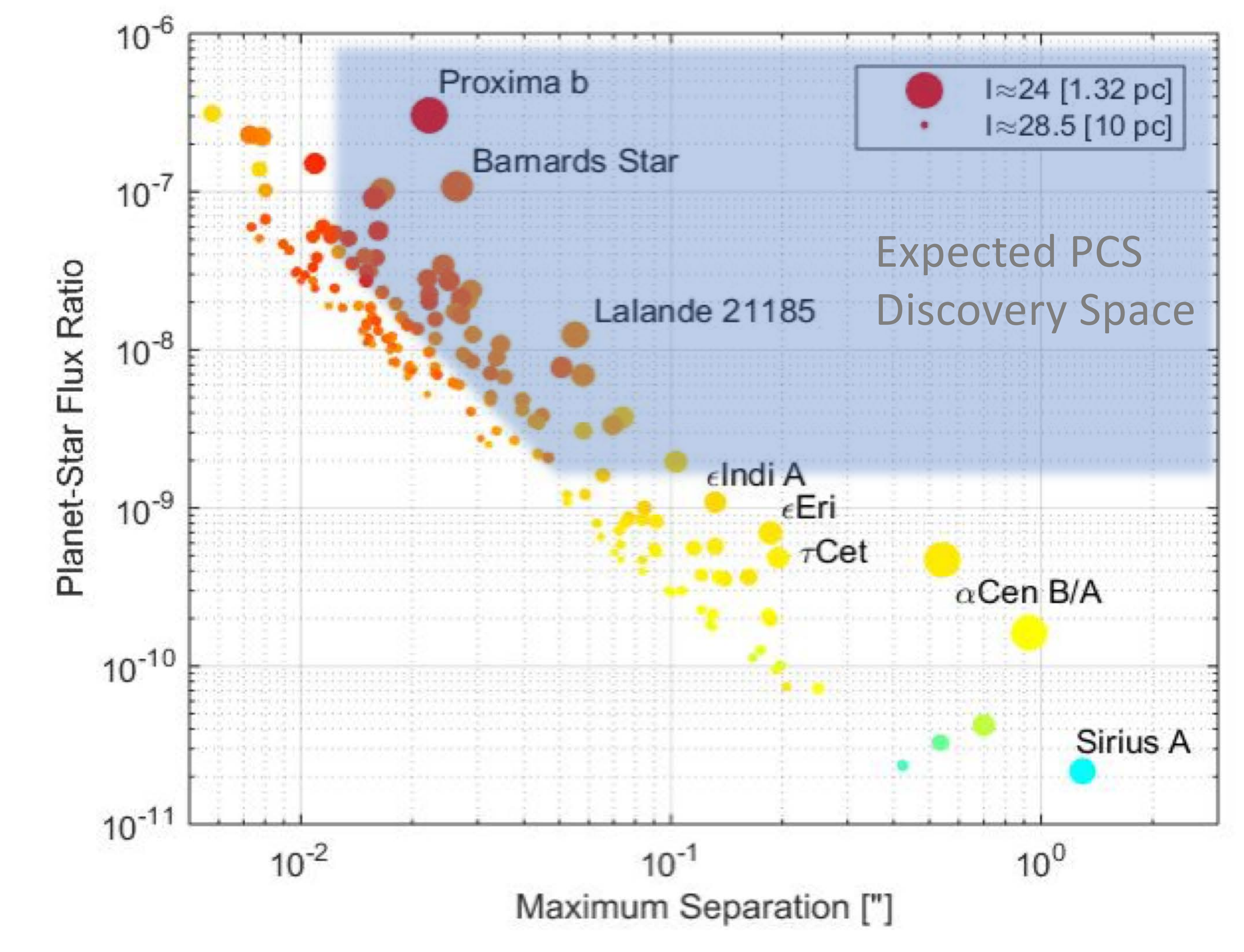


Figure: Markus Kasper

Reflected light
(M-stars within 6-7 pc)

1st gen. instrument:
METIS (~2027)

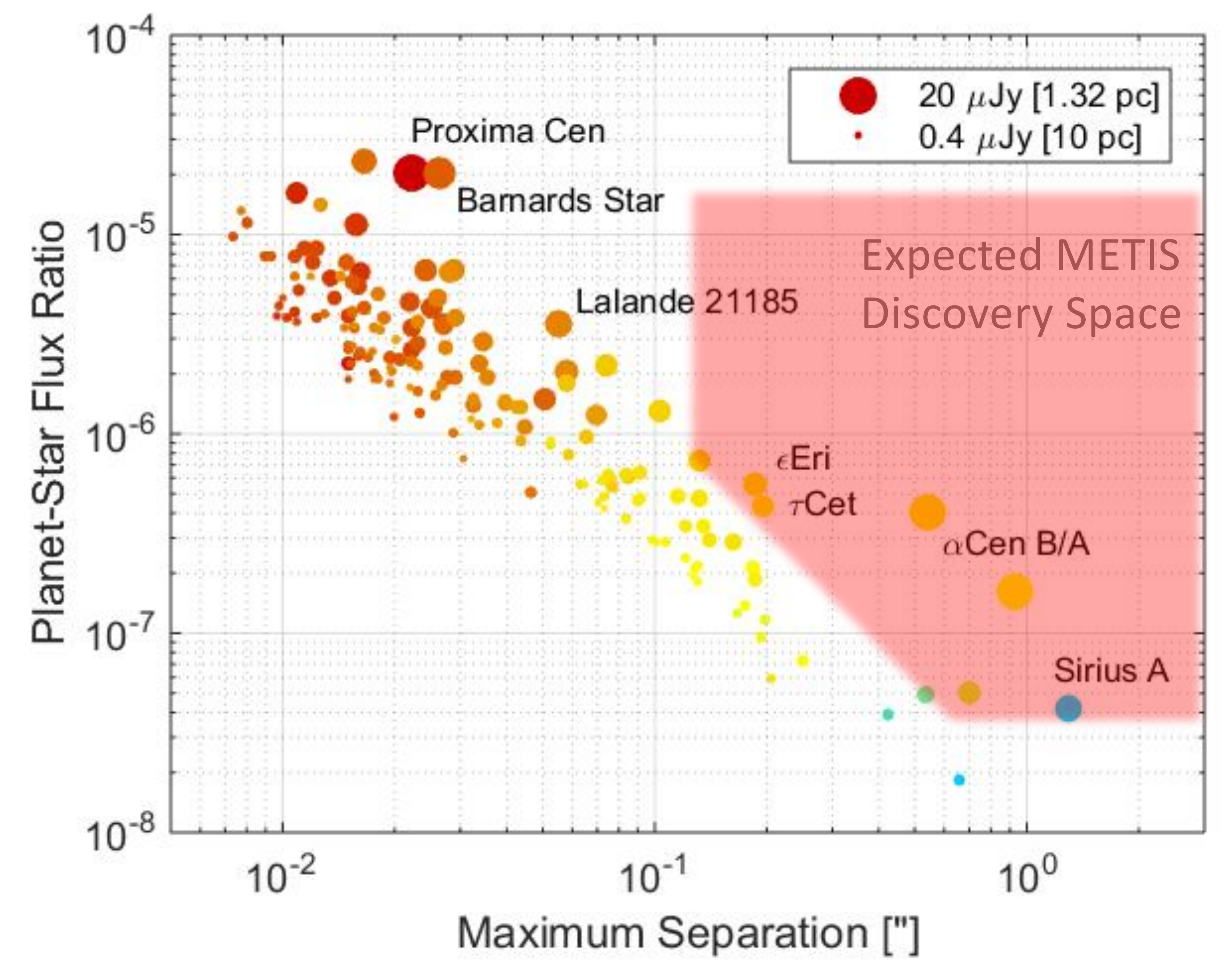


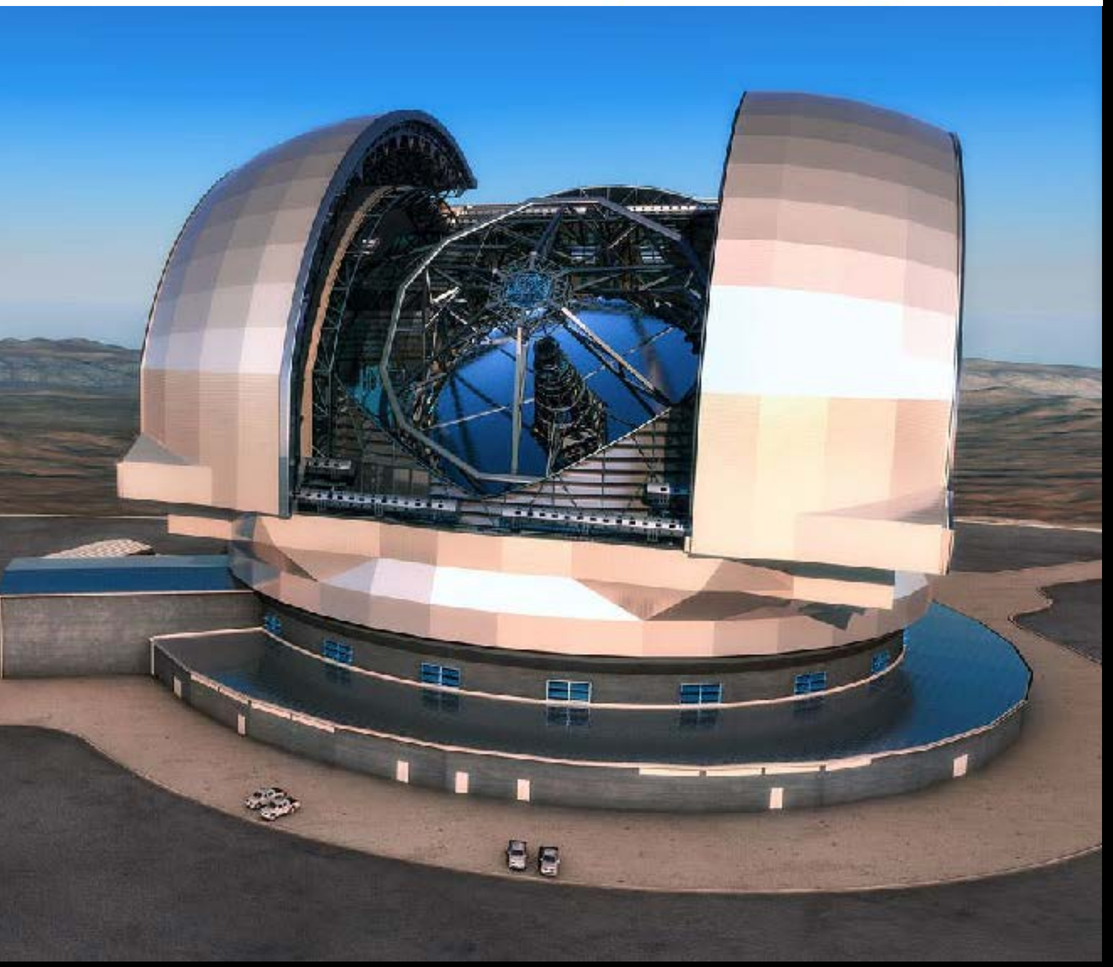
Figure: Markus Kasper

Thermal emission
(AFG-stars within 4 pc)

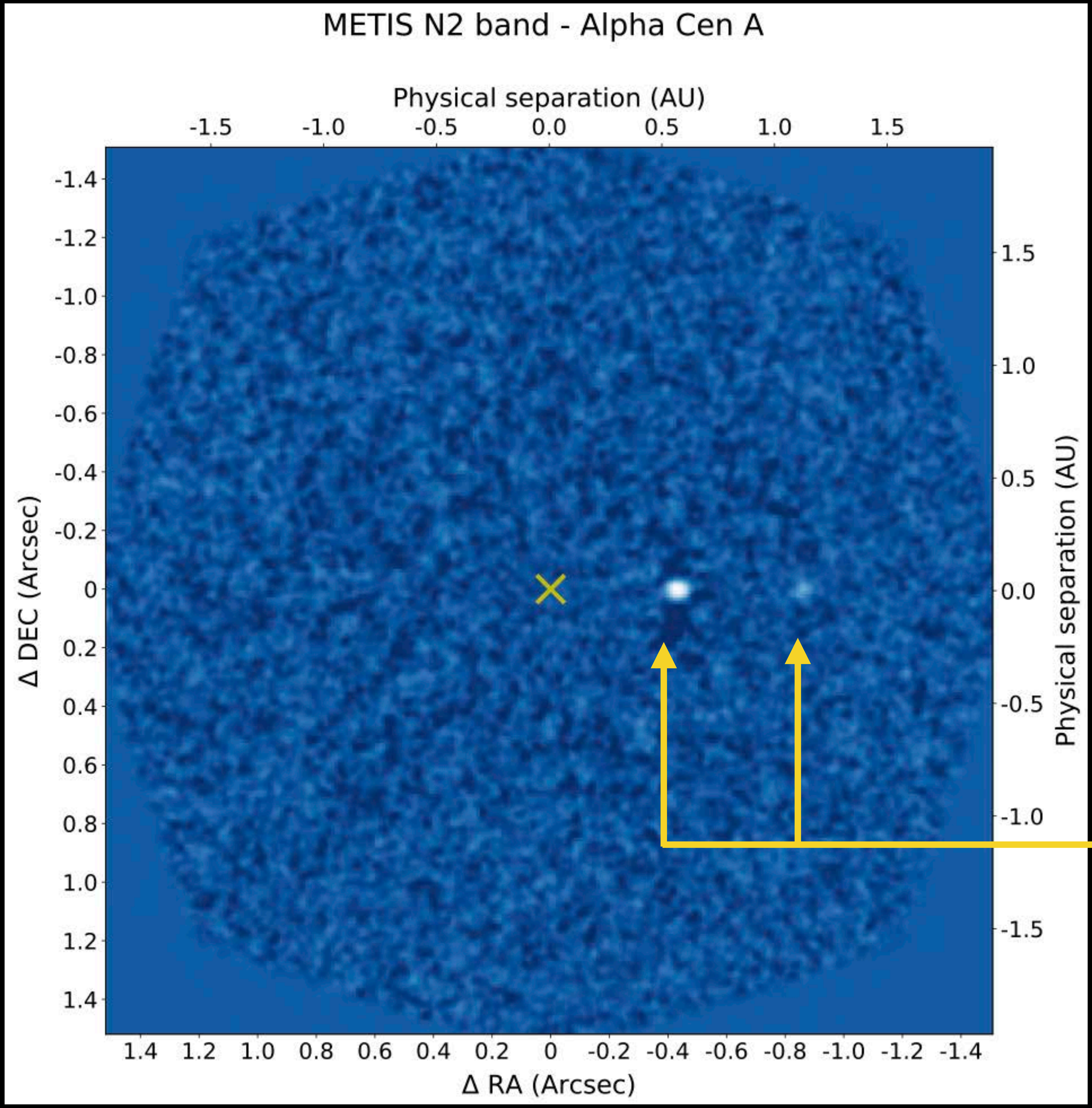
The direct detection of terrestrial exoplanets from the ground

Science and Technology Facilities Council
UK Astronomy Technology Centre
KU LEUVEN
LIÈGE université
Universität zu Köln
UNIVERSITY OF MICHIGAN
ETH zürich
centra multidisciplinary centre for astrophysics

METIS
Mid-infrared E-ELT Imager and Spectrograph



IPA ETH zürich



2 Earth-sized planets (0.55 AU and 1.1 AU)

1 night of telescope time

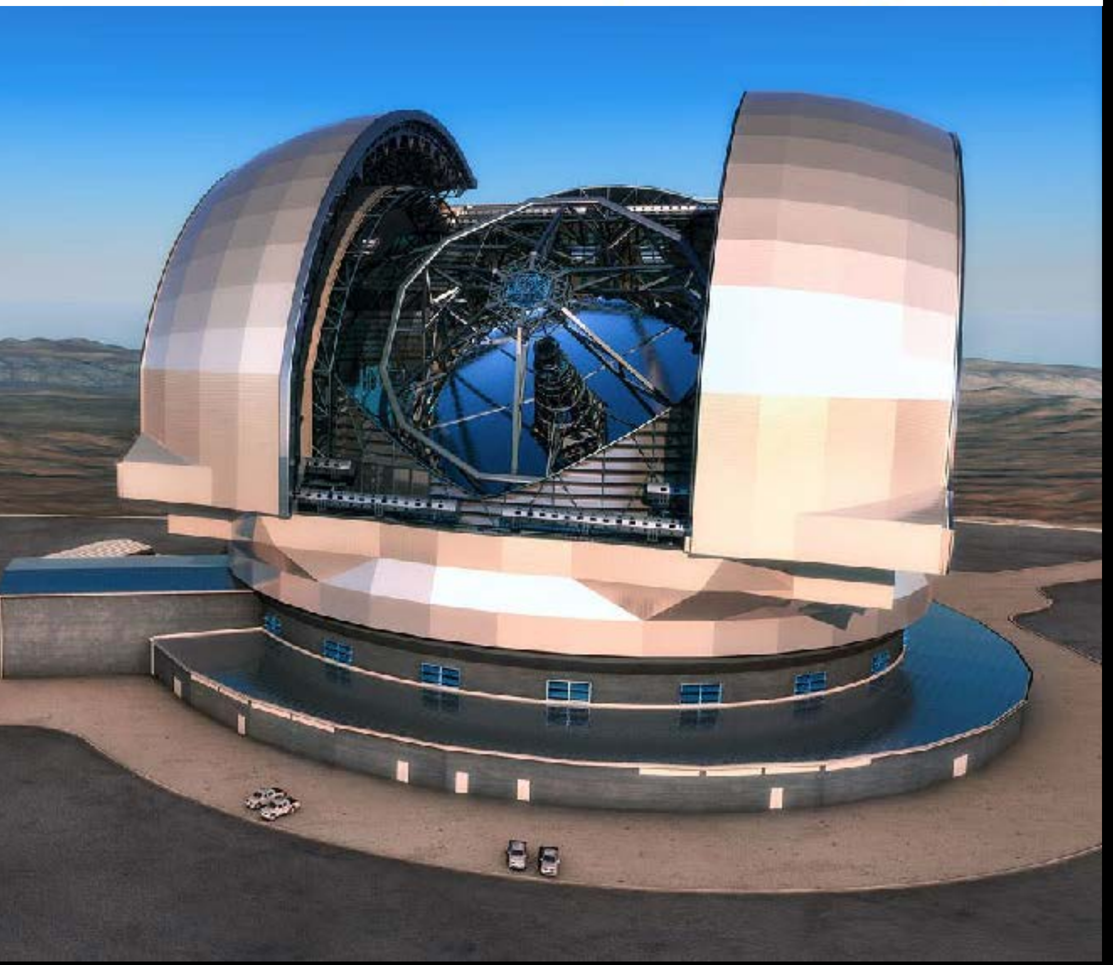
Do these planets exist?

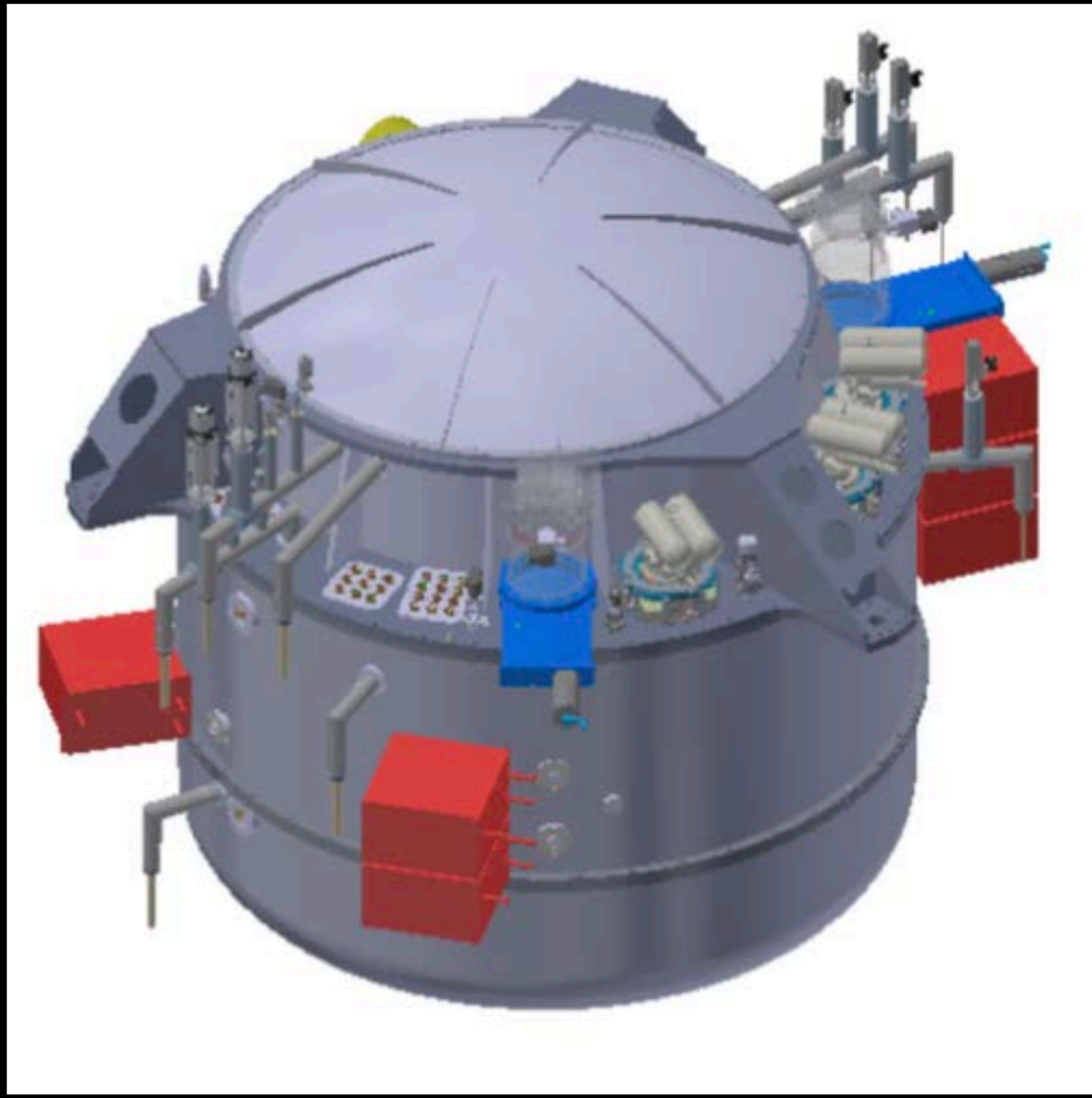
cf. Quanz et a.l. 2015

The direct detection of terrestrial exoplanets from the ground

METIS

Mid-infrared
E-ELT Imager and
Spectrograph





cf. Glauser et al. 2018

The direct detection of terrestrial exoplanets from the ground

2nd gen. instrument:
PCS (~2035)

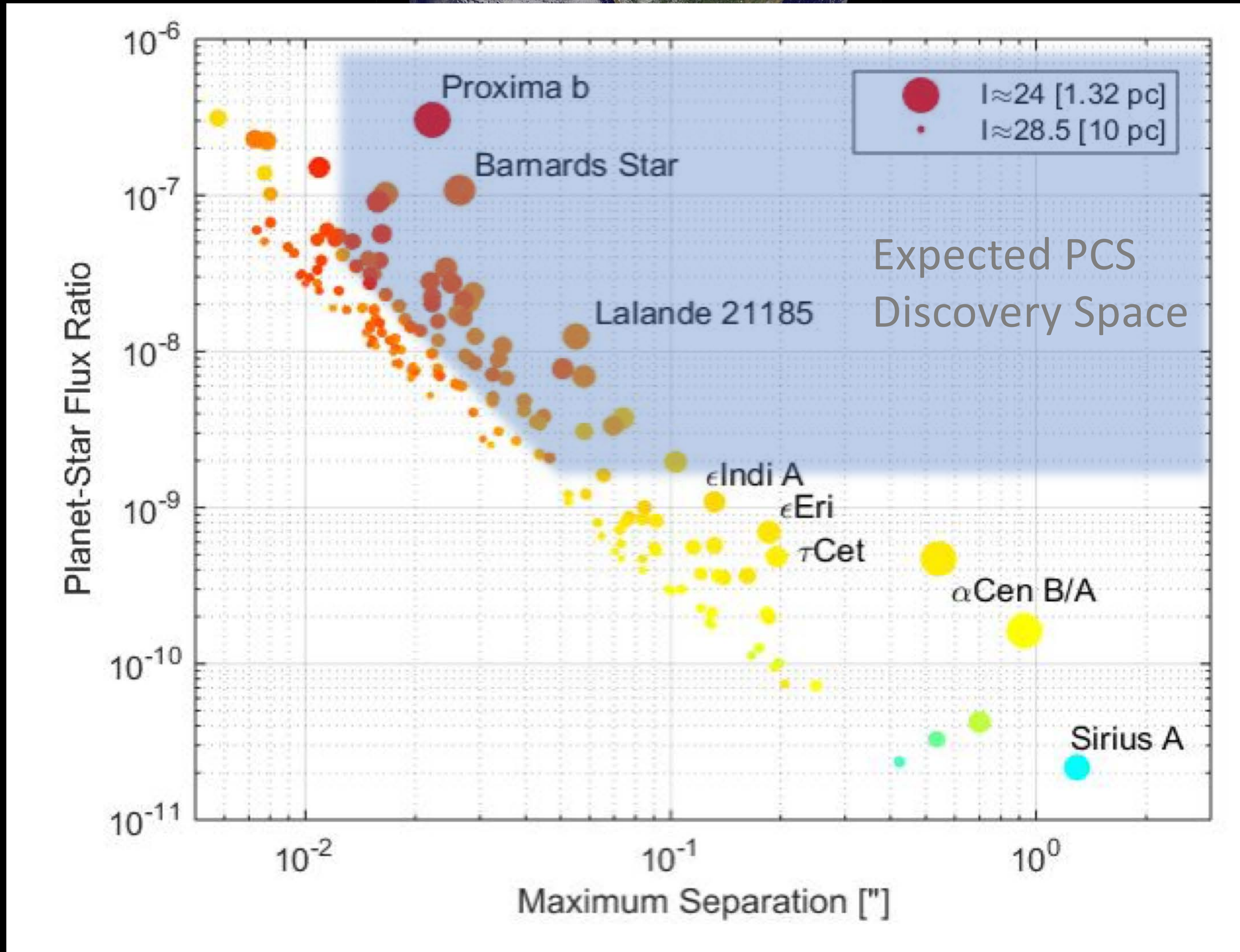


Figure: Markus Kasper

Reflected light
(M-stars within 6-7 pc)

1st gen. instrument:
METIS (~2027)

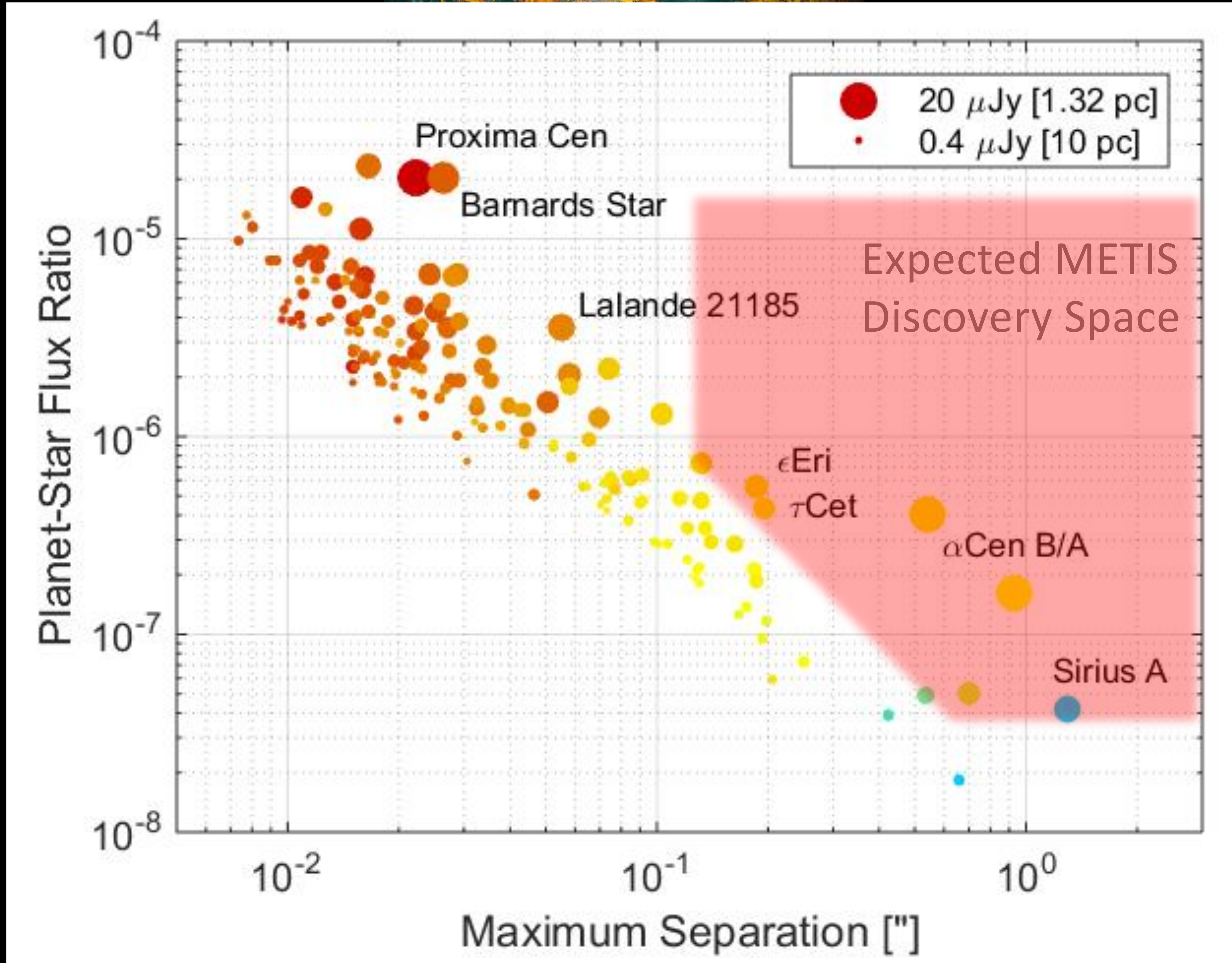


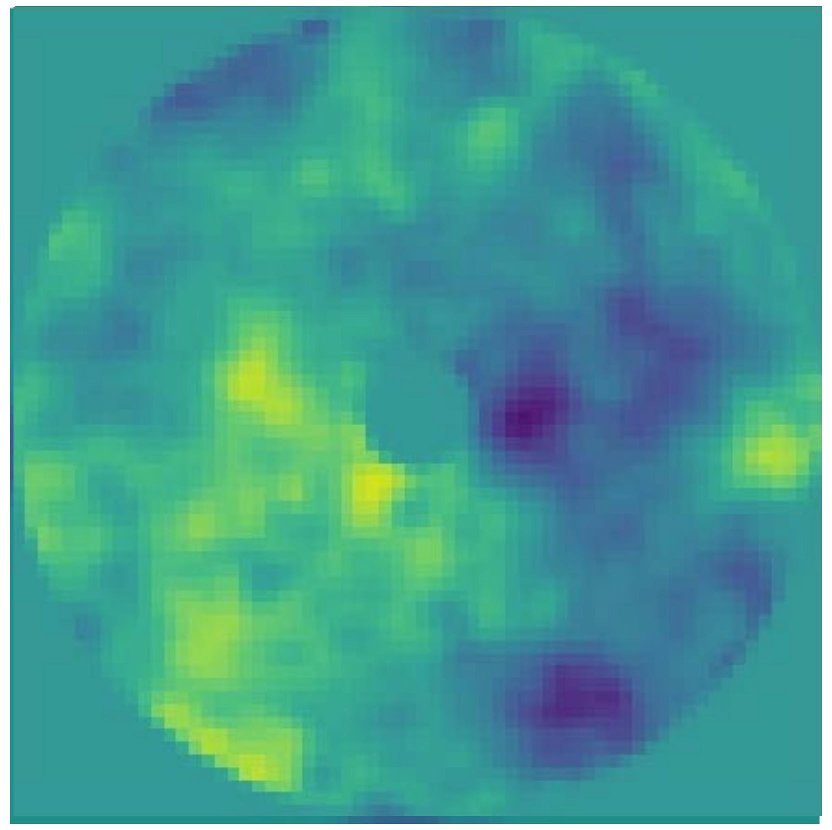
Figure: Markus Kasper

Thermal emission
(AFG-stars within 4 pc)

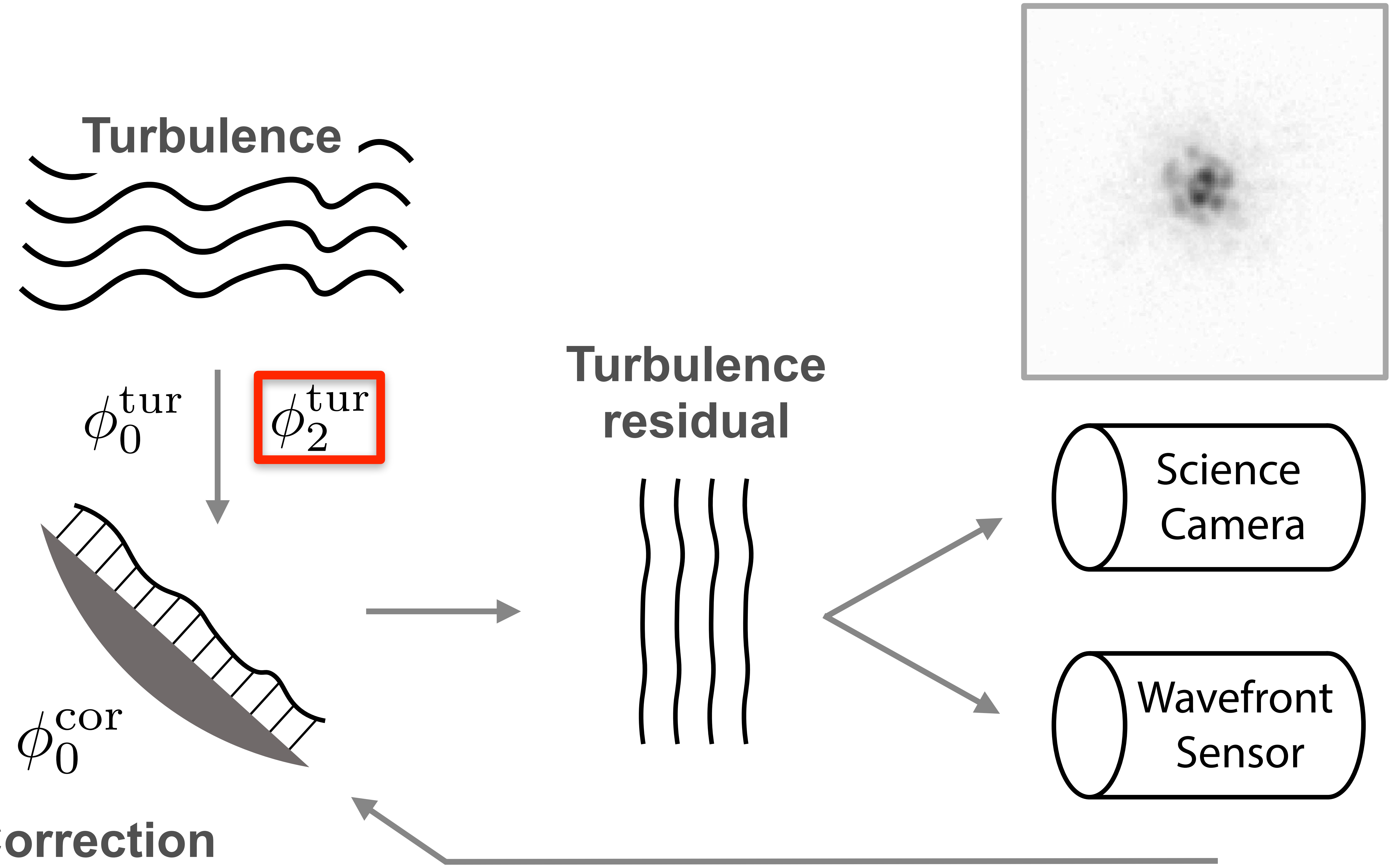
eXtreme Adaptive Optics

Loop speed ~ 4kHz
~ 120x120 actuators

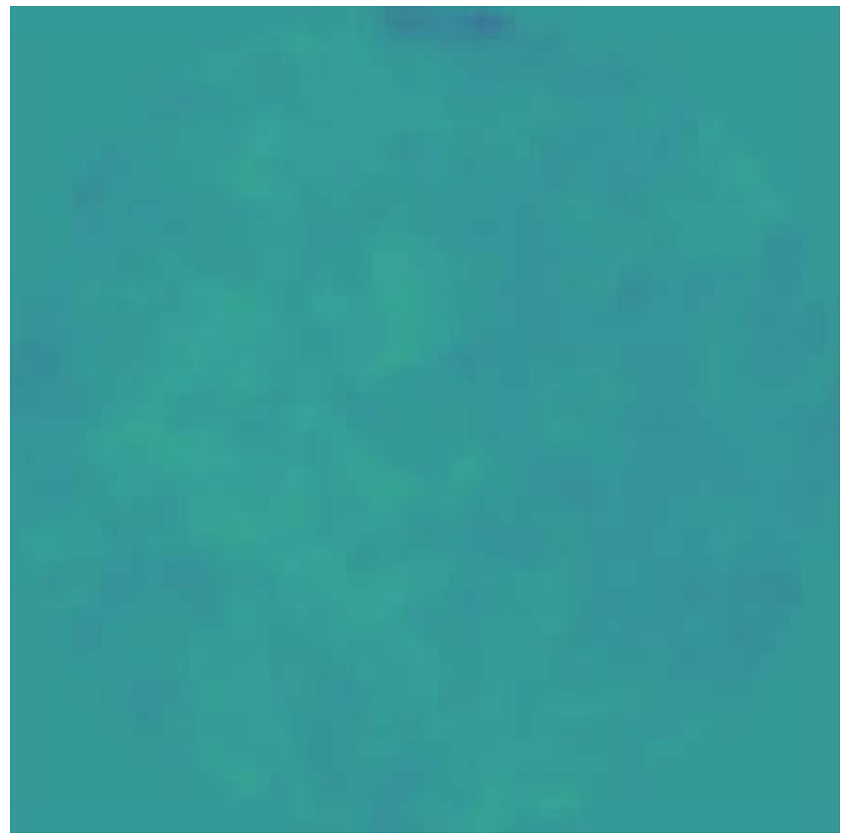
Turbulence



1 sec. - 1000 frames



Turbulence residual



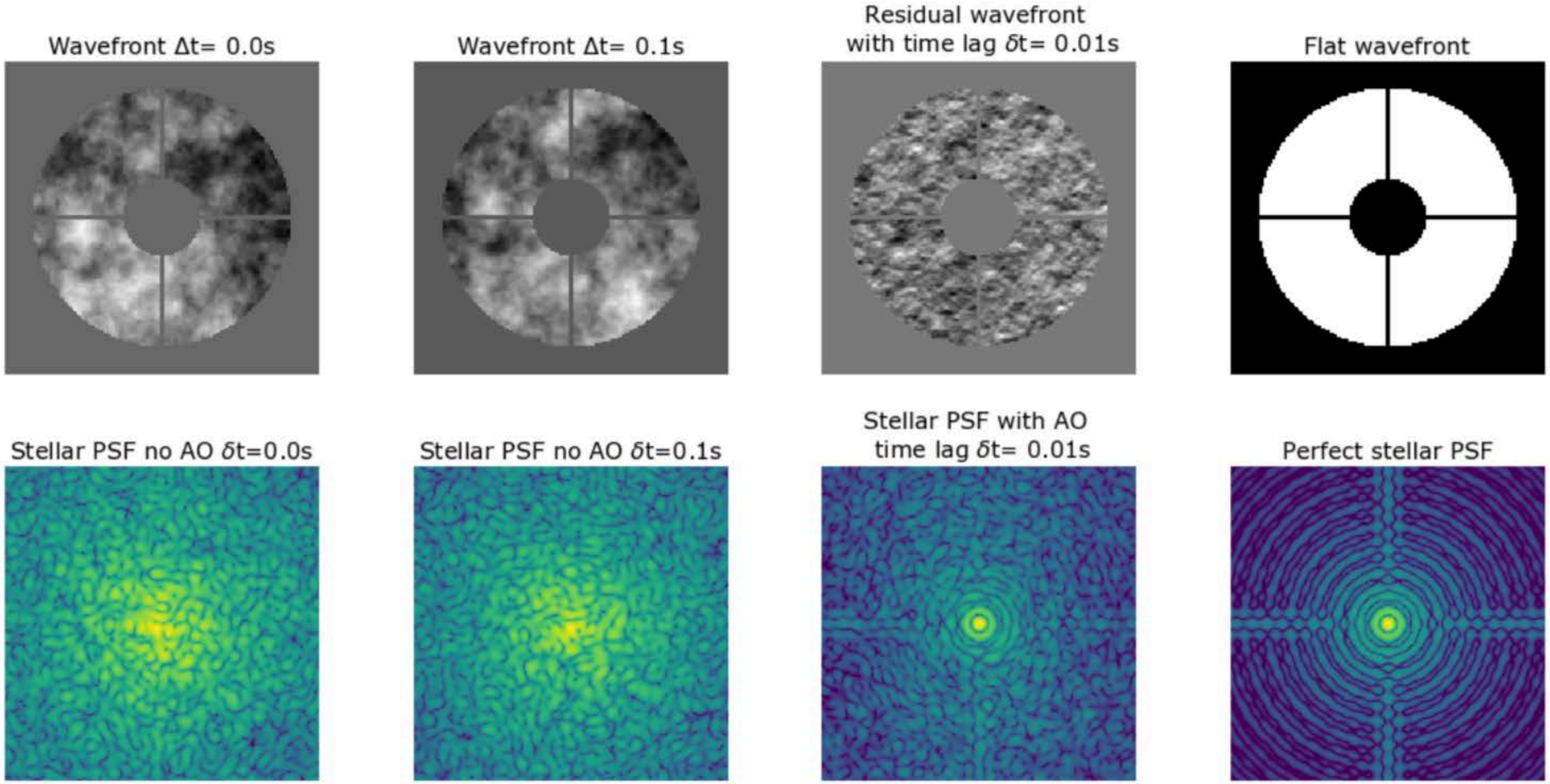
1 sec. - 1000 frames

Problem: Measurements are lagging behind the turbulence evolution

ETH zürich

Credit: Markus Bonse

Temporal error in XAO

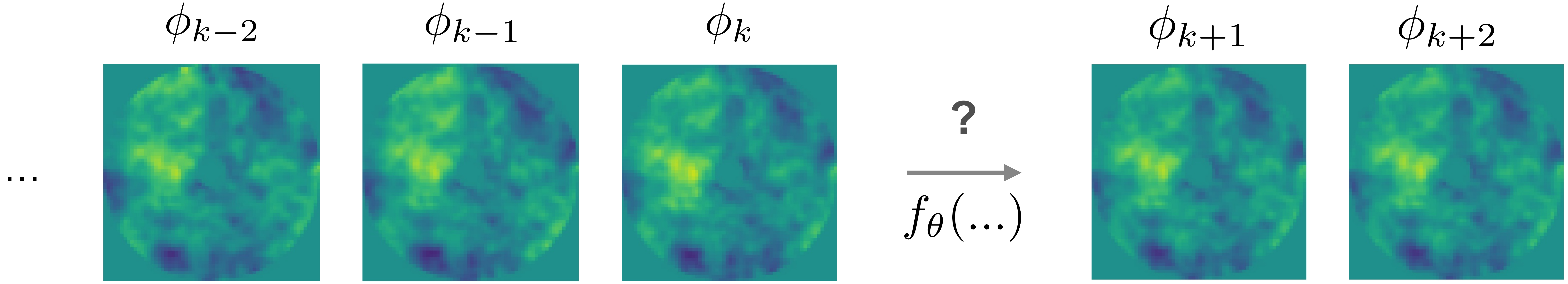


ETH zürich ESO

Credit: Markus Bonse

Open-loop prediction task: Convolutional Long Short Term Memory Networks

Combine **CNNs** with **Long Short Term Memory Networks**



Goal: Find a model $f_\theta(\ldots)$ which predicts the future $\hat{\phi}_{k+d}$

$$f_\theta\left(\phi_k, \phi_{k-1}, \phi_{k-2}, \ldots\right) = \hat{\phi}_{k+d}$$

Implement at ESO AO-testbench in 2021/2022

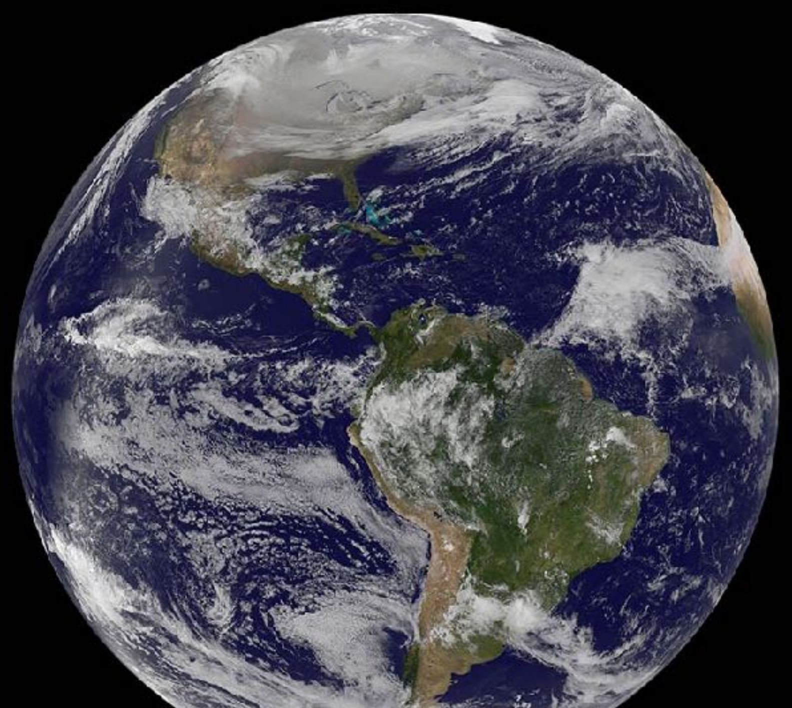
Implement at Subaru Telescope in 2023

ETH zürich

Credit: Markus Bonse

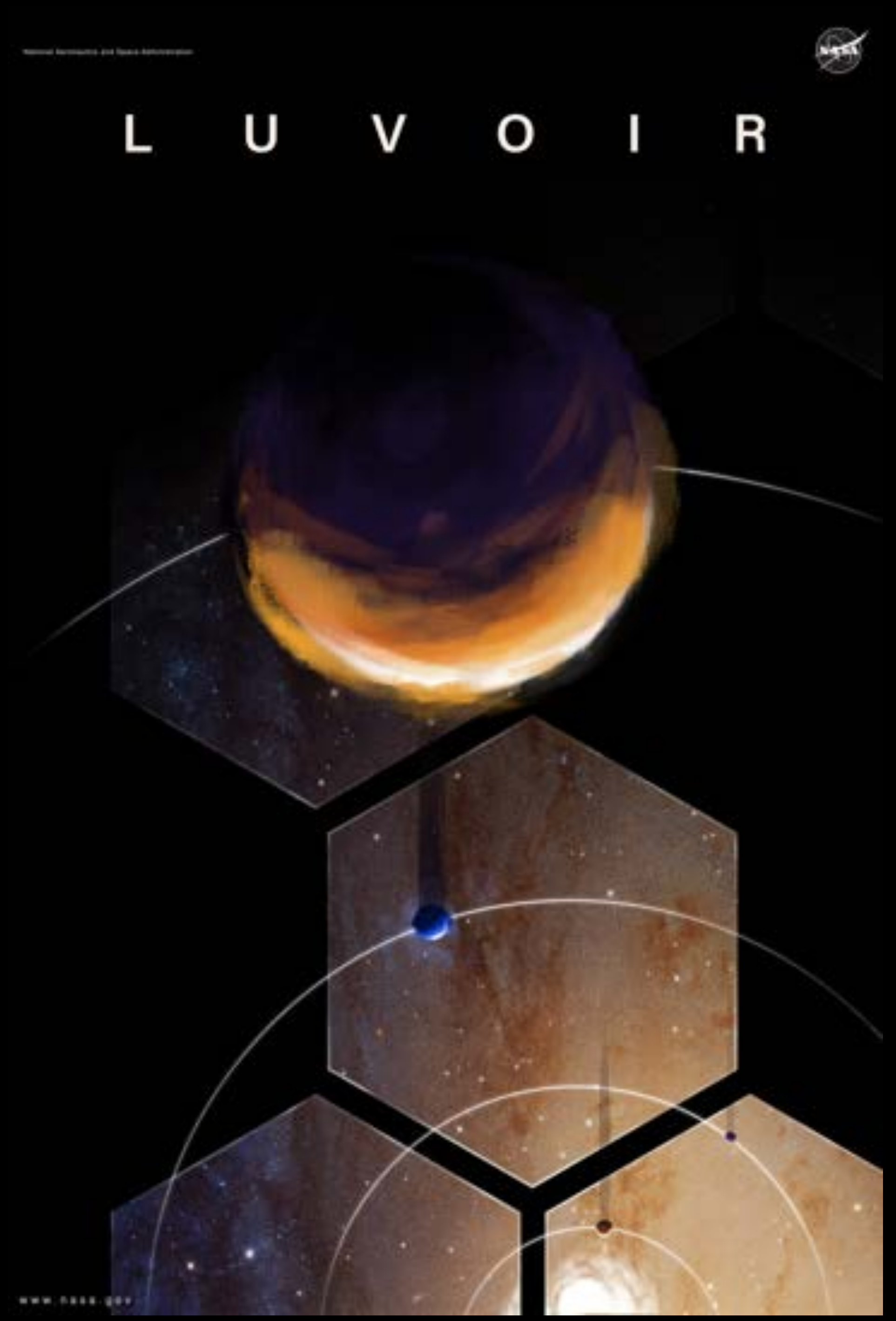
NEXT FLAGSHIP MISSIONS

Space mission to the rescue



Reflected light (UV - NIR)

Thermal emission (MIR)



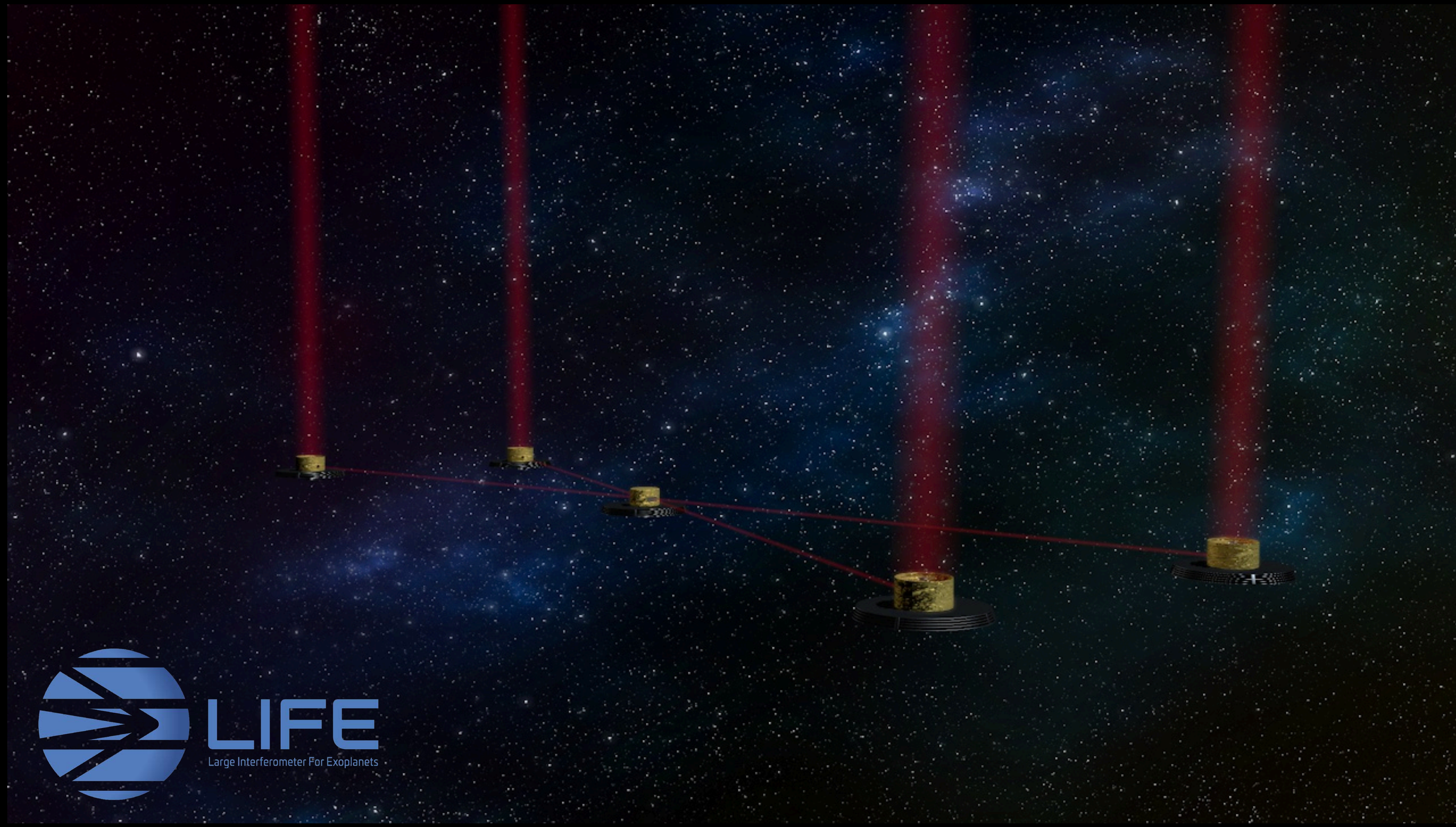
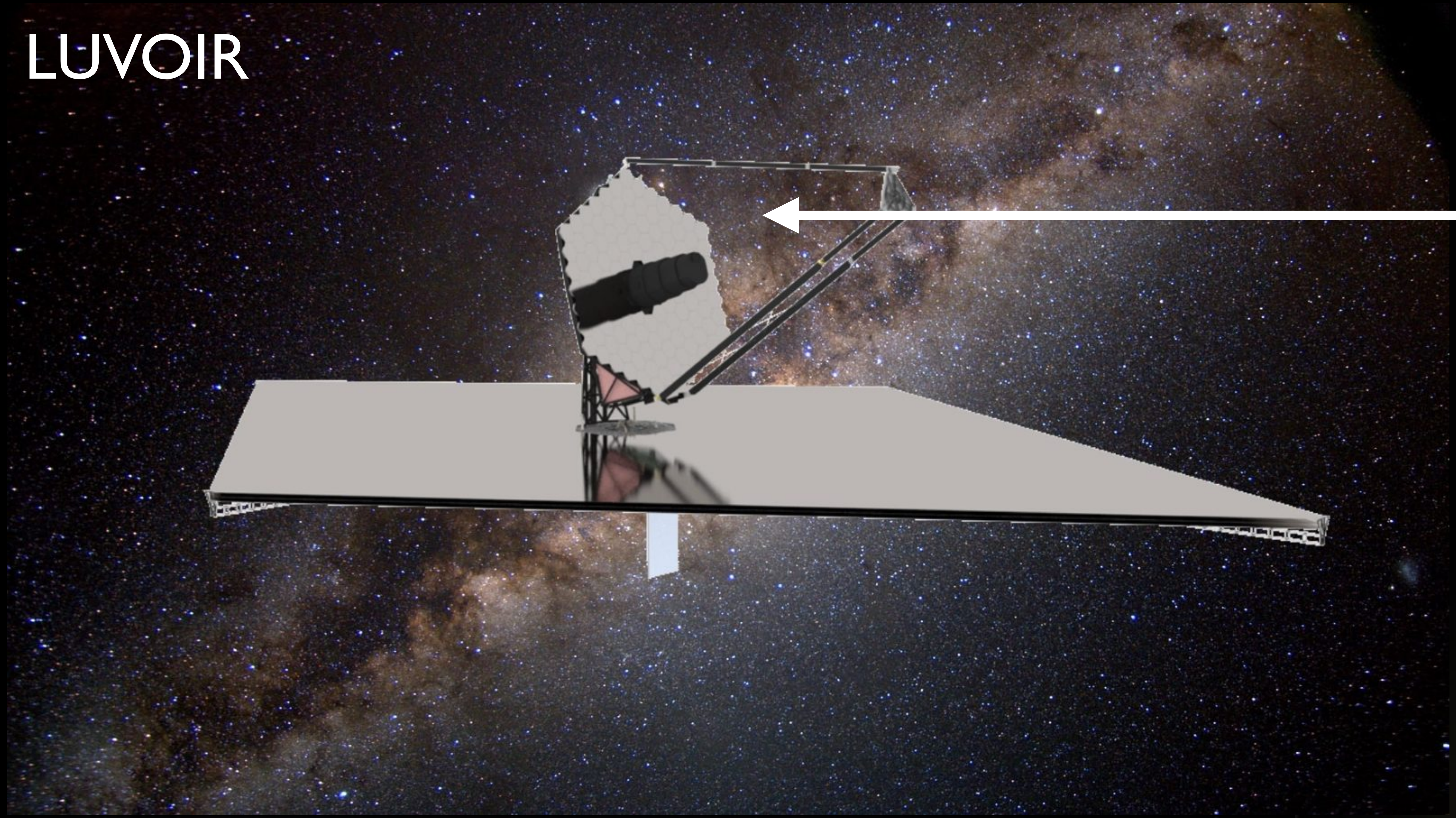


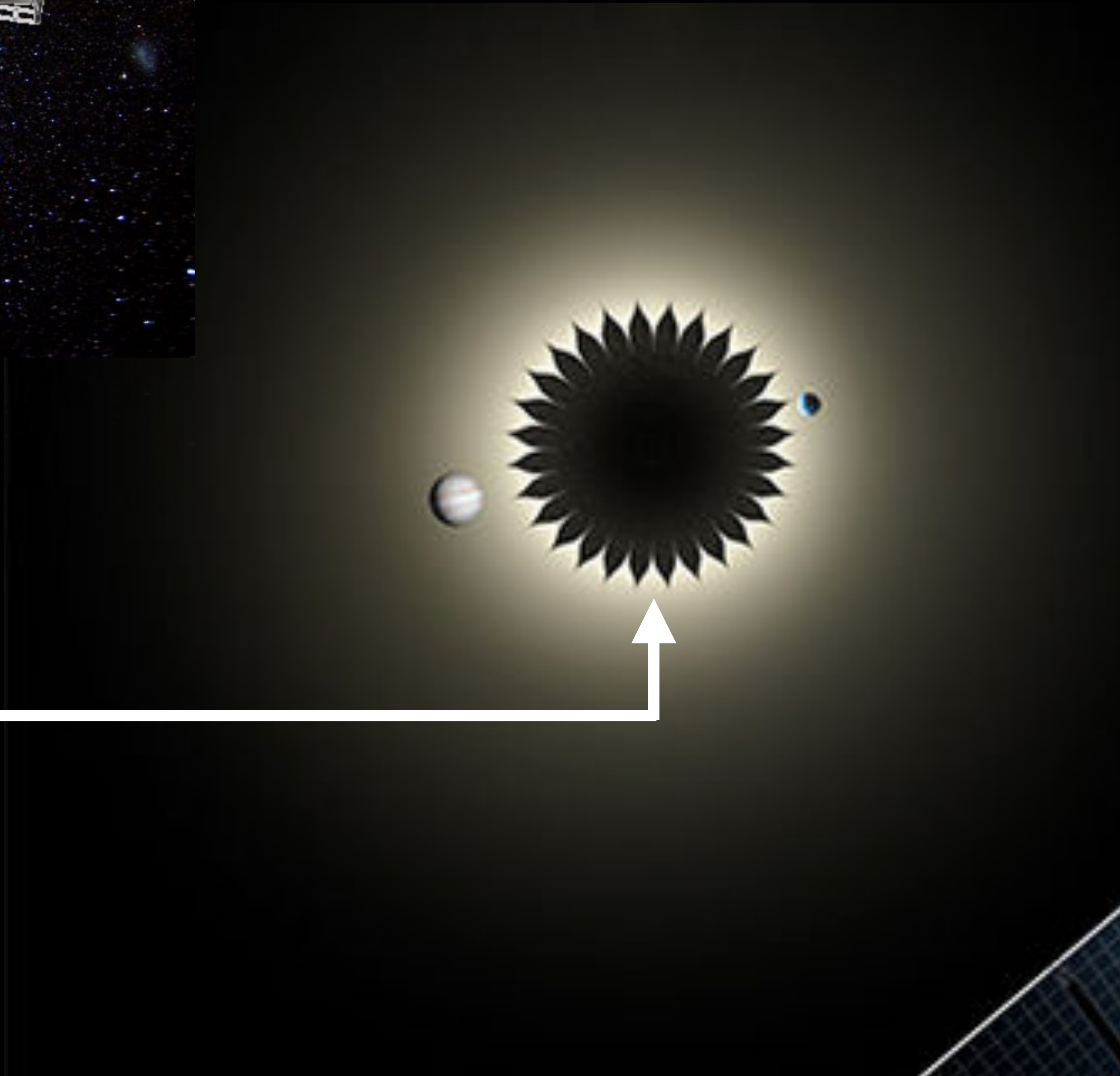
Image credit: NASA/NOAA; NASA/NOAA GOES Project; NASA; LIFE initiative

Direct detection and characterization in reflected light



Much bigger mirrors than Hubble Space Telescope

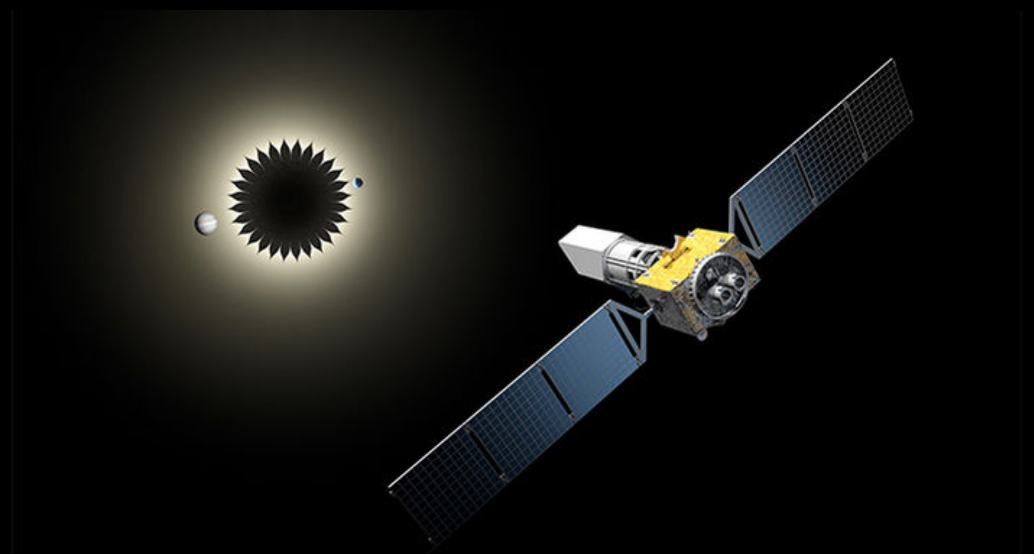
HabEx

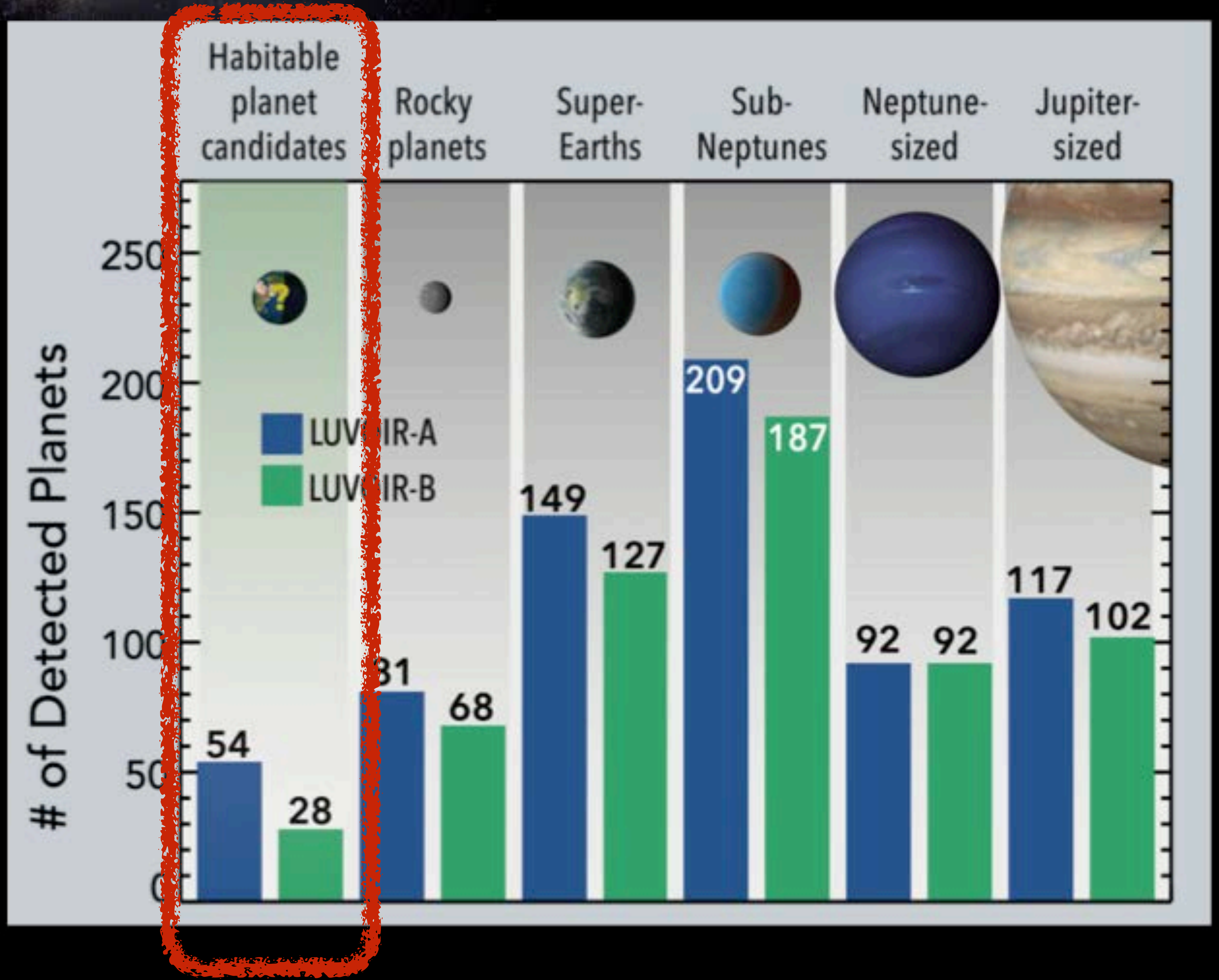


Star-shade to suppress stellar light

Image credit: LUVOIR / HabEx definition team; NASA

Direct detection and characterization in reflected light





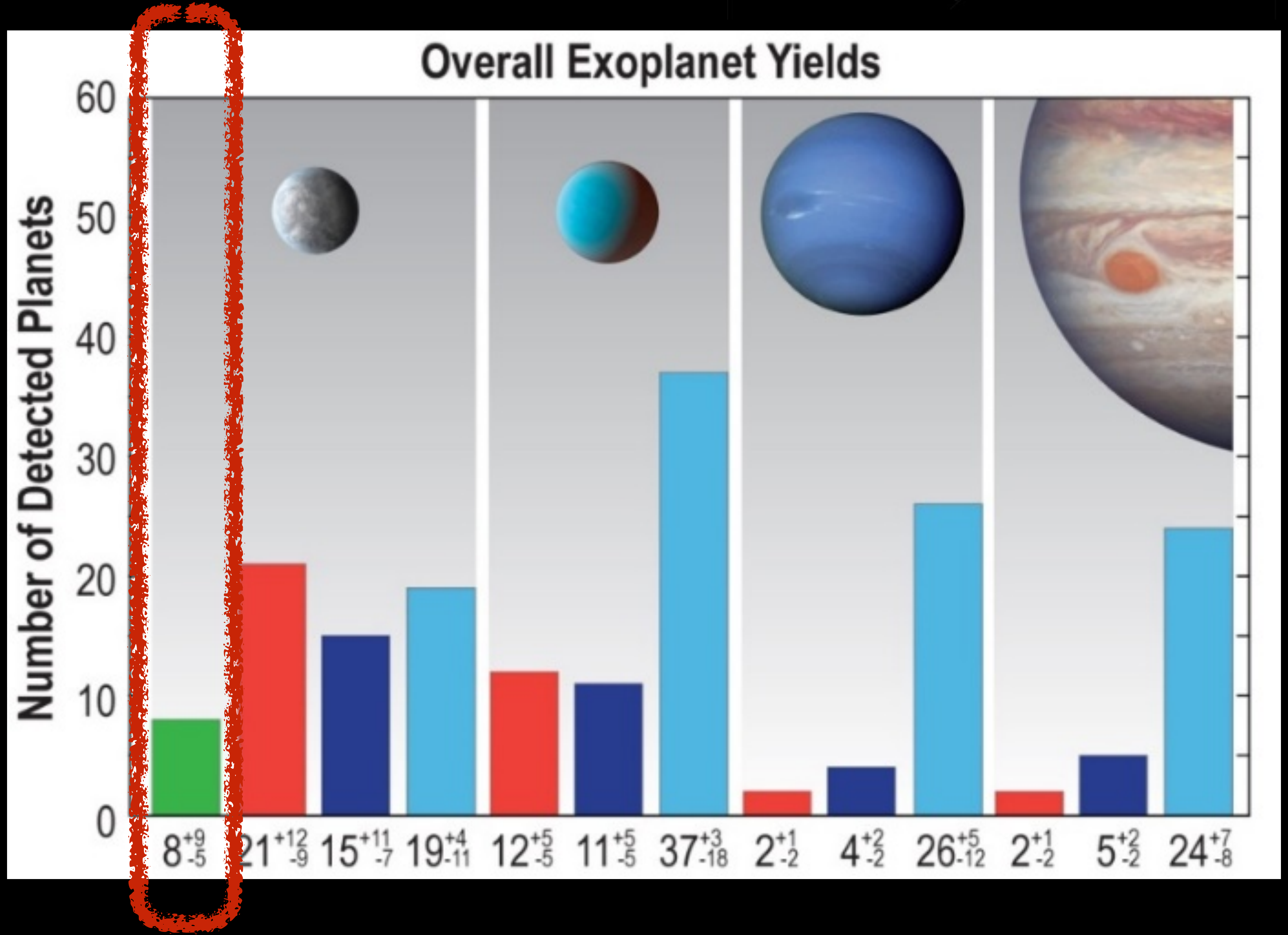


Image credit: LUVOIR / HabEx definition team

Direct detection and characterization in thermal emission

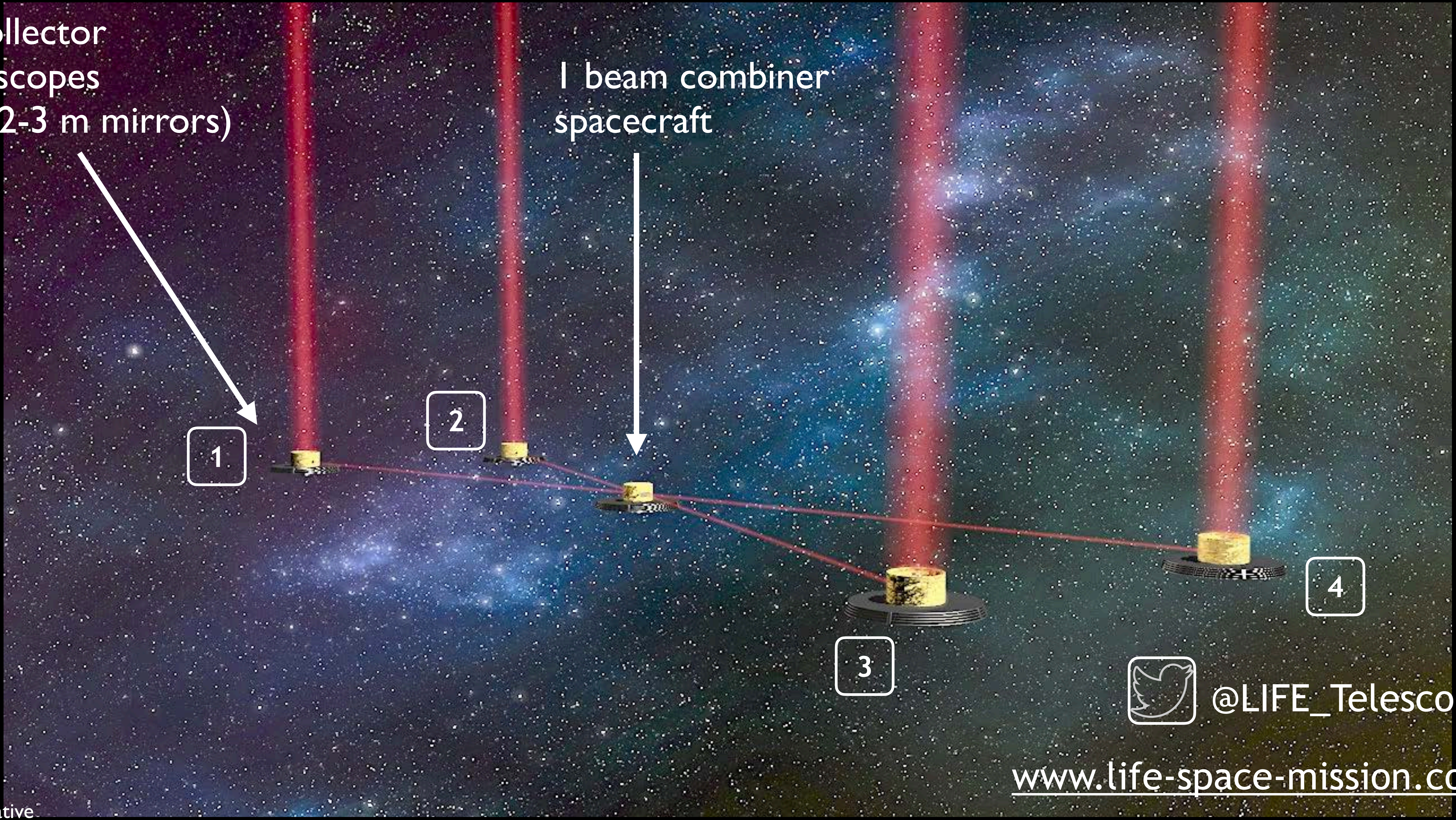


Image credit: LIFE initiative

Nulling interferometry in a nutshell

- Combine high angular resolution and starlight rejection
- First proposed in 1978 to detect non-solar planets (Bracewell 1978)

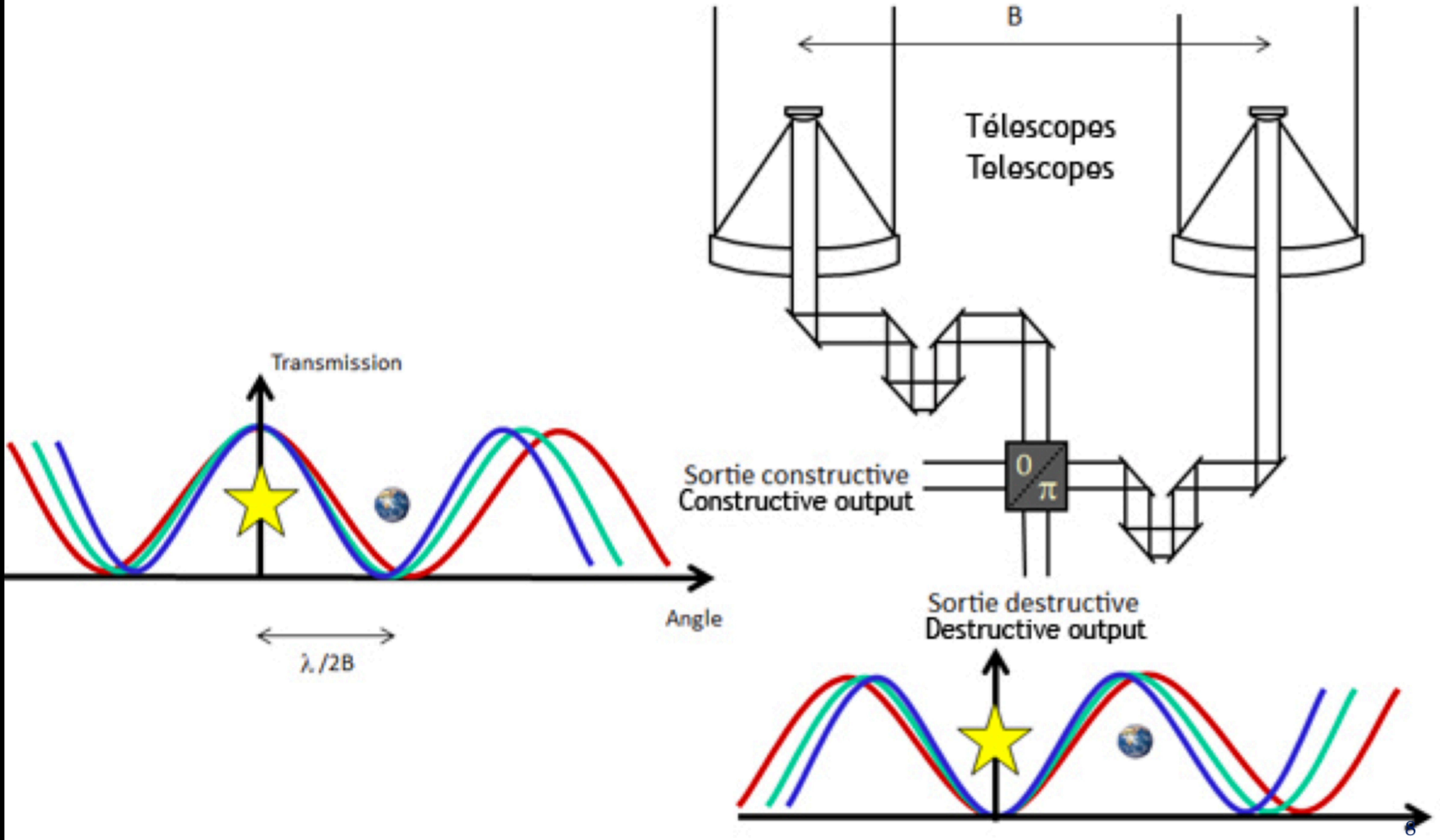
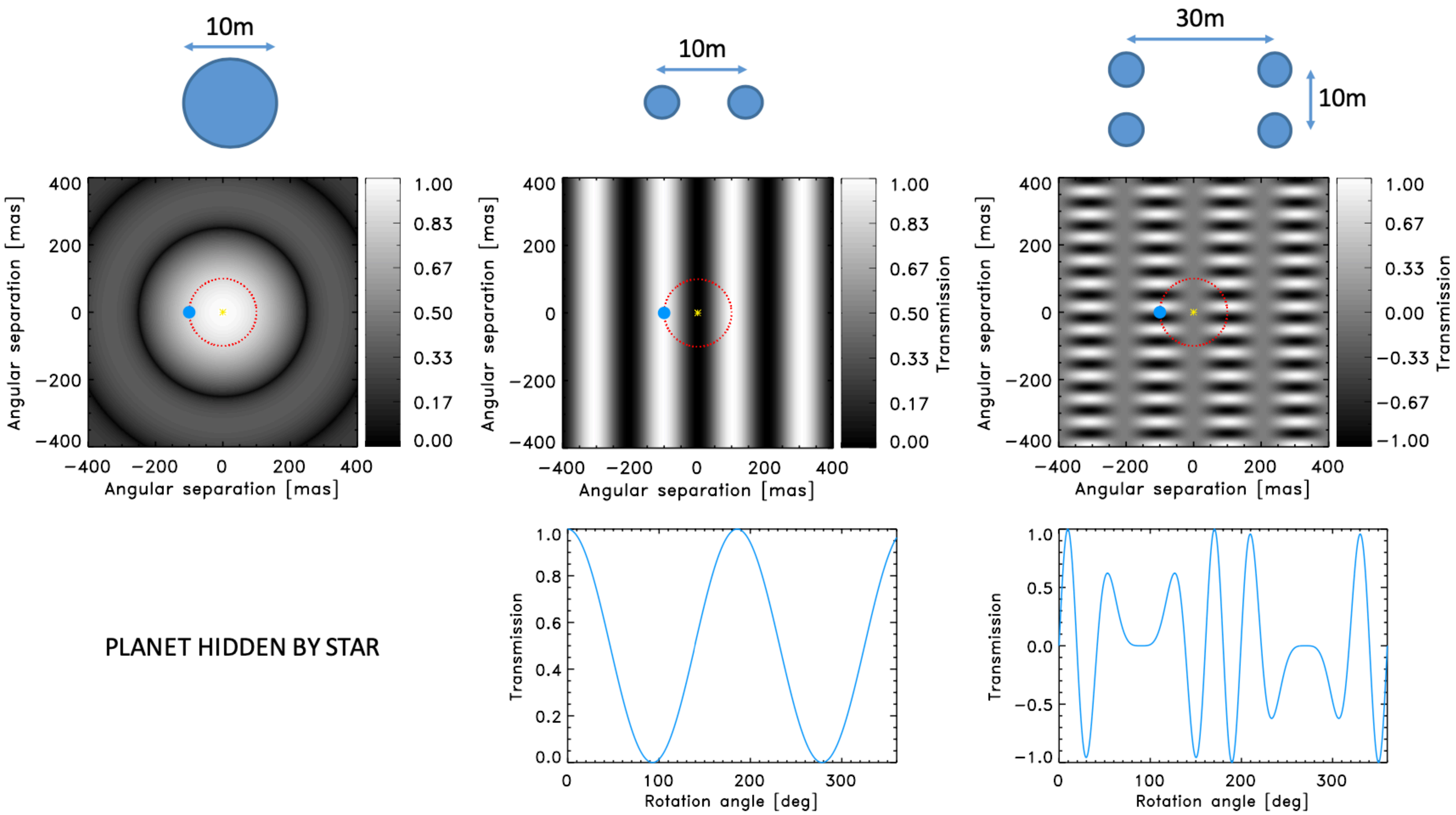


Image courtesy O. Absil

Credit: Denis Defrere

Nulling interferometry in a nutshell

- Transmission map for 2 and 4 telescopes



PLANET HIDDEN BY STAR

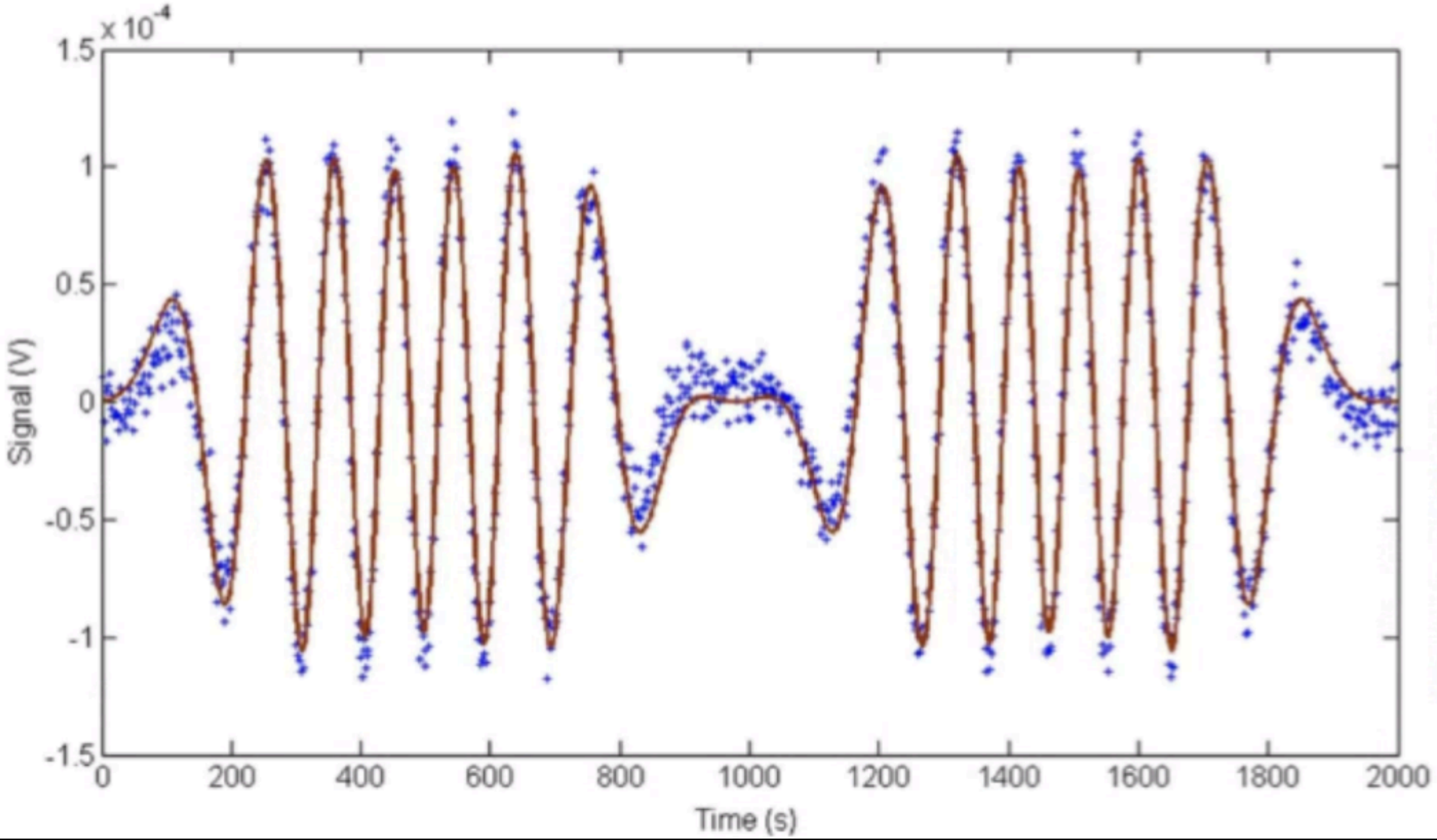
Earth-Sun system @ 10pc observed at 10 μm

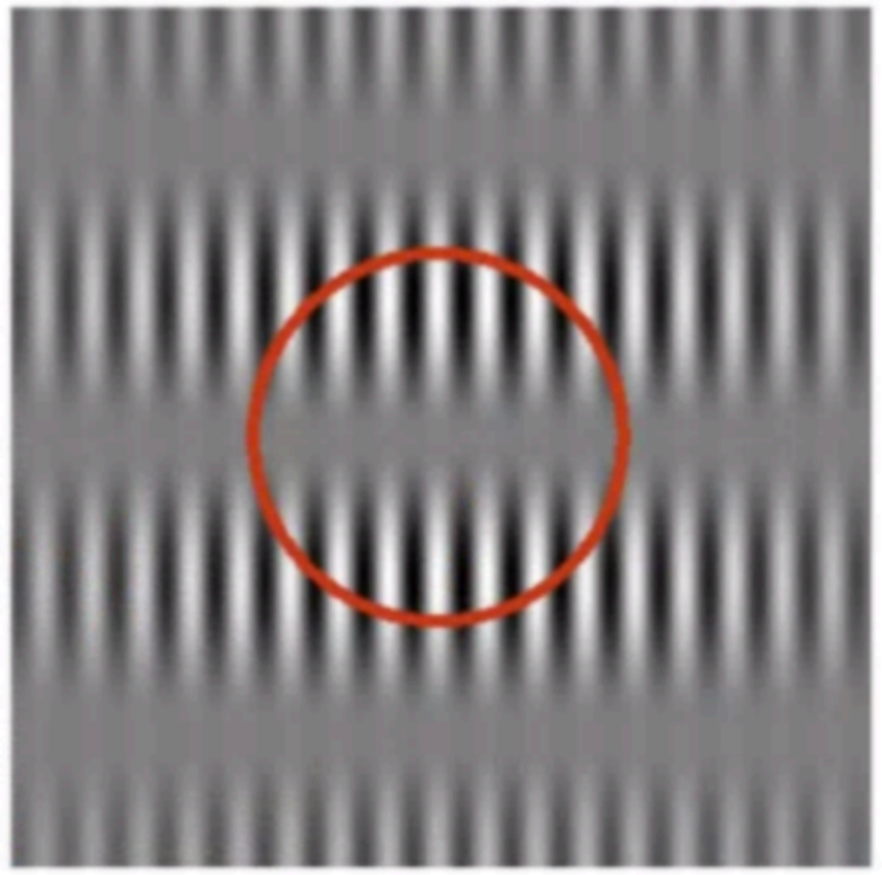
Credit: Denis Defrere

Current activities and plans: NICE

- Nulling Interferometric Cryogenic Experiment for LIFE
- ETH's cryogenic testbench
- Goals of the testbench:
  - Enhance technology readiness level of broadband nulling interferometry for LIFE and ground based nullers
  - Demonstrate broadband nulling beyond 10% bandwidth @10μm

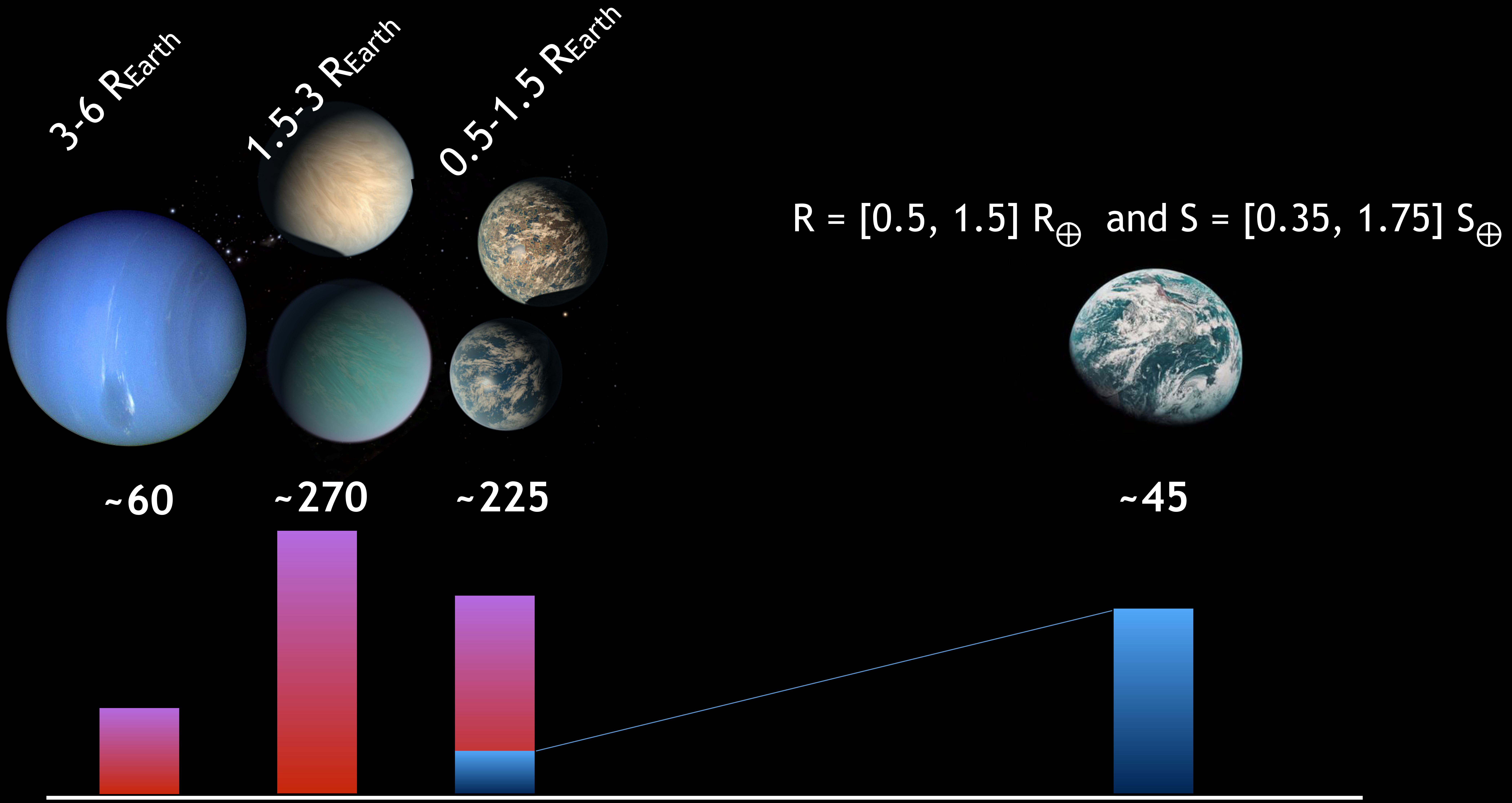
Planet Detection Testbed at JPL





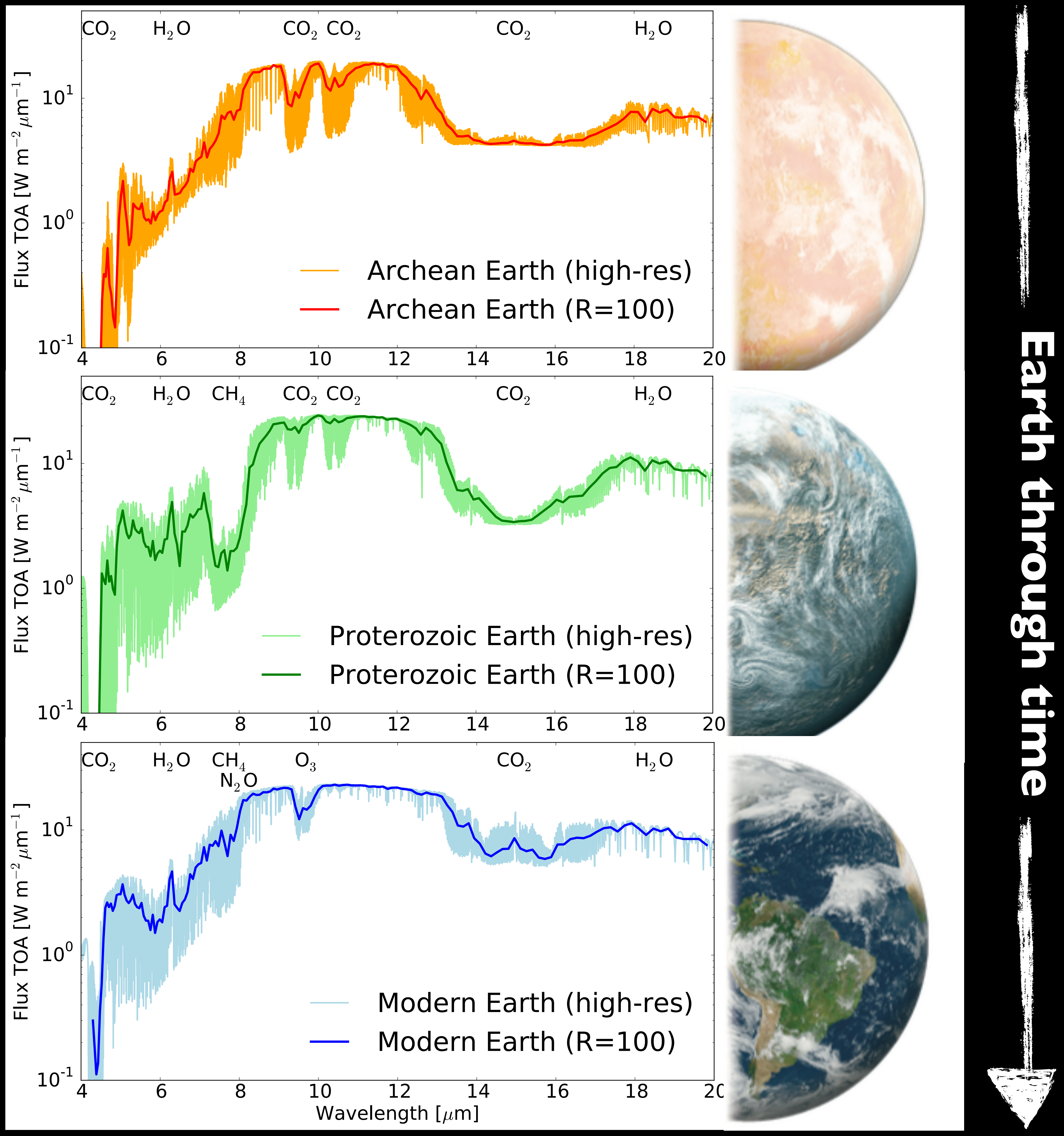
Credit: Denis Defrere

Direct detection and characterization in thermal emission



Quanz et al. in prep.; cf. Kammerer & Quanz 2018; Quanz et al 2018

Direct detection and characterization in thermal emission



- (Better) access to radius and temperature-pressure profile
- Access to ground temperature (if atmospheric windows exist)
- Access to O_3, CO_2, H_2O, CO, N_2O, PH_3, CH_4, $(N_2)_2$

Based on models from Rugheimer & Kaltenegger 2018, Rugheimer et al. 2015; Planet images from LUVOIR Final Study Report (2019)

Take away messages

We have detected thousands of exoplanets via indirect techniques; rocky / terrestrial exoplanets are common

A direct imaging approach is needed to investigate the atmospheres of these objects

The primary challenges are the large contrast difference between star+planet and the spatial resolution to separate the two signals

Planets can be imaged in reflected light or via their intrinsic thermal emission; each regime offers specific diagnostic power

A few nearby rocky exoplanets can be imaged from the ground with the ELTs; in-depth atmospheric characterization of dozens of Earth-like exoplanets requires optimized space missions

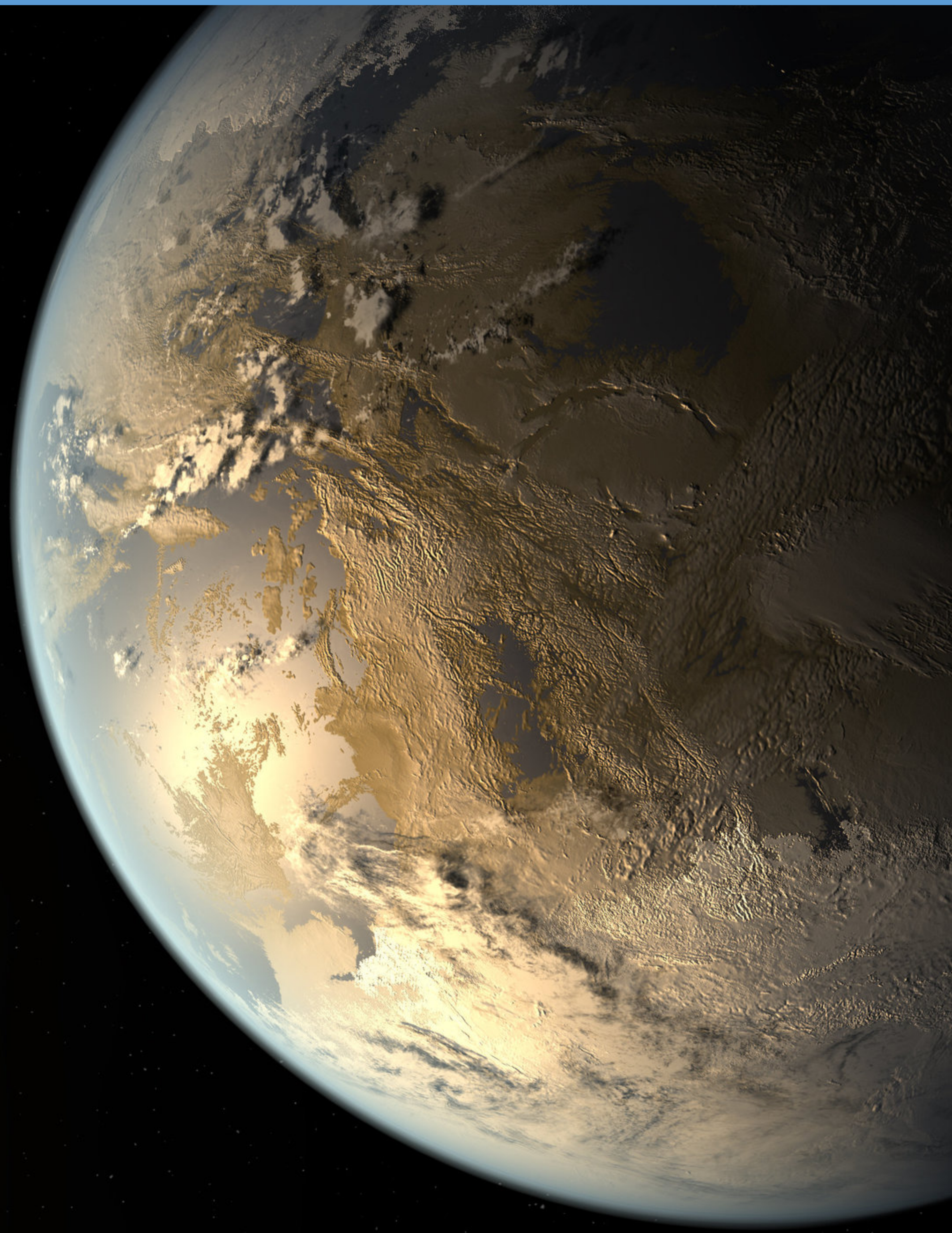


Image credit:NASA Ames/JPL-Caltech/T. Pyle