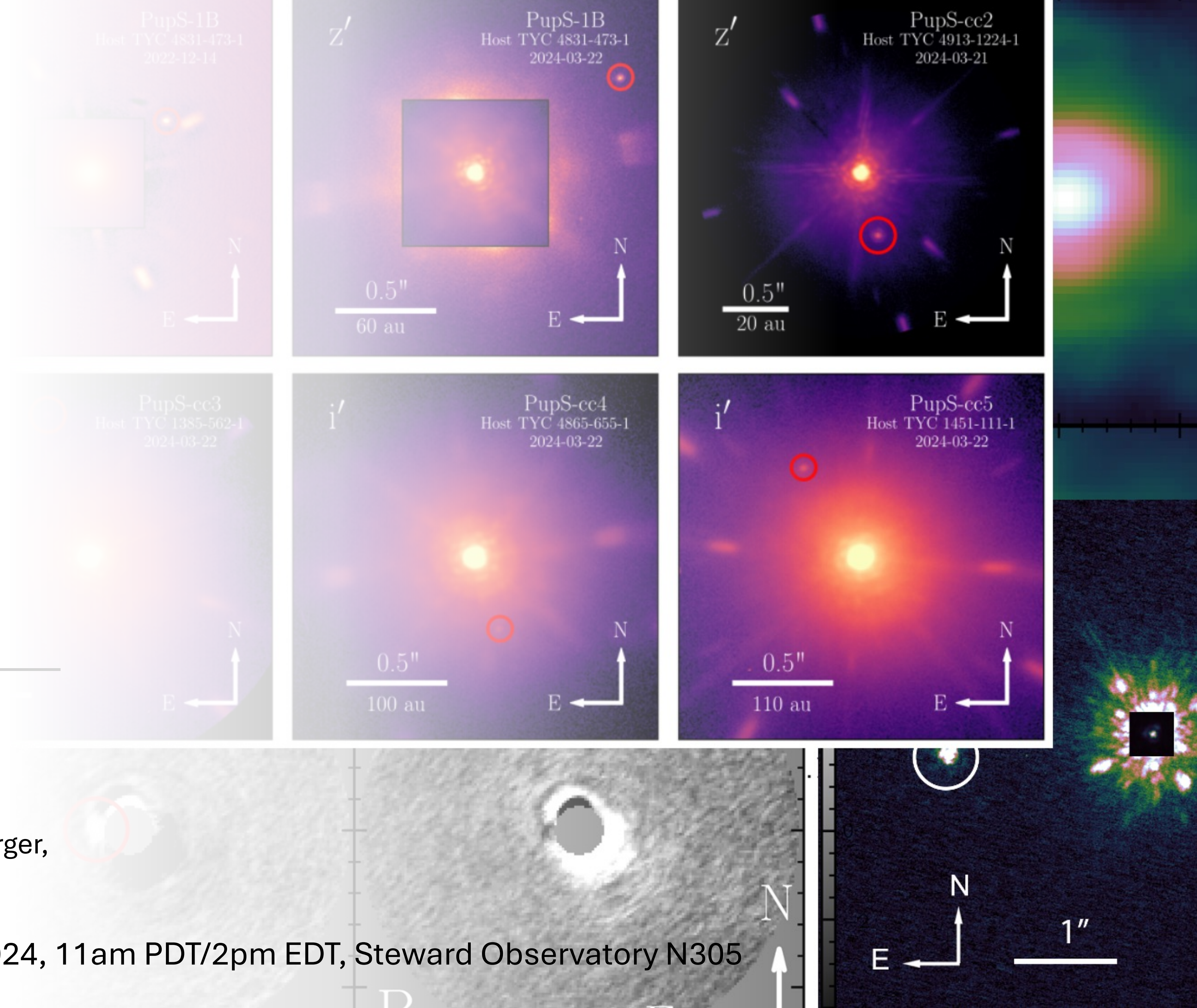
Stellar and Substellar Astrophysics with Extreme Adaptive Optics

Logan Pearce

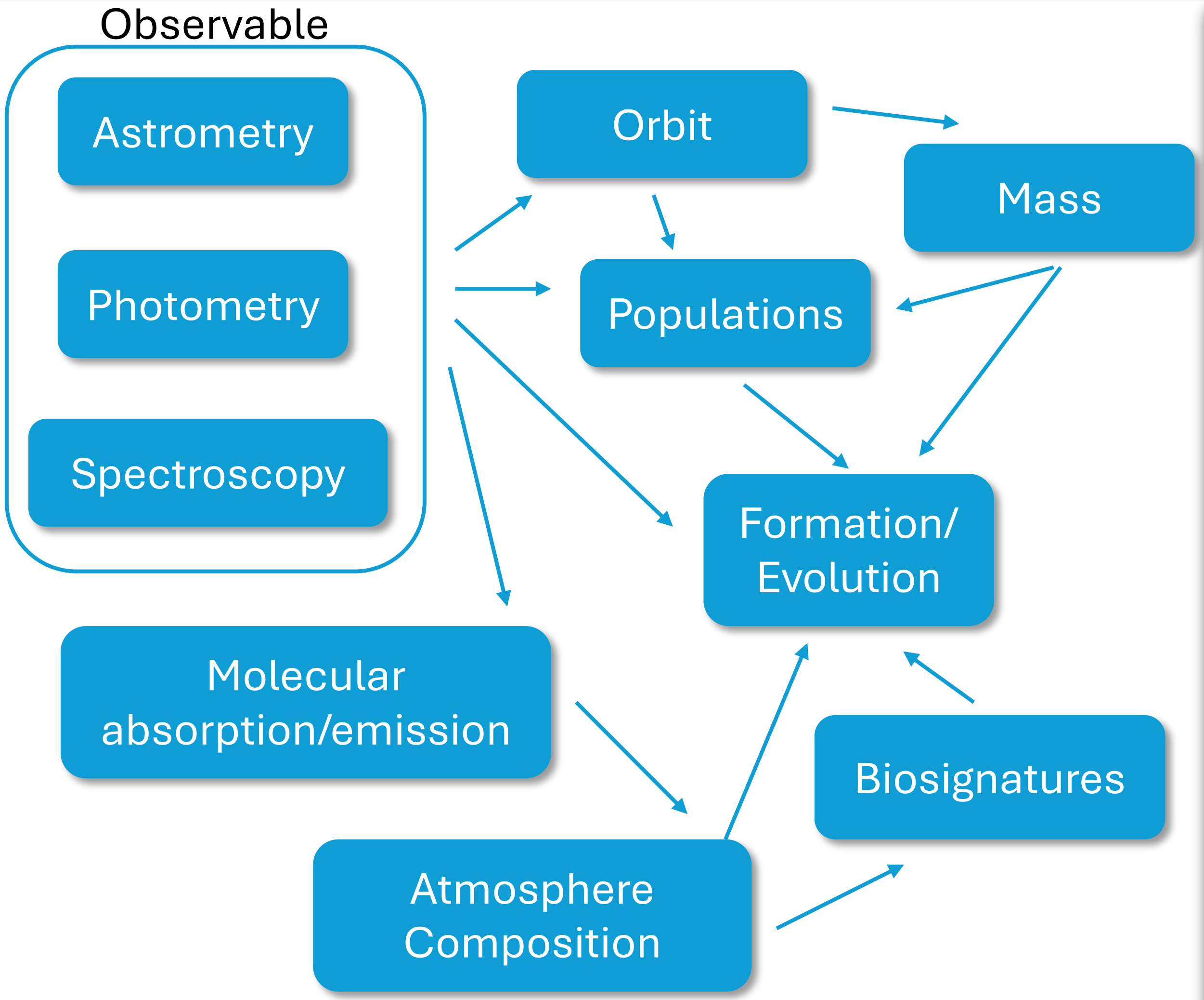
Advisor: Jared Males

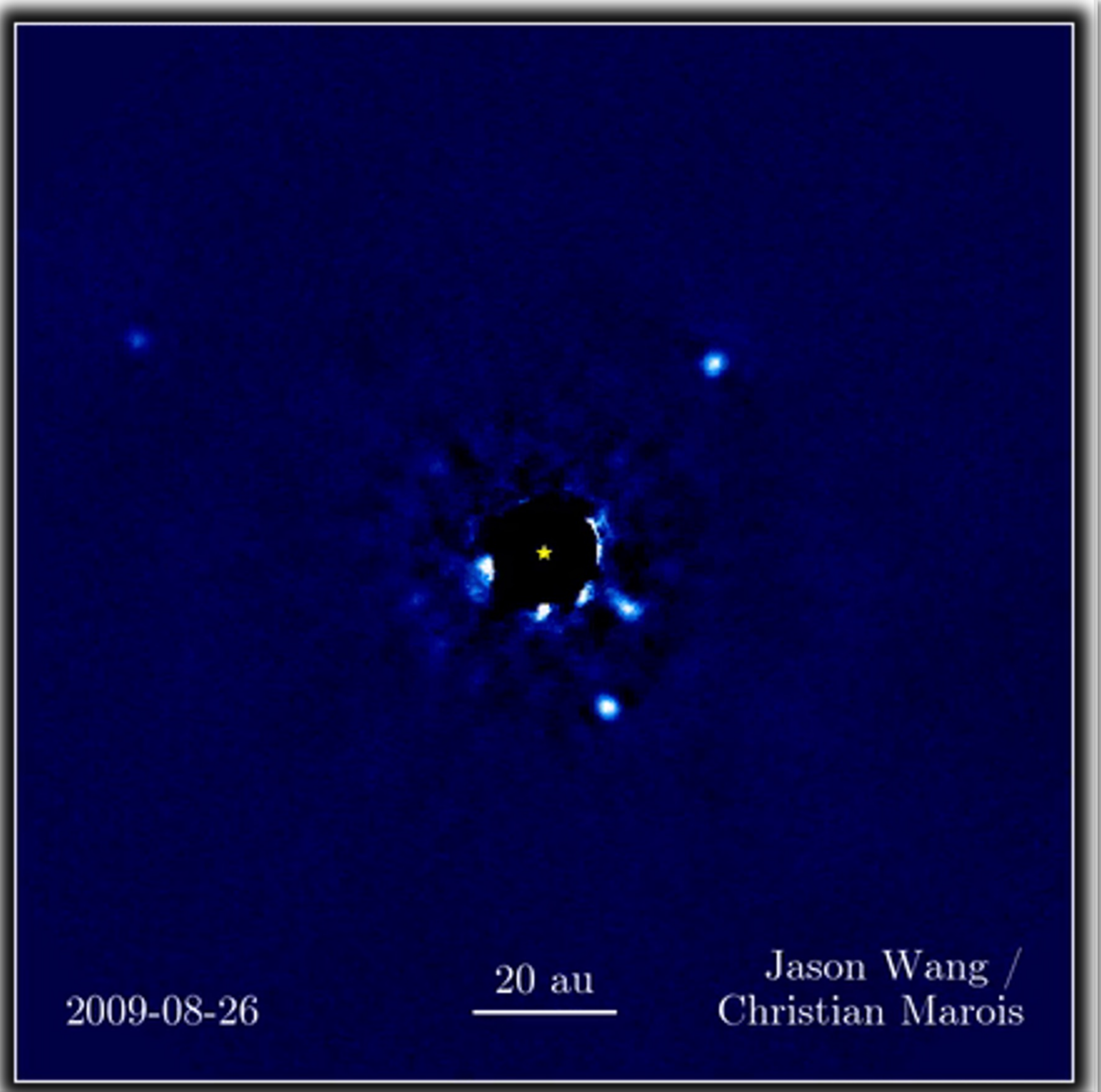
Committee: Laird Close, Alycia Weinberger, Chad Bender, Natasha Batalha

11 June 2024, 11am PDT/2pm EDT, Steward Observatory N305

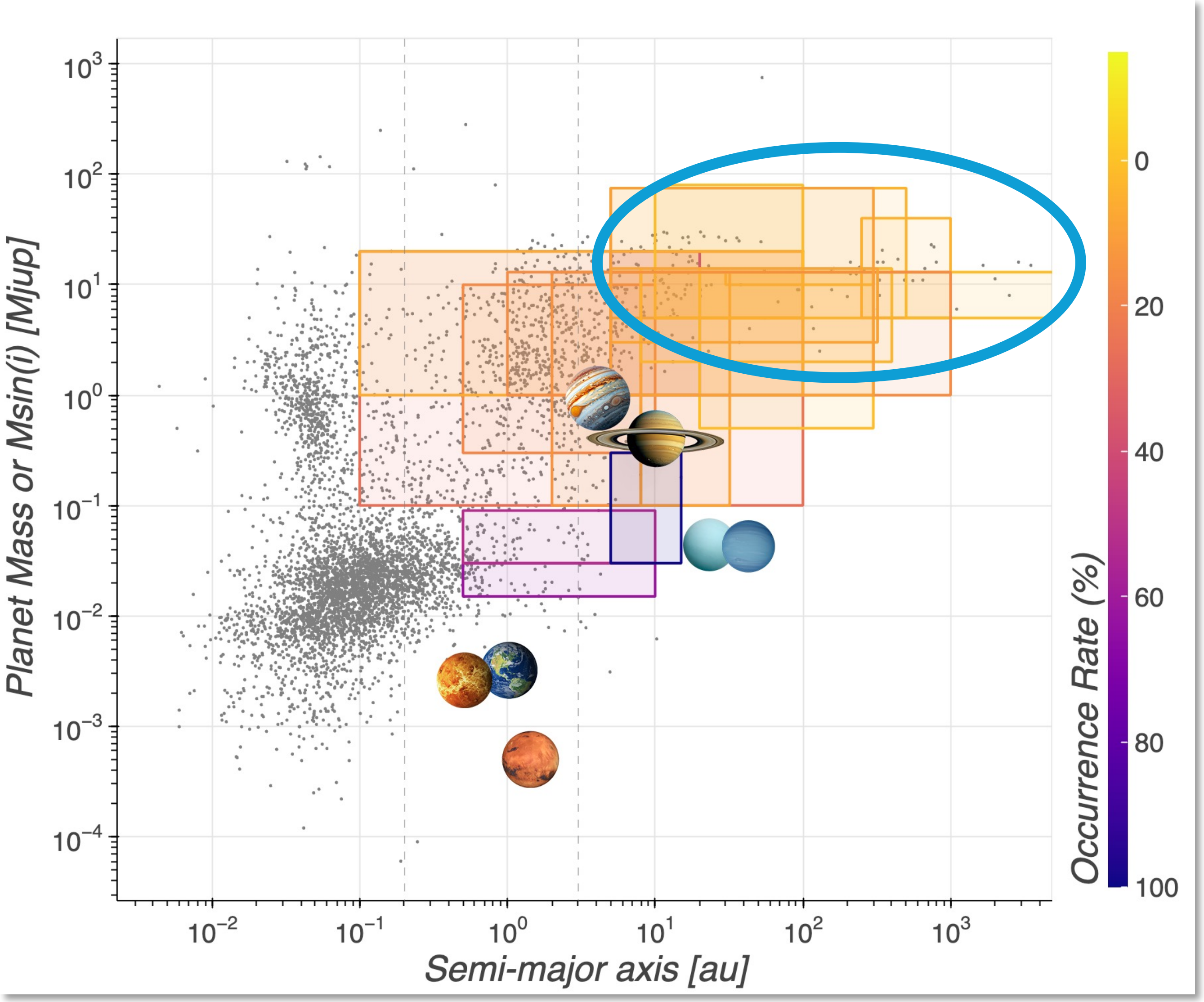


Direct Imaging is the future of exoplanet science





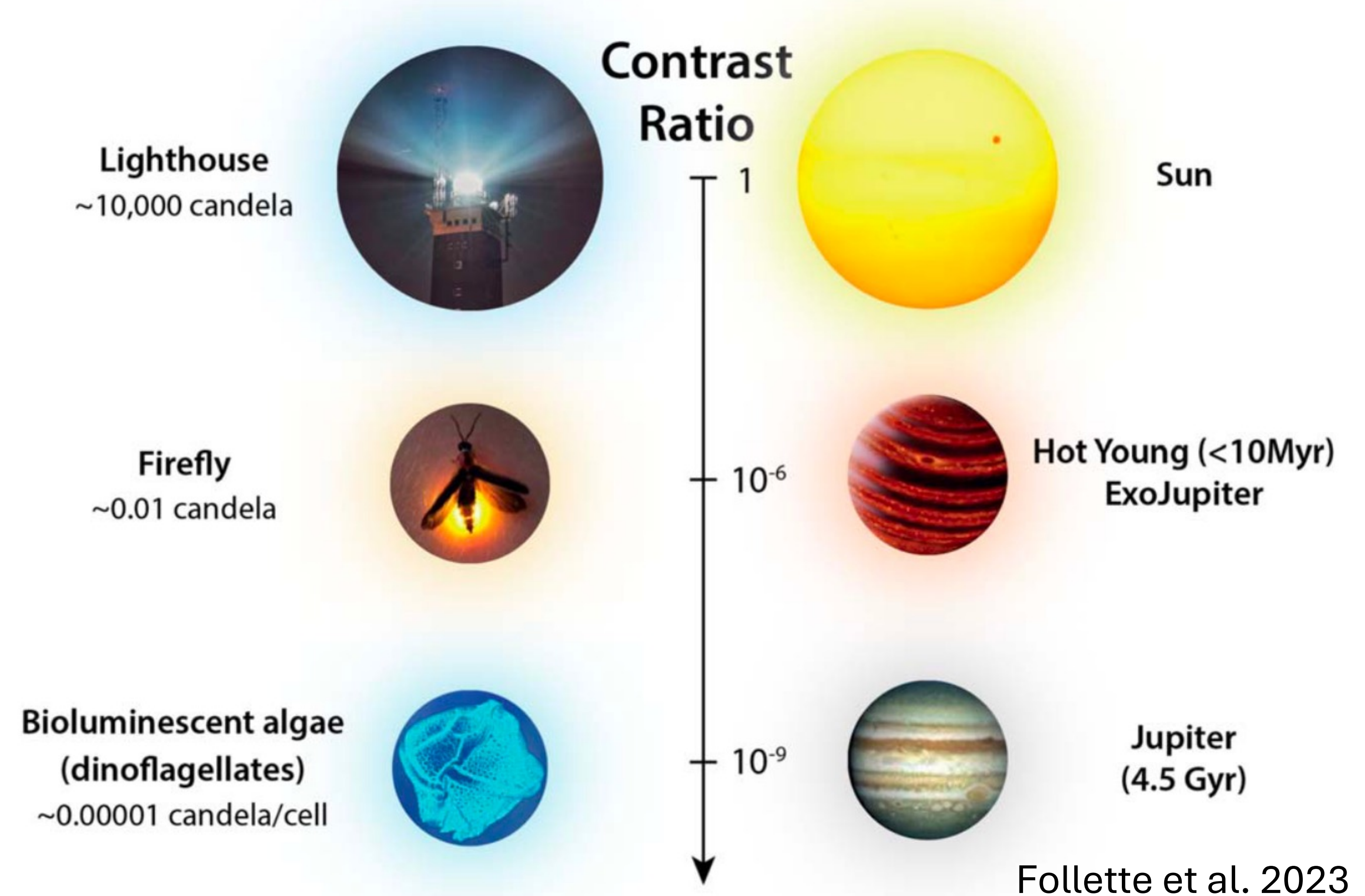
Regions where DI is sensitive currently have detected very few planets



DI is very hard!

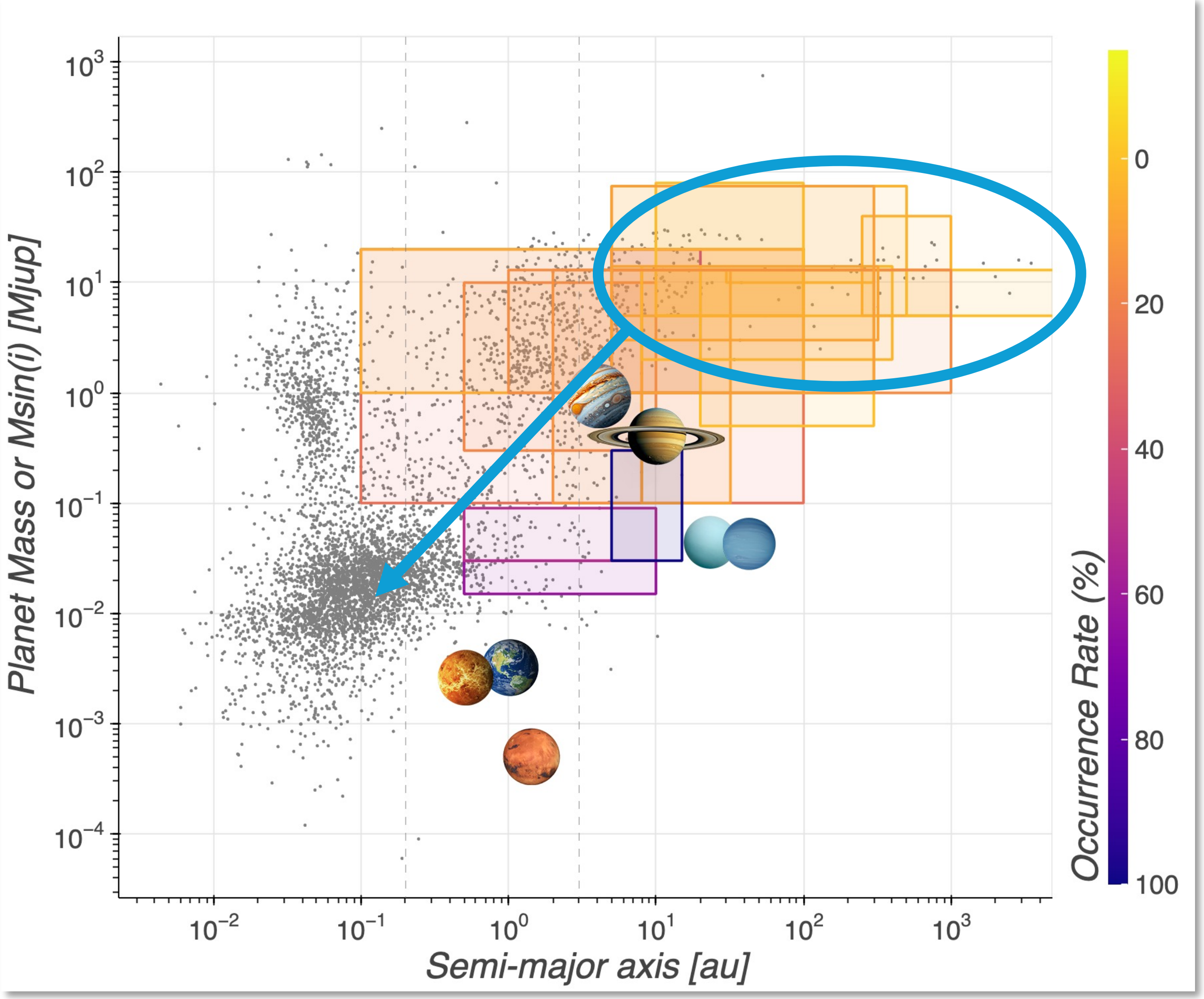
Stars are bright

Planets are faint
and close to stars

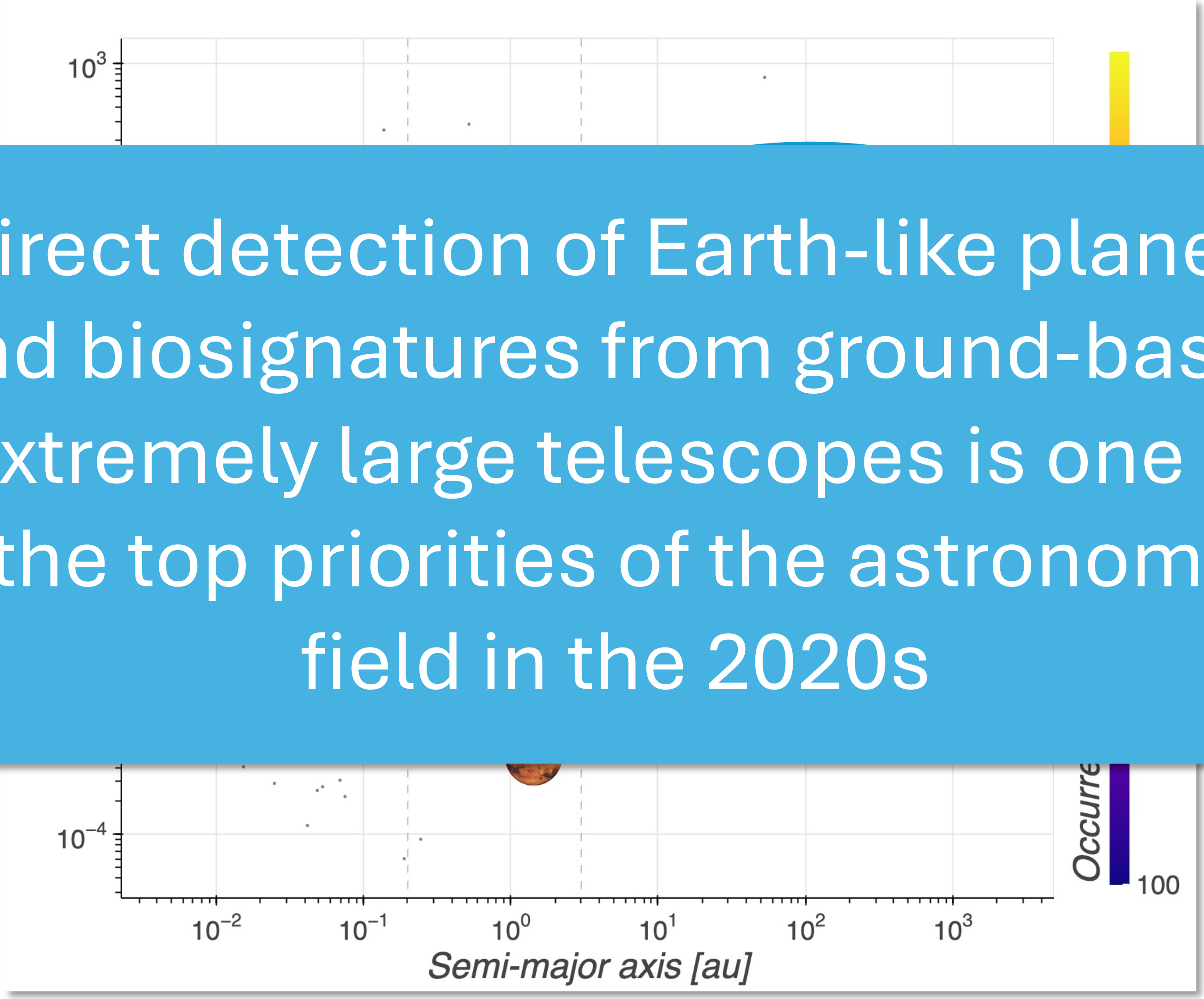


Follette et al. 2023

Need to push detection to fainter and closer planets

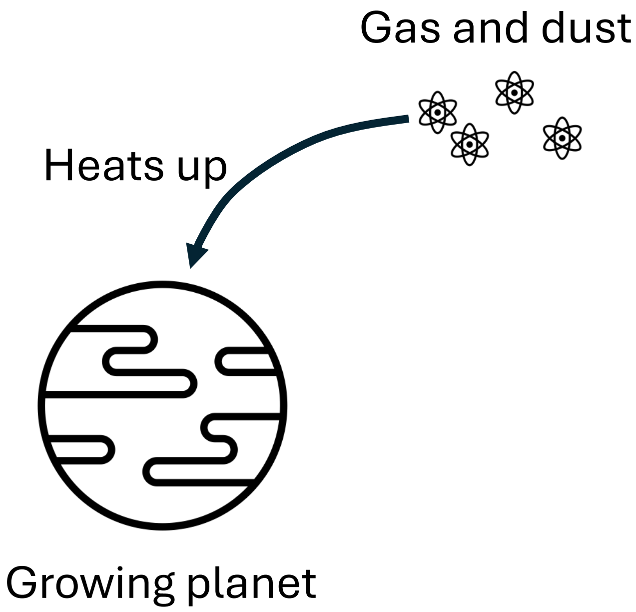


Need to push detection to fainter and closer planets

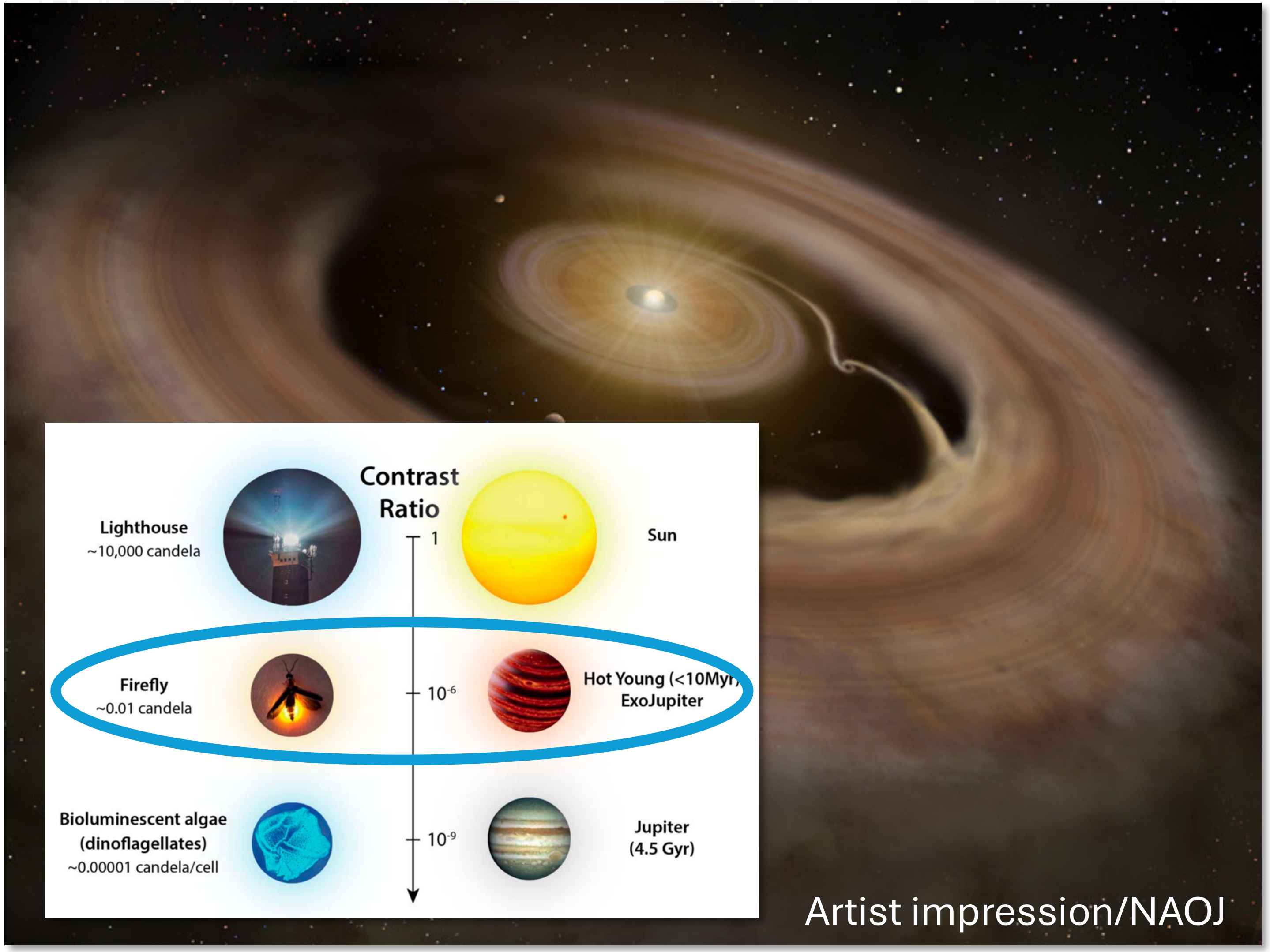


Direct detection of Earth-like planets and biosignatures from ground-based extremely large telescopes is one of the top priorities of the astronomy field in the 2020s

How we directly detect planets: Thermal Emission



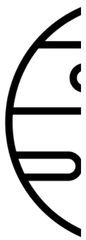
Young planets are hot and glow in IR wavelengths



Artist impression/NAOJ

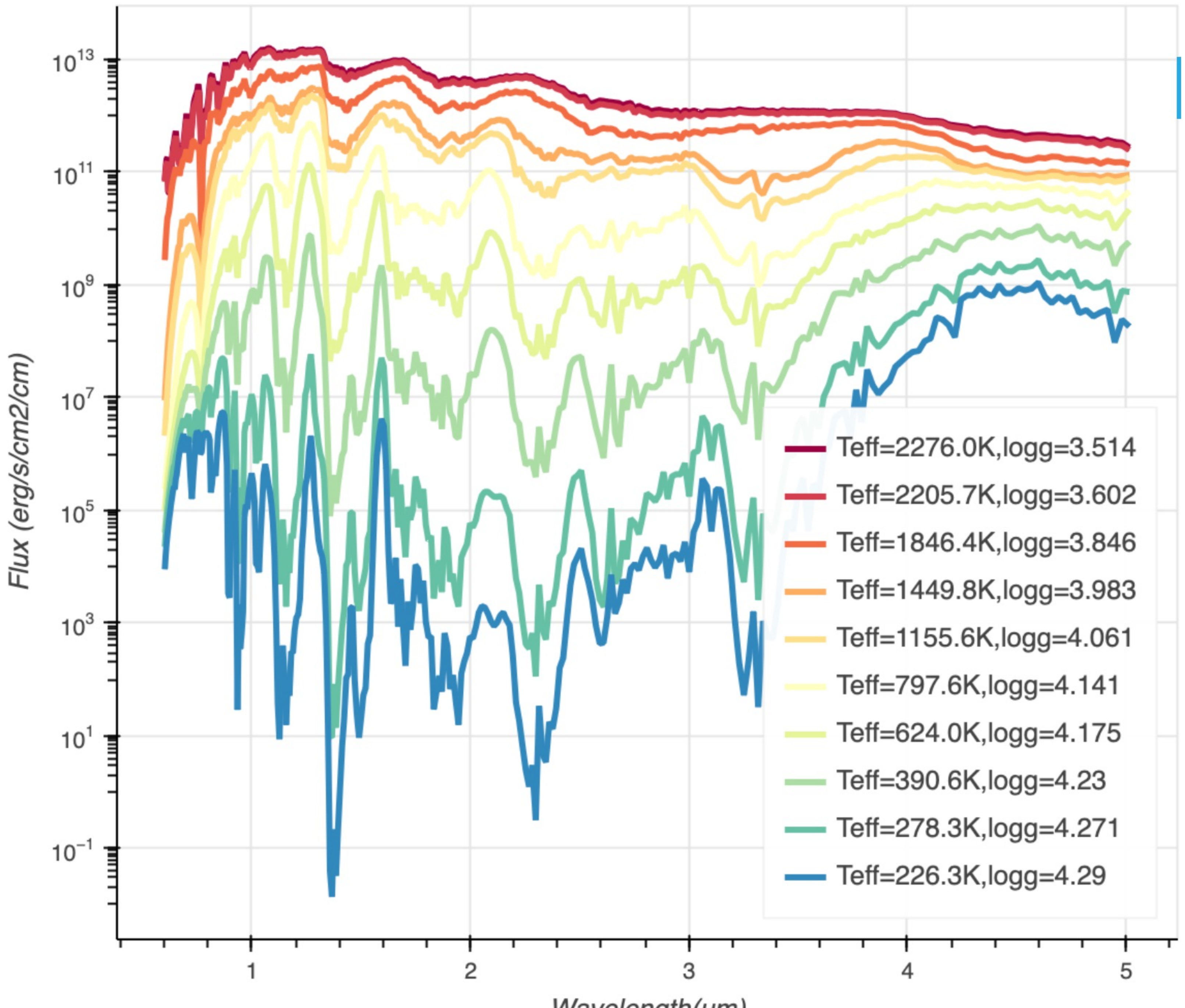
How we … nission

Hea

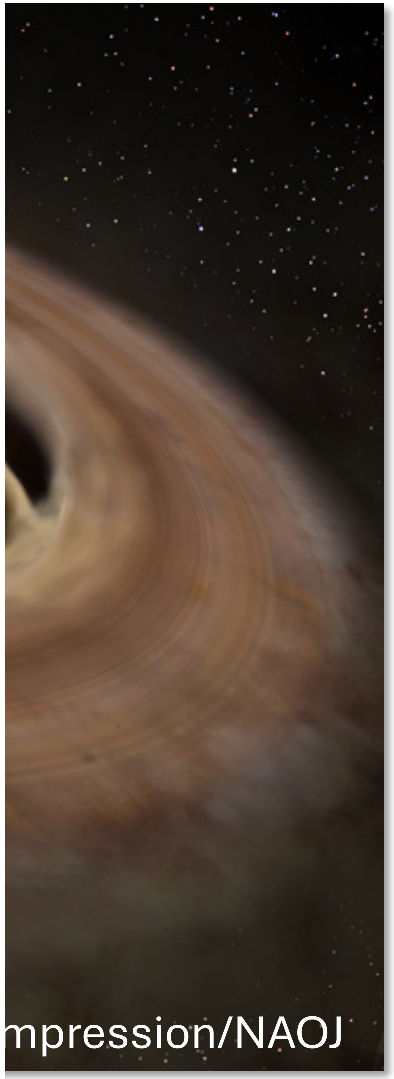


Grow

Young pl
and g
wav

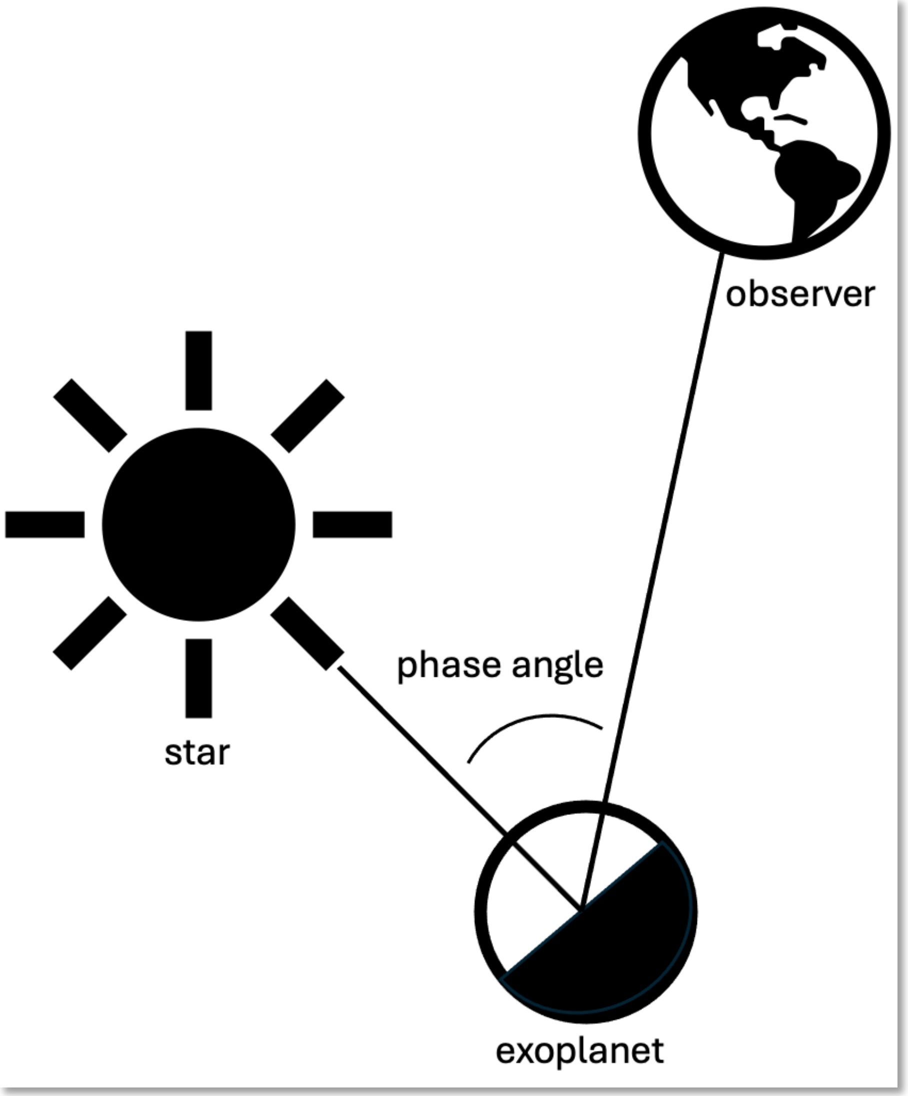


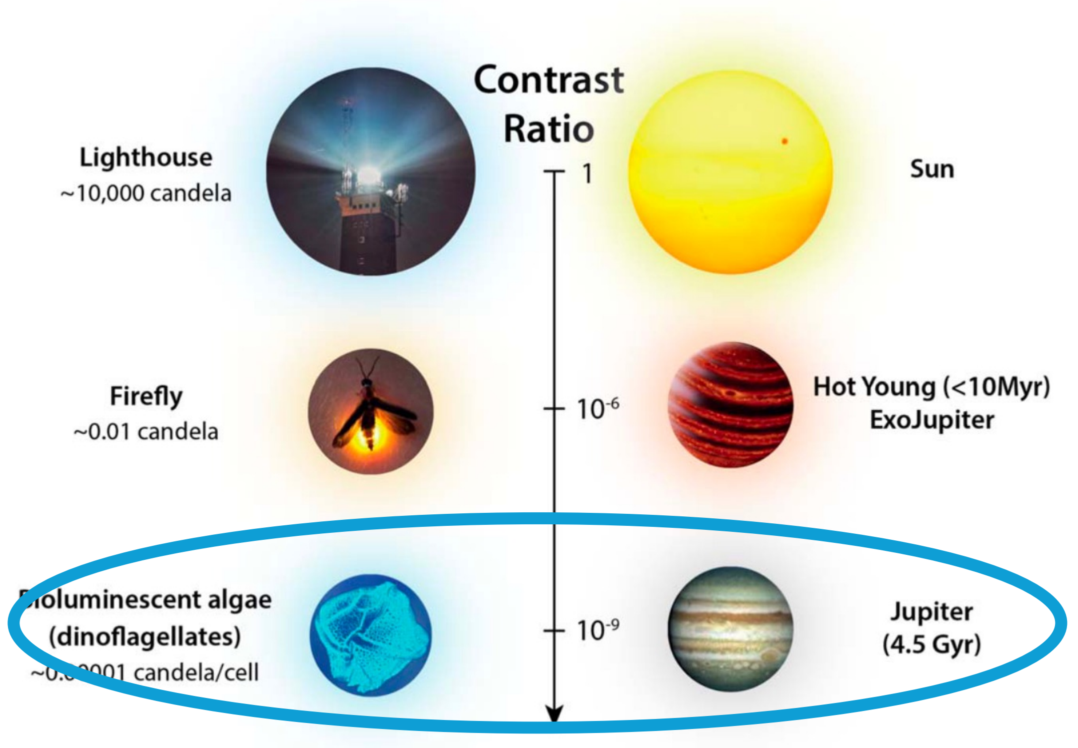
Credit: PICASO documentation



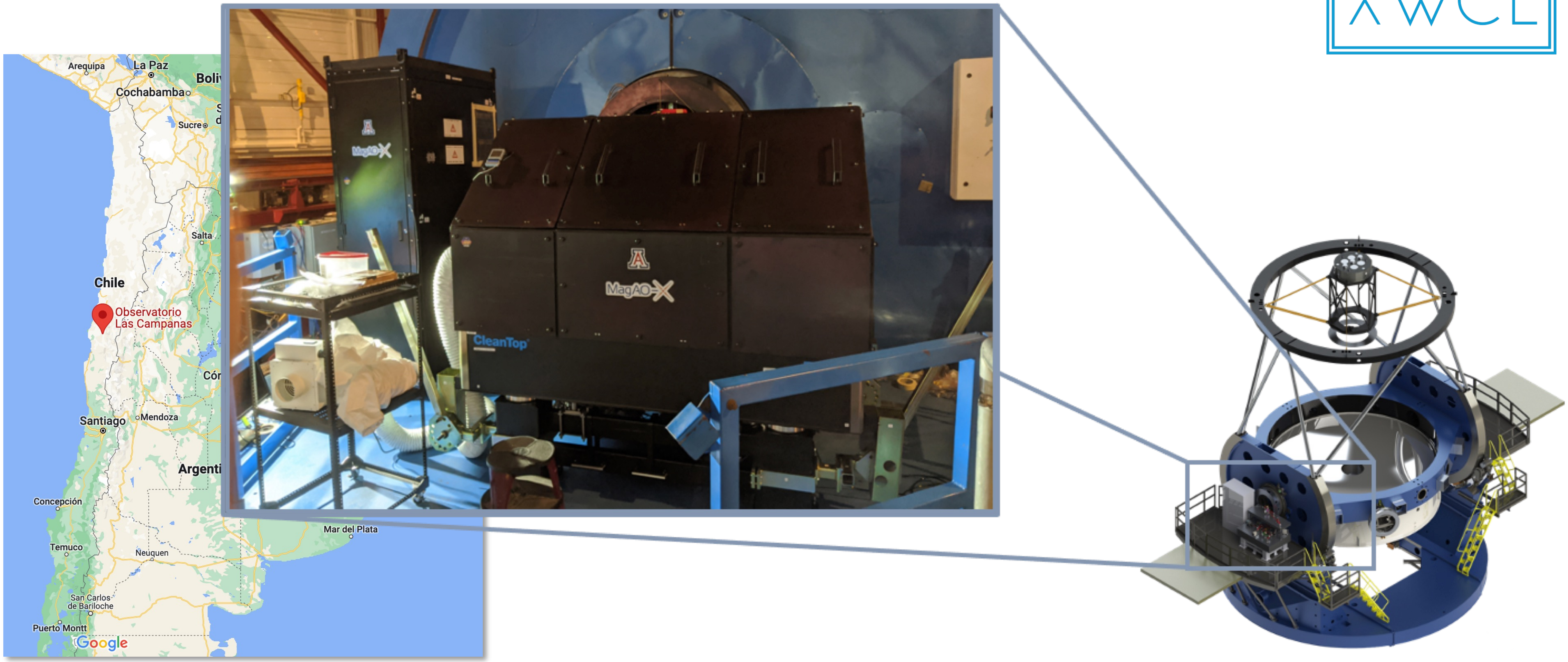
oganpearce1@arizona.edu

How we directly detect planets: Reflected Light



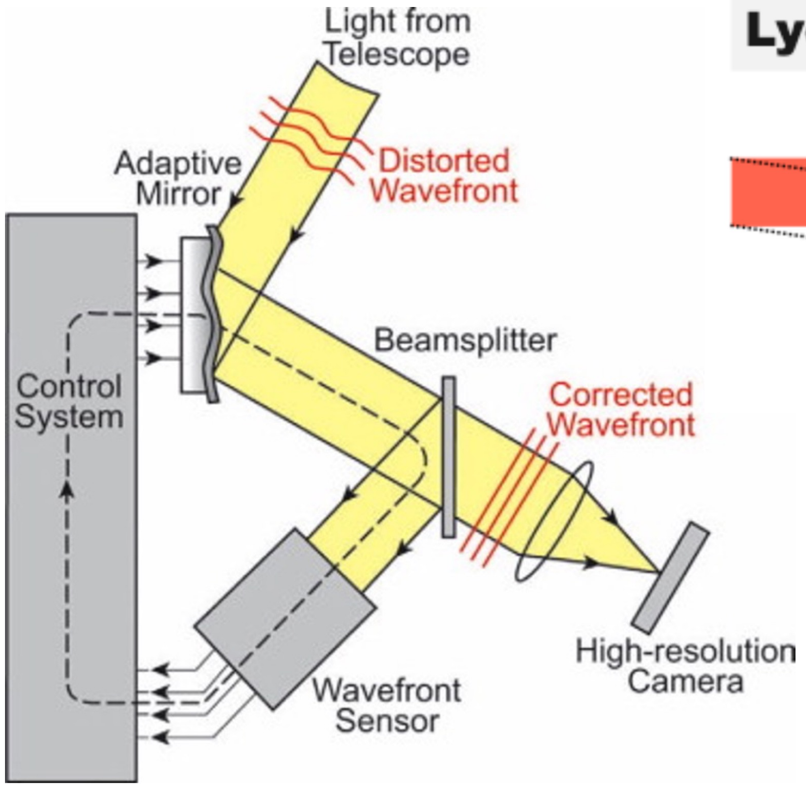


Detecting nearby planets in reflected light is the ultimate science goal of MagAO-X



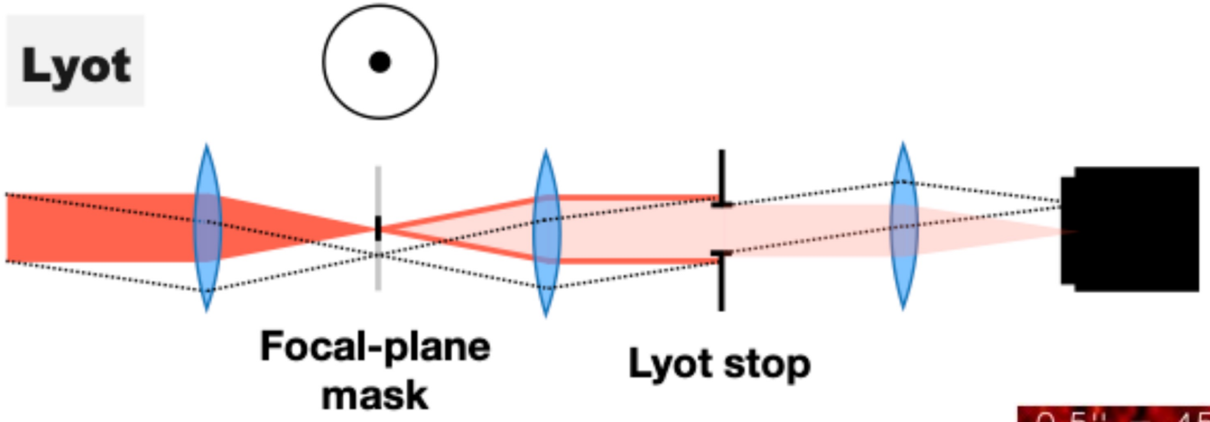
High contrast imaging is achieved through AO + Coronagraphy + post-processing

Adaptive Optics



Diffraction-limited imaging from the ground

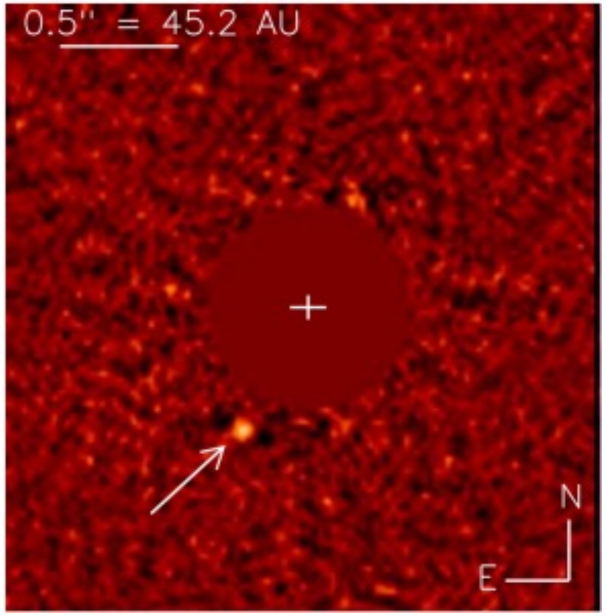
Coronagraphy



Block on-axis light (star) while allowing off-axis light to pass through -> “dark hole” region of high contrast

Post-Processing

Remove starlight and speckles to reveal faint objects

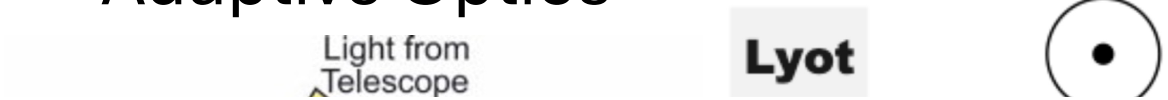


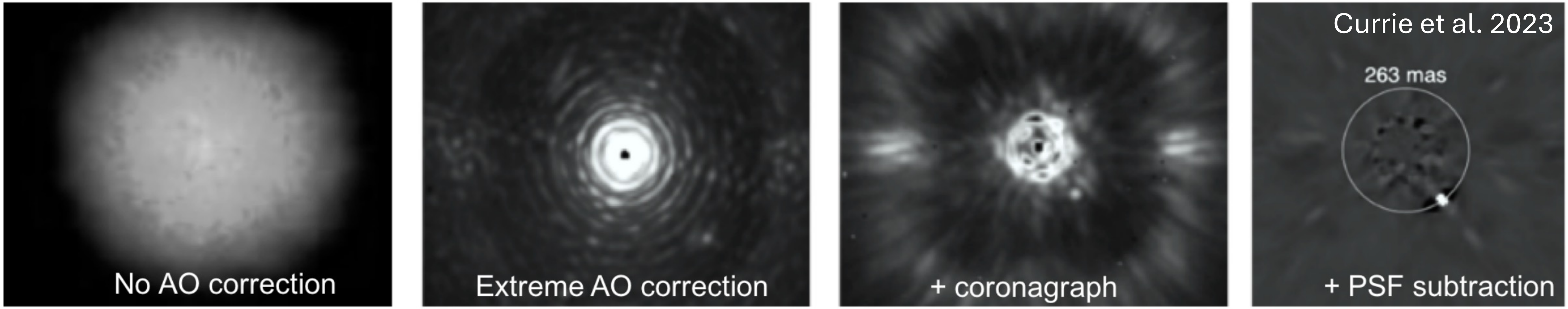
High contrast imaging is achieved through AO + Coronagraphy + post-processing

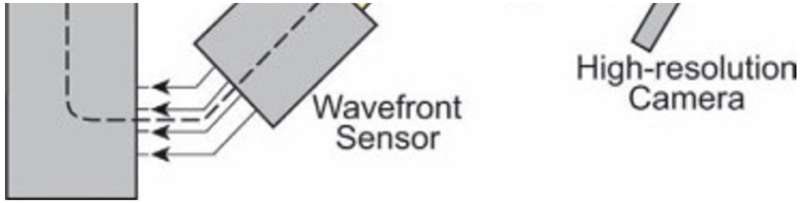
Adaptive Optics

Coronagraphy

Block on-axis light (star) while

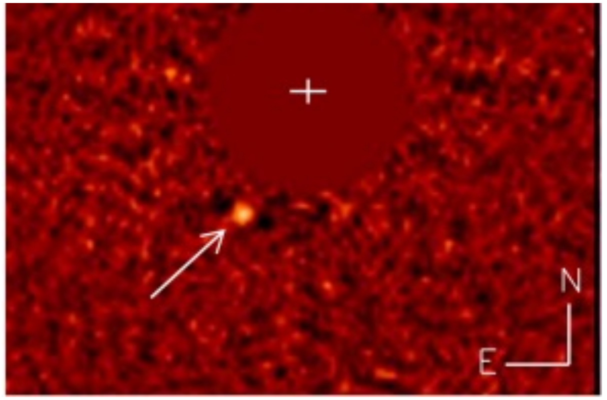




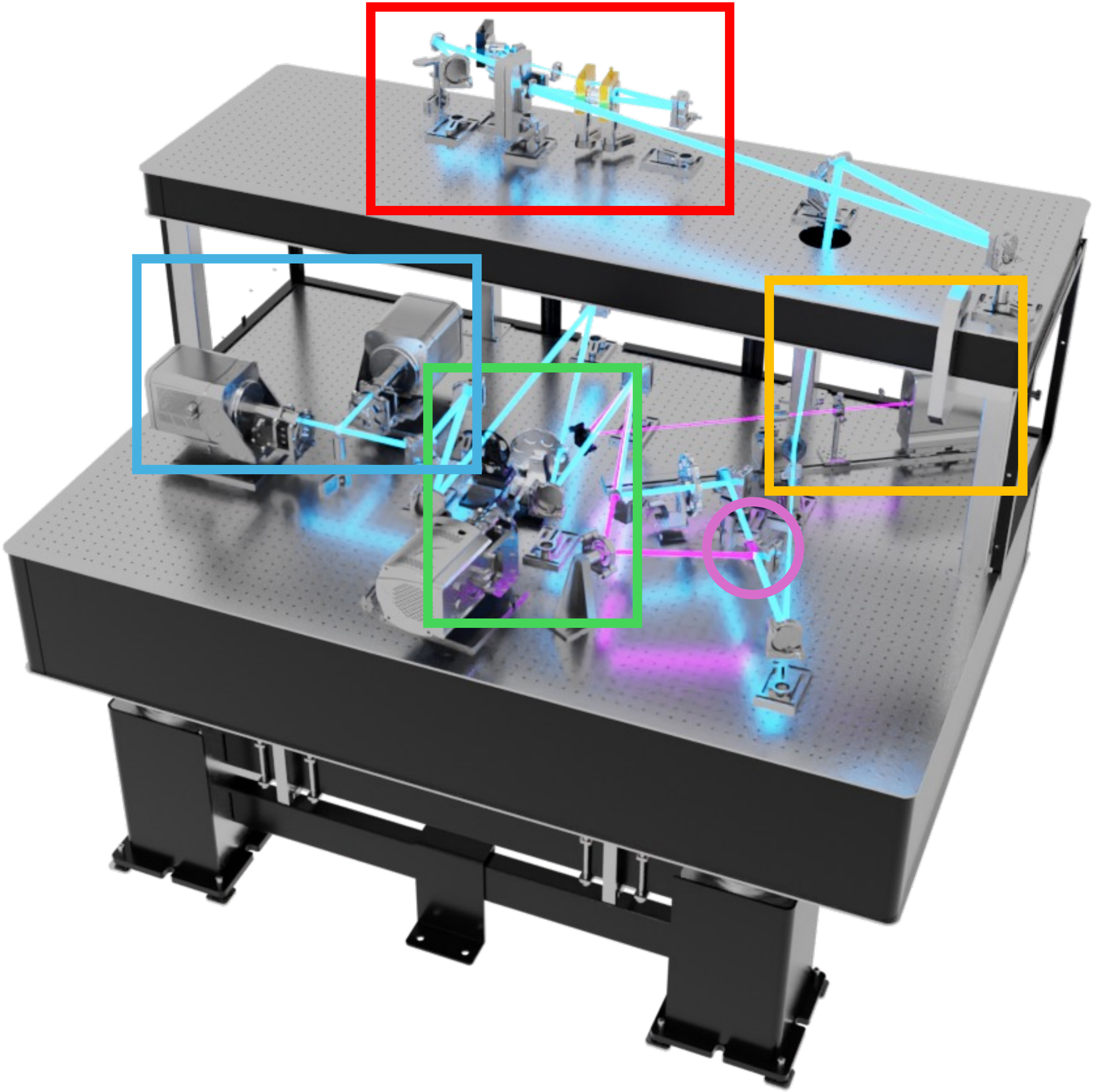


Post-Processing

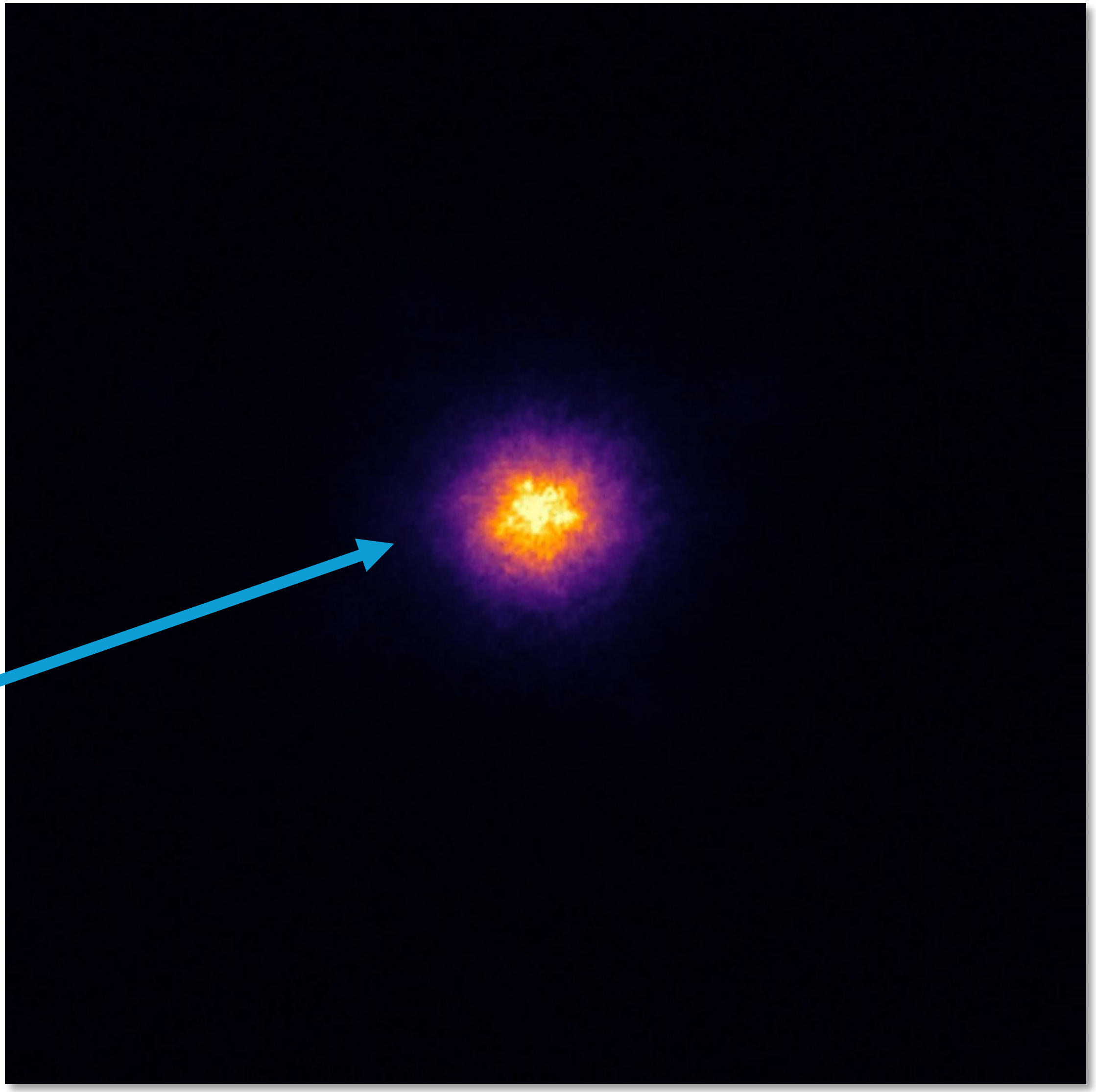
Remove starlight and speckles to reveal faint objects



Diffraction-limited imaging from the ground



AO Off -> AO On: Pi Pup



Watch for the planet

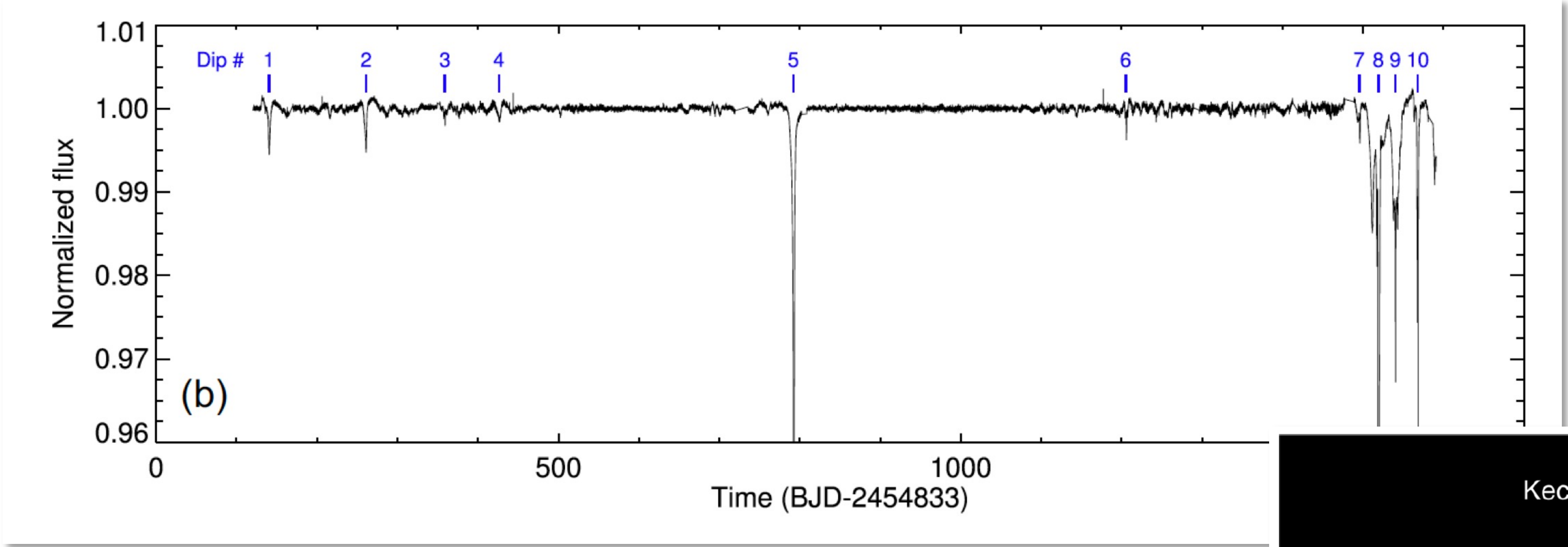
Credit: Joseph Long

Dissertation Chapters

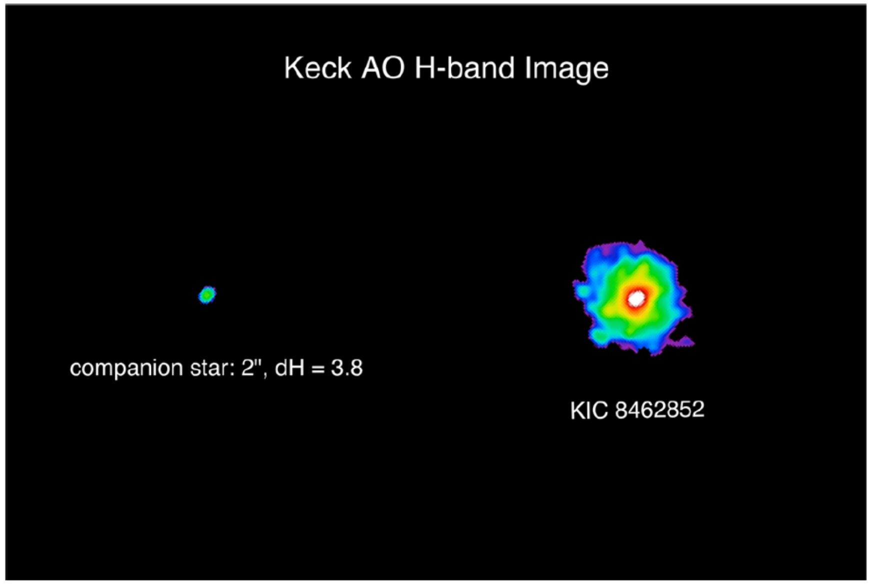
- Boyajian's Star with Keck/NIRC2
- Binary Differential Imaging with MagAO
- HIP 67506
- White Dwarf + Main Sequence Star Binaries with MagAO-X
- Exoplanet Reflected Light Imaging with MagAO-X and GMagAO-X

loganpearce1@arizona.edu

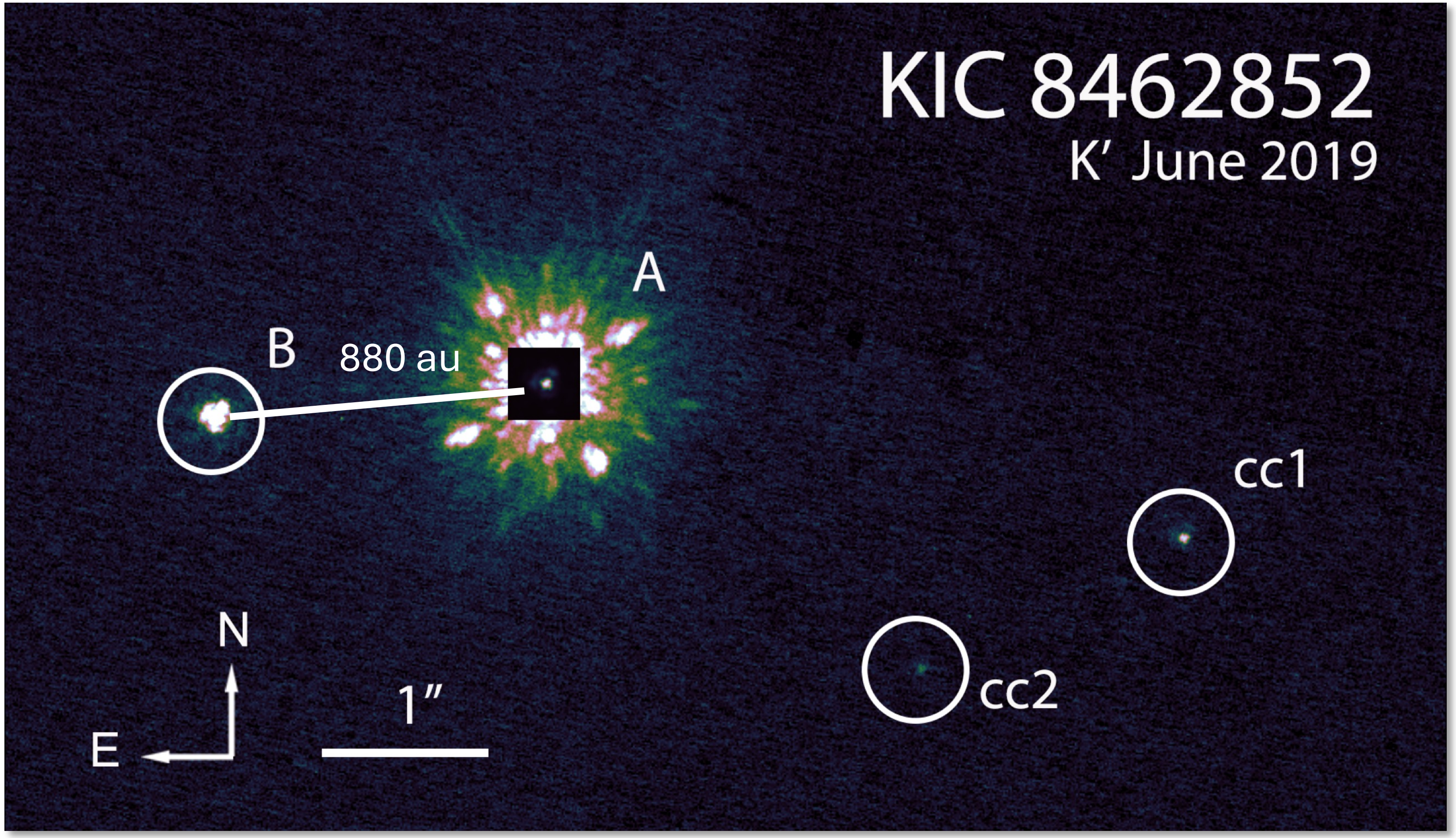
Boyajian's Star has an unexplained light curve



Boyajian et al. 2016



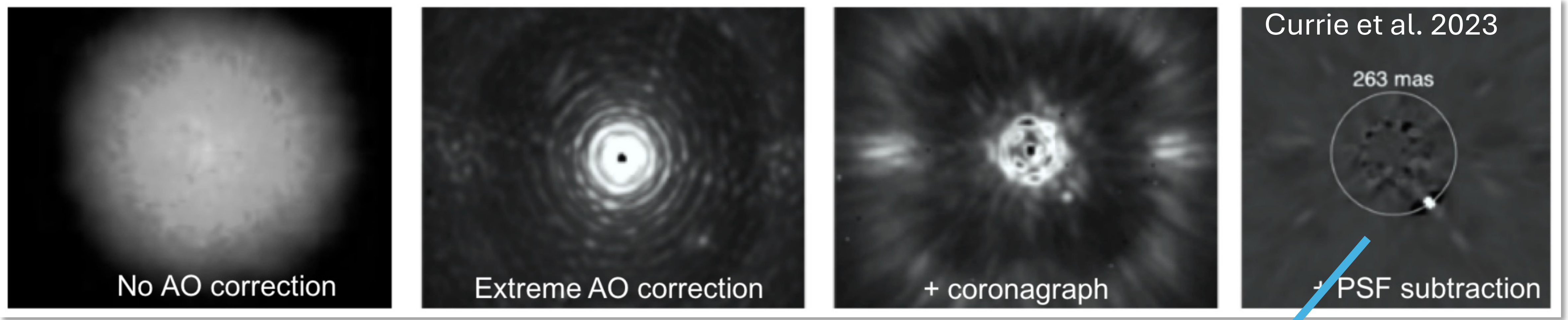
Boyajian’s Star has a wide stellar companion



This does not explain the light curve!

But long-term orbital evolution may contribute to chaos in the planetary regime

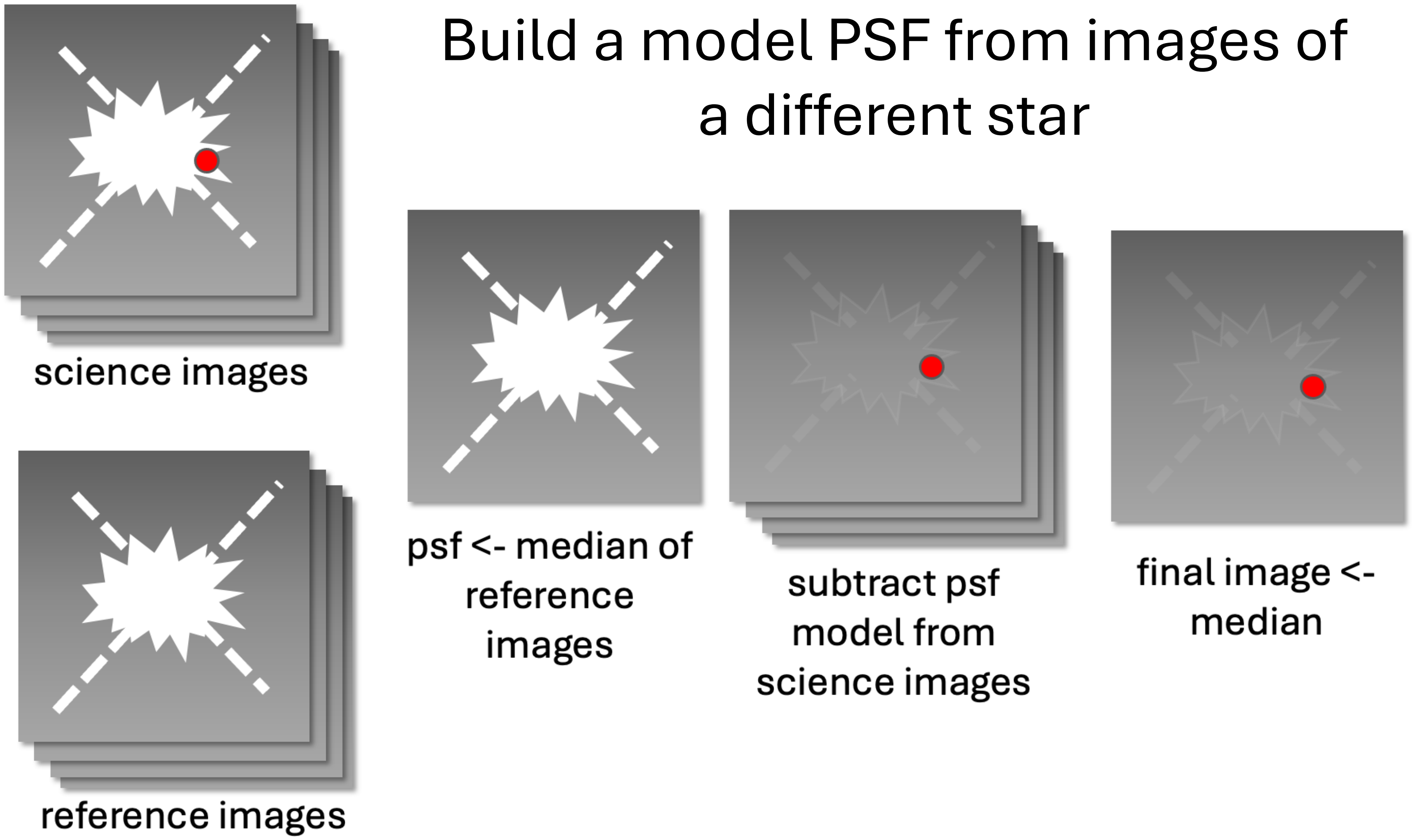
Post-processing with Binary Differential Imaging



Need to make a model of the star's point spread function (PSF) without a companion signal and subtract

Reference Differential Imaging

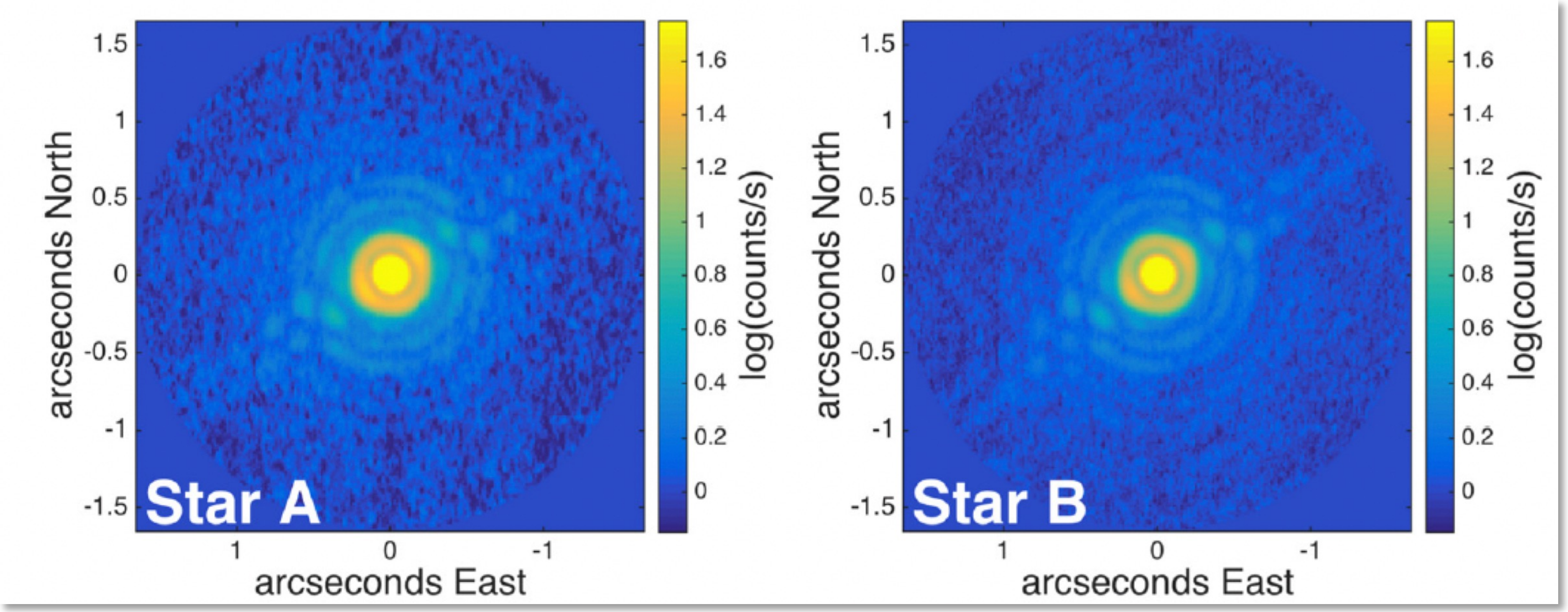
Build a model PSF from images of a different star

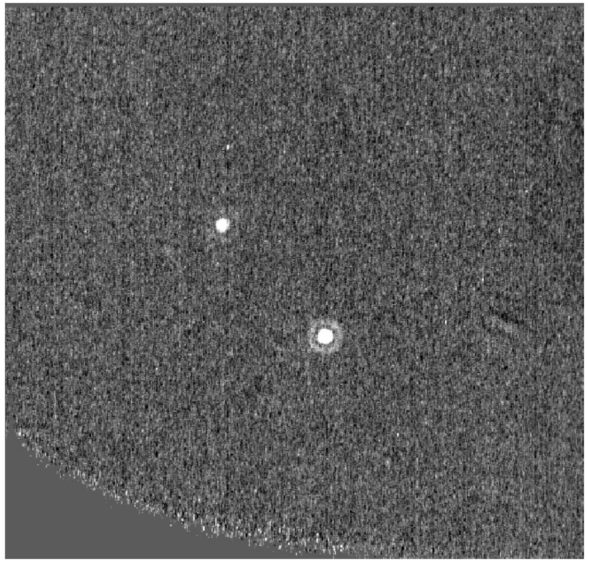


Binary Differential Imaging

Image stellar binary -> both science and reference target should have exact same PSF

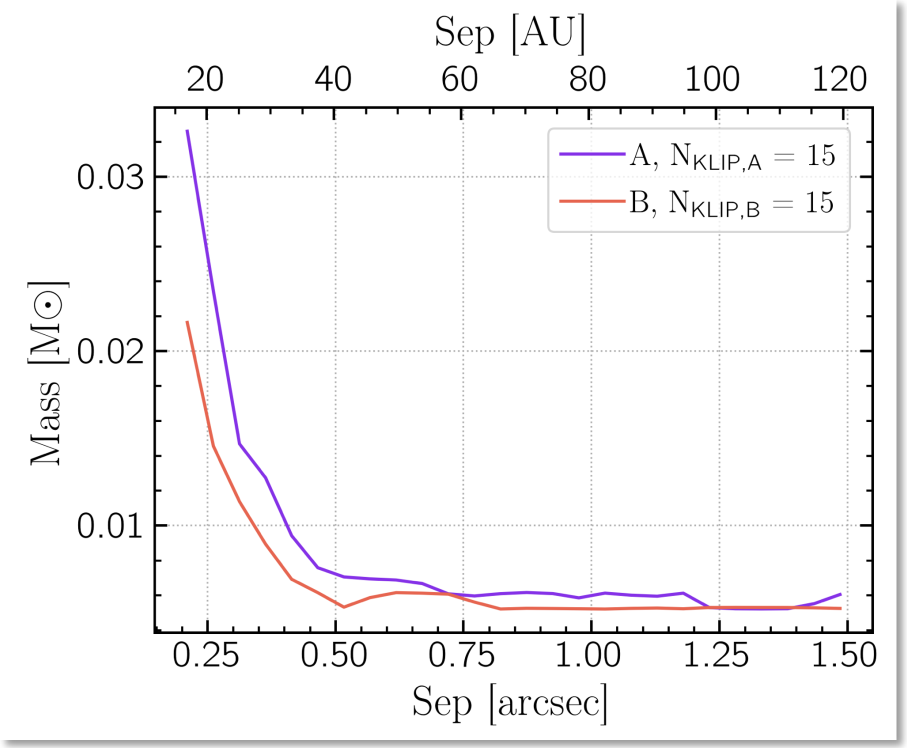
Rodigas et al. 2015

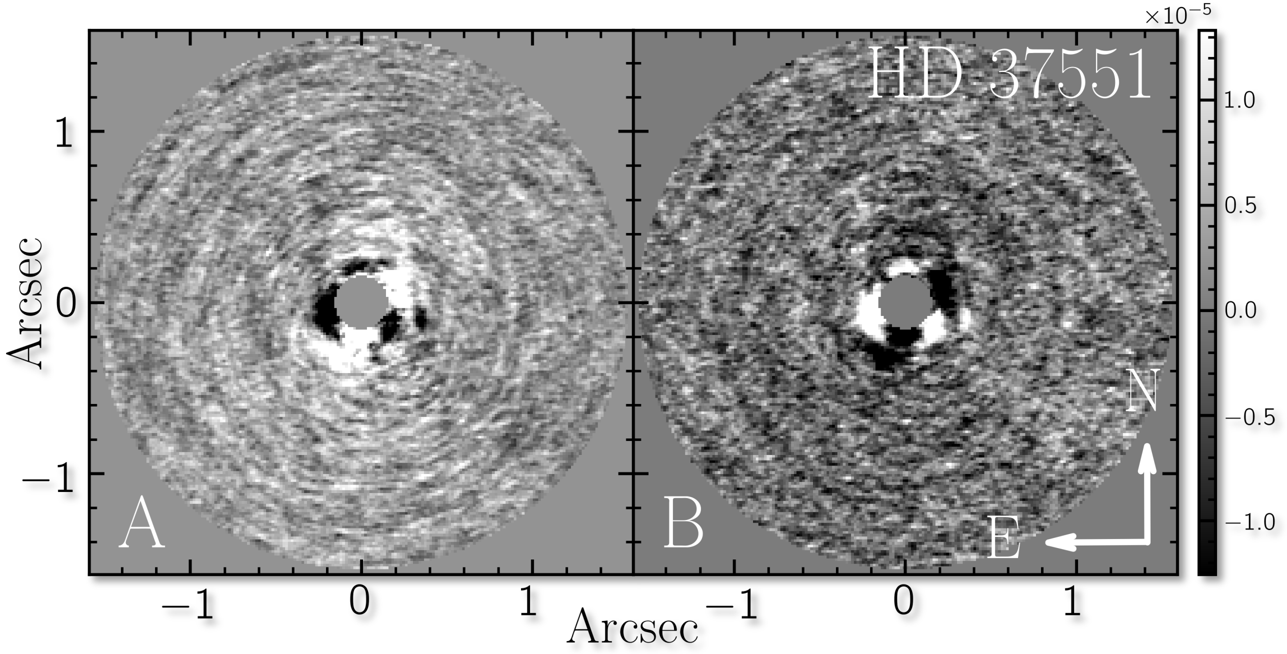




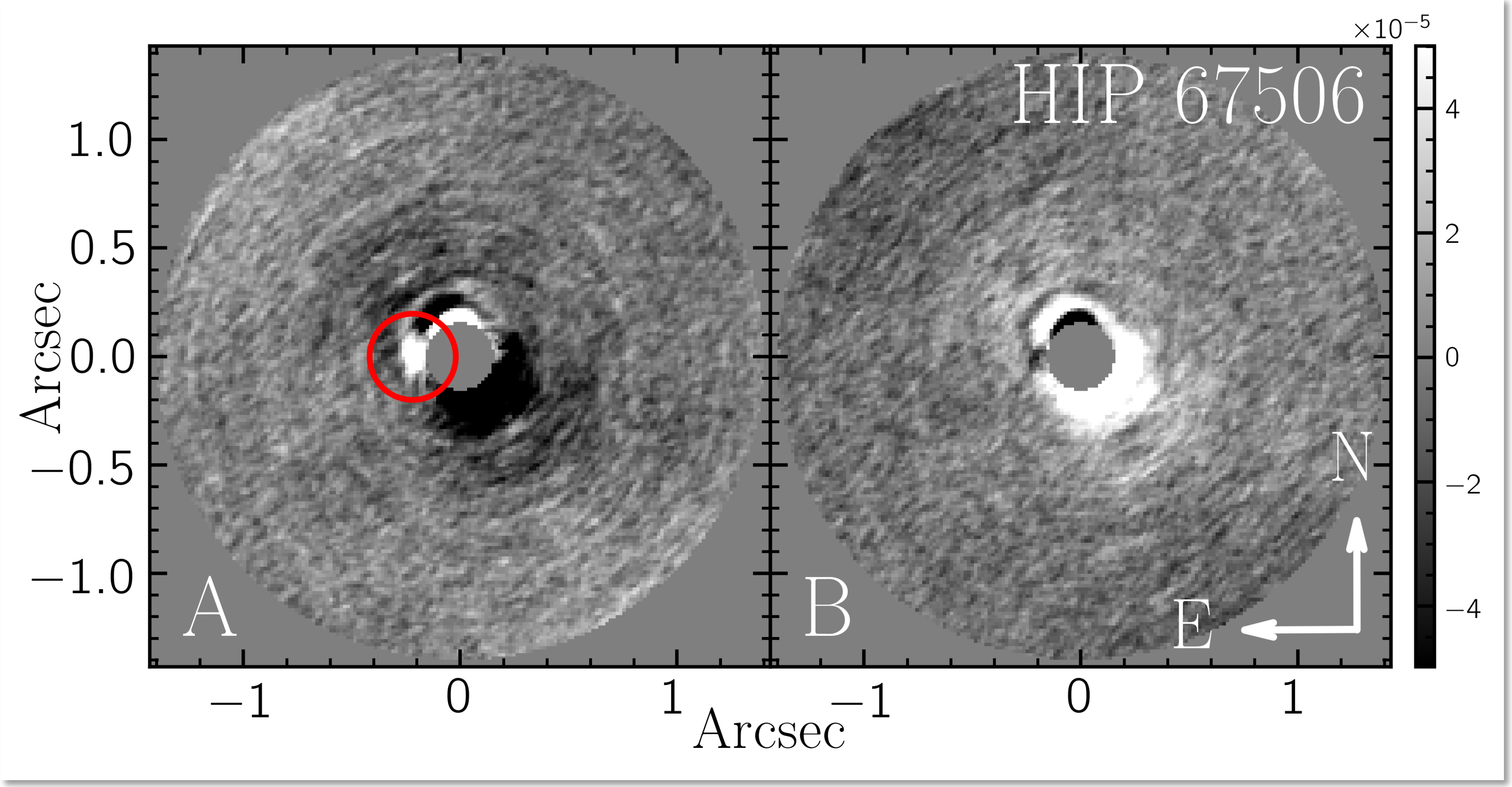
17 BDI systems observed from 2015-2017 with MagAO

I reduced the data using a bespoke Principal Component Analysis (PCA) pipeline

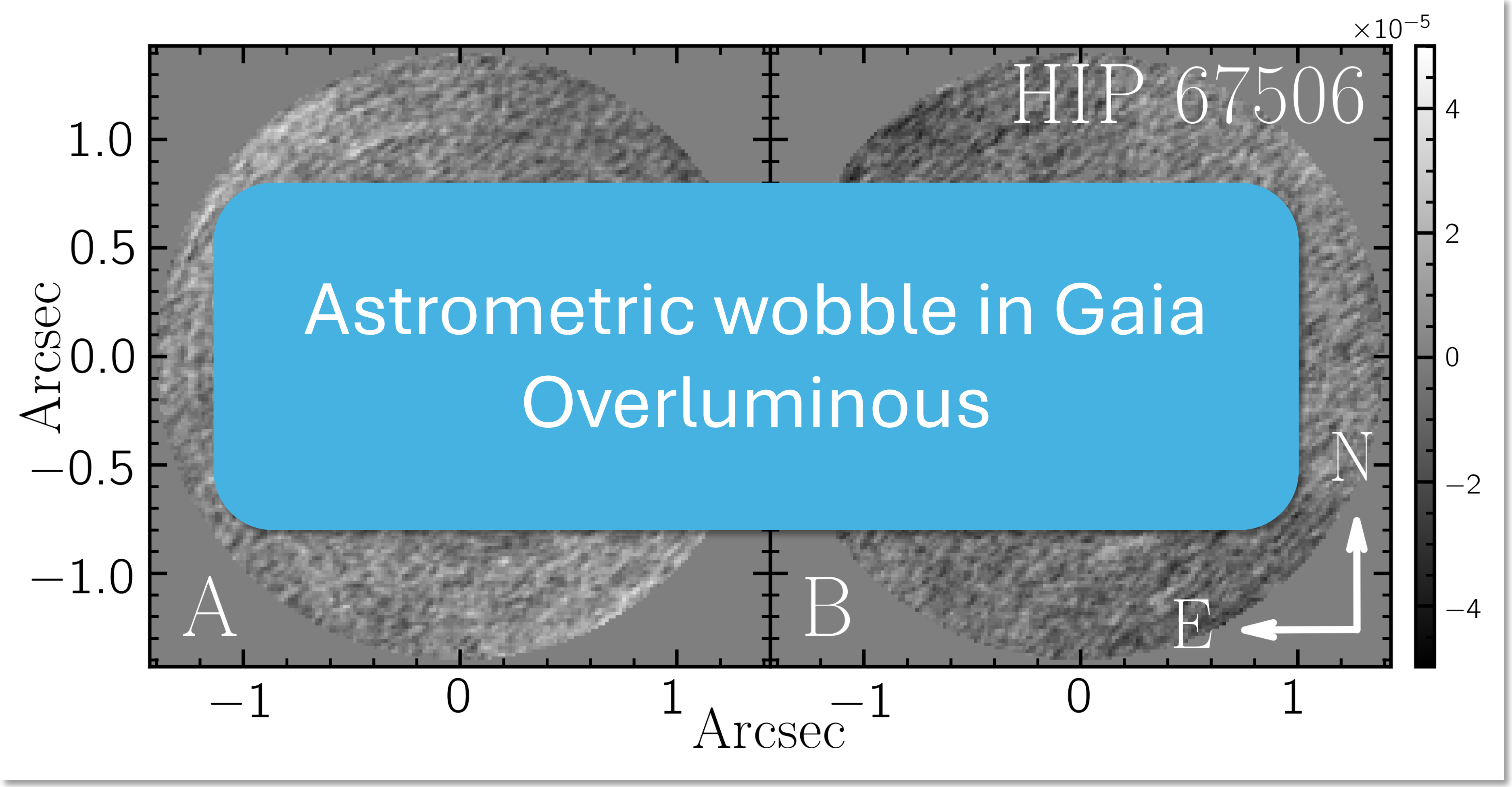




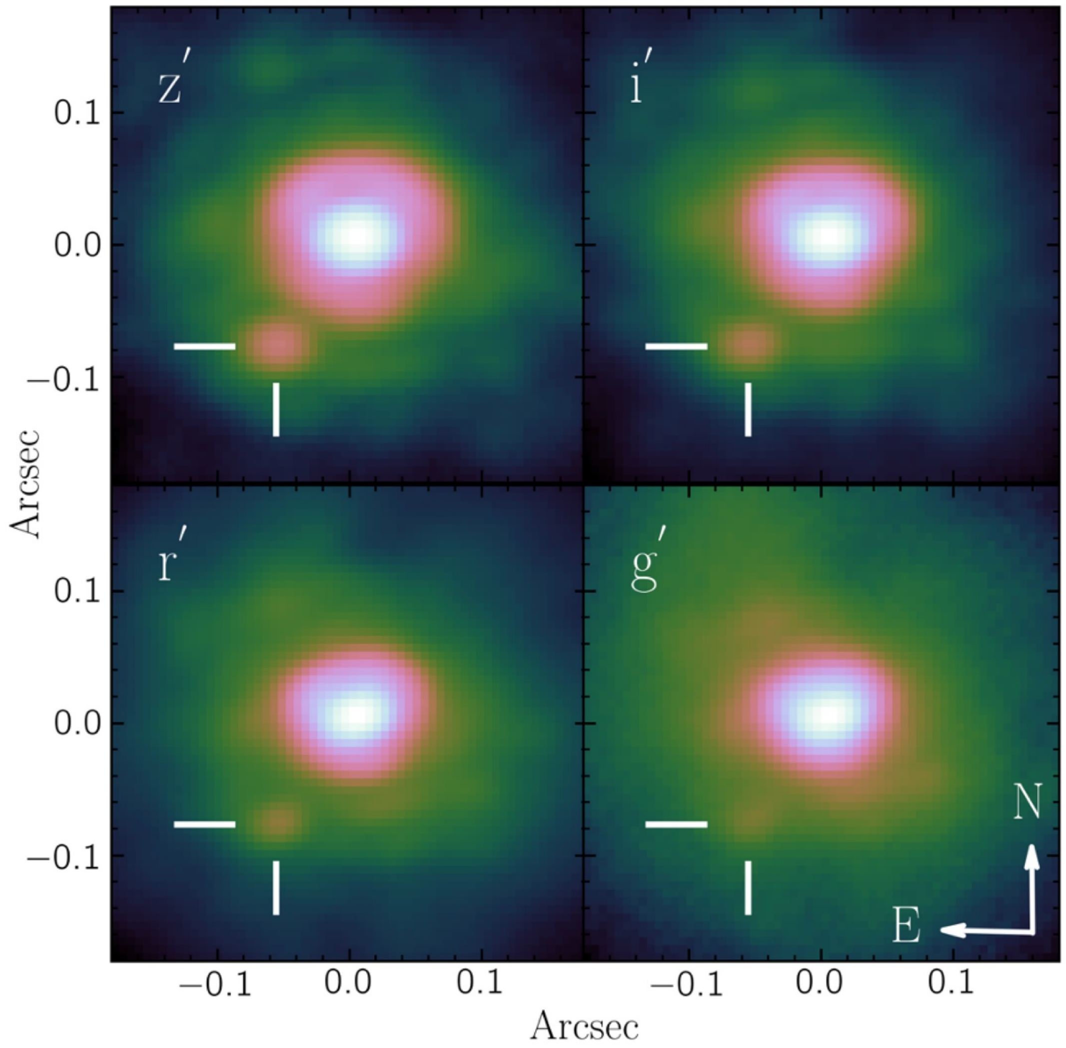
HIP 67506 A: a candidate signal



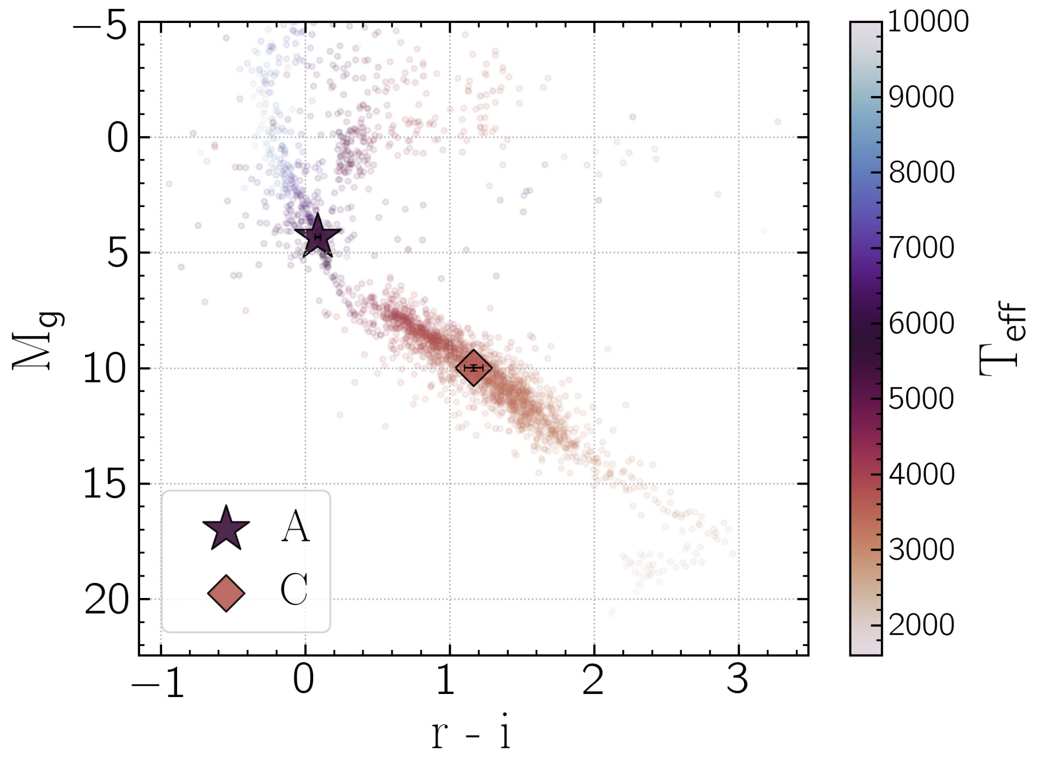
HIP 67506 A: a candidate signal



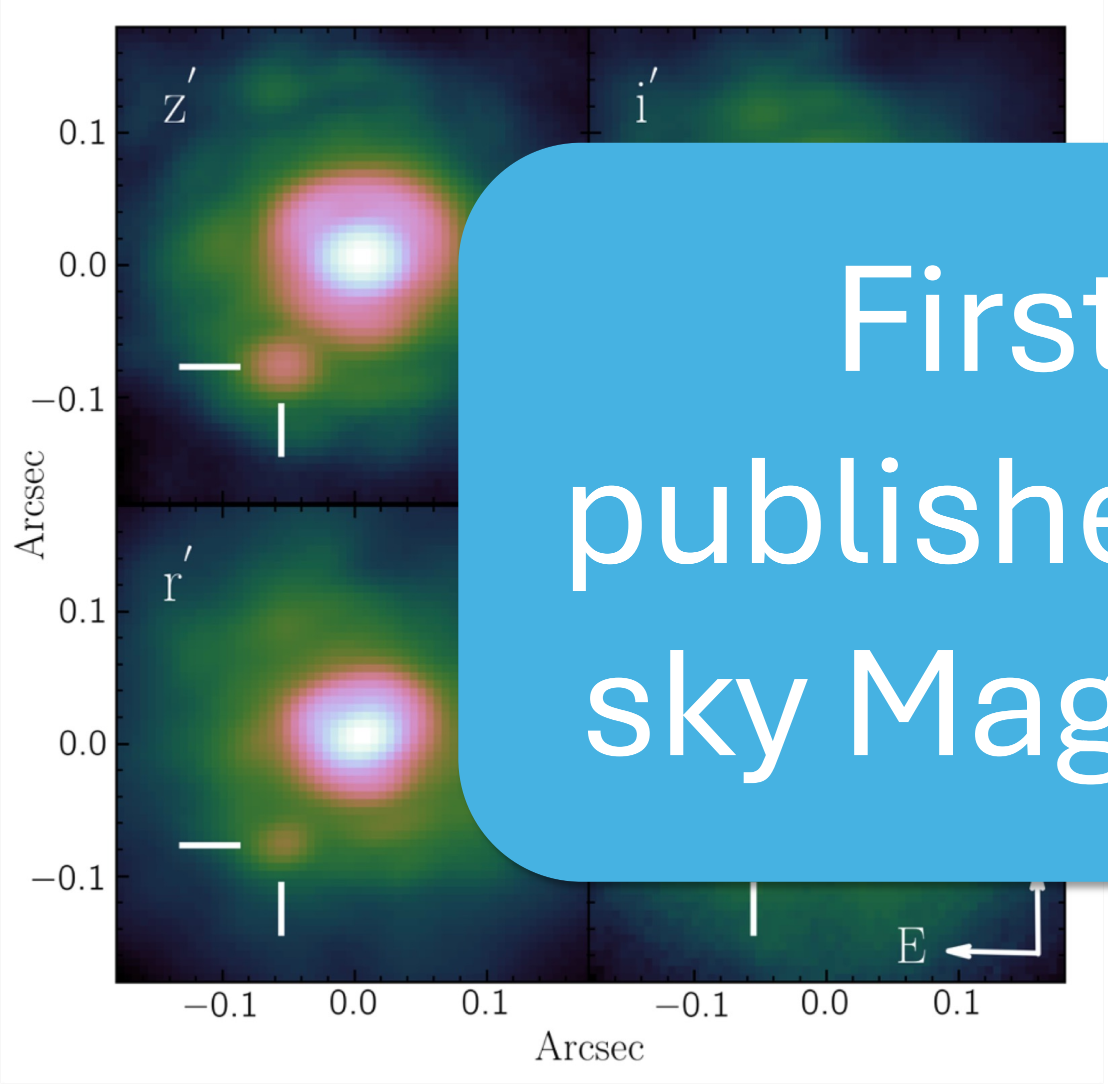
HIP 67506 AC with MagAO-X



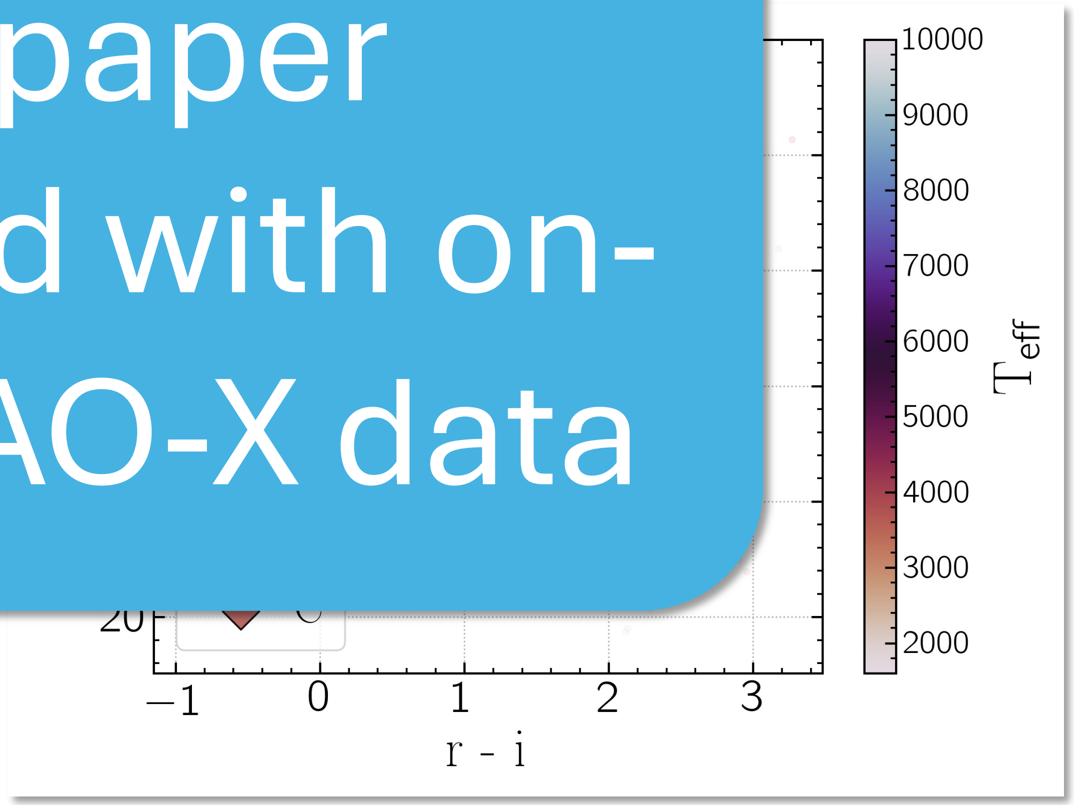
I observed HIP 67506 A with MagAO-X in April 2022 and easily detected the low mass star companion



HIP 67506 AC with MagAO-X



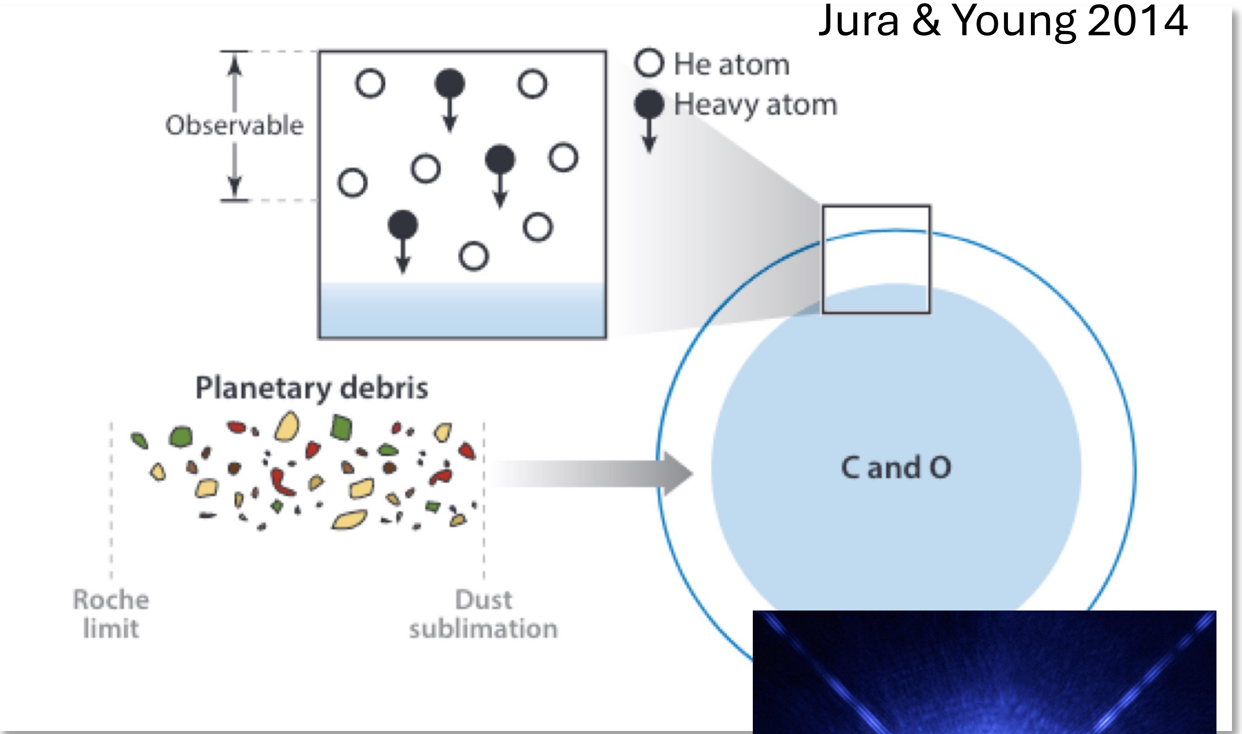
I observed HIP 67506 A with MagAO-X in April 2022 and easily detected
nion



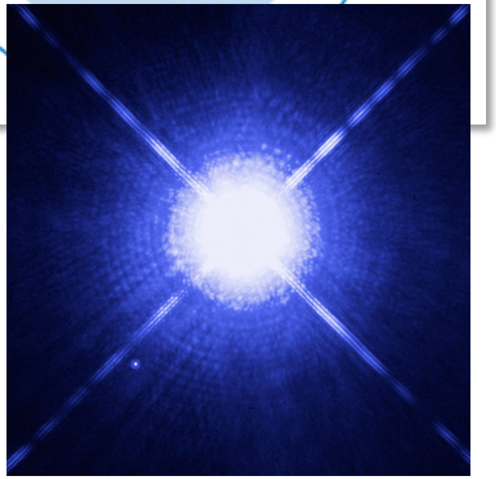
First paper published with on-sky MagAO-X data

The influence of wide companions on the planetary regime through WD+MS binaries

- White dwarfs are probes of planet composition
- "Polluted" WDs with wide main sequence companions can probe influence of companion on planetary regime.
- "Sirius-like" systems (WD + AFGK) are difficult to detect b/c star outshines WD
- ExAO can contribute to both exoplanet and WD communities



HST image of Sirius A, the "dog star" & Sirius B, the "pup"

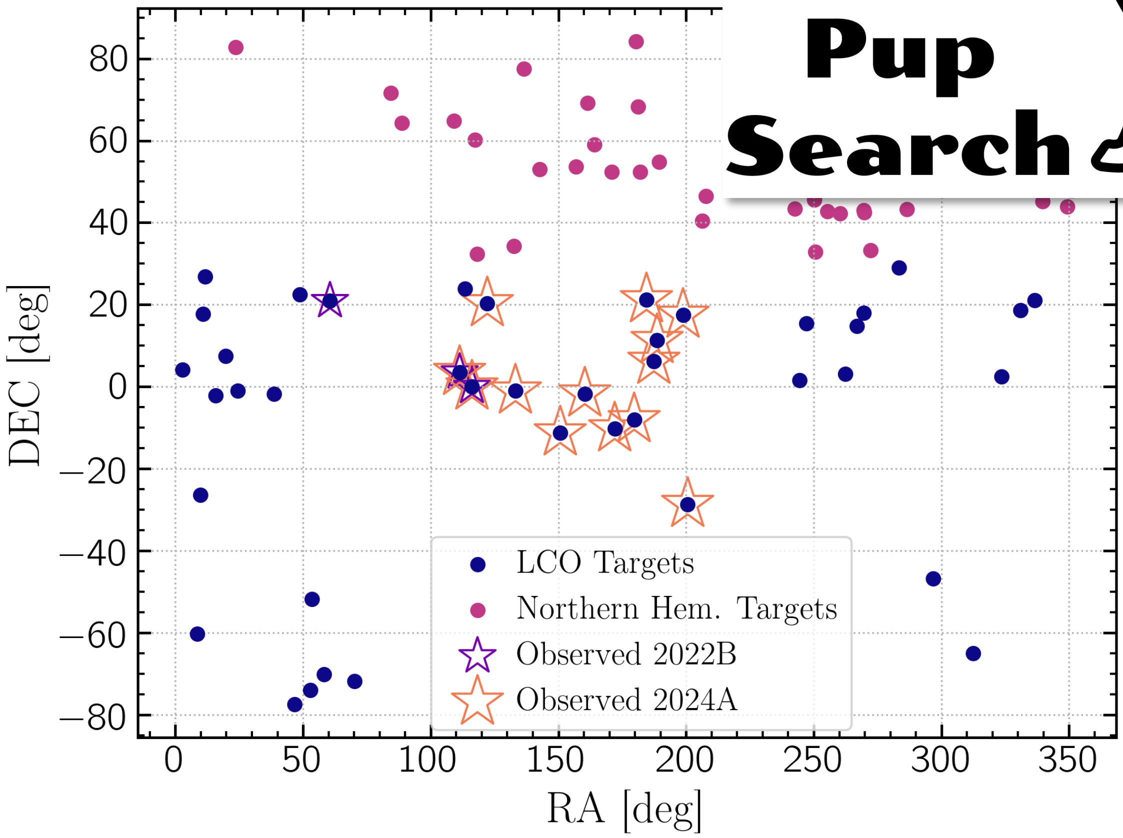


The ExAO Pup Search

The ExAO Pup Search

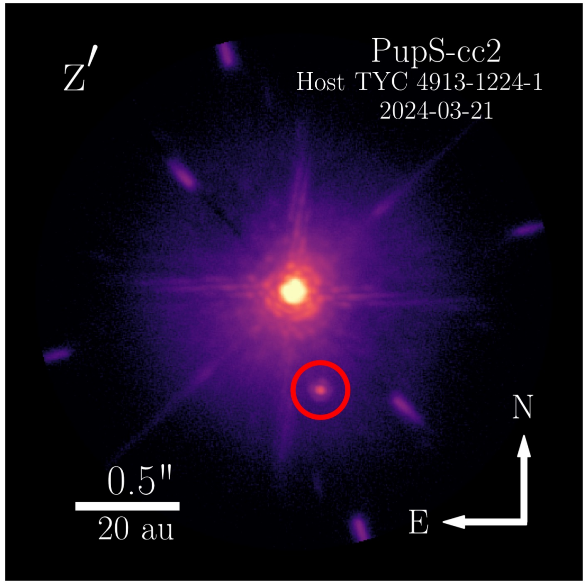
1. Detect new SLS w/ MagAO-X
2. Observe new and known SLS for pollution
3. Monitor orbits

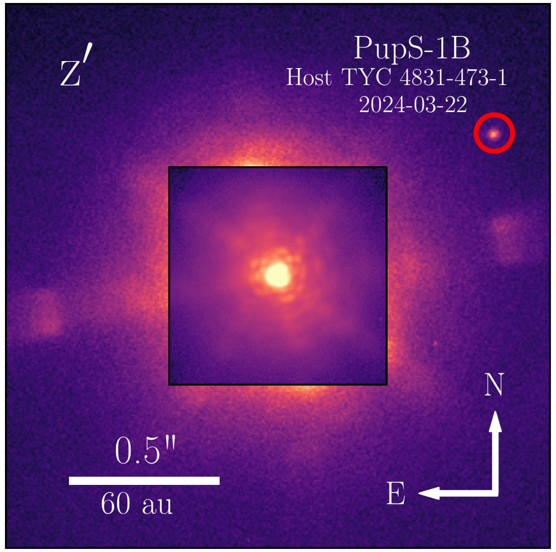
High quality target list built from UV Excess and RV data in Ren et al. 2020

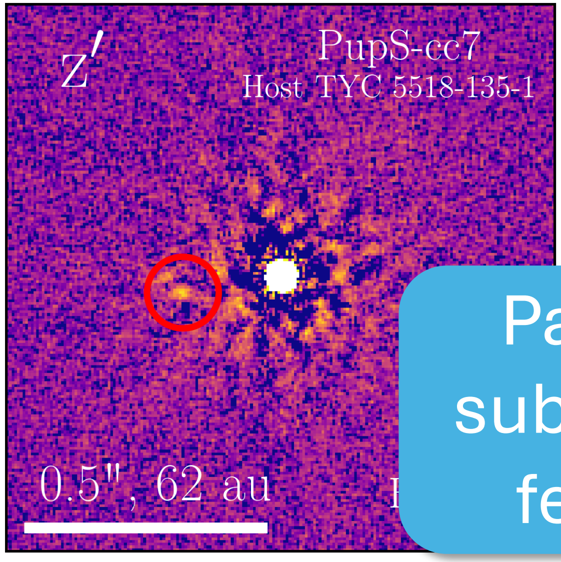


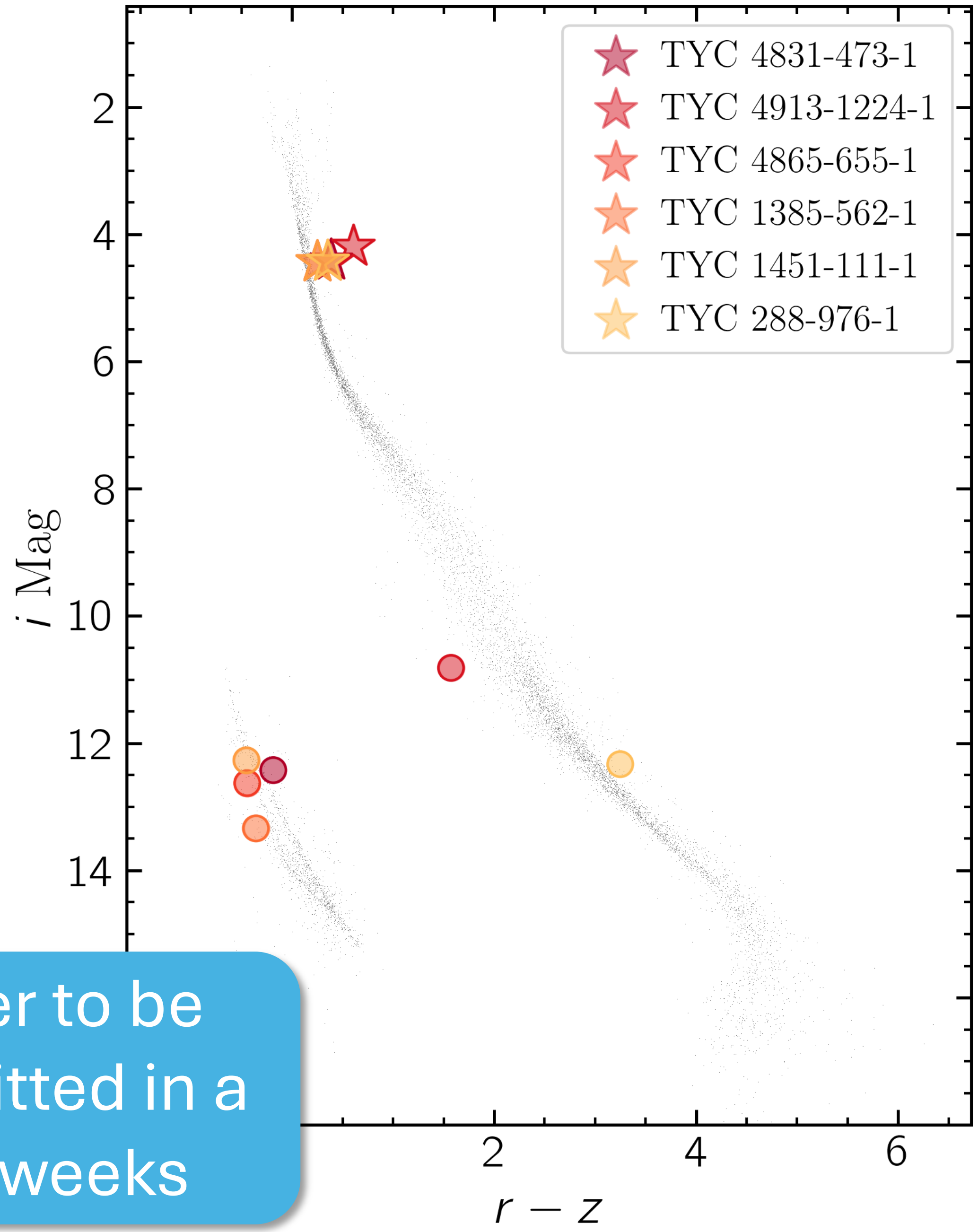
14 observed, 8 new candidate companions

- 4 WD candidate companions, 1 confirmed
- 1 subdwarf
- 1 M dwarf
- 1 undetermined



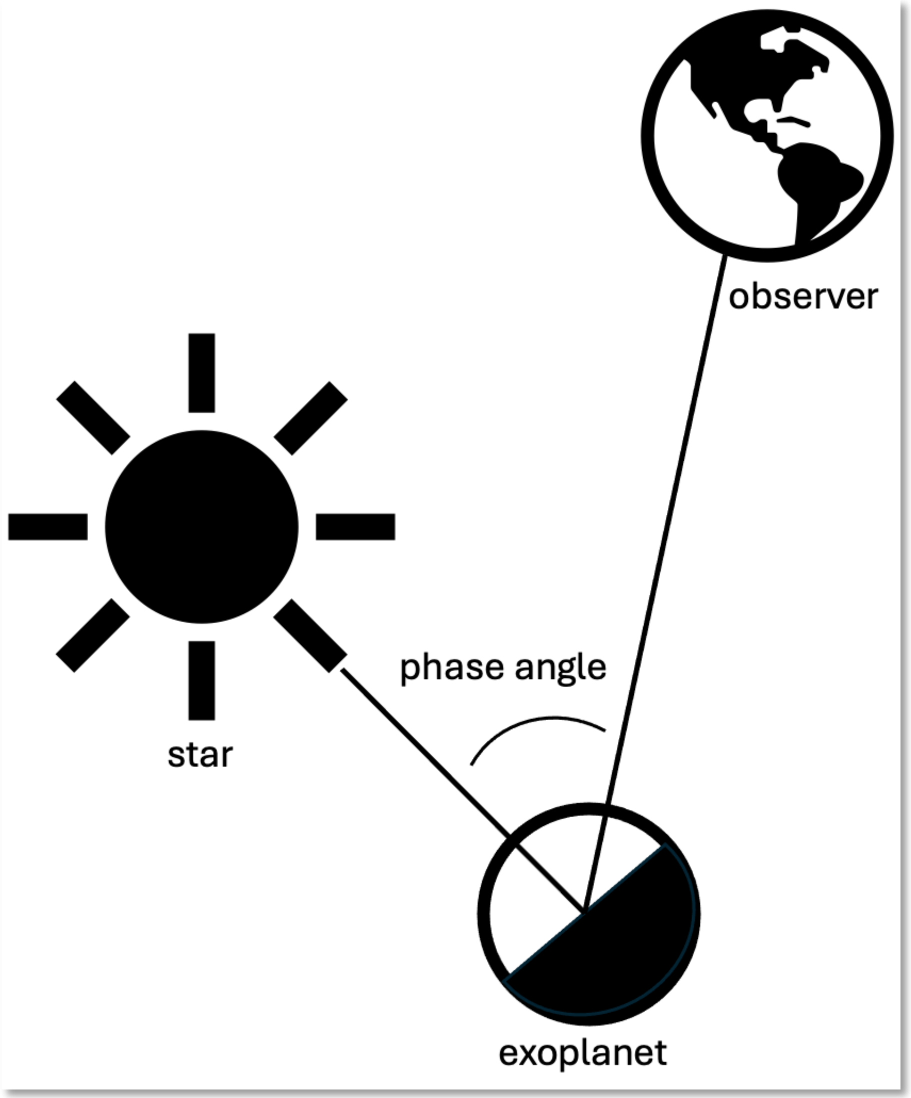


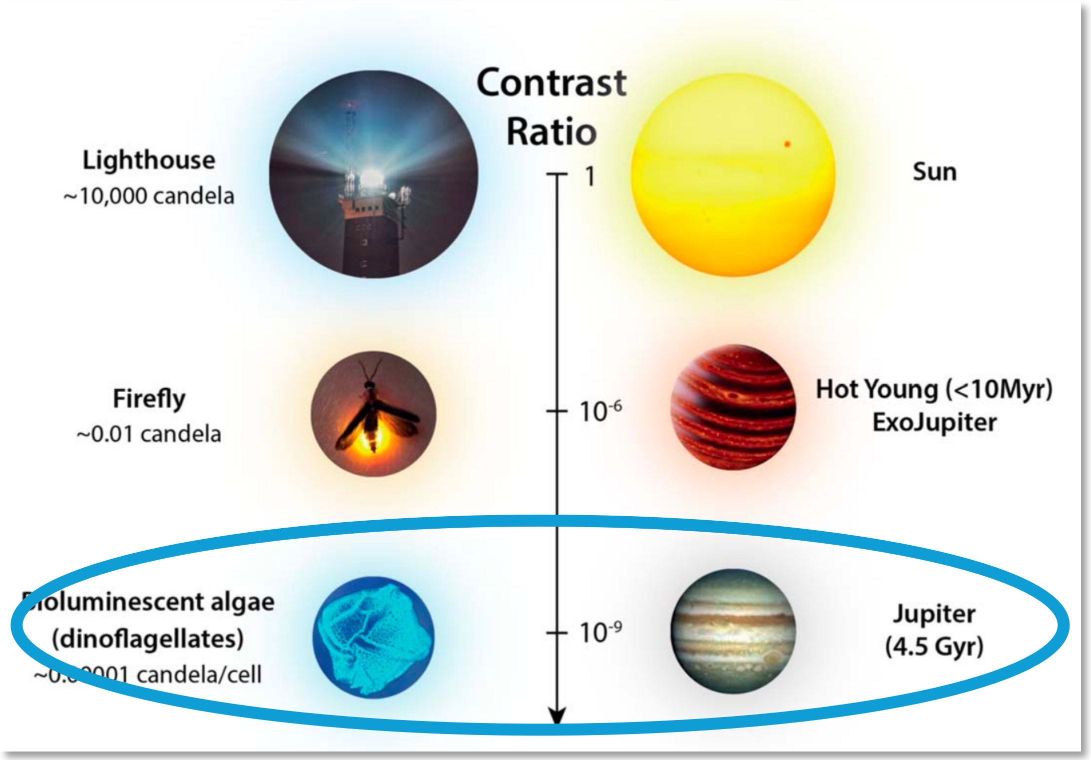




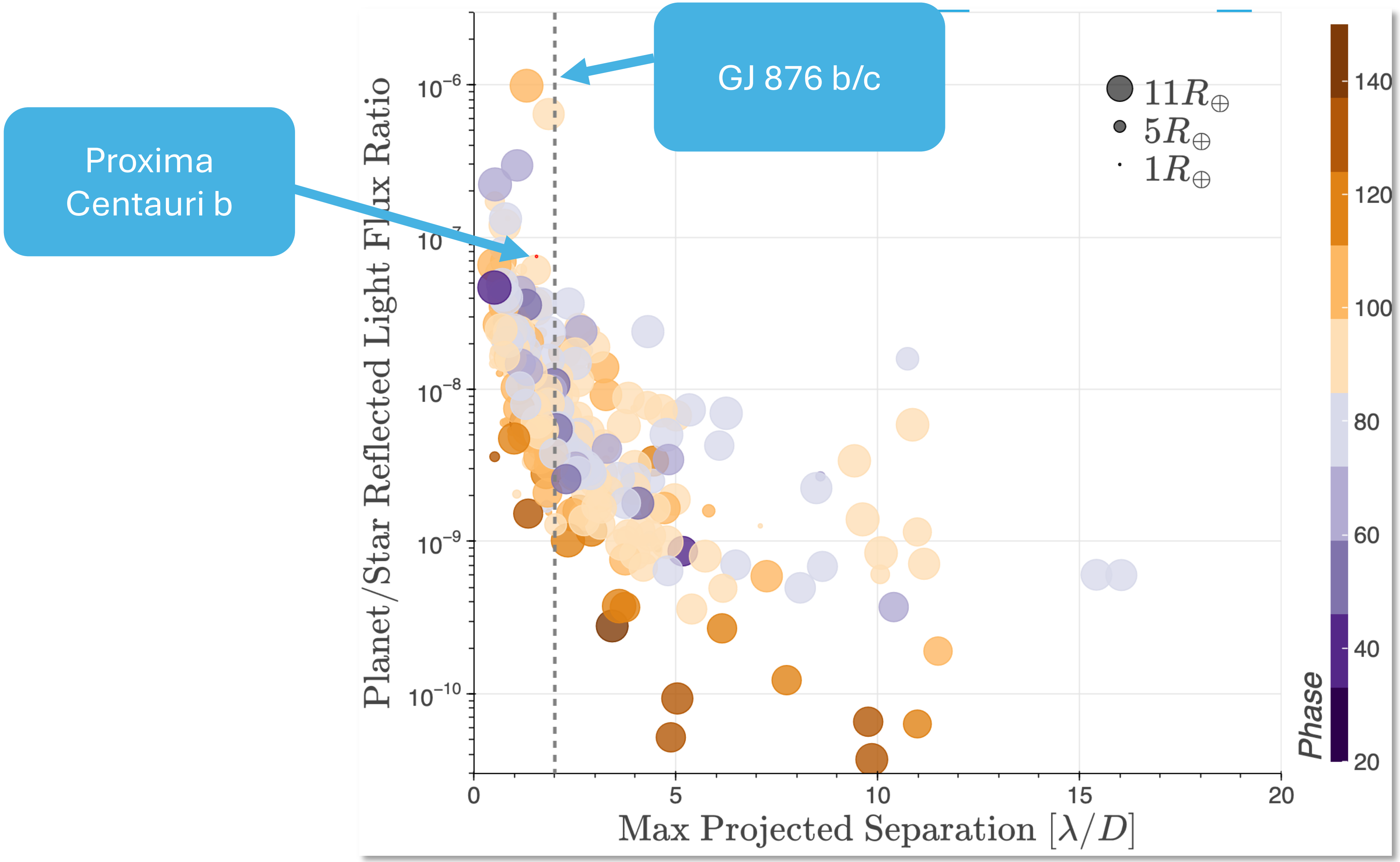
Paper to be submitted in a few weeks

Reflected Light Exoplanet Detection





Exoplanet Reflected Light Imaging with MagAO-X

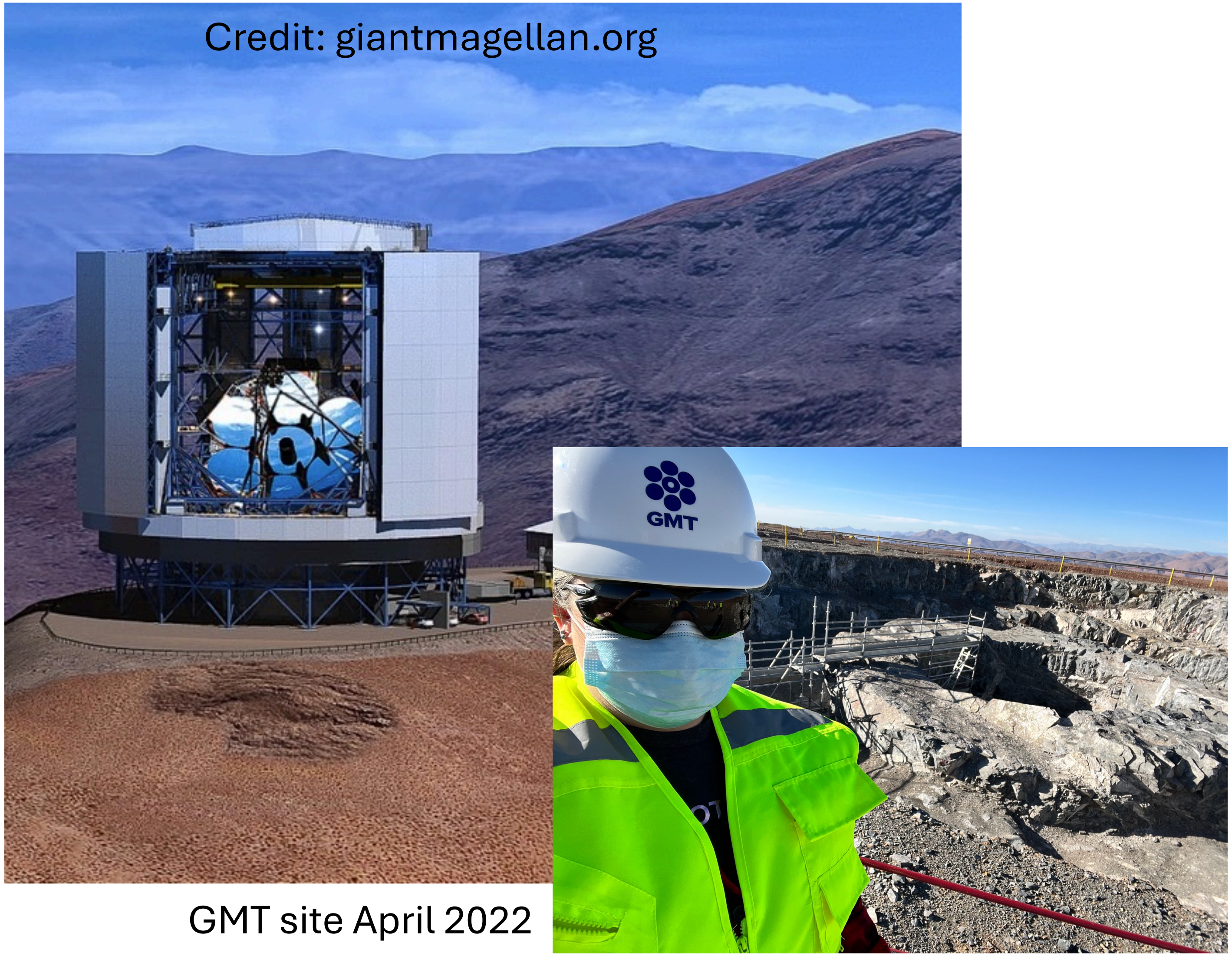


Detecting nearby planets in reflected light is the ultimate science goal of MagAO-X

loganpearce1@arizona.edu

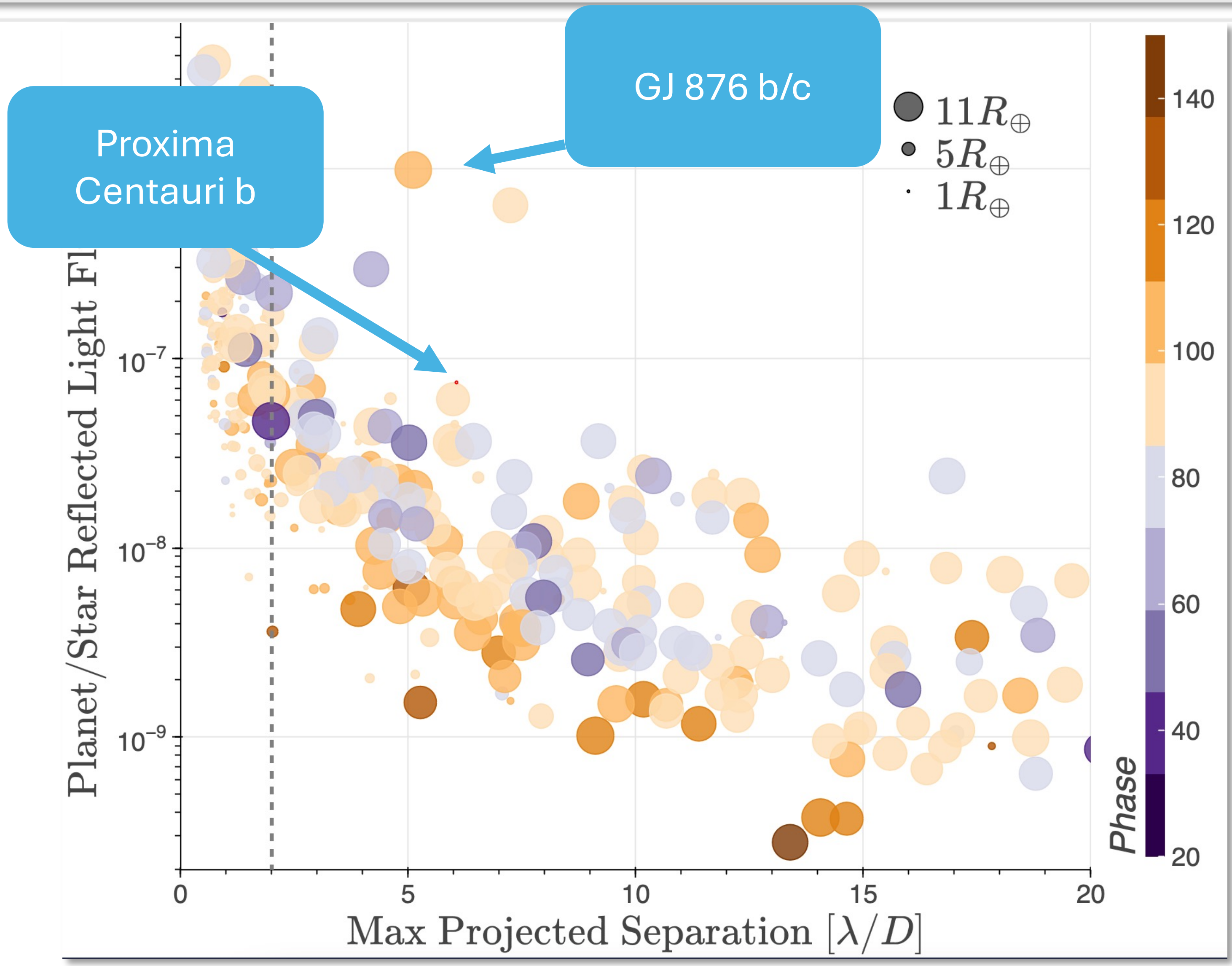
MagAO-X is a pathfinder for GMagAO-X

- GMT: 25.4 m primary being built in Chile planned for 2030's
- GMagAO-X: ExAO coronagraphic instrument planned to be ready at first light being built by XWCL



Credit: giantmagellan.org
GMT site April 2022

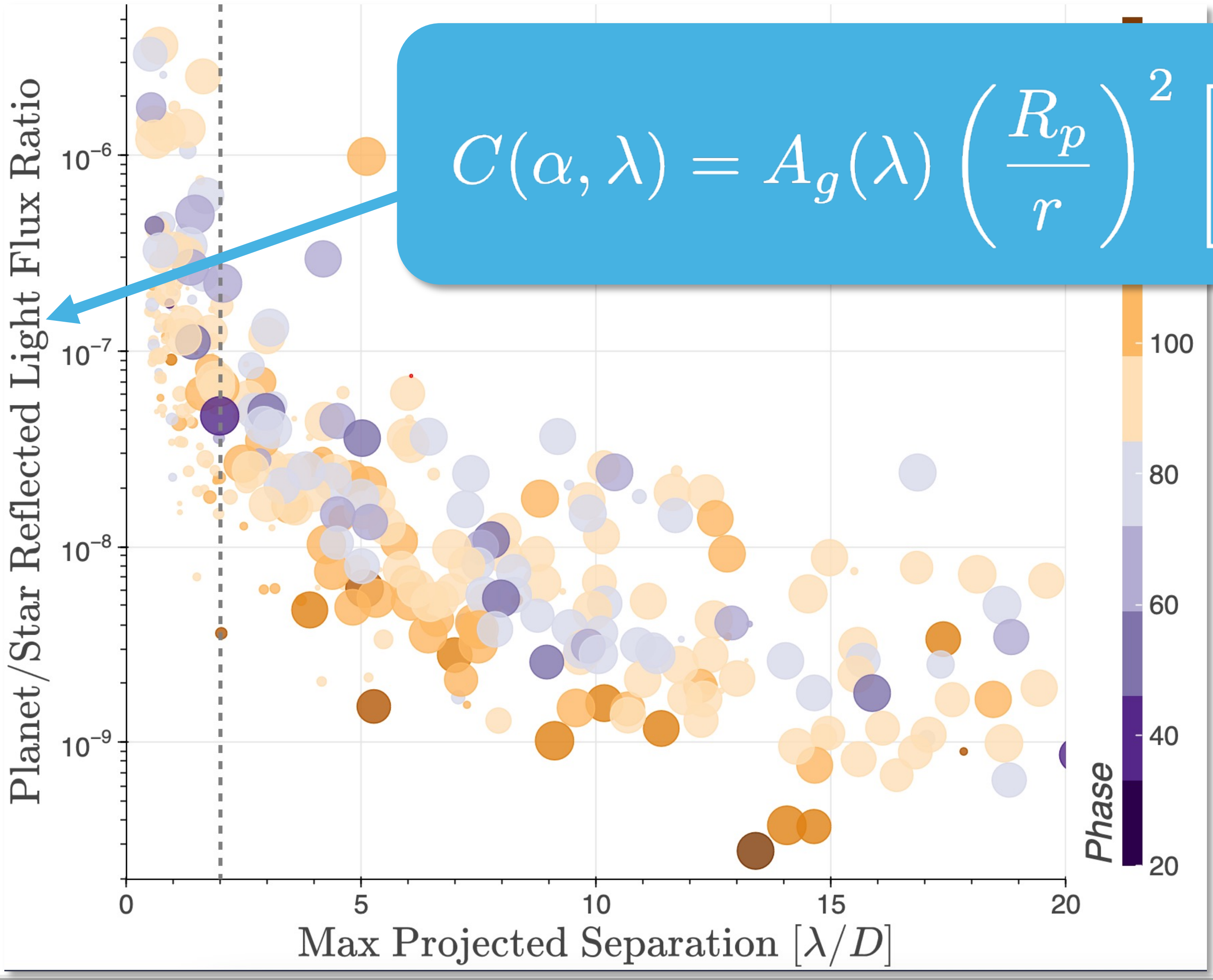
That same plot for GMagAO-X



- Bigger light bucket -> collect more photons!
- Larger mirror -> able to resolve closer things!

Contrast depends on atmosphere, separation, radius, and phase

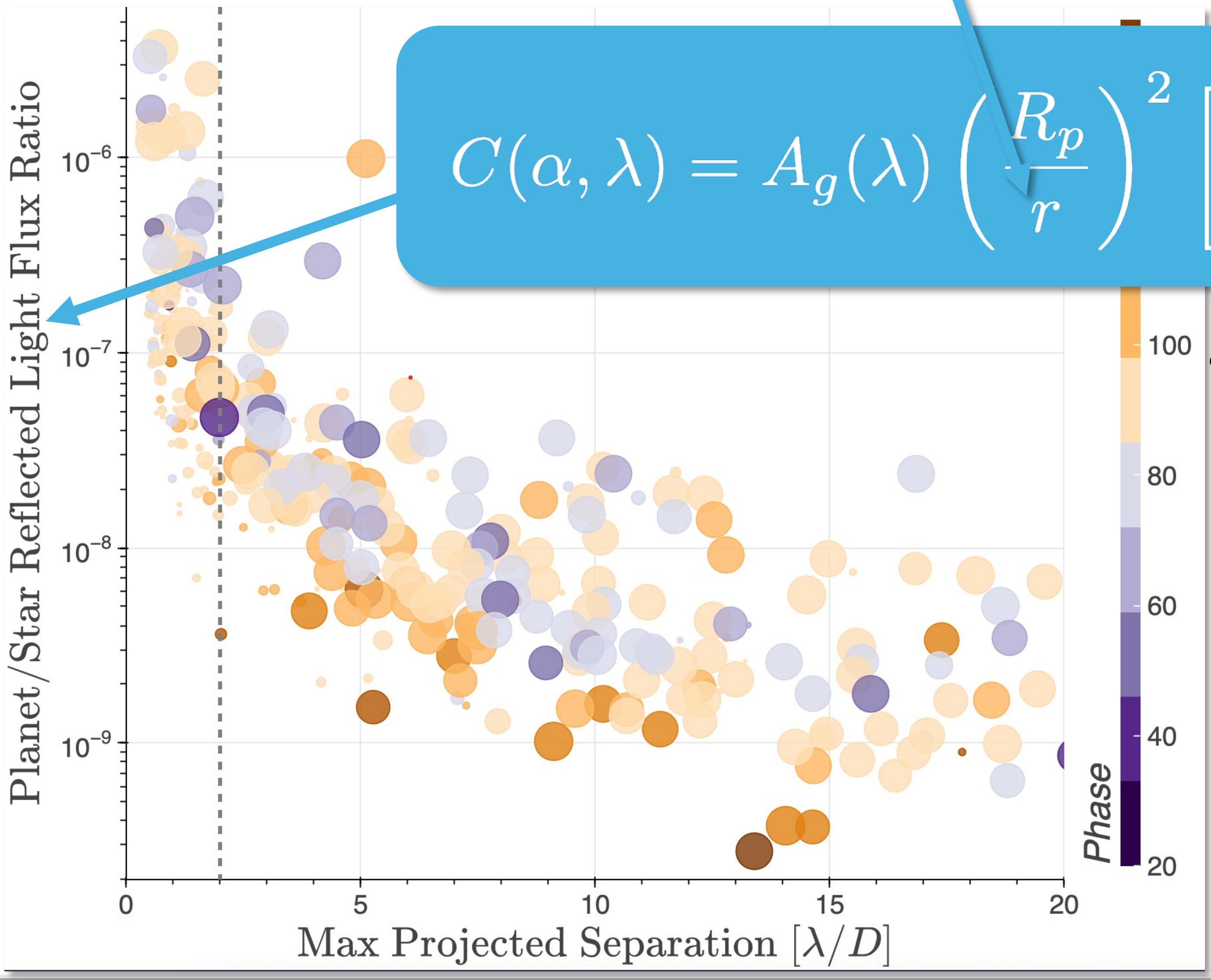
$$C(\alpha, \lambda) = A_g(\lambda) \left(\frac{R_p}{r} \right)^2 \left[\frac{\sin\alpha + (\pi - \alpha)\cos\alpha}{\pi} \right]$$



loganpearce1@arizona.edu

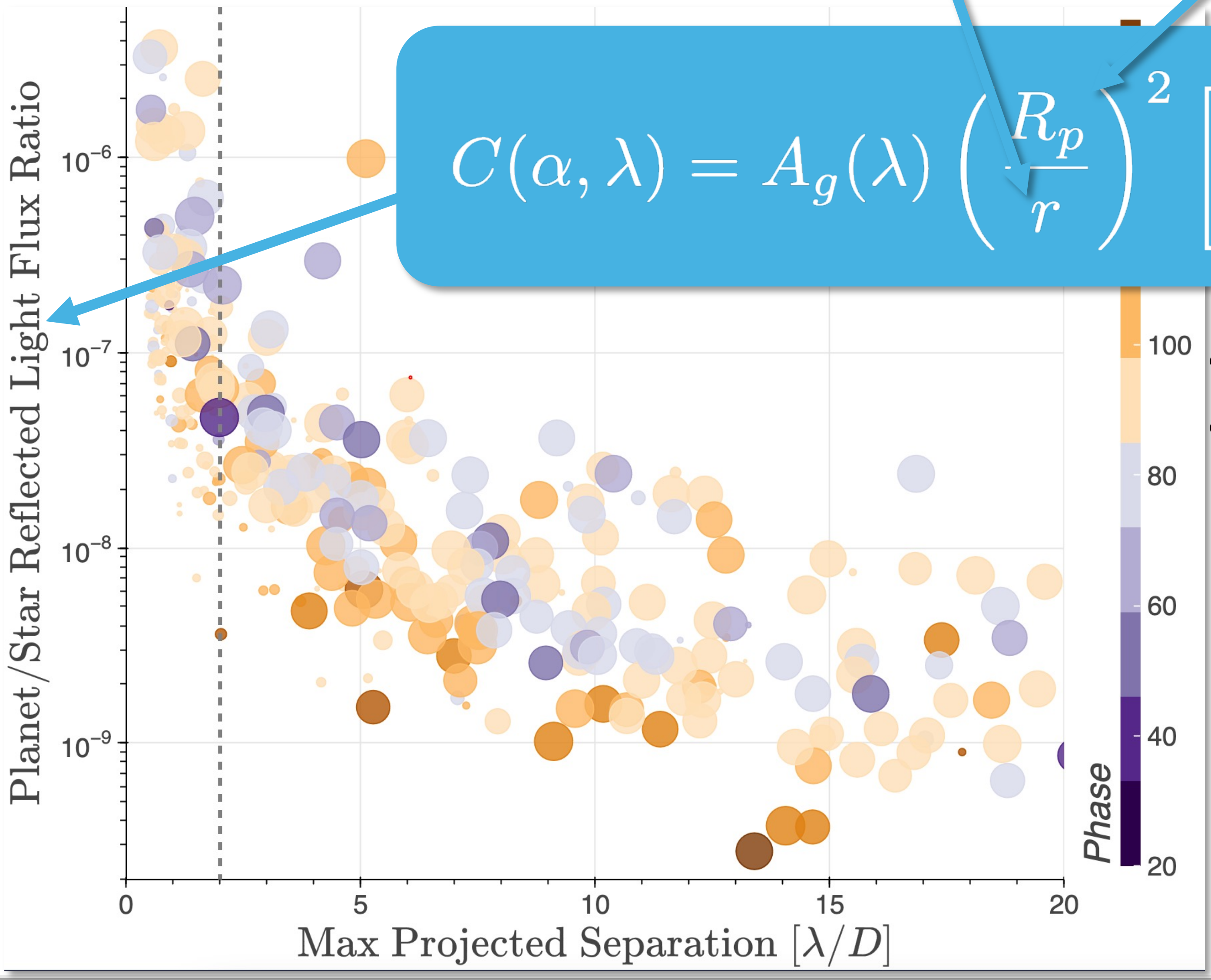
Contrast depends on atmosphere, separation, radius, and phase

$$C(\alpha, \lambda) = A_g(\lambda) \left(\frac{R_p}{r}\right)^2 \left[\frac{\sin\alpha + (\pi - \alpha)\cos\alpha}{\pi}\right]$$



- Closer to star = brighter

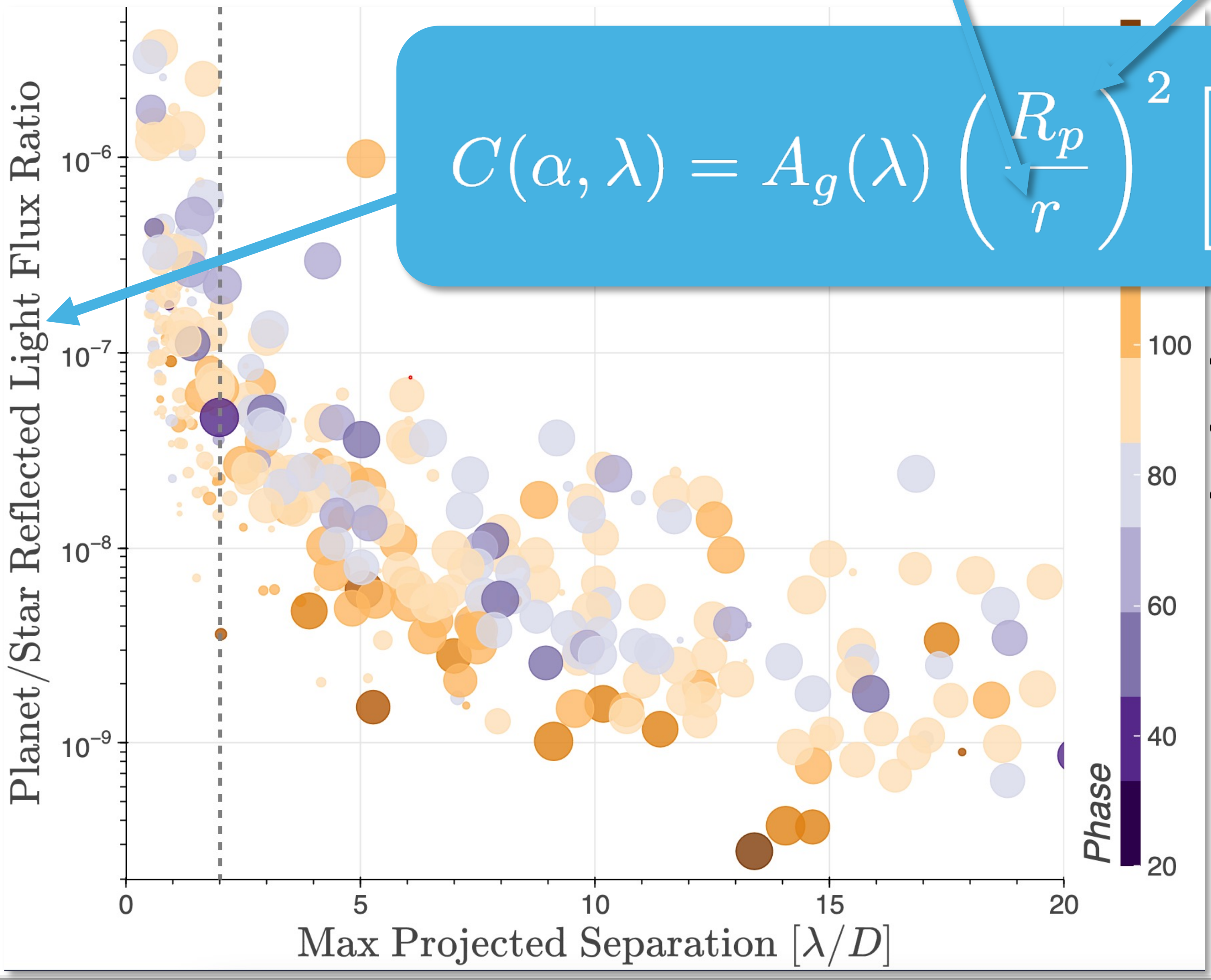
Contrast depends on atmosphere, separation, radius, and phase



$$C(\alpha,\lambda) = A_g(\lambda)\left(\frac{R_p}{r}\right)^2\left[\frac{\sin\alpha + (\pi-\alpha)\cos\alpha}{\pi}\right]$$

- Closer to star = brighter
- Larger radius = brighter

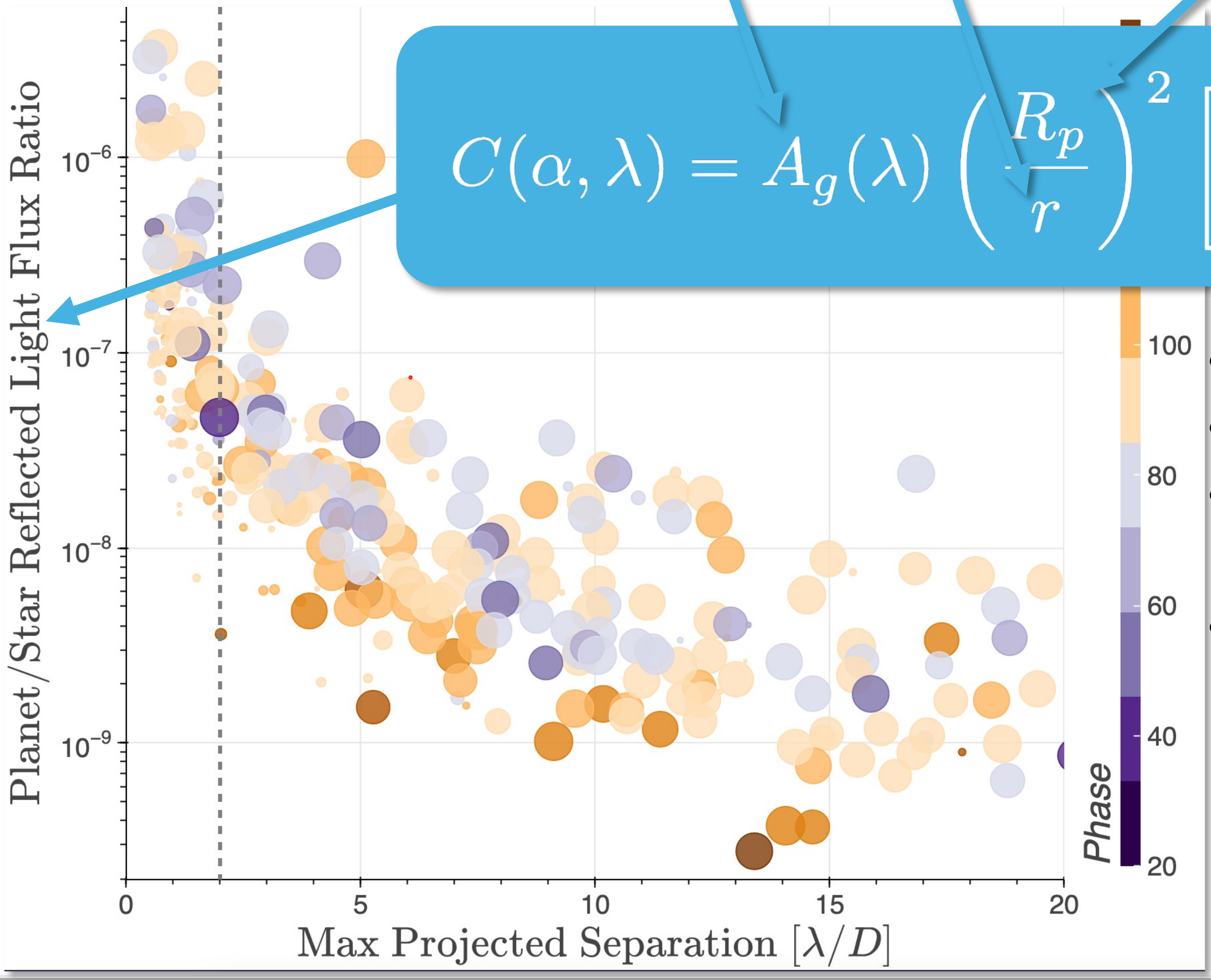
Contrast depends on atmosphere, separation, radius, and phase



$$C(\alpha, \lambda) = A_g(\lambda) \left(\frac{R_p}{r}\right)^2 \left[\frac{\sin\alpha + (\pi - \alpha)\cos\alpha}{\pi}\right]$$

- Closer to star = brighter
- Larger radius = brighter
- Smaller phase angle = brighter

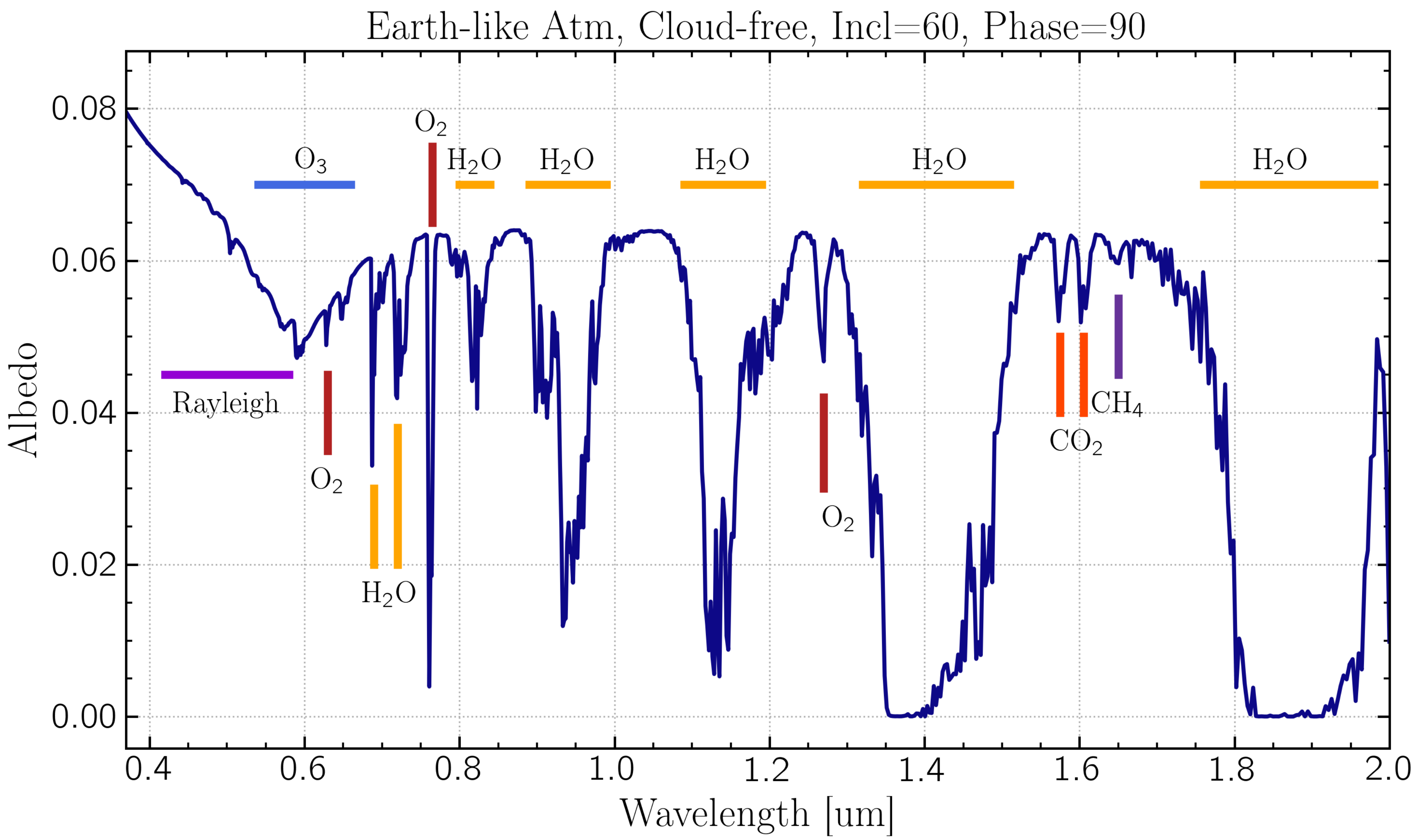
Contrast depends on atmosphere, separation, radius, and phase



$$C(\alpha, \lambda) = A_g(\lambda) \left(\frac{R_p}{r}\right)^2 \left[\frac{\sin\alpha + (\pi - \alpha)\cos\alpha}{\pi}\right]$$

- Closer to star = brighter
- Larger radius = brighter
- Smaller phase angle = brighter
- And atmospheric albedo….

Atmospheric features as a function of wavelength



The ReflectX model suite is designed to prepare for ExAO reflected light observations

ReflectX

Observing Characteristics

Star Magnitude

Observing conditions

Instrument configuration:
- Speckle noise
- WFC configuration
- Coronagraph char.

Males et al. 2021

Star properties
- Mass
- Radius
- Metallicity
- Log(g)
- Teff

Planet properties
- Mass
- Radius
- Met.
- C/O
- Separation
- Phase
- Atm comp

PICAS VIRGA

Batalha et al. 2019

Noise characteristics

ReflectX spectra

Detectable planets & features

→ Survey yields
Instrument design
Survey Design
Forward models

The ReflectX model suite is designed to prepare for ExAO reflected light observations

Star properties

- Mass
- Radius
- Log(g)
- Teff

Planet properties

- Mass
- Radius
- Separation
- Phase
- Atm comp

Observing Characteristics

Star Magnitude

Observing conditions

Instrument configu
- Speckle noi
- WFC configurati
- Coronagraph char.

Males et al. 2021

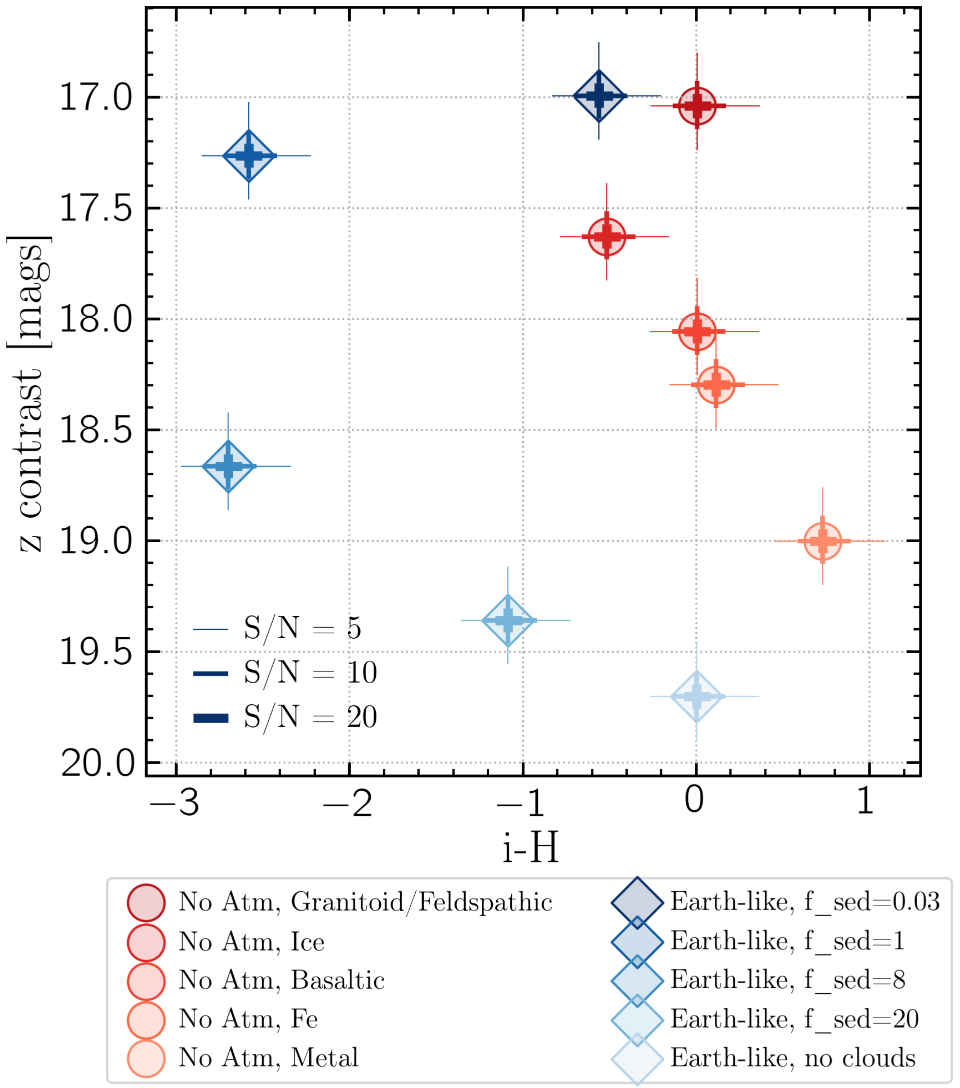
Publication of first model results expected in 2024

Detectable planets & features

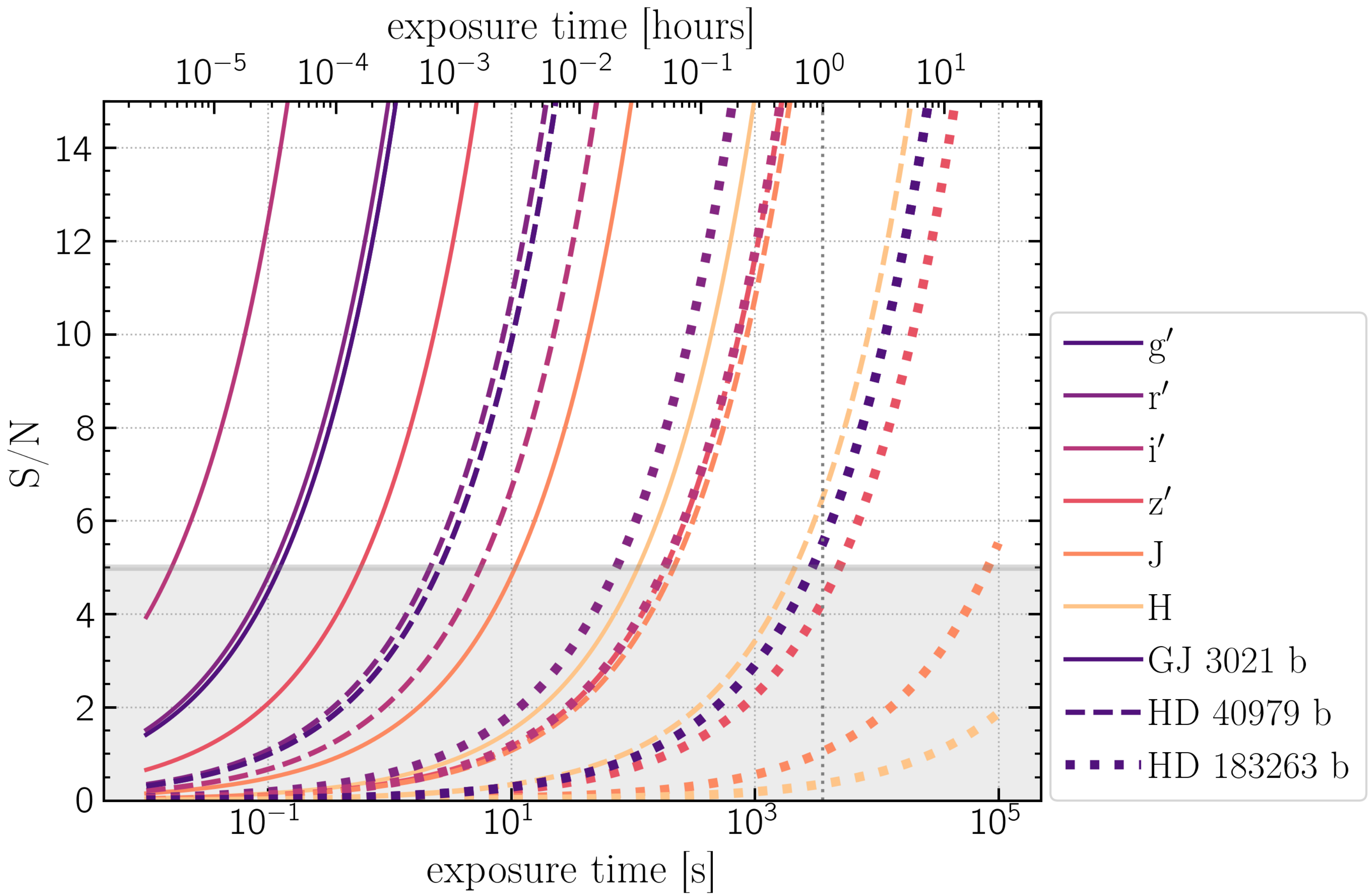
Survey yields
Instrument design
Survey Design
Forward models

ReflectX will consist of

- A generic grid of reflected light models spanning star and planet parameters
- A suite of models of specific known planets
- A tool for producing predictions based on the models

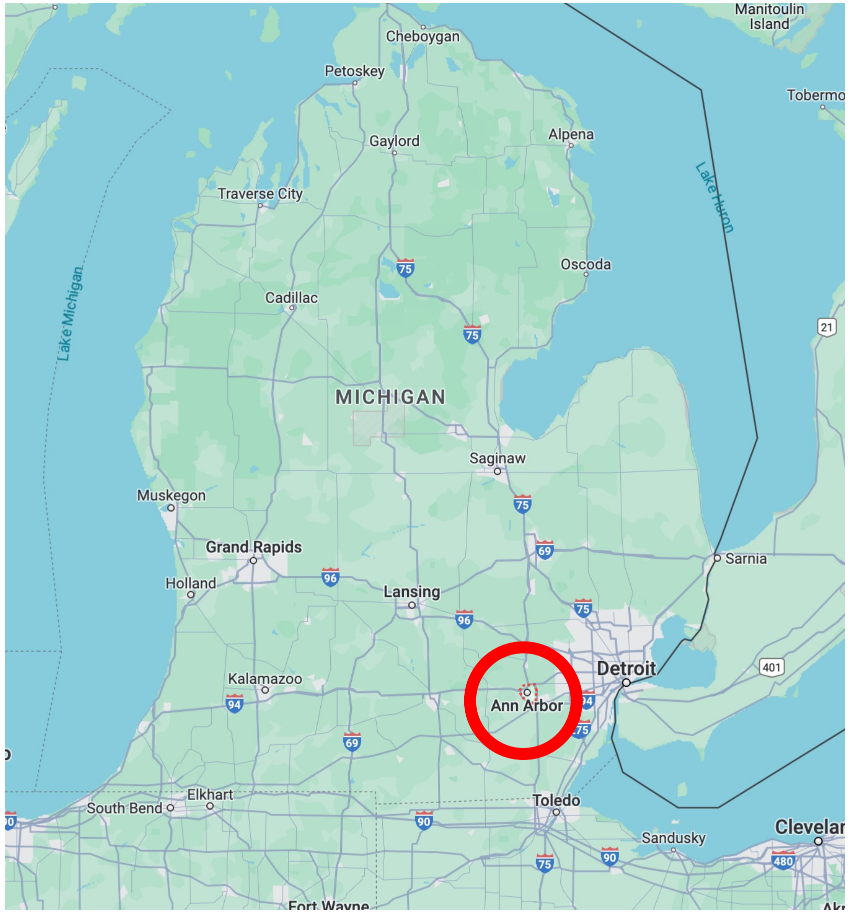


Prox Cen b airless and Earth-like atmosphere models in color-magnitude space


exposure time [hours]
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
S/N
0
2
4
6
8
10
12
14
10^{-1}
10^{1}
10^{3}
10^{5}
exposure time [s]
g′
r′
i′
z′
J
H
GJ 3021 b
HD 40979 b
HD 183263 b

ReflectX + Pup Search will comprise the bulk of my post-doc

Inaugural ELT Fellow at University of Michigan
Starting Sep 2024




XWCL
MagAO-X
ÚLTIMA LLAMADA
645
Ruby Tuesday


DELL
GovEvolve

Summary

- DI with extreme AO is the future of exoplanet science.
- MagAO-X is a technology development platform for reflected light imaging.
- I showed that Boyajian's Star has a wide companion which got me interested in how wide companions affect the planetary regime.
- I analyzed a binary differential imaging survey data and uncovered a new companion at around 2 lambda/D.
- I am using MagAO-X for the novel application of ExAO to WD+MS binaries with the ExAO Pup Search.
- I am preparing the ReflectX model suite to prepare for exoplanet reflected light imaging.