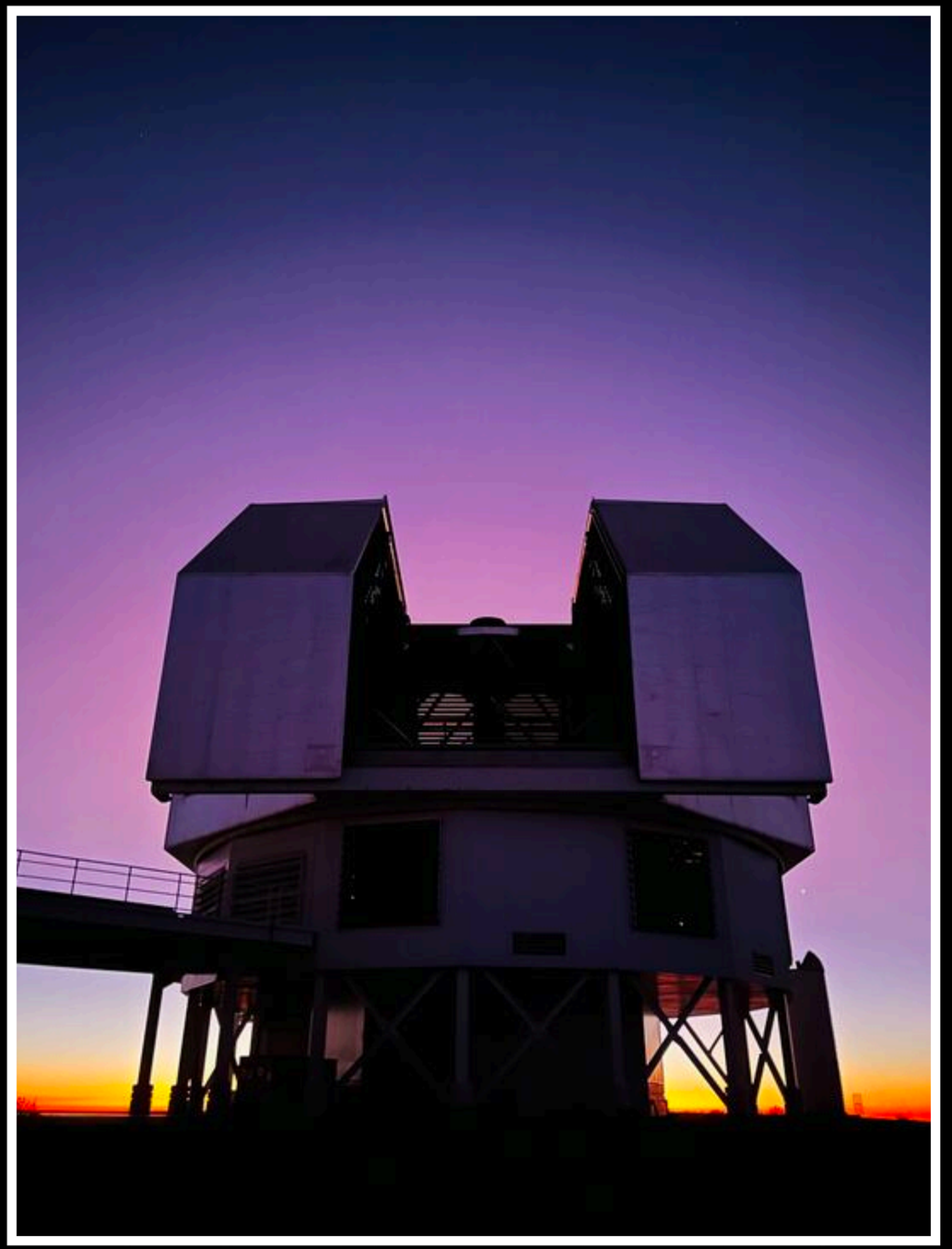
EXOPLANET SCIENCE AT STEWARD OBSERVATORY WITH MAGAO-X AND GMAGAO-X

LOGAN PEARCE
UNIVERSITY OF ARIZONA/STEWARD OBSERVATORY

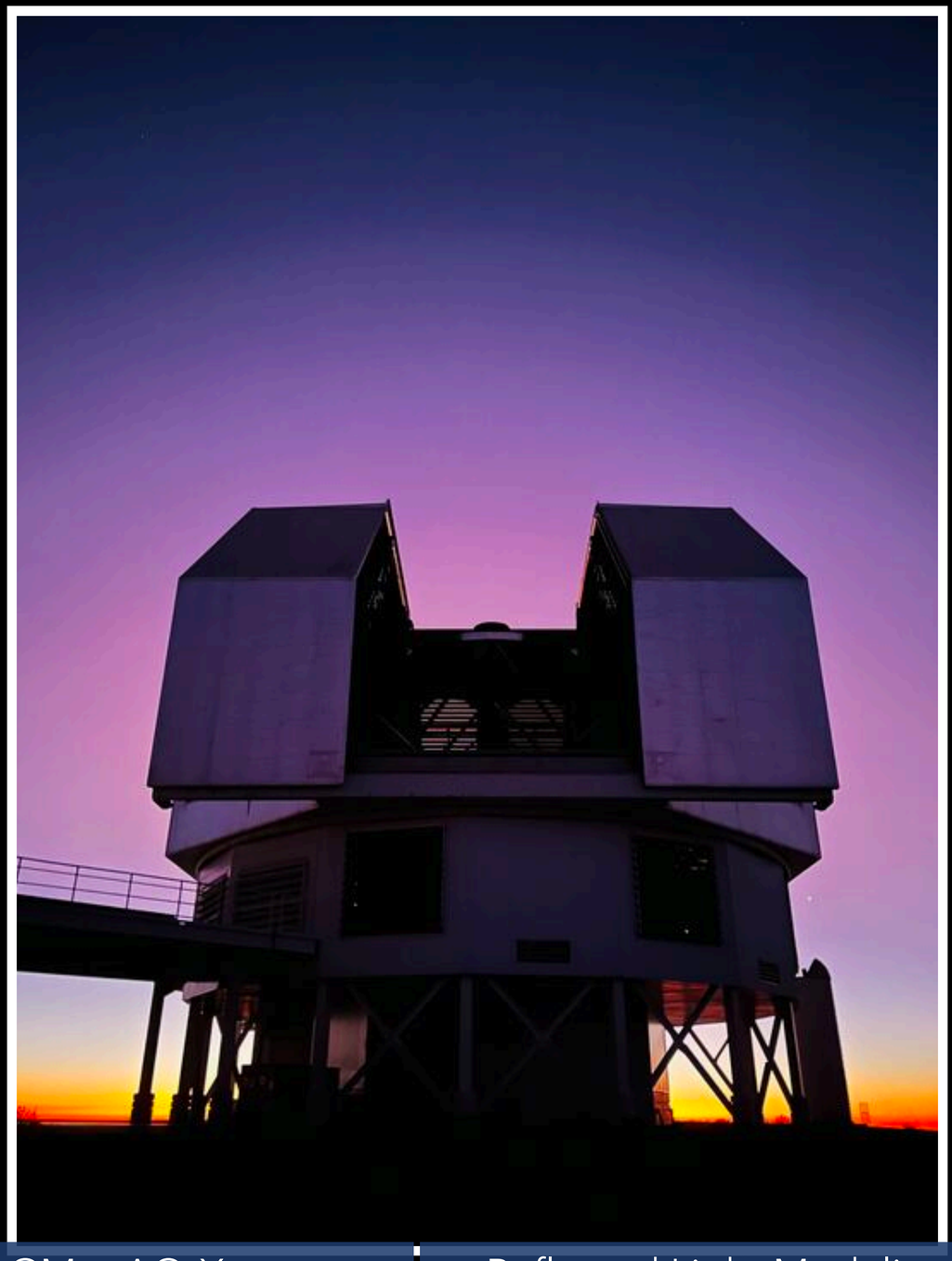
UCSC LAO MEETING JUNE 1ST, 2023



OUTLINE

- Introduction to MagAO-X and XWCL
- Ongoing science programs with MagAO-X
- MagAO-X Upgrades Towards Reflected Light Imaging
- Introduction to GMagAO-X
- My ongoing work at NASA Ames on Reflected Light Imaging with GMagAO-X

OVERVIEW OF MAGAO-X

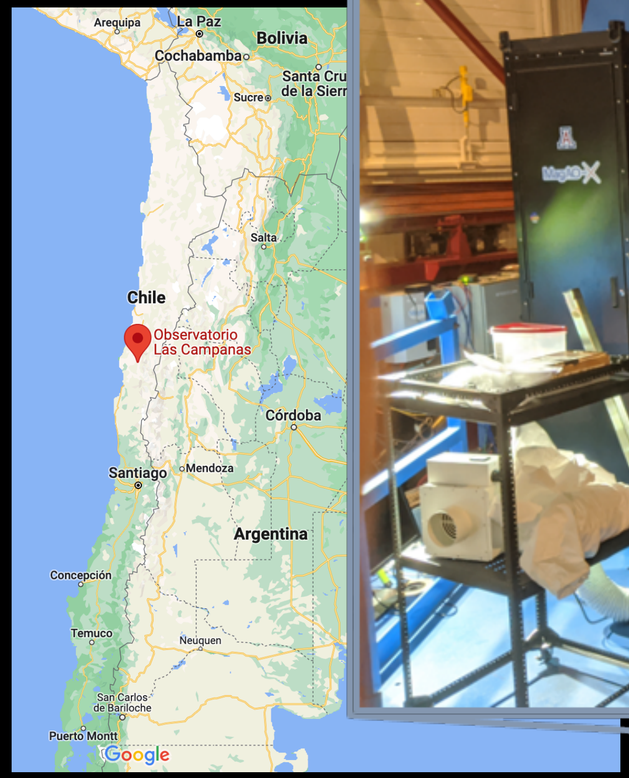


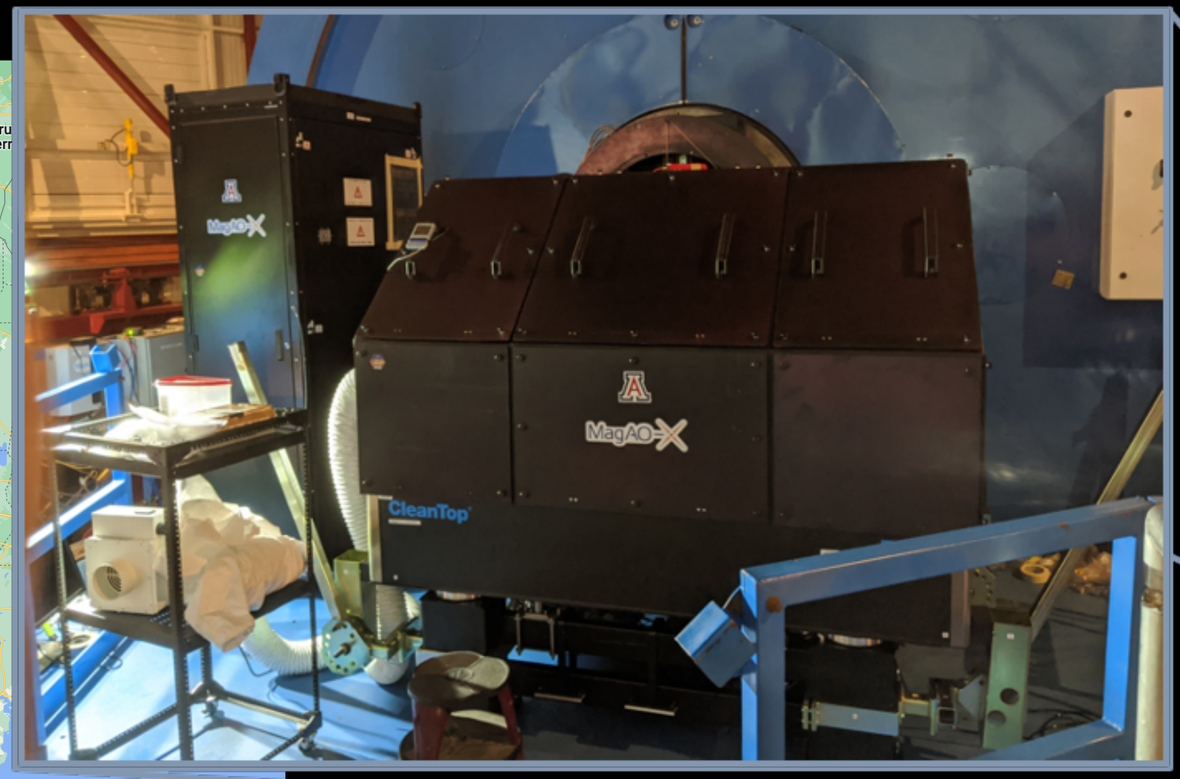
MagAO-X

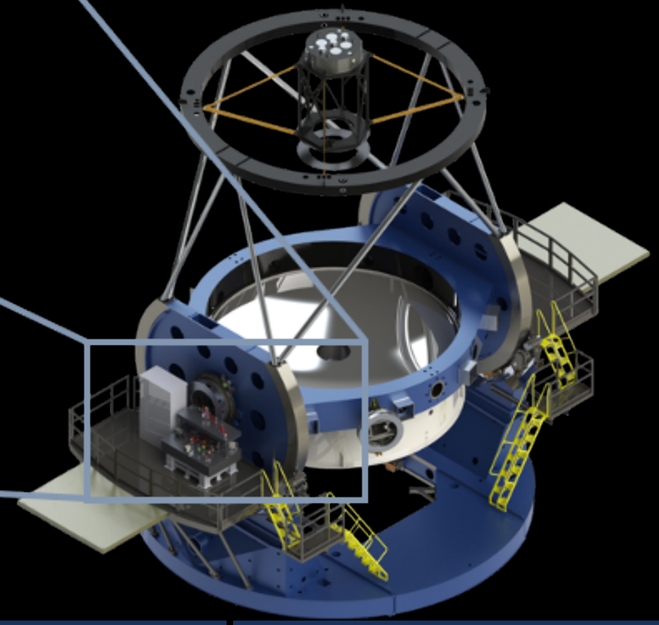
XWCL

"Extreme" adaptive optics instrument on the Magellan Clay Telescope, Las Campanas Observatory

- 6.5m telescope
- Magellan Consortium: Carnegie, Arizona, Harvard, Michigan, MIT

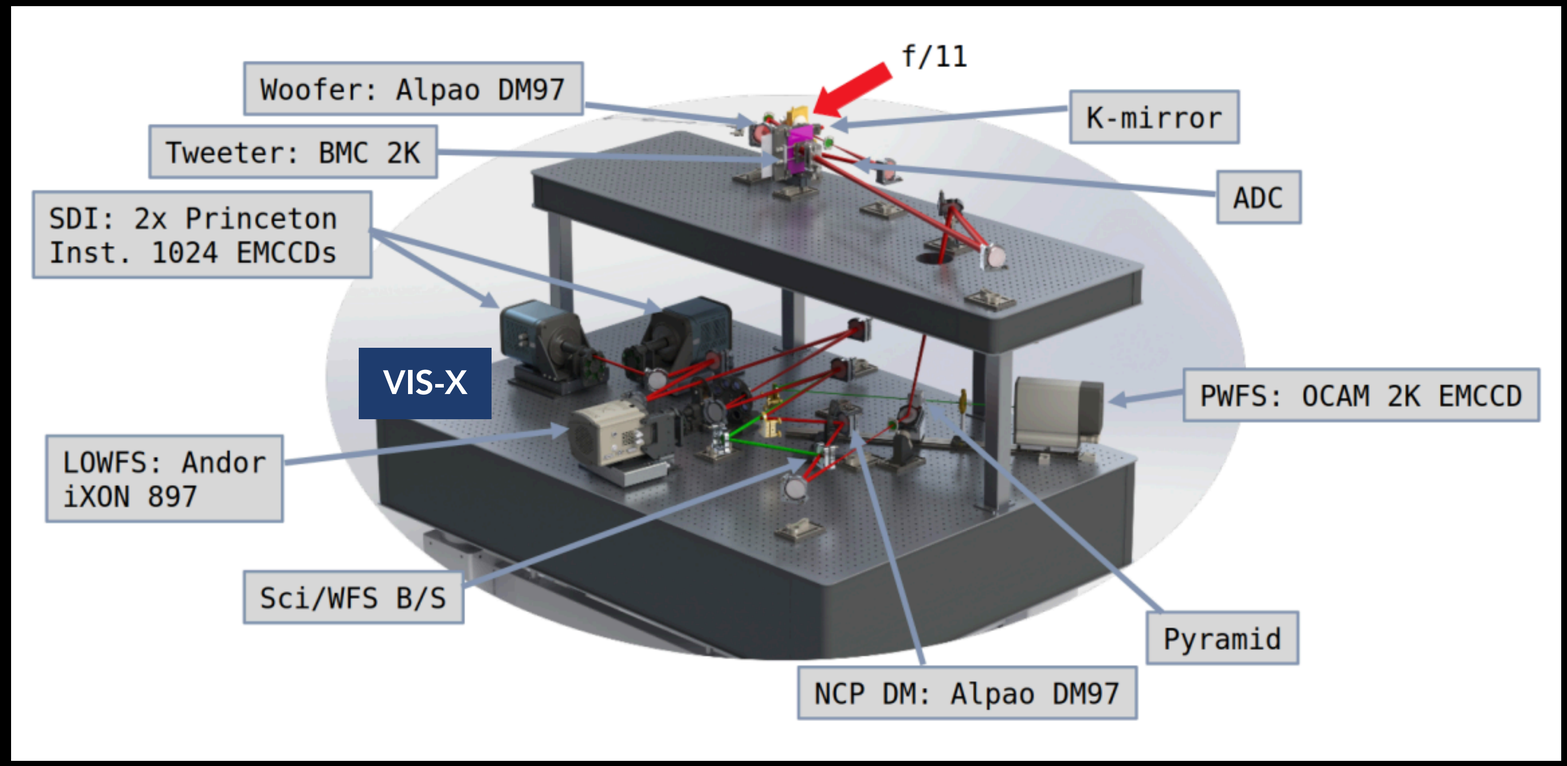






MagAO-X

- 3.6 kHz AO system
- 3 deformable mirrors, including “woofer”, 2000 actuator “tweeter”, and non-common path correction DM
- 2 science cameras
- Optimized for visible: g’, r’, i’, z’, Narrowband H-alpha, Methane
- VIS-X IFU



Males et al. 2022

MagAO-X

Schedule:

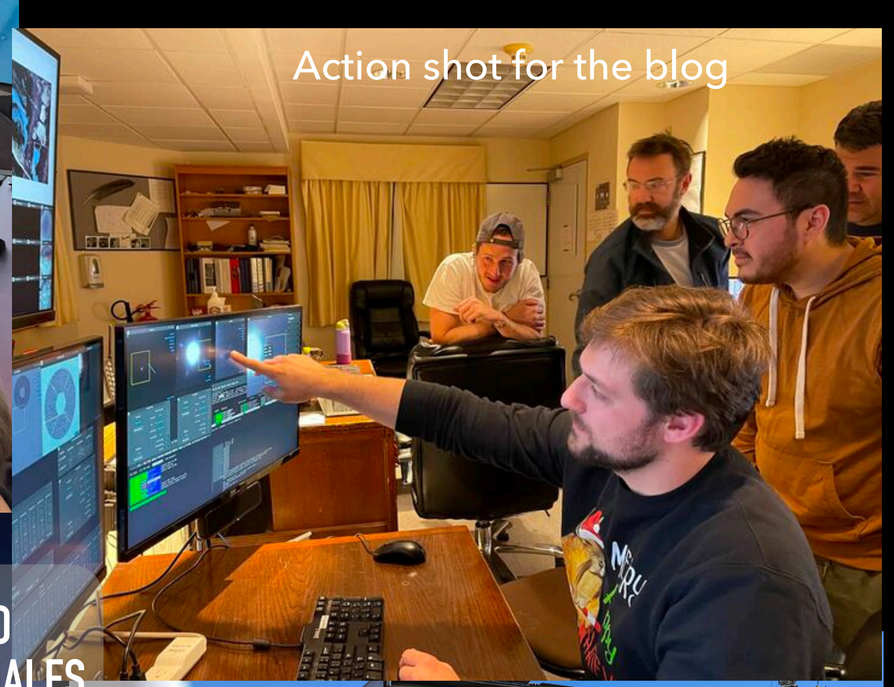
- First light fall 2019
- Upgrades, lab experiments 2020-2021
- Returned to telescope April 2022, Nov/Dec 2022, Feb/March 2023
- Phase II Upgrades/lab time rest of 2023

Mission patch genius:
Joseph Long

Jared Males - PI

Alycia Weinberger (Carnegie) and assorted grad students

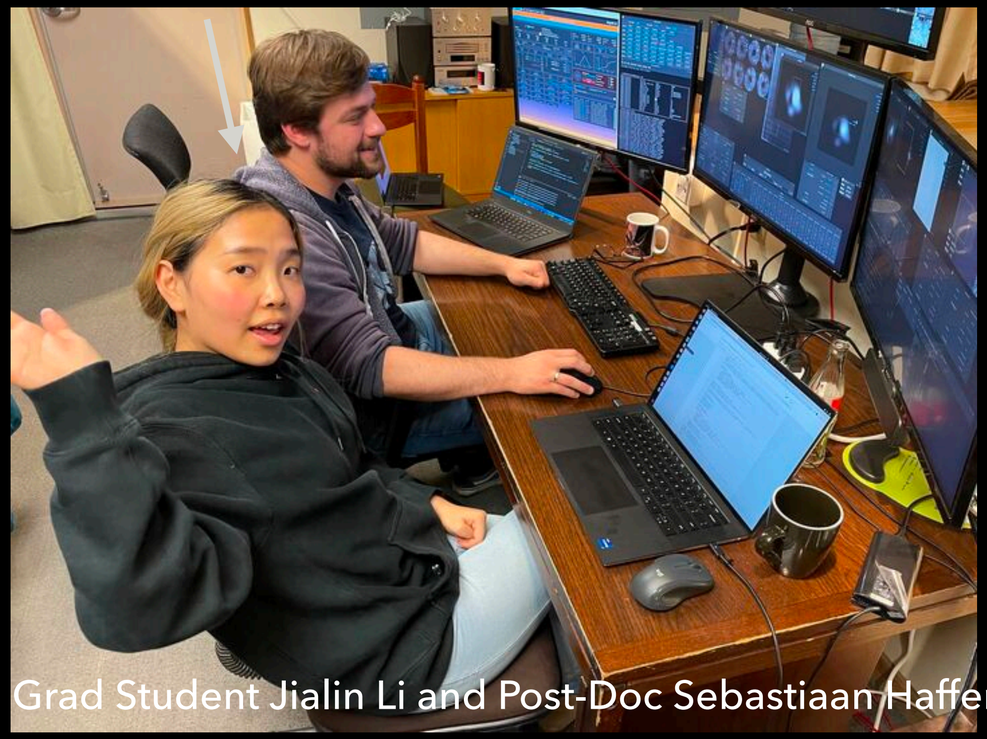
We're a woman-heavy group!



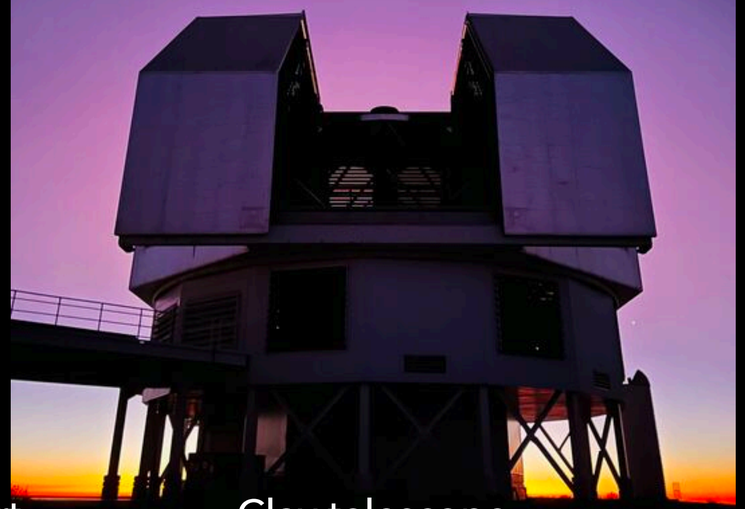
Action shot for the blog

"THE REASON WE DO THINGS IS TO GENERATE BLOG CONTENT" – JARED MALES

XWCL.SCIENCE



Grad Student Jialin Li and Post-Doc Sebastiaan Haffert



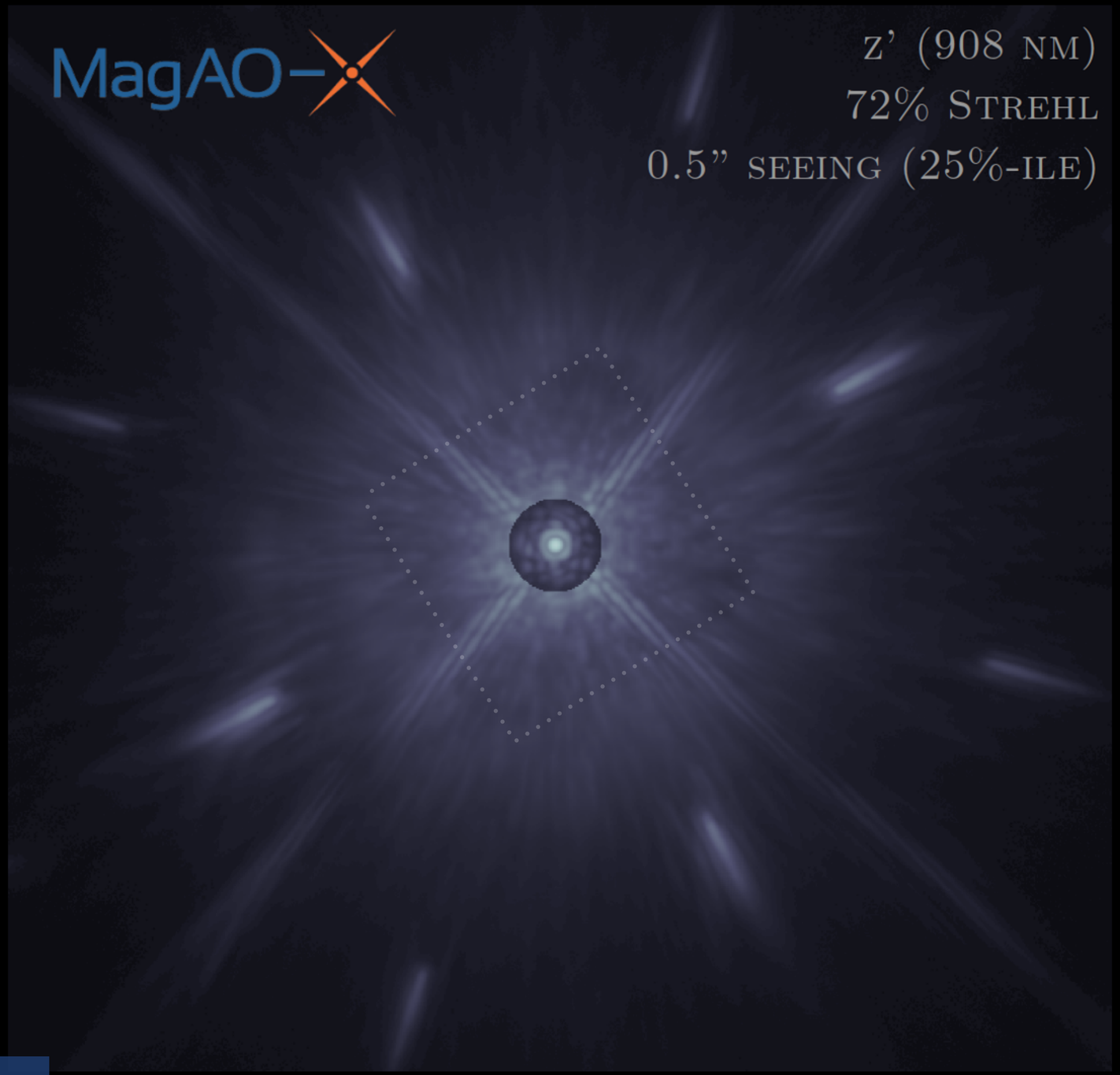
Clay telescope

Shipping out from Tucson

Being trucked up to the telescope

1376 modes controlled at 2 kHz

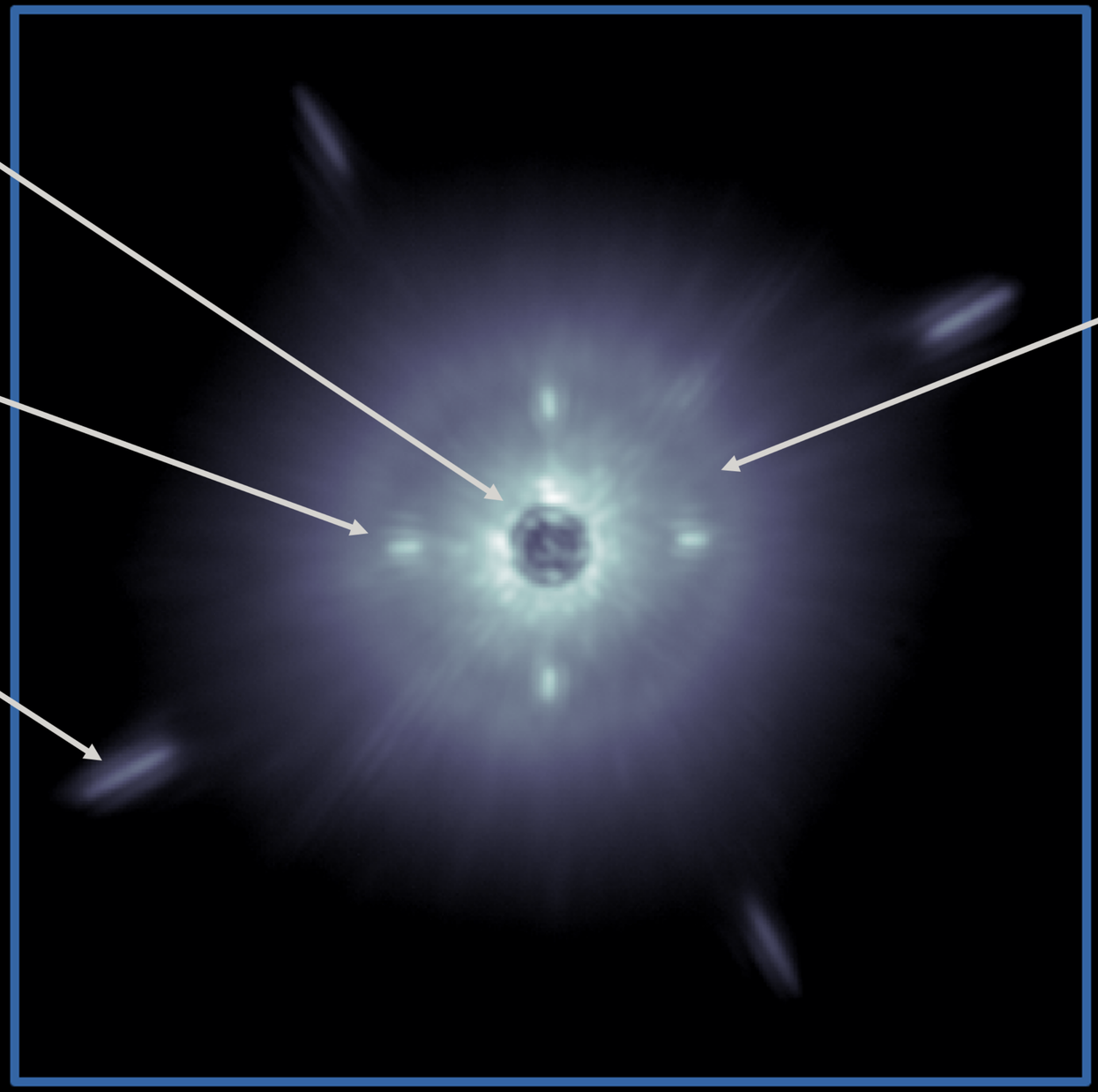
22 λ/D dark hole



Coronagraph
4.3 λ/D

Calibration speckles
"Sparkles"

Speckles from
DM

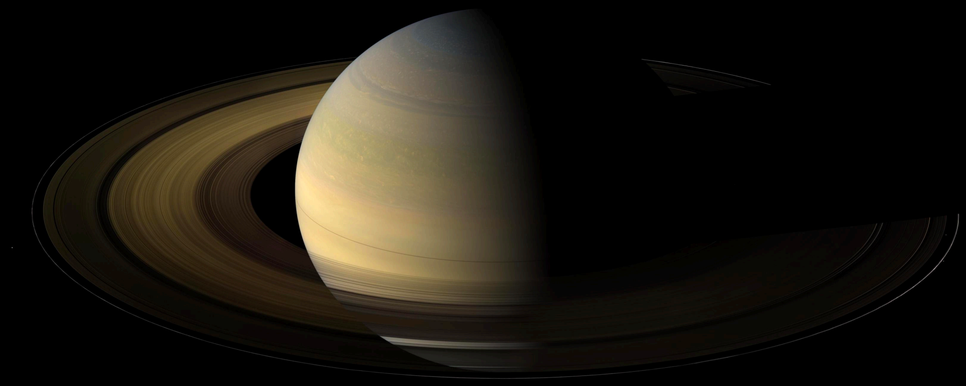


"Dark hole" AO
control radius

MagAO-X

Ultimate Science goal: Image nearby exoplanets in reflected light

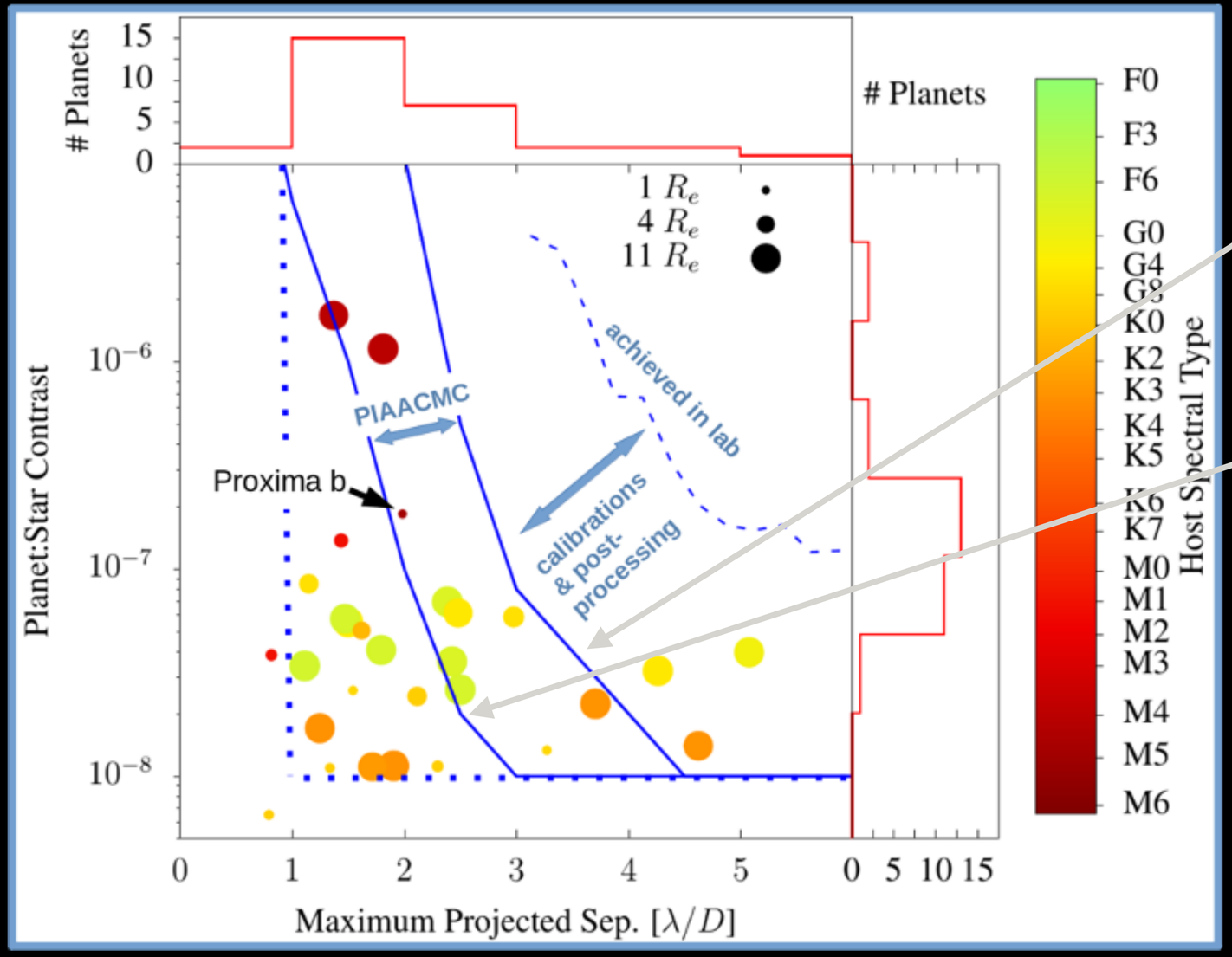
- Necessary to directly image & characterize evolved systems, small planets
- Very hard!
- 1e-7 contrast needed to image Proxima Centauri b
- Need to work very close to star where stellar irradiation sets brightness



Source: NASA/JPL

PHASE II UPGRADES

Direct reflected light imaging of the nearest, habitable zone planet (Proxima b)



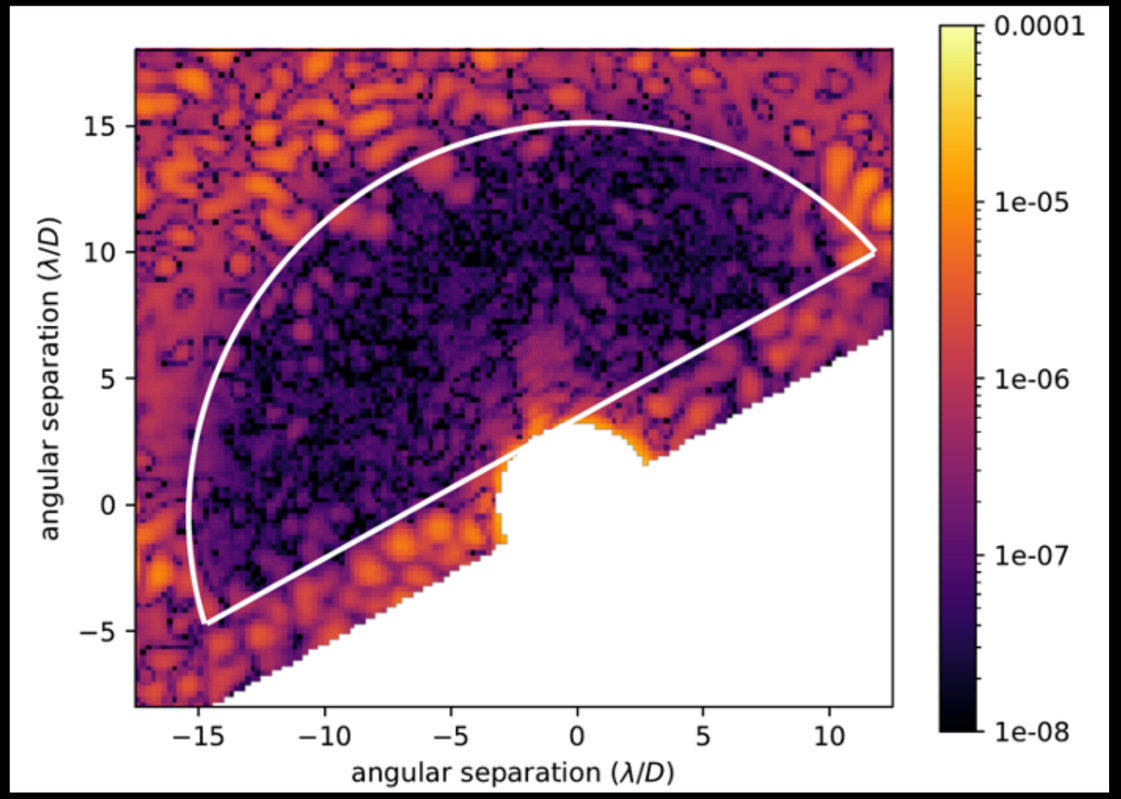
Post-processing improvements

After Phase II upgrades

PHASE II UPGRADES

- DARKNESS MKID IFU was tested behind MagAO-X in Feb 2023
- Control computer upgrades to GPUs -> reduce latency and enable real-time processing
- NCPC DM upgrade to 1k DM - Sebastiaan Haffert

5e-8 contrast dark hole created in the lab



PHASE II UPGRADES

- Low-order wavefront sensor (LOWFS) and linear dark field control (LDFC) - Avalon McLeod

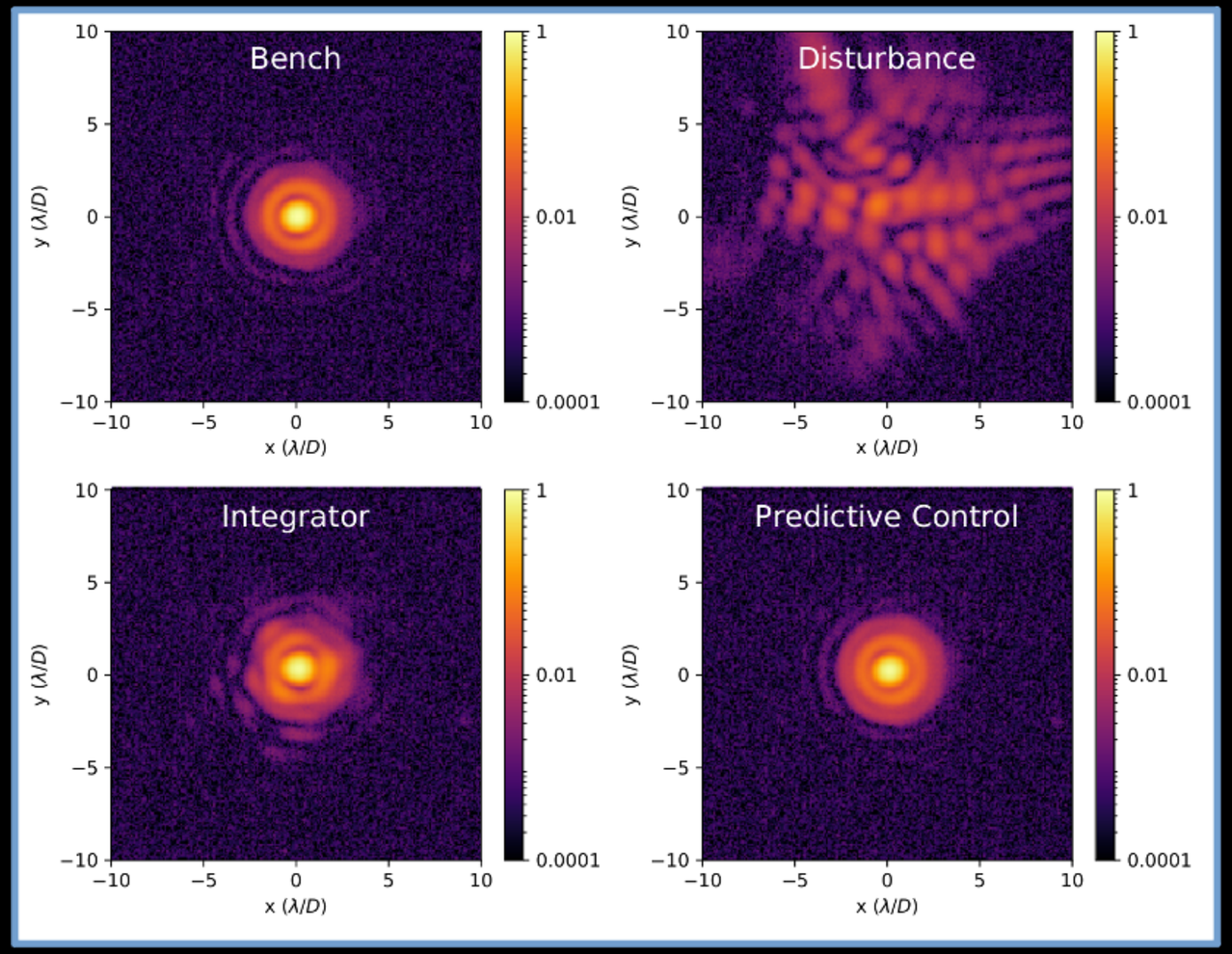
- Phase-Induced Amplitude Apodization (PIAA) - Warren Foster

PHASE II AND BEYOND

- Developing new post-processing technique using WFS telemetry for PSF/speckle reconstruction- Joseph Long

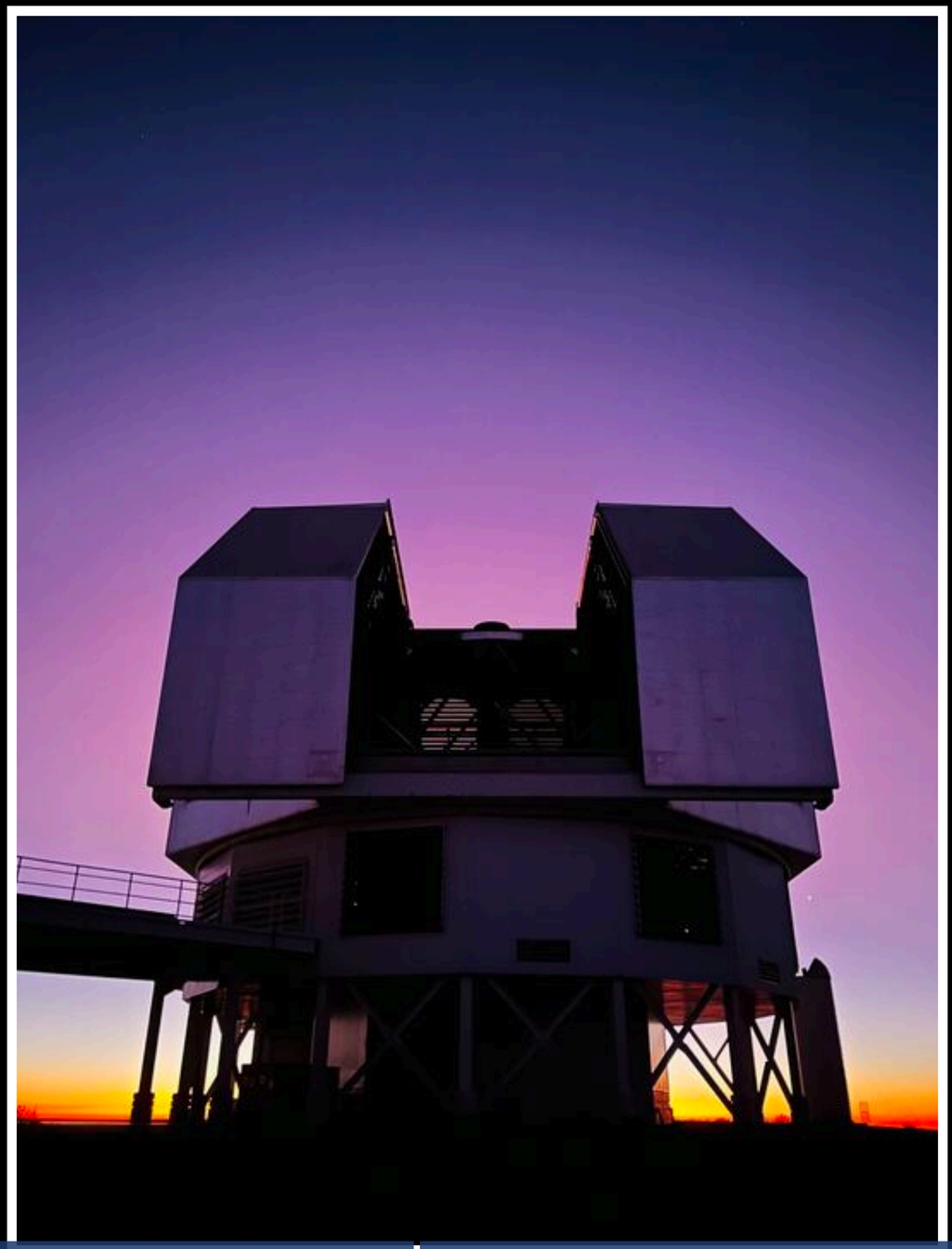
- Real time optical gain measurements for PSD reconstruction and predictive control - Eden McEwan

- Getting Data-Driven Predictive Control working on-sky - Sebastiaan Haffert



See Haffert et al., JATIS, 2021

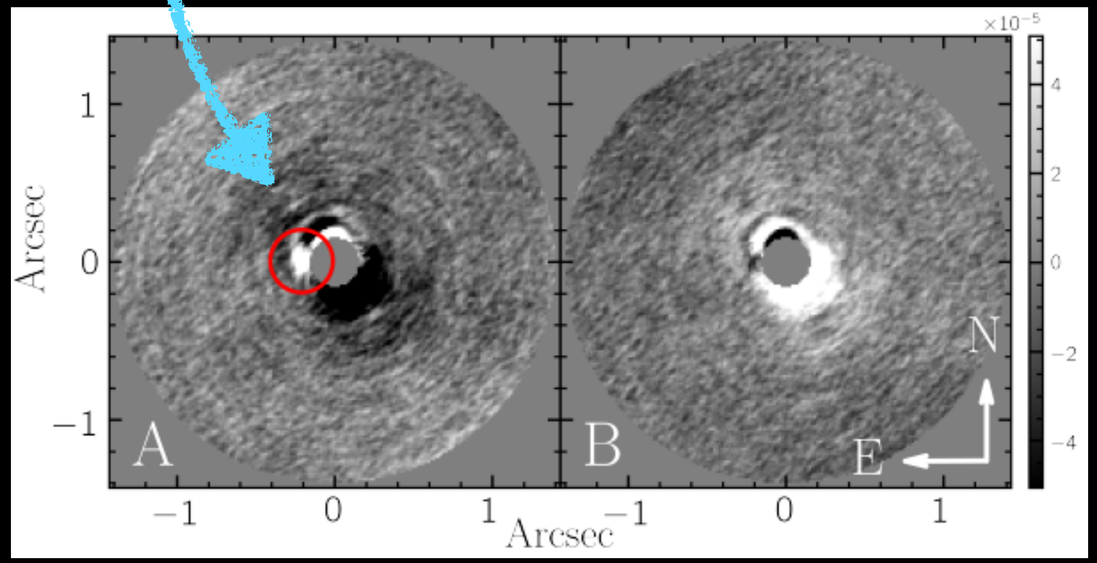
MAGAO-X SCIENCE PROGRAMS

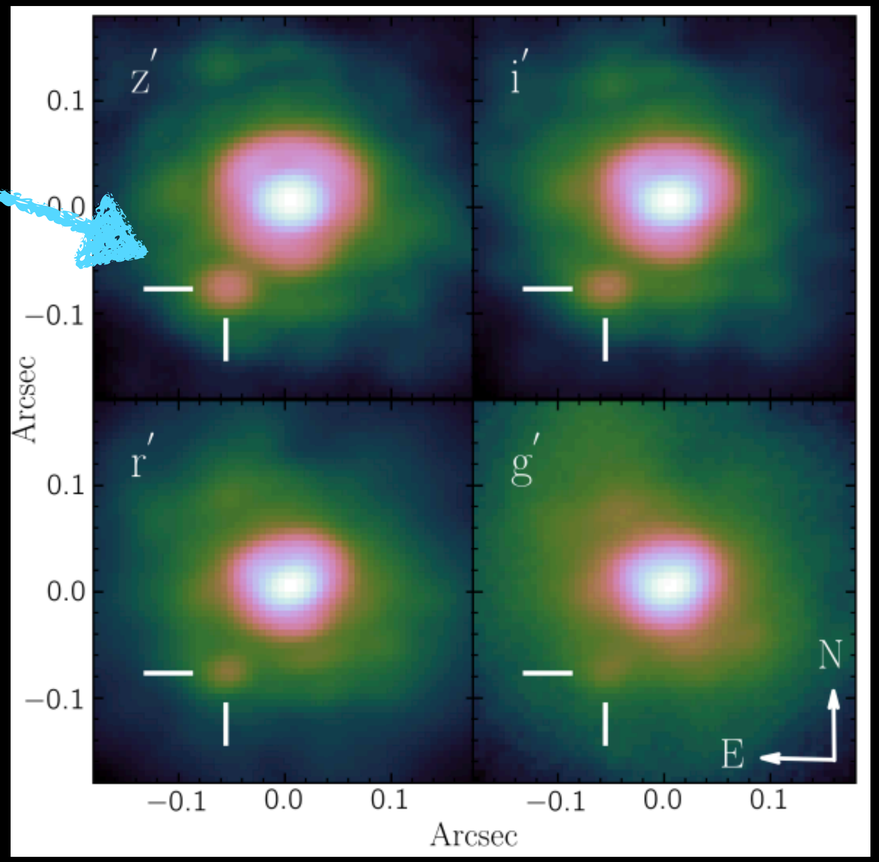


FIRST SCIENCE RESULTS ARE JUST COMING OUT!

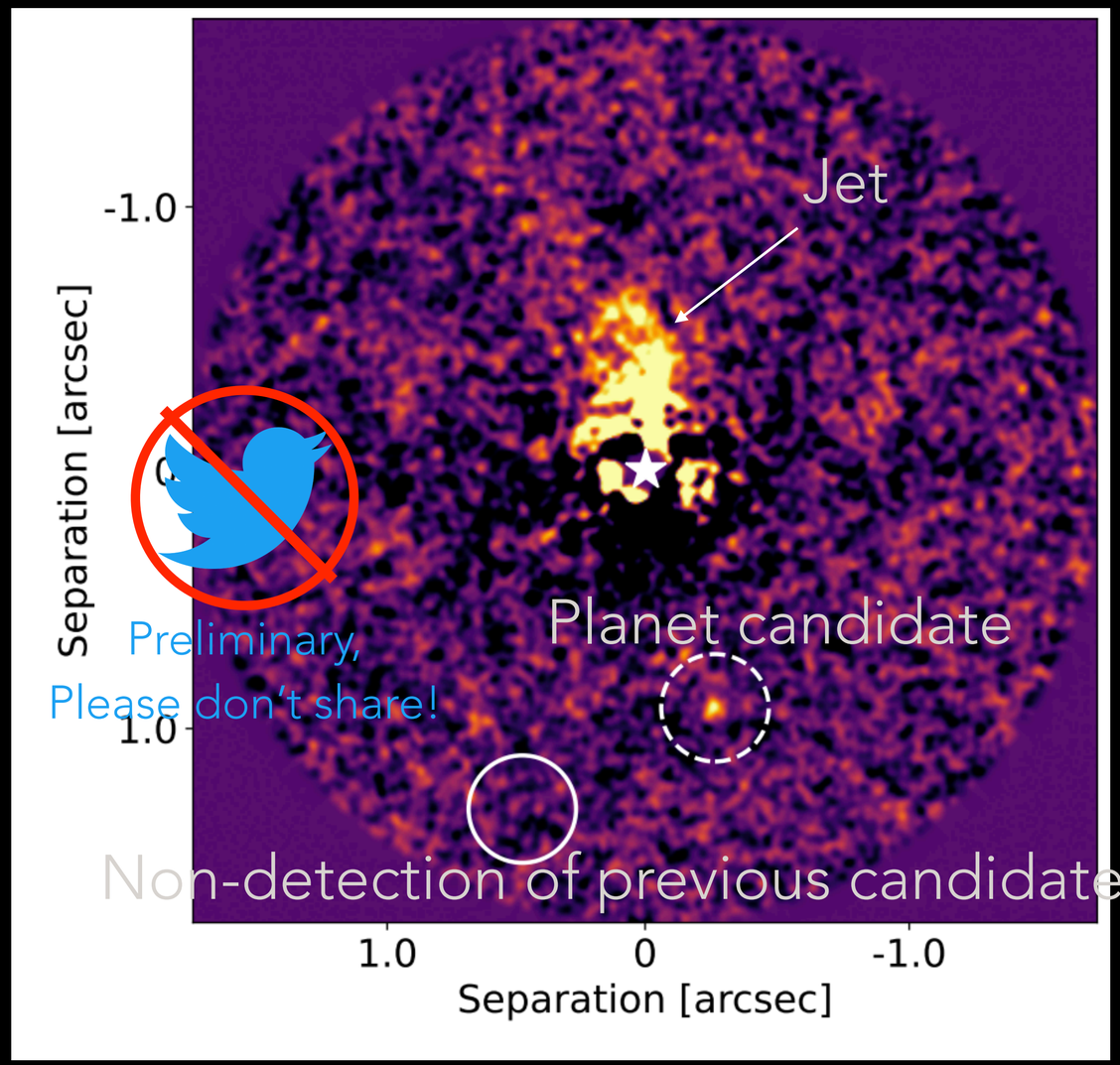
In Pearce et al. 2022 we found a candidate companion signal at 2 λ/D in L′ with MagAO.

Followed up with MagAO-X and found it is a star





Pearce et al. 2023. Not the most exciting, but the first MagAO-X astrophysics paper.



A new accreting protoplanet and jet emission detected in H alpha

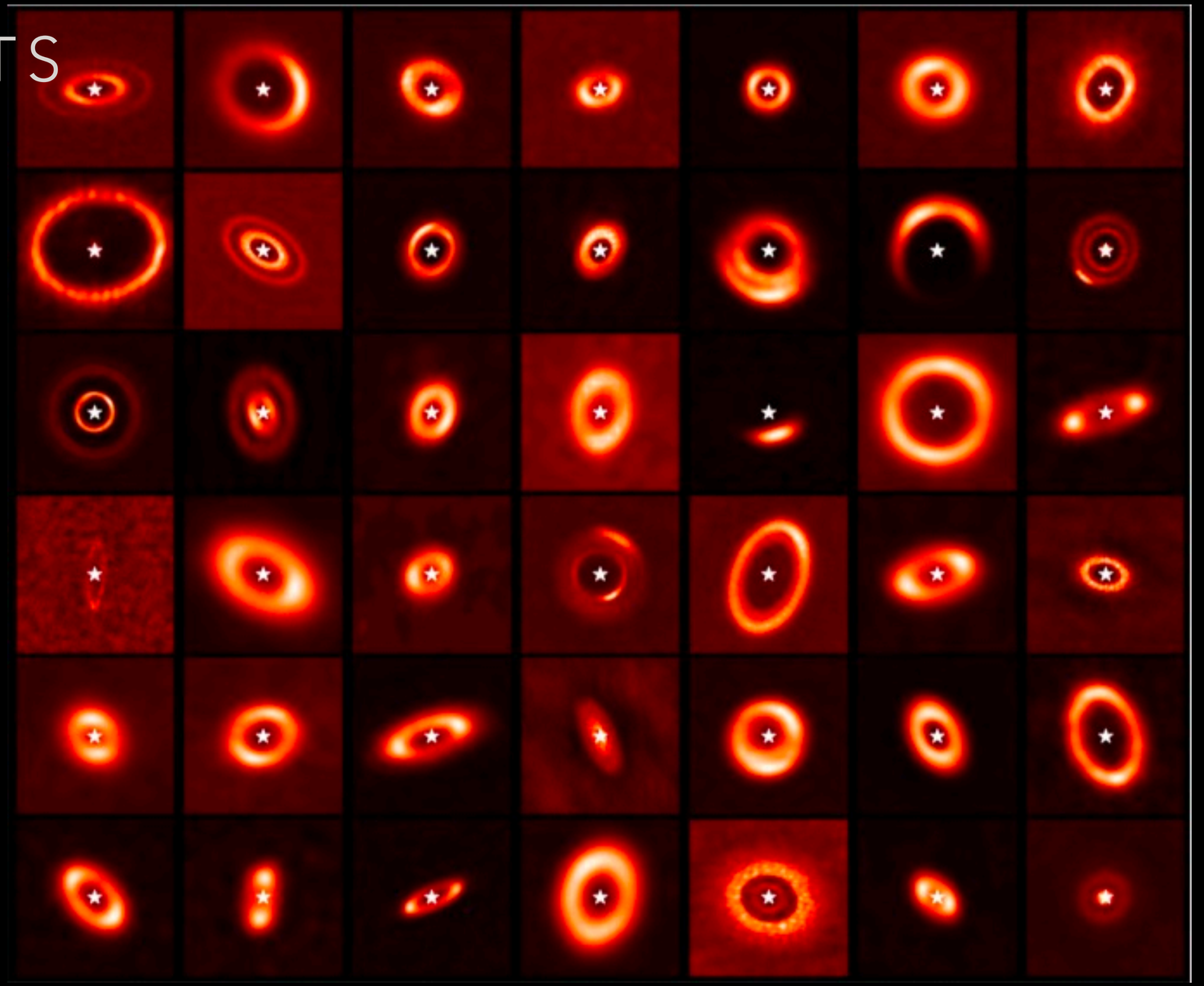
Found better data/results with MagAO-X than HST!

PI: Gabriele Cugno, U. Michigan

Keep an eye out for this paper!

MAXPROTOPLANETS

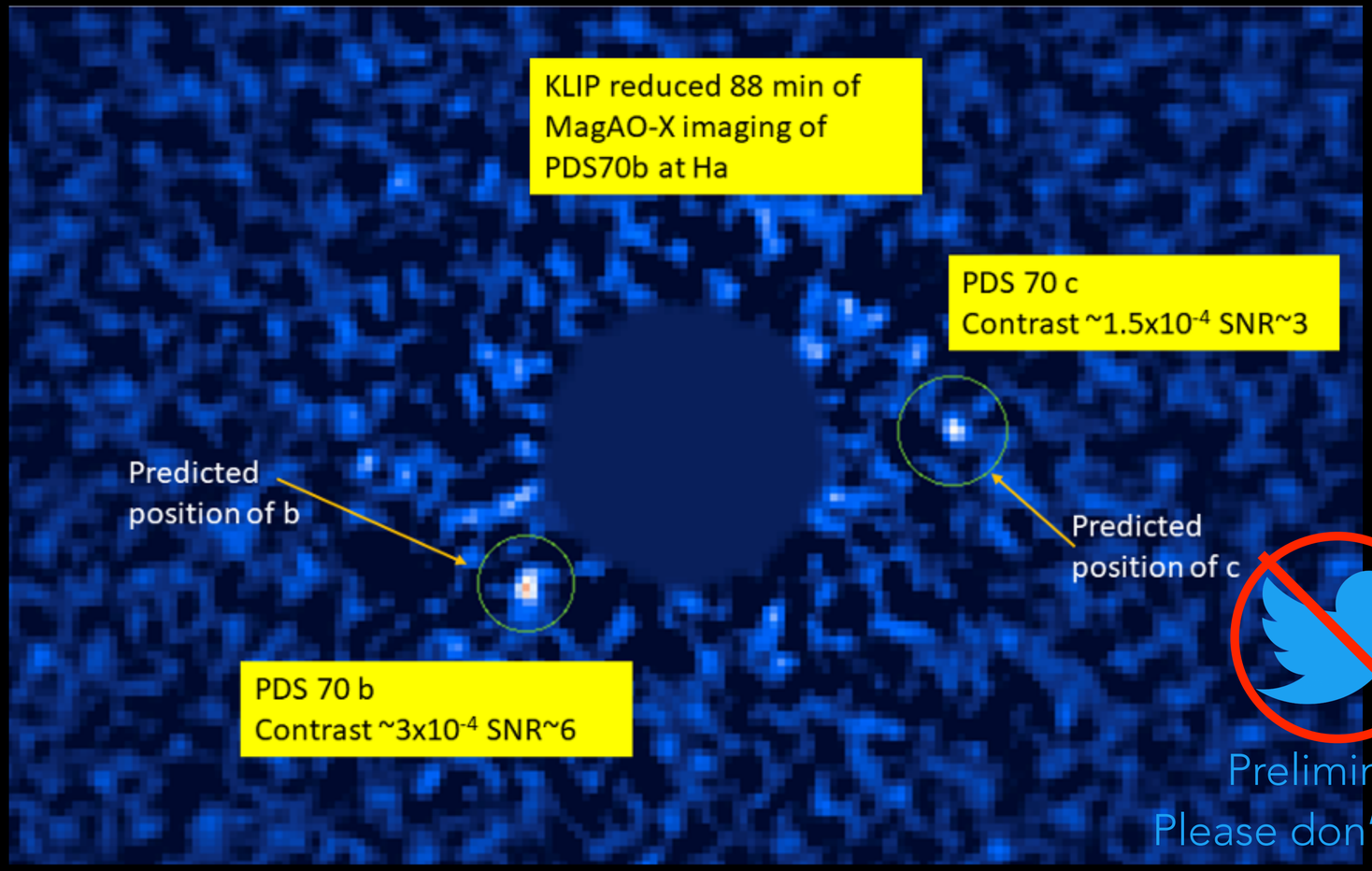
- Image accreting planets in disk gaps in Halpha
- PI: Laird Close



Van Der Marel 2023

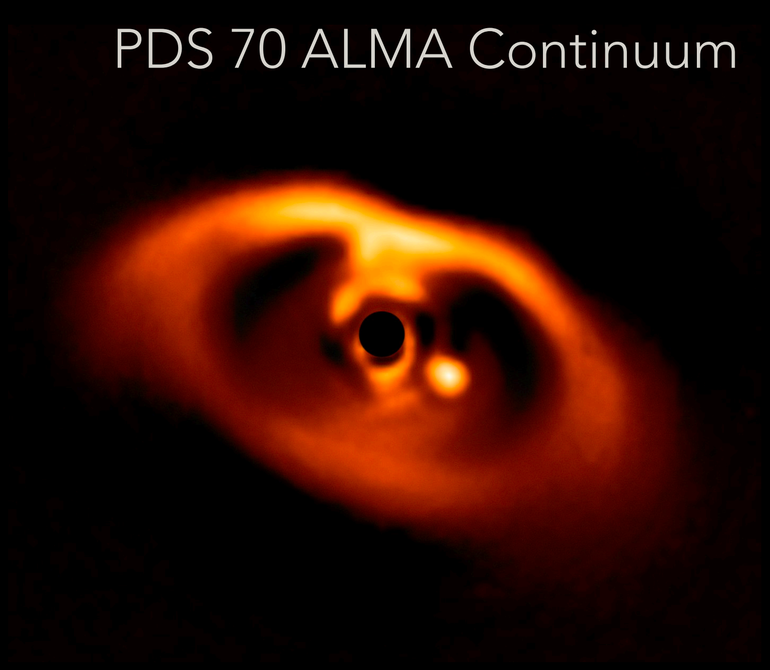
MAXPROTOPLANETS

PDS 70 MagAO-X Halpha



Preliminary,
Please don't share!

PDS 70 ALMA Continuum



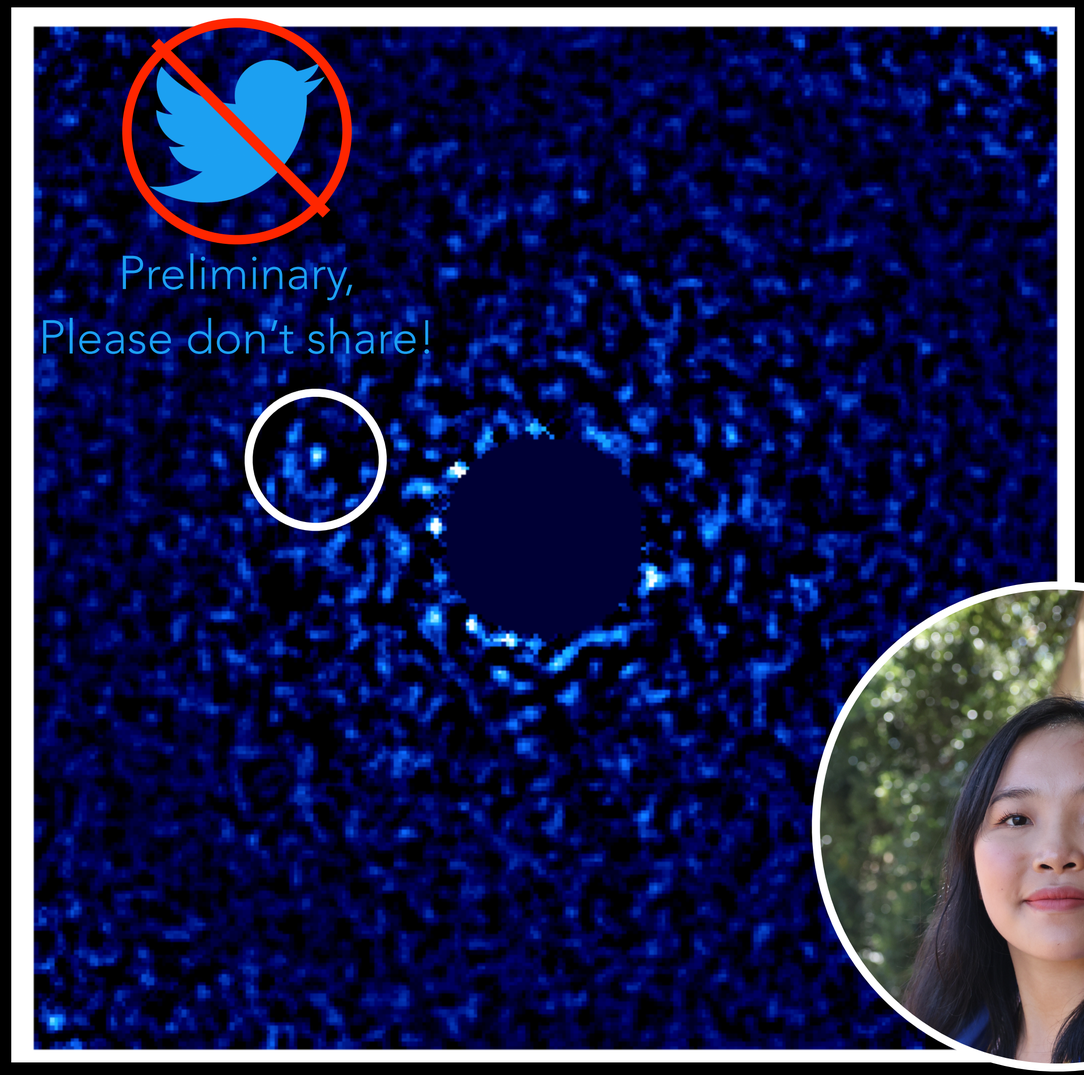
Source: ESO/ A. Muller et al.

Close et al., in prep

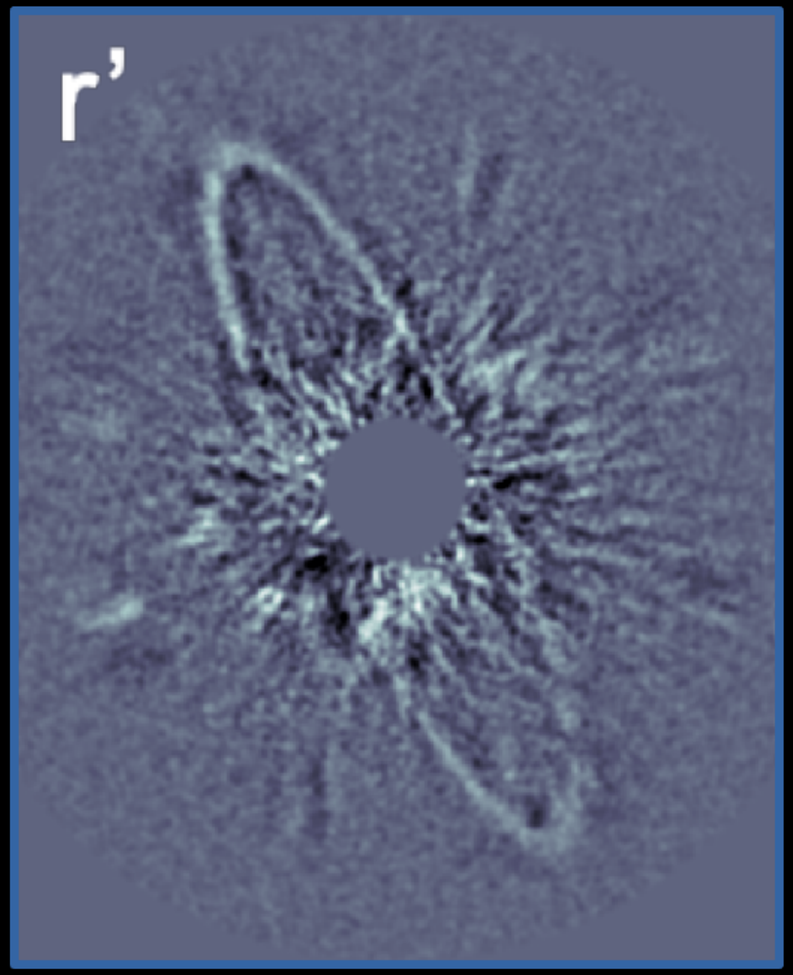
MaxProtoPlanetS discovery of a new accreting protoplanet candidate embedded in a disk

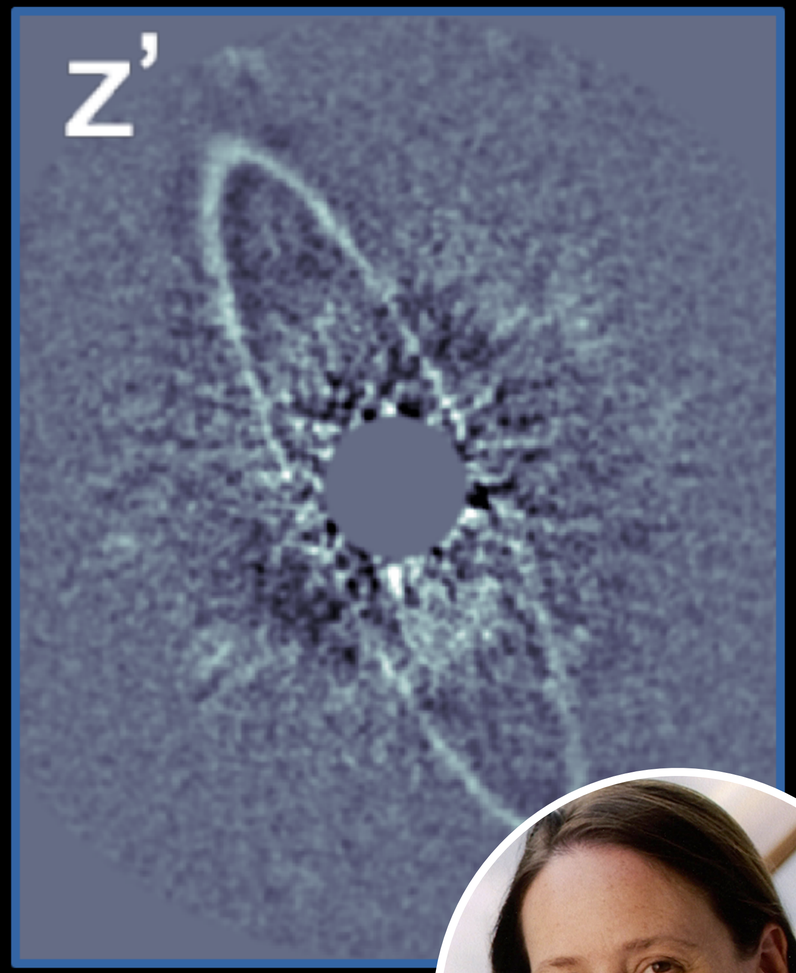
Led by graduate student Jialin Li

Keep an eye out for this paper!

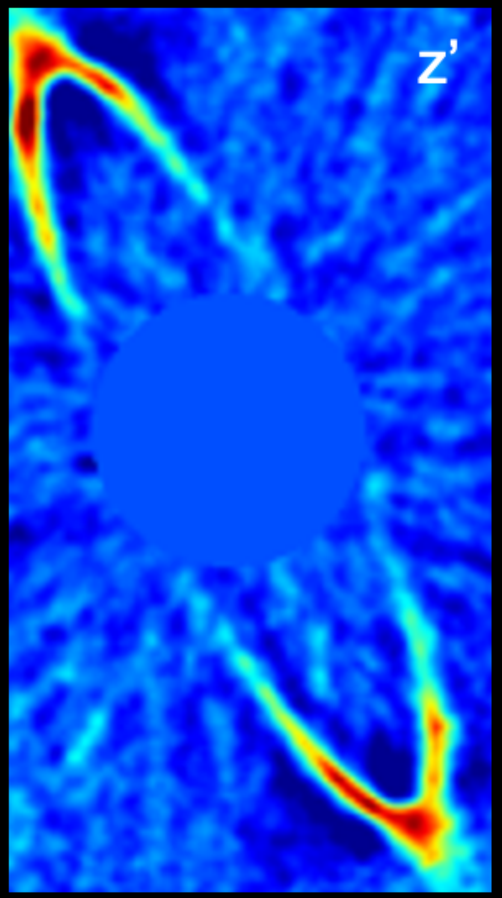


PI: Alycia Weinberger, Carnegie





HR 4796 A (Weinberger et al., in prep)



VisAO for comparison (Rodigas et al, 2015

MagAO-X

MagAO-X Science Programs

GMagAO-X

Reflected Light Modeling

EXAO PUP SEARCH

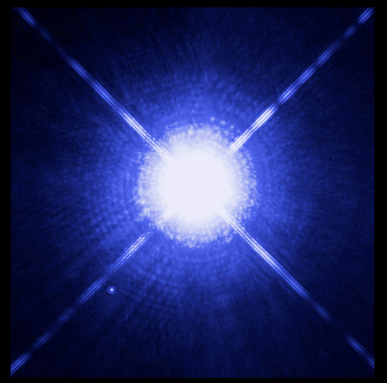
- White Dwarfs are excellent (the only!) probes of exoplanetary non-volatile material composition through pollution of photospheres.

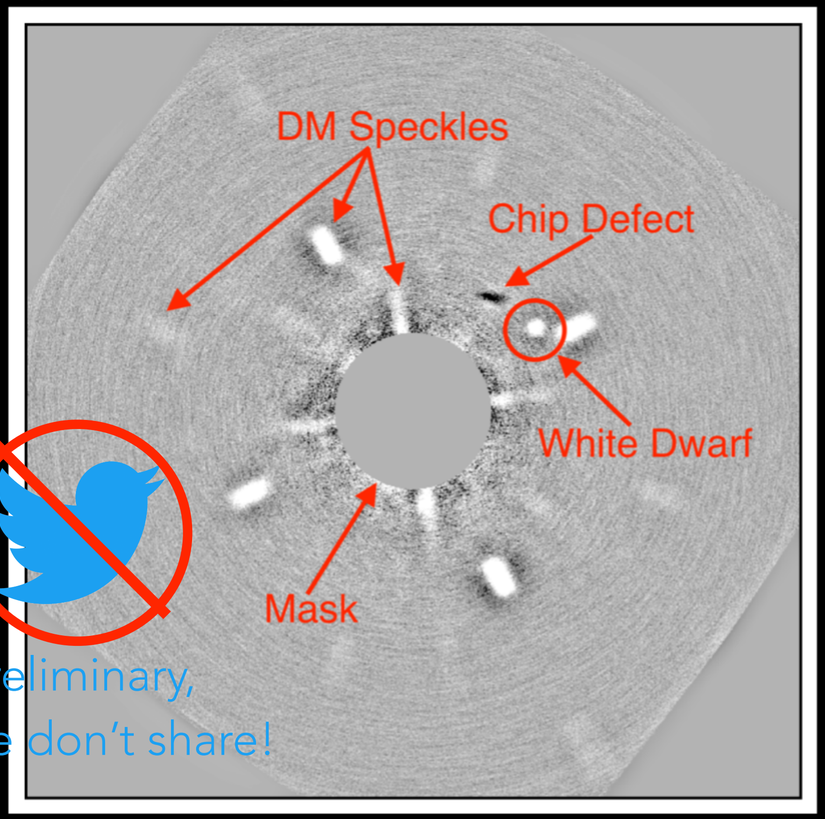
- I am using MagAO-X to discover new WD-MS systems for follow-up for pollution

- Probe of planetary systems in binaries at end of star's lifetime

The ExAO Pup Search

The search for non-interacting white dwarf - main sequence binaries with MagAO-X and SCExAO





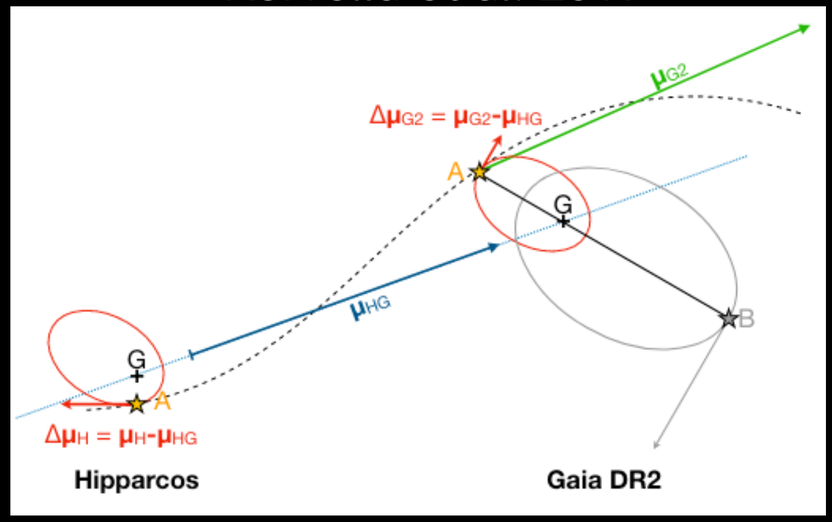
Preliminary,
Please don't share!

XOOMIES

The MagAO-X survey to fetch companions of accelerating stars

Searching for hidden planet/ brown dwarf companions around young accelerating stars In Sco Cen with MagAO-X

Kervella et al. 2019



A ~0.75 Msun star

A ~14 Mjup planet

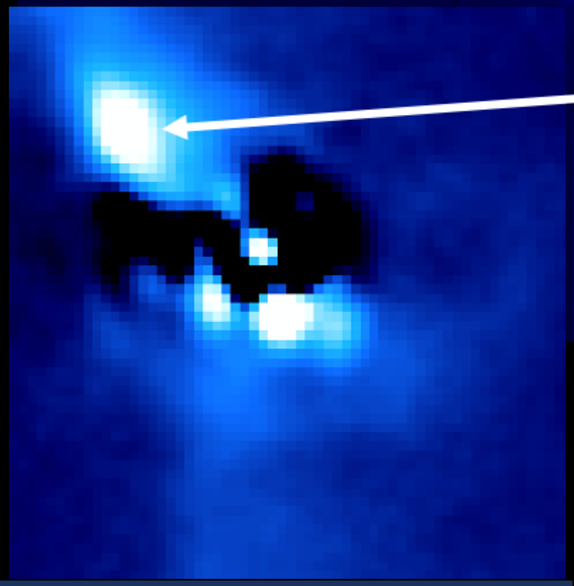
An in-progress MagAO-X action shot

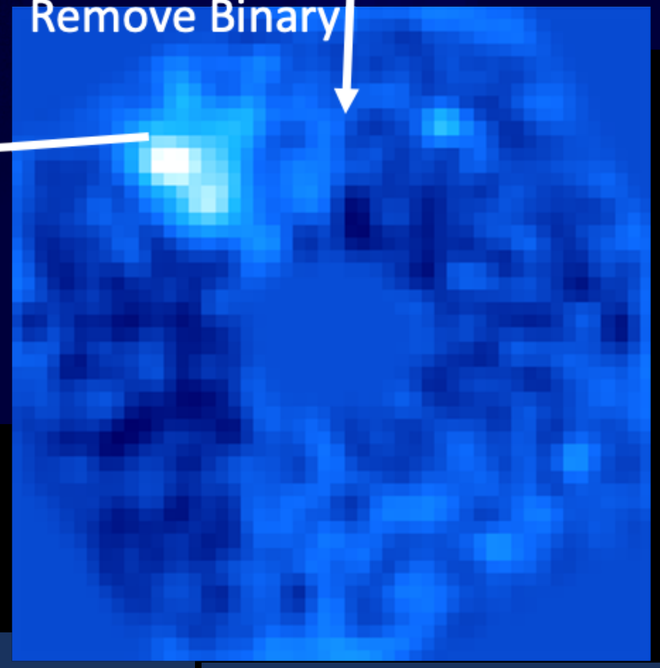
R Aqr: interacting binary with jet

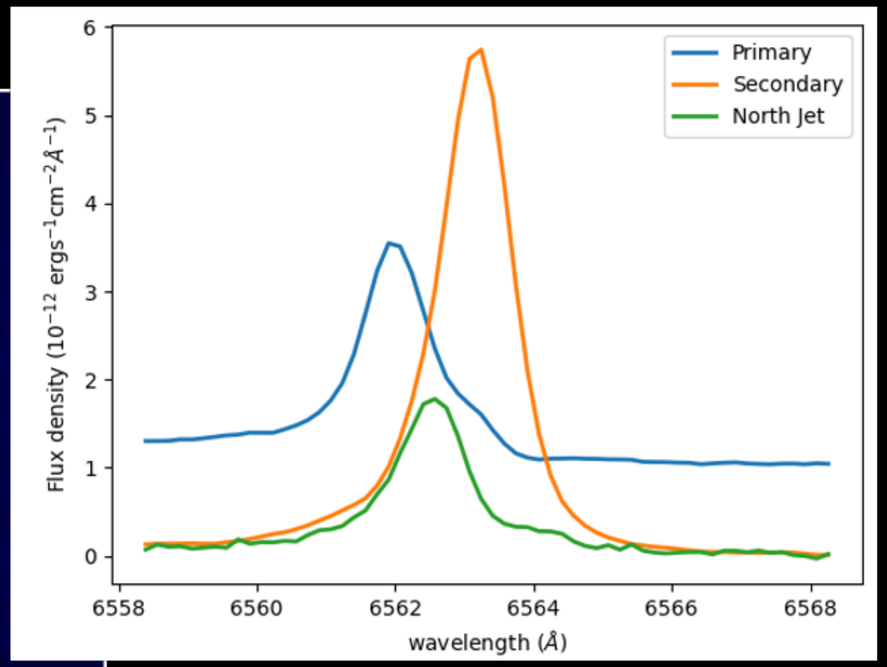
VIS-X IFU

MagAO-X to VIS-X

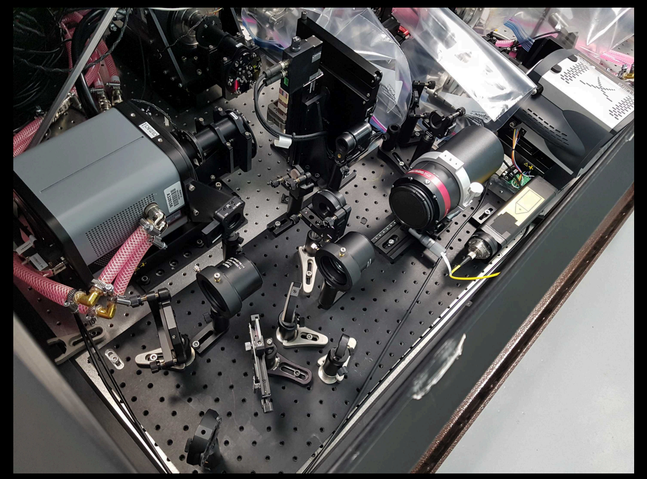
Remove Binary



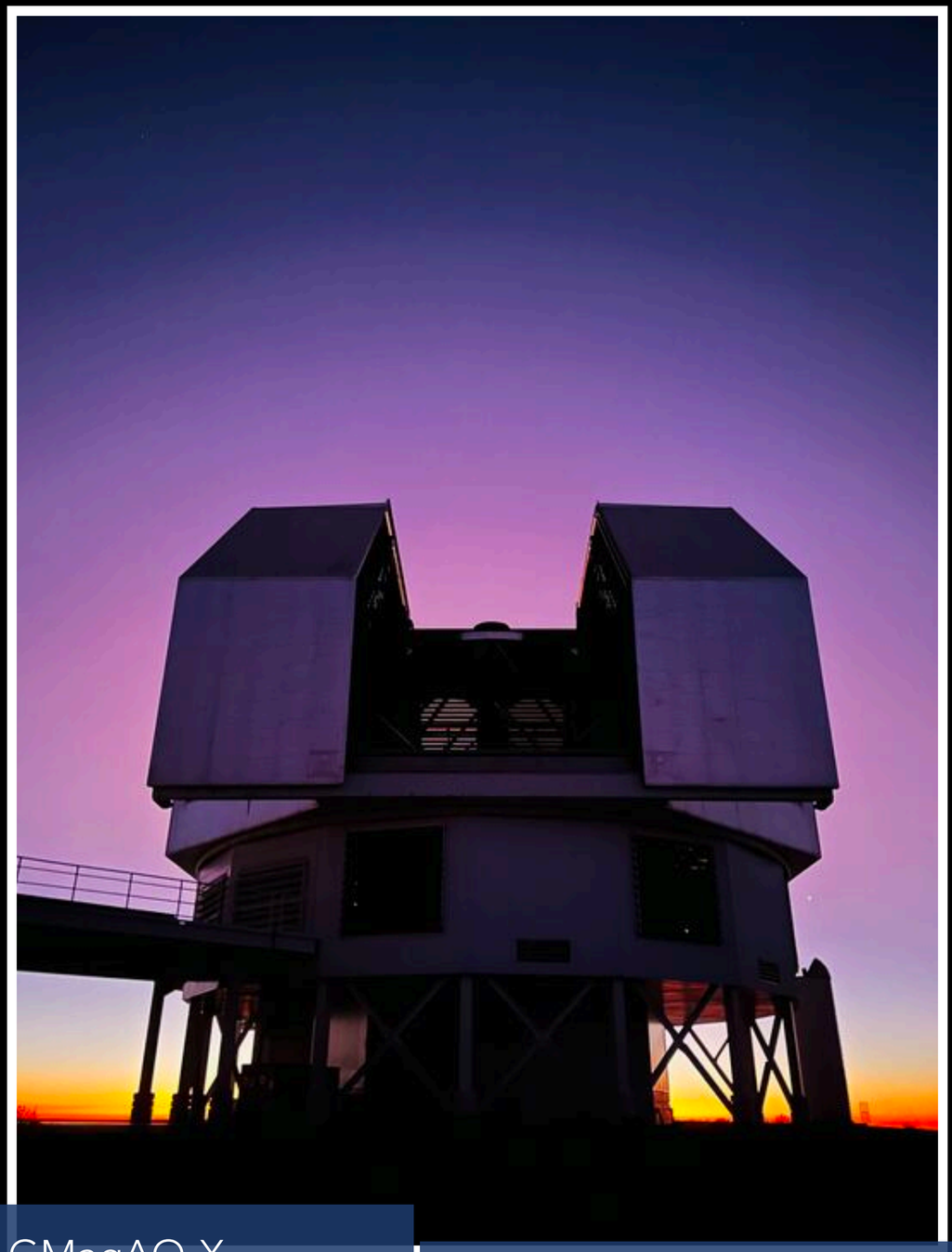


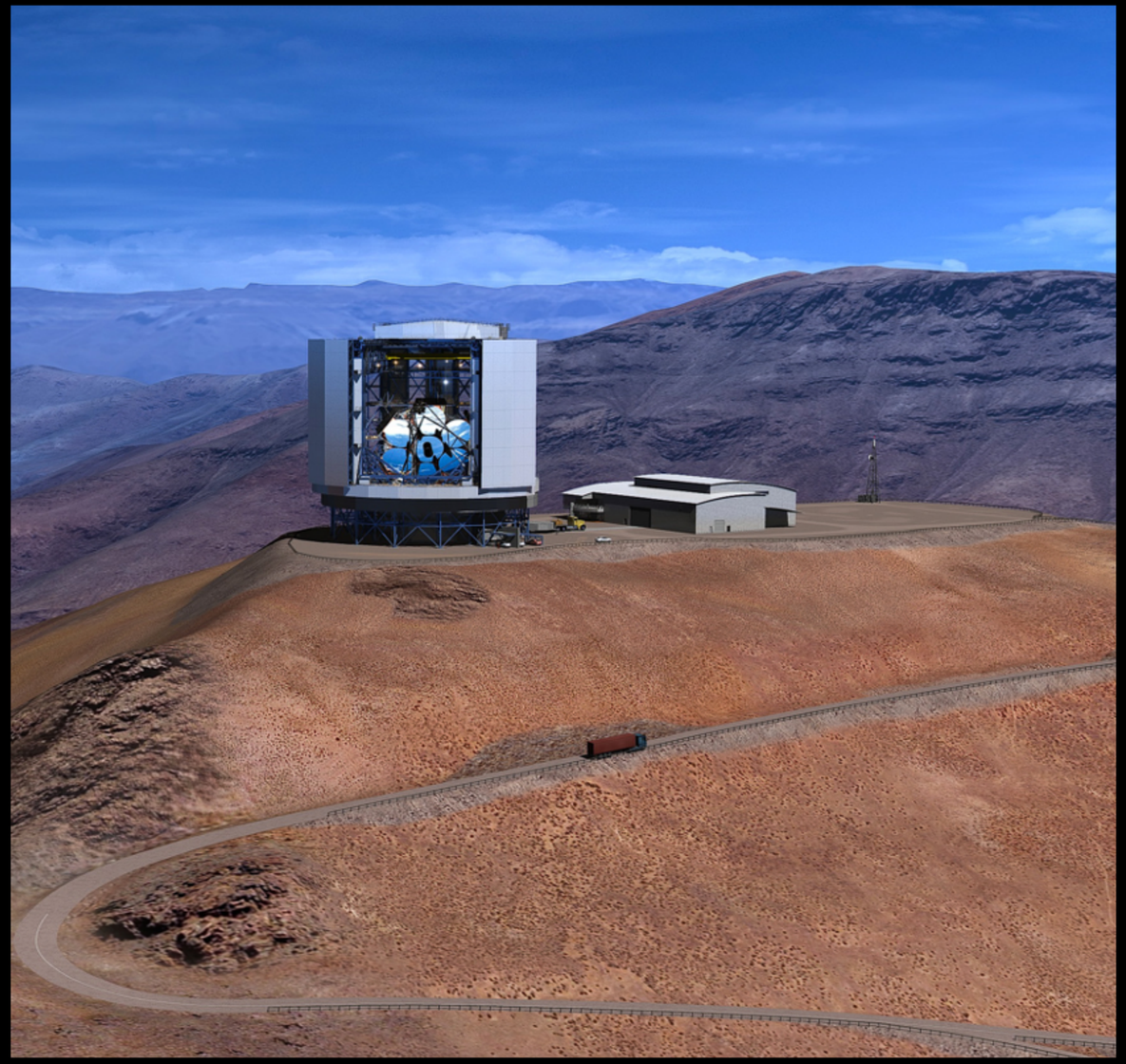


H alpha emission from accretion and jet



OVERVIEW OF GMAGAO-X



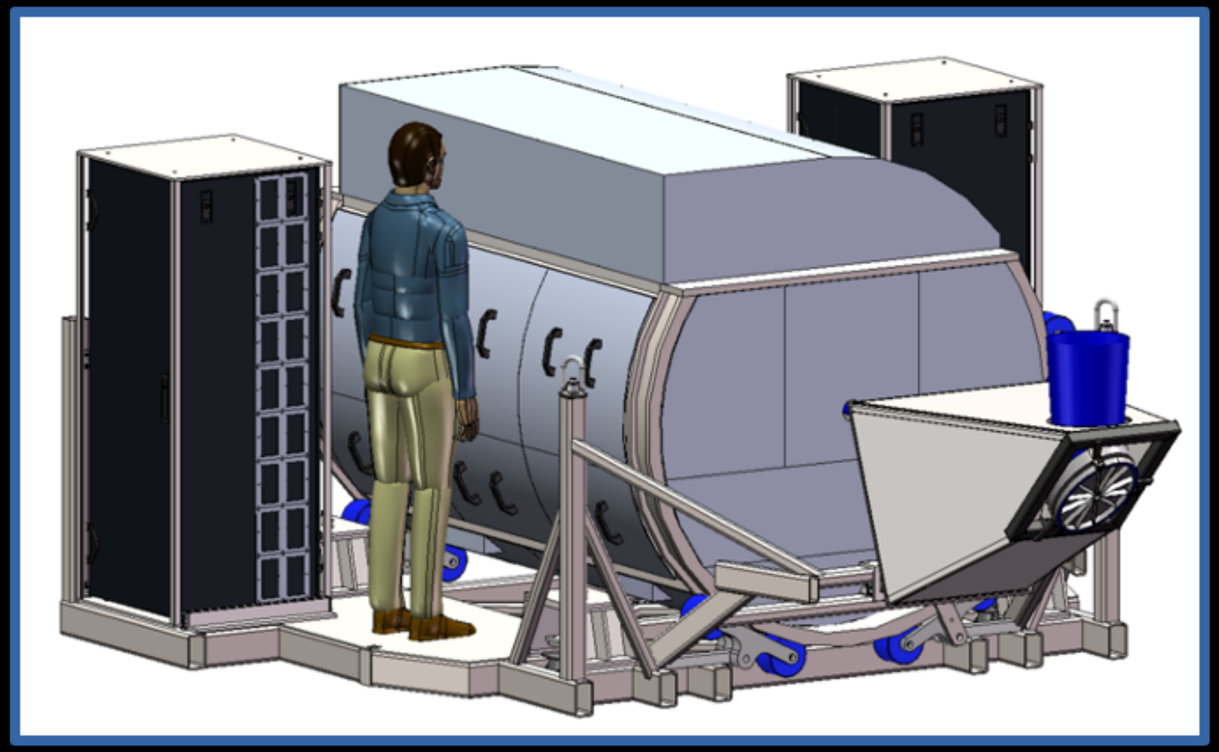


GMagAO-X

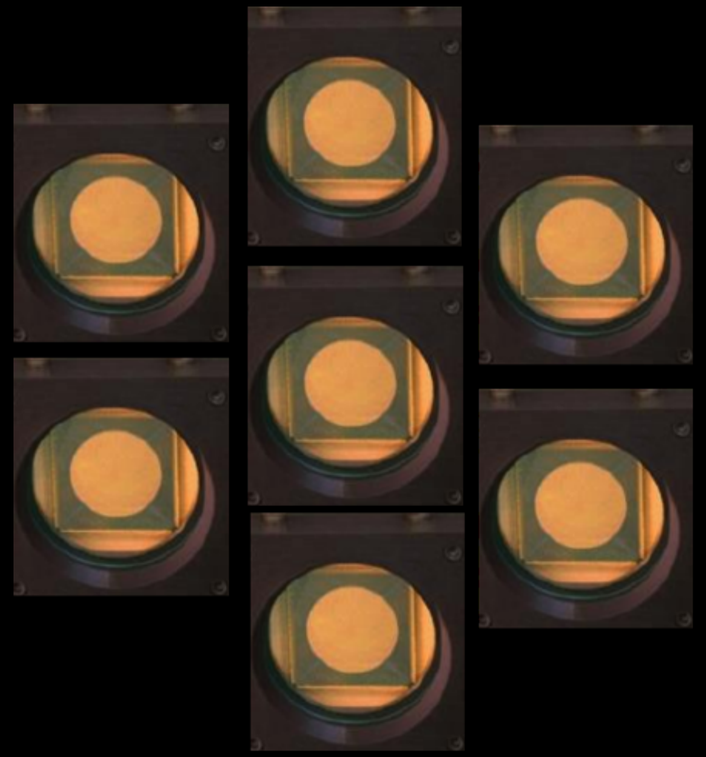
GMT status April 2022

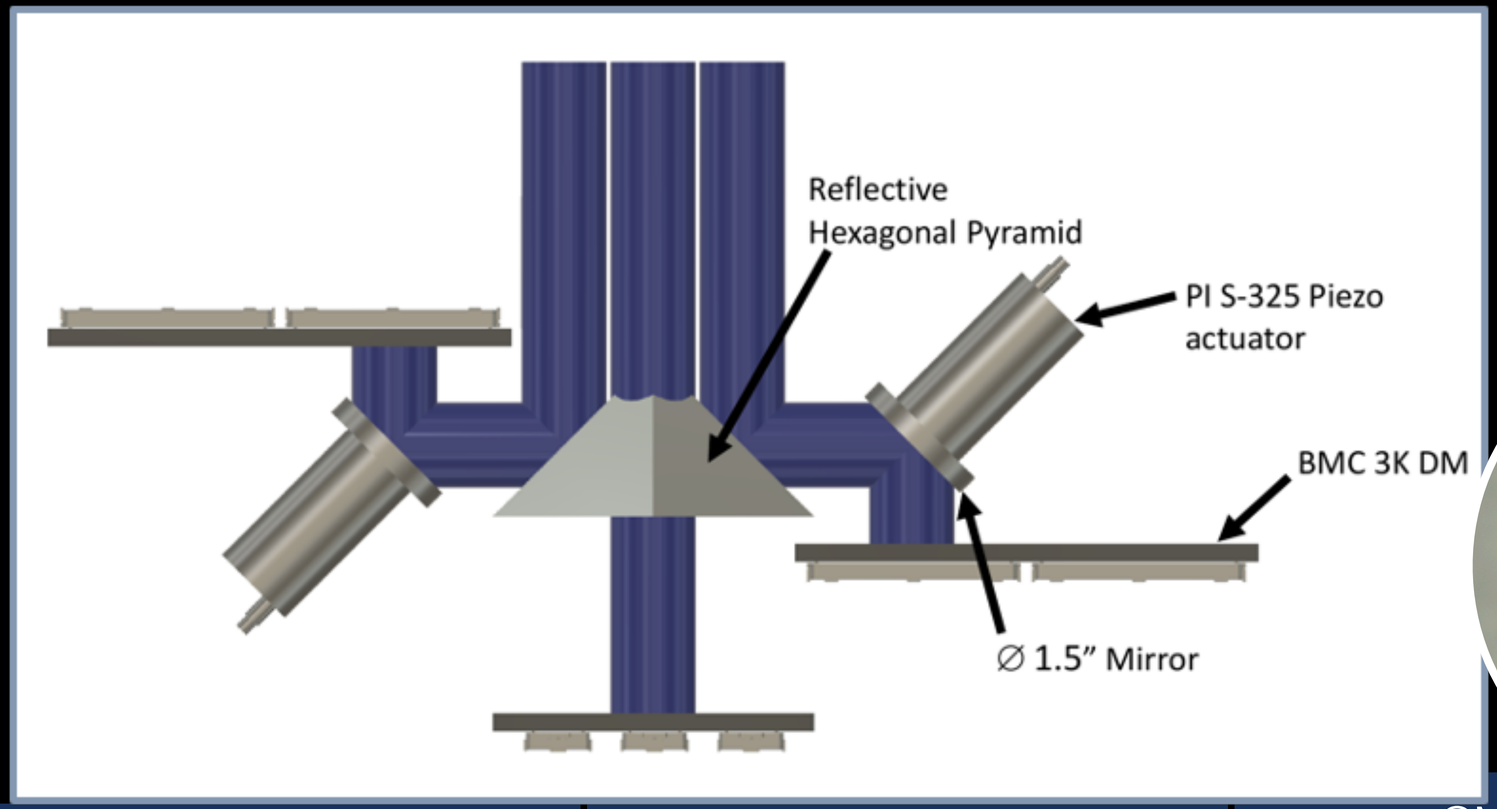
GMagAO-X

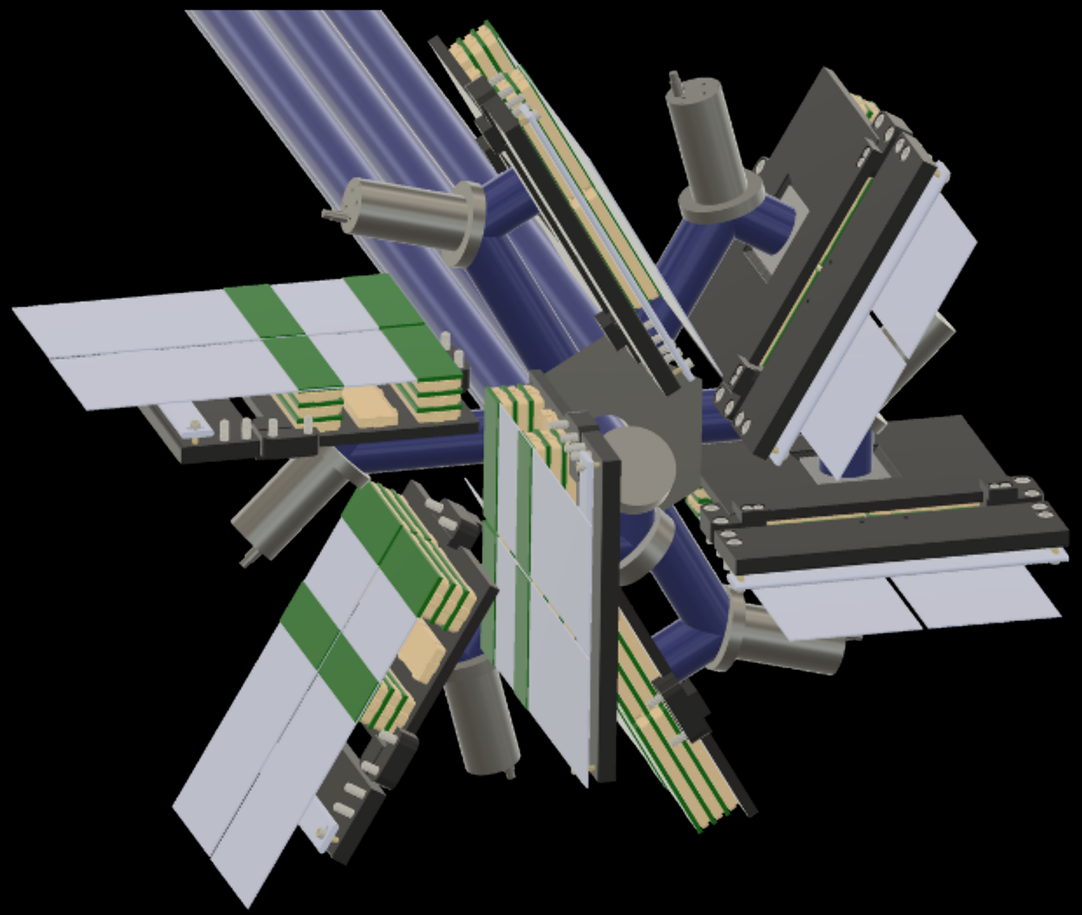
- GMT: 25.4m; made of seven 8.4m mirrors
- ExAO + coronagraph system to be ready at or shortly after first light
- Completed Conceptual Design Review Sept 2021
- Preliminary Design Review in progress

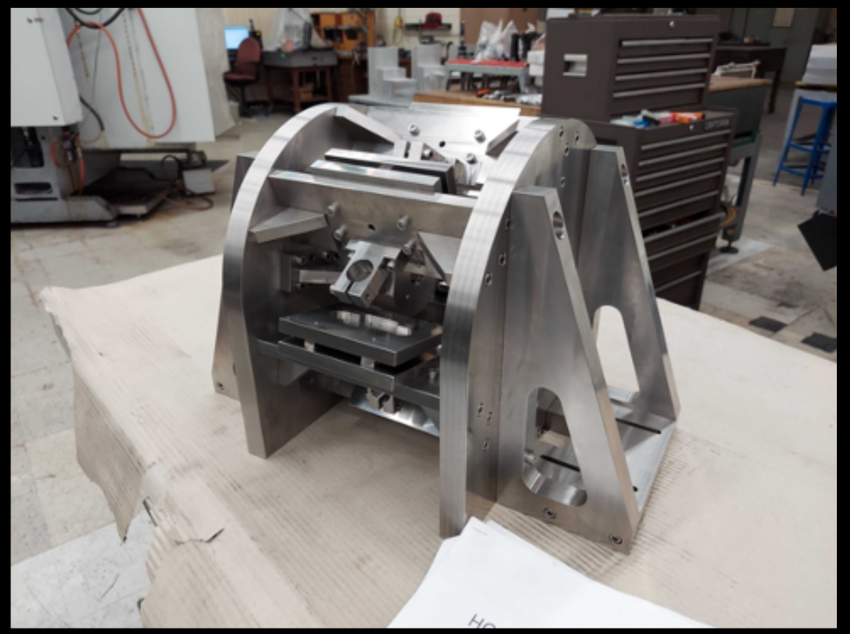


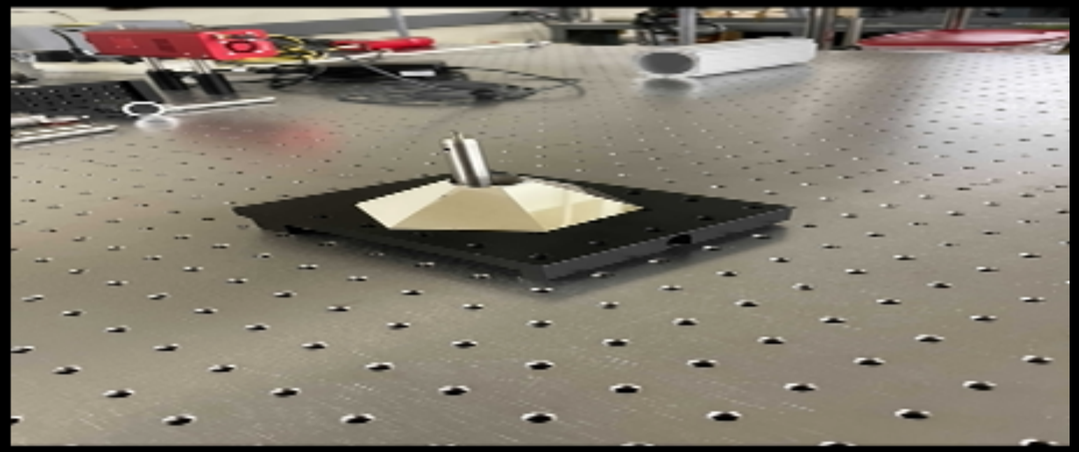
- One 3k actuator MEMS DM per mirror -> 21k actuator “tweeter”
- Opto-mech design: Alex Hedglen
- Pyramid design: Maggie Kautz





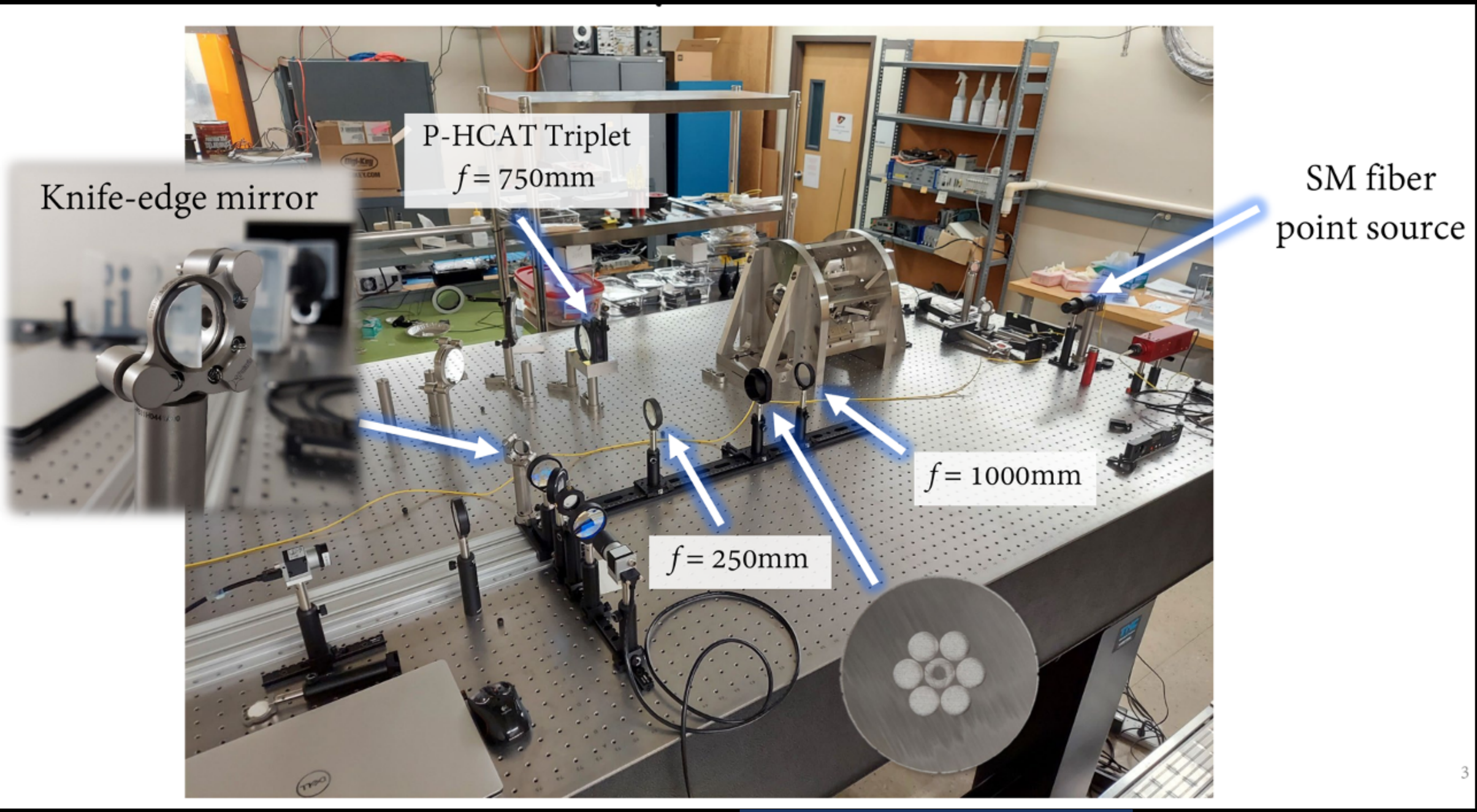






TOWARDS GMAGAO-X

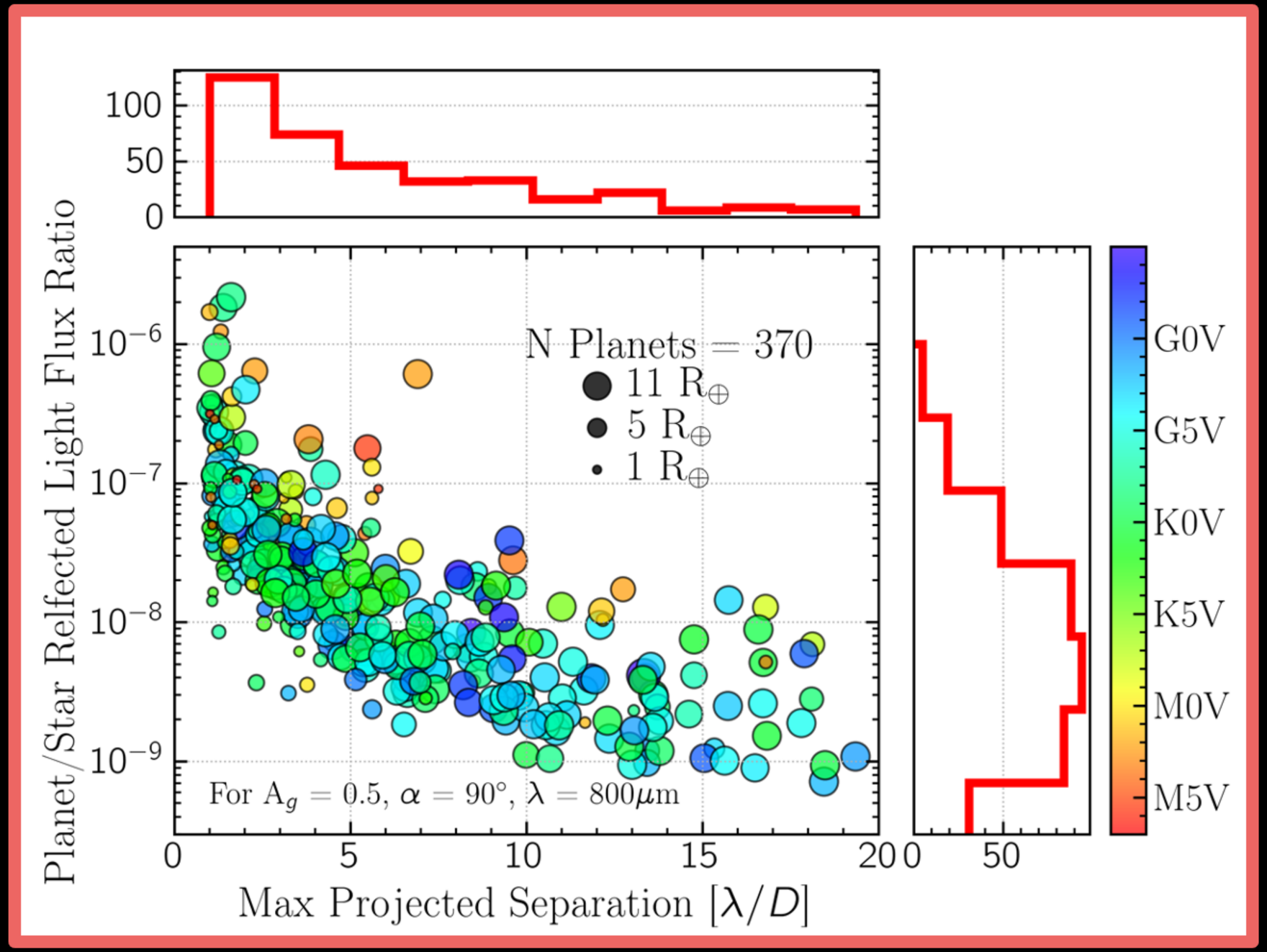
- HCAT: High-contrast AO phasing testbed — how do we phase the GMT mirrors? - Maggie Kautz and Alex Hedglen
    - MagAO-X serves as AO system for HCAT
- Holographic Dispersed Fringe Sensor - Sebastiaan Haffert


Knife-edge mirror
P-HCAT Triplet
$f = 750$mm
SM fiber
point source
$f = 1000$mm
$f = 250$mm

IMAGING PLANETS IN REFLECTED LIGHT WITH GMAGAO-X

Or: Why am I in CA for 6 months?

REFLECTED LIGHT IMAGING WITH GMAGAO-X

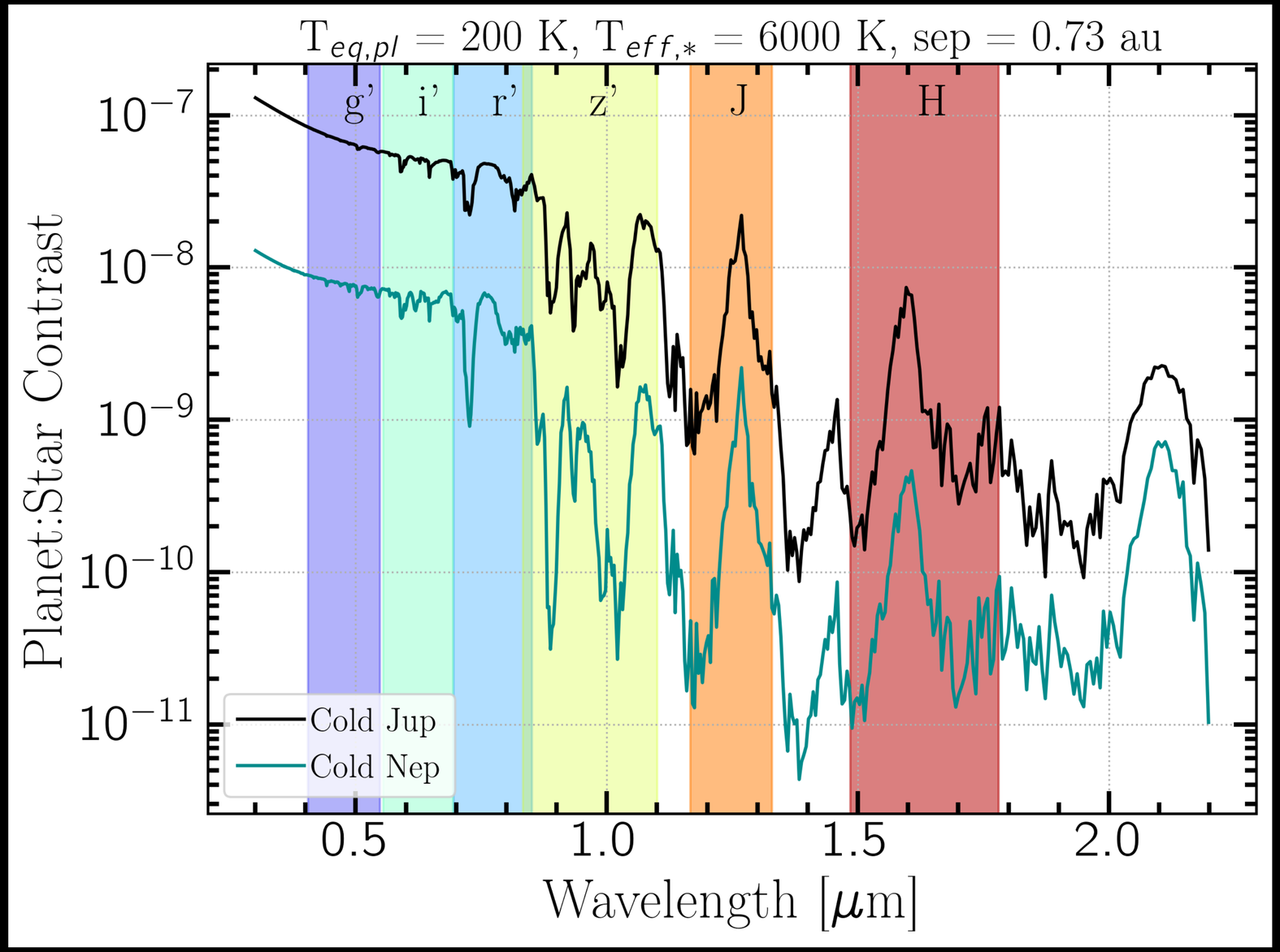


M/R relation used when radius unknown

Msini used when mass unknown

WHY AM I HERE?

- NSF GRFP INTERN program funded internship working with Natasha Batalha at Ames using PICASO to model reflected light spectra



Star Properties

- Magnitude

Observing Conditions

- Seeing

Instrument Configuration

- Speckle noise characteristics
- WFC config
- Coronagraph char.

Star Properties

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

Planet Properties

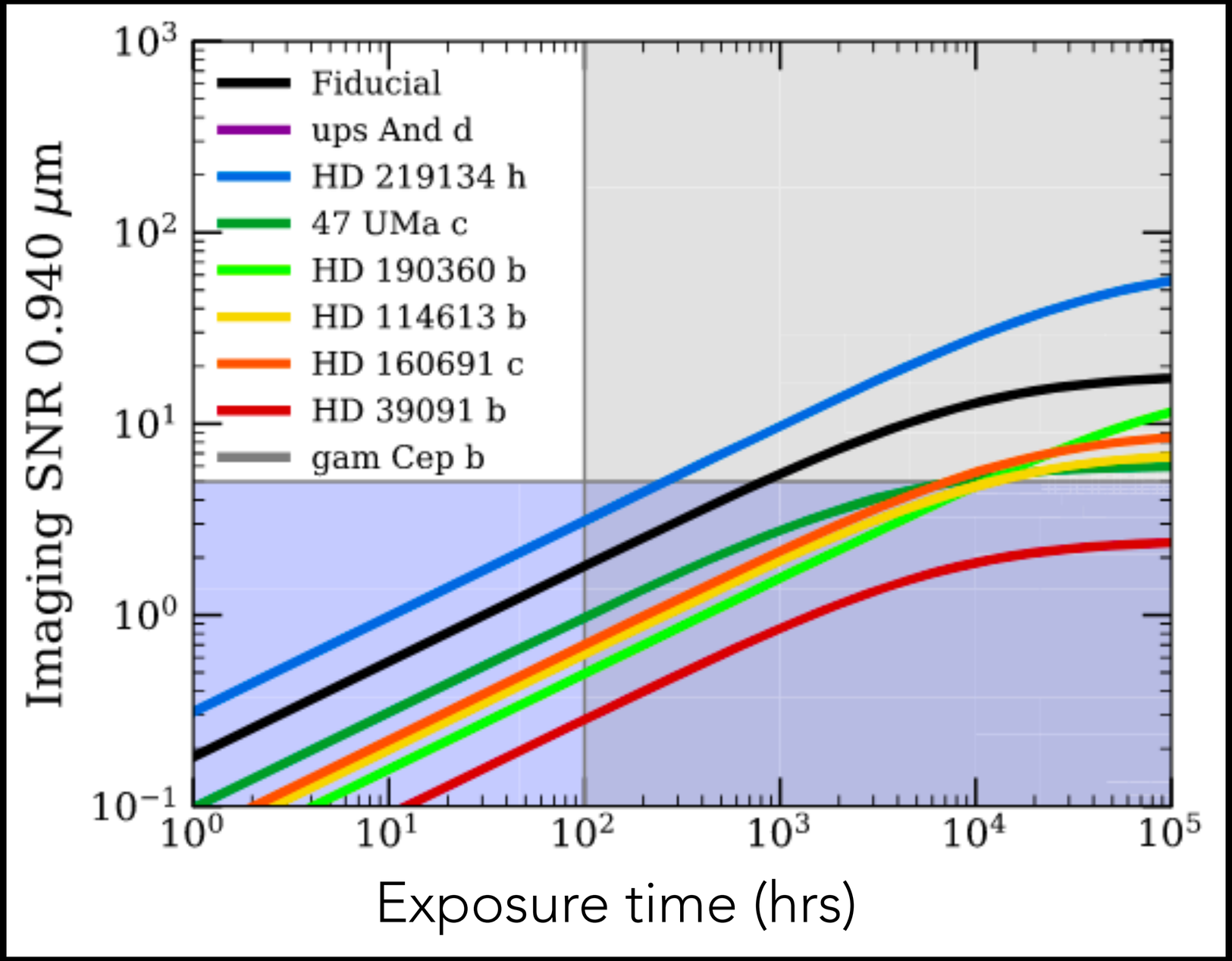
- Mass
- Radius
- Metallicity
- C/O
- Semi-major axis
- Phase

Reflected light spectrum

Detectable Planets
Detectable features

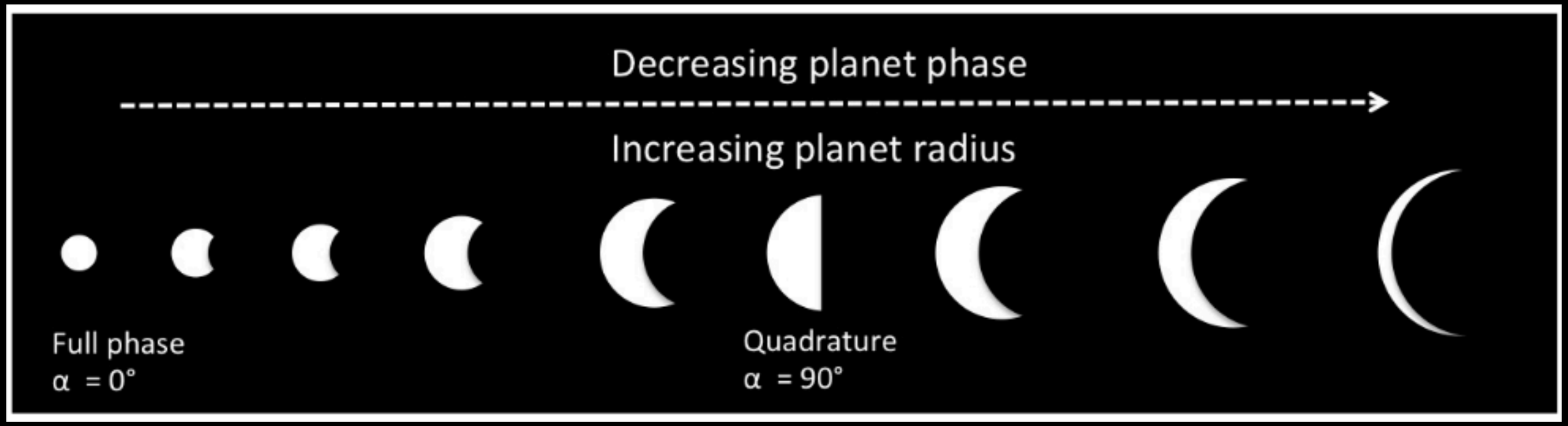
Ex:
Lacy et al. 2019 did a similar study of reflected light detections with Roman CGI.

(All previous work on this is with space-based. It seems no one thinks we can do this from the ground!)



OBSERVATIONAL CHALLENGES

- Mass:
    - Most RV planets have only Msini
    - Mass can be obtained if we can observe planet over time and constrain incl.
- Radius:
    - Can be estimated if mass known from M/R relation
- Phase:
    - Can be estimated if orbital params known



Nayak et al. 2017

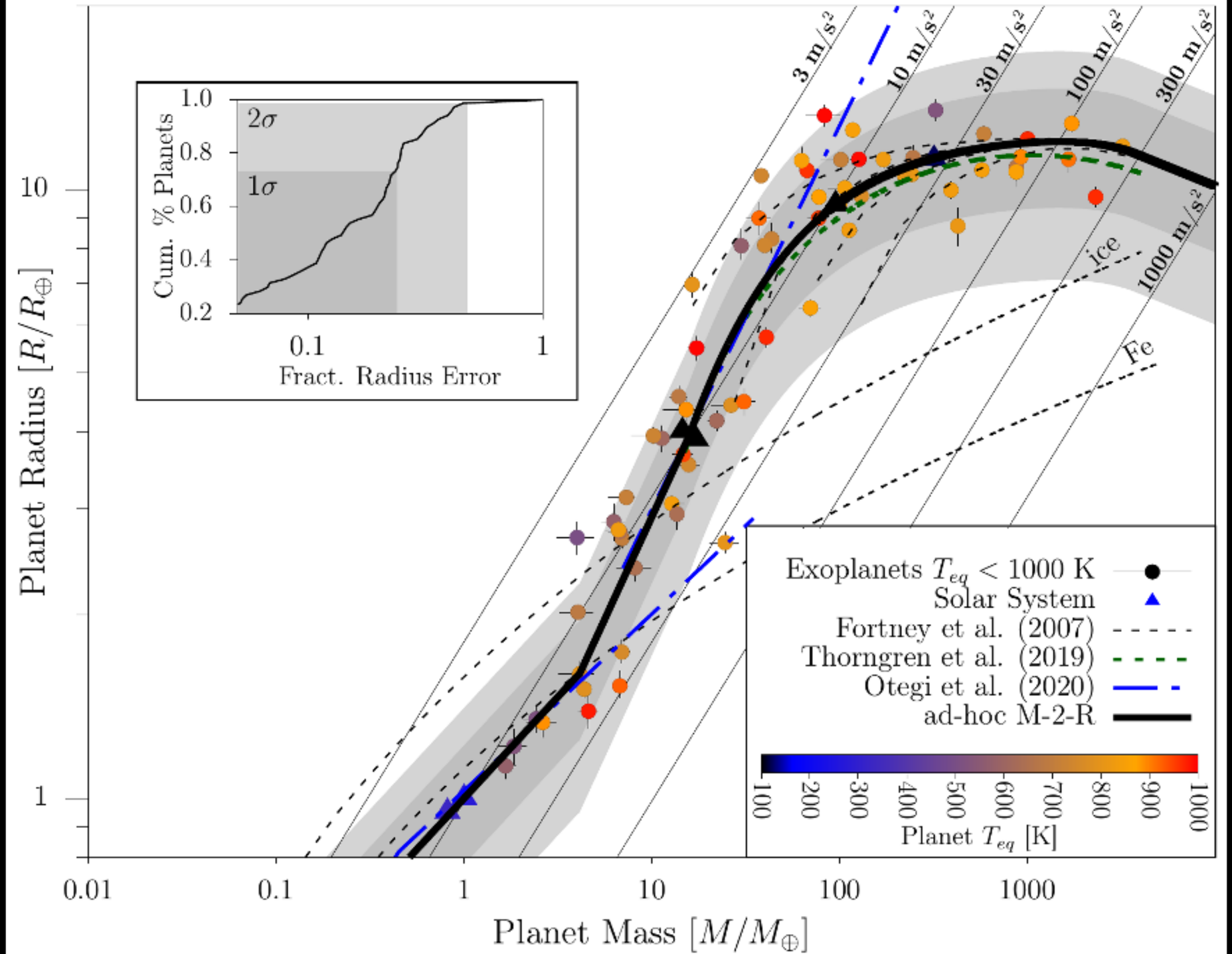
CONCLUSION

- XWCL is pushing innovation in ExAO with MagAO-X and eventually GMagAO-X
- The first planets detected in reflected light are right around the corner *from the ground*
- Proxima Centauri b is reachable in a few short years with MagAO-X, and GMagAO-X will deliver hundreds
- MagAO-X is conducting exciting ExAO science on-sky now

Visit my website for more on my science, and info about GRFP & INTERN program

www.loganpearcescience.com

EXTRA SLIDES


Planet Radius $[R/R_\oplus]$
Planet Mass $[M/M_\oplus]$
10
1
0.01
0.1
1
10
100
1000
3 m/s²
10 m/s²
30 m/s²
100 m/s²
300 m/s²
1000 m/s²
ice
Fe
Cum. % Planets
1.0
0.8
0.6
0.4
0.2
2σ
1σ
0.1
1
Fract. Radius Error
Exoplanets $T_{eq} < 1000$ K
Solar System
Fortney et al. (2007)
Thorngren et al. (2019)
Otegi et al. (2020)
ad-hoc M-2-R
100
200
300
400
500
600
700
800
900
1000
Planet T_{eq} [K]