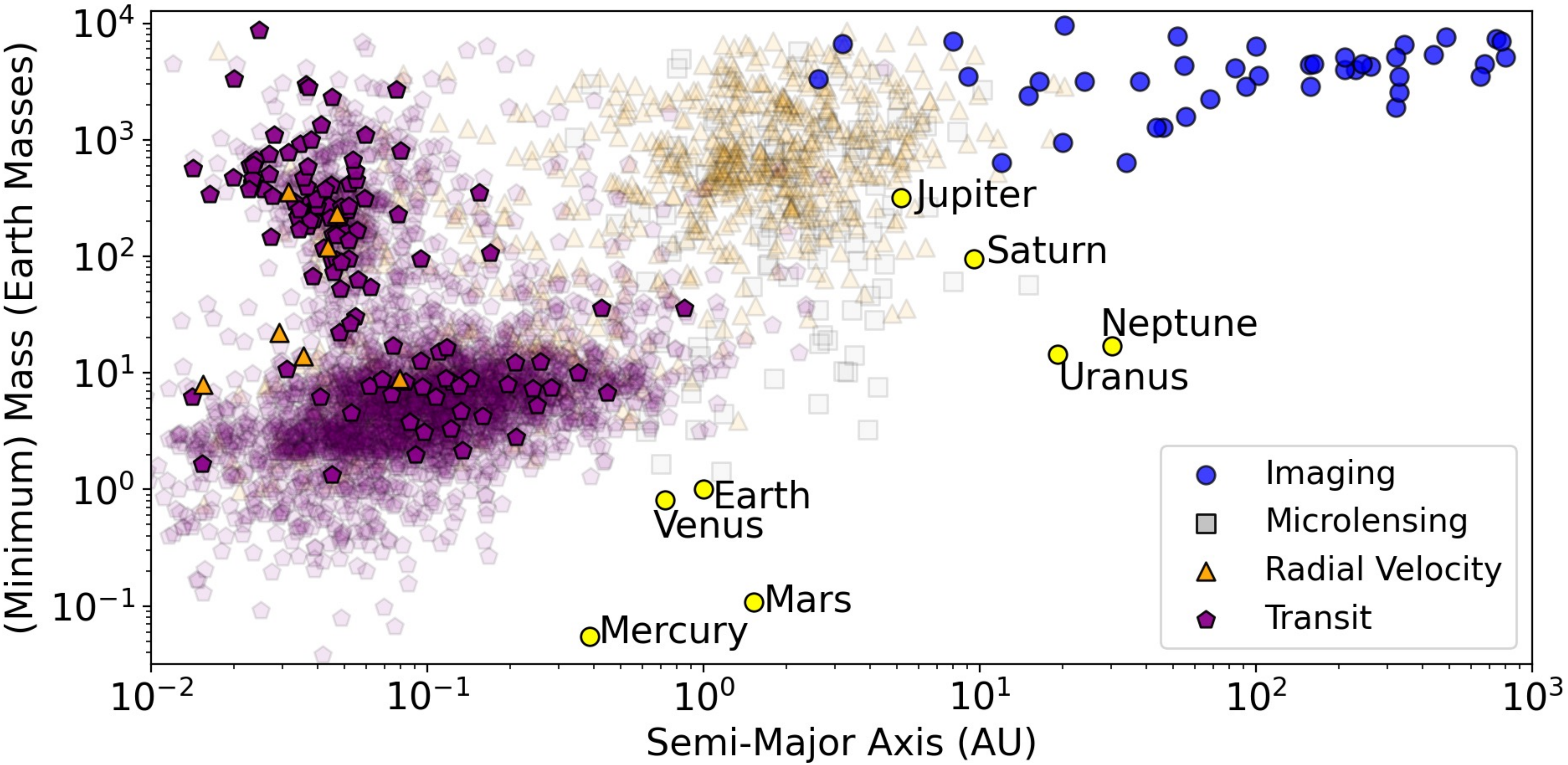
From Jupiters to Earths: Current Status and Future Prospects with Direct Imaging

Beth Biller, University of Edinburgh,

The Exoplanet Zoo

Figure from Currie et al. 2022, courtesy of Dmitry Savransky, using data from the NASA Exoplanet Archive.



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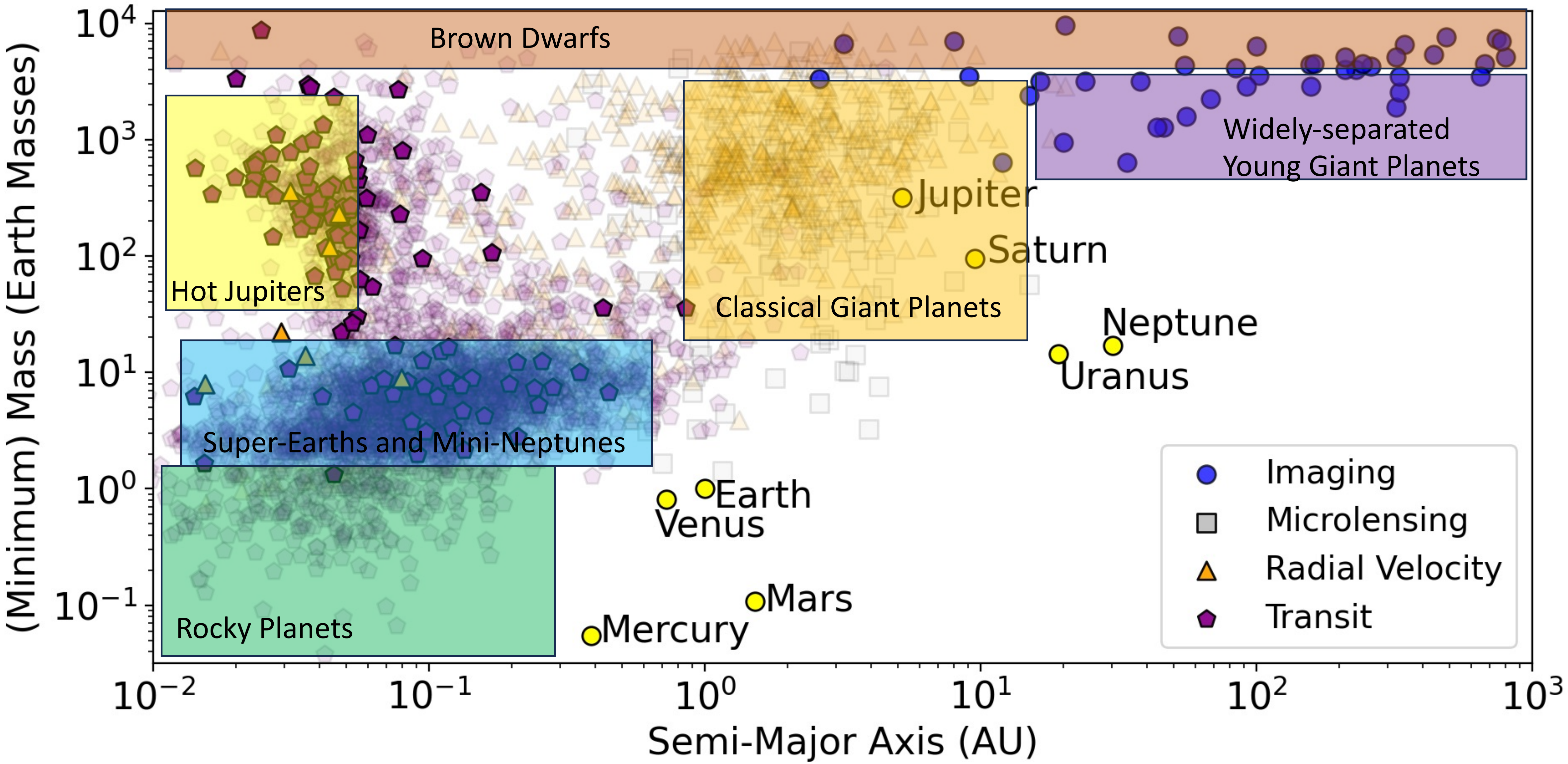


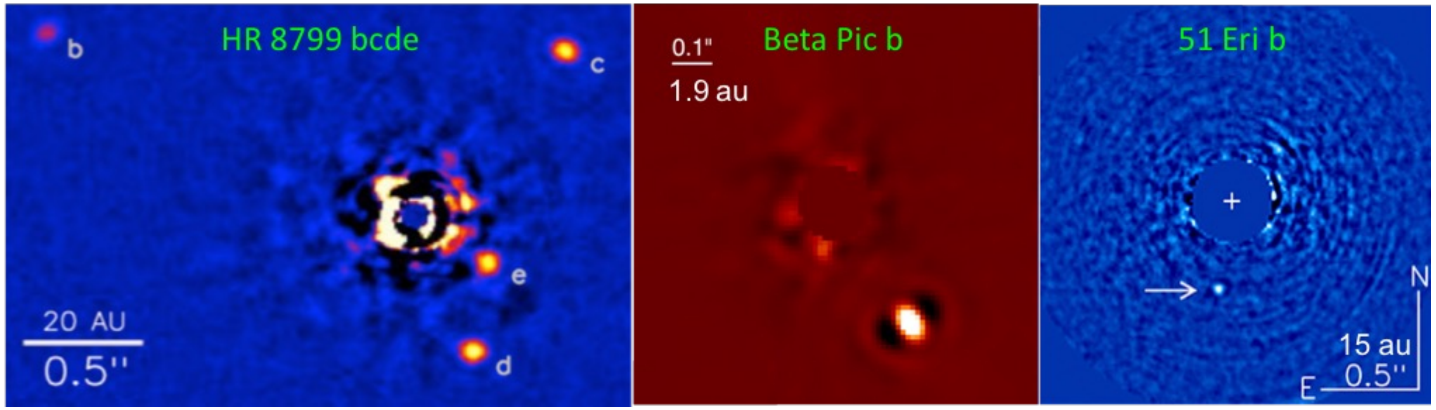
Why Direct Imaging?

Test of Planet Formation Theories – direct imaging probes planets in formation, sometimes still embedded in their natal disk

Physical Properties – direct spectra = direct probe of atmospheres, enables comparative planetology

In coming decades, this is the most **sensitive technique for discovery and characterization of Exo-Earth twins**

State-of-the-art in 2024: ~2 dozen directly imaged exoplanets



Marois et al. 2008, 2010, Lagrange et al. 2008, 2010, Macintosh et al. 2015

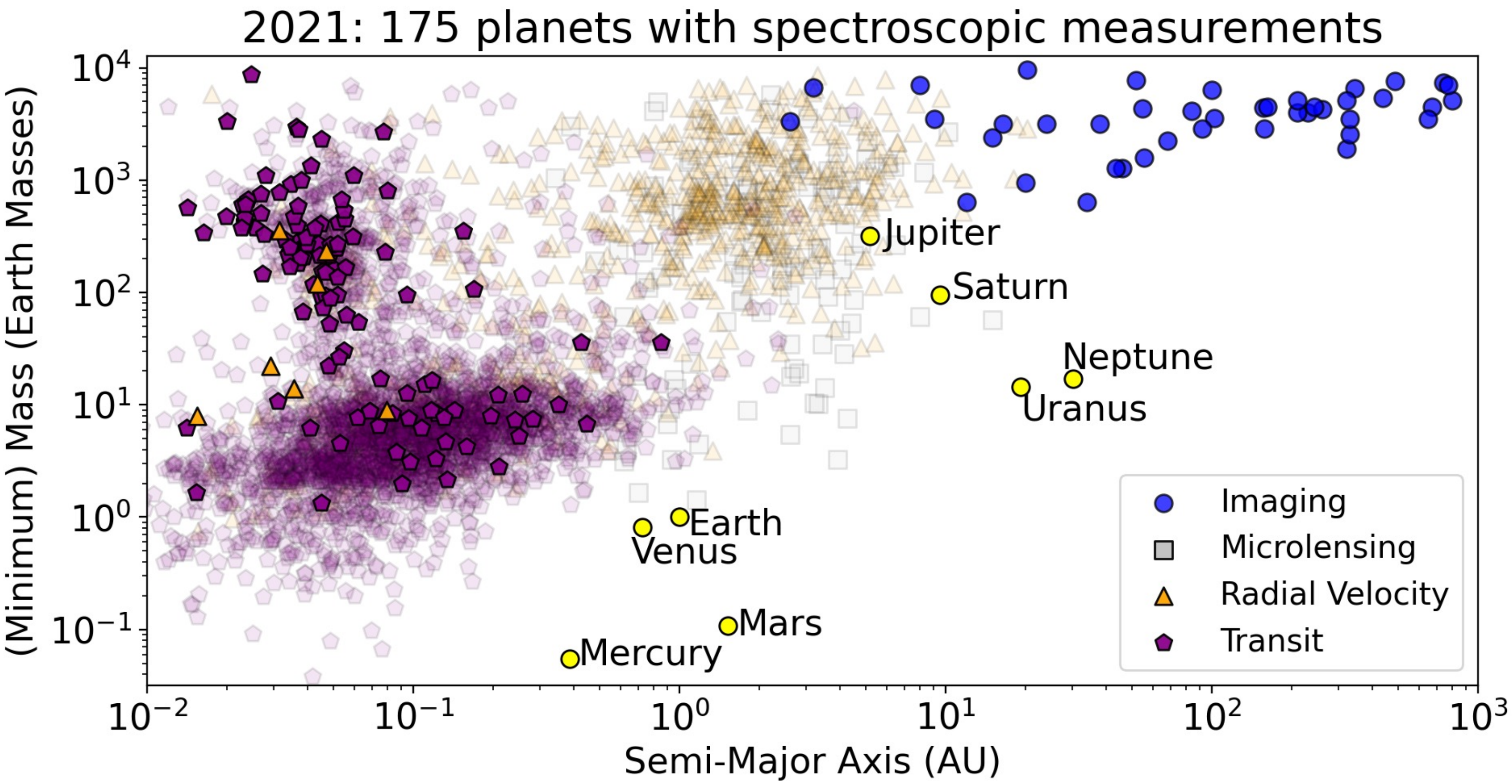


Figure courtesy of Dmitry Savransky, using
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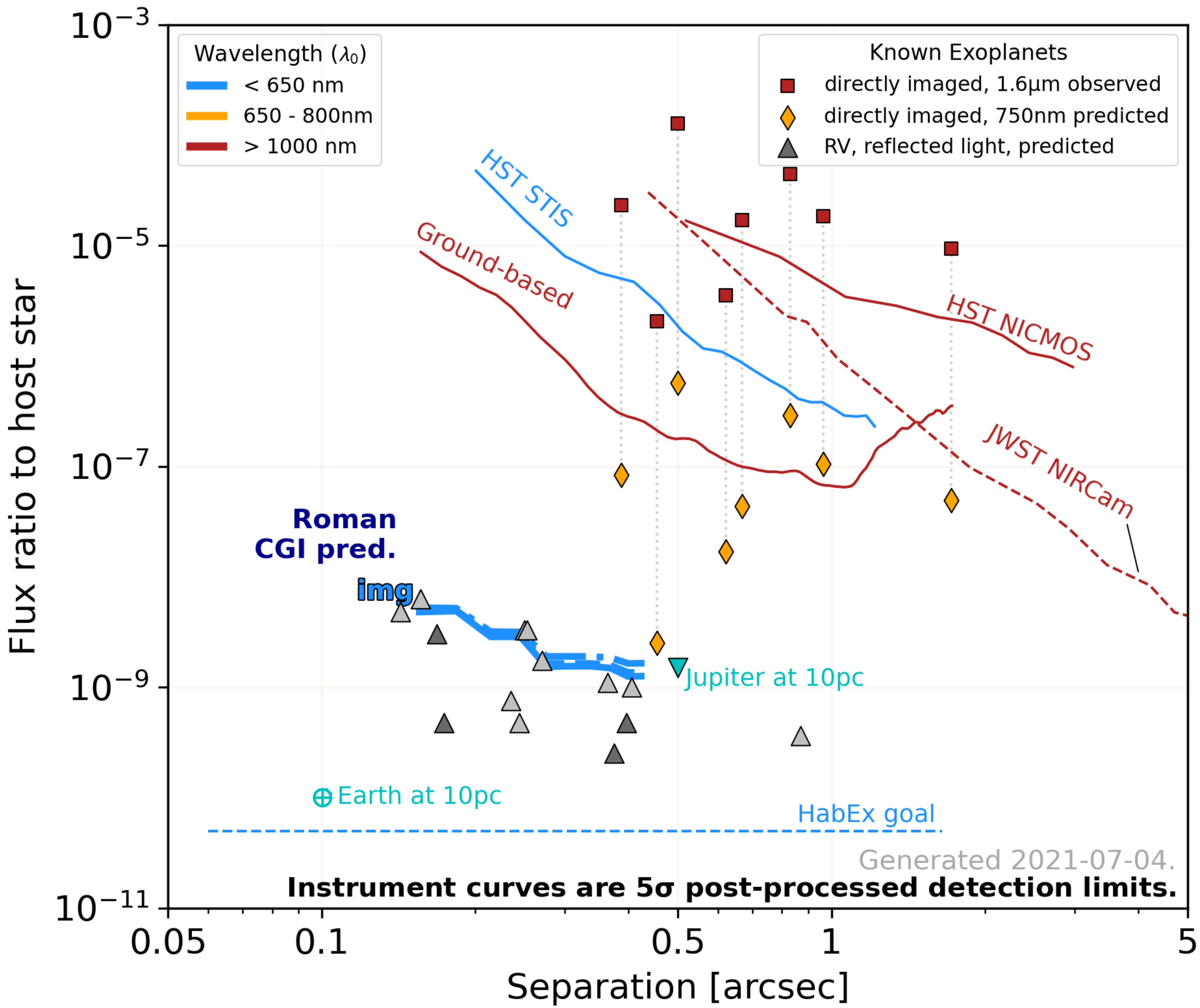
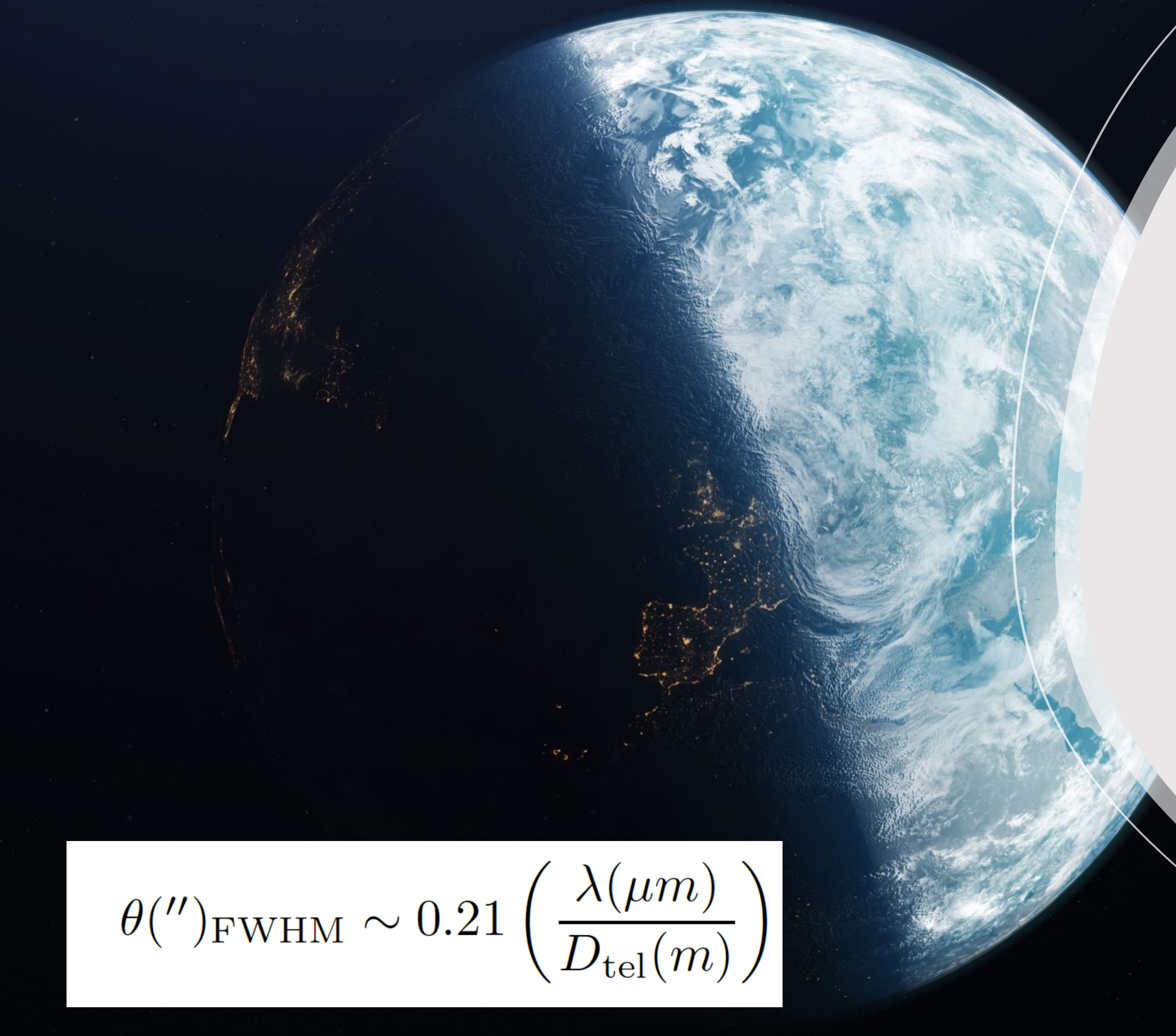


Current status: directly imaging young, hot Jovian planets, next decade will push down to RV planets, eventually exo-Earth twins

Generated using tools developed by Vanessa Bailey, which are available at: https://github.com/nasavbailey/DI-flux-ratio-plot

How to image a planet



$$\theta('')_{\mathrm{FWHM}} \sim 0.21 \left(\frac{\lambda(\mu m)}{D_{\mathrm{tel}}(m)} \right)$$

What resolution do you need to image a planet?

For instance, an Earth twin orbiting 1 au from a sunlike star at 10 pc subtends 0.1", resolvable with diffraction limited imaging in the near-IR with an 8-10 m telescope

What contrast do you need to image a planet in reflected light?

$$C_{\mathrm{optical},\lambda} \sim A_{\mathrm{g}}(\lambda)\, \phi(\lambda, \alpha) \left(\frac{r_{\mathrm{p}}}{a_{\mathrm{p}}}\right)^2$$

At V band at 10 pc:

Jupiter: V ~ 27 at 0.5", requiring contrast of one part in 10^{-9}

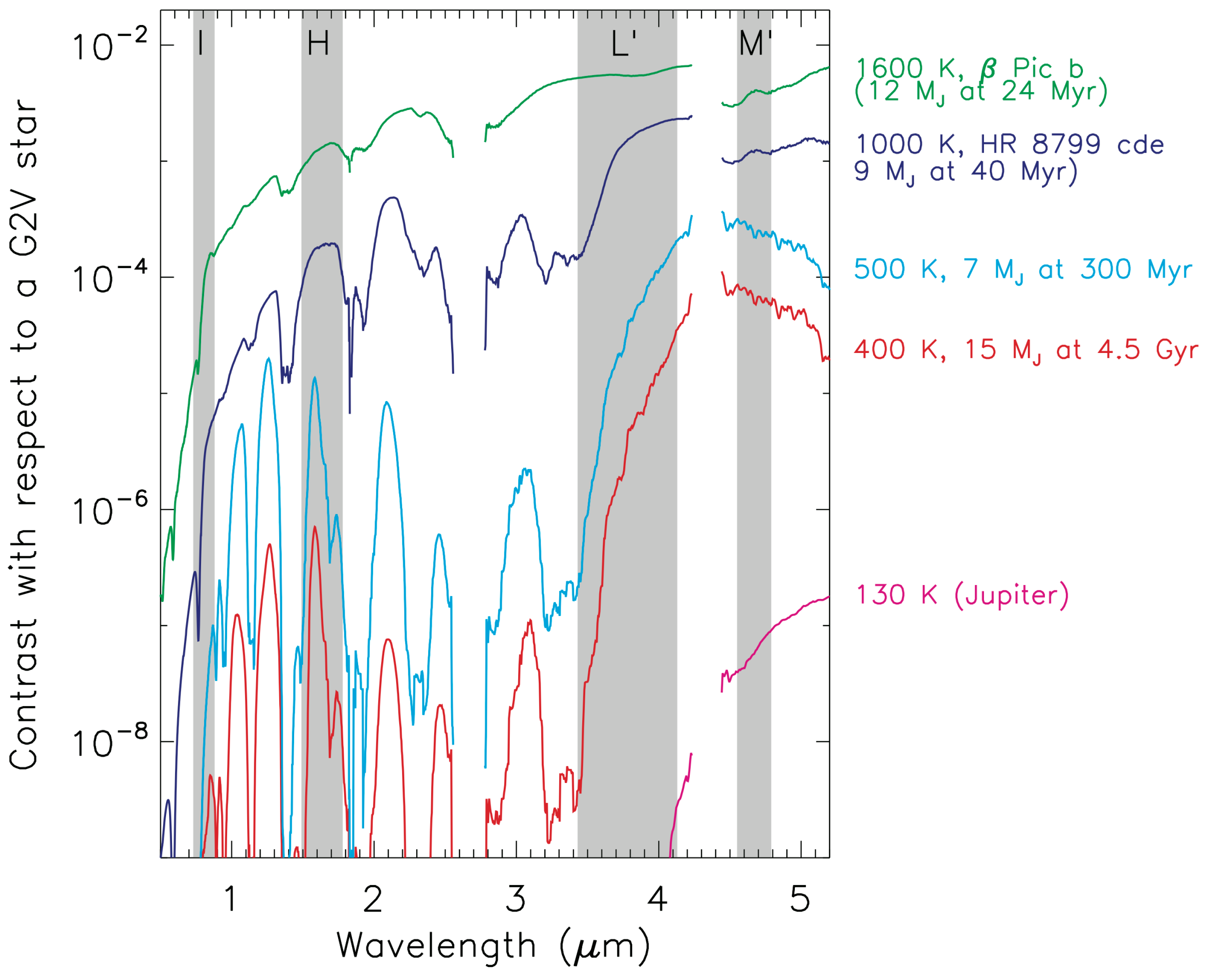
Earth: V~29 at 0.1", requiring contrast of one part in 10^{-10}

where r_{p} is the planet radius, a_{p} is the planet-to-star physical separation, A_{g} is the visible geometric albedo spectrum, ϕ is the phase function as a function of α, the phase angle, which is the angle between the star, planet, and observer

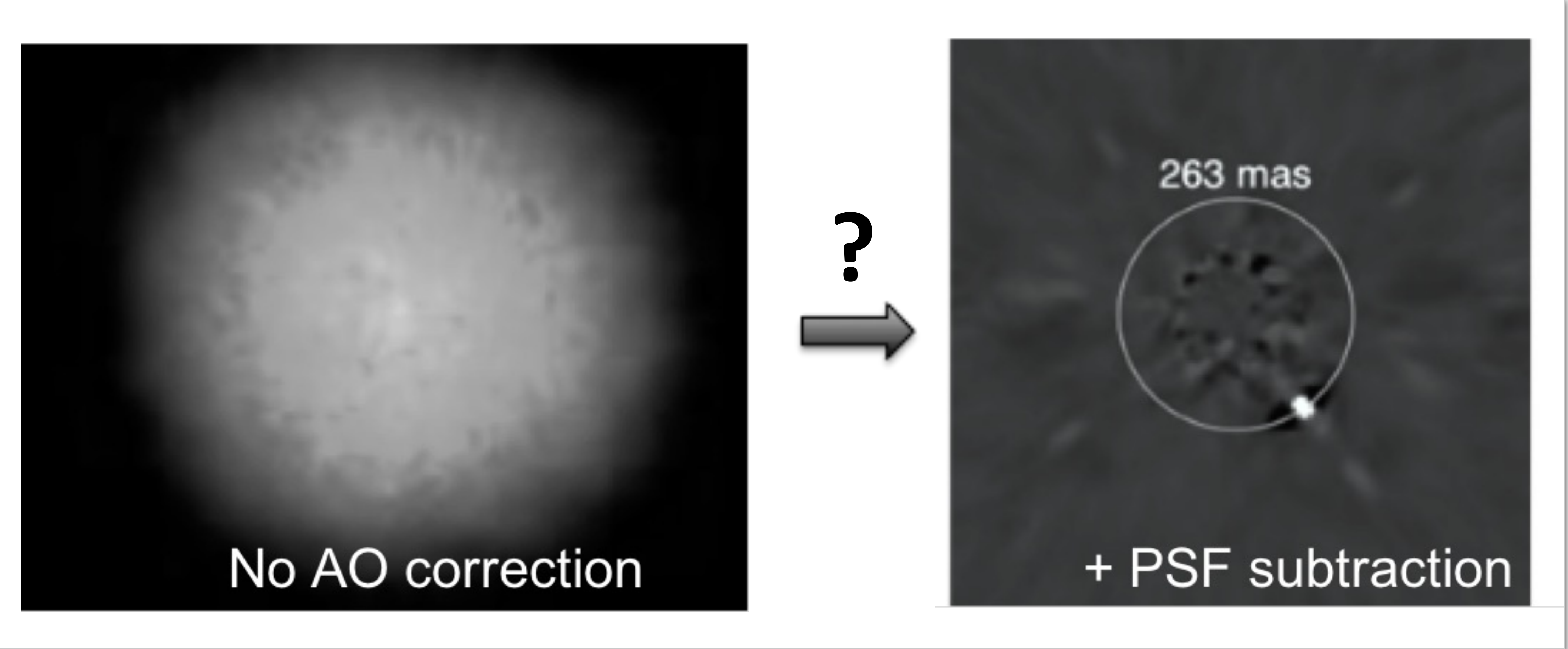
What contrast do you need to image a planet in thermal emission?

$$C_{\mathrm{IR},\lambda} \sim \frac{F_{\lambda,p}(T,X)\, r_{\mathrm{p}}^2}{F_{\lambda,s}(T)\, r_{\mathrm{s}}^2}$$

where $F_{\lambda,p}(T,X)$ is the thermal flux from the planet as a function of wavelength, $F_{\lambda,s}(T)$ is the thermal flux from the star as a function of wavelength, and X depends on the planet's atmospheric characteristics, such as clouds, chemistry, and gravity.



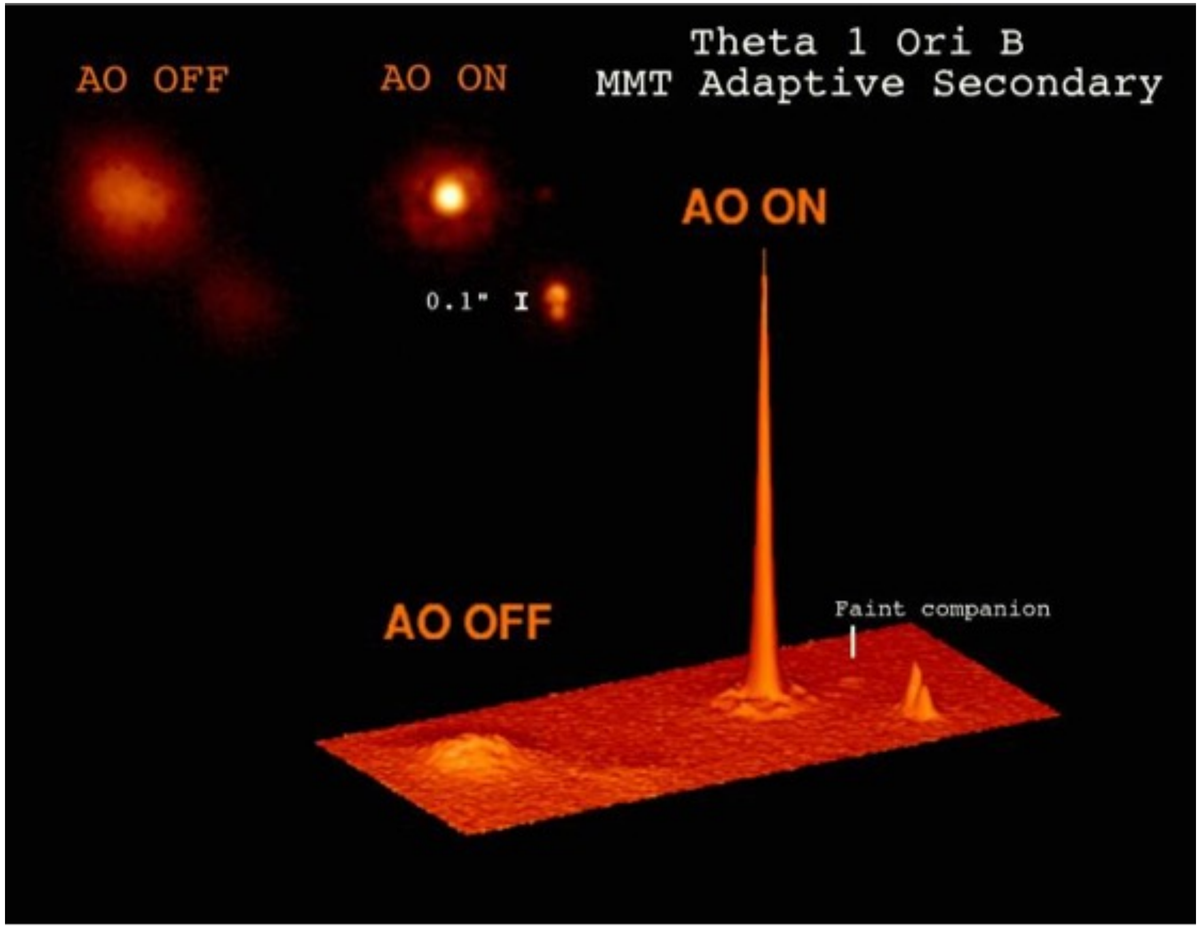
We know what resolution and contrast we need – how do we get there?



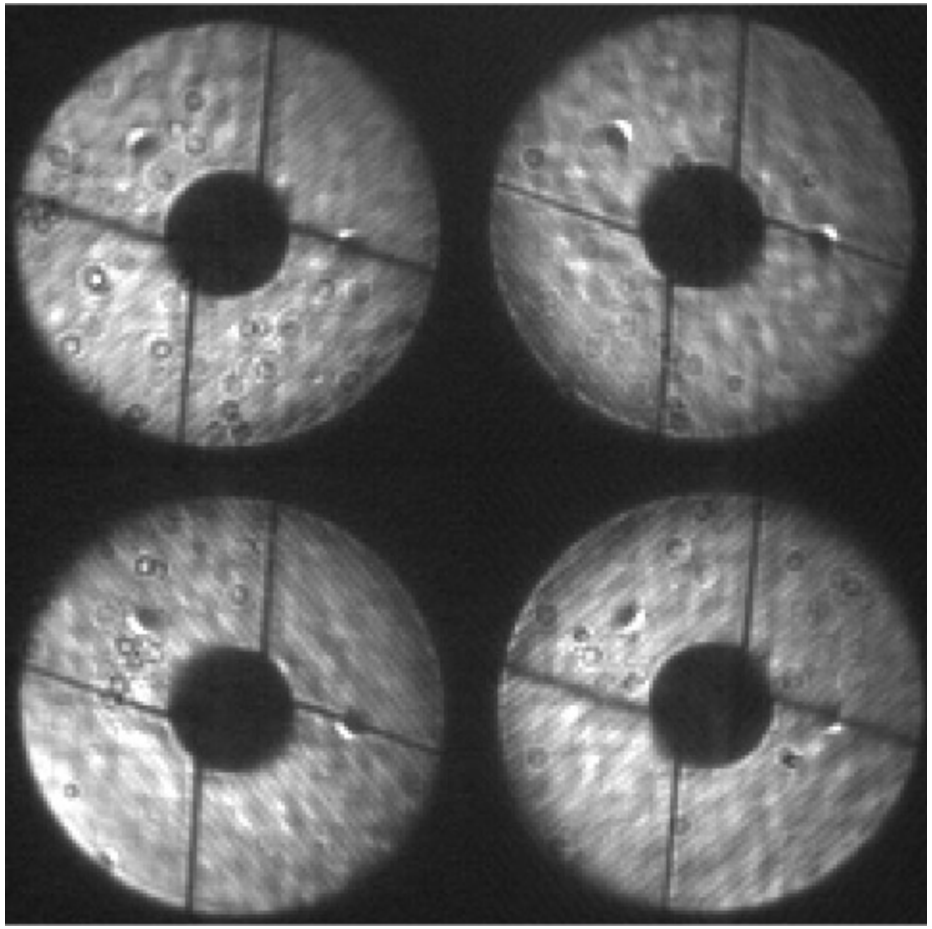
Data from VLT/SPHERE, Currie et al. 2022

See talk by Becky Jensen-Clem

Atmospheric Wavefront Control for Direct Imaging

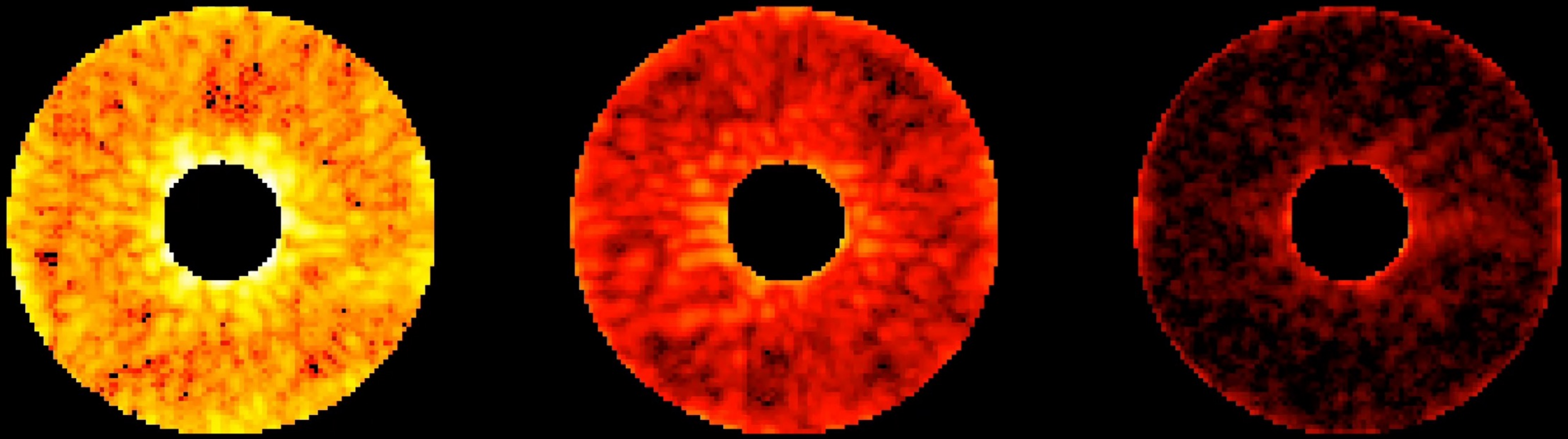


Close et al. 2003



Example: the Pyramid Wavefront Sensor, Jovanovic et al. 2015

Data from vacuum testing of the Roman Coronagraph Instrument, NASA/JPL-Caltech



Similar wavefront control techniques will be vital for space-based exoplanet imaging as well

See talk by Bertrand Mennesson

See talks by Iva Laginja, David Doelman, and Sebastiaan Haffert

Optical Starlight Suppression

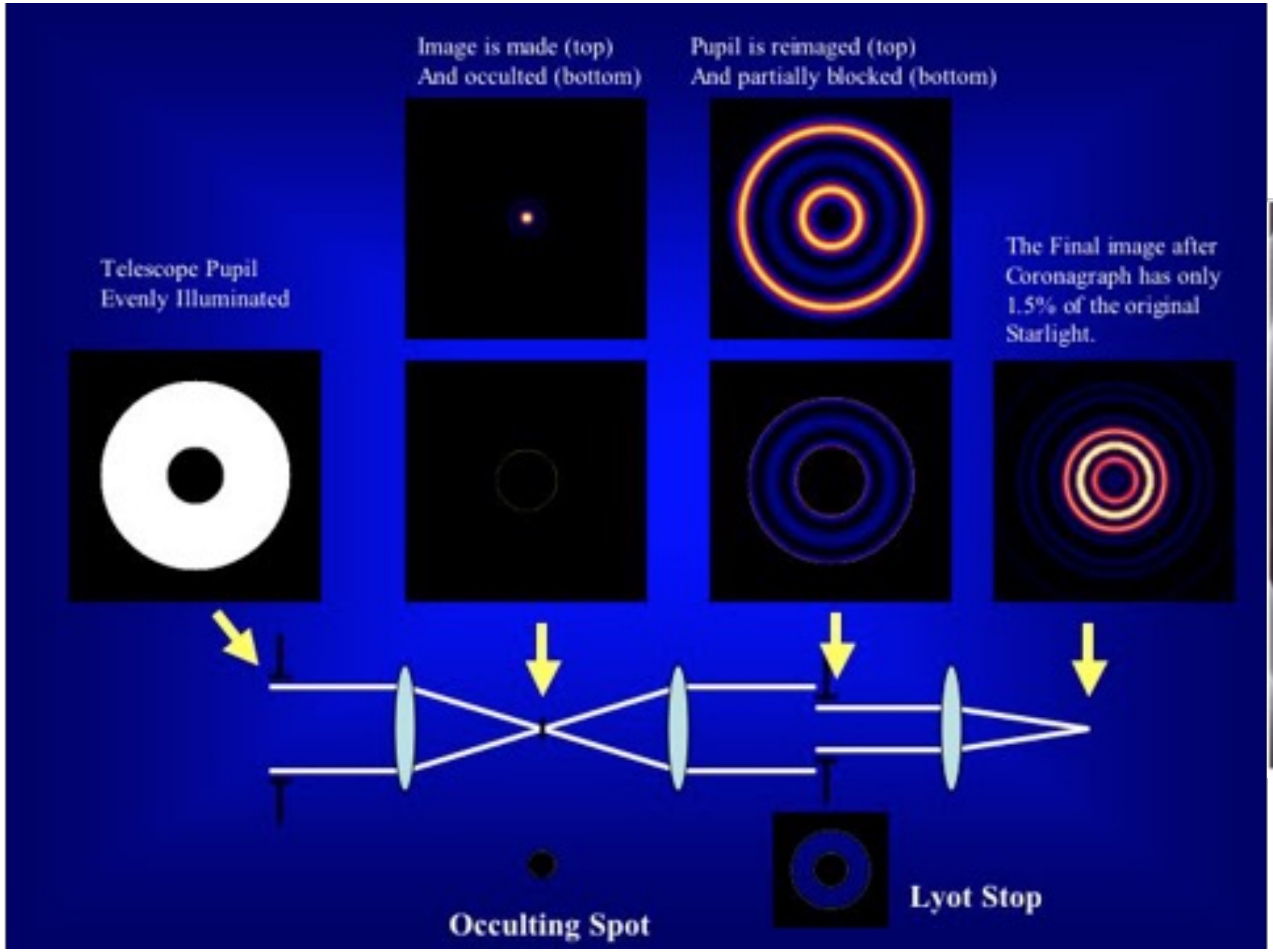
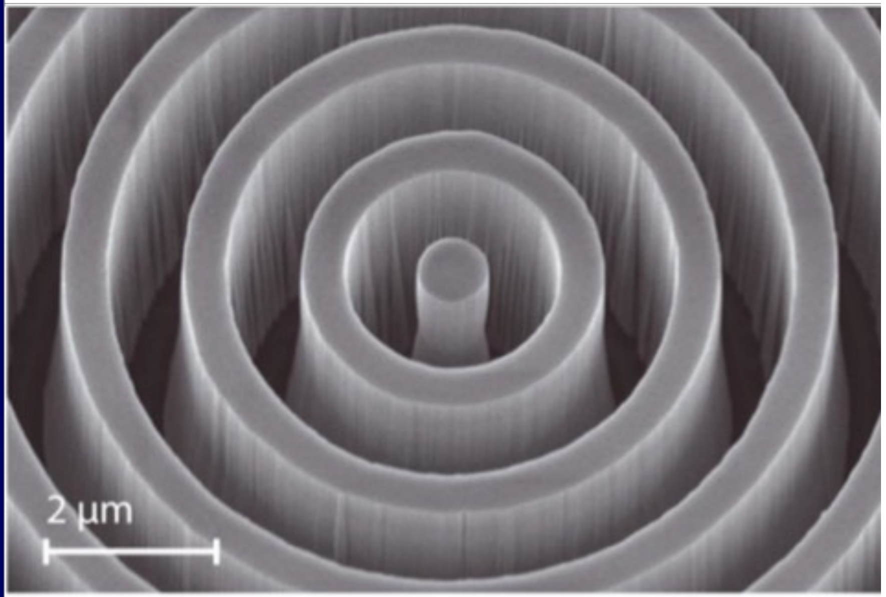


Figure courtesy of A. Sivaramakrishnan

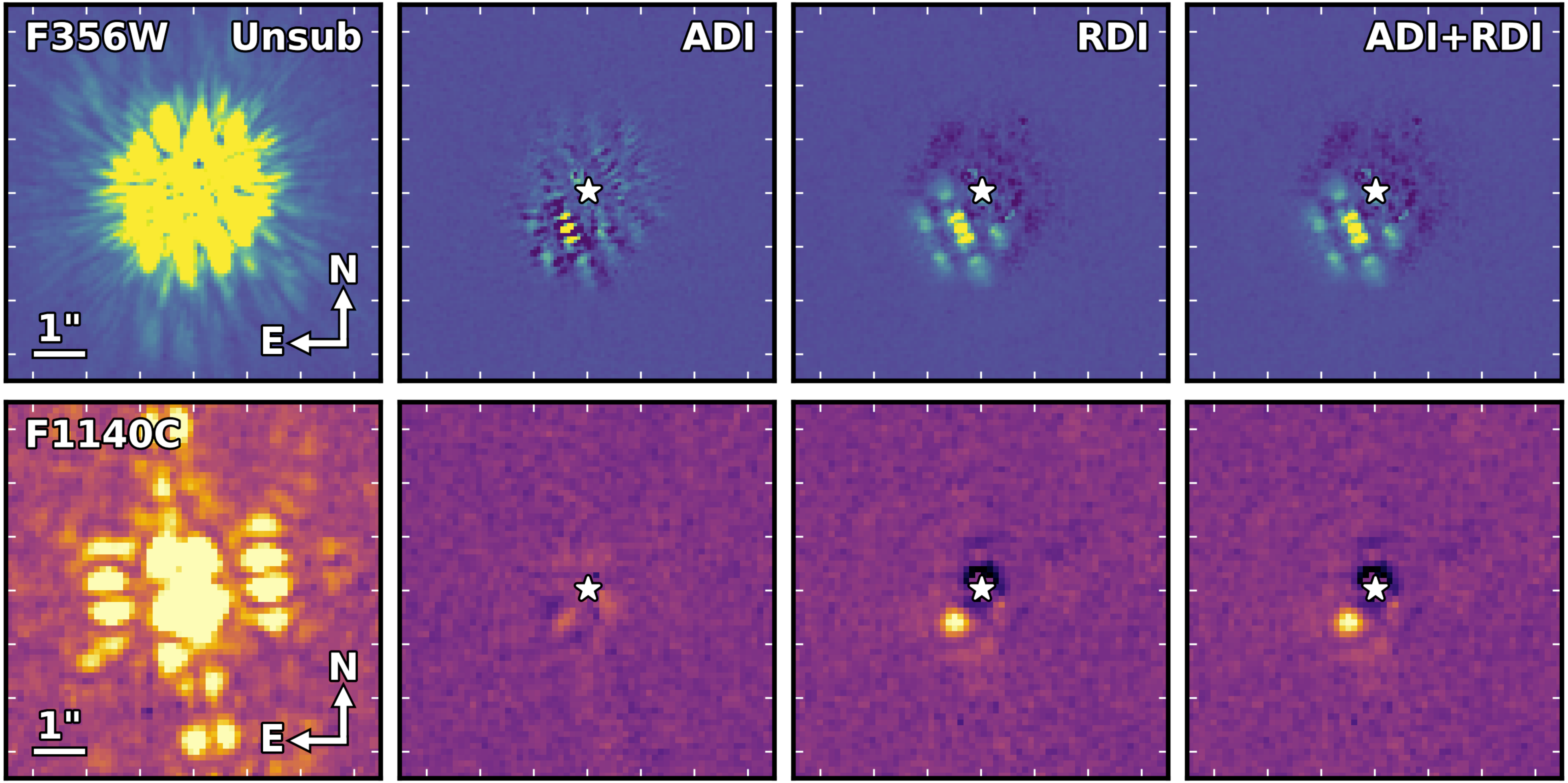
Mawet et al. 2012,
Delacroix et al. 2013



Example: the Vector Vortex Coronagraph

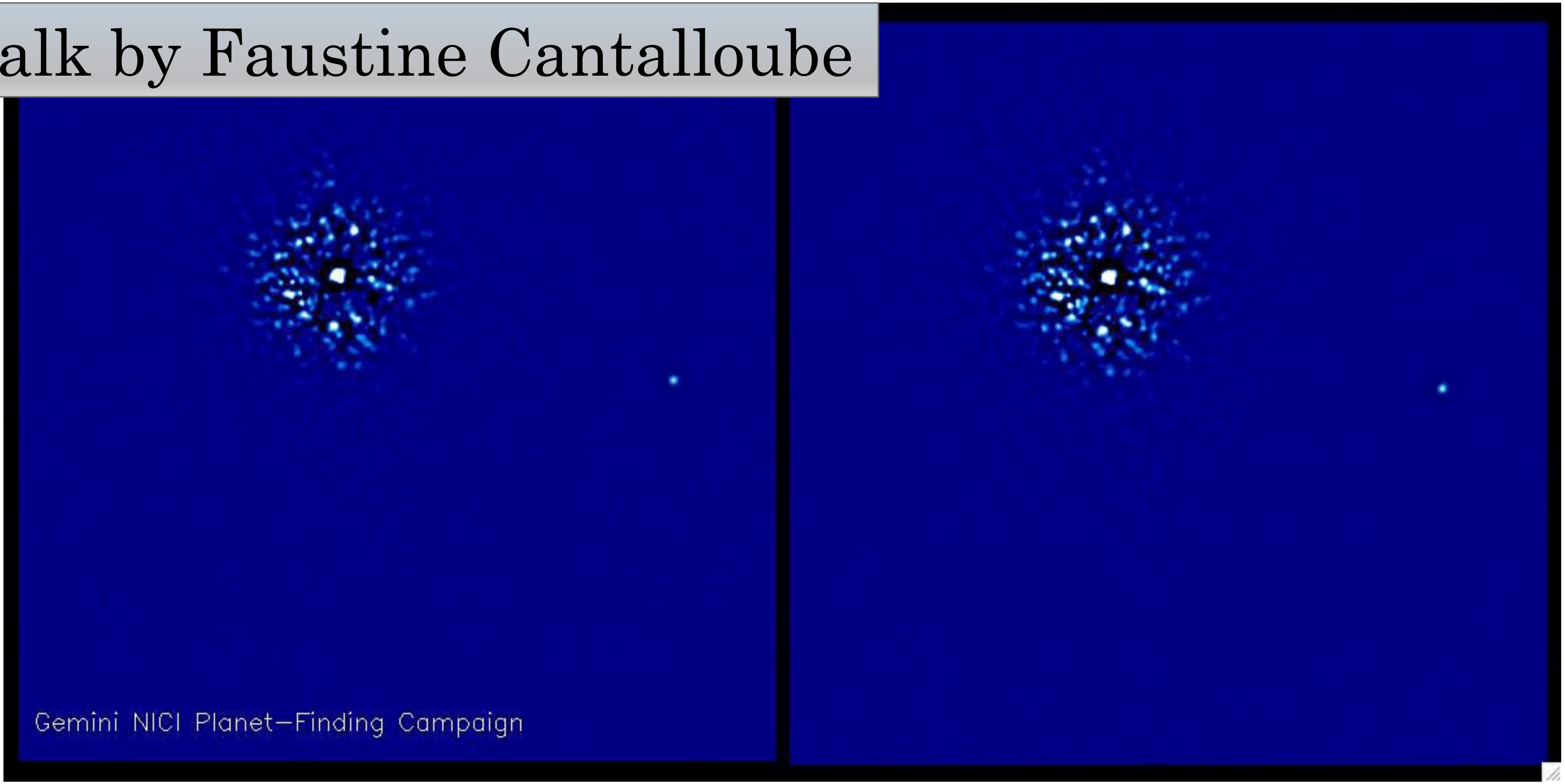
Speckle noise remains even from space – need dedicated post-processing techniques to fully remove speckle noise

Carter et al. 2023

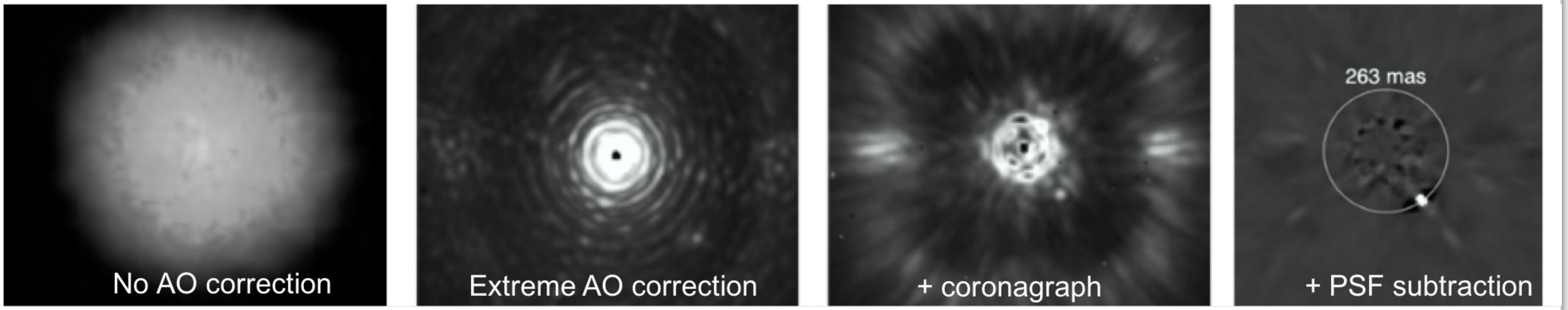


Angular Differential Imaging (ADI) and Reference Differential Imaging (RDI)

See talk by Faustine Cantalloube



Putting all the pieces together



Data from VLT/SPHERE, Currie et al. 2022

What are directly imaged planets like?

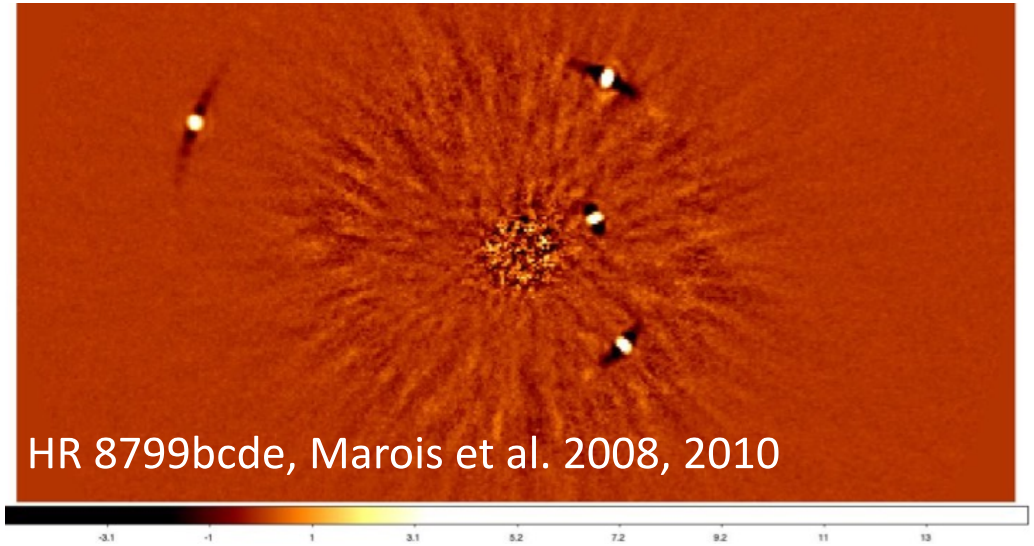
Right now, we can image "baby Jupiters":

- Masses >3 Jupiter masses
- Effective temperatures ~ 600-1400 K
- Ages < 100 Myr – close to epoch of formation
- Separations from 10s to hundreds of AU
- Factor of 10^4 to 10^6 contrast with star
- Mostly detected in near-IR using 8-m ground-based telescopes + adaptive optics + coronagraphy

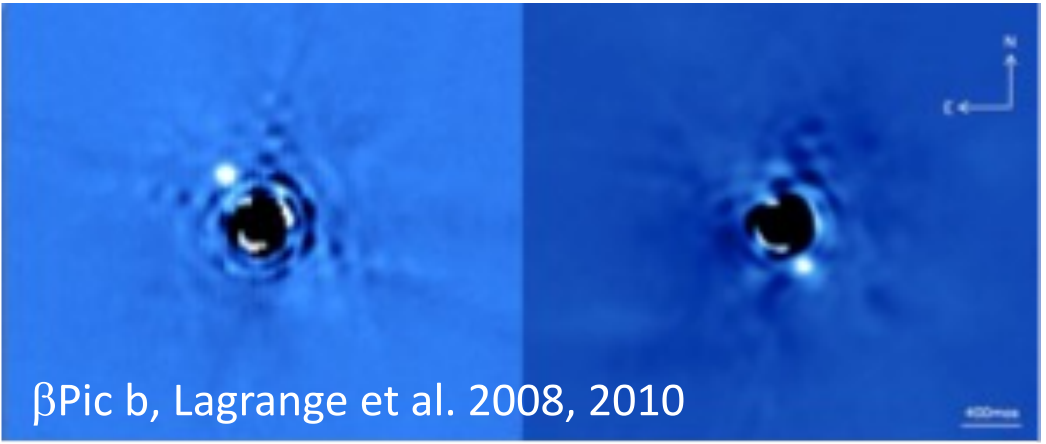
Examples of Directly Imaged Exoplanets

See talks by Julien Milli and Rob de Rosa, on lessons learned from these observations.

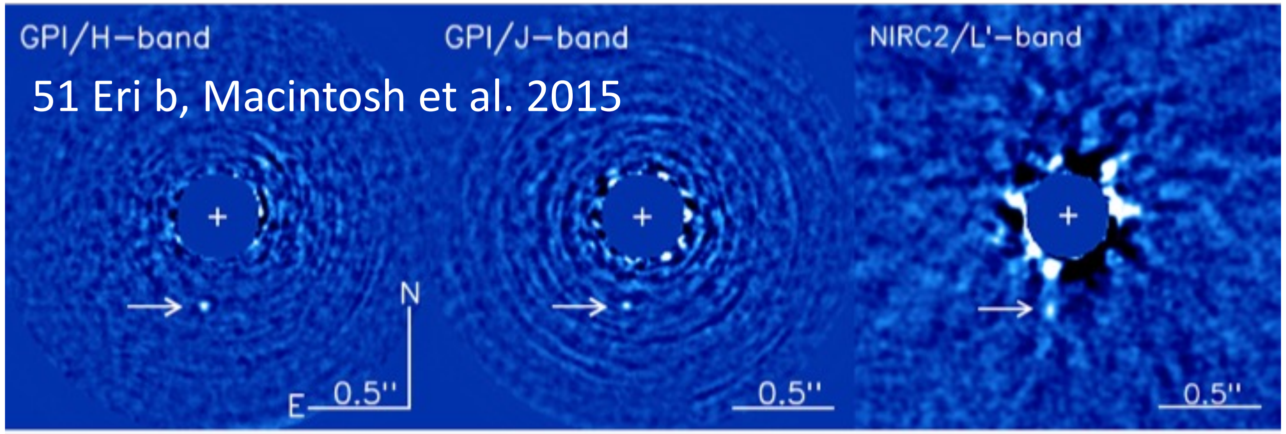
First Discoveries



HR 8799bcde, Marois et al. 2008, 2010

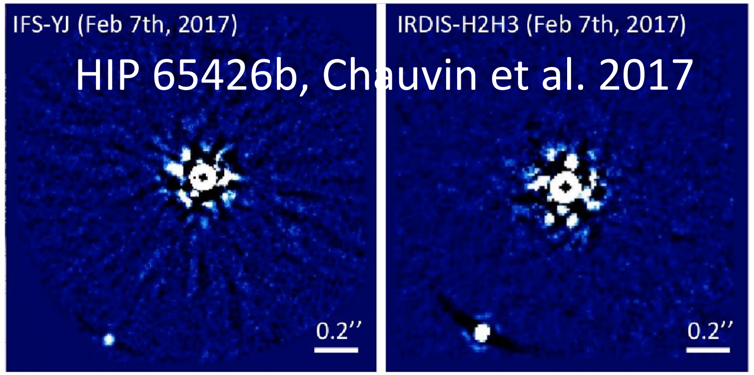


βPic b, Lagrange et al. 2008, 2010



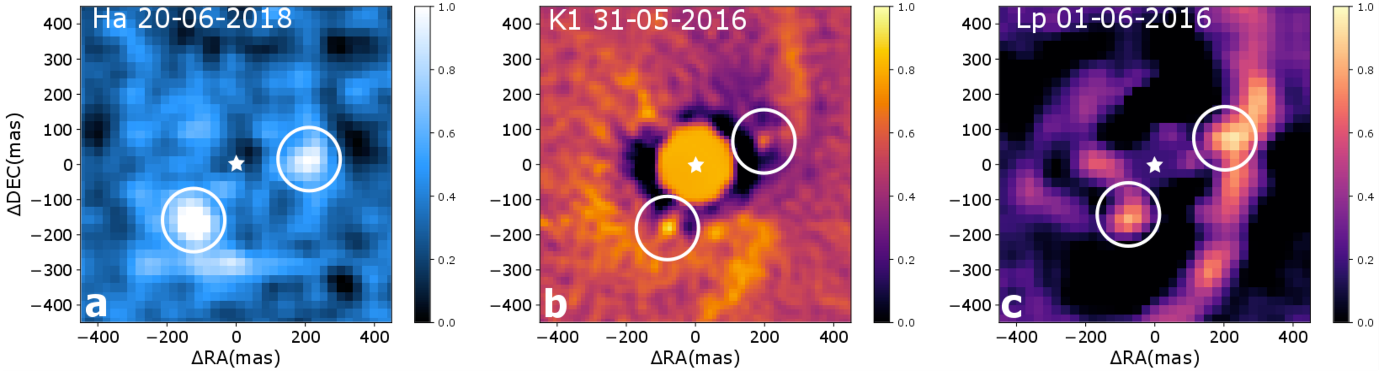
51 Eri b, Macintosh et al. 2015

Discoveries from GPI and SPHERE



HIP 65426b, Chauvin et al. 2017

PDS70bc, Keppler et al. 2018, Haffert et al. 2019



The evolution of an exoplanet

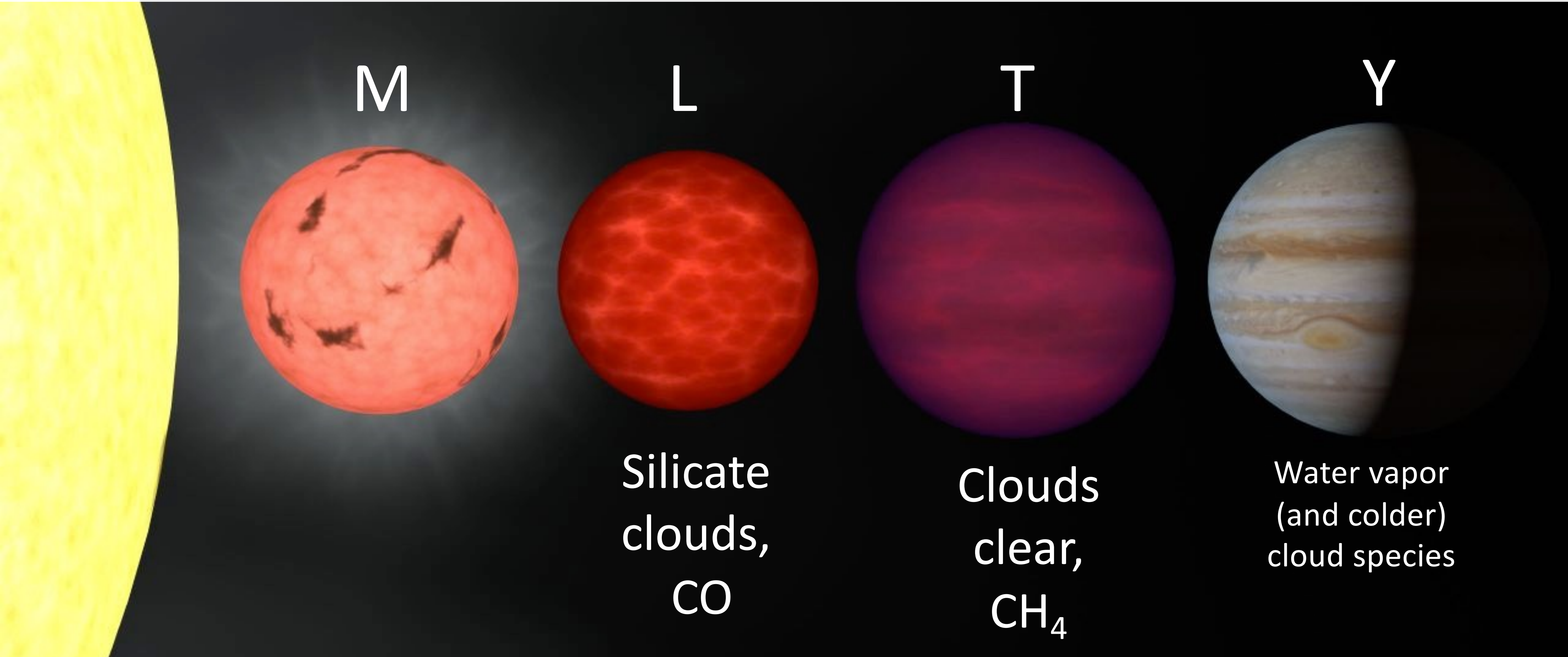
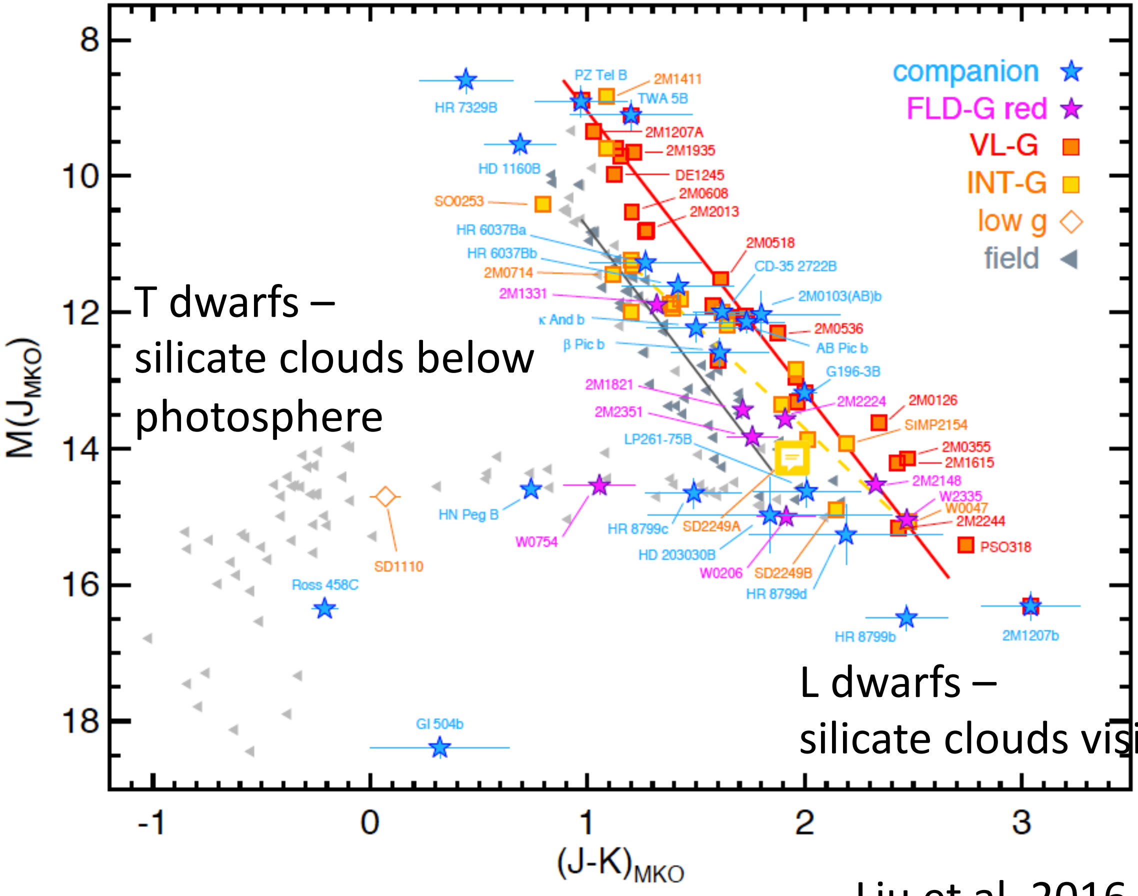


Image credit: Robert Hurt, IPAC, NASA

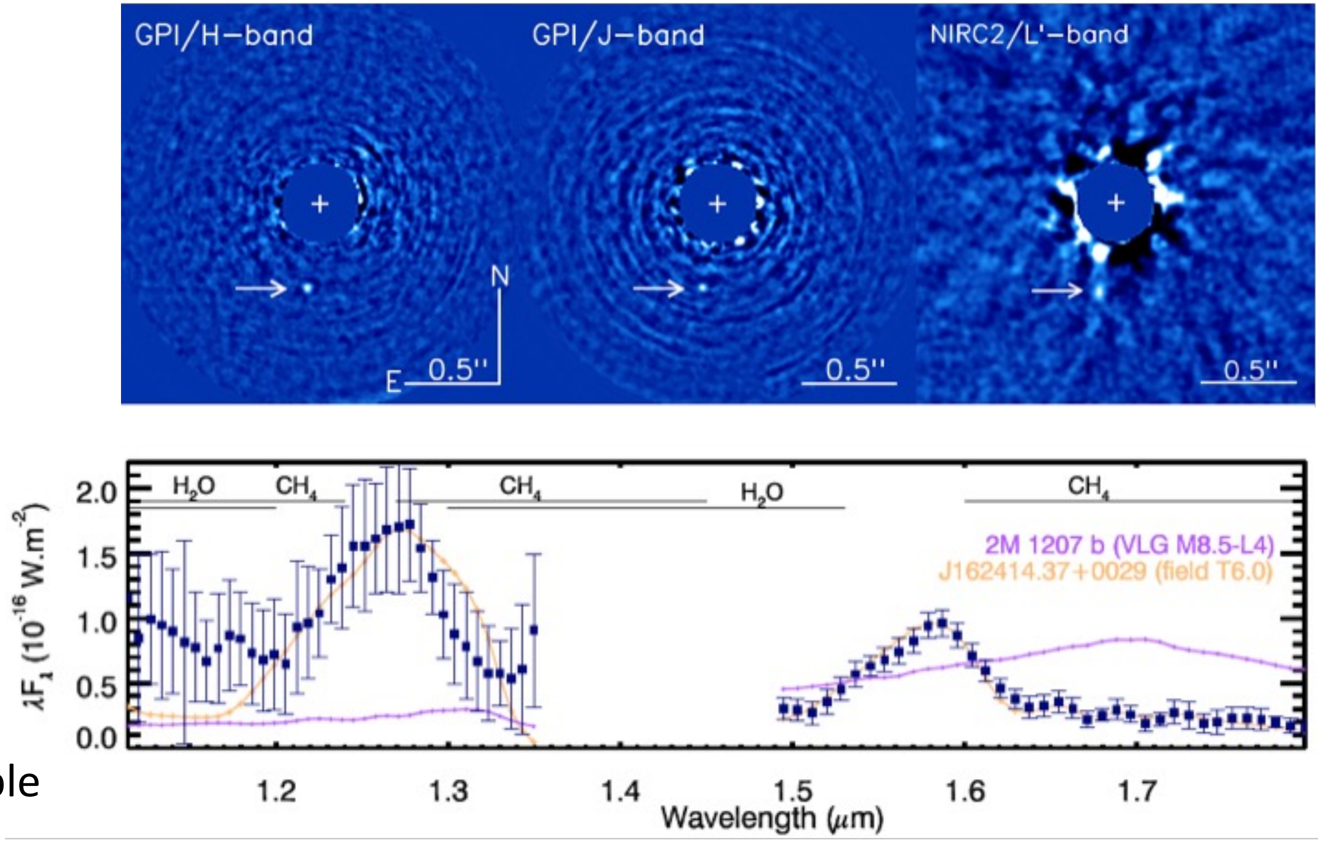
Spectroscopy and Photometry reveal primarily red, dusty photospheres for young exoplanets and exoplanet analogs:



T dwarfs – silicate clouds below photosphere

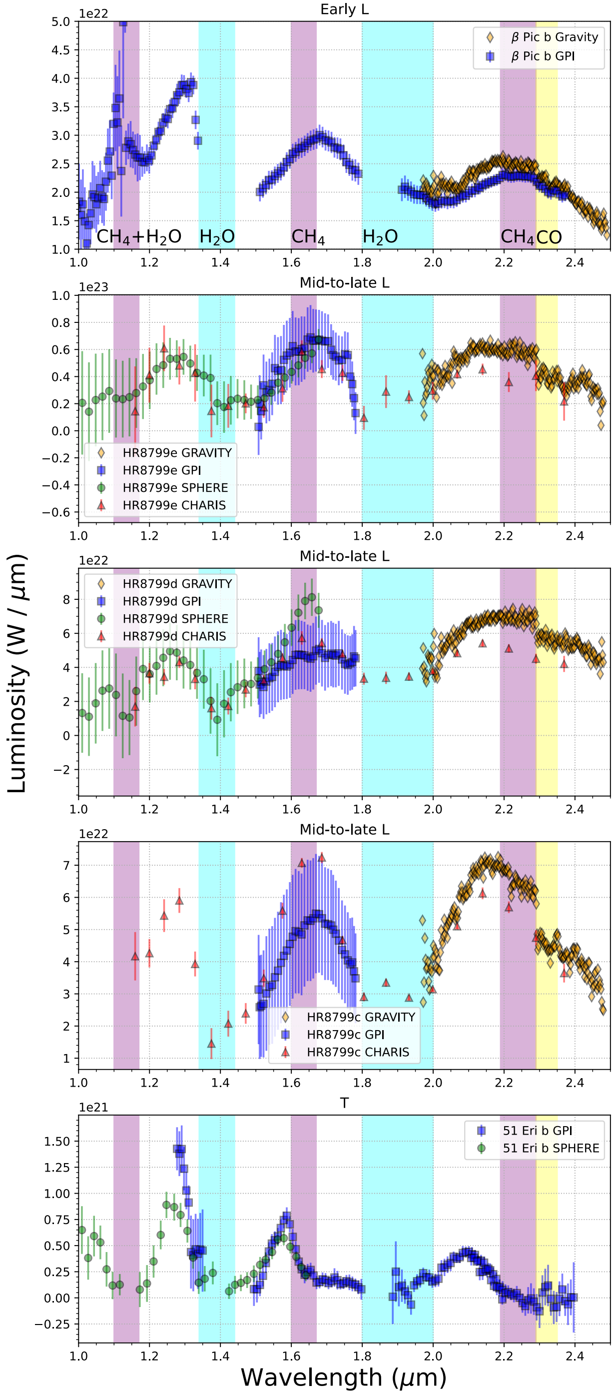
L dwarfs – silicate clouds visible

Liu et al. 2016

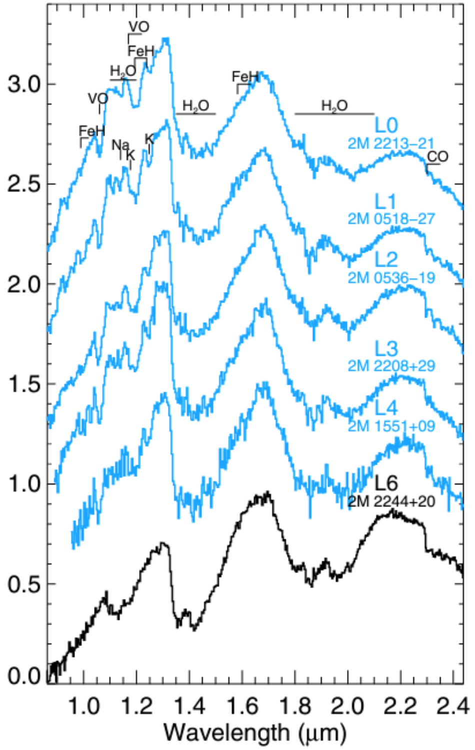


Macintosh et al. 2015

Exoplanet Properties – Low Resolution Spectroscopy



Young free-floating L-dwarf spectra from Allers et al. 2013

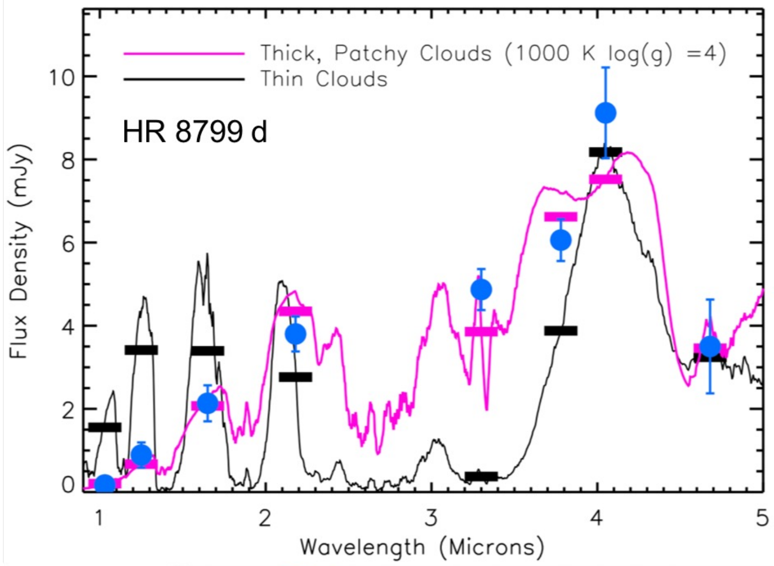


Compiled from: Chilcote et al. 2017, Gravity Consortium 2019, 2020, Bonnefoy et al. 2016, Zurlo et al. 2016, Greenbaum et al. 2018, Wang et al. 2020, Nasedkin et al. 2024, Wang et al. 2022, Macintosh et al. 2015, Rajan et al. 2017, Samland et al. 2017

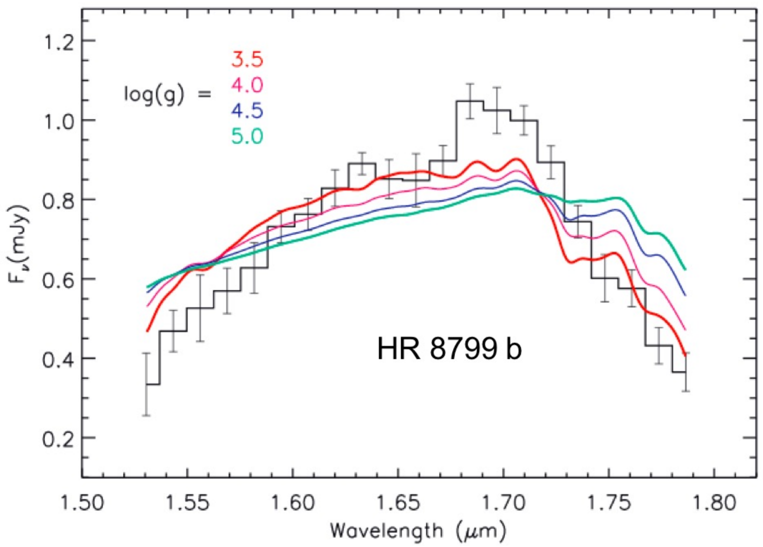
Key take-aways from spectroscopy to date

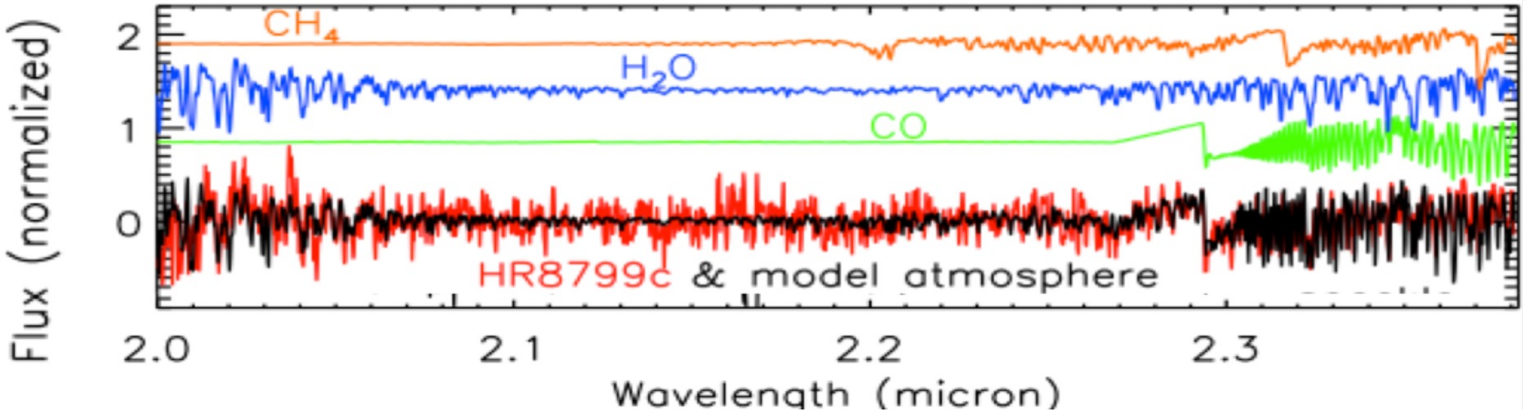
- Silicate cloud models required to fit observed spectra
- Peaky spectral shape in H-band indicates low surface gravity
- At higher resolution, features from CO, CH_4, and H_2O are abundant – but CO features are much stronger than methane features for most objects.

Currie et al. 2011



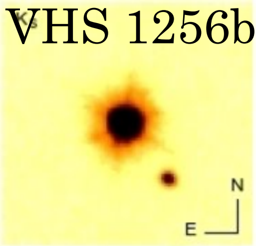
Barman et al. 2011

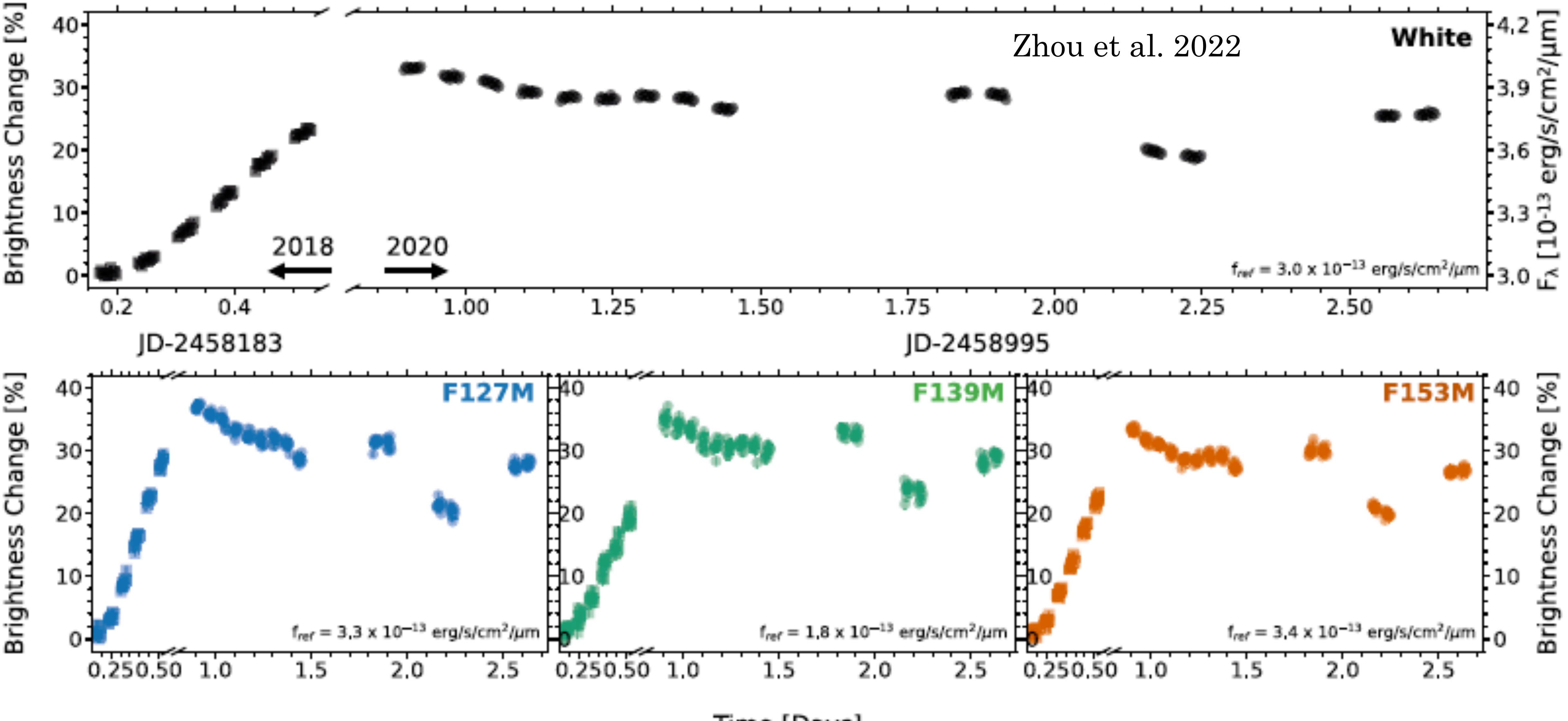




Konopacky et al. 2013

Young giant exoplanets are very variable – likely due to evolving cloud structures + fast rotation





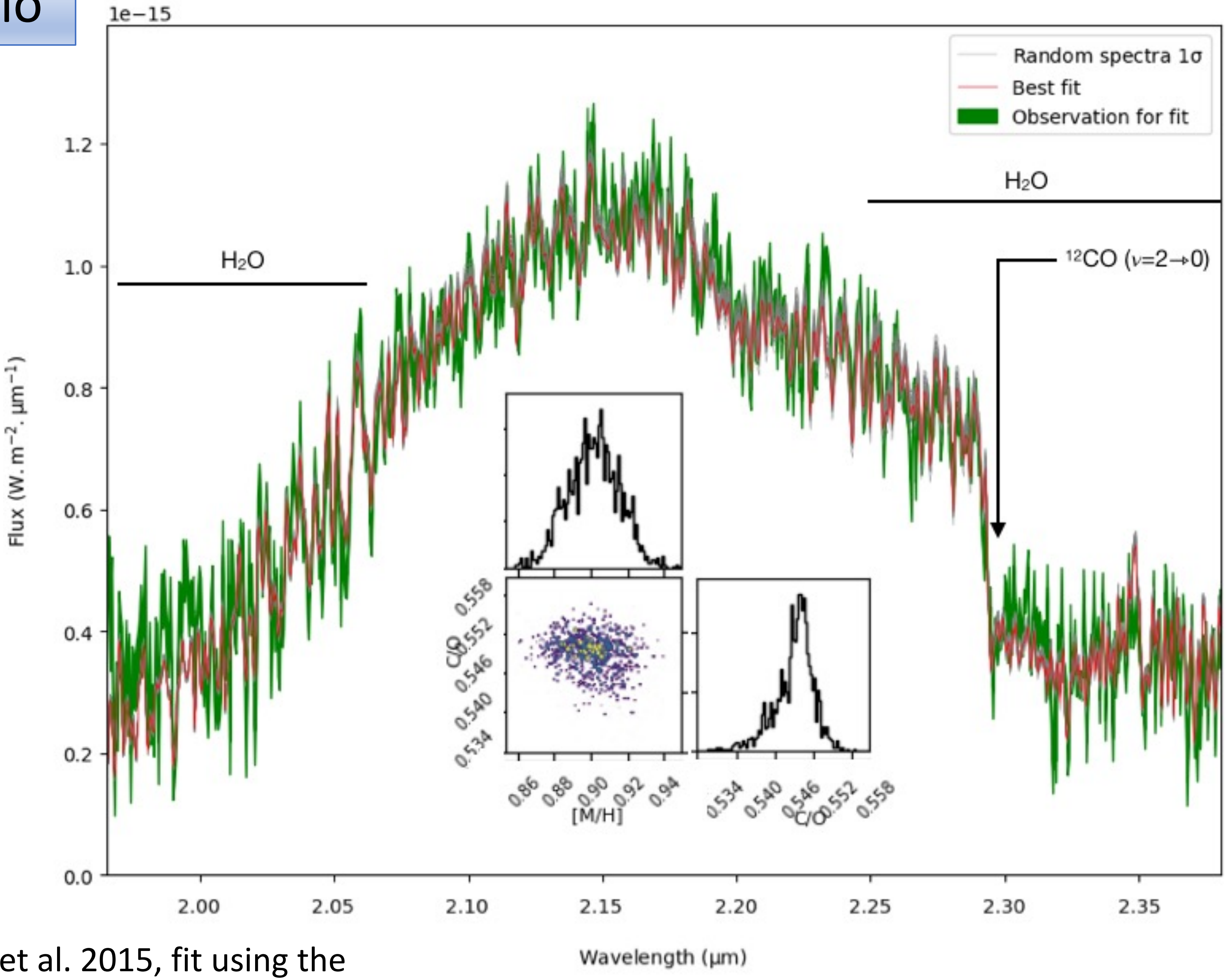
Modeling approaches

- Forward modeling – shares heritage with stellar and brown dwarf models (Chabrier et al. 2000, Baraffe et al. 2002, Burrows et al. 2003, Allard et al. 2012, Baraffe et al. 2015), challenges in explaining red colors solved either with clouds (Ackerman & Marley 2001, Marley et al. 2021, Phillips et al. 2020, Charnay et al. 2018) or additional thermochemical instabilities (Tremblin et al. 2016, 2017, 2019, 2020)
- Inversion techniques -- a parameterized pressure-temperature profile is adopted and other fundamental parameters (mass, effective temperature, cloud properties, abundances, etc.) are then retrieved given the observed spectrum (Madhusudhan and Seager 2009, Line et al. 2017, Burningham et al. 2017, 2021, Lavie et al. 2017, Molliere et al. 2020, Whiteford et al. 2022, Vos et al. 2022).

See talks by Eileen Gonzales and Jacob Lustig-Yaeger

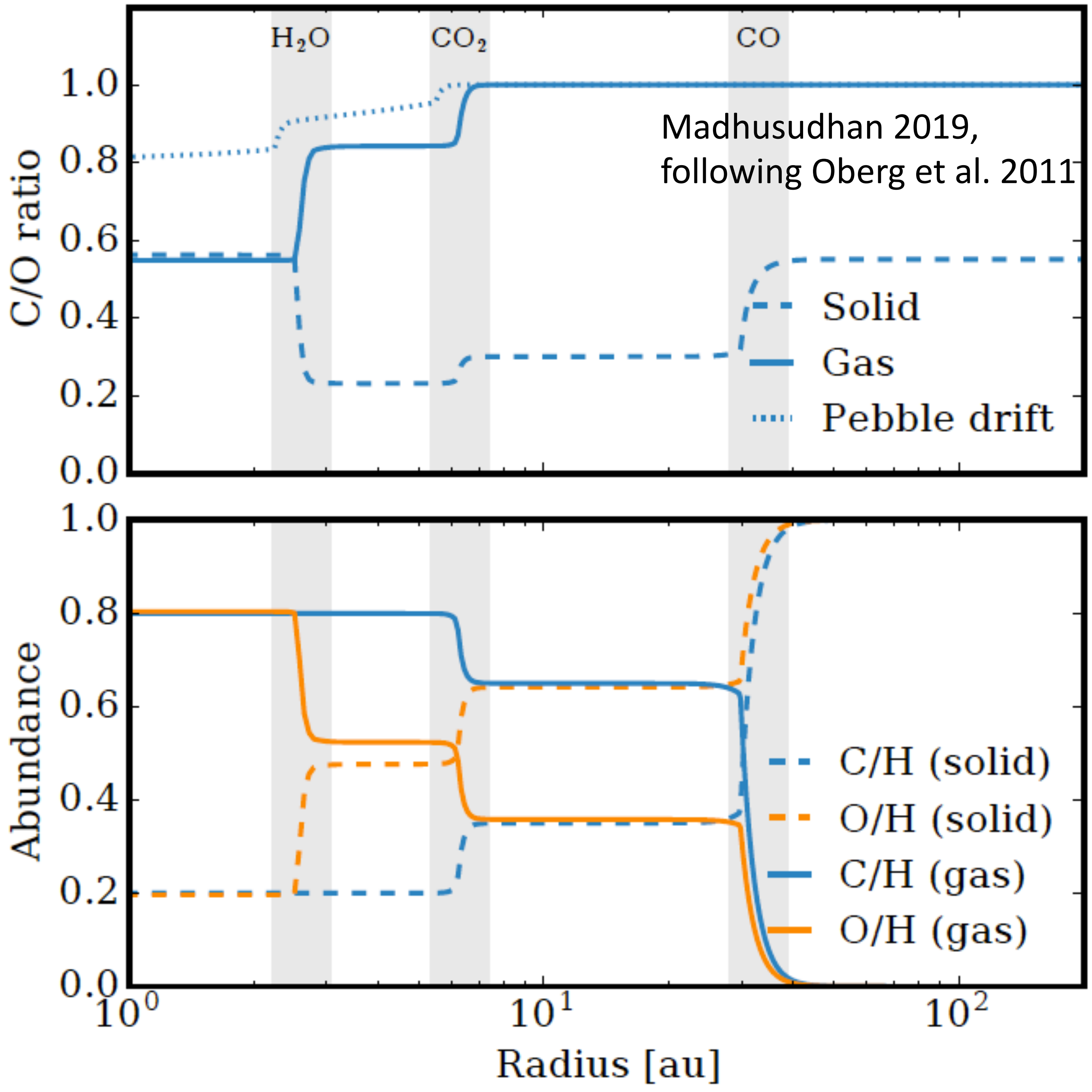
See talk by Jean Baptiste-Ruffio

Modeling of medium resolution spectroscopy enables measurements of atomic / molecular abundances



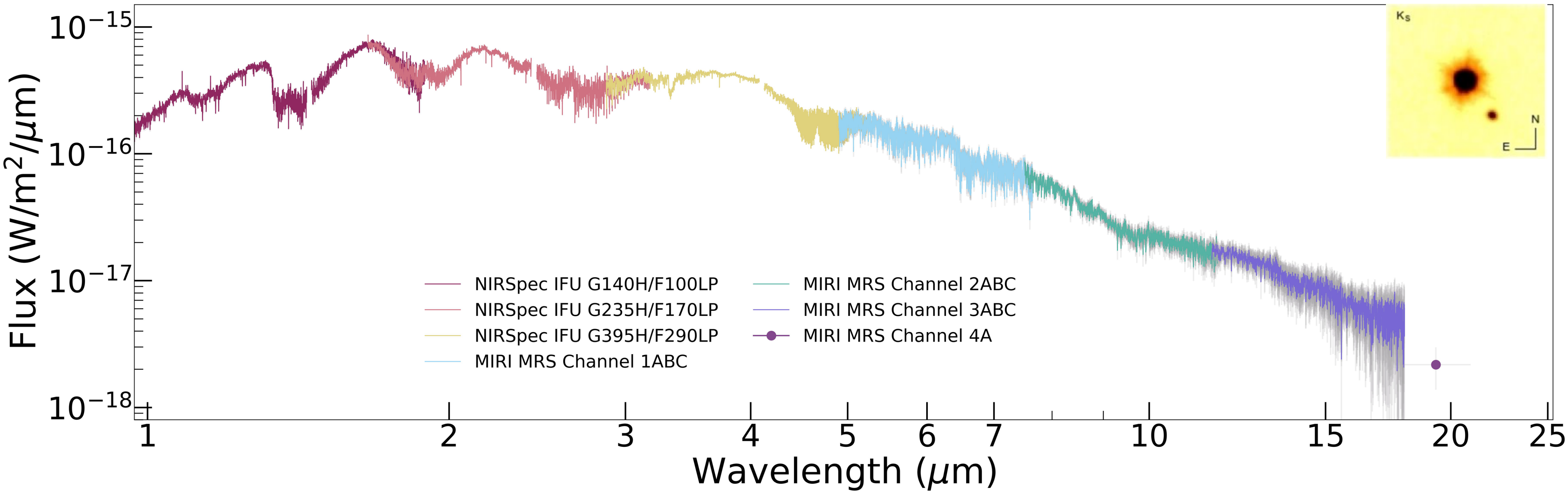
Keck Osiris HR 8799b spectrum from Barman et al. 2015, fit using the ForMoSA Bayesian forward modeling code (Petrus et al. 2020, 2021)

Connecting atmospheric chemical abundances to exoplanet formation and migration histories



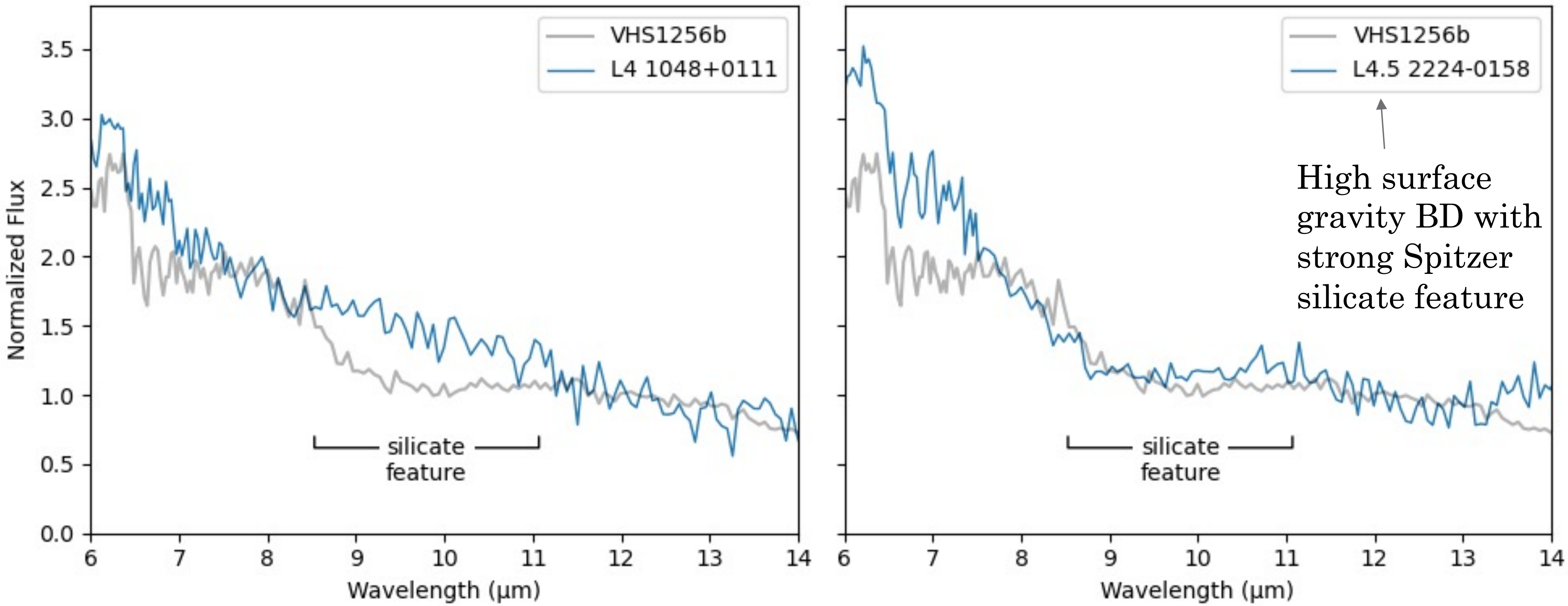
Next Steps with JWST – the most detailed spectrum of an exoplanet to date

VHS 1256b



Miles et al. 2023

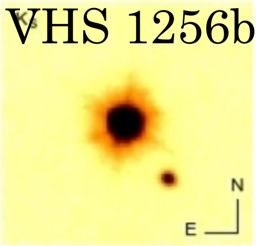
Direct evidence for silicate clouds

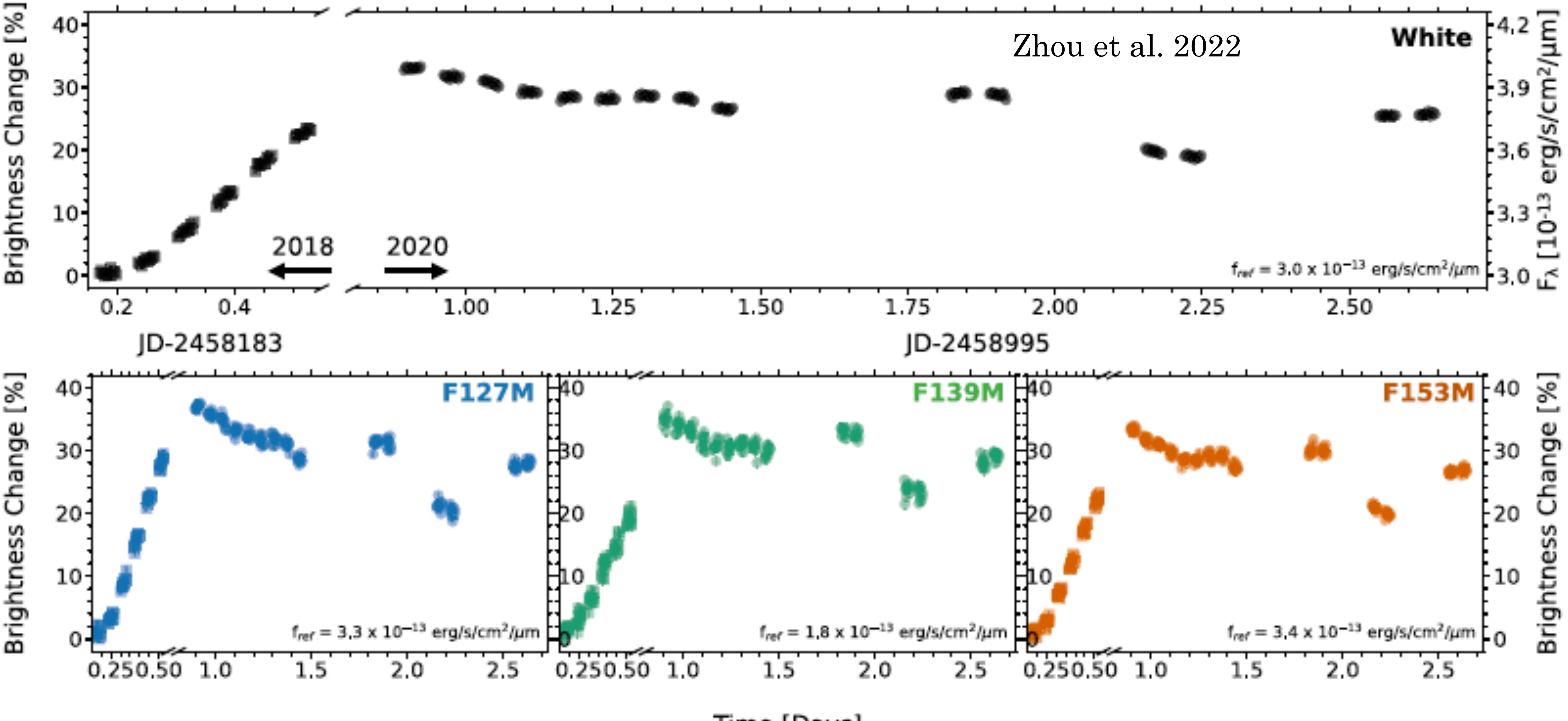


High surface gravity BD with strong Spitzer silicate feature

Miles et al. 2023

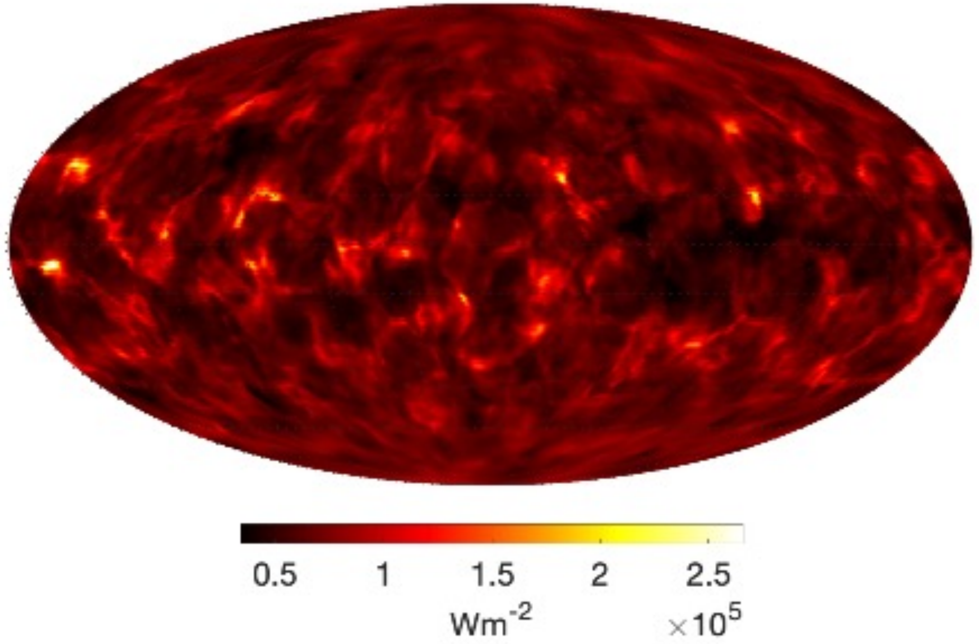
Young giant exoplanets are very variable – likely due to evolving cloud structures + fast rotation



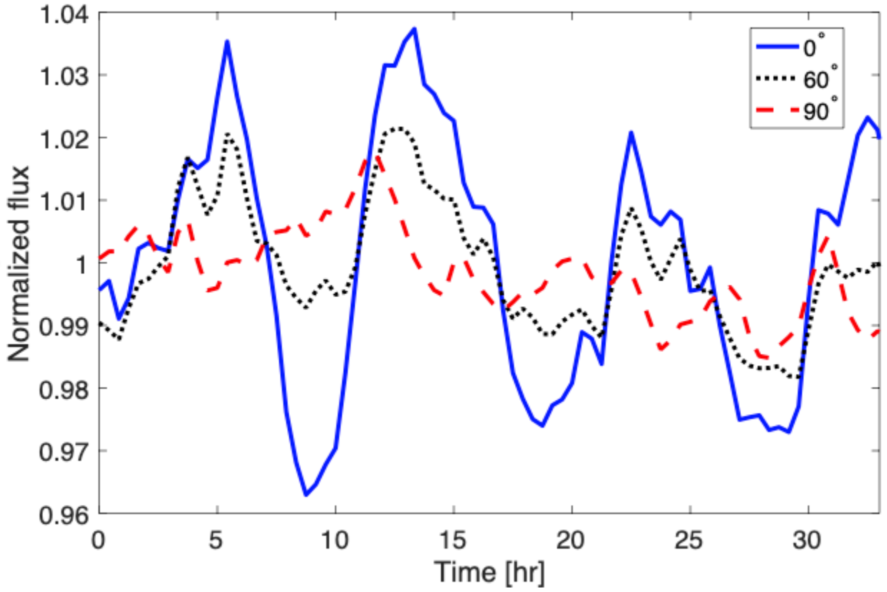


Planets are not 1-D – the need for 3-D models

Top-of-atmosphere flux map

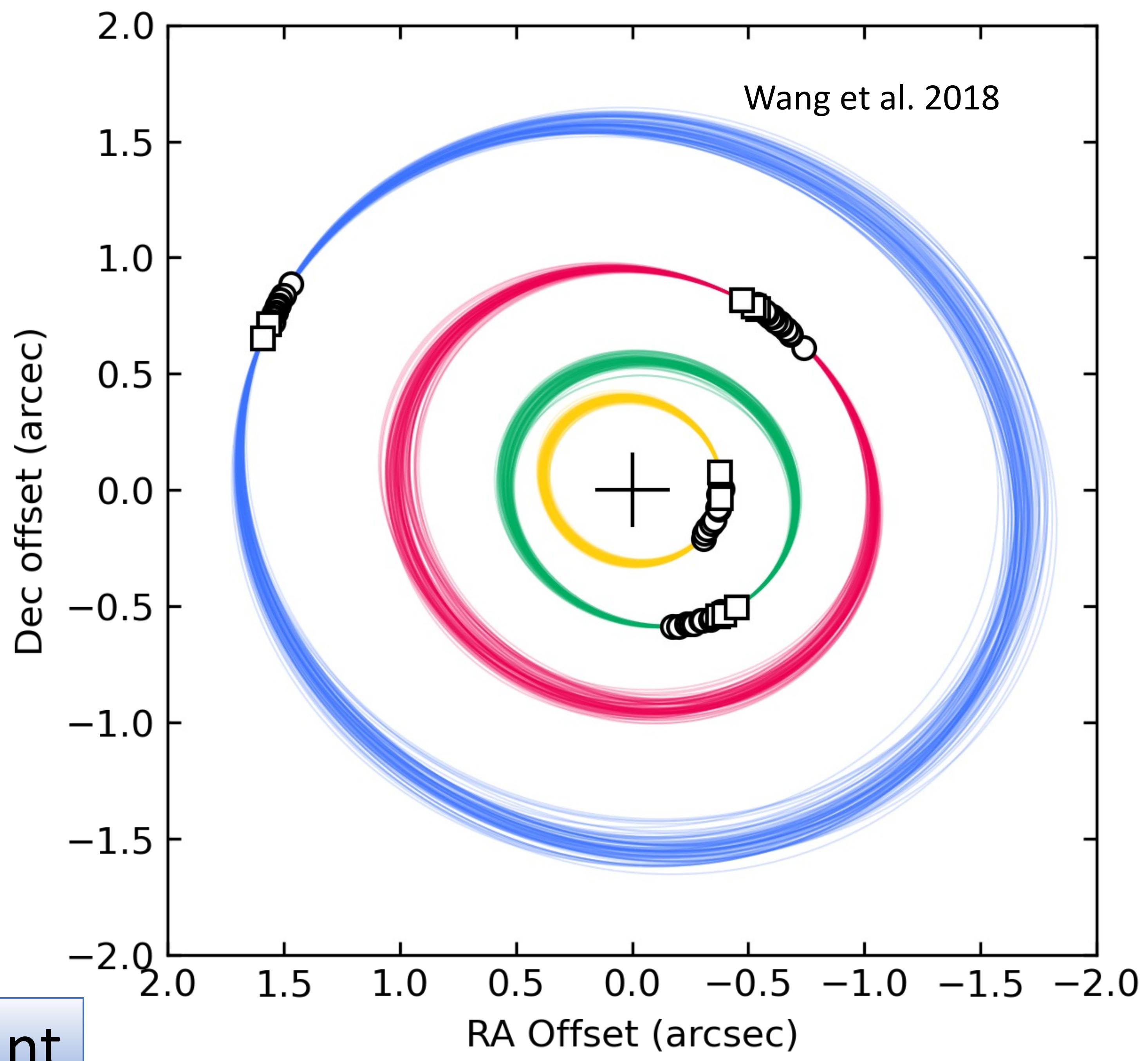


Resulting bolometric lightcurve:



General Circulation Model of a young exoplanet analogue using the model from Tan & Showman 2021, figures courtesy of Xianyu Tan

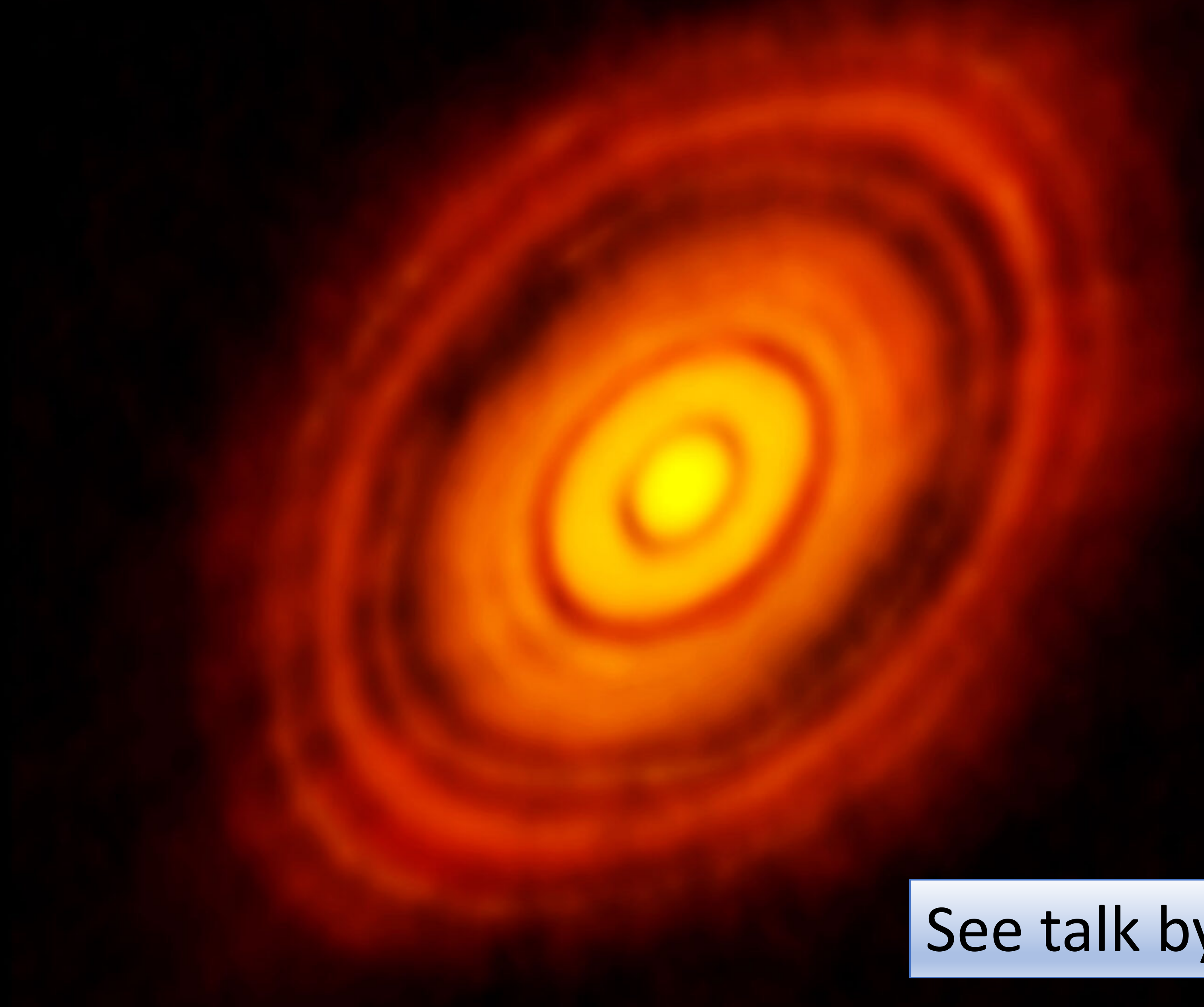
Exoplanet Properties – Orbits and mass determination



See talk by Sarah Blunt

The Exoplanet-Disk connection

Credit: ALMA (NRAO/ESO/NAOJ)



See talk by John Debes

How to image a planet, part 2:

Where to look for planets and how many stars do you need to search to find one?

A 20+ year legacy of surveys

1990s – 2005: AO-enabled and HST efforts

(Masciadri et al. 2005, Chauvin et al. 2003, Lowrance et al. 2005)

2005–2010: 8m telescope + AO + speckle suppression techniques

(Biller et al. 2007, Lafreniere et al. 2007, Chauvin et al. 2010)

2010–2015: 8m telescope + AO + coronagraphs + speckle suppression techniques

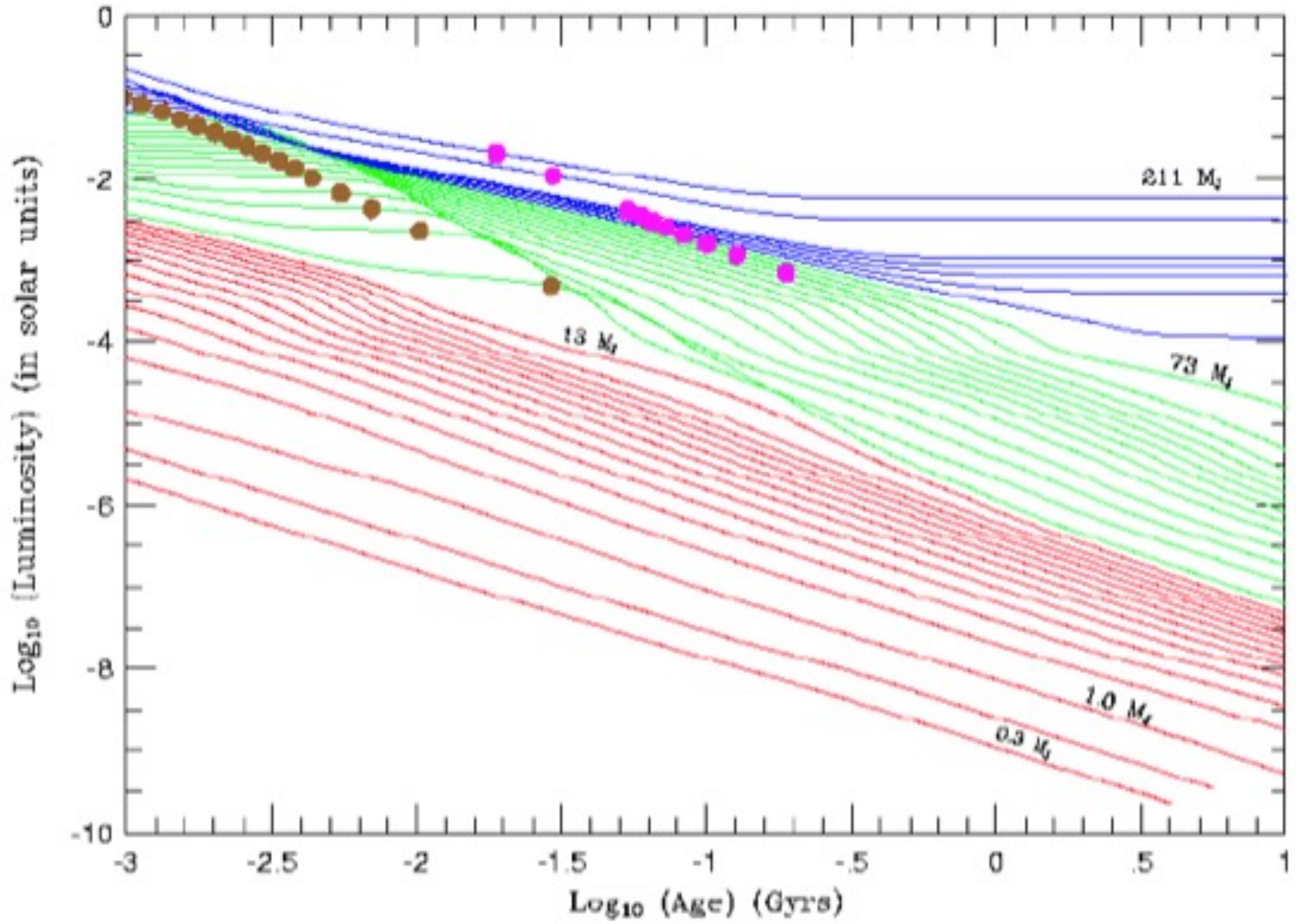
(Desidera et al. 2015, Chauvin et al. 2015, Vigan et al. 2017, Biller et al. 2013, Wahhaj et al. 2013, Nielsen et al. 2013, Vigan et al. 2012, Galicher et al. 2016, Tamura et al. 2016, Brandt et al. 2014, and others)

2015 – The Era of Extreme AO coronagraphs such as VLT/SPHERE, Gemini/GPI, and Subaru/SCExAO

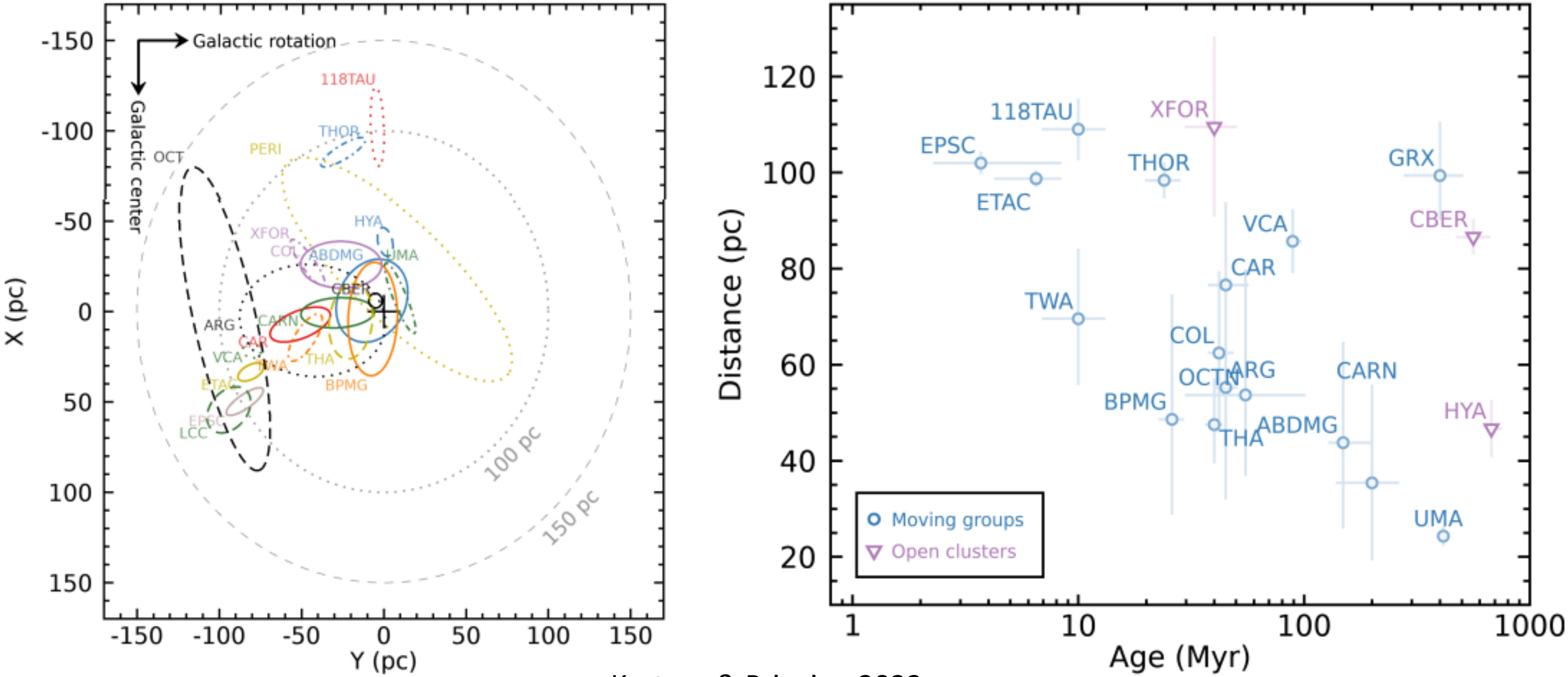
(Nielsen et al. 2019, Vigan et al. 2021, Desidera et al. 2021, Langlois et al. 2021, Bonavita et al. 2016, Janson et al. 2019, Bohn et al. 2021, Launhardt et al. 2020, and others)

See talk by Clémence Fontanive

Previous and on-going surveys focus on thermal emission from young planets



Burrows et al. 2001

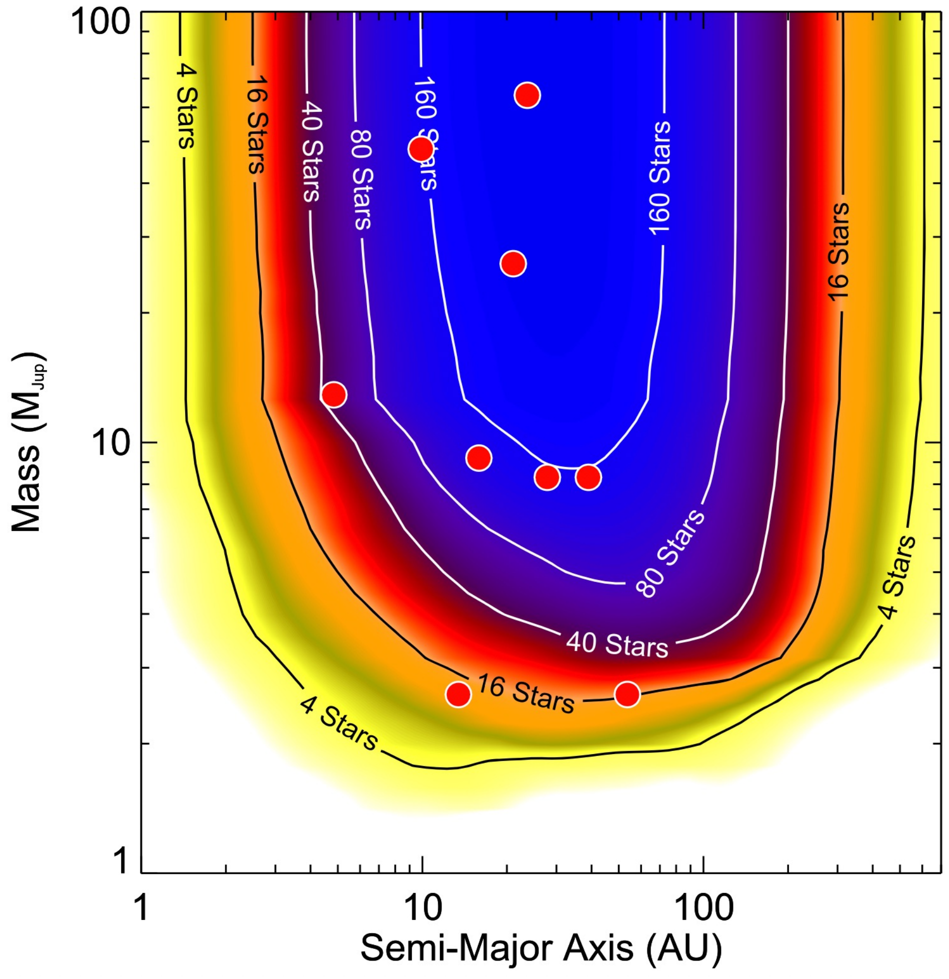


Kastner & Principe 2022

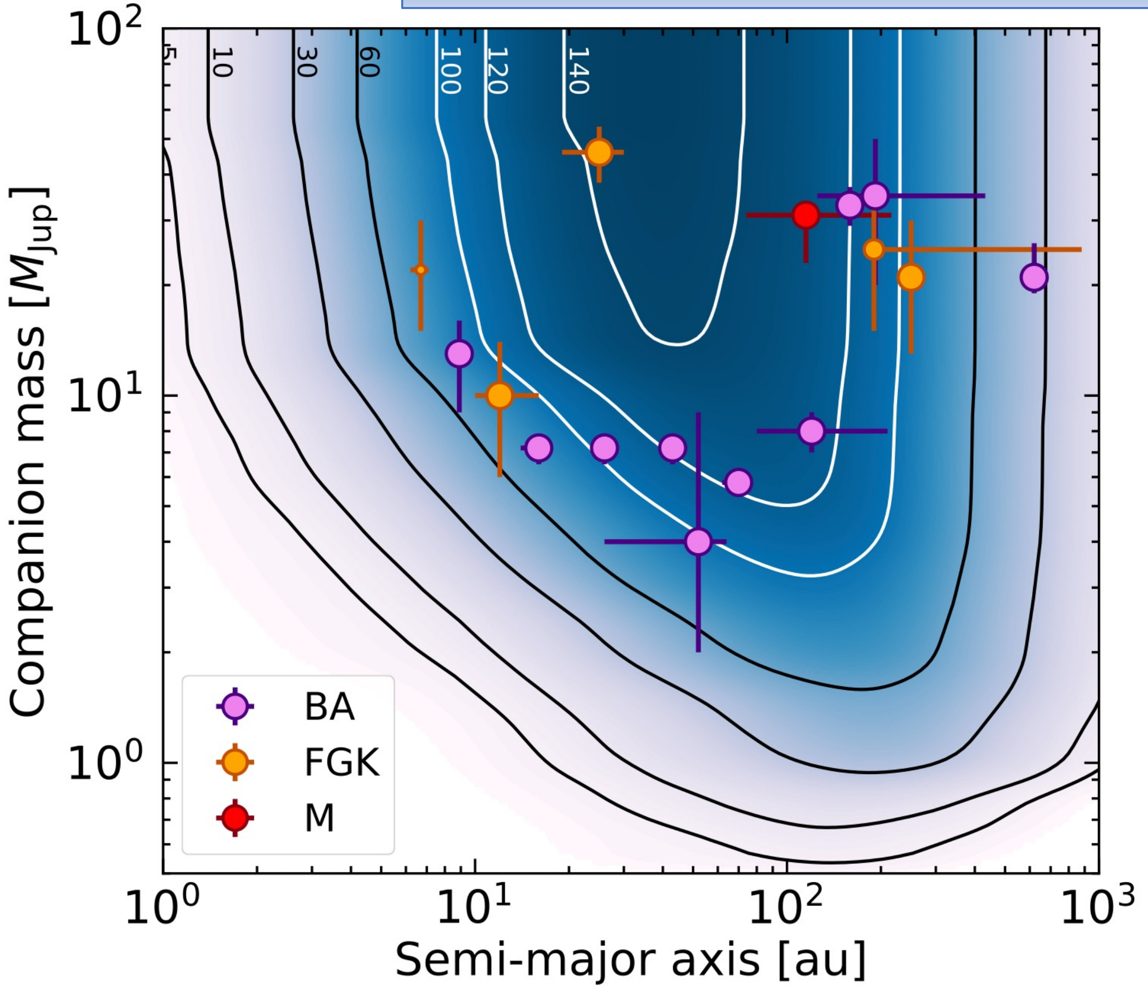
Where to look for exoplanets?

Extreme AO surveys (Gemini GPIES and VLT SHINE) are very sensitive to wide, young giant planets – but such planets appear to be rare

See talk by Clémence Fontanive



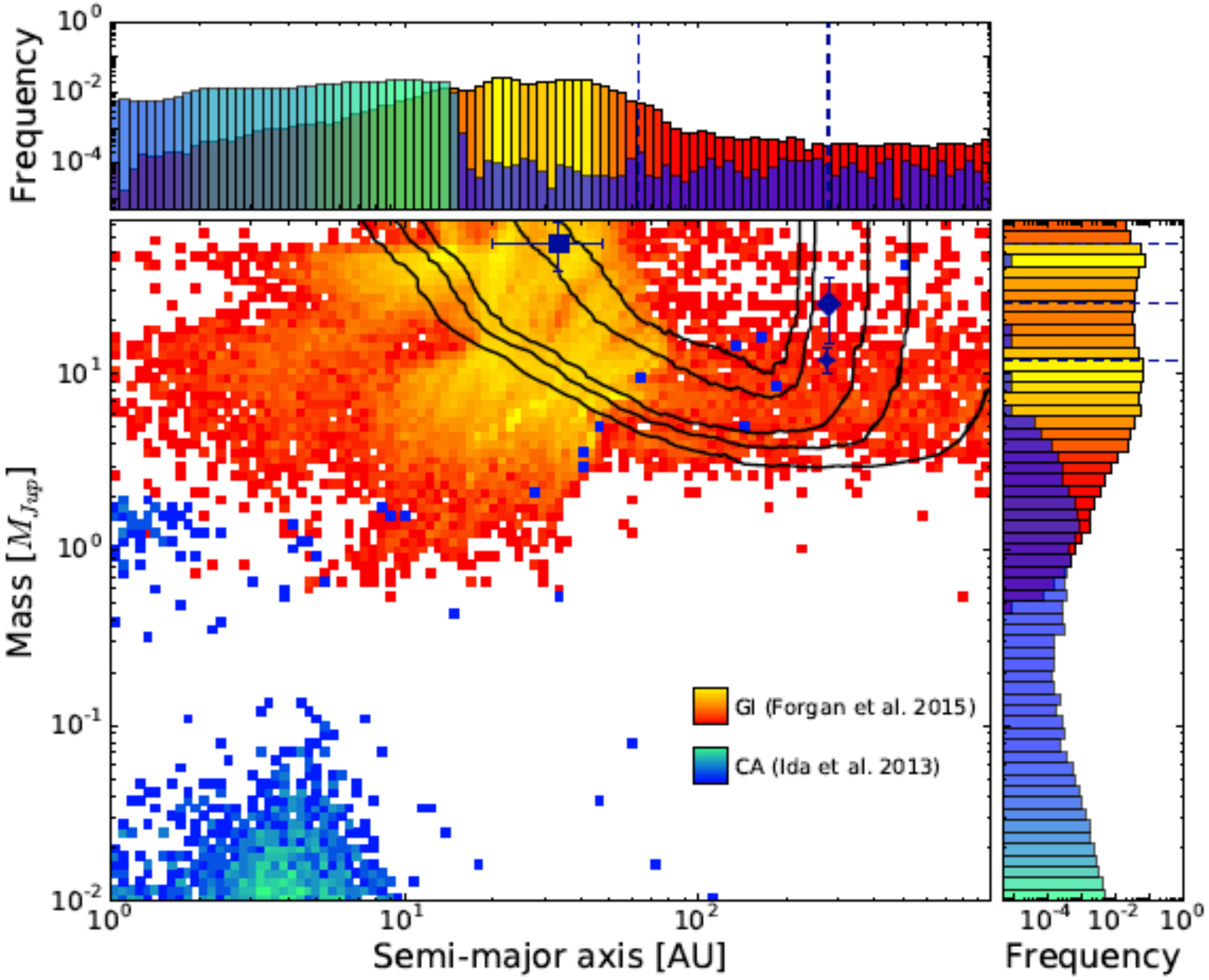
Nielsen et al. 2019 – Gemini GPIES, 300 stars



Vigan et al. 2021 – VLT SHINE, 150 stars

The properties (and frequencies) of directly imaged exoplanets as a population can test formation mechanisms

- Core accretion – mostly generates close-in companions
- Gravitational Instability within a disk – mostly generates wider companions

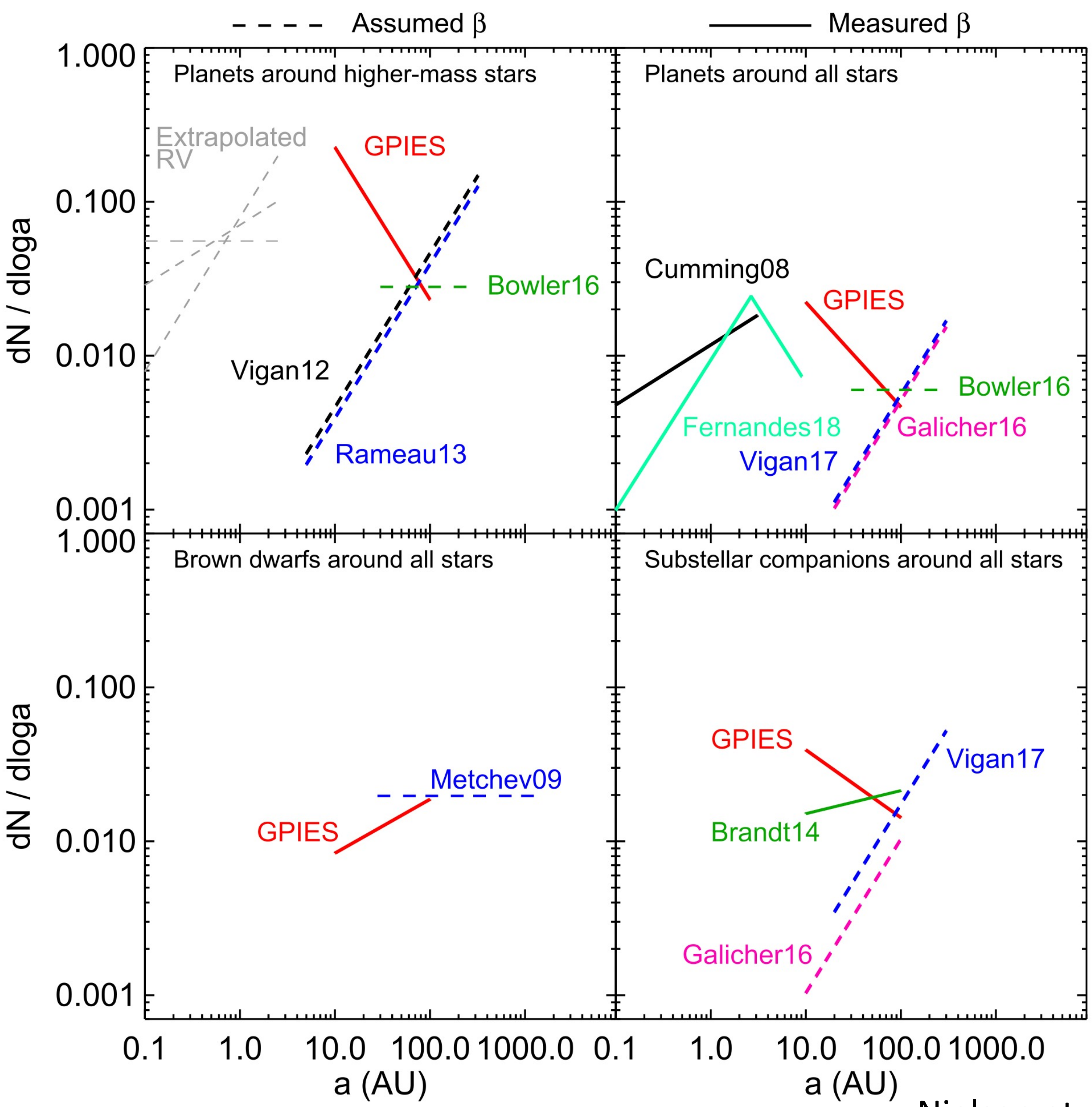


Vigan et al. 2017

Key take-aways from demographics studies (Nielsen et al. 2019, Vigan et al. 2021):

1) Strong evidence that giant planets are more common around higher-mass stars

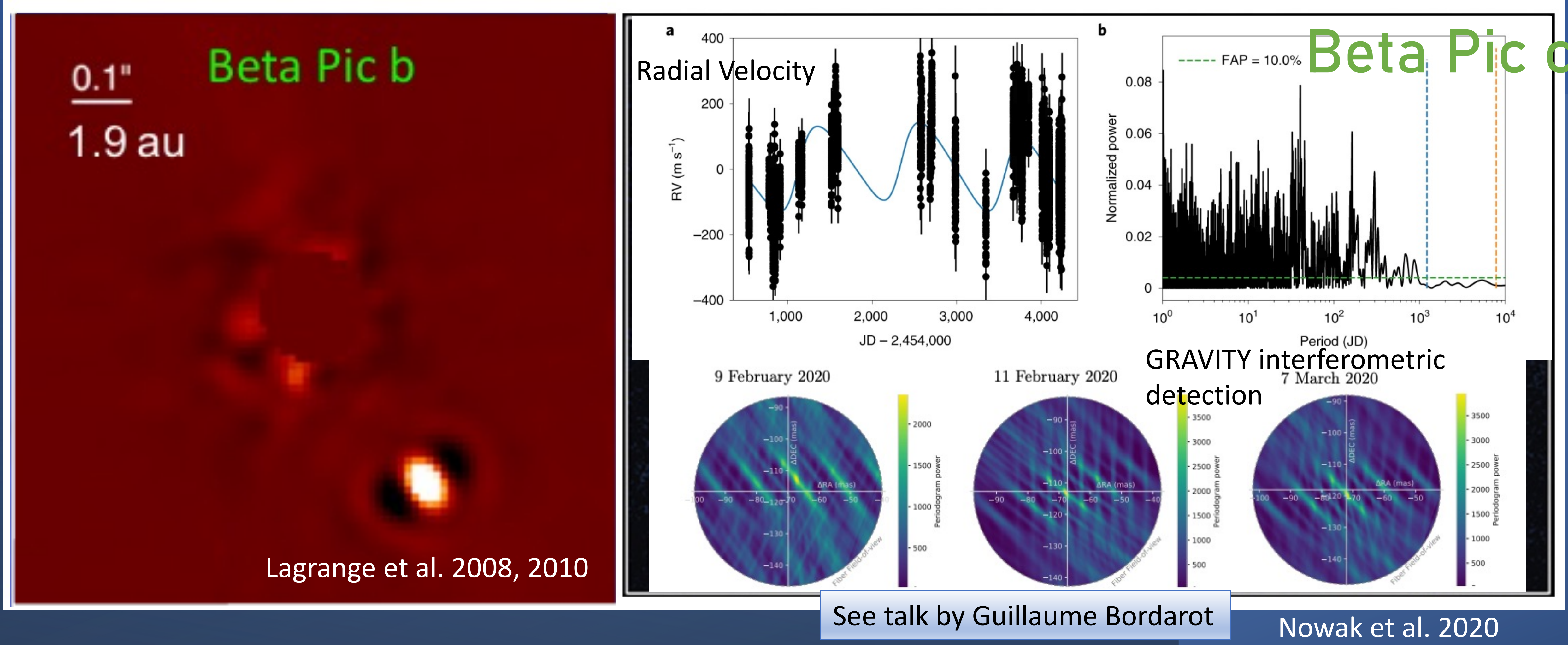
2) Weaker evidence that giant planets and brown dwarfs follow different underlying distributions (i.e. giant planets more likely to form via core accretion, brown dwarfs via disk instability)



Nielsen et al .2019

Synergies – combining detection techniques

Lagrange et al. 2019

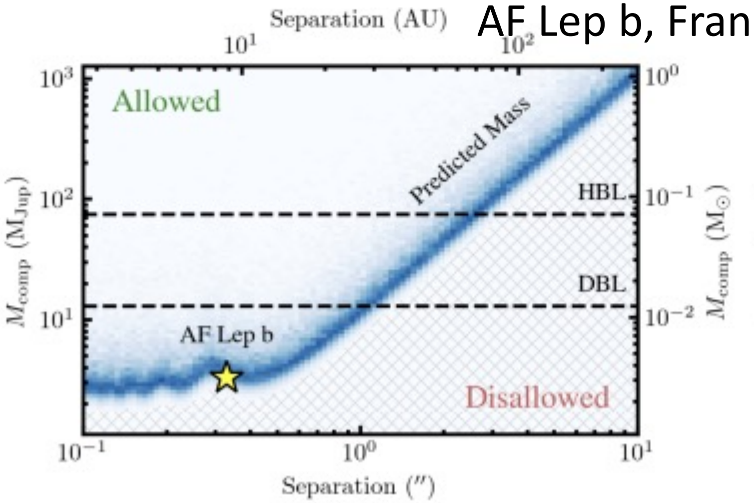


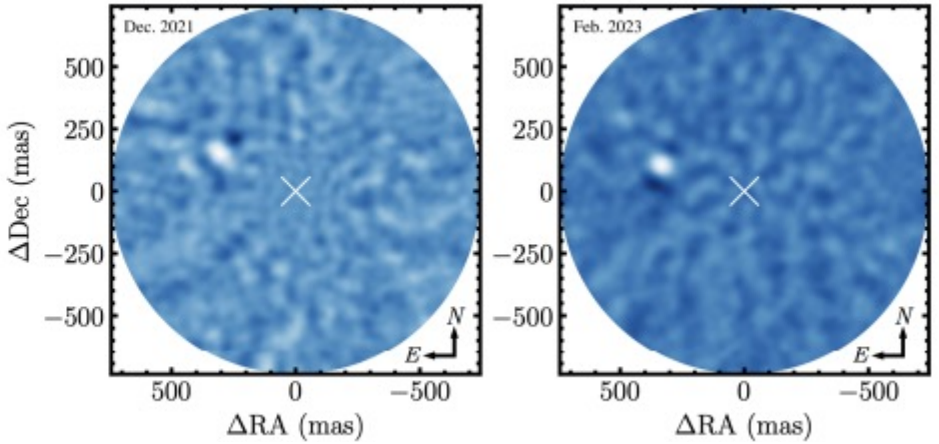
Nowak et al. 2020

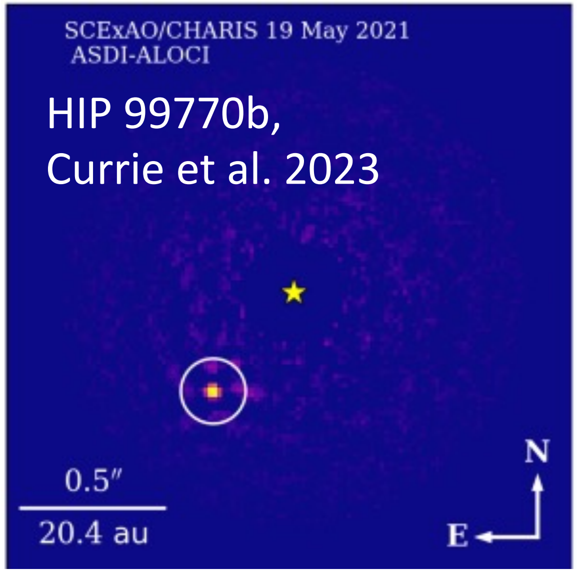
The Example of the Beta Pic system

Combination of Hipparcos / Gaia accelerations + direct imaging has proven particularly fruitful

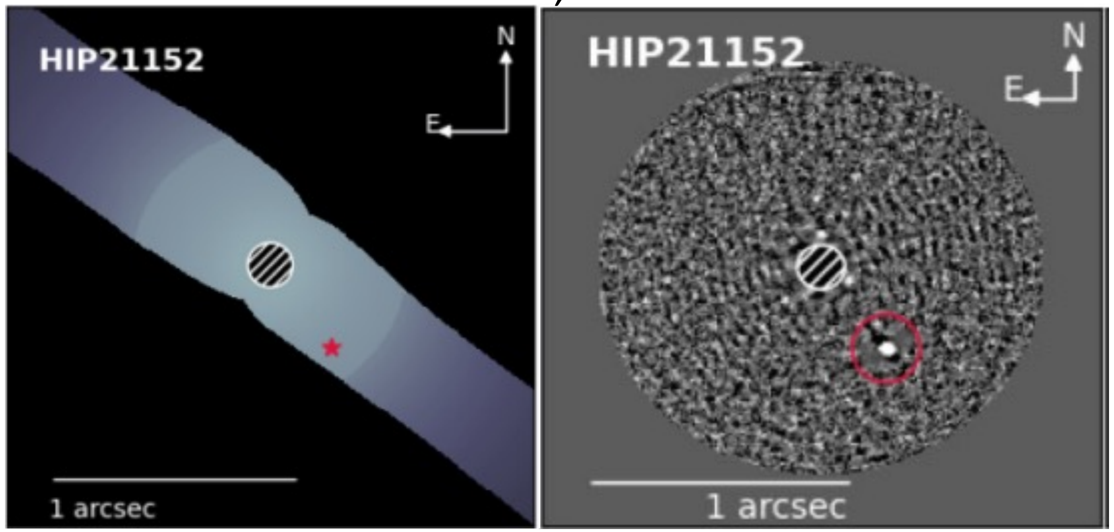
AF Lep b, Franson et al. 2023, Mesa et al. 2023, de Rosa et al. 2023

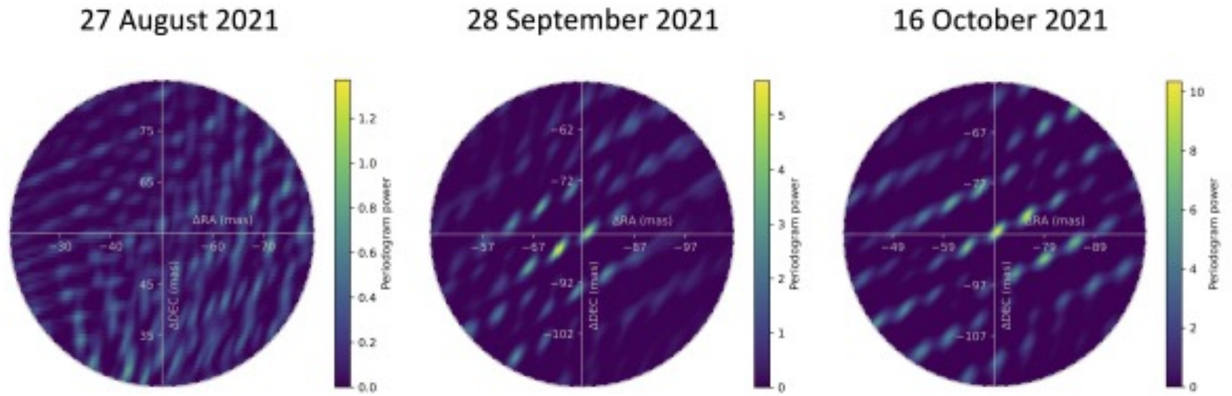






Bonavita et al. 2022, Kuzuhara et al. 2022





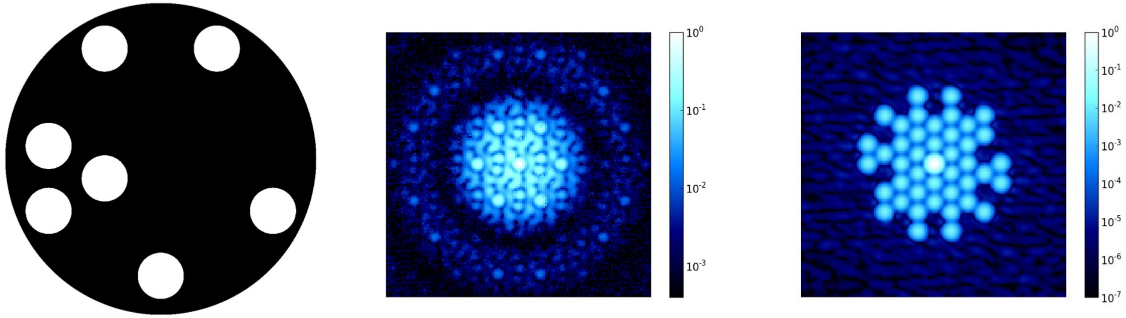
HD 206893b, predicted by Grandjean et al. 2019, detected with GRAVITY by Hinkley et al. 2023

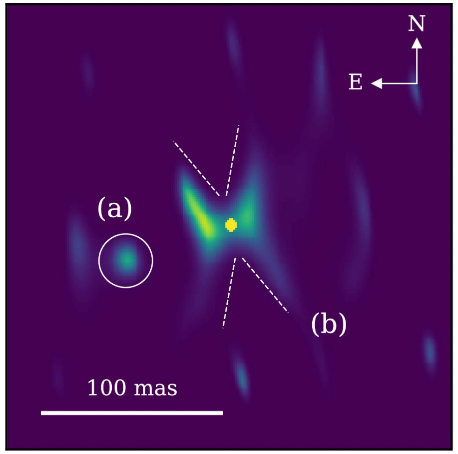
Interferometric Techniques

Non-redundant Masking, see talk by Steph Sallum

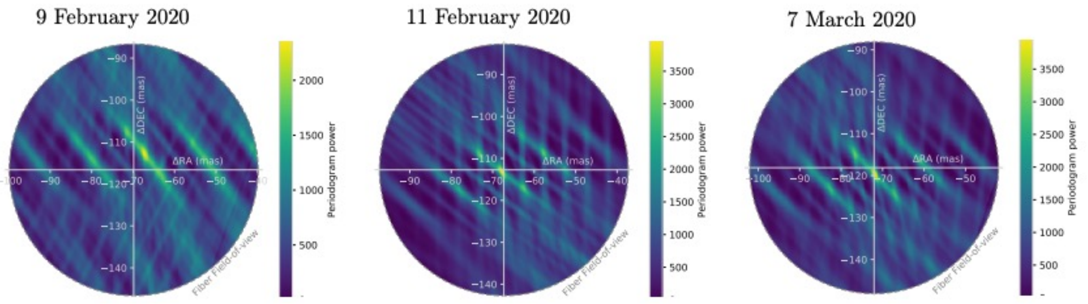
High contrast interferometry, with multiple apertures, see talk by Guillaume Bourdarot

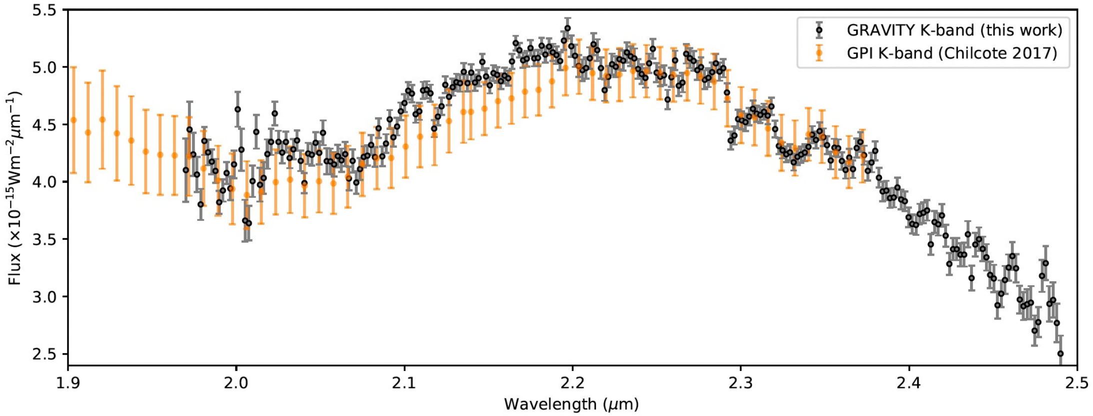
Cheetham et al. 2016



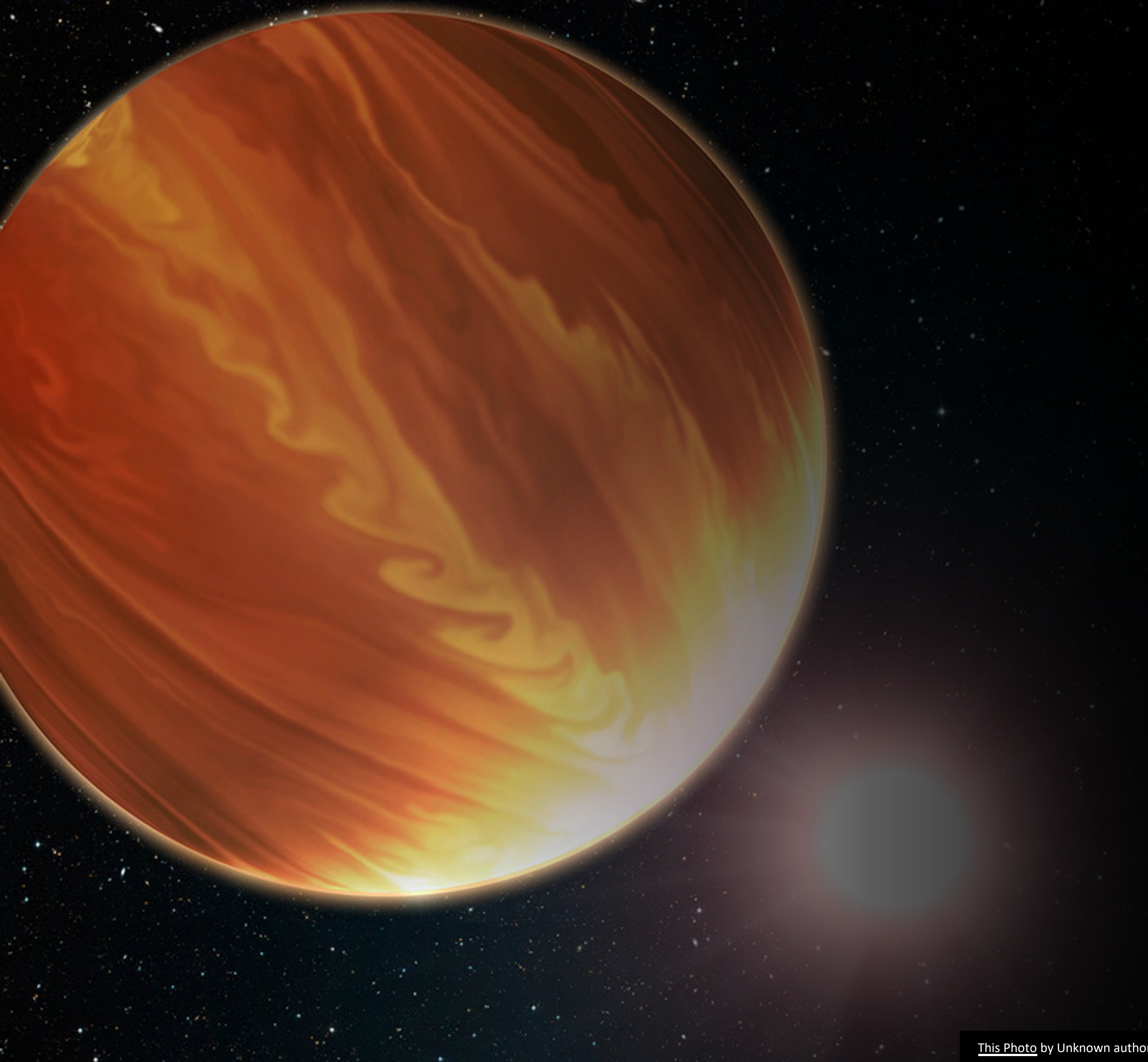


Sallum et al. 2021

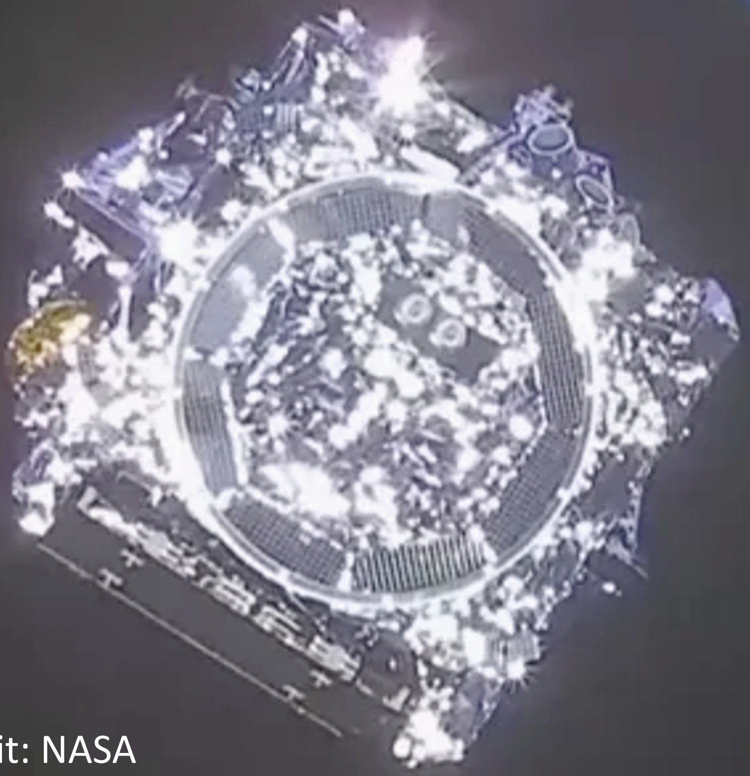




GRAVITY consortium et al. 2019, 2020, Hinkley et al. 2023, Nasedkin et al. 2024



Next Steps – what does the future hold for directly imaged exoplanets?

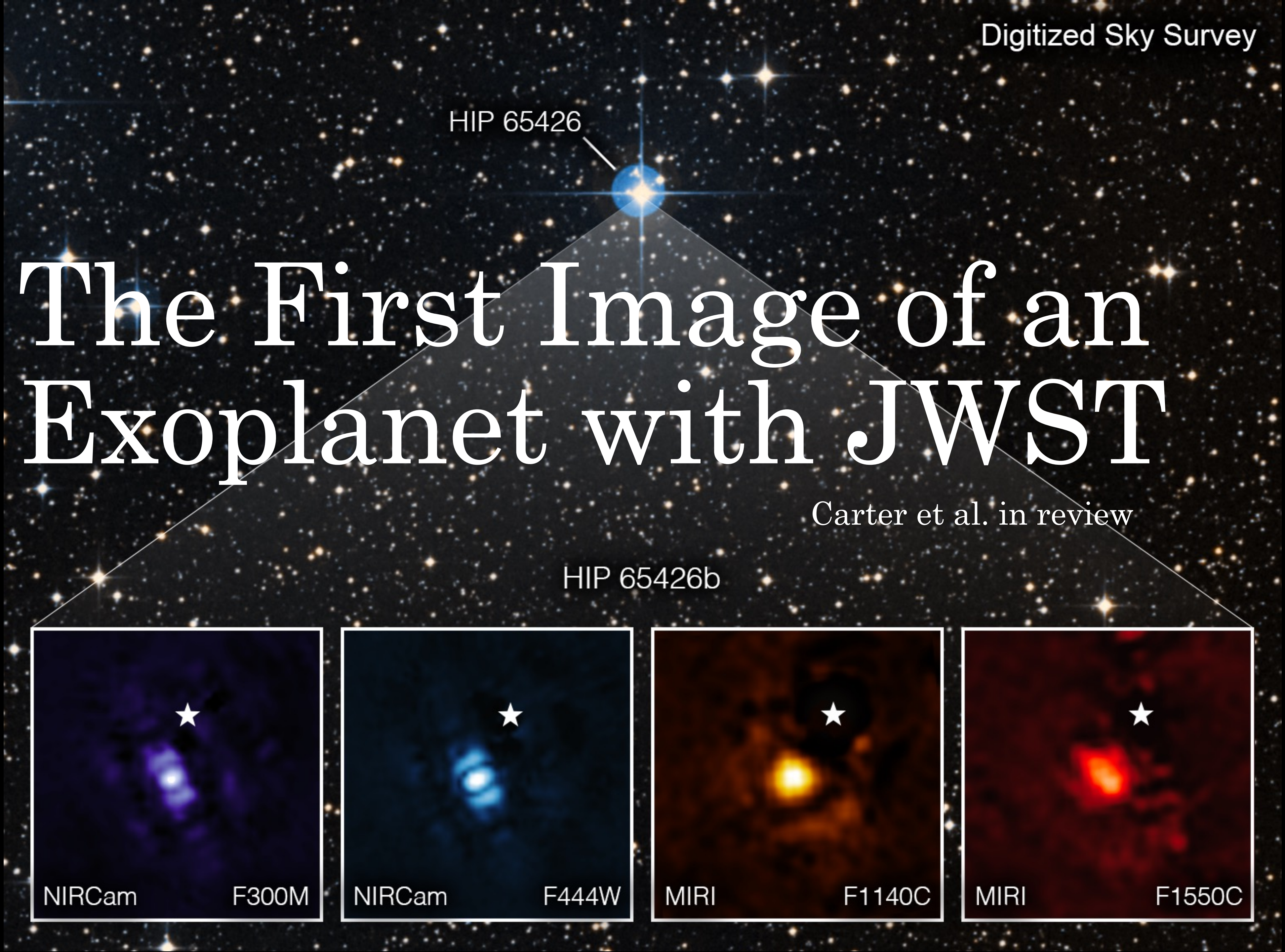


Credit: NASA

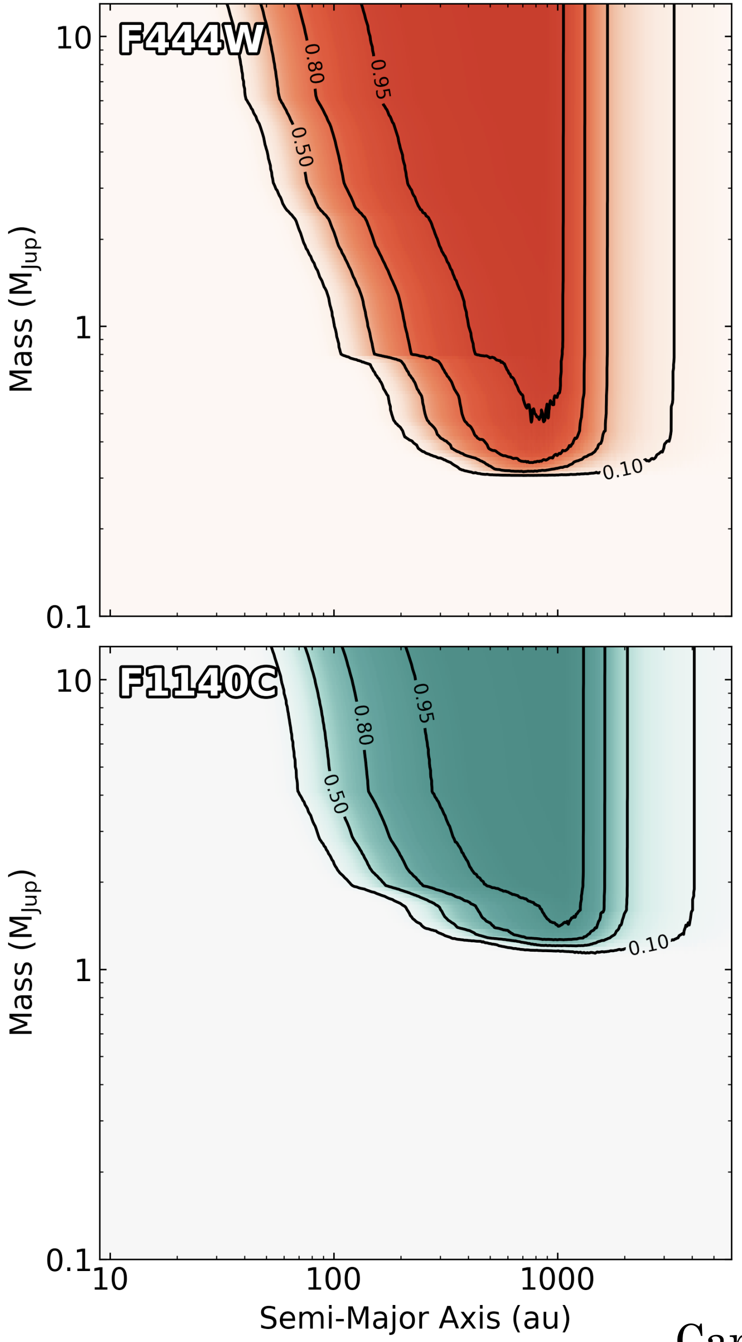
The Next 5 years: Breakthroughs with JWST

The First Image of an Exoplanet with JWST

Carter et al. in review



See talk by Kim Ward-Duong



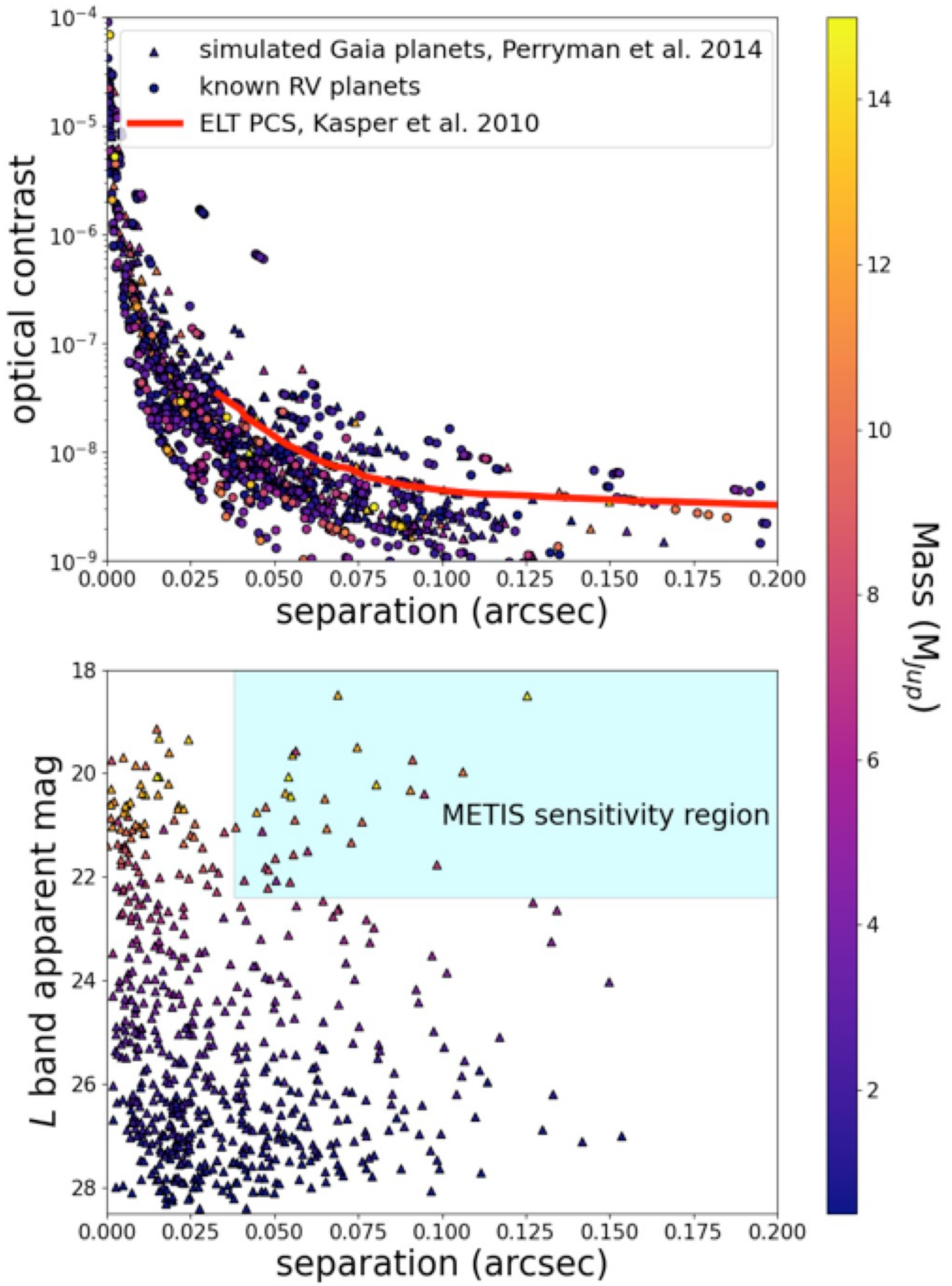
These observations had the sensitivity to image widely separated Saturn-mass planets!

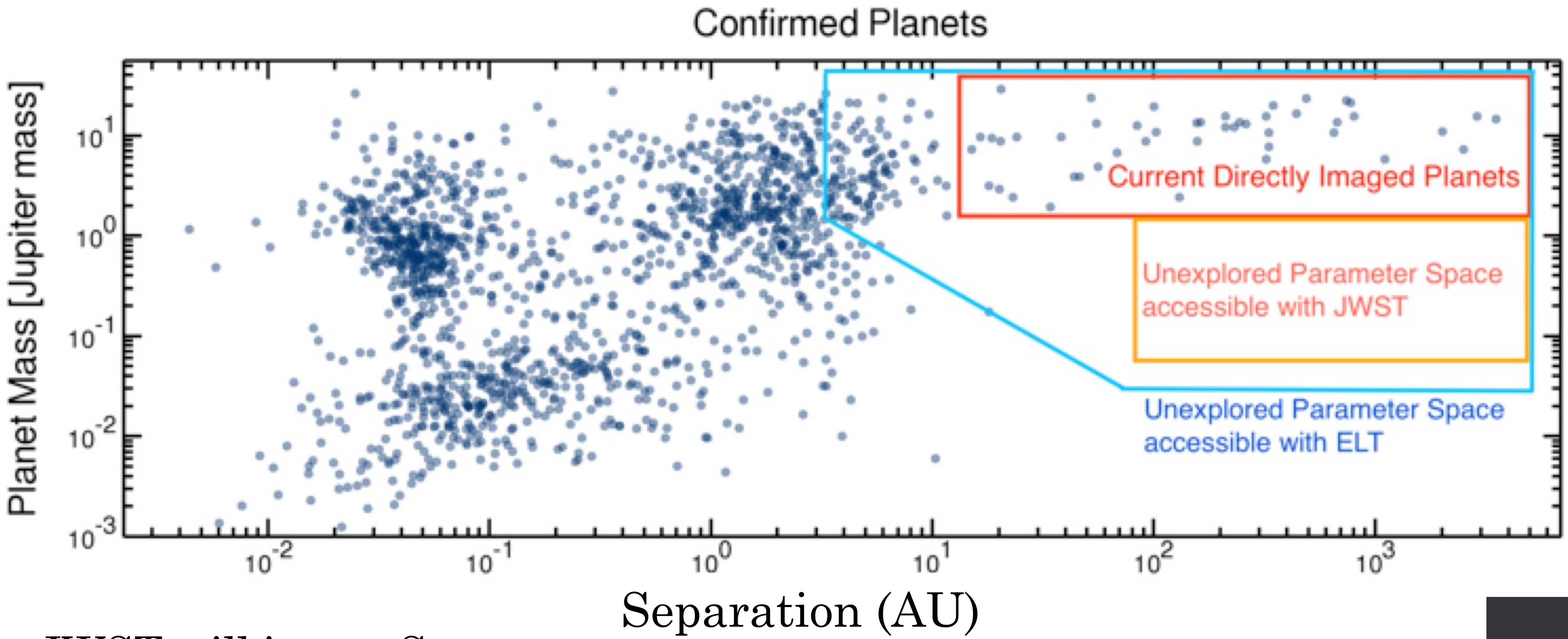
Carter et al. submitted, using Mariangela Bonavita's EXO-DMC code

The next 10 years – imaging reflected light planets with ELTs

Credit: ESO

Imaging of RV and Gaia-detected planets with ELTS

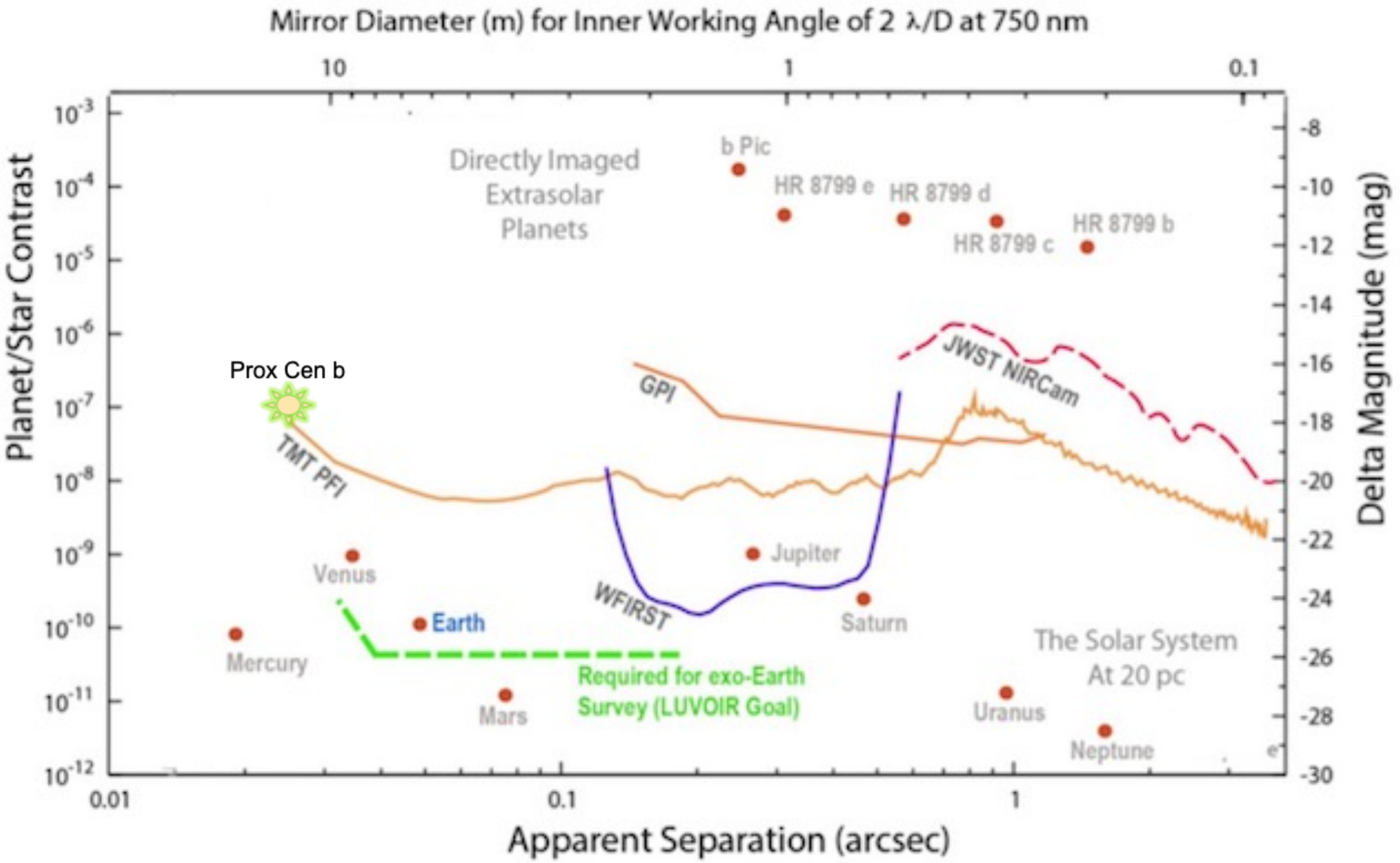




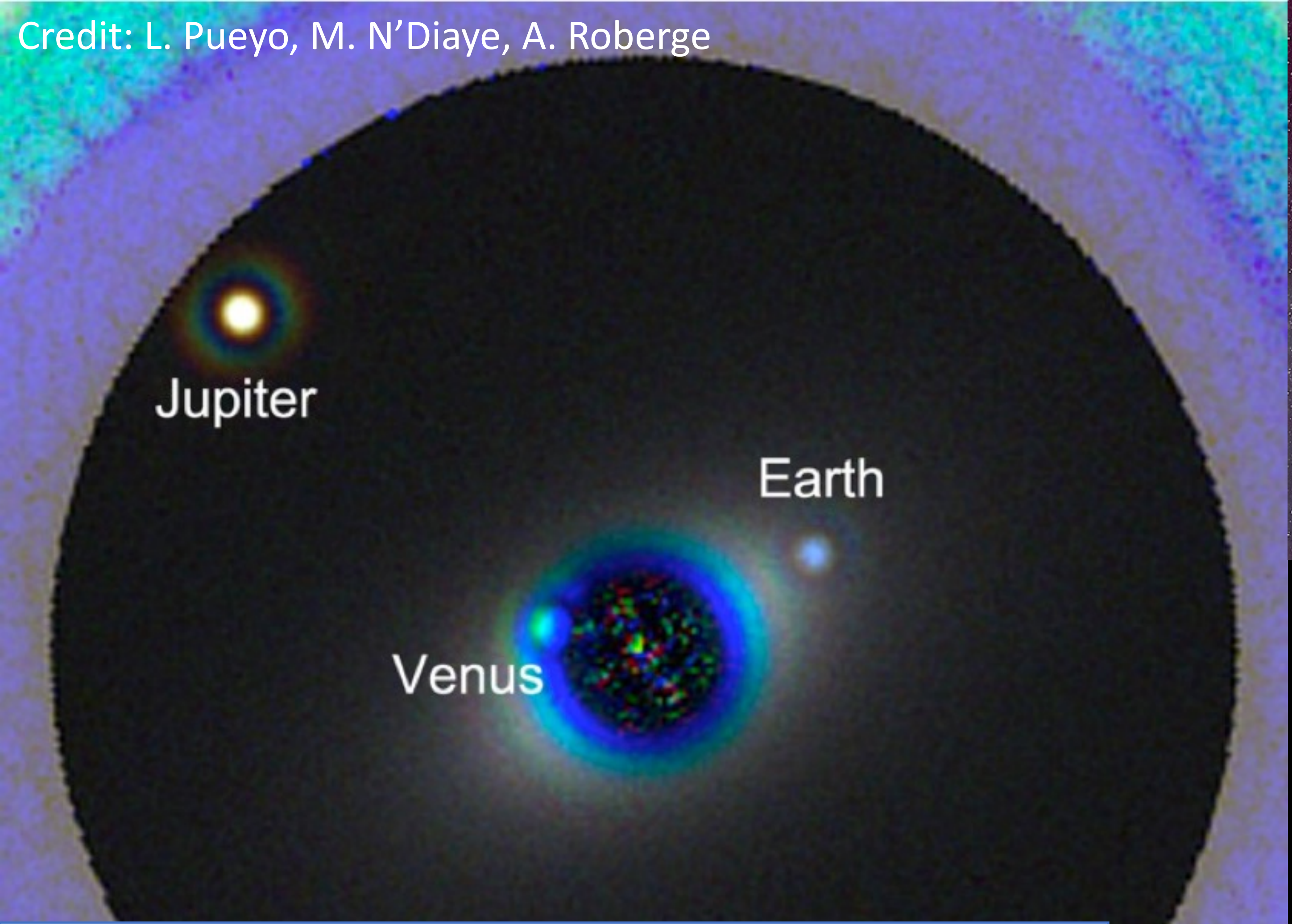
JWST will image Saturn-mass planets; Roman may image RV-detected planets; ELTs will image cold, solar-system age planets

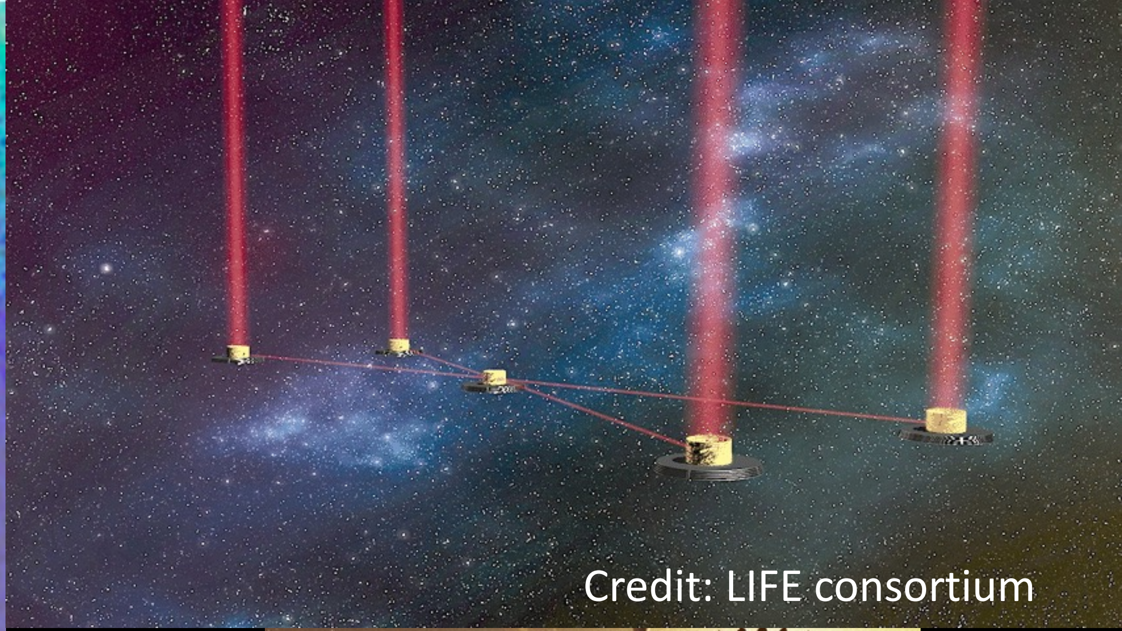
Contrasts estimated from Carter et al. 2023, Kasper et al. 2010, Quanz et al. 2015

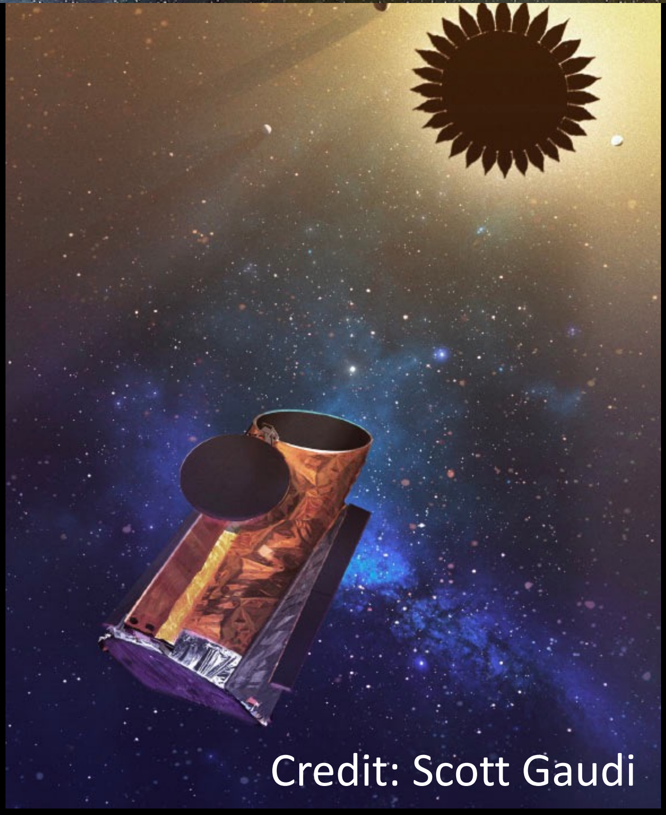
See talks by Gilles Orban de Givry, Jared Males, and Aline Dinkelaker for more detail on prospects with ELTs and beyond



Predicted contrasts for next generation imagers, adapted from Lawson et al. 2012, Mawet et al. 2012





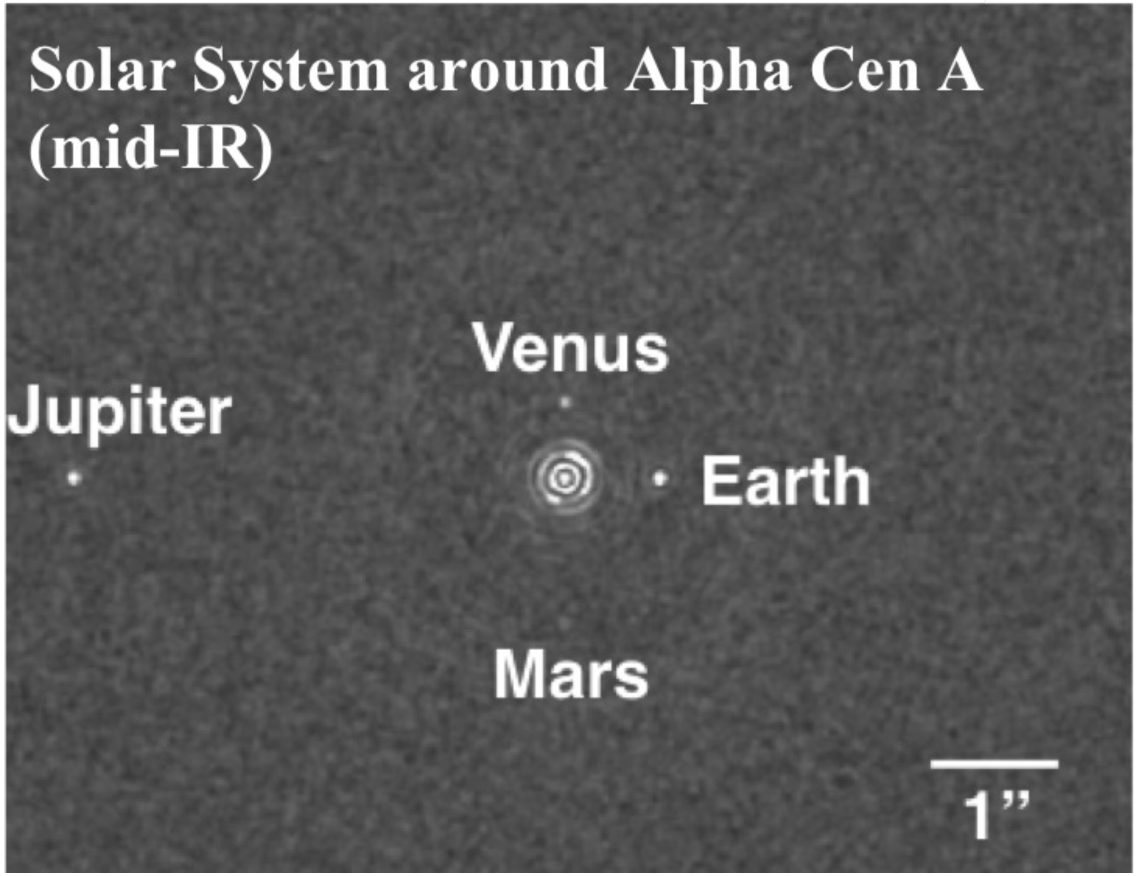


The Habitable Worlds Observatory and LIFE interferometer

Critical Future Goals : Direct Imaging of Exo-Earth twins

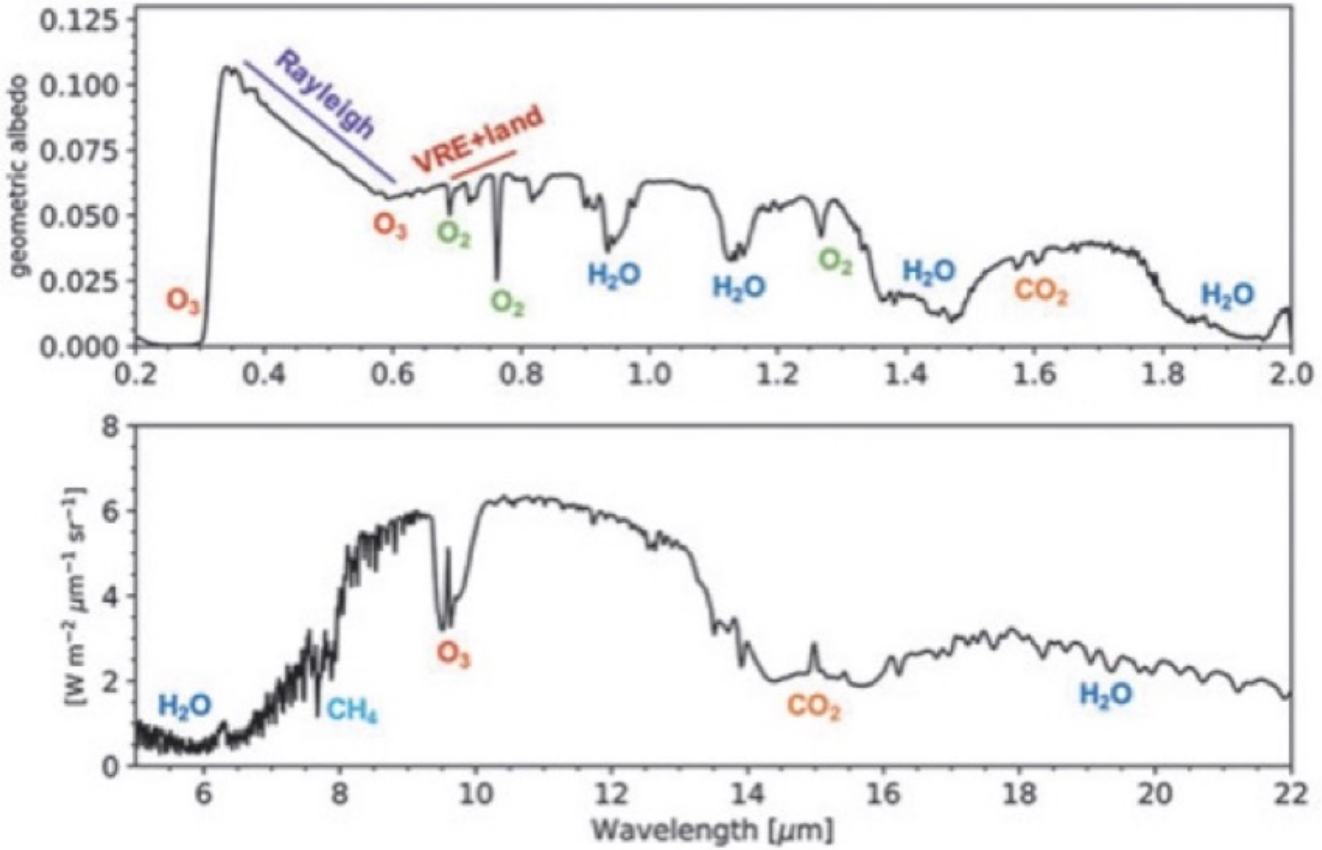
See talks by Courtney Dressing and Chris Stark

Thermal Emission



Lopez-Morales et al. 2019

Reflected Light



Schwieterman et al. 2017

Why Direct Imaging?

Test of Planet Formation Theories – direct imaging probes planets in formation

Physical Properties – direct spectra = direct probe of atmospheres

In coming decades, this is the most **sensitive technique for discovery of Exo-Earth twins**

Thank you!


Digitized Sky Survey
HIP 65426
HIP 65426b
NIRCam F300M
NIRCam F444W
MIRI F1140C
MIRI F1550C