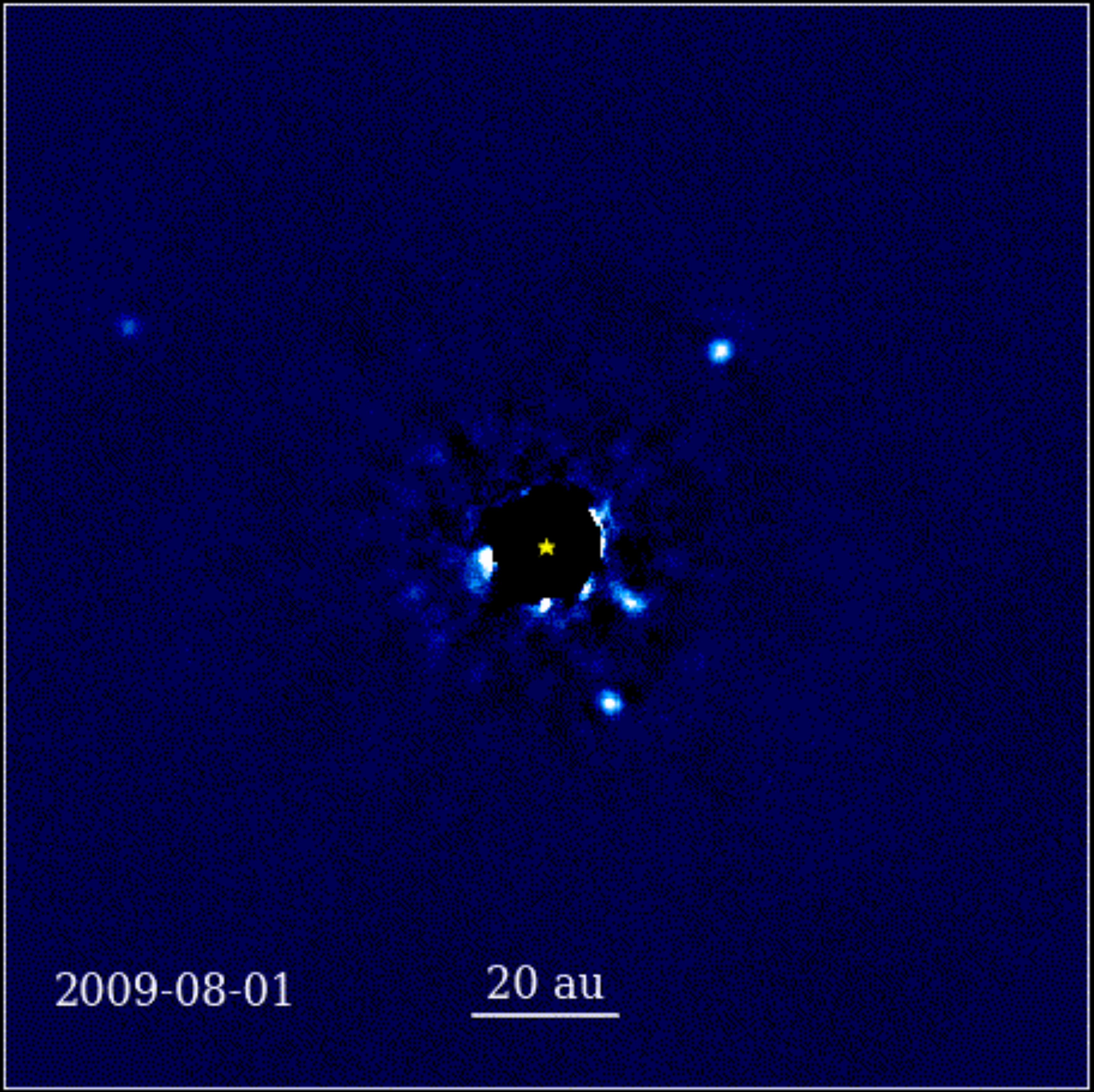
Direct Imaging

Eric Nielsen
New Mexico State University

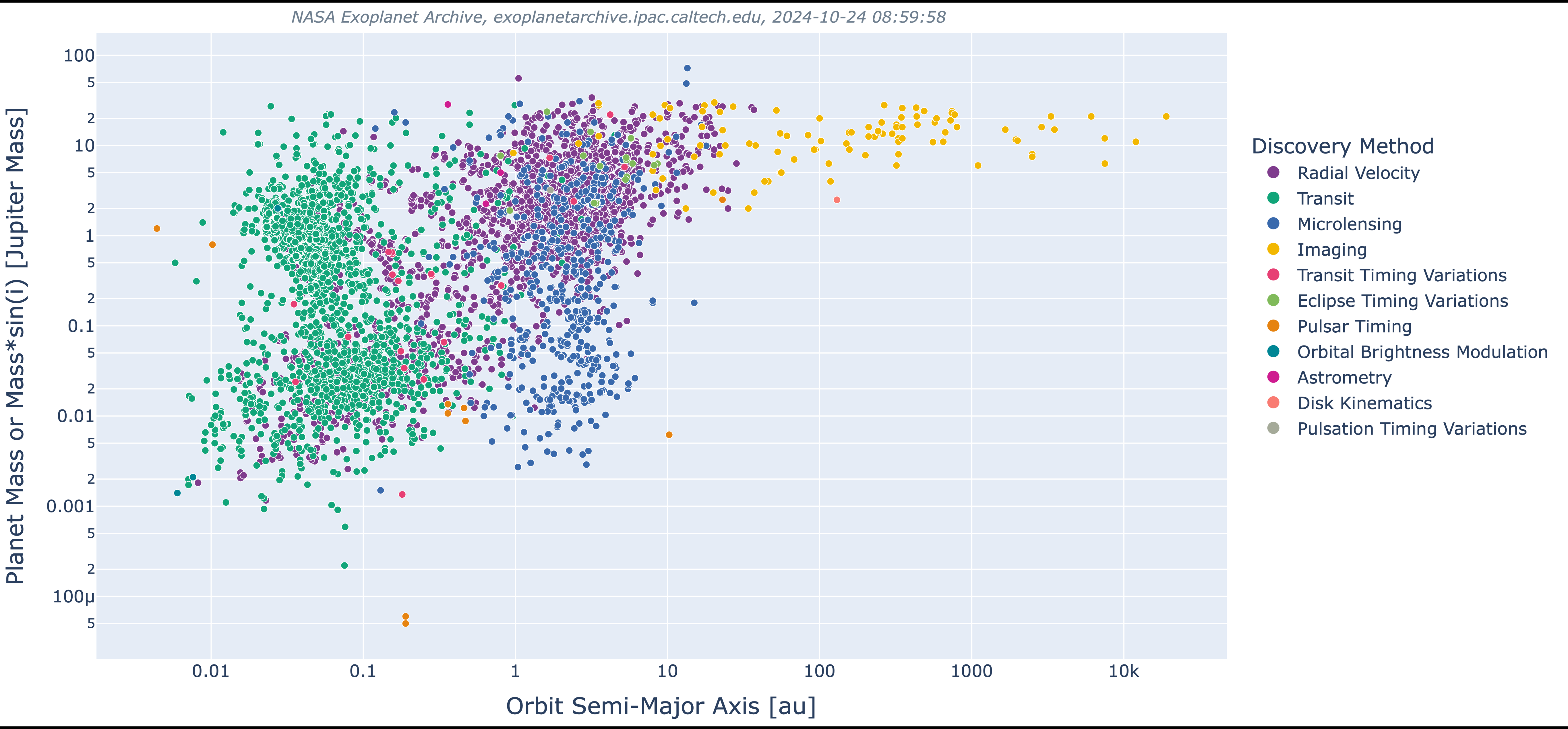
Sagan Summer Workshop
July 23, 2025

HR 8799: four directly imaged exoplanets

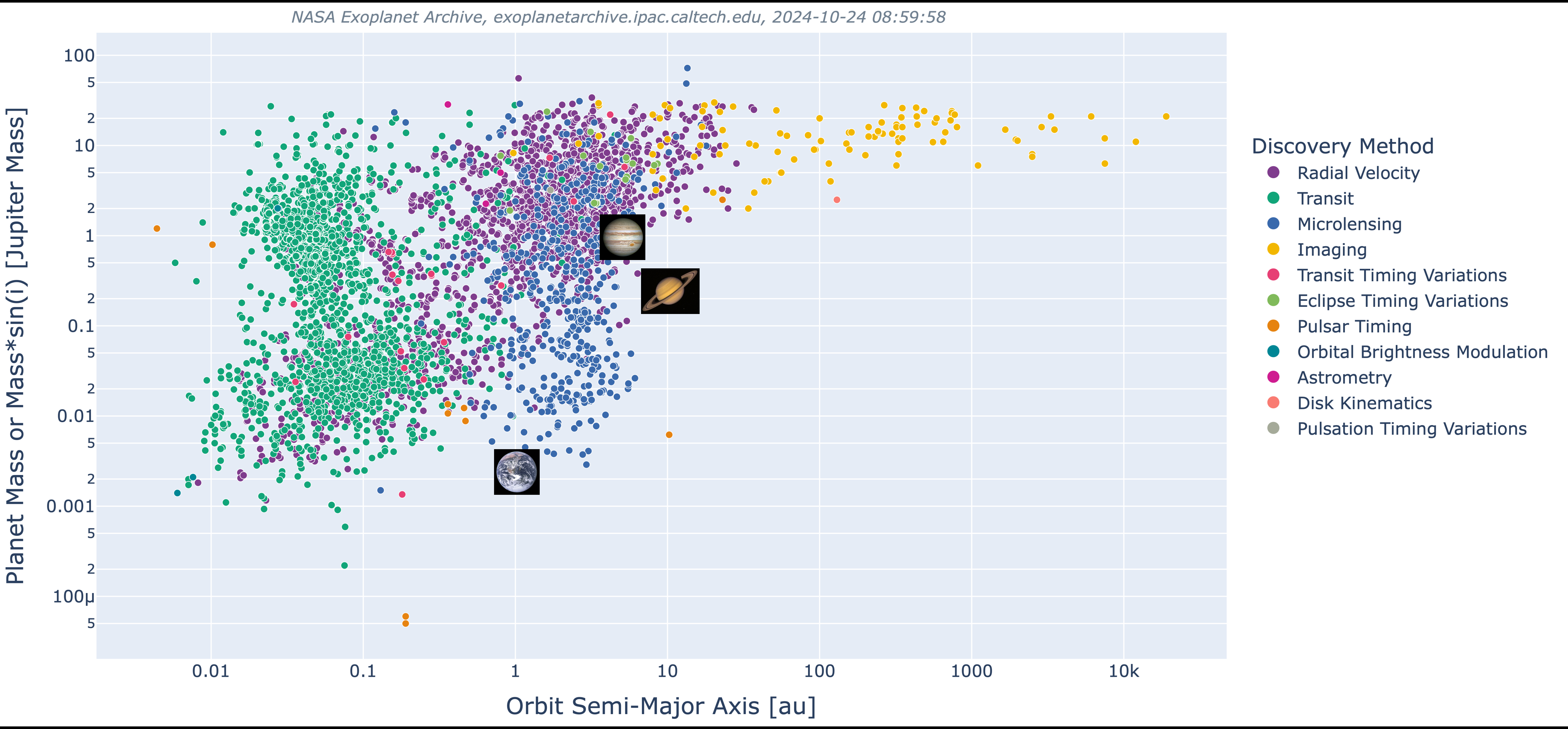


Jason Wang, William Thompson, Christian Marois, and Quinn Konopacky

Exoplanet Populations



Exoplanet Populations

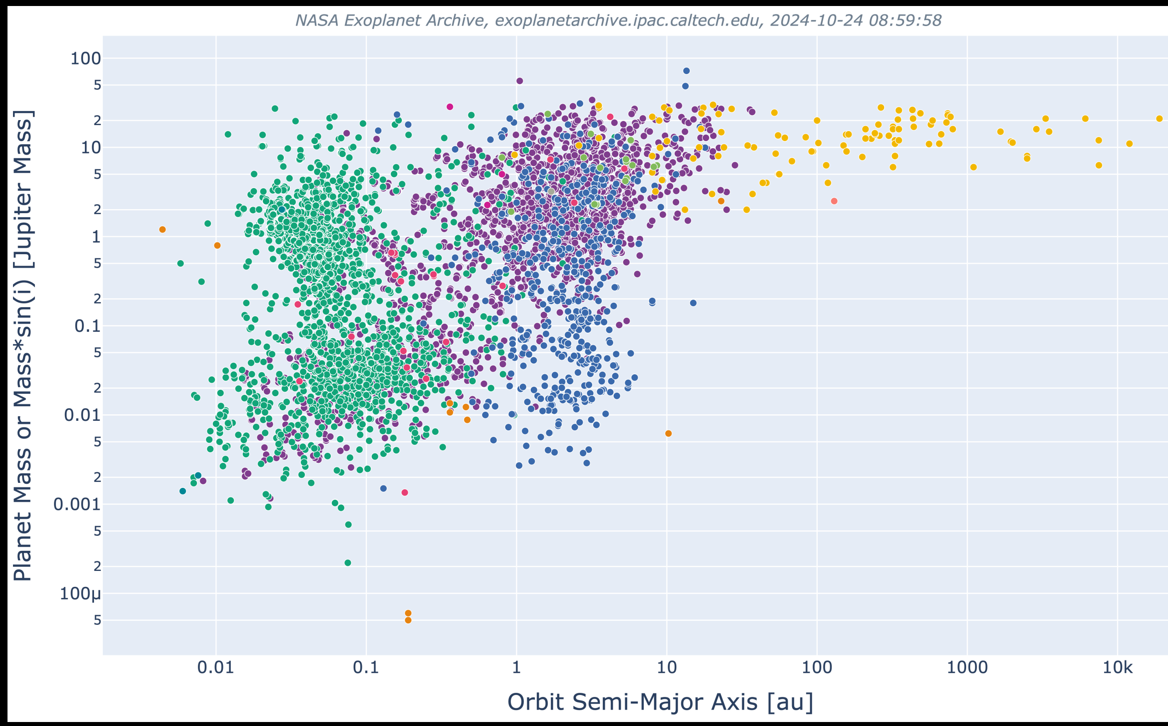


Direct Imaging Today

Self-luminous planets (not reflected light)

Planets are easier to detect further from their star

Brighter planets are easier to detect



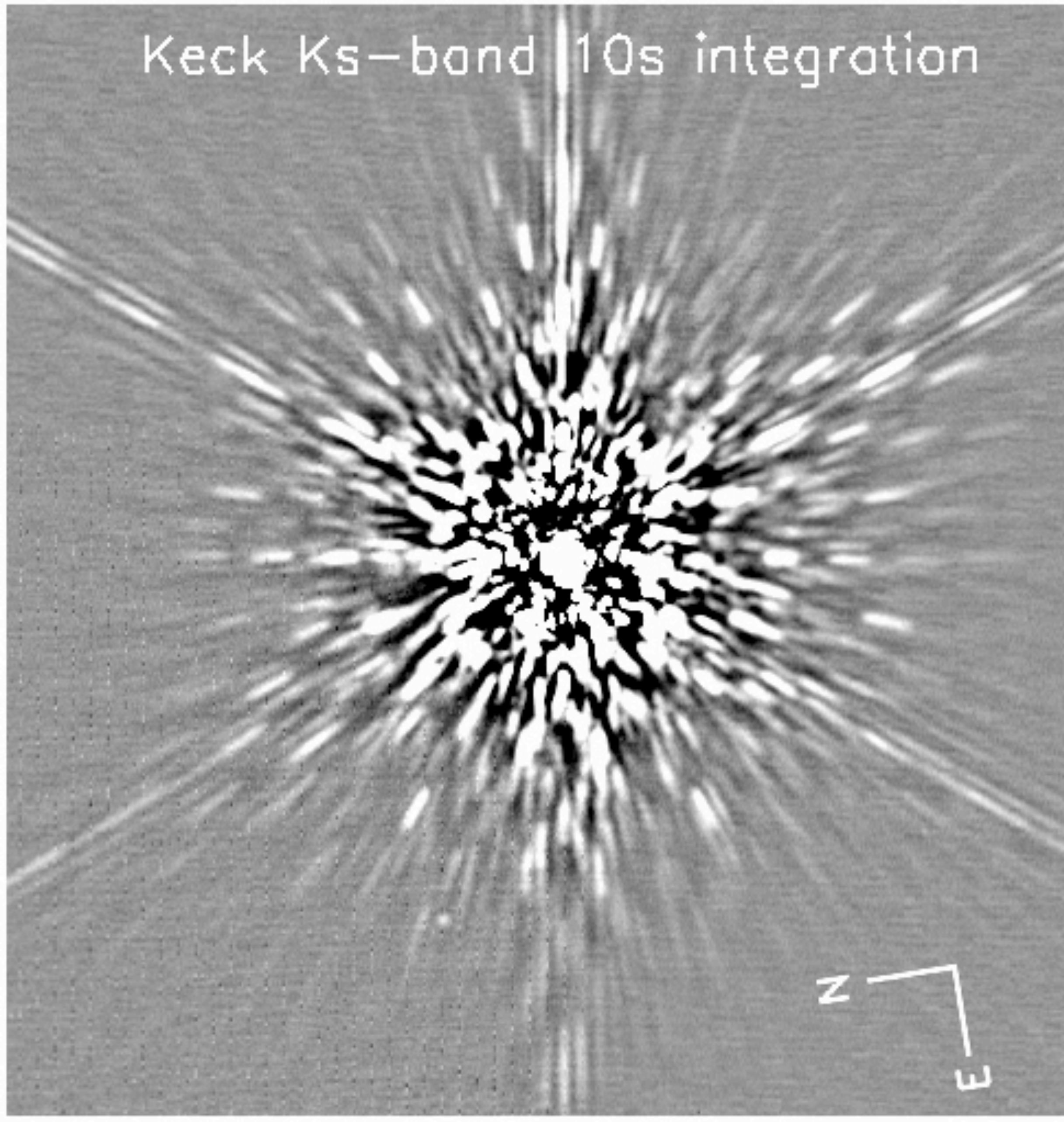
Star/Planet Contrast

Contrast: $\dfrac{\text{Planet Flux}}{\text{Star Flux}}$

Depends on wavelength

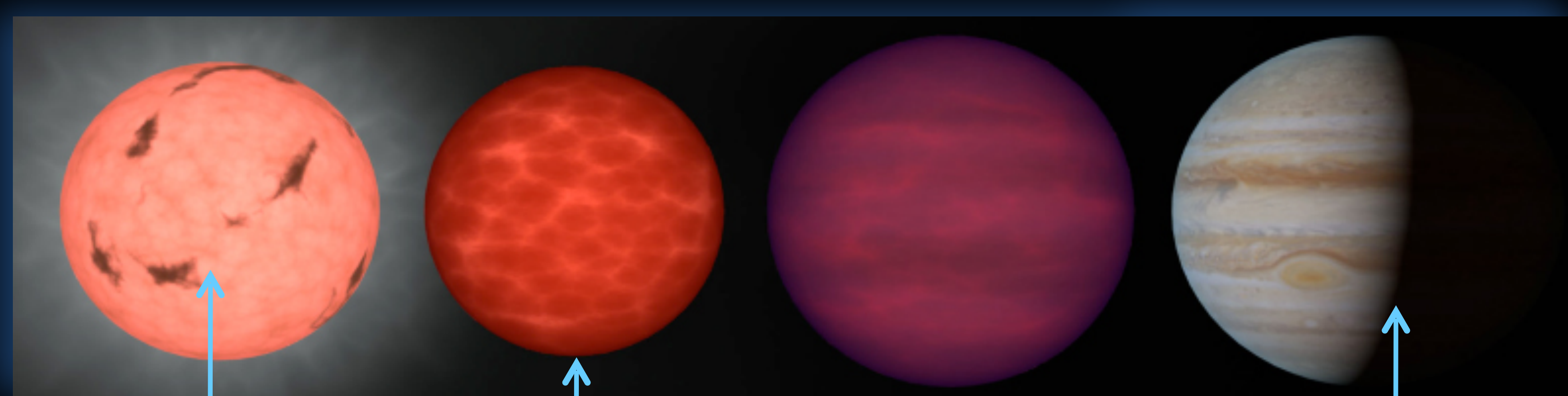
In the visible for the Sun and the Earth (reflected light):

Contrast $\approx 10^{-10}$



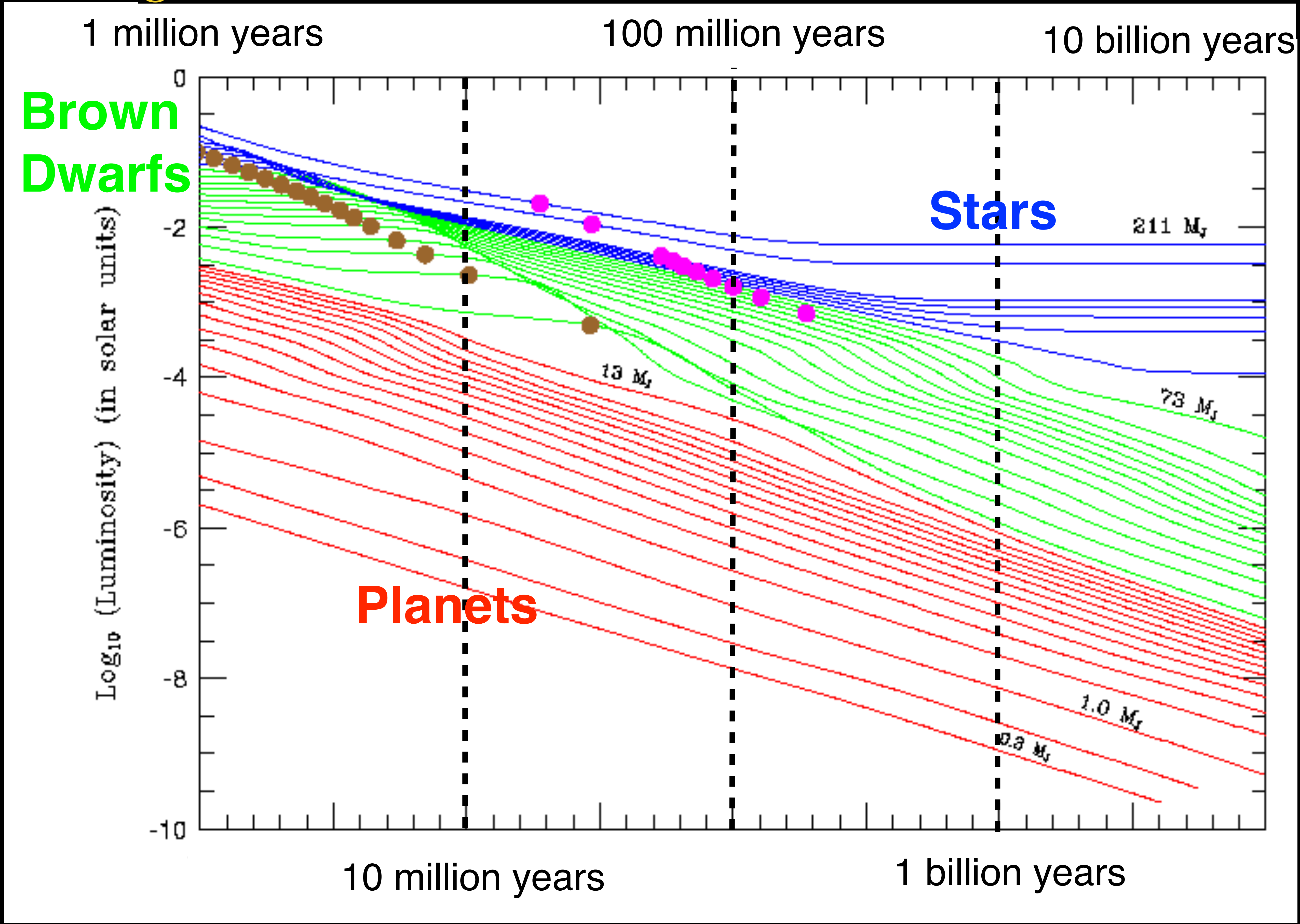
Christian Marois

Young planets are the easiest to see



NASA/IPAC/R. Hurt (SSC)

Cooling with time



Adam Burrows

2M 1207

~10 Myr

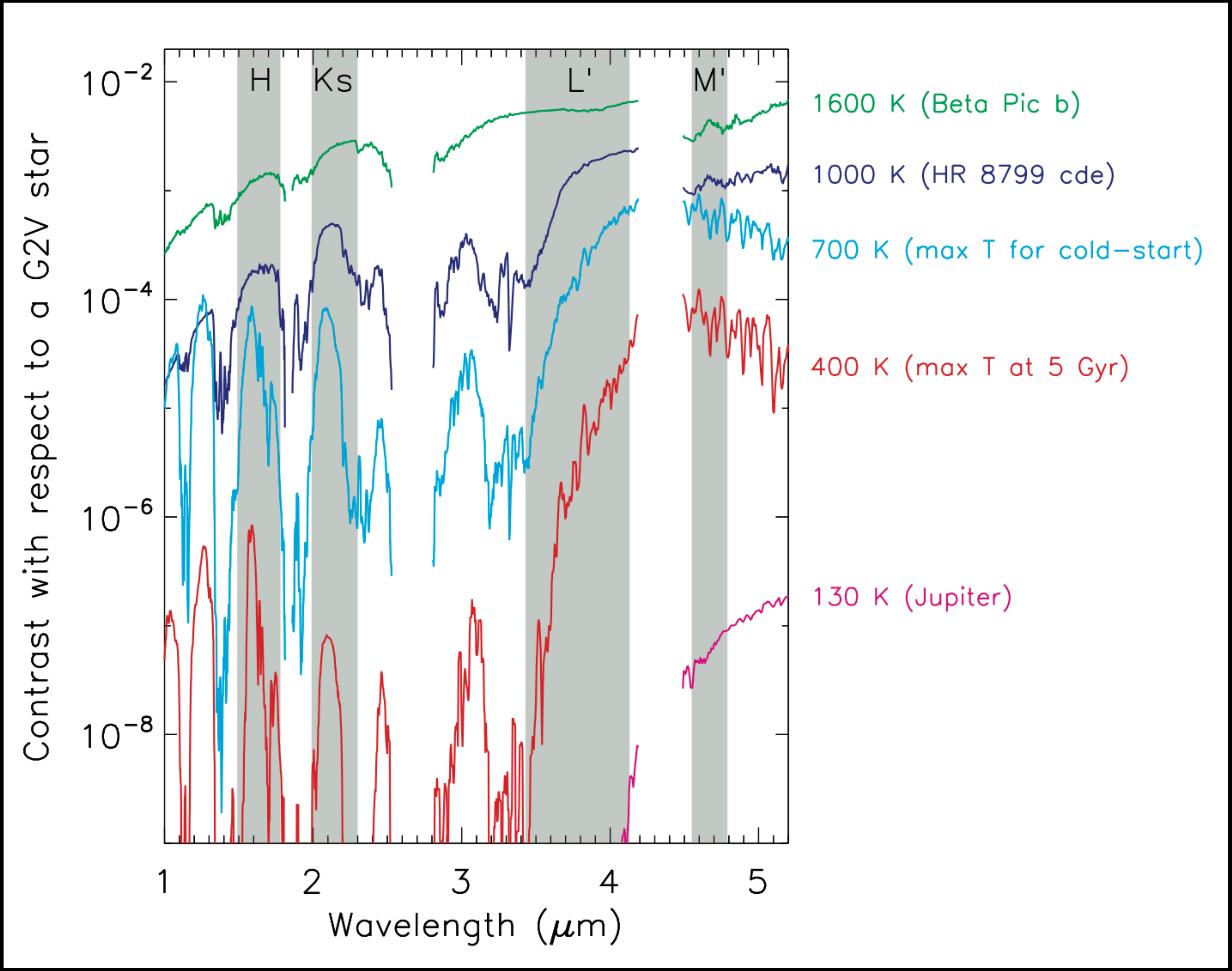
Primary is a ~25 M_{Jup} brown dwarf

Contrast (H): $5x10^{-3}$

Contrast (L): $3x10^{-2}$

Chauvin et al. 2004

Contrast also depends on temperature and wavelength



Skemer et al. 2014

Angular Resolution

(most) Exoplanets are <1″ from their host star

At 10 pc:

- Earth is ~0.1″ from the Sun
- Saturn is ~1″ from the Sun

Better angular resolution:

- bigger telescopes
- shorter wavelengths

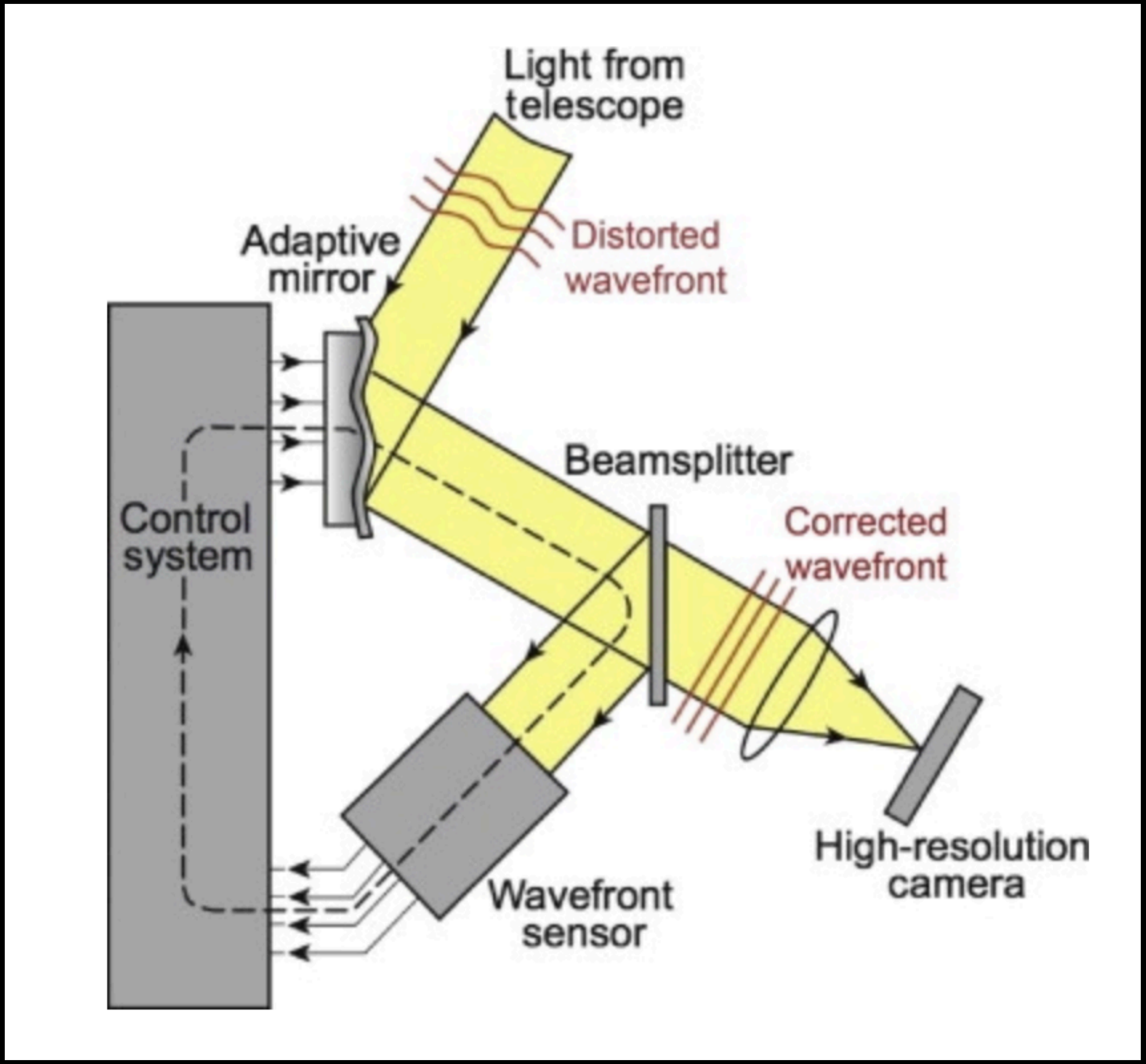
Inner Working Angle (IWA)

Chauvin et al. 2004

Adaptive Optics

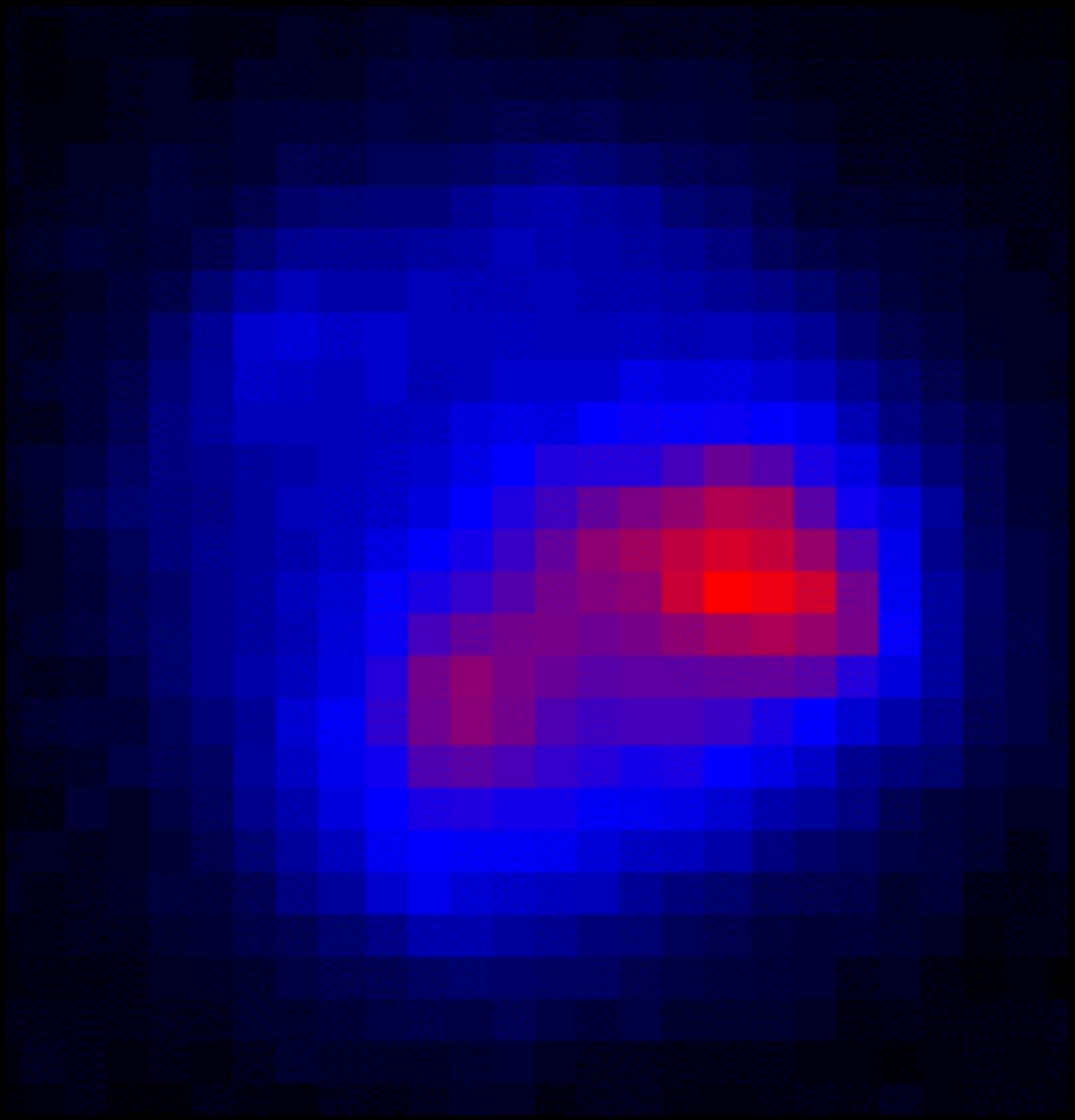
Deformable mirror corrects light distorted by Earth's atmosphere

Modern AO systems make changes 1000x per second or faster



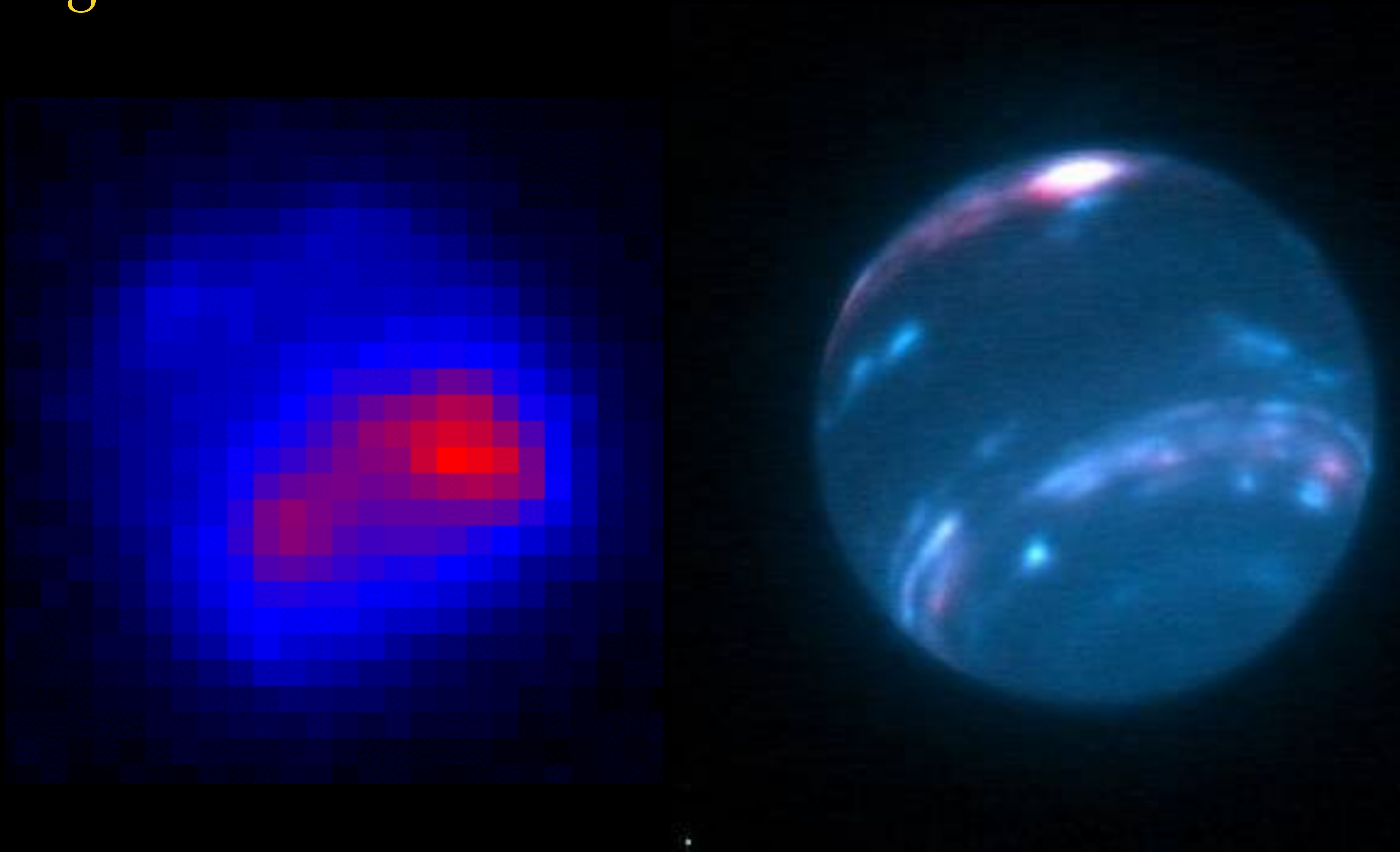
Claire Max

Angular Resolution



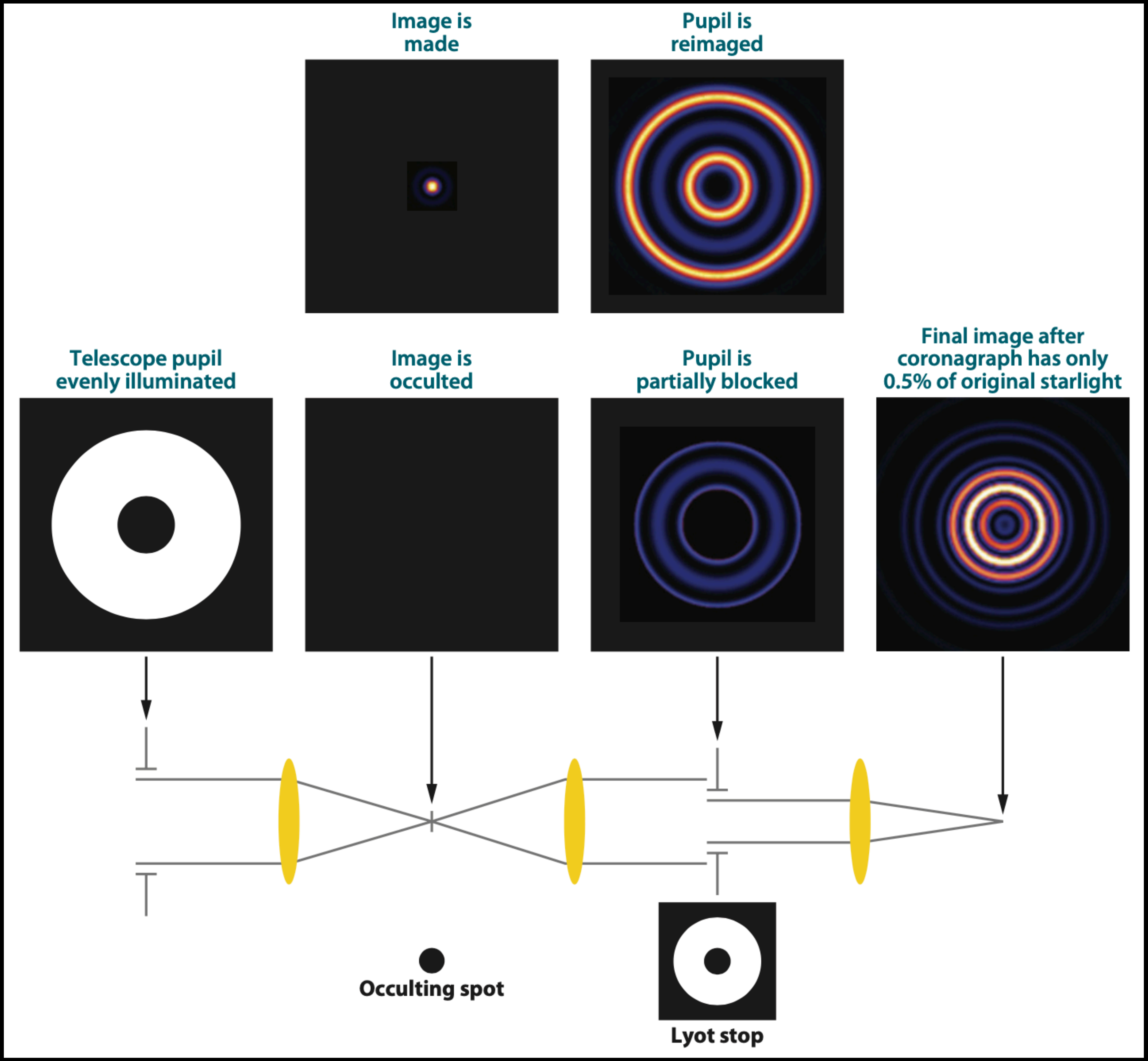
UCO/Lick

Angular Resolution



UCO/Lick

Coronagraphs



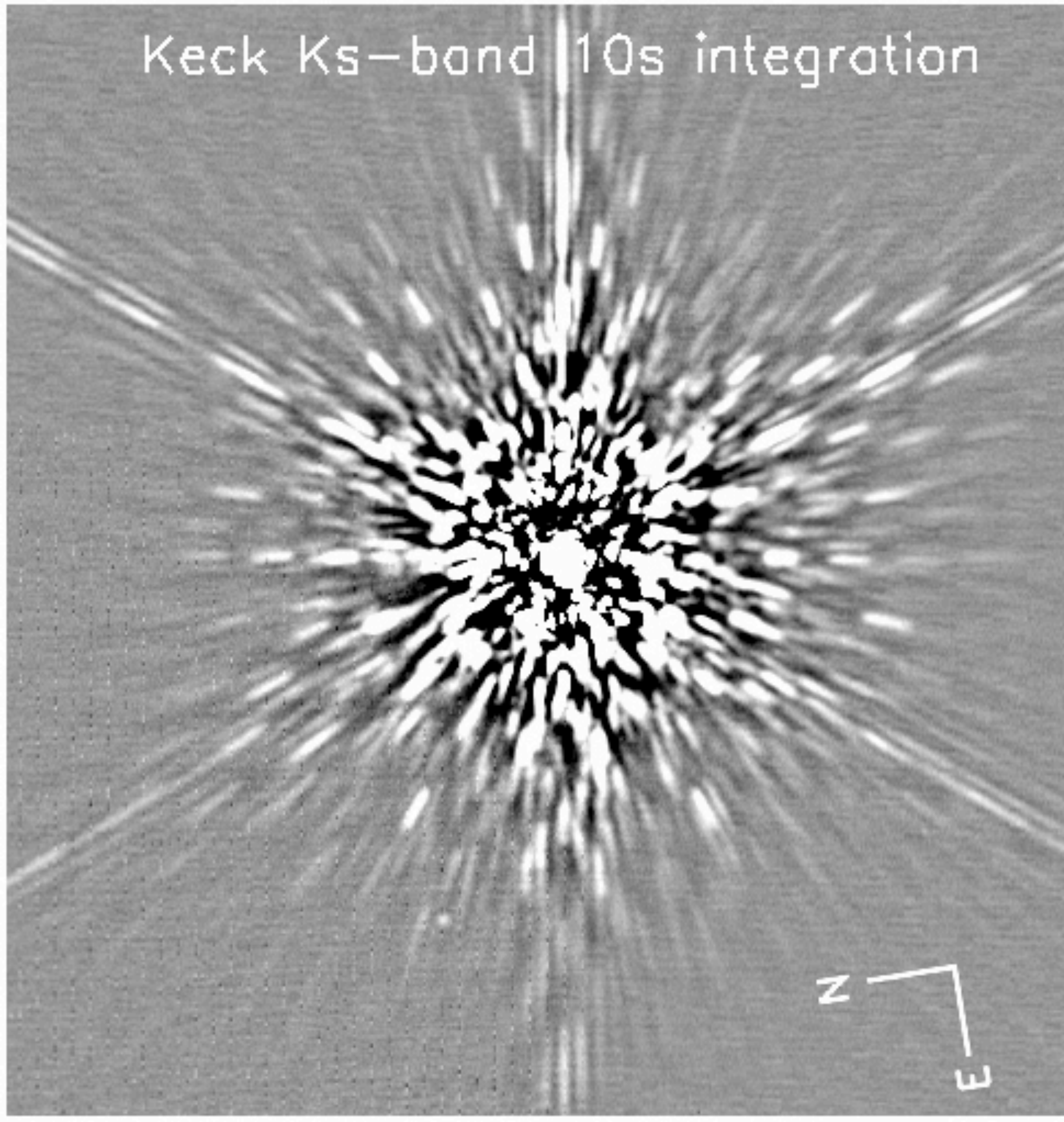
Oppenheimer & Hinkley 2009

Speckles

Uncorrected starlight

Imperfections in telescope and instrument

Vary with timescales of minutes to hours



Christian Marois

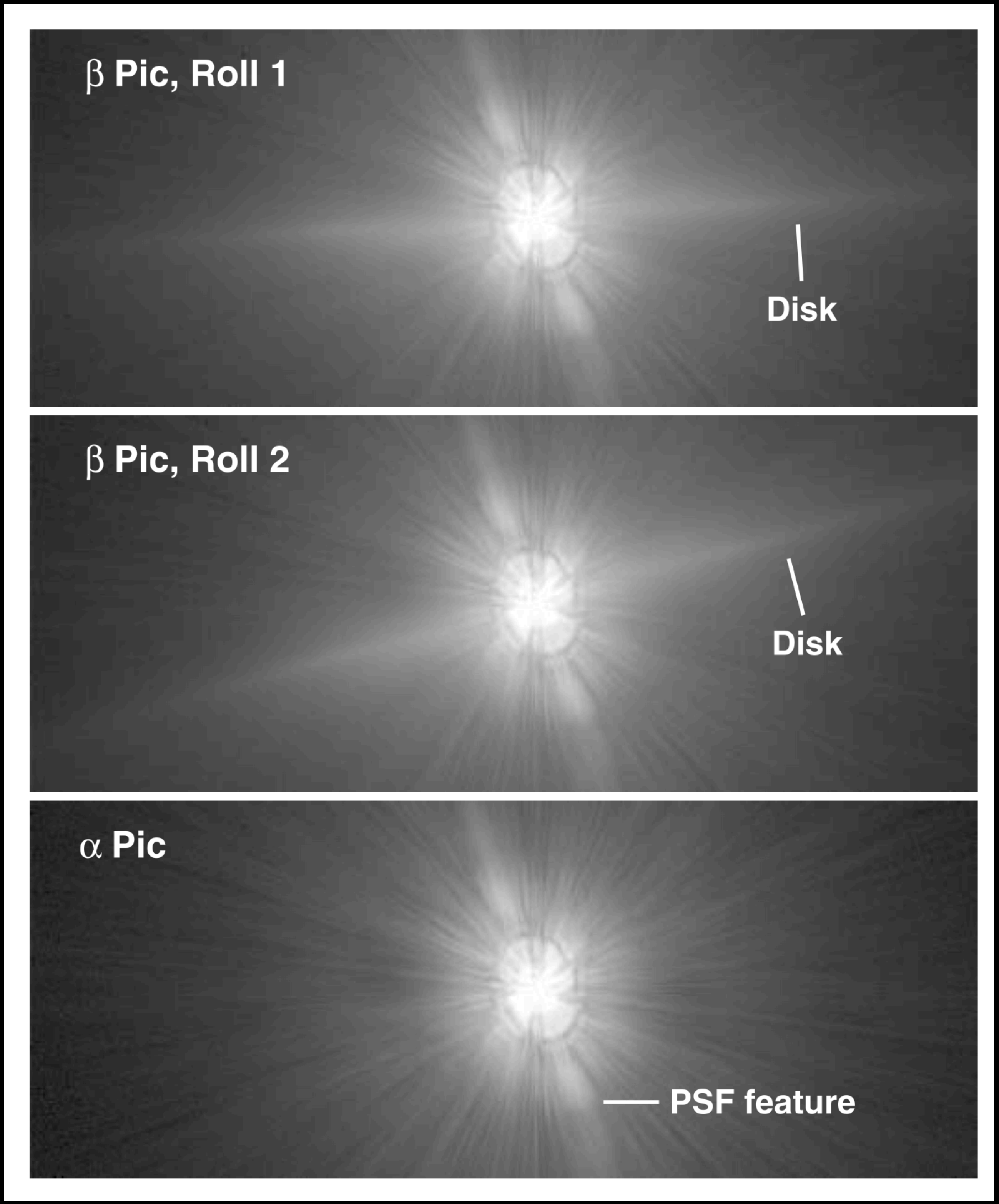
Differential Imaging

PSF Subtraction

Subtract two images:

- star + planet
- star only

Need an image of the star (PSF) without the planet!



Golimowski et al. 2006

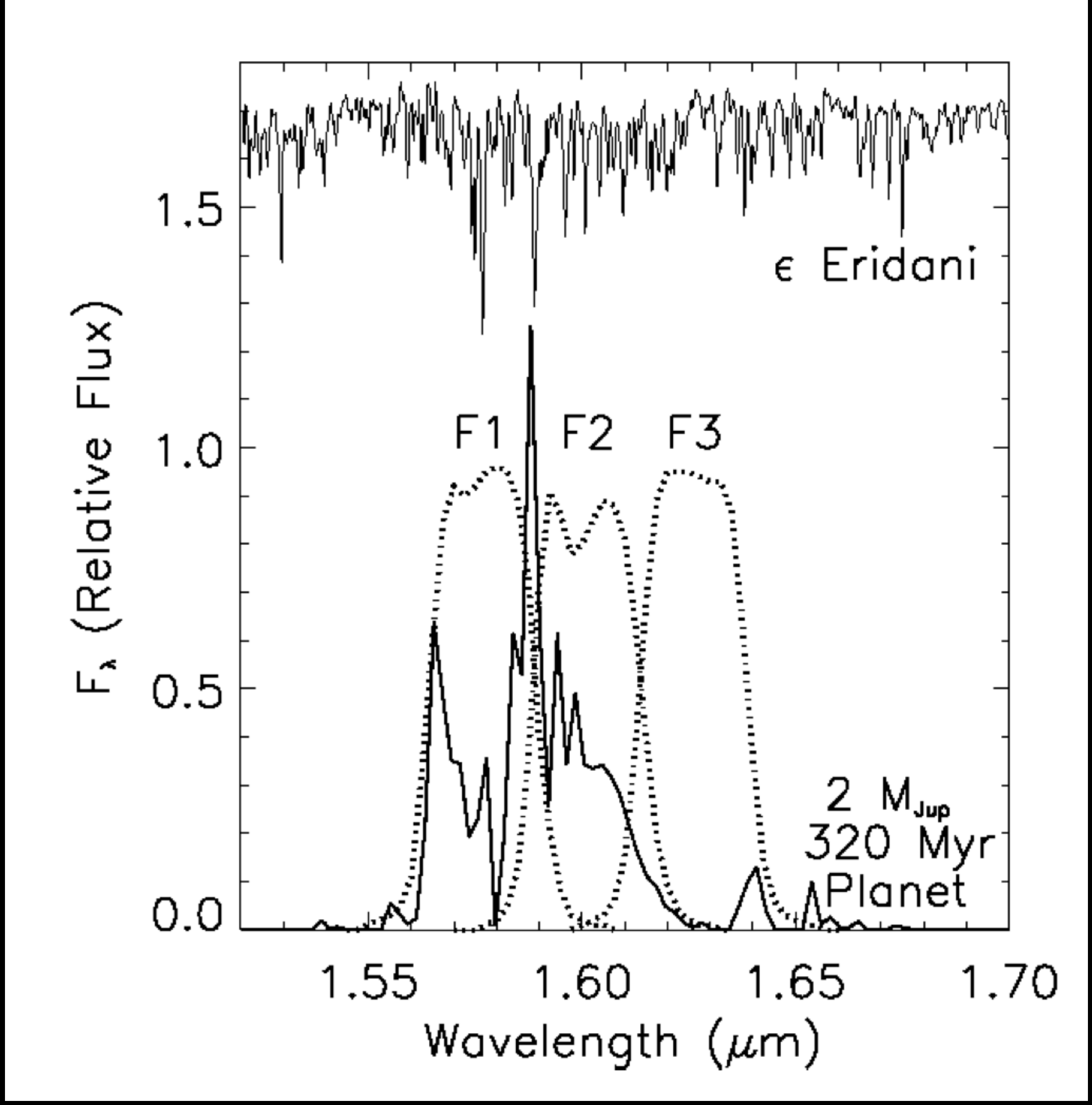
Spectral Differential Imaging (SDI)

Find 2 nearby wavelengths:

- planet bright in one, faint in the other
- star equally bright in both

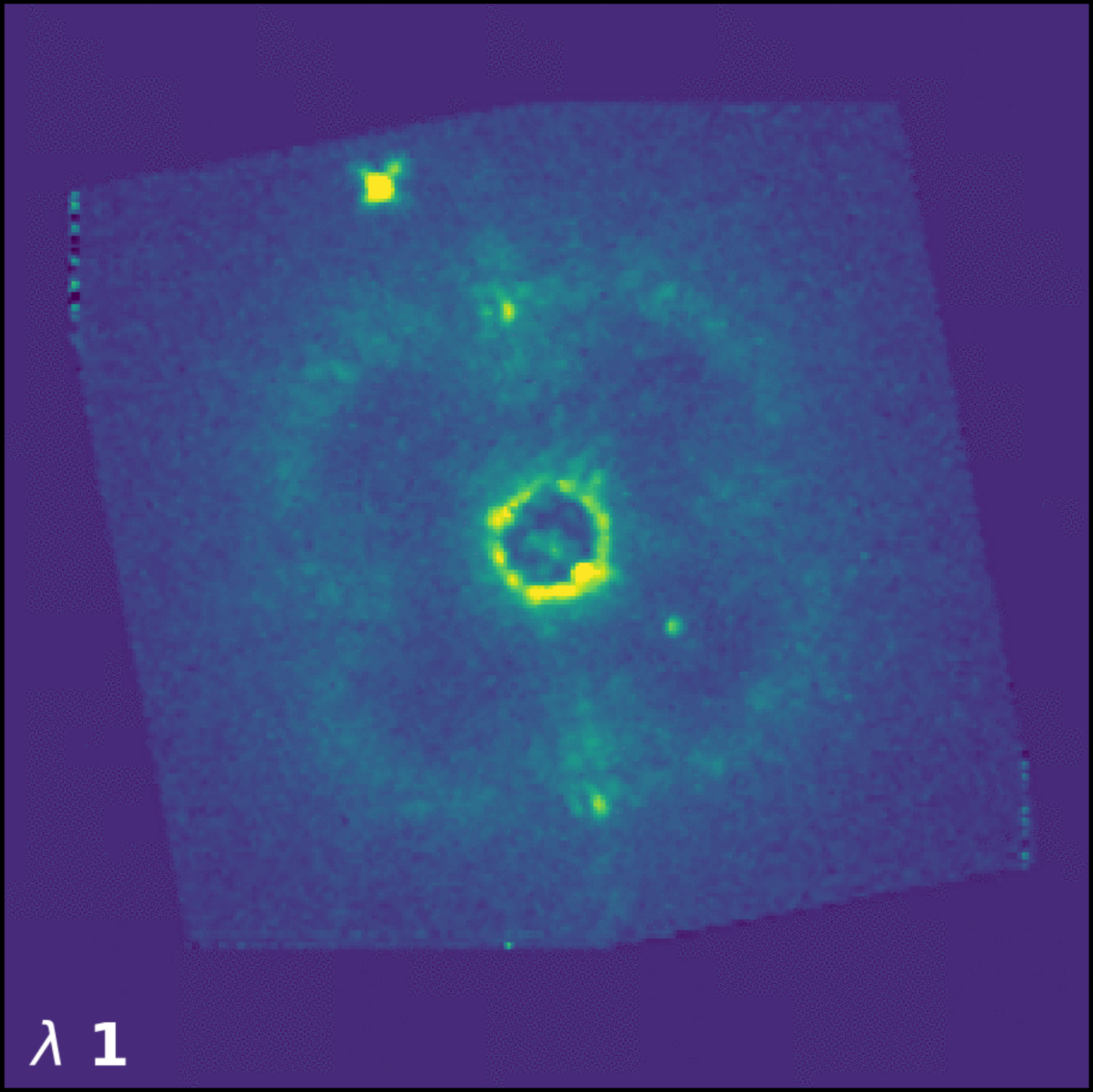
Narrowband filters or IFU

Speckles (starlight) should be same in both wavelengths



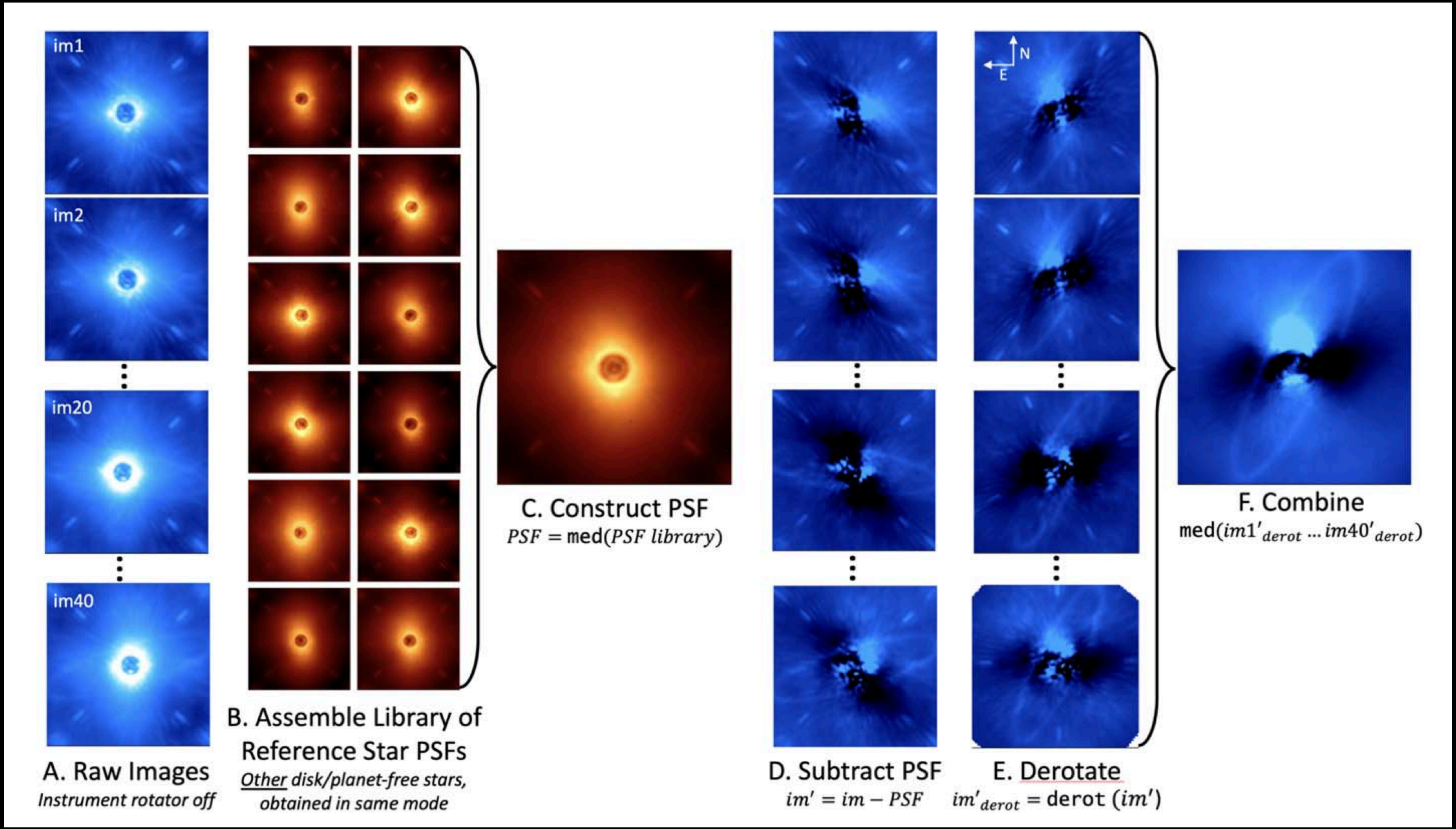
Janson et al. 2007

Spectral Differential Imaging (SDI)



Exoplanet Imaging Challenge

Reference Differential Imaging (RDI)

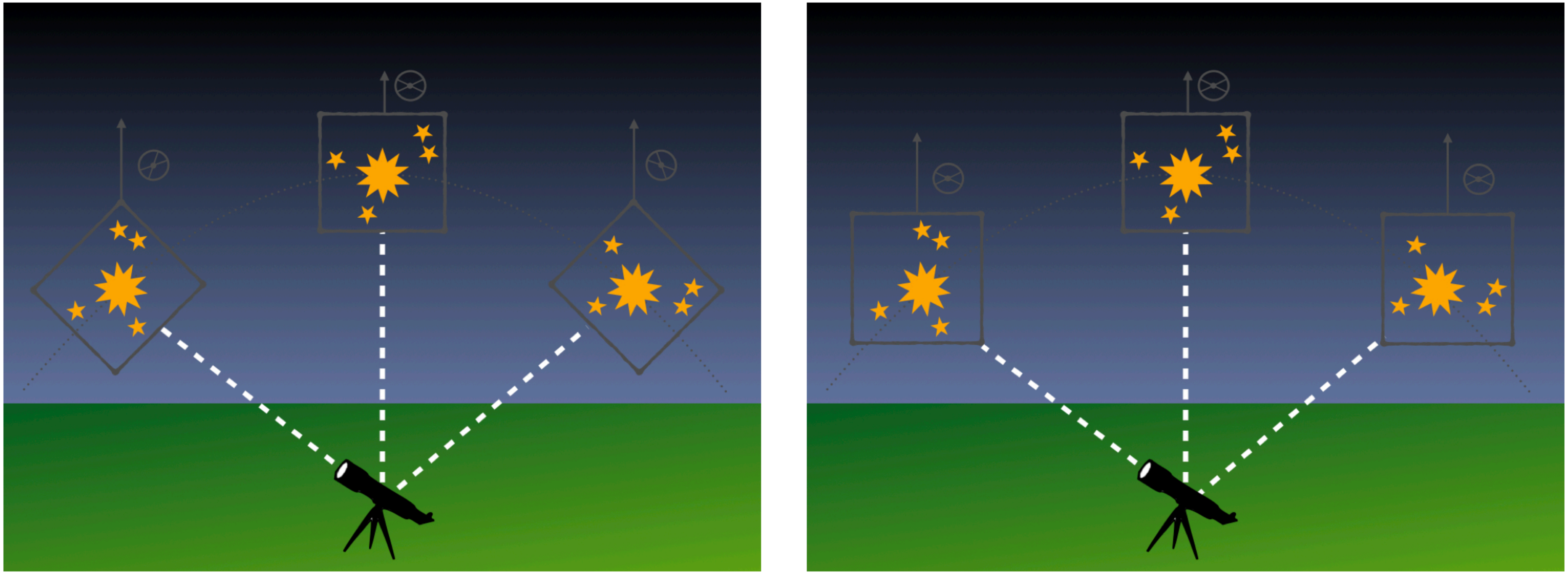


Follette 2023

Find similar observation of another star

Or: linear combination of library of other stars

Angular Differential Imaging (ADI)



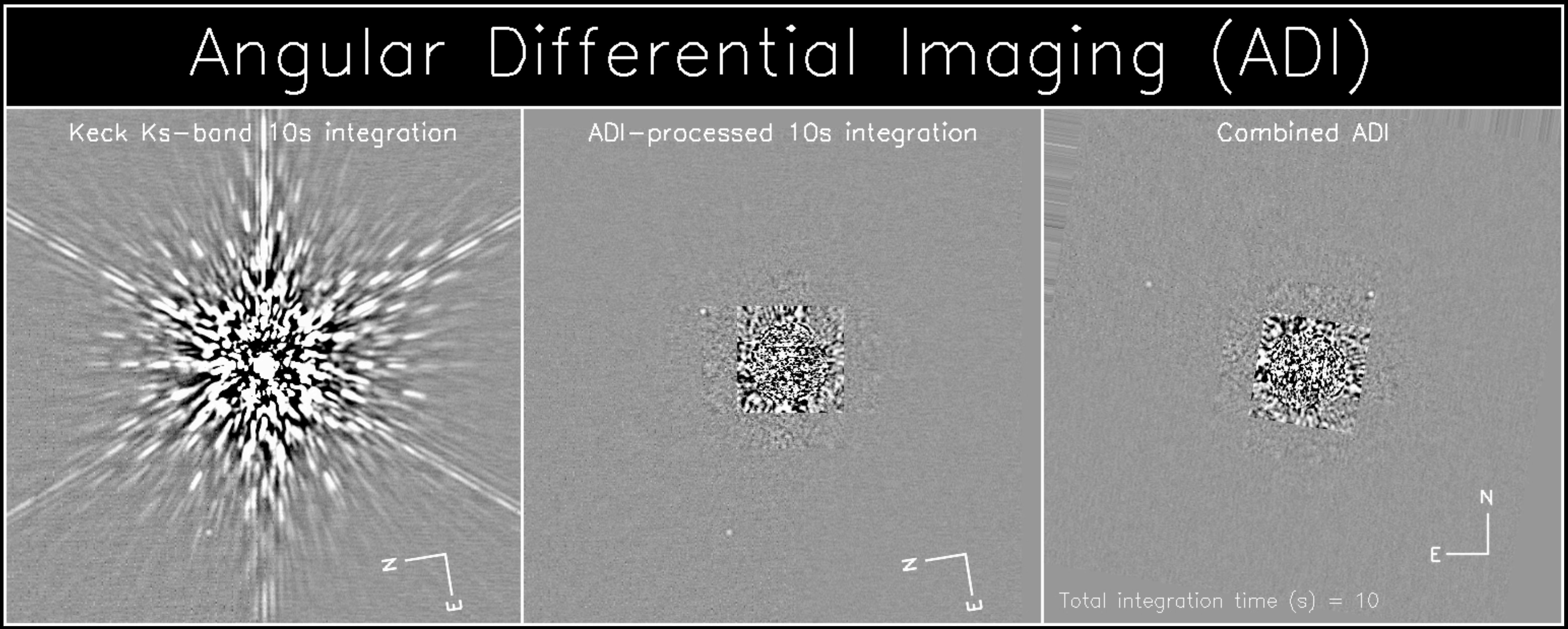
(a) Normal Telescope Rotation (b) ADI without Telescope Rotation

Johnson-Groh 2014

For an Alt/Az telescope field of view rotates over the night

Turn off telescope rotator:

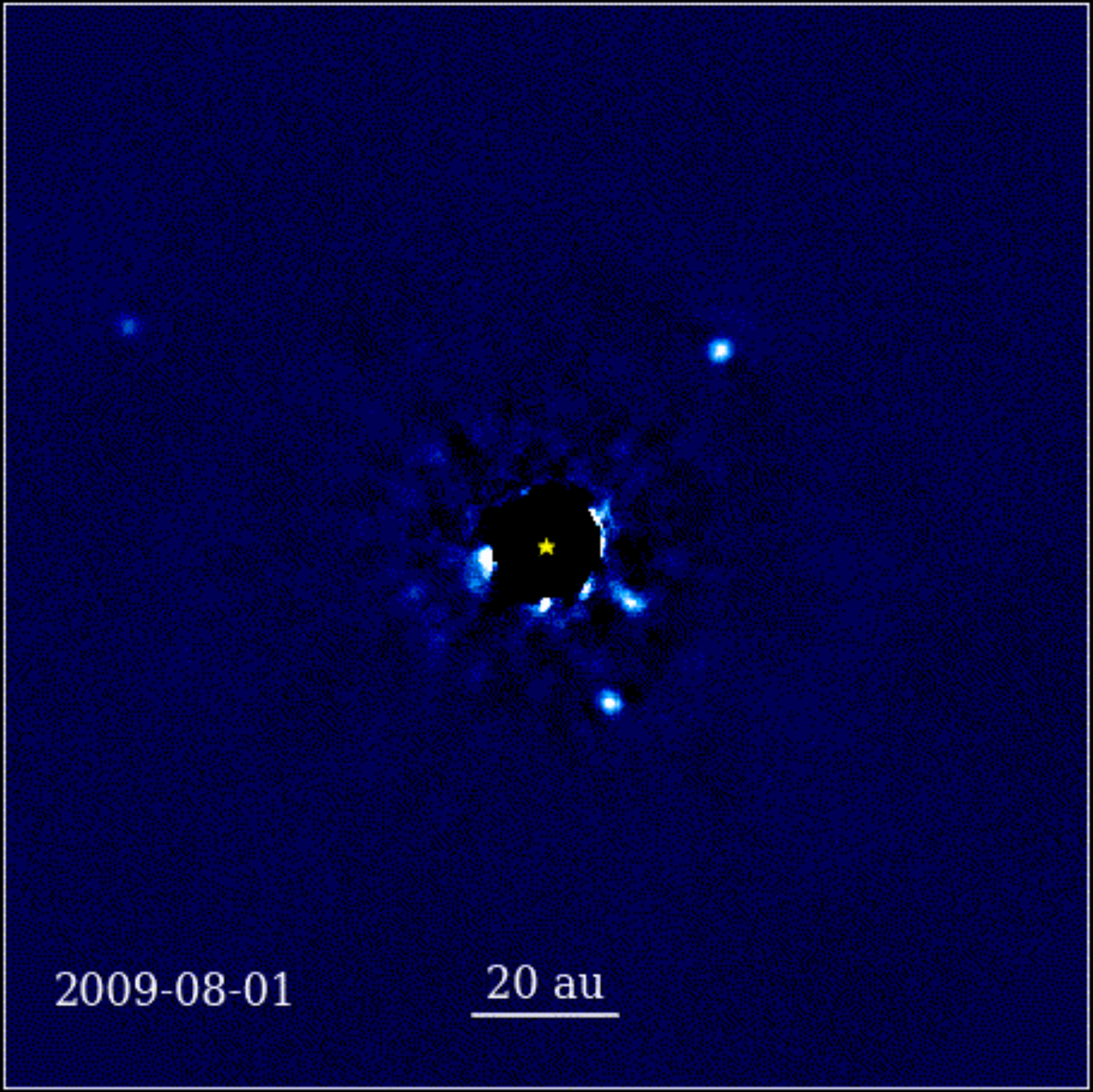
- real objects (like planets!) rotate in the field
- Speckles and other PSF features stay fixed



Christian Marois

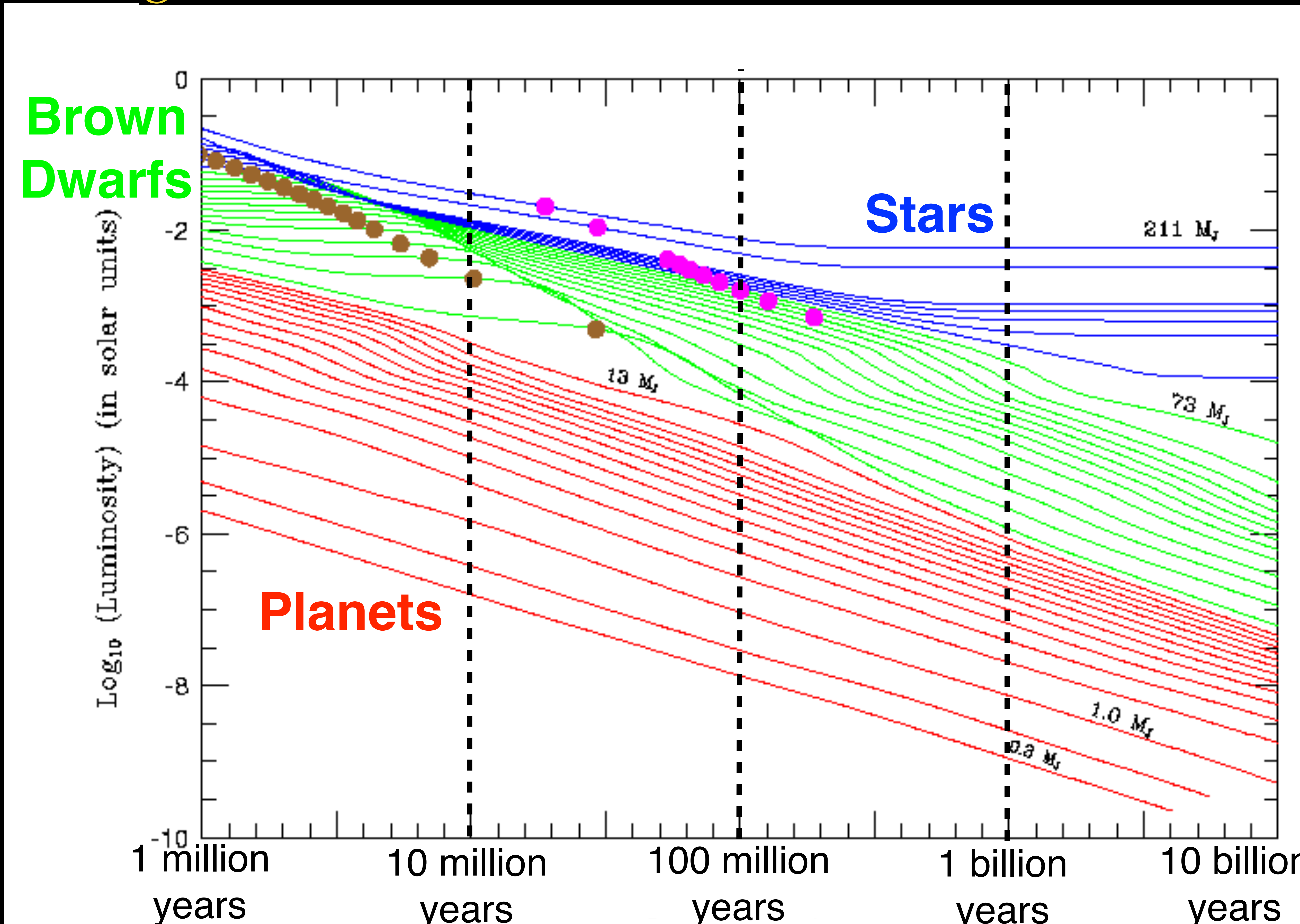
HR 8799

5-7 M_{Jup}
15-70 AU
~40 Myr



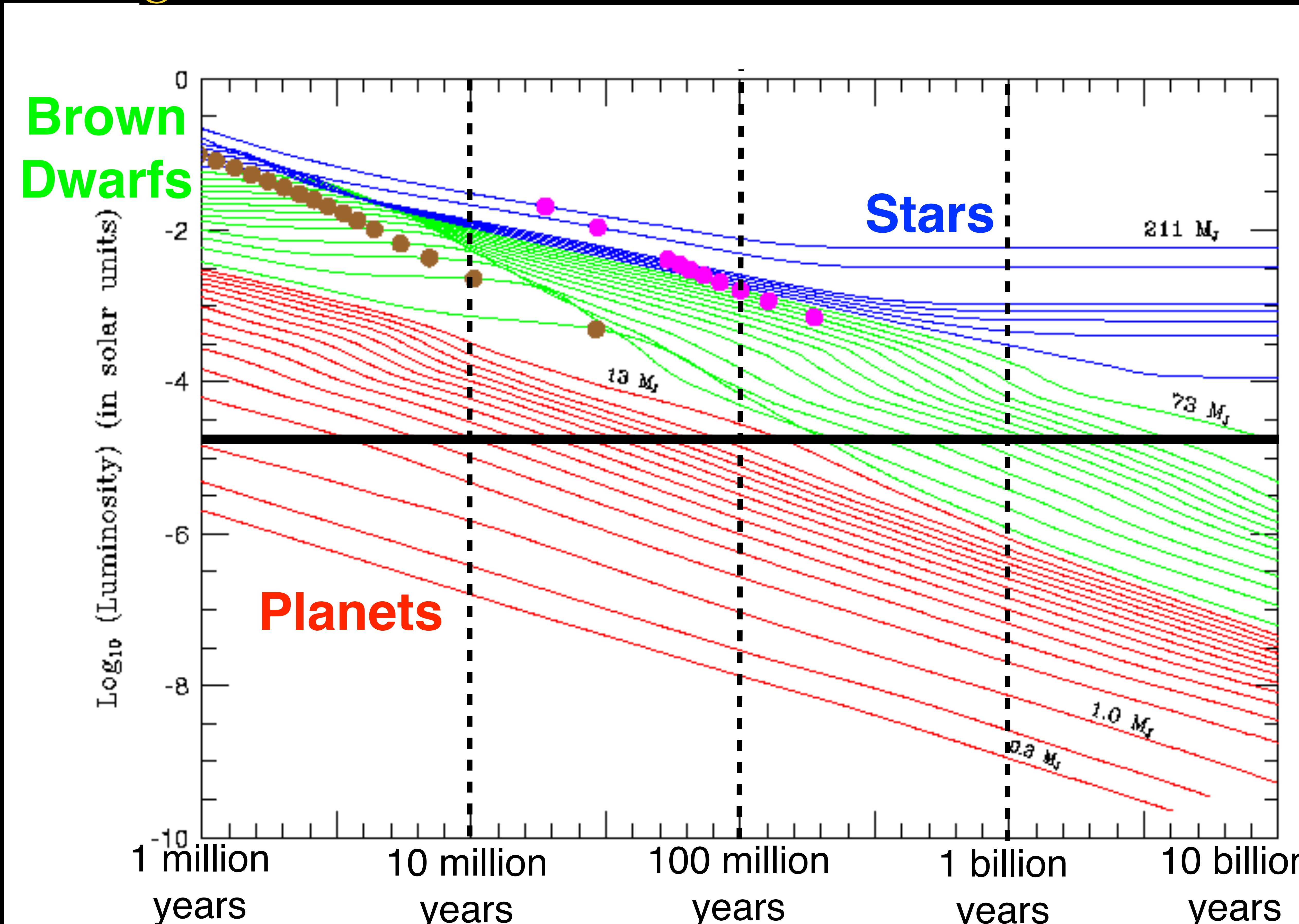
Jason Wang, William Thompson, Christian Marois, and Quinn Konopacky

Cooling with time



Adam Burrows

Cooling with time



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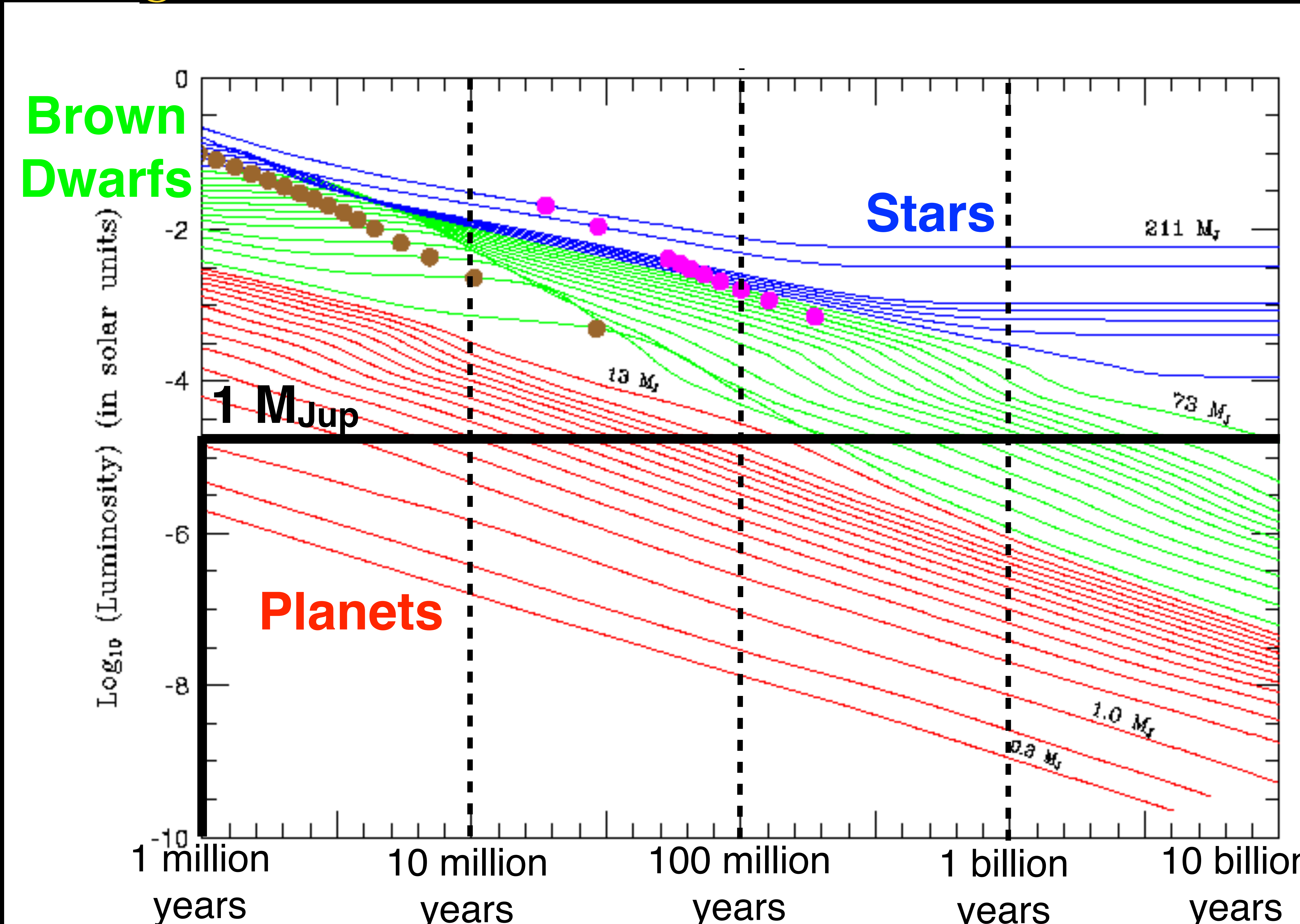

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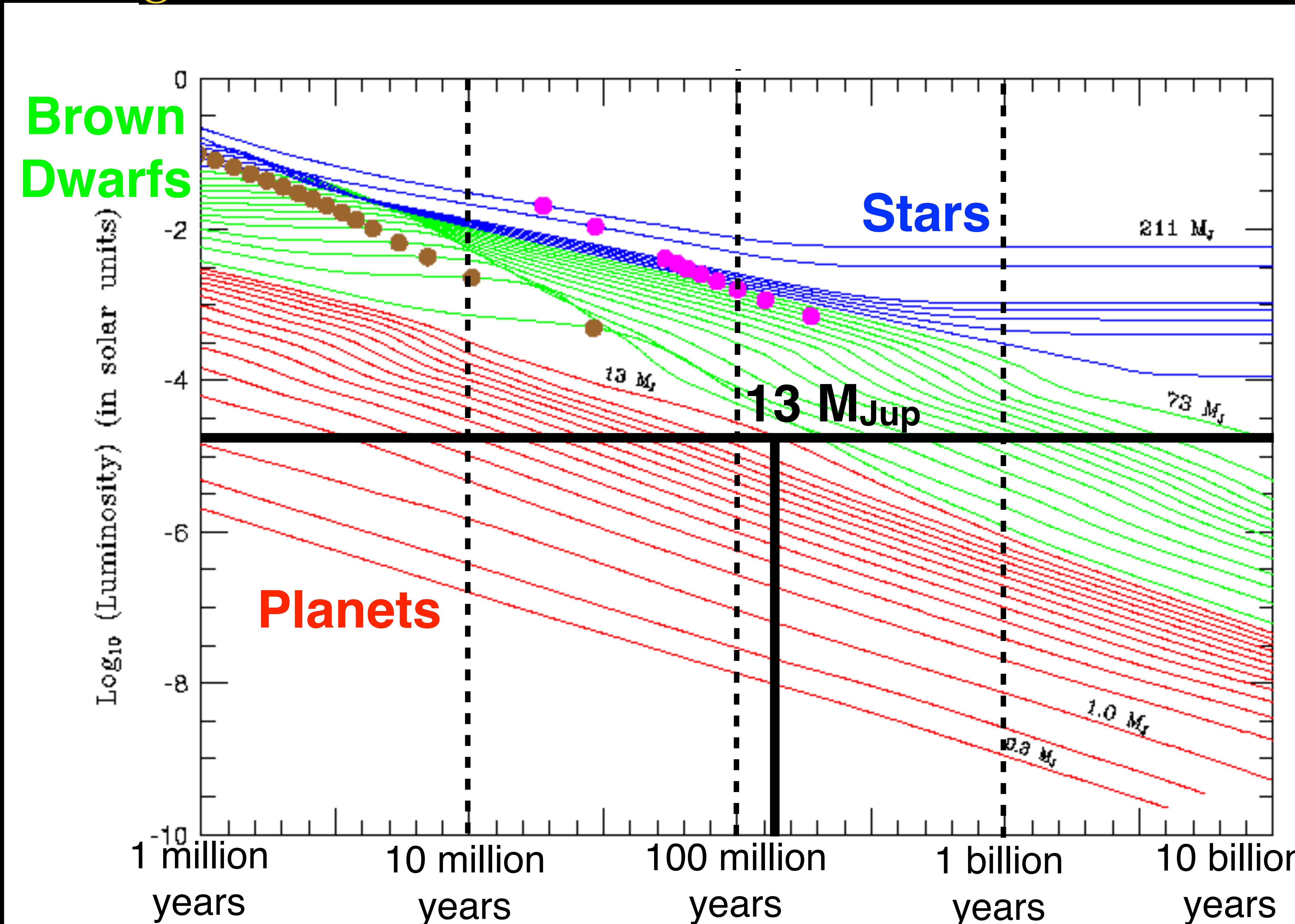

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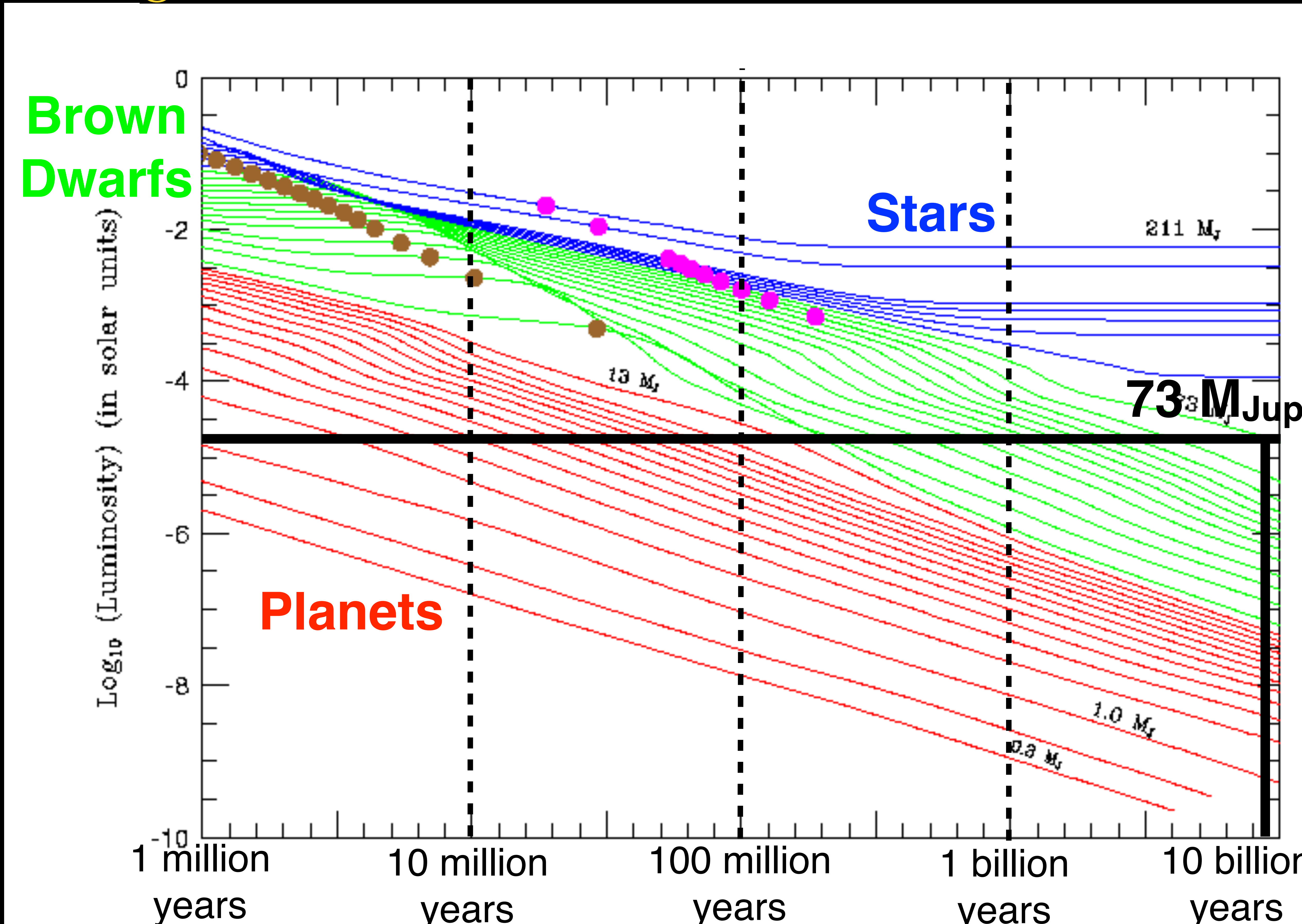
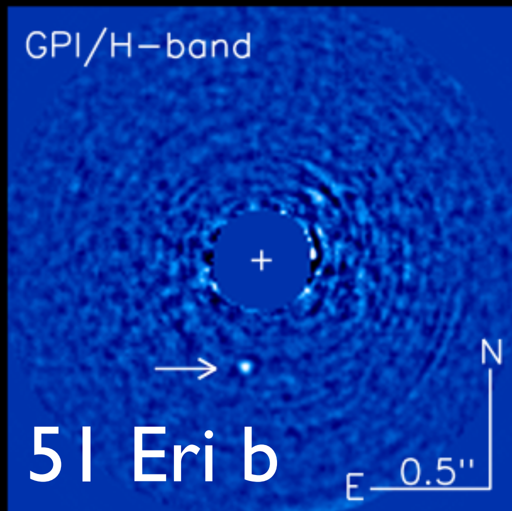
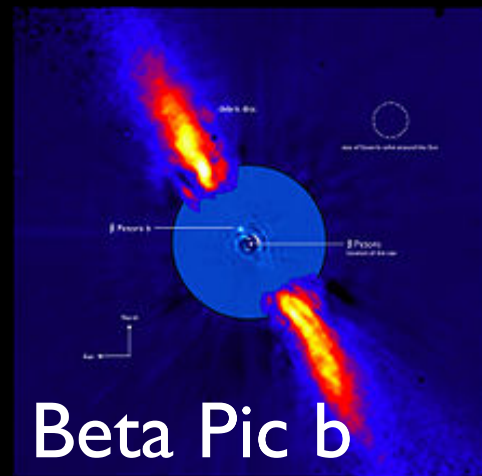
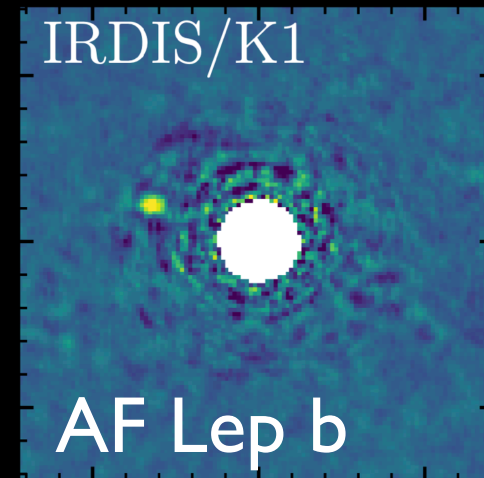


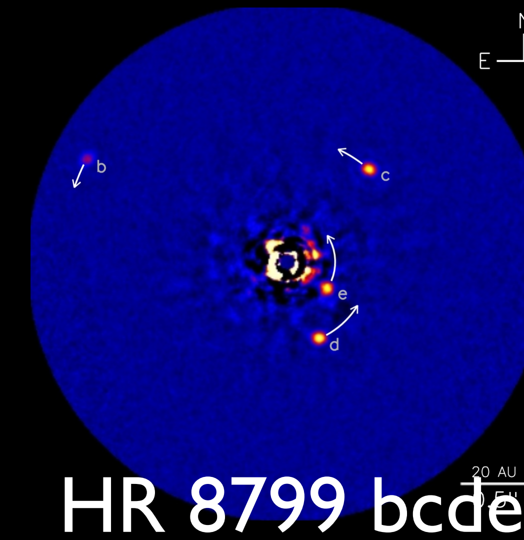
Adam Burrows

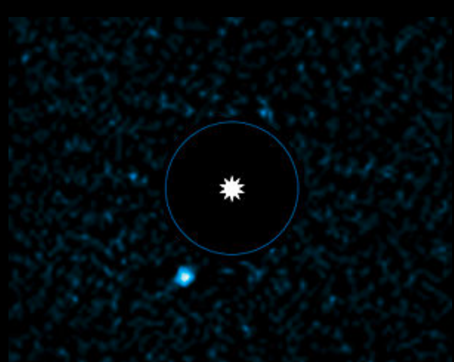
Directly Imaged Planets



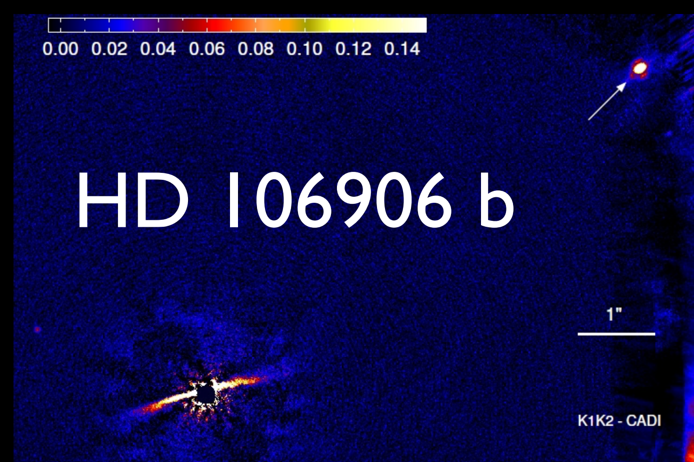


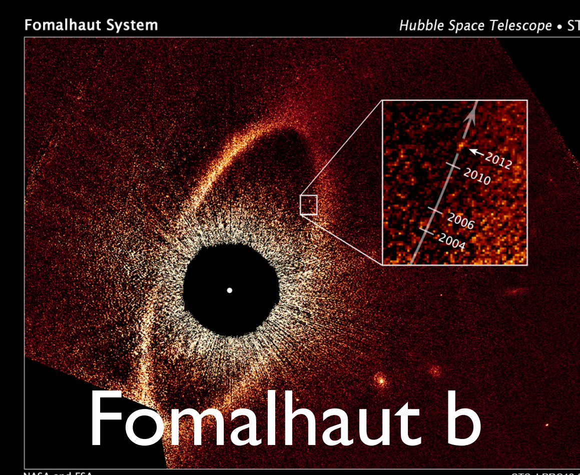


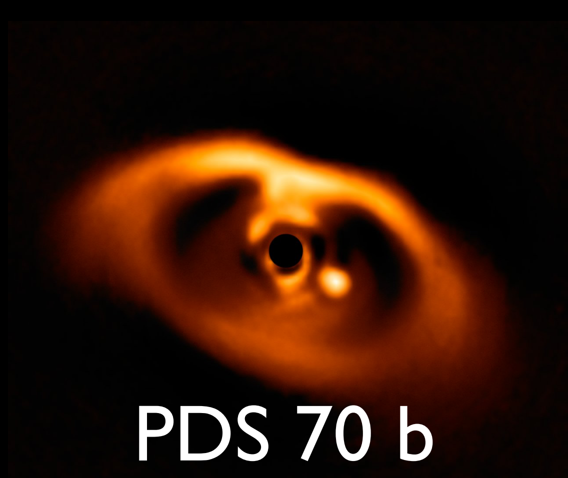


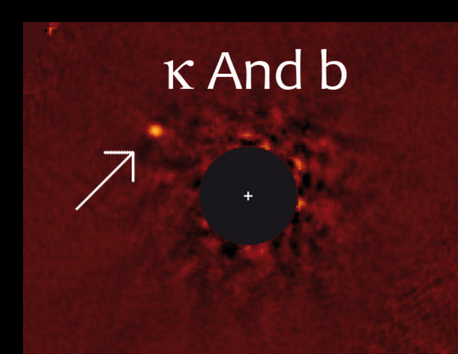


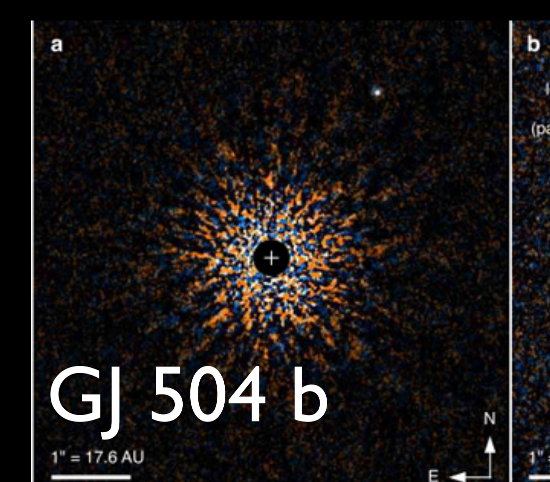
HD 95086 b











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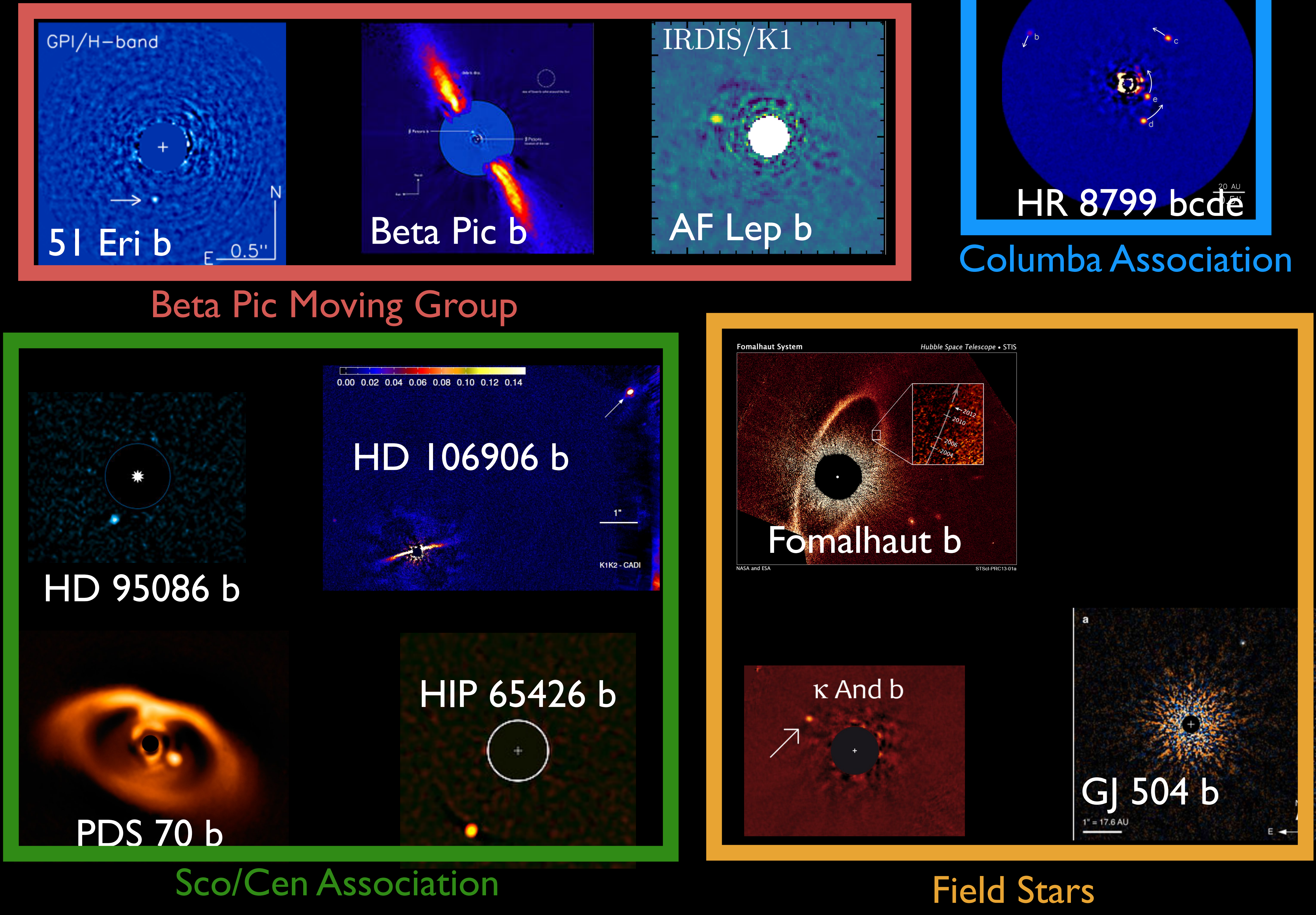


Ages of Stars

Moving group stars:

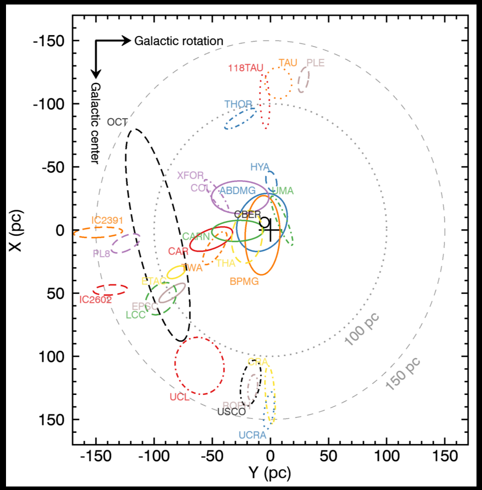
BANYAN (http://www.exoplanetes.umontreal.ca/banyan/ , Gagne et al. 2018)

LACEwING (https://github.com/ariedel/lacewing , Riedel et al. 2017)

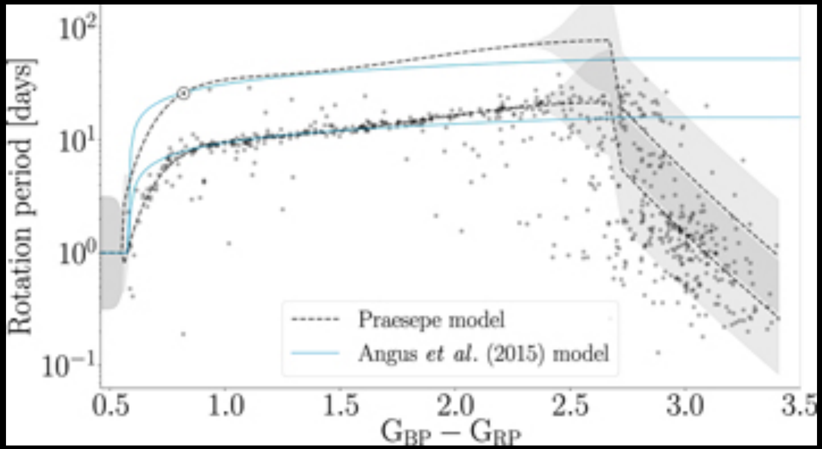
Field stars:

Rotation and Isochrones: stardate (https://github.com/RuthAngus/stardate , Angus et al. 2019), gyro-interp (https://github.com/lgbouma/gyro-interp , Bouma et al. 2023)

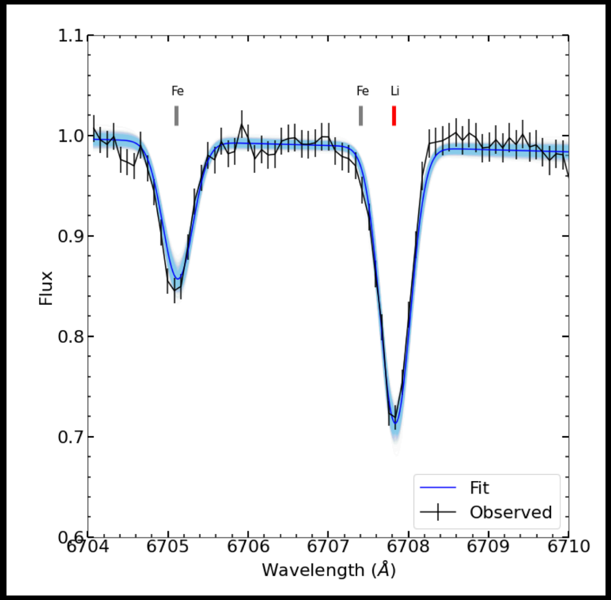
Calcium and Lithium: BAFFLES (https://github.com/adamstanfordmoore/BAFFLES , Stanford-Moore et al. 2020), EAGLES (https://github.com/robdjeff/eagles , Jeffries et al. 2023)



Gagne et al. 2018



Angus et al. 2019



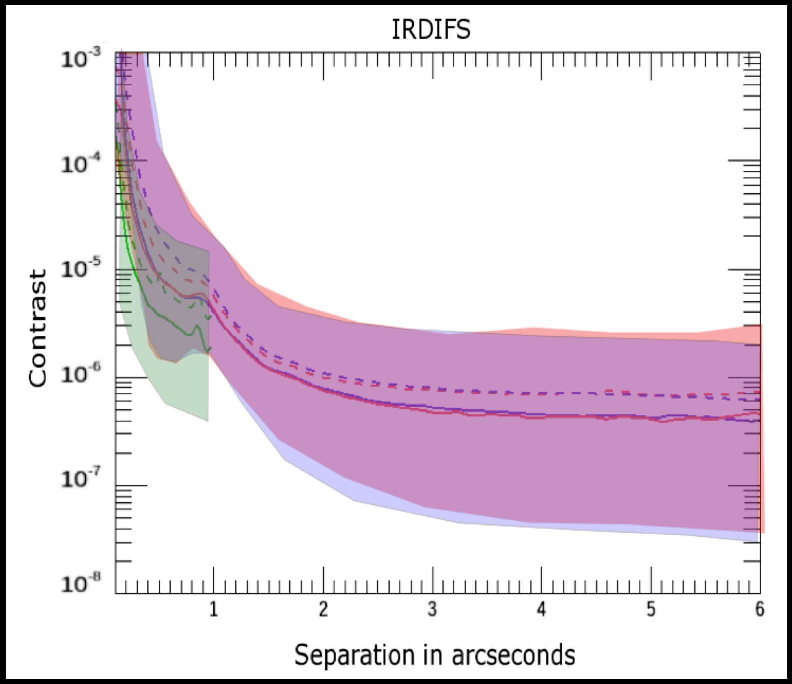
Peck et al. 2025

Contrast Curves

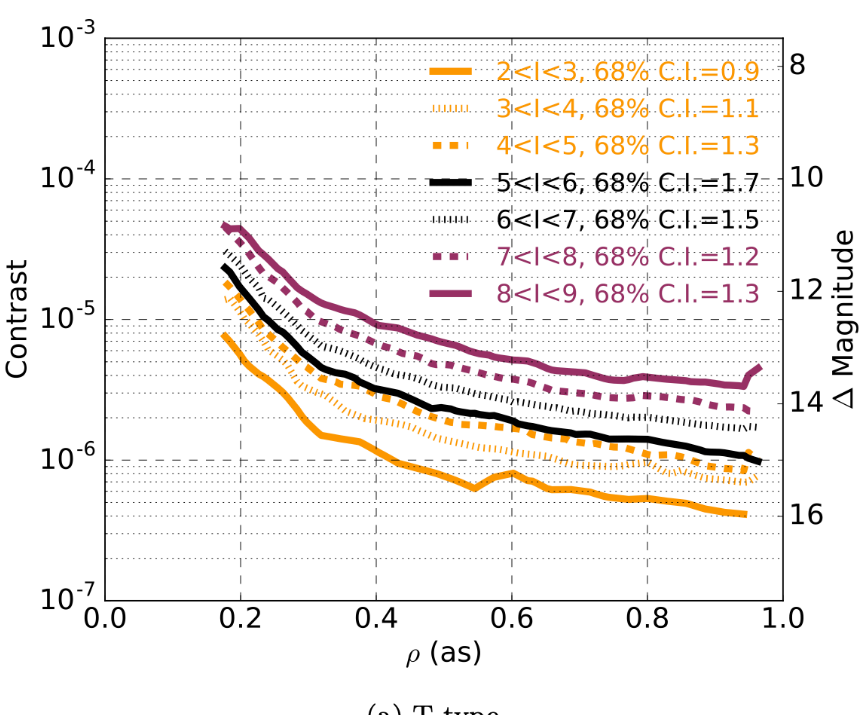
Limiting flux ratio (or magnitude difference) where a companion can be detected

Typically less sensitive closer to the star, more sensitive further out

Depends on: instrument, data reduction, brightness of star, airmass, amount of rotation, weather…



Langlois et al. 2019



(a) T-type

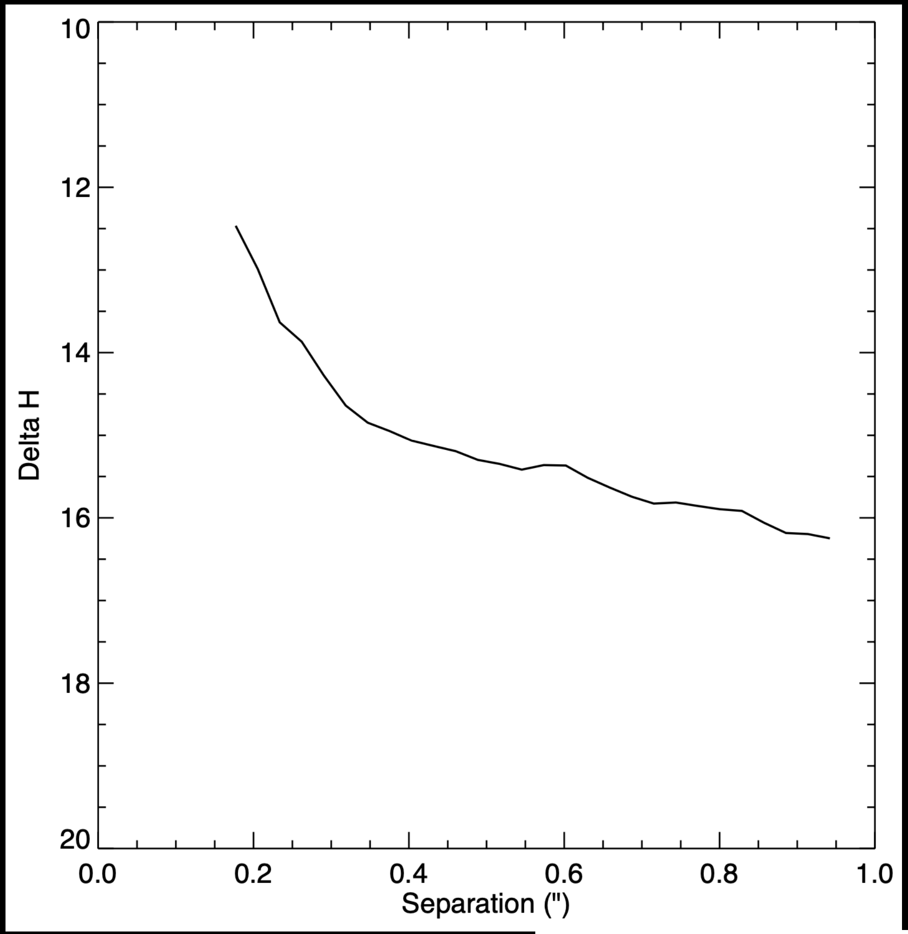
Ruffio et al. 2017

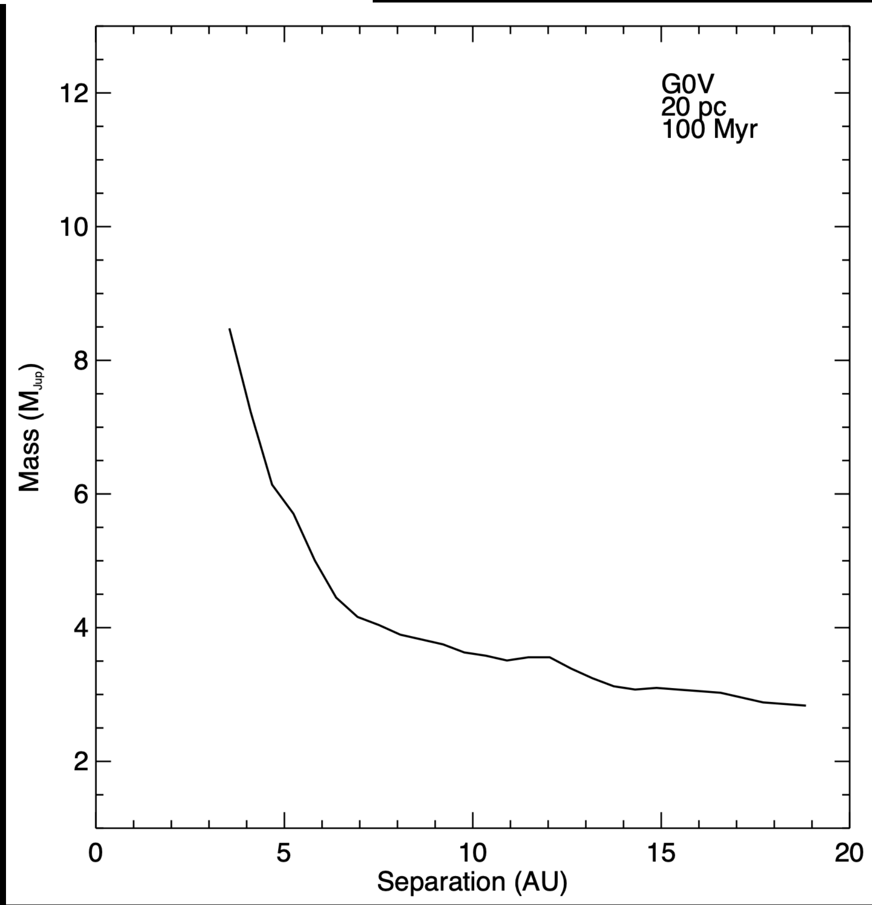
Contrast Curves and Stellar Properties

Contrast curves are delta-magnitude (or flux ratio) vs. projected separation in arcseconds

Use the star's absolute magnitude, the star's age, and evolutionary models (e.g. COND, Sonora, BT-Settl, etc) to convert to planet mass

Use the star's distance to convert to separation in AU

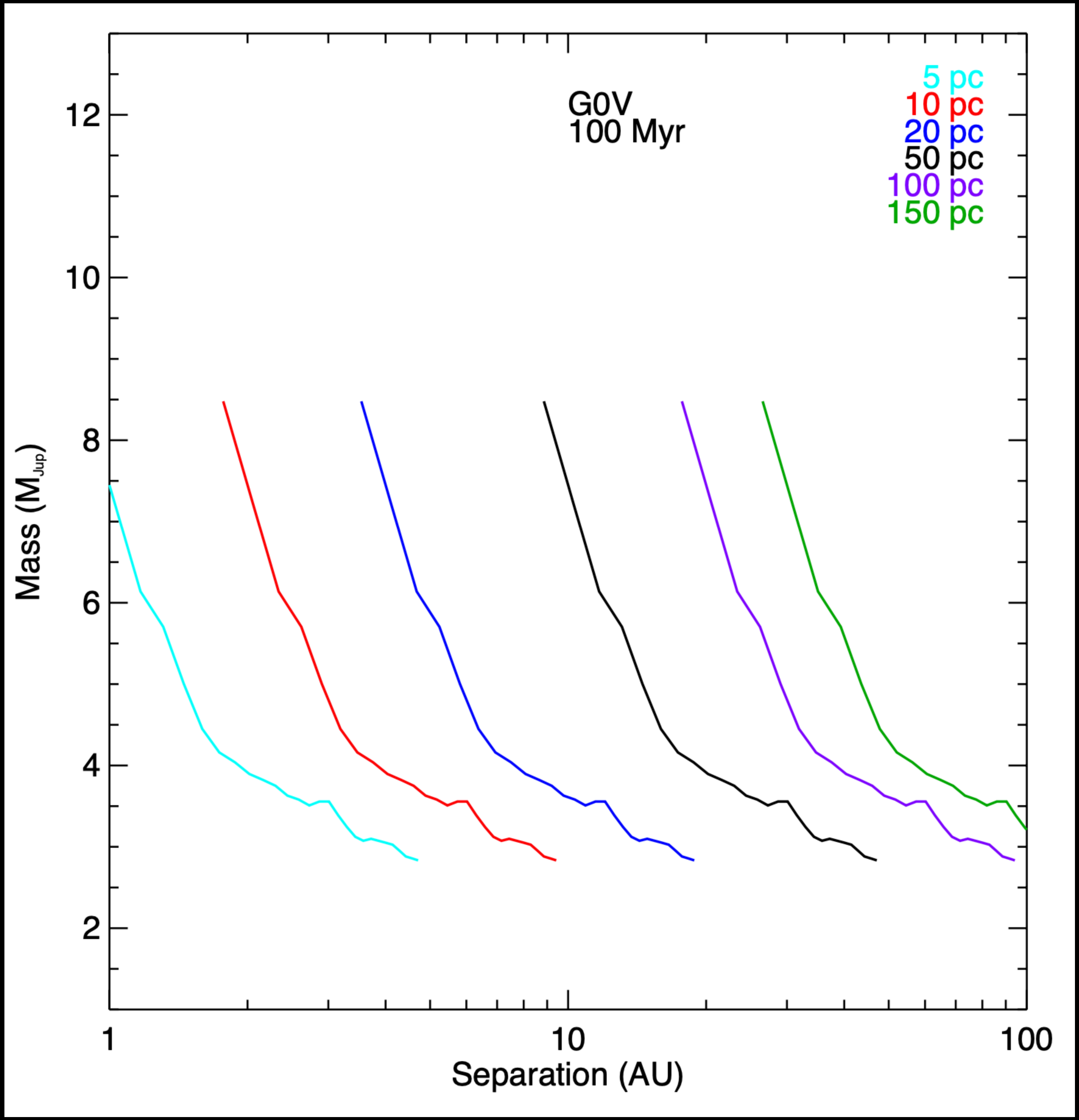




Contrast Curves and Distance

The same contrast curve reaches closer physical separations for closer stars

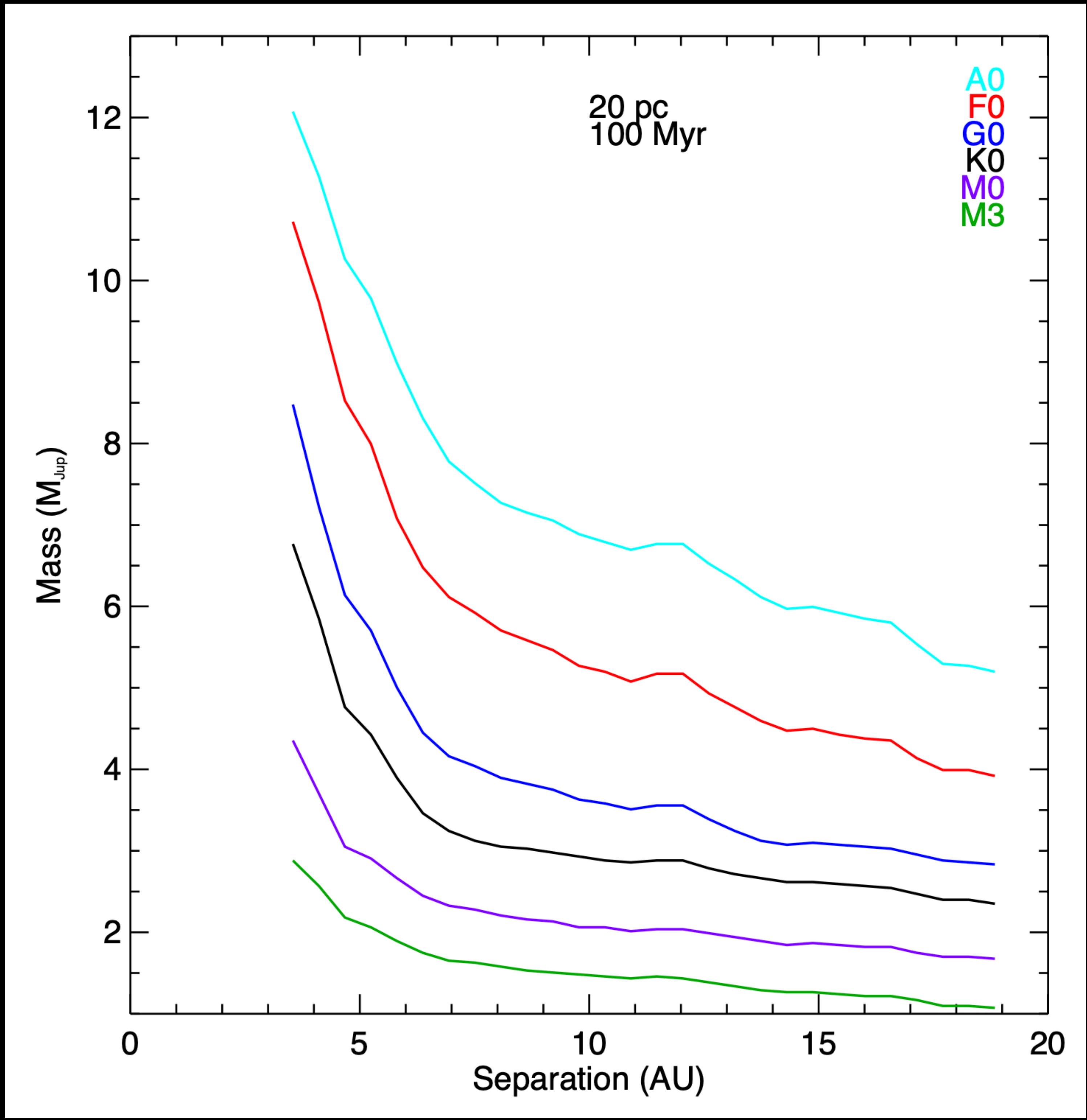
(Another effect: more distant stars have a fainter apparent magnitude, leading to worse AO performance and more significant read noise)



Contrast Curves and Spectral Type

Earlier-type stars are intrinsically brighter

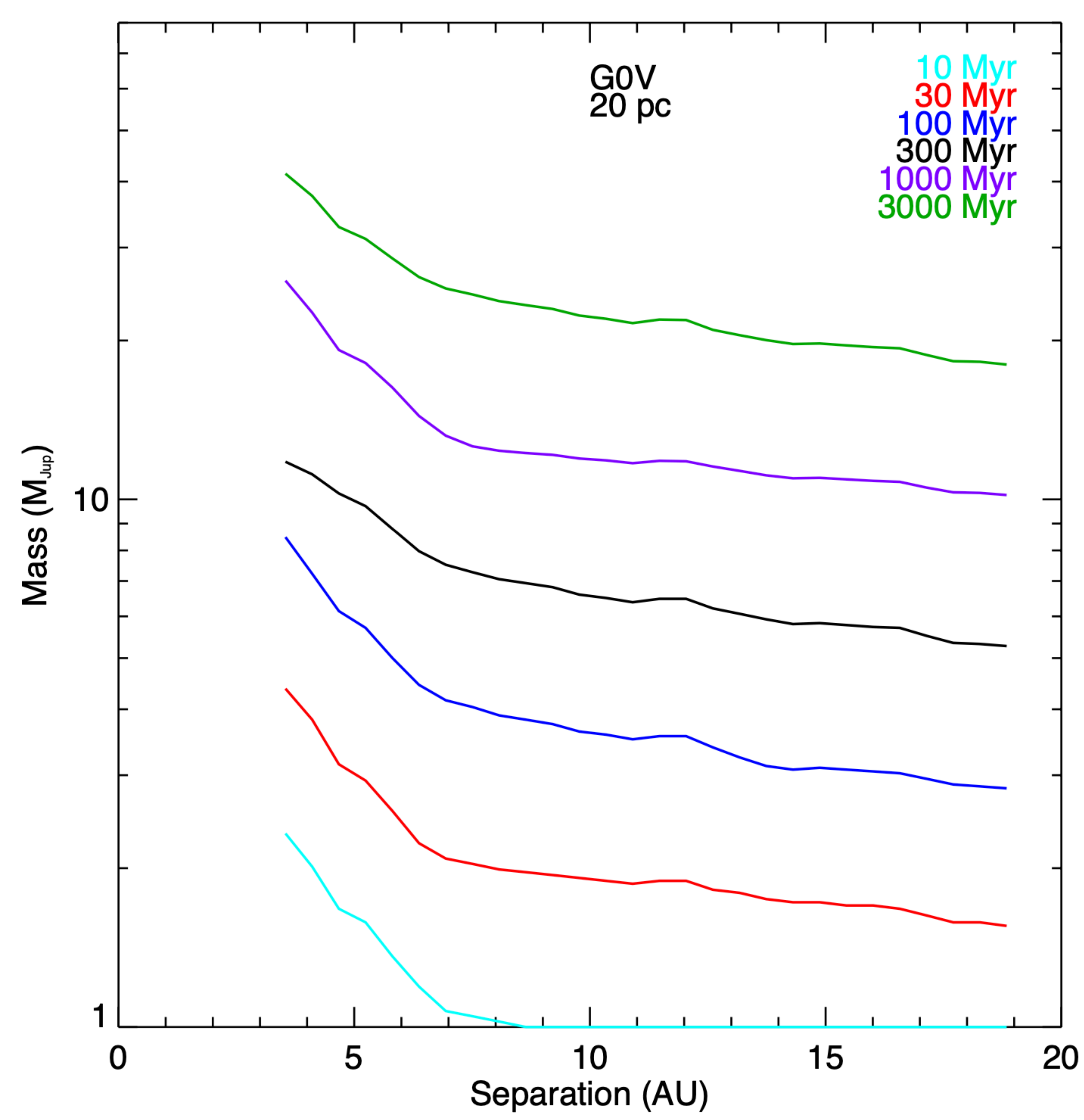
The same contrast curve will reach lower-mass planets for later-type stars



Contrast Curves and Age

Younger planets are brighter and easier to detect

The same contrast curve can detect Jupiter-mass planets around a younger star, and only brown dwarfs around an older star



The Gemini Planet Imager (GPI)

Installed at Gemini South in 2014

Optimized for direct imaging of exoplanets:

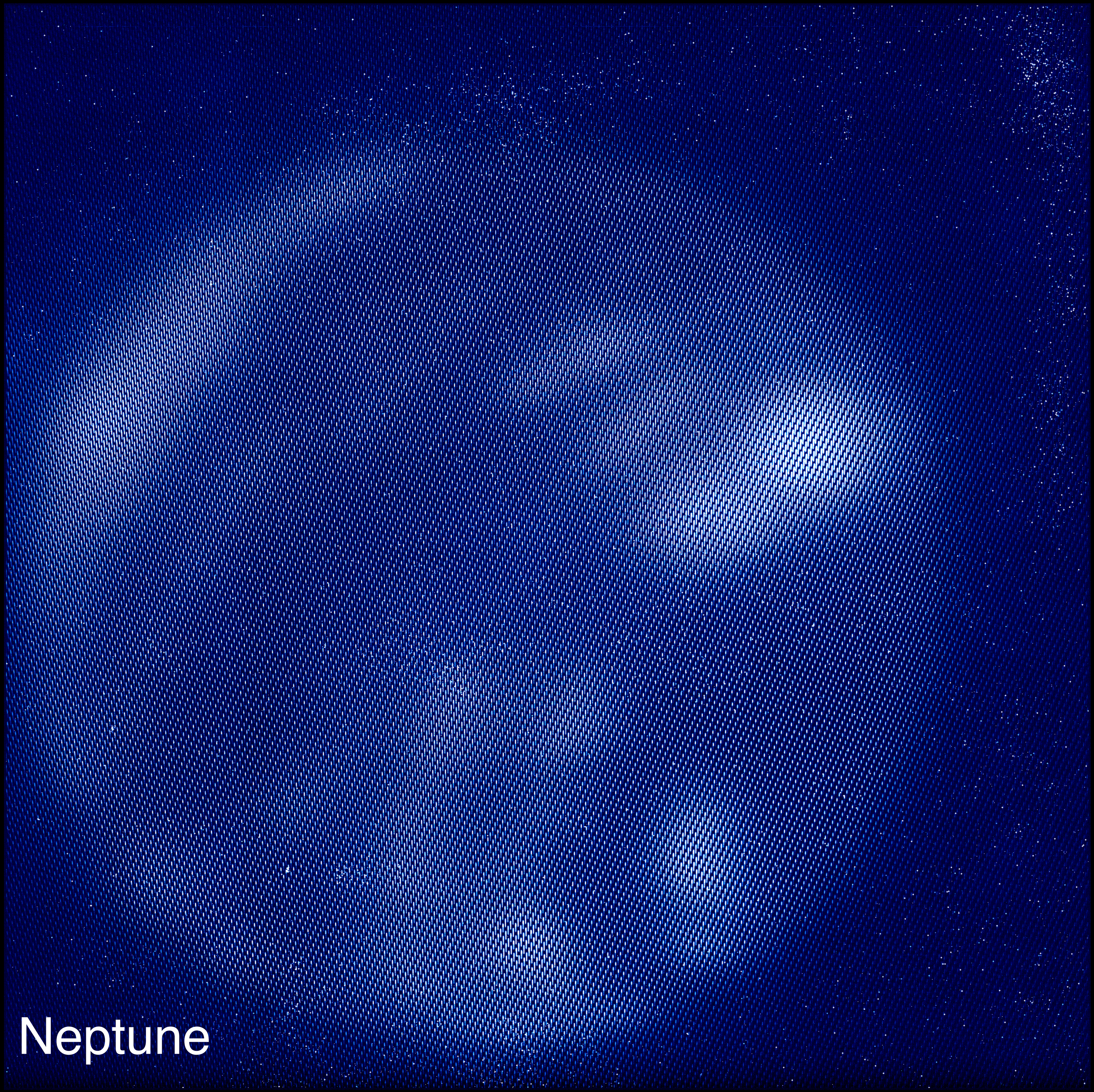
—High-order AO system
—Advanced coronagraphs
—NIR Integral Field Spectrograph
—Data reduction using SDI and ADI

Dmitry Savransky

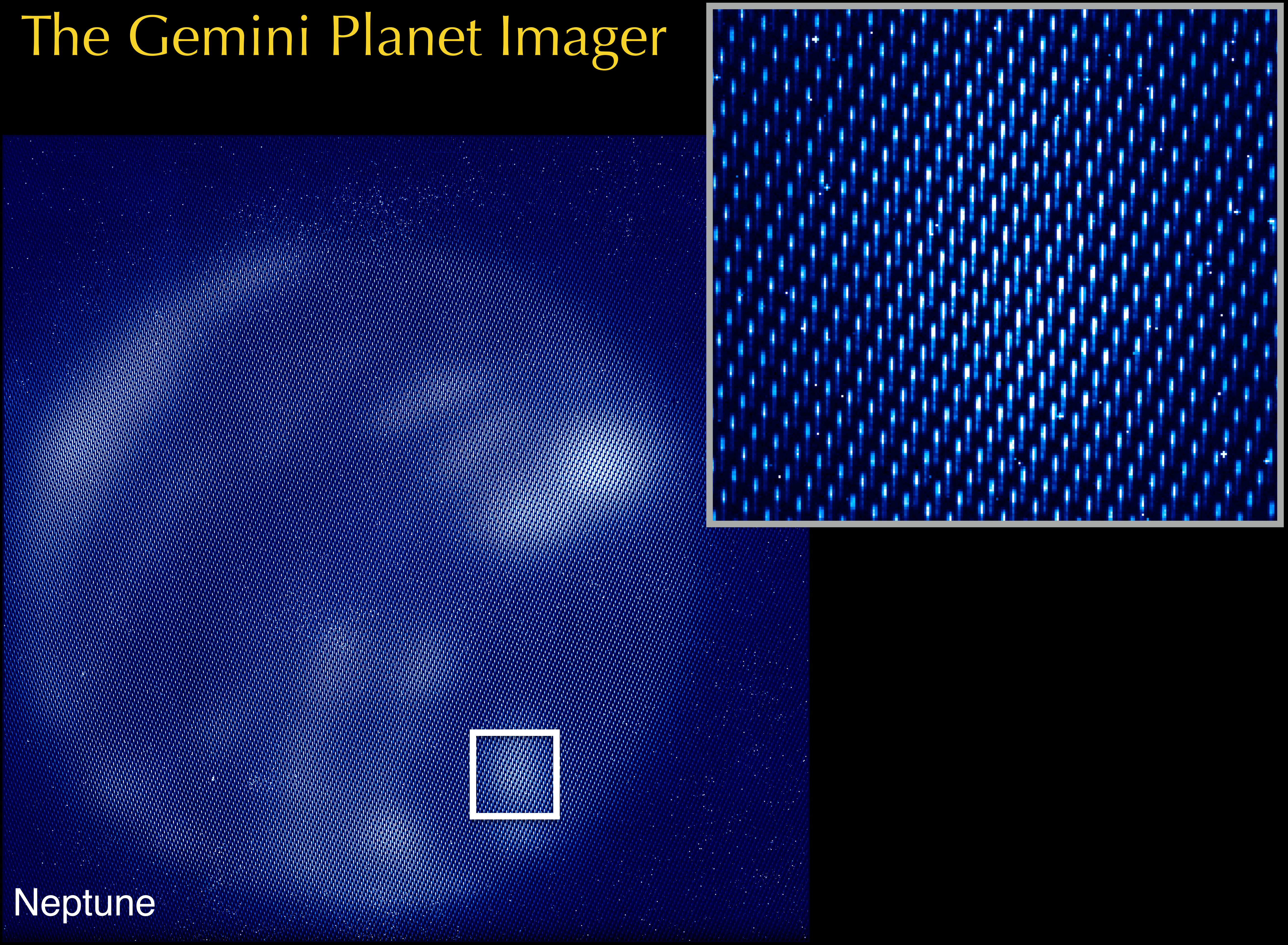
The GPI team (a subset)

Jonathan Aguilar, S. Mark Ammons, Pauline Arriaga, Etienne Artigau, Vanessa Bailey, Travis Barman, Steve Beckwith, Sarah Blunt, Sebastian Bruzzone, Joanna Bulger, Ben Burningham, Adam S. Burrows, Eric Cady, Christine Chen, Eugene Chiang, Jeffrey K. Chilcote, Rebekah I. Dawson, Robert J. De Rosa, Ruobing Dong, René Doyon, Zachary H. Draper, Gaspard Duchêne, Thomas M. Esposito, Daniel Fabrycky, Michael P. Fitzgerald, Katherine B. Follette, Jonathan J. Fortney, BJ Fulton, Benjamin Gerard, James R. Graham, Alexandra Z. Greenbaum, Pascale Hibon, Sasha Hinkley, Lea Hirsch, Justin Hom, Andrew Howard, Tara Hufford, Li-Wei Hung, Patrick Ingraham, Rebecca Jensen-Clem, Mara Johnson-Groh, Paul Kalas, Quinn Konopacky, David Lafreniere, James E. Larkin, Samantha Lawler, Eve Lee, Jinhee Lee, Michael Line, Bruce Macintosh, Jerome Maire, Franck Marchis, Mark S. Marley, Christian Marois, Brenda C. Matthews, Stanimir Metchev, Max Millar-Blanchaer, Caroline V. Morley, Katie M. Morzinski, Ruth Murray-Clay, Eric L. Nielsen, Andrew Norton, Rebecca Oppenheimer, David W. Palmer, Rahul Patel, Jenny Patience, Marshall D. Perrin, Charles Poteet, Lisa A. Poyneer, Laurent Pueyo, Roman R. Rafikov, Abhijith Rajan, Julien Rameau, Fredrik T. Rantakyrö, Emily Rice, Malena Rice, Patricio Rojo, Jean-Baptiste Ruffio, M. T. Ruiz, Dominic Ryan, Maissa Salama, Didier Saumon, Dmitry Savransky, Adam C. Schneider, Jacob Shapiro, Anand Sivaramakrishnan, Inseok Song, Rémi Soummer, Sandrine Thomas, Gautam Vasisht, David Vega, J. Kent Wallace, Jason J. Wang, Kimberly Ward-Duong, Sloane J. Wiktorowicz, Schuyler G. Wolff, Joe Zalesky, Ben Zuckerman

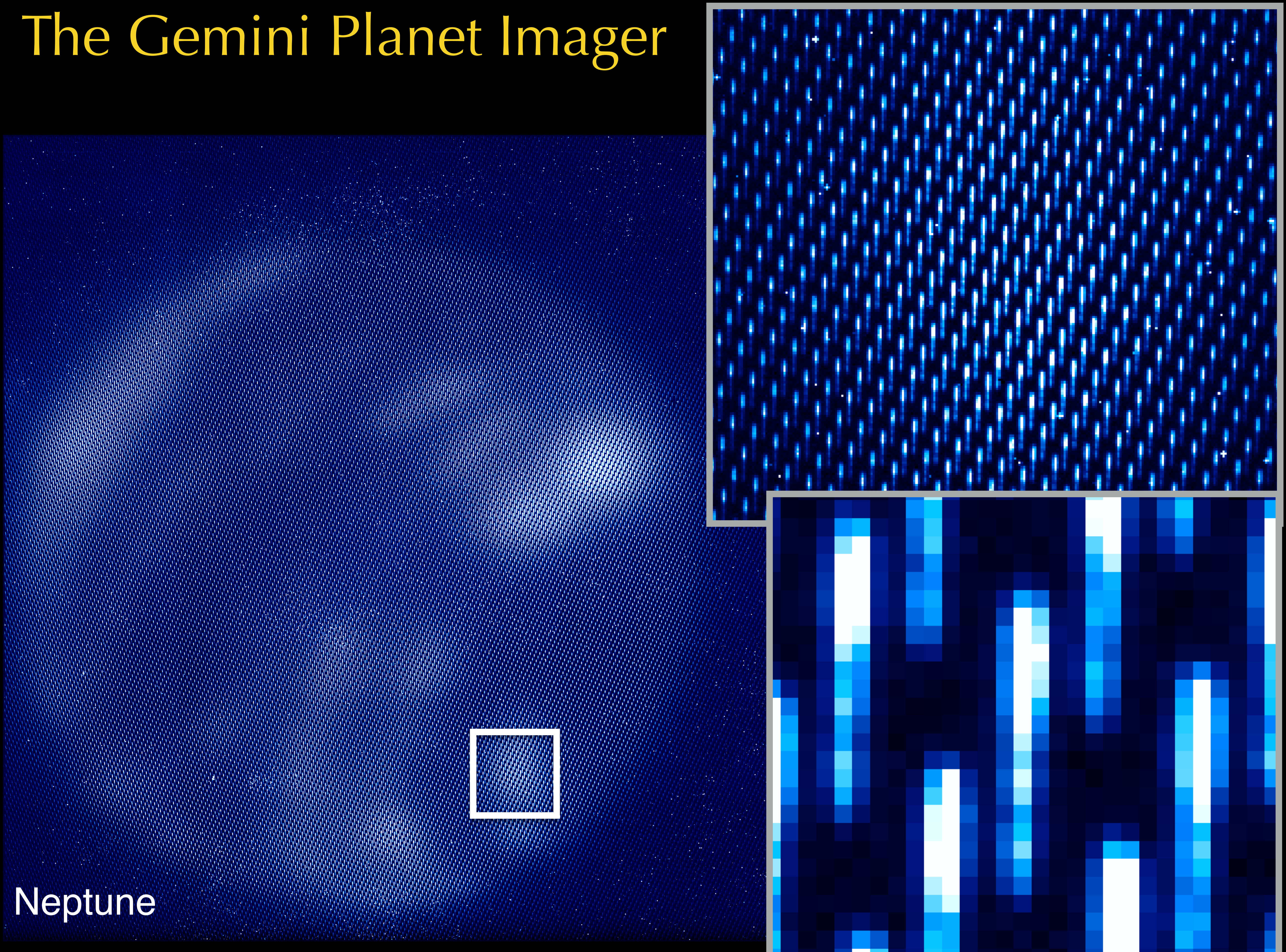
The Gemini Planet Imager



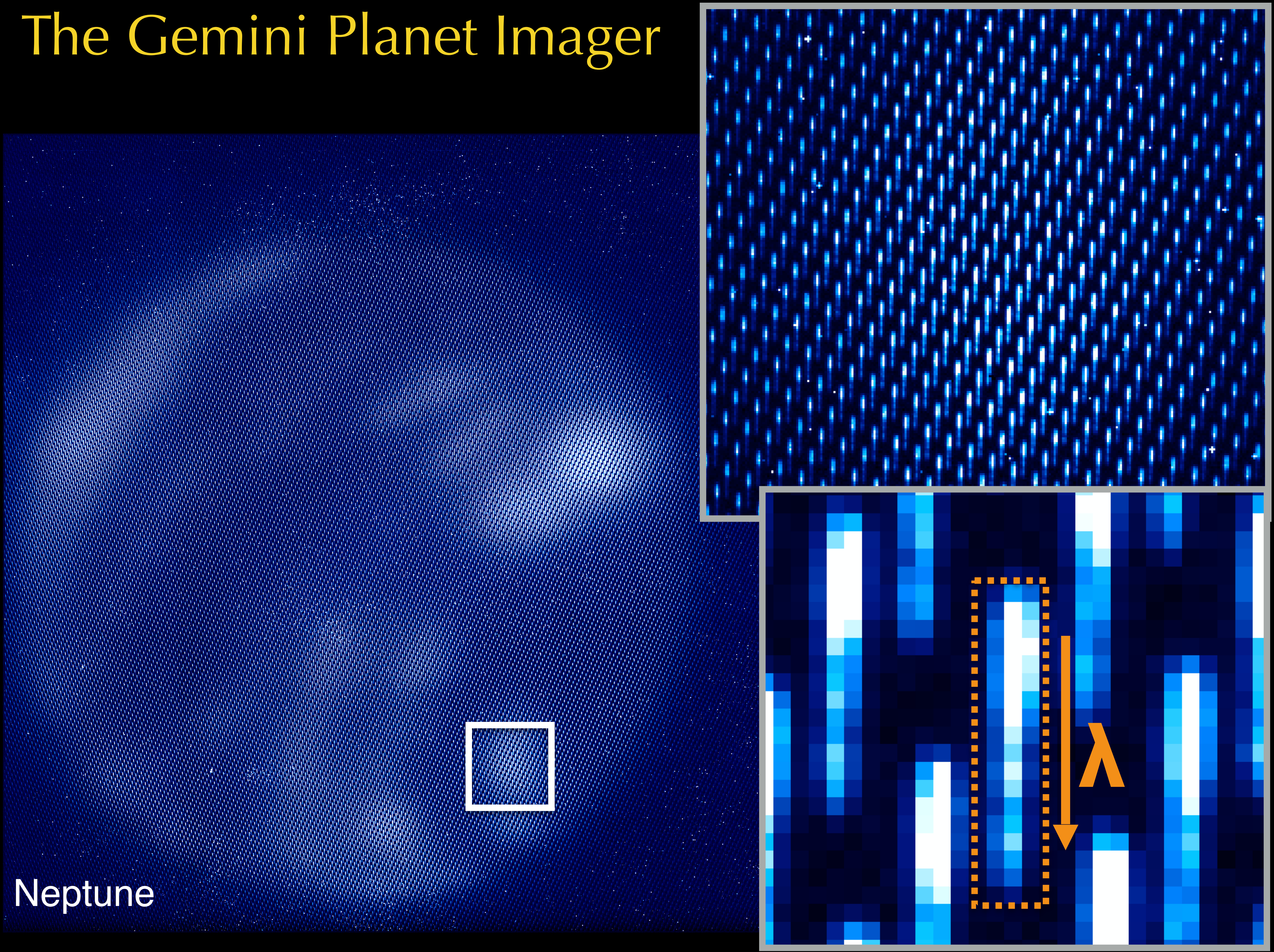
The Gemini Planet Imager



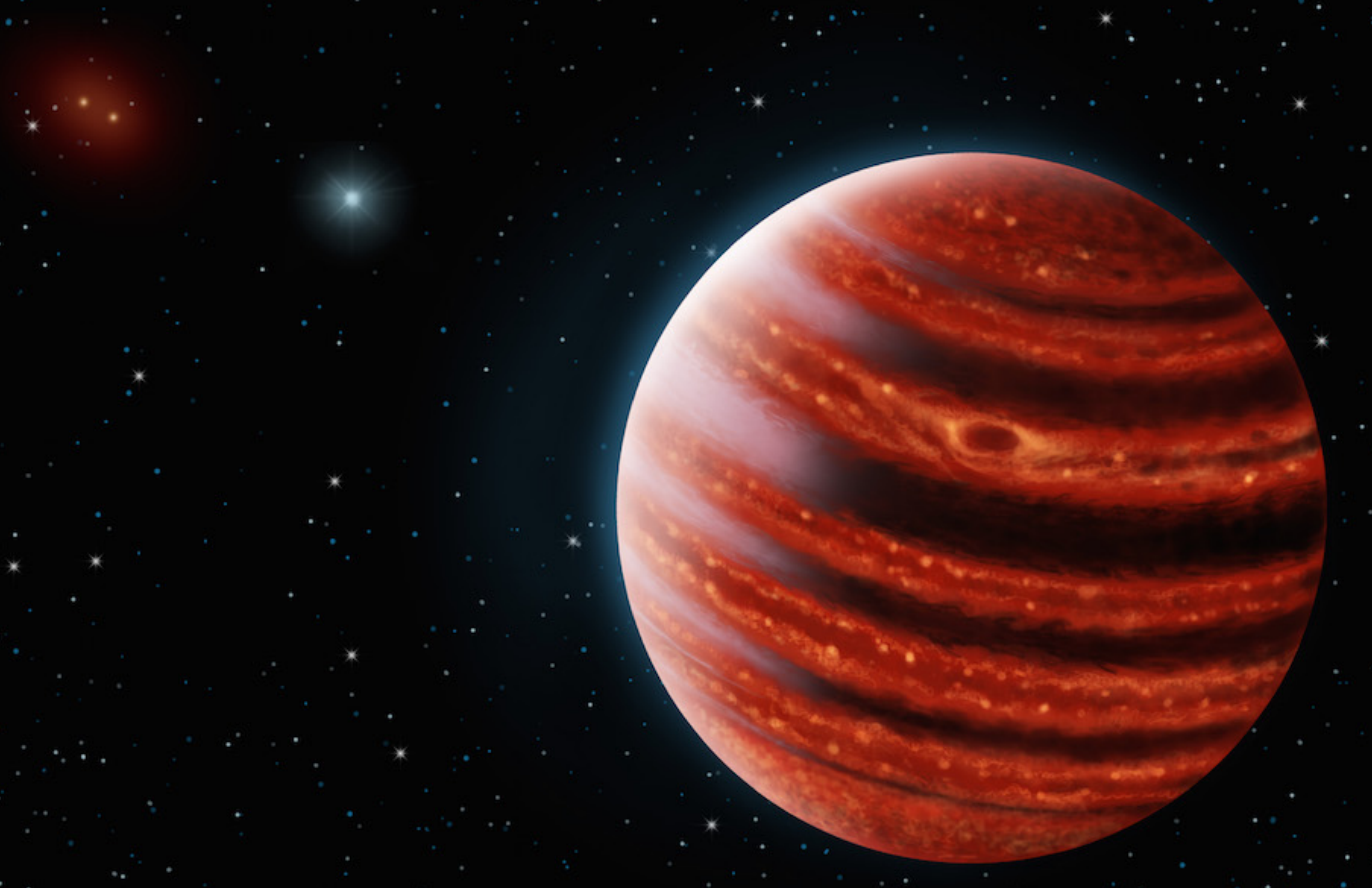
The Gemini Planet Imager



The Gemini Planet Imager

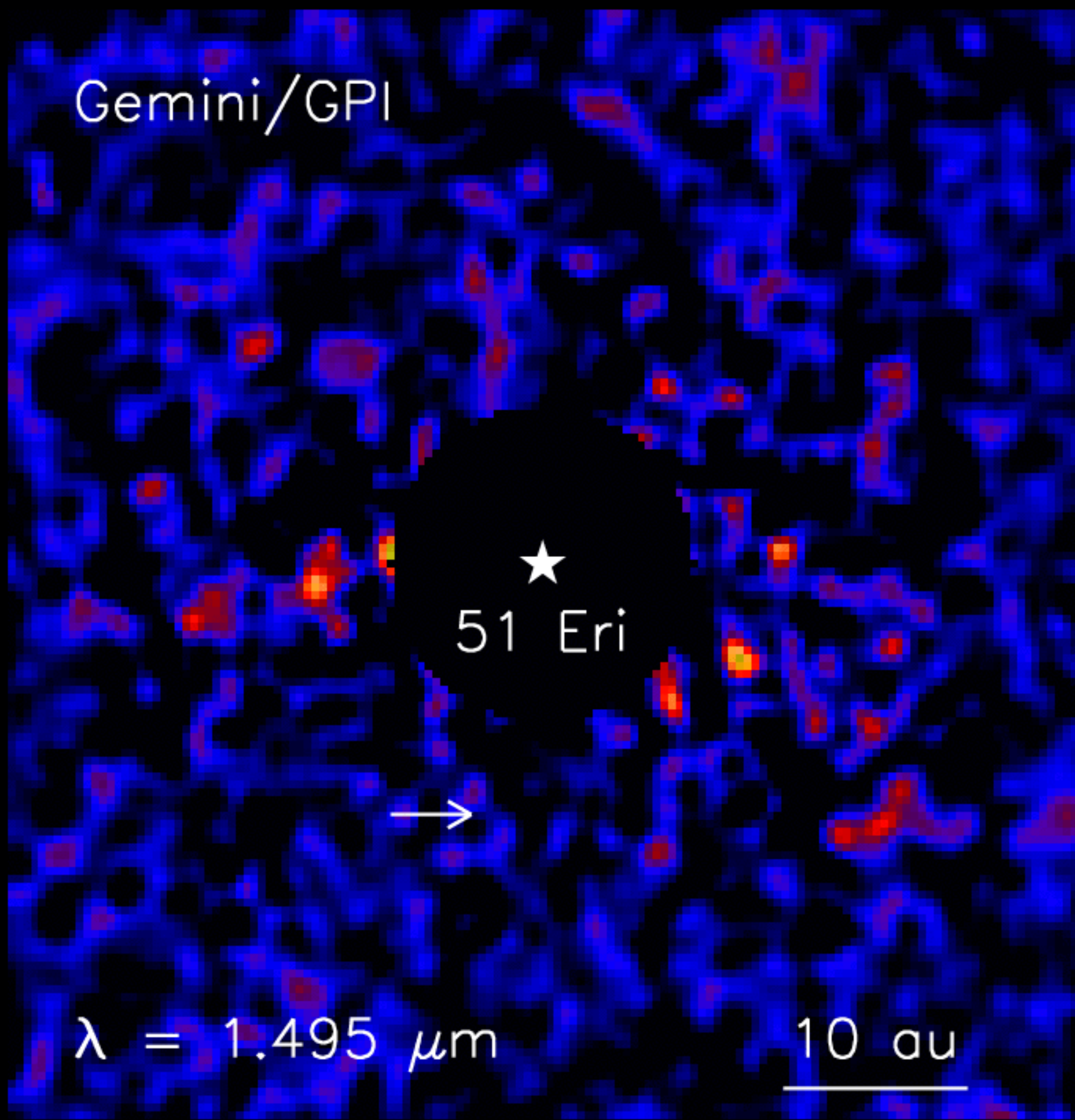


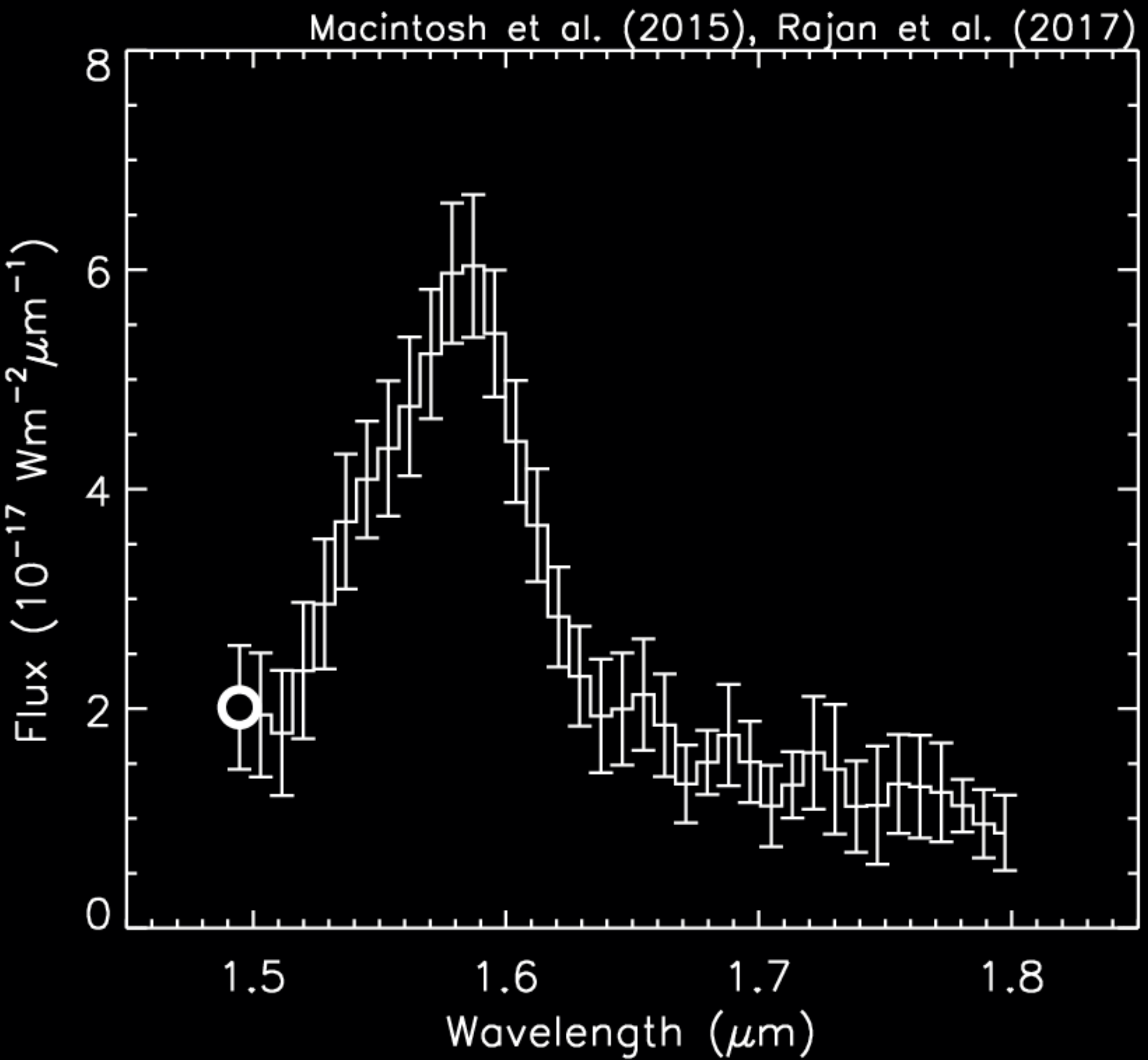
51 Eri b: GPI's first new planet



Danielle Futselaar & Franck Marchis, SETI Institute

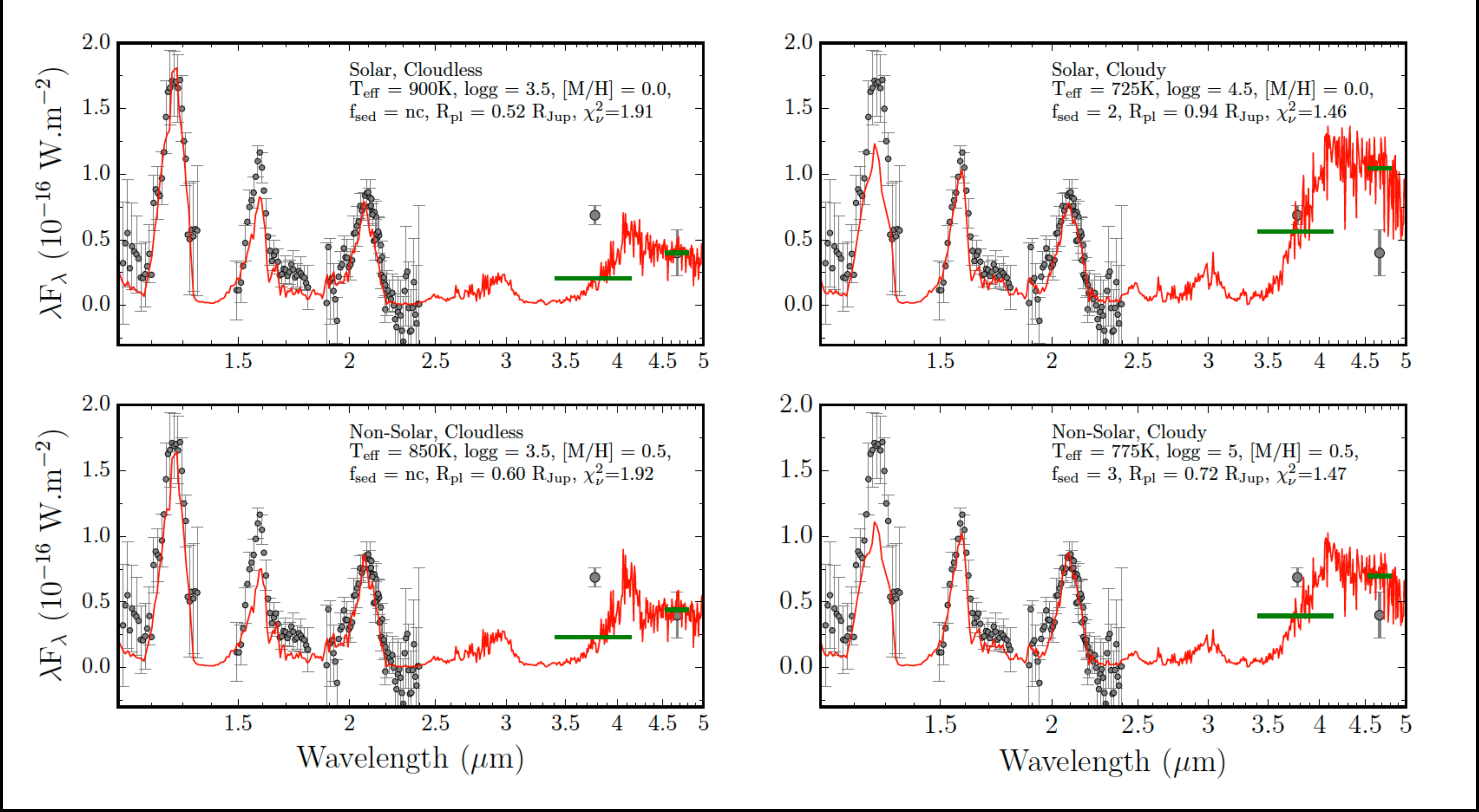
51 Eri b: GPI's first new planet





2 M_{Jup}
13 AU
~24 Myr

51 Eri b: GPI's first new planet



Rajan et al. 2017

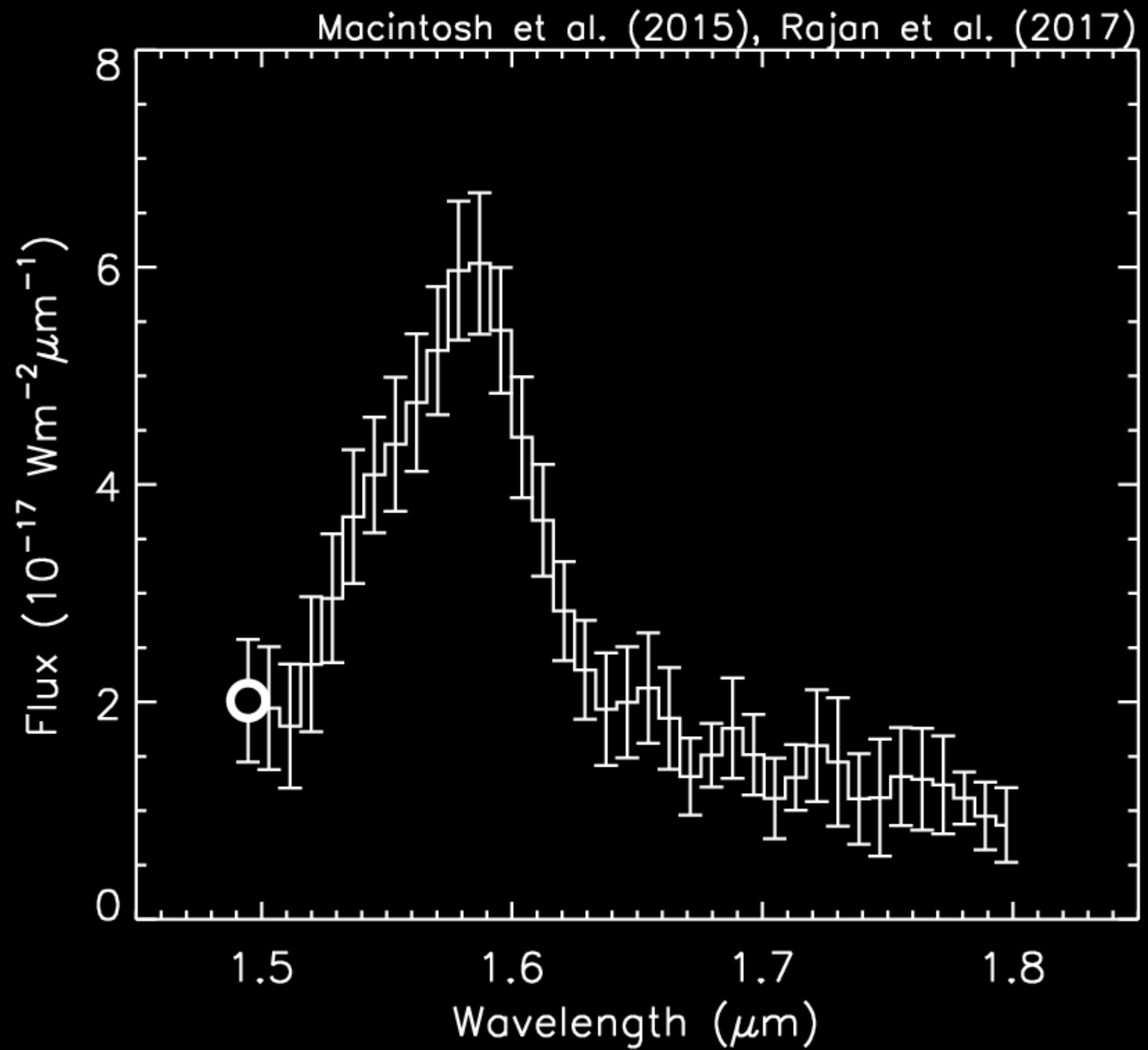
Spectra

Direct imaging allows measurement of planet's:

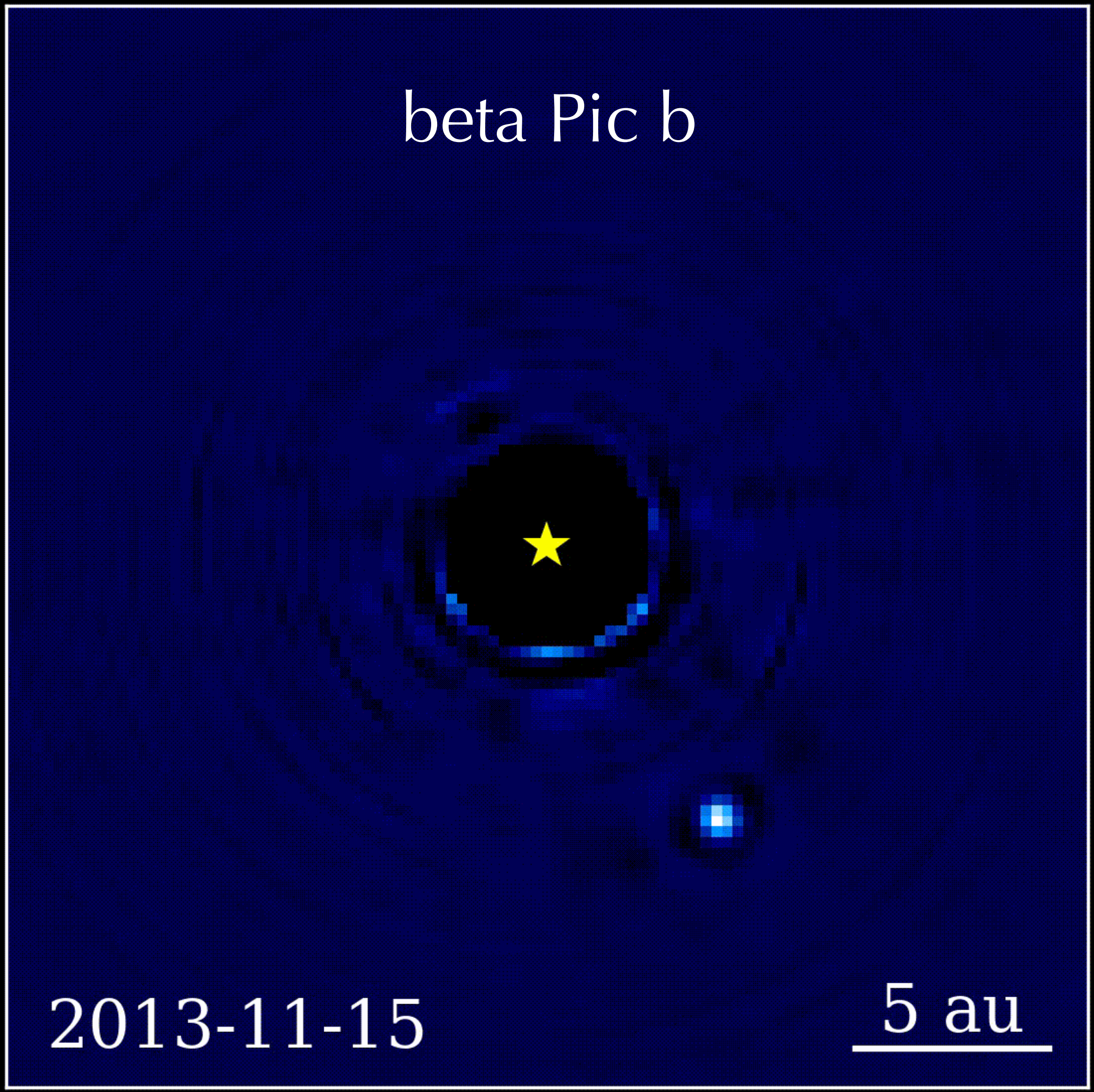
- spectra
- photometry

Measure planet's:

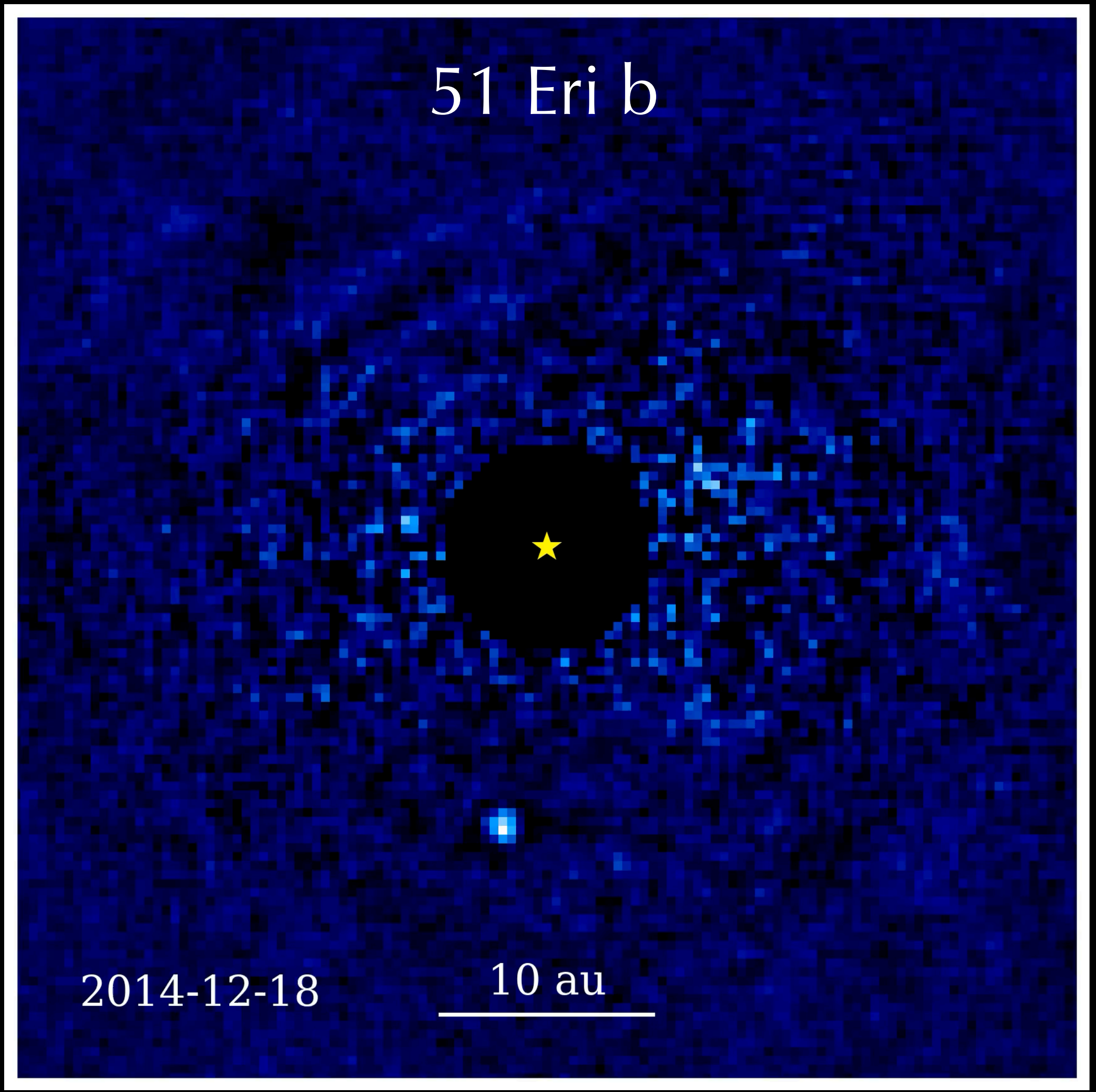
- luminosity
- temperature
- abundances
- …



Orbits



Jason Wang, Malachi Noel



Jason Wang, GPIES

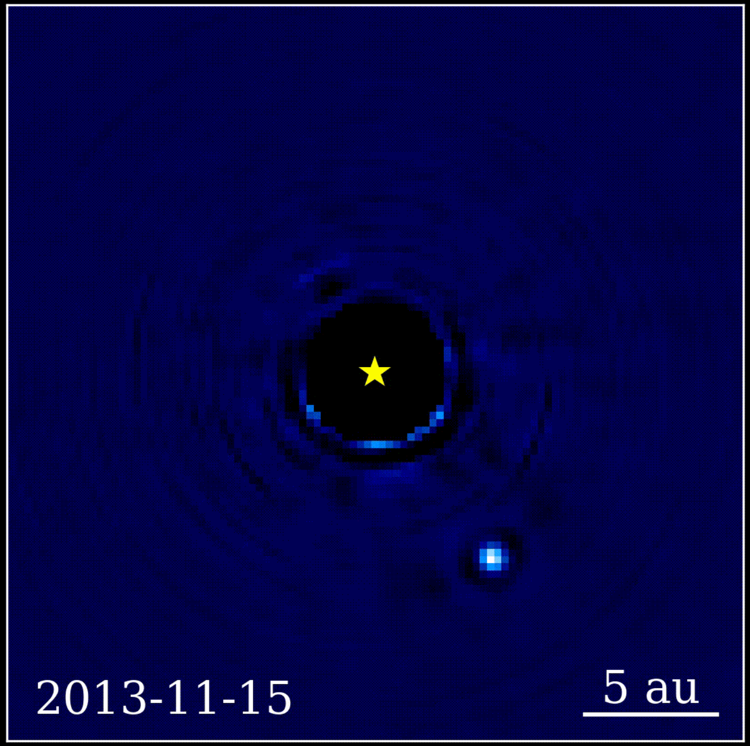
12 M_{Jup}
9 AU
~24 Myr

2 M_{Jup}
13 AU
~24 Myr

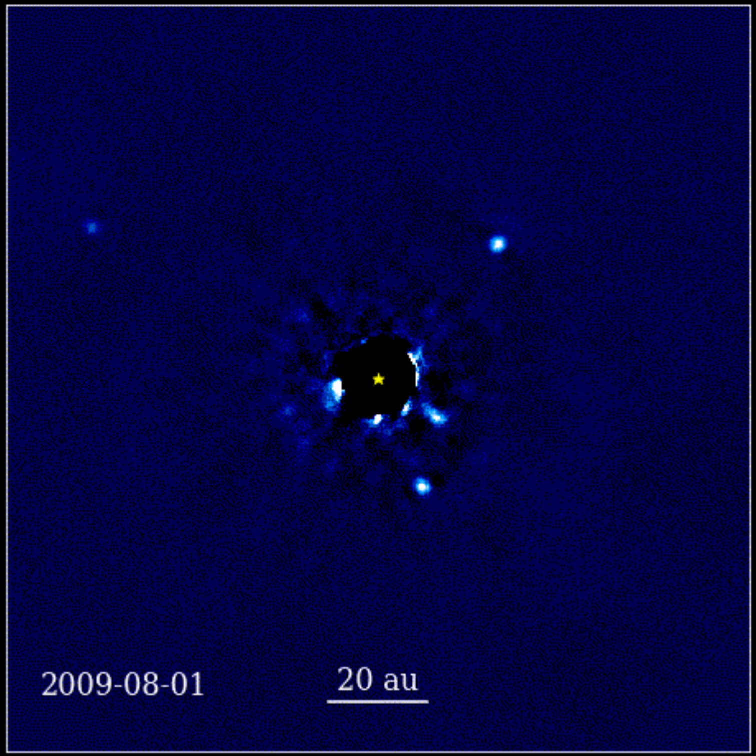
Orbits

Measure planet's: semi-major axis, period, eccentricity, inclination angle

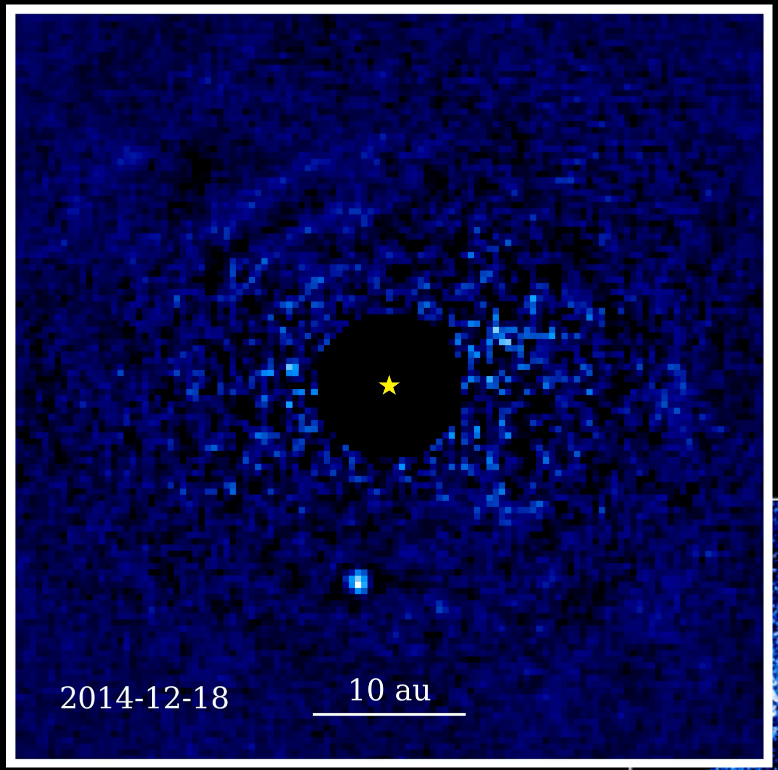
Don't get planet mass with imaging alone: need evolutionary model, star age, and planet brightness



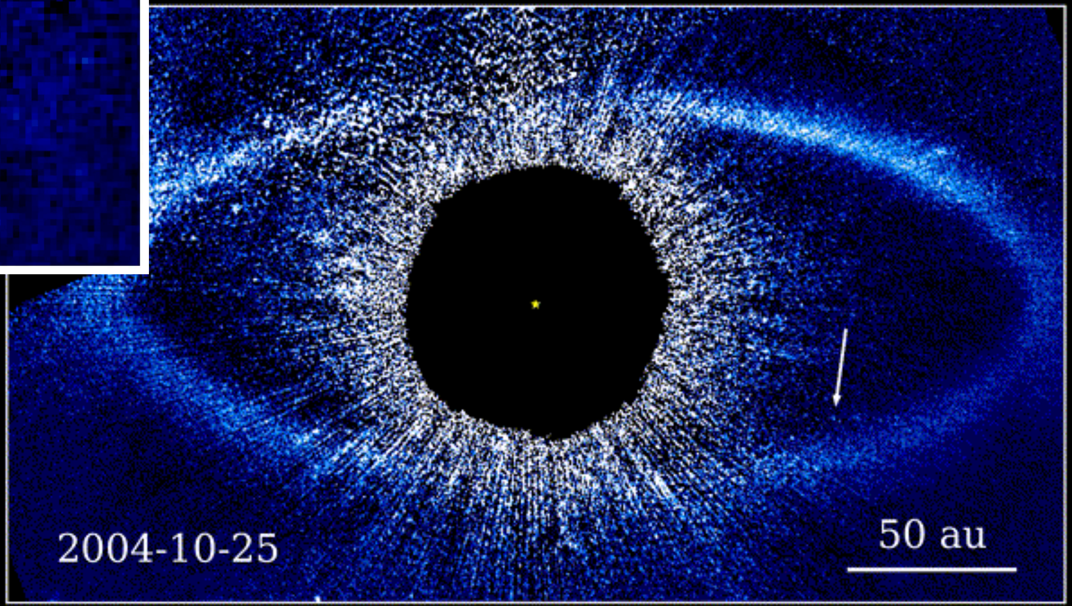
Jason Wang, Malachi Noel



Jason Wang, William Thompson, Christian Marois, Quinn Konopacky



Jason Wang, GPIES



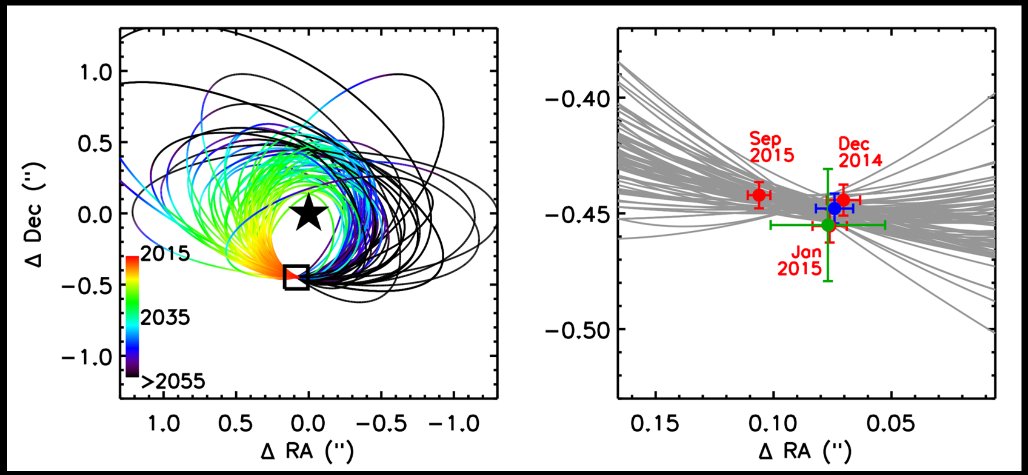
Jason Wang, Paul Kalas

Orbit-fitting

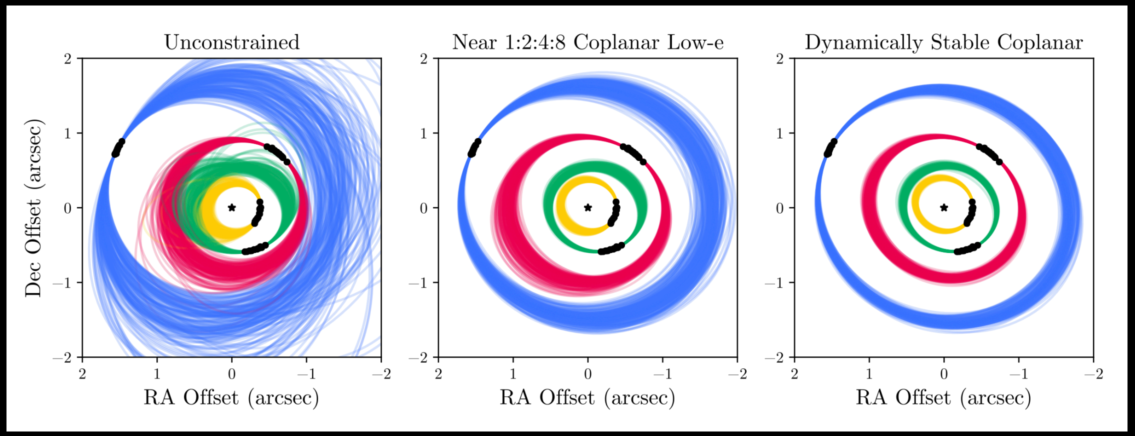
orbitize! (https://github.com/sblunt/orbitize , Blunt et al. 2007, 2024)

orvara (https://github.com/t-brandt/orvara , Brandt et al. 2021)

octofitter (https://sefffal.github.io/Octofitter.jl/stable/ , Thompson et al. 2024)

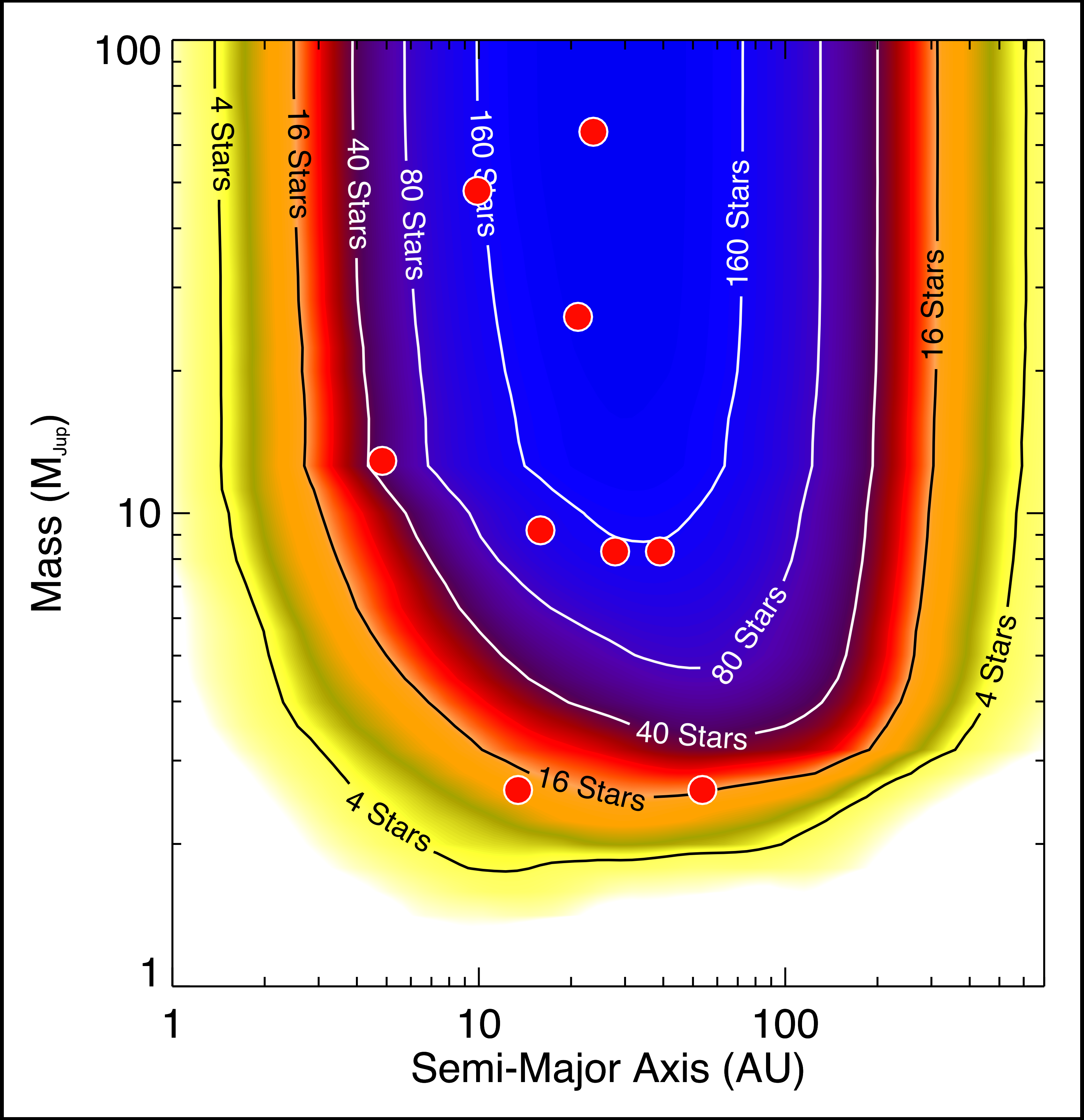


De Rosa et al. 2015



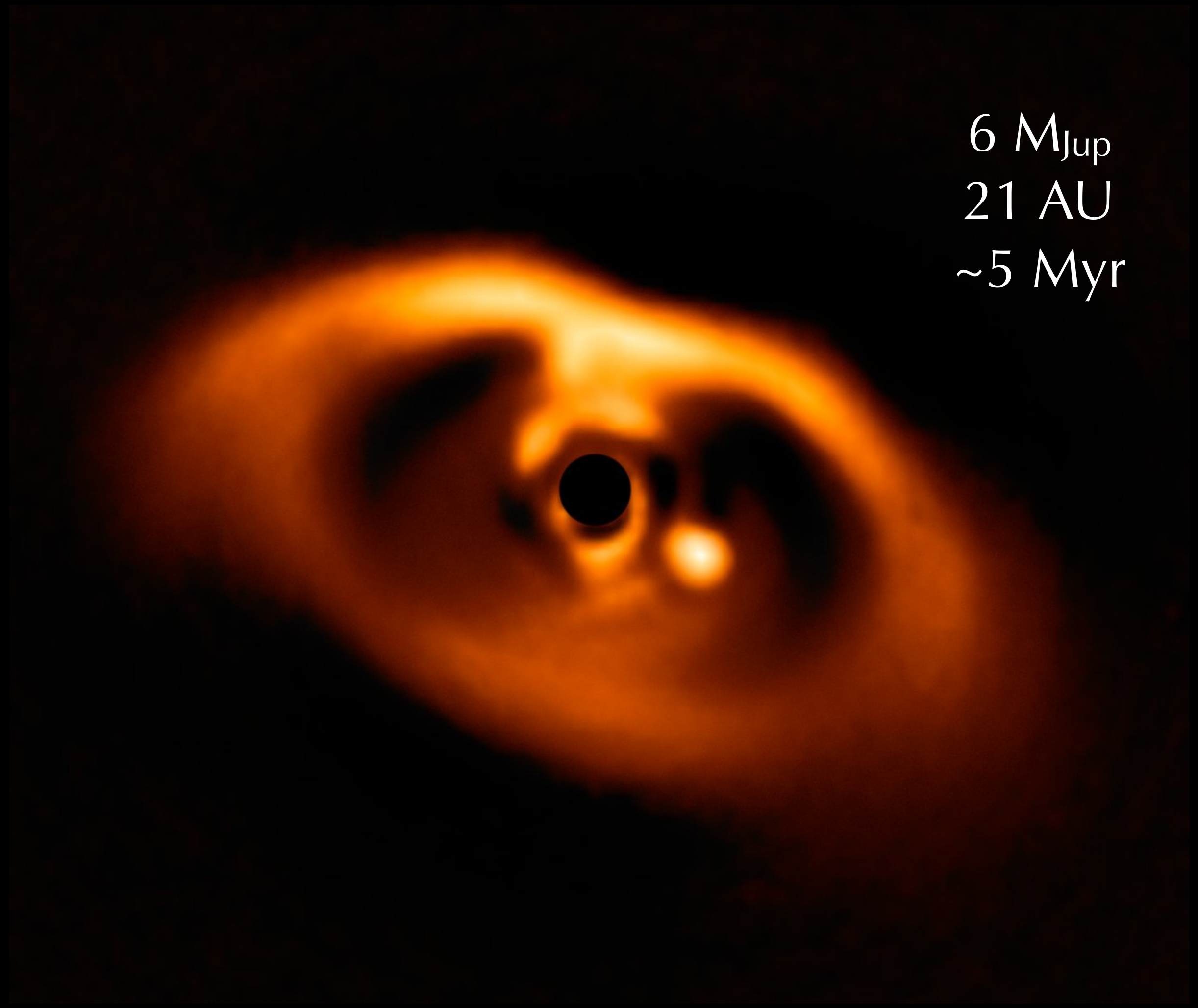
Wang et al. 2018

Demographics

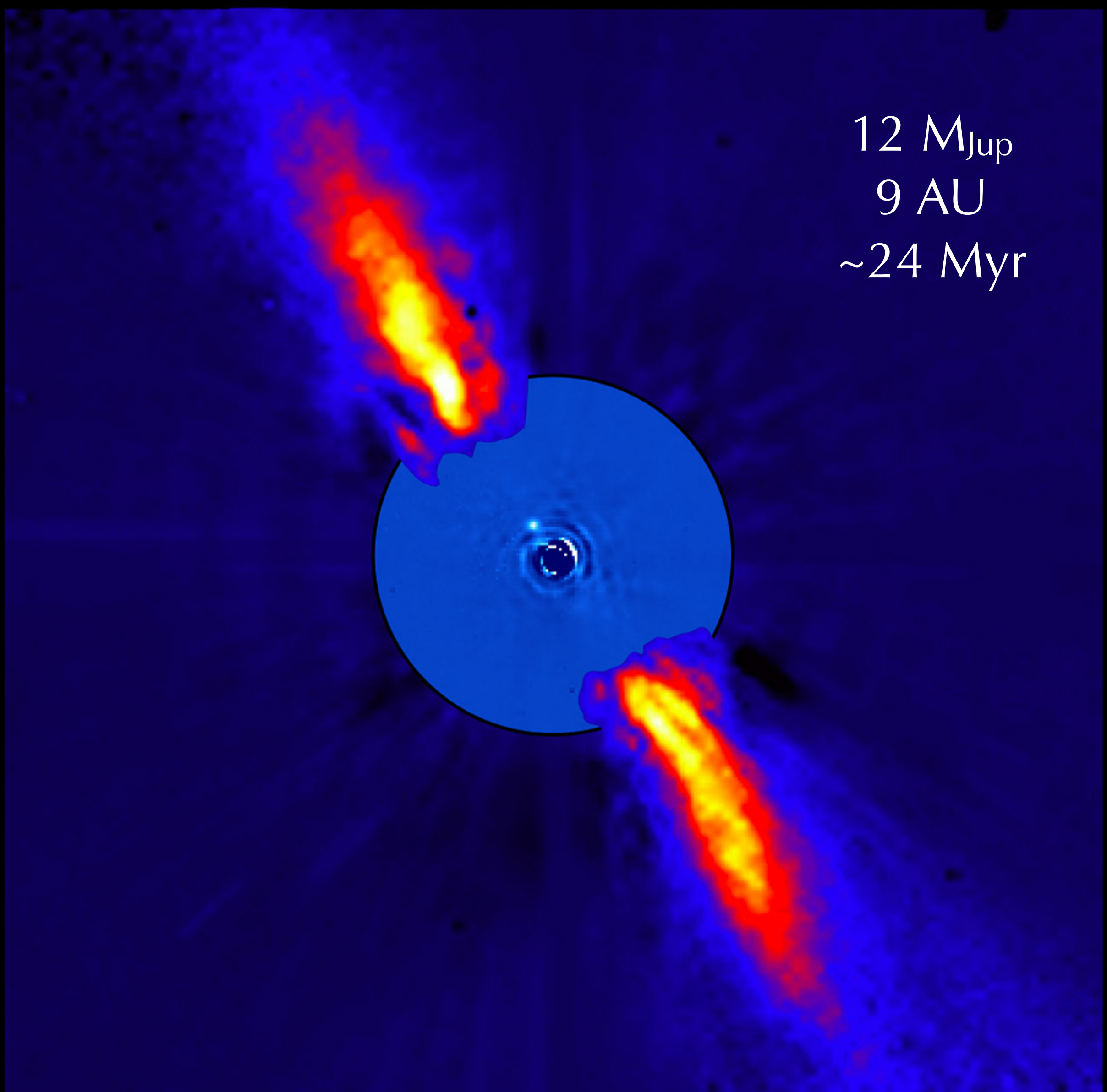


Nielsen et al. 2019

Planets and Disks



VLT/SPHERE, PDS 70 b, Muller et al. 2018



VLT/NACO and ESO/ADONIS, beta Pic b,
Lagrange et al 2008

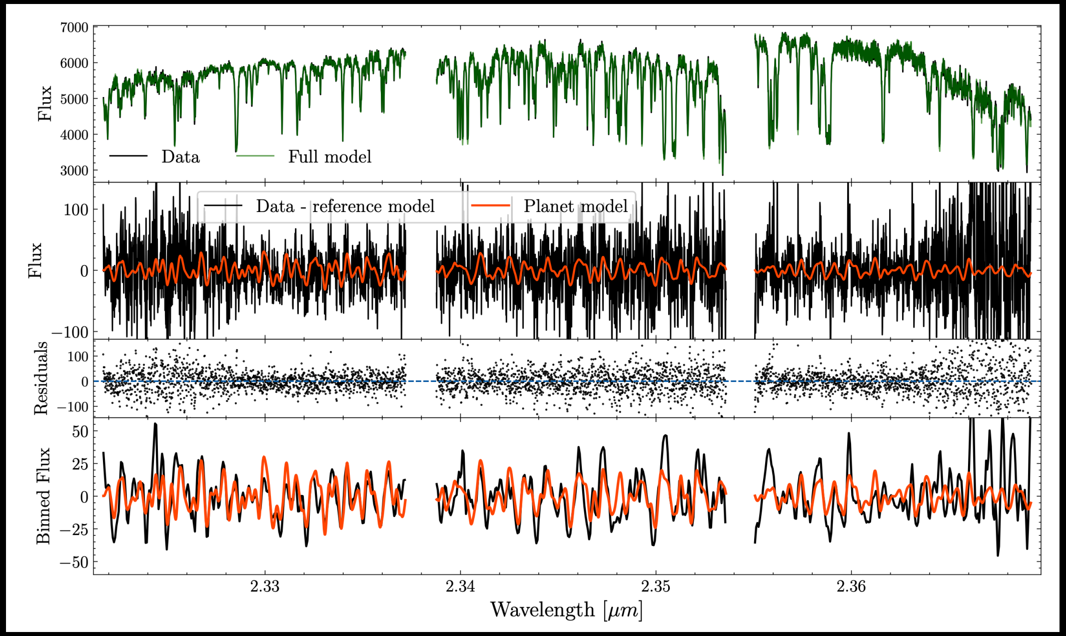
High-Resolution Exoplanet Spectroscopy

Combine high-contrast imaging with high-resolution (R~30,000 - 100,000) spectra

VLT/CRyongenic high-resolution InfraRed Echelle Spectrograph (CRIRES)

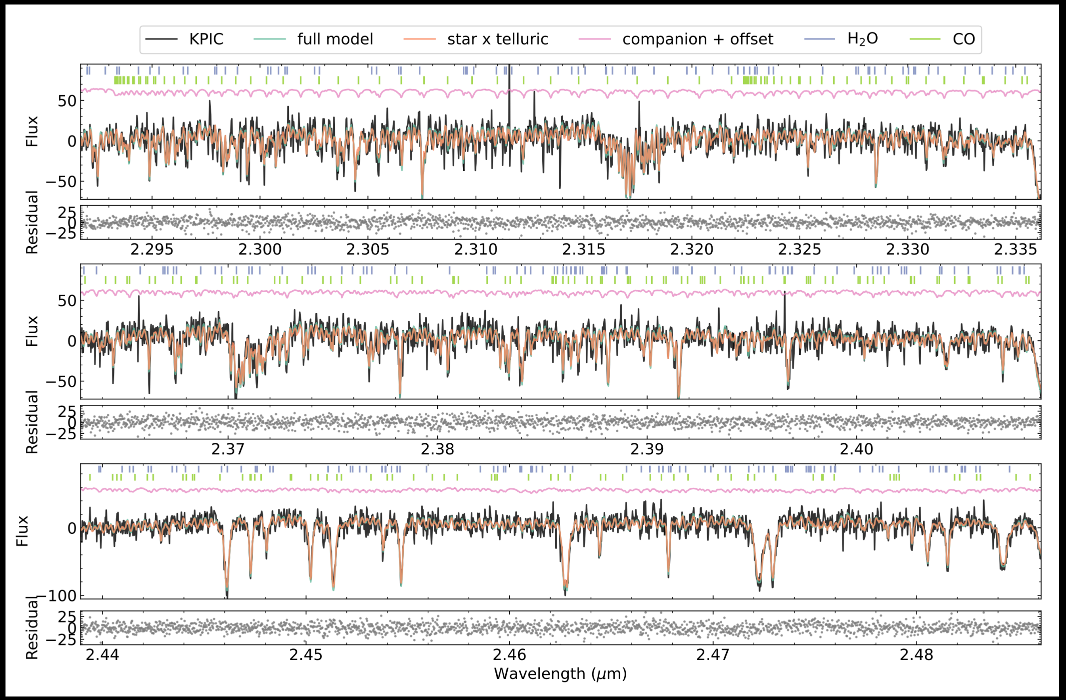
Keck Planet Imager and Characterizer (KPIC)

12 M_{Jup}
9 AU
~24 Myr



beta Pic b, Landman et al. 2024

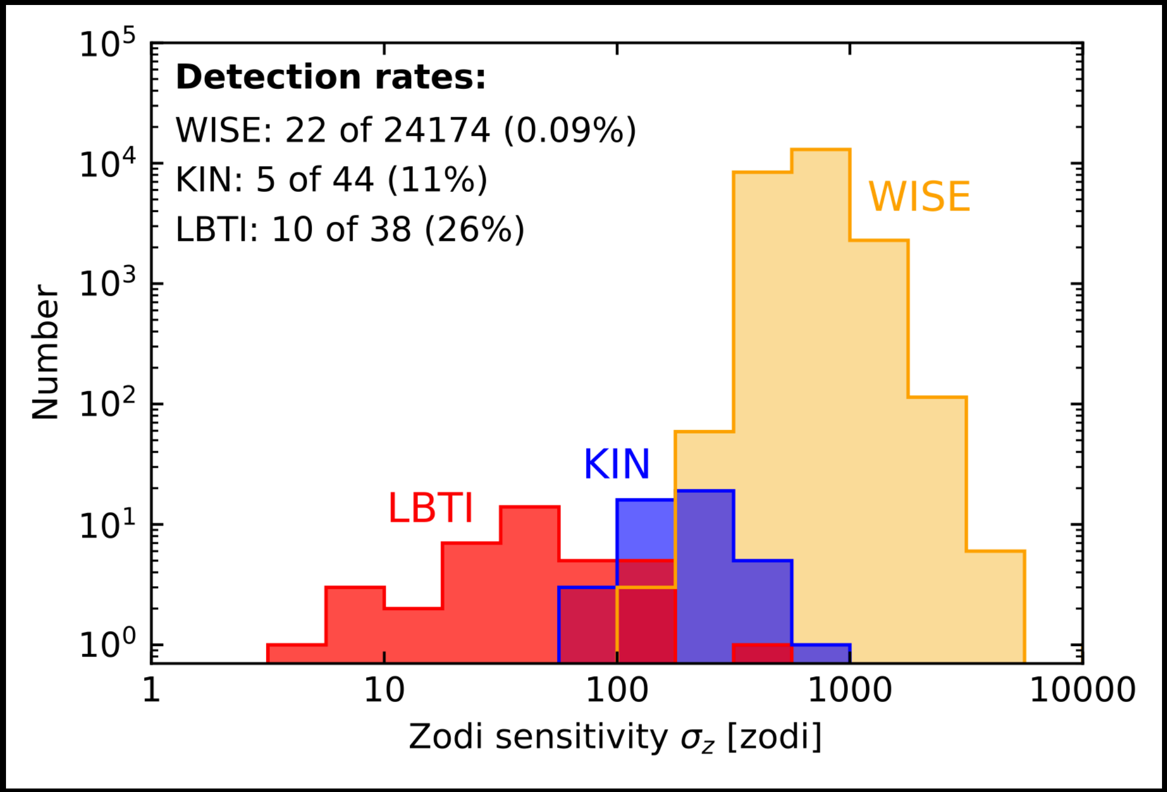
17 M_{Jup}
16 AU
~100-200 Myr



HIP 99770 b, Zhang et al. 2024

Interferometry

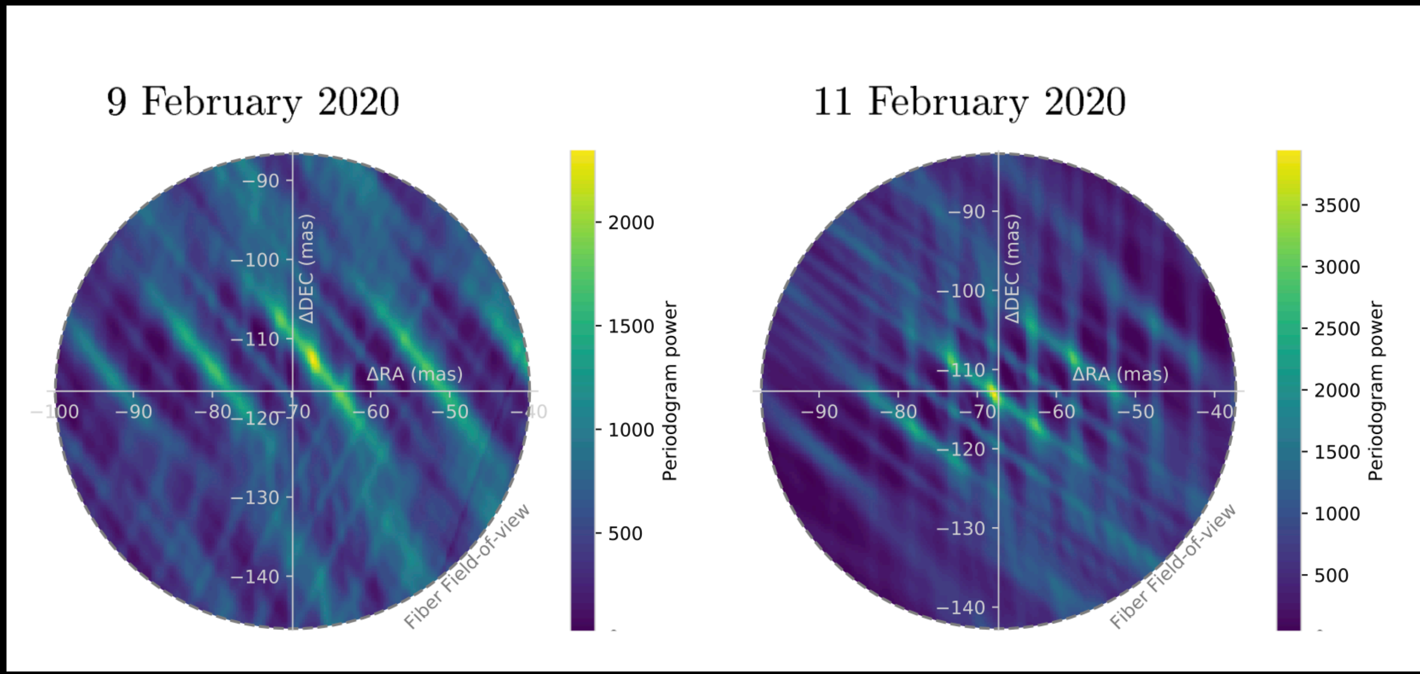
Large Binocular Telescope Interferometer (LBTI)



Ertel et al. 2020

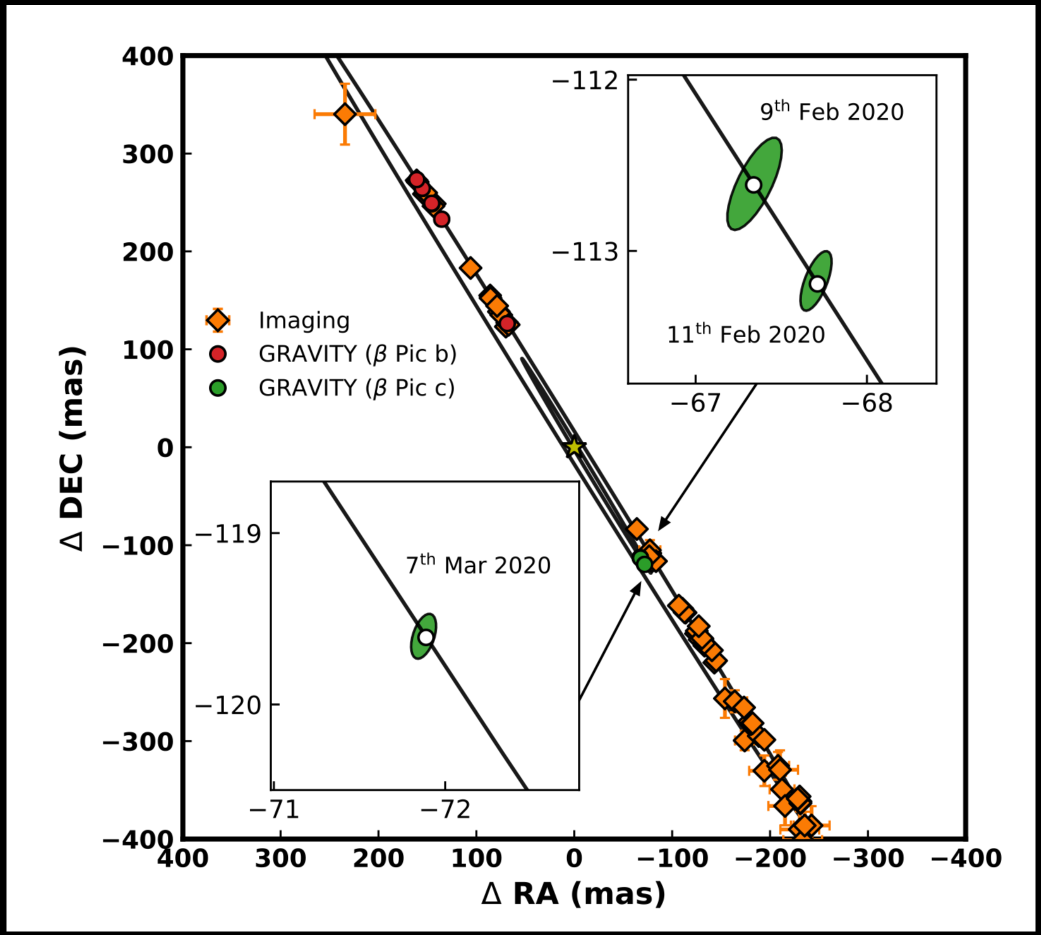
VLTI/GRAVITY

10 M_{Jup}
3 AU
~24 Myr

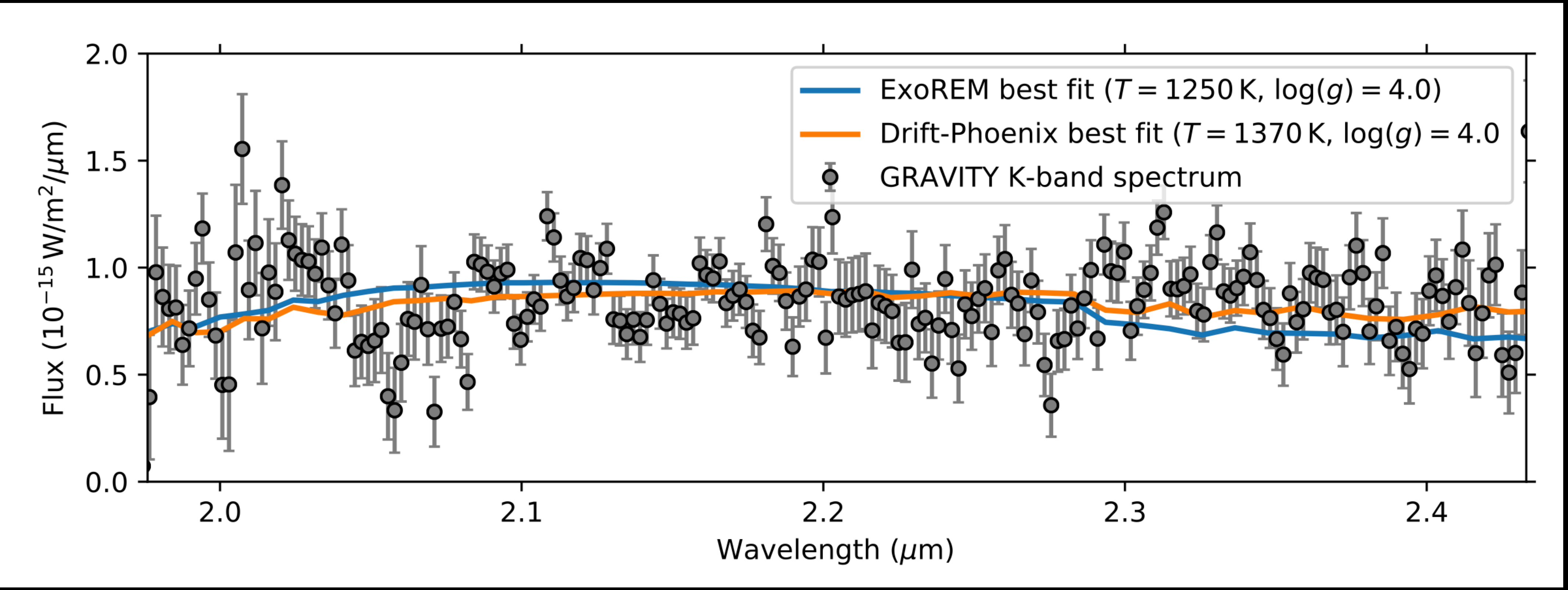


beta Pic c, Nowak et al. 2020

VLTI/GRAVITY



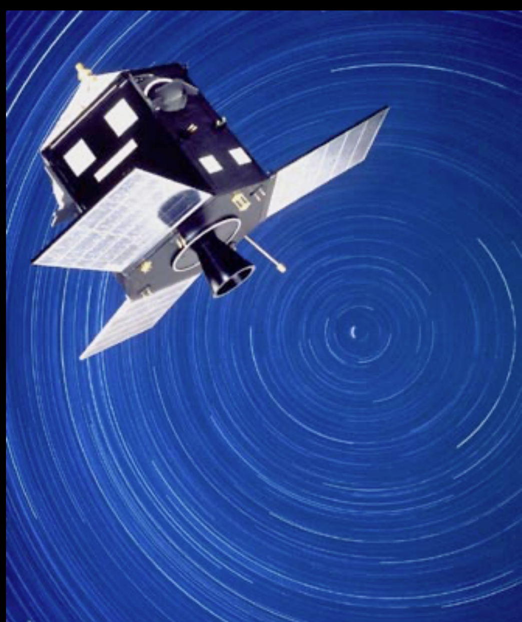
10 M_{Jup}
3 AU
~24 Myr



beta Pic c, Nowak et al. 2020

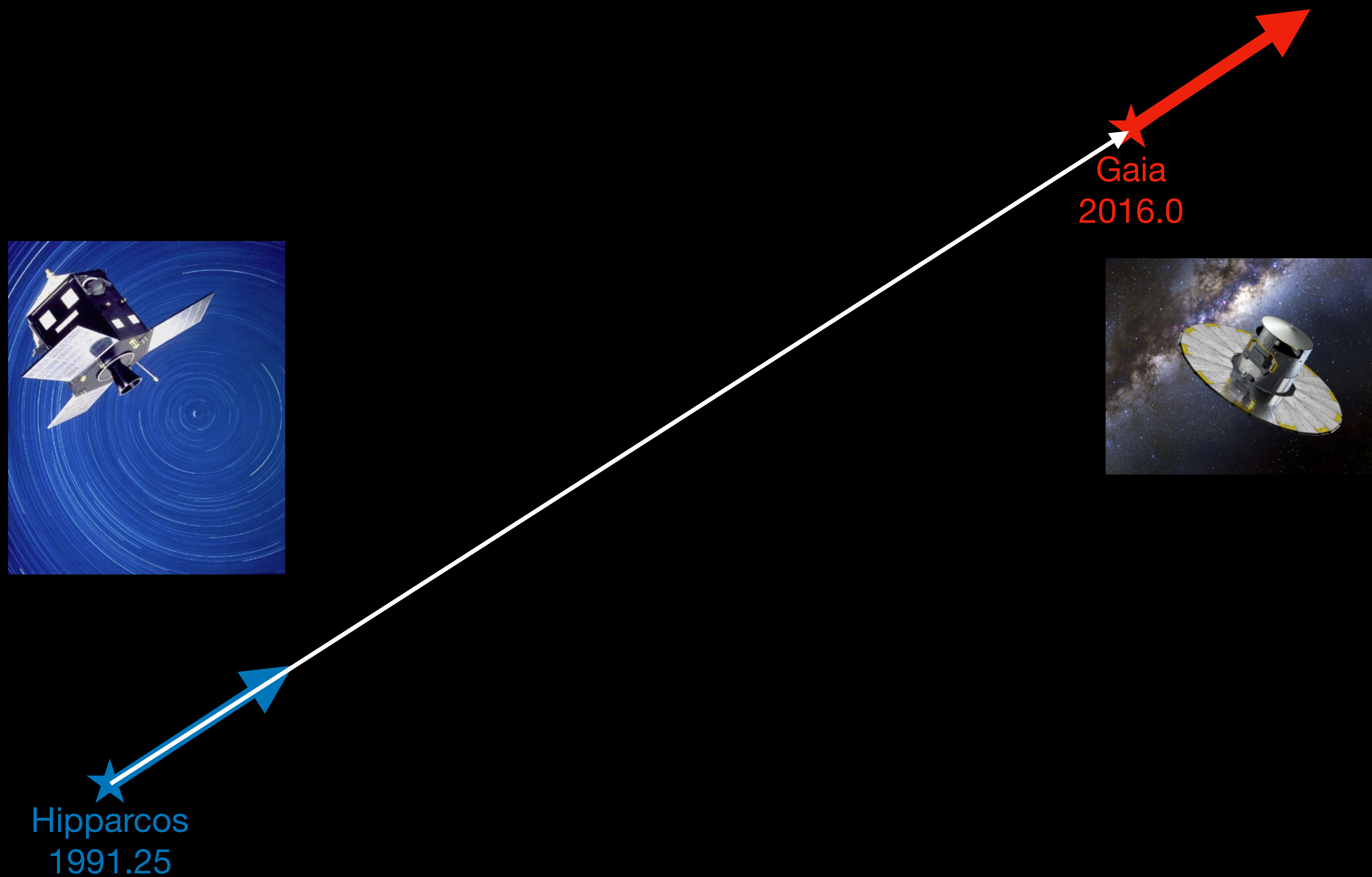
Direct Imaging and Astrometry

Gaia
2016.0

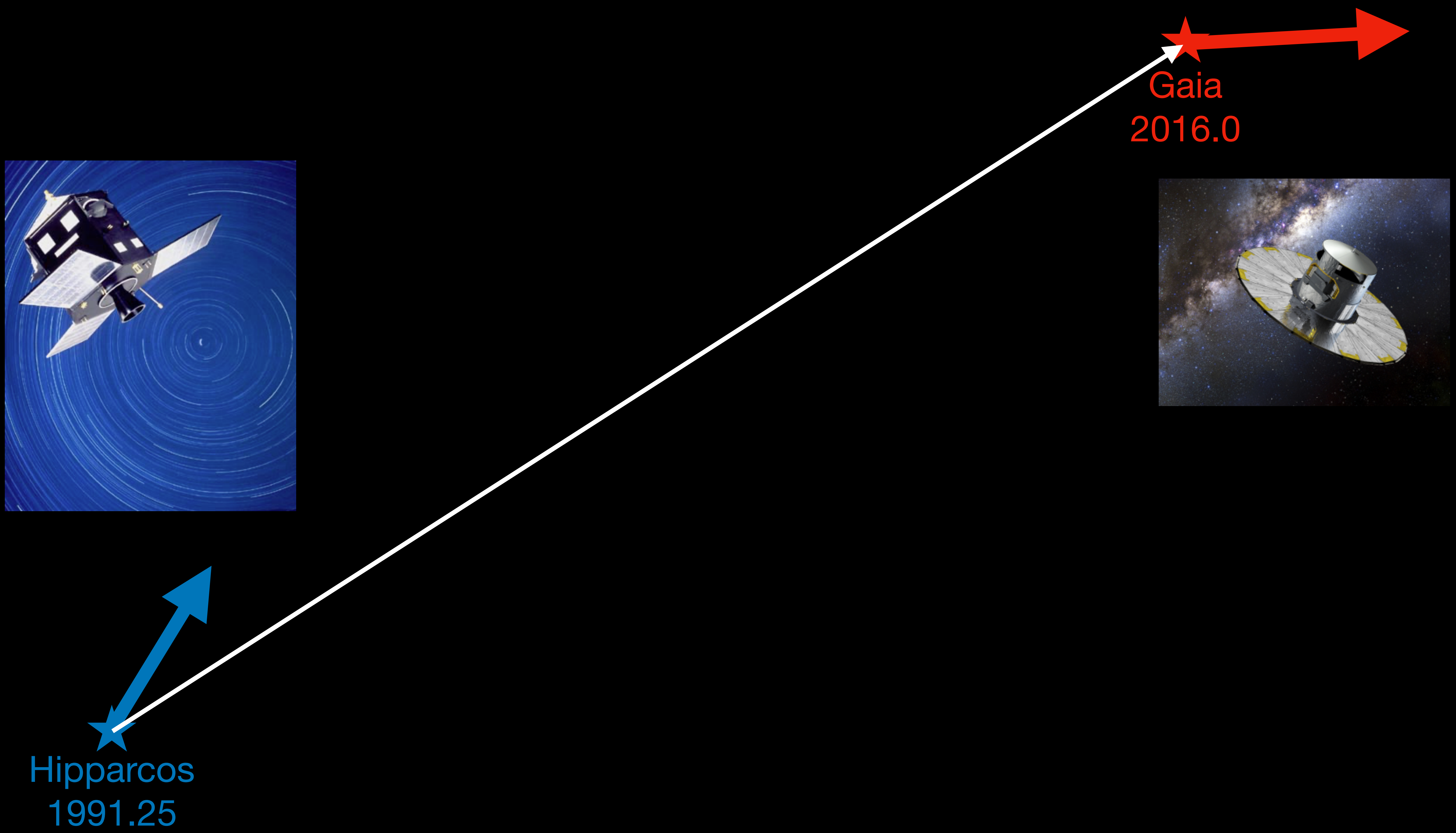


Hipparcos
1991.25

Direct Imaging and Astrometry

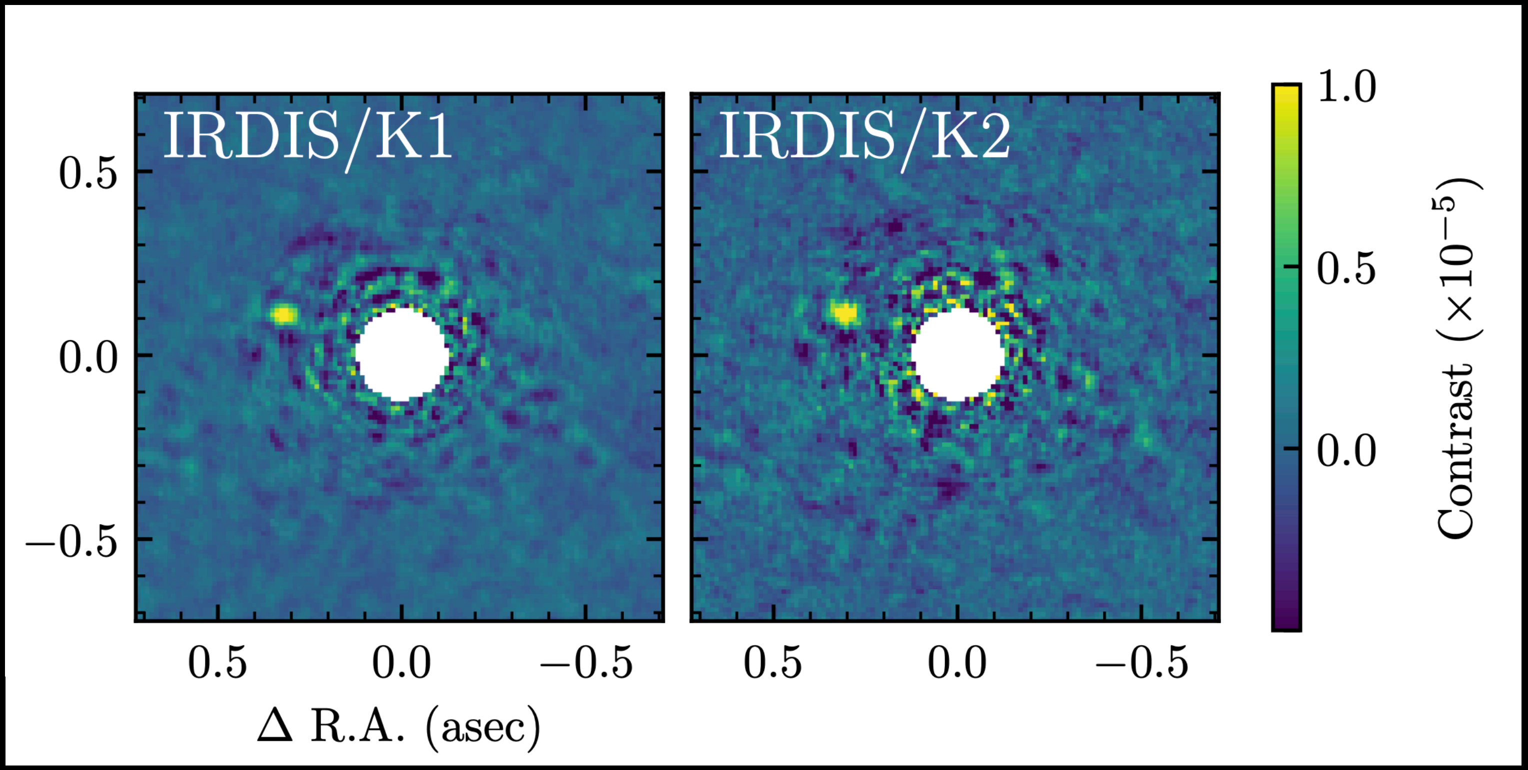


Direct Imaging and Astrometry



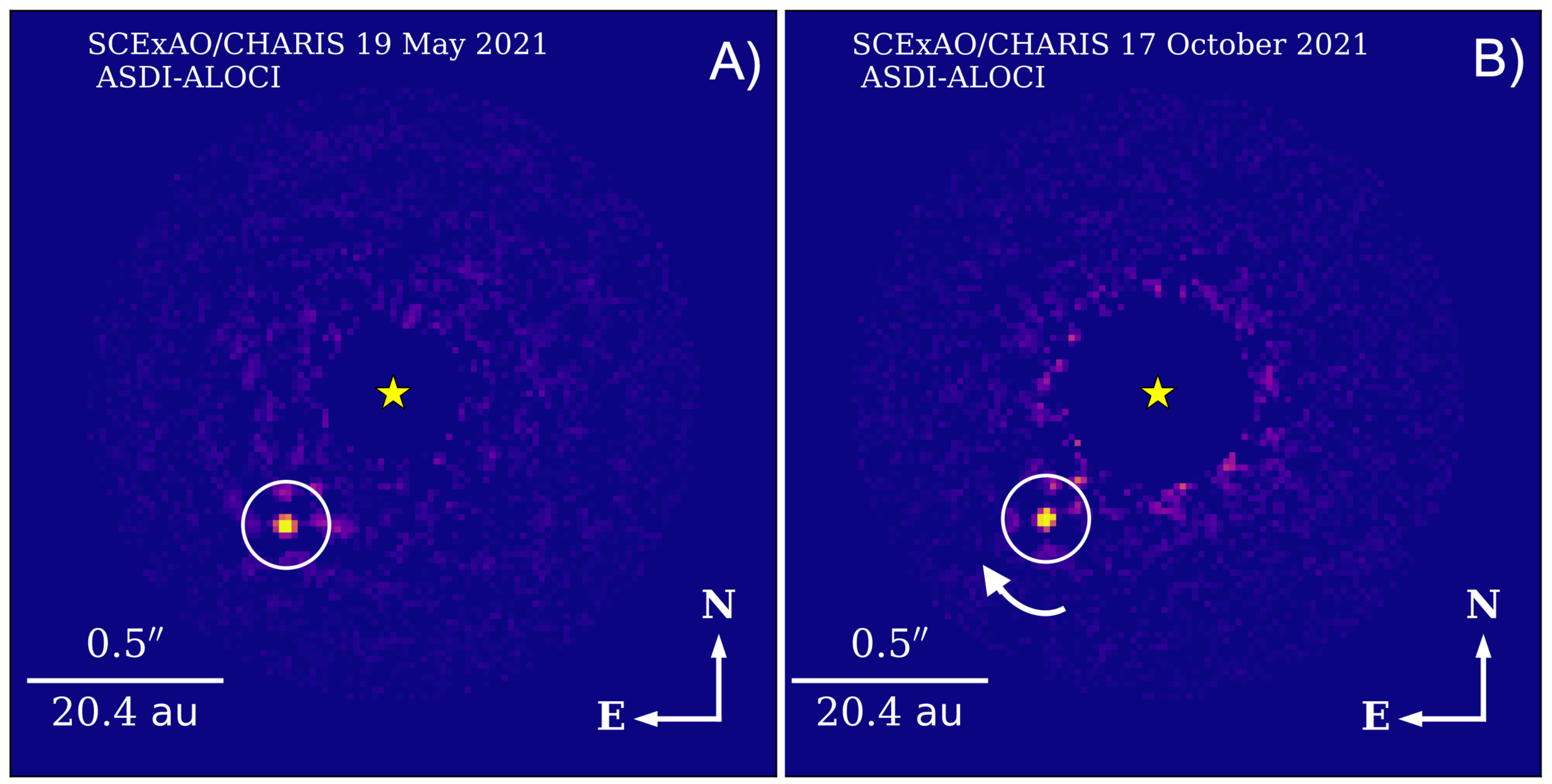
Hipparcos/Gaia and Direct Imaging

4 M_{Jup}
9 AU
~24 Myr



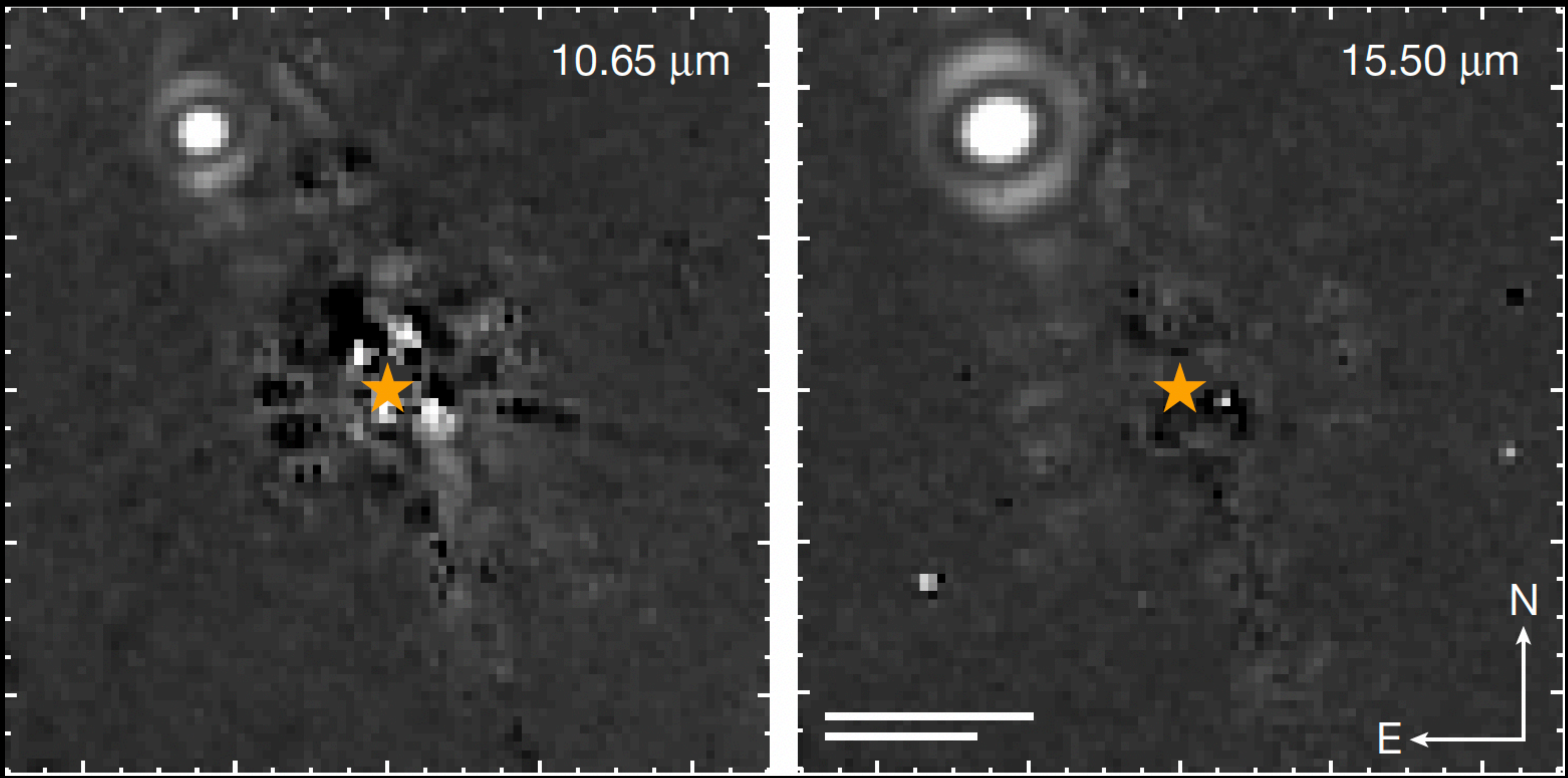
AF Lep b, De Rosa et al. 2023
(also Mesa et al. 2023, Franson et al. 2023)

17 M_{Jup}
16 AU
~100-200 Myr



HIP 99770 b, Currie et al. 2023

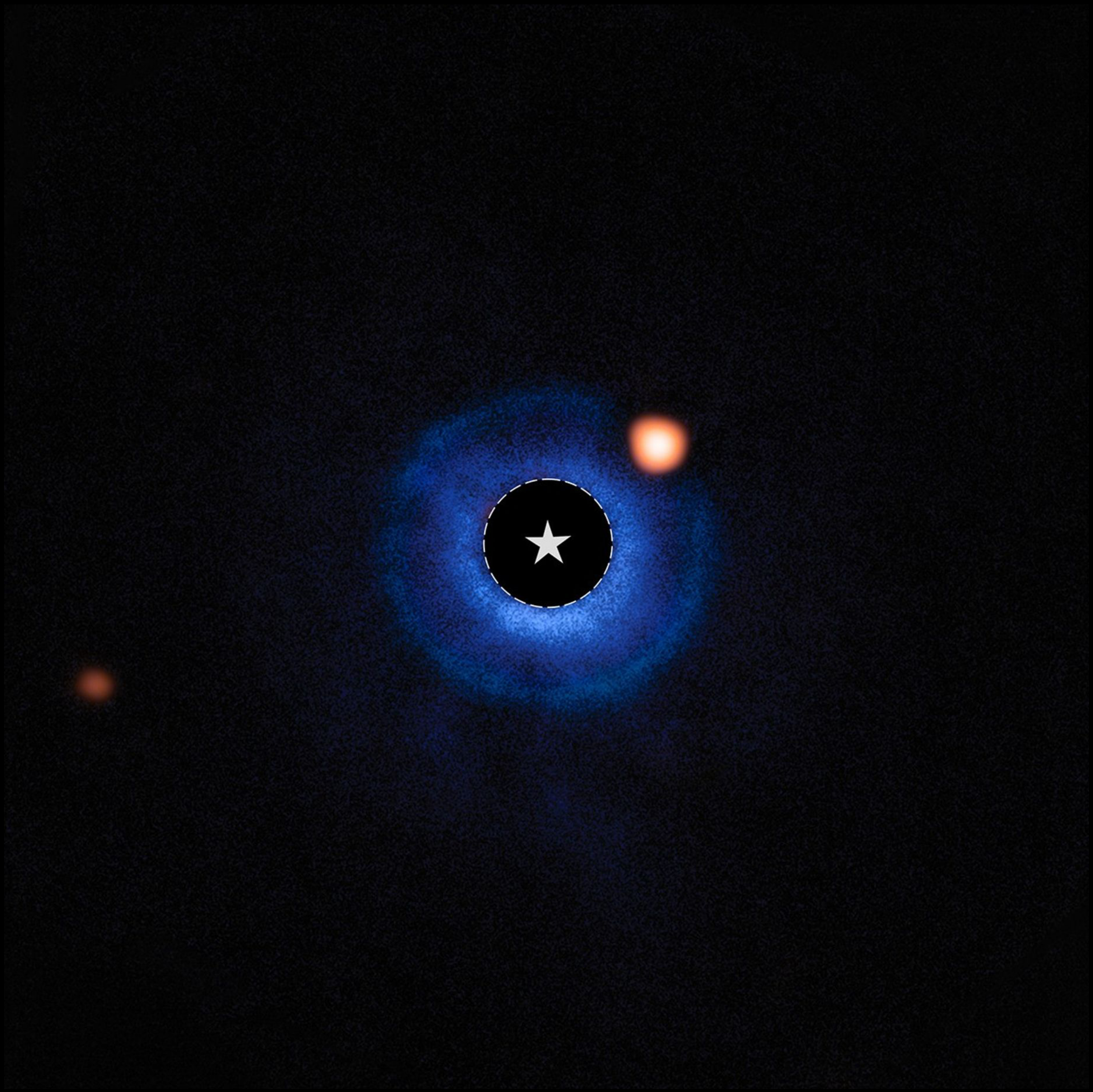
Direct Imaging and Radial Velocity



6 M_{Jup}
28 AU
~4-6 Gyr

eps Indi Ab, Matthews et al. 2024

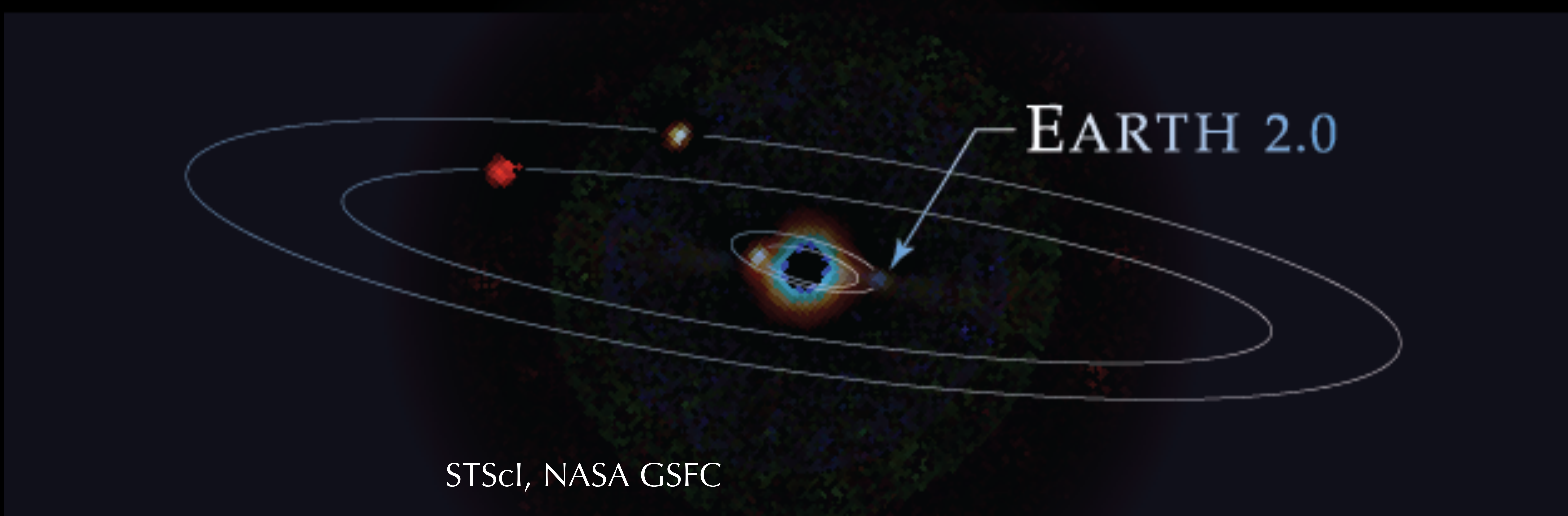
James Webb Space Telescope



0.3 M_{Jup}
52 AU
~10 Myr

TWA 7b, Lagrange et al. 2025


Habitable Worlds
OBSERVATORY


EARTH 2.0
STScI, NASA GSFC

Further reading

“Direct Imaging and Spectroscopy of Extrasolar Planets”, Protostars and Planets VII, Currie et al. 2023

“Direct Imaging of Exoplanets”, Encyclopedia of Exoplanets, Zurlo 2024

“An Introduction to High Contrast Differential Imaging of Exoplanets and Disks”, PASP, Follette 2023

“Imaging Extrasolar Giant Planets”, PASP, Bowler 2016

Conclusions

Direct imaging gives spectra, photometry, orbits, and demographics of exoplanets

Exoplanet detections have been in the NIR and MIR, the planet's thermal emission

Direct imaging has been most sensitive to exoplanets that are <100 Myr, >10 AU, >1 M_{Jup}

Improvements in telescopes, instrumentation, and data analysis are pushing toward older, closer, lower-mass planets

The Habitable Worlds Observatory will improve contrast and IWA to detect and characterize Earth-like planets around nearby stars using direct imaging