ASTR 405
Planetary Systems
Direct Imaging

Fall 2025

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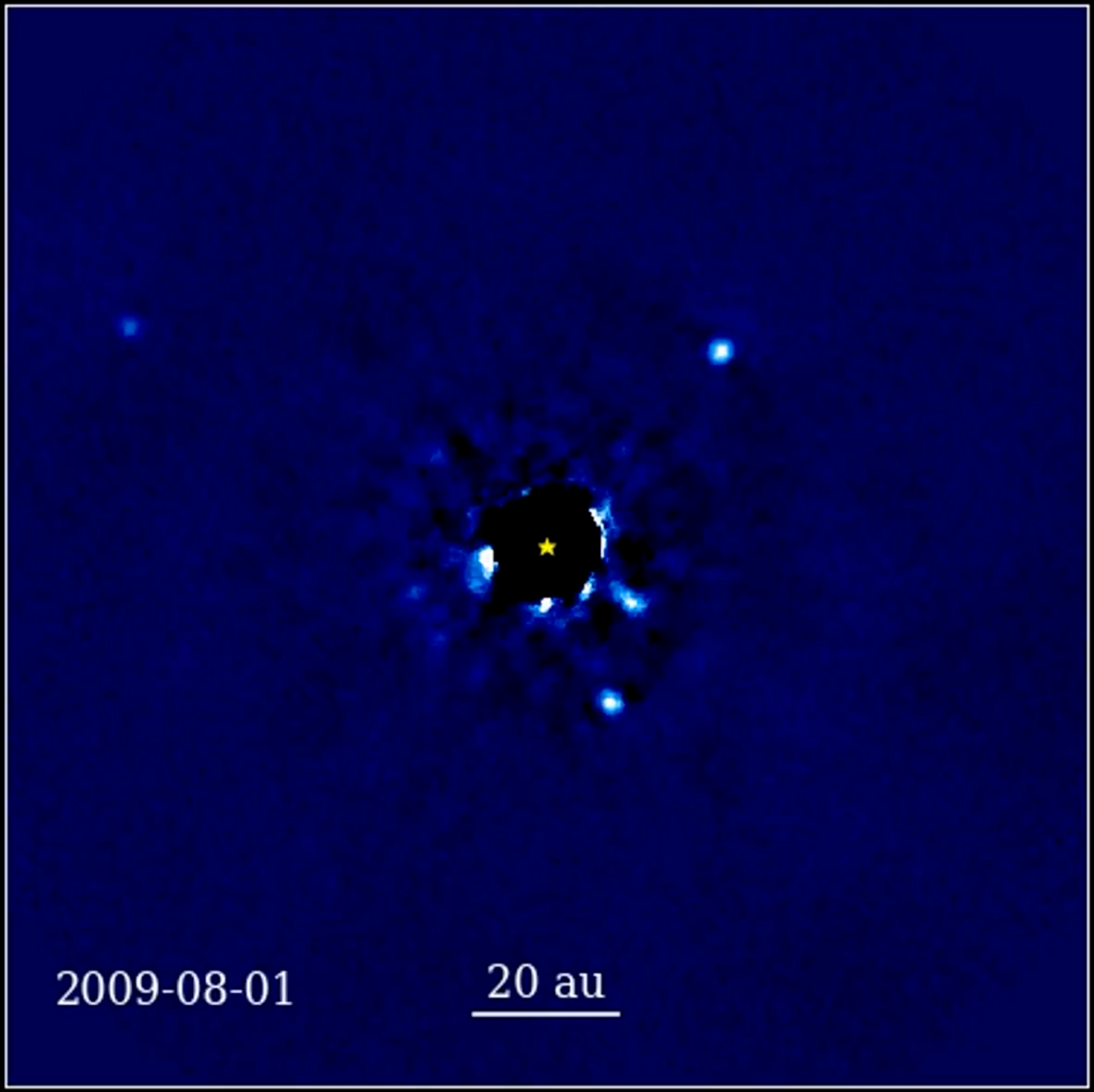
Module I: Exoplanet Detection Methods

- Radial Velocity: detecting exoplanets by measuring Doppler shifts from a star's radial reflex motion along our line of sight
- Astrometry: detecting exoplanets by measuring tiny changes in a star's sky position from its tangential reflex motion
- Transit: detecting exoplanets by observing the dimming of a star's light when a planet passes in front of it
- Microlensing: observing the brightening of a background star caused by the gravity of a planet-hosting foreground star acting as a lens
- Direct Imaging: detecting exoplanets by blocking the star's light to **directly capture light from the planet** itself

Pale Blue Dot

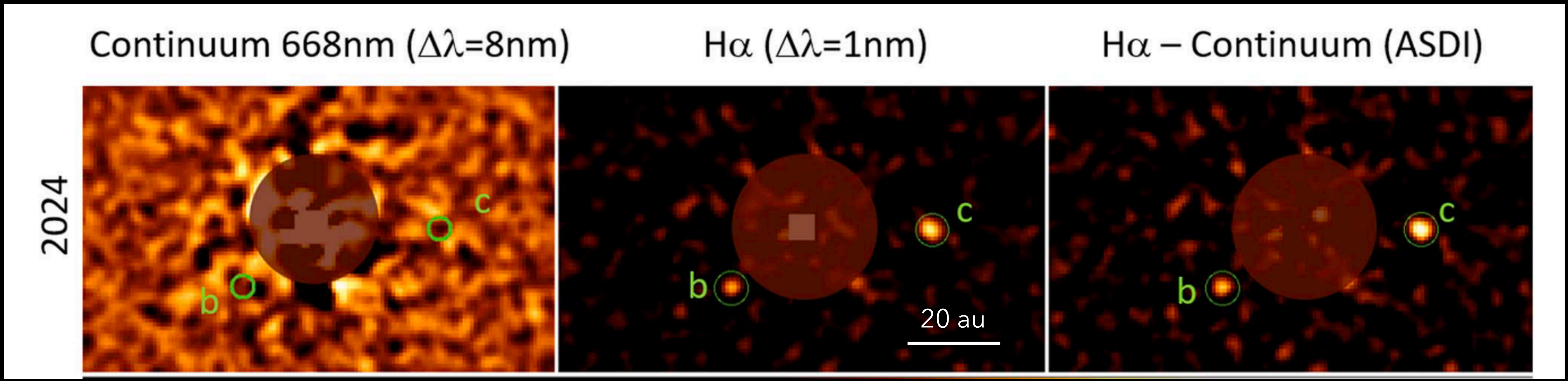
The original photo was taken on February 14, 1990 as the Voyager 1 spacecraft sped past Neptune and turned its camera back towards Earth for one last look.

HR 8799 (30 Myr): Four directly imaged planets



HR 8799 (center) with HR 8799 b, c, d, and e (Wang+22)
Taken from Keck from 2009 – 2021

PDS-70 (5 Myr): Two accreting planets with circumplanetary disks

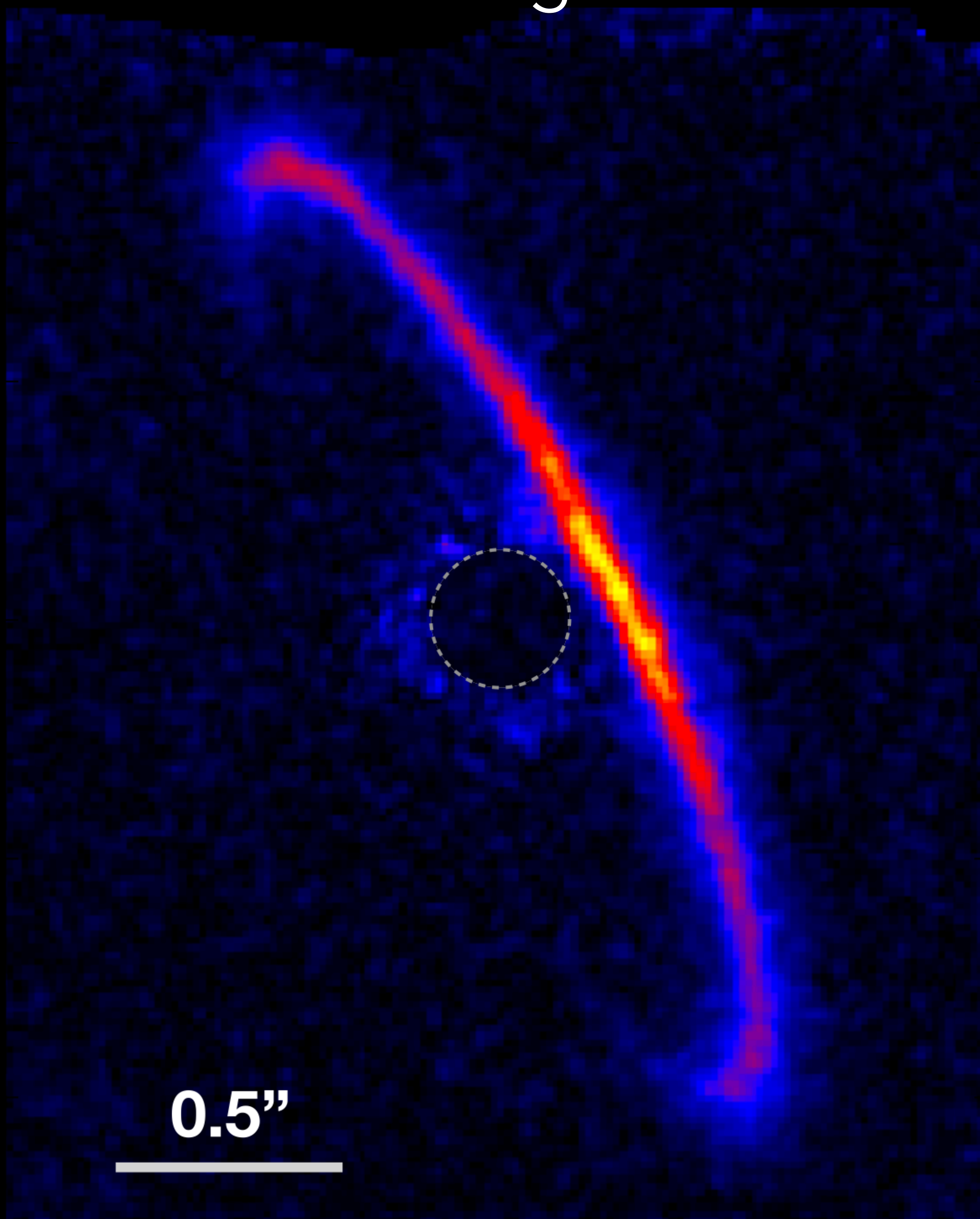


Close+25

MagAO-X

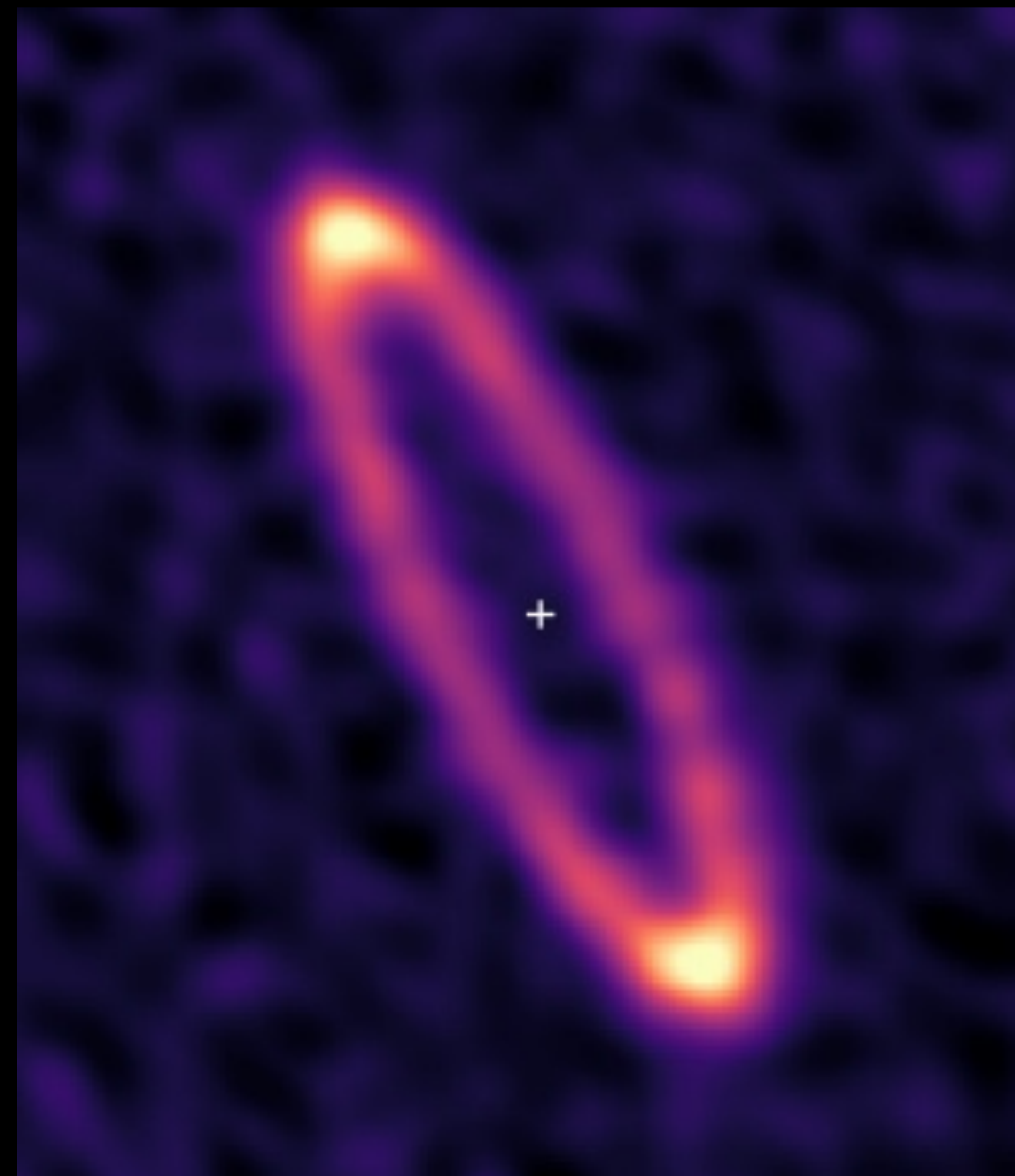
Debris disk of HR 4796A

Polarized image with GPI



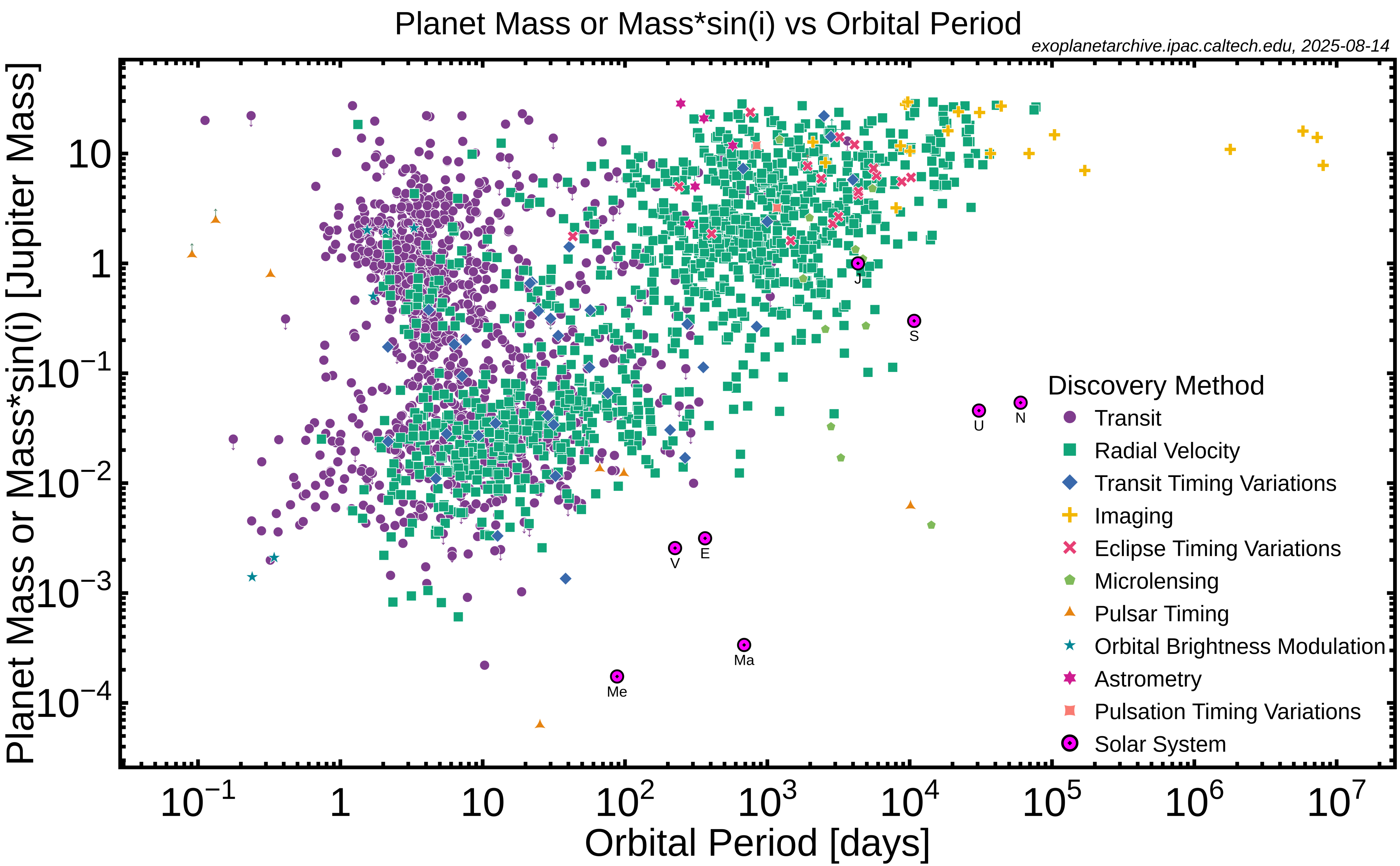
Perrin+15

Sub-mm emission with ALMA



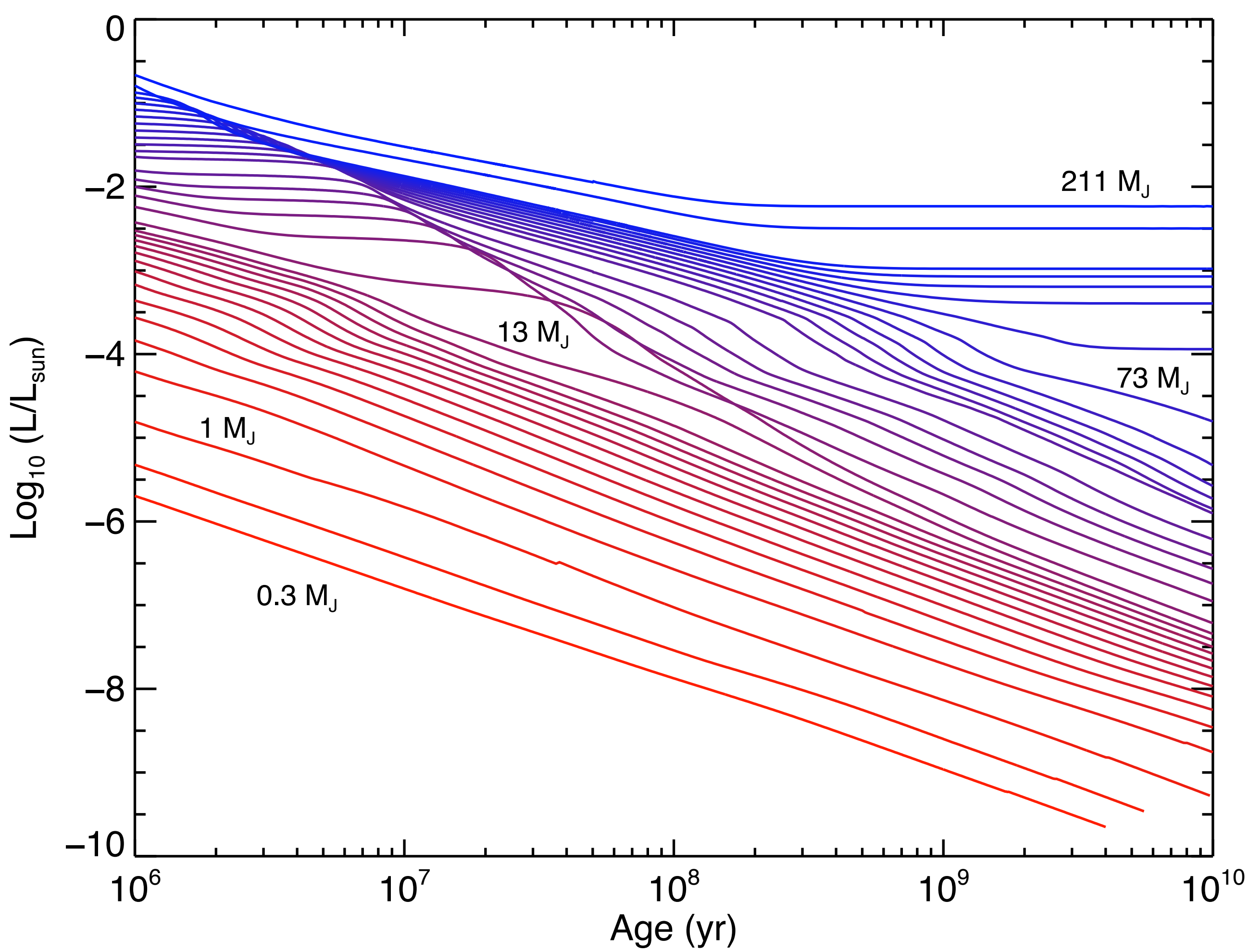
Kennedy+18

Exoplanet Mass–Period Distribution



Direct Imaging Exoplanets

Cooling curves of giant planets and brown dwarfs



Burrows 97

- All directly imaged planets are young, self-luminous planets (not reflected light)
- Brighter planets are easier to detect → requires **large planet-star contrast** $F_p/F_\star$
- Planets are easier to detect further from their star → requires **large angular separation** a/d**, high telescope angular resolution** λ/D
  - a: semimajor axis of planet
  - d: host star distance
  - λ: observed wavelength
  - D: telescope aperture size

Planet-to-star Contrast

Planet has two light components: **thermal emission** + **reflected light**

Thermal emitted light from planet itself

- Contrast $F_{p,\lambda}/F_{\star,\lambda} = \left(\frac{R_p}{R_\star}\right)^2 \frac{B_\lambda(T_p)}{B_\lambda(T_\star)}\Phi_{\rm em}(\lambda,\alpha)$, where B_λ is the Planck function and $\Phi_{\rm em}$ is the phase function for emission, which depends on wavelength λ and the star-planet-observer phase angle α.
- In the Rayleigh-Jeans tail of the Planck function, the contrast is

$$\boxed{F_{p,\lambda}/F_{\star,\lambda} \approx \left(\frac{R_p}{R_\star}\right)^2 \frac{T_p}{T_\star}\Phi_{\rm em}(\lambda,\alpha)}$$

Planet-to-star Contrast

Planet has two light components: **thermal emission** + **reflected light**

Reflected light from host star

How much stellar light is reflected by the planet compared to the star

$\boxed{F_{p,\lambda}/F_{\star,\lambda} = \left(\frac{R_p}{a}\right)^2 A_g(\lambda)\Phi_{\text{ref}}(\lambda, \alpha)}$, where A_g is the wavelength-dependent geometric albedo and Φ_{ref} is the phase function in reflected light

Planet-to-star Contrast

Planet has two light components: **thermal emission** + **reflected light**

Reflected light from host star

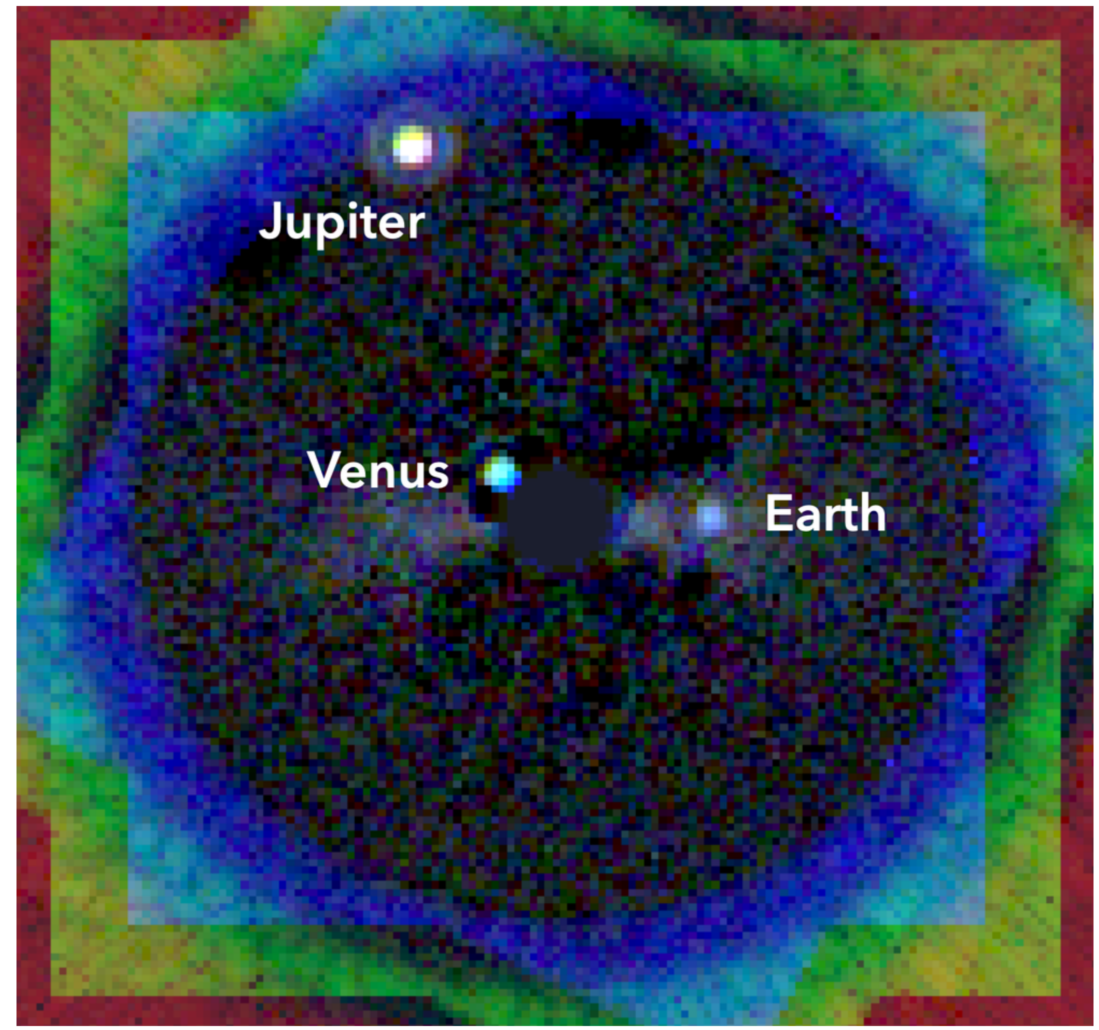
Planet equilibrium temperature $T_{\rm eq} = T_\star \left[\frac{1 - A_{\rm B}}{4f}\right]^{1/4} \sqrt{\frac{R_\star}{a}}$

- A_B is the Bond albedo ≡ the fraction of **total** energy incident on the planet that is not absorbed and re-radiated
- f is the heat redistribution factor ≡ how the received heat from the star across the planet. $f = 1$ for full redistribution of the incident stellar radiation

Planet-to-star Contrast

Typical planet-to-star contrast $F_p/F_\star$

- Young, self-luminous giant planets $\sim 10^{-6} - 10^{-4}$ (**currently achievable** with ground-based telescopes)
- Jupiter around the Sun $\sim 10^{-8}$
- Earth around the Sun $\sim 10^{-9}$



Simulated image of our Solar System as viewed in reflected light from a distance of 10 pc by a ***Habitable Worlds Observatory****-like mission.*

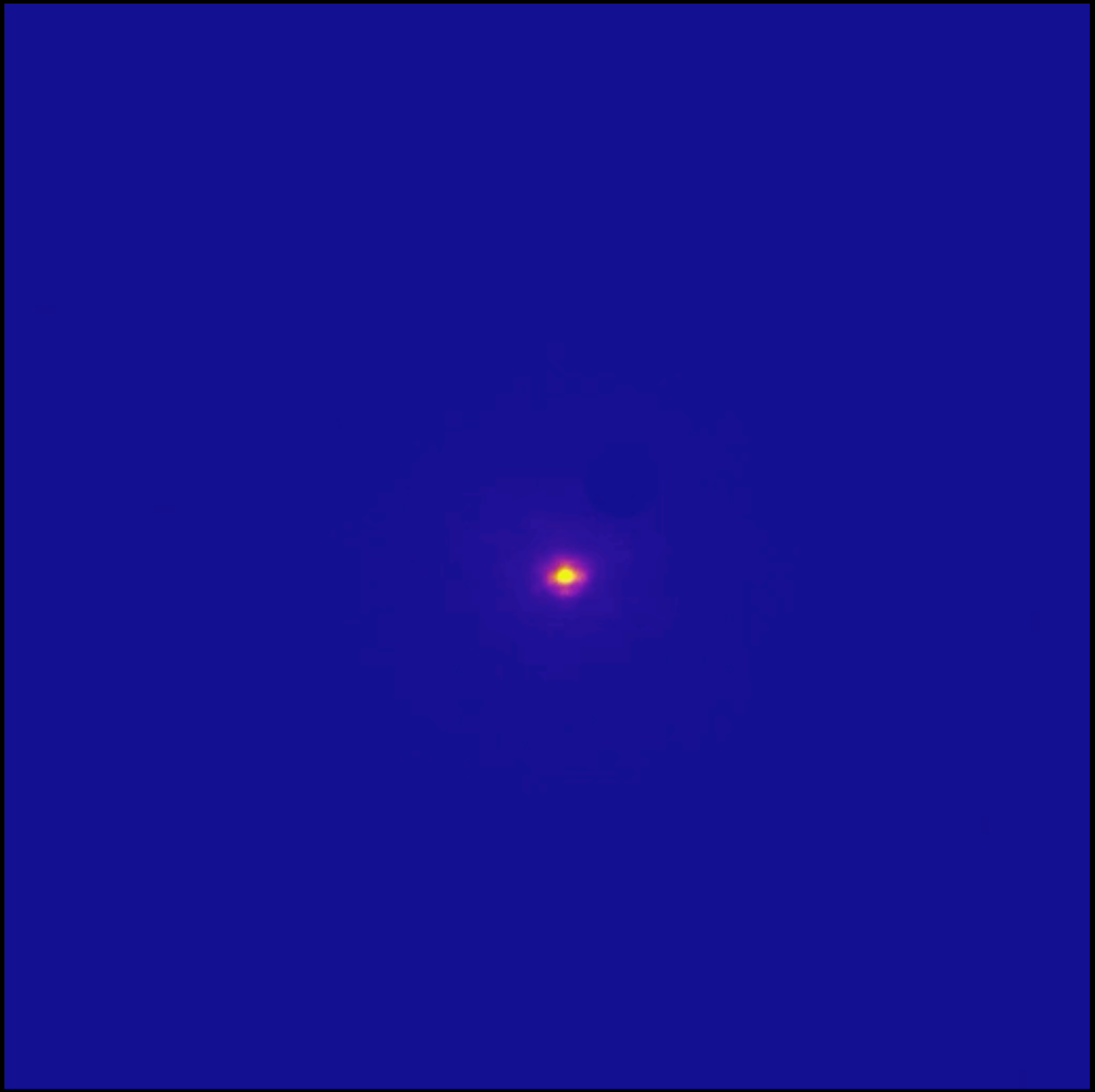
In-Class Activity

Why Direct Imaging is Hard

Modern Direct Imaging Techniques

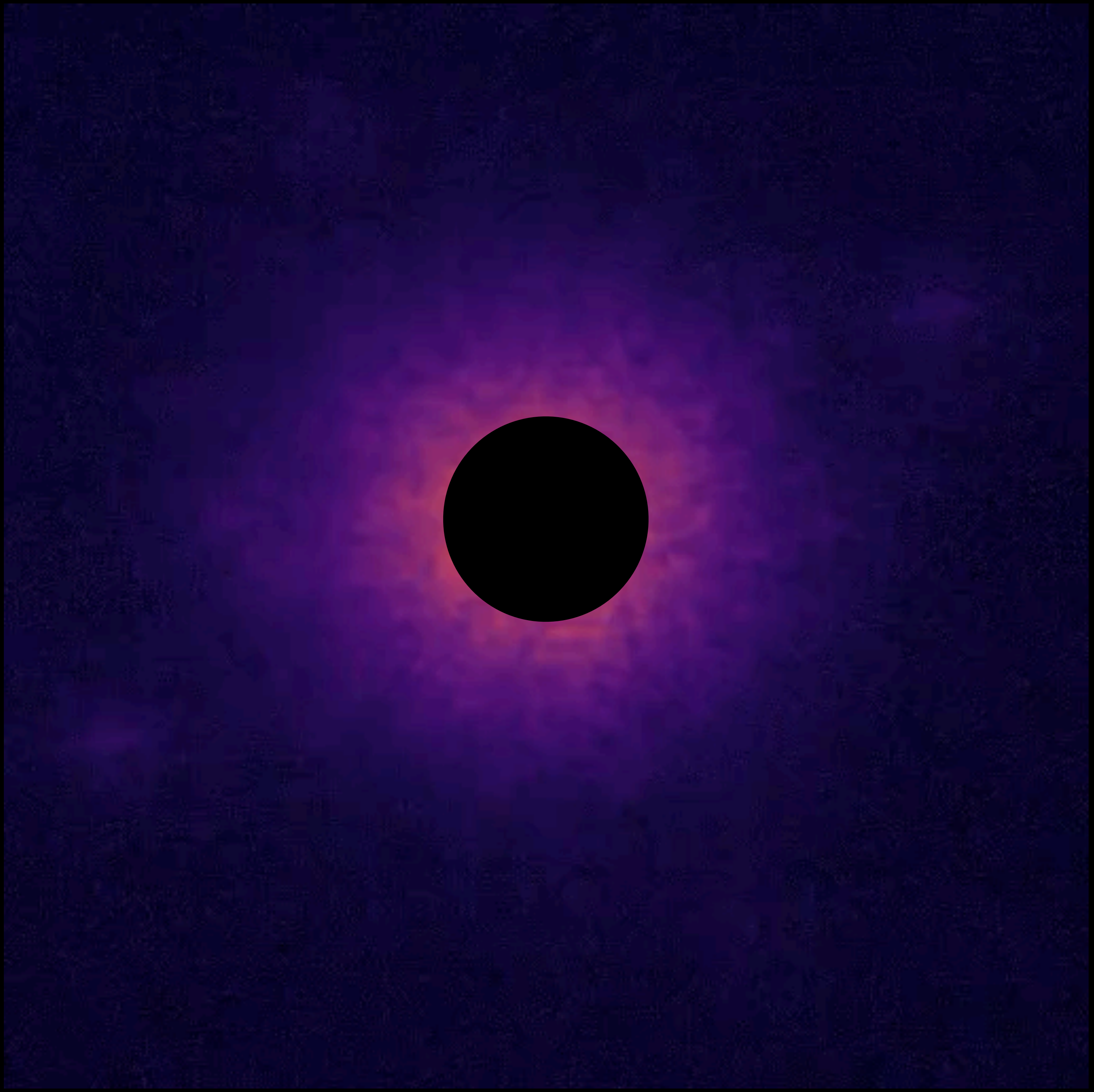
- **Coronagraph:** blocks stellar PSF to suppress diffracted starlight; enhances contrast for close-in planetary companions
- **Adaptive Optics (AO):** corrects wavefront distortions from Earth's atmosphere; enables diffraction-limited imaging from ground-based telescopes
- **Angular Differential Imaging (ADI):** utilizes field rotation in alt-az mounts; subtracts quasi-static speckles to reveal faint off-axis sources

A coronagraph blocks the bright core of a star's light.



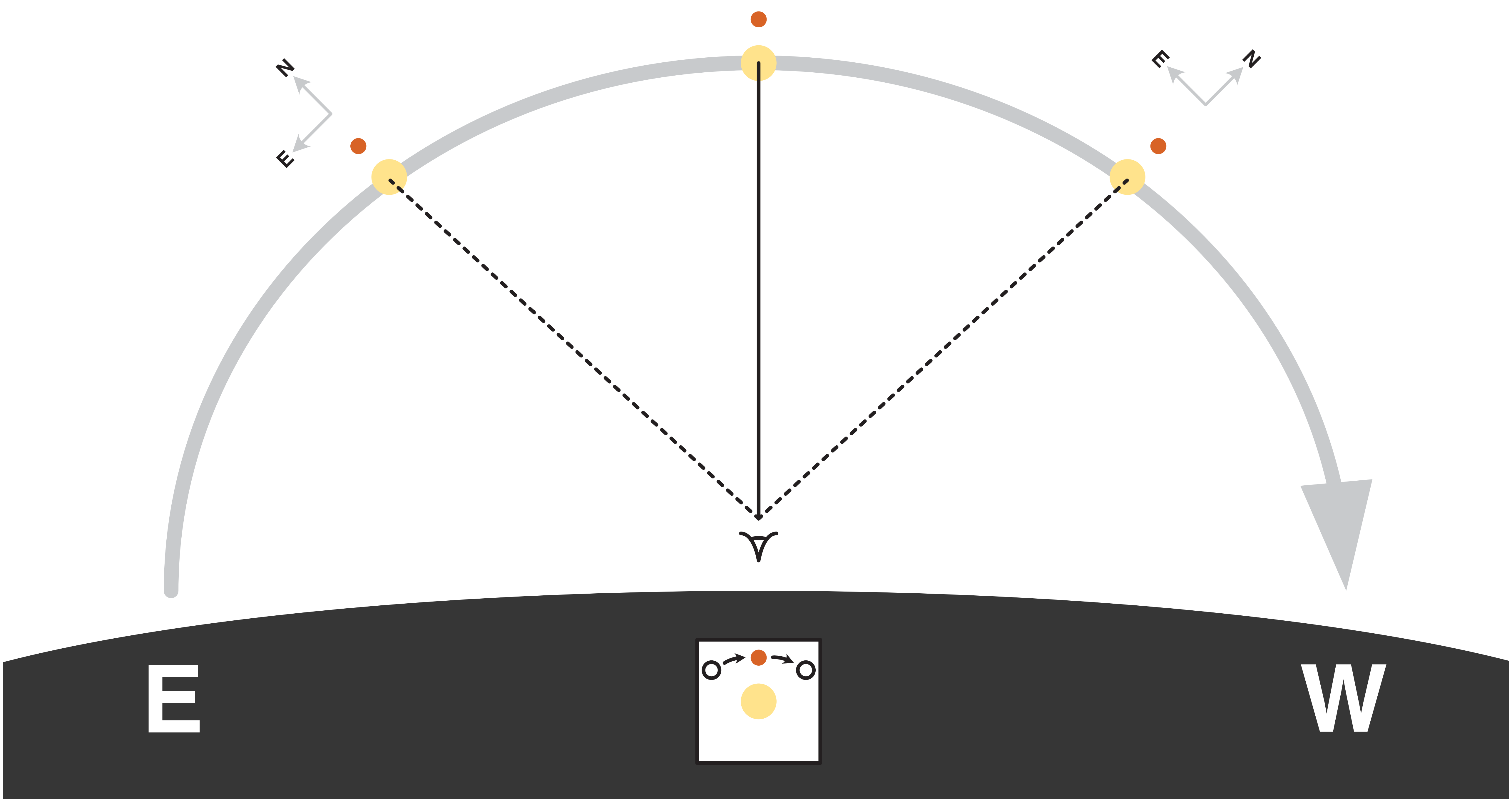
Credit: Joseph Long

AO enhances image quality by correcting atmospheric turbulence and reducing speckle noise.



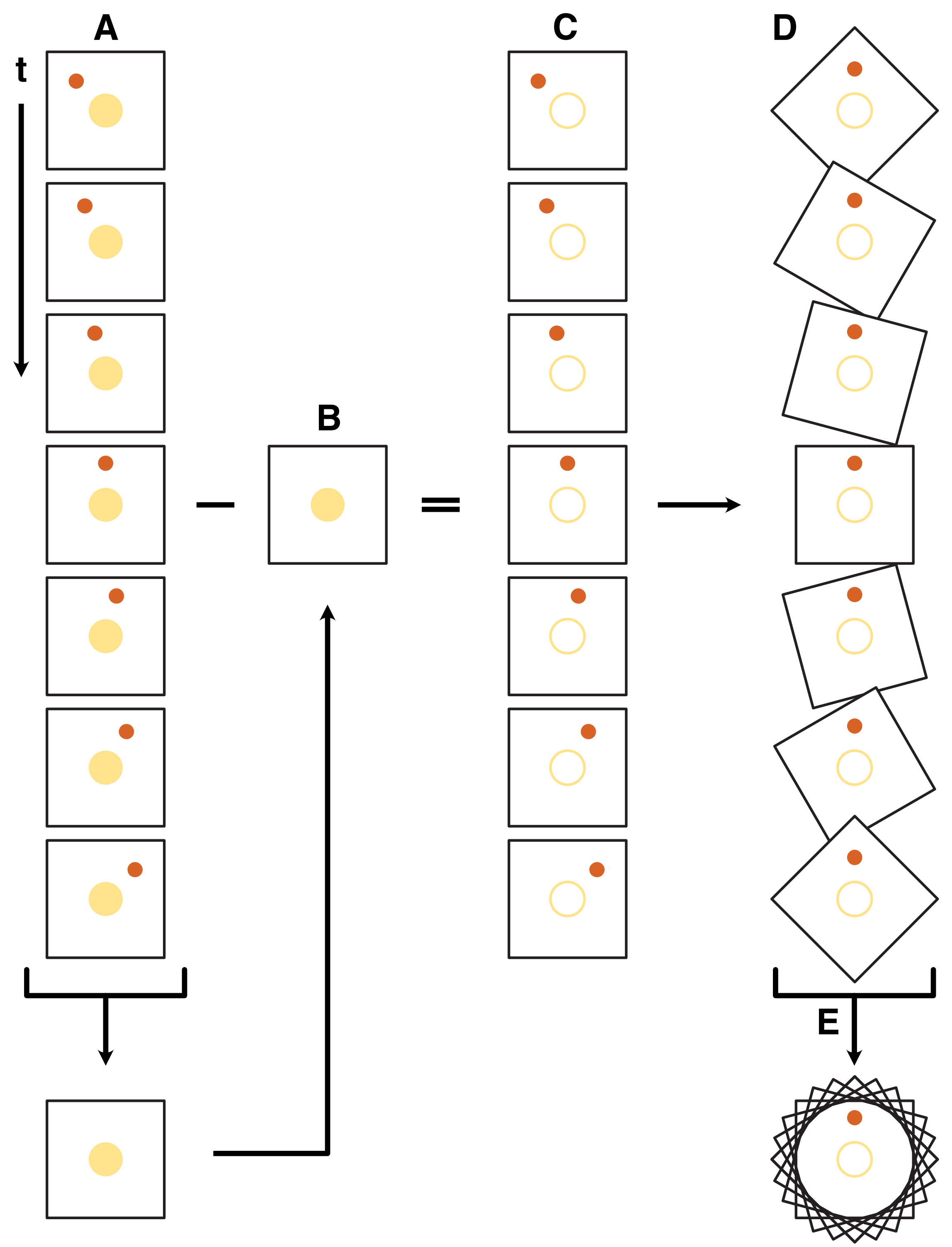
Credit: Joseph Long

Angular differential imaging (ADI)



Credit: Joseph Long

Angular differential imaging (ADI)



Credit: Joseph Long

Exoplanet Mass–Period Distribution