Brown dwarfs keep their cool.
30 years of substellar science

La Gomera, 4 September 2025

High-resolution and high-contrast studies of substellar companions

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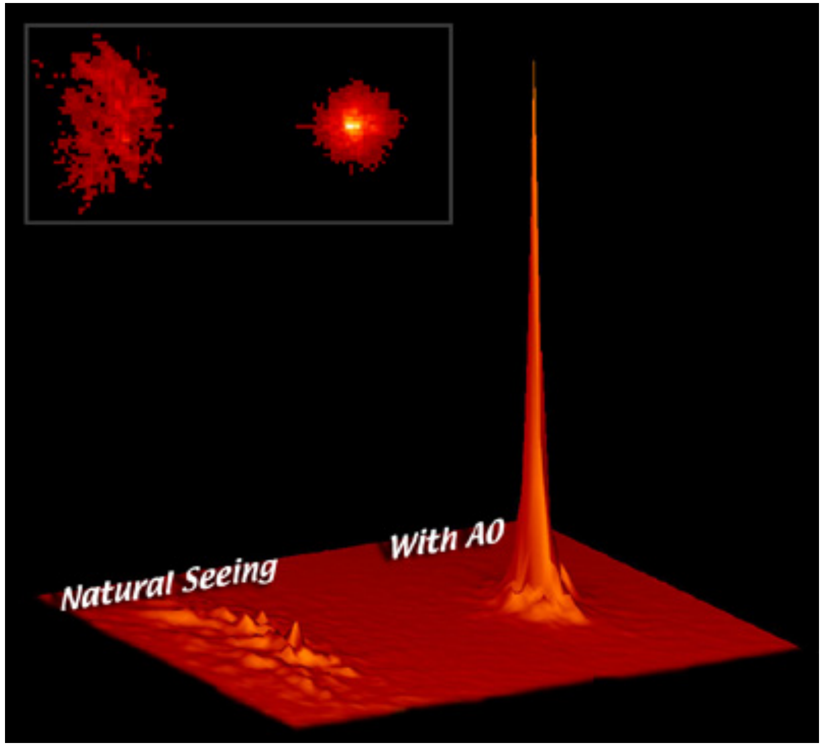
Outline

- Introduction
- Searches for substellar companions with AO
- Planet detection with ExAO
- Future detection of Earth-like planet with ELT

What is high resolution?

- Seeing limited observations: **FWHM ~ λ / r_0**, r_0 (Fried parameter) = 20-10 cm (seeing= **0.5-1.0 arcsec**)
- Diffraction limited observations: **FWHM ~ λ / D**, where D is telescope diameter (**50-100 mas** at 8-10m)
- Interferometry: resolution ~ λ / B, where B is baseline

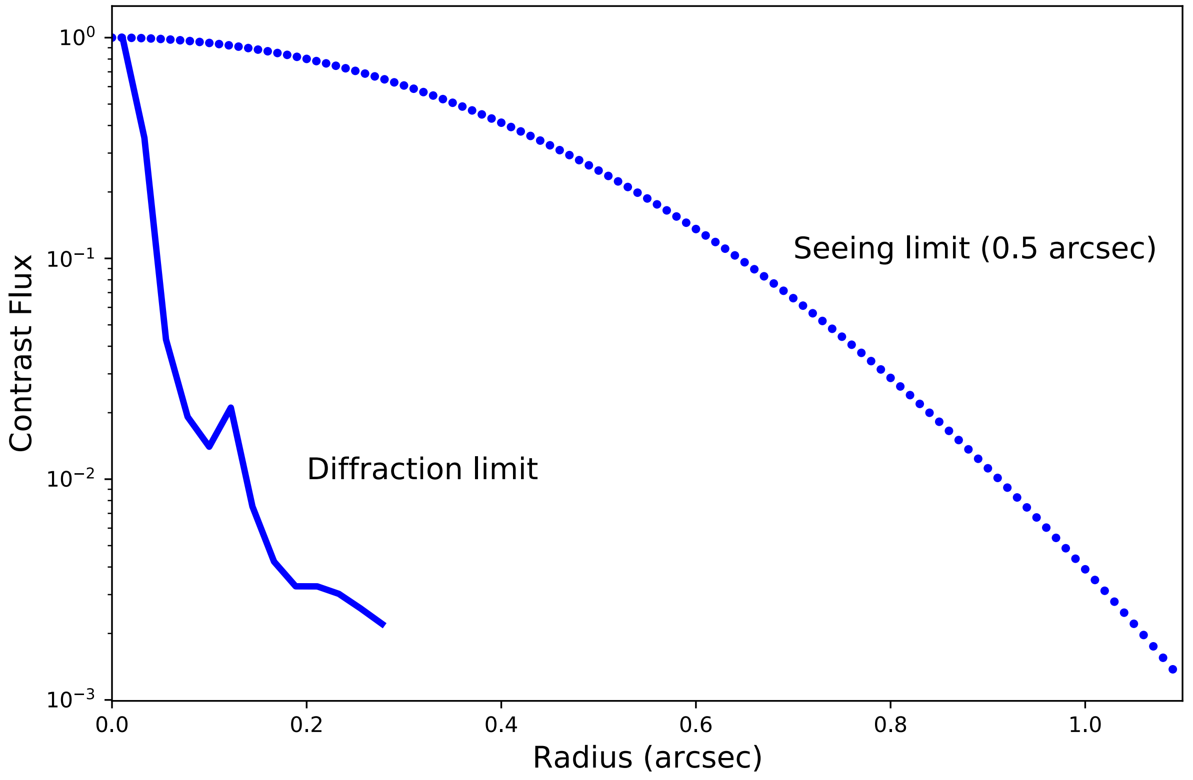
Hereafter, we will consider **high** resolution to observations with **sub-seeing** conditions (**<< 0.5 arcsec**)



What is high constrast?

- Definition **constrast ~ flux companion / flux central source**
- Dynamical range of non saturated images is ~ 5-6 mag (10^{-2} -4 10^{-3})

Hereafter, we will consider **high constrast** observations to contrast **<<10^{-3}** below **0.5-1 arcsec**



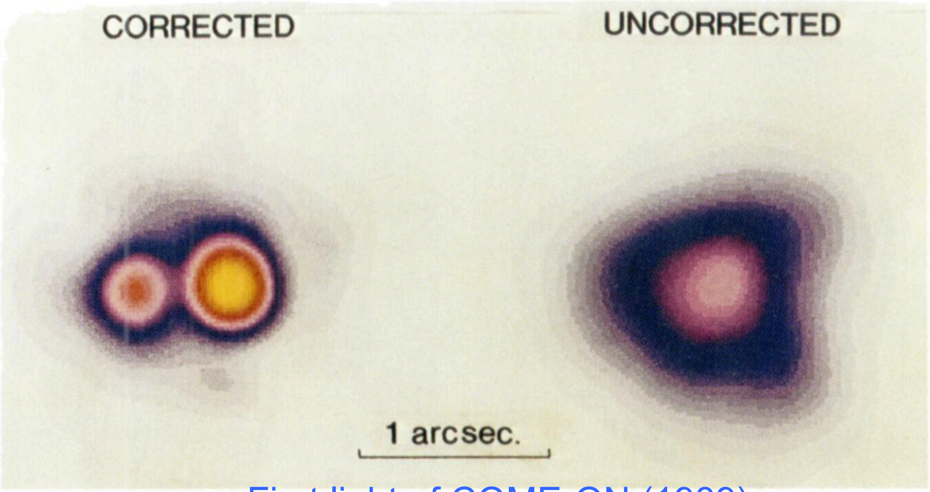
Historical Background

- **Interferometry**: 3-15m baseline (resolution **~10 mas**):
Stellar diameter (Michelson & Pearse 1921, Pearse et al. 1931)

- **Radio interferometry** (1946): Payne-Scott et al. 1947, solar flare.
VLA (1980), VLBA (1993), ALMA (2011), EHT (2019).

- **Speckle interferometry**: Labeyrie (1970), Gezari et al. 1972

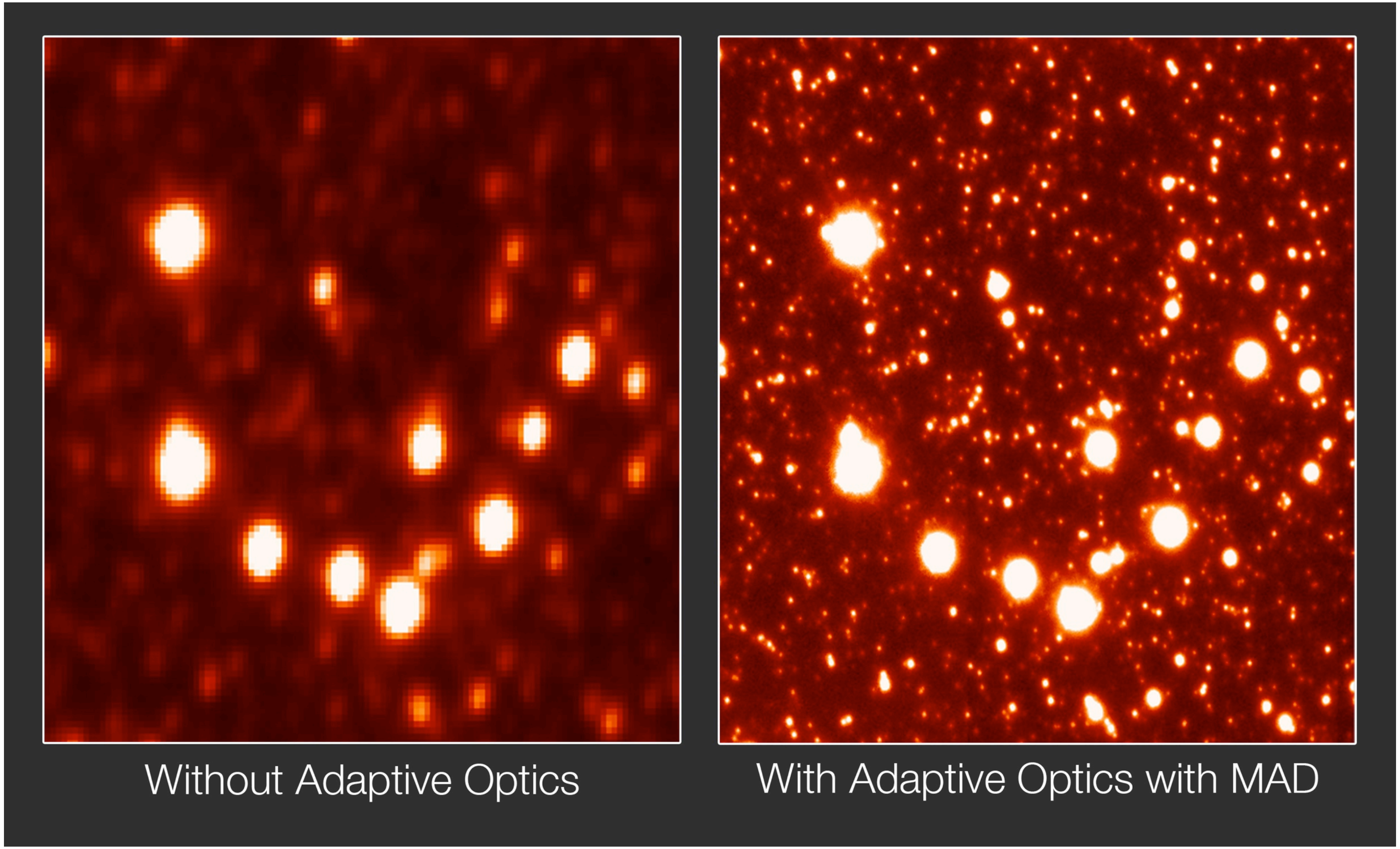
- **Adaptive Optics**:
    - Basic principles: Babcock (1953), Linnik (1957)
    - Early applications: Leighton (1957), Hardy (1978)
    - Early military developments: 70-80s, declassified in 1992
    - Development for astronomy: 90-00s:
        - ➢ **COME-ON**/1.5m OHP (1989): Rigaut et al. (1992)
        - ➢ AOC/2.2m MPI, DuPont, 1.5m Palomar (1990-1992): Golimowski et al. (1994)
        - ➢ ACE/1.5m Mount Wilson (1992): Baliunas et al. (1994)
        - ➢ **AO at 2.5-5m telescopes**: ADONIS/3.5m ESO (1993), ACE/Hooker-2.5m Mount Wilson (1994?), AO/Shane-3m Lick (1994), PUEO/CFHT (1996), ALFA/3.5m CAHA (1997), AdOpt/TNG (1997), NAOMI/WHT (1999), PALAO/Hale-5.1m Palomar (2000)
        - ➢ **AO at 8-9m telescopes**: Keck AO (1999), , Hokupa,Altair/Gemini, (1999,2005), Subaru AO (2000), NAOS-CONICA,SINFONI/VLT (2001, 2004).
    - **GLAO, LTAO, MCAO, ExAO**: GeMS, GPI/Gemini (2011, 2013), SCExAO/Subaru (2011), MUSE, SPHERE, ERIS/VLT (2014, 2014, 2022), KPIC/Keck (2021)



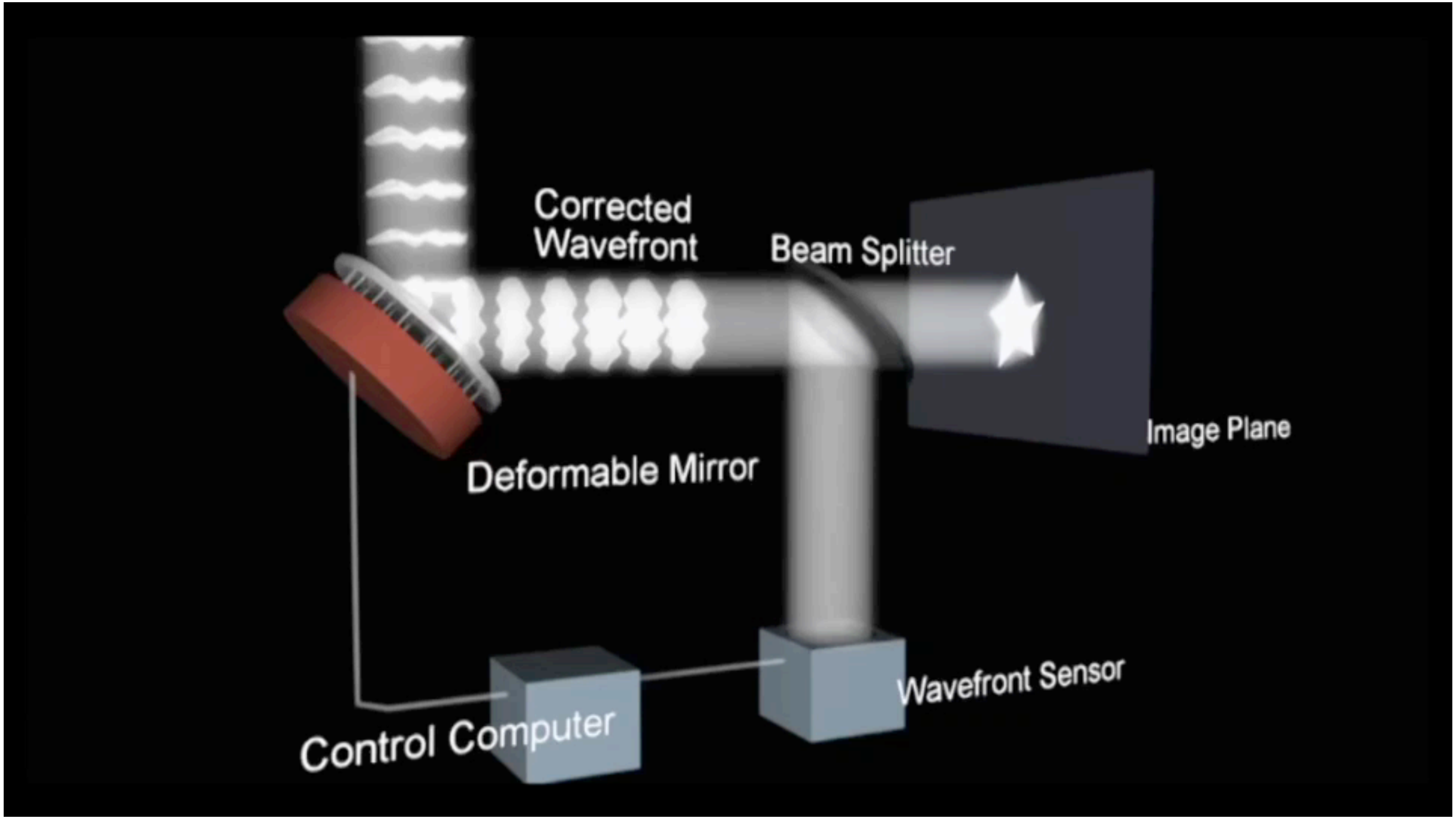
First light of COME-ON (1989)

What is Adaptive Optics?

AO is a technique that mitigates atmospheric turbulence (and other aberrations) based on fast wave-front sensing and correction

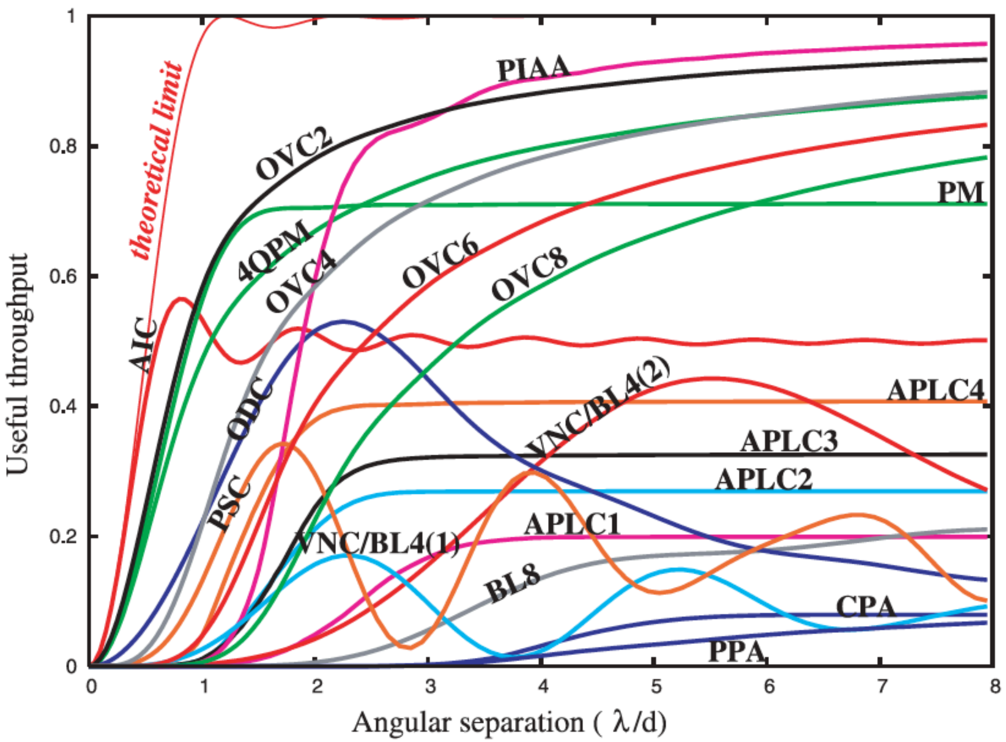


Adaptive Optics

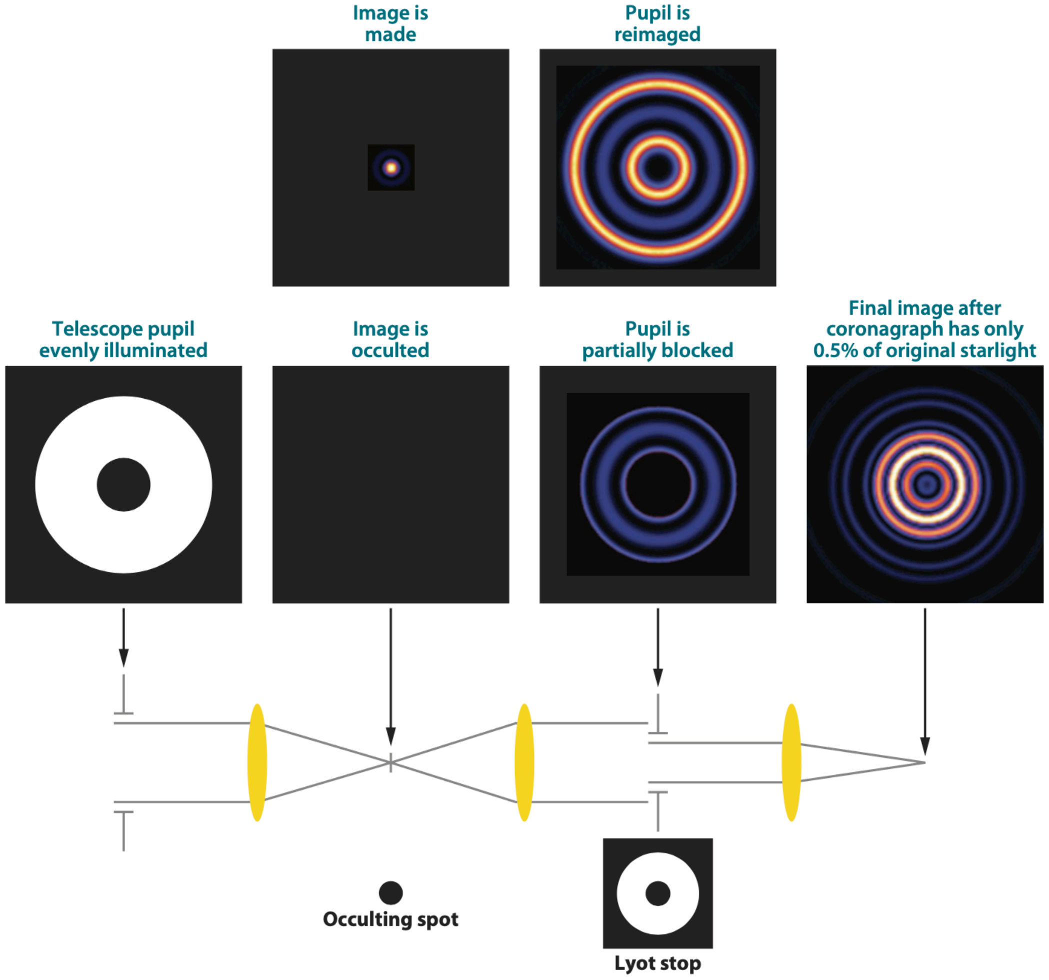


Coronography

- Lyot coronograph: Lyot (1939) to study solar corona
- Phase mask coronographs: OVC, 4QPM (Roddier & Roddier 1997, Rouan 2000)
- Pupil apodization coronographs: APLC, PIAAC (Soummer et al. 2003, Guyon et al. 2003)



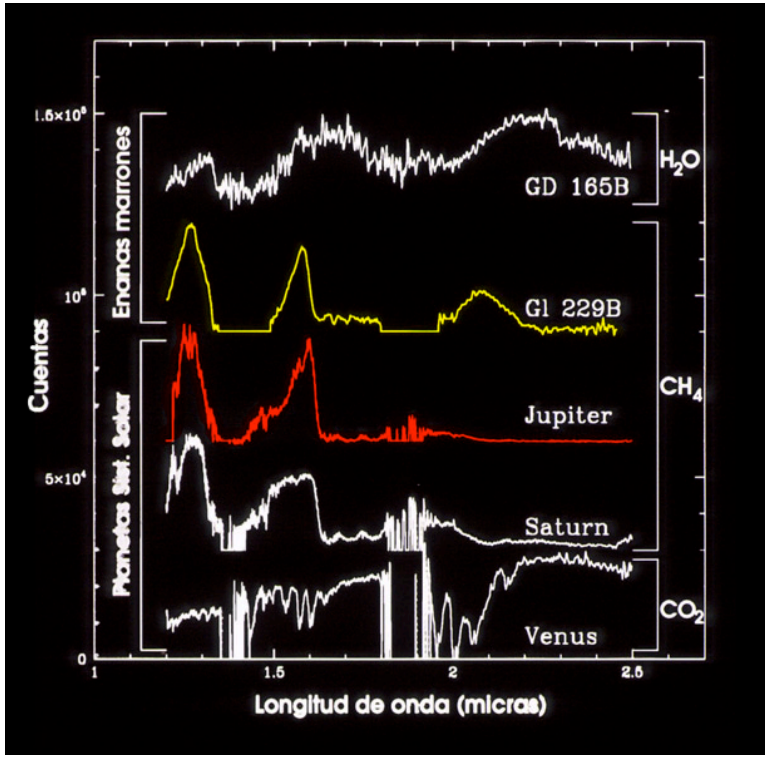
Guyon et al. 2006



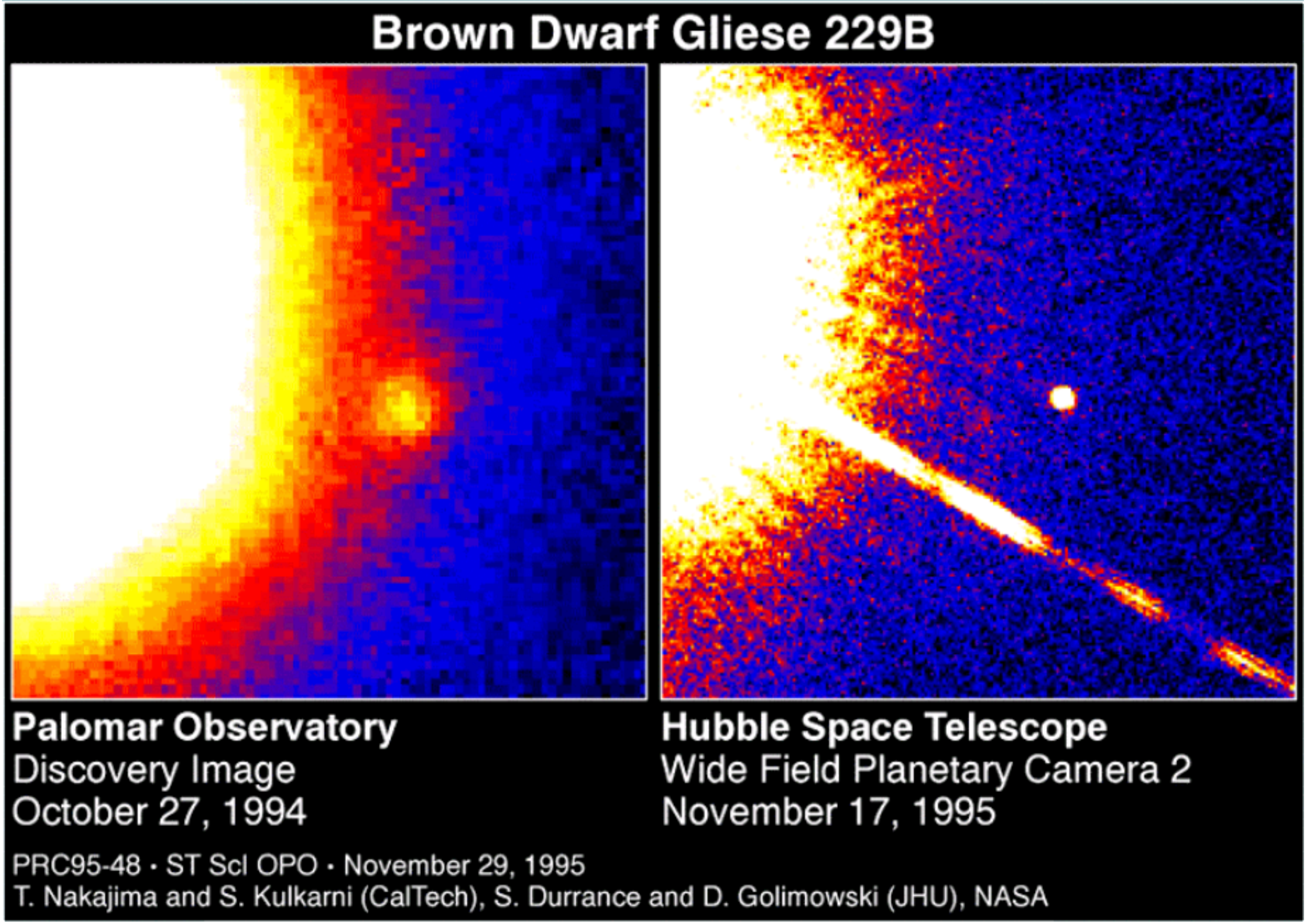
MIRI JWST user manual

First substellar companion: Gl229B

A **coronographic survey** for companions of stars **within 8pc** with AOC at 1.5m Palomar (Oppenheimer et al. 2001)

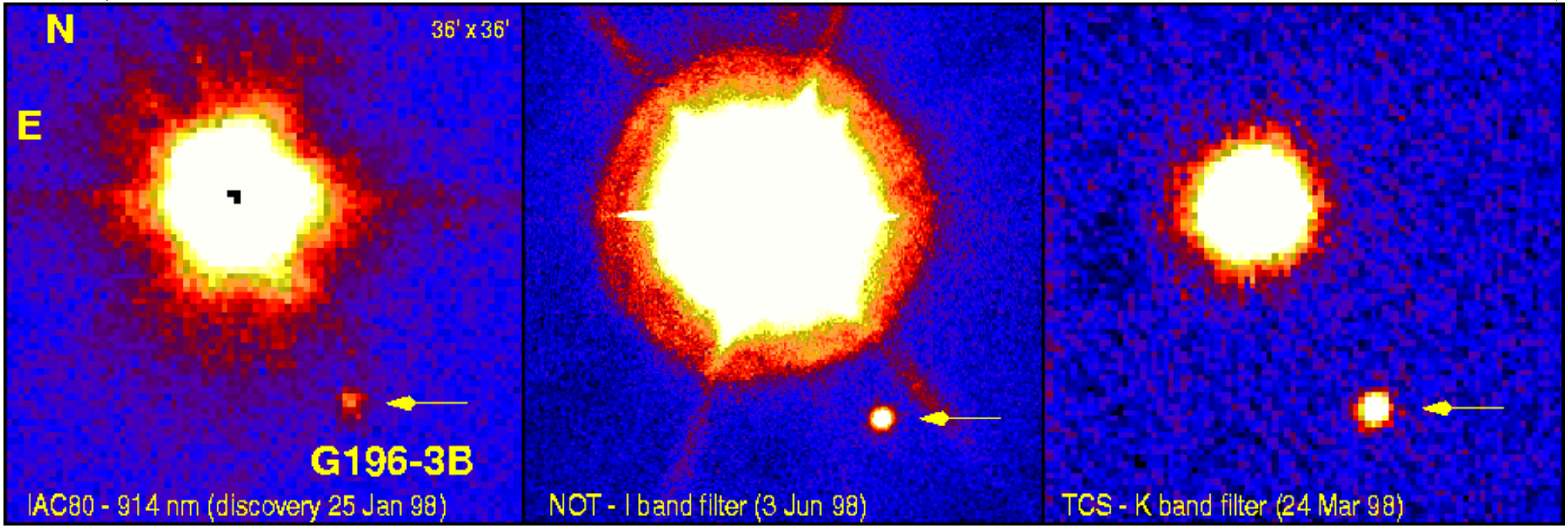


Nakajima et al. 1995,
Oppenheimer et al. 1995



Susbstellar companions around young nearby stars

- First substellar companions around young nearby stars: G196-3B (Rebolo et al. 1998), GG TauBb (White et al. 1999), LHS102B (Goldman et al. 1999)
- **Frequency** of **wide** (>50 UA) **substellar companions**: **<5 %** (McCarthy & Zuckerman 2004, Masciandri et al. 2005). AO systems at 2-5m telescopes

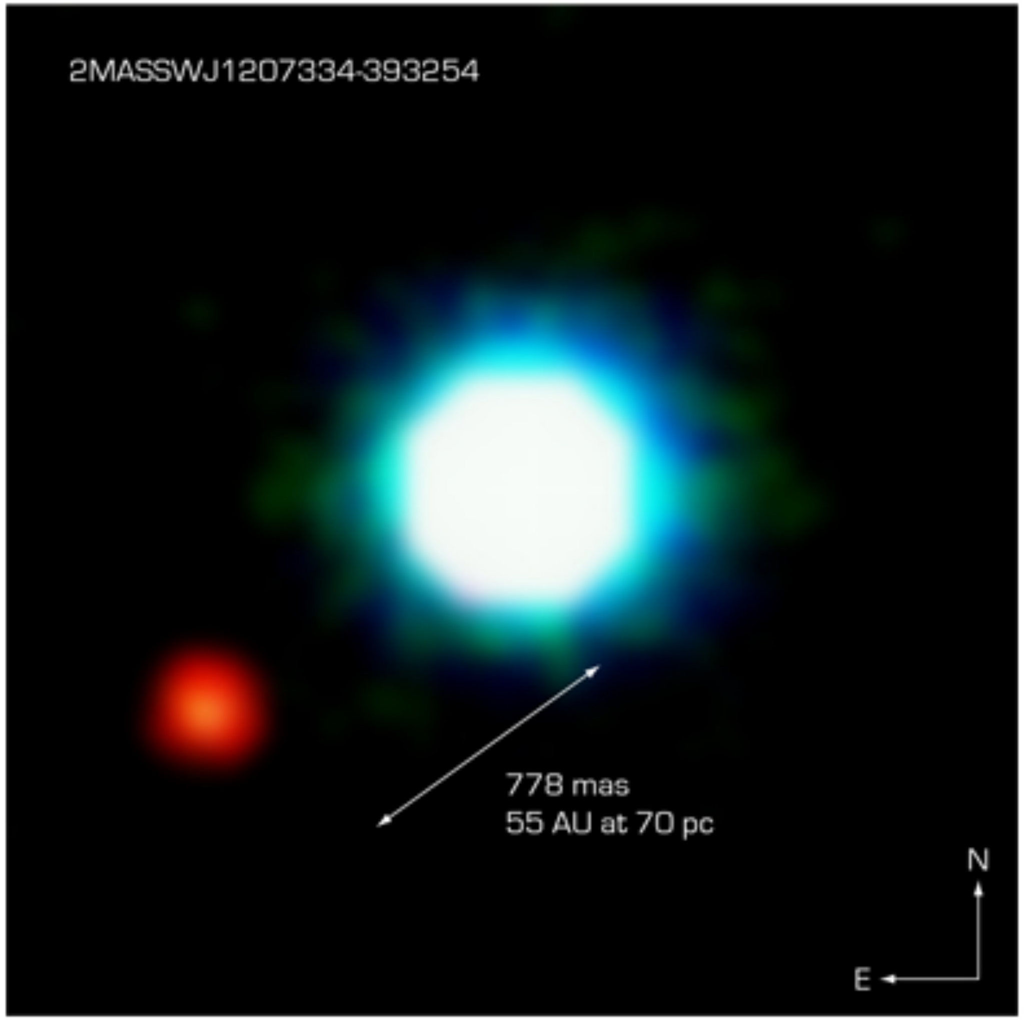


Rebolo et al. 1998

First planetary mass companion: 2M1207b

- First searches for substellar objects with **AO in 8-10m** led to the direct imaging of planets

- **2M1207b**: Brown dwarf/**planetary mass companion** in TW Hya moving group (Chauvin et al. 2004, 2005)



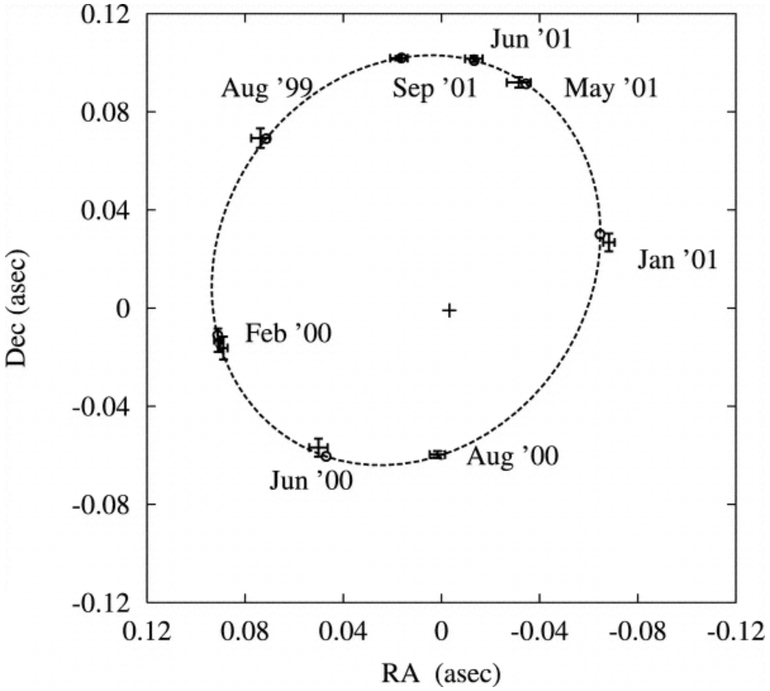
NACO Image of the Brown Dwarf Object 2M1207 and GPCC

ESO PR Photo 26a/04 (10 September 2004)

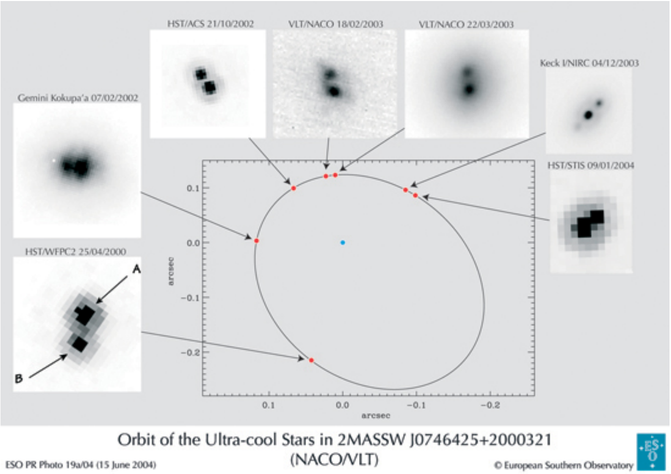
First dynamical masses of brown dwarfs: GJ569Bab

- GJ569Bab: First measurement of the **individual dynamical masses** of brown dwarfs: 70 and 55 M_{jup} (Zapatero Osorio et al. 2004)

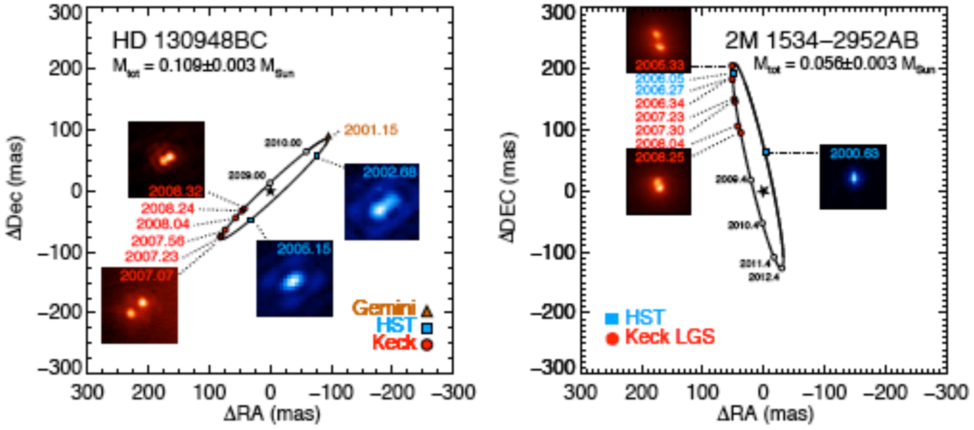
- The **substellar frontier** is from **late M** to **late L/early T** depending on the age



Zapatero Osorio et al. 2004

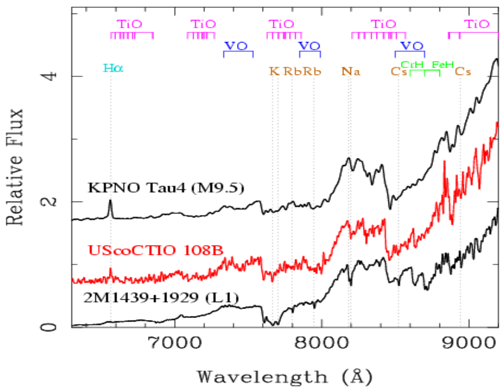


Bouy et al. 2004

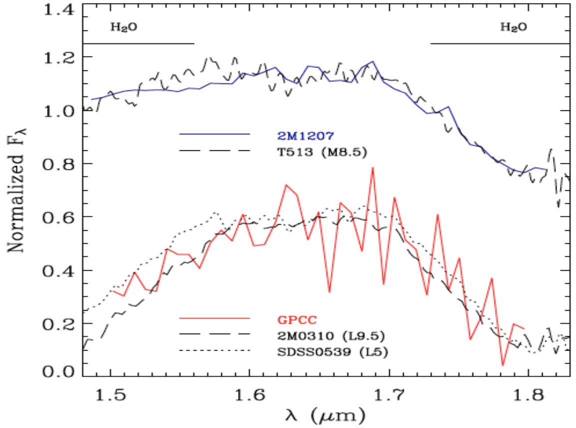


Liu et al. 2008; Dupuy et al. 2009, 2016

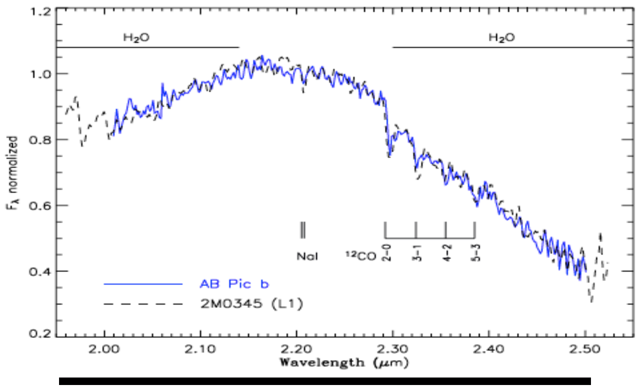
Young planetary systems



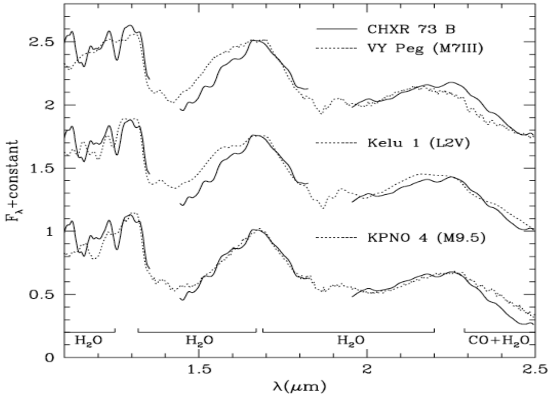
(Béjar et al. 2008)



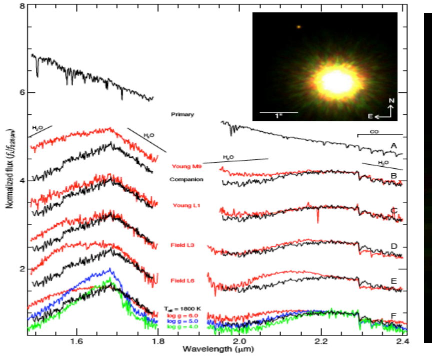
(Chauvin et al. 2004)



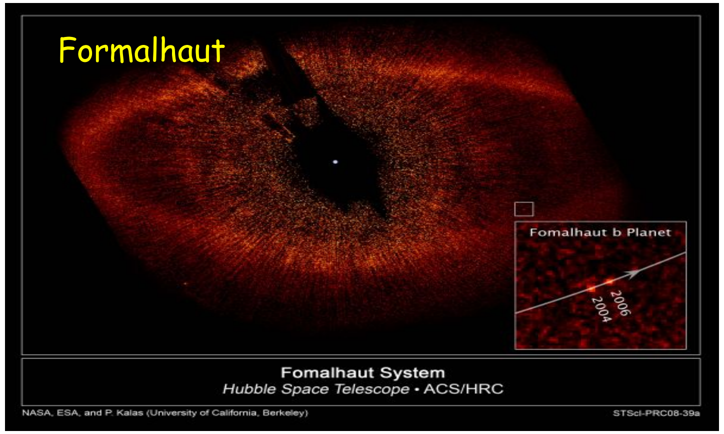
(Chauvin et al. 2005)



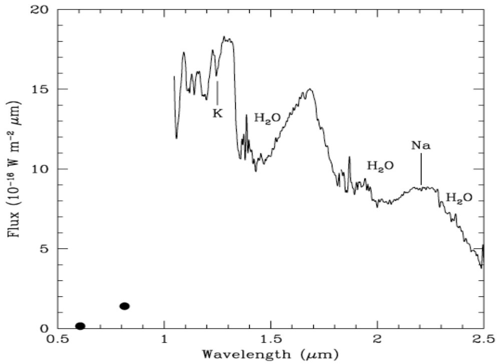
(Luhman et al. 2006)



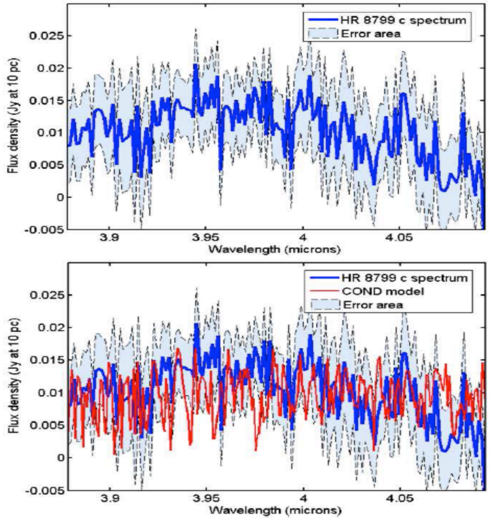
(Lafeniere et al. 2008)



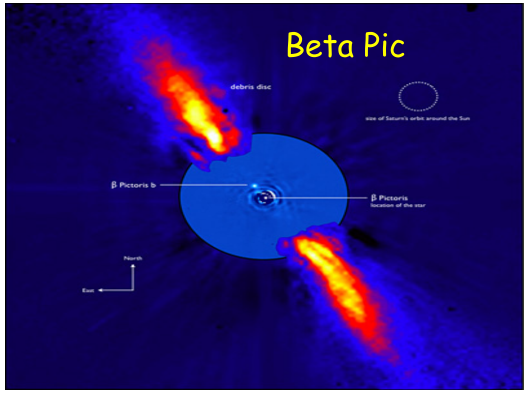
(Kalas et al. 2008)



(Itoh et al. 2005)



(Janson et al. 2010)

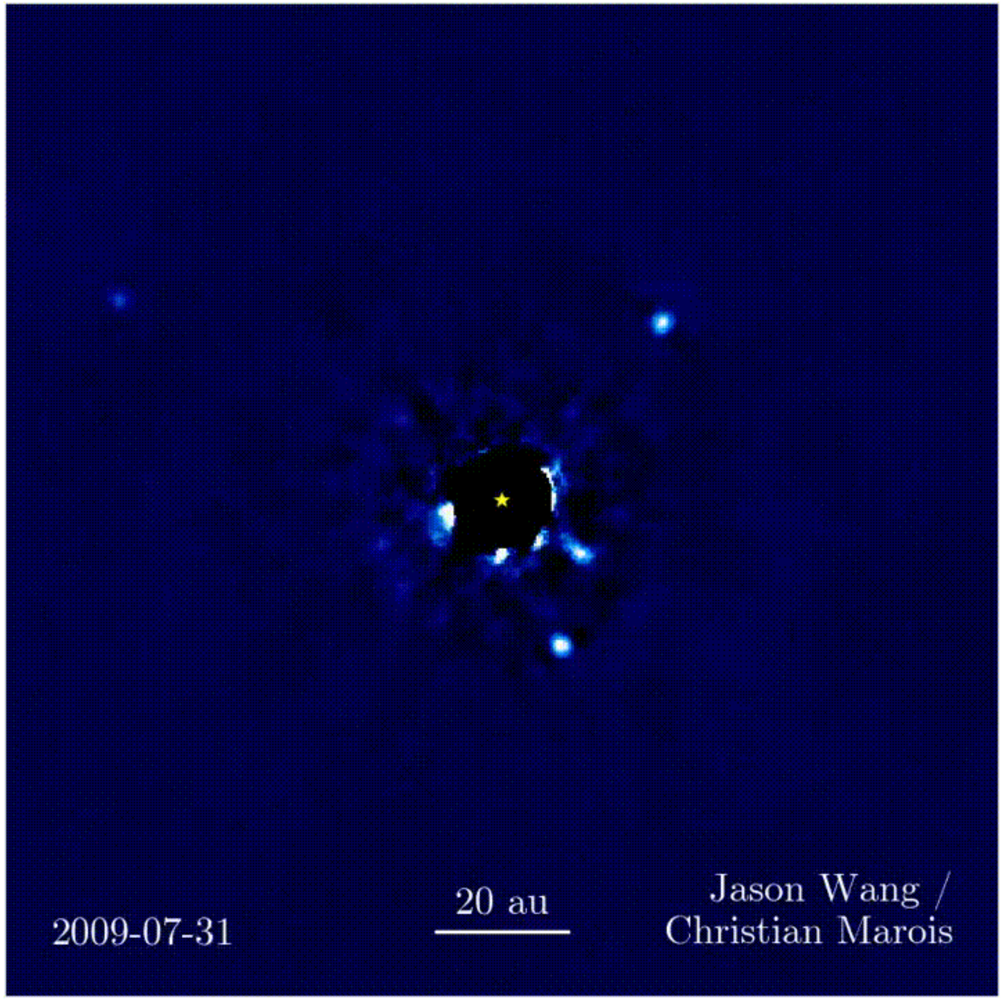


(Lagrange et al. 2009, 2010)

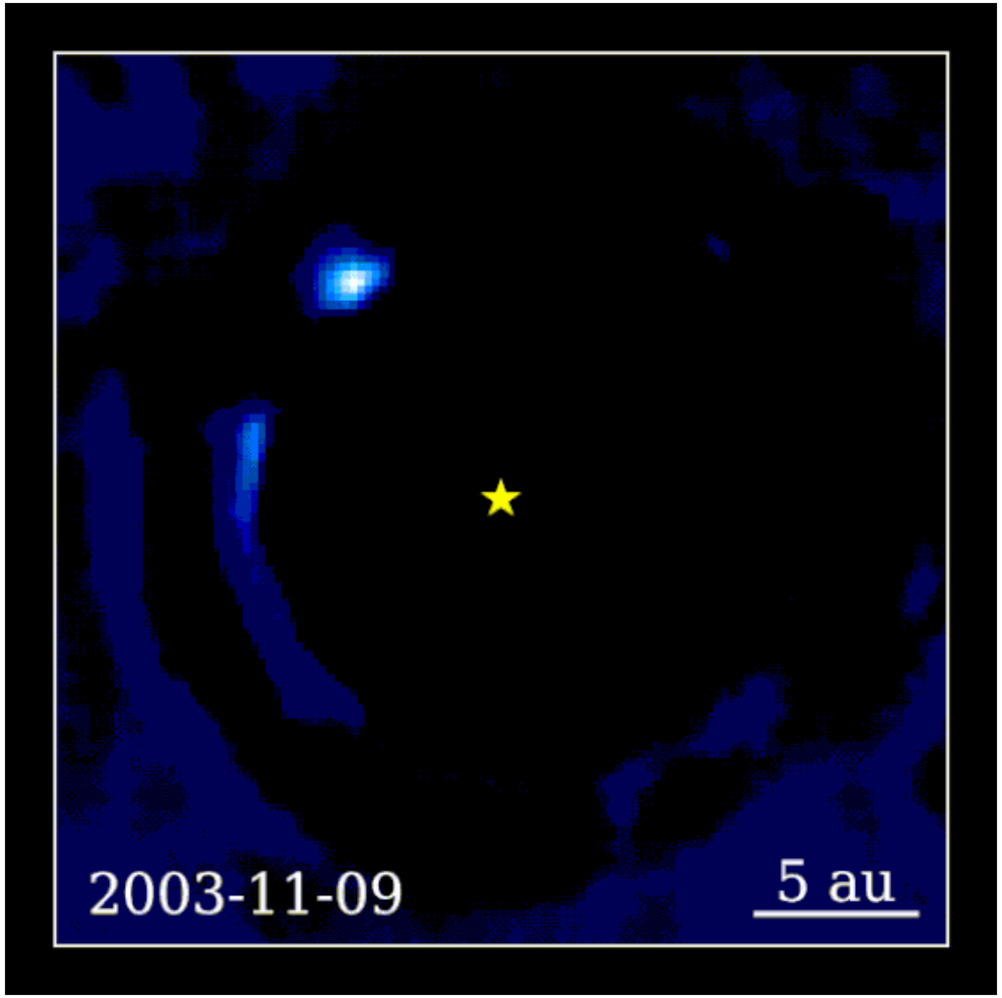
Frequency of substellar companions ~6-20%, strongly depends on primary mass (Vigan et al. 2021)

First multi-planetary systems

- Angular Differential Imaging (ADI), Spectral Differential Imaging (SDI) or Locally Optimized Combination of Images (LOCI)



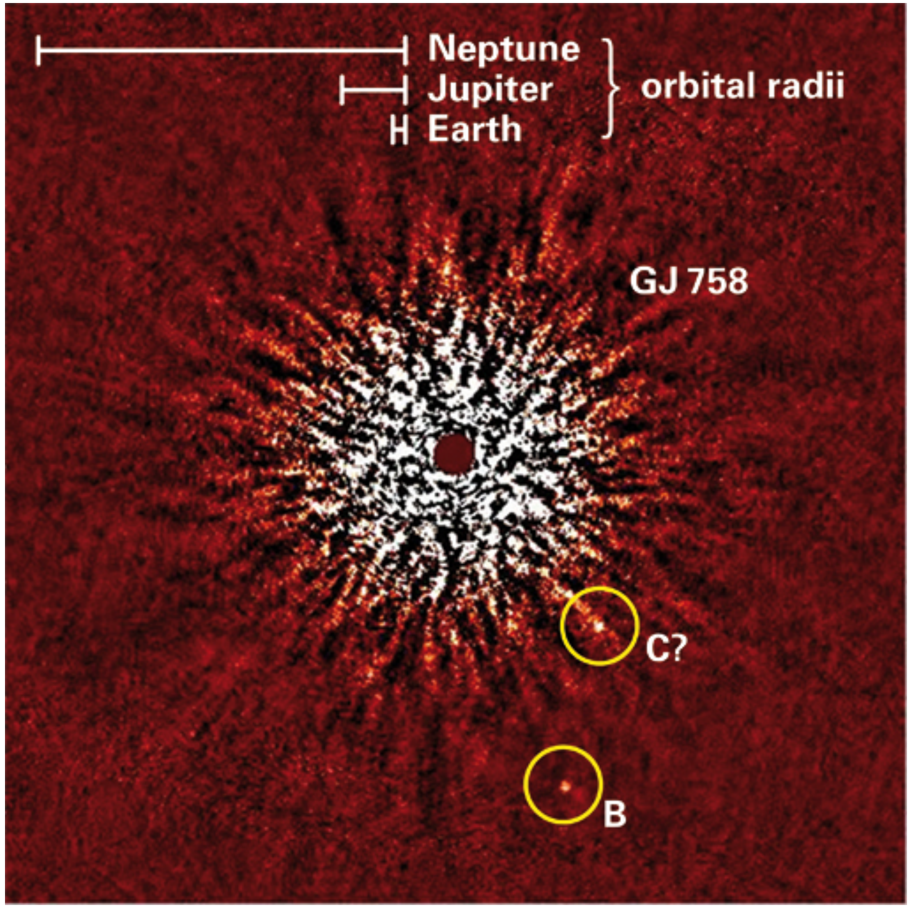
HR8799 bcde (Marois et al. 2008)



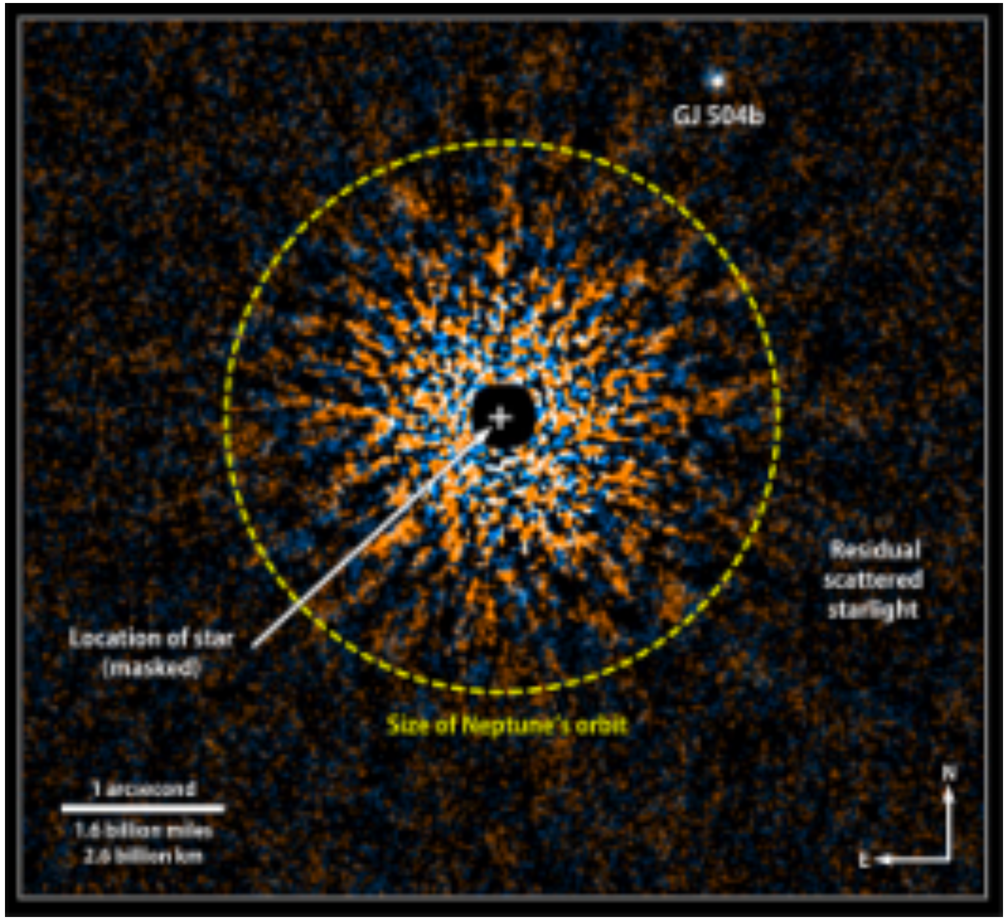
β Pic bc (Lagrange et al. 2008, 2019)

The coolest substellar companions

- Late T and Y companions: Teff **<750 K**



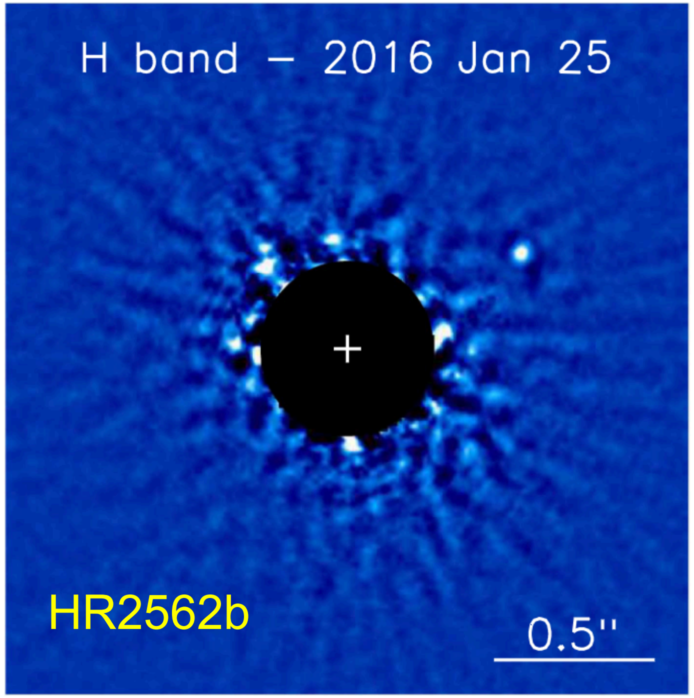
GJ758: G8V at 15.5pc
GJ758B: Sep. = 1.9” (29UA)
M_{comp} = 38 M_{Jup}
SpT~ late T/early Y



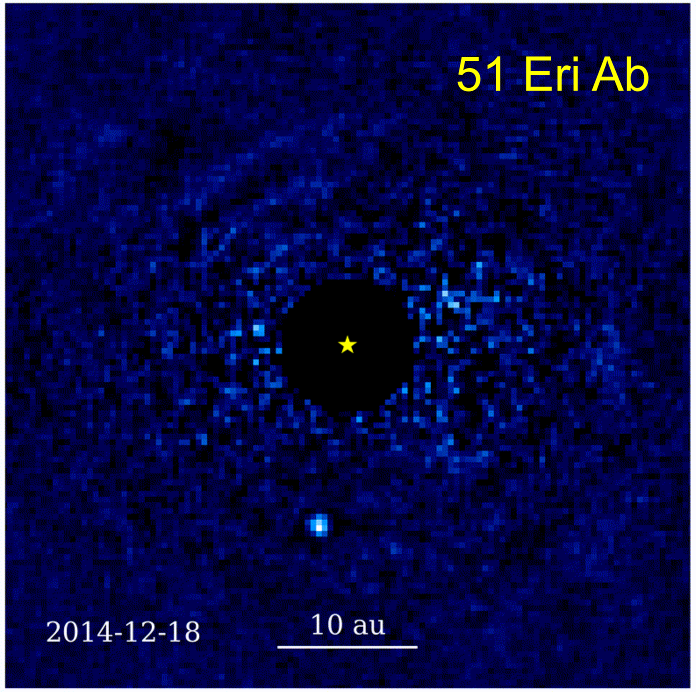
GJ504: G0V at 17.6pc
GJ504b: Sep. = 2.5” (43.5 AU)
M_{comp} ~ 4 M_{Jup}
SpT~ late T/early Y

Extreme Adaptive Optics systems (ExAO)

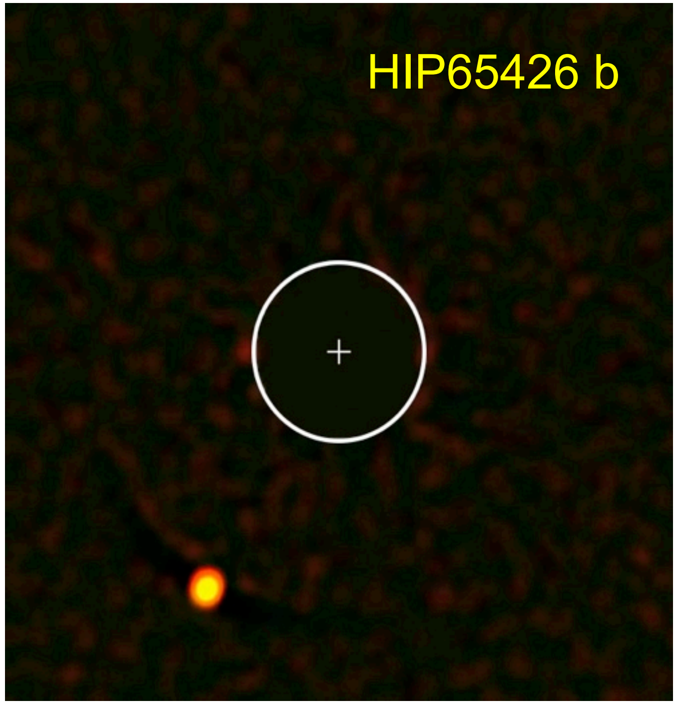
- **GPI**: HR2562b (Konopacky et al. 2016), 51 Eri Ab (Macintosh et al. 2015, de Rosa et al. 2015)
- **SCExAO/CHARIS**: AB Aur b (Currie et al. 2022), HIP99770b (Currie et al. 2023)
- **SPHERE**: HIP 65426b (Chauvin et al. 2017), AF Lep b (de Rosa et al. 2024), HD135344b (Stolker et al. 2025), HD 135344B (Maio et al. 2025), WISPIT 2b (Van Capelleveen et al. 2025)



Konopacky et al. 2016



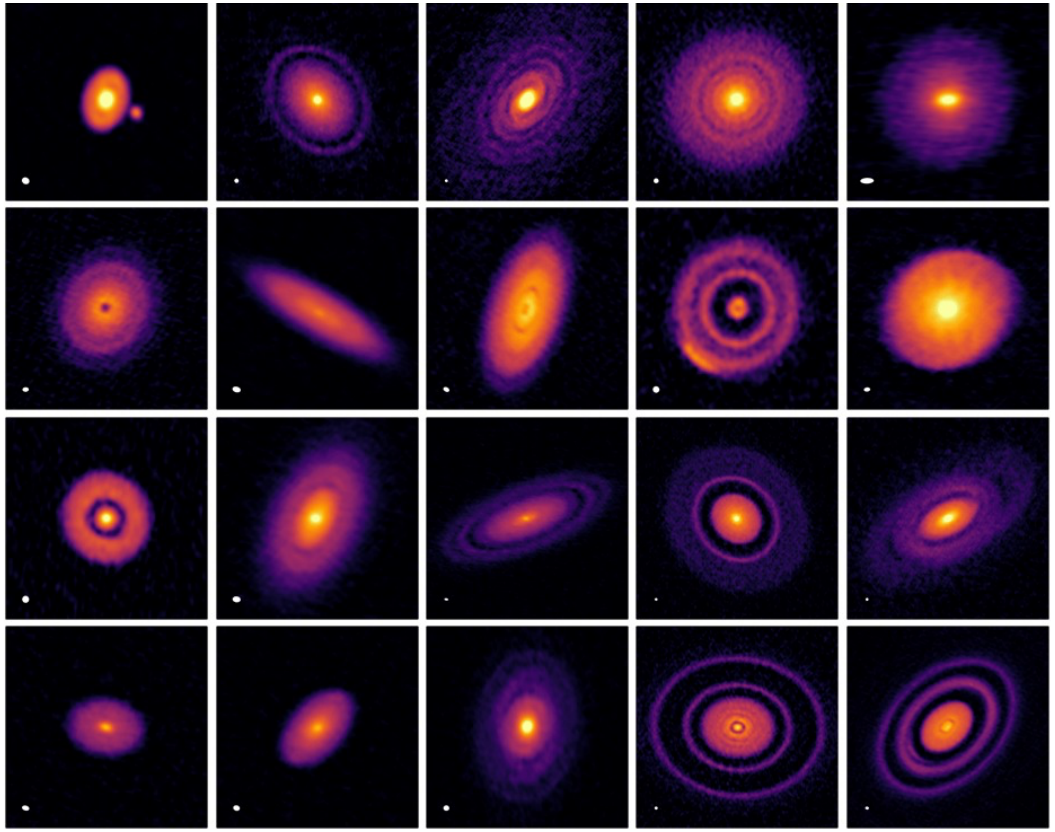
Macintosh et al. 2015, de Rosa et al. 2015



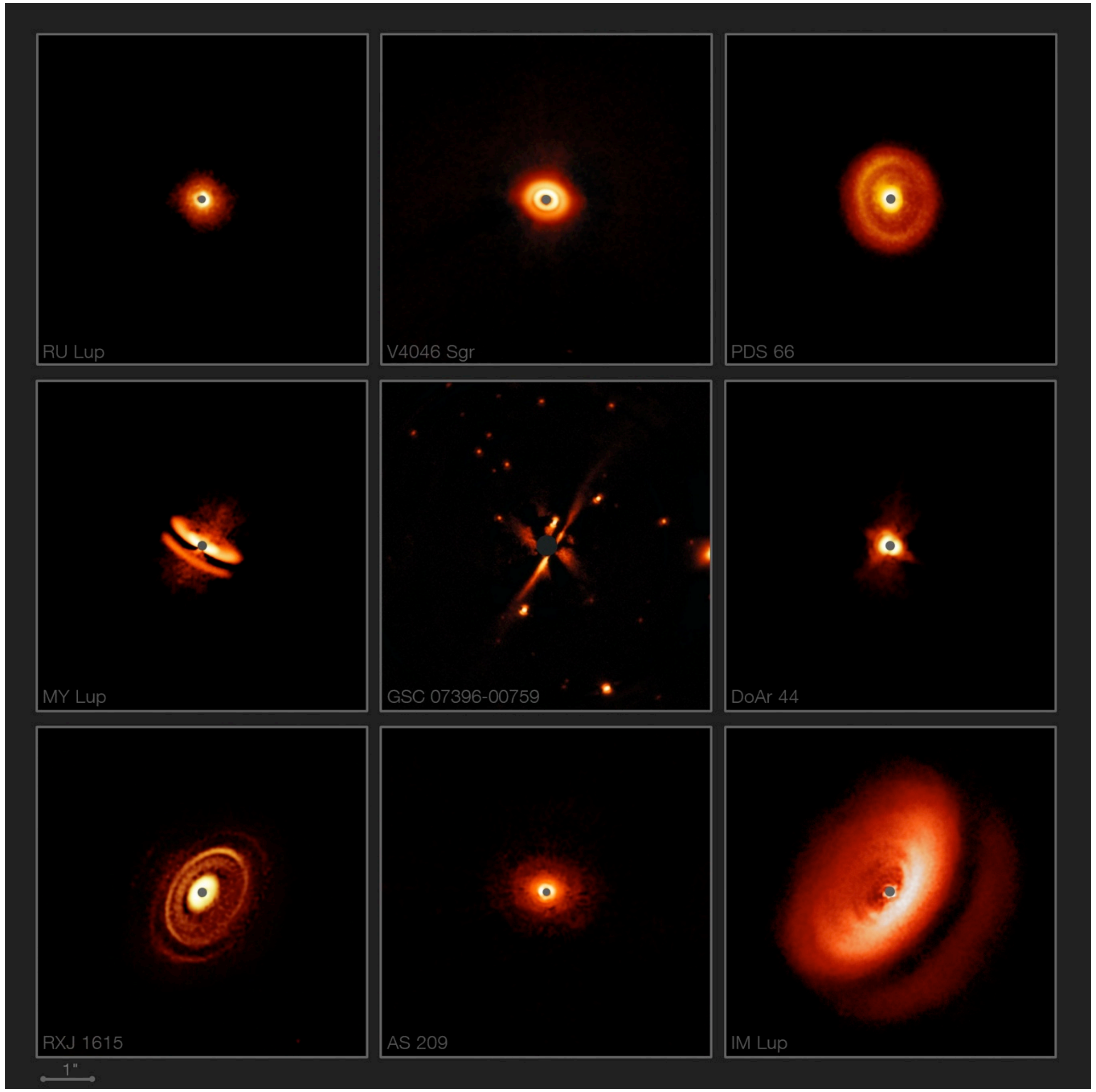
Chauvin et al. 2017

Protoplanetary disks with ALMA and ExAO

- ALMA and SPHERE provides unique information of protoplanetry discs structures: rings, gaps, spirals



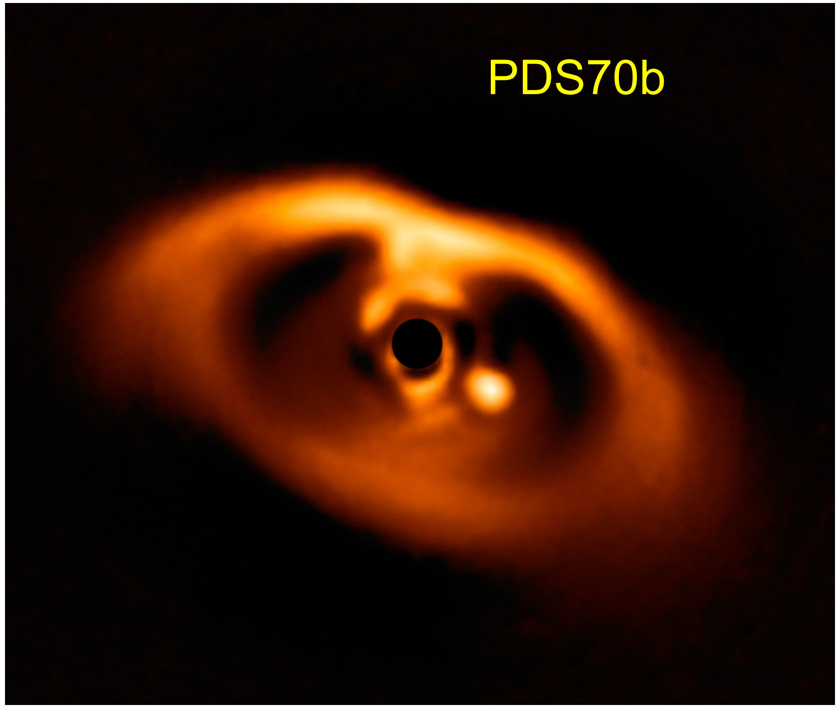
(Andrews, S. et al. 2018)



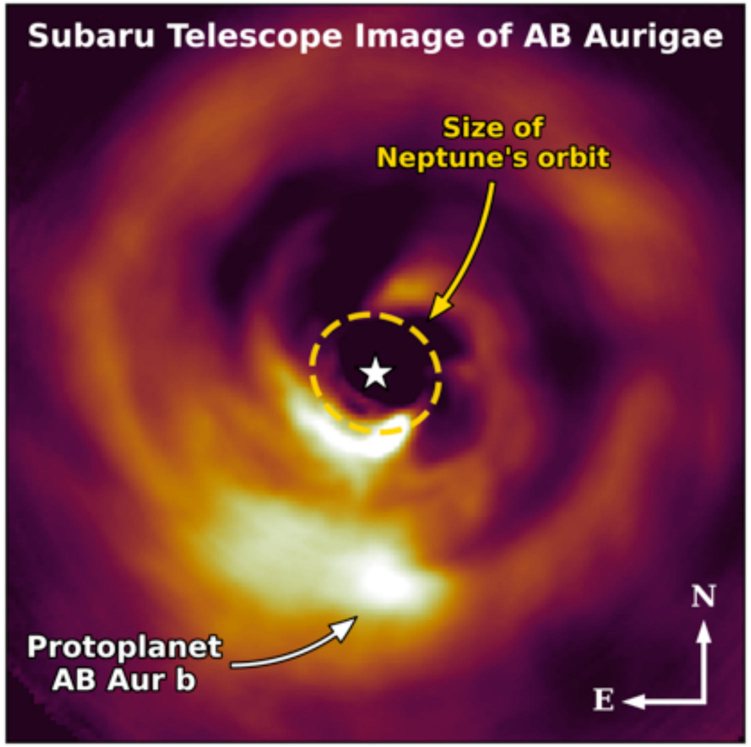
(Avenhaus et al. 2018, Sissa et al. 2018)

Embedded (proto)planets

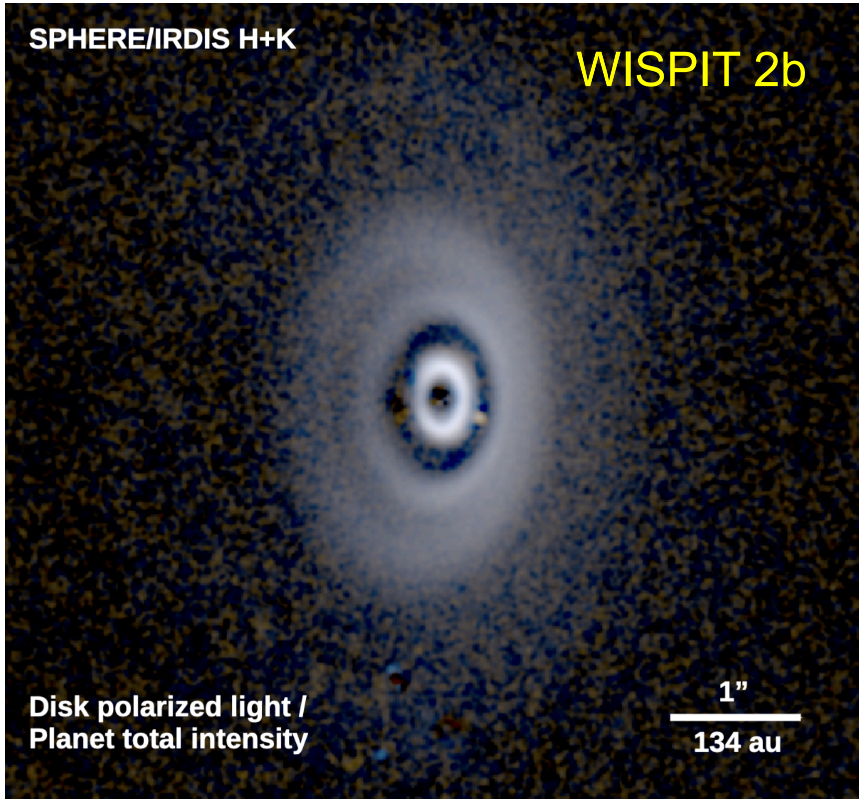
- ExAO systems have allowed to detect embedded planets (<5 Myr) in the gaps of protoplanetary disks



Kepler et al. 2018



Currie et al. 2022

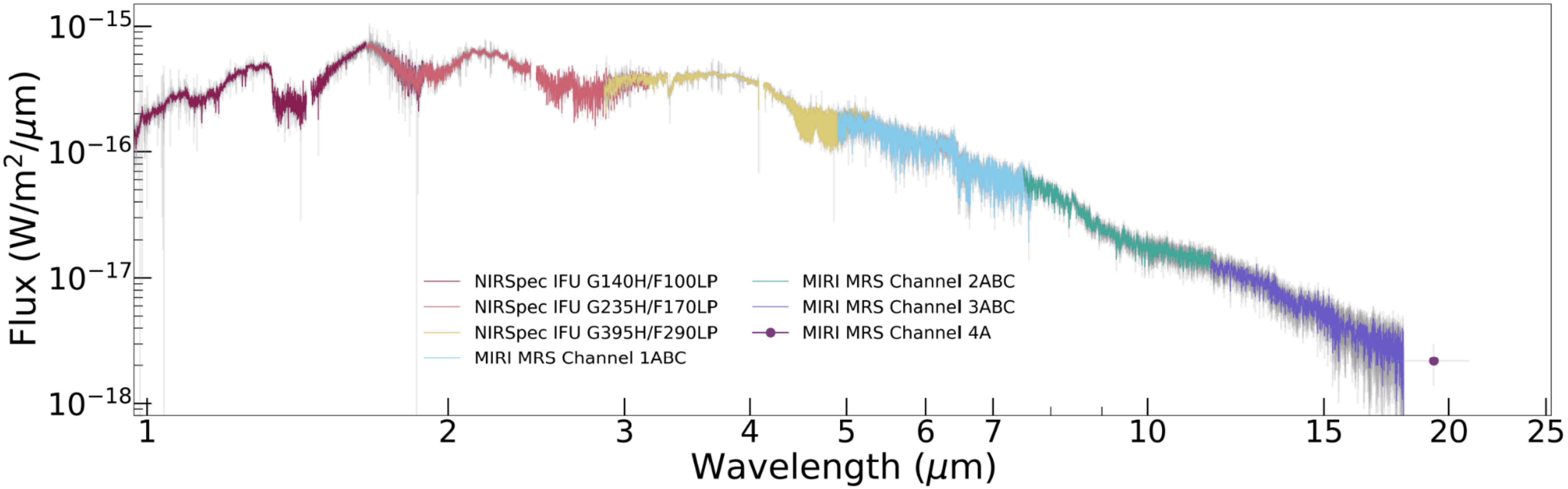


Van Capelleveen et al. 2025

JWST observations of substellar companions

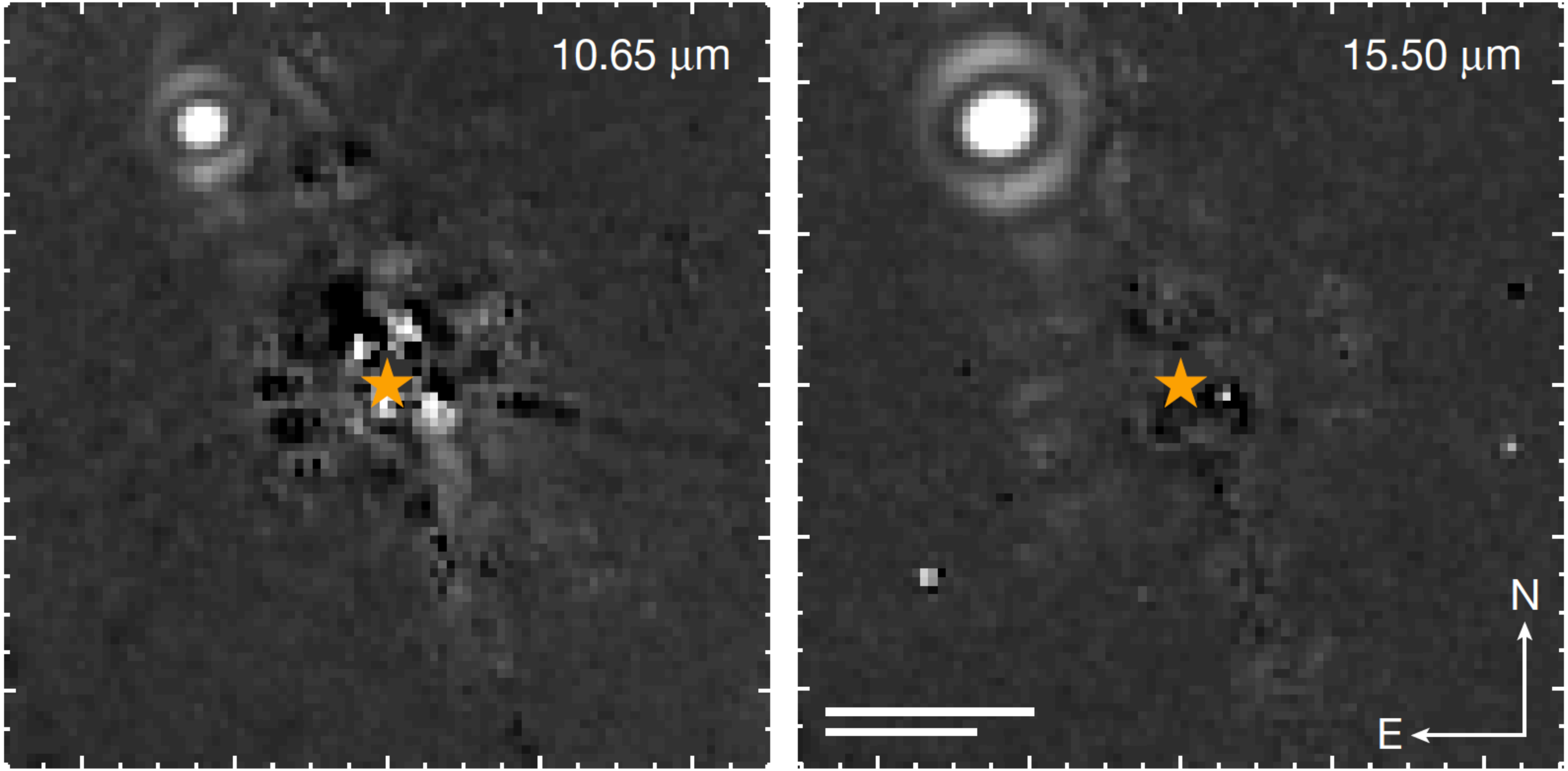
- Detection of numerous **molecular absorption** bands: **H_20, CO, CH_4**, silicates
- Full **spectral energy distribution** from **1 to 20 µm**

JWST OBSERVATIONS OF VHS 1256 B



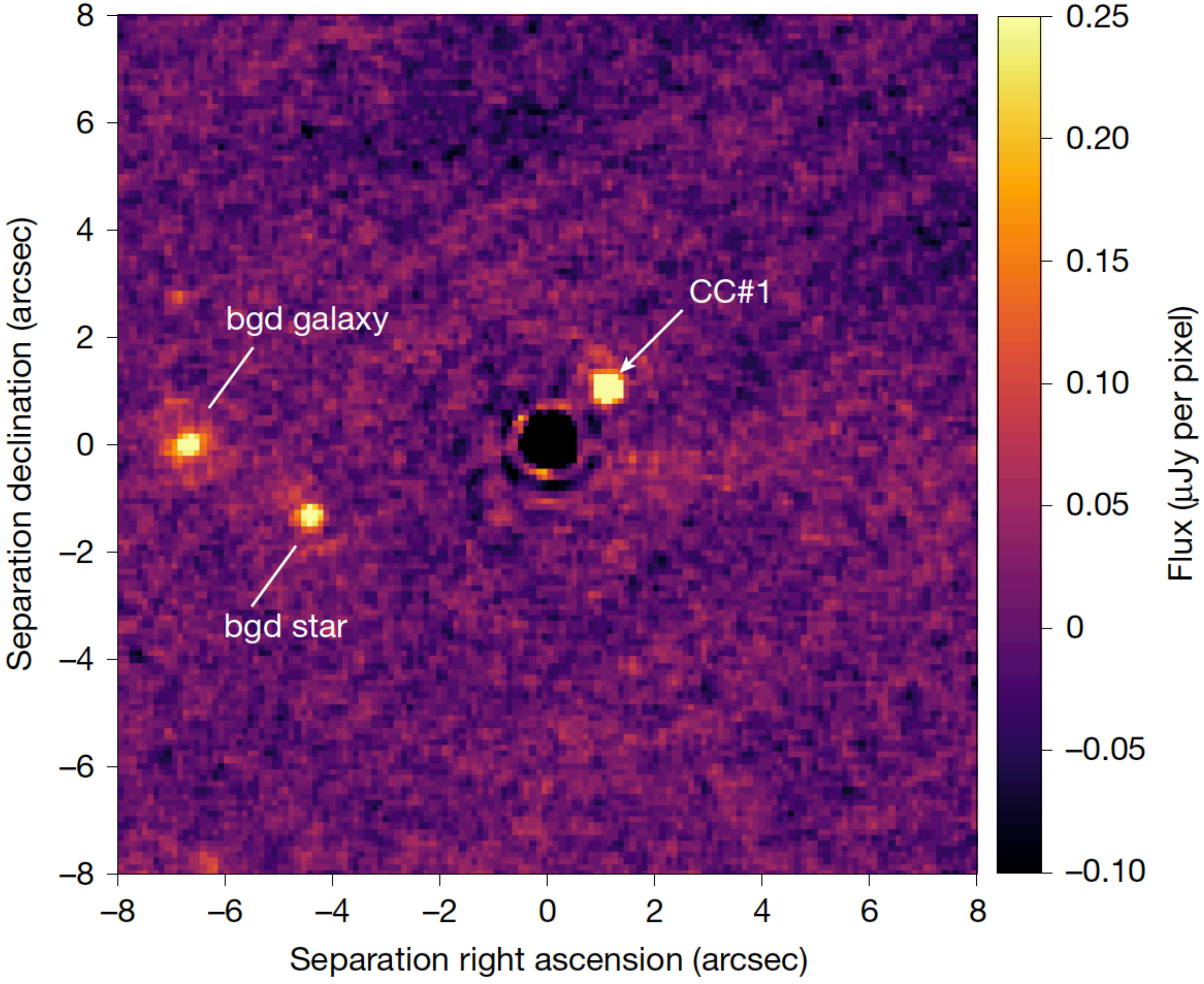
JWST detection of the coolest planets

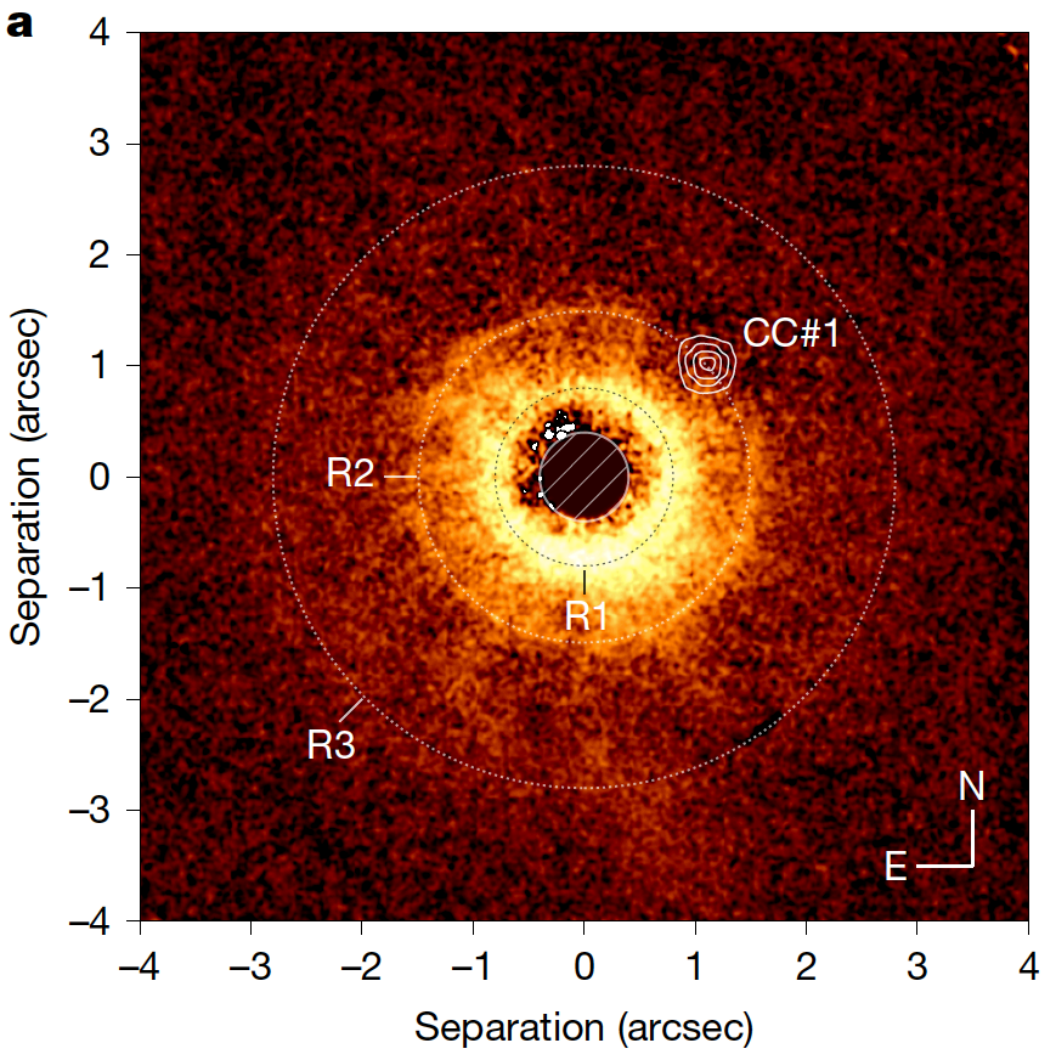
Discovery of a 6 M_{Jup} planet of ~300 K at 15 AU of Eps Indi A in the mid-IR (Matthews et al. 2024)



JWST detection of sub-Jovian planets

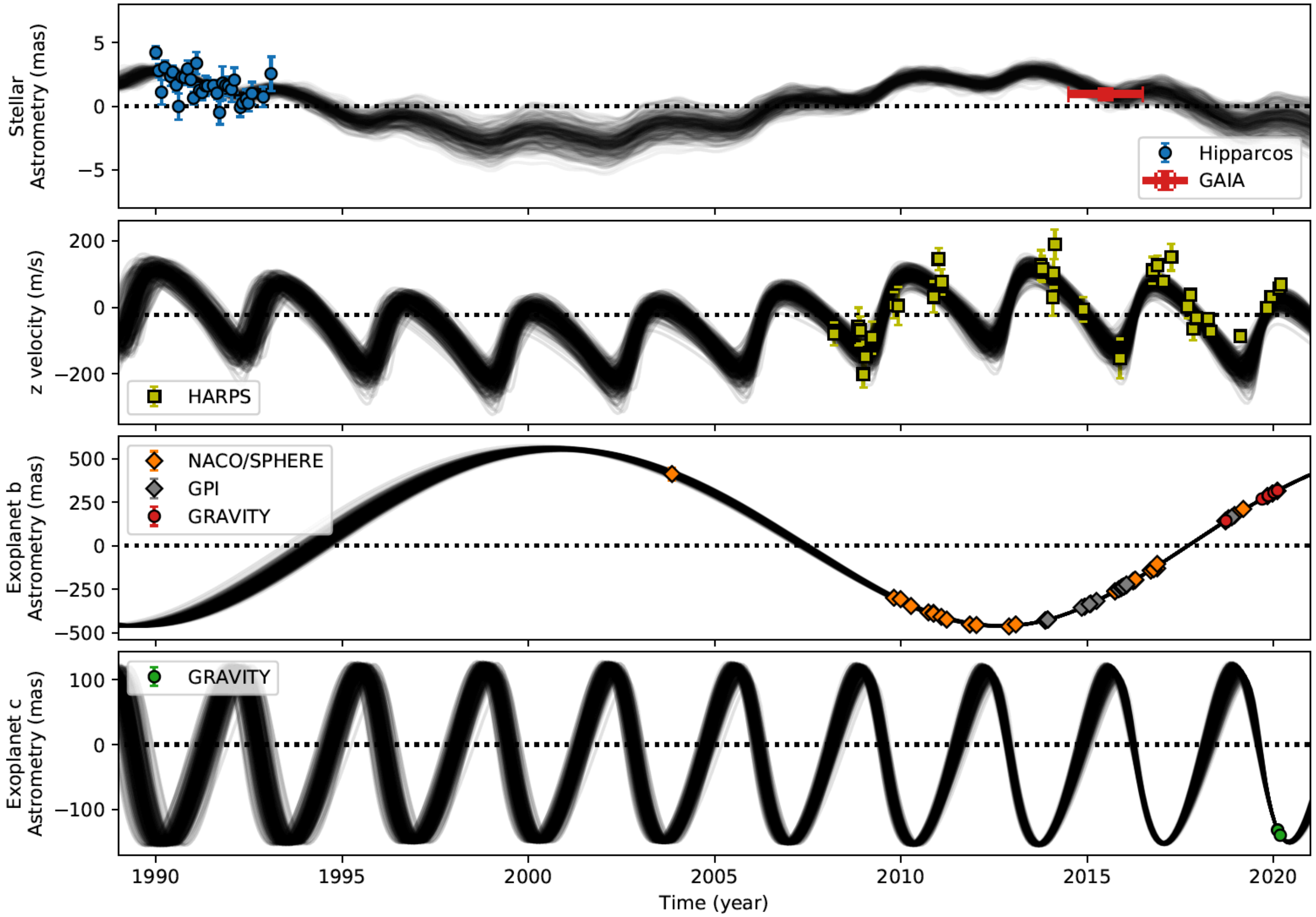
Discovery of a 0.34 Mjup planet at 52 AU of TWA7 (~10 Myr) in the mid-IR (Lagrange et al. 2025)





Determination of planet's masses and orbits

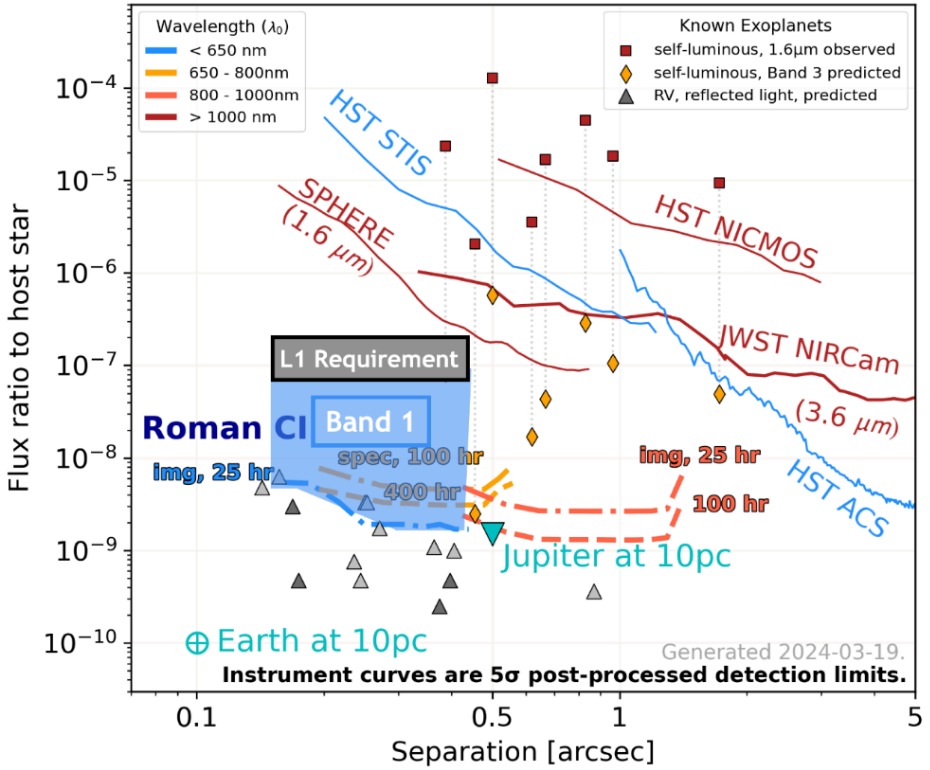
- Direct imaging + Radial Velocities + Astrometry (Gaia/GRAVITY) provides precise masses and orbits of planets: HR8799 e (~10 M_{Jup}) and β Pic b, c (~9, 8 M_{Jup}) (Nowak et al. 2020, Brandt et al. 2021 a,b)



Nowak et al. 2020

Future detection of mature planets

- Detection of old Jupiter-like planets require contrast of 10^{-8}-10^{-9} in the VIS/NIR (reflected light)



For V~ 5 stars

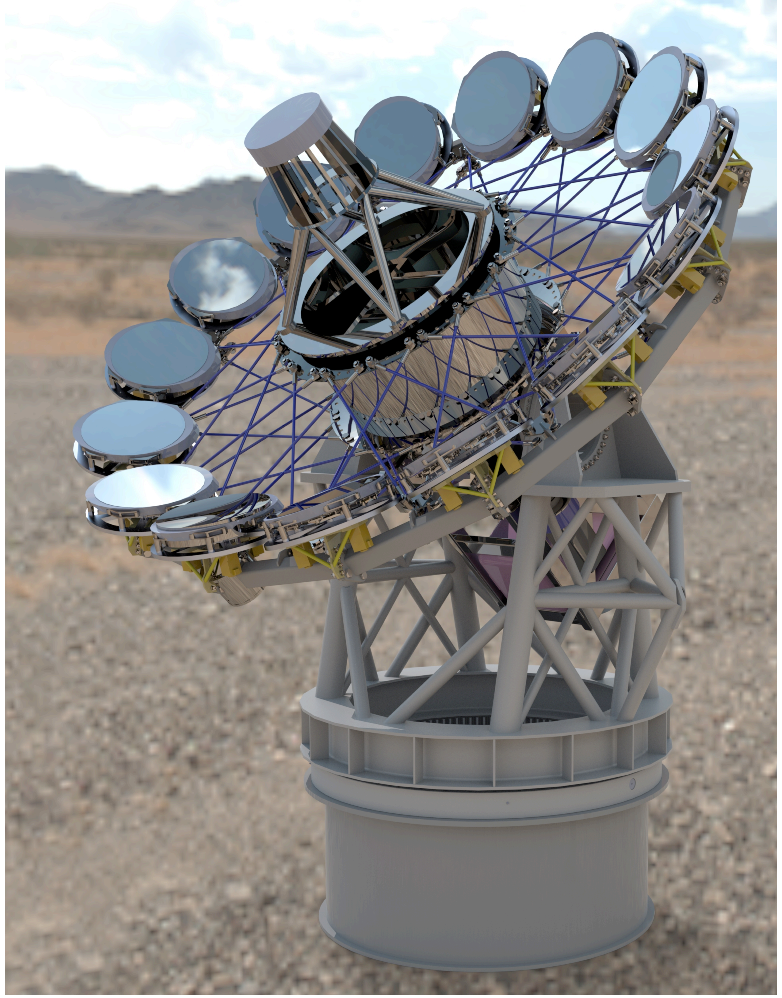
The expected contrast is

< 10^{-7} (L1 requirement)

~ 10^{-8} - 10^{-9} (predicted/goal)

100 to 1,000 times better than current facilities. Optimistically, image mature "Jupiters"

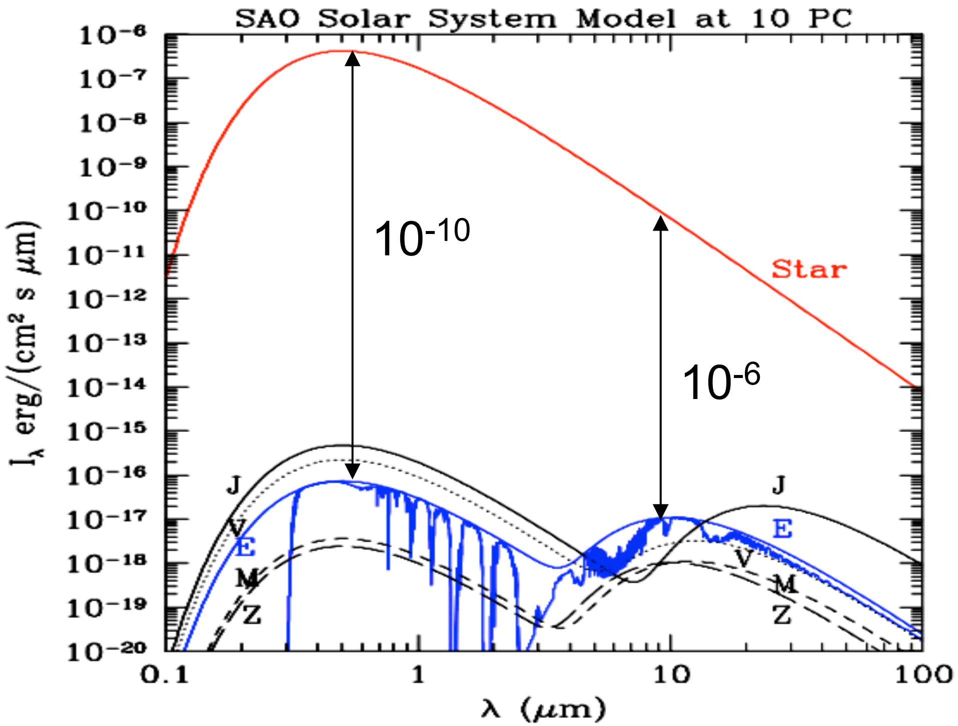
@ 10-50pc in reflected light!



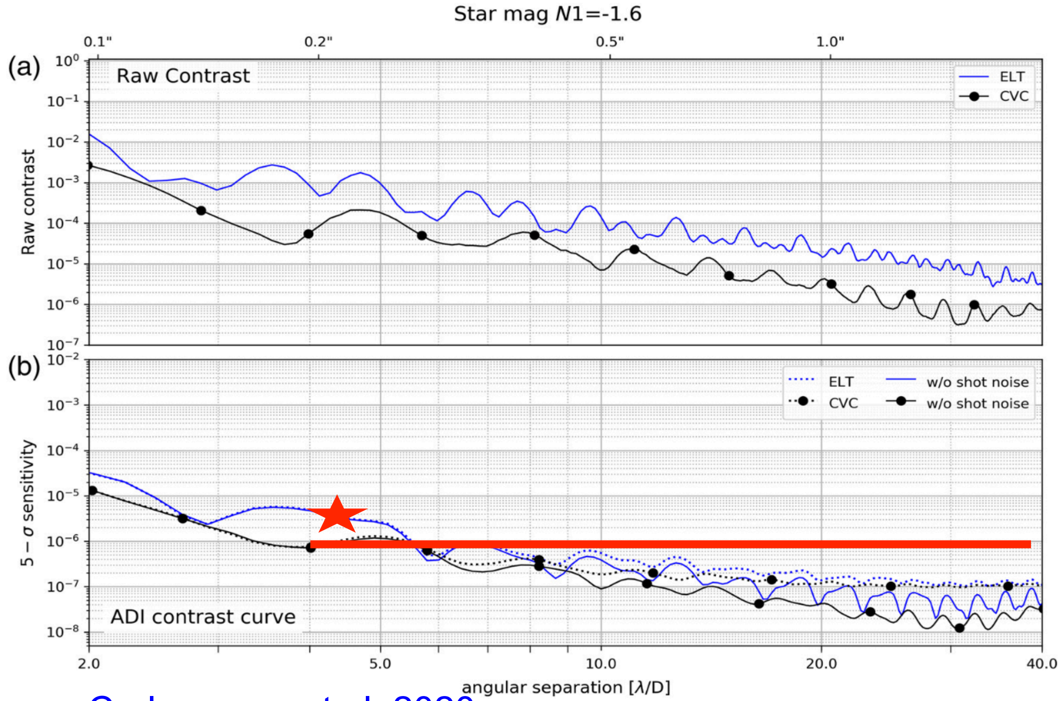
Small ELF (Lodieu et al.2023)

Future detection of Earth-like planets

Contrast ~10^{-10} is requiried in the VIS/NIR, 10^{-6} in the MIR



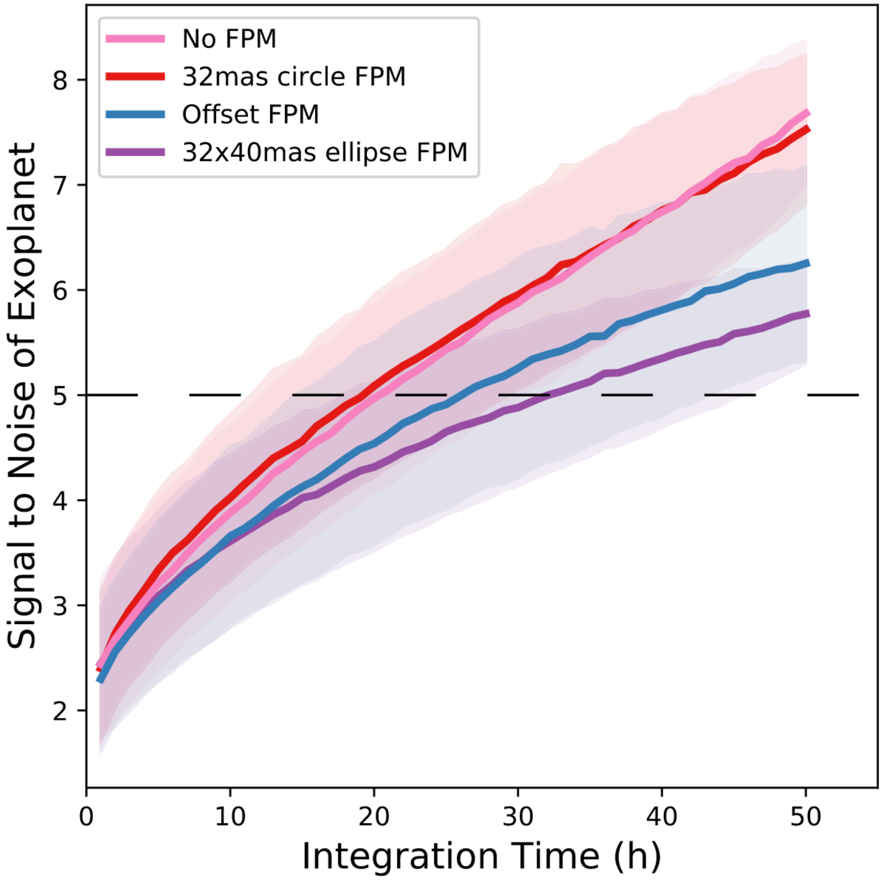
Adaptado de Traub 2004



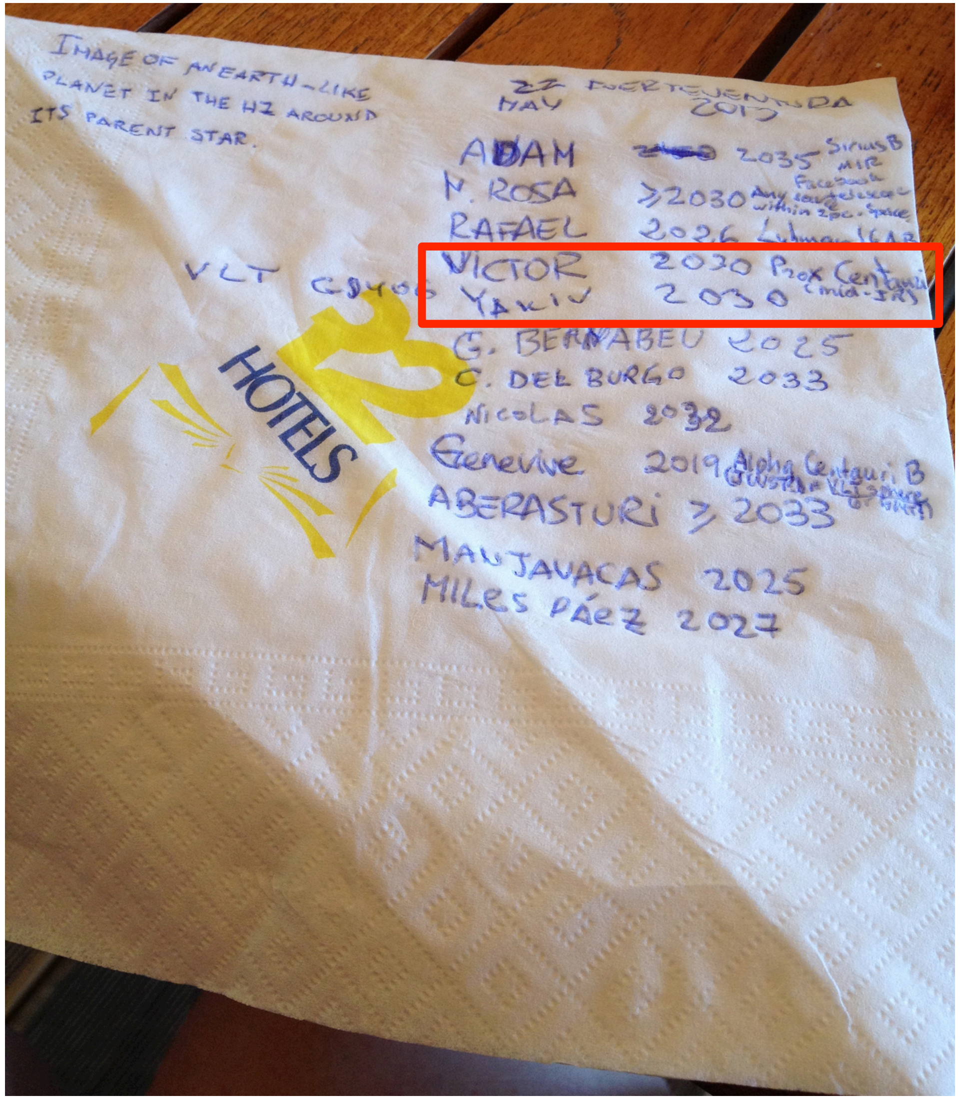
Carlomagno et al. 2020

Earth-like planets with ELTs

Simulations to detect Proxima Centauri b with HARMONI, METIS@ELT or future Habitable World Observatory (HWO) may lead to direct image of rocky planets in the habitable zone (Vaughan et al. 2024, Zhang et al. 2024)



Vaughan et al. 2024



Summary

- High resolution and high contrast capabilities provided by AO have allowed the detection of first substellar companion GL229B, and numerous young substellar companions including the first planetary mass companion 2M1207.

- ExAO systems and ALMA have detected disks structures, such as rings, gap, spirals and embedded protoplanets

- JWST is detecting some of the coolest and least massive planets

- The combination of AO, RV, interferometry (ALMA/GRAVITY) is providing dynamical masses of substellar companions

- Future detection of mature planets with Roman Space telescope and other facilities (small-ELF) and Earth-like planets with ELT and HWO is expected