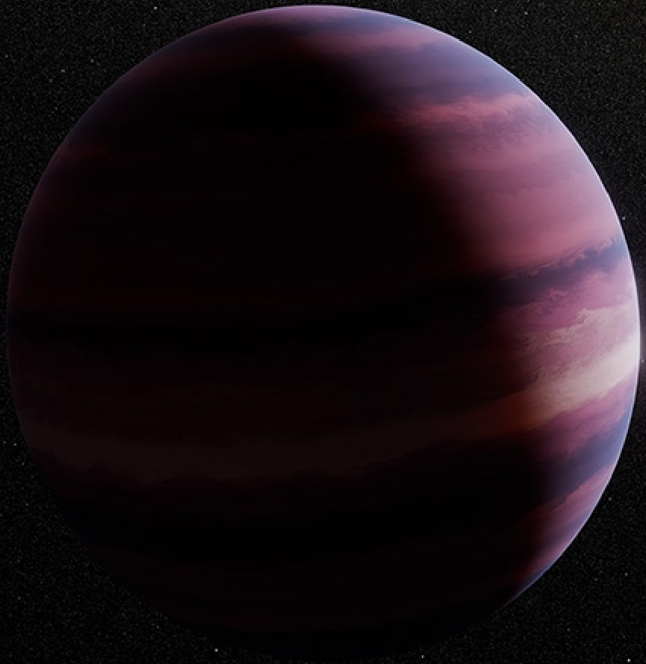


Across the Orbits:
Wide Substellar Companions to Stars

Bartek Gauza
(Institute of Astronomy Univ. of Zielona Góra, Poland)

30 Years Of Substellar Science
La Gomera, 1-5 Sept. 2025

- ★ Early surveys and first discoveries
- ★ Demographics of companions
- ★ Systems architectures as fossils of formation
- ★ Substellar benchmarks
- ★ The path(s) forward

Early surveys and first discoveries

Back in the 1980s and early 90s, brown dwarfs were still "*just*" an elegant, appealing theory and, the only known planets were those of the Solar System

SEARCHES TARGETING M DWARFS

Jan 1986 (McCarthy) "The search for substellar companions to nearby stars: **infrared imaging** from the ground and from space"; Near-IR speckle interferometry, 50 nearby stars have been examined

Apr 1988 (Ianna et al.) "The Nearby Low-Mass Astrometric Binary LHS 1047"
astrometric measurements from plates observations over ~7 yrs

Sep 1989 (Marcy and Benitz) "A Search for Substellar Companions to Low-Mass Stars"
RV variations measurements for a sample of 70 low-mass stars, precision +/- 230 m/s

Oct 1989 (Skrutskie et al.) "**An infrared search** for low-mass companions of stars near the Sun"
55 stars in the solar neighborhood, Ks-band

Feb 1990 (Henry & McCarthy) "A systematic search for brown dwarfs orbiting nearby stars"
27 target M dwarfs within 5 pc, **infrared** speckle interferometry

TARGETING SOLAR TYPE STARS

Aug 1988 (Campbell et al.) "A Search for Substellar Companions to Solar-type Stars"
RV measurements

TARGETING EVOLVED STARS

Nov 1987 (Zuckerman and Becklin) " Excess infrared radiation from a white dwarf—an orbiting brown dwarf?"

Dec 1988 (Becklin and Zuckerman) "A low-temperature companion to a white dwarf star"

Early surveys and first discoveries

To date, no objects which are unambiguously substellar have been found, although there are several interesting candidates – Henry & McCarthy (ApJ; 1990)

Within 5 pc, objects near the stellar/substellar break

- **Wolf 424AB,** astrometry, measured masses, ~0.06 and 0.05 Msun (Heintz 1989), significant uncertainty
- **Ross 614B,** with a mass estimated to be 0.08 Msun (Liebert and Probst 1987),
- **G208-44B,** astrometry + imaging, the lowest luminosity object known in a binary for which a mass has been determined, 0.10 Msun (McCarthy et al 1988).

More distant objects

- **LHS 1047B,** of mass 0.055 Msun (Ianna, Rohde, and McCarthy 1988),
- **GL 623B,** of mass 0.09 Msun (McCarthy and Henry 1987; Marcy and Moore 1989),
- **GL 569B,** (Forrest, Skrutskie, and Shure 1988) probably a very low-mass stellar companion,
- **GD 165B,** a very low-mass companion to a white dwarf, cooler than M dwarfs (Becklin and Zuckerman 1988)

Early surveys and first discoveries

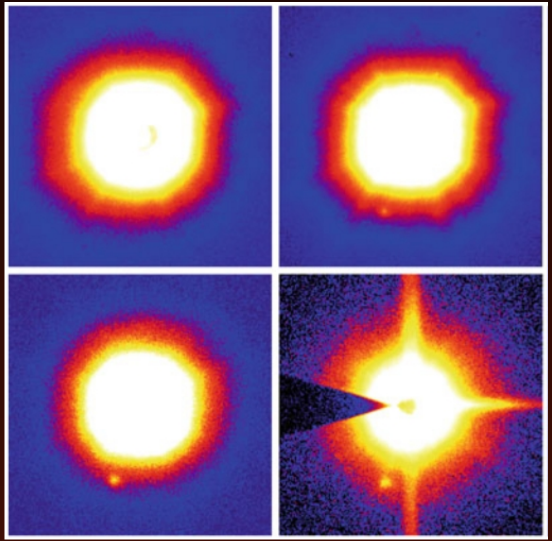
NATURE · VOL 378 · 30 NOVEMBER 1995

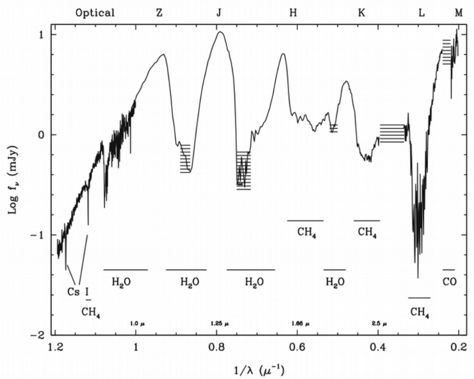
LETTERS TO NATURE

Discovery of a cool brown dwarf

T. Nakajima*, B. R. Oppenheimer*, S. R. Kulkarni*, D. A. Golimowski†, K. Matthews* & S. T. Durrance†

* Palomar Observatory 105-24, California Institute of Technology, Pasadena, California 91125, USA
† Department of Physics and Astronomy, The Johns Hopkins University, Baltimore, Maryland 21218, USA





Optical and infrared images of Gl229. Each field is 25″ × 25″. Top left, *r*-band; top right, *i*-band, bottom left, *z*-band; bottom right, K_s-band. The brown dwarf companion Gl229B is located 7.6 arcsec to the SSE of Gl229A.

REPORTS SCIENCE VOL 282 13 NOVEMBER 1998

Discovery of a Low-Mass Brown Dwarf Companion of the Young Nearby Star G 196-3

Rafael Rebolo,* María R. Zapatero Osorio, Santiago Madruga, Víctor J. S. Béjar, Santiago Arribas, Javier Licandro

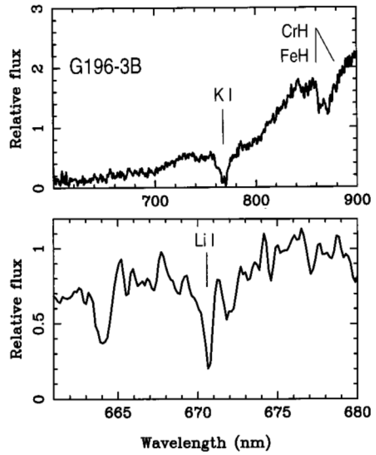


Fig. 2. (**Top**) Optical low-resolution spectrum of the substellar companion G 196-3B obtained at the NOT. The spectrum (normalized to unity

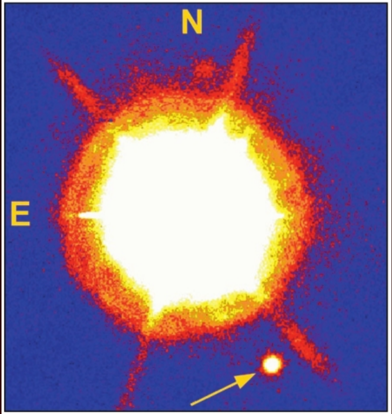


Fig. 1. *I*-band image taken at the NOT (36 × 36 arc sec^2) showing the substellar companion G 196-3B, discovered at 16.2 arc sec SW (position angle = 210°) of the young nearby red star G 196-3.

Early surveys and first discoveries

meanwhile…

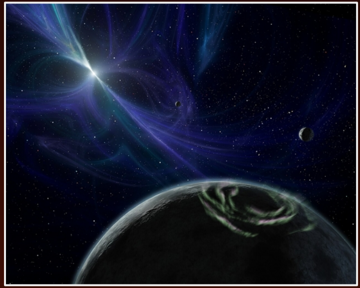
Letter | Published: 09 January 1992

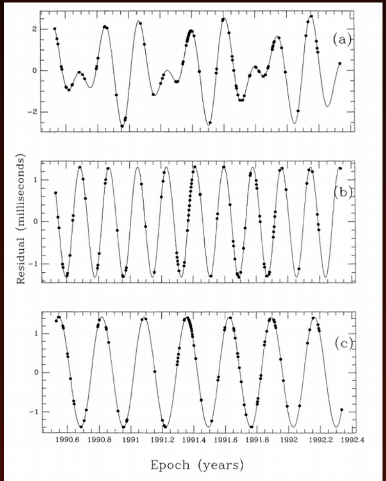
A planetary system around the millisecond pulsar PSR1257+12

A. Wolszczan & D. A. Frail

Nature **355**, 145–147 (1992) | Cite this article

12k Accesses | **1280** Citations | **704** Altmetric | Metrics





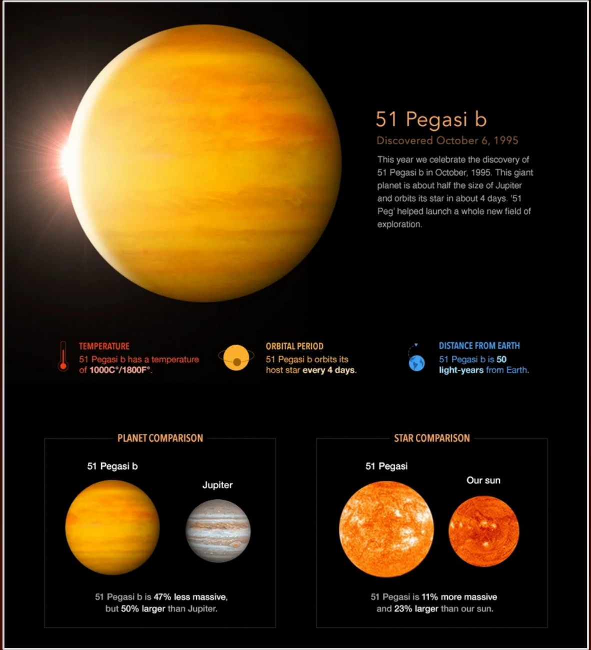
Articles | Published: 01 November 1995

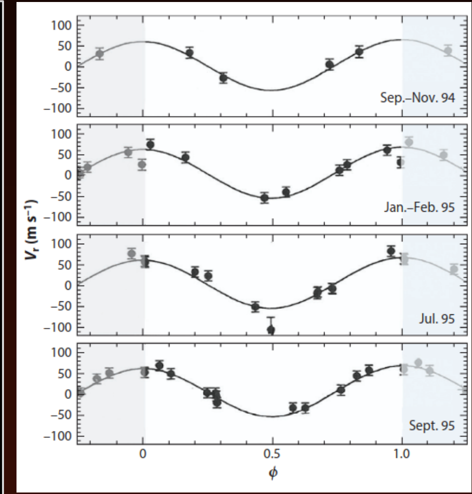
A Jupiter-mass companion to a solar-type star

Michel Mayor & Didier Queloz

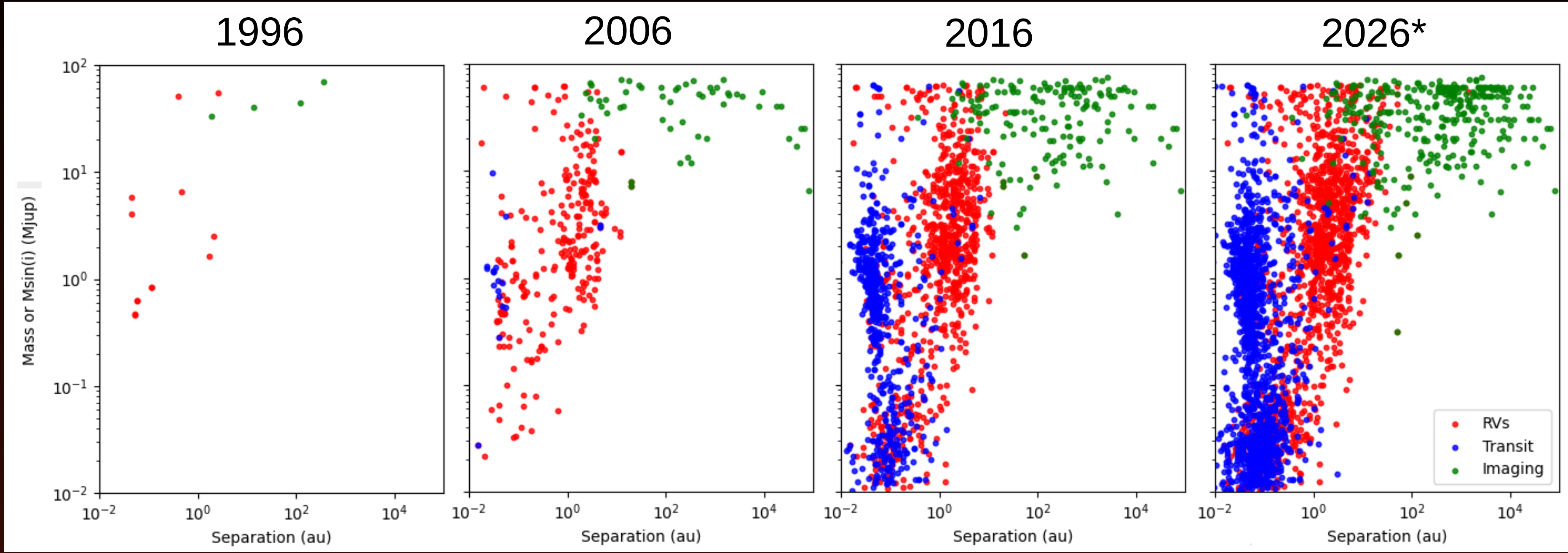
Nature **378**, 355–359 (1995) | Cite this article

41k Accesses | **3496** Citations | **1333** Altmetric | Metrics





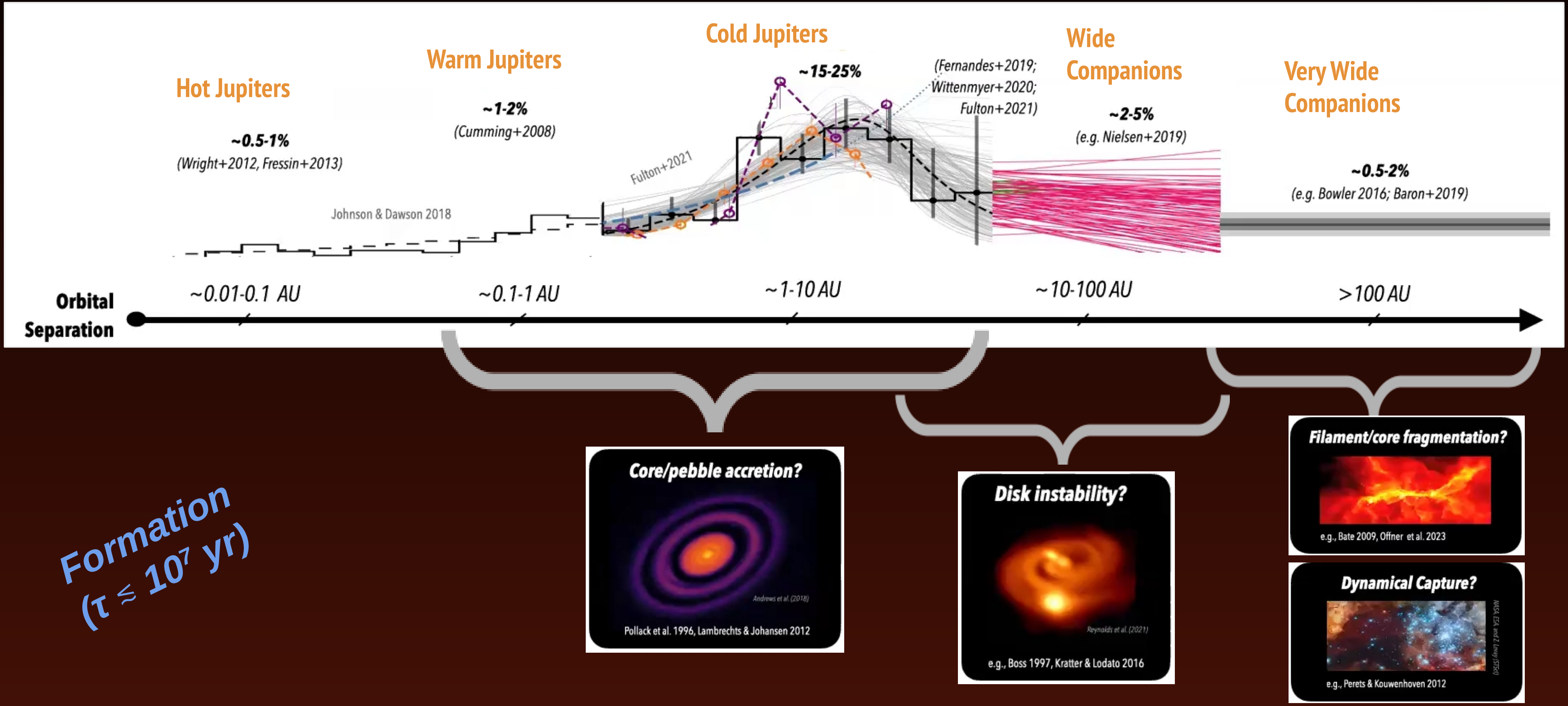
Demographics of companions



Substellar companions (brown dwarfs and exoplanets) detected via transit, RVs and direct imaging over the past three decades. Data from exoplanet.eu

Demographics of companions

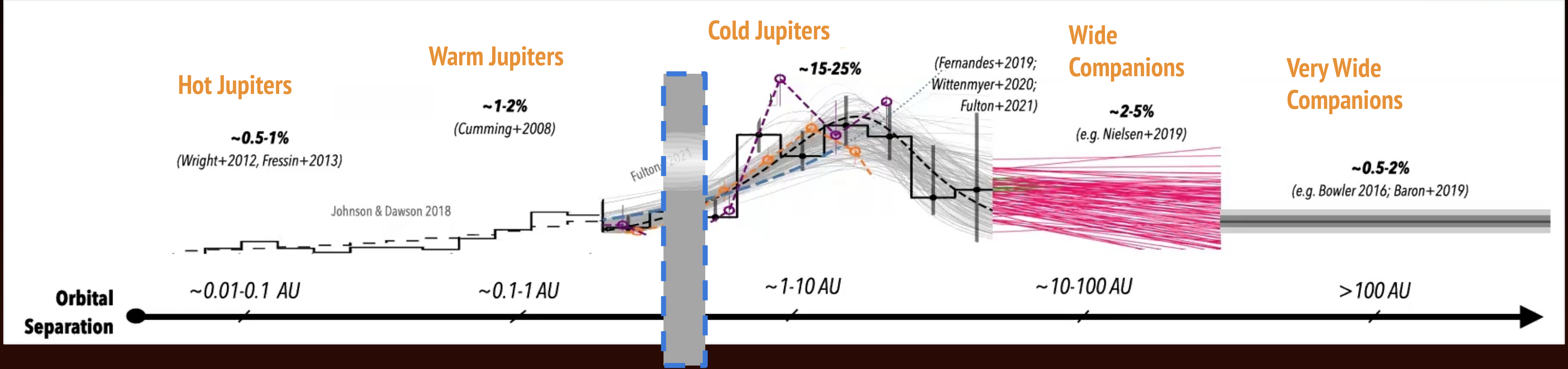
Compilation credits: B. Bowler (2025, Sagan Summer Workshop)



Formation
($\tau \lesssim 10^7$ yr)

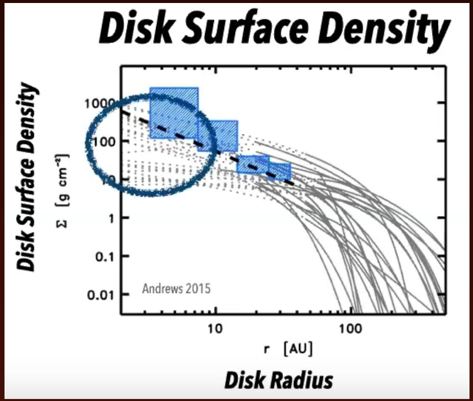
Demographics of companions

Compilation credits: B. Bowler (2025, Sagan Summer Workshop)

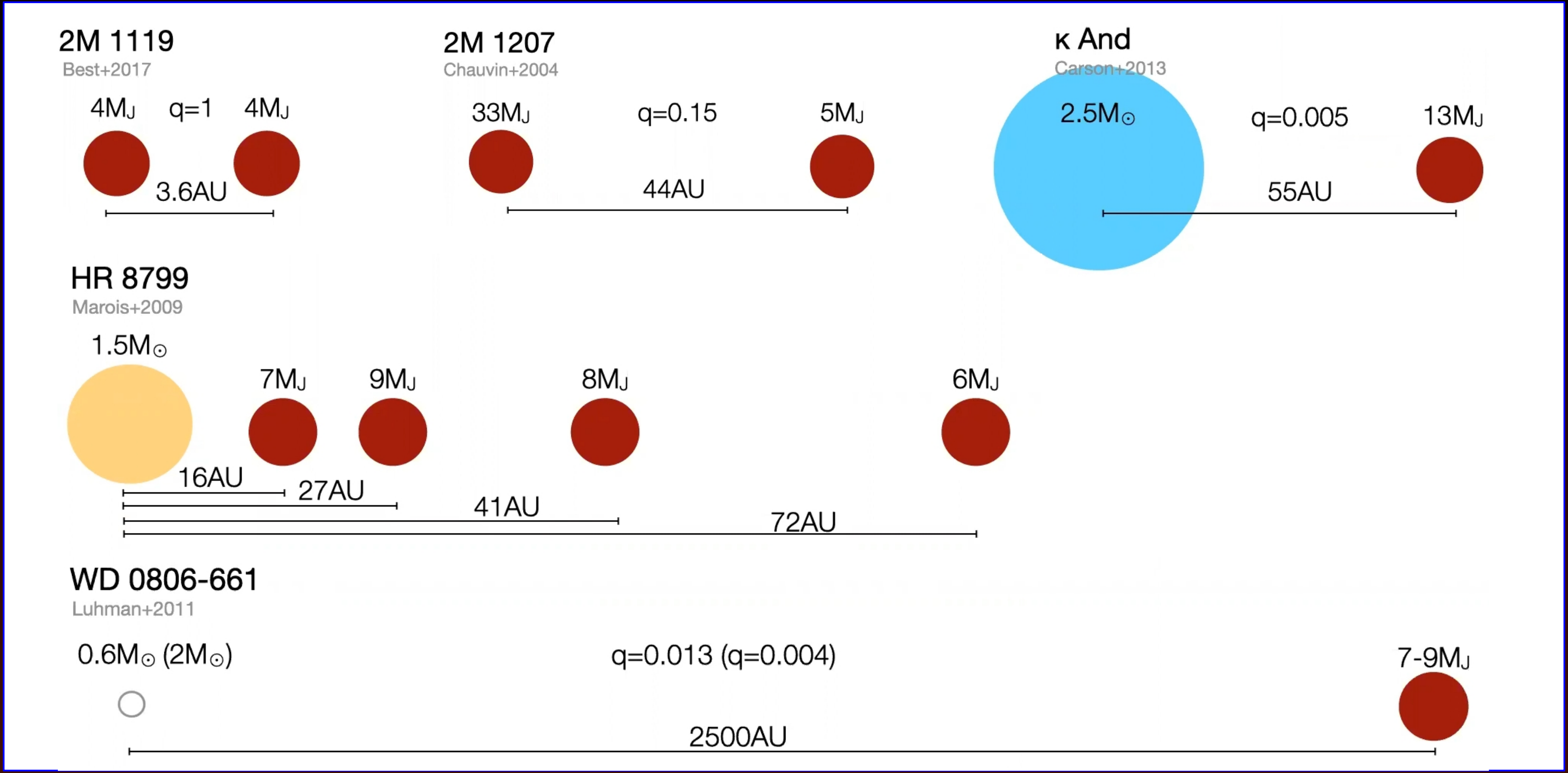


water ice line


Credit: A. Angelich (NRAO/AUI/NSF)/ALMA (ESO/NAOJ/NRAO)



Systems architectures as fossils of formation



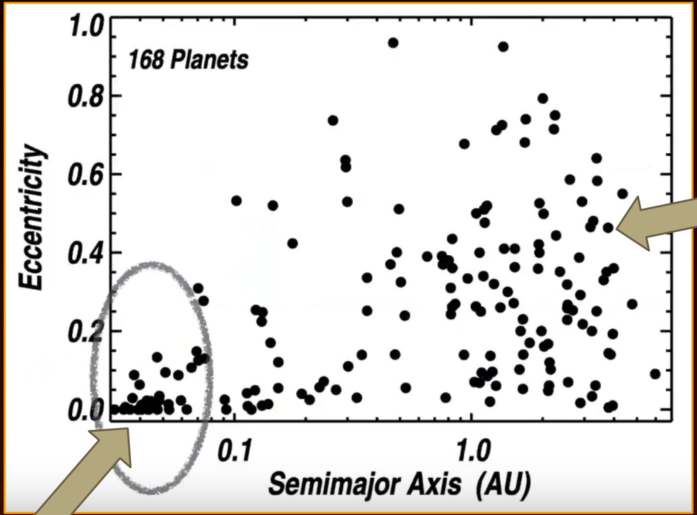
Systems architectures as fossils of formation

orbital eccentricities

Are there any clear trends?

What clues on formation and dynamical evolution?

Butler et al. (2006)



Most of massive close-in planets are on eccentric orbits (dynamically hot)

Hot Jupiters, tidally circularized

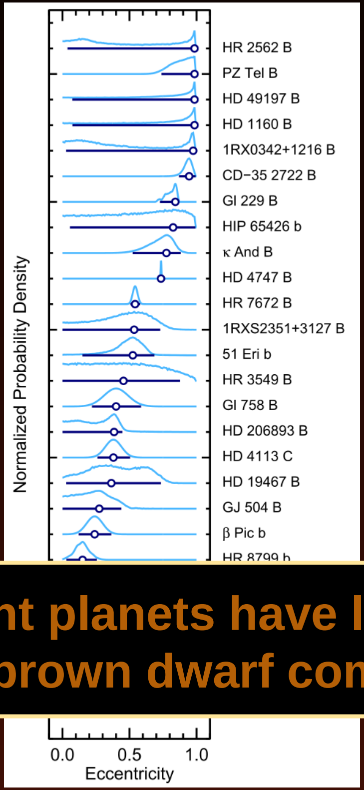
Systems architectures as fossils of formation

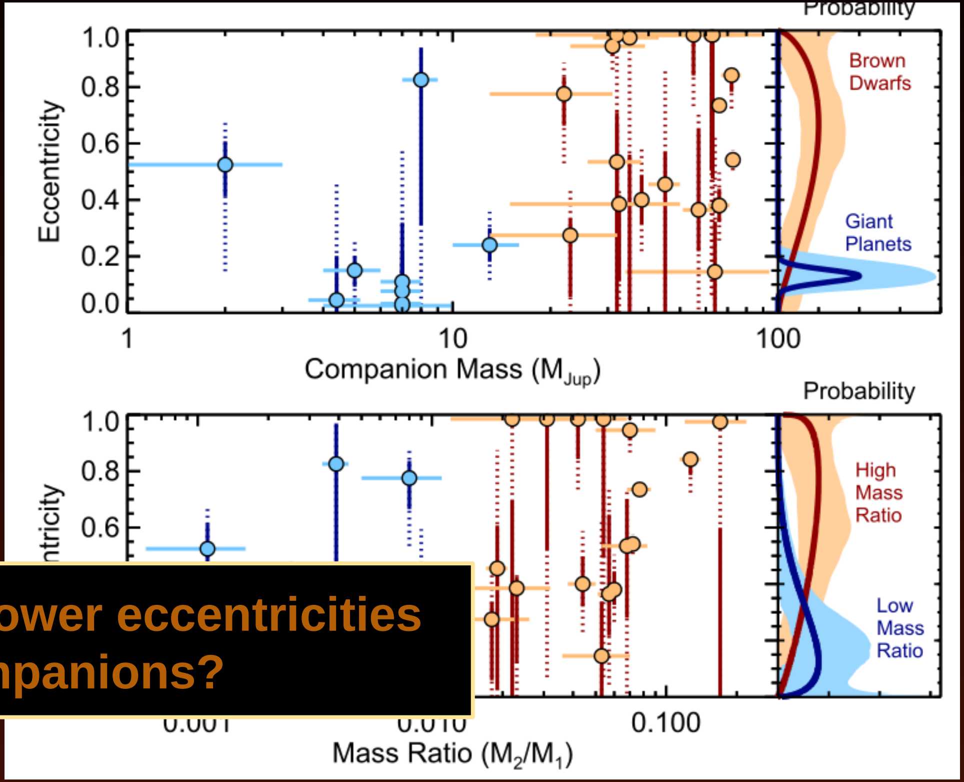
Bowler et al. (2020)

orbital eccentricities

Are there any clear trends?

What clues on formation and dynamical evolution?

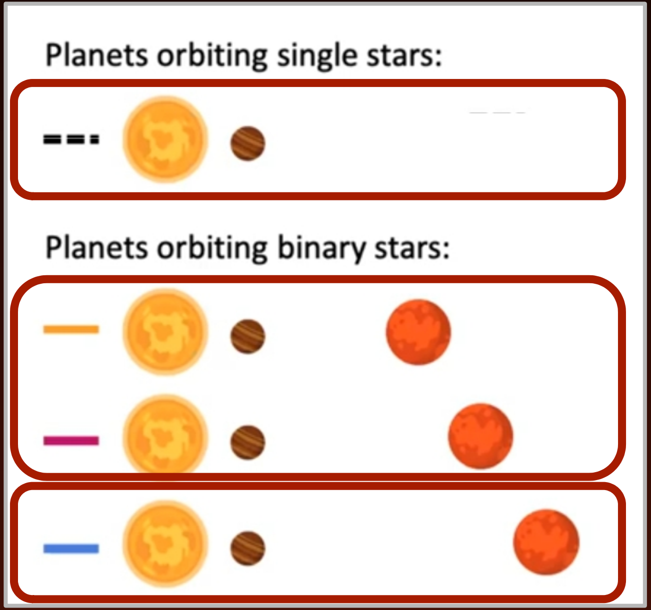




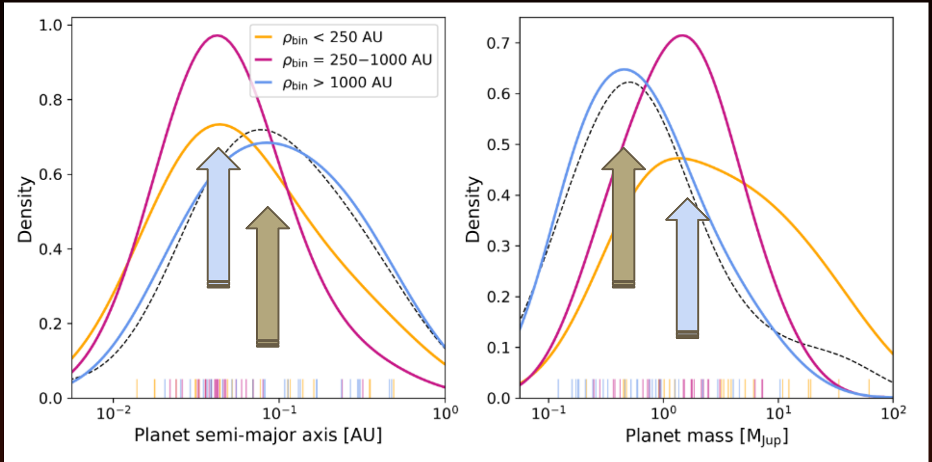
wide-orbit giant planets have lower eccentricities than brown dwarf companions?

Systems architectures as fossils of formation

Effects of binarity and separations of stellar systems



Fontanive & Bardalez Gagliuffi (2021)
planet (/BD) mass > 0.1 Mjup
planet (/BD) separation < 1 au

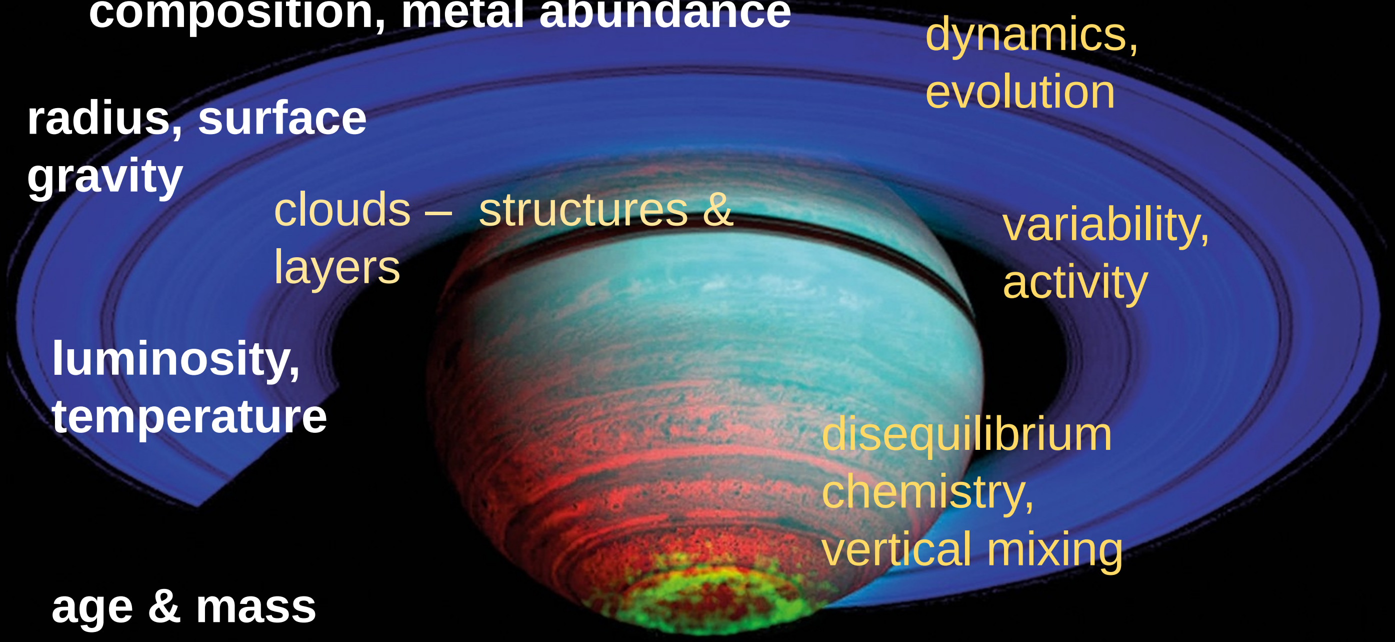


Substellar companions in very wide binaries have the same properties as those around single stars (Fontanive et al. 2024)

Giant planets in binaries of a few hundred AU separations tend to have higher masses and shorter orbits (Mustill et al. 2022; Fontanive et al. 2024)

Substellar benchmarks

[what makes a perfect substellar benchmark?]()



composition, metal abundance

dynamics, evolution

radius, surface gravity

clouds – structures & layers

variability, activity

luminosity, temperature

disequilibrium chemistry, vertical mixing

age & mass

rotation

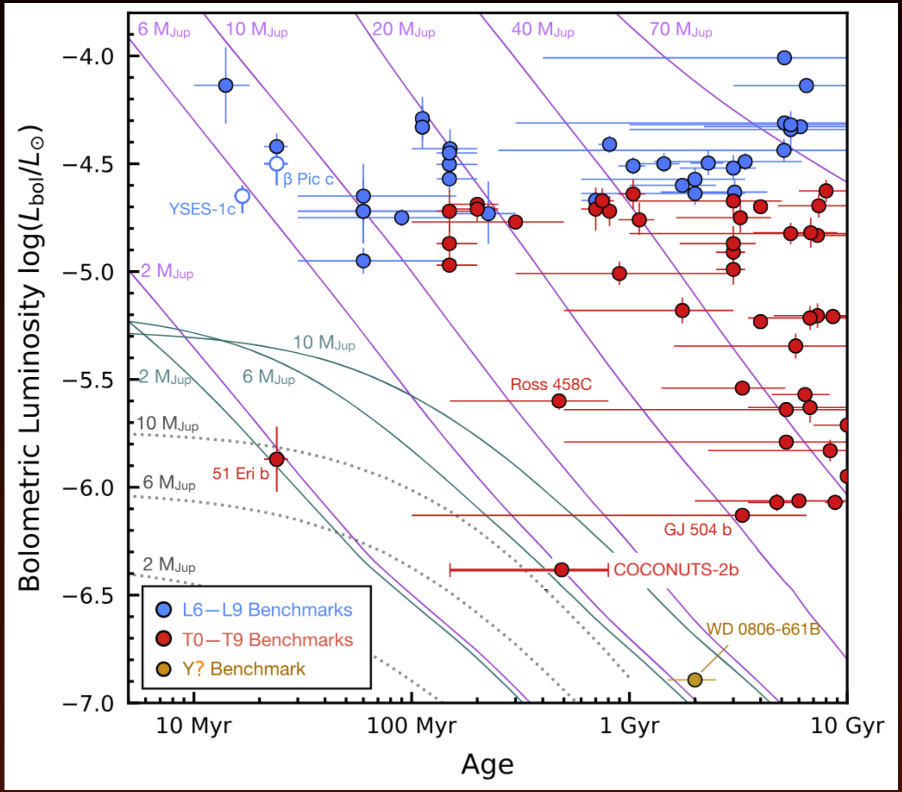
interaction with starlight

Substellar benchmarks

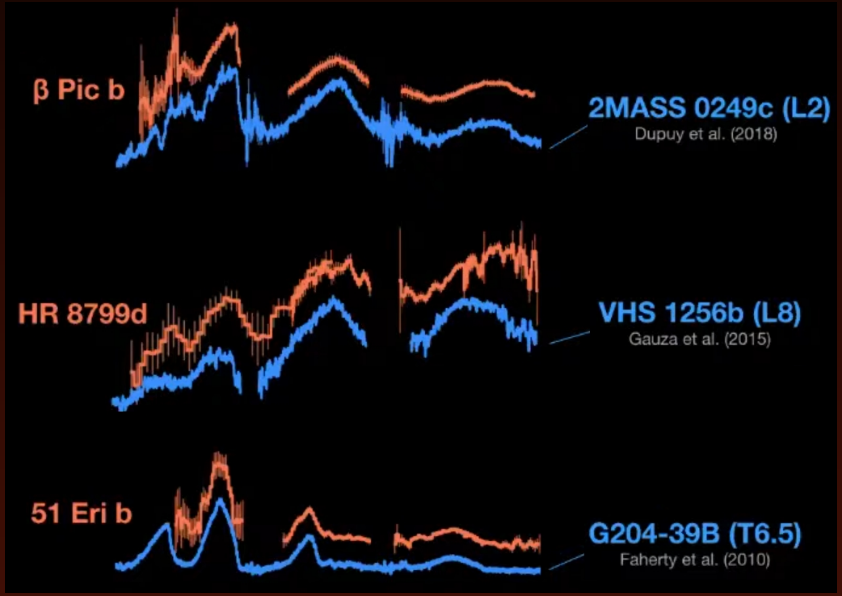
directly imaged planets and BDs

wide orbit (≳100 au) planets and BDs

Zhoujian Zhang et al. (2021)



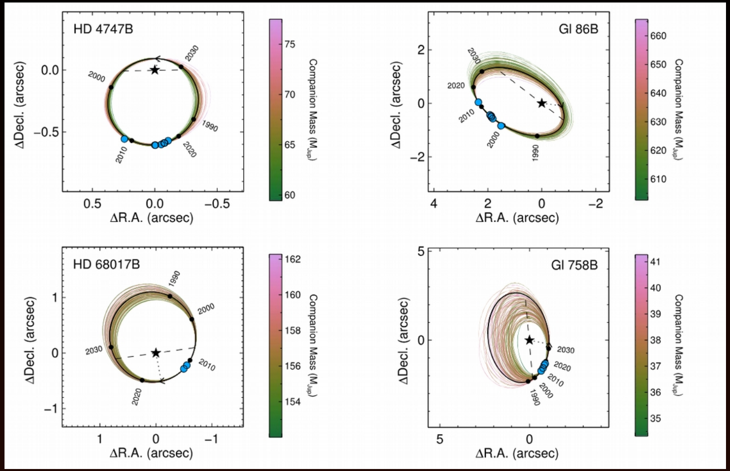
distance, age, metallicity + high quality spectroscopy

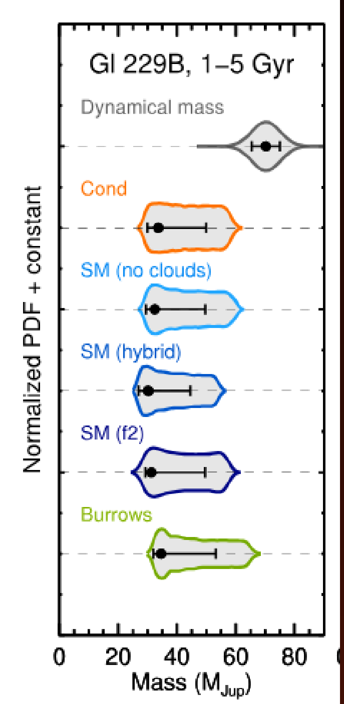


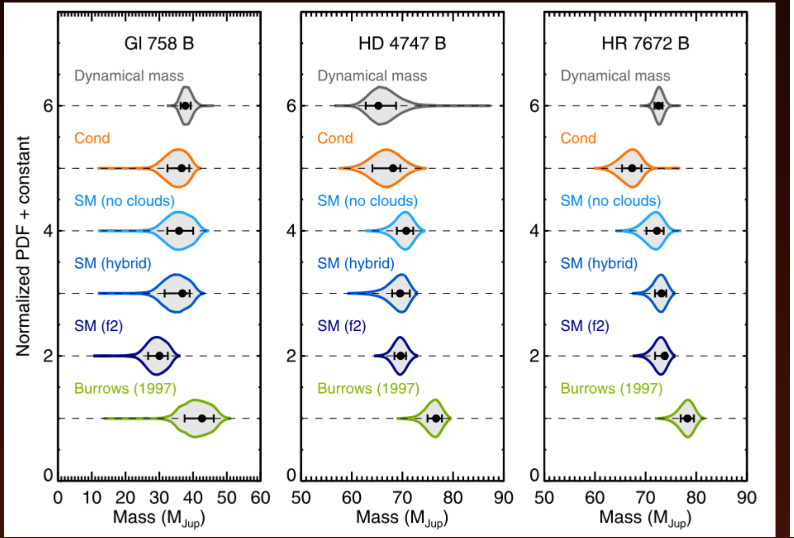
Substellar benchmarks

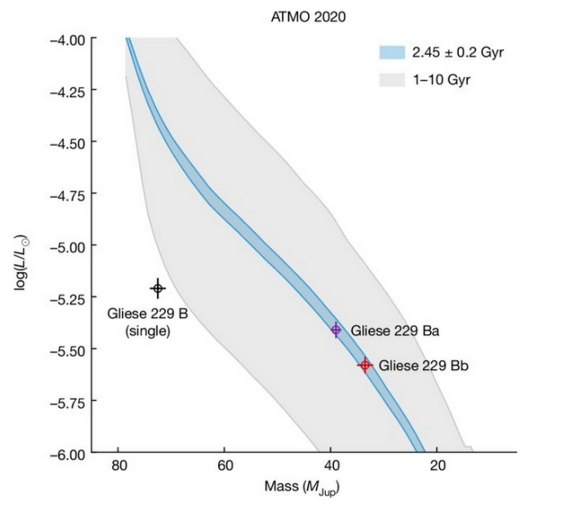
astrometry (orbital motion) + RVs = model-independent mass

Brandt et al. (2019, 2020)
Xuan et al. (2024)



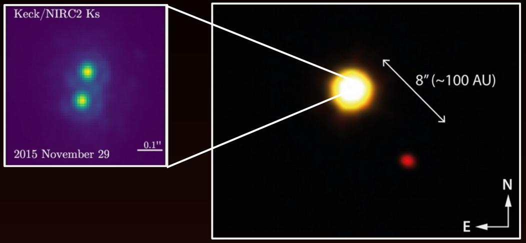






Substellar benchmarks

VHS 1256 (Gauza et al. 2015, Stone et al. 2015)

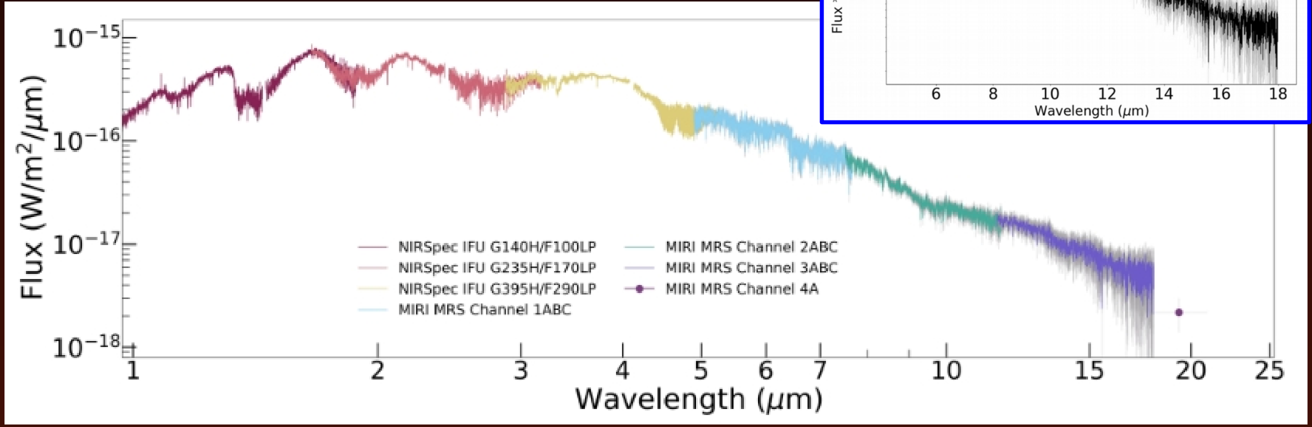


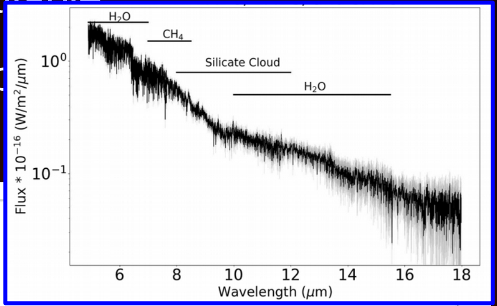
<u>bolometric luminosity</u>

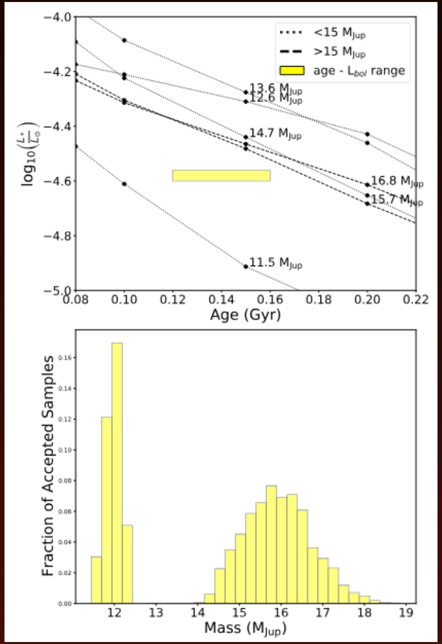
log (*L/Lsun*) = –4.55 +/- 0.009

98% of the measured luminosity is derived directly from the spectrum. Plus precise Gaia distance avai

Most of the uncertainty comes from the ab calibration standard star.



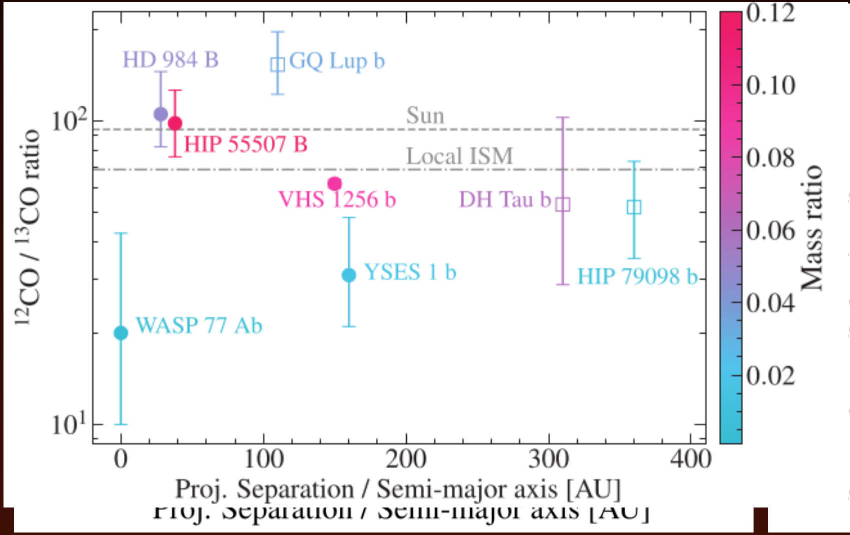


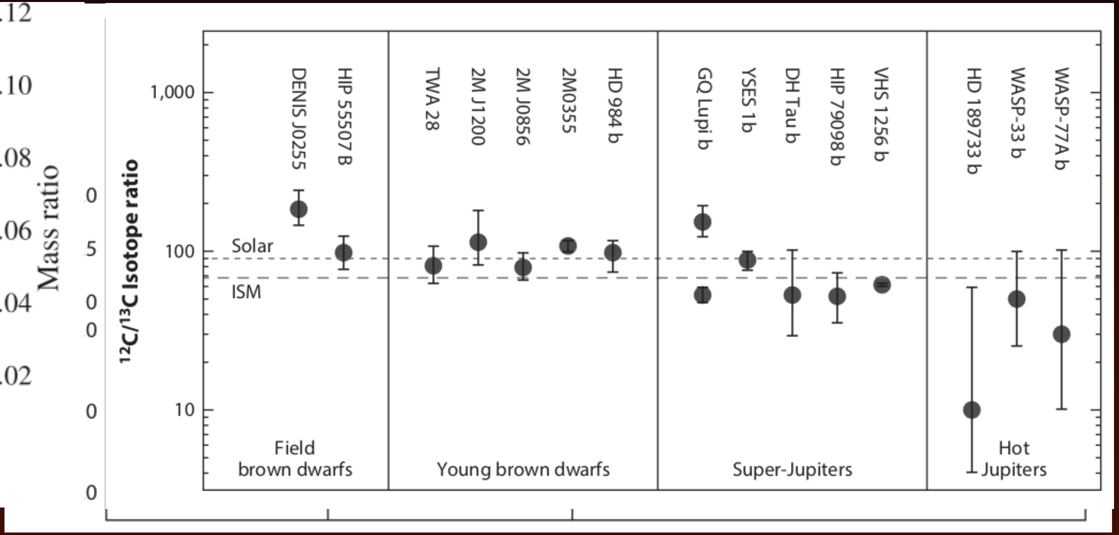


Substellar benchmarks

C/O ratios – may provide insights on formation processes, so far almost all are consistently measured to be within the C/O = 0.5–0.65 range. Xuan et al. (2024); Snellen (2025).

Individual isotope measurements and isotope ratios – a new avenue of BD and exoplanet atmospheric characterization Morley et al. (2019), Snellen (2025).





The path(s) forward

Detection and characterization of substellar objects in globular clusters

BDs around stars of the Magellanic Clouds (*and other extragalactic?)

Completing the census of substellar companions → lower masses, closer orbits [guided searches]

Tracing formation pathways via D/H, C O , other compositional studies

Direct observations of rocky planets around M dwarfs (atmospheres?), time-domain studies of massive planet atmospheres

Ground-based

- Vera C. Rubin Observatory
- ELT, GMT, TMT
- ELF

Space-based

- Euclid
- Plato mission
- Roman Space Telescope
- Gaia NIR
- NEO Surveyor
- LIFE