Combining Astrometry and Direct Imaging Targets

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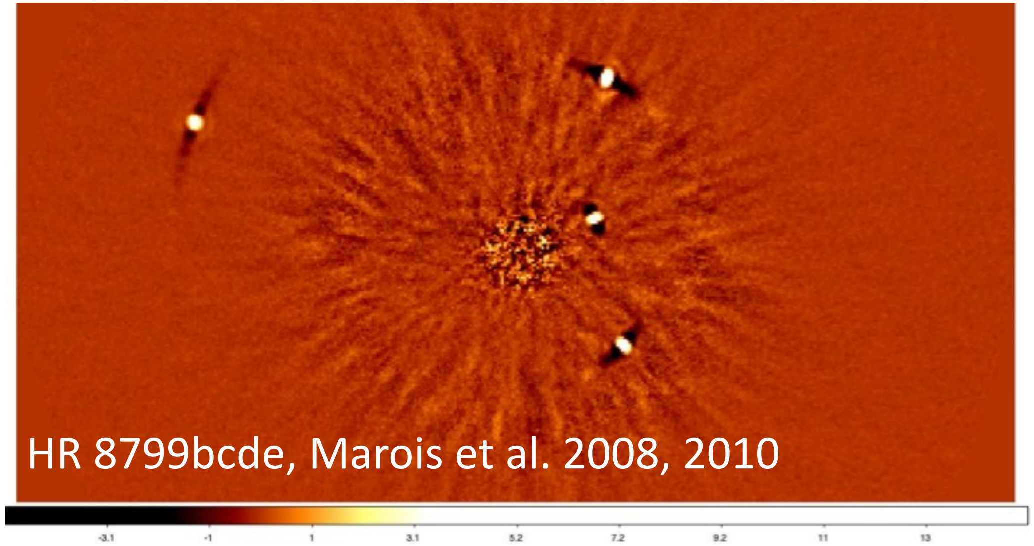
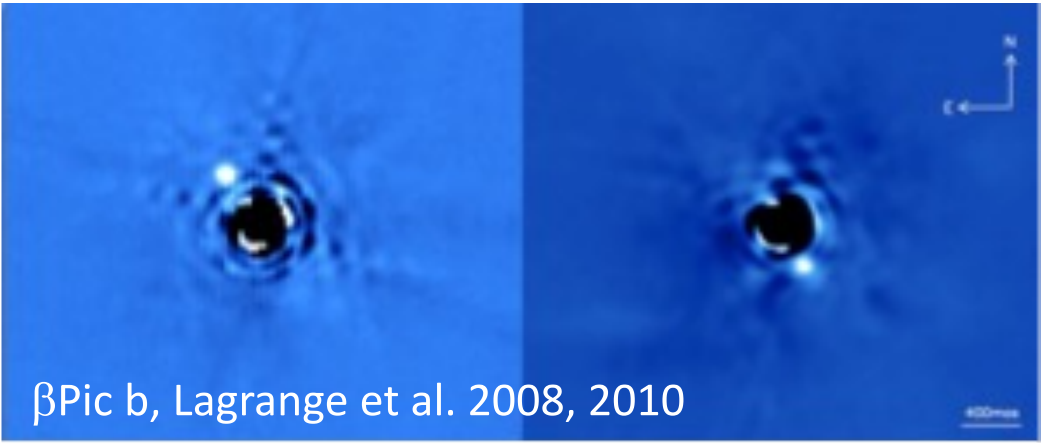
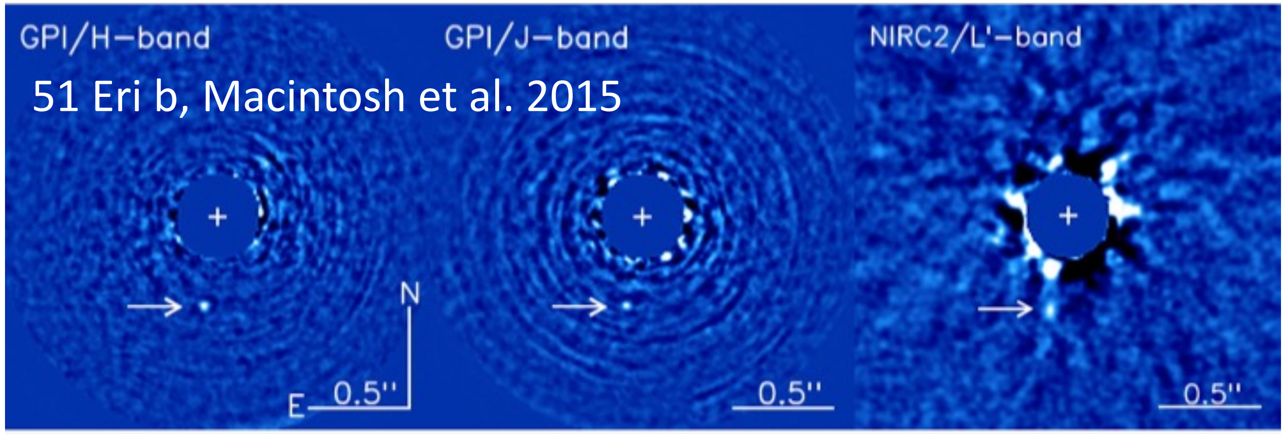
Examples of Directly Imaged (DI) Exoplanets

First Discoveries



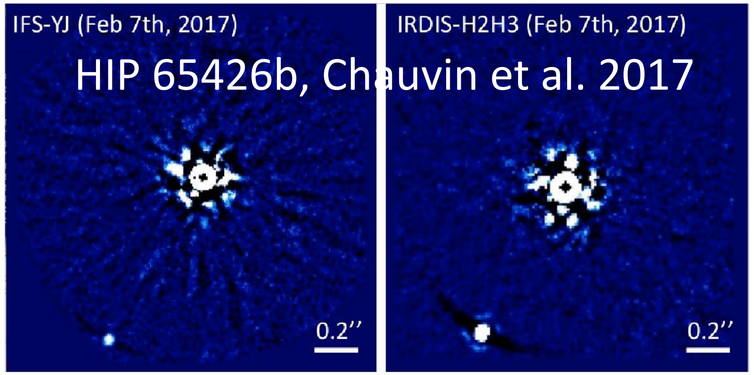
HR 8799bcde, Marois et al. 2008, 2010


βPic b, Lagrange et al. 2008, 2010



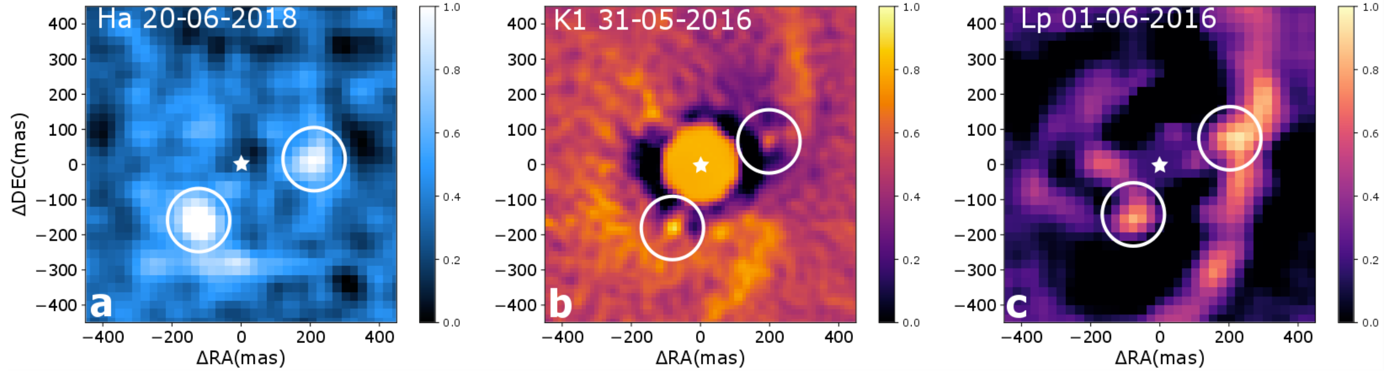
51 Eri b, Macintosh et al. 2015

Discoveries from GPI and SPHERE



HIP 65426b, Chauvin et al. 2017

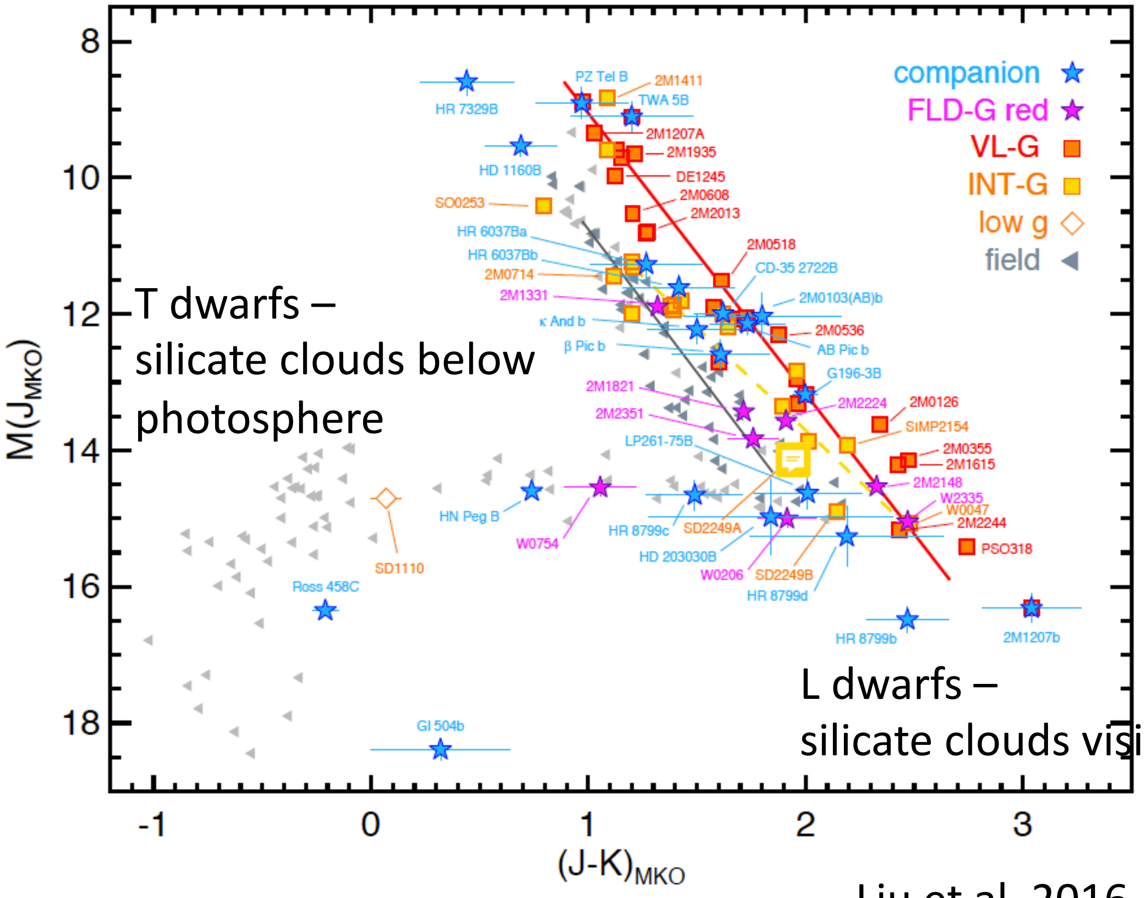
PDS70bc, Keppler et al. 2018, Haffert et al. 2019



Right now, we can detect "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

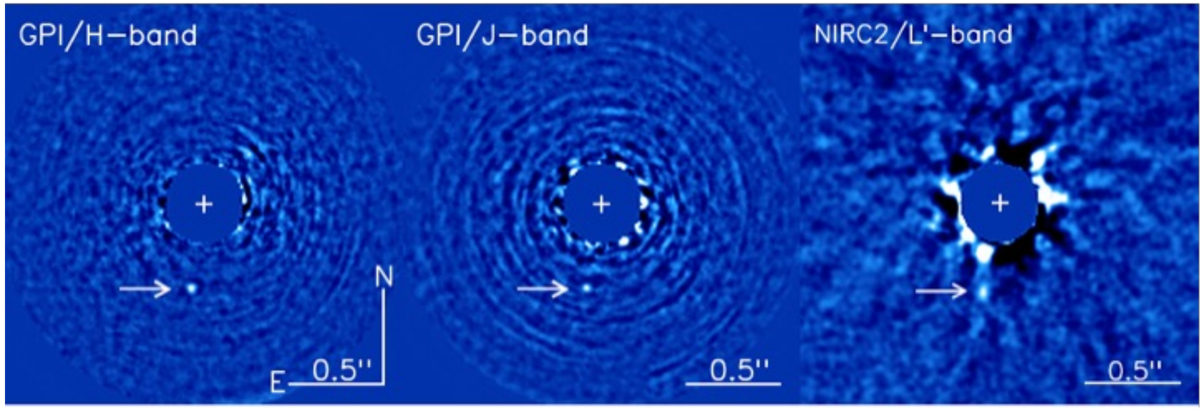
Spectroscopy and Photometry reveal primarily red, dusty photospheres for young exoplanets and exoplanet analogs:

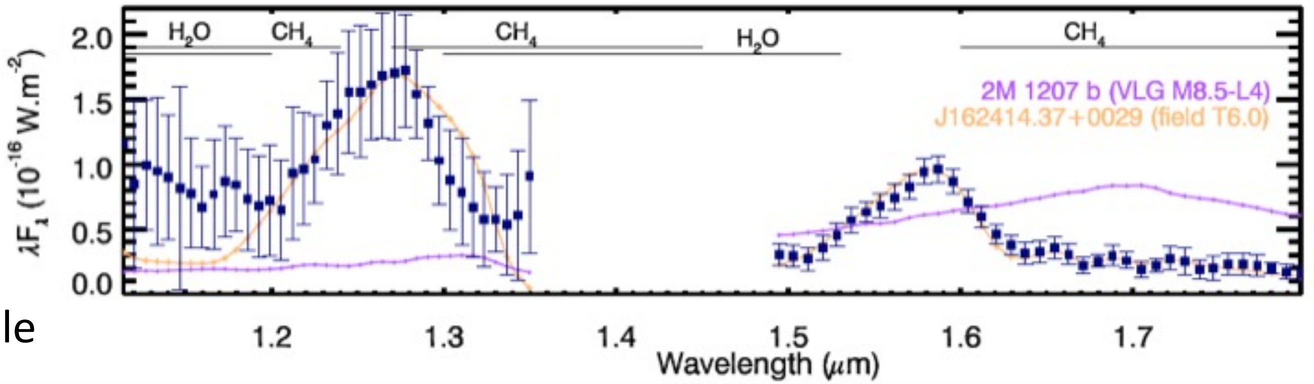


T dwarfs – silicate clouds below photosphere

L dwarfs – silicate clouds visible

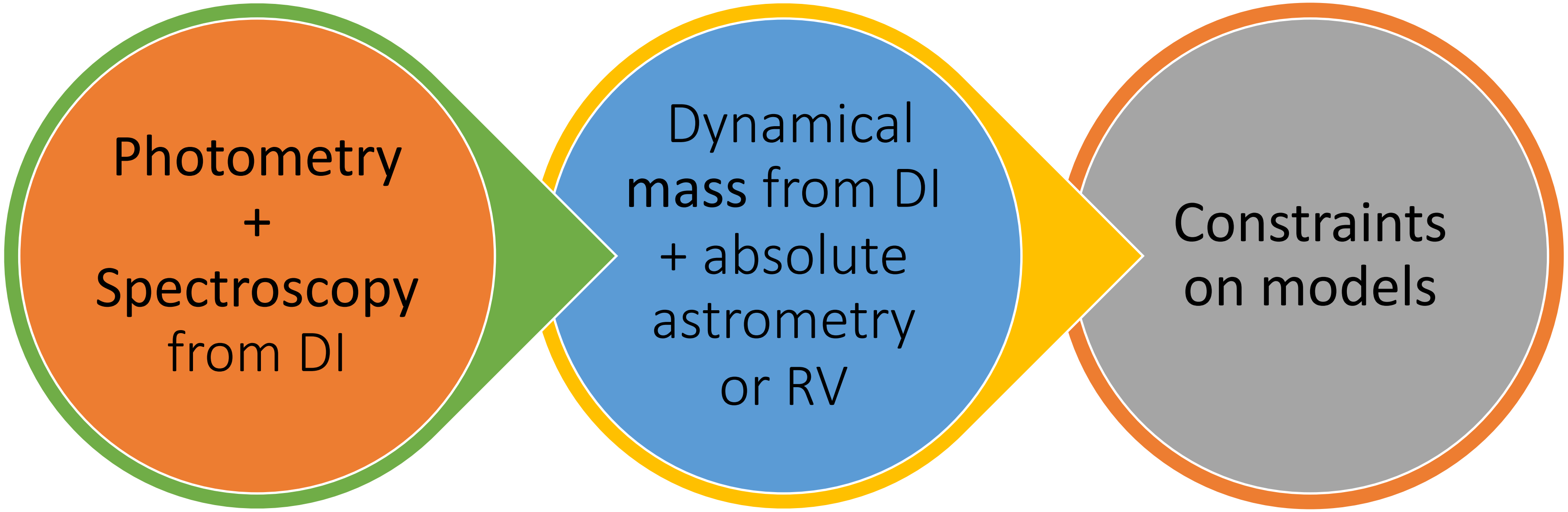
Liu et al. 2016



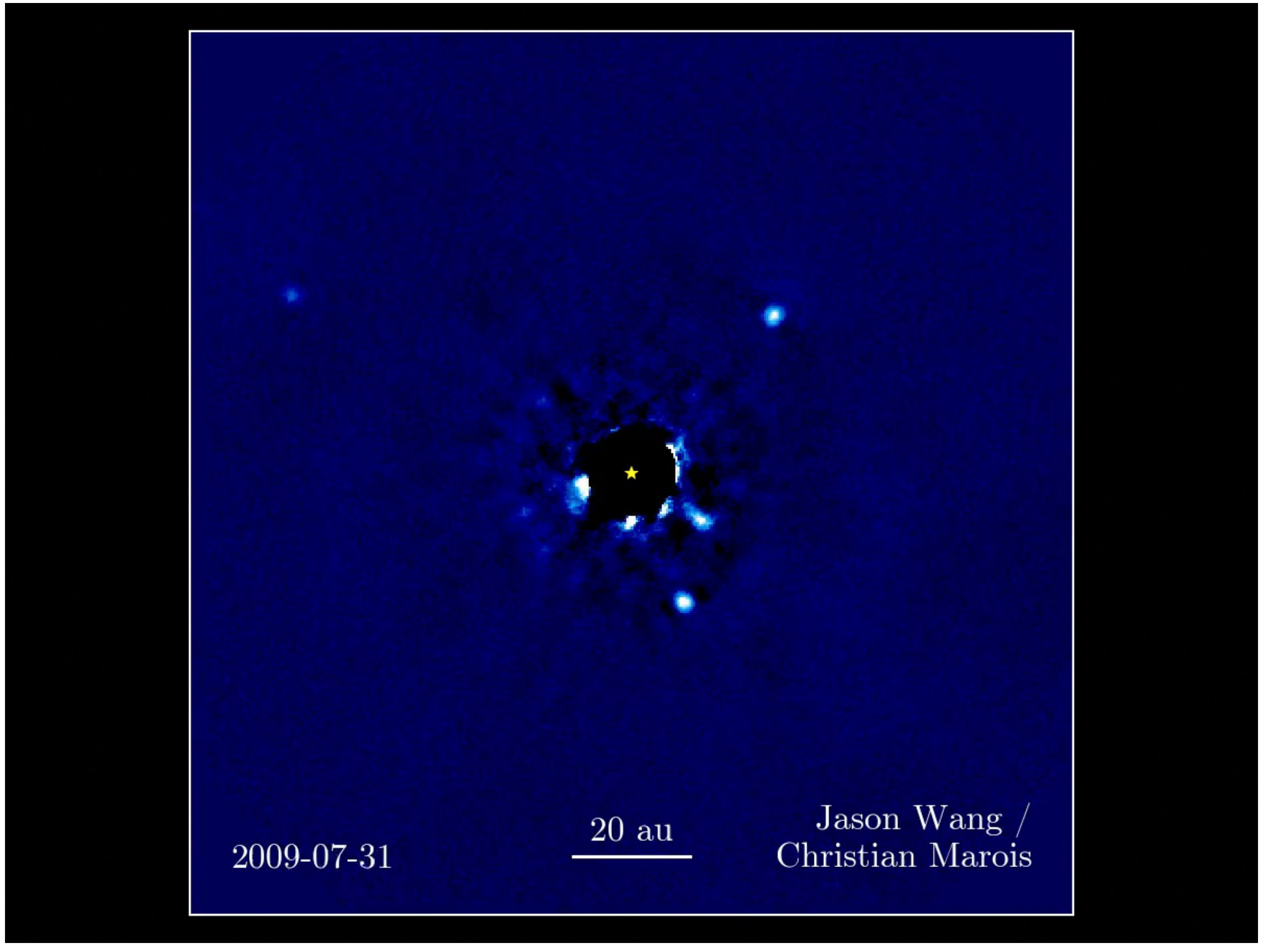


Macintosh et al. 2015

Combining techniques enables in-depth characterization and breaks the age-mass degeneracy:

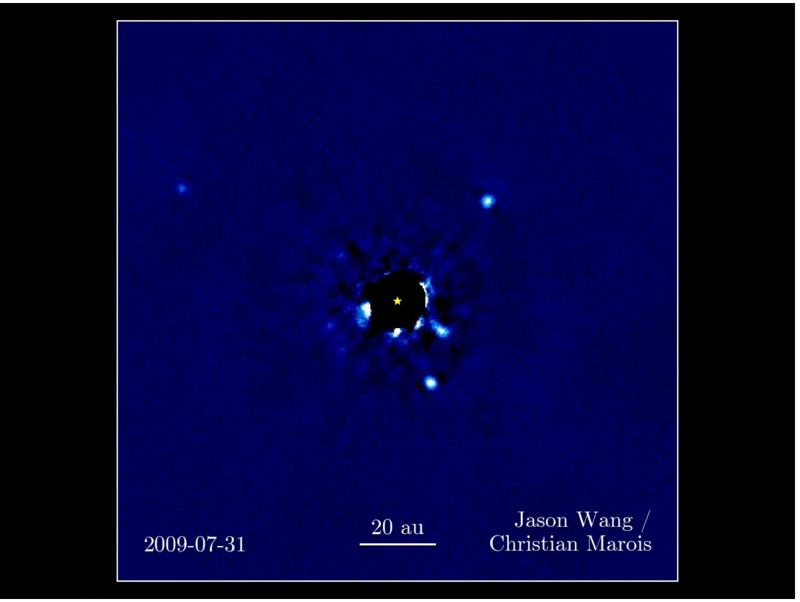


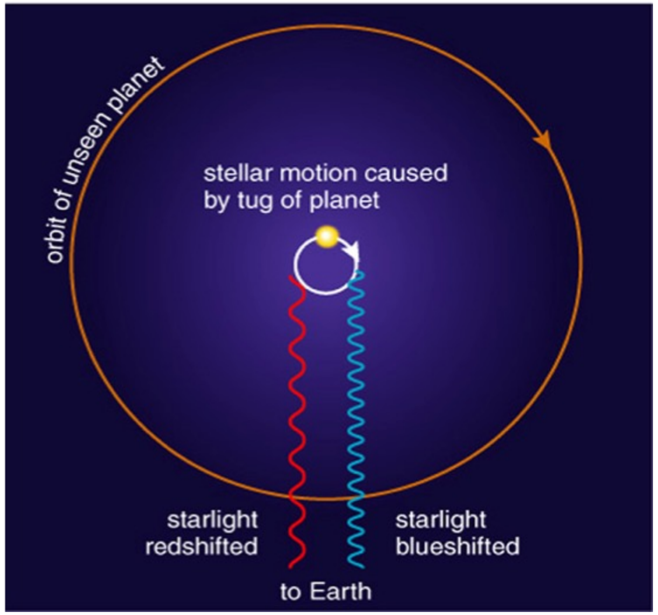
Direct Imaging astrometry is relative to the star and can only determine the total mass of the system

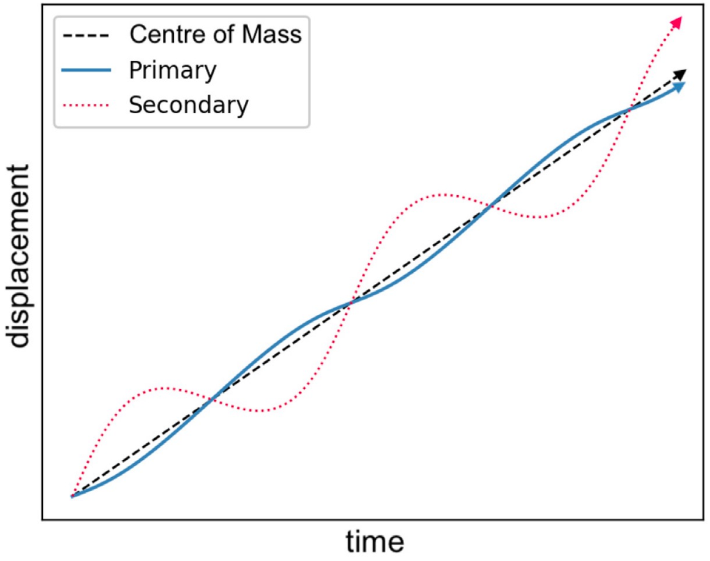


$$a = \left(P^2\ M_{tot}\right)^{1/3}$$

We need to combine with another technique to find absolute motion of the star



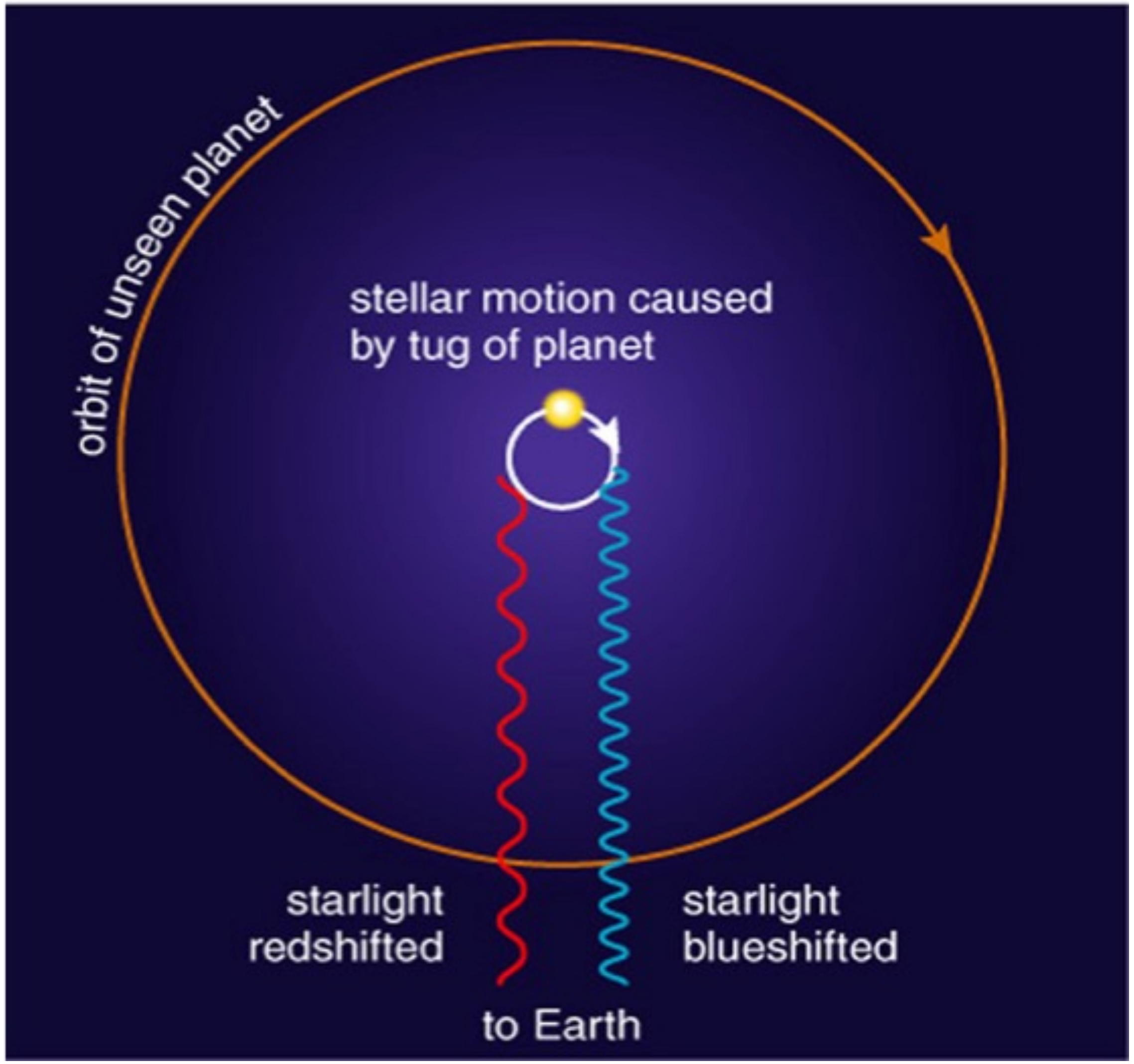




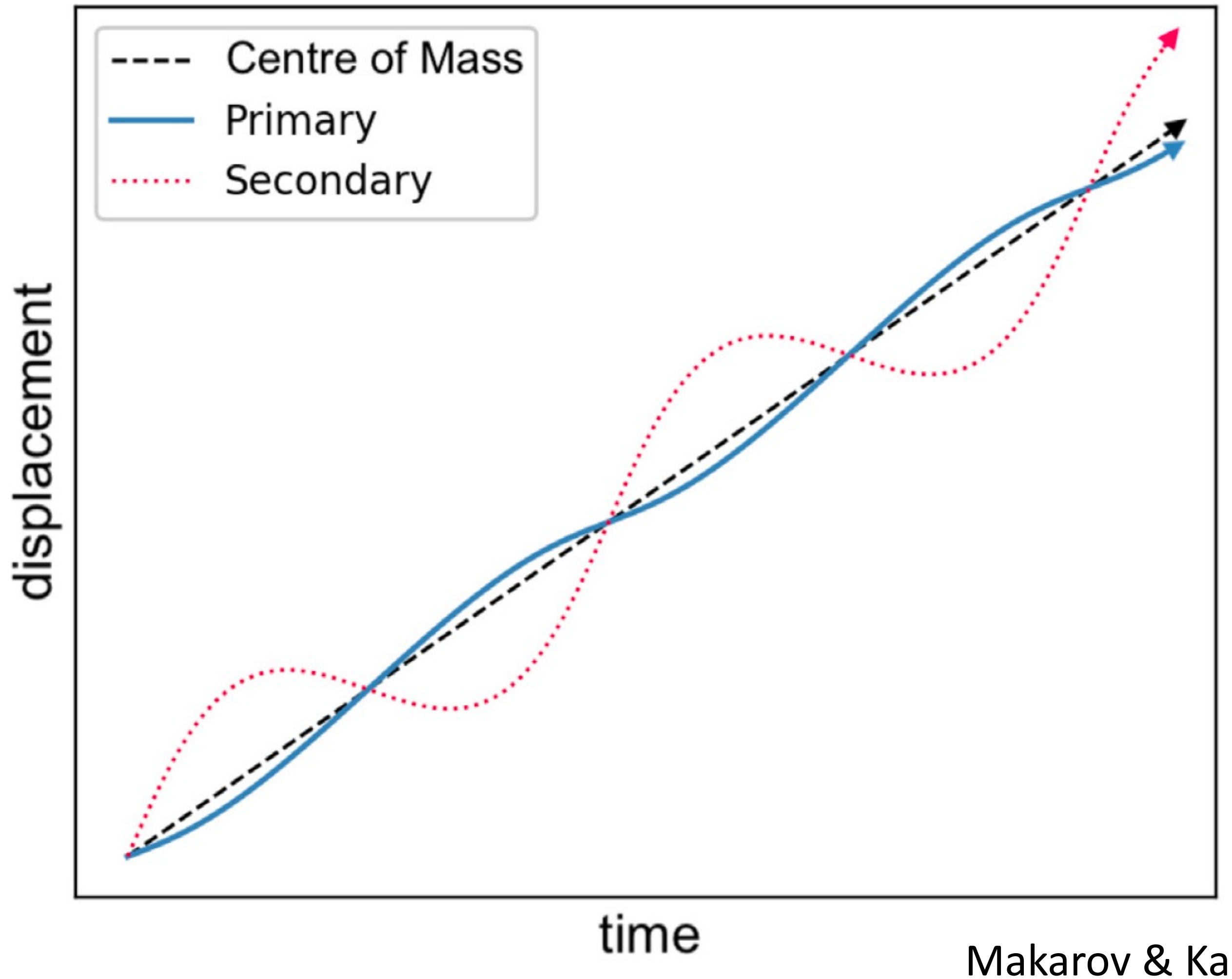
Combine with radial velocity (RV)

Radial velocity semi-amplitude:

$$K = \left(\frac{2\pi G}{P(sec)}\right)^{\frac{1}{3}} \frac{M_2 \, sin(i)}{(1-e)^2 M_{tot}^{\frac{2}{3}}}$$



Or combine with absolute astrometry

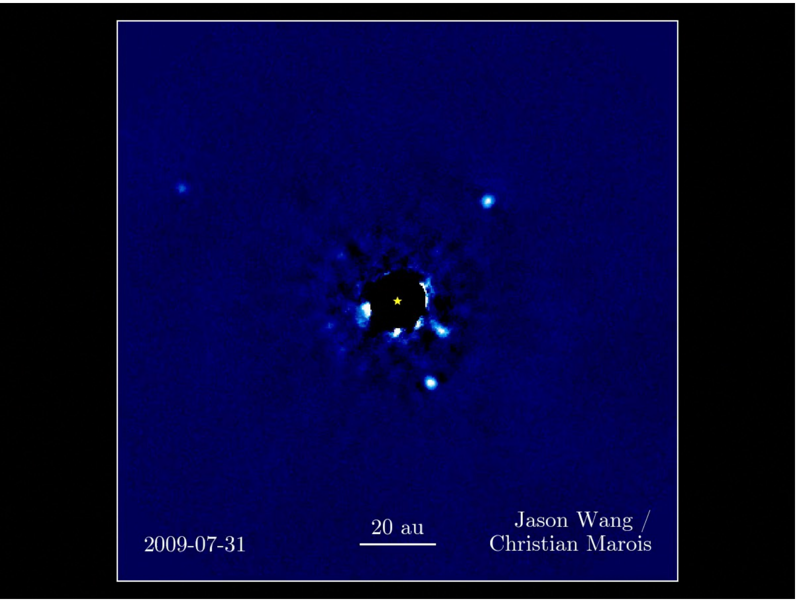


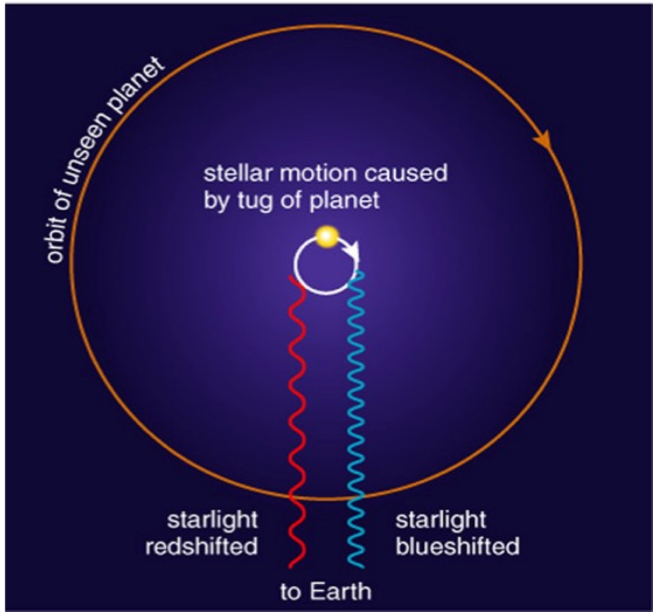
Makarov & Kaplan 2005, Fontanive et al. 2019

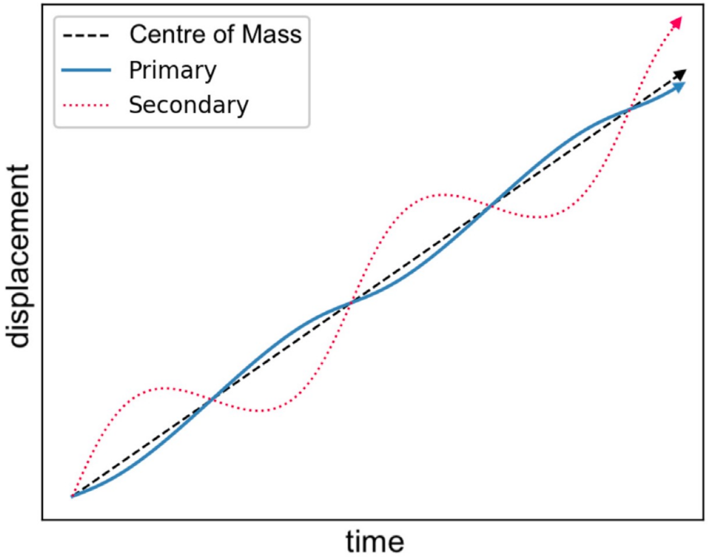
$$\Delta\mu \leq \frac{2\pi\, \varpi\, \mathcal{R}_0 M_2}{\sqrt{a\, M_{\rm tot}}}$$

$$\mathcal{R}_0 = \left(\frac{1 + e\cos E}{1 - e\cos E}\right)^{1/2}$$

A combination of techniques will yield both components' masses





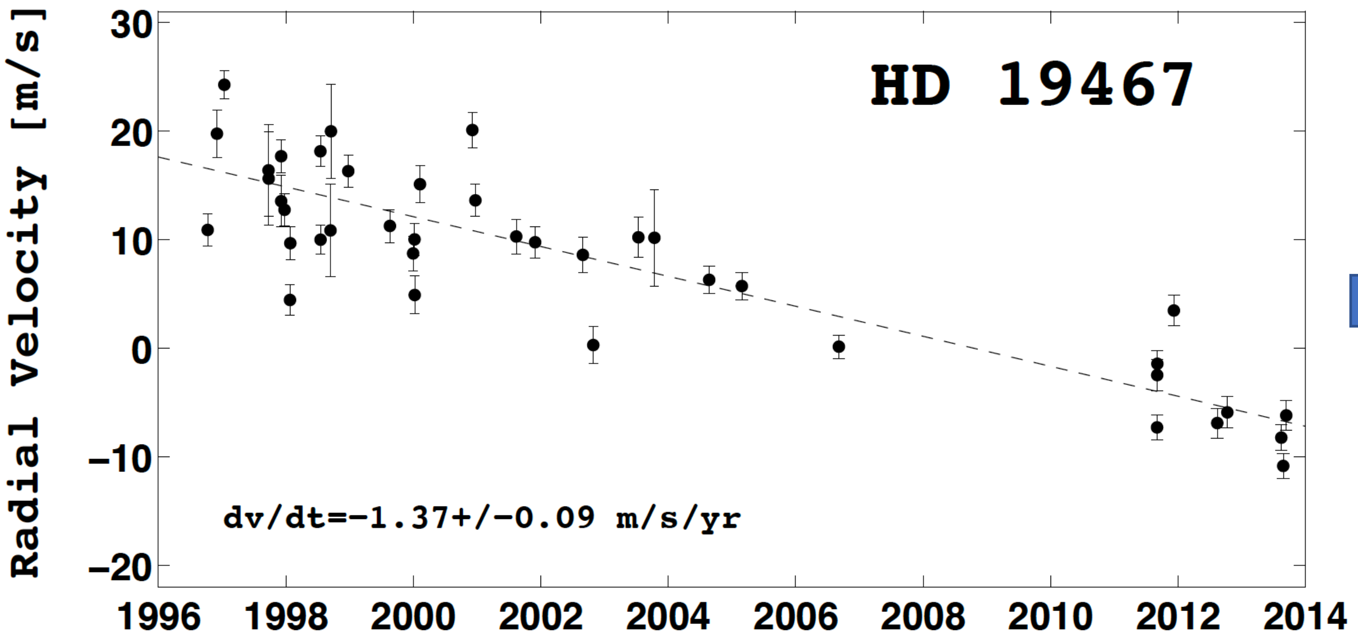


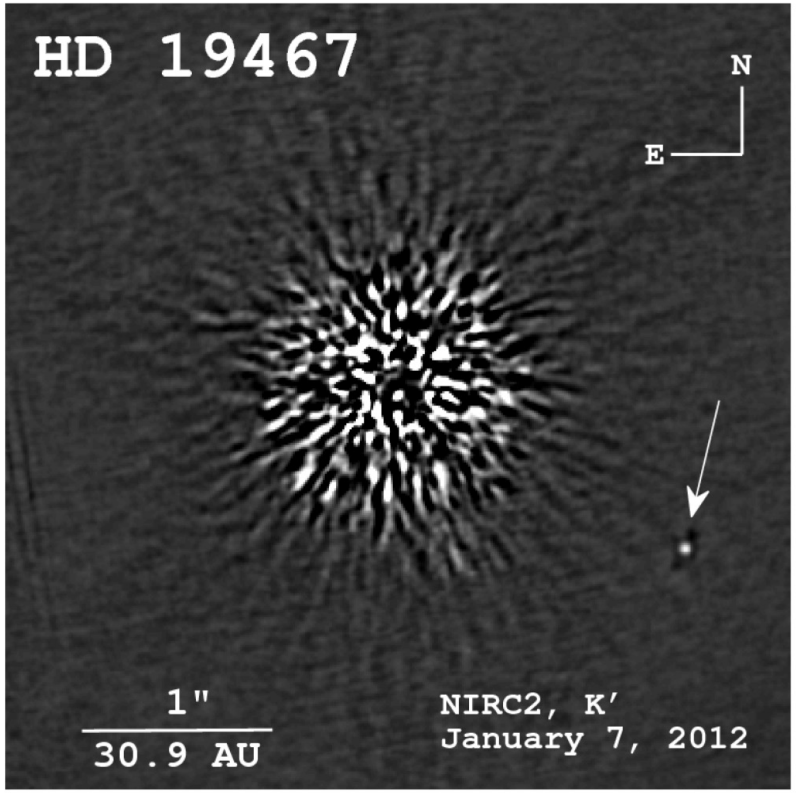
$$a = \left(P^2\, M_{tot}\right)^{1/3}$$

$$K = \left(\frac{2\pi G}{P(sec)}\right)^{\frac{1}{3}} \frac{M_2\, sin(i)}{(1-e)^2 M_{tot}^{\frac{2}{3}}}$$

$$\Delta\mu \leq \frac{2\pi\, \varpi\, \mathcal{R}_0 M_2}{\sqrt{a\, M_{\rm tot}}}$$

First detections of substellar companions from RV trends

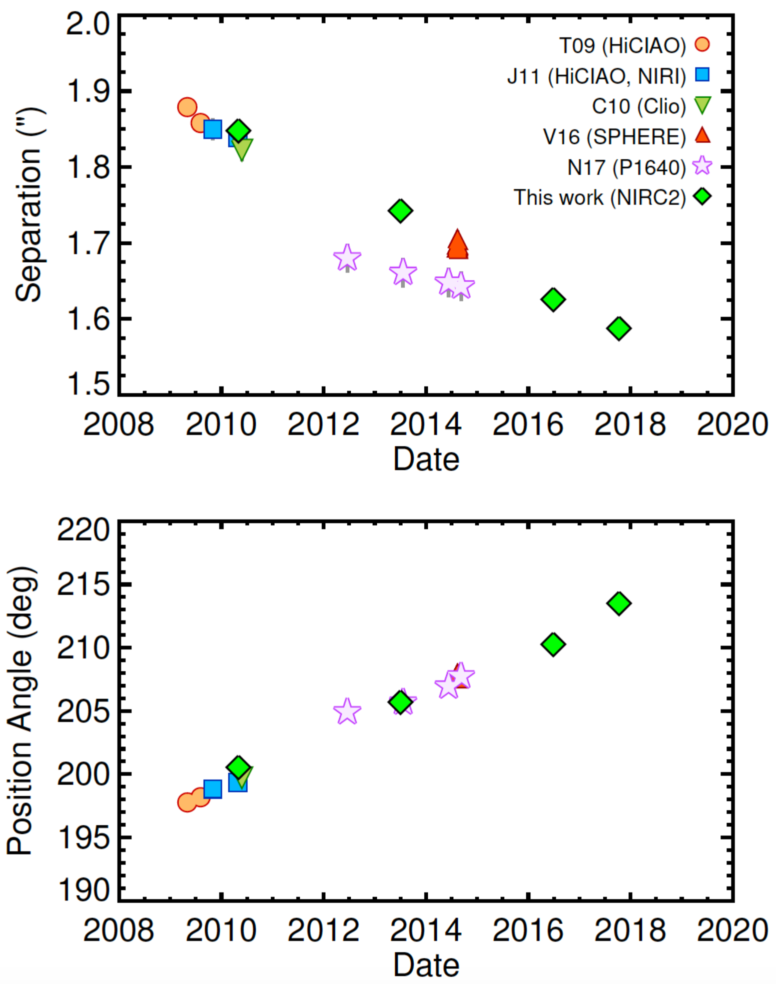




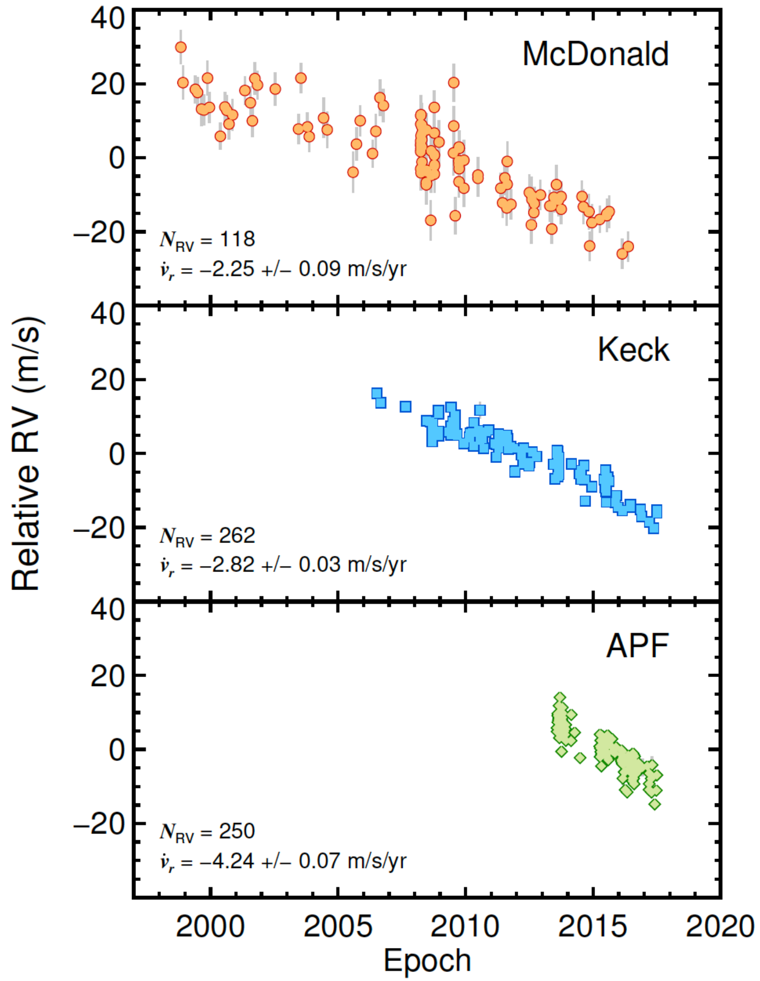
Crepp et al. 2014, see also: Liu et al. 2002, Crepp et al. 2012, 2016

Full orbit determination for brown dwarf GJ 758 B combining DI and RV

Direct Imaging Astrometry

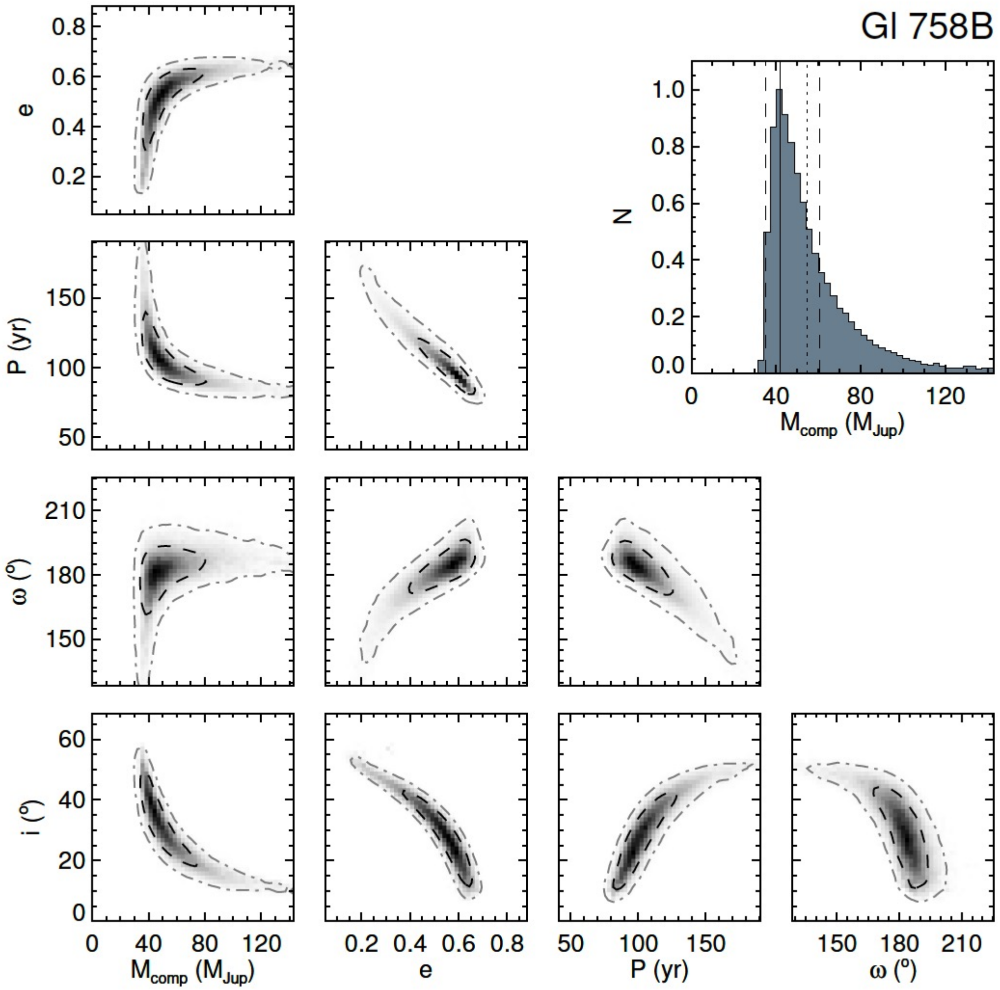


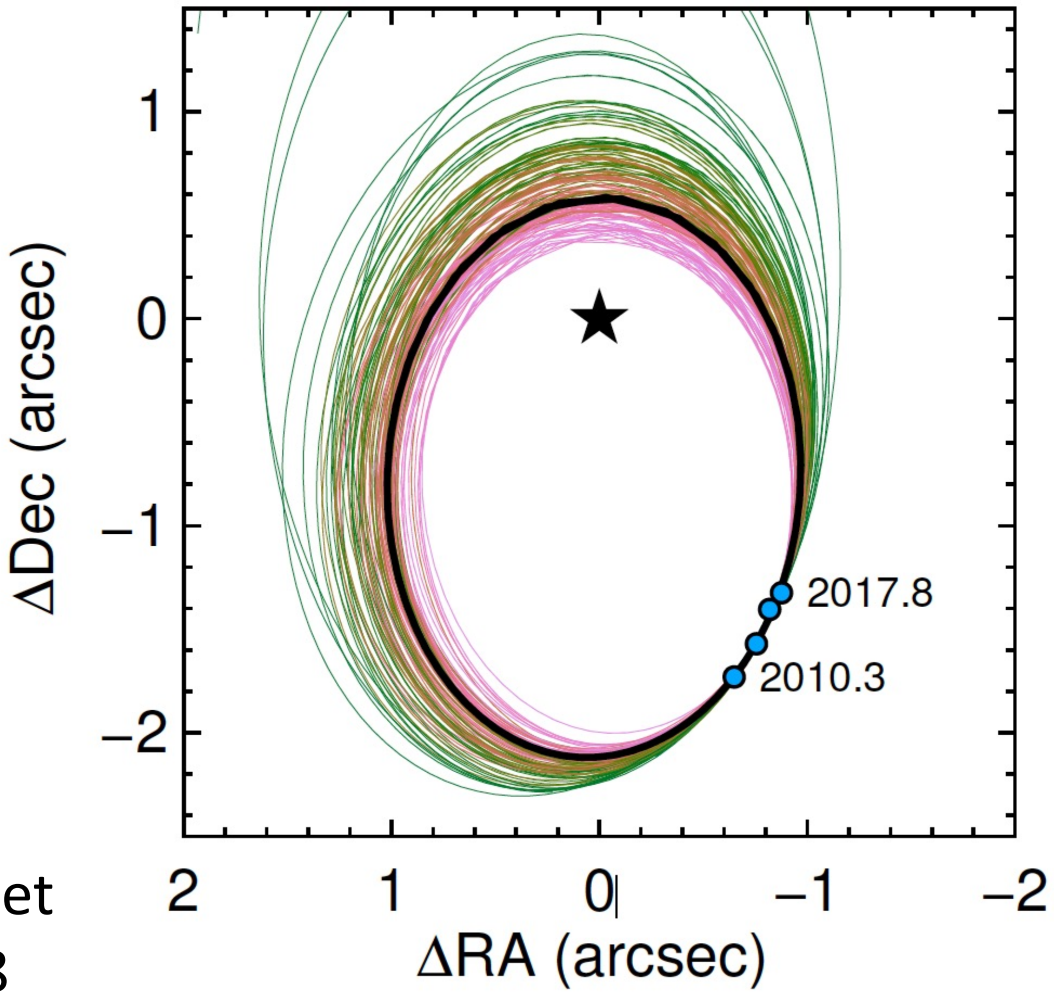
Radial Velocity



Bowler et al. 2018

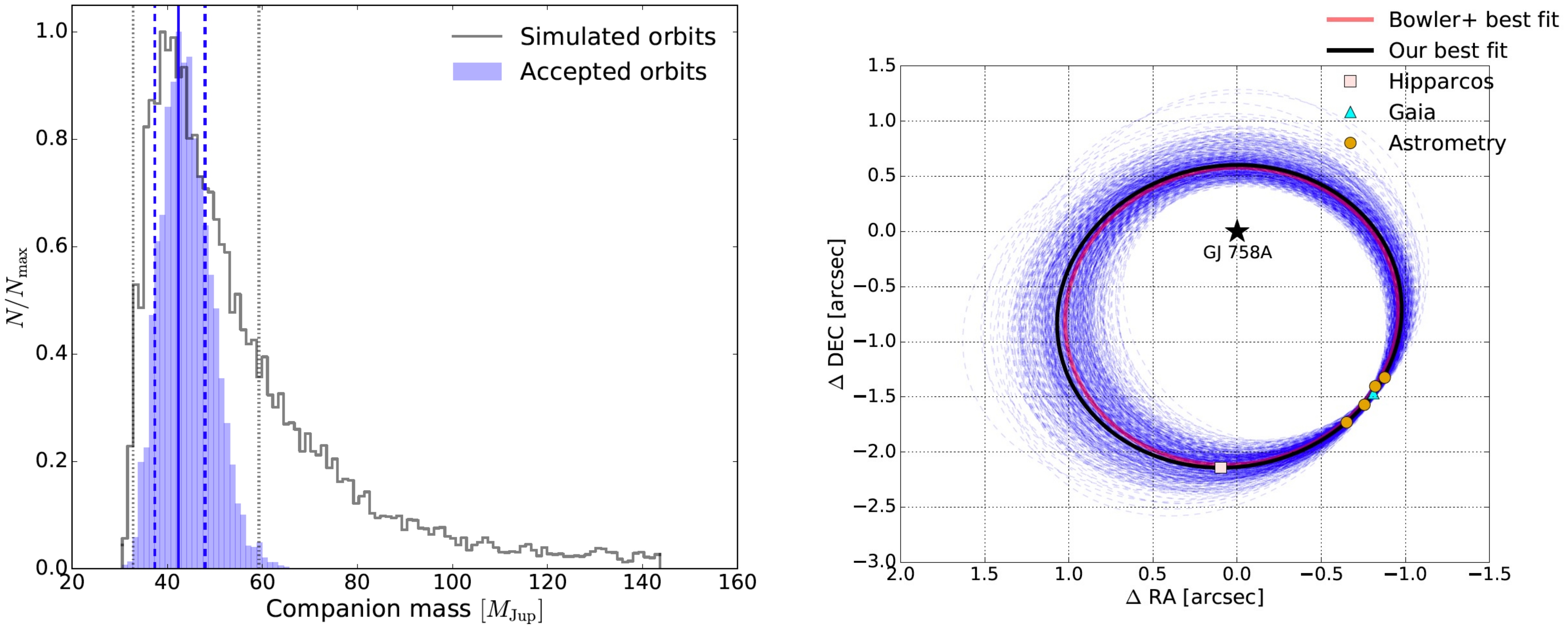
Full orbit determination for brown dwarf GJ 758 B combining DI and RV





Bowler et al. 2018

Combining with Gaia / Hipparcos astrometry further constrains the orbit



Calissendorff et al. 2018

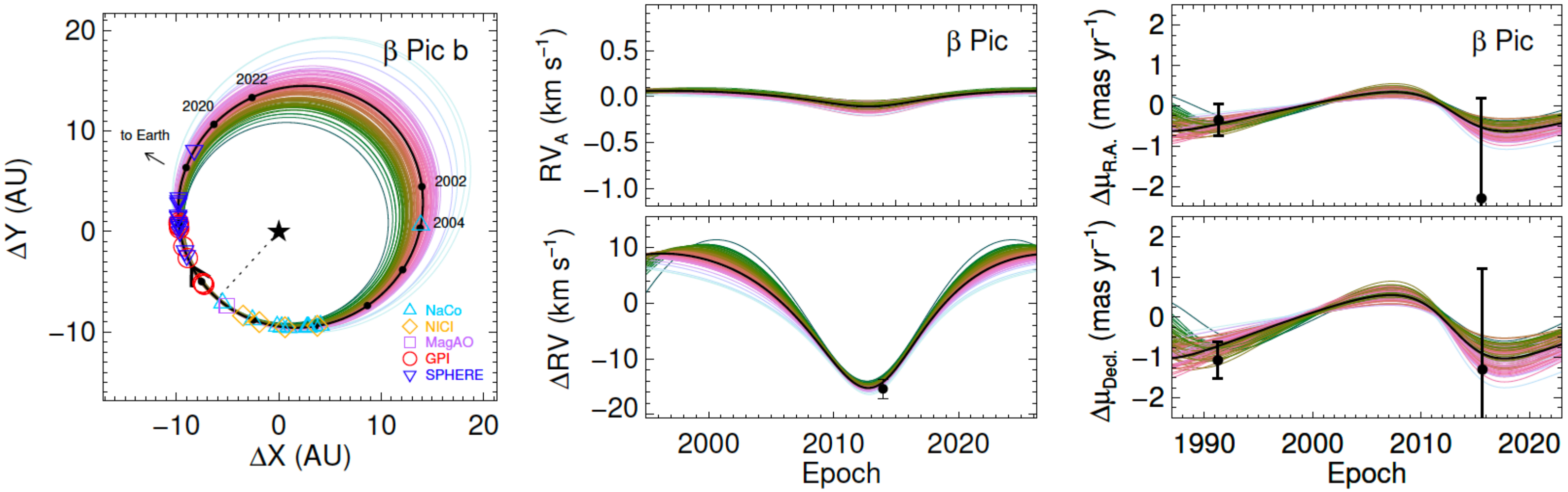
A note on what we are actually fitting here:

- Epoch-by-epoch relative astrometry is fitted
- Epoch-by-epoch RVs are fitted
- However – Gaia epoch astrometry won't be released until DR4, so absolute astrometric constraints are generally incorporated by looking up the epochs of the Hipparcos and Gaia observations, then calculating the measurement of PM that each model orbit would yield with observations at those epochs.

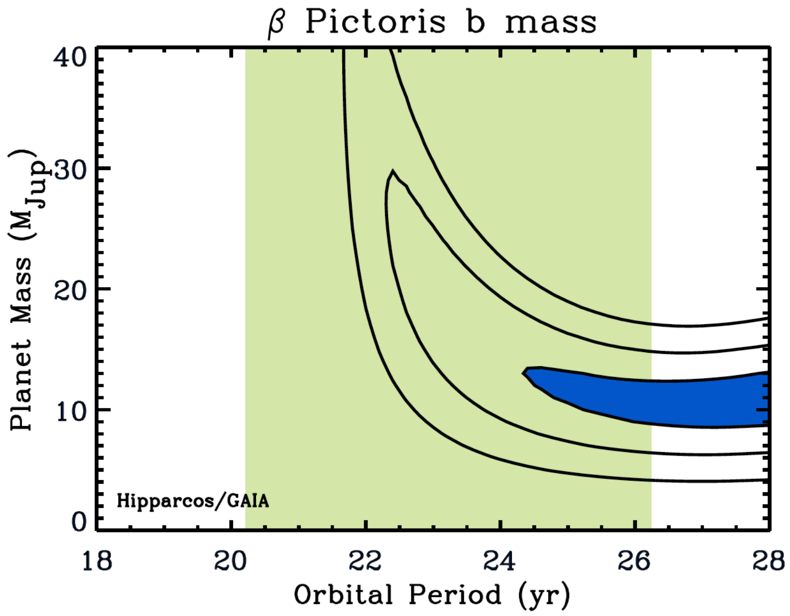
From 2018 on, we saw a bumper crop of dynamical mass determinations for exoplanets combining DI and astrometry

- β Pic b – Snellen & Brown 2018, Dupuy et al. 2019, G.M. Brandt et al. 2021a
- β Pic c – G.M. Brandt et al. 2021a
- HR 8799e – G.M. Brandt et al. 2021b
- 51 Eri b – Dupuy et al. 2022

β Pic b

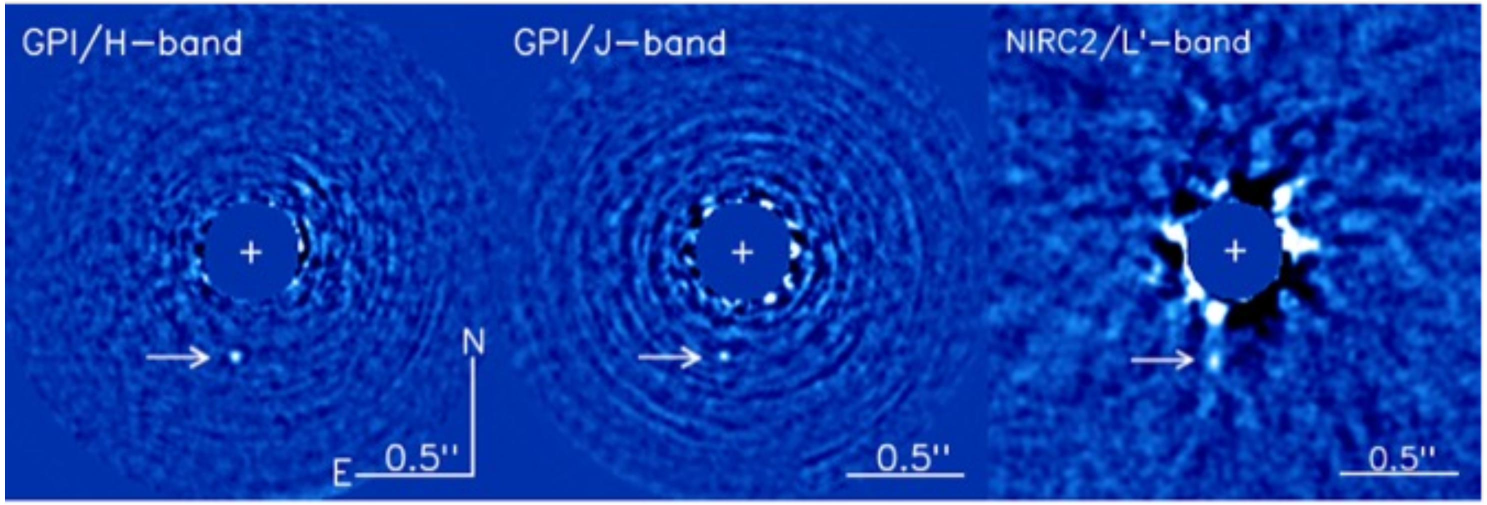


Dupuy et al. 2019

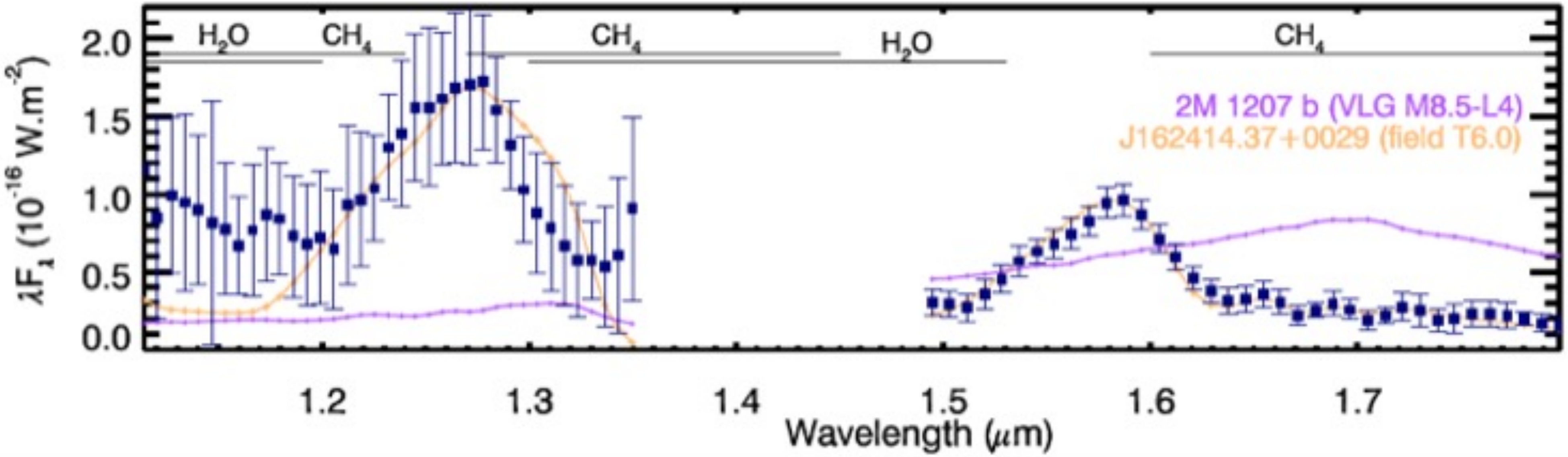


Snellen & Brown 2018

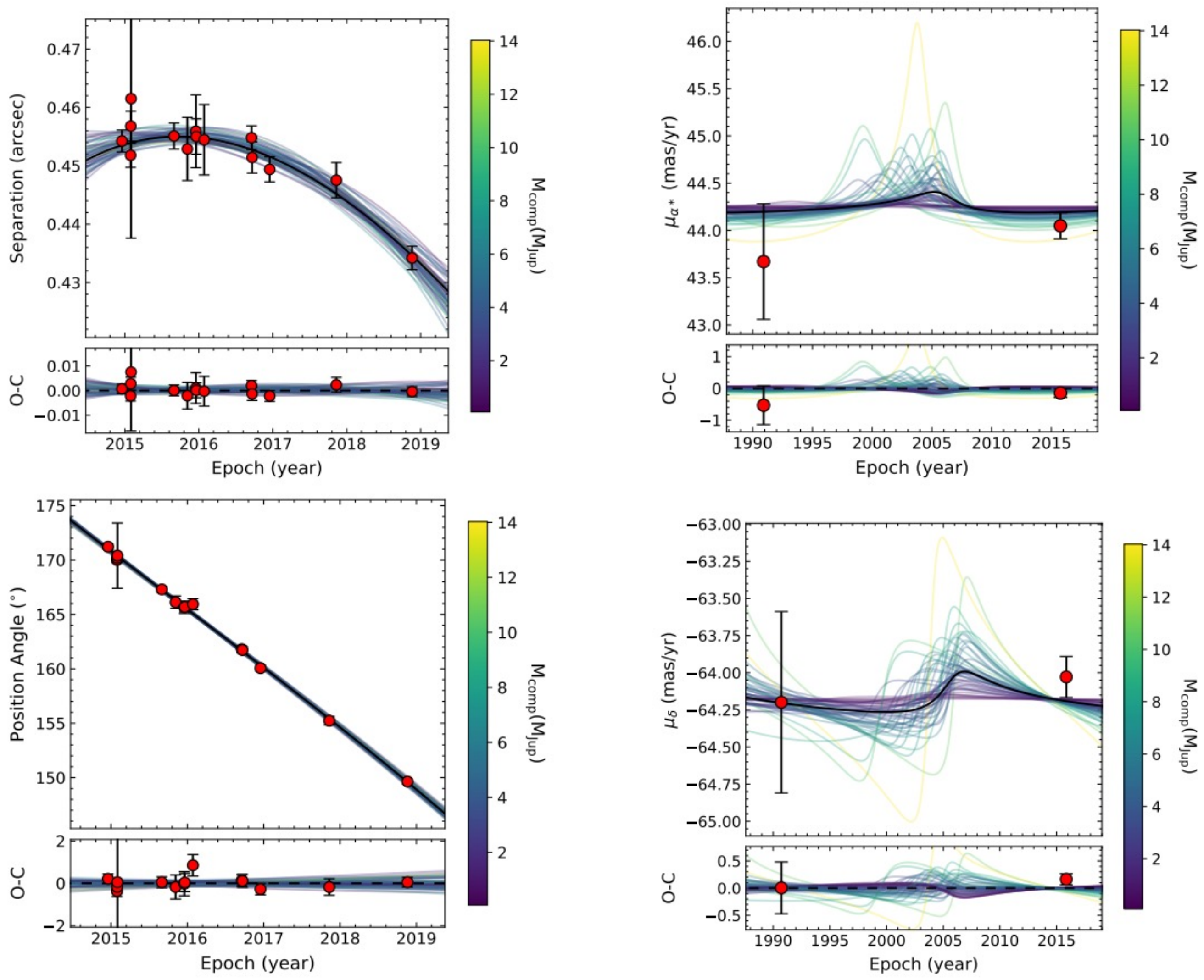
51 Eri b – one of the coldest exoplanets imaged to date

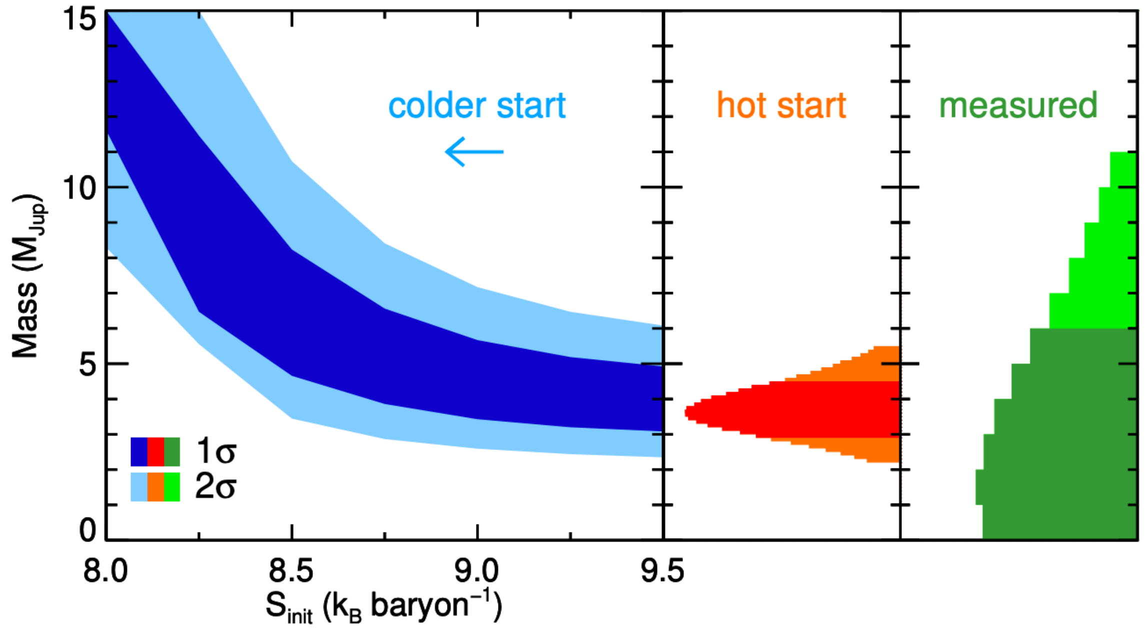


Macintosh et al. 2015



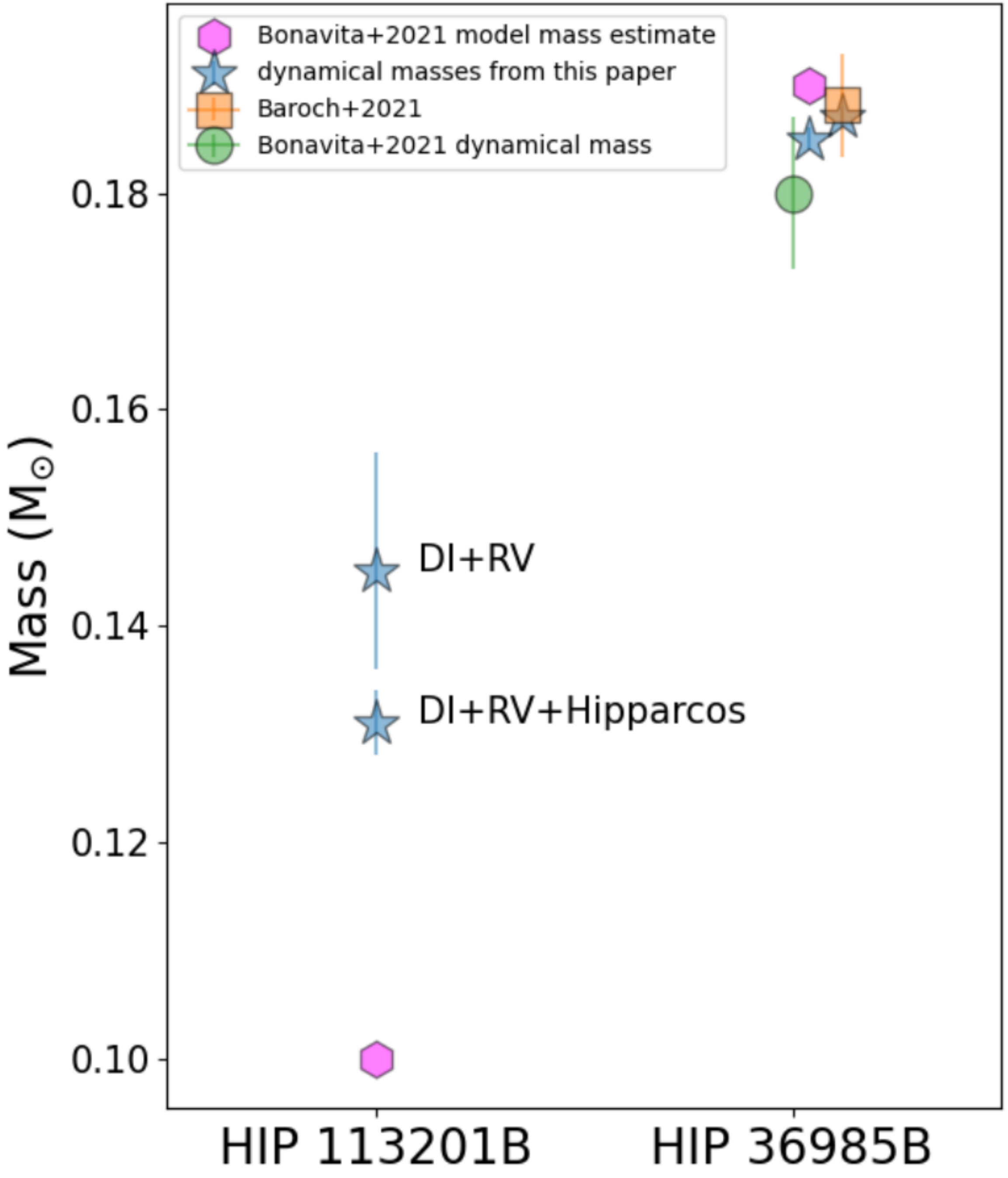
51 Eri b – the dynamical mass sets constraints on formation mechanism





Dupuy et al. 2022

What if there are additional companions in the system?



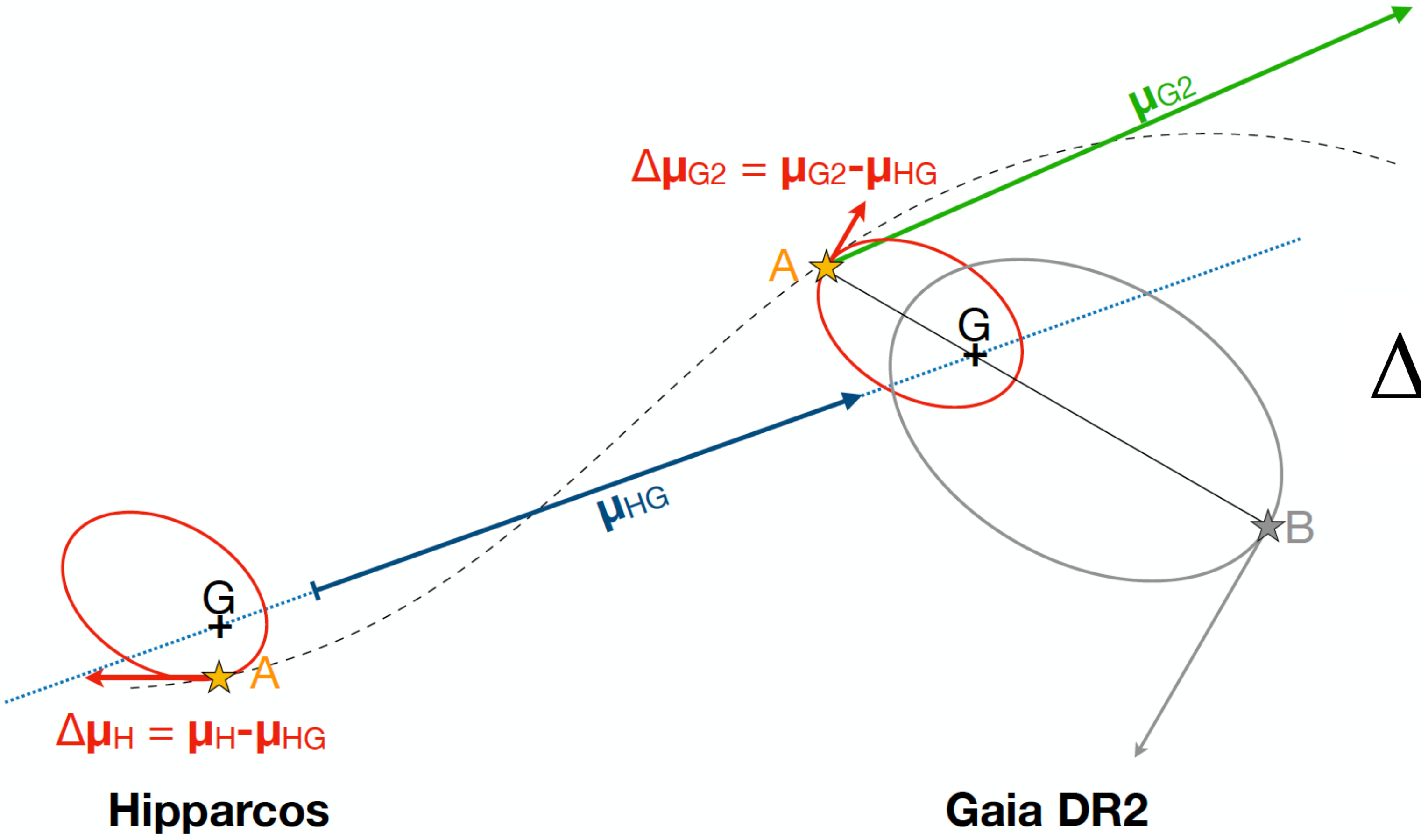
Biller et al. 2022

Can astrometry tell us where to look for directly imaged exoplanets?

Multiple approaches to this problem:

- Proper-motion anomaly – Kervella et al. 2019
- The $\Delta\mu$ method – Fontanive et al. 2019, Bonavita et al. 2020, 2022
- Instantaneous accelerations – Brandt et al. 2018, 2019, 2021

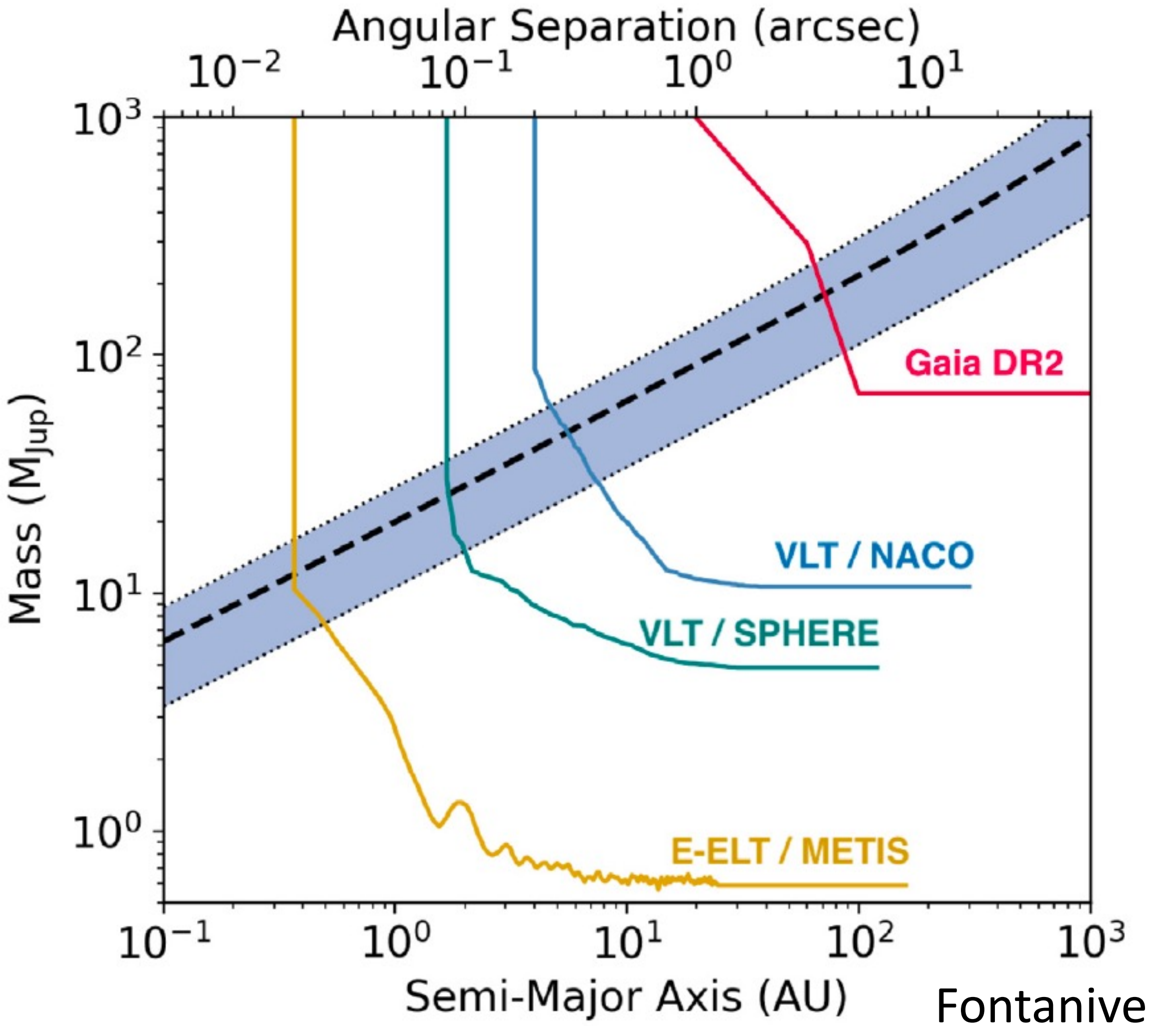
The Proper Motion Anomaly Method



$$\Delta\mu_{\mathrm{H/G2}} = \mu_{\mathrm{H/G2}} - \mu_{\mathrm{HG}}$$

Kervella et al. 2019

The COPAINS Δμ method



Fontanive et al. 2019

$$\Delta\mu \leq \frac{2\pi\, \varpi\, \mathcal{R}_0 M_2}{\sqrt{a\, M_{\rm tot}}}$$

$$\mathcal{R}_0 = \left(\frac{1 + e\cos E}{1 - e\cos E}\right)^{1/2}$$

Makarov & Kaplan 2005

Instantaneous Accelerations by combining RV + Hipparcos/Gaia

$$a_{\alpha\delta} = \frac{GM_{\rm B}}{r_{\rm AB}^2} \cos\phi,$$

$$a_{\rm RV} = \frac{GM_{\rm B}}{r_{\rm AB}^2} \sin\phi, \quad \text{and}$$

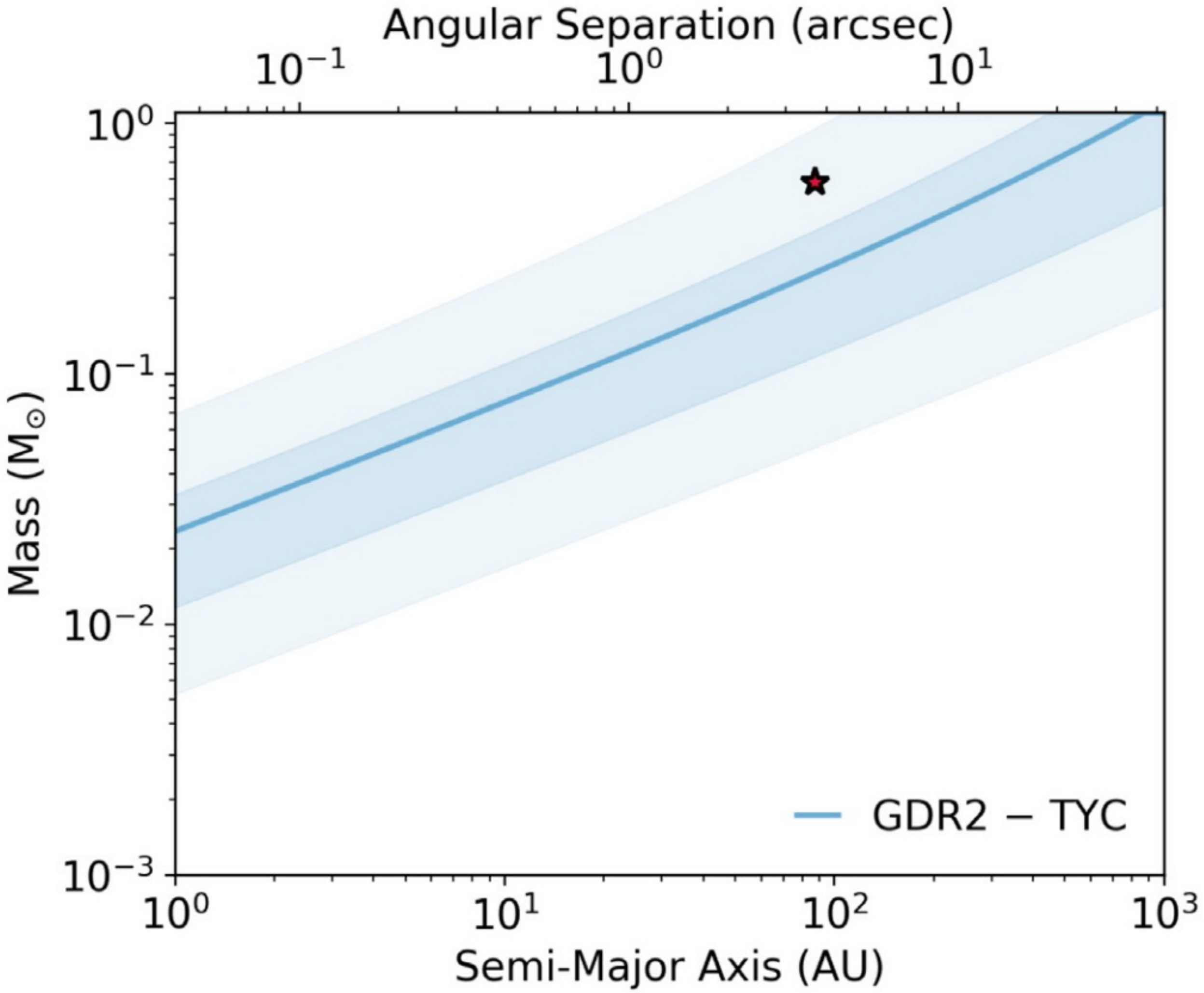
$$\rho = r_{\rm AB} \varpi \cos\phi,$$

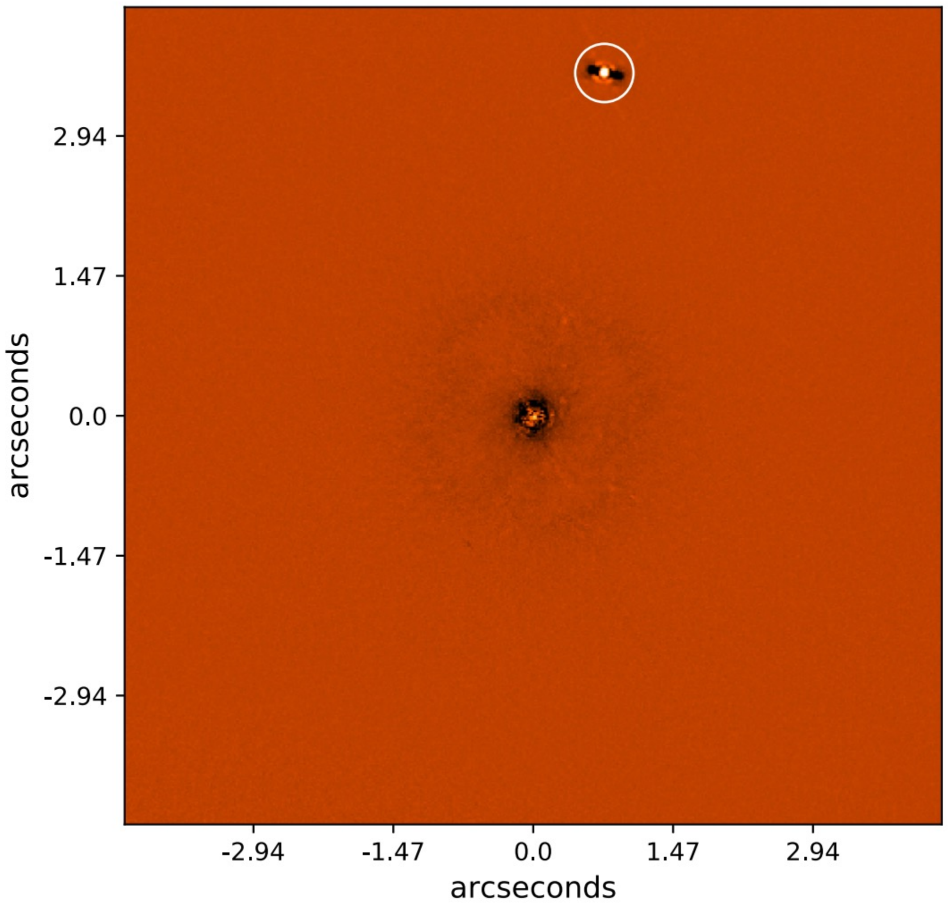
=

$$M_B = \frac{\rho^2 (a_{\alpha\delta}^2 + a_{\rm RV}^2)^{3/2}}{\varpi^2 G a_{\alpha\delta}^2}$$

Brandt et al. 2019

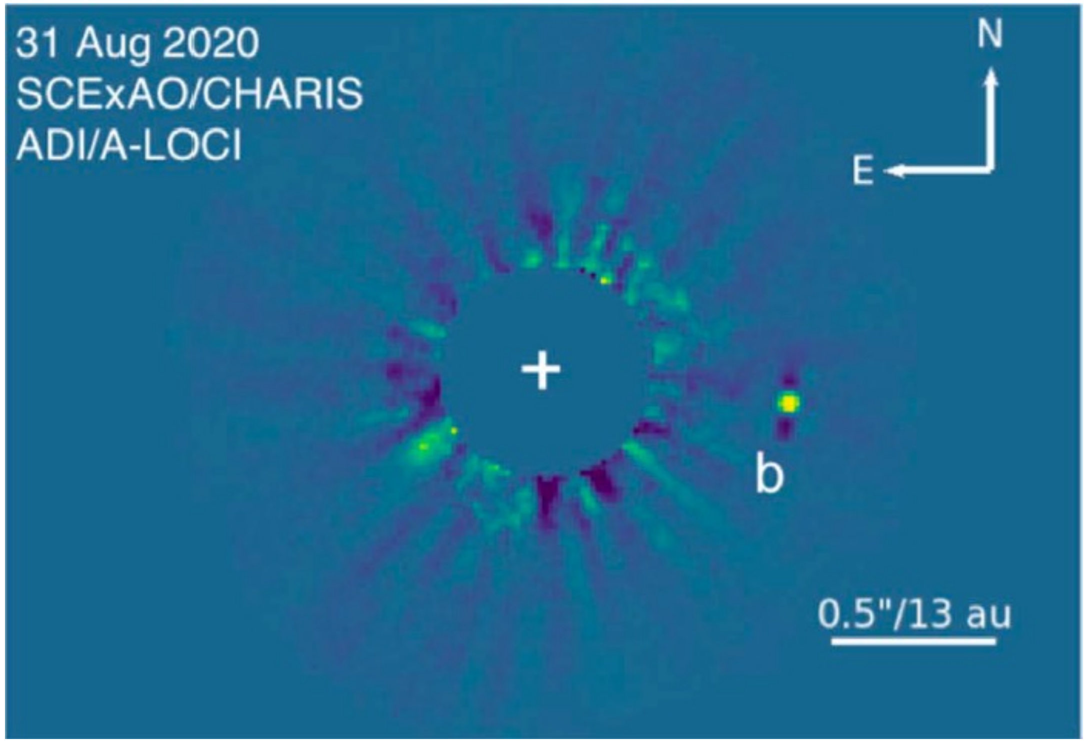
First direct imaging companion detections with these methods – a white dwarf companion to GJ 4436



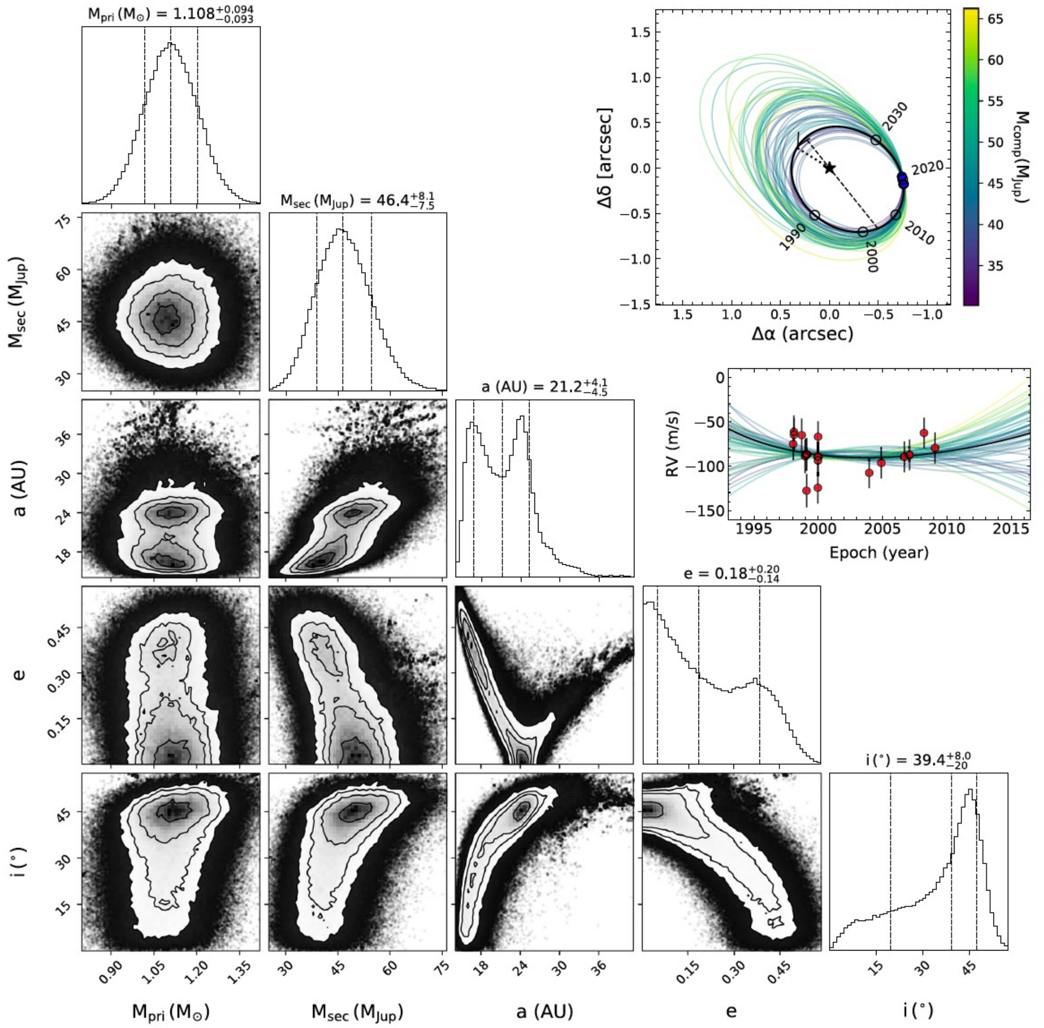


Bonavita et al. 2020

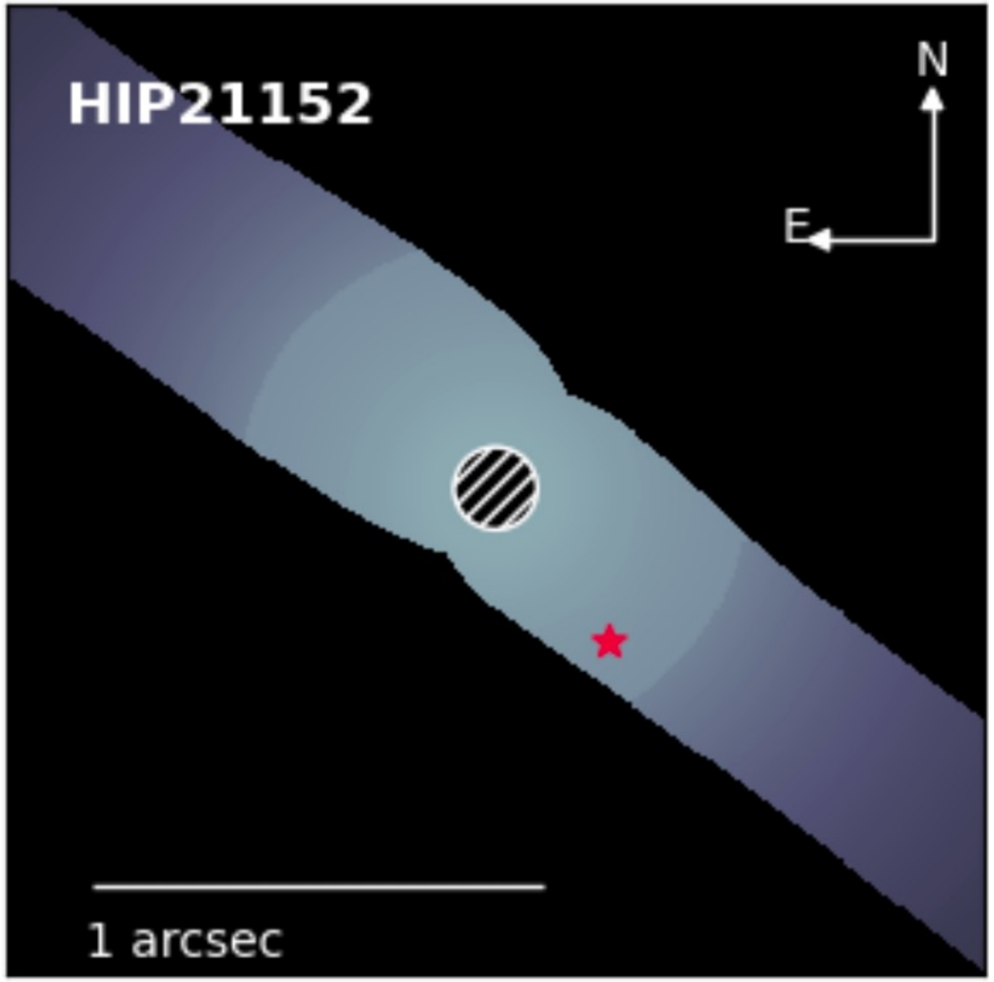
First direct imaging companion detections with these methods – a brown dwarf companion to a sun-like star



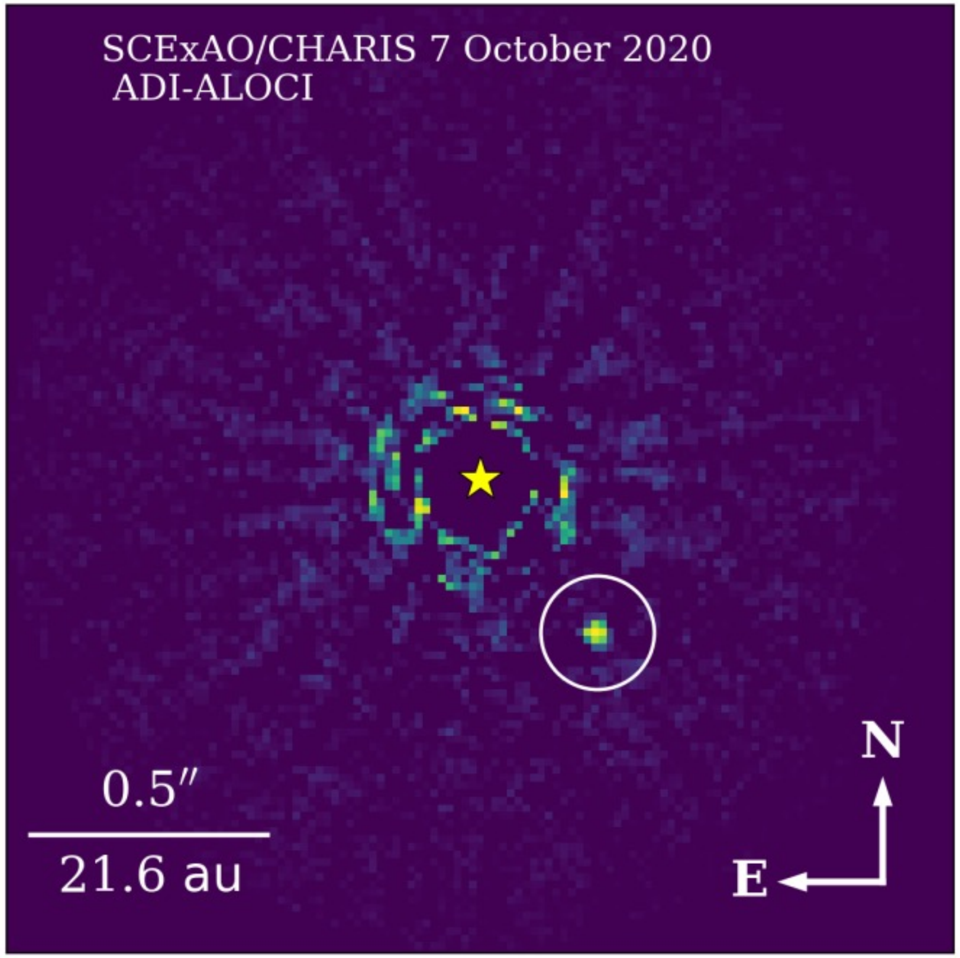
Currie et al. 2020



Pushing down to lower masses – a 20-30 M_{Jup} brown dwarf companion in the Hyades

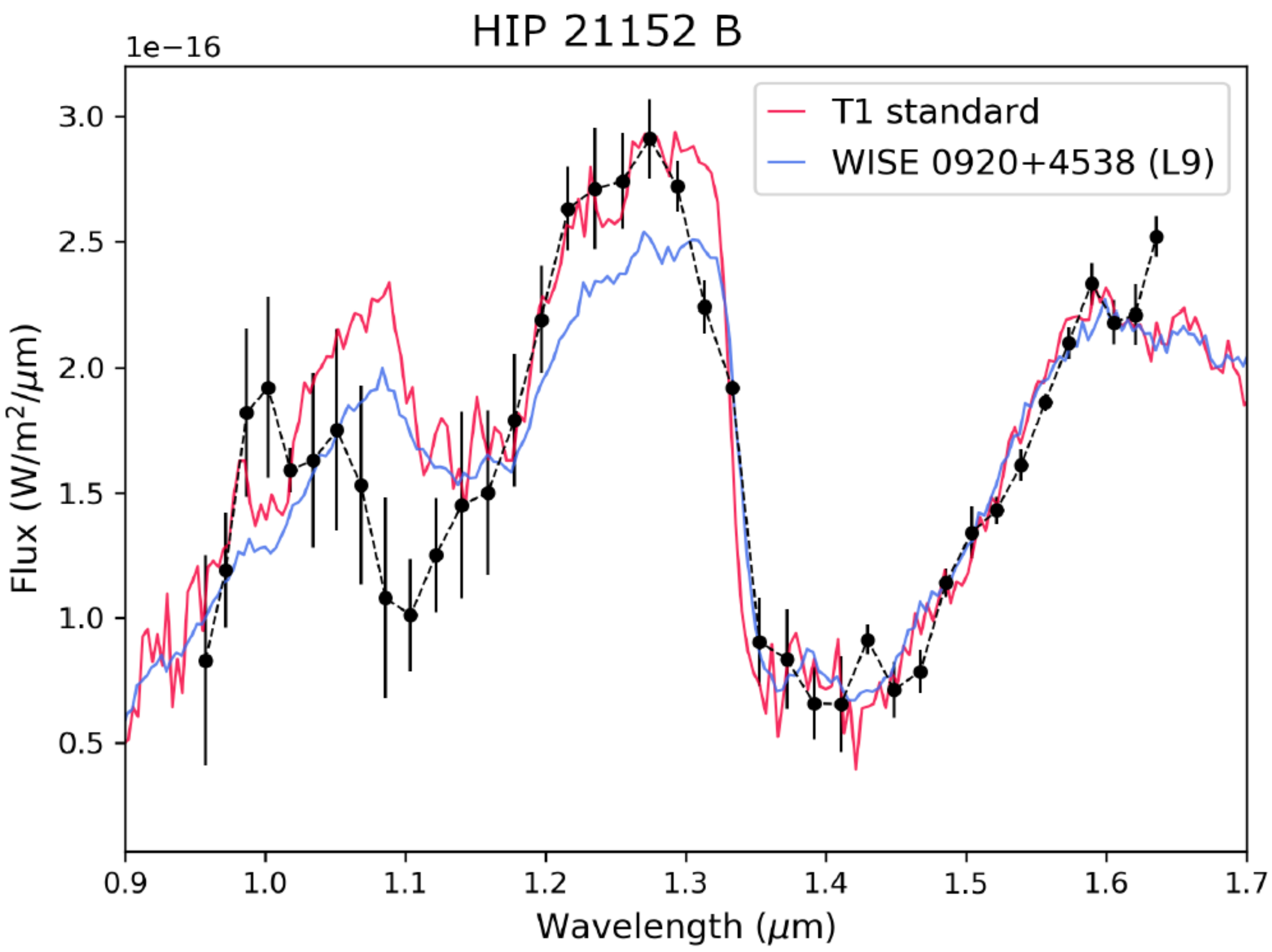


Bonavita et al. 2022

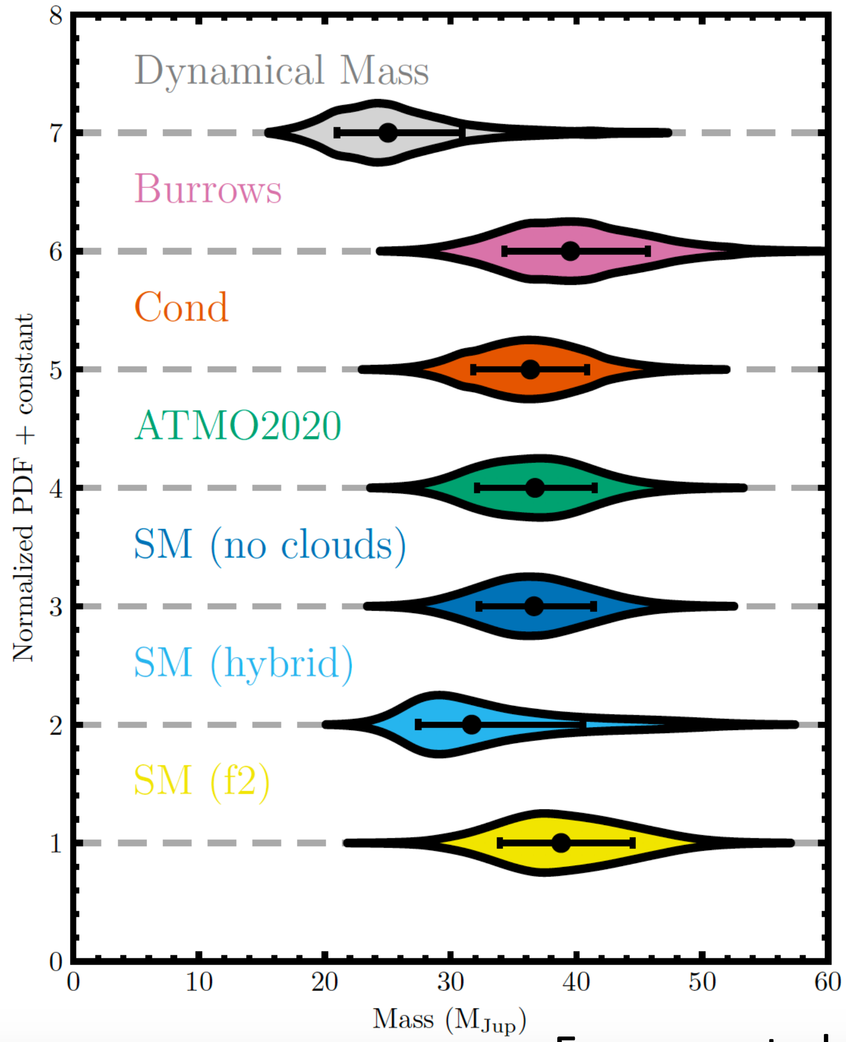


Kuzuhara et al. 2022

Pushing down to lower masses – a 20-30 M_{Jup} brown dwarf companion in the Hyades

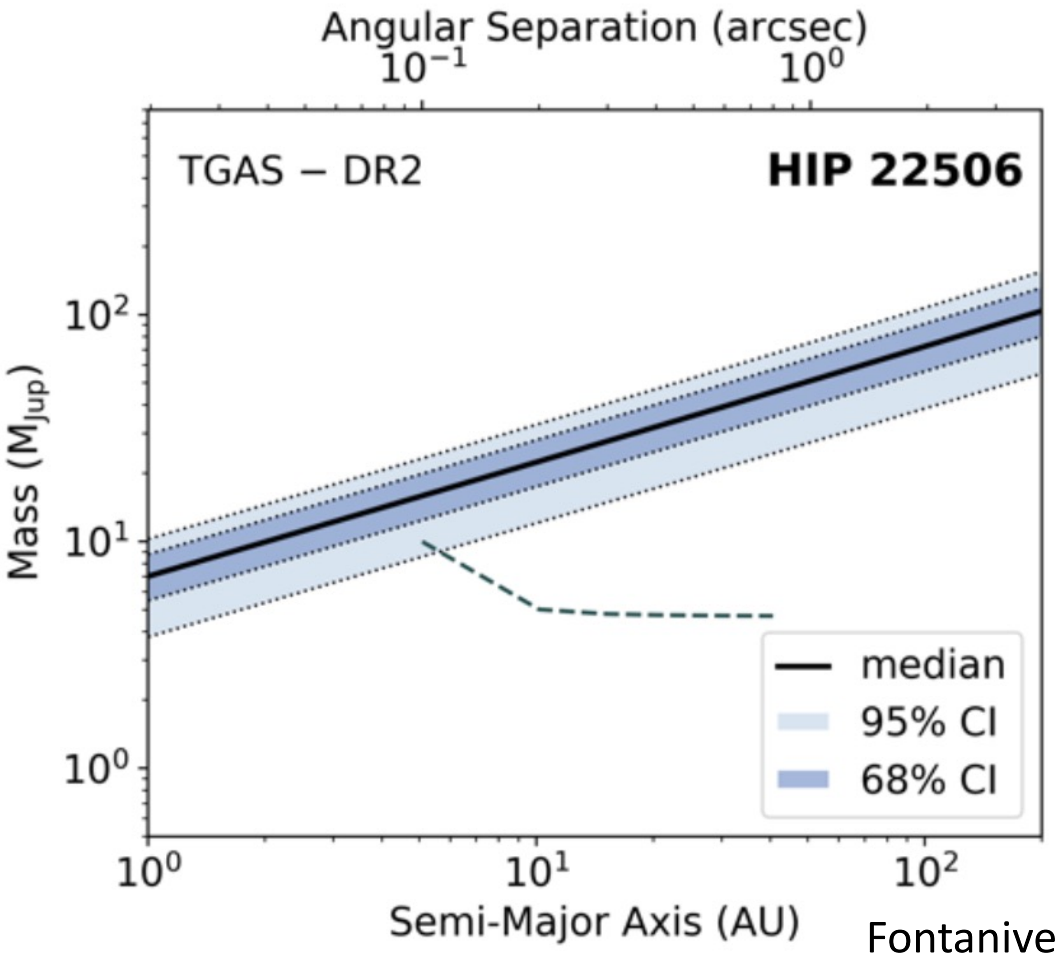


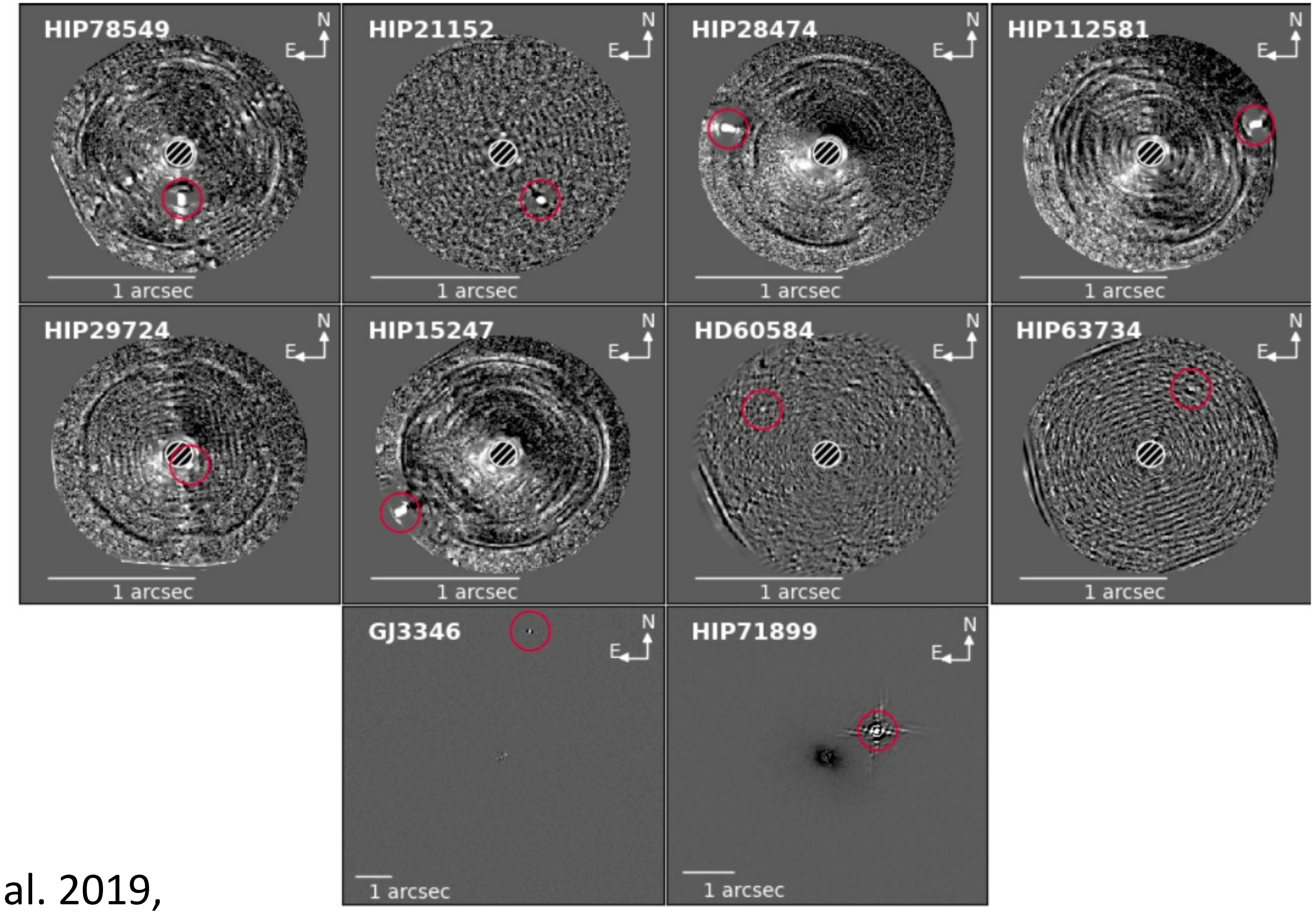
Bonavita et al. 2022



Franson et al. in prep

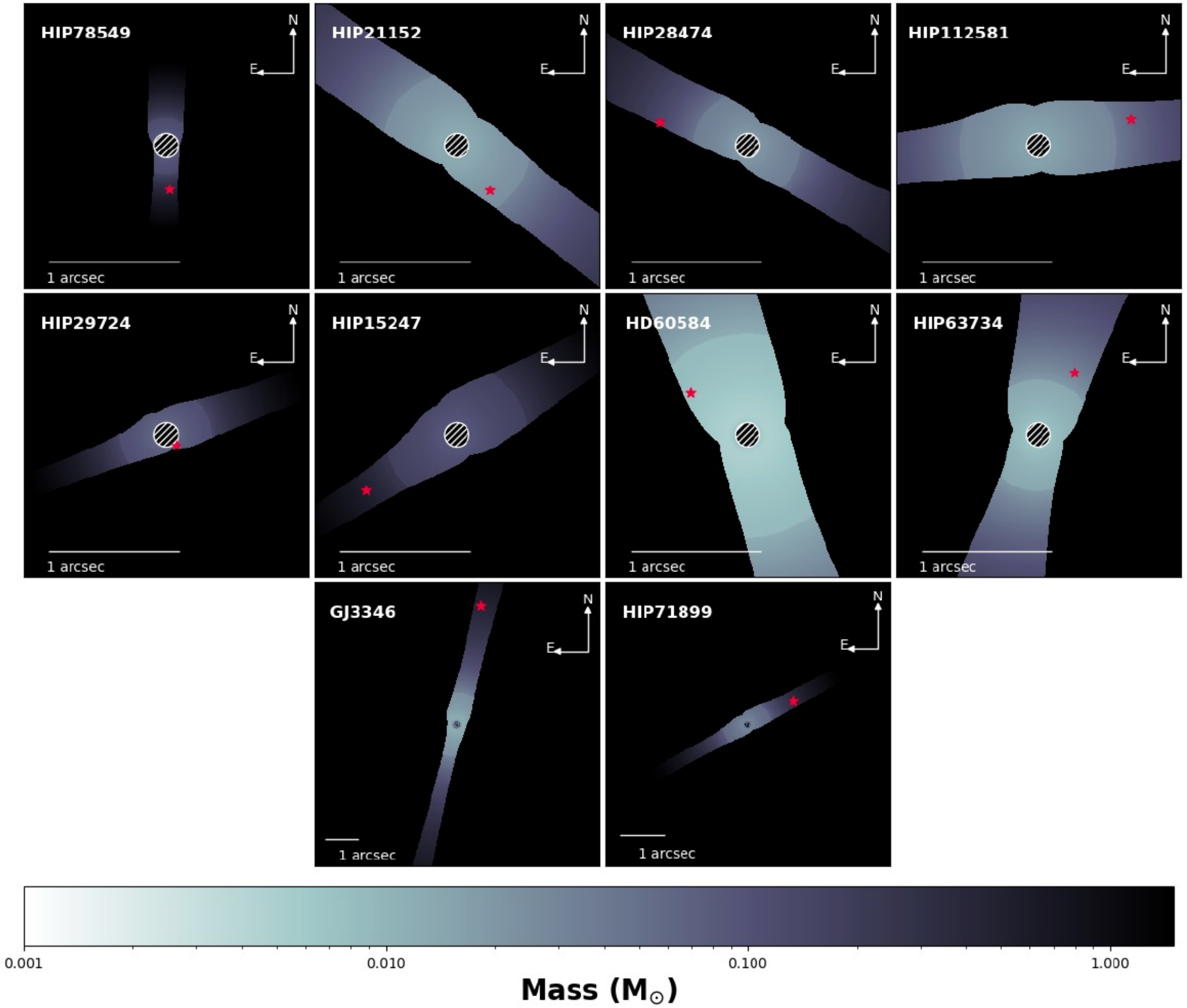
The COPAINS survey –
Δμ selected survey yields 4 new brown dwarf companions

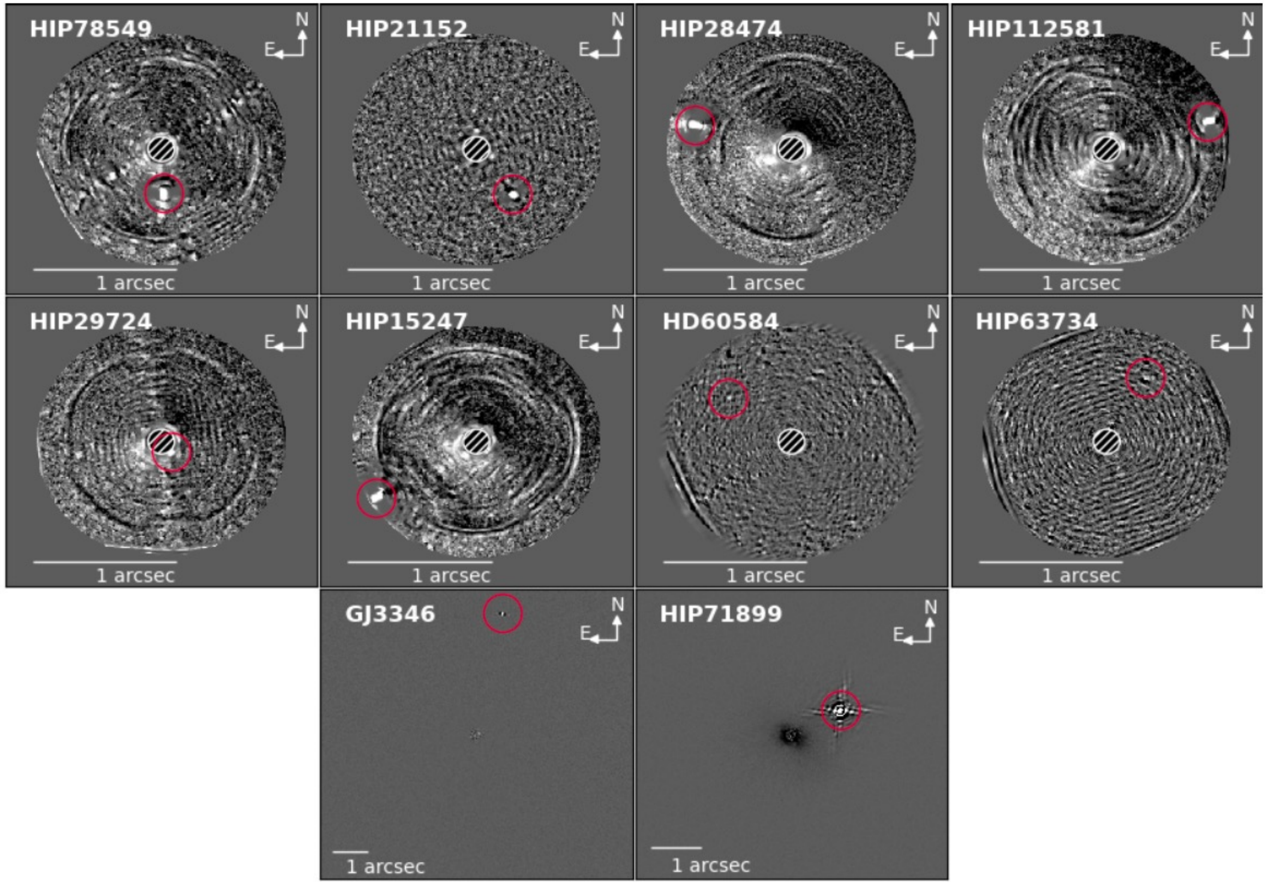




Fontanive et al. 2019,
Bonavita et al. 2022

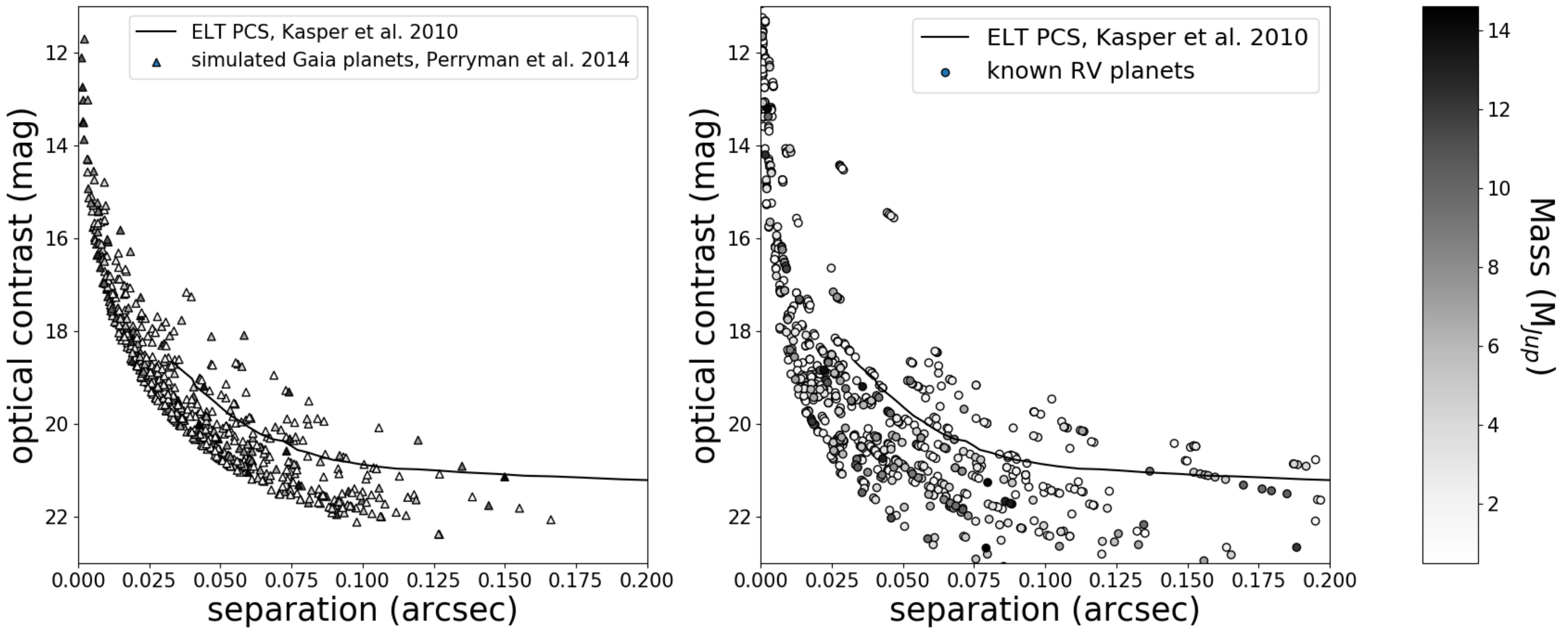
The FORECAST tool: http://maps.exoplanetsforecast.com





Bonavita et al. 2022

Can we image the thousands of new planets expected in Gaia DR4?



Currie, Biller et al. 2022, PPVII review

Conclusions

Dynamical masses are vital to fully characterize exoplanets

Direct imaging only measures relative astrometry – must combine with another technique to get individual masses

DI + Hipparcos/Gaia (+ often RV too) have yielded dynamical masses for several exoplanets and brown dwarfs

Hipparcos/Gaia measurements can also pinpoint hidden planets / brown dwarfs – first direct imaging detections with this technique in the last few years