exoplanets *in* stellar multiples

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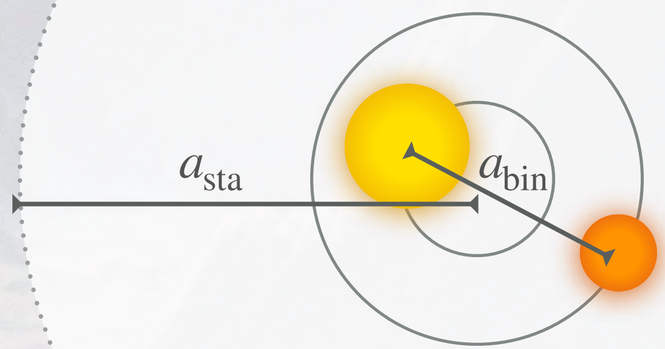
Circumbinary planets
p-type

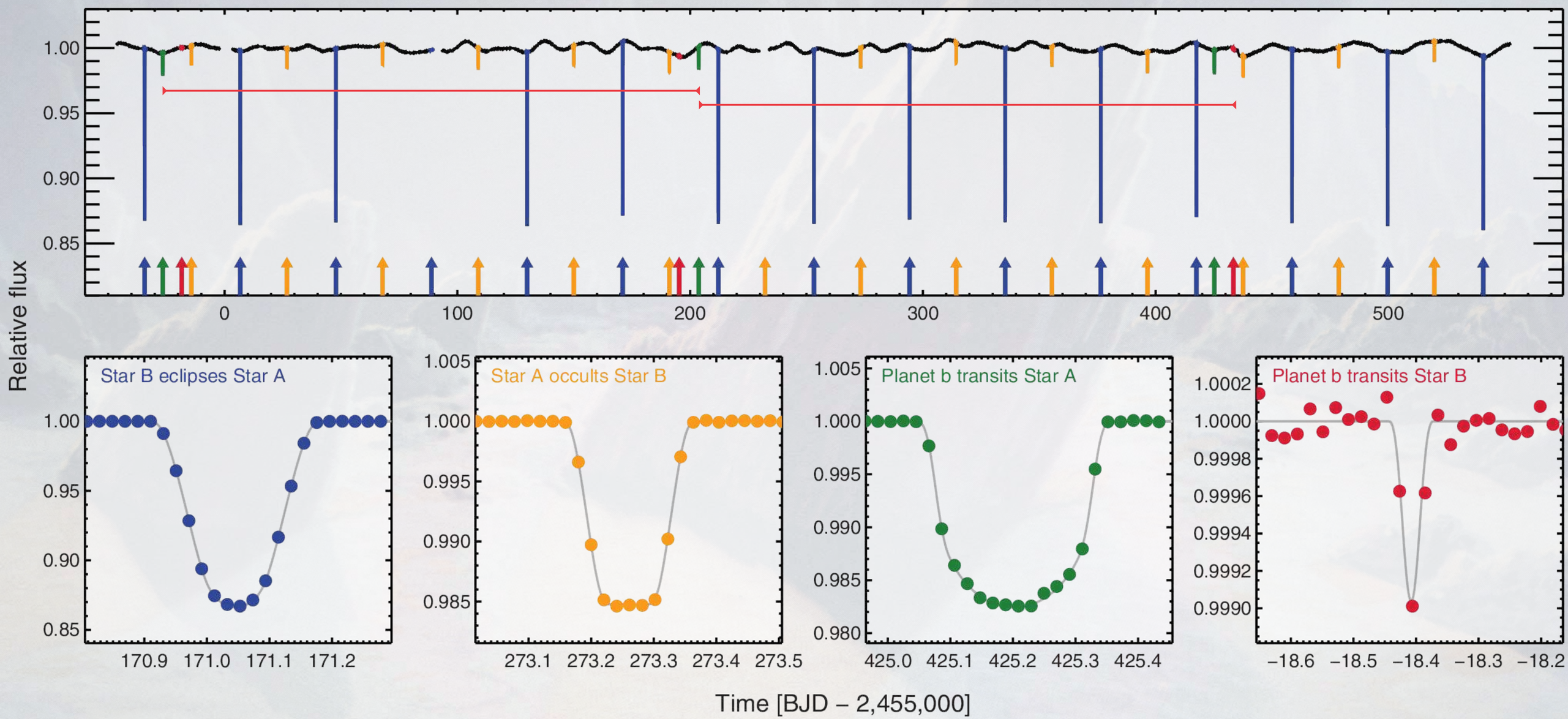


$$a_{\rm sta} > 2.7 a_{\rm bin}$$
$$P_{\rm sta} > 5 P_{\rm bin}$$

Georgakarakos+ 2024

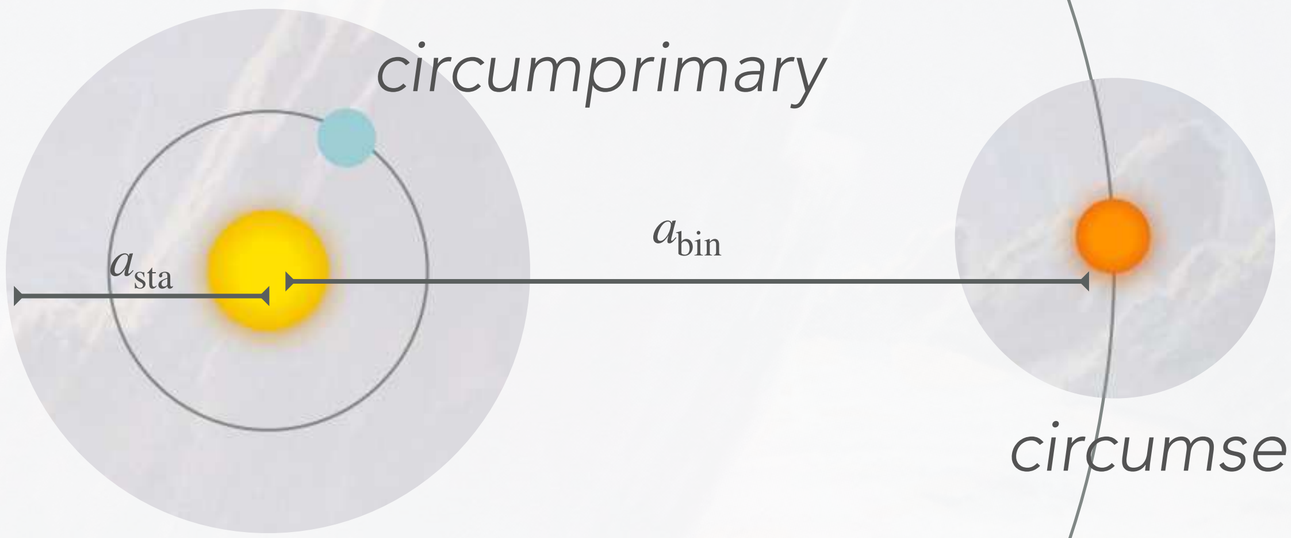
Dvorak 1986,89, Holman & Wiegert 1999

Kepler-16 AB b



Doyle et al., 2011

Circumstellar planets
s-type



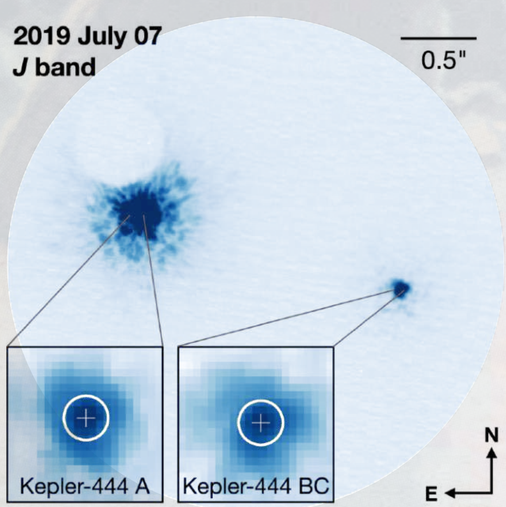
$$a_{\mathrm{sta}} < 3a_{\mathrm{bin}}$$
$$P_{\mathrm{sta}} < 5P_{\mathrm{bin}}$$

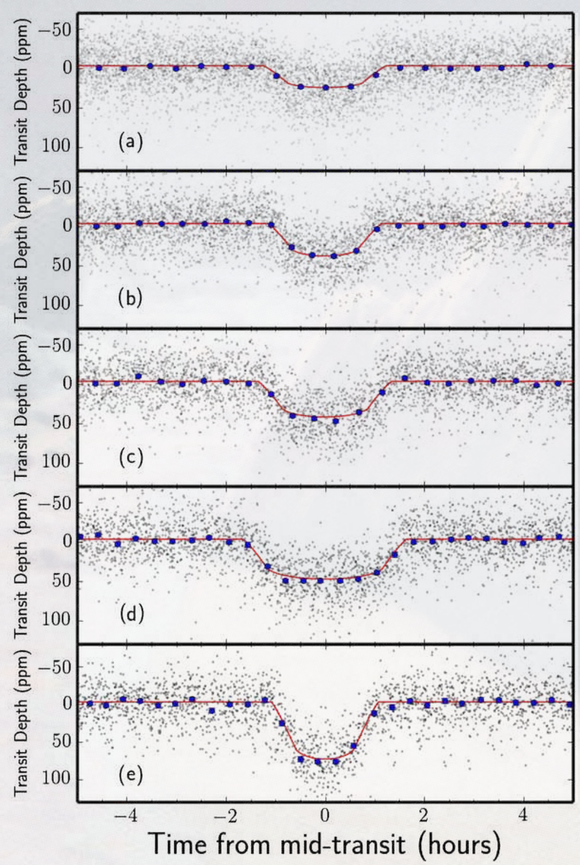
Dvorak 1986,89, Holman & Wiegert 1999

Kepler-444A bcdef

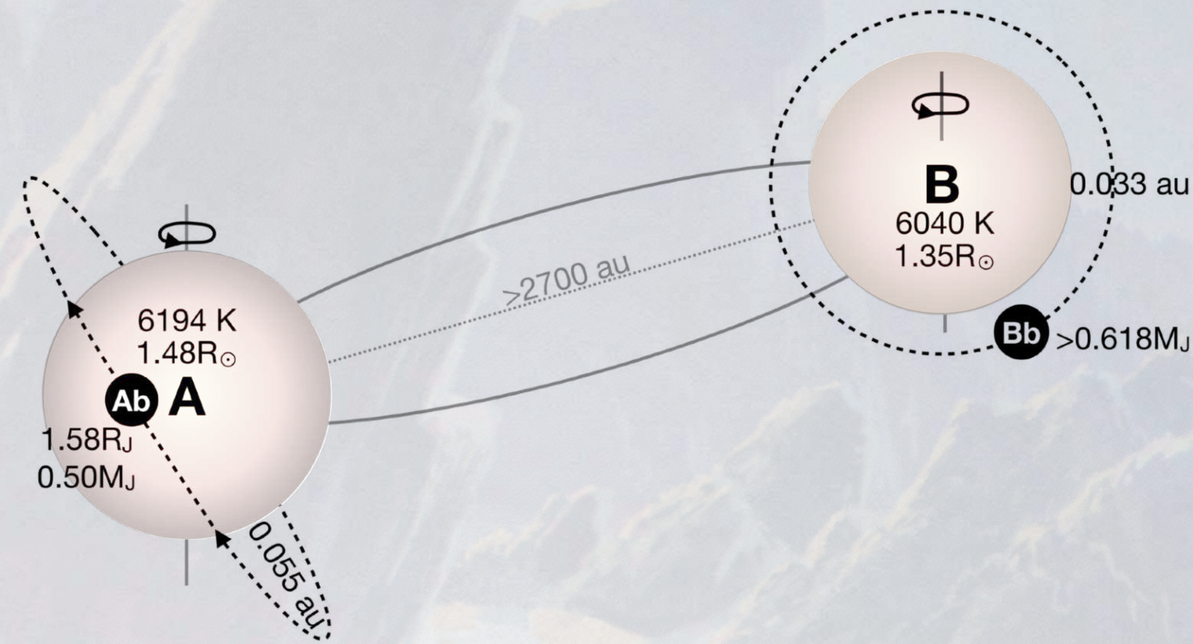
5 sub-Earth planets
4:5, 3:4, 4:5, 4:5 chain
11 Gyr (thick disc)

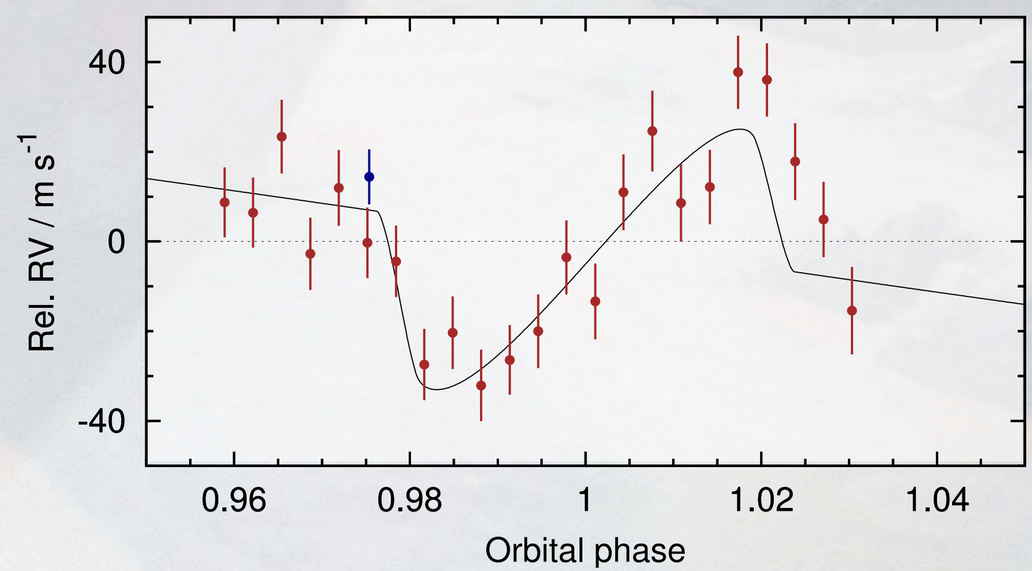
secondary star's periastron: 5 AU





WASP-94Ab and Bb





Talk by Su

Campante+ 2015, Zhang+ 2017

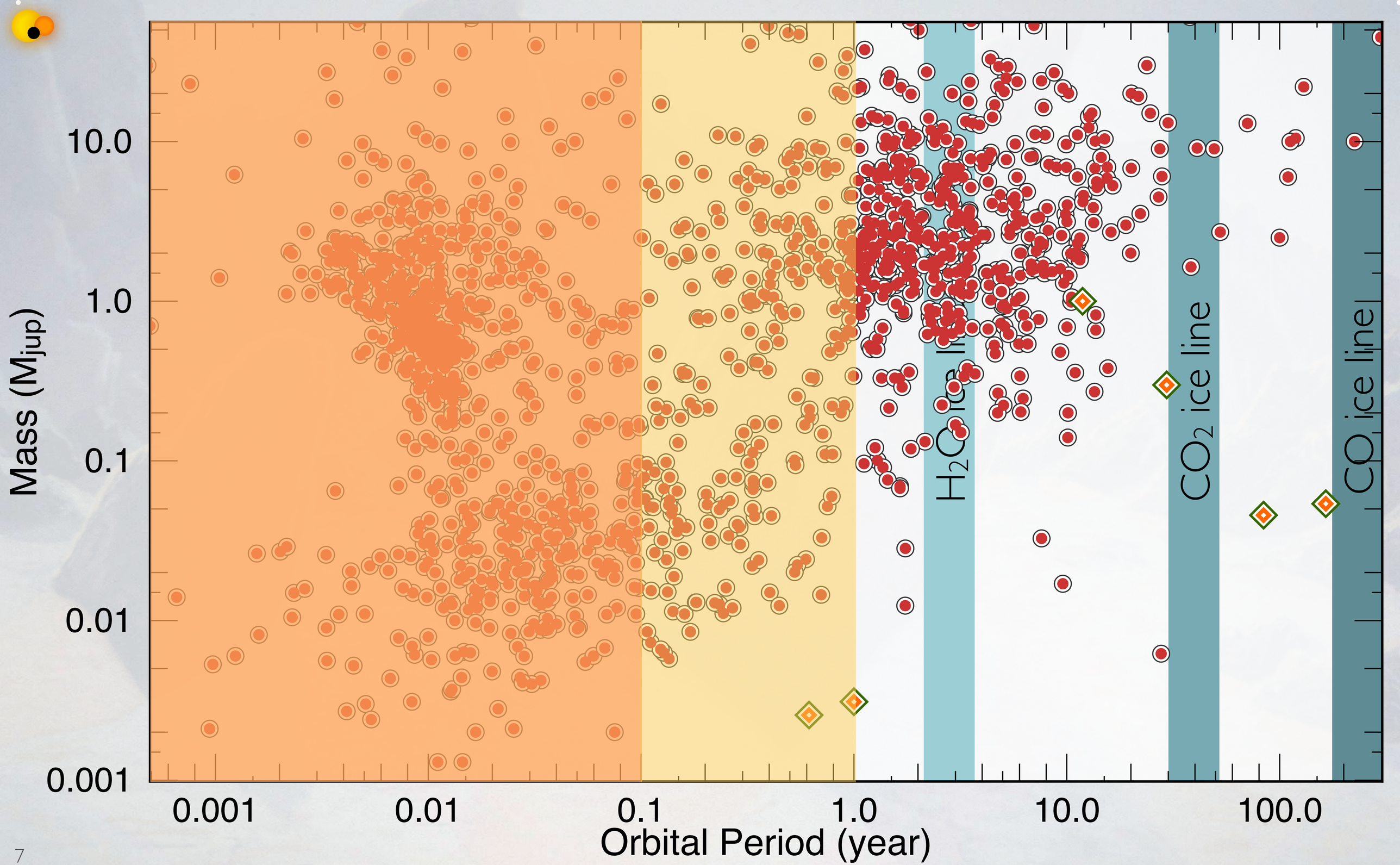
Neveu-VanMalle., 2014, Ahrer+ 2025

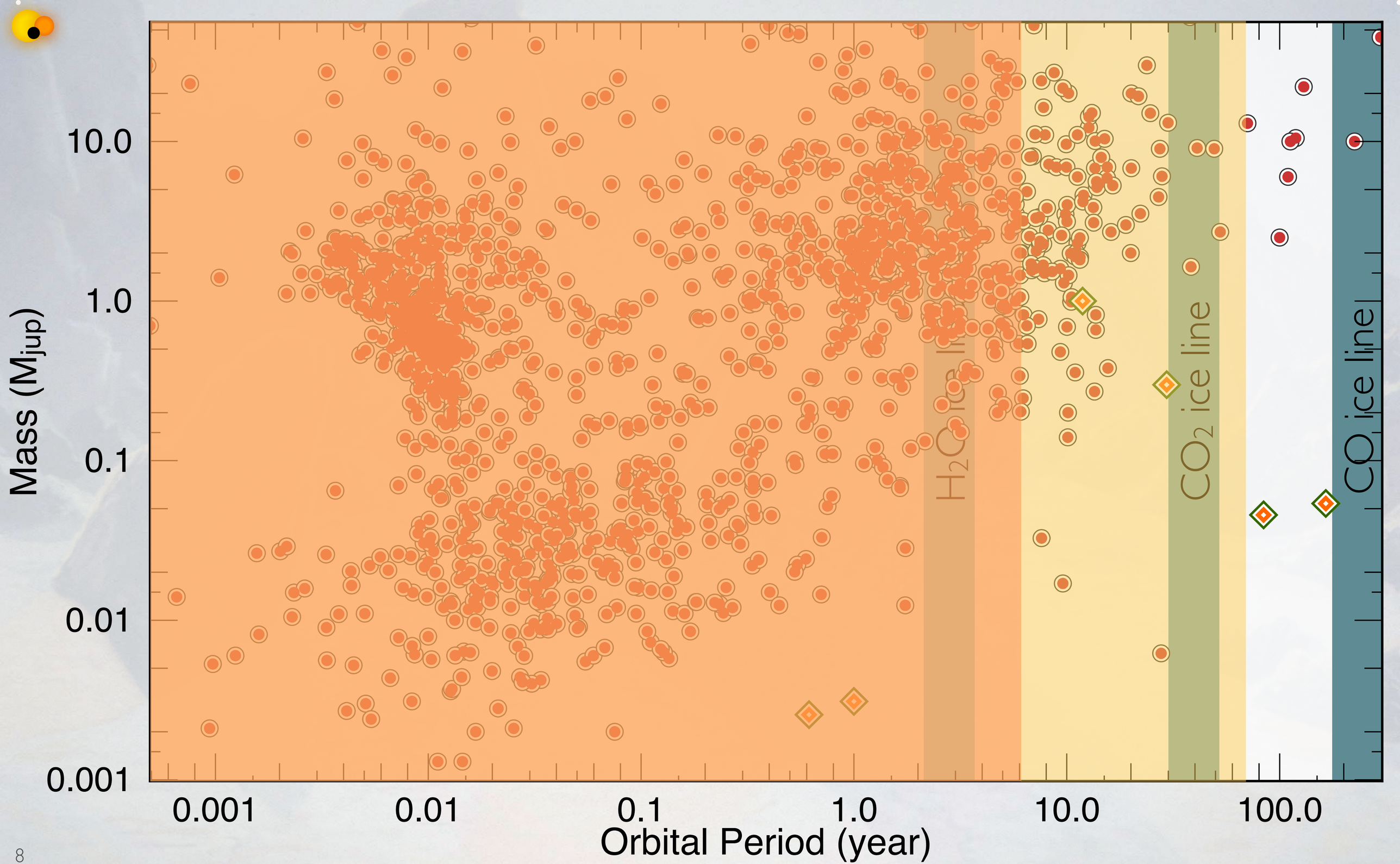
Core accretion is **less** efficient

planetesimal accretion possible if > 50 binary separation

$$\frac{dm}{dt} = \frac{1}{2}\Sigma\,\Omega\,\pi\,r^2\,(1+\Theta) \qquad \text{with} \qquad \Theta = \frac{v_{\rm esc}^2}{v^2}$$

Circumbinary super-Earths show super-Earths can **form far** & **migrate**


Mass (M_{jup})
10.0
1.0
0.1
0.01
0.001
0.001
0.01
0.1
1.0
10.0
100.0
Orbital Period (year)
H_2O ice line
CO_2 ice line
CO ice line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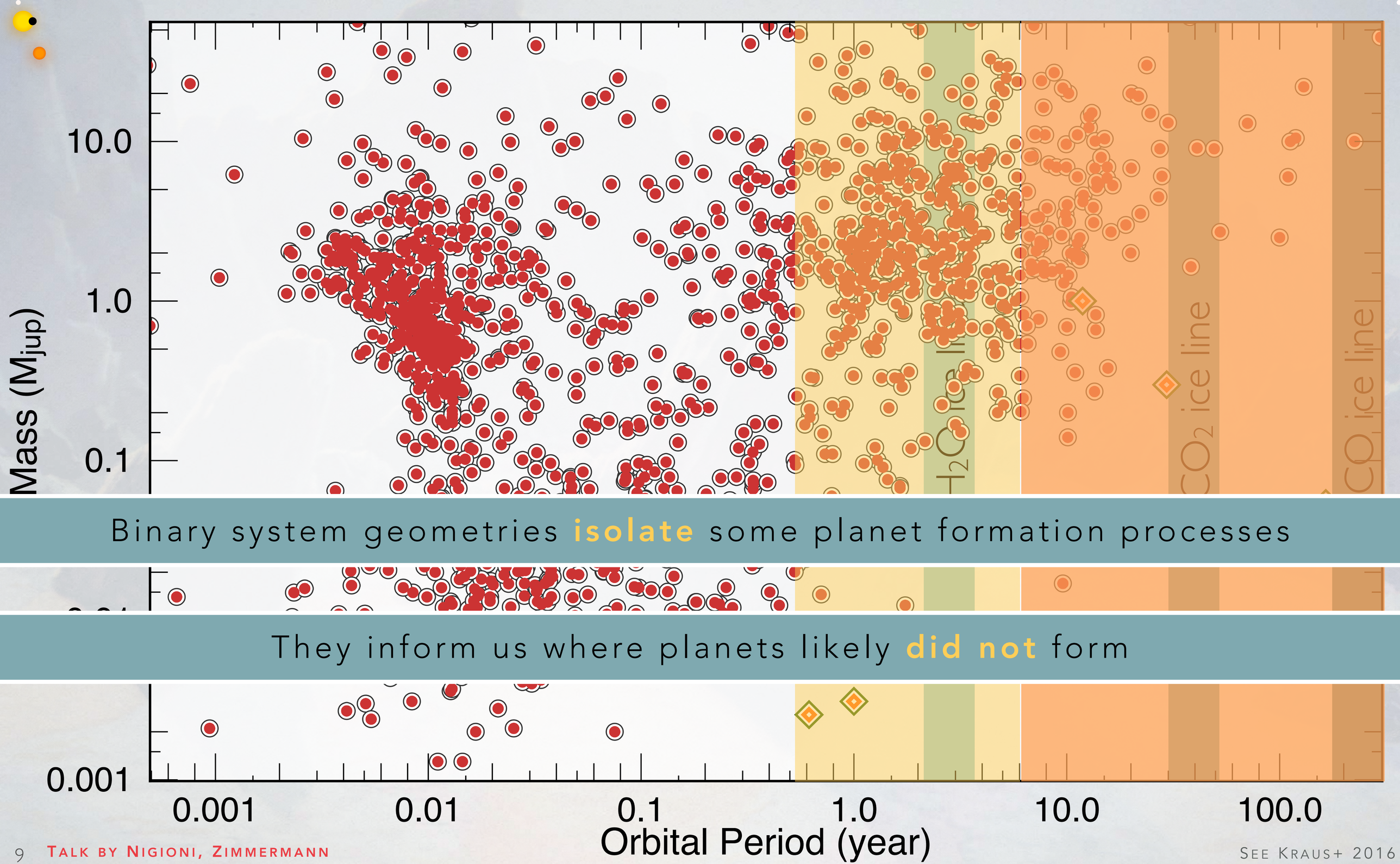


Binary system geometries **isolate** some planet formation processes

They inform us where planets likely **did not** form

Talk by Nigioni, Zimmermann

See Kraus+ 2016

Core accretion is **less** efficient

planetesimal accretion possible if > 50 binary separation

$$\frac{dm}{dt} = \frac{1}{2}\Sigma\,\Omega\,\pi\,r^2\,(1+\Theta) \qquad \text{with} \qquad \Theta = \frac{v_{\rm esc}^2}{v^2}$$

Circumbinary super-Earths show super-Earths can **form far** & **migrate**

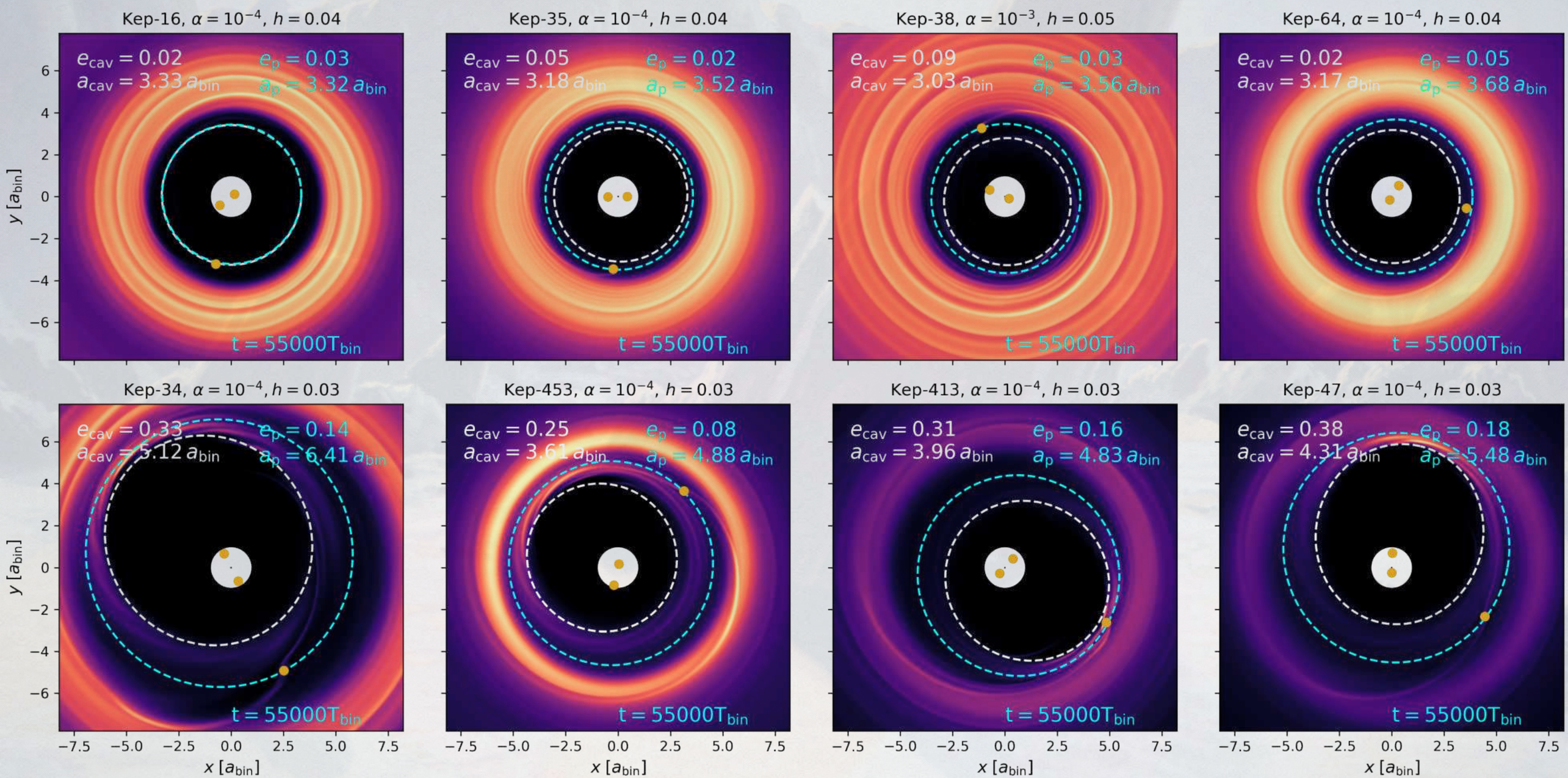
Trackers of disc-driven migration

More massive planets are expected further out (Pierens & Nelson 2008)

The orbital parameters consistent with low h/r and low alpha discs (Pierens & Nelson 2013, Penzlin, Kley & Nelson 2020)

Circumbinary orbits contain **fossil** information about disc conditions

Circumbinary Parking is disc-specific



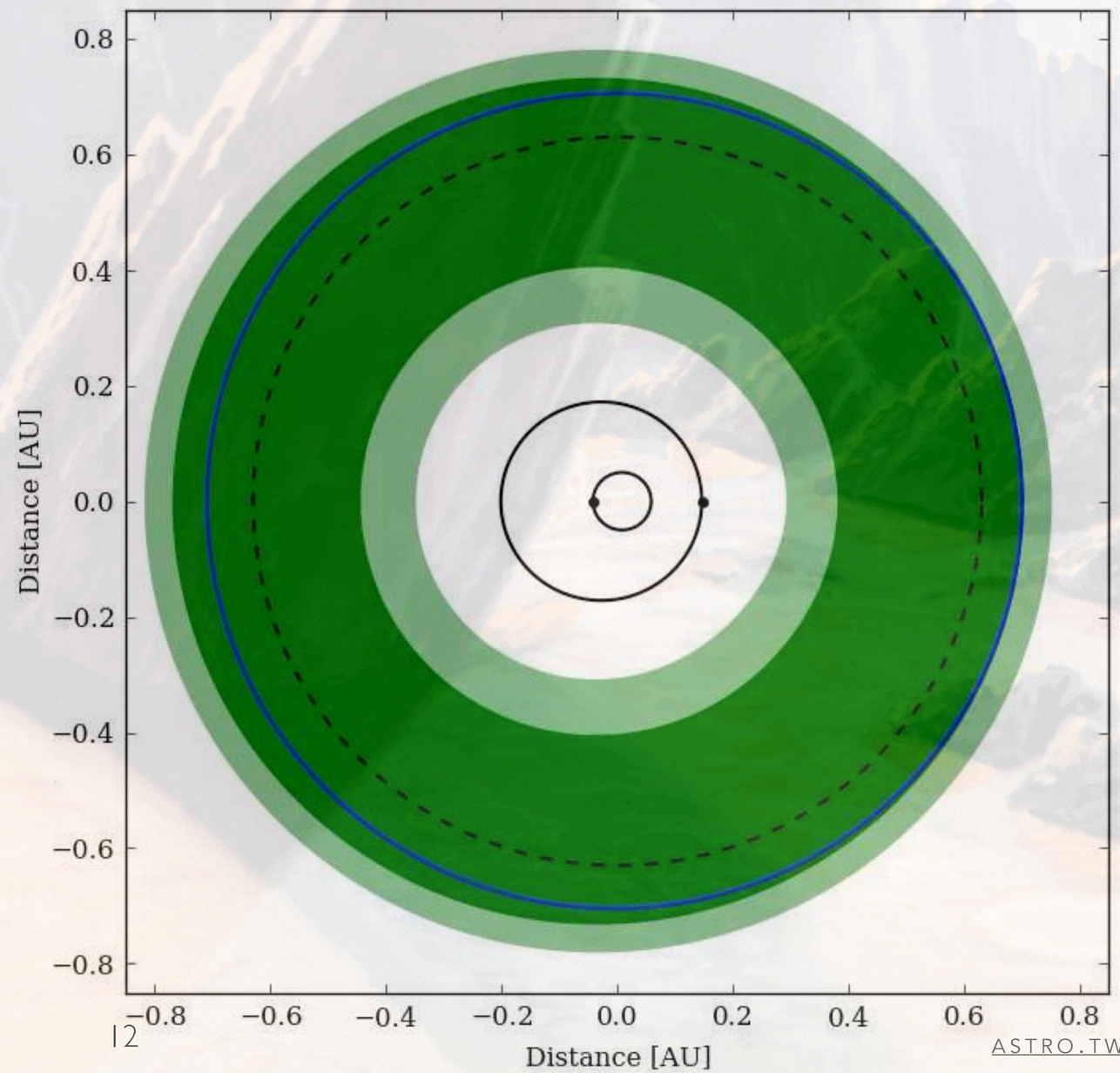
Penzlin+ 2020

Circumbinary planets & atmospheres

seasonal variations

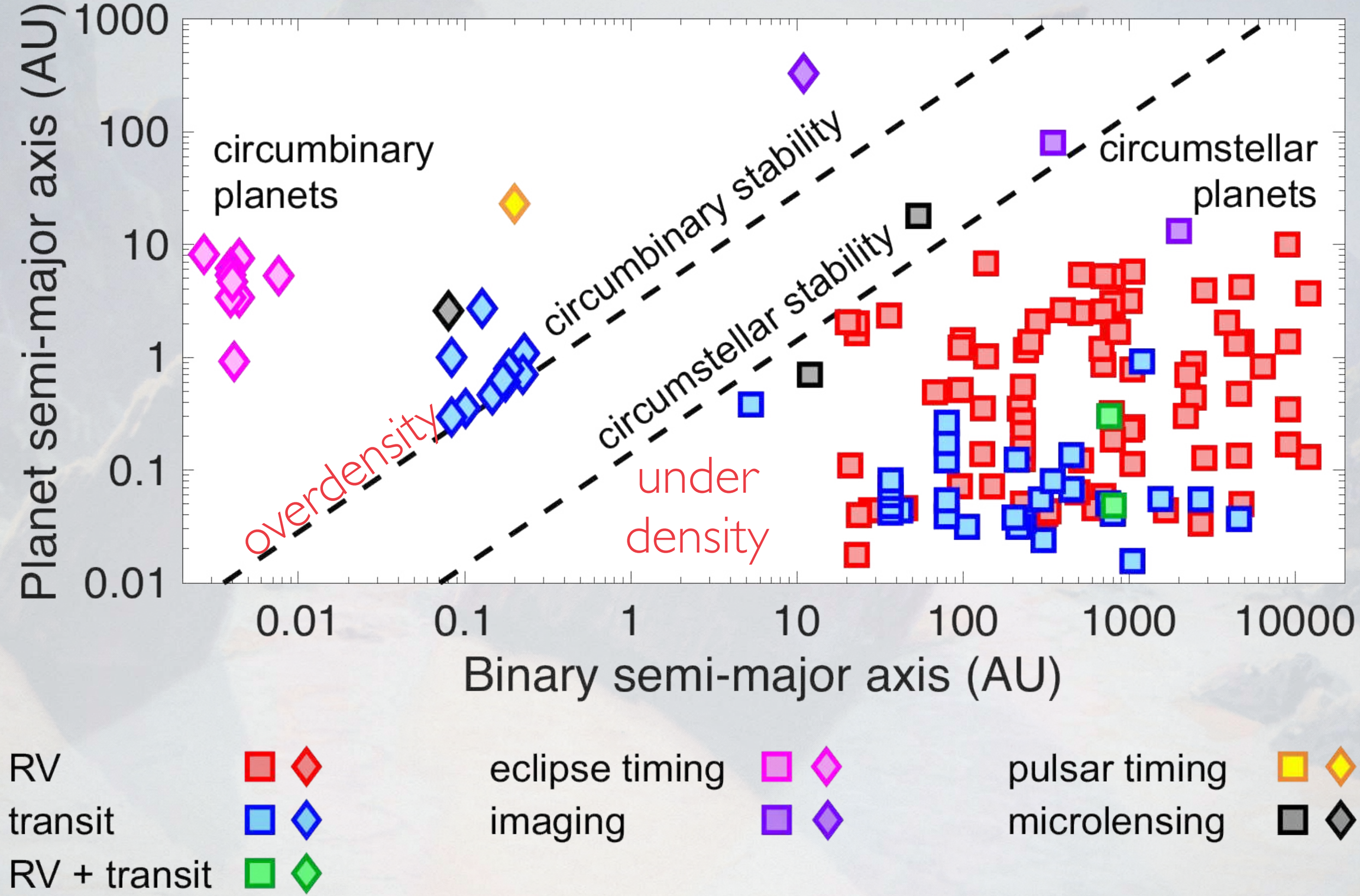
The habitable zone is affected by the motion of the two stars, and their relative brightness.

This means the stellar flux received by the planet changes as a sort of short seasonal variation.



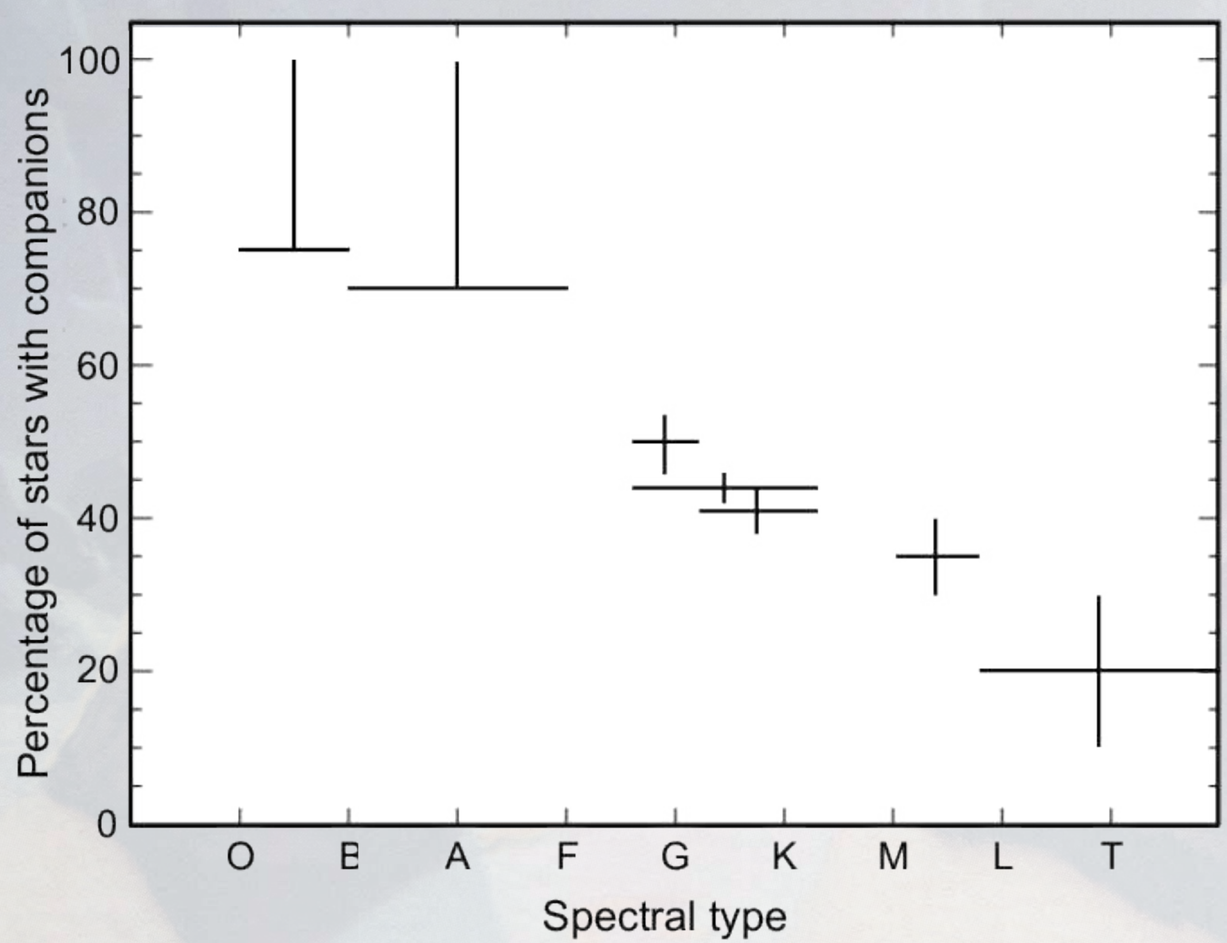
global trends *for* exoplanets in multiples

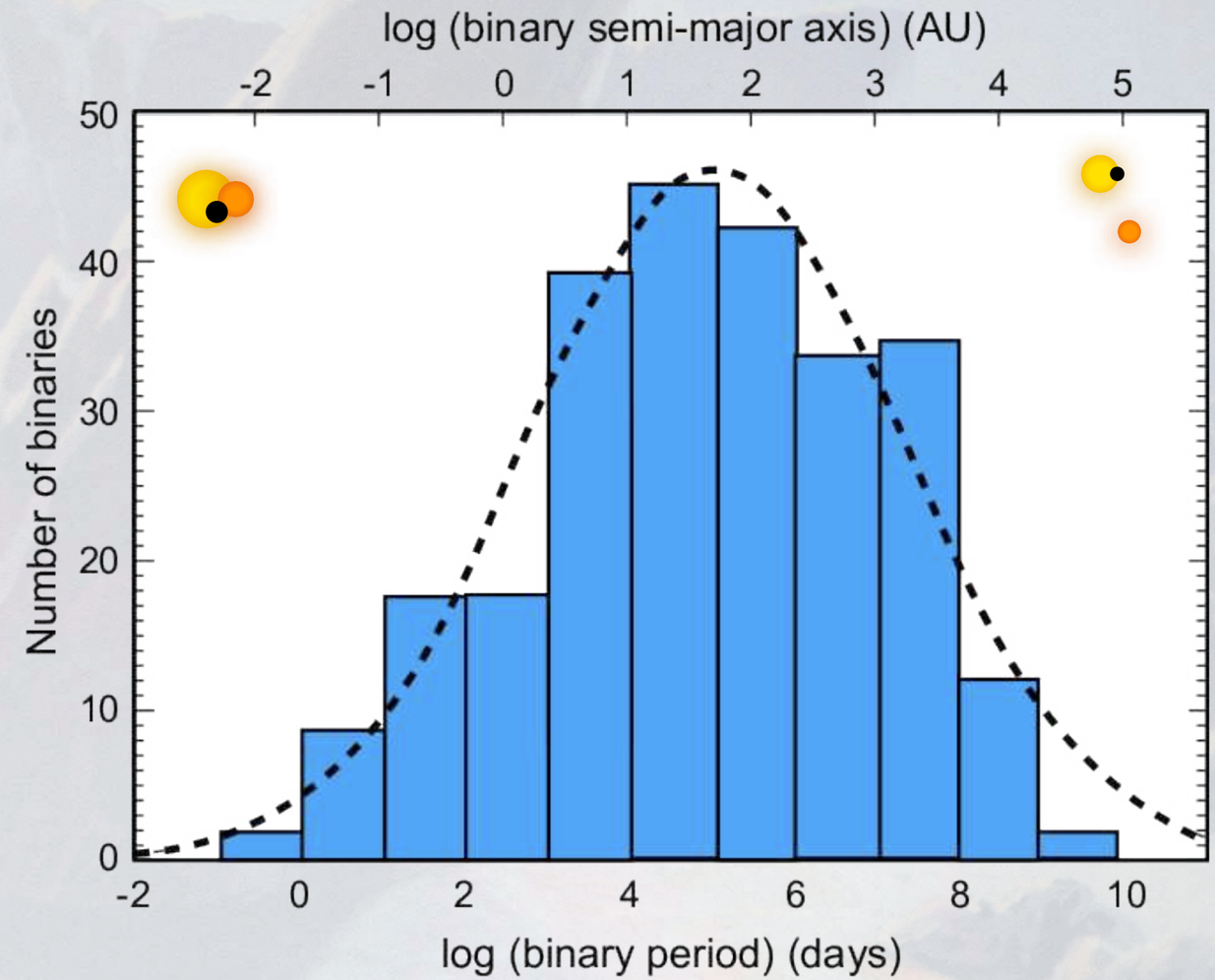
RUDAUX 1937



Martin, D.V. 2018

Binarity affects occurence rates





for $a_{\mathrm{bin}} < 50\ \mathrm{AU}$, planet occurence rates decrease by **factor 3** (Kraus+ 2016)

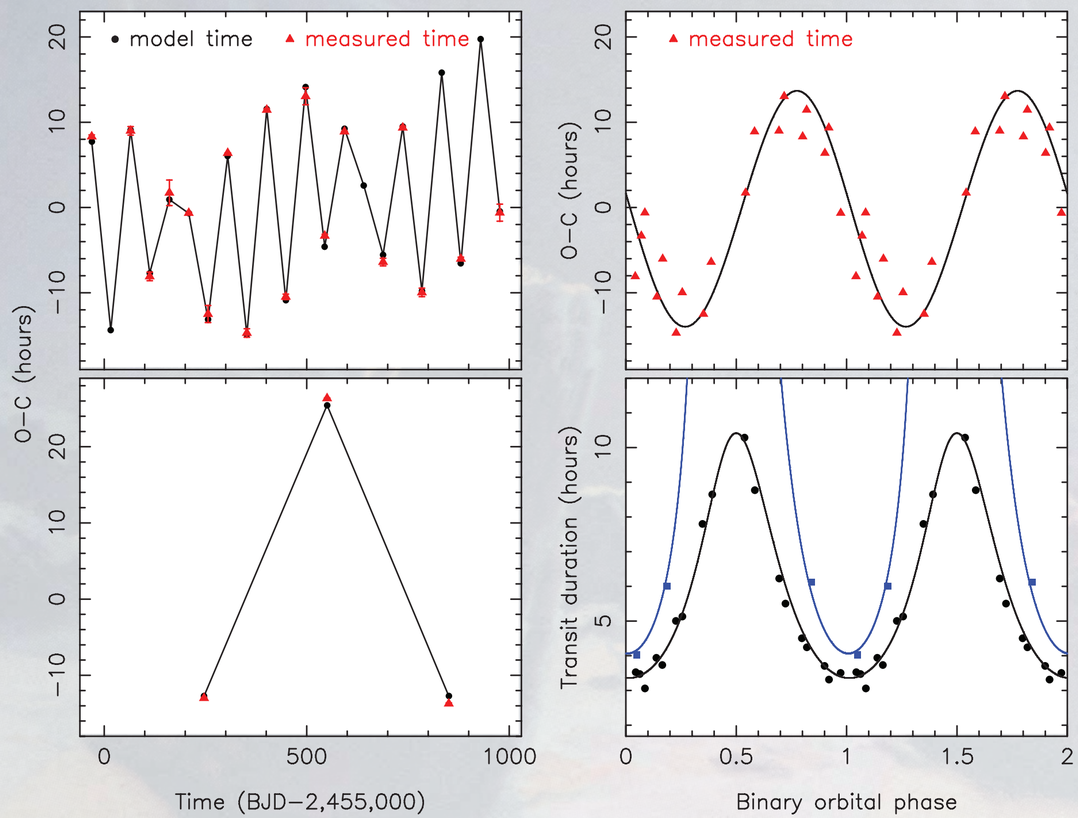
Lack of binarity explains half of the increased planet occurence in Ms

 Talks by Nigioni, Dupuy, Cifuentes, Eeles-Nolle

See Raghavan+ 2010, Kraus+2016, Martin, D.V. 2018, Moe & Kratter 2021

circumbinary
exoplanets
where
observations
require dynamics

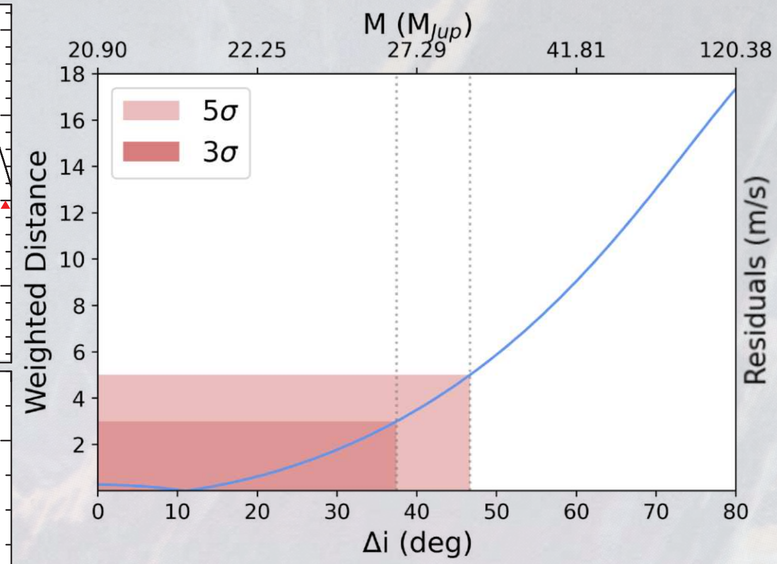
Timing & Duration variations

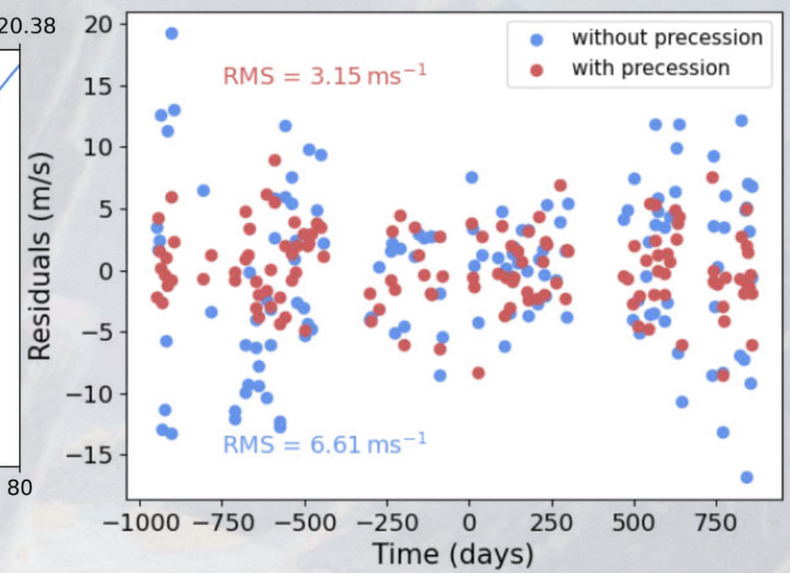


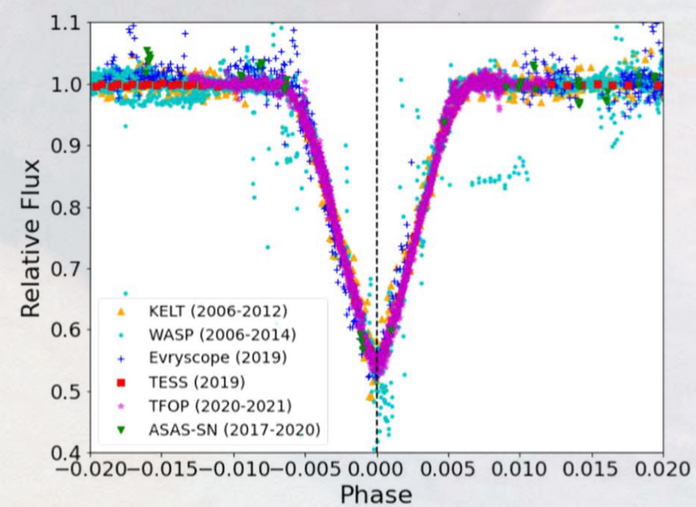
transits can be severely asymmetric

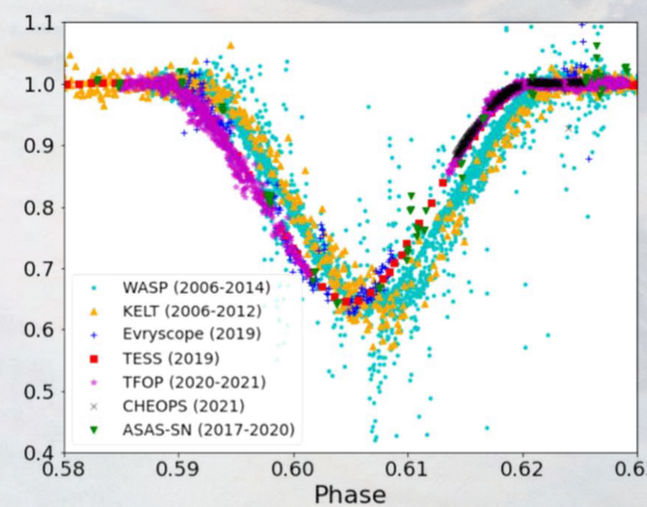
⇒ photo-dynamical modelling

Apsidal precession









Talks by Baycroft, Montet

Orosz+ 2012

Kostov+ 2020, Baycroft+ 2023, Triaud+ in prep

Circumbinary gas-giant occurrence

$> 0.15\,\mathrm{M_{jup}}, > 6\,\mathrm{R_\oplus}, P_{\mathrm{bin}} > 5$ days

No circumbinary planets where $P_{\mathrm{bin}} < 7$ days

Farhat+, Mogan+

Assuming coplanarity ($\Delta i = 0^\circ \pm 0^\circ$)

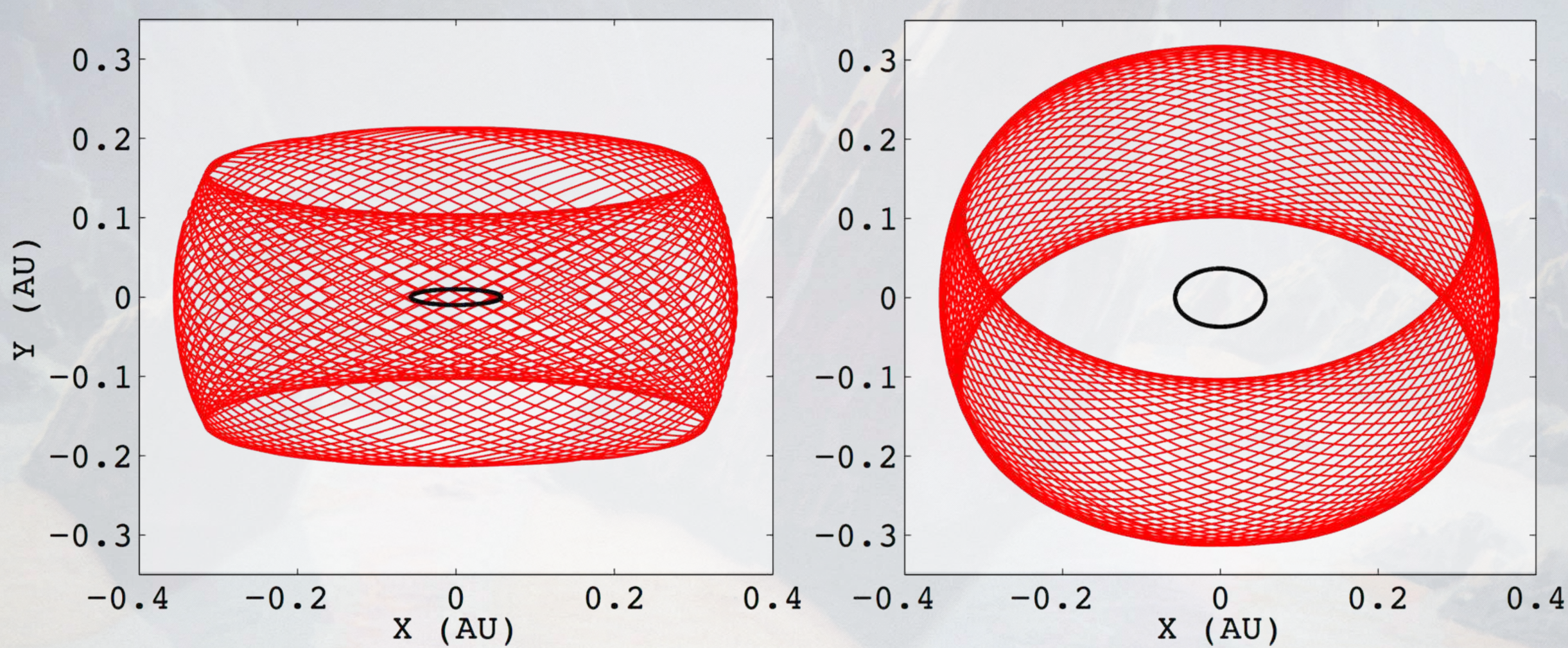
Armstrong et al. 2014:	~9.8% (P< 300 days)★
Martin & Triaud 2014:	~15% (P< 10 years)★

Single Sun-like stars:

Mayor+ 2011:	13.7% (P< 10 years)
	5.4% (P< 400 d)
Santerne+ 2016:	4.6% (P< 400 d)

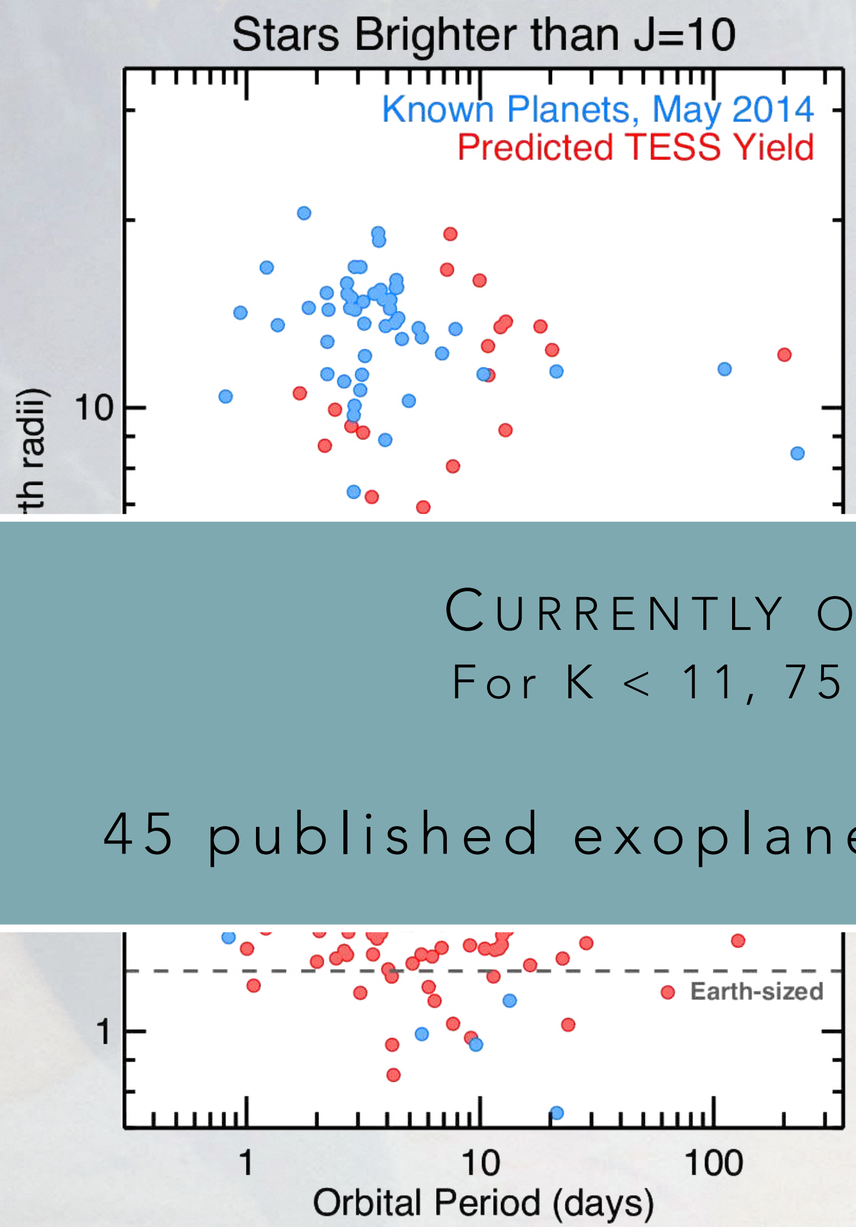
★ corrected by removing triples

Orbital inclination = large solid angle



Martin & Triaud 2014

Circumbinary planets are over-represented



Projected results by TESS

very few temperate planets

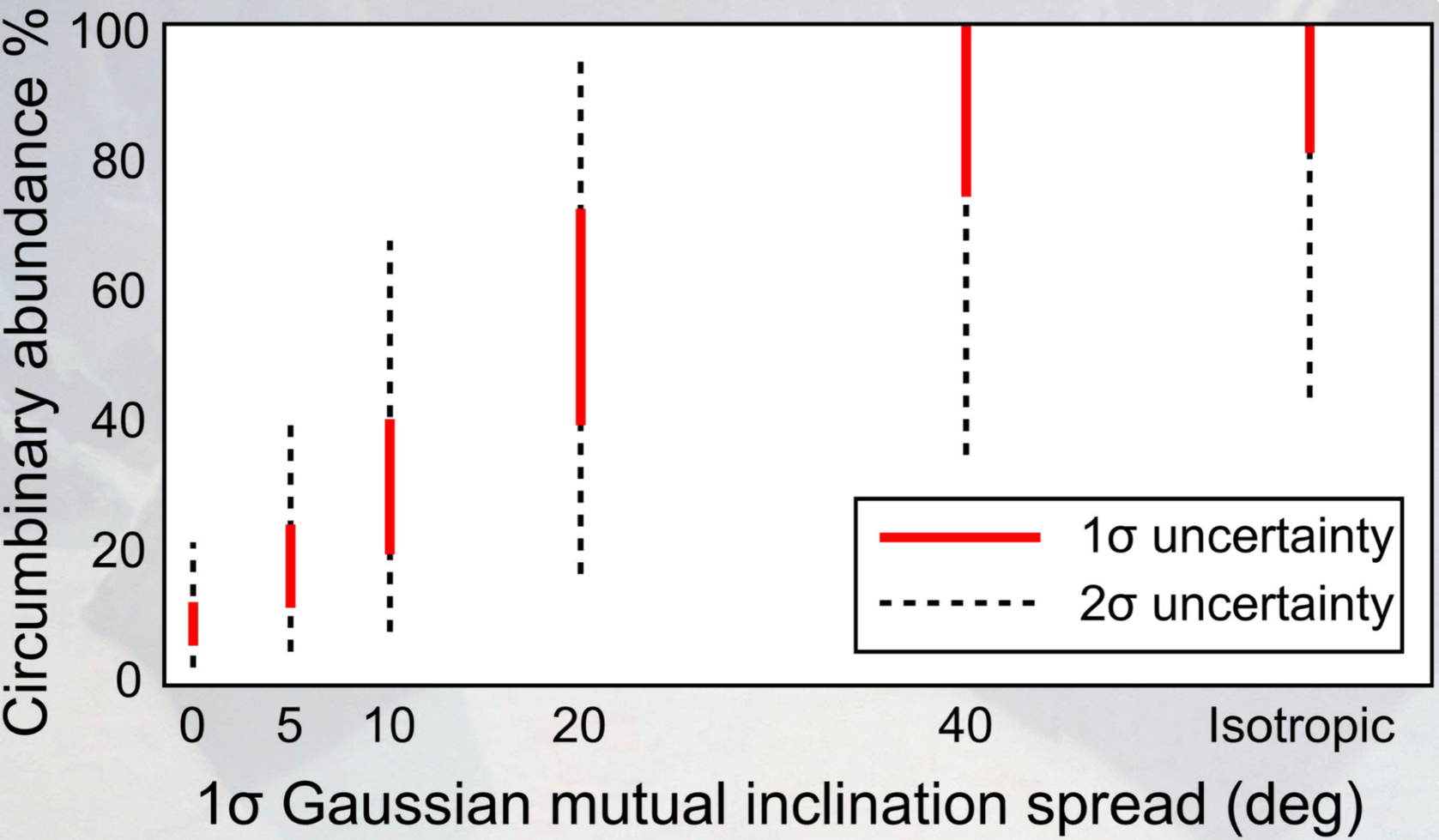
Currently on NASA exoplanet archive

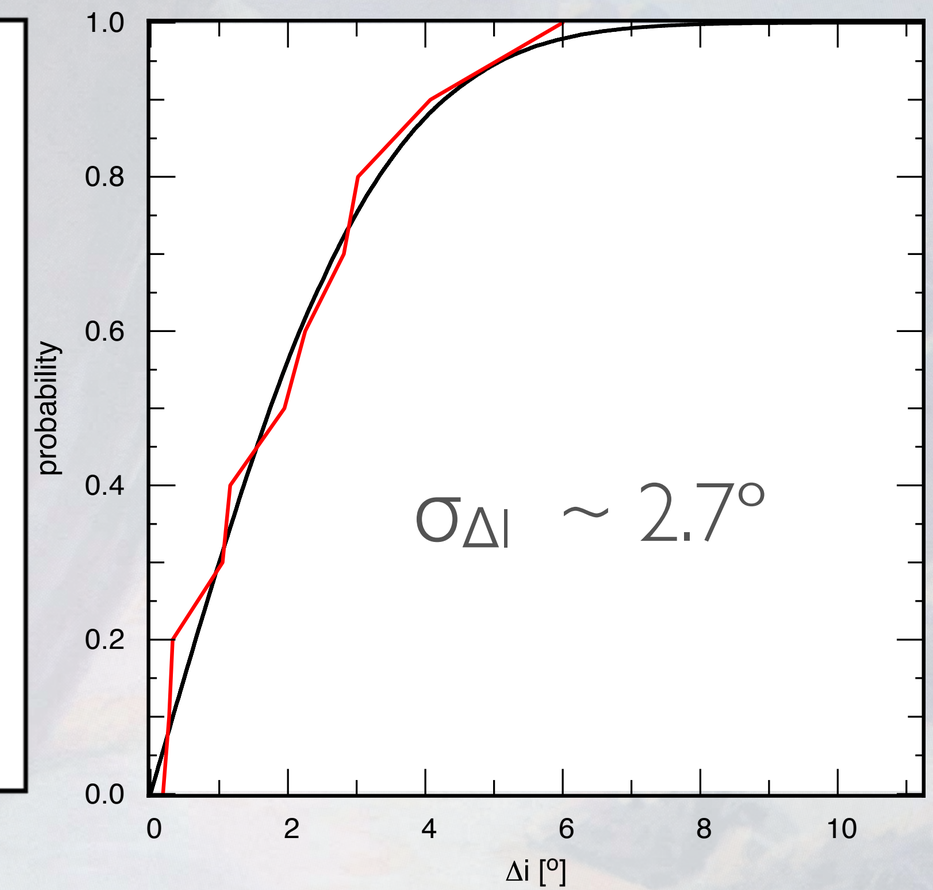
For K < 11, 75 d < P < 1000 d, and radii > 2 Re

45 published exoplanets, including 4 circumbinary planets

Ricker+ 2014

Effect of mutual inclination





Martin & Triaud 2014,15, Armstrong+ 2014, Li+ 2016

The BEBOP survey: the goals

Binaries Escorted By Orbiting Planets

demonstrate circumbinary planets can be detected with RV
for SB1 and SB2

complete a first survey and measure occurrence rates

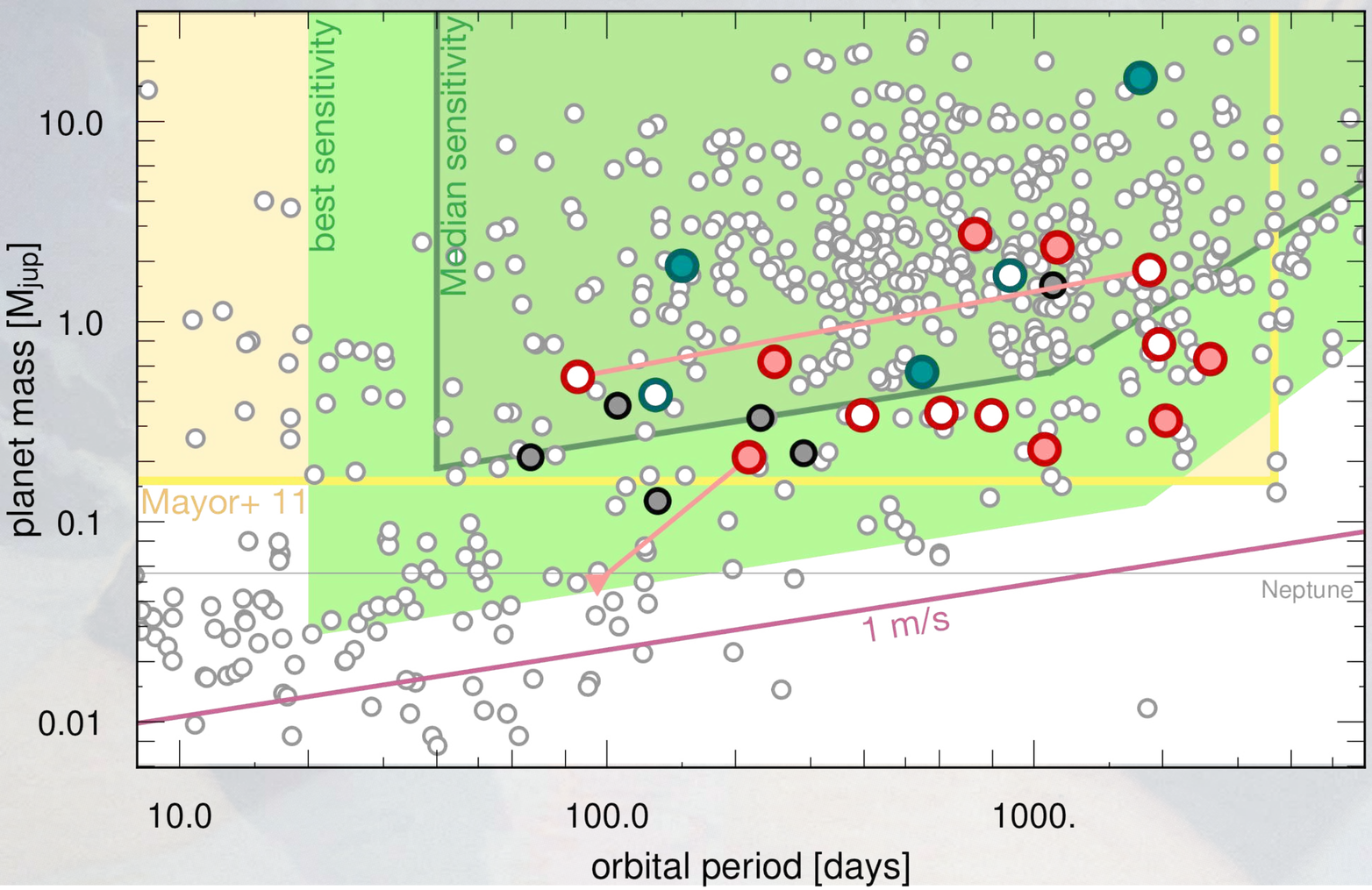
attempt to get dynamical masses of the binary
to get absolute planet masses

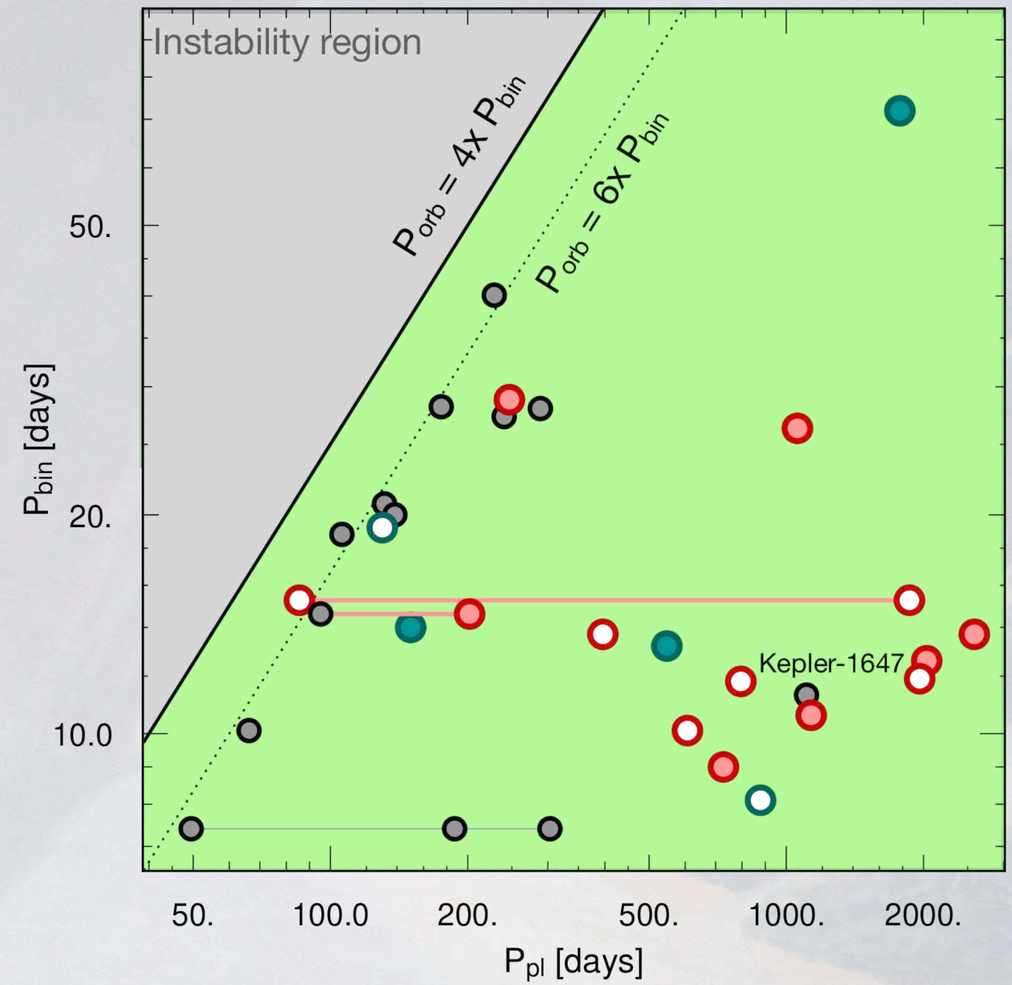
Compare the properties of circumbinary planets to circumstellar planets in order to distinguish various pathways of planet formation

To have the precursor population to post-AGP planets

The BEBOP survey: *results, so far*

Binaries Escorted By Orbiting Planets





very preliminary results

BEBOP - Phase I: preliminary results

Binaries Escorted By Orbiting Planets

Circumbinary planets can be detected with RVs in SB1s

Physical properties

Circumbinary planets $> 3\,\mathrm{M_{Jup}}$ are $5\times$ rarer than for single stars

Orbital properties

Circumbinary planets can have significant eccentricities

Circumbinary planets are most not at $\sim 6\,P_{\mathrm{bin}}$

Big result

RV and transit circumbinary planet population are different.

Solution? **Exoplanets with low masses and large radii**

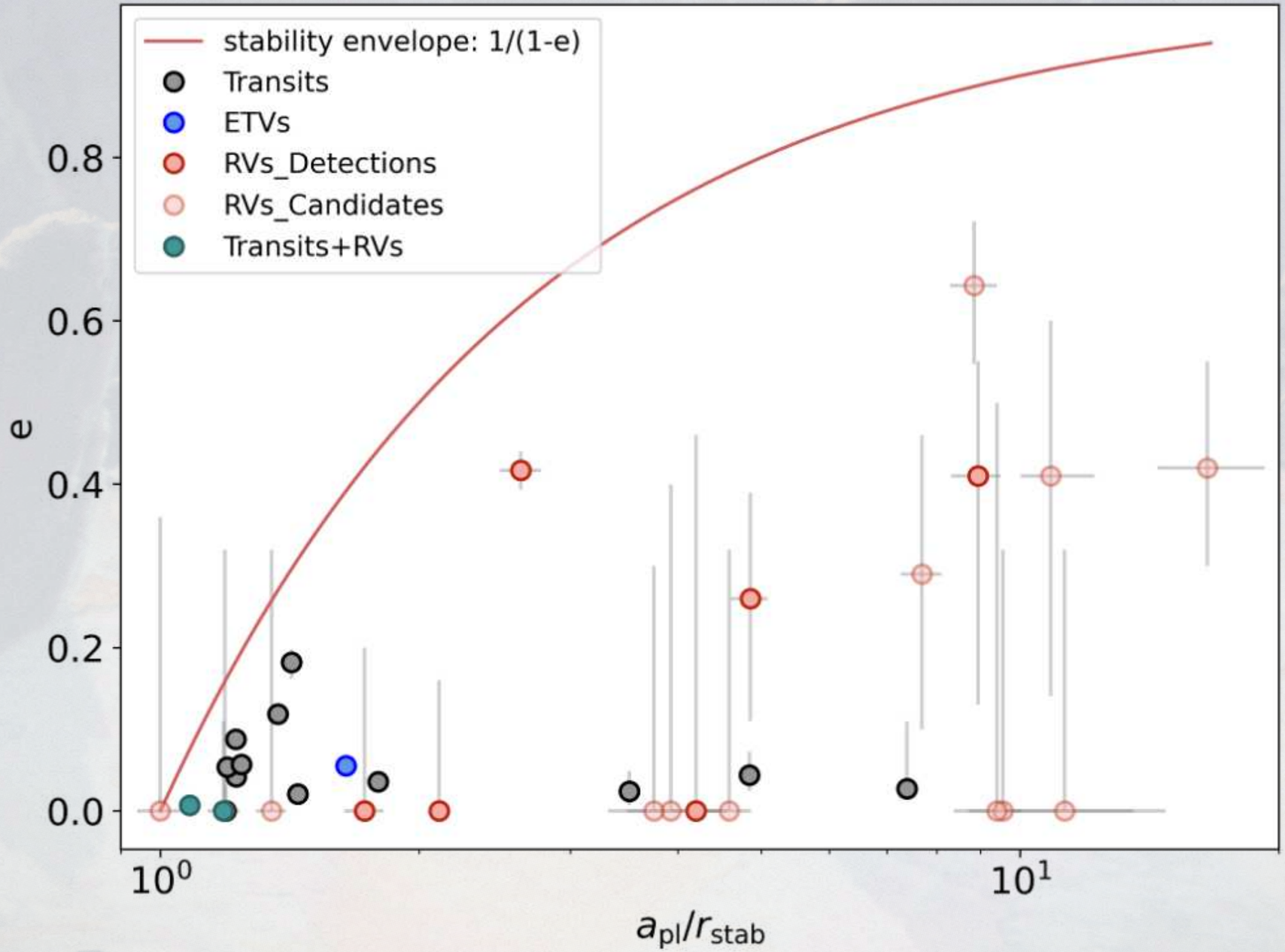
Occurrence rate

Correcting for completeness, ~ 12% of binaries have a planet

CONSISTENT $\sigma_{\Delta i} = 0^{\circ}$, CONSISTENT WITH LOW H/R

BEBOP - Phase I: preliminary results

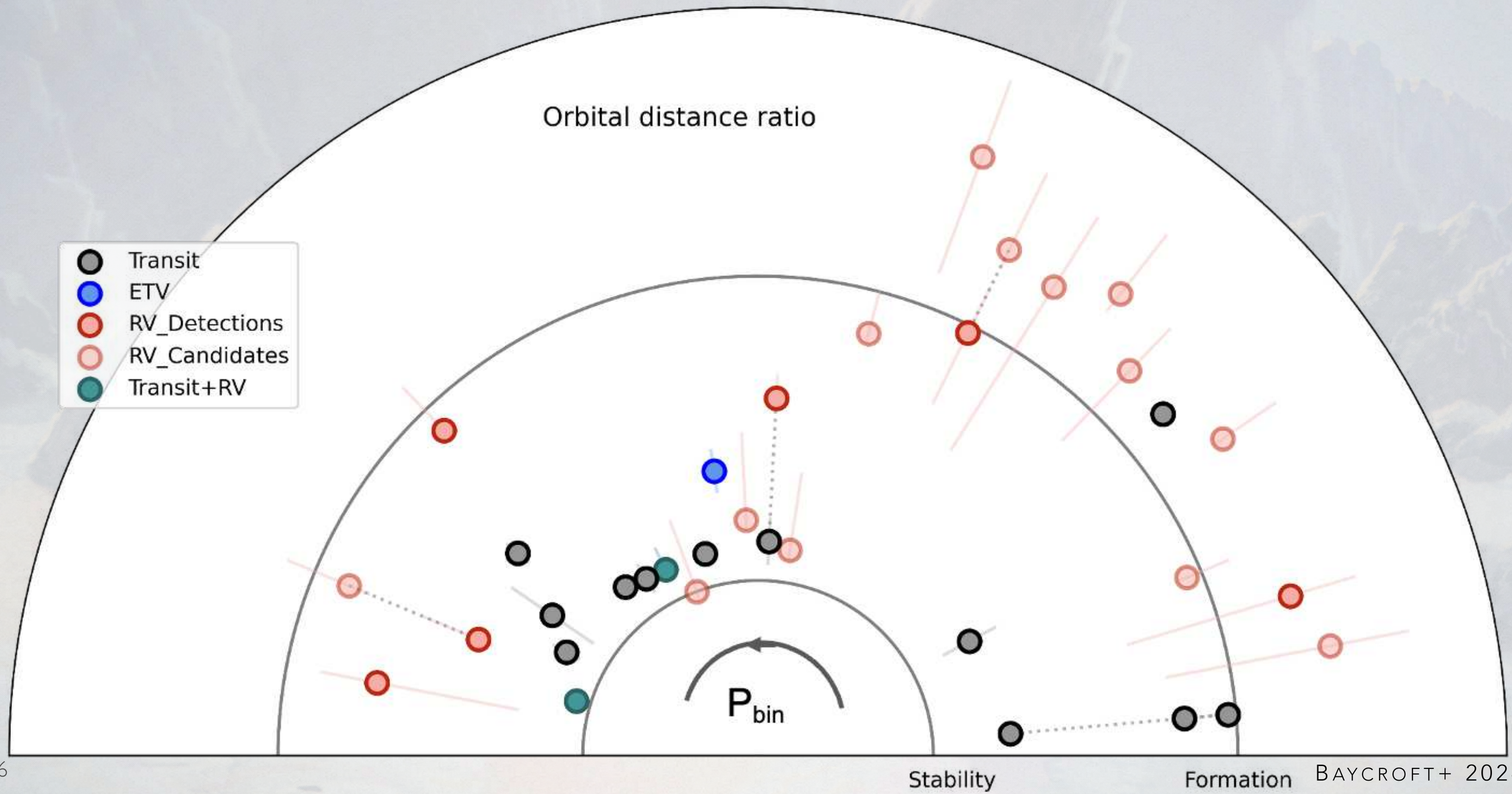
Binaries Escorted By Orbiting Planets



Baycroft+ 2024

BEBOP - Phase I: preliminary results

Binaries Escorted By Orbiting Planets



Baycroft+ 2024

additional thoughts

Observational difficulties

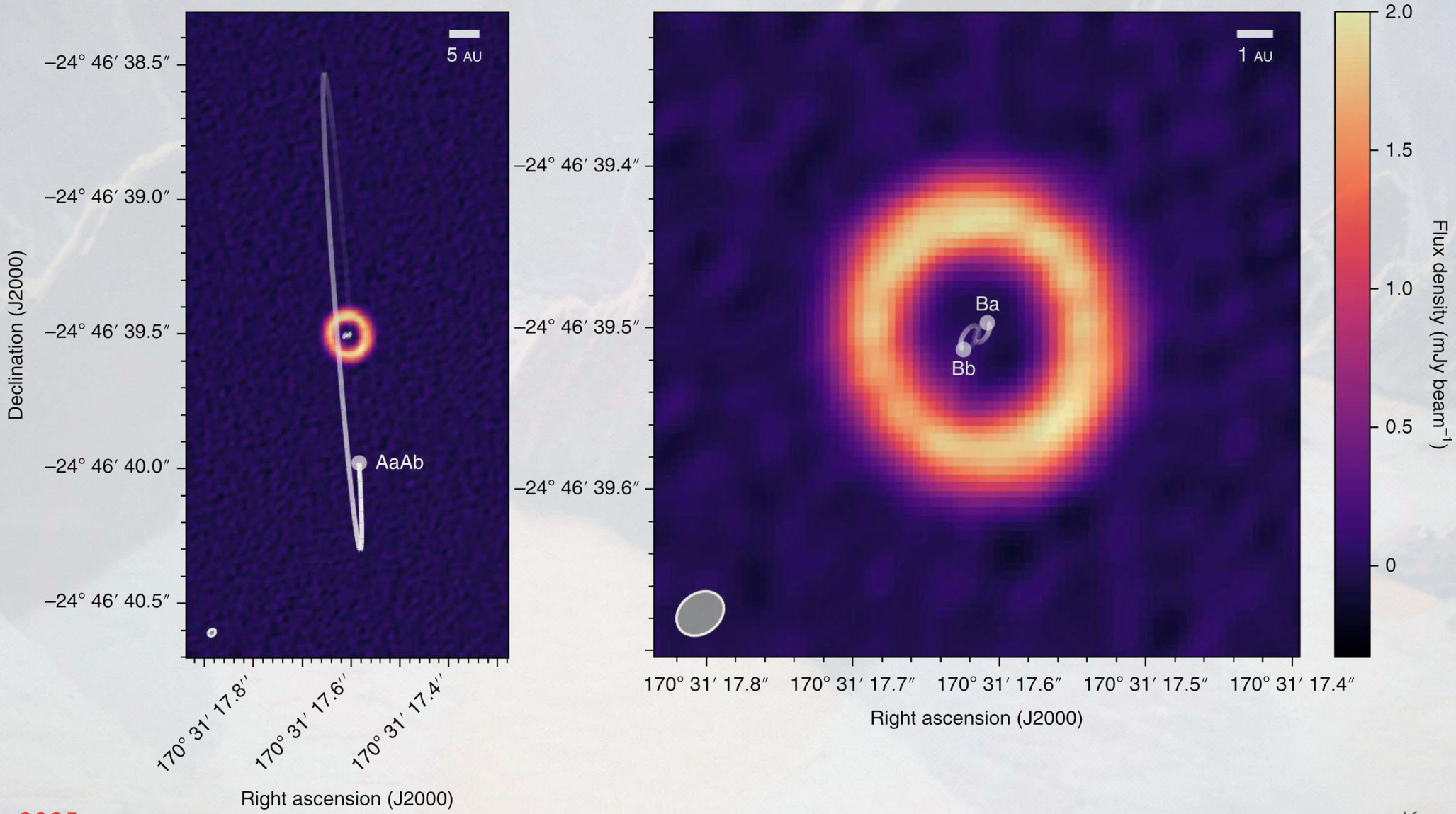
Knowing there is another star (if tight, or very loose system)
Confusion about which star has the planet (similar aperture/fibre)
Effects caused by blending + observer confusion (which star is A vs B)
Disentangling spectra / RV contamination

Observational practicalities

Gaia is very complete: common proper motion
Gaia: anomalous proper motion, RUWE + RV trends Talk by Kiefer
New codes to deal with spectral disentangling (DOLBY)
Direct imaging more readily available in *TESS* follow-up
When one star is active the other might not => longer timeseries
AO systems (like NIRPS) help stabilise, and resolve companions
Poster by Messamah

A POLAR CIRCUMBINARY DISC: HD98800

outer pair is about to be eclipsed by the disc!



KENNEDY+ 2019

INSTITUT
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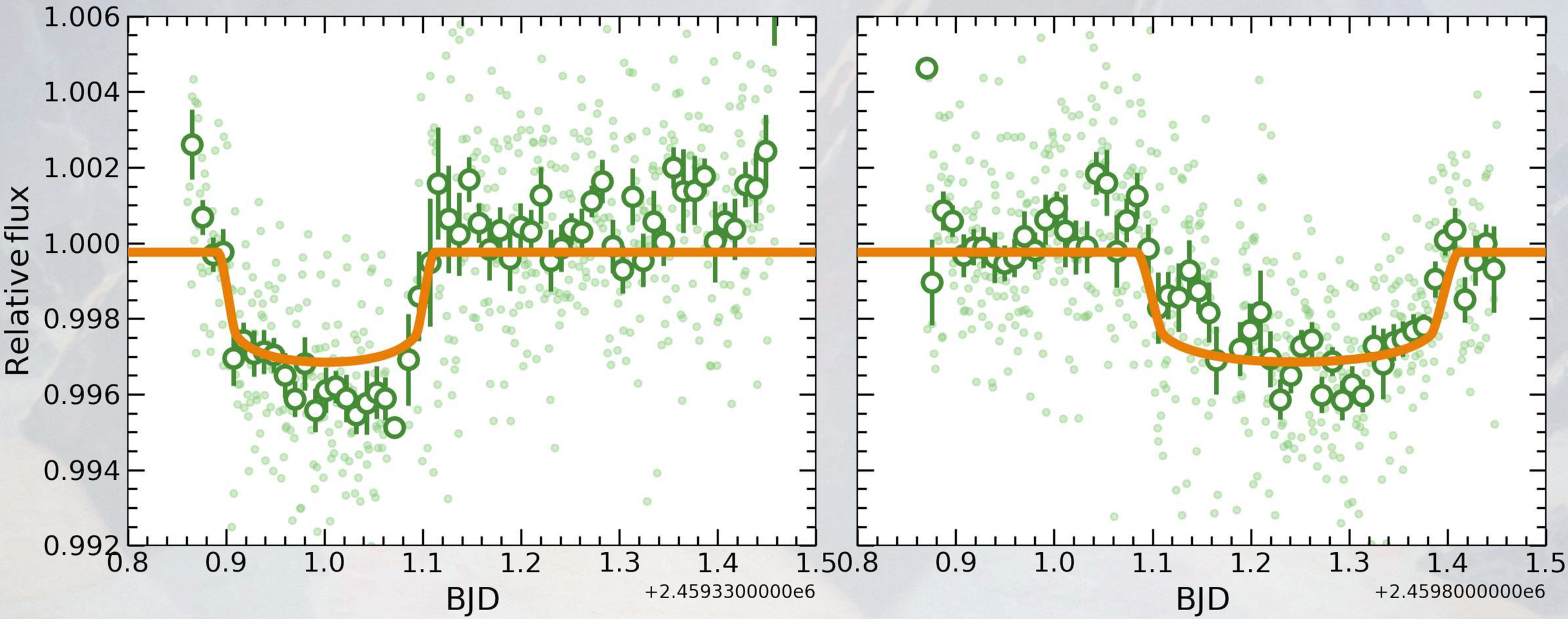
Detecting circumbinary planets

TOI-1338 / BEBOP-1b - from Antarctica



Transits are 5hr and 10hr long, with TTVs of ~10hrs

Triaud, Dransfield et al. in prep

Exoplanet properties

IN STELLAR MULTIPLES

help understand formation

Detecting planets in

CIRCUMBINARY GEOMETRIES

require dynamics

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