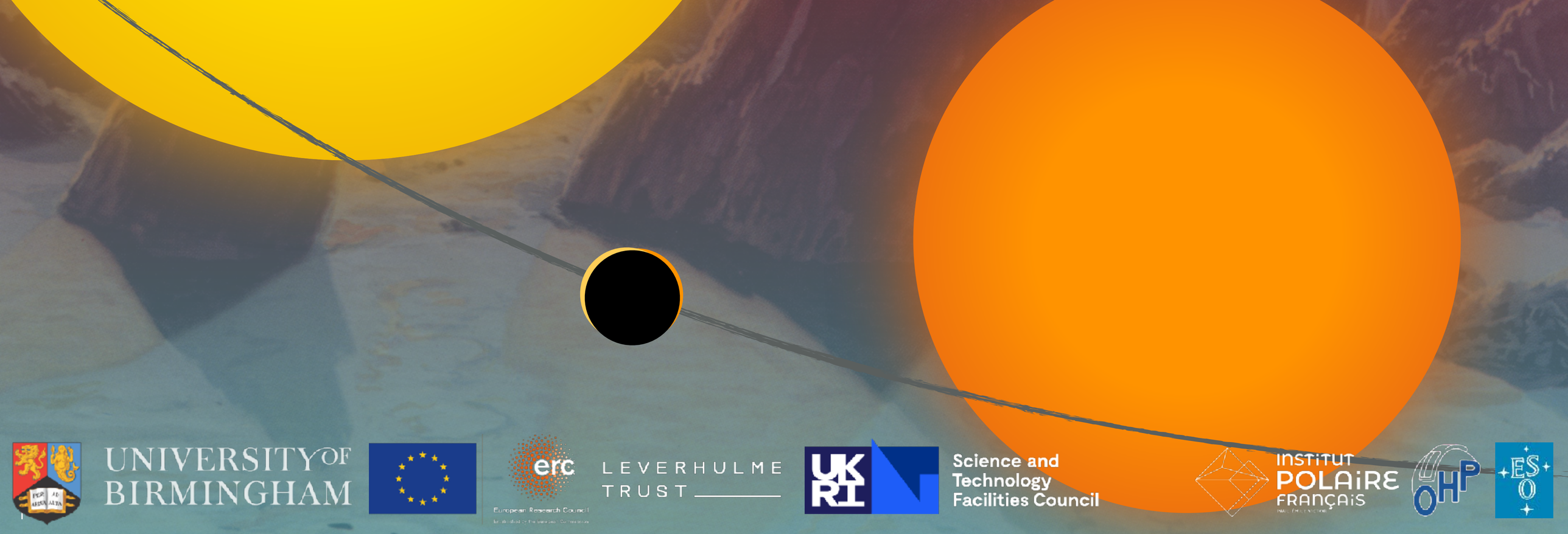
Circumbinary planets, with radial velocities

Amaury H.M.J. Triaud



First, a bit of history and context

Circumbinary gas-giant occurrence

> 0.15 Mjup, >8 Rearth

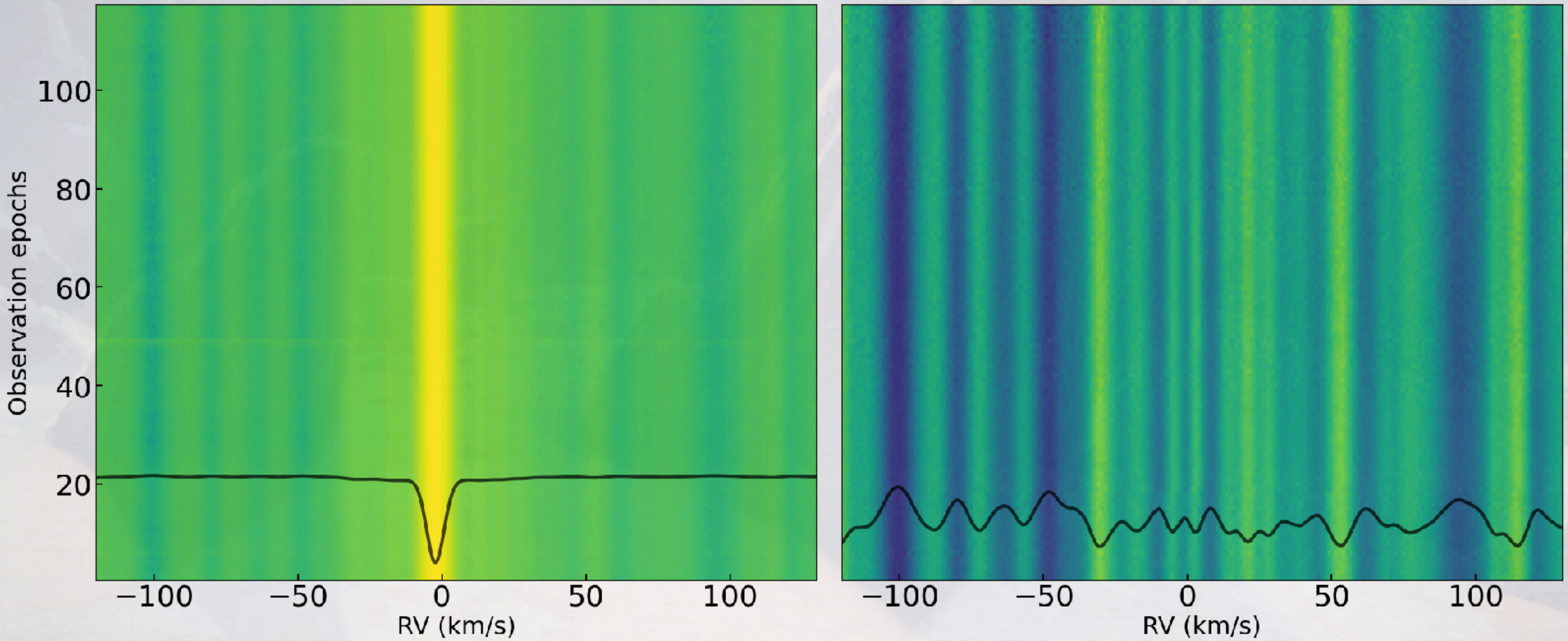
Assuming coplanarity ($\Delta i = 0° \pm 0°$)

Armstrong et al. 2014:	~6.4% (P< 300 days)
Martin & Triaud 2014:	~10% (P< 10 years)

Single Sun-like stars:

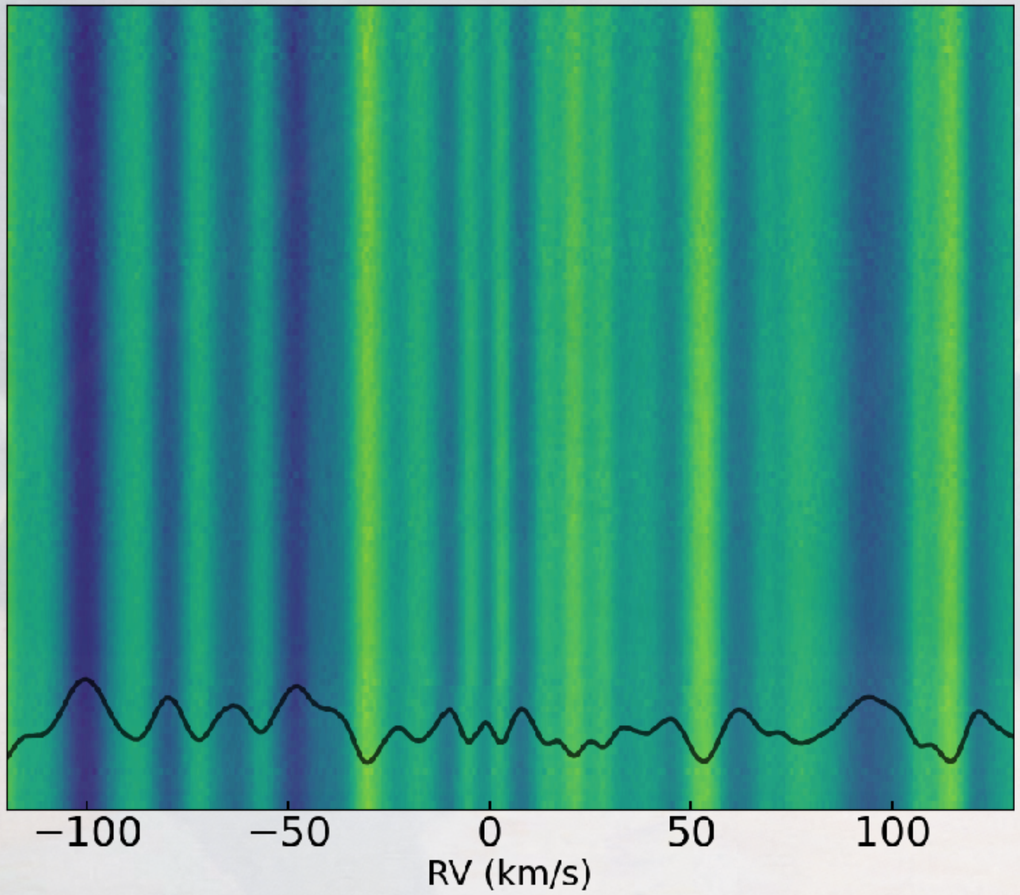
Mayor+ 2011:	13.7% (P< 10 years) 5.4% (P< 400 d)
Santerne+ 2016:	4.6% (P< 400 d)

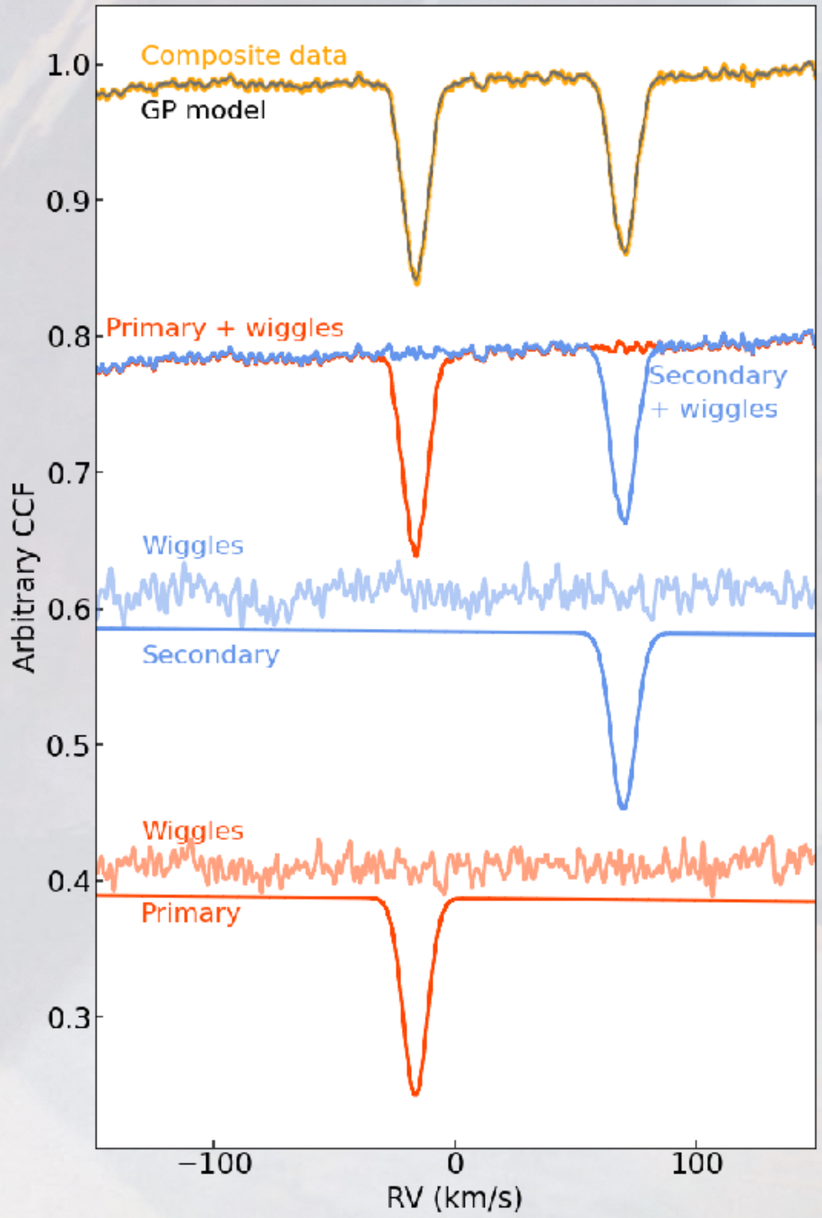
Detecting circumbinary planets
in double-lined systems



Lalitha, Triaud et al. 2024

DETECTING CIRCUMBINARY PLANETS
in double-lined systems





LALITHA, TRIAUD ET AL. 2024

DETECTING CIRCUMBINARY PLANETS
in double-lined systems

FROM KONACKI ET AL. 2010

Current state-of-the-art precision is at the level of $\sim$1 m s^{-1}. It is however important to note that such a precision refers to single stars or at best single-lined spectroscopic binaries where the influence of the secondary spectrum can be neglected. In

can be determined. It is quite surprising that the RV precision of double-lined binary stars on average has not improved much over the last 100 years (see Figure 1). With the exception of our previous work (Konacki 2005, 2009), the RV precision for such targets typically varies from $\sim$0.1 km s^{-1} to $\sim$1 km s^{-1} and clearly is much worse than what has been achieved for stars with planets or single-lined binary stars. The main problem with

The start of BEBOP, as an RV survey

Binaries Escorted By Orbiting Planets

The main premises

A focus on eclipsing SB1 (to avoid the SB2 problem)
Binaries with period > 5 days
Binaries without obvious tertiary stars

Two main initial assumptions

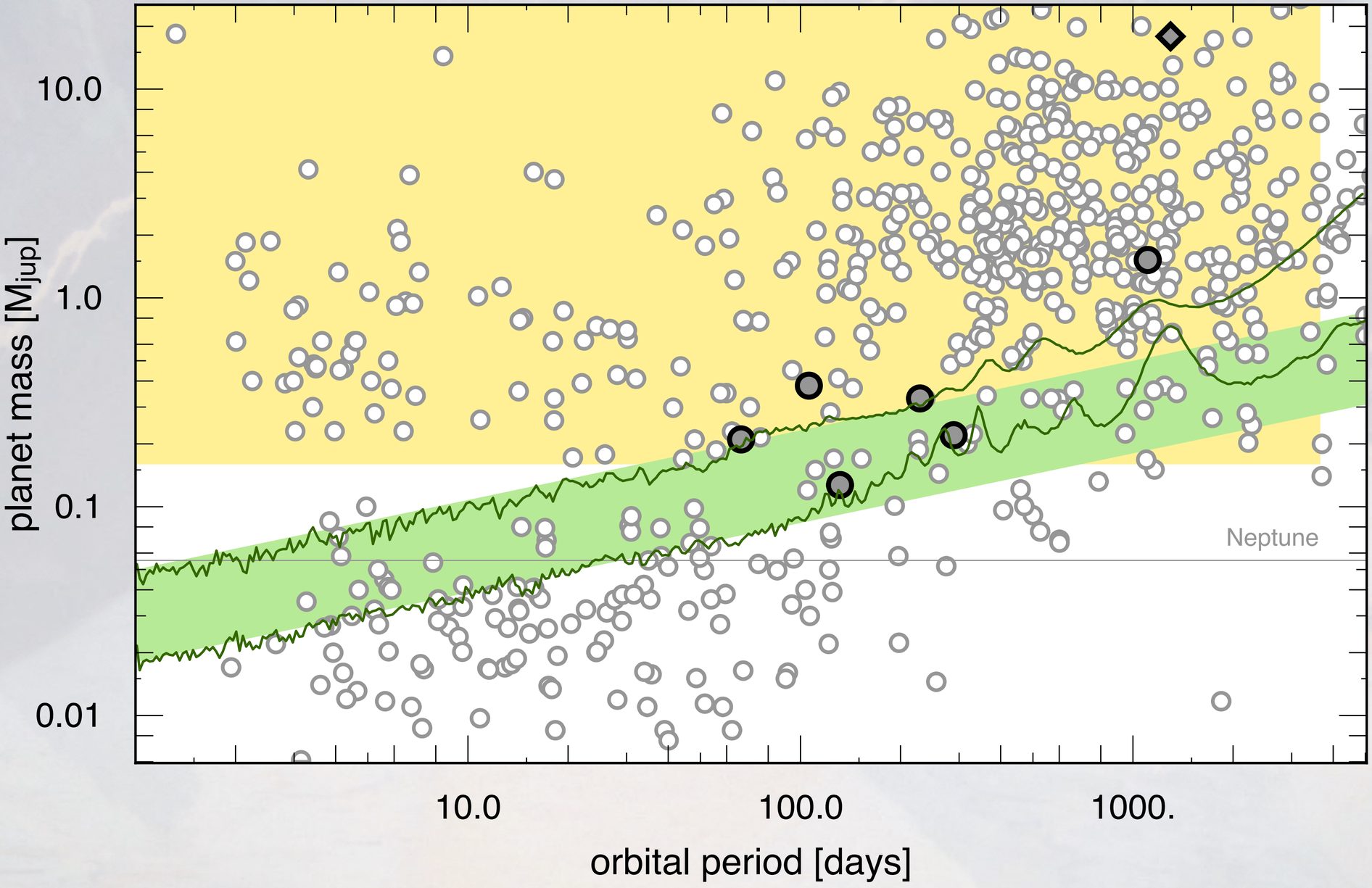
Planets expected @ 6x the binary period
Planets with Jupiter-masses (similar to single stars)

Main source of binary systems

The EBLM catalog; false-positives from WASP

The start of **BEBOP**, as an RV survey

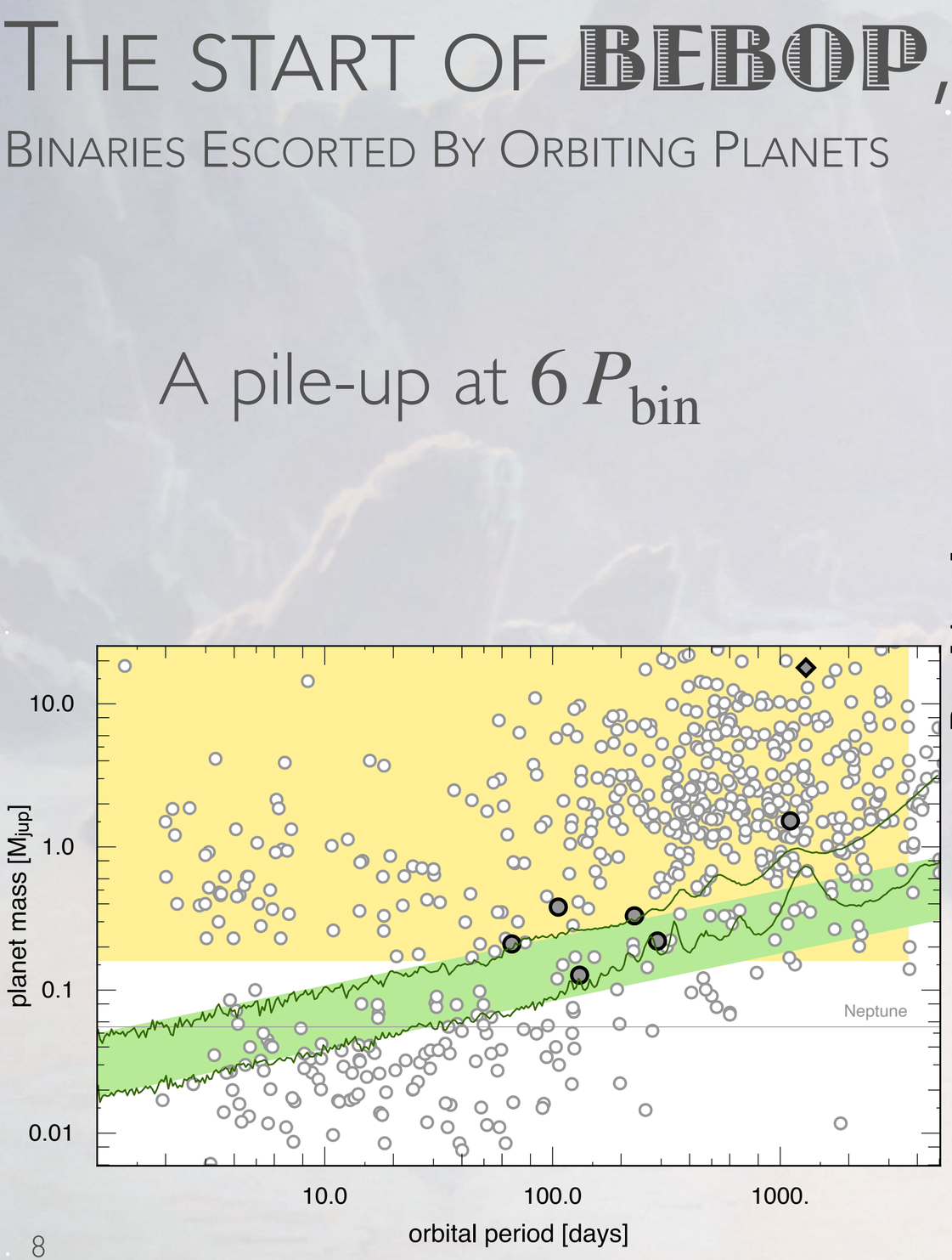
Binaries Escorted By Orbiting Planets

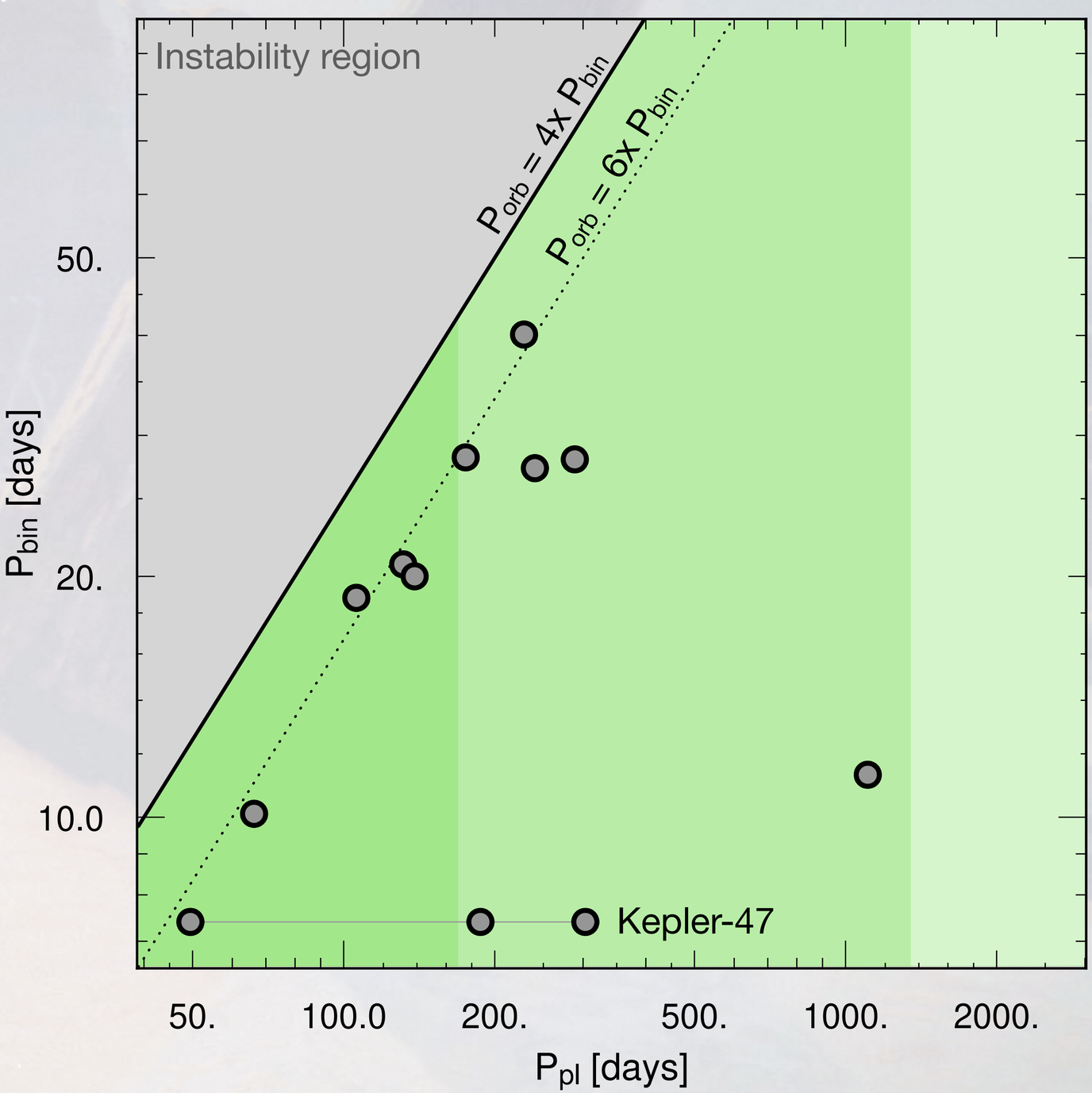


The start of **BEBOP**, as an RV survey

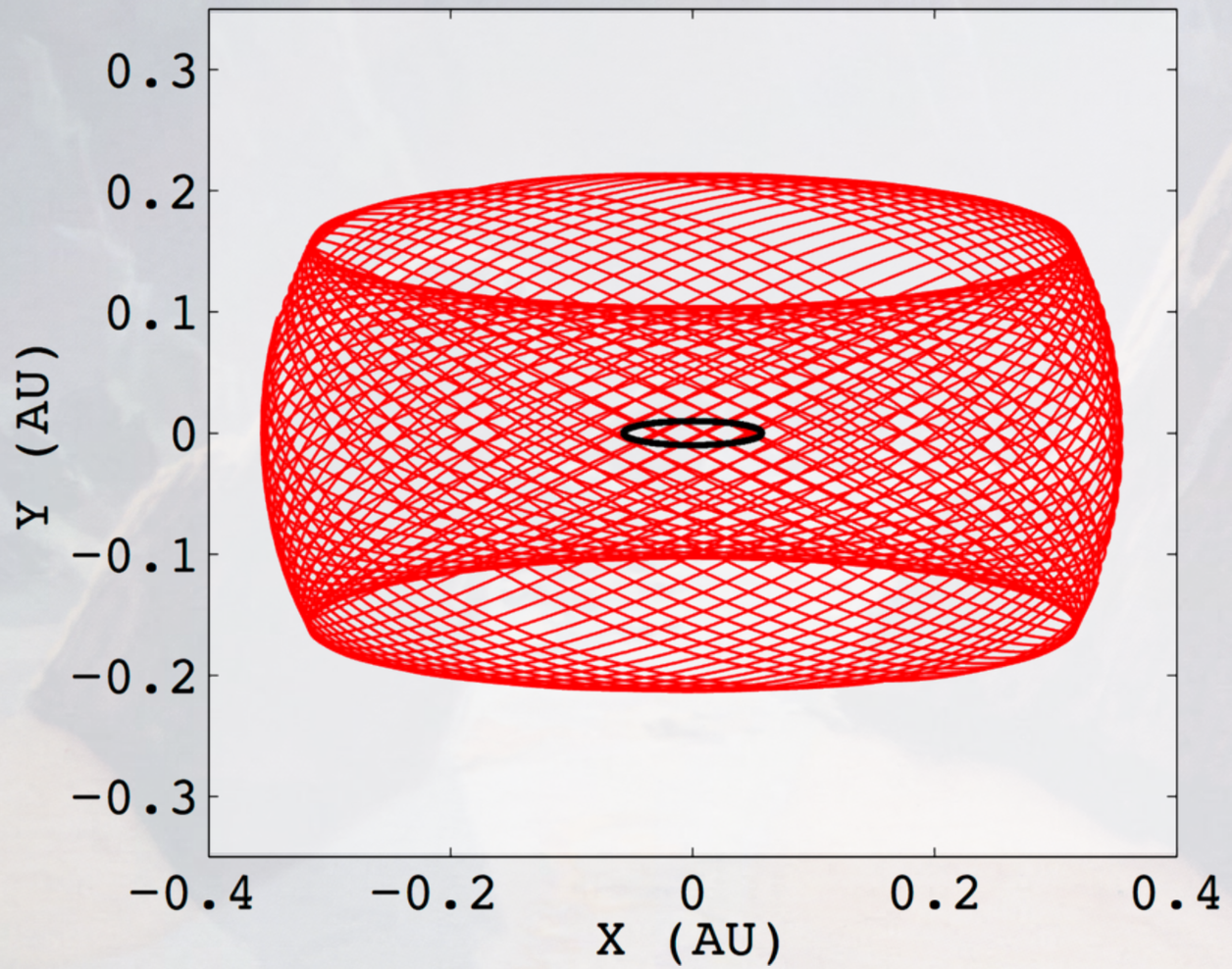
Binaries Escorted By Orbiting Planets

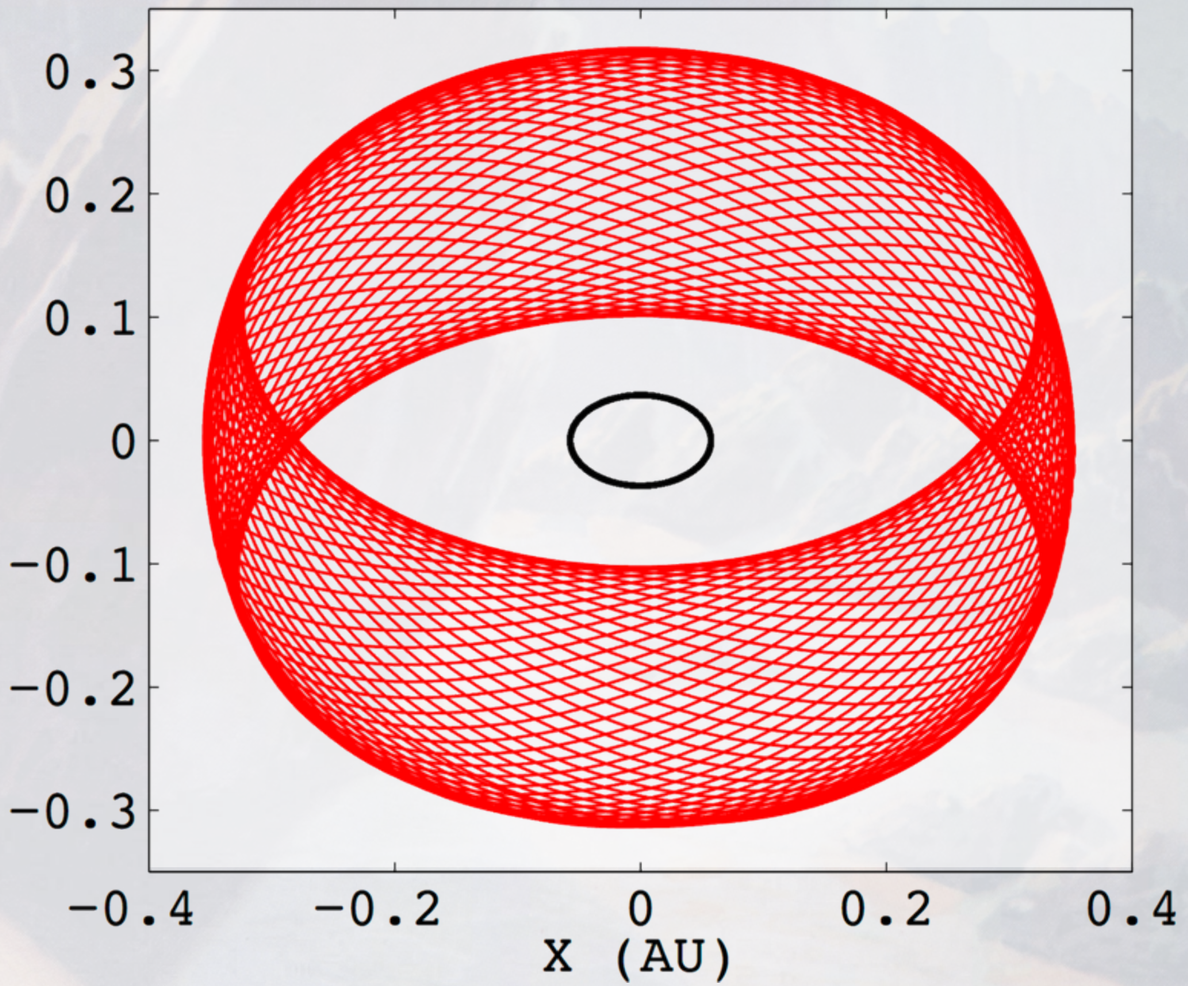
A pile-up at $6\,P_{\rm bin}$





ORBITAL INCLINATION = LARGE SOLID ANGLE

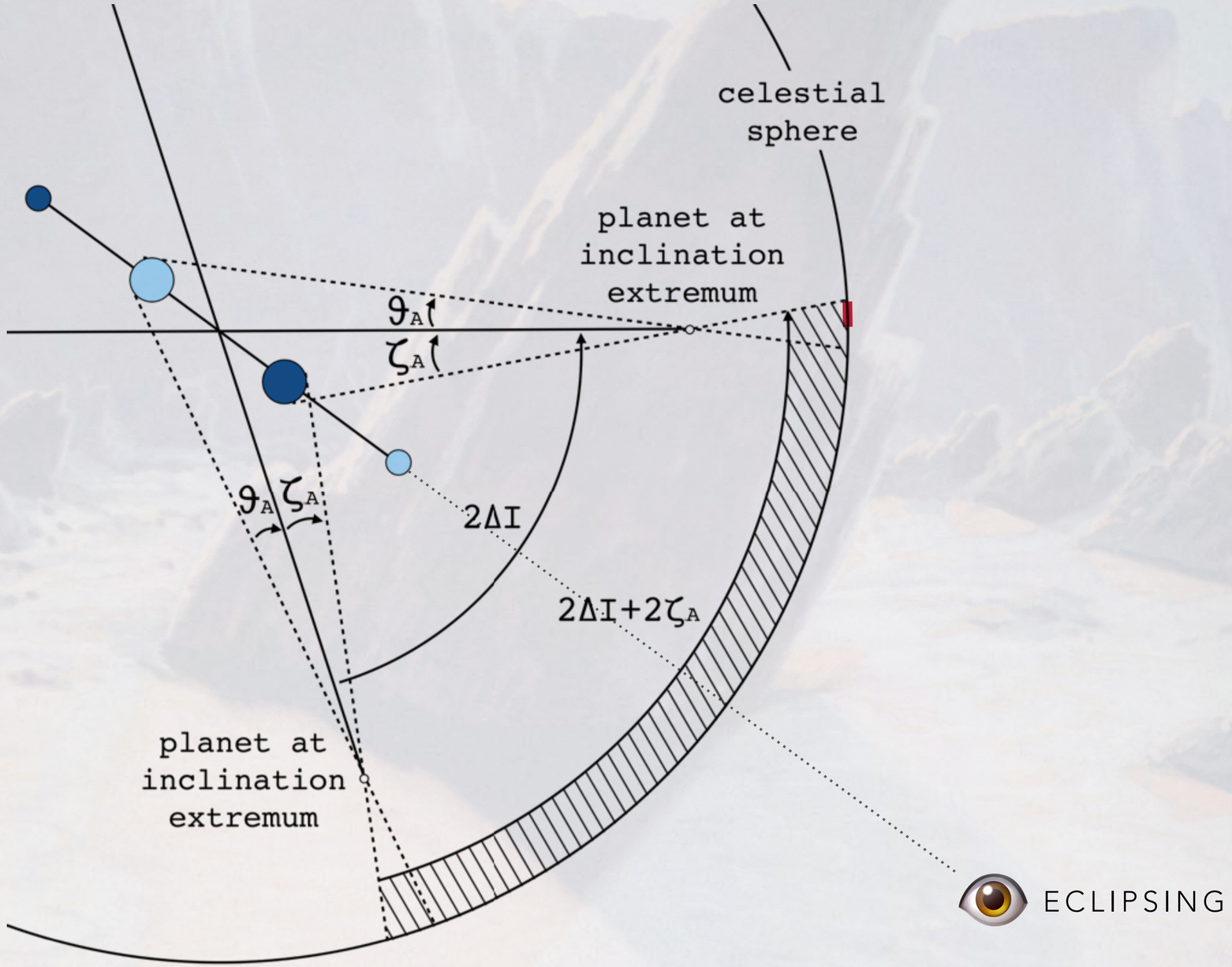




MARTIN & TRIAUD 2014

FOR $\Delta I > 0.6°$

AN IMPROVED PROBABILITY OF TRANSIT

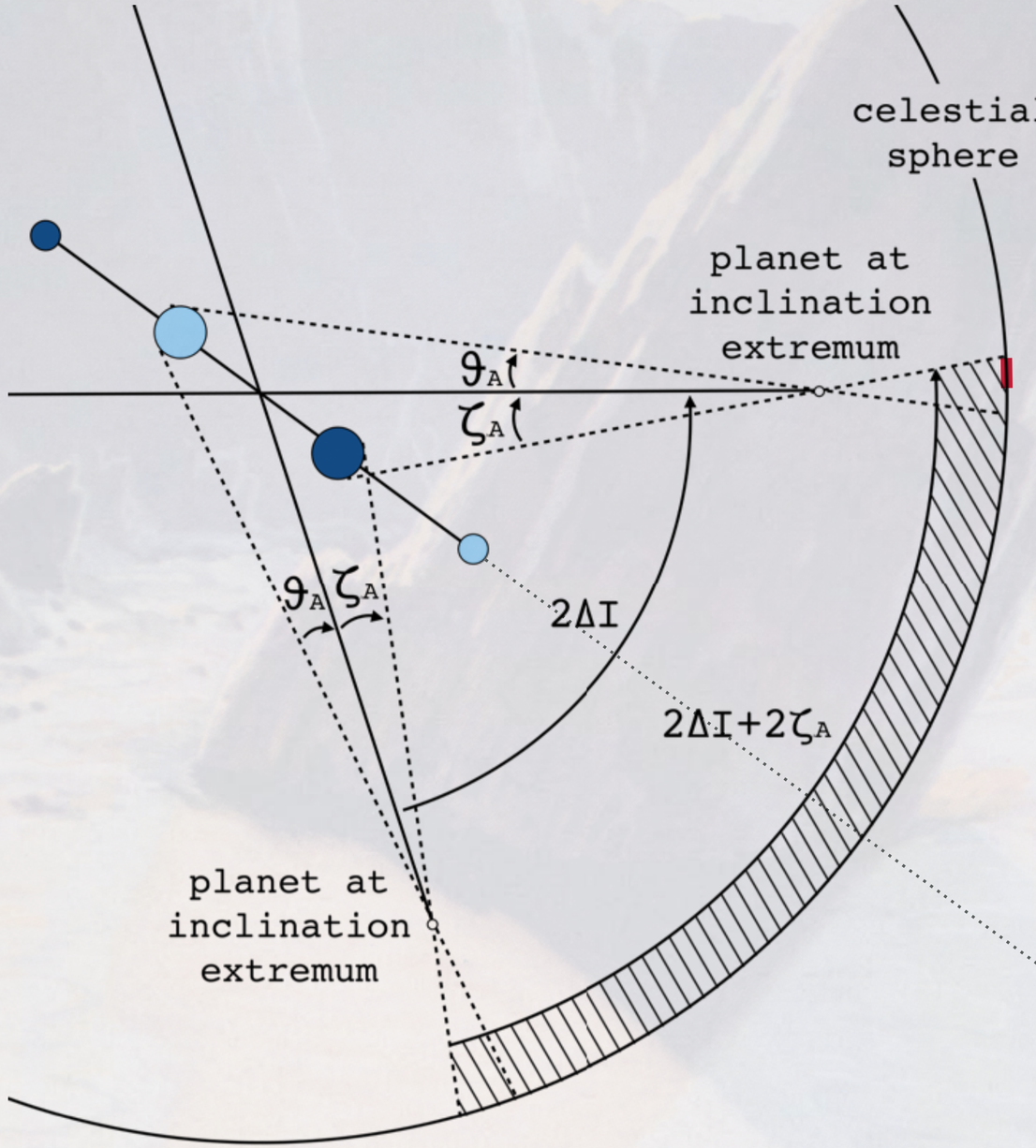


$$\mathscr{P} \sim \sin \Delta i$$

MARTIN & TRIAUD 2015

AN IMPROVED PROBABILITY OF TRANSIT

FOR $\Delta I > 0.6°$



$$\mathscr{P} \sim \sin \Delta i$$

ECLIPSING

MARTIN & TRIAUD 2015

FOR $\Delta I > 0.6°$

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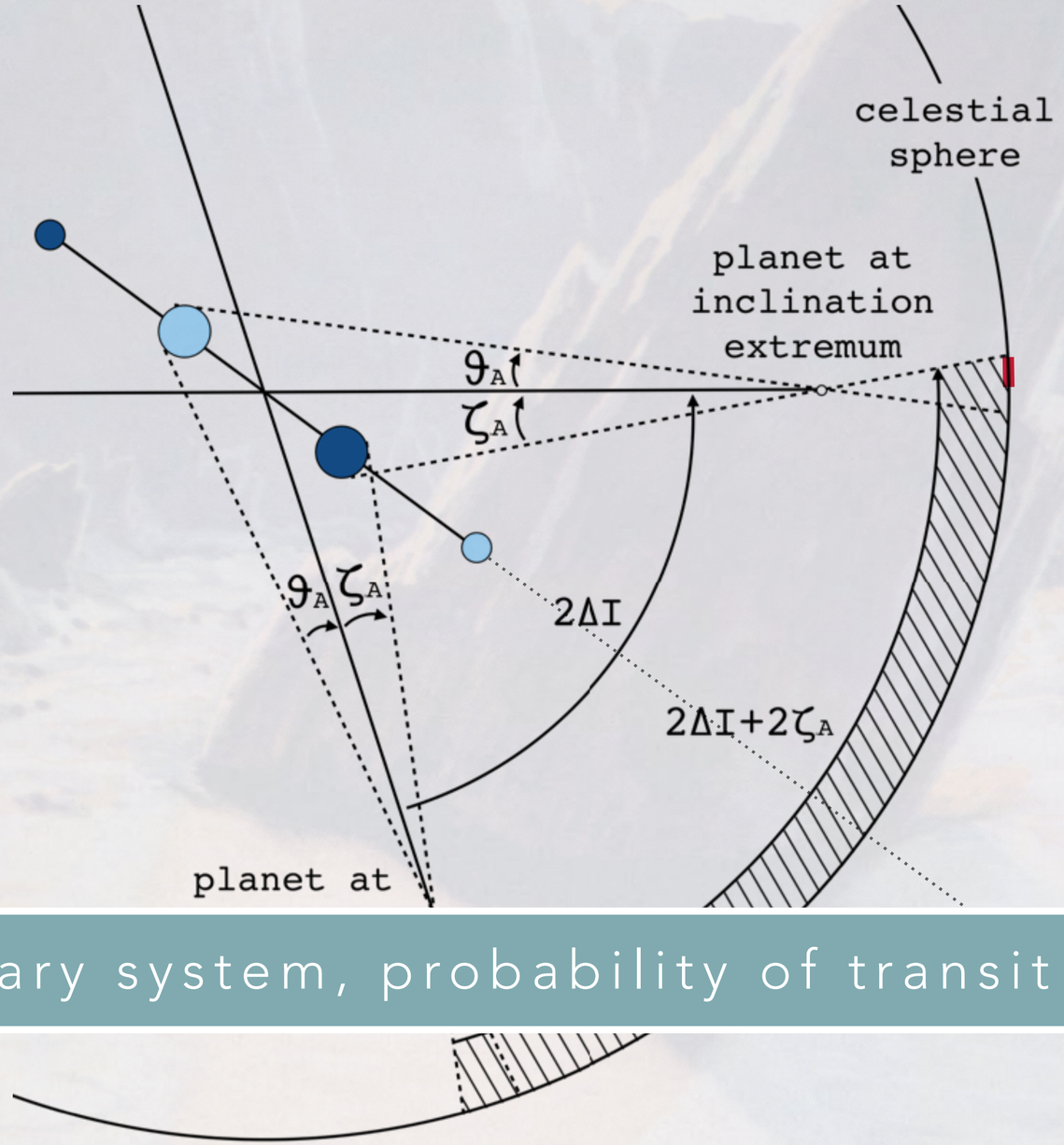
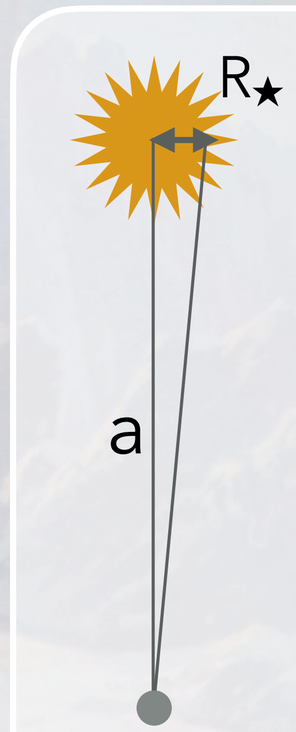


$$\mathscr{P} \sim \sin \Delta i$$



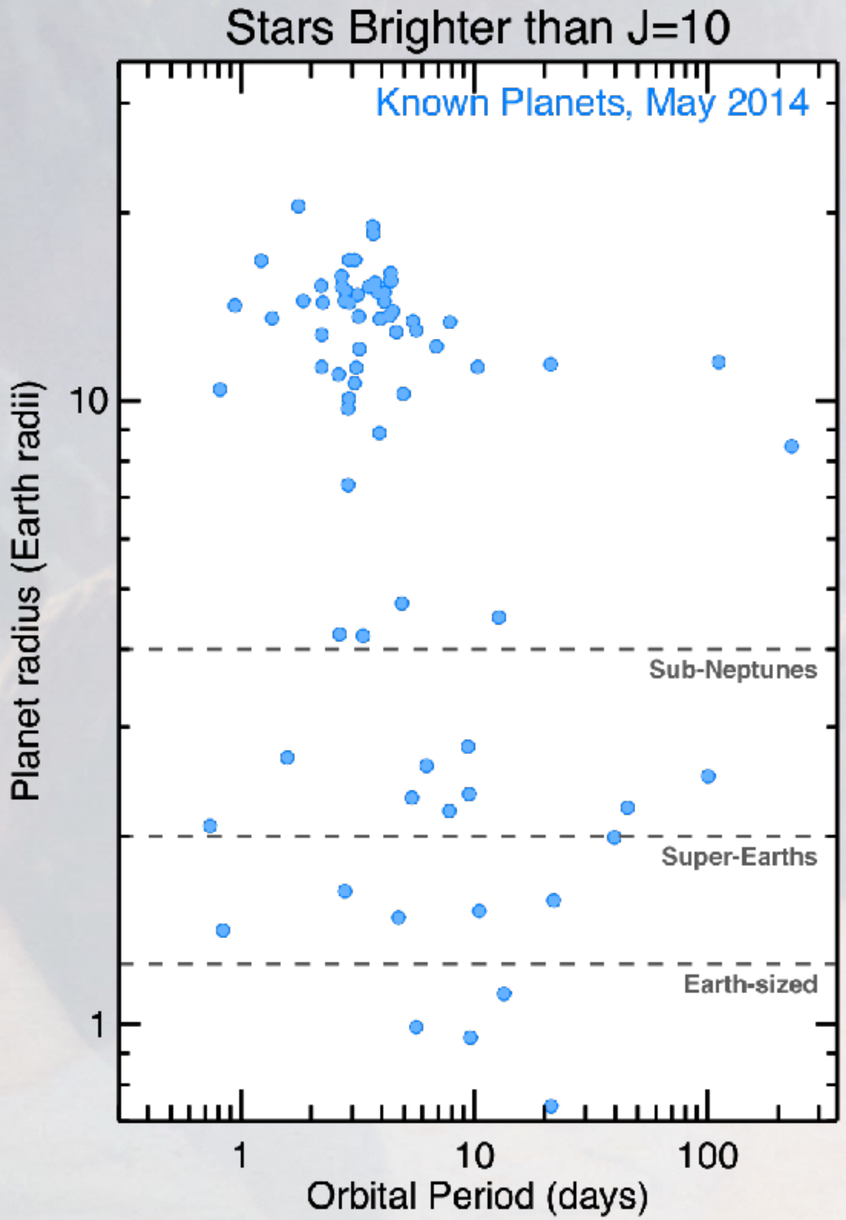
$$\mathscr{P} \sim R_\star / a$$

For **eclipsing** binary system, probability of transit approaches **100%**

ECLIPSING

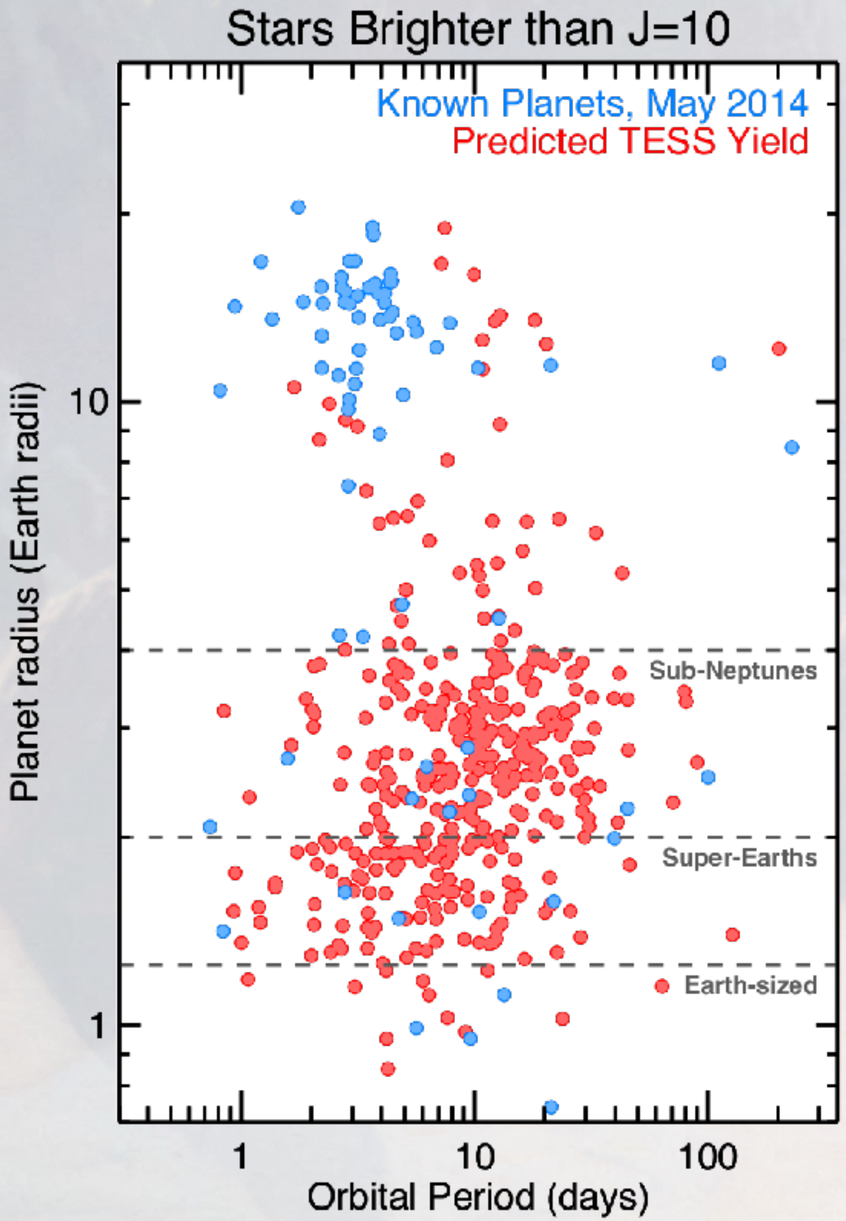
MARTIN & TRIAUD 2015

ACCESSING TEMPERATE PLANETS



RICKER+ 2014

ACCESSING TEMPERATE PLANETS



Projected results by TESS

very few temperate planets

Compared to the natural frequency of eclipsing binaries, circumbinary planets are over-represented.

RICKER+ 2014

ACCESSING TEMPERATE PLANETS

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

36 published exoplanets, including 4 circumbinary planets

RICKER+ 2014

The BEBOP survey: the goals

Binaries Escorted By Orbiting Planets

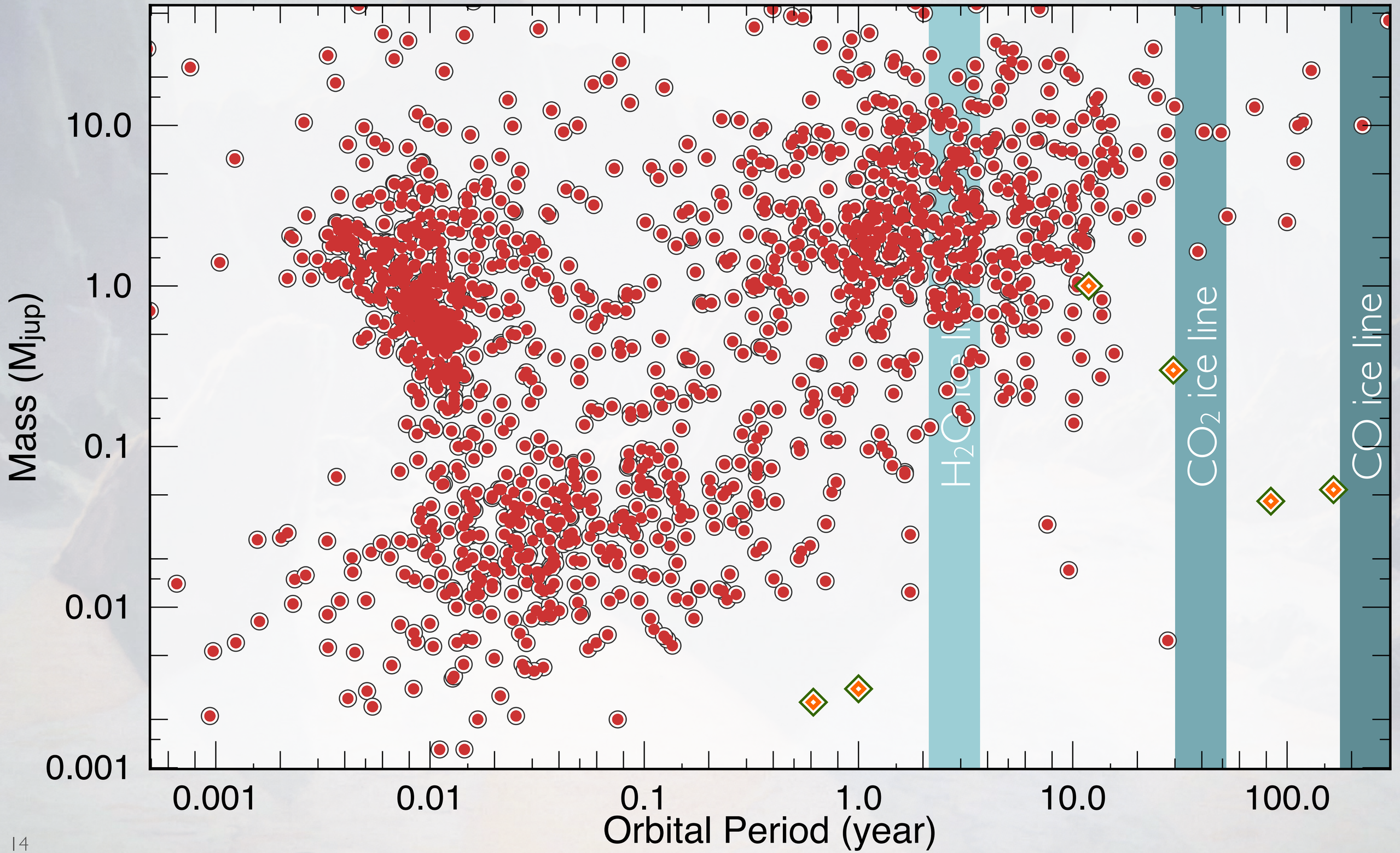
demonstrate circumbinary planets can be detected with RV
for SB1 and SB2

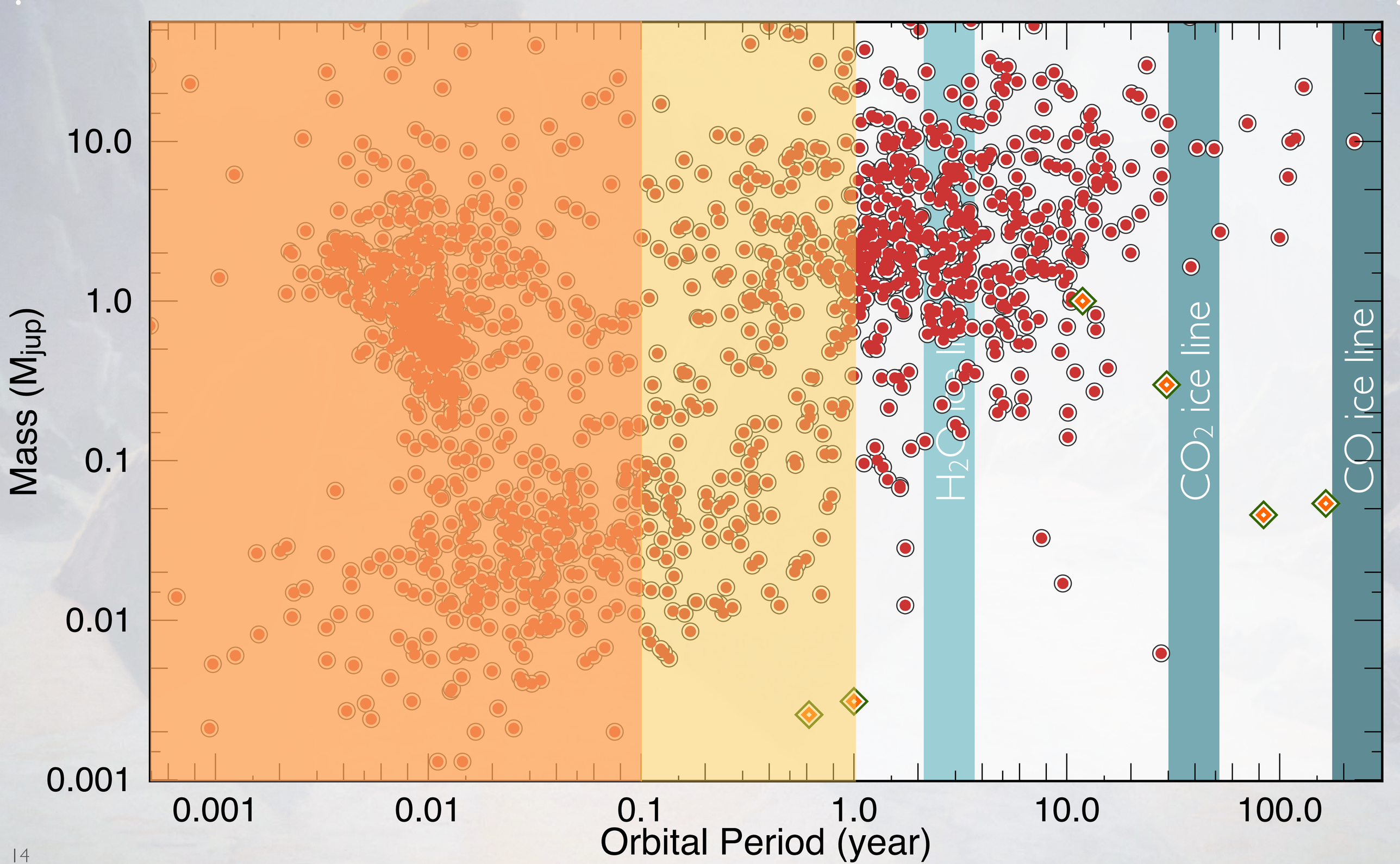
complete a first survey and measure occurrence rates

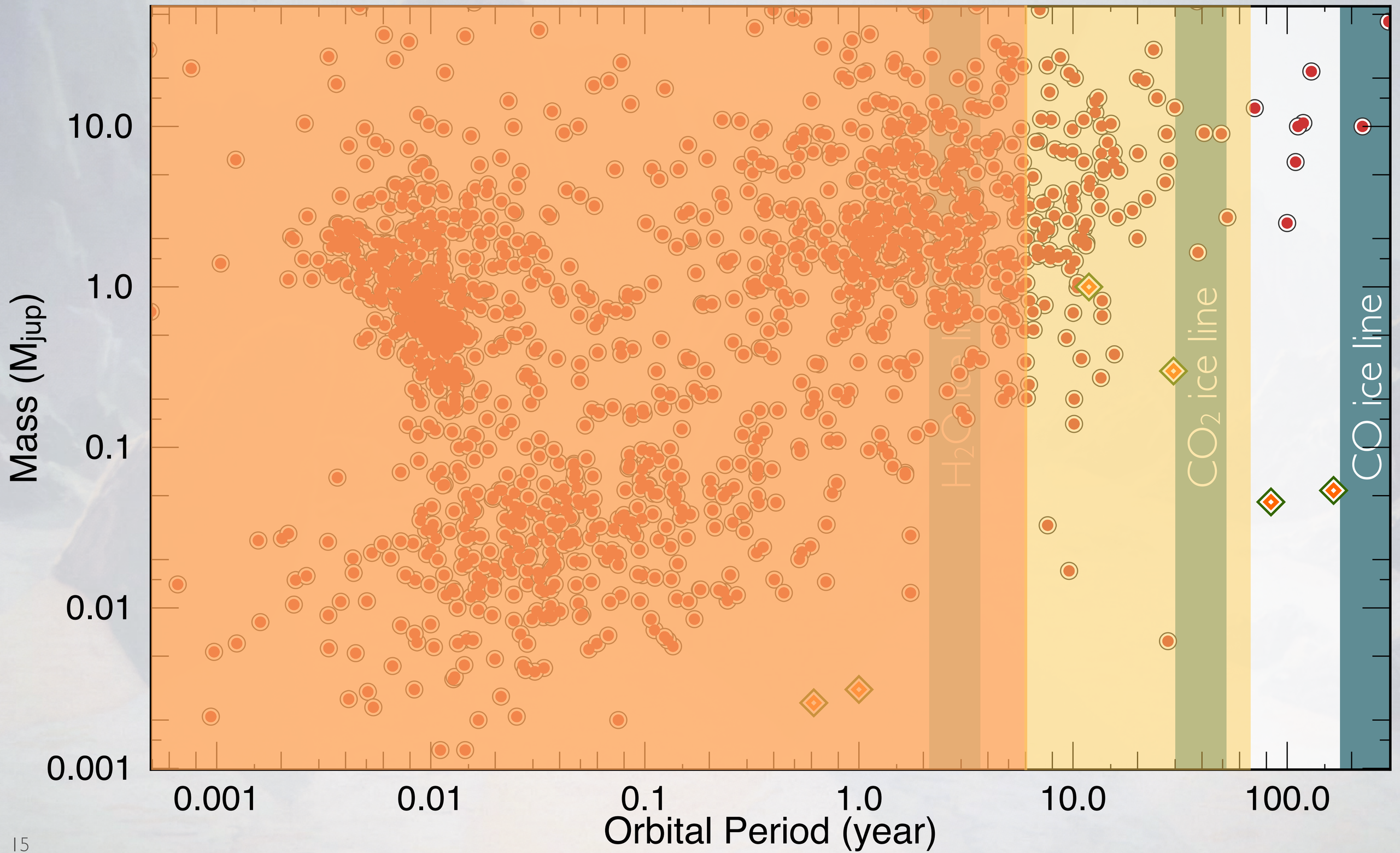
attempt to get dynamical masses of the binary
to get absolute planet masses

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


10.0
1.0
0.1
0.01
0.001
Mass (M_{jup})
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


10.0
1.0
0.1
0.01
0.001
Mass (Mjup)
0.001
0.01
0.1
1.0
10.0
100.0
Orbital Period (year)
H2O ice line
CO2 ice line
CO ice line


10.0
1.0
0.1
0.01
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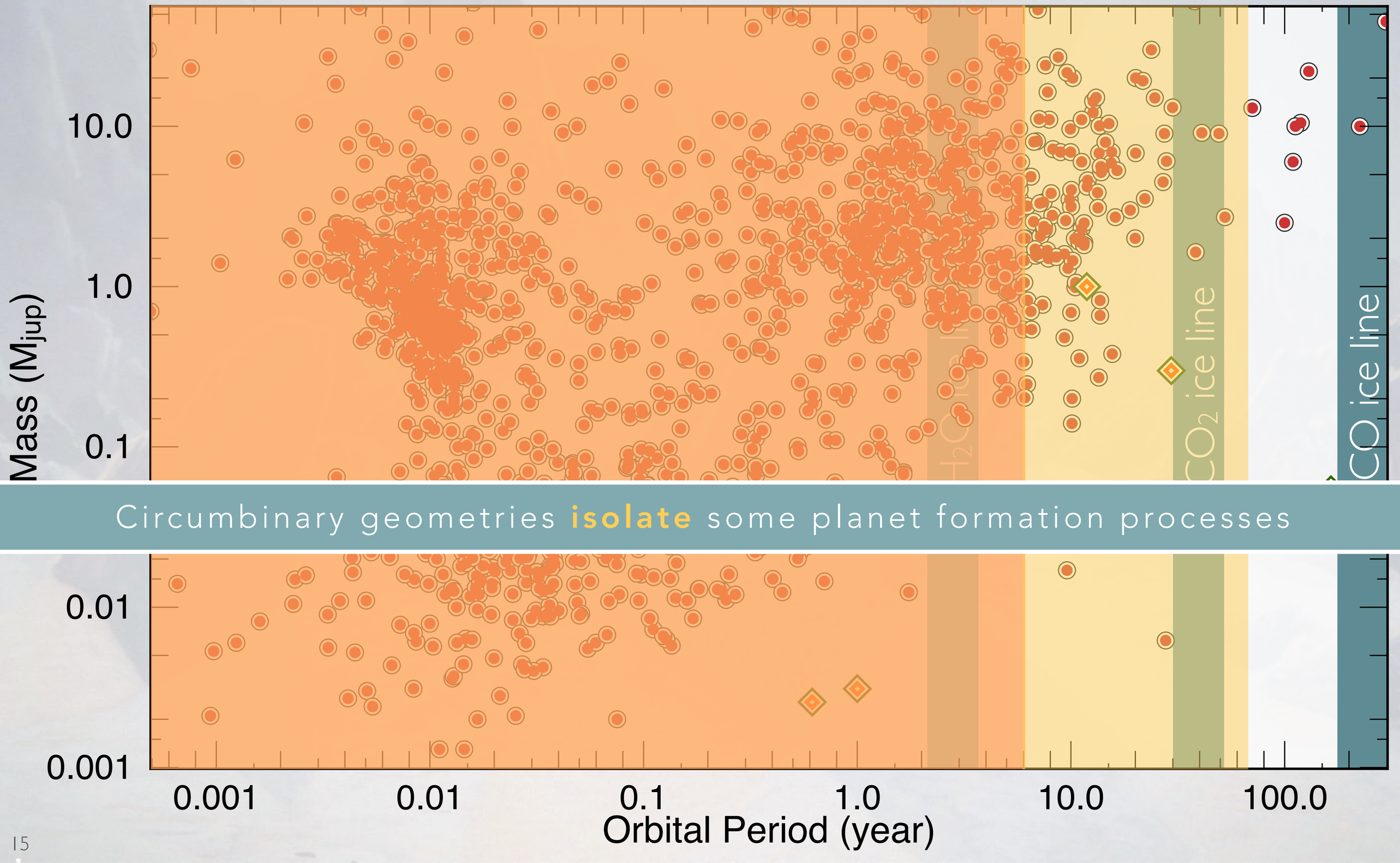


Circumbinary geometries **isolate** some planet formation processes

THE BEBOP SURVEY: WHAT DID WE DO

BINARIES ESCORTED BY ORBITING PLANETS

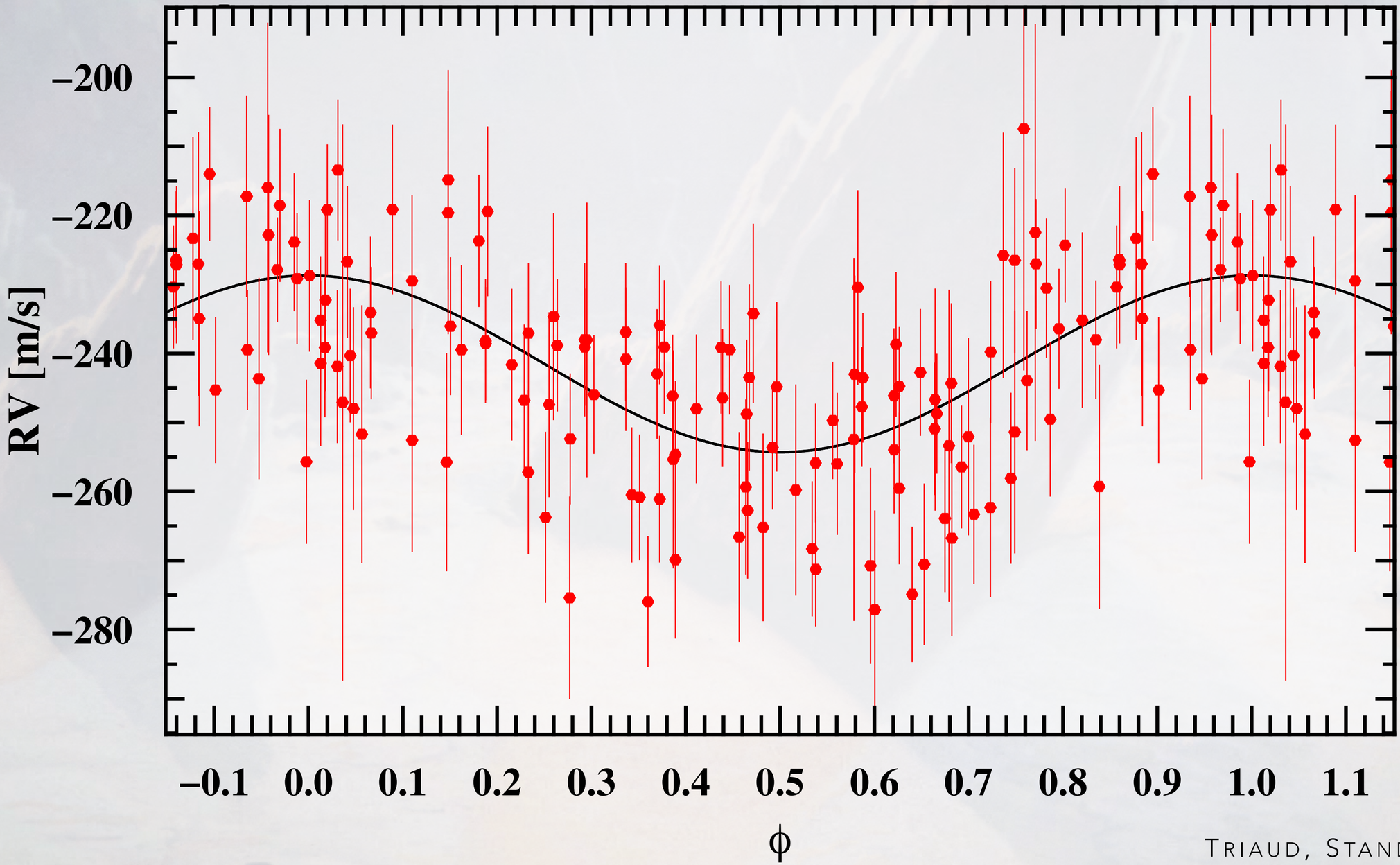
We monitored intensively ~110 binaries with $5 < P_{\rm bin} < 70\,{\rm d}$

We collected 3700 spectra with SOPHIE (North) and
2300 with HARPS (South)

We also monitored 10 SB2 systems
(6 from Konacki, TIC 172, and 3 Kepler ETV systems)
to do some R&D and solve the SB2 problem

BEBOP milestones: Kepler-16

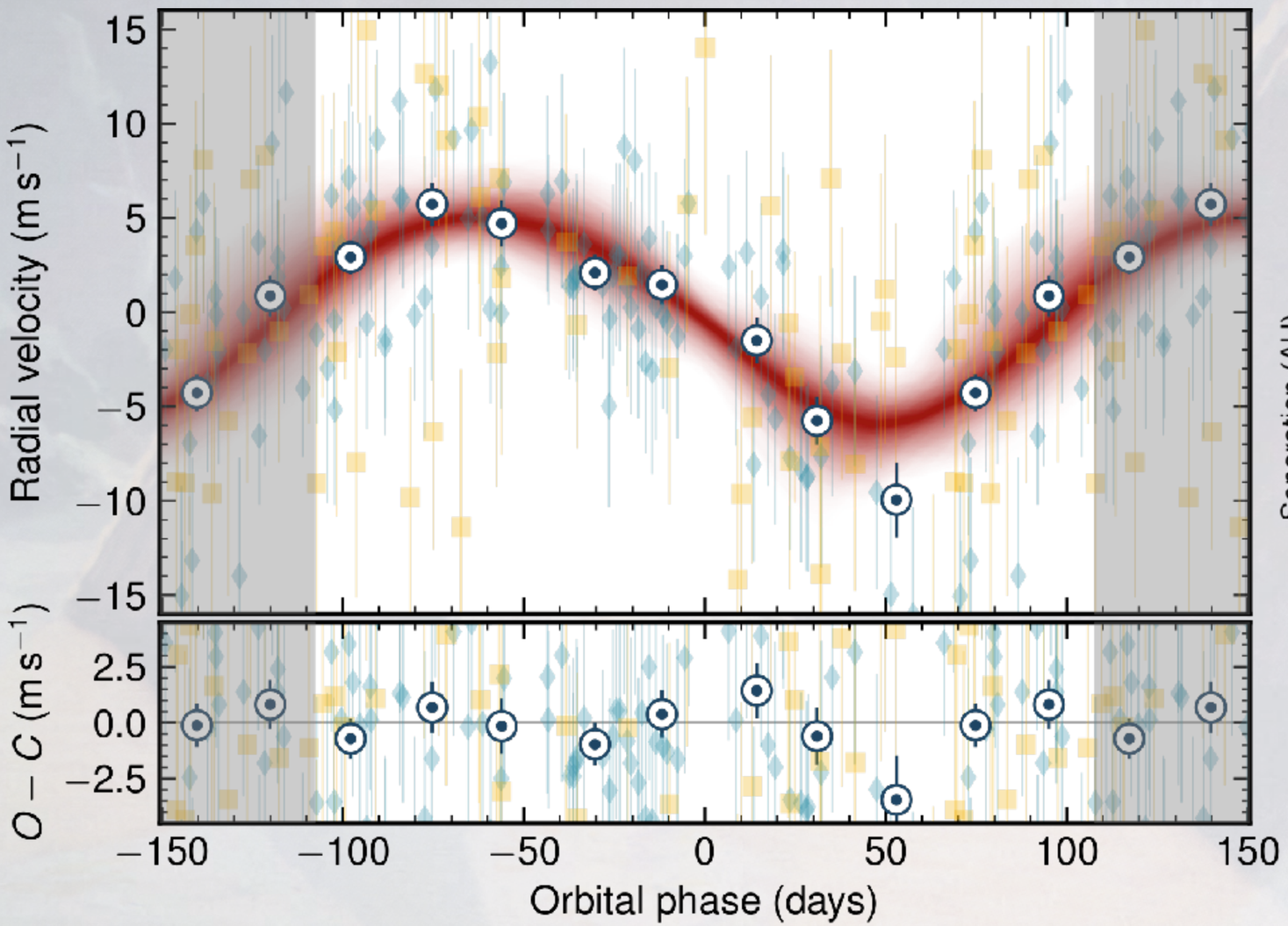
Binaries Escorted By Orbiting Planets

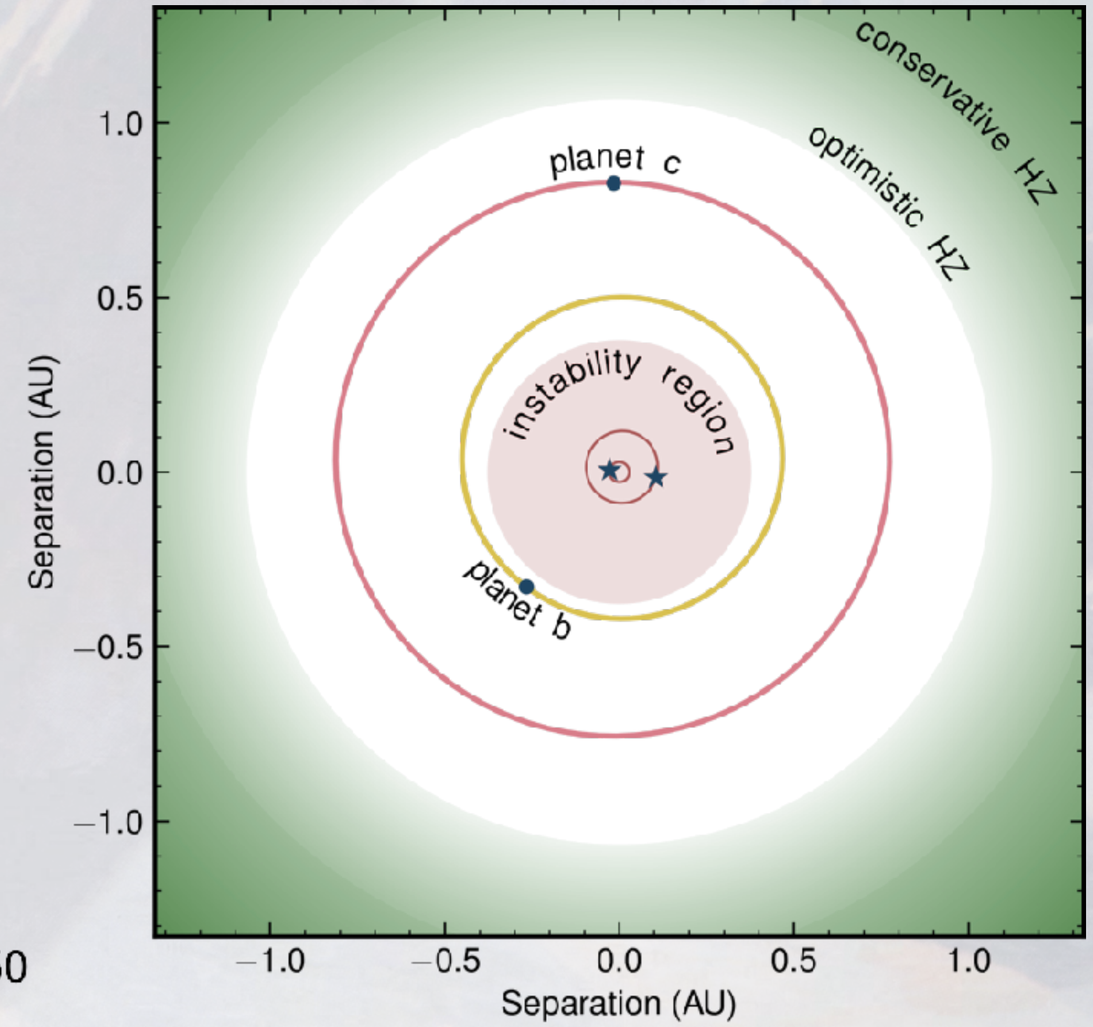


Triaud, Standing et al. 2022

BEBOP MILESTONES: TOI-1338 / BEBOP-1

BINARIES ESCORTED BY ORBITING PLANETS





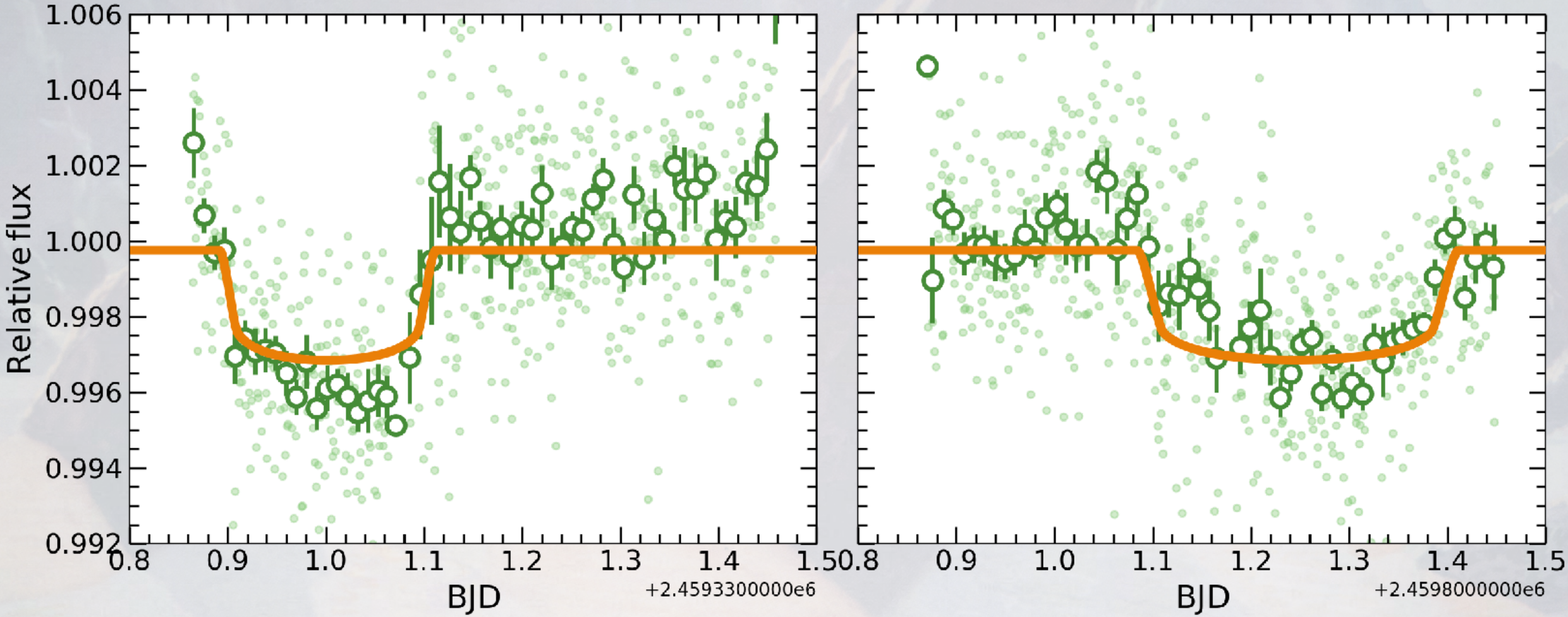
$P_b = 95$ d, $R_b = 6.9$ $R_\oplus$, $M_b < 22$ $M_\oplus$

$P_c = 215$ d, $M_c = 65$ $M_\oplus$

STANDING, LALITHA ET AL. 2023

BEBOP MILESTONES: CIRCUMBINARY TRANSITS

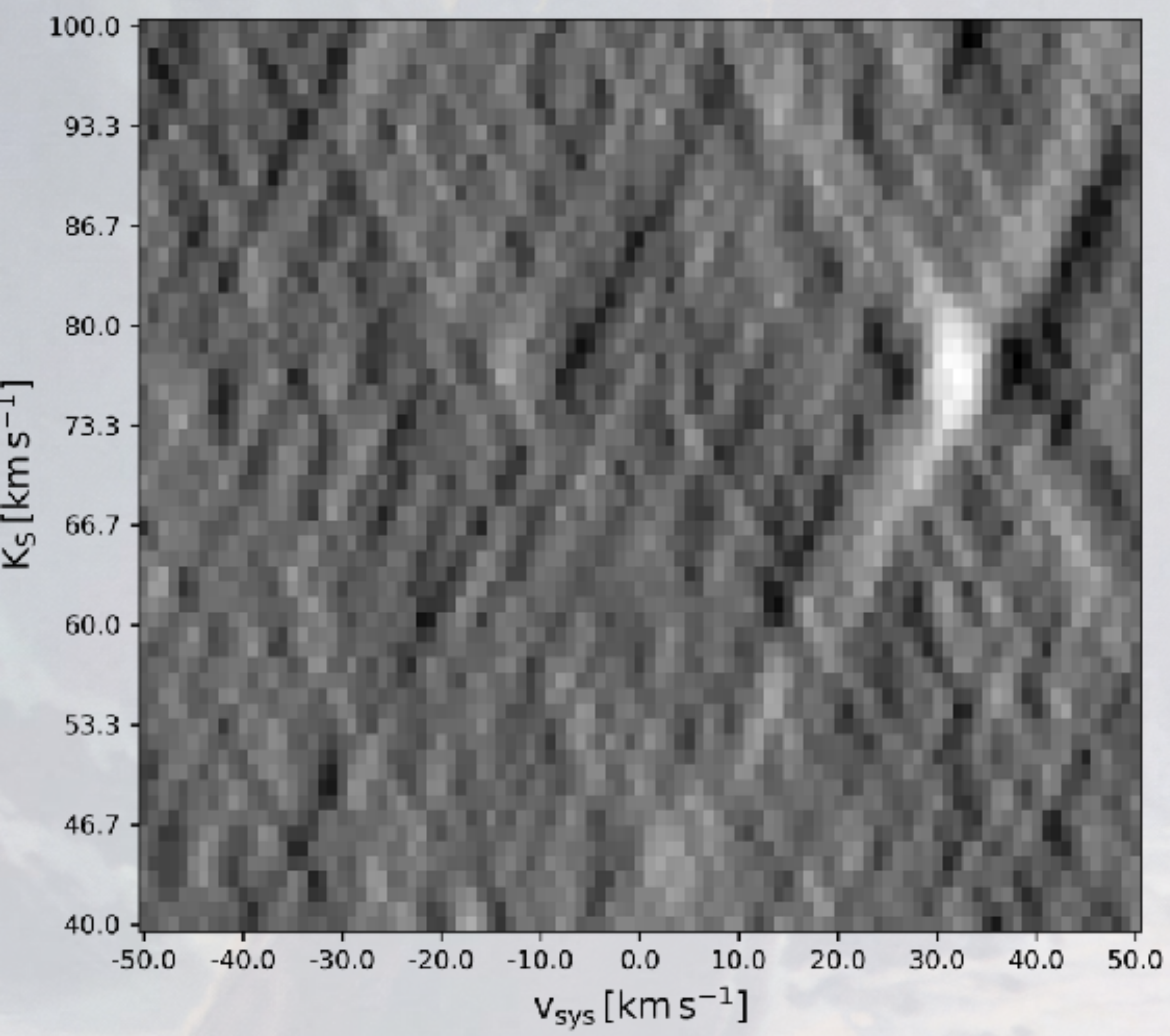
TOI-1338 / BEBOP-1b - from Antarctica

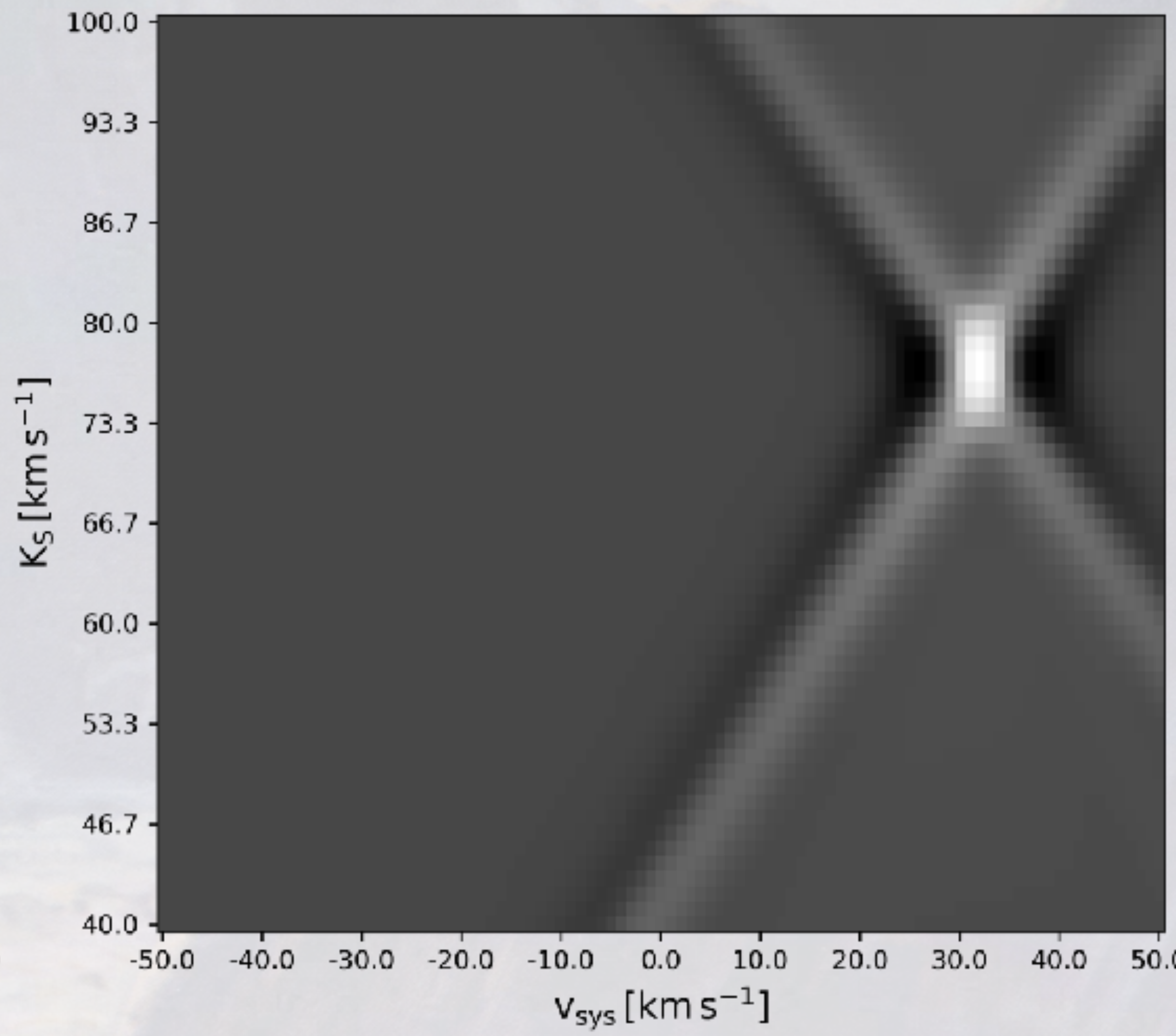


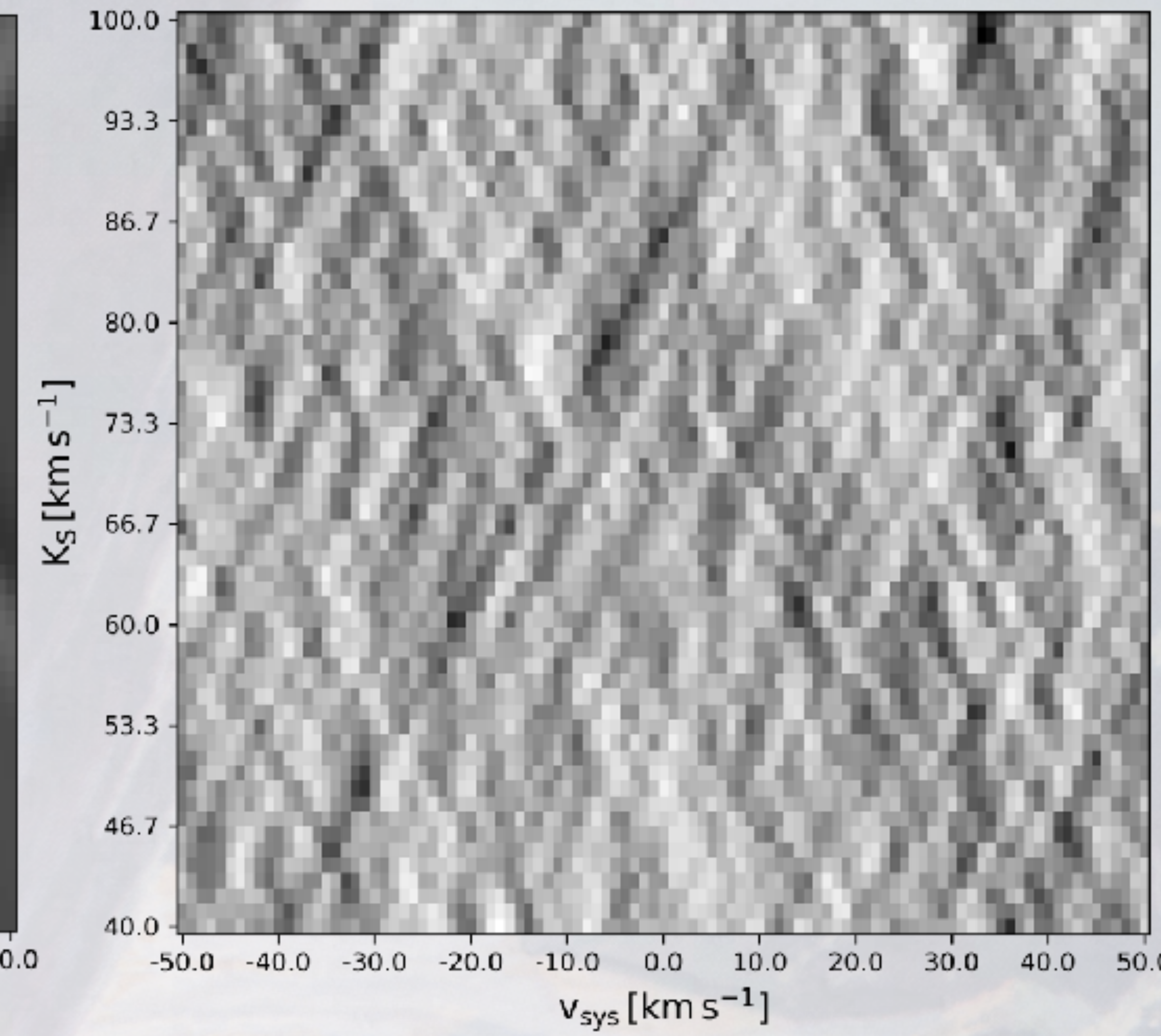
Transits are 5hr and 10hr long, with TTVs of ~10hrs

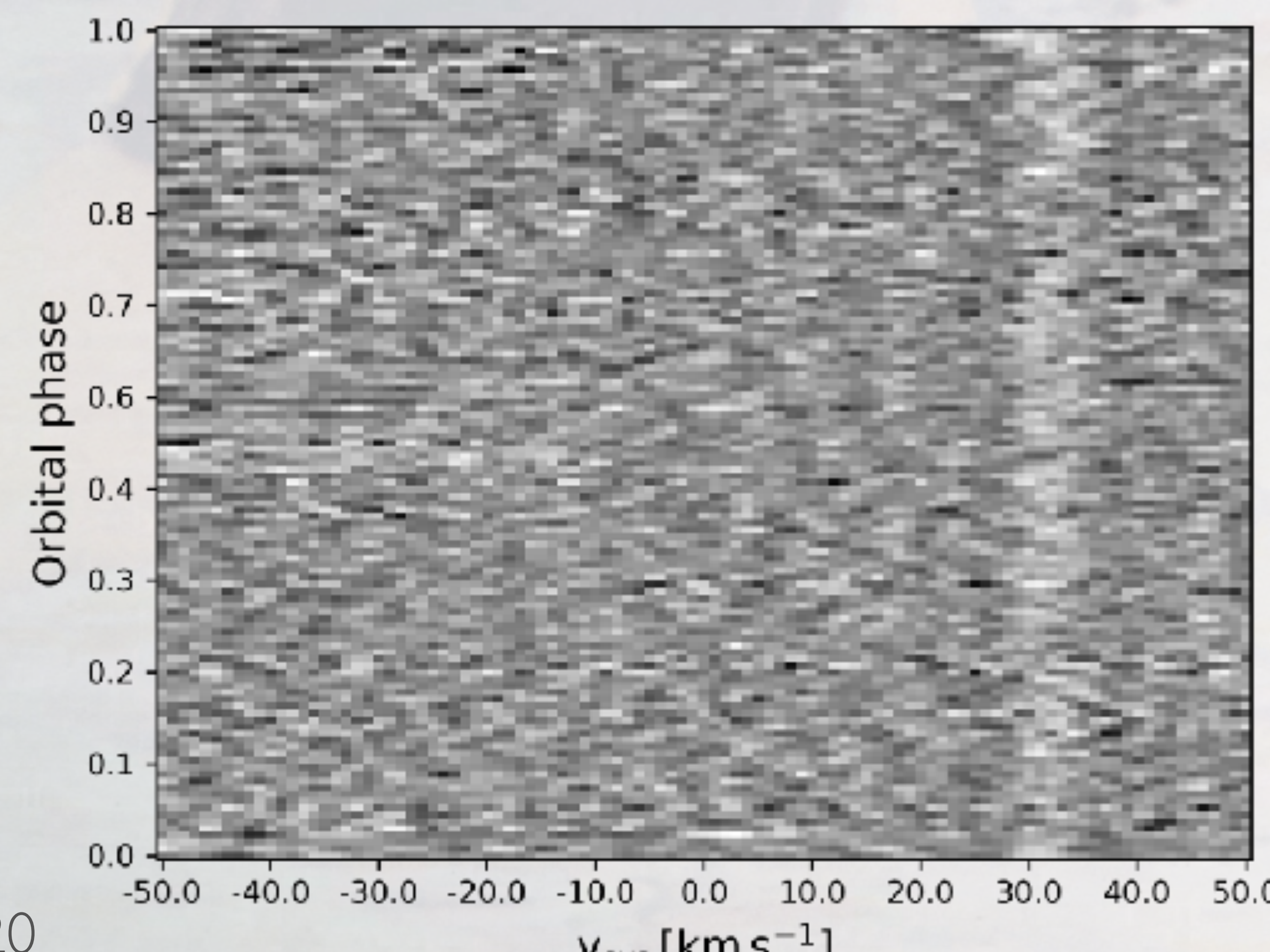
TRIAUD, OROSZ ET AL. IN PREP

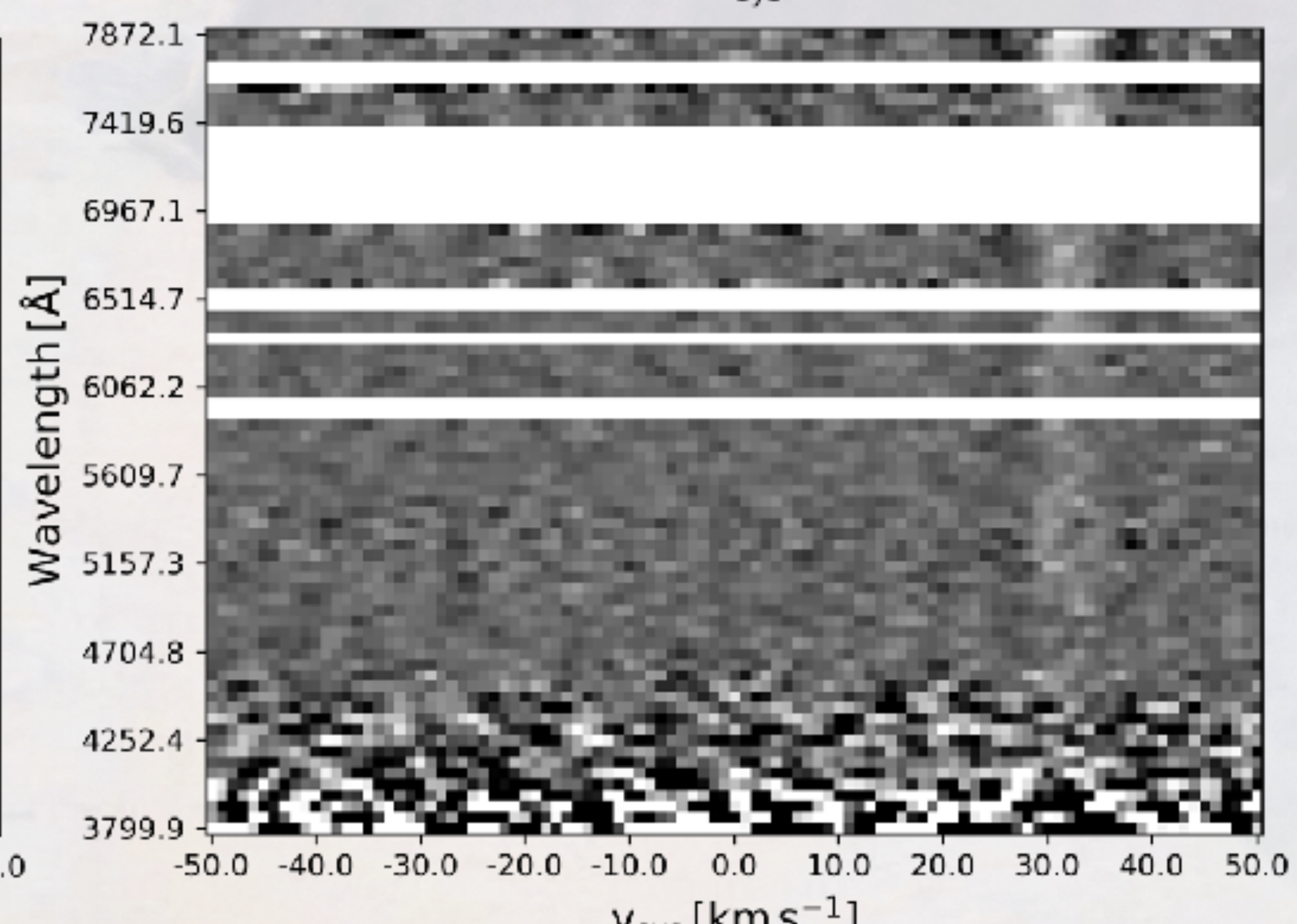
BEBOP MILESTONES: ABSOLUTE MASSES









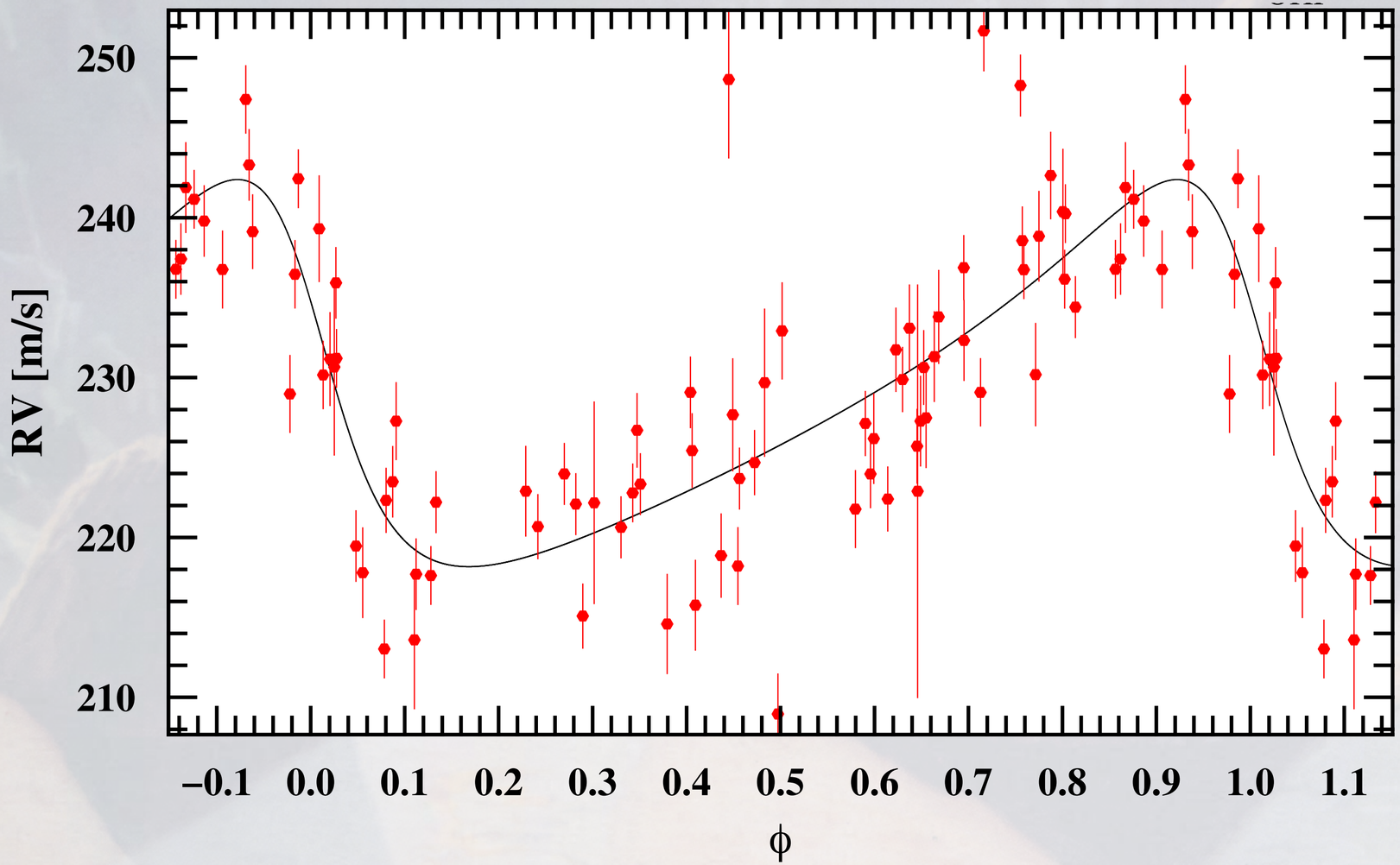


Using Singular Value Decomposition (SVD)
⇒ retrieval of the weak lines of the secondary star
⇒ mass with 0.1% precision

SEBASTIAN, TRIAUD ET AL. 2024

BEBOP RESULTS: BEBOP-3 - ECCENTRIC

BINARIES ESCORTED BY ORBITING PLANETS



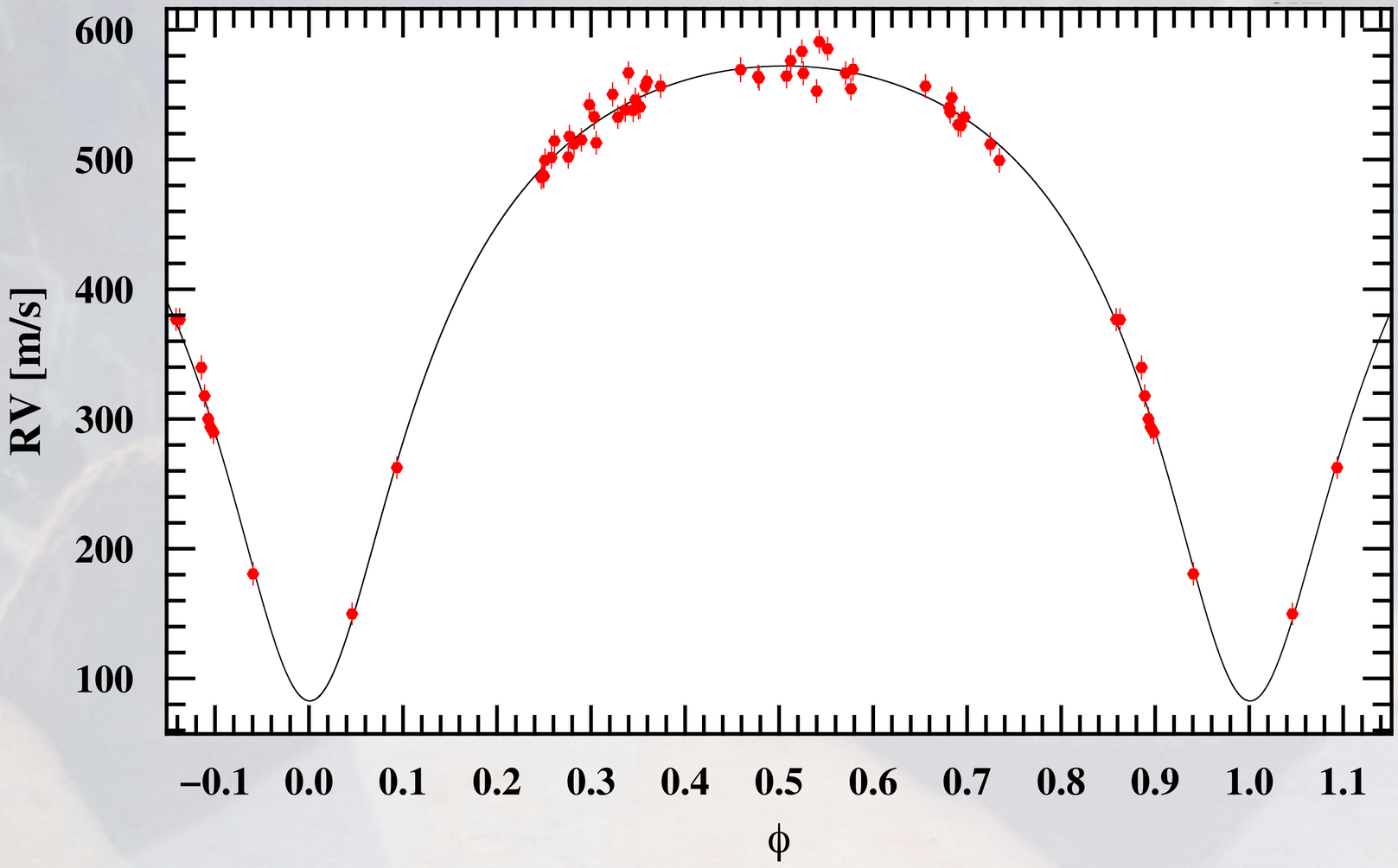
$M_1 = 1.0$ Msol
$M_2 = 0.22$ Msol
$P_{bin} = 13$d
$e = 0.12$

P [days]	: 562.679	$a_1.\sin(i)$ [1E−3 au]	= 0.56353
e	: 0.436	f(m) [1E−9 Msol]	= 0.07541
ω [deg.]	: 68.2	m_1 [Msol]	=1.00
phi_0	: 59674.25	$m_2.\sin(i)$	= 0.44262[M_{jup}], 8.178[M_{nept}], 140.67[M_{earth}]
K1 [m/s]	: 12.1	a (relative orbit)[au]	= 1.334

BAYCROFT, TRIAUD ET AL. IN PREP

BEBOP RESULTS: BEBOP-4 - A BROWN DWARF

BINARIES ESCORTED BY ORBITING PLANETS



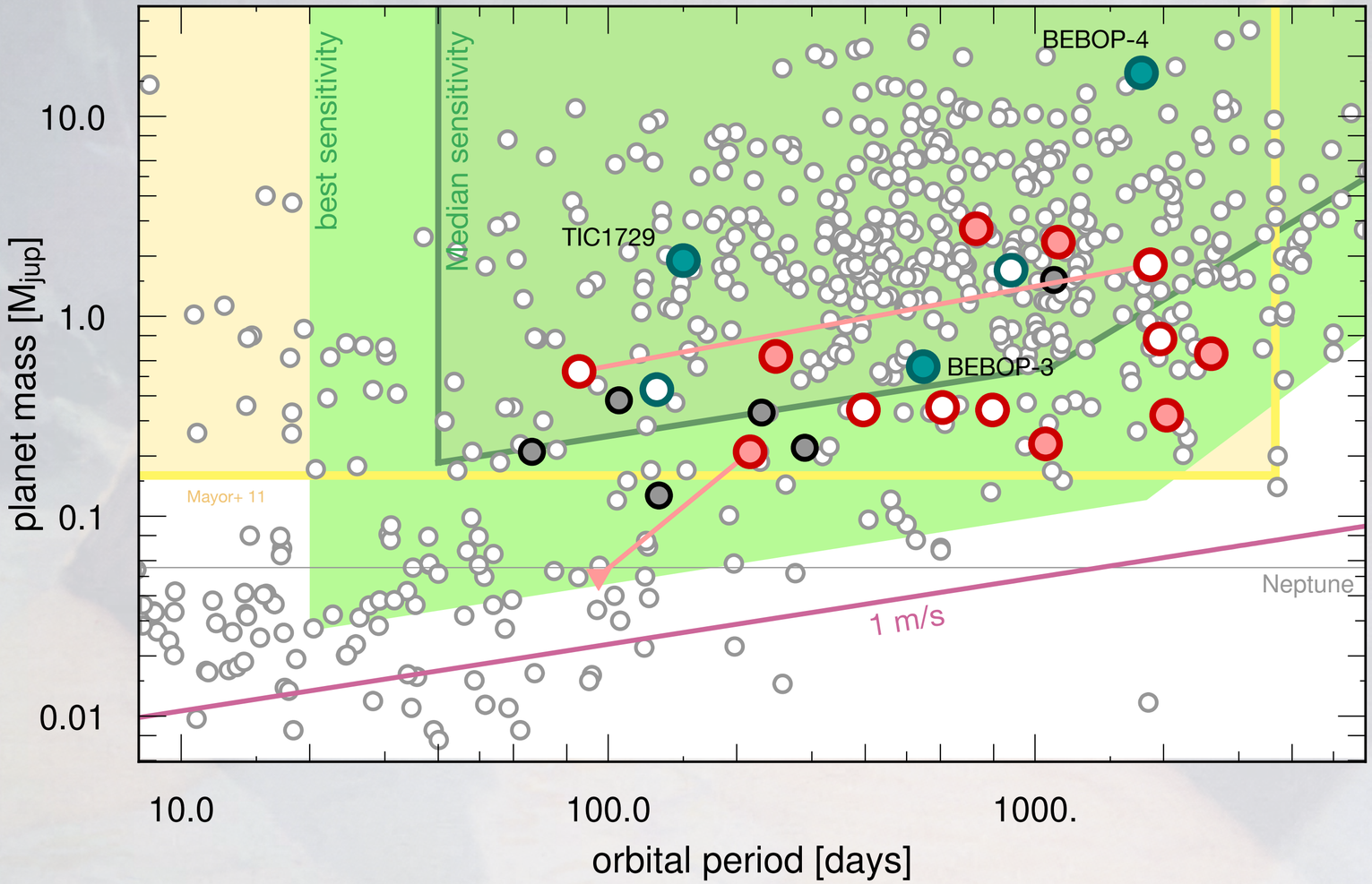
$M_1 = 1.1$ Msol
$M_2 = 0.35$ Msol
$P_{bin} = 72$d
$e = 0.27$

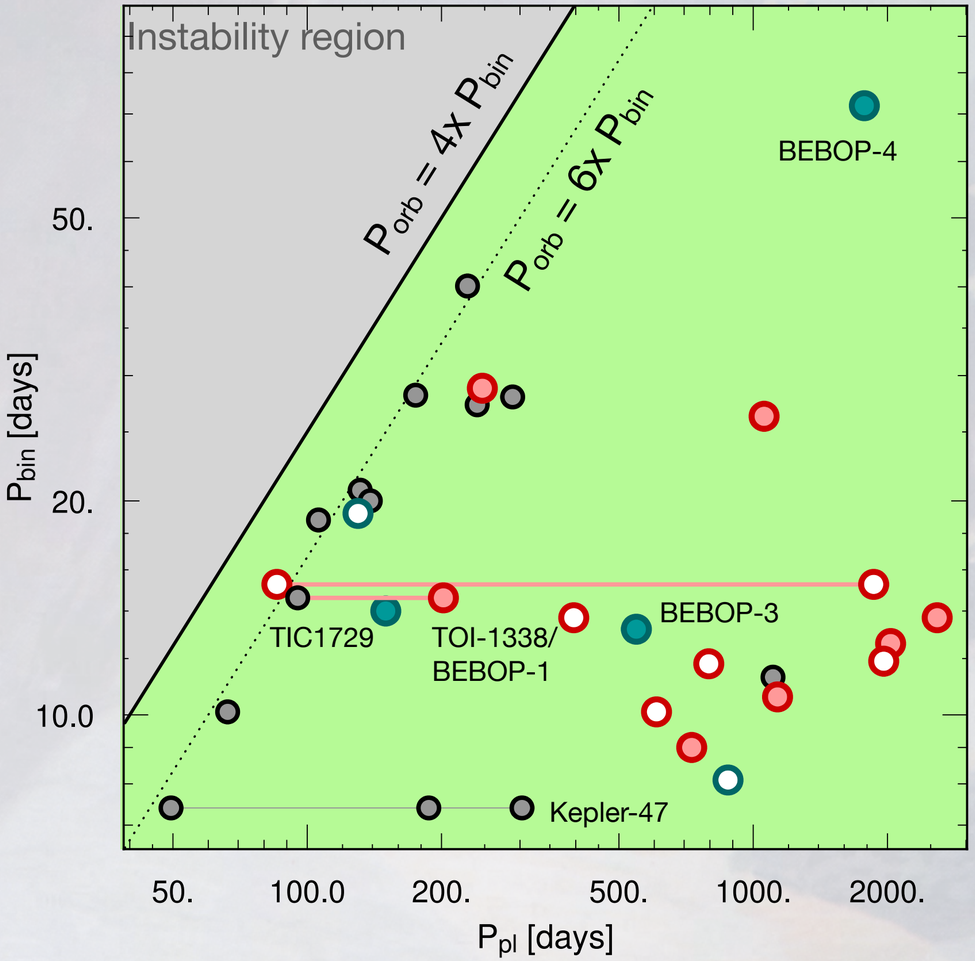
P [days]	: 1778.716	$a_1.\sin(i)$ [1E−3 au]	= 36.20469
e	: 0.426	f(m) [1E−9 Msol]	= 2001.13725
ω [deg.]	: 179.1	m_1 [Msol]	=1.30
phi_0	: 60883.86	$m_2.\sin(i)$	= 15.72574[M_{jup}], 290.560[M_{nept}], 4997.64[M_{earth}]
K1 [m/s]	: 244.7	a (relative orbit)[au]	= 3.148

TRIAUD, BAYCROFT ET AL. IN PREP

BEBOP RESULTS: THE EMERGING POPULATION

BINARIES ESCORTED BY ORBITING PLANETS





BEBOP - PHASE I: PRELIMINARY RESULTS

BINARIES ESCORTED BY ORBITING PLANETS

Circumbinary planets can be detected with RVs in SB1s

Physical properties

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

Orbital properties

Circumbinary planets can have significant eccentricities

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

Big result

RV and transit circumbinary planet population are different.

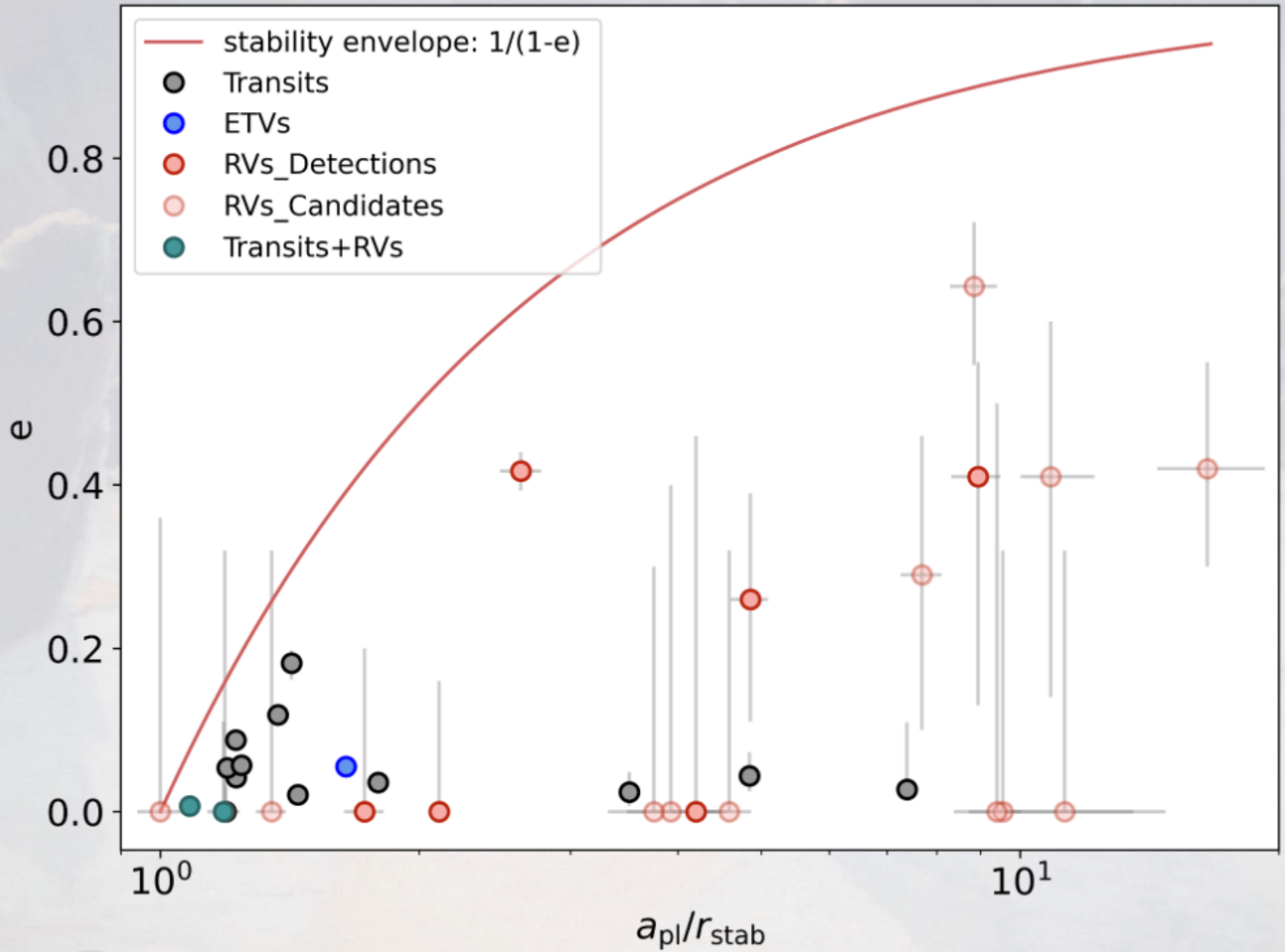
Solution? **Icy planets with low masses and large radii**

Occurrence rate

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

BEBOP - Phase I: preliminary results

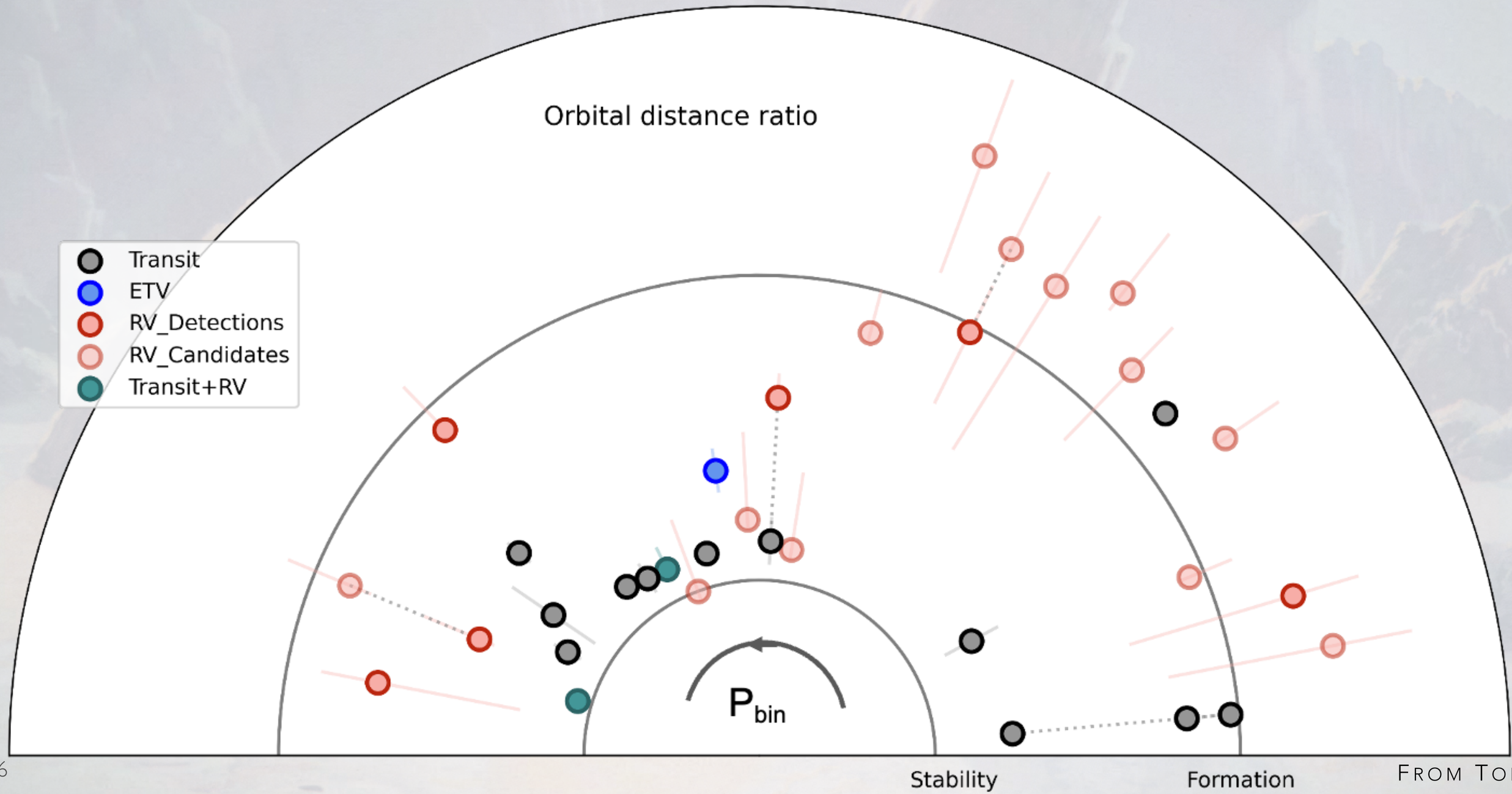
Binaries Escorted By Orbiting Planets



From Tom

BEBOP - Phase I: preliminary results

Binaries Escorted By Orbiting Planets



From Tom

BEBOP GOING INTO PHASE II

BINARIES ESCORTED BY ORBITING PLANETS

New goals

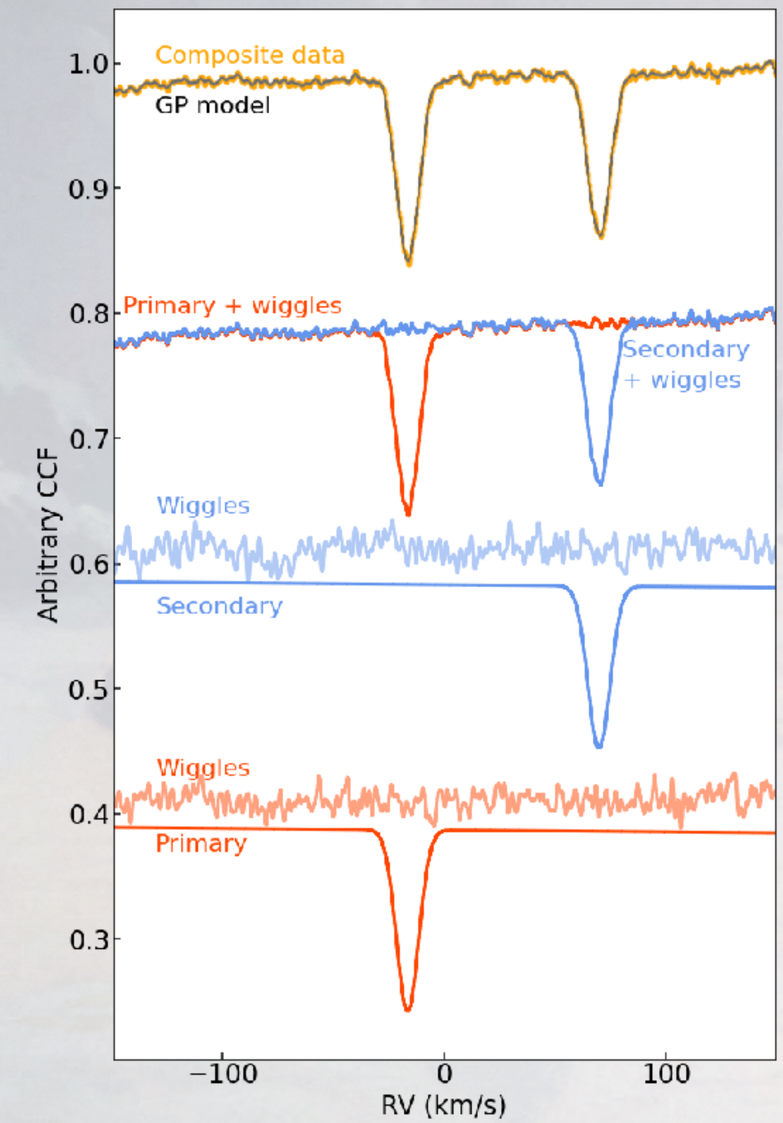
A survey of SB1 and SB2 to compare their planet populations.
Do higher mass systems, have higher mass circumbinary planets?
Solve the transit/RV population dichotomy
Demonstrate a sensitivity to rocky planets

How to reach those goals

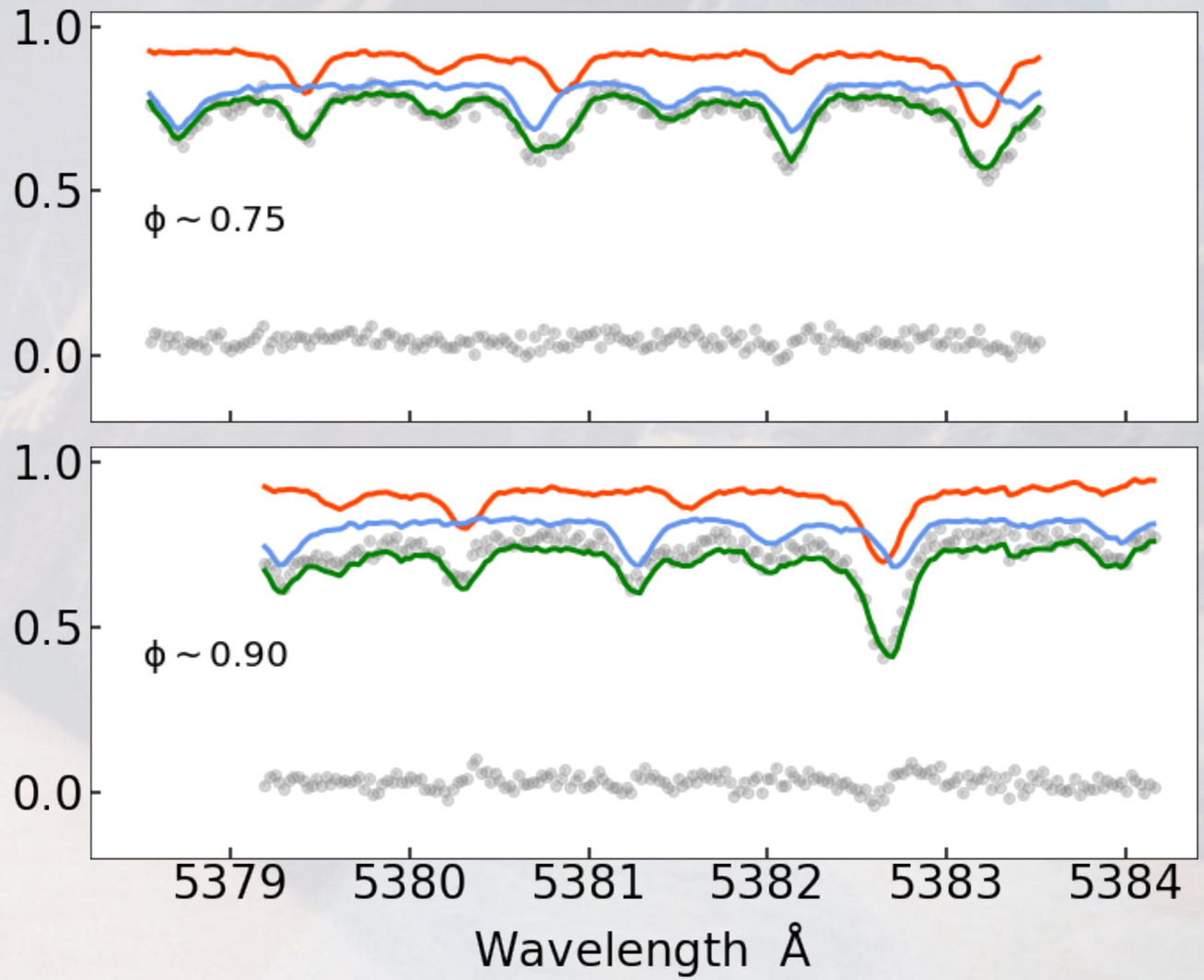
High cadence RV observations => remove stellar activity
Observe SB2 at high RV precision and accuracy (brighter systems)

DETECTING CIRCUMBINARY PLANETS
in double-lined systems

DOLBY-CCF



DOLBY-SD



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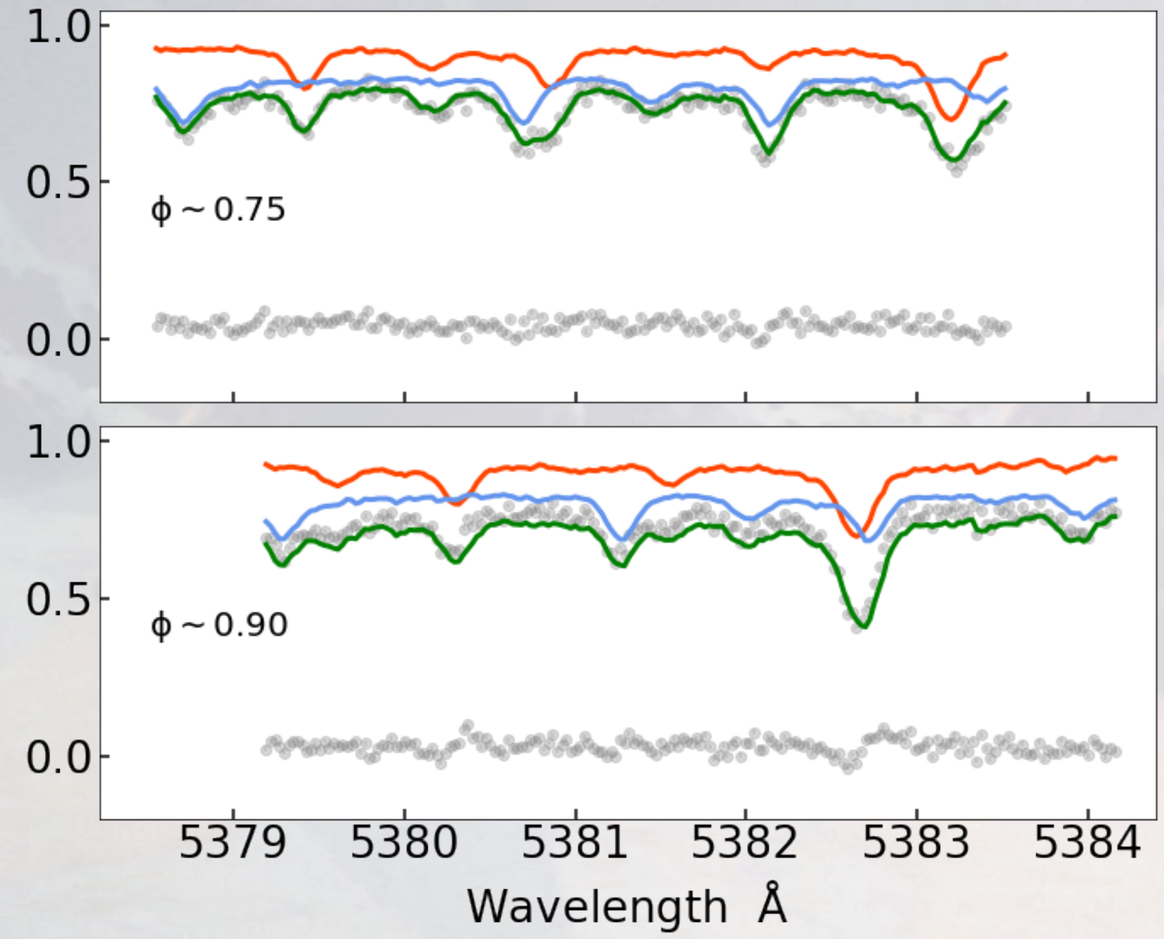
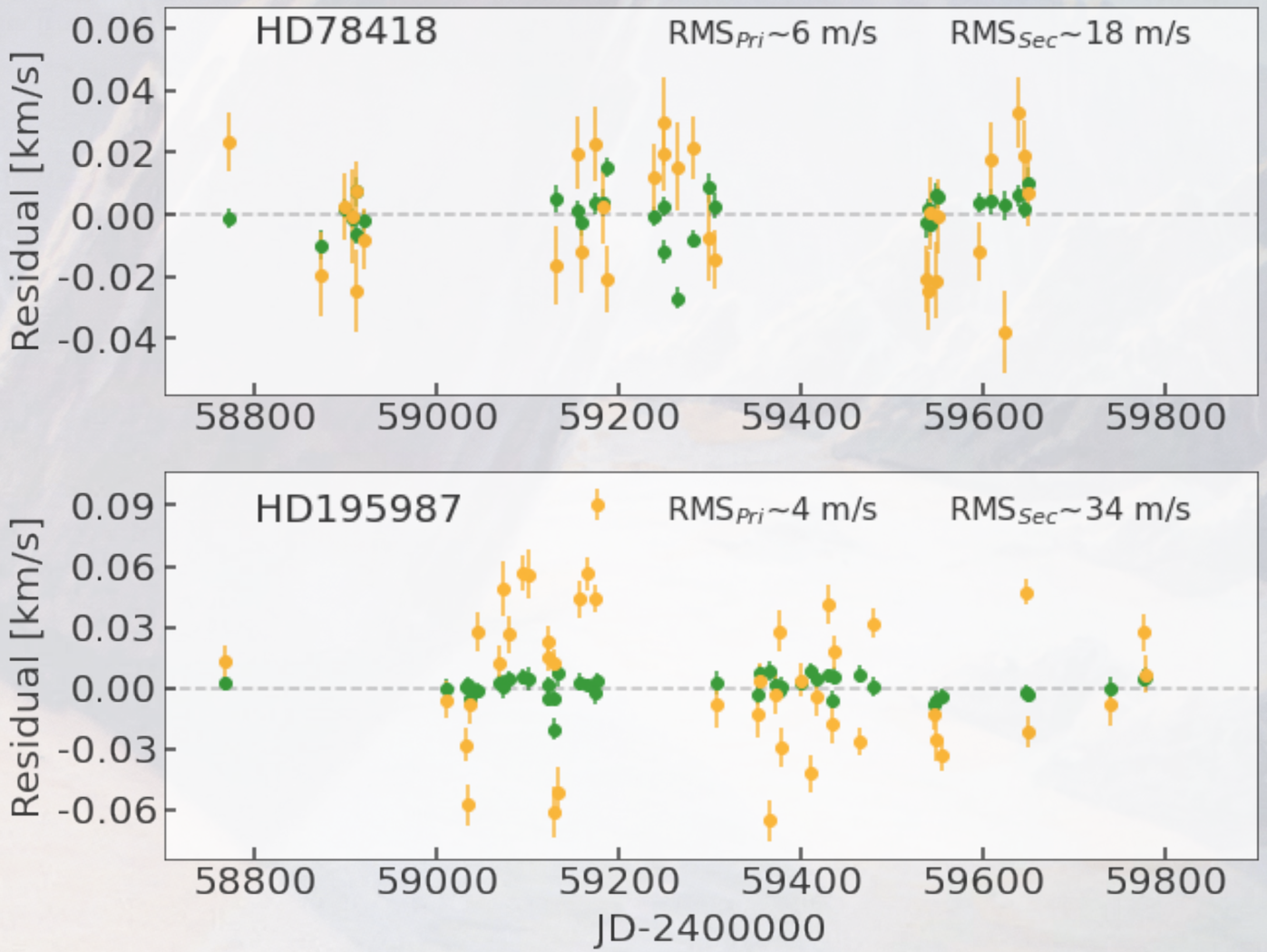
DETECTING CIRCUMBINARY PLANETS
in double-lined systems

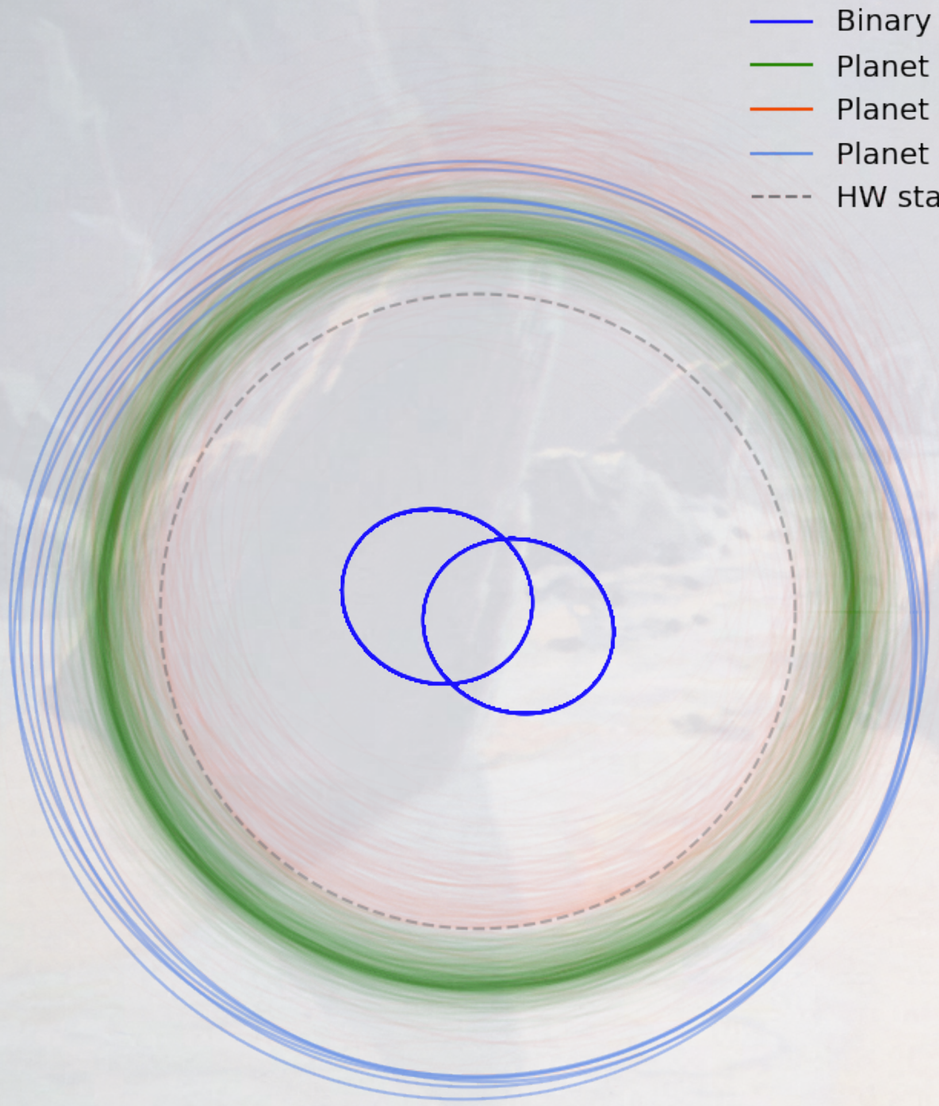
DOLBY-SD

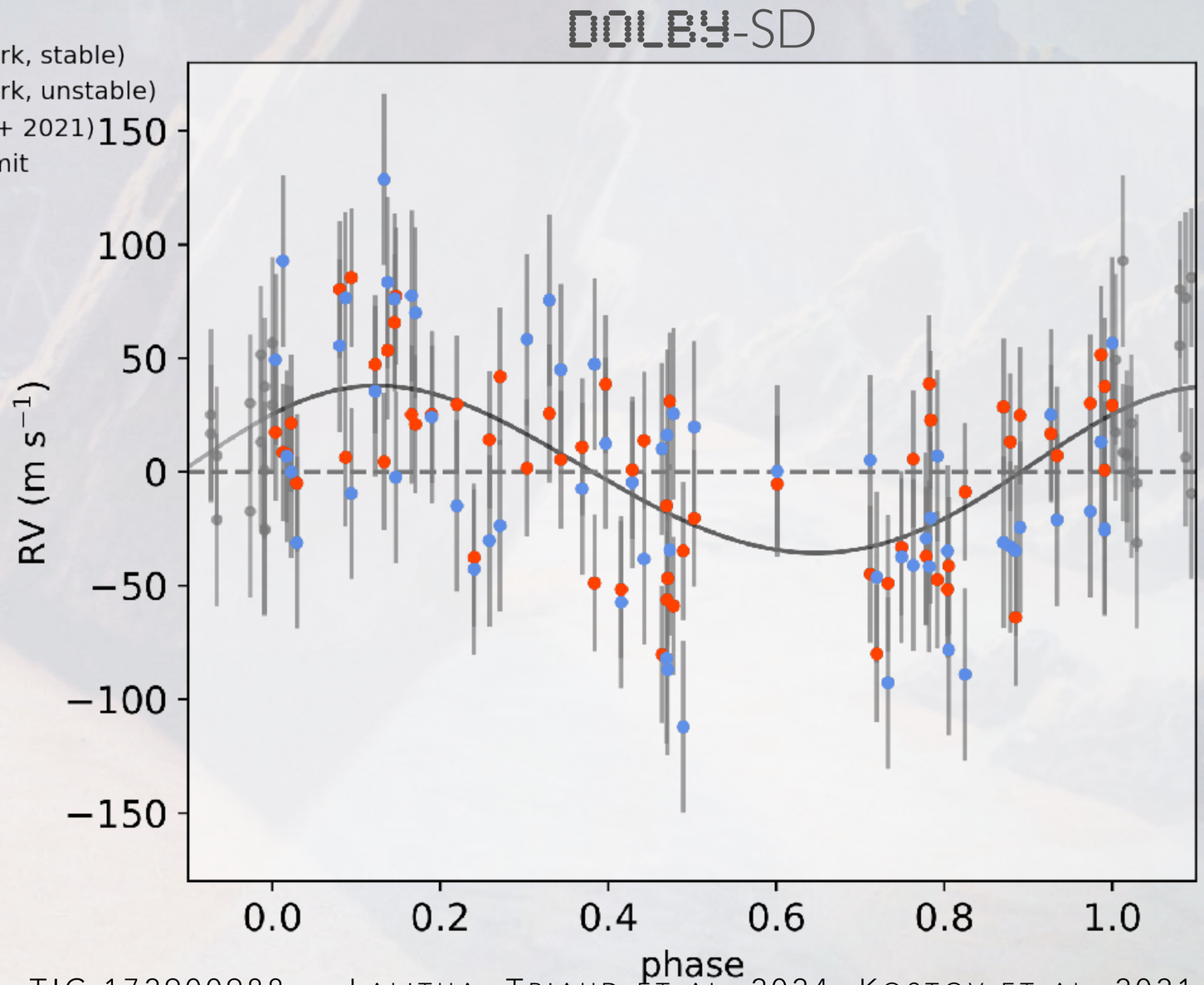




LALITHA, BAYCROFT ET AL. IN PREP

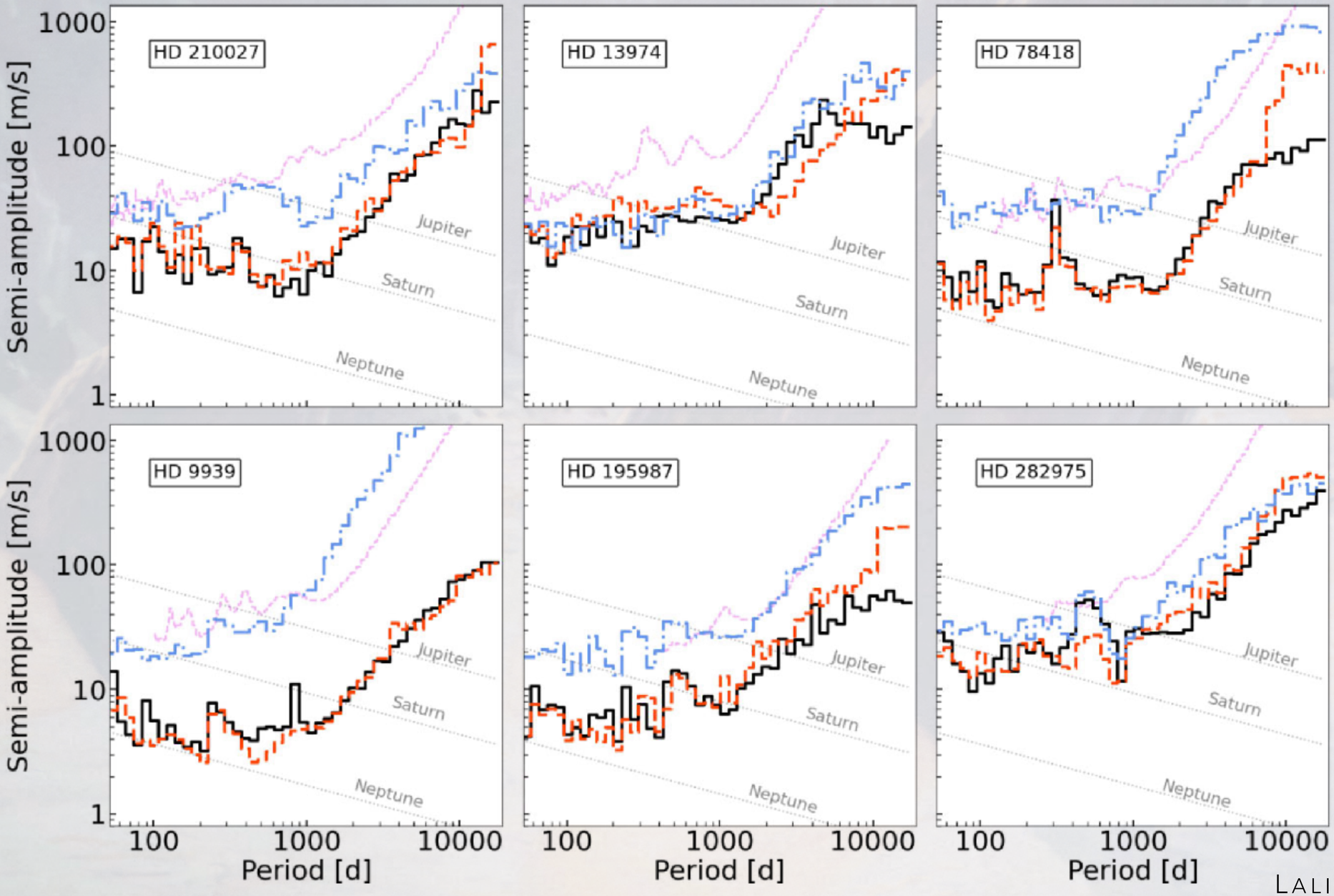
Detecting circumbinary planets
in double-lined systems





TIC 172900988 — Lalitha, Triaud et al. 2024, Kostov et al. 2021

DETECTING CIRCUMBINARY PLANETS
in double-lined systems



DOLBY-CCF

LALITHA, BAYCROFT ET AL. 2024

Radial-velocity detections of CIRCUMBINARY PLANETS are only starting

students

Vedad Kunovac
Matthew Standing
Thomas Baycroft
Yasmin Davis
Maddy Scott
Aleyna Adamson

postdocs

Lalitha Sairam
Daniel Sebastian
Georgina Dransfield
Jenni French
Mathilde Timmermans
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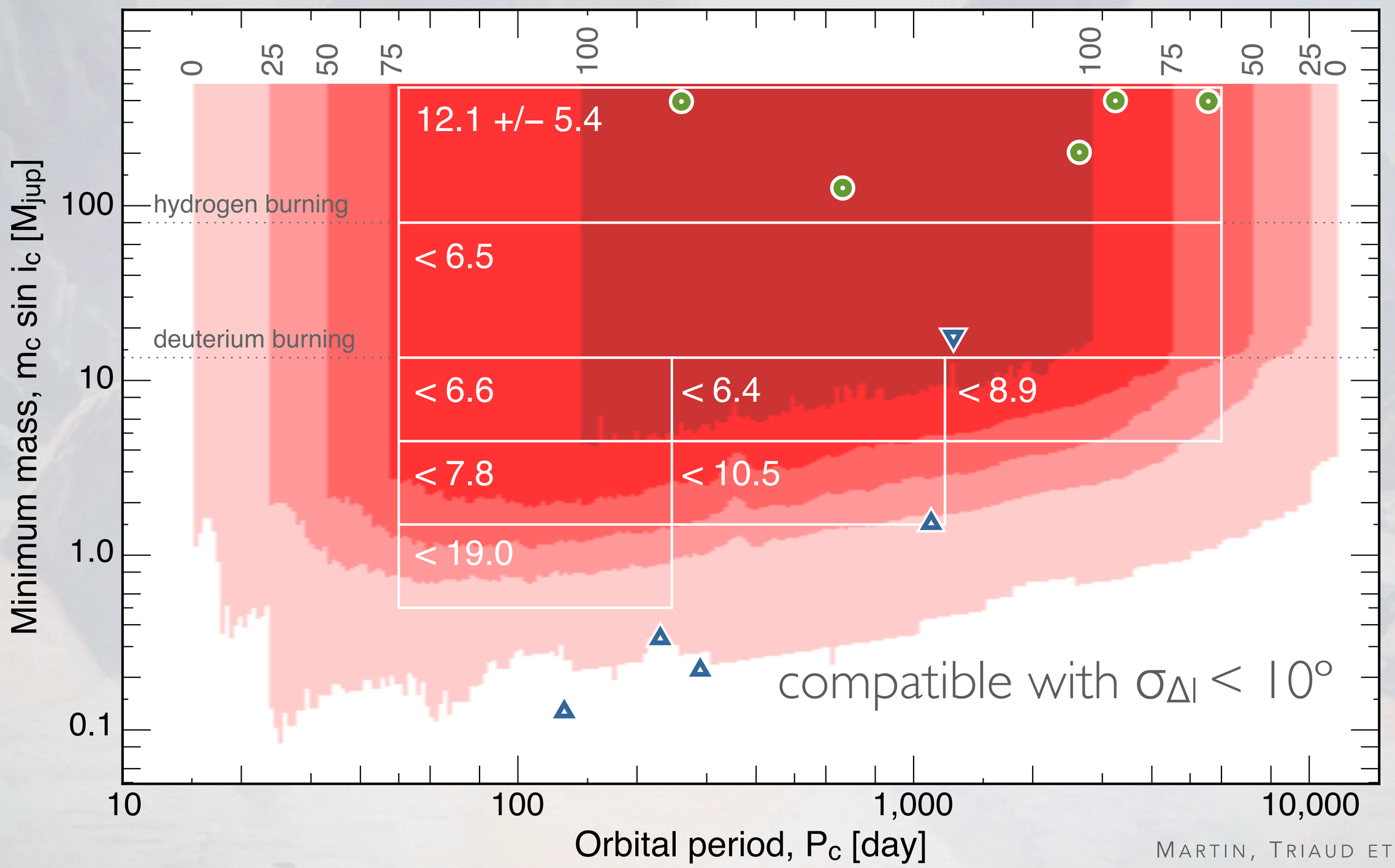
BEBOP Binaries Escorted by Orbiting Planets



Martin, Triaud et al. 2019