

oblique multiples & COOL

AMAURY H.M.J. TRIAUD



UNIVERSITY OF
BIRMINGHAM



LEVERHULME
TRUST

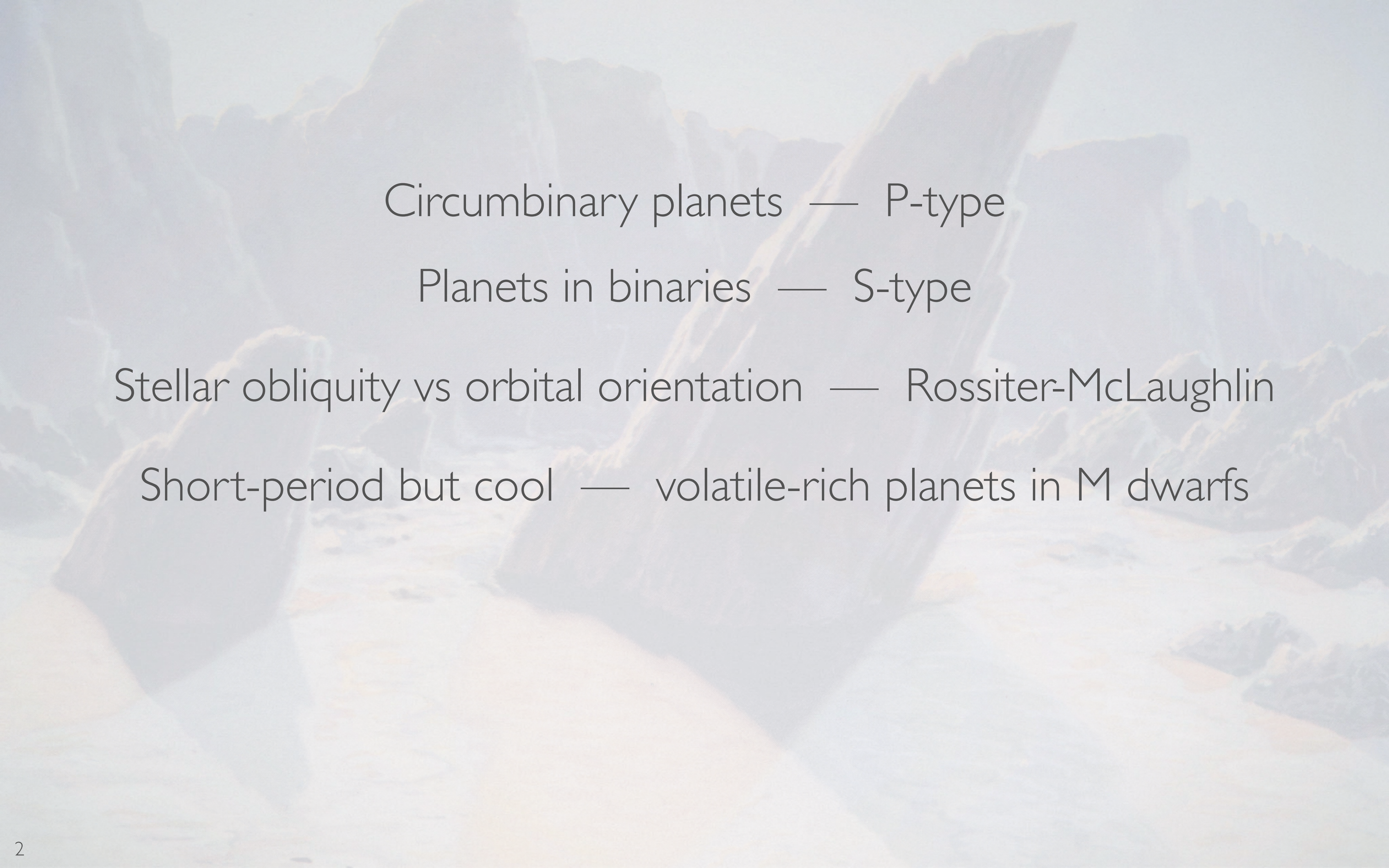


Science and
Technology
Facilities Council



INSTITUT
POLAIRE
FRANÇAIS
PAUL-ÉMILE VICTOR





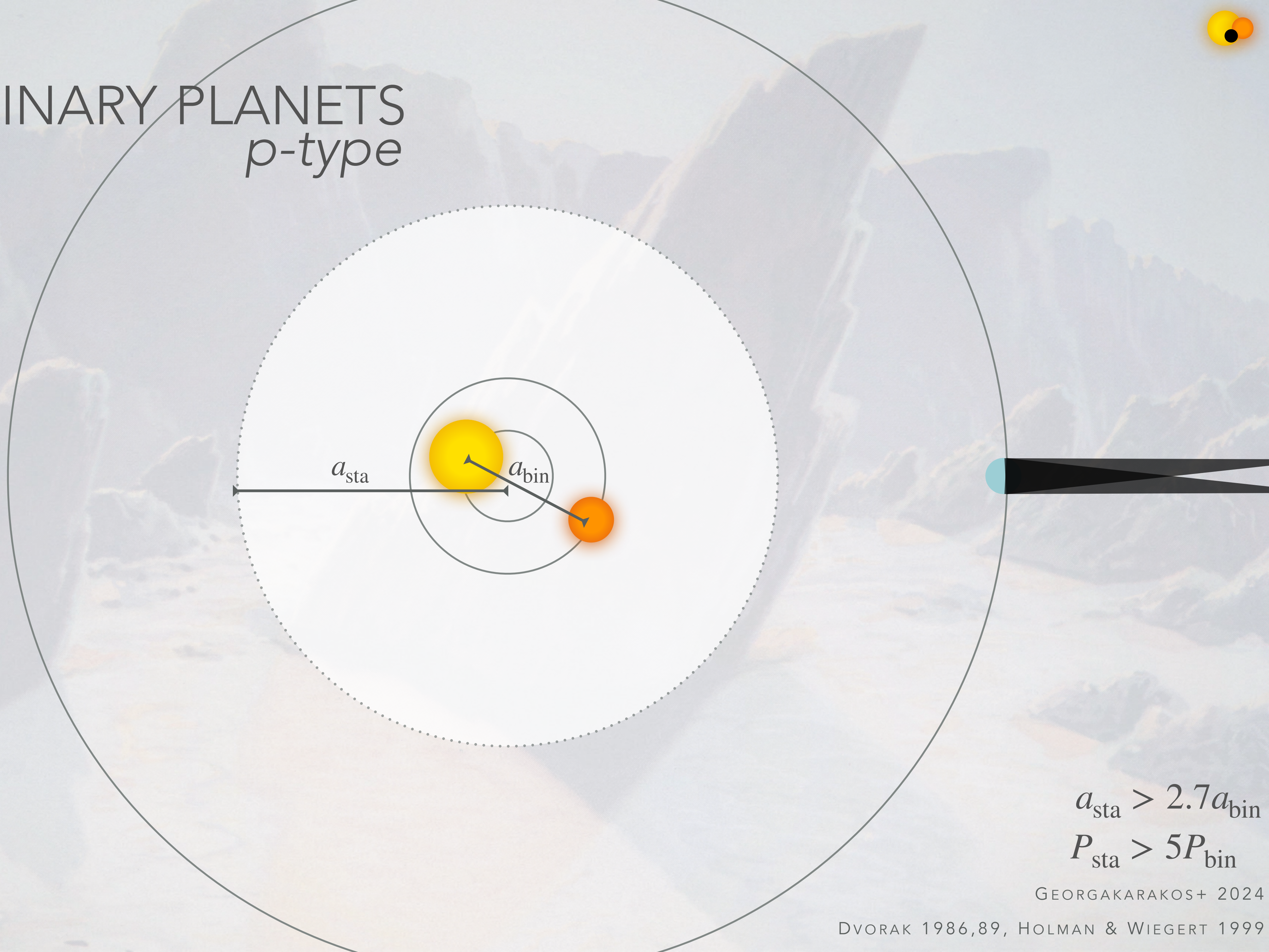
Circumbinary planets — P-type

Planets in binaries — S-type

Stellar obliquity vs orbital orientation — Rossiter-McLaughlin

Short-period but cool — volatile-rich planets in M dwarfs

CIRCUMBINARY PLANETS *p*-type

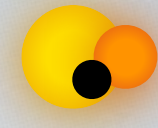


$$a_{\text{sta}} > 2.7a_{\text{bin}}$$

$$P_{\text{sta}} > 5P_{\text{bin}}$$

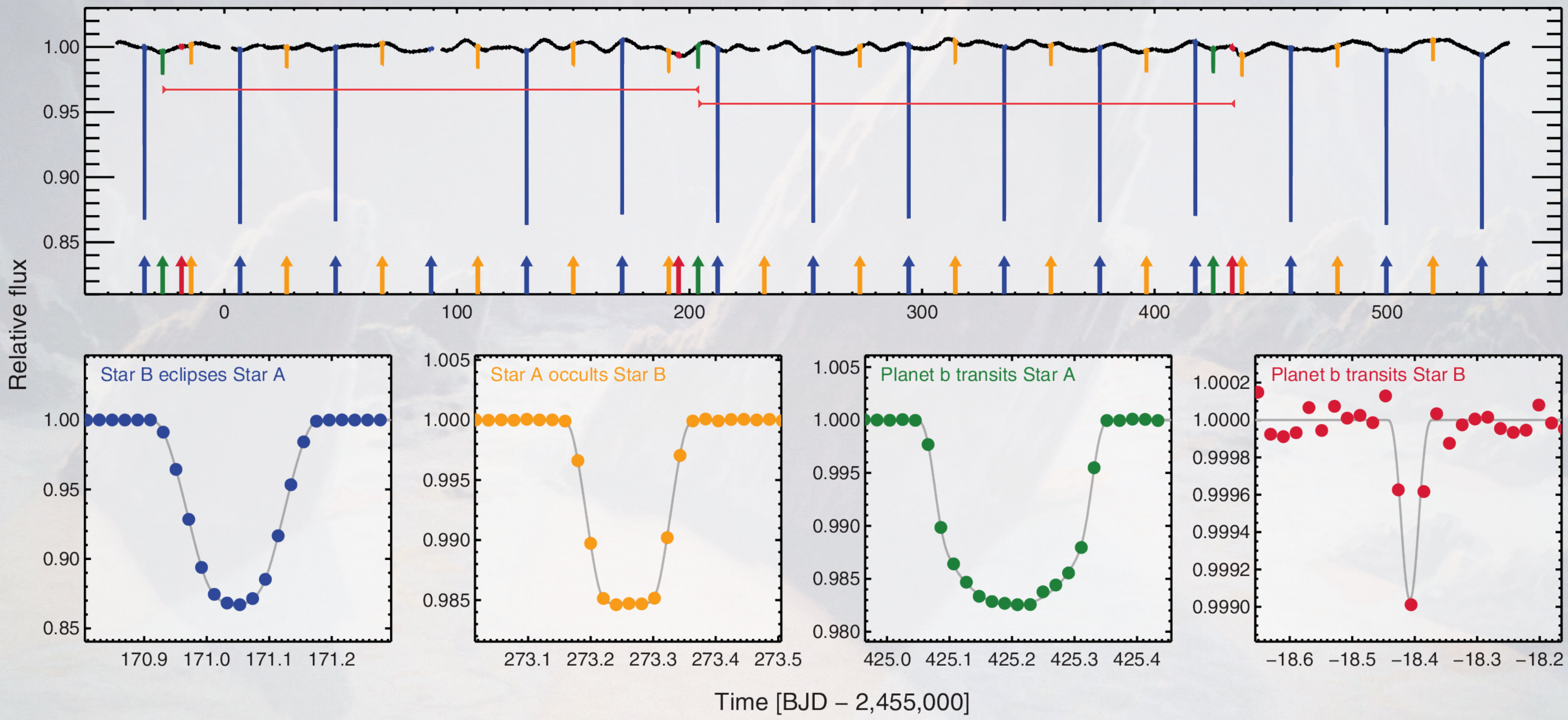
GEORGAKARAKOS+ 2024

DVORAK 1986,89, HOLMAN & WIEGERT 1999

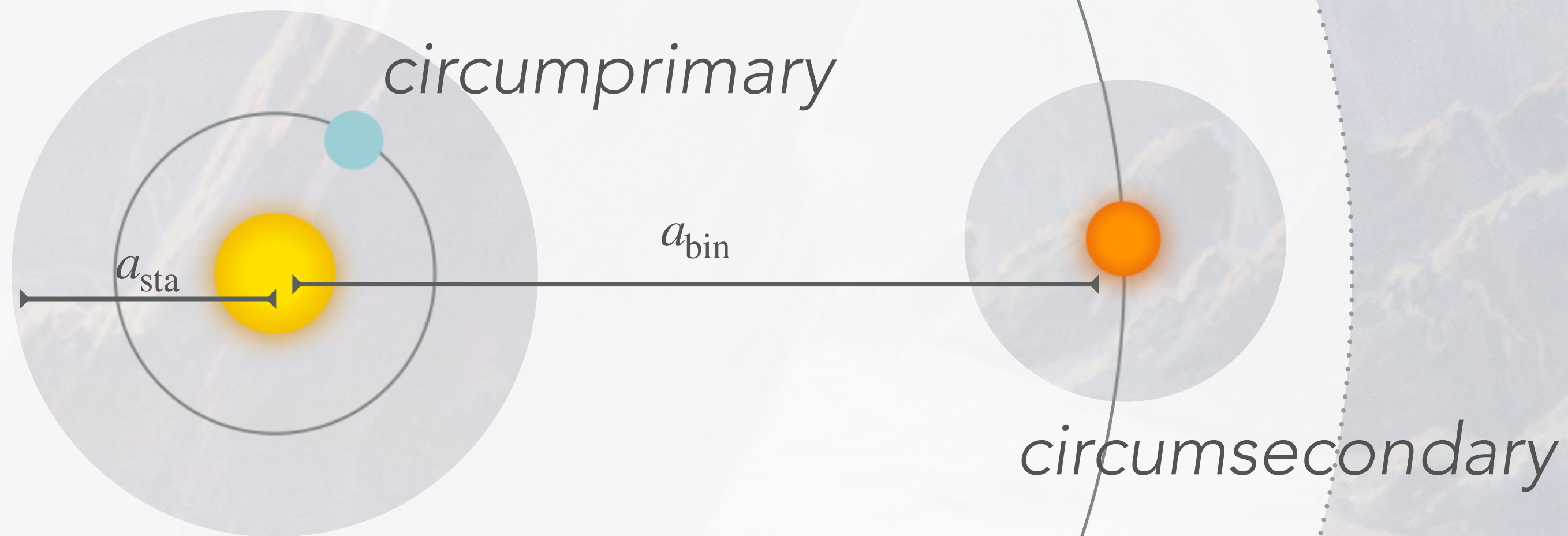




KEPLER-16 AB b



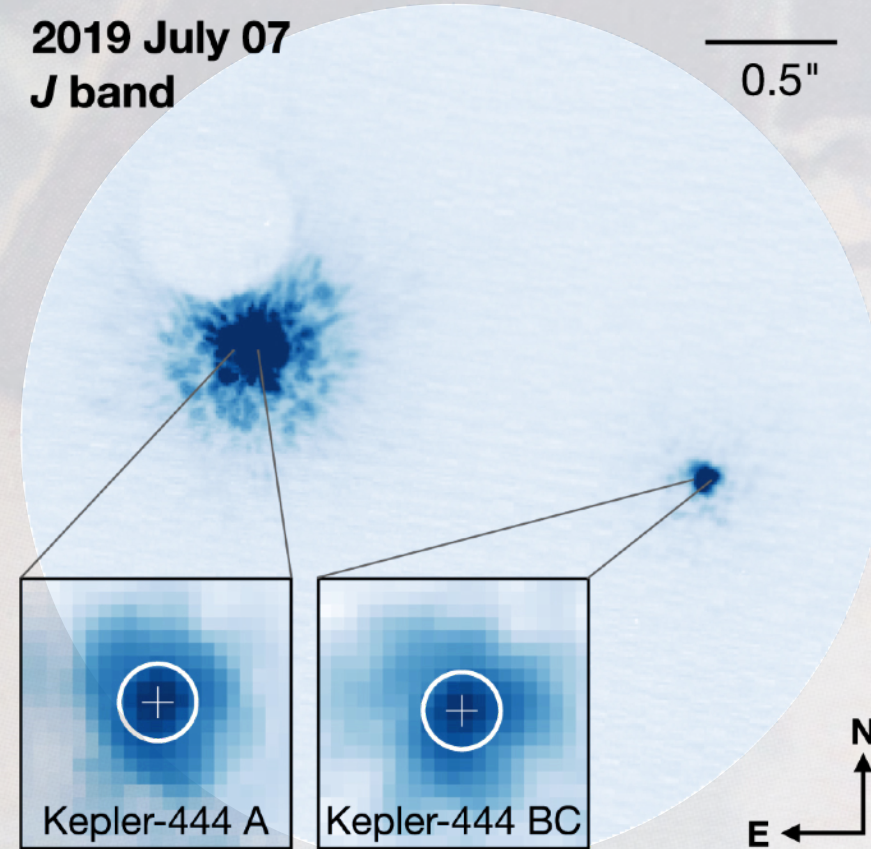
CIRCUMSTELLAR PLANETS *s-type*



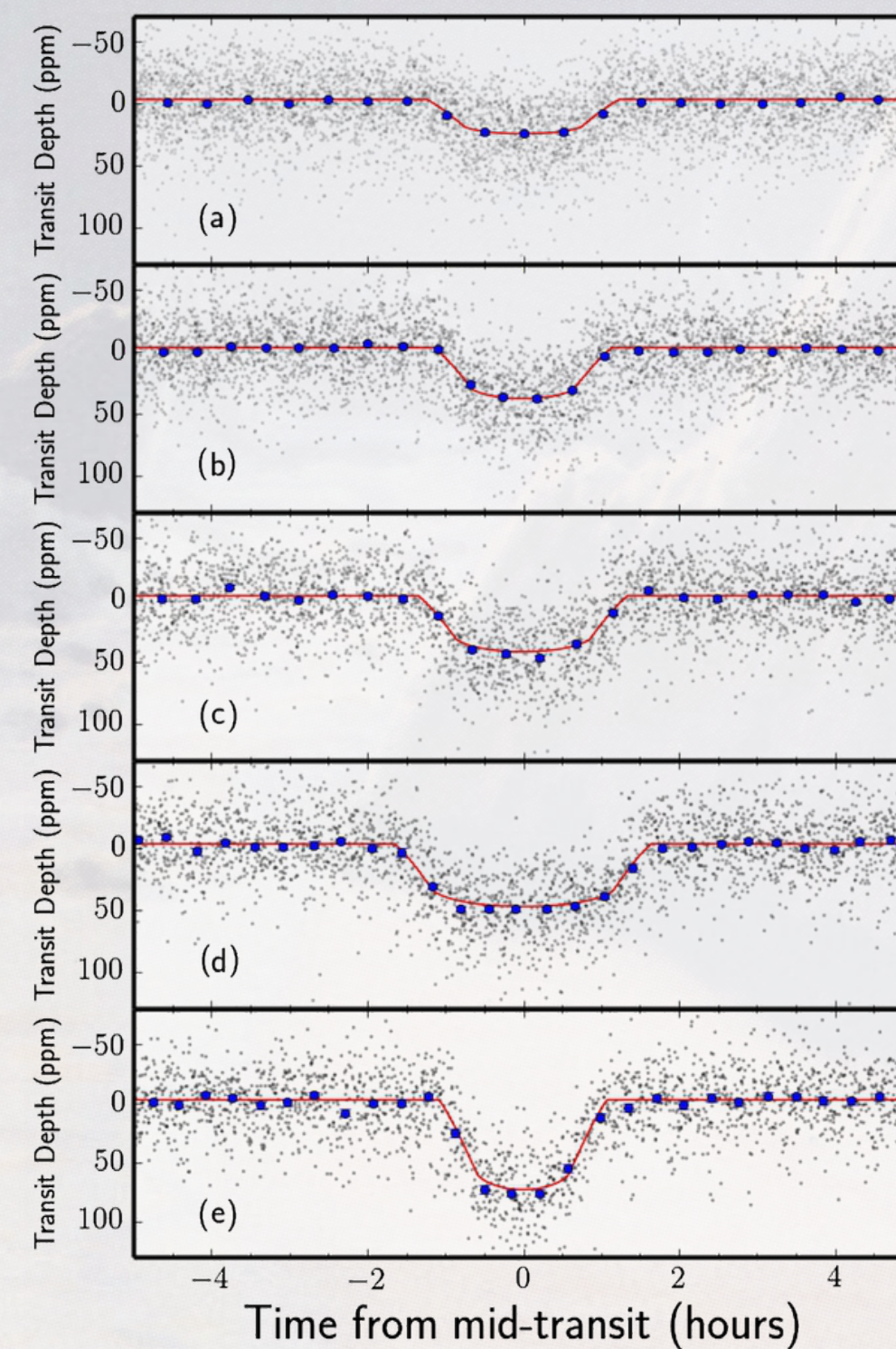
$$a_{\text{sta}} < 3a_{\text{bin}}$$
$$P_{\text{sta}} < 5P_{\text{bin}}$$

KEPLER-444A BCDEF

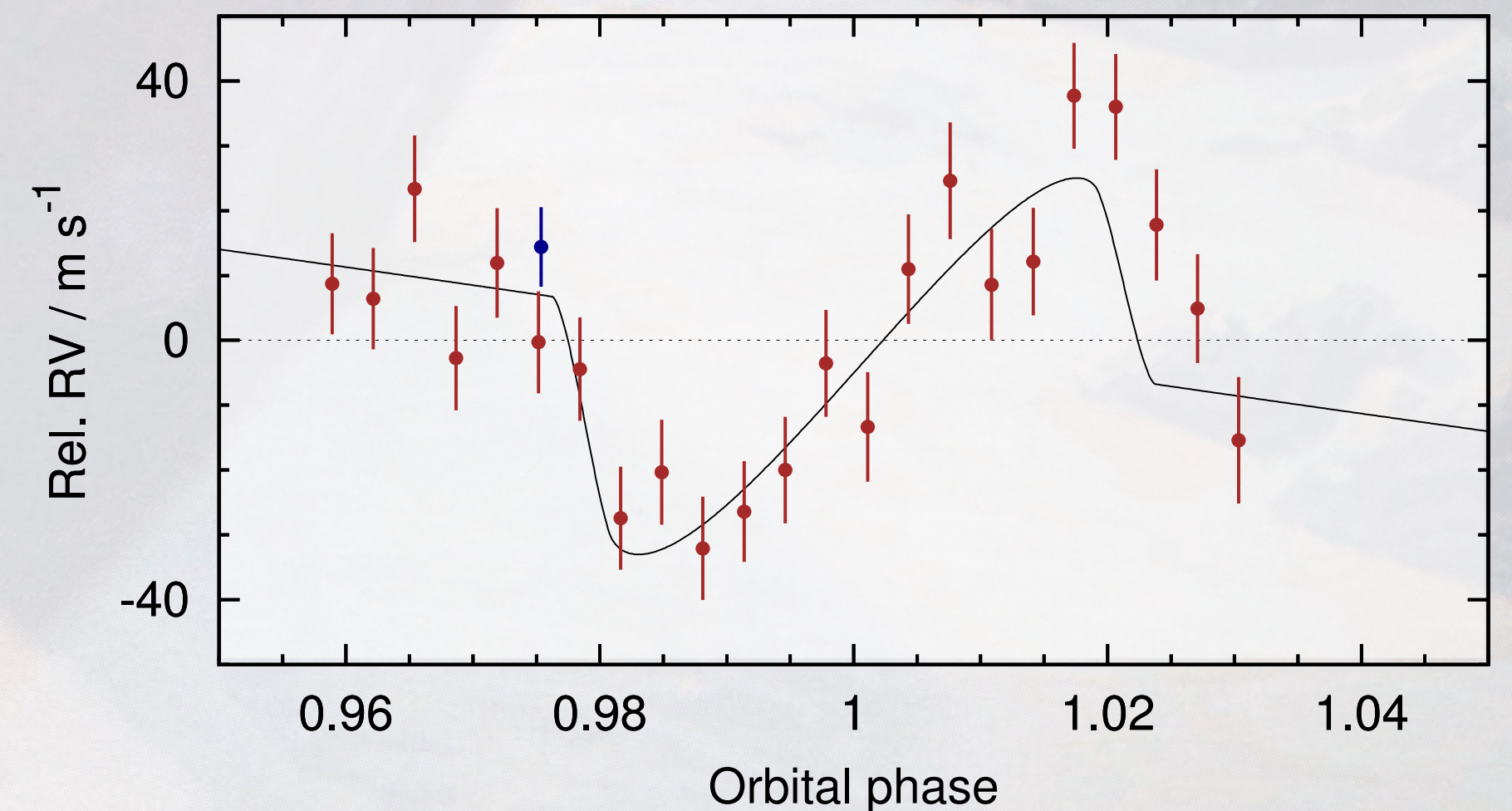
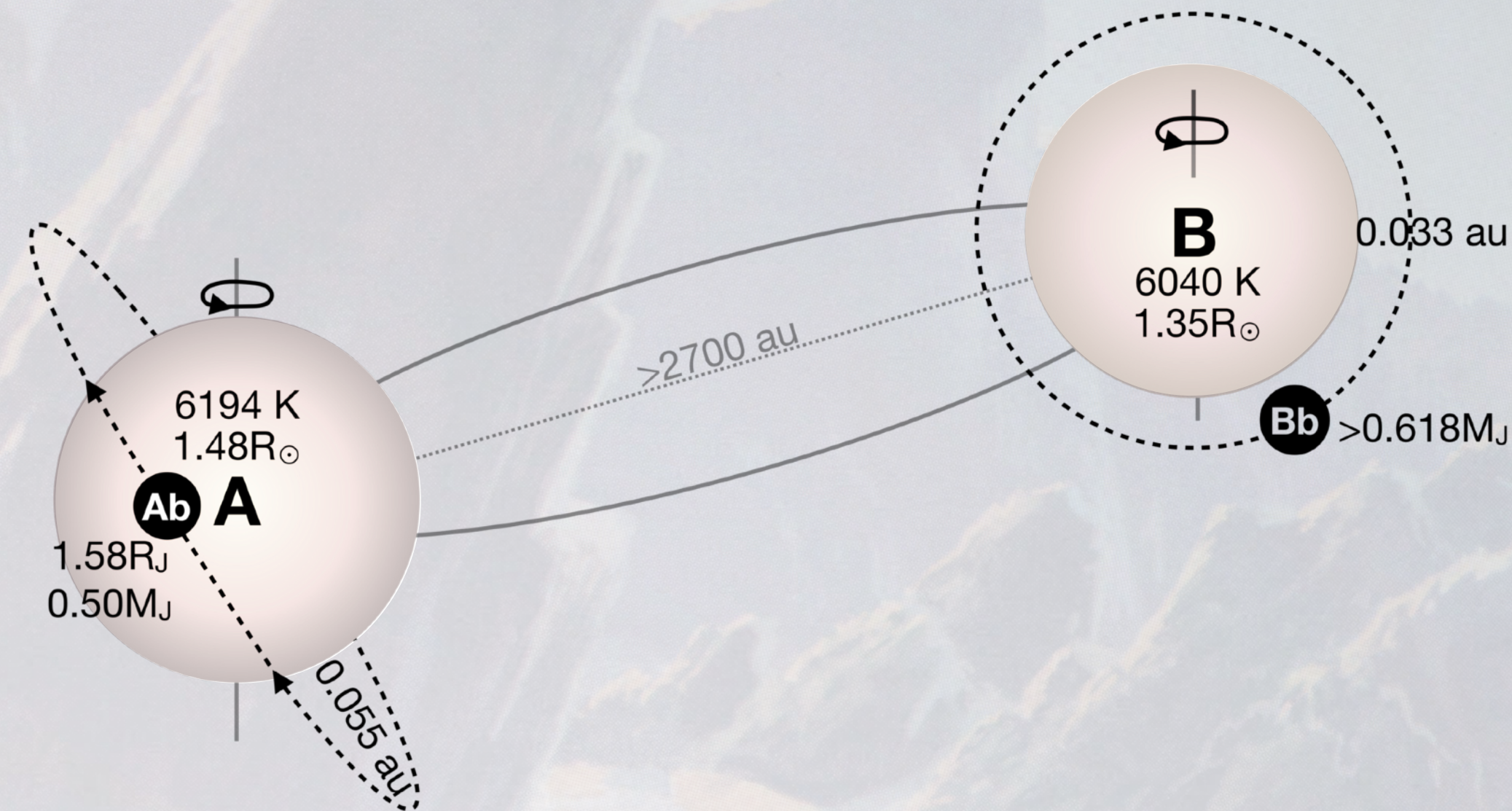
5 sub-Earth planets
4:5, 3:4, 4:5, 4:5 chain
11 Gyr (thick disc)

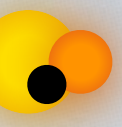


secondary star's
periastron: 5 AU



WASP-94AB AND Bb



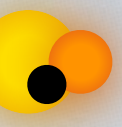


CORE ACCRETION IS **LESS** EFFICIENT

planetesimal accretion possible if > 50 binary orbital periods

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

Meschiari 2012 a&b, Paardekooper+ 2012, Rafikov+ 2013

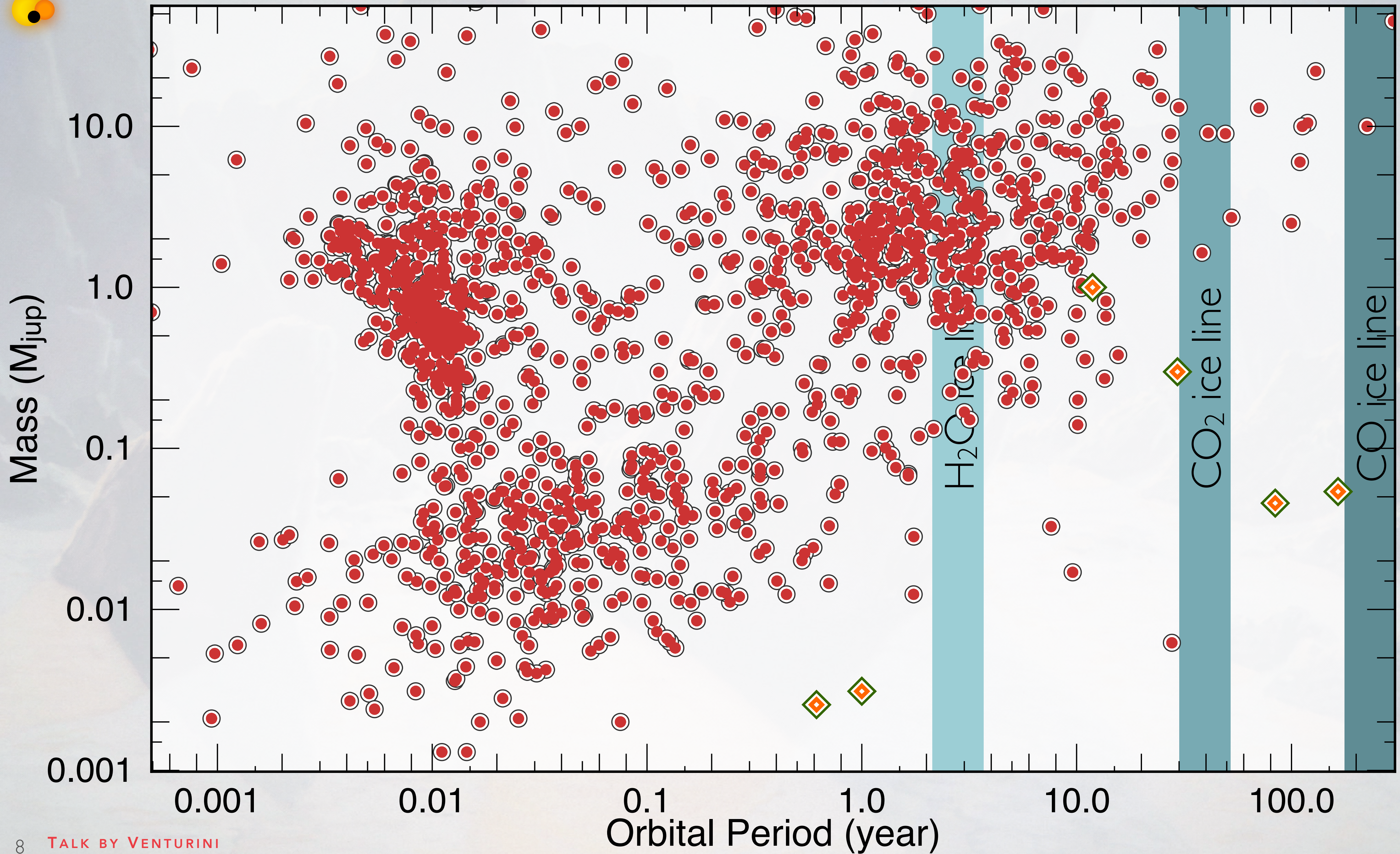


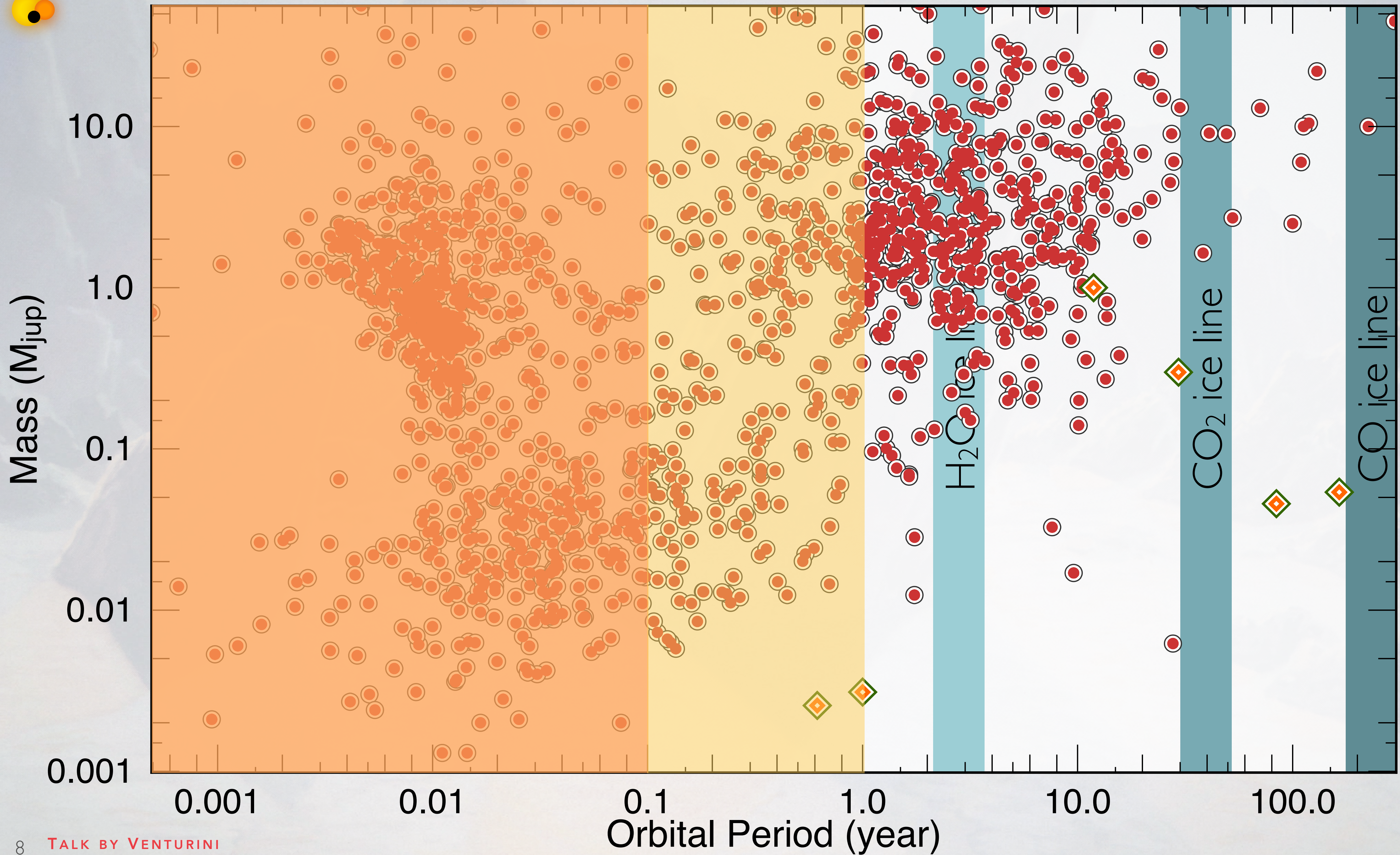
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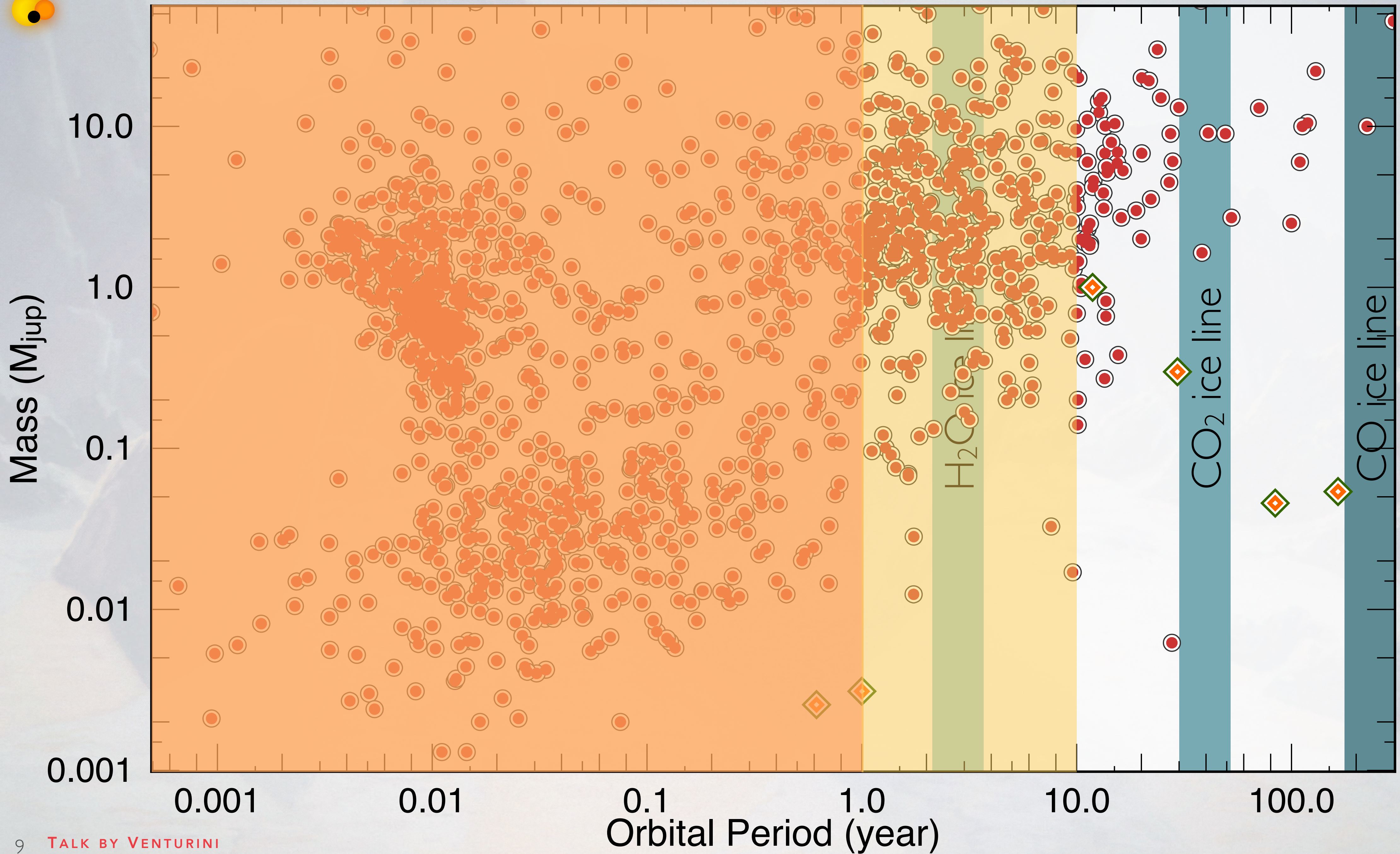
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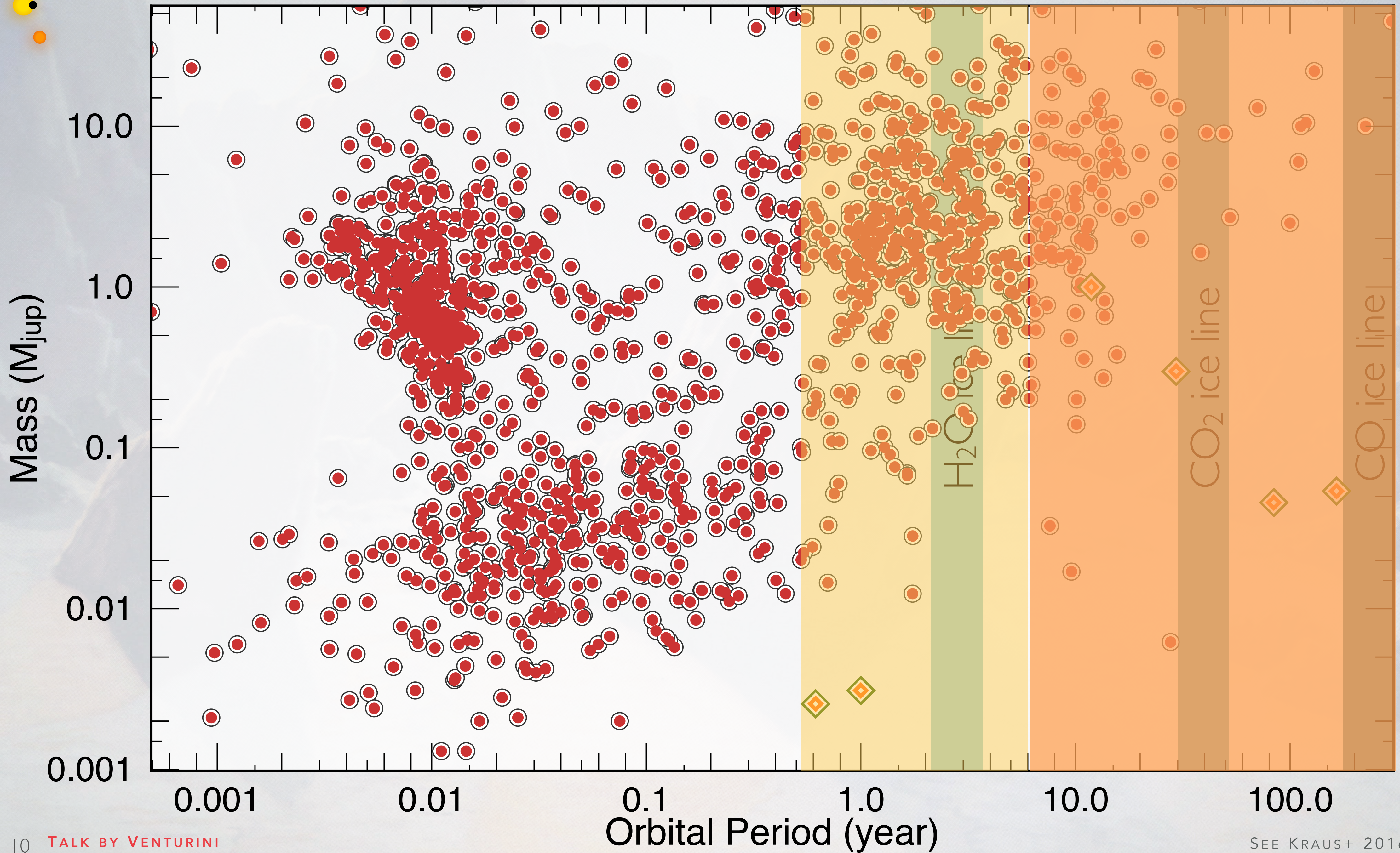
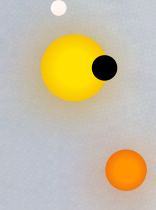
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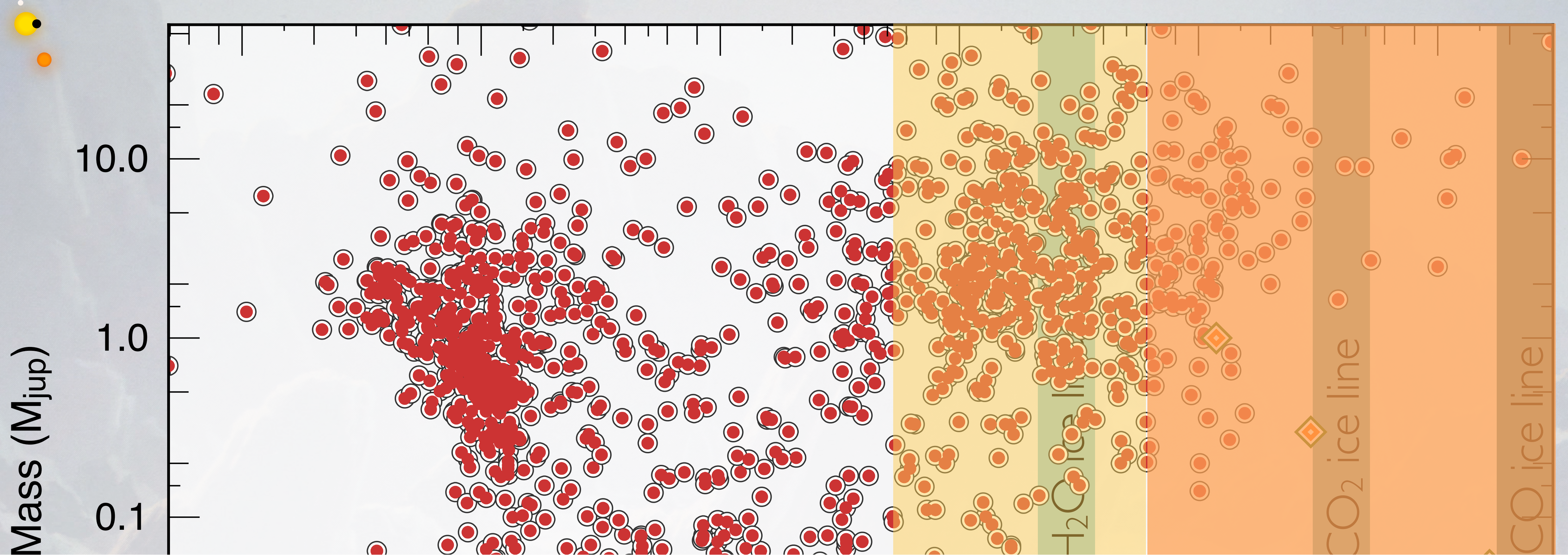
Circumbinary super-Earths show super-Earths can **form far** & **migrate**





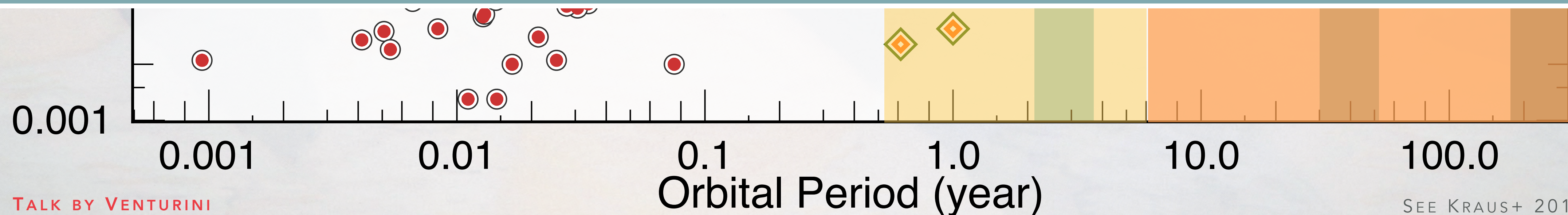


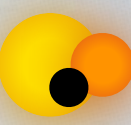




Binary system geometries **isolate** some planet formation processes

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





CORE ACCRETION IS **LESS** EFFICIENT

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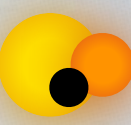
Circumbinary super-Earths show super-Earths can **form far** & **migrate**

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 α discs
(Pierens & Nelson 2013, Penzlin, Kley & Nelson 2020)

see also Kley & Haghighipour 2014



CORE ACCRETION IS **LESS** EFFICIENT

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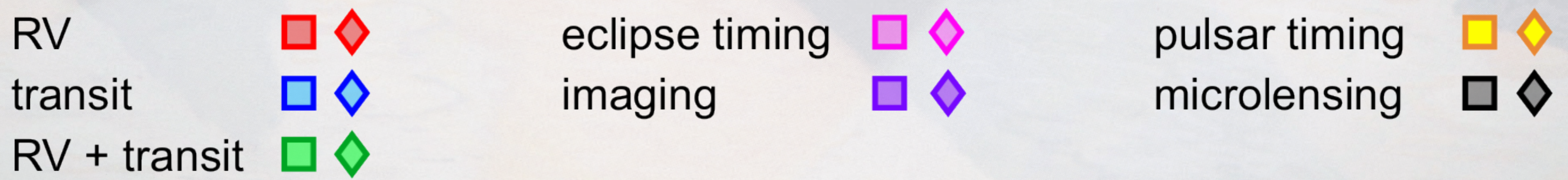
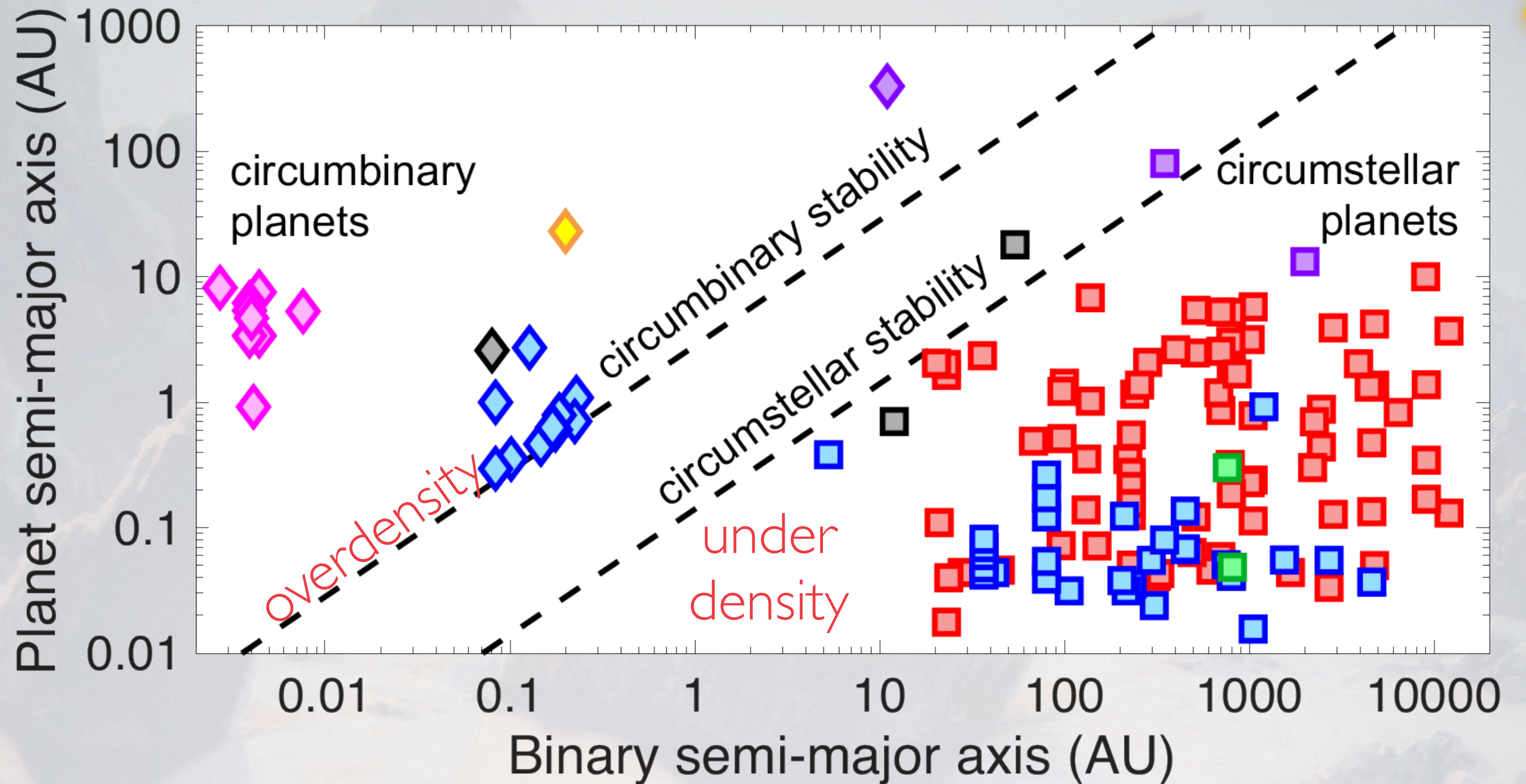
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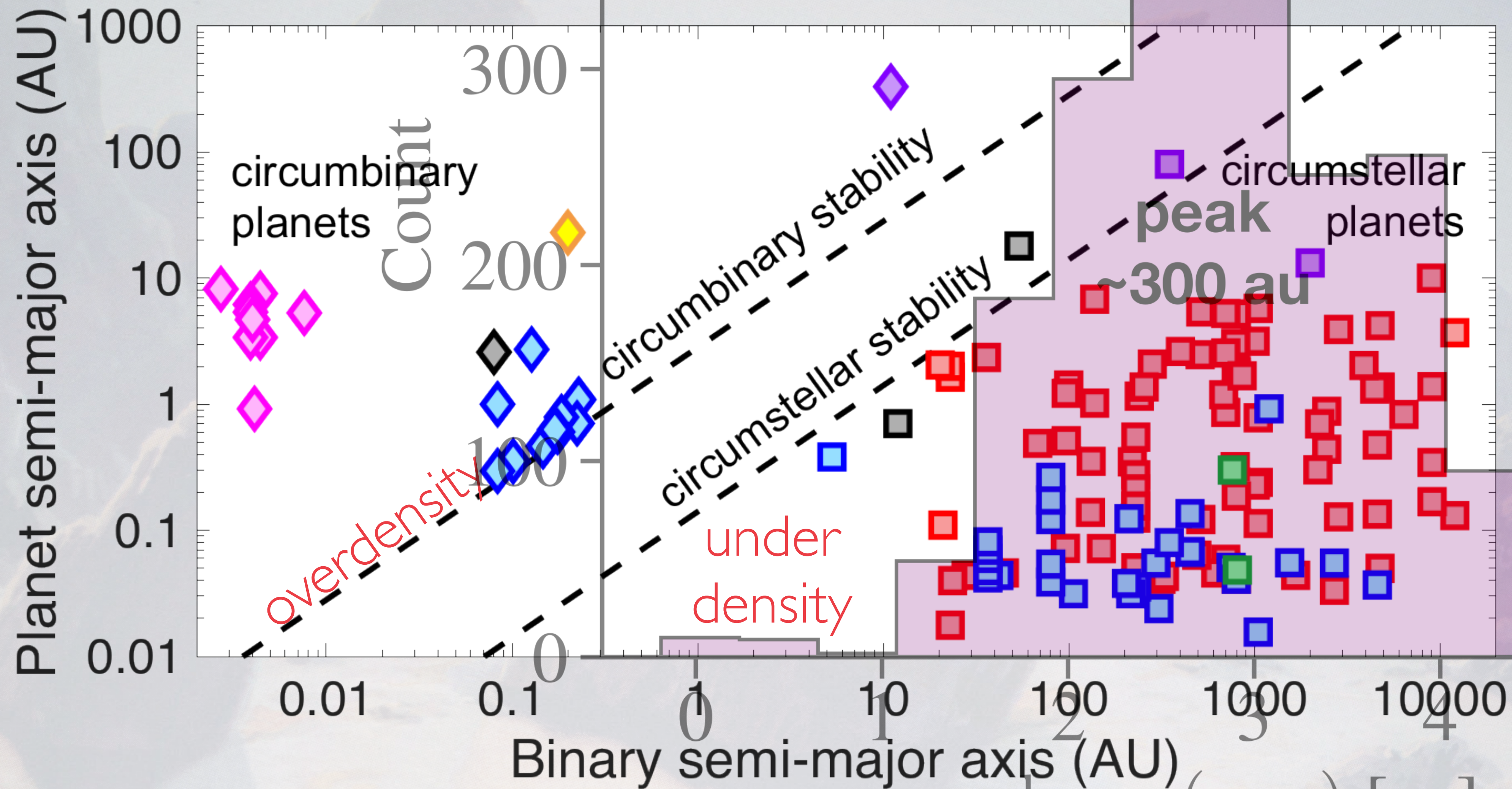
The orbital parameters consistent with low h/r and low α discs
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Circumbinary orbits contain **fossil** information about disc conditions

A painting of a rocky coastline with a white text box in the center. The scene features dark, jagged rock formations and a body of water with a sandy beach in the foreground. The text is centered within a white rectangular frame.

global trends
for
exoplanets
in multiples



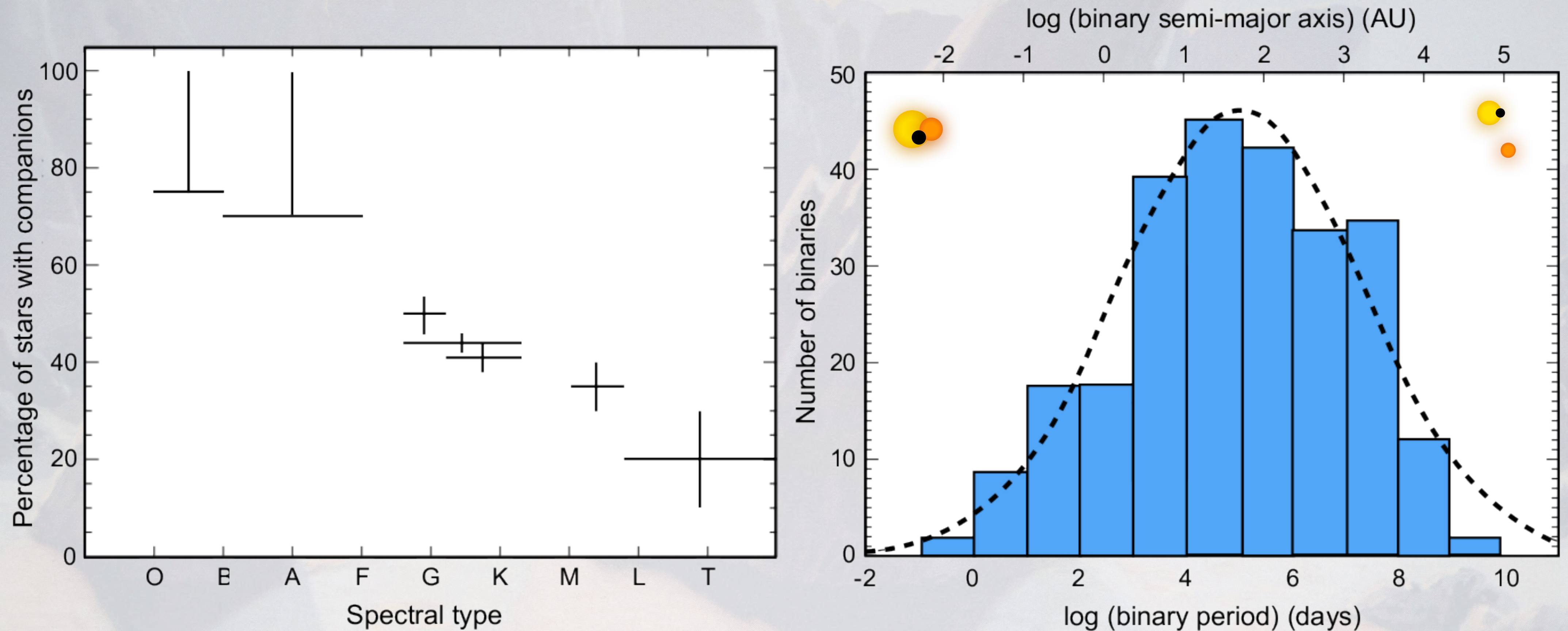


RV ■ ◆
transit ■ ◆
RV + transit ■ ◆

eclipse timing ■ ◆
imaging ■ ◆

pulsar timing ■ ◆
microlensing ■ ◆

BINARITY AFFECTS OCCURENCE RATES

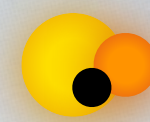


for $a_{\text{bin}} < 50 \text{ AU}$, planet occurrence rates decrease by **factor 3** (Kraus+ 2016)

Lack of binarity explains **half** of the increased planet occurrence in Ms

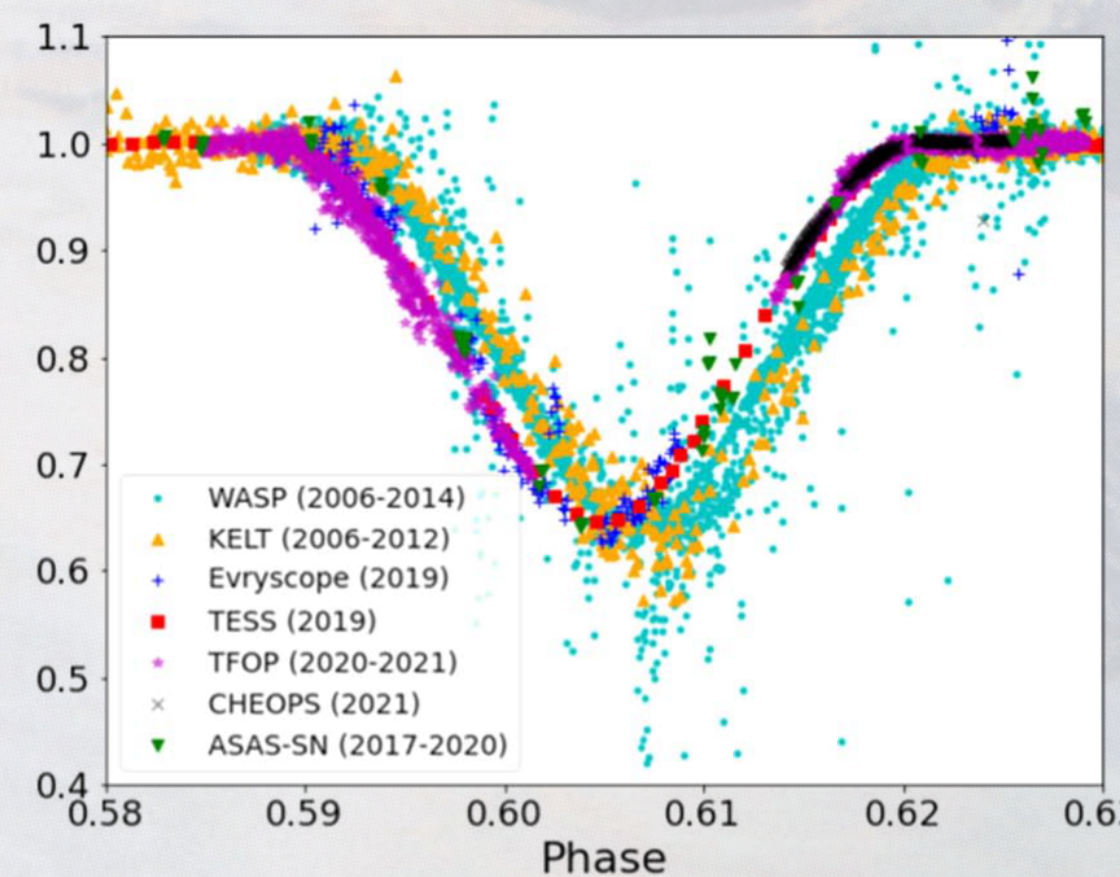
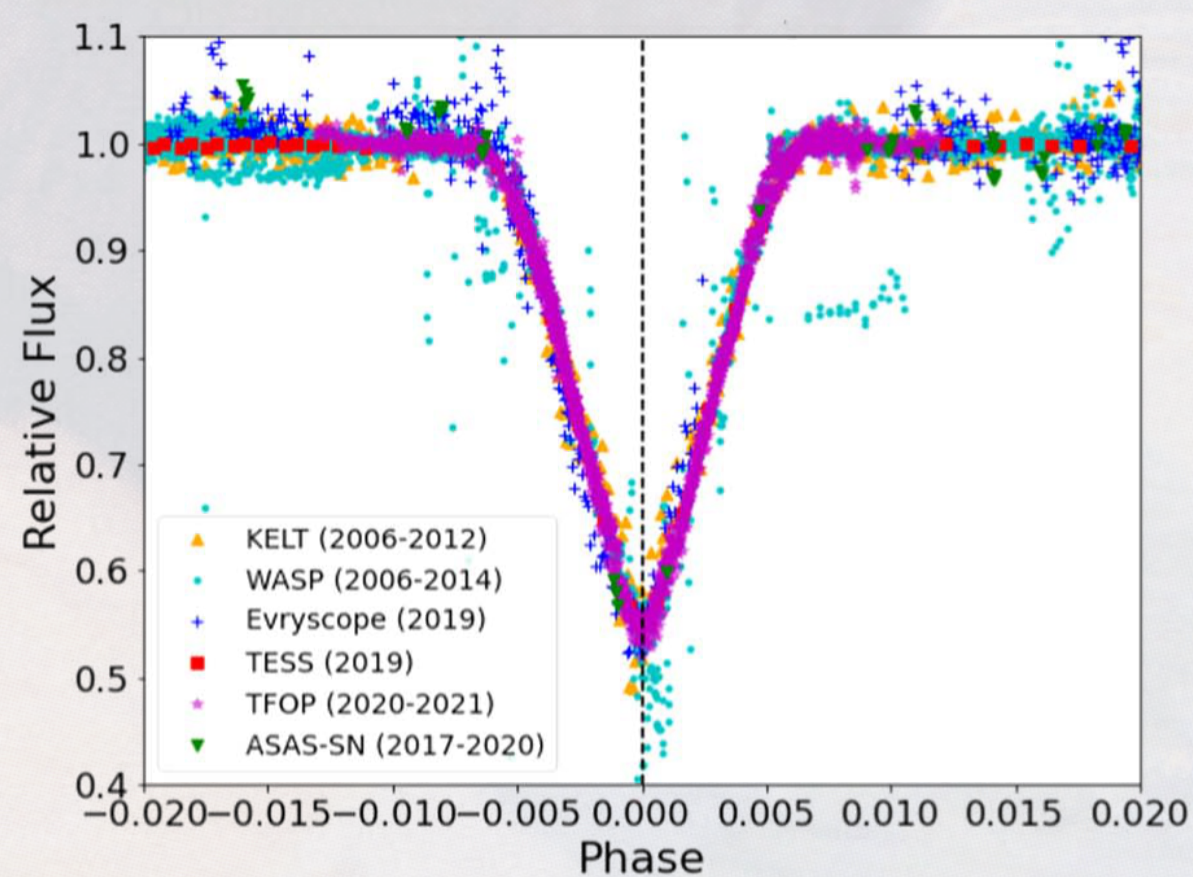
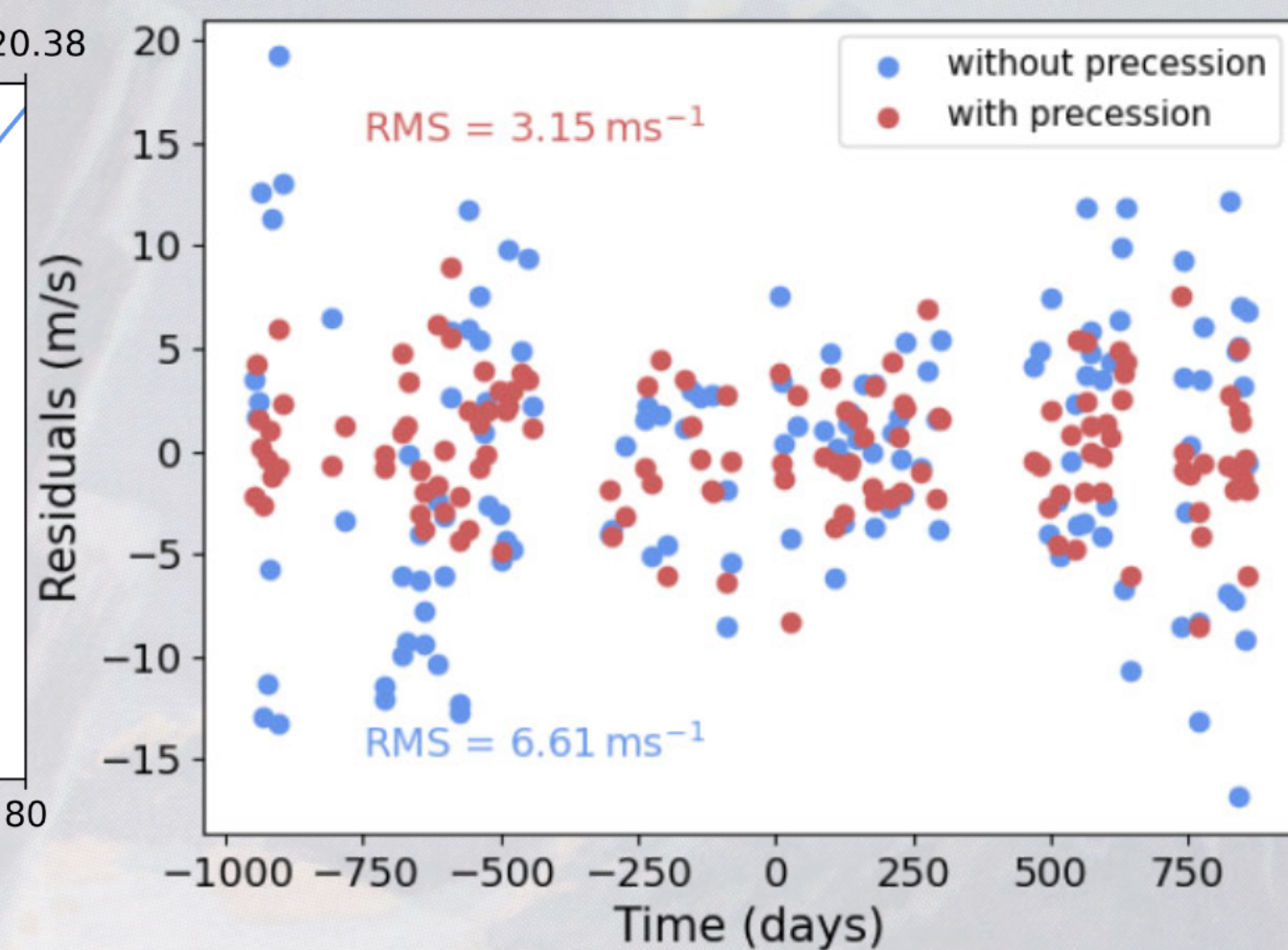
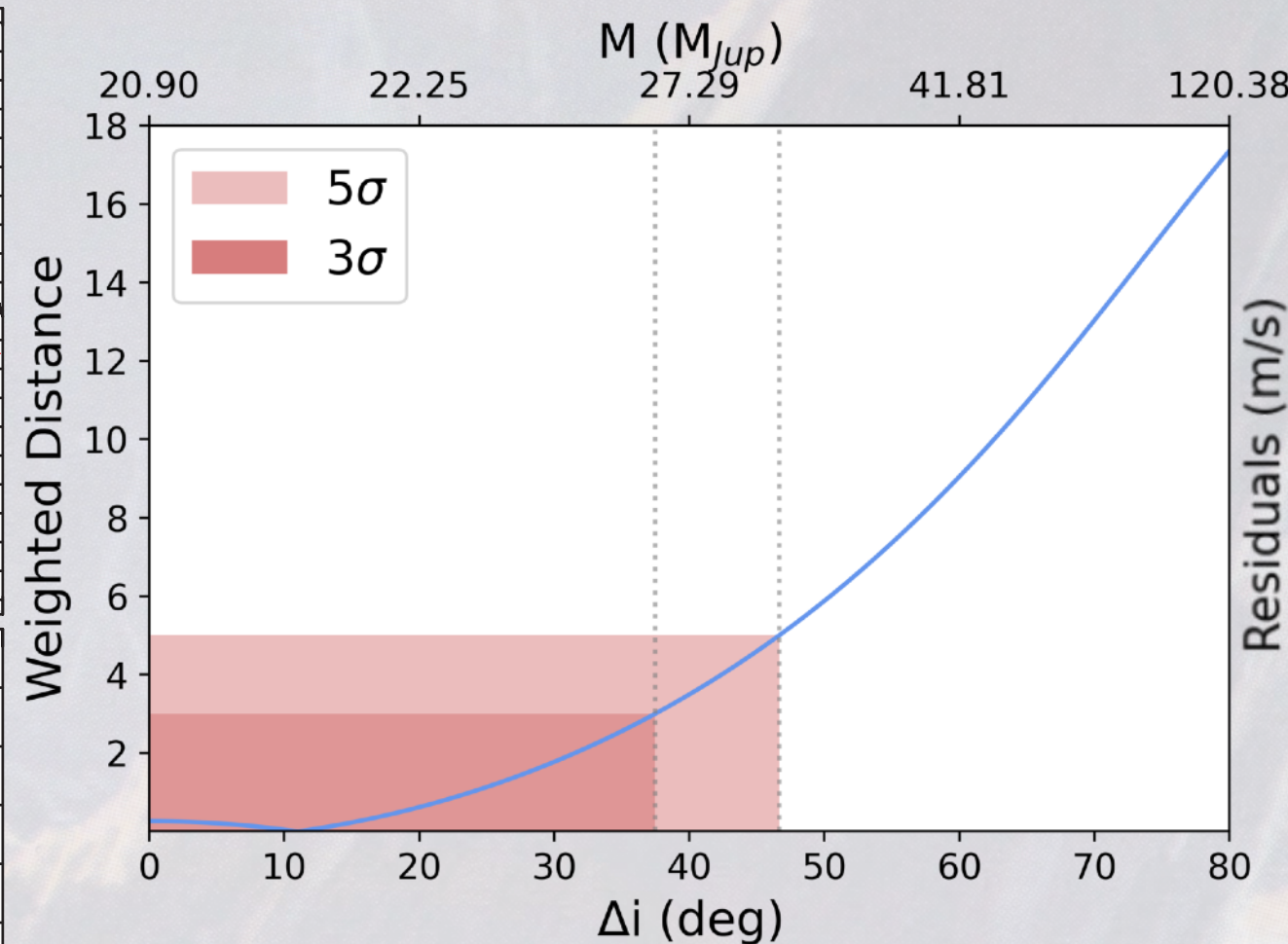
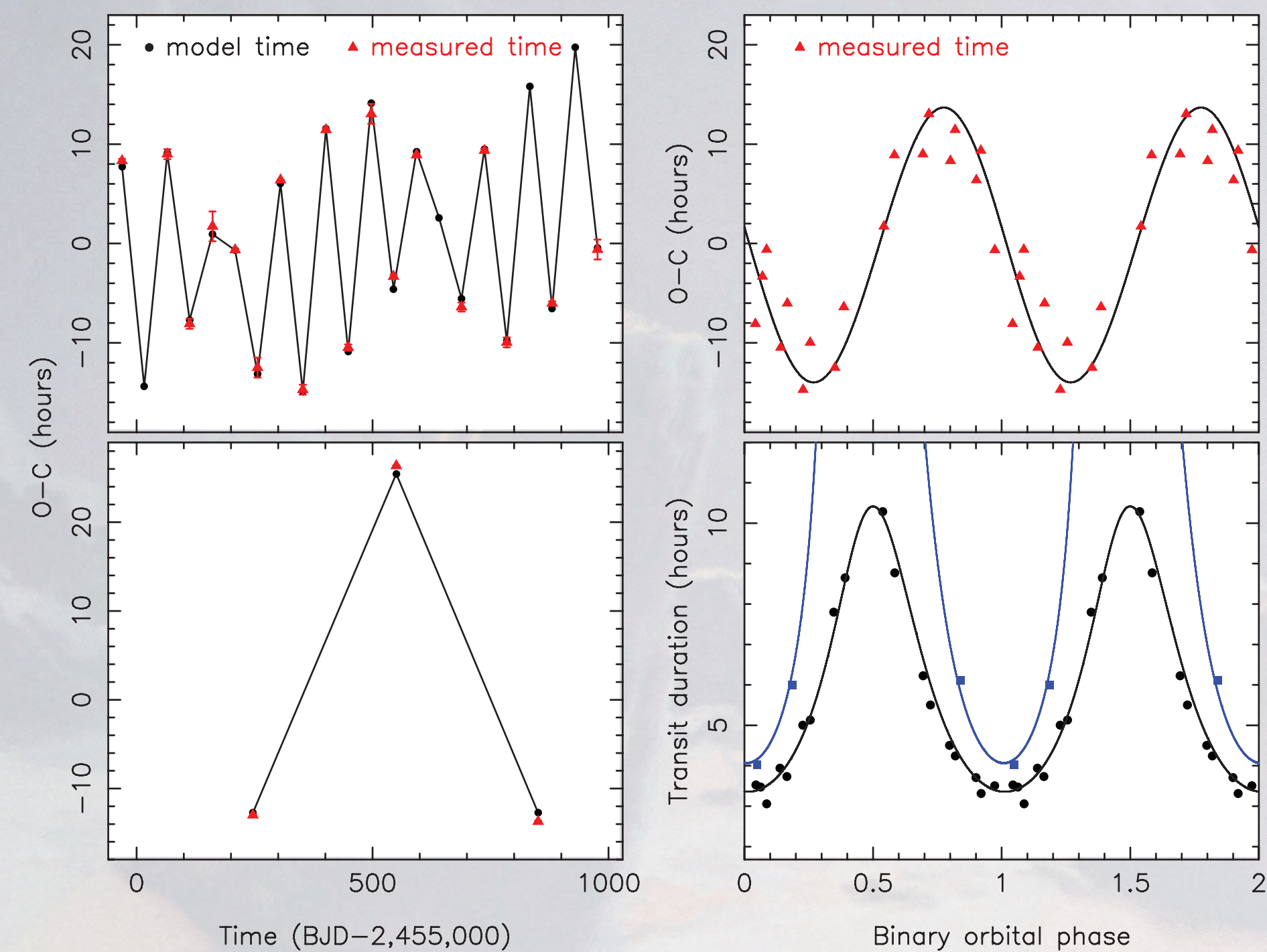
A dramatic landscape painting of a rocky coastline. In the foreground, two large, dark, jagged rock formations stand prominently on a sandy beach. The ocean is visible in the lower right, with gentle waves lapping at the shore. In the background, a series of steep, layered cliffs rise from the water, their surfaces textured with shadows and highlights. The sky is a pale, hazy blue. Overlaid on the center of the image is a white rectangular box containing text.

circumbinary
exoplanets
where
observations
require dynamics



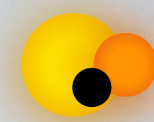
TIMING & DURATION VARIATIONS

APSIDAL PRECESSION



transits can be severely asymmetric

⇒ photo-dynamical modelling



CIRCUMBINARY GAS-GIANT OCCURRENCE

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

NO CIRCUMBINARY PLANETS WHERE $P_{\text{bin}} < 7 \text{ days}$

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

Armstrong et al. 2014:

~9.8% ($P < 300 \text{ days}$)★

Martin & Triaud 2014:

~15% ($P < 10 \text{ years}$)★

SINGLE SUN-LIKE STARS:

Mayor+ 2011:

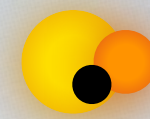
13.7% ($P < 10 \text{ years}$)

5.4% ($P < 400 \text{ d}$)

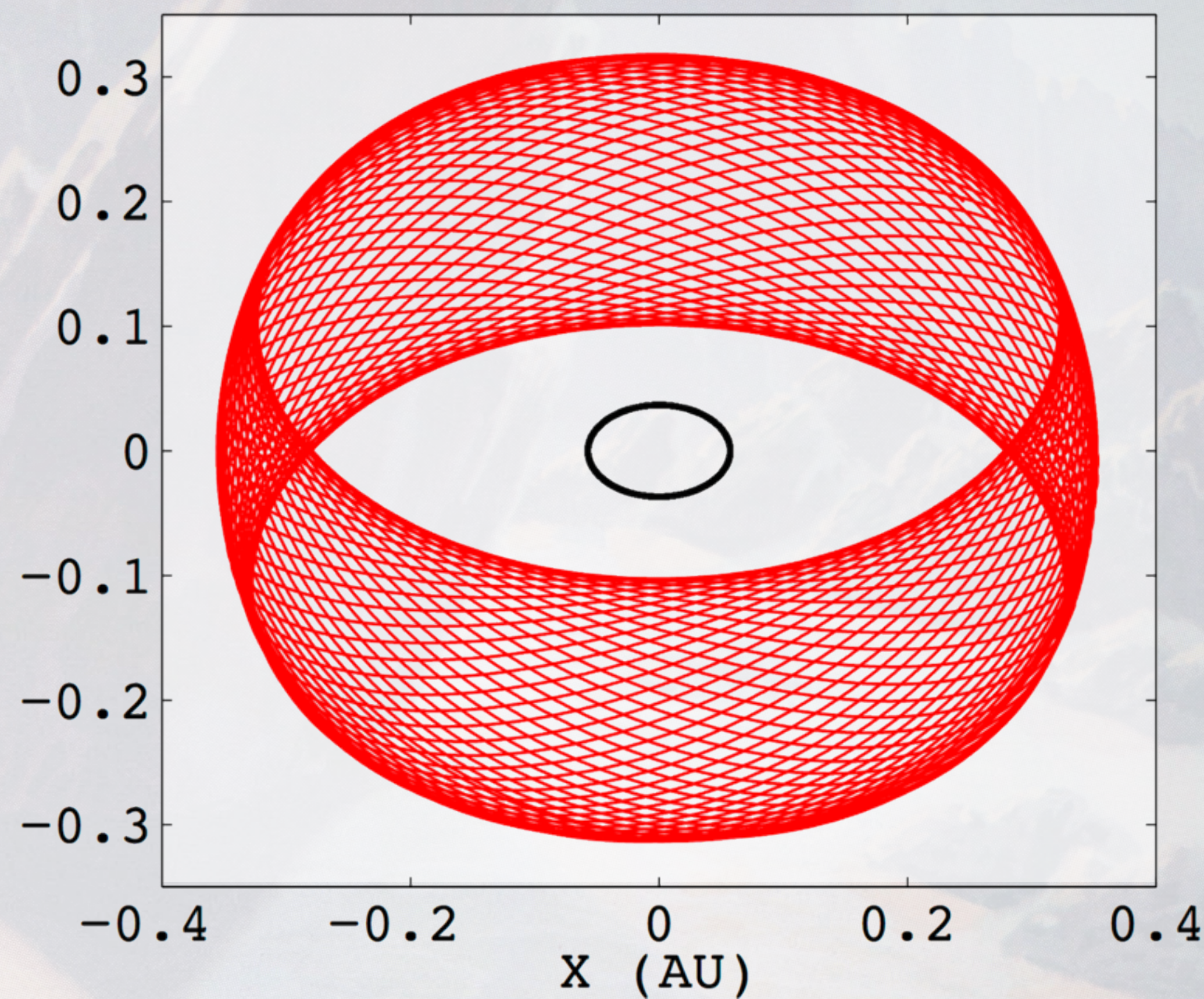
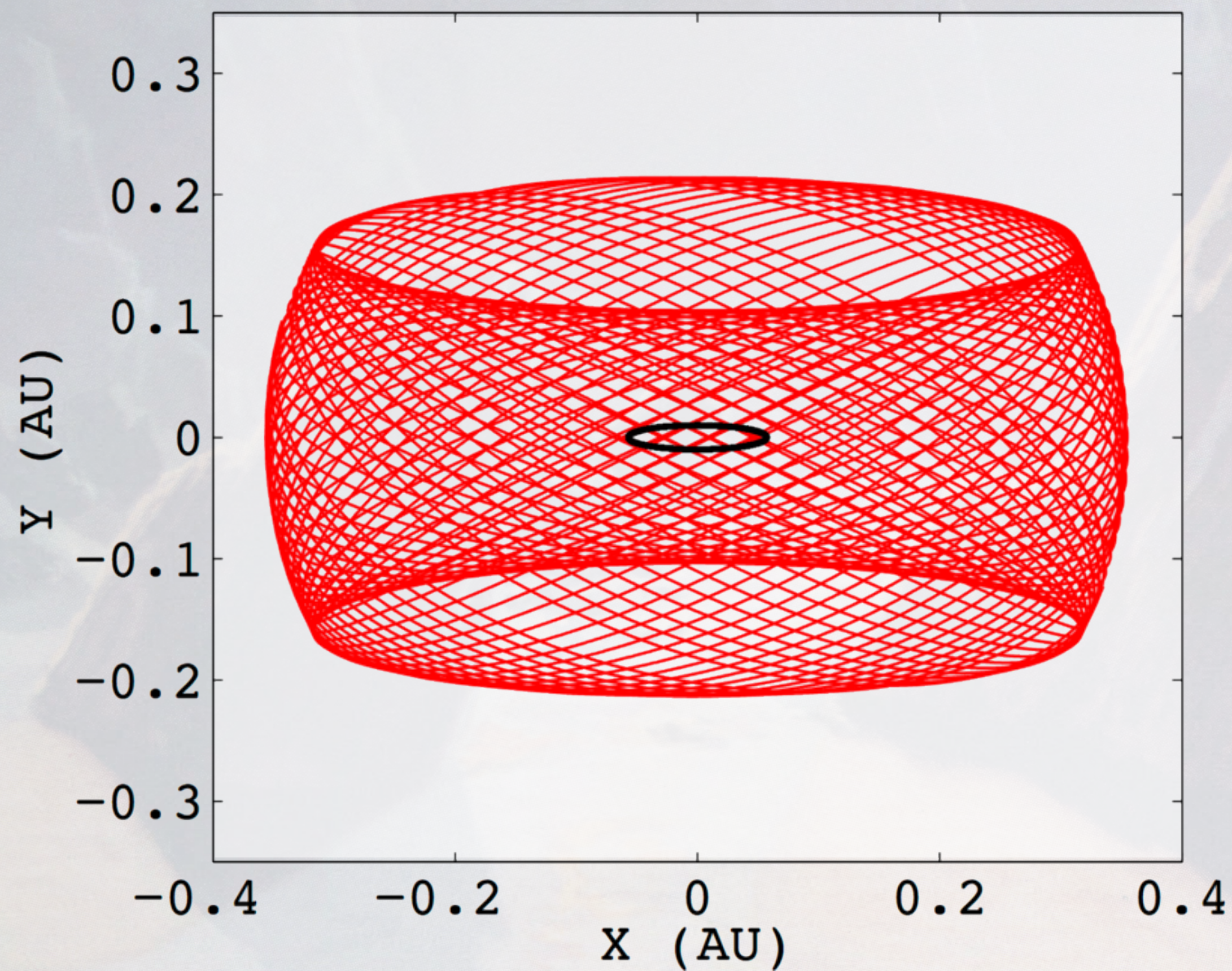
Santerne+ 2016:

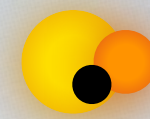
4.6% ($P < 400 \text{ d}$)

★corrected by removing triples

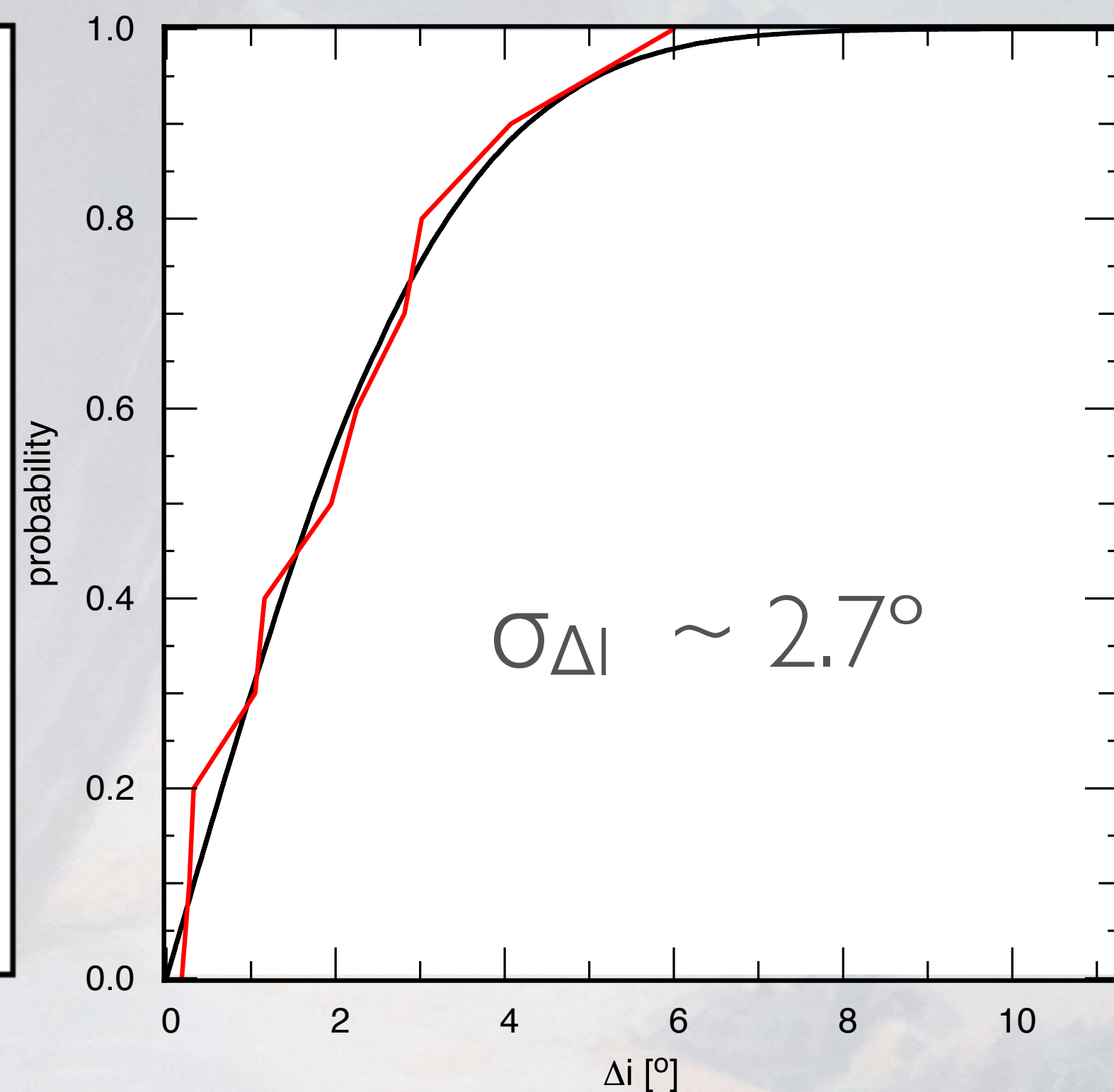
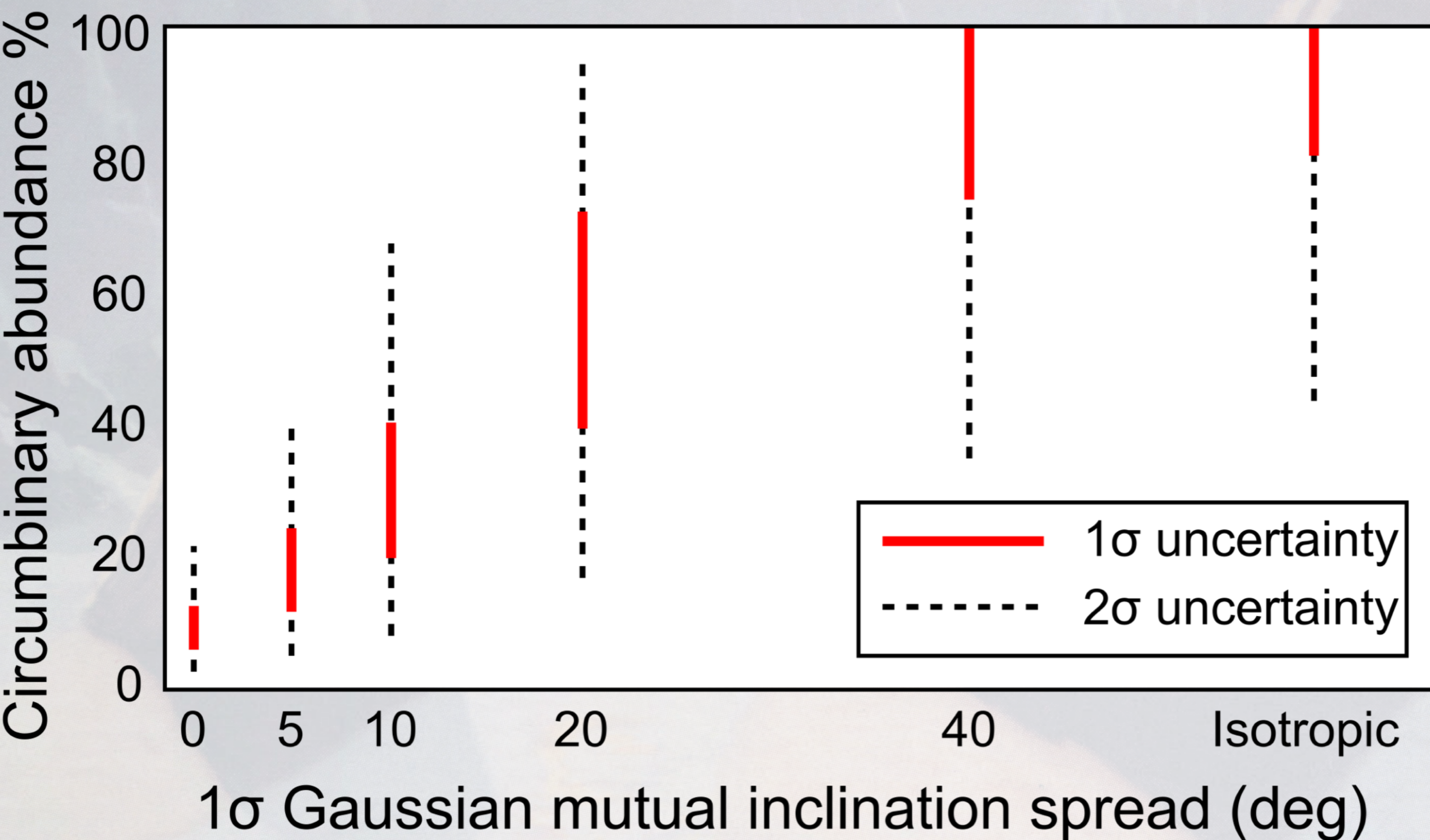


ORBITAL INCLINATION = LARGE SOLID ANGLE

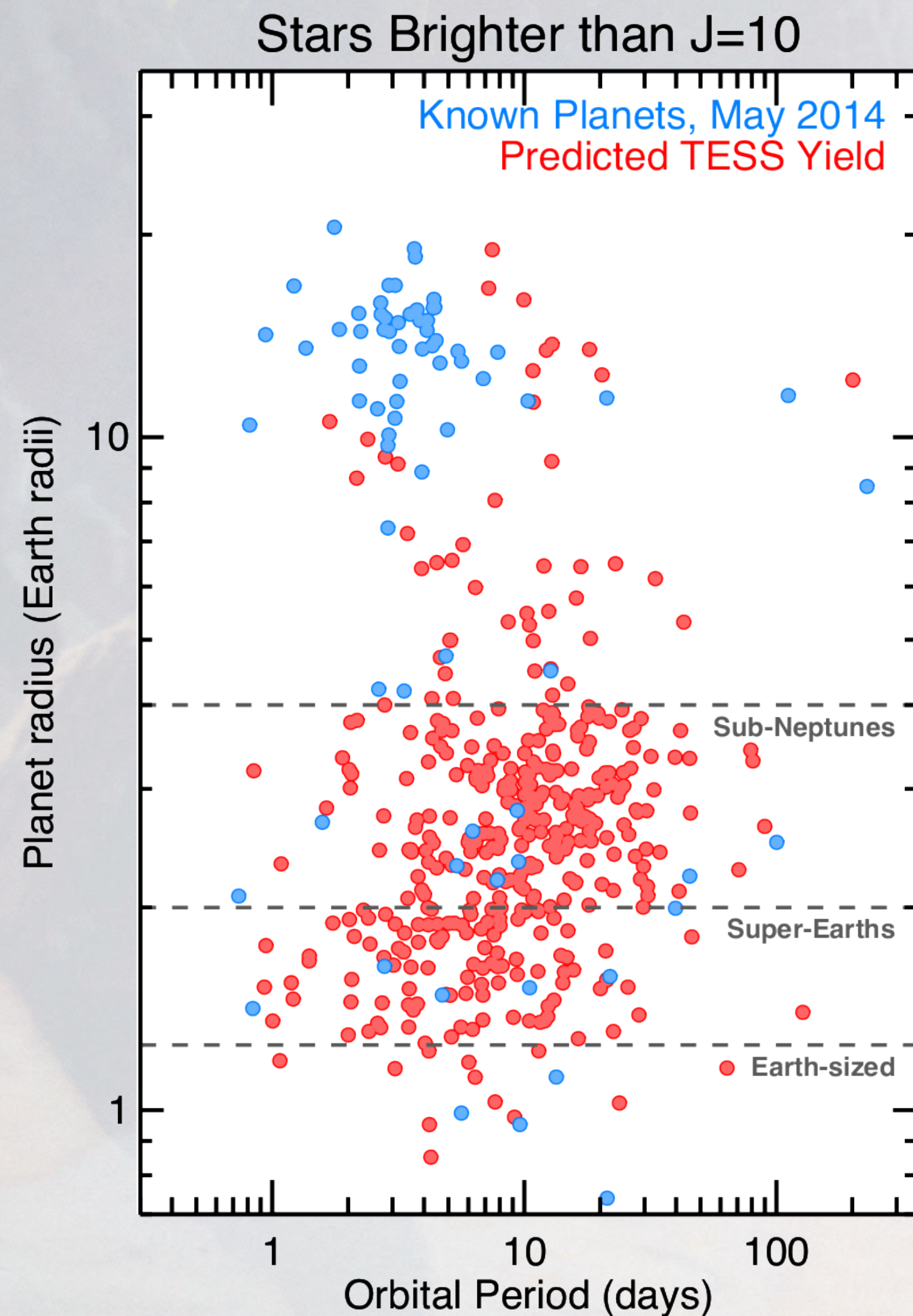
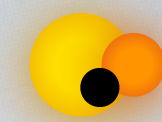




EFFECT OF MUTUAL INCLINATION



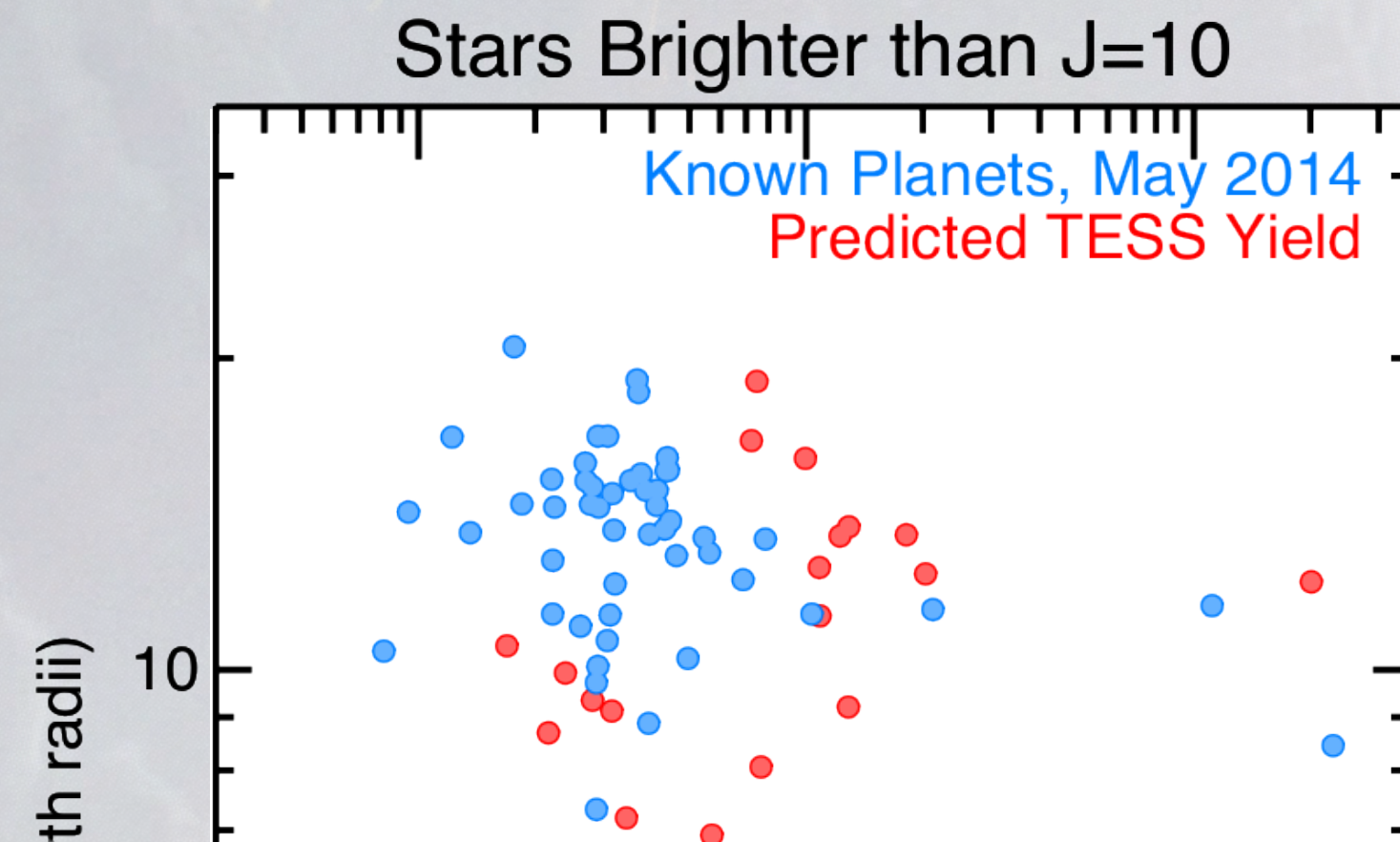
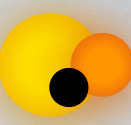
CIRCUMBINARY PLANETS ARE OVER-REPRESENTED



Projected results by TESS
very few temperate planets

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

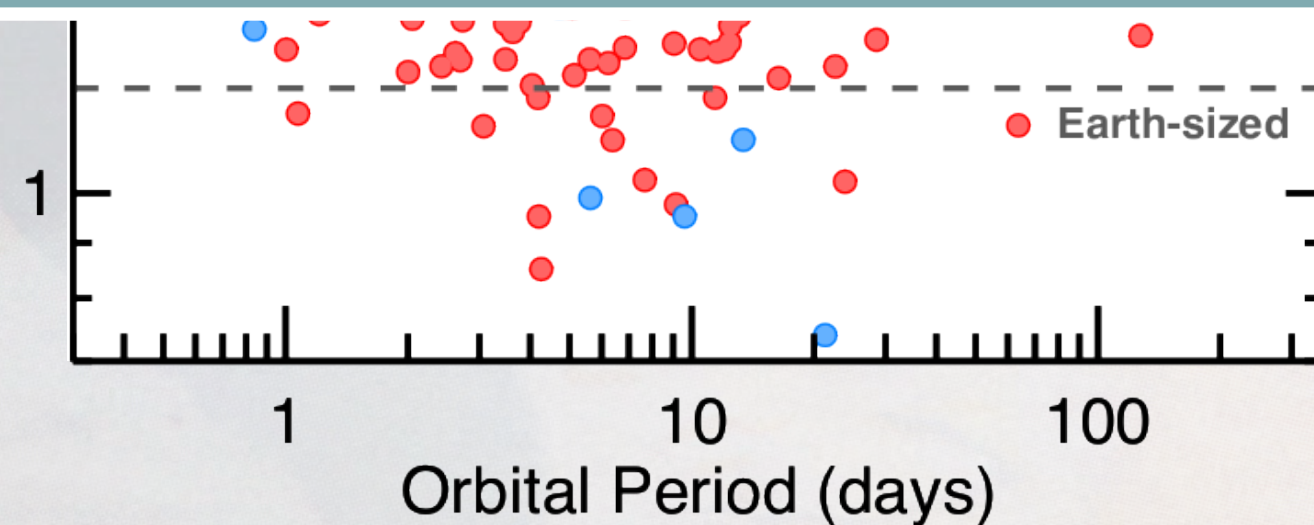
CIRCUMBINARY PLANETS ARE OVER-REPRESENTED



Projected results by TESS
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CURRENTLY ON NASA EXOPLANET ARCHIVE
For $K < 11$, $75 \text{ d} < P < 1000 \text{ d}$, and $\text{radii} > 2 R_{\oplus}$

45 published exoplanets, including 4 circumbinary planets

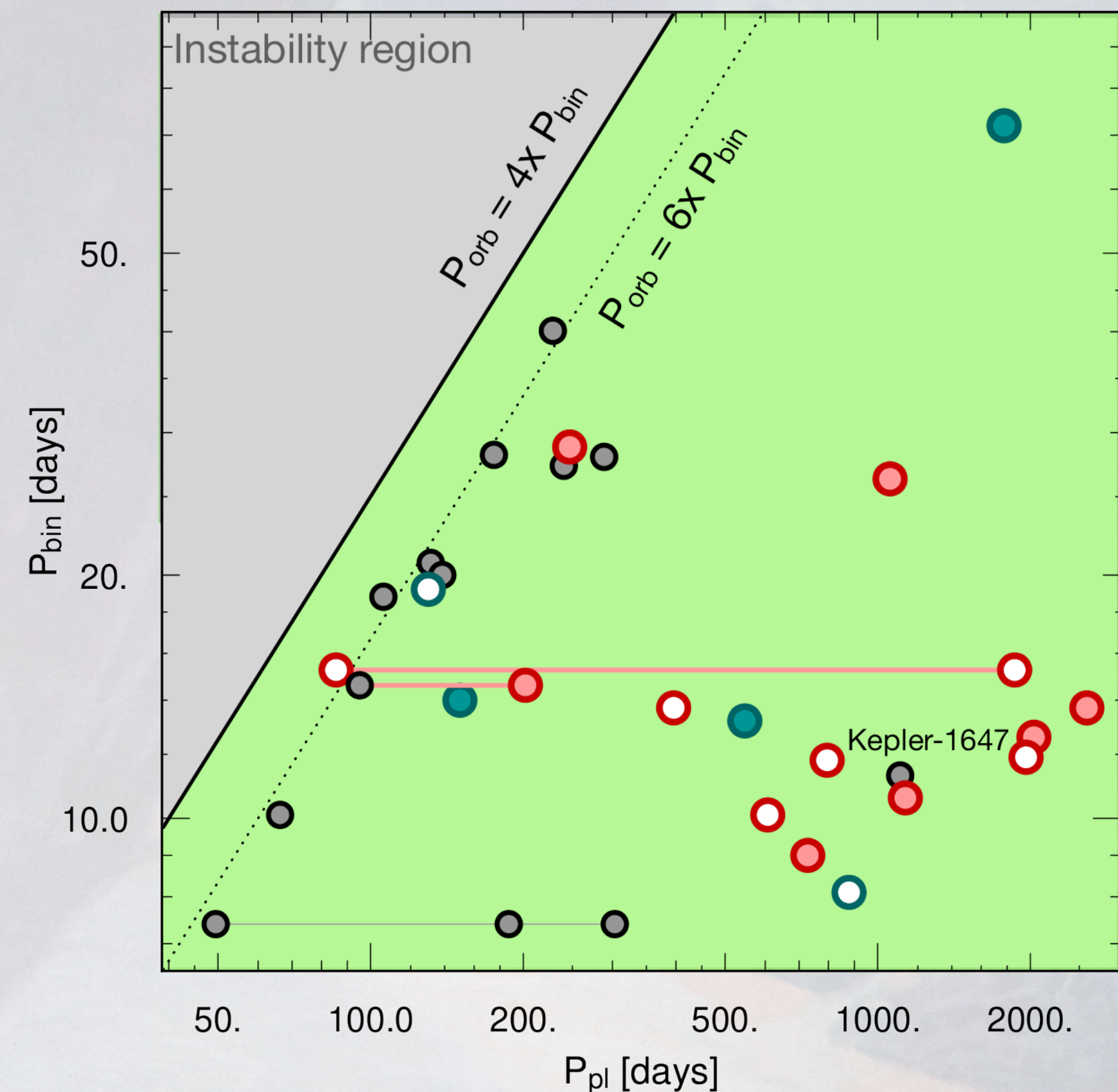
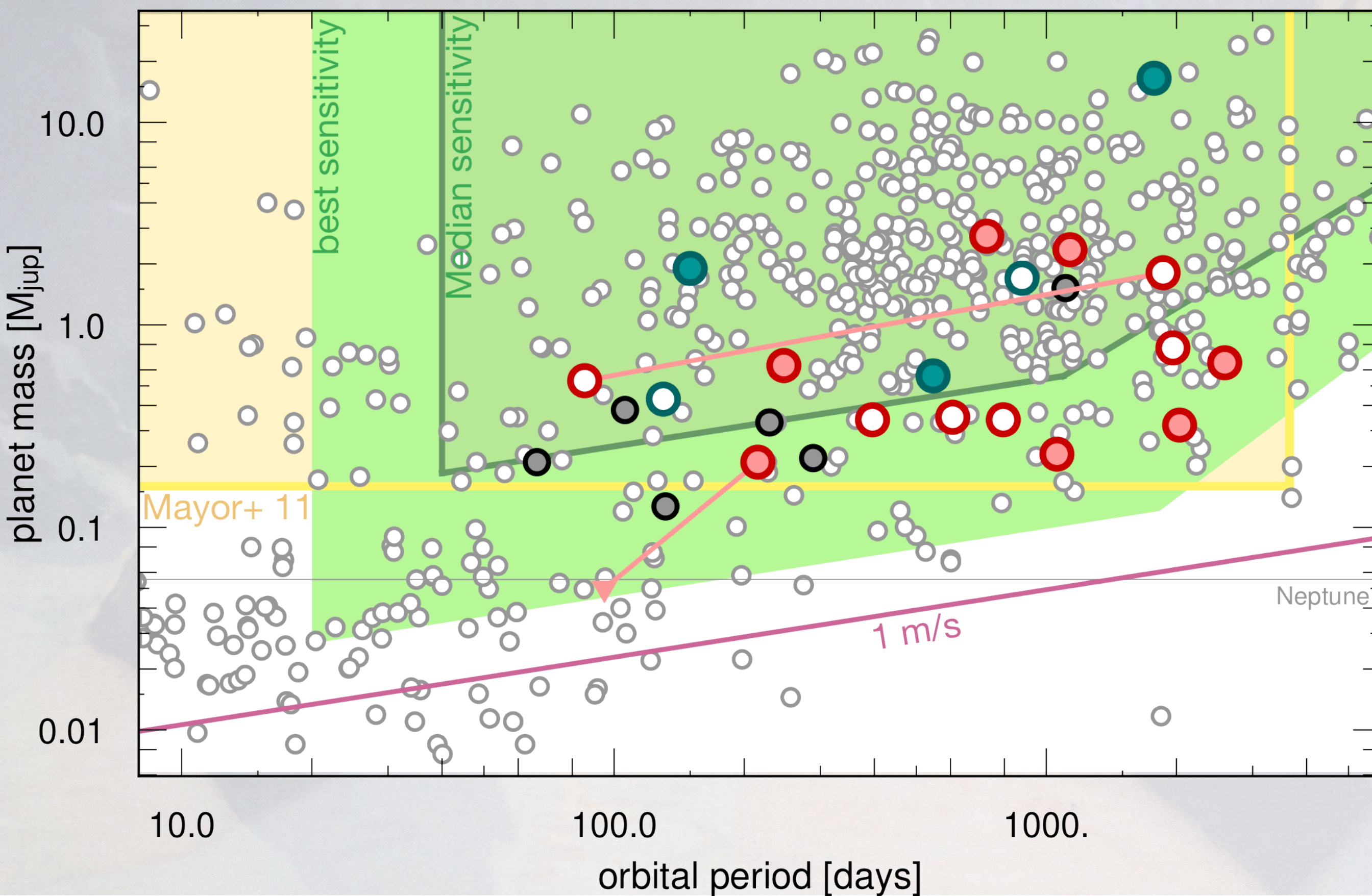




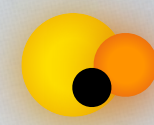
THE BEBOP SURVEY: *results, so far*

BINARIES ESCORTED BY ORBITING PLANETS

TALK BY ADAMSON



very preliminary results



THE BEBOP SURVEY: *preliminary results*

BINARIES ESCORTED BY ORBITING PLANETS

TALK BY ADAMSON

Occurrence rate

Correcting for completeness, $\sim 12\%$ of binaries have a gas giant

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

Physical properties

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

WITNESSING THE EFFECT ON THE SAFRONOV NUMBER? LATE SOLID ACCRETION? SLOWER GAS ACCRETION

Puzzling result

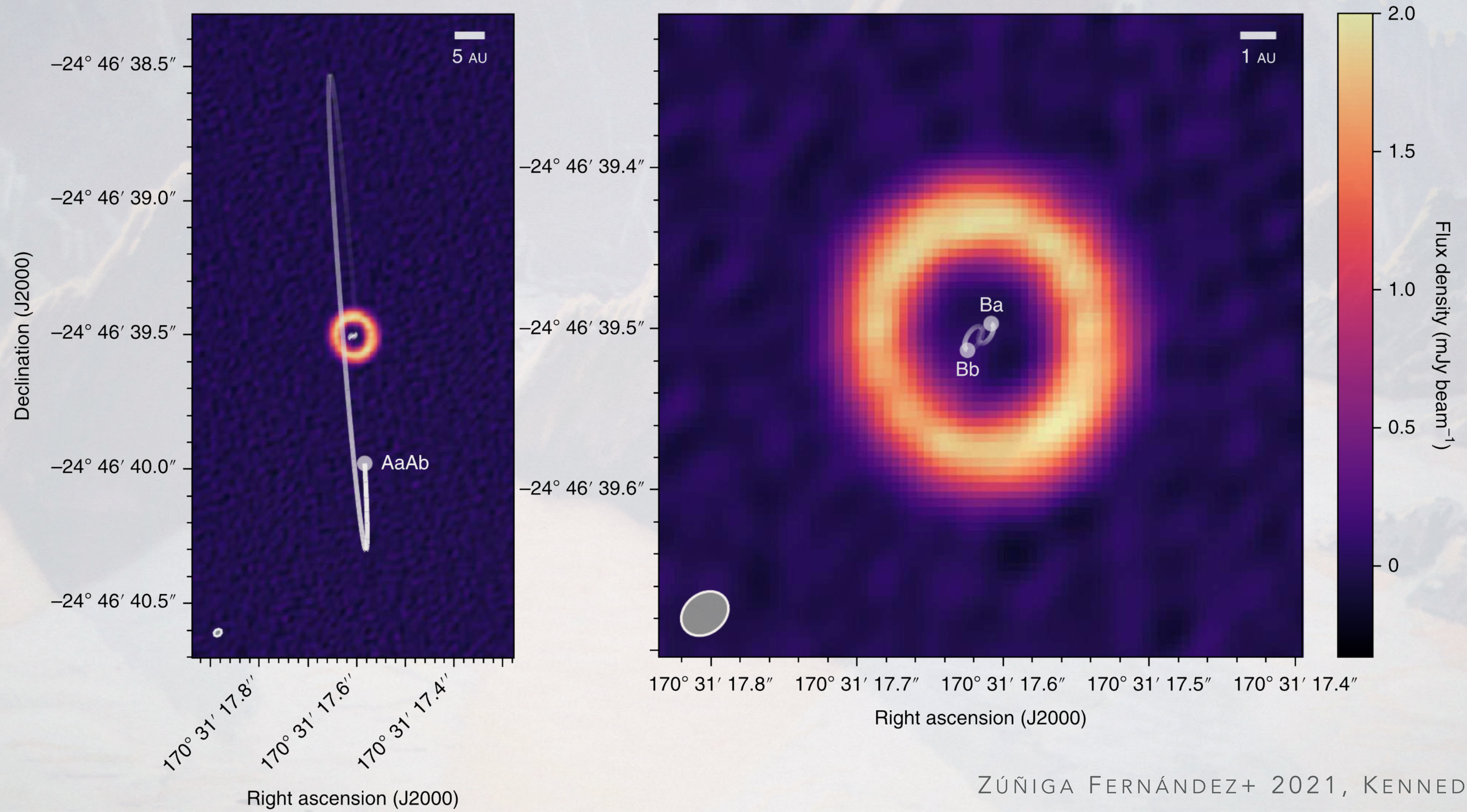
RV and transit circumbinary planet population are different.

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

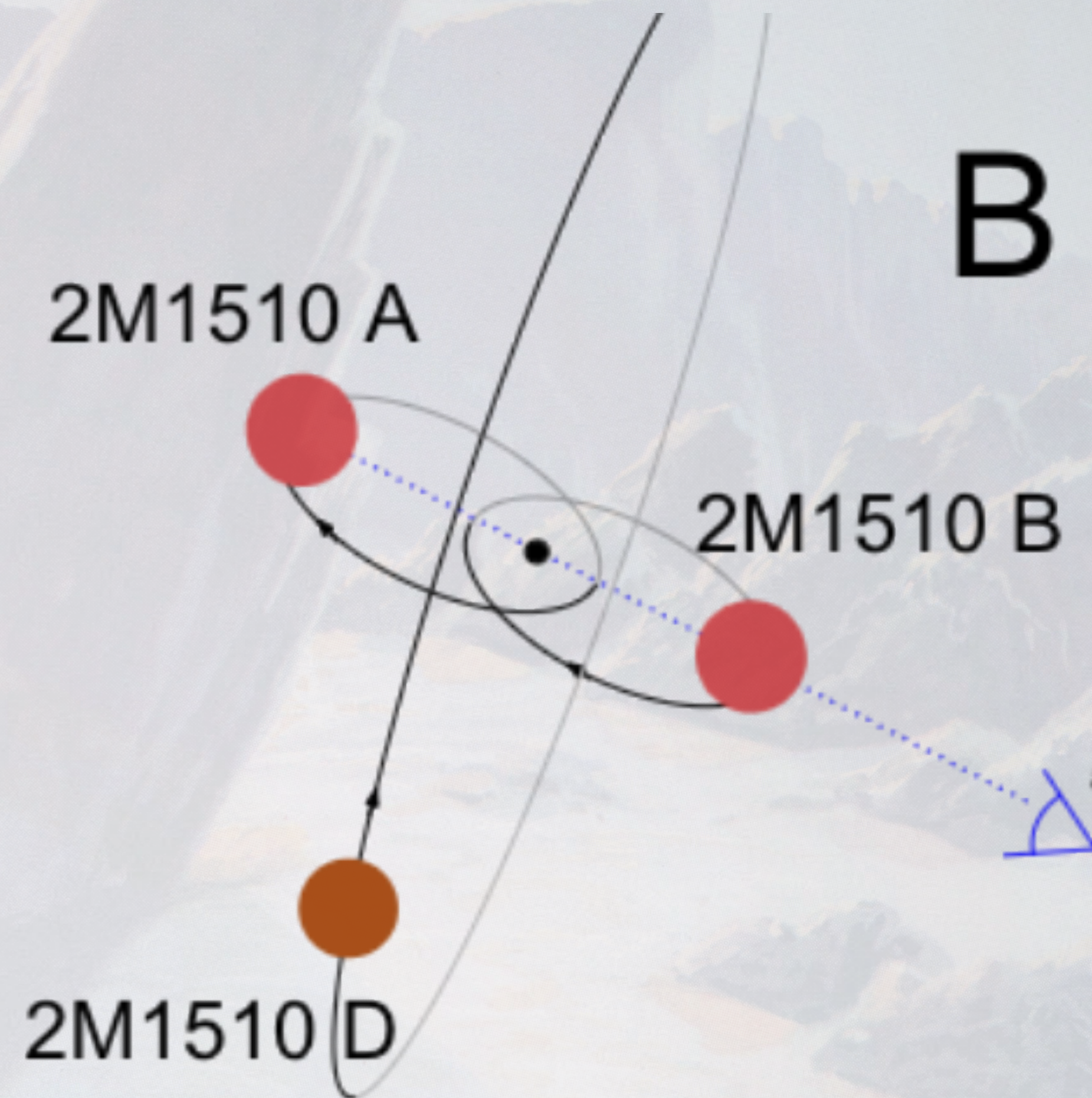
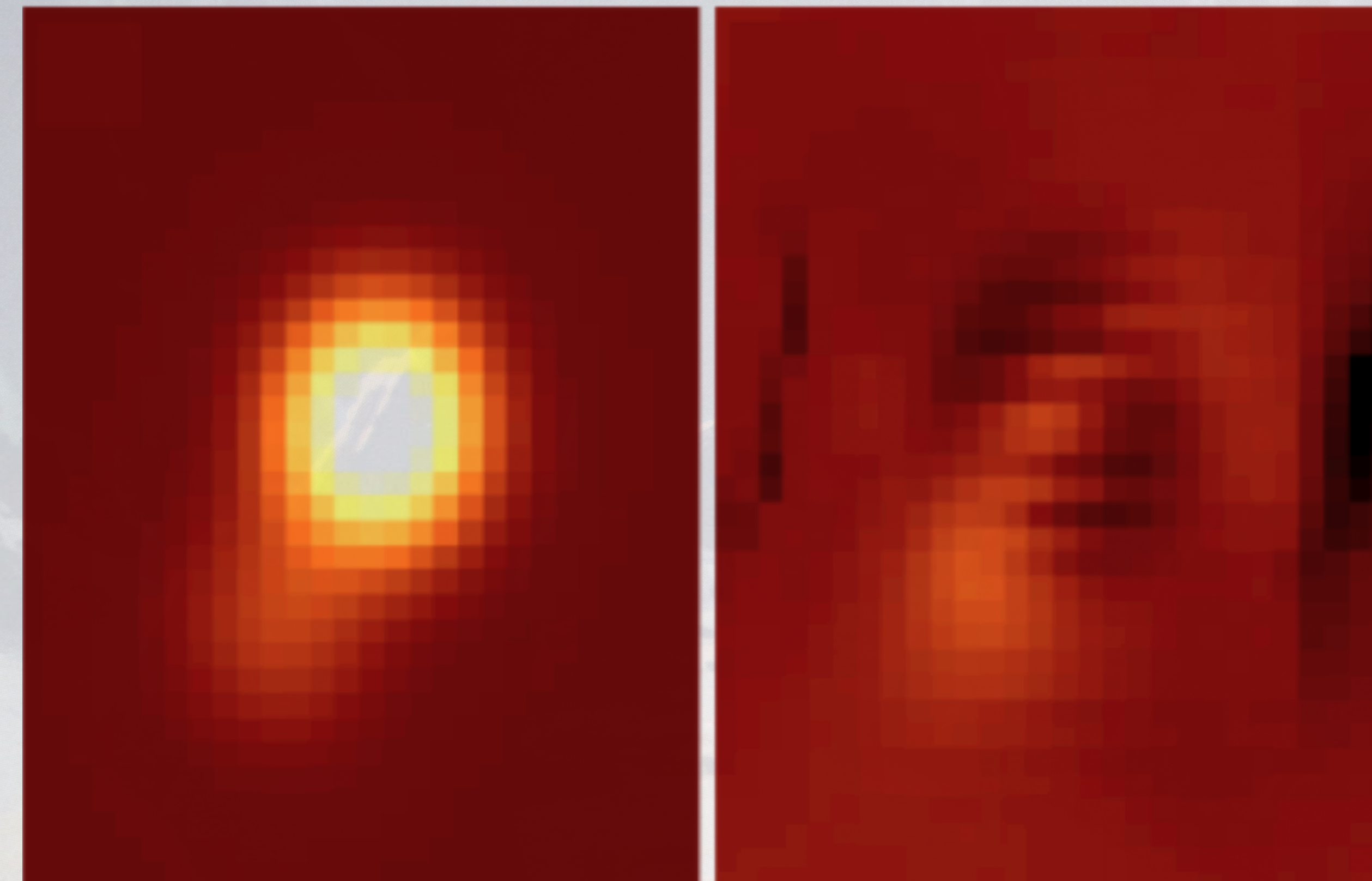
IS THIS A FOSSIL TRACE OF FORMATION BEYOND THE SNOW LINE?

A POLAR CIRCUMBINARY DISC: HD98800

outer pair is about to be eclipsed by the disc during 2026-27!



A POLAR ECCENTRIC ORBIT: 2M1510 D



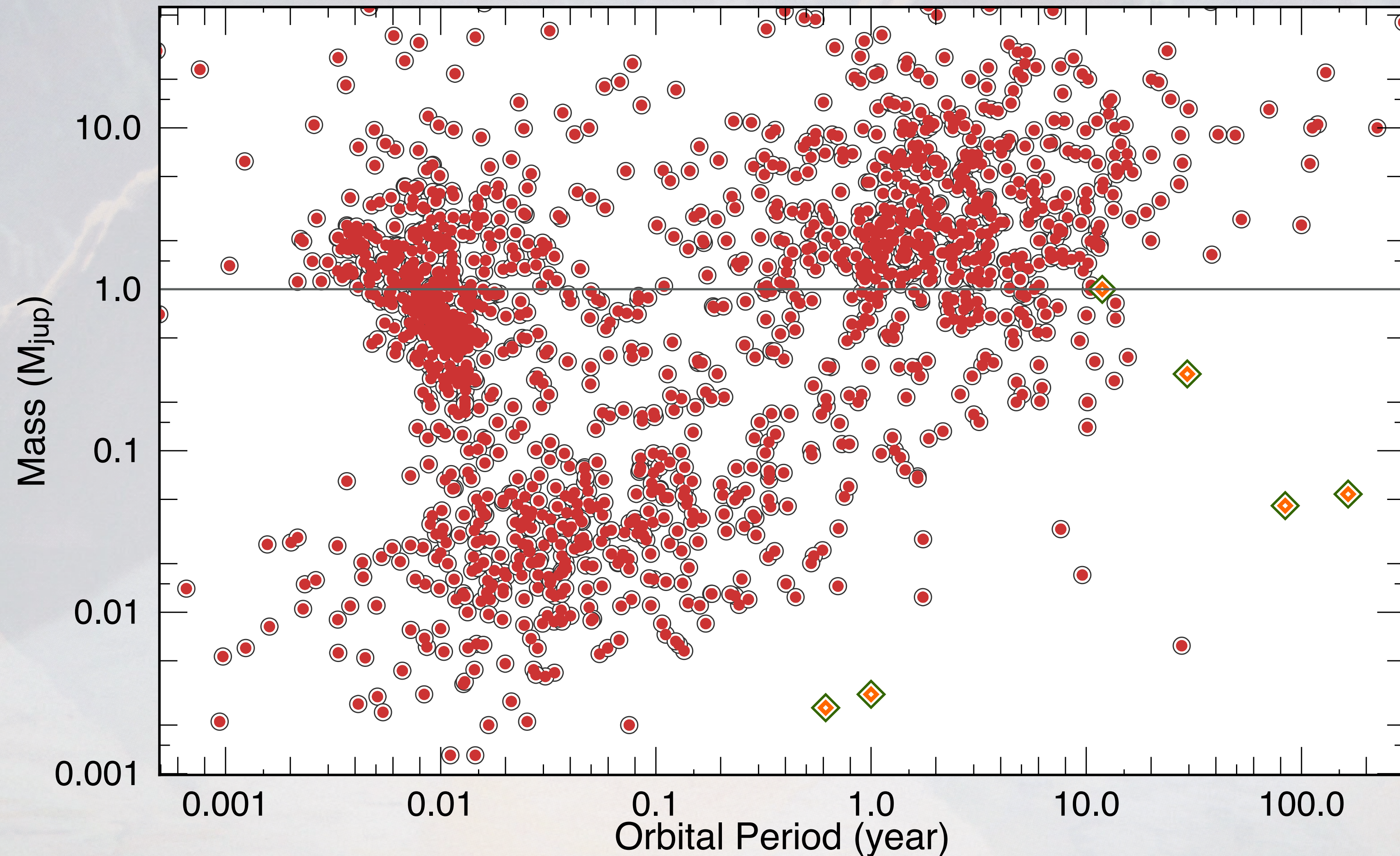
in principle, obliquities and orbital inclinations to be measured!
two other similar objects: VHS 1256 and Delorme-1

A dramatic landscape painting of a rocky coastline. In the foreground, a large, dark, craggy rock formation juts out from a sandy beach. The beach is composed of light-colored sand with patches of darker, wet sand reflecting the sky. In the background, more rugged rock formations rise from the sea, their peaks and cliffs illuminated by a low sun, creating a warm, golden glow. The sky is a pale, hazy blue. A white rectangular text box is centered over the middle of the image, containing the title in a clean, sans-serif font.

cool giant
exoplanets
at the
origin of
hot Jupiters

EVIDENCE RELATED TO HOT JUPITERS

They tend to have lower masses (amplified by transit method)



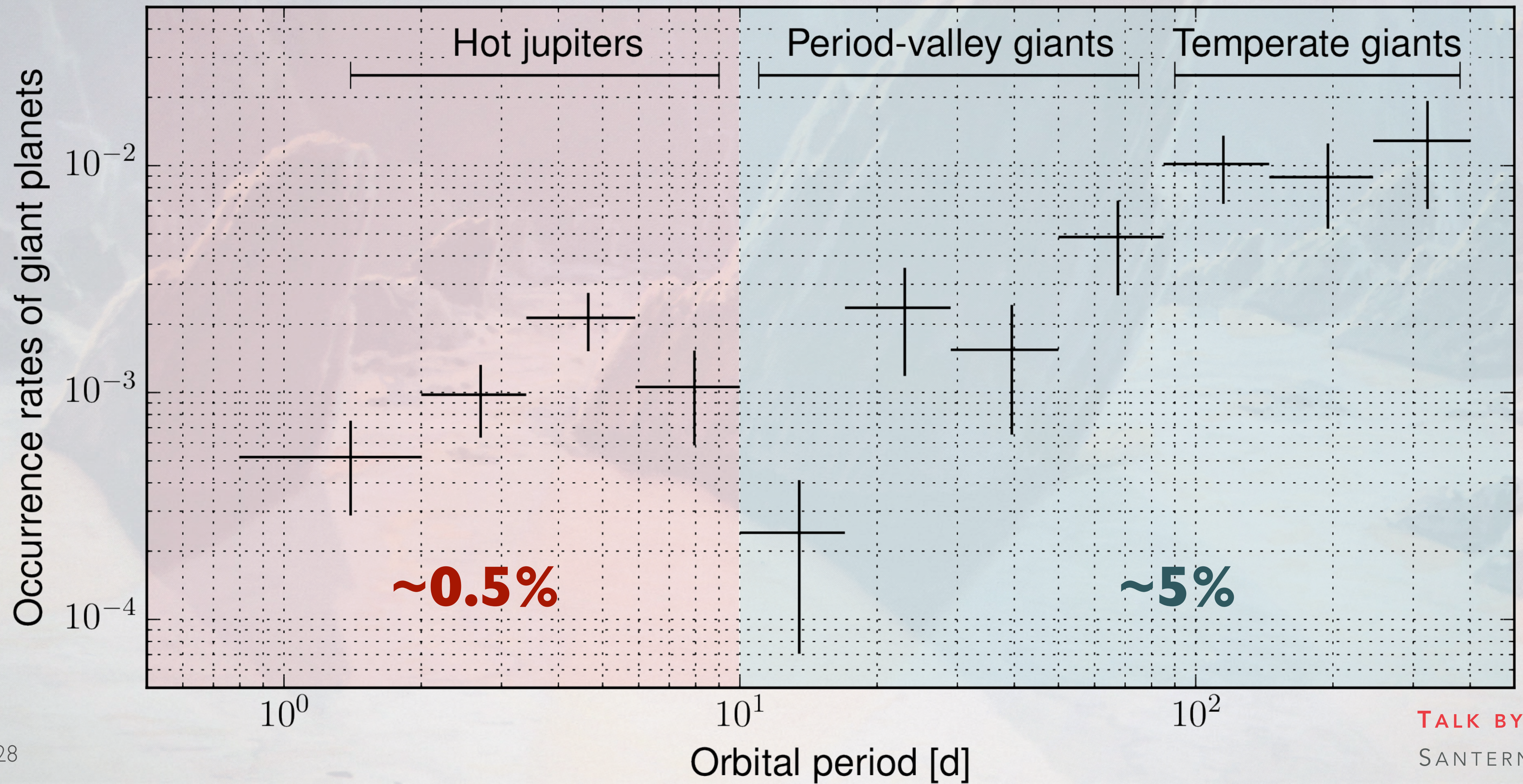
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They tend to have lower masses (amplified by transit method)

There is a peak around 3 days (consistent with circularisation)

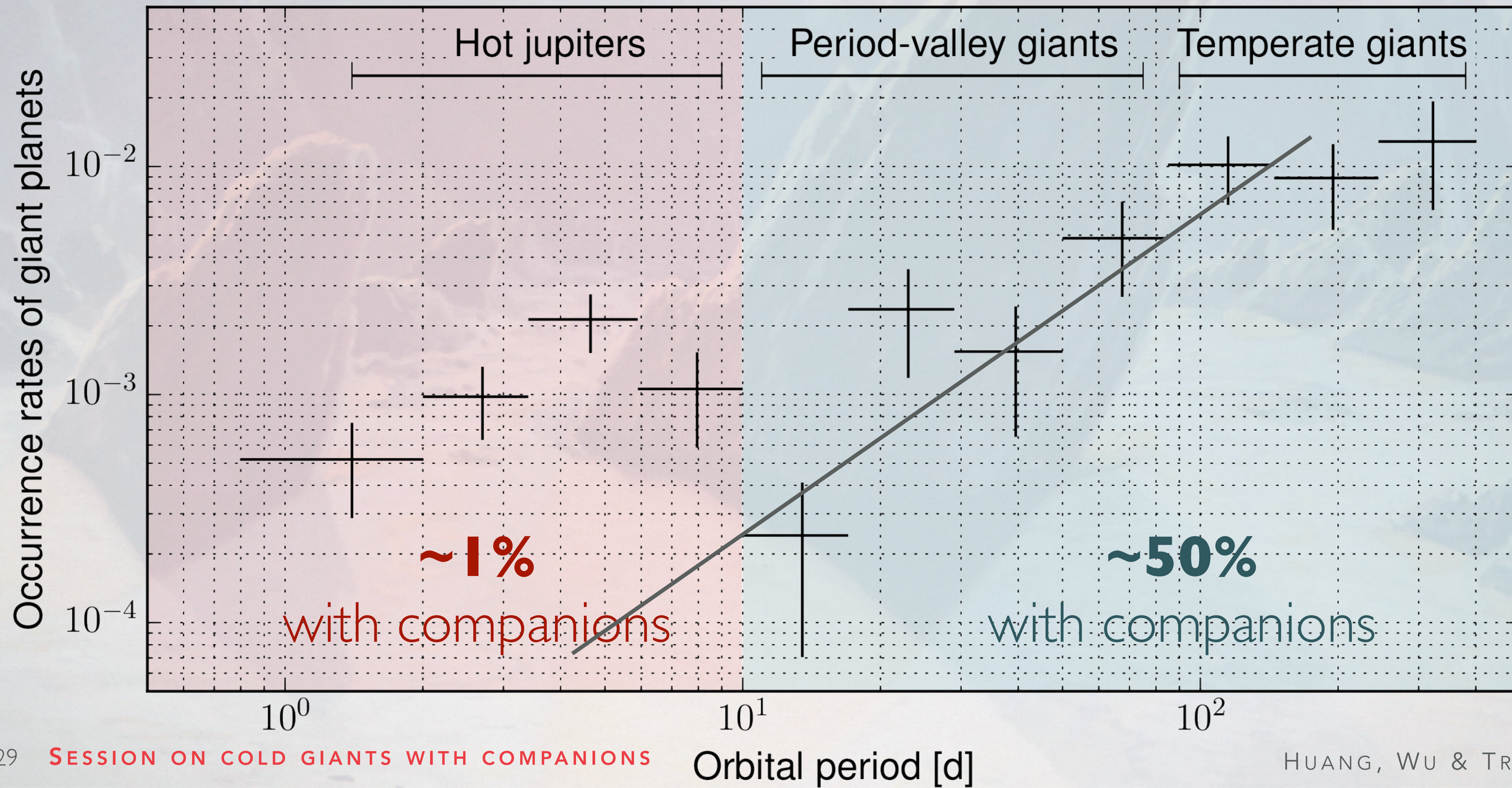
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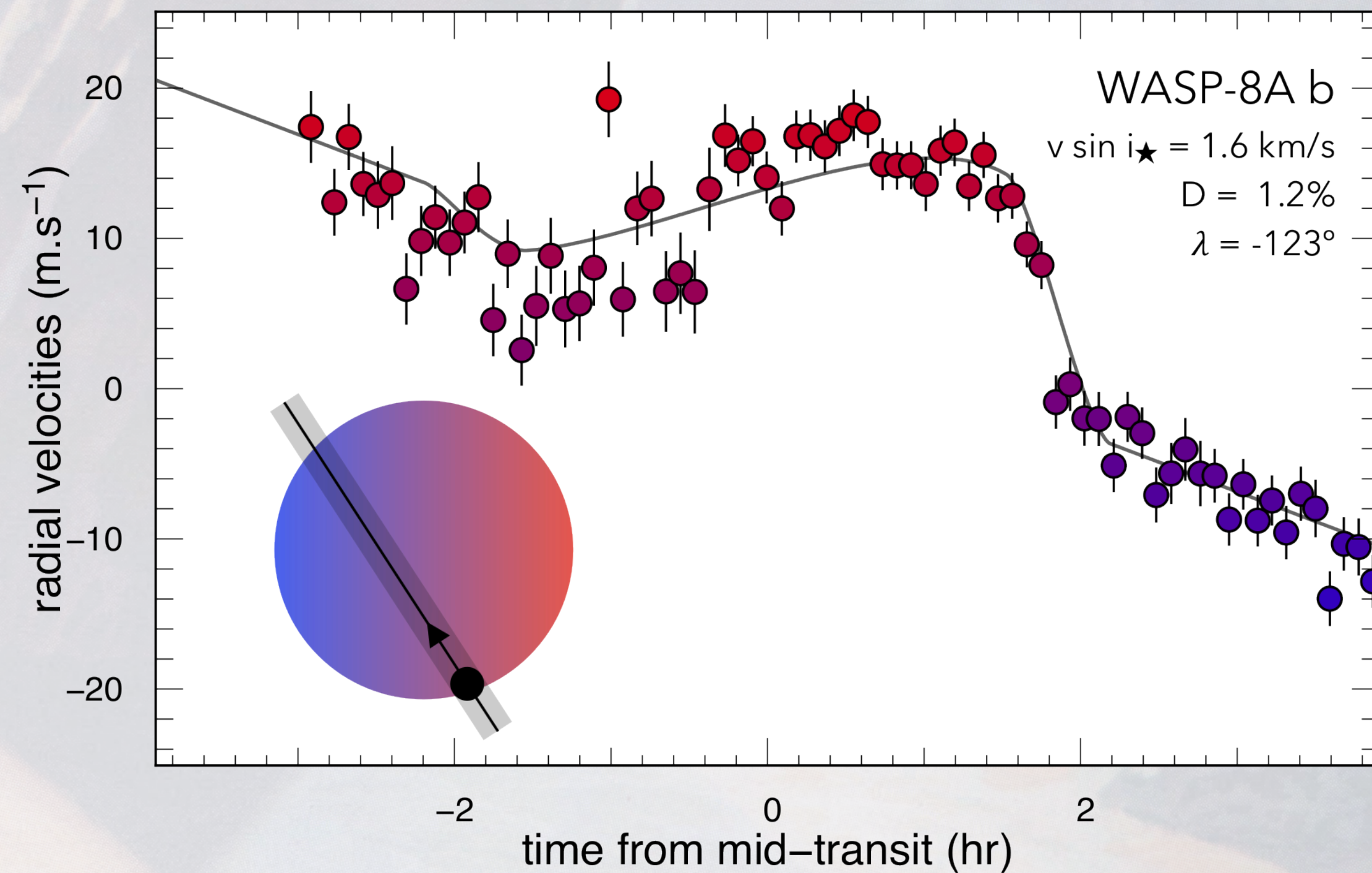
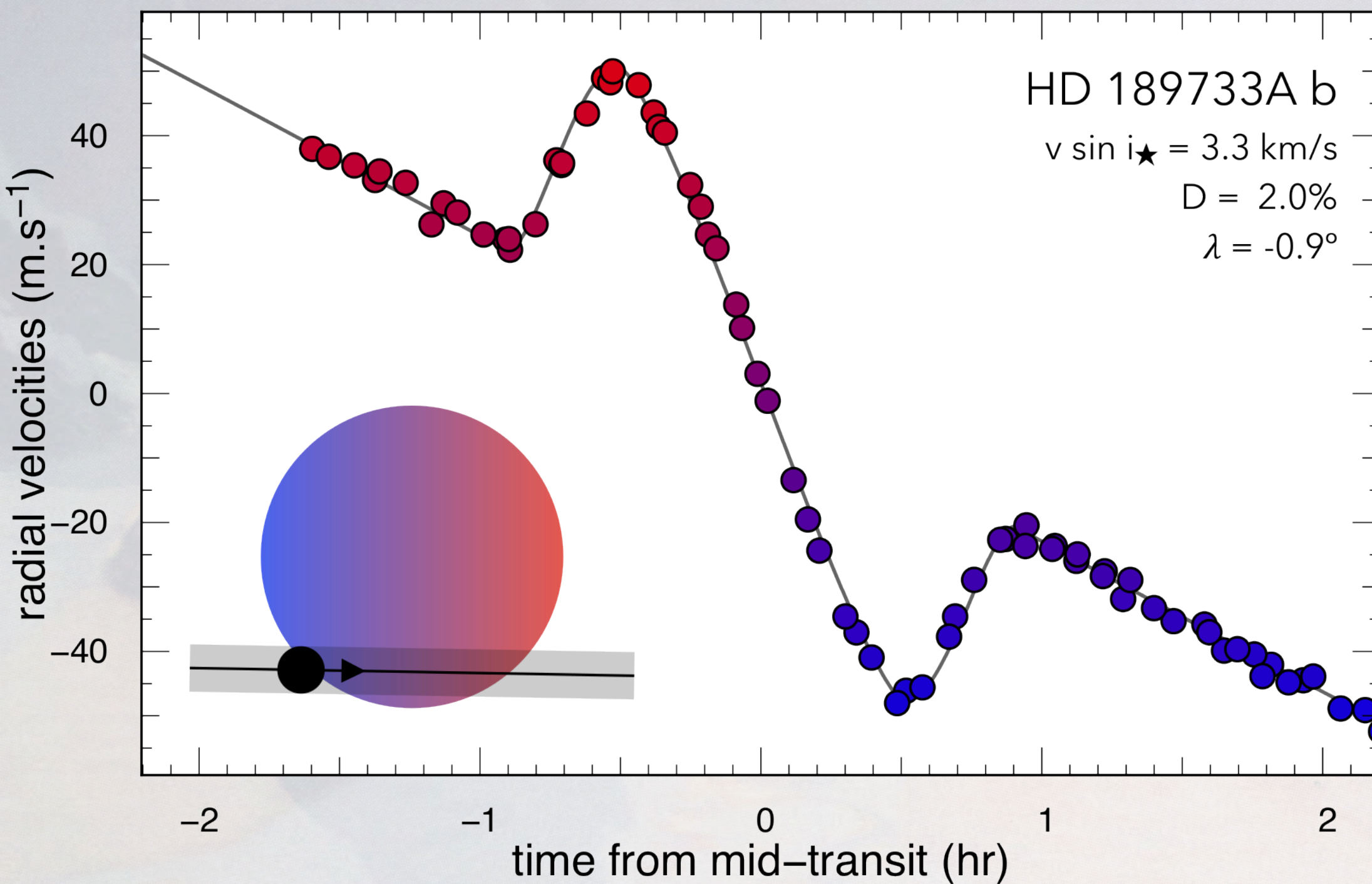
EVIDENCE RELATED TO HOT JUPITERS

Warm Jupiters (> 10 days, for solar type stars) have companions



EVIDENCE RELATED TO HOT JUPITERS

The orbit of many hot Jupiters is misaligned to the stellar axis



EVIDENCE RELATED TO HOT JUPITERS

They tend to have lower masses (amplified by transit method)

There is a peak around 3 days (consistent with circularisation)

Warm Jupiters have companions, many are eccentric

TALK BY MORGAN

The orbit of many hot Jupiters is misaligned to the stellar axis

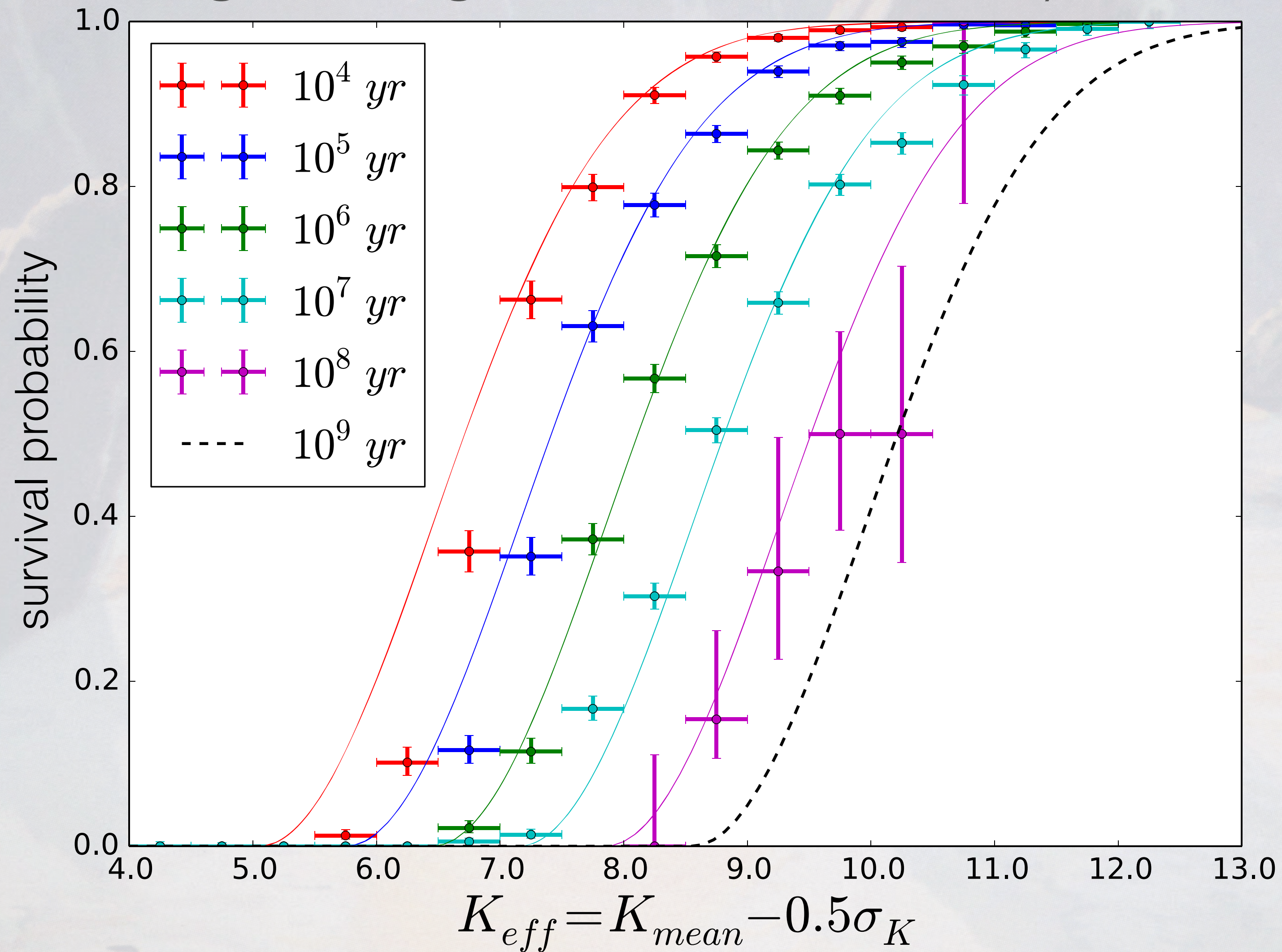
Systems in tight configurations break linearly with log time.

Anecdotaly, many transiting gas giants are in pairs, and show TTVs

TALK BY GUILLOT

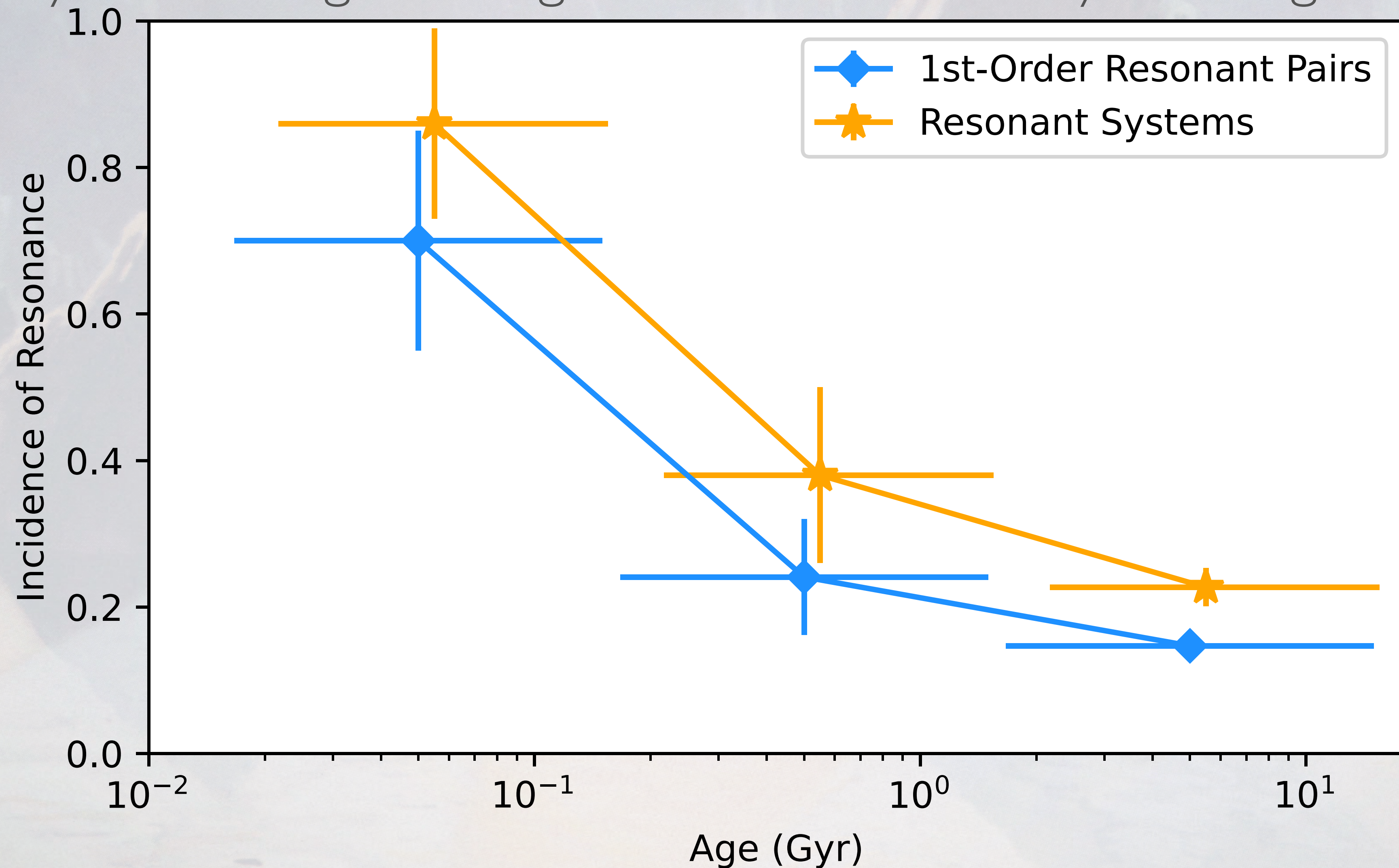
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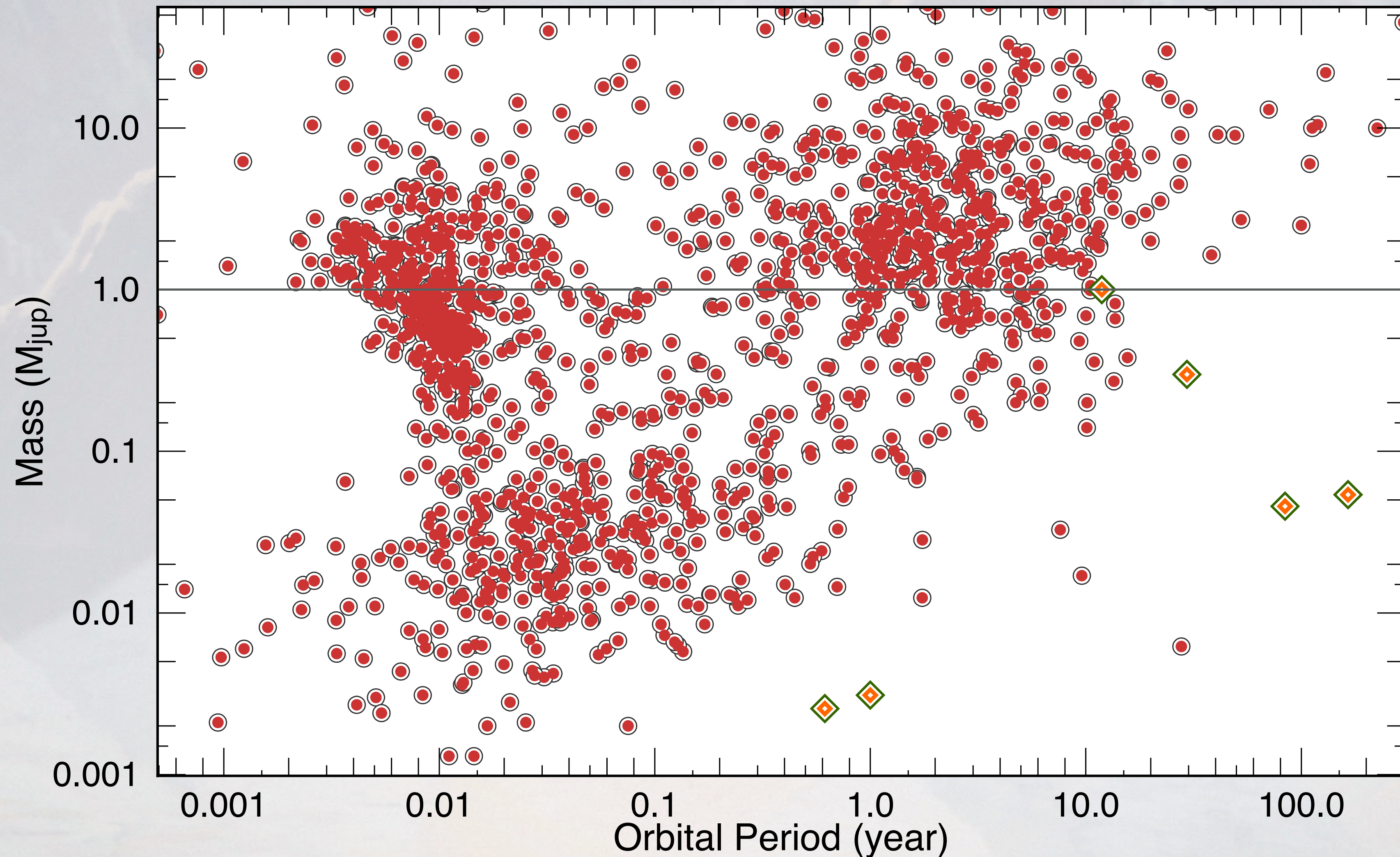
EVIDENCE RELATED TO HOT JUPITERS

Systems in tight configurations break linearly with log time.



EVIDENCE RELATED TO HOT JUPITERS

I think hot Jupiters are former, broken pairs of warm Jupiters



HOW TO TEST THIS SCENARIO? *Answer at 51 Peg 40th?*

Orbital inclinations for long-period gas giants (RM, or Gaia)

TALKS BY SAHLMANN, SMITH, MIRELES, ULMER-MOLL

Rossiter-McLaughlin measurements for young planets

Improved statistics on the occurrence of gas giants

TALKS BY HÉBRARD, OSBORN, WEISS, ULMER-MOLL, GUILLOT + GAIA SESSION

Studying volatile-rich planets in low mass stars

SESSION ON M DWARFS HOSTING GIANTS

Occurrence rate as a function of time

TALK BY SCHMIDT

Composition of hot Jupiters should be similar to warm Jupiters

TALK BY BIRKBY, GUILLOT

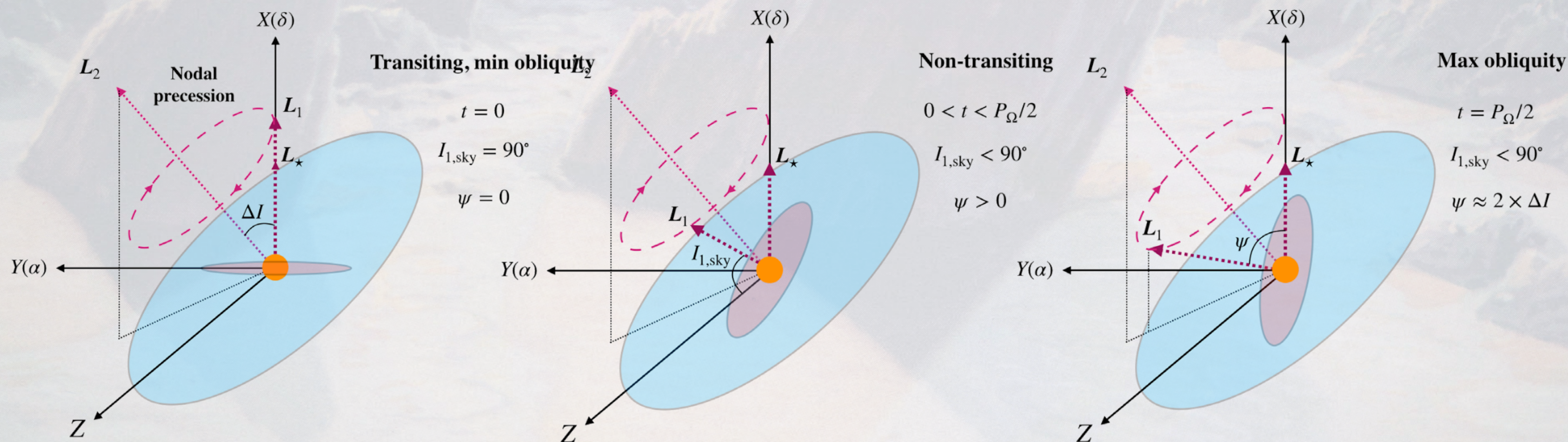
Checking the incidence of gas giant pairs, particularly at long P.

GAIA'S ORBITAL INCLINATIONS

Mutual inclinations, some intriguing clues
how regular? mixing transit & Gaia for inner vs outer systems

POSTER BY BOURRIER & 2 SESSIONS ON GAIA DATA

π Men has an inner transiting planet, and outer inclined giant



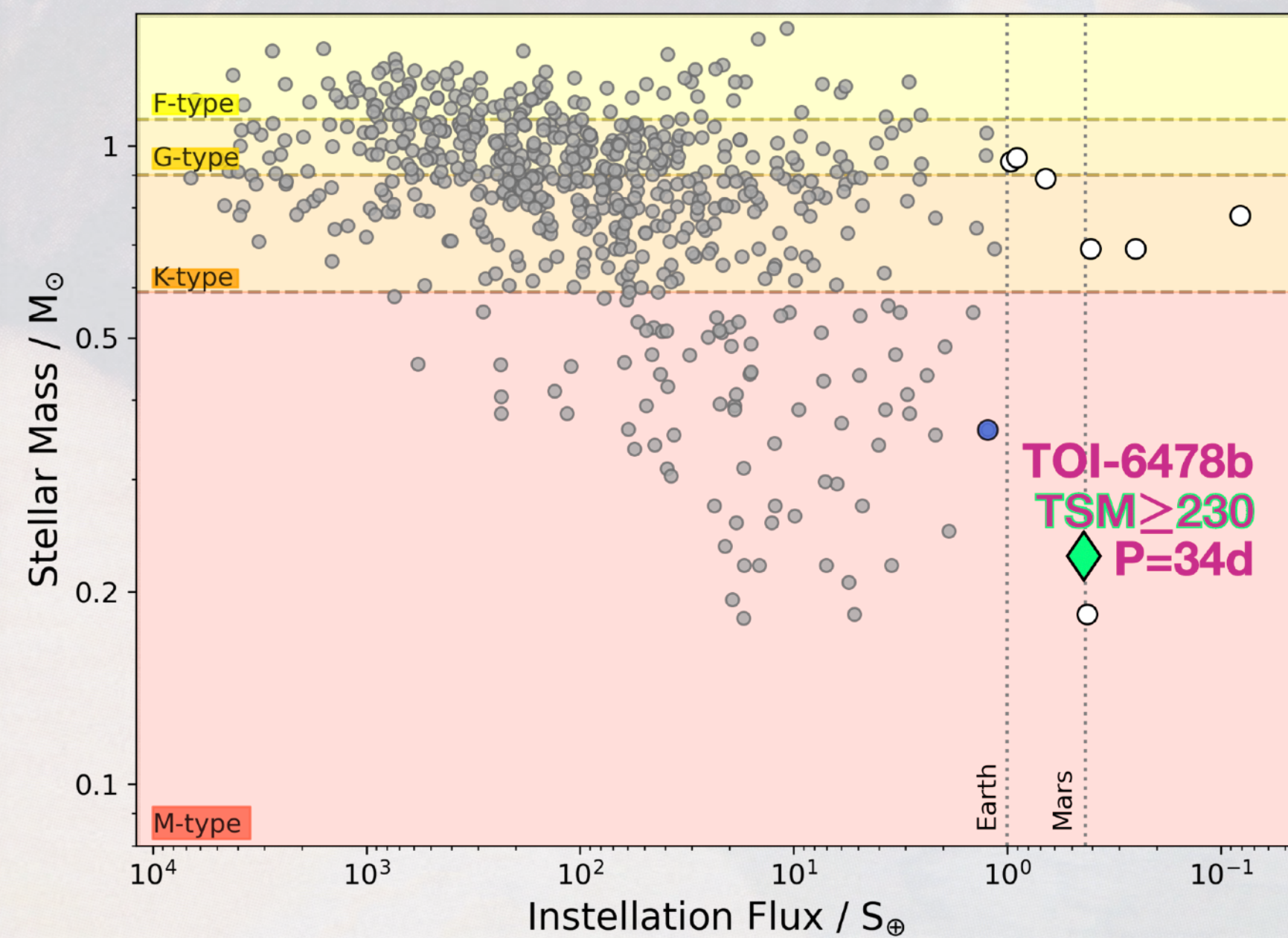
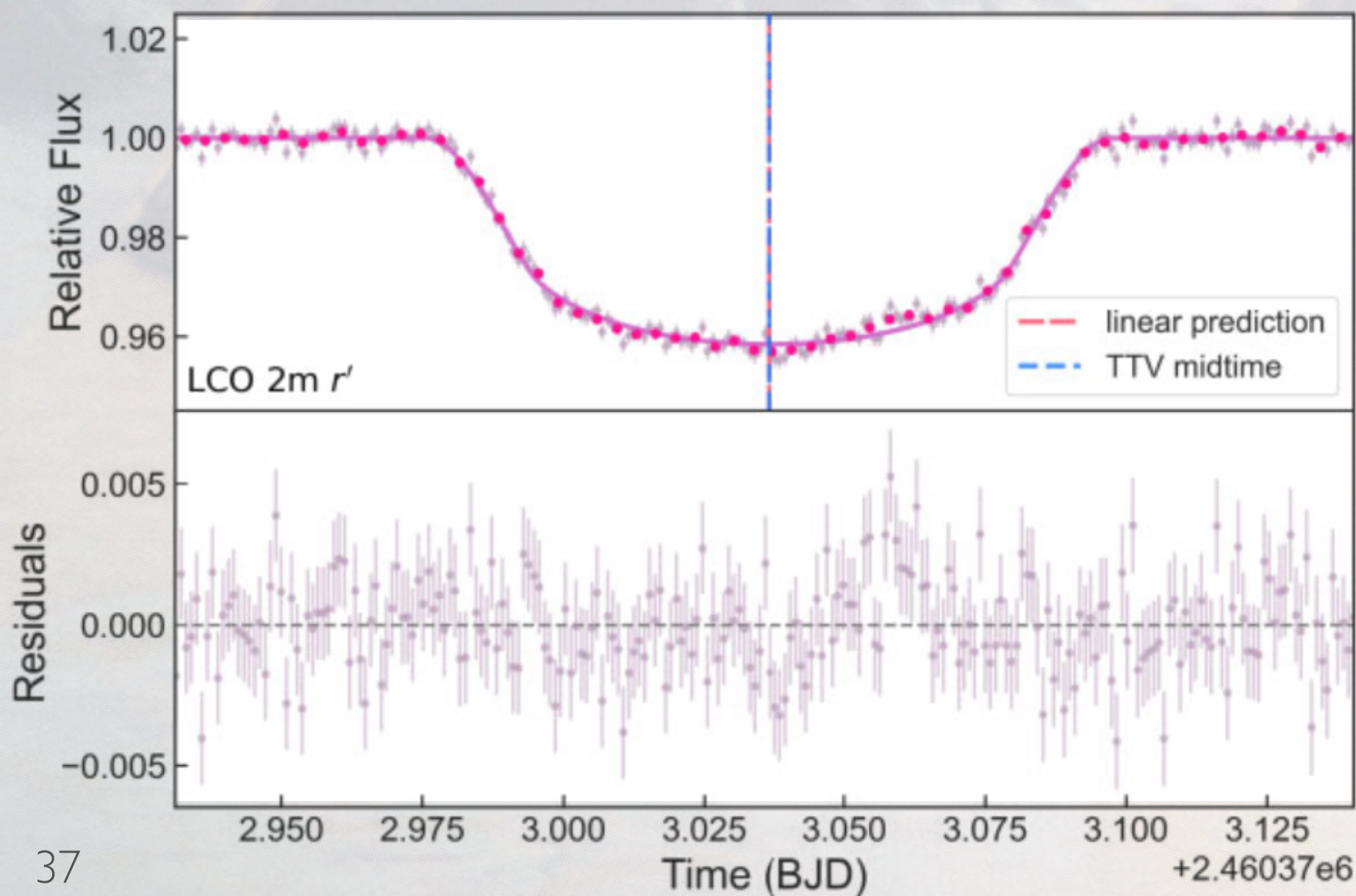
MANGOs, GEMs & TOI-6478B

MANGOs & GEMs: two dedicated programmes to detect gas giants transiting M dwarfs

SESSION ON M DWARFS HOSTING GIANTS

Is the 3d peak the same? the period valley? eccentricity? atmosphere?

TOI-6478b: a 34d period Neptune, beyond the ice-line (200K)
mass? stellar obliquity? atmospheric composition? planet near MMR?



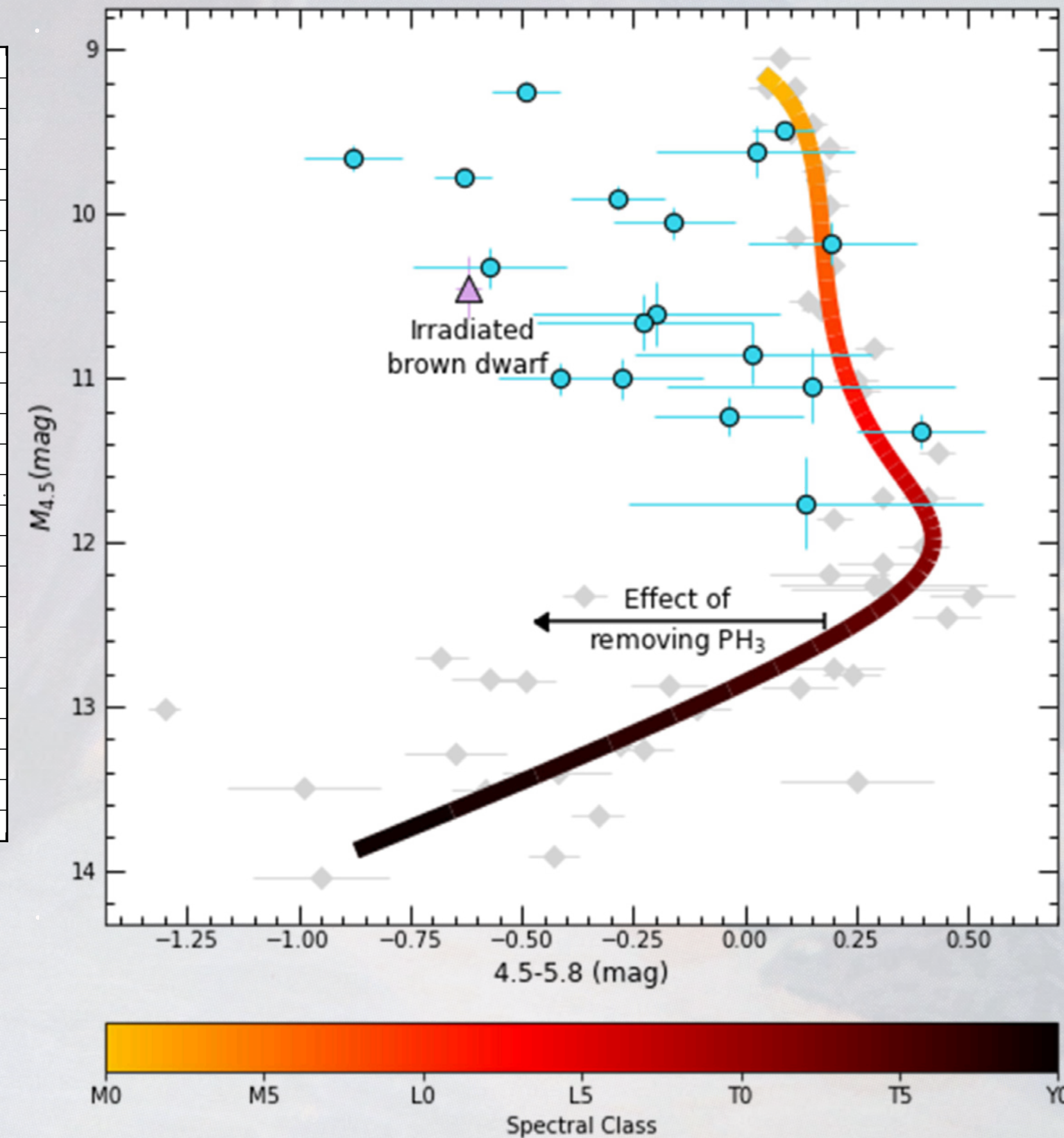
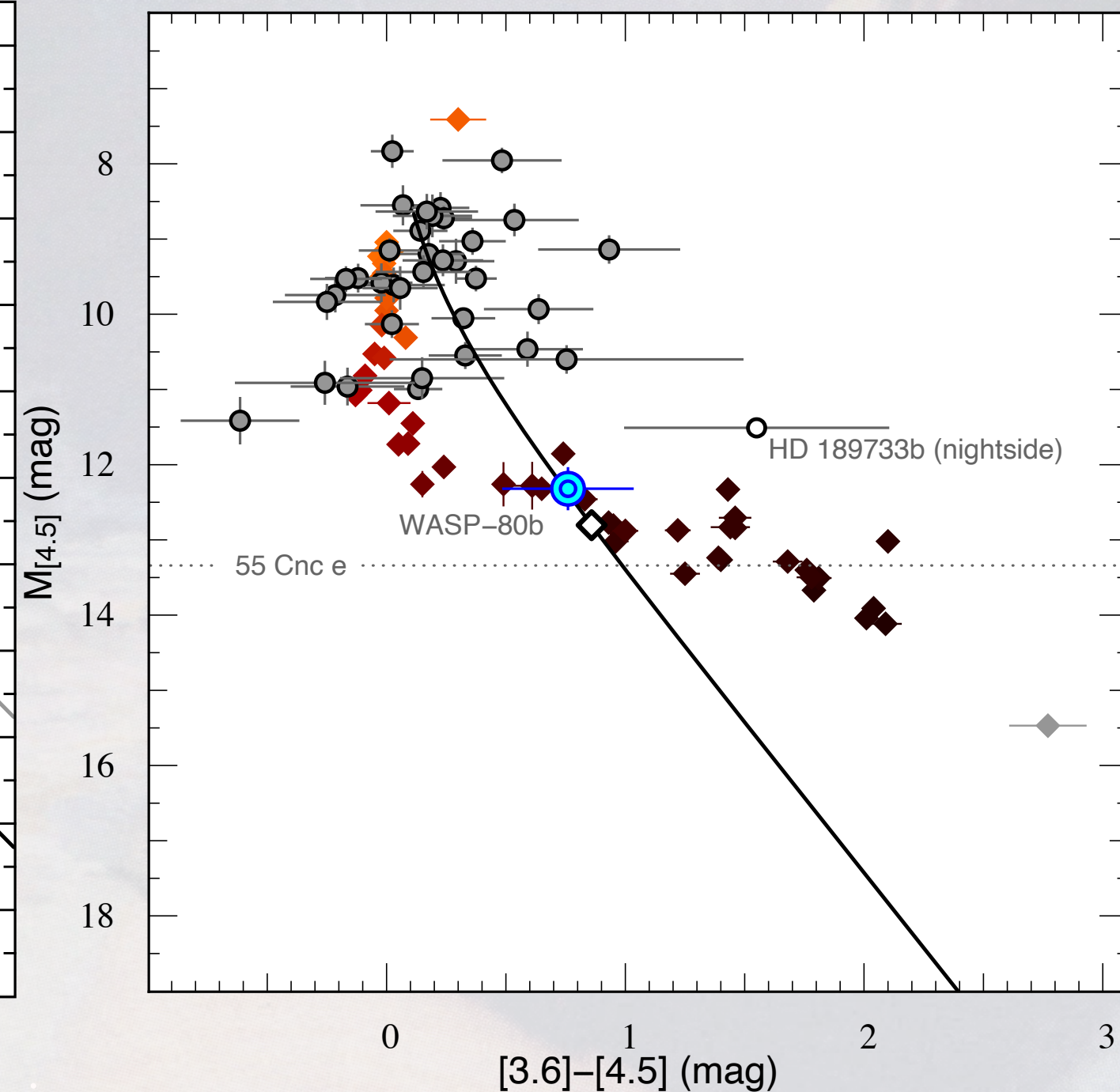
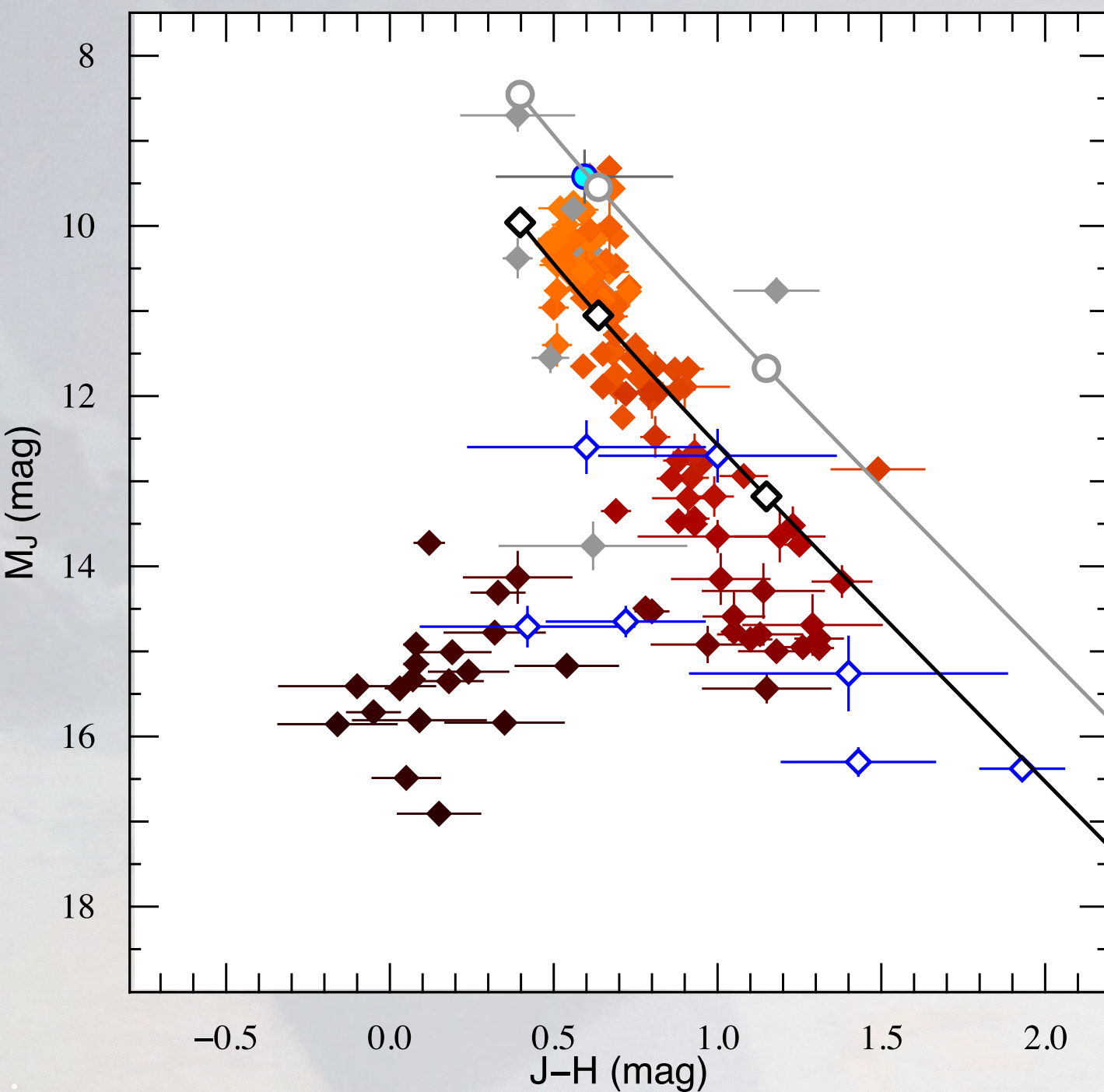
SCOTT+ 2025

A dramatic landscape painting of a rocky coastline. In the foreground, a large, dark, craggy rock formation juts out from a sandy beach. The beach is composed of light-colored sand with patches of darker, wet sand reflecting the sky. In the background, more rugged cliffs and rock formations rise from the sea. The sky is a pale, hazy blue. A white rectangular text box is centered over the middle of the image, containing the text "young planets", "hot Jupiters", "&", and "brown dwarfs" in a white, sans-serif font.

young planets
hot Jupiters
&
brown dwarfs

COLOUR-MAGNITUDE DIAGRAMS

To compare hot Jupiters to Brown Dwarfs and directly imaged planets



Exoplanet properties
IN DYNAMICALLY RICH ENVIRONMENTS
help understand formation

Comparing sub-populations is key to progress

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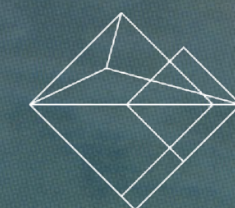
UNIVERSITY OF
BIRMINGHAM



LEVERHULME
TRUST



Science and
Technology
Facilities Council



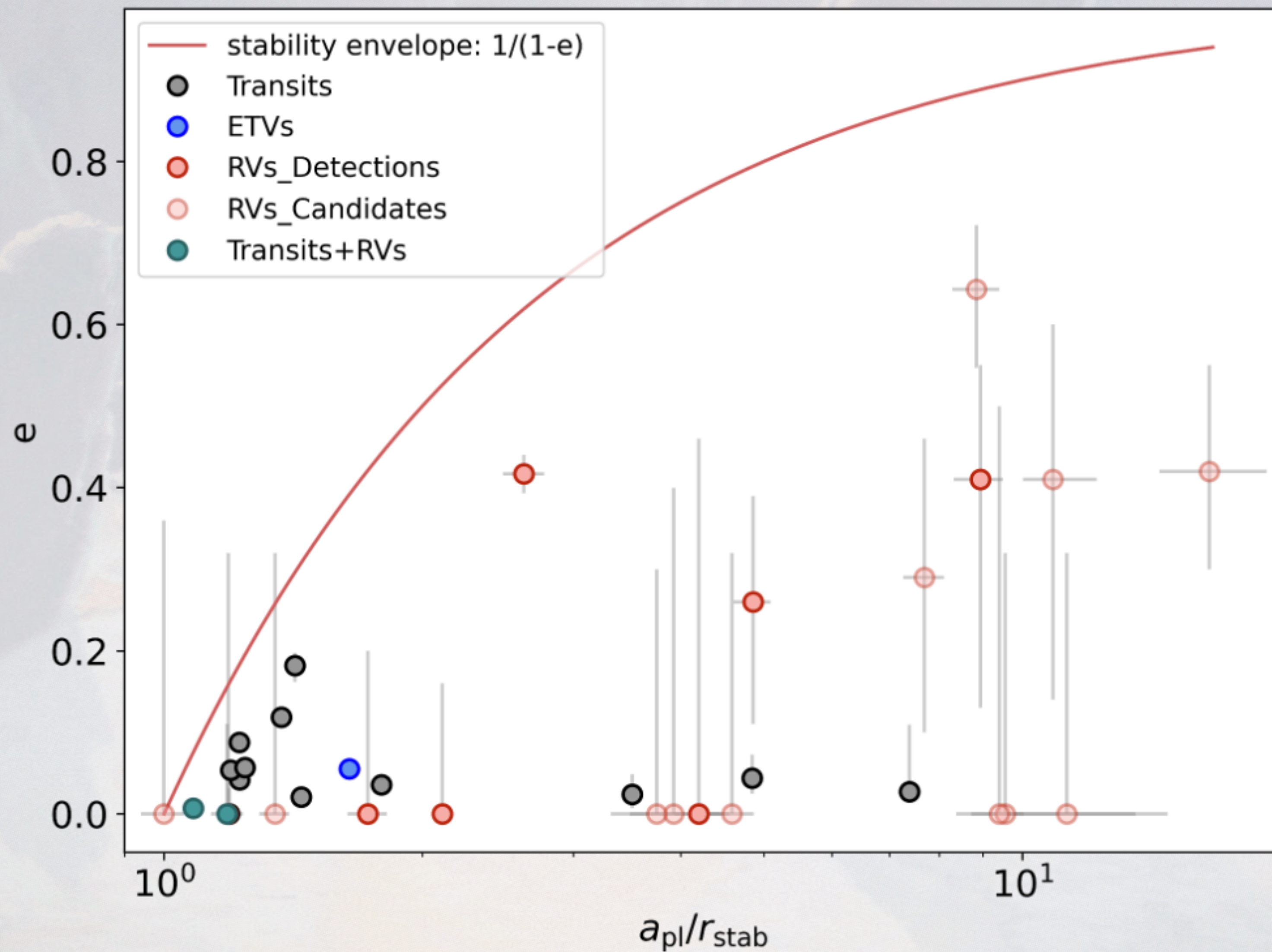
INSTITUT
POLAIRE
FRANÇAIS
PAUL-ÉMILE VICTOR





BEBOP - PHASE I: PRELIMINARY RESULTS

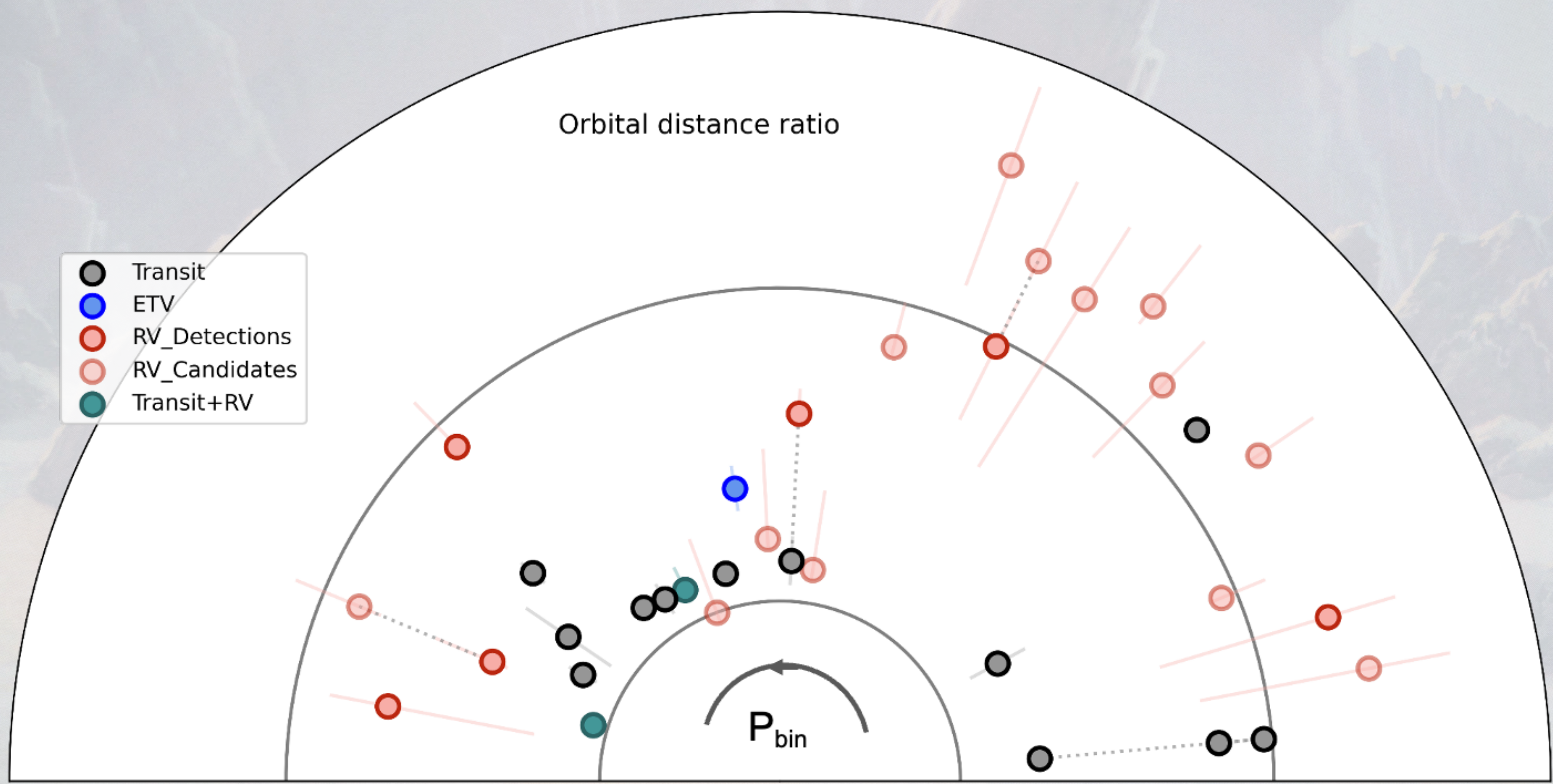
BINARIES ESCORTED BY ORBITING PLANETS





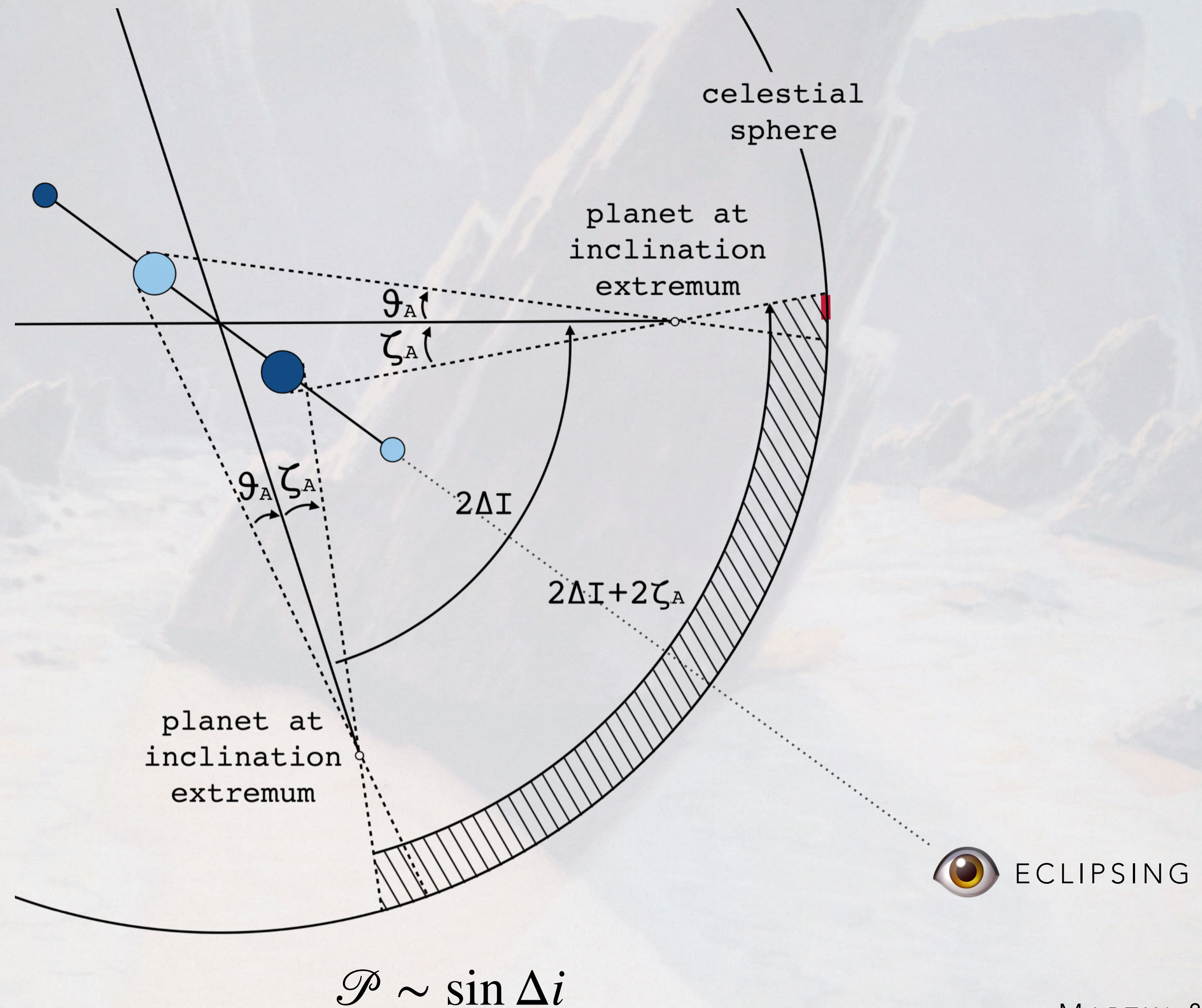
BEBOP - PHASE I: PRELIMINARY RESULTS

BINARIES ESCORTED BY ORBITING PLANETS



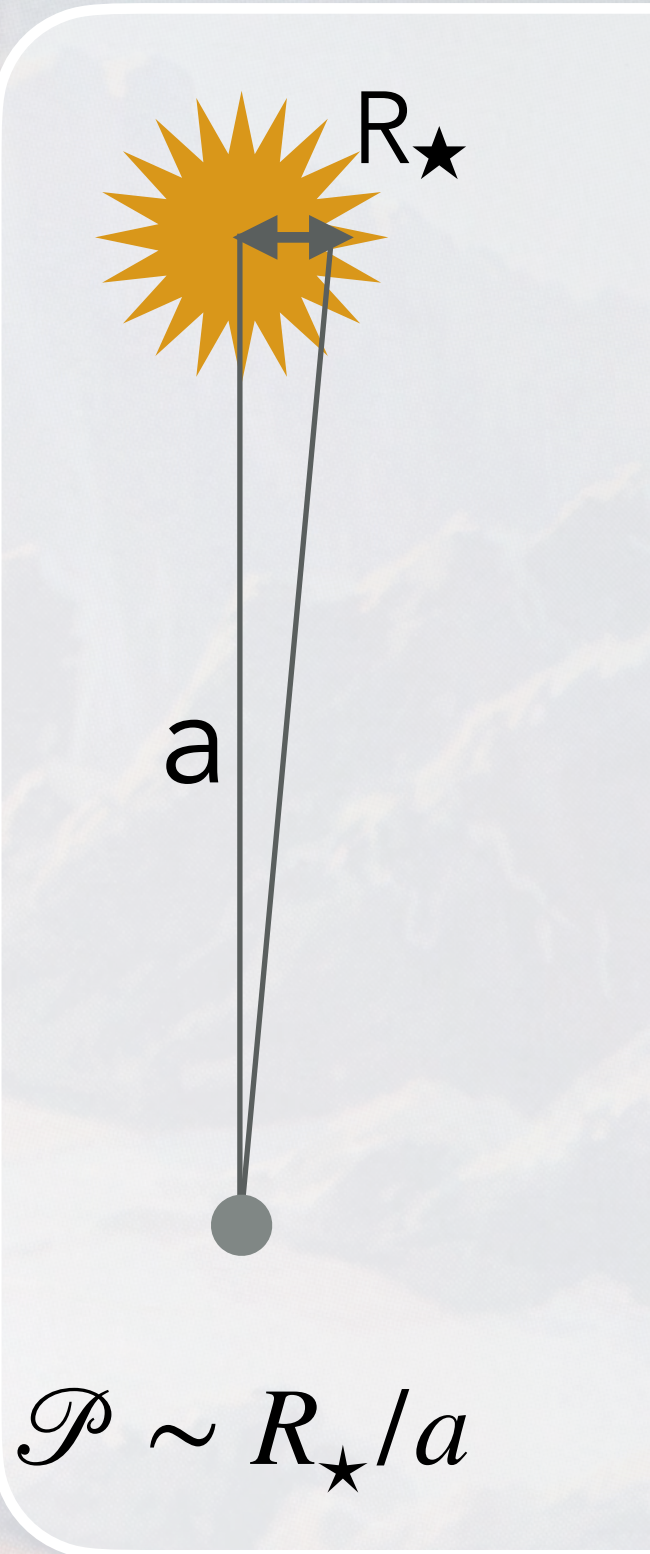
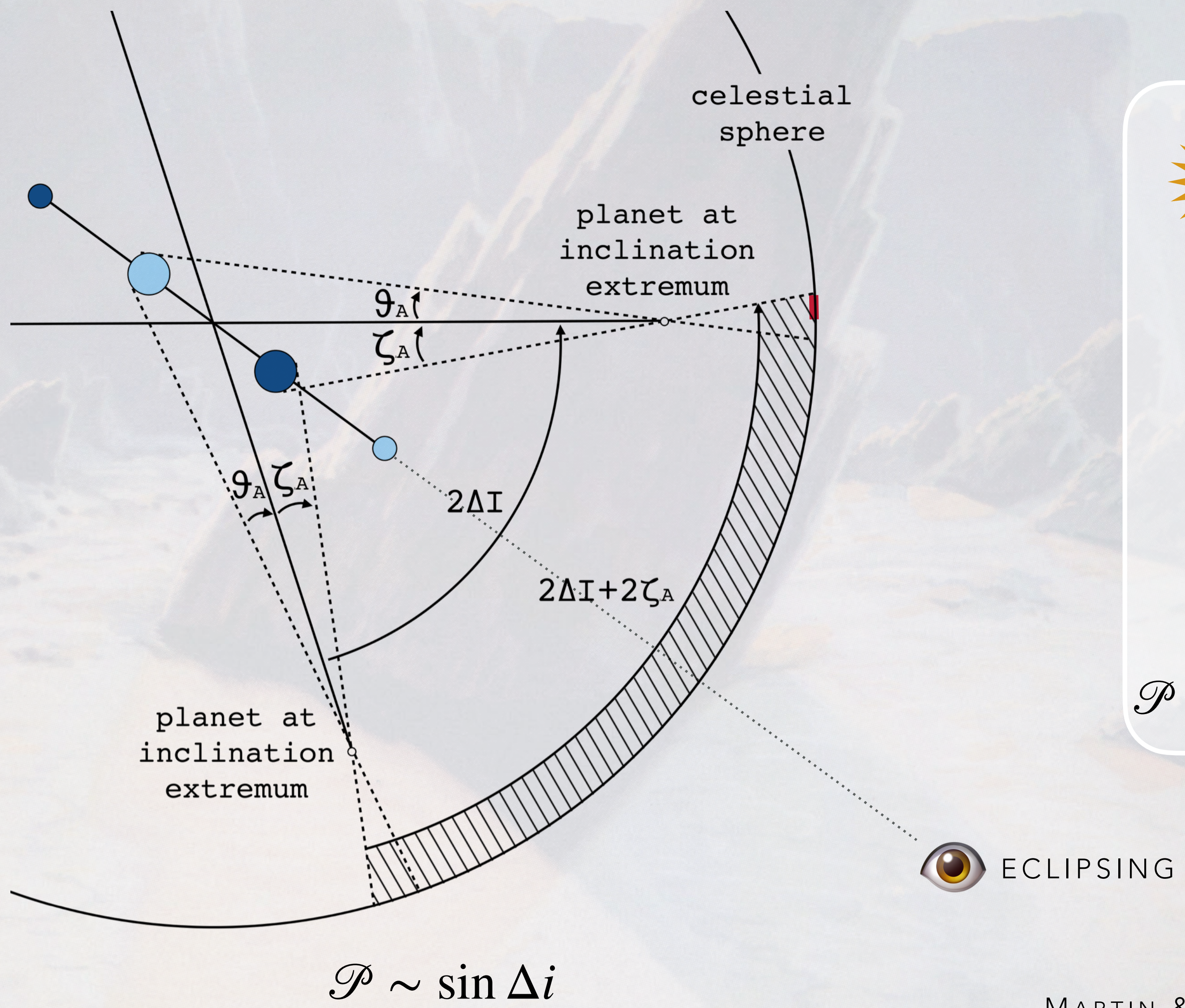
FOR $\Delta I > 0.6^\circ$

AN IMPROVED PROBABILITY OF TRANSIT



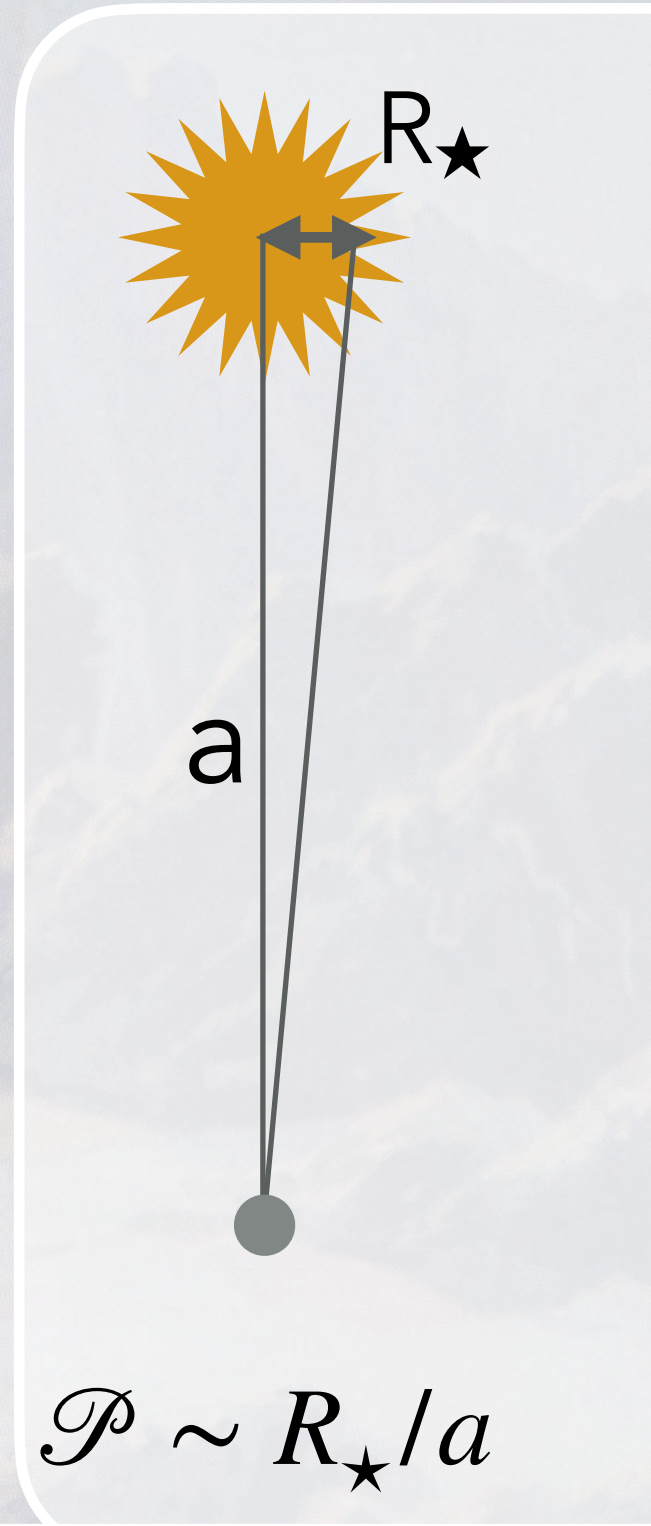
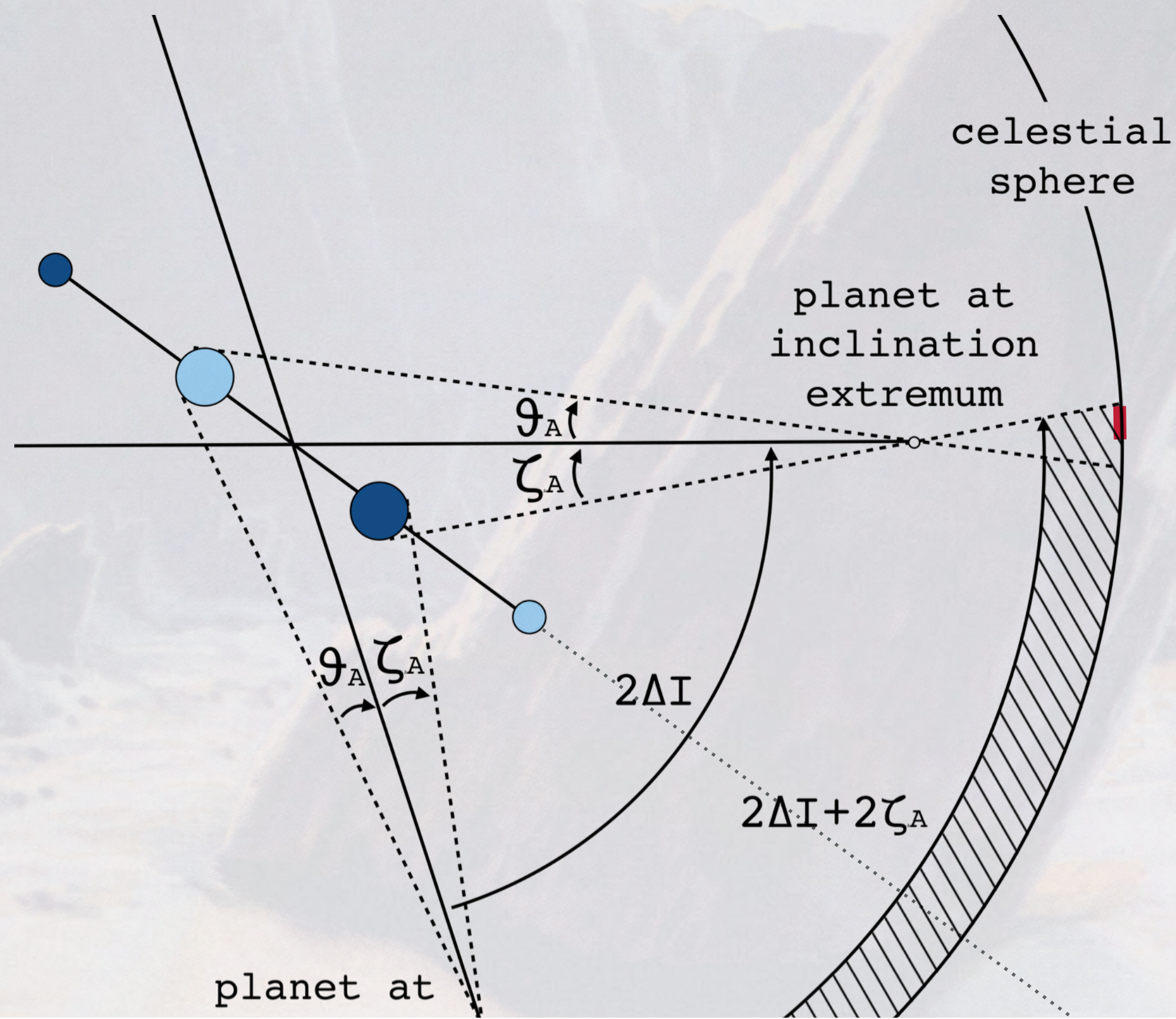
FOR $\Delta i > 0.6^\circ$

AN IMPROVED PROBABILITY OF TRANSIT

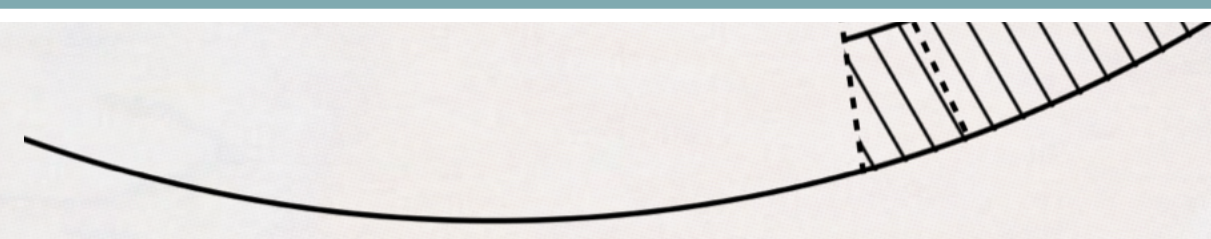


FOR $\Delta i > 0.6^\circ$

AN IMPROVED PROBABILITY OF TRANSIT



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



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