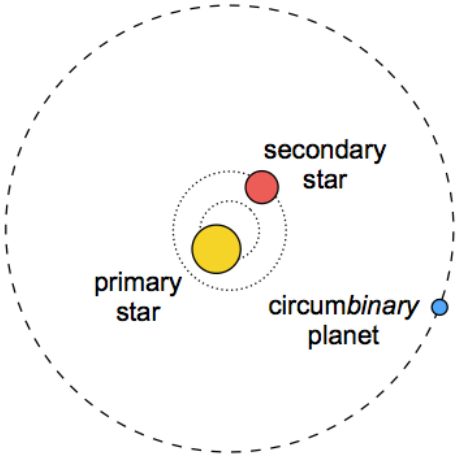
Circumbinary planet populations: Status and expectations for PLATO

Hans Deeg
Instituto de Astrofísica de Canarias

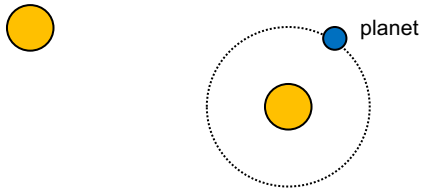
and
PLATO WP 112 510
(Circumbinary Planet Detection)

P and S-type planet systems

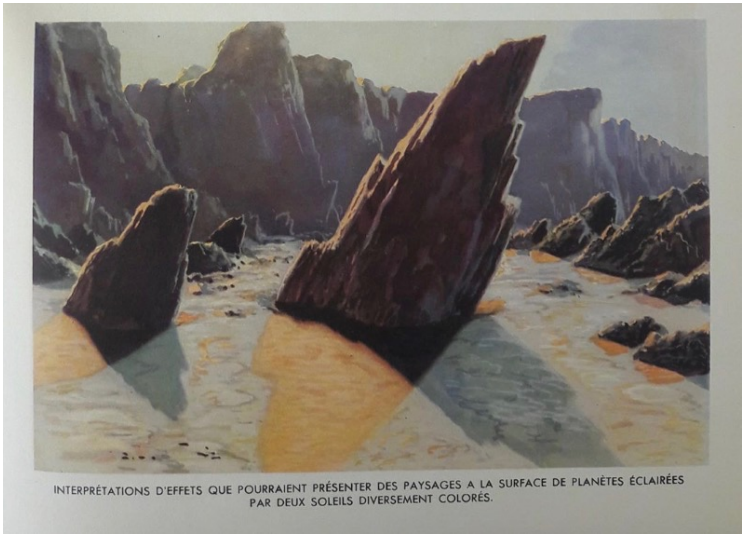
p-type (Circumbinary) planet



s-type planet (around one binary component)



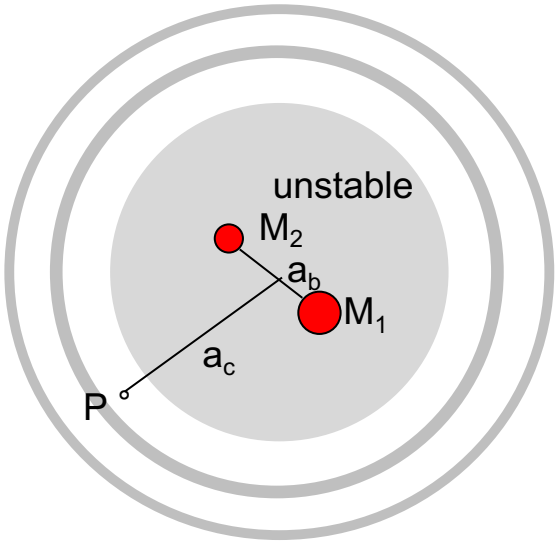
We only talk about these!



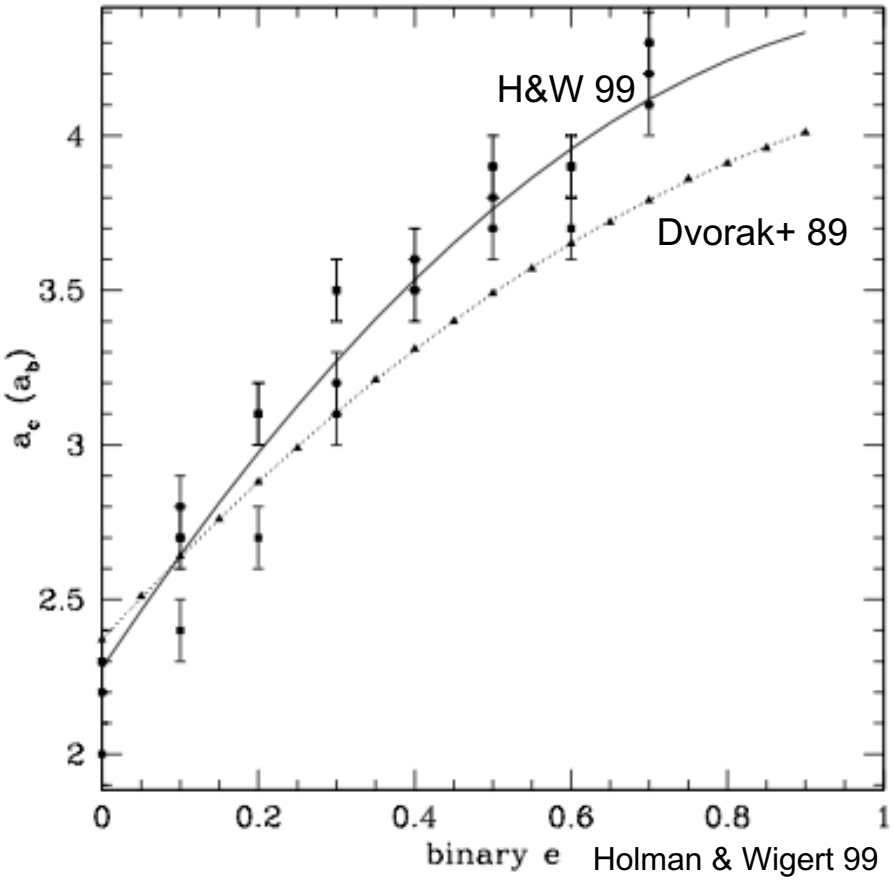
INTERPRÉTATIONS D'EFFETS QUE POURRAIENT PRÉSENTER DES PAYSAGES A LA SURFACE DE PLANÈTES ÉCLAIRÉES PAR DEUX SOLEILS DIVERSEMENT COLORÉS.

From 'Sur les autres mondes'
Lucien Rudaux, 1937

Stability of P-type planet orbits



a_b: Binary separation
a_c: planet minimum stable semimajor axes



Holman & Wigert 99

Dvorak+ 1989, Holman & Wiegert 1999, coplanar case:

Ratio of semimajor axes: $a_c/a_b \gtrsim 2.3$
Ratio of planet period and binary period: $P_c/P_b \gtrsim 3.5$

Little dependency on binary mass ratio $\mu = M_2/(M_1+M_2)$

CBP Detection Methods

With PLATO:

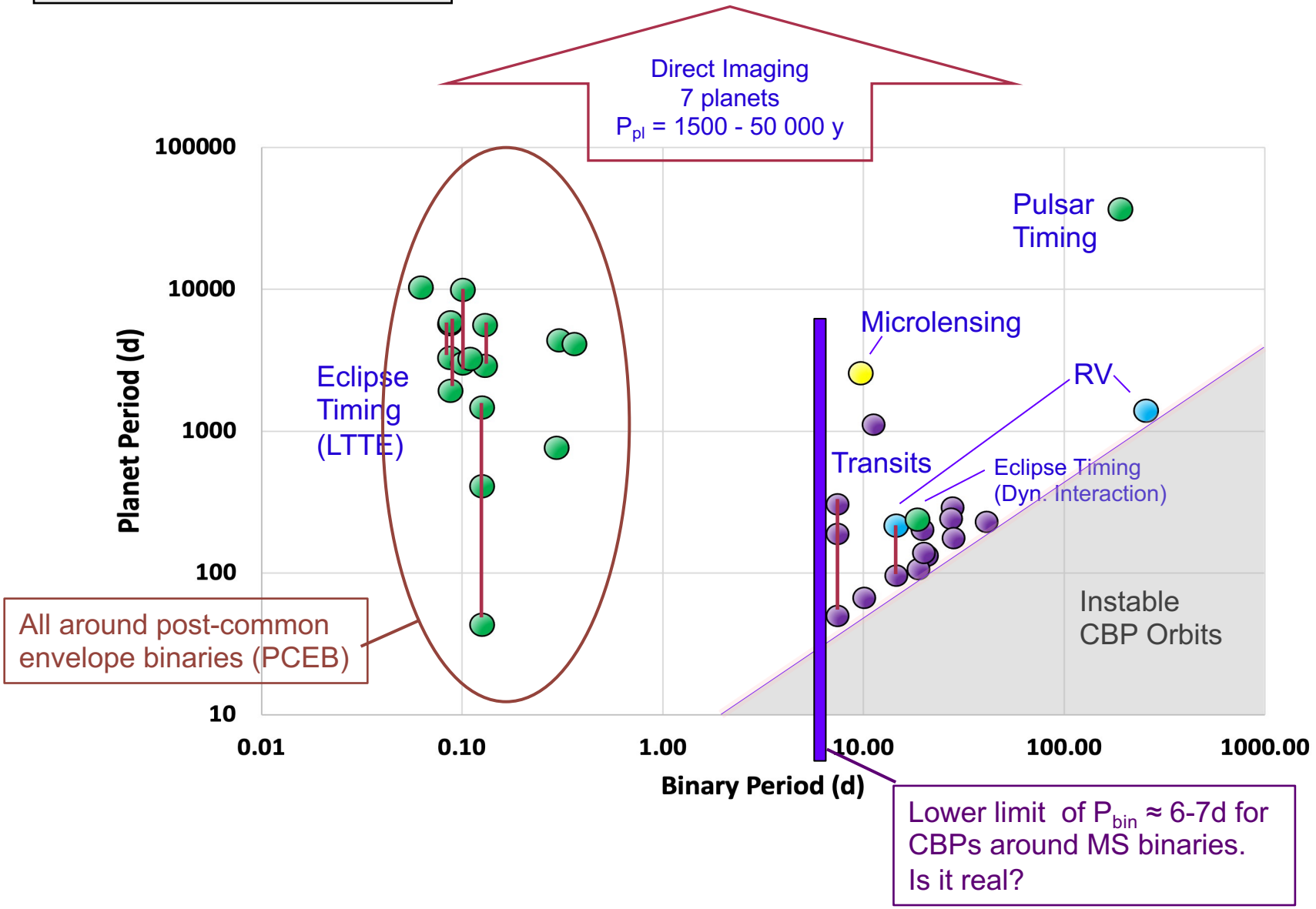
- Transits

- Timing of binary eclipses: ETVs (Eclipse time variations)
  - Light-time/Rømer effect: Distance to binary varies due to orbiting planet (binary orbit unperturbed)
  - Dynamical effects: Perturbations of binary orbit due to gravitational interaction with planet

Others:
- Radial Velocities
- Microlensing
- Direct imaging (of wide-orbit young planets)

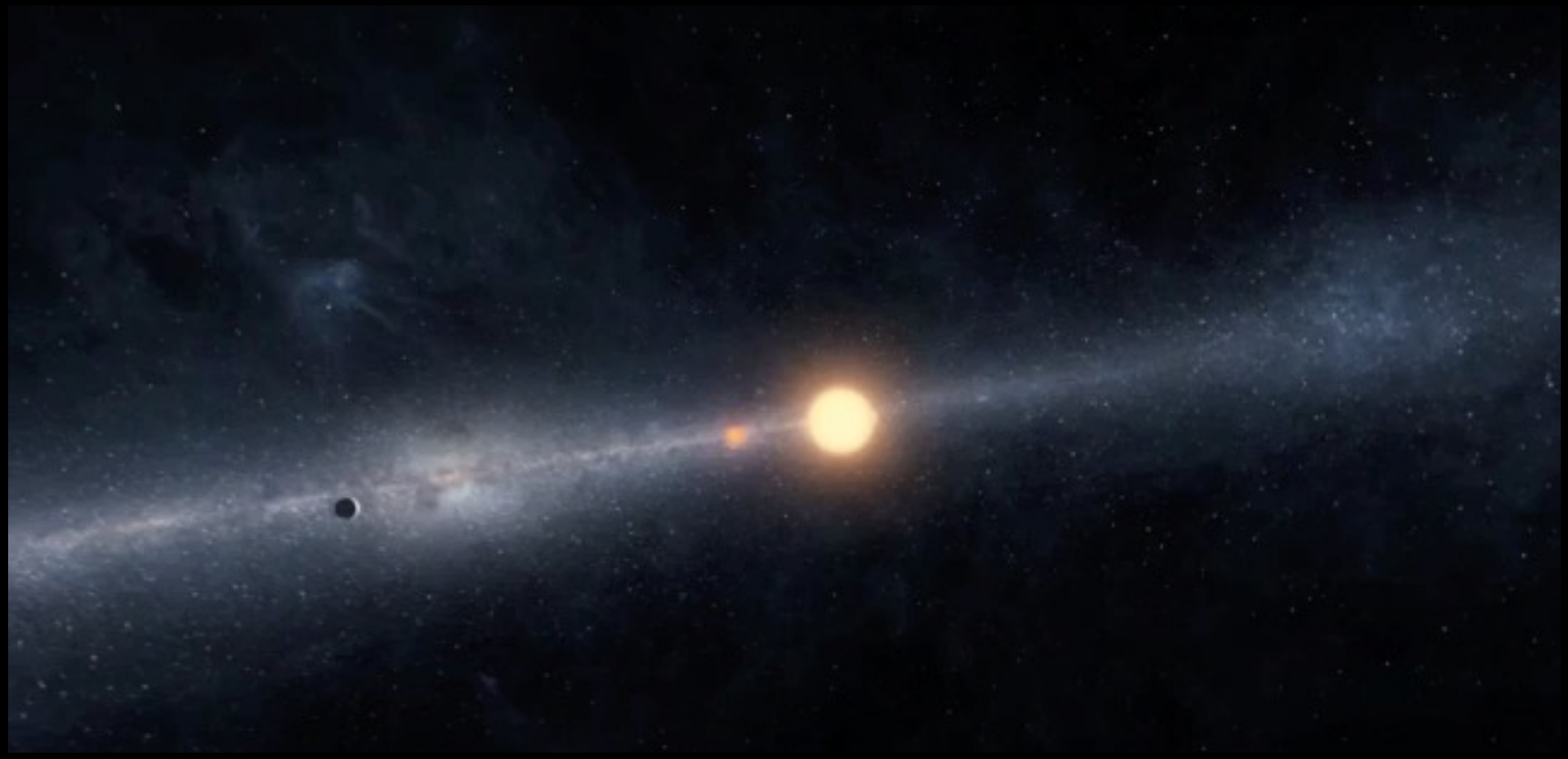
Current zoo of CBPs:
45 known CBPs[1]

Distinct populations pending on discovery method

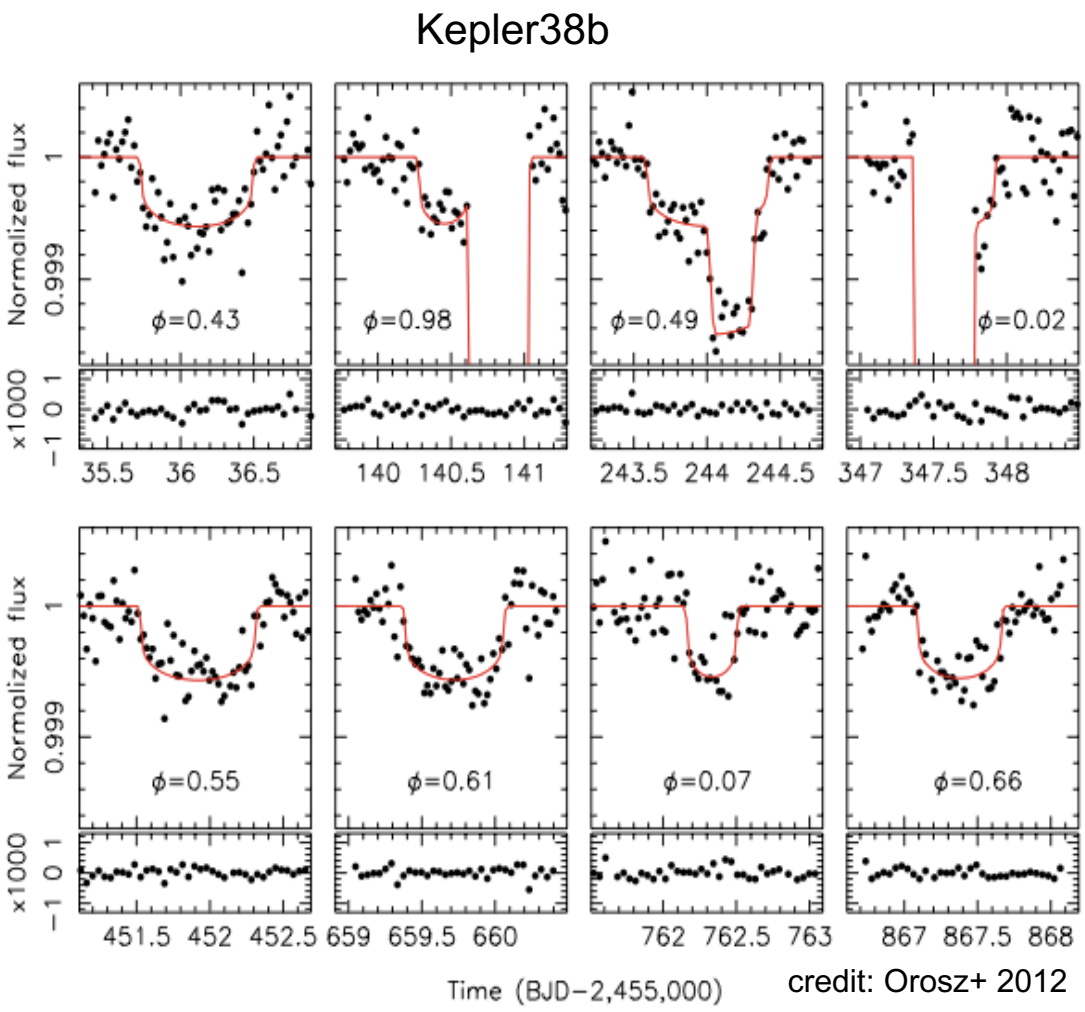


[1] Nasa Exoplanet Archive, May 2024, circumbinary flag =1

Kepler 16 (AB) b: First CBP detected by transit



CBP detection by transit



credit: Orosz+ 2012

CBP transits have …

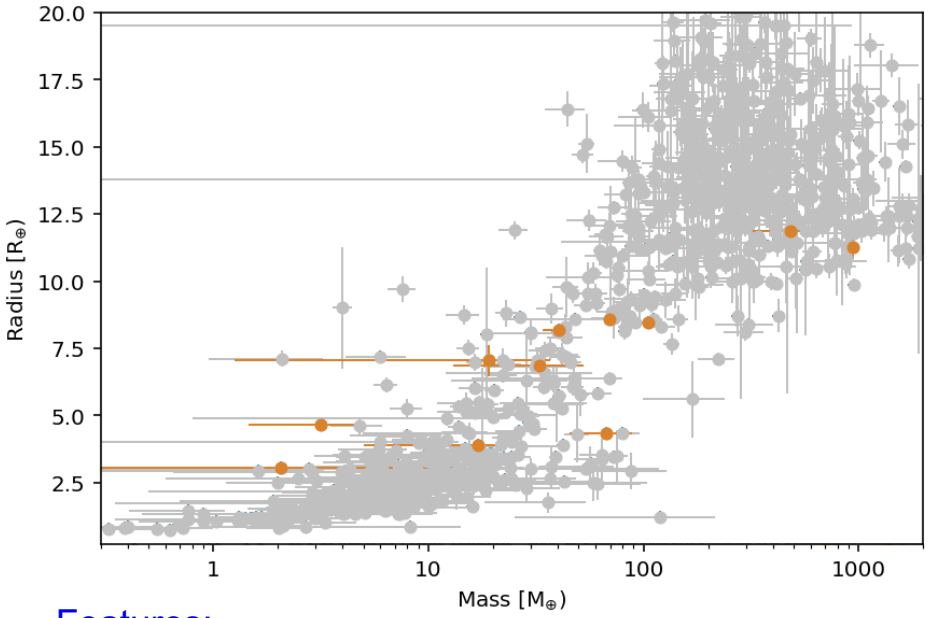
- Unique transit signal,
- Details of transit depend on EB phase.
- Low False Alarm probability

Specific detection algorithms needed: (Doyle+ 2000, Ofir+ 2009, Kostov+ 2013, Klagyivik+ 2017)

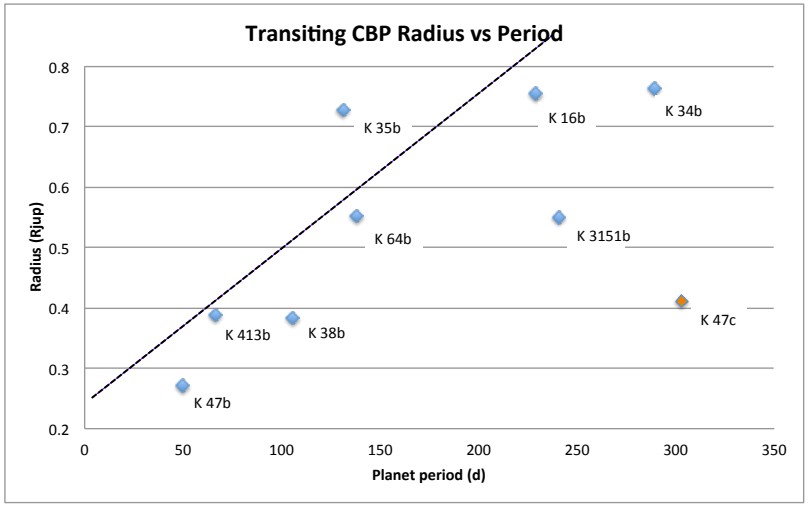
- Removal of binary signal
- Detection of semi-periodic transits within 'transit window' (Doyle+ 2000, Armstrong+ 13)

Features of CBPs around Main-sequence binaries (13 from Kepler, 2 from TESS)

Mass - radius plot: all planets vs CBPs (all CPBs from transits)



Radius - period relation of the *inner* CBPs



Source Exoplanet archive

Features:

Most planets in lesser populated sub-giant (Neptune – Saturn like) regime

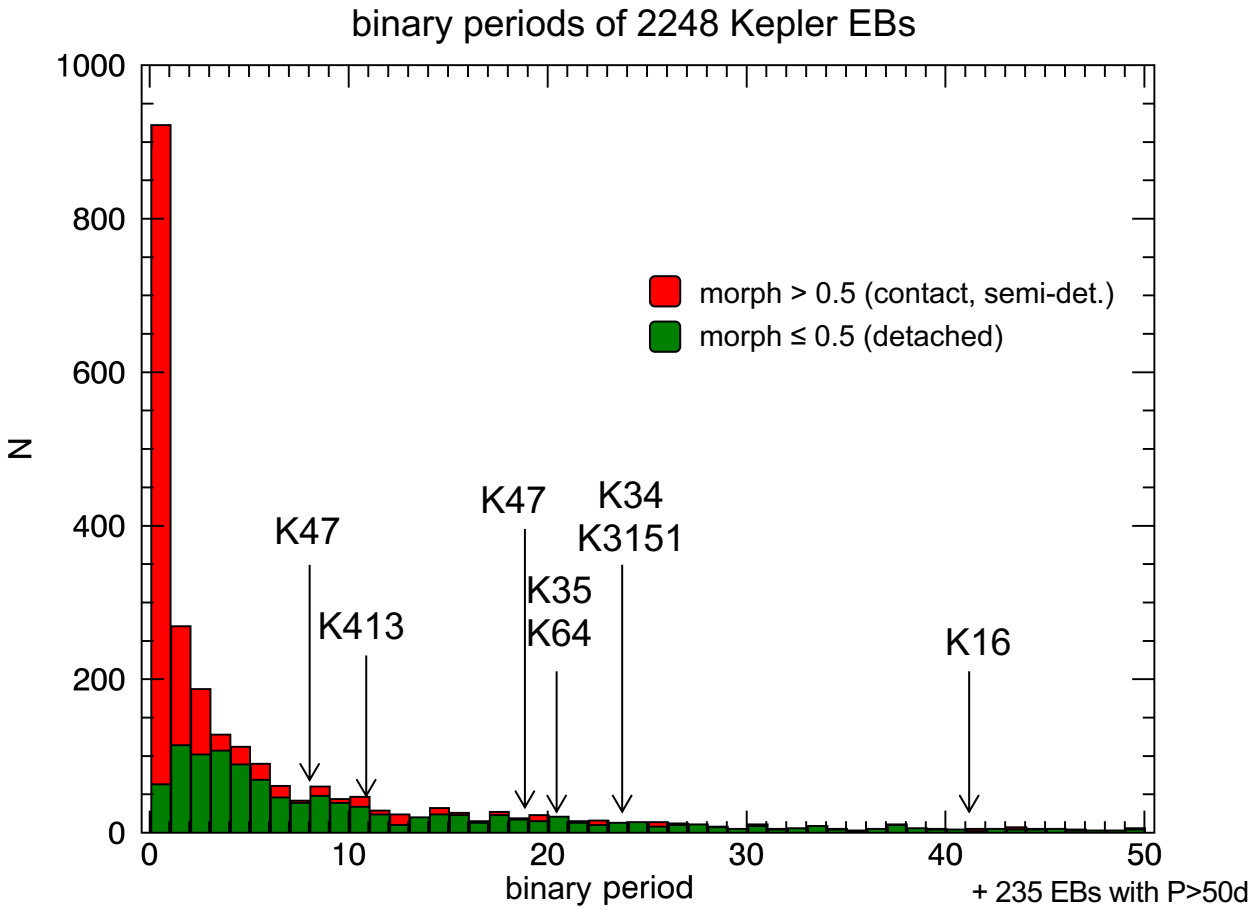
Periods of (inner) planets close to stability limit (inwards migration and pile-up)

Central binaries have period > 7d

All system have mutual inclination $\Delta i \lesssim 3.5^\circ$ between binary and planet orbital planes

Is this a consequence of sampling issues in a limited sample, or are these properties universal for CBPs around MS binaries?

Periods Distribution of CBP host-binaries



No planets around binaries with P_{bin} < 7day ?

Also Klagyivik+ (2017): No CBPs on short-period binaries in COROT sample (2290 EBs); some would have been detected

Martin+ (2015), Hamers+ (2016):
- Short periodic binaries form in triple systems

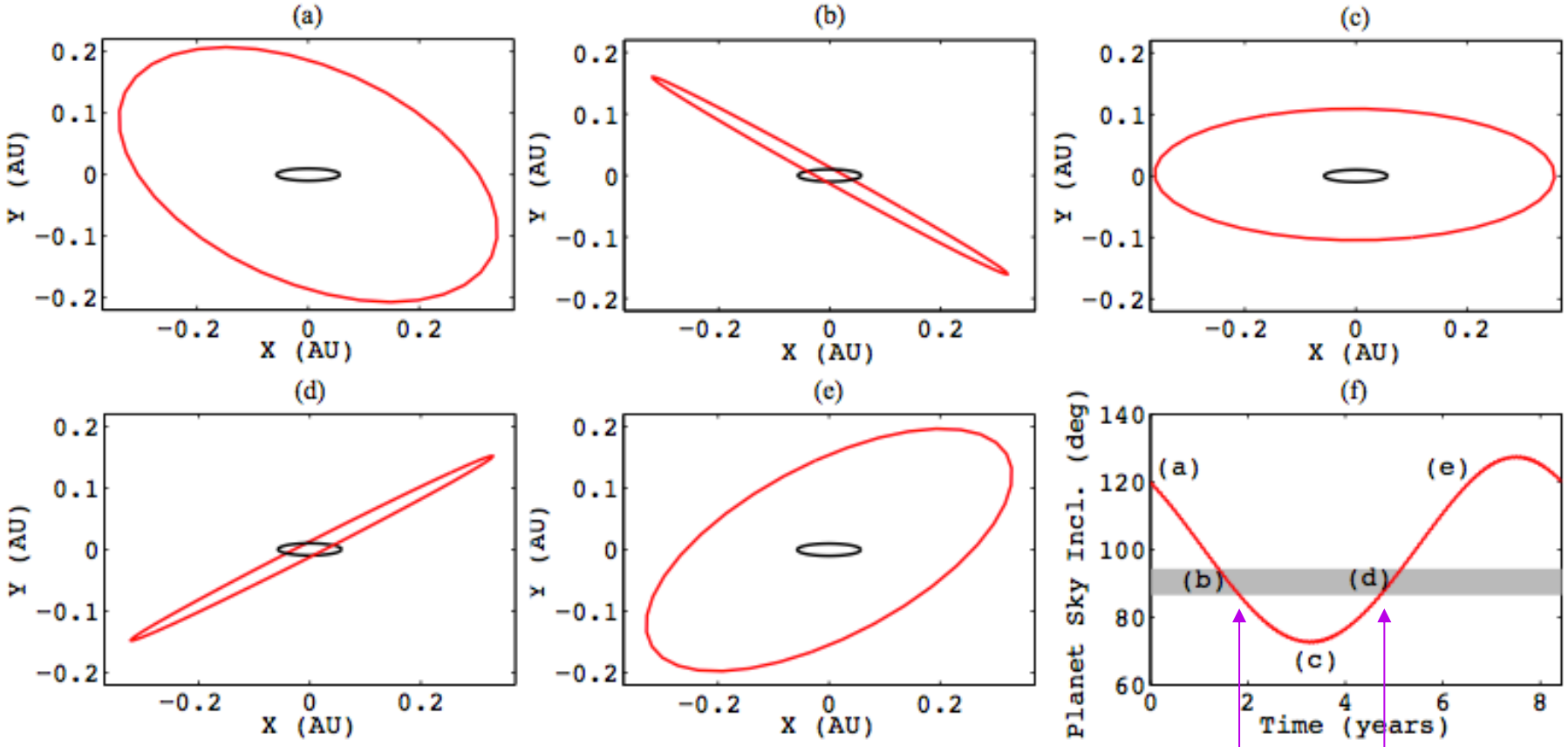
- posterior dynamical evolution either ejects planets, or moves to undetectable (wide, inclined) orbits

Source: Kepler EB catalog, http://keplerebs.villanova.edu/

Strongly mutually inclined orbits

IF they exist …

CBP transits only observable during short sections of precession cycle

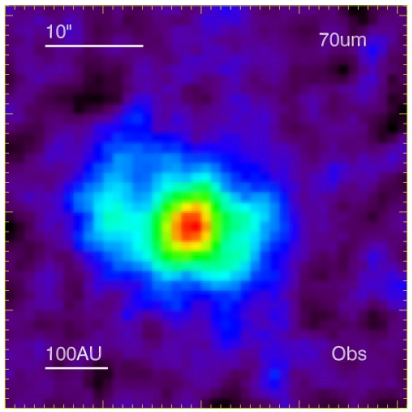


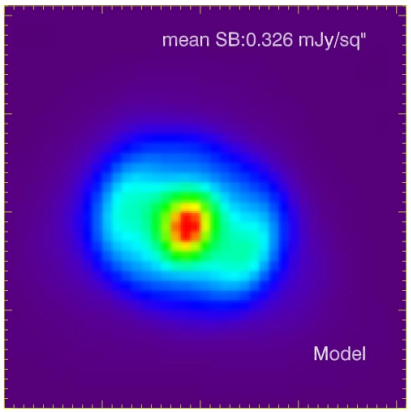
Martin & Triaud 2014

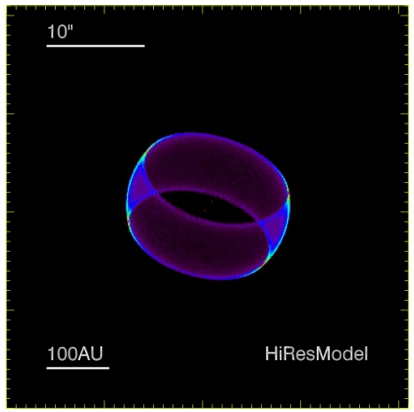
Observable transits

Still not clearly detected: CBPs with strong mutual inclinations

Polar CBPs around eccentric EBs?







Herschel obs. of
99 Hercules
e_{bin}=0.76, P_{bin} = 56yr

Kennedy + 2012:
best fit for $\Delta i = 90^\circ$

70μm

num. sim $\Delta i = 90^\circ$

num. sim $\Delta i = 90^\circ$

Martin R.G & Lubow 2017: CB protoplanetary disks align perpendicular to eccentric binary if initially above critical inclination (for 99 Her: above $\Delta i = 20^\circ$)

Zanazzi & Dong 2017: long-term numerical sims: inclination evolution faster than planet formation
-> polar CBP's around eccentric EBs likely

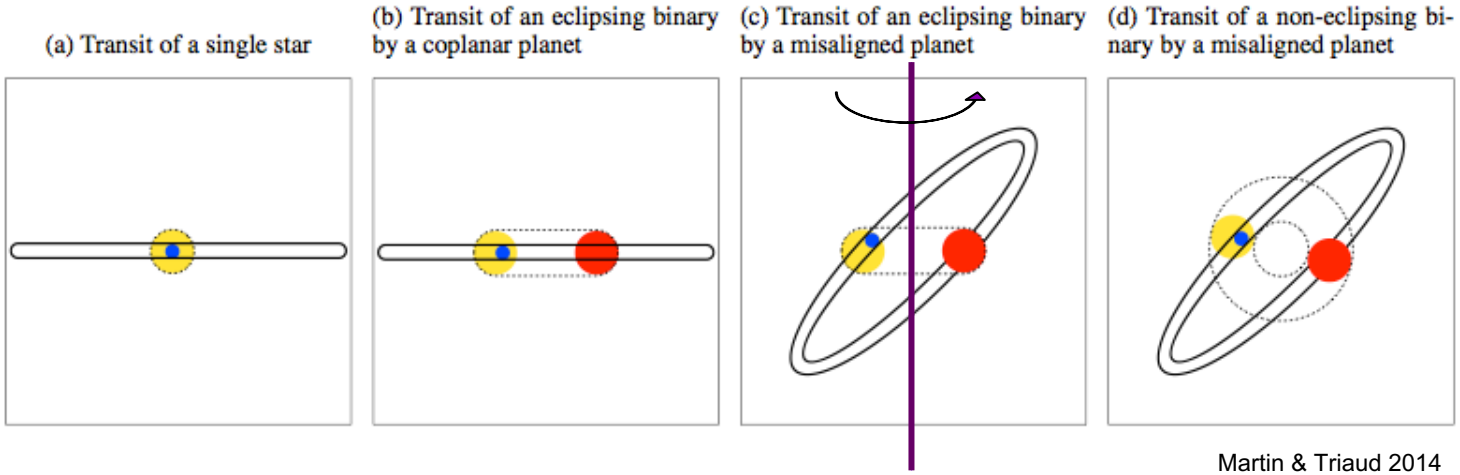
Childs & Martin 2022: Misaligned terrestrial circumbinary planets may be able to form in the presence of a misaligned circumbinary gas disk (from n-body sims)

Getley + 2017: candidate Kepler 1660 AB b of a strongly inclined CBP (ETVs due to dyn. interactions)
RV follow-up by Goldberg+ 2023: CBP is close to binary orbital plane

Also: 'winking binaries': inclined precessing disk?

KH15D circumb. disk with $\Delta i = 10^\circ$ - 20° ; (Winn+ 2004 etc.)
WL 4 (Plavchan+ 2008)
YSO YLW 16A (Plavchan+ 2013)

Potential (PLATO) discoveries:
CBP transiting non-eclipsing binaries (requiring large Δi)



Martin & Triaud 2014

Fig. 1: Transit configurations of a planet that moves within the solid lines, around single and binary stars that move within the dashed lines.

Planet transits across non-eclipsing binary would occur only in some fraction of planet orbits
(IF they can occur at all: “transitability is given” : when transits may *potentially* occur)

CBPs discovered by timing

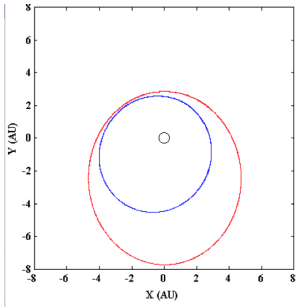
- ETVs due to light-time (Rømer) effect

- 16 CBPs detected, all around evolved stars with short-period compact component:

  Binaries w. pulsars, WD; sdB/dM binary;
  Post-common envelope binaries (PCEB)

- Several doubtful cases

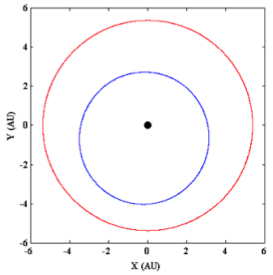
unstable



HW Vir

Recently Removed from Exoplanet Archive

likely stable



NN Ser

Horner+ 2014

- IF real planet(s) :
  - first generation planets? Formed when binary was on MS (e.g. Bear & Soker 14)
  - second generation? Post MS planets formed from ejecta during CE phase (e.g. Horner+ 14; Schleicher & Dreizler 14)

- Kepler 1660 AB b by ETVs from dynamical interactions + RV followup
  (candidate: Getley+2017, confirmed CBP: Goldberg+ 2023)

- ETV detections: Long observing coverage needed;
  PLATO may deliver good candidates that require long-term eclipse timings from ground or RVs.

PLATO CBP detection: expectations for CBP detections

PLATO WP 112 510 Circumbinary Planet Detection

PLATO 2.0 paper (Rauer+ 2014):
PLATO will increase number of transiting CBPs several times over Kepler

PLATO Long Duration observations, 2-3 yrs: ~ 267k stars 80ppm/√h

To first order, multiply Kepler detection rates by 1.66 -> 15-20 'Kepler-like' CBP

(more detailed estimates in the works, with input from TESS, GAIA based EB-catalogues)

(about 1100 known EBs in LOPS2, talk by Yoshi Eschen yesterday)

PLATO Step & Stare, 2-5 months: 10^6 stars

Reduced detection capability for longer-periodic (p>0.2yr) CBPs

Assuming that ½ of known Kepler CBP detected in such data: -> 20-40 CBP

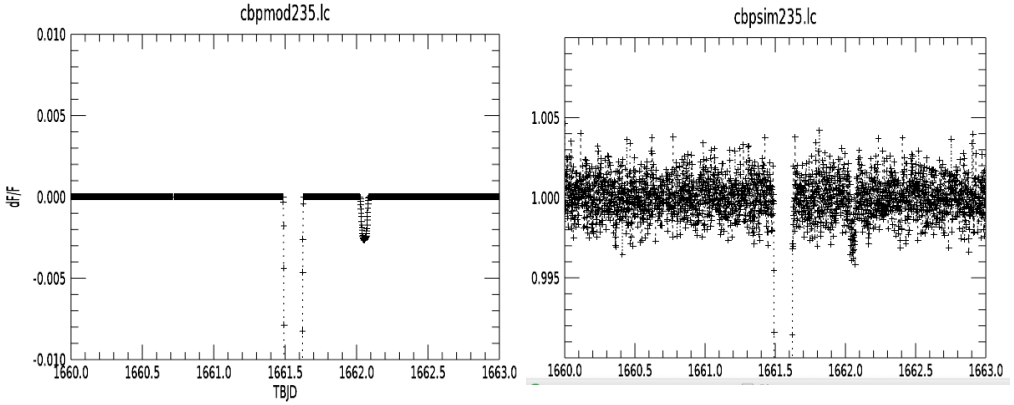
(The 2 TESS CBPs are motivating)

Community challenge for detection of CBPs in simulated PLATO data

Aim: let interested researchers try their own/their favorite CBP detection algorithm

In prep for early 2025 with participation open to community
Sample will contain lc's with /without CBPs and PLATO-like noise characteristics.
CBPs will go (to reasonable extend) beyond currently known CBP parameter-space.
Presence of exotic configurations is TBD.

Simulated EB eclipse and CBP transit (S/N ~10)



Noise-less model

Model with noise (S/N of transit 10)

-> Define algorithm(s) for PLATO sample; knowing their strengths and/or application cases