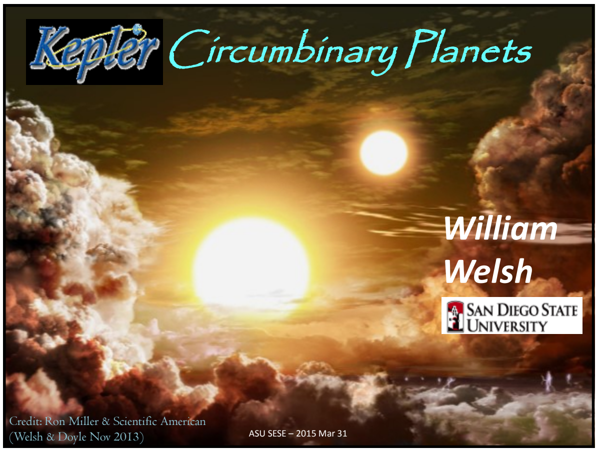
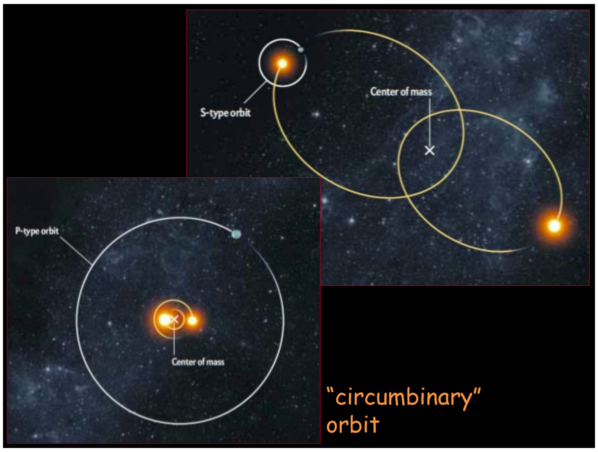
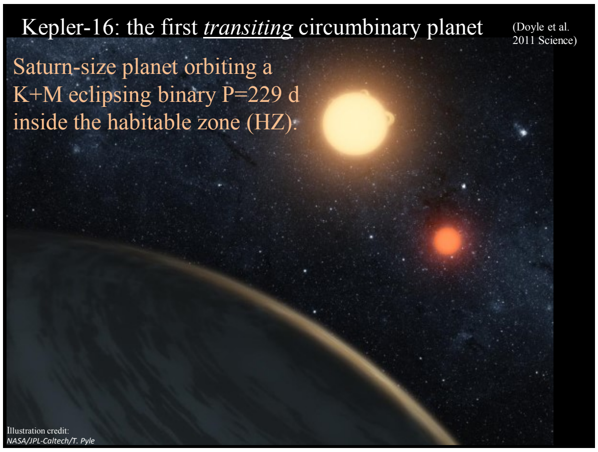


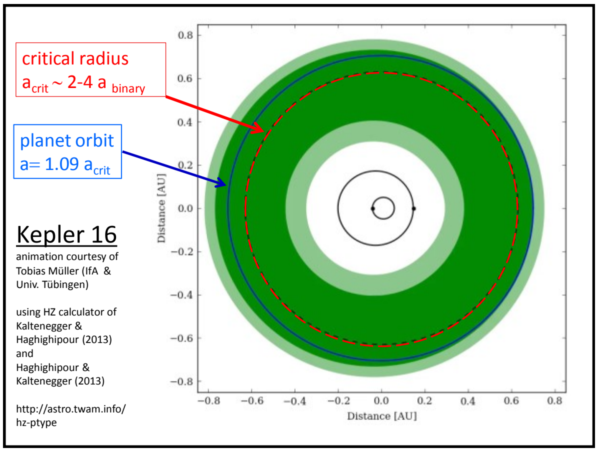
Binary Stars

The Sun is single, but binary and higher multiple star sytems are *very* common:

- massive O, B stars: ~70%
- Sun-like G stars: ~50%
- small M stars: ~10-30%







Kepler-16 b: The first transiting circumbinary planet (Doyle et al. 2011)

But many questions left unanswered: *e.g.*

- what kinds of planetary & stellar orbits are possible?
- what stellar mass ratios?
- what planetary radii, masses, and temperatures?
- pure luck that it is in the HZ?
- why so close to the critical radius for instability?
- *Was Kepler-16 just a rare accidental quirk?*

Need to find more circumbinary planets

But they is much more difficult to find than single-star planets:

- non-periodic transits
- changing transit durations
- blended with stellar eclipses
- (possibly changing transit depths)

→call cases have been found "by eye"

But if a candidate is found, it is much easier to confirm:

"smoking gun": transit timing variations (TTVs) & transit duration variations (TDVs) produce an unambiguous signature

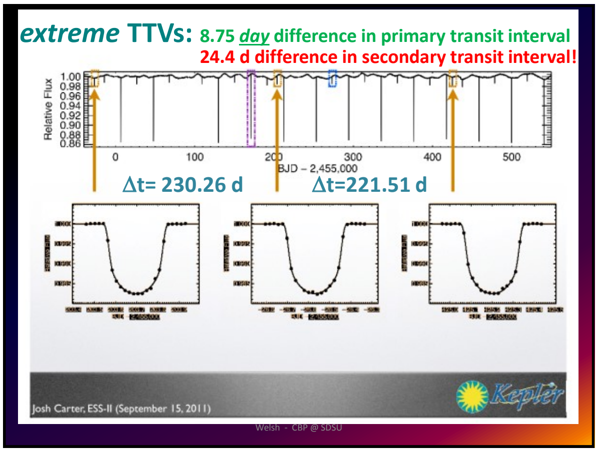
The circumbinary planet "smoking gun":

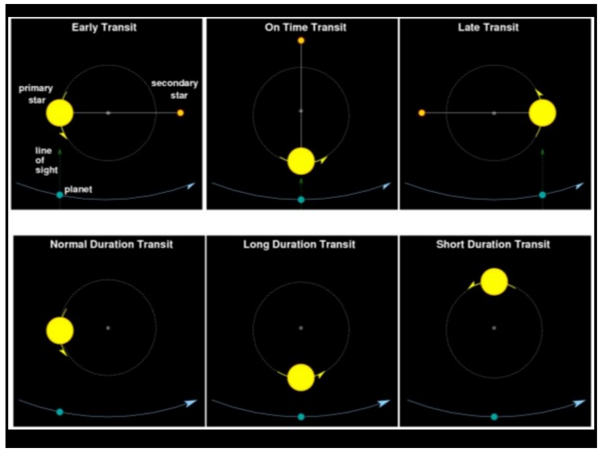
- 0) transits
- 1) TTV: transit timing variations
- *2) TDV: transit duration variations*

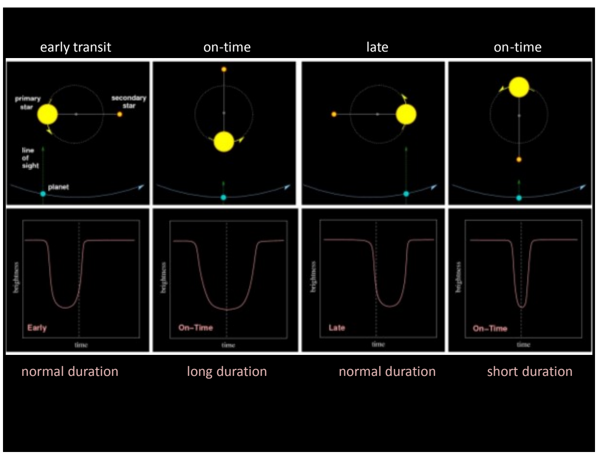
"moving target"

Also very helpful (allows mass measurement):

- 3) ETV: eclipse timing variations (dynamics)
- 4) LITE: light travel time delays



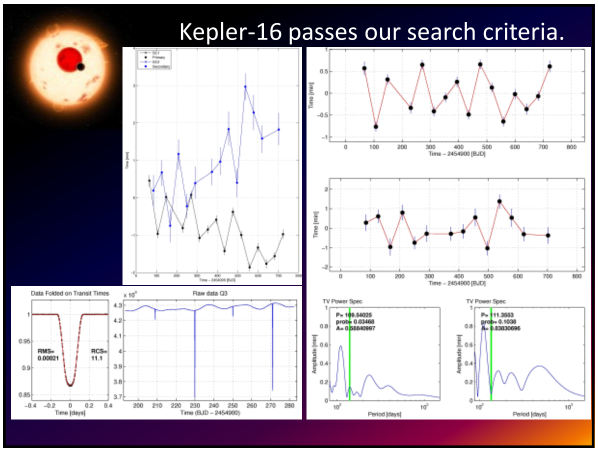


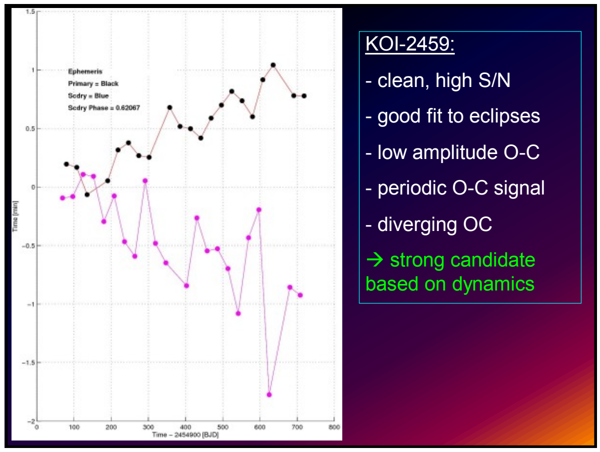


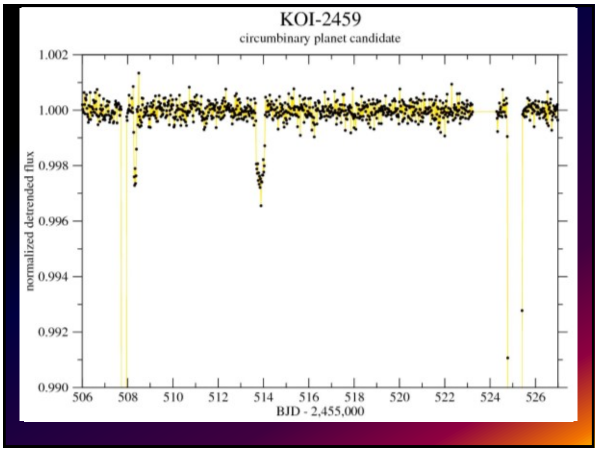
Note: For every transiting circumbinary planet, there should be *many* more non-transiting cases.

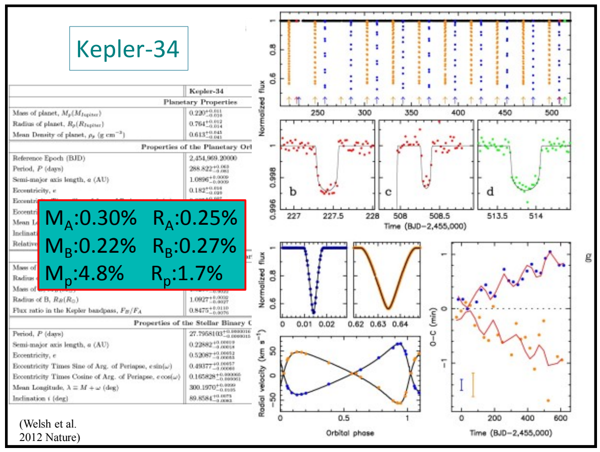
So search for non-transiting systems, based on dynamical perturbations of the binary stars' orbits:

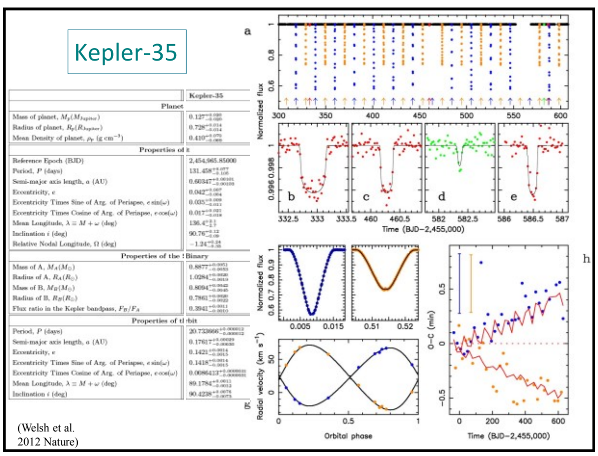
- ➔ eclipse timing variations (ETVs)
- ➔ Observed-minus-Computed (O-C) diagrams
- ➔ divergence in orbital period between primary and secondary eclipse.

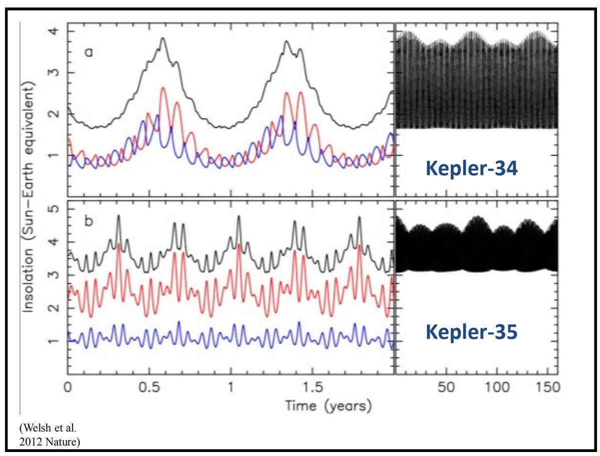

Kepler-16 passes our search criteria.
Data Folded on Transit Times
Raw data Q3
TV Power Spec
Time − 2454900 [BJD]
Period [days]

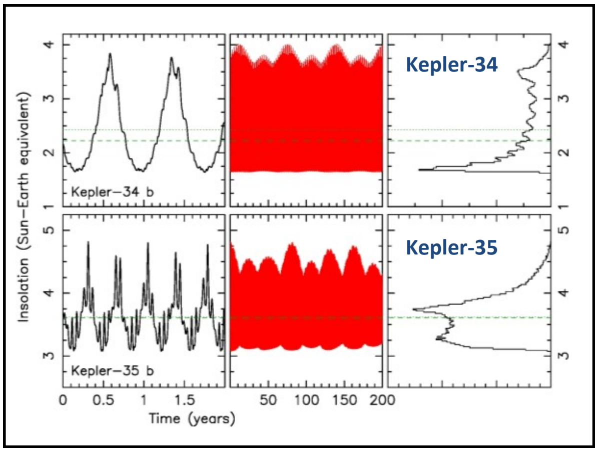

Ephemeris
Primary = Black
Scdry = Blue
Scdry Phase = 0.62067
Time − 2454900 [BJD]
KOI-2459:
- clean, high S/N
- good fit to eclipses
- low amplitude O-C
- periodic O-C signal
- diverging OC
→ strong candidate based on dynamics

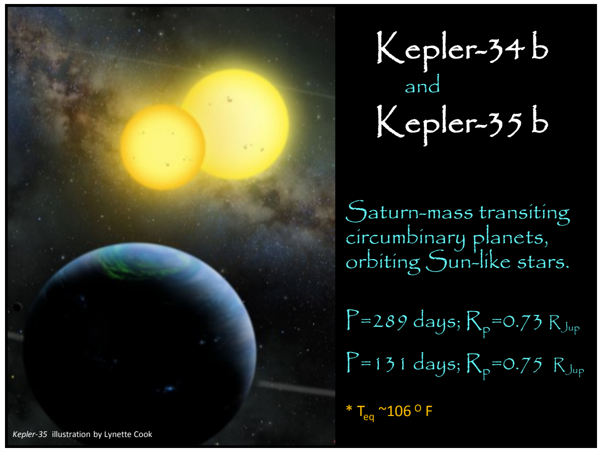

KOI-2459
circumbinary planet candidate
normalized detrended flux
BJD - 2,455,000

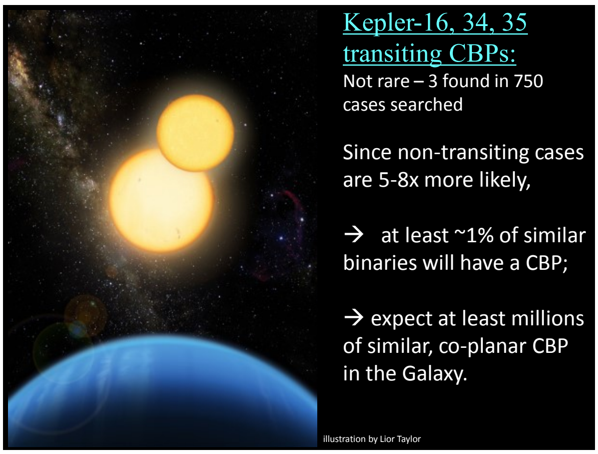

Kepler-34
M_A:0.30% R_A:0.25%
M_B:0.22% R_B:0.27%
M_p:4.8% R_p:1.7%
Normalized flux
Time (BJD−2,455,000)
Radial velocity (km s⁻¹)
Orbital phase
O−C (min)
(Welsh et al. 2012 Nature)

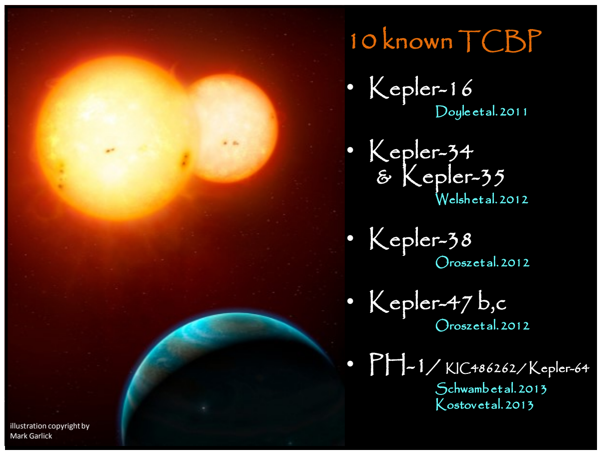

Kepler-35
Normalized flux
Time (BJD−2,455,000)
Radial velocity (km s⁻¹)
Orbital phase
O−C (min)
(Welsh et al. 2012 Nature)

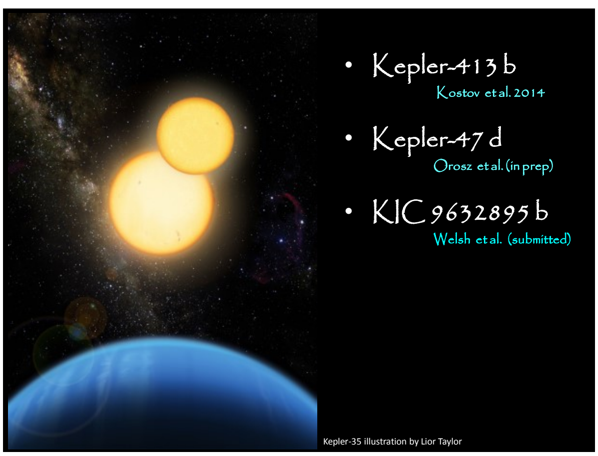

Insolation (Sun−Earth equivalent)
Kepler-34
Kepler-35
Time (years)
(Welsh et al. 2012 Nature)

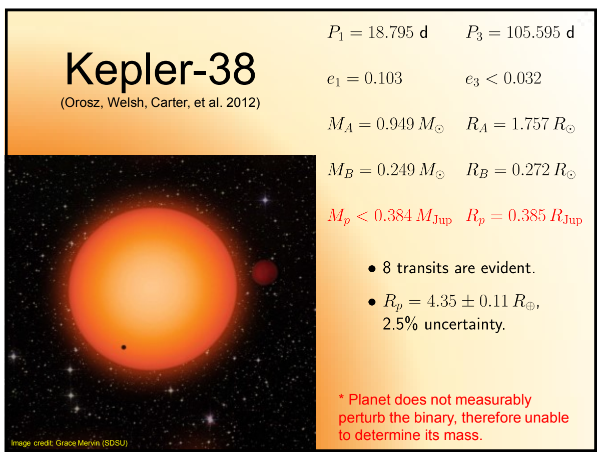

Kepler-34
Kepler-35
Kepler−34 b
Kepler−35 b
Insolation (Sun−Earth equivalent)
Time (years)
0 0.5 1 1.5
50 100 150 200

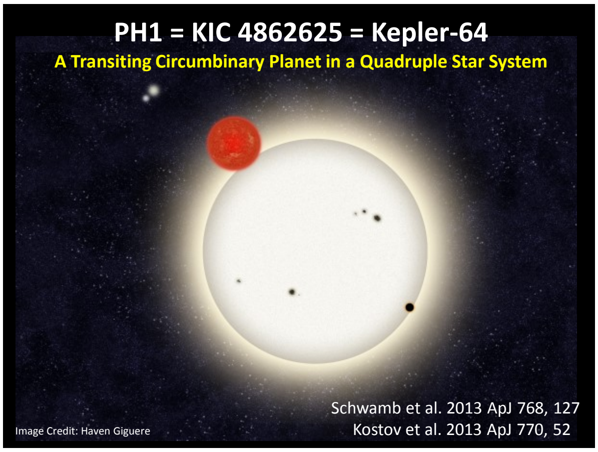

Kepler-34 b
and
Kepler-35 b
Saturn-mass transiting circumbinary planets, orbiting Sun-like stars.
P=289 days; R_p=0.73 R_{Jup}
P=131 days; R_p=0.75 R_{Jup}
* T_{eq} ~106 ° F
Kepler-35 illustration by Lynette Cook

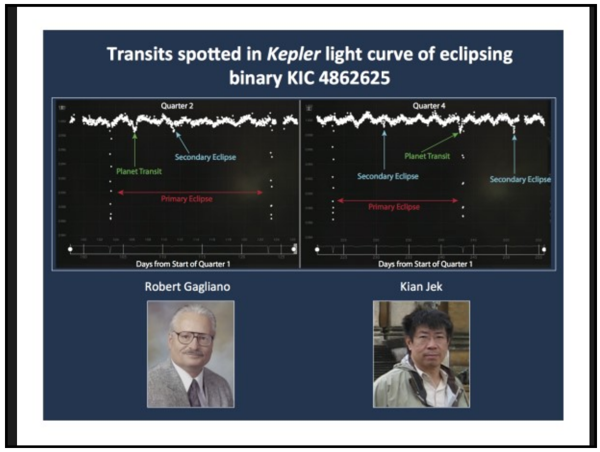

Kepler-16, 34, 35 transiting CBPs:
Not rare – 3 found in 750 cases searched
Since non-transiting cases are 5-8x more likely,
→ at least ~1% of similar binaries will have a CBP;
→ expect at least millions of similar, co-planar CBP in the Galaxy.
illustration by Lior Taylor

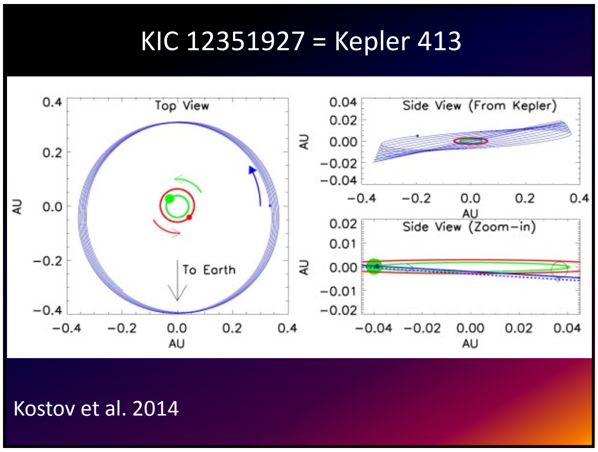

10 known TCBP
• Kepler-16
Doyle et al. 2011
• Kepler-34
& Kepler-35
Welsh et al. 2012
• Kepler-38
Orosz et al. 2012
• Kepler-47 b,c
Orosz et al. 2012
• PH-1 / KIC4862625 / Kepler-64
Schwamb et al. 2013
Kostov et al. 2013
illustration copyright by Mark Garlick

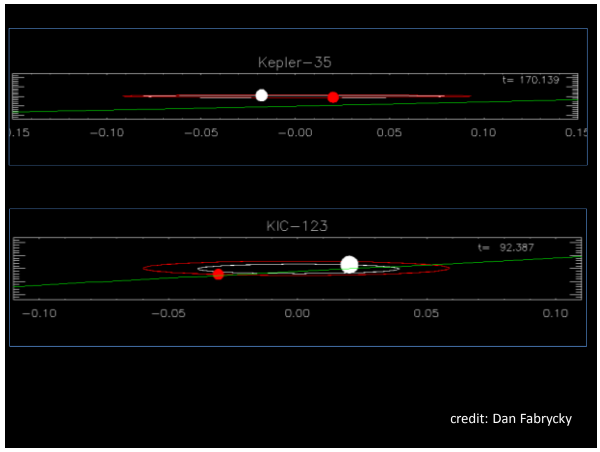

• Kepler-413 b
Kostov et al. 2014
• Kepler-47 d
Orosz et al. (in prep)
• KIC 9632895 b
Welsh et al. (submitted)
Kepler-35 illustration by Lior Taylor

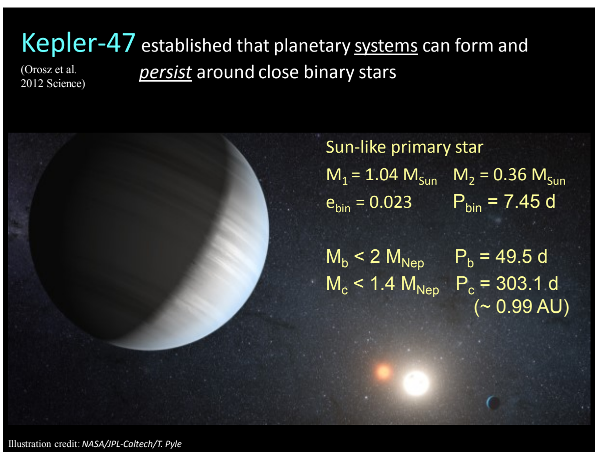

Kepler-38
(Orosz, Welsh, Carter, et al. 2012)
$P_1 = 18.795$ d
$P_3 = 105.595$ d
$e_1 = 0.103$
$e_3 < 0.032$
$M_A = 0.949\,M_\odot$
$R_A = 1.757\,R_\odot$
$M_B = 0.249\,M_\odot$
$R_B = 0.272\,R_\odot$
$M_p < 0.384\,M_{\rm Jup}$
$R_p = 0.385\,R_{\rm Jup}$
• 8 transits are evident.
• $R_p = 4.35 \pm 0.11\,R_\oplus$, 2.5% uncertainty.
* Planet does not measurably perturb the binary, therefore unable to determine its mass.
Image credit: Grace Mervin (SDSU)

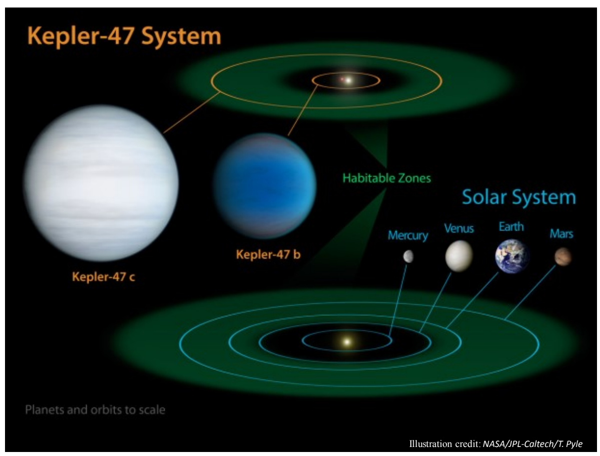

PH1 = KIC 4862625 = Kepler-64
A Transiting Circumbinary Planet in a Quadruple Star System
Schwamb et al. 2013 ApJ 768, 127
Kostov et al. 2013 ApJ 770, 52
Image Credit: Haven Giguere

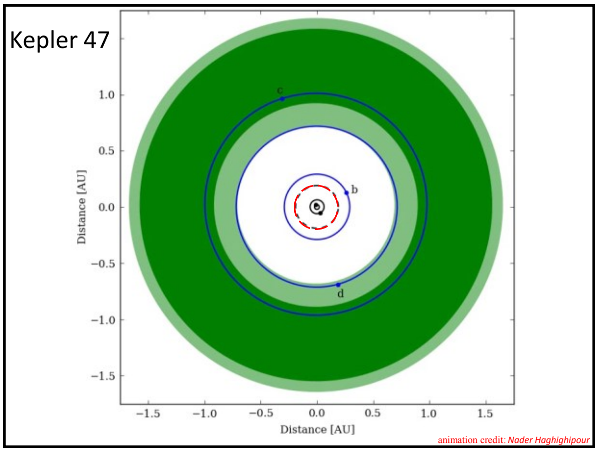

Transits spotted in Kepler light curve of eclipsing binary KIC 4862625
Quarter 2
Quarter 4
Secondary Eclipse
Planet Transit
Primary Eclipse
Days from Start of Quarter 1
Robert Gagliano
Kian Jek

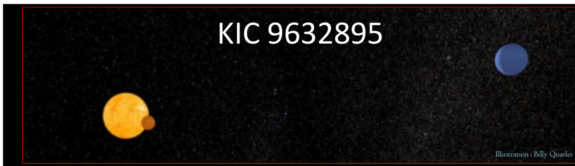

KIC 12351927 = Kepler 413
Top View
To Earth
Side View (From Kepler)
Side View (Zoom−in)
AU
Kostov et al. 2014


Kepler−35
t= 170.139
KIC−123
t= 92.387
credit: Dan Fabrycky


Kepler-47 established that planetary systems can form and persist around close binary stars
(Orosz et al. 2012 Science)
Sun-like primary star
M_1 = 1.04 M_{Sun} M_2 = 0.36 M_{Sun}
e_{bin} = 0.023 P_{bin} = 7.45 d
M_b < 2 M_{Nep} P_b = 49.5 d
M_c < 1.4 M_{Nep} P_c = 303.1 d
(~ 0.99 AU)
Illustration credit: NASA/JPL-Caltech/T. Pyle


Kepler-47 System
Habitable Zones
Solar System
Mercury
Venus
Earth
Mars
Kepler-47 b
Kepler-47 c
Planets and orbits to scale
Illustration credit: NASA/JPL-Caltech/T. Pyle





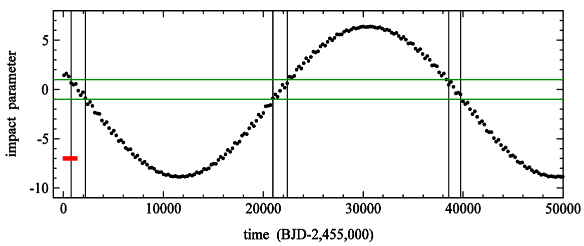
Eclipsing Binary

- P = 27.3220 d
- e = 0.05
- M_1 = 0.93 M_{Sun}
- M_2 = 0.194 M_{Sun}
- T_1 = 5527 K

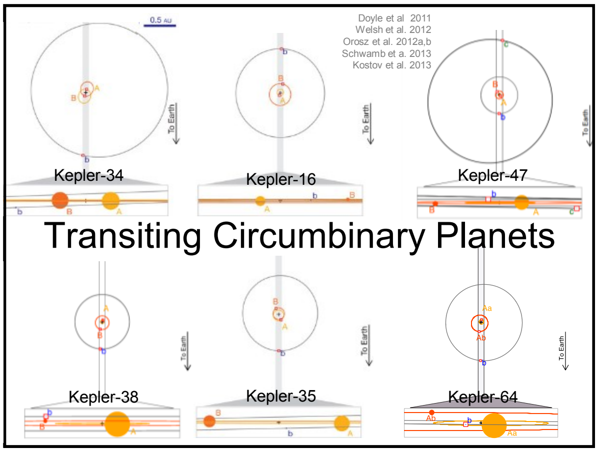
Planet

- P_p = 240.5 d (=0.79 au)
- e = 0.04
- R_p = 6.2 R_e
- M_p < 16 M_e at 1-σ
- mutual incl. 2.3 deg

KIC 9632895



- ~ 103-year precession period
- transits only ~9% of the time
- 2015 July 2 transit is the last one until 2066!



Transiting Circumbinary Planets

- Difficult to find…

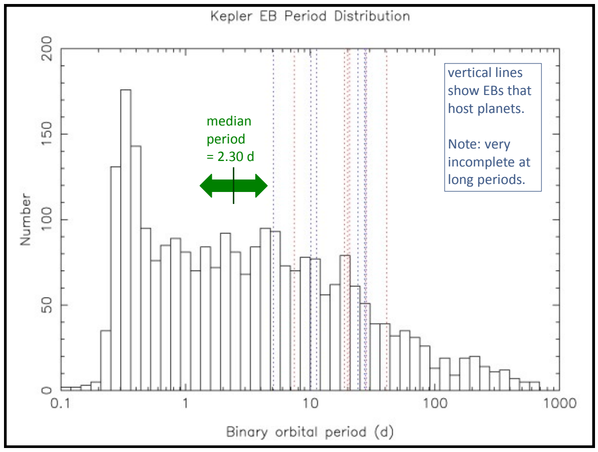
  …even more difficult to model.
- Requires a "photodynamic" code:
  - orbits not Keplerian, so we must integrate the equations of motion (with light-travel-time effect)
  - in some cases GR and non-spherical corrections needed (apsidal motion)
  - ~ 40-50 free parameters, some highly correlated
  - need robust optimization, e.g. MCMC

Emerging trends:

- diverse planet and stellar orbits
  - no resonances seen; precession very important
- planets all smaller than Jupiter
  - even though larger planets would be easier to find
- *CBP not seen in short P binaries*
  - *why not? past 3rd body interaction?*
- *Planets are close to the critical orbital radius*
  - *8 out of 11 systems have P < 2 P_{crit}*
  - *observational bias or migration pile-up?*

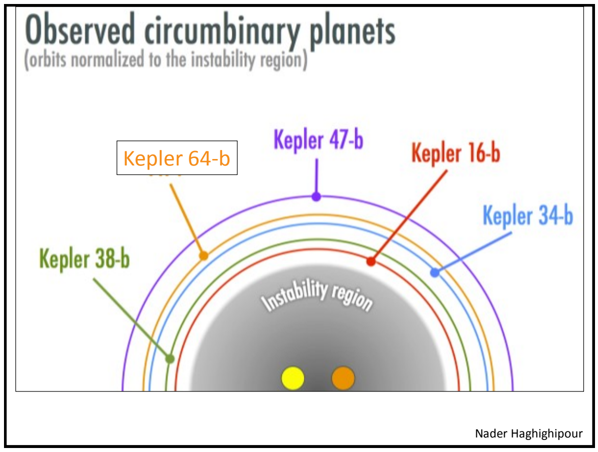
Emerging trends:

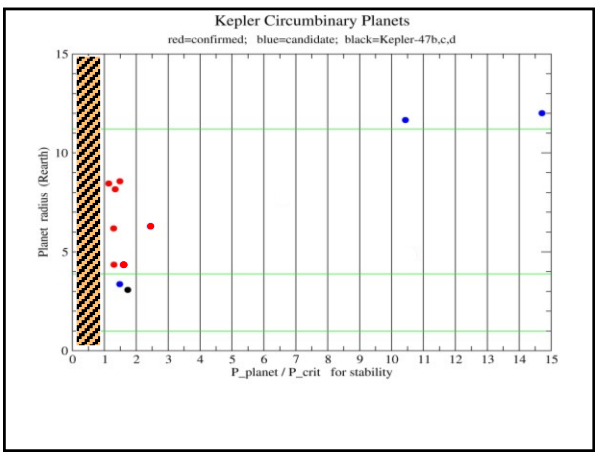
- diverse planet and stellar orbits
  - no resonances seen; precession very important
- planets all smaller than Jupiter
  - even though larger planets are easier to find
- *CBP not seen in short period binaries*
  - *why not? 3rd body interaction?*
- *Planets are close to the critical orbital radius*
  - *8 out of 11 systems have $P < 2 P_{crit}$*
  - *observational bias or migration pile-up?*



Emerging trends:

- diverse planet and stellar orbits
  - no resonances seen; precession very important
- planets all smaller than Jupiter
  - even though larger planets would be easier to find
- *CBP not seen in short P binaries*
  - *why not? past 3rd body interaction?*
- *Planets are close to the critical orbital radius*
  - *8 out of 11 systems have $P < 2 P_{crit}$*
  - *observational bias or migration pile-up?*





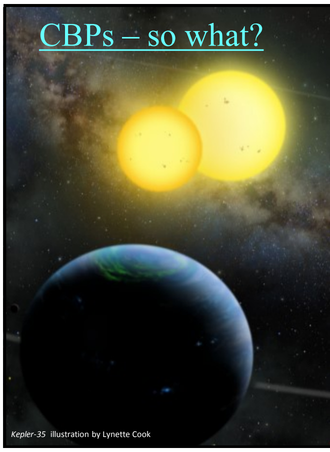
- As a consequence of being close to critical radius, Kepler CB Planets are close to the HZ.
  - → *3 out of 10 CBPs are in the conservative HZ*
  - → *5 out of 12 candidates are in the optimistic HZ* *(~42%)*
- Note: tidal torques due to a binary companion can slow stellar rotation → decrease stellar activity → safer HZ.

- Binarity can decrease stellar activity, thereby extending the HZ:

Rotational Synchronization May Enhance Habitability for Circumbinary Planets: Kepler Binary Case Studies - P. Mason, et al. 2013 ApJL 724, L26.

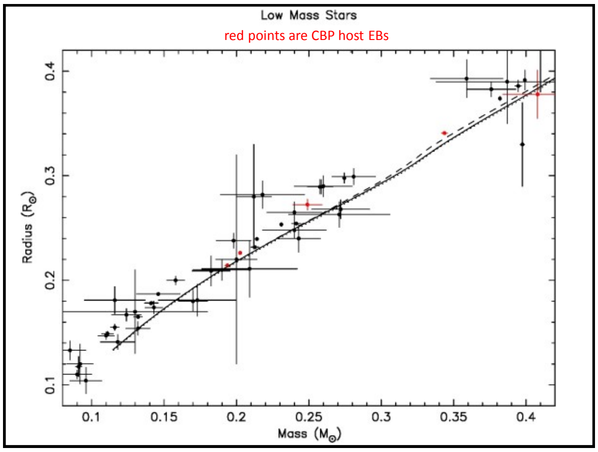
"Tidal rotational breaking reduces magnetic activity, thus reducing harmful levels of X-ray and ultraviolet (XUV) radiation and stellar mass-loss that are able to erode planetary atmospheres."

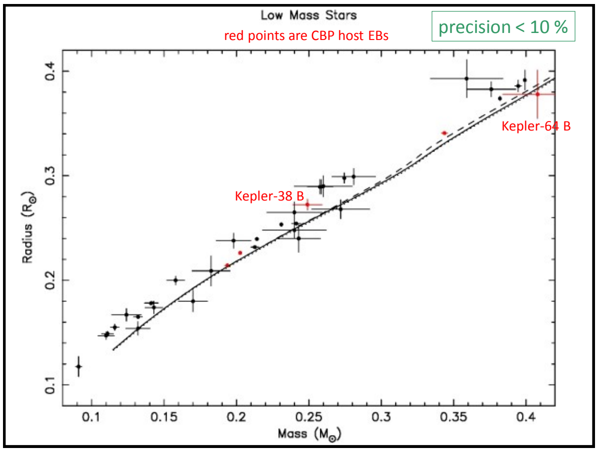
→ binarity may increase the number of HZ environments

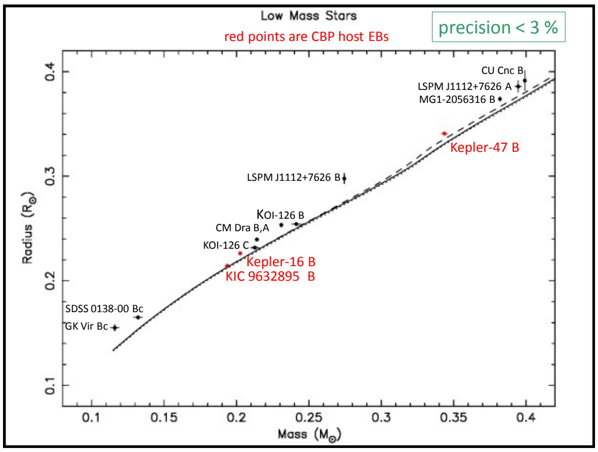


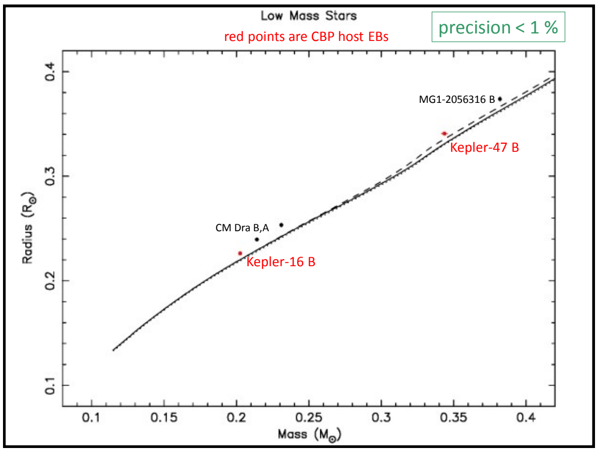
Important because:

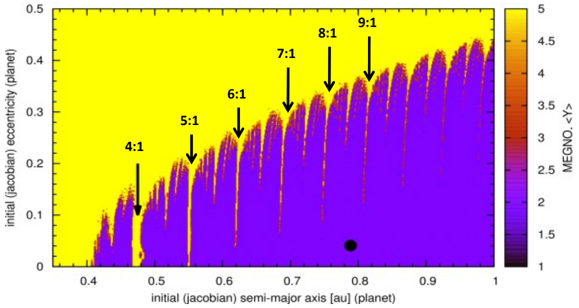
1. Tatooine!
2. Precision Masses & Radii
3. Planet Formation
4. (Binary) Star Formation











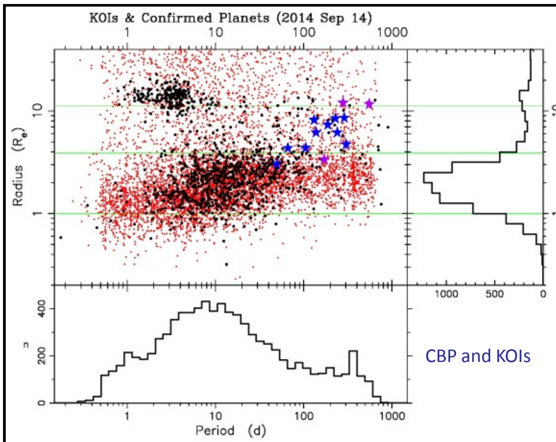
MEGNO map (Mean Exponential Growth factor of Nearby Orbits)

Yellow → chaotic → ~ unstable

Blue → quasi-periodic → ~stable

Summary Kepler Circumbinary Planets:

- 10+ systems show a wide variety of stellar and orbital properties
- Emerging trends:
  - smaller than Jupiter in size
  - tend to orbit close to the (in)stability limit
  - do not exist around short-period binaries
  - large fraction are in the Habitable Zone
- Provide rich rewards:
  - challenges for planet formation & migration theories
  - very precise stellar information, esp. for M-stars
  - stellar ages
  - most accurate exoplanet masses and radii



CBP and KOIs

Circumbinary Planets

CBP provide very rich rewards:

- challenges for planet formation theory
- very precise stellar information, esp. for M-stars
- most accurate exoplanet masses and radii
- more precise age of system
- a large fraction are in the Habitable Zone
- multi-periodic variable insolation → wild climates
- their existence shows that planet formation is vigorous and robust
- *At least tens of millions of such systems in the Galaxy*