Discovery of exoplanets using transits

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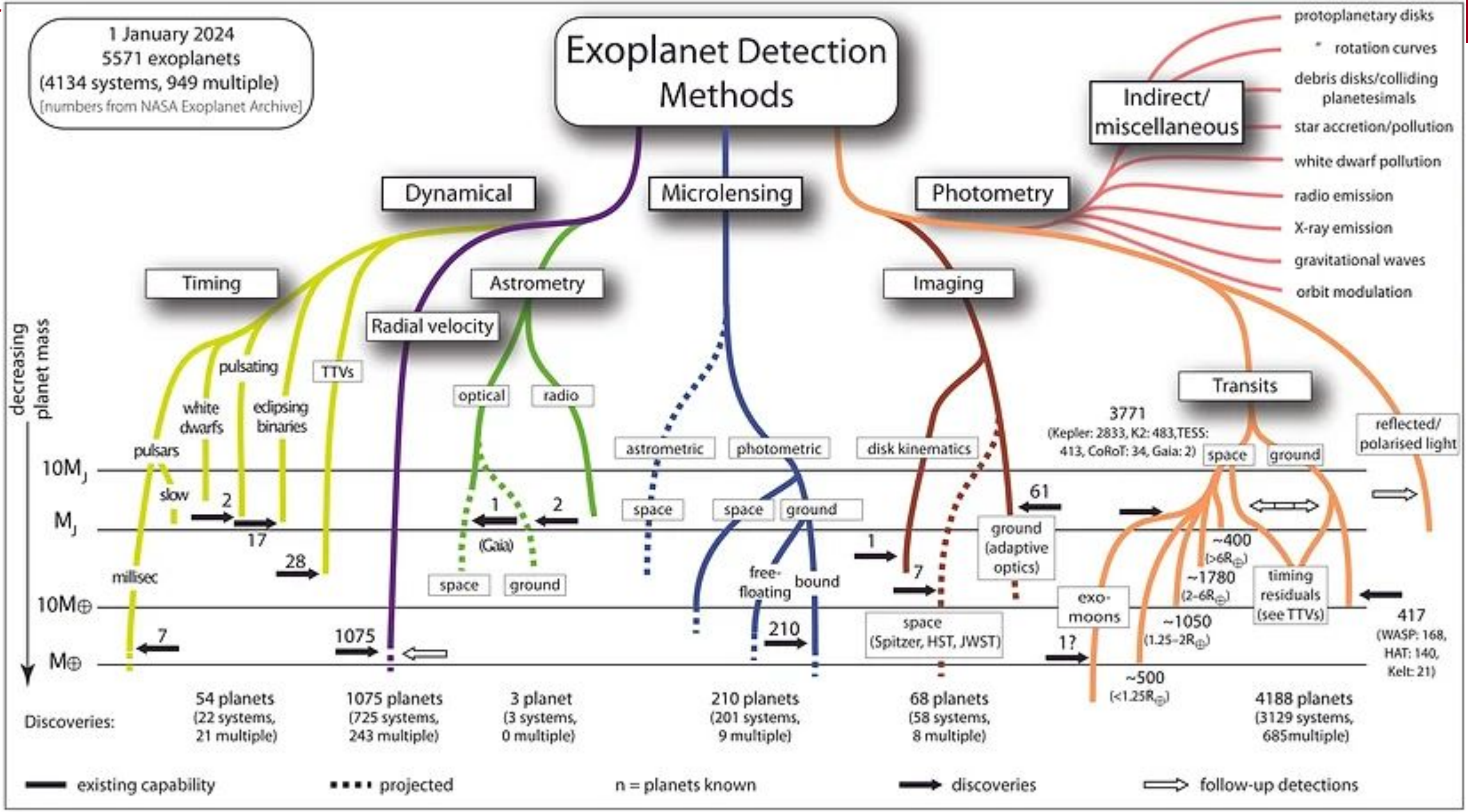
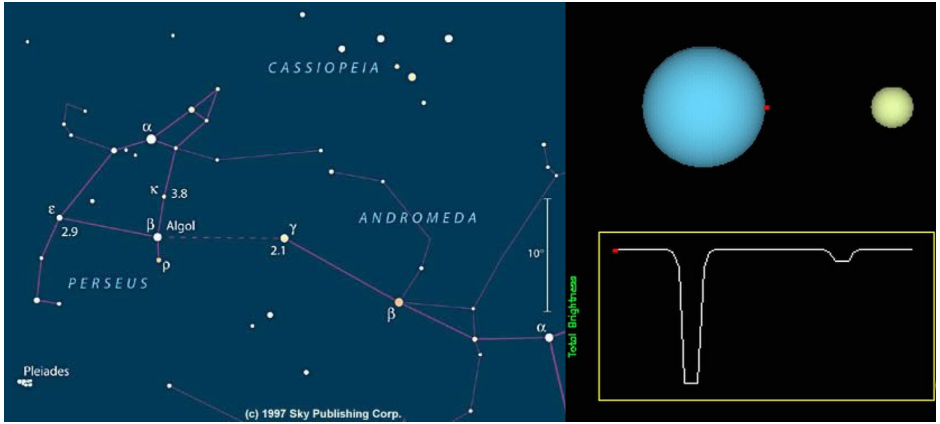


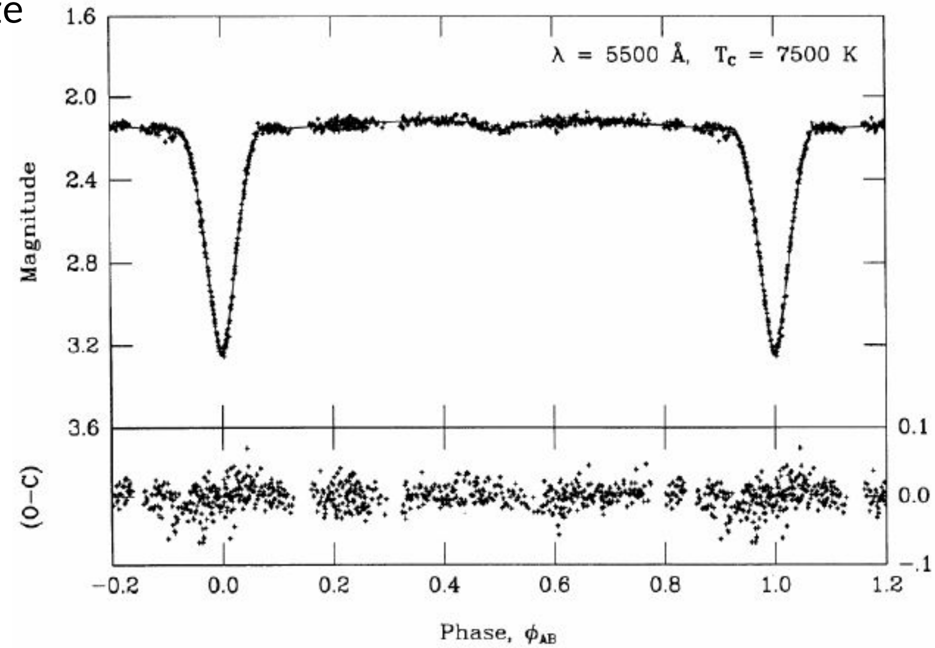
M. Perryman, European Space Agency and University of Leiden (2000)

Discovery of exoplanets using transits

The first eclipses: Algol star (an eclipsing binary)

- Perseus constellation - V=2.1- 92 light-years
- Beta Per A (B8V)+ B (K0IV), orbit at 0.06 au (2.85 days) + Beta Per C (A5V) at 2.7 au (680 days)
- Its variability could have been known by the Egyptians more than 3000 years ago.
- 1783: John Goodricke proposed that it is due to eclipses.
  → Geometrical effect depending on the stars size
- End of 19th century: radial velocities show the multiple nature of the star.

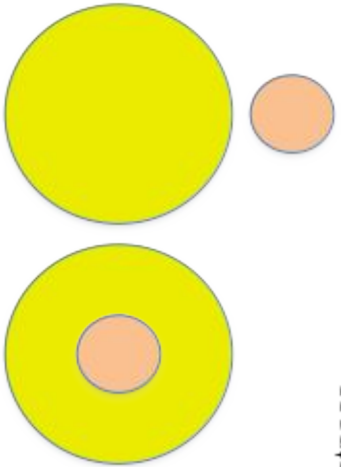




Discovery of exoplanets using transits

What about transiting planets?

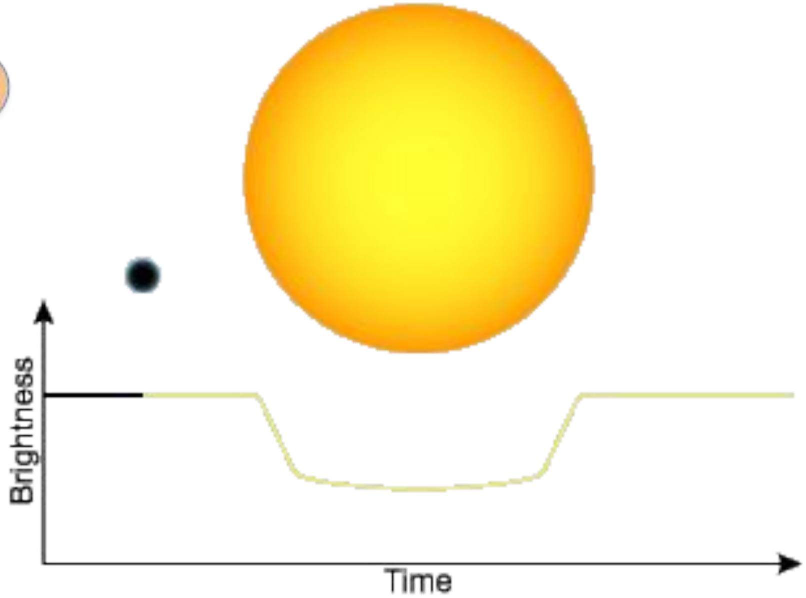
- Planet/Star size ratio is much smaller
  - Flux out-of-transit/occultation
    $$F_{out} = f_{\star}A_{\star} + f_P A_P$$
  - Flux in transit
    $$F_{tra} = f_{\star}A_{\star} + f_P A_P - f_{\star}A_P$$



$$\delta_{tra} = \frac{R_P^2}{R_*^2}$$

→ Jupiter around the Sun
flux drop ~ 1% = 10000 ppm

→ Earth around the Sun
flux drop ~ 0.008% = 80 ppm



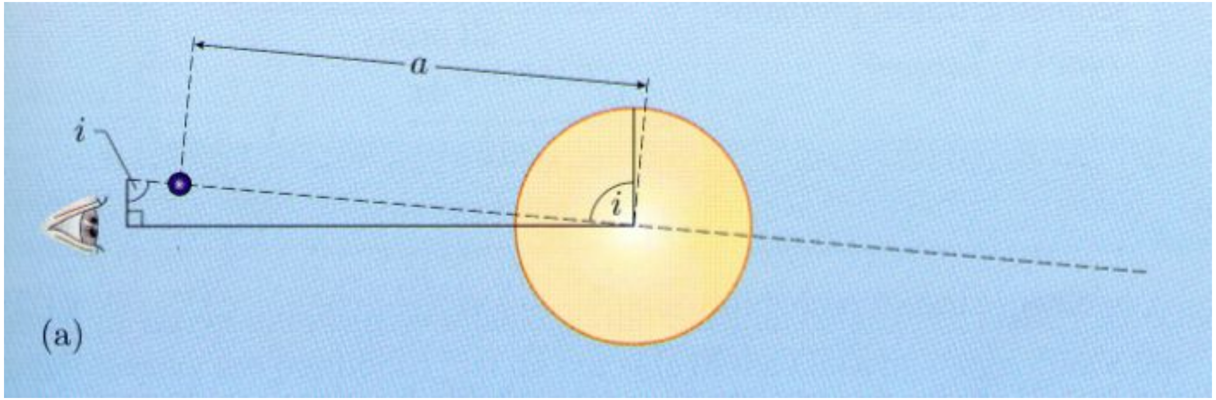
Discovery of exoplanets using transits

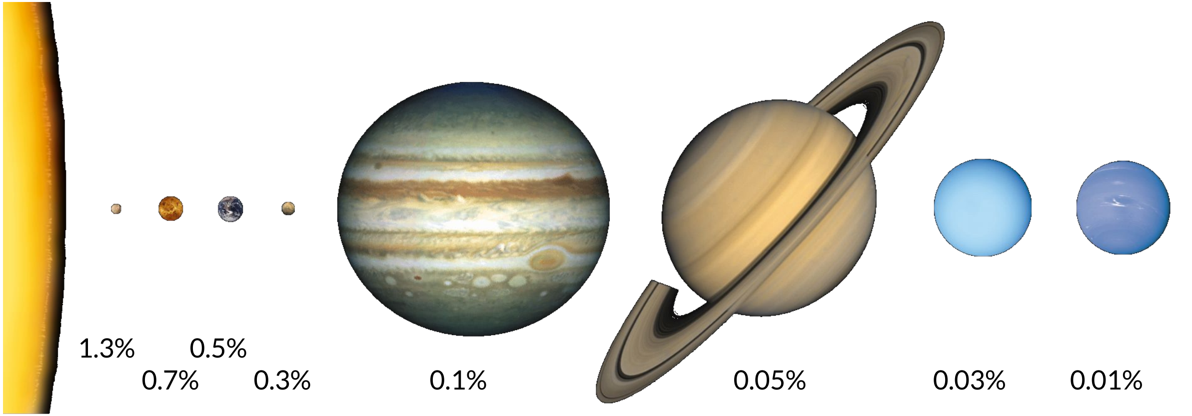
What about transiting planets?

- Probability of transit, decreases with the distance between the star and the planet

$$p_{tra} = \frac{R_*}{a}$$

$$p_{tra} = \frac{R_*}{a} \approx 0.005 \frac{R_*}{R_{Sun}} \left(\frac{a}{1\,au} \right)^2$$



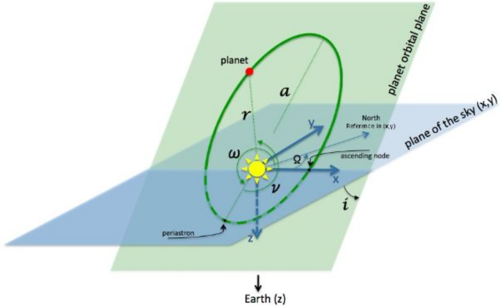


Discovery of exoplanets using transits

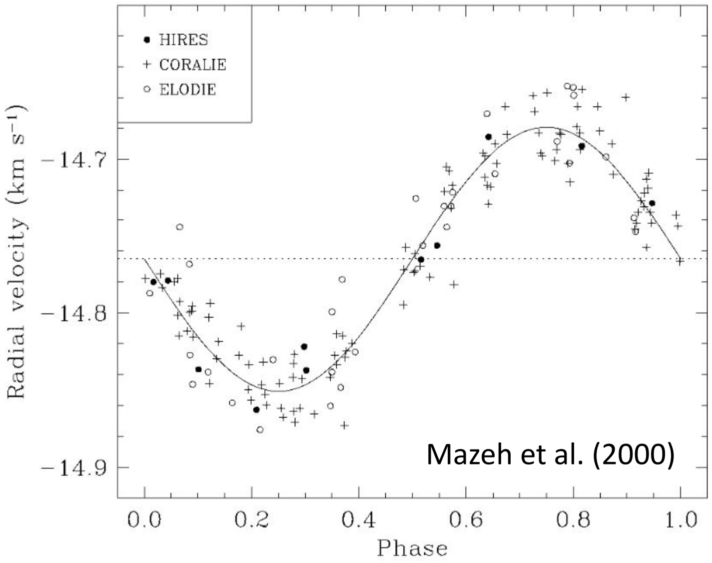
First actual exoplanets transits

- HD 209458

  → Jupiter-like planet orbiting a solar type star



Already known by RVs!



Transit time from radial velocities

→ Transit time occurs at:

$$f_{\rm tra} = +\frac{\pi}{2} - \omega$$

→ Radial velocity

$v_r = \gamma + K\,[\cos(\omega + f) + e\cos\omega]$

→ The time between transit and periastron is:

$\Delta t = P\,(E_{tra} - P\sin E_{tra})/(2\pi)$

where E_{tra} is the eccentric anomaly at transit.

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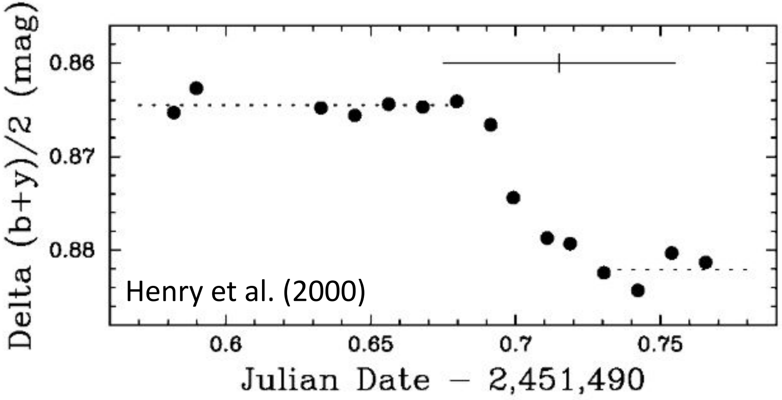
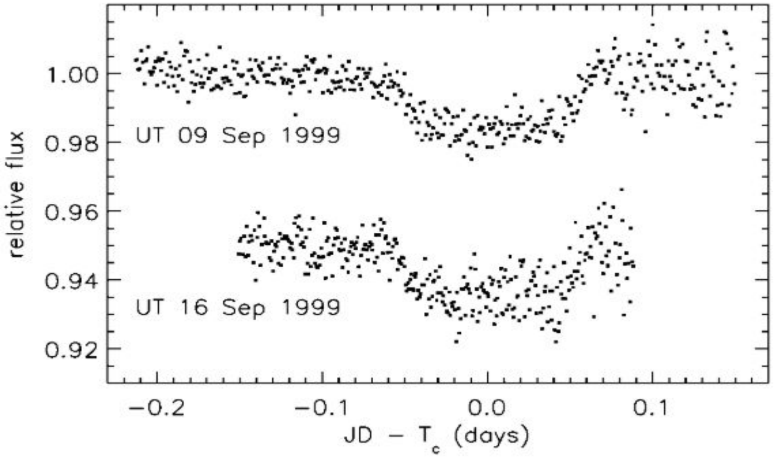
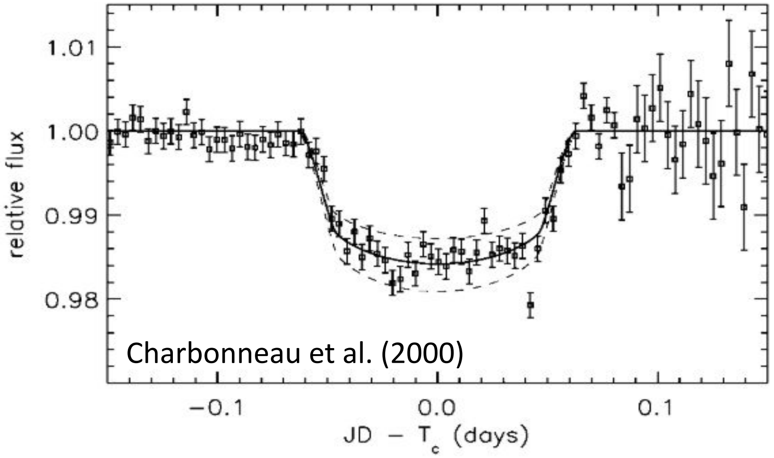


Henry et al. (2000)



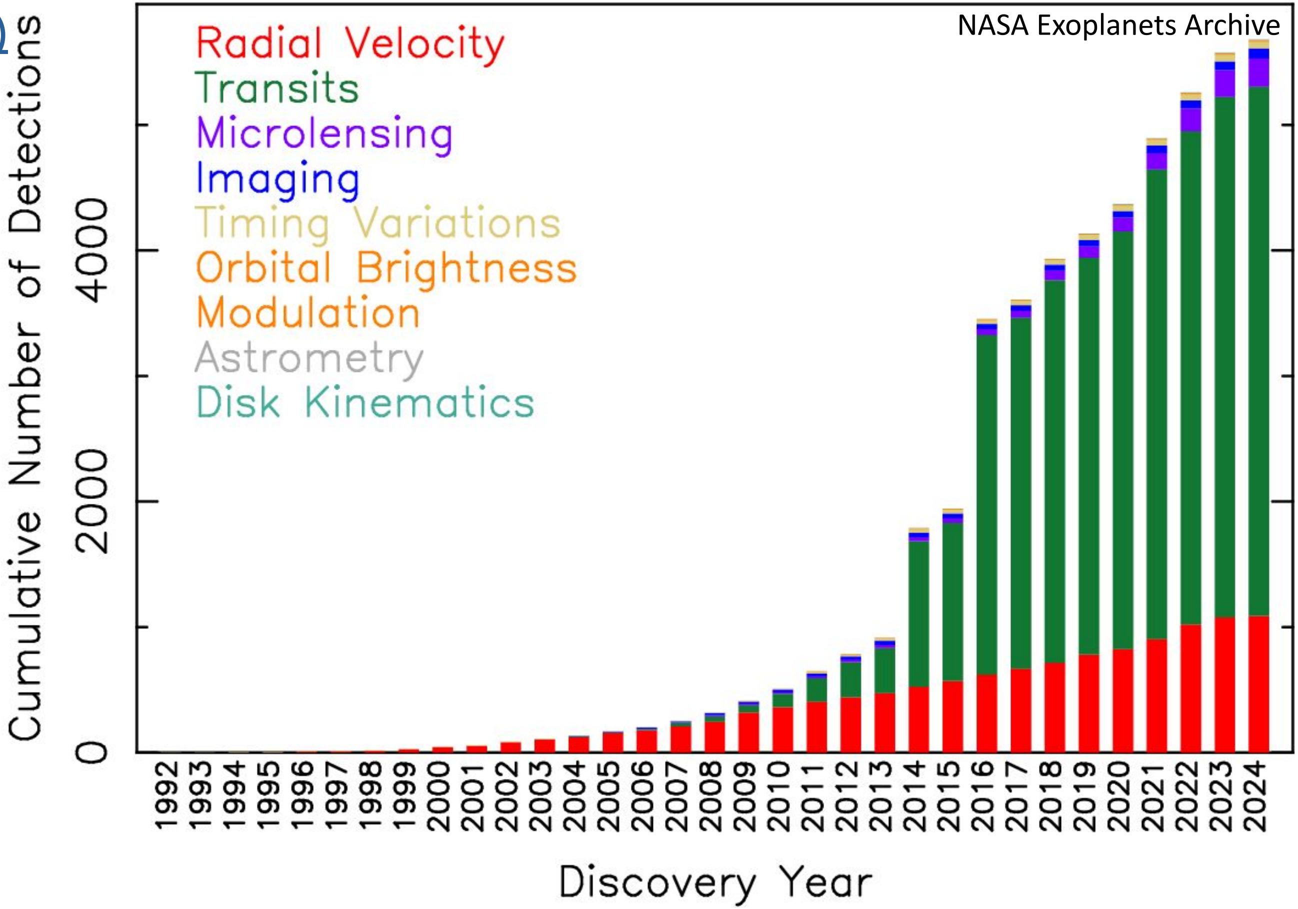


Charbonneau et al. (2000)

Discovery of exoplanets using transits

Transiting surveys (ground based)

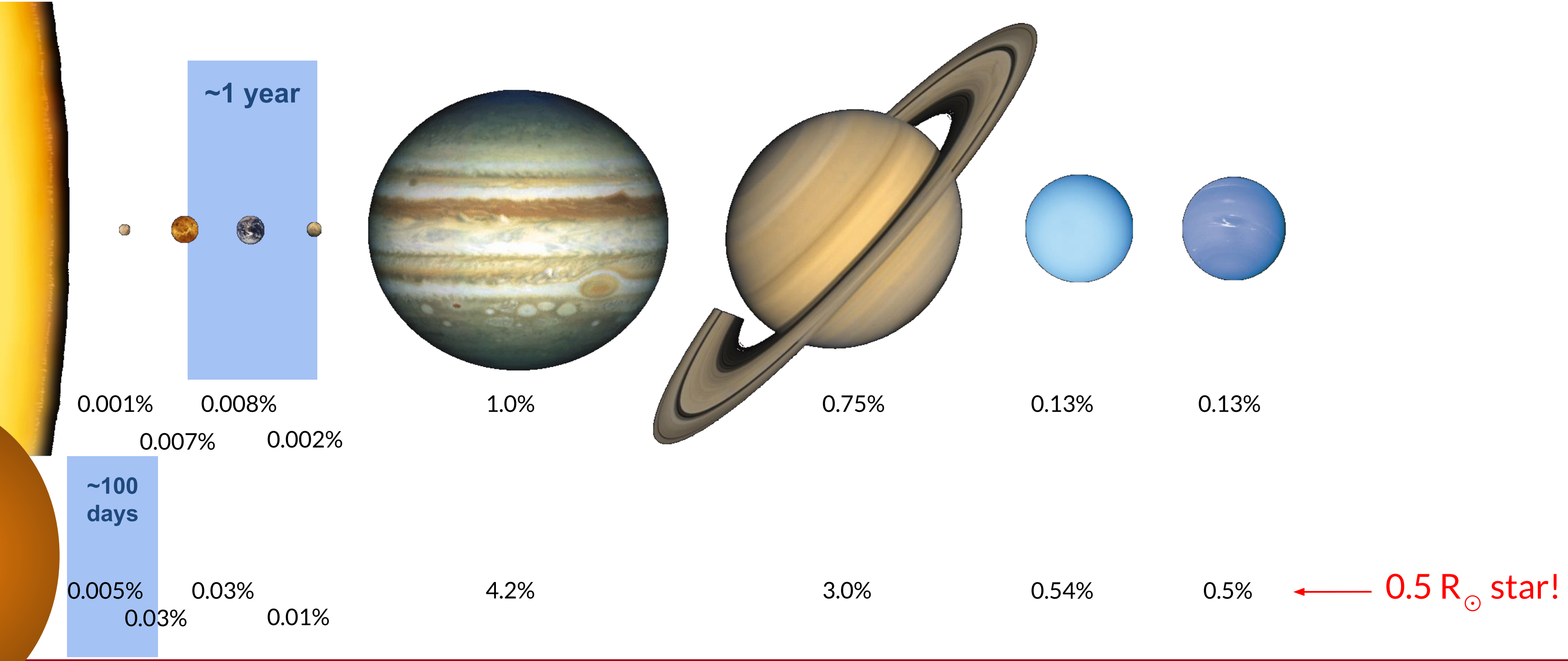
- OGLE-III
  (Udalski et al. 1997)
  → 8 transiting planets
  → first in 2003
- TrES
  (Brown et al. 2004)
  → 5 planets
  → first in 2004
- XO
  (Irwin et al. 2009)
  → 7 planets
  → first in 2006
- MEarth
  (Irwin et al. 2009)
  → 4 planets
  → first in 2009



Discovery of exoplanets using transits

The importance of M dwarfs

- The signal of transiting exoplanets is much larger
- The habitable zone is closer



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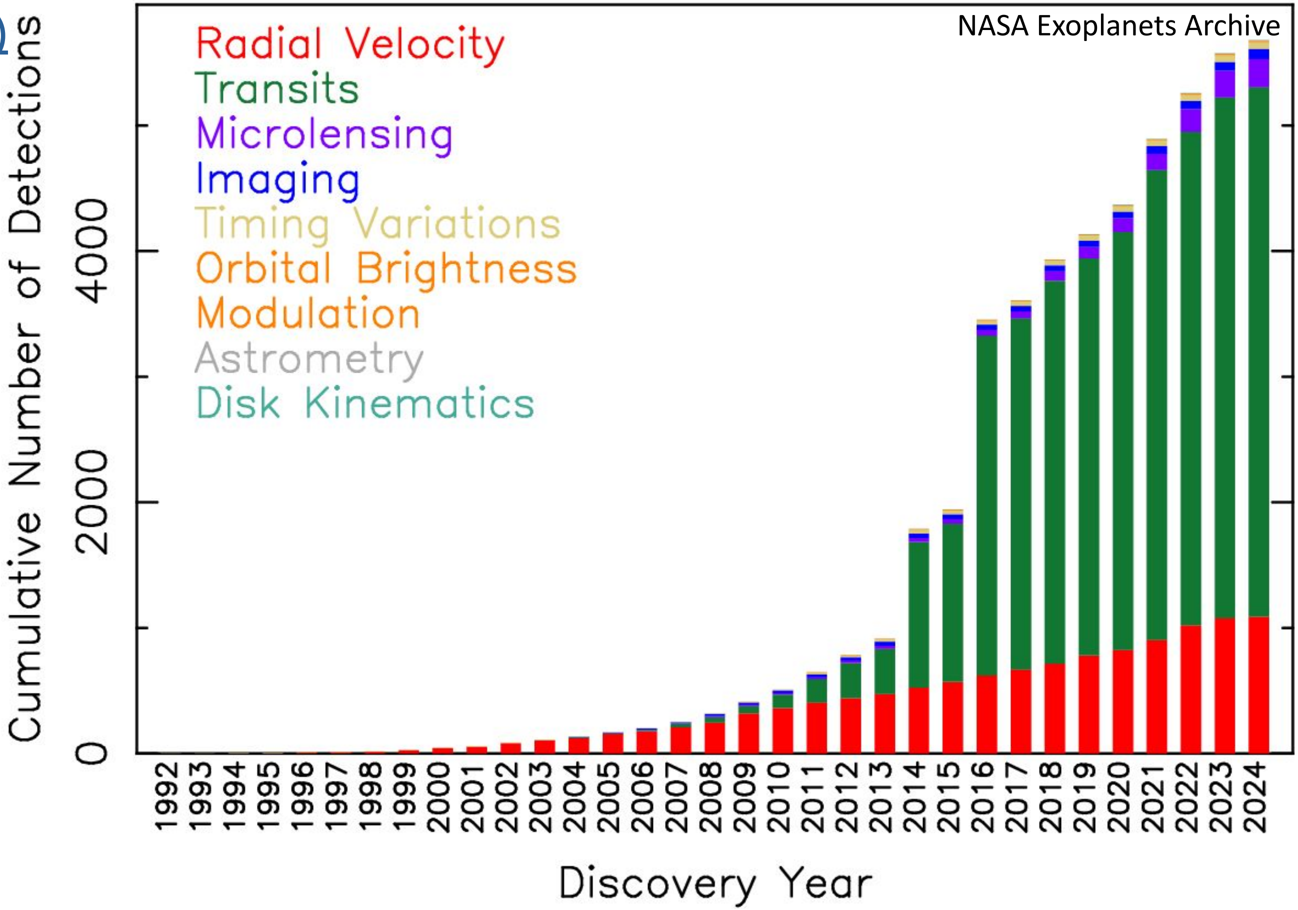
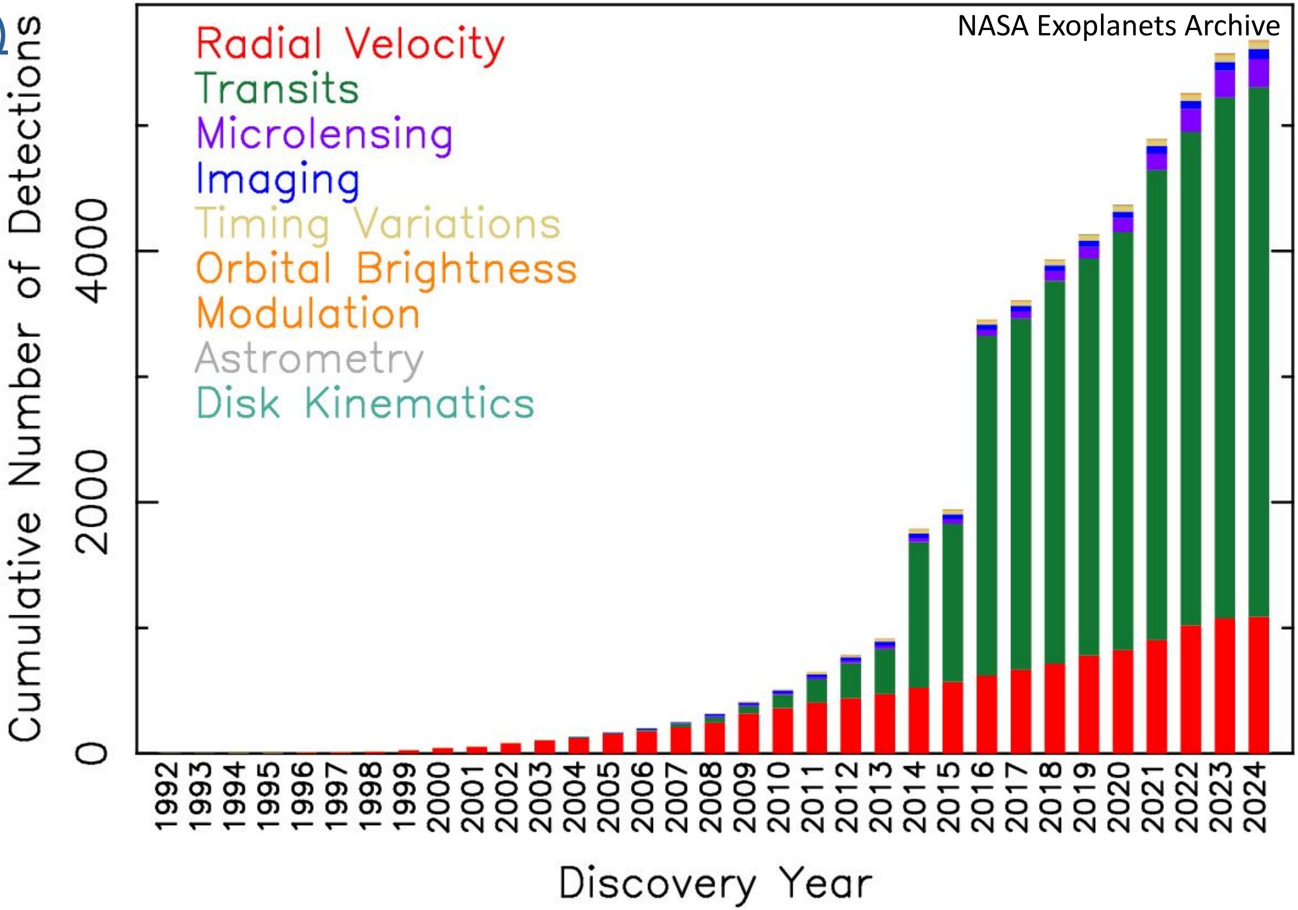


Discovery of exoplanets using transits

Transiting surveys (ground based)

- WASP/SuperWASP
  (Pollacco et al. 2006)
  → ~180 planets
  → first planet 2007



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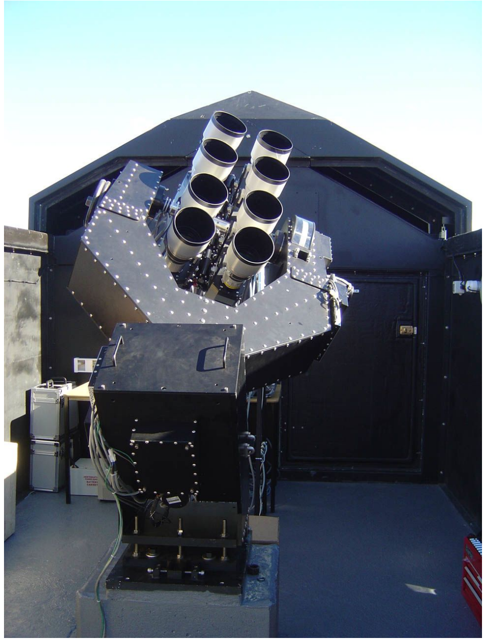
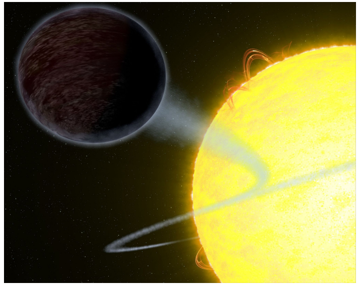
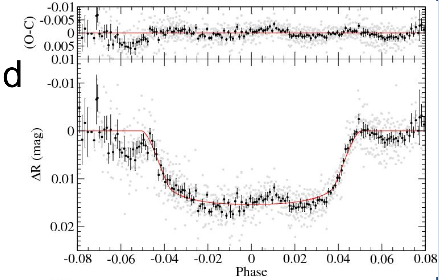


Wide Angle Search for Planets

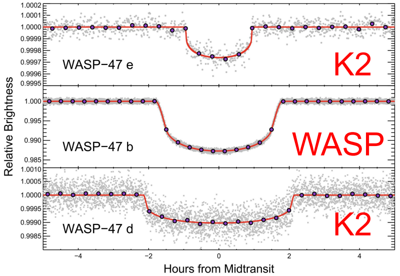
- WASP-12 b: one of the most heavily irradiated planets
  (Hebb et al. 2009)
  P ~ 1 day
  T_P ~ 2500 K





- WASP-33 b: heavily irradiated planet around δ-Scuti pulsator A-type star
  (Collier Cameron et al. 2010, Herrero et al. 2011)
  P ~ 1.2 days

- WASP-47: first case of a hot Jupiter with other low-mass exoplanets in close orbits
  (Hellier et al. 2012, Becker et al. 2015)



Discovery of exoplanets using transits

Transiting surveys (ground based)

- WASP/SuperWASP
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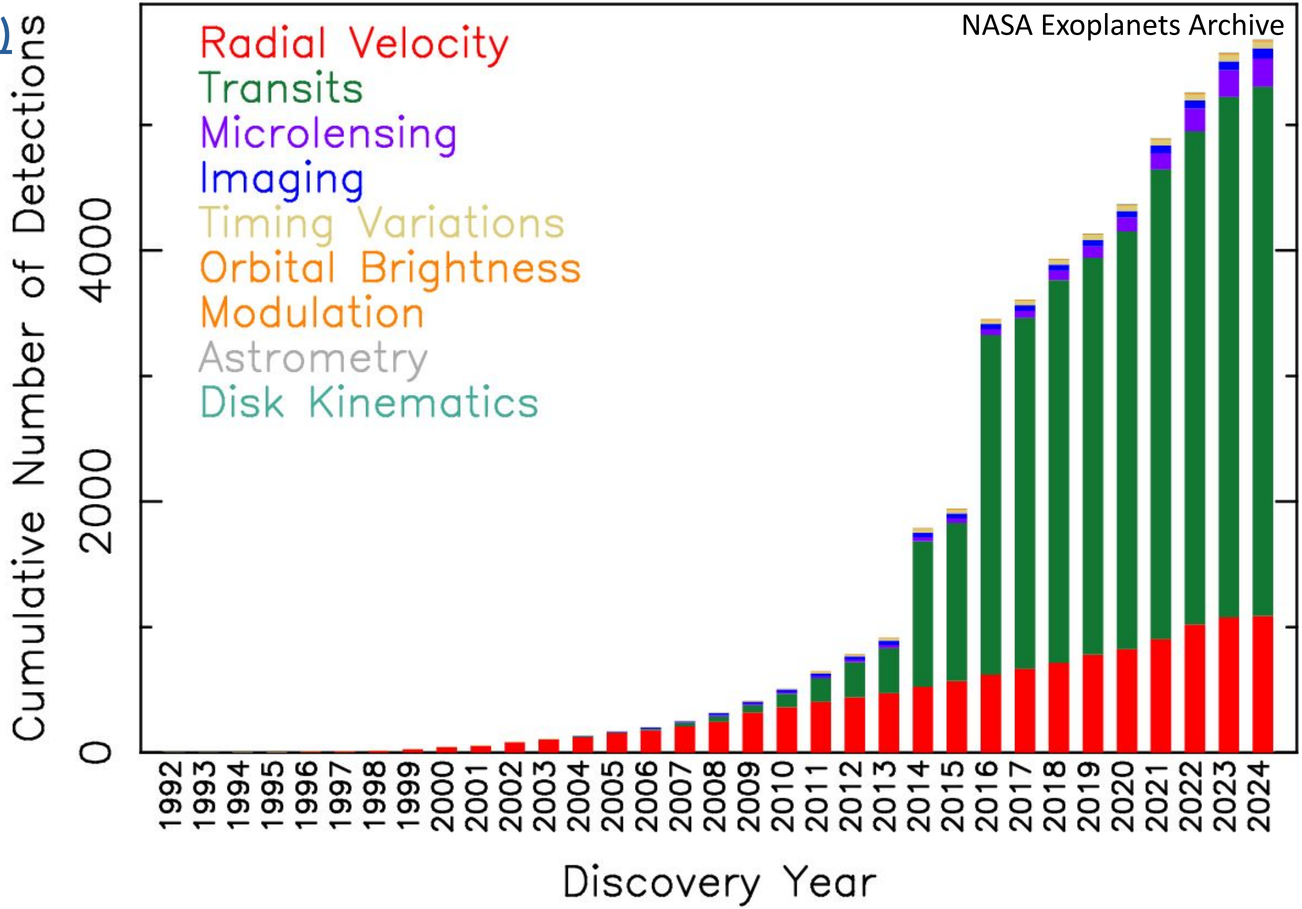
  → ~180 planets
  → first planet 2007
- HATNet
  (Bakos et al. 2004)
  → ~150 planets
  → first planet 2006
- NGTS
  (Wheatley et al. 2018)
  → ~25 planets
  → first planet 2017



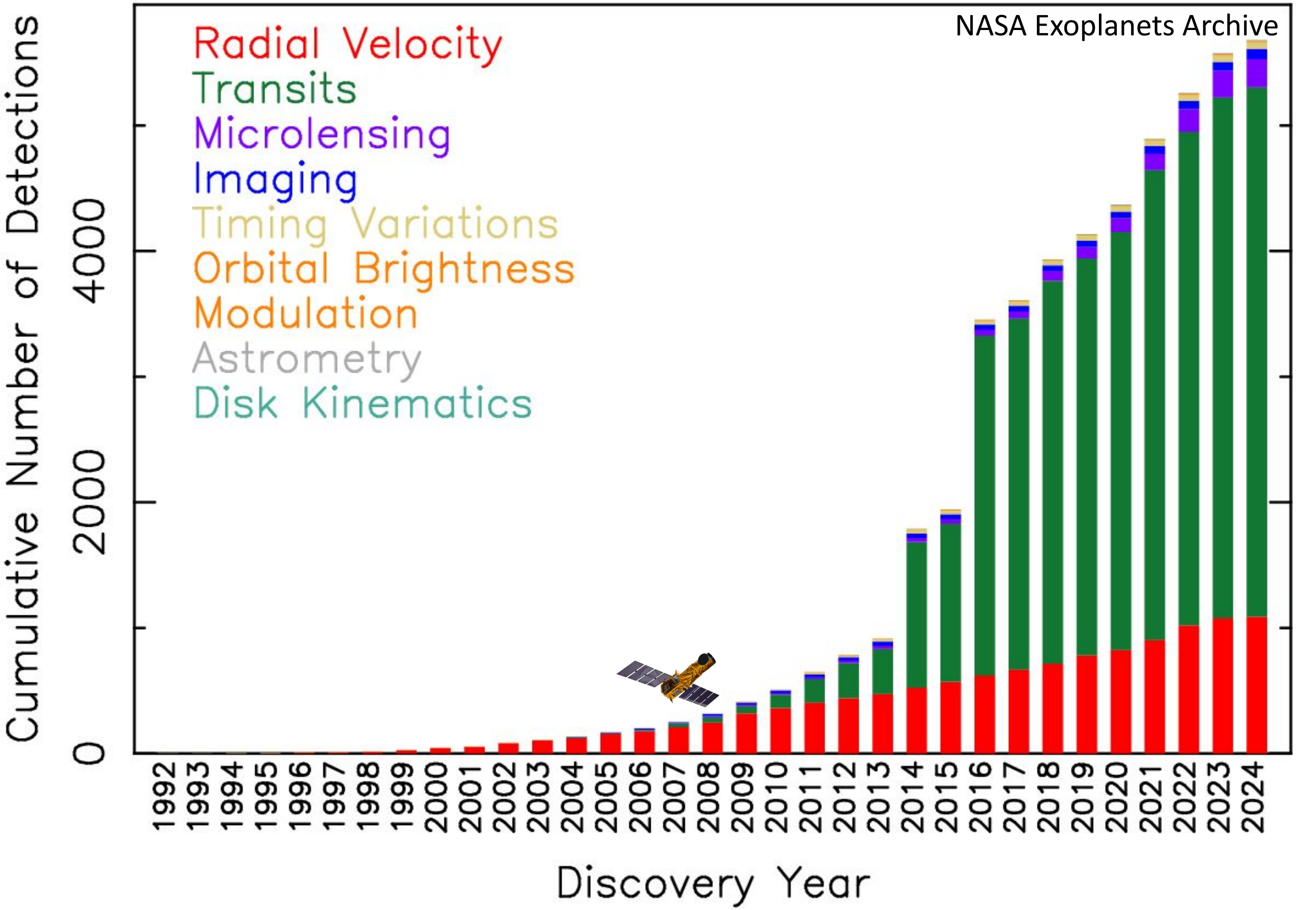
Discovery of exoplanets using transits

Transiting surveys (space based)

- *CoRoT*

  (Baglin et al. 2002)

  → ~40 planets



Discovery of exoplanets using transits

Transiting surveys (space based)

- *CoRoT*

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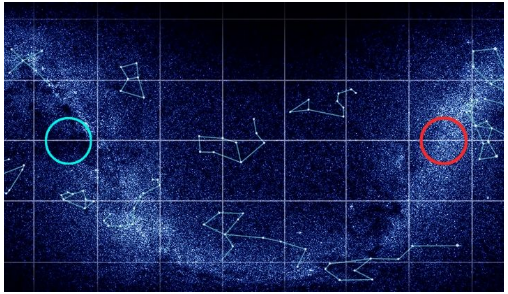
  → ~40 planets

Convection, Rotation and planetary Transists (CNES/ESA)

- First space mission to study stars and detect exoplanets from space
- Launch 27 December 2006
- Geocentric orbit
- 27 cm telescope, 3.5 deg² field of view



CoRoT-7 b (Leger et al. 2009)

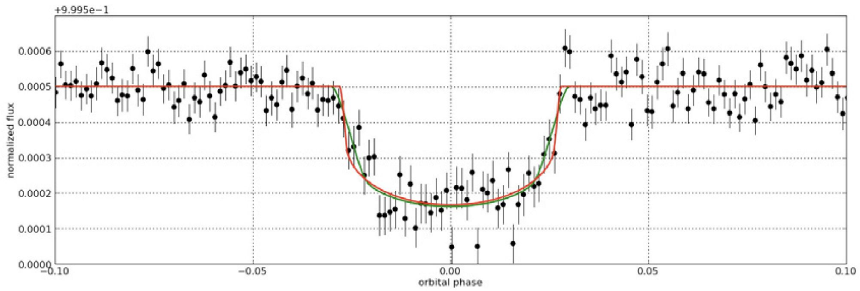
→ the first transiting super-Earth

→ solar type star (0.91 $M_\odot$)

→ ~1.7 $R_\oplus$ and ~5 $M_\oplus$

→ P = 20.5 hours (very hot planet)

Corot-7b best-fit transit model



Discovery of exoplanets using transits

Transiting surveys (space based)

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- Kepler/K2
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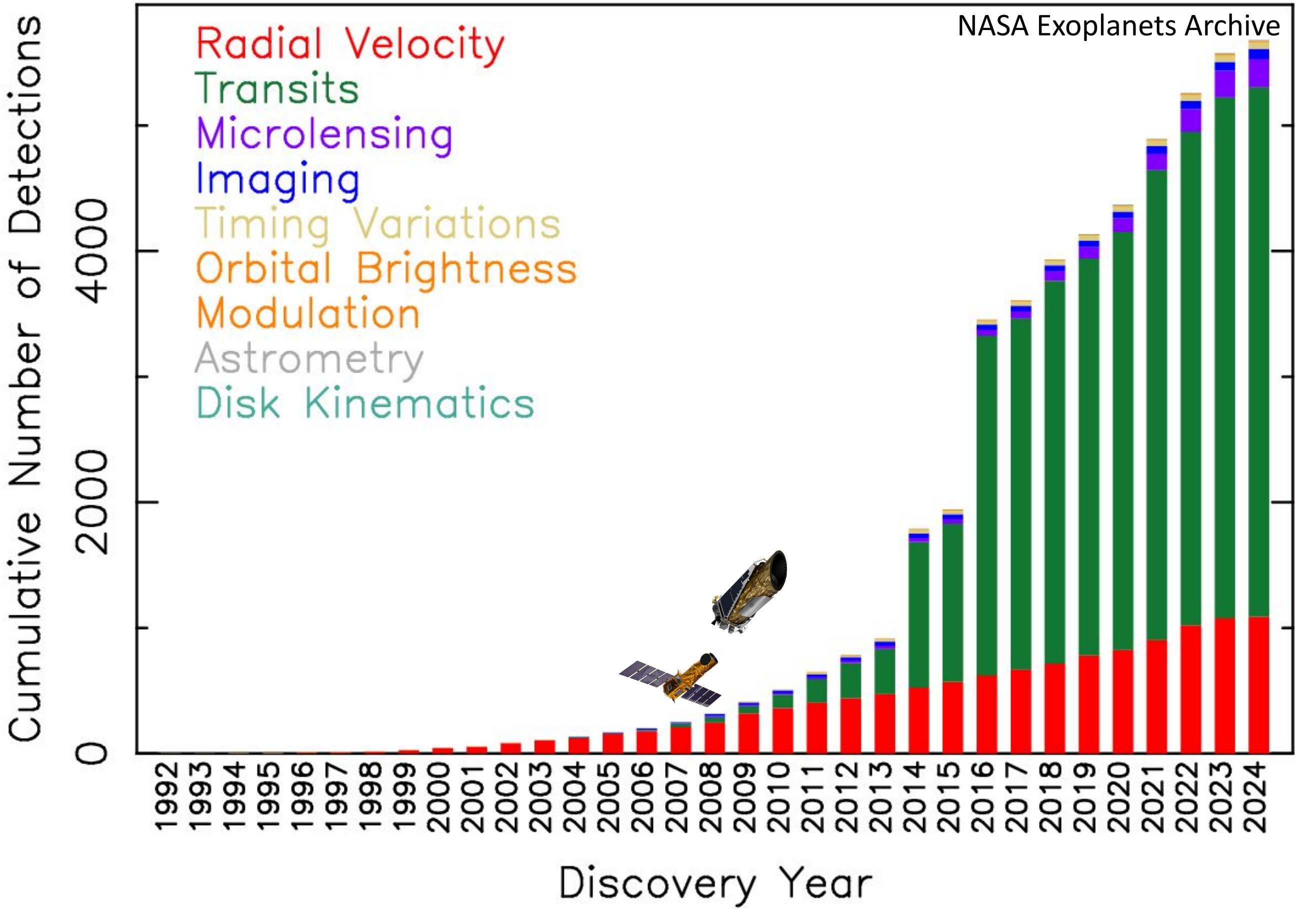
  → ~3300 planets
  → ~3000 candidates



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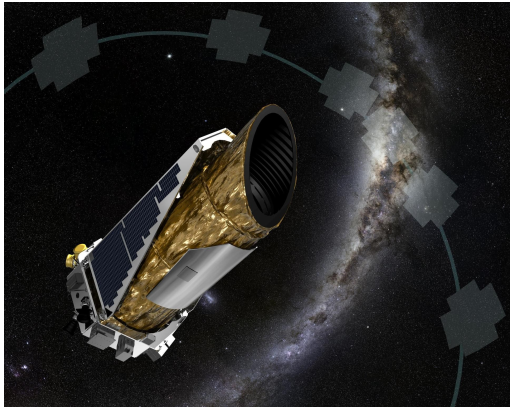
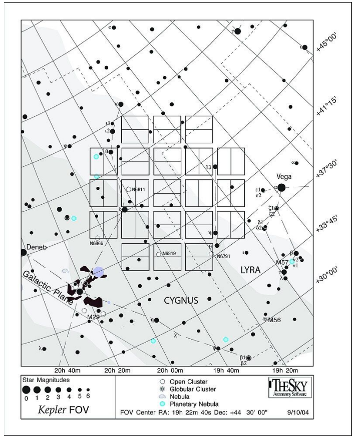


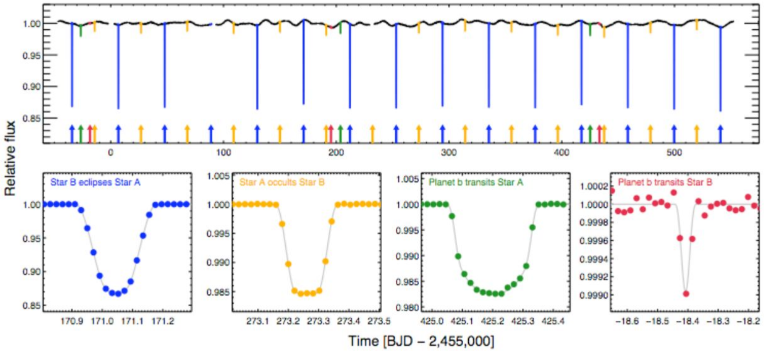
Kepler/K2 (NASA)

- Space mission to look for transiting exoplanets
- Launch 7 March 2009
- Heliocentric orbit
- 95 cm telescope, 115 deg² field of view
- Single field of view
  - 2013 failure of 2 reaction wheels → K2



Kepler-16 b (Doyle et al. 2011)

→ First circumbinary candidate
→ P_{binary} ~ 41 days
→ P_P ~ 230 days
→ Saturn-like planet
→ Precise mass



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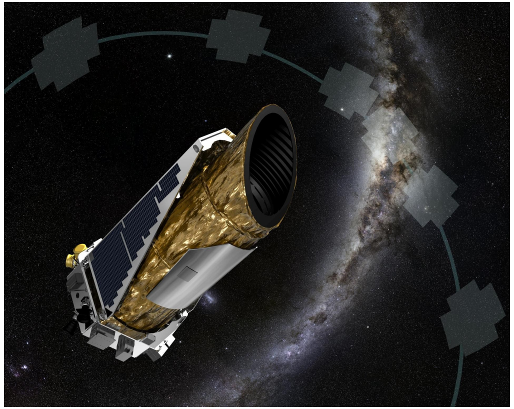
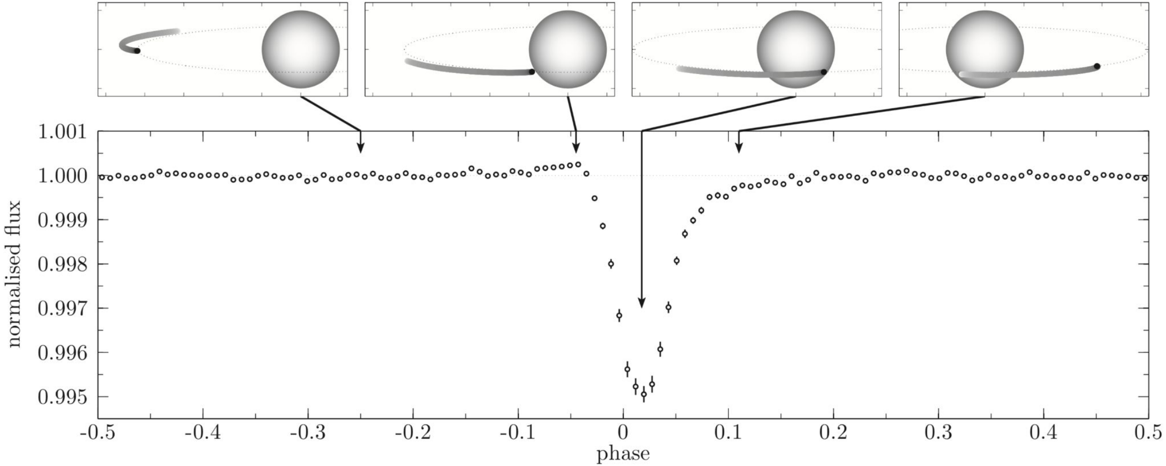


Kepler/K2 (NASA)

Kepler-1520 b (Rappaport et al. 2011)
→ First disintegrating planet
→ Host star mass 0.76 $M_\odot$
→ P_P ~ 15.7 hours
→ Mercury size



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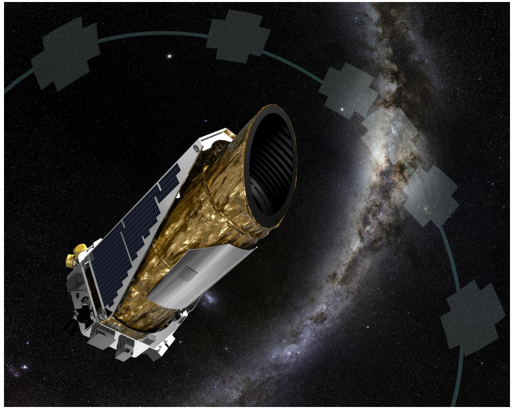
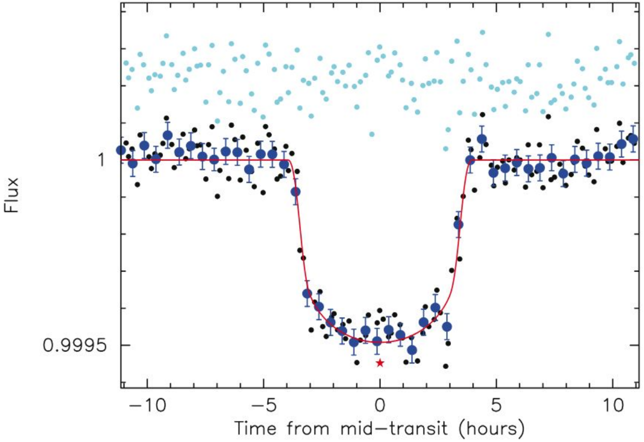
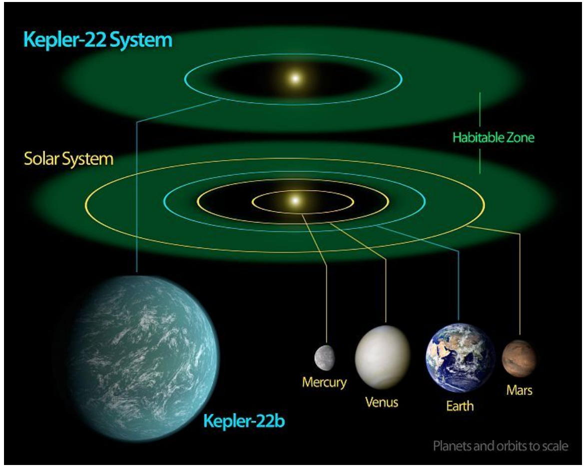


Kepler/K2 (NASA)

Kepler-22 b (Borucki et al. 2012)
→ First transiting super-Earth in the habitable zone
→ Host star mass 0.86 $M_\odot$
→ P_P ~ 290 days
→ ~2.4 $R_\oplus$ and <36 $M_\oplus$





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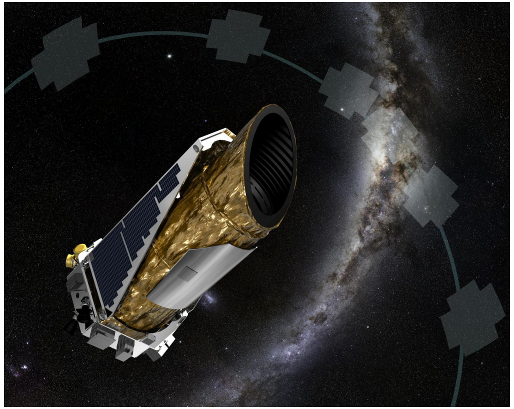
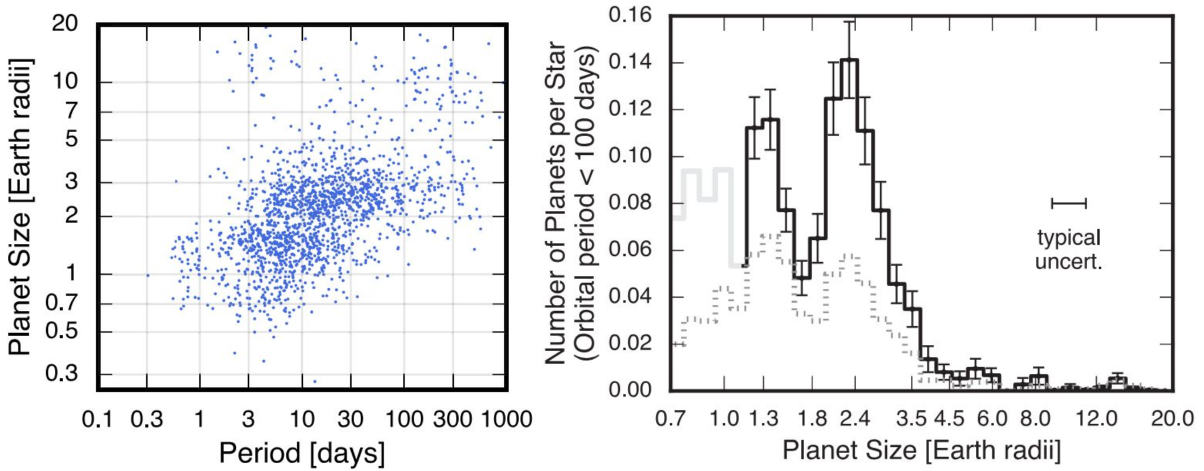


Kepler/K2 (NASA)

Statistical studies

→ Radius valley (Fulton & Petigura 2017, 2018)
→ Occurrence rates: stars with planets
→ 50% of FGK stars (Fressin et al. 2013)
→ 90% of M-dwarfs (Dressing & Charbonneau 2013)



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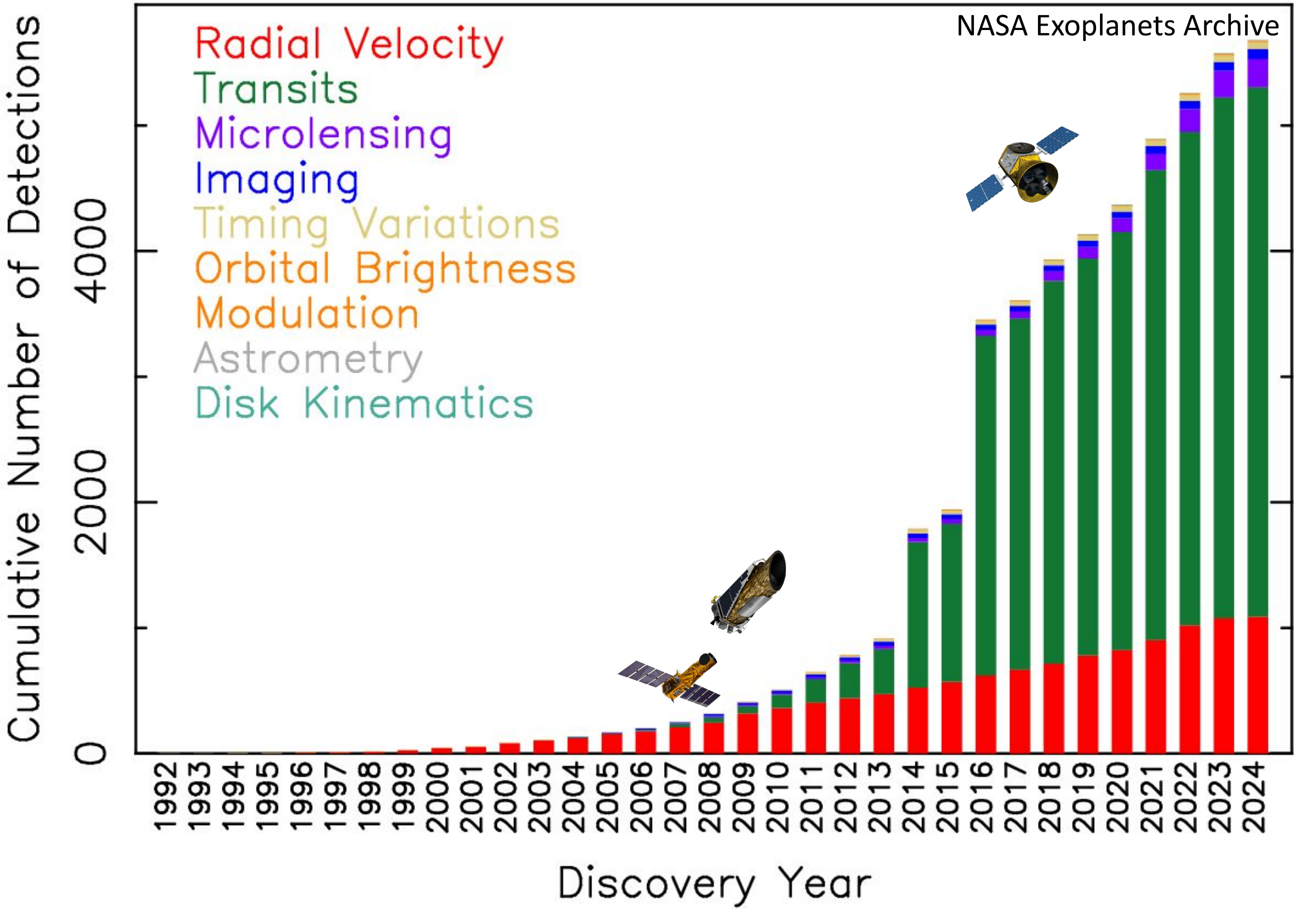
- TESS
  (Ricker et al. 2015)
  → ~480 confirmed
  → ~4600 candidates



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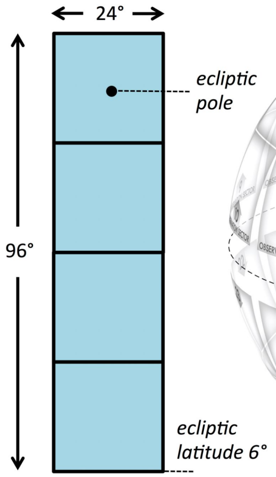
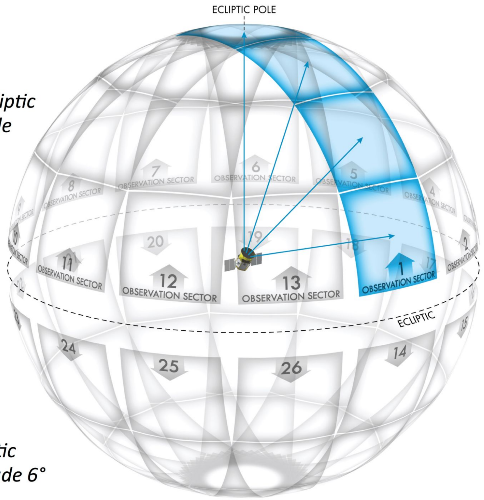
Transiting Exoplanet Survey Satellite

- Space mission to look for transiting exoplanets
- Launch 18 April 2018
- Geocentric orbit
- 4x10 cm cameras, 24x24 deg field of view
- All sky survey in sectors of 27 days

https://tess.mit.edu/





Institute of
Space Sciences

Discovery of exoplanets using transits

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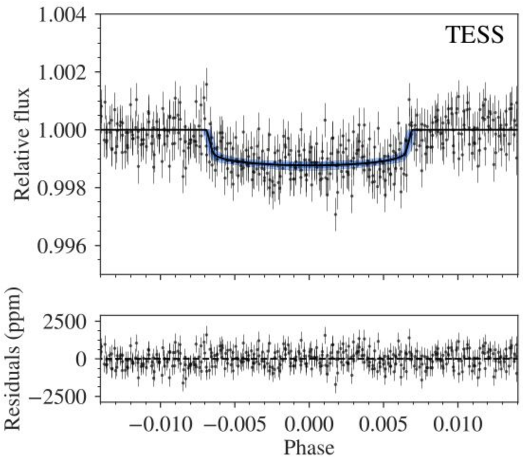
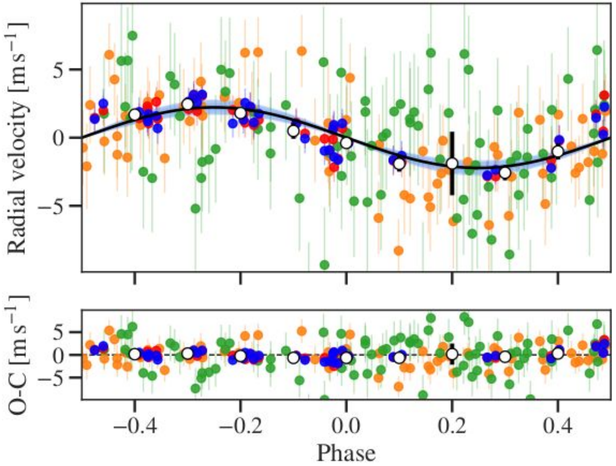
Transiting Exoplanet Survey Satellite

Synergies with other instruments: TESS & CARMENES

- Gl 357 b (Luque et al. 2019)
  → Host star mass 0.36 $M_\odot$
  → P_P ~ 3.93 days
  → ~1.2 $R_\oplus$ and ~1.8 $M_\oplus$
  → + 2 planets (RVs)
- Gl 806 b (Pallé et al. 2023)
  → Host star mass 0.41 $M_\odot$
  → P_P ~ 0.92 days
  → ~1.3 $R_\oplus$ and ~1.9 $M_\oplus$
  → + 2 planets (RVs)





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- TESS
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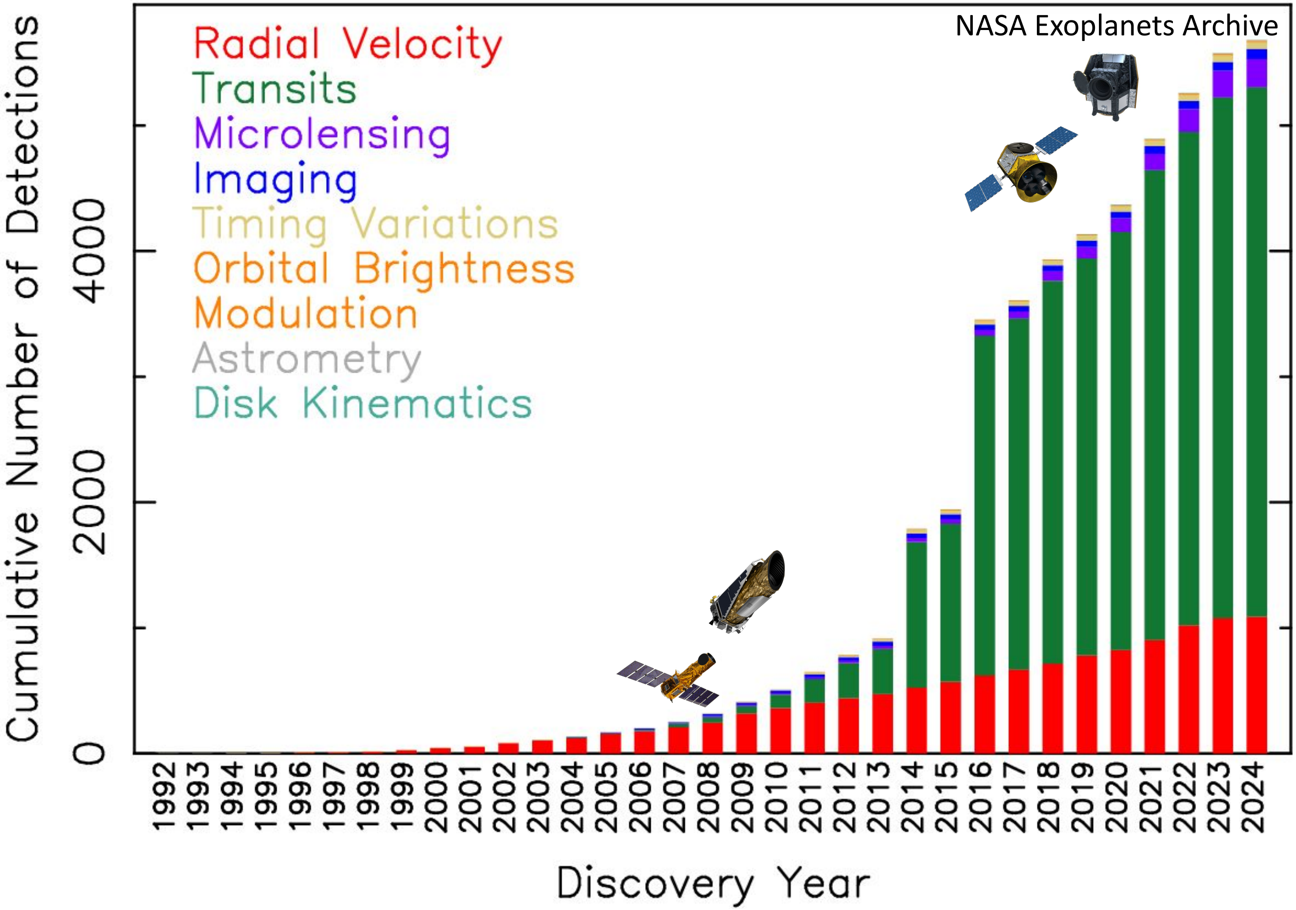
  → ~4600 candidates
- CHEOPS
  (Benz et al. 2021)
  → Transit of RV planets
  → Multiple systems



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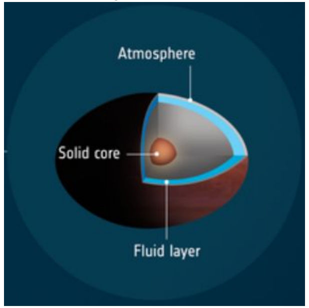
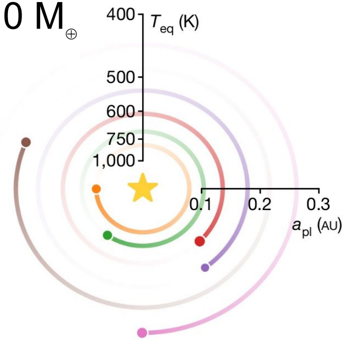
Characterization ExoPlanet Satellite

- Space mission to precisely characterize known exoplanets
- Launch 18 December 2019
- Geocentric orbit
- 30 cm telescope

Precise photometry and targeted transit search

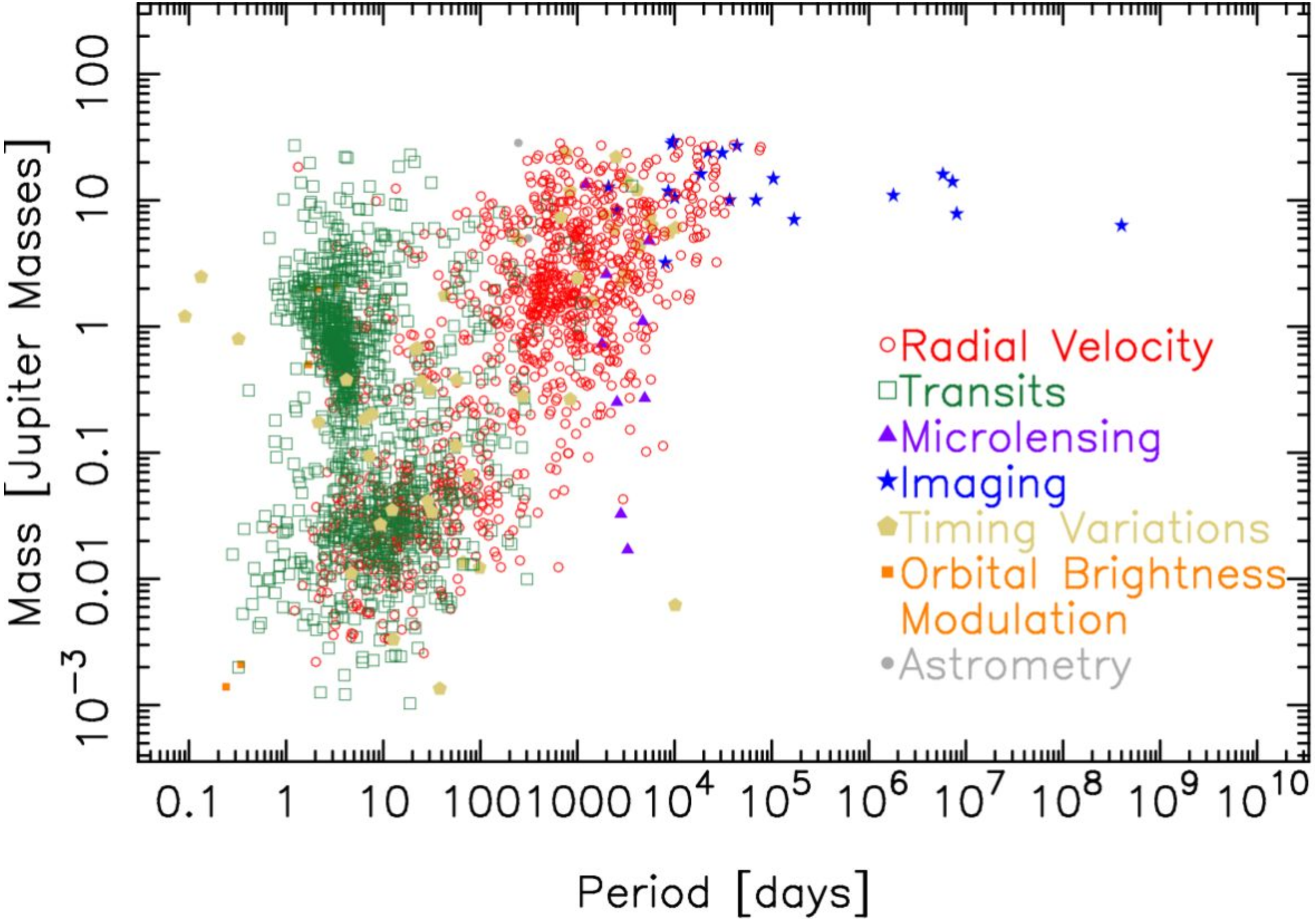
- WASP-103 b (Barros et al. 2021)
  → Host star mass 0.72 $M_\odot$
  → P_P ~ 0.92 days
  → ~1.5 R_J and ~1.4 M_J
  → Tidally deformed
- HD110067 b (Luque et al. 2023)
  → Host star mass 0.80 $M_\odot$
  → P_P ~ 9.1 - 13.7 - *20.5*
  30.8 - 41.0 - 54.7 days
  → ~ 5-10 $M_\oplus$





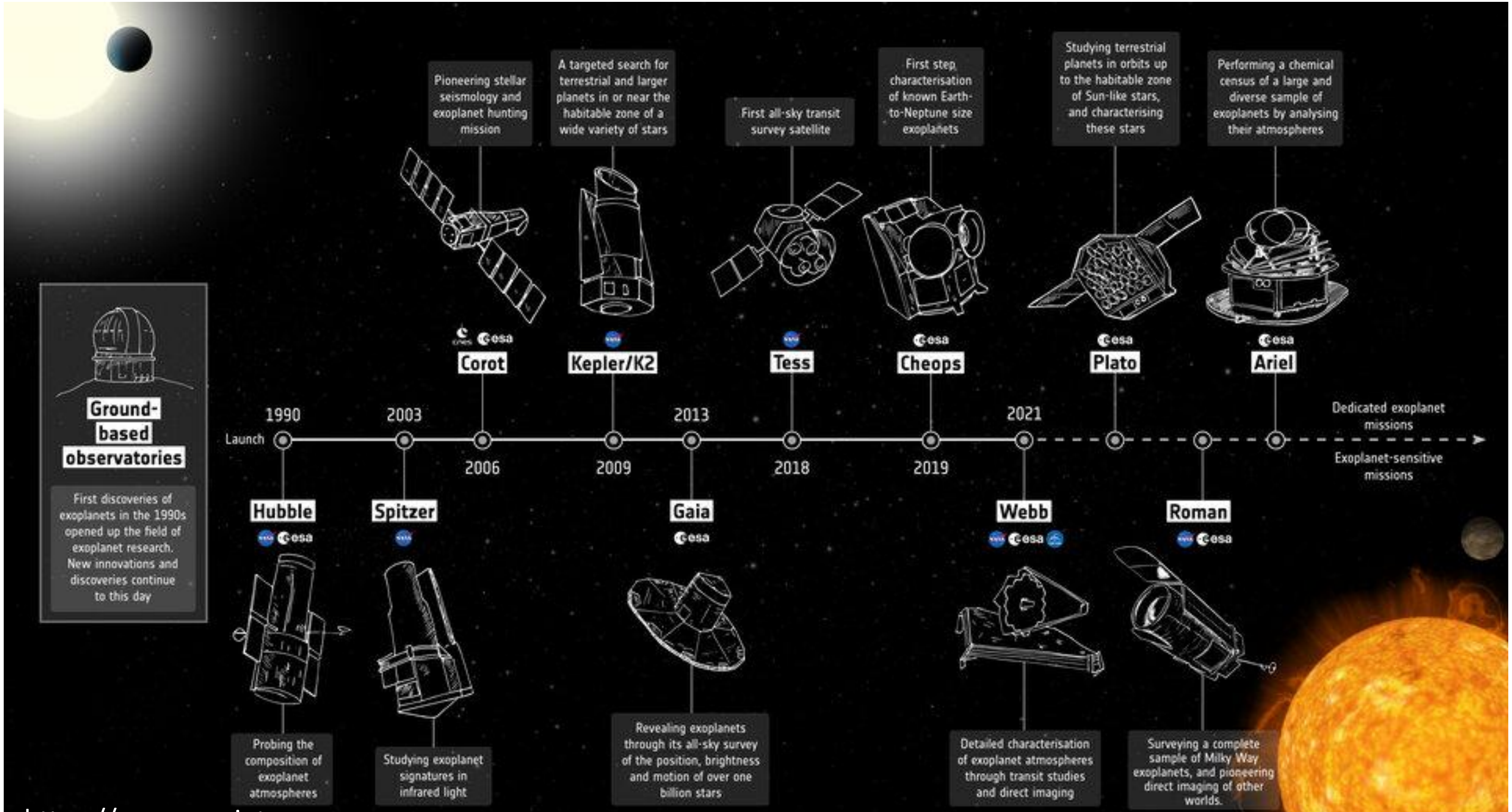
Discovery of exoplanets using transits

Today



The future

Discovery of exoplanets using transits

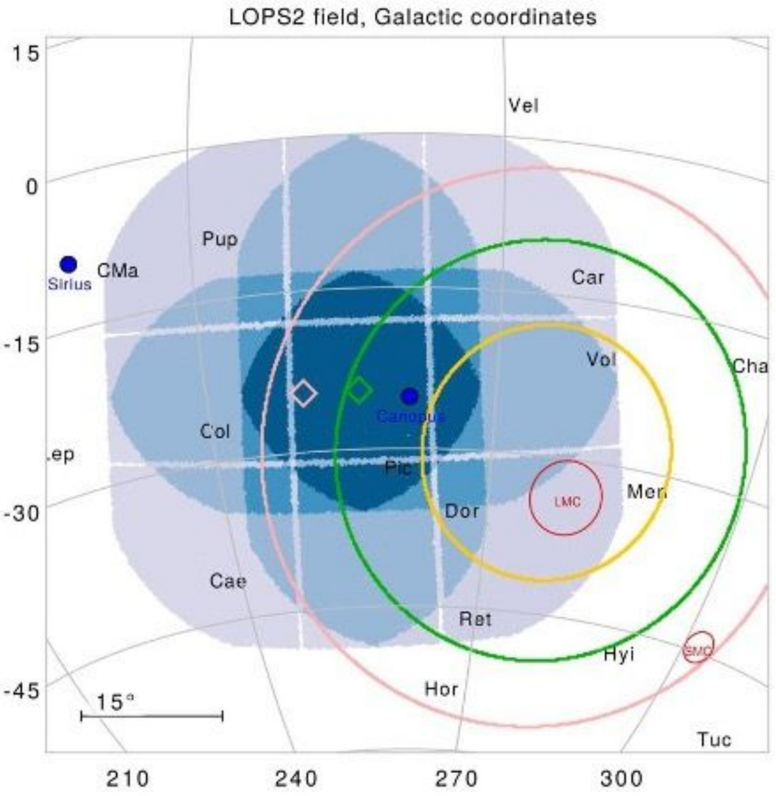


https://www.esa.int

Discovery of exoplanets using transits

Plato: Planetary Transits and Oscillations

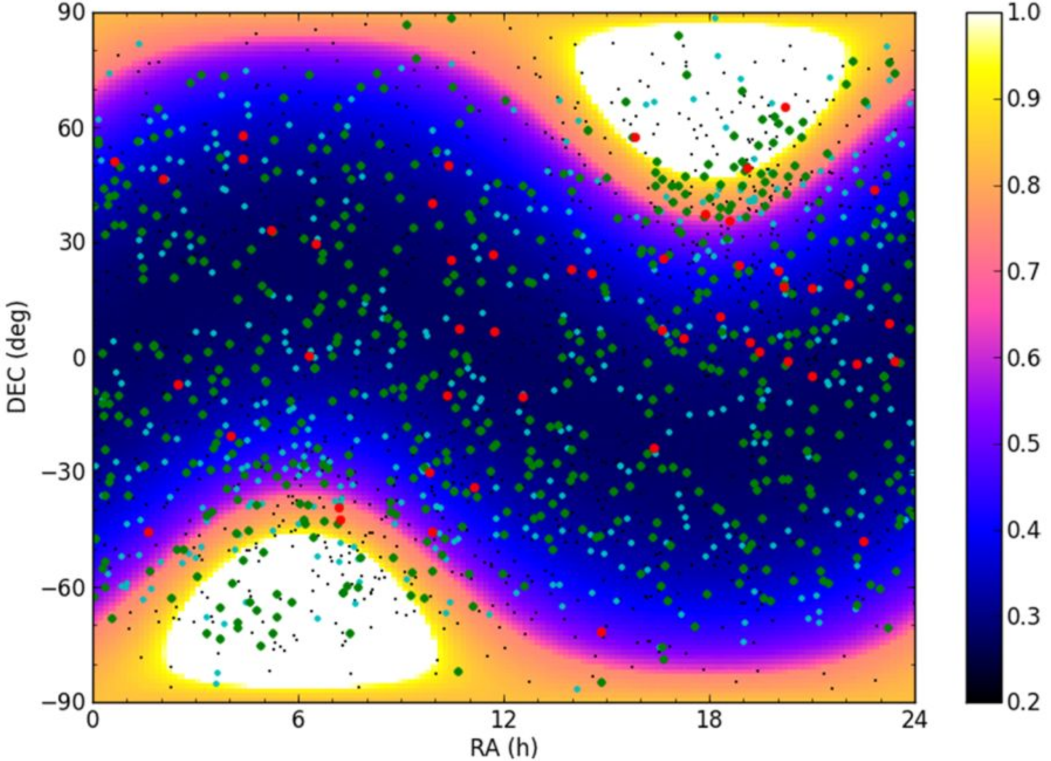
- ESA M3 mission, expected launch in 2026
- Goal:
  - → Discover and characterize hundreds of exoplanets
  - → Focus on Earth twins
- L2 orbit, 4.5 years (extension up to 8.5 years)
- 26x 12cm cameras
- Field of view: 49x49 deg
  - → LOPS2 field selected (Nascimbeni et al. 2022)
  - → Strategy to be defined



Discovery of exoplanets using transits

Ariel: Atmospheric Remote-sensing Infrared Exoplanet Large-survey

- ESA M4 mission, expected launch in 2029
- Goal:
  - → ~1000 known planets
  - → statistical survey of atmospheres
- L2 orbit, 3.5 years (+ extension)
- 1 meter class telescope

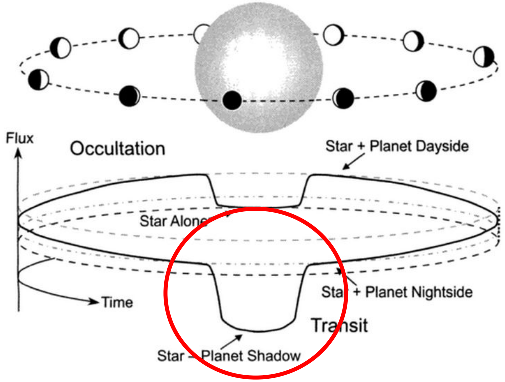


Discovery of exoplanets using transits

Ariel: Atmospheric Remote-sensing Infrared Exoplanet Large-survey

- Methodology: broad-band & low resolution spectroscopy
- 0.5 - 8 μm

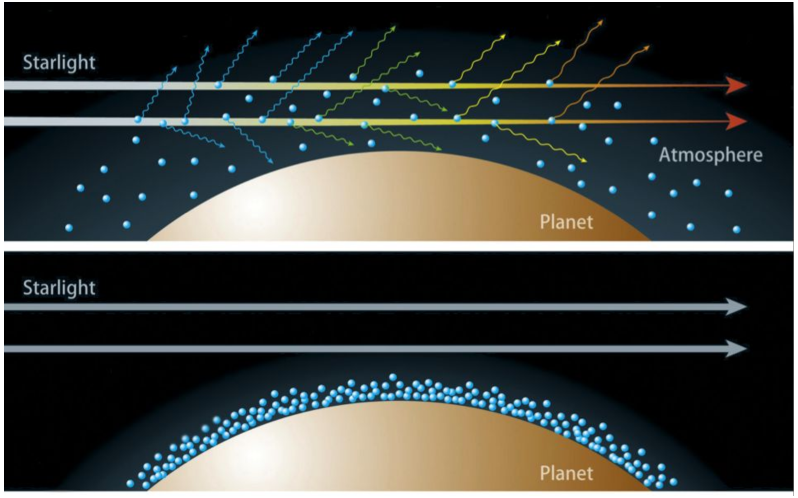
  → transmission: properties and composition at terminator

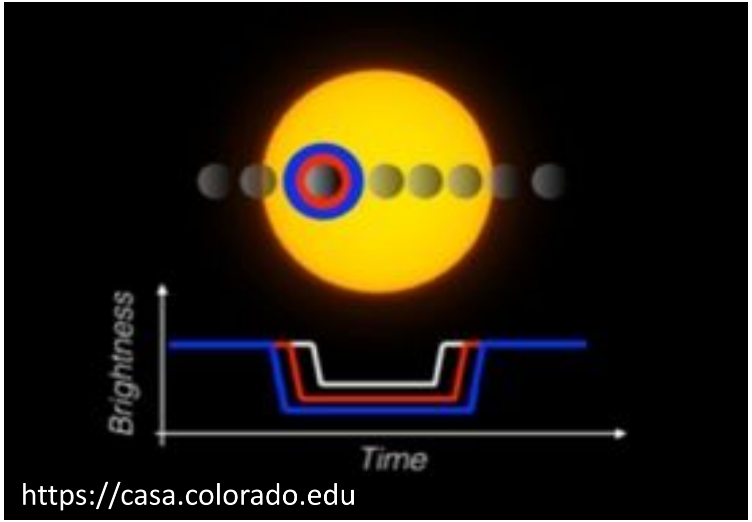


$$\Delta\delta = \frac{\pi(R_p + N_H H)^2}{\pi R_\star^2} - \frac{\pi R_p^2}{\pi R_\star^2} \approx 2N_H\delta\left(\frac{H}{R_p}\right)$$

pressure scale height

$$H = \frac{kT}{\mu m_H g}$$

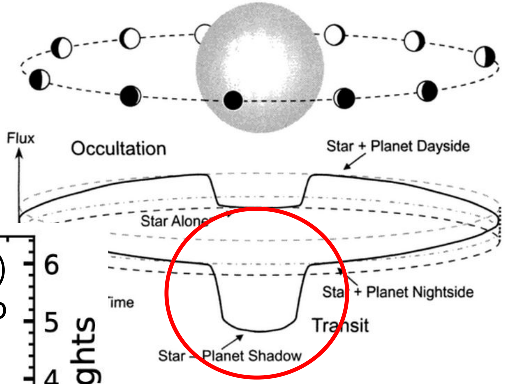


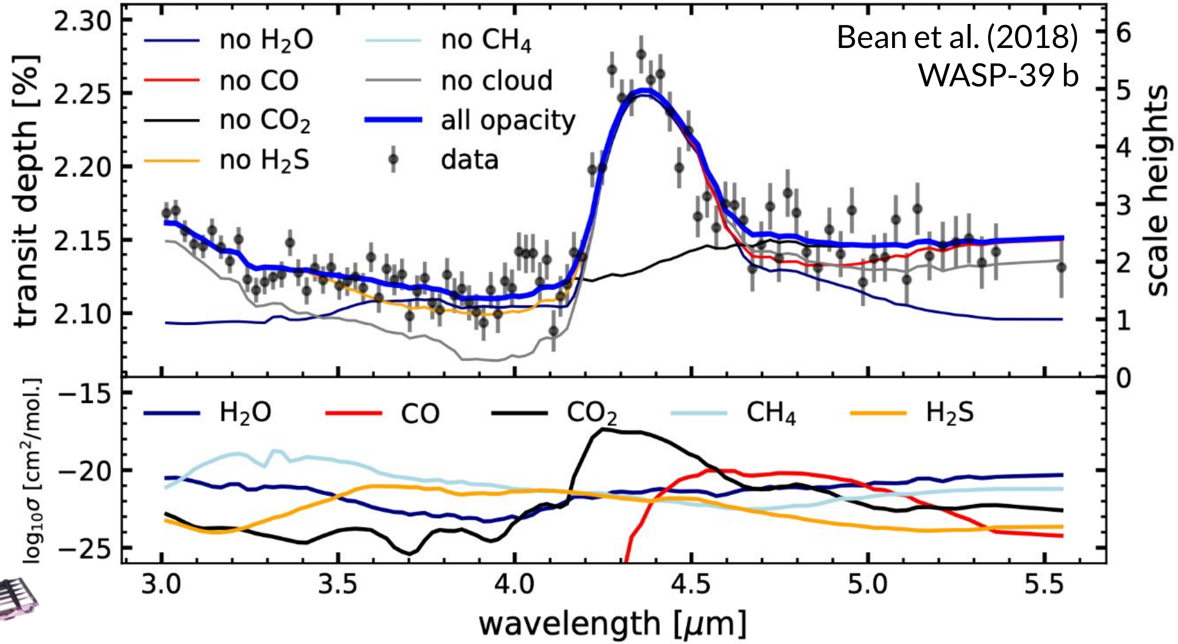


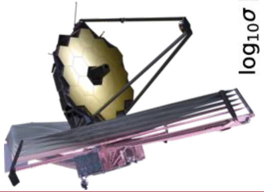
Discovery of exoplanets using transits

Exoplanet spectroscopy

- High & low resolution (Lisa's talk tomorrow):
  → transmission: properties and composition at terminator



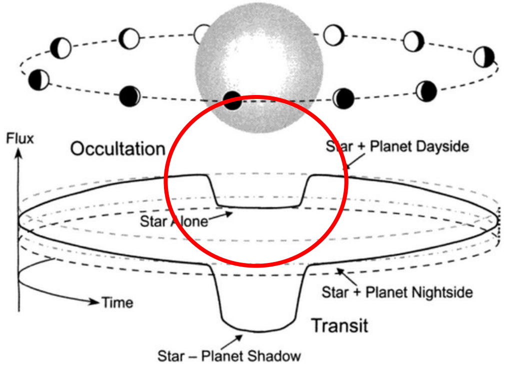


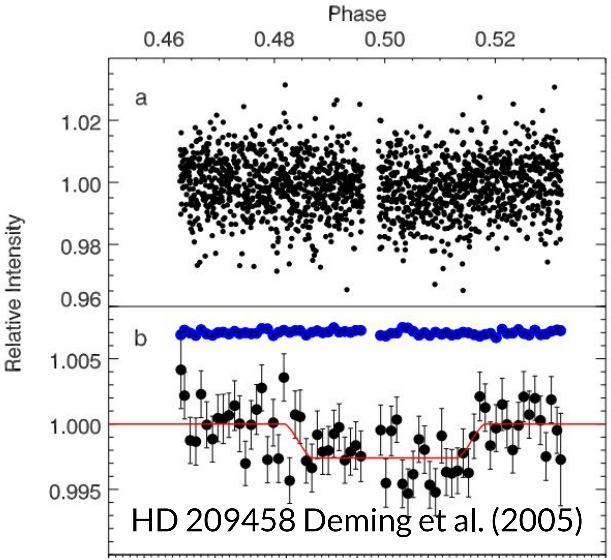


Discovery of exoplanets using transits

Exoplanet spectroscopy

- High & low resolution (Lisa's talk tomorrow):
  - → transmission: absorption at terminator
  - → emission: dayside spectra
    - VIS → reflected light (albedo)
    - NIR → thermal emission (planet temperature)





HD 209458 Deming et al. (2005)

First detection of the light from an exoplanet

$T_{dayside} = 1130$ K

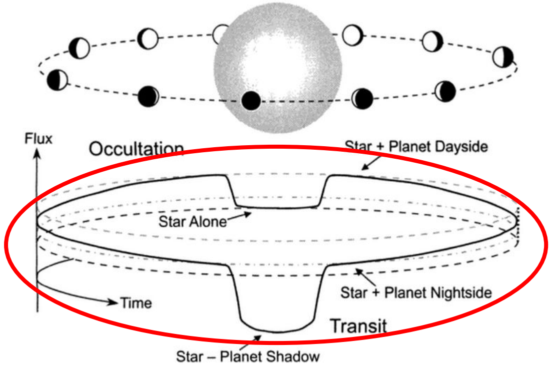
Spitzer space telescope:

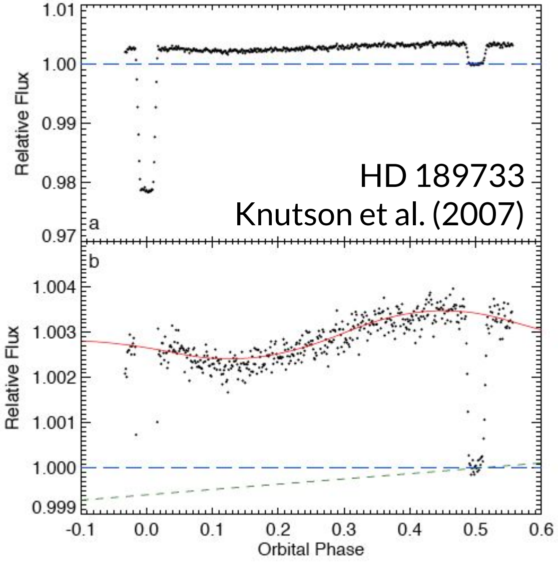
- 3.6 - 40 μm
- Broadband and spectra

Discovery of exoplanets using transits

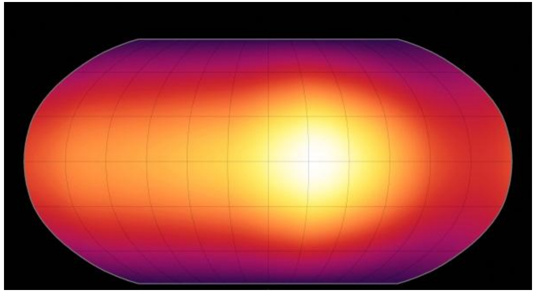
Exoplanet spectroscopy

- High & low resolution (Lisa’s talk tomorrow):
  - → transmission: absorption at terminator
  - → emission: dayside reflection/emission
  - → phase curve: atmosphere circulation





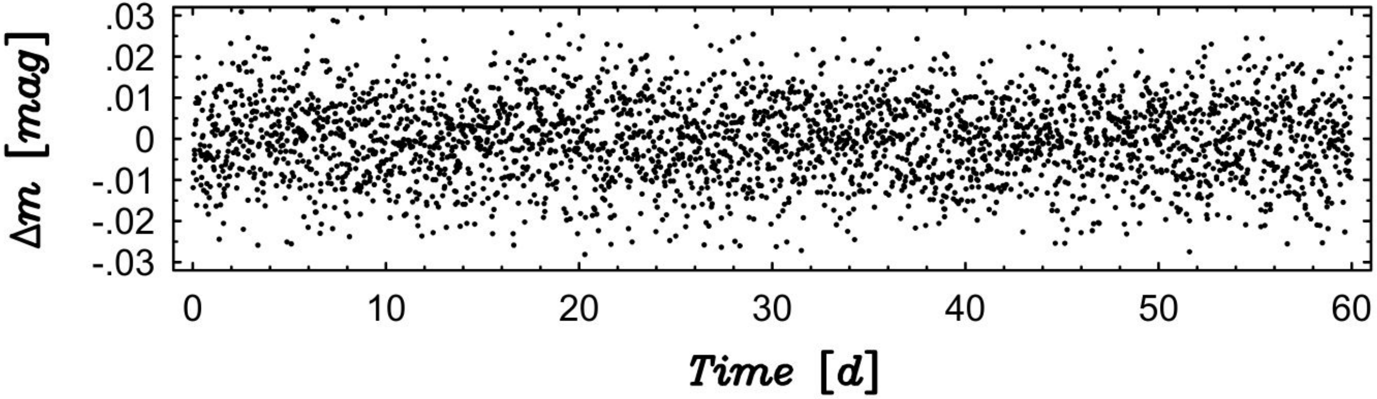
→ Albedo
→ Temperature maps
→ Atmosphere circulation



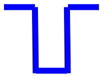
Discovery of exoplanets using transits

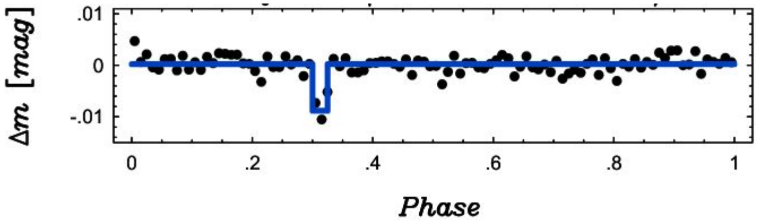
Detection of exoplanets transits in time series

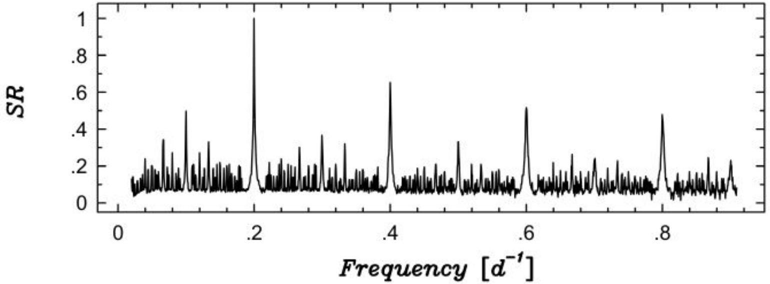
- Search for periodic box-shape signals consistent with transits
  → **BLS code** (Kóvacs et al 2002) or variants



- A transit has approximately a box-shape:
  → 4 parameters: epoch, periodicity, depth, width



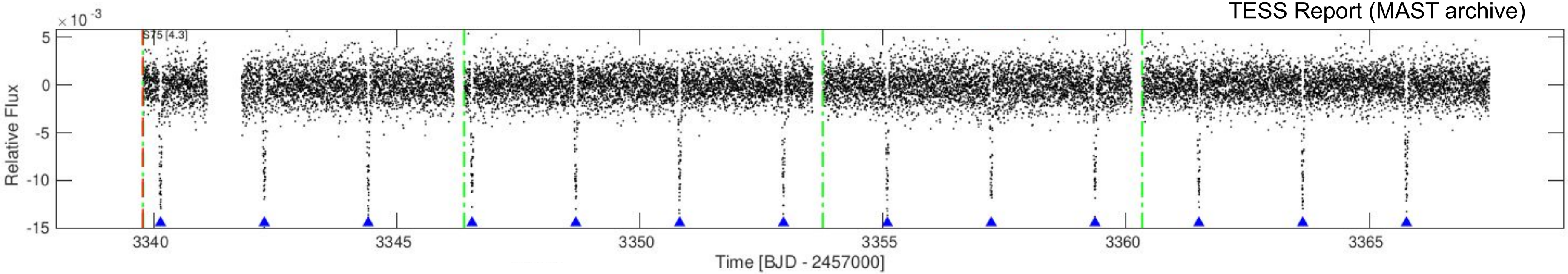




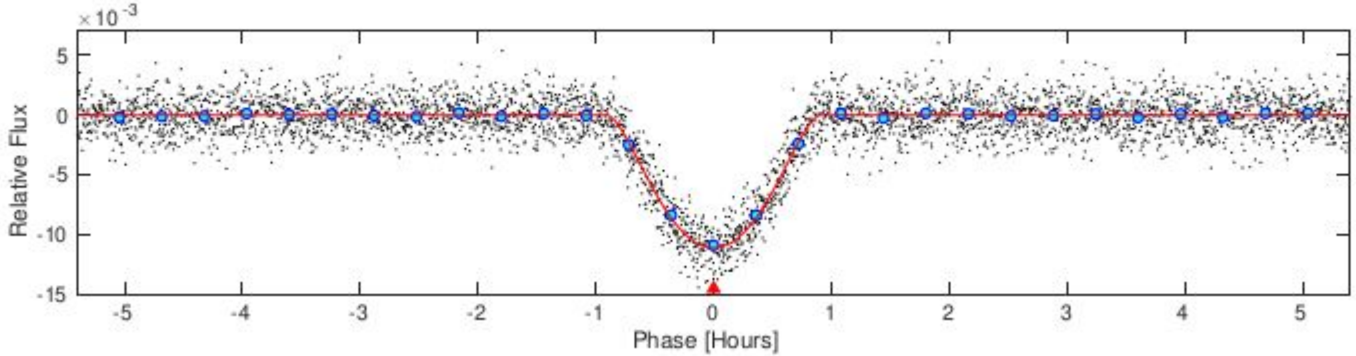
Discovery of exoplanets using transits

Challenges of exoplanet transits

TESS Report (MAST archive)



Are these transits due to a planet?

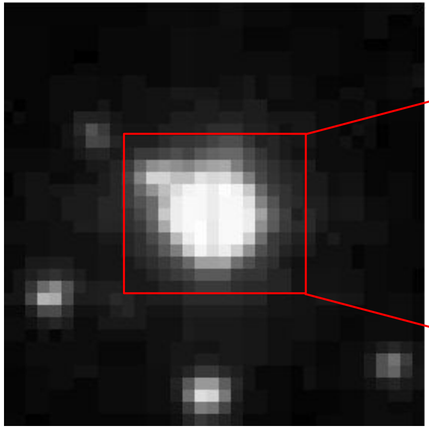


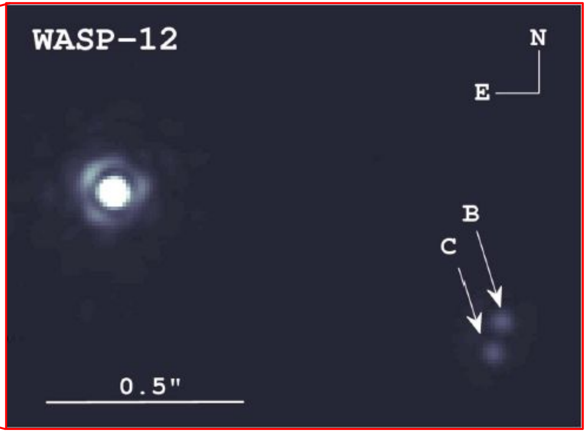
Discovery of exoplanets using transits

Challenges of exoplanet transits: false positives

Not all detected transit-like features are due to transiting planets.

- Usually in the field of view, there are other stars → blends





AO Image, Bechter et al. (2013)

- Photometric time series correspond to the integration of the light of all stars in the aperture.

$$L = L_A + L_B + L_C + \ldots$$

→ From which one comes the transit?

Discovery of exoplanets using transits

Challenges of exoplanet transits: false positives

False positive cases

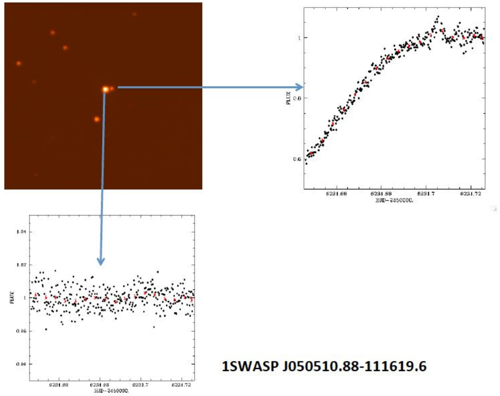
- Background eclipsing binary

$$L = L_{EB} + L_3$$

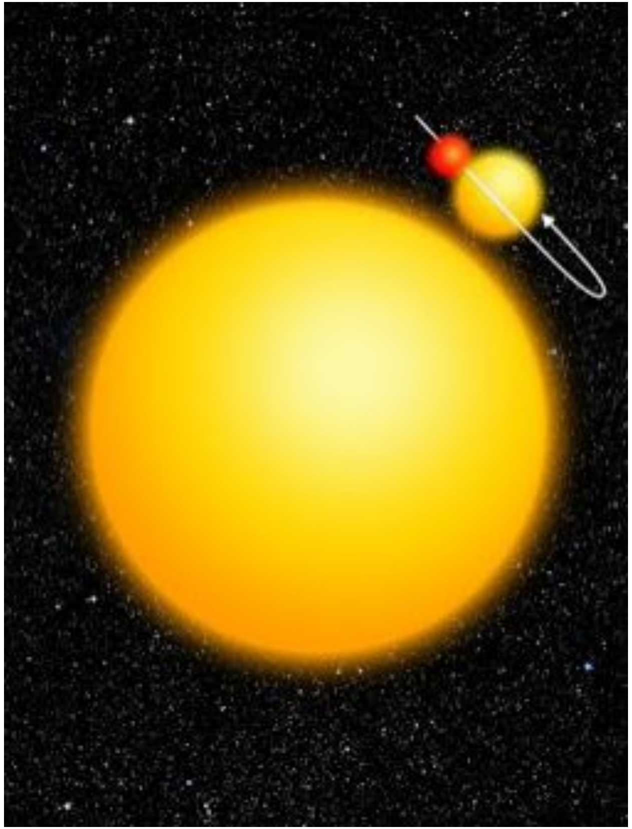
Diluting factor L_3/L → eclipses of the binary are shallower!

Solution!

→ Photometry at higher spatial resolution



1SWASP J050510.88-111619.6



Discovery of exoplanets using transits

Challenges of exoplanet transits: false positives

False positive cases

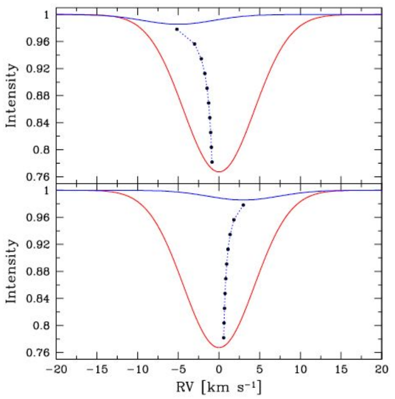
- **Aligned** background eclipsing binary

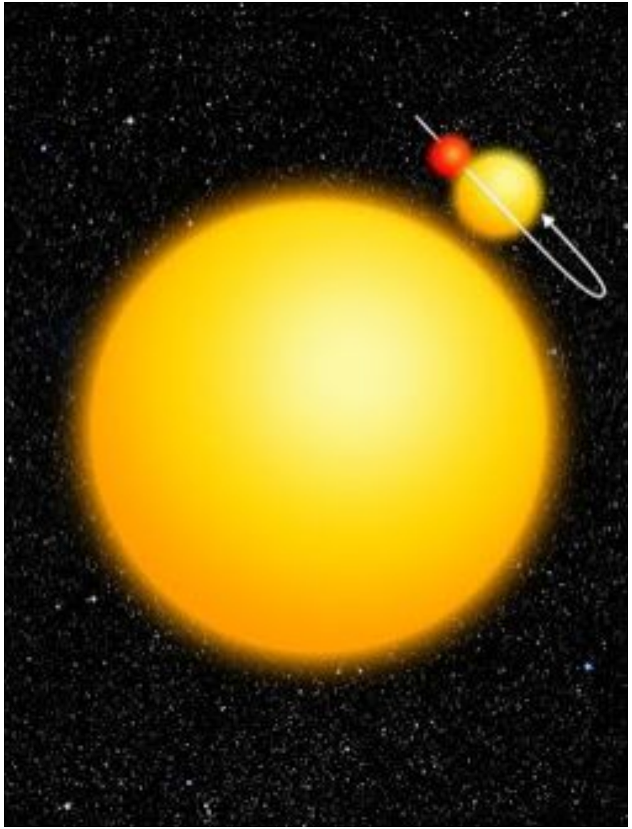
$$L = L_{EB} + L_3$$

Diluting factor L_3/L → eclipses of the binary are shallower!

Solution!

→ Spectroscopic follow-up (bisector variability)





Discovery of exoplanets using transits

Challenges of exoplanet transits: false positives

False positive cases

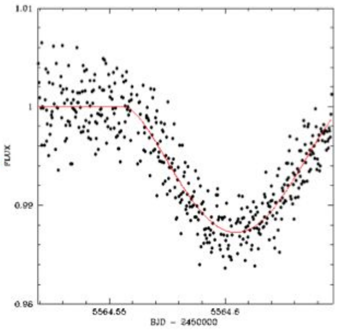
- <u>Grazing eclipsing binary</u>

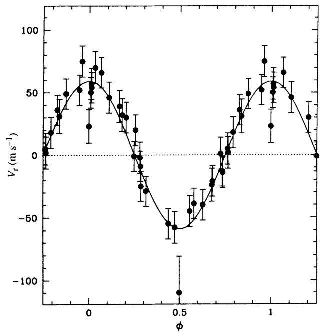
→ Shallow eclipses similar to exoplanet transits!

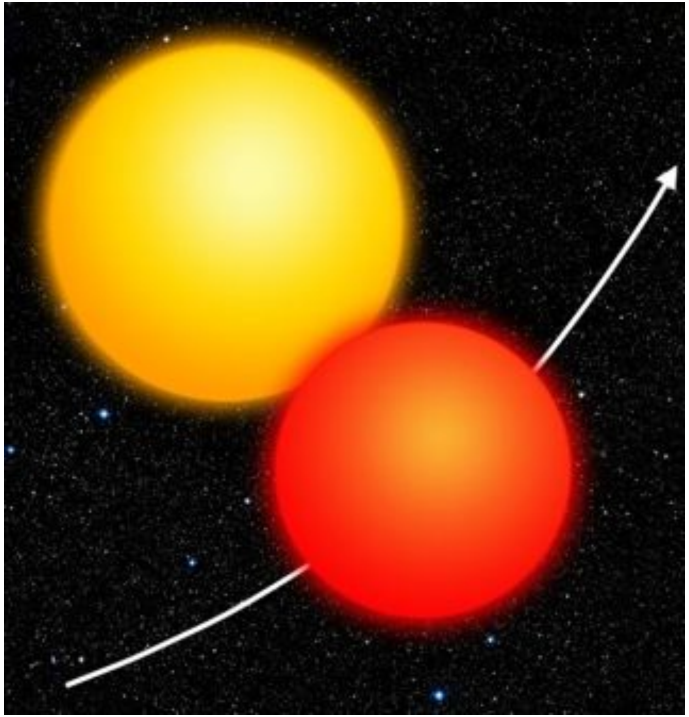
Solution!

→ High-precision photometry (eclipse shape)

→ Doppler spectroscopy (mass estimation)





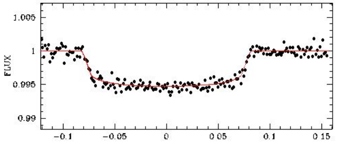


Discovery of exoplanets using transits

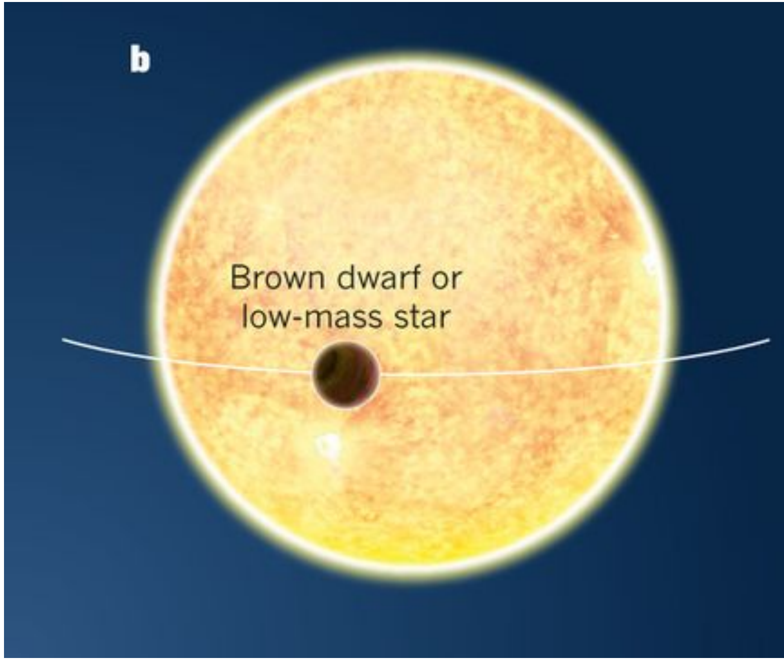
Challenges of exoplanet transits: false positives

False positive cases

- Eclipses of objects with small light ratio



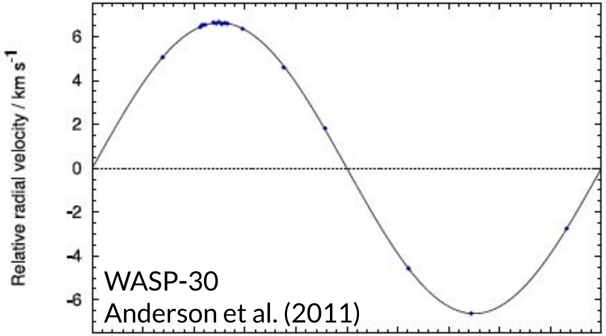
→ Eclipses similar to exoplanet transits!



Solution!

→ Doppler spectroscopy (mass estimation)

→ Occultation high-precision photometry



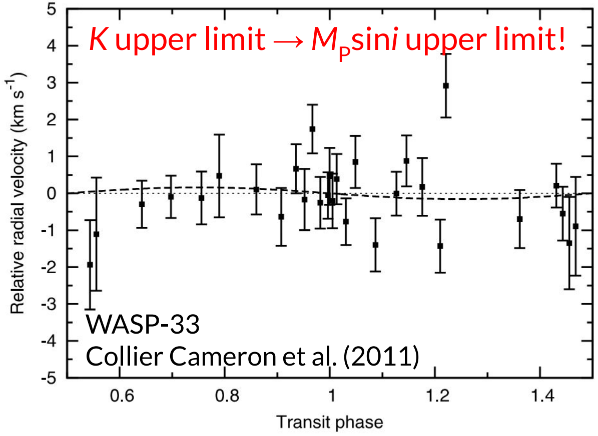
Discovery of exoplanets using transits

Challenges of exoplanet transits: false positives

- Precise RV's are sometimes challenging
  → faint stars
  → massive stars
  → fast rotating stars
  → low-mass planets

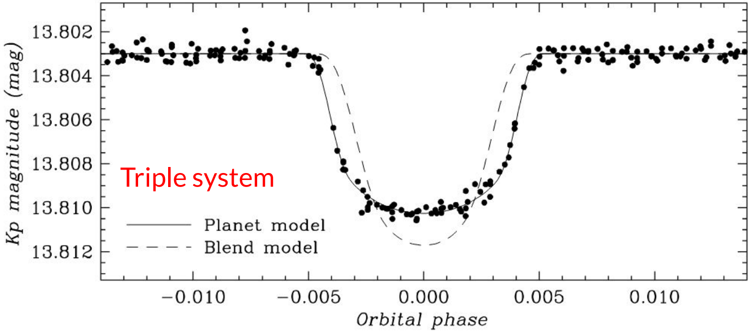
RV limits

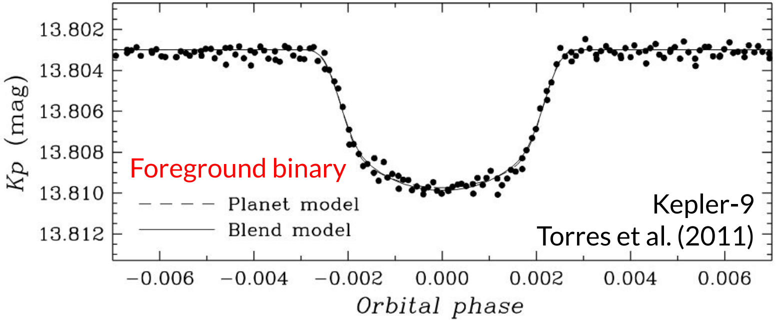
→ Companion mass limits from spectroscopy (RVs)



Model comparison

→ Compare planet and false positive fits
(BLENDER, Torres et al. 2004)





Discovery of exoplanets using transits

Challenges of exoplanet transits: false positives

- Precise RV's are sometimes challenging
  - → faint stars
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  - → low-mass planets

Alternatives!

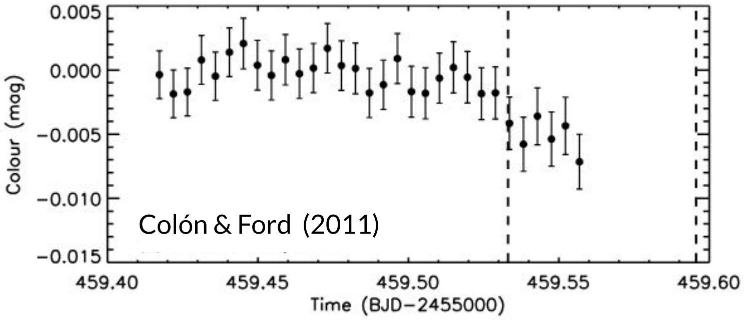
→ Companion mass limits from spectroscopy (RVs)

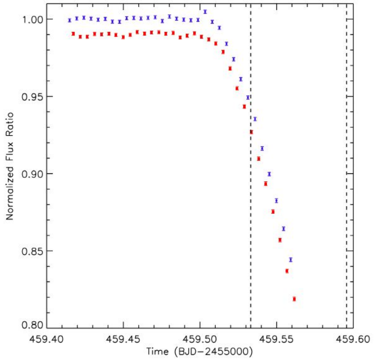
→ Model comparison
(BLENDER, Torres et al. 2004)

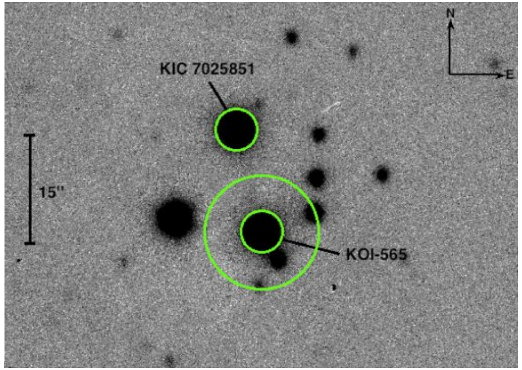
→ Precise multicolor photometry

Precise multicolor photometry

(Tingley et al. 2004)







Discovery of exoplanets using transits

Challenges of exoplanet transits: false positives

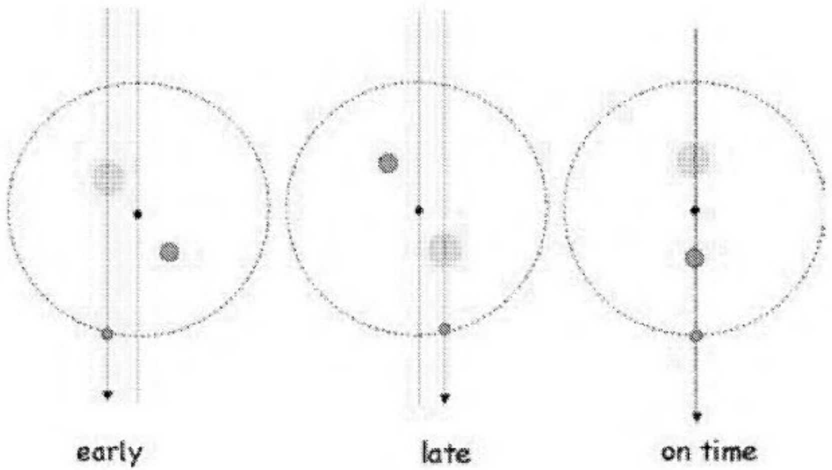
- Precise RV's are sometimes challenging
  - → faint stars
  - → massive stars
  - → fast rotating stars
  - → low-mass planets

Alternatives!

→ Companion mass limits from spectroscopy (RVs)
→ Model comparison
(BLENDER, Torres et al. 2004)
→ Precise multicolor photometry
→ Planet mass determination by other means
Transit time variations (multiple systems)

Transit time variations

(Agol et al. 2005, Holman et al. 2005)



→ masses for multiple planets systems

$$\Delta t \sim a_\star \sim M_P/M_\star$$

→ dynamical interaction

Discovery of exoplanets using transits

Challenges of exoplanet transits: false positives

- Precise RV's are sometimes challenging
  - → faint stars
  - → massive stars
  - → fast rotating stars
  - → low-mass planets

Alternatives!

→ Companion mass limits from spectroscopy (RVs)
→ Model comparison
(BLENDER, Torres et al. 2004)
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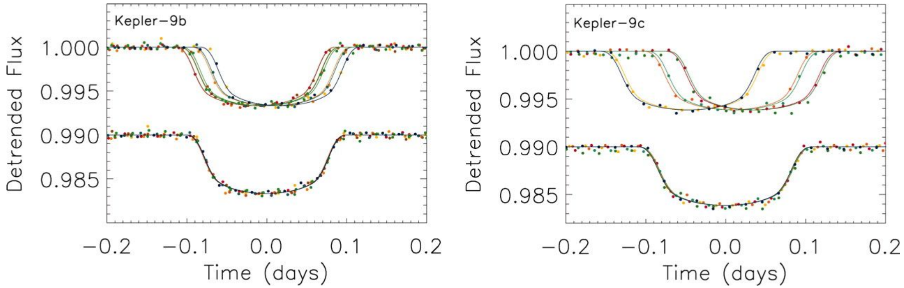
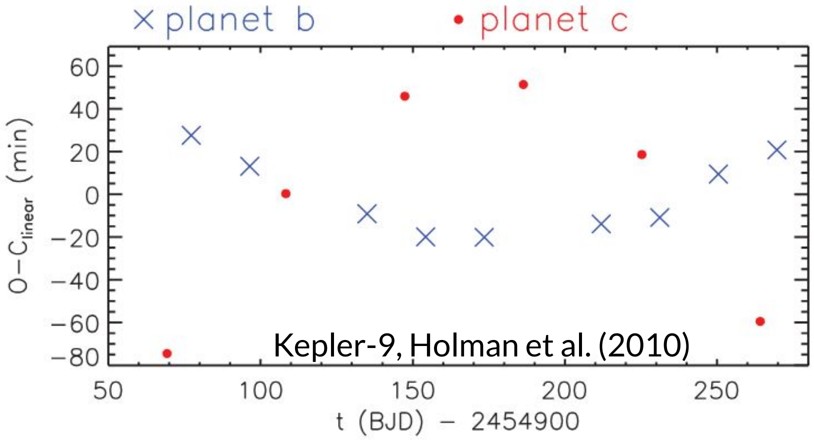
Transit time variations

(Agol et al. 2005, Holman et al. 2005)





Kepler-9, Holman et al. (2010)

Discovery of exoplanets using transits

Challenges of exoplanet transits: false positives

- Precise RV's are sometimes challenging
  - → faint stars
  - → massive stars
  - → fast rotating stars
  - → low-mass planets

Alternatives!

→ Companion mass limits from spectroscopy (RVs)
→ Model comparison
(BLENDER, Torres et al. 2004)
→ Precise multicolor photometry
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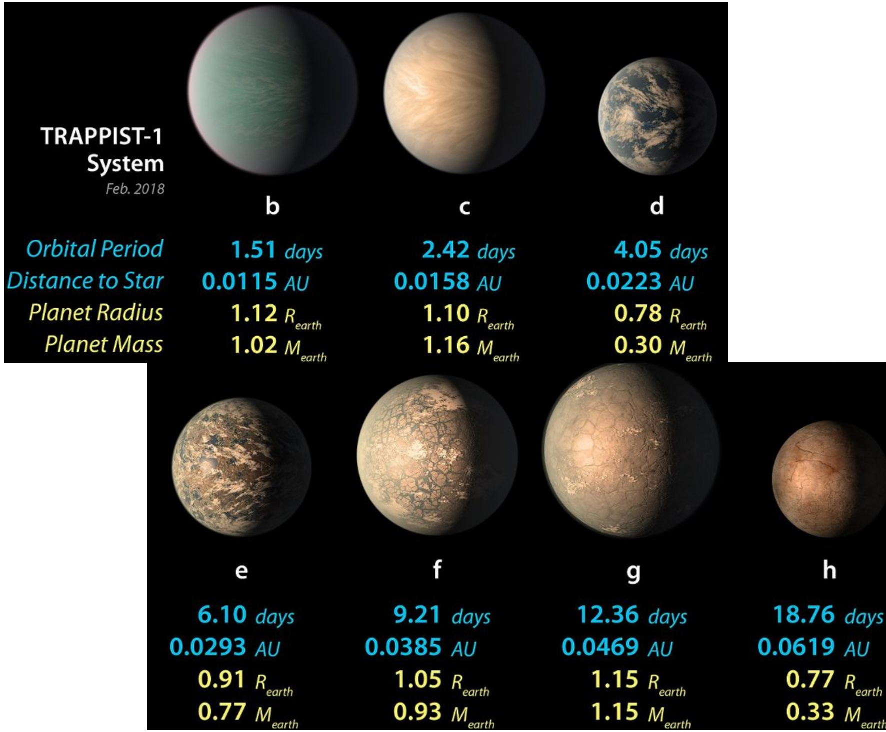
Transit time variations (multiple systems)

Transit time variations

→ Interesting case: TRAPPIST-1
(Gillon et al. 2016, 2017)

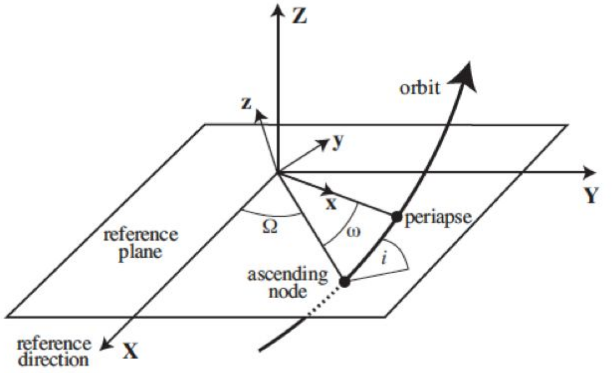


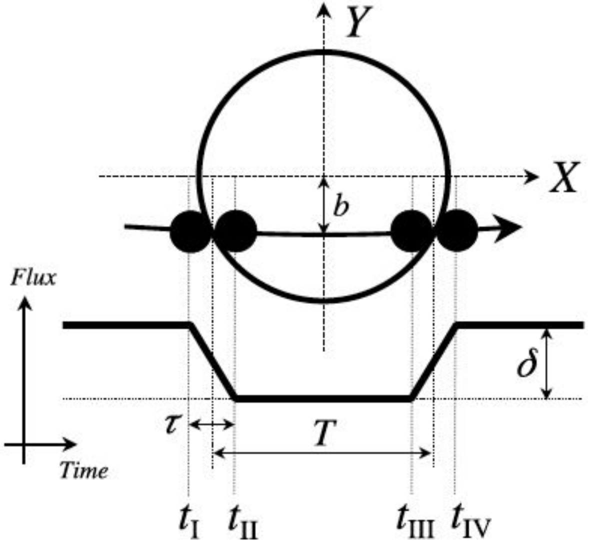
Discovery of exoplanets using transits

Information from transits/occultations

Assumptions:

- Longitude of ascending node Ω unknown
  → Ω=180 deg
- X-axis is the reference axis.
- Spherical bodies





$$r = \frac{a(1-e^2)}{1+e\cos f}$$

$$X = -r\cos(\omega + f)$$

$$Y = -r\sin(\omega + f)\cos i$$

$$Z = r\sin(\omega + f)\sin i$$

$$r_{sky} = r\sqrt{1-\sin^2(\omega + f)\sin^2 i}$$

Discovery of exoplanets using transits

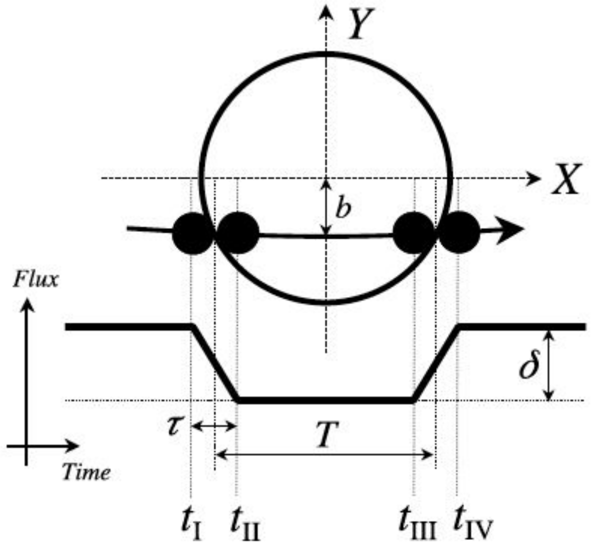
Information from transits/occultations

- Transit time, when X=0 at inferior conjunction
  → impact parameter ($b=r_{sky}/R_\bigstar$) is:

$$f_{\rm tra} = +\frac{\pi}{2} - \omega \qquad b_{\rm tra} = \frac{a\cos i}{R_\star}\left(\frac{1-e^2}{1+e\sin\omega}\right)$$

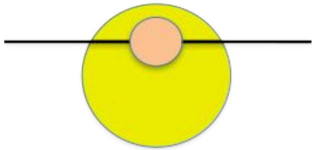
- Occultation time, when X=0 at superior conjunction
  → impact parameters ($b=r_{sky}/R_\bigstar$) is

$$f_{\rm occ} = -\frac{\pi}{2} - \omega \qquad b_{\rm occ} = \frac{a\cos i}{R_\star}\left(\frac{1-e^2}{1-e\sin\omega}\right)$$



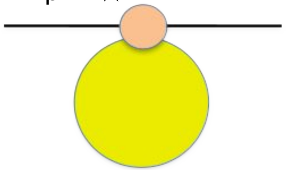
Full transit/occultation

$b \leq 1-R_p/R_\bigstar$



Grazing transit/occultation

$1-R_p/R_\bigstar \leq b \leq 1+R_p/R_\bigstar$



Discovery of exoplanets using transits

Information from transits/occultations

From first (I), second (II), third (III), and fourth (IV) contacts:

- Total transit/occultation duration (t_{IV}-t_I)

$$W = \frac{P}{\pi}\sin^{-1}\left[\frac{R_\star}{a}\frac{\sqrt{(1+k)^2-b^2}}{\sin i}\right]\frac{\sqrt{1-e^2}}{1\pm e\sin\omega}$$

- Full transit/eclipse duration (t_{III}-t_{II})

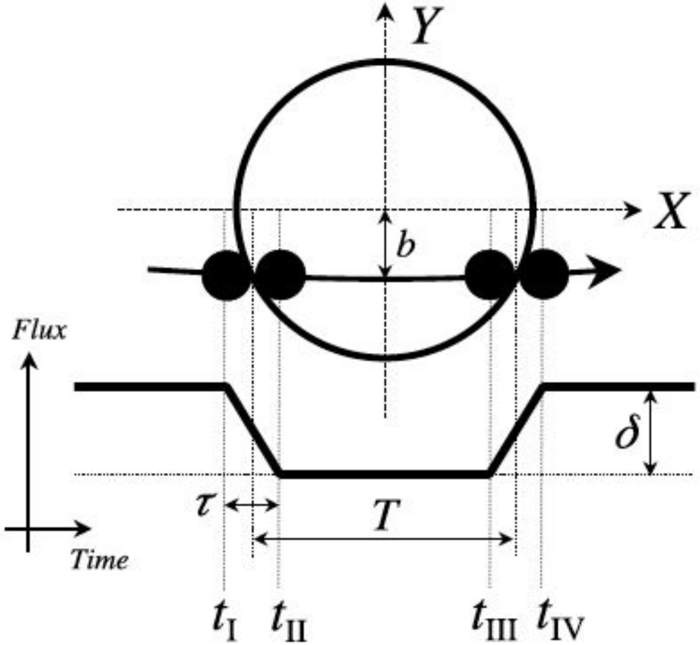
$$\frac{P}{\pi}\sin^{-1}\left[\frac{R_\star}{a}\frac{\sqrt{(1-k)^2-b^2}}{\sin i}\right]\frac{\sqrt{1-e^2}}{1\pm e\sin\omega}$$

$k = R_p/R_\star$
+ → transit
– → occultation

- Information of k, b, e, ω
- Information of P if multiple transits are available
- Density of the star from Kepler's third law

$a/R_\star = f\,(W/P, b, e, \omega)$

$$a^3 = \left(\frac{P^2GM_*}{4\pi^2}\right) \longrightarrow \frac{a^3}{R_*^3} = \left(\frac{P^2GM_*}{4\pi^2}\right)\frac{1}{R_*^3} = \left(\frac{P^2G}{3\pi}\right)\frac{\rho_*}{\rho_{sun}}$$

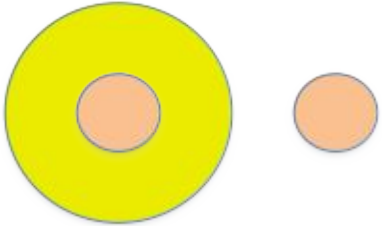


Discovery of exoplanets using transits

Information from transits/occultations

From the transit/occultation depth:
(assuming uniform disks)

- Flux out-of-transit/occultation
  $F_{out} = f_{\star} A_{\star} + f_P A_P$
- Flux in transit
  $F_{tra} = f_{\star} A_{\star} + f_P A_P - f_{\star} A_P$
- Flux in occultation
  $F_{occ} = f_{\star} A_{\star}$



- Transit depth

$$\delta_{tra} = 1 - \frac{F_{tra}}{F_{out}} = \frac{f_* R_P^2}{f_* R_*^2 + f_P R_P^2} \qquad \delta_{tra} = \frac{R_P^2}{R_*^2}$$

- Occultation depth depth

$$\delta_{occ} = 1 - \frac{F_{occ}}{F_{out}} = 1 - \frac{f_* R_*^2}{f_* R_*^2 + f_P R_P^2} \qquad \delta_{occ} = \frac{f_P R_P^2}{f_* R_*^2}$$

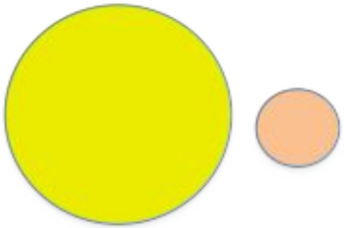
If $f_{\star} R_{\star}^2 >> f_P R_P^2$

$$\frac{1}{1 + \frac{f_P R_P^2}{f_* R_*^2}} \sim 1 - \frac{f_P R_P^2}{f_* R_*^2}$$

Discovery of exoplanets using transits

Information from transits/occultations

From the transit/occultation depth:
(assuming uniform disks)



- Transit depth

$$\delta_{tra} = \frac{R_P^2}{R_*^2}$$

- Occultation depth depth

$$\delta_{occ} = \frac{f_P R_P^2}{f_* R_*^2}$$

From δ_{tra} radius ratio
- If $R_\star$ is known $\rightarrow R_P$

From δ_{tra} and δ_{occ}
- If $f_\star$ is known $\rightarrow f_P$ (planet spectrum)

Discovery of exoplanets using transits

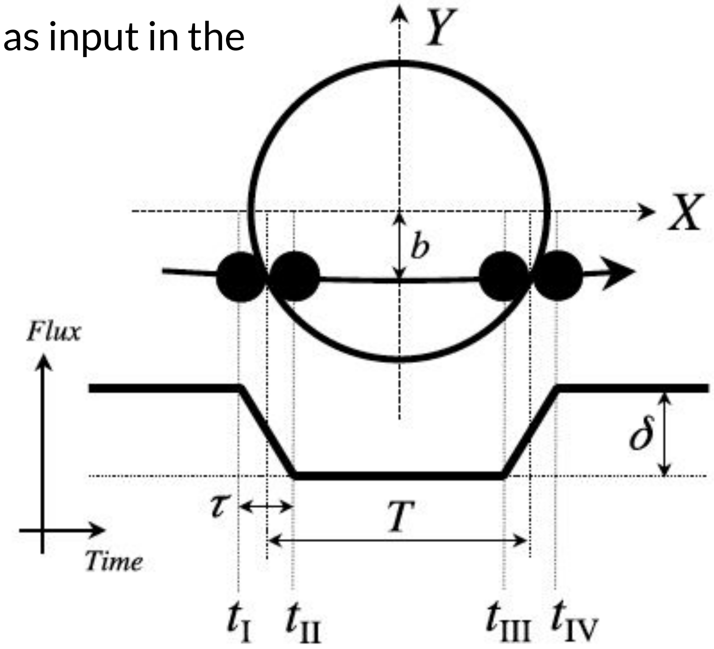
Physical parameters of the planet

- Transits provide $R_P/R_\star$, $a/R_\star$, and $\rho_\star$. How to obtain the individual parameters?

$$a^3 = \left(\frac{P^2GM_*}{4\pi^2}\right)$$

Option 1: independent spectroscopic analysis provides T_{eff}, [Fe/H], and logg. Analysis based on stellar evolution models gives $M_\star$.

Option 2: after (or during) the analysis of the transits, $\rho_\star$ is added as input in the determination of $M_\star$ from stellar evolution models.



Discovery of exoplanets using transits

Physical parameters of the planet

$$a^3 = \left(\frac{P^2 G M_*}{4\pi^2}\right)$$

- Transits provide $R_P/R_\bigstar$, $a/R_\bigstar$, and $\rho_\bigstar$. How to obtain the individual parameters?

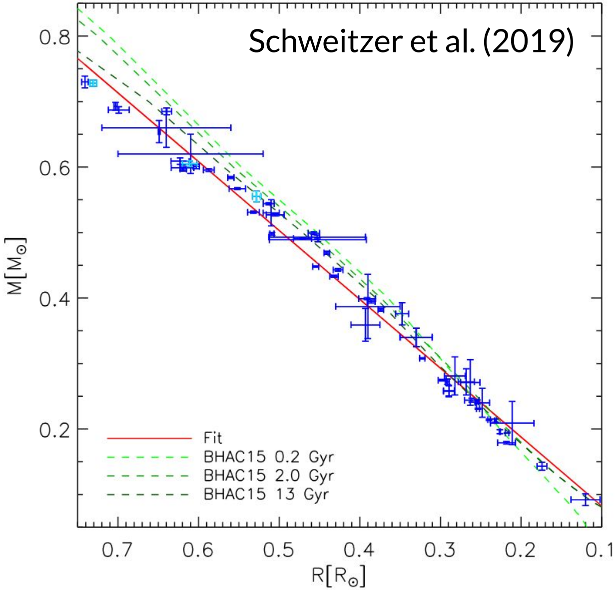
Option 1: independent spectroscopic analysis provides T_{eff}, [Fe/H], and logg. Analysis based on stellar evolution models gives $M_\bigstar$.

Option 2: after (or during) the analysis of the transits, $\rho_\bigstar$ is added as input in the determination of $M_\bigstar$ from stellar evolution models.

Option 3: same as option 1 and 2, but stellar evolution models are replaced by empirical laws $M_\bigstar(T_{eff}$, [Fe/H], logg) or $M_\bigstar(T_{eff}$, [Fe/H], $\rho_\bigstar)$, or $M_\bigstar(R_\bigstar)$ or $M_\bigstar(L_\bigstar)$ (e.g. Torres et al. 2010, Schweitzer et al. 2019).

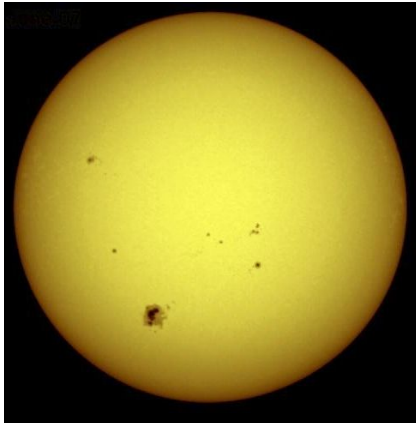
Option 4: determination of $R_\bigstar$ by interferometry or with luminosity + parallax + T_{eff} (nearby star)
$\rightarrow \rho_\bigstar$ from the transits is then used to determine $M_\bigstar$

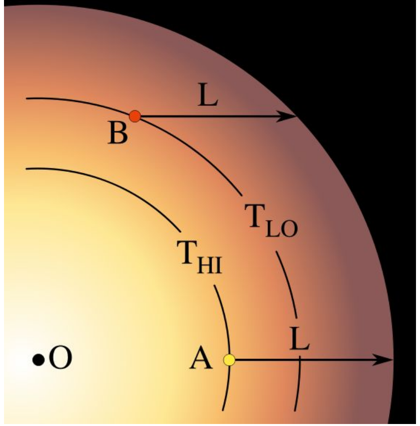
Option 5: if $\rho_\bigstar$ is poorly constrained by transits (low SNR, small planet), a priori values are assumed for $M_\bigstar$ and $R_\bigstar$, or a measurement of $\rho_\bigstar$ obtained by asteroseismology is used.



Discovery of exoplanets using transits

Limb darkening



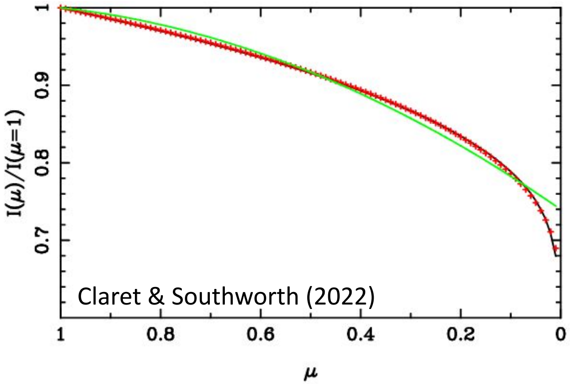


- The intensity of the star is different across the star
- At the center, emission comes from hotter deeper layers → intensity is larger

- Parameterized as a function of the angle of incidence using power laws

$$\frac{I(\mu)}{I(1)} = 1 + \sum_{k=1}^{N} c_k (1-\mu)^k \qquad \frac{I(\mu)}{I(1)} = 1 + \sum_{n=1}^{N} c_n \left(1-\mu^{n/2}\right) \qquad \mu = \cos\varphi$$

- Intensity ∝ $1/\lambda^4$
  → limb darkening effect decreases with λ
- For exoplanets: typically quadratic (k=2) or 4 parameters (n=4)



Claret & Southworth (2022)

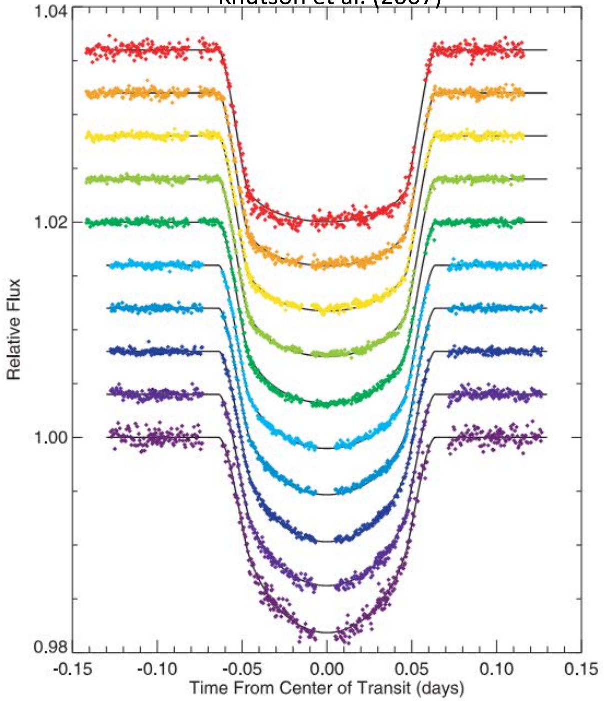
- Bibliography:
  - Southworth (2023): limb darkening laws

Discovery of exoplanets using transits

Limb darkening

- Consequence for transits: the drop of brightness varies with μ
  → δ_{tra} is larger than k^2 near the center, smaller near the limb

Knutson et al. (2007)



Solution

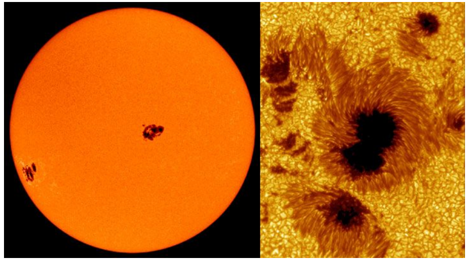
- Assume limb darkening law from tables
  → Claret (2000, 2004, 2012, 2017, 2022…)
  → Sing (2010)
  → …

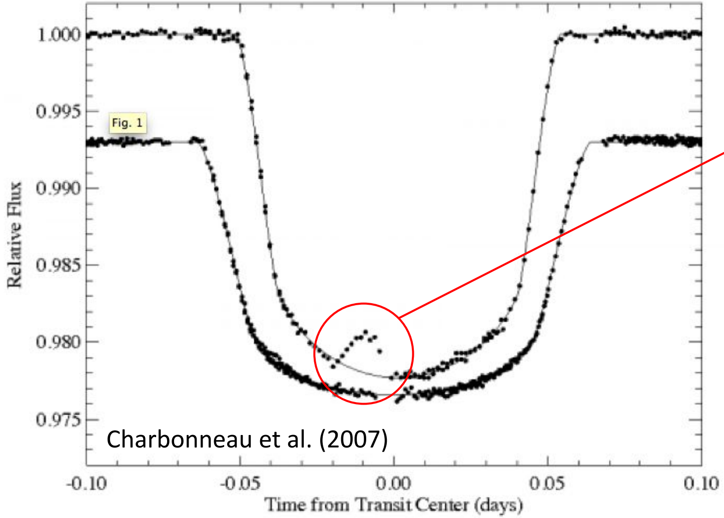
- Very precise photometry
  → add the parameters to the fit

Discovery of exoplanets using transits

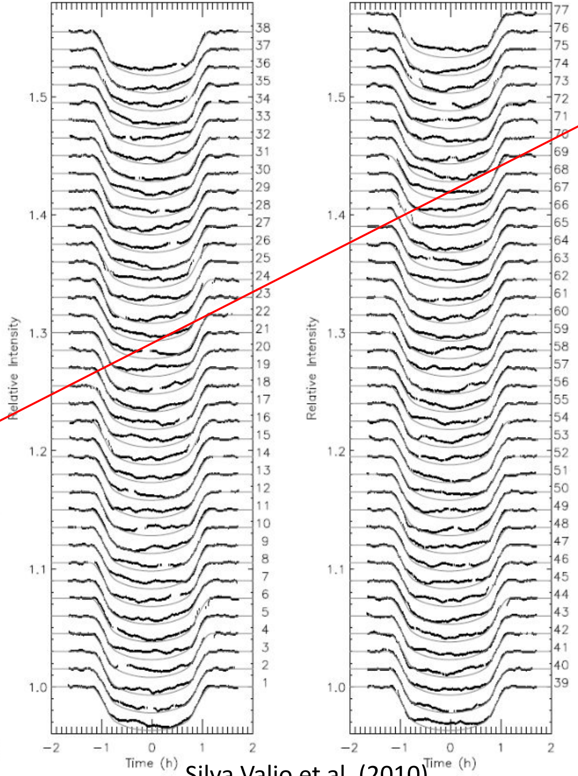
Stellar spots

- Other effects affecting the shape of eclipse: stellar activity



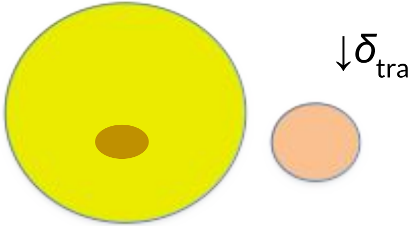


Charbonneau et al. (2007)



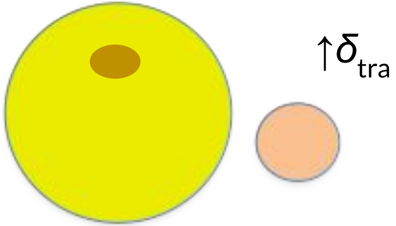
Silva Valio et al. (2010)

Occulted spots



$$F_{out} = f_\bigstar(A_\bigstar - A_S) + f_S A_S$$
$$F_{tra} = f_\bigstar A_\bigstar - f_\bigstar A_P$$

Unocculted spots

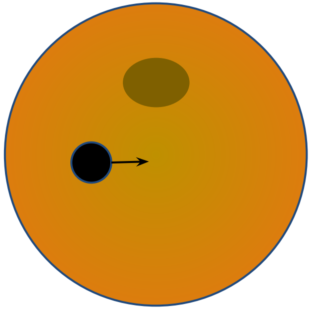


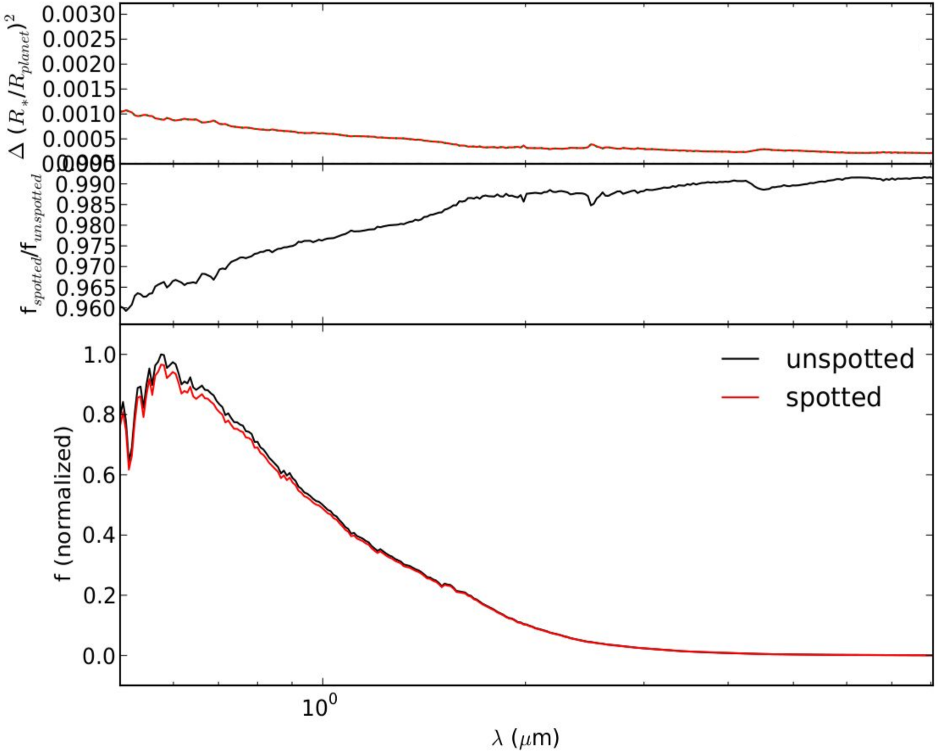
$$F_{out} = f_\bigstar(A_\bigstar - A_S) + f_S A_S$$
$$F_{tra} = f_\bigstar(A_\bigstar - A_S) + f_S A_S - f_\bigstar A_P$$

Discovery of exoplanets using transits

Stellar spots

- The problem of spots over different wavelengths
  → Spots have chromatic effects

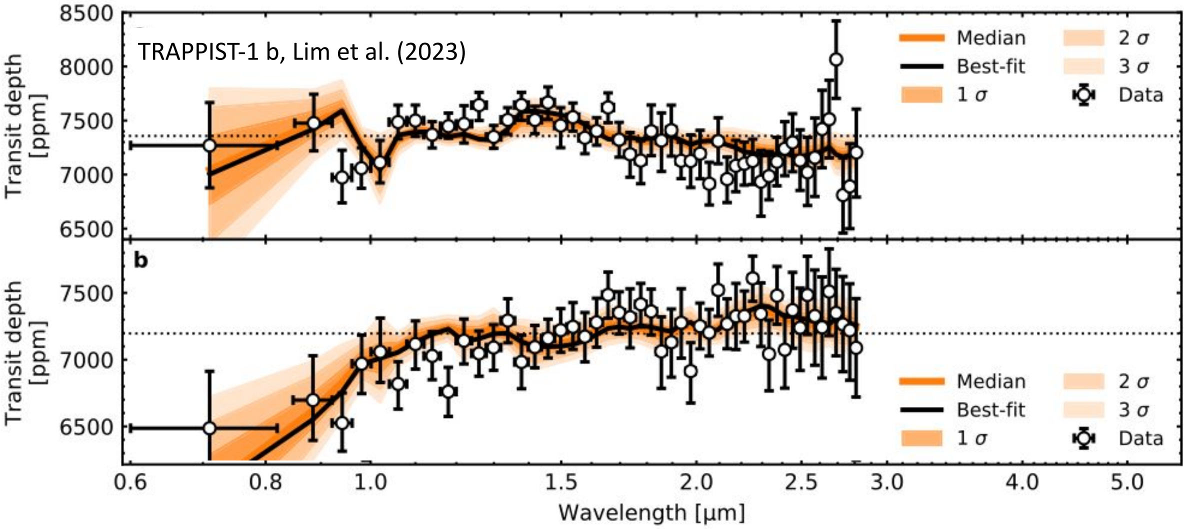




Discovery of exoplanets using transits

Stellar spots

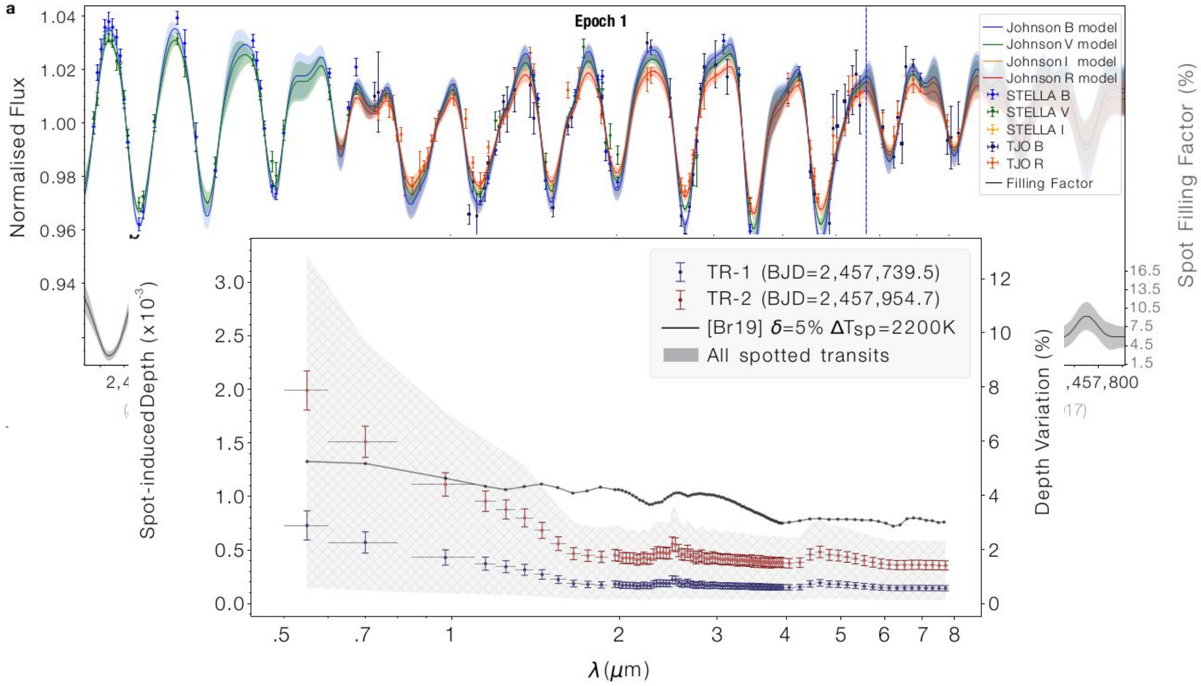
- The problem of spots over different wavelengths
  - → Spot have chromatic effects
  - → Mask of atmosphere features



Discovery of exoplanets using transits

Stellar spots

- The problem of spots over different wavelengths
  - → Spot have chromatic effects
  - → Mask of atmosphere features



How to correct the effect of spots?

Morning sessions on stellar activity!
Nadège Meunier
Manuel Perger

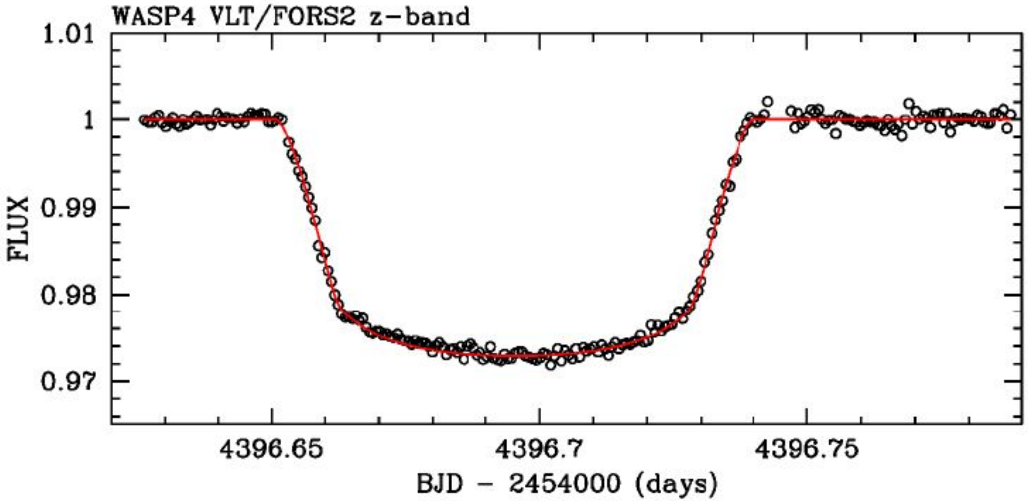
→ Stellar activity models
(StarSim, Herrero et al 2016, Rosich et al. 2020)
→ Machine learning

Discovery of exoplanets using transits

Modeling of transit light curves

- For each photometric measurement, the position of the planet relative to the star is computed, and from that, the fraction of stellar disk occulted by the planetary disk (assuming spherical shapes)
- Time dependence is carried by the true anomaly *f*

$$\frac{r_{sky}}{R_*} = \frac{r}{R_*}\sqrt{1-\sin^2(\omega+f)\sin^2 i}$$



Discovery of exoplanets using transits

Modeling of transit light curves

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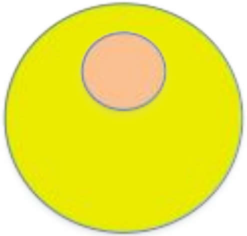
$$\frac{r_{sky}}{R_*} = \frac{r}{R_*}\sqrt{1-\sin^2(\omega+f)\sin^2 i}$$

$$f_{tra} = \pi/2 - \omega$$

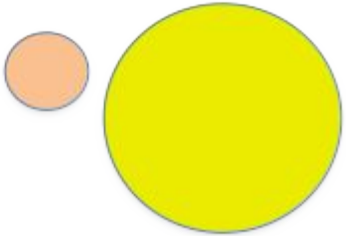
Full superposition

$$\frac{r_{sky}}{R_*} < 1 - \frac{R_p}{R_*}$$



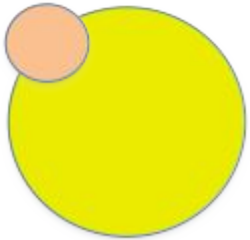
Zero superposition

$$\frac{r_{sky}}{R_*} > 1 + \frac{R_p}{R_*}$$



Partial superposition

$$1 - \frac{R_p}{R_*} \leq \frac{r_{sky}}{R_*} \leq 1 + \frac{R_p}{R_*}$$

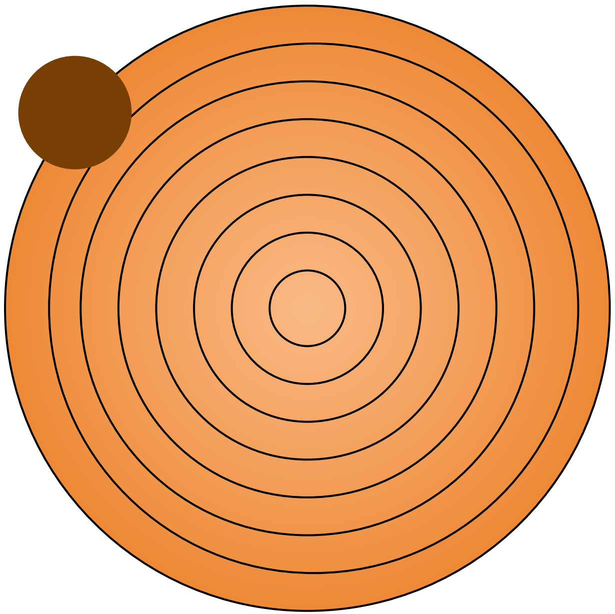


Discovery of exoplanets using transits

Modeling of transit light curves

- Computation of the drop of brightness with an algorithm adapted to the selected limb-darkening law (e.g., Mandel & Agol 2002).

- Relevant parameters
  → orbital period (P)
  → eccentricity (e)
  → argument of periastron (ω)
  → time of eclipse (T_0)
  → impact parameter (b)
  → transit duration (W)
  → transit depth (δ)



Discovery of exoplanets using transits

Modeling of transit light curves

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  - → impact parameter (b)
  - → transit duration (W)
  - → transit depth (δ)

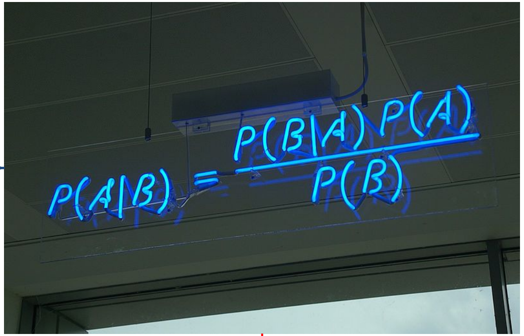
It is always preferable to use all the available information and data to maximize the constraints and to identify the most consistent solutions… or to reveal a consistency problem.

Radial velocities

Transit lightcurve

Stellar properties

Limb darkening



A posteriori probability distributions for $M_\star$, $R_\star$, M_P, R_P, i, a, e…

Discovery of exoplanets using transits

Modeling of transit light curves: some example codes

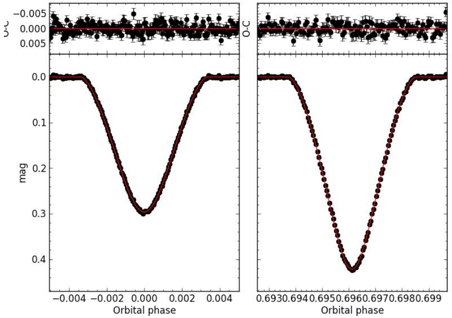
- Computation of the drop of brightness with an algorithm adapted to the selected limb-darkening law (e.g., Mandel & Agol 2002).

+ other Python packages!

JKTEBOP

Southworth et al. (2004, ...)

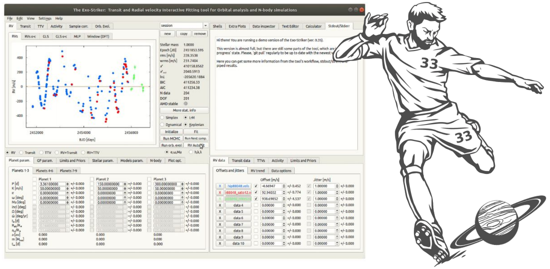
- Transit & RV time series
- Exoplanets and binary systems
- Sinusoidal variability
- MonteCarlo uncertainties
- Fortran code (python wrapper)
- https://www.astro.keele.ac.uk/jkt/codes/jktebop.html



Exo-Striker

Trifonov (2019)

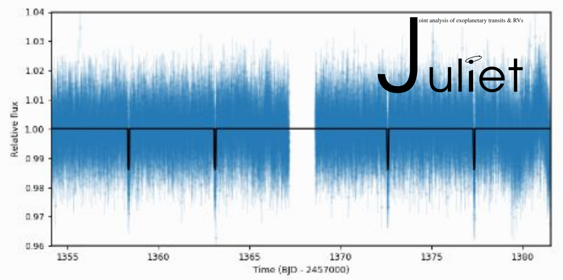
- Transit, RV, astrometry, TTV time series
- Exoplanets
- Gaussian Process
- Nested and MCMC samplers
- Python code (including GUI)
- https://github.com/3fon3fonov/exostriker



Juliet

Espinoza et al. (2019)

- Transit, RV, TTV time series
- Exoplanets
- Gaussian Process
- Nested sampler
- Python code
- https://juliet.readthedocs.io



Thank you!