Exoplanets

Fall/Winter 2024/2025

Lecture 5

8.11.2024

Outline

- Space mission detecting exoplanets
- Planetary candidates turning into planets

Exoplanet detection process

- Detection by a space mission (or by RVs)
- Spectroscopic characterization of the system
- High resolution imaging
- Precise Radial Velocities (RVs)
- Confirmed planet

Need for ground based follow-up

Case of the CoRoT space mission

- Ground based support of CoRoT

- Contribution to the follow-up observations

- Observations of the CoRoT target fields
  about 1 year ahead of CoRoT

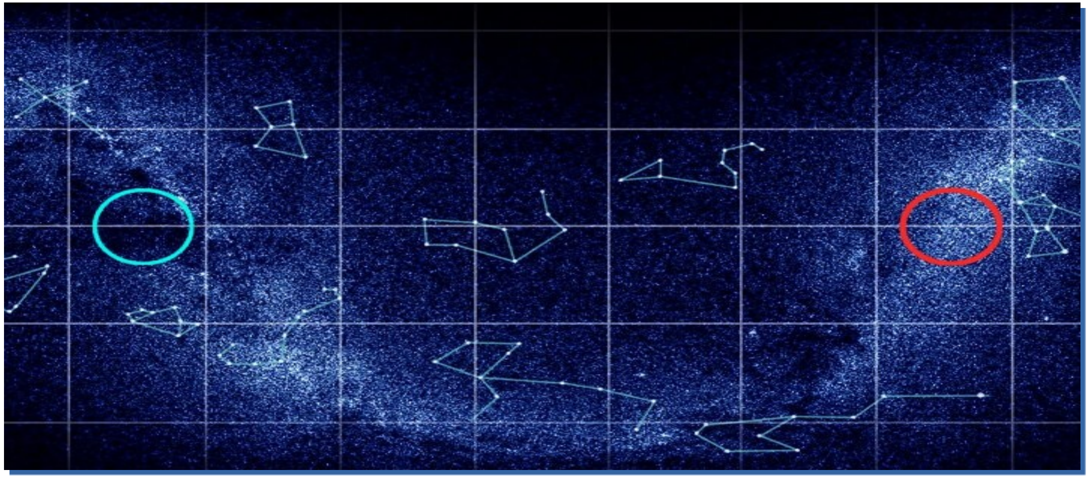
- Contribution to additional science programme

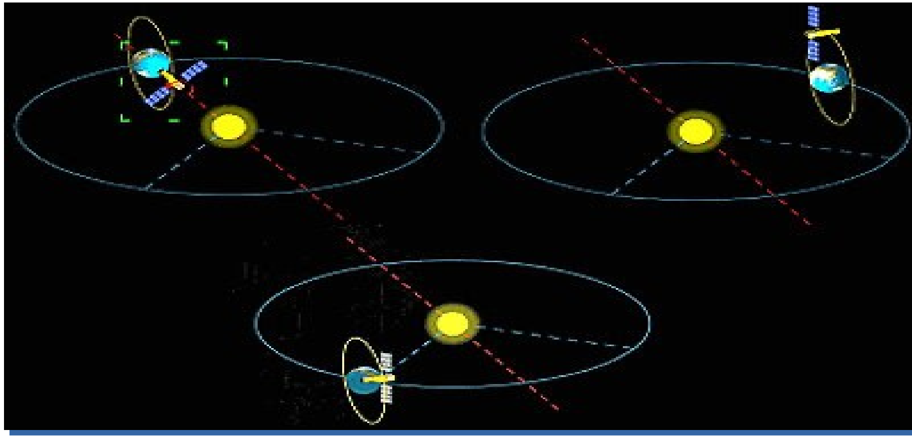
CoRoT space mission

- Small aperture -27cm
- Exoplanets, Asteroseismology
- Launched 2006
- Mission end 2014
- More than 30 confirmed and fully characterized exoplanets
- Several hundreds of candidates

Corot Observing Strategy

- Long run fields up-to 150 days
- Several shorter fields

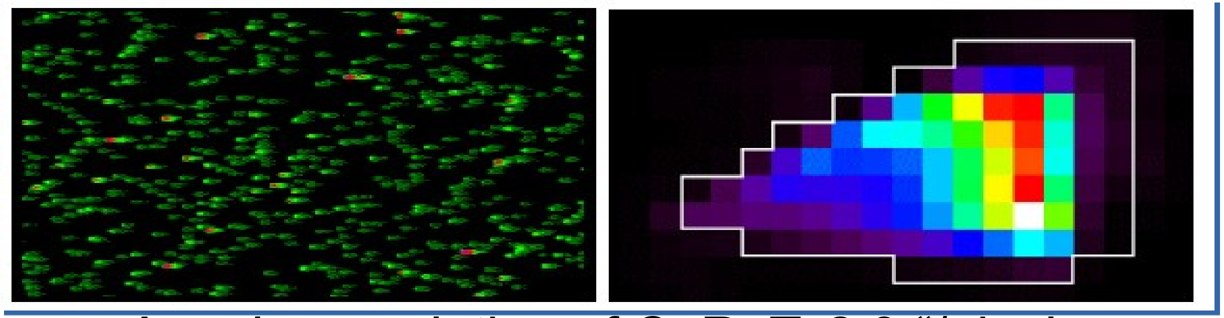




https://www.esa.int/Science_Exploration/Space_Science/COROT/COROT_mission_strategy

Need for ground based follow-up

Up to 12000 masks for objects



Angular resolution of CoRoT: 2.3 “/pixel

↓

Broadening of stellar PSF due to prisms

↓

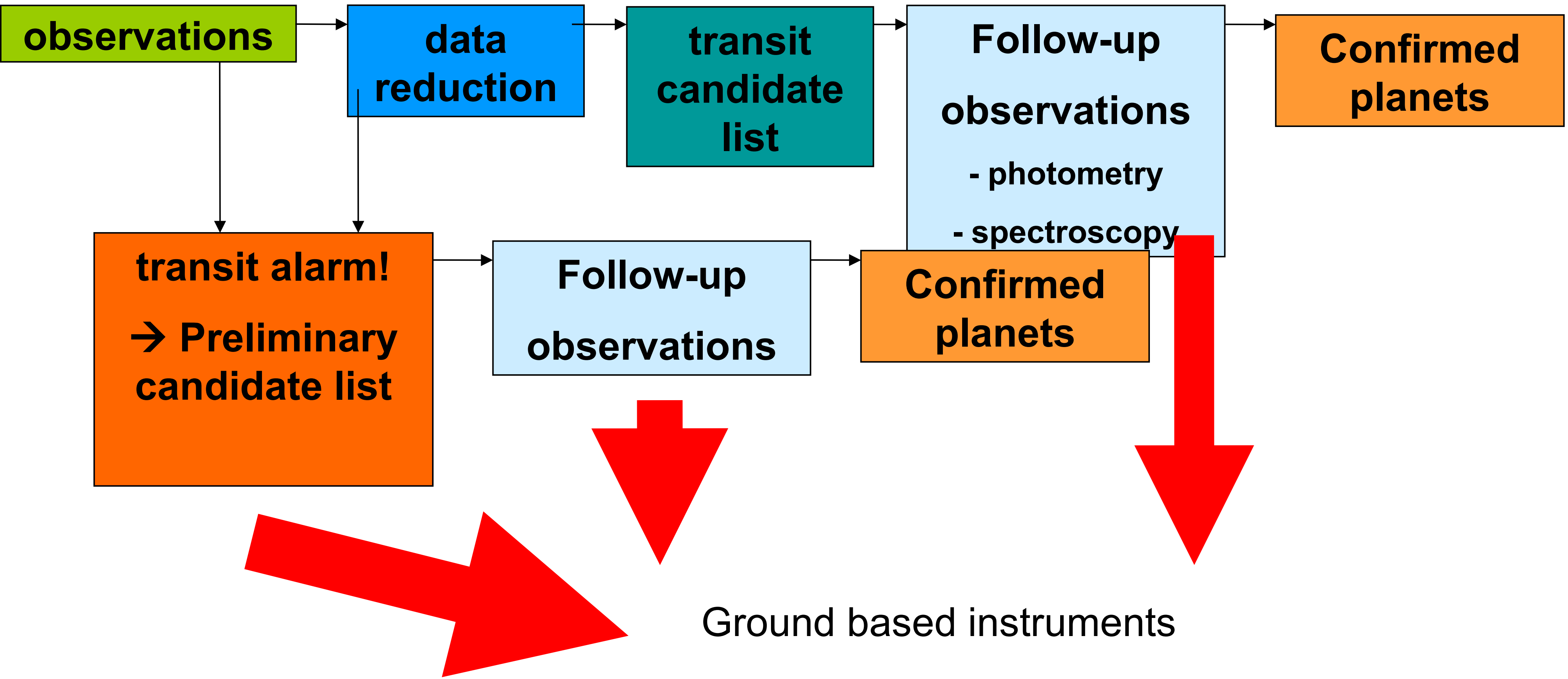
FLASE POSITIVE ALARMS

↓

GROUND BASED FOLOW-UP

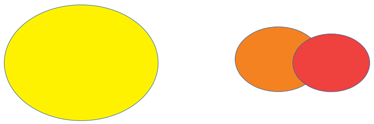
Follow-up for CoRoT - BEST II

Confirmtation of candidates (Case of CoRoT)

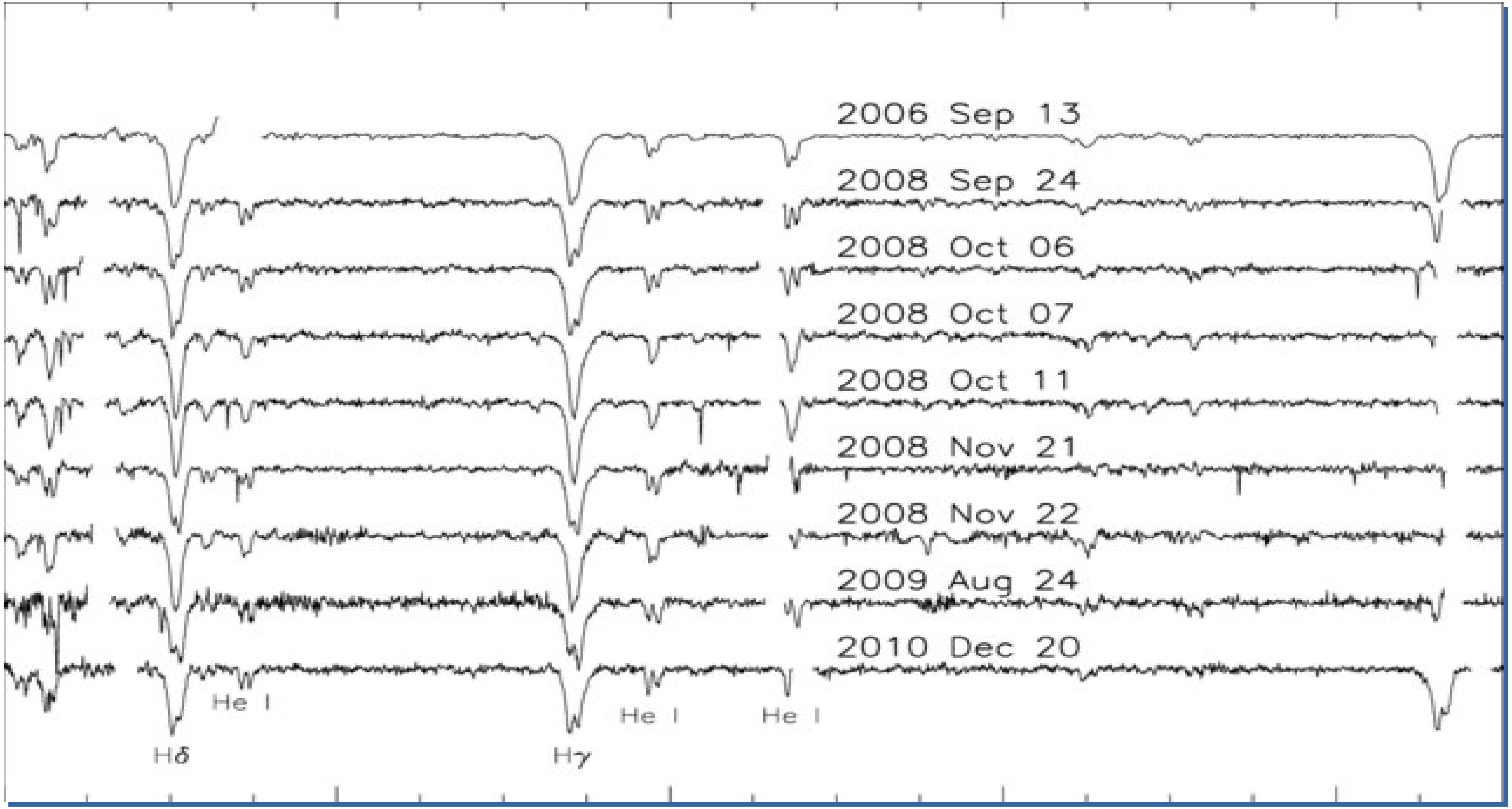


False positives

- Eclipsing binaries
- Triple systems
- Background eclipsing binaries
- Background eclipsing BD/WD
- Star is not at main sequence
- False positives estimates Santerne et al. 2012 – around 40% for close-in giant planets Kepler candidates (from observing)
- Santerne et al. 2013 evaluates global false positive probability to about 11% for Kepler candidates



Example of a binary from spectra



Joel B. Lamb et al., 2015, The Astrophysical Journal 817(2)

Characterization of exoplanets combination of methods

- Transits

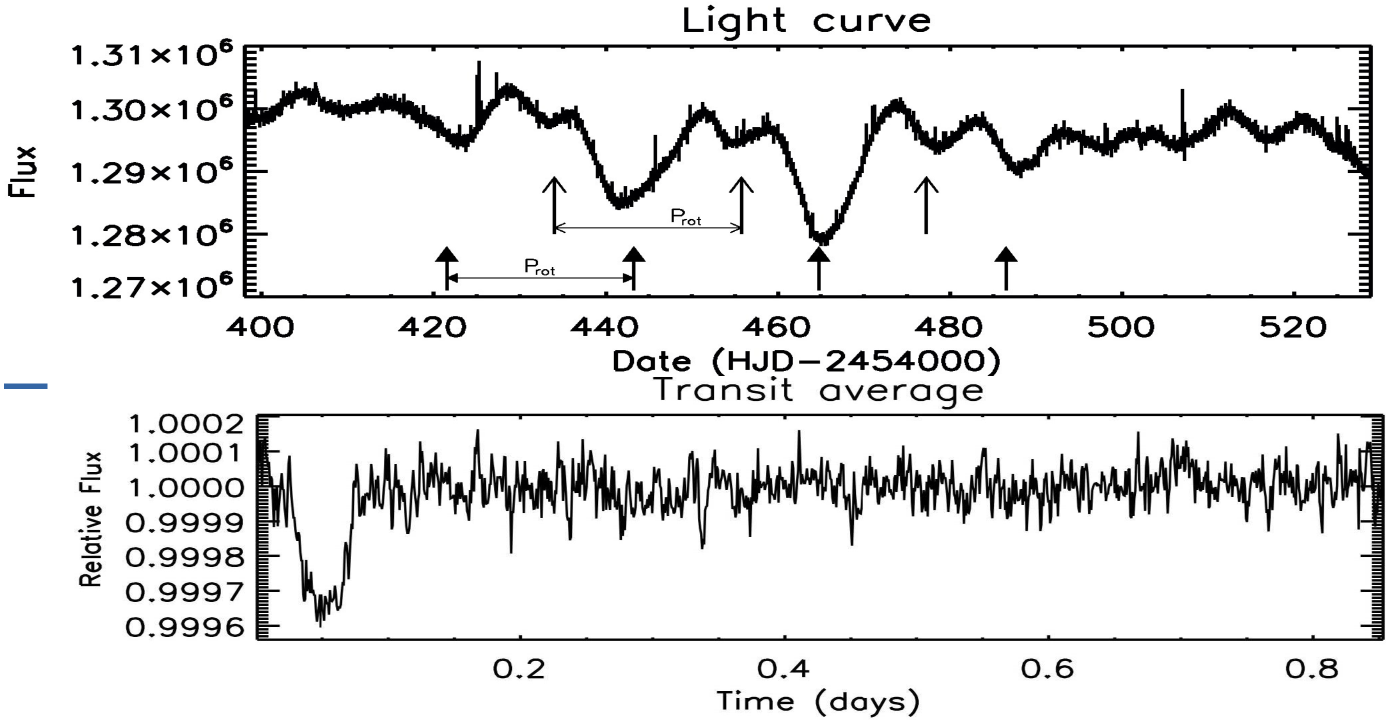
  Radius of the planet (if stellar params known), inclination

- Spectroscopy

  Mass limit, stellar parameters

- STELLAR PARAMETERS NEEDED (spectroscopy)

The case of CoRoT-7b



From Leger et al. 2007, A&A

CoRoT-7b

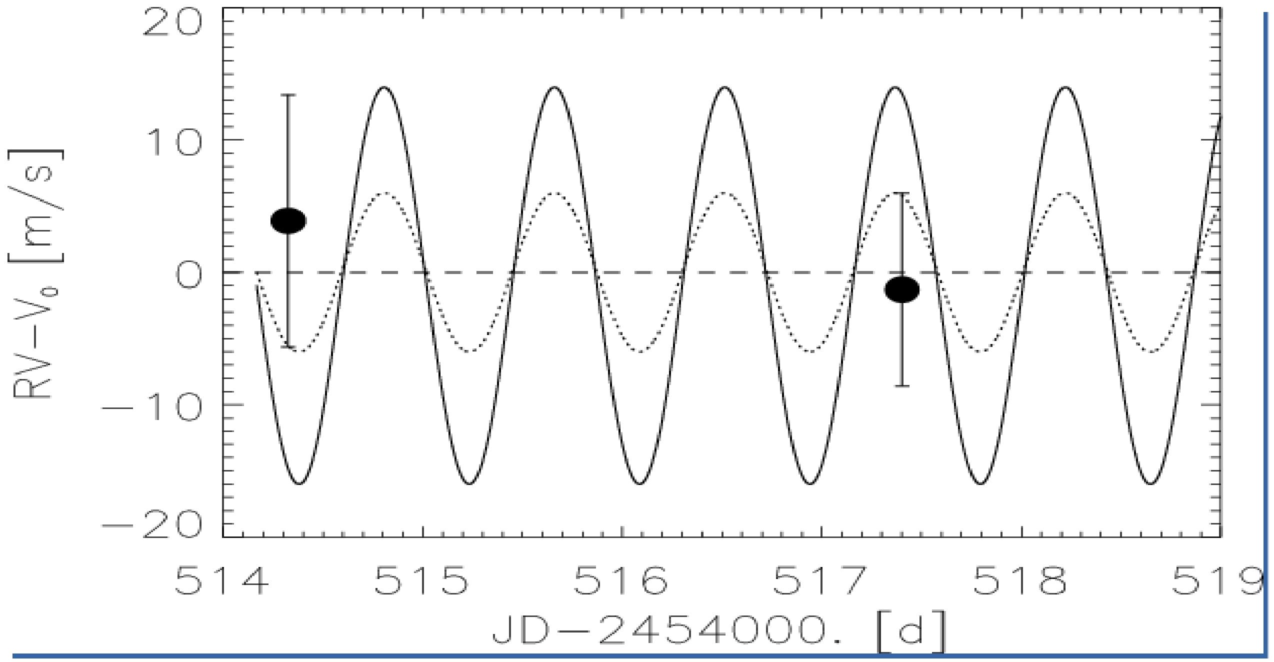
Orbital Period 0.85 days

Mass $<9M_{Earth}$

Radius $1.51R_{earth}$

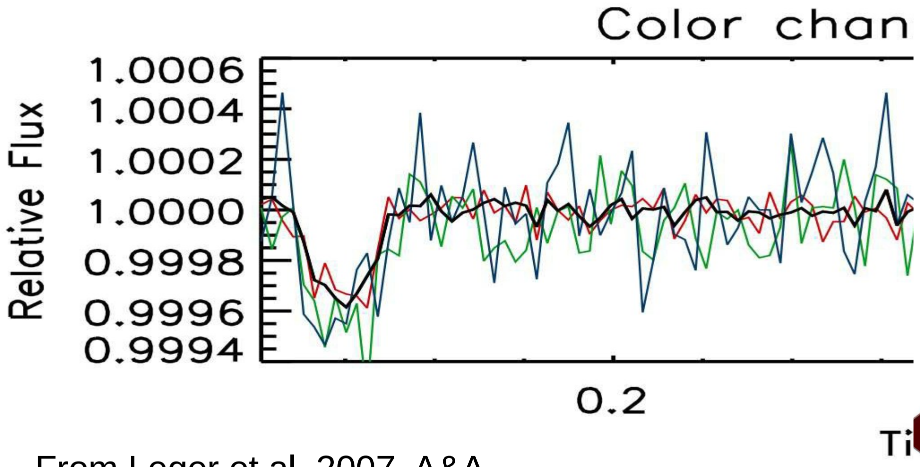
CoRoT-7b

- SOPHIE at OHP
- Excluded large companion
- Case for small telescope



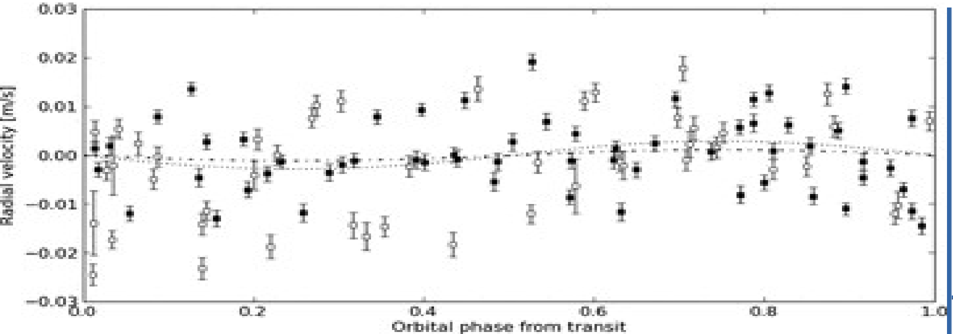
From Leger et al. 2007, A&A

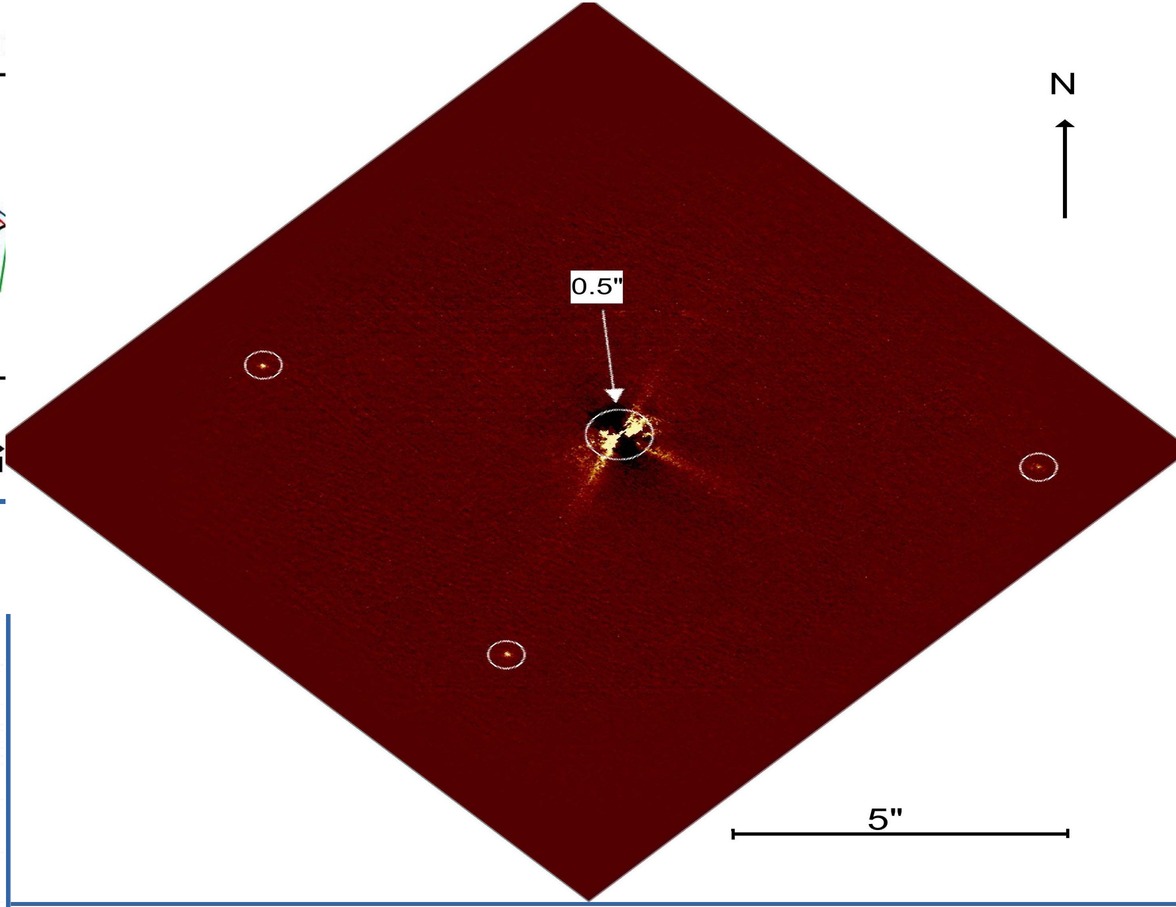
CoRoT-7b



From Leger et al. 2007, A&A

Bottom from F. Pont 2011, MNRAS

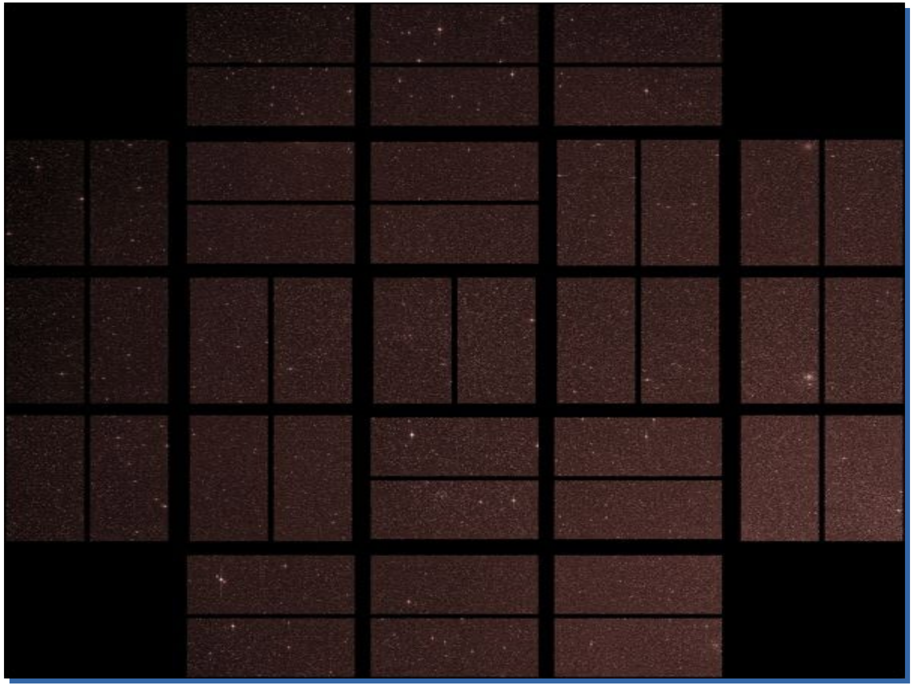


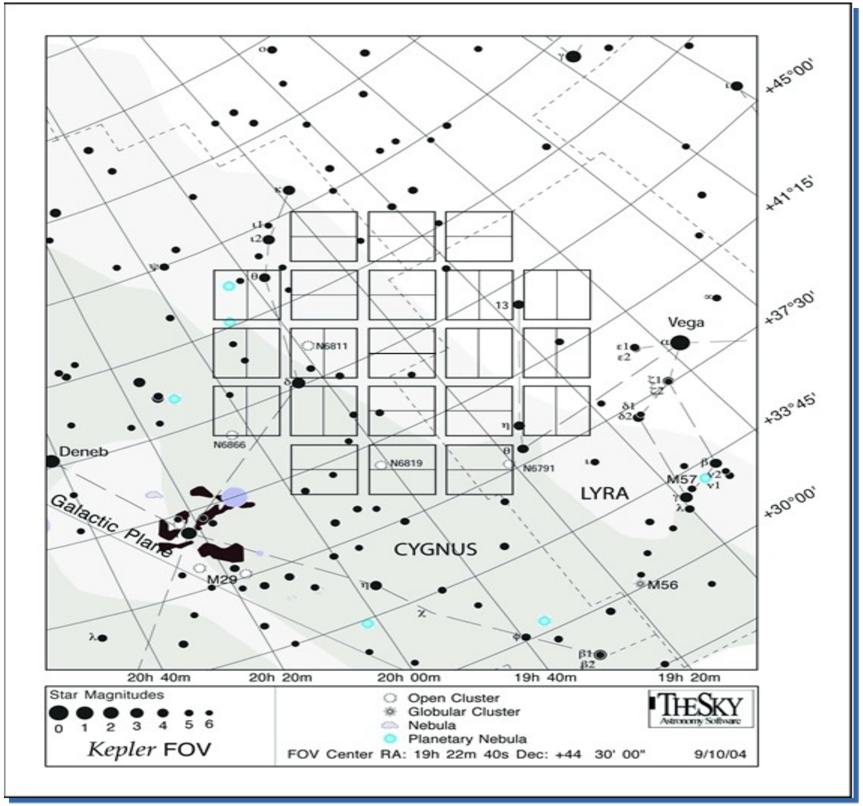


The era of Kepler

- Detections of exoplanets
- Launched 2009
- 1.4-m primary mirror
- Monitored 100k stars in Cygnus
- Around 2000 planets
- K2 continuation with different observing strategy
- Many stars were faint 13+ mag!

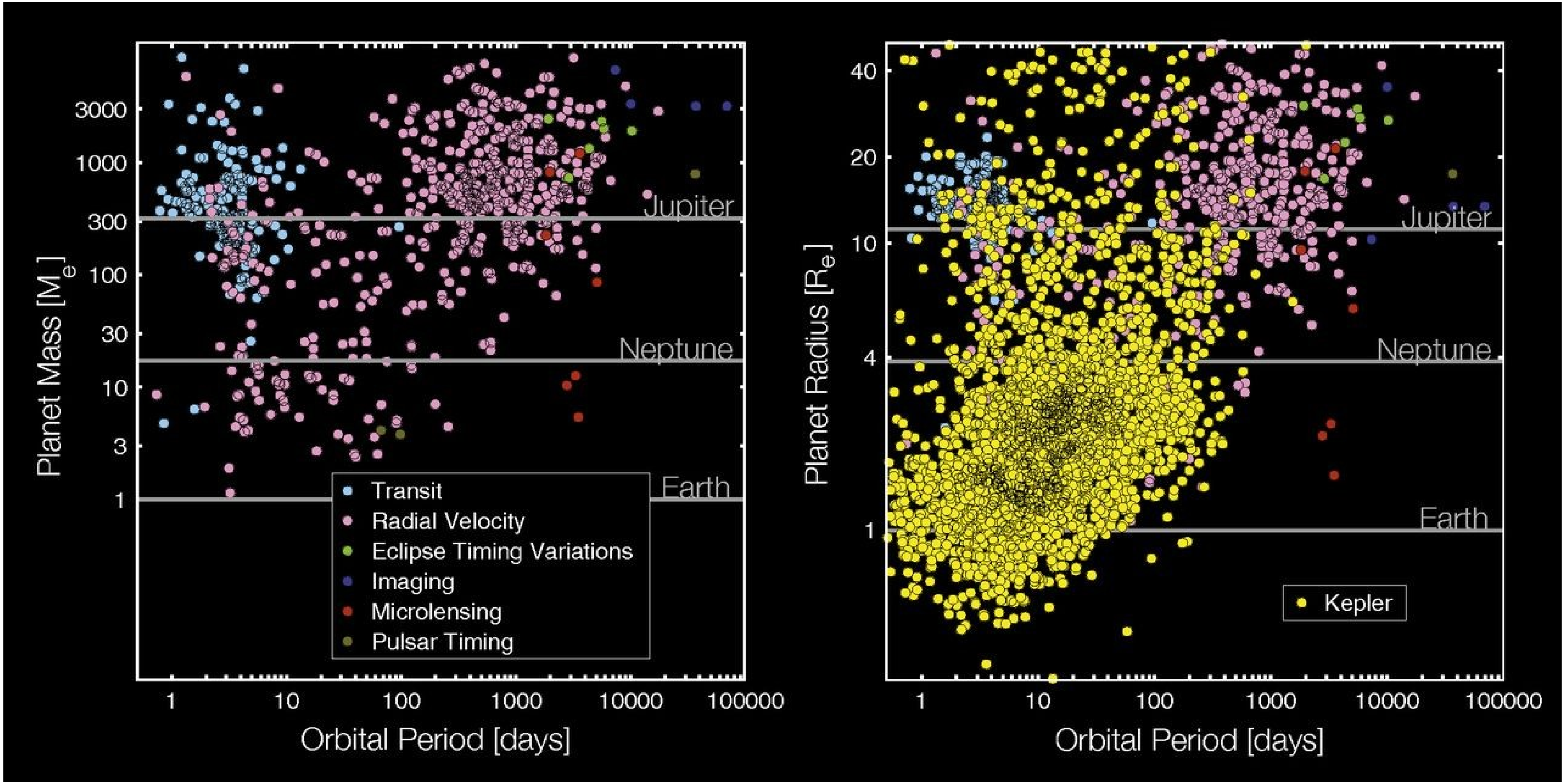
Kepler observing strategies





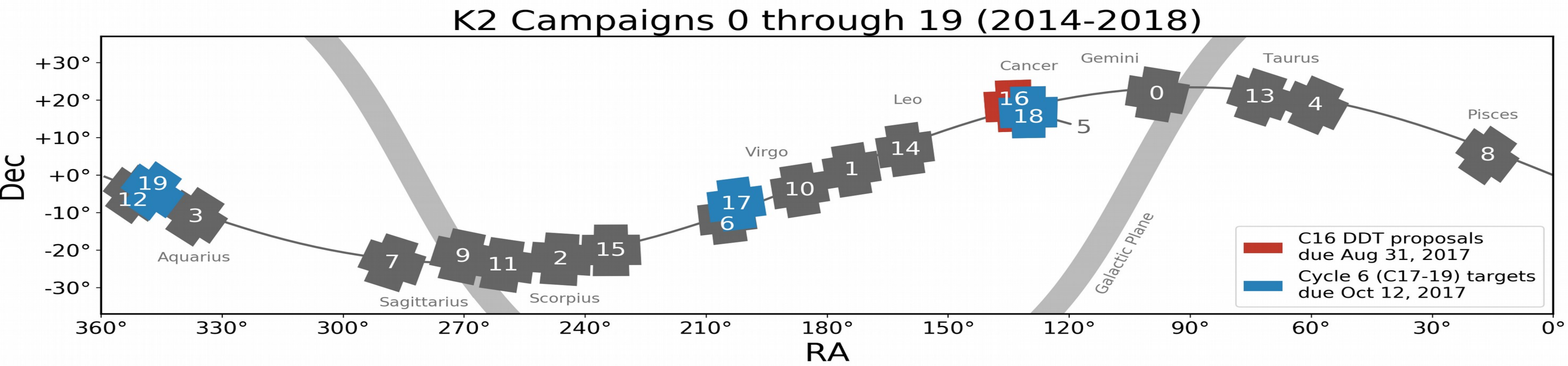
https://keplerscience.arc.nasa.gov/the-kepler-space-telescope.html

KEPLER planets



Credit: NASA

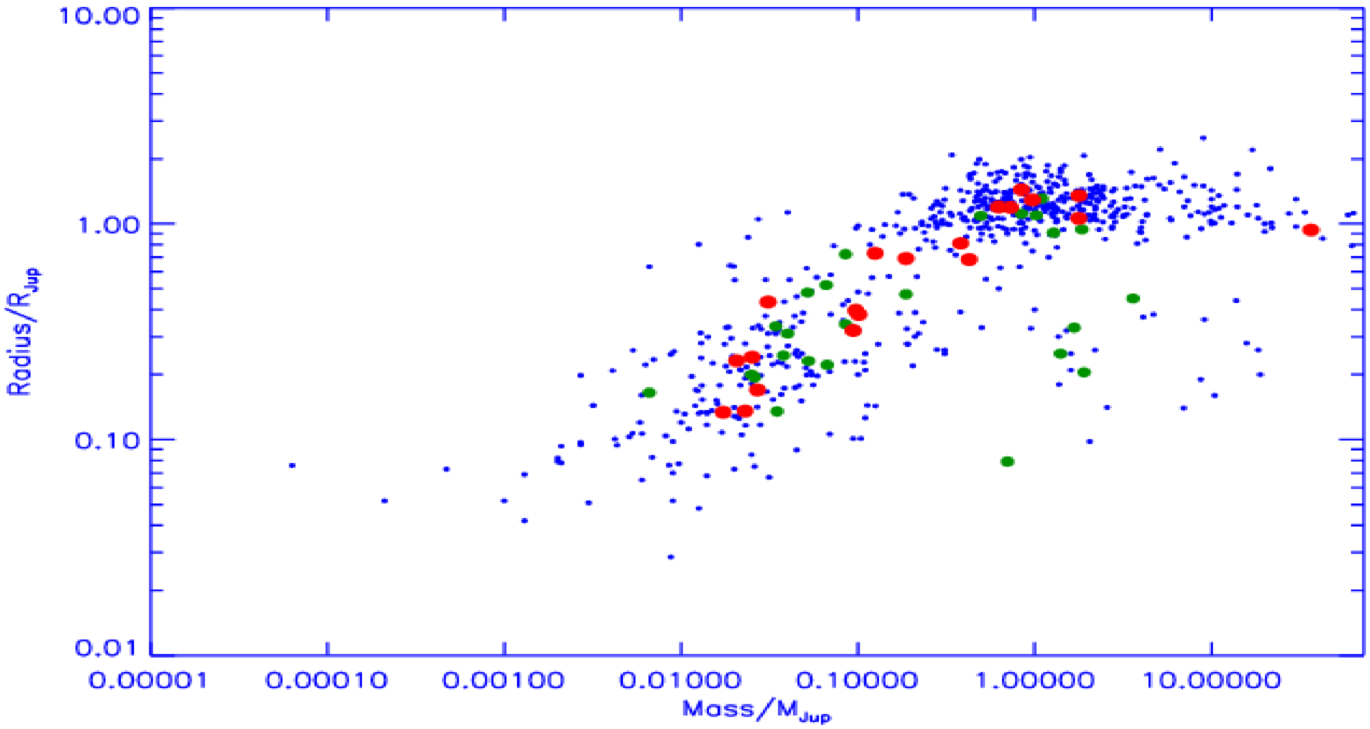
K2 continuation of Kepler



Credit: Nasa

- Nowadays 325 planets from K2 (Sep 2018)
- About 400 candidate (Sep 2018)
- Need for ground-based RV

Great but…..



From Csizmadia et al. Plato mission conference 2017

In Sep. 2017 – approx. 120 K2 planets

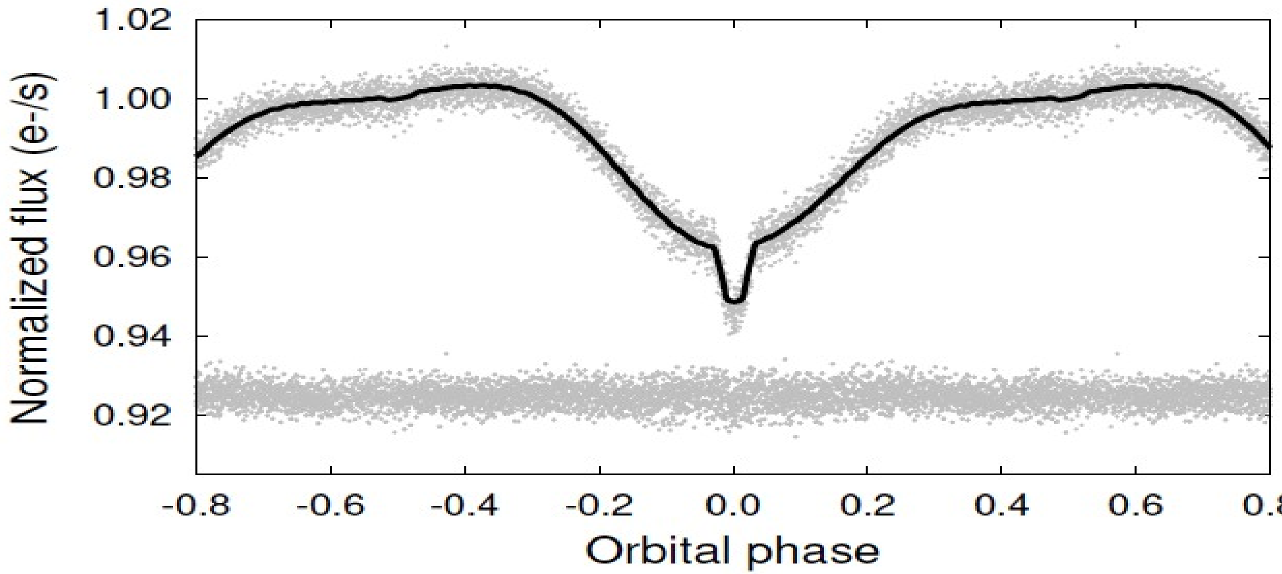
Blue – all planets around 4000
Green – K2 planets with masses (40)
Red – KESPRINT (21)

Numbers from Csizmadia et al. 2017

The case of HD99458

- Planetary candidate with
- Transit depth of a few %
- Suspected hot Jupiter
- Follow-up with OES at Ondrejov

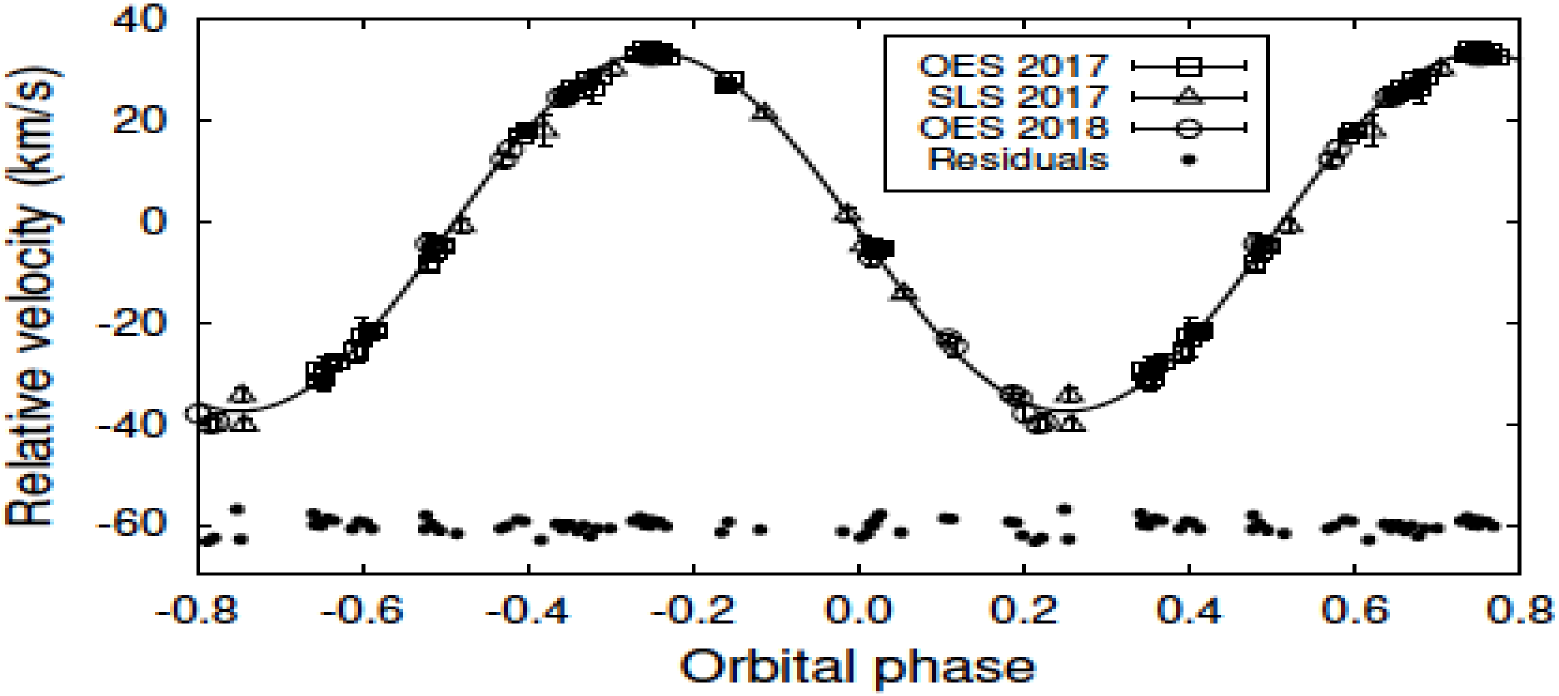
Intriguing system?



Skarka, Kabath, et al. 2019, MNRAS

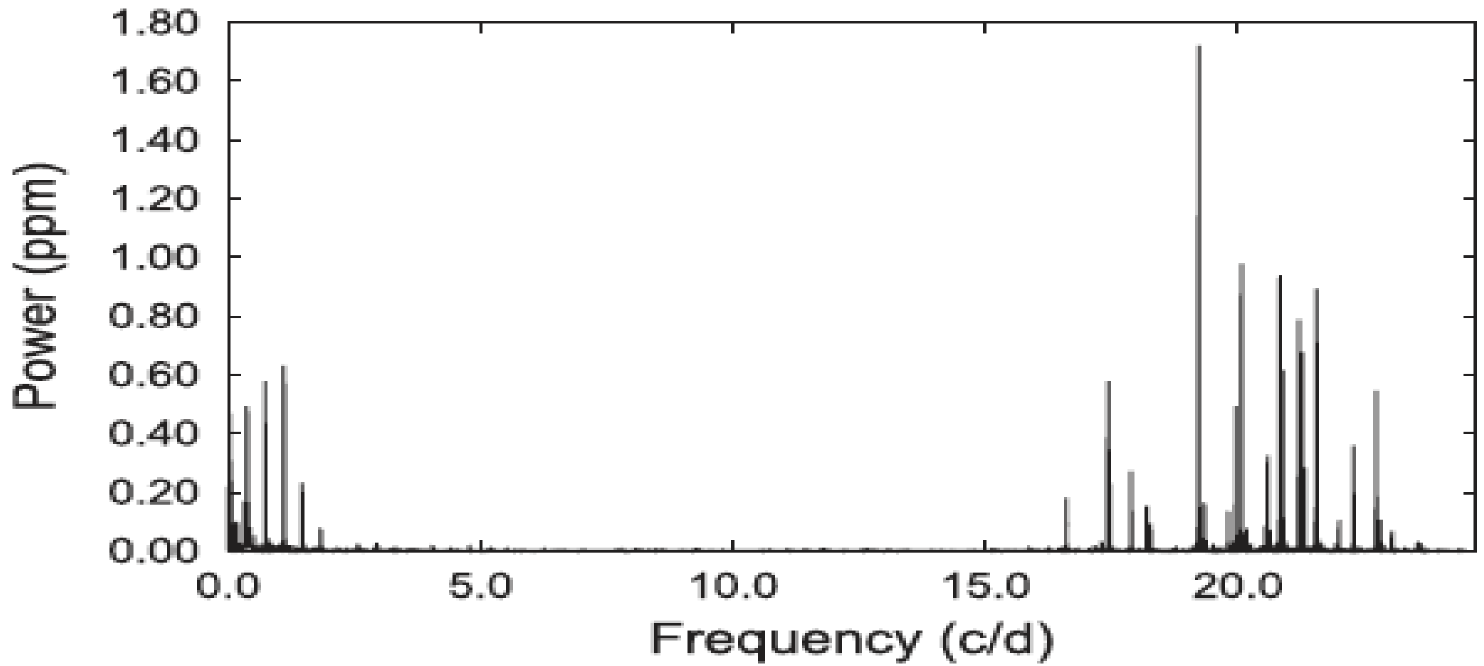
- Kepler candidate for Jupiter-sized planet
- Obsevring with OES and at Stará Lesná, SK
- Short period binary, magnetic star with DSCT pulsations and spots
- NO EXOPLANET

A false positive



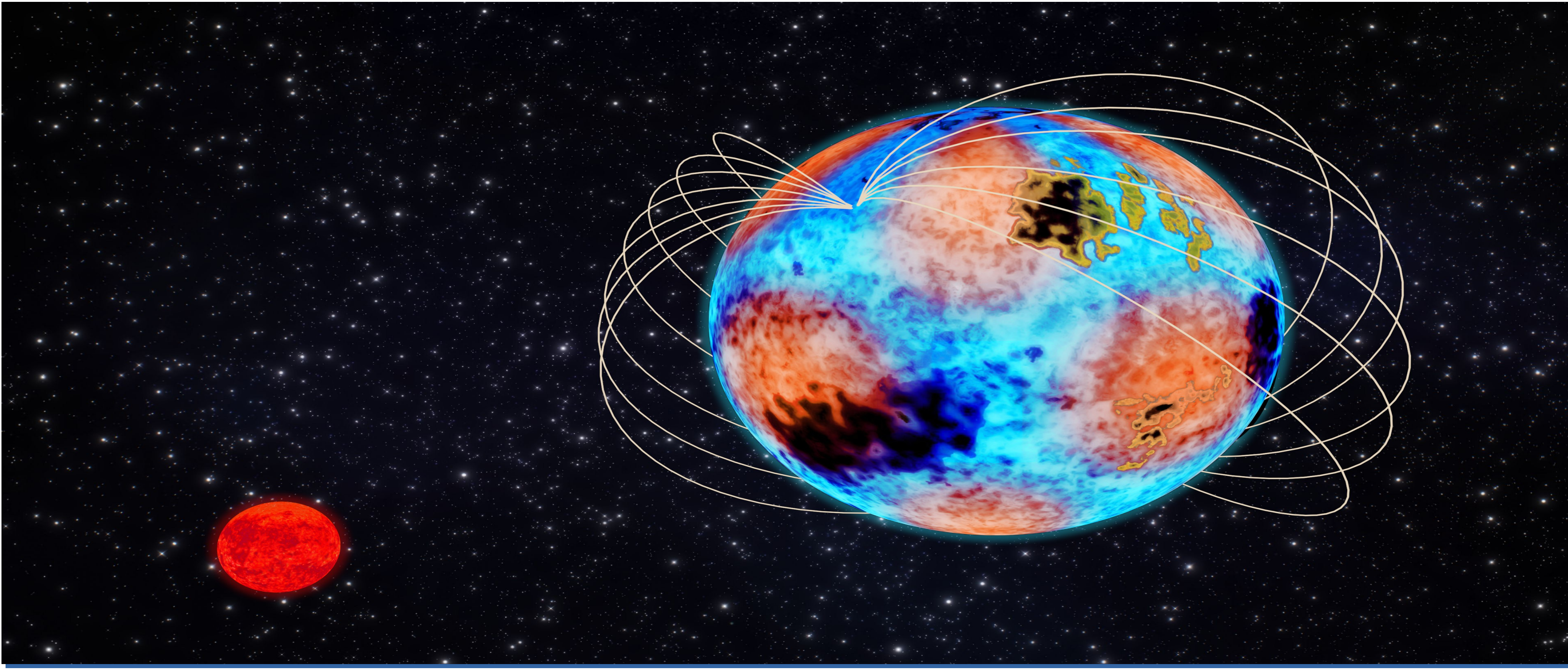
Skarka, Kabath, et al. 2019, MNRAS

Pulsations



Skarka, Kabath, et al. 2019, MNRAS

Artists impression



Skarka, Kabath, et al. 2019, MNRAS

Need for coordination

- spectroscopic follow-up

  - spectral typing, stellar parameters (1-2-m class)

  - RV follow-up (1-8+ m class)

  - exo-atmospheres (2-8+ m class)

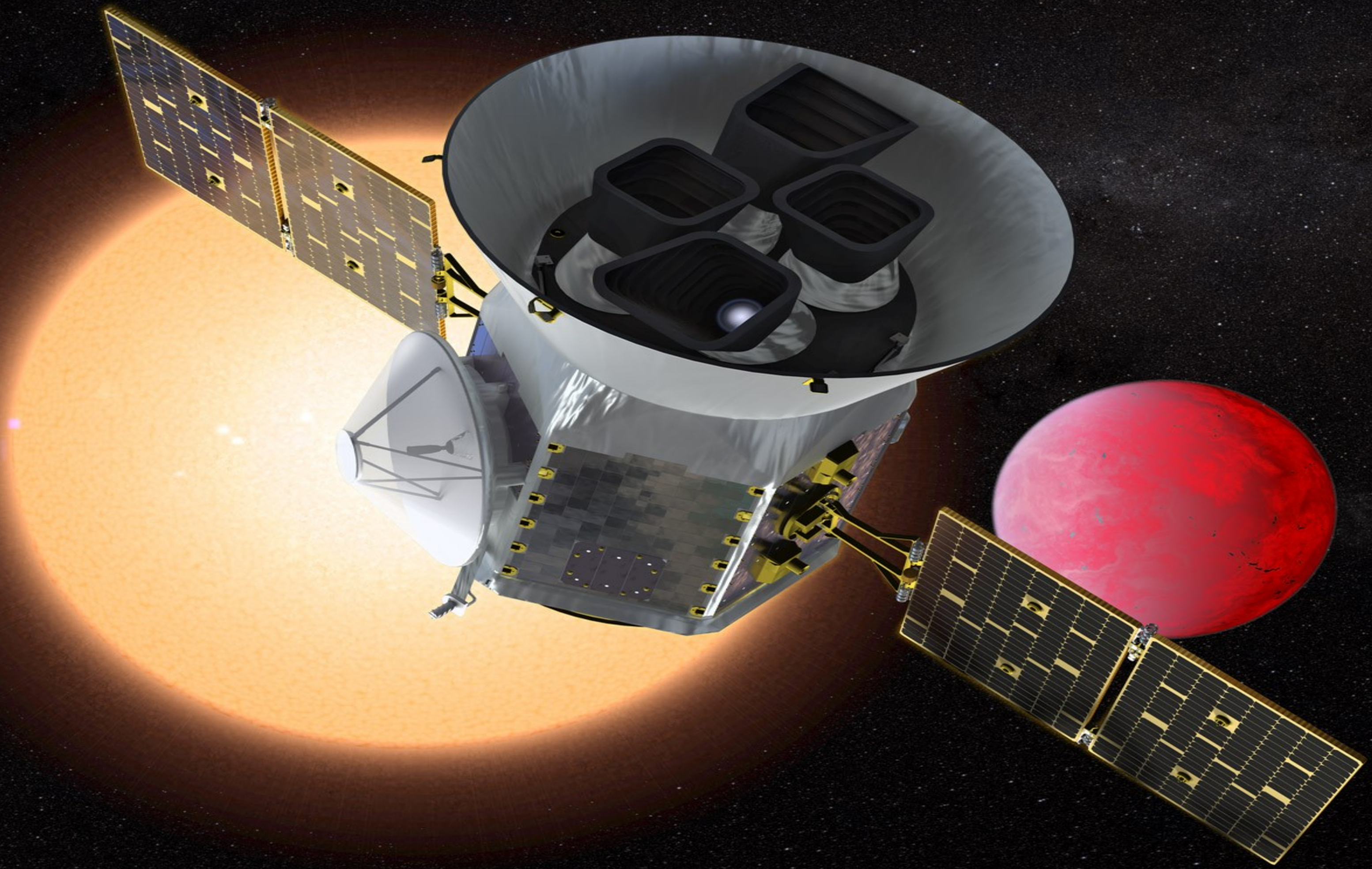
- Photometric follow-up

  - high spatial resolution imaging (small telescopes)

  - on-off photometry (small telescopes)

  - high-res. (AO) imaging (typicall 8-m)

TESS



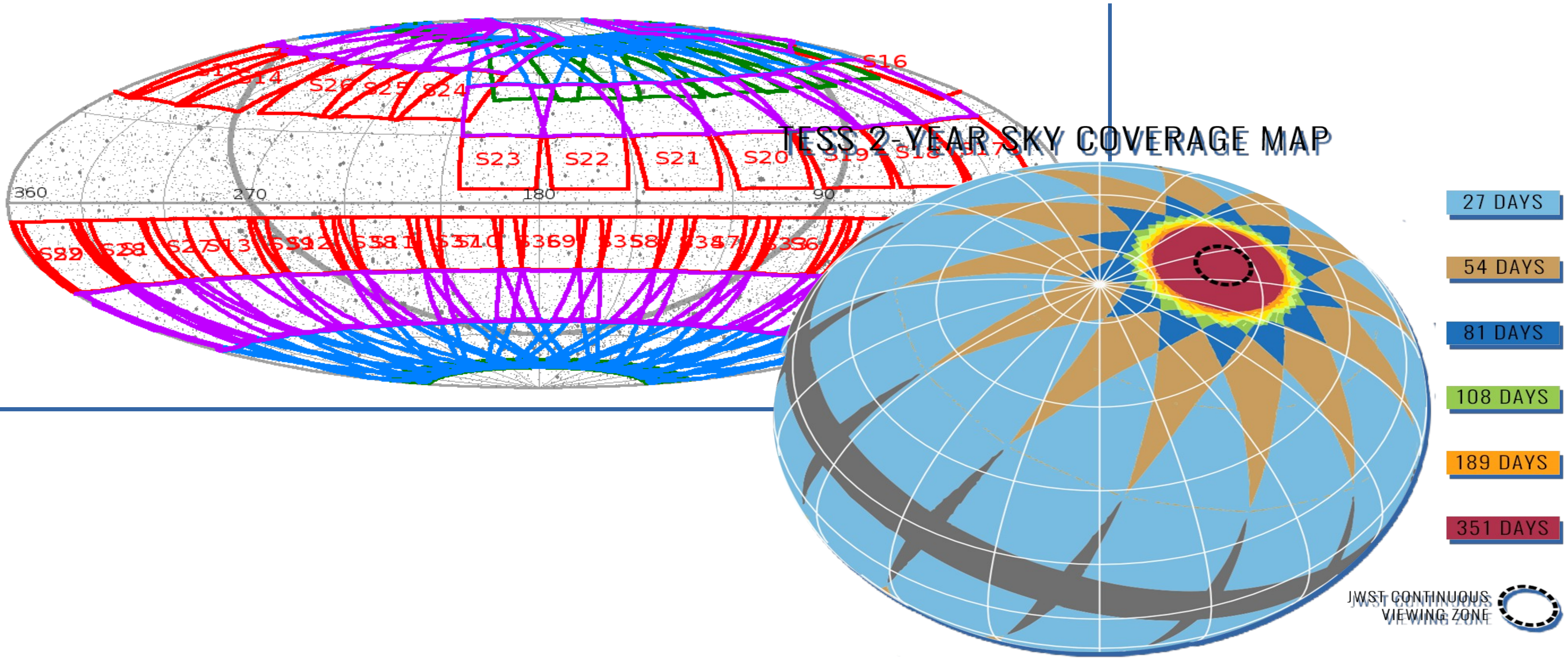
TESS

- Almost all sky coverage
- 4 x 100mm lenses
- Monitoring of more than 200k bright stars
- Targets will suitable for ground-based follow-up
- Perfect for small telescopes!!!
- First 73 candidates list delivered

  - Brightest TESS candidate is 5.1 mag

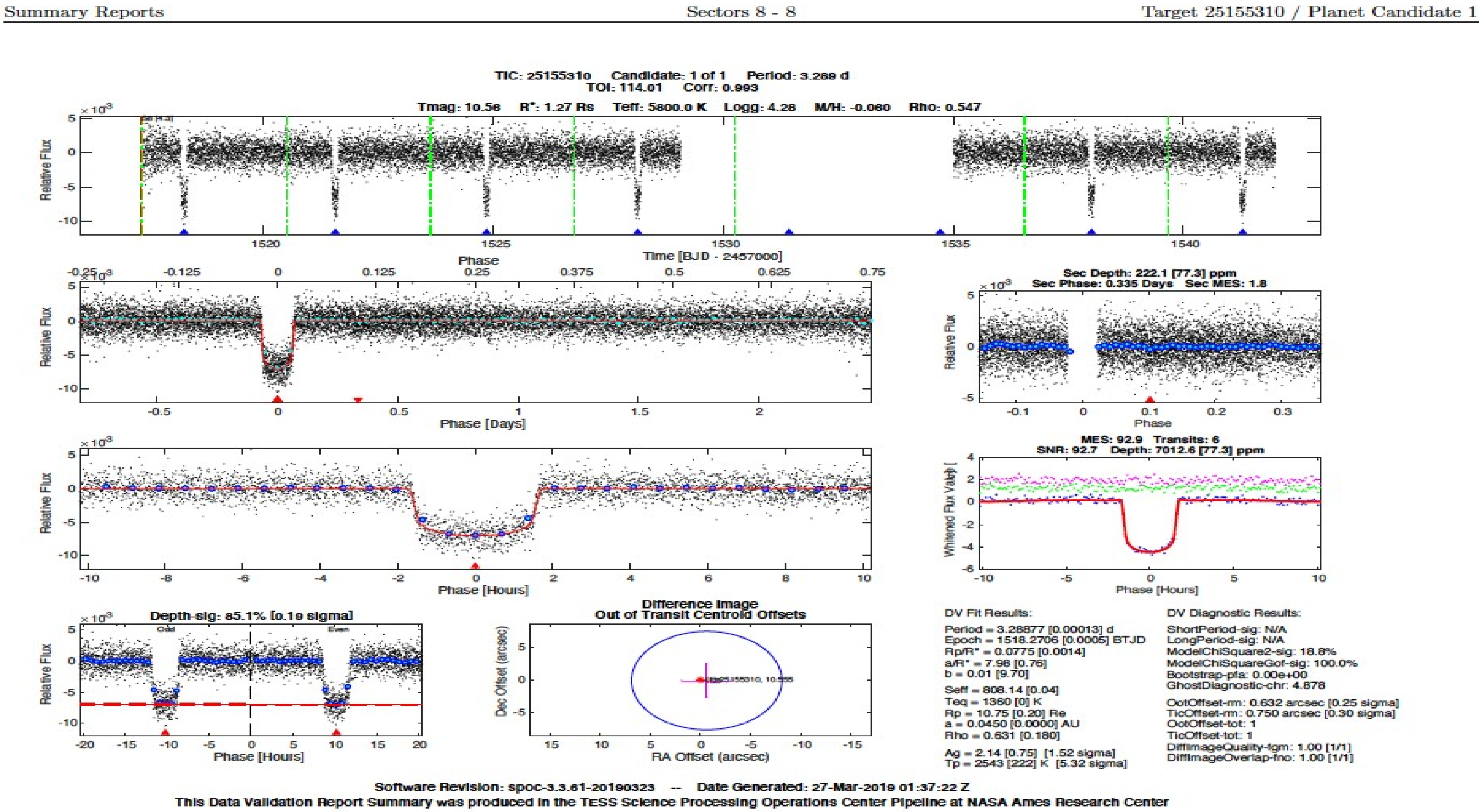
  - Most of targets brighter than 12 mag

TESS observing fields

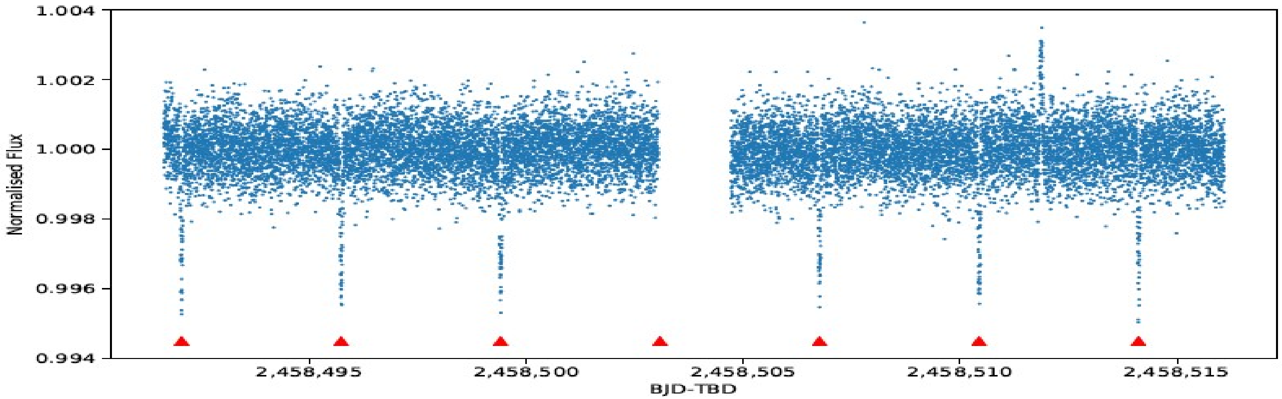


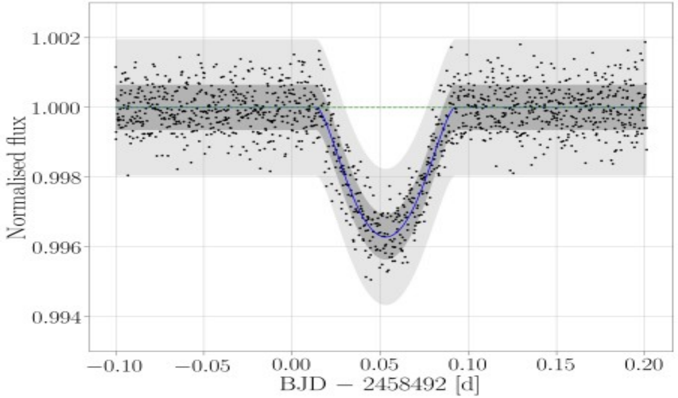
://archive.stsci.edu/missions-and-data/transiting-exoplanet-survey-satellite-tess

Example of a validation report



Candidate from TESS
TOI-503?



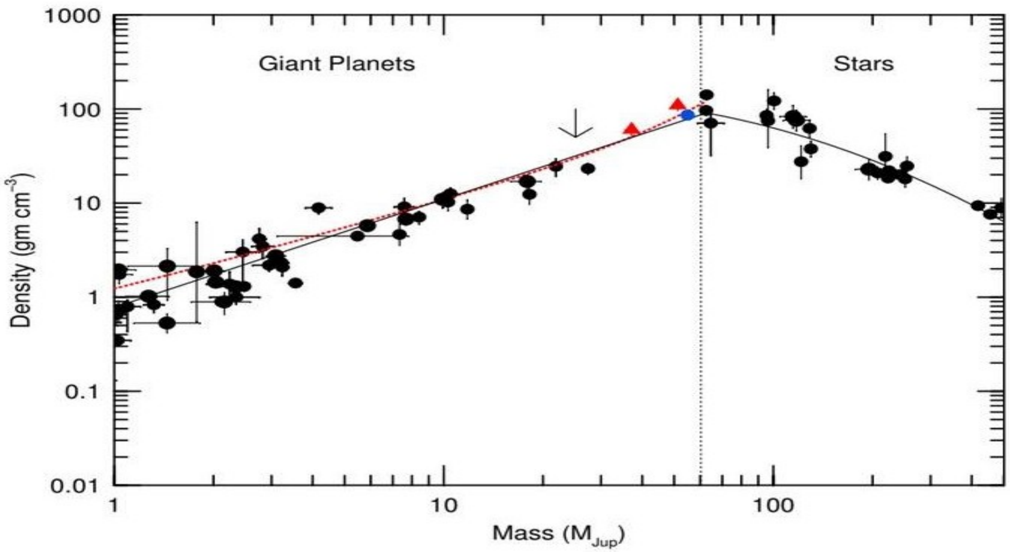


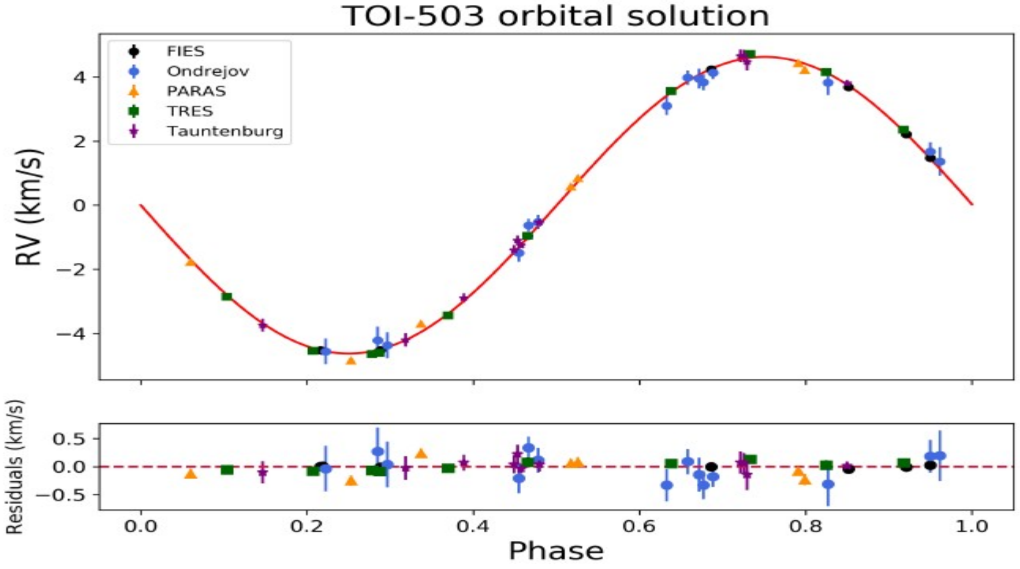
- TESS detected a Period around 3 days for TOI-503 A type star
- 3% depth – border line planet

Subjak et al. 2020AJ....159..151S

First Brown Dwarf from Ondřejov

- Mass – 53 Jupiter masses
- Radial velocities between -5 a +5 km/s

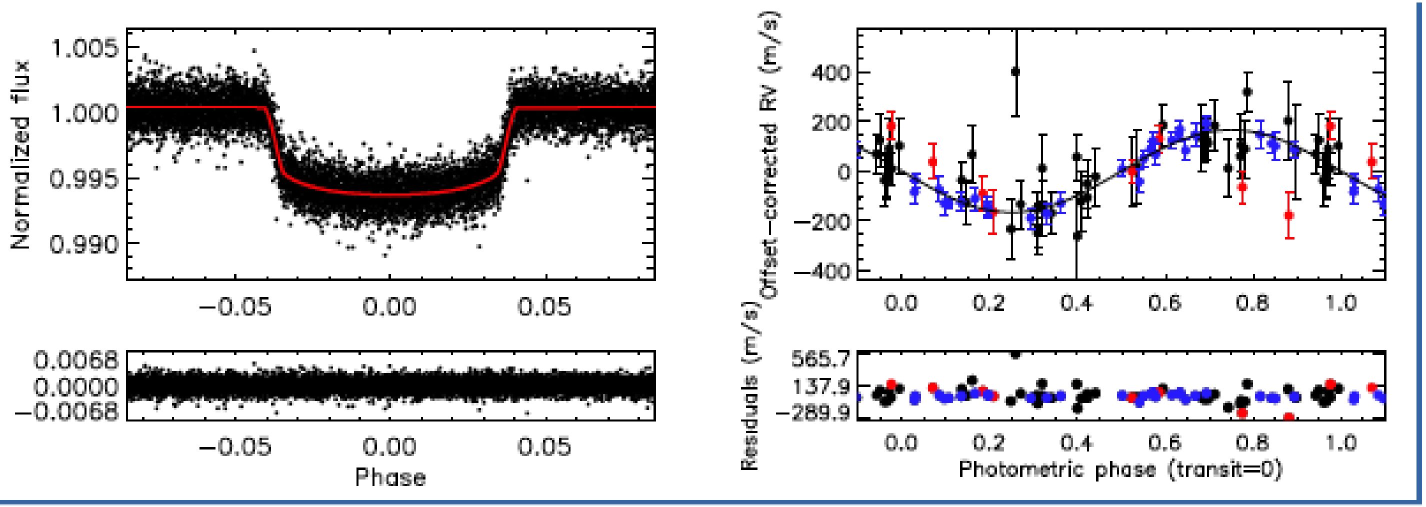




Parsson et al. 2019A&A...628A..64P and Subjak et al. 2020AJ....159..151S

TOI-1181b

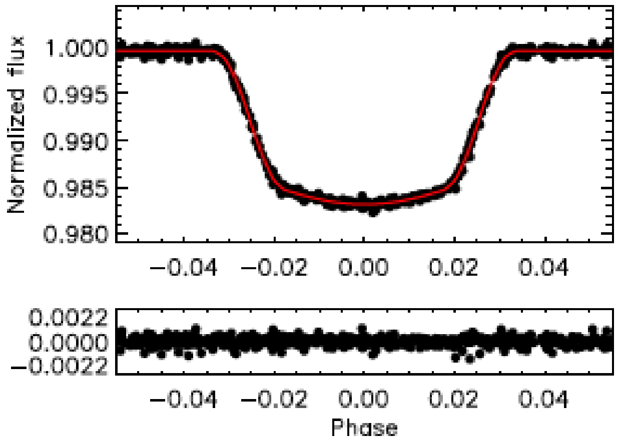
- A hot Jupiter around a G subgiant star
- Period 2.1 days
- Radius 1.3 $R_{Jupiter}$ and Mass 1.18 $M_{Jupiter}$

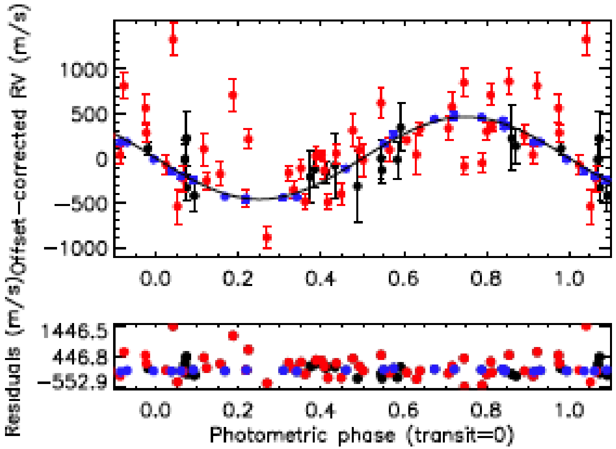


From Kabath et al. 2021 MNRAS

TOI-1516b

- A regular hot Jupiter
- Period 2.06 days
- Radius 1.36 $R_{Jupiter}$ and Mass 3.16 $M_{Jupiter}$

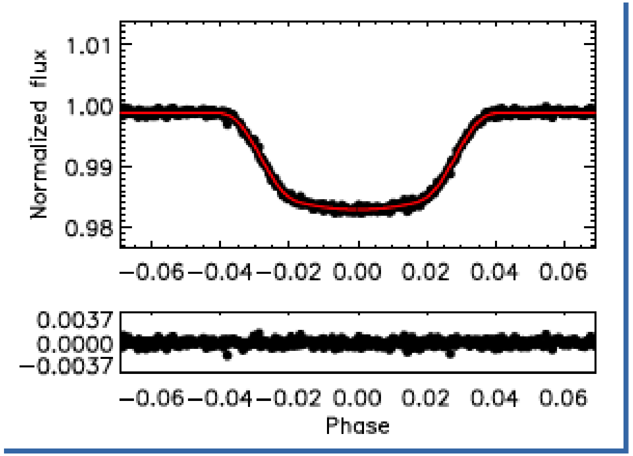


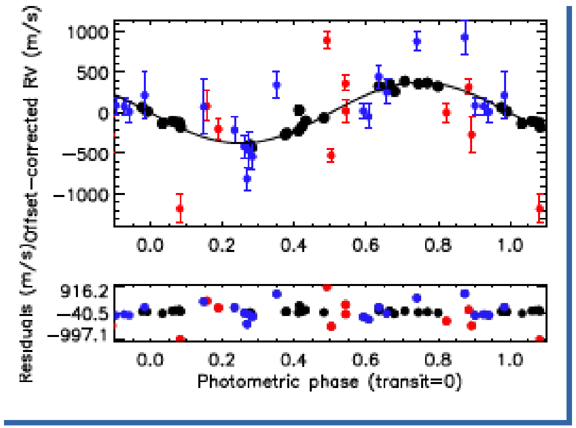


From Kabath et al. 2021 MNRAS

Hot Jupiter around young star, TOI-2046b

- Young system perhaps 100-400 Myr (Li line)
- Period 1.5 days
- Radius 2.44 $R_{jupiter}$ and Mass 2.3 $M_{Jupiter}$

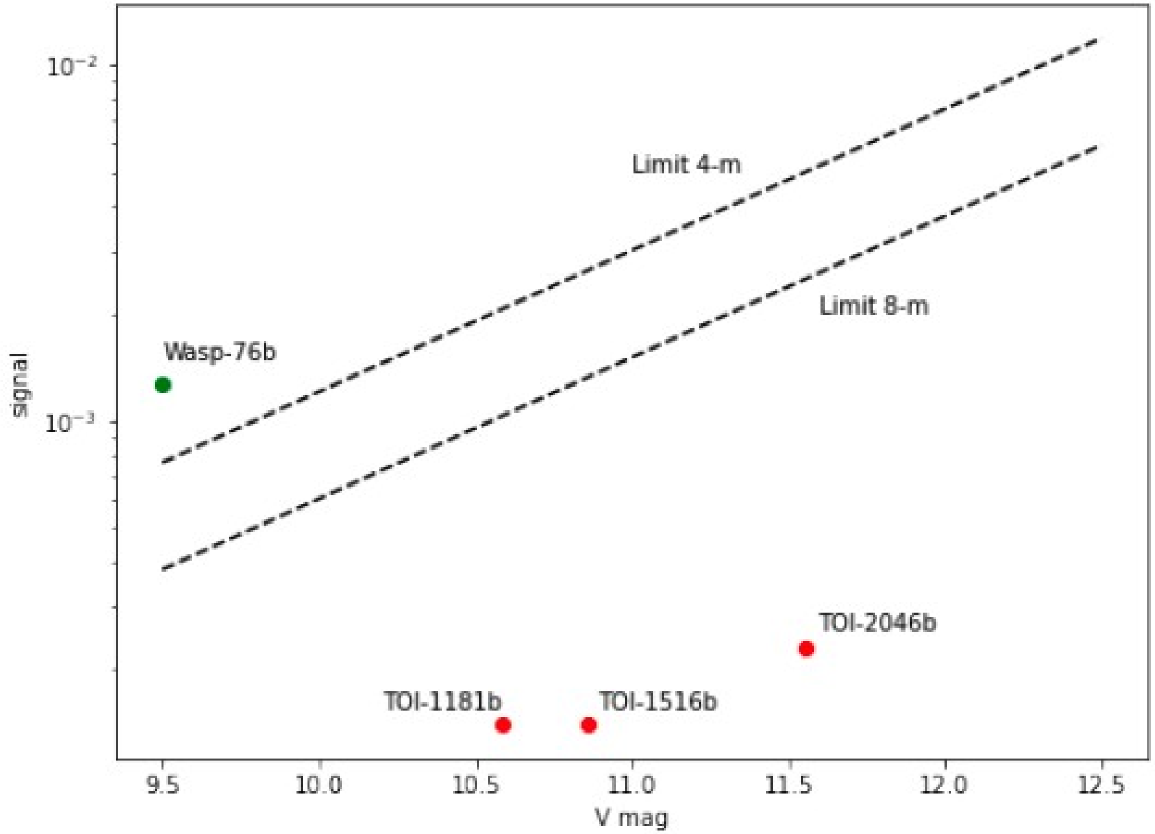




From Kabath et al. 2021 MNRAS

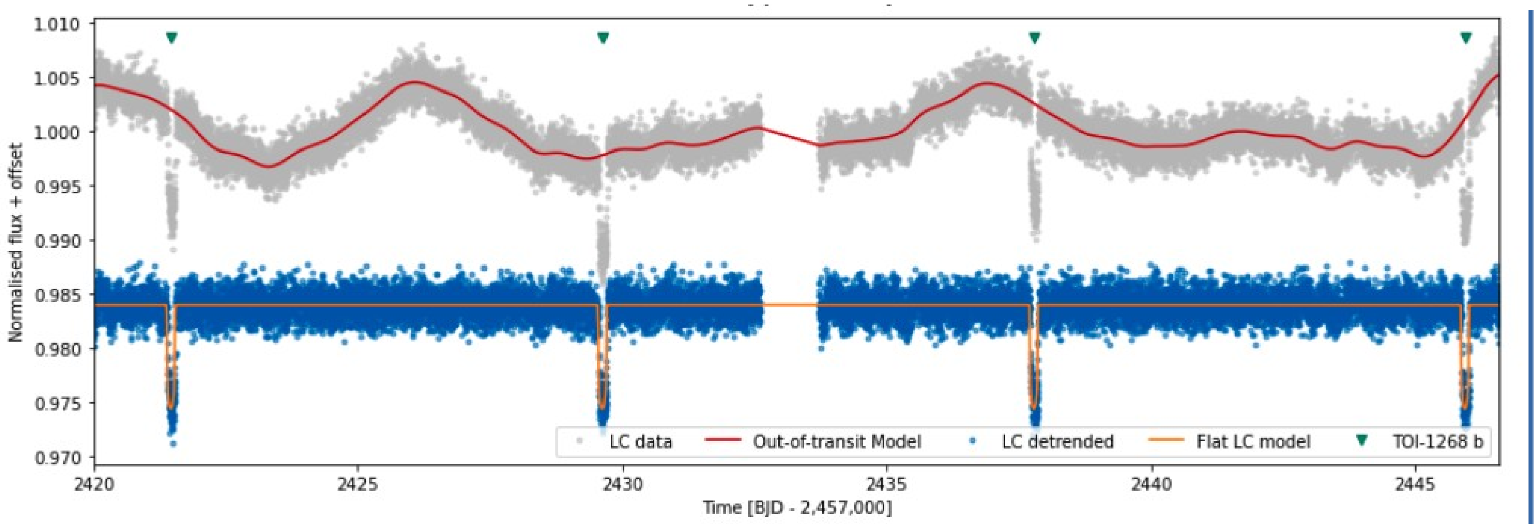
Astronomický ústav AV ČR

Further characterization?



TOI-1268 warm Saturn around a young K star

- A warm Saturn
- Period 8.1 days
- Paper J. Subjak et al. 2022, A&A



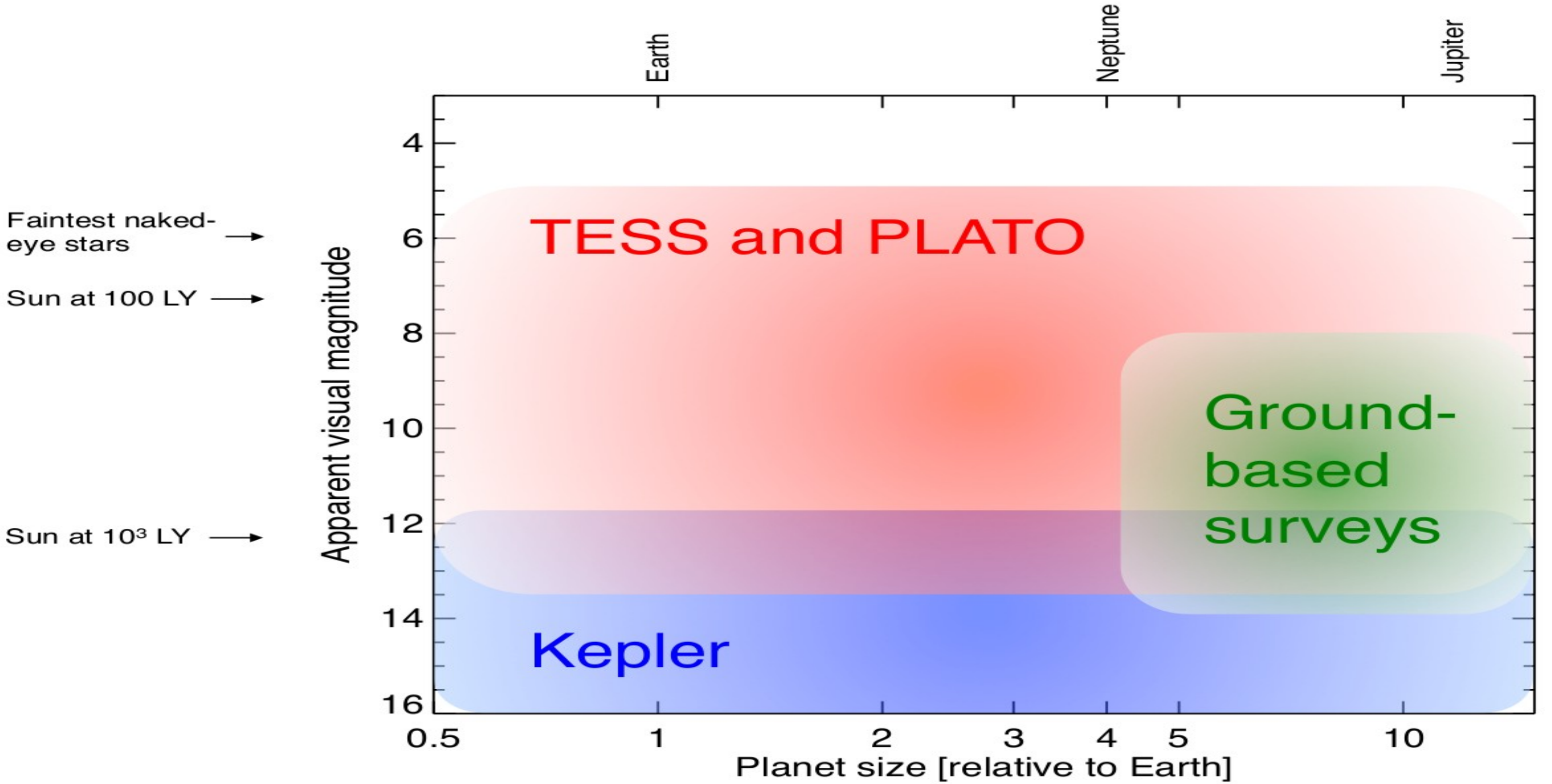
Conclusions

- Detection of a candidate is the very first step
- Ground based follow-up is extremely important
- Confirmation process has several steps

  - stellar parameters, high. Res photometry, high precision RVs
- Only candidates passing all steps above are planets
- The mission strategy and follow-up strategy need to be synchonized
- The follow-up can take more than 6 months

Astronomický ústav AV ČR

Space missions compared



Credit: PLATO Space mission

Exoplanet types

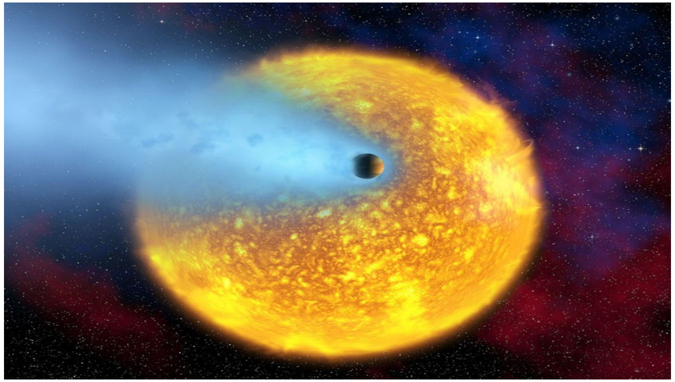
State of the art in 2006

- Hot Jupiters – gas planets
- Super Earths – small terrestrial planets

Types of planets (2006)

Giant planets (hot Jupiters)

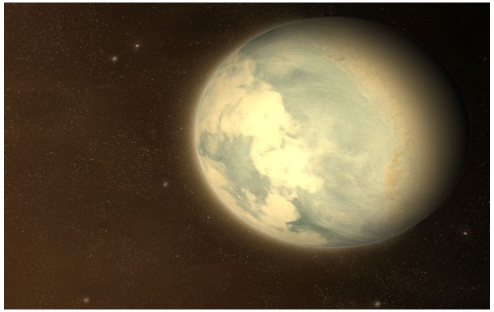
- close-in orbits
- short orbital periods (a few days)
- Jupiter-sized
- In transit with intensity decrease of a few %
- 1995 first detection 51 Peg (Mayor & Queloz 1995)



Vidal-Madjar et al. (2004)

Super Earths

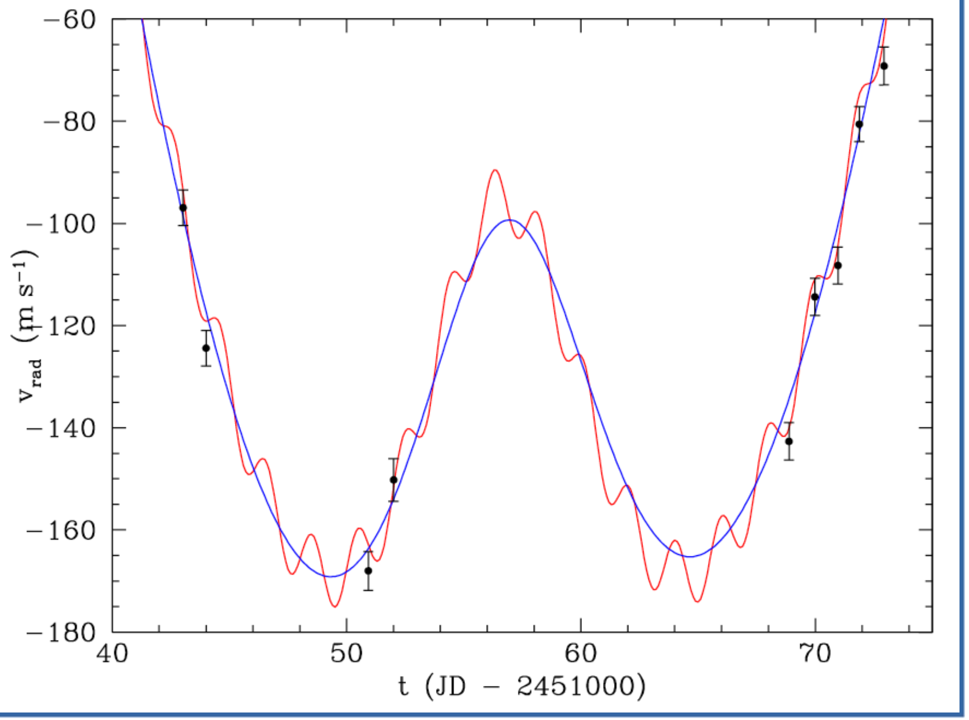
- masses up to 10 M_{Earth} (Valencia 2007)
- constraint on radius: 10 M_{Earth} – max 1.9 R_{Earth} (Valencia 2007)
- consist of rocks and iron & planetary ice (Fortney 2007)
- Gliese 581 system (Mayor, Udry 2009)

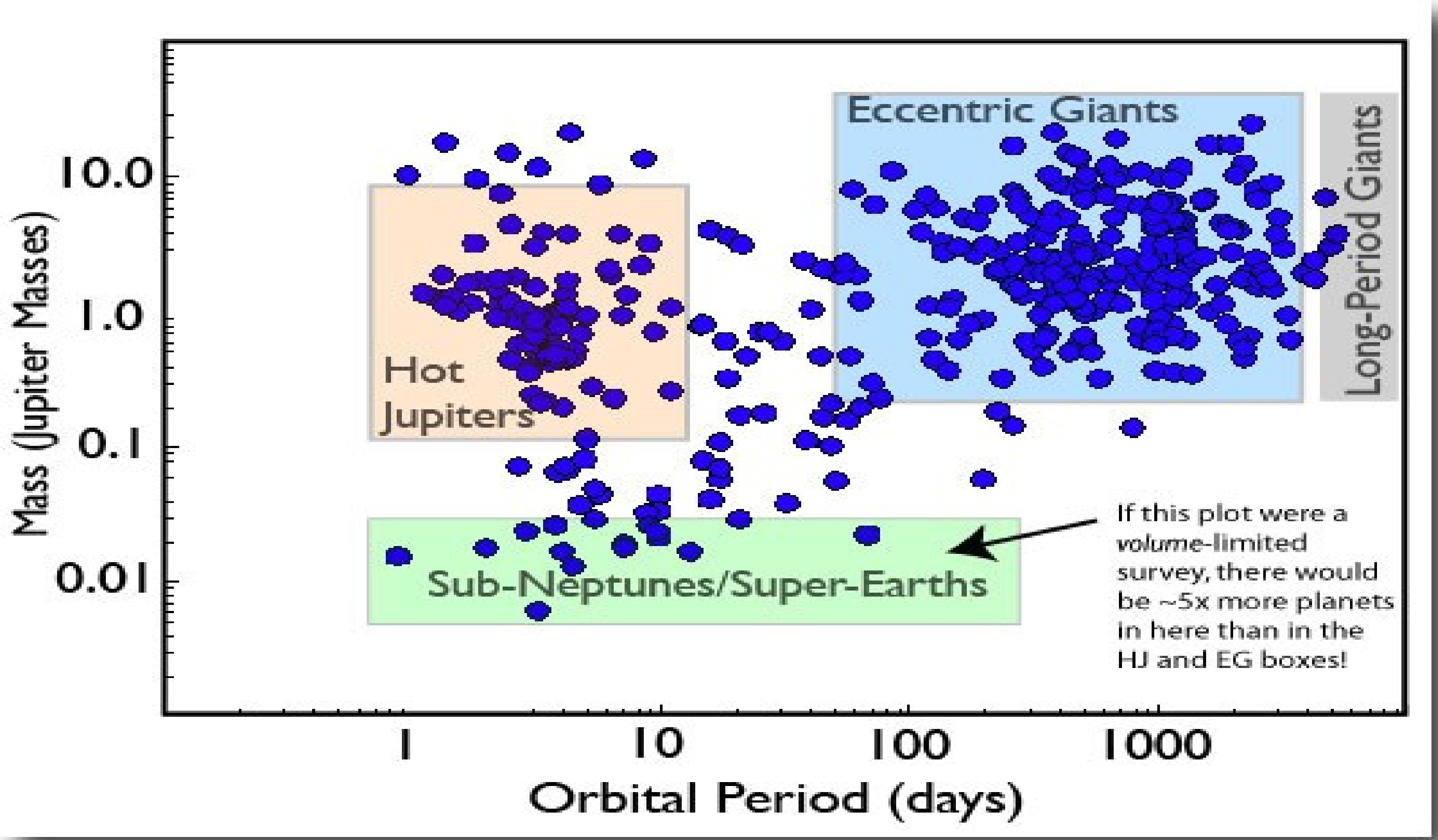


The first Super Earth

- GJ 876d Rivera et al. 2005 (Figure with RVs) https://arxiv.org/pdf/astro-ph/0510508.pdf
- M=7.5Mearth
- The first model
- - Valencia et al. 2006

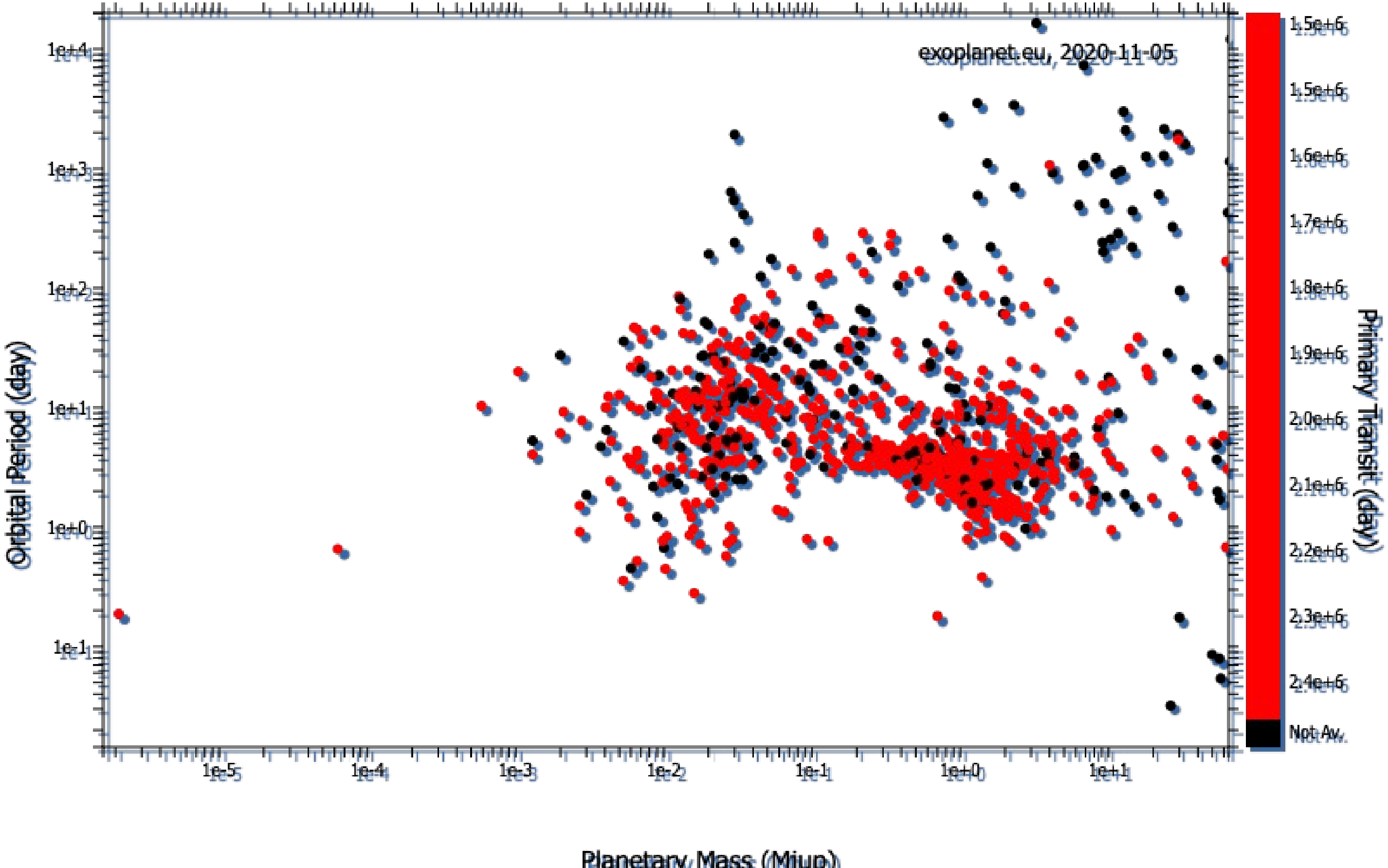
  https://iopscience.iop.org/
- article/10.1086/509800/pdf



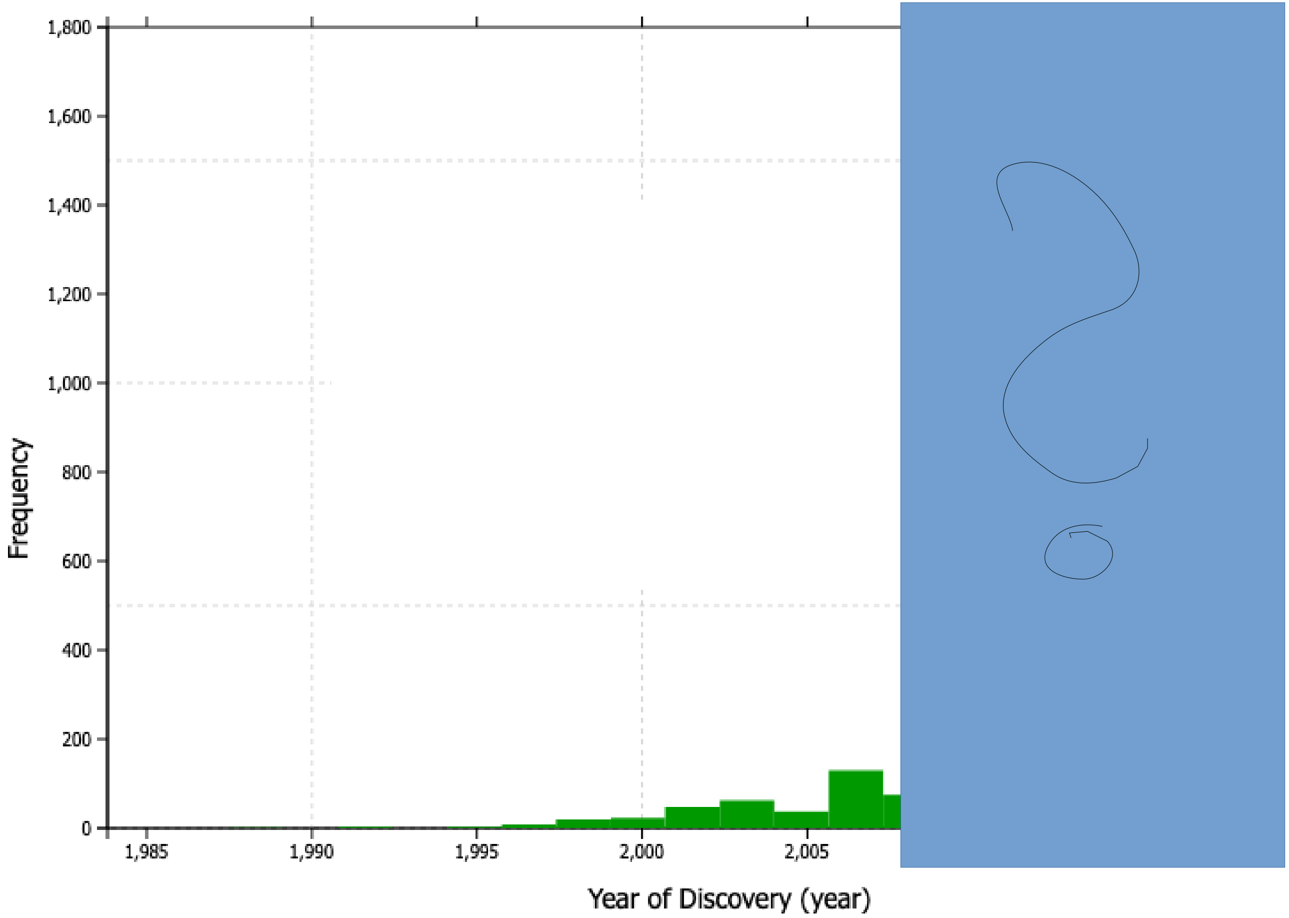


Mass (Jupiter Masses)
10.0
1.0
0.1
0.01
Eccentric Giants
Long-Period Giants
Hot
Jupiters
Sub-Neptunes/Super-Earths
If this plot were a
volume-limited
survey, there would
be ~5x more planets
in here than in the
HJ and EG boxes!
1
10
100
1000
Orbital Period (days)

Mass vs. Period

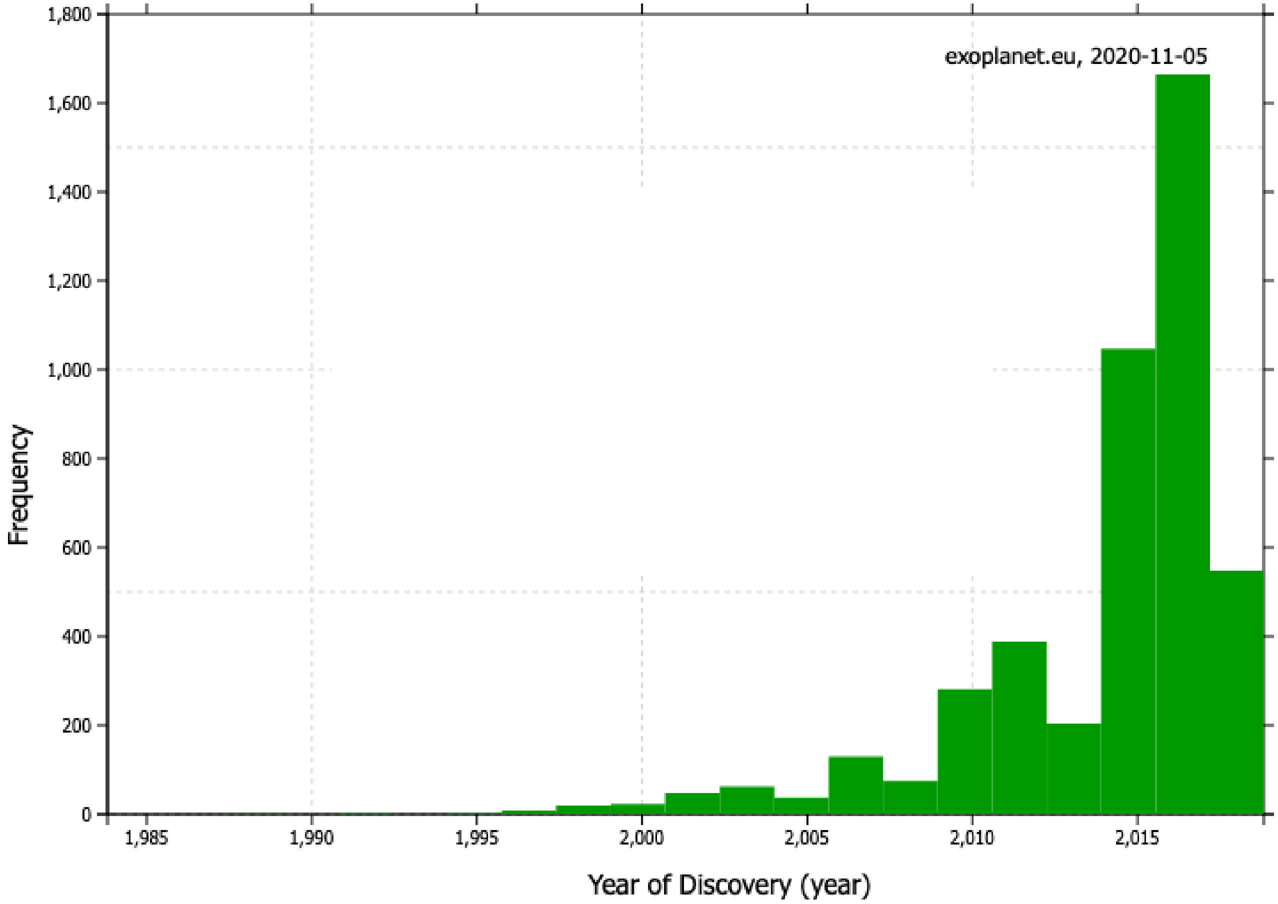


Status 2006



1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
Frequency
1,985
1,990
1,995
2,000
2,005
Year of Discovery (year)

How is the status today?



Then came mini-Neptunes

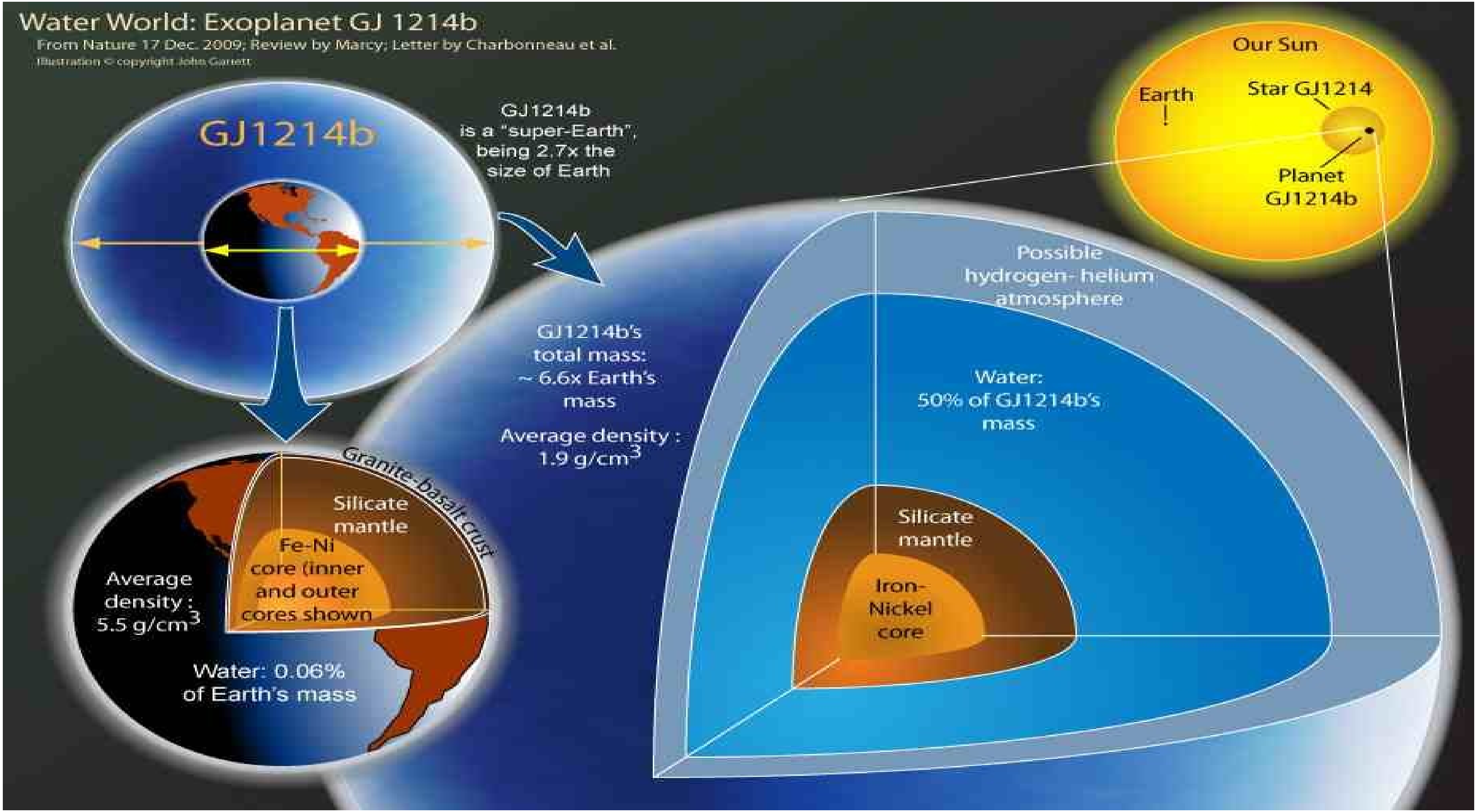
GJ1214b

- **Super-Earth-sized planet detected in 2010**

Charbonneau et al. 2010, Nature

PARAMETERS

- **Orbiting M dwarf star (V=14.71 mag) in 1.58 days**
- **Only 14pc distance**
- **M=0.02Mj**
- **R=0.245Rj**
- **Mysterious atmosphere?**


Water World: Exoplanet GJ 1214b
From Nature 17 Dec. 2009; Review by Marcy; Letter by Charbonneau et al.
Illustration © copyright John Garrett
GJ1214b
GJ1214b is a "super-Earth", being 2.7x the size of Earth
Our Sun
Earth
Star GJ1214
Planet GJ1214b
Possible hydrogen- helium atmosphere
GJ1214b's total mass: ~ 6.6x Earth's mass
Average density : 1.9 g/cm3
Water: 50% of GJ1214b's mass
Silicate mantle
Iron-Nickel core
Granite-basalt crust
Silicate mantle
Fe-Ni core (inner and outer cores shown
Average density : 5.5 g/cm3
Water: 0.06% of Earth's mass

Super Earths and Rocky planets

- Super Earths < 10 M Earth (Valencia et al. 2006)
- Planets with a solid surface
- Sub-group of SupearEarths
- They can have an atmosphere or not
- Kepler discovered the most of them

Super Earths mass limits

- 1-10 Mearth
- Ida et al. 2004, ApJ, https://iopscience.iop.org/article/10.1086/381724/fulltext/58801.text.html

  - 10MEarth is the limit where H. He gas can be retained

  - lower bound is for historical reasons
- In this group belong planets with oceans, rocky and massive Earths planets

Warm Jupiters

- Gas giants with orbital periods 10-200 days
- HD 80606 b – 111 days period

  - binary component HD 80607

  - 4 Jupiter masses

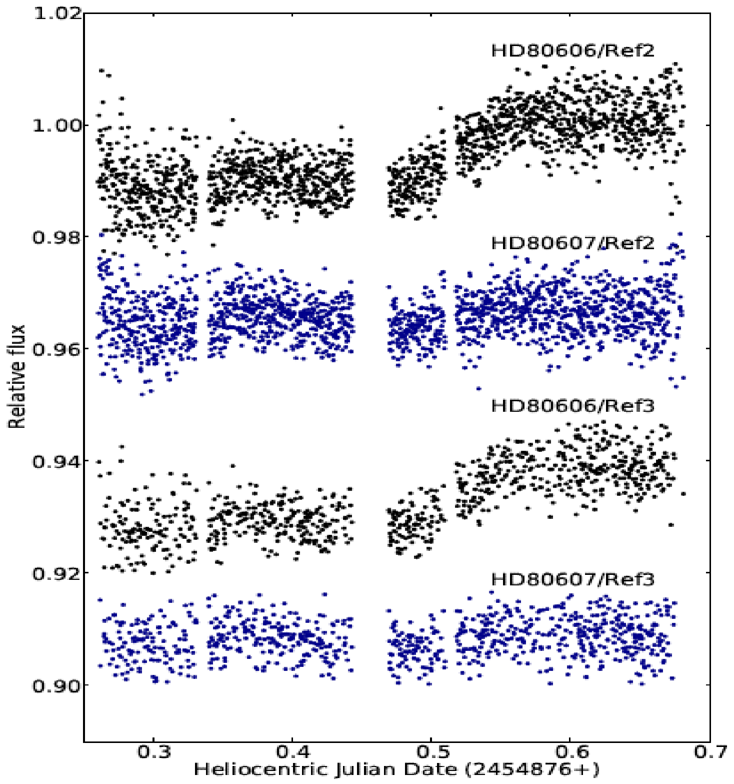
  - 12 hrs. Transit

  - 0.93 eccentricity (very high)
- Orbital parameters

  might be the key to formation?
- Discovery:

  Naef et al. 2001

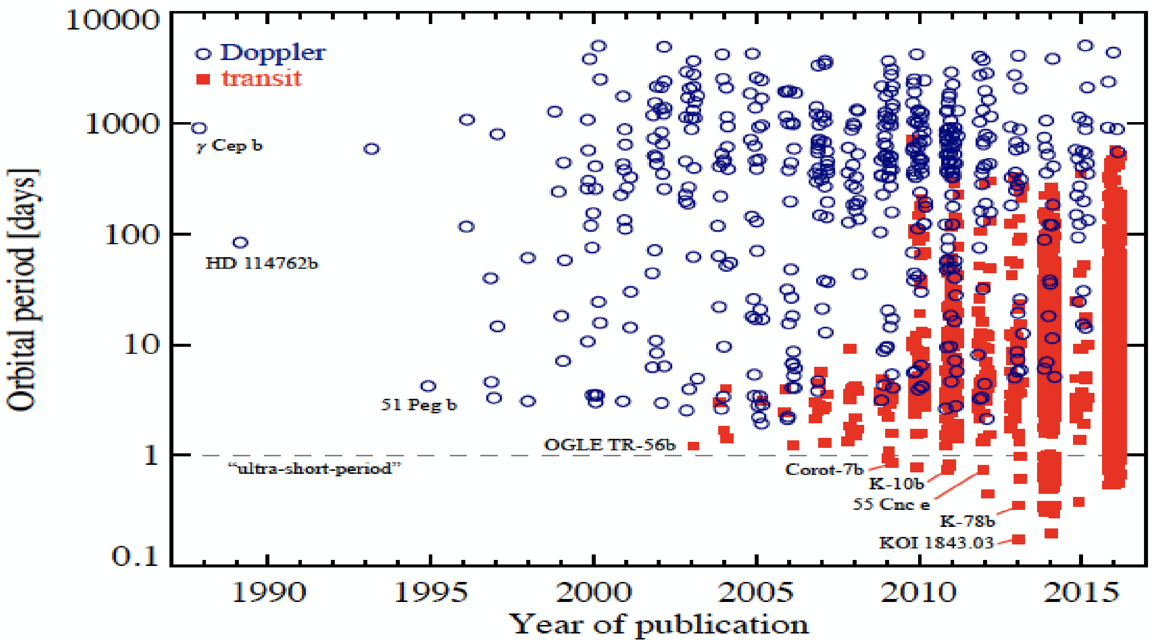
  https://www.aanda.org/articles/aa/pdf/2001/32/aade293.pdf



Fossey et al. - https://arxiv.org/pdf/0902.4616.pdf

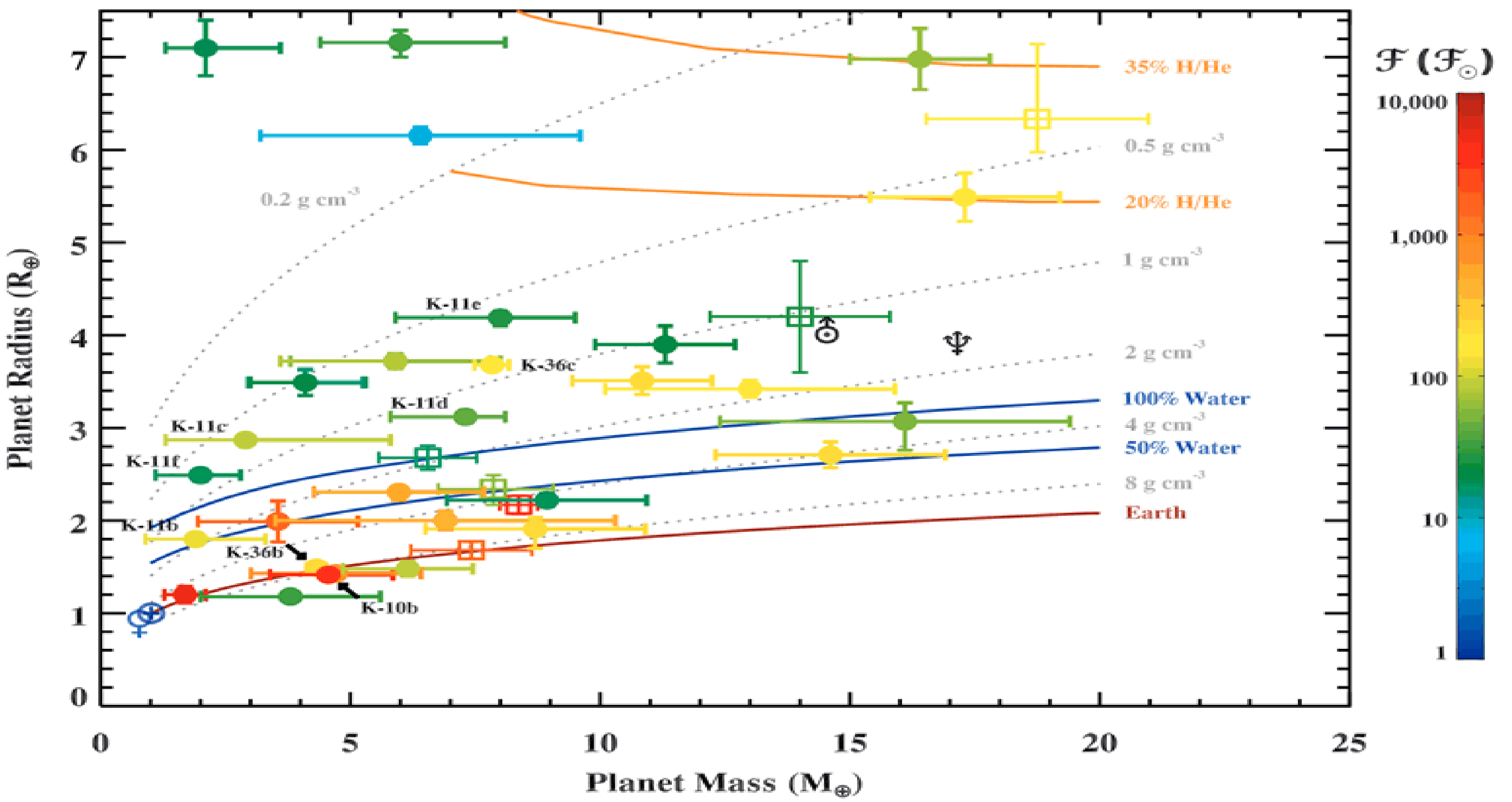
Ultrashort period planets (USPs)

- Small planets often called Lava worlds
- Orbital periods < 1 day
- Very close to host stars
- Very high surface temperature

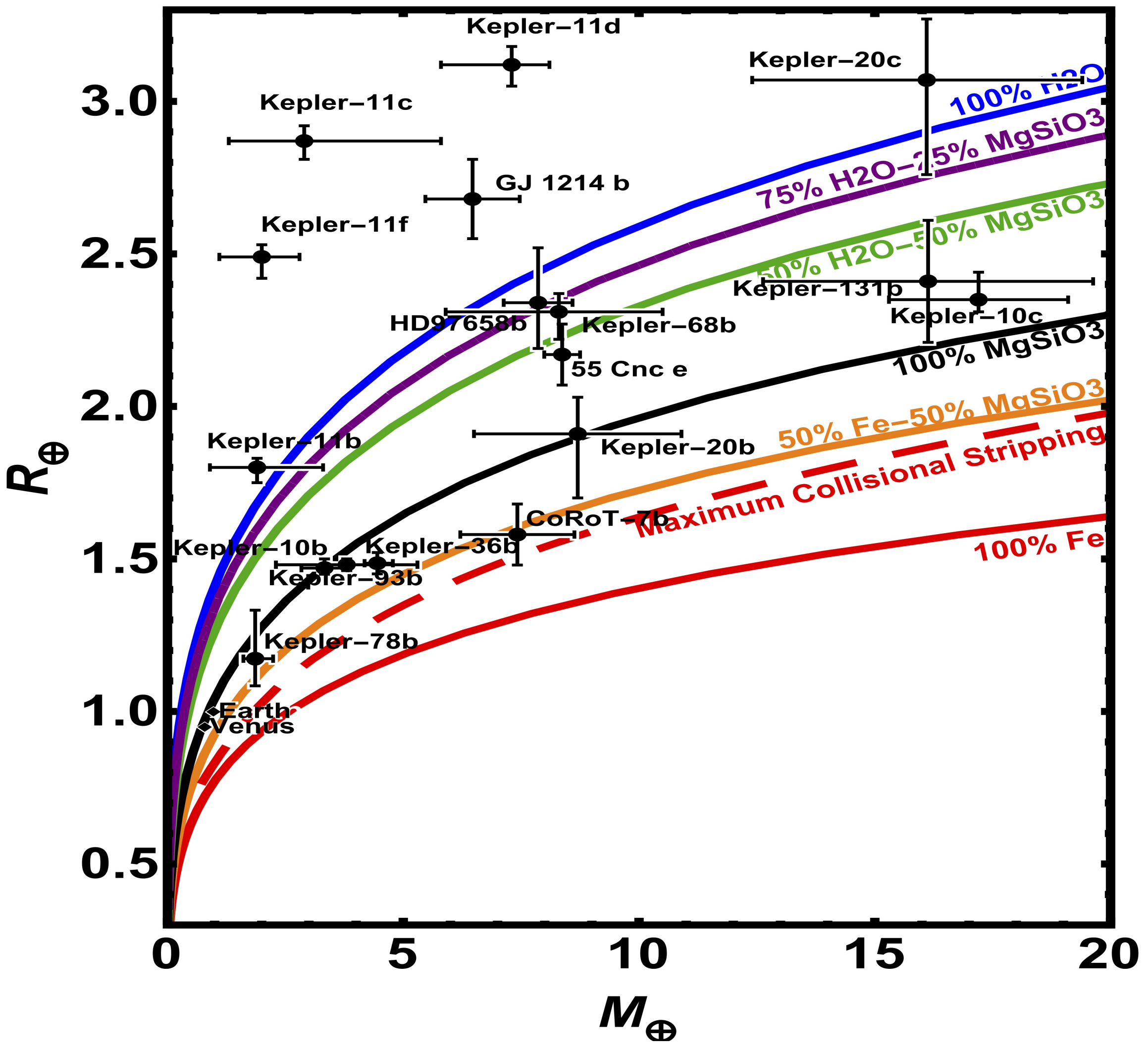


Winn et al 2020 https://arxiv.org/pdf/1803.03303.pdf

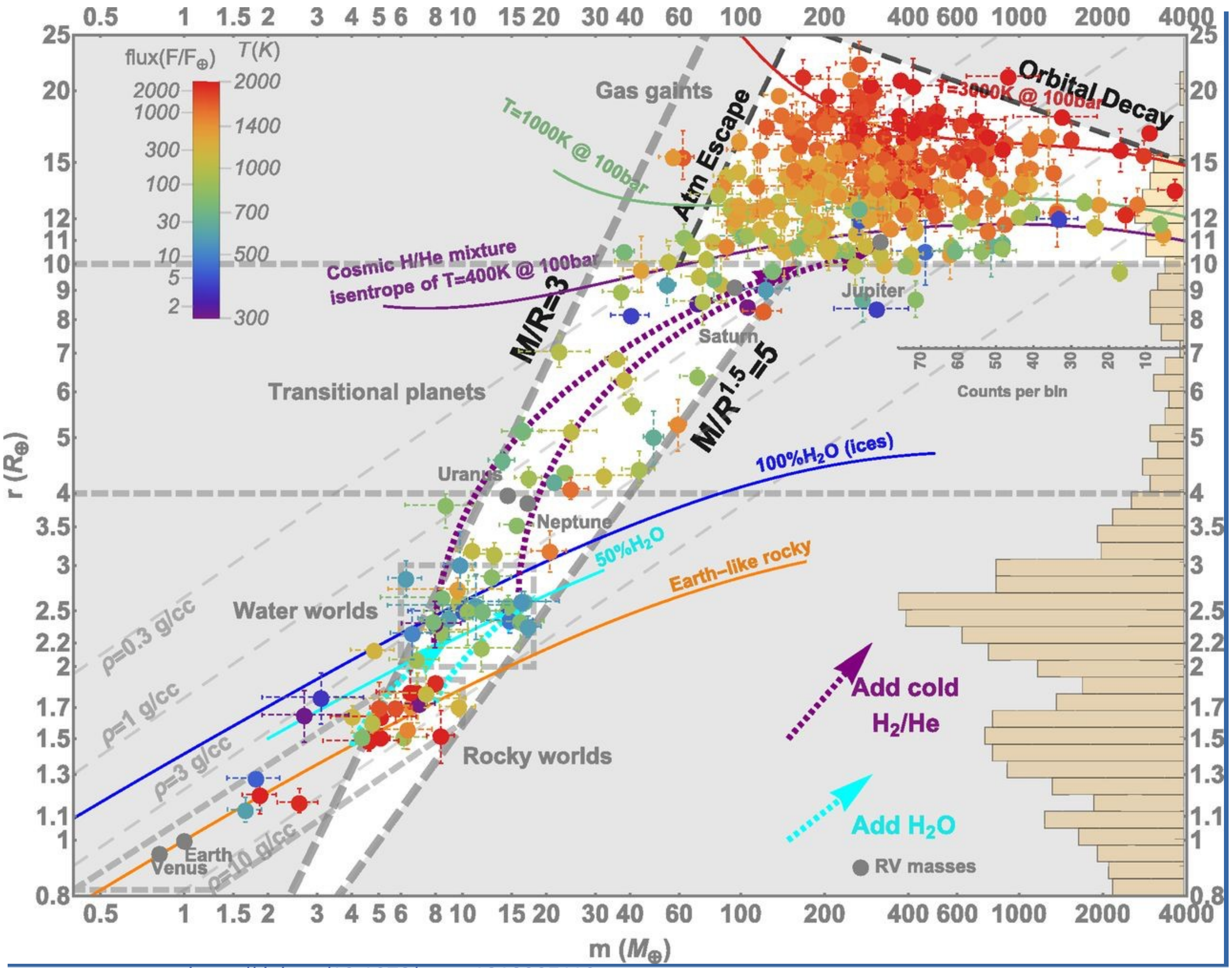
Mass radius diagrams



http://arxiv.org/abs/1409.1595

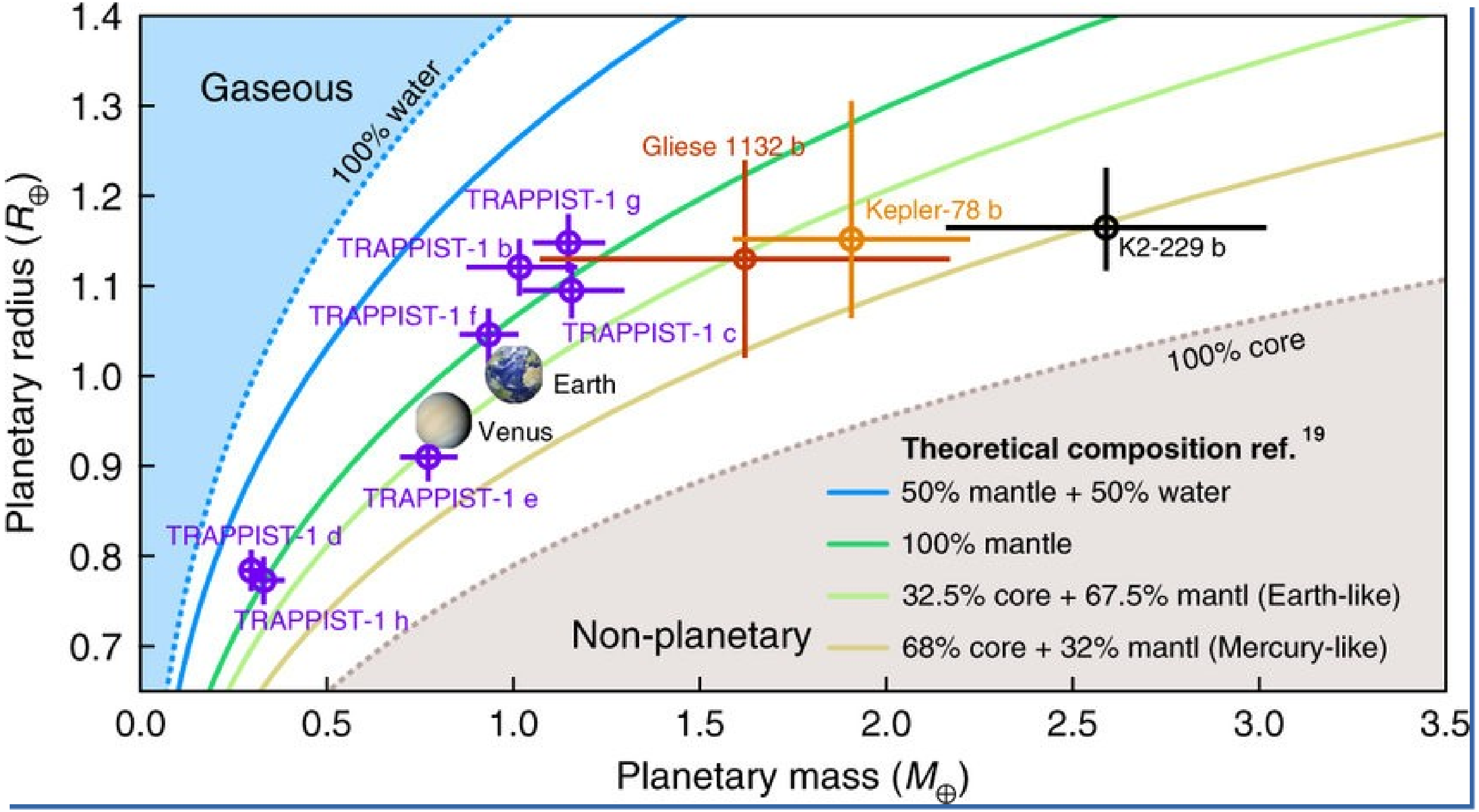


https://www.cfa.harvard.edu/~lzeng/Exoplanet%20Models.html



Zeng et al. 2019, PNAS, https://doi.org/10.1073/pnas.1812905116

Getting closer to the Earth-like



Santerne et al. 2018, https://www.nature.com/articles/s41550-018-0420-5

Next lecture

- Evolution of our Solar System
- Evolution of exoplanetary systems
- The place of our Solar system in the Universe