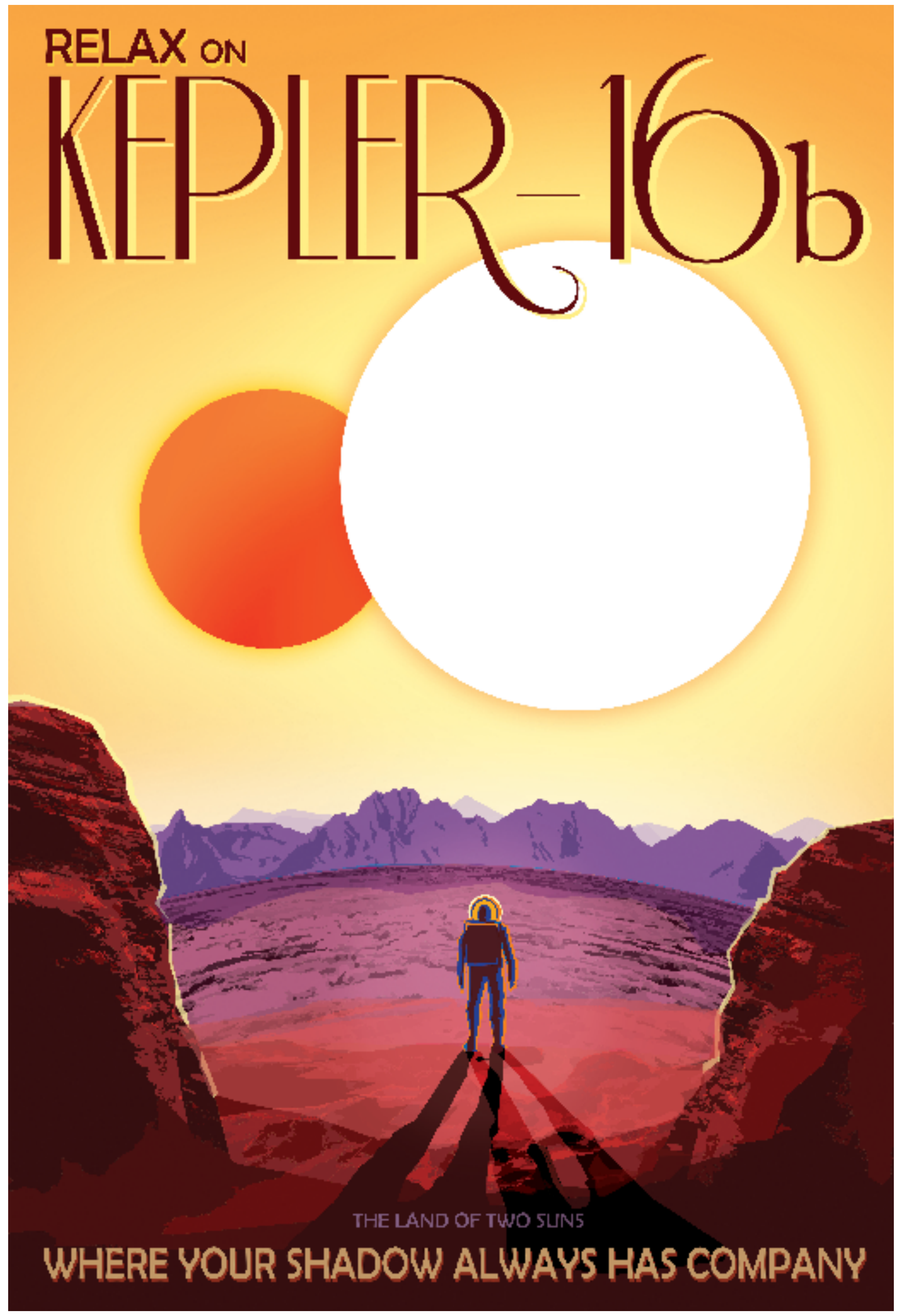


Exoplanets

Fran Bartolić
Petnica Summer School on Astrophysics

fbartolic

University of St Andrews
St Andrews Centre for Exoplanet Science

About me

St Andrews Centre for Exoplanet Science

- PhD student in data-intensive astronomy at the University of St Andrews in Scotland
- I'm interested in probabilistic modelling of astrophysical data

Overview of the lectures

Lecture 1 (Today)

- General introduction to exoplanet science
- The two-body problem and planetary dynamics (whiteboard)

Lecture 2 (Tomorrow)

- Hands on Python exercises on N-body simulations

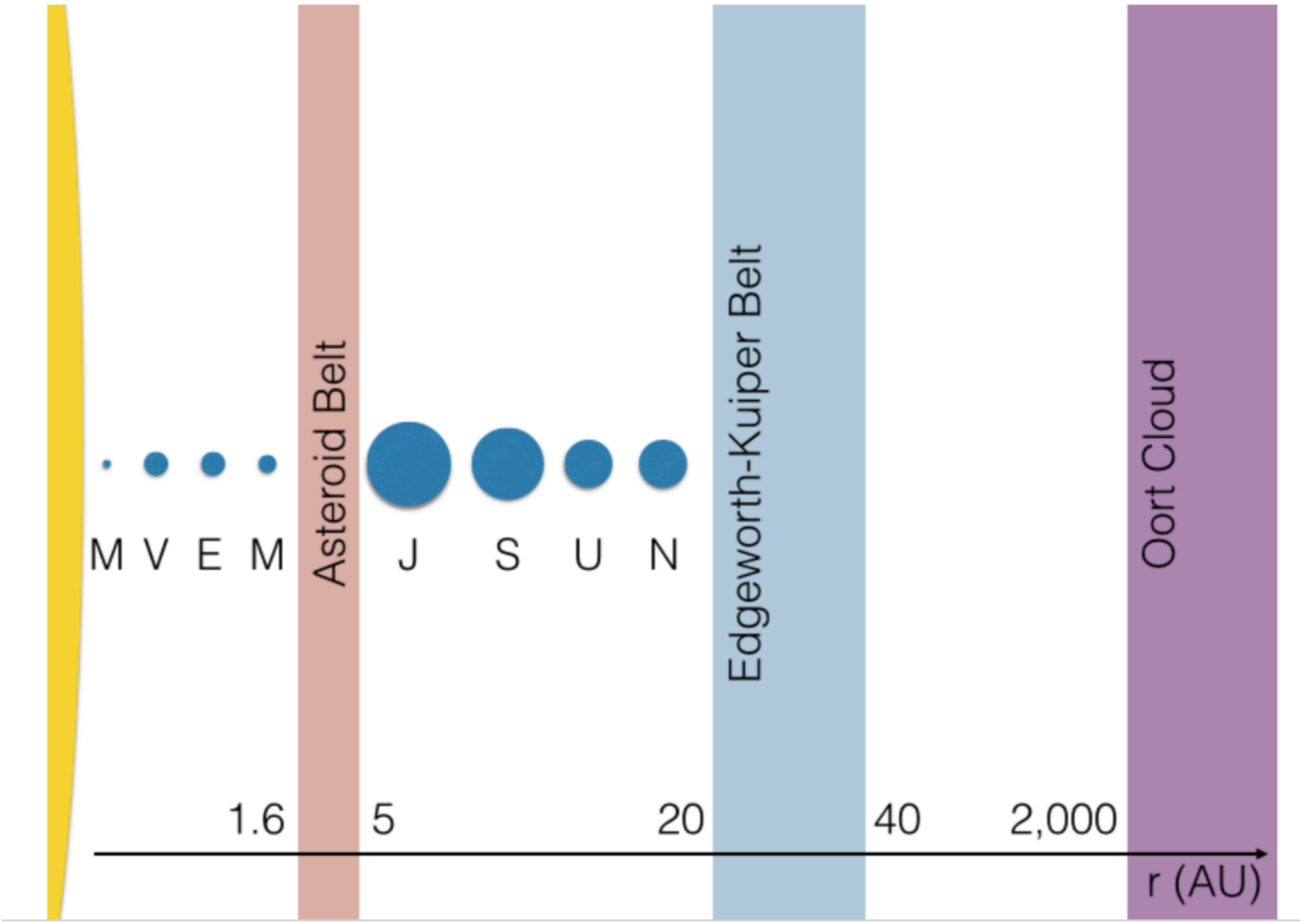
Lecture 3 (Monday)

- A (very) brief intro to Bayesian data analysis
- Hands on Python exercises on fitting an exoplanet transit light curve with MCMC

Outline of this lecture

1. The Solar System
2. Detection Methods
3. Observed population of exoplanets
4. Planet Formation
5. Exoplanet atmospheres
6. Habitability

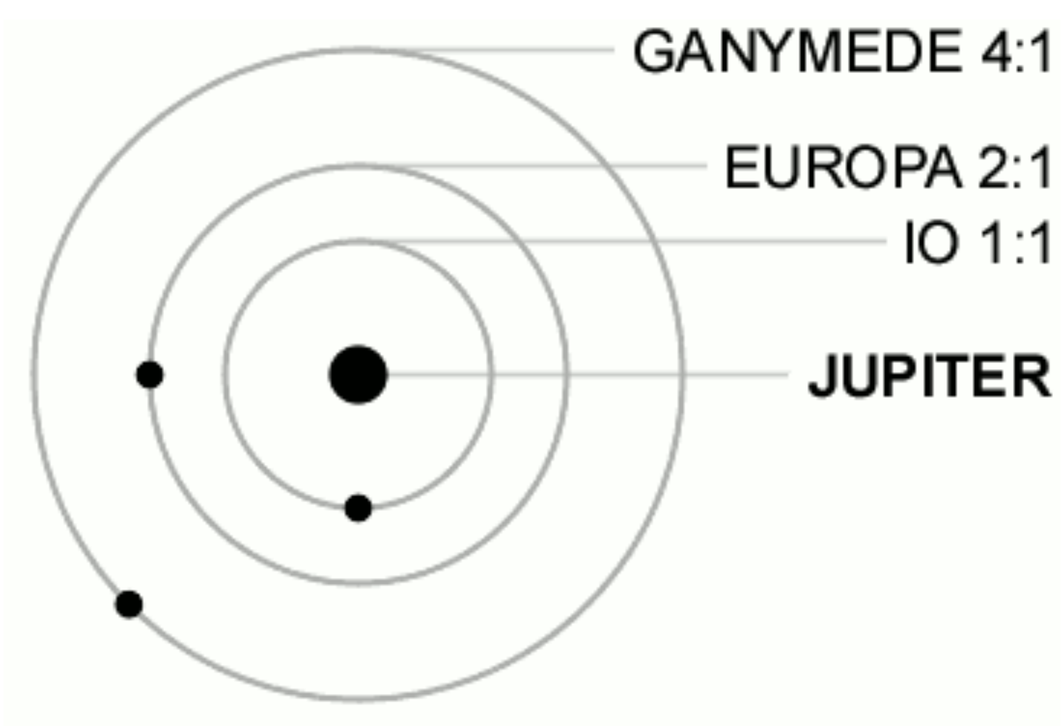
The Solar System

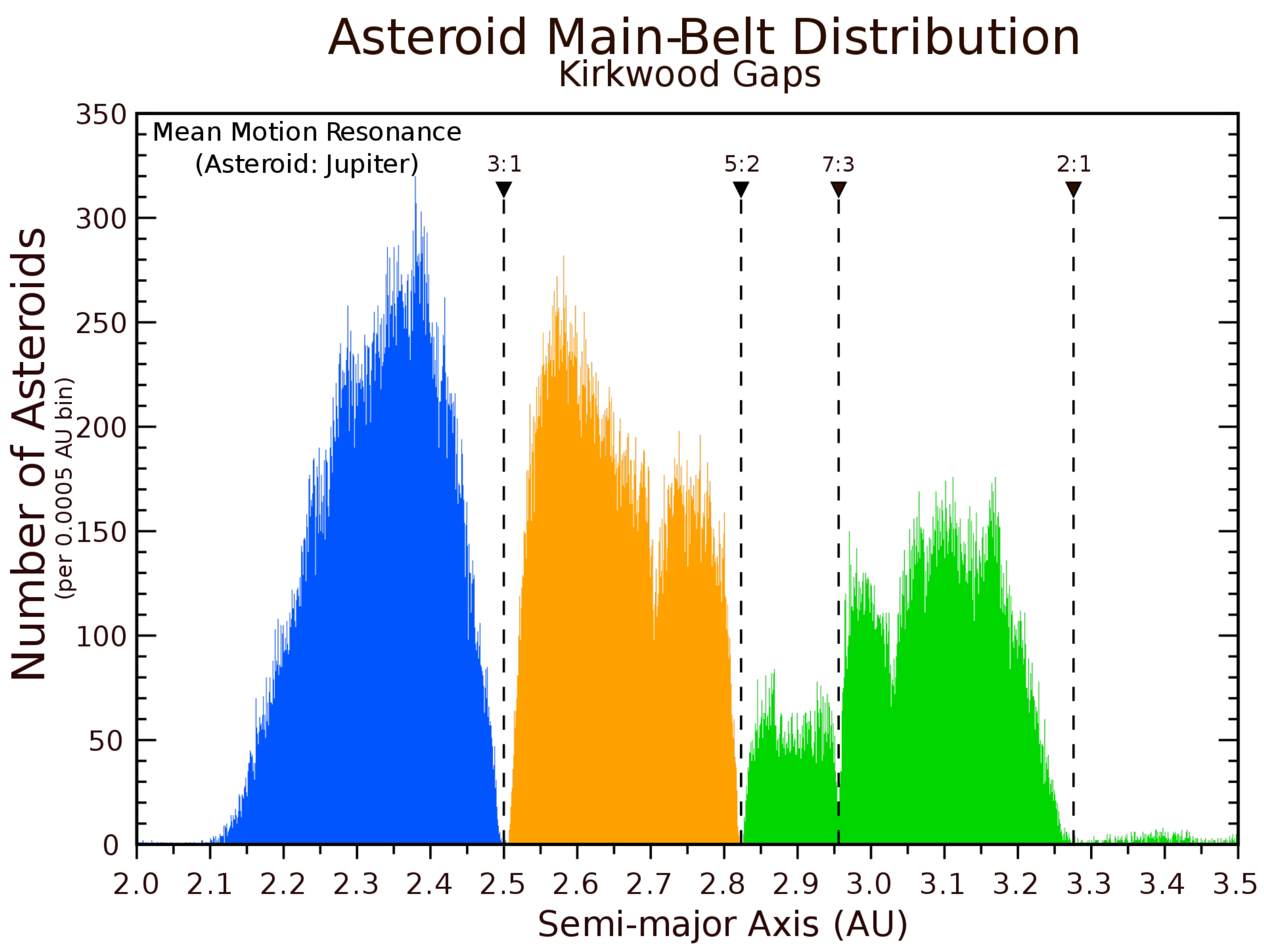


© Duncan Forgan

- 8 planets, 5 dwarf planets (Ceres, Pluto, Eris, Makemake, Haumea)
- TNOs, asteroids, comets, meteorites and dust
- Rocky inner planets, gaseous outer planets
- 4.5B years old (radioactive dating of rocks)
- Mostly co-planar circular orbits
- $> 99\,\%$ of mass in the Sun
- $> 99\,\%$ of angular momentum in the planets
- Dynamically full

The Solar System - Resonances



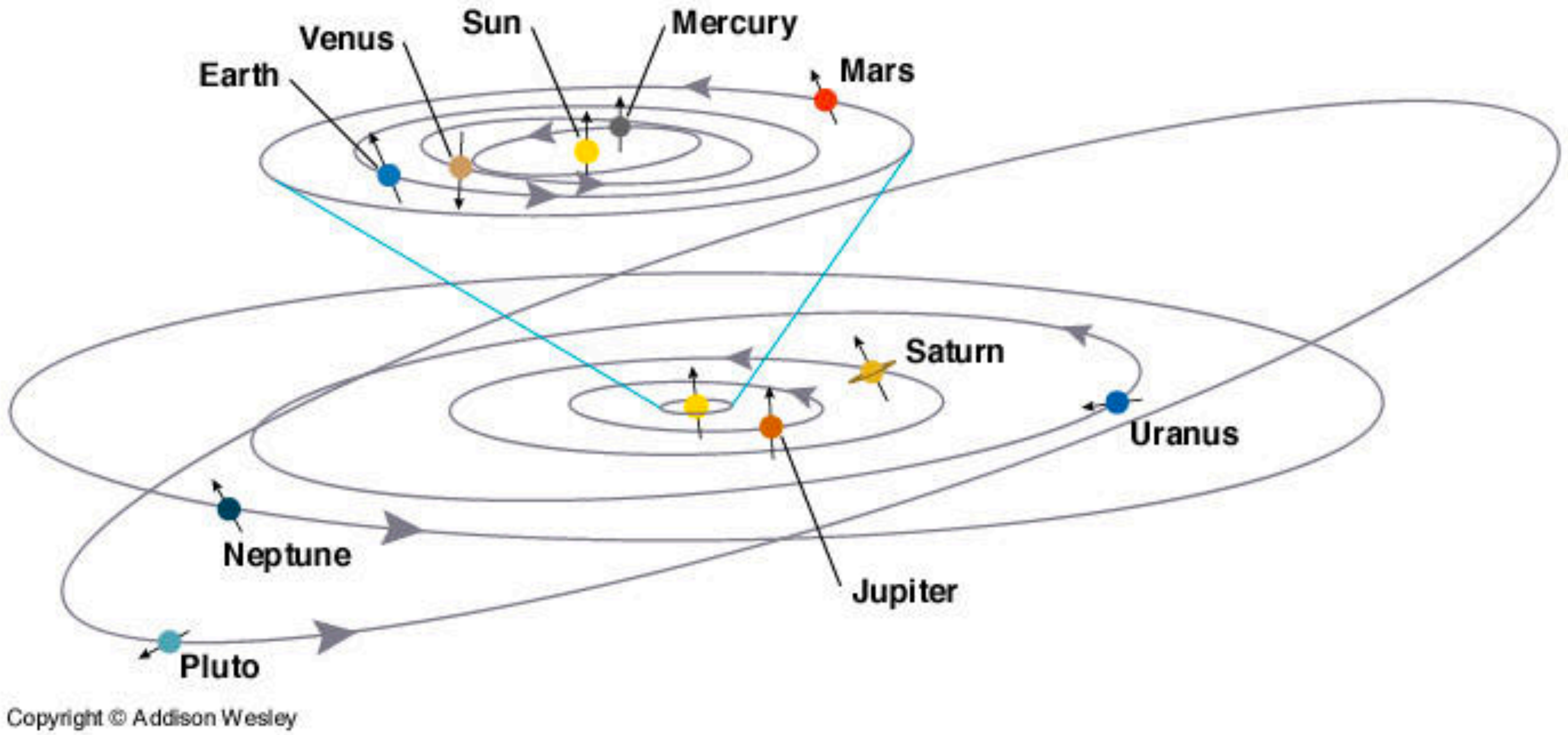


- Mean motion resonances occur when two bodies have near-integer period ratios

$$\frac{P_2}{P_1} \approx \frac{p}{q} \quad \text{where } p, q \text{ are integers}$$

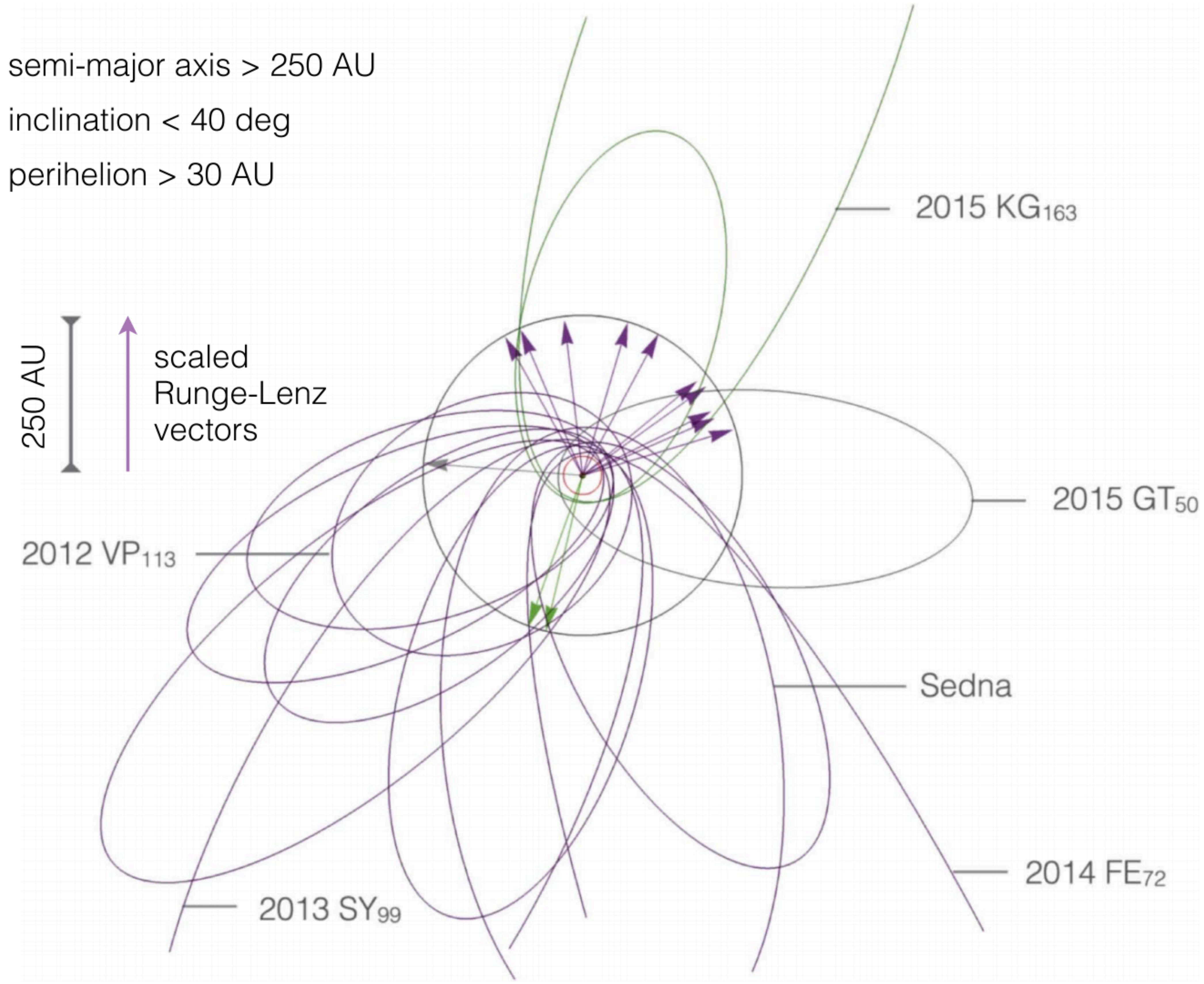
- Galilean moons are in a 4:2:1 resonance
- Neptune and Pluto in a 3:2 resonance
- Resonances in the asteroid belt - Kirkwood gaps
- Resonant configurations *a priori* unlikely

The Solar System - Formation



- Orbits circular and co-planar, spin and orbital angular momentum vectors mostly aligned
- **Inner terrestrial planets**
  - Small, dense, made of rocks and metals, warm
- **Outer gaseous planets**
  - Larger and more massive, made of mostly Hydrogen and Helium, cool
- These characteristics point to formation in a disc of dust and gas
  - Terrestrial planets formed in inner parts of the disc where it's too for ices to form
  - Gas giants formed further out

The Solar System - Planet Nine



Batygin & Morbidelli 2017

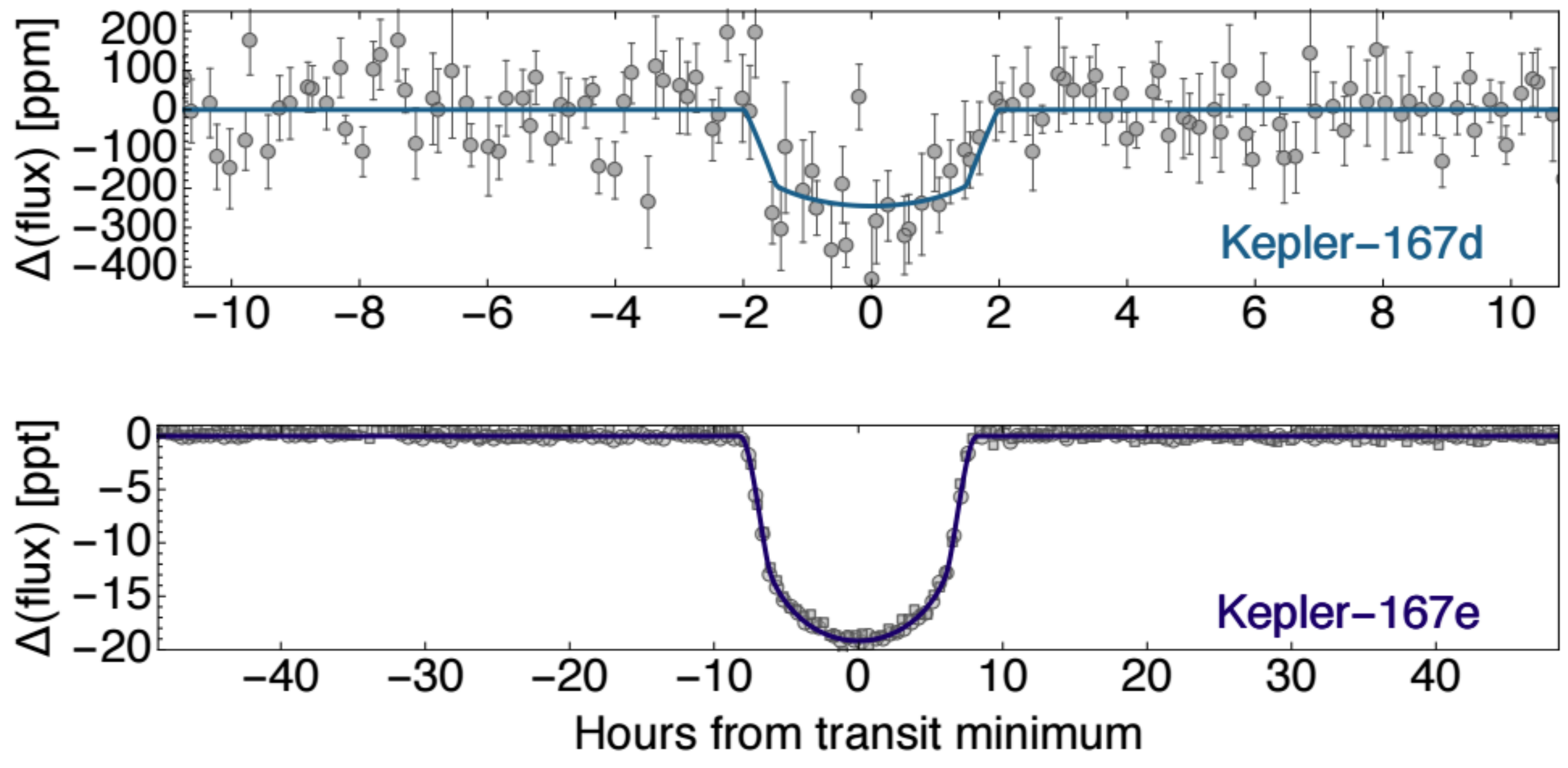
- Orbits of a few distant Kuiper Belt objects beyond > 250 AU cluster in an unexpected way
- Several people, most notably Batygin & Brown (2016) proposed a distant massive planet beyond Neptune to explain the clustering
- “Planet Nine” is estimated to be 5-10 Earth masses, orbiting at 650-700 AU in an eccentric orbit
- No observational evidence as of yet, if it exists it’s likely very cool and dim hence difficult to spot

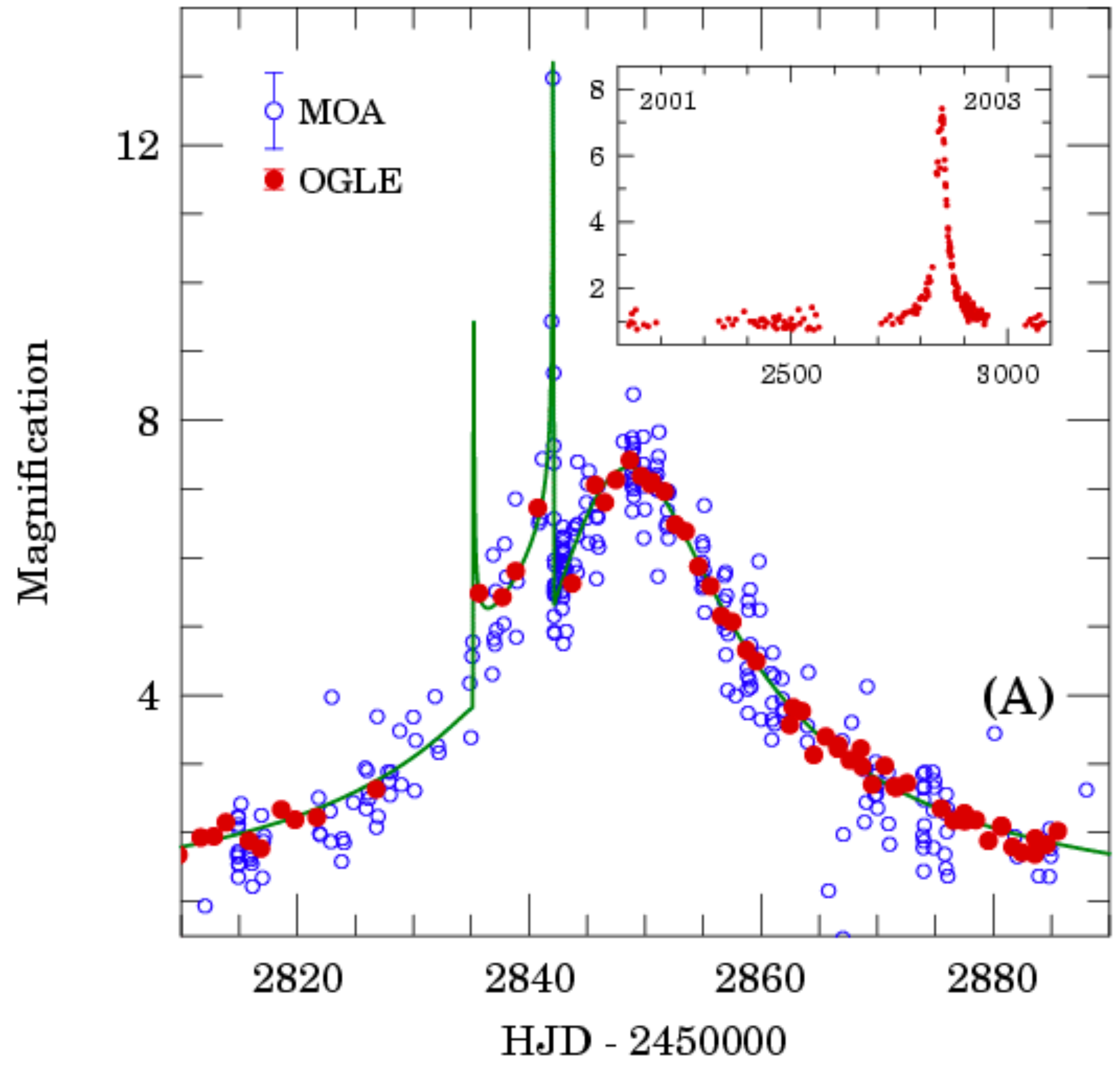
Beyond the Solar System

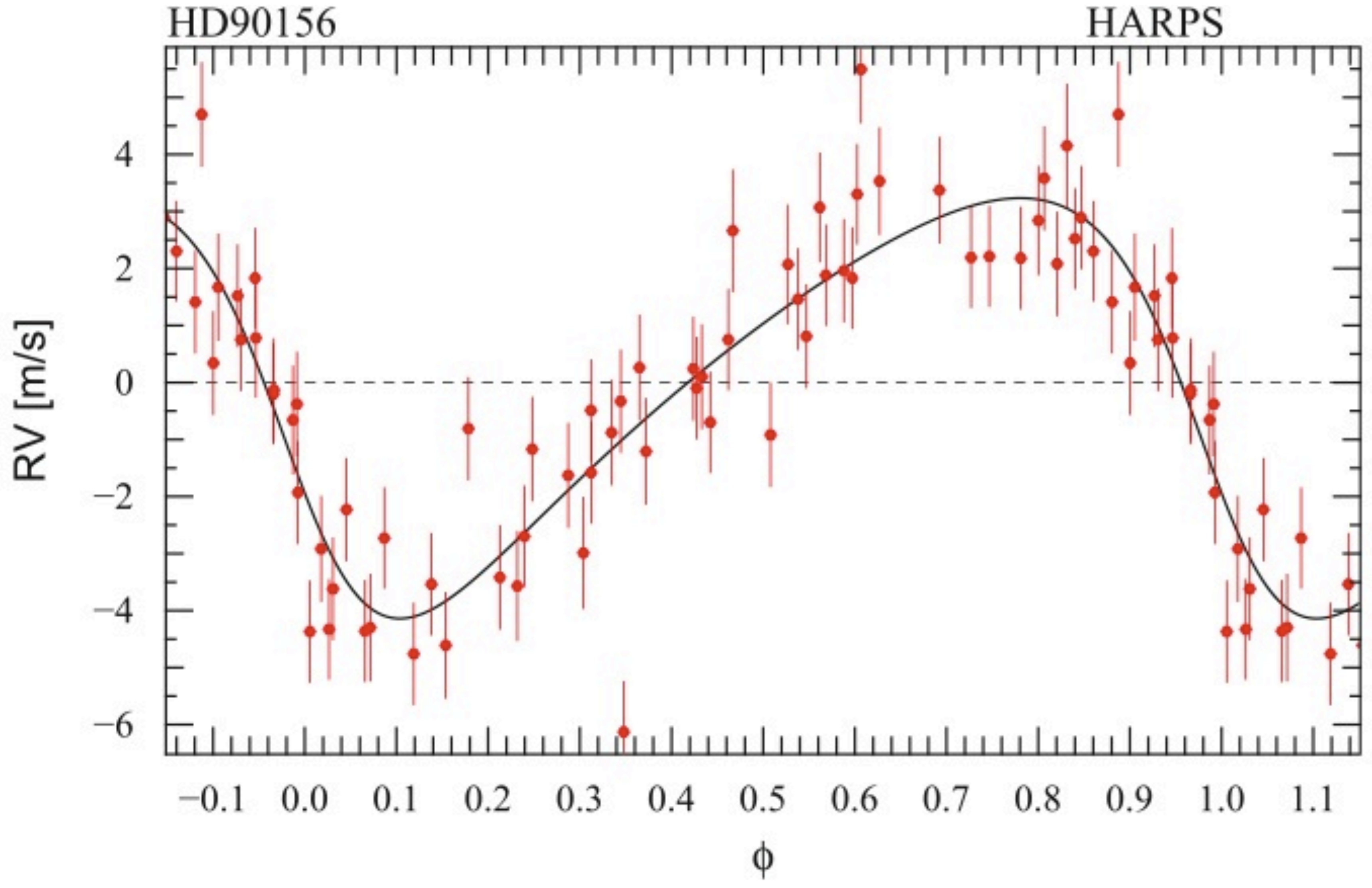
What is an exoplanet?

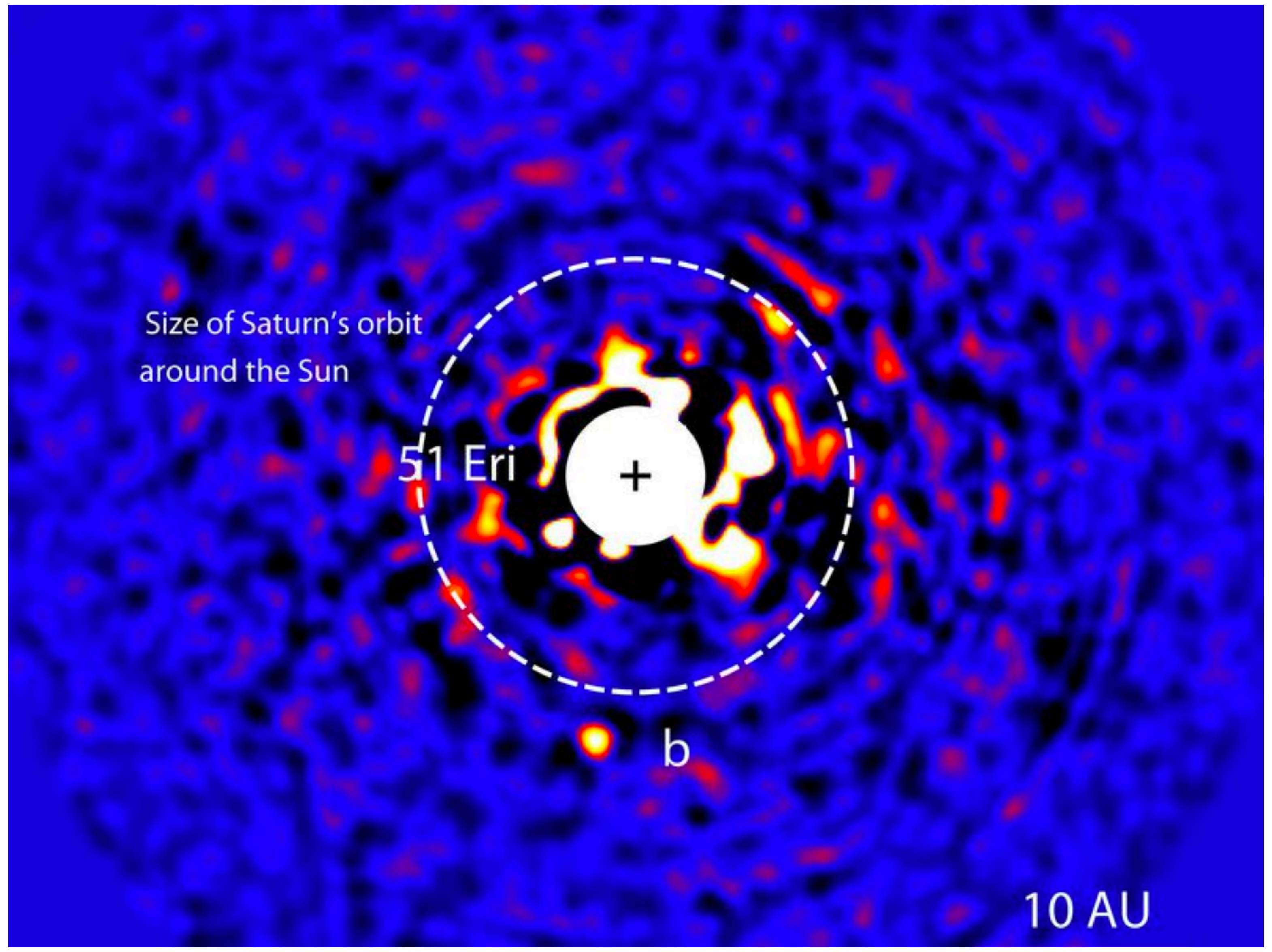
Not an exoplanet

An Exoplanet

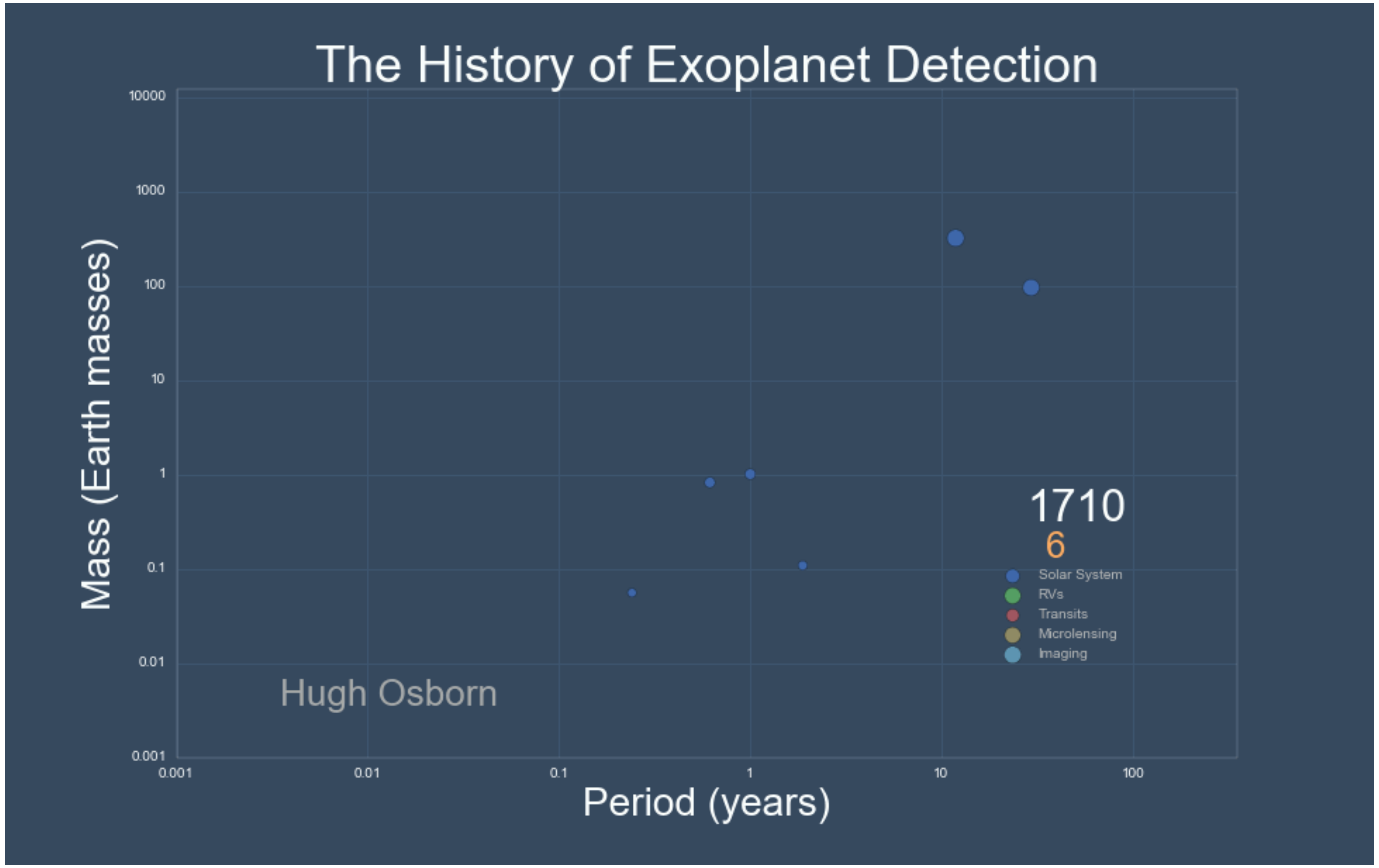








History of exoplanet discovery



© Hugh Osborne

- First confirmed exoplanet PSR B1257+12 discovered in 1992, orbiting a Neutron star!
- First planet orbiting a Sun-like star, 51 Pegasi b, discovered in 1995
- > 4000 exoplanets known today

We search for exoplanets by looking at stars instead

Exoplanet detection methods

Measuring flux from target star(s)

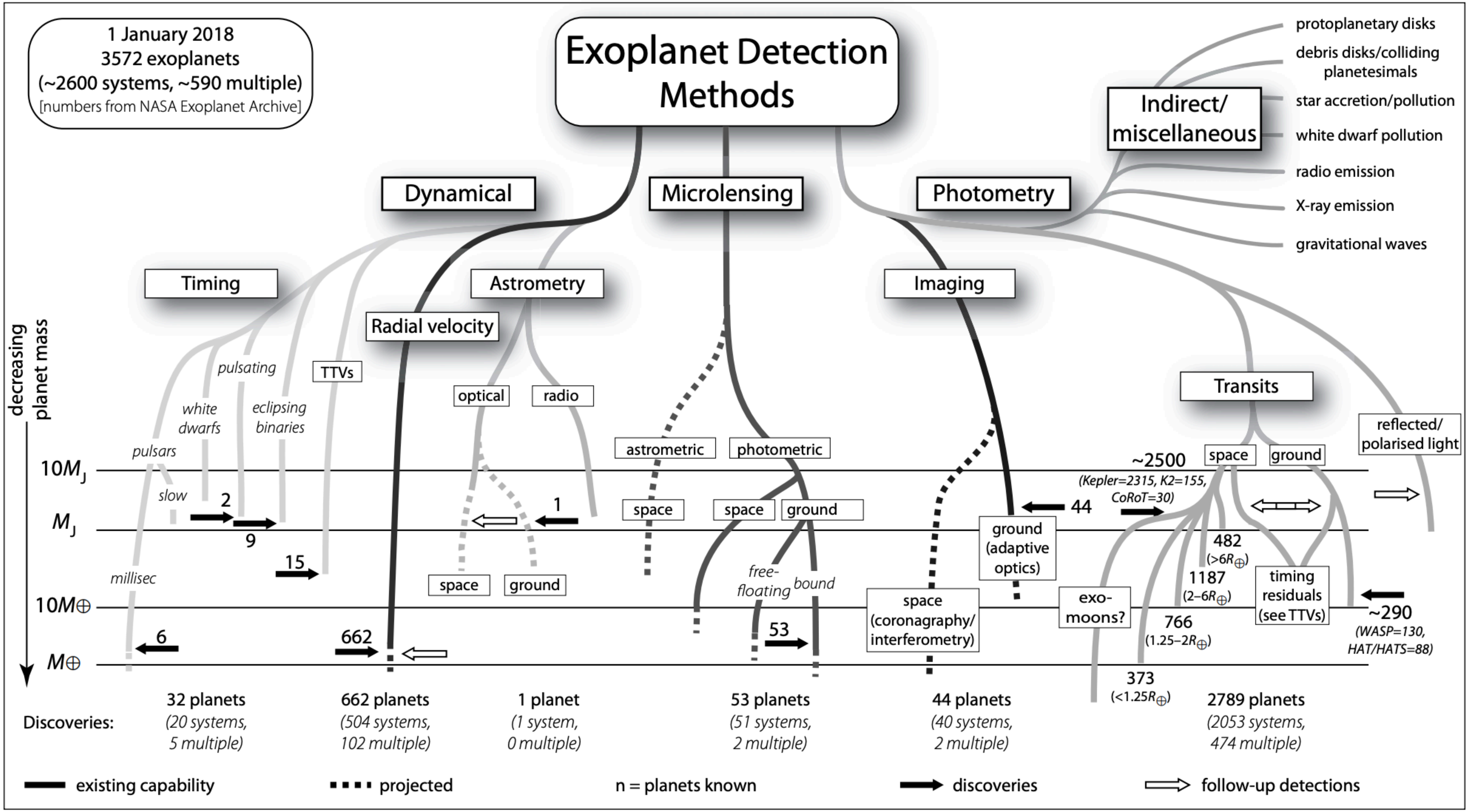
- Transits
- Gravitational microlensing

Measuring the motion of the star(s)

- Radial velocity
- Astrometry
- Transit timing variations

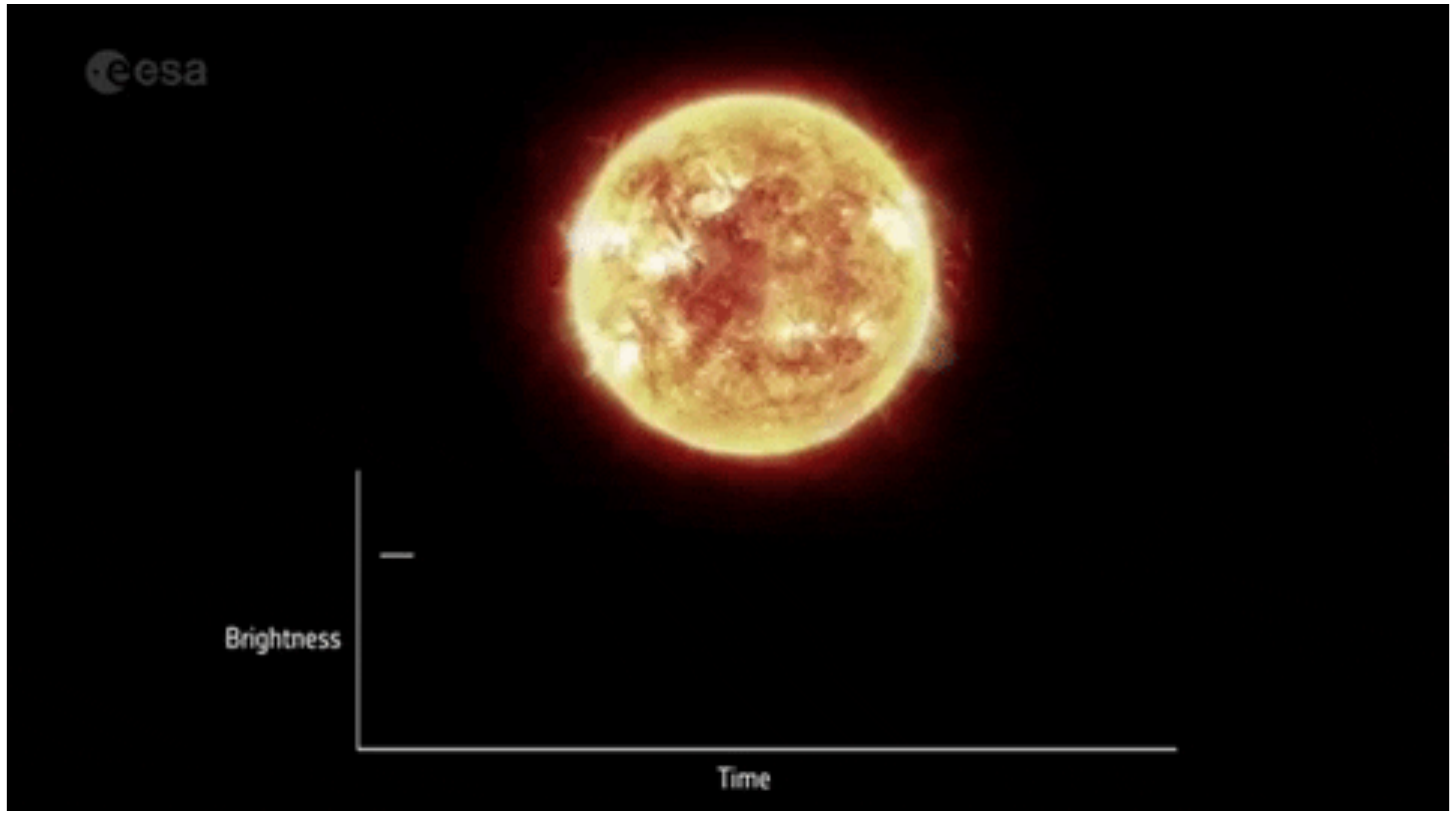
Direct detection

- Direct imaging



1 January 2018
3572 exoplanets
(~2600 systems, ~590 multiple)
[numbers from NASA Exoplanet Archive]
Exoplanet Detection Methods
Dynamical
Microlensing
Photometry
Indirect/ miscellaneous
protoplanetary disks
debris disks/colliding planetesimals
star accretion/pollution
white dwarf pollution
radio emission
X-ray emission
gravitational waves
Timing
Astrometry
Radial velocity
Imaging
Transits
pulsating
white dwarfs
eclipsing binaries
TTVs
pulsars
slow
millisec
optical
radio
space
ground
astrometric
photometric
space
space
ground
free-floating
bound
ground (adaptive optics)
space (coronagraphy/ interferometry)
reflected/ polarised light
space
ground
~2500
(Kepler=2315, K2=155, CoRoT=30)
exo-moons?
timing residuals (see TTVs)
482 (>6R⊕)
1187 (2–6R⊕)
766 (1.25–2R⊕)
373 (<1.25R⊕)
~290
(WASP=130, HAT/HATS=88)
decreasing planet mass
10MJ
MJ
10M⊕
M⊕
2
9
15
6
662
1
53
44
Discoveries:
32 planets (20 systems, 5 multiple)
662 planets (504 systems, 102 multiple)
1 planet (1 system, 0 multiple)
53 planets (51 systems, 2 multiple)
44 planets (40 systems, 2 multiple)
2789 planets (2053 systems, 474 multiple)
existing capability
projected
n = planets known
discoveries
follow-up detections

Exoplanet detection - Transits

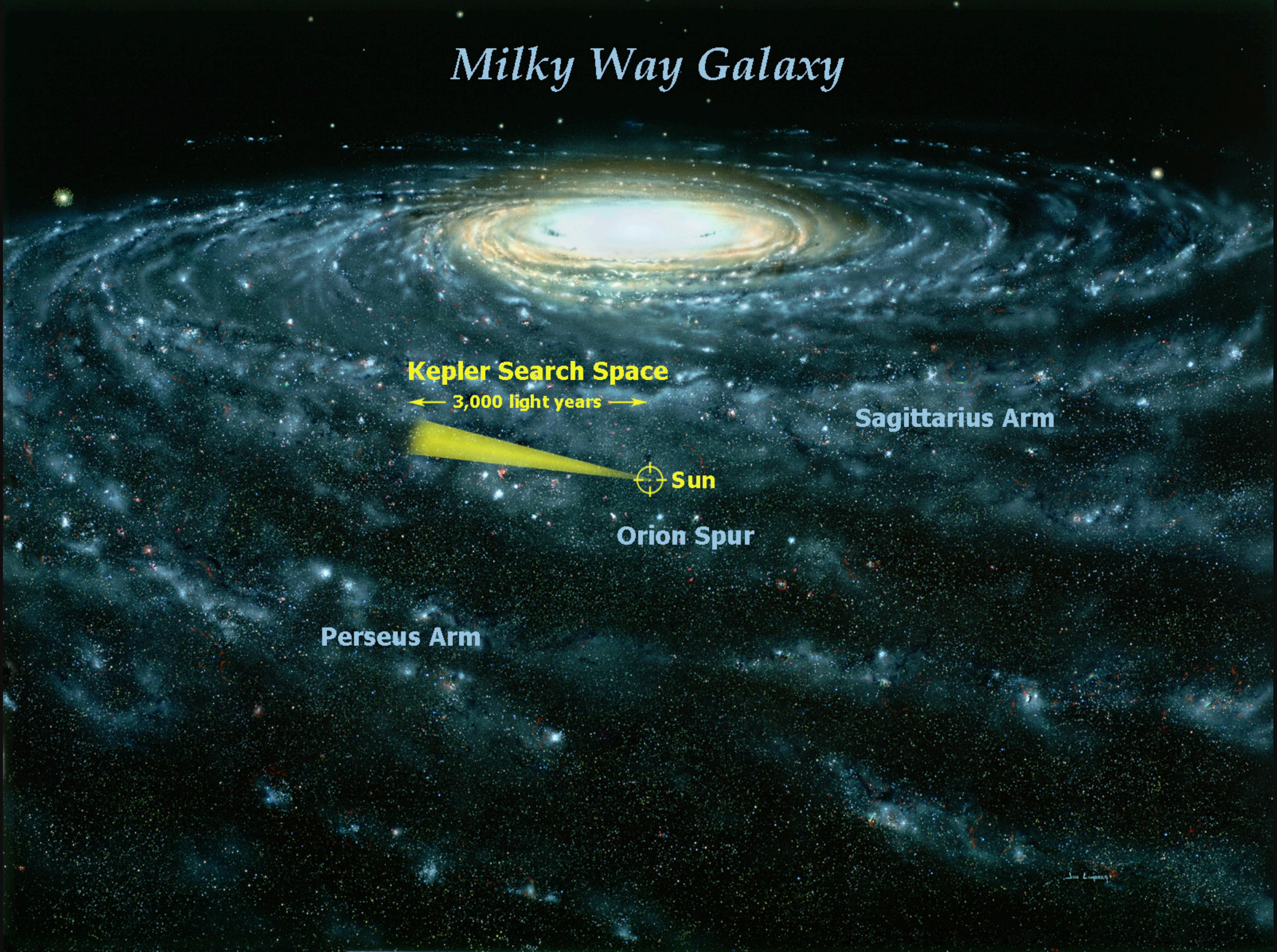


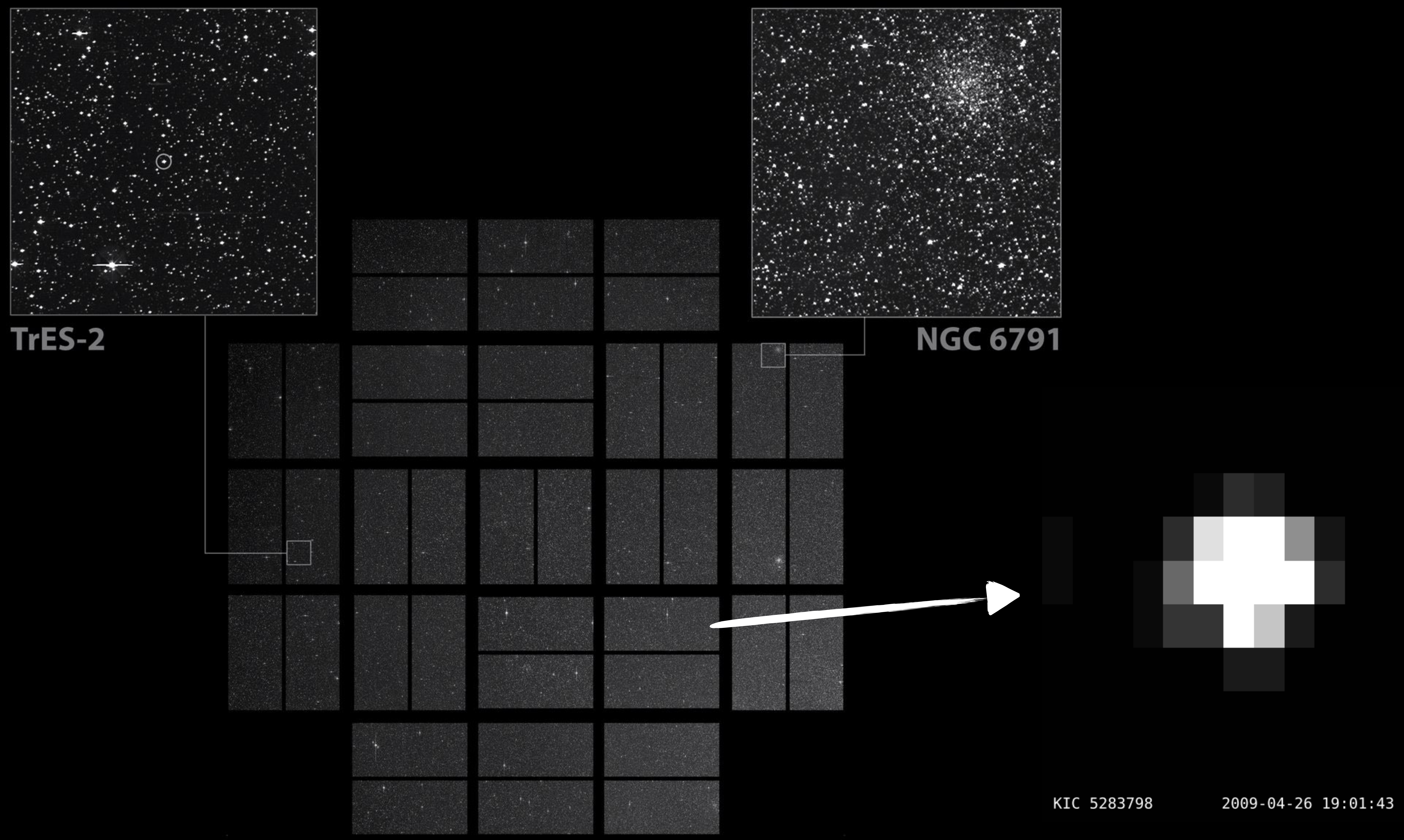
- Periodic eclipses of the target star
- Change in flux $\Delta F \propto (R_p/R_*)^2$
- Transit probability $\propto (R_*/a)$
- Need to measure repeated transits to confirm planet
- Transits give you the planet radius R_p but not the mass

NASA Kepler mission

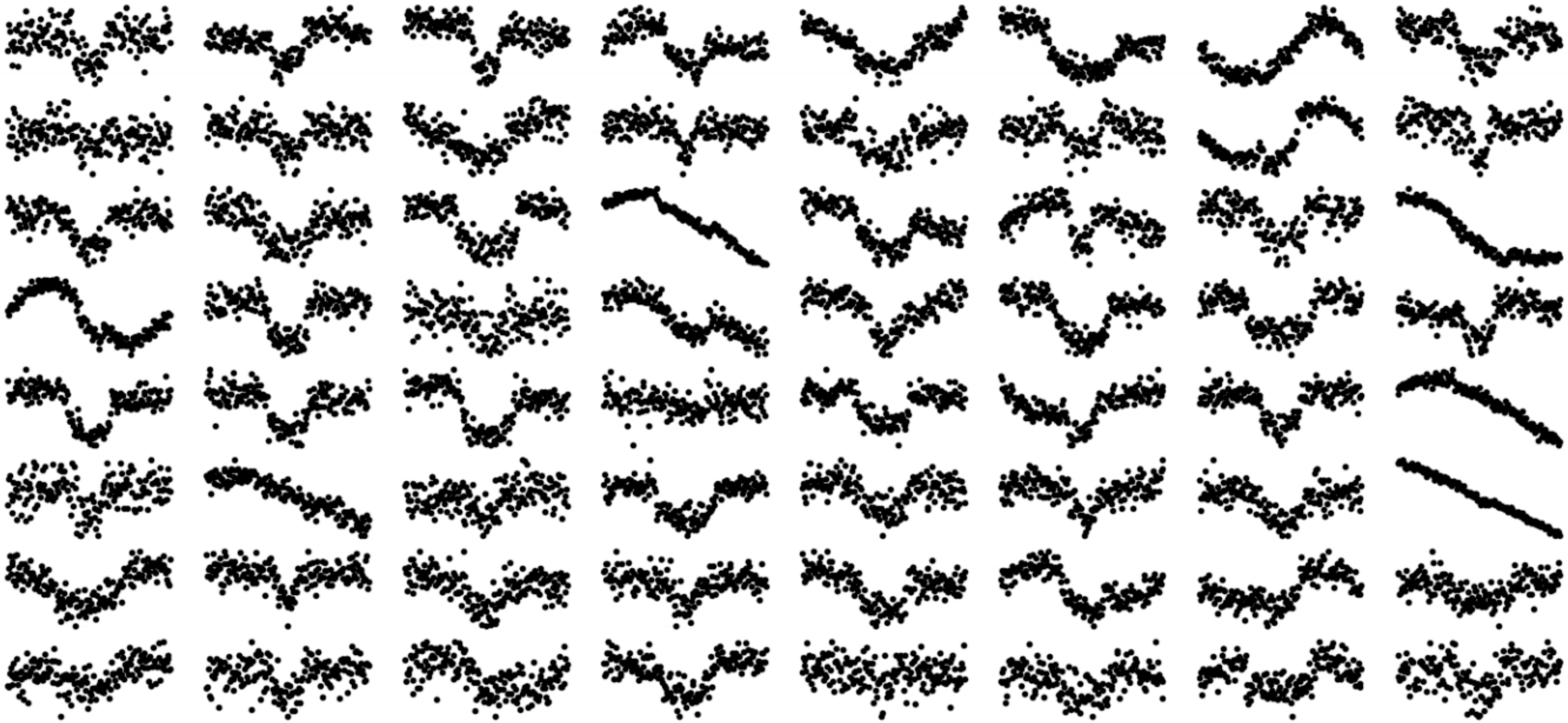
© NASA

- Space telescope designed to monitor brightness of ~200k stars every ~30min
- Operational 2009 – 2018
- Discovered ~2600 planets
- Designed with the goal of answering the question of how common are Earth size planets


Milky Way Galaxy
Kepler Search Space
3,000 light years
Sagittarius Arm
Sun
Orion Spur
Perseus Arm

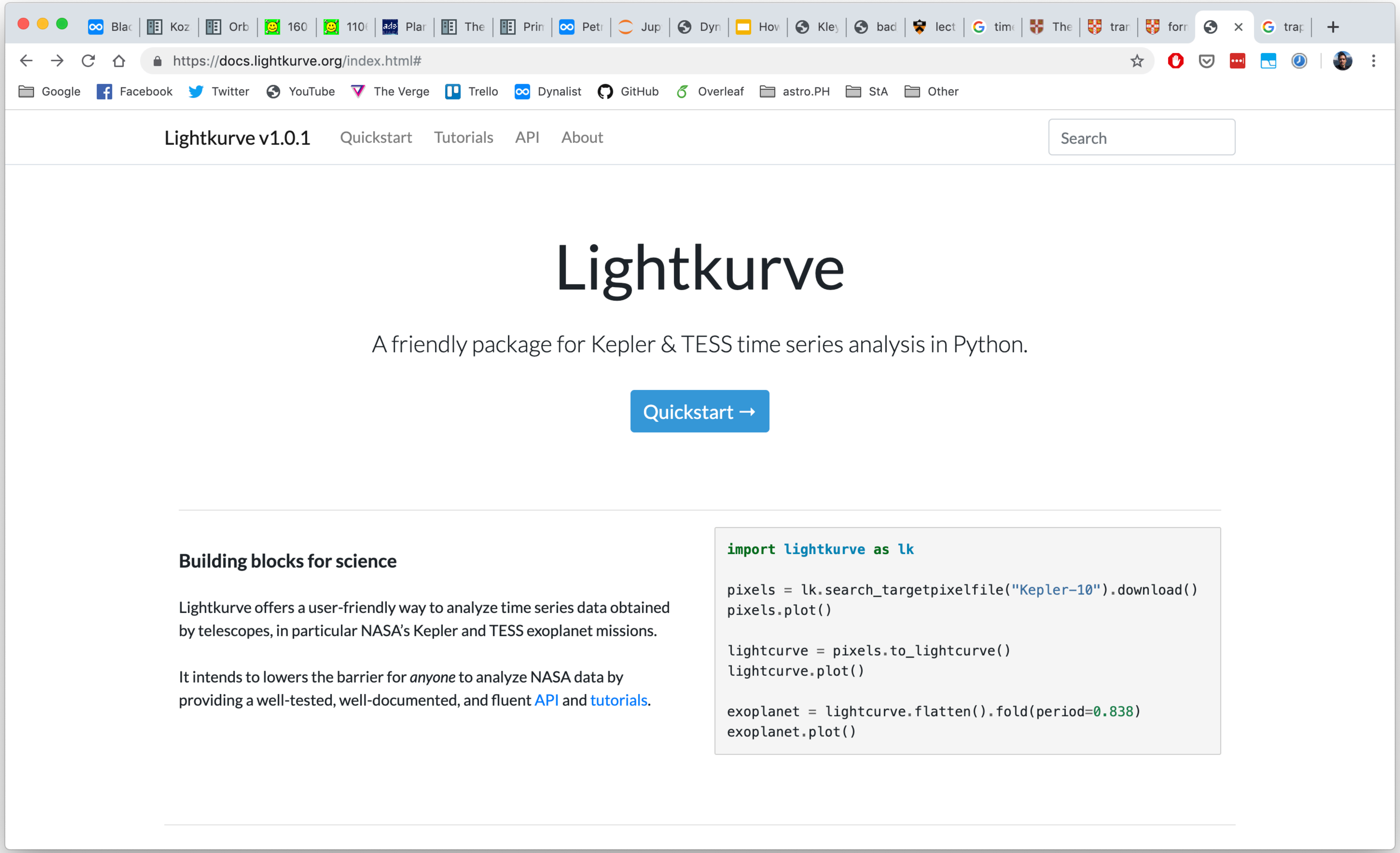

TrES-2
NGC 6791
KIC 5283798
2009-04-26 19:01:43

Needle in a haystack

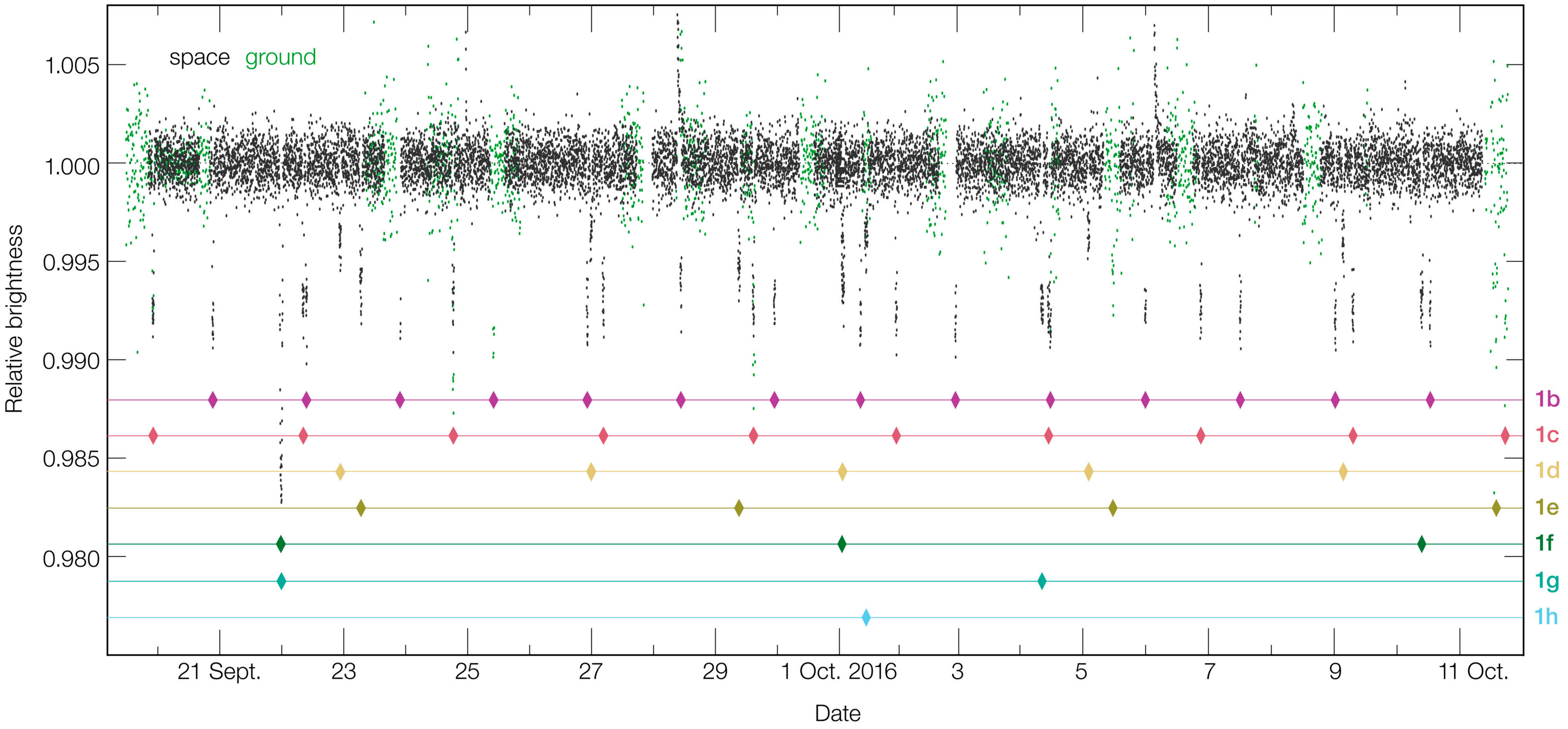


Pearson et. al. 2017

Explore Kepler data using Python



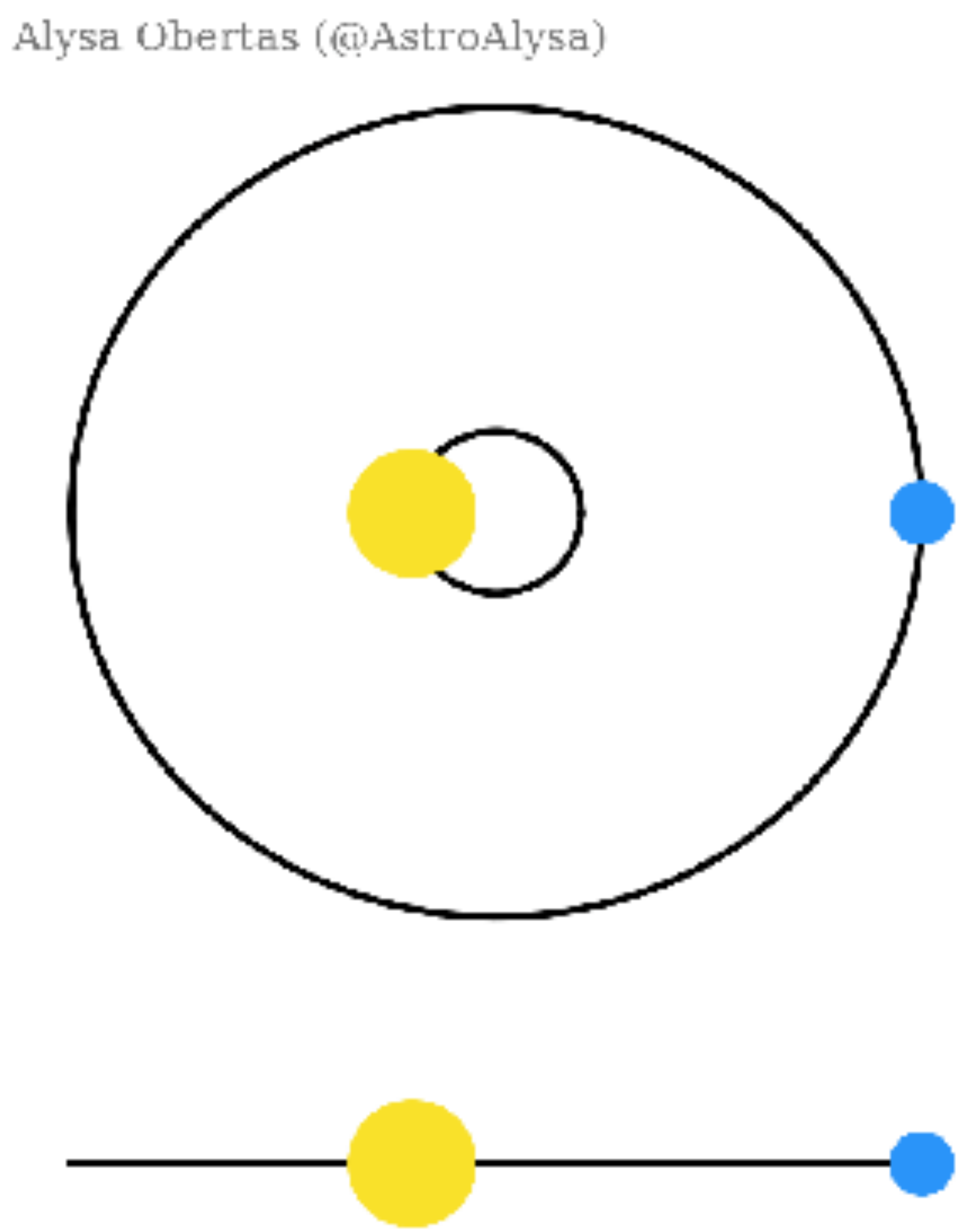
The Trappist-1 system

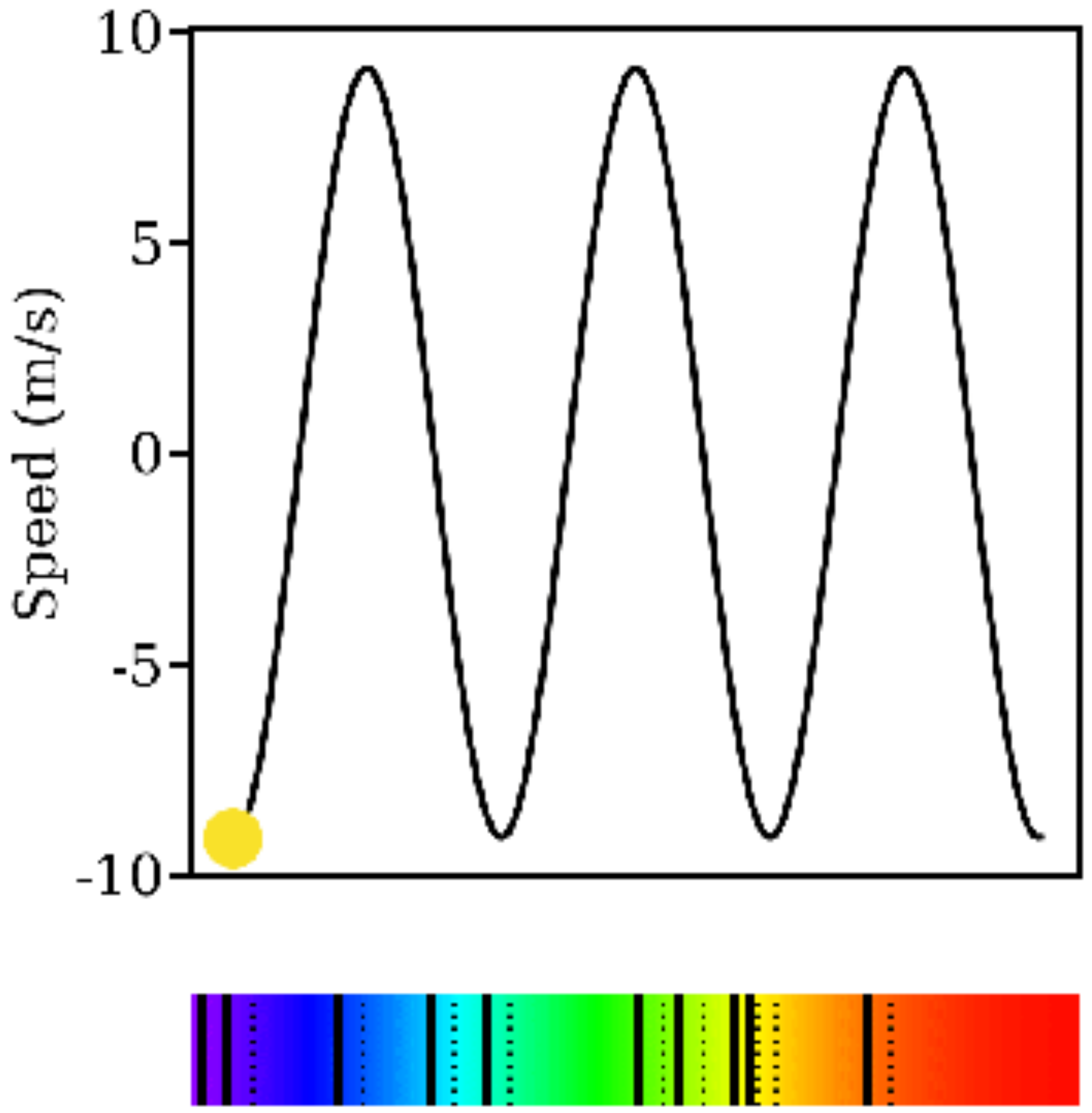


- System of 7(!) transiting exoplanets orbiting a Red Dwarf at a distance of only 39 light years
- All planets roughly Earth mass or less
- Several planets in the habitable zone
- All planets form a resonant chain!

Jupiter & Major Moons
Io
Europa
Ganymede
Callisto
TRAPPIST-1 System
Sun
(relative size)
b
c
d
e
f
g
h
Orbits Enlarged 25x
Inner Solar System
Mercury
Venus
Earth
Mars

Radial velocity





- Reflex motion of the star causes a Doppler shift in spectral lines

$$v_r \approx c\,\frac{\Delta\lambda}{\lambda_{em}}$$

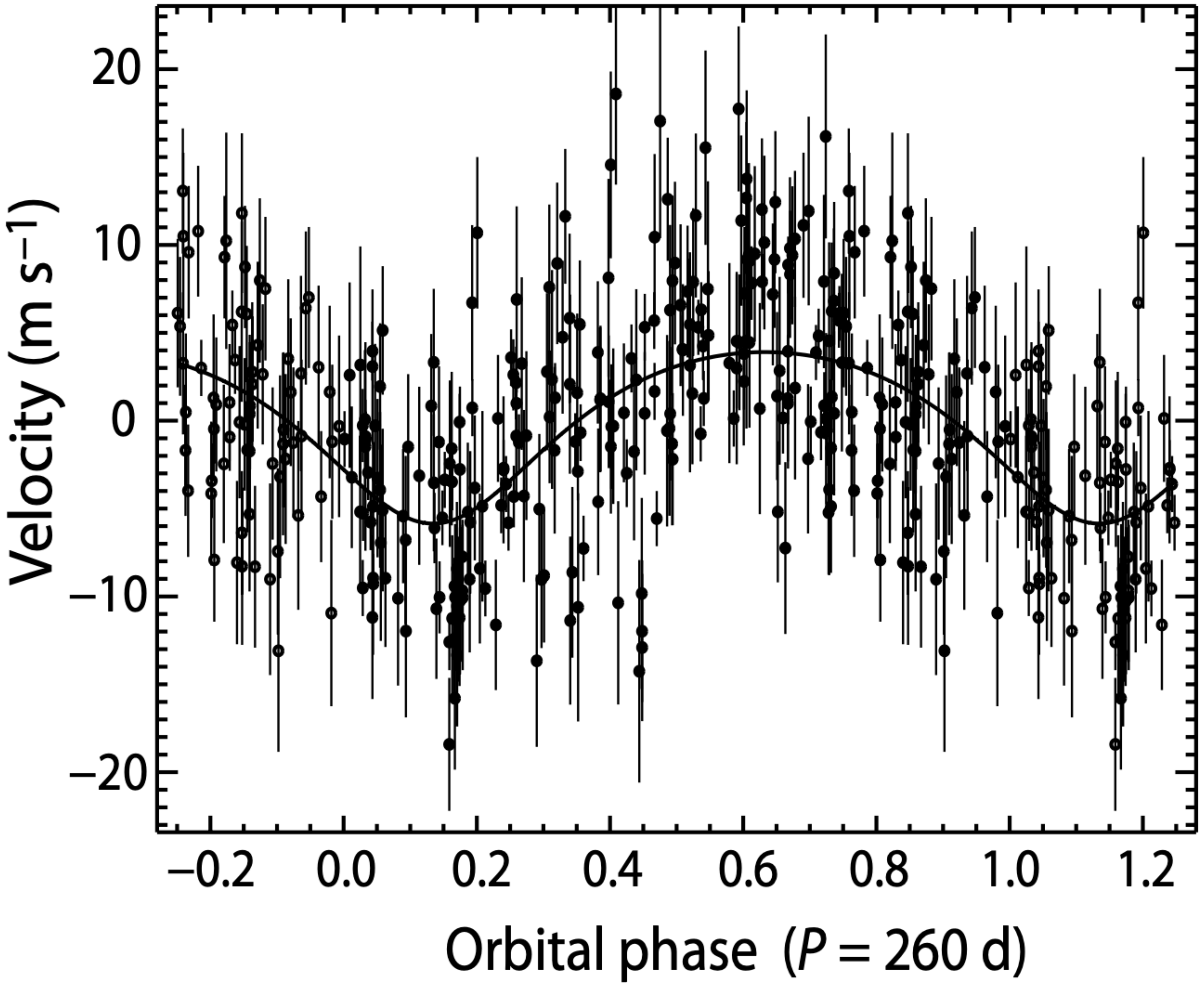
- RV semi-amplitude:

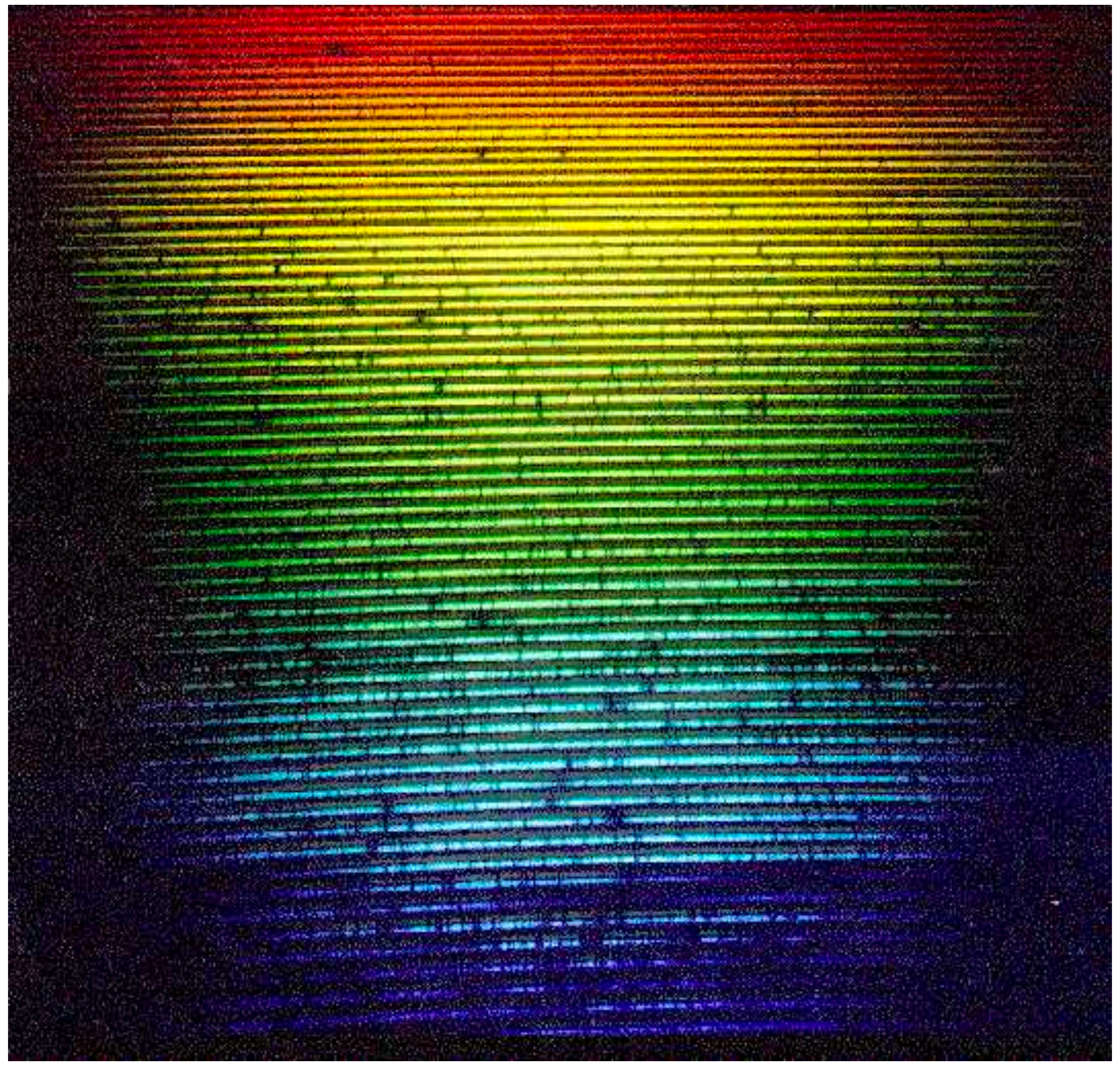
$$K = \left(\frac{2\pi G}{P}\right)^{1/3} \frac{M_\mathrm{p}\sin i}{\left(M_\star + M_\mathrm{p}\right)^{2/3}} \frac{1}{\left(1-e^2\right)^{1/2}}$$

- Variations typically on the order of m/s (!)

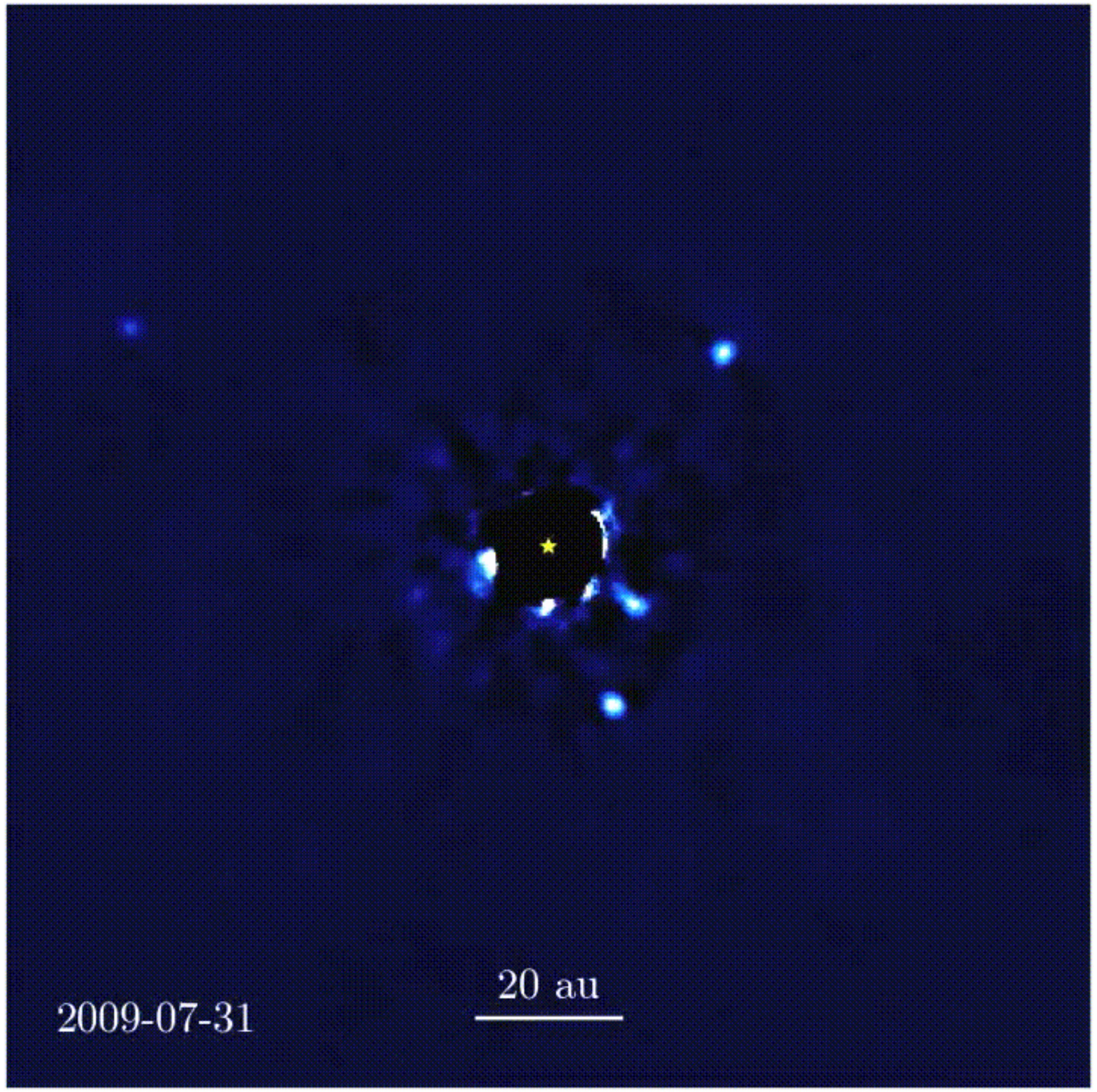
- Ultra high resolution spectroscopy needed -> bias towards bright stars

Radial velocity



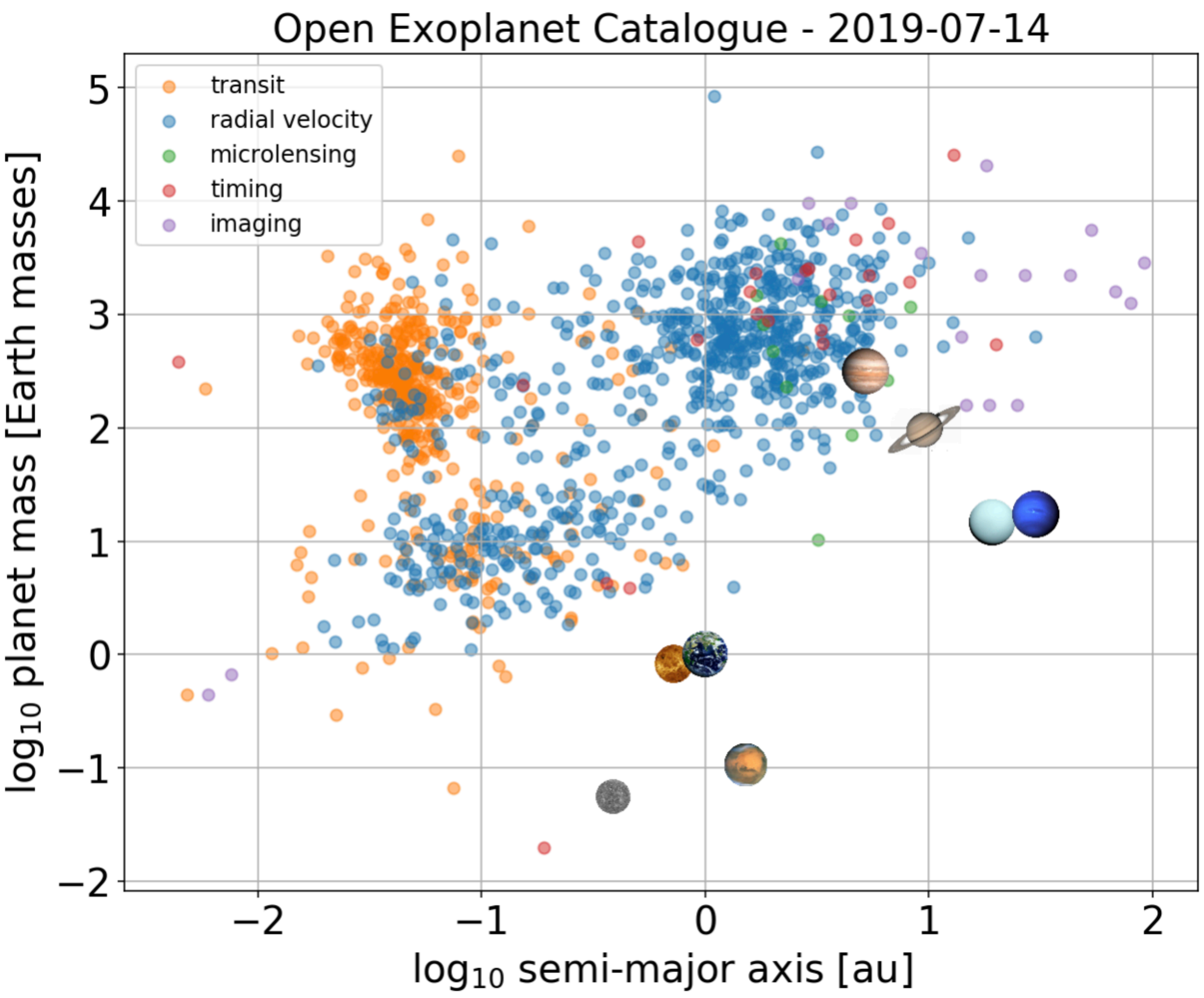


Direct Imaging



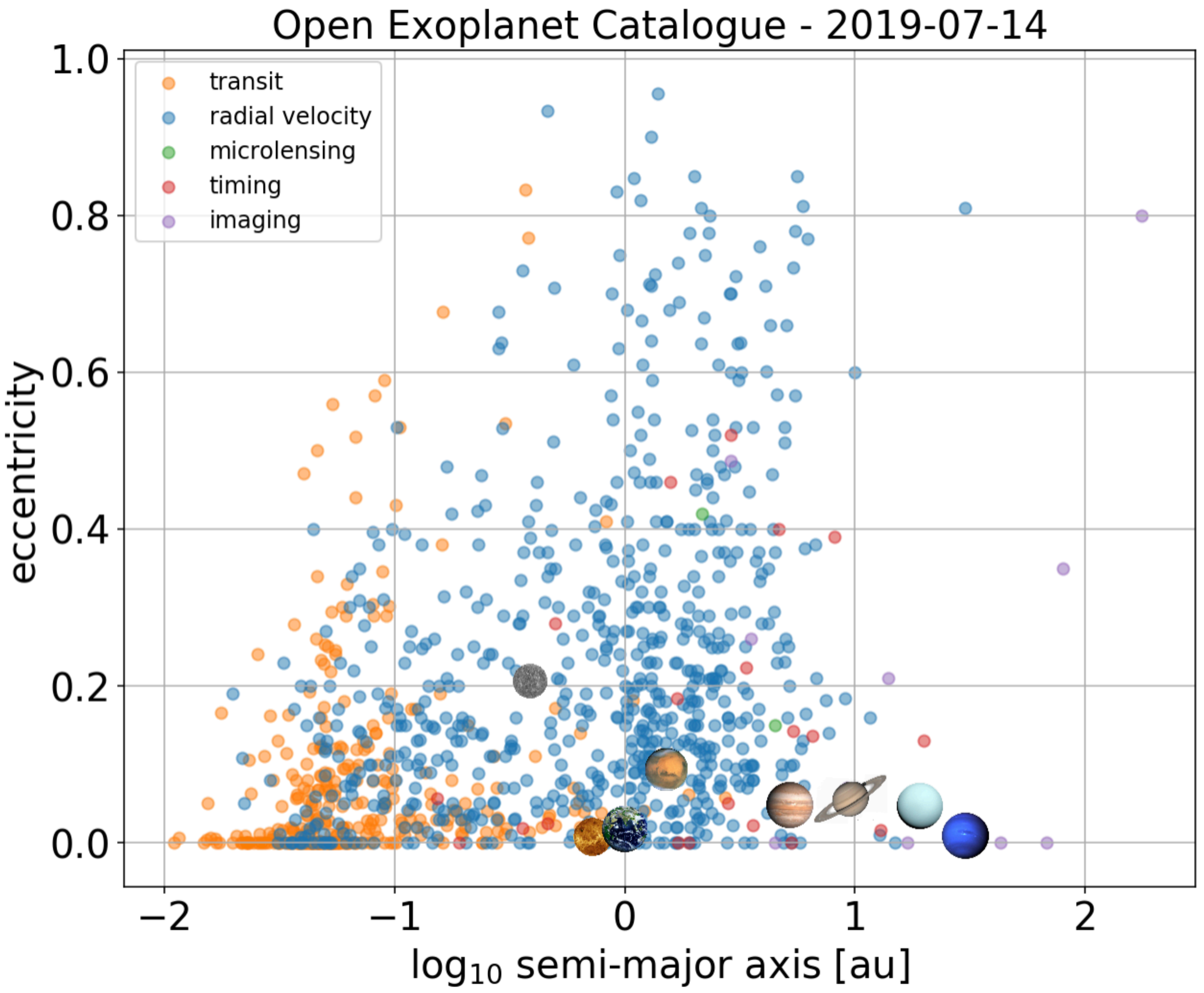
- Taking pictures of exoplanets
- Planet star flux ratio f_p/f_* in the range of $10^{-10} - 10^{-5}$
- Major challenge is to separate light from star vs. light from planet
- Biased towards massive planets on very wide orbits

Observed exoplanets - Masses and orbits



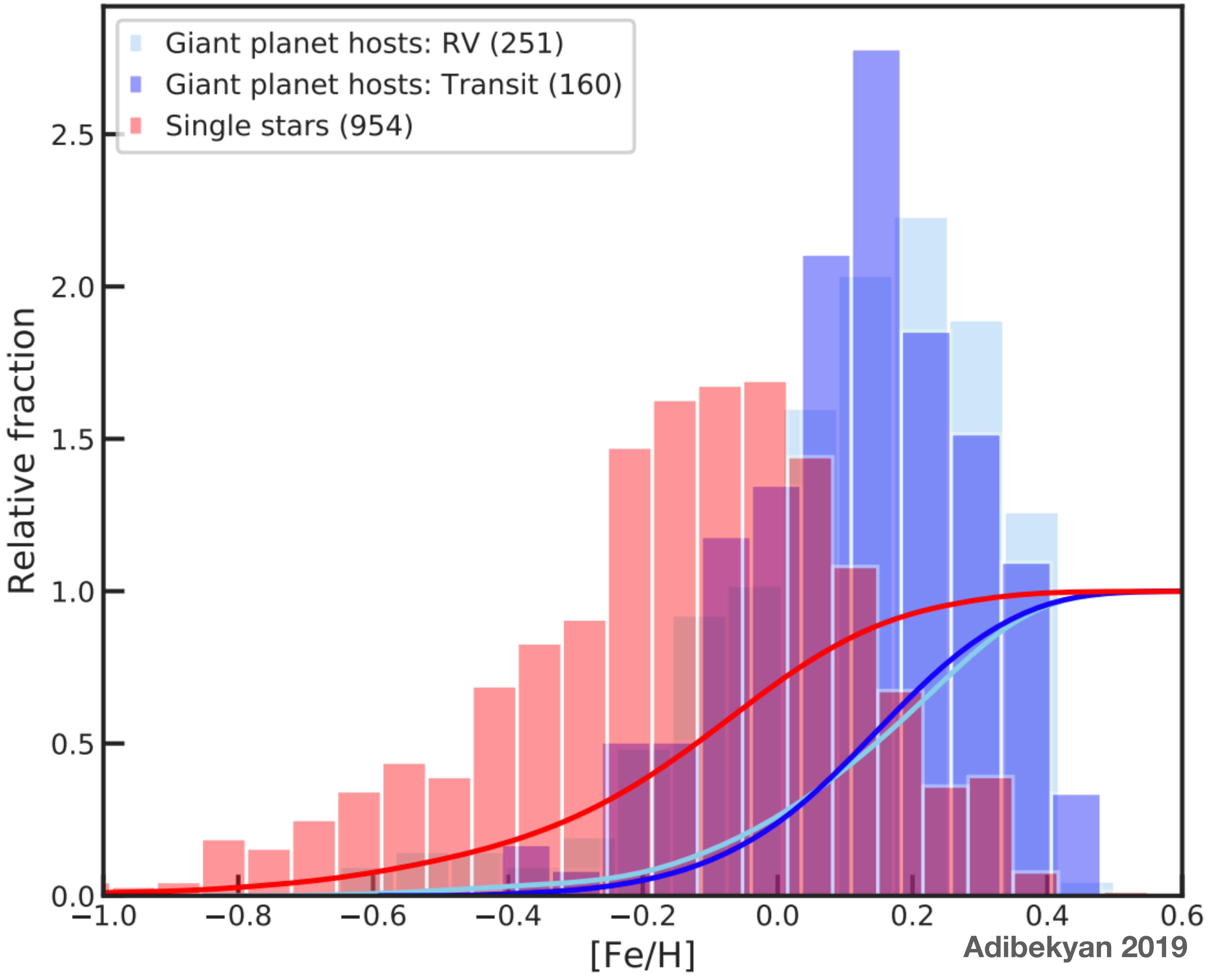
- Lots missing from this plot
- Majority of observed exoplanets like those in our Solar System
- "Hot Jupiters" easiest to detect but only ~1% of stars have them
- "Super Earths" observed in 30-50% of all systems

Observed exoplanets - Eccentricities



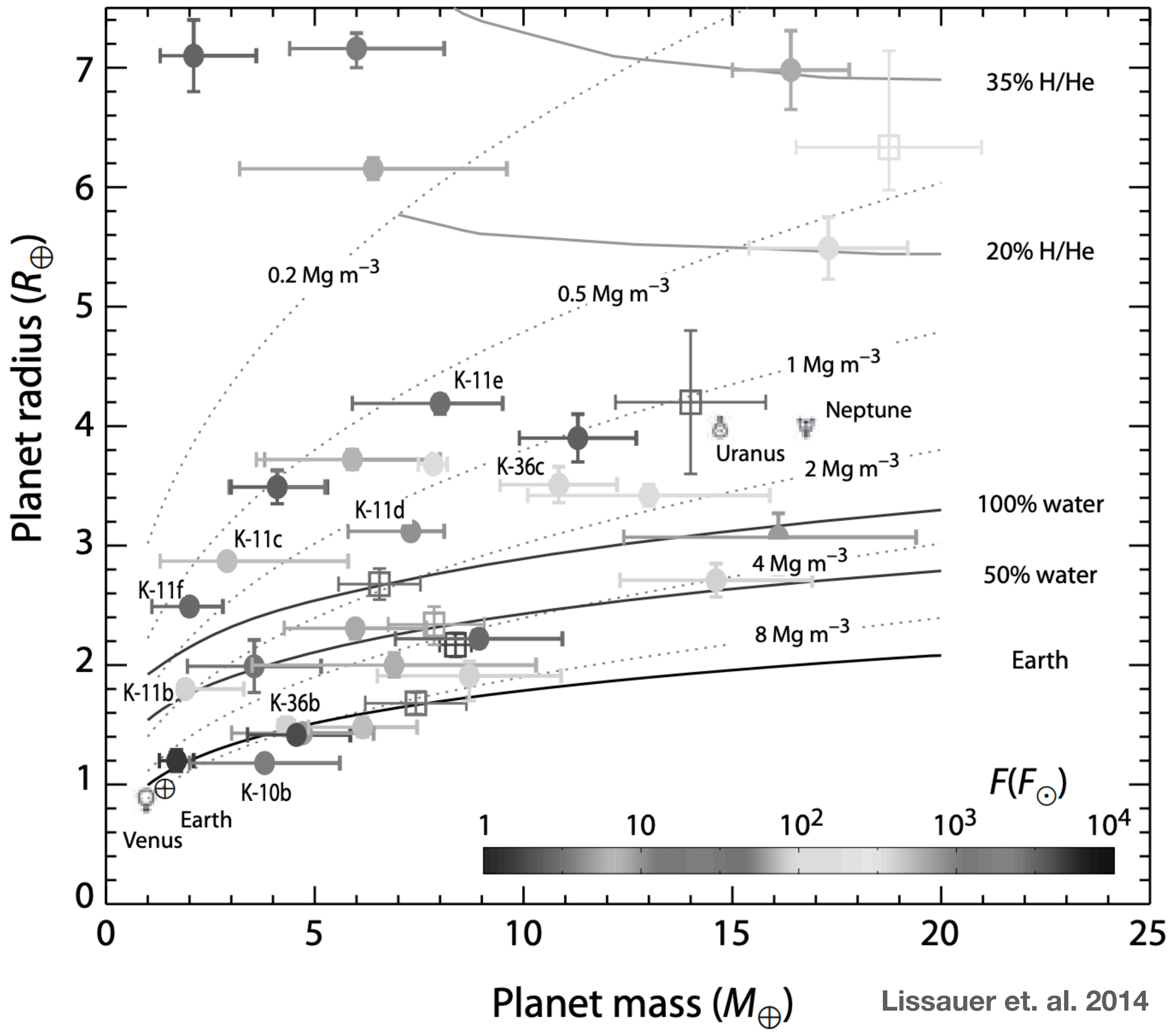
- Absence of very high eccentricity planets among multi planet systems
- Giant planets around metal rich stars more eccentric than those around metal poor stars
- Smaller planets tend to have lower eccentricities
- Eccentricity distribution explained well by long term dynamical simulations

Observed exoplanets - Stellar metallicity



- Giant ($> 1\,M_J$) gaseous planets found predominately around metal-rich stars
- Supports core accretion theory of planet formation

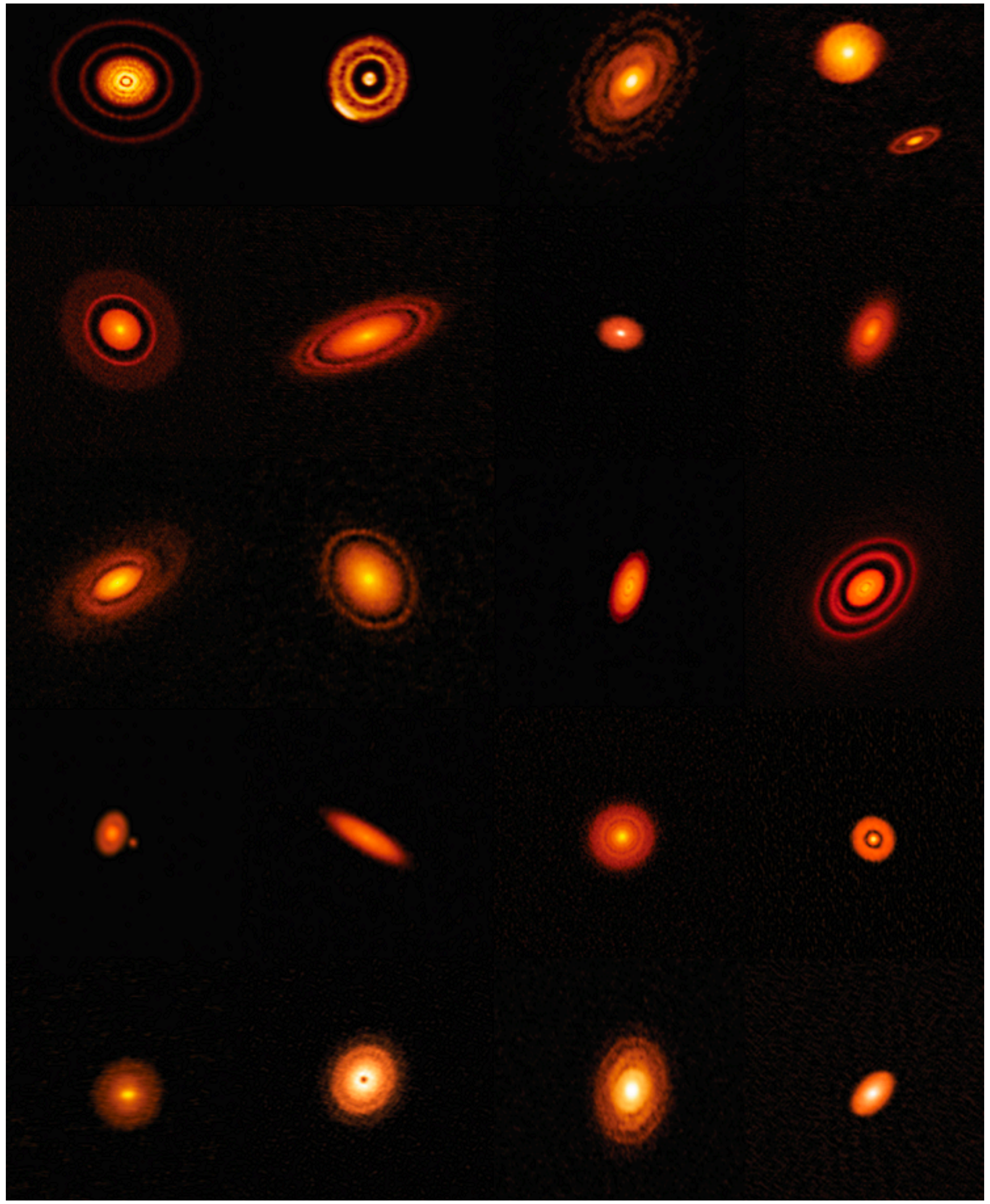
Observed exoplanets - Interior structure



Lissauer et. al. 2014

- Combining radial velocity and transit observations gives us estimate of mean density
- Plot shows mass-radius diagram for low mass planets ($M_p < 20\,M_\oplus$)
- Measure of mean density degenerate with respect to models of internal structure

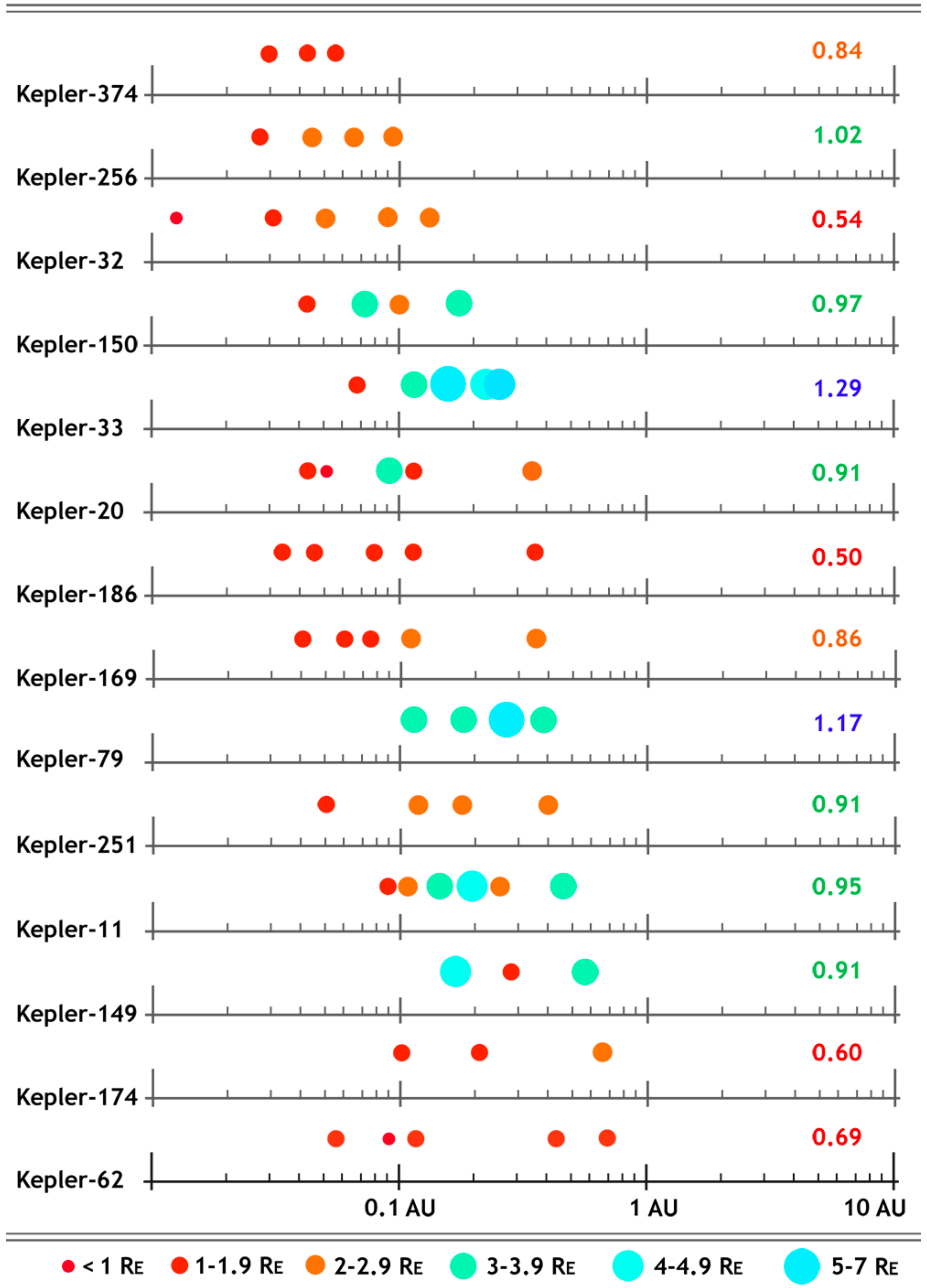
Planet Formation - Observations



© ESO

?

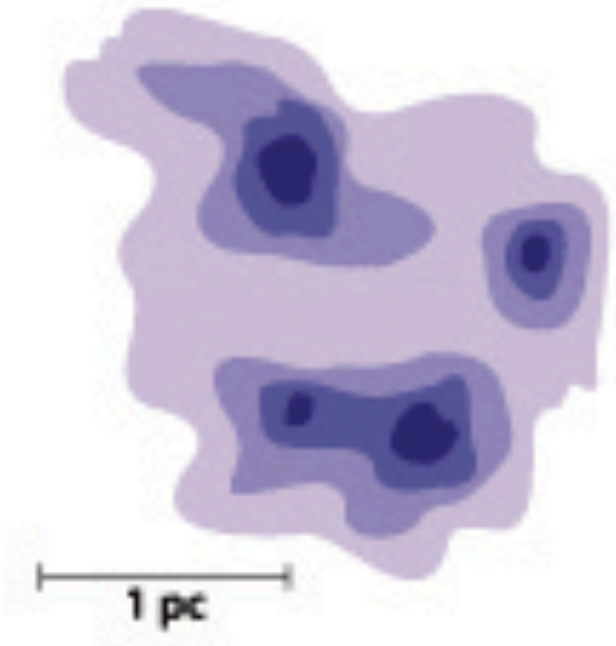
Planet formation



© Bucky Harris

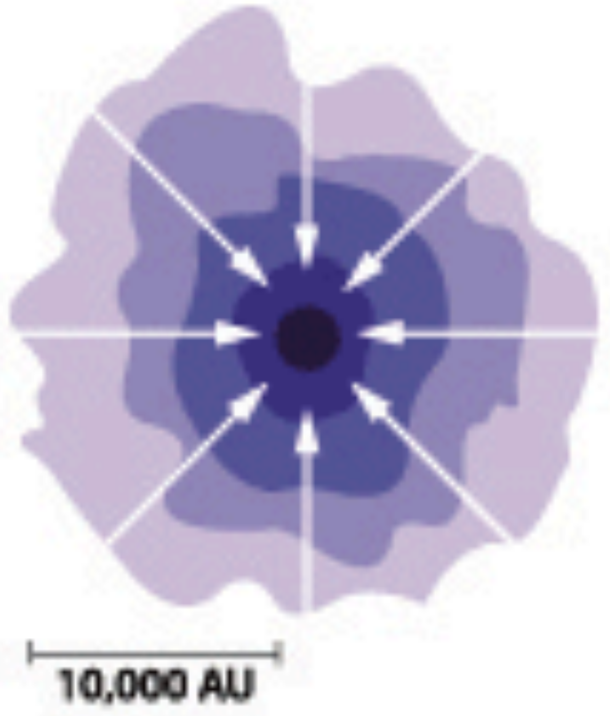
Star formation

Dark cloud cores



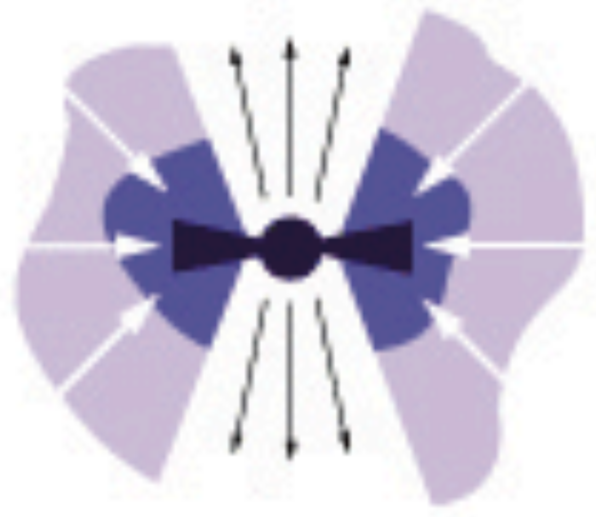
$t = 0$

Gravitational collapse



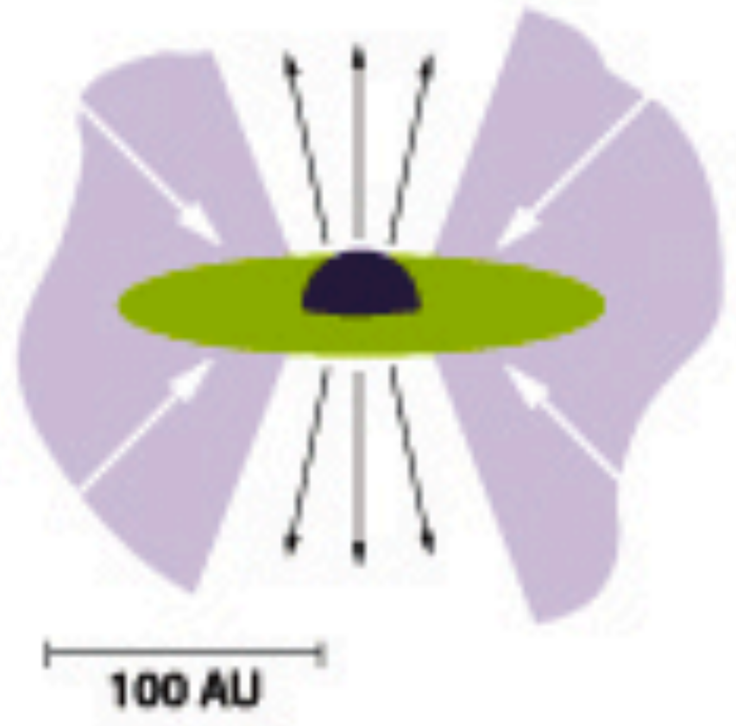
$t = 10^5 - 10^6$ yr

T Tauri star, disc, outflow



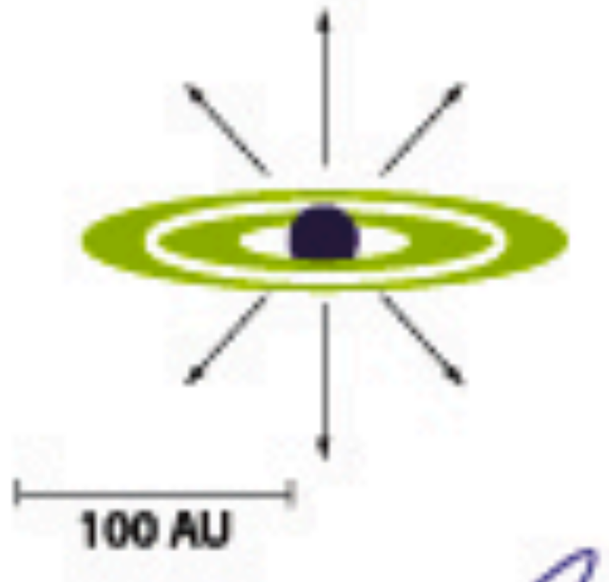
$t = 10^4 - 10^5$ yr

Protostar, embedded in ~80000 AU envelope



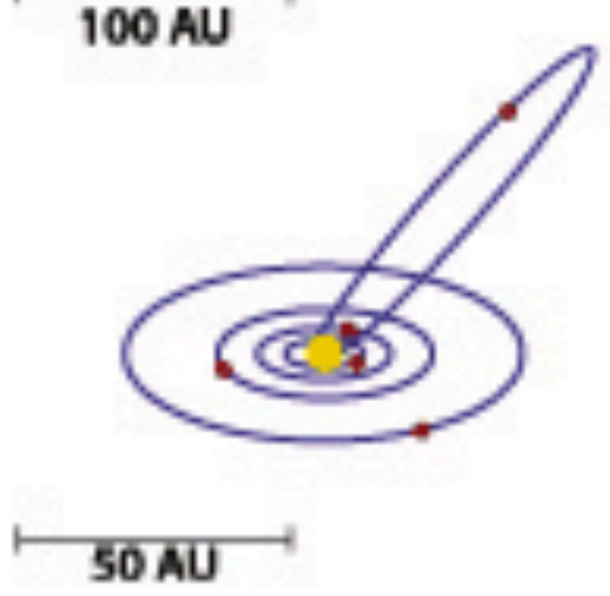
$t = 10^6 - 10^7$ yr

Pre main-sequence star, remnant disc



$t > 10^7$ yr

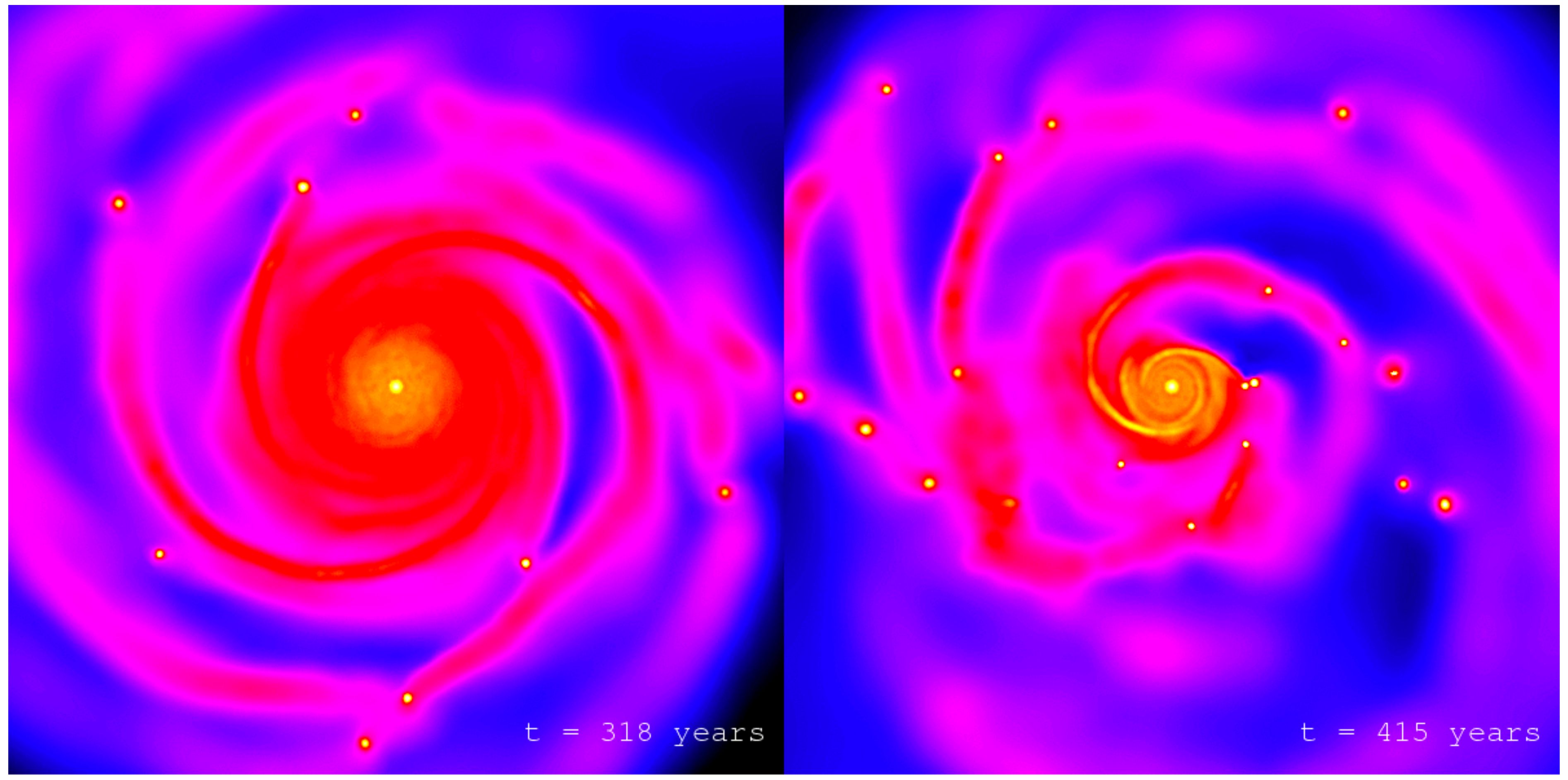
Main-sequence star
Planetary system(?)



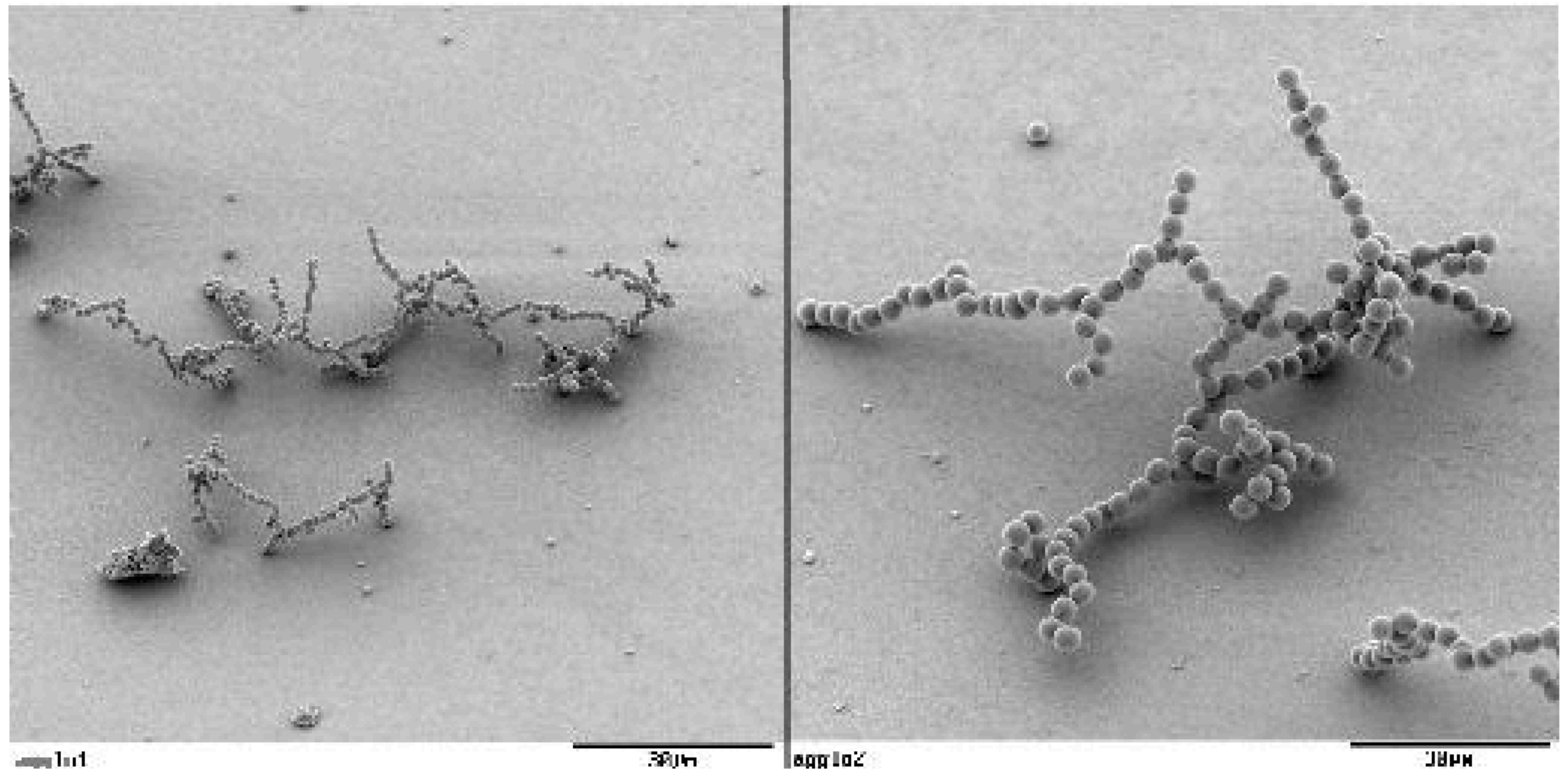
Casasola 2008

Two models of planet formation

- **Gravitational instability (top down)**
  - Parts of disc collapse under its own gravity
  - Fast formation on timescales of 10^3 years
  - Can’t really explain terrestrial planet formation
- **Core accretion (bottom up)**
  - Collisional growth from sub-micron dust particles to km sized planetesimals and cores of planets
  - Longer timescales ($\sim 10^6$ years)
  - Does a decent job at explaining terrestrial as well as gas giant formation



Lufkin et. Al.

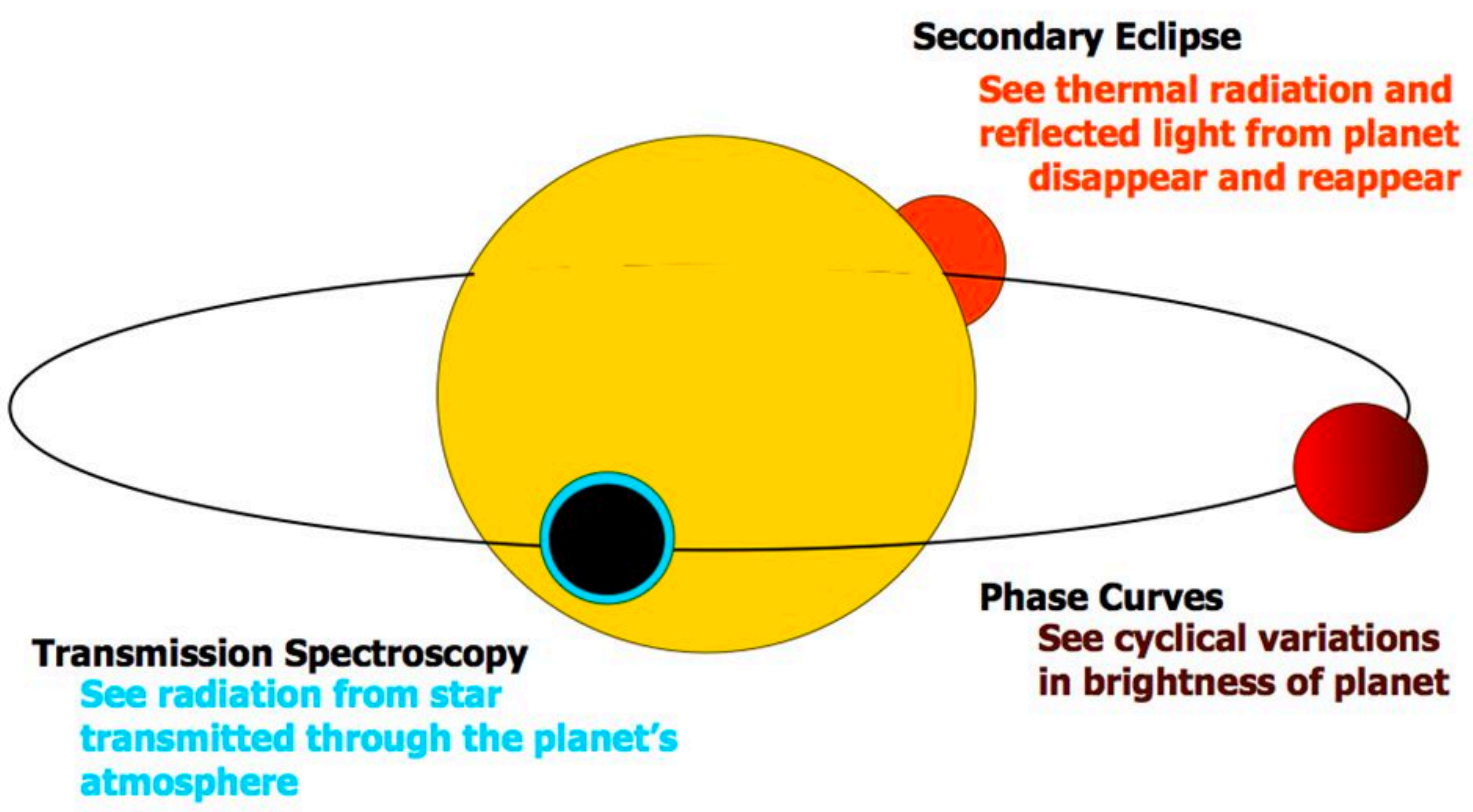


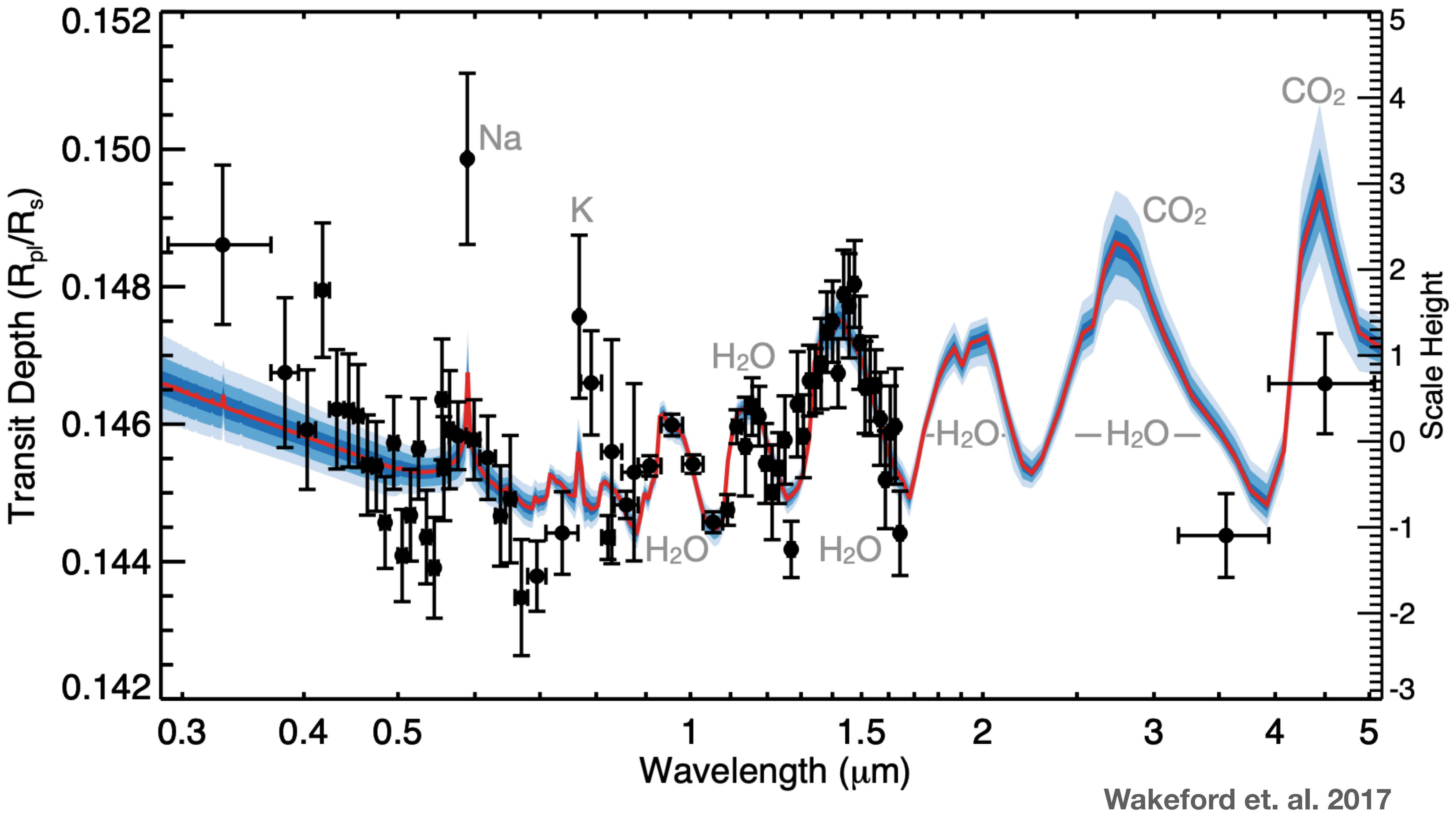
Jurgen Blum

Planet formation - Phases

1. **Dust grains to planetesimals**
    - μm grains → cm sized pebbles - Van der Waals forces make grains stick
    - cm sized pebbles → km sized planetesimals - pebble accretion??
2. **Planetesimals to protoplanets**
    - km sized planetesimals → $\sim 10^3$ km sized protoplanets - gravity
3. **Protoplanets to planets**
    - Terrestrial planets grow by collisional evolution
    - Gas giants accrete gas envelope onto a rocky core
4. **Planets migrate in discs!**

Exoplanet atmospheres

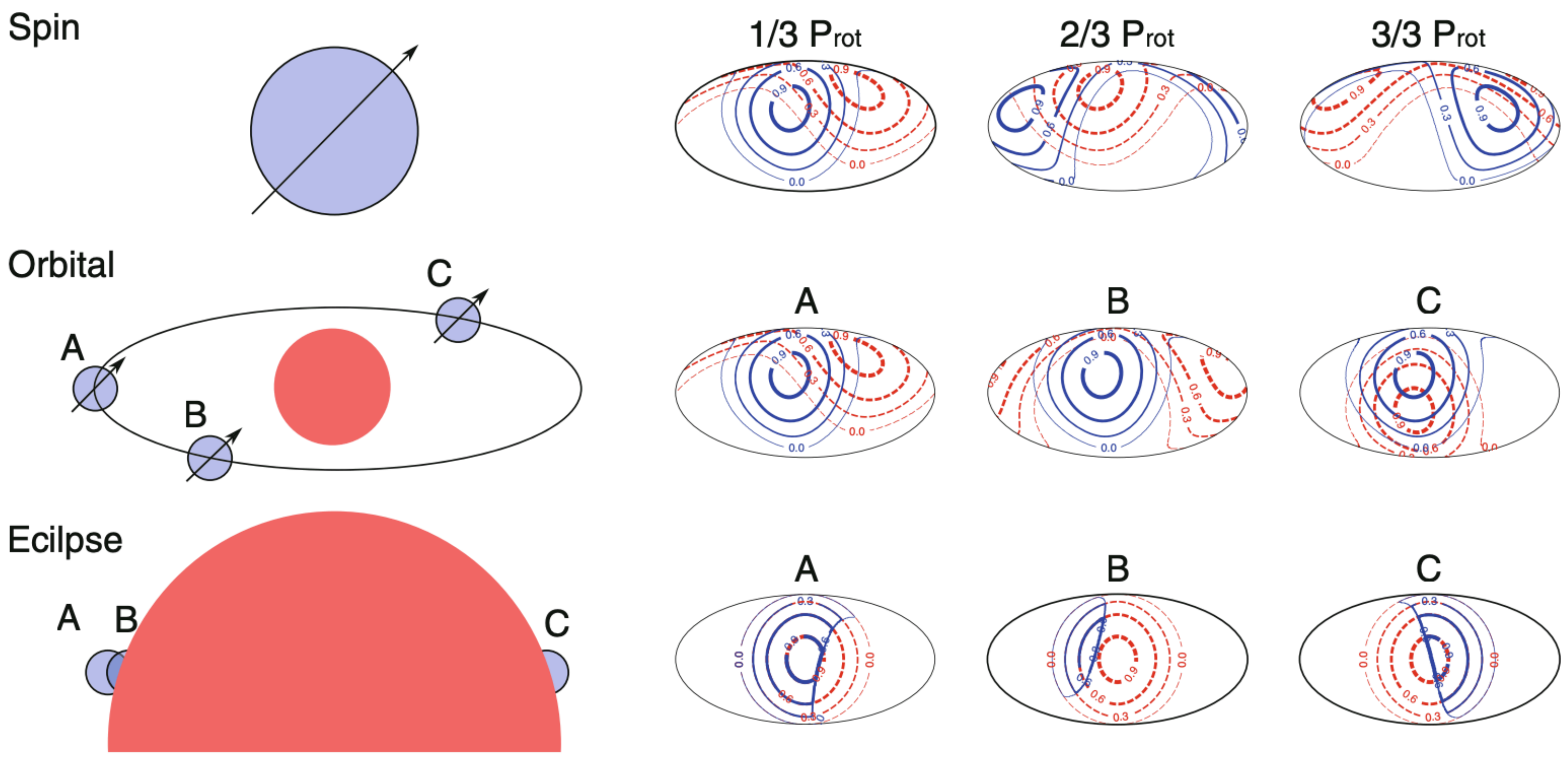




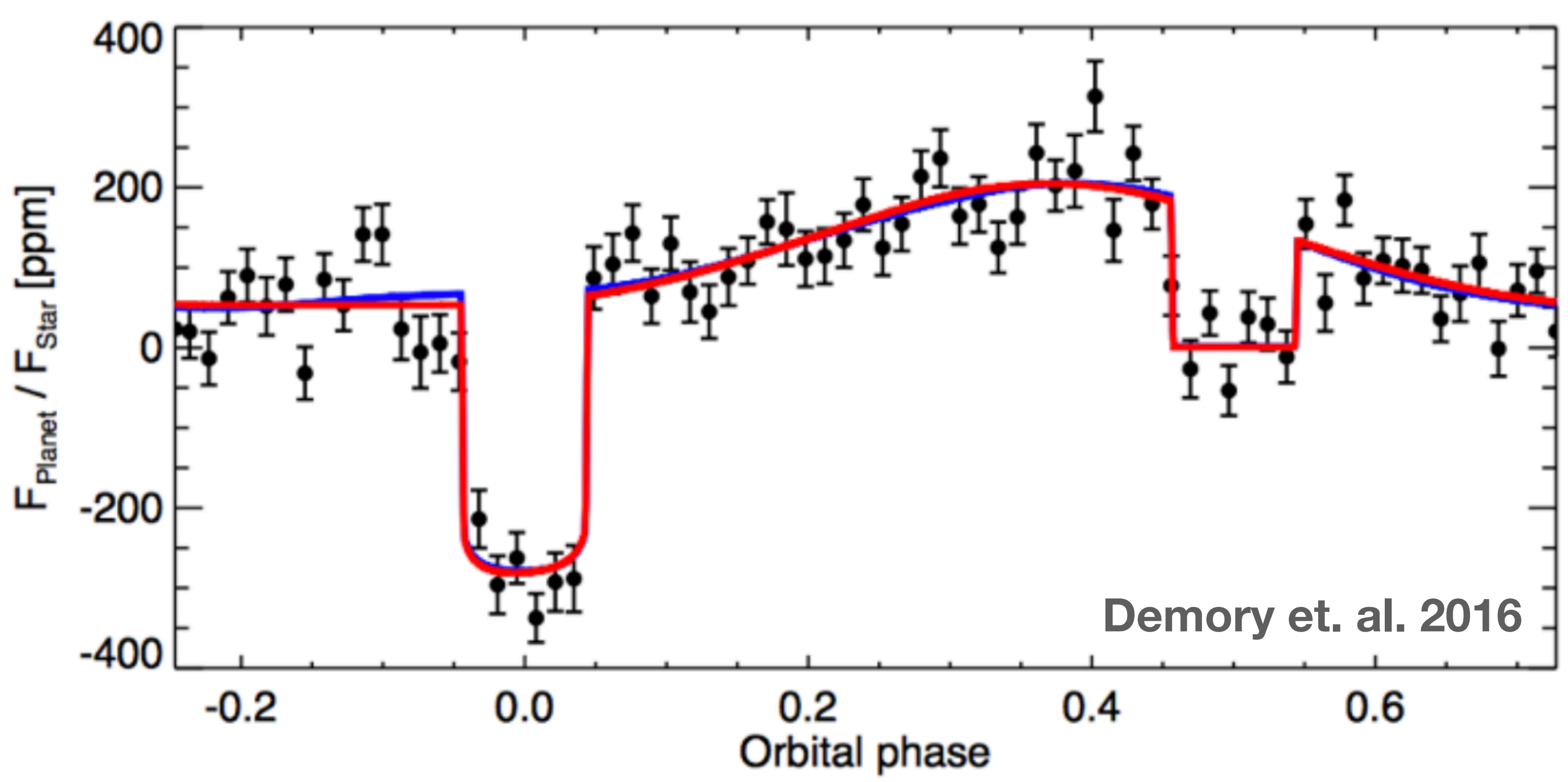
Wakeford et. al. 2017

Challenge: how to infer element and molecular abundances from the spectra?

Mapping surfaces of exoplanets



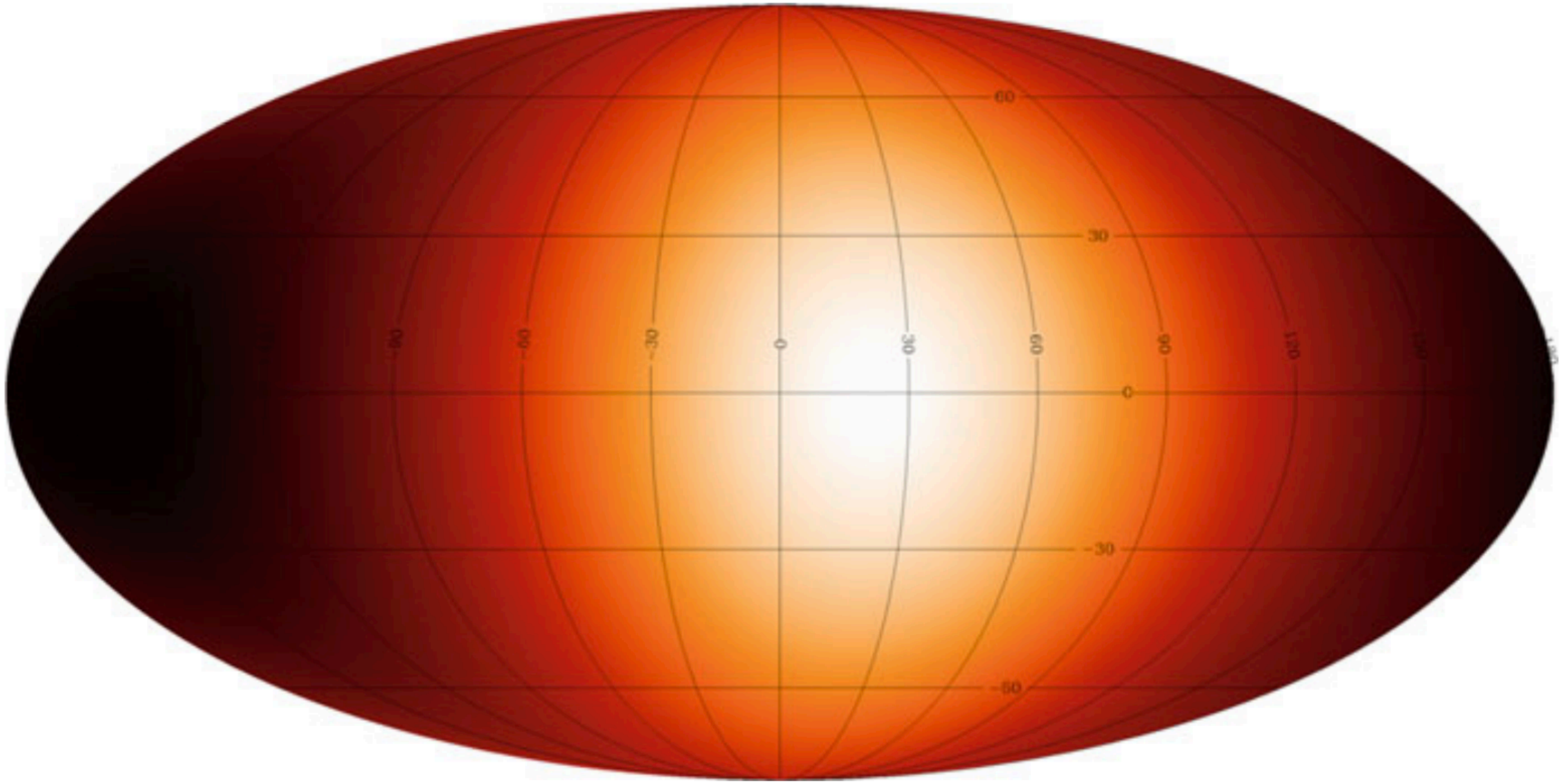
Cowan & Fujii 2017



Demory et. al. 2016

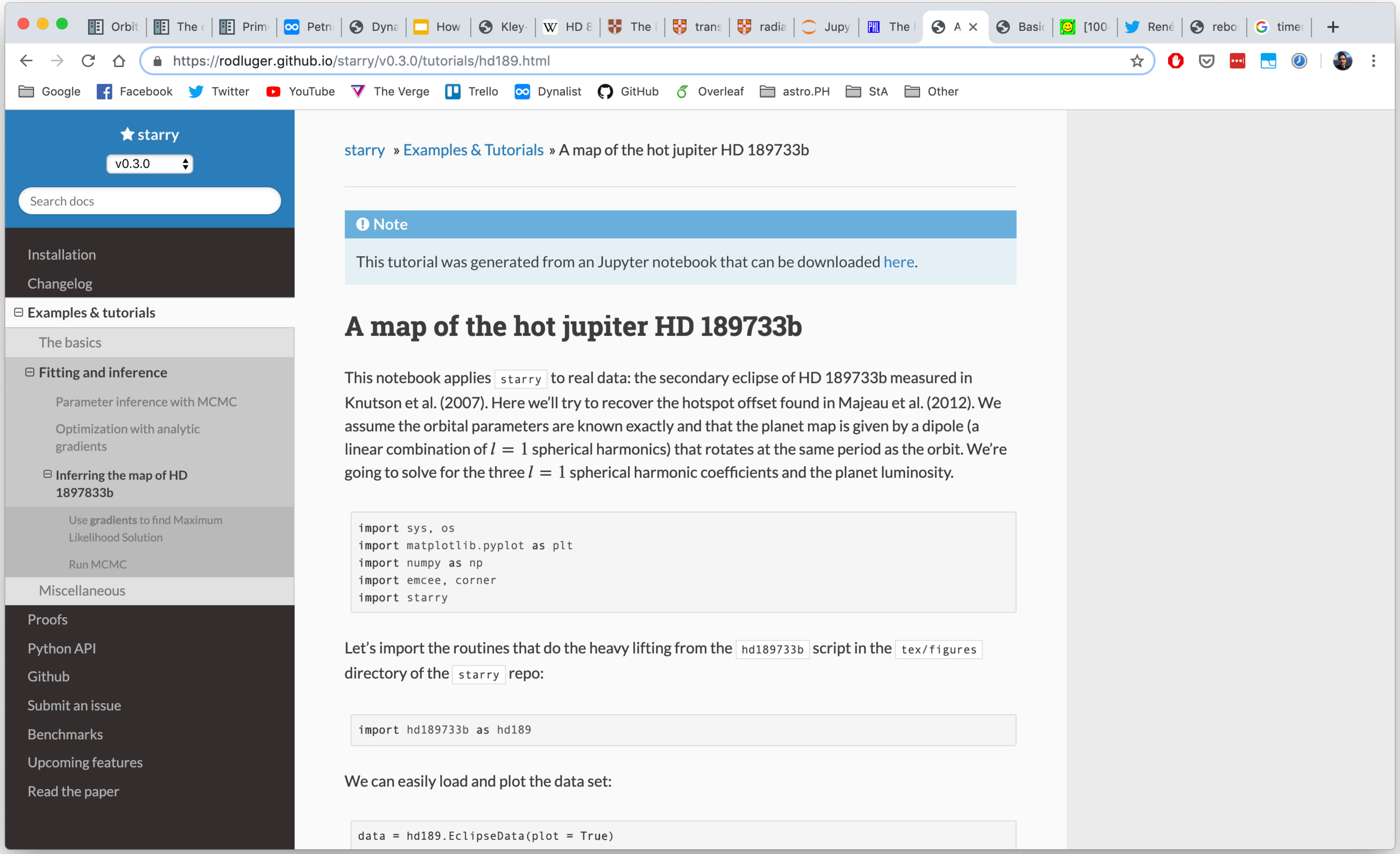
- To resolve Earth sized planet at 10pc, we need an optical telescope (or multiple telescopes) ~24km across - not feasible
- As long as we don't always see the same parts of the planet's surface and the surface is inhomogenous, in principle we can extract the information on surface features from integrated light - "exocartography"
- Rotations, orbital motion and occultations expose different surface features

Map of the hot Jupiter HD 189733b



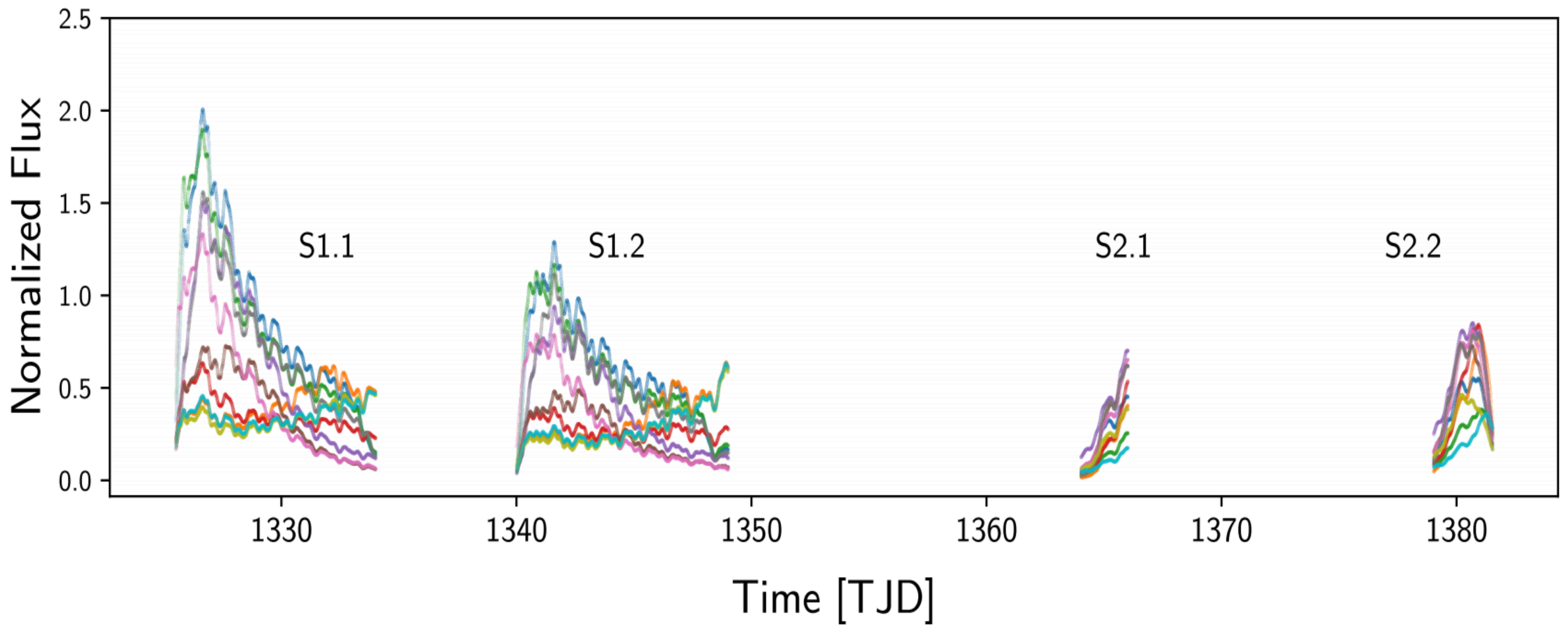
Majeau et. al. 2012

Do it yourself using starry!

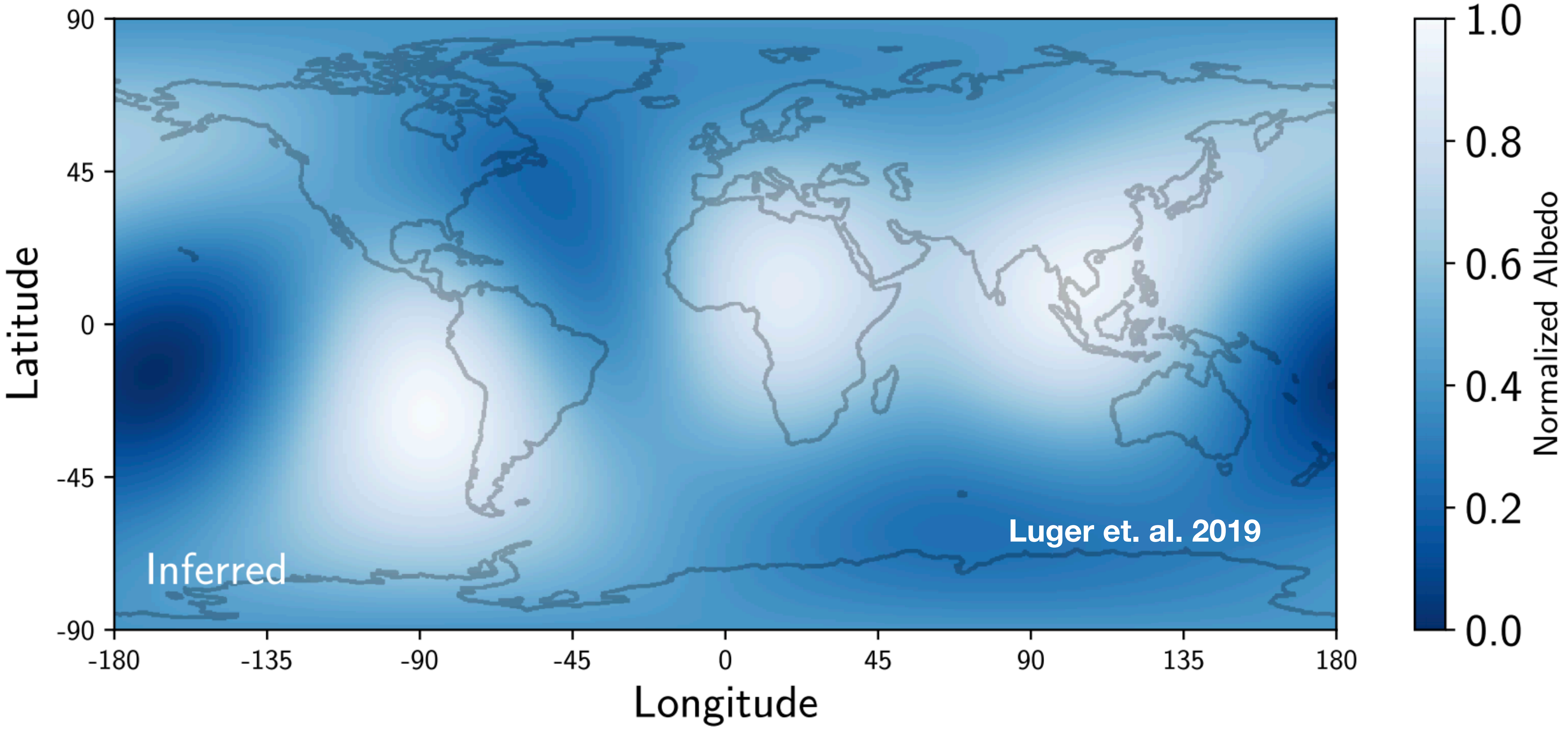


Mapping the surface of Earth

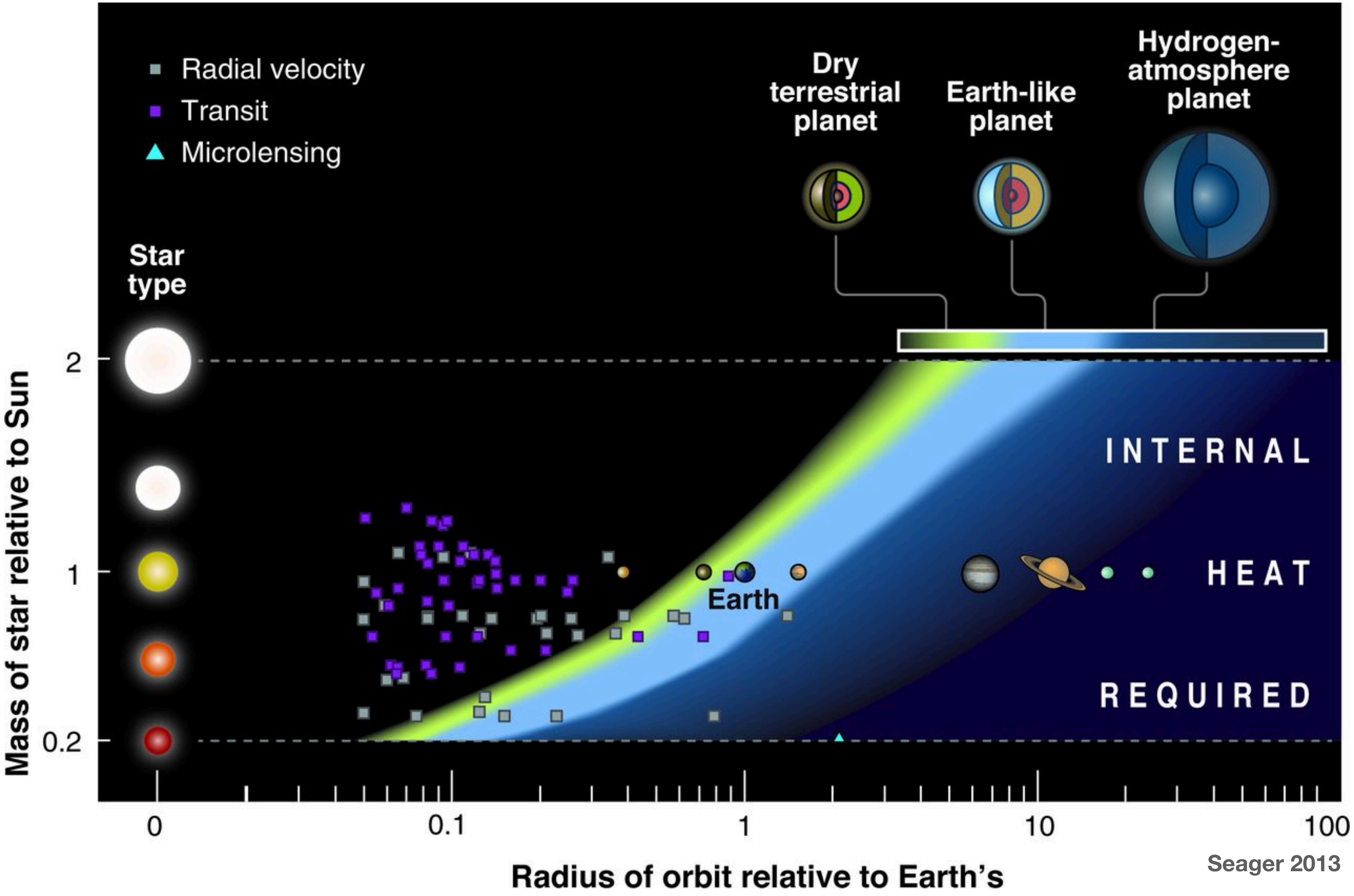
Data (reflected light)



Inferred map



Astrobiology and the search for life

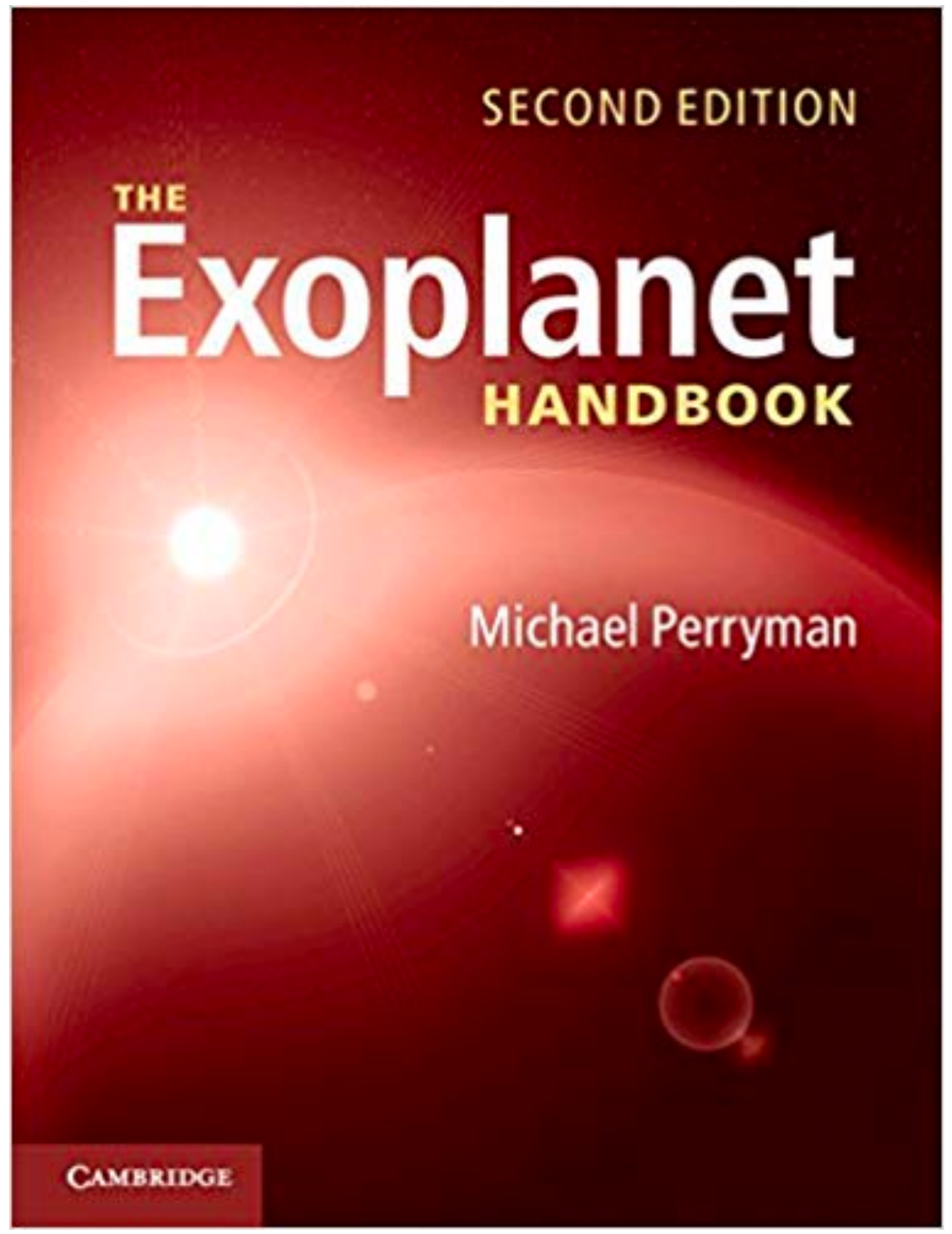


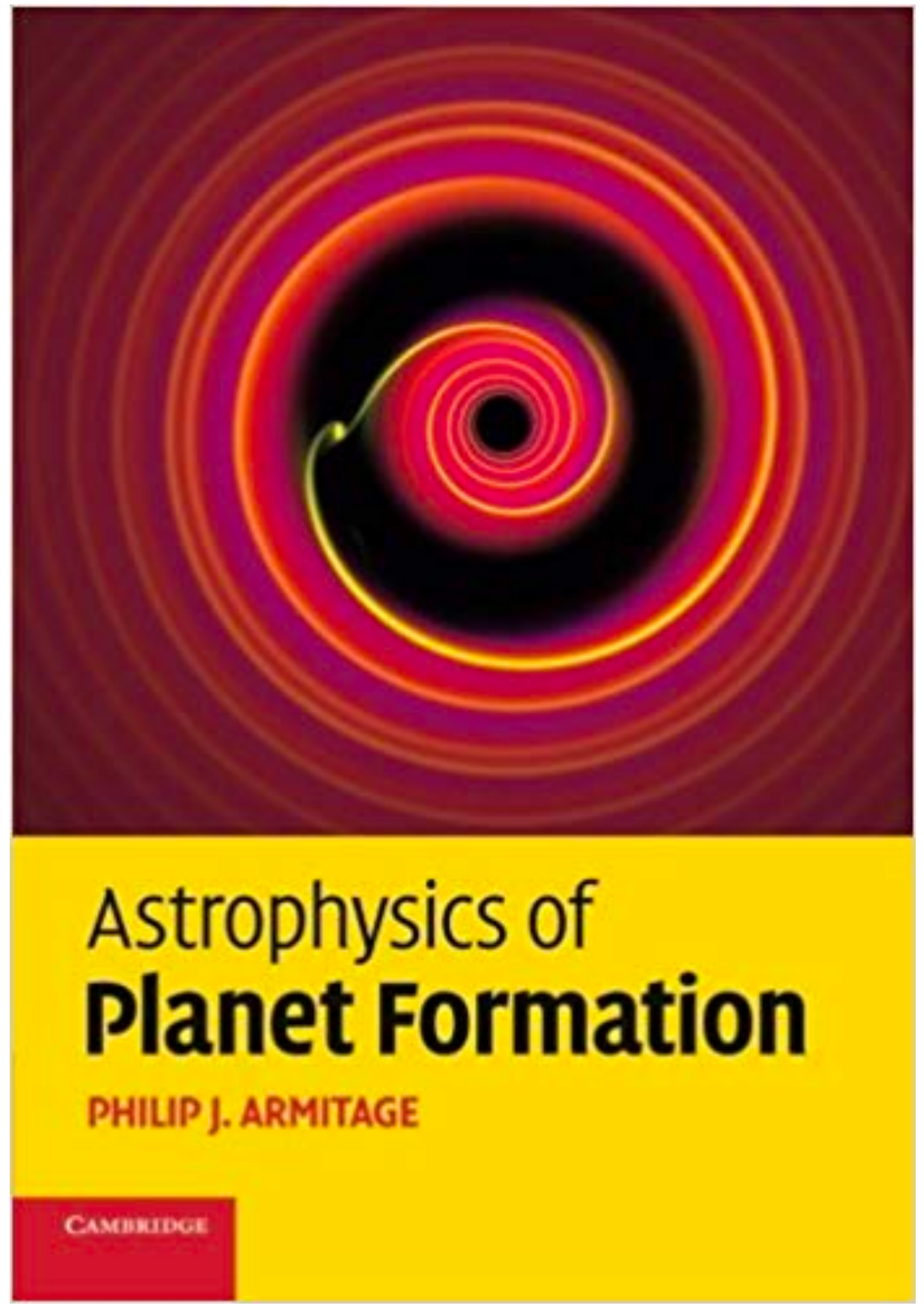
- Habitable zone is loosely defined as region in orbital space where liquid water can exist

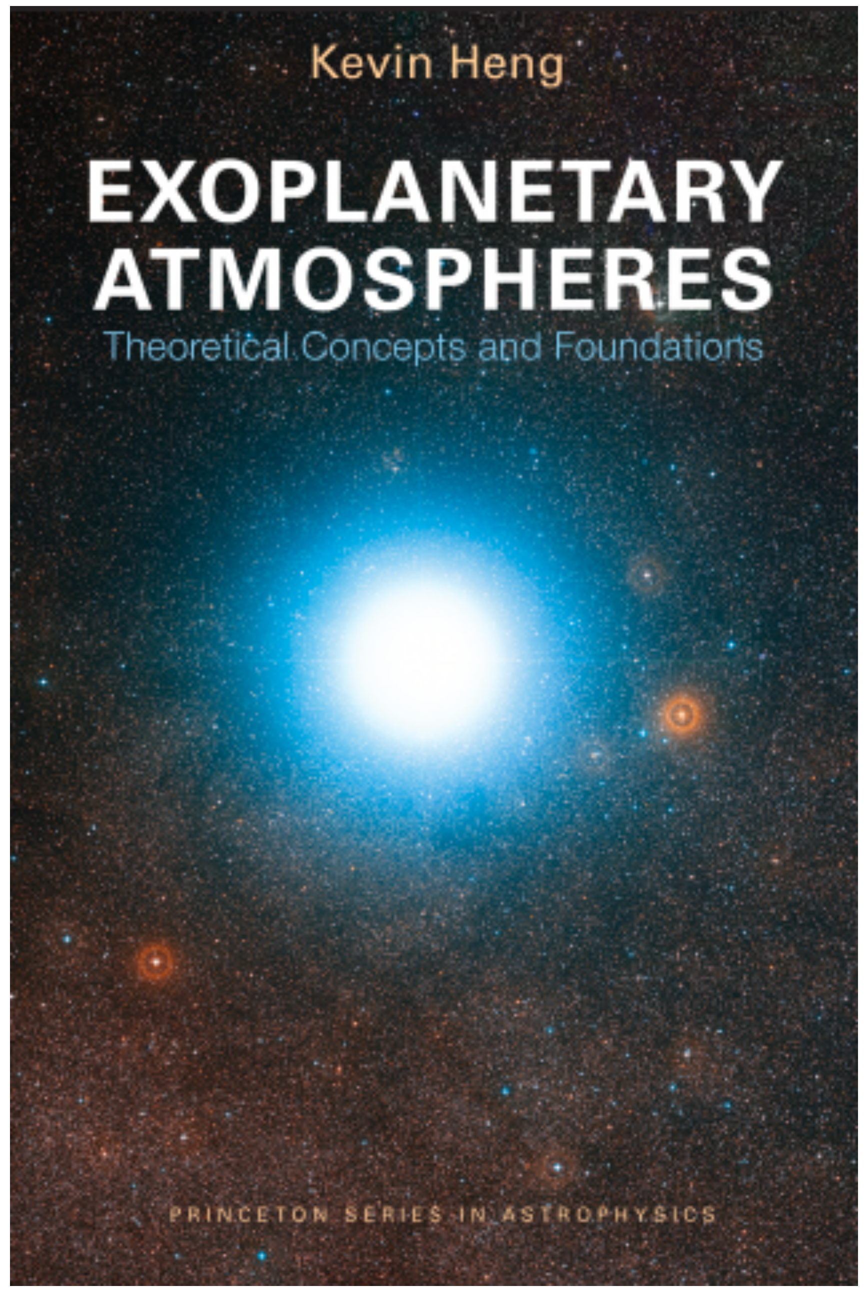
Summary

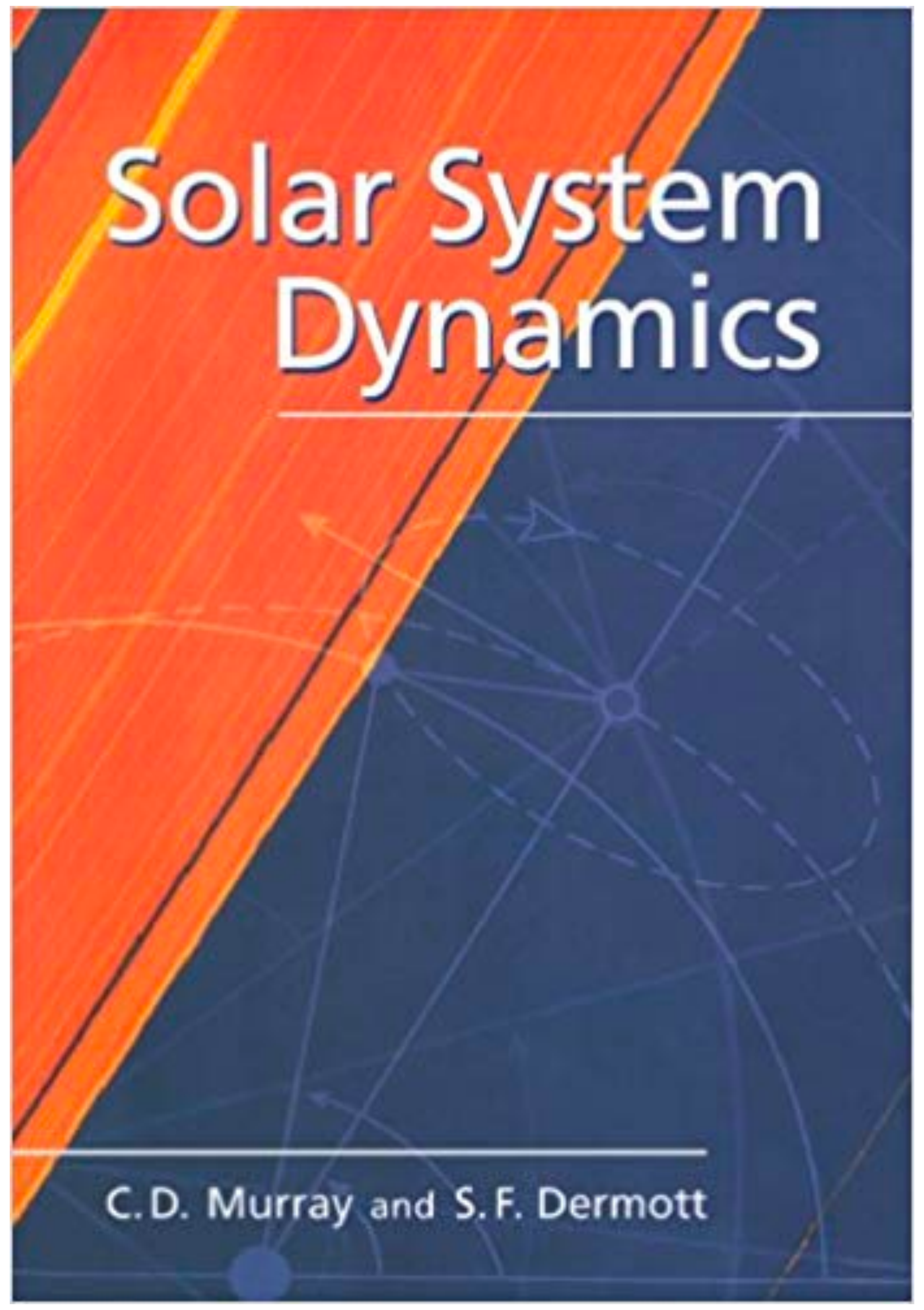
- Planetary systems are ubiquitous, they readily form around all kinds of stars (even binary and neutron stars)
- Most planetary systems are very different from our own Solar System
- Earth sized planets are common!
- Lots of unanswered questions in planet formation (need input from planetary sciences, chemistry, star formation…)
- Characterizing exoplanet atmospheres and mapping surfaces possible in some cases
- We don’t know what conditions are required for a “habitable” planet

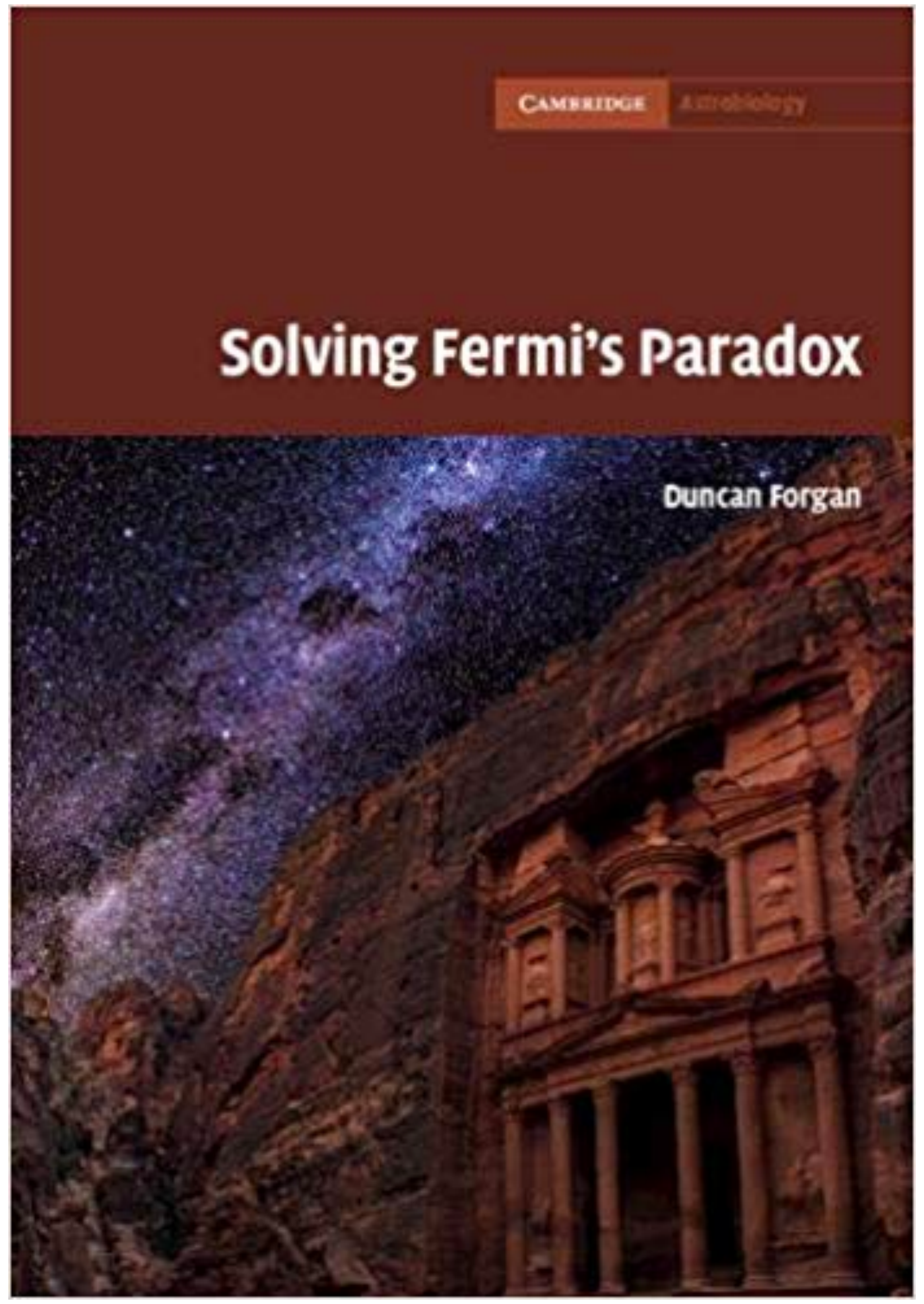
Additional reading





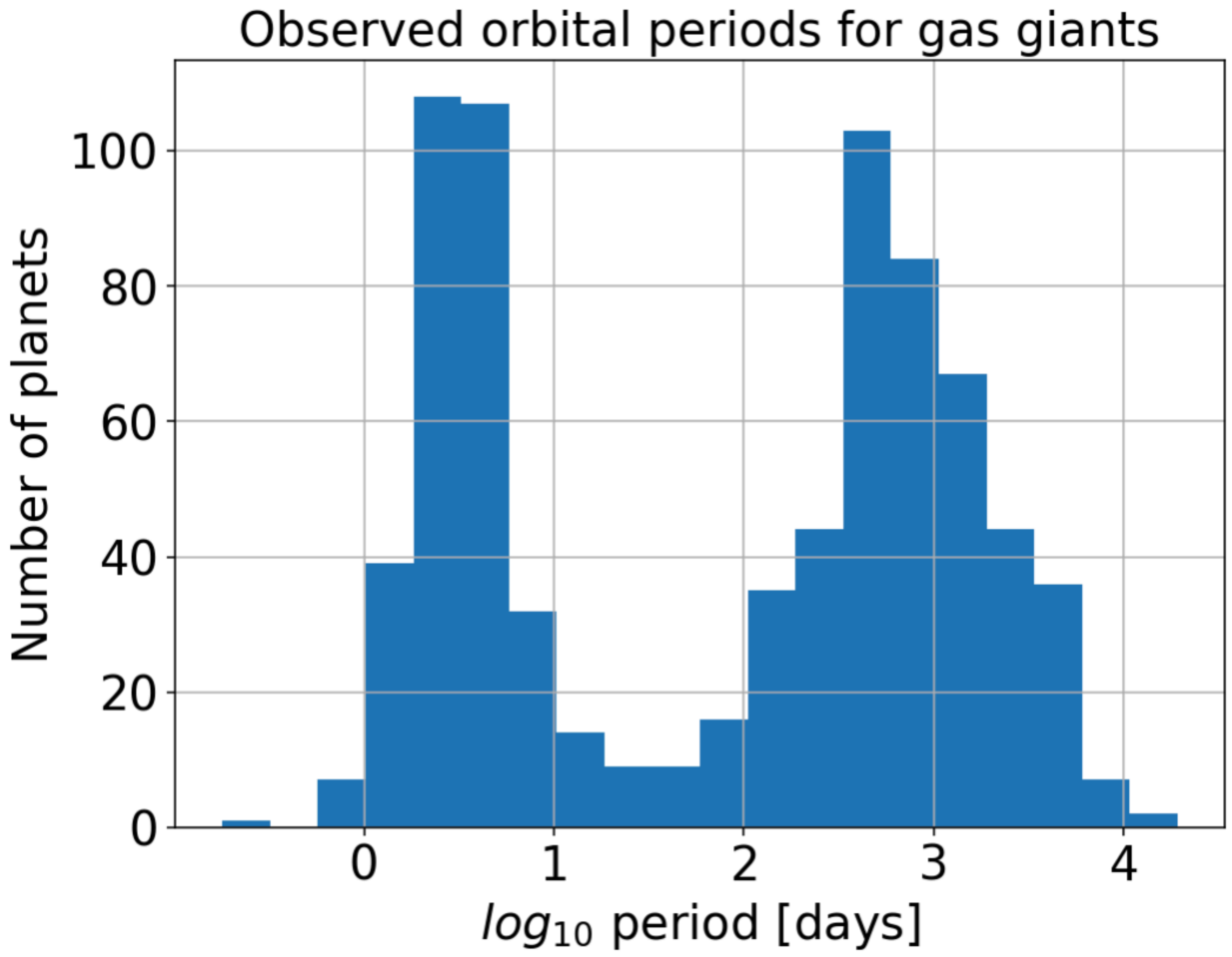






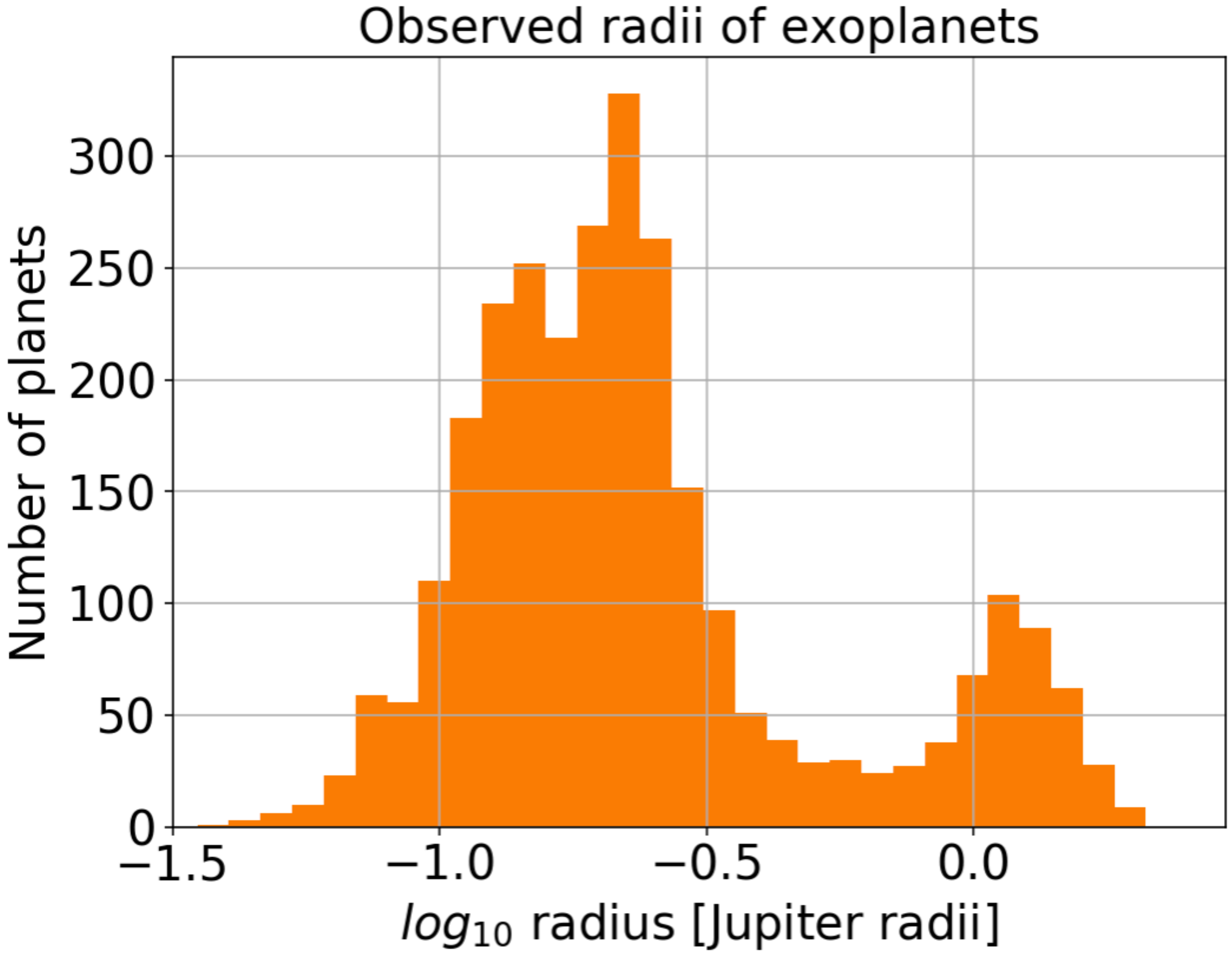
Additional slides

Observed exoplanets - orbital periods



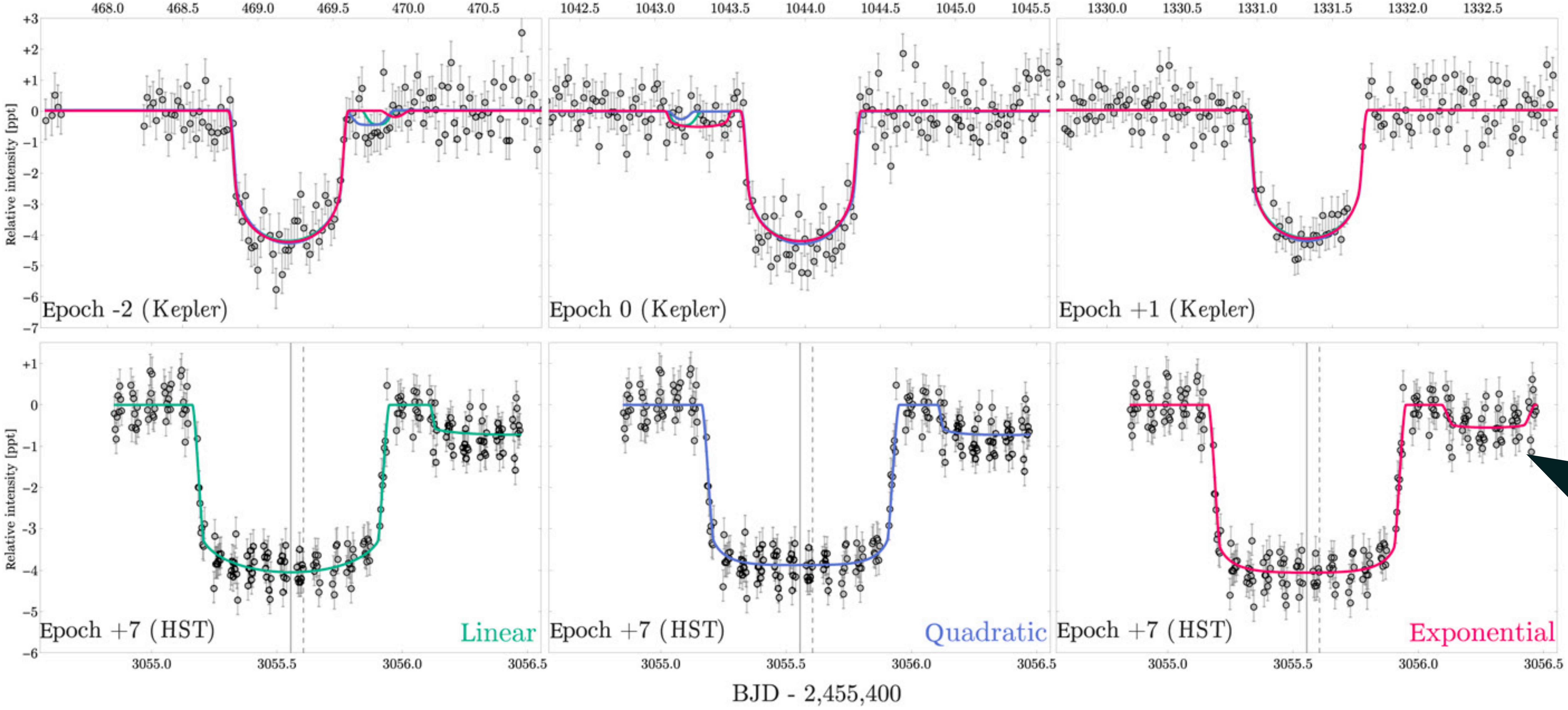
- Period gap in range 10-100 days for observed giant planets
- Possible explanation is a stopping mechanism in the protoplanetary disc

Observed exoplanets - radii



- Very few planets with radii in the range of 1.5-2.0 Earth radii
- Mass loss timescale for evaporation peaks for planets with H/He envelope mass of order a few percent
- Photoevaporation then gives rise to bimodal radius distribution peaking at naked core size and twice its value

Exomoons



Exomoon?