Physics of planetary atmospheres

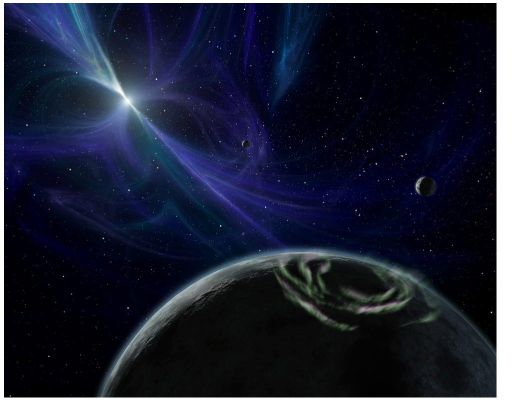
Lecture 1:
Detection and Observations of Exoplanetary Atmospheres

Course info

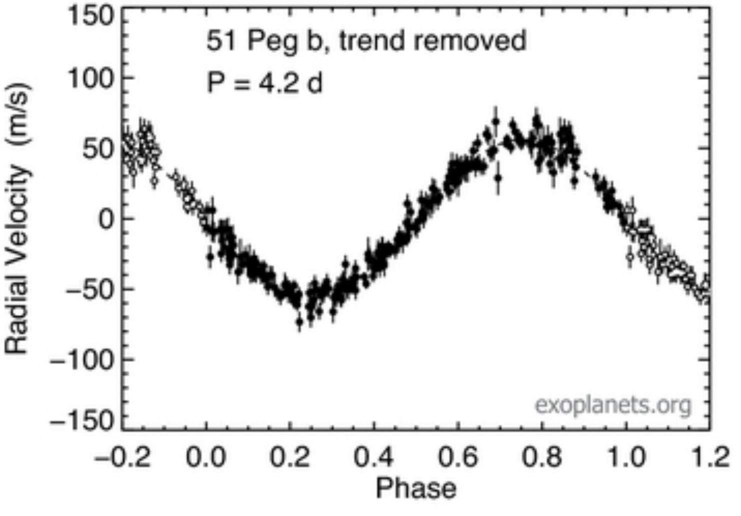
- PhD course (master students should talk to Andreas Korn about getting credits).
- Book: "Exoplanetary atmospheres: theoretical concepts and foundations" by Kevin Heng, Princeton University Press, 2017.
- Web page: http://www.astro.uu.se/~piskunov/TEACHING/PLANETARY_ATMOSPHERES/index.html
- No exam, but homework, project and class presentations.

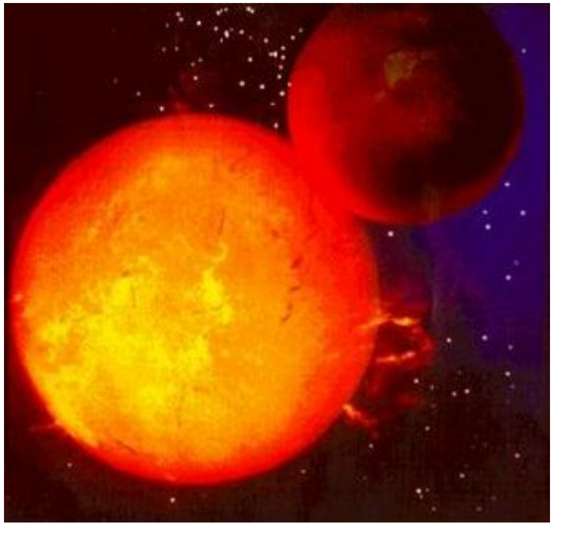
The First Discoveries

- Planets around pulsars



- Planets around solar-type stars

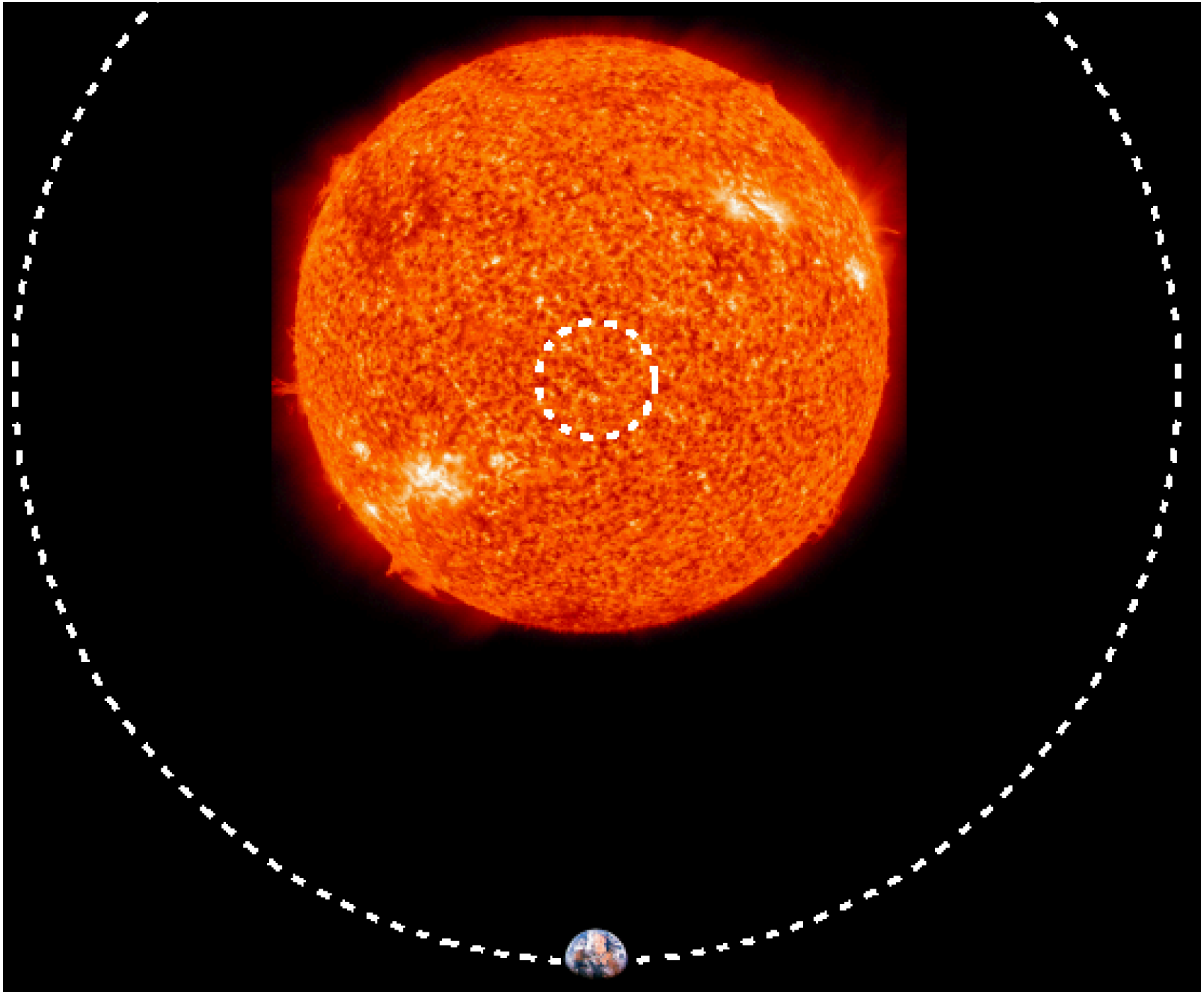




Discovery of exoplanets

- Pulsars timing methods: <10
- Radial Velocity (RV) method >1000
- Transit photometry method >2500
- Direct imaging method >20
- Gravitational microlensing method >30
- Astrometry method =1

Radial Velocities



Radial Velocity method

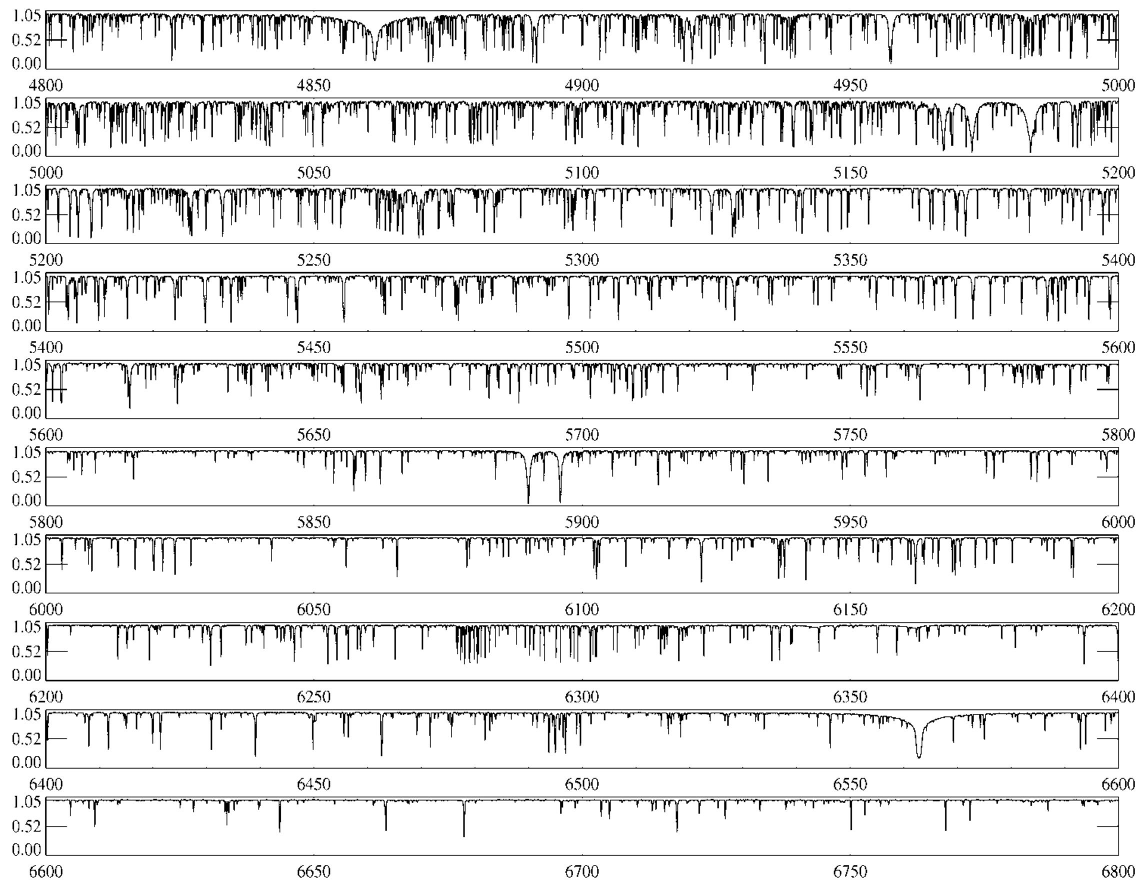
- Typical amplitude of planetary orbital velocity along any given direction is between 1 and 300 km/s.
- We do not see the planet ☹
- The star also moves around common gravity centre but velocities are between 1 cm/s and 100 m/s.
- Measuring such velocity requires advanced instrumentation, simultaneous calibrations and long observing sets.

RV observations

The HARPS Spectrograph and the 3.6m Telescope

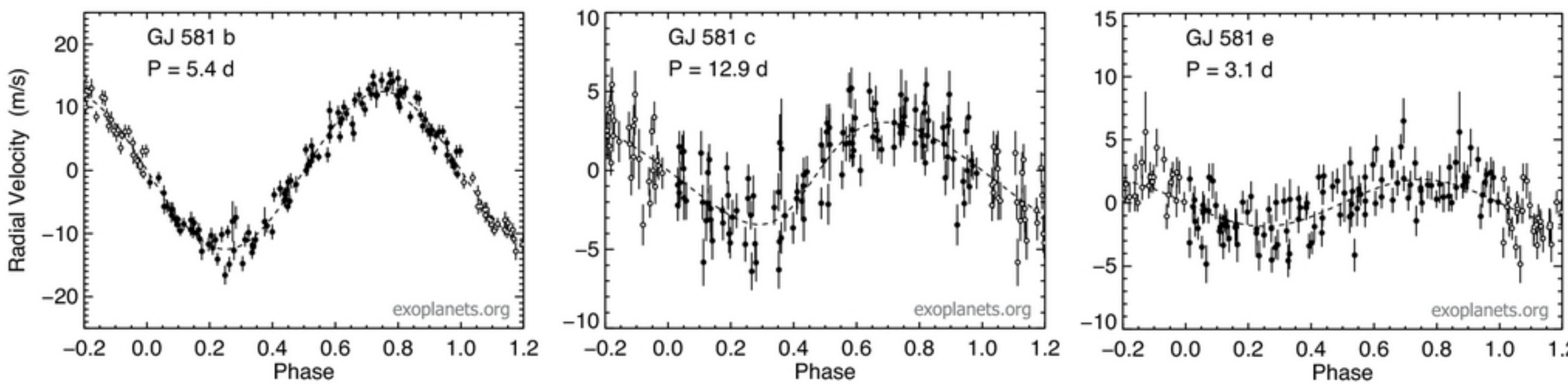
ESO PR Photo 25a/04 (25 August 2004)

Cross-correlation of spectra like the one below gives the change of radial velocity.



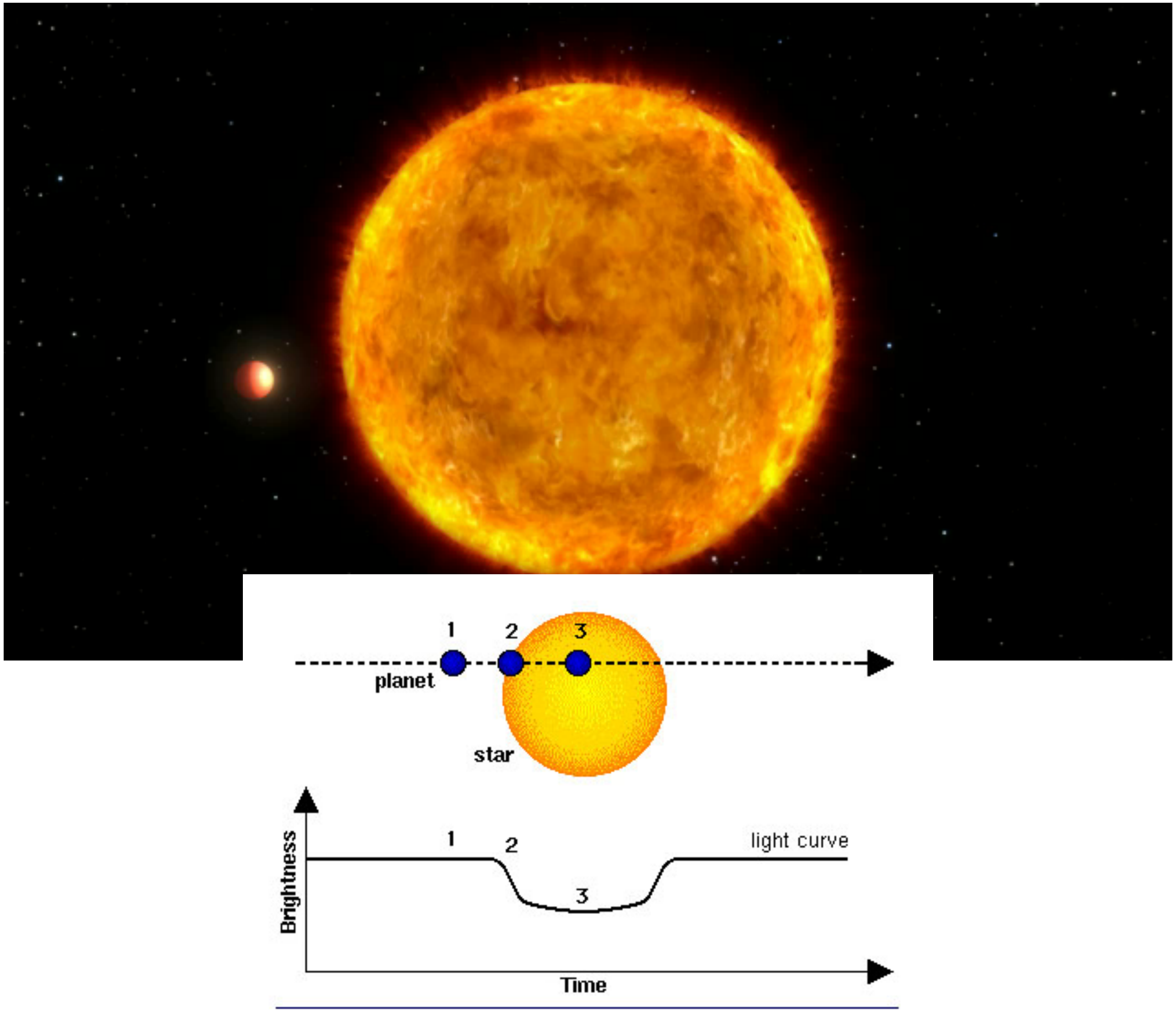
RV analysis

- This method can also discover multiple planets



- What do we get from RV curves?
  - Period
  - Amplitude of RV
  - Eccentricity
  - $M_p \sin i$ (i − is the inclination of the orbit to the line of sight)

Transit photometry

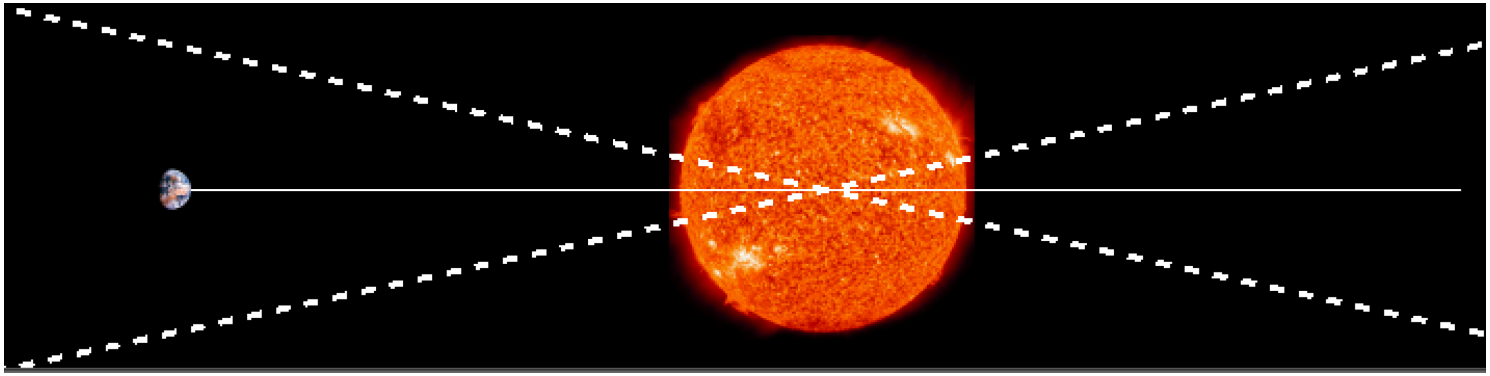


What are the chances to see a transit?

- Assuming random inclination of the orbital plane to the line of sight we can see the transit if:

$$-\frac{R_\star}{a} \leq \tan\theta \leq \frac{R_\star}{a}$$

where a is the radius of the orbit and $R_\star$ is the radius of the star.



- Of course, we will still see the eclipse from any side along the orbit.

Probability of transit

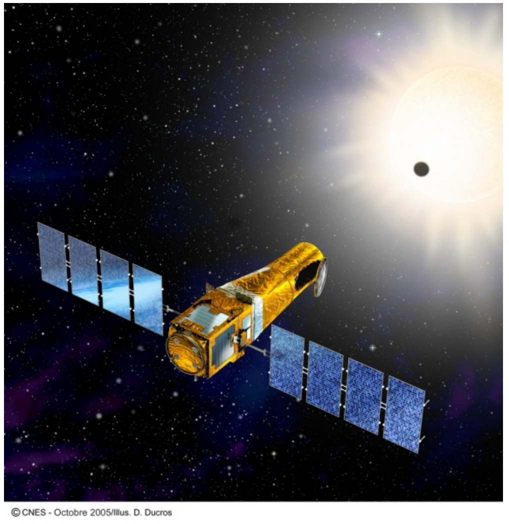
- The probability is:

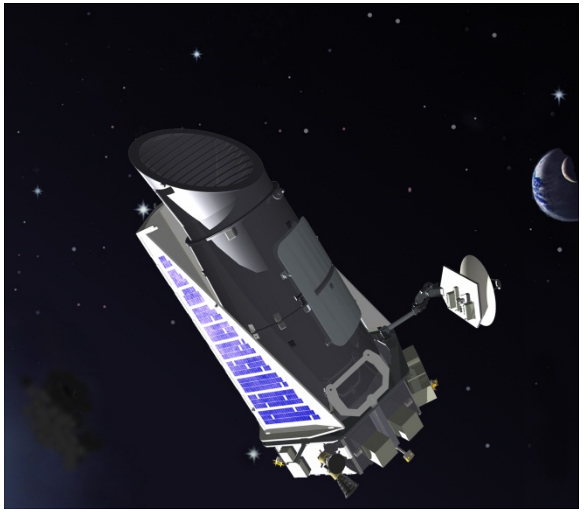
$$\frac{2\pi \cdot 2\theta}{4\pi} = \theta \approx \frac{R_\star}{a}$$

- We ignored the size of the planet and assumed θ to be small.
- None of these is true for hot jupiters but is good enough for most other planets.

Transit search

- First, as confirmation for RV result
- Then, independent massive searches: COROT and KEPLER from space, WASP, TRAPPIST from the ground

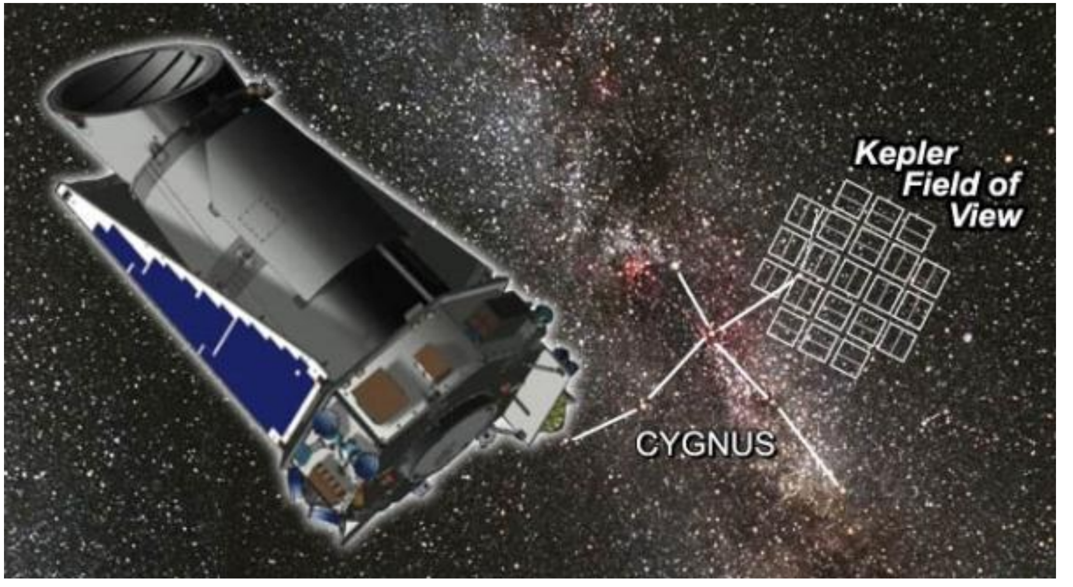




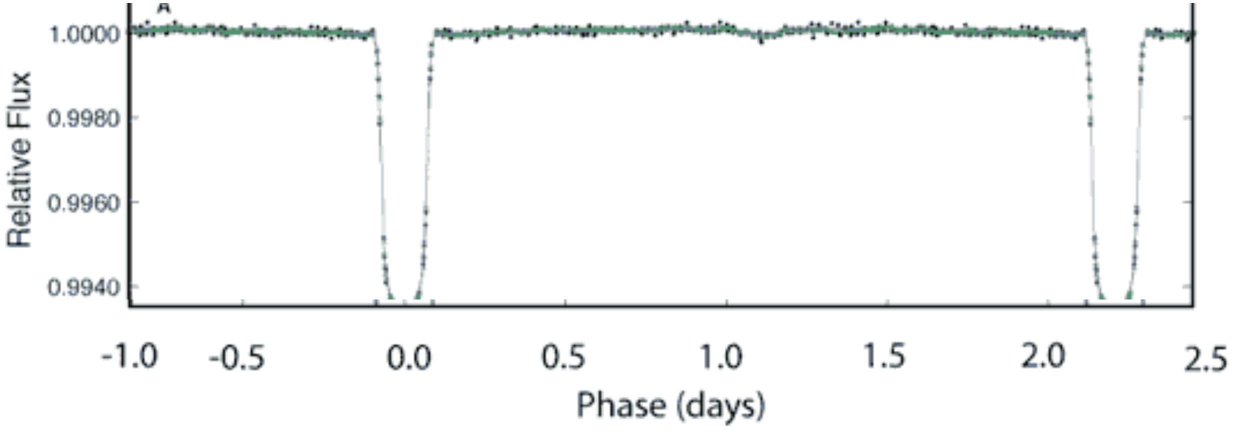
- Main idea: Looking at many stars continuously

Kepler

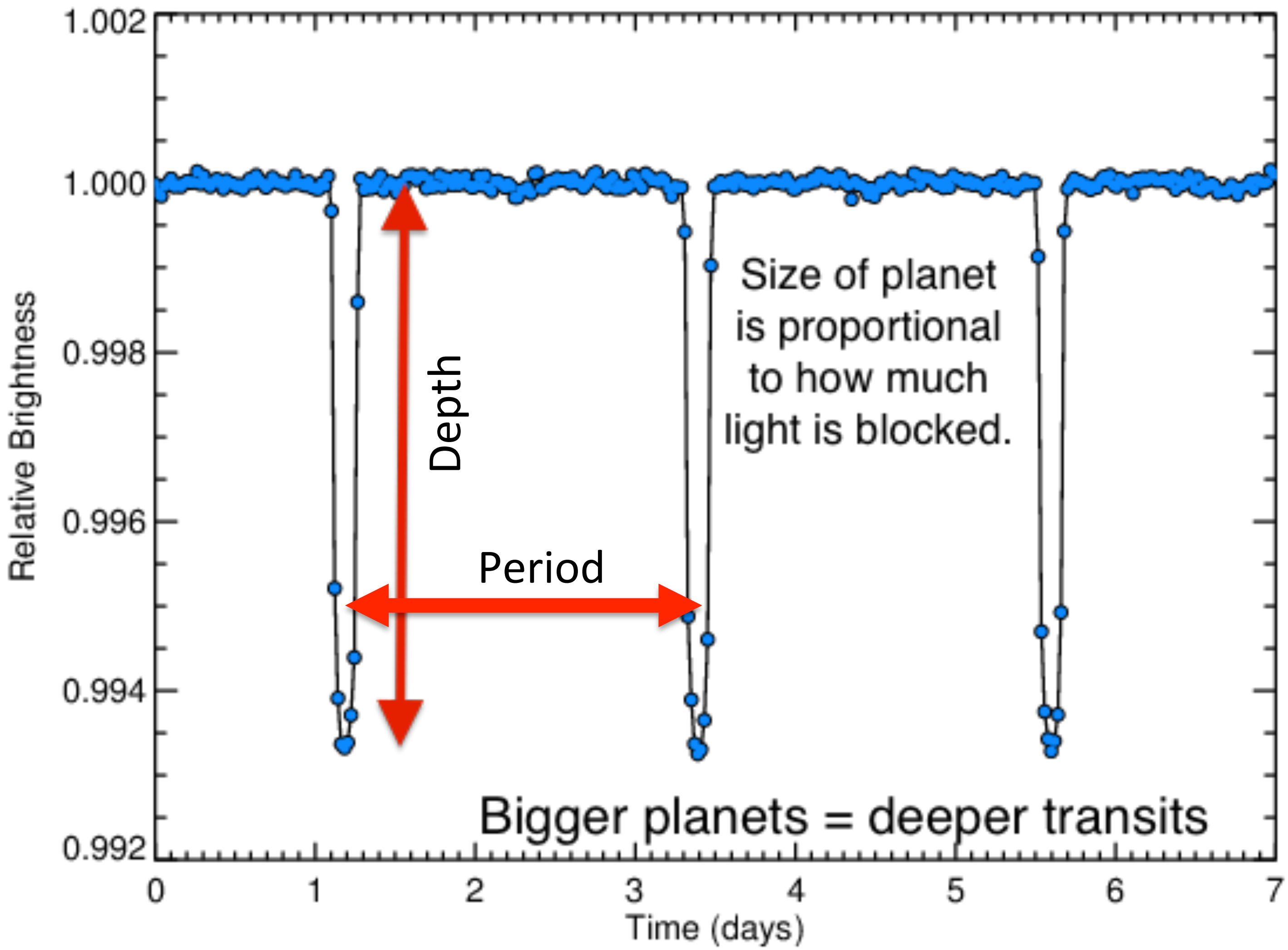
- Kepler field
  140000 stars



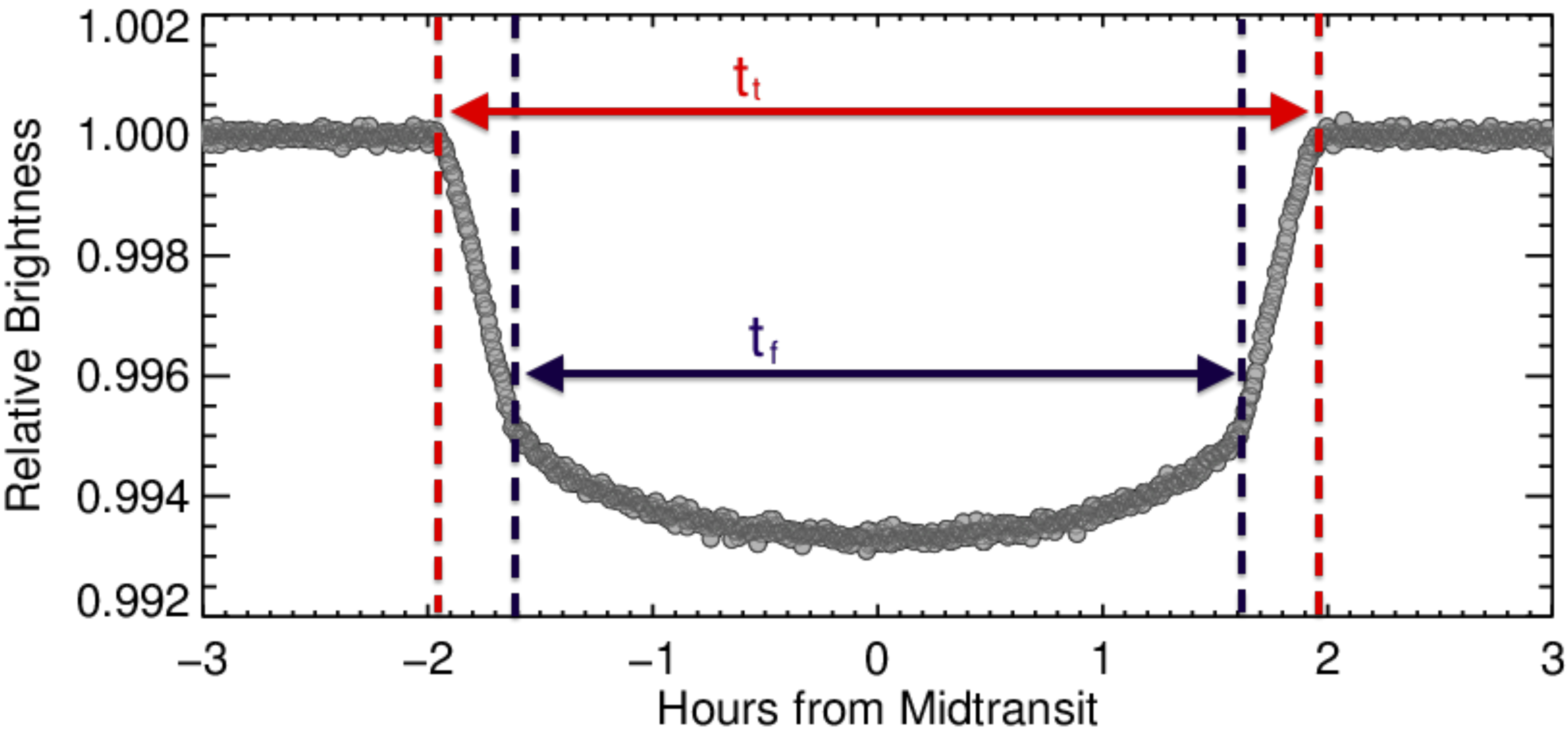
- Kepler light curves



Closer look at the light curve

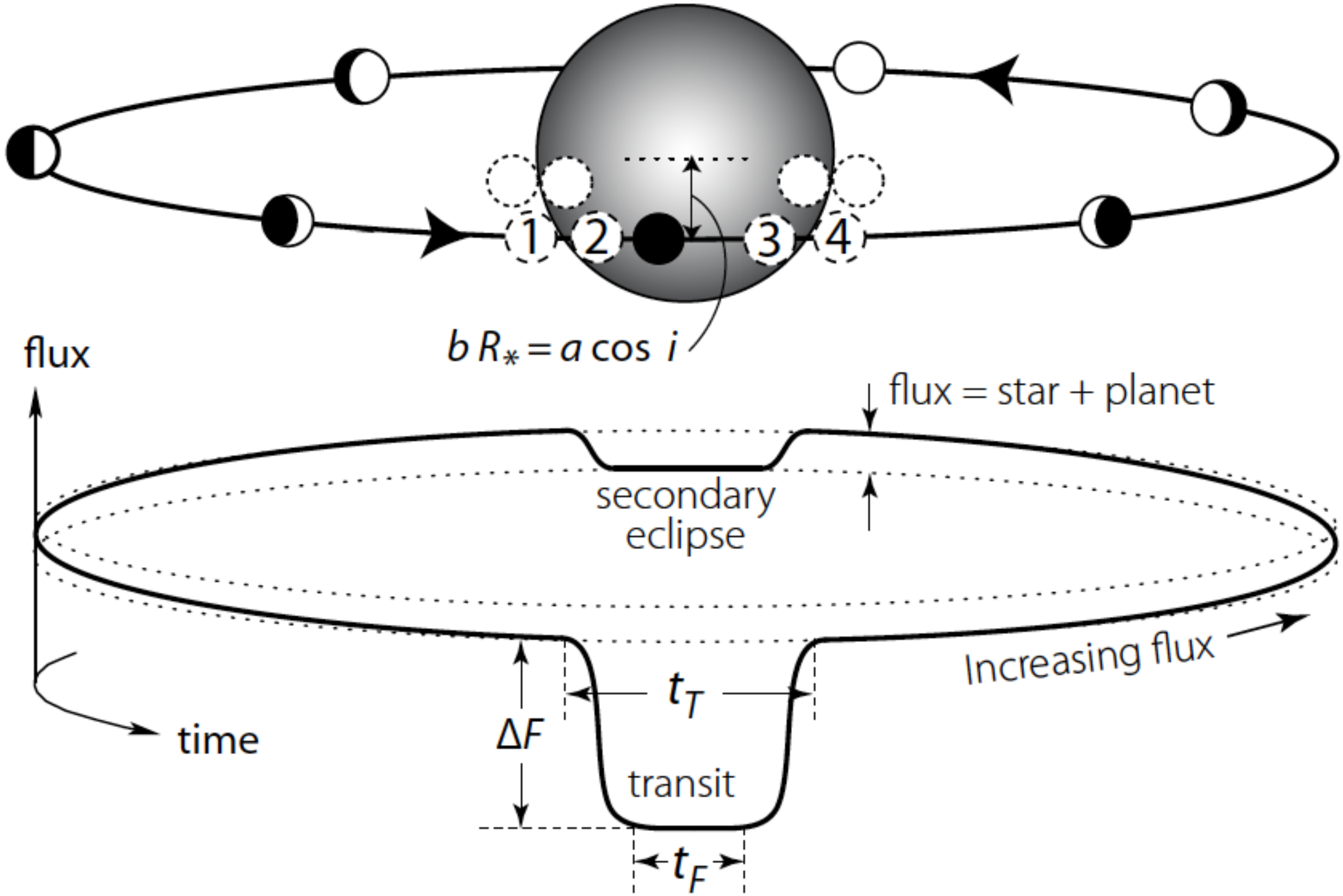


Even closer look



The comparison of the two times combined with depth gives the inclination of the orbital plane and the ratio of planet-to-star radii.

Ingres, egress etc.



If observations were perfect …

We could derive transit would also provide:

- Period
- Size of the planet (relative to the star)
- Stellar limb darkening
- Planet albedo (fraction of reflected light)

and combined with the RV orbital solution:

- Planet mass density (Earth, Neptune, Jupiter)
- Variation of planet irradiation (elliptic orbit)
- Presence of other planets

… but observations are not perfect

- Spatial resolution is usually poor. There is a chance to have more than one star contributing the the light curve.

- In this case an eclipsing binary star with a third star on the line of sight can mimic planetary system.

- Large amplitude of RV variations will reveal such cases.

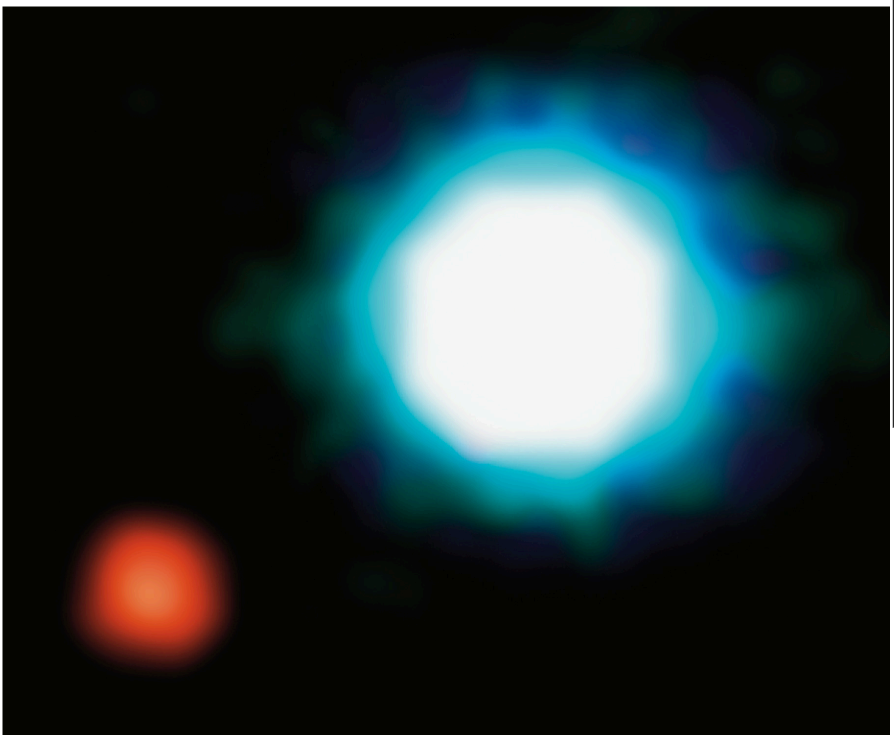
- This was not understood when COROT and KEPLER missions were launched. Thus many of discoveries remain unconfirmed (too faint for spectroscopy).

Direct Imaging Method

- The goal is to see (reflected) light from a planet next to a star that is 10^9 times brighter!
- Three crucial ingredients: spatial resolution, image quality and coronagraphy.
- Spatial resolution and image quality are defined by the size and quality of the telescope and the atmosphere. The goal is concentrate the light and make targets on optical axis to be perfectly symmetric.

Example from the ESO VLT

8m telescope with Adaptive Optics (AO) imaging system:

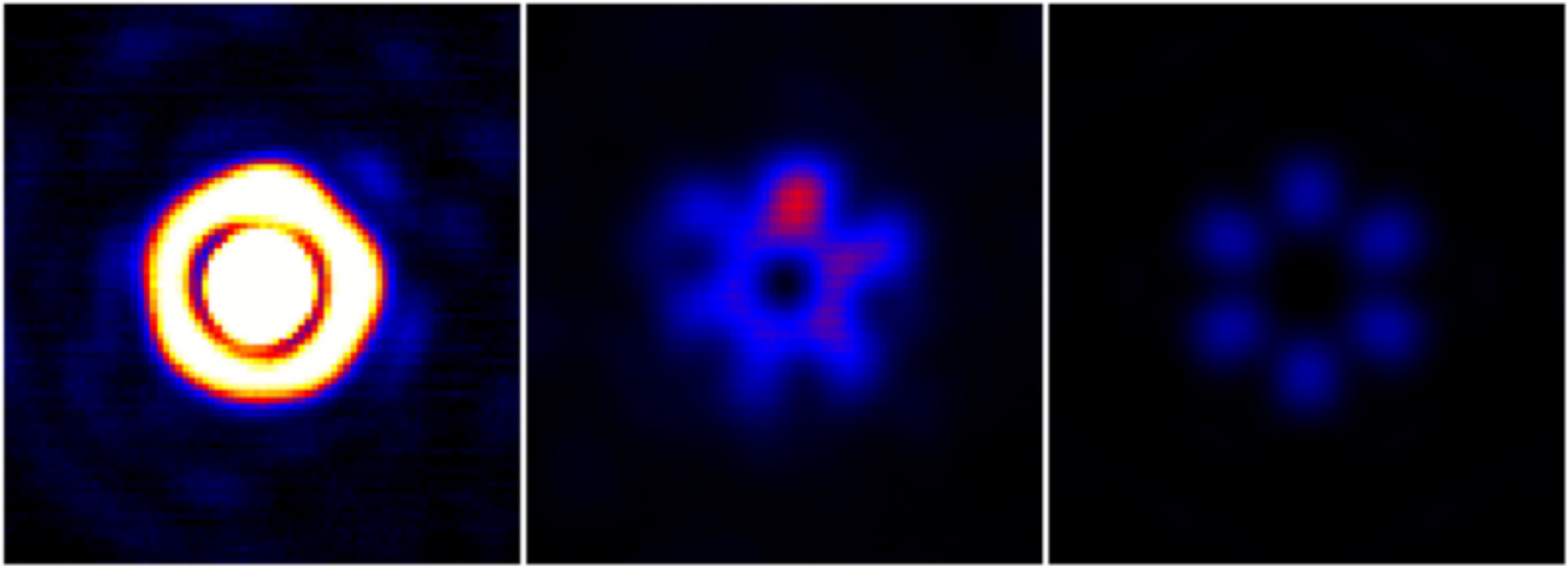


Atmospheric correction of Neptune images with the latest ESO AO system.

The separation between the star and the planet is 11 times larger than the orbit of Jupiter. The star is much fainter than the Sun.

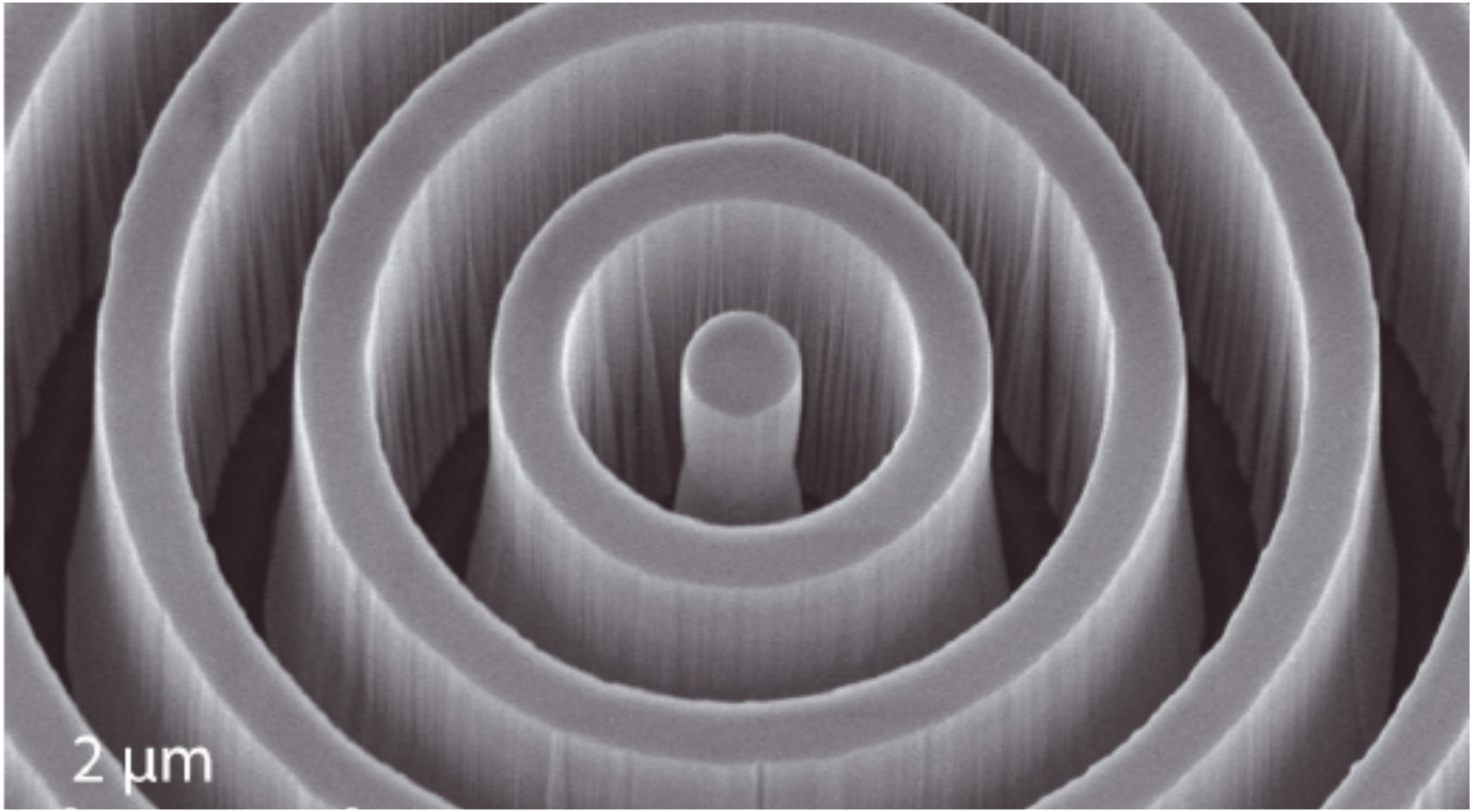
Coronagraphy

Suppressing stellar light (Keck Vortex coronagraph):



Original (log scale) Measured residuals <10^{-3} Predicted residuals <10^{-8}

Made in Uppsala



AO-Coronagraphy results

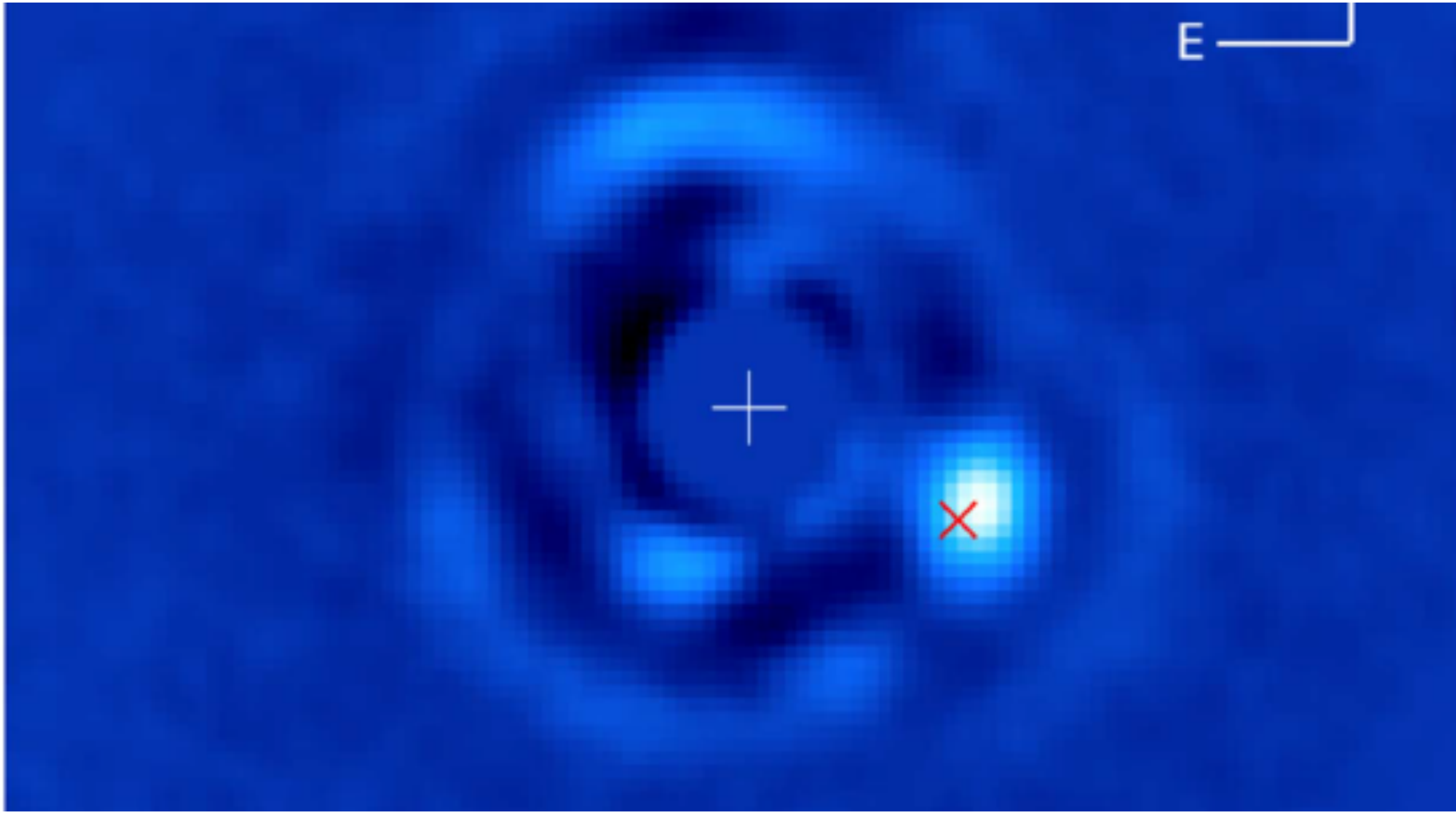
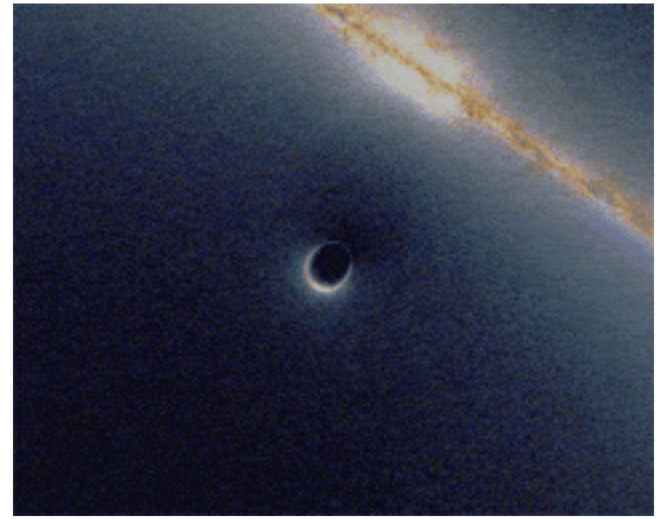


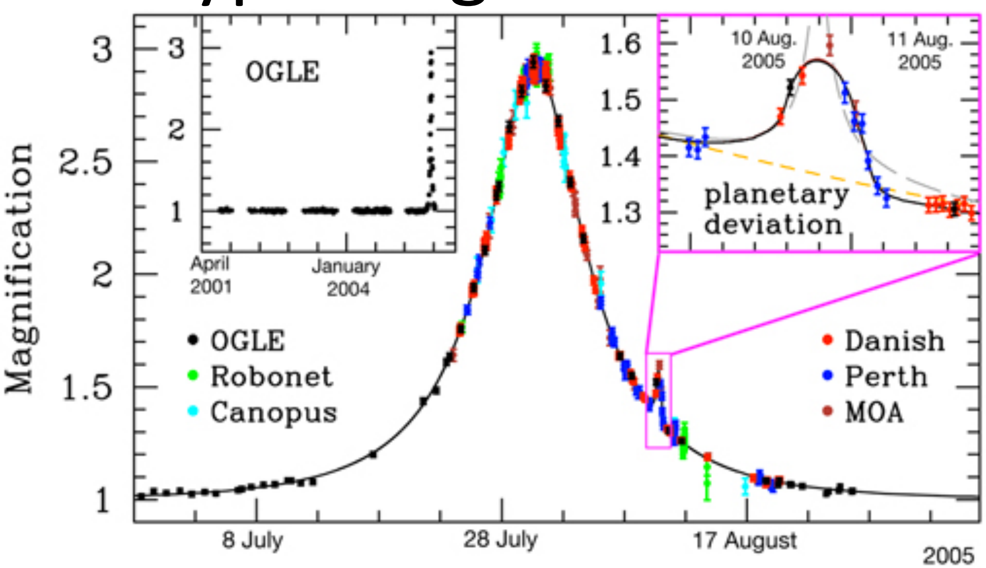
Image of HIP 79124b planet in 2017. X marks planet position in 2015. The orbit 5 times larger than the orbit of Jupiter. Serabyn et al, 2017, AJ 153, 43.

Gravitational Microlensing

- Gravitational lens
  Black hole in front
  of a galaxy (simulation,
  Wikipedia).

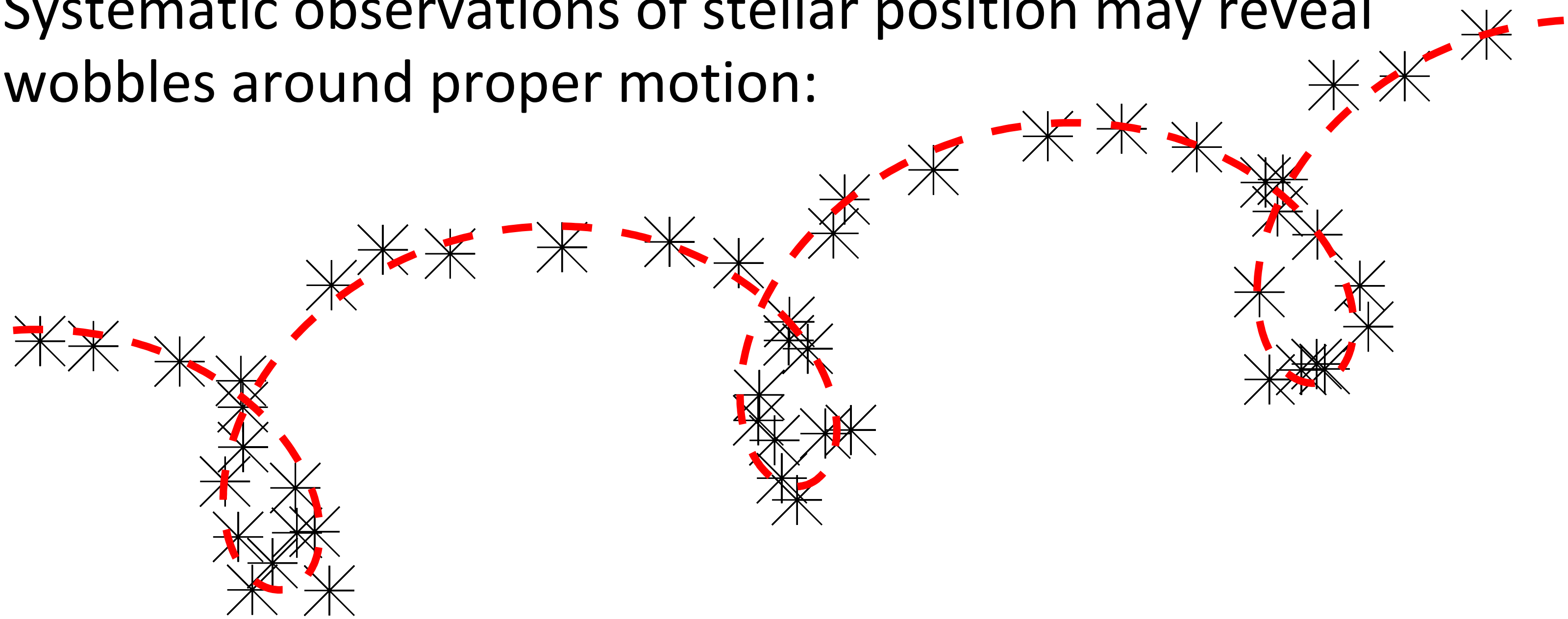


- Typical light curve:



Astrometry

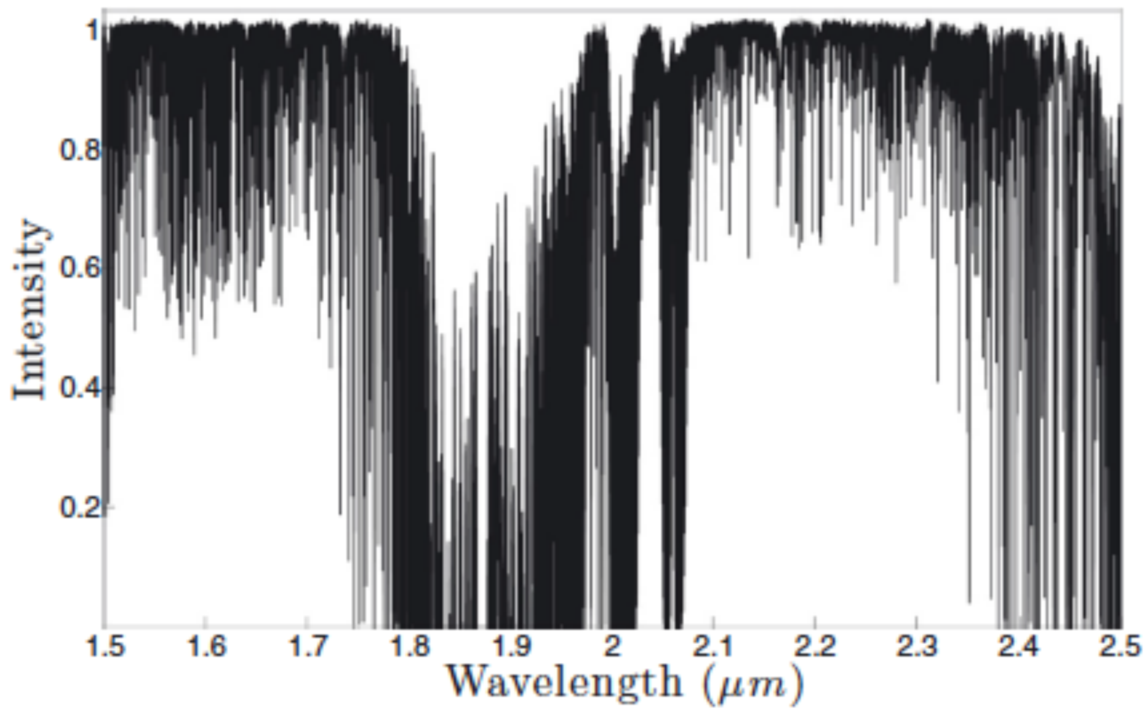
Systematic observations of stellar position may reveal wobbles around proper motion:



Fitting an orbital solution would give the period and mass ratio. Gaia satellite with its high-precision and long mission will discover many such systems. They are invisible to transit or RV search.

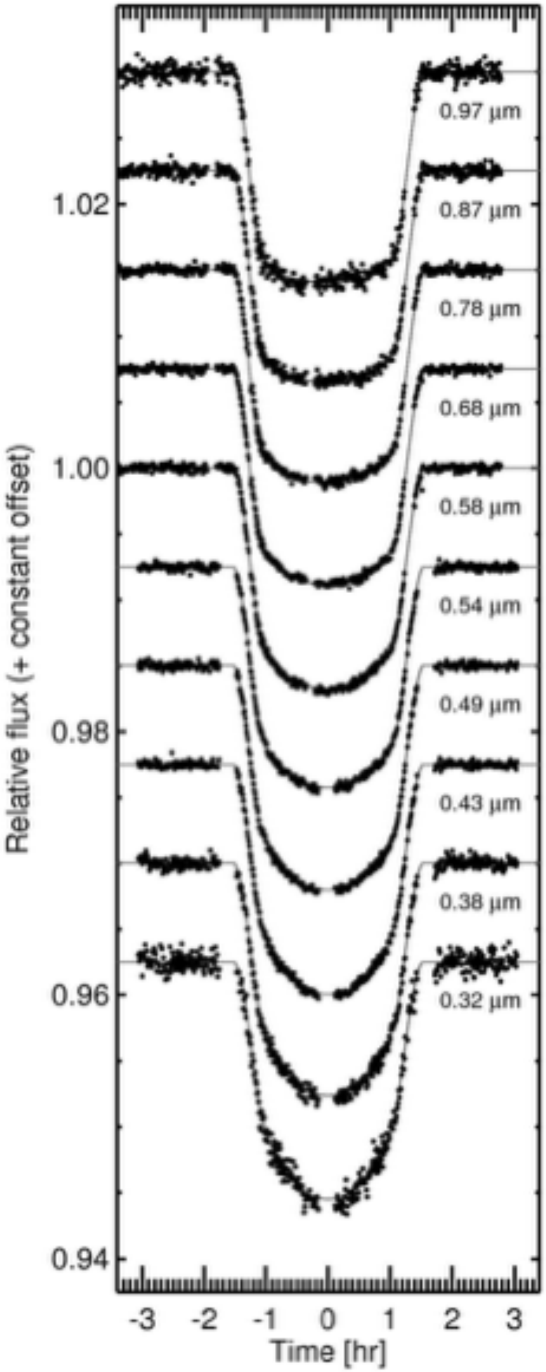
Characterisation of planetary atmospheres

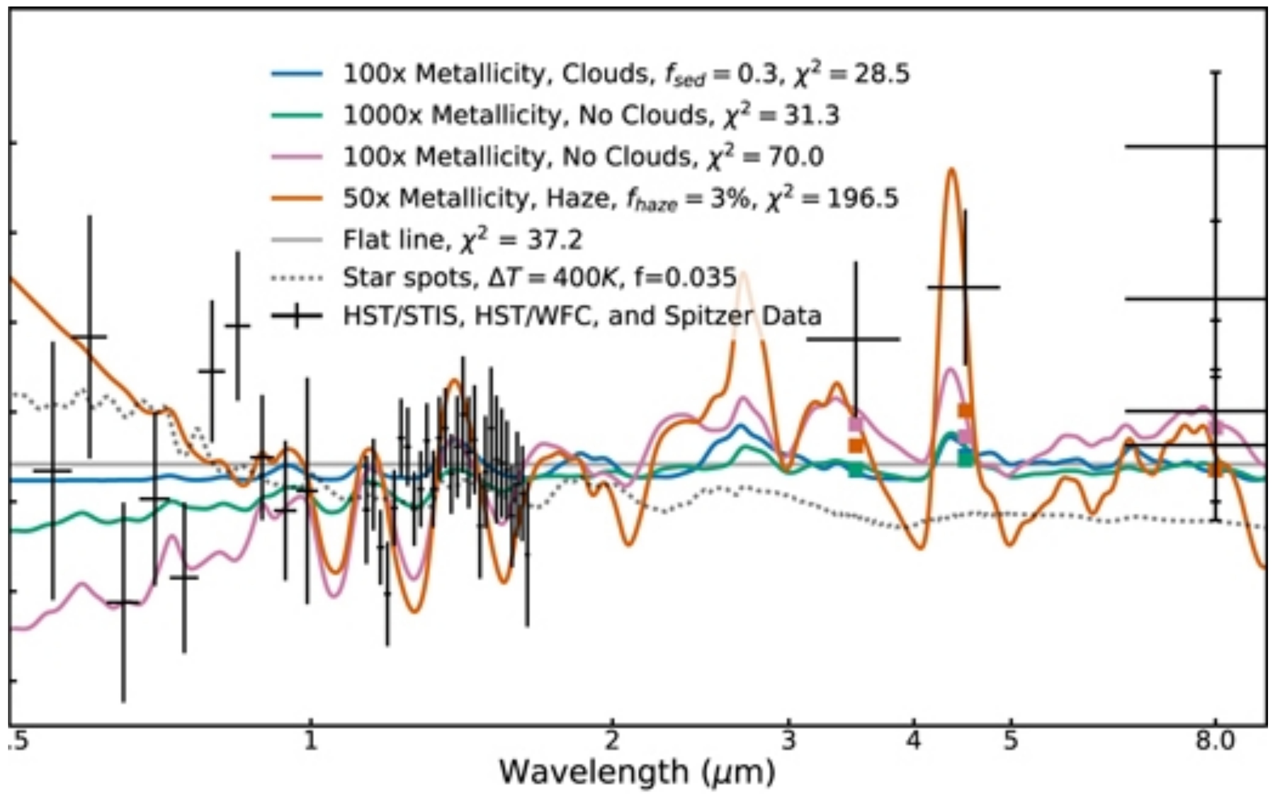
- Planetary atmospheres may have dramatically different transmission as function of wavelength.



- In these cases transition photometry in narrow-band filters will show different planet radius.

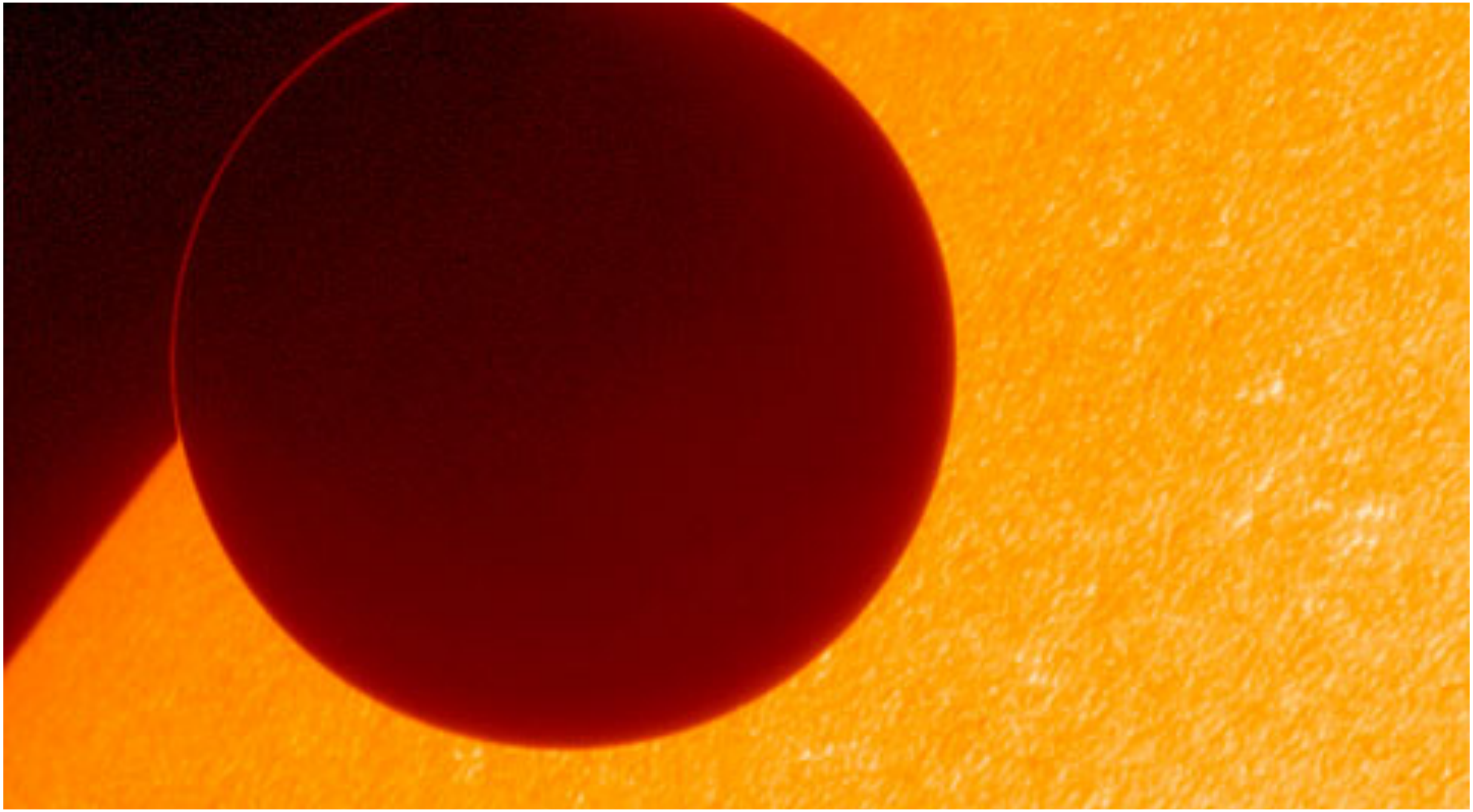
Transit spectrophotometry





GJ 436b: a Neptune-size planet orbiting and and M-dwarf at Mercury orbit.

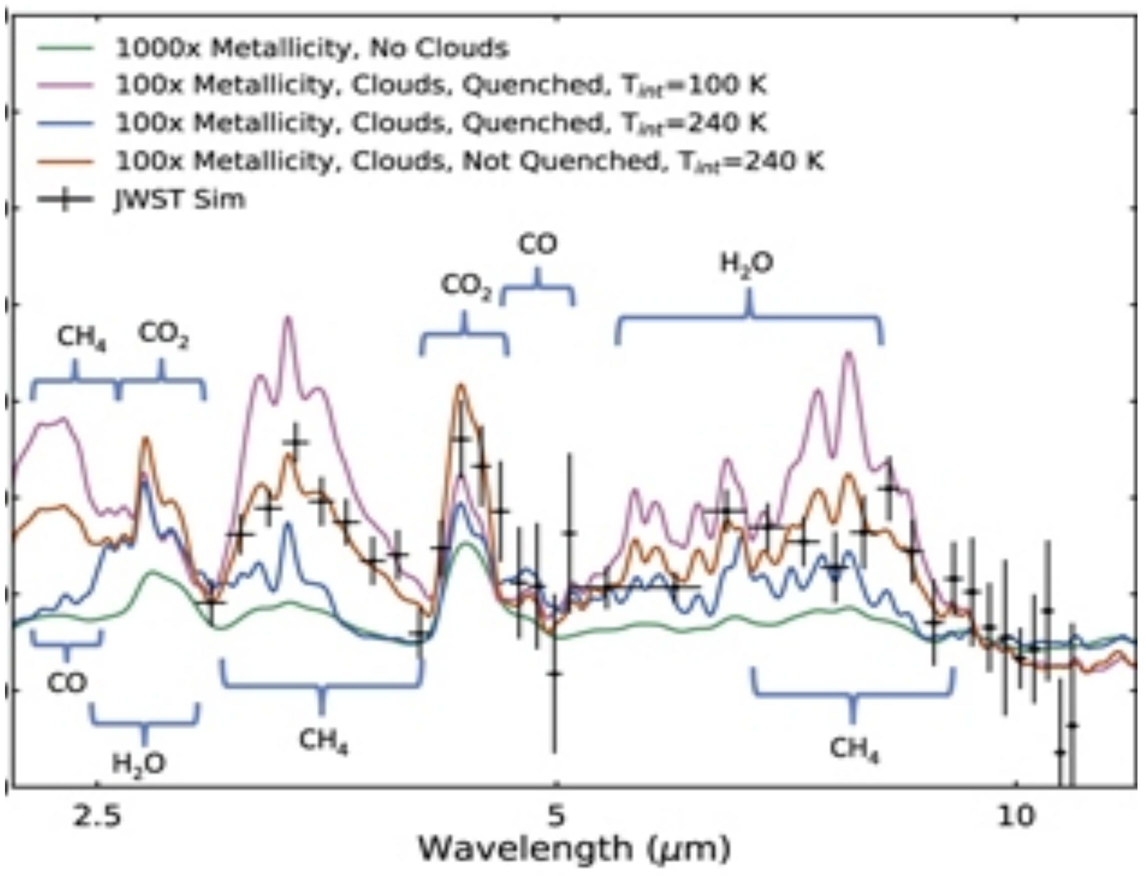
Why is it so bad?



Venus transit of the Sun 2012-06-06

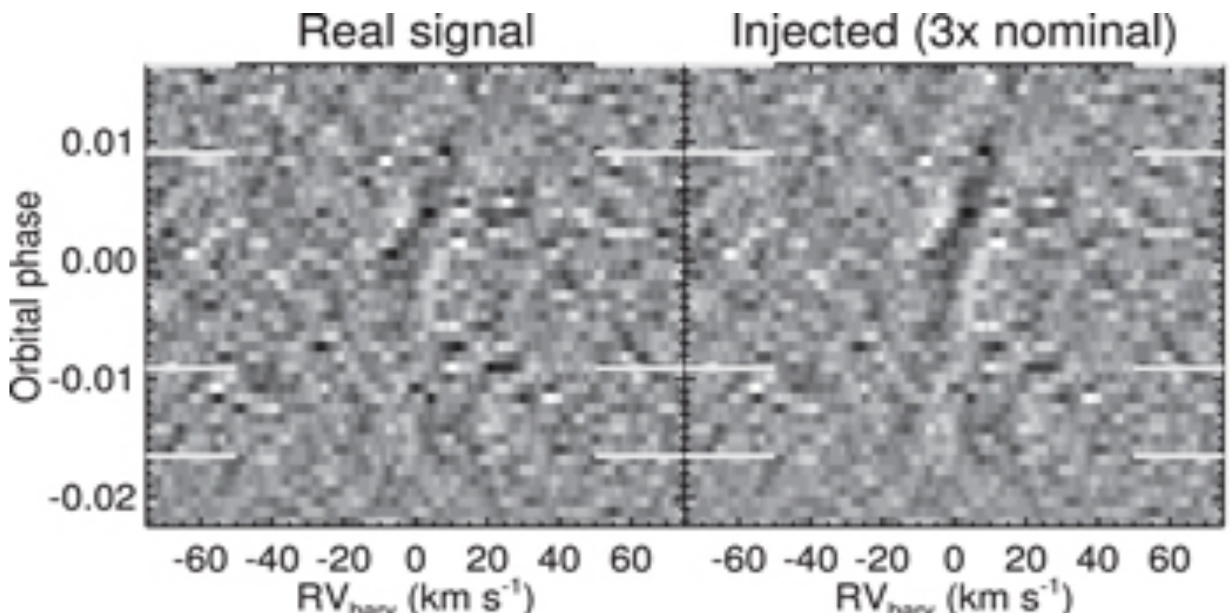
Future Instruments

James Webb Space Telescope (6m in space) will do much better:



Transit Spectroscopy

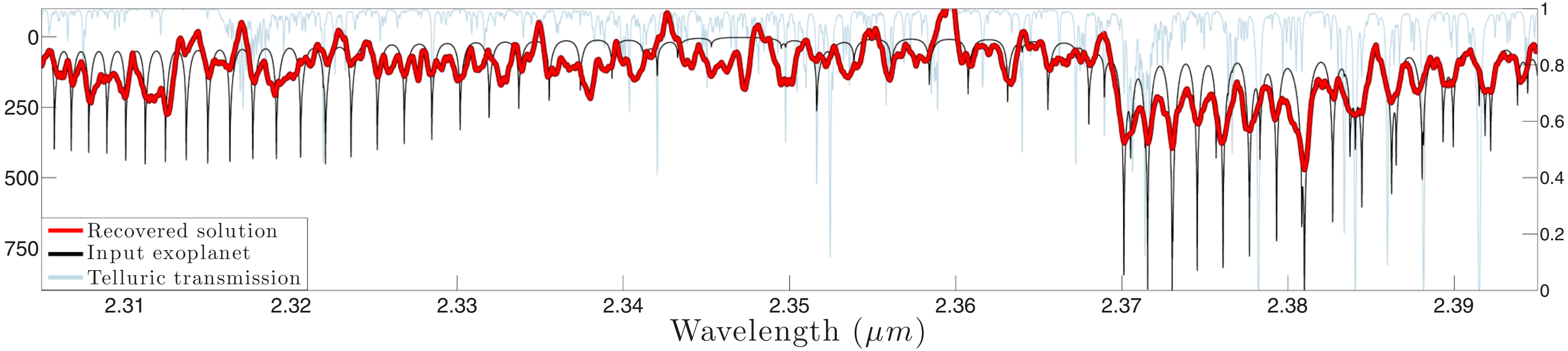
- High spectral resolution with huge telescopes on the ground.
- Cross-correlation method (Ignas Snellen):



Water in the atmosphere of HD189733b with 3.6m telescope

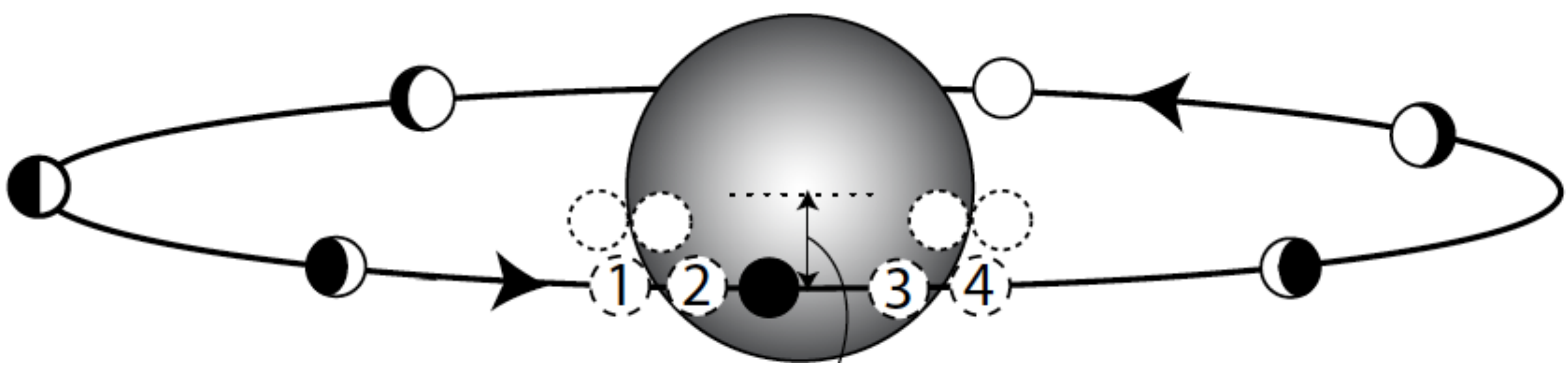
Future of Transit Spectroscopy

- One of the main tasks for the coming 30m telescopes ELT, GMT and TMT.
- Even with an 8m telescope already next year we expect to get this:



Reflected light

- Much larger signal.
- Probing most of the planetary atmosphere.
- Either in direct imaging (but low spectral resolution) or with high-resolution by measuring before and after secondary eclipse.



Future in general

- No matter what technique proves to be first or best we would need planetary atmosphere models to interpret observations.
- Such models must be based on sound physical principles of energy conservations, interaction between particles and particles with radiation.
- Astronomy already today provides some important basic knowledge abut planetary orbits and host stars.
- Modelling must be made sufficiently flexible to describe exoplanets.

Home work

- What would happen with orbital period of the Earth if we reduce the mass of the Sun by 50% but keep the same orbit?
- Compute transit duration for Venus and Mars observed from a distant planet that happens to be in the same plane as the orbits of these two Earth neighbours.