THE ROYAL SOCIETY

European Research Council

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Galactic planetary science

(Introduction)

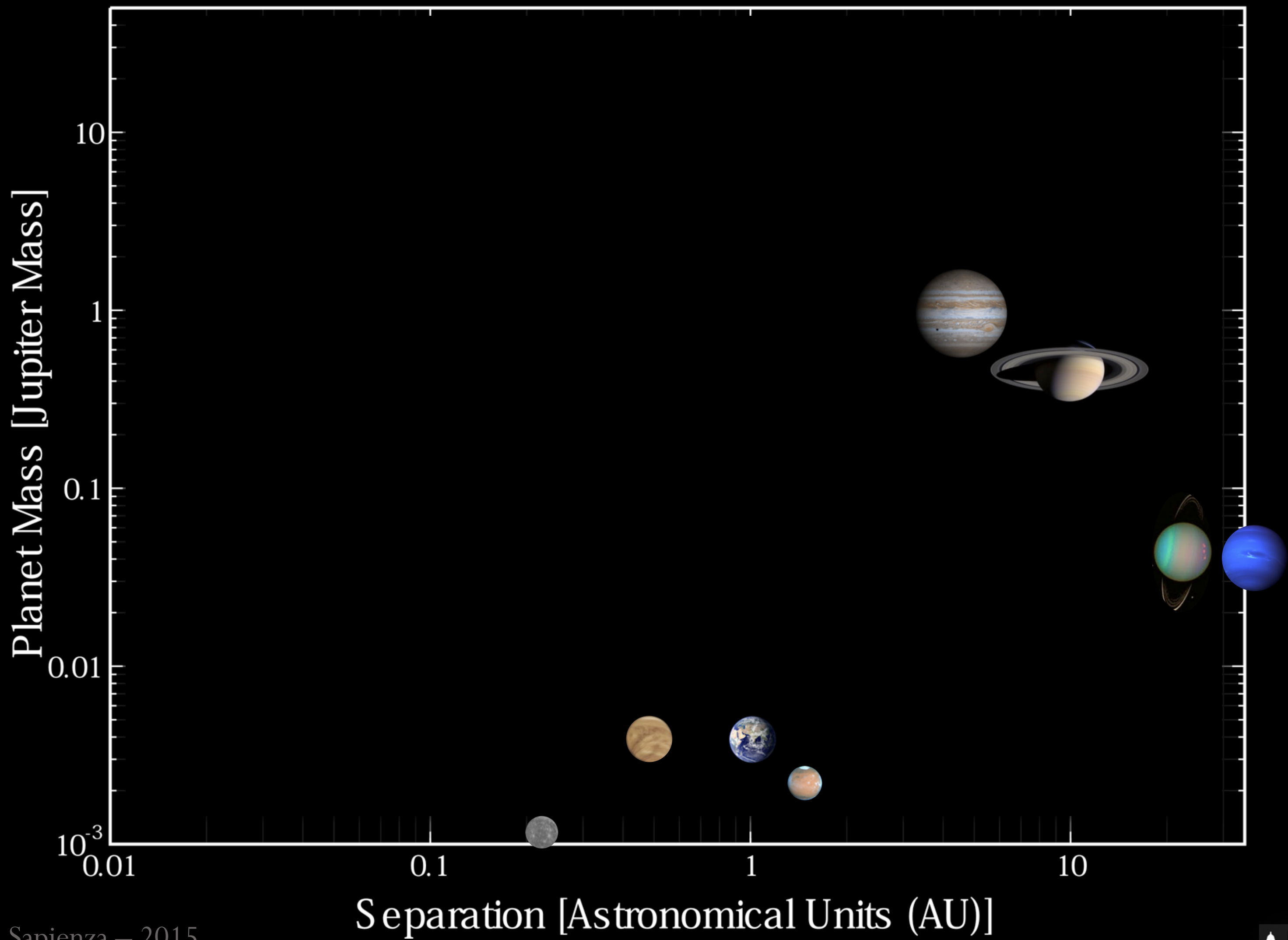
Giovanna Tinetti

University College London & Royal Society

La Sapienza – 2015

The Exoplanet Revolution

9 to 2000 in 20 years!



Planets before 1995...

Small rocky planets close to the Sun
Gas-giant planets more distant from the star

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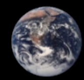
The first extrasolar planet

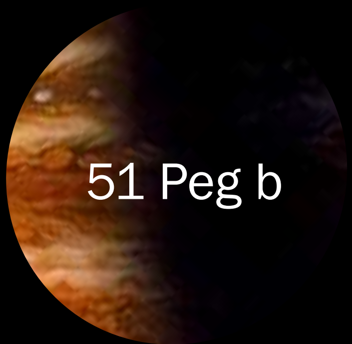
Mercury

Venus

Earth



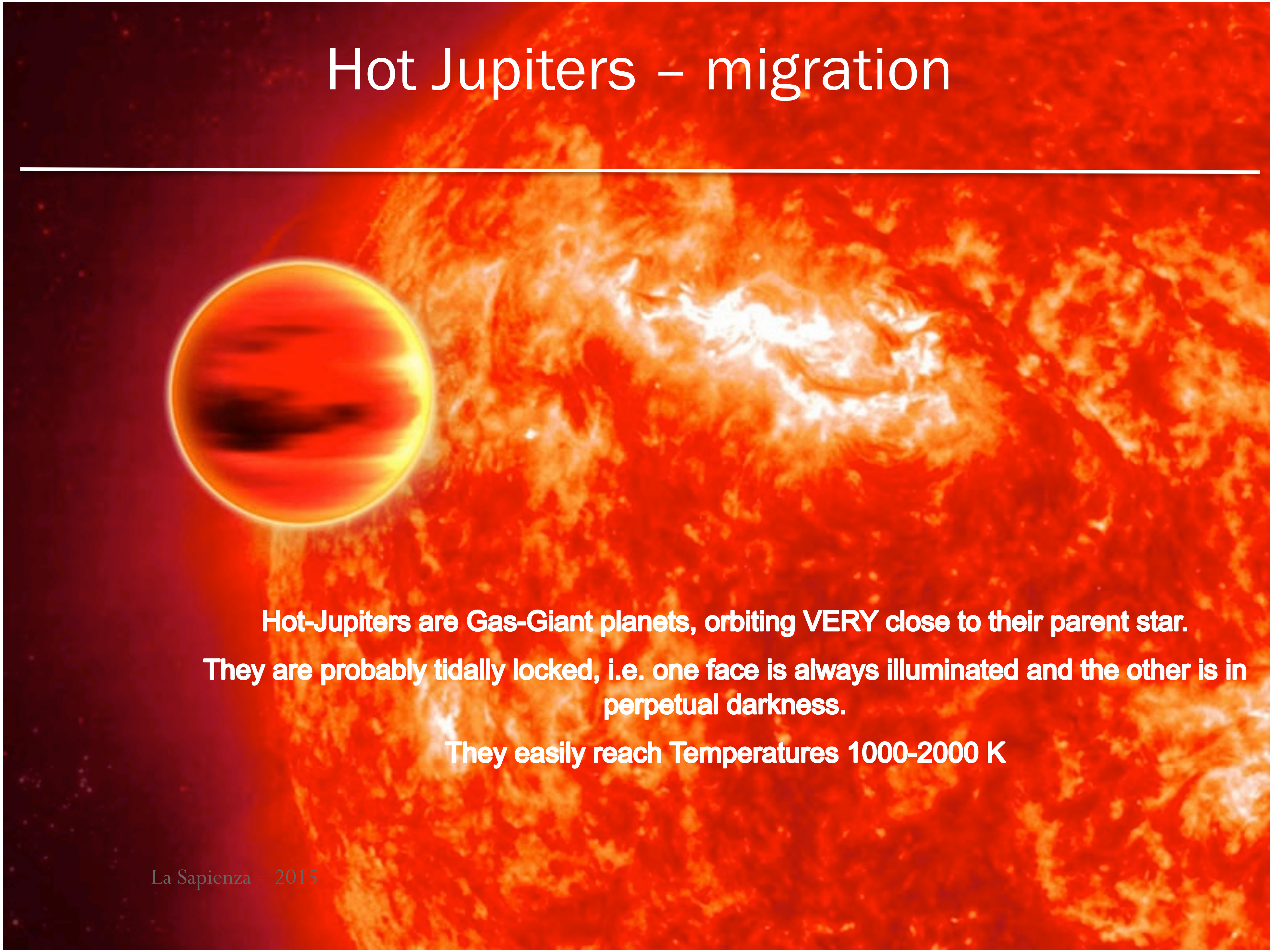
Solar system:
small rocky planets close to the Sun
gas-giant planets more distant from the star → →



51 Pegas: a gas-giant very close to its parent star (hot-Jupiter)

(✱) M. Mayor & D. Queloz, 1995, *Nature* **378** p. 355

Hot Jupiters – migration

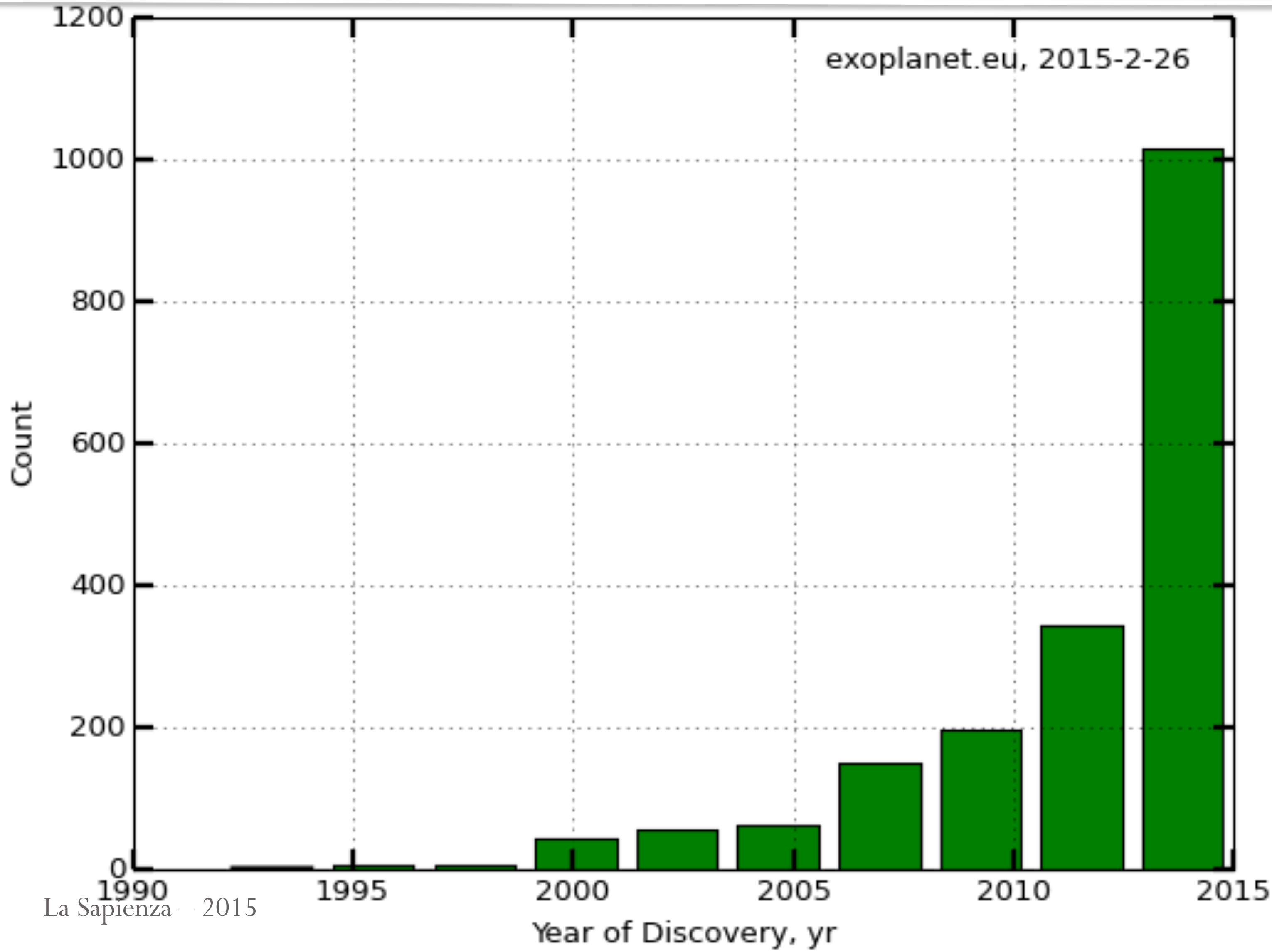


Hot-Jupiters are Gas-Giant planets, orbiting VERY close to their parent star.

They are probably tidally locked, i.e. one face is always illuminated and the other is in perpetual darkness.

They easily reach Temperatures 1000-2000 K

~2000 Exoplanets!



Exoplanet today

The lightest
Mercury’s mass (KOI-1843 b)

The heaviest
30 Jupiter masses (HD 284149 b)

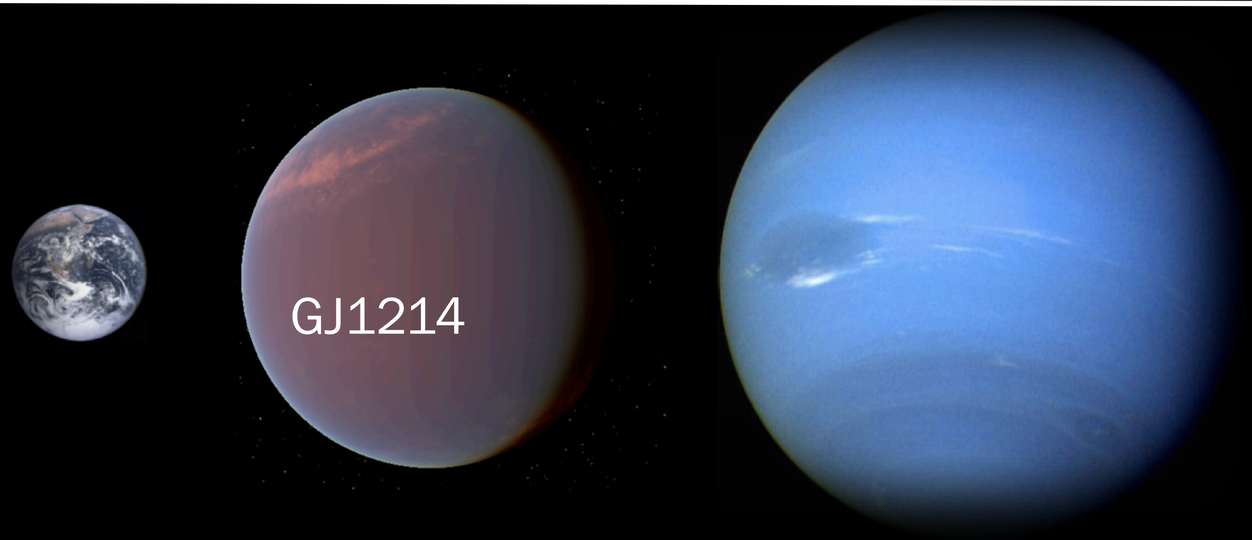
The shortest year
4.5 hours (KOI-1843 b)

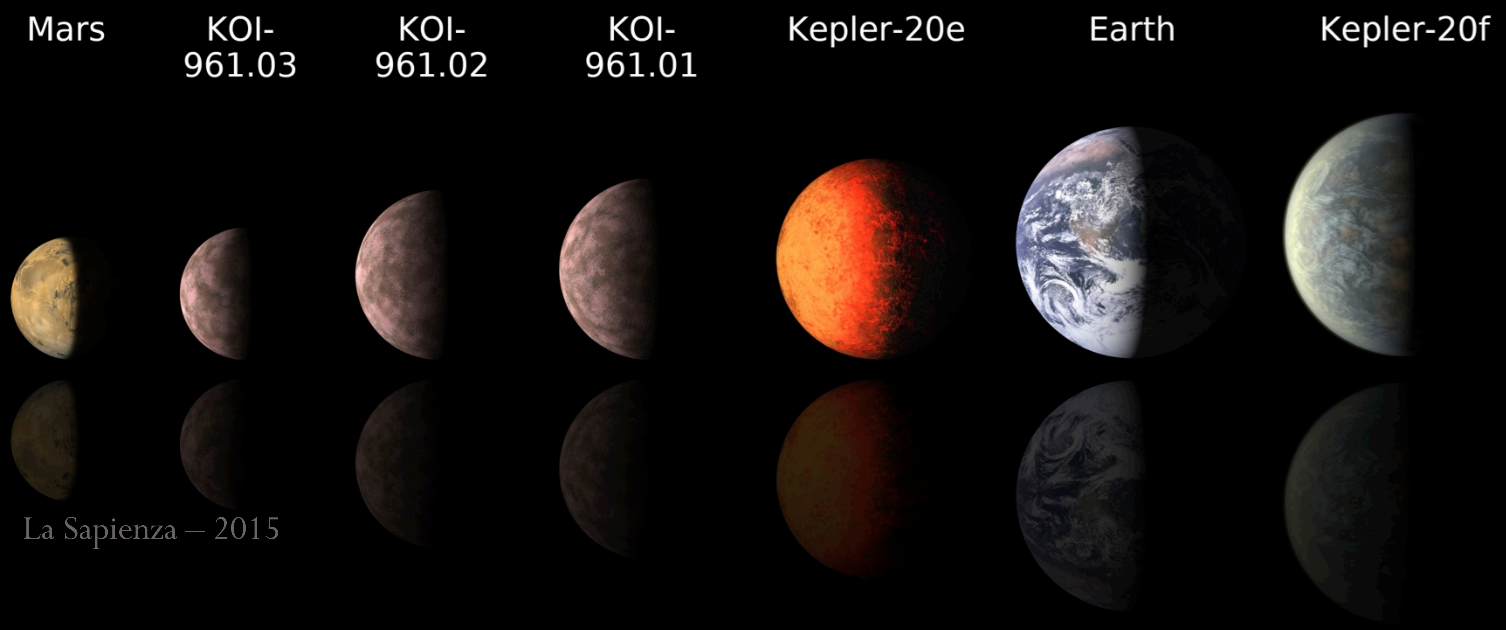
The longest year
730000 days (Oph 11 b)

The closest to the Earth
4.4 light years (Alpha Cent Bb)

The farest to the Earth
22000 light years (OGLE-390 b)

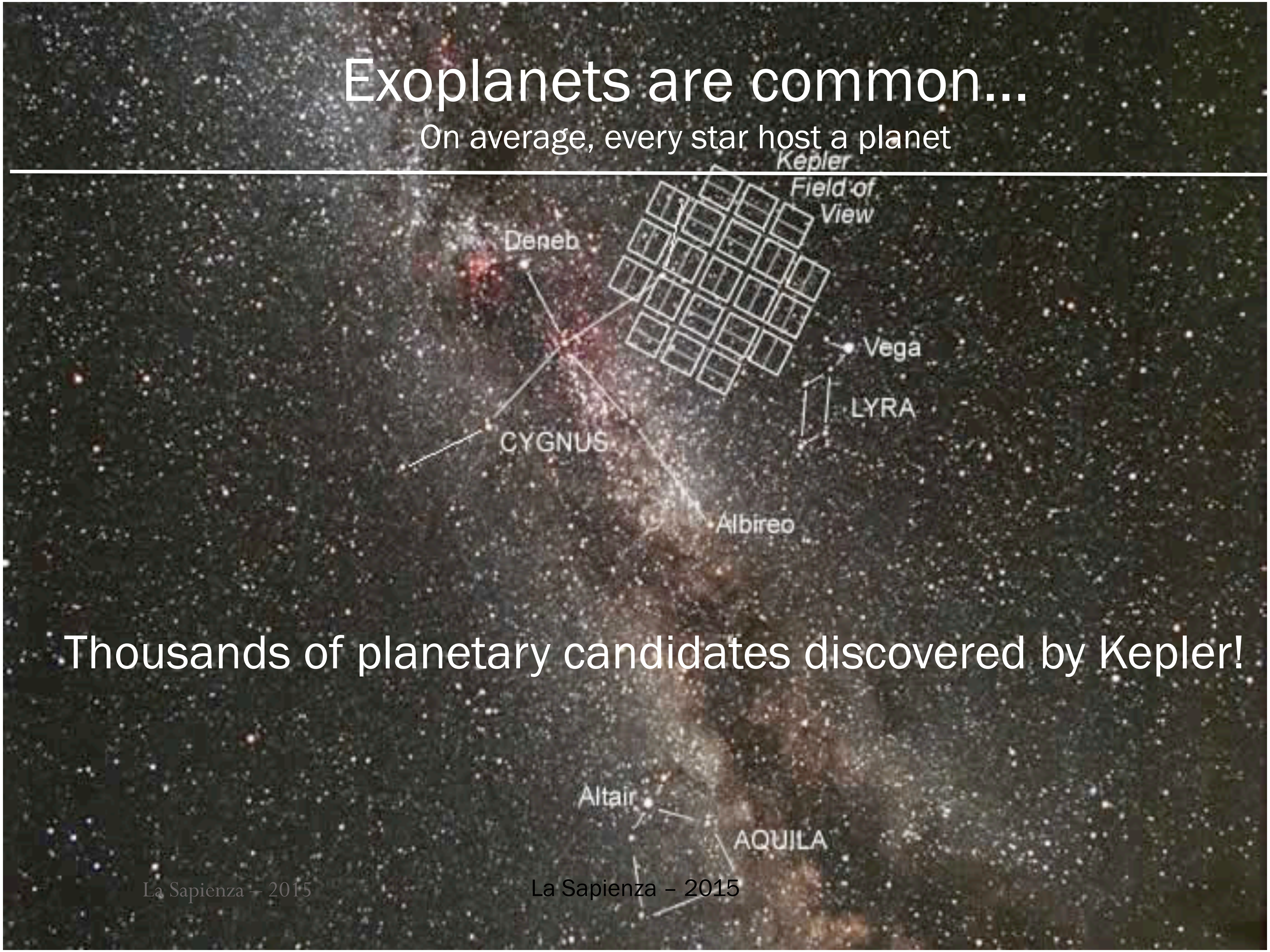
Sub- and Super-Earths





Exoplanets are common…

On average, every star host a planet



Thousands of planetary candidates discovered by Kepler!

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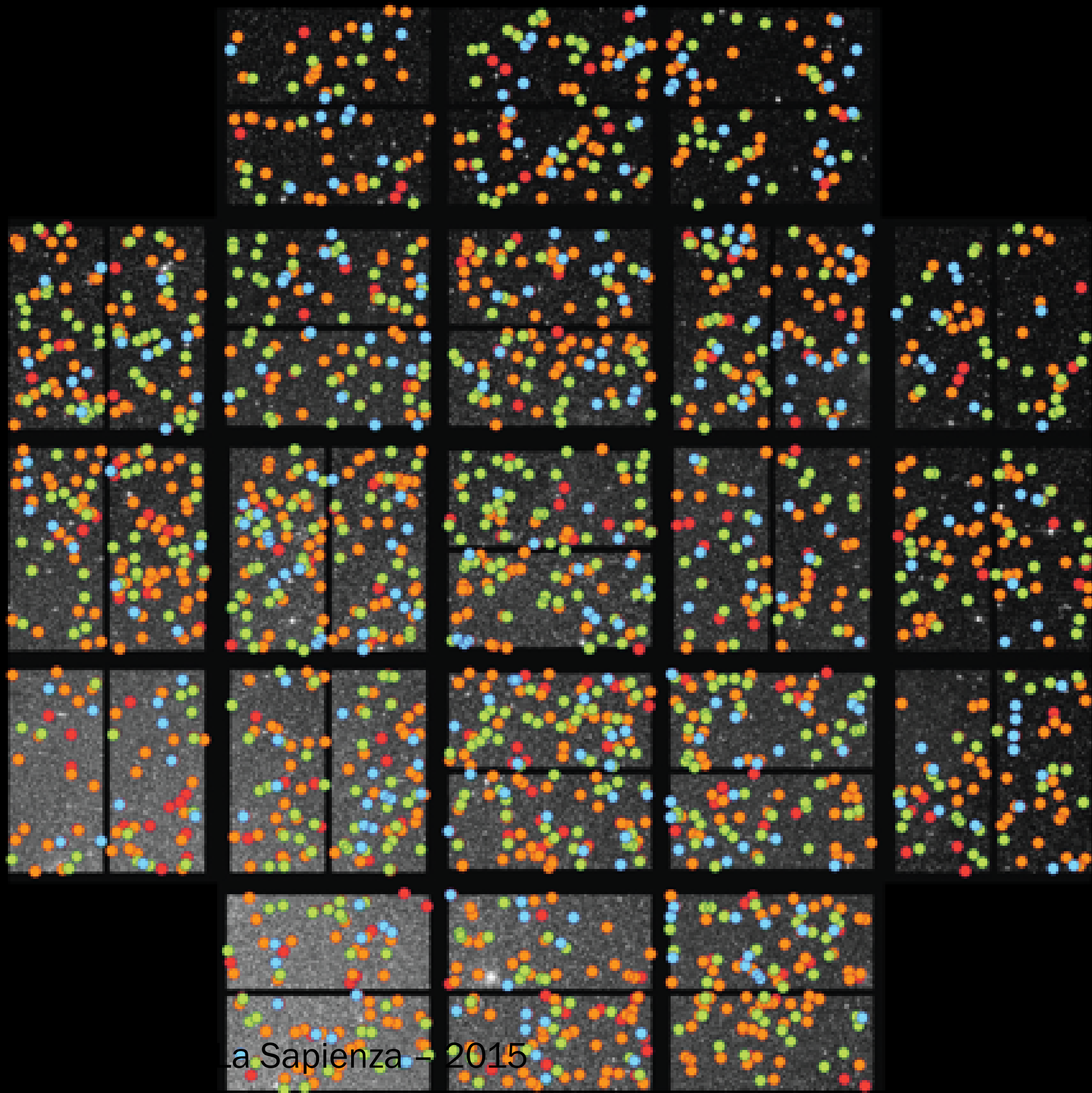
Locations of Kepler Planet Candidates

As of January 7, 2013



Earth-size

Super-Earth size
1.25 - 2.0 Earth-size

Neptune-size
2.0 - 6.0 Earth-size

Giant-planet size
6.0 - 22 Earth-size

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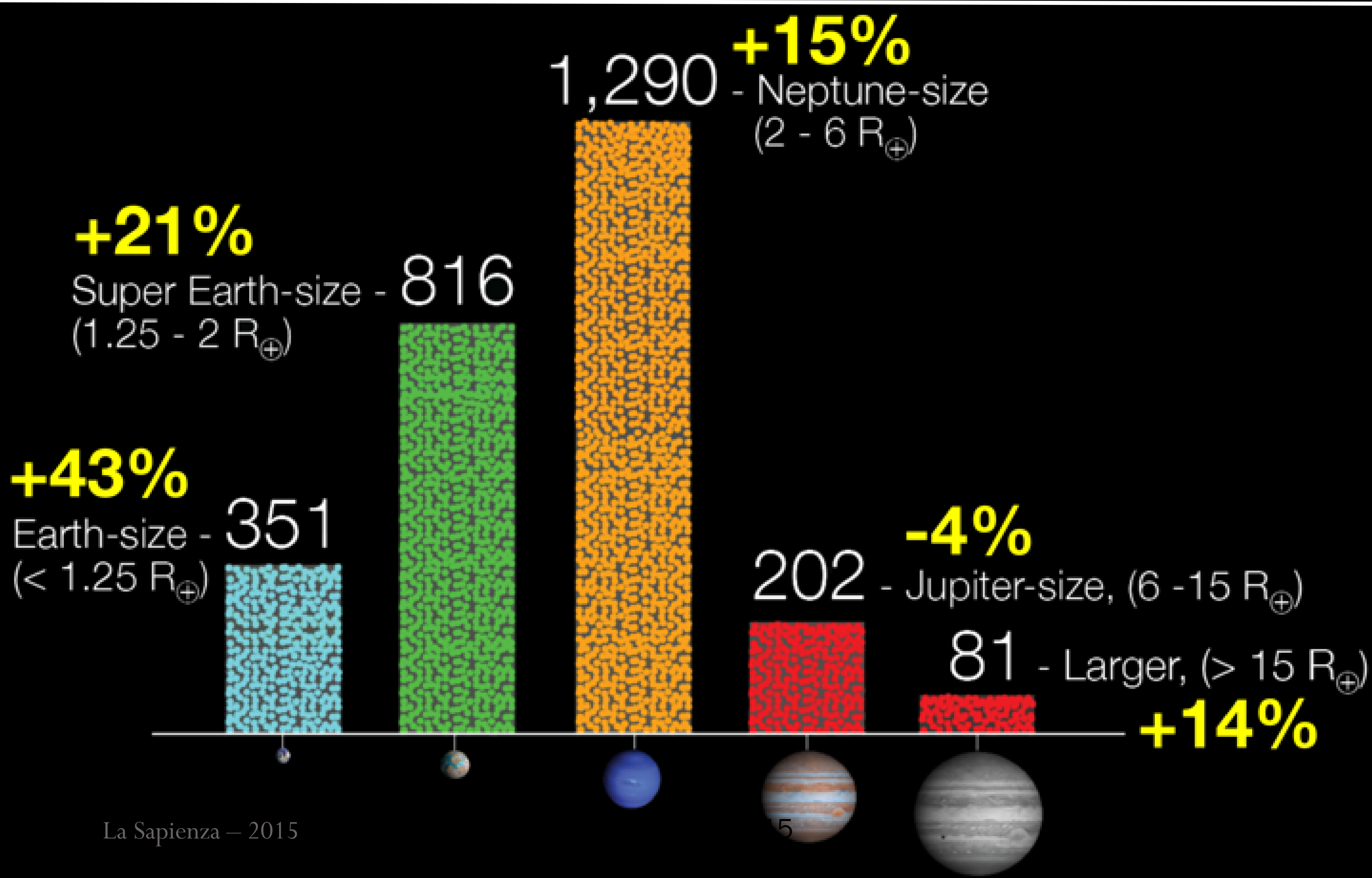
Sizes of Planet Candidates

As of January 7, 2013



Pulsar timing

In 1992 Aleksander Wolszczan and Dale Frail used this method to discover planets around the pulsar PSR 1257+12.
Their discovery was quickly confirmed, making it the first confirmation of planets outside our Solar System.

A pulsar is a neutron star: the small, ultradense remnant of a star that has exploded as a supernova. Pulsars emit radio waves extremely regularly as they rotate. Slight anomalies in the timing of its observed radio pulses can be used to track the pulsar's motion. Like an ordinary star, a pulsar will move in its own small orbit if it has a planet.

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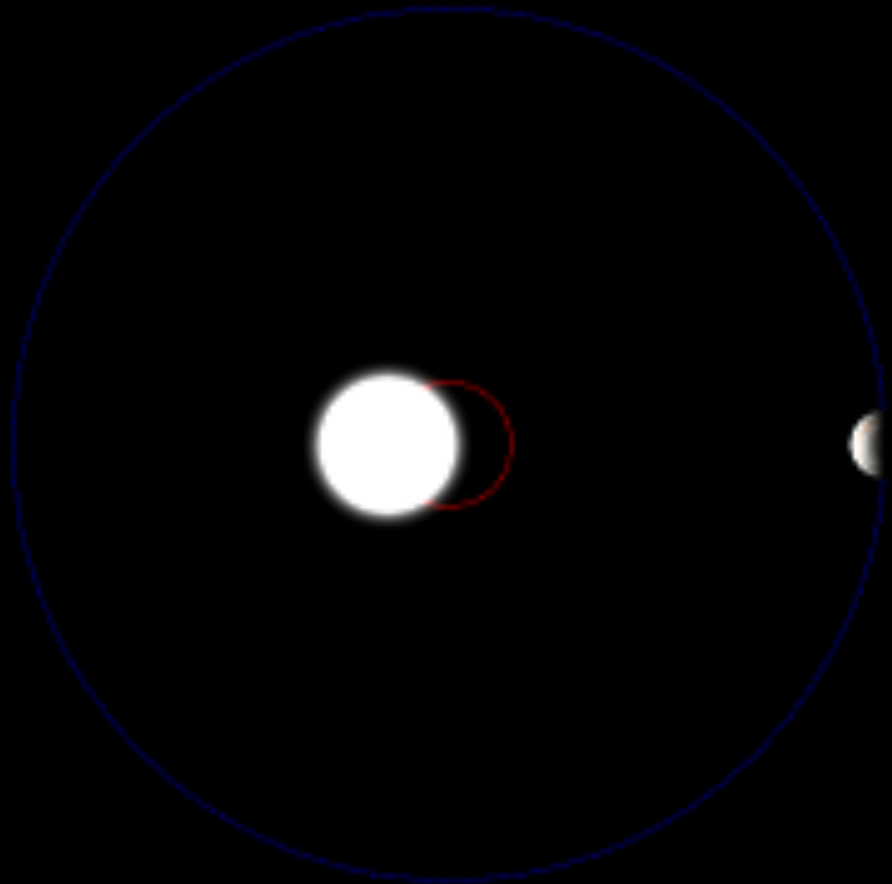
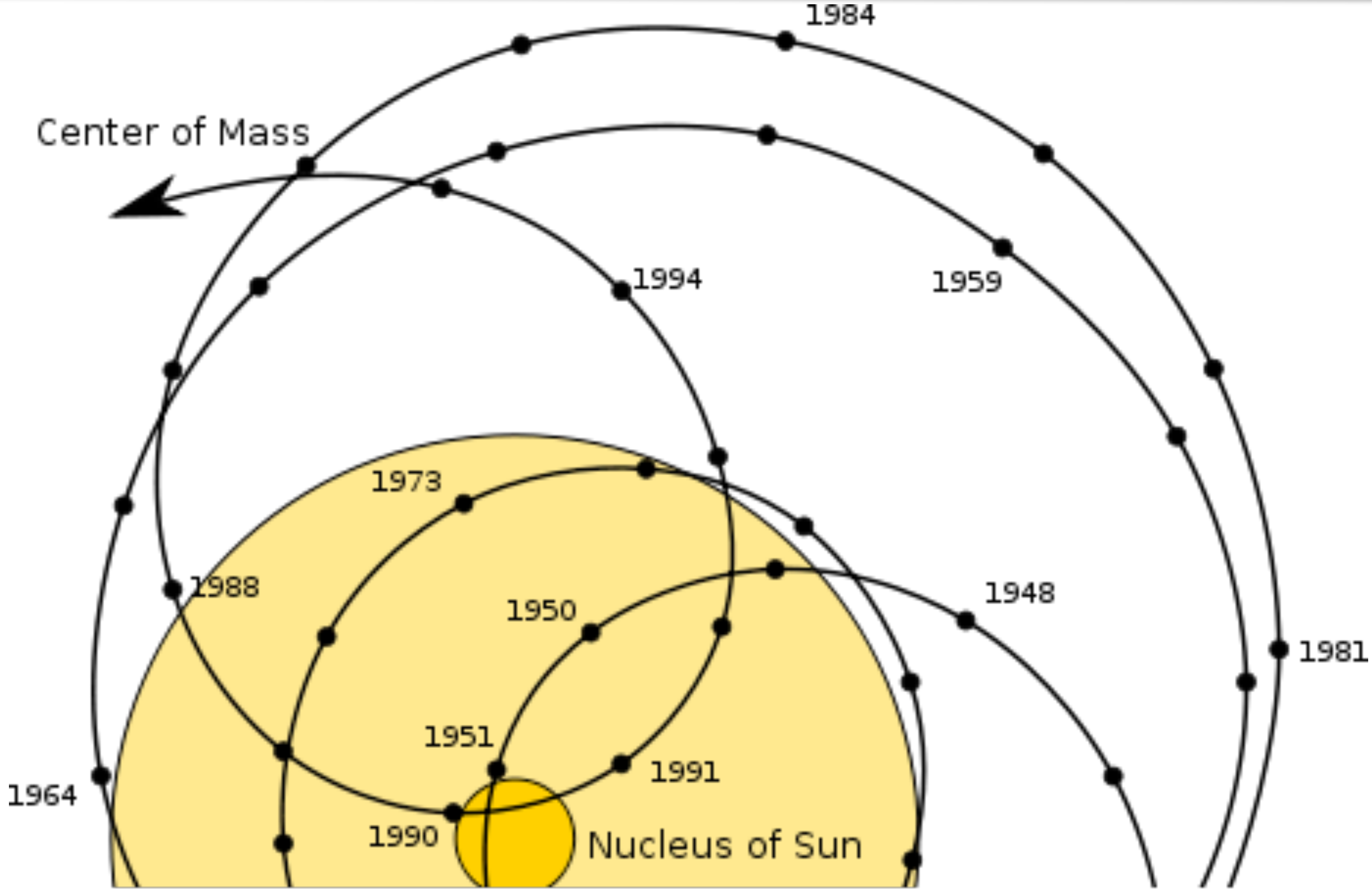
Radial velocity & astrometry



Astrometry

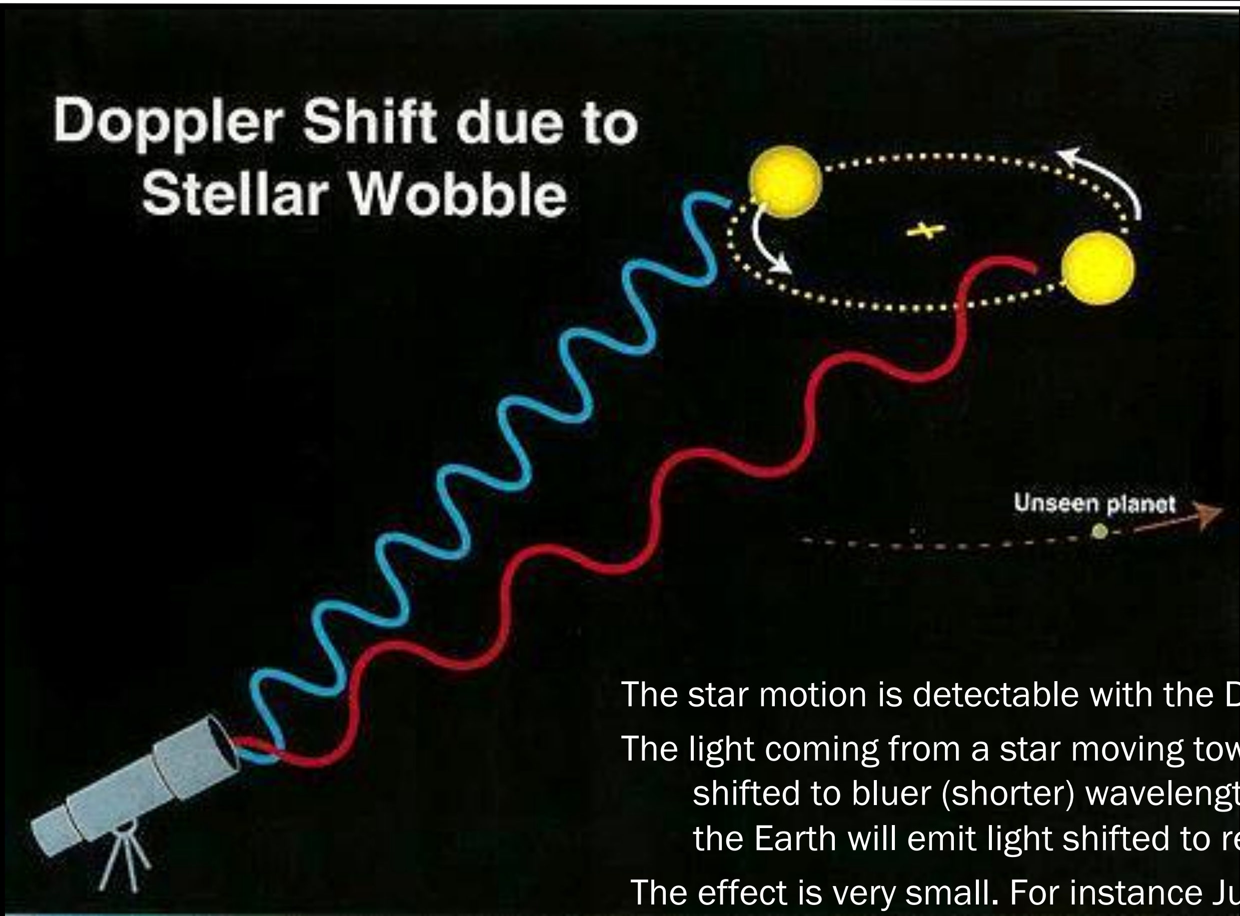
Motion of the Solar System barycenter relative to the Sun



Detections of exoplanets using astrometry

- So far no planets detected
- Gaia space mission will measure stellar parallaxes with unprecedented precision
- Gaia space mission will feature accuracy of ~30micro arc-sec
- Gaia is predicted to discover 10,000 planets using astrometry in our local surrounding alone

Radial velocity

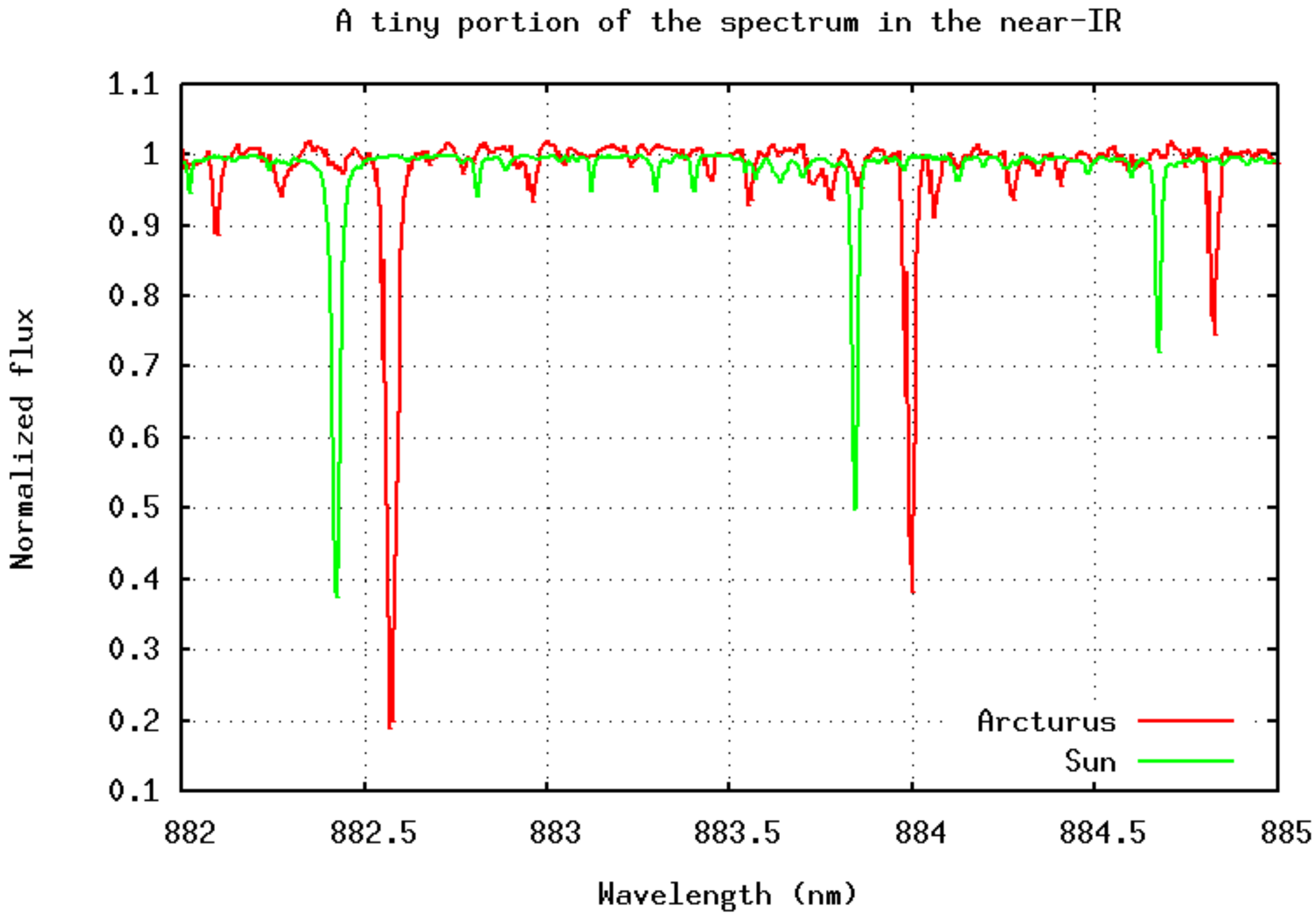


The star motion is detectable with the Doppler Effect.

The light coming from a star moving toward the Earth will be Doppler shifted to bluer (shorter) wavelengths, while a star receding from the Earth will emit light shifted to redder (longer) wavelengths.

The effect is very small. For instance Jupiter induces a 12 m/s velocity change on the Sun for an extern observer whereas the Saturn effect is only 2.7 m/s.

Doppler spectroscopy



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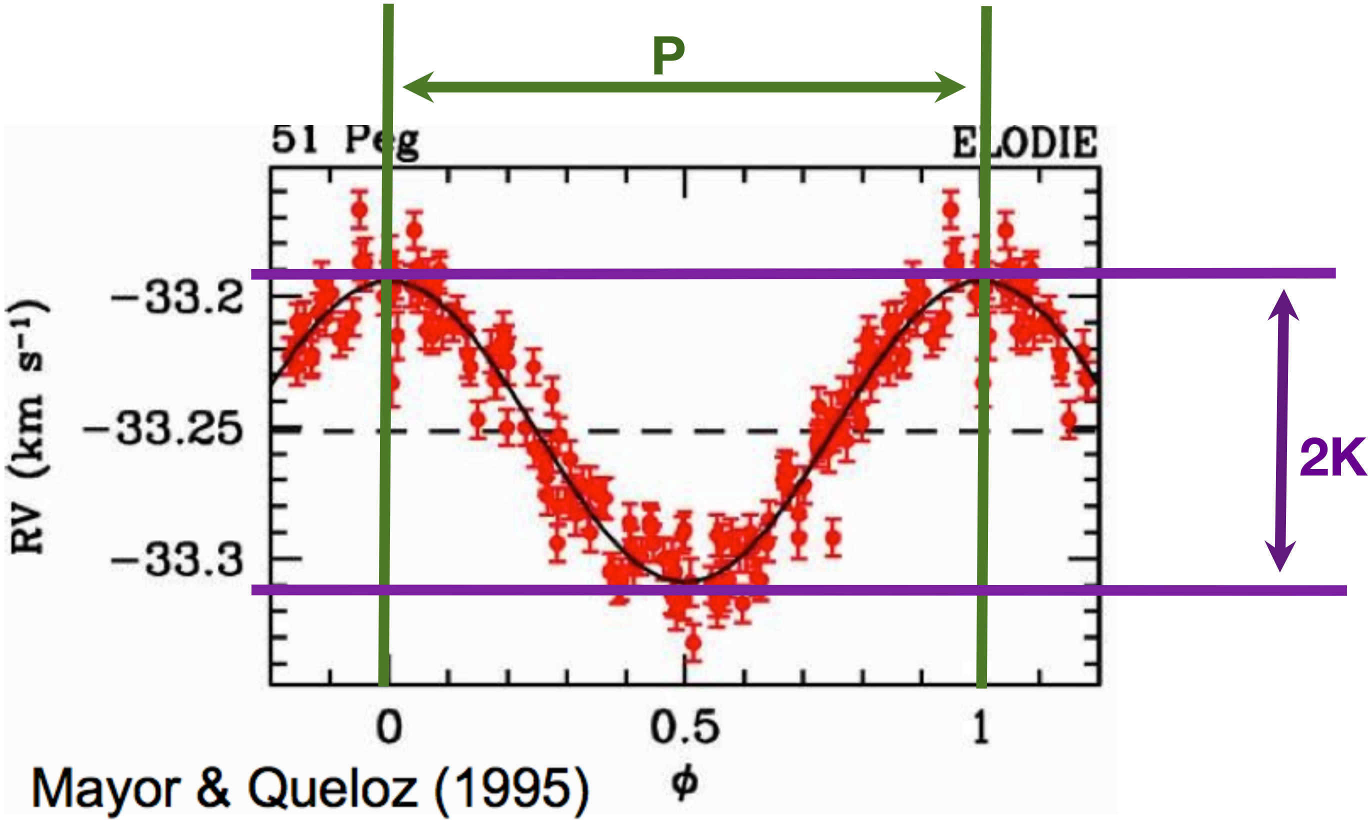
Doppler spectroscopy

```
Look at the line which appears in the Sun at about 882.4 nm.
In the spectrum of Arcturus, it appears at about 882.55 nm.

   shift (Arcturus - Sun)  =  882.55 nm - 882.4 nm

                           =  0.15 nm


                               0.15 nm
   radial velocity  =  ------------- * (300,000 km/s)
                               882.4 nm


                    =  50 km/s


So Arcturus was moving AWAY from us at about 50 km/s
when the spectrum was taken.
```

Measuring the radial velocity parameters



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Summary of equations

Kepler's third law:

$$a^3 = \frac{GM_*}{4\pi^2}P^2$$

Conservation of momentum:

$$M_p v_p = M_* v_*$$

Radial velocity curve amplitude:

$$K_* \simeq v_* \mathrm{sin}i = \frac{M_p \mathrm{sin}i}{M_*} v_p$$

Planetary speed:

$$v_p = \frac{2\pi a}{P}$$

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Which parameters can we observe directly?

Kepler's third law: $$a^3 = \frac{GM_*}{4\pi^2} P^2$$

Conservation of momentum: $$M_p v_p = M_* v_*$$

Radial velocity curve amplitude: $$K_* \simeq v_* \sin i = \frac{M_p \sin i}{M_*} v_p$$

Planetary speed: $$v_p = \frac{2\pi a}{P}$$

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Which parameters need to be observed otherwise?

Kepler's third law: $a^3 = \frac{GM_*}{4\pi^2} P^2$ (derived: a^3)

Conservation of momentum: $M_p v_p = M_* v_*$ (derived: M_p, v_p)

Radial velocity curve amplitude: $K_* \simeq v_* \sin i = \frac{M_p \sin i}{M_*} v_p$ (derived: M_p)

Planetary speed: $v_p = \frac{2\pi a}{P}$ (derived: v_p, a)

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Examples of RV of measurements

Planet Mass	Distance AU	Radial velocity
Jupiter	1	28.4 m/s
Jupiter	5	12.7 m/s
Neptune	0.1	4.8 m/s
Neptune	1	1.5 m/s
Super-Earth (5 M⊕)	0.1	1.4 m/s
Super-Earth (5 M⊕)	1	0.45 m/s
Earth	1	9 cm/s

For MK-type stars with planets in the habitable zone

Stellar Mass (M☉)	Planet Mass (M⊕)	Lum. (L0)	Type	RHAB. (AU)	RV (cm/s)	Period (days)
0.10	1.0	8e-4	M8	0.028	168	6
0.21	1.0	7.9e-3	M5	0.089	65	21
0.47	1.0	6.3e-2	M0	0.25	26	67
0.65	1.0	1.6e-1	K5	0.40	18	115
0.78	2.0	4.0e-1	K0	0.63	25	209

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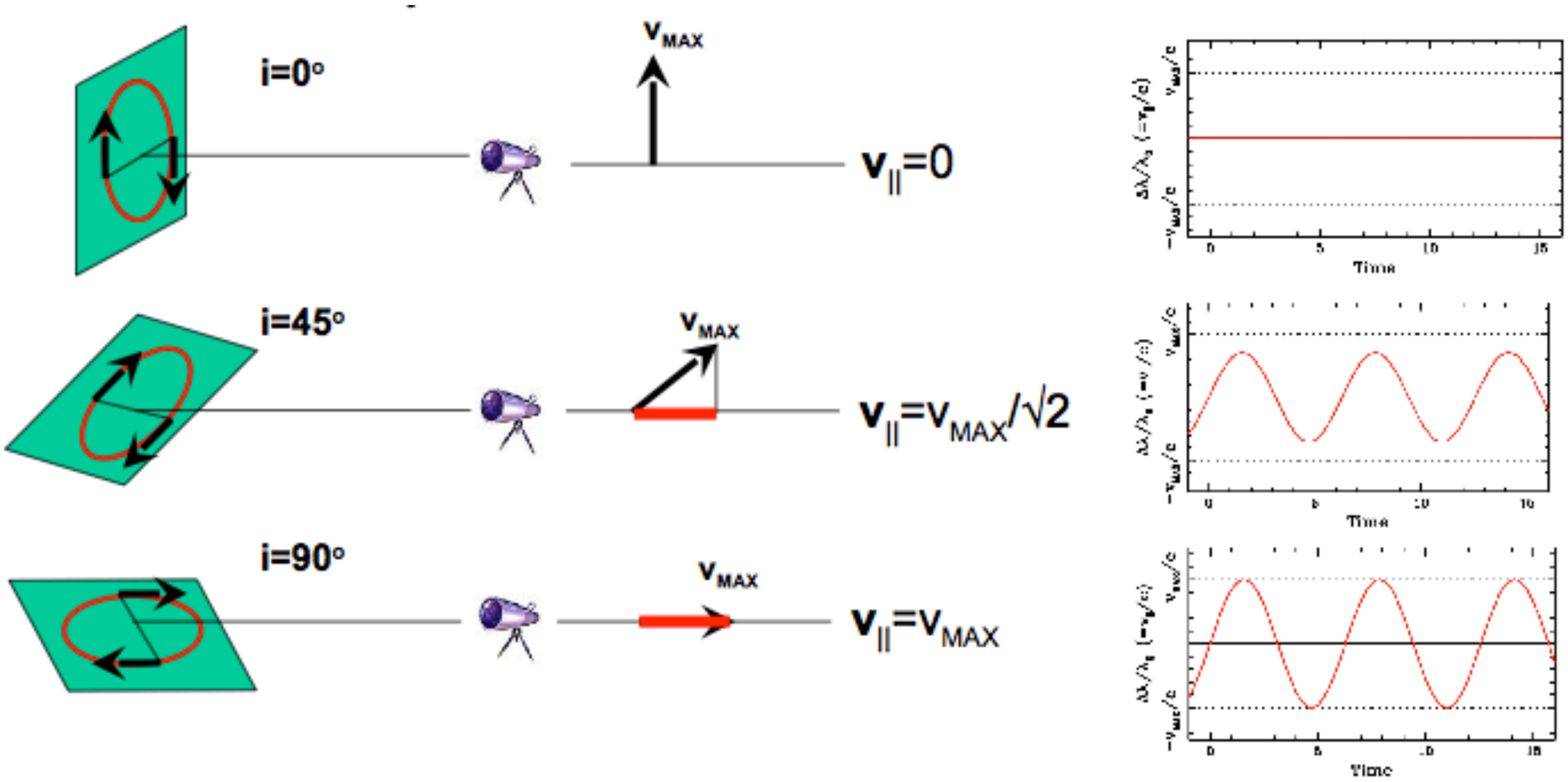
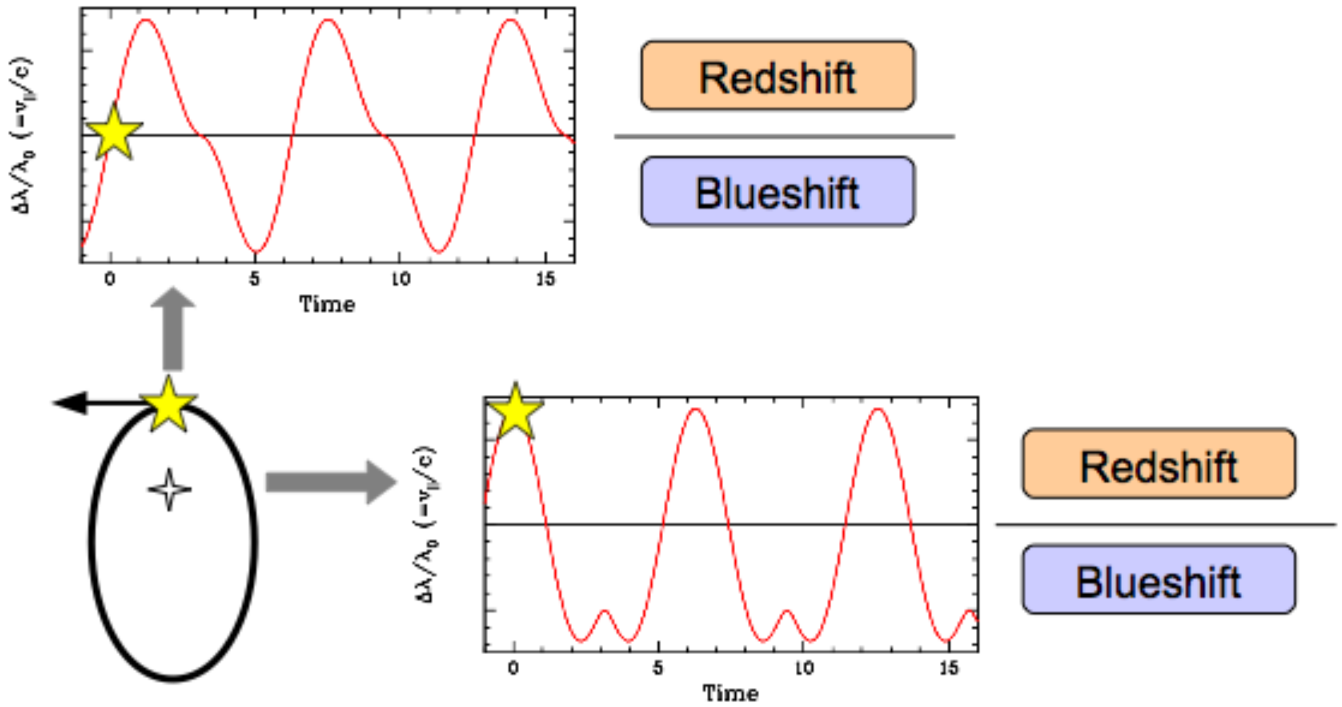
Effect of orientation

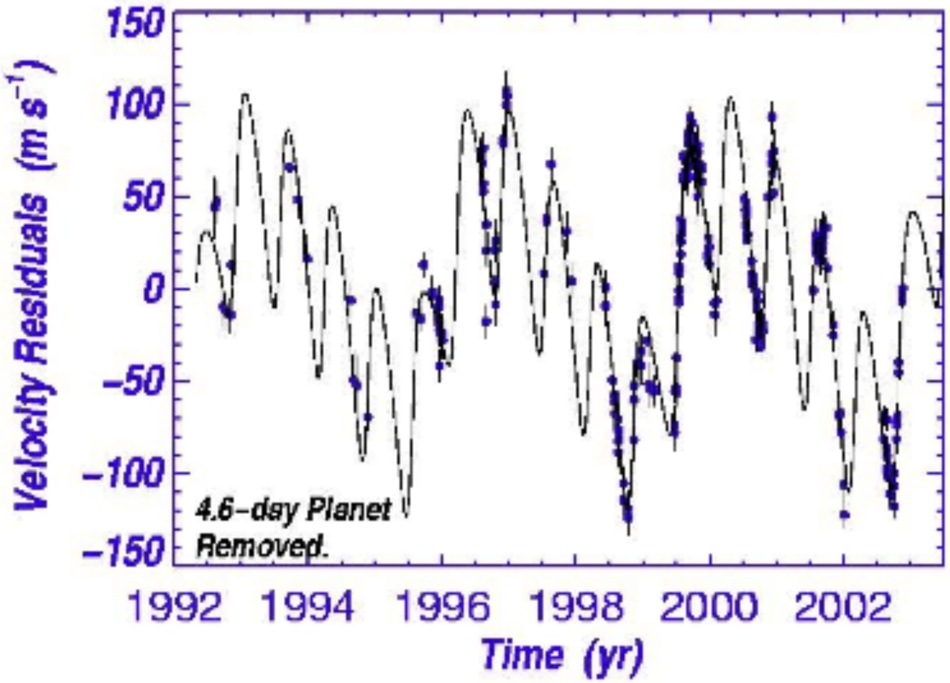


The effect of ellipticity

- A different ellipticity will also change the variation of the line-of-sight velocity with time
- For simplicity, let us assume that the plane of the orbit is aligned parallel to the line of sight



Upsilon Andromedae
A complex system



This system shows a much more complex velocity structure revealing the presence of a multiple planetary system.

Host star F8V (1.3$M_\odot$)

Distance:44 lyr

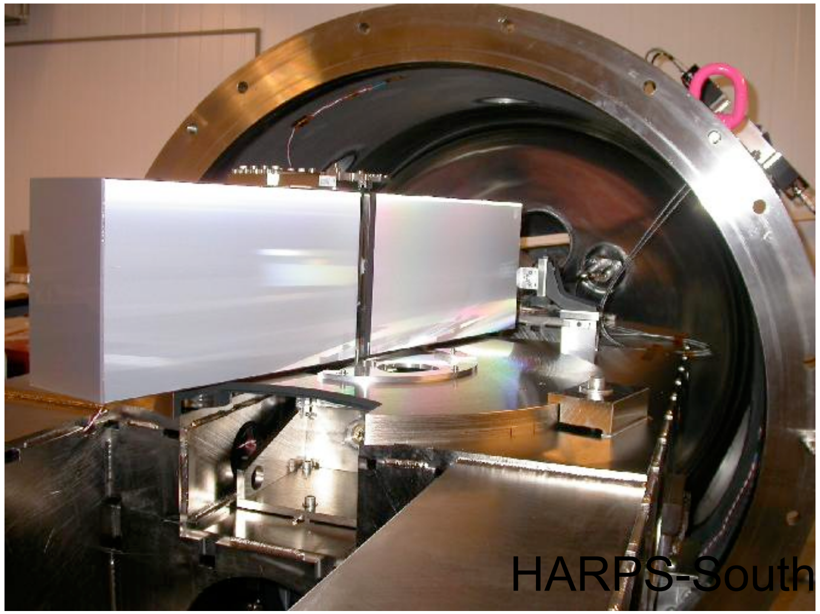
Radial velocity instruments

• HARPS-South and HARPS-North (High Accuracy Radial velocity Planet Searcher) are the most accurate spectrographs ever built.

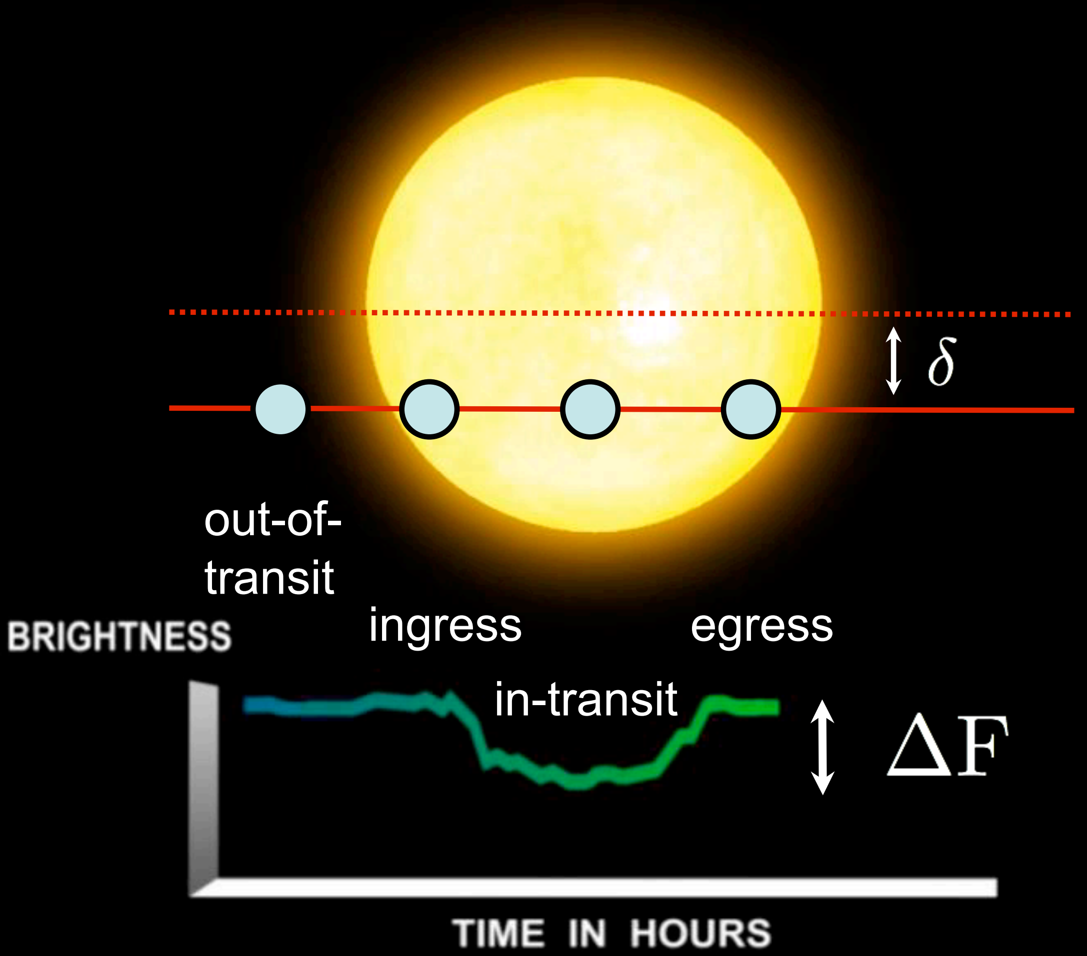
• It can detect the wobble of a star by with a precision of 30cm per second. As a guide, 51 Peg b has a radial velocity amplitude ~ 16 times larger.

• Multiple Super-Earths and complex multi-planet systems were discoved

• Current sites: 3.6m telescope on La Silla (Chile), 3.58m TNG on La Palma (Spain)



Transit of an exoplanet

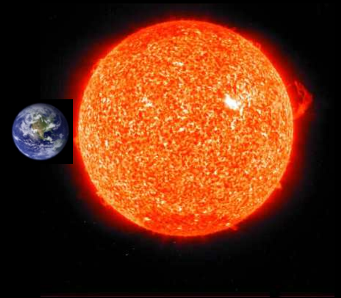


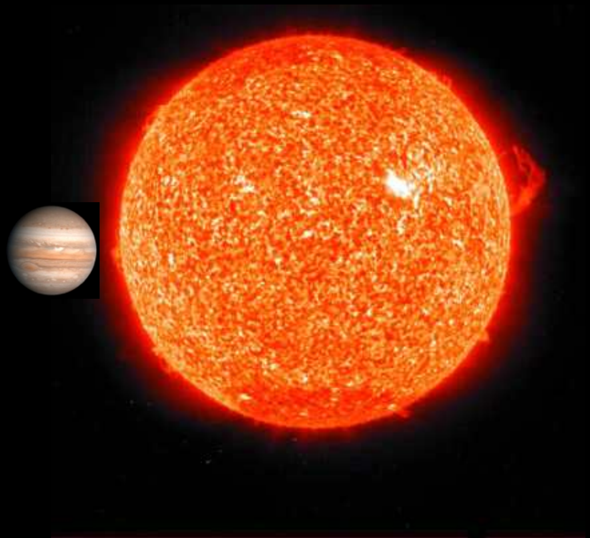
Even a Jupiter size planet will only obscure ~ 1% of the stellar light.

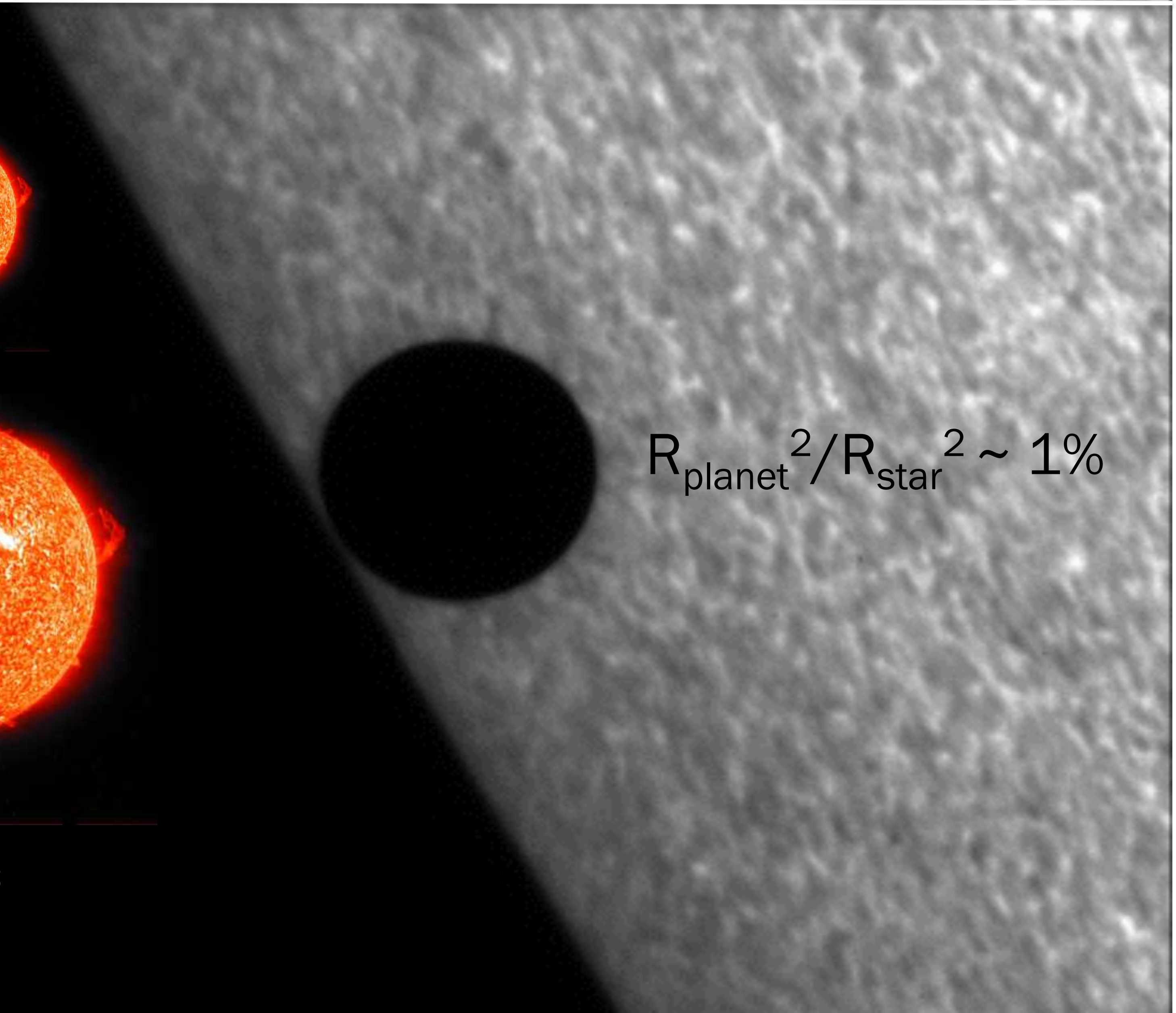
The transit depth is proportional to the surface ratios of the planet and the star:

$$\Delta F = \left(\frac{R_{planet}}{R_{star}} \right)^2$$

Transit of an exoplanet



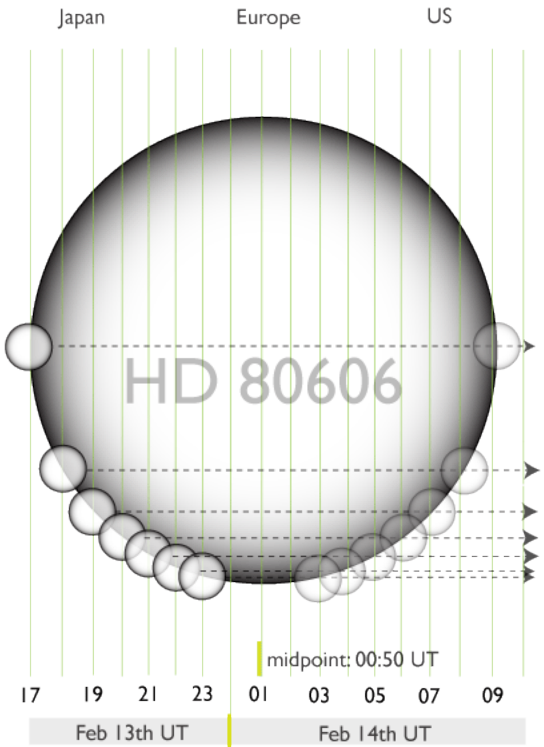


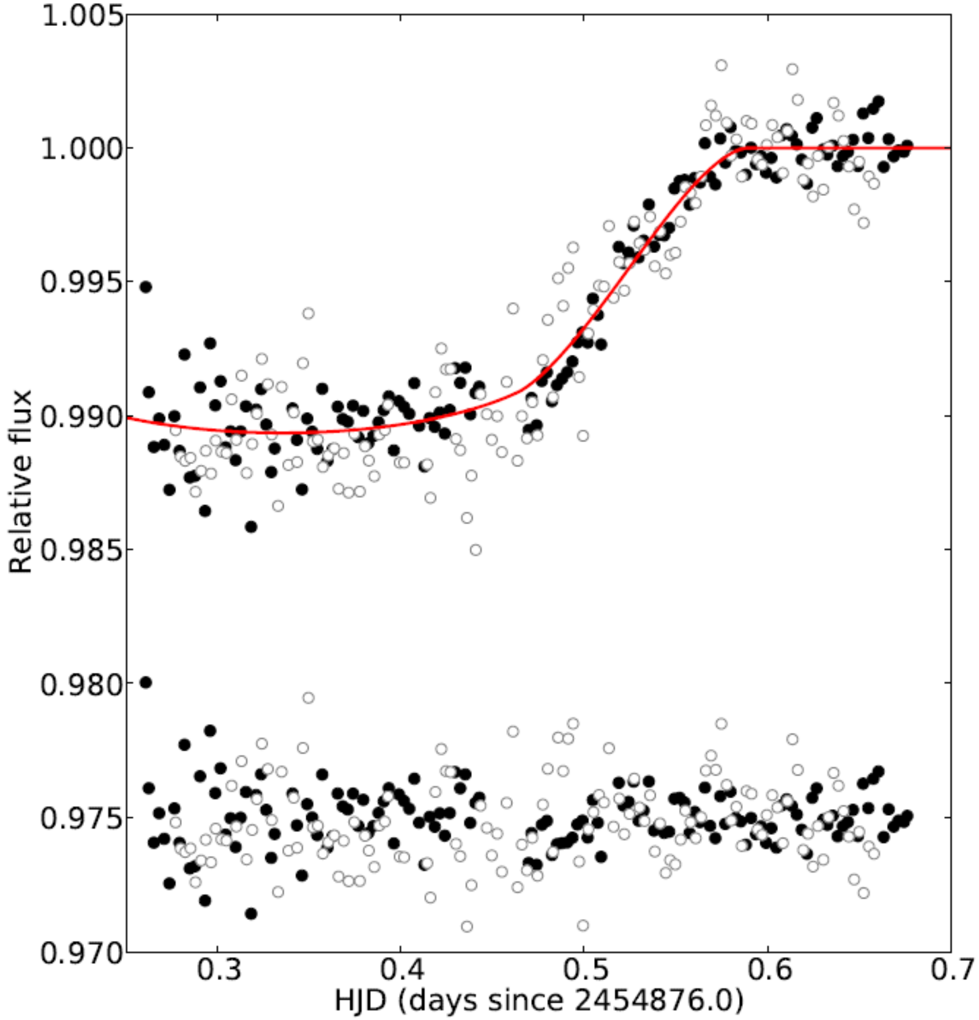


$R_{planet}^2/R_{star}^2 \sim 1\%$

You can do it from London,

with 35 cm telescope...





Fossey, Waldmann, Kipping, *MNRAS*, 2009

THE ASTROPHYSICAL JOURNAL, 552:699–709, 2001 May 10
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HUBBLE SPACE TELESCOPE TIME-SERIES PHOTOMETRY OF THE TRANSITING PLANET OF HD 209458[1]

TIMOTHY M. BROWN,[2] DAVID CHARBONNEAU,[2,3] RONALD L. GILLILAND,[4] ROBERT W. NOYES,[3] AND ADAM BURROWS[5]
Received 2000 November 21; accepted 2001 January 18

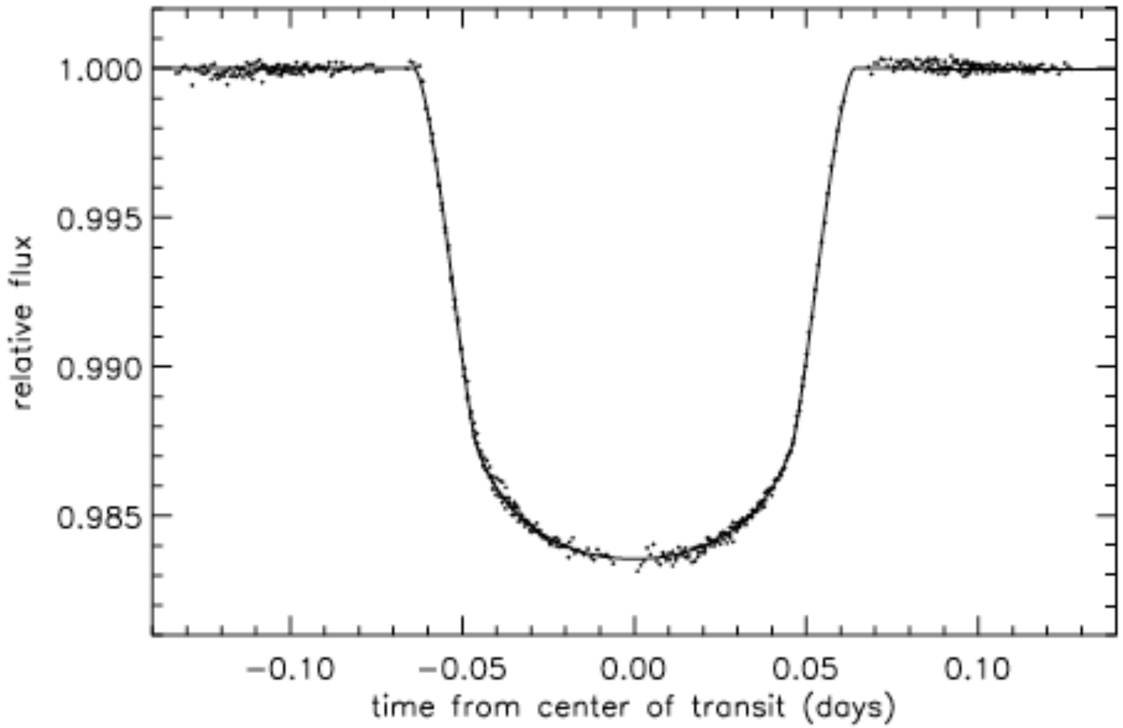
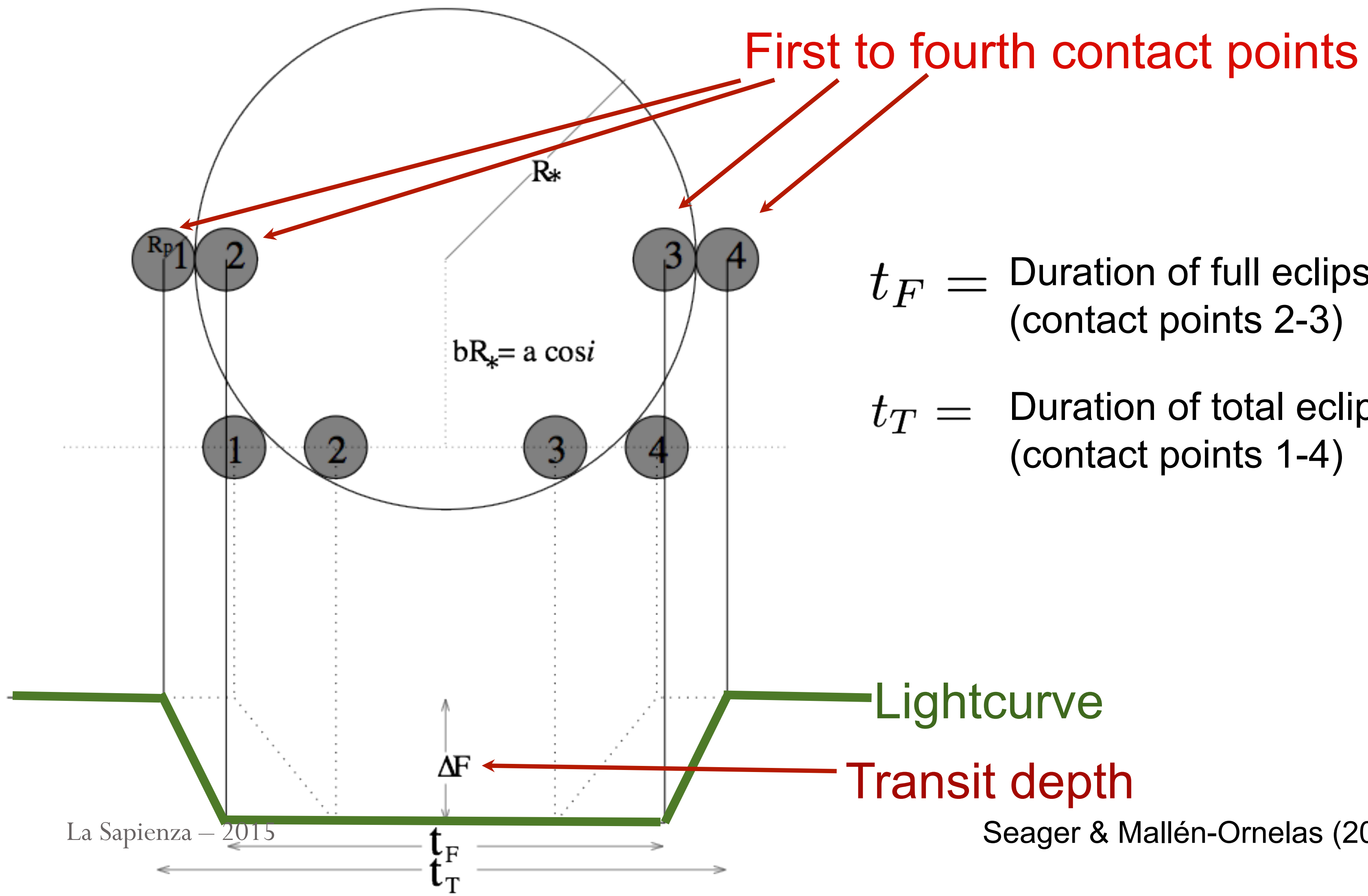


FIG. 3.—Phased light curve for all four transits, assuming a planetary orbital period of 3.52474 days. The time series for each transit has been scaled to have the same average intensity over the second and fifth (out-of-transit) orbits.

Solving the star-planet system



$t_F =$ Duration of full eclipse (contact points 2-3)

$t_T =$ Duration of total eclipse (contact points 1-4)

Seager & Mallén-Ornelas (2003)

Solving the star-planet system

From Kepler's third law and radial velocity we have:

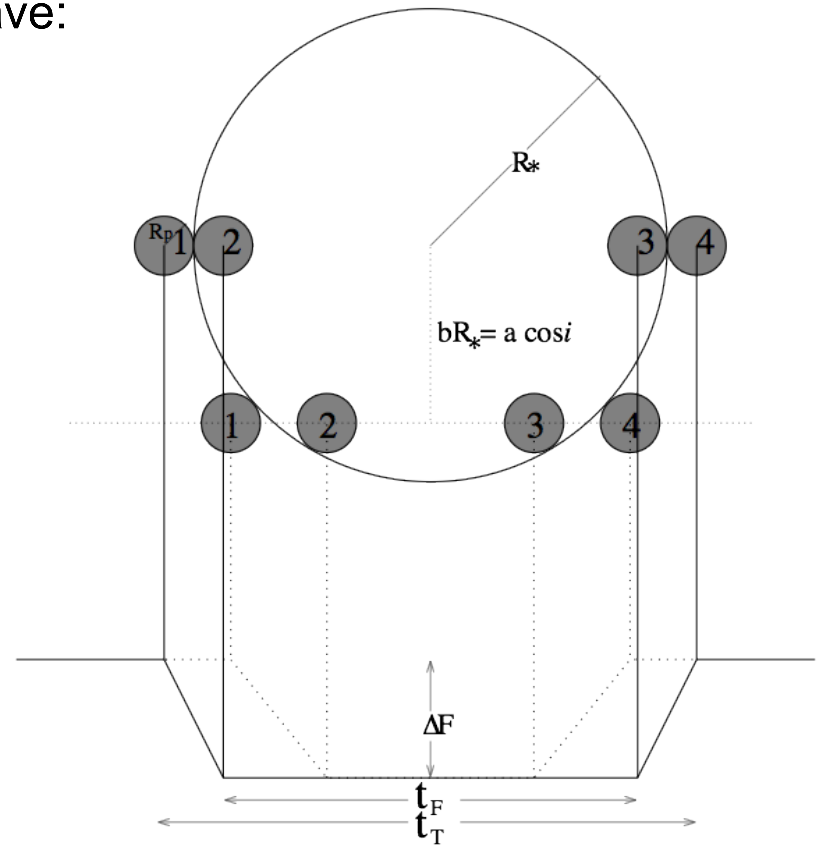
$$P^2 = \frac{4\pi^2 a^3}{G(M_* + M_p)}$$

From the transit depth measurement we have the planet/star ratio:

$$\frac{R_p}{R_*} = \sqrt{\Delta F}$$

We can now calculate the orbital inclination:

$$i = \cos^{-1}\left(b\frac{R_*}{a}\right)$$



Seager & Mallén-Ornelas (2003)

Solving the star-planet system

We can now calculate the orbital inclination:

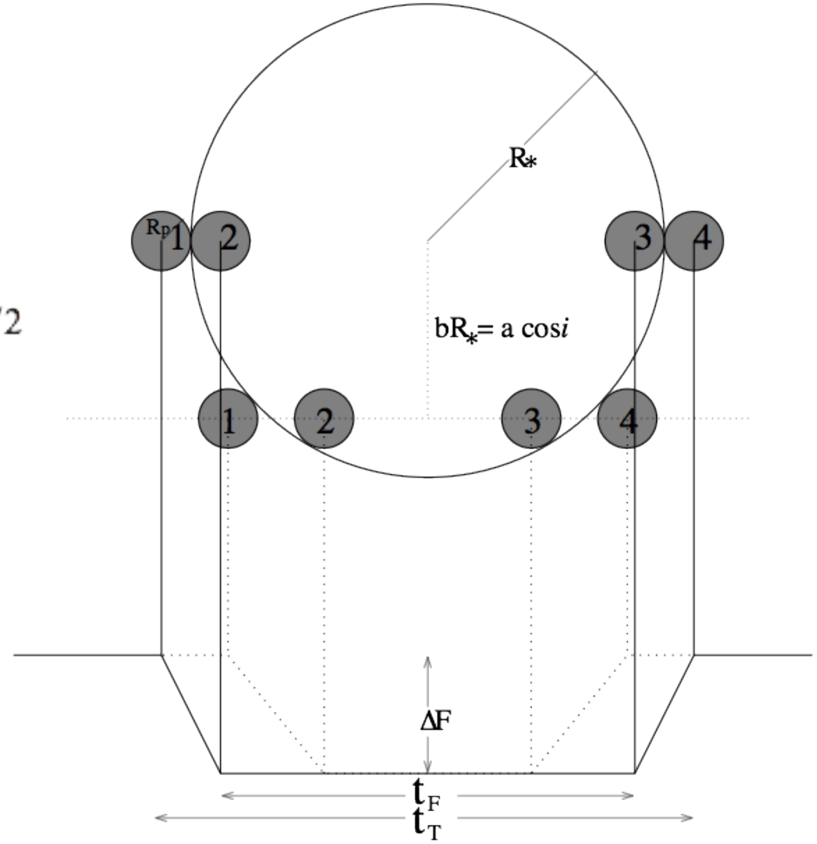
$$i = \cos^{-1}\left(b\frac{R_*}{a}\right)$$

What is b?? - it's called the impact parameter:

$$b = \left[\frac{\left(1-\sqrt{\Delta F}\right)^2 - (t_F/t_T)^2\left(1+\sqrt{\Delta F}\right)^2}{1-(t_F/t_T)^2}\right]^{1/2}$$

We can even calculate the stellar density:

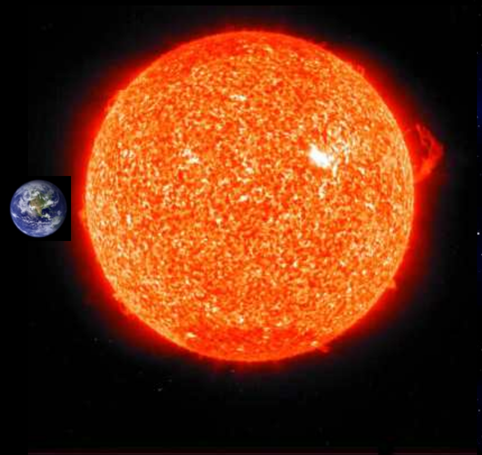
$$\rho_* = \frac{32}{G\pi}P\frac{\Delta F^{3/4}}{\left(t_T^2 - t_F^2\right)^{3/2}}$$

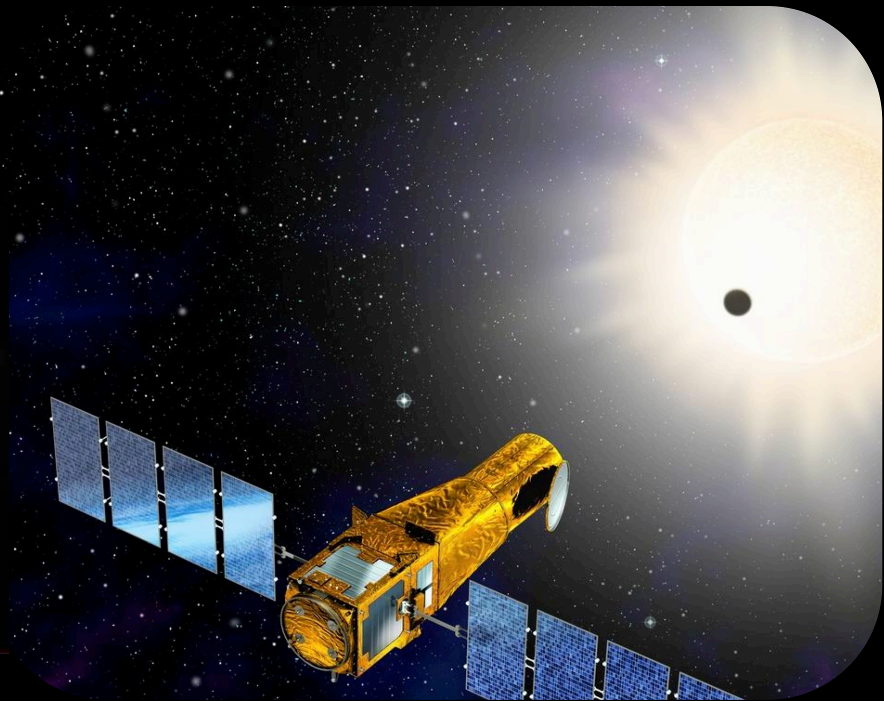


Seager & Mallén-Ornelas (2003)

Transit hunters

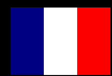
Earth-size planet transiting Sun-type star ~ 0.01 %





Kepler (NASA)
2009 - present

COROT (CNES/ESA)
2006-2013



Transits from the ground

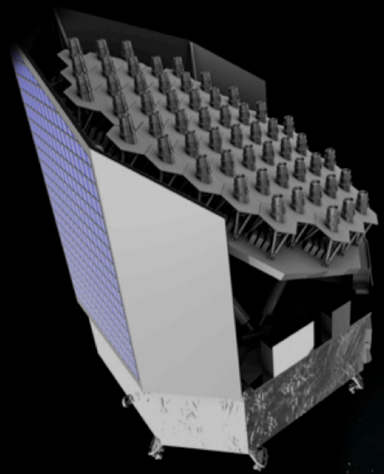
MEarth

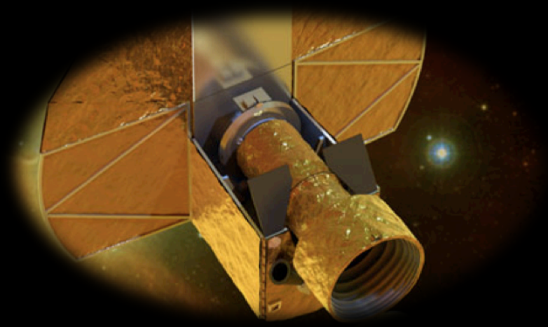
Hat-NET

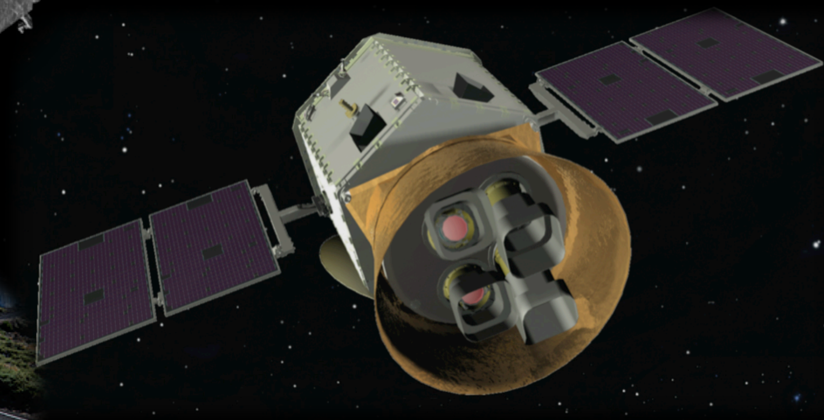
Super-WASP

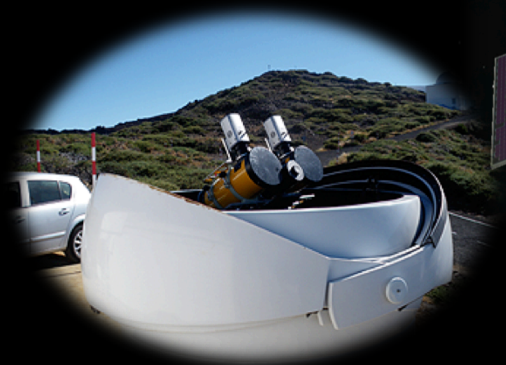
Future transit missions/surveys

- ESA-Cheops
- NASA-TESS
- ESA-PLATO
- NGTS







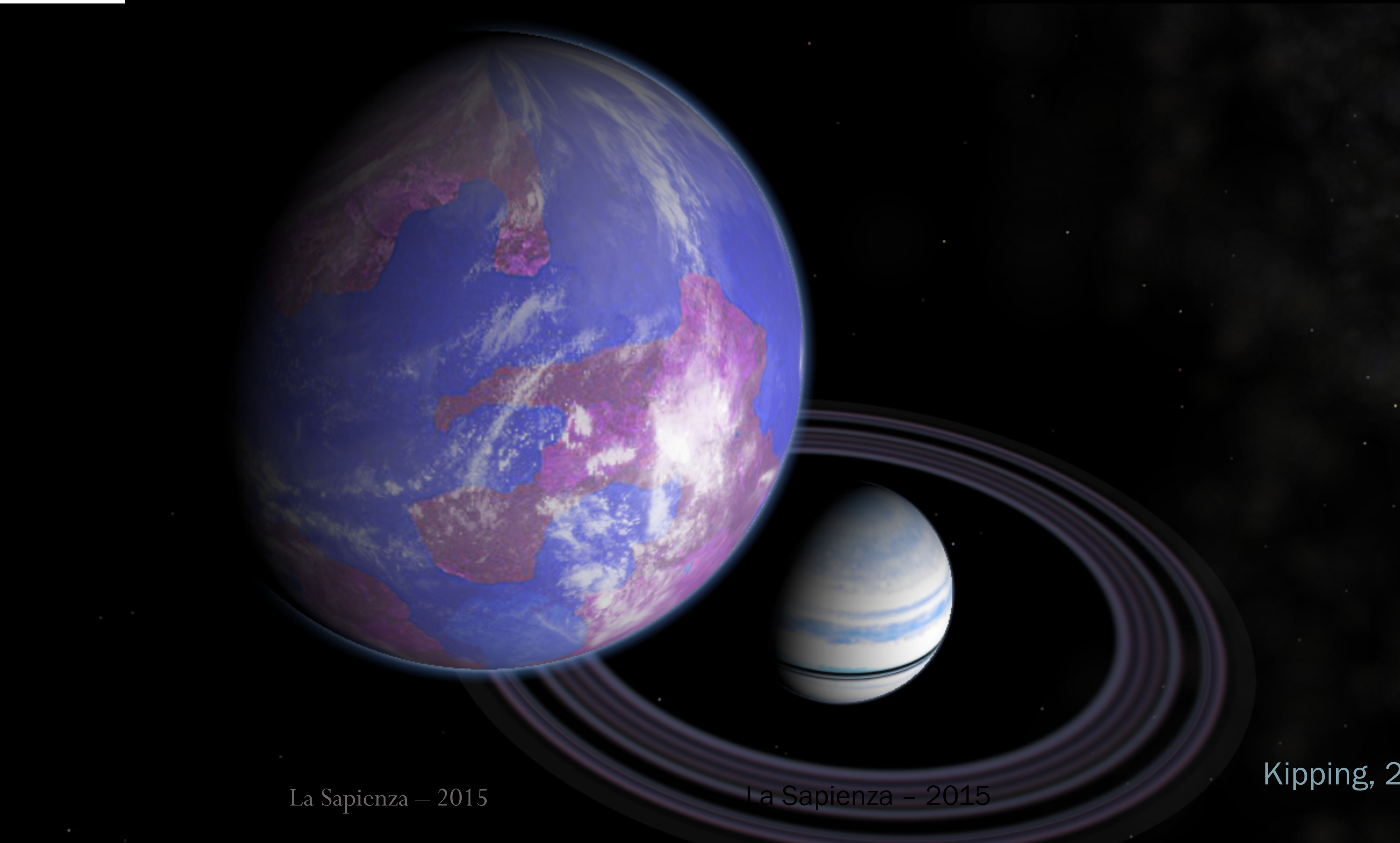


From Jupiter's moons…

Galileo (the mission), 1989

Galileo « *Sidereus Nuncius* » 1610

Search for Exomoons



Kipping, 2008, 2009

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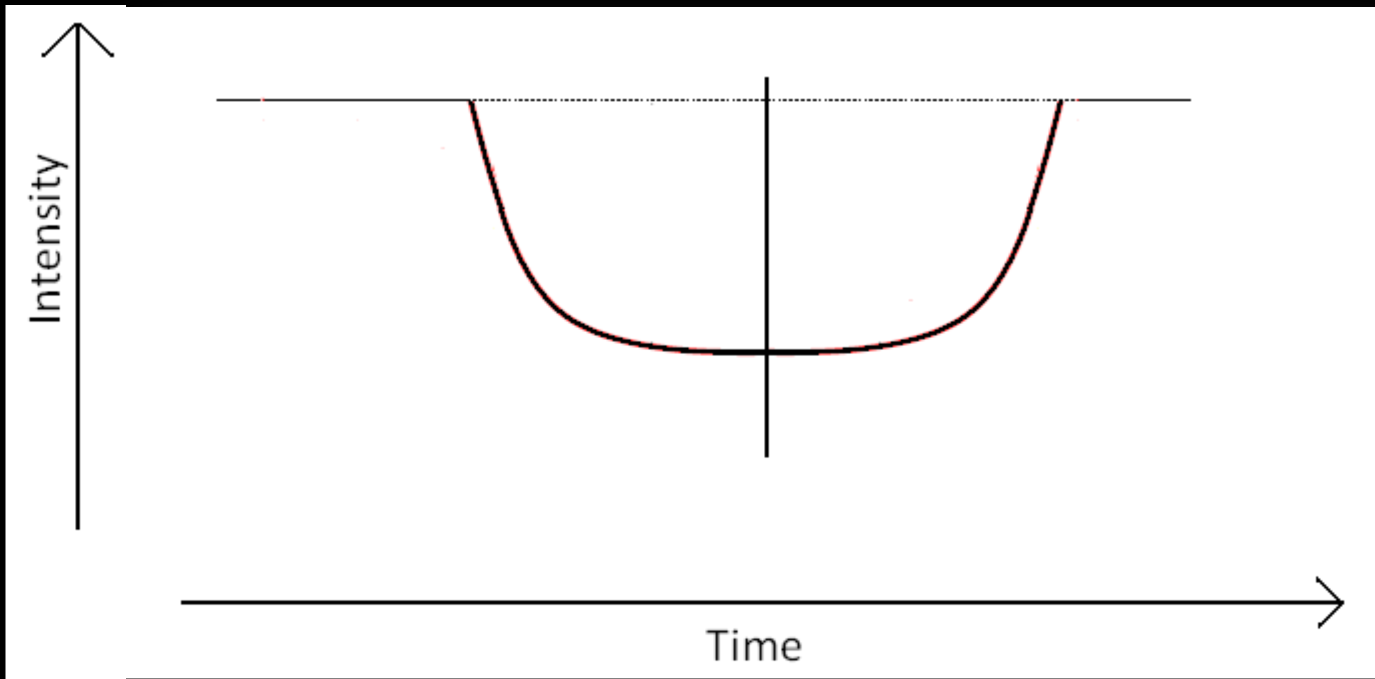
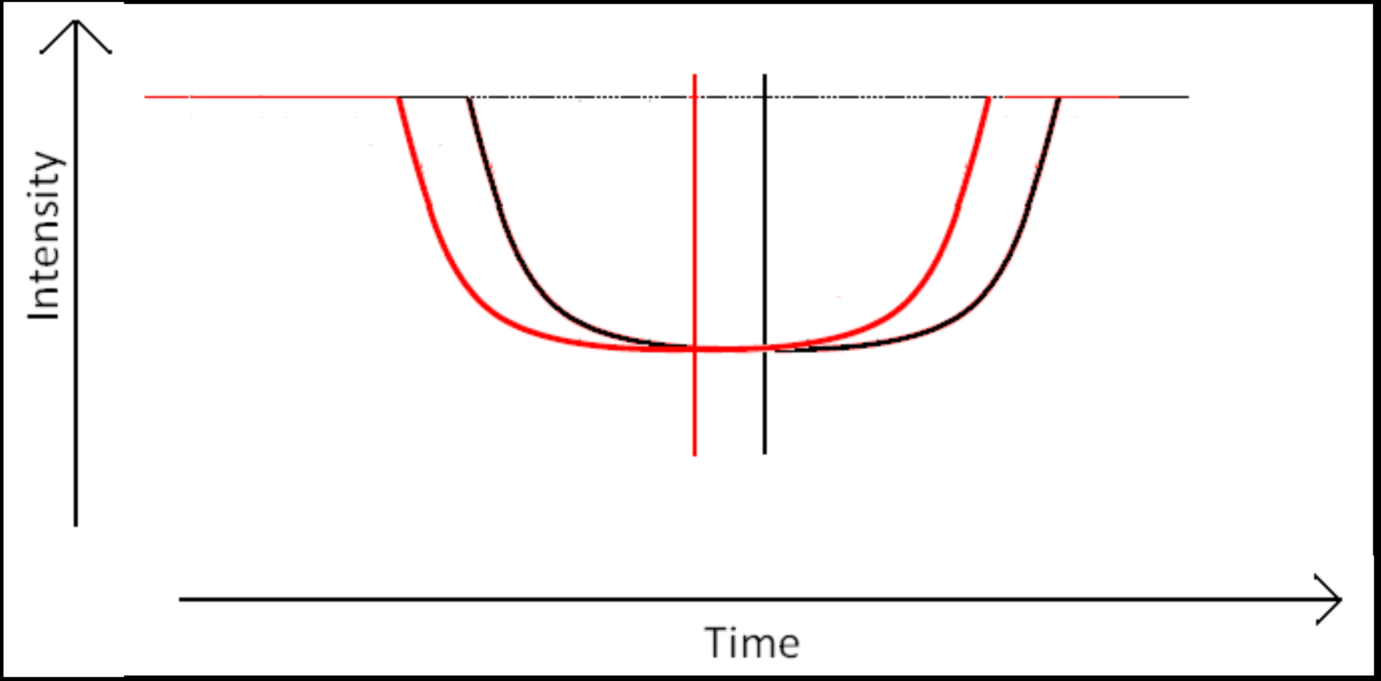
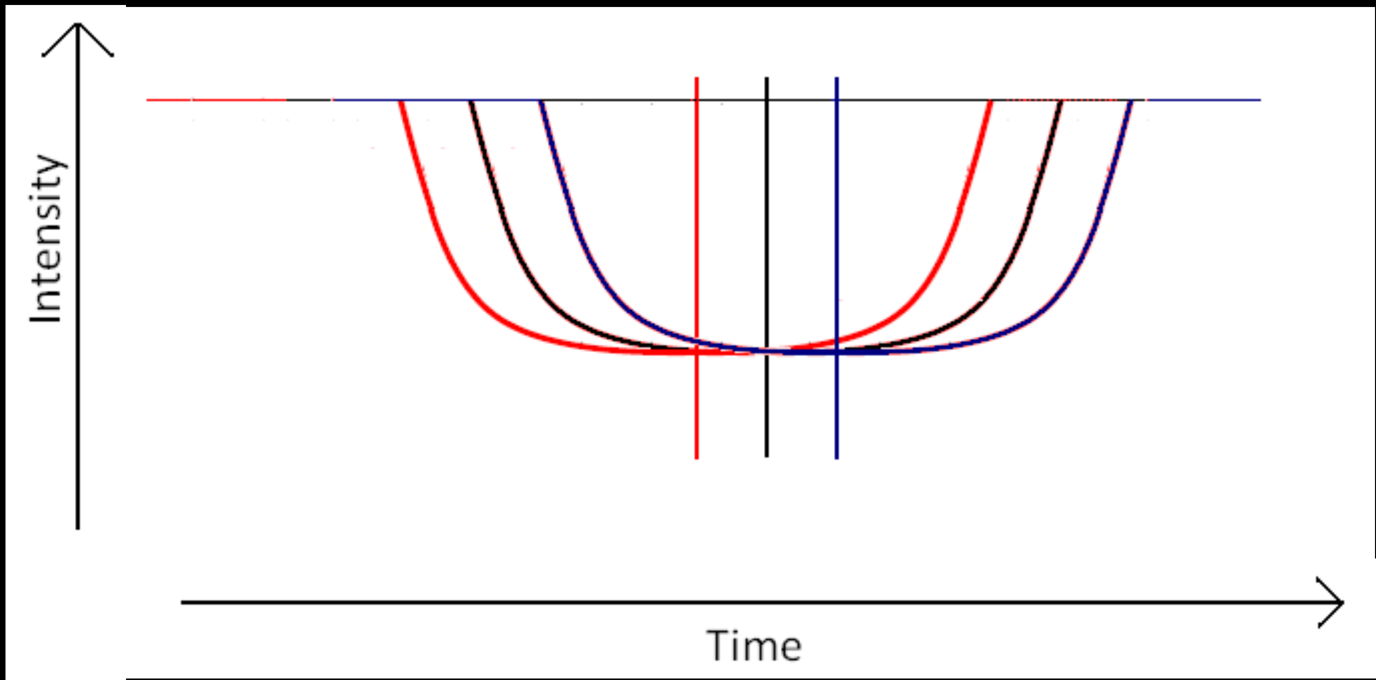
Transit duration variation (TDV)



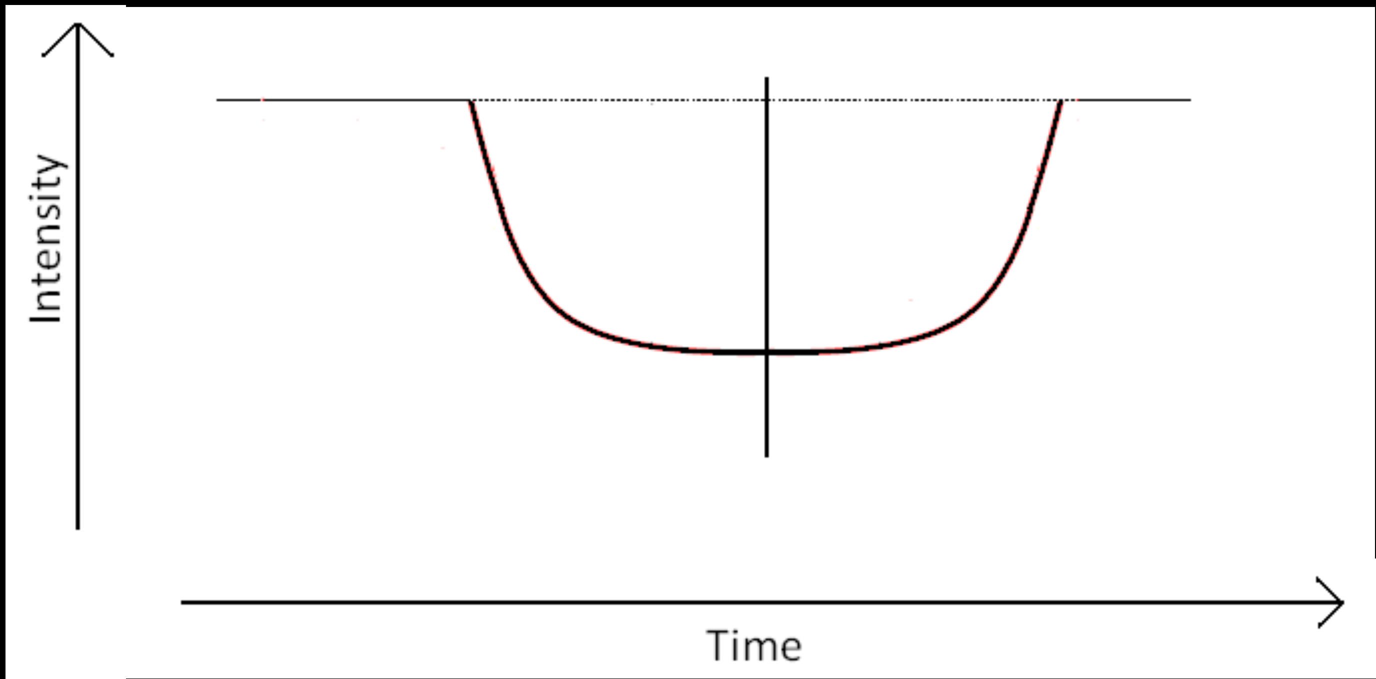
Transit duration variation (TDV)



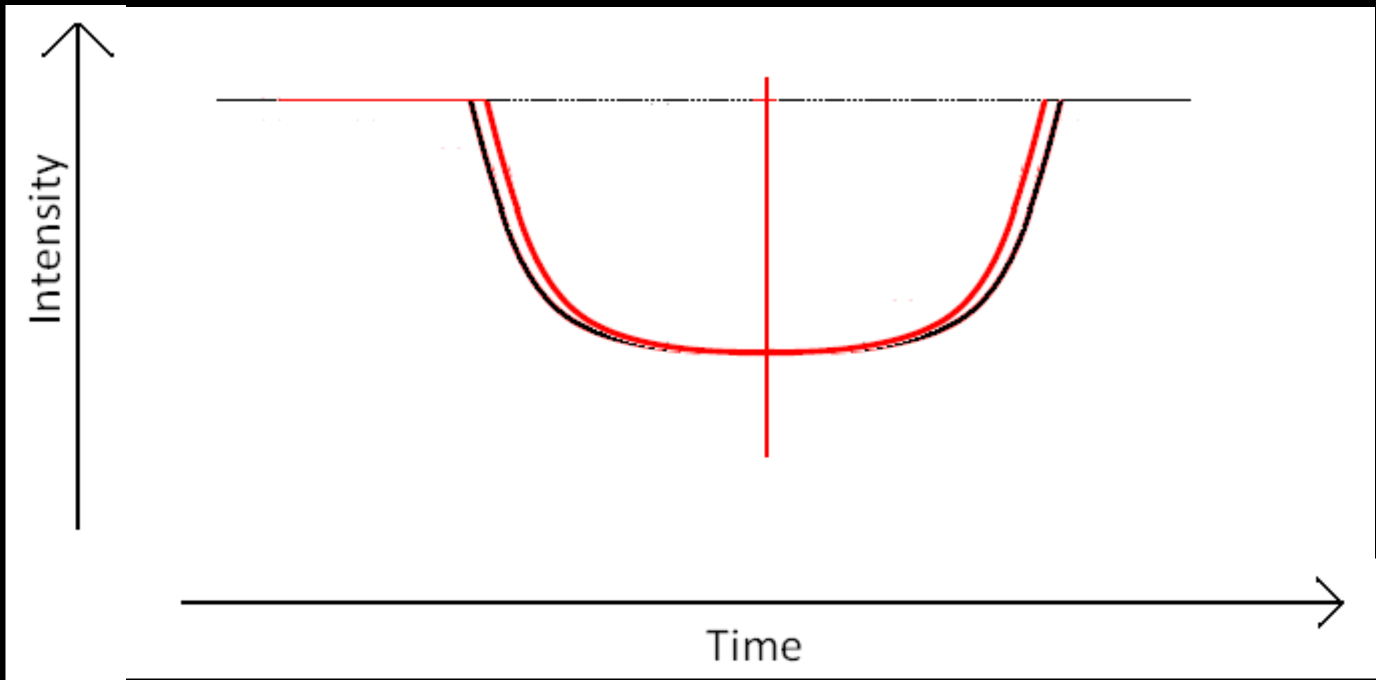
Transit duration variation (TDV)



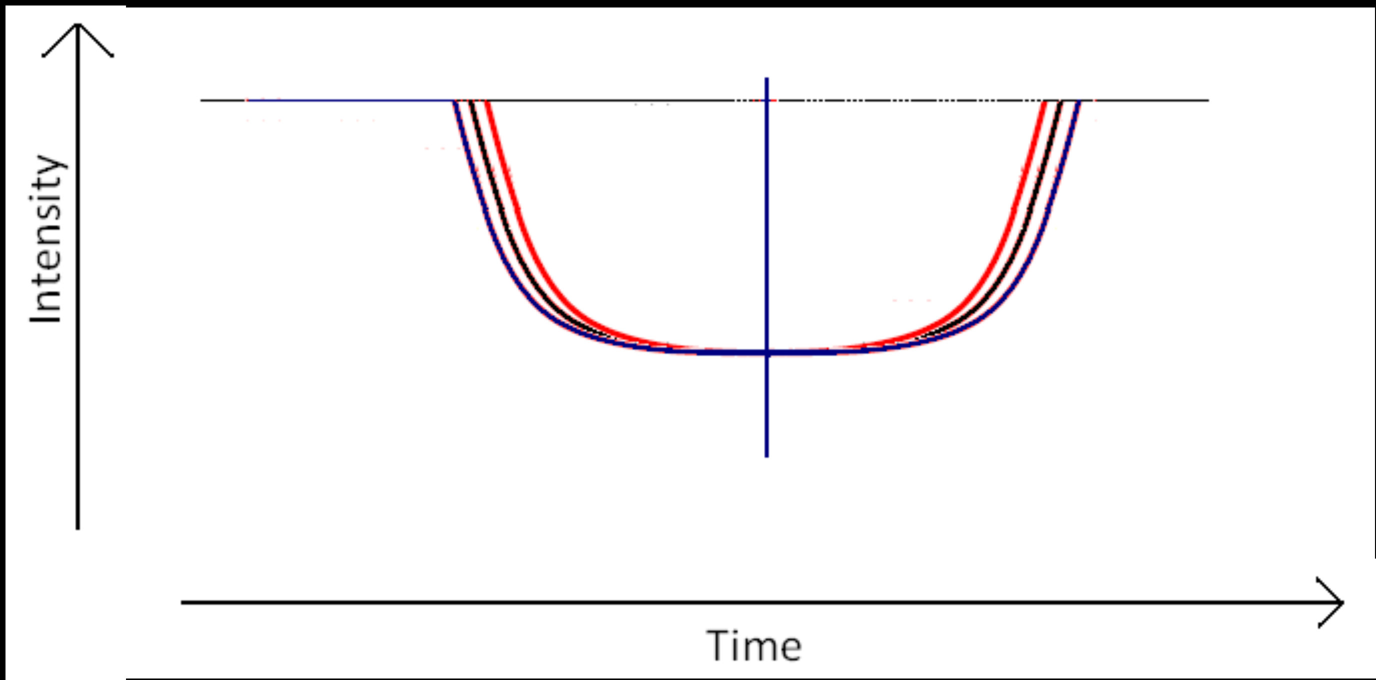
Transit duration variation (TDV)



Transit duration variation (TDV)

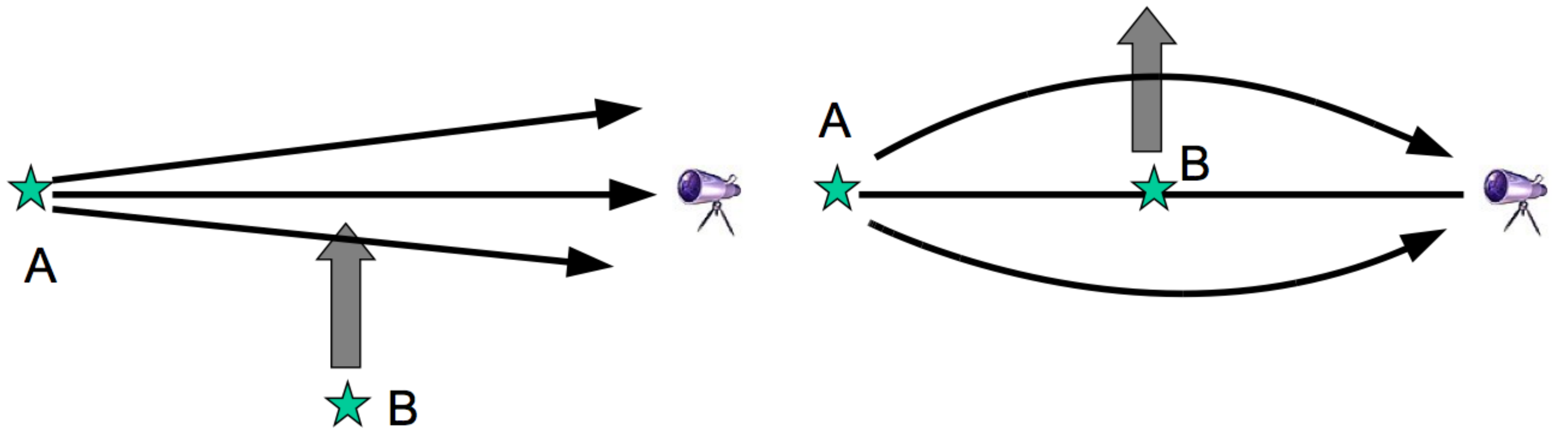


Transit duration variation (TDV)



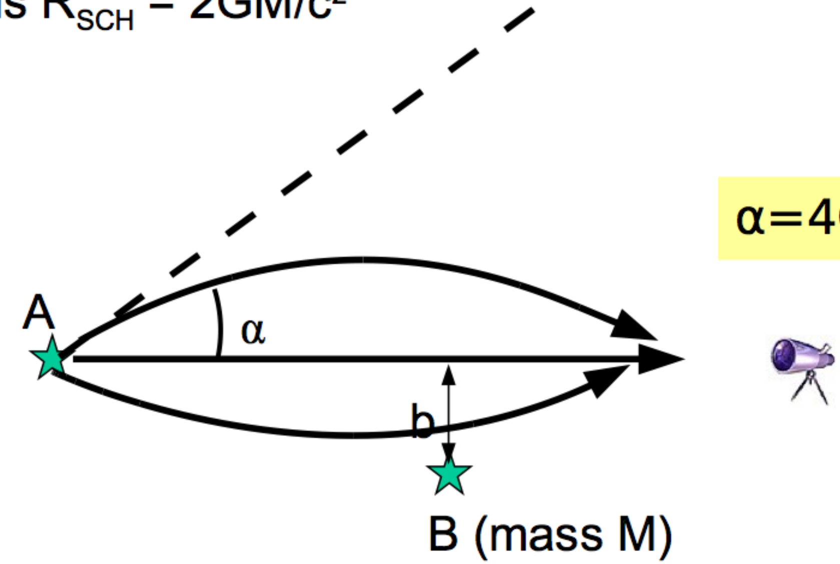
Gravitational Lensing

- Einstein's General Theory of Relativity: light rays can be bent by a sufficiently strong gravitational field.
- Take 1 background (A) and 1 foreground star (B)
- Light rays from A will be bent by the gravitational field of B → more light from the distant star reaches the Earth than would otherwise be the case



Gravitational Lensing

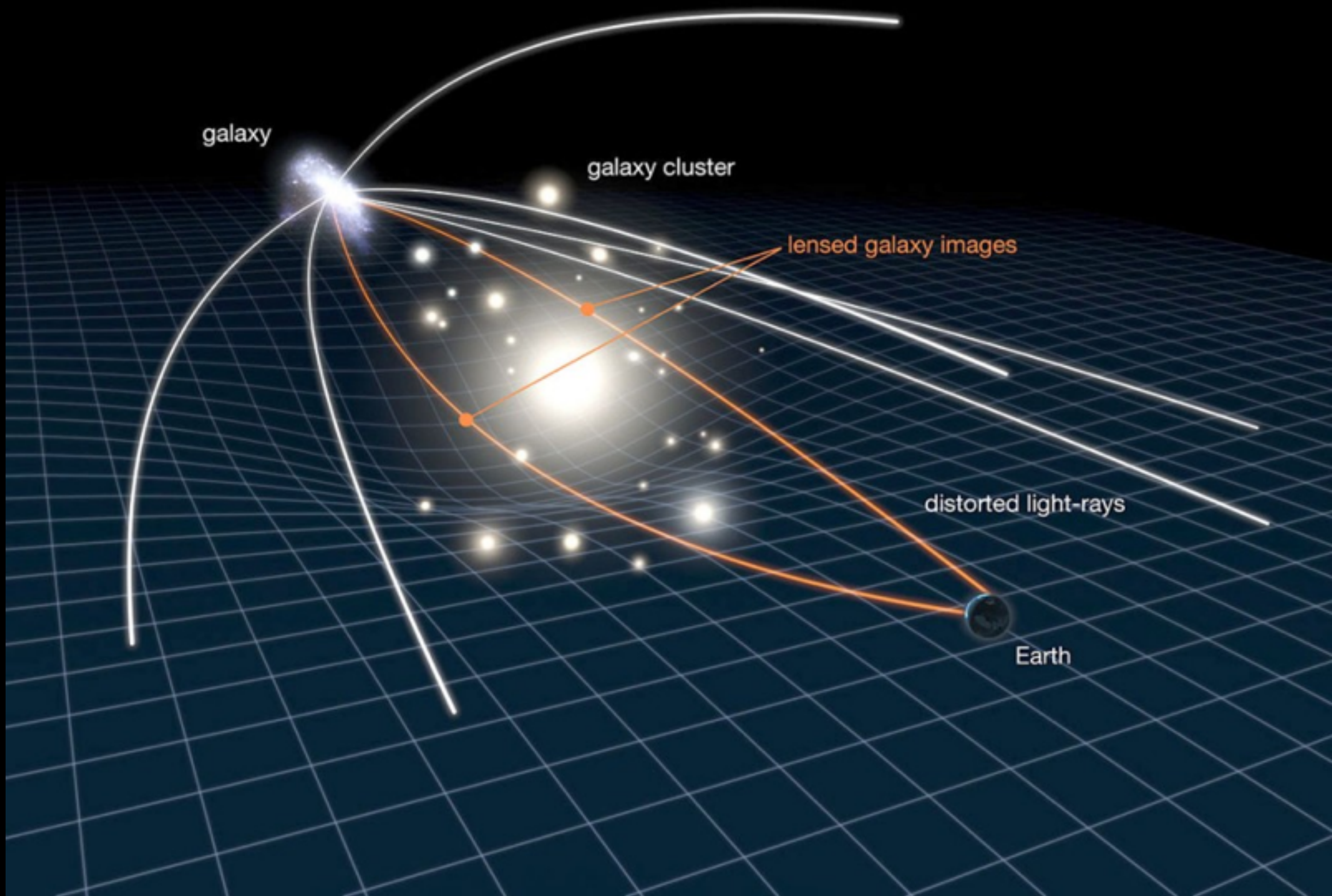
- This amount of bending is very small and is related to the size of a black hole with the mass of the lensing star (B): Schwarzschild radius $R_{SCH} = 2GM/c^2$



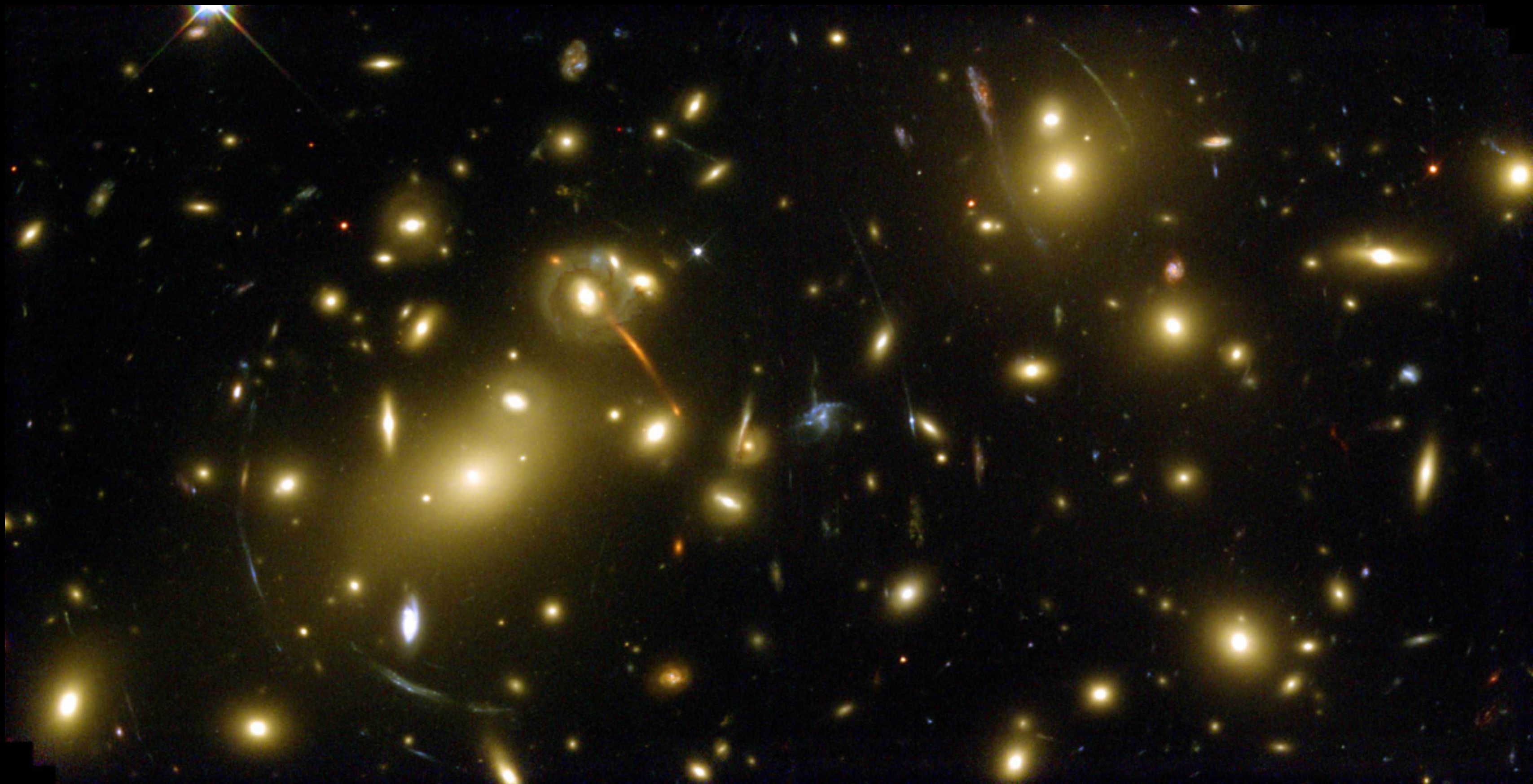
$\alpha = 4GM/c^2b = 2R_{SCH}/b$

For the Sun:
$R_{SCH} = 2.95\text{km}$
$\alpha = 2R_{SCH}/R_{\odot} = 1.74''$

Gravitational Lensing

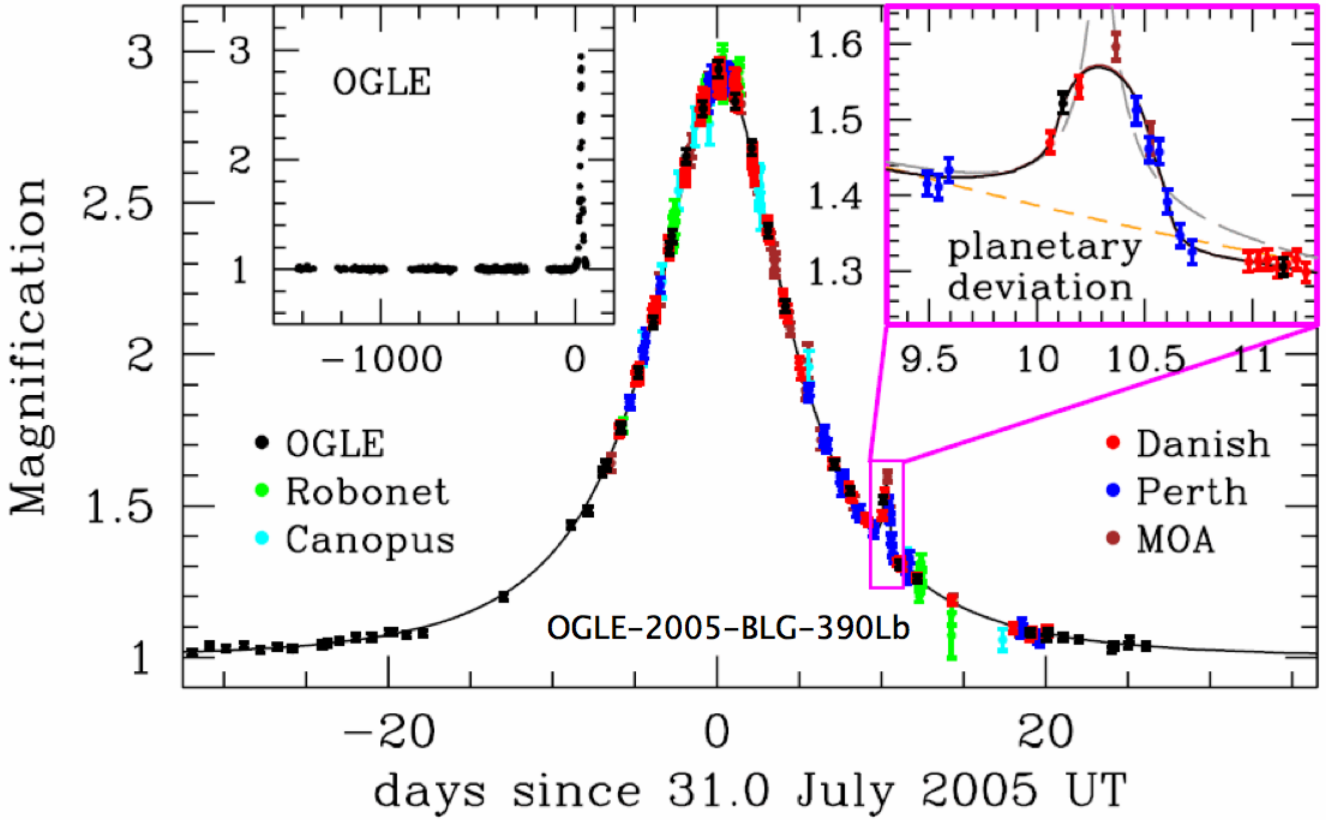


Gravitational Lensing

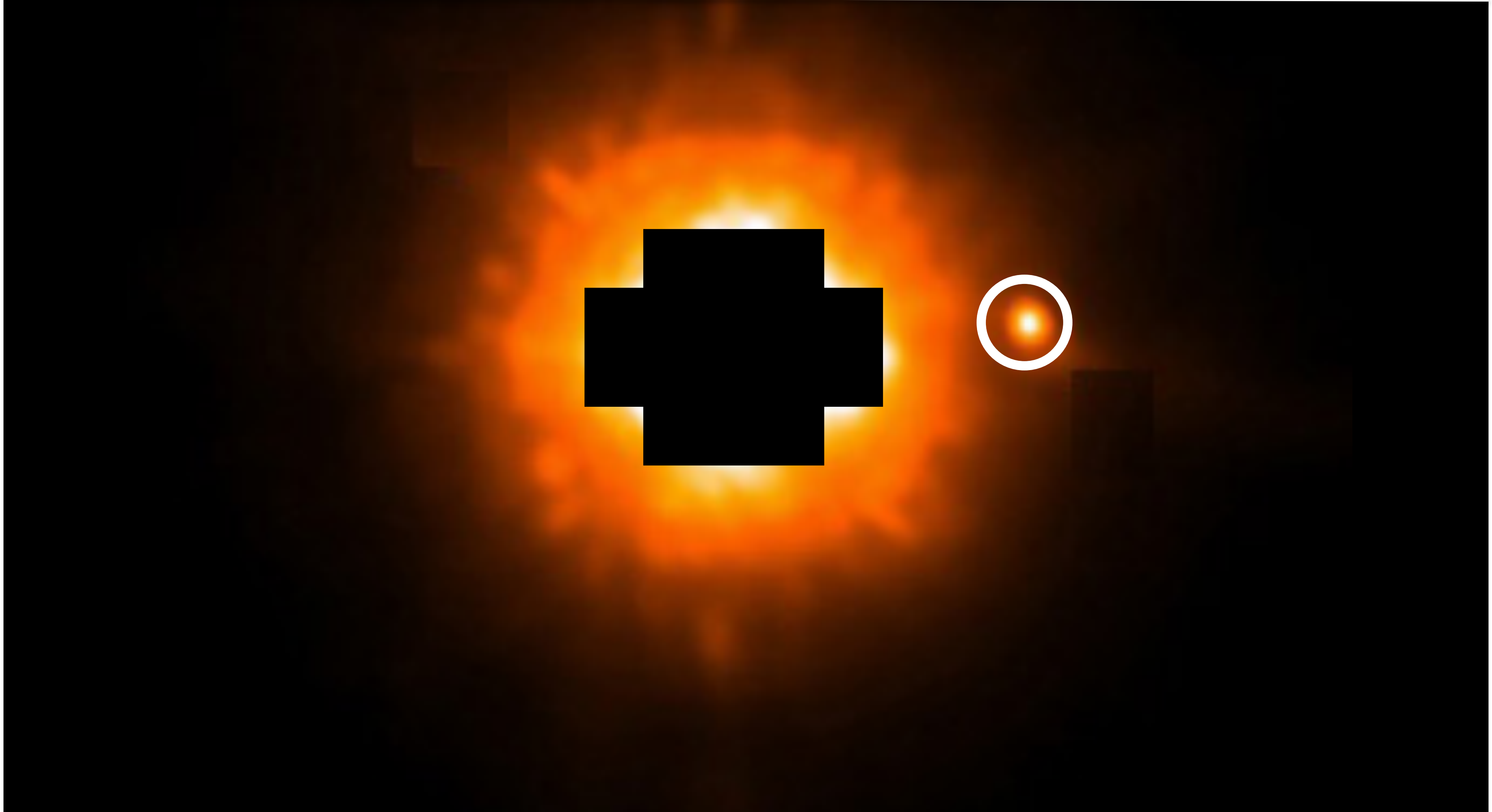


Microlensing and exoplanets

- If the lensing star has a planet, it could be seen as a small glitch in the light curve



Direct detection



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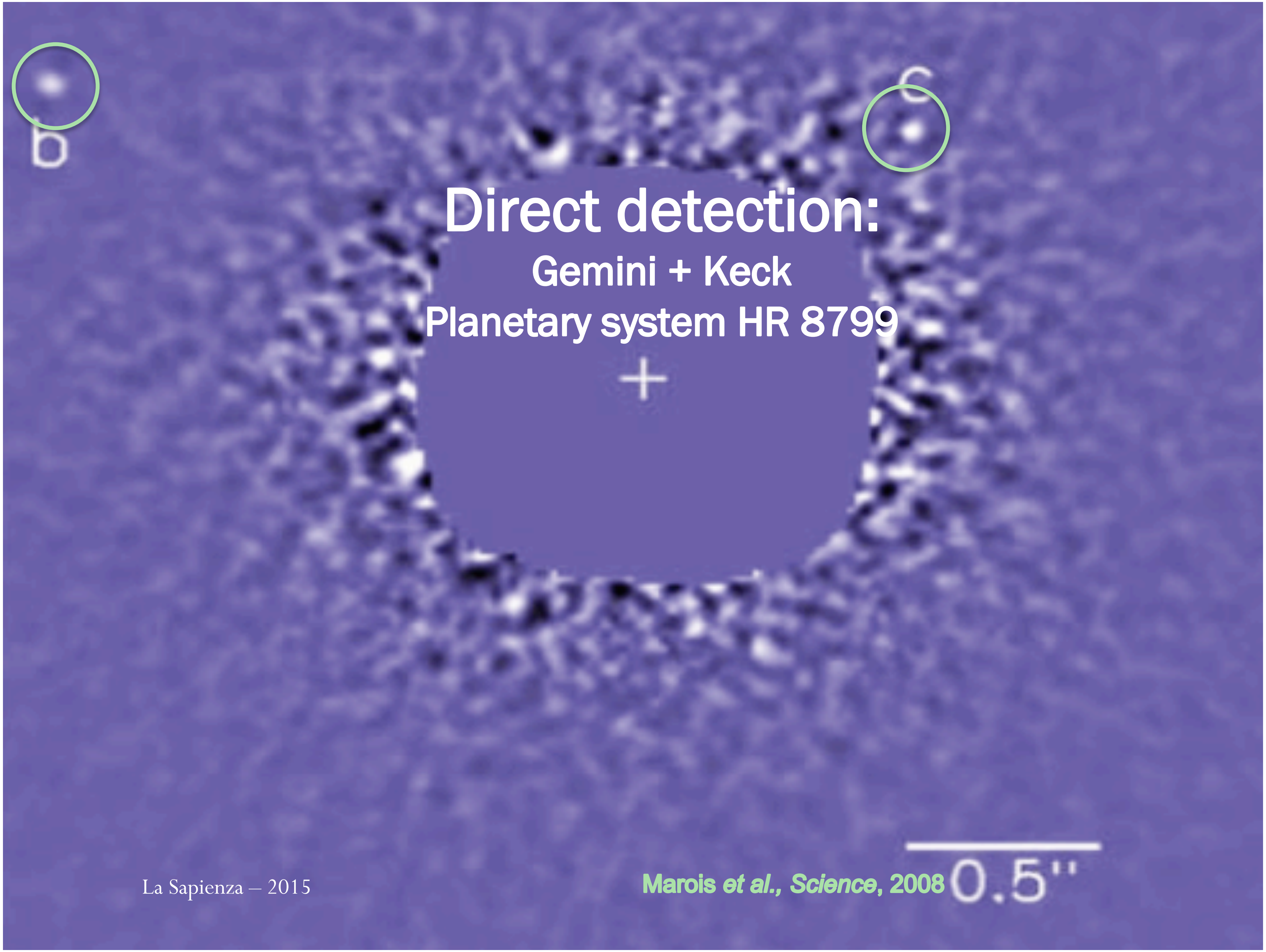
Direct detection:

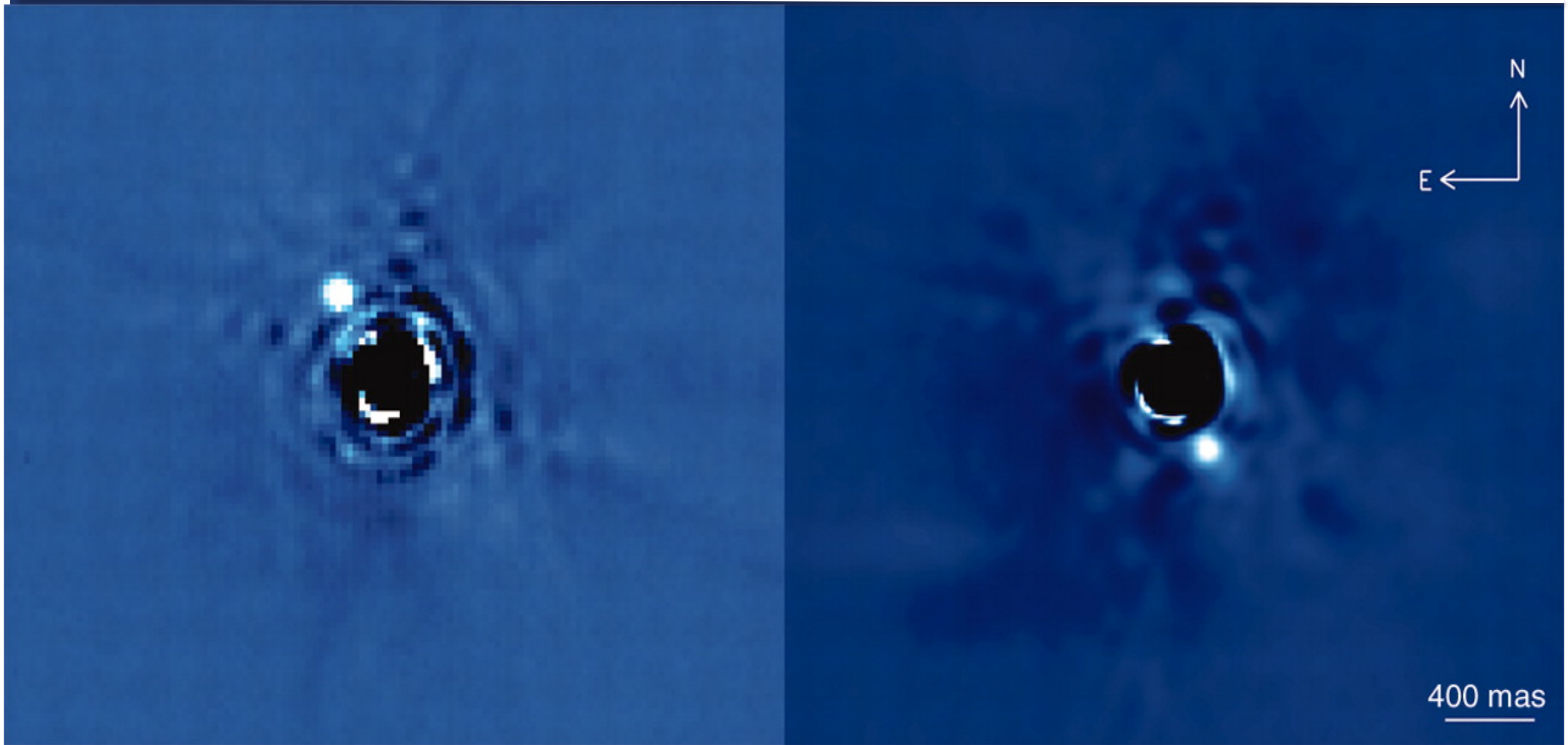
Gemini + Keck

Planetary system HR 8799



Marois *et al.*, *Science*, 2008

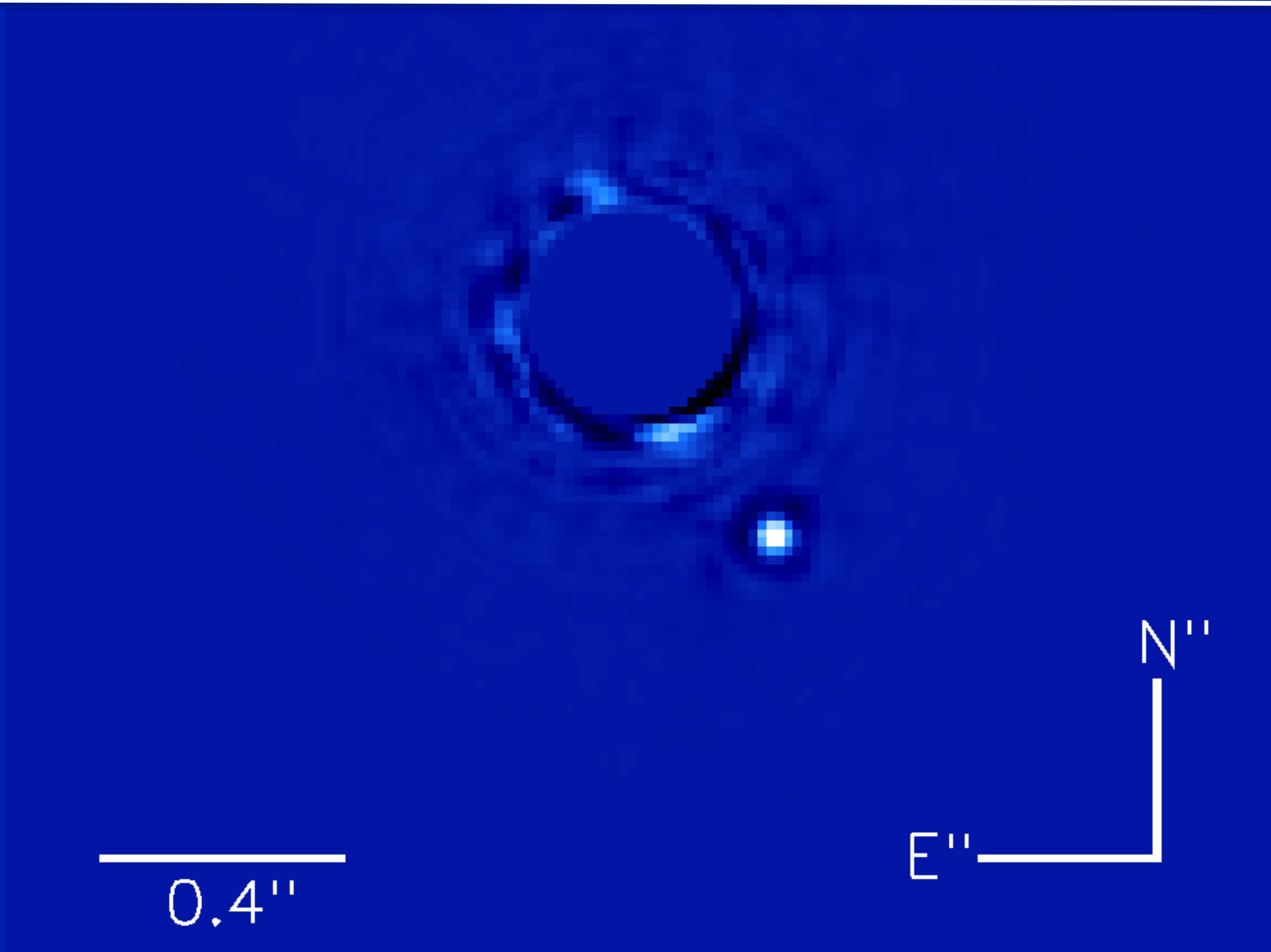
Direct detection:
VLT-NACO β-Pictoris b (~8 AU)



Lagrange *et al.*, *ApJ*, 2008

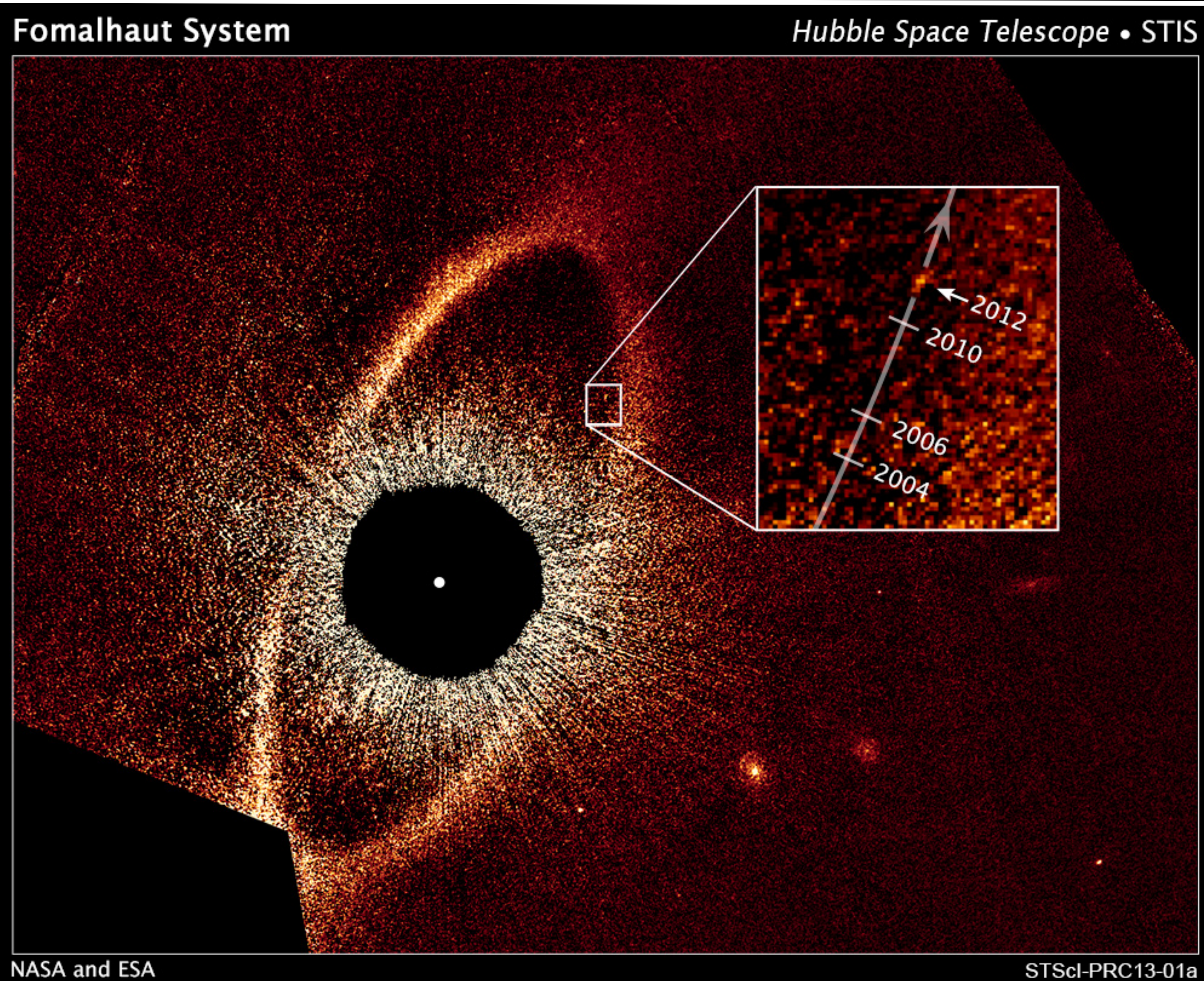
New generation of DI instruments:

GPI, SPHERE, SUBARU



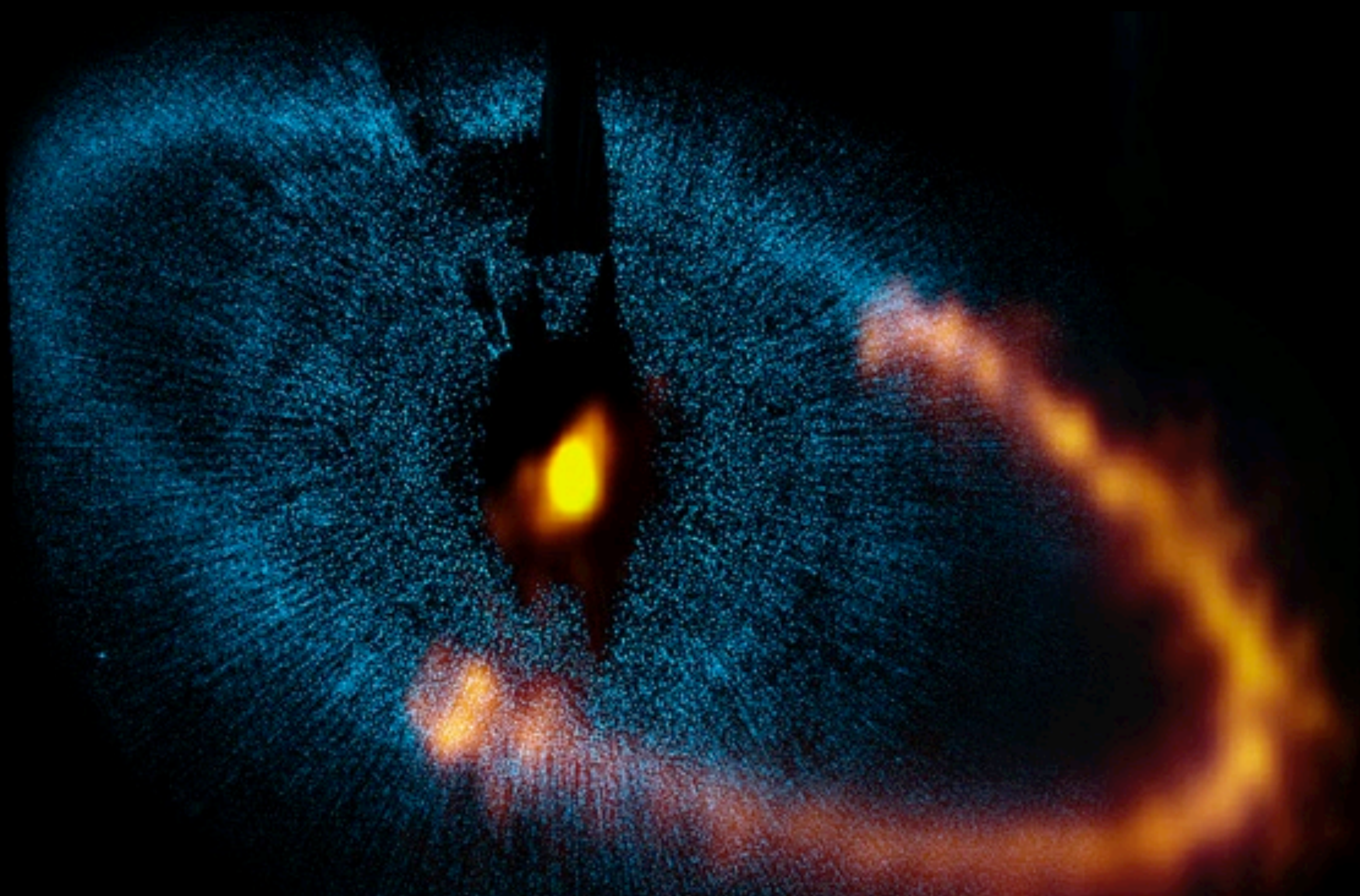
Macintosh *et al., 2014*

Formalhaut b (HST)



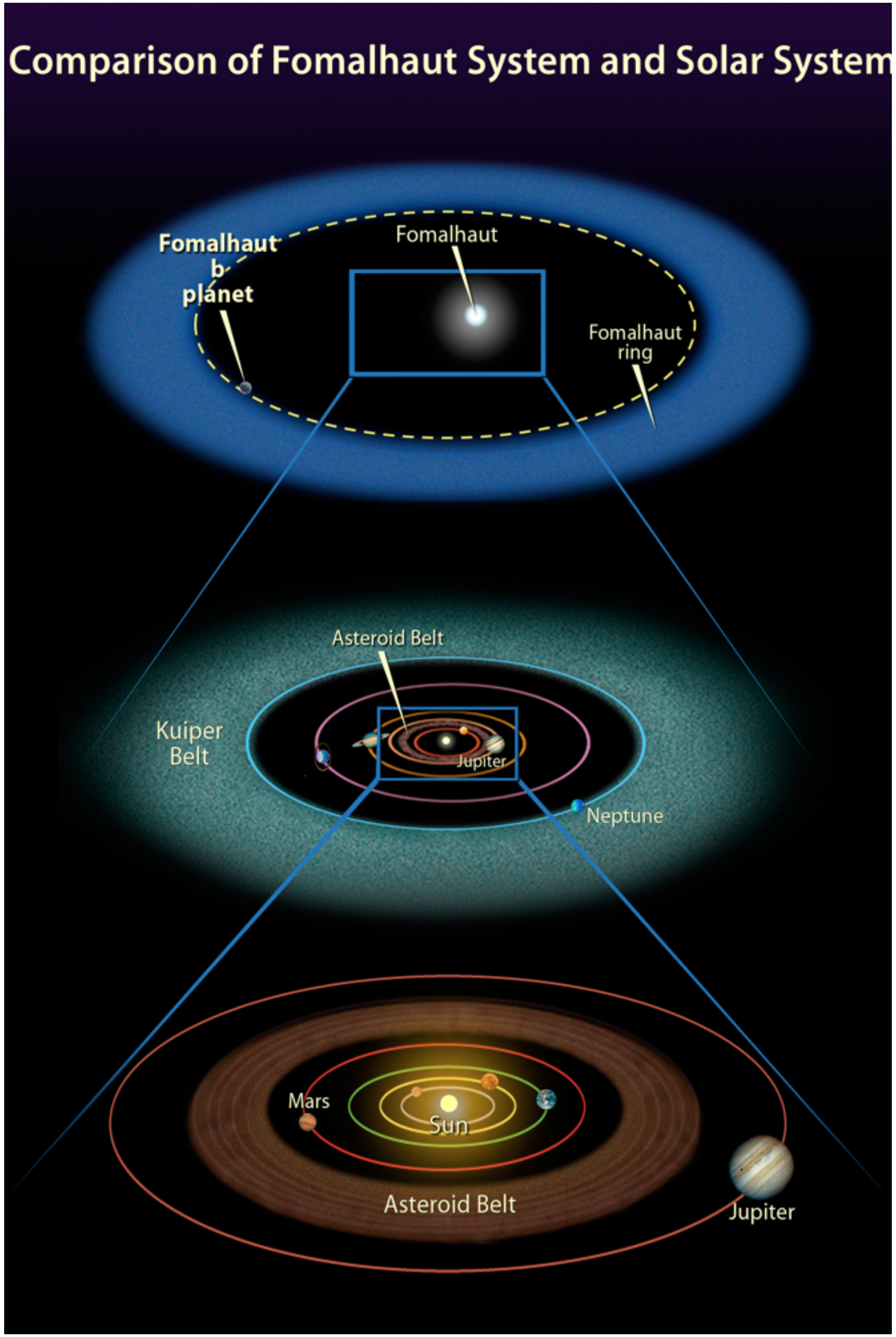
Kalas et al. 2008

Formalhaut b (Alma)

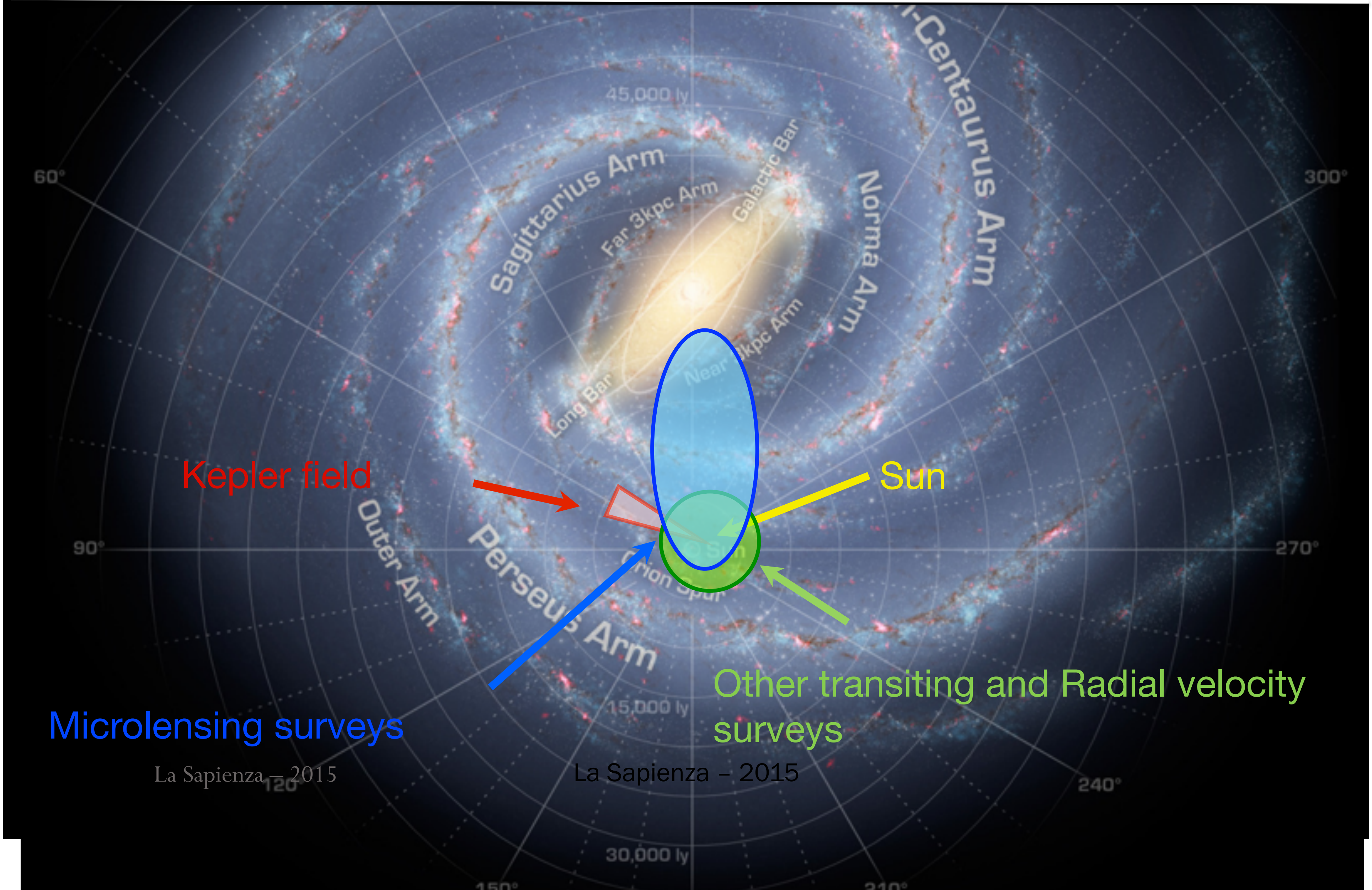


Formalhaut b

- Hot Jupiter first discovered in 2008
- Orbital parameters: a = 115au, e= 0.11, i = 66 degrees
- Orbital period of 872 years
- Some debates on its existence in the literature but is now thought to be confirmed.



Where are these planets?



La Sapienza – 2015