Searching for Other Worlds: The Methods

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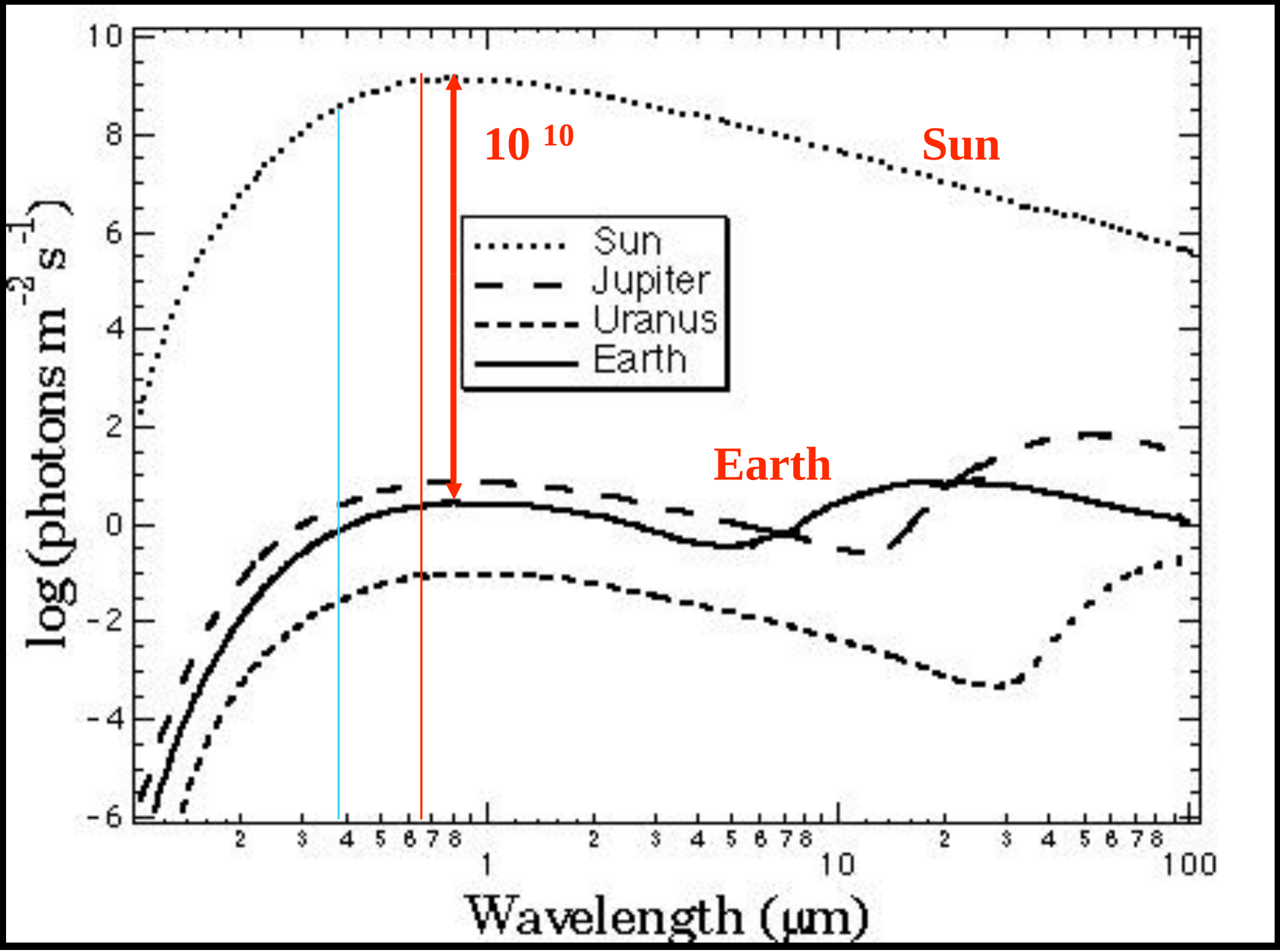
The Search Extra-Solar Planets

Hard: Earth 10^{10} (10 billion) x fainter than Sun!

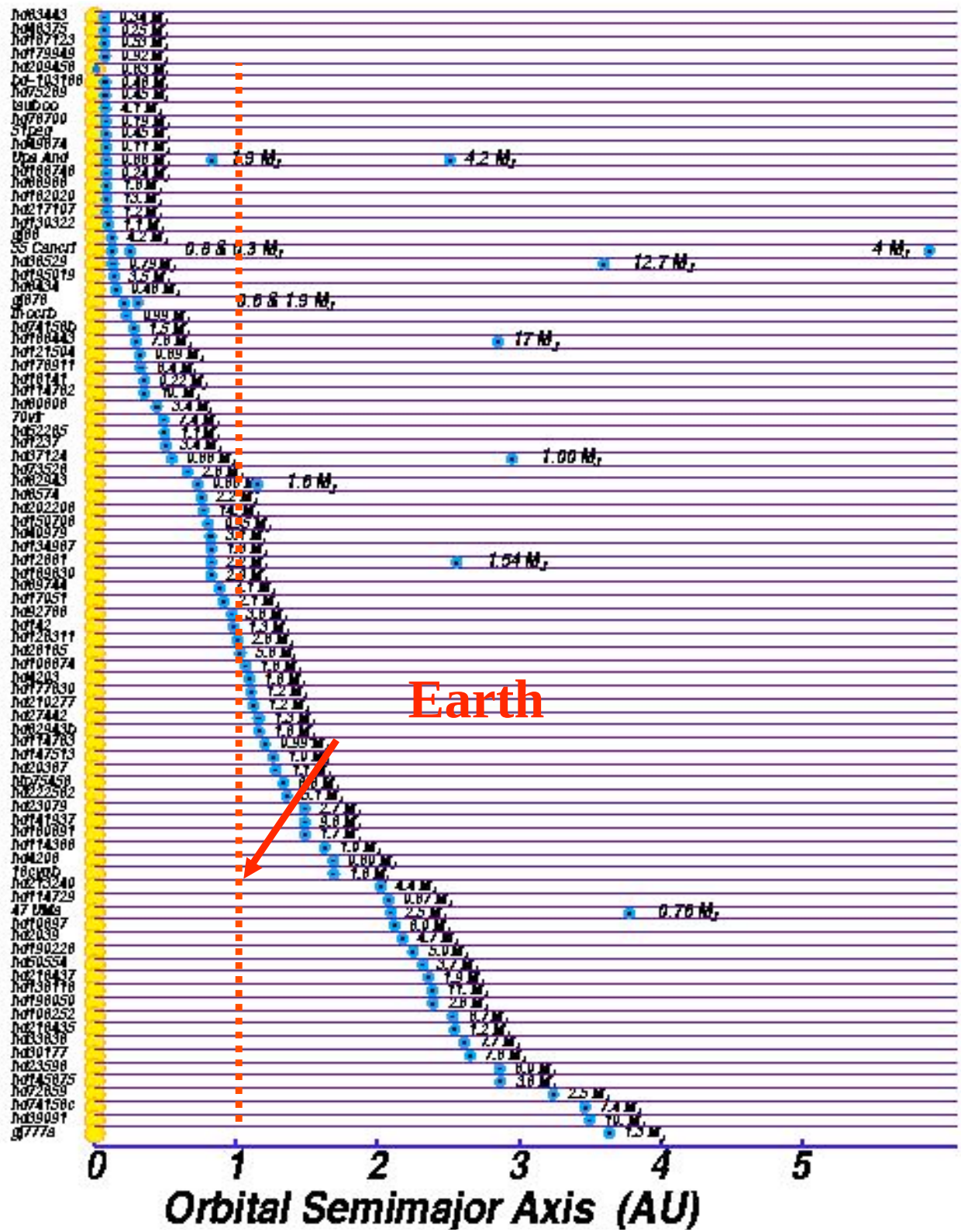
- Stellar Reflex Motion:
  - Periodic Doppler variation
  - Periodic Position change
- Transits (planet blocks light)
- Gravitational Lensing
- Direct detection in images

Direct imaging of exo-planets is Hard:



> 200 planets:

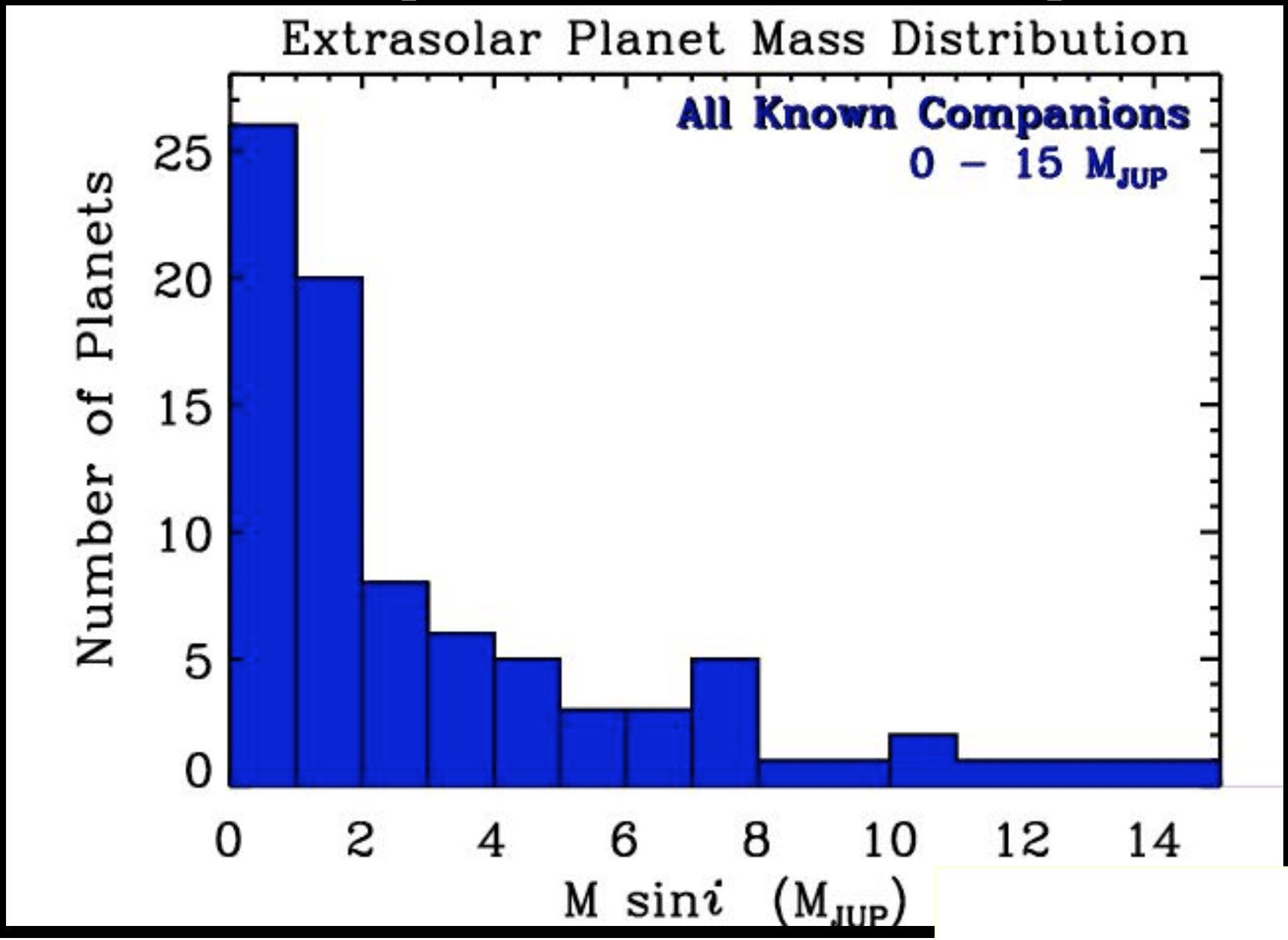
Most located inside Earth's orbit



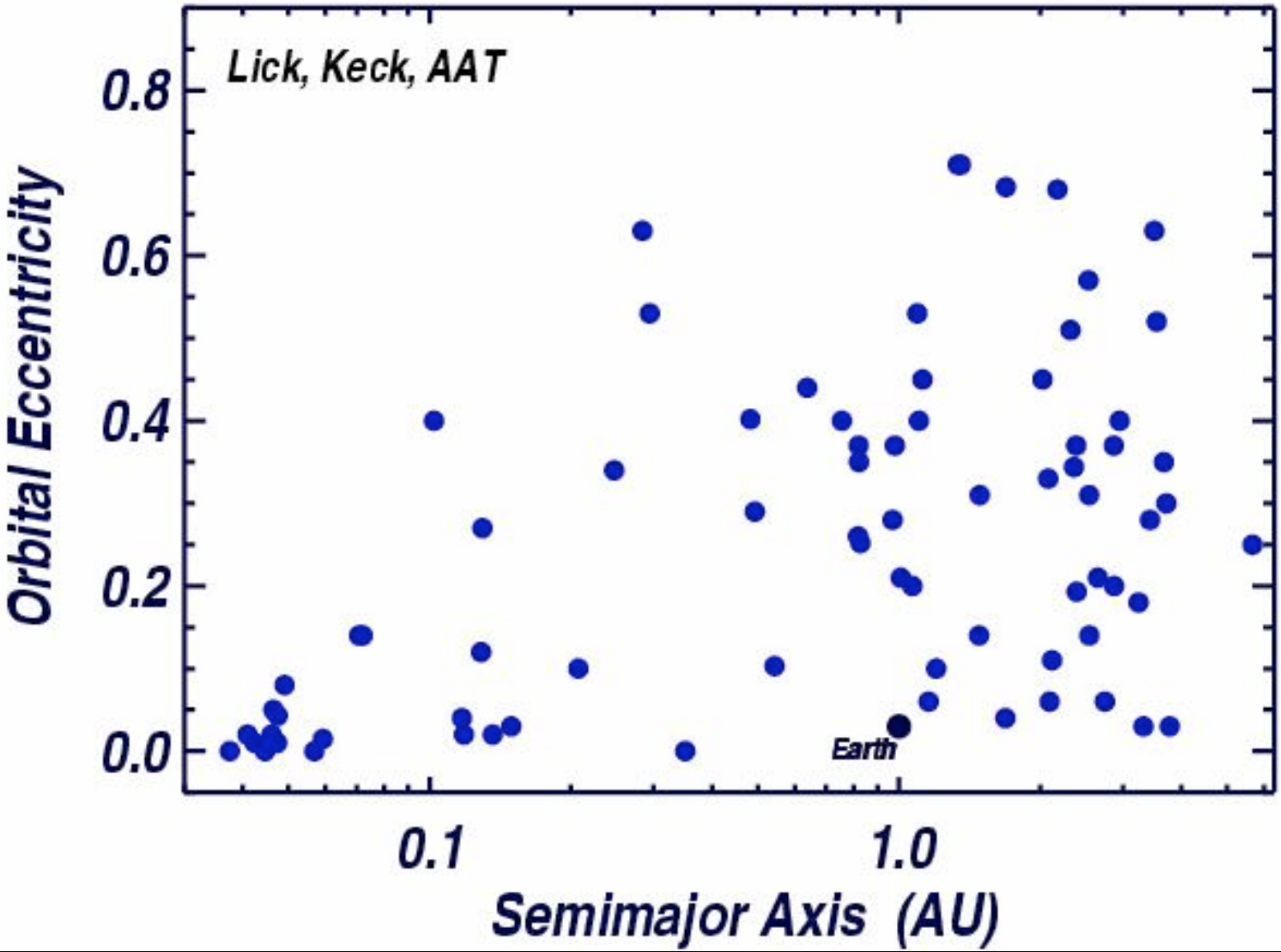
Goeff Marcy
Paul Butler

radial velocity method

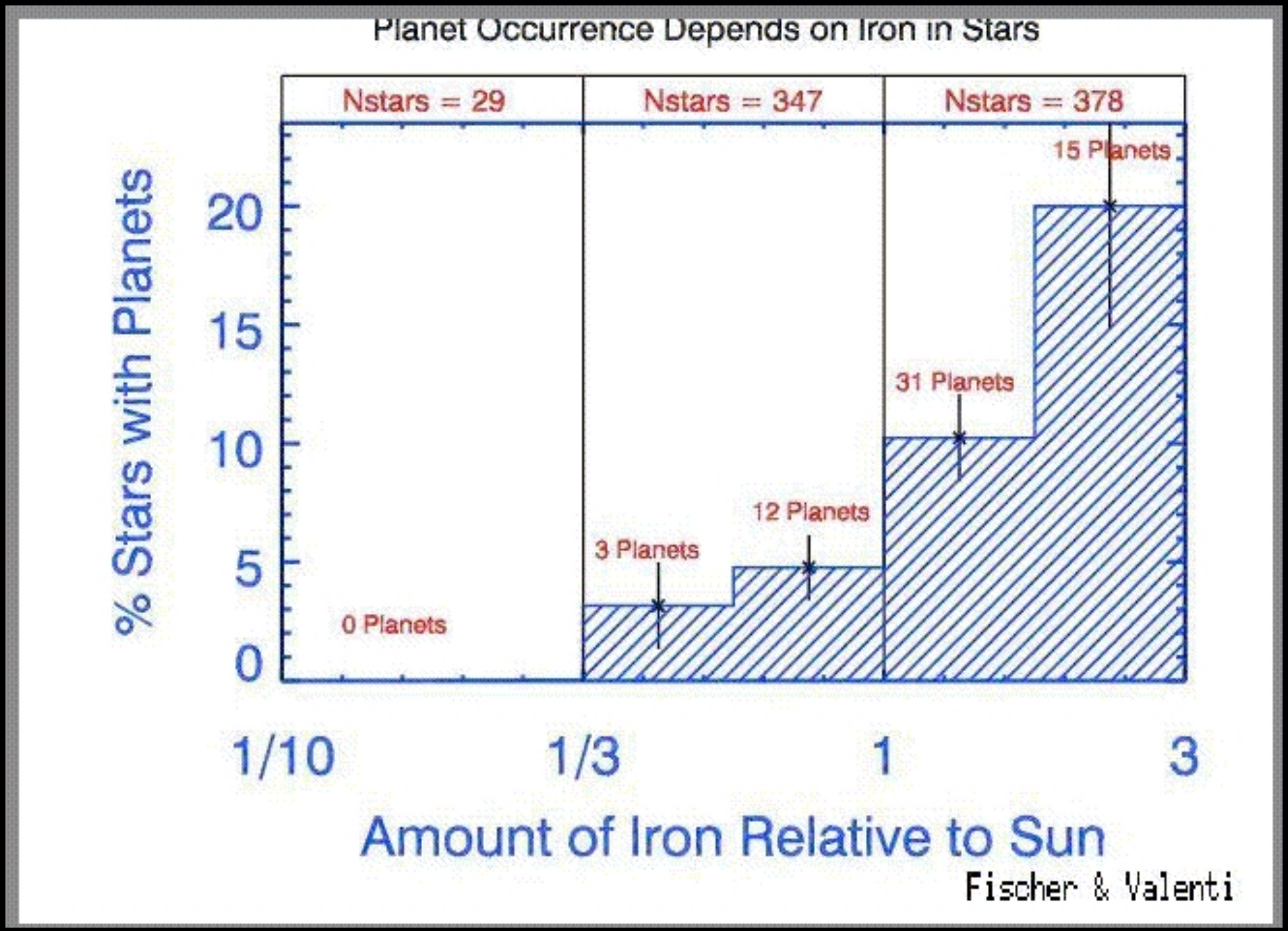
> 200 planets: Gas Giants like Jupiter



Orbit eccentricity



The Metallicity Effect:



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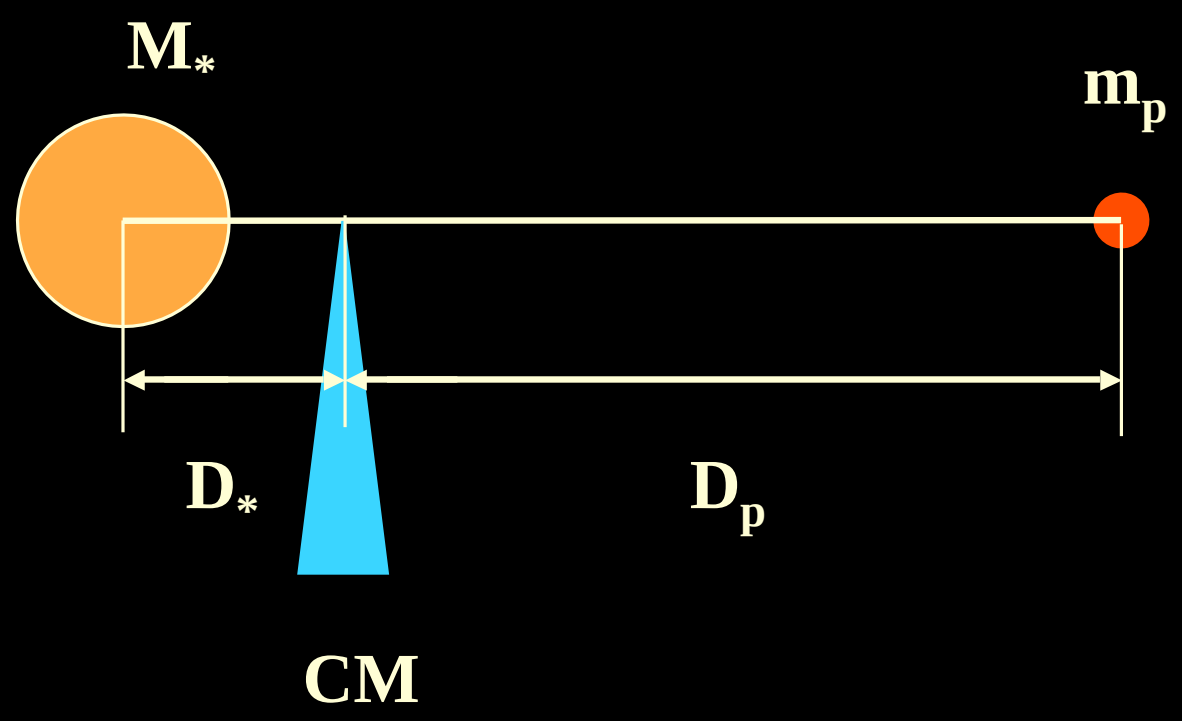
Quantitative estimate of reflex motion:



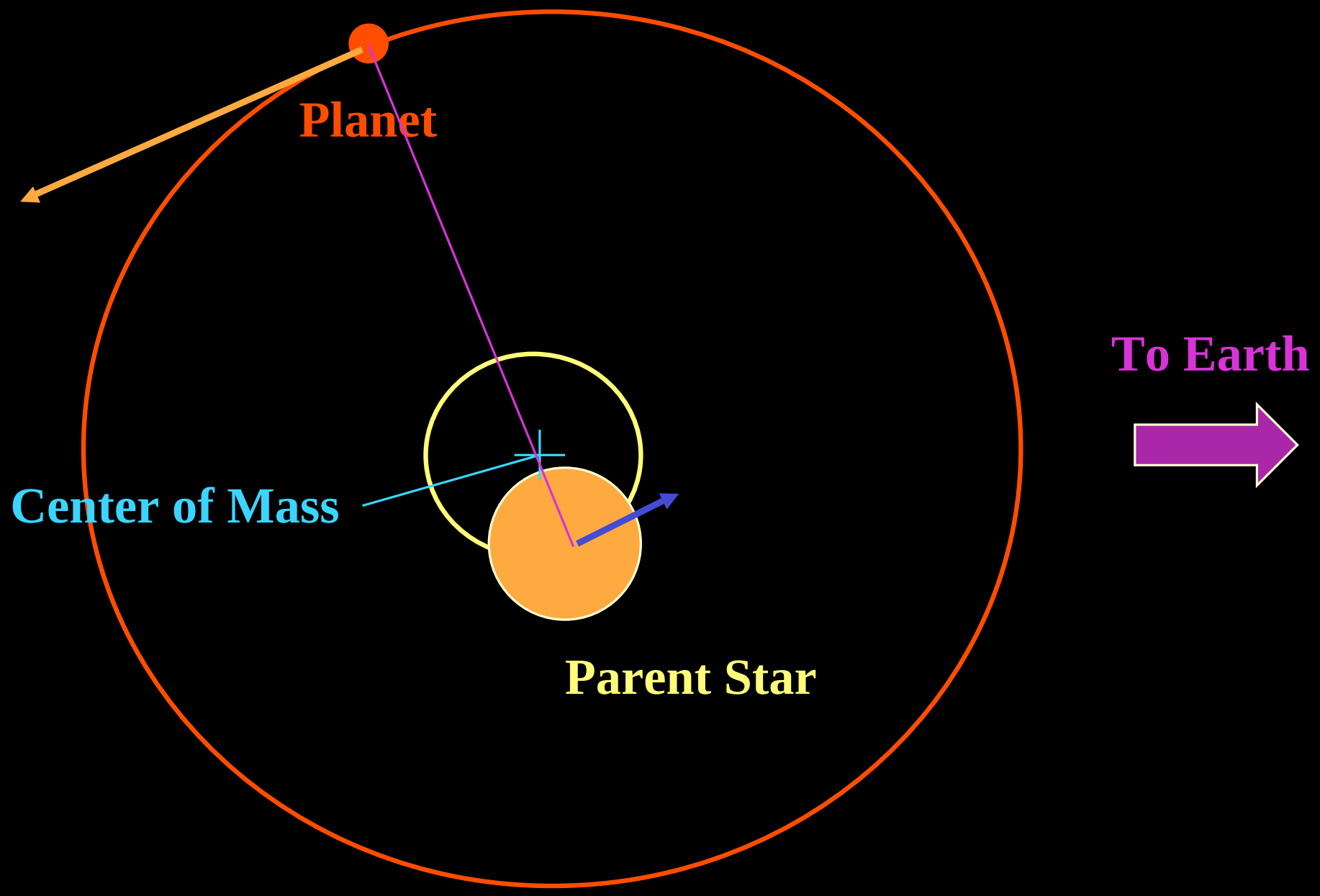
$$D_* M_* = D_p m_p$$

$$D_p \sim r_{orbit}$$

$$D_* = (m_p/M_*)\, r_{orbit}$$

$$V_* = (m_p/M_*)\, V_{orbit}$$

Reflex Motion:



Quantitative estimate of reflex motion:

$M_{Earth} = 6 \times 10^{27}$ g

$M_{Jupiter} = 1.7 \times 10^{30}$ g

$M_{Sun} = 2 \times 10^{33}$ g

$D_{Earth} = 1.5 \times 10^{13}$ cm (1AU)

$D_{Jupiter} = 7.8 \times 10^{13}$ cm

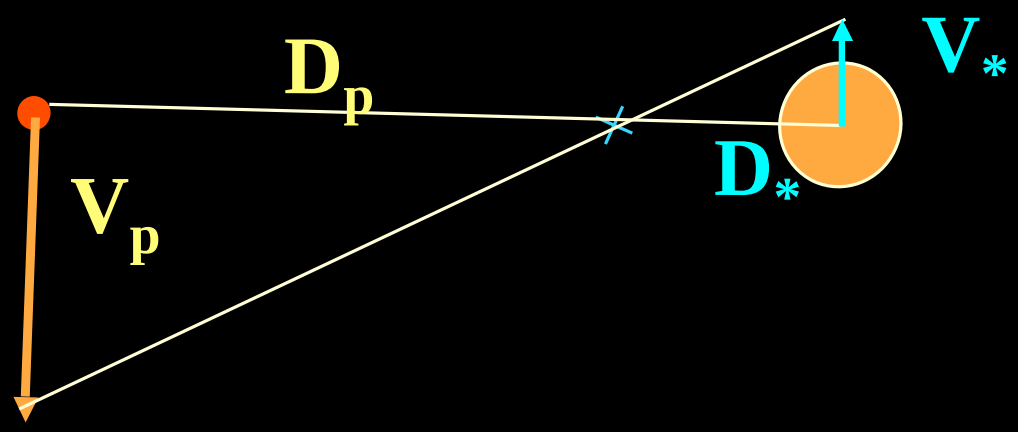
$D_* = (m_p/M_*)\, r_{orbit}$

Earth @ 1AU	4.5×10^{7} cm
Jupiter@ 1AU	1.3×10^{10} cm
Jupiter @ 5.2 AU	6.6×10^{10} cm

Quantitative estimate of reflex motion:

Orbital speed of planet: $V_p = (GM_* / D_p)^{1/2}$

Orbital speed of star: $V_* = V_p \ (D_* / D_p)$



	V_*
Earth @ 1AU	8.9 cm/s
Jupiter@ 1AU	25.4 m/s
Jupiter @ 5.2 AU	11.1 m/s

The Doppler Effect:

$$\Delta \nu / \nu = \Delta \lambda / \lambda = V_* / c \qquad (v << c)$$

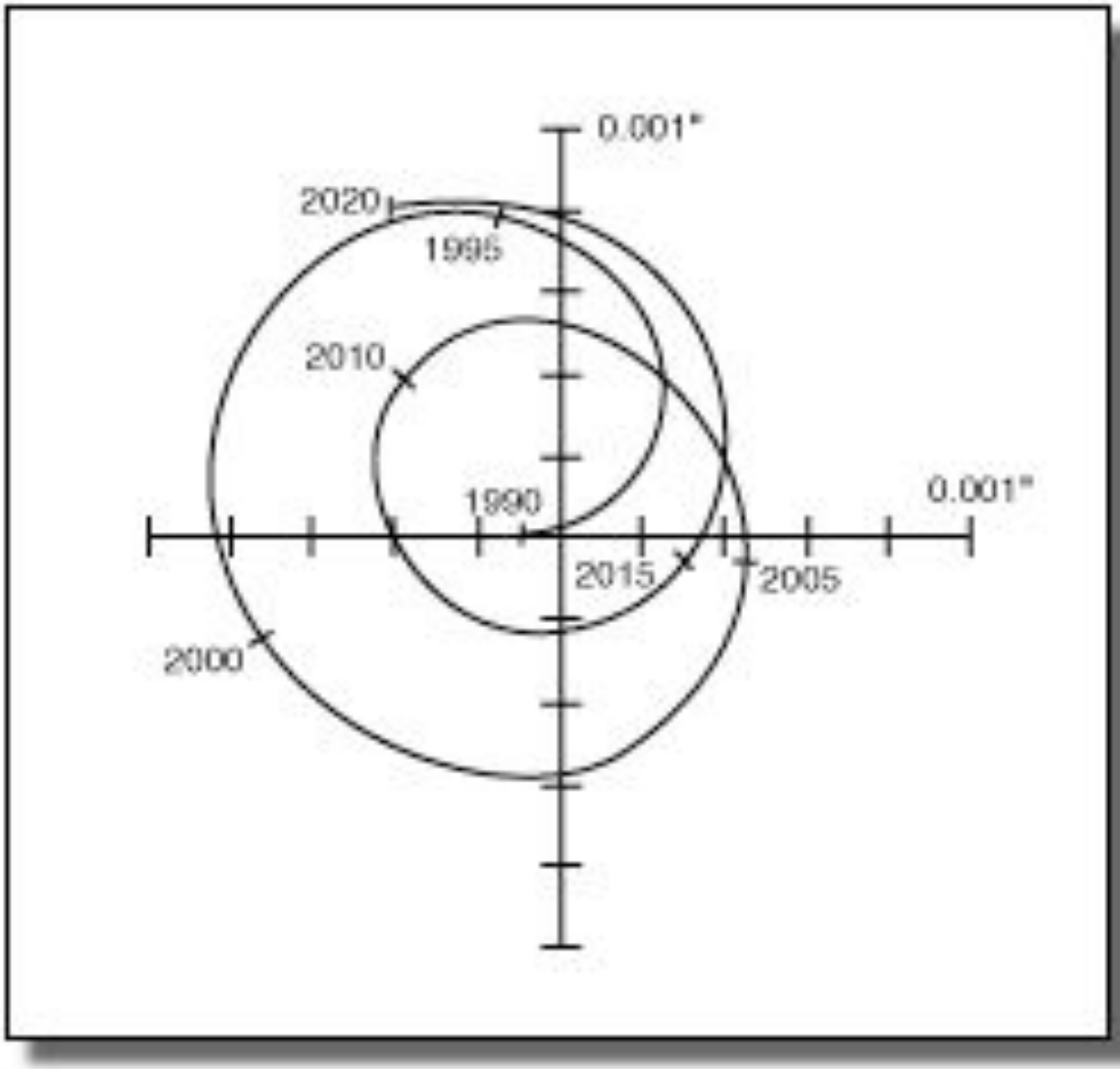
ν = Frequency

λ = Wavelength

$$\lambda \nu = c \qquad \text{(speed of light)}$$

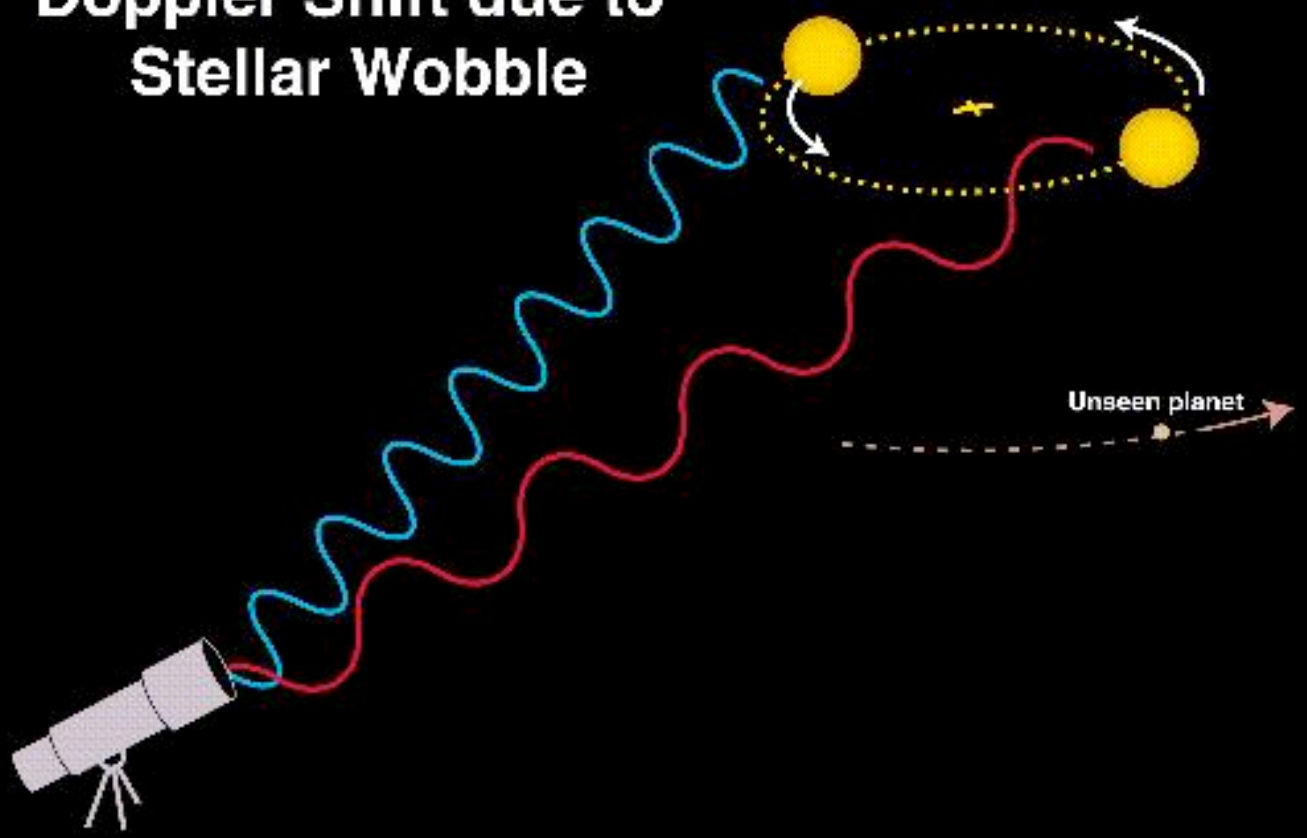
	V_*	$\Delta \lambda / \lambda$
Earth @ 1AU	8.9 cm/s	3×10^{-10}
Jupiter@ 1AU	25.4 m/s	8×10^{-8}
Jupiter @ 5.2 AU	11.1 m/s	4×10^{-8}

The Sun's Wobble



Astrometric displacement of the Sun due to Jupiter as seen from 10 parsecs.

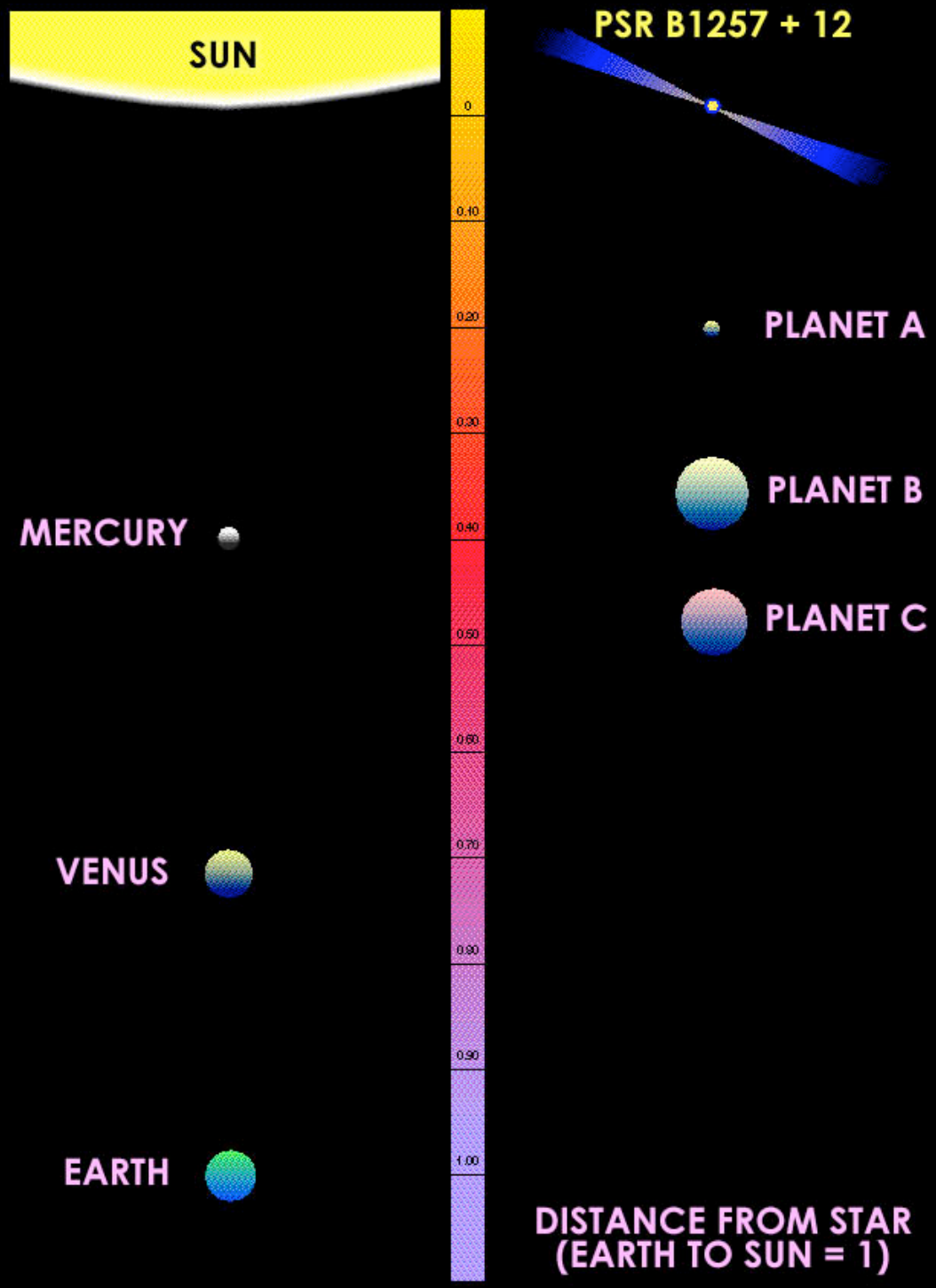
Doppler Shift due to Stellar Wobble

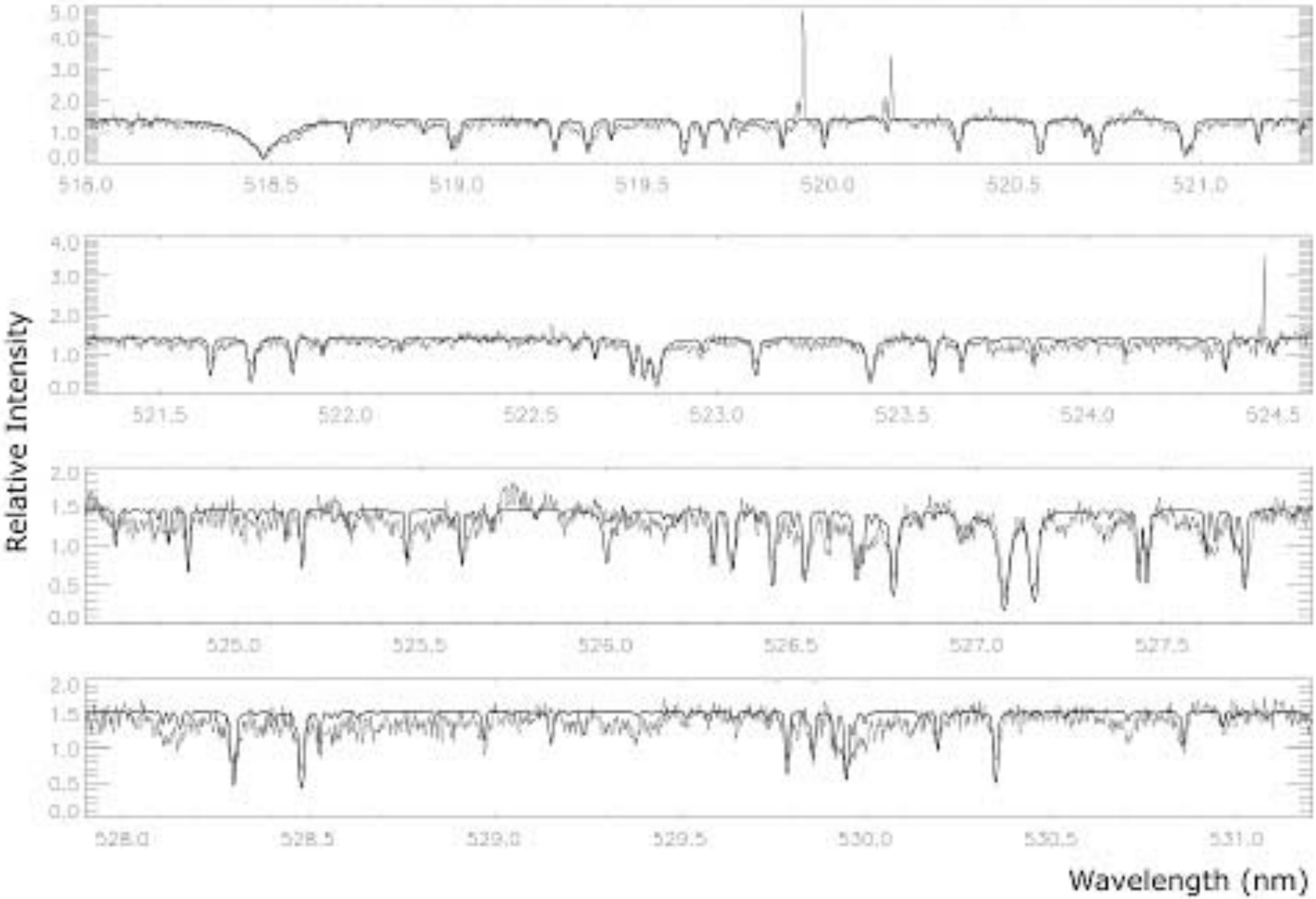


The first exo-planets:

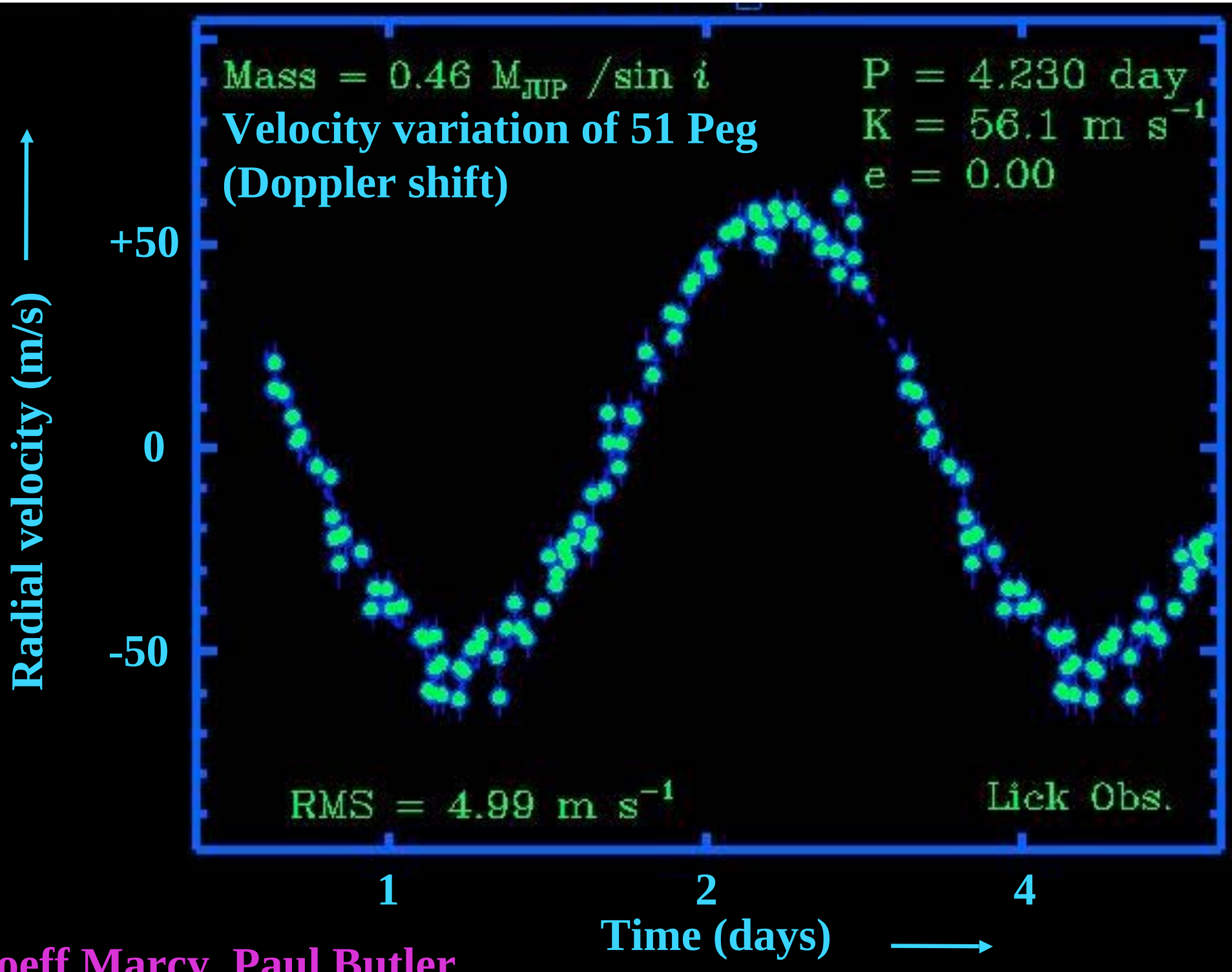
Use radio timing of Pulse-arival

- Doppler





Spectrum of OGLE-TR-3
(VLT KUEYEN + UVES)



Goeff Marcy, Paul Butler

Gas-Giants Close-In: "Hot Jupiters"

Oribital Periods: 1 day => 1 year

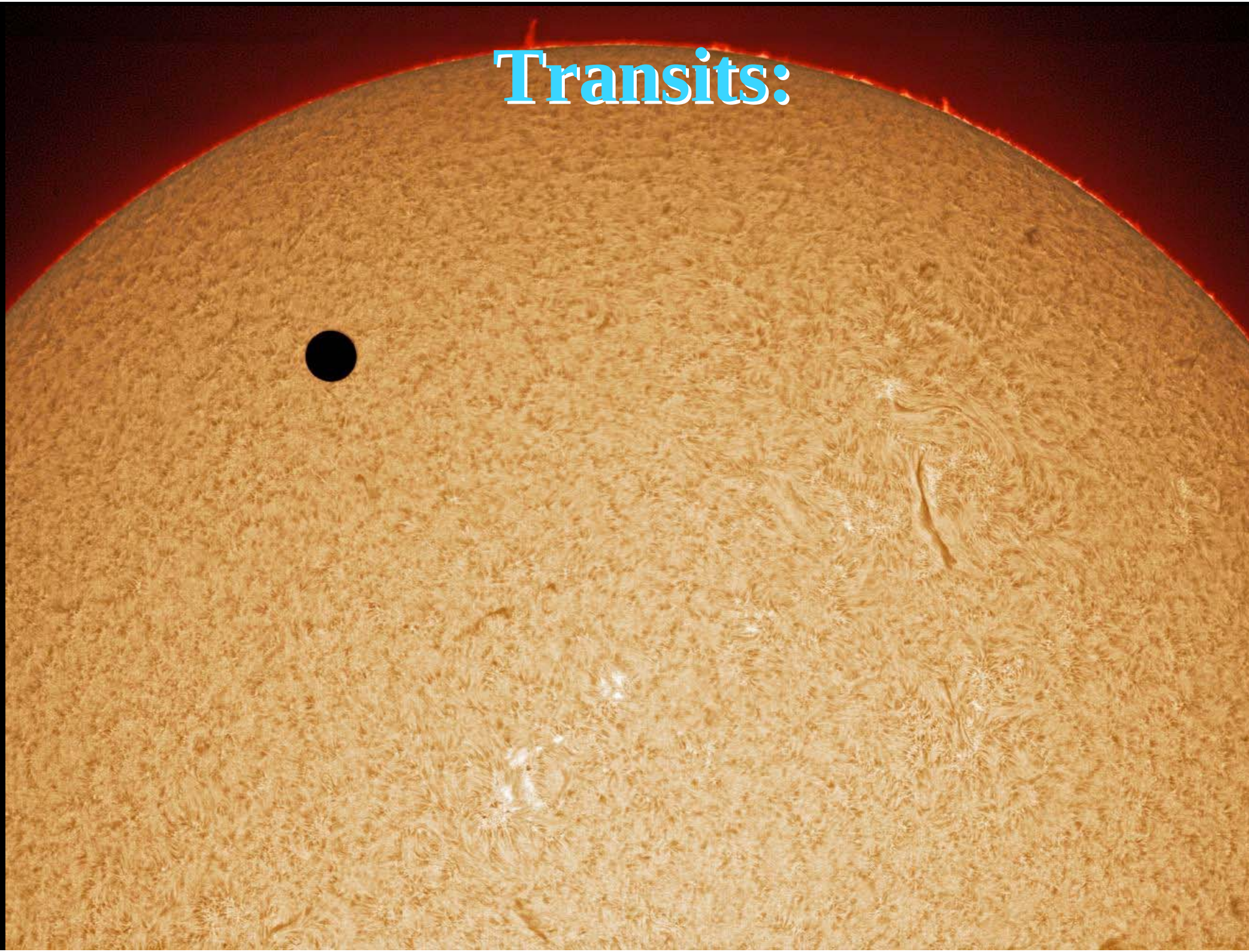
D ~ 0.05 AU to > 1 AU

T ~ 1400 K to < 300 K

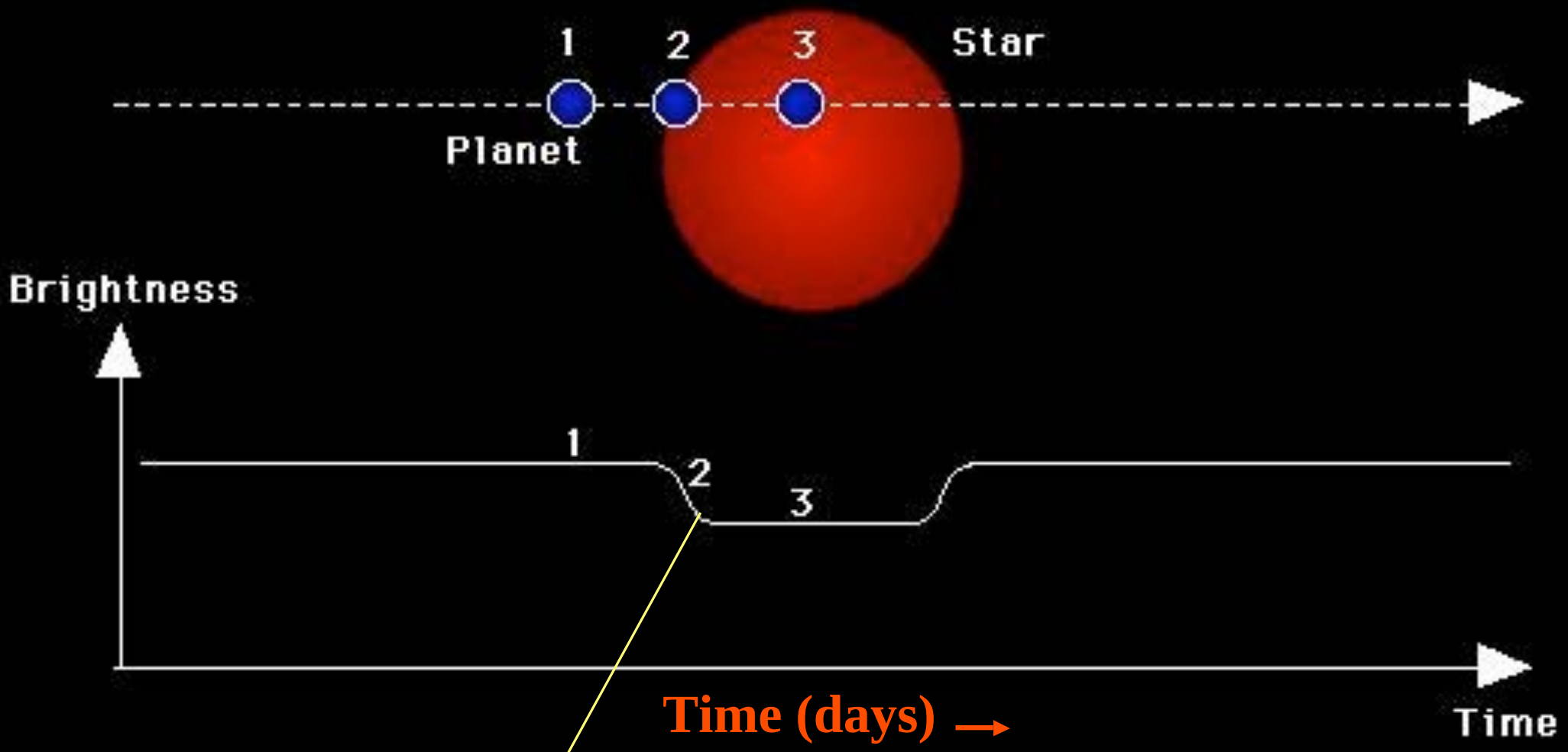
Giants => Composed of H, He (like Jupiter)
Evaporation of outer H in atmosphere

Earth-like planets, moons ?

Transits:

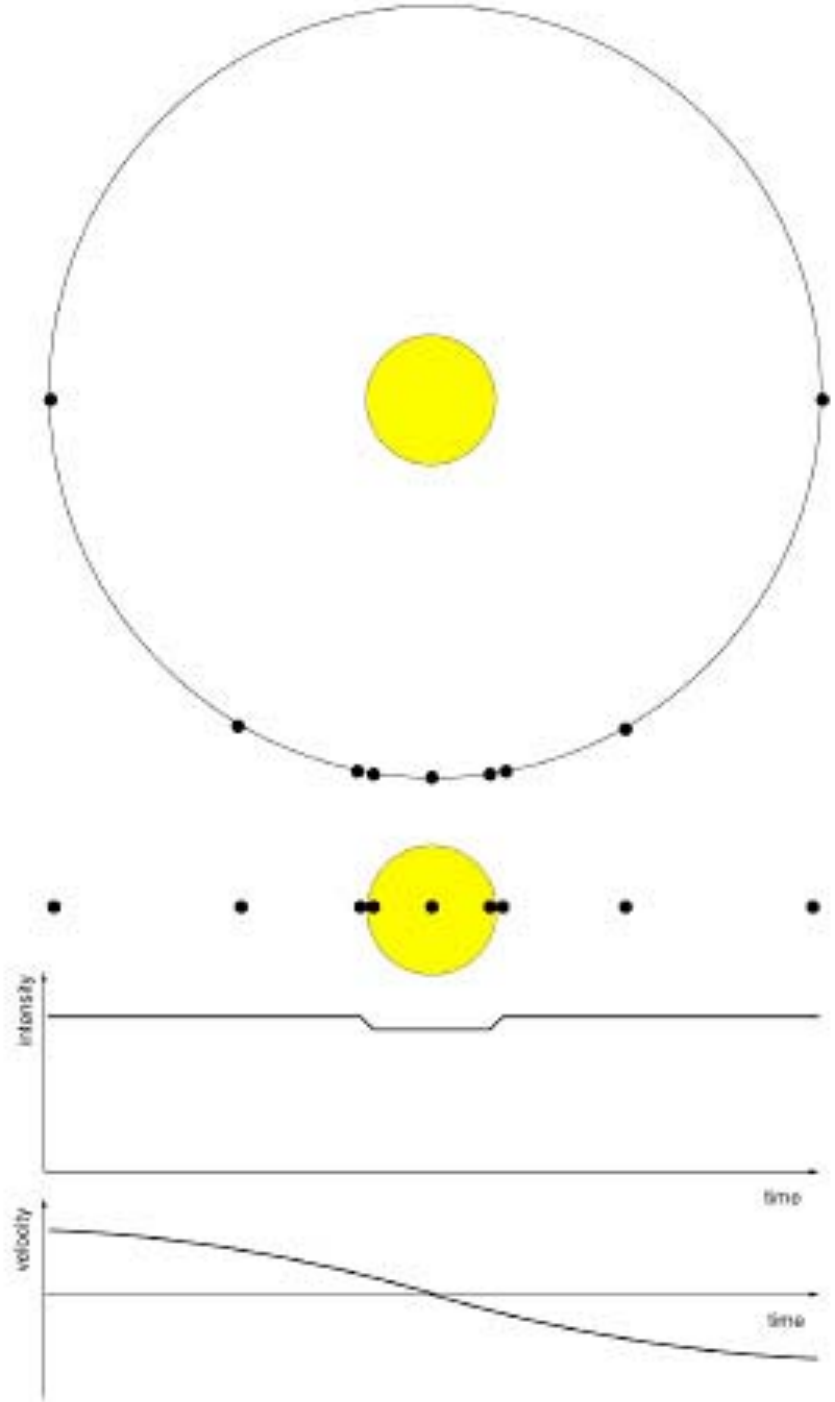


Transits:



Time (days) →

Transit decreases light of star



A Transiting Exoplanet - Stellar Brightness and Velocity

ESO PR Photo 10c/03 (22 April 2003)

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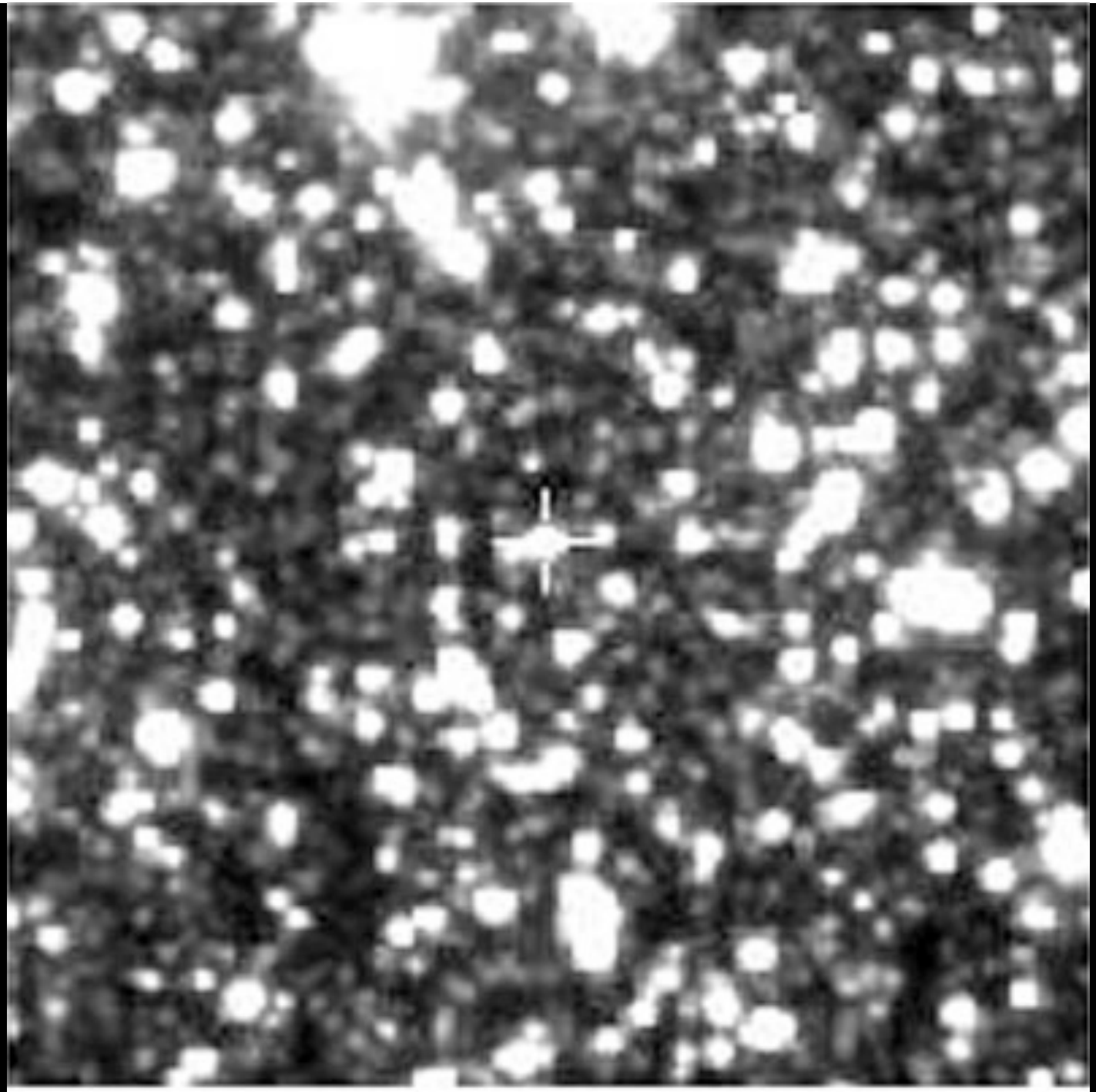
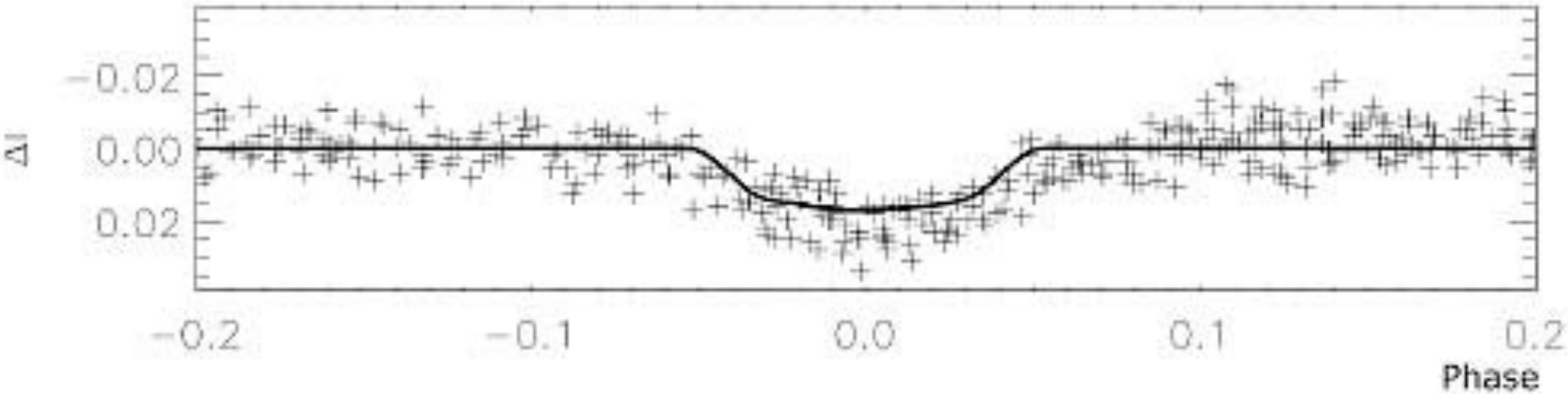
First planet Discovered Using the Transit method



The Galactic Star OGLE-TR-3
(OGLE Project)

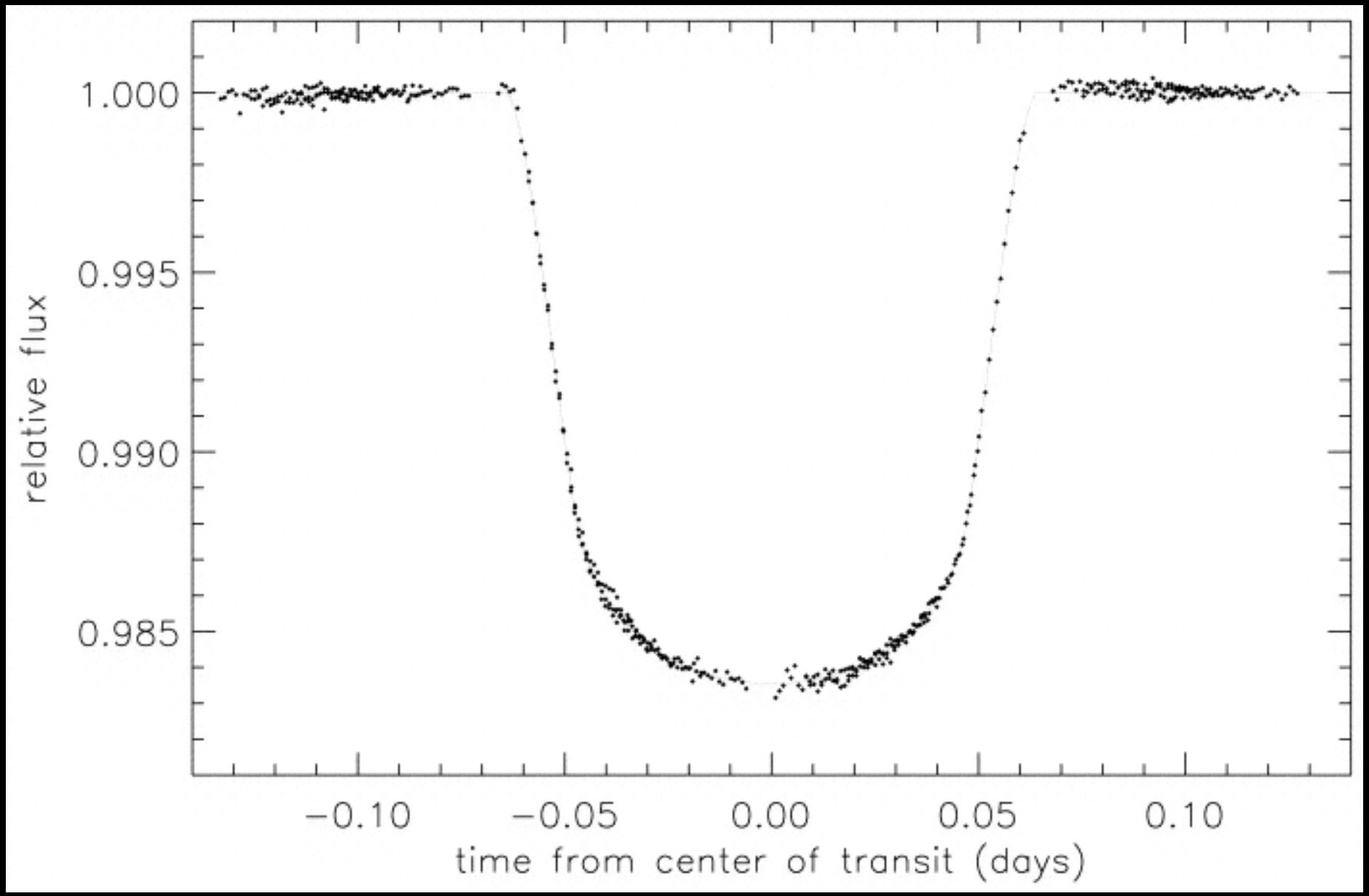


Brightness Dip Due to Planetary Transit at OGLE-TR-3
(OGLE Project)

ESO PR Photo 10e/03 (22 April 2003)

© European Southern Observatory

Transit of HD209458b (HST)

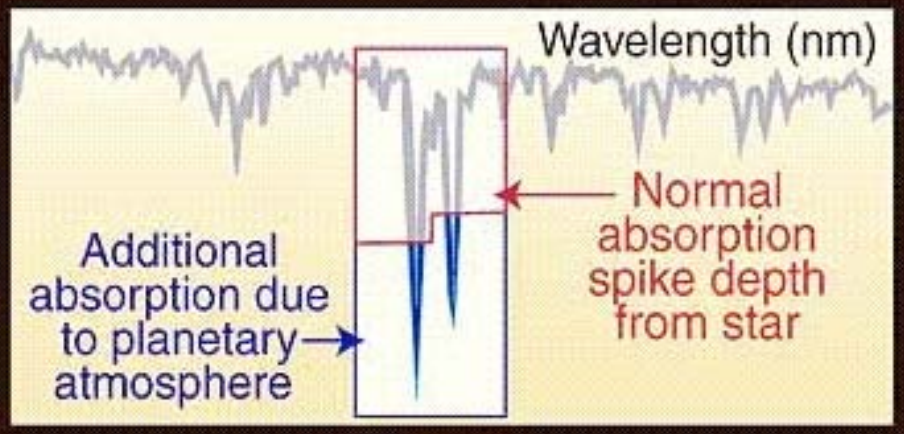


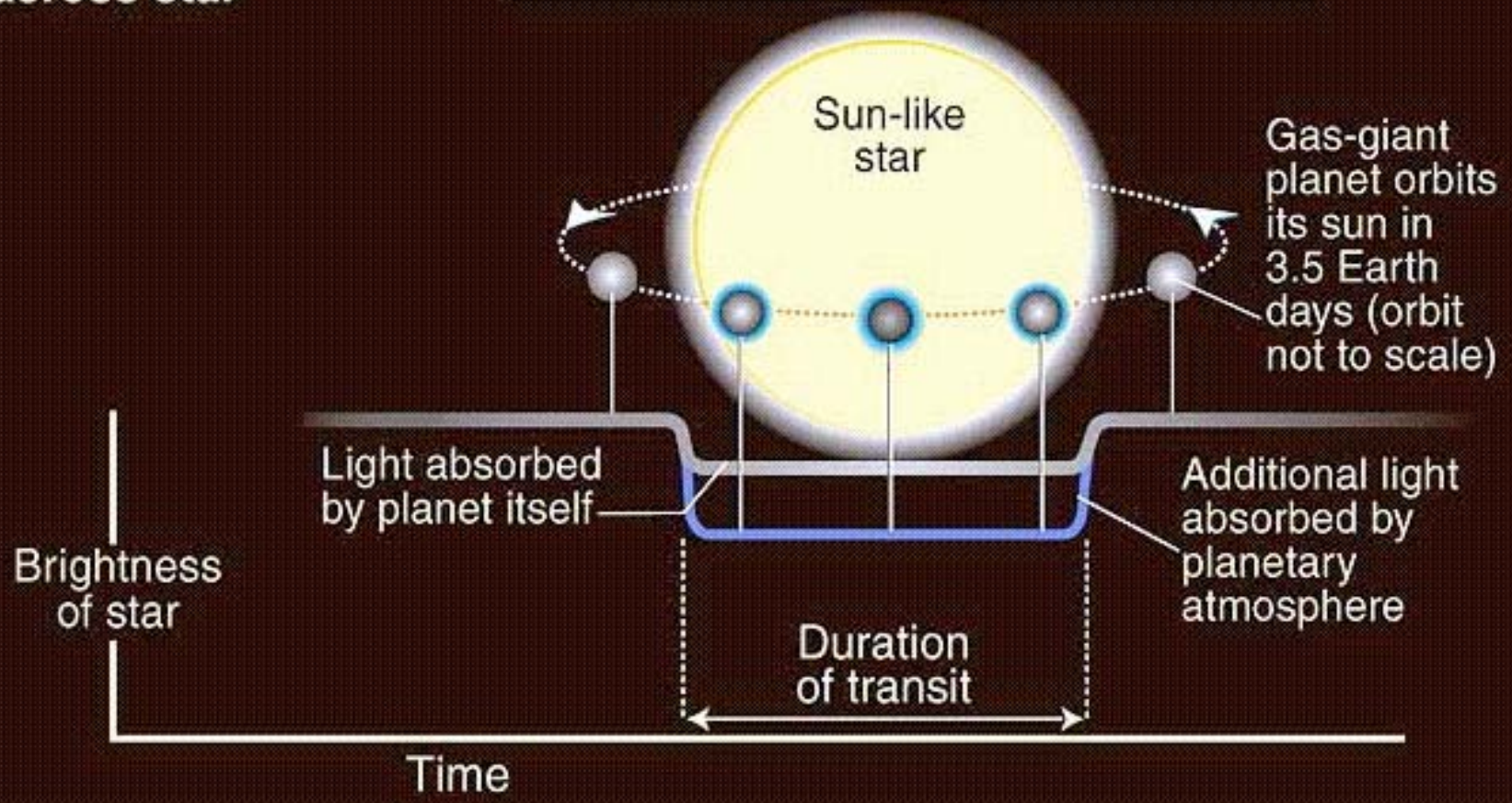
UV absorption:

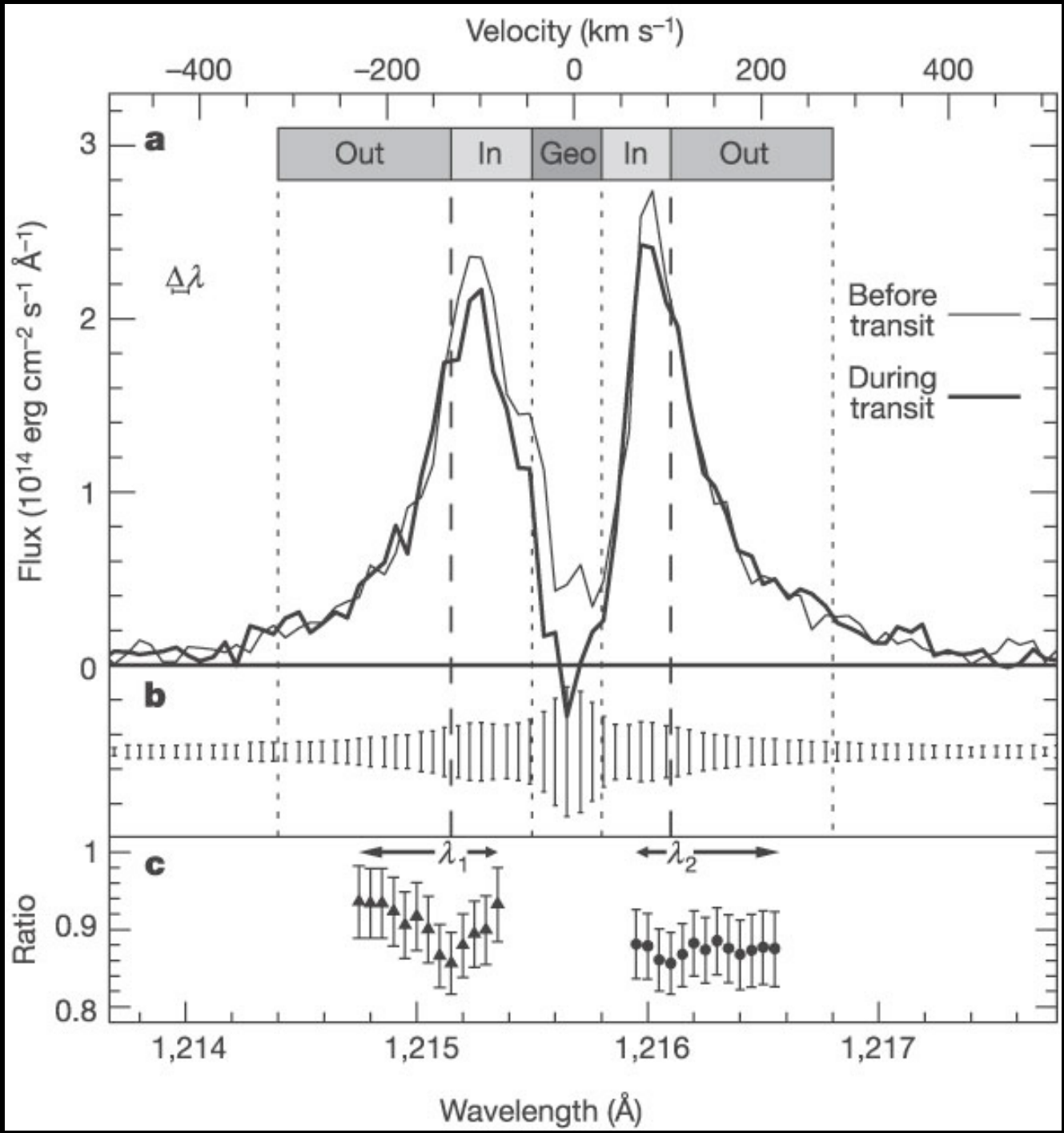
Escaping H and Na Detected towards HD209458

Recently, C and O Have been detected - escaping atmosphere!

HST detects additional sodium absorption due to light passing through planetary atmosphere as planet transits across star

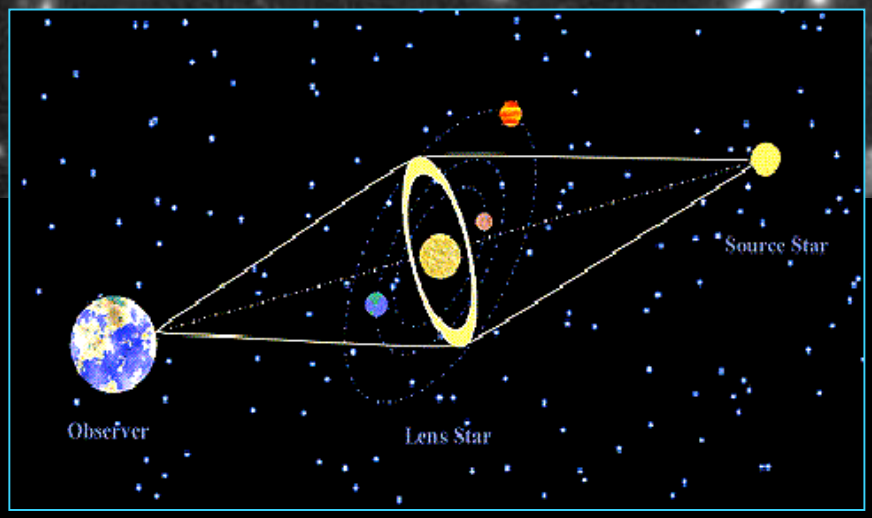





Velocity (km s⁻¹)
−400
−200
0
200
400
a
Out
In
Geo
In
Out
Δλ
Before transit
During transit
Flux (10¹⁴ erg cm⁻² s⁻¹ Å⁻¹)
3
2
1
0
b
c
λ1
λ2
Ratio
1
0.9
0.8
1,214
1,215
1,216
1,217
Wavelength (Å)

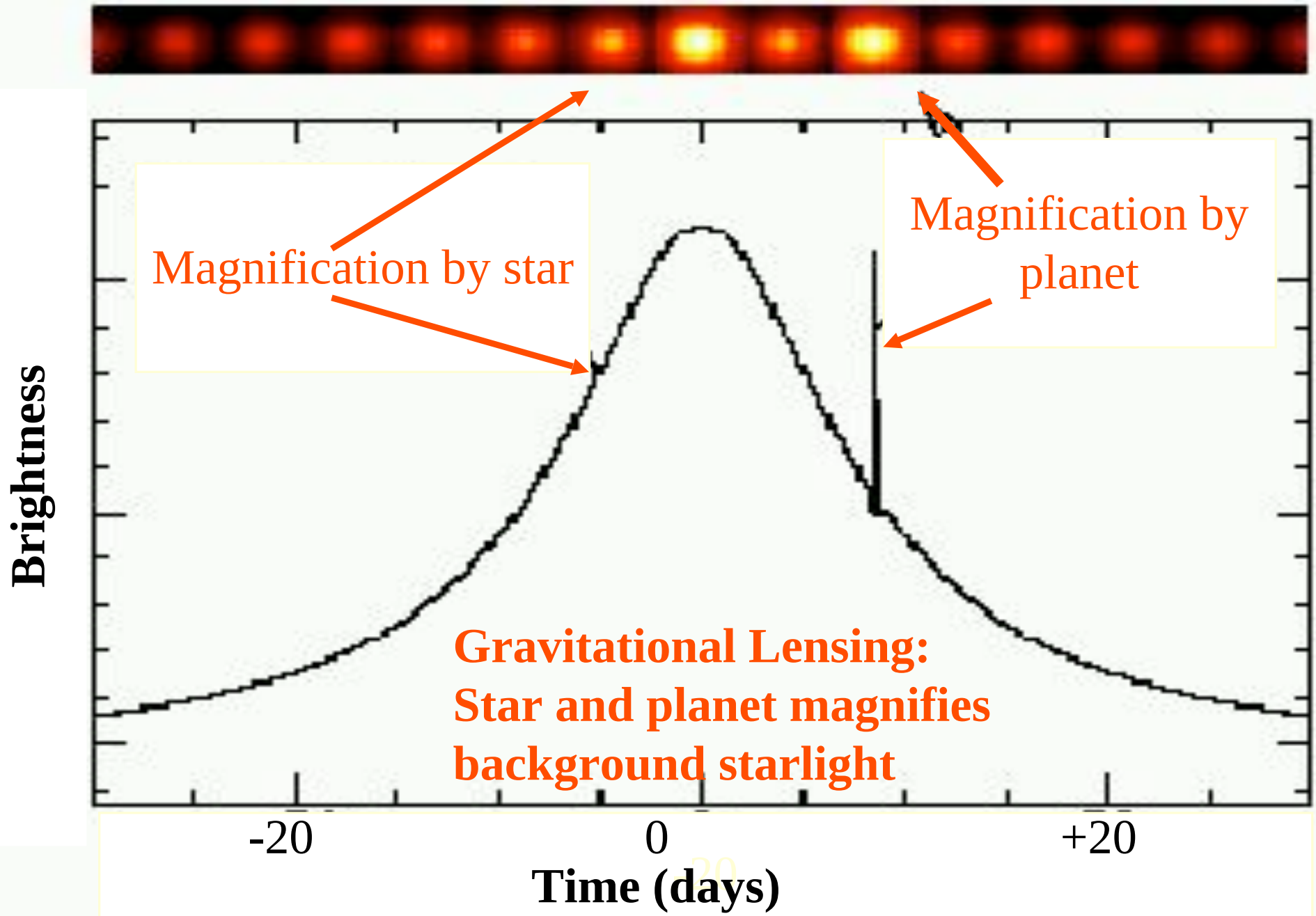
Gravitational Lensing:

A cluster of galaxies `lensing' more distant objects …

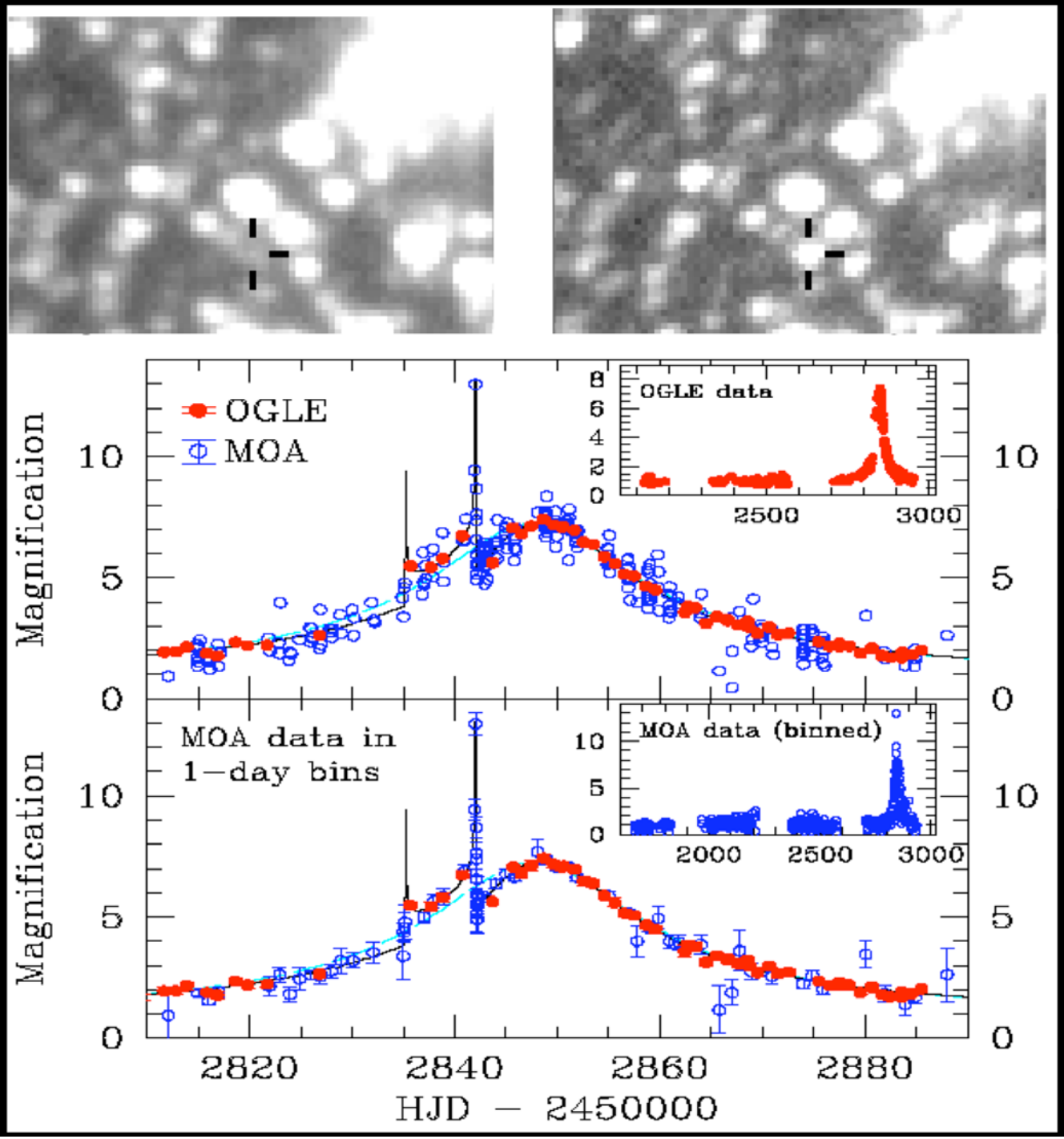


A star & its planets magnifying a more distant star

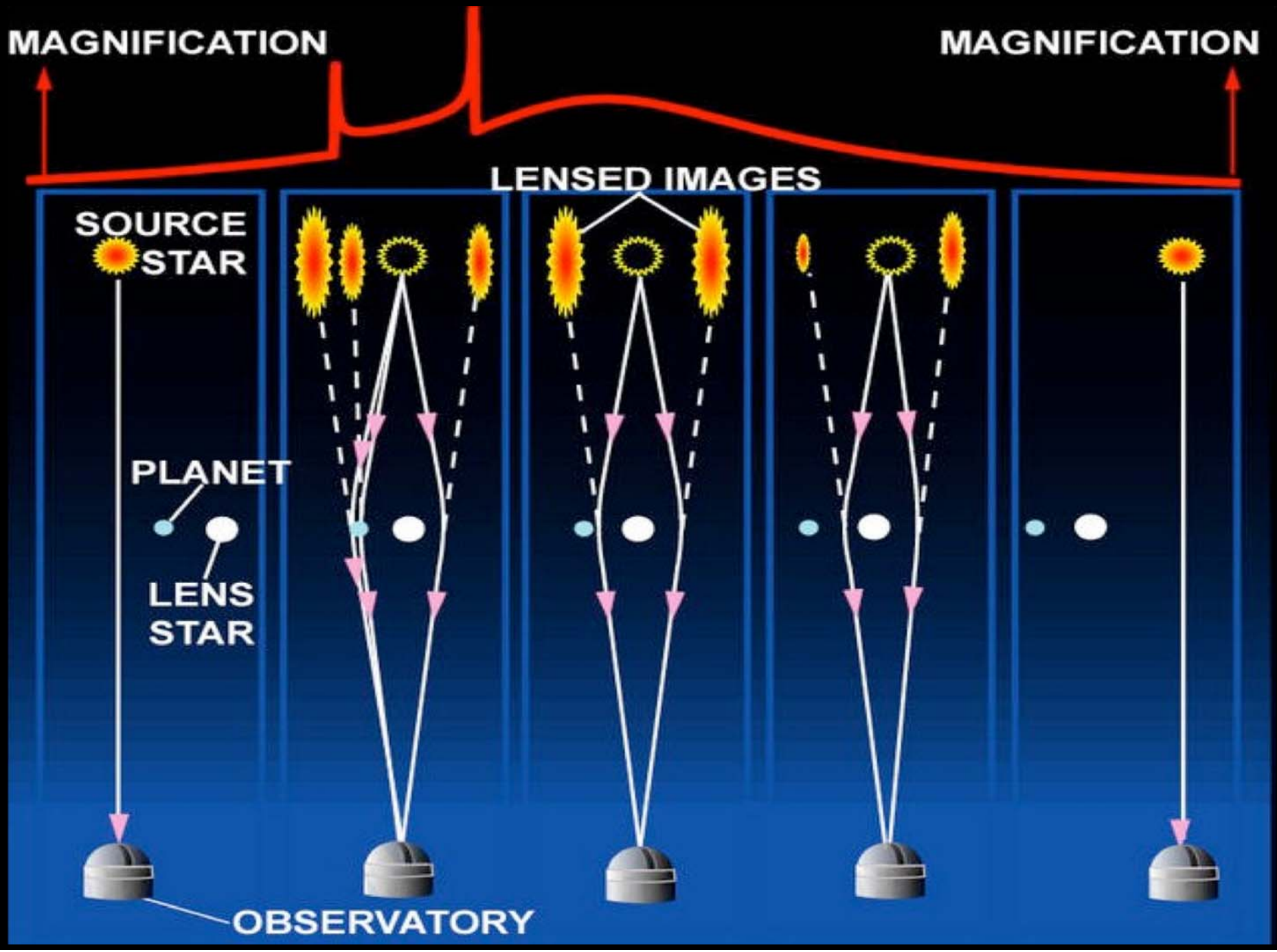
Gravitational Lensing:



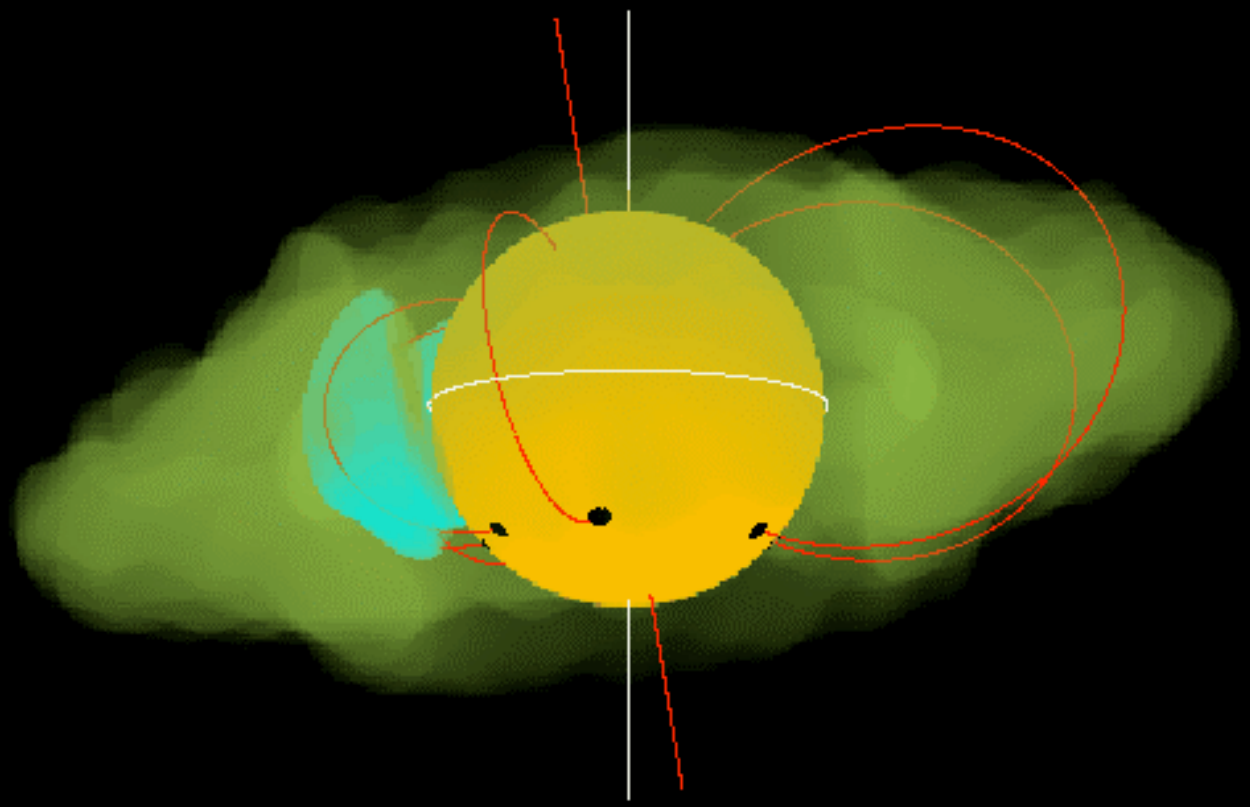
Gravitational Lensing: OGLE 2003-BLG0253



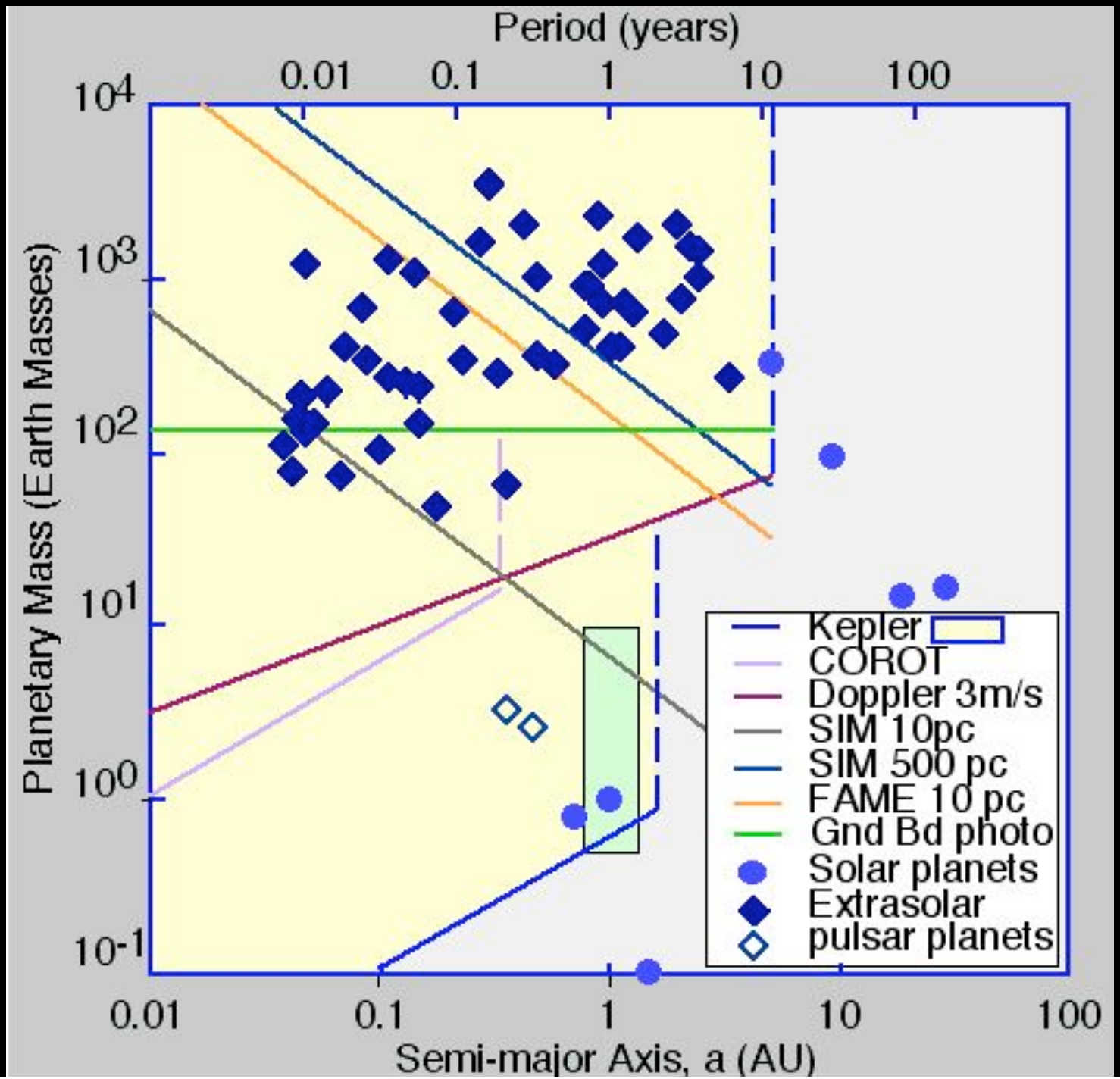
Gravitational Lensing:



Radio emission: Jupiters



Exo-planet detection methods



Methods for direct detection and characterization of exo-planets :

Direct imaging with a coronagraph:

UV, visual, near IR

Mask light of star
control scattered light, diffraction
Large filled-aperture telescope

Interferometry

IR, radio

Link several telescope
pre-detection/post-detection

Ground vs. Space:

Ground:

- 10 – 100 meter vis/NIR
- Extreme adaptive optics to correct turbulent images
- radio interferometry (VLA, eVLA, SKA)

Space:

- 10 m + UV,VIS, NIR
- Interferometers

Future Projects for finding Planets:

Kepler: transits (2008+)

Atacama Large Millimeter Array (ALMA): 2010+

- **mm interferometer:**

  direct detection of young gas giants

Next Generation Space Telescope

James Webb Space Telescope (JWST):

- **direct imaging of forming gas giants?**

Space Interferometry Mission (SIM):

- **Astrometry ("defered")**

Terrestrial Planet Finder (TPF): ("defered")

- **Coronagraph**
- **IR interferometer**
- **Star Shade (Web Cash et al.)**

Terrestrial Planet Imager (TPI): (?)

ALMA (Atacama Large Millimeter Array)

Panoramic View of the Proposed Site for ALMA at Chajnantor

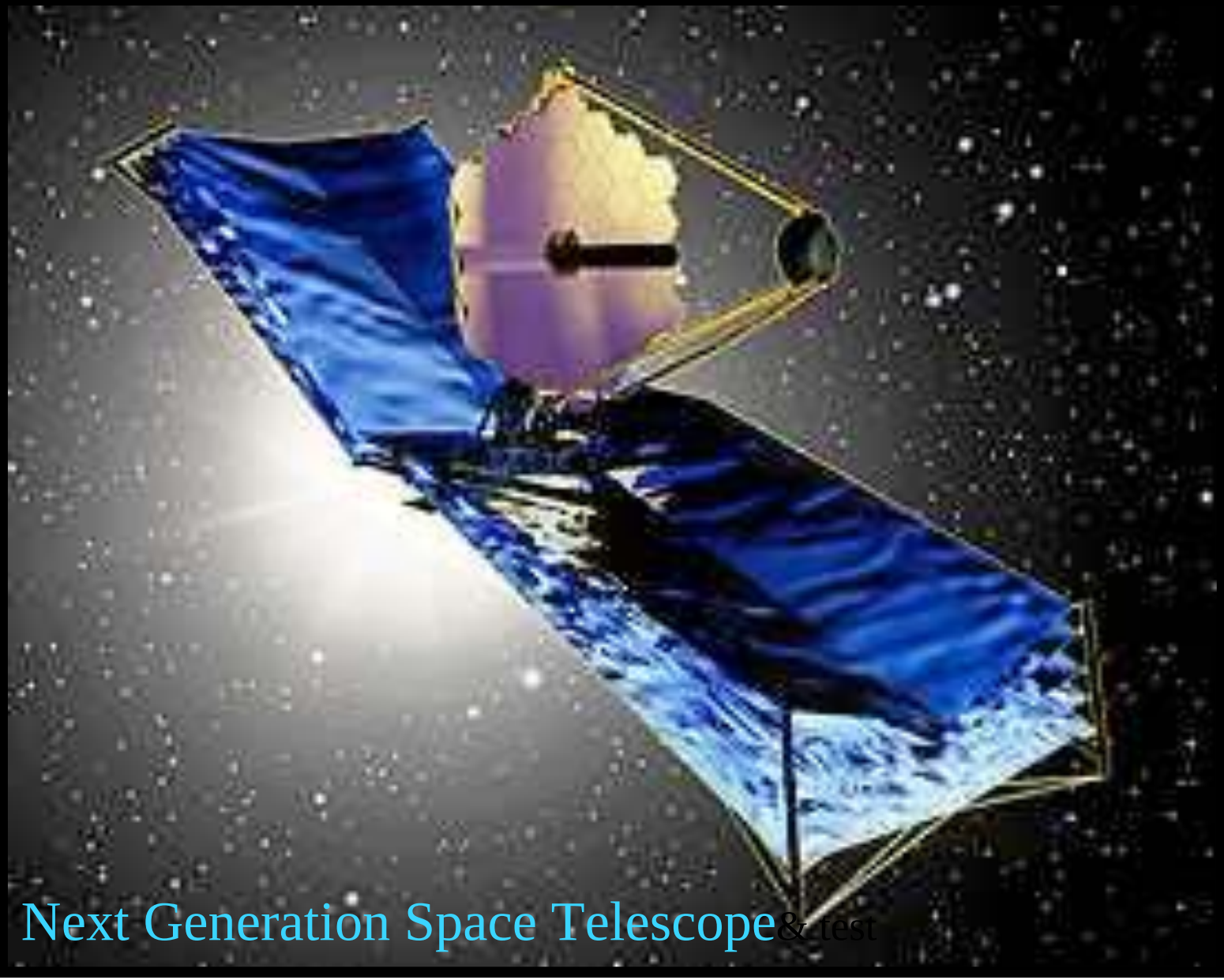
ESO PR Photo 24e/99 (8 June 1999)

© European Southern Observatory

- **Large next-generation space telescopes**

  (near-infrared & visual wavelength)

  block parent star's light



& test

Finding planets around other stars: (2010+)

-Space Interferometry Mission (SIM)

measure stellar `wobble'

- Terrestrial Planet Finder (TPF)

Direct detection of Earth-sized planets

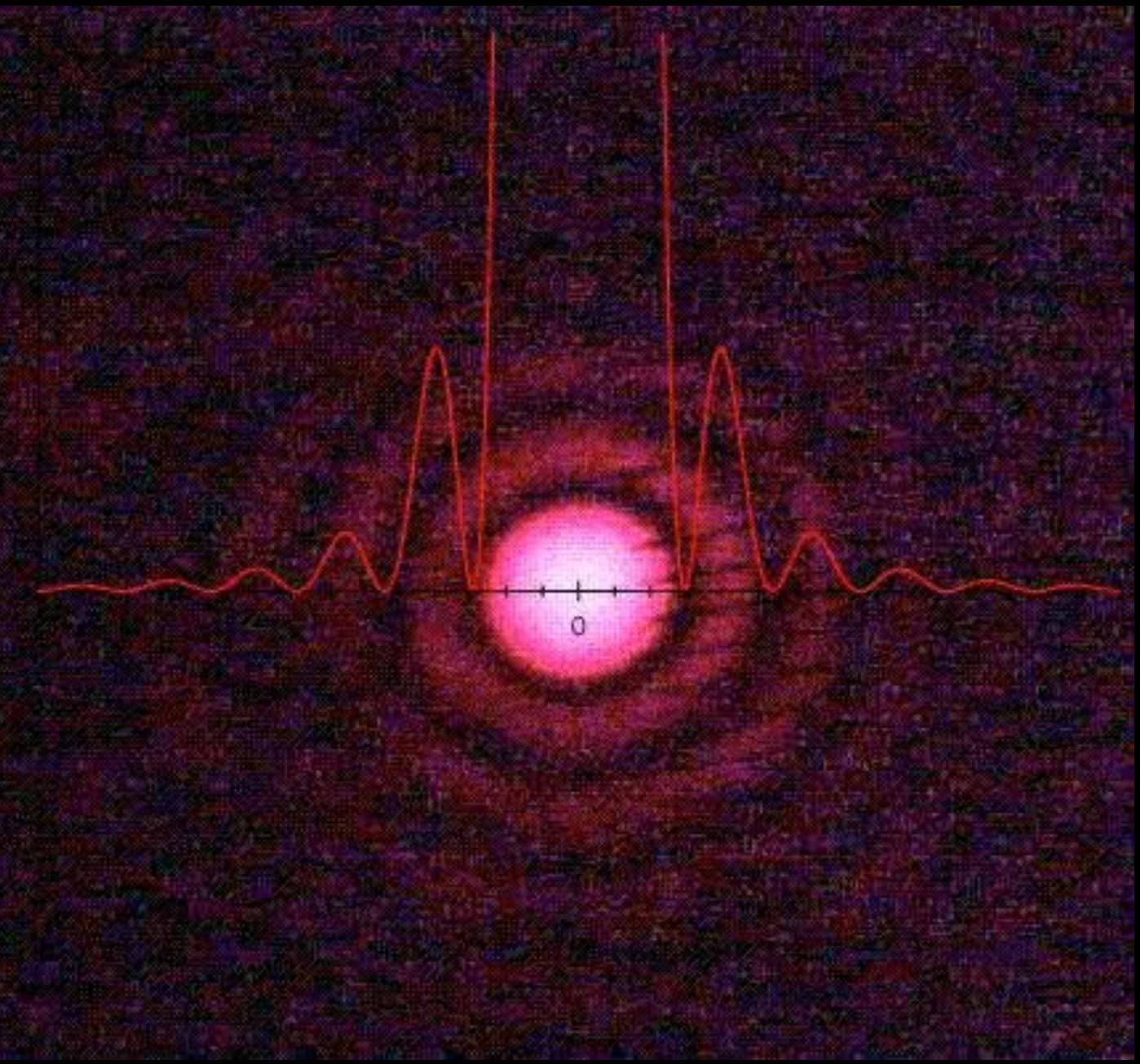
- Infrared `interferometer'

or

- visual `coronagraph'

Darwin interferometer

Diffraction pattern of a circular aperture



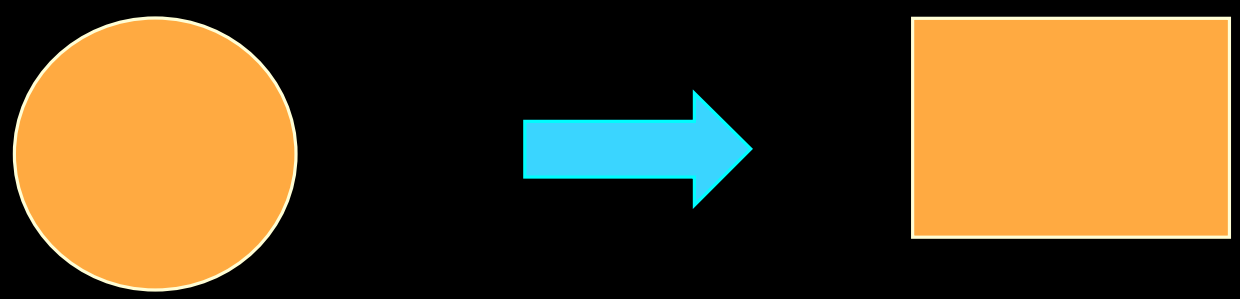
Shaped telescopes: $0.3 < \lambda < 3\ \mu m$

- Circular aperture diffracts light in all directions.

- Light is scattered perpendicular to edges.

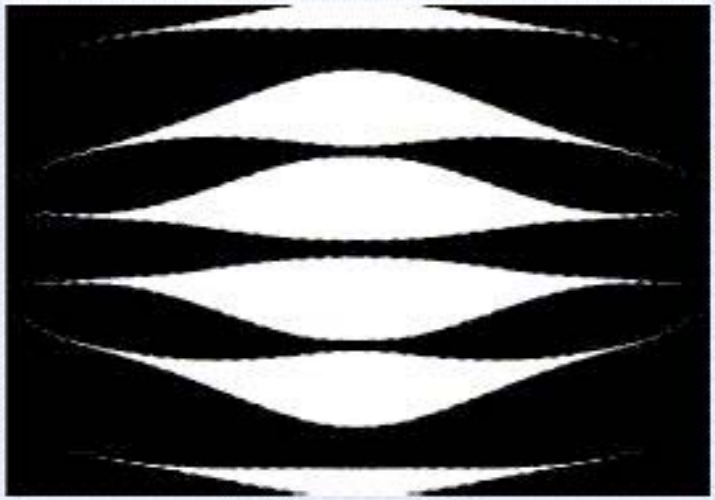
- Shaped aperture: Edges have limited orientations

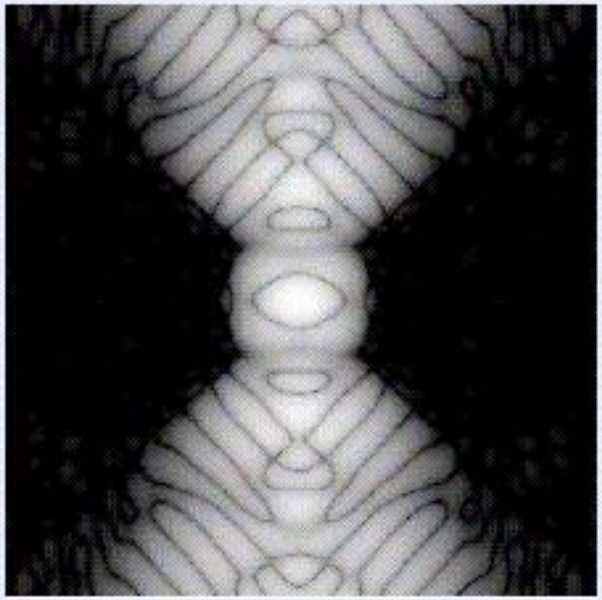
- Scatter light only into selected (unwanted) directions

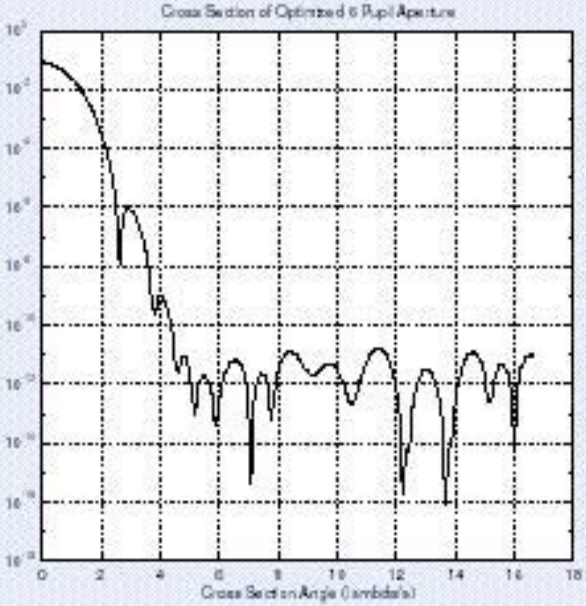


Diffraction patterns of shaped apertures

6-Pupil Rectangular

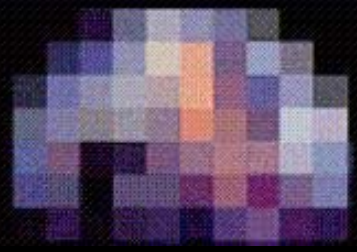






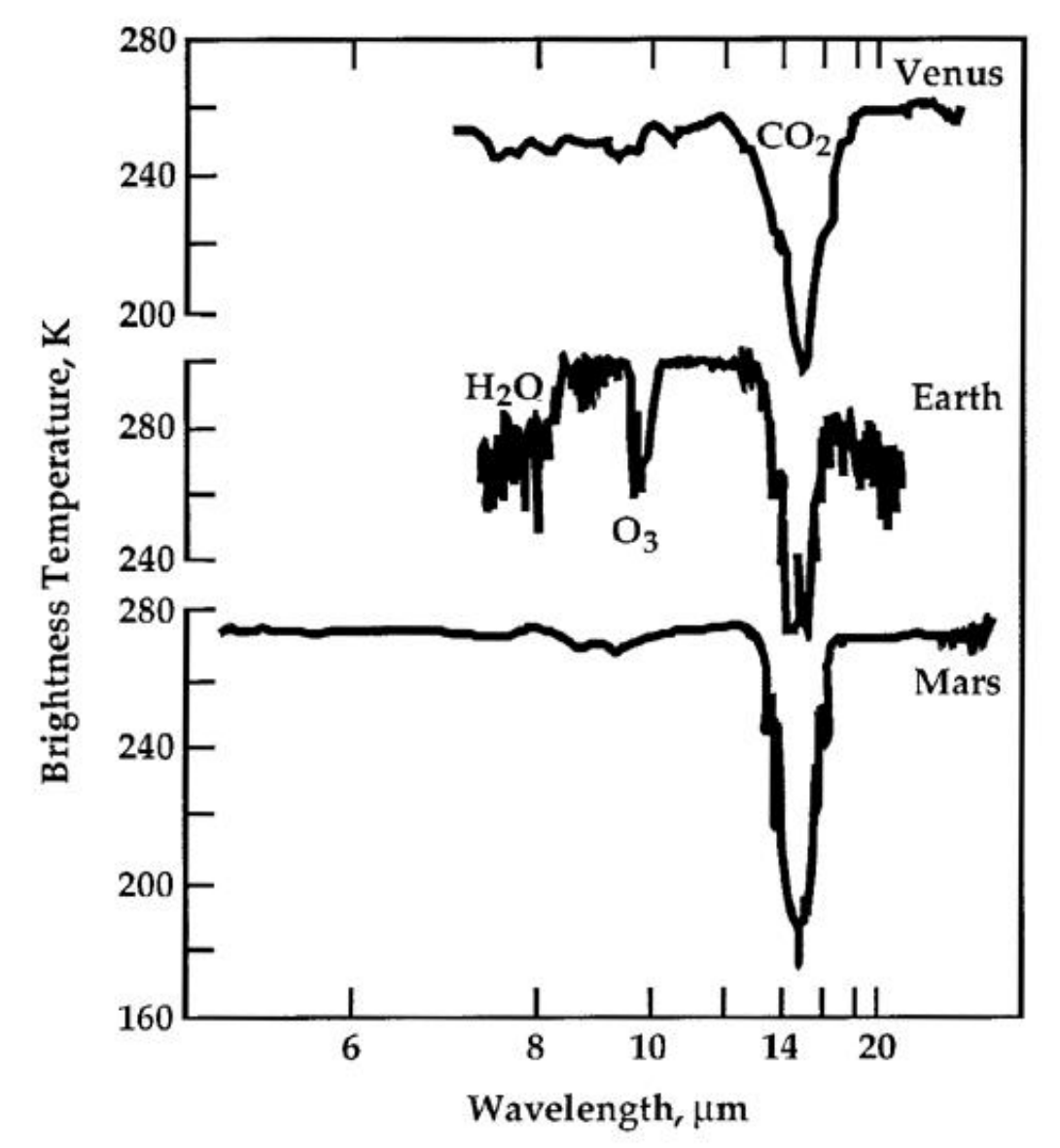
Earth as seen from 10 pc with various interferometers

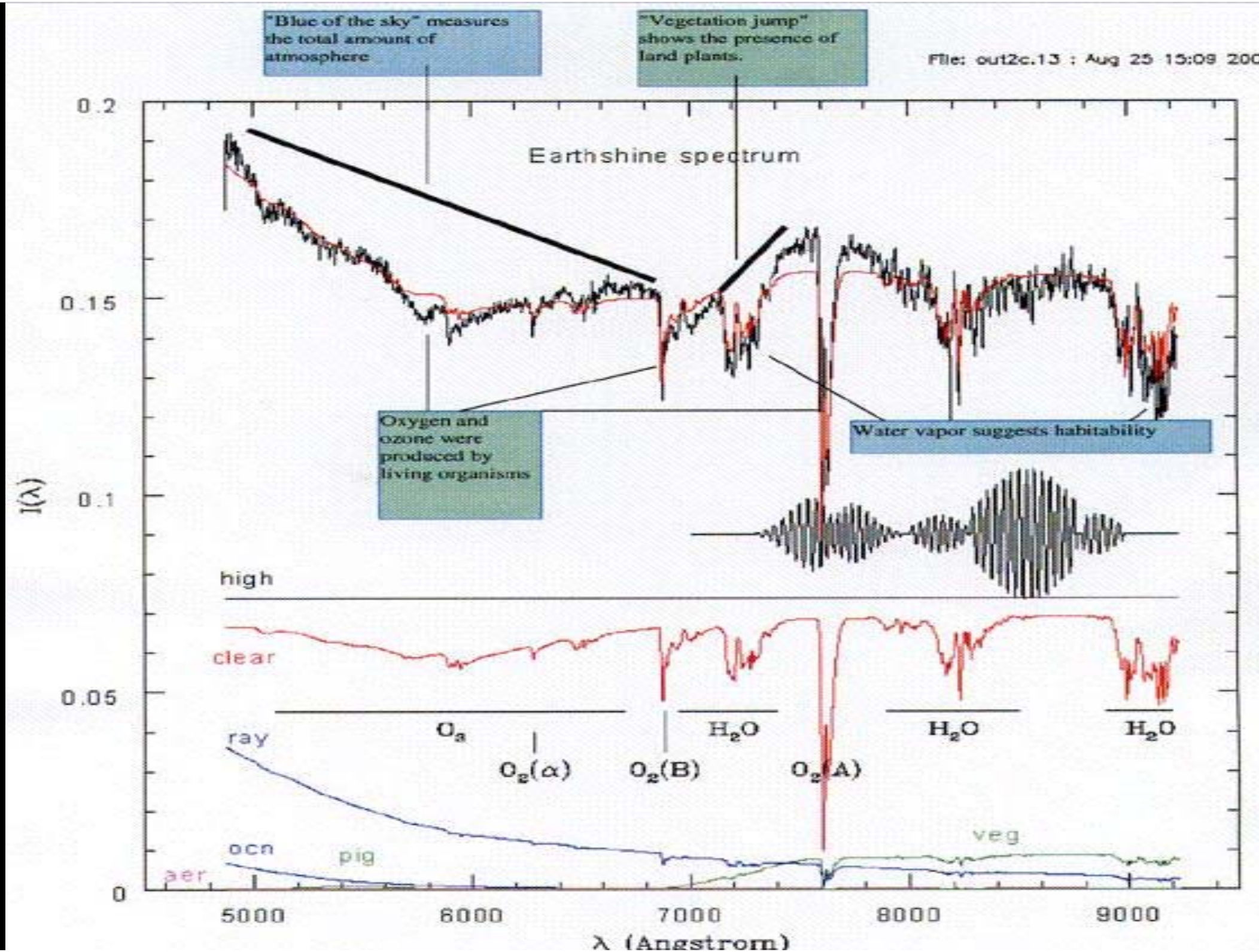
Pixel / Diameter	Pixel size @ planet (km)	Image	Interferometer Requirements		
				Collecting Area	Baseline
400	32		IR Visible	144 km² 1,296 km²	100,000 km 5,000 km
100	128		IR Visible	0.64 km² 5.76 km²	24,000 km 1,200 km

Pixel / Diameter	Pixel size @ planet (km)	Image	Interferometer Requirements		
				Collecting Area	Baseline
25	510		IR Visible	1,024 m² 9,216 m²	6,000 km 303 km
10	1275		IR Visible	64 m² 576 m²	2,4km 120 km

Biosignatures: Spectra of various planets

IR (Stratosphere) vs. visible (Ground)




"Blue of the sky" measures the total amount of atmosphere
"Vegetation jump" shows the presence of land plants.
File: out2c.13 : Aug 25 15:09 200
Earthshine spectrum
Oxygen and ozone were produced by living organisms
Water vapor suggests habitability
I(λ)
0.2
0.15
0.1
0.05
0
high
clear
ray
ocn
pig
aer
veg
O_3
$O_2(\alpha)$
$O_2(B)$
$O_2(A)$
H_2O
H_2O
H_2O
5000
6000
7000
8000
9000
λ (Angstrom)

The End