The gas inside the galaxy
&
the interstellar medium

Gas at large scales in spiral galaxies

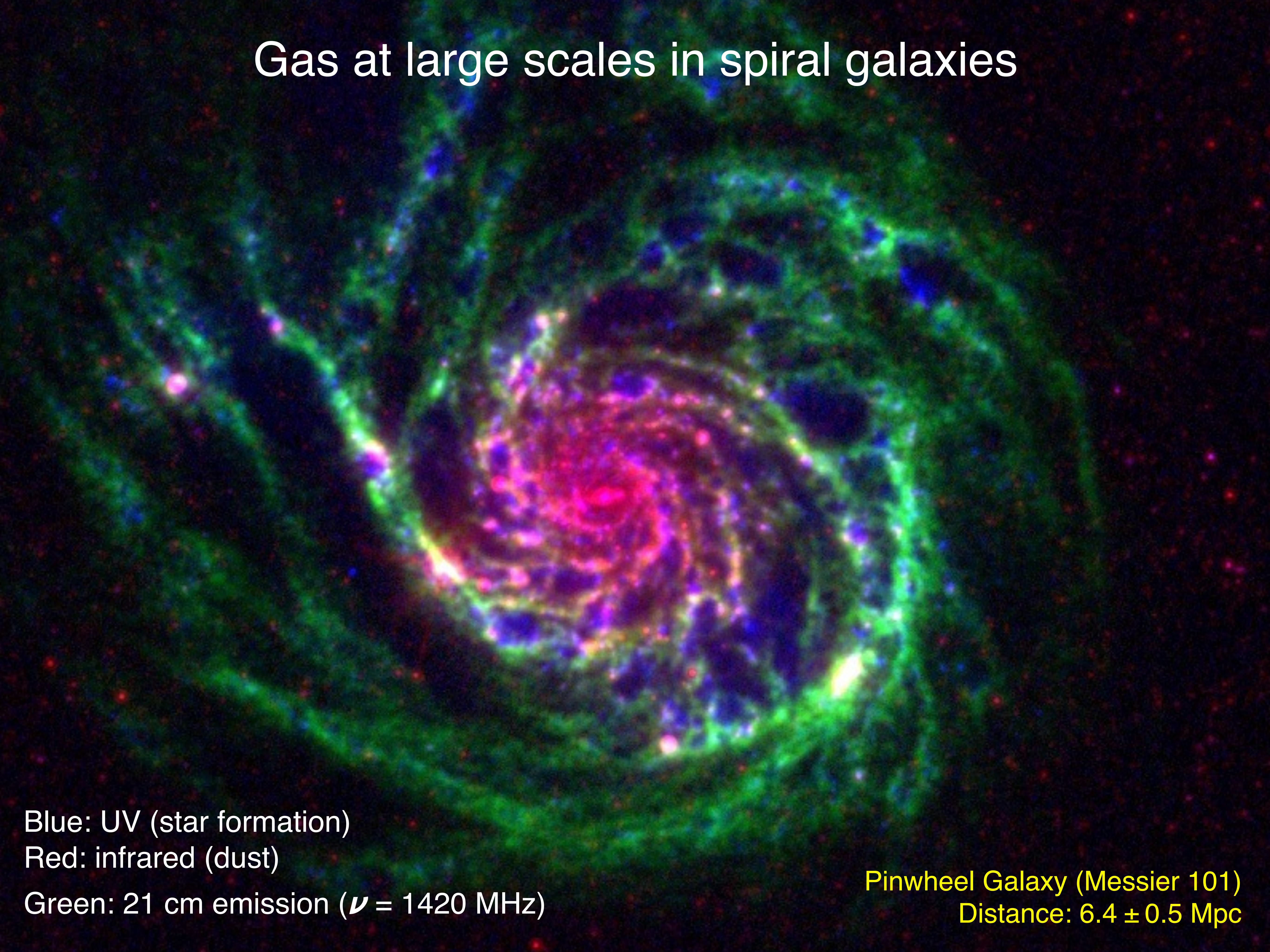
Pinwheel Galaxy (Messier 101)
Distance: 6.4 ± 0.5 Mpc

Gas at large scales in spiral galaxies

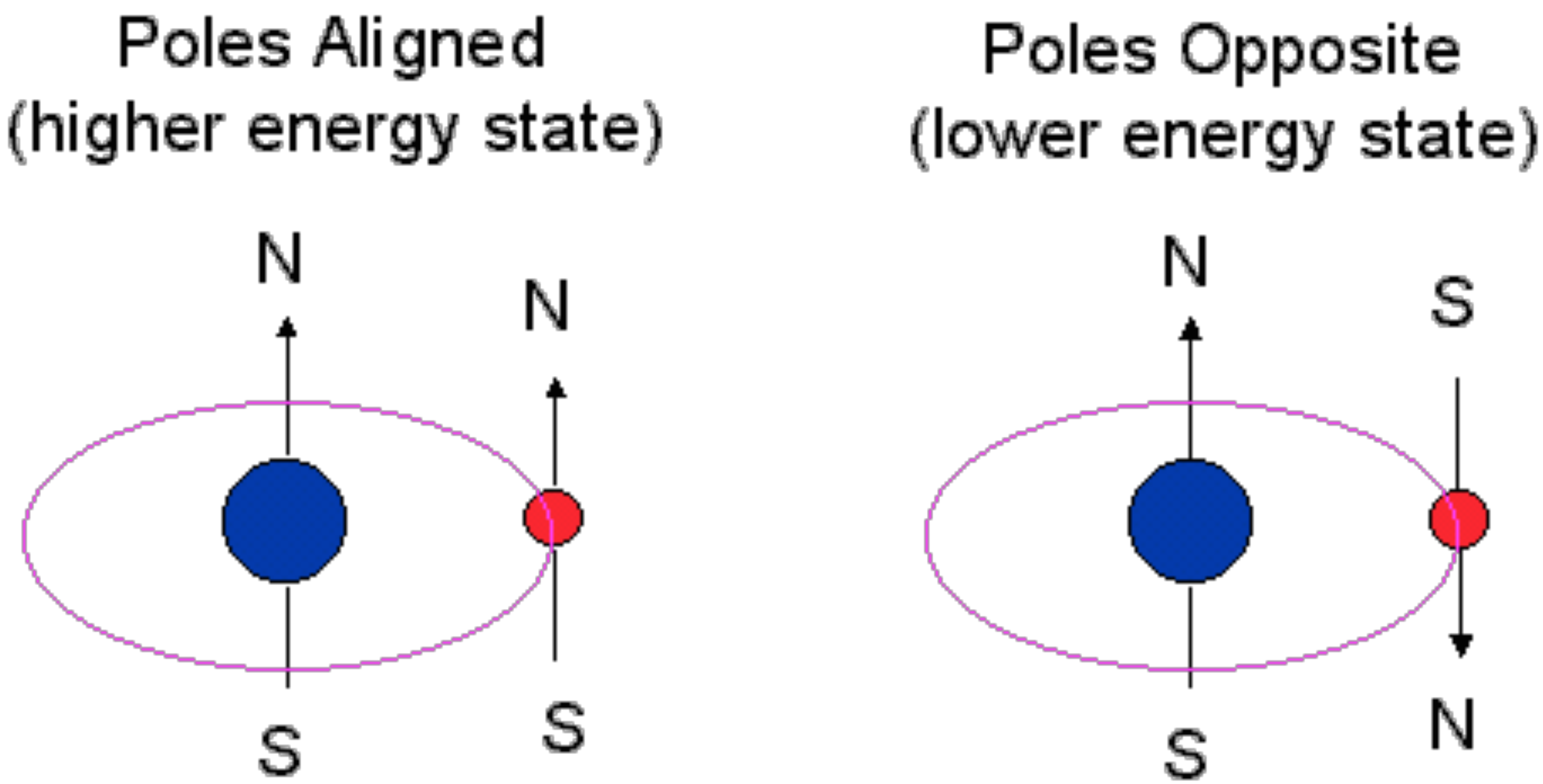
Infrared + visible + X-ray

Pinwheel Galaxy (Messier 101)
Distance: 6.4 ± 0.5 Mpc

Gas at large scales in spiral galaxies



Radio detection: 21-cm emission from neutral hydrogen gas



A 21-cm photon is emitted when poles go from being aligned to opposite (a spin flip)

Highly forbidden transition (**probability:** 2.9×10^{-15} s^{-1} = one transition every 10 million years)

BUT: galaxies are big and have a lot of hydrogen!

Dense gas clouds

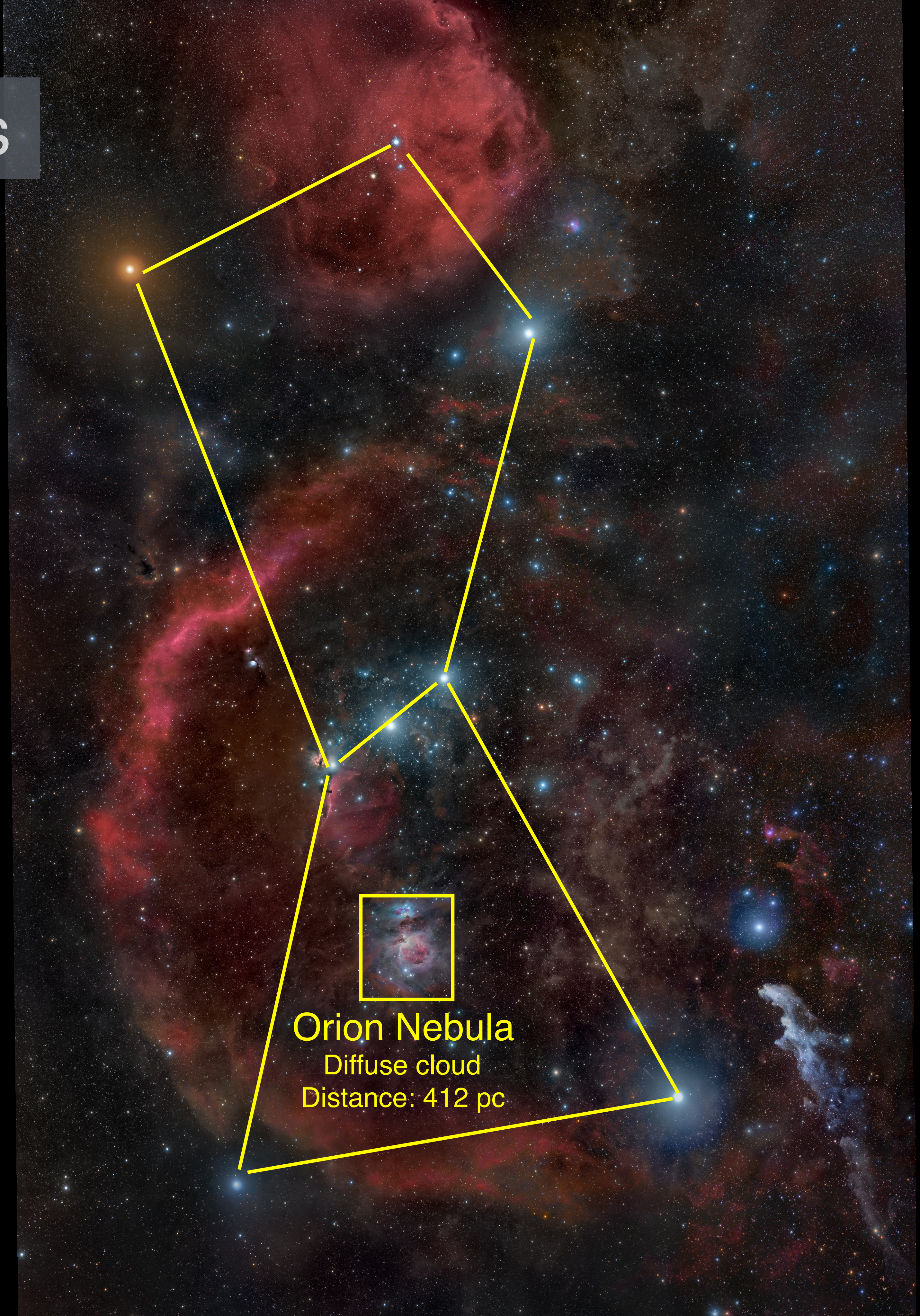
Dense cloud
“Black Cloud” B68
Distance: 160 pc
Diameter: ~ 0.2 pc

H II regions: ionised hydrogen in star forming regions

Inside dense clouds

Giant molecular clouds

Orion Giant Molecular Cloud
Average distance: 400 pc
Size: ~ 100 pc



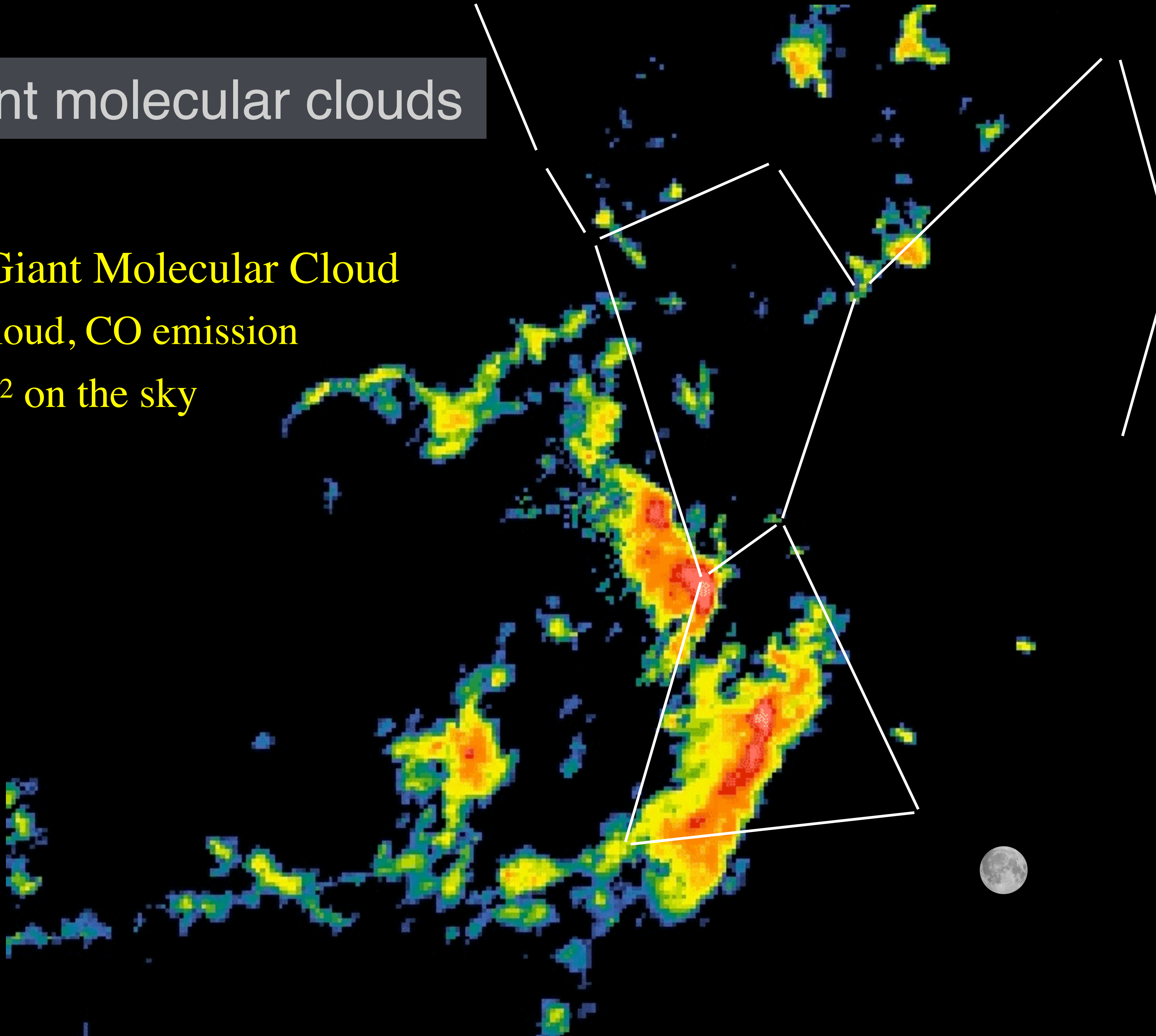
Orion Constellation

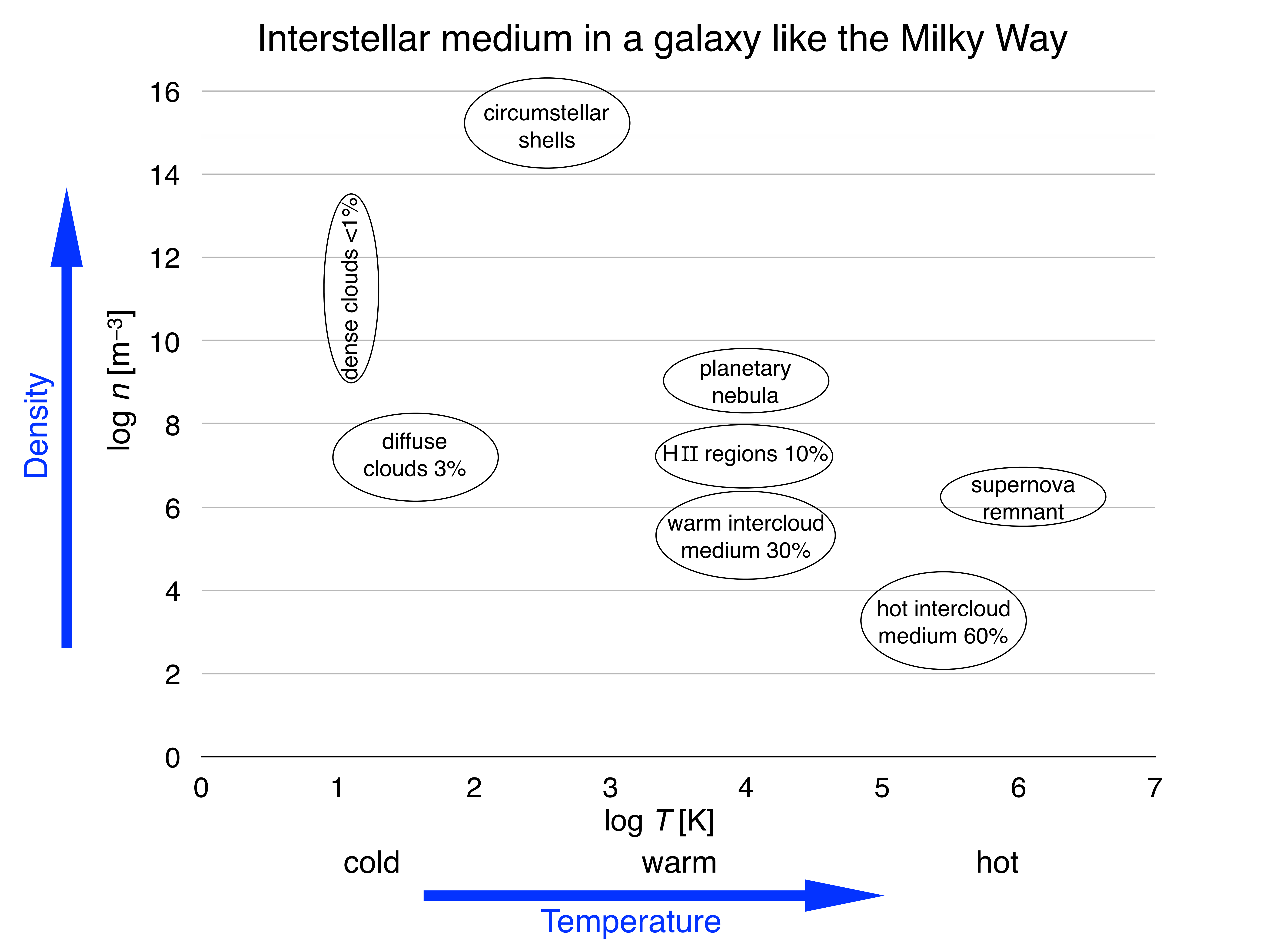
Giant molecular clouds

Orion Giant Molecular Cloud

Dense cloud, CO emission

432 deg^2 on the sky




Interstellar medium in a galaxy like the Milky Way
16
14
12
10
8
6
4
2
0
log n [m−3]
Density
circumstellar shells
dense clouds <1%
planetary nebula
diffuse clouds 3%
H II regions 10%
supernova remnant
warm intercloud medium 30%
hot intercloud medium 60%
0
1
2
3
4
5
6
7
log T [K]
cold
warm
hot
Temperature

Interstellar medium in a galaxy like the Milky Way

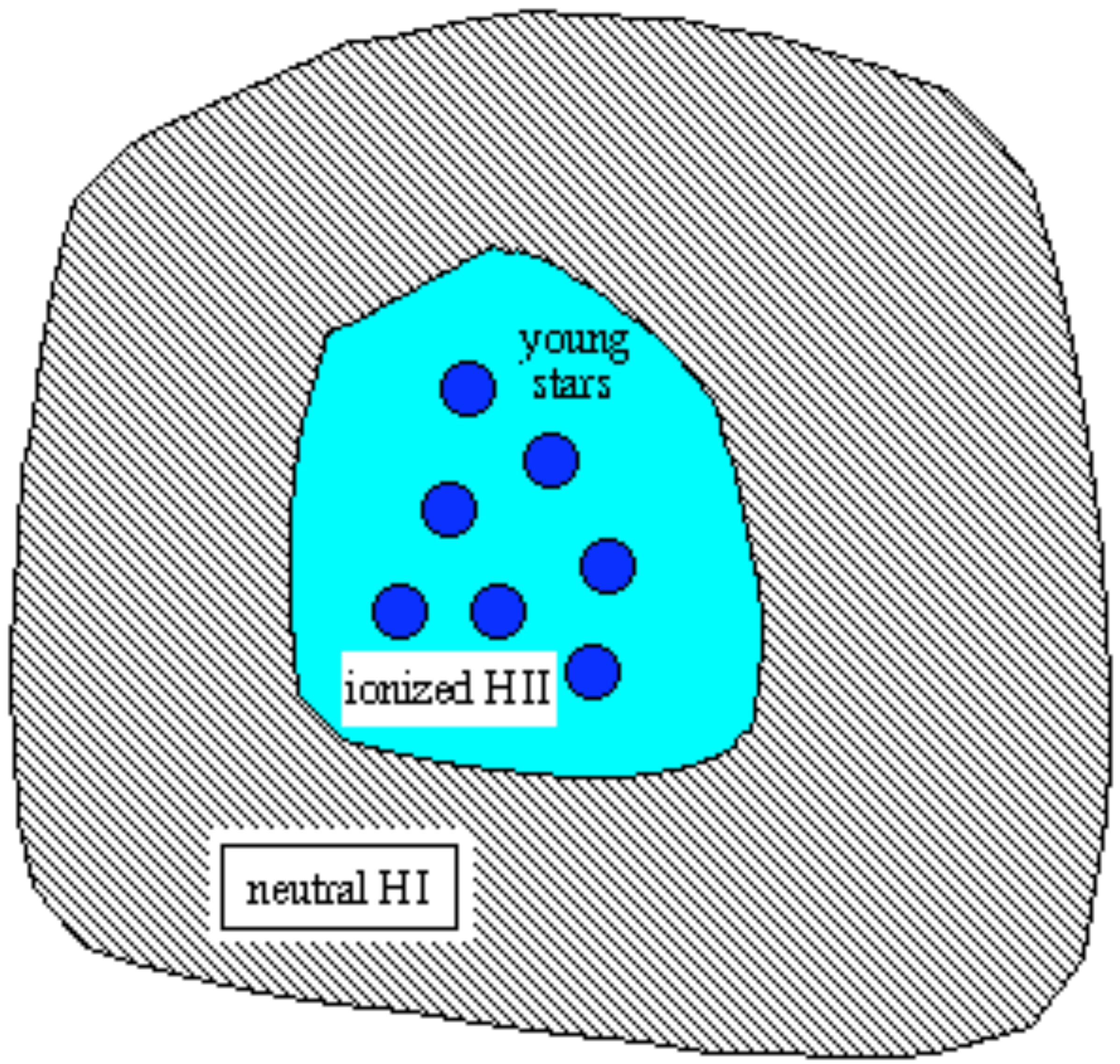
Dominating in terms of volume

Type of region	Fraction ISM (% by volume)	Fraction ISM (% by mass)	Typical size (pc)	Typical mass ($M_\odot$)	Form of hydrogen	Abundance of molecules
Hot intercloud medium	~60	≤0.1	–	–	H^+	very low
Warm intercloud medium	~30	~20	–	–	H^+ or H	very low
Diffuse clouds	~3	~30	3 – 100	1 – 100	H or H_2	CO
Dense clouds	≤1	~45	0.1 – 20	1 – 10^4	H_2	HCN, OH, CS, CO
HII regions	~10	~1	1 – 20	10 – 10^4	H^+	very low

Dominating in terms of mass

Regions of star formation (H II regions)

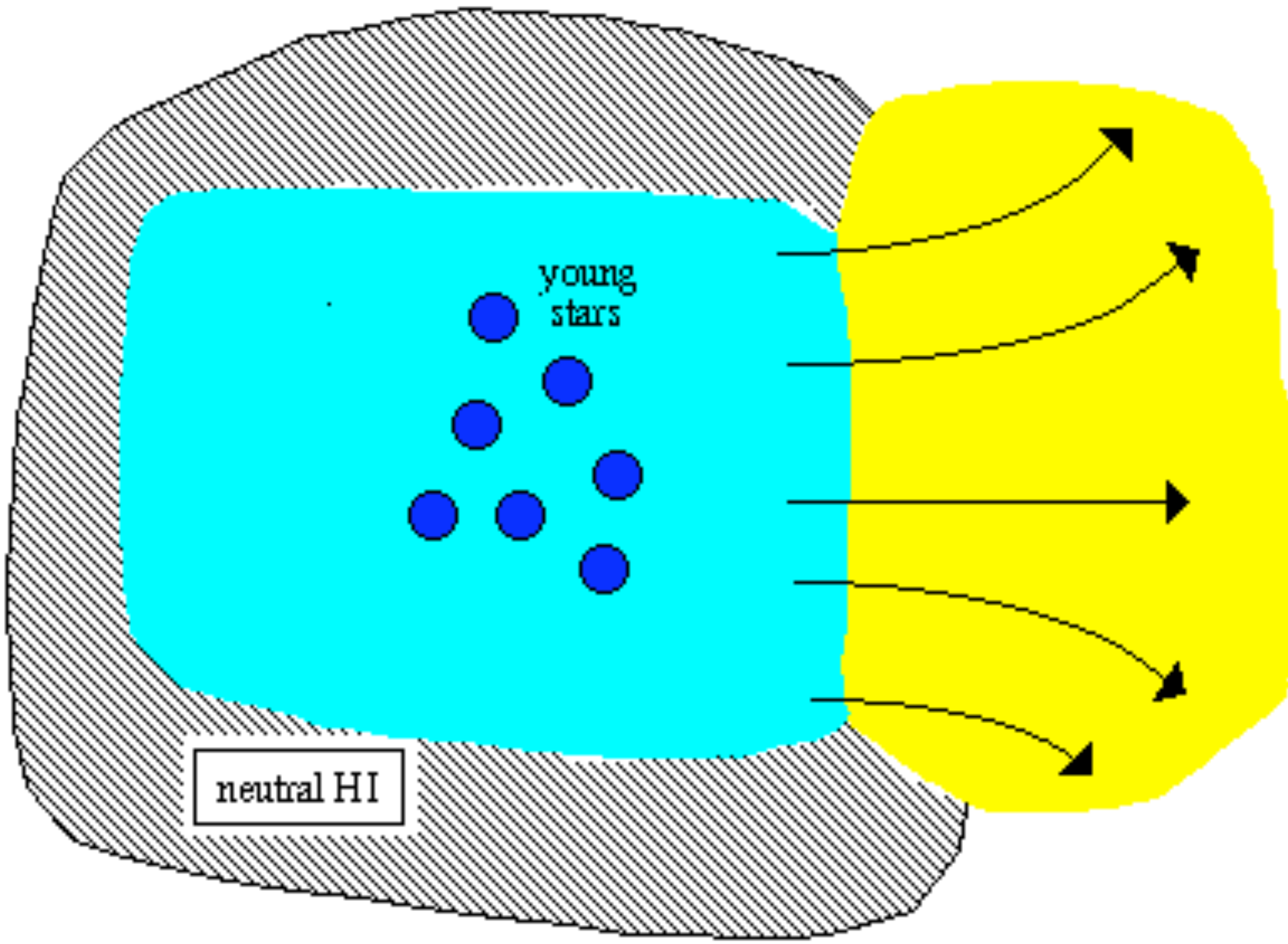
Young stars will heat and ionize a region inside the molecular cloud where they are born.



Ionised hydrogen in a star-forming region (H II region)

Regions of star formation (H II regions)

As the heated region grows, it will eventual breakthrough the clouds exterior to become a visible HII region.



Jeans mass: critical mass for gravitational contraction

If mass of gas cloud higher than Jeans Mass $\Longrightarrow$ gravitational collapse

Jeans mass → $$M_J = \frac{P^{3/2}}{G^{3/2}\rho^2}$$ (ρ: mass density)

Gas pressure → $$P = nkT$$

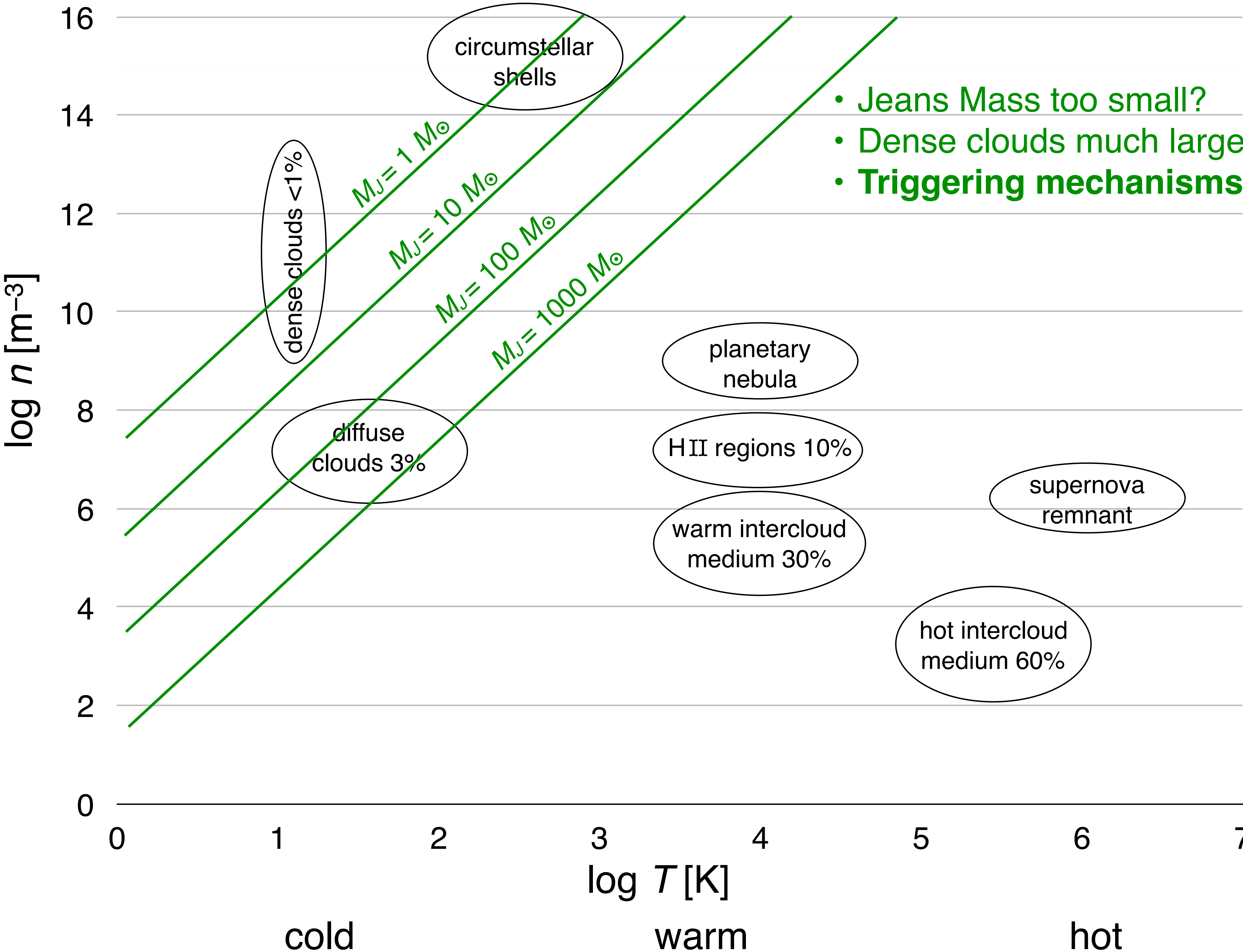
Number density → $$n = \frac{\rho}{m}$$ (m: mass of molecular hydrogen, close to average mass)

$$M_J = \left(\frac{kT}{mG}\right)^{3/2} \frac{1}{\rho^{1/2}}$$

$$M_{cloud} > M_J = \frac{9}{4}\frac{1}{\sqrt{2\pi n}}\frac{1}{m^2}\left(\frac{kT}{G}\right)^{3/2}$$

- In principle, dense clouds with few solar masses contracts
- In practice, more massive clouds are necessary

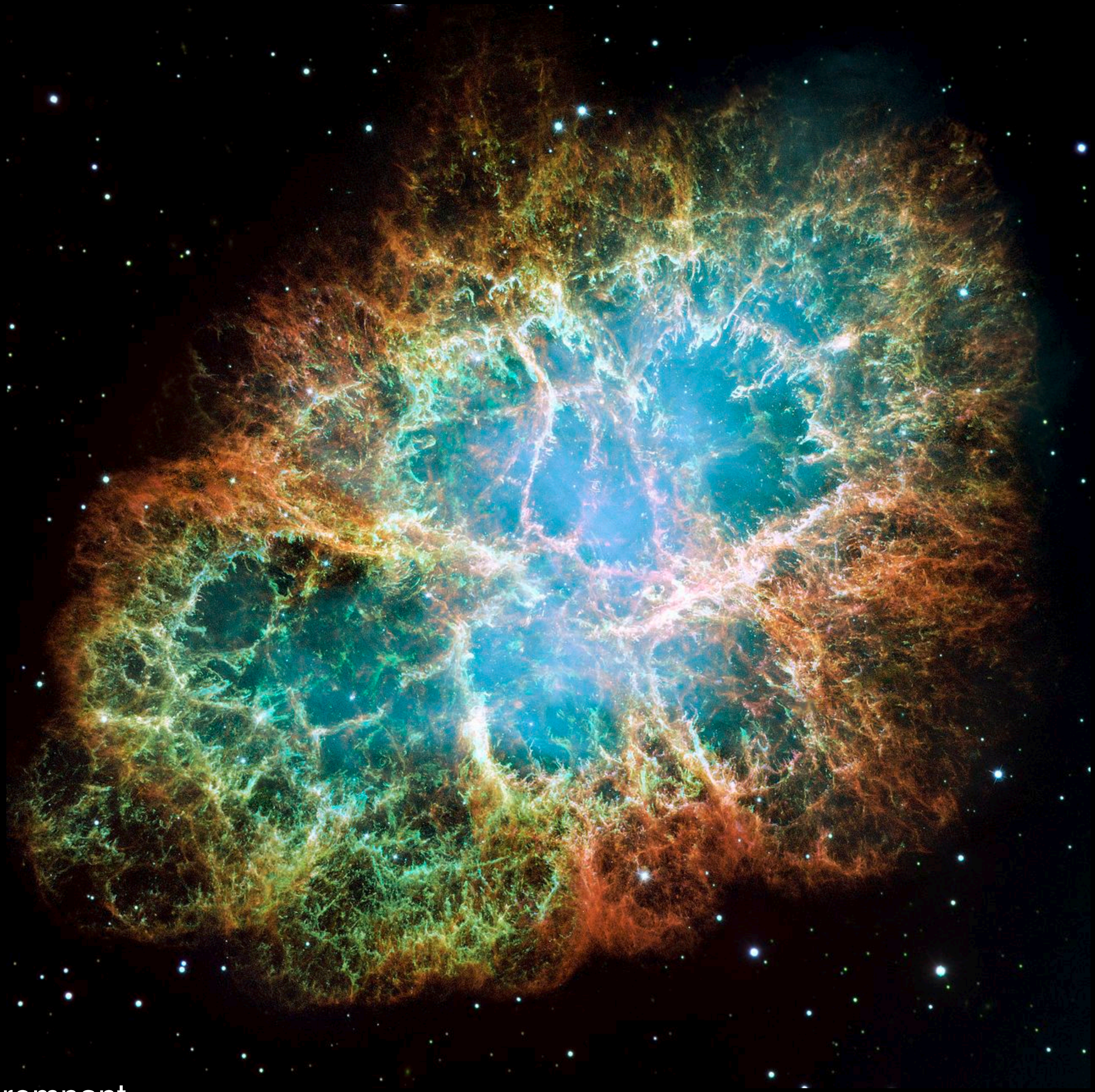
Interstellar medium in a galaxy like the Milky Way



- Jeans Mass too small?
- Dense clouds much larger
- **Triggering mechanisms help**

Mechanisms triggering the formation of stars

1. **Shocks** from supernova explosions trigger star formation



Supernova 1054 remnant

2. **Shocks from radiation pressure** in hot stars trigger star formation in nearby regions

OB associations (groups of O & B stars) produce strong UV emission ⟹ radiation pressure ⟹ gas compression ⟹ star formation

Young star cluster ***R136*** in region of star formation inside ***Tarantula nebula*** of galaxy ***Large Magellanic Cloud***

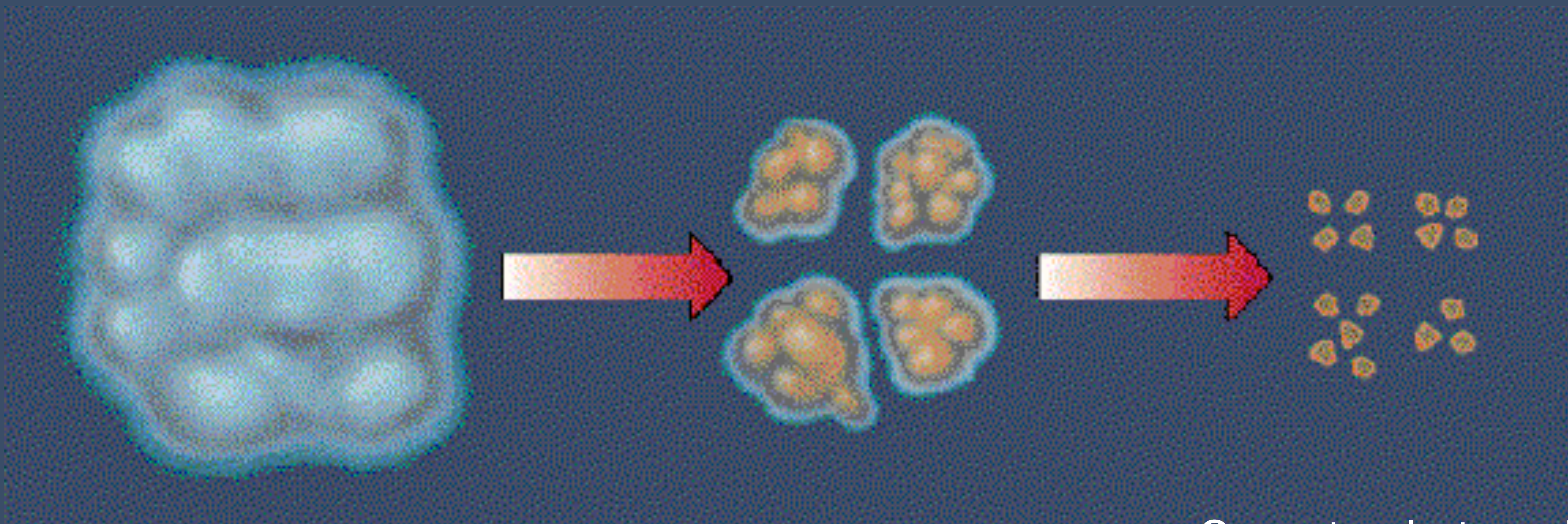
3. **Spiral density waves** trigger star formation

Pinwheel Galaxy (Messier 101)
Distance: 6.4 ± 0.5 Mpc

4. **Interaction between galaxies** triggers star formation

Merging galaxies *“The mice”*
Distance: 89 Mpc

Next: **fragmentation** of dense clouds to smaller clouds
This takes to formation of stars



Cloud initial mass:
$M_{\text{cloud}} = 100–1000\ M_\odot$

- Open star clusters with hundreds stars
- Massive stars form first

Final total number: hundreds of stars only, a few % of initial mass

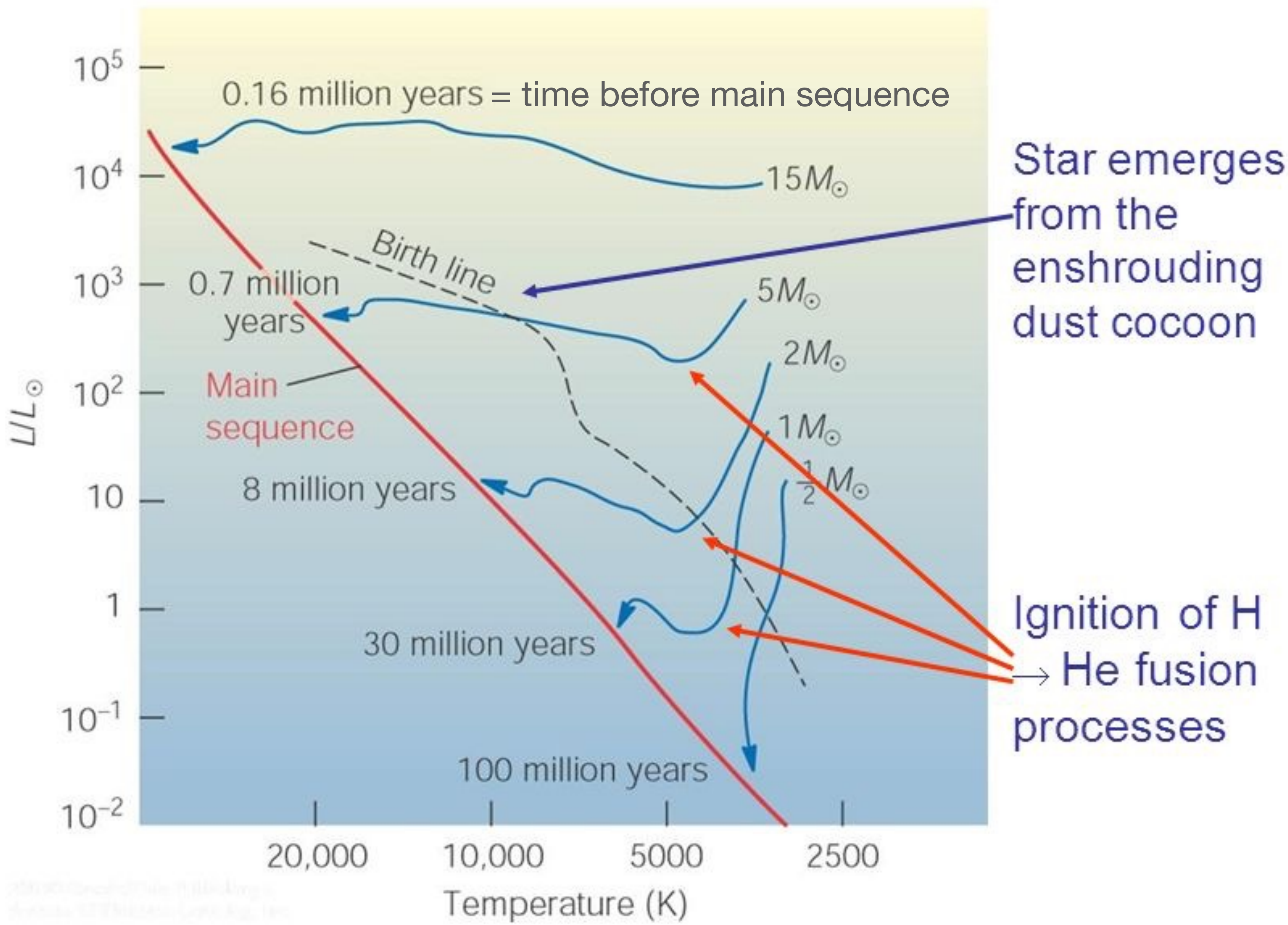
Inefficiency due to combination of turbulence, magnetic field, feedback

Feedback: energy released in environment by nearby supernovae, stellar winds, radiation pressure, UV photons (destroying H_2 , molecules, dust) & cosmic rays

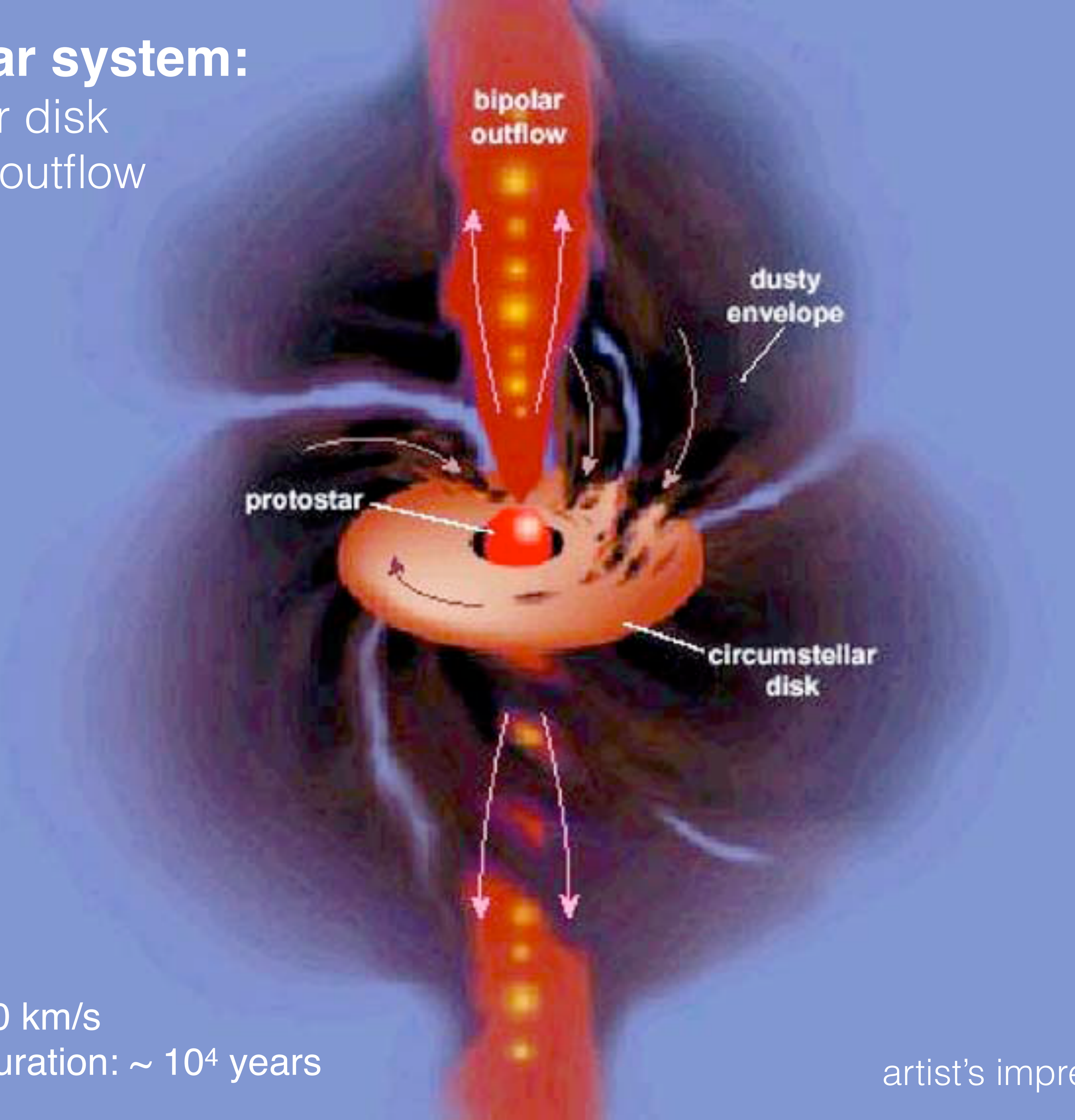
Before the formation of a star: **protostar**

From protostars to stars

Hayashi tracks: theoretical tracks describing how protostars reach **Main Sequence**
More massive stars form first (longest time for small stars: $t \approx 10^8$ years)



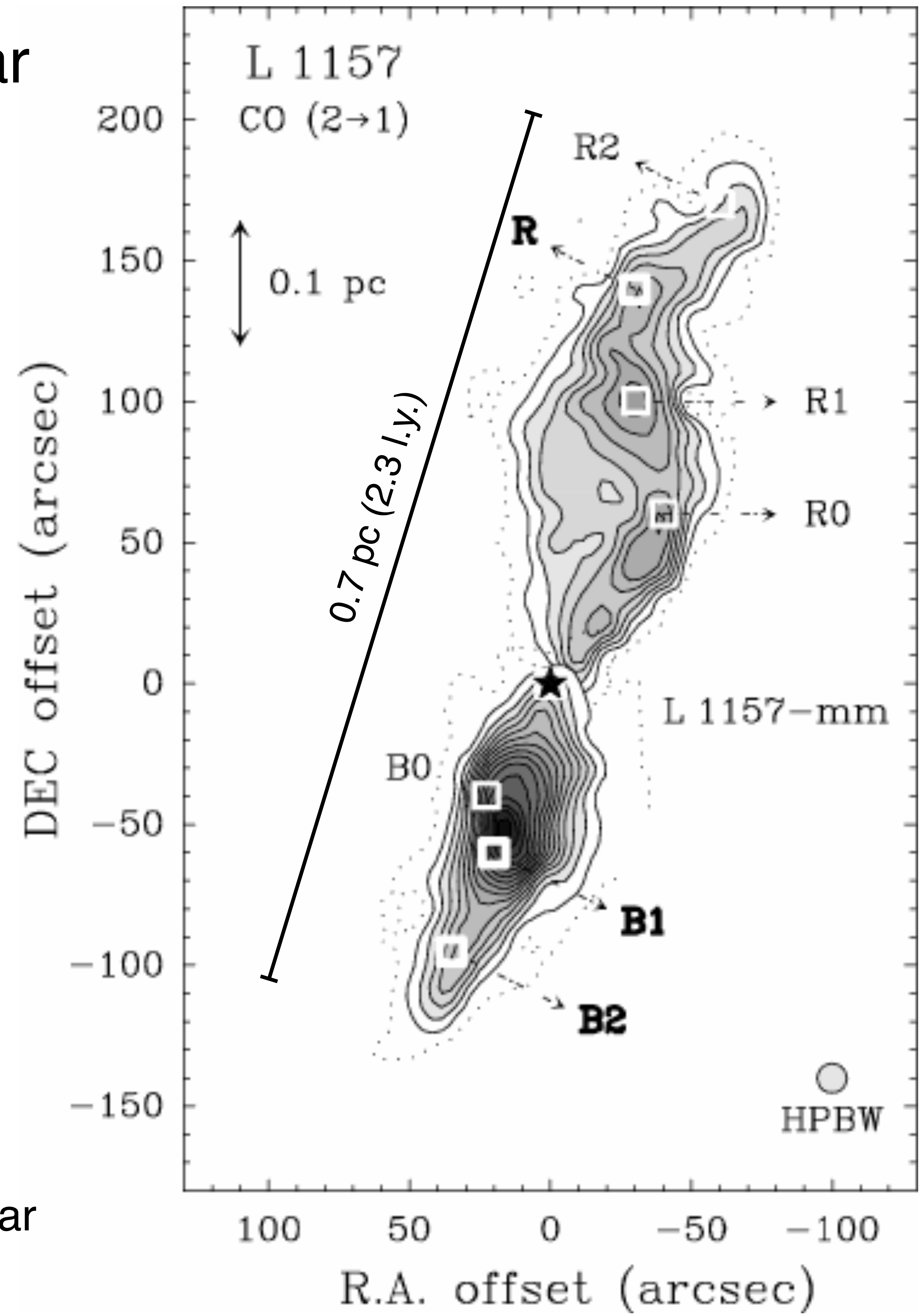
Protostellar system:
circumstellar disk
with bipolar outflow



Jet speed: ~ 50 km/s
Outflow time duration: ~ 10^4 years

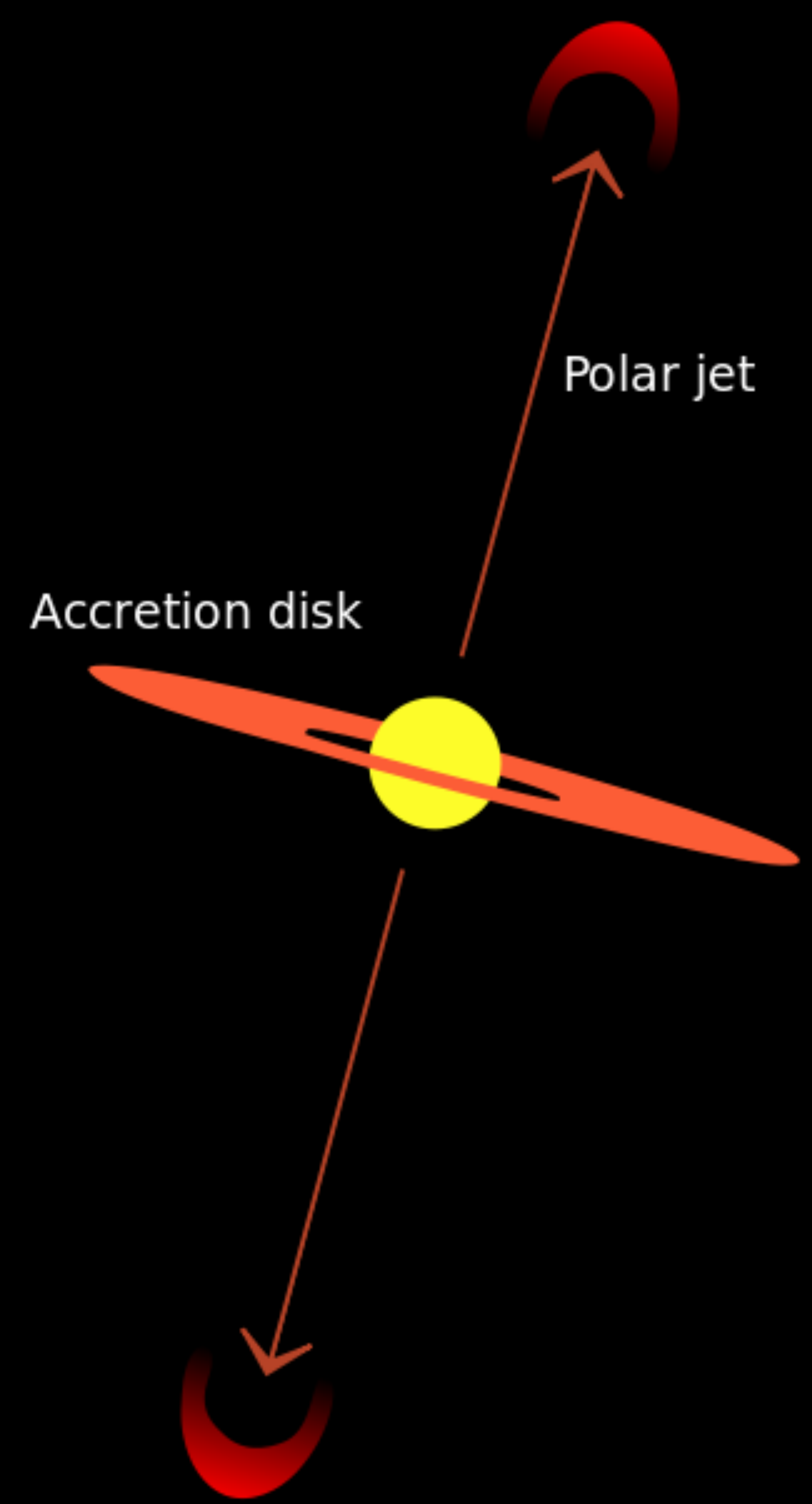
artist's impression

Bipolar outflow in protostar



Emission of CO molecule
in bipolar outflow of a protostar
Observed in radio waves

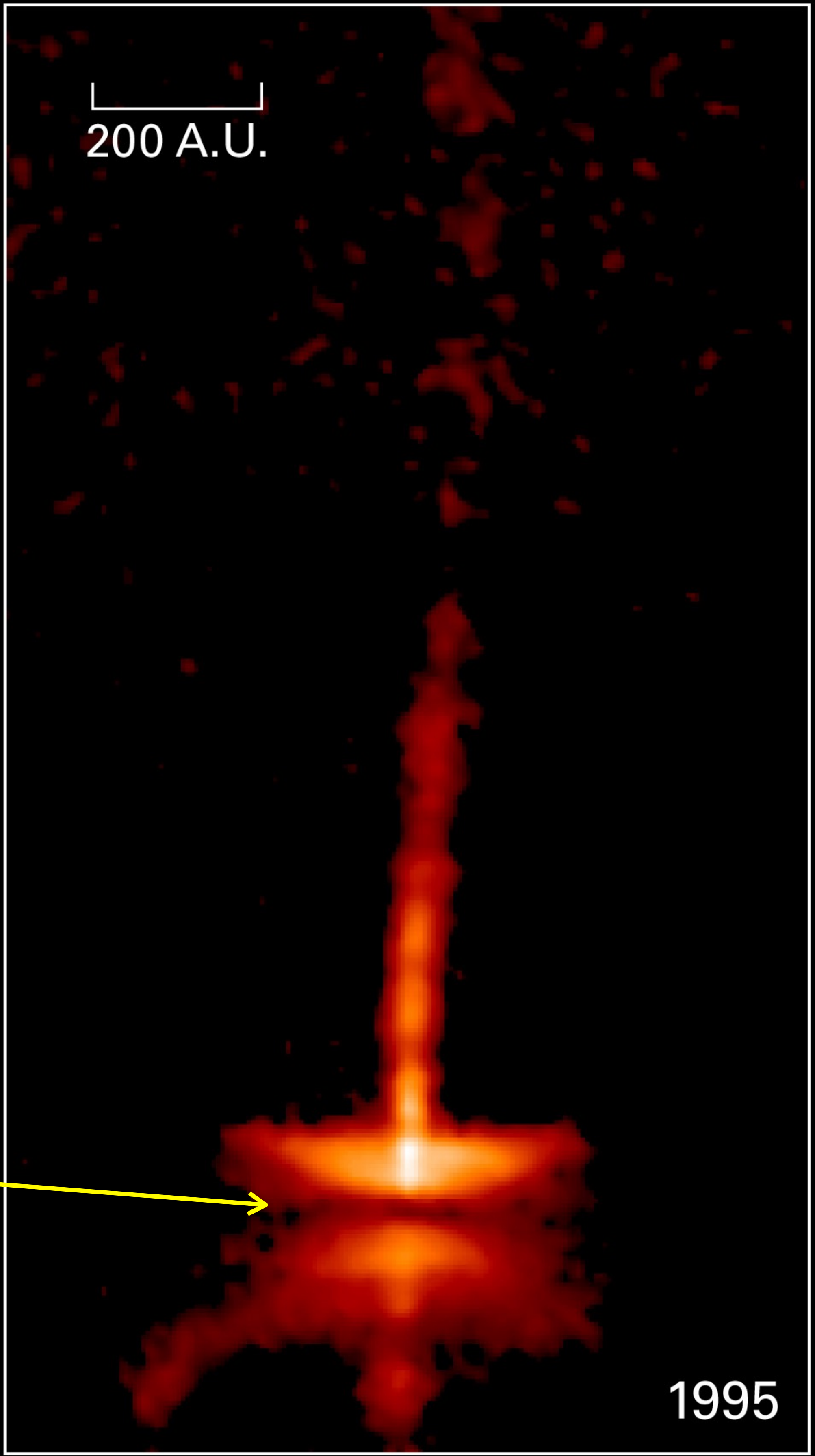
Protostellar systems are called ***Herbig–Haro* object**



Protostellar systems are called ***Herbig–Haro* object**

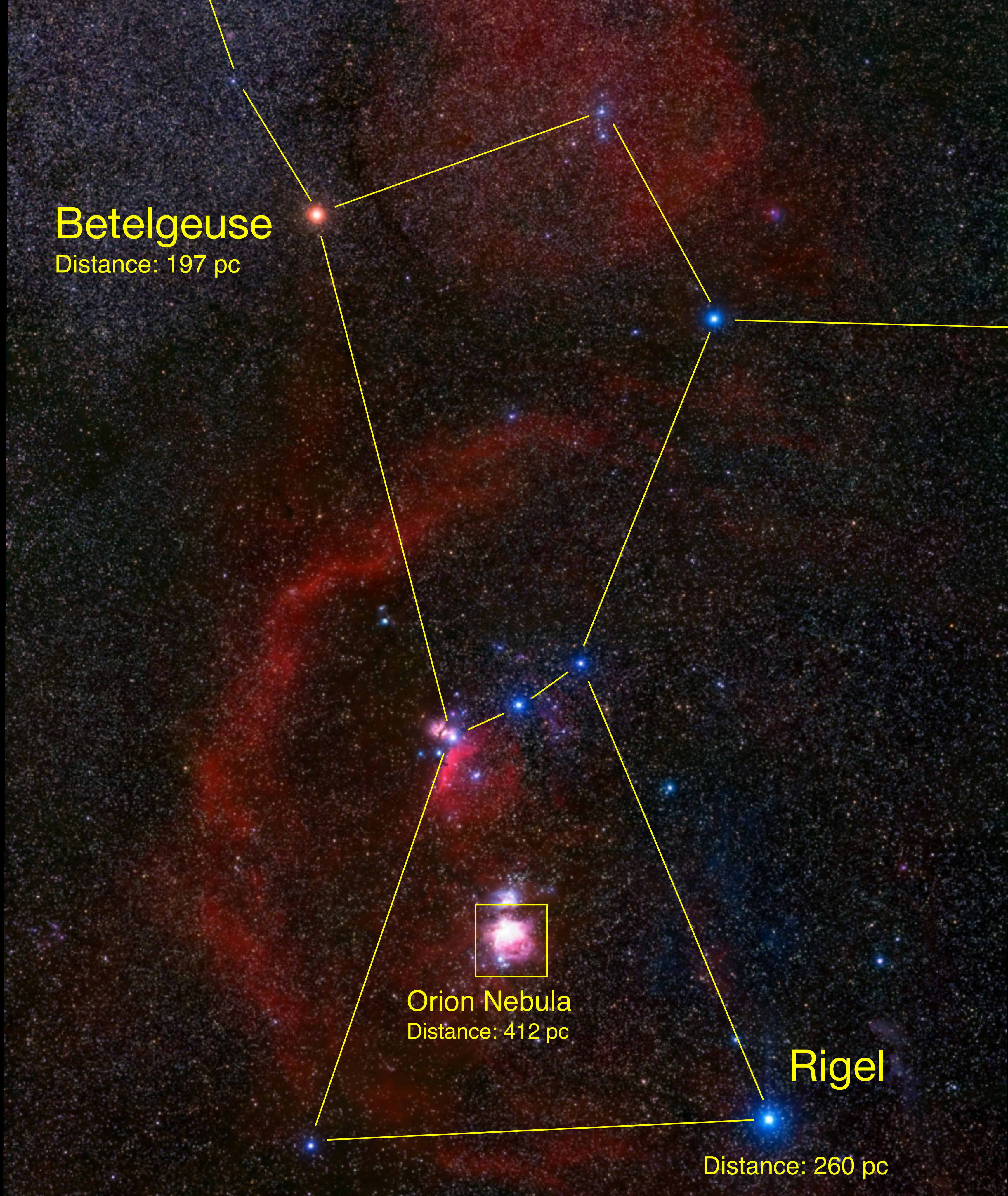
Herbig–Haro 30
Observed with HST
Protostellar disk and jet
Gas speed in jets: ~ 200 km/s

Dark disk of dust which encircles the star



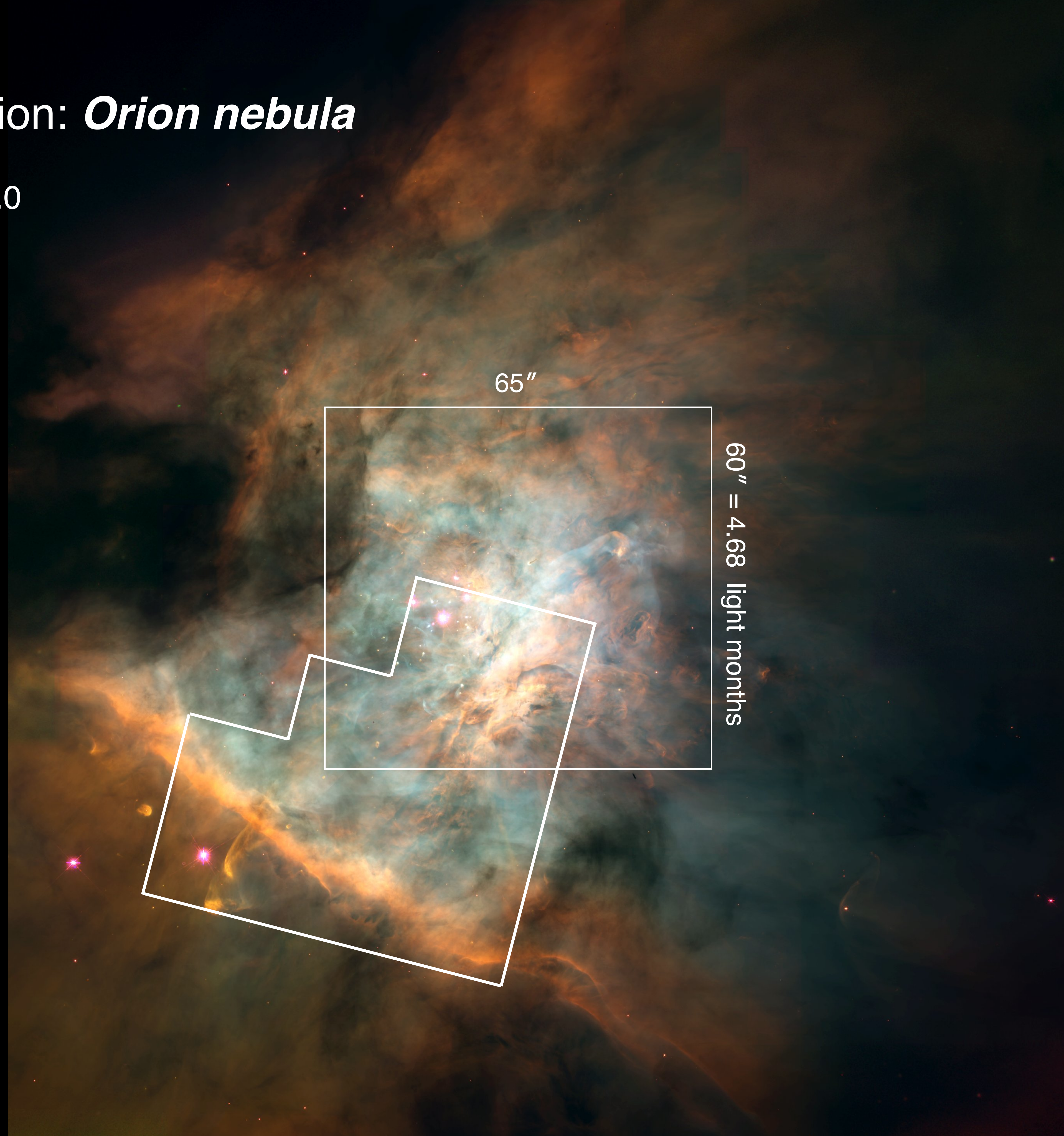
Protoplanetary systems
&
extrasolar planets

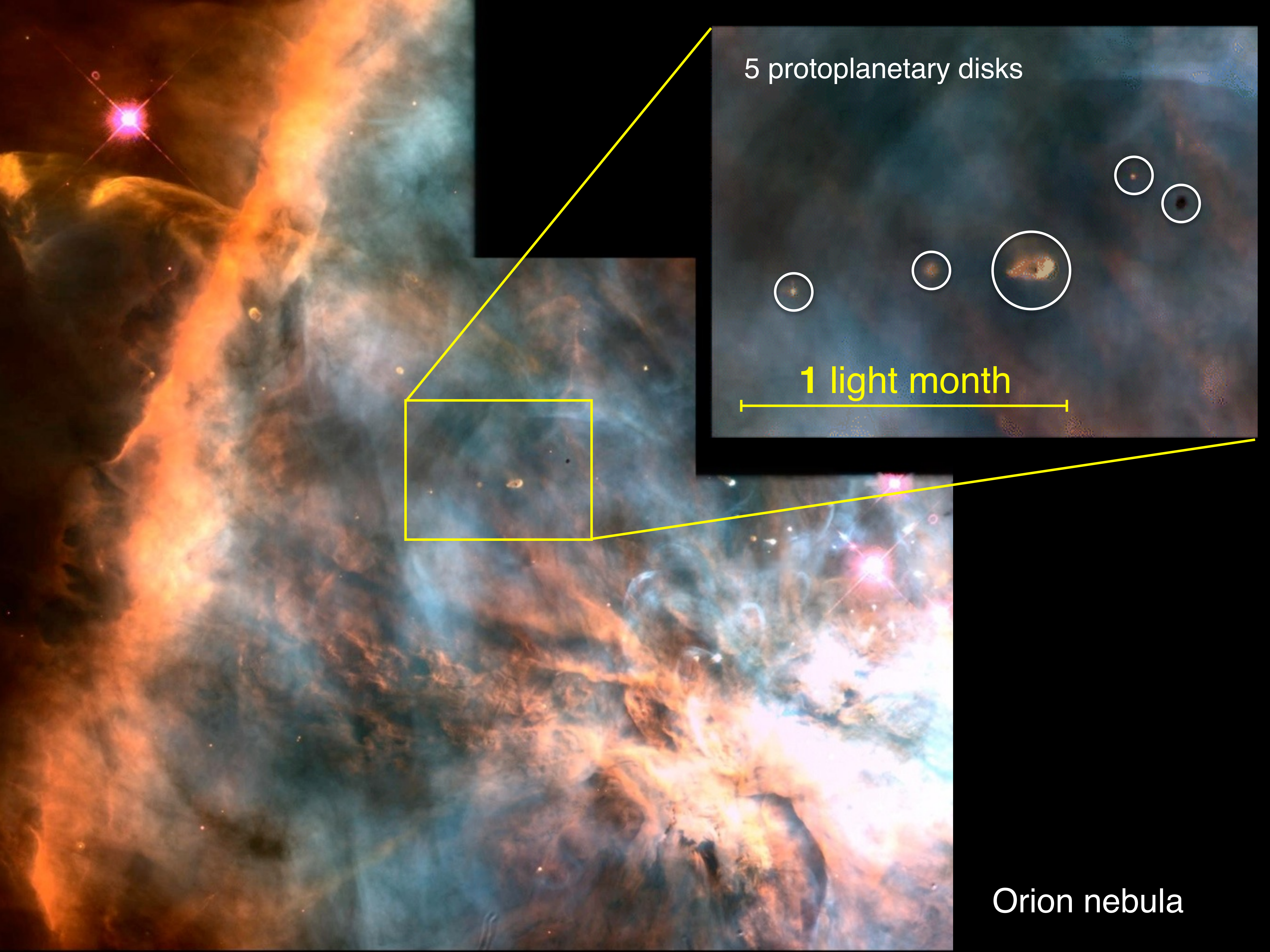
Orion Constellation



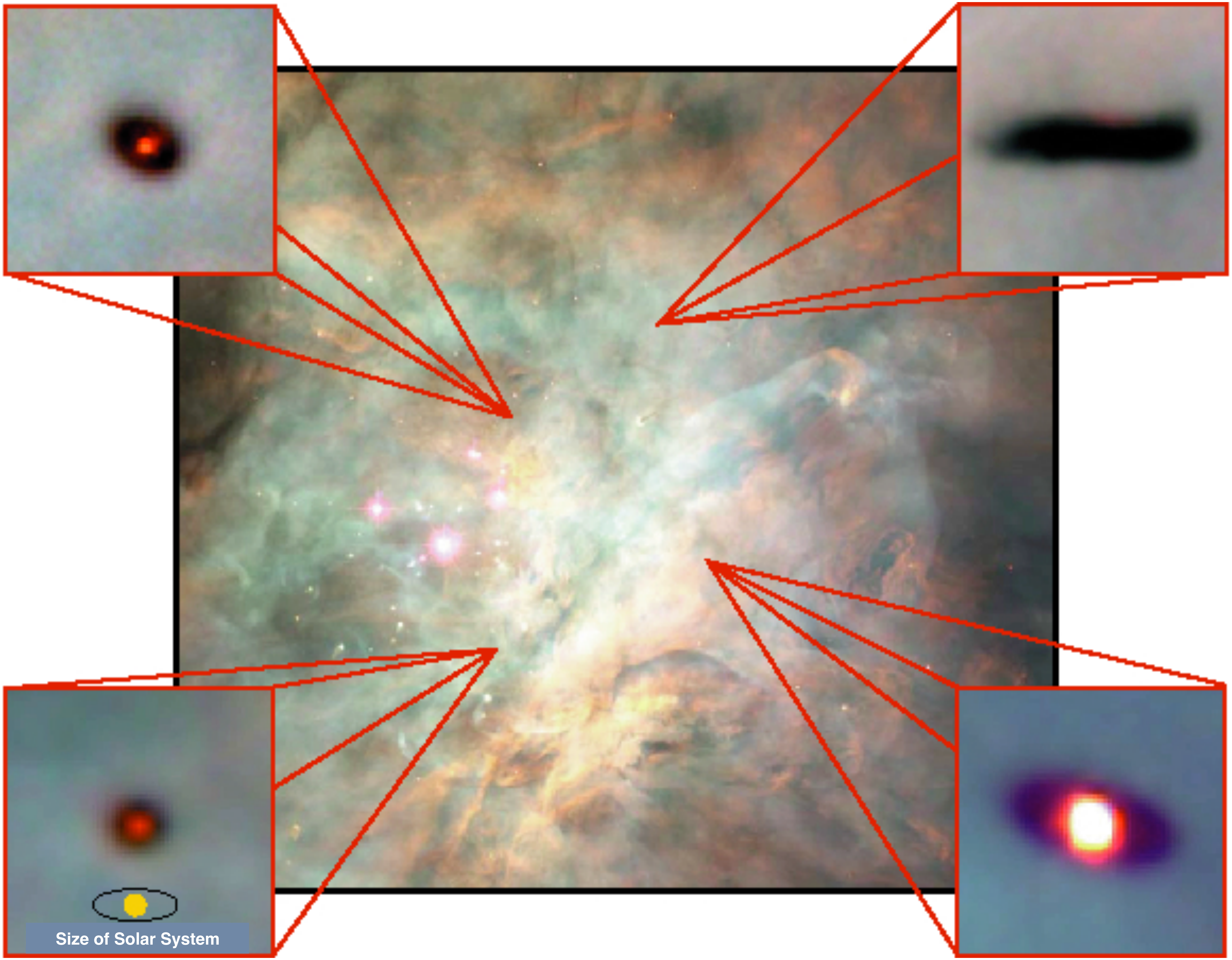
Region of star formation: ***Orion nebula***

Distance: 412 pc
Apparent magnitude: $m = +4.0$
Age: 300,000 years old



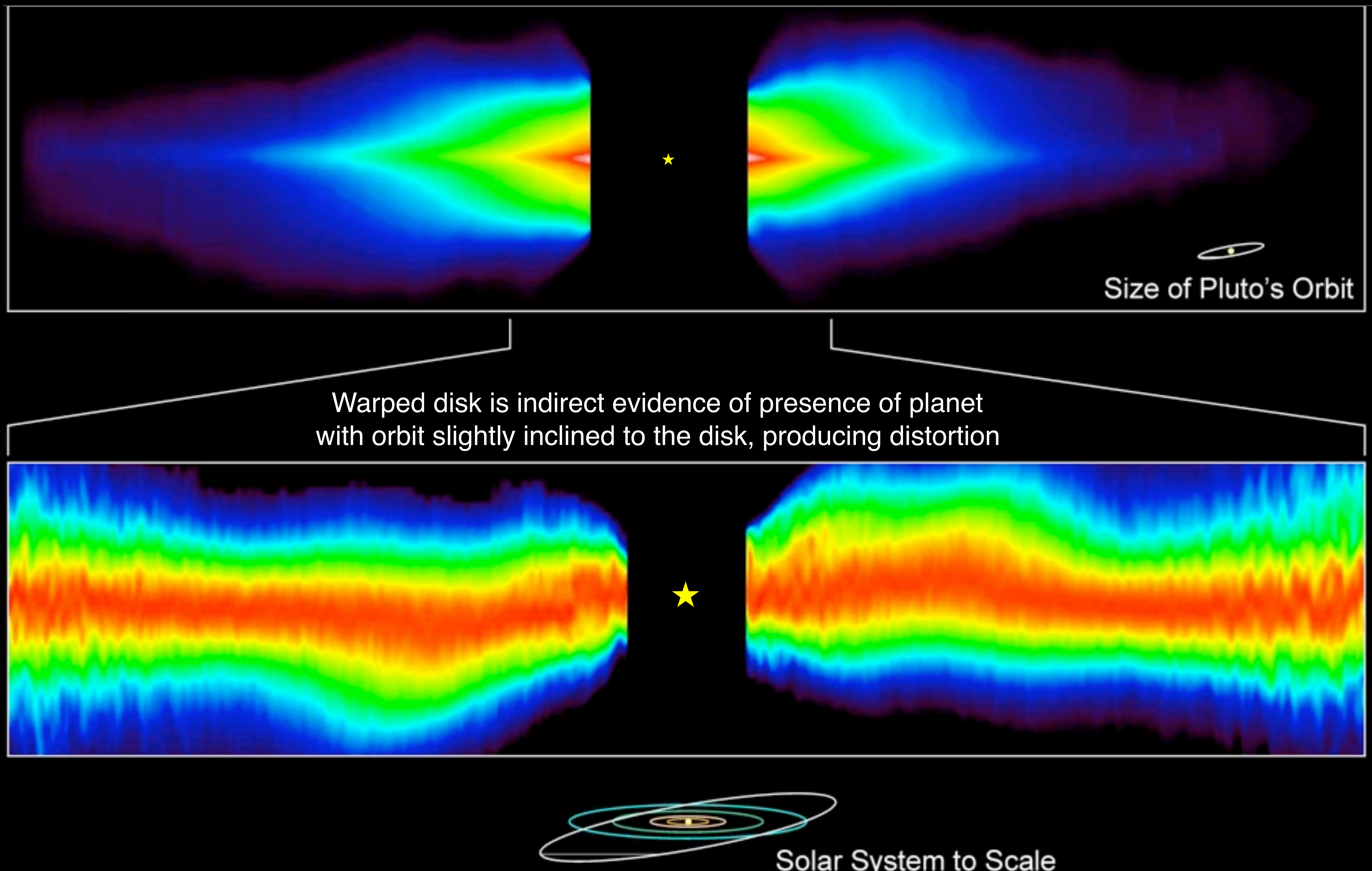

5 protoplanetary disks
1 light month
Orion nebula

Protoplanetary disks in Orion nebula



The young star ***Beta Pictoris***

Distance: $d = 19.44 \pm 0.05$ pc
Mass: $M = 1.75\ M_{\odot}$
HST images in infrared taken with coronagraph
Seen disk of gas & dust

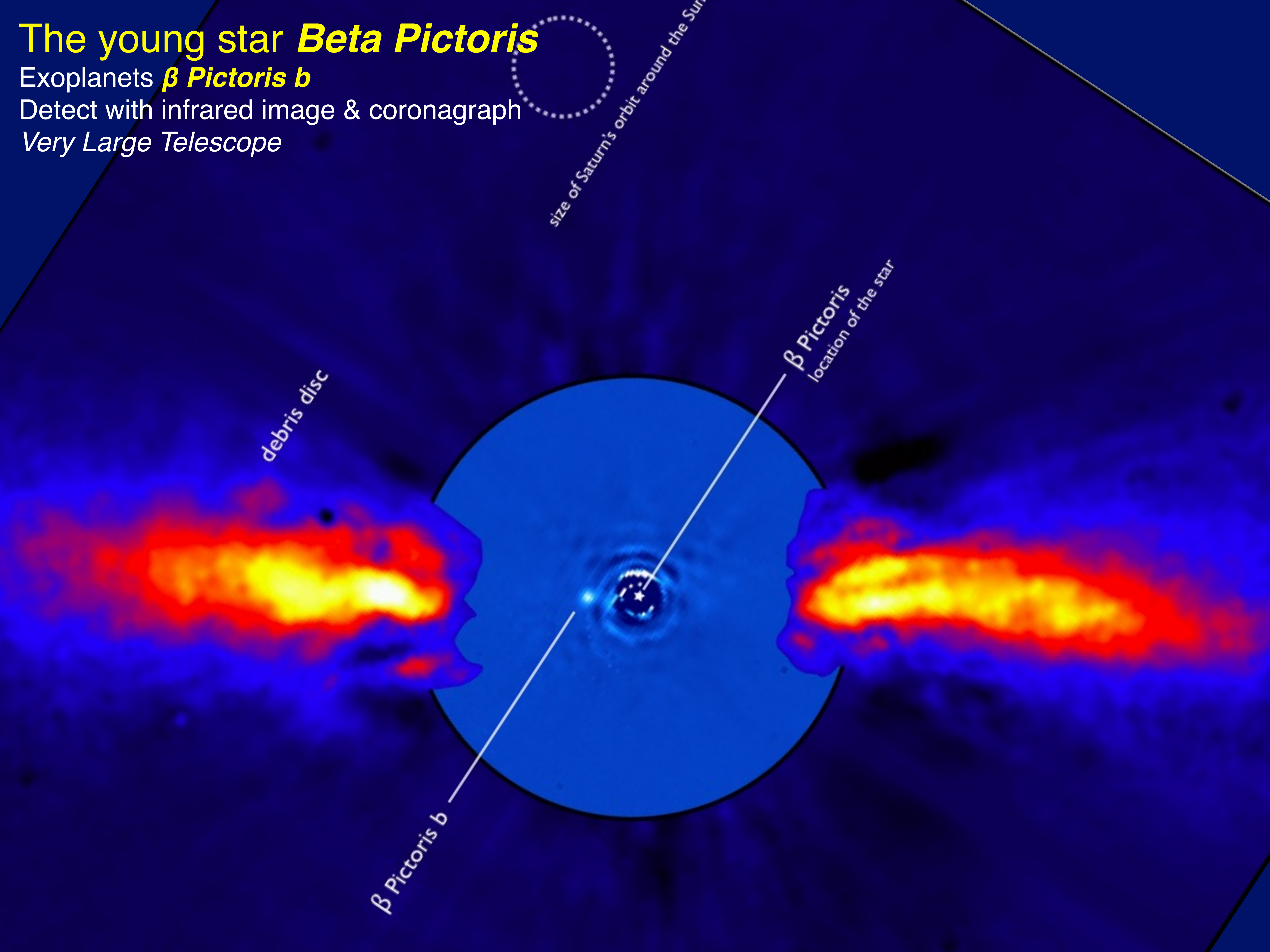


The young star ***Beta Pictoris***

Exoplanets ***β Pictoris b***

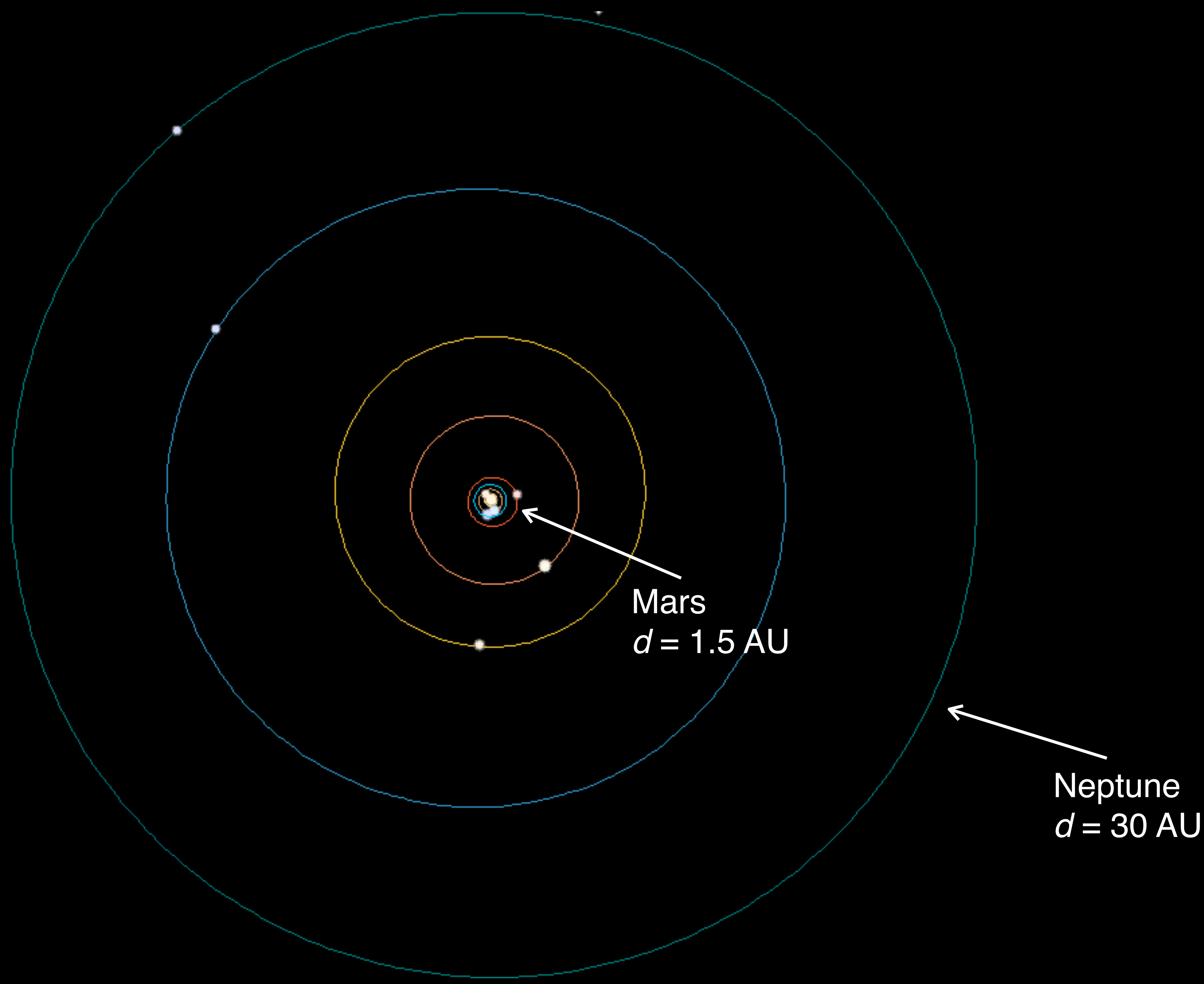
Detect with infrared image & coronagraph

Very Large Telescope



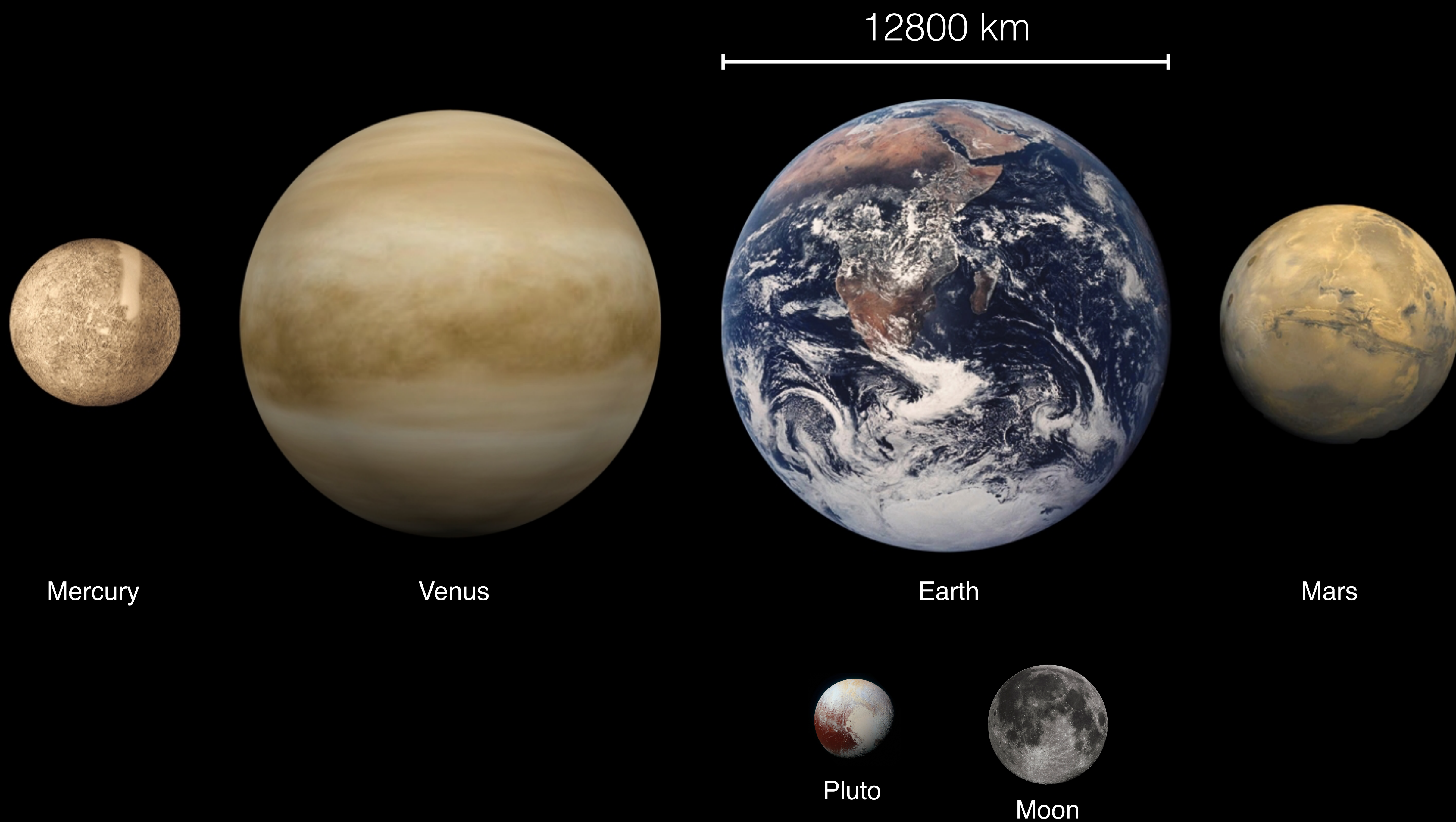
Eight planets in the solar system

1 Astronomical Unit (AU) = distance Earth-Sun = 150 000 000 km

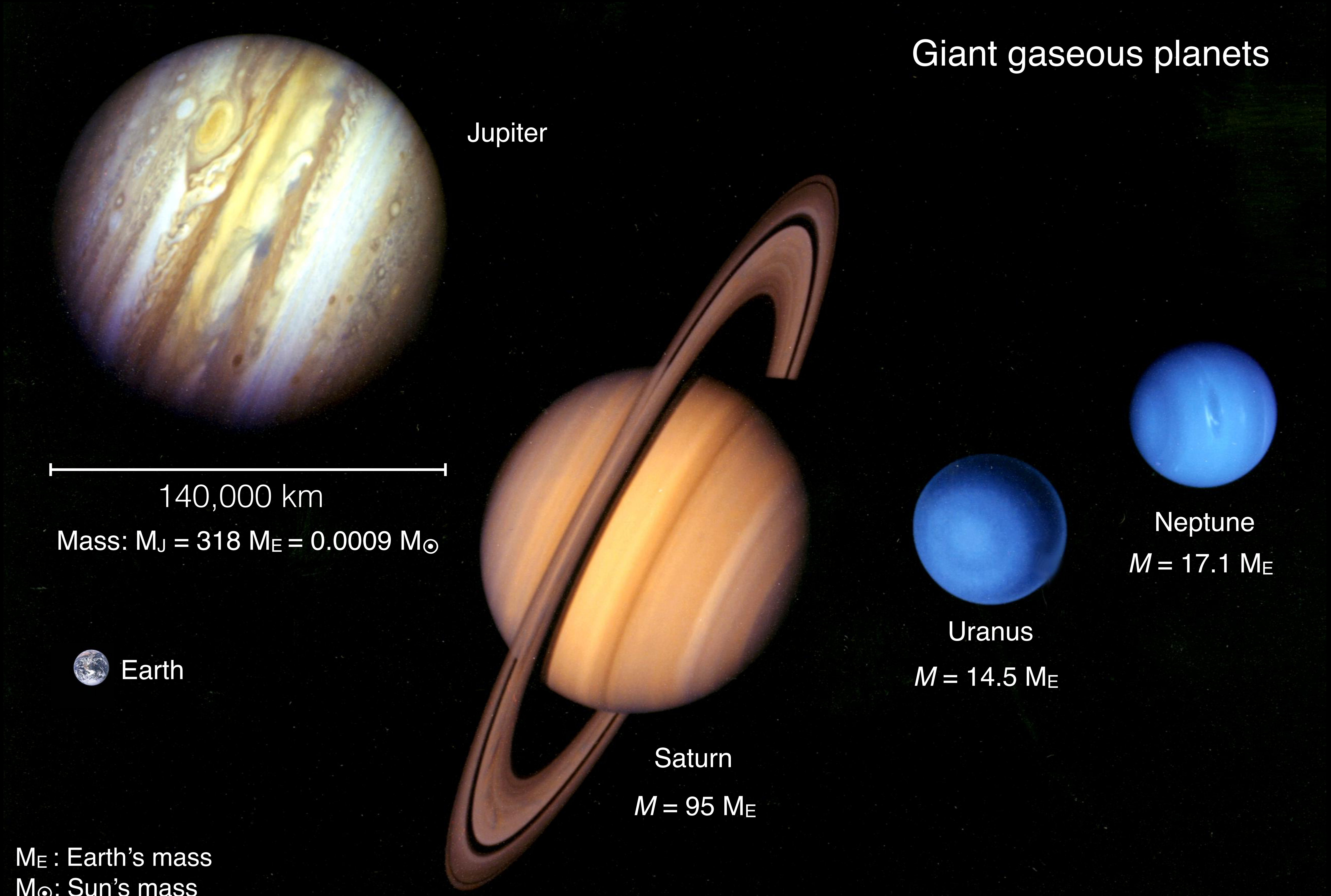


Planets in the Solar System

Telluric (rocky) planets



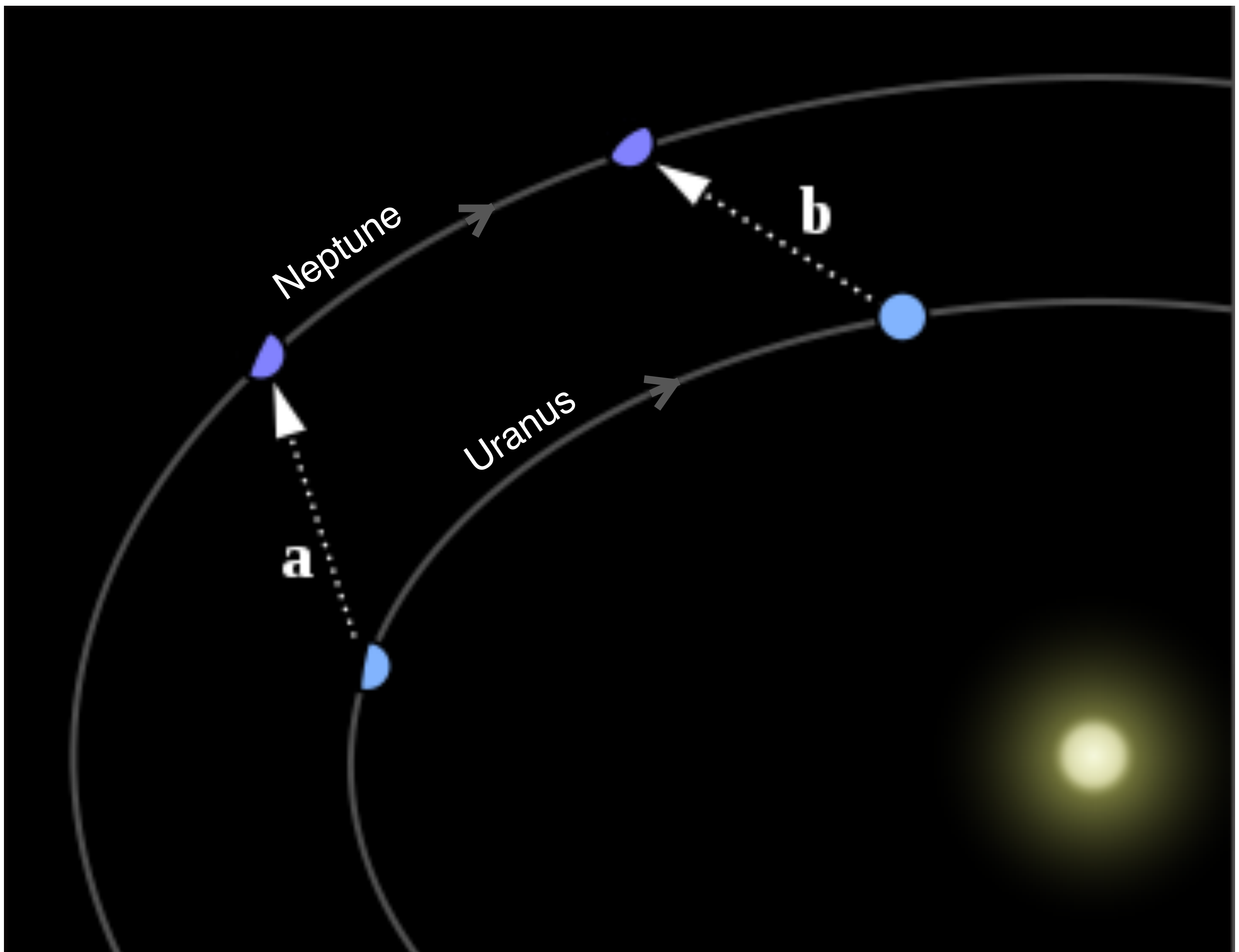
Planets in the Solar System



Discovery of planet Neptune

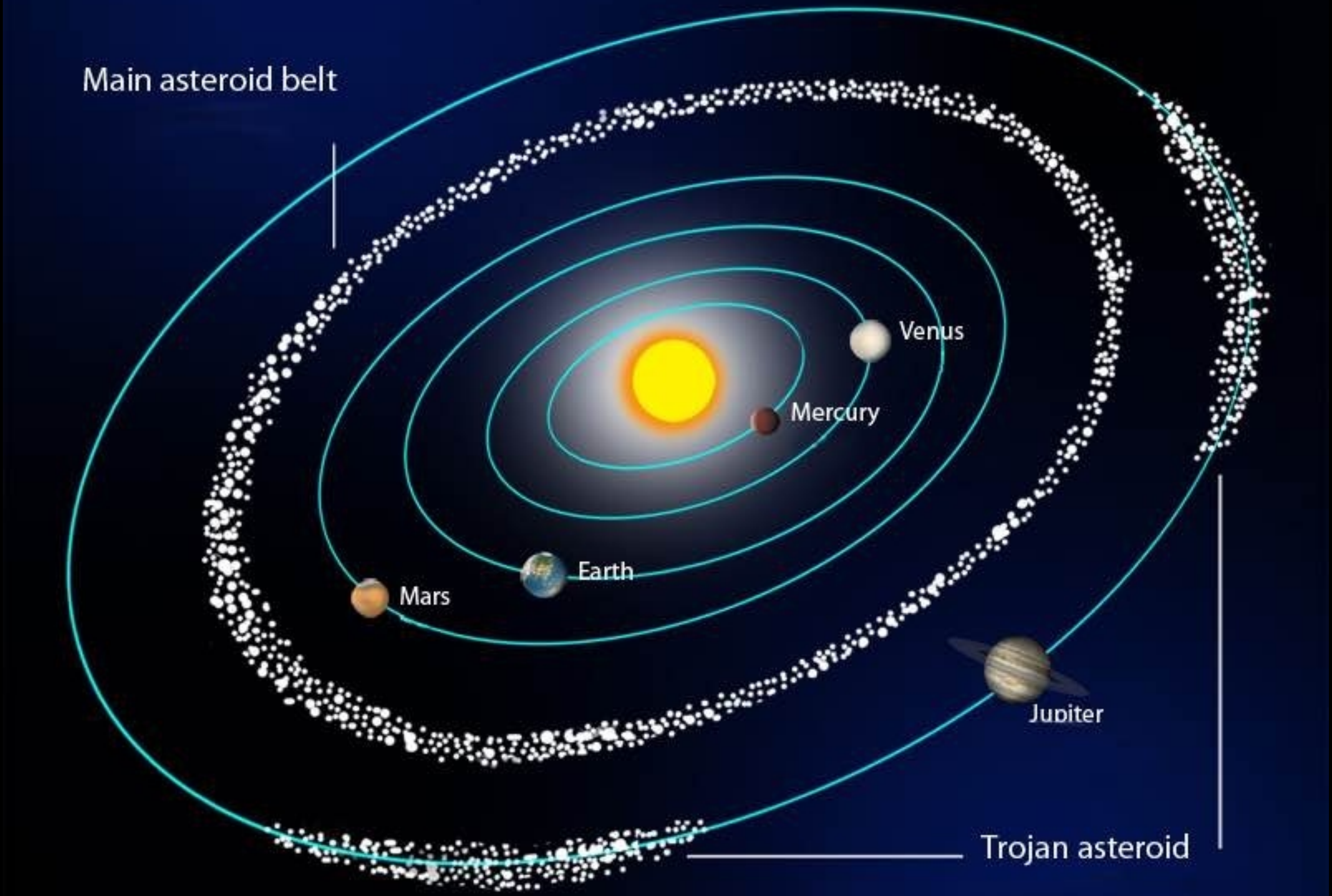
Gravitational perturbation induced by planets

Used for the discovery of Neptune (1846)
confirmed Newton's Laws of gravitation



Mathematician Urbain Le Verrier

Inner planets in solar system & **Main Asteroid Belt**

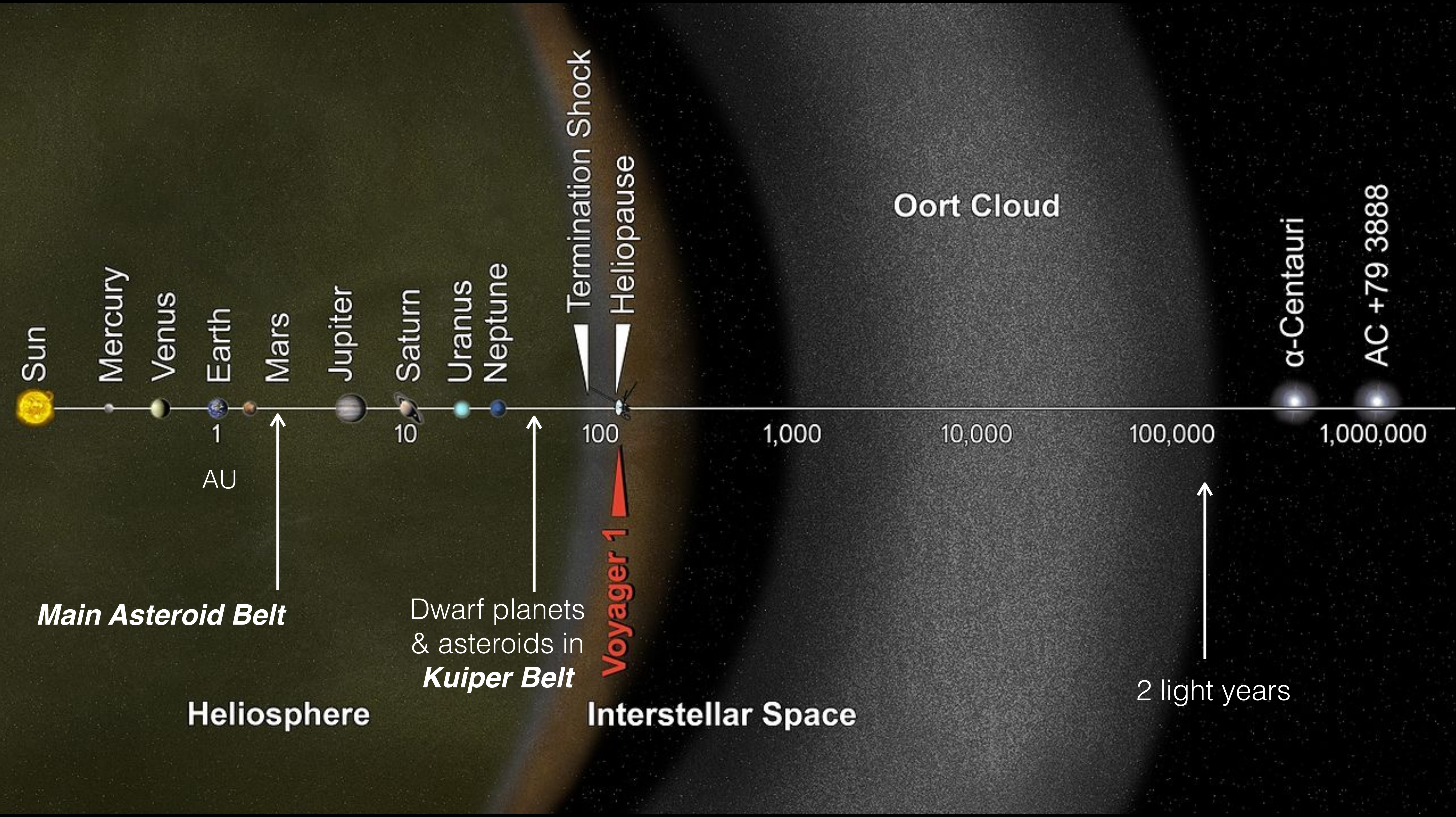


Planetesimals in asteroid belt were strongly perturbed by Jupiter's gravity to form a planet

Oort cloud

Where most comets are

Outer limit defines the boundary of the solar system

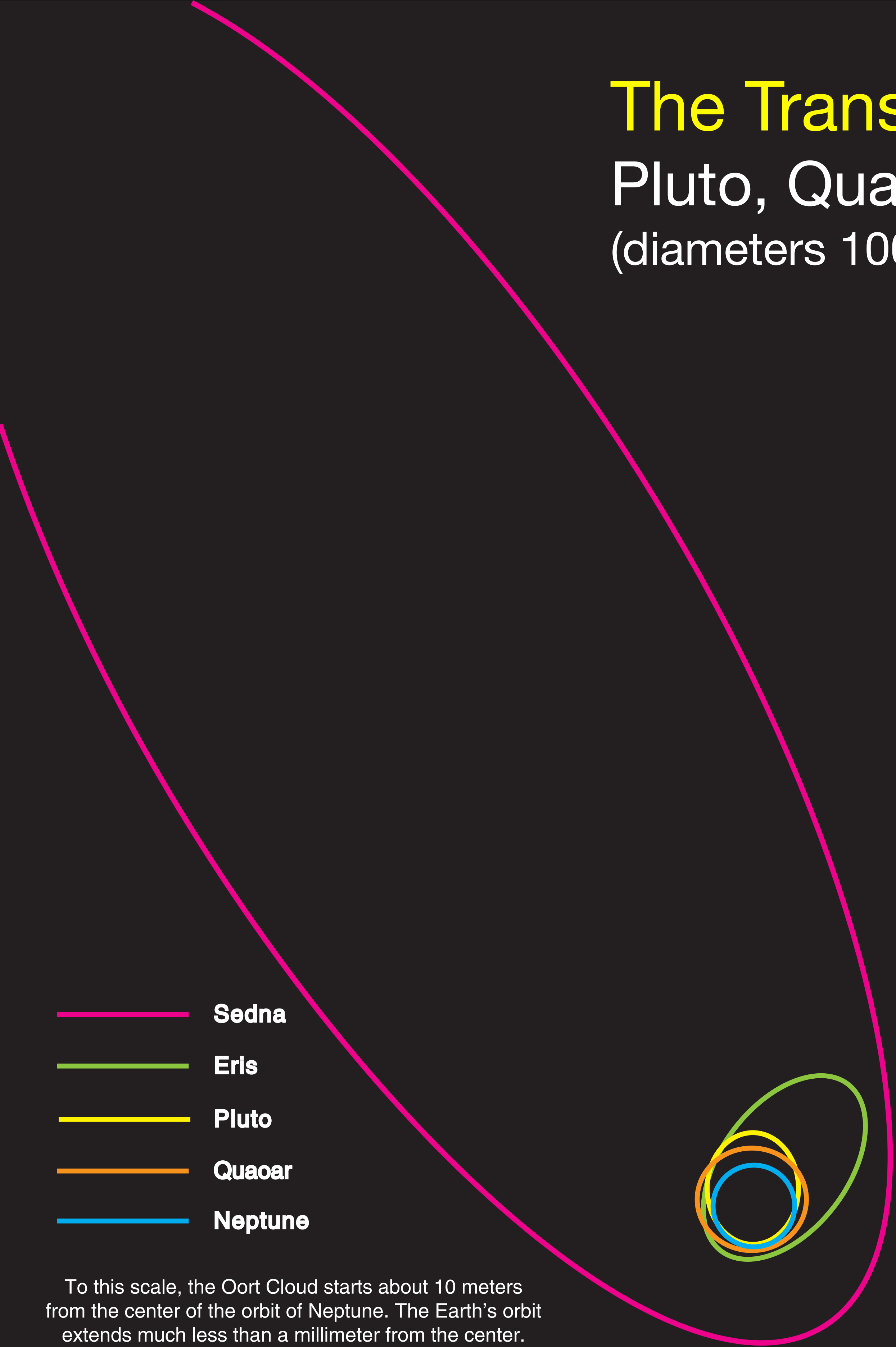


More than 99% of small bodies in Solar System are in *Kuiper Belt* and *Oort Cloud*

The Trans Neptunian Objects (TNO):

Pluto, Quaoar, Eris, and Sedna

(diameters 1000 – 2400 km, dwarf planets)



Sedna as seen by Hubble Space Telescope
Discovered in 2003
Diameter: d = 995 ± 80 km
Aphelion ≈ 936 AU
Perihelion = 76.0917±0.0087 AU
Perihelion foreseen for 2076

About 10 dwarf planets with diameters 900 — 2400 km
Over 200 dwarf planets with diameters 400— 900 km
Distance between 30 AU and 50 AU

Largest known trans-Neptunian objects (TNOs)

1995: confirmed discovery of **first planet outside solar system**

Star: 51 Pegasi

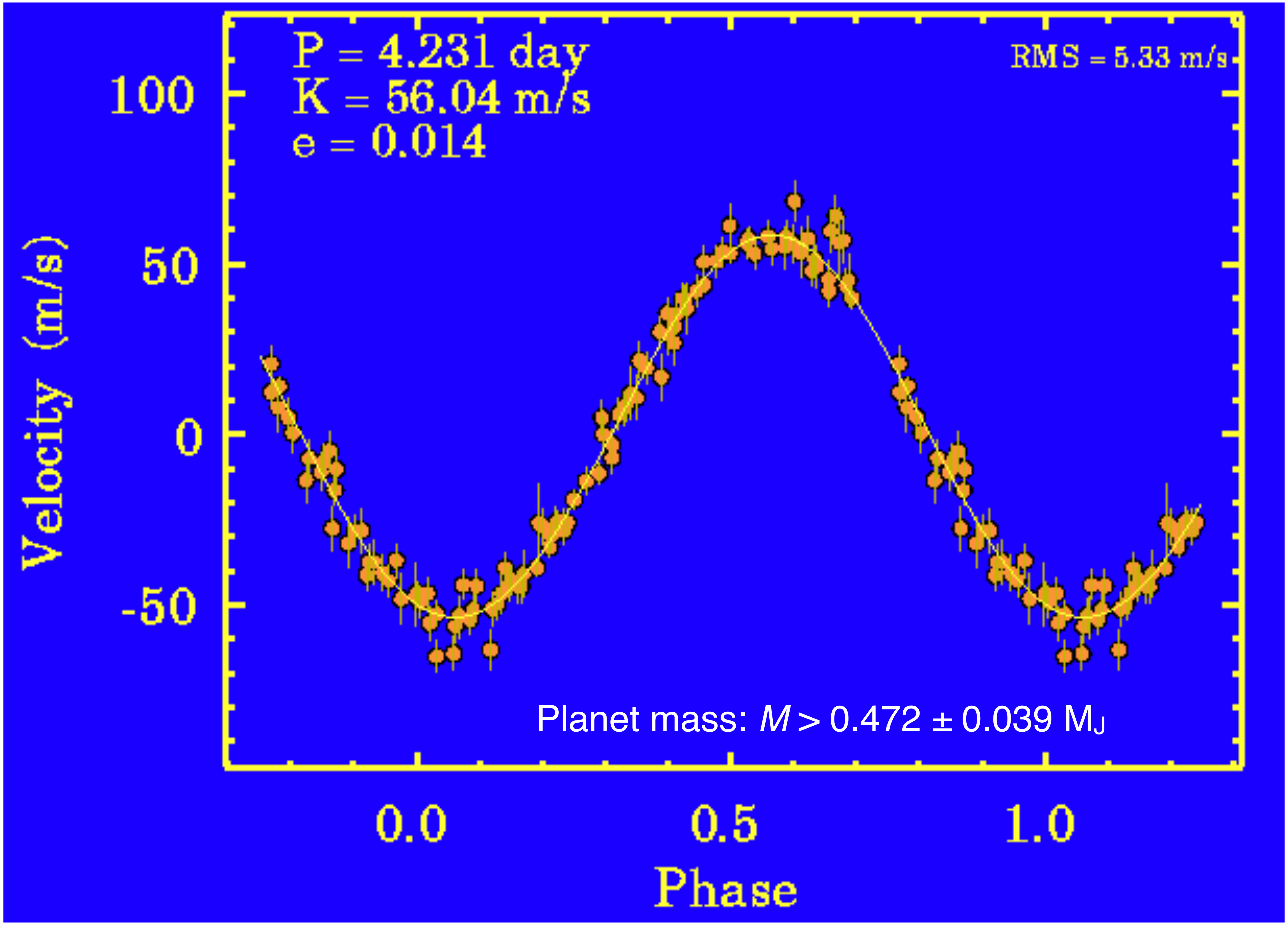
Apparent magnitude (V): $m = 5.49$

Mass: $M = 1.11\ M_\odot$

Distance: $d = 15.6$ pc (50.9 l.y)

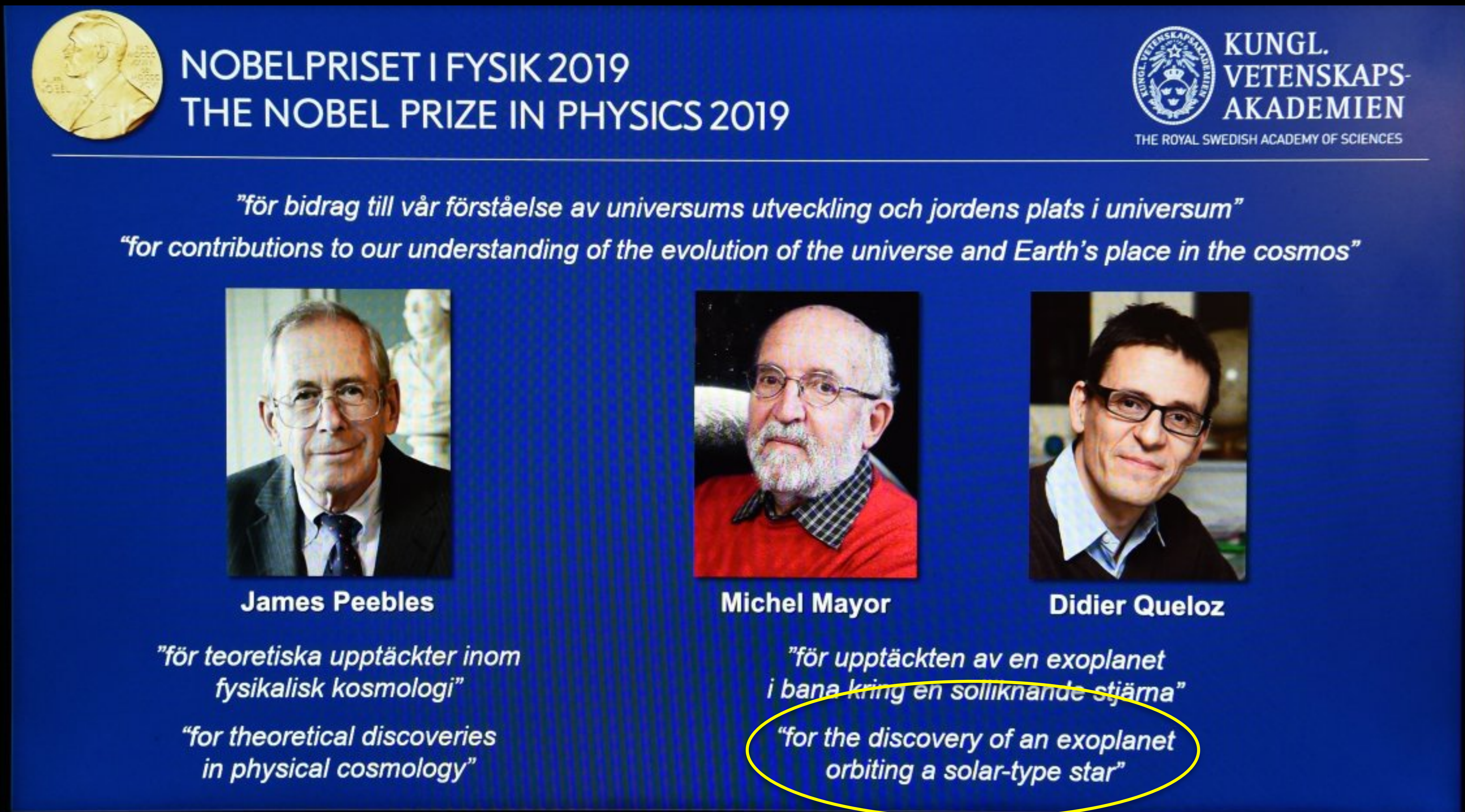
1995: confirmed discovery of **first planet outside solar system**

Radial velocity of 51 Pegasi



M_J: mass of Jupiter

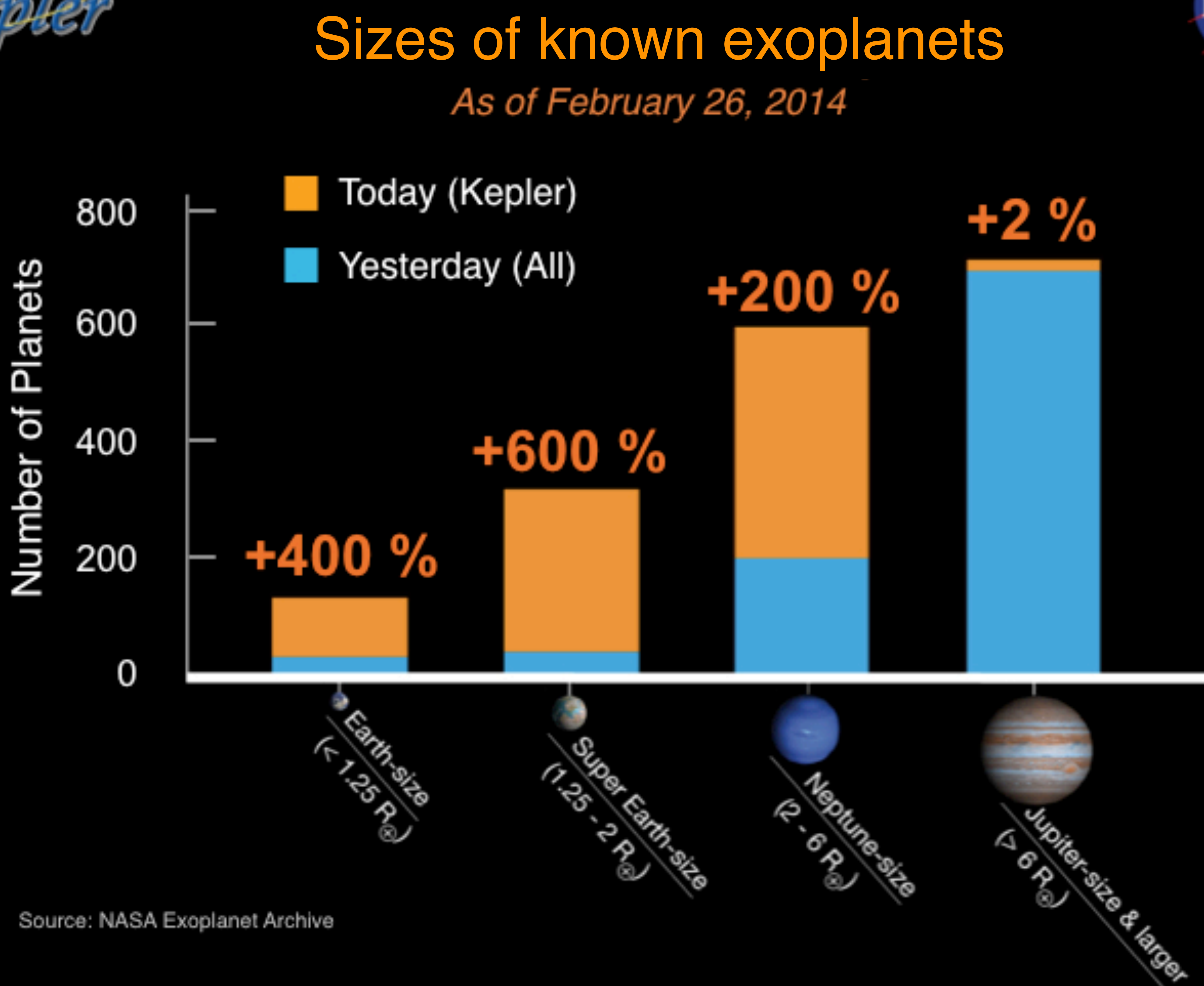
Nobel Prize 2019 given to those who discovered ***51 Pegasi b***



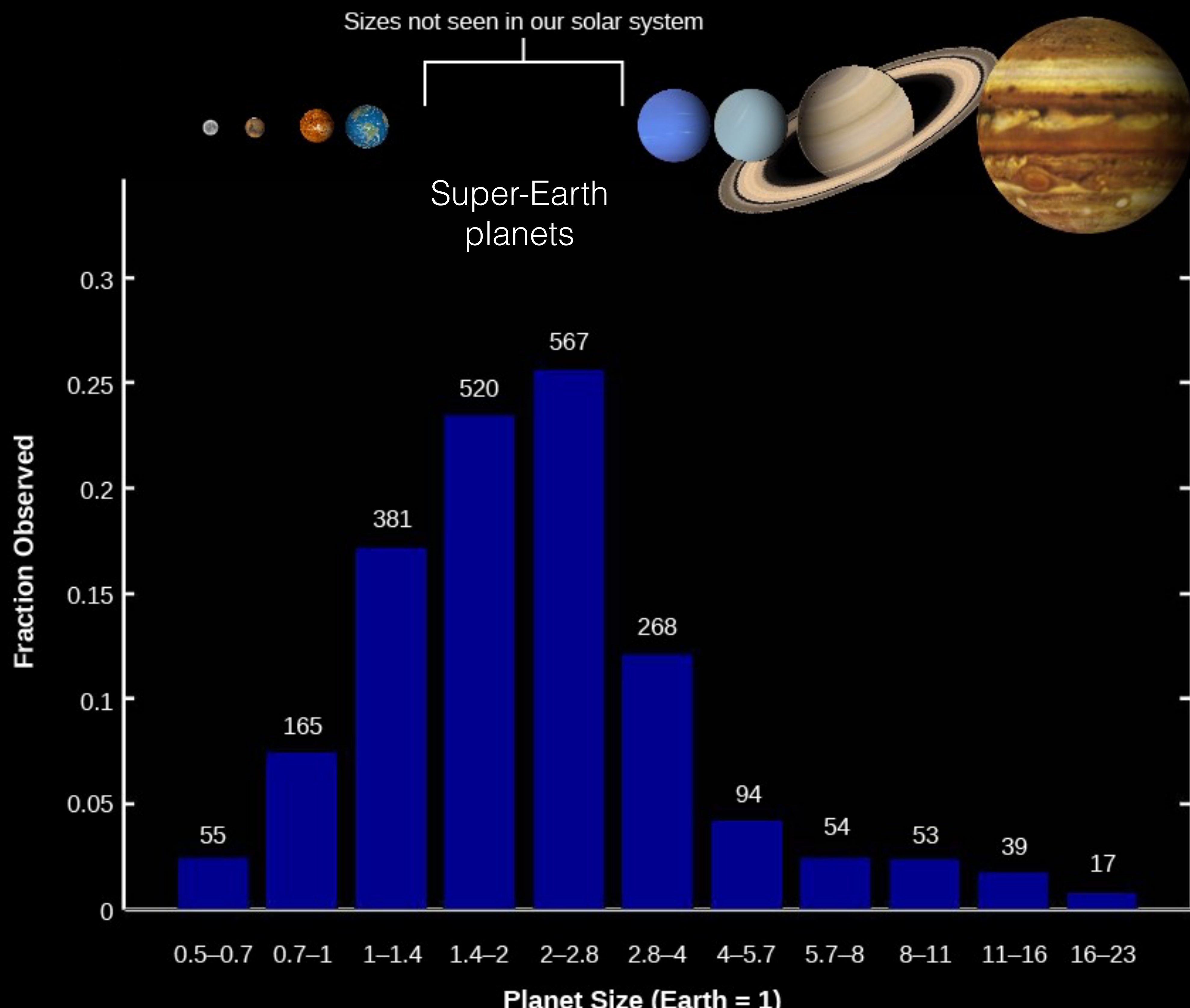
Kepler space observatory (NASA)
to discover extrasolar Earth-size planets

Launch date: March 2009
Deactivated: November 2018

Exoplanet discoveries before and after Kepler mission



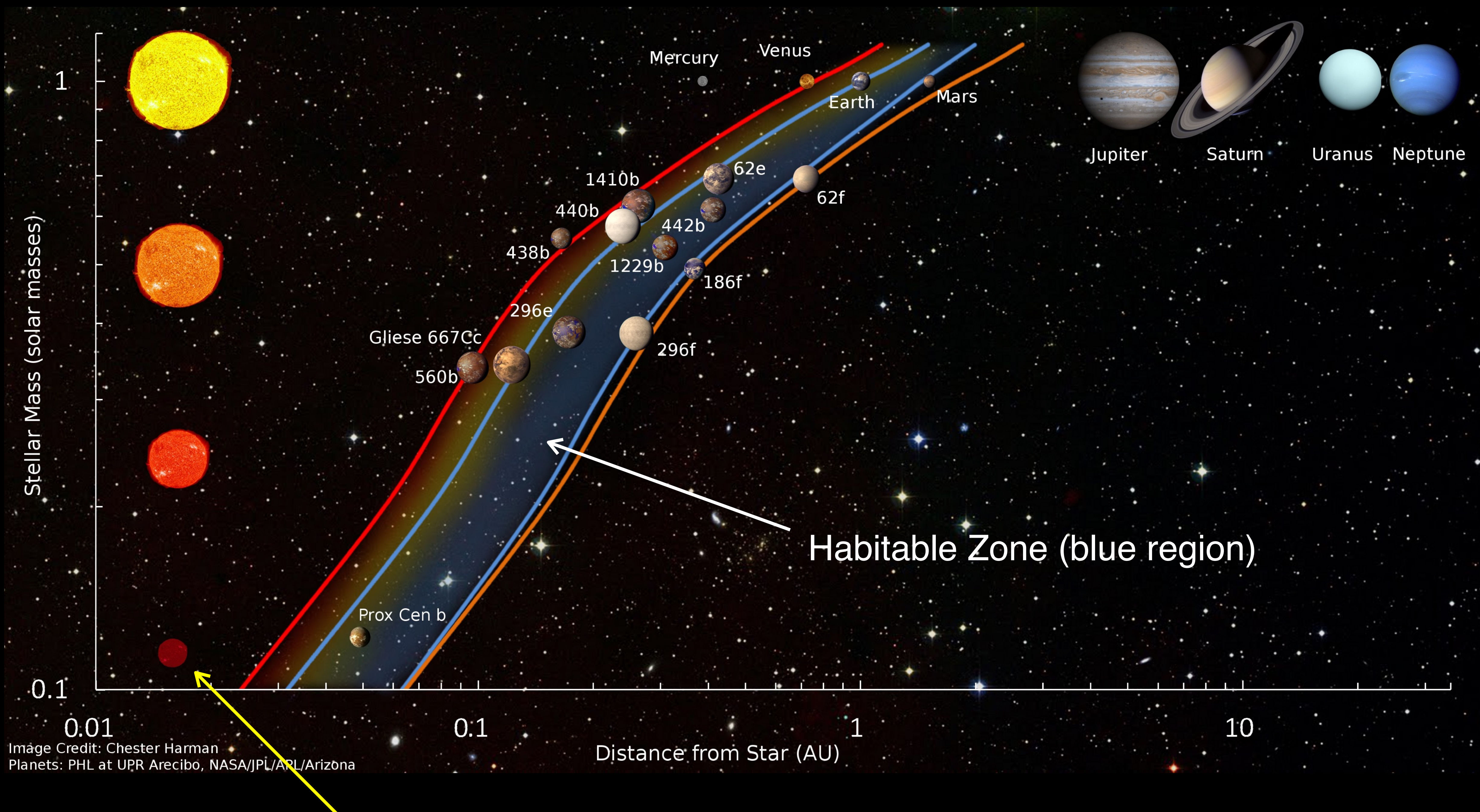
Number of planets per size range among first 2213 Kepler discoveries



Earth-size planets are most common type of exoplanets around Sun-like stars

Habitable zone as a function of stellar mass

Definition: orbital region around a star in which an Earth-like planet can possess liquid H_20

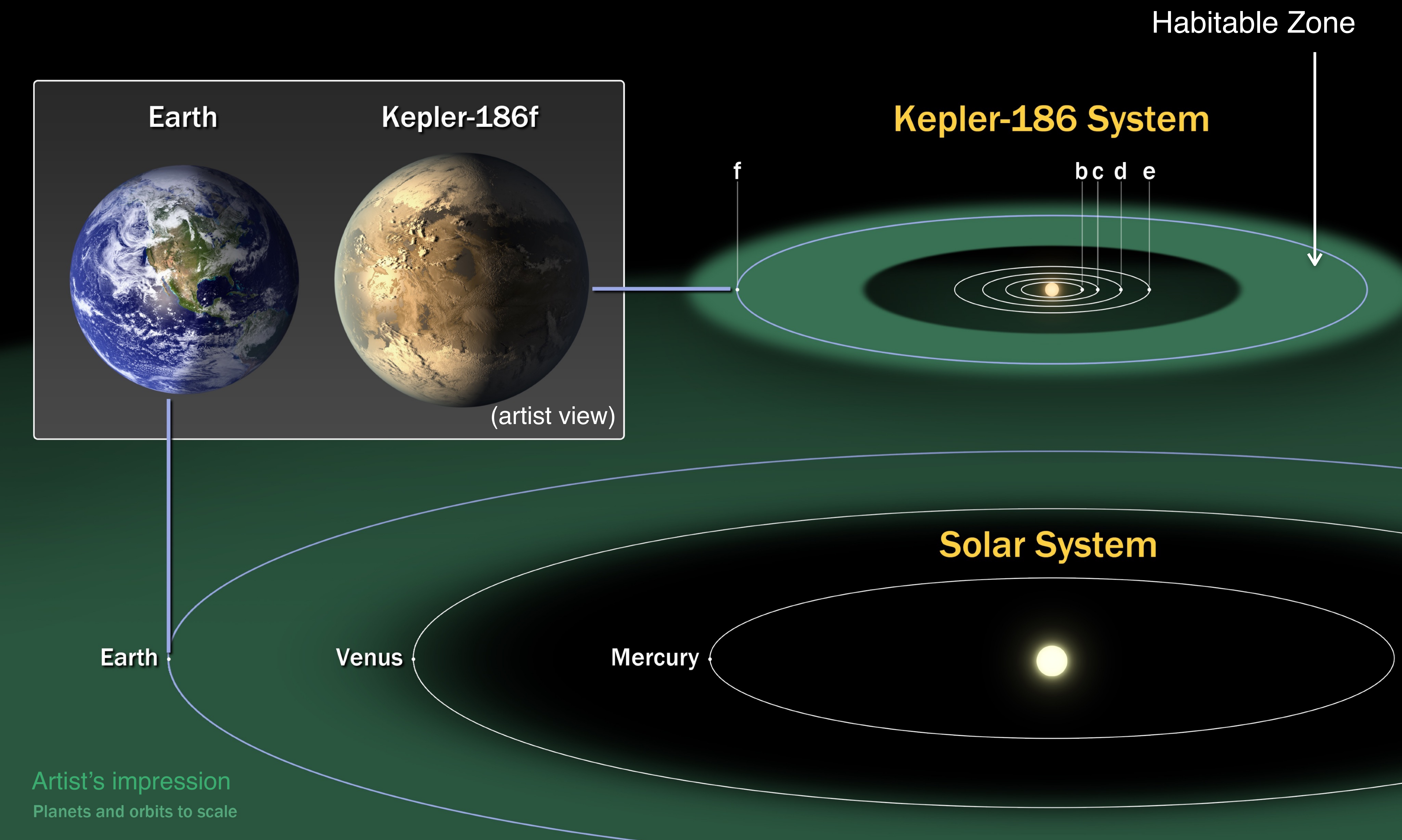


Proxima Centauri: the closest star to the Sun

July 2015: ***Kepler-186f*** first Earth-size planet in *Habitable Zone*

Main-sequence M1 dwarf star: *Kepler-186*

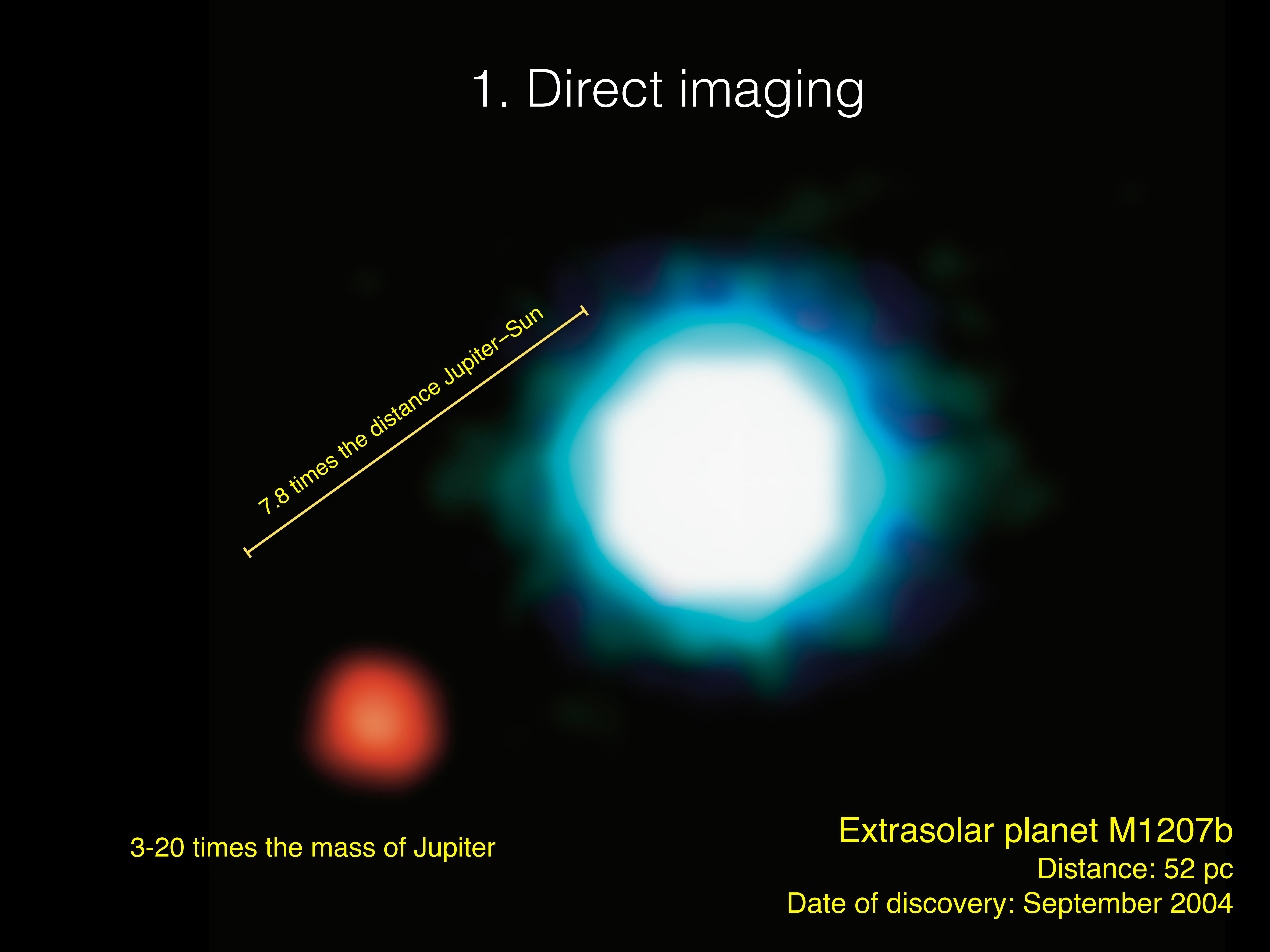
Distance from Earth: $d = 151 \pm 18$ pc



How extrasolar planets are found

Most successful

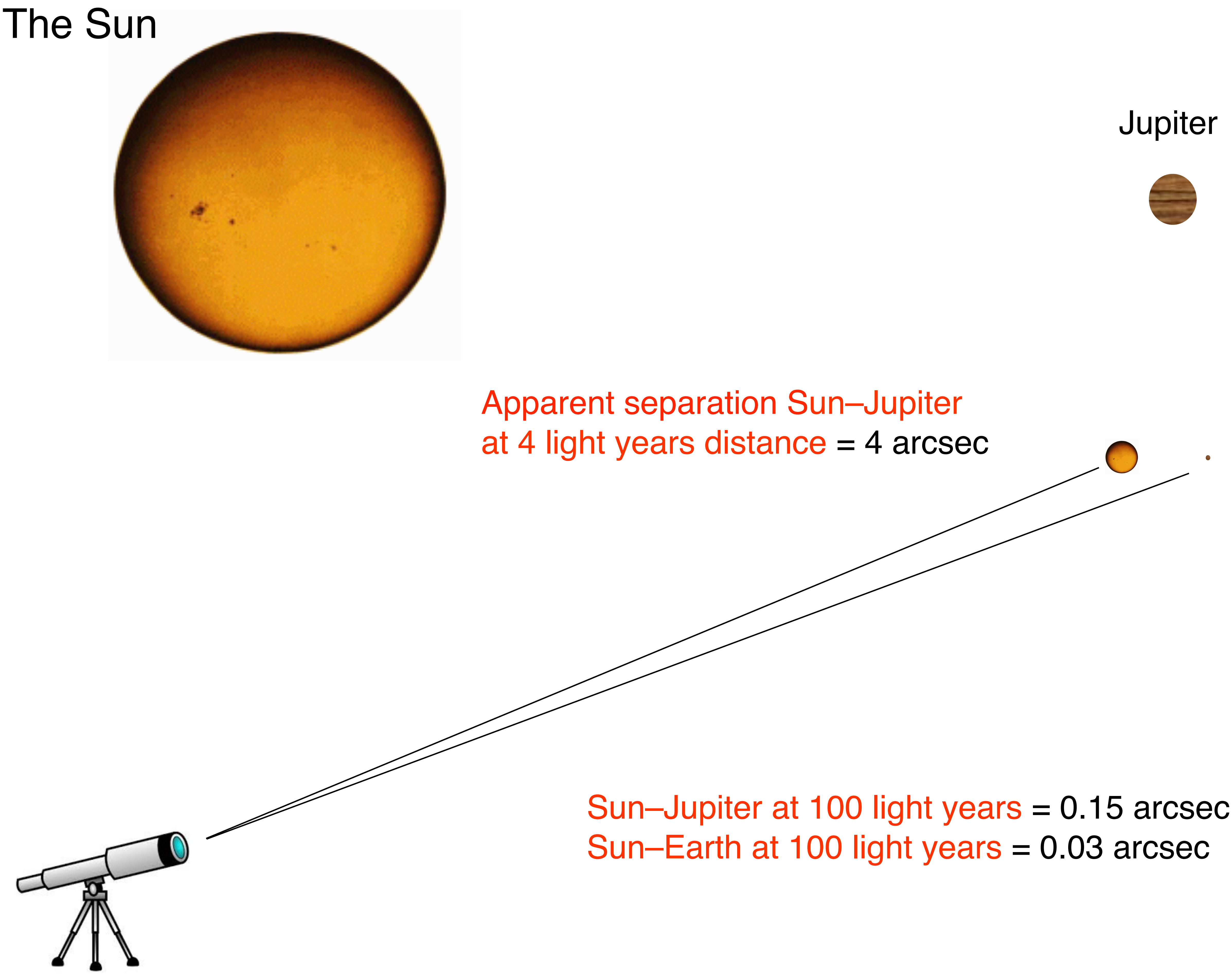
1. Direct imaging
2. Radial velocity
3. Transiting
4. Gravitational lensing
5. Transit-timing variation


1. Direct imaging
7.8 times the distance Jupiter–Sun
3-20 times the mass of Jupiter
Extrasolar planet M1207b
Distance: 52 pc
Date of discovery: September 2004

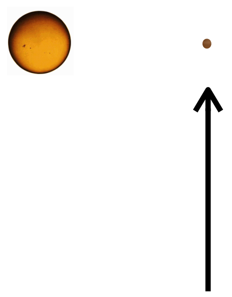
1. Direct imaging

Two main difficulties:

a) Angular separation very small
b) Large contrast in luminosity


The Sun
Jupiter
Apparent separation Sun–Jupiter
at 4 light years distance = 4 arcsec
Sun–Jupiter at 100 light years = 0.15 arcsec
Sun–Earth at 100 light years = 0.03 arcsec

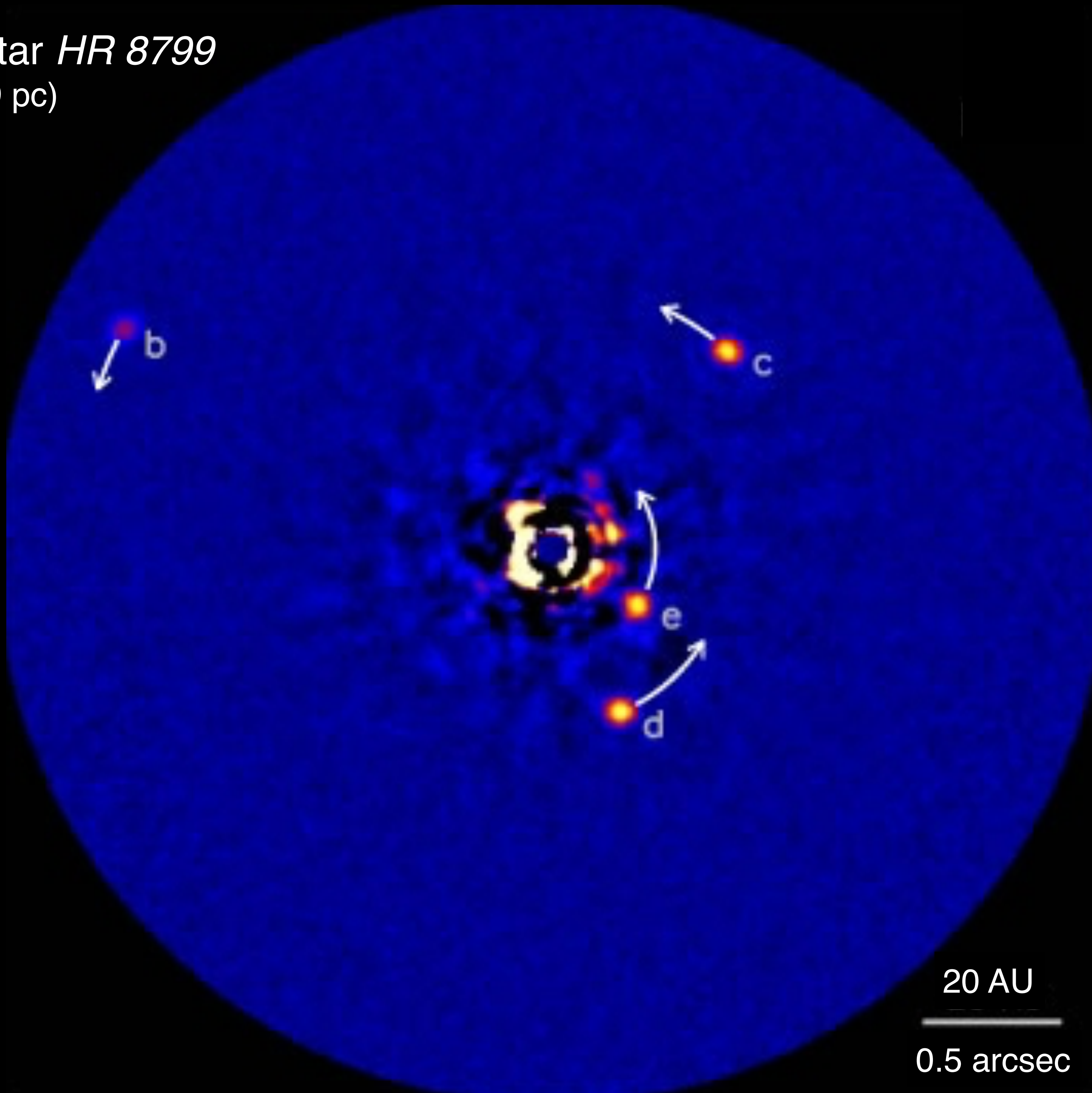
Star up to 10^9 times brighter than planet



Star up to 10^9 times brighter than planet

One solution: coronograph to block light

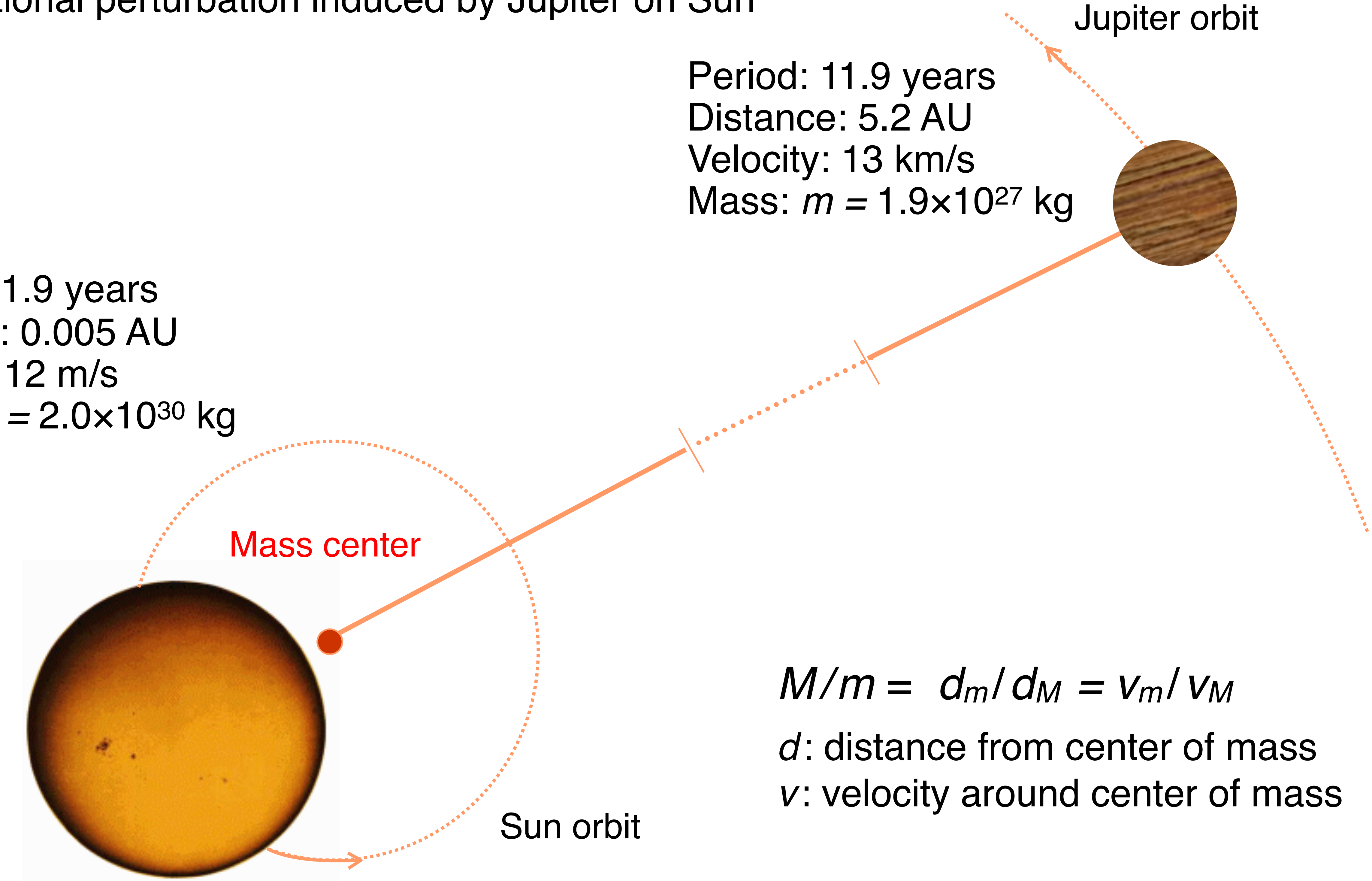
Main-sequence star *HR 8799*
Distance: 129 l.y. (39 pc)
Mass: $M = 1.5\ M_\odot$



Possible several alternative methods to direct imaging

2. Radial Velocity

Gravitational perturbation induced by Jupiter on Sun



Period: 11.9 years
Distance: 5.2 AU
Velocity: 13 km/s
Mass: $m = 1.9\times10^{27}$ kg

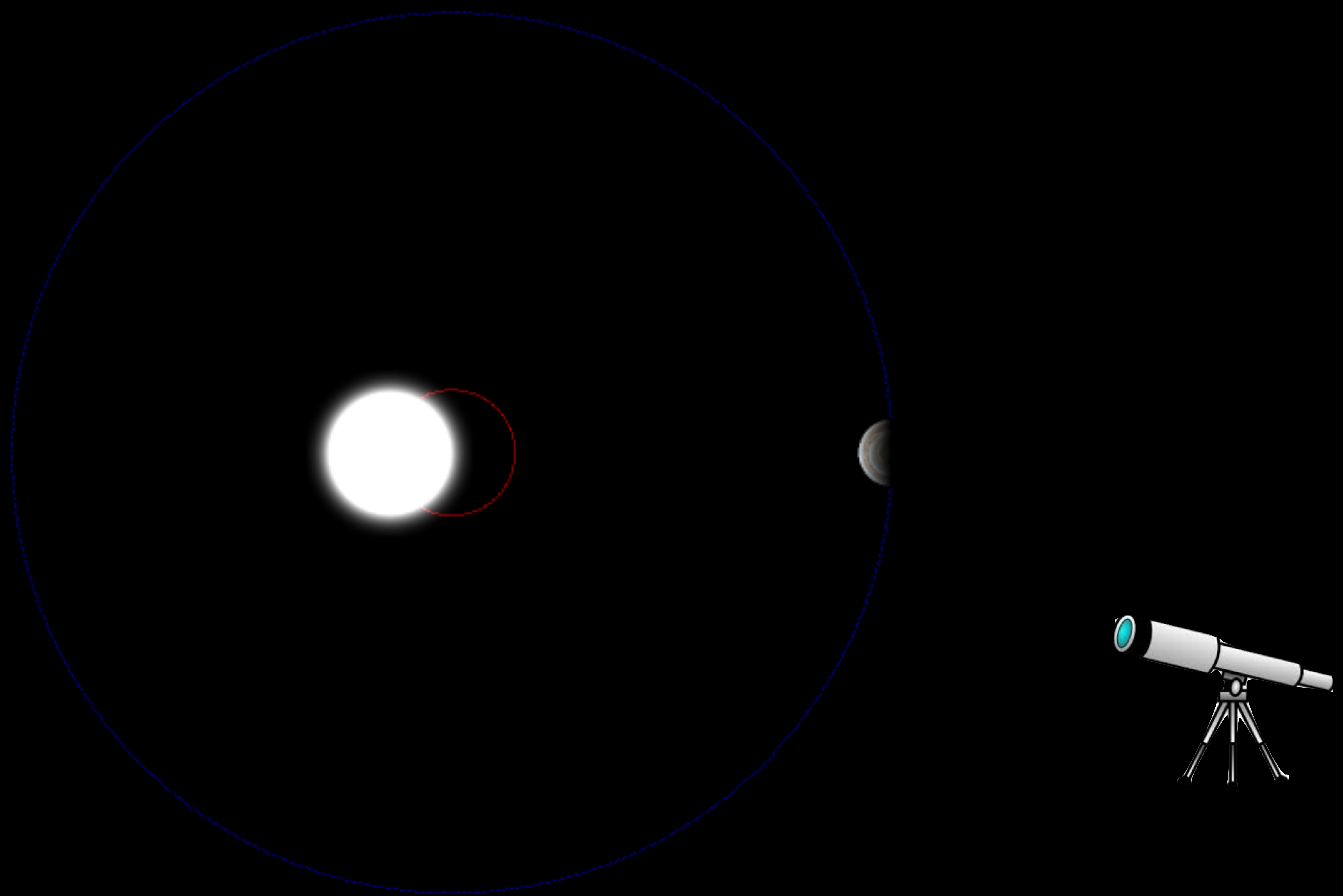
Period: 11.9 years
Distance: 0.005 AU
Velocity: 12 m/s
Mass: $M = 2.0\times10^{30}$ kg

$$M/m = d_m/d_M = v_m/v_M$$

d: distance from center of mass
v: velocity around center of mass

Radial Velocity

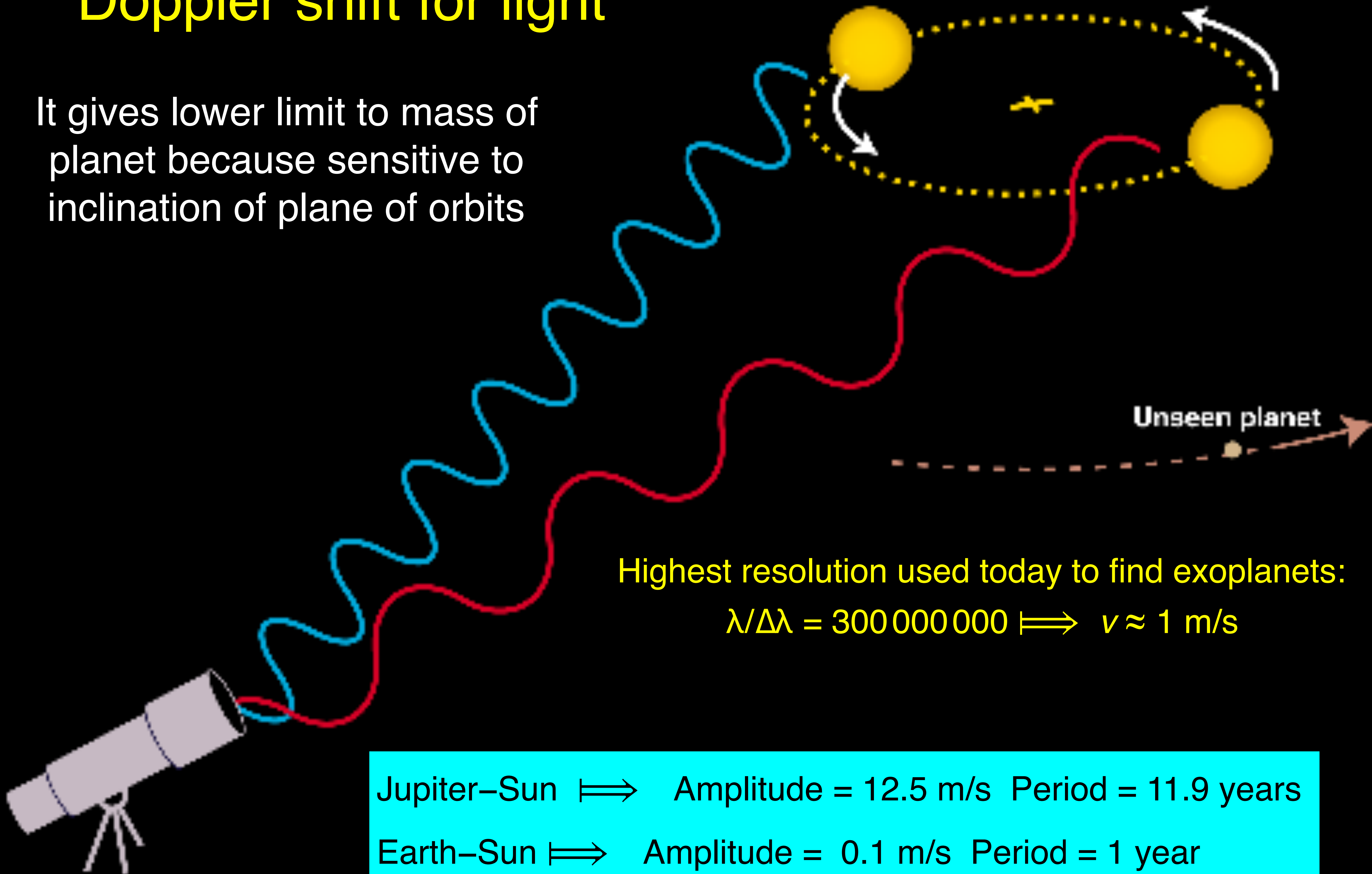
Sensible to short periods and massive planets



Animation: https://www.youtube.com/watch?v=nTq0gG_PpgU

Doppler shift for light

It gives lower limit to mass of planet because sensitive to inclination of plane of orbits



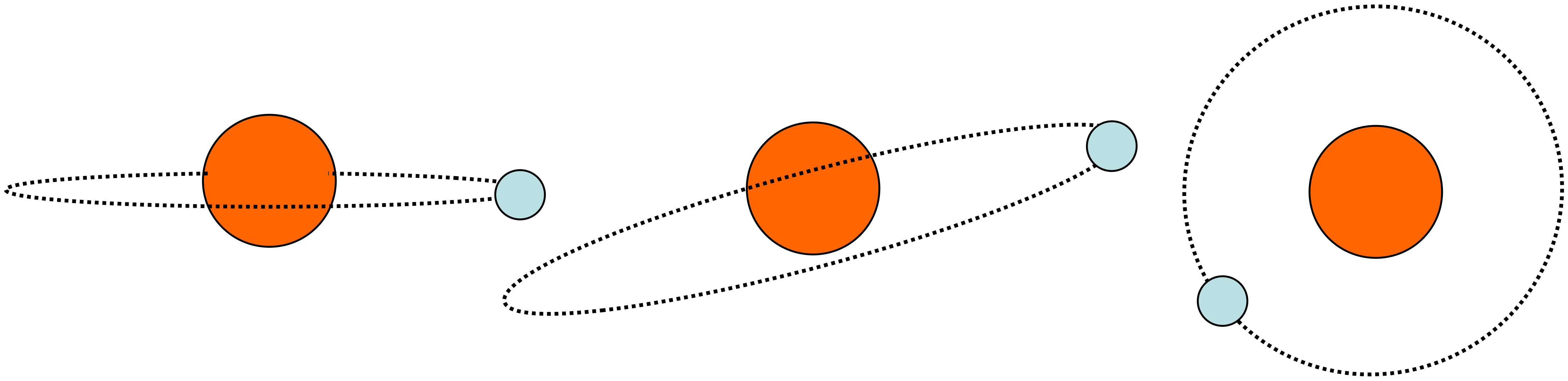
Highest resolution used today to find exoplanets:

$\lambda/\Delta\lambda = 300\,000\,000 \Longrightarrow \; v \approx 1$ m/s

Jupiter–Sun $\Longrightarrow$ Amplitude = 12.5 m/s Period = 11.9 years

Earth–Sun $\Longrightarrow$ Amplitude = 0.1 m/s Period = 1 year

Mass of the planet depend on inclination of plane of orbit

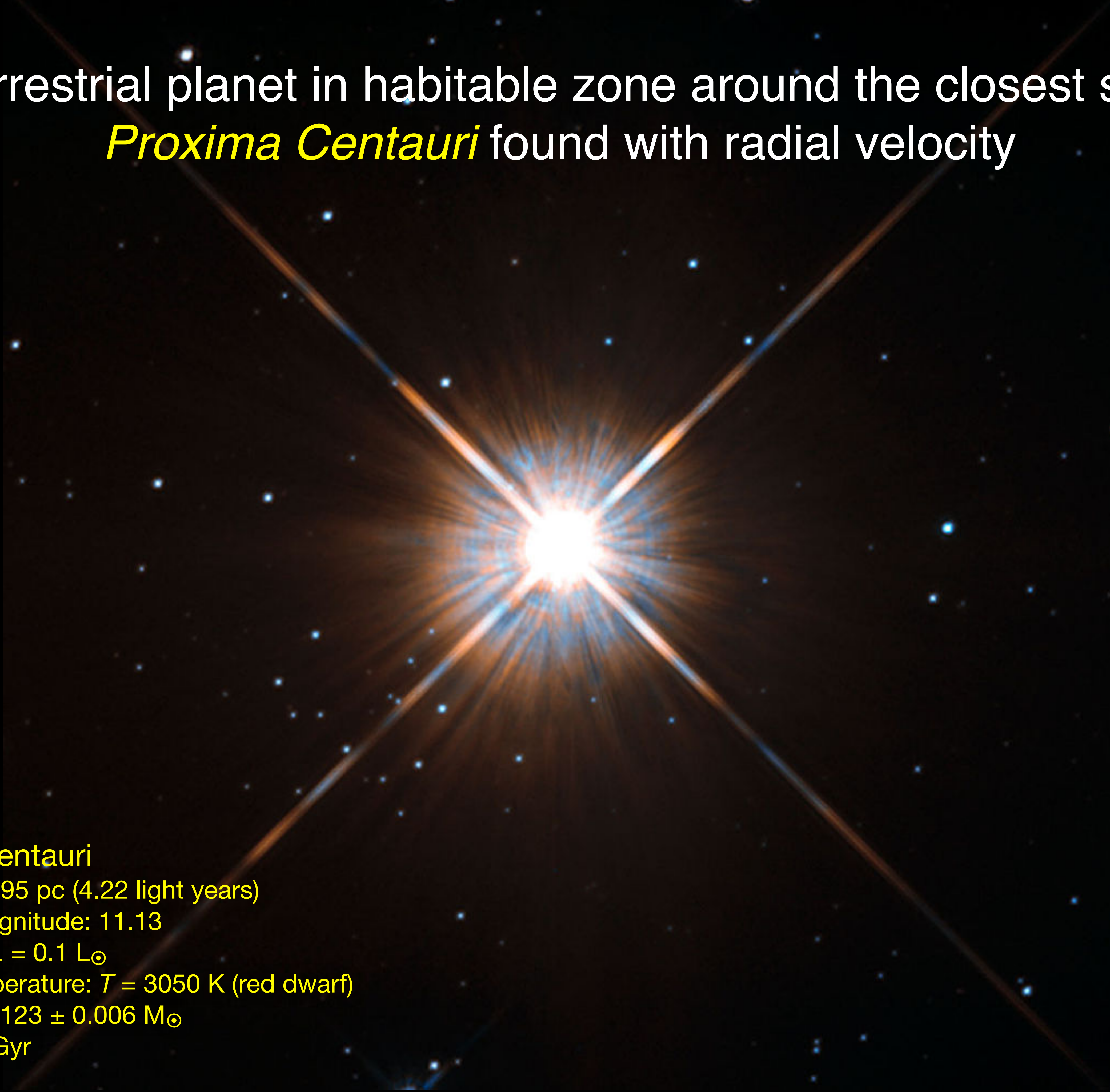


Edge-on orbit (angle $i = 90^o$)
Maximum radial velocity can be measured

Face-on orbit (angle $i = 0^o$)
Mass estimate is not possible

Mass of planet is proportional to $\sin(i)$ thus only upper limit on mass possible

Terrestrial planet in habitable zone around the closest star *Proxima Centauri* found with radial velocity



Proxima Centauri

Distance: 1.295 pc (4.22 light years)

Apparent magnitude: 11.13

Luminosity: $L = 0.1\ L_{\odot}$

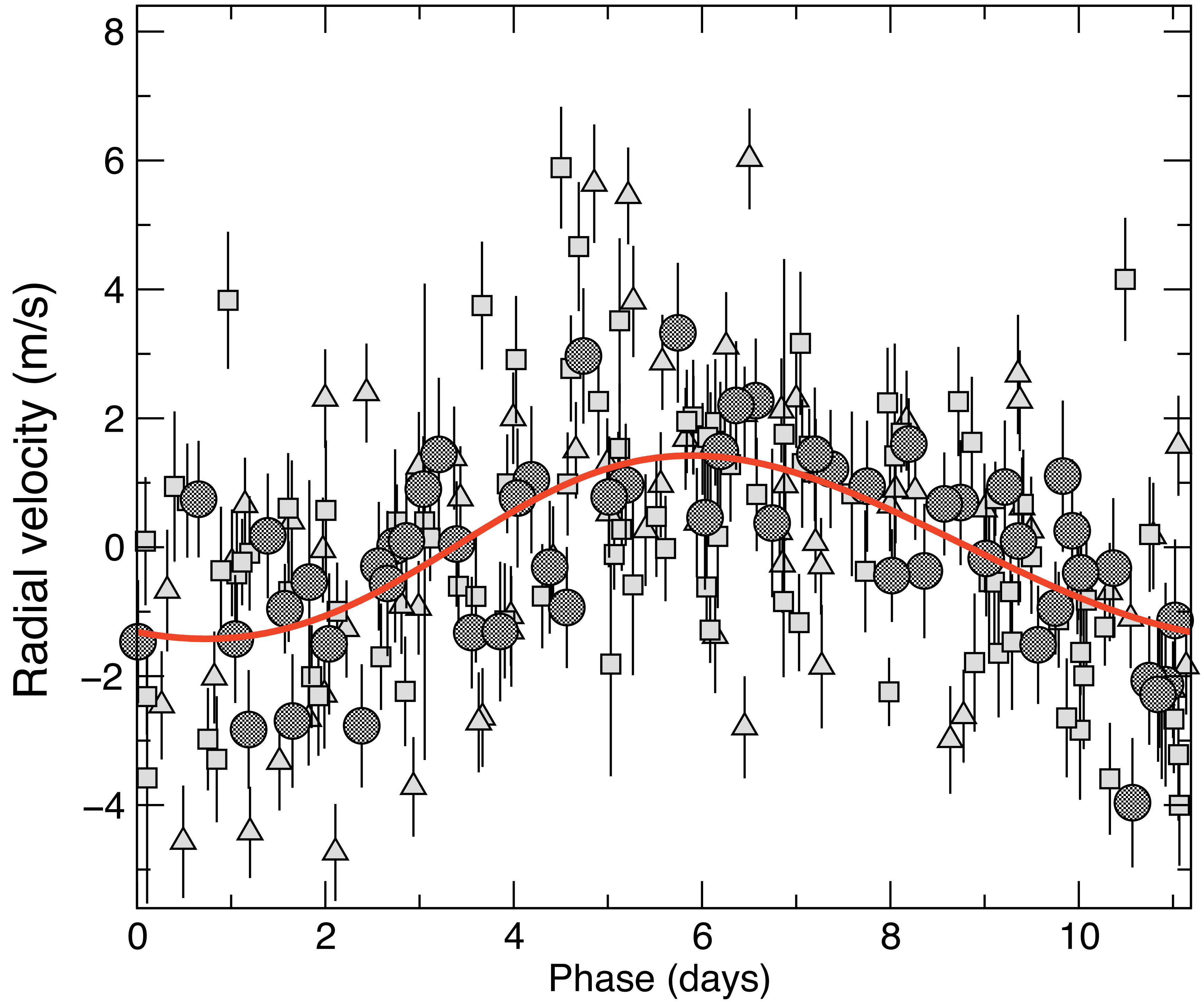
Surface temperature: $T = 3050$ K (red dwarf)

Mass: $M = 0.123 \pm 0.006\ M_{\odot}$

Age: $t = 4.8$ Gyr

Radial Velocity of Proxima Centauri
and discovery in August 2016 of planet ***Proxima b***

Radial Velocity:
v ~ 1.4 m/s



Planet: *Proxima b*

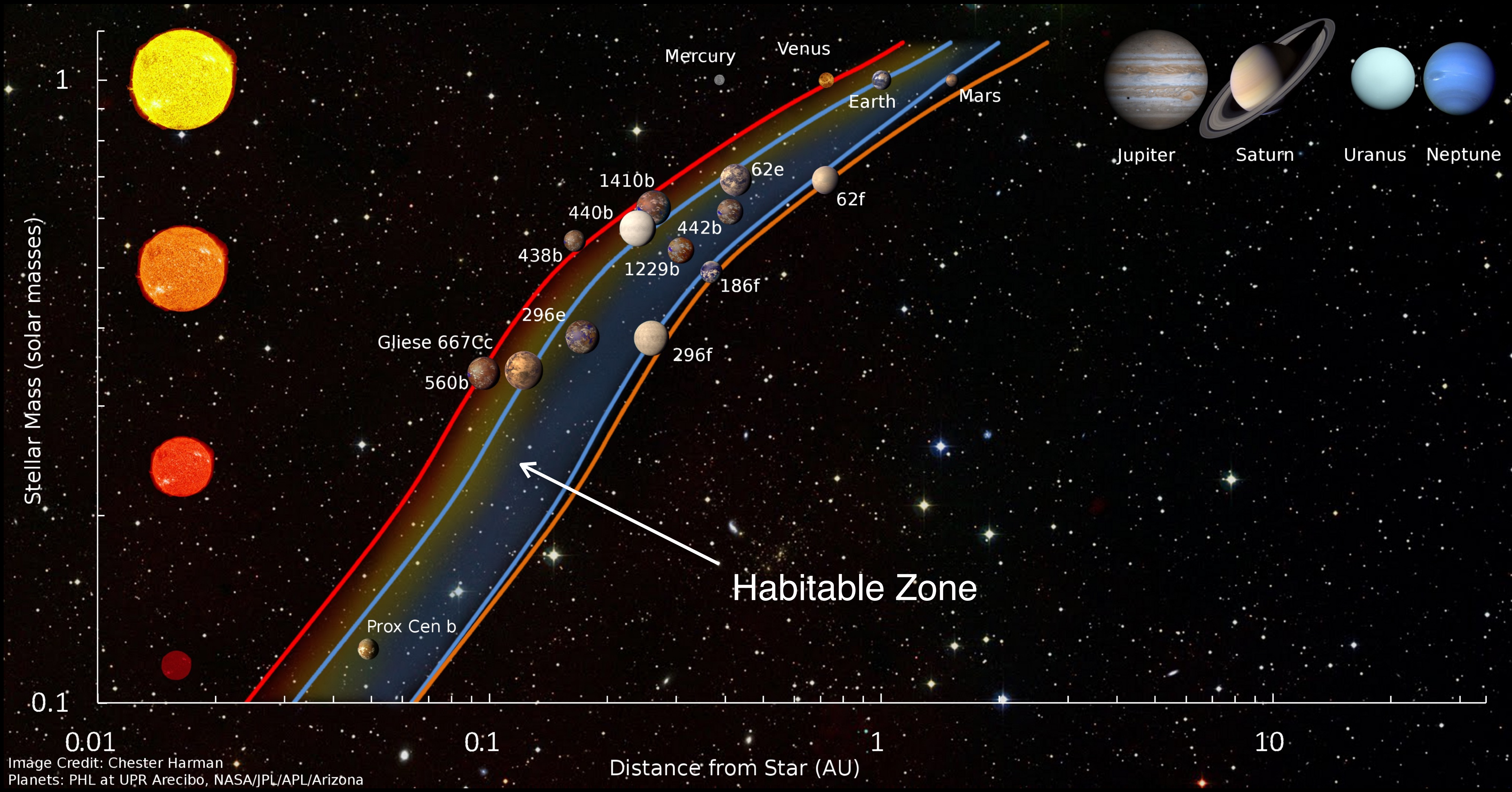
Orbital period: 11.2 days

Mass: $M > 1.27$ M$_E$

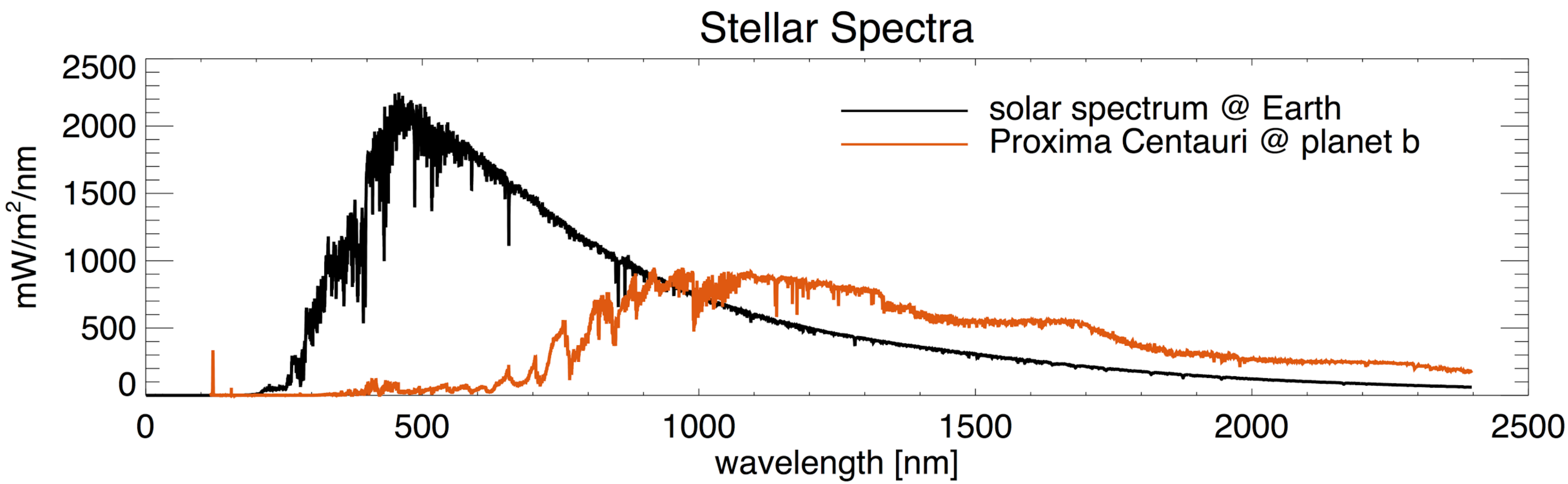
Distance from star: d ~ 0.05 AU (7.5 million km)

M$_E$: Earth's mass

Habitability of planets orbiting *M*-dwarf stars



Spectrum of Proxima Centauri at the distance of planet *Proxima b* (compared to solar spectrum)



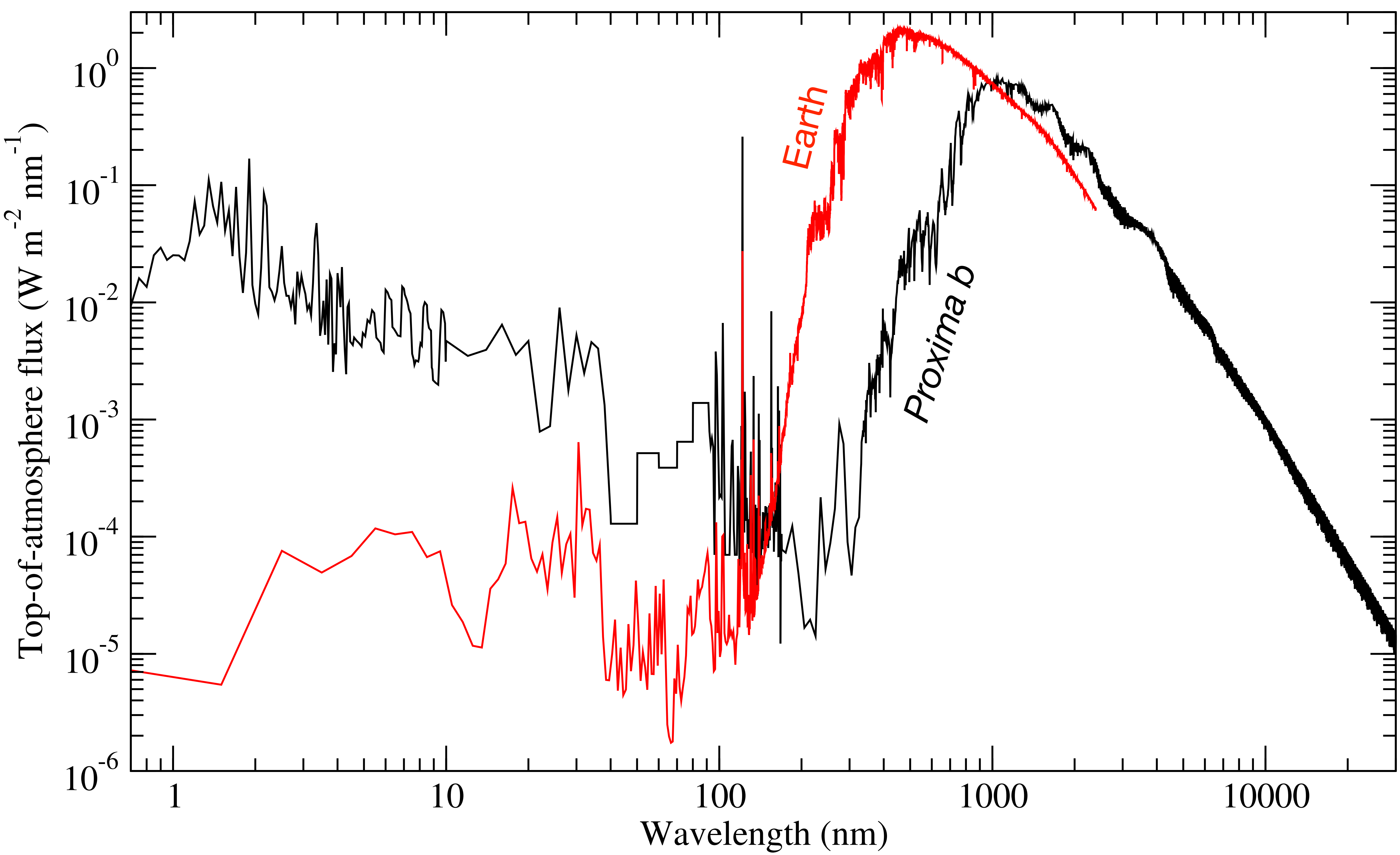
Proxima b receives ~0.66 times the stellar flux of Earth at 1 AU from the Sun

But habitability is not guaranteed:

1. In case of no atmosphere surface temperature: $T \sim -40°C$ ✘
2. If atmosphere present with CO_2 or CH_4 $\Longrightarrow$ greenhouse effect ✔
3. If H_2O present $\Longrightarrow$ in liquid form ✔
4. But red dwarf stars have strong magnetic activity $\Longrightarrow$ More intense X-ray and UV flux from flares than for Sun ✘
5. More intense stellar wind will erode planet atmosphere ✘
6. Temperature depends on coverage of vegetation, ice and ocean $\Longrightarrow$ effect on the Albedo (reflection of stellar radiation)

Top-of-atmosphere full **spectral irradiance received** by *Proxima b* (orbital distance of 0.0485 AU) and the Earth

Almost 60 times higher than Earth

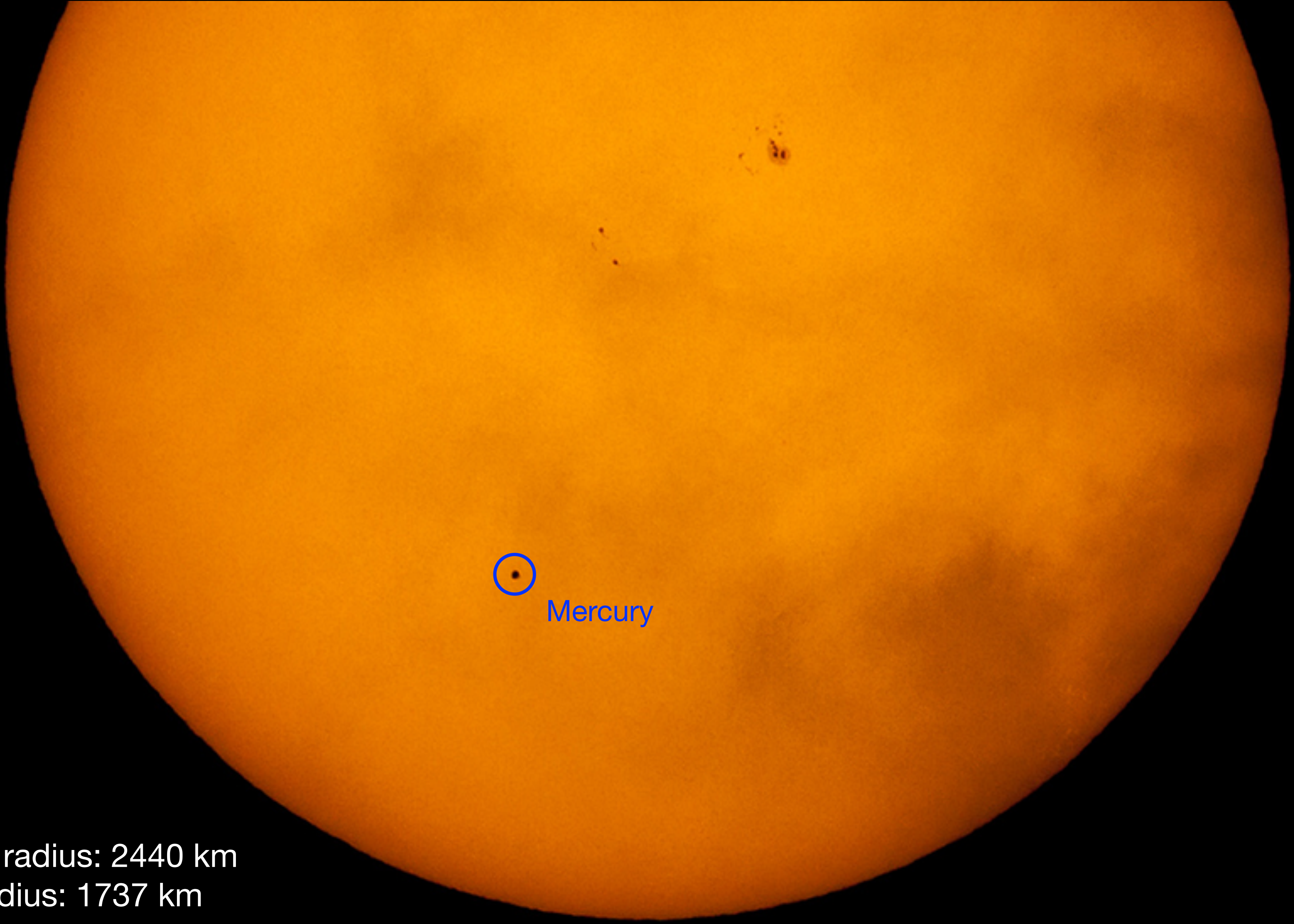


3. Occultation or transit

If small stars are observed, this method is sensitive to planets as small as Mercury

Eclipse 4/01/2011
& International Space Station

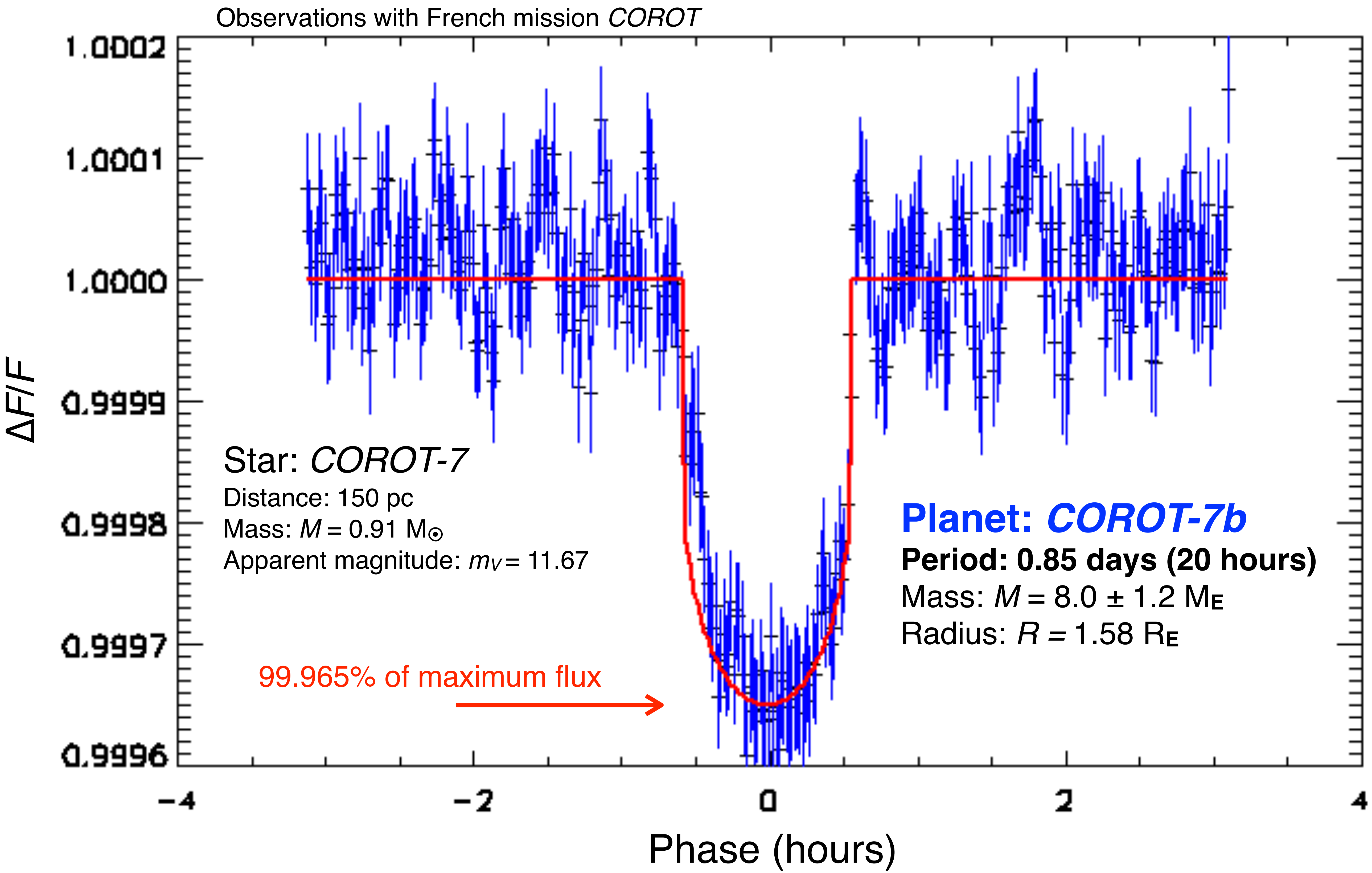
Image Credit: Thierry Legault



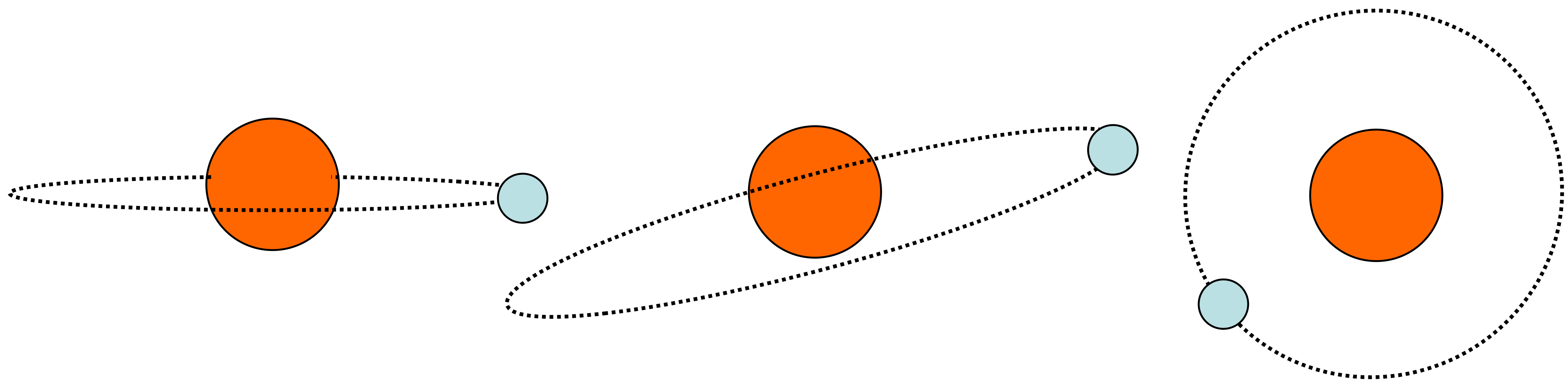
Mercury's radius: 2440 km
Moon's radius: 1737 km

Mercury transiting in front of the Sun (09/05/2016)

Light curve of star with transiting planet



Transit probability depends on inclination of plane of orbit



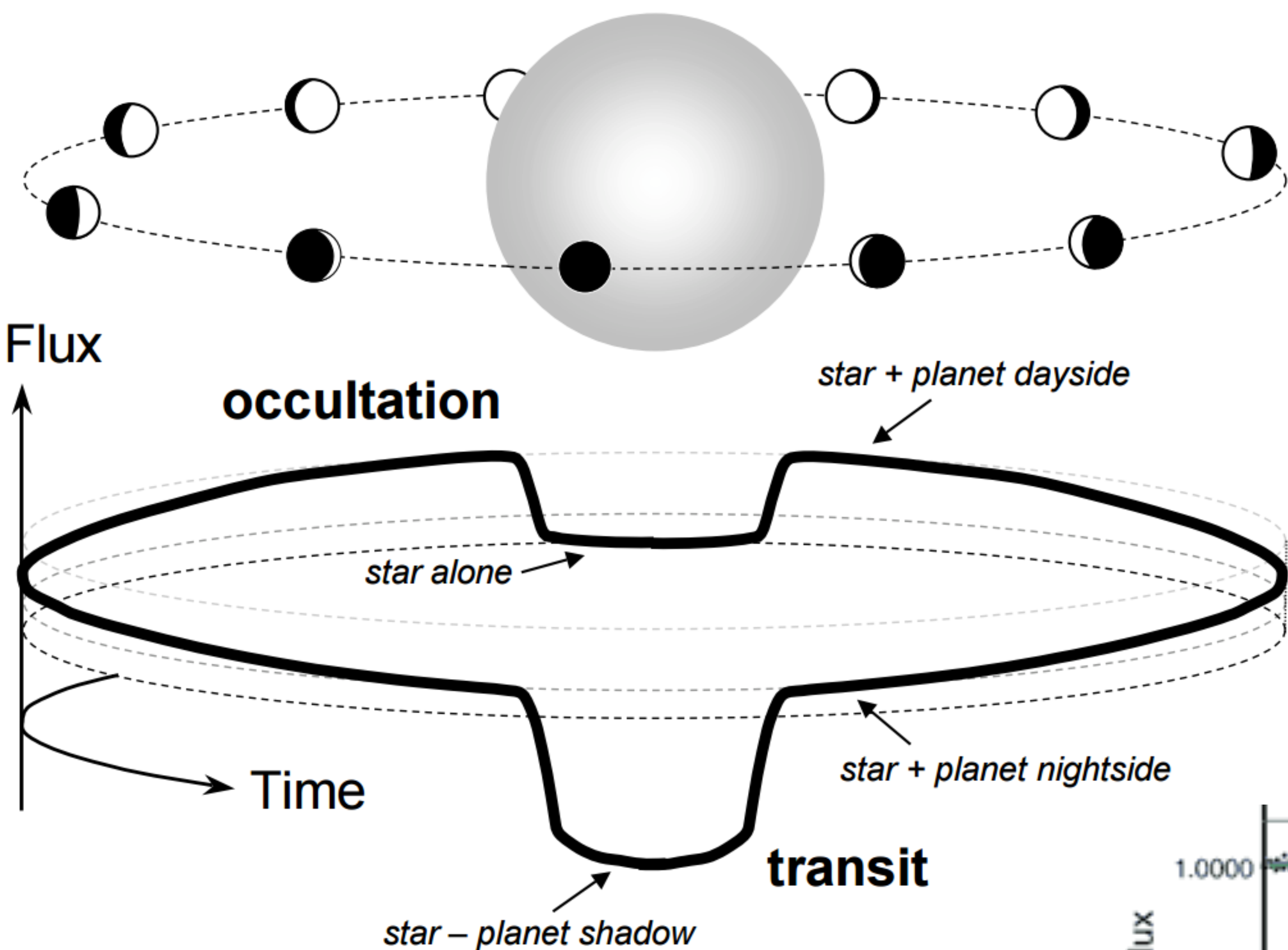
Edge-on orbit
(angle $i = 90^o$)

Face-on orbit
(angle $i = 0^o$)

Consequences: physical parameters of planet are uncertain

Transits allow measurements not possible with other methods

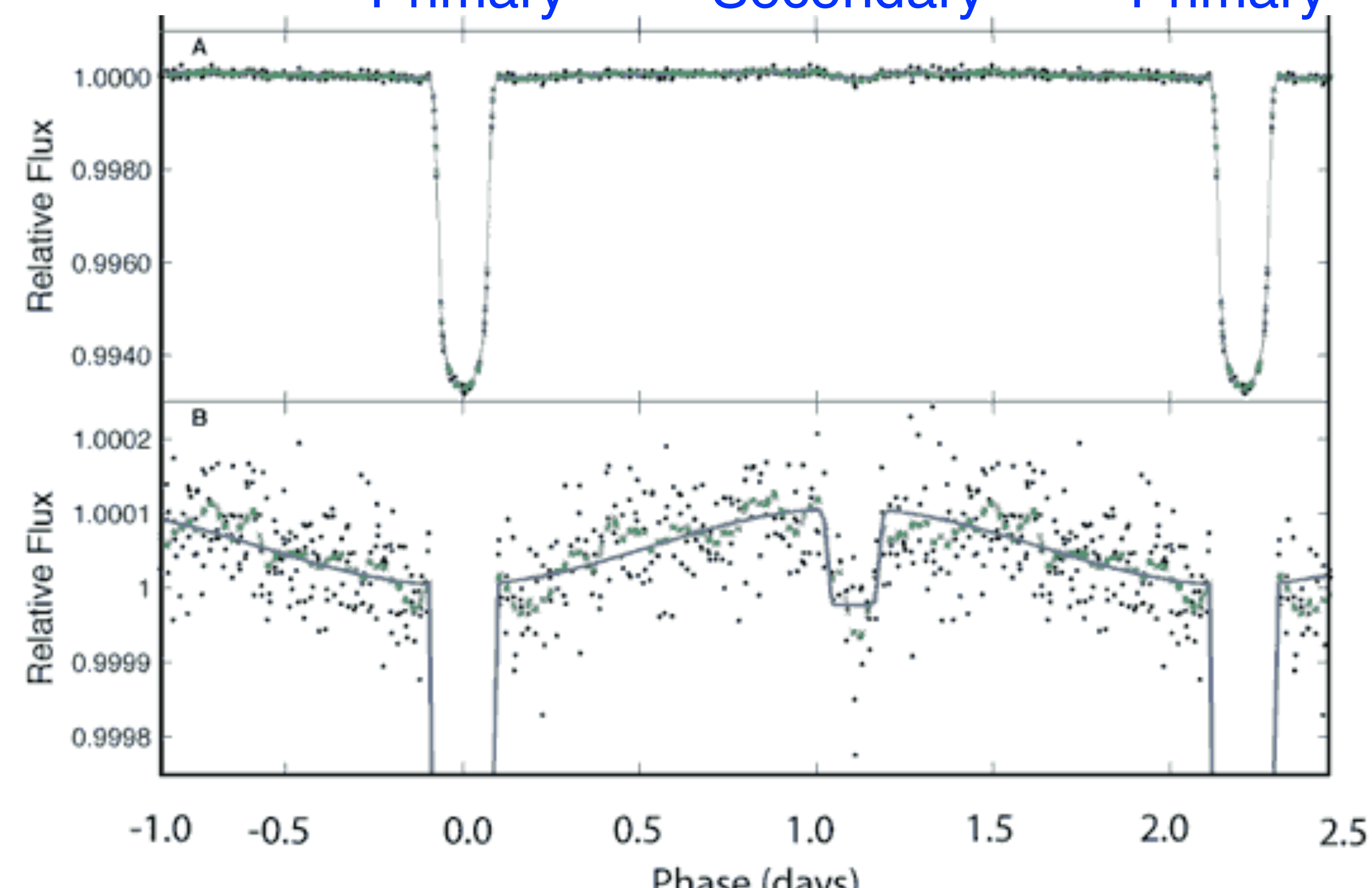
⟹Secondary eclipse



Primary eclipse

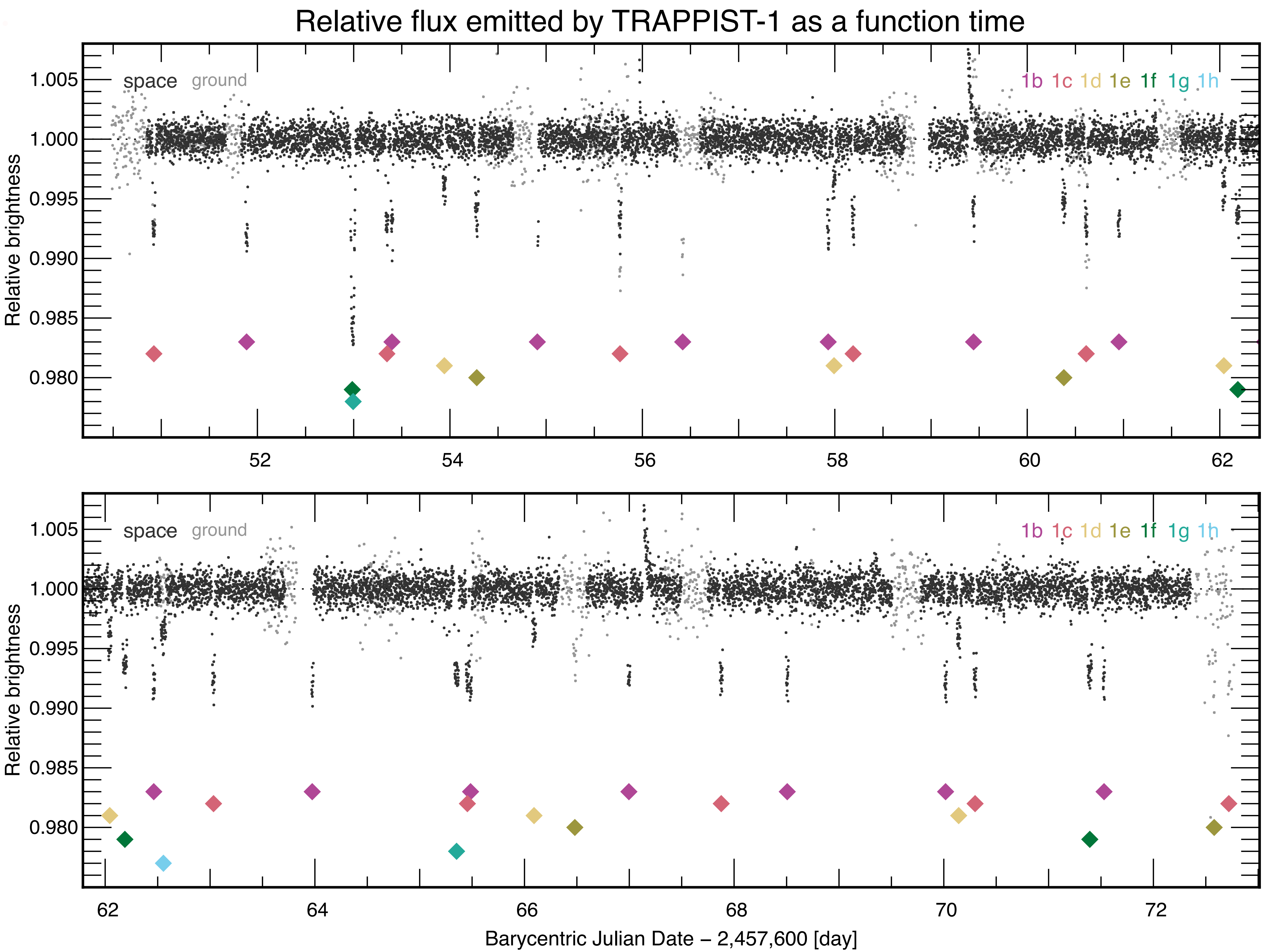
- **Size** of transiting planet
- If mass is known (radial velocity) planet's **density**
- Thus, physical structure
- Radiation of star through planet's ⟹ planet's **atmosphere**
- Planet's orbital **eccentricity**
- Planet's **temperature** (subtraction of signal during different phases)

Primary Secondary Primary



February 2017: **found 7 terrestrial planets**

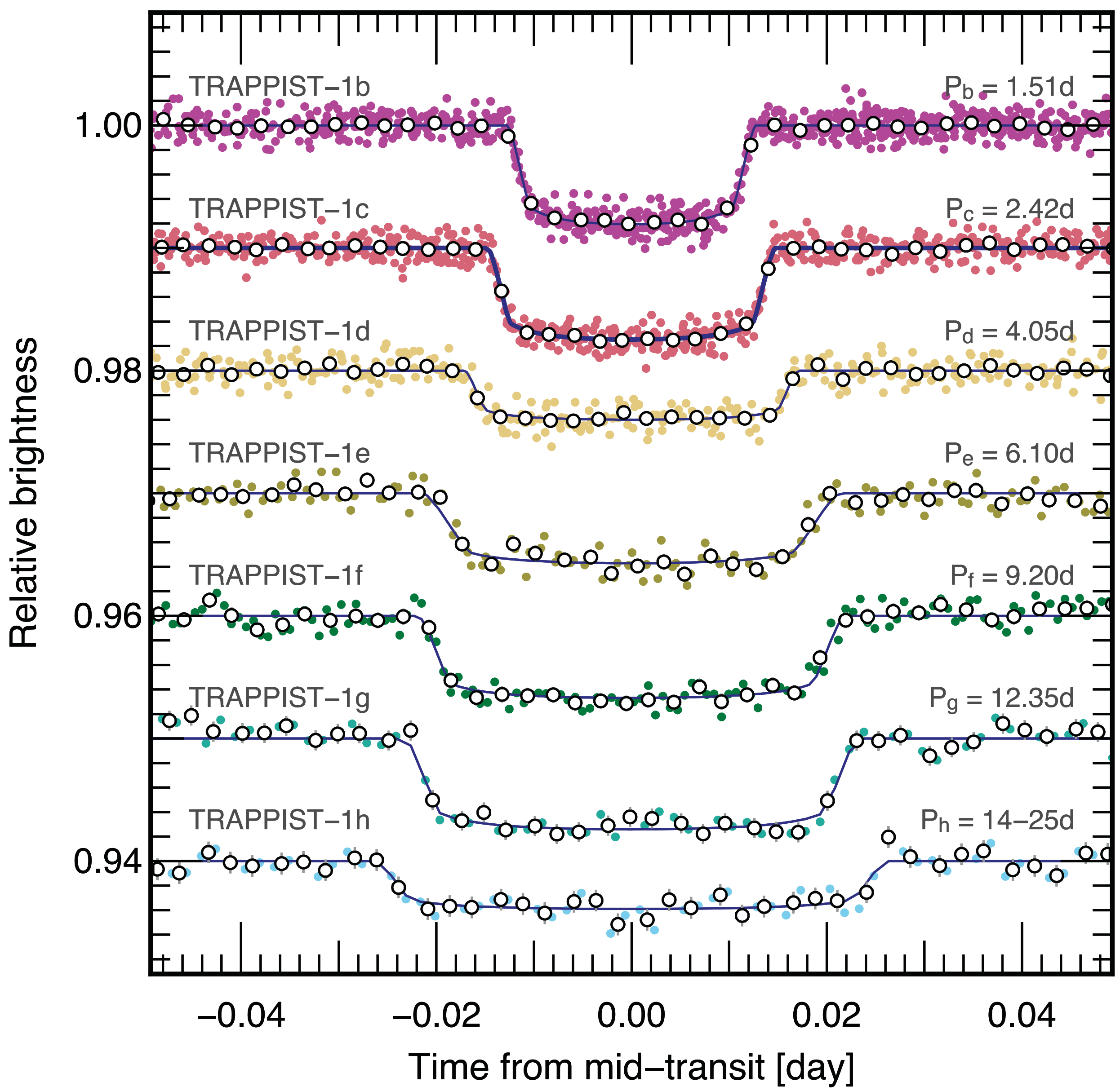
Around dwarf star *TRAPPIST-1* (mass: $M = 0.089\ M_{\odot}$, distance from Earth: $d = 12.1 \pm 0.4$ pc)



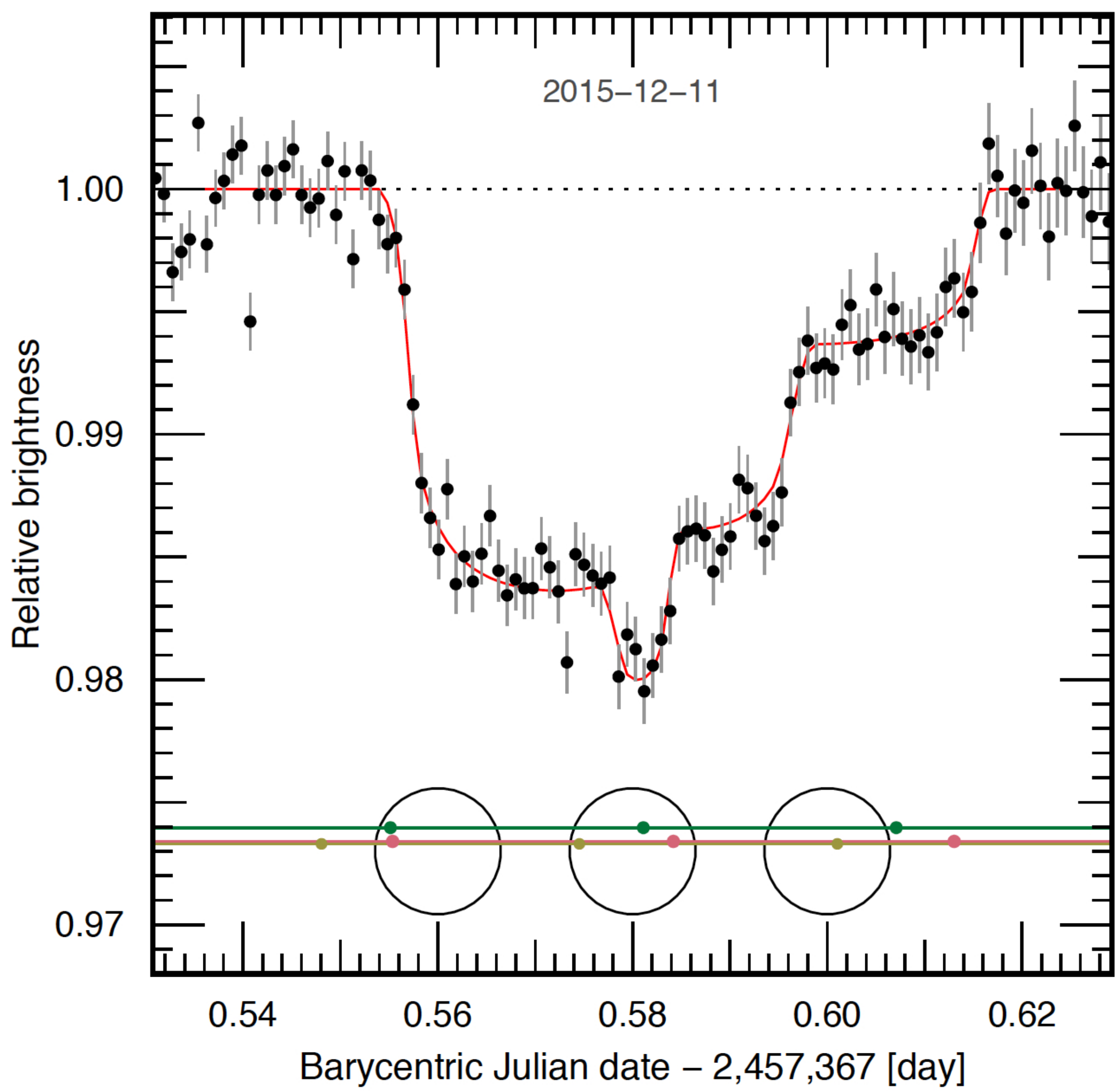
February 2017: **found 7 terrestrial planets**

Around dwarf star *TRAPPIST-1* (mass: $M = 0.089\ M_{\odot}$, distance from Earth: $d = 12.1 \pm 0.4$ pc)

Relative flux emitted by TRAPPIST-1 as a function time

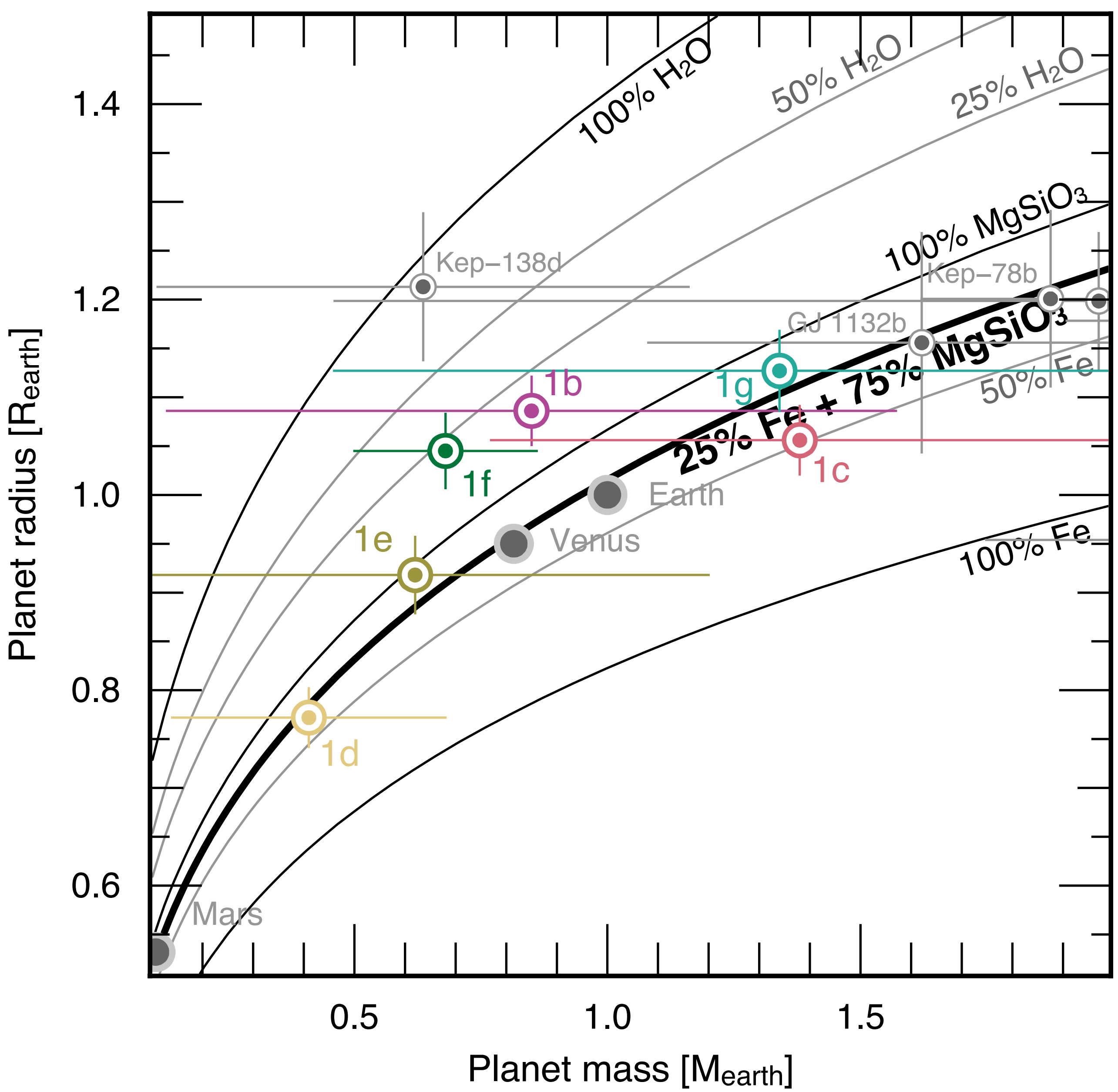


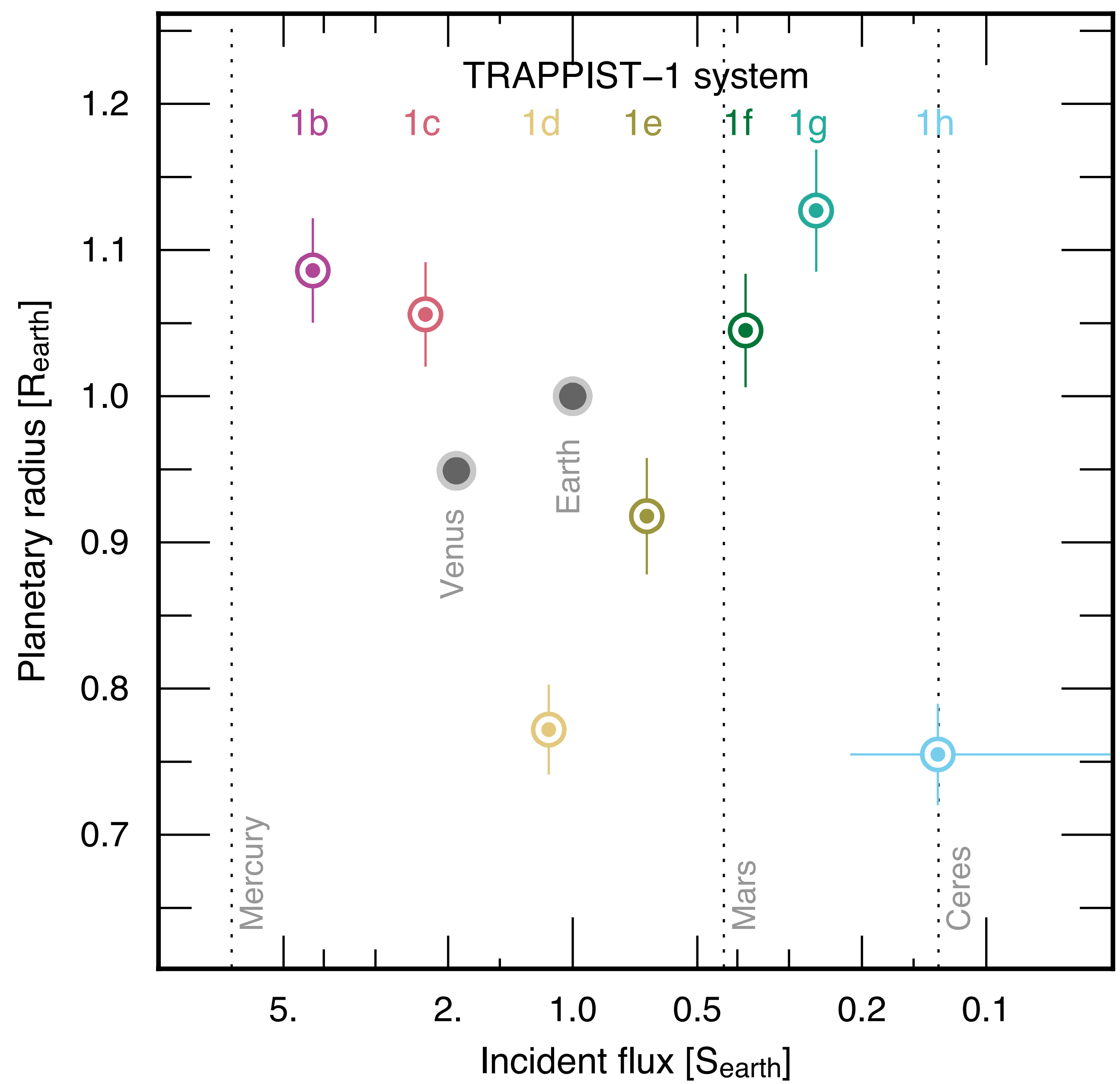
Multiple transits



Radius & **mass** of planets around *TRAPPIST-1*

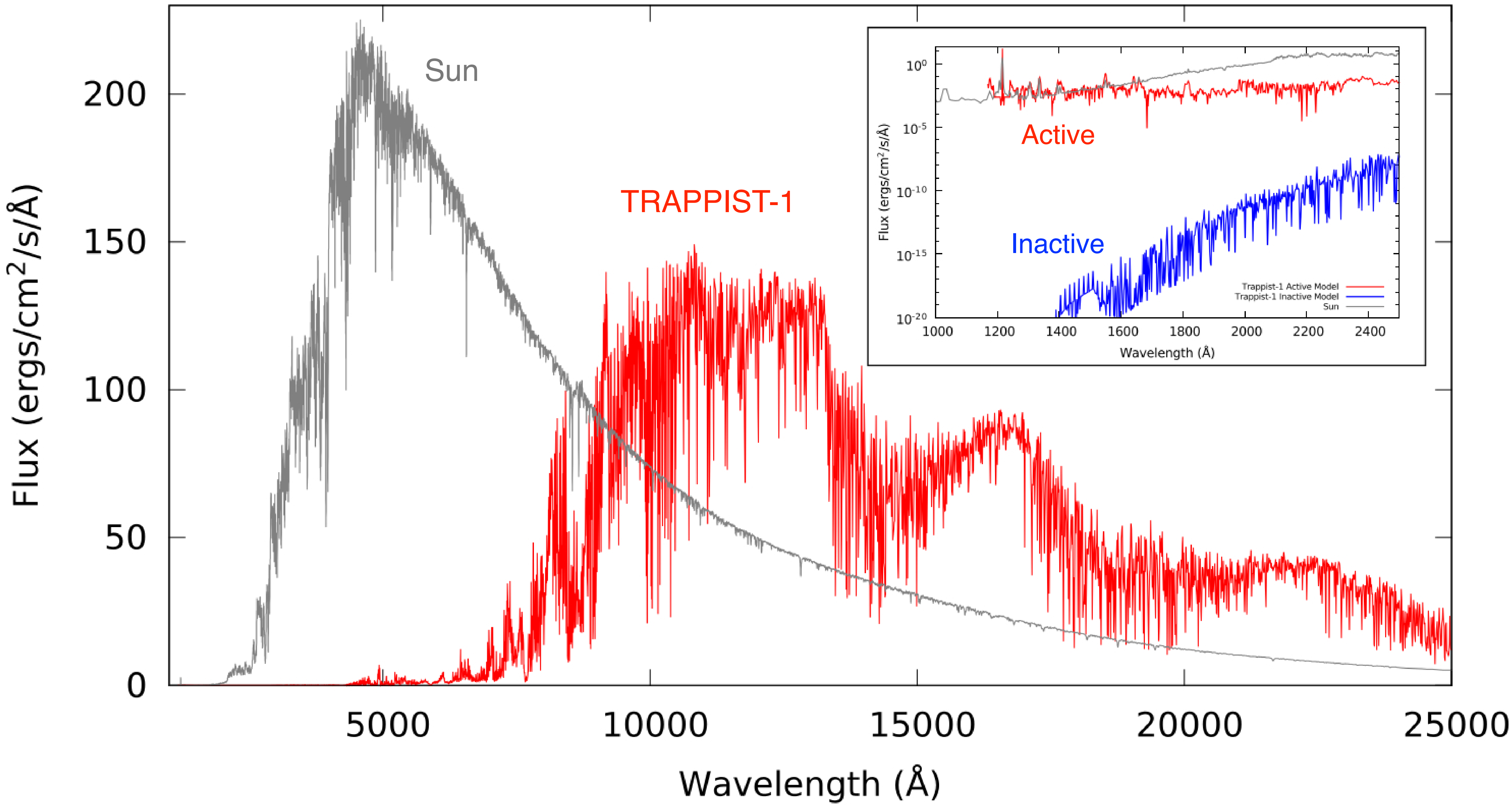
Radius-mass relation depends on chemical composition





Comparison with planets in the solar system

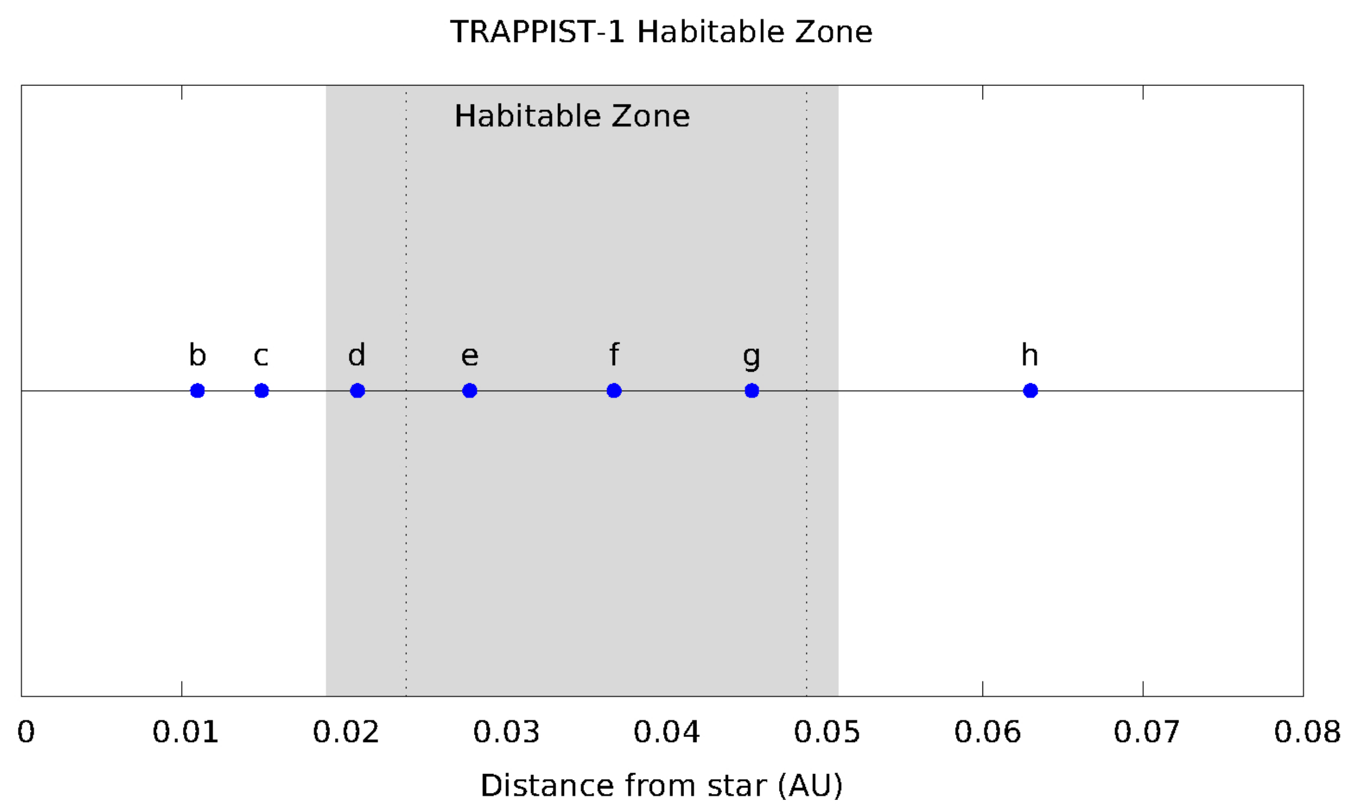
Habitability of planets around dwarf star *TRAPPIST-1*



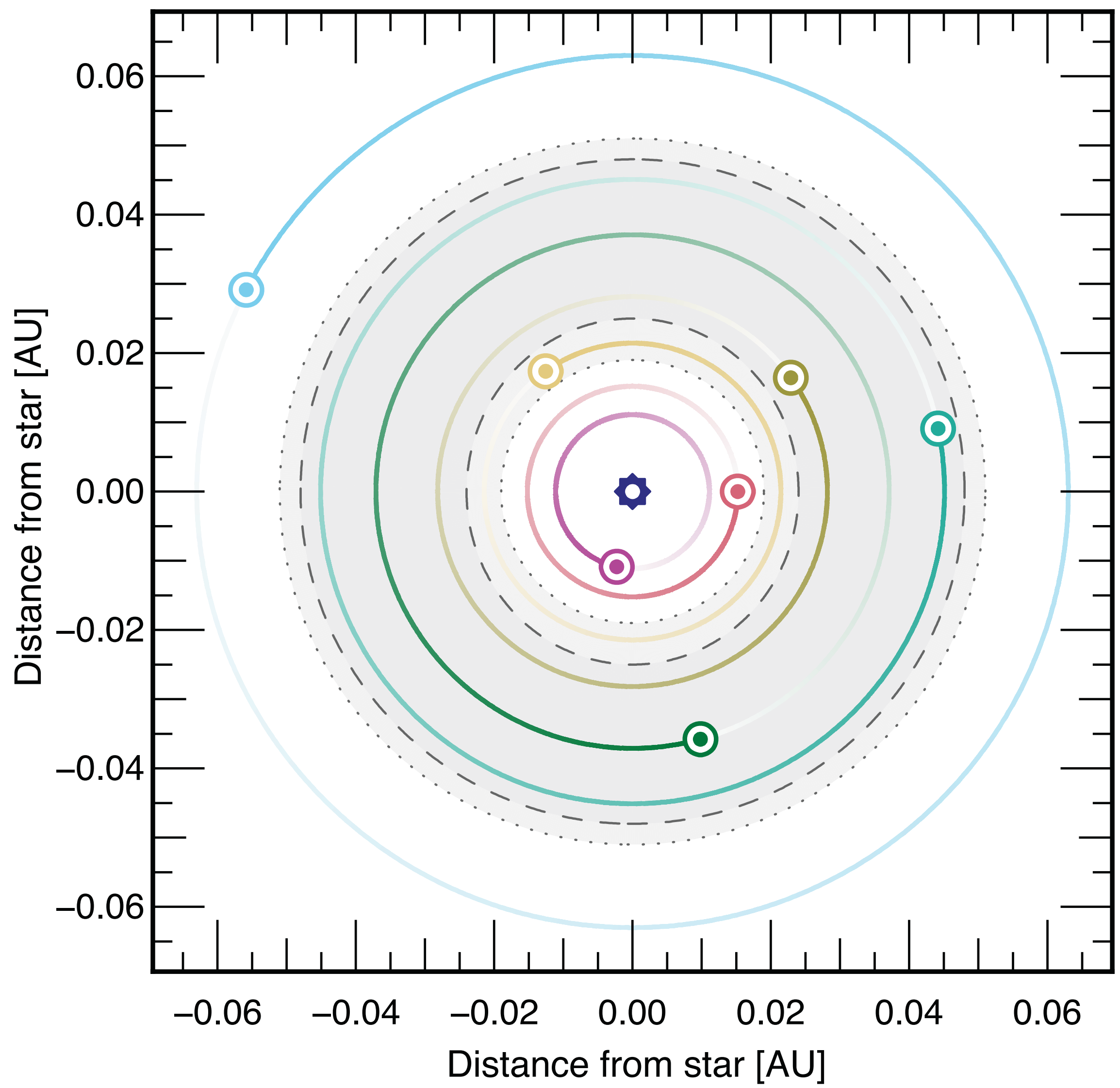
The star is strong variable coronal X-ray source similar to Sun but at short distance

Habitability is not guaranteed (same as in planet *Proxima b* around star Proxima Centauri)

Habitability of planets around dwarf star *TRAPPIST-1*



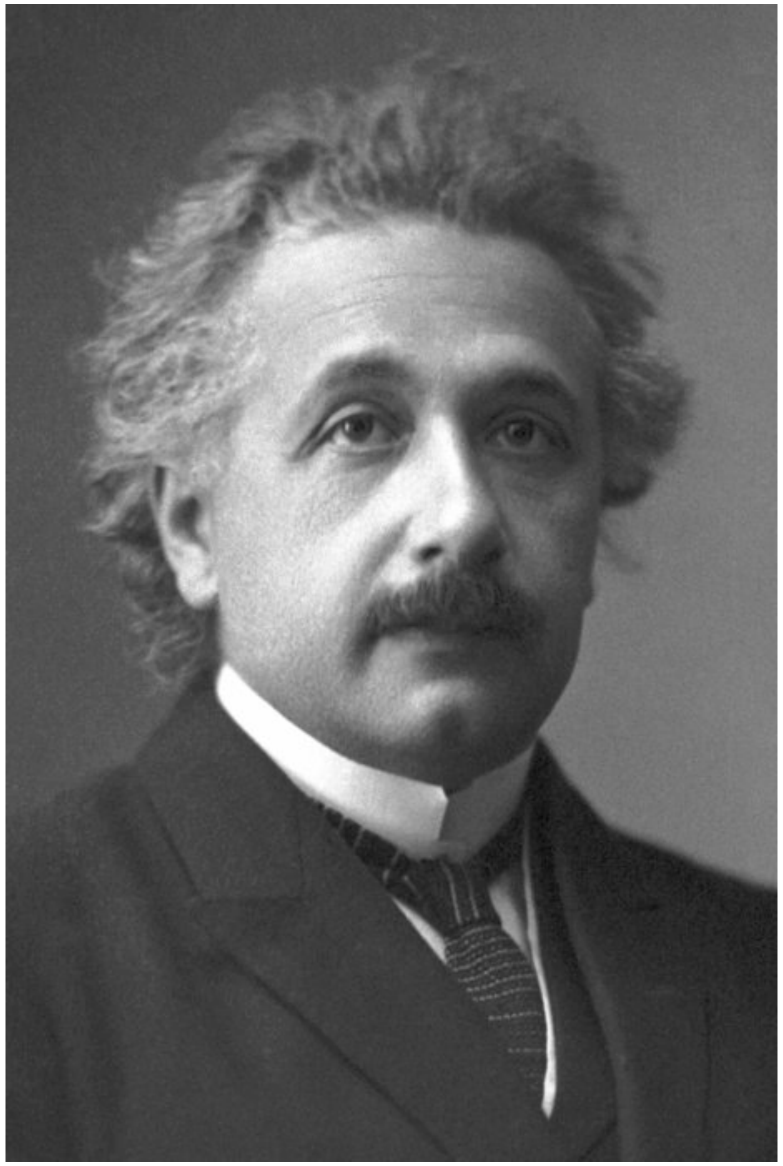
Planets close to resonance
(ratios of periods close to integers)



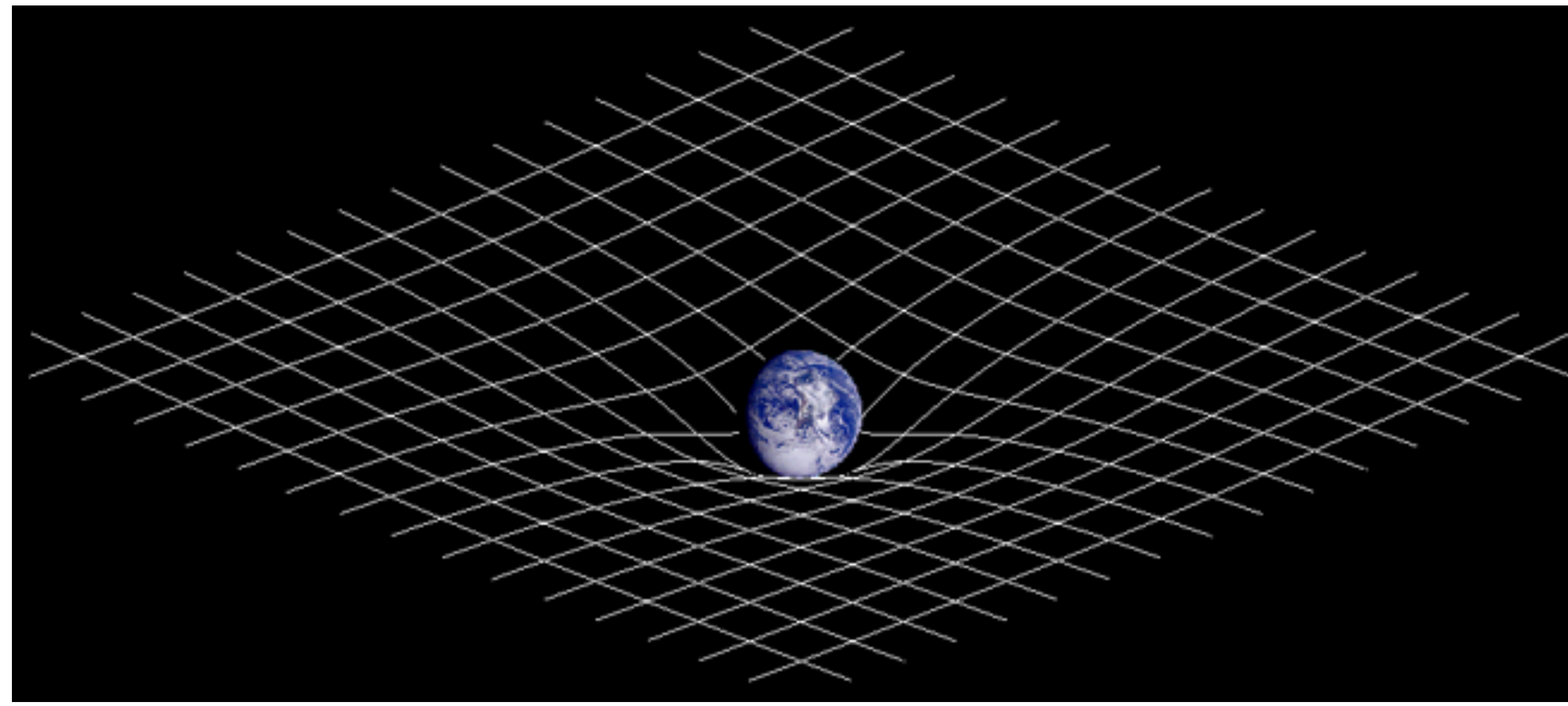
Litho-panspermia in *TRAPPIST-1* much more efficient than on Earth because planets are close

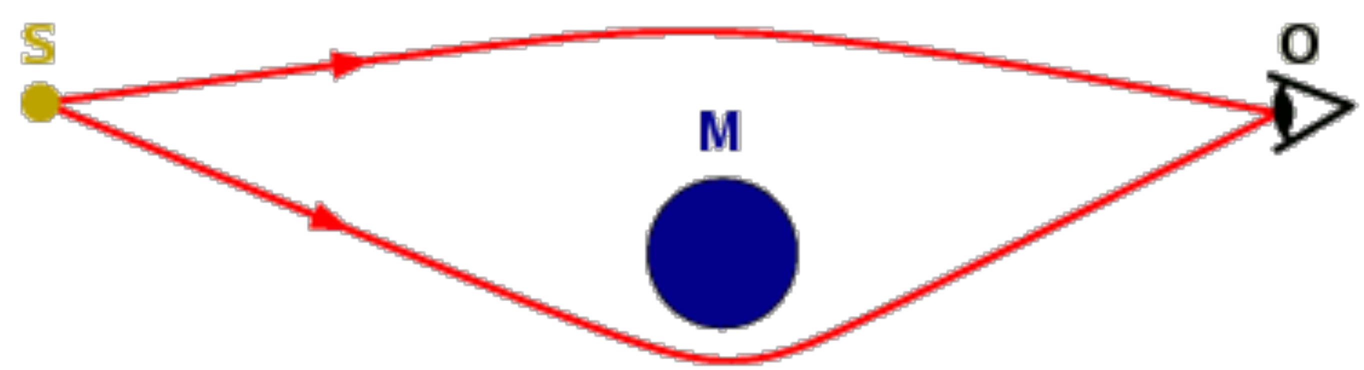
Litho-panspermia: life distributed from one planet to another by meteoroids, asteroids, comets

4. Gravitational lensing

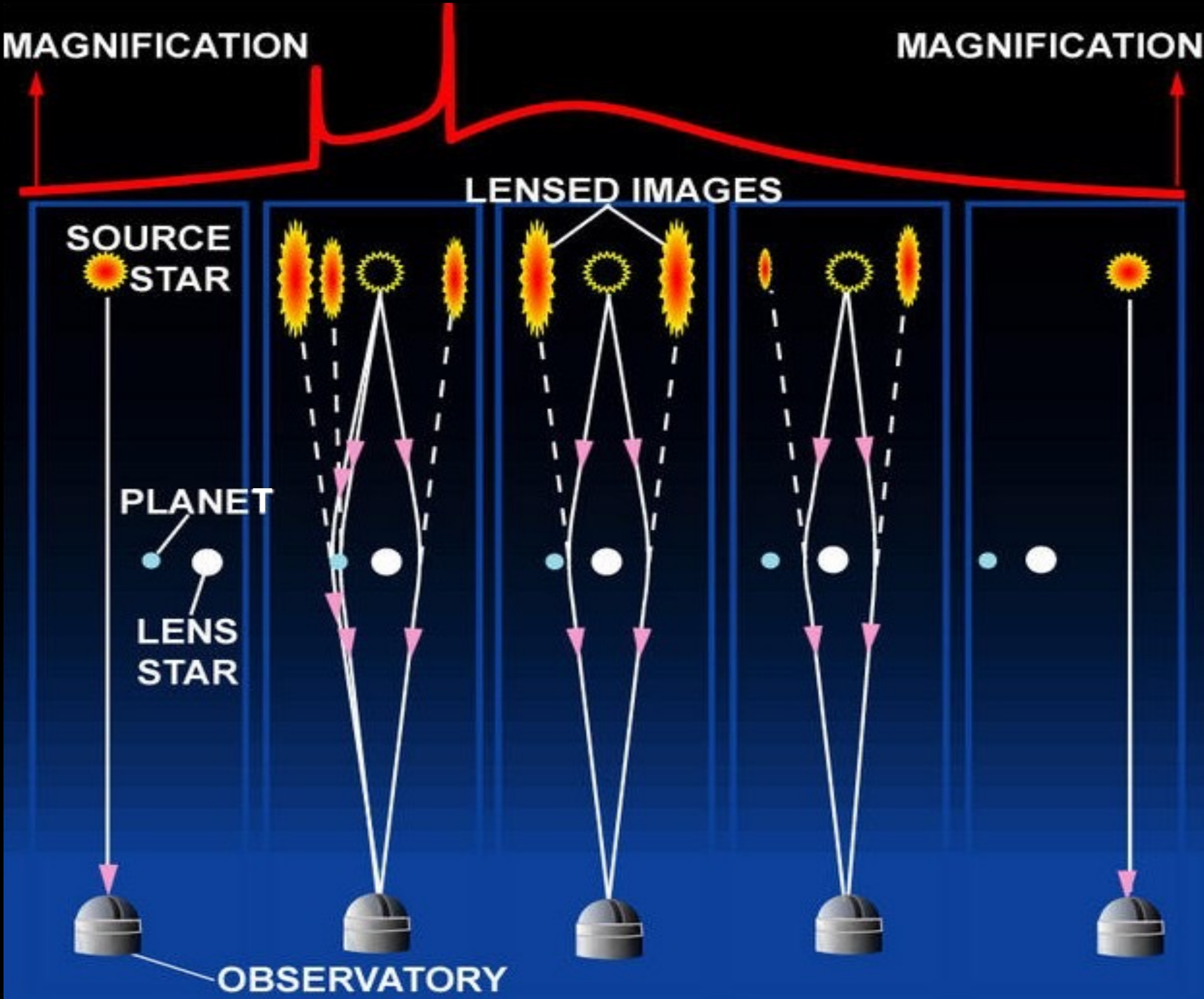


Albert Einstein

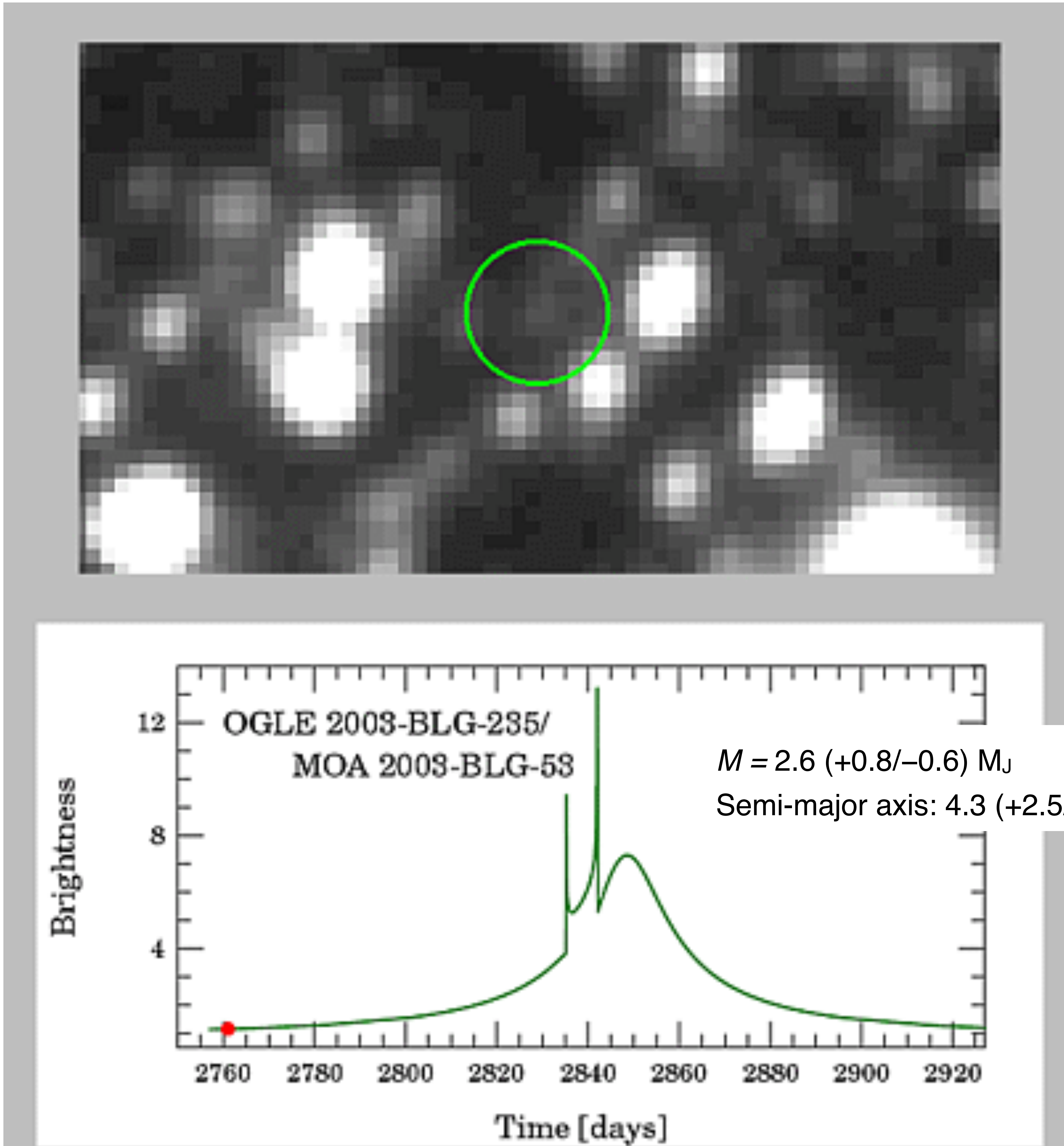




Effect predicted by theory of General Relativity: deformation of geometry of space-time due to presence of mass


MAGNIFICATION
MAGNIFICATION
LENSED IMAGES
SOURCE STAR
PLANET
LENS STAR
OBSERVATORY

Gravitational (micro)-lensing 78 candidates (in 2019)



$M = 2.6\ (+0.8/{-0.6})\ M_J$

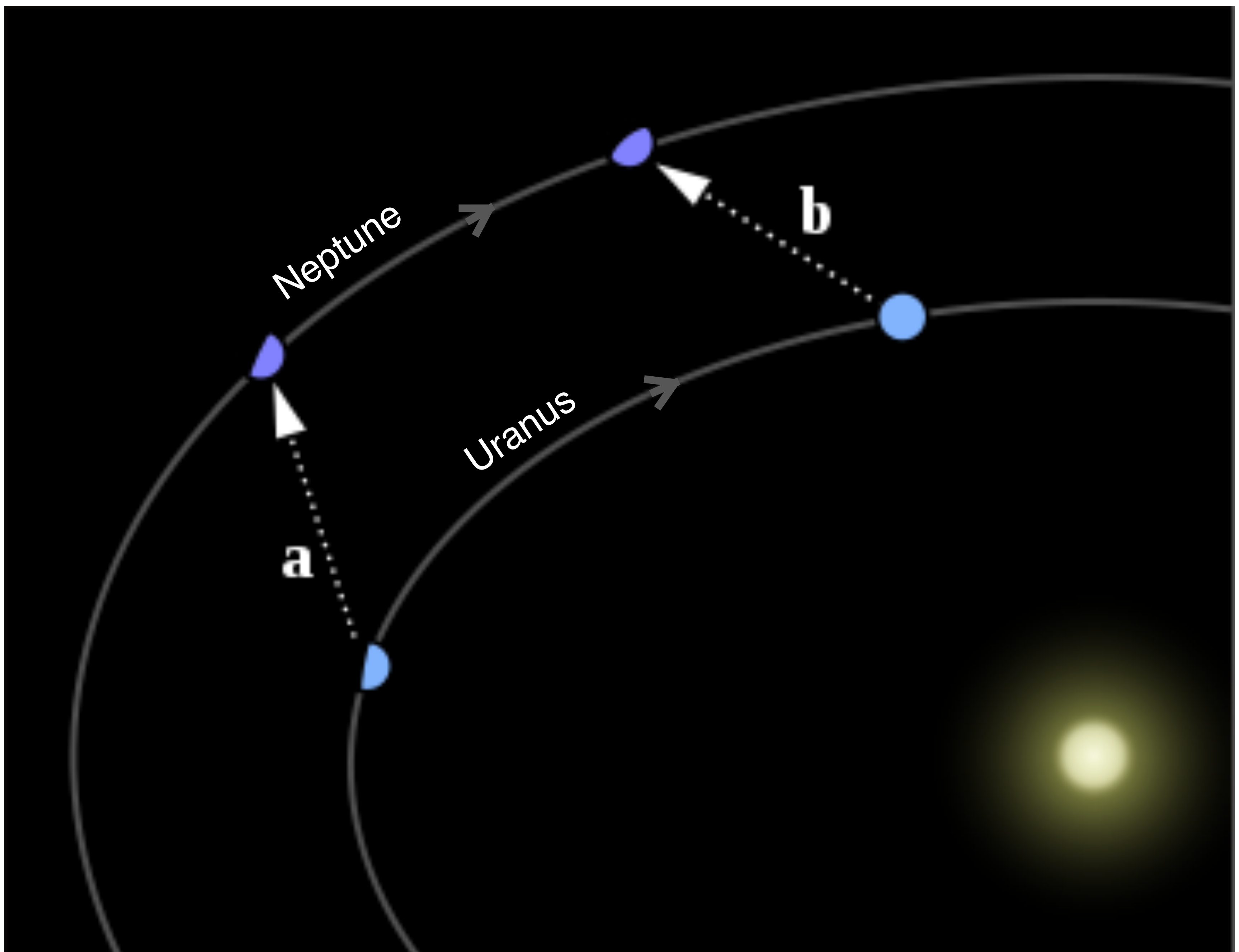
Semi-major axis: 4.3 (+2.5/−0.8) AU

Video: http://www3.nd.edu/~bennett/moa53-ogle235/

5. Transit-timing variation

Gravitational perturbation induced by planets

Used for the discovery of Neptune (1846)
confirmed Newton's Laws of gravitation



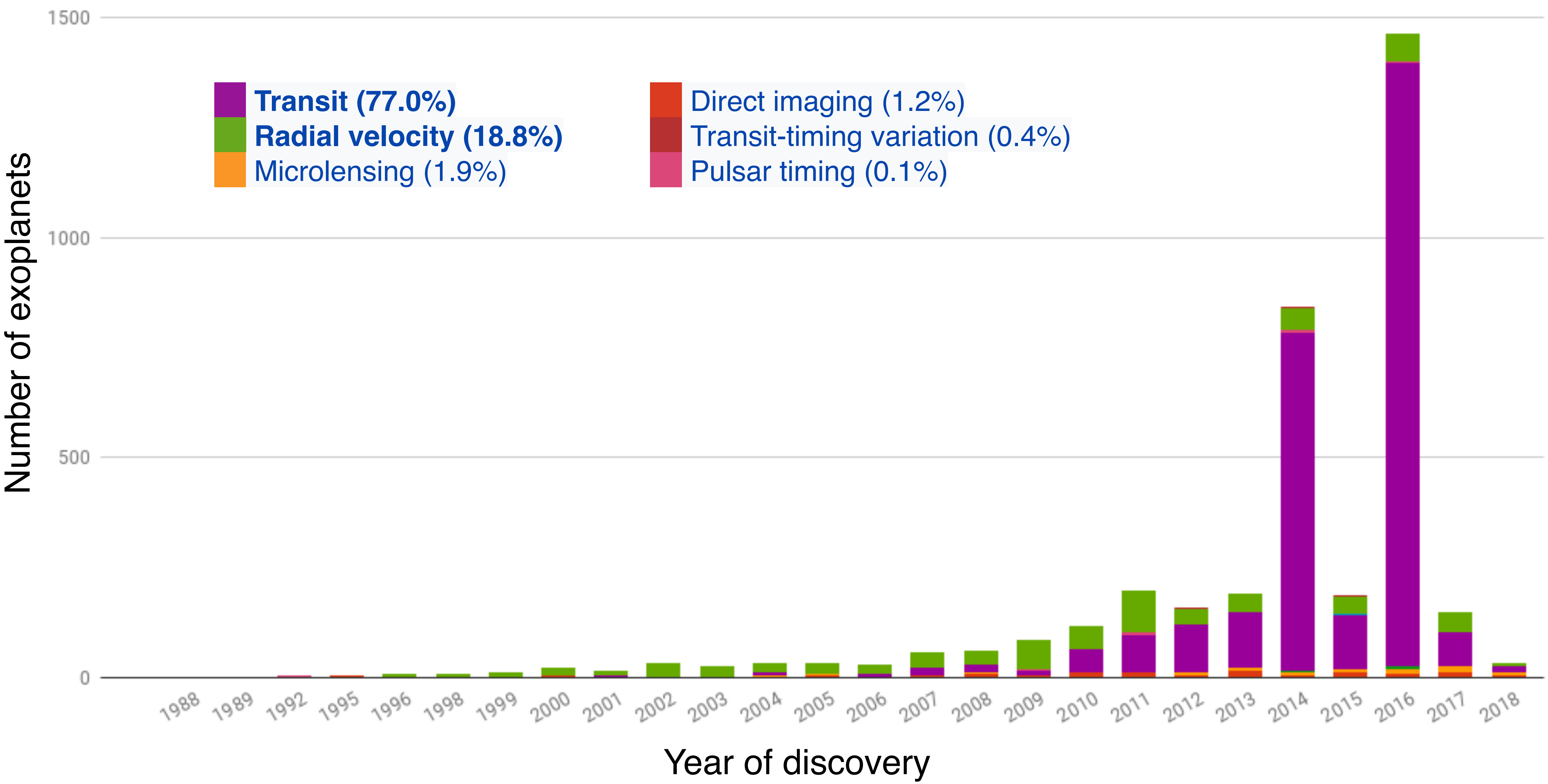
Mathematician Urbain Le Verrier

Transit-timing variation

Animation: https://www.youtube.com/watch?v=rqQ1xKsNIQE

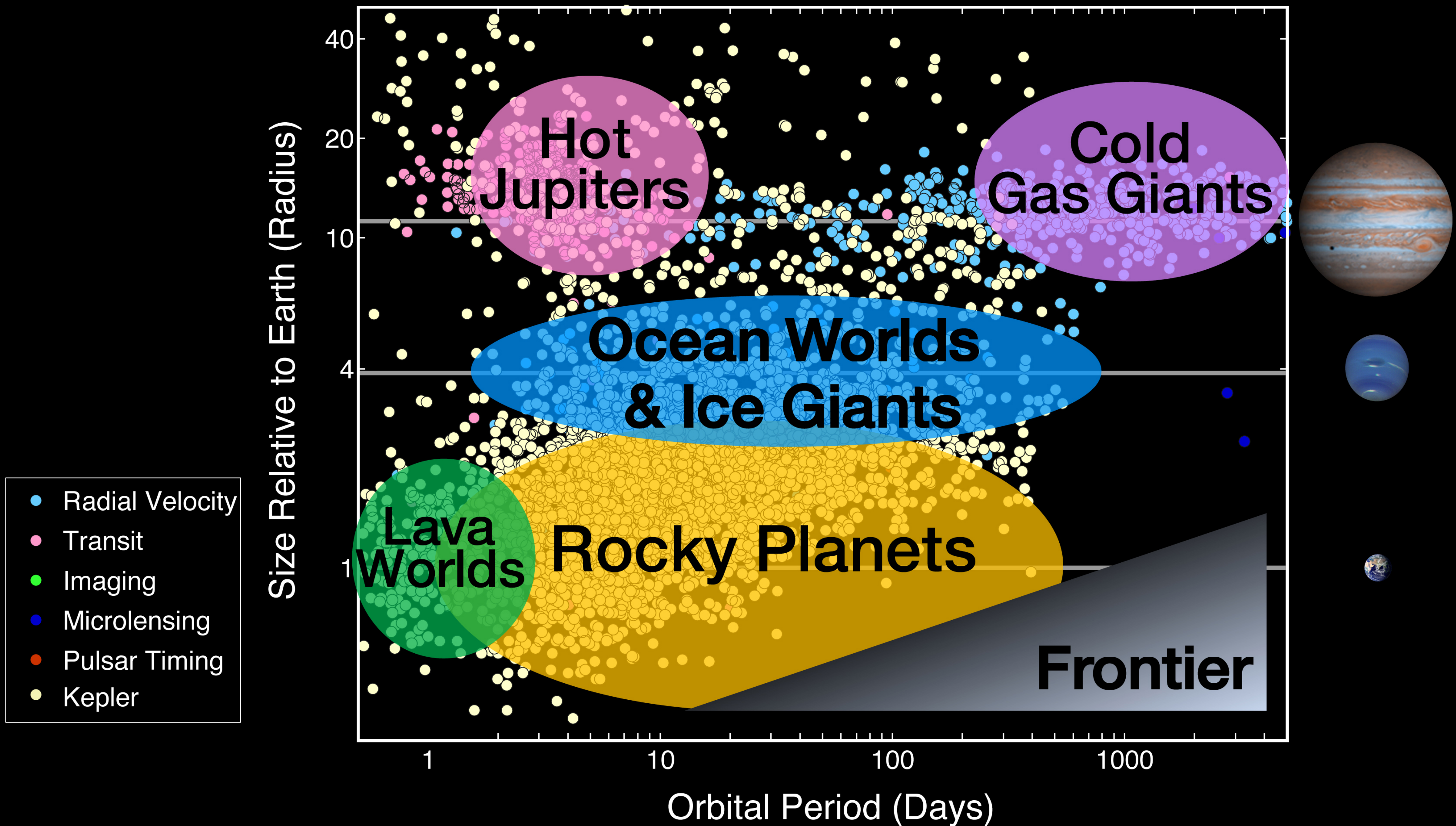
Discovered extrasolar planets per year and by detection method

(as of April 2018)



Total number of **confirmed** exoplanets as of October 2019: **4073** (mostly from *Kepler*)
In addition, **3297 candidate** exoplanets (from *Kepler*)
New NASA mission: Transiting Exoplanet Survey Satellite (*TESS*)

Exoplanet Populations



Present: atmosphere

Future: bio signatures