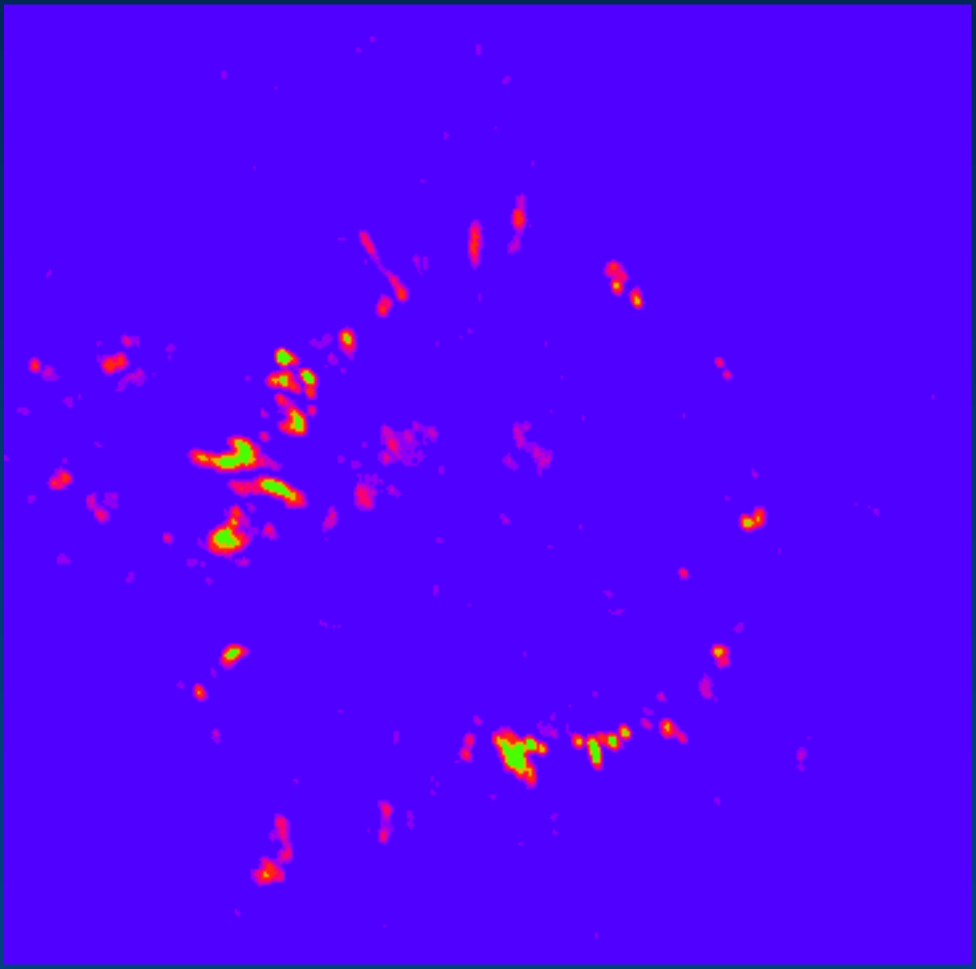
Ejection of stellar material

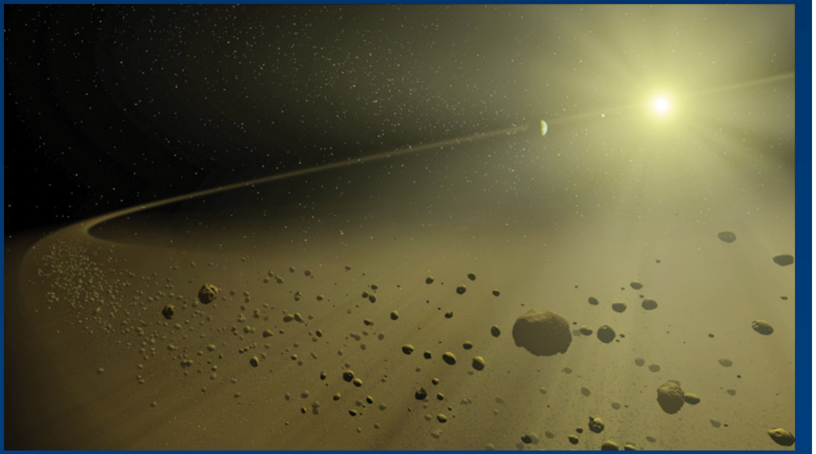
- Tx Cam - a Mira variable



Icy bodies and comets

- Leftover bodies from planet building in Jovian planet zone. Hence more icy than asteroids.

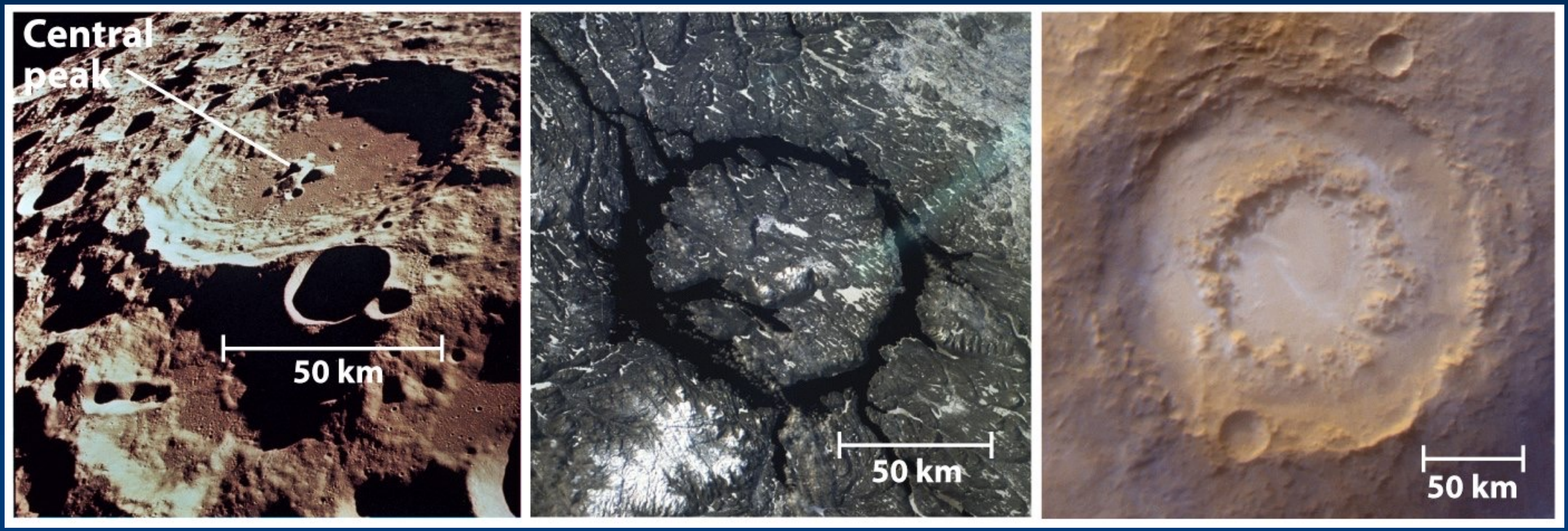
- Gravitational encounters with giant planets flung them outwards beyond Neptune.



- Result is TNOs, some of which encounter Neptune and sent into inner Solar System, where they appear as comets.

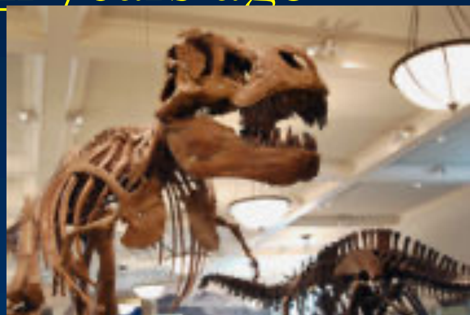
Cratering on terrestrial planets

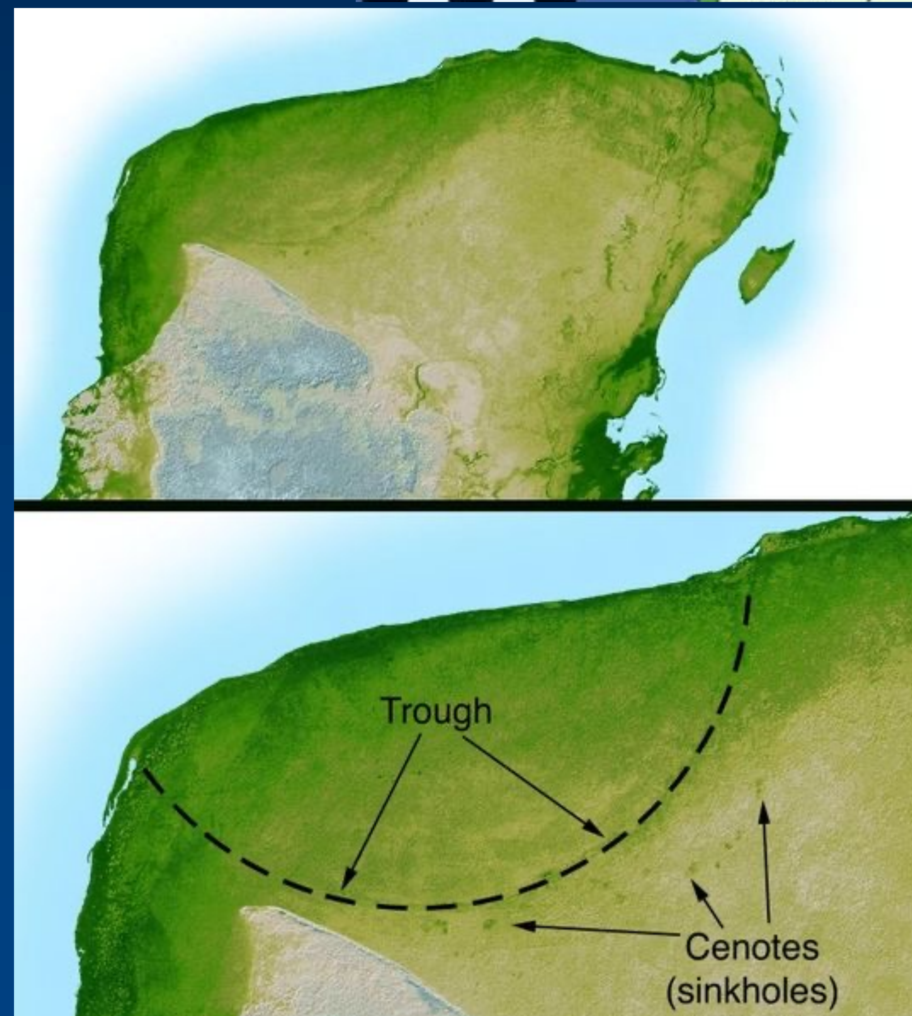
- Result of impacts from interplanetary debris



- Geological activity =>
  - Many craters means old surface and low geological activity
  - Smaller objects lose heat faster: more cratered

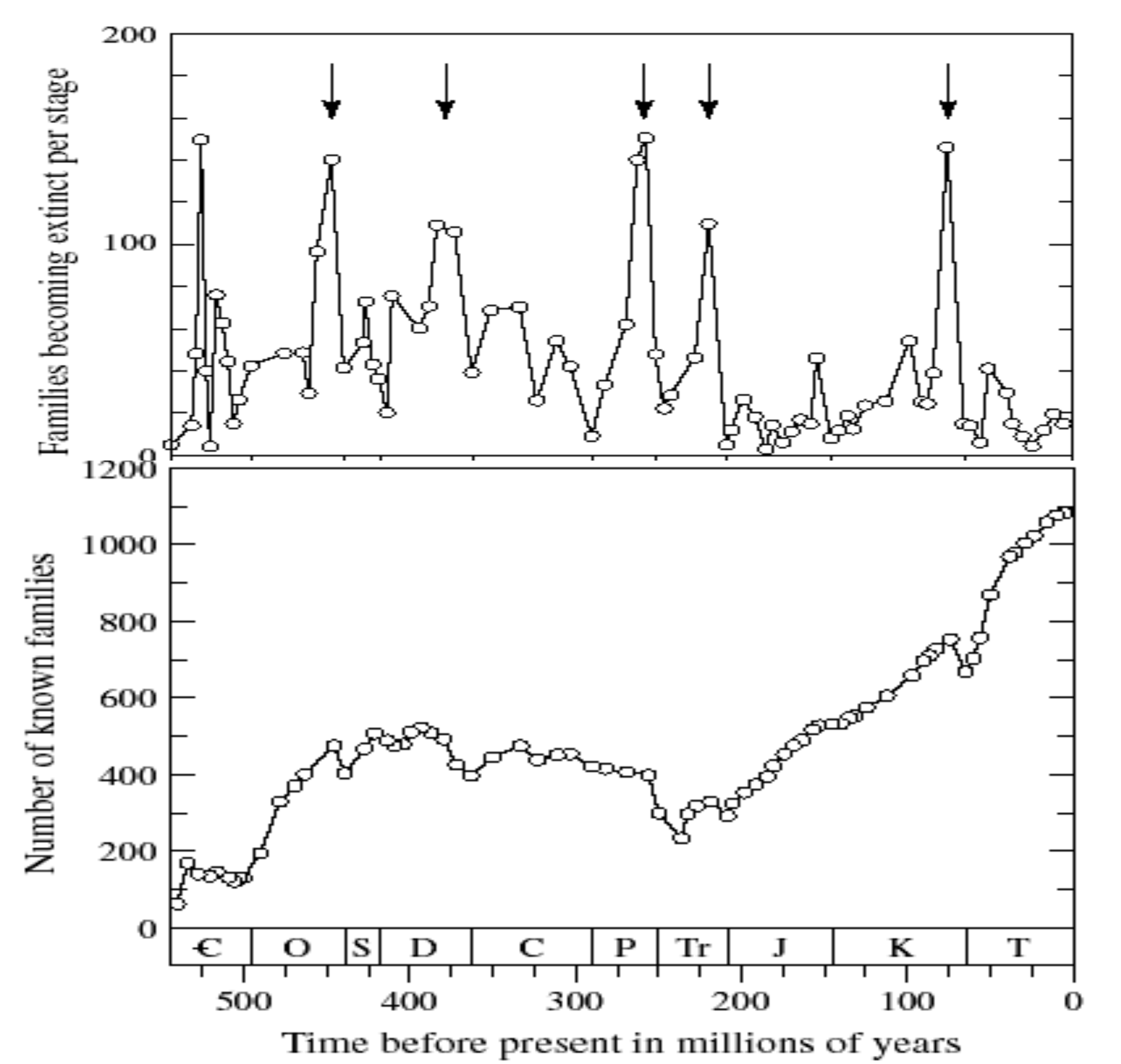
Dinosaur Killer Impact 65 million years ago





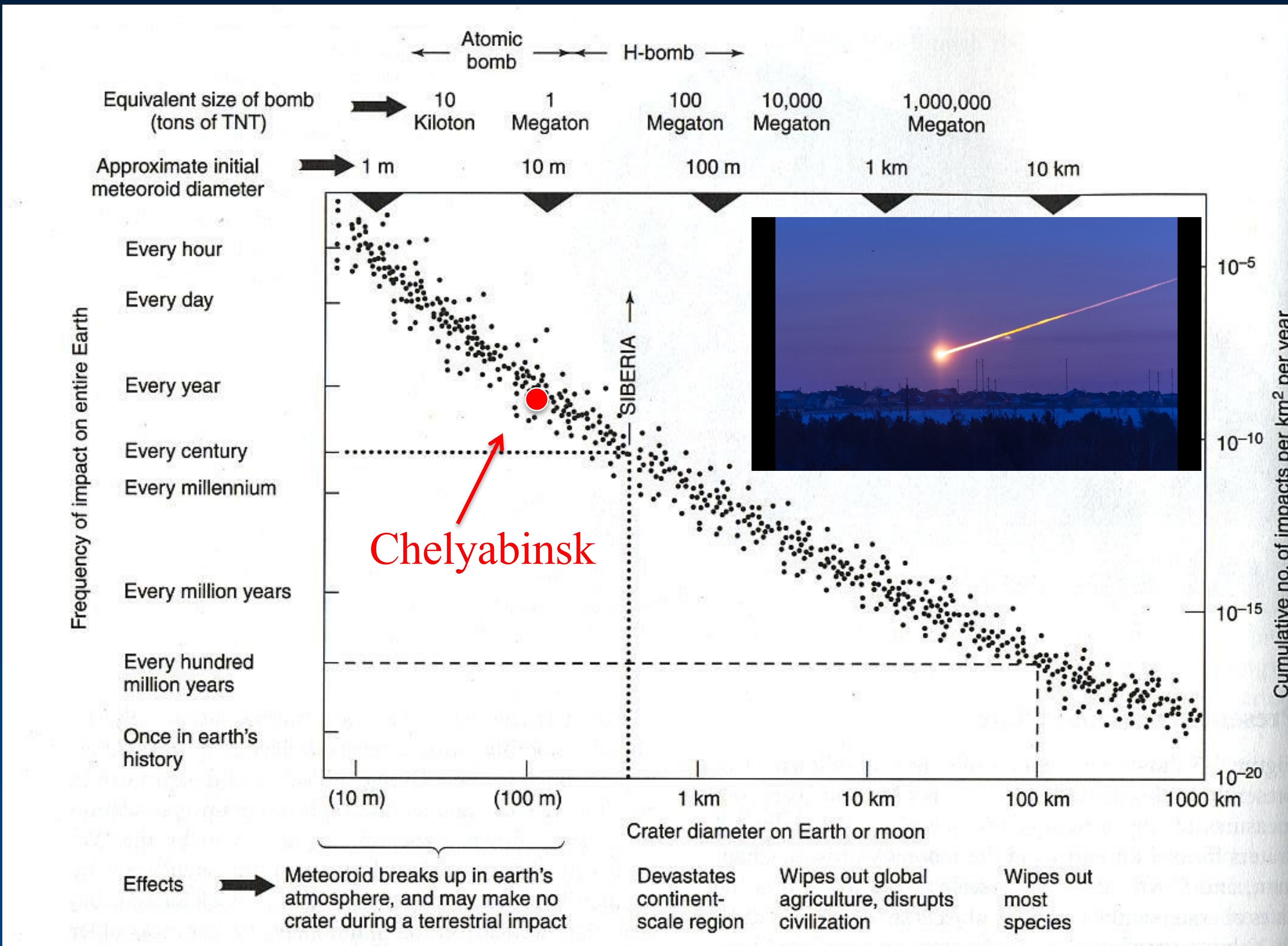
High levels of iridium in Raton Pass (I25)

The Fossil Record is Marked by Mass Extinction Events



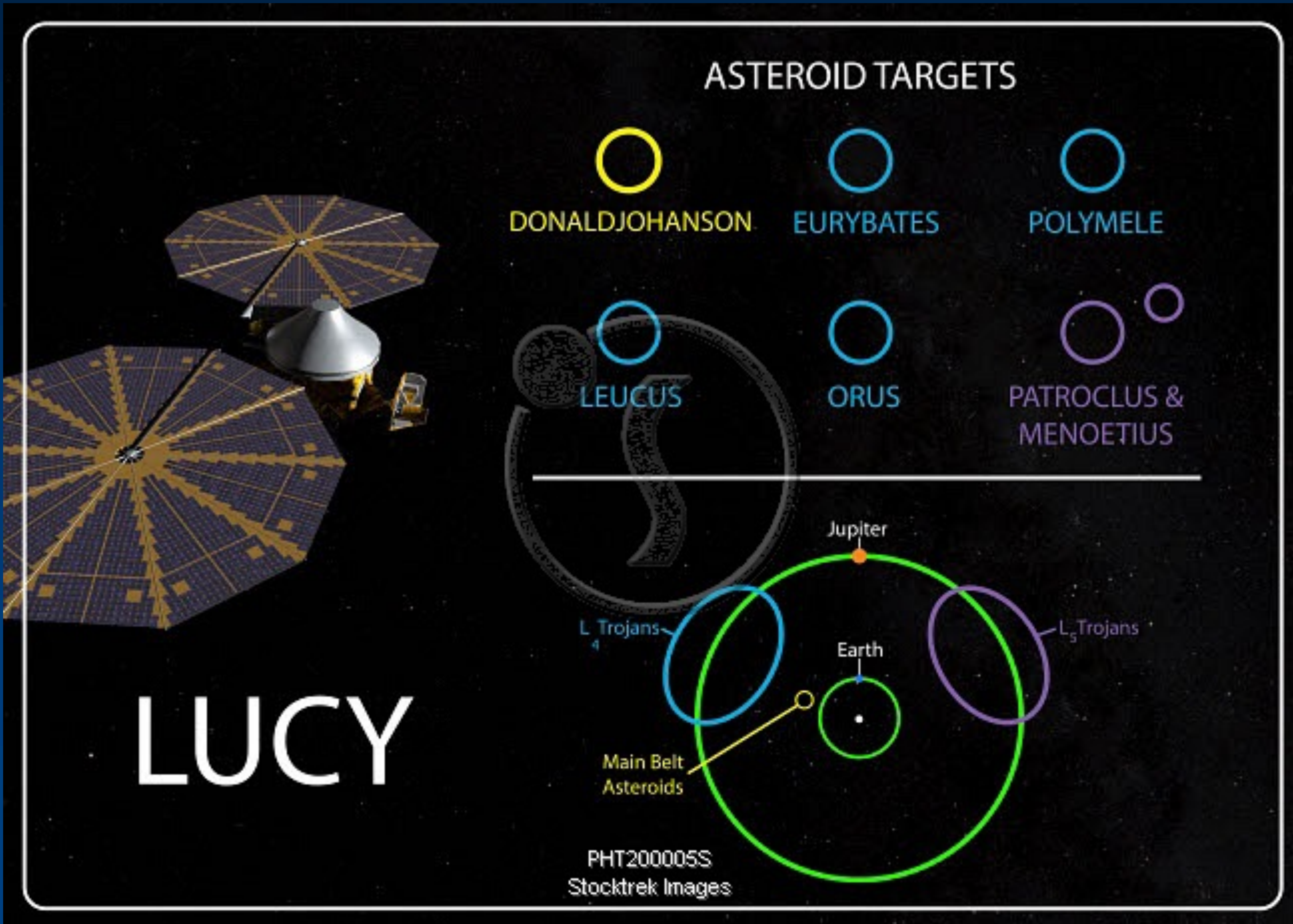
Extinction	Genus loss
End Ordovician	60%
End Devonian	57%
End Permian	82%
End Triassic	53%
End Cretaceous	47%

From Solé & Newman 2002



Atomic bomb
H-bomb
Equivalent size of bomb (tons of TNT)
10 Kiloton
1 Megaton
100 Megaton
10,000 Megaton
1,000,000 Megaton
Approximate initial meteoroid diameter
1 m
10 m
100 m
1 km
10 km
Frequency of impact on entire Earth
Every hour
Every day
Every year
Every century
Every millennium
Every million years
Every hundred million years
Once in earth's history
SIBERIA
Chelyabinsk
10^{-5}
10^{-10}
10^{-15}
10^{-20}
Cumulative no. of impacts per km² per year
(10 m)
(100 m)
1 km
10 km
100 km
1000 km
Crater diameter on Earth or moon
Effects
Meteoroid breaks up in earth's atmosphere, and may make no crater during a terrestrial impact
Devastates continent-scale region
Wipes out global agriculture, disrupts civilization
Wipes out most species

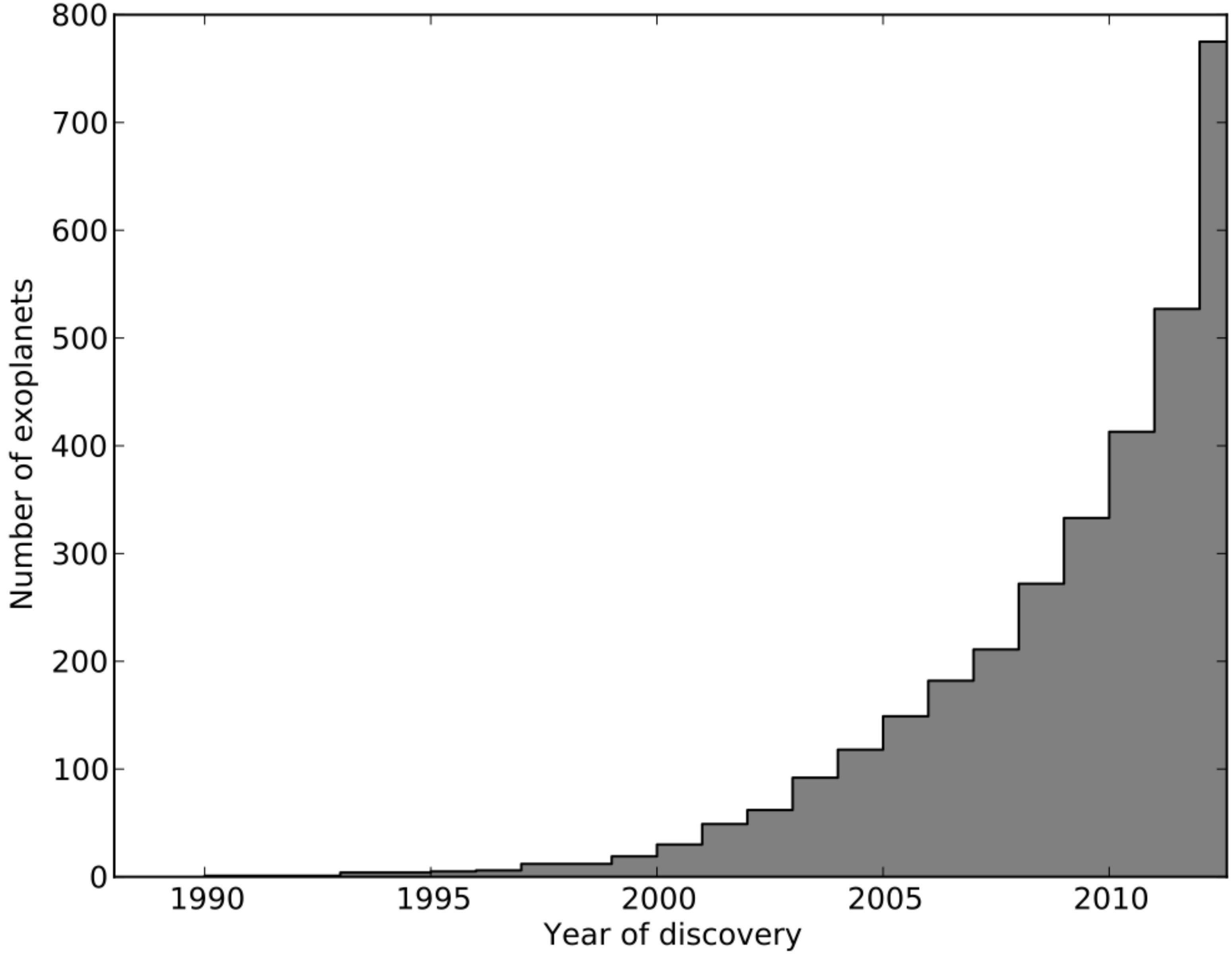
Lucy Mission



Announcements

- HW6 Due Thursday March 21
- Final Project due May 2nd
- Pick up your proto-planet today
- Evan David office hours now Mondays 4-5pm

Exoplanets are a hot topic



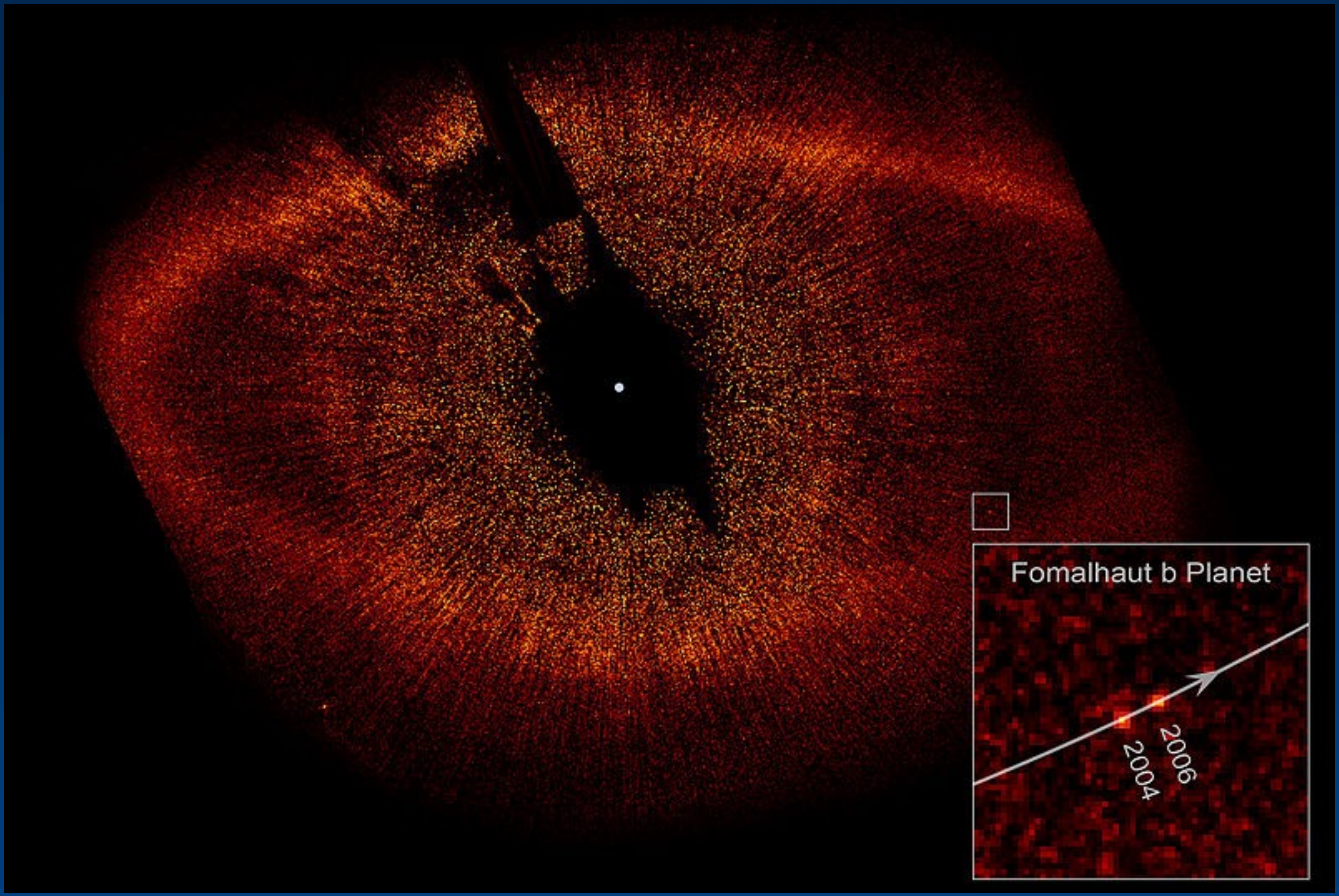
Planets around other stars

- Test solar system formation process
- Possibility of life on other planets

Techniques:

- Direct detection (images)
- Transit of star by planet
- Microlensing
- Detection of star's wobble by spectroscopy
- Detection of star's wobble by imaging
- Detection of radio bursts

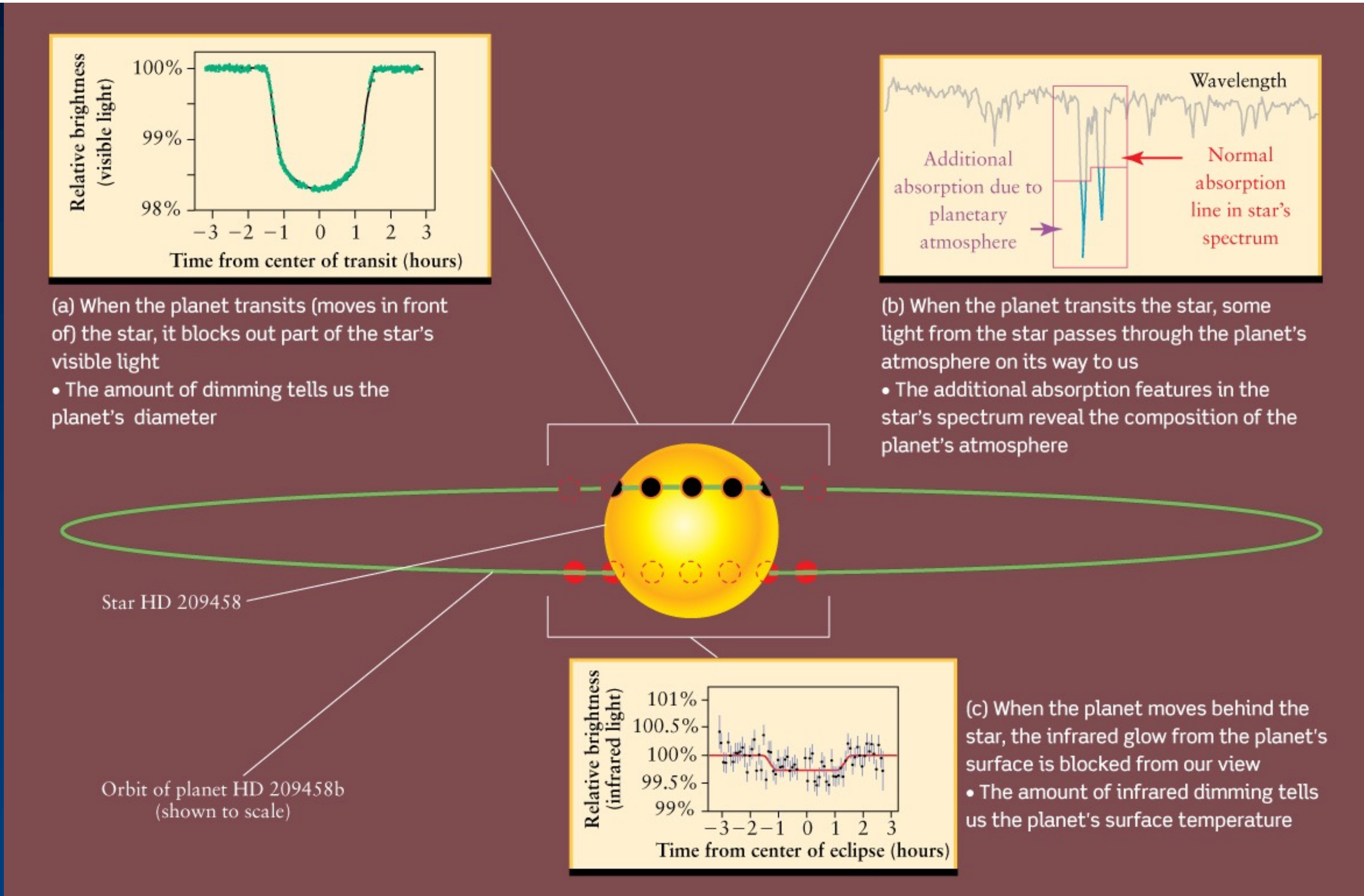
Direct Imaging



~88 found this way as of October 2017

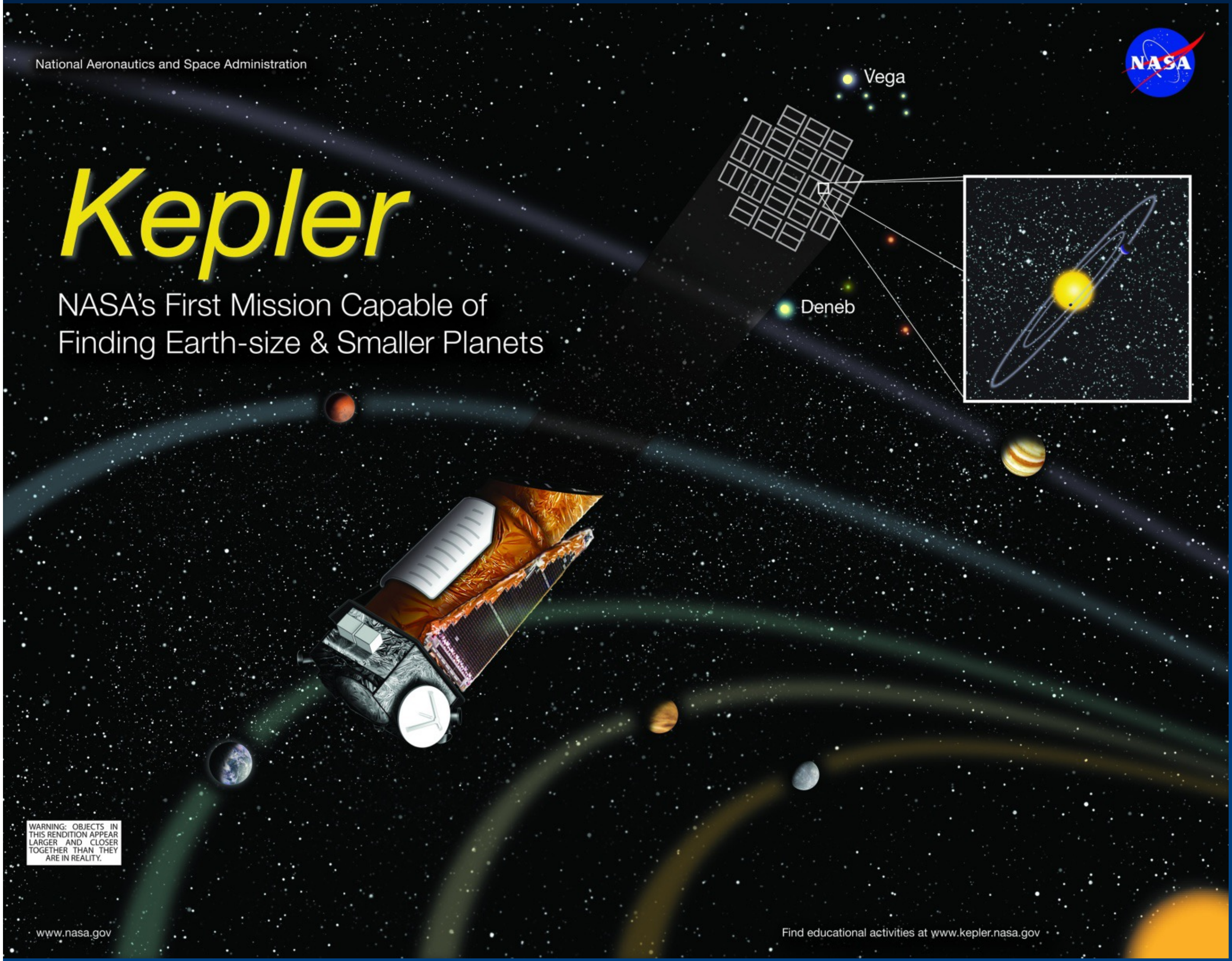
Planetary transits

If orbital plane of extrasolar planet is aligned with the line of sight, planet will transit face of parent star



- Dims by about 1-2% during the transit
- Requires precision photometry, better done from space
- Can extract info on planet's atmosphere, size, temp!

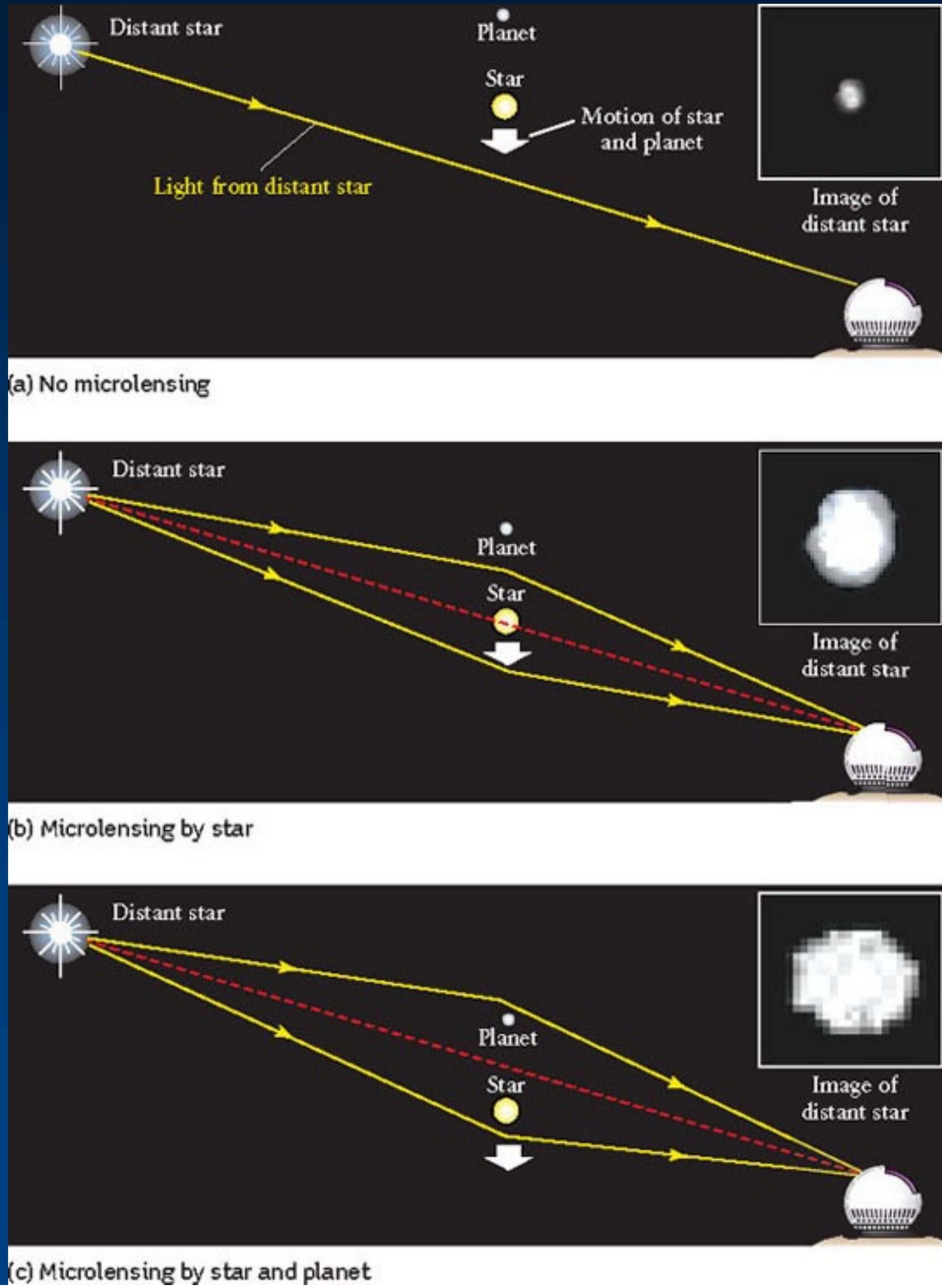
Kepler transit mission – 3000+ candidates, confirmed list smaller.



also CoRoT mission in Europe

Gravitational microlensing

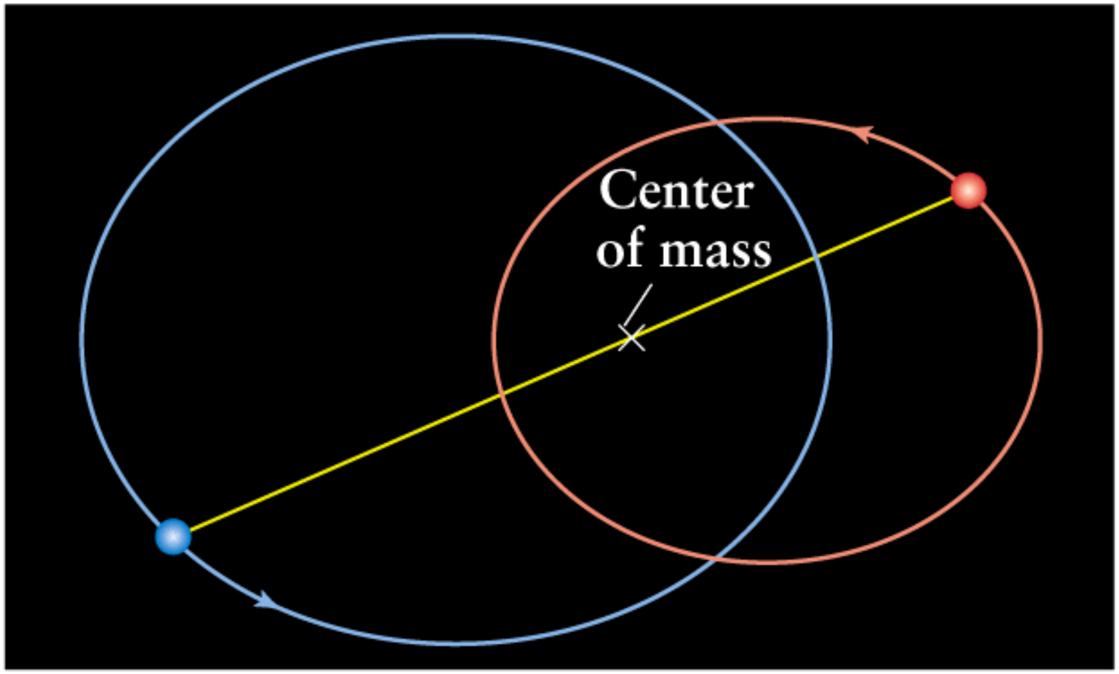
- If two stars line up, one near and one far, the light from the background star will bend around the foreground star (due to gravity)
- A planet around the foreground star will cause an intense amplification if passing close to the line of sight
- only 15 planets found this way



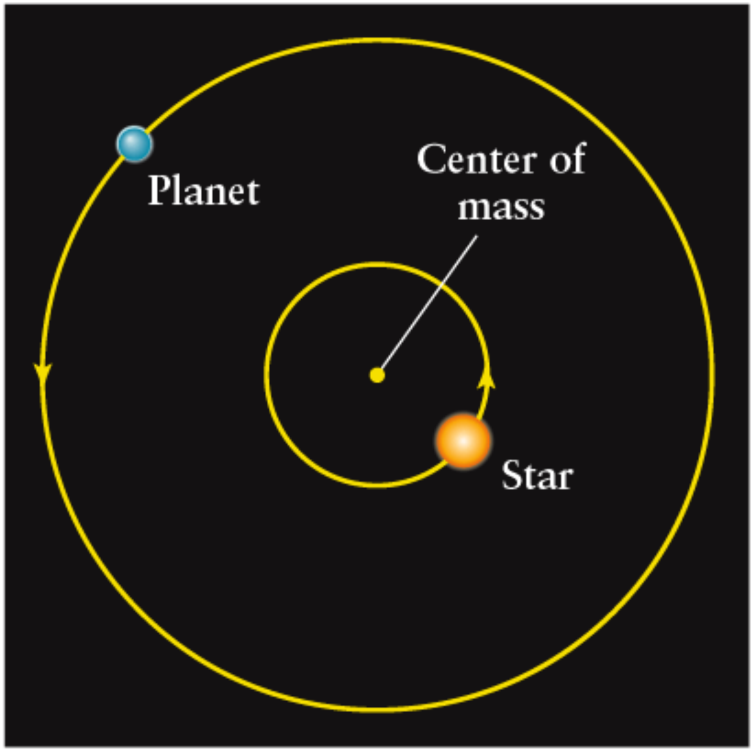
Distant star
Planet
Star
Motion of star and planet
Light from distant star
Image of distant star
(a) No microlensing
Distant star
Planet
Star
Image of distant star
(b) Microlensing by star
Distant star
Planet
Star
Image of distant star
(c) Microlensing by star and planet

Detecting a star's wobble

Idea: a planet and its star both orbit around their common center of mass, staying on opposite sides of this point. Creates a "wobble".

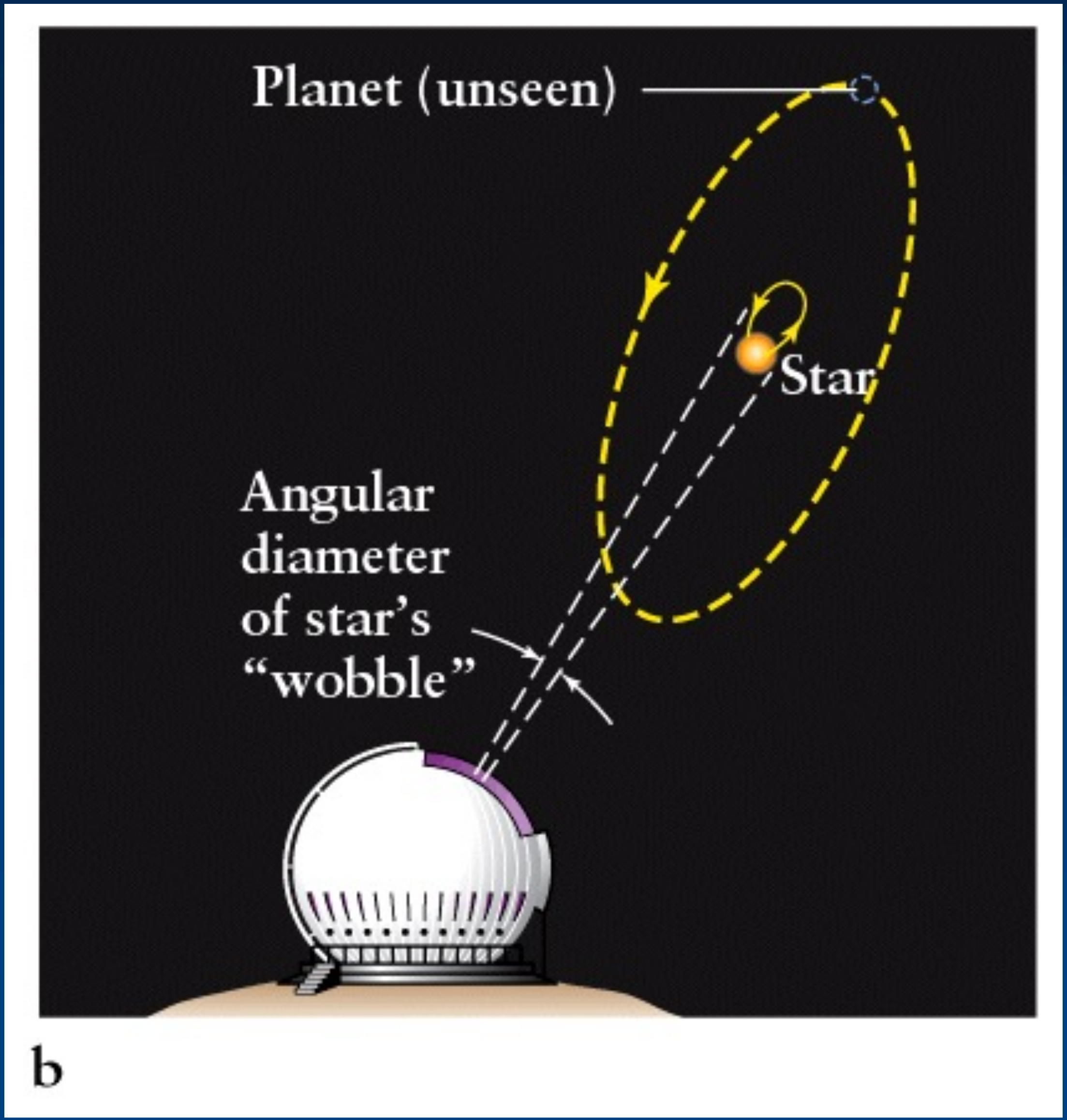


b

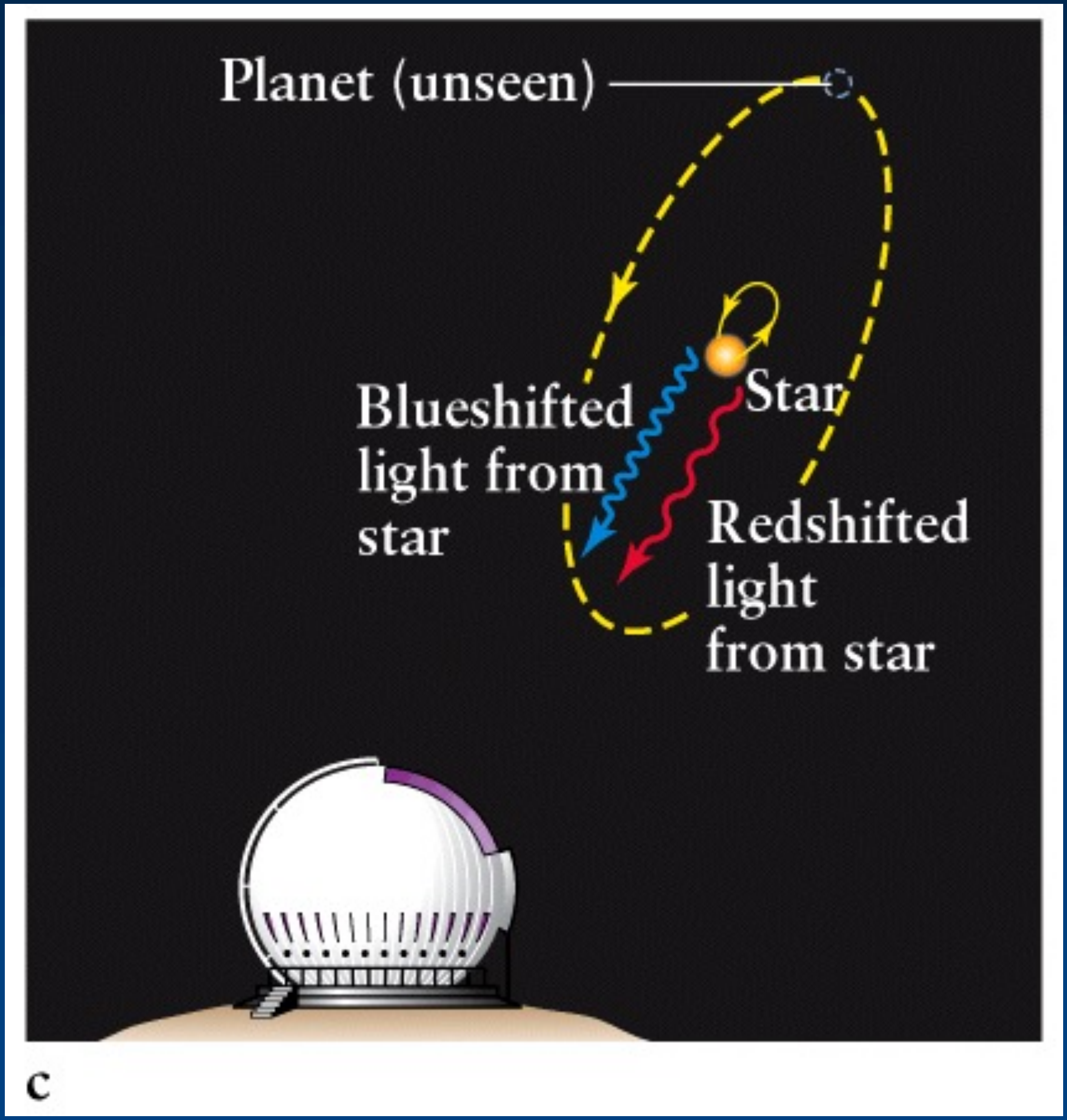


a

A wobbling star might be seen by careful observations, called “astrometry”:



Most successful method: Use the Doppler shift of star's spectral lines due to its radial (= back and forth) motion:



The massive star is closer to center of mass, and moves more slowly than the planet, but it does move!

WS#11: Sun and Jupiter orbit their common center of mass every 11.86 years.

Note M_J / M_Sun = 1/1047

What is the orbital speed of the Sun?

What is the astrometric displacement for a similar system at a distance of 10 pc?

Solution: First calculate the semi-major axis of the Jupiter's orbit

$P^2 = a^3$ so $a = 5.2$ AU $= 780 \times 10^9$ m

$M_s r_s = M_j r_j$ so $r_s = 740 \times 10^6$ m

Angular size $= 2 \times 740 \times 10^6$ m$/10 \times 3.09 \times 10^{16}$ m

$= 4.8 \times 10^{-9}$ radians x 206265000 mas/rad

$= 0.99$ mas

Calculate orbital speed of Sun assuming Jupiter is only planet:

Moves in circular orbit of radius 742,000 km

$$V = \frac{2\pi r}{P} = \frac{2\pi(742{,}000\ \text{km})}{11.86\ \text{years}} = 12.5\ \text{m/s}$$

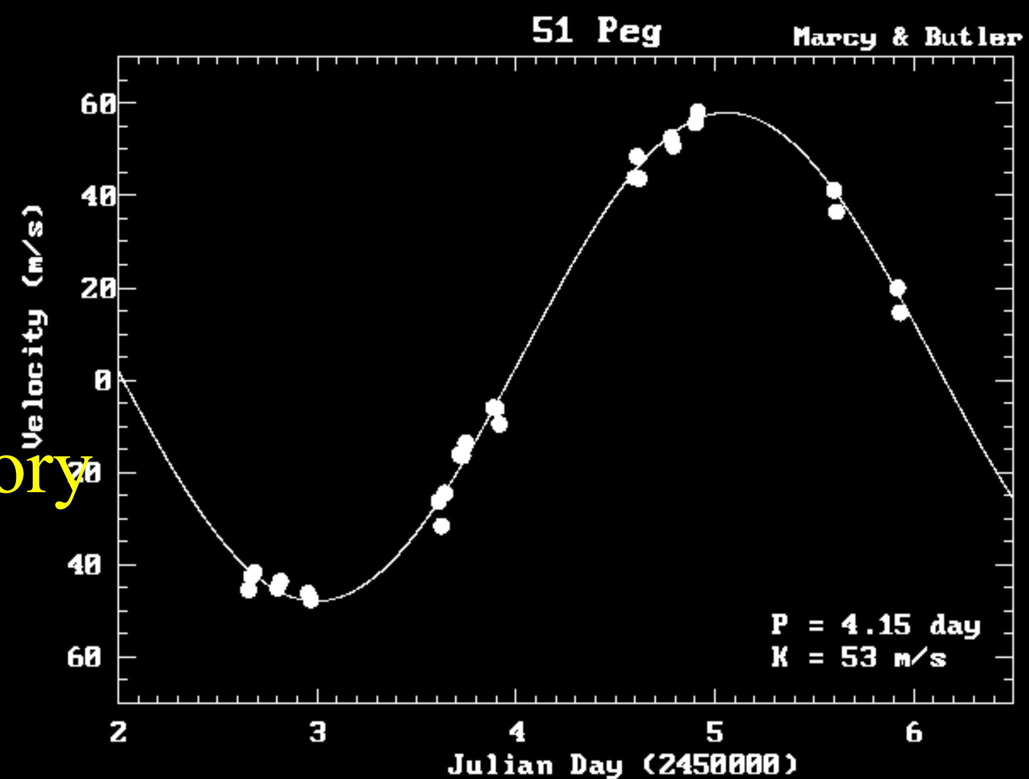
How much Doppler shift? Consider H-alpha absorption line, at rest wavelength 656 nm:

$$\Delta\lambda = \frac{V}{c}\lambda_0 = \frac{12.5\ \text{m/s}}{3\times 10^8\ \text{m/s}} 656\ \text{nm} = 2.7\times 10^{-5}\ \text{nm}$$

This is tiny!

51 Pegasi

- Michel Mayor & Didier Queloz at Geneva Observatory observed wobble in 1995
- Sun-like star 15 pc distance
- Wobble was 53 m/s, period 4.15 days
- Implied a planet with 0.5 Jupiter mass orbiting at 0.05 AU!
- First planet found around sun-like star



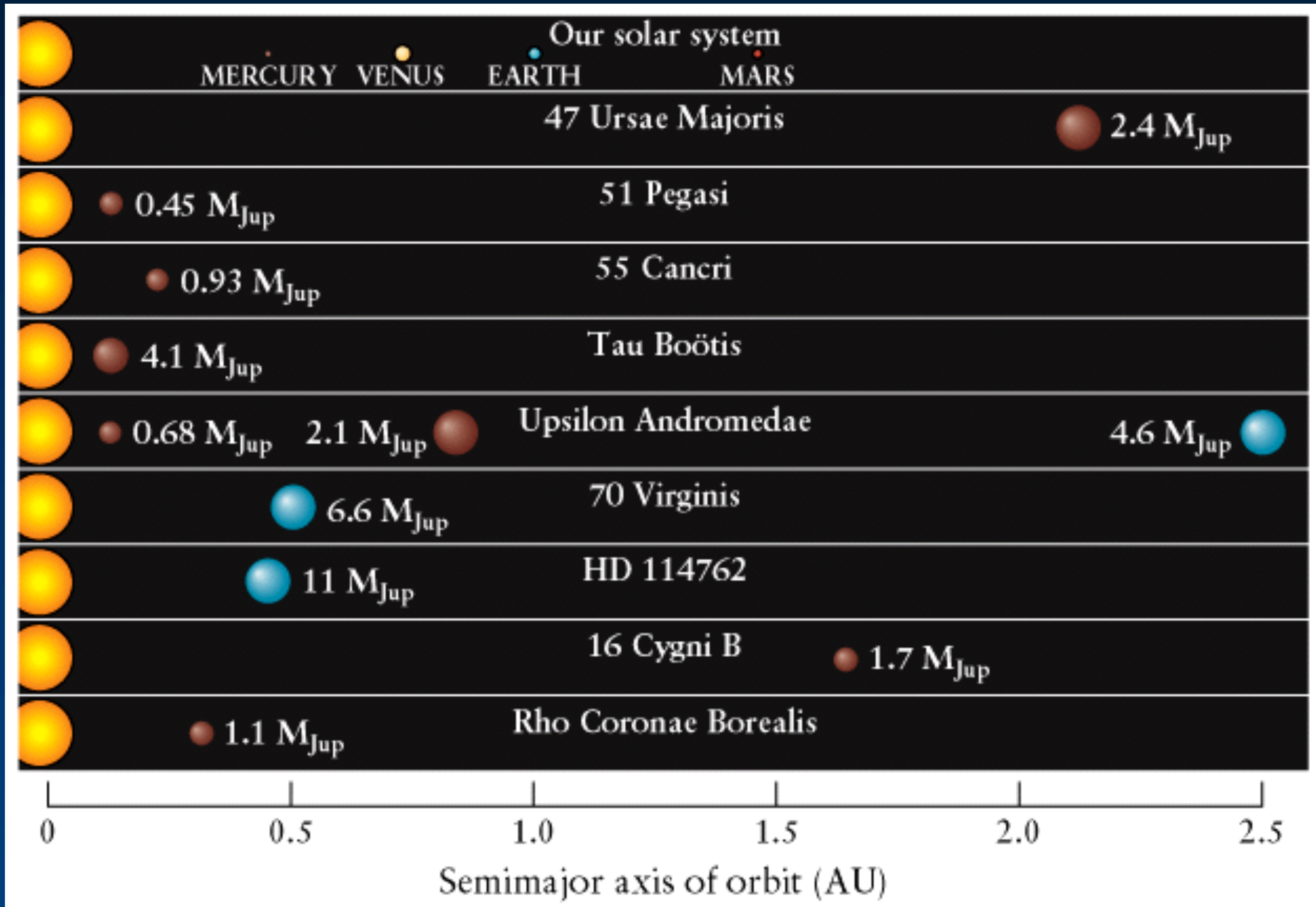
Michel Mayor & Didier Queloz
Nobel Prize 2019

Selection effects

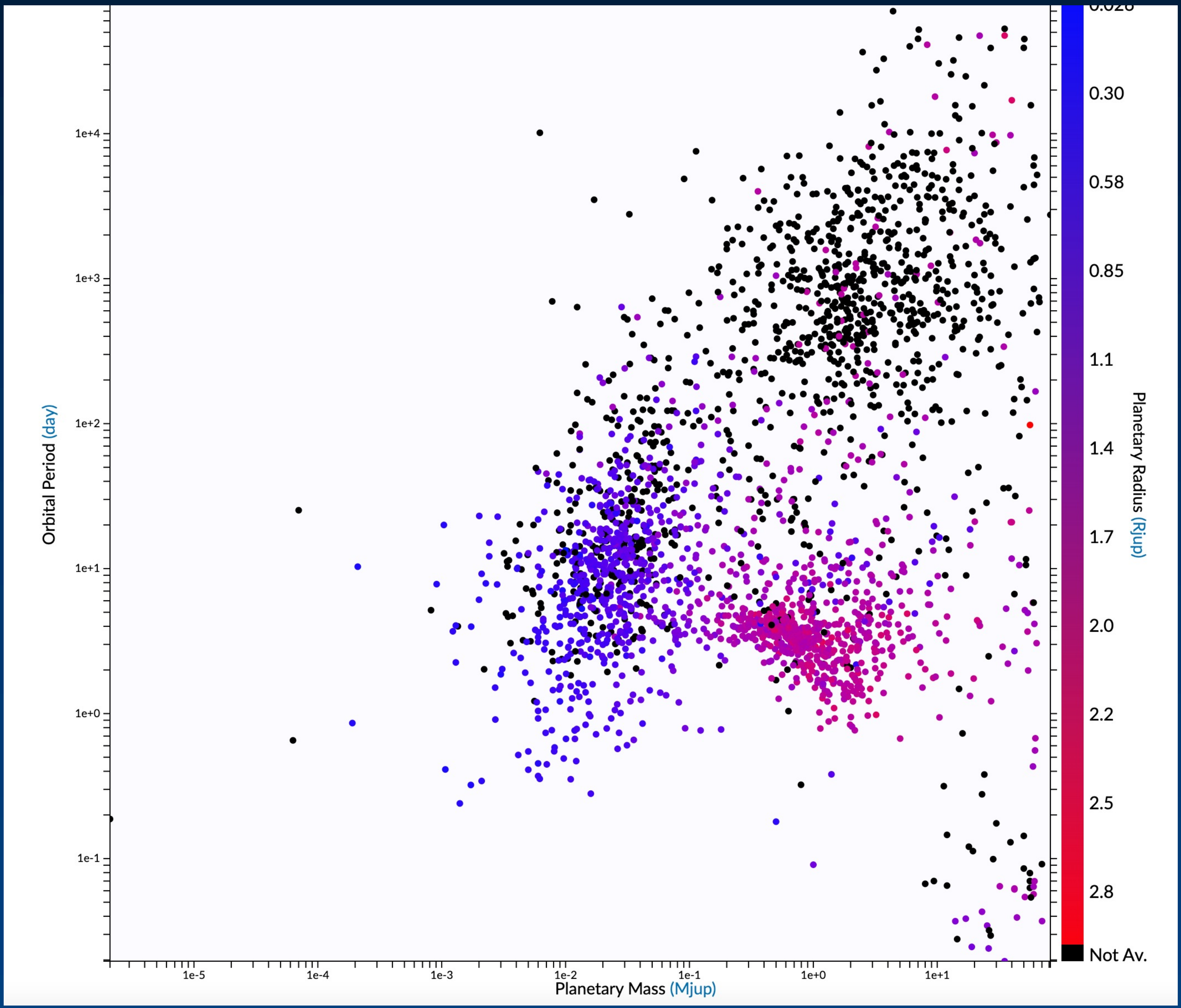
- Doppler wobble biased towards massive planets close to their star (leads to larger velocities and shorter periods). Now getting close to Earth-mass planets.
- Limited by the orbital speed sensitivity (few m/s but always improving) and length of orbital period: for more than several year periods, hard to tell if motion is periodic
- Inclination of binary orbit unknown (unless transits observed). More likely to be close to edge-on for detection. If not, wobble is larger than measured and so is planet.

Characteristics of detections

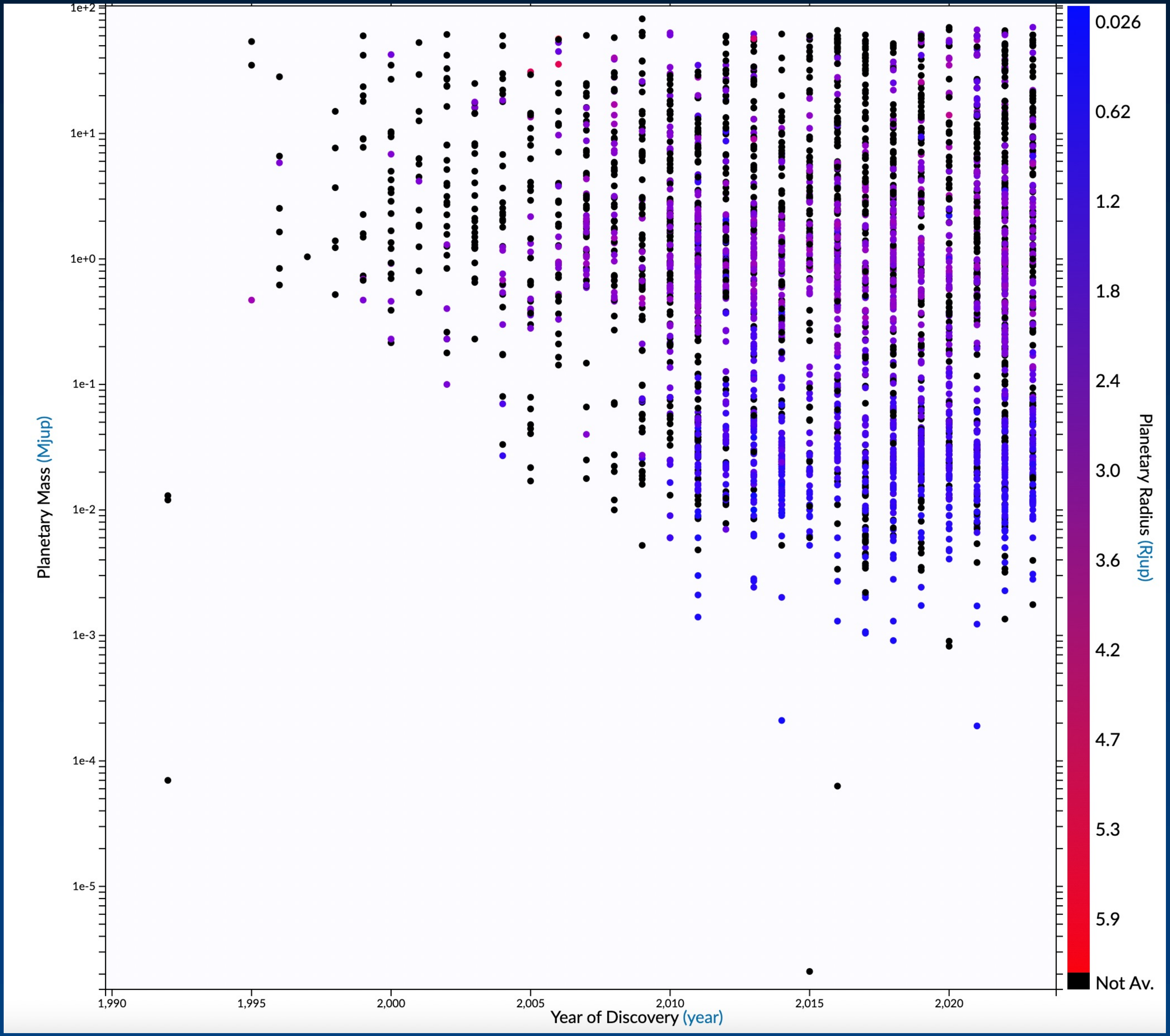
- Some hot Jupiters on small orbits (migration or formation?)
- Some with very elliptical orbits (in the Solar System this is a sign of perturbation => supports migration idea?)
- Rare around low-mass stars (smaller disks thus less material)
- Rare around metal-poor stars



Current (August 2021) extrasolar planet count: 4472 planets! What about these "hot Jupiters"?

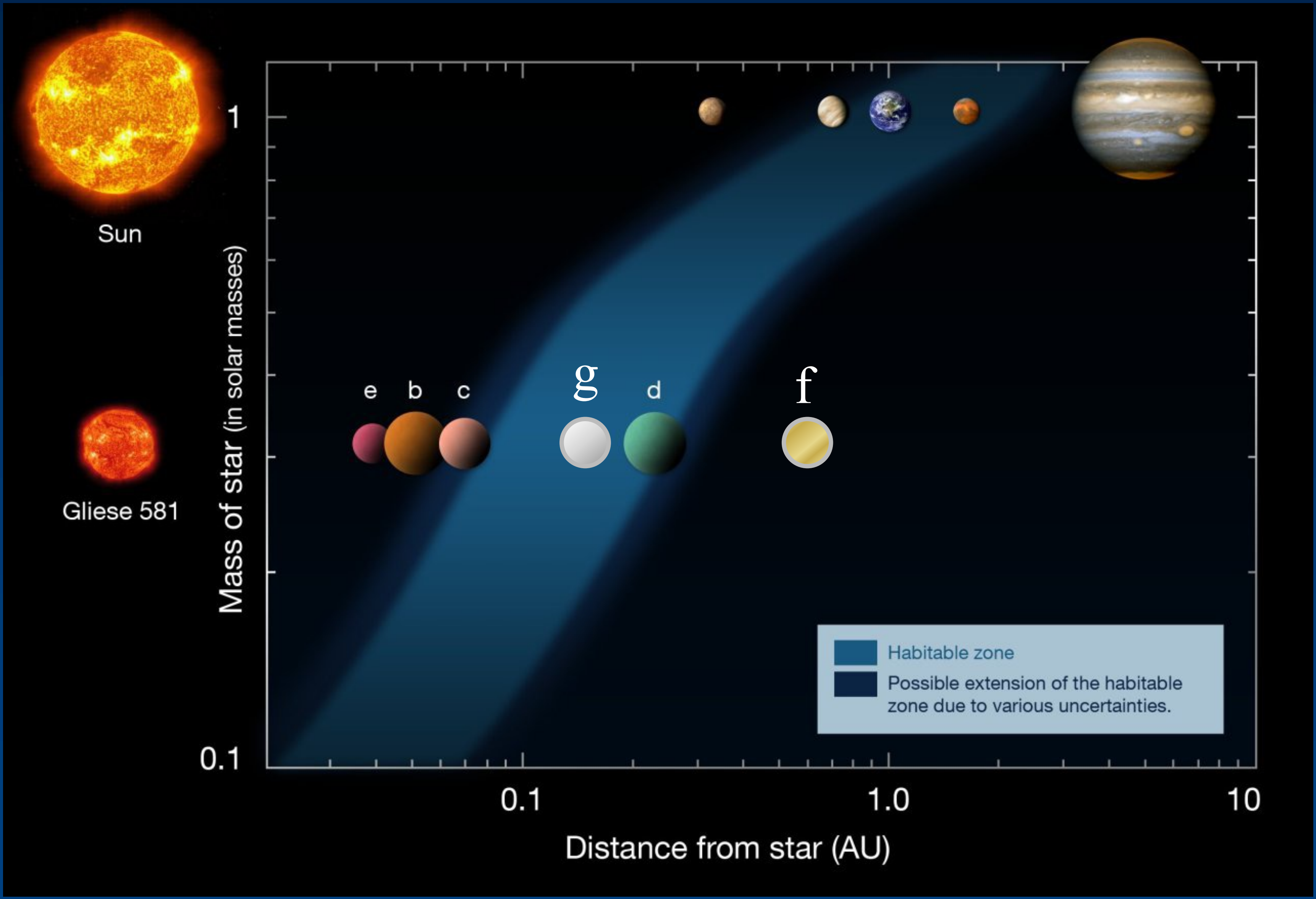


Current count: 5586 planets, around 4419 stars as of 1/11/2024

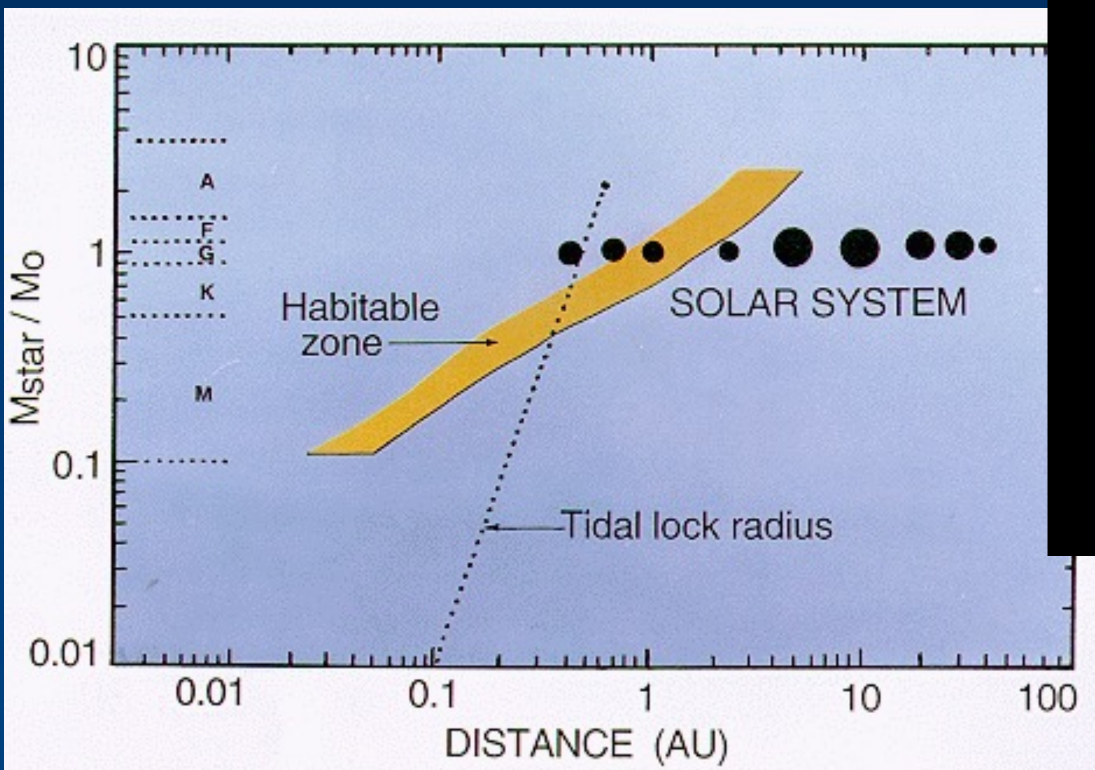


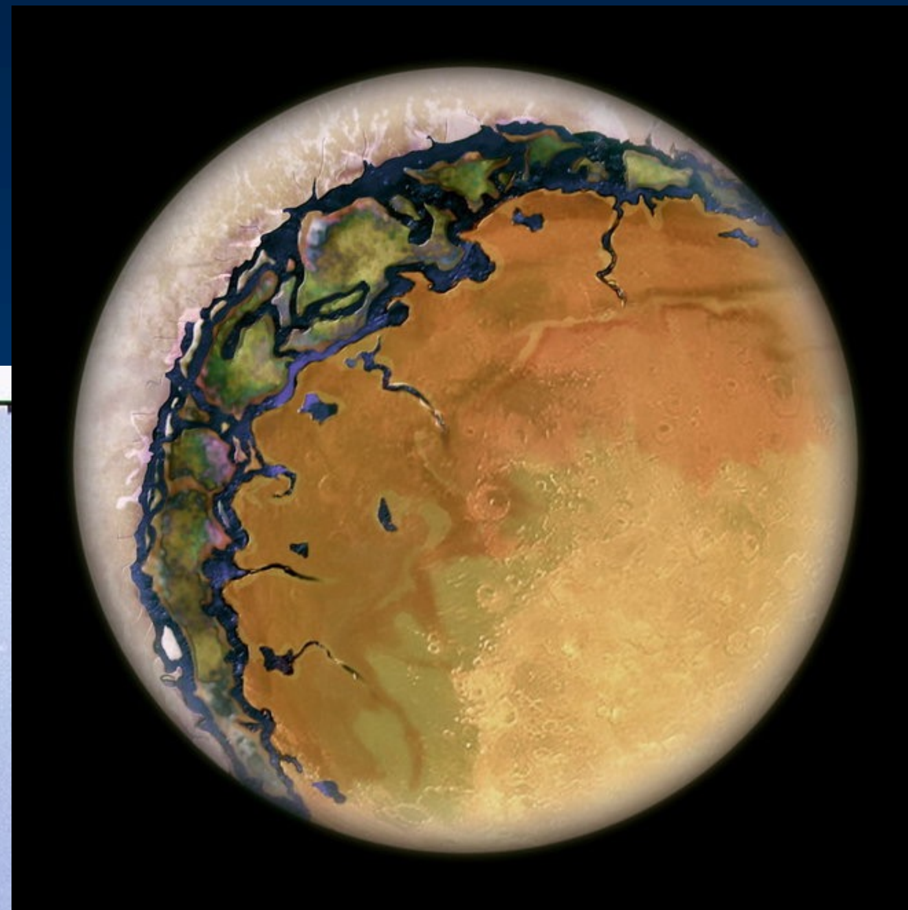
Number and Mass of planets discovered with time

Extrasolar planet 3 – 4 Earth masses (Gliese 581g) found in star's habitable zone by Doppler method – Sept 2010

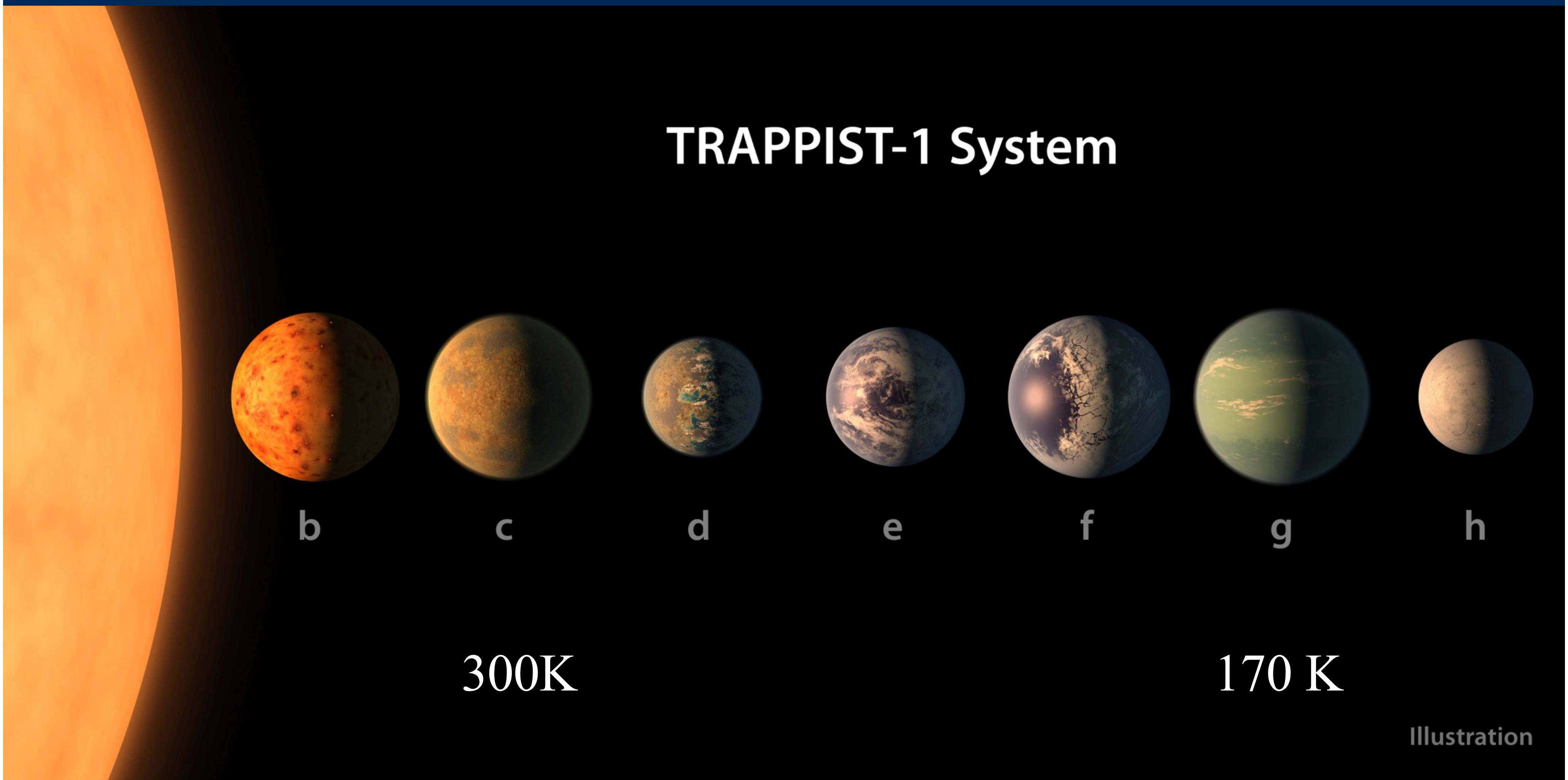


Eyeball planets – tidally locked to their star

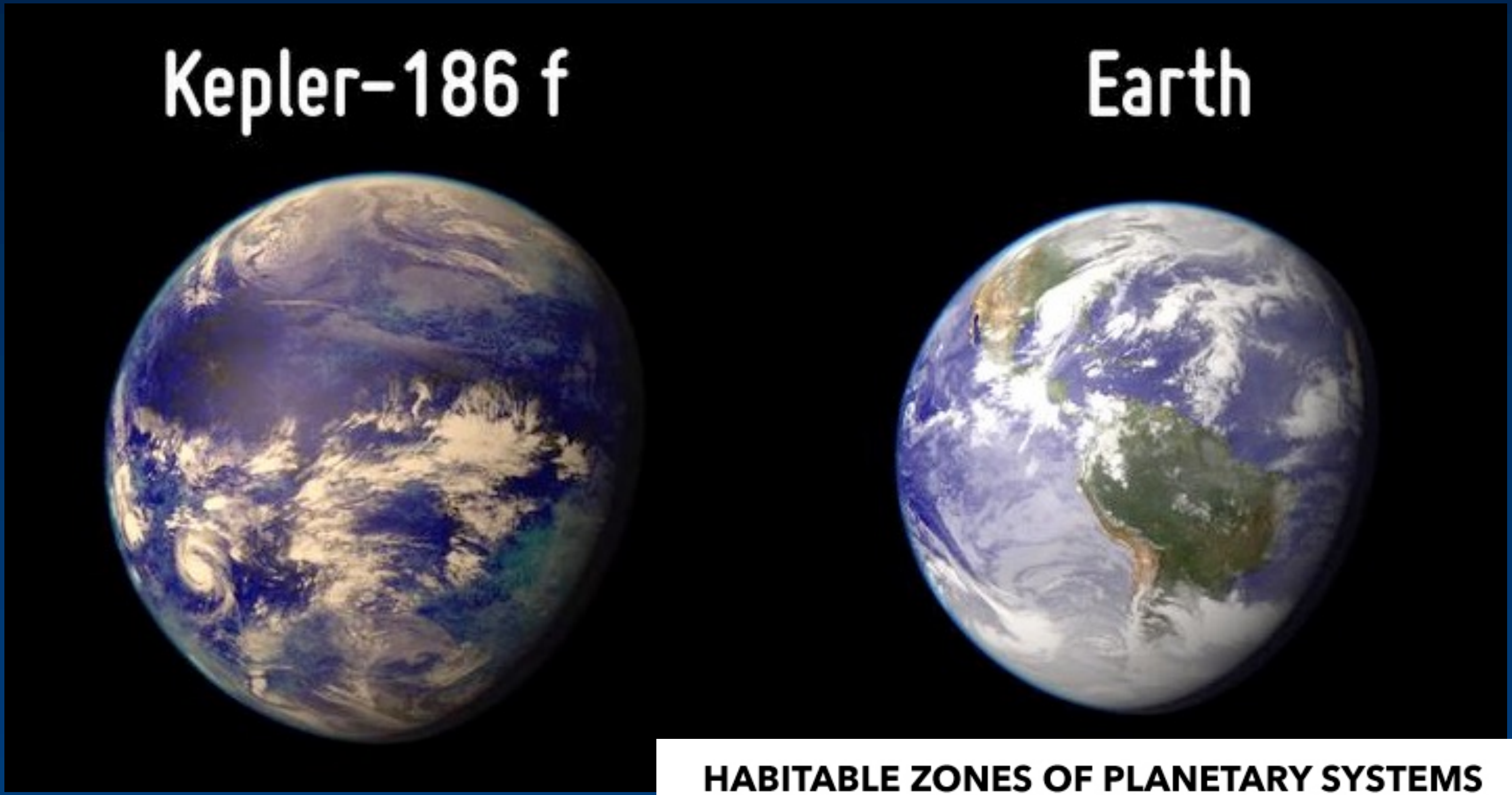


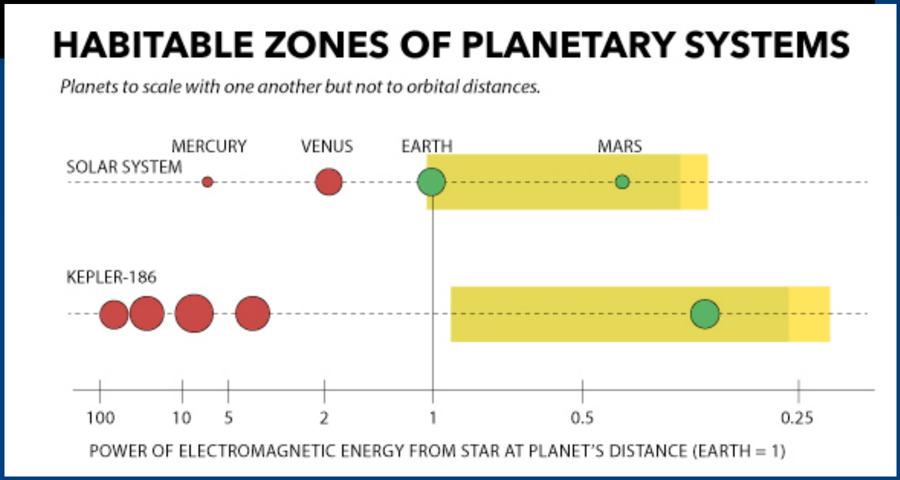


Eyeball planets – tidally locked to their star

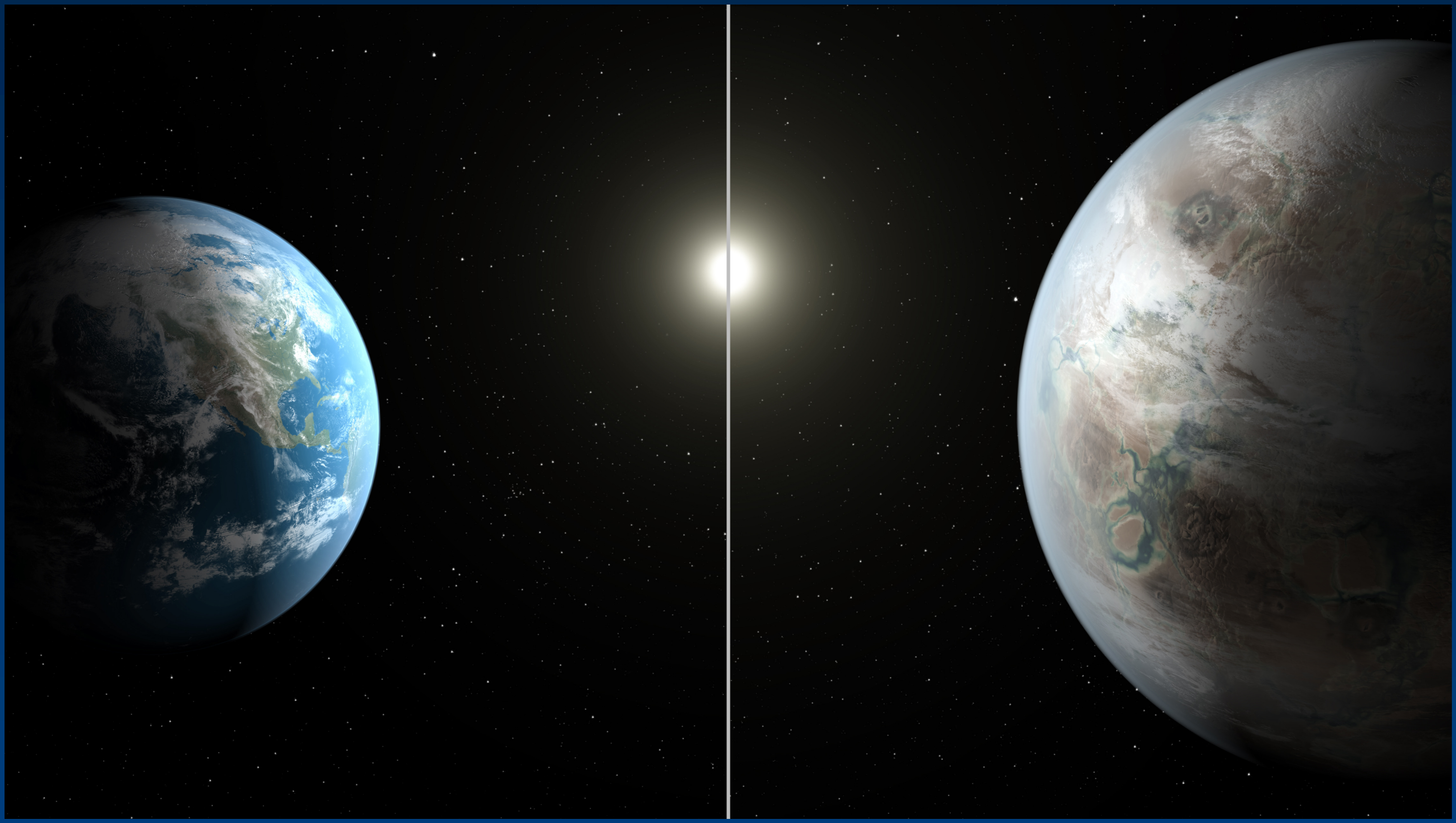


Extrasolar planet 1.1 Earth masses (Kepler-186f) found in star's habitable zone by Doppler method – April 2014





Extrasolar planet 3.3 Earth masses (Kepler-442b) found in G2 star's habitable zone by Transit method – 2015

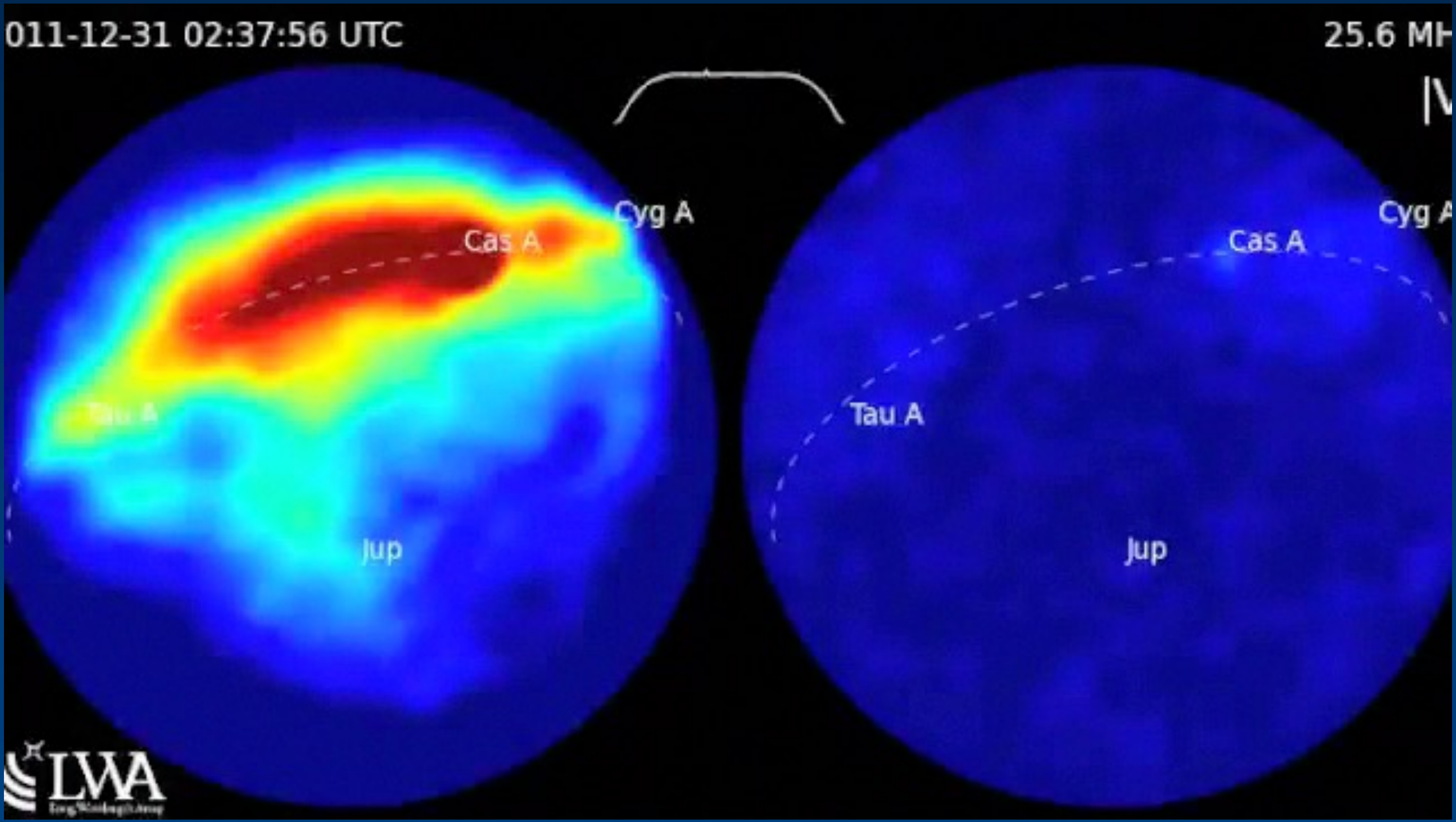


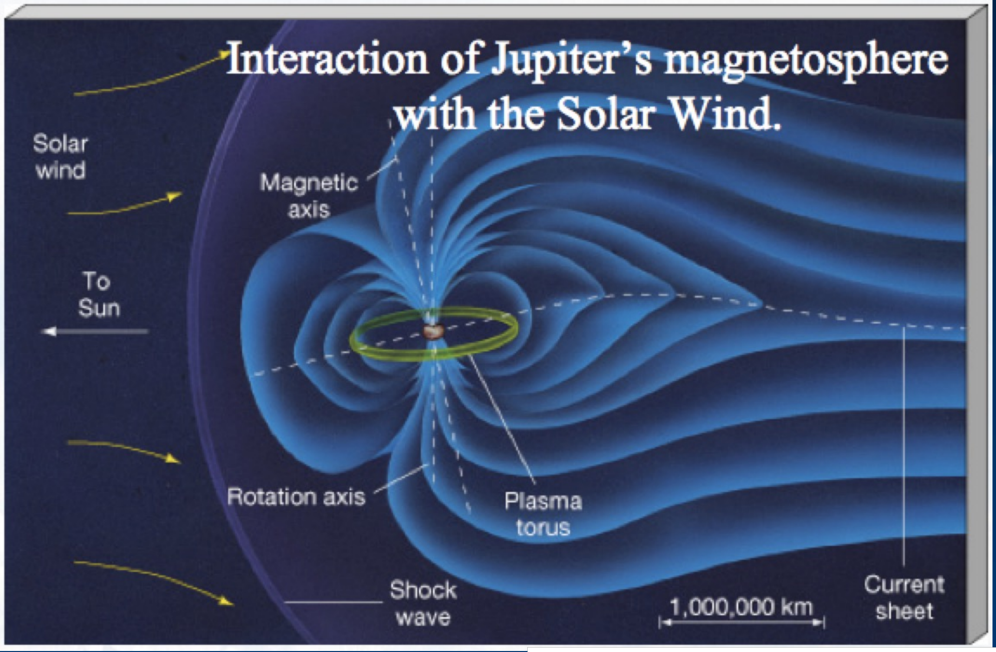
One of the closest earth-like planets at 370 pc.
How many Earth-like planets in our galaxy?

Detecting Radio Bursts from Exoplanets

- Suitability of the LWA1
- Observations to date
- Near future: Owens Valley
- Farther future: the LWA swarm

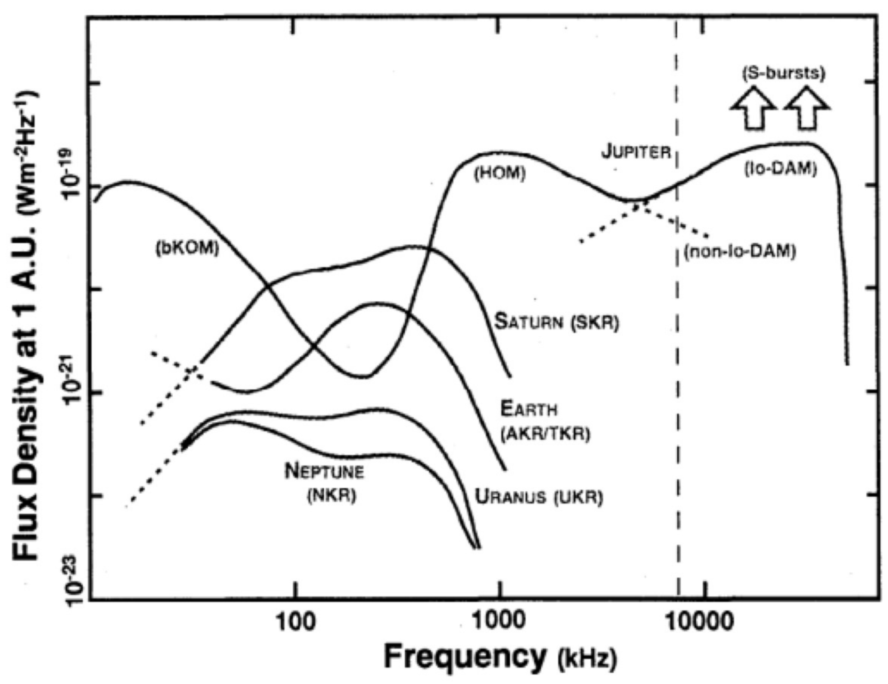
Emission from Jupiter





Interaction of Jupiter's magnetosphere with the Solar Wind.
Solar wind
Magnetic axis
To Sun
Rotation axis
Plasma torus
Shock wave
1,000,000 km
Current sheet

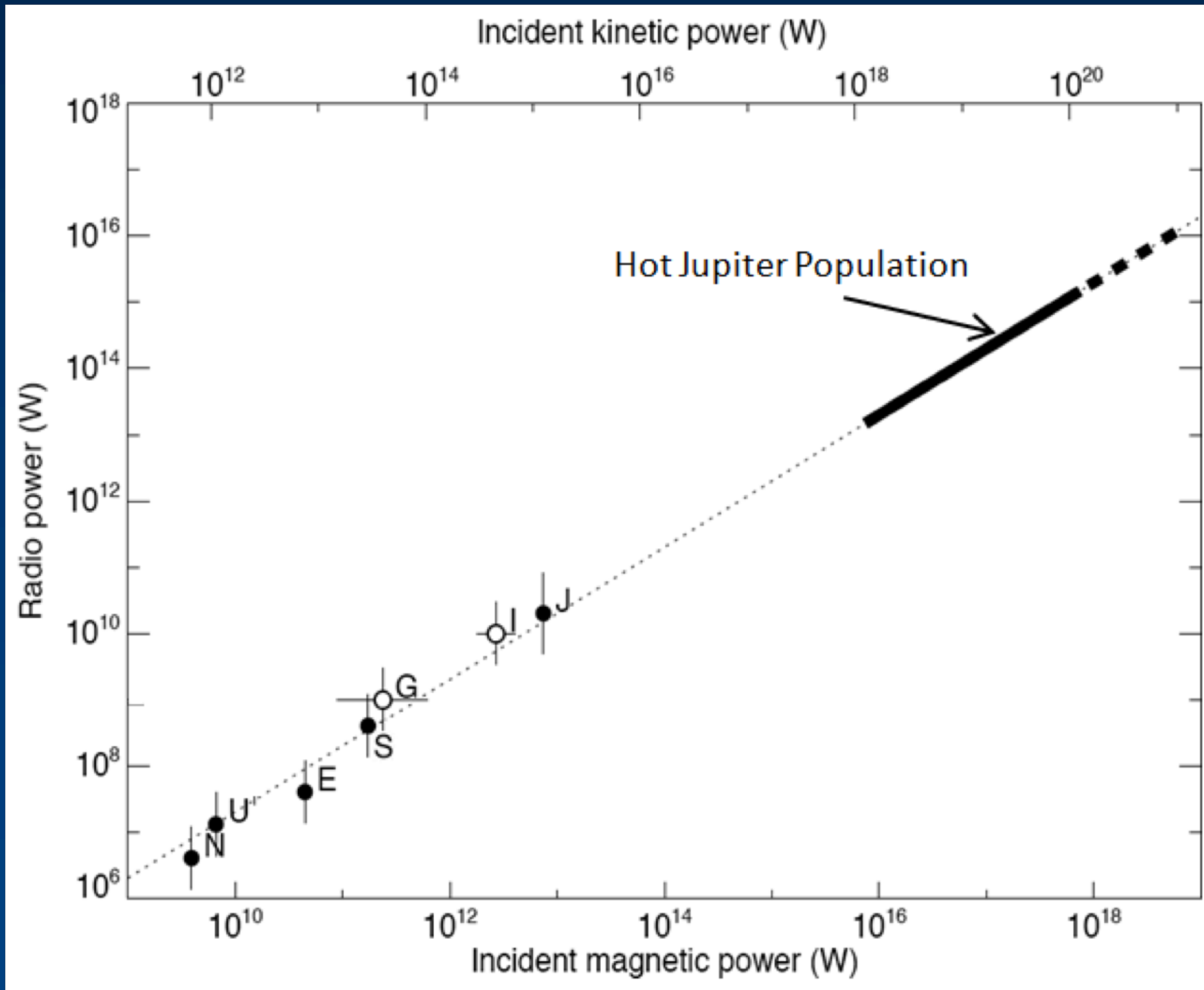
Jupiter Aurora
HST • STIS
NASA and J. Clarke (University of Michigan) • STScI-PRC00-38



Flux Density at 1 A.U. (Wm⁻²Hz⁻¹)
10-19
10-21
10-23
100
1000
10000
Frequency (kHz)
(S-bursts)
JUPITER
(HOM)
(Io-DAM)
(non-Io-DAM)
(bKOM)
SATURN (SKR)
EARTH (AKR/TKR)
NEPTUNE (NKR)
URANUS (UKR)

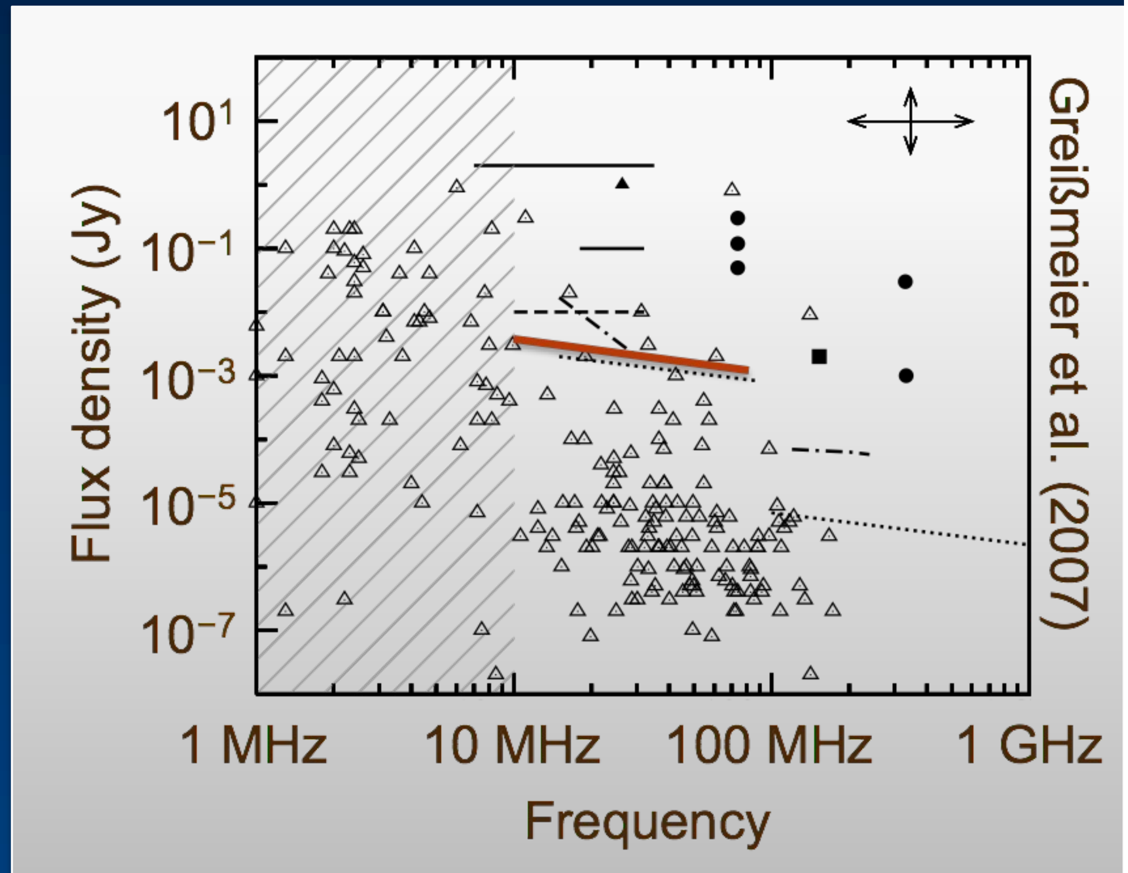
Zarka (1998)

Extrapolating to Hot Jupiters



Emission from Hot Jupiters

- Low frequency:
  $eB / 2\pi m_e$ = 28 MHz at 10 G
- Bright!
  ~100 mJy fluxes predicted
  (but less than confusion)
- High circular polarization:
  LWA1 is very good at this!
- Predictably time-variable:
- pulsar-like emission
- secondary eclipses
- periastron passages of high-eccentricity HJs
- However, substantial observing time is required for good upper limits

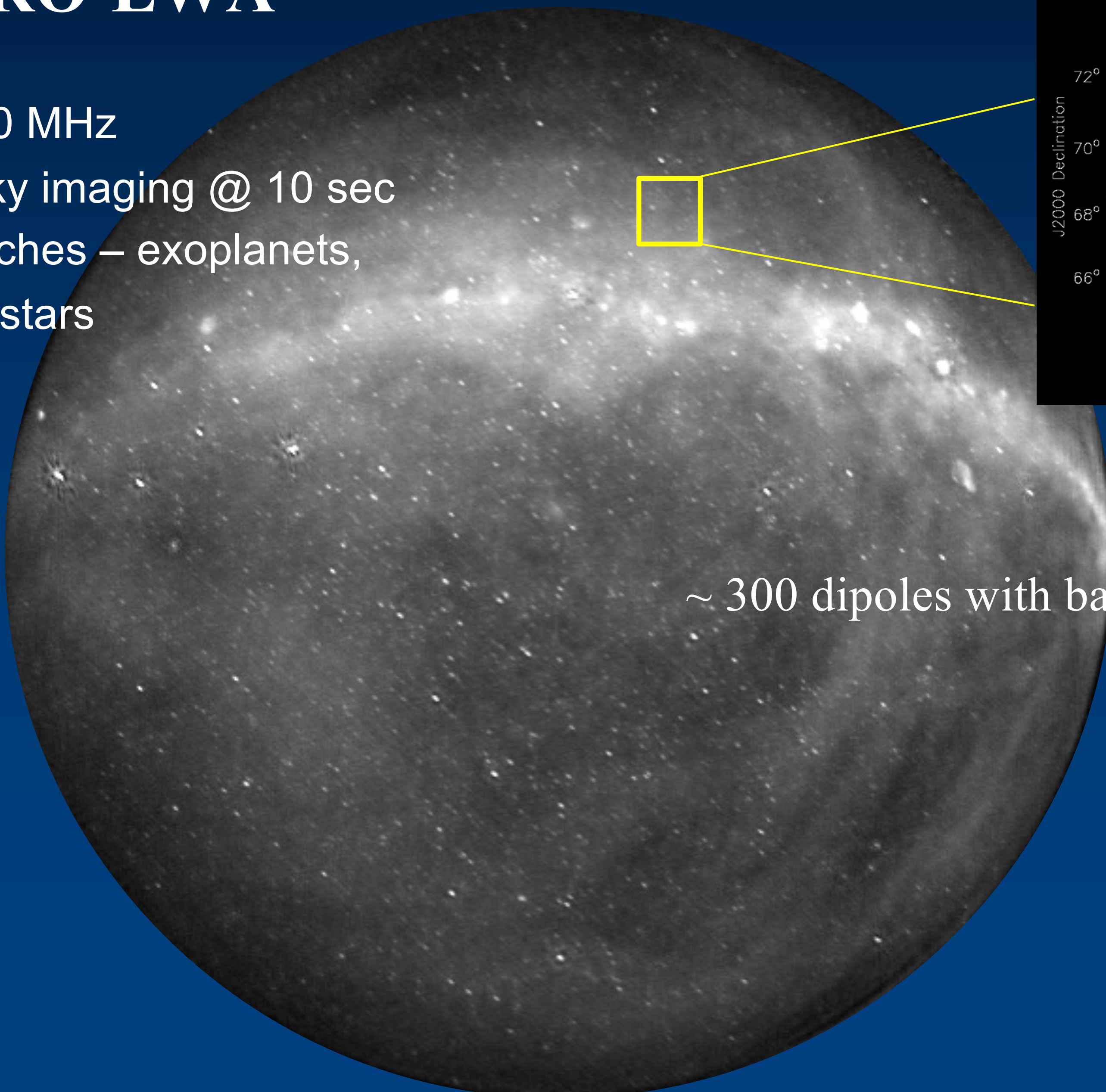


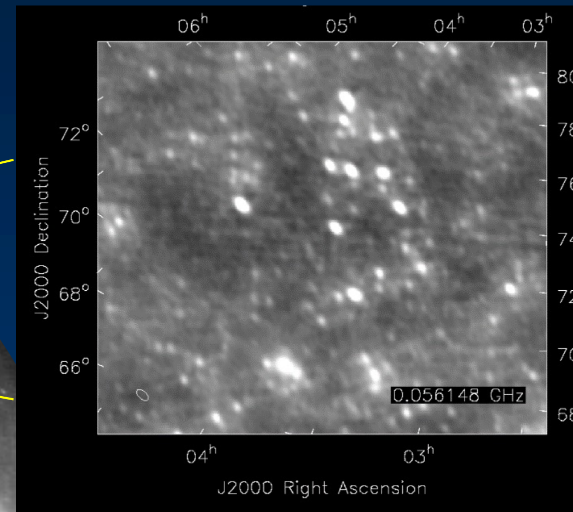
Long Wavelength Array

LWA Tools

OVRO-LWA

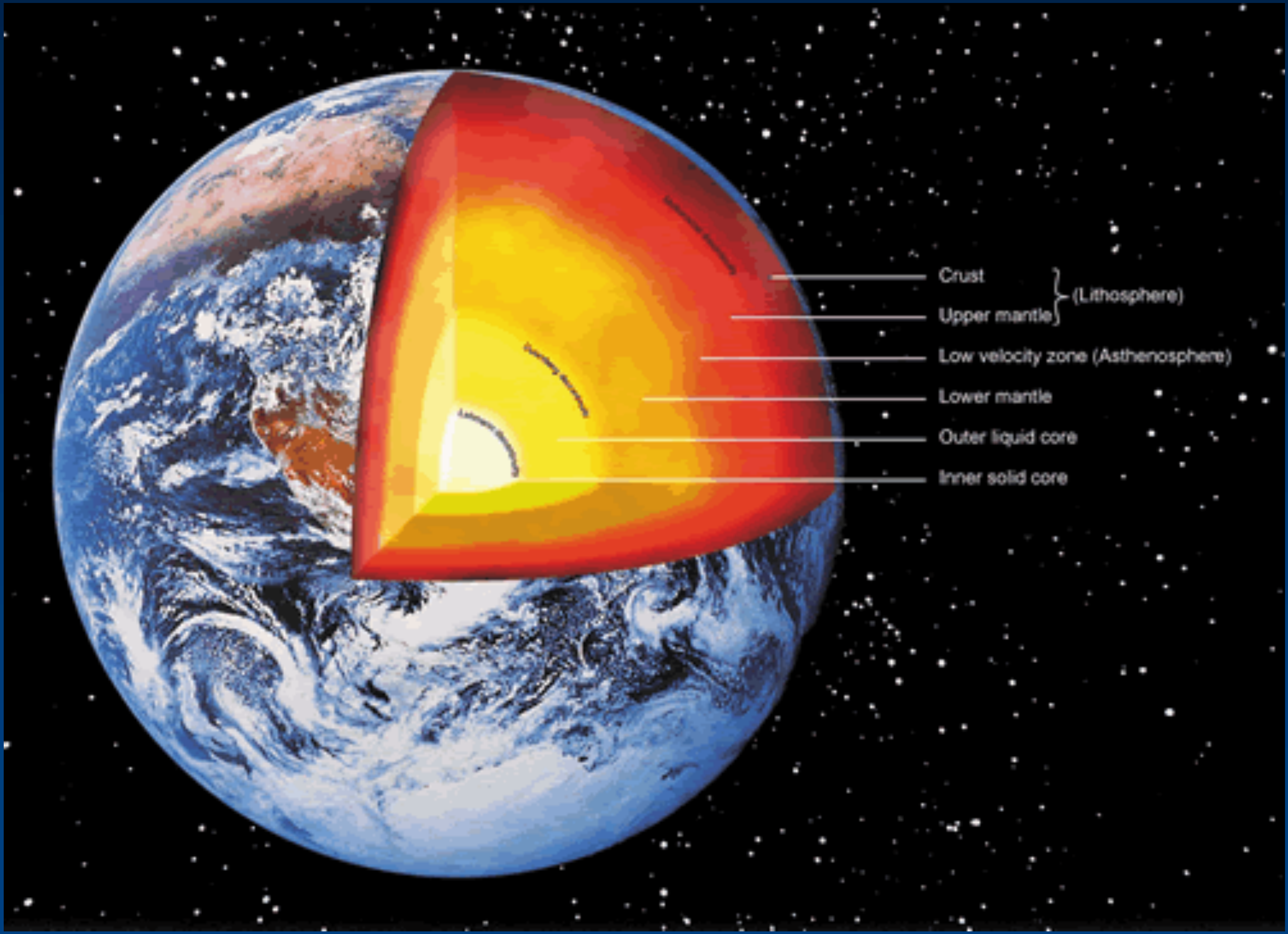
- 30-80 MHz
- All sky imaging @ 10 sec
- Searches – exoplanets, flare stars





~ 300 dipoles with baselines to 2 km

Earth's Interior



Earthrise, Apollo 8, 1968

Earth from Apollo 17, 1972

71% water, 29% continents

The Earth - Surface and Interior

Basic Data

Diameter	12,756 km (equator)
Mass	6×10^{24} kg
Density	$5.5\ g/cm^3$
	$5500\ kg/m^3$
Escape velocity	11.2 km/s
Temp	-130 ° F to 140 ° F
	183K to 333K
Albedo	0.31

= fraction of incoming sunlight that a planet reflects

Densities of typical surface rocks:

$\approx 3000\ \mathrm{kg/m^3}$

Average density of Earth as a whole (its mass/volume):

$\approx 5500\ \mathrm{kg/m^3}$

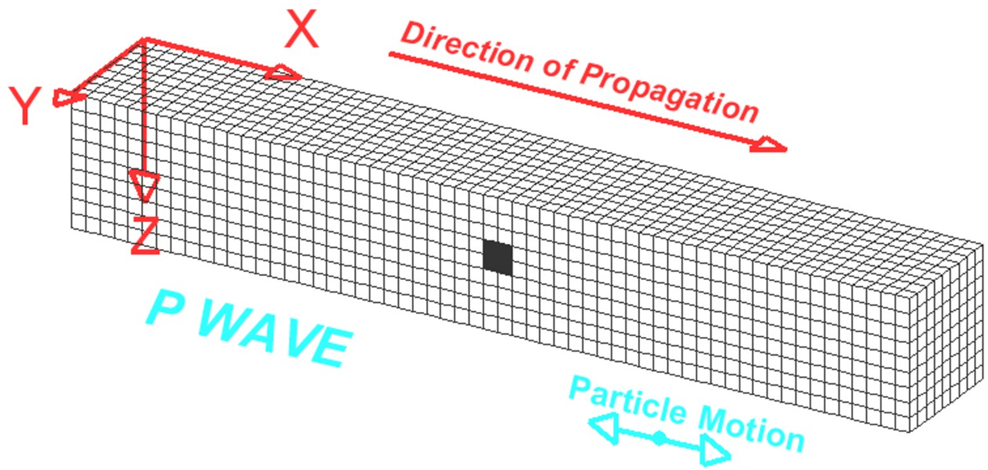
$\Rightarrow$ Interior must be much denser than the crust!

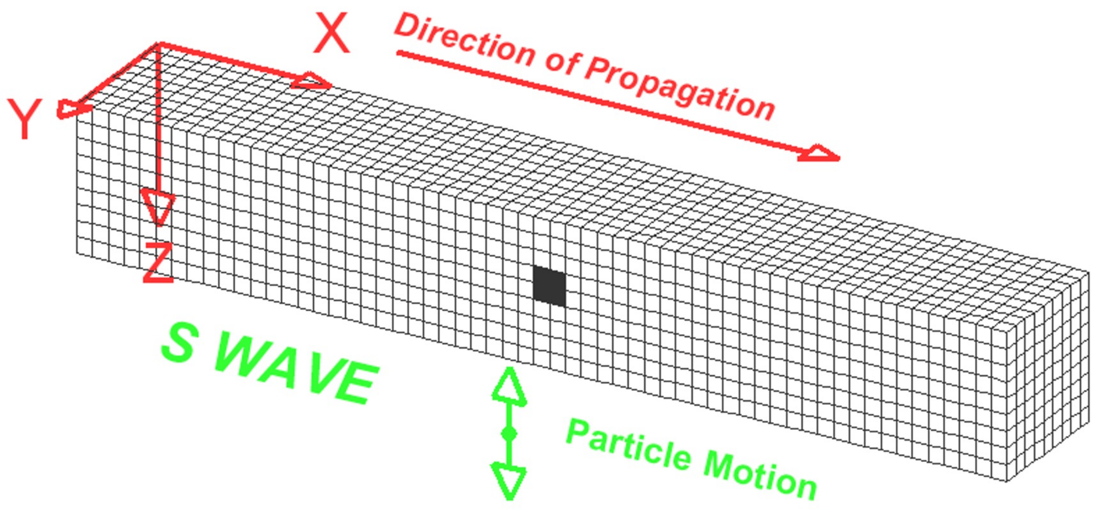
How can we probe the interior?

Seismology

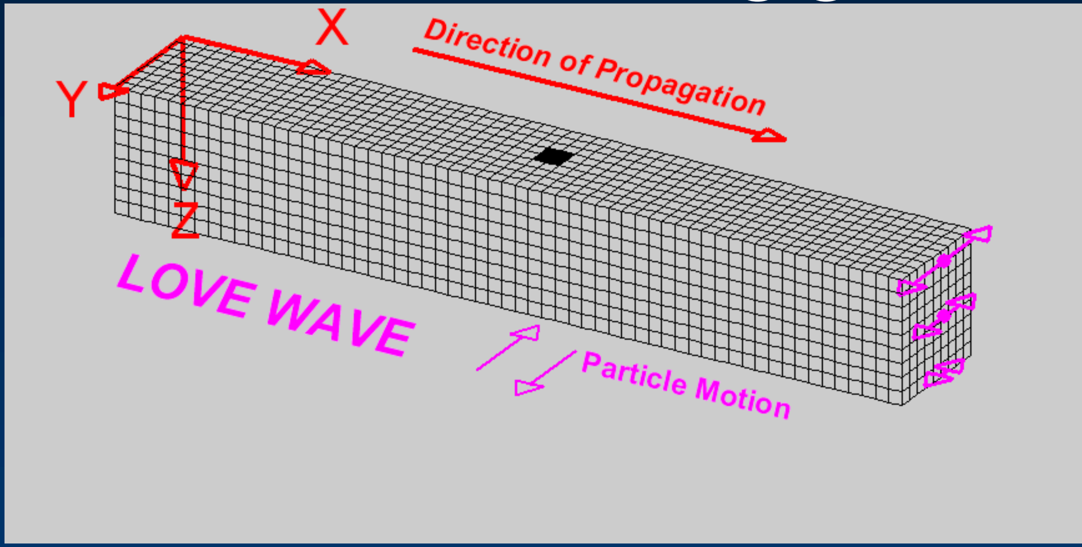
- Study of earthquakes and seismic waves that move through and around the Earth
- Primary and Secondary waves move through the Earth. Love and Rayleigh waves move around surface.

- P waves – “primary”, pressure or longitudinal. Fastest waves. Can pass through liquid.
- S waves – “secondary”, shear or transverse. Cannot travel far in liquid

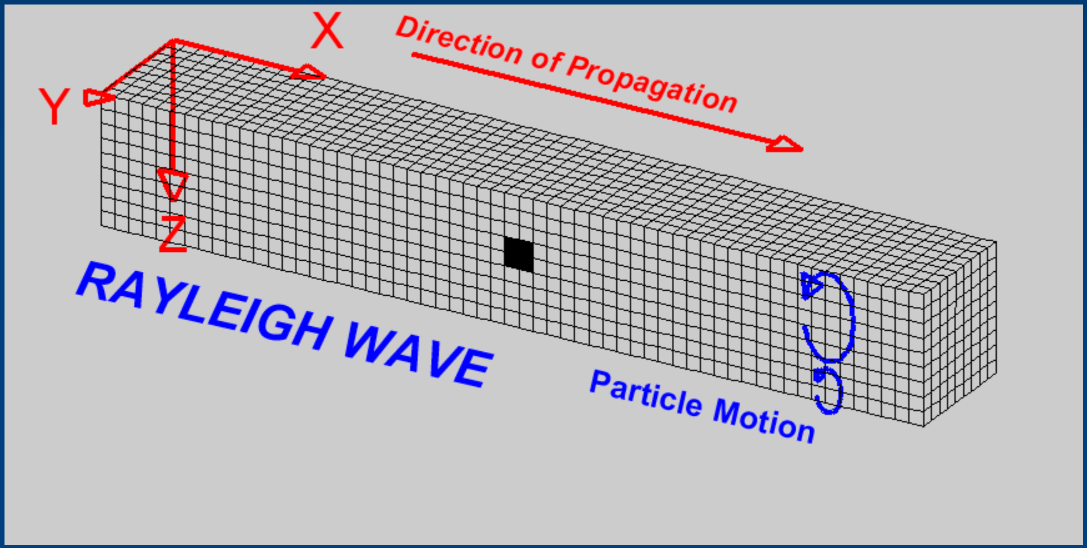




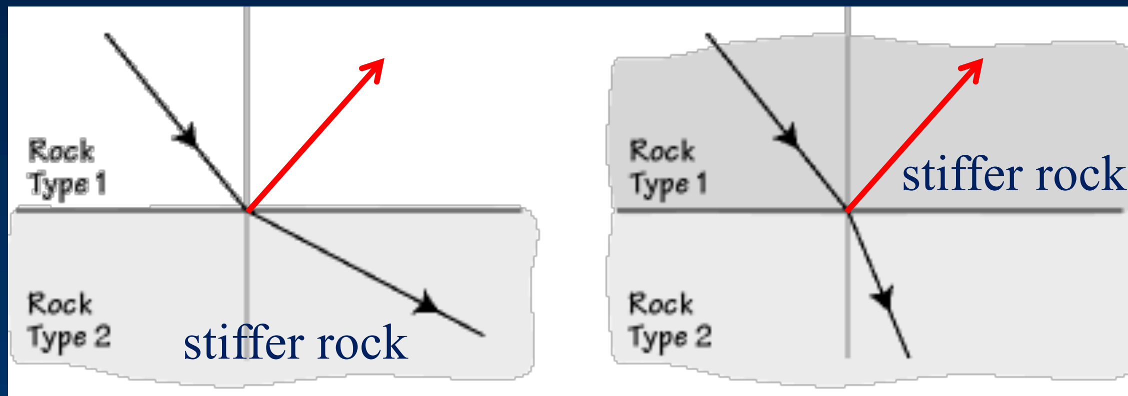
- Love waves - surface waves moving ground side-to-side

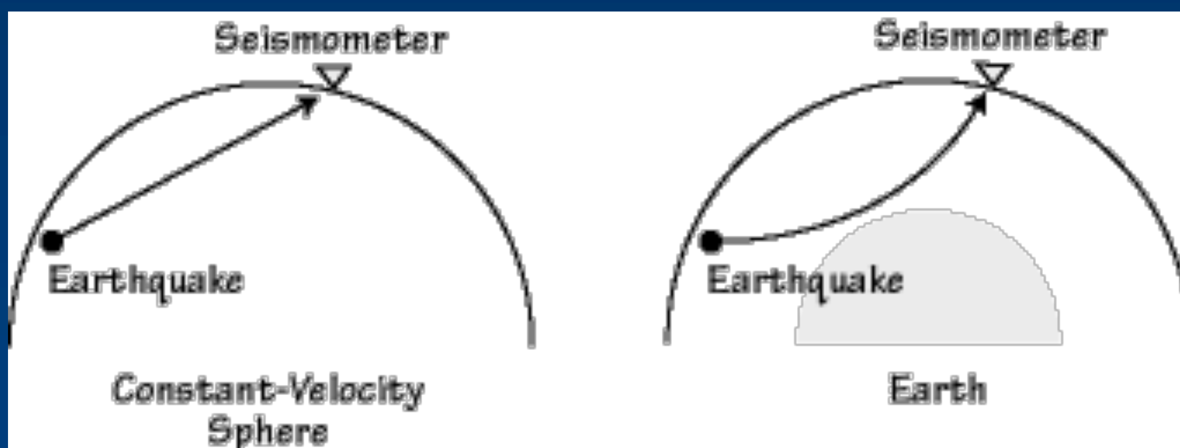


- Rayleigh waves - surface waves rolling the ground (up-down, back-forward)



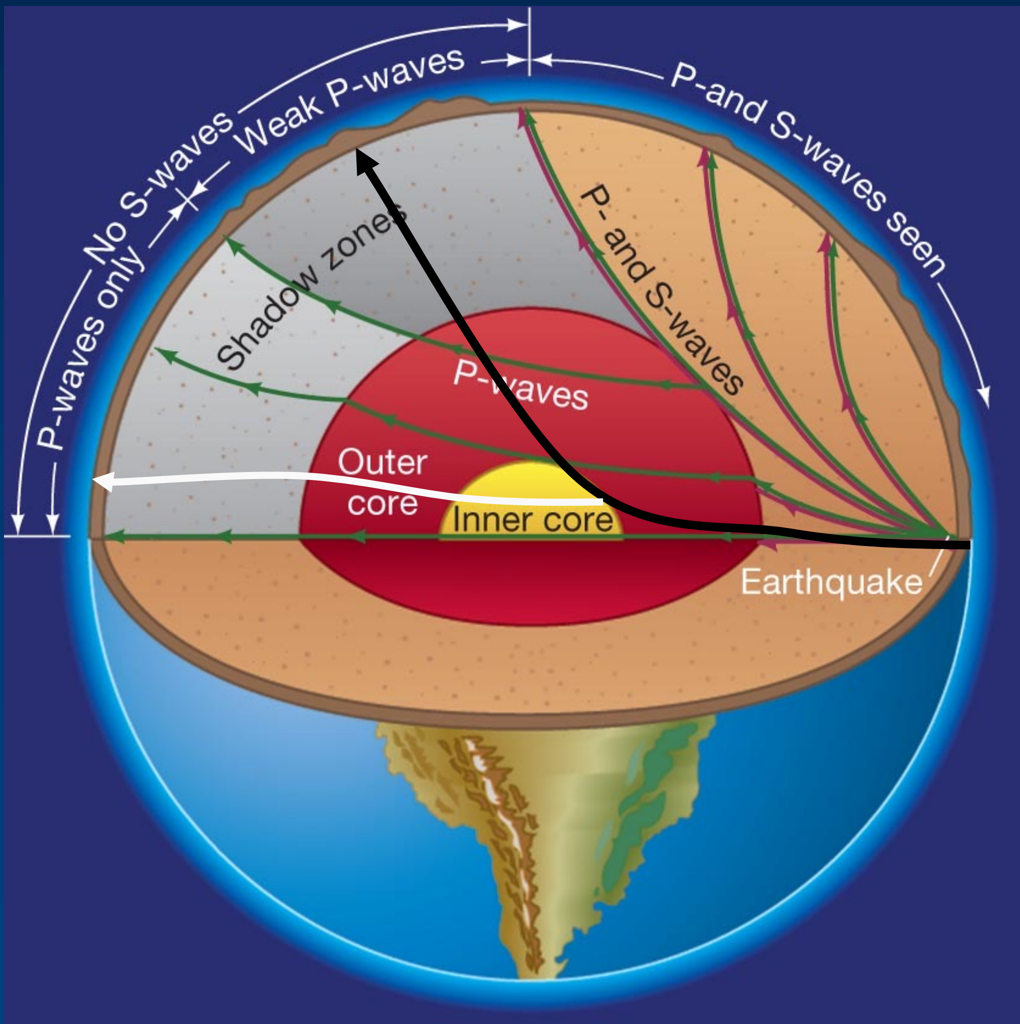
Refraction of seismic waves





Also get reflected wave component at a sharp boundary, angle of incidence = angle of reflection

P and S waves measured around the surface reveal interior structure



⇒ The Earth must have a liquid core! Also fairly sharp density increase when you hit the core.

Later, faint P waves found in part of shadow zone – solid inner core inferred