KABOOM

- Chelynabinsk, Russia, Feb. 15 2013
  - 500-kton kerpow caused by a 10,000 ton asteroid moving 60,000 km/hr

Fig.9.26

Again an airburst – fragments recovered

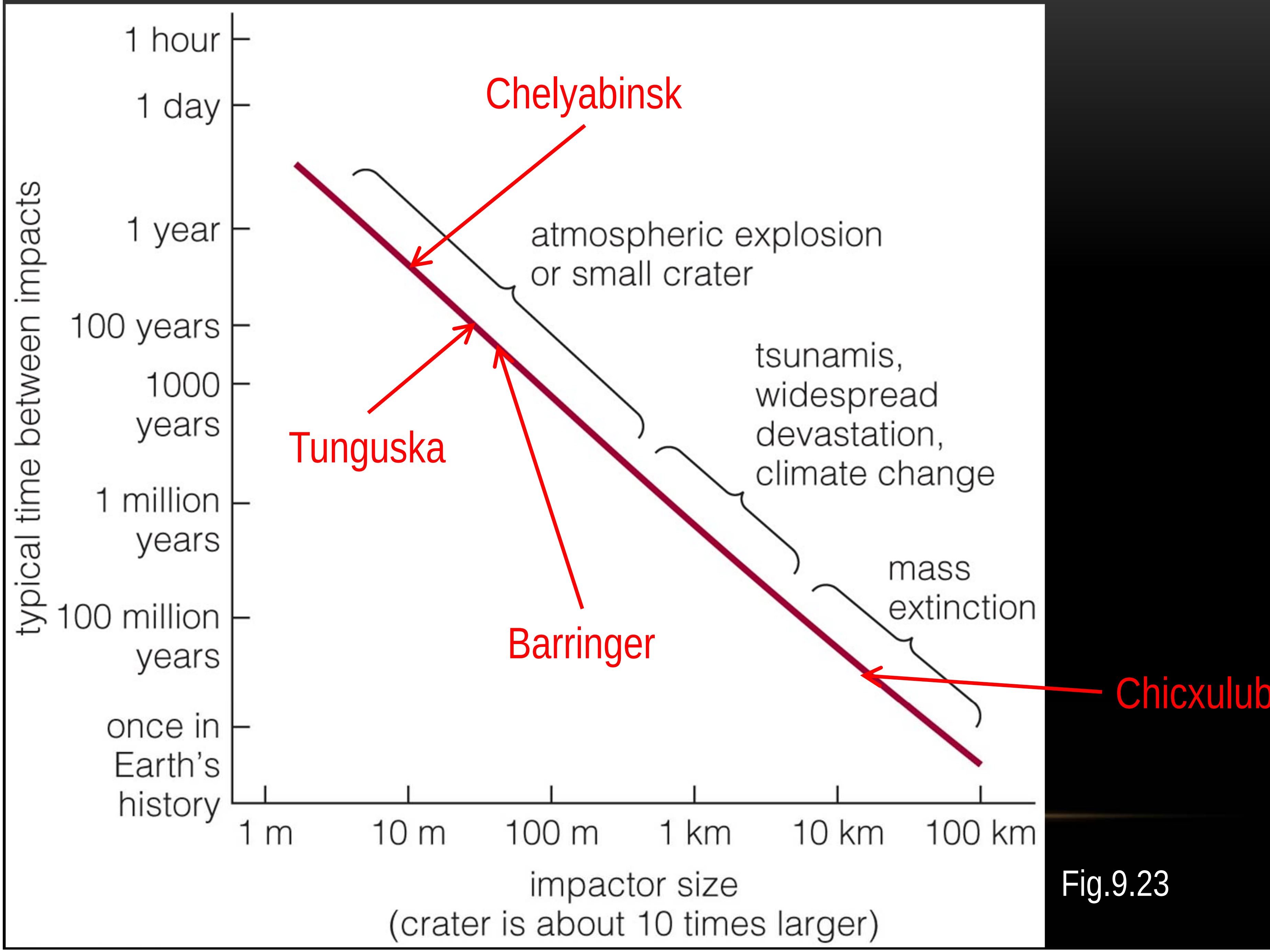
1000 people injured by broken glass

Good thing it came in at such an angle!

BUT ANECDOTES AREN'T DATA

- Measuring things carefully, how often do things hit Earth?
- How big how often?
- We can figure this out:
  - For smaller, more frequent things the nuclear test monitoring system is helpful: registers small/medium sized things all the time
  - For bigger things, look carefully at the geological record of known impact sites
  - Google Earth now playing a big role in this, people are finding lots of craters in satellite photos

List of airburst meteors on Wikipedia
11 decent ones since Chelyabinsk!



typical time between impacts
1 hour
1 day
1 year
100 years
1000 years
1 million years
100 million years
once in Earth's history
1 m
10 m
100 m
1 km
10 km
100 km
impactor size
(crater is about 10 times larger)
atmospheric explosion or small crater
tsunamis, widespread devastation, climate change
mass extinction
Chelyabinsk
Tunguska
Barringer
Chicxulub

Fig.9.23

METEOR STRIKES…

- are Mother Nature’s way of saying:
- “Hey, how’s that space program coming along?”
- See here for lots of links about what NASA’s doing about it

ASTEROID WITH OUR NAME ON IT?

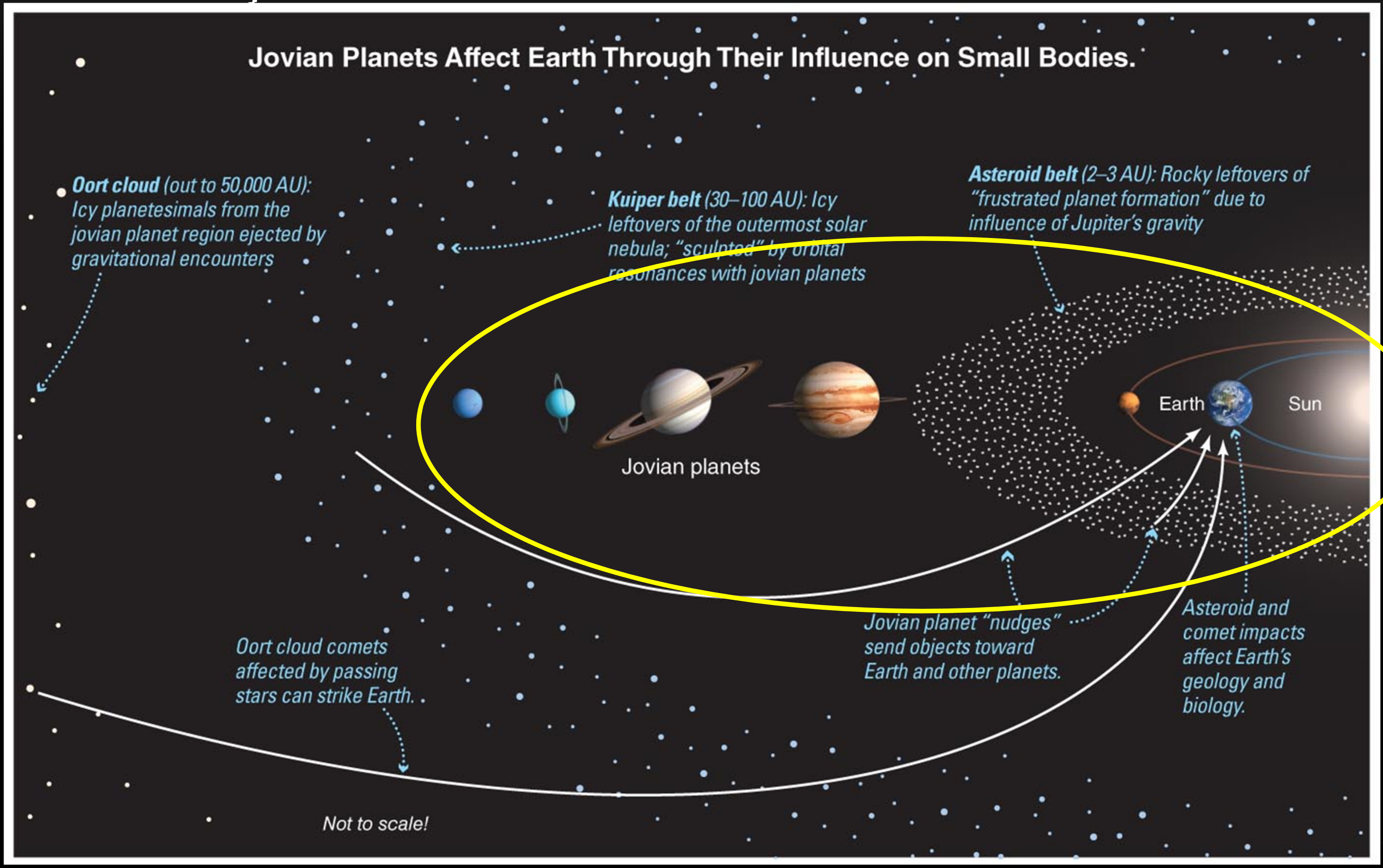
- We haven't seen it yet.
  - Have seen many “near misses” that are worth keeping an eye on
- Deflection is more probable with years of advance warning (*ala “Armageddon” movie*)
  - Control is critical: Breaking a big asteroid into a bunch of little asteroids is unlikely to help.
- We’d get less advance warning of a killer comet.
  - They’re coming from way out there, not cruising around for a while in our neighborhood

JUPITER?

- We saw that Jupiter's gravity can sometimes take a long-period comet and redirect it into becoming a short-period comet which comes back more regularly (like Halley's comet)
- So, is Jupiter sitting back there essentially throwing his lightning bolts at Earth?

SURE, BUT…

Fig.9.28



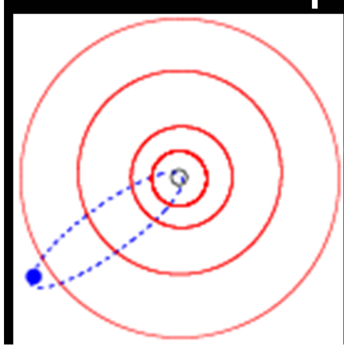
While Jovian planets redirect some comets in our general direction

EG, HALLEY'S COMET

- A=17.8 AU, p=75.3 y
  - Retrograde, 162º inclination
  - Gets very close to earth, we have passed right through tail
  - Last seen in 1986.
  - First recorded in 240 BC

Photo by W. Liller, 1986

Bayeaux Tapestry, 1066

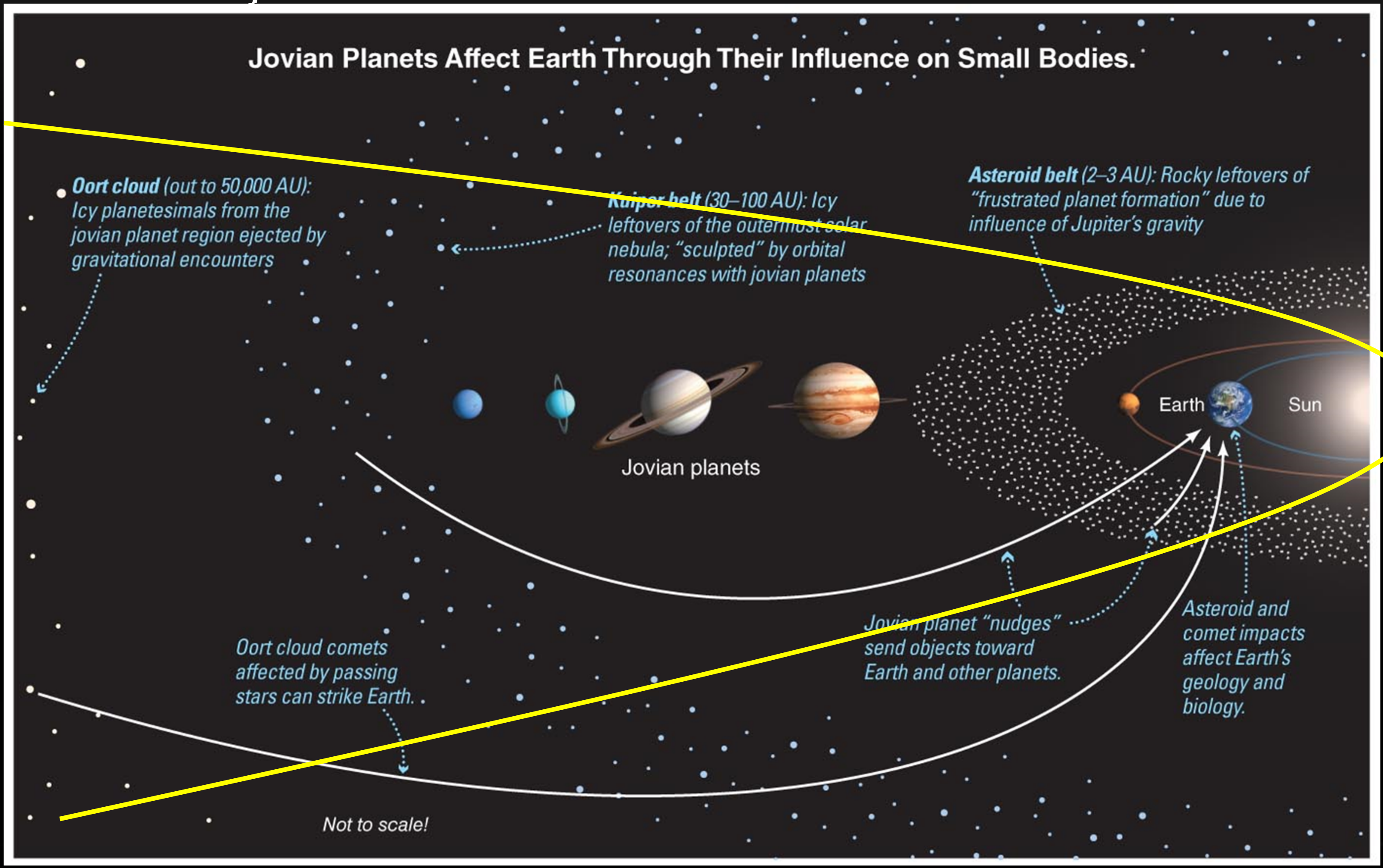


Orbit compared to outer four planets

SURE, BUT…

(more ways to catch up to planet than to come in from the front)

Fig.9.28



Many more get sent out the other way

(remember how the Oort cloud was formed in the first place?)

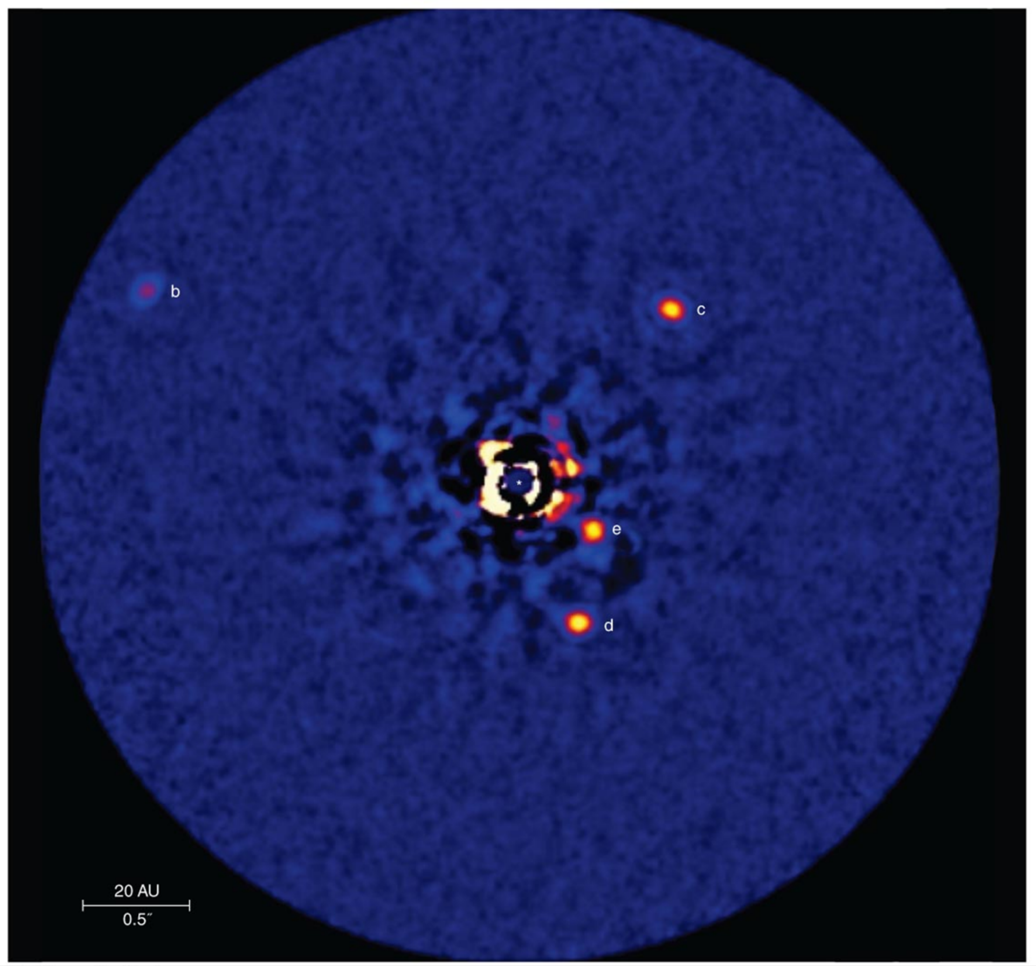
IS HAVING A JUPITER NECESSARY FOR LIFE ON EARTH??

- So much so, that there is some speculation that in a solar system without a Jupiter running interference for Earth:
  - The extra big impacts would have kept the conditions on earth too brutal for life to have evolved over the eons
- One of many factors that influence potential life in solar systems
  - More in Ch.18

OTHER SOLAR SYSTEMS

Ch.10

OTHER SOLAR SYSTEMS?

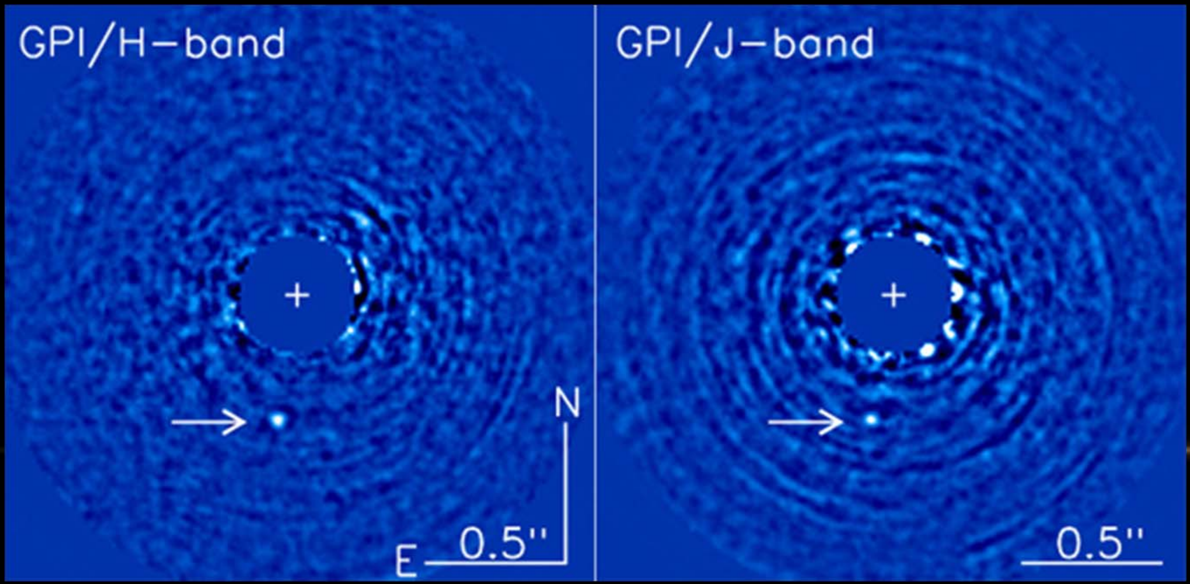


- A direct picture of four planets around HR 8799 from the Keck scope
- This, however, turns out to be the *really hard way* of doing it
  - Mostly done indirectly

AND ANOTHER…

(NOW 19 SYSTEMS, 44 PLANETS TOTAL)

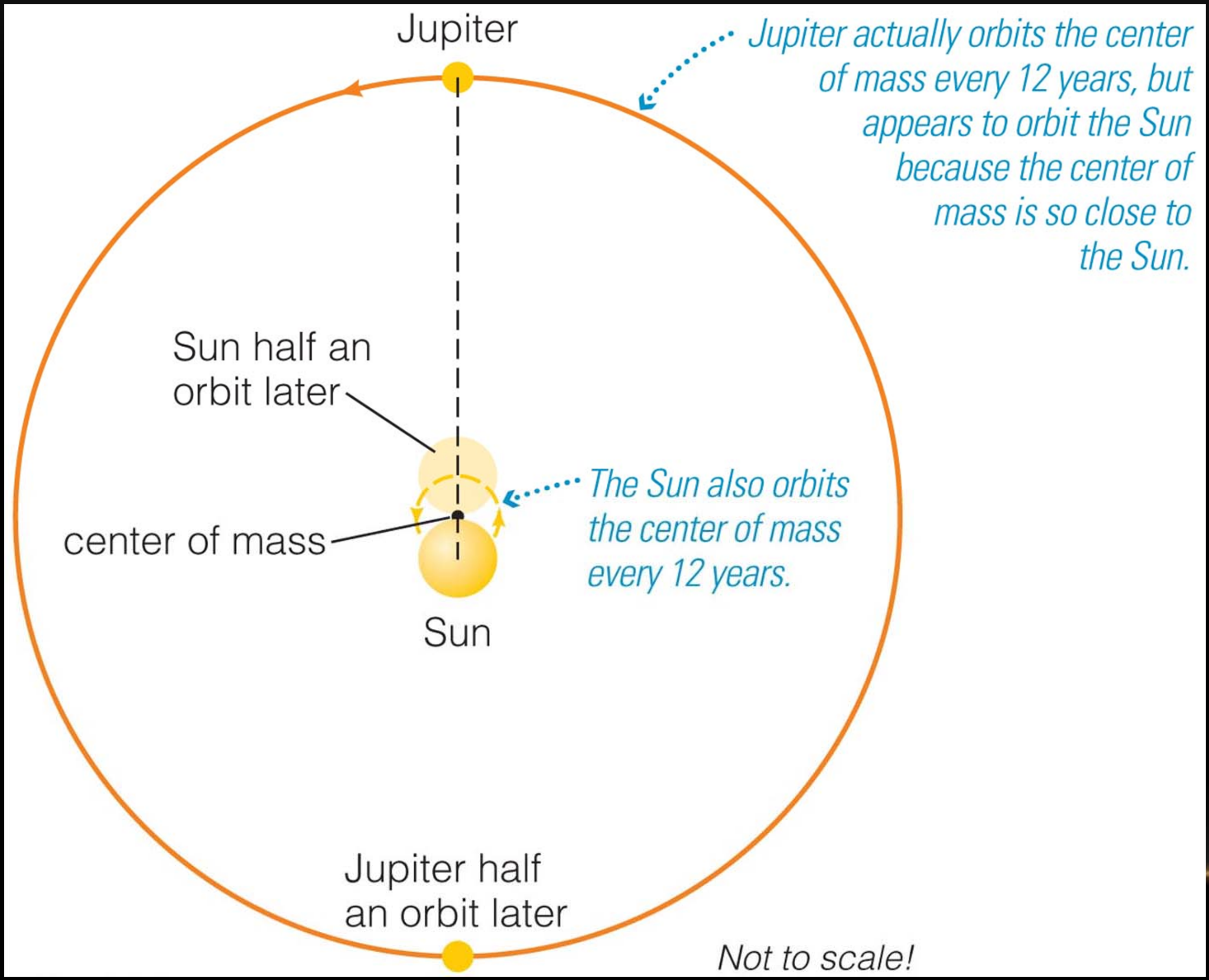
- 51 Eridani b
- 2-12 Jupiter masses, orbiting at 2x Saturn's distance
- 100 ly from earth



WHY SO HARD TO DIRECTLY SEE?

- A Sun-like star is about a billion times brighter than the light reflected from its planets.
- Planets are close to their stars, relative to the distance from us to the star.
    - This is like being in San Francisco and trying to see a pinhead 15 meters from a grapefruit in Washington, D.C.
        - … while the grapefruit was burning brightly

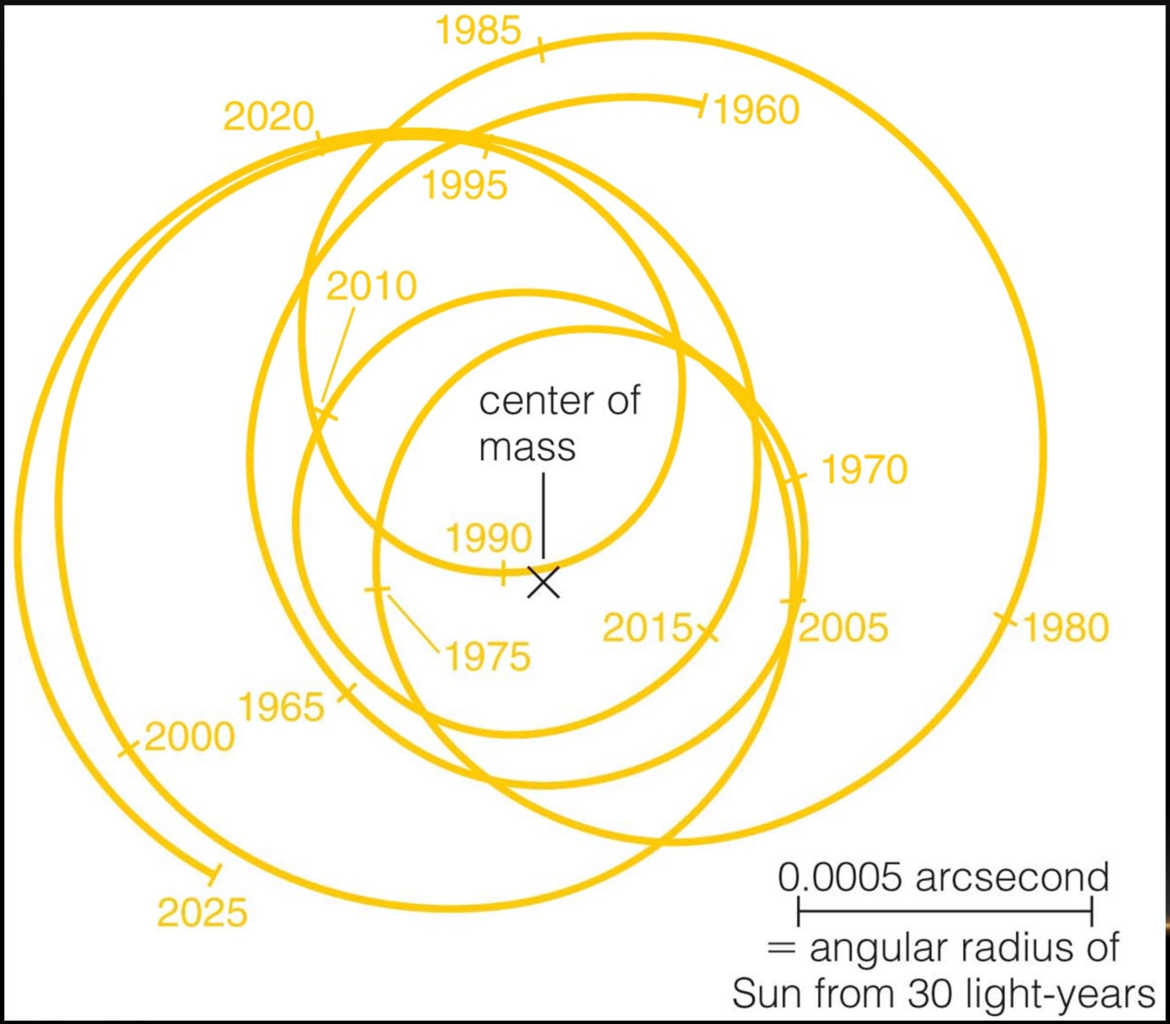
ORBITS REVISITED…



- Newton's 3rd Law: for every action, there is an equal and opposite reaction
- Could we see some other star wobble like this?

Fig.10.1

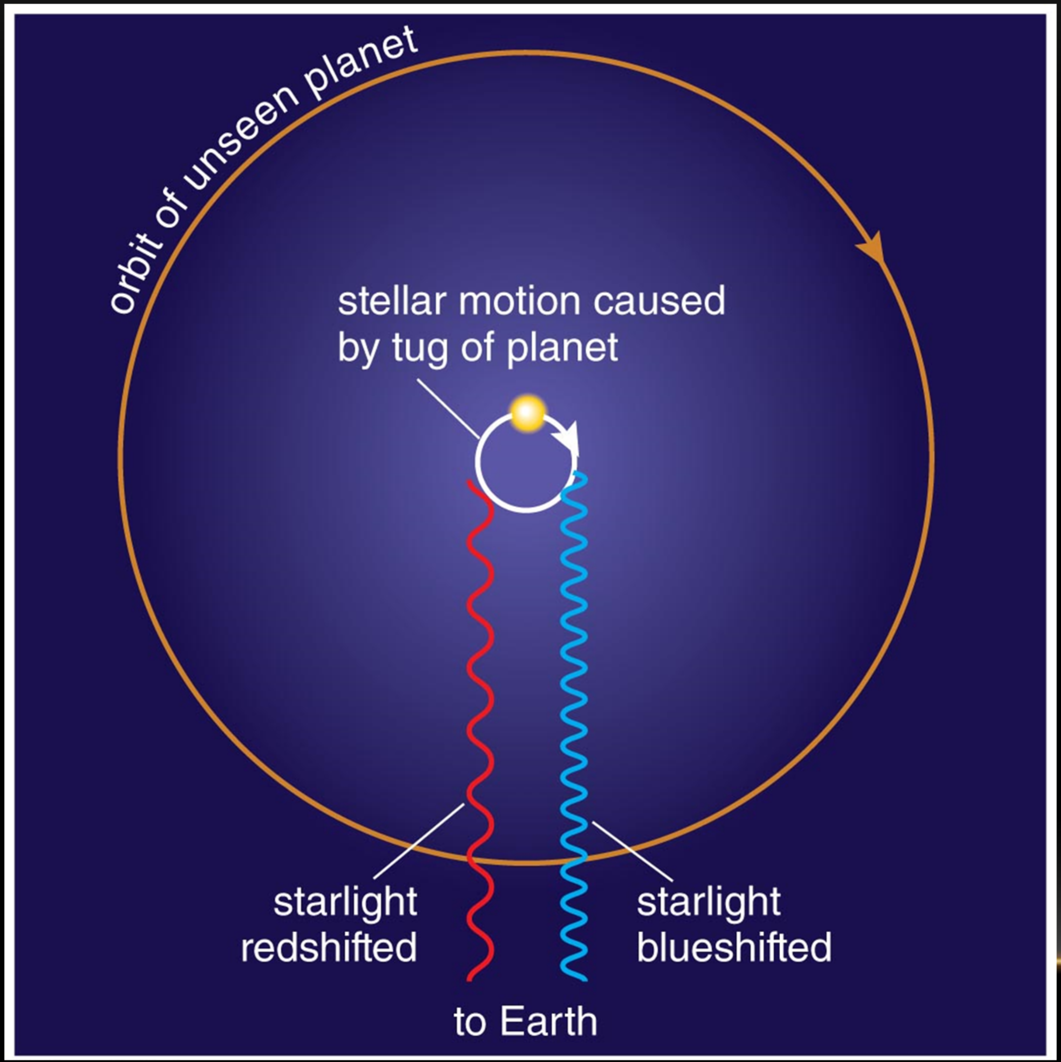
AND ALL THE OTHER PLANETS TOO



- Plotting out the positions is called "astrometry"
- This "Astrometric technique" is very hard to do given small motions and a large sun
- The Gaia mission has been working on doing this for a few years now

Fig.10.2

MEASURE VELOCITY INSTEAD

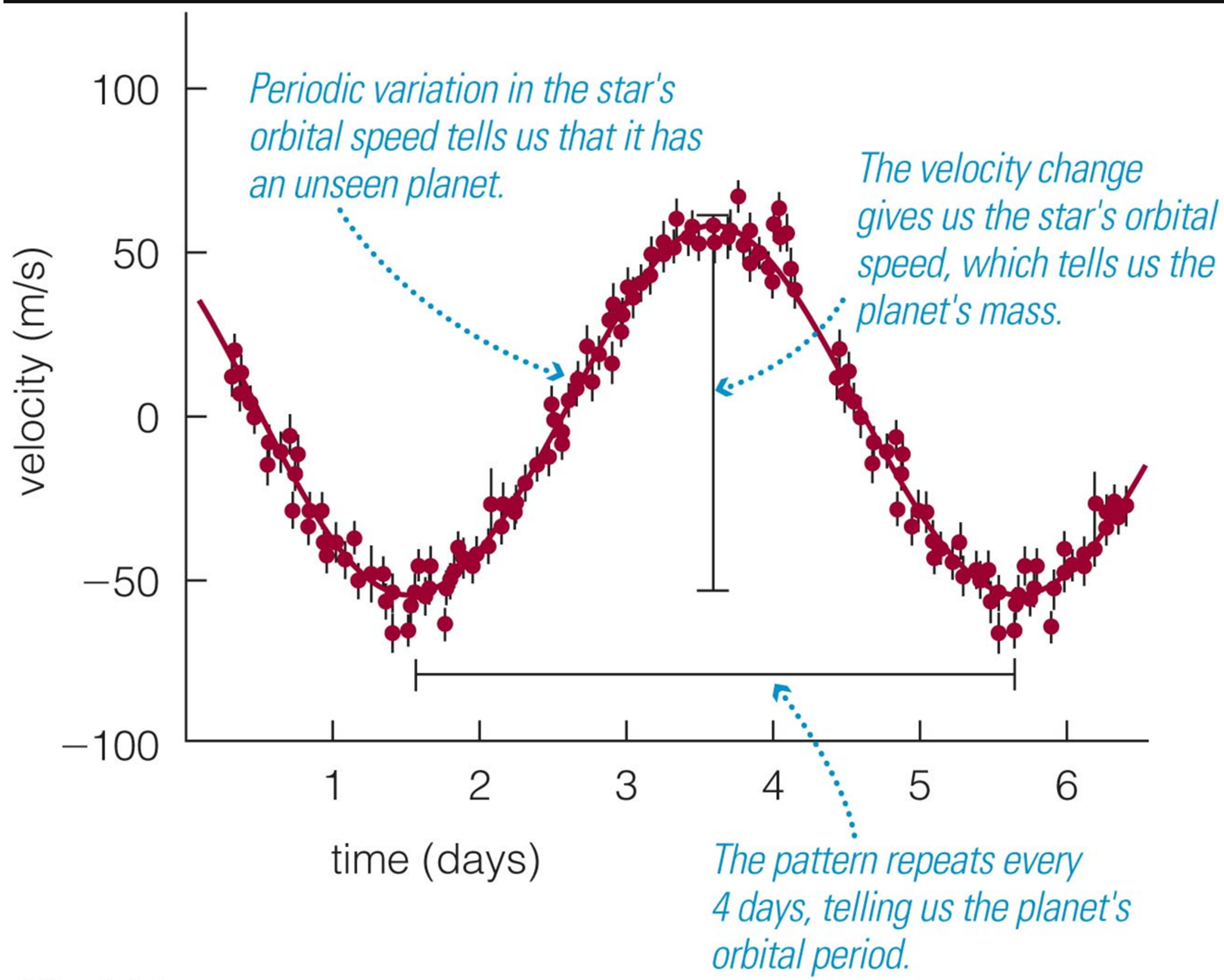


- Use the Doppler Effect to see how fast a star is wobbling towards or away from us
- Can measure speeds as small as 1 m/s!

PLAY

Fig.10.3

51 PEGASI

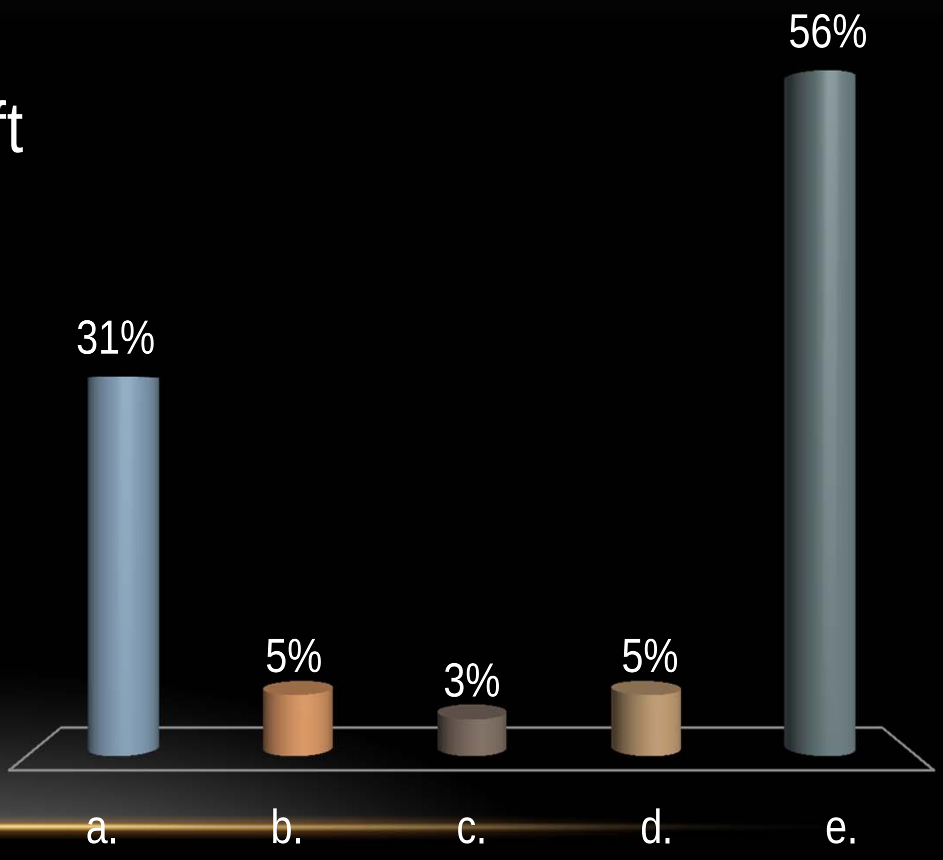


- First extrasolar planet discovered this way in 1995
- (*note data points, error bars = this is very precise*)

Fig.10.4

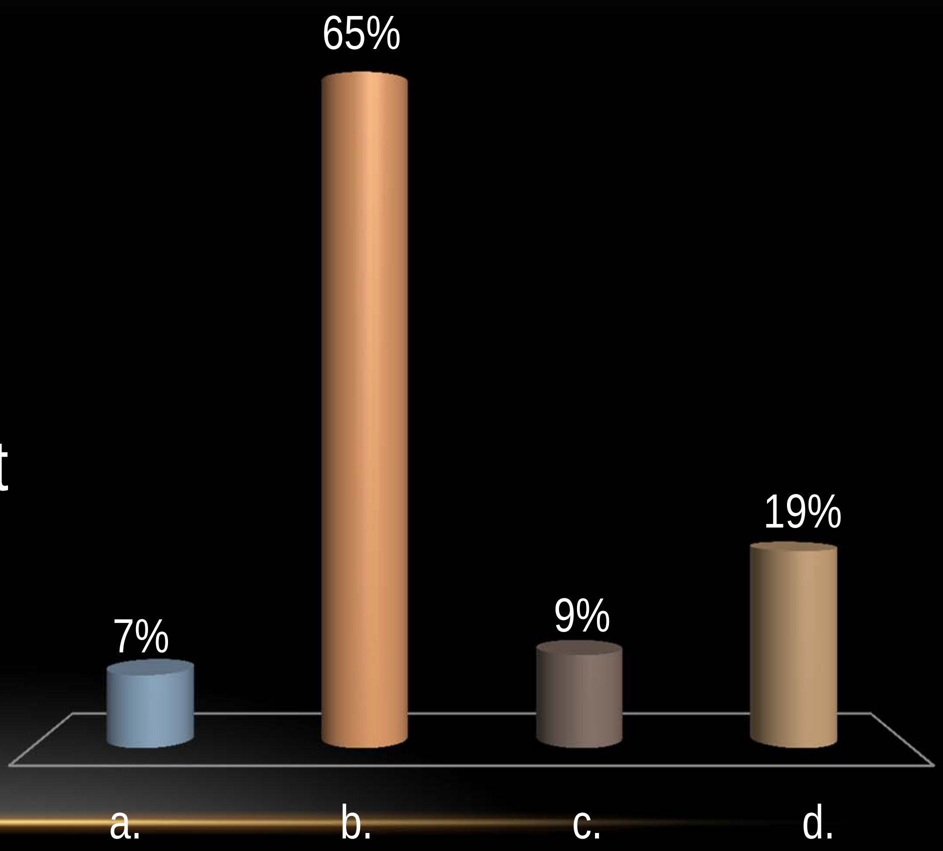
THE LARGER THE MASS OF THE UNSEEN PLANET,

a. the larger the Doppler shift of the star. ✓
b. the smaller the Doppler shift of the star.
c. the faster the period of the star's Doppler shift.
d. the slower the period of the star's shift.
e. A and C



SUPPOSE YOU FOUND A STAR SIMILAR TO THE SUN MOVING BACK AND FORTH WITH A PERIOD OF 2 YEARS. WHAT COULD YOU CONCLUDE?

a. It has a planet orbiting at less than 1 AU.
b. ✓ It has a planet orbiting at greater than 1 AU.
c. It has a planet orbiting at exactly 1 AU.
d. It has a planet, but we don't know its mass so we can't know its orbital distance for sure.

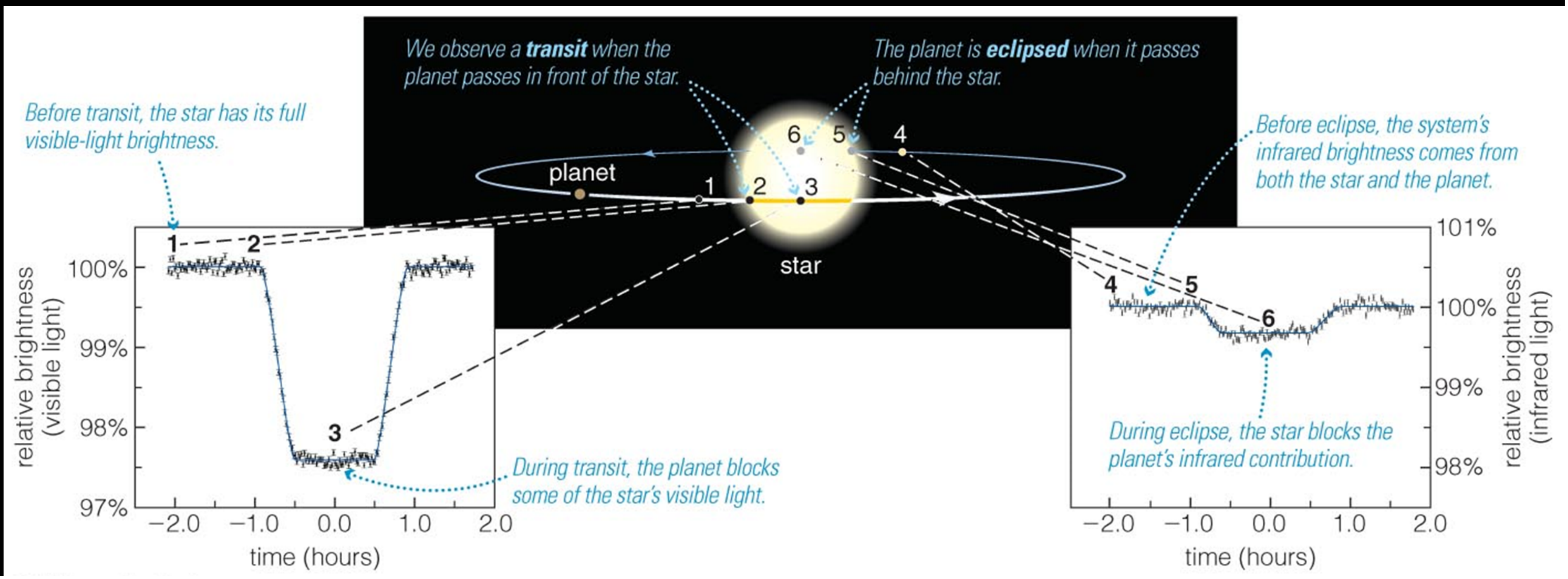


TRANSITS AND ECLIPSES

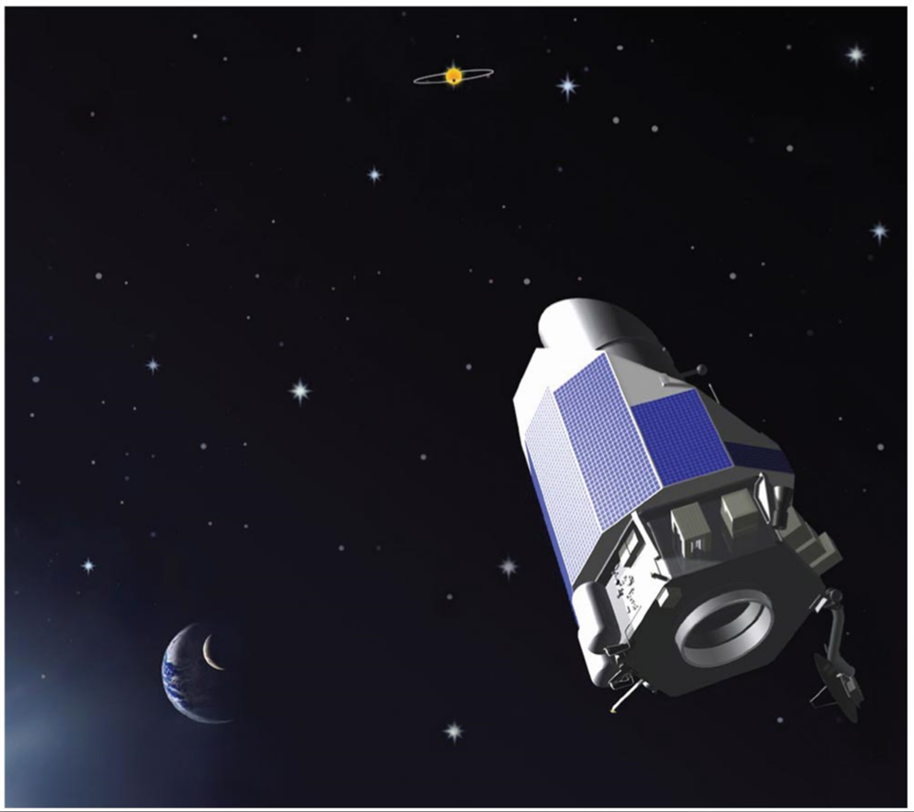
- Rarely (~1% of the time) the orbital plane of some star's planets will line up with us
- Look for planets blocking out some of the starlight

PLAY

Fig.10.5



KEPLER



- (*the mission not the guy*)
- Ran full strength 2009-2013
  - Is now running in a limited mode called “K2” due to two gyro failures
- Can measure the 0.008% dip in brightness of an earth-sized planet transiting a sun-sized star

FIGURING OUT THE DETAILS

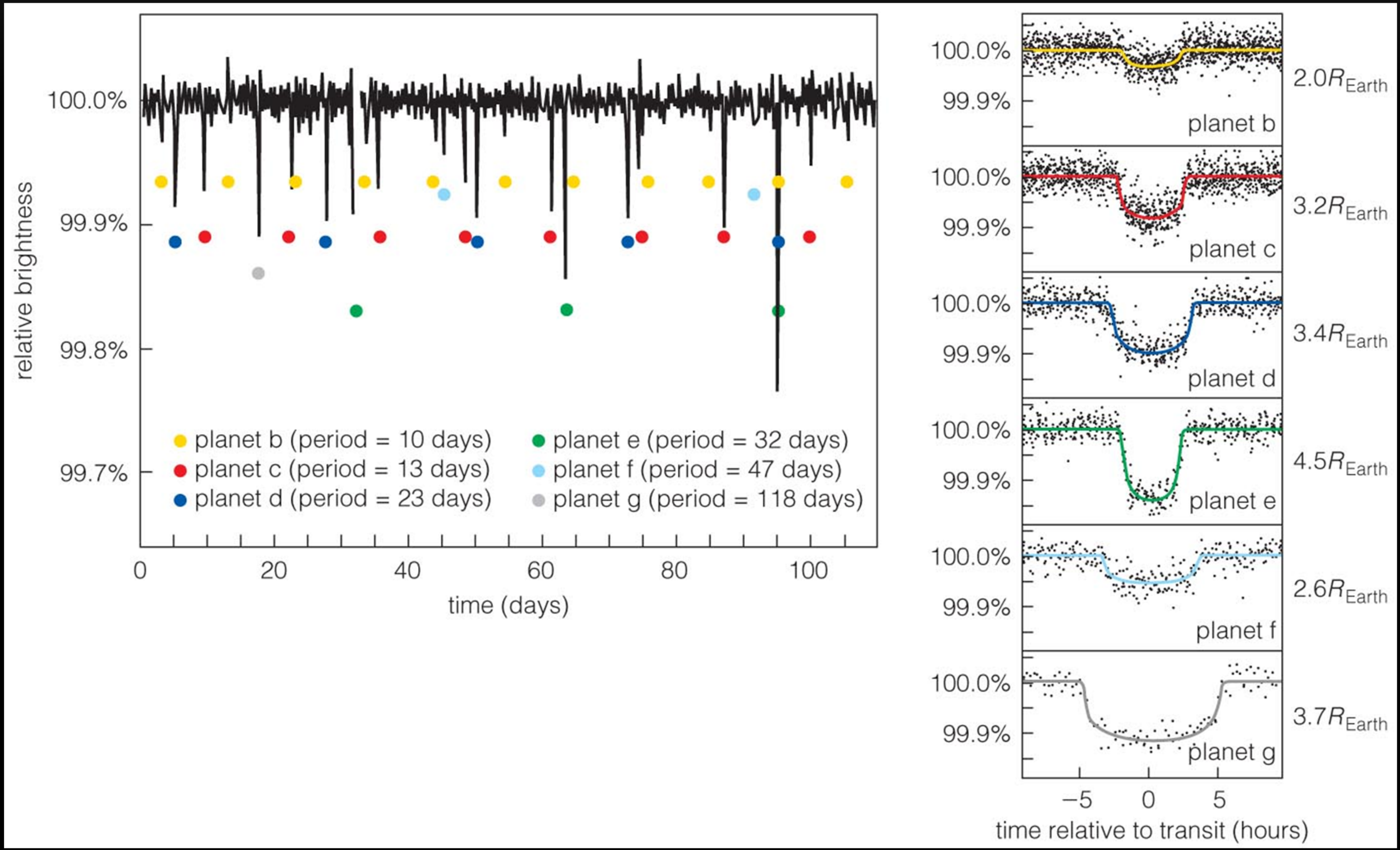
- Lots of things could cause brightness to change
  - Starspots, pulsing stars, etc.
- So watch for it to happen repeatedly
  - Once per that planet’s “year”: now we know period
  - If we know period, we know size of orbit from Kepler’s Laws

FIGURING OUT THE DETAILS

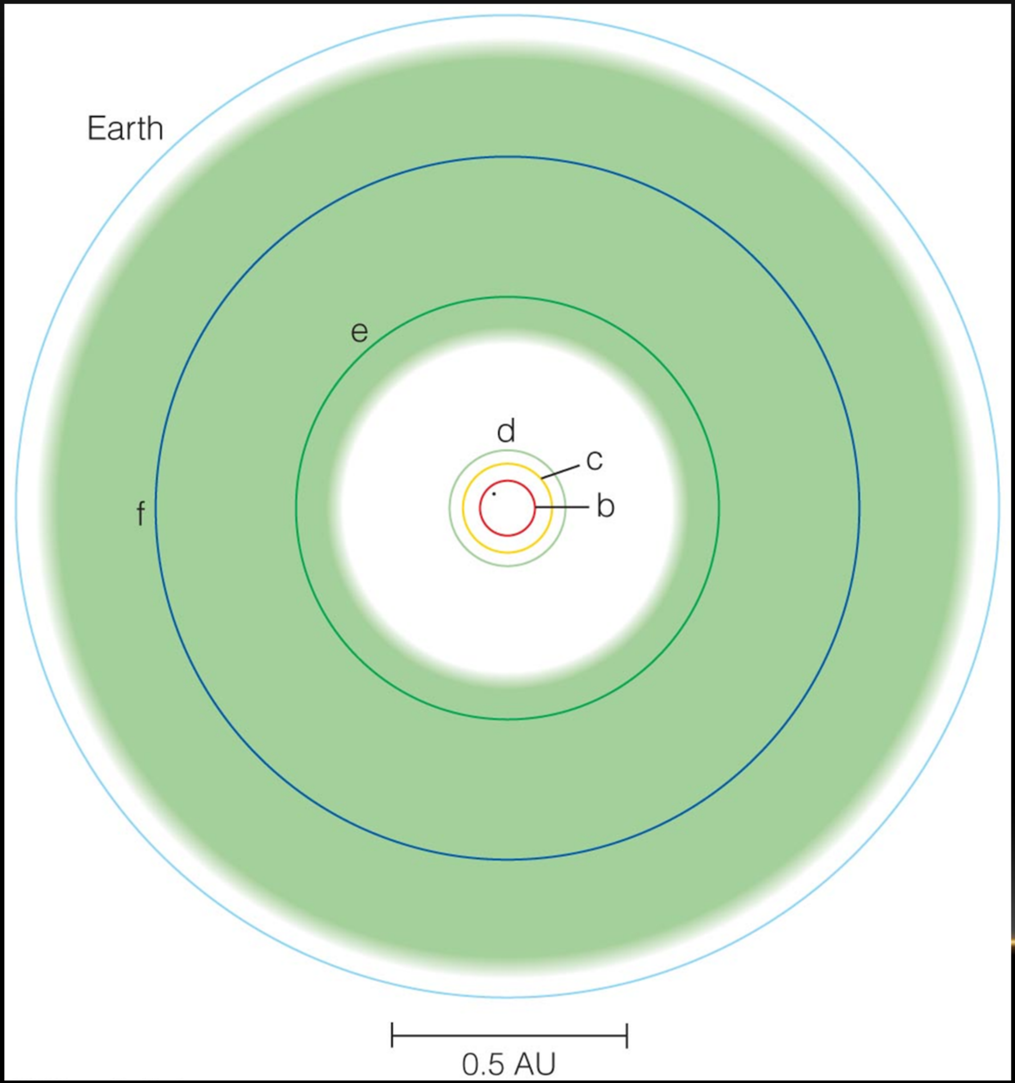
- How deep is the dip?
  - Bigger planet covers up more of the star, bigger dip, easier to see
  - Jupiter is about 10% the radius of the sun.
    - Area of a circle is πr^2
    - $(10\%)^2 = 1\%$
    - So would make a 1% sized brightness dip

FOR EXAMPLE, KEPLER 11'S SIX PLANETS

Fig.10.7



A MAP OF ANOTHER SOLAR SYSTEM!



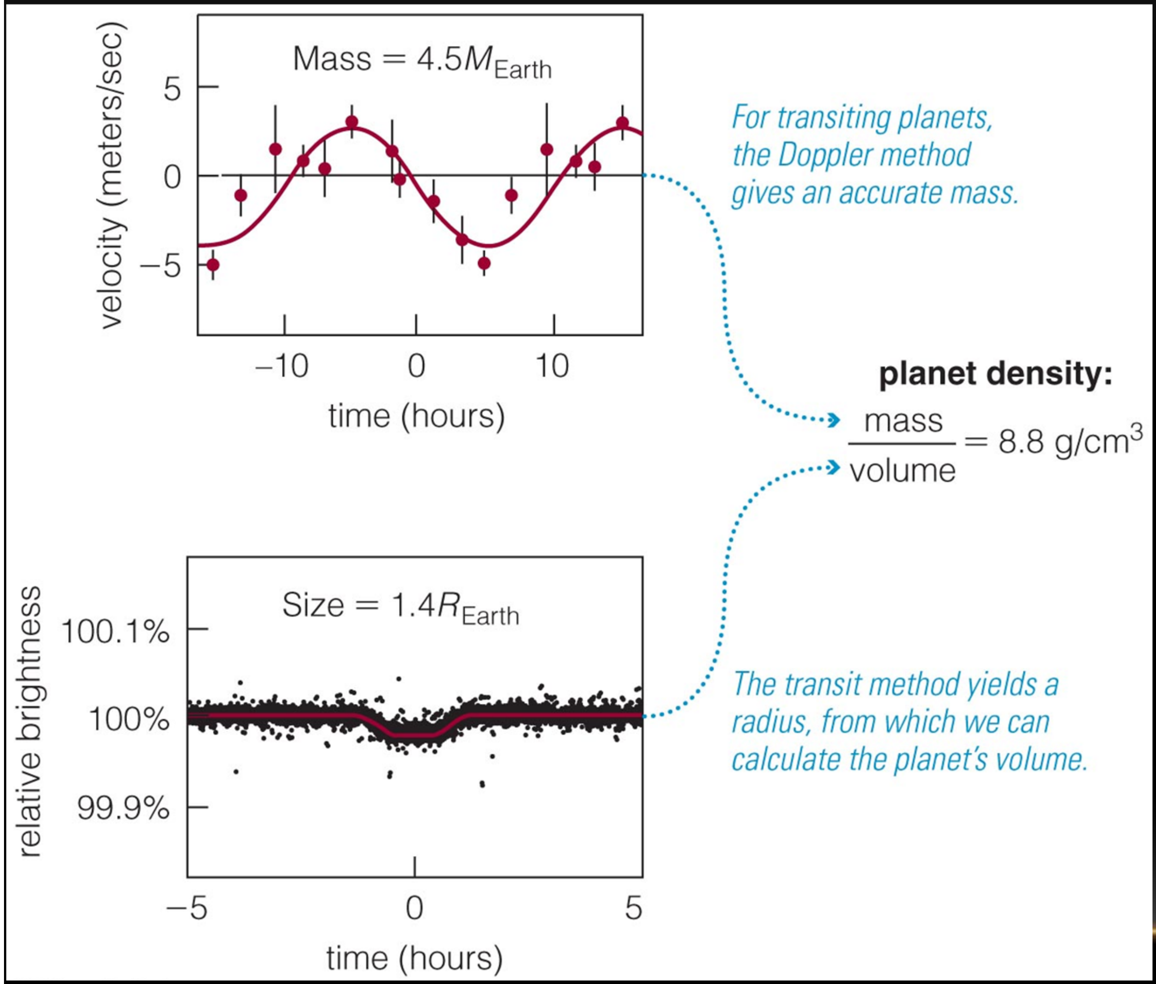
- Kepler 11 is only ~20% as bright as our Sun
- So even though all the planets are closer in than Earth is to our sun, two would be in the “Goldilocks Zone”
  - Planets e and f are “super-earths”, half again as large as us

Fig.10.9

FIGURING OUT THE DETAILS

- Planet's temperature?
  - Look for the drop in the infrared coming from star+planet when planet ducks behind the star
  - Use Stefan-Boltzman law: energy radiated per area is σT^4, solve for temperature
- Can also sometimes get spectral lines from planet by comparing spectra before and after an eclipse, subtracting the two
  - In which case, we now know a bit about chemical composition of the planet's atmosphere!

FIGURING OUT THE DETAILS

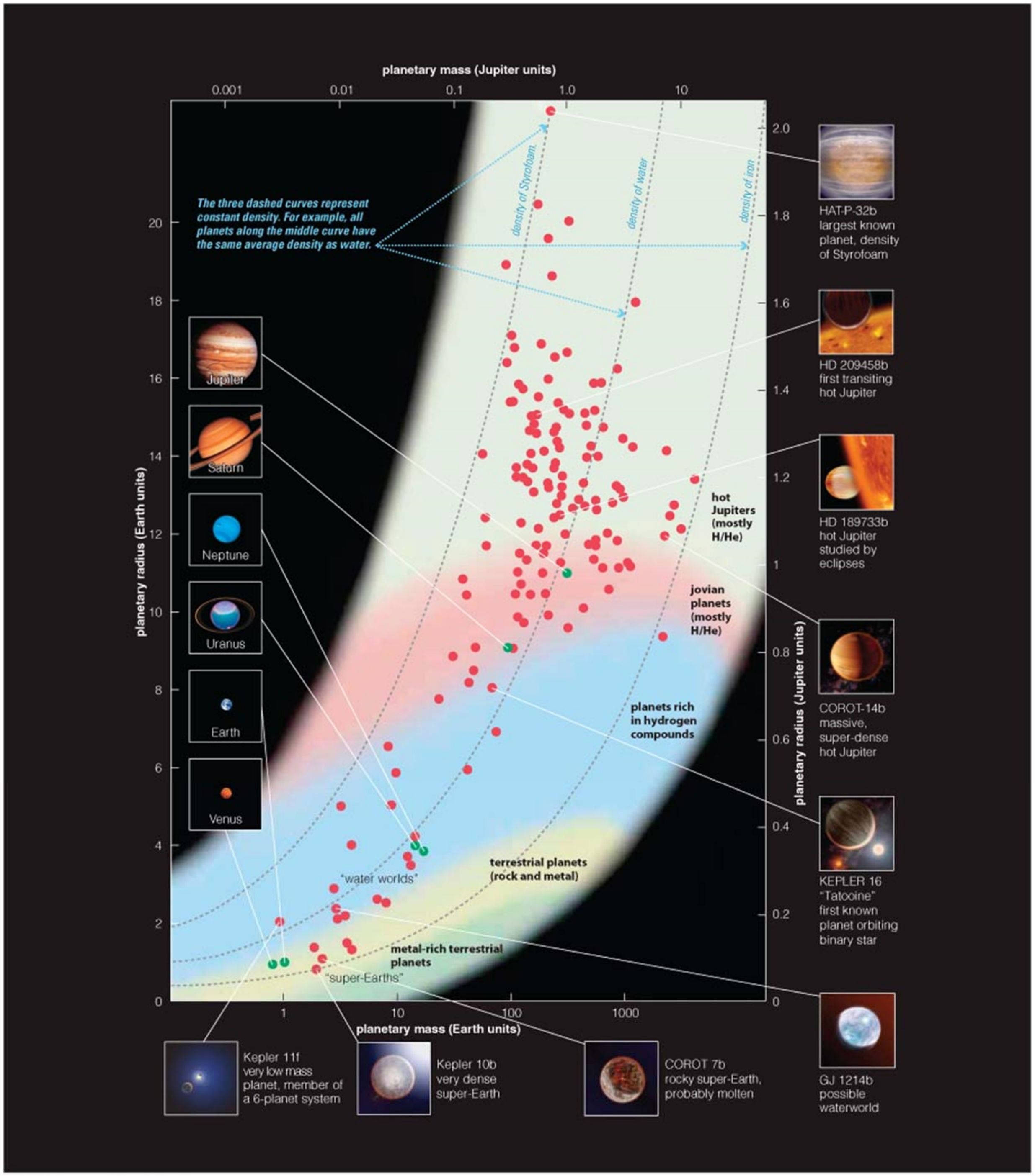


- Mass? Go back to doppler shift and see how strongly the planet is pulling around the star
- Now we have mass, size, density, temperature…
  - Can do a lot of the same comparisons we were doing in our own solar system

Fig.10.8

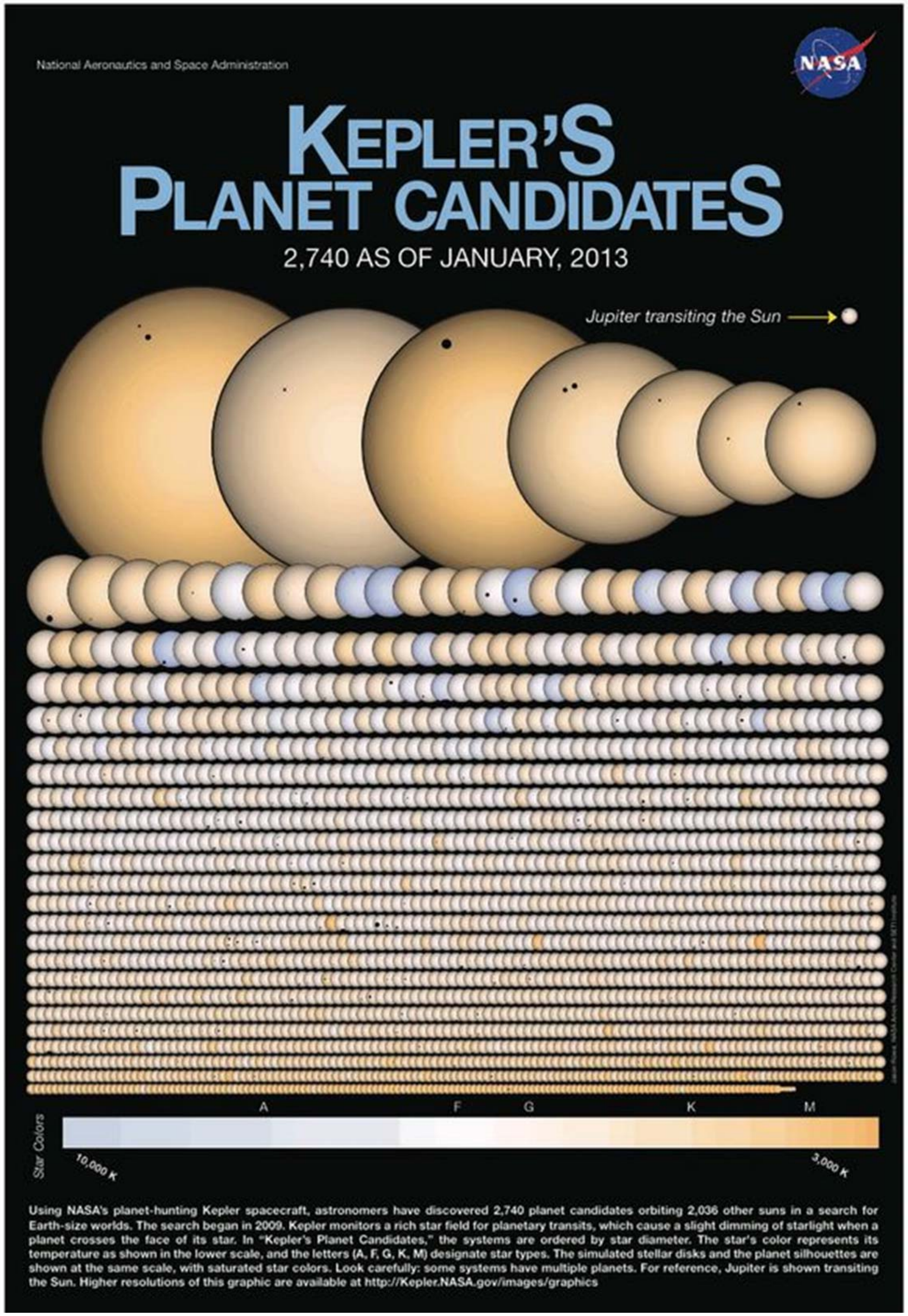
Sometimes, the details are weird

MASS VS RADIUS…



- Gets you density
- A cool figure that doesn't translate well to the big screen
- Includes our own solar system's planets

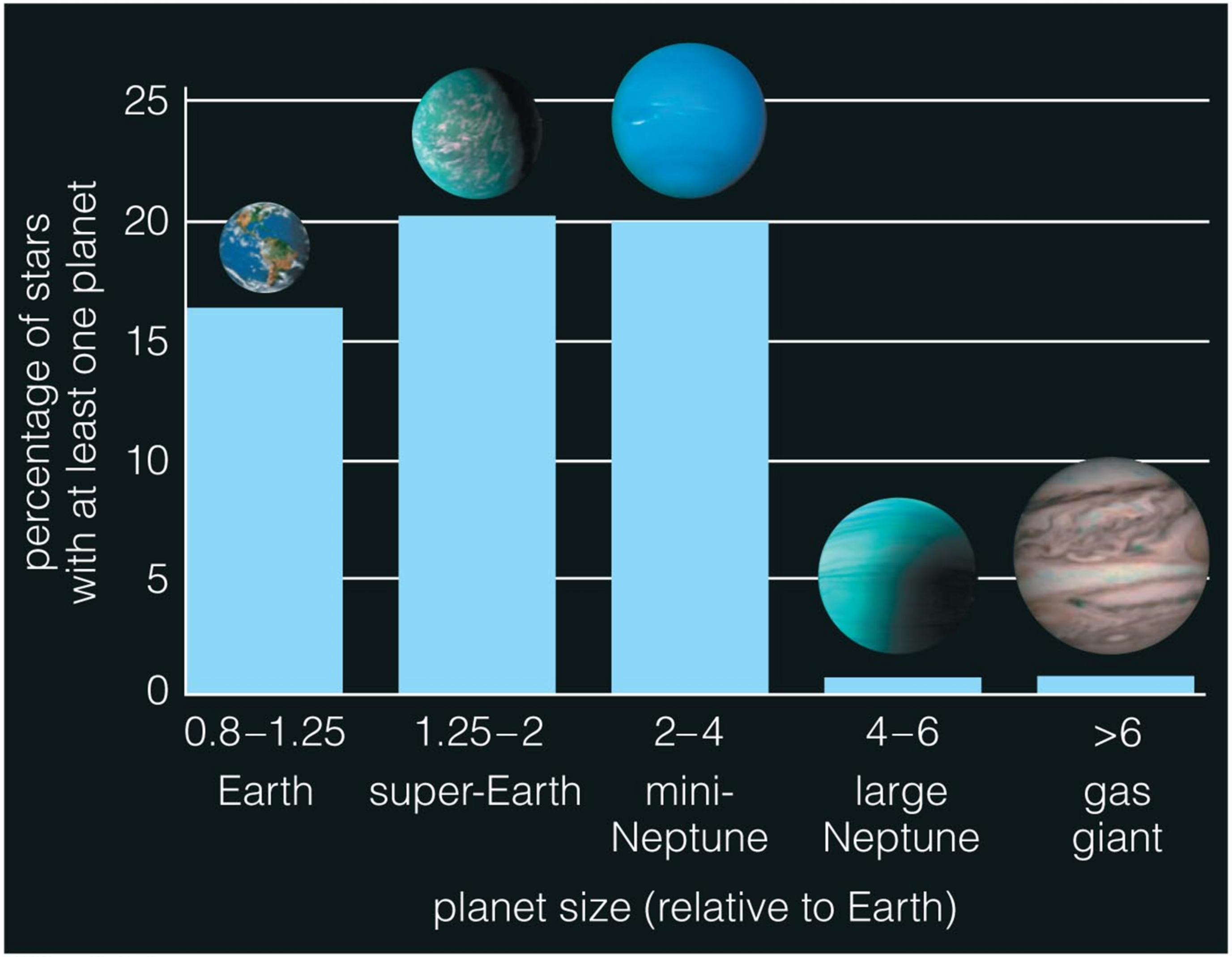
Fig.10.12



LOTS OF PLANETS

- So far 3,529 confirmed planets (*as of last week*)
- 4,496 unconfirmed planets
- >2,100 eclipsing binary stars found too (*more later…*)

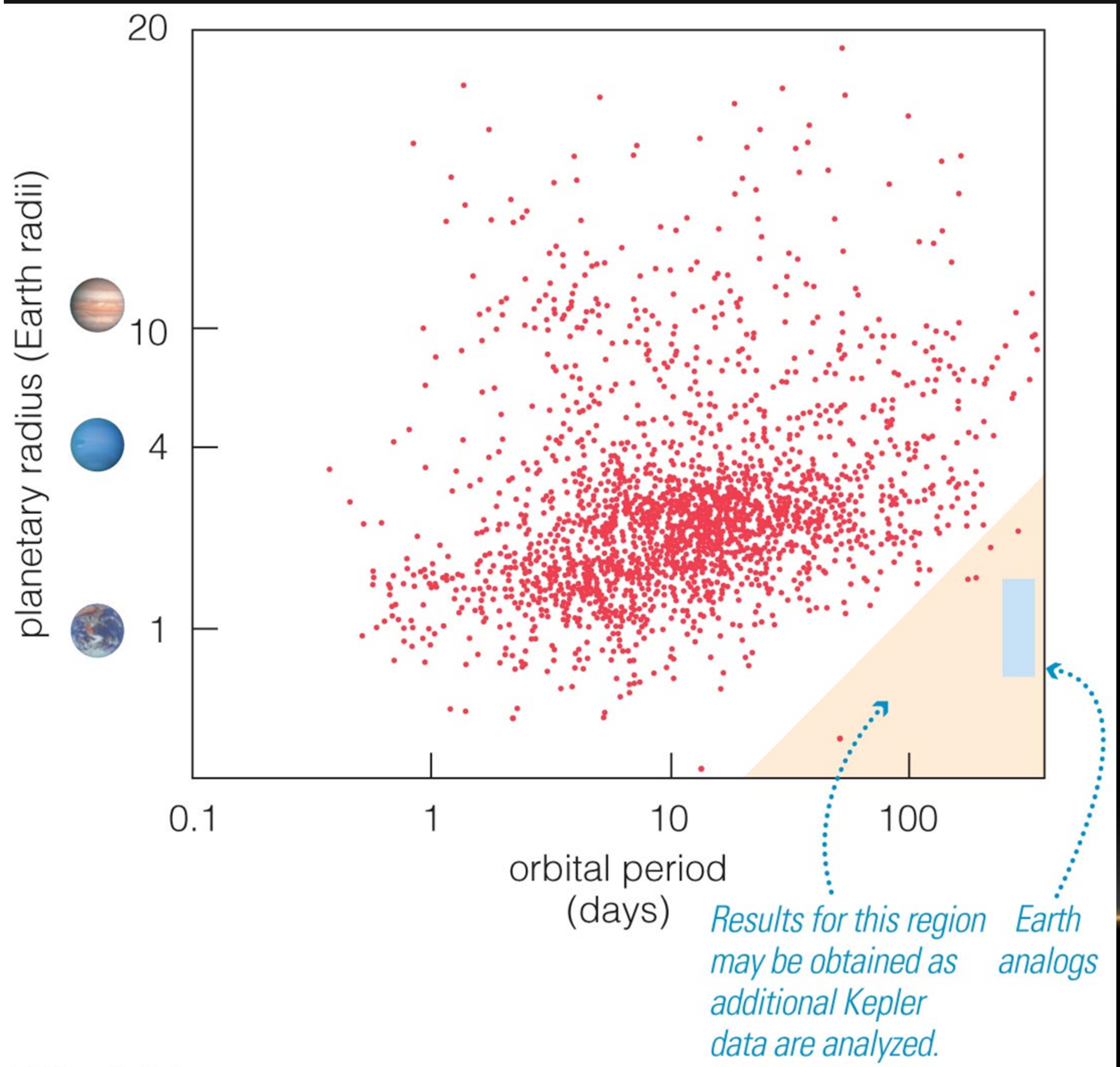
THAT'S ENOUGH TO LEARN A LOT



- >70% of all stars have planets!
- Most planets found are smallish

Fig.10.10

WHY?



- You'd think the bigger ones are easier to find
  - They make a star wobble more
  - And block more light

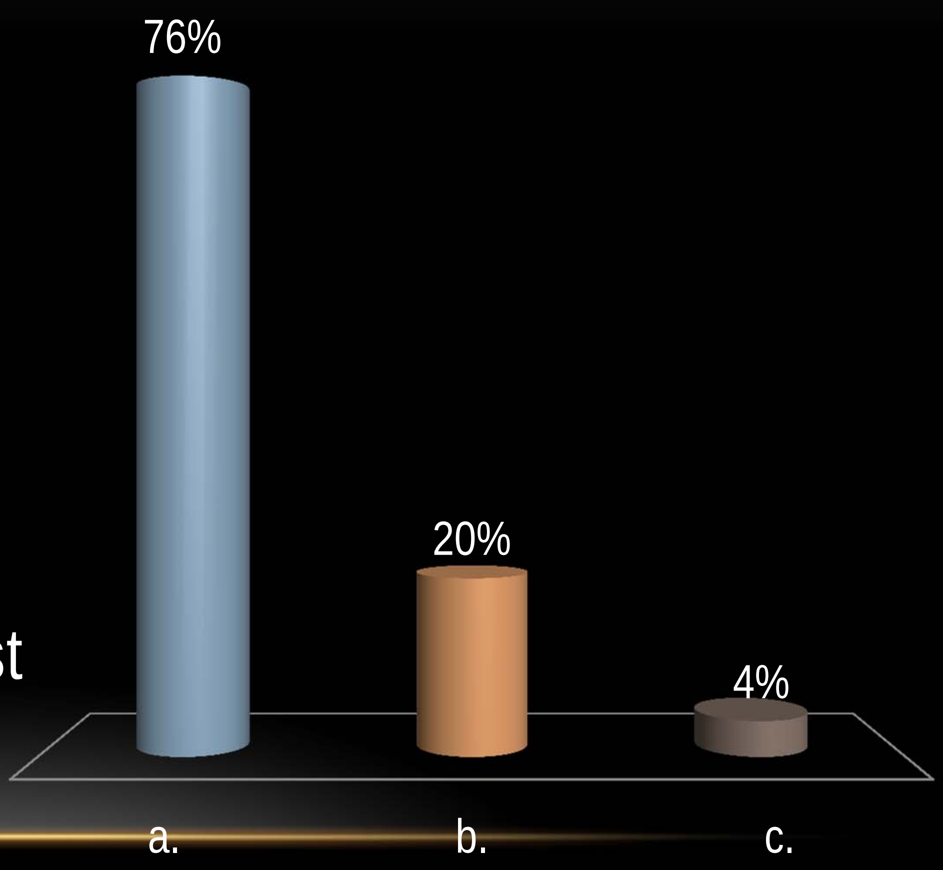
Fig.10.11

SO WHY DO WE NOT SEE SO MANY BIG PLANETS?

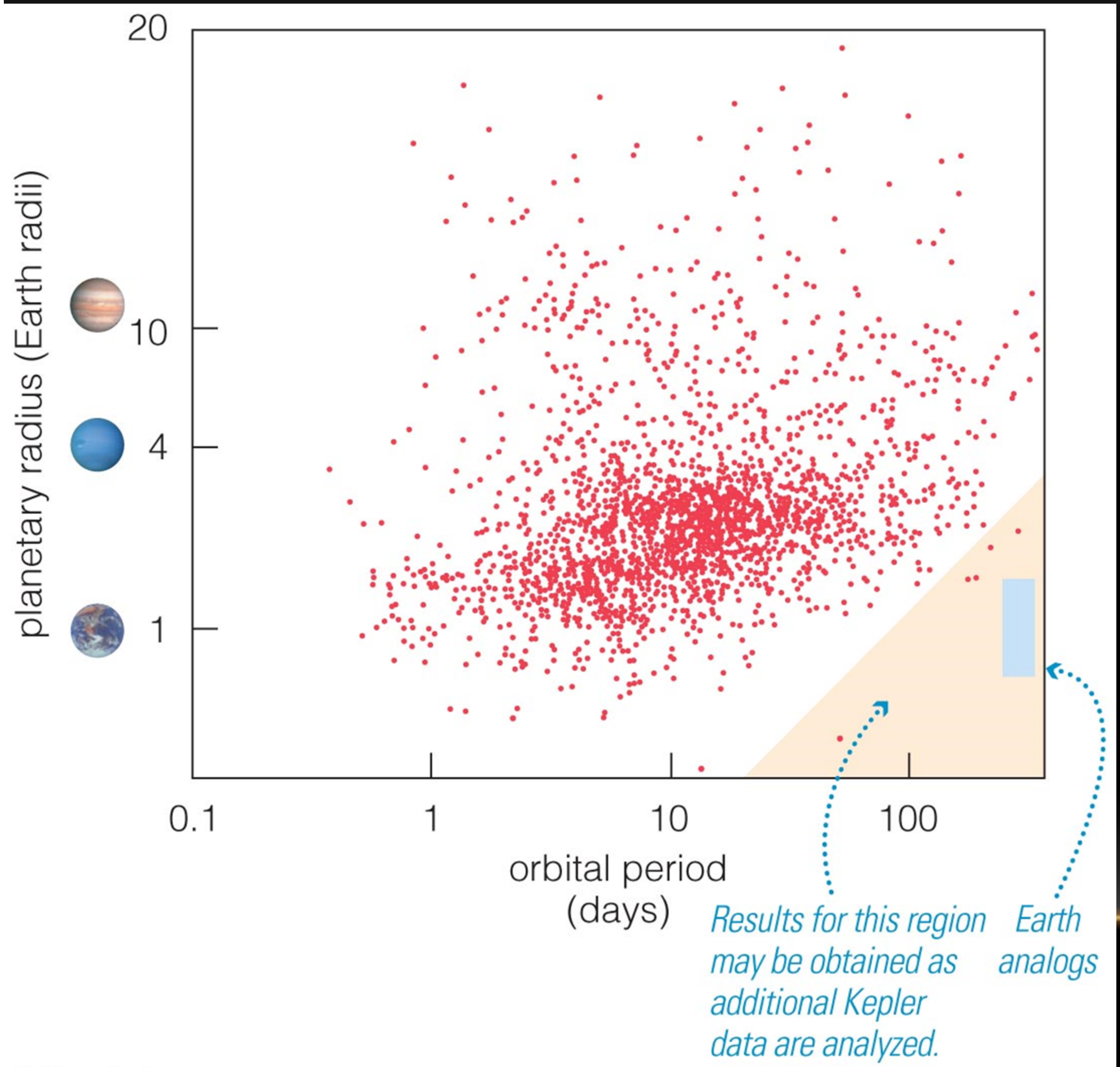
✓ a. The big gas giants form outside the frost line, take longer to orbit, we haven't seen them go around even once yet

b. Our own solar nebula had much more H and He than other stars, so gas giants couldn't form elsewhere

c. Other solar systems are just plain smaller than ours



WHY?



- Even though bigger planets are easier to see when they transit…
- We need to watch longer to see longer orbits!

Fig.10.11