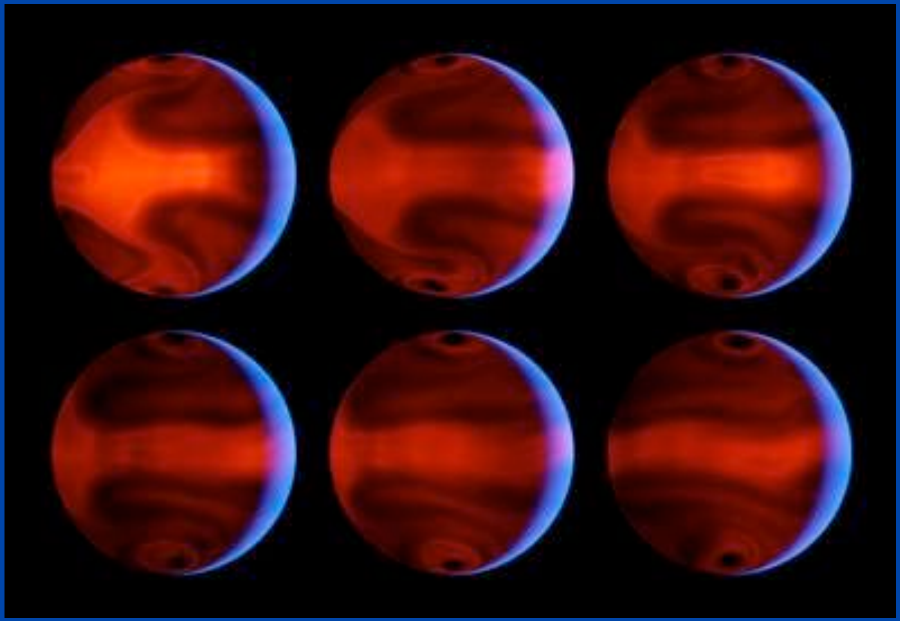
Lecture 9:
More About Extrasolar Planets

Please remind me to take a break at 12:45 pm!



Predicted weather patterns on HD80606

Claire Max

May 1, 2014

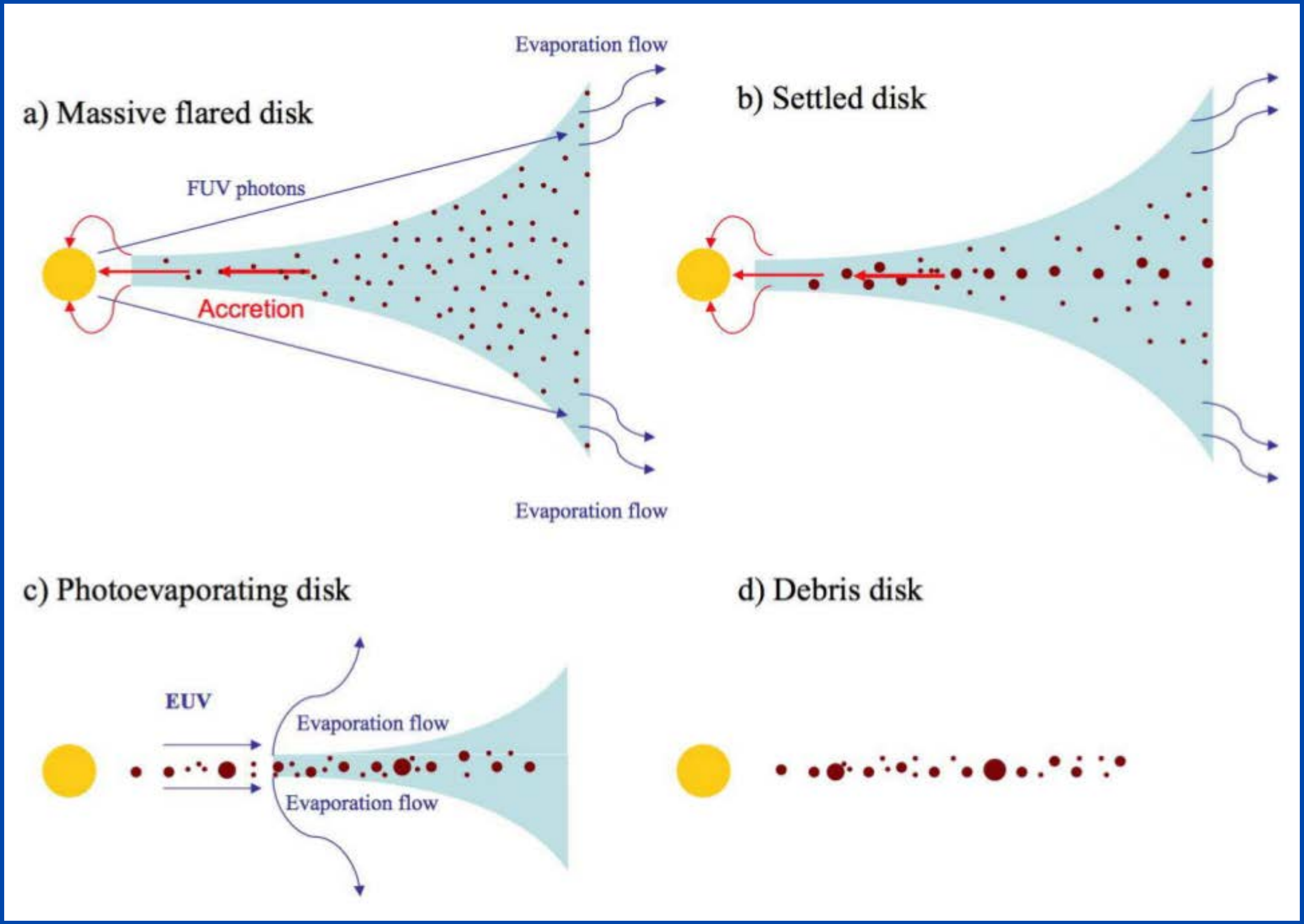
Astro 18: Planets and Planetary Systems

UC Santa Cruz

Outline of lecture

- Formation of protoplanetary disks
- Orbits and masses of exoplanets
- Planet formation in the light of what we know about exoplanets today
- Atmospheres of exoplanets
- Future exoplanet detection plans

Phases in the evolution of protplanetary disks: theory



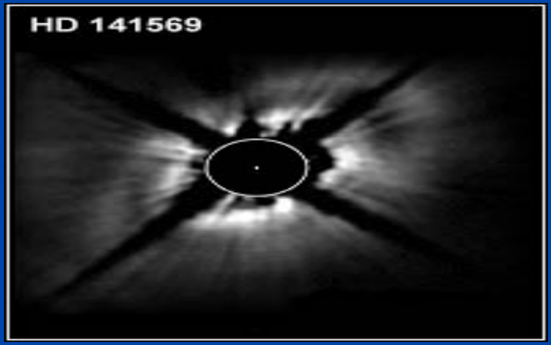
Credit: Jonathan Williams and Lucas Cieza

Phases in the evolution of protplanetary disks: data

1 Myr

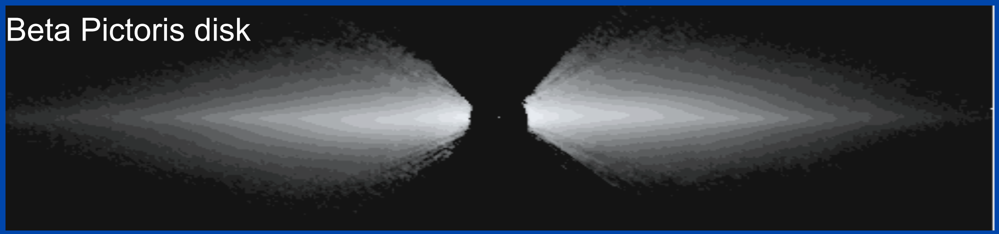
Young protoplanetary disks: lots of dust and gas. Opaque. Planets and low-mass stars within disk can create features.

5 Myr



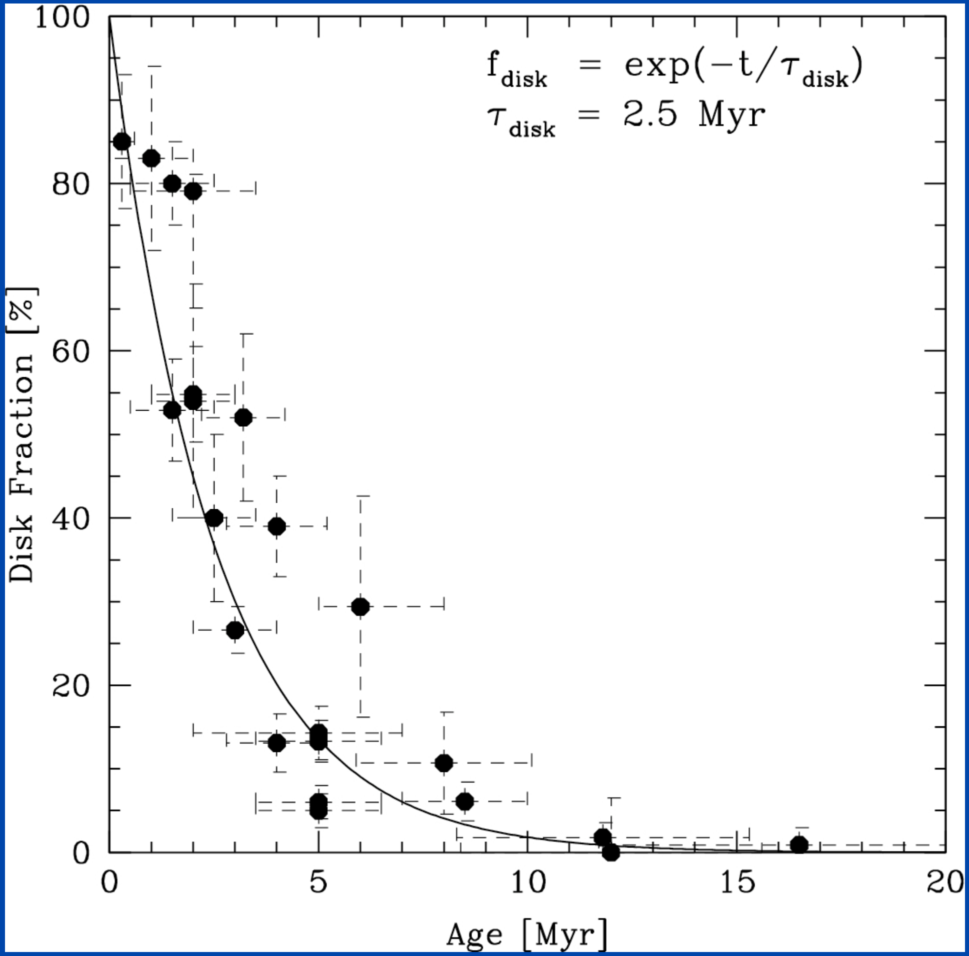
Transitional disks: much less dust and gas. No longer opaque.

12-20 Myr



Old disks: dust is replenished by collisions of rocky bodies.
Very little gas.

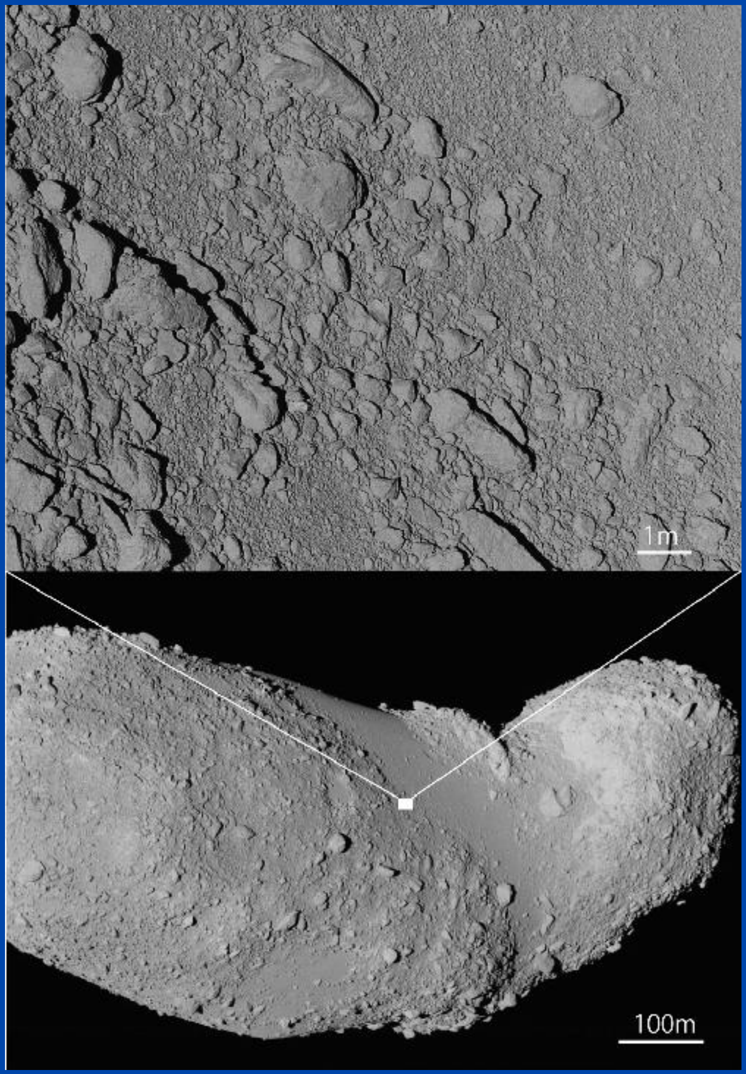
Protoplanetary disks have short lifetimes: a few million years



Slide credit: Jonathan Fortney

- This means that giant planet formation must be very fast.
- Giant planets must accumulate tens to hundreds of Earth masses of nebular gas, before gas is lost from the disk.

Core accretion: dust grains + pebbles stuck together to form larger bodies

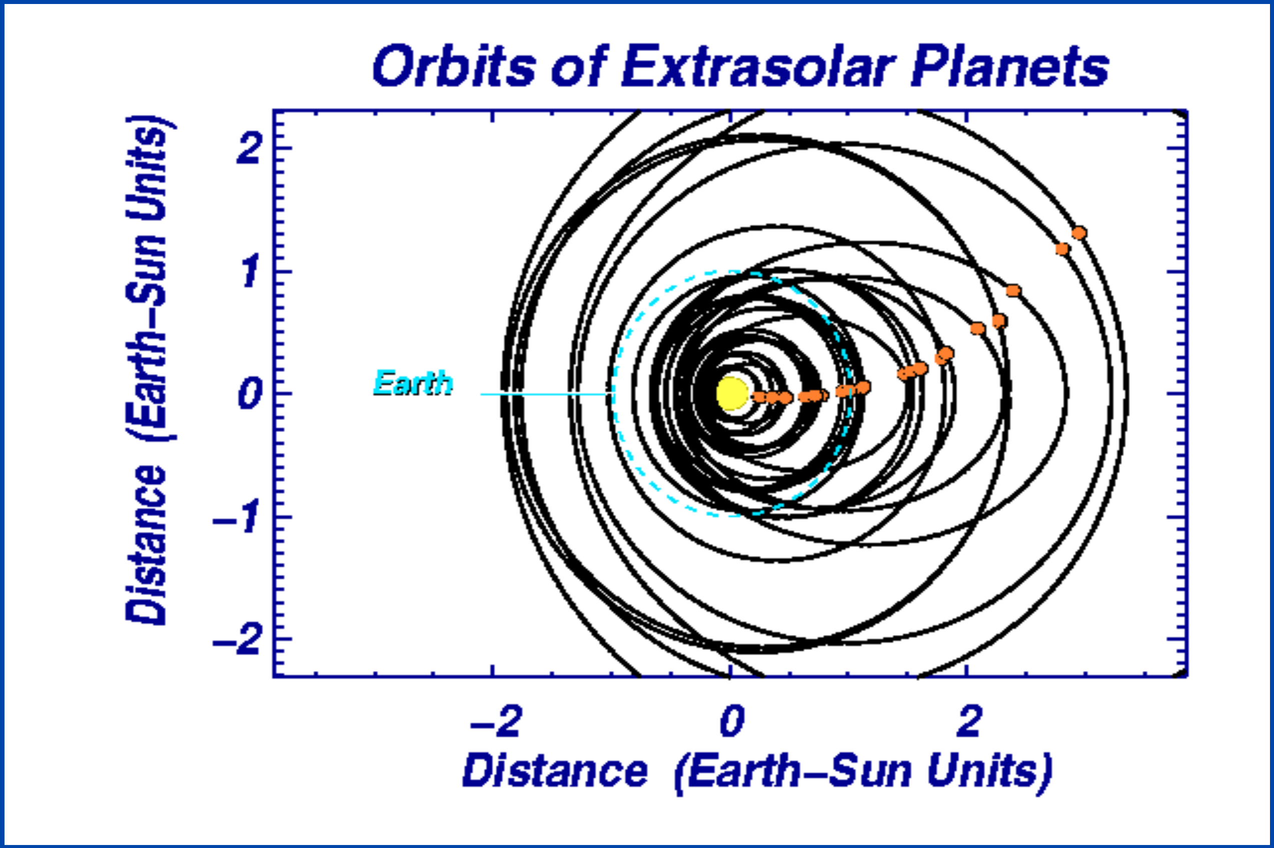


- Asteroid Itokawa in our own Solar System may be a close-up example
- Called a “rubble pile”
- Self gravity not large enough to make it round

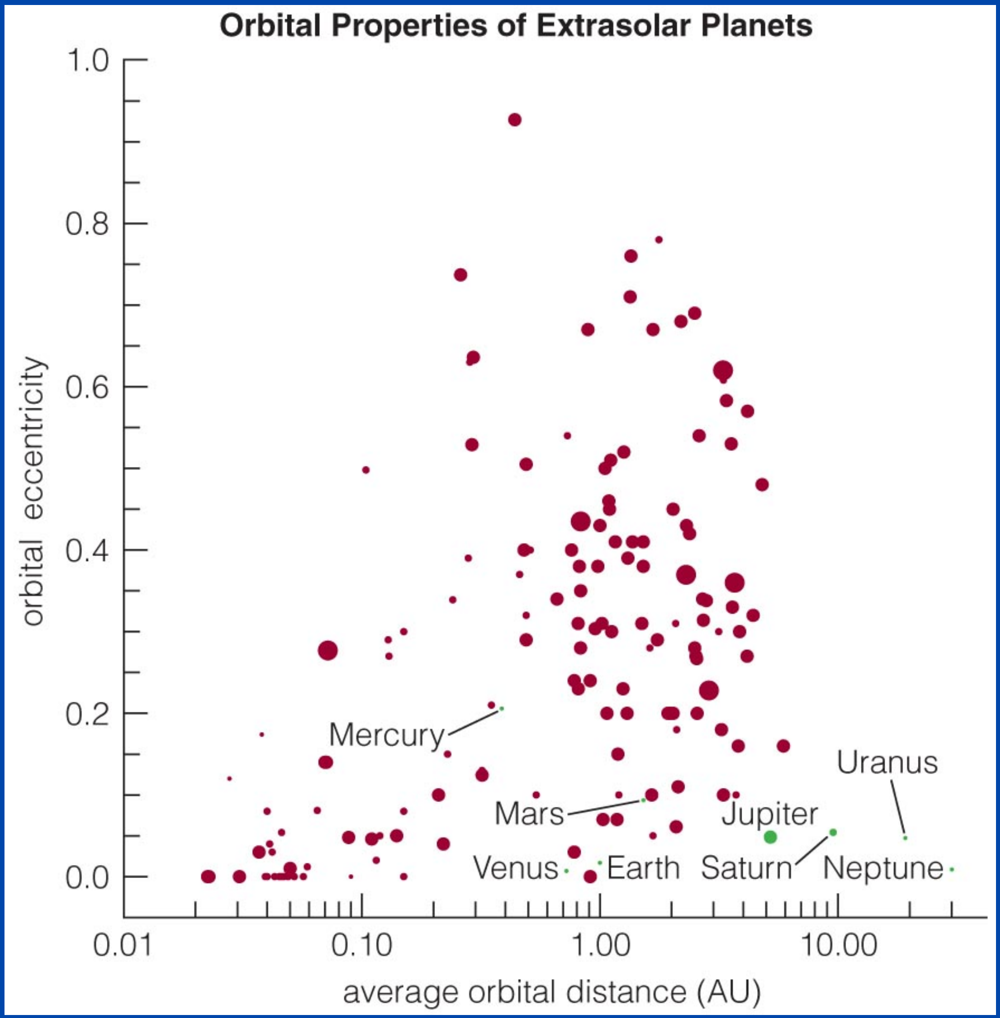
Unanticipated characteristics of extra-solar planets

- Much higher eccentricity in most of their orbits
- Much higher fraction of planets very close to their parent stars.
- Many of these have masses comparable to Jupiter's.
- Many planets are "super-Jupiters" (up to 10 times more massive than Jupiter)

Eccentric Orbits

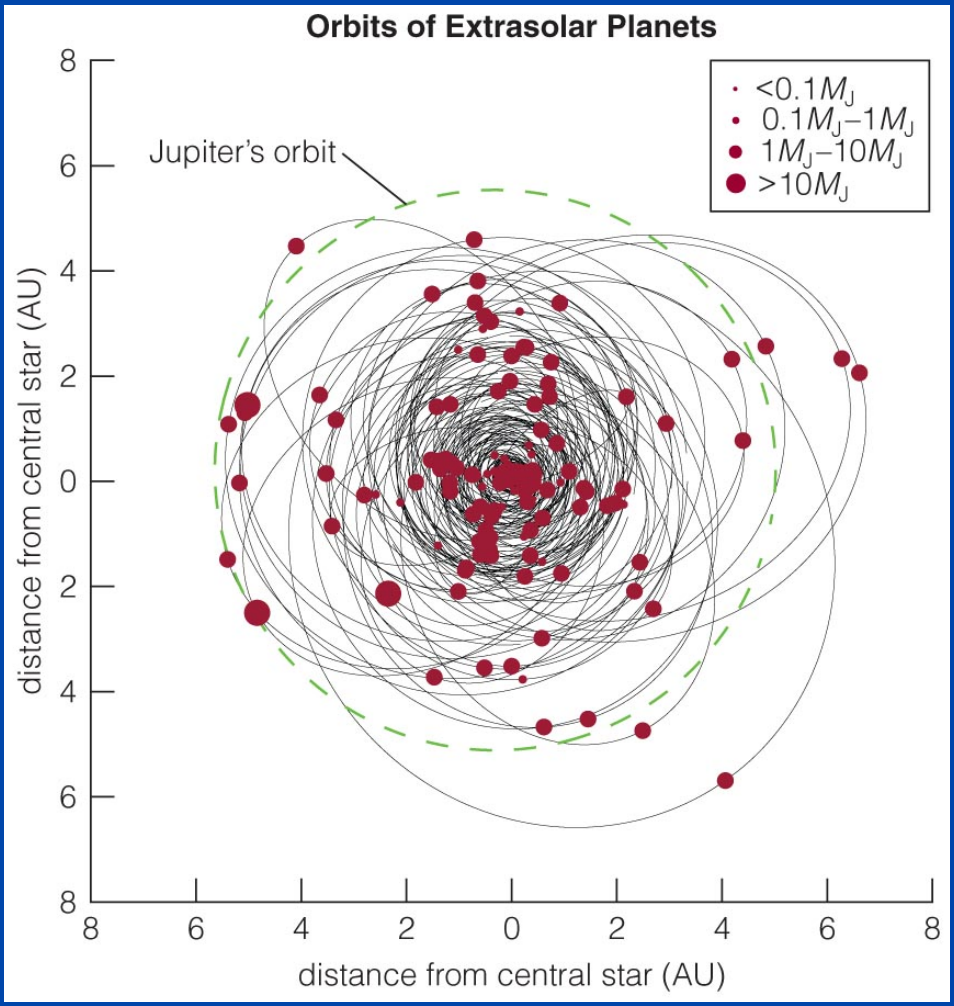


Eccentric Orbits



- Orbits of some extrasolar planets are much more elongated (have a greater eccentricity) than those in our solar system.

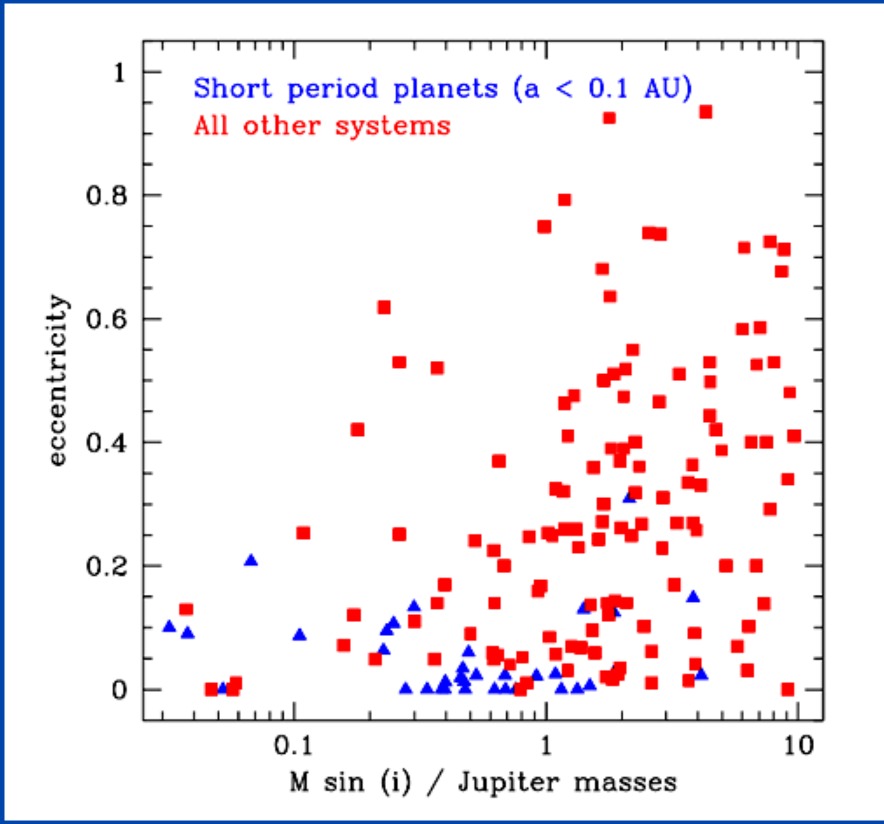
Eccentric Orbits



- A significant number of the detected planets have orbits smaller than Jupiter's.
- But note that planets at greater distances are harder to detect with the Doppler and transit techniques.

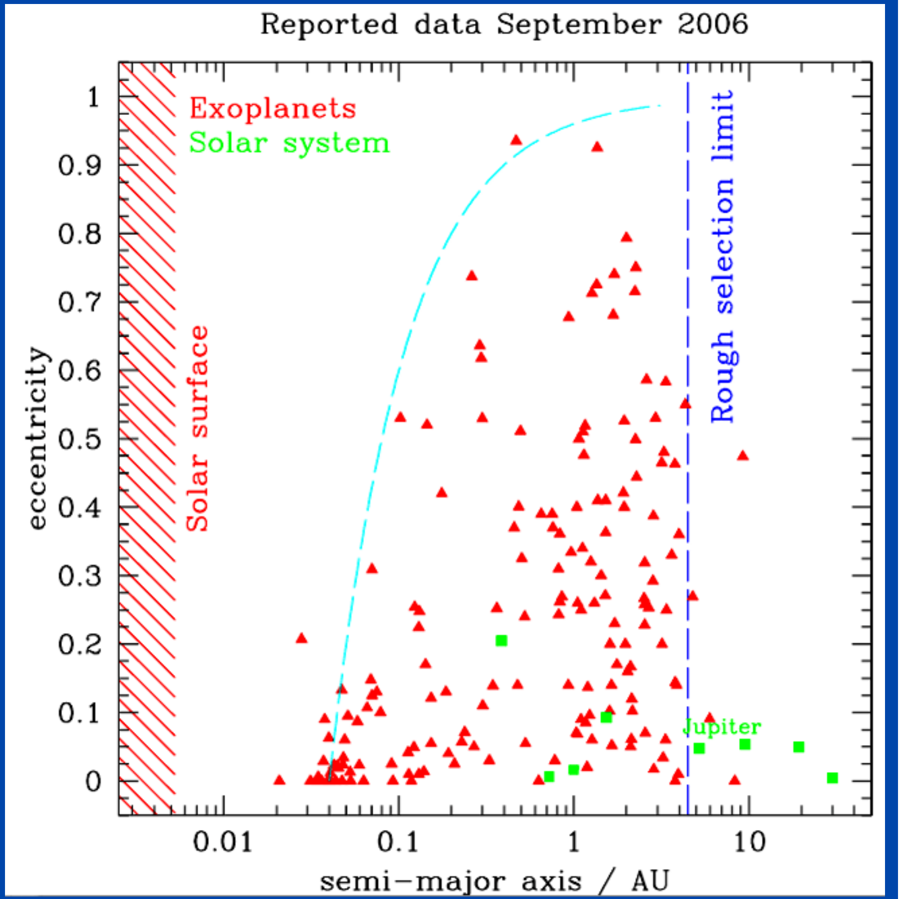
The shortest period exoplanets have orbits close to circular

- Short period planets:
  - Very close to parent stars, very low eccentricity
  - Same process that moved planets close to star circularized their orbits

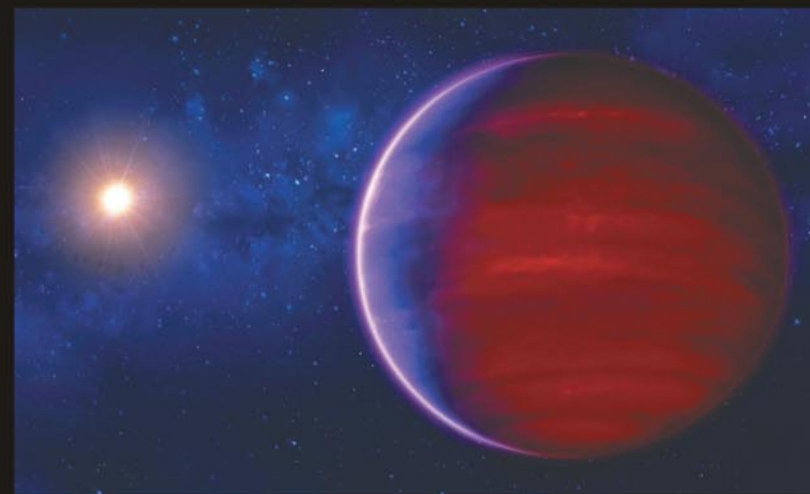


Many extrasolar planets are very close to parent stars

- Much of this is a selection effect
  - Radial velocity and transit methods more sensitive to planets close to parent stars
- Nevertheless, there are many more close-in exoplanets than were expected
- Our Solar System is very different (green points)



Hot Jupiters: very close to parent stars



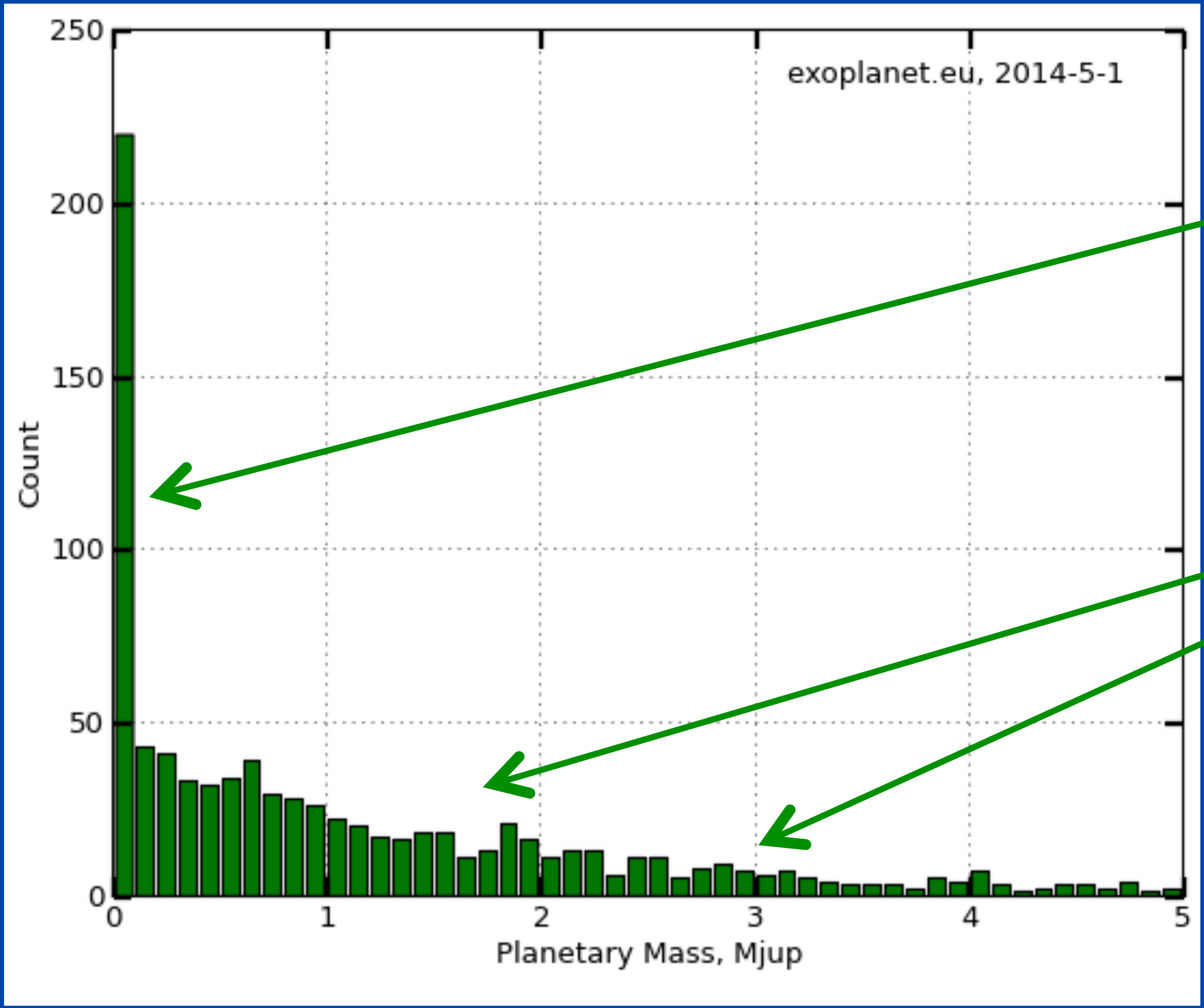
Jupiter

Composed primarily of hydrogen and helium
5 AU from the Sun
Orbit takes 12 Earth years
Cloudtop temperatures ≈130 K
Clouds of various hydrogen compounds
Radius = 1 Jupiter radius
Mass = 1 Jupiter mass
Average density = 1.33 g/cm^3
Moons, rings, magnetosphere

Hot Jupiters orbiting other stars

Composed primarily of hydrogen and helium
As close as 0.03 AU to their stars
Orbit as short as 1.2 Earth days
Cloudtop temperatures up to 1300 K
Clouds of “rock dust”
Radius up to 1.3 Jupiter radii
Mass from 0.2 to 2 Jupiter masses
Average density as low as 0.2 g/cm^3
Moons, rings, magnetospheres: unknown

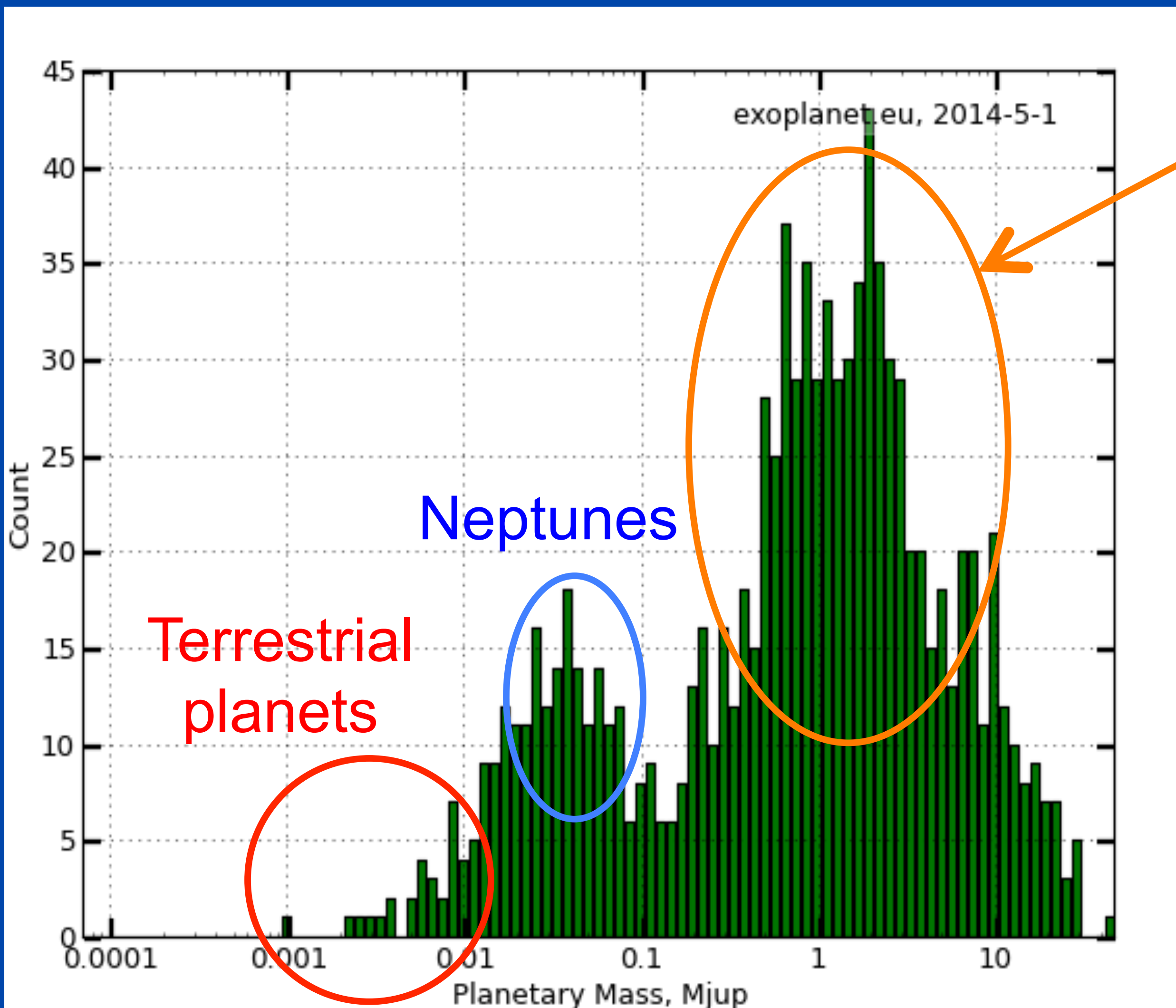
Characteristics of Extra-Solar Planets: Mass



Starting to see Neptunes and terrestrial planets

Significant number of planets much more massive than Jupiter

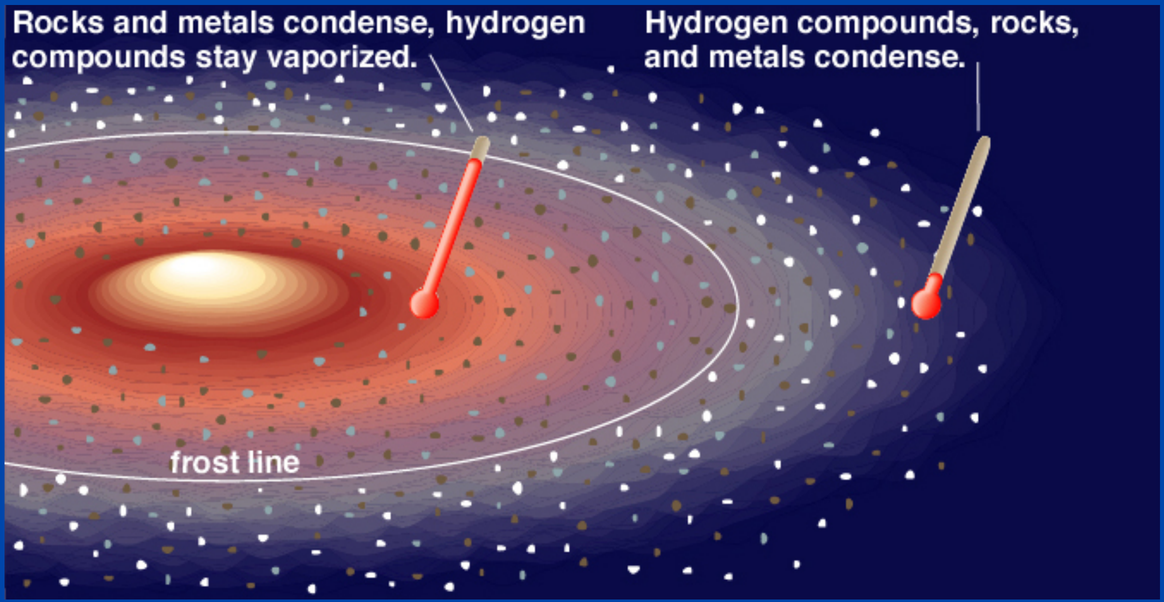
Characteristics of Extra-Solar Planets: Mass



Jupiters and Super-Jupiters

Role of the "frost line" or "ice line"

- Our Solar System has small rocky planets close to star, large gas giants further away
  - no experience of large massive planets close to sun in our Solar System
- Theory of giant planet formation says they have to form outside "frost line"

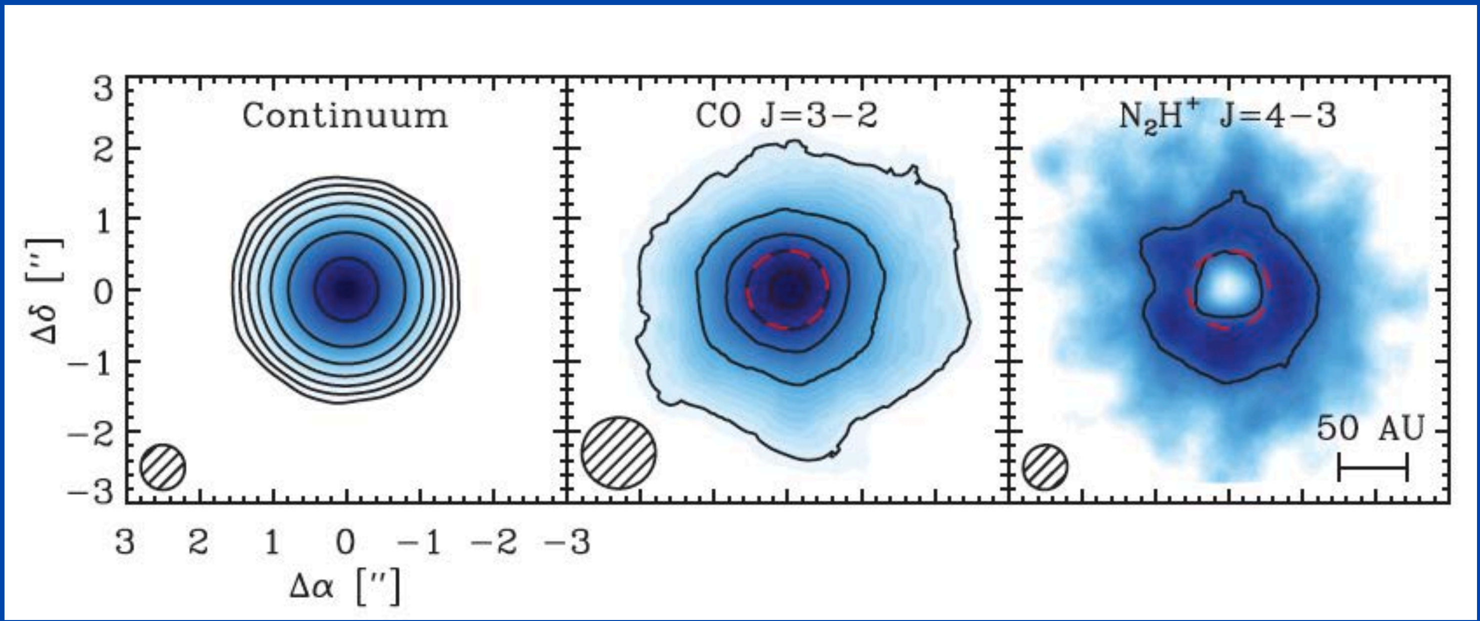


New evidence that the "ice line" is real in other solar systems

- Disk around young star TW Hydra
- Observed at brand new Atacama Large Millimeter Array (ALMA) by Qi and colleagues

New evidence that the “ice line” is real in other solar systems

- Disk around young star TW Hydra
- Observed at brand new Atacama Large Millimeter Array (ALMA) by Qi and colleagues
- Red dashed line shows position of “ice line” of CO



How are giant extrasolar planets formed?

- Theory for our Solar System:
  - Stellar wind from young Sun blew volatiles outwards
  - “Snowstorm” at 5 AU where water-ice solidified
  - Fast accretion of large icy planet (~10 M_{Earth}) which then collected H/He atmosphere
    - » Gas giants Jupiter, Saturn just outside “frost line”
    - » Small rocky planets inside
    - » Slowly accreting icy planets in outer system (Uranus, Neptune)

- Extrasolar giant planets:
  - Do they form in situ?
    - » looks impossible: too hot for ices, too little material for rock
  - Do they form outside frost line and migrate inwards?
    - » planet forms in gas/dust disc around star
    - » drag from remaining gas/dust causes it to spiral inwards
    - » or scattering from other giant planets causes migration
    - » why does it stop?

This is the "paradigm shift"

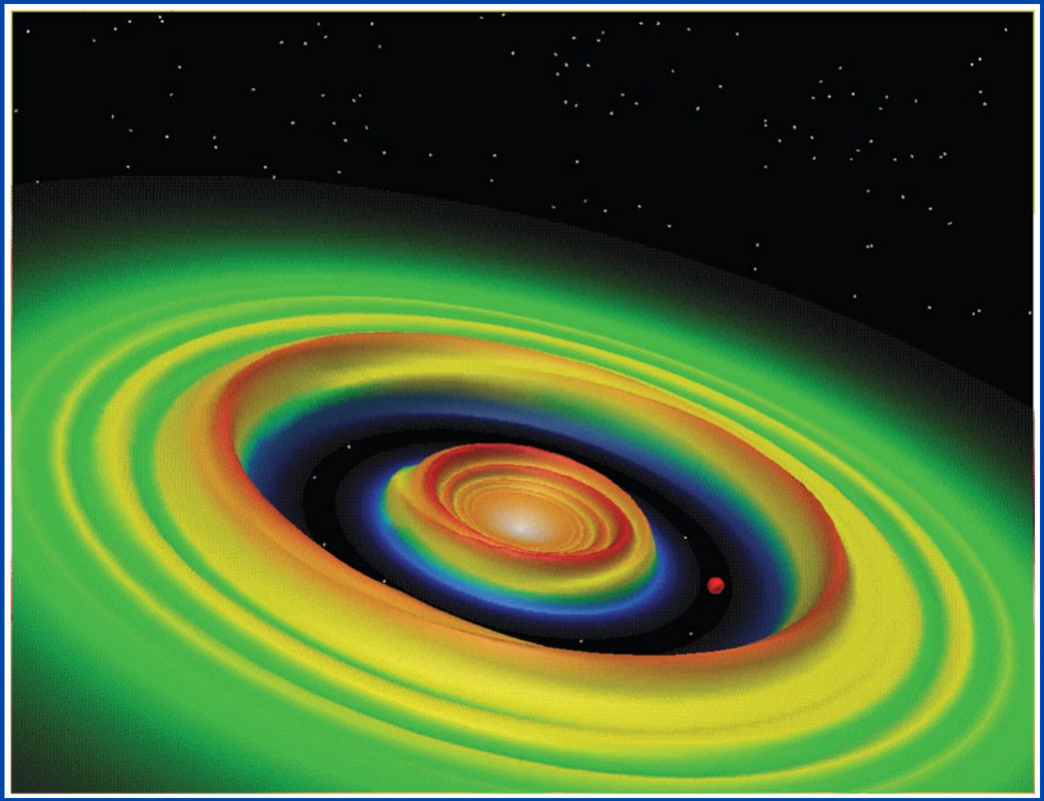
- Original theories of solar system formation developed when our own Solar System was the only one
  - Mostly circular orbits
  - Giant planets in outer solar system, terrestrial planets inside
- New Solar Systems are (in general) not like ours
- Needs a new theory
- How to arrive at a new paradigm?
  - Mostly use computer simulations to develop ideas, test hypotheses, make predictions
  - Test predictions against observed young solar systems, disks

Theories for how giant planets got so close to their stars

1. Interactions between individual new planets and gaseous disk. "*Migration*"
2. After gas disk cleared away, several giant planets in outer parts of solar system were left
   – Three-body gravitational interactions between them
   – One giant planet got slung outwards, a second was slung inwards and got "captured" by the star in a close orbit
   – But why isn't the close orbit very elliptical?

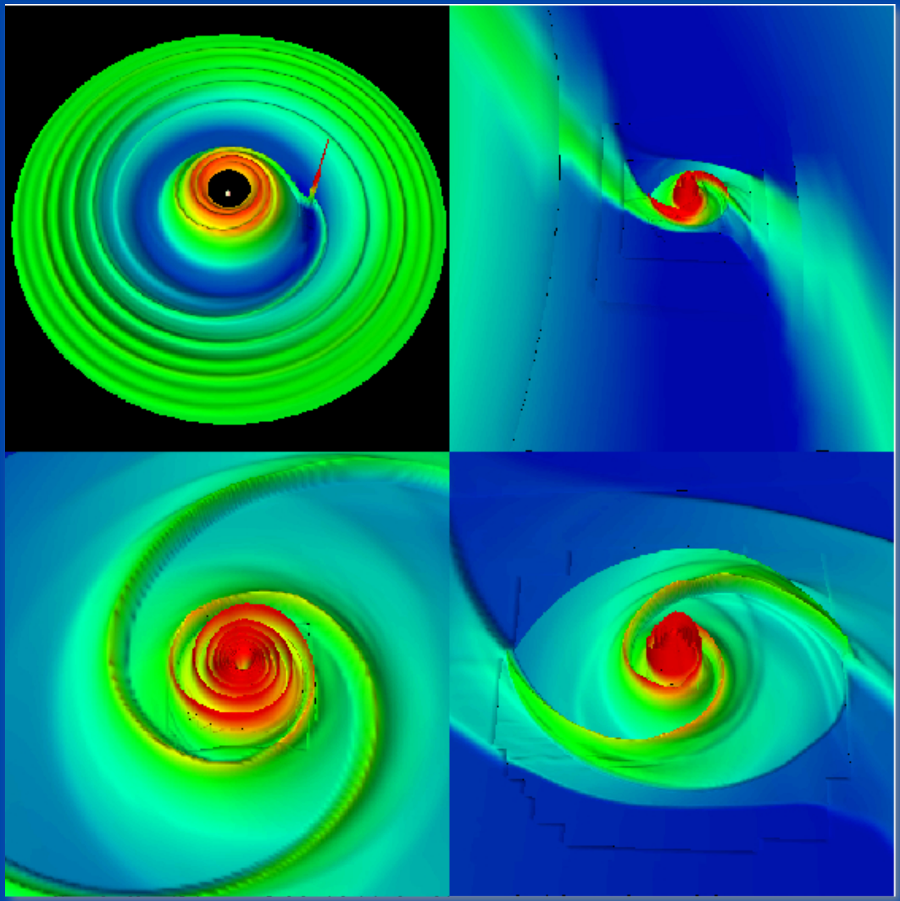
- Why didn't our own Jupiter migrate inwards close to Sun?

Planetary Migration in a massive disk



- A young planet's motion can create waves in a planet-forming disk.
- Models show that matter in these waves can tug on a planet, causing its orbit to migrate inward.

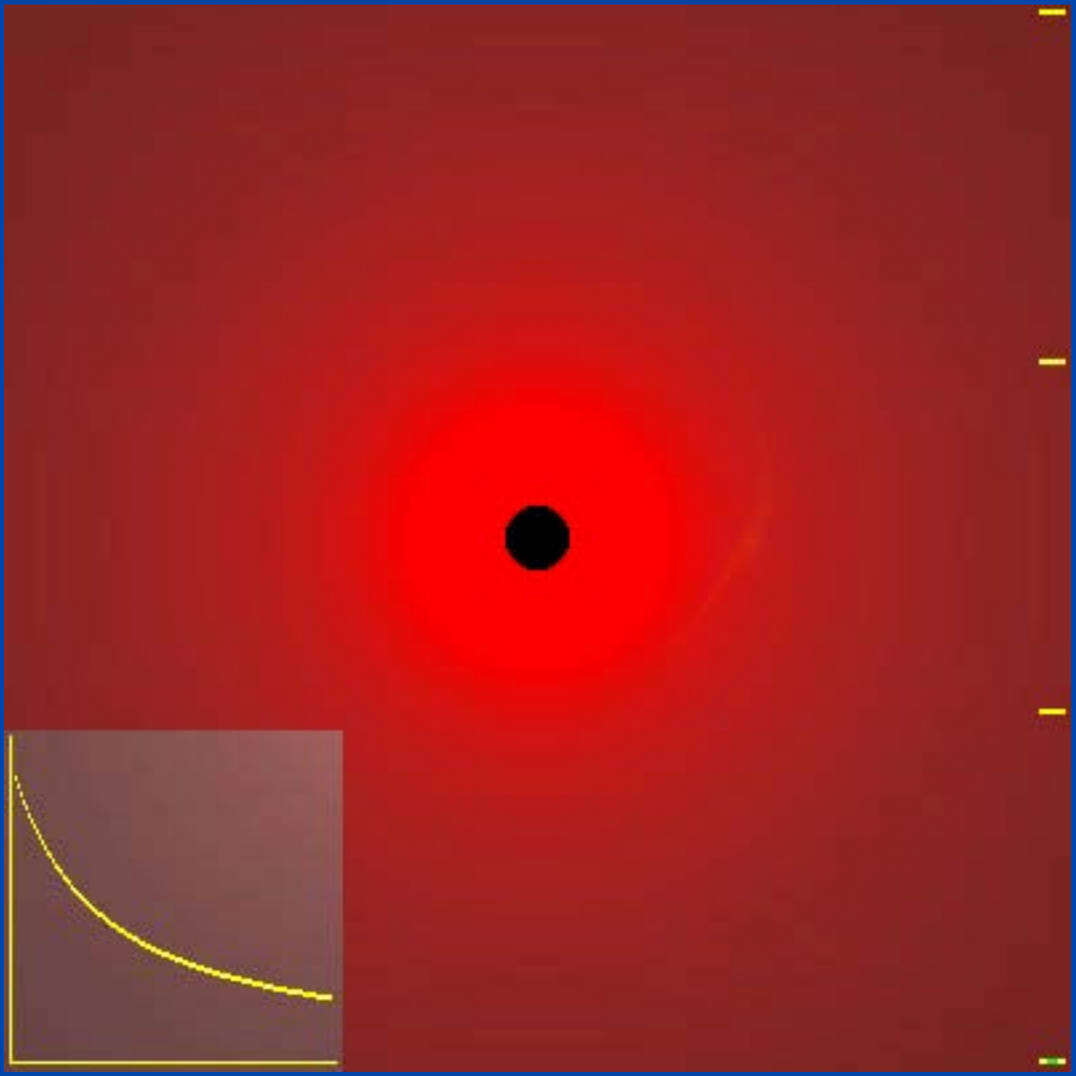
1. Planet formation in gaseous disk



- One planet in a gaseous disk
- Accretion begins, gap starts to form
- Planet can continue to accrete mass even after a "gap" in disk has formed
- From computer simulation by Pawel Ciecielag

Computer simulation by Armitage

- Formation of planet and gap within a protostellar disk
- Planet can continue to accrete mass even after a “gap” in disk has formed
- As a result of the interaction with the disk, the planet moves in
- Philip Armitage



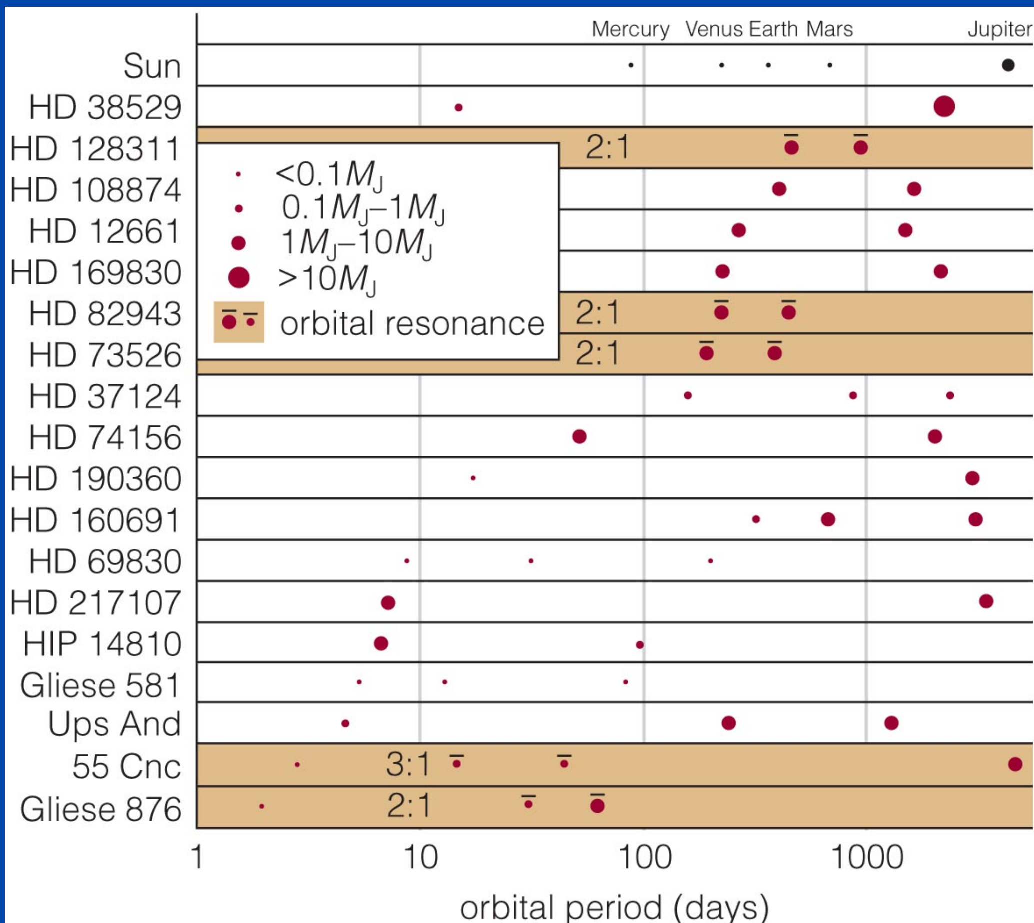
YouTube videos: planet migration

- https://www.youtube.com/watch?v=ko52m9jJGTQ
- https://www.youtube.com/watch?v=nwSNU3-m0ew

Hypothesis 2: Gravitational Encounters

- Close gravitational encounters between two or three massive planets can eject one planet while flinging the other((s) into a highly elliptical orbit.
- Multiple close encounters with smaller planetesimals can also cause inward migration.

Orbital Resonances



- Resonances between planets can also cause their orbits to become more elliptical.

Thought Question

What happens in a gravitational encounter that allows a planet's orbit to move inward?

A. It transfers energy and angular momentum to another object.
B. The gravity of the other object forces the planet to move inward.
C. It gains mass from the other object, causing its gravitational pull to become stronger.

Thought Question

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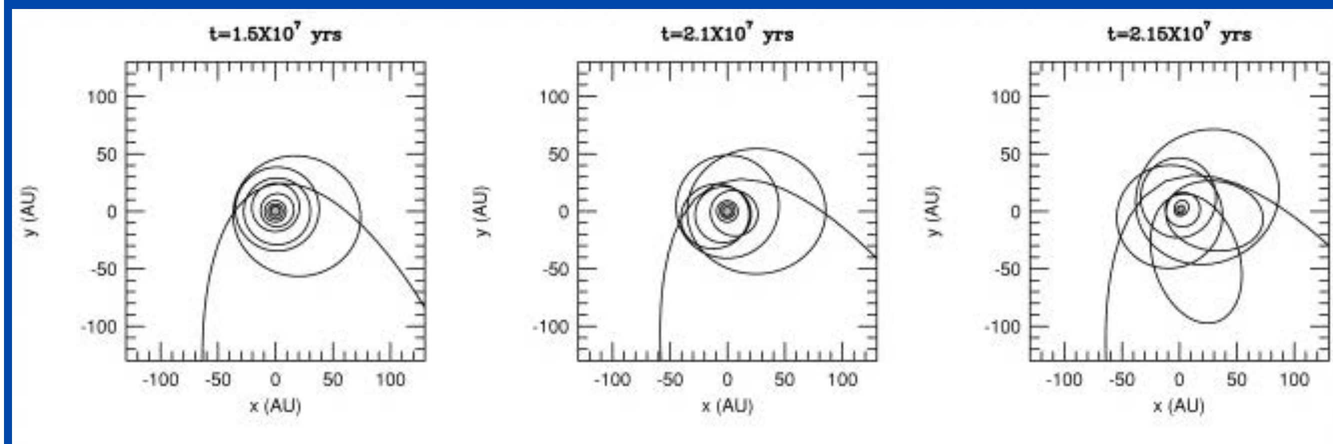
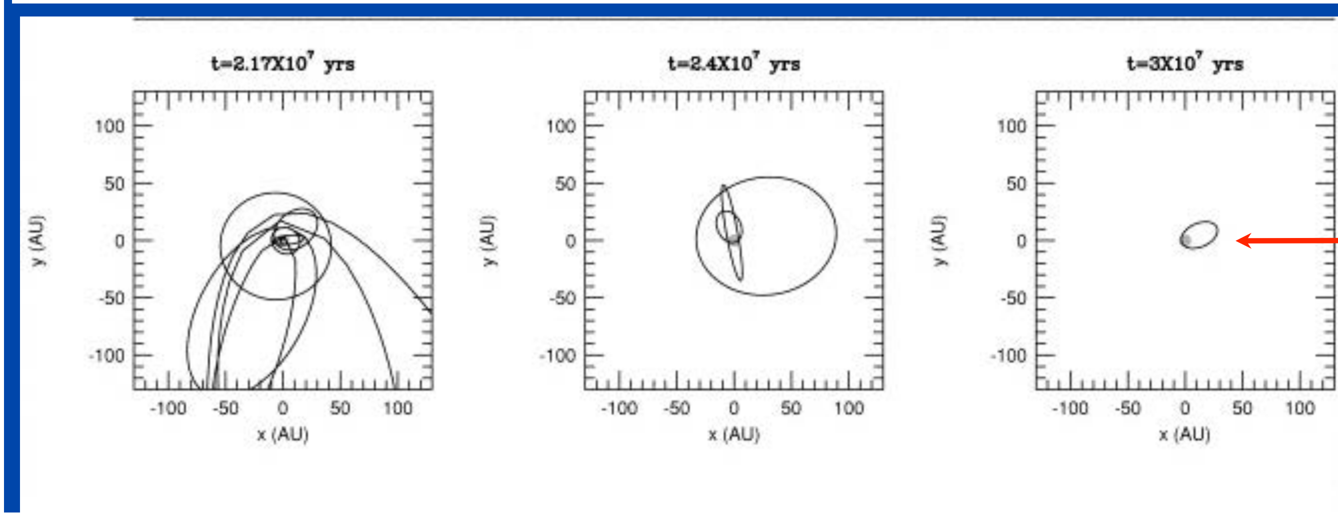
Hypothesis 2: Multi-Planet Interactions as Cause of Planetary Migration

- Simulation: start with 100 Planet "Embryos"
- Scatter, Collide, Stick, Accrete Gas



After 21.5 Myr:

Chaos



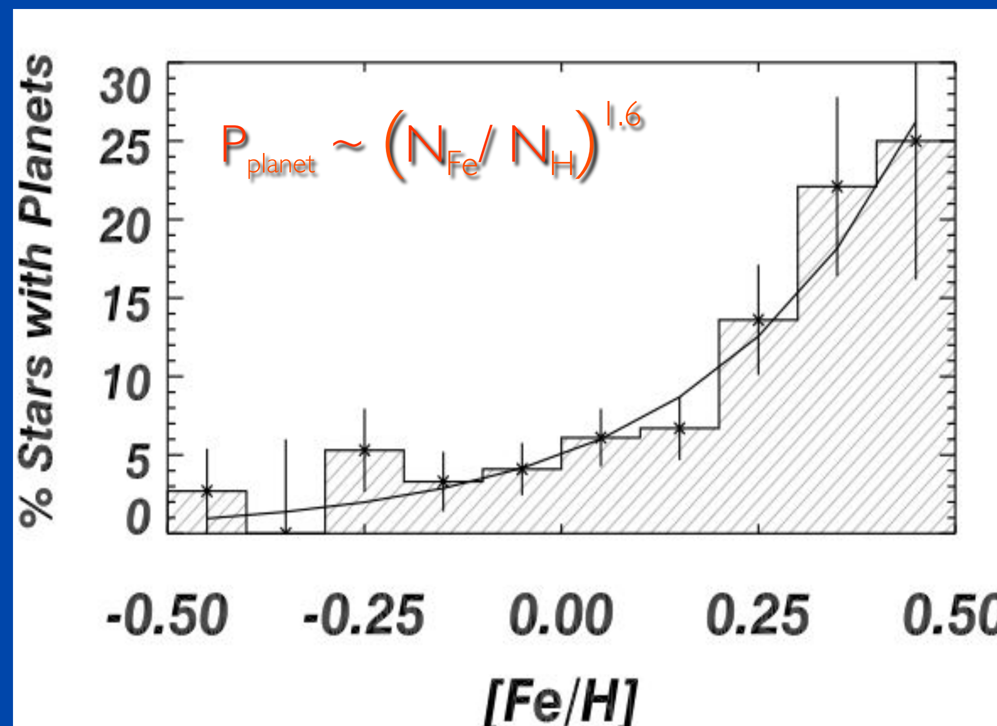
After 30 Myr: Lone Close-in Jupiter in Eccentric Orbit.

What have we learned?

- Can we explain the surprising orbits of many extrasolar planets?
  - Original nebular theory cannot account for the existence of hot Jupiters.
  - Planetary migration or gravitational encounters may explain how Jupiter-like planets moved inward.
- Can we explain large eccentricities of exoplanets?
  - Migration and encounters may play a larger role than previously thought.

Parent stars of extrasolar planets

- High in elements heavier than hydrogen and helium
- Reasonable: planets form from dust, which is made of elements heavier than hydrogen and helium
- Probability of finding a planet increases as heavy element content of parent star increases



Gas giant planets prefer stars with high metallicity

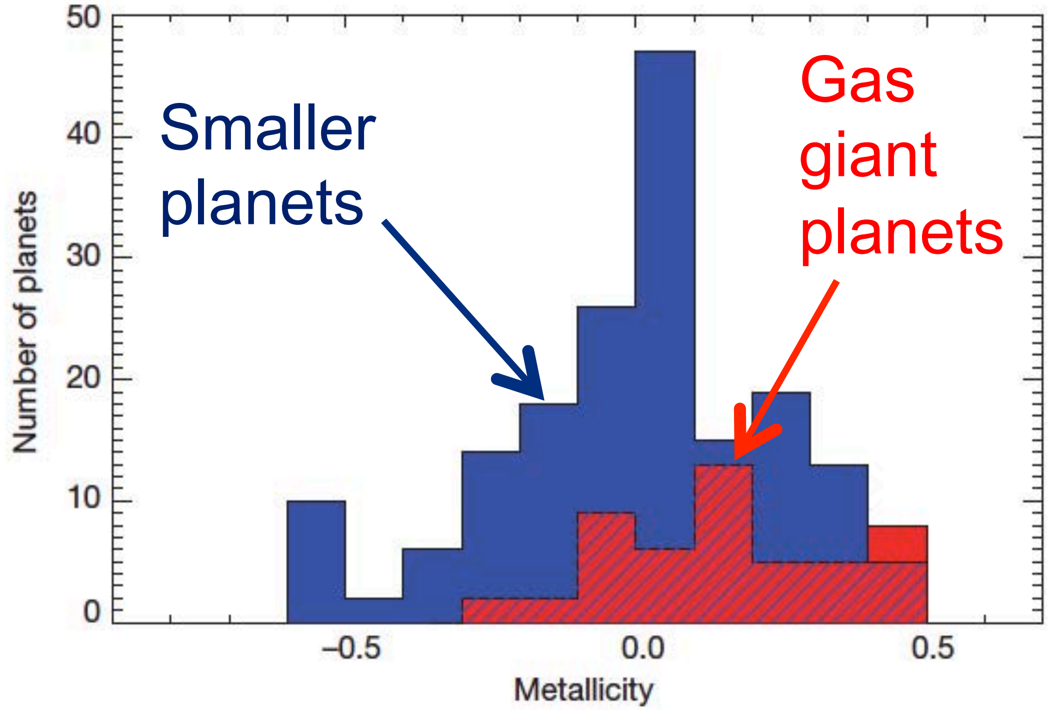


Figure 2 | Comparison of host-star metallicities for small and large planets. The histograms compare the metallicities of two samples of stars hosting planets by dividing the sample at $R_P = 4R_\oplus$. The host stars of the gas giant planets ($R_P \geq 4R_\oplus$; red histogram) are clearly more metal rich than those of the smaller planets ($R_P < 4R_\oplus$; blue histogram), which have a much wider range of metallicities. The hatched area represents the area where the histograms overlap. A Kolmogorov–Smirnov test shows that the probability that the two

Smaller planets seem to form around stars with a wider range of metallicity

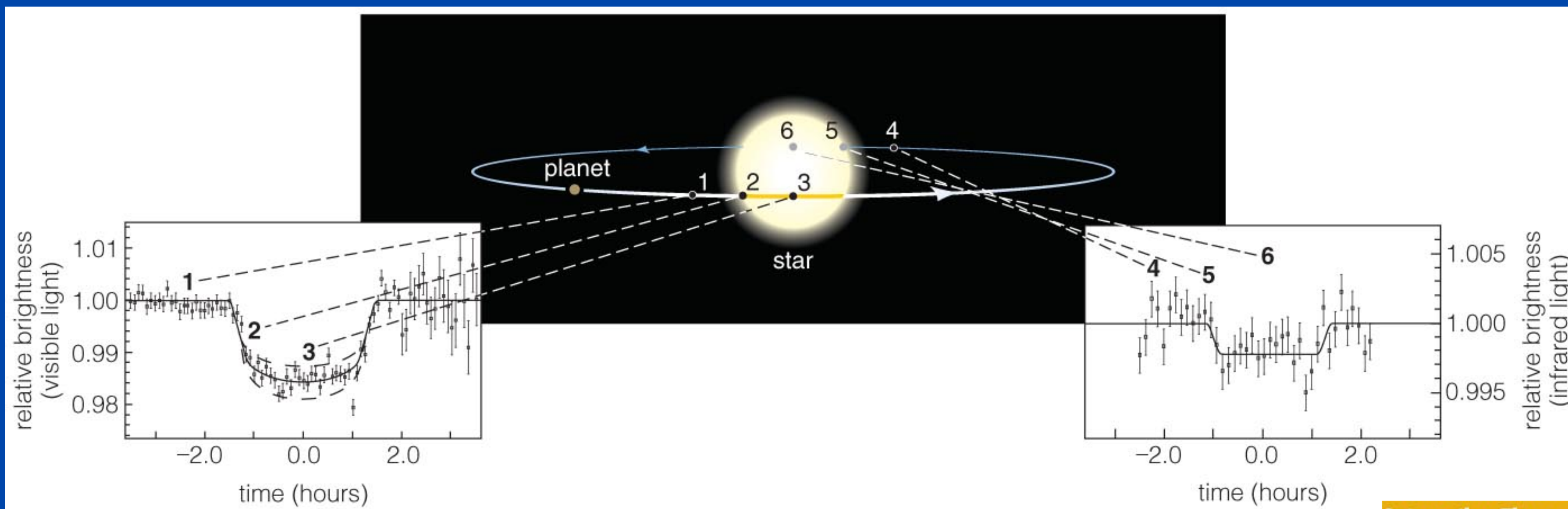
Credit: Buchhave, Nature article

Atmospheres of exoplanets: How do we learn about them?

- Transit method: subtract spectrum of star from spectrum of star plus planet, to see spectrum of planet alone

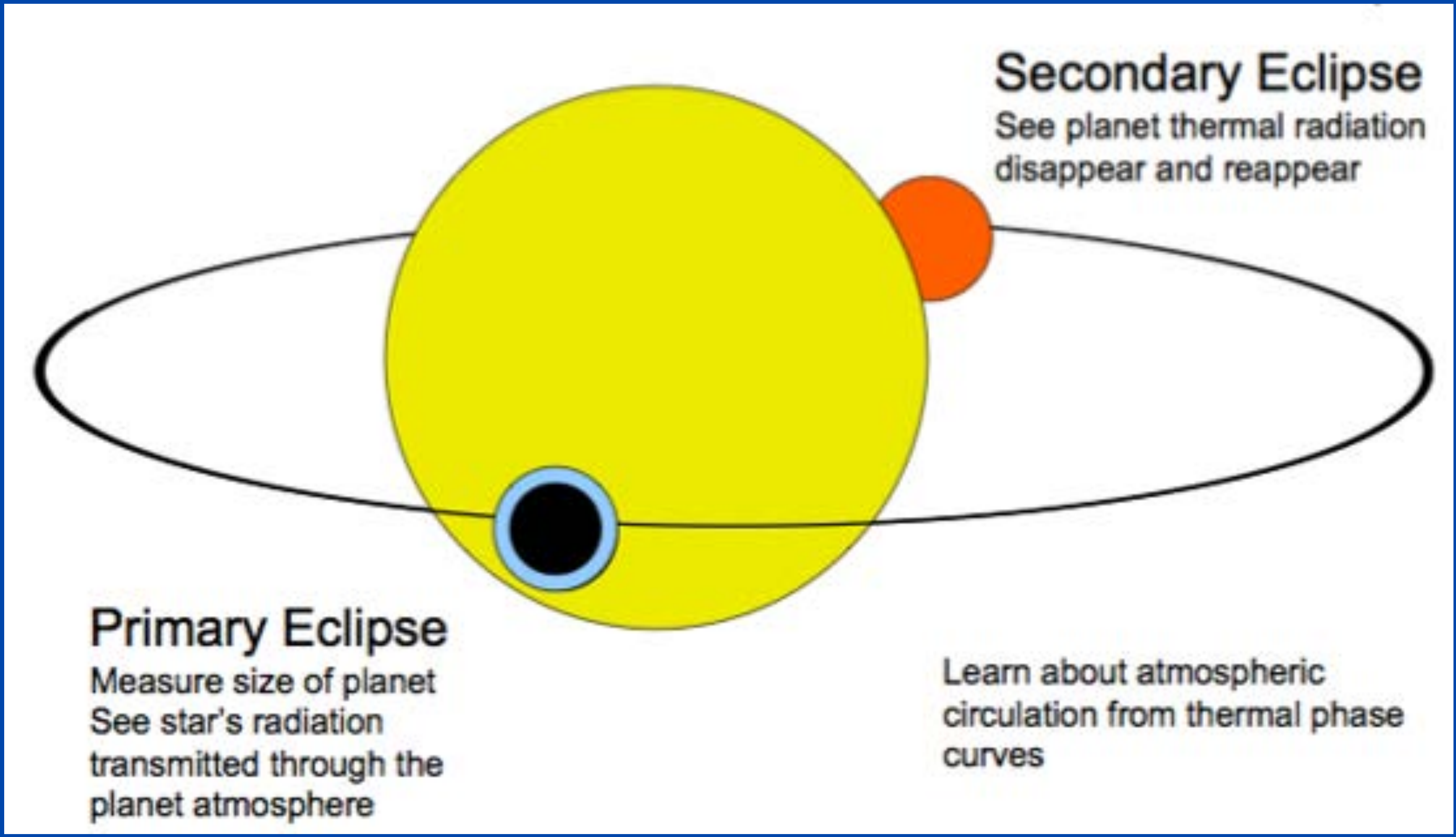
- Direct imaging method: take spectrum of planet directly, since it is spatially separated from the parent star

Transits and Eclipses

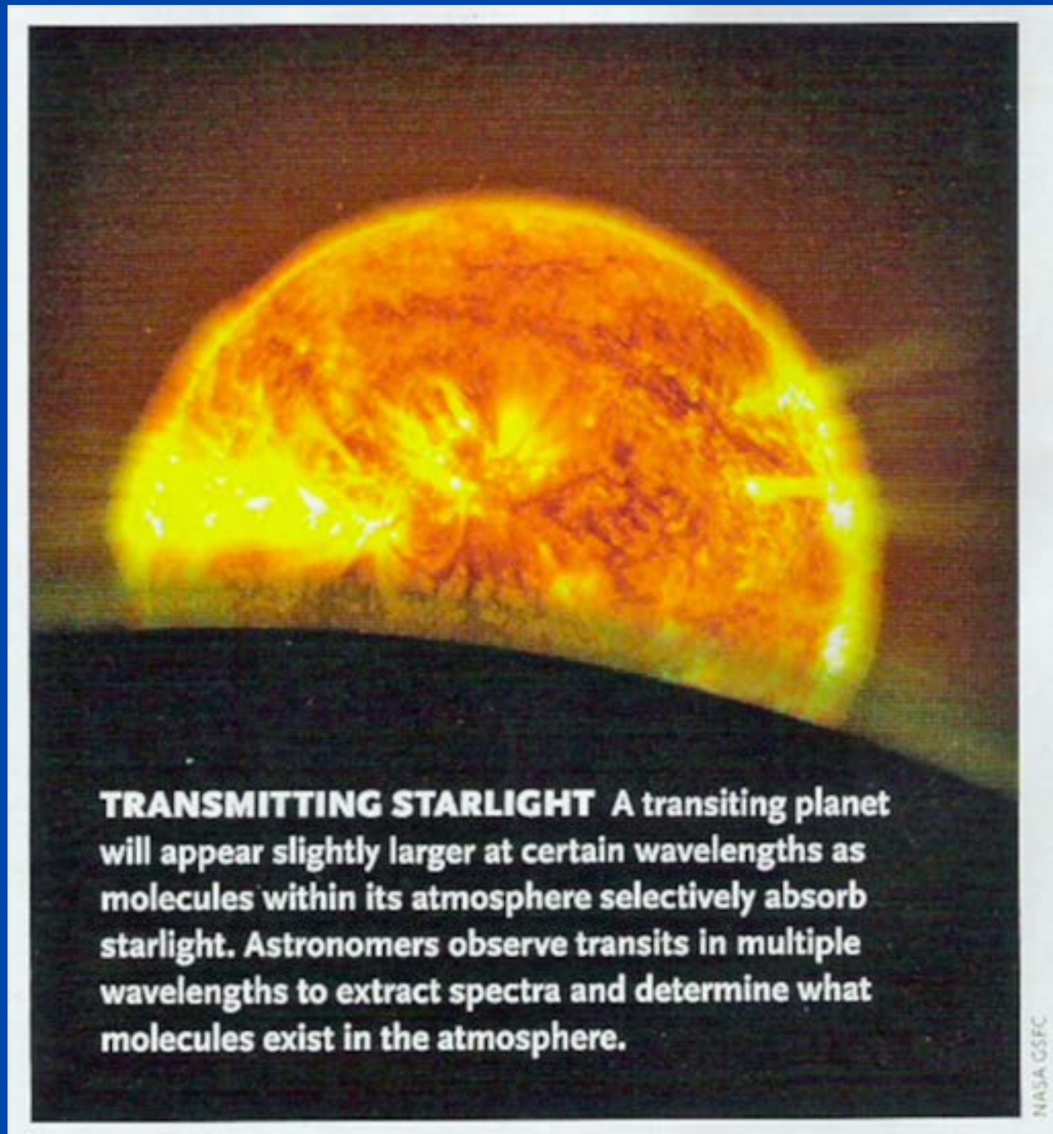


Interactive Figure

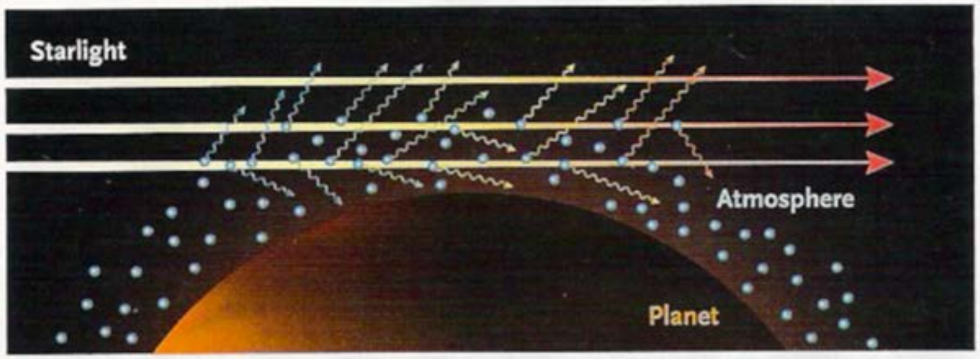
- **Transit:** when a planet crosses in front of a star.
- **Eclipse:** when star passes between us and the planet
- No orbital tilt: accurate measurement of planet mass (planet wouldn't transit at all if orbit were tilted)



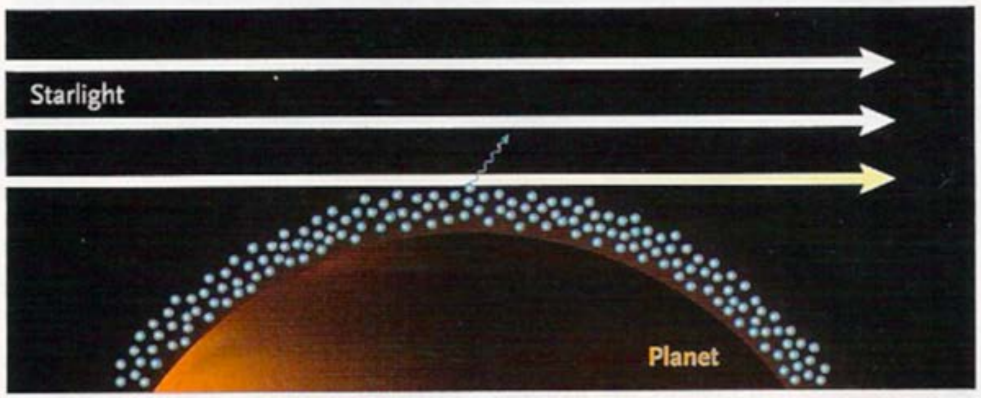
Seager & Deming, Annual Reviews of Astronomy & Astrophysics (September 2010)



Credit: Jonathan Fortney, Sky and Telescope Magazine

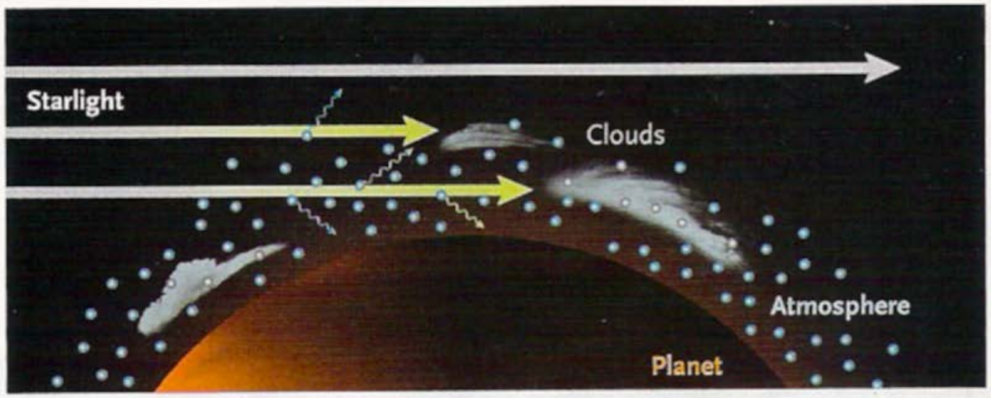


IDEAL TRANSMISSION SPECTRUM As the host star's light passes through a planet's atmosphere during the planet's transit, molecules in the atmosphere reveal themselves by absorbing some wavelengths and not others.

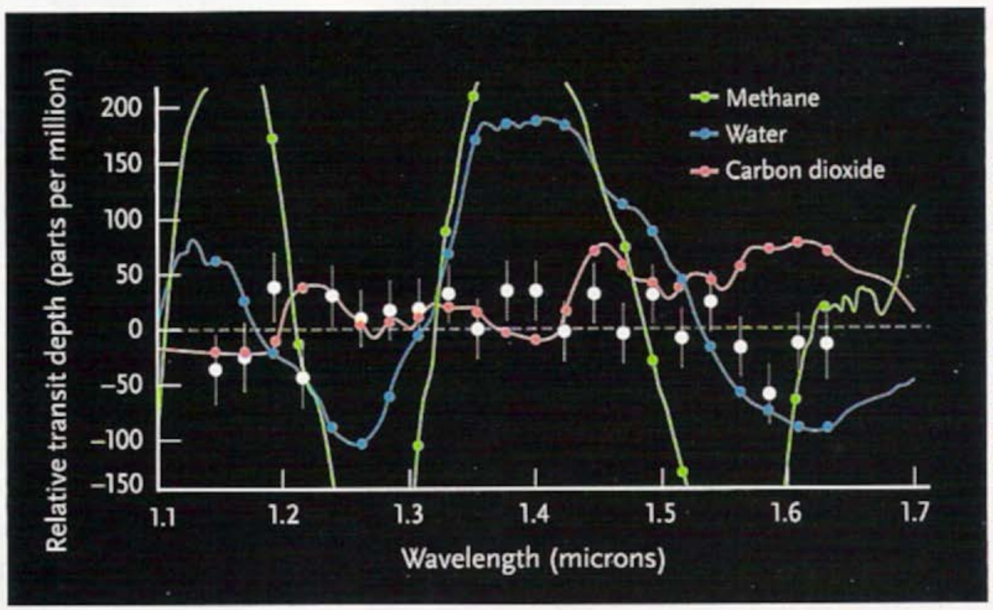


HEAVY MOLECULES But an atmosphere made mostly of heavy molecules, such as water vapor or carbon dioxide, will hug the planet more closely. Most starlight will pass by unabsorbed, and the resulting transmission spectrum will appear featureless. Detecting molecules in such atmospheres is still possible, but requires much more observing time.

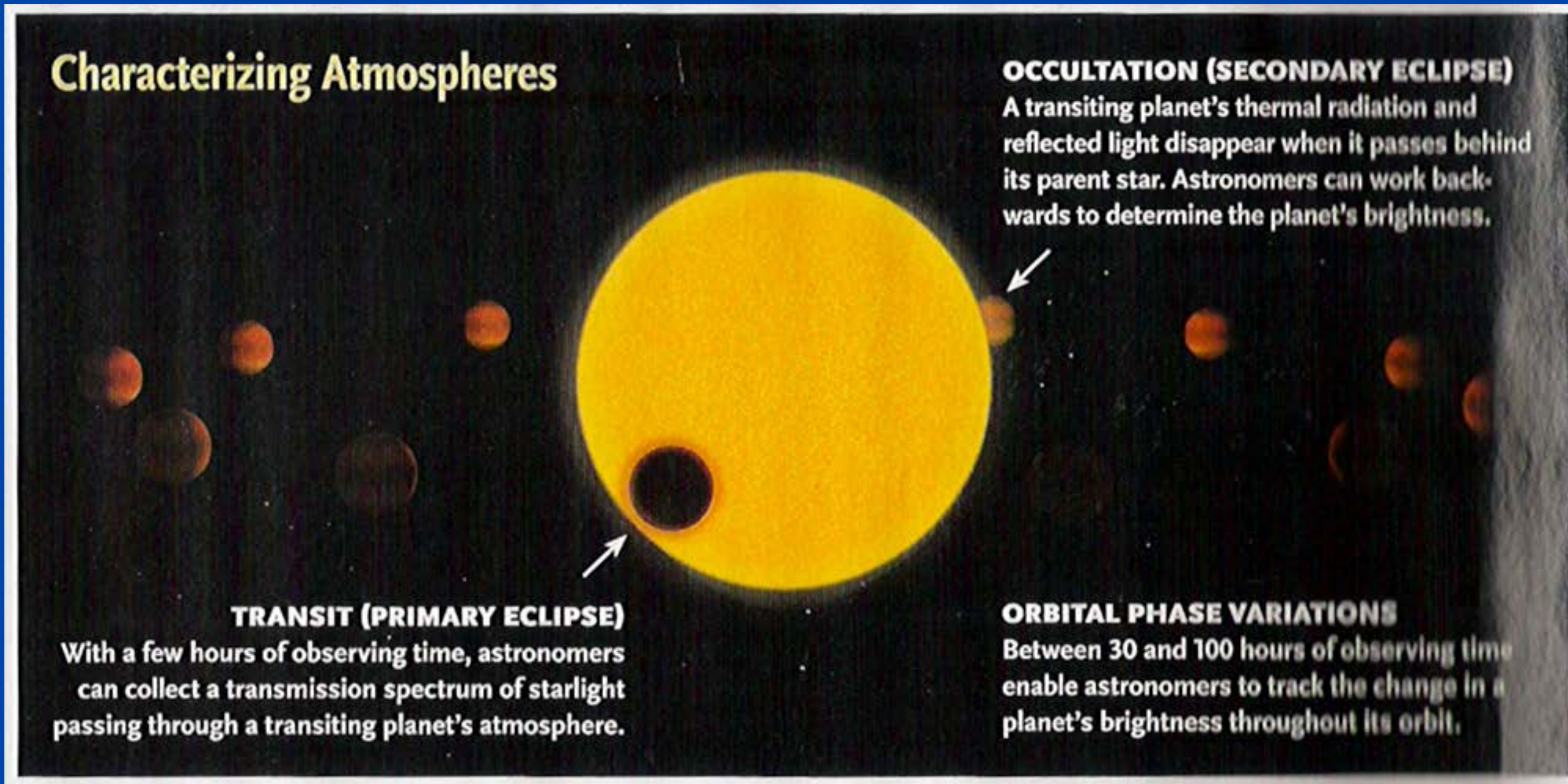
Credit: Jonathan Fortney, Sky and Telescope Magazine



CLOUDY FORECAST It's also possible that thick clouds in the atmosphere might block the host star's light. In that case, even longer observing times will not enable astronomers to detect the atmosphere's molecular imprint.



Credit: Jonathan Fortney, Sky and Telescope Magazine



Credit: Jonathan Fortney, Sky and Telescope Magazine

Water in the spectrum of planet Hat-p-1b

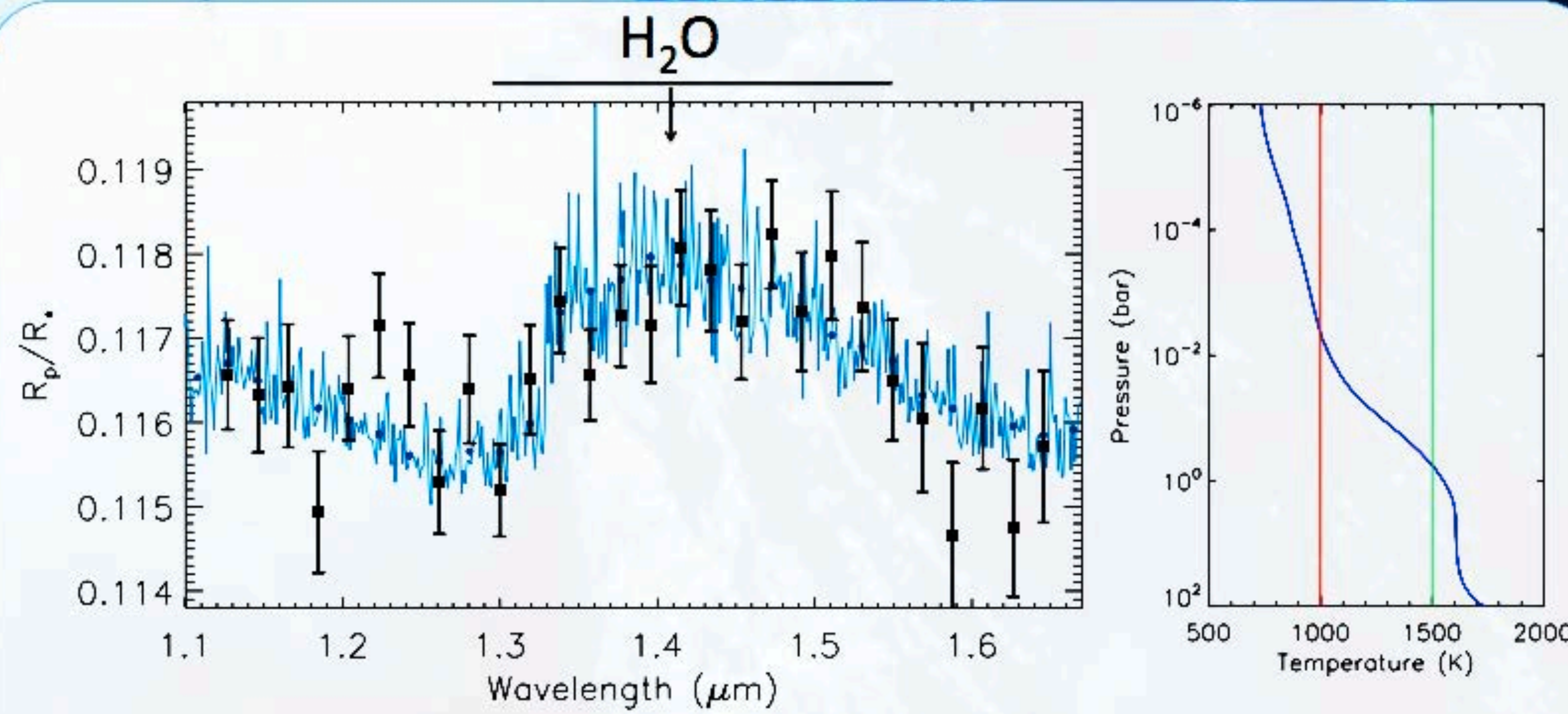
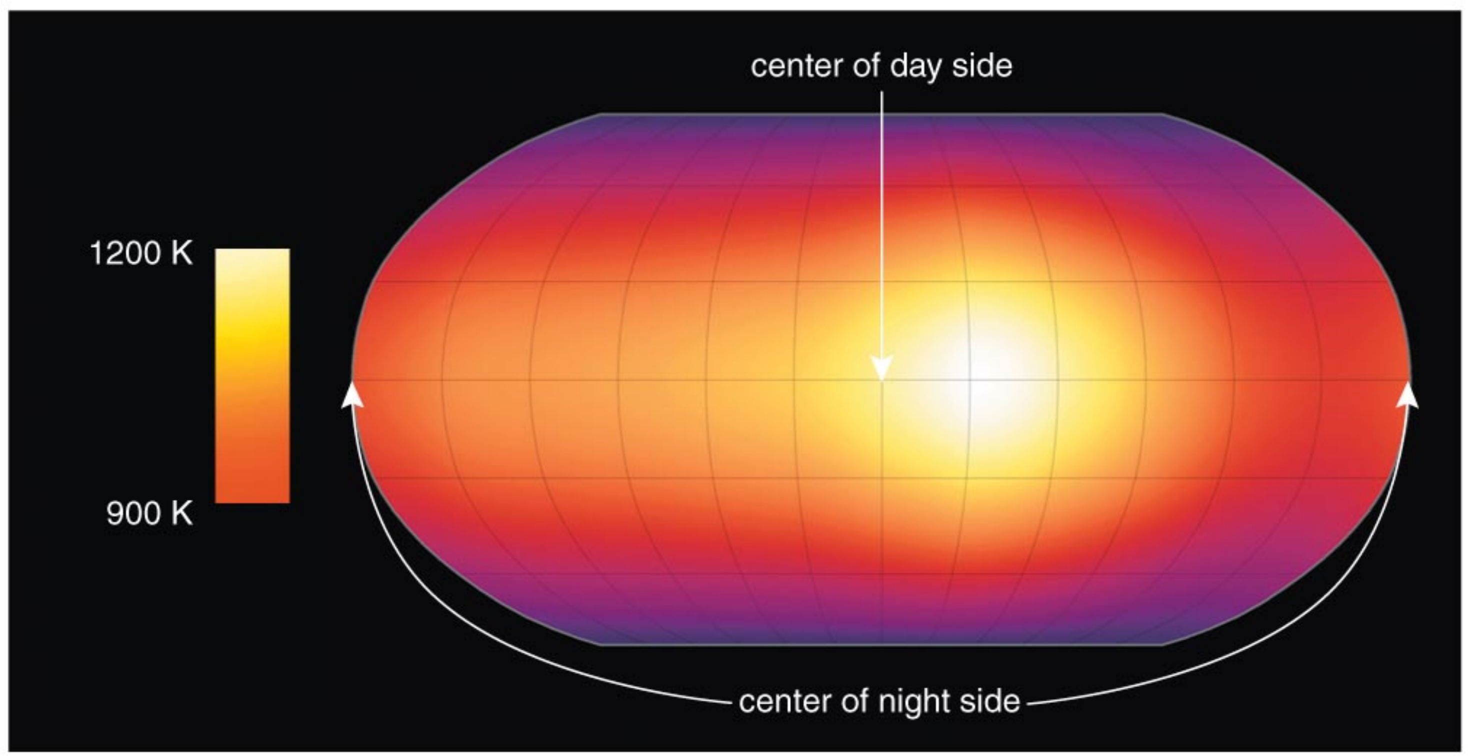


Fig 3: Left - The transmission spectrum of HAT-P1b, using differential photometry with individual parameter fitting. The full resolution planetary-averaged HAT-P-1b specific model plotted in blue (based on the Fortney et al. 2008,2010 models), which has a >5σ significance over that of a featureless atmosphere corresponding to a straight line through the average R_p/R_*. Right – Temperature-Pressure profiles for two isothermal cases at 1000K (red) and 1500K (green) and the planetary-averaged HAT-P-1b specific model (blue).

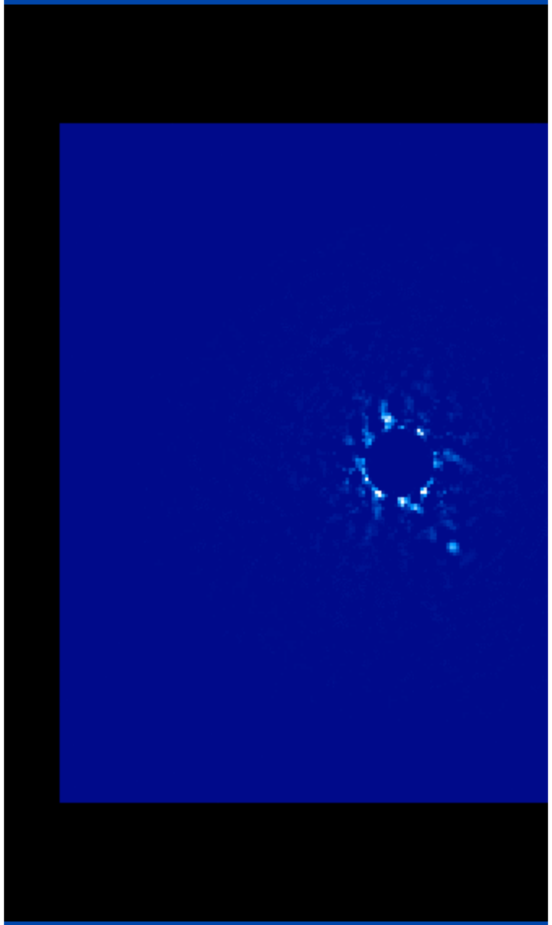
Credit: Wakeford, 2013

Surface Temperature Map

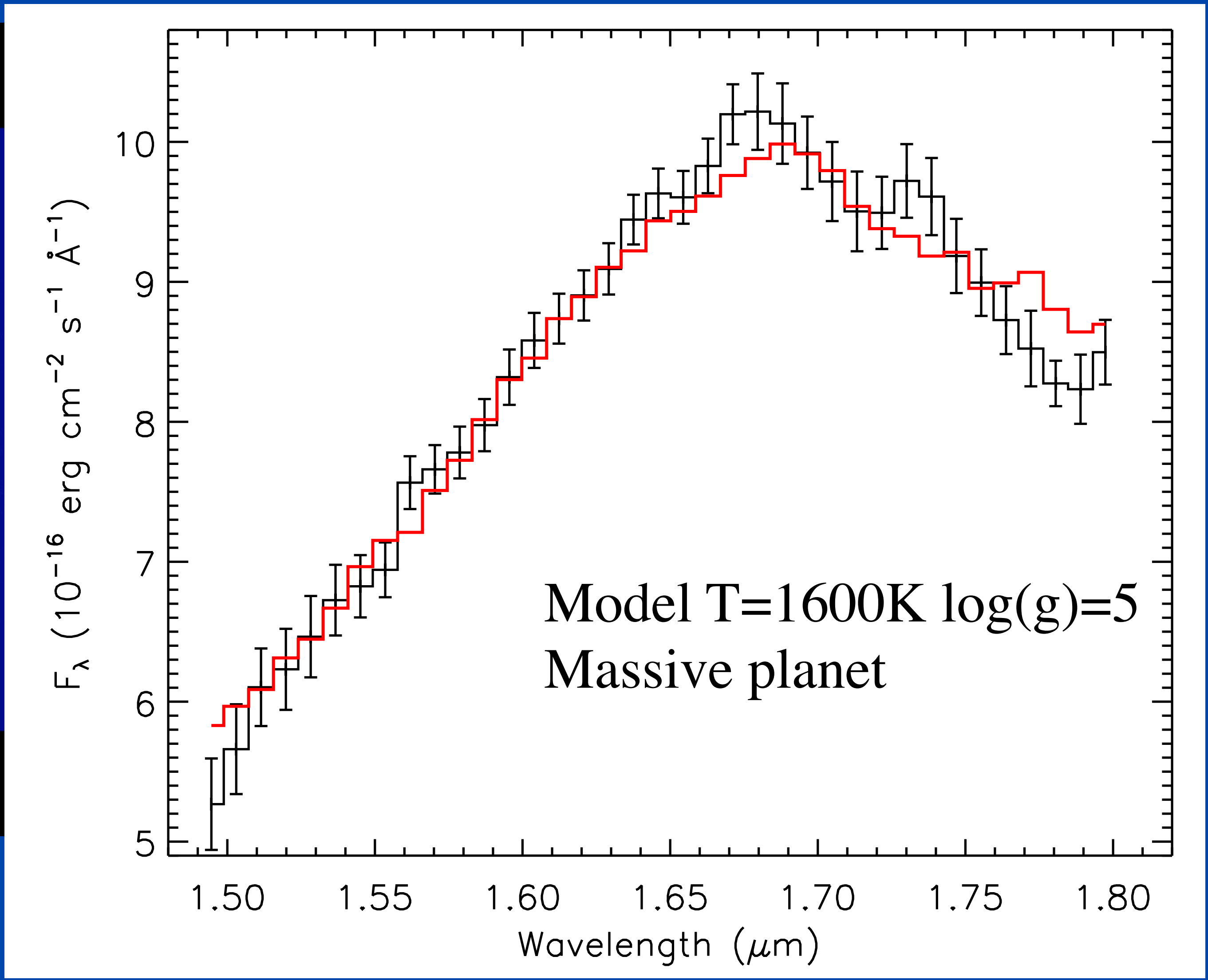


- Measuring the change in infrared brightness during an eclipse enables us to map a planet's surface temperature.

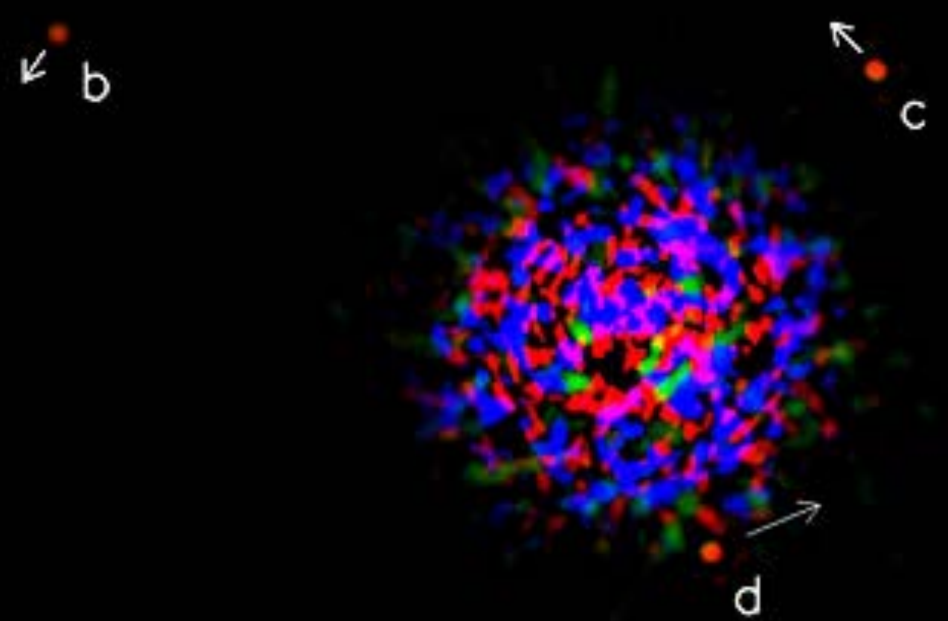
Beta Pictoris b spectrum, Gemini Planet Imager (direct imaging with adaptive optics)



Credit: GPI Team

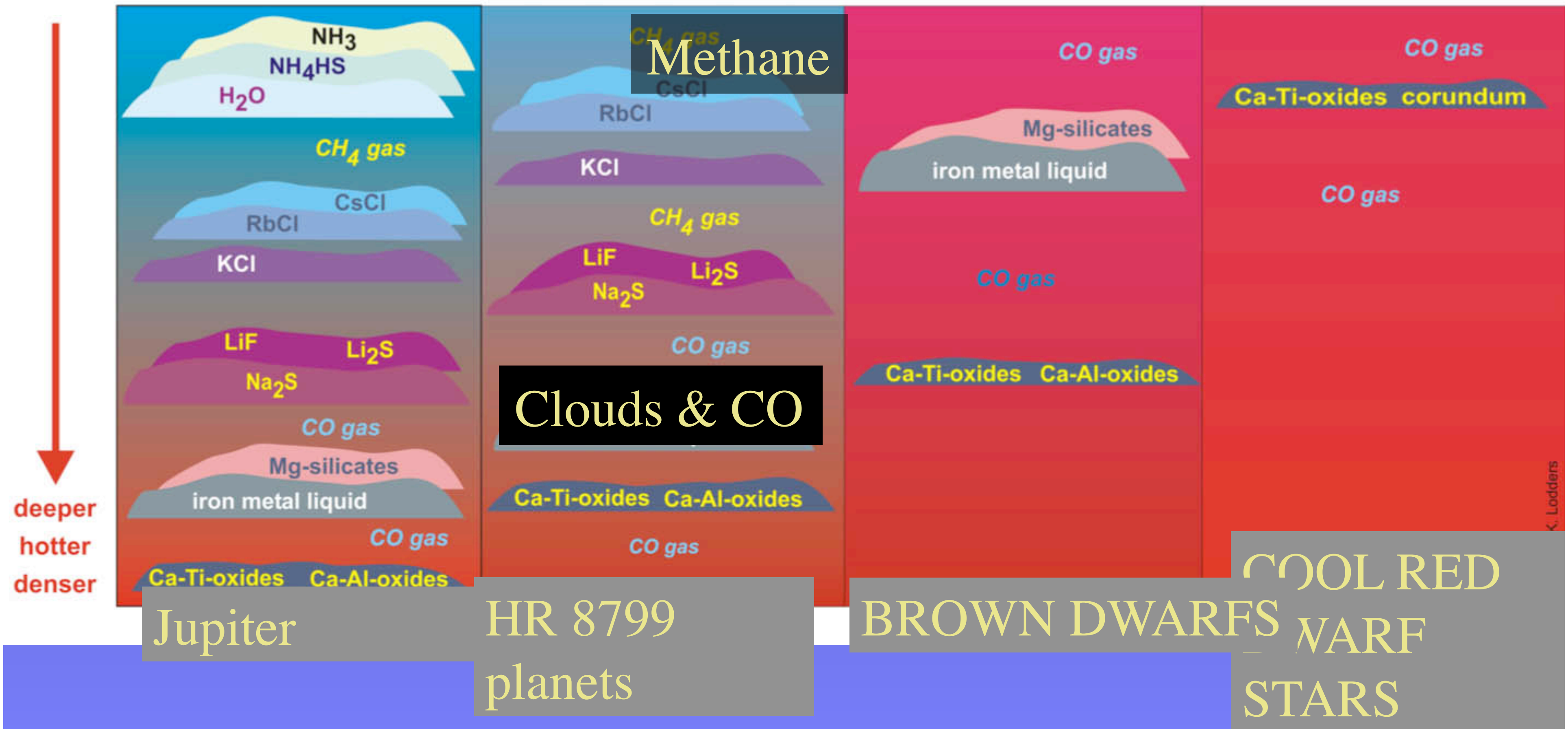


First Images of Exoplanets:
HR 8799 Solar System



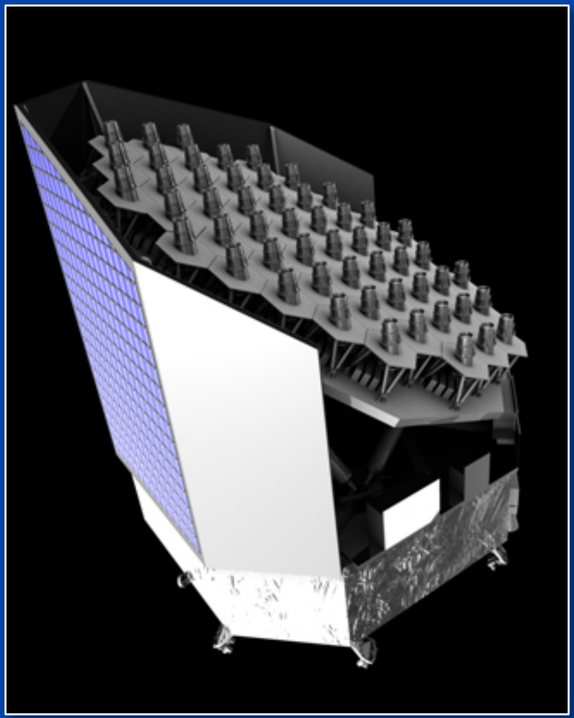
Marois et al. 2008, Science Magazine

Atmosphere of HR8799 planets

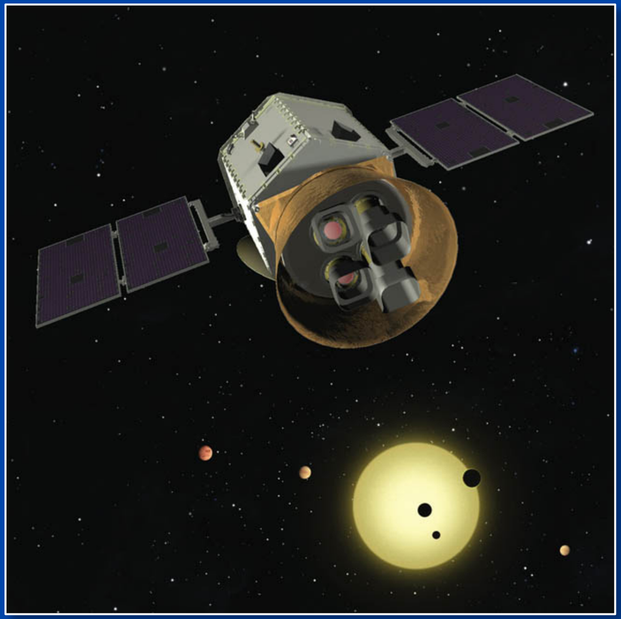


Burgasser et al. 2009 white paper / after Lodders & Fegley 2006

Future ambitious space missions to detect Earth-like planets



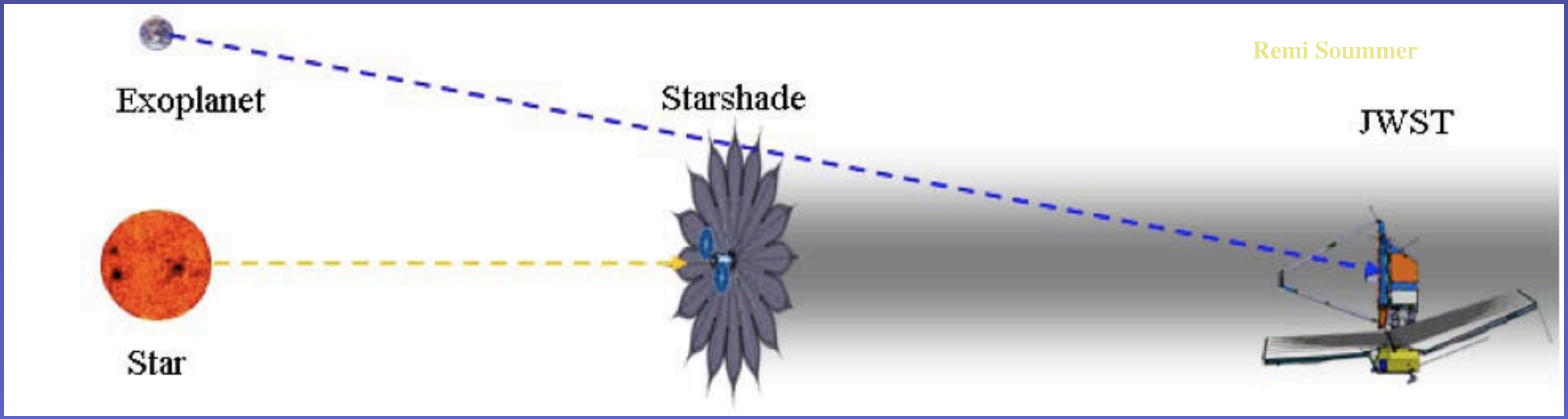
PLATO:
European
Space Agency

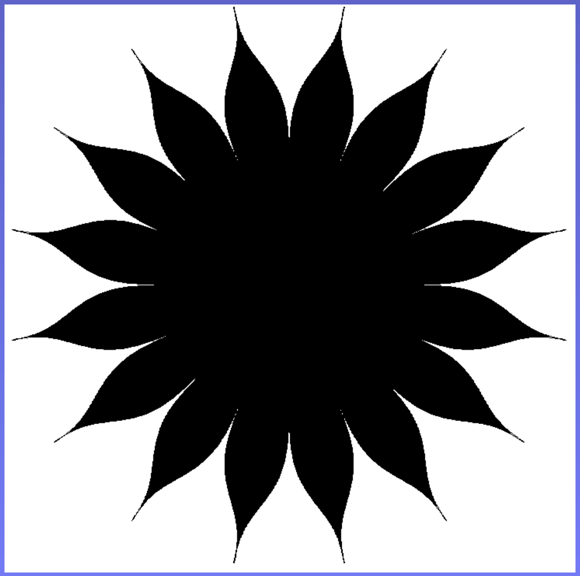


TESS:
NASA

WFIRST:
NASA

Occultor missions





Giant starshade free-floating in space

James Webb Space Telescope (2018 launch)

Jeremy Kasdin