The Formation of Stars and Planets

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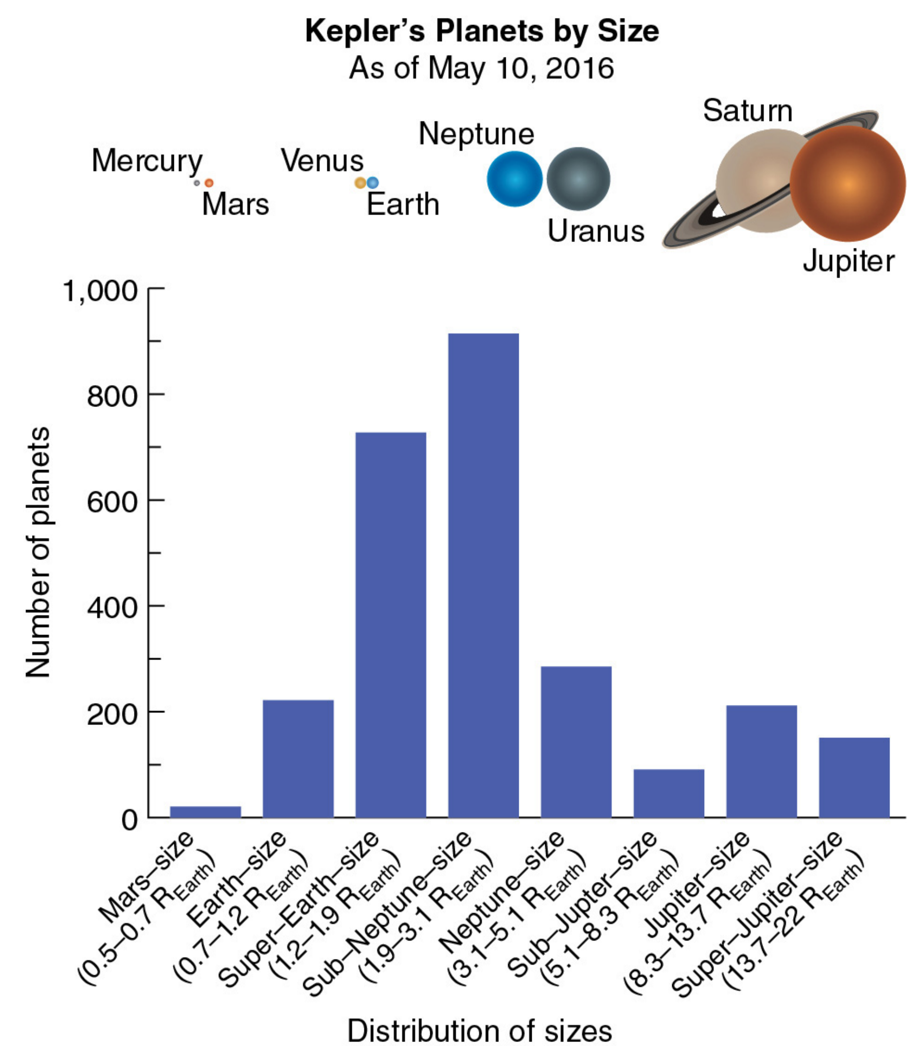
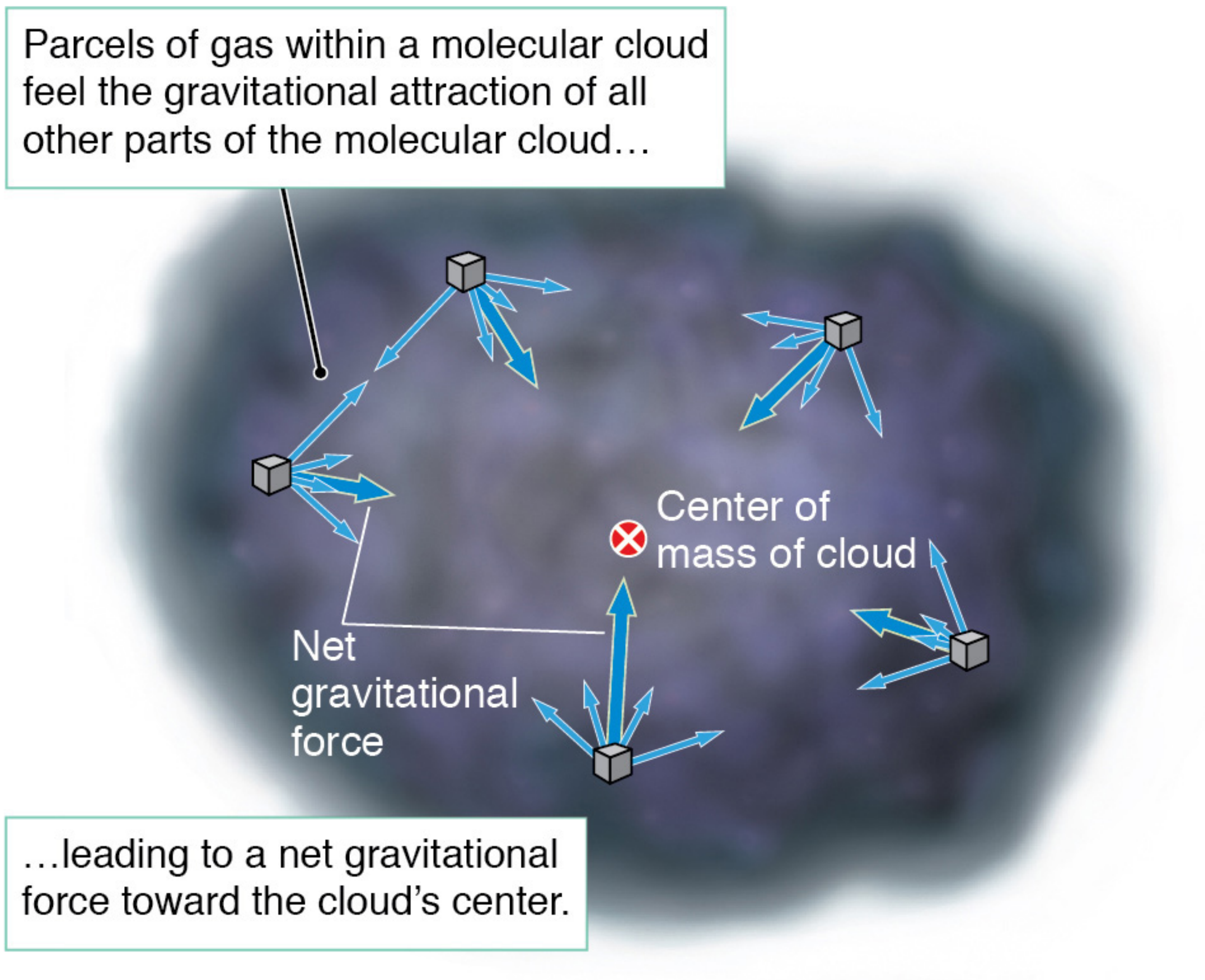
The formation of stars and planets

- Stars and planets form from clouds of gas and dust
- Star: dense cloud of gas that produces energy in its core by fusing light atoms into heavier ones
- Stars shine due to the heat produced during fusion
- Planets are very common in the Milky Way galaxy

Hubble image of the Eagle Nebula



Molecular clouds



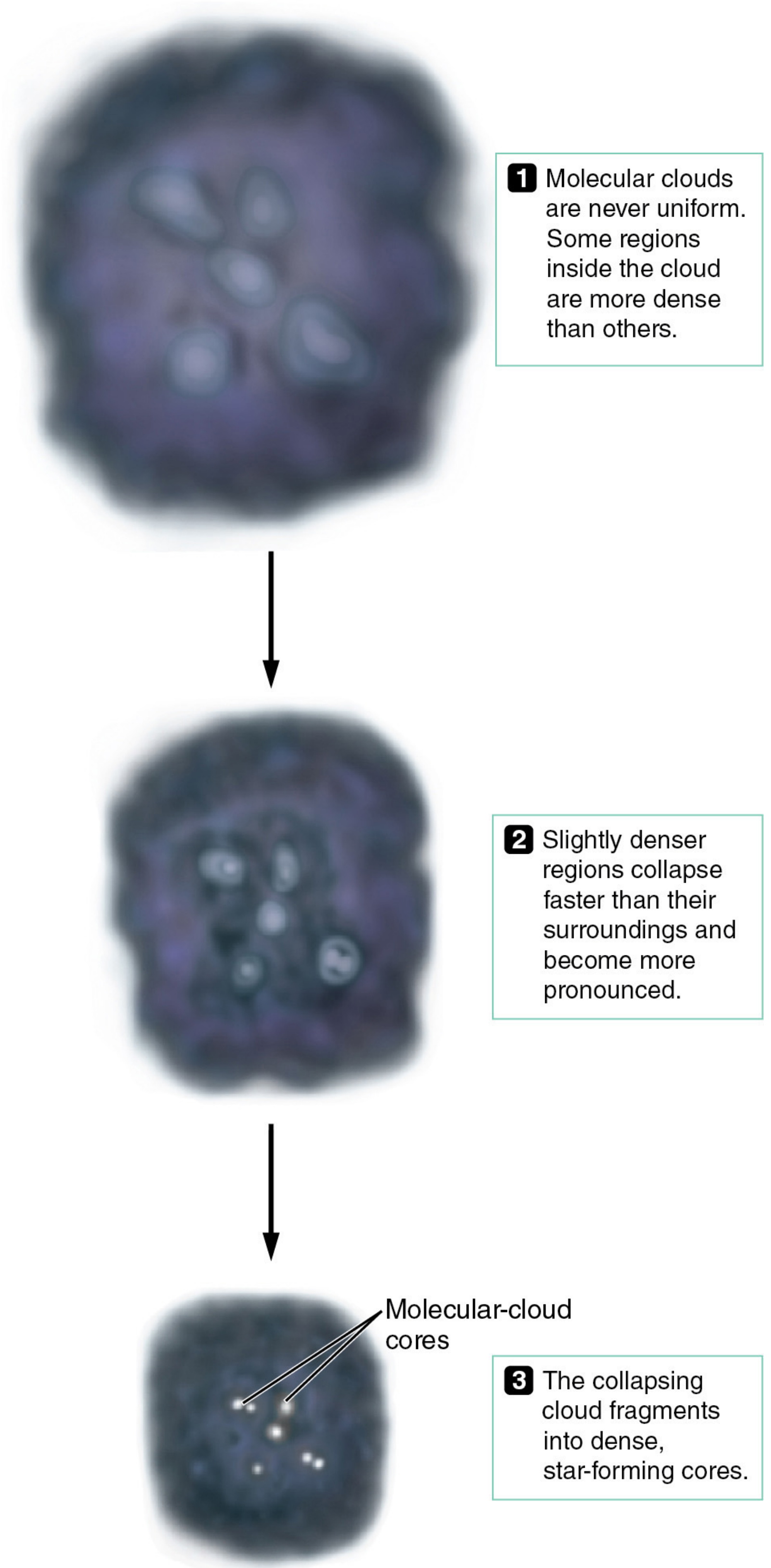
- Molecular cloud: large cloud of gas (mostly H_2) and dust
- Molecular clouds are the densest and coolest of interstellar clouds
- Molecular clouds have self-gravity: the net force on each gas or dust particle points towards the center of the cloud

Forces in a molecular cloud

- Self-gravity pulls gas and dust inward ⇒ cloud collapse
- Hot gas pressure pushes gas and dust outward ⇒ cloud expansion
- Hotter gas exerts more pressure than colder gas—individual gas molecules move faster in hotter gases, exerting more force on the colder dust they interact with

Molecular cloud collapse and fragmentation

- Eventually, self-gravity > hot gas pressure, and the molecular cloud collapses
- Density fluctuations ⇒
  - Some regions of the cloud collapse faster than others
  - Self-gravity amplified in denser regions
  - Cloud fragments into molecular-cloud cores: the seeds of new stars

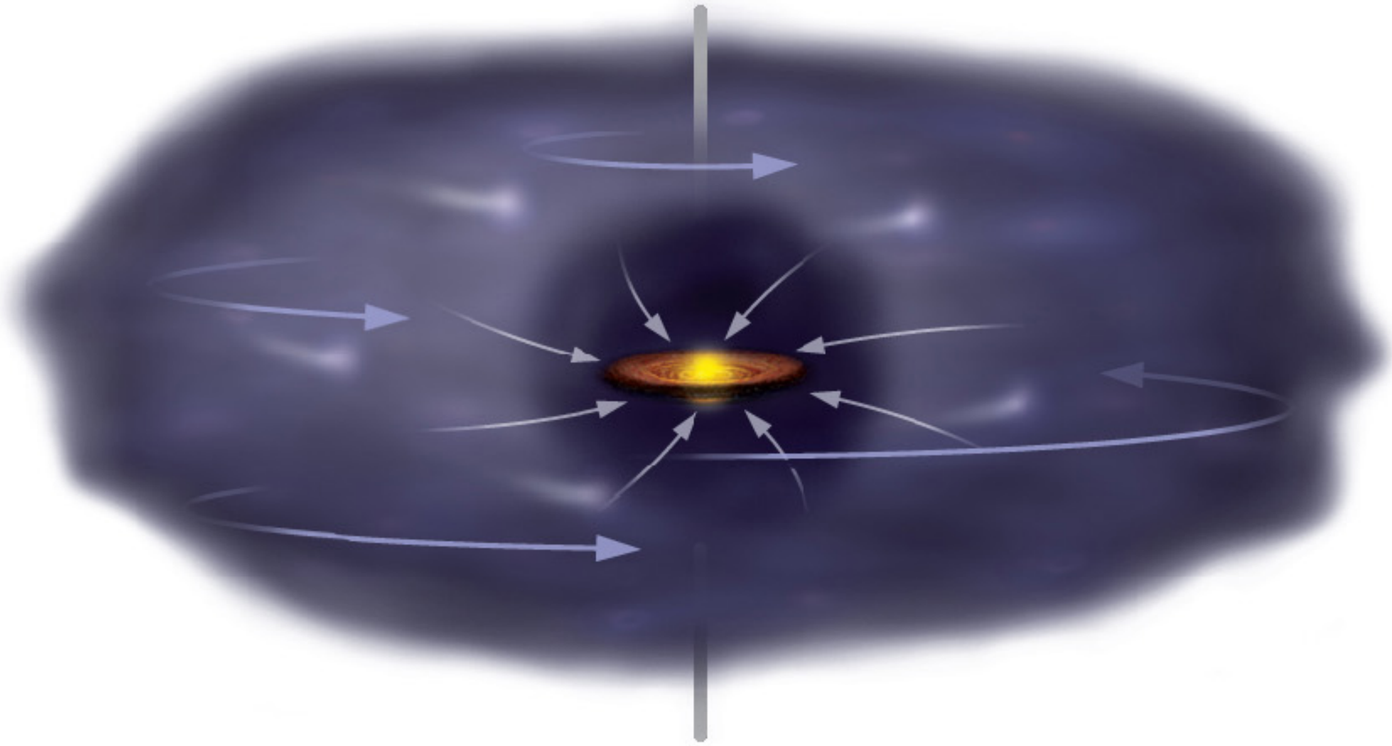


Protostar

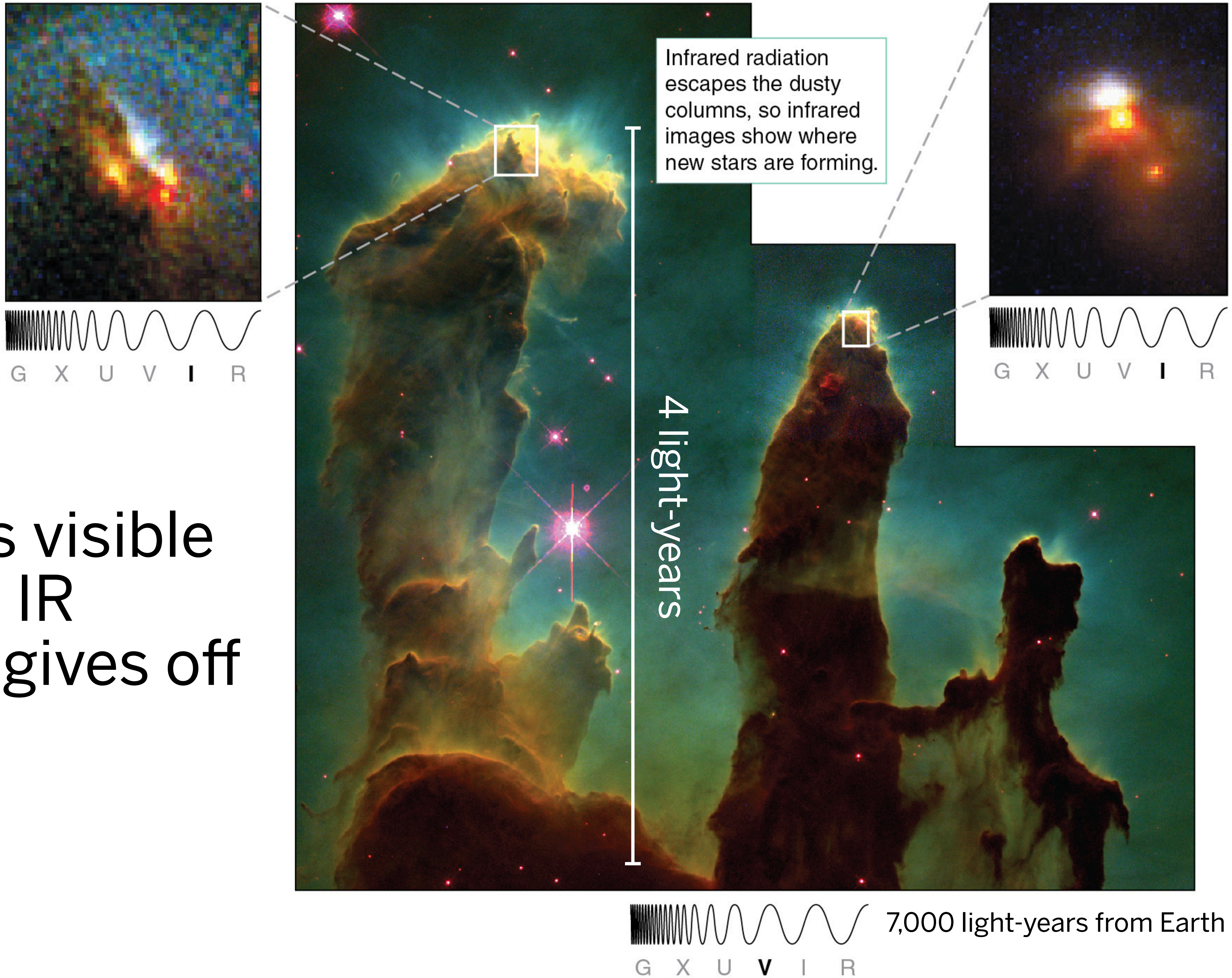
- Gas and dust rapidly falling inward moves faster and faster, raising the temperature of the protostar

- Hot (thousands of degrees Kelvin) protostar radiates —“shines”

- Gravitational potential energy of distributed molecular cloud converted to thermal energy of protostar

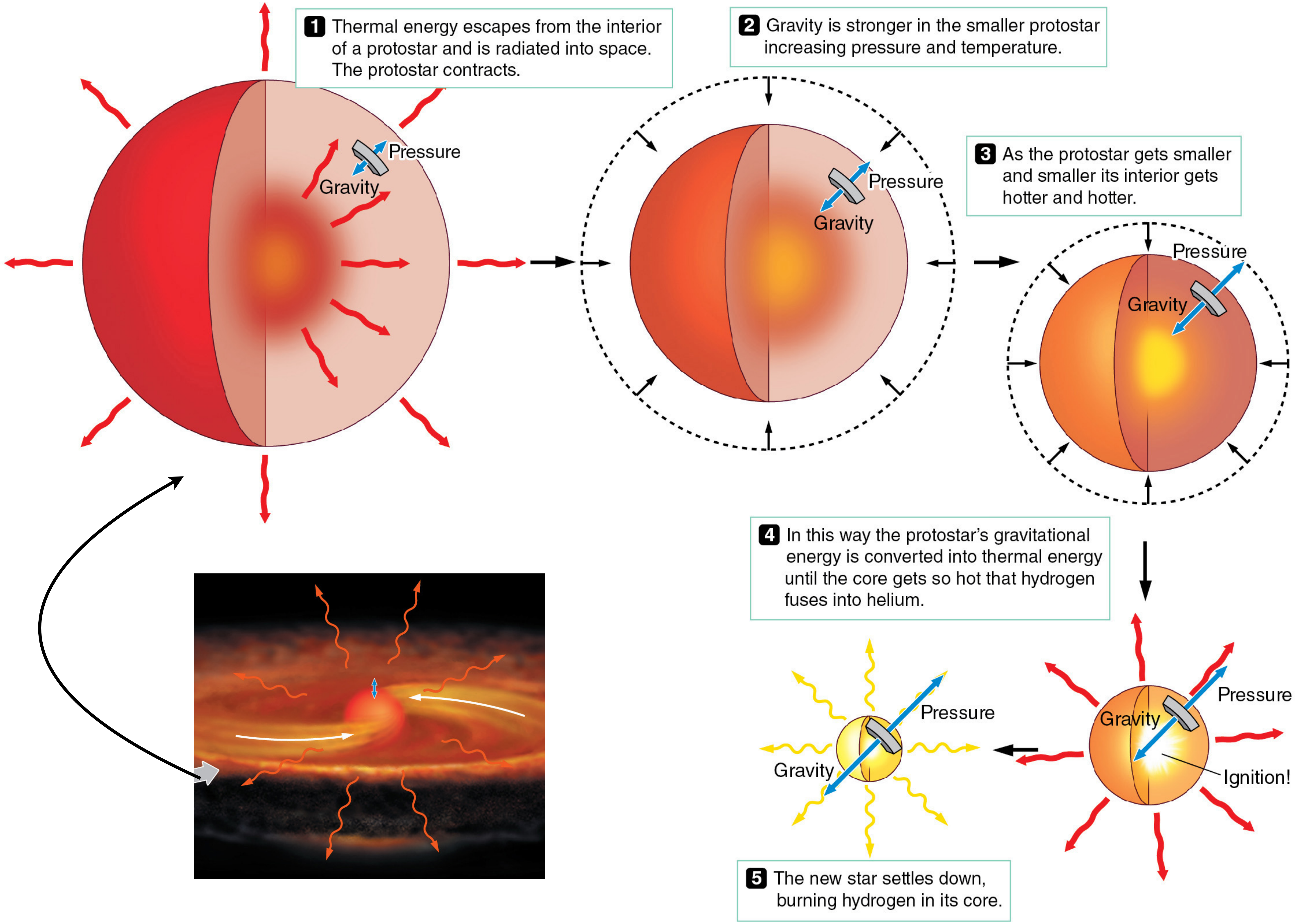


Protostars emit in the IR



- Dust absorbs visible light, but not IR
- Heated dust gives off its own IR

From protostar to star

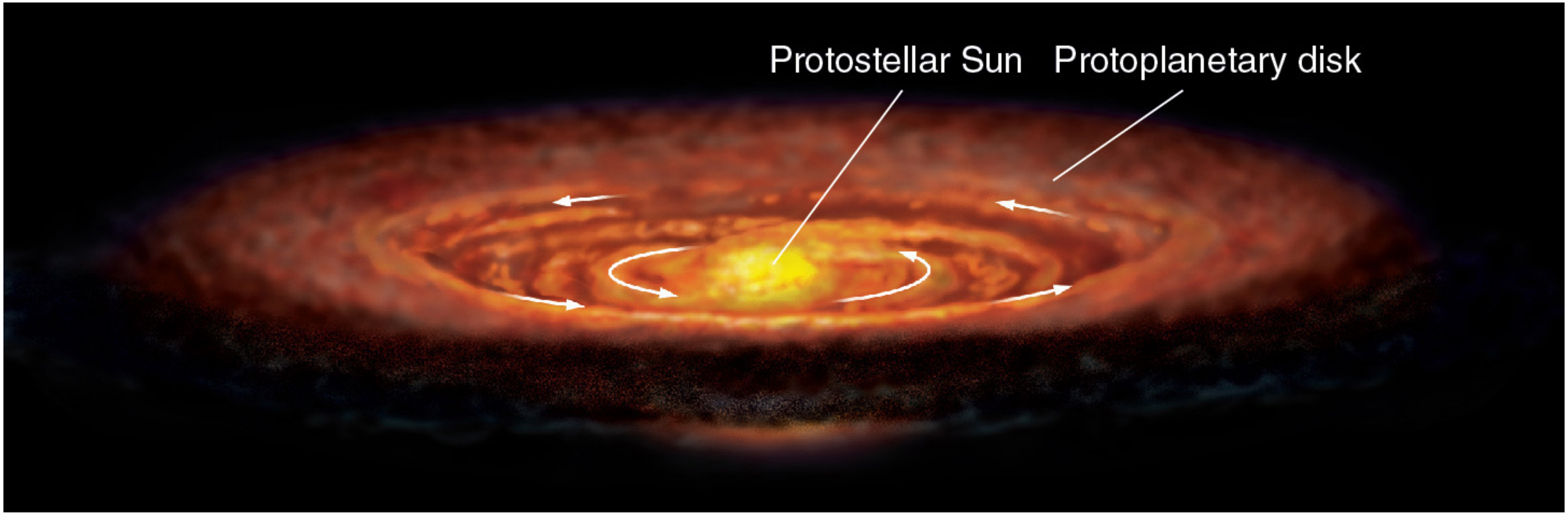


To be or not to be…a star

If the protostar's mass is…	…its core temperature will reach…	…and it will become a…	…powered by
$\gtrsim 0.08\ M_\odot$	10^7 K	Star	Nuclear fusion
$\lesssim 0.08\ M_\odot$	$<10^7$ K	Brown dwarf	Gravitational collapse

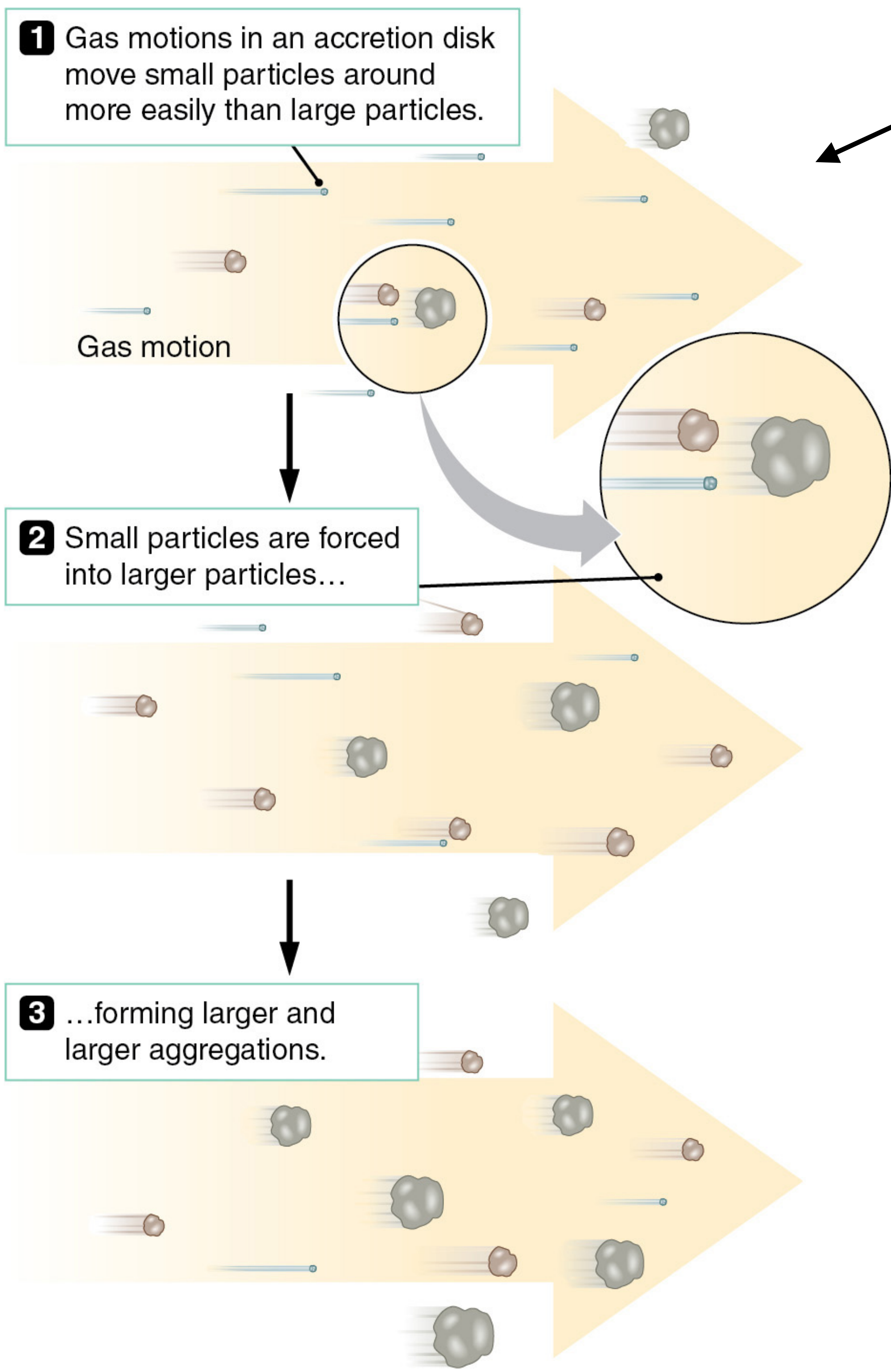
$$1\ M_\odot = 1.9891 \times 10^{30}\ \text{kg}$$

Planet formation

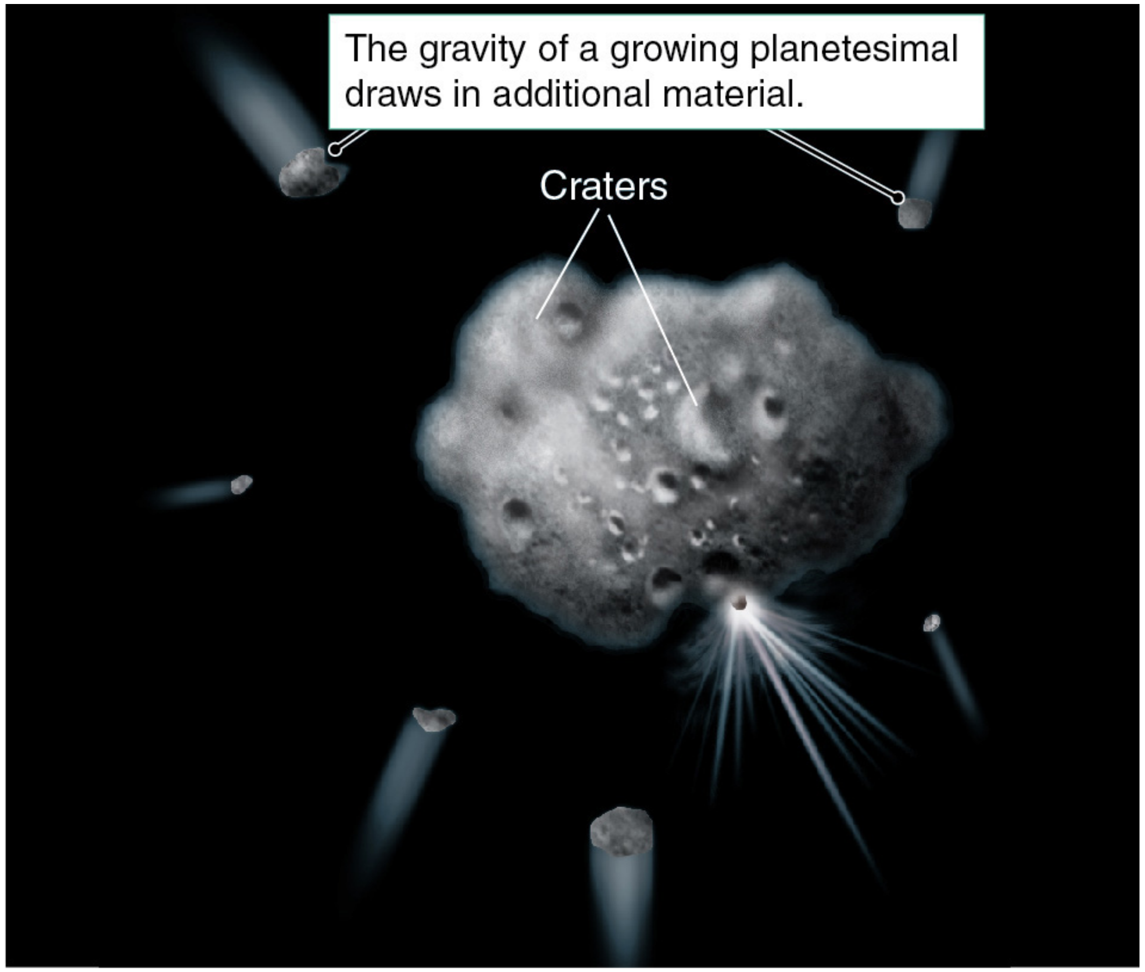


- Protostar is surrounded by protoplanetary accretion disk of gas and dust
- Rotating molecular cloud core collapses into accretion disk due to conservation of angular momentum

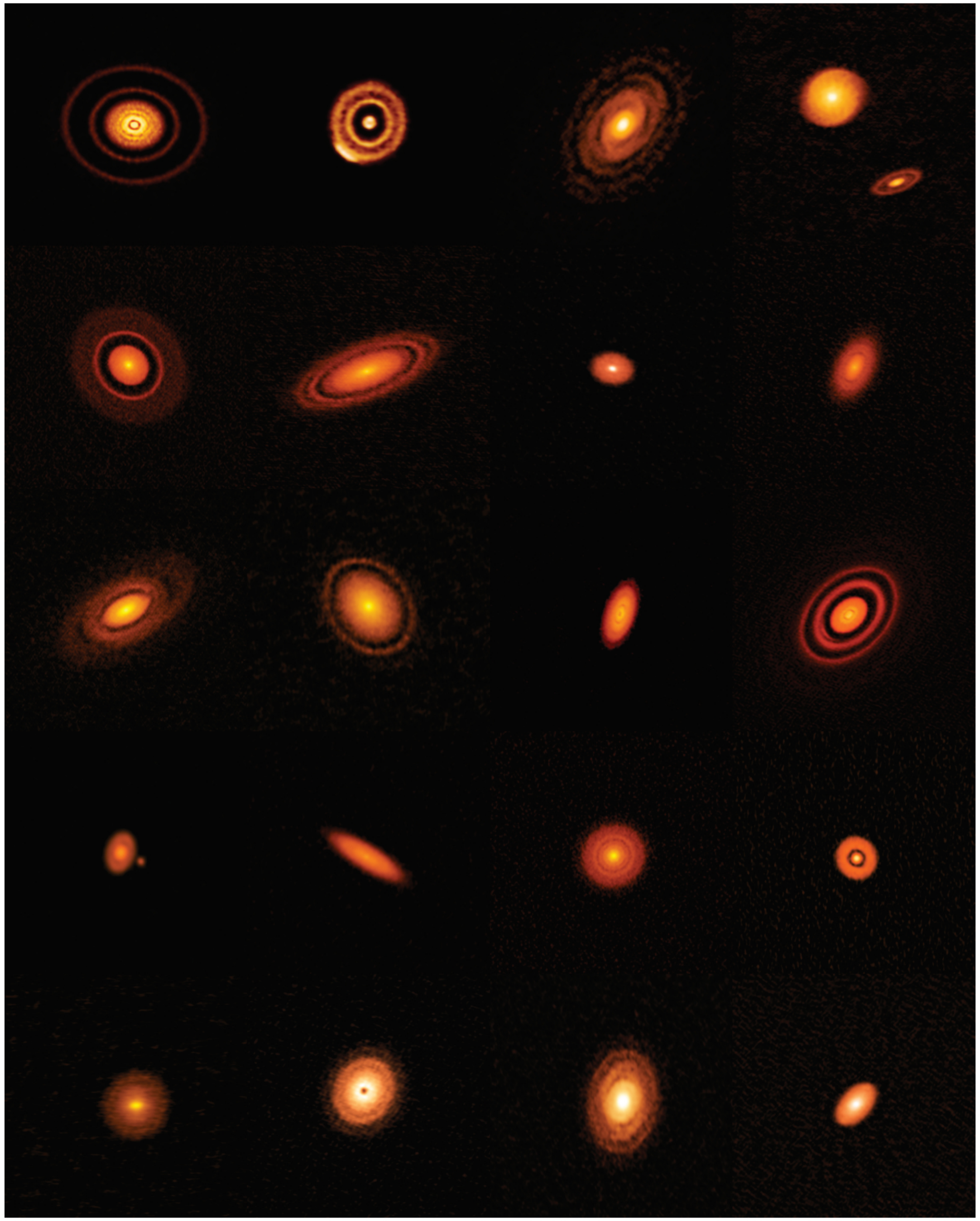
Creation of large objects



- Large objects sweep up smaller objects, sticking together via static electricity
- Slow (0.1 m/s) collision speeds
- At a diameter of ~1 km, gravity starts to play a role



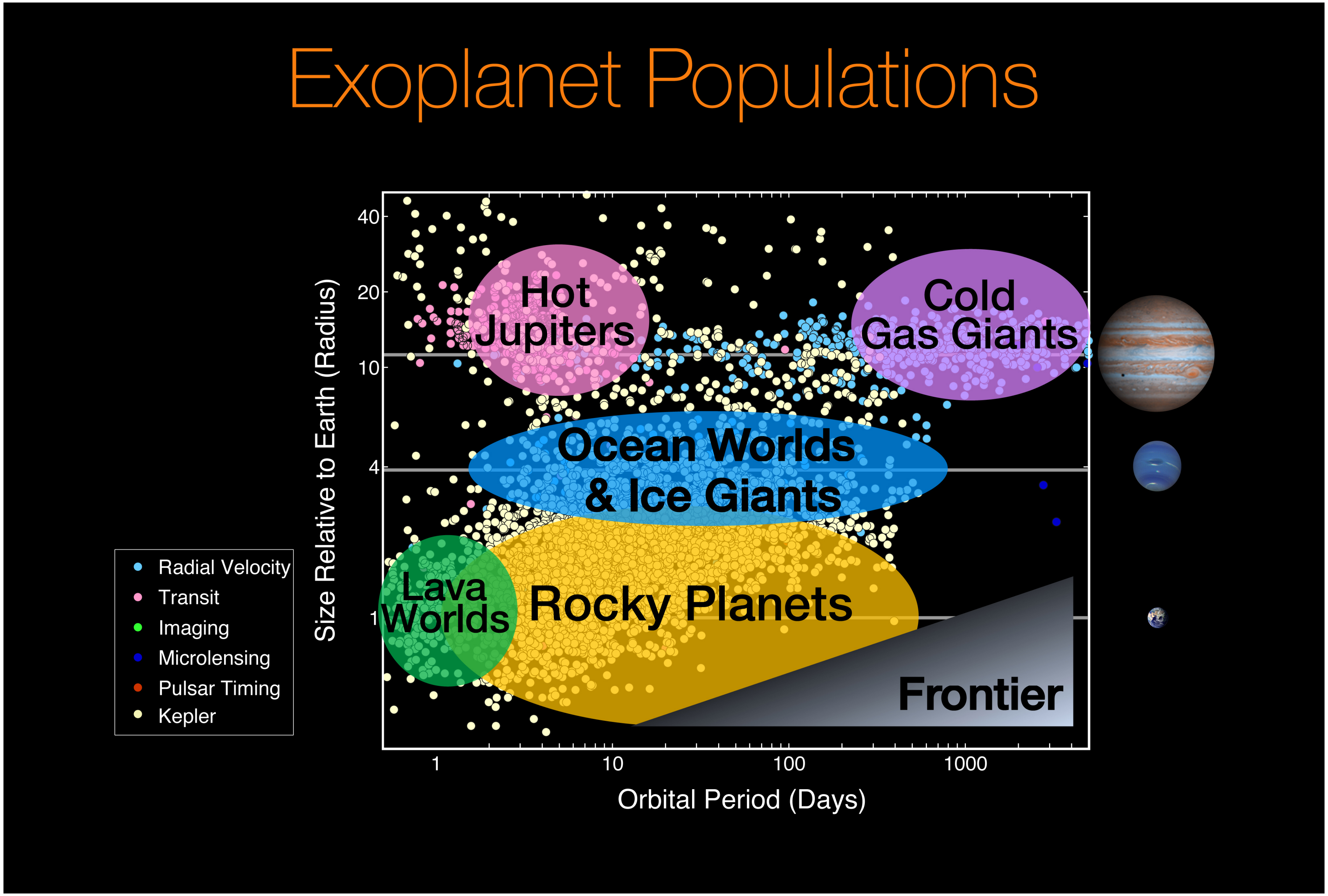
Protoplanetary disks



Credit: ALMA (ESO/NAOJ/NRAO), S. Andrews et al.; NRAO/AUI/NSF, S. Dagnello

- Radio and IR from dust heated by starlight
- Arrays can resolve gaps in the dust where nascent planets are forming

Credit: (NRAO/AUI/NSF)



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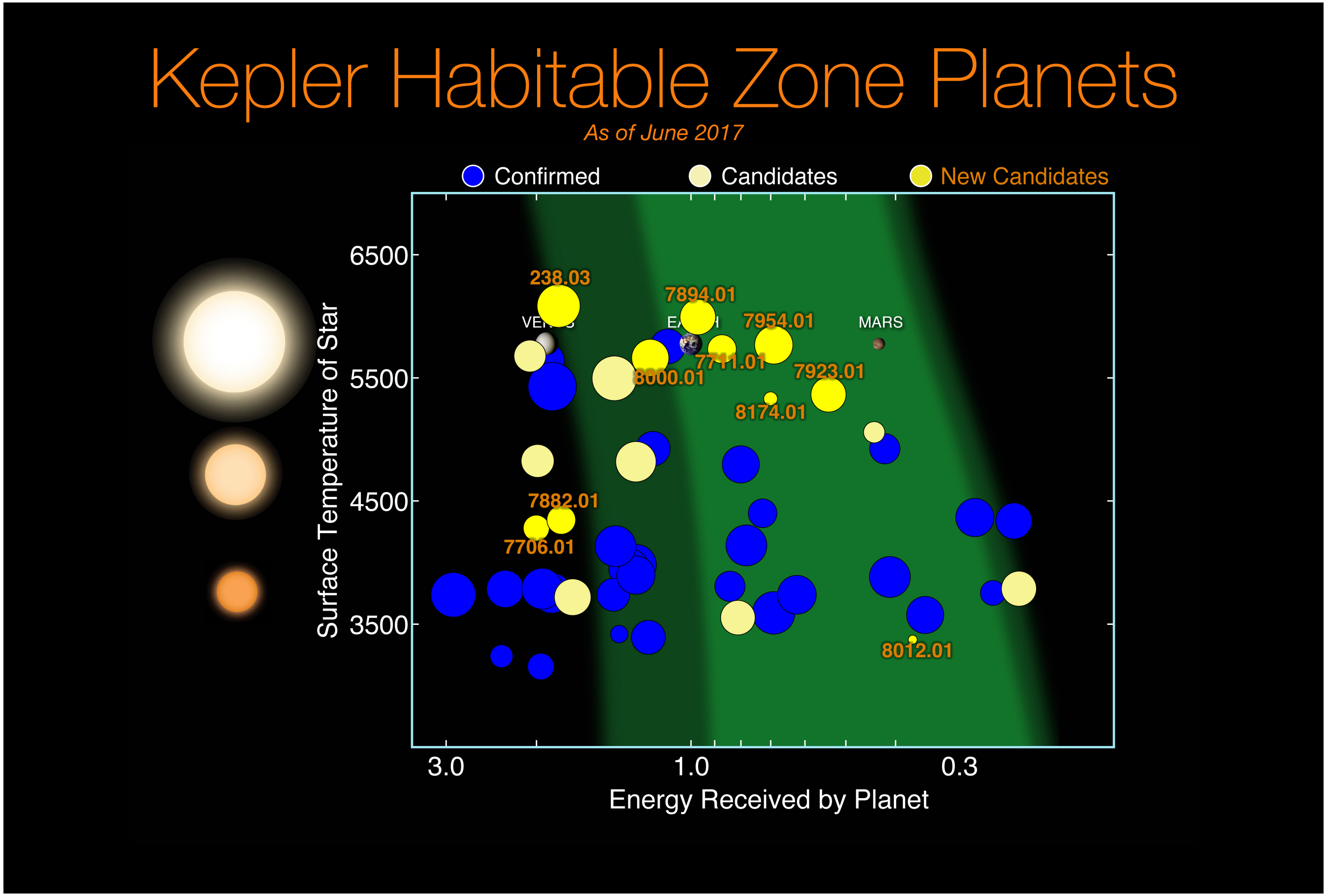
Exoplanets



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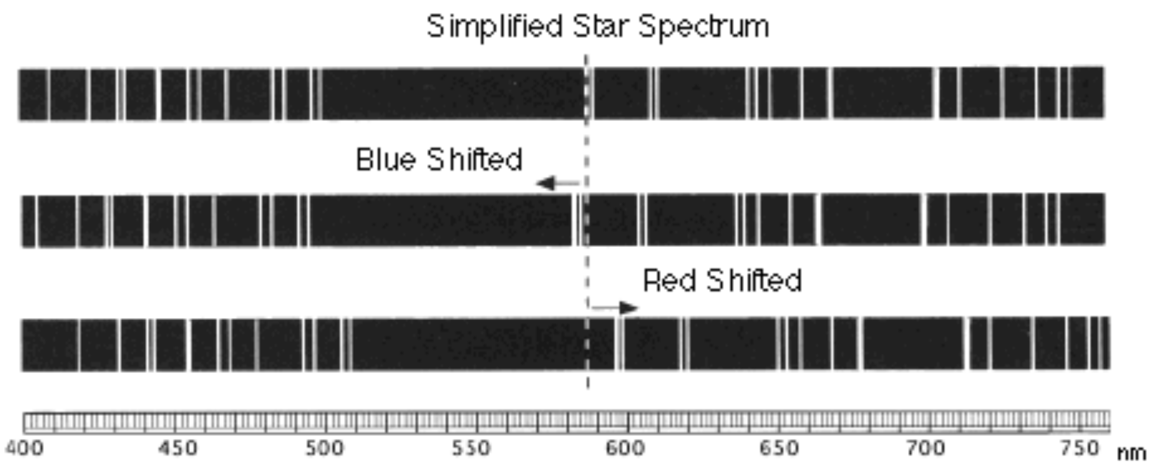
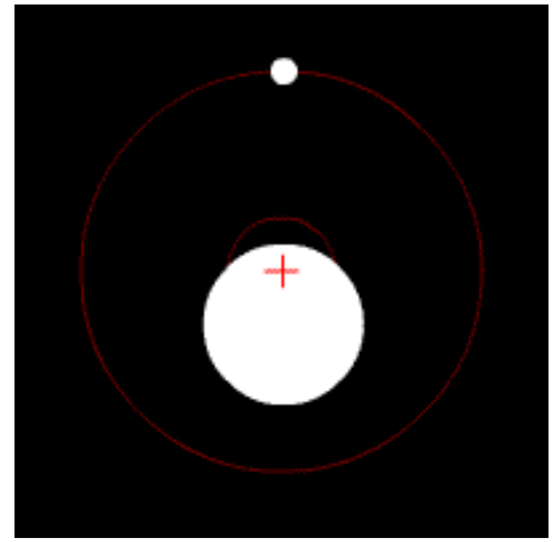
Detection by radial velocity method





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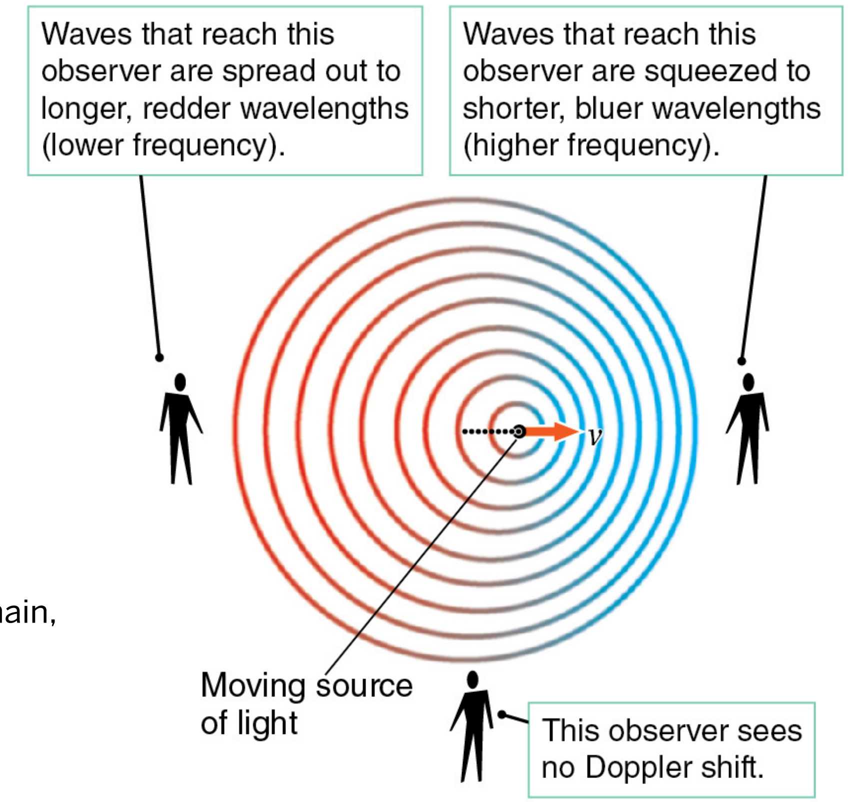
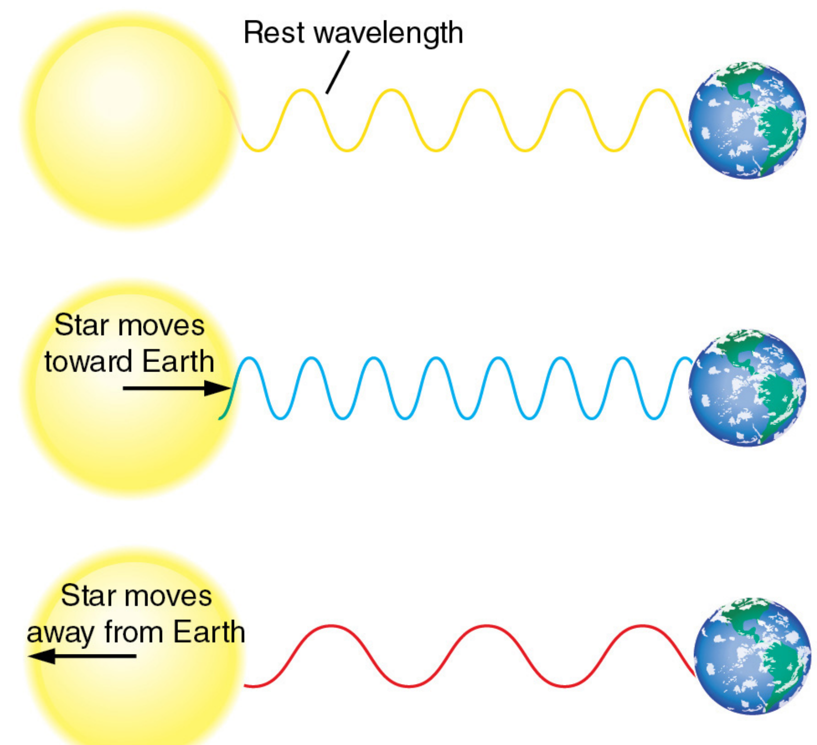
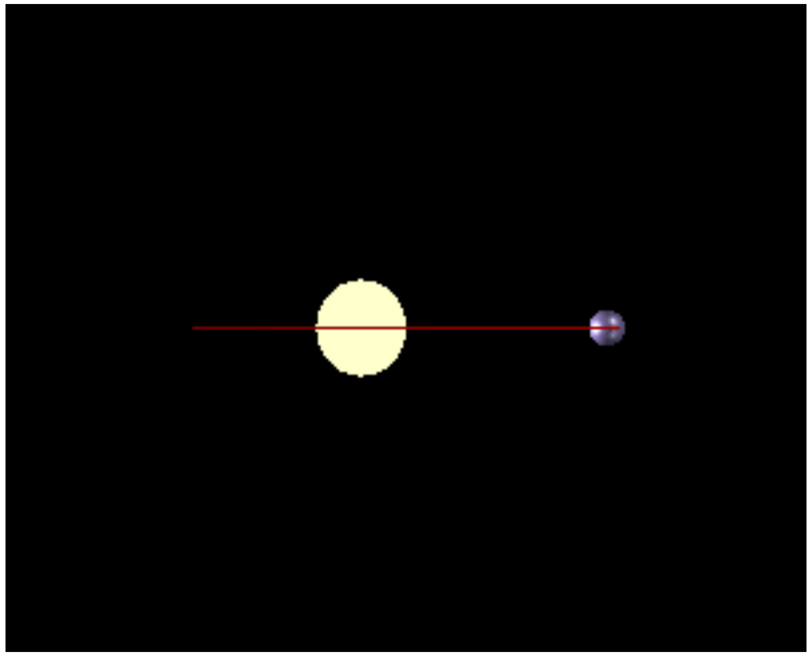
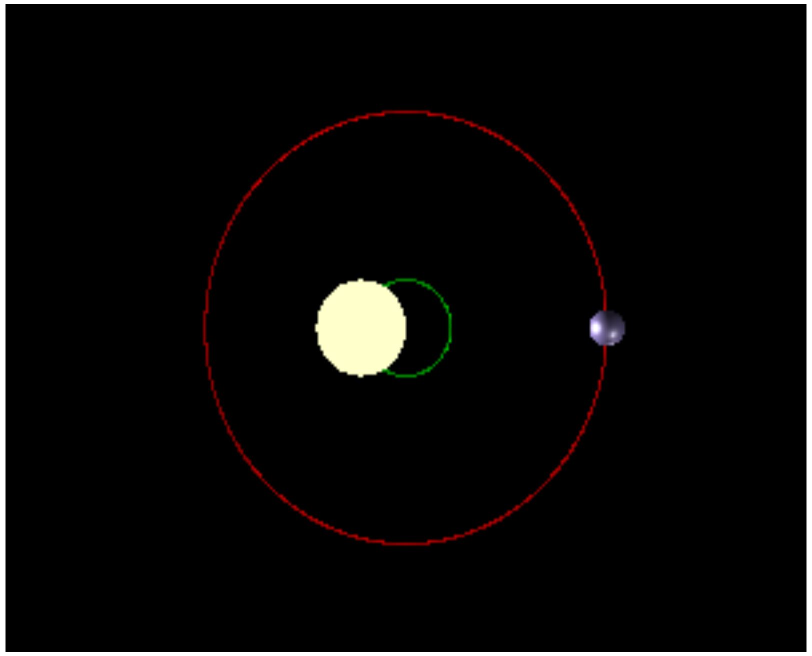


- Planet and star orbit a common center of gravity
  - When $M_{star} >> M_{planet}$, center of gravity is very close to star and star is ~stationary with respect to planet
  - But, stars are bright—there can be enough EM radiation given off by the star to detect its tiny "wobble" due to the mass of a planet
- Need a well known source of photons at a specific wavelength to detect Doppler shift, e.g. state transitions in hydrogen



Limitations of the radial velocity method





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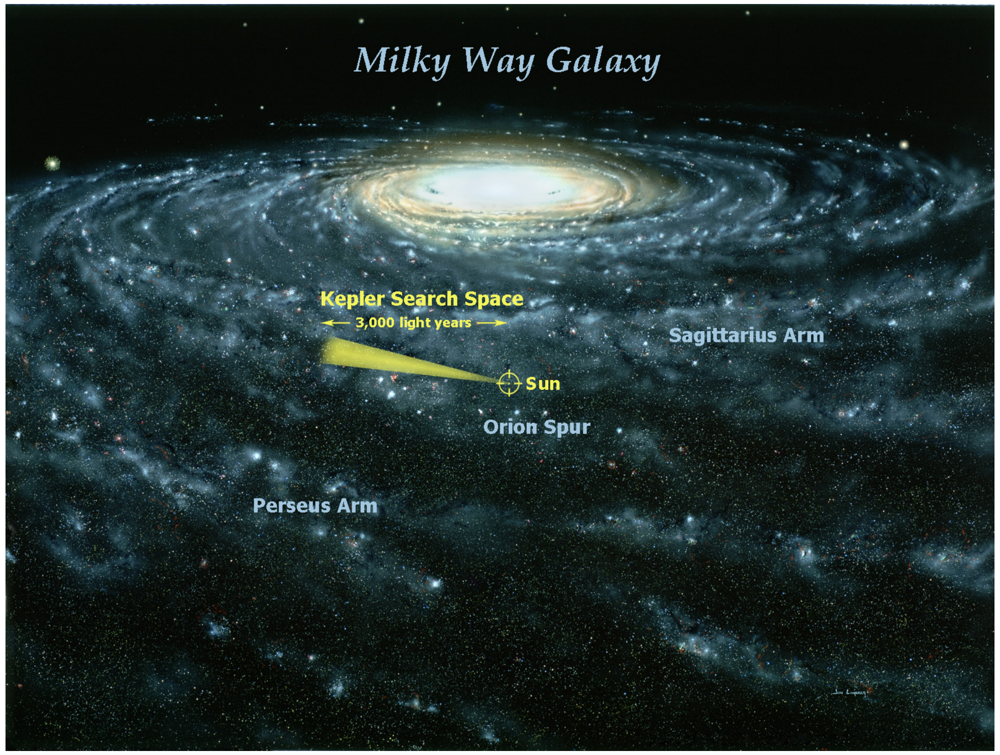
- Only sensitive to the component of velocity along the direction between the observer and the star
- Bright (nearby) stars required
- Requires large gravitational pulls ⇒ not as sensitive to smaller planets

Detection by transit method

- Detected star luminosity decreases as planet passes in front of it
- Requires Earth to lie in the orbital plane of the exoplanet
- Sensitive to planet's size, not mass



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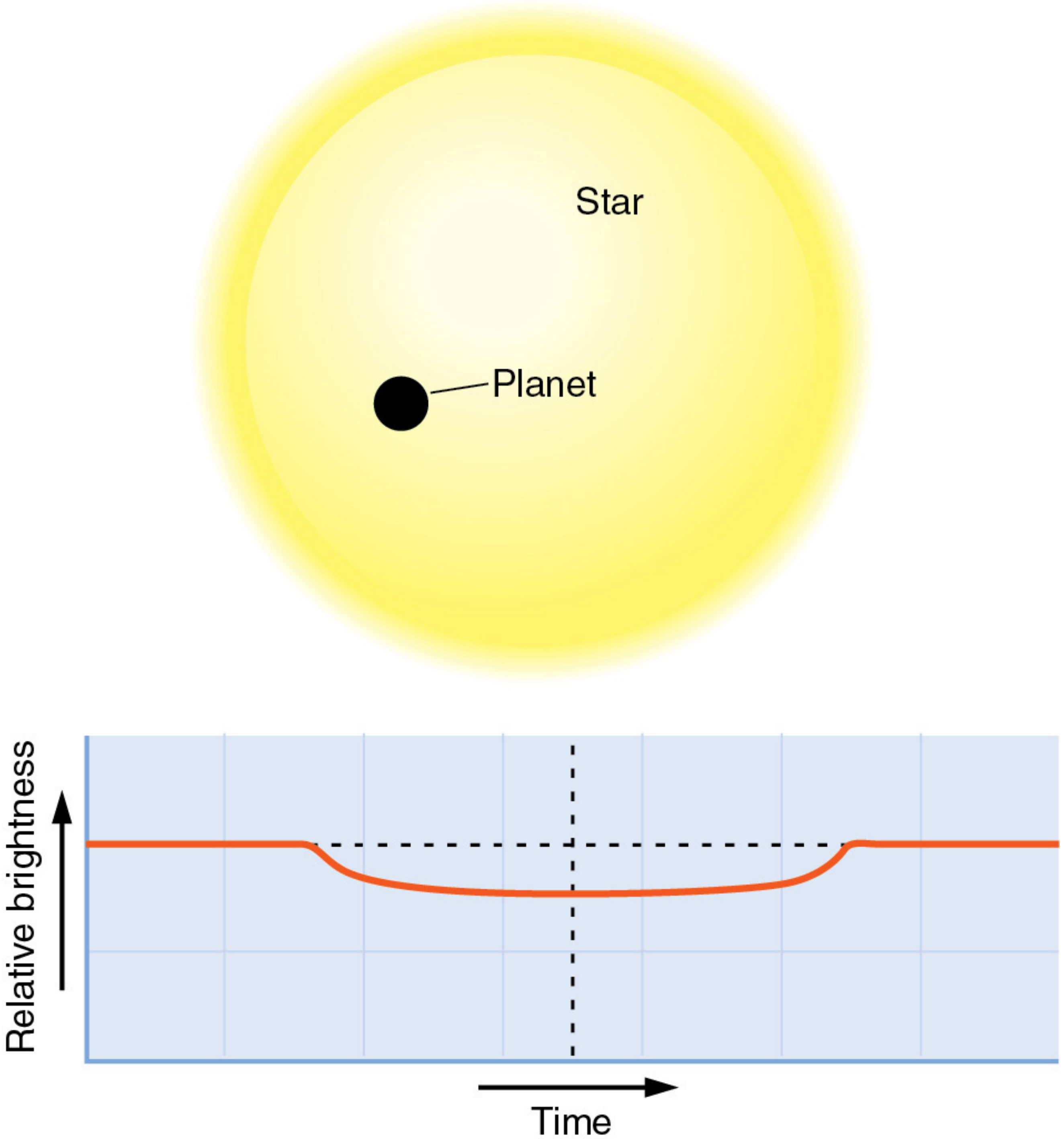
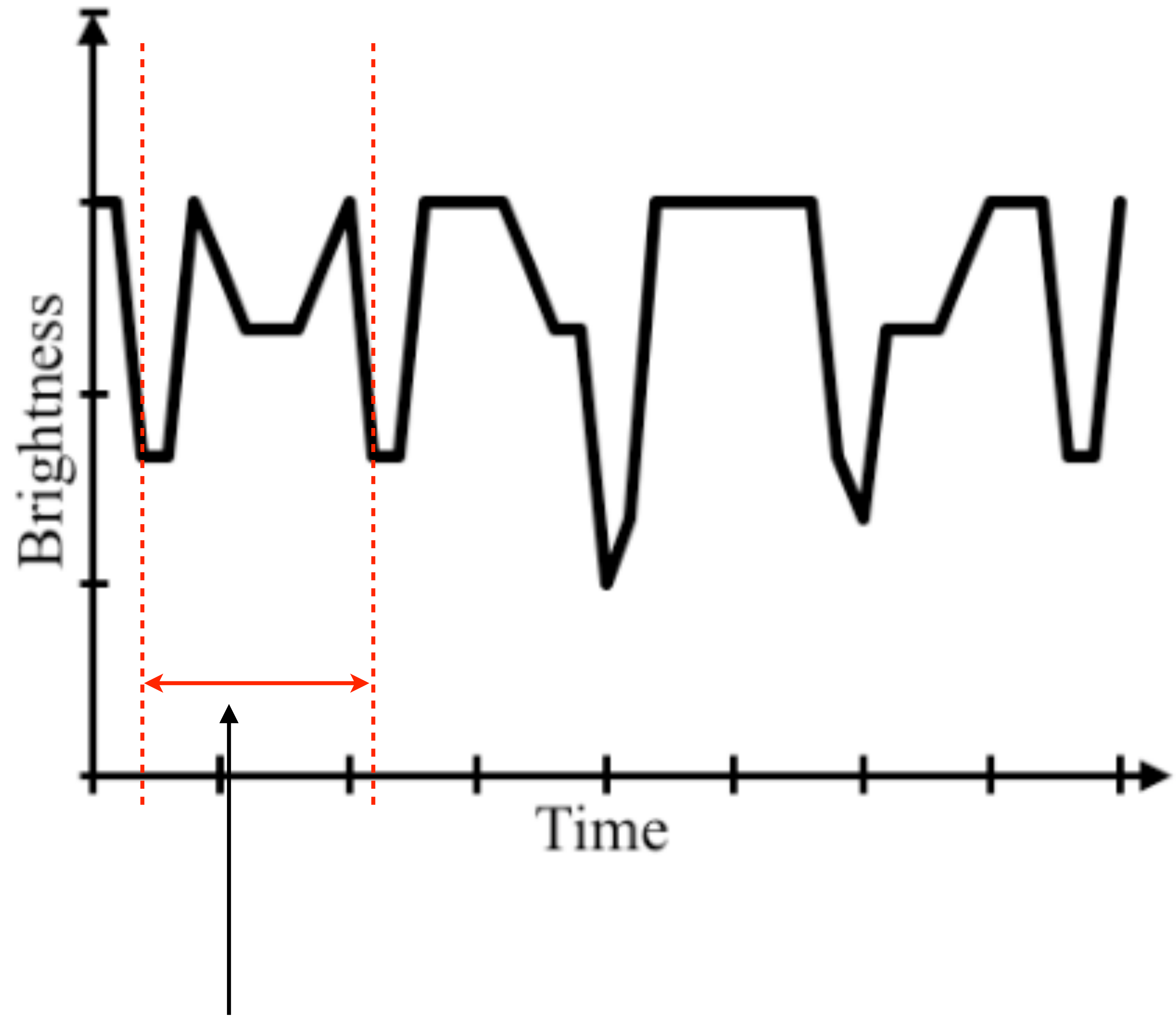
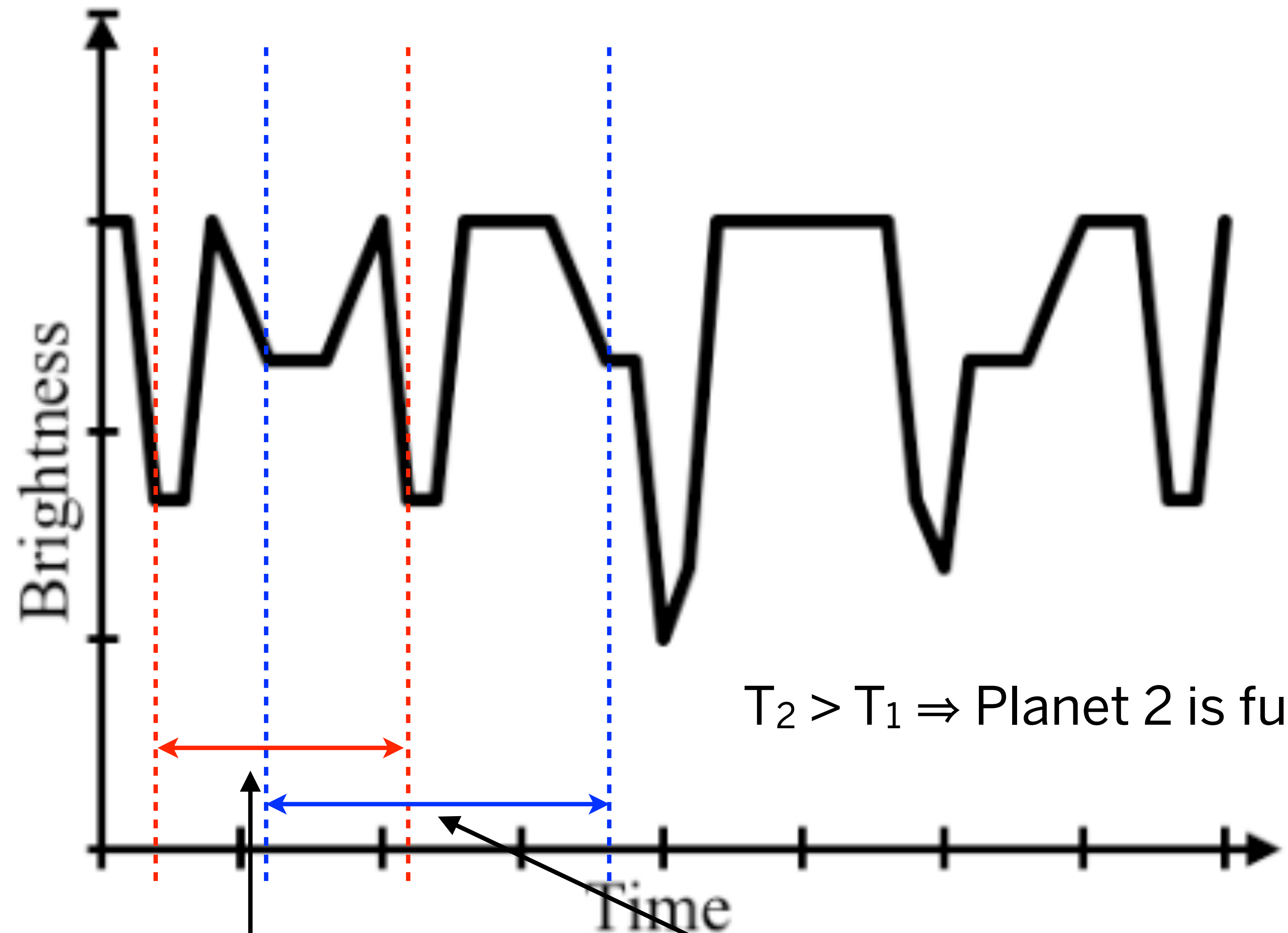


Transit method with two planets



Orbital period of Planet 1

Transit method with two planets

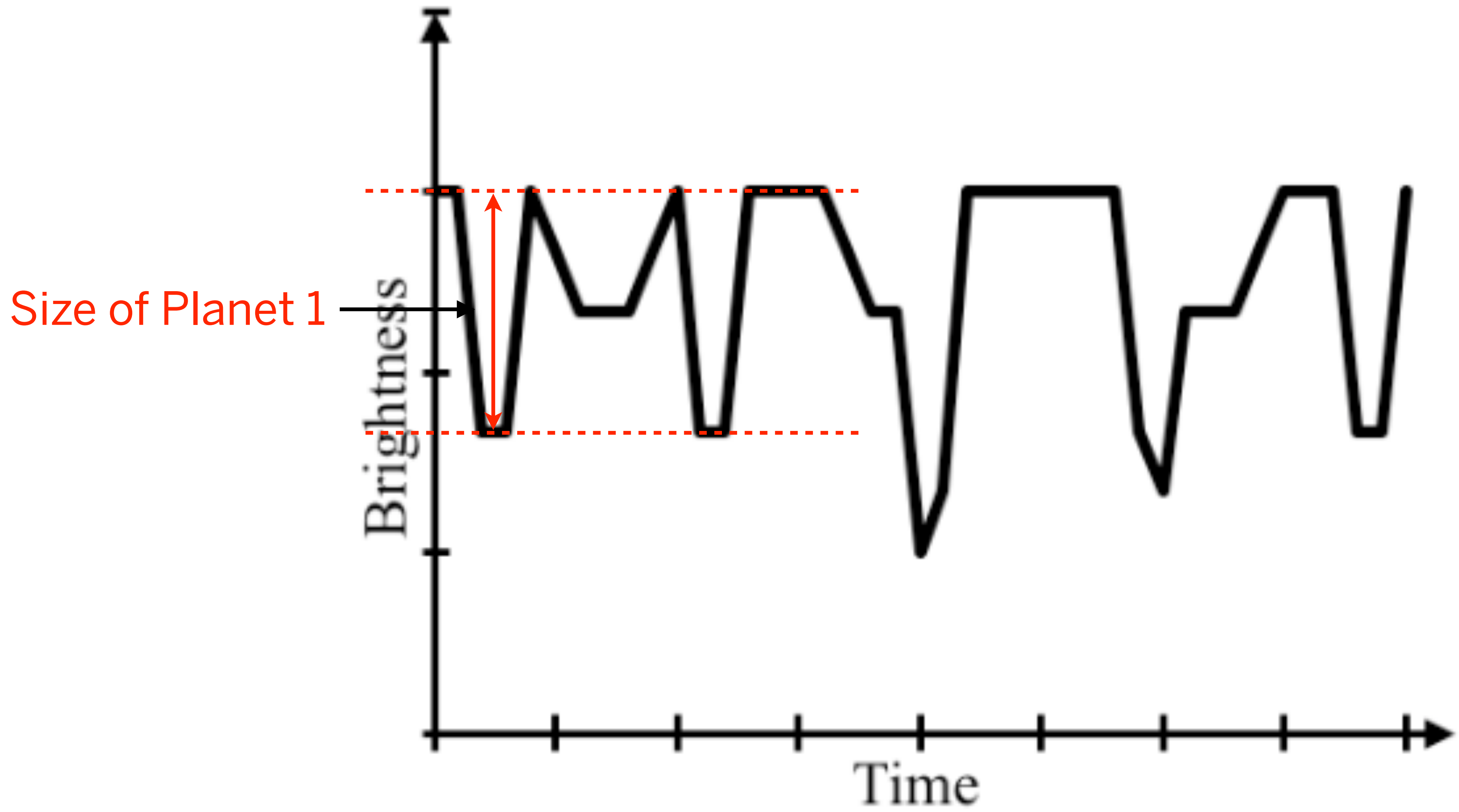


$T_2 > T_1 \Rightarrow$ Planet 2 is further from the star

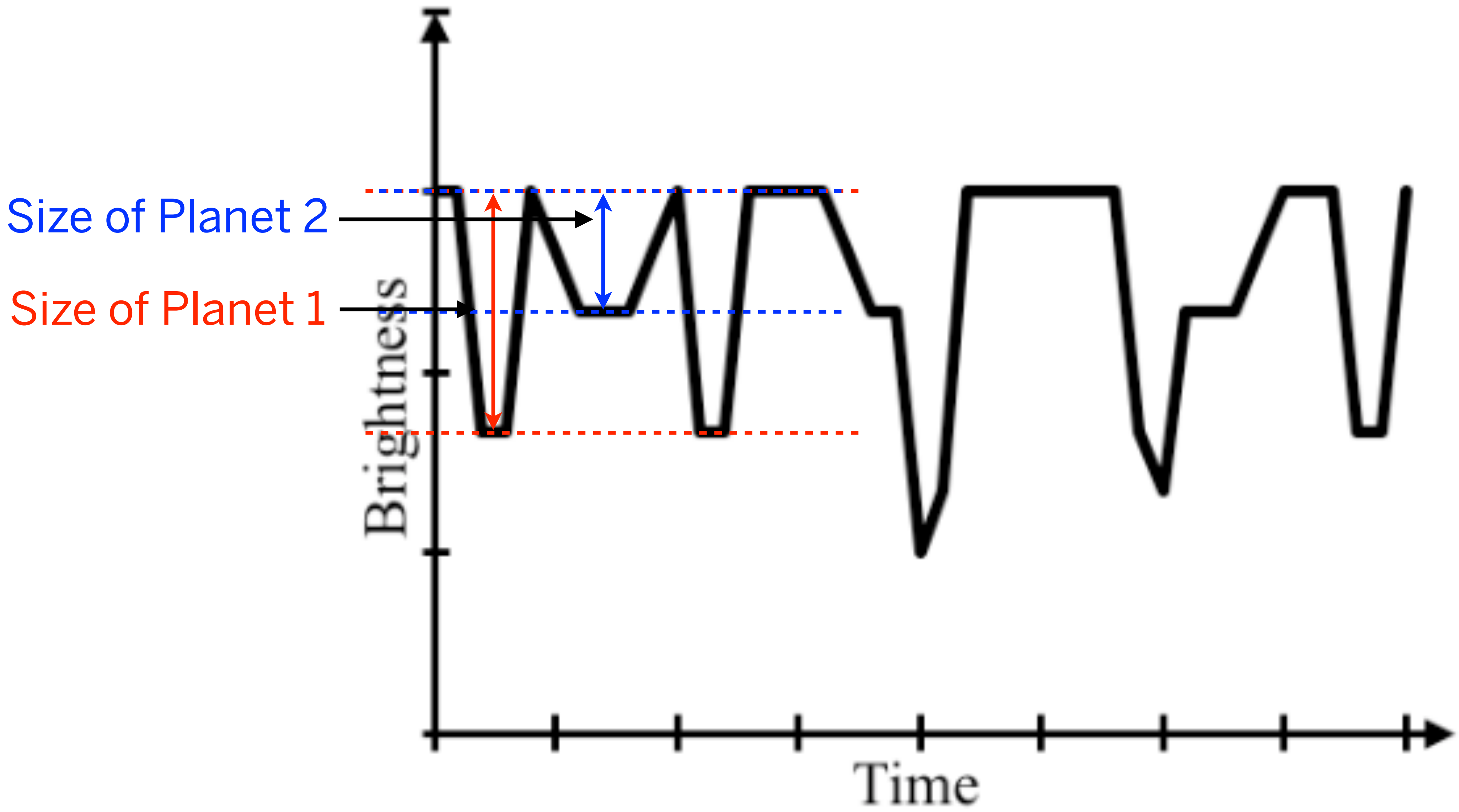
Orbital period of Planet 1

Orbital period of Planet 2

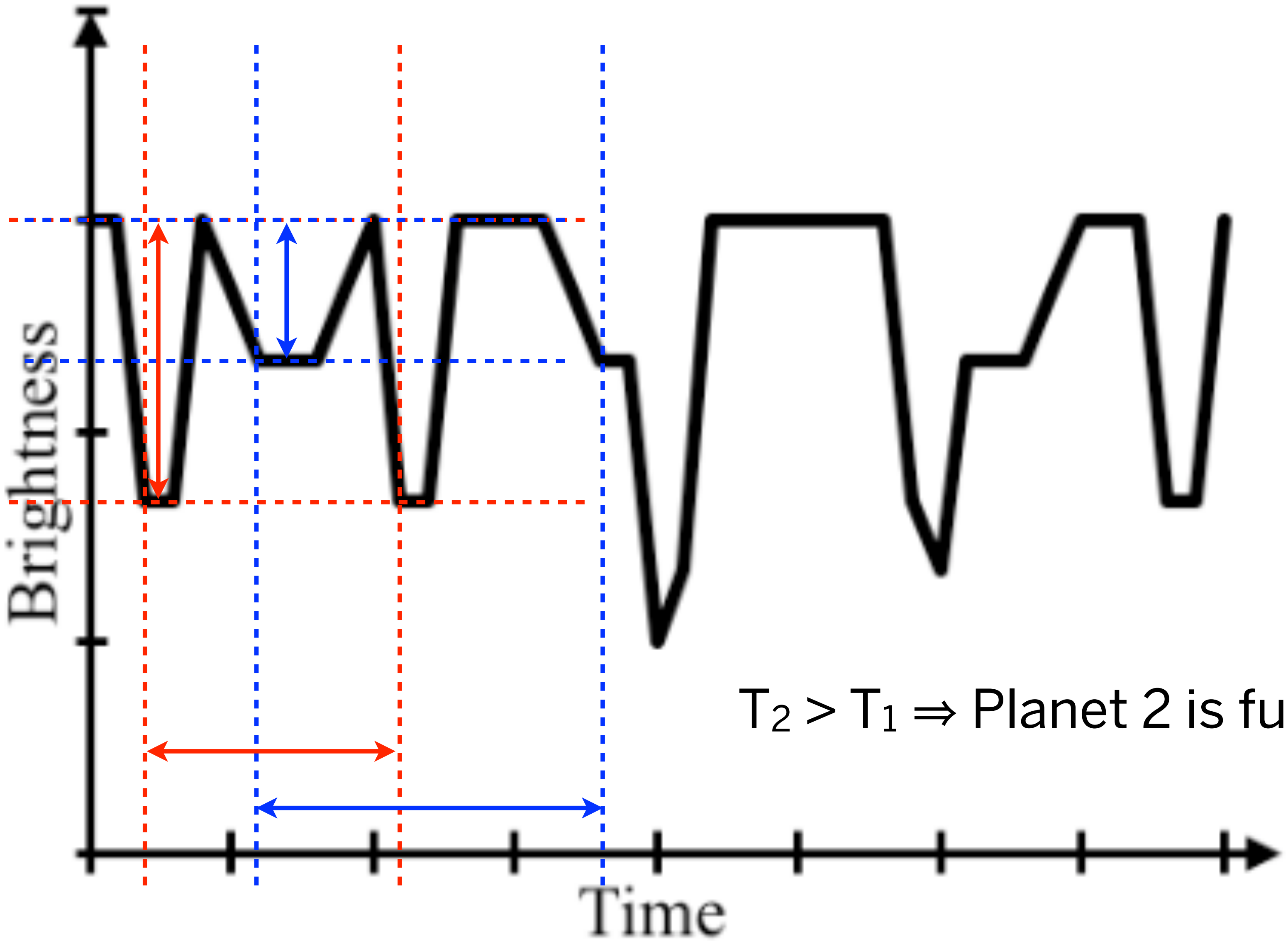
Transit method with two planets

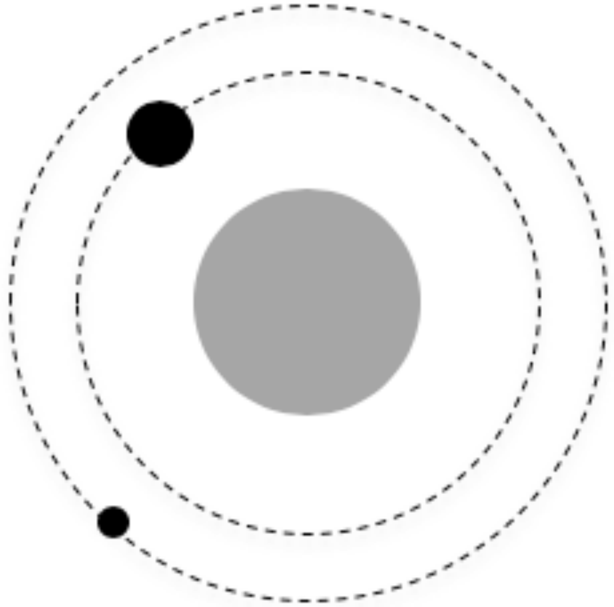


Transit method with two planets



Brightness decrease due to Planet 1 is larger than for Planet 2 ⇒ size of Planet 1 is larger than Planet 2





$T_2 > T_1 \Rightarrow$ Planet 2 is further from the star

Brightness decrease due to Planet 1 is larger than for Planet 2 ⇒ size of Planet 1 is larger than Planet 2

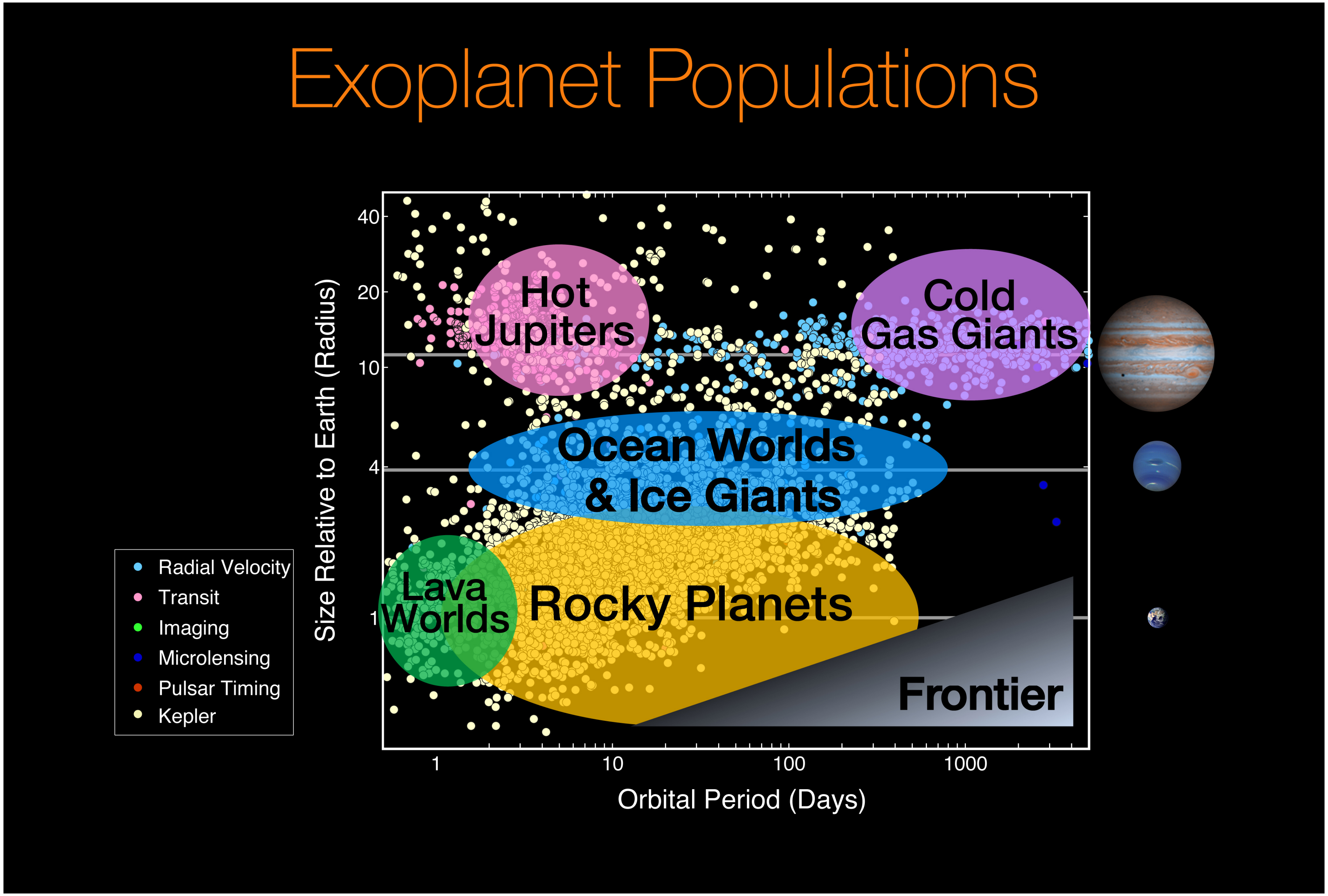
Other detection methods

- Gravitational microlensing
  - Planet's gravity bends spacetime, causing starlight to bend and focus
  - Star’s brightness increases as planet passes in front of it
  - Requires observer to be in the plane of the exoplanet’s orbit
  - Gives mass estimate
- Astrometry
  - Precise measurement of star’s position to detect gravitational wobble from presence of exoplanet
  - Only method that works out of exoplanet orbital plane
- Direct imaging

Exoplanet detection summary

	Mass	Diameter	Orbital plane orientation	Sensitivity
Radial velocity	Yes	No	In plane	Large, Jupiter-sized
Transit	No	Yes	In plane	Earth-size
Microlensing	Yes	No	In plane	Earth-size
Astrometry	No	Maybe with blackbody spectrum	Any	Large planets
Direct imaging	No	No	Any	Not so great

Exoplanets



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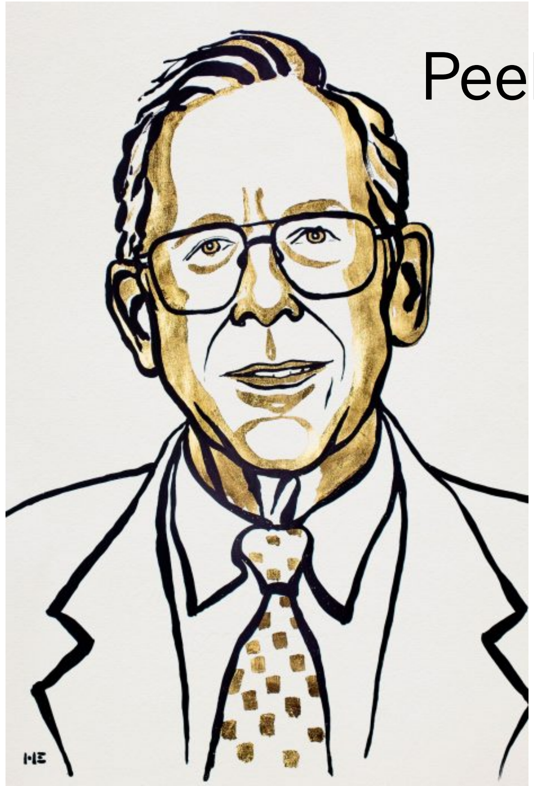
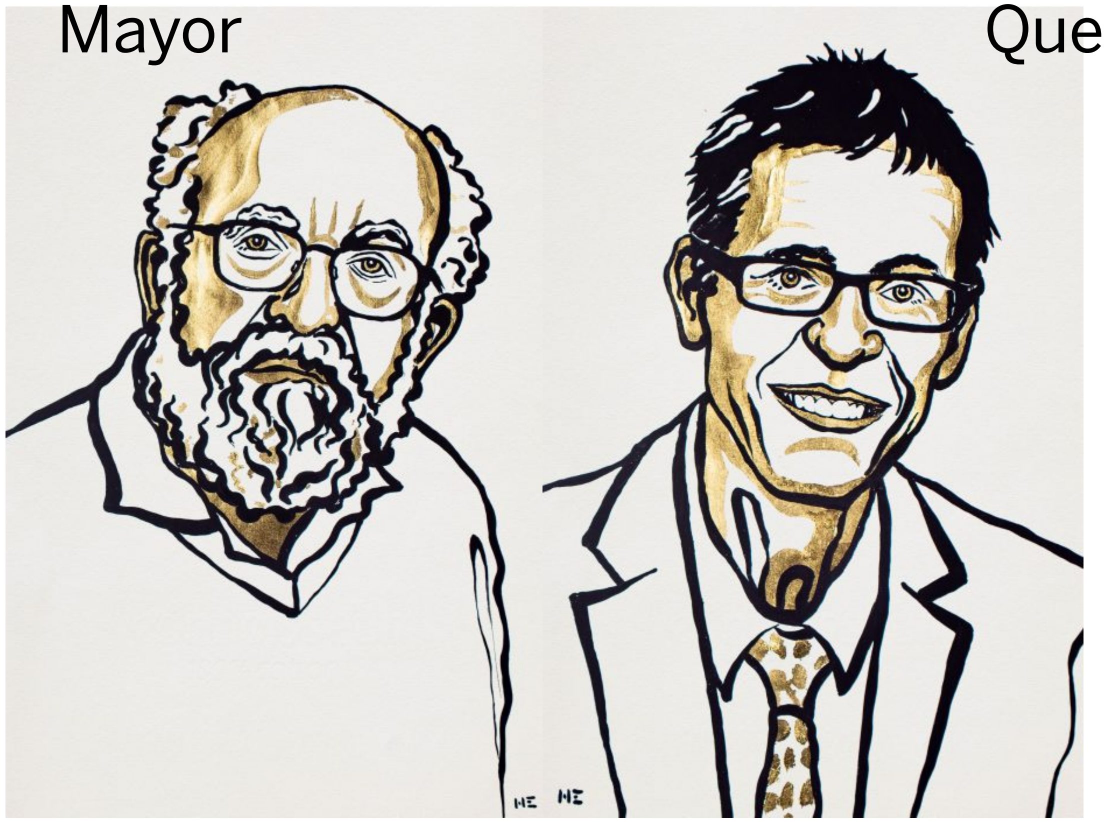
What have we learned?

- Hot Jupiters—easiest to discover, but how did they come to be?
- A variety of orbit types, but most solar systems tend to have a single orbital plane—further evidence for the accretion disk theory
- Planet formation seems to be a byproduct of star formation

Nobel Prize 2019

- The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics 2019 “for contributions to our understanding of the evolution of the universe and Earth’s place in the cosmos” with one half to
  - James Peebles
    Princeton University, USA
  - “for theoretical discoveries in physical cosmology”
- and the other half jointly to
  - Michel Mayor
    University of Geneva, Switzerland
  - Didier Queloz
    University of Geneva, Switzerland and University of Cambridge, UK
  - “for the discovery of an exoplanet orbiting a solar-type star”





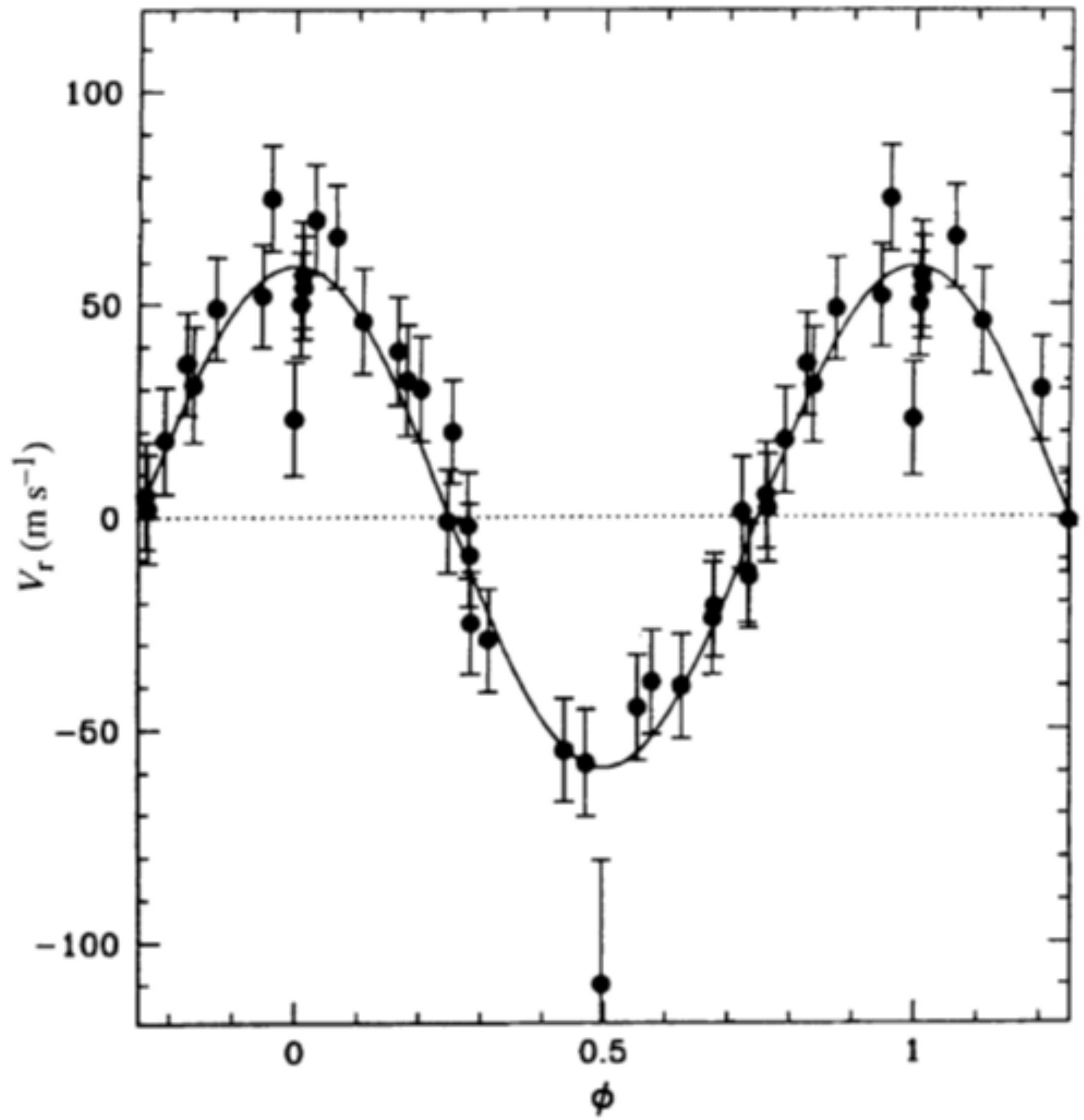
From nobelprize.org

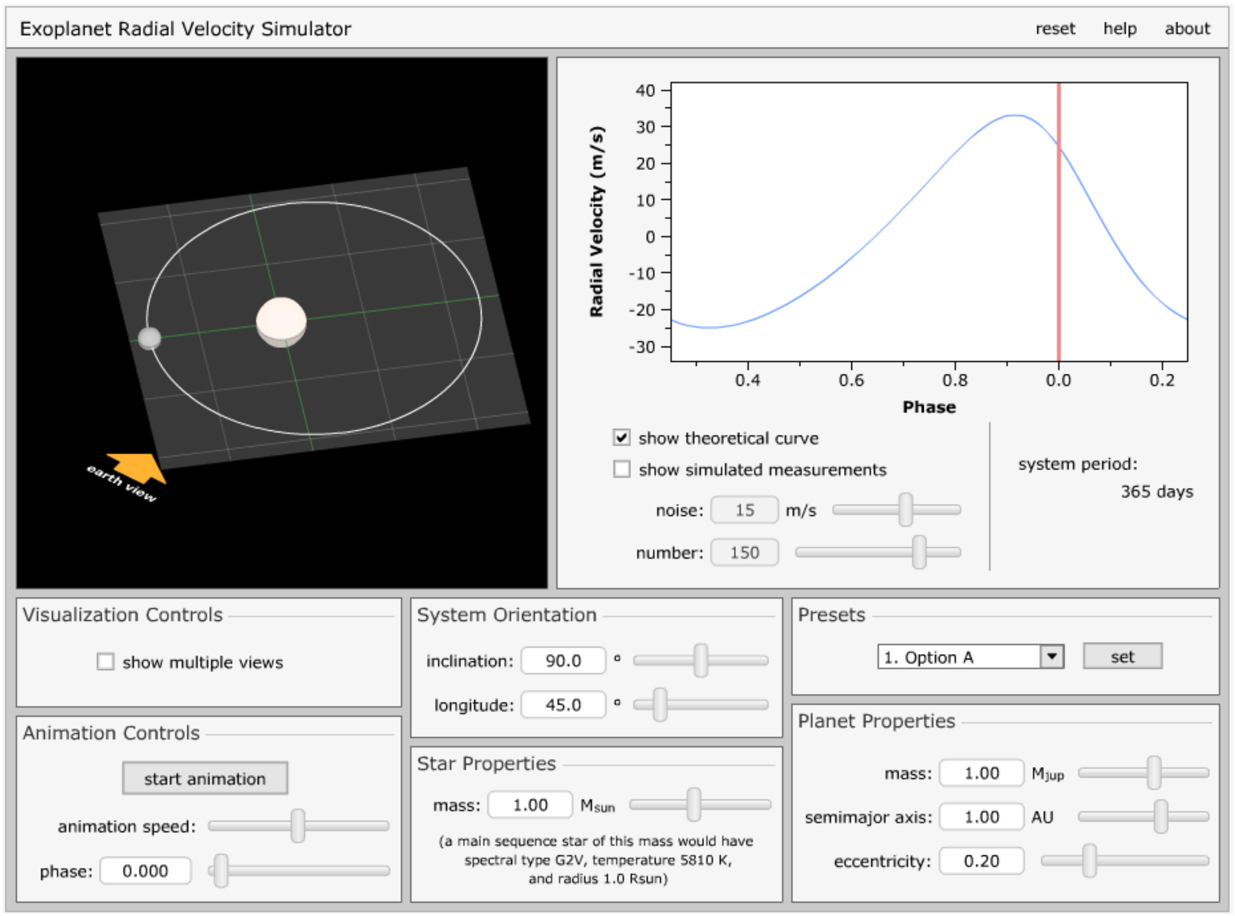
- In October 1995, Michel Mayor and Didier Queloz announced the first discovery of a planet outside our solar system, an exoplanet, orbiting a solar-type star in our home galaxy, the Milky Way. At the Haute-Provence Observatory in southern France, using custom-made instruments, they were able to see planet 51 Pegasi b, a gaseous ball comparable with the solar system's biggest gas giant, Jupiter.

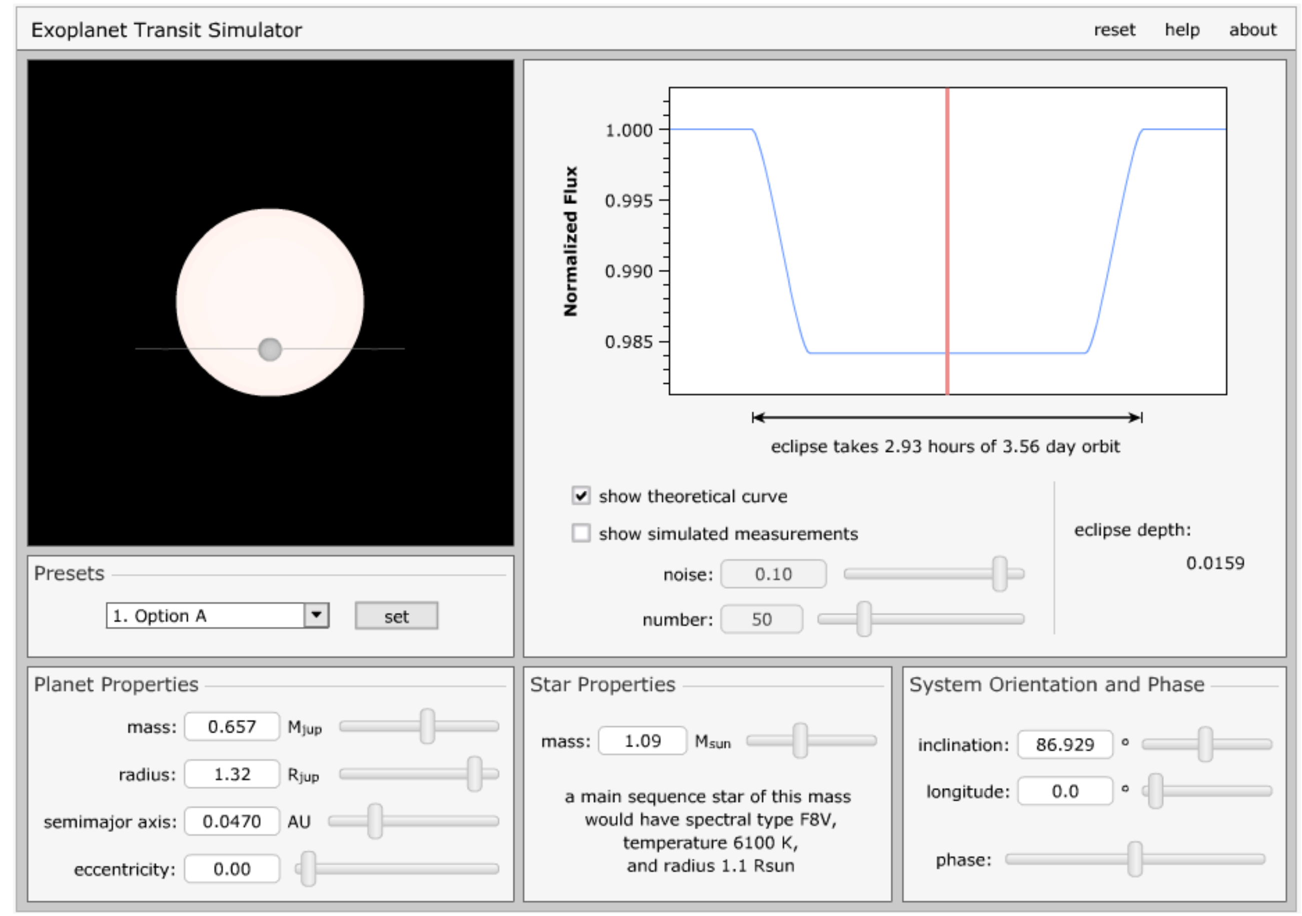
- This discovery started a revolution in astronomy and over 4,000 exoplanets have since been found in the Milky Way. Strange new worlds are still being discovered, with an incredible wealth of sizes, forms and orbits. They challenge our preconceived ideas about planetary systems and are forcing scientists to revise their theories of the physical processes behind the origins of planets. With numerous projects planned to start searching for exoplanets, we may eventually find an answer to the eternal question of whether other life is out there.

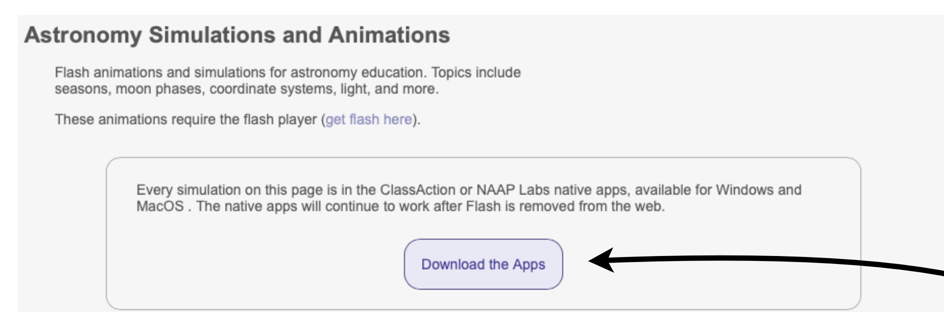
Nobel Prize 2019

- First exoplanet detection with the radial velocity method









- Radial velocity method simulator
- Transit method simulator
- Runs with Flash while still supported, but OS X and Windows native apps are also available