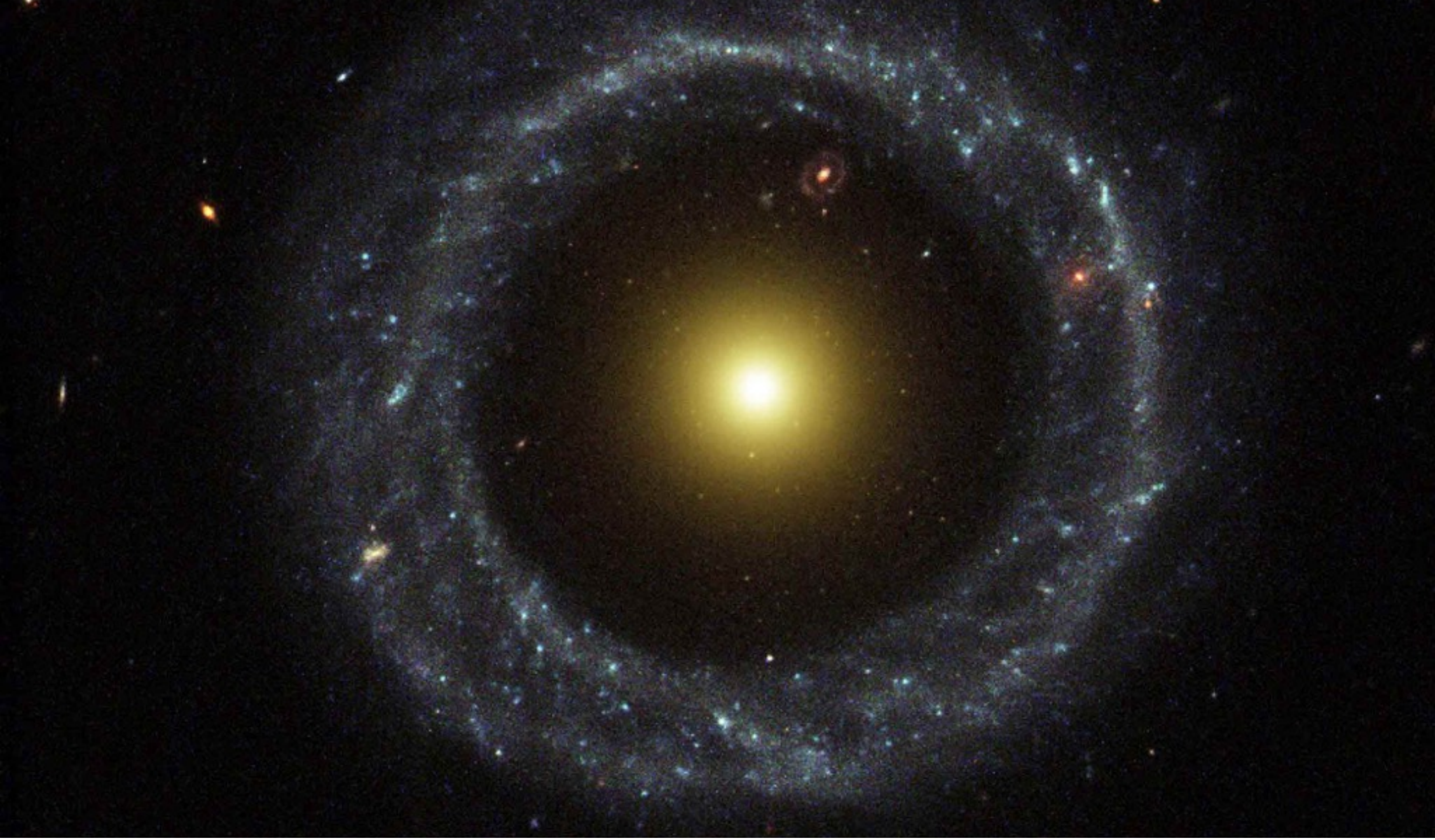
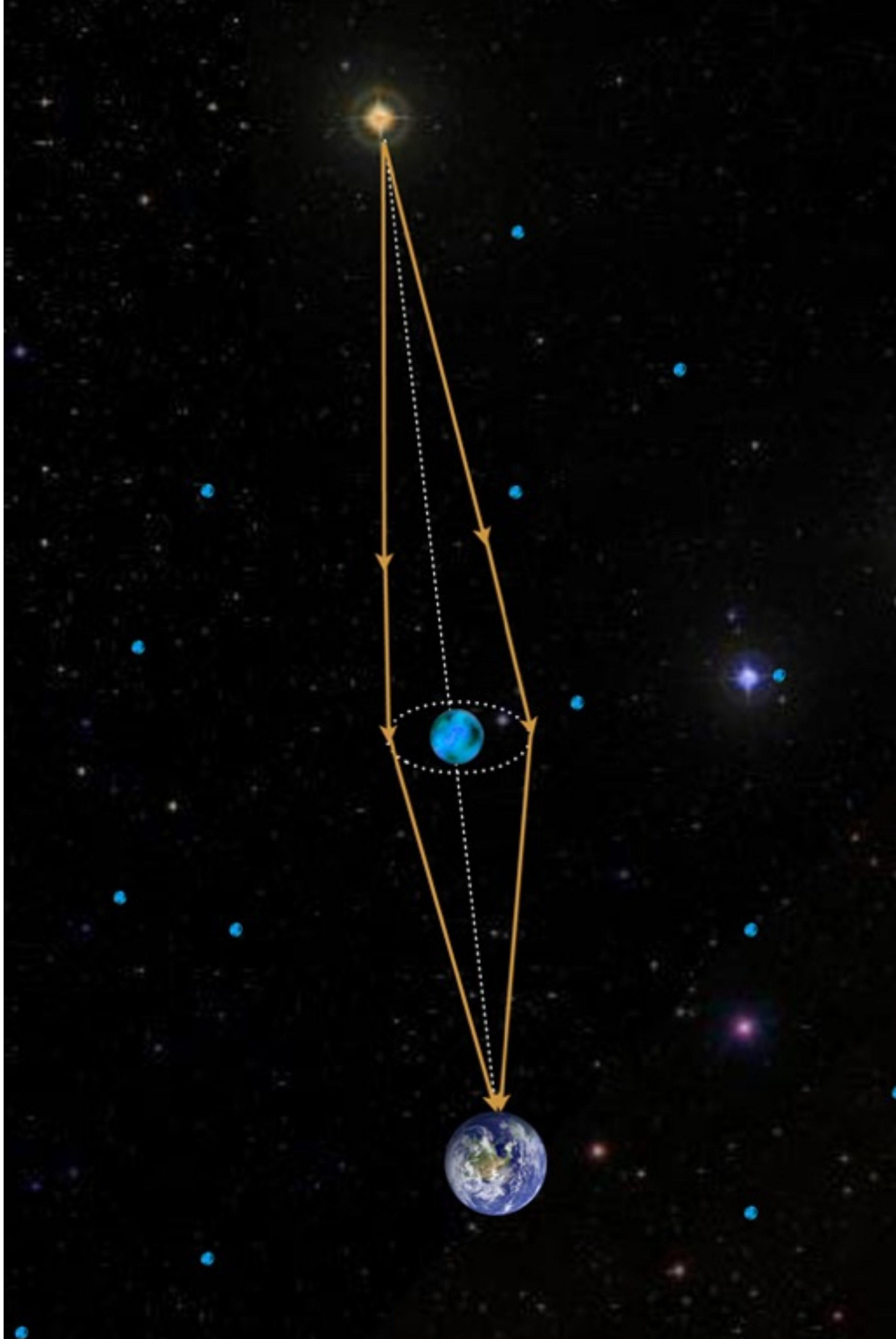


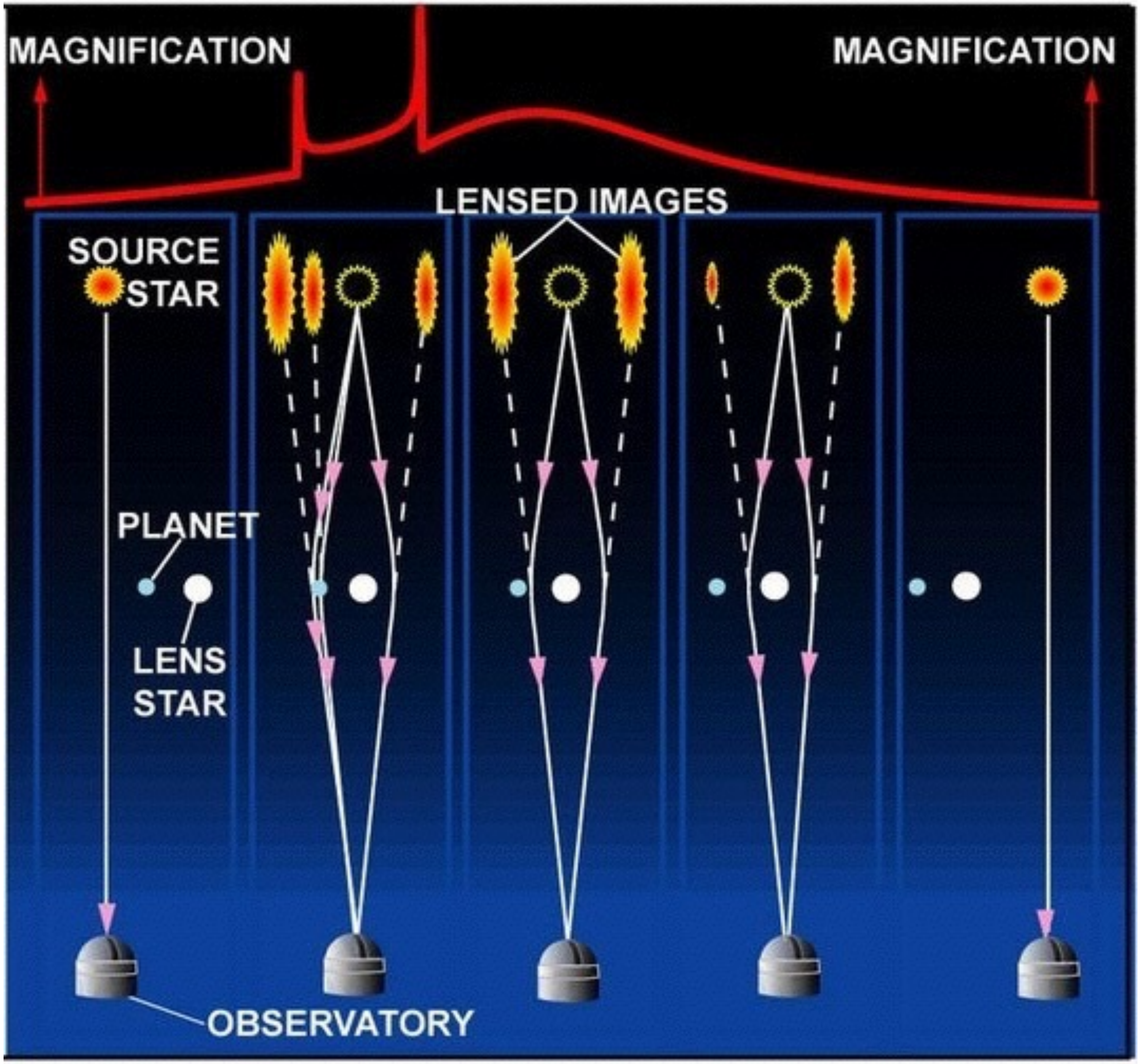
Gravitational Microlensing

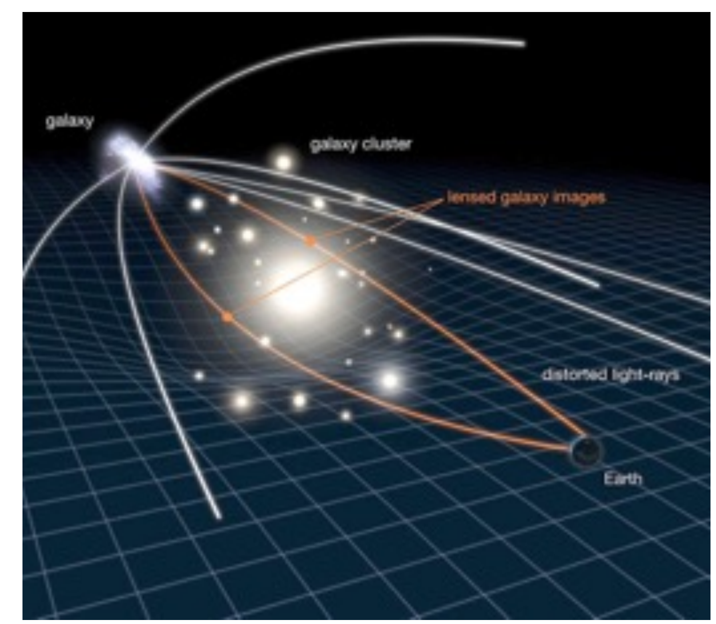
"It is during our darkest moments that we must focus to see the light." — Aristotle Onassis

Brief History

- Suggested by Newton (1704)
- Predicted by Einstein (1915)
- Einstein predicted that a gravitational source could bend light like a lens
- Wasn't observed until 1979
- In 1986 Bohdan Paczyński proposed using microlensing to hunt for dark matter
- In 1992 Andrew Gould demonstrated how microlensing could be used to find exoplanets

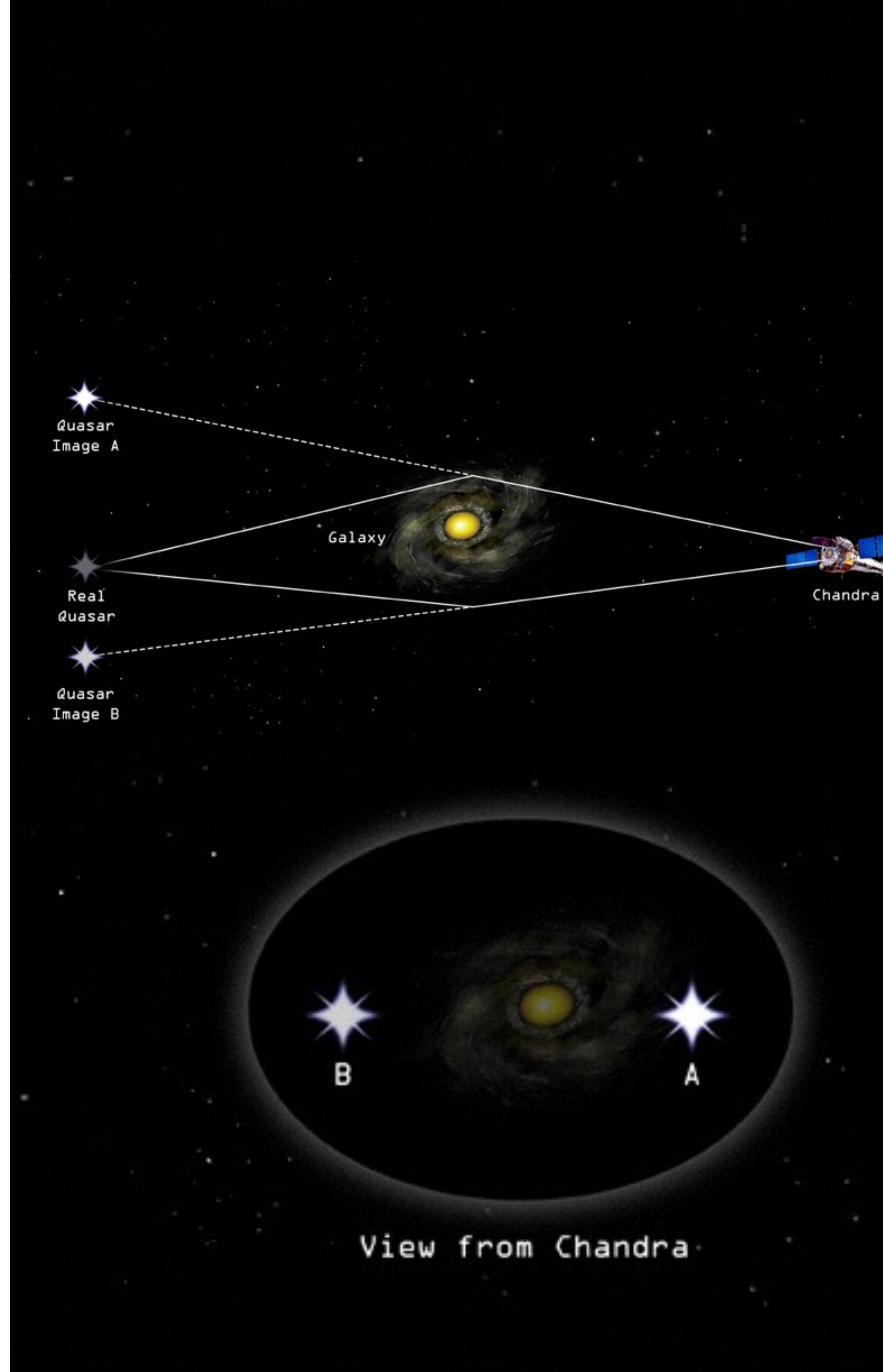


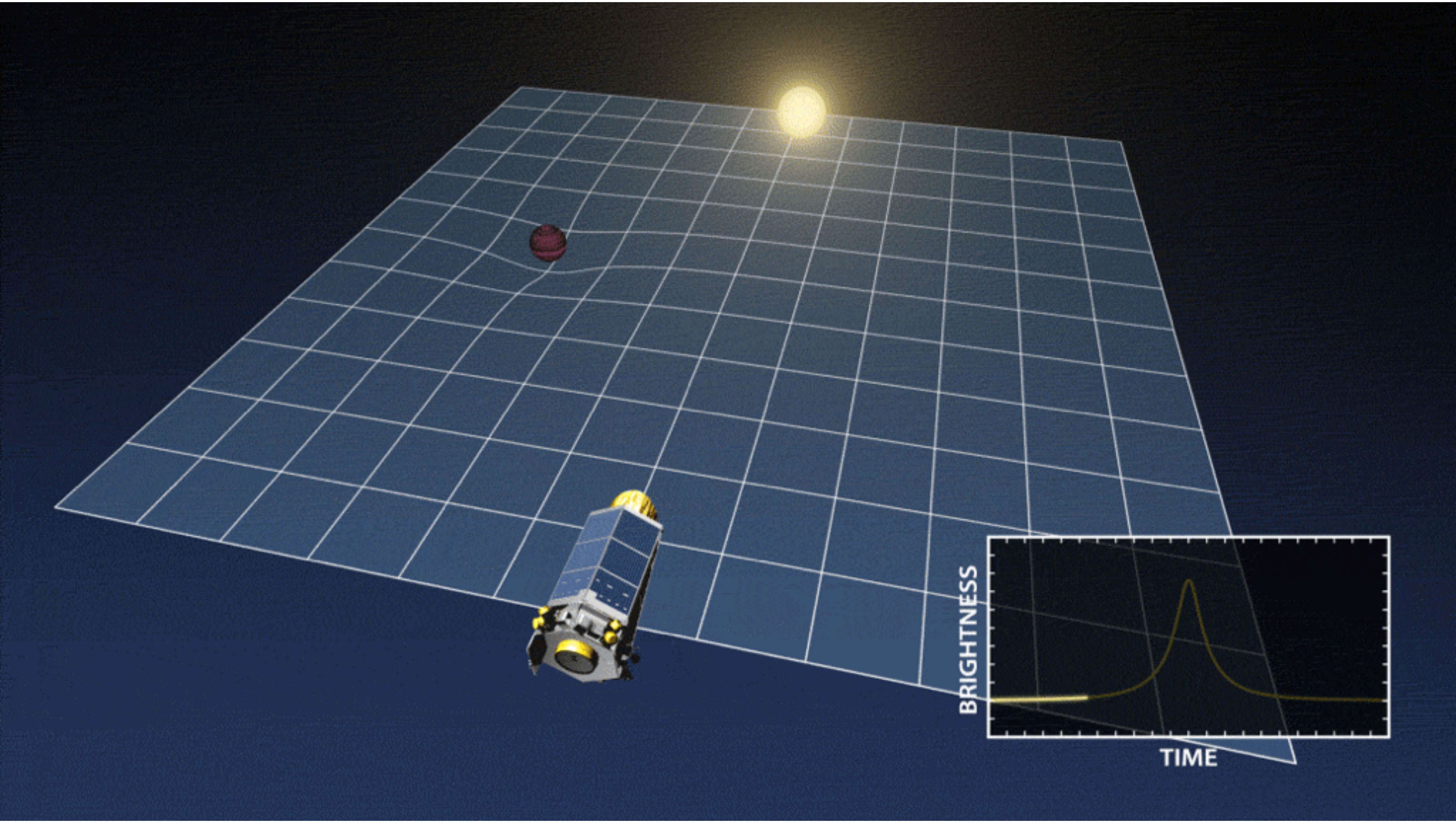

MAGNIFICATION
MAGNIFICATION
LENSED IMAGES
SOURCE STAR
PLANET
LENS STAR
OBSERVATORY

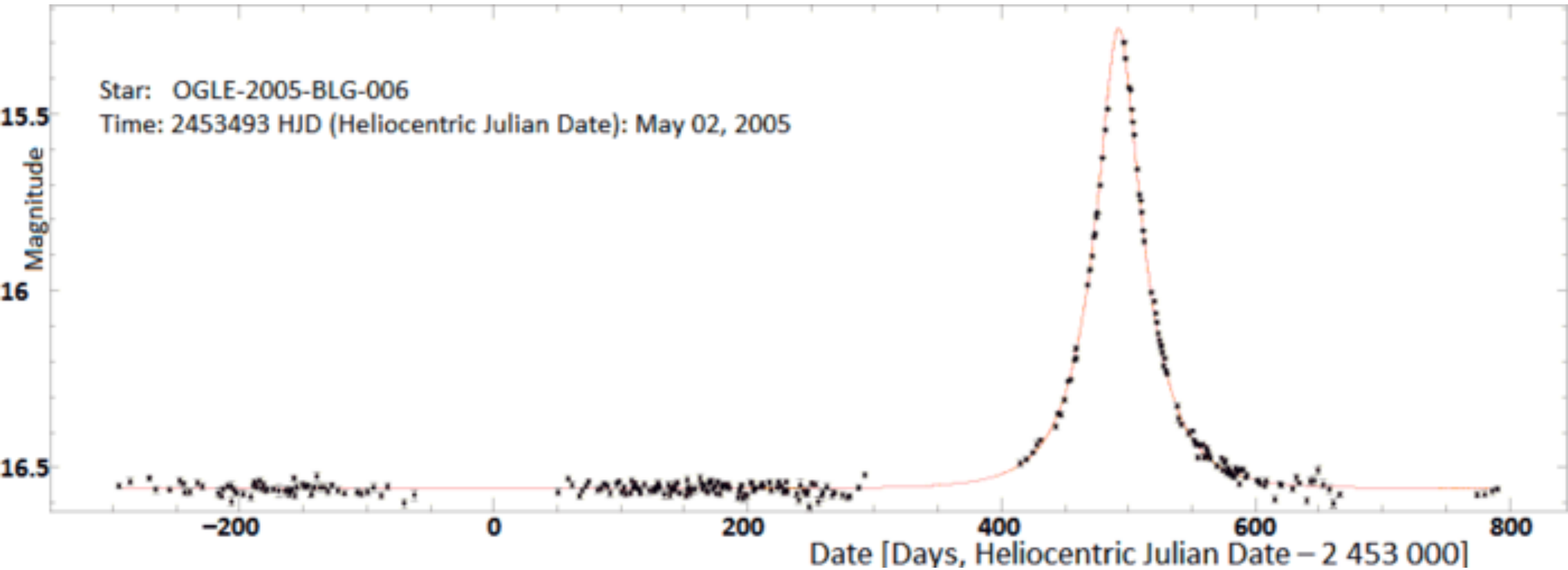

galaxy
galaxy cluster
lensed galaxy images
distorted light-rays
Earth

How It Works

- A massive object (the lens) will bend the light of a bright background object (the source)
  - This can generate multiple distorted, magnified, and brightened images of the background source
- With a strong lens (like a whole galaxy), the distortion is big enough to view with Hubble
- With a weak lens (like a planet or star), you can't directly observe the distortion
  - Instead, measure the apparent brightening




BRIGHTNESS
TIME



Microlensing Light Curve

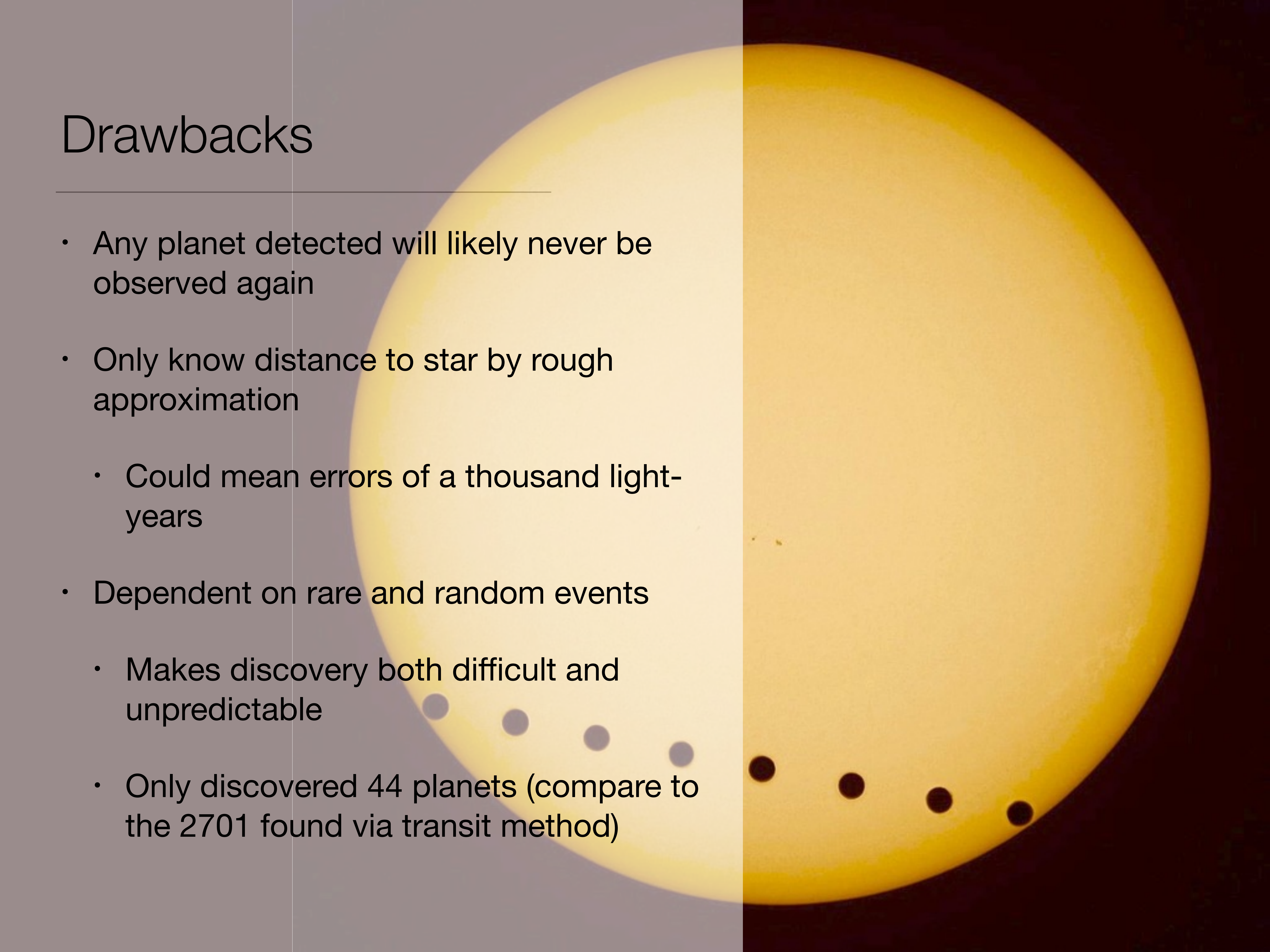
From OGLE, 2005

Advantages

- Capable of finding the furthest and smallest planets of any current planet-finding method
  - Jan. 2006: 5 Earth masses, orbiting near center of galaxy, 22,000 light-years away!
- Best at finding planets that orbit moderate to large distances from their star
  - A perfect compliment to the transit and radial velocity methods that work best for planets orbiting near their star
- Microlensing searches are massive
  - Can target tens of thousands of planets simultaneously

Drawbacks

- Any planet detected will likely never be observed again
- Only know distance to star by rough approximation
  - Could mean errors of a thousand light-years
- Dependent on rare and random events
  - Makes discovery both difficult and unpredictable
  - Only discovered 44 planets (compare to the 2701 found via transit method)

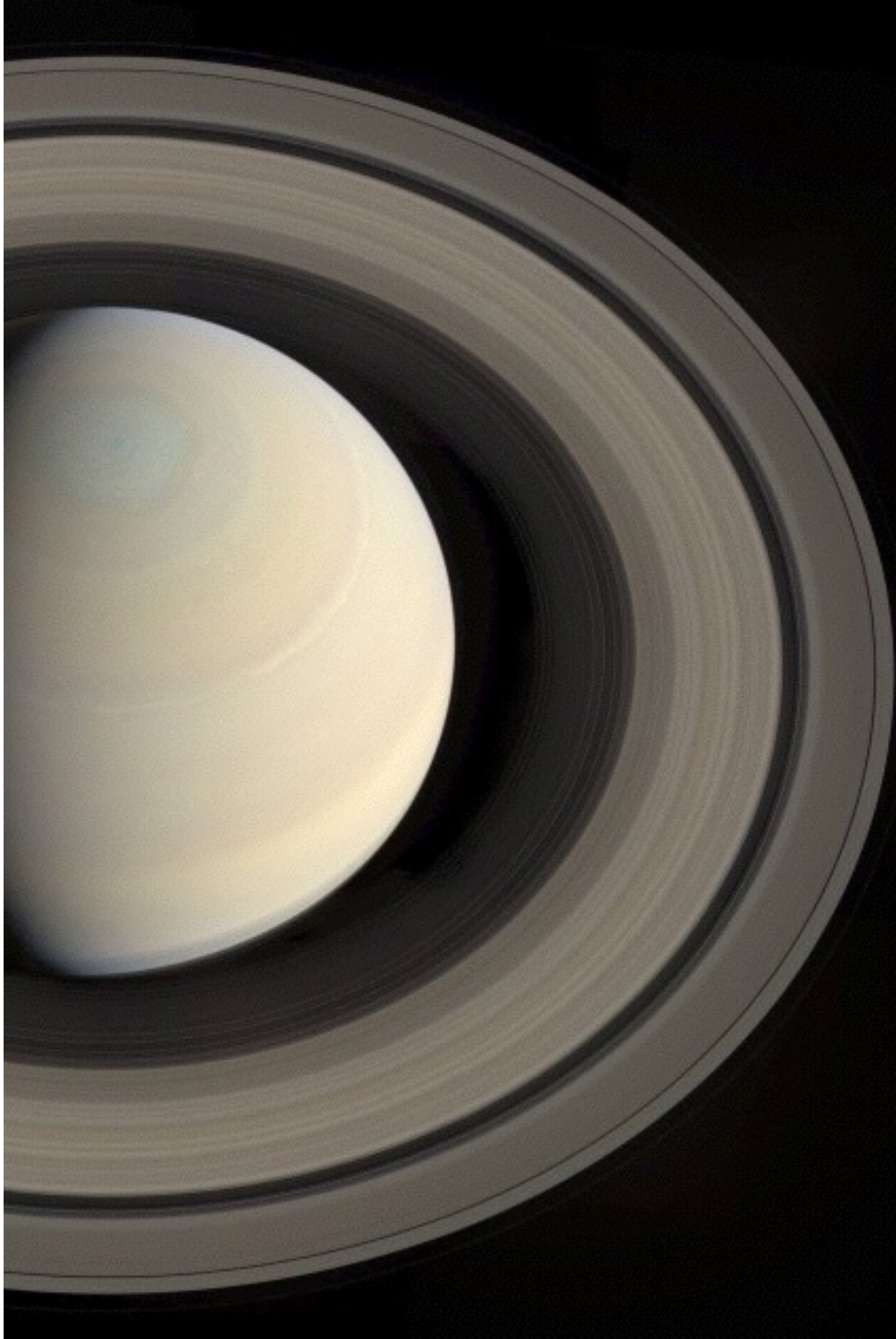


Microlensing Projects

- OGLE - Optical Gravitational Lensing Experiment, led by Andrzej Udalski of Warsaw University
- Makes use of the 1.3 meter telescope at Las Campanas, Chile
- Every night, pointed toward same dense field of 100 million stars around galactic bulge
- Armed with complex array of CCD cameras
- Detects ~500 microlensing events every year (but planet detections are extremely rare)
- Whenever OGLE detects a microlensing event, a network of over a dozen other observatories around the world are notified

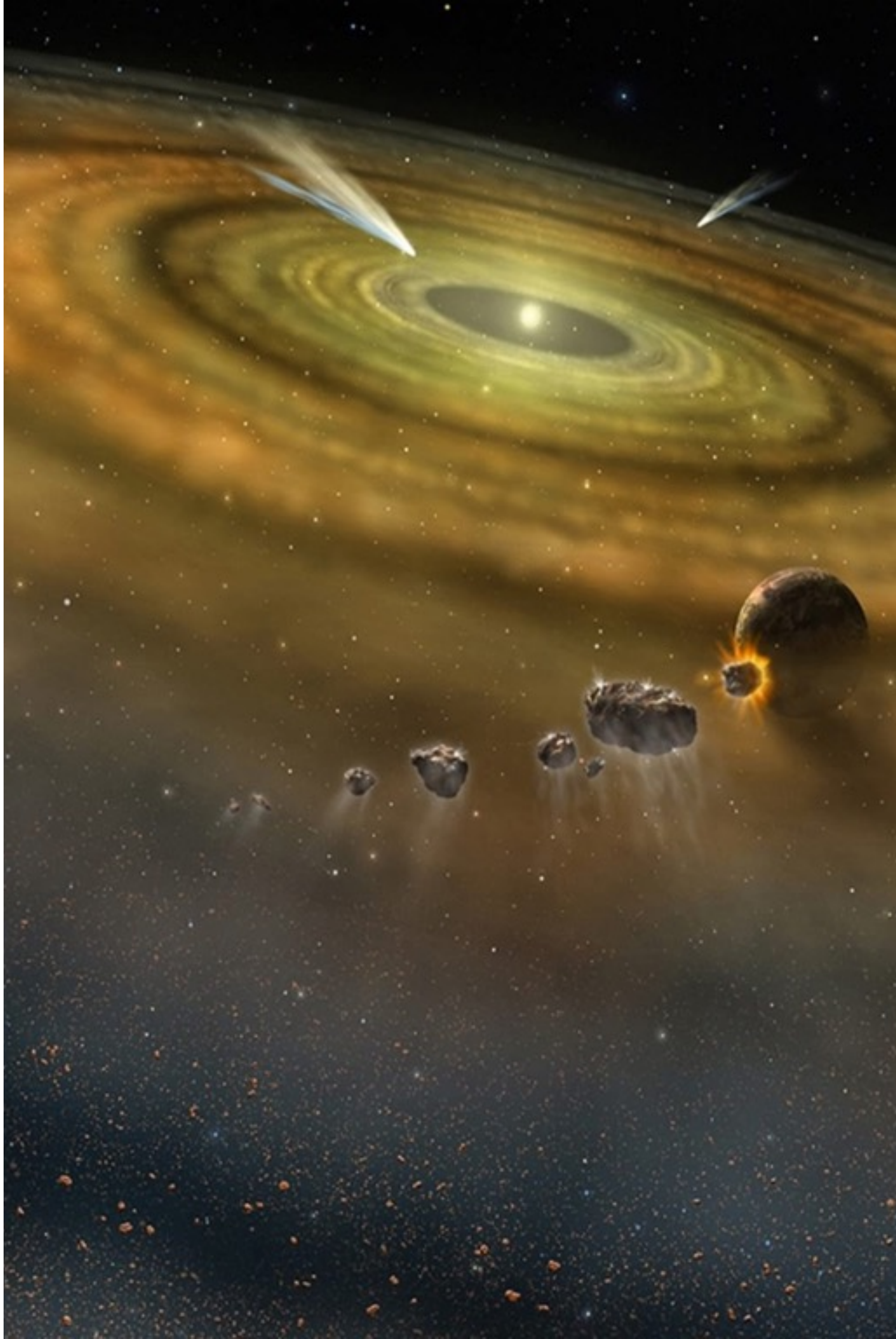
What Have We Learned?

- No super-massive planets have been found that are dense enough to be terrestrial
    - Most ≥1.6R_E are not rocky but have voluminous, volatile atmospheres
- Gas giants seem to have formed quickly (w/in few Myr) in presence of gas disk
- *Ongoing question*: Do planets form in situ (where we find them now) or outward, beyond the snow line, and migrate in?



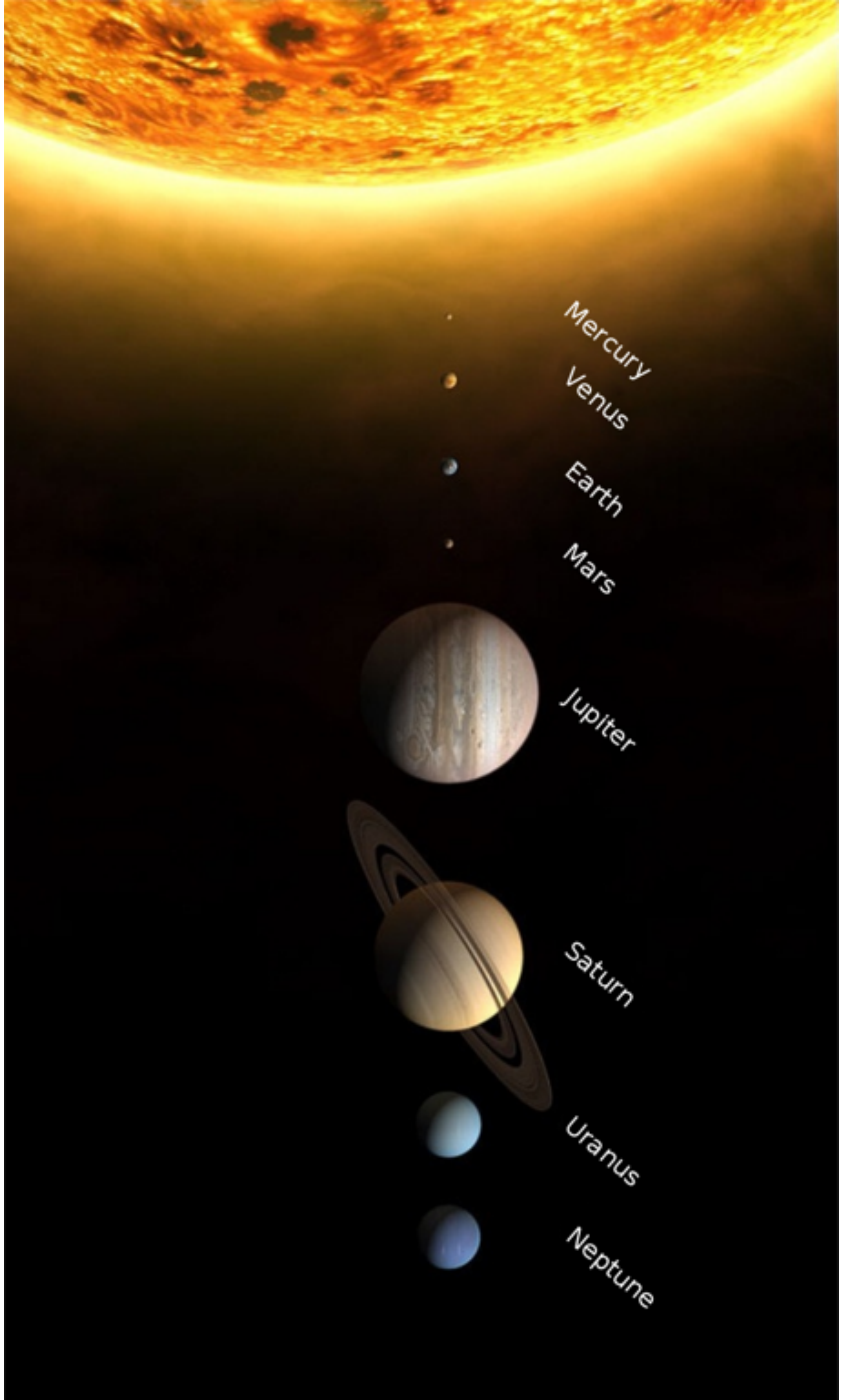
What Have We Learned?

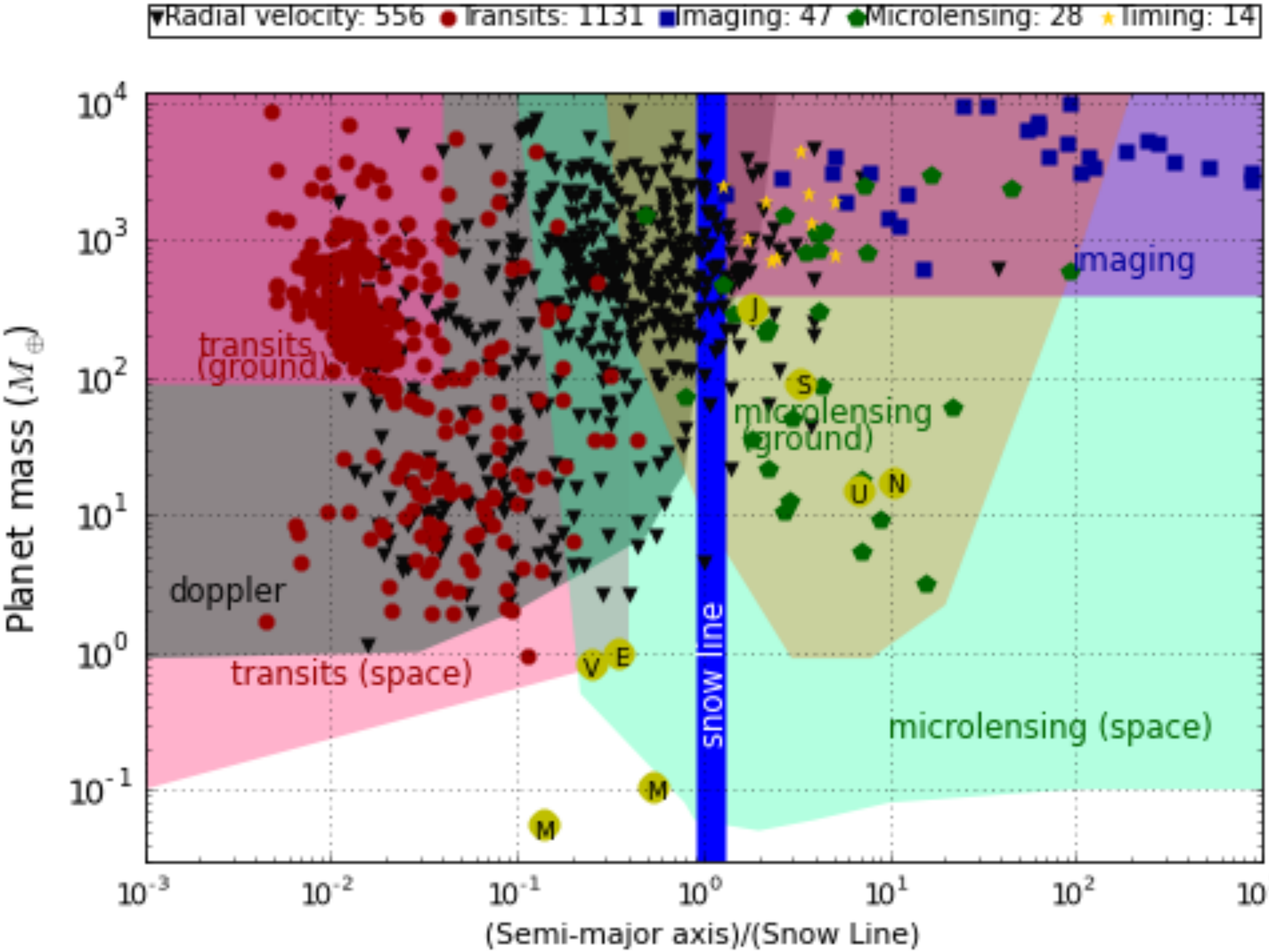
- Rocky planets could be remnant cores of gaseous planets
- Roche Limit - how close a satellite can get to the main body without being torn apart by tidal forces
- Supporting evidence: Earth 32.5% iron by mass, Mercury is 70% iron by mass



What Have We Learned?

- We haven't found very many planets like our own solar system at all (mass and orbital radius)
    - Our instruments aren't sensitive enough to find them very well

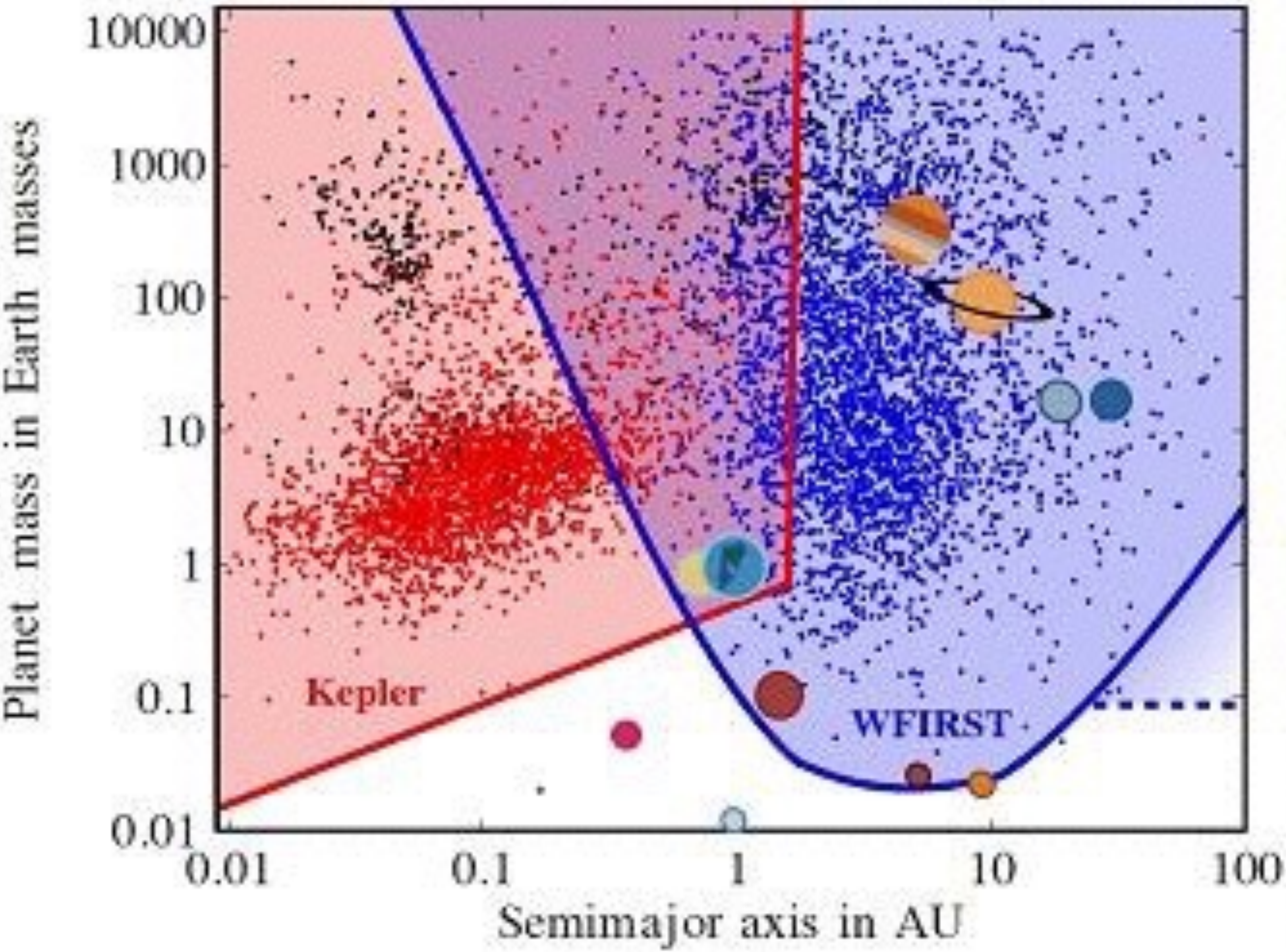




Radial velocity: 556
Transits: 1131
Imaging: 47
Microlensing: 28
Timing: 14
Planet mass ($M_\oplus$)
(Semi-major axis)/(Snow Line)
transits (ground)
doppler
transits (space)
snow line
microlensing (ground)
imaging
microlensing (space)
J
S
U
N
V
E
M
M

What Have We Learned?

- Huge push to combine data from many different experiments
- Major projects: OGLE, Kepler, WFIRST, Spitzer, Chandra, Hubble Space Telescope



10000
1000
100
10
1
0.1
0.01
Planet mass in Earth masses
0.01
0.1
1
10
100
Semimajor axis in AU
Kepler
WFIRST