

Astronomical Optics

6. High contrast imaging techniques (nulling interferometry & coronagraphy)

6.1. High contrast imaging science and challenges

Exoplanets

- Exoplanet types: Giants, rocky planets
- Contrast ratio, Angular separation: why is it difficult ?
- Visible vs. Infrared
- Complementarities between direct imaging and indirect techniques
- Life finding

Disks

- Planetary formation
- Debris disks

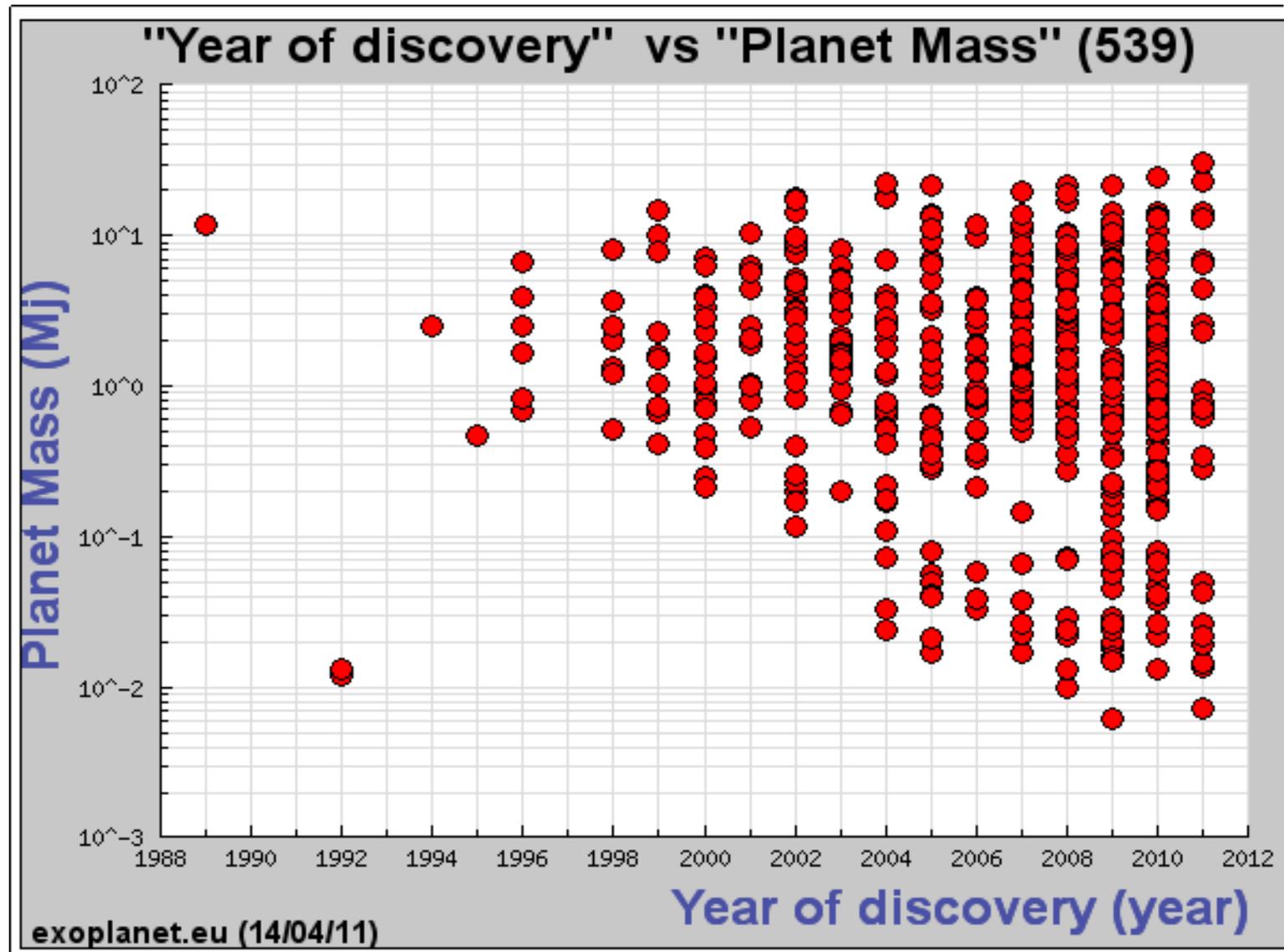
Brief introduction to approaches to the high contrast imaging challenge

- Why don't normal telescopes work for high contrast imaging ?
- Coronagraphy
- Nulling interferometry
- Ground vs. space

Exoplanet discoveries

New but very active research topic

Most planets are discovered with indirect techniques → limited ability to characterize them, and strong need for direct imaging to learn more about the planets and their environments



Exoplanet discoveries

Techniques to detect exoplanets around main sequence stars (many of them covered in this course):

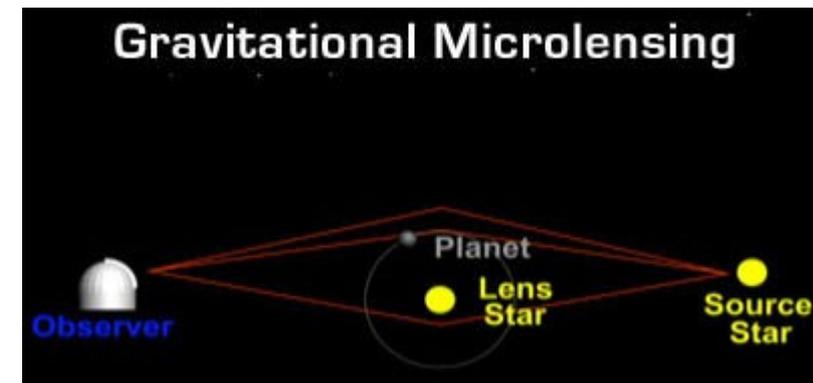
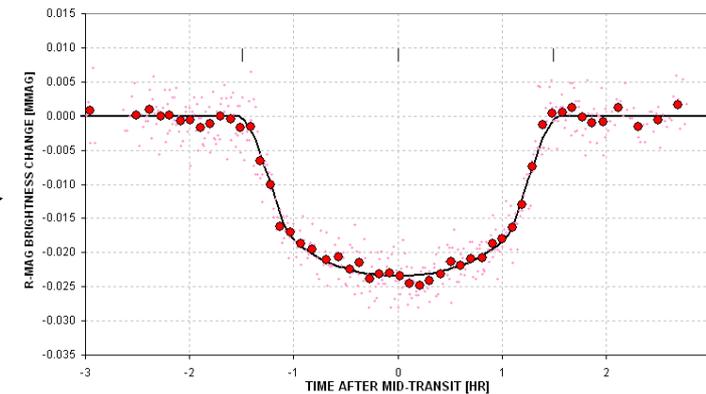
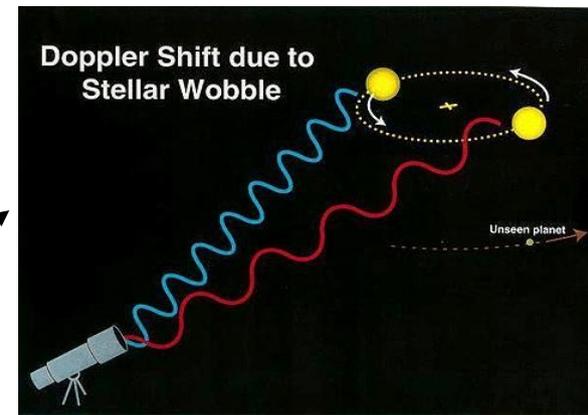
Radial velocity: measure small shift in star's spectra to compute its speed along line of sight.

Astrometry: measure accurate position of star on sky to identify if a planet is pulling the star in a small periodic orbit around the center of mass

Transit photometry: if planet passes in front of its star, the star apparent luminosity is reduced

Microlensing: planet can bend light, and amplify background starlight through gravitational lensing

Direct imaging (with telescope or interferometer): capture high contrast image of the immediate surrounding of a star



Habitable planets

Potentially habitable planet :

- **Planet mass** sufficiently large to retain atmosphere, but sufficiently low to avoid becoming gaseous giant
- **Planet distance to star** allows surface temperature suitable for liquid water (habitable zone)

Habitable zone = zone within which Earth-like planet could harbor life

Location of habitable zone is function of star luminosity L . For constant stellar flux, distance to star scales as $L^{1/2}$

Examples:

Sun

→ habitable zone is at ~1 AU

Rigel (B type star):

17 solar mass

40000x Sun luminosity

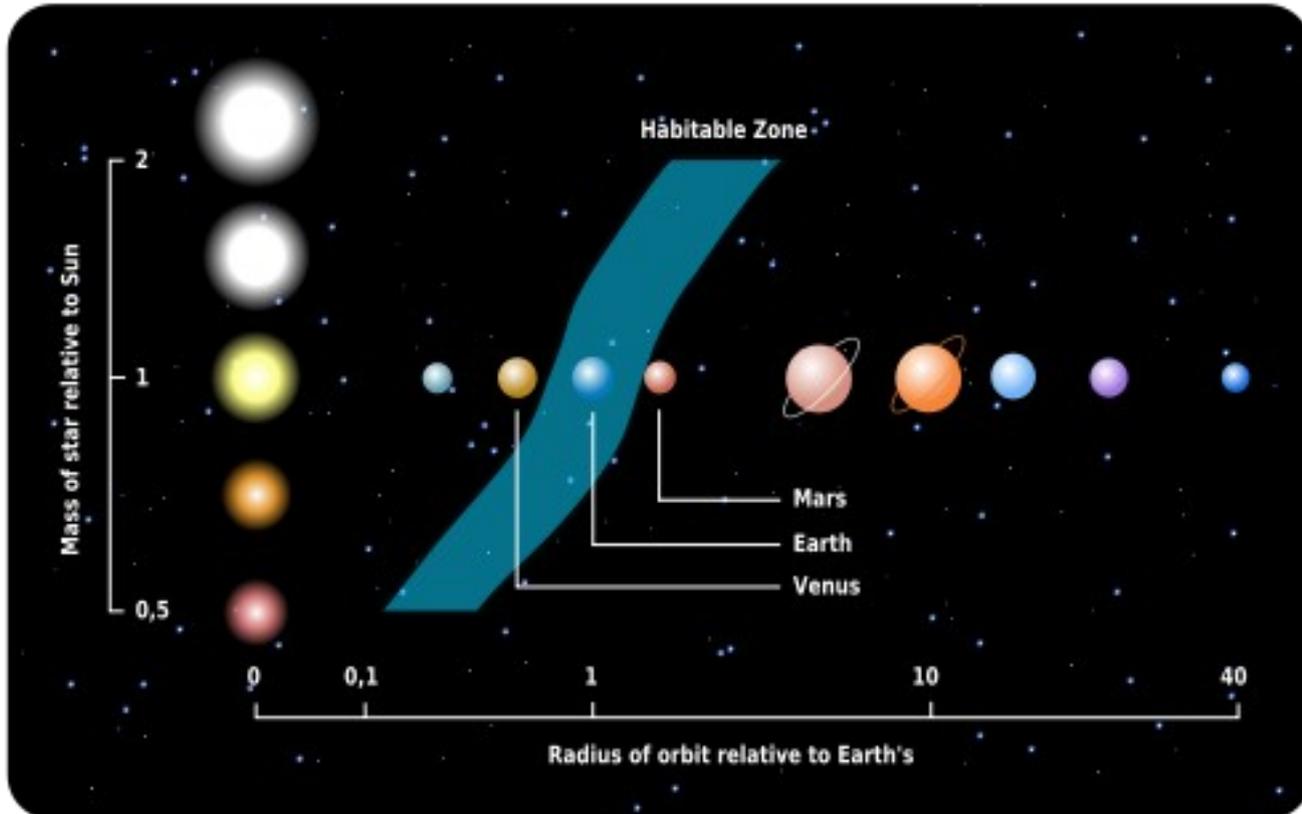
→ habitable zone is at ~200 AU

Proxima Centauri (M type star):

0.123 solar mass

1/600 Sun luminosity

→ habitable zone is at ~0.04 AU



Direct imaging of Exoplanets (incl. Habitable planets) allows ...

Orbit

Atmosphere composition

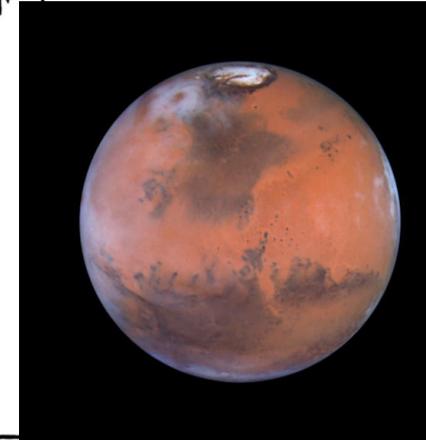
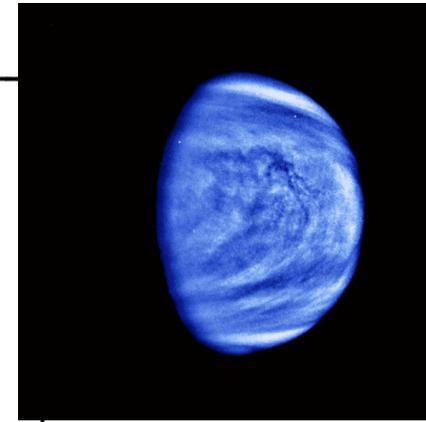
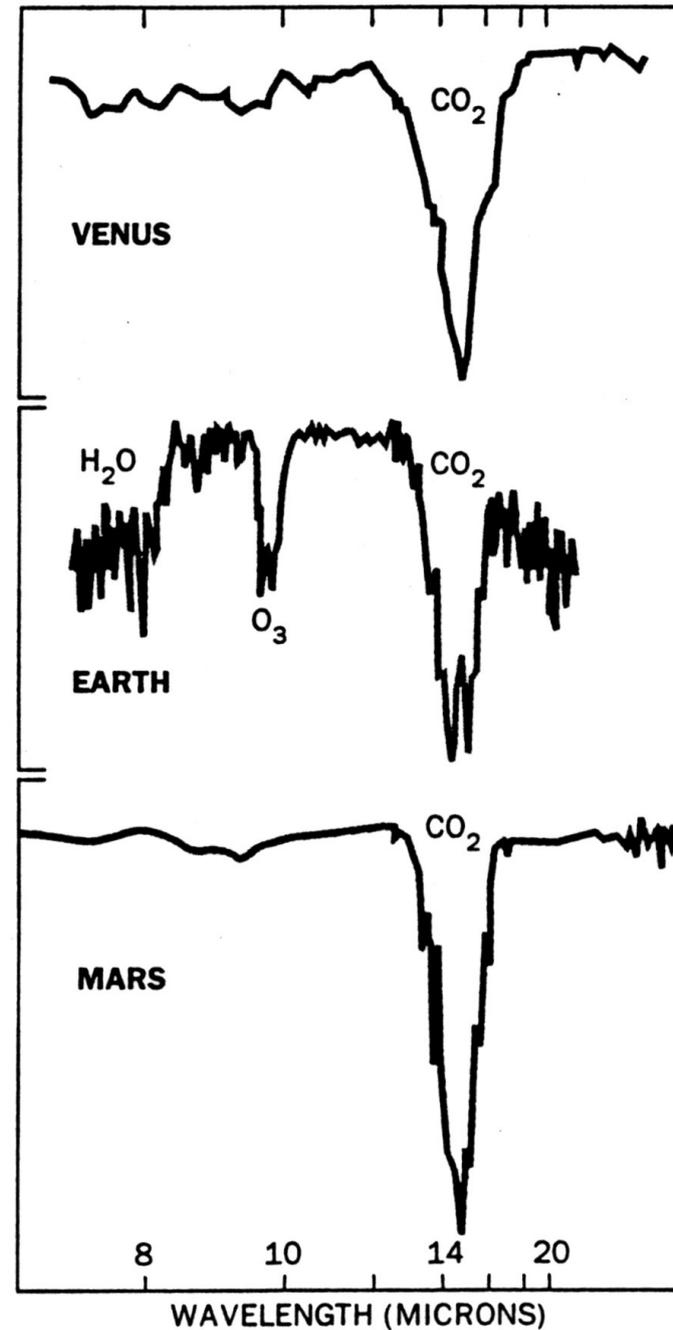
Continents vs. Oceans ?

Rotation period

Weather patterns

Planetary environment :

Planets + dust

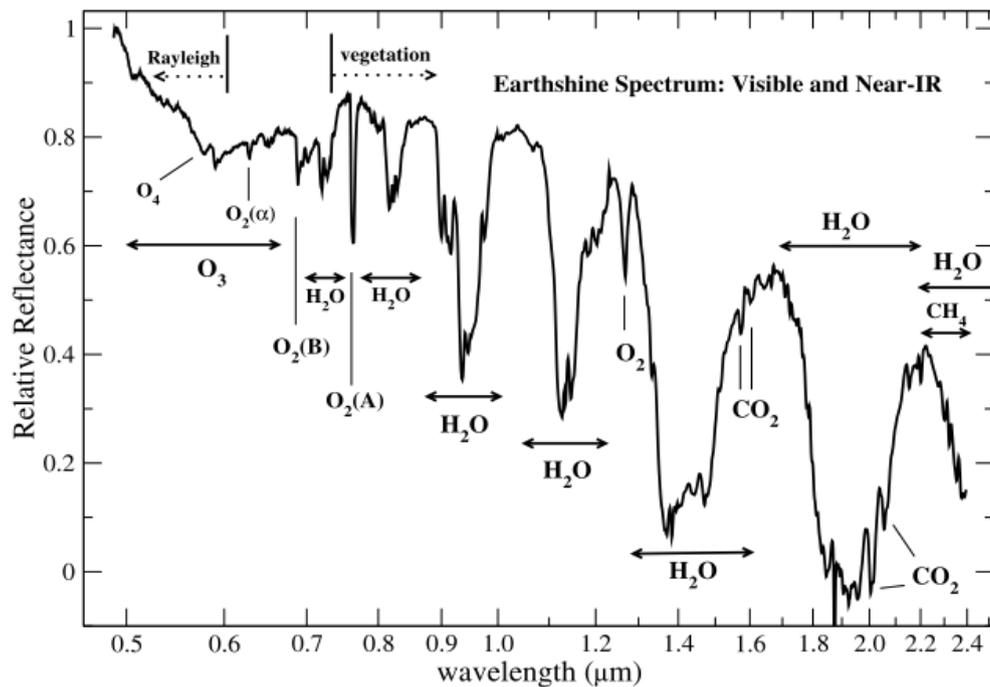


Spectroscopy of Earth-like planets ... may allow detection of life

Spectroscopy can identify biomarkers: molecular species, or combinations of species that can only be explained by biological activity

On Earth: water + O₂ + O₃ + CH₄

Spectra of Earth obtained through Earthshine observation also reveals vegetation's red edge !



Turnbull et al. 2006



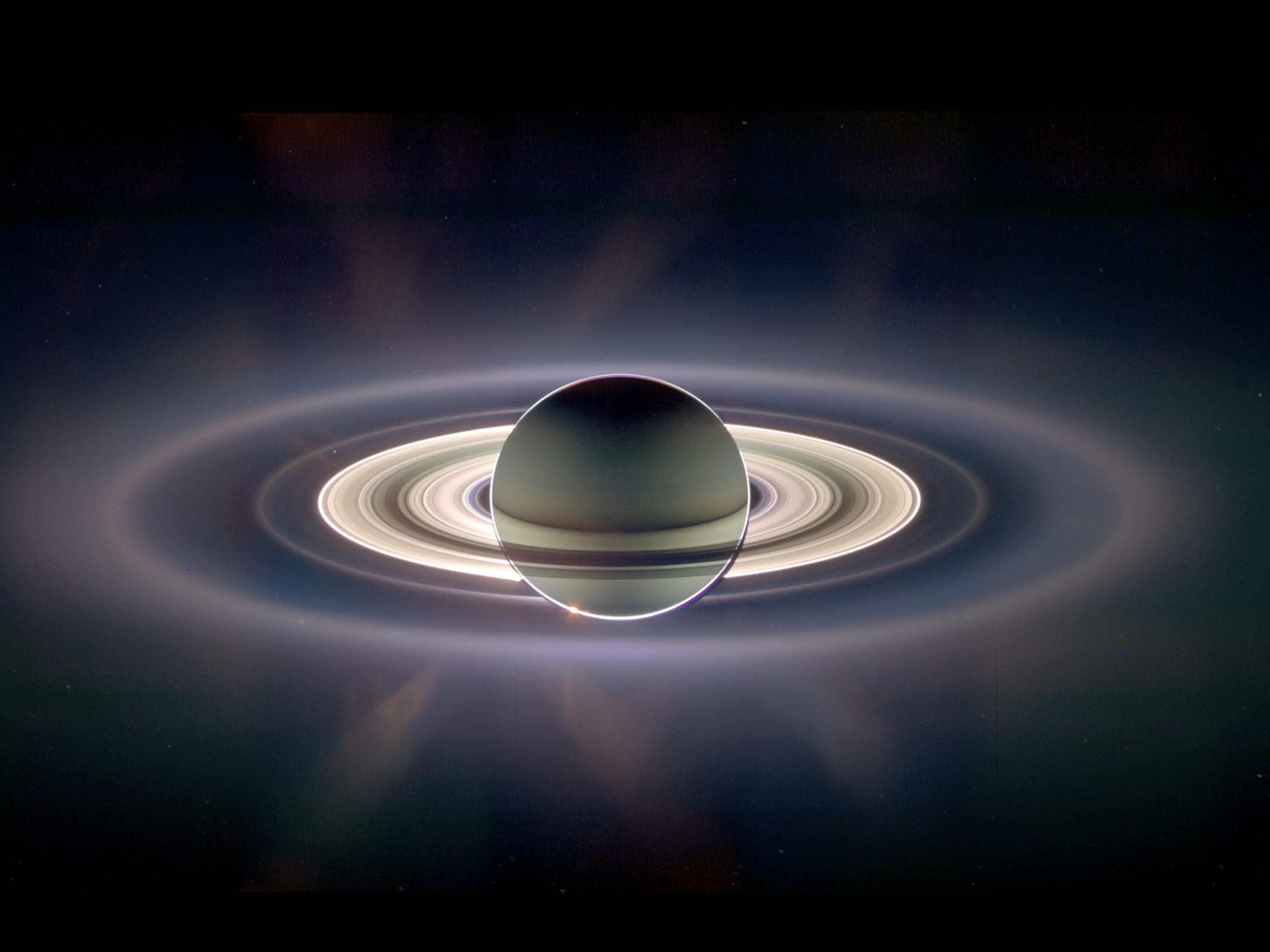
FIG. 7.—Earth's observed reflectance spectrum, at visible and near-infrared wavelengths, created from a composite of the data in this paper (0.8–2.4 μm) and the data presented in Paper I (0.5–0.8 μm). The strongest molecular signatures are indicated, as are the wavelengths where Rayleigh scattering and vegetation reflection are most significant.

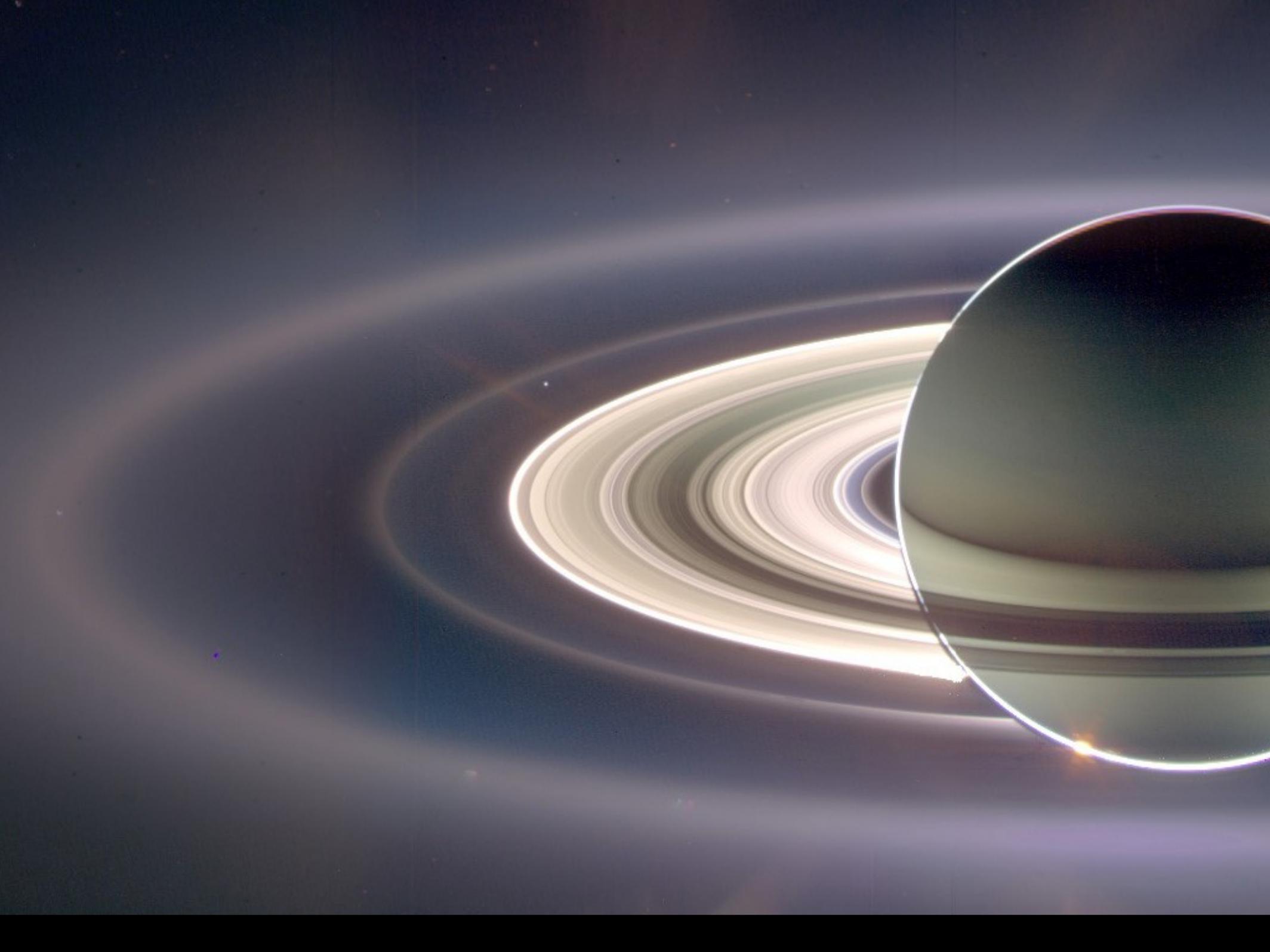
Exoplanets imaging

angular separation, contrast: why is it difficult ?

What would our solar system look like from 10pc away ?

- Sun would be $m_V = 4.8$ star (faint naked-eye star)
- Sun diameter would be 0.001" (diffraction limit of a 200m telescope in the near-IR)
- Sun-Earth separation would be 0.1" (diffraction limit of a 2-3m telescope in the near-IR)
- Earth diameter = 0.00001" (diffraction limit of a 20km diameter telescope in near-IR)
- In the visible:
 - Earth at $1e-10$ contrast would be $m_V \sim 30$ sources (very faint, would be challenging even for Hubble without the host star)
 - Jupiter in the visible would be $\sim 10x$ brighter than Earth, at 0.5"
 - Zodiacal light would be several 100x brighter than Earth when integrated, and brightest near Sun
- In the near IR ($\sim 2 \mu\text{m}$): similar contrasts
- In the thermal IR ($\sim 10 \mu\text{m}$):
 - Contrasts are much more favorable
 - Earth is brightest planet, at $\sim 1e-6$ contrast







Exoplanets: Contrast ratio, visible vs. infrared

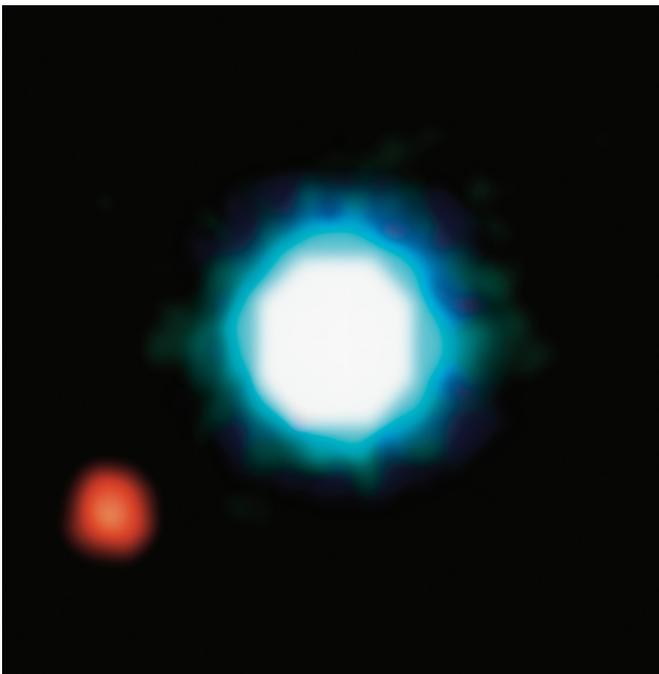
In the visible, planets are very faint unless they are very close to their star (luminosity goes as d^{-2})

Planets in or near habitable zone cannot be imaged from the ground, and would require dedicated space telescope+instrument.

In the near-IR, giant and young planets (“young Jupiters”) can be imaged:

- AO systems work well in the near-IR
- Giant planets emit their own light (thermal emission)
- Young planets are still very hot, and slowly cool after formation

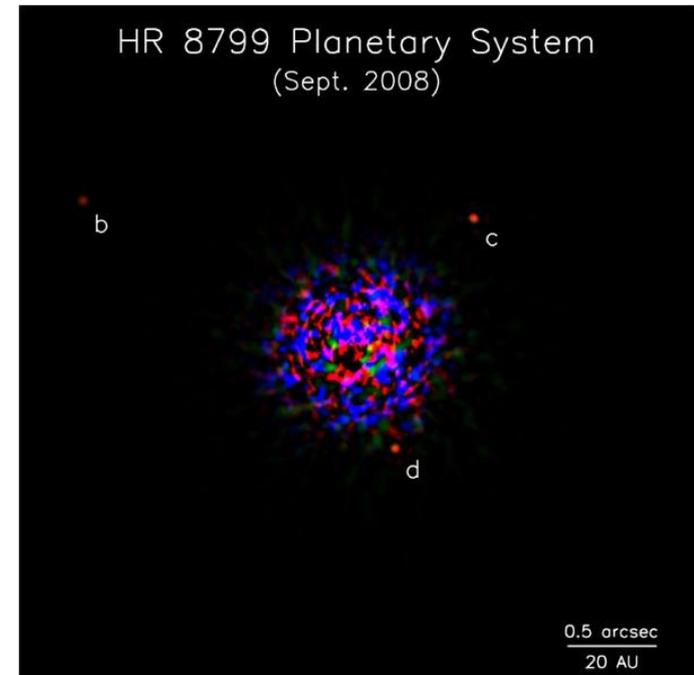
In the Thermal IR (~10 μm & longer), contrast is even more favorable, and older giant planets can be imaged (this is one of the key science goals of JWST)



2M1207 exoplanet
(Chauvin et al., ESO,
2004)

Probably the first
direct image of an
exoplanet

HR8799: first image
of exoplanetary system
with multiple planets
(Marois et al. 2009)



HR 8799 Planetary System
(Sept. 2008)

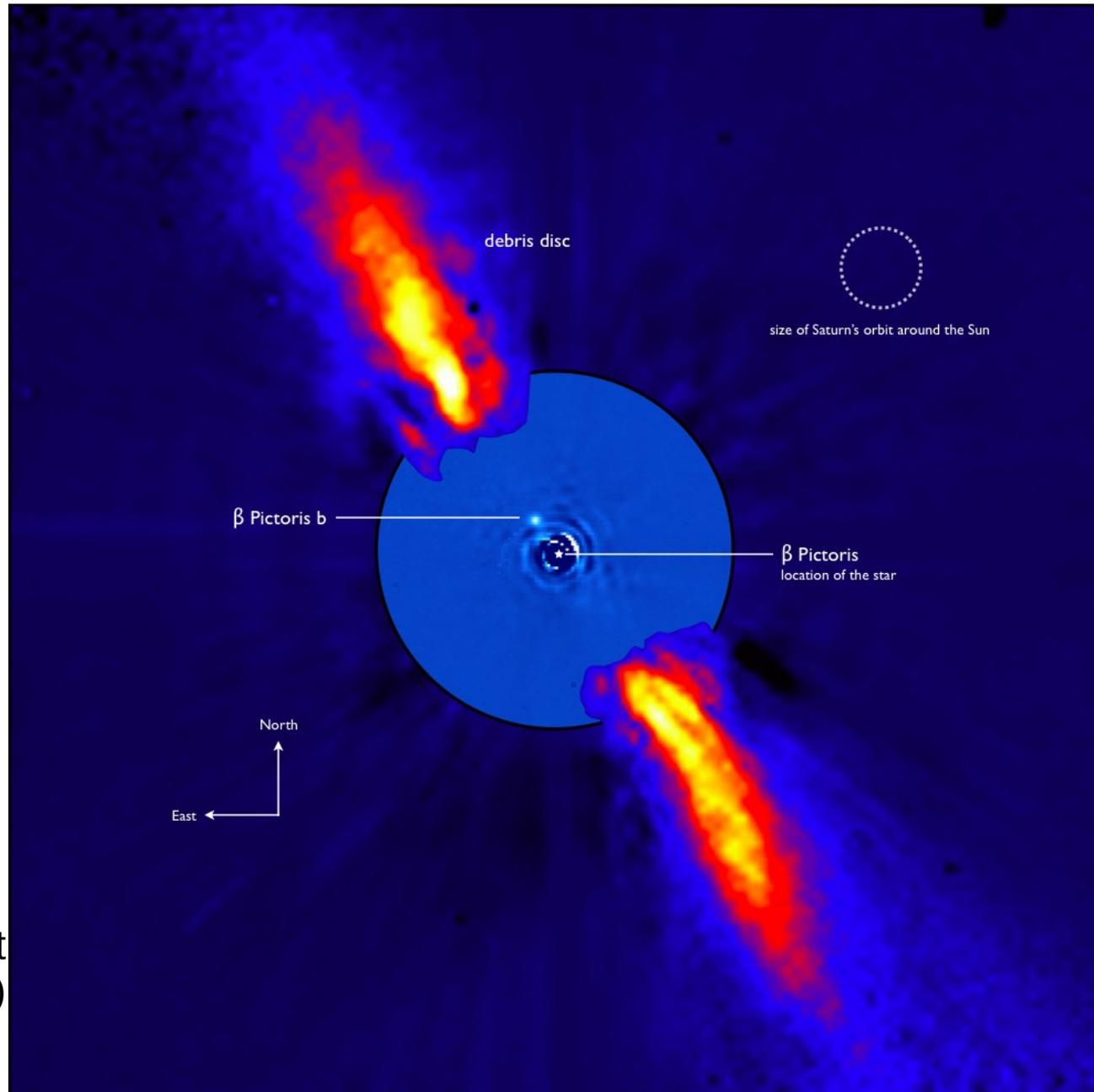
Exoplanets & dust disks

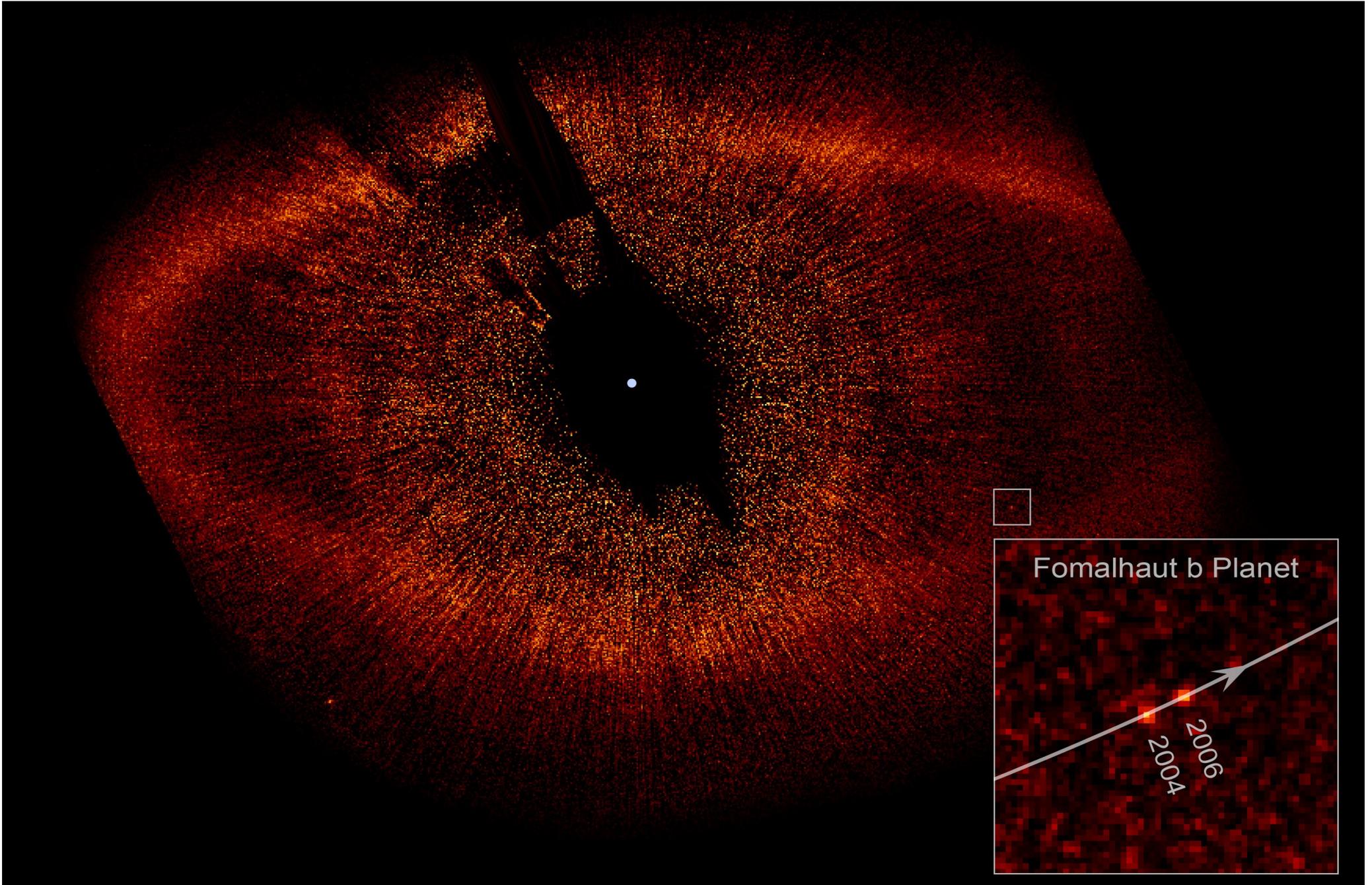
Protoplanetary disk:
Disk in the process of forming planets

Debris disk:
Disk generated by collision between small bodies

Ability to image planets and disks → study planetary formation and evolution of planetary systems

Beta Pic exoplanet and dust disk (Lagrange et al. 2009)





Kalas et al., HST image

What is a high contrast imaging system (ground or space) ?

Imaging system optimized to provide high contrast at small angular separation.

Key elements:

- **Coronagraph** or nulling interferometer to optically remove starlight and isolate planet light (overcomes diffraction)
- **Wavefront correction system** to reduce and calibrate residual wavefront errors
 - For coronagraphs: Extreme-AO system to flatten wavefront
 - For interferometers: Optical pathlength sensing / correction (+ AO on individual apertures of the interferometer)
- **Science detector** for imaging, spectroscopy and polarimetry
(note: the science detector can be part of the wavefront control system, and measure residual scattered light to be removed)

Why coronagraphy ?

Conventional imaging systems are not suitable for high contrast (even if perfect) due to diffraction

