Observing Exoplanets with High contrast imaging techniques

nulling interferometry & coronagraphy

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

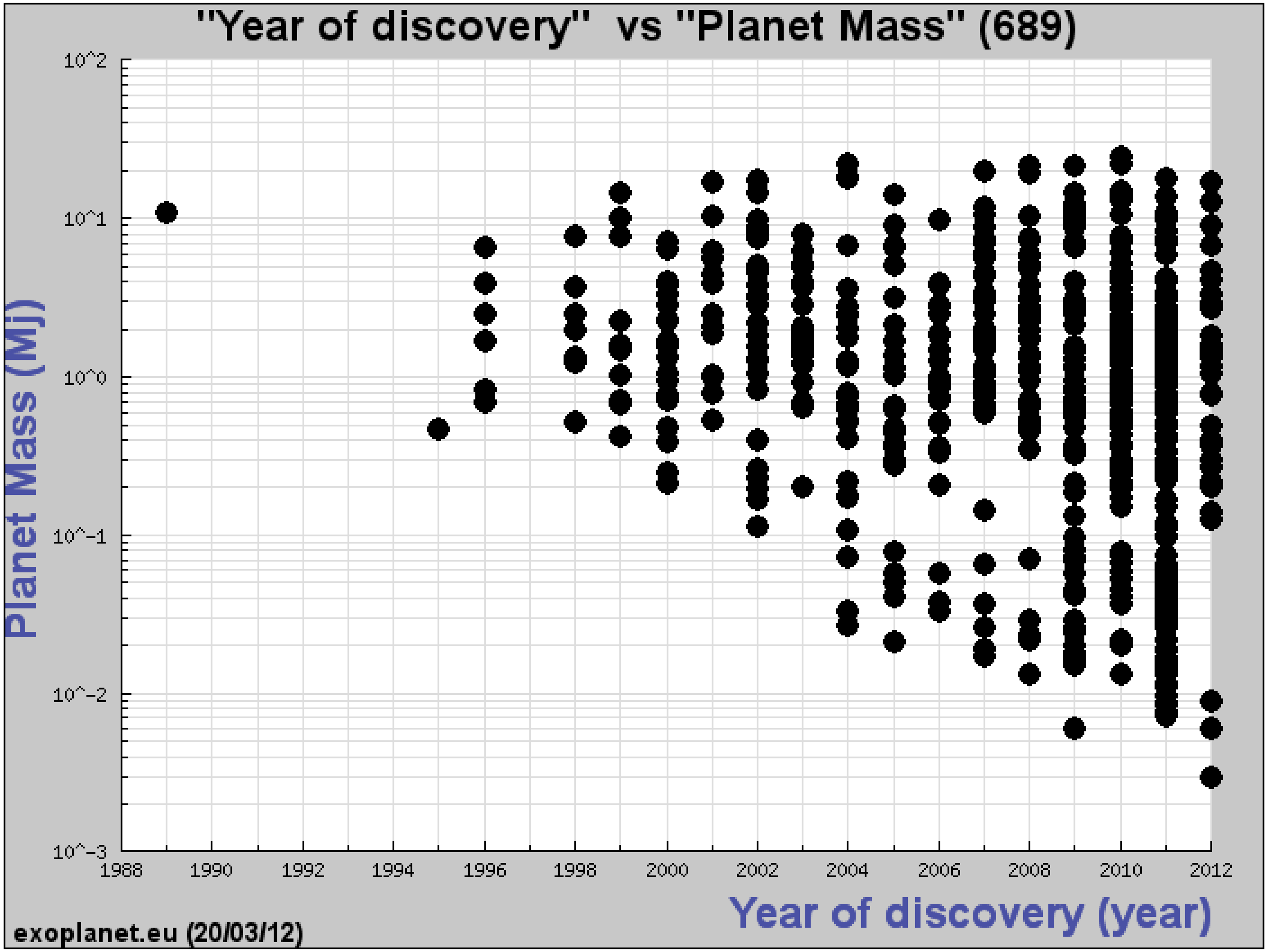
- Planetary formation
- Debris disks

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

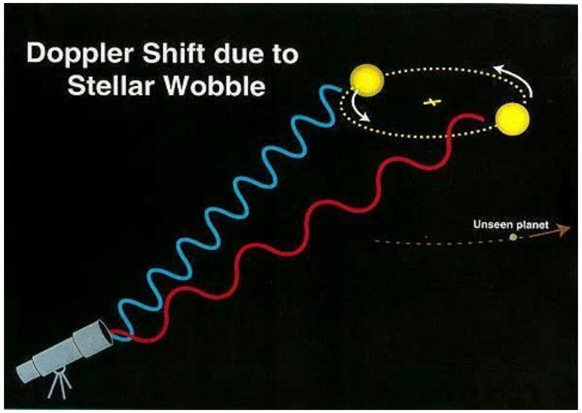
New but very active research topic
Most planets are discovered with indirect techniques → limited ability to characterize them, and strong need for direct imaging to learn more about the planets and their environments



Exoplanet discoveries

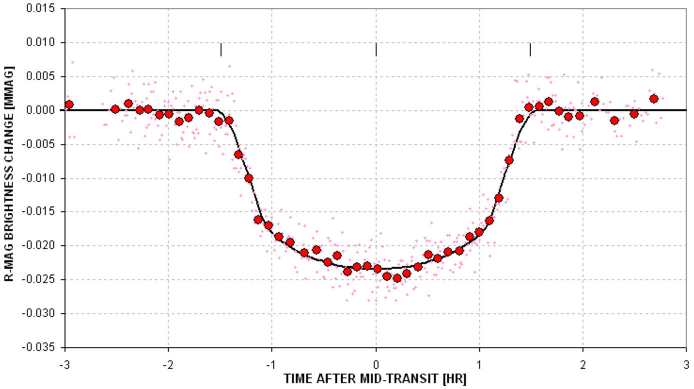
Techniques to detect exoplanets around main sequence stars (many of them covered in this course):

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

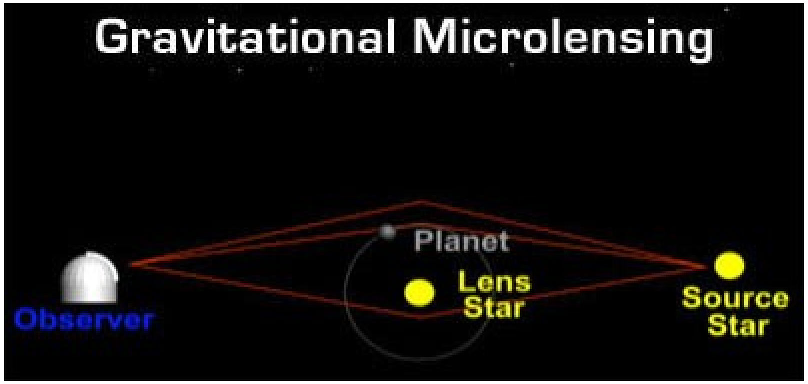


Astrometry: measure accurate position of star on sky to identify if a planet is pulling the star in a small periodic orbit around the center of mass

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)

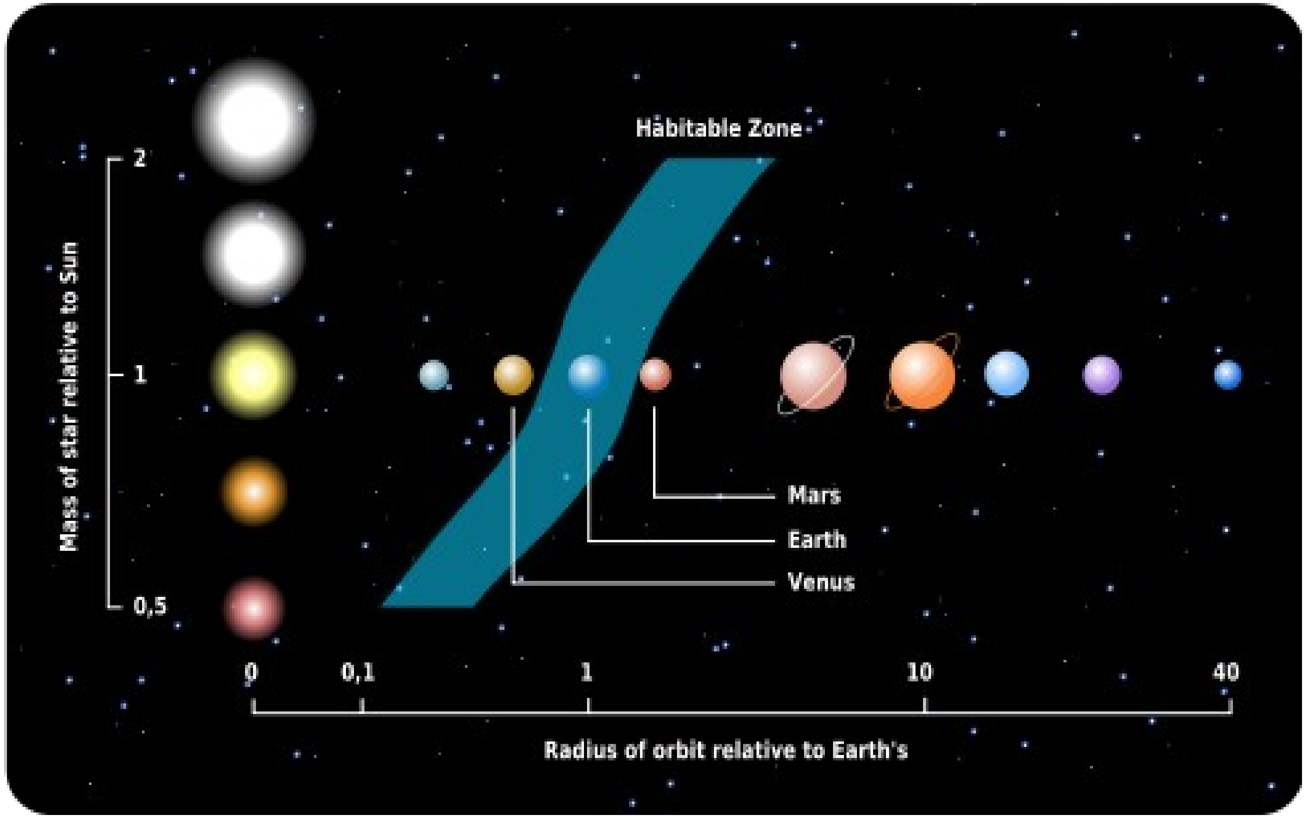
Habitable zone = zone within which Earth-like planet could harbor life
Location of habitable zone is function of star luminosity L. For constant stellar flux, distance to star scales as $L^{1/2}$

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

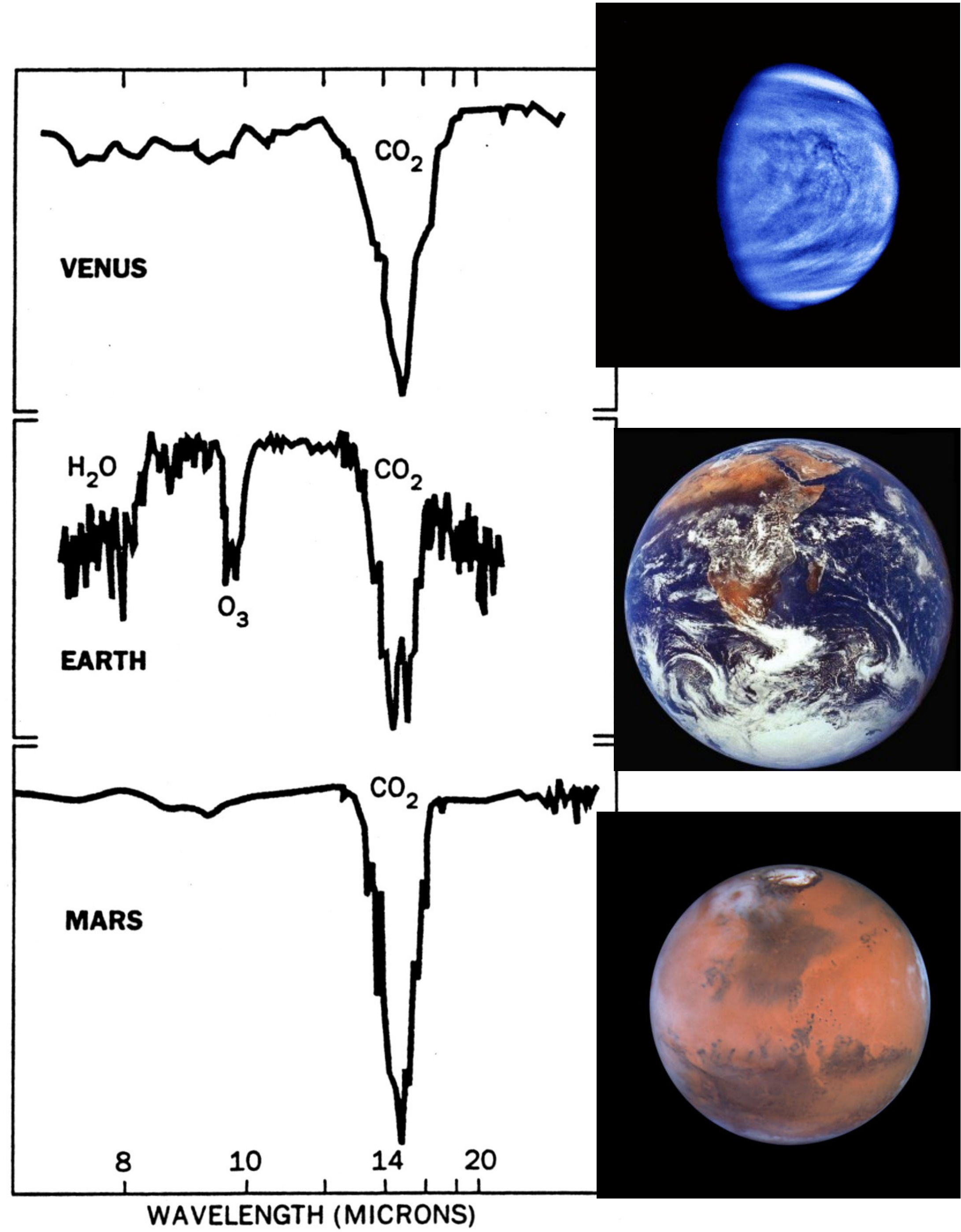
Atmosphere composition

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 + O_2 + O_3 + CH_4

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

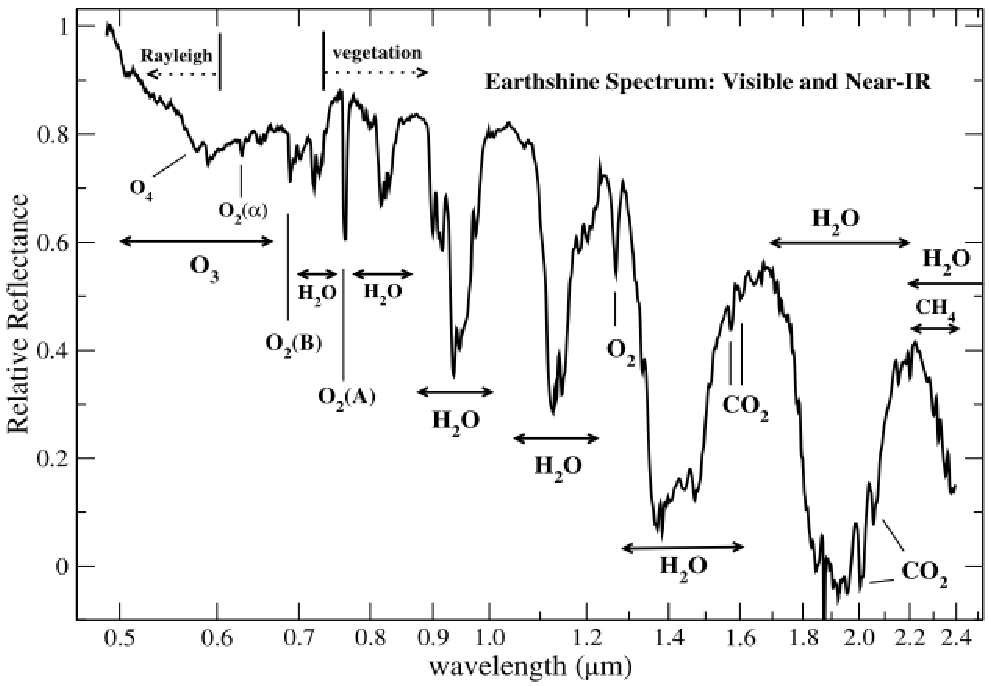
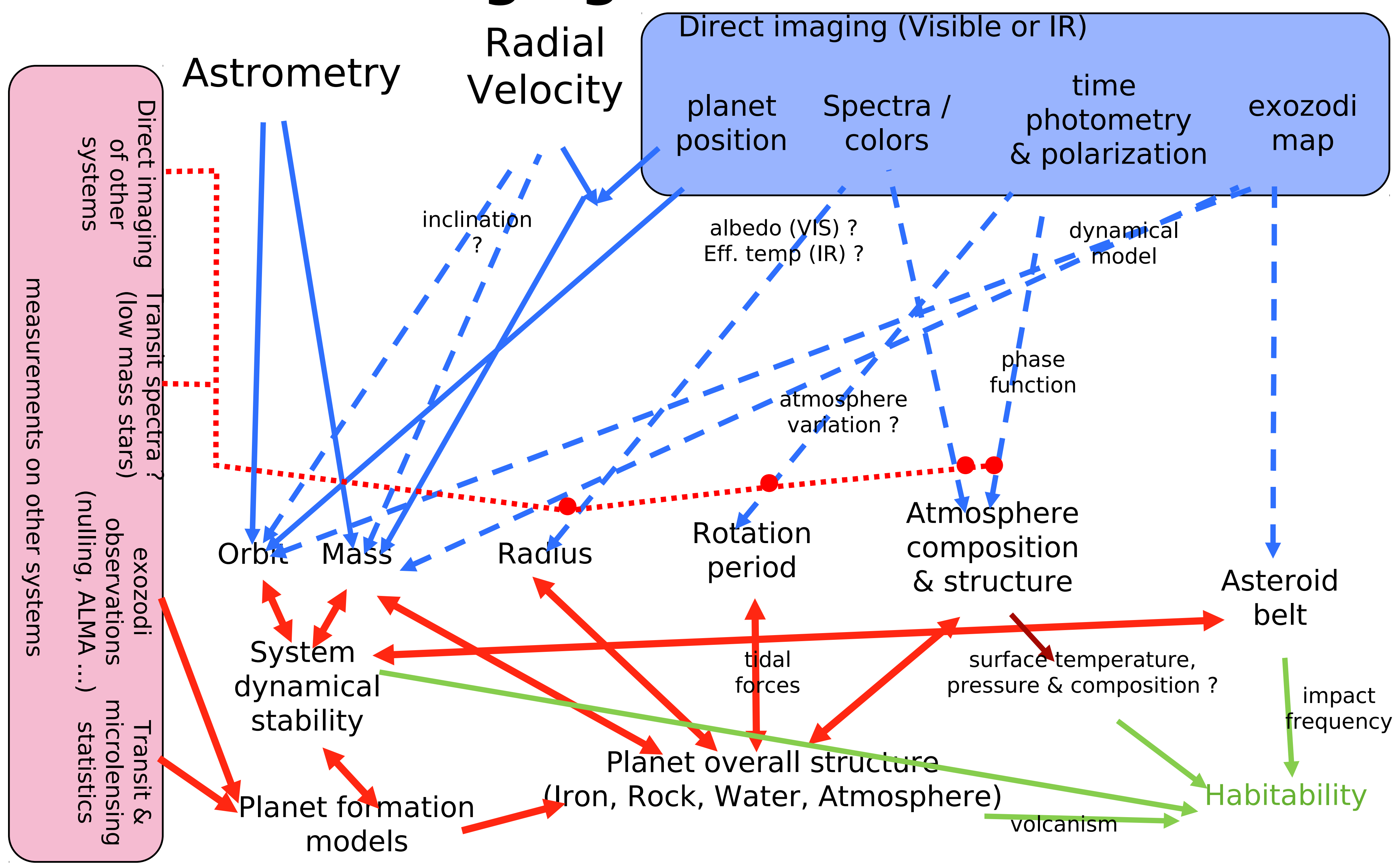


Fig. 7.—Earth's observed reflectance spectrum, at visible and near-infrared wavelengths, created from a composite of the data in this paper (0.8–2.4 μm) and the data presented in Paper I (0.5–0.8 μm). The strongest molecular signatures are indicated, as are the wavelengths where Rayleigh scattering and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

Turnbull et al. 2006

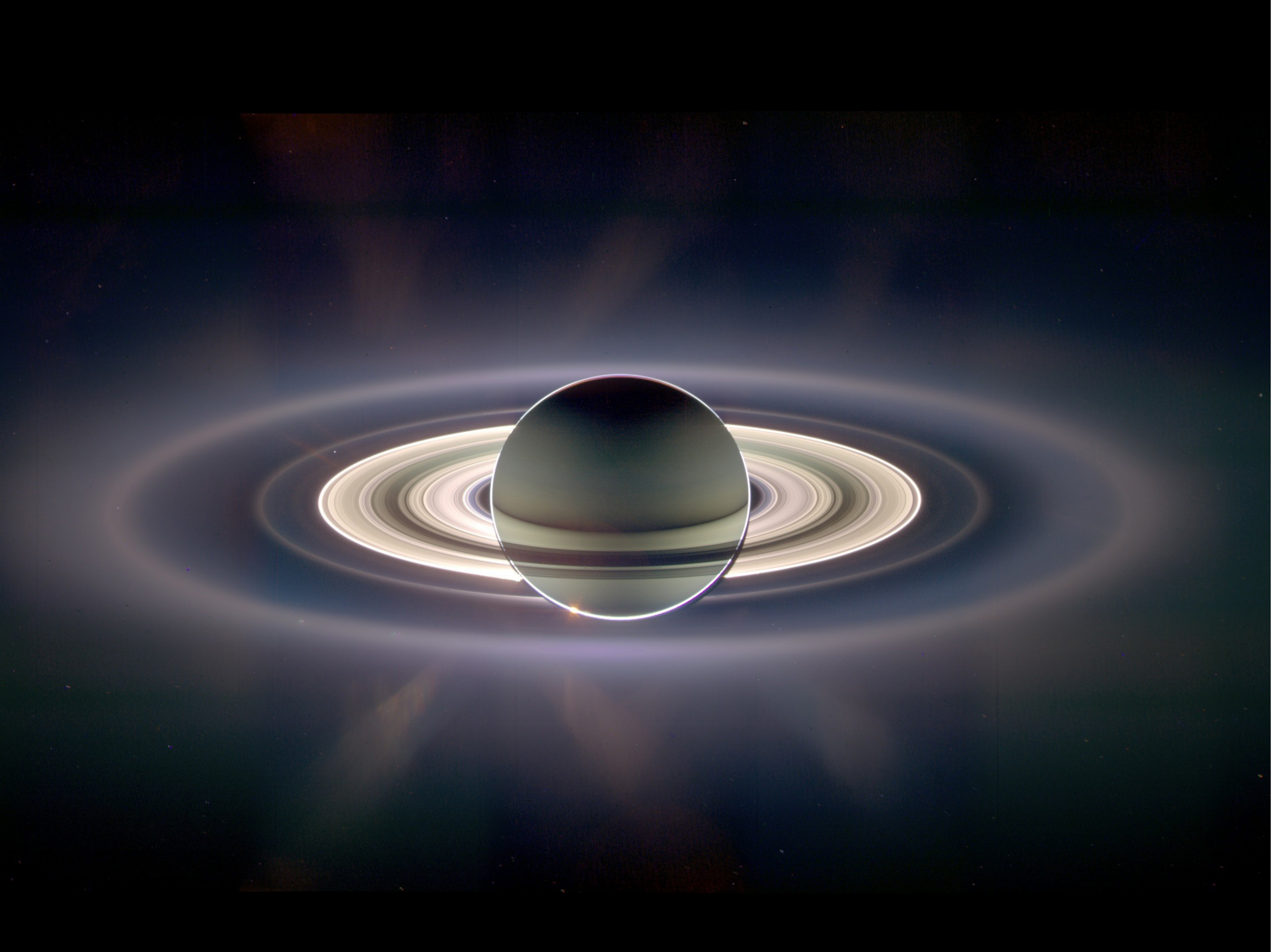
Habitable exoplanet characterization with direct imaging

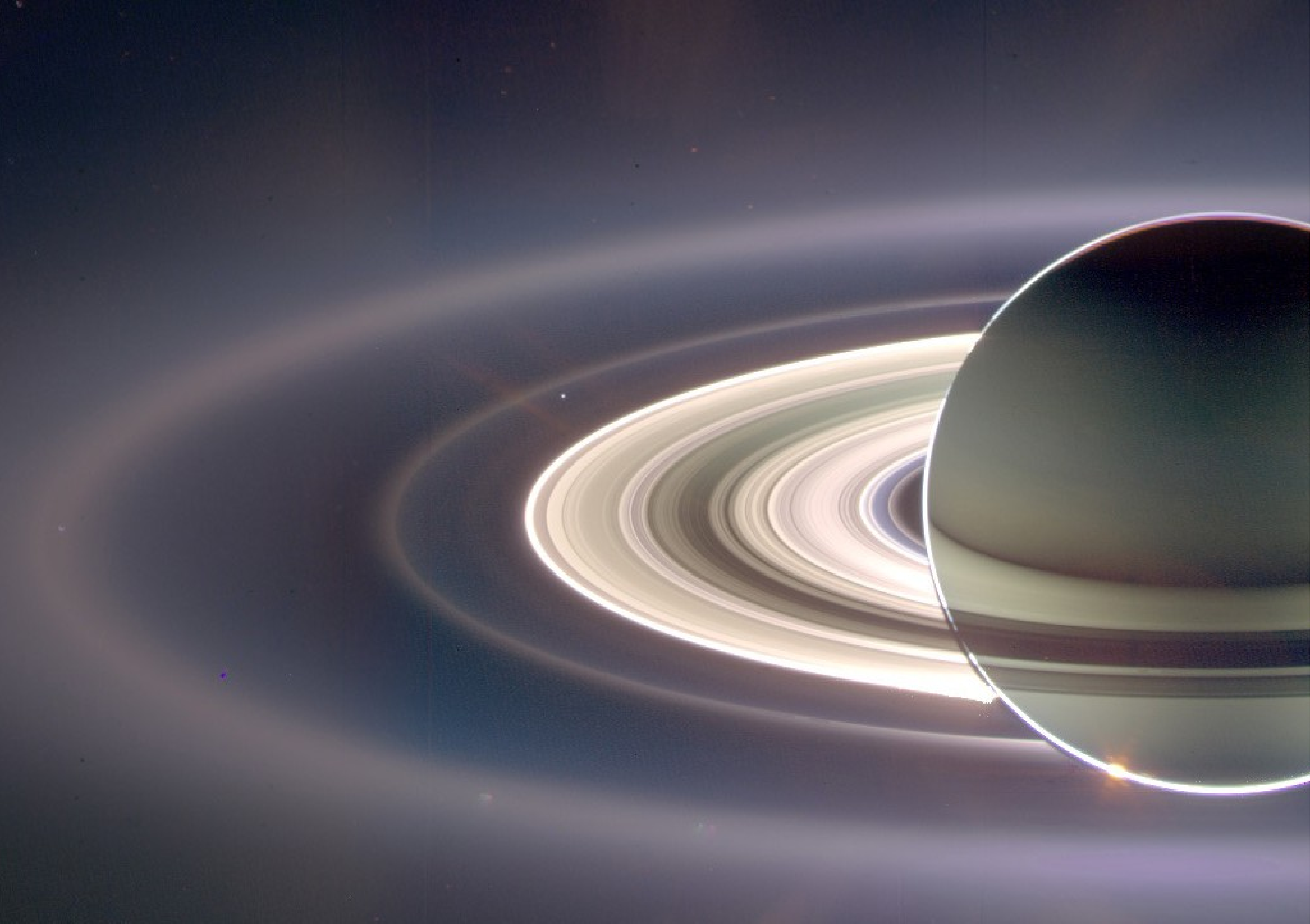


Exoplanets imaging
angular separation, contrast: why is it difficult ?

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~ 30 sources (very faint, would be challenging even for Hubble without the host star)
  - Jupiter in the visible would be ~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 (~2 um): similar contrasts
- In the thermal IR (~10 um):
  - Contrasts are much more favorable
  - Earth is brightest planet, at ~1e-6 contrast





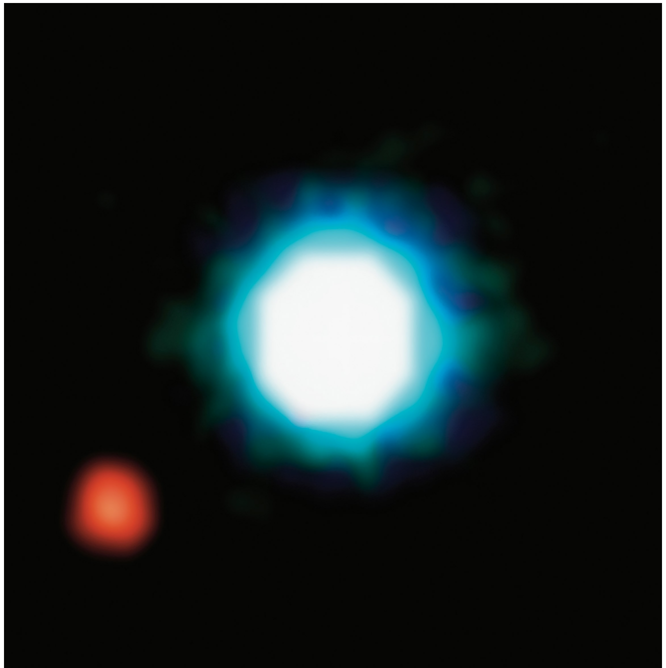
Exoplanets: Contrast ratio, visible vs. infrared

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:

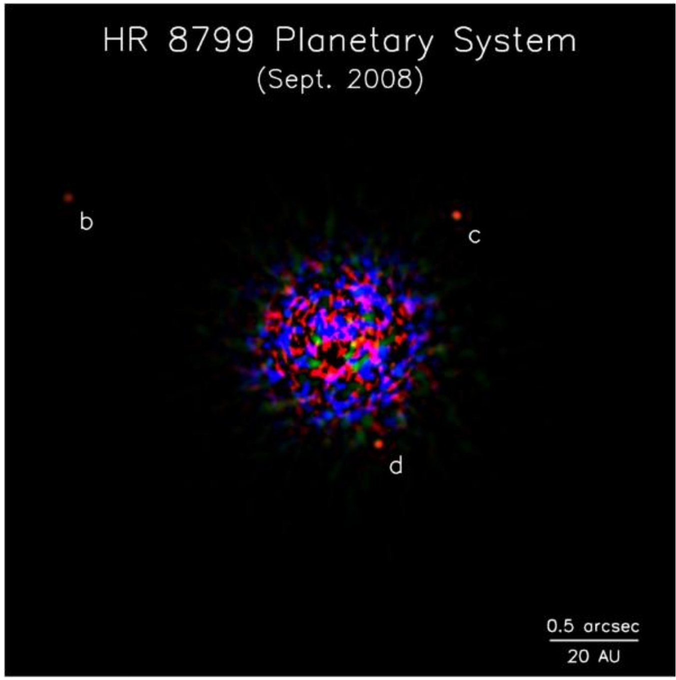
- AO systems work well in the near-IR
- Giant planets emit their own light (thermal emission)
- Young planets are still very hot, and slowly cool after formation

In the Thermal IR (~10 um & 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 sytem with multiple planets (Marois et al. 2009)

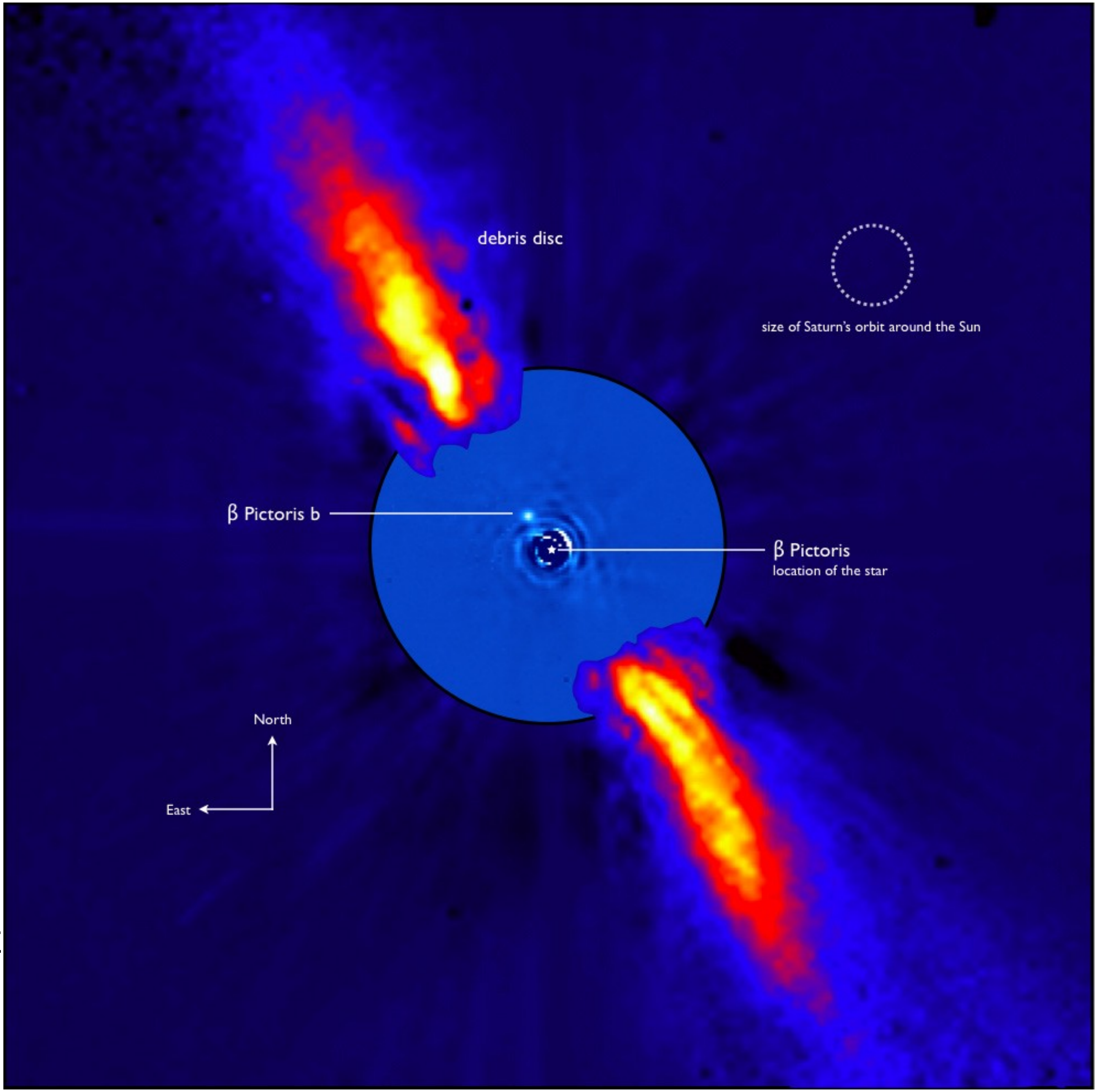


Exoplanets & dust disks

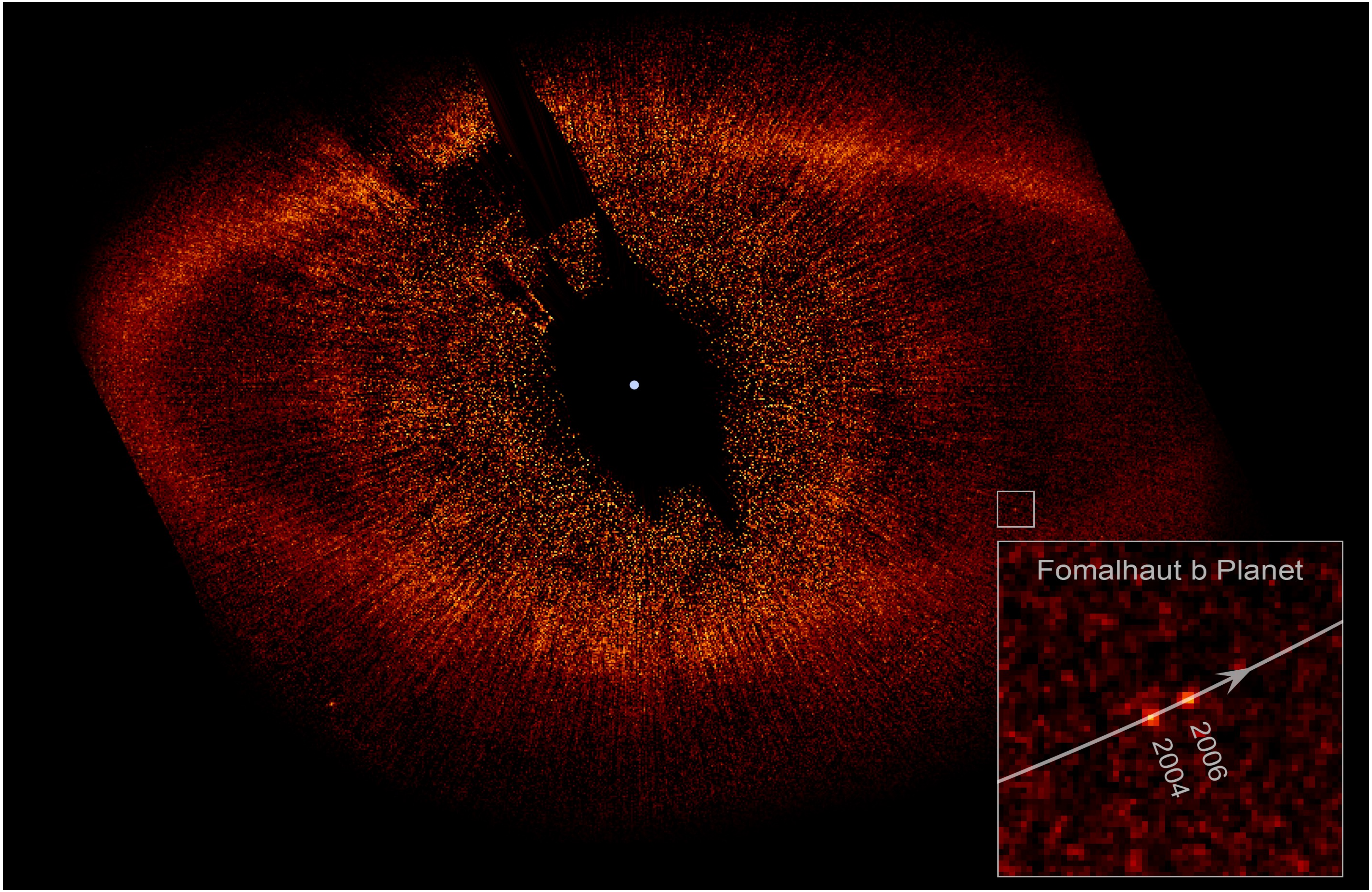
Protoplanetary disk:
Disk in the process of forming planets

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

Challenges

- **Contrast**
  - Visible:
    - 1e10 for Earth/Sun -> space
    - 1e9 for Jupiter/Sun -> space / ELTs ?
    - ~1e8 for close-in planets -> ground ExAO ?
  - Near-IR (~1.6 micron)
    - 1e10 for Earth/Sun
    - ~1e12 for Jupiter/Sun
    - ~1e7 for young giant planet / Sun -> Ground ExAO
  - Thermal IR (~10 micron)
    - 1e6 for Earth/Sun
    - 1e7 for Jupiter/Sun
- **Angular separation** (HZs at ~0.1”)
- **Exozodiacal light**

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

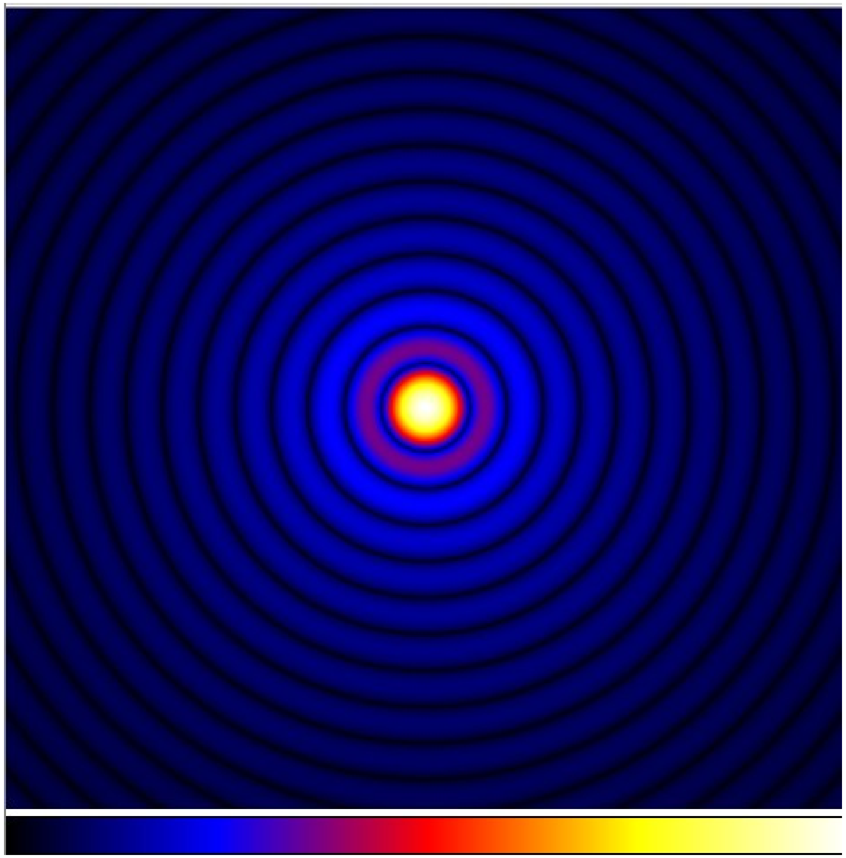
For interferometers: Optical pathlength sensing / correction (+ AO on individual apertures of the interferometer)

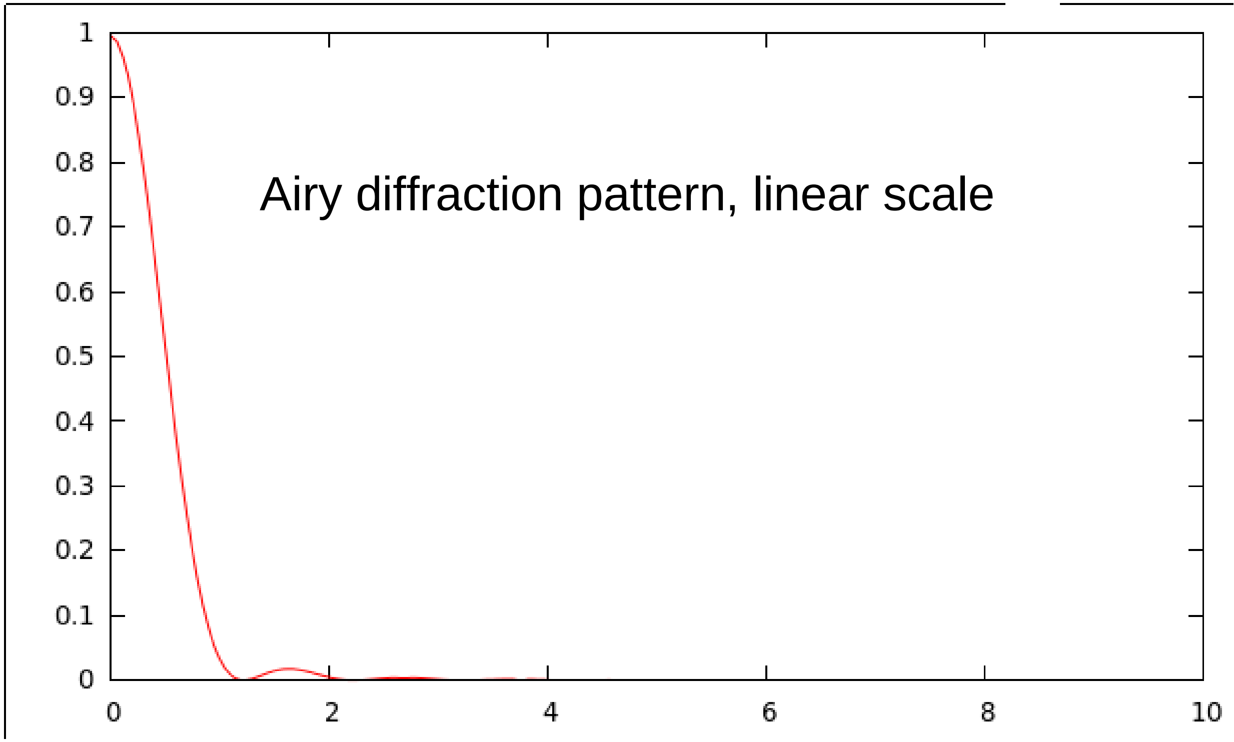
- Science detector for imaging, spectroscopy and polarimetry

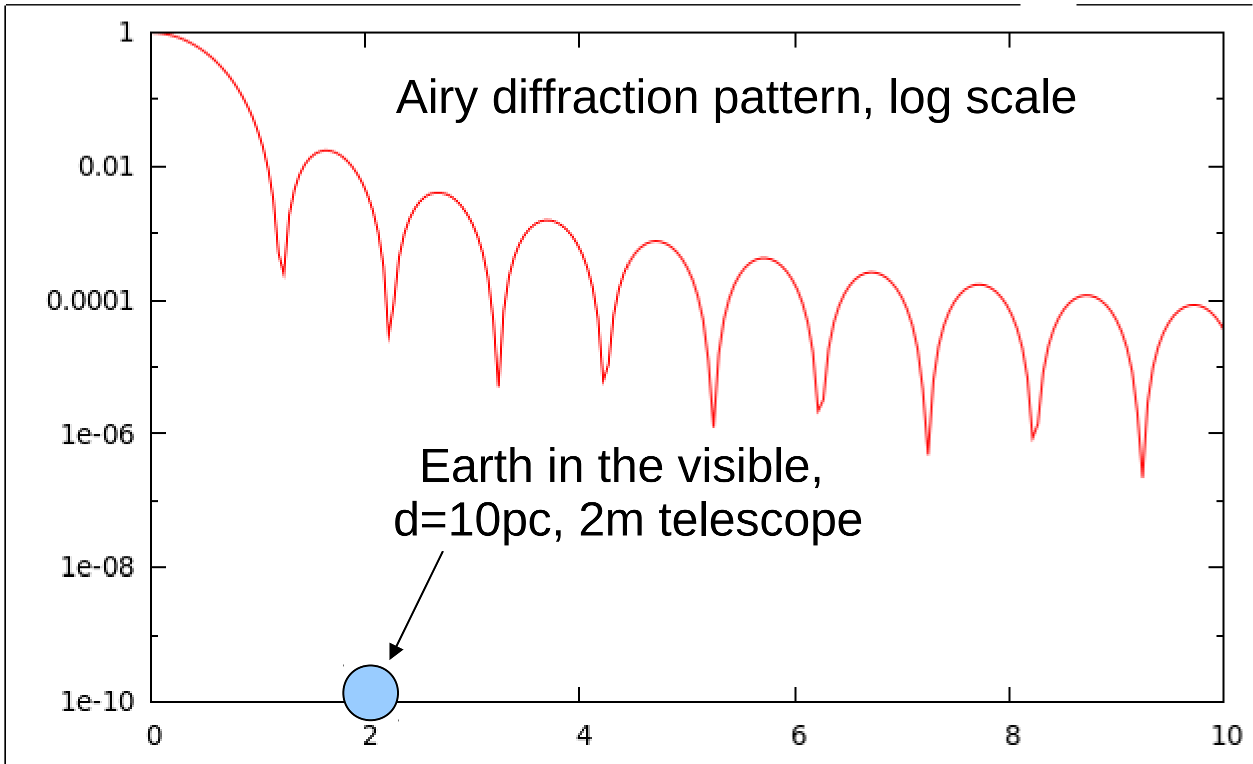
(note: the science detector can be part of the wavefront control system, and measure residual scattered light to be removed)

Why coronagraphy ?

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







Why do we need coronagraphs ?

Coronagraph can only remove known & static diffraction pattern
BUT:
- static & known diffraction can be removed in the computer
- coronagraphs don’t remove speckles due to WF errors

Fundamental reasons:
(1) Photon Noise
(2) Coherent amplification between speckles and diffraction pattern

Practical reasons:
(3) Avoid detector saturation / bleeding
(4) Limit scattering in optics -> “stop light as soon as you can”

Coherent amplification between speckles and diffraction pattern

Final image = PSF diffraction (Airy) + speckle halo

This equation is true in complex amplitude, not in intensity.
Intensity image will have product term -> speckles are amplified by the PSF diffraction.

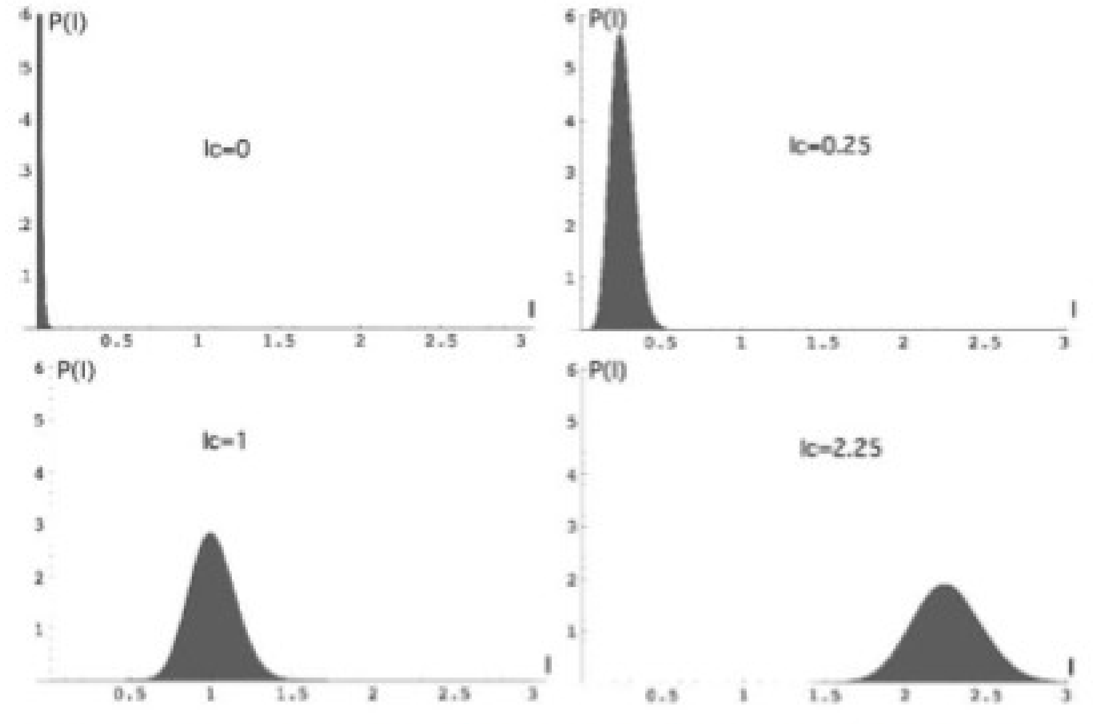


FIG. 3.—PDF of the light intensity at four different constant background intensity levels I_c and a single value of $I_s = 0.1$. High values of I_c correspond to locations near the perfect PSF maxima (rings), and low values of I_c correspond to locations near the zeros of the perfect PSF or far from the core. For $I_c = 0$ we have the pure speckle exponential statistics. The width of the distribution increases with an increase in the level of I_c. This explains speckle pinning; speckle fluctuations are amplified by the coherent addition of the perfect part of the wave.

Aime & Soummer 2004

When do we need coronagraphs ?

Coronagraphs serve no purpose if dynamic speckle halo is > diffraction
-> Very important to keep in mind to **avoid over-designing the coronagraph**, as this usually would mean giving up something (usually throughput)

“Side effects” of coronagraphs :

- (Usually) requires very good pointing. Risk of low order aberrations (for example pointing) creating additional scattered light in the region of interest

- data interpretation & analysis can be challenging (especially at inner working angle)

- Astrometry more difficult (solutions exist)