Exoplanets
Direct imaging

Planets and Astrobiology (2020-2021)
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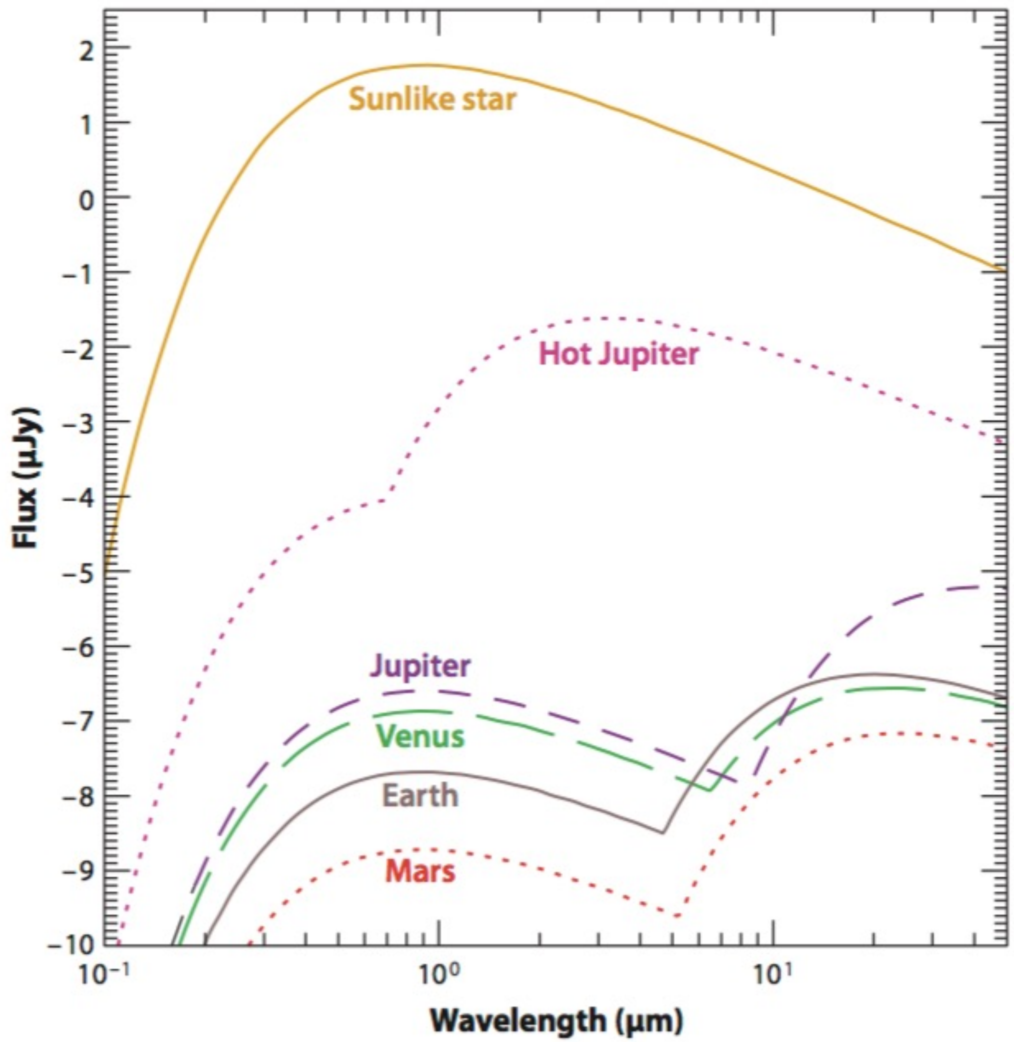
Direct method of exoplanet detection

- Direct imaging
  - The image of the planet is searched for in the field of the star

- Observational challenges
  - Planet-star luminosity contrast
  - Planet-star angular separation

- Both challenges set strong constraints on the observational techniques
  - The luminosity contrast can be quantified with simulations of stellar and planet spectra

Black body flux (in units 10^{-26} W m^{-2} Hz^{-1}) of some Solar System bodies as "seen" from 10 pc. A putative hot Jupiter is also shown. The planets have two peaks in their spectra. The short-wavelength peak is due to sunlight scattered from the planet using the planet's albedo. The long-wavelength peak is from the planet thermal emission estimated by a black body of the planets's effective temperature.



Seager & Deming (2010)

Direct imaging: observational challenges

- Luminosity contrast

  L_p/L_*

  – Optical spectral band

  reflected stellar radiation

  varies with the orbital phase

  contrast ~ 10^9-10^{10}

  – Infrared spectral band (~10 μm)

  intrinsic planetary emission

  contrast ~ 10^6-10^7

Optical band

$$L_p \sim L_* \left(\frac{R_p}{a}\right)^2 \Phi(t)$$

$$\Phi(t) = 1 - \sin i \, \sin\left(\frac{2\pi t}{P}\right)$$

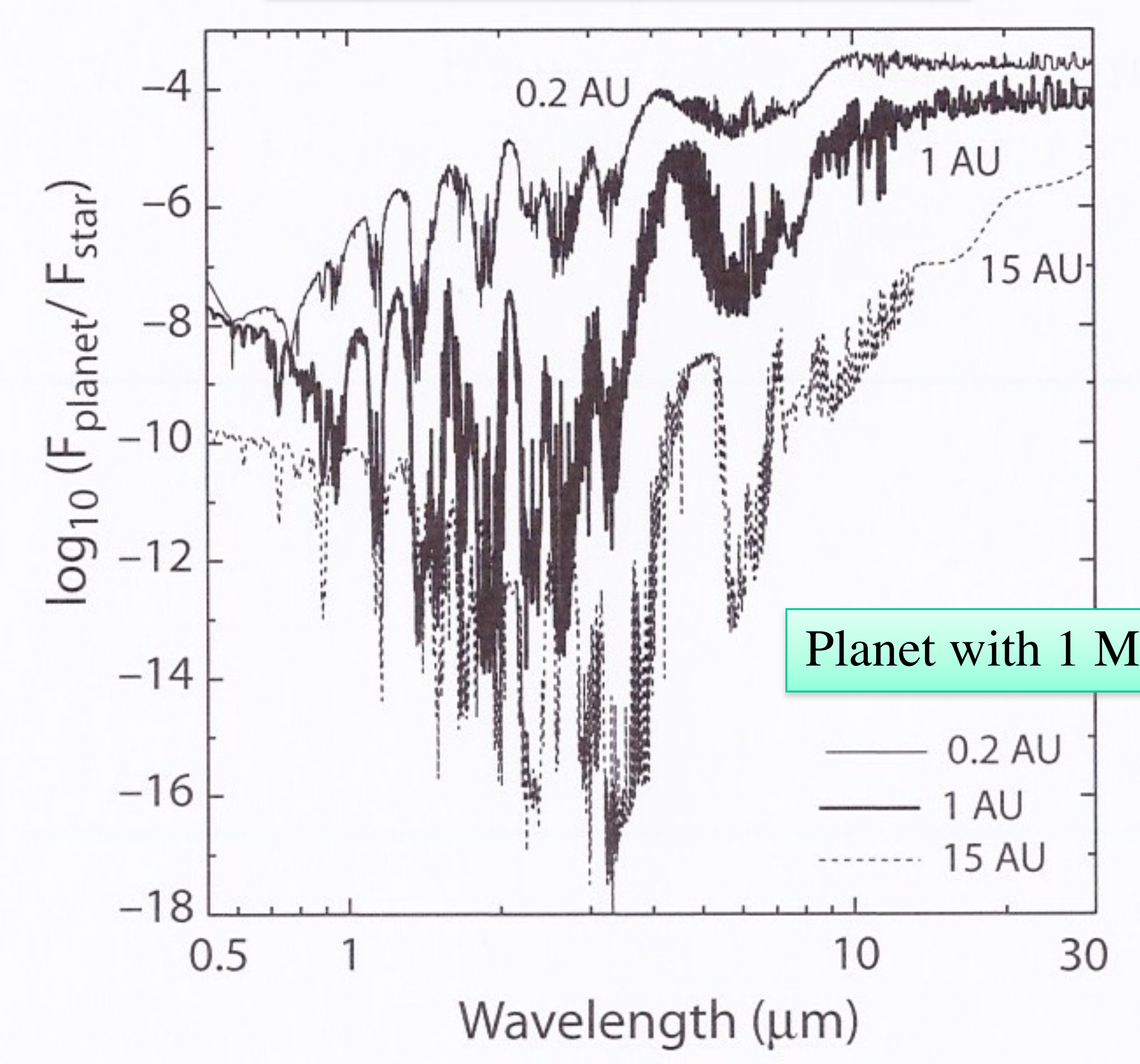
Infrared band

$$L_p \sim L_* \, (M_p/M_*)$$

Luminosity constrast versus wavelength

Models for giant planets orbiting a solar-type star, cloud effects included

Dependence on orbital distance

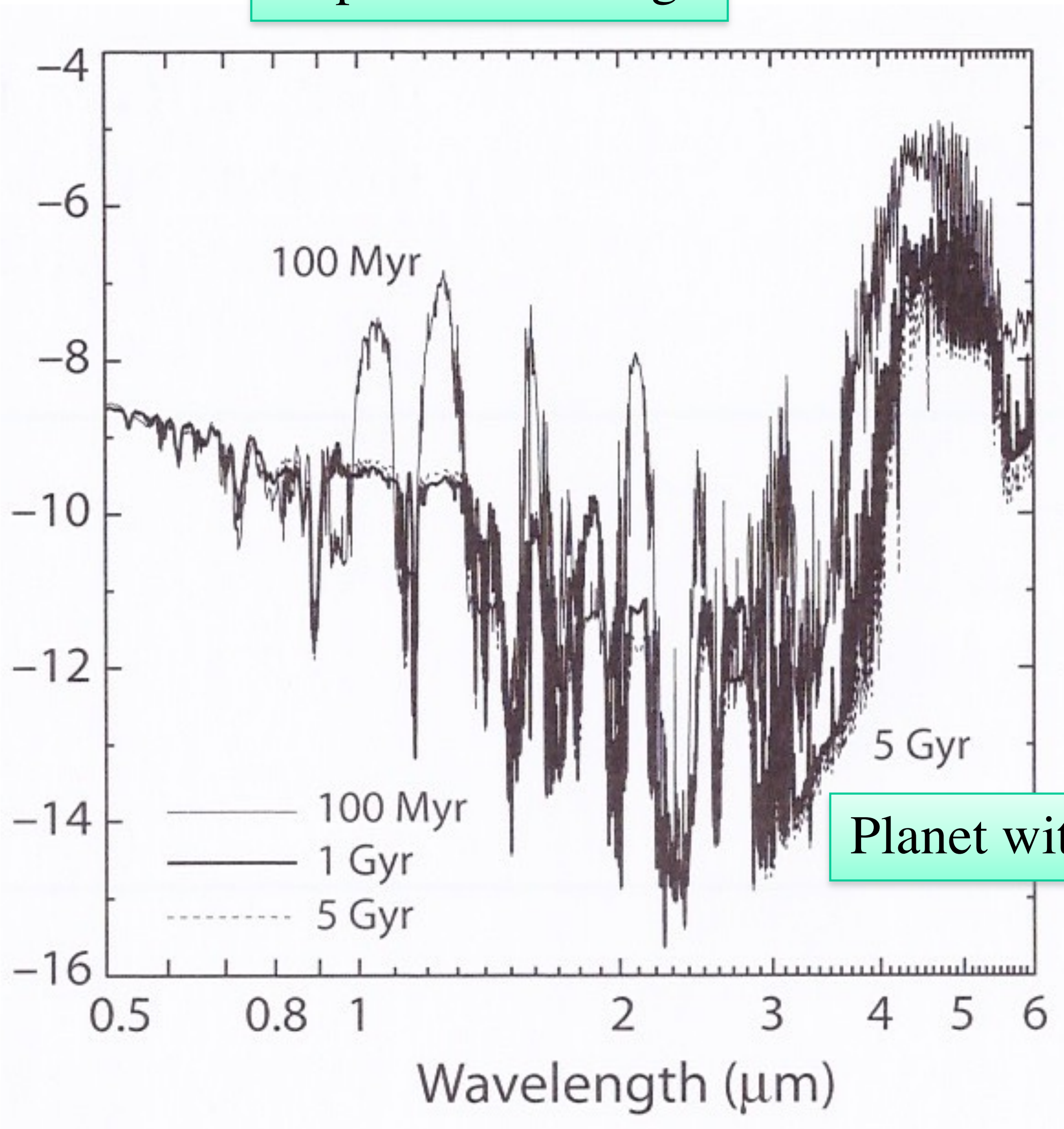


Planet with 1 M_J, age 5 Gyr

Luminosity constrast versus wavelength

Models for giant planets orbiting a solar-type star, cloud effects included

Dependence on age

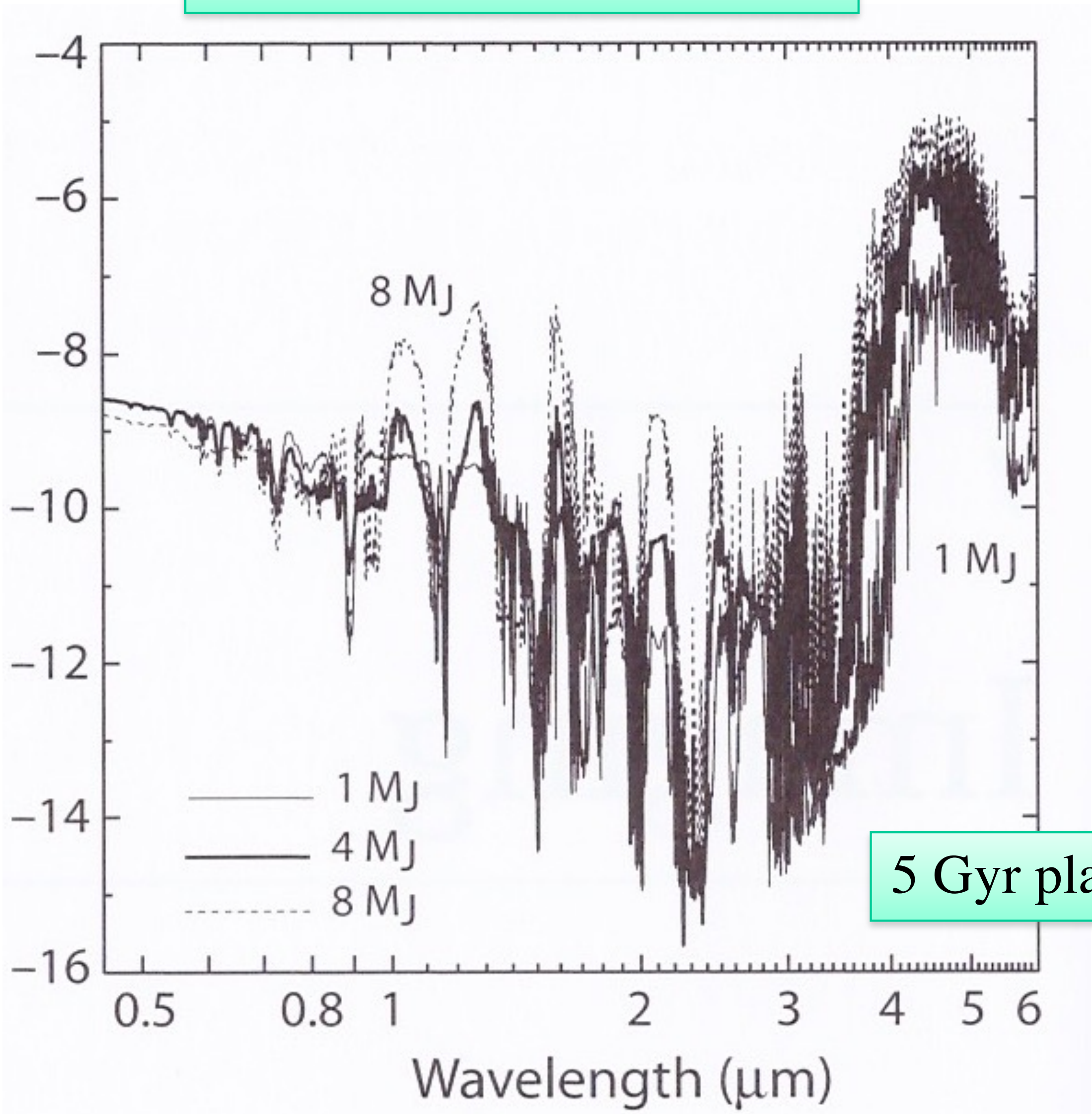


Planet with 1 M_J at 4 AU

Luminosity constrast versus wavelength

Models for giant planets orbiting a solar-type star, cloud effects included

Dependence on planet mass



5 Gyr planet at 4 AU

Direct imaging: observational challenges

- Planet-star angular separation

The angular separation is estimated as a function of stellar distance, *l*, and orbital semimajor axis of the planet, *a*

$$\vartheta = \arctan \frac{a}{\ell}$$

Typical values are lower than 1 arcsec
e.g., the Earth-Sun separation as seen from 20 pc is 50 mas

The luminosity contrast makes hard to attain the theoretical diffraction limit $\delta\vartheta \cong \lambda/D$ (radius of the Airy disk)

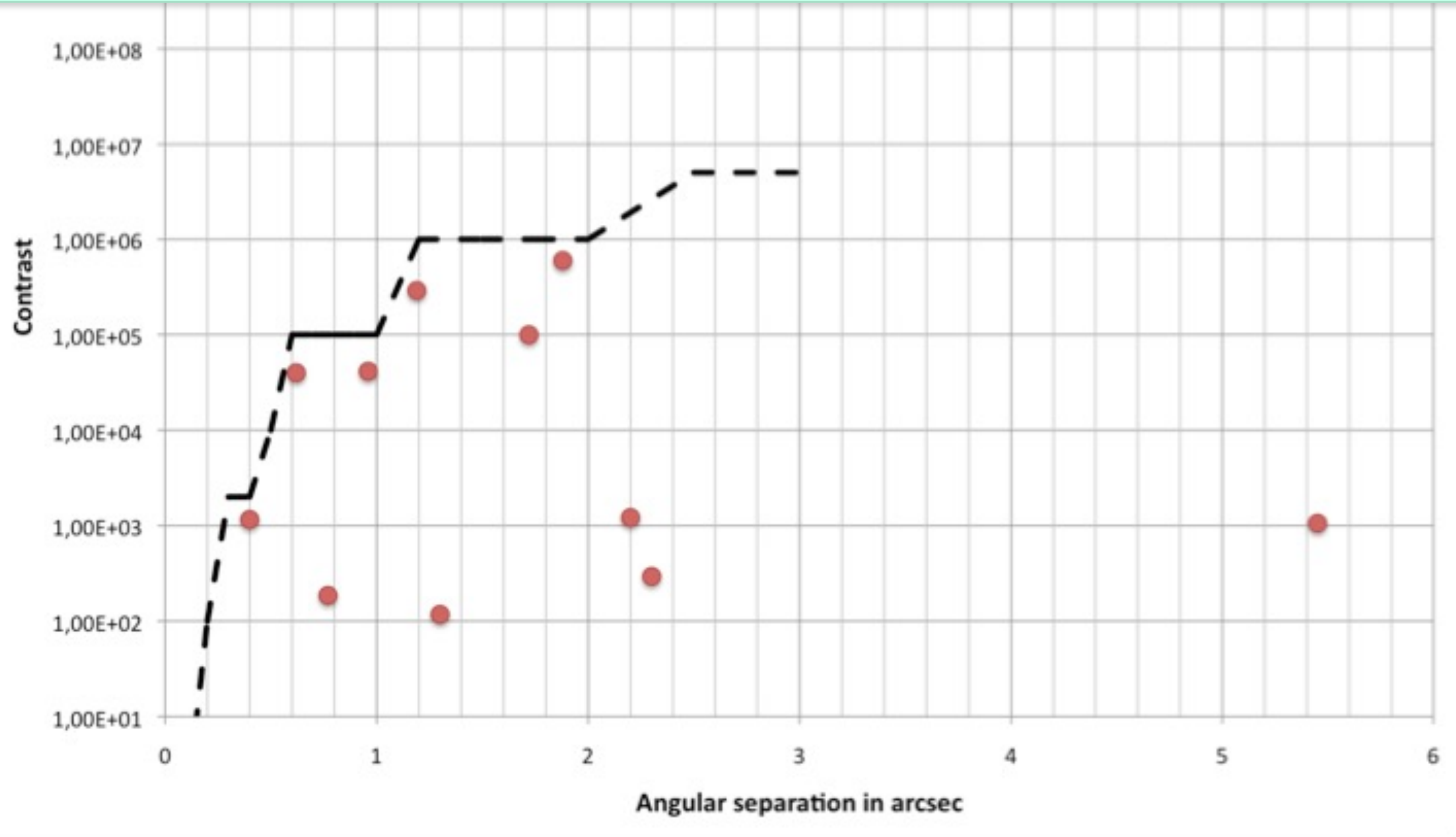
D : telescope diameter

λ : wavelength of the observations

Angular separation and luminosity contrast

The maximum luminosity contrast increases with angular separation

Dashed line: example of maximum luminosity constrast that can be attained for a given instrumental setup



Direct imaging of exoplanets

- Observational bias
  - Due to the observational challenges specific of the direct imaging method, the following types exoplanets are preferentially found

    (1) around nearby stars (small l)

    (2) with wide orbits (large a)

    (3) with high intrinsic emission (e.g. young and massive)

    (4) with high planet/star mass ratio M_p/M_*

Direct imaging of exoplanets

- Observable quantities
  - Orbital parameters

    Given the stellar distance l, one can determine the orbital semimajor axis a from the angular separation ϑ

    Given a, the orbital period P is estimated with the third Kepler's law

  - Effective temperature

    The effective temperature can be determined from the energy distribution of the planet spectrum

    The spectral distribution can be estimated by comparing photometric measurements taken in different spectral bands

  - Emission spectrum of the planet

    If the source is sufficiently bright, a spectrum can be taken

    The spectrum can be used to study the (atmospheric) chemical composition of the planet

Direct imaging of exoplanets

- Model-dependent planetary parameters
  - Planet mass and size

    Mass and size can be estimated combining the measurement of planet emissivity with a model of planet evolution

    The error on the masses estimated in this way can be quite large and is also related to the uncertain age of the system

- Advantages of the direct imaging method
  - Allows us to study planets distant from the star
  - Not affected by the temporal baseline bias (a single observation yields a, from which one can determine P)
  - Not affected by variability of the central star
  - Best way to obtain *direct* informations on the properties of exoplanets

Direct imaging of exoplanets:
Techniques to deal with the luminosity contrast

- Coronagraphic techniques
  - High contrast can be achieved by rejecting the stellar light from the area of interest in the focal plane
  - The technique, employing some form of mask in the telescope focal plane, is referred to as *coronagraphy*

    Coronagraphy was originally developed to study solar corona, a tenuous structure of higly ionized gas that surrounds the Sun, which is hard to observe due to the extremely high luminosity constrast with the solar disk

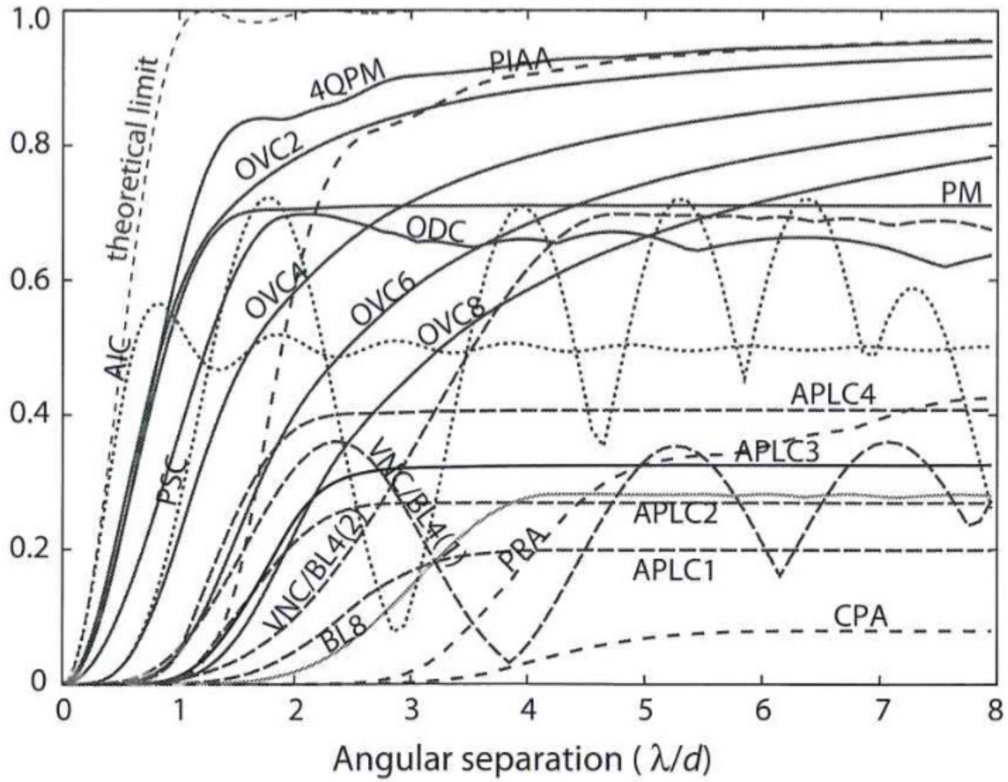
Ideally, a coronagraph coupled to an adaptive optics system would perform as if placed above the atmosphere

Direct imaging of exoplanets:

Techniques to deal with the luminosity contrast

- Developments and limits of coronagraphic techniques
  - Alternative concepts for high-rejection coronagraphs have been stimulated by the interest in exoplanet imaging
  - A variety of designs theoretically able to achieve 10^{10} constrast within 5 λ/D are being developed

Throughput at the 10^{10} contrast level



Direct imaging of exoplanets:

Atmospheric turbulence

Ground-based telescopes do not attain the theoretical diffration limit because the resolution is limited by the turbulence in the atmosphere

The atmosphere has density enhancements (turbulent cells) of size d_o~0.1m that are carried across the telescope line of sight by high-altitude winds

Segments of the wavefront comparable to the size of the turbulent cells will be nearly planar (isophase patches)

Each isophase patch uses ~ 0.1m of the telescope aperture and its image is the Airy disk of a 0.1m telescope, i.e. $\lambda/d_o \sim 1''$

The summation of the images from all the isophase patches across the line of sight will yield an image with size ~1″, much larger than the theoretical angular resolution $\delta\vartheta \sim \lambda/D$

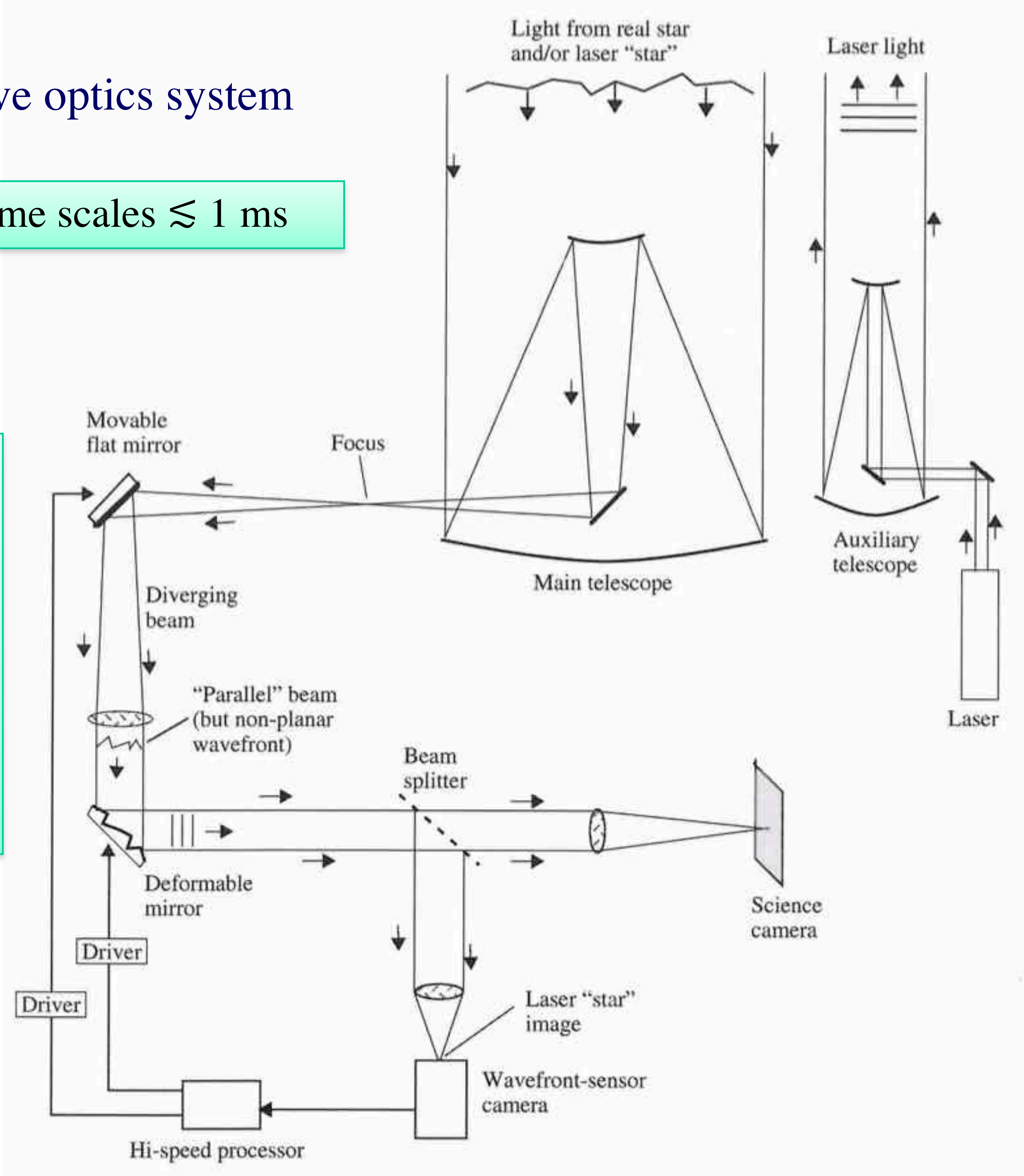
Techniques to deal with atmospheric turbulence:
Adaptive optics

- Consists in the real time control of the optics of a telescope to counteract atmospheric turbulence
- Must be very fast to track the atmospheric turbulence, which varies with a time scale of order ~1 millisec
- Requires an ancillary system that senses the instantaneous shape of the atmospheric wavefront
  - Wavefront sensing is performed using a bright reference star and/or the atmospheric reflection of a laser beam (“artificial star”)
- The information on the wavefront is used to detect deviations from a planar wave with proper centroid location
  - Corrections are then applied to deformable mirrors located along the optical path
  - The modified beam is then sensed and the feedback-loop process continues

Sketch of an adaptive optics system

The loop must work on time scales $\lesssim$ 1 ms

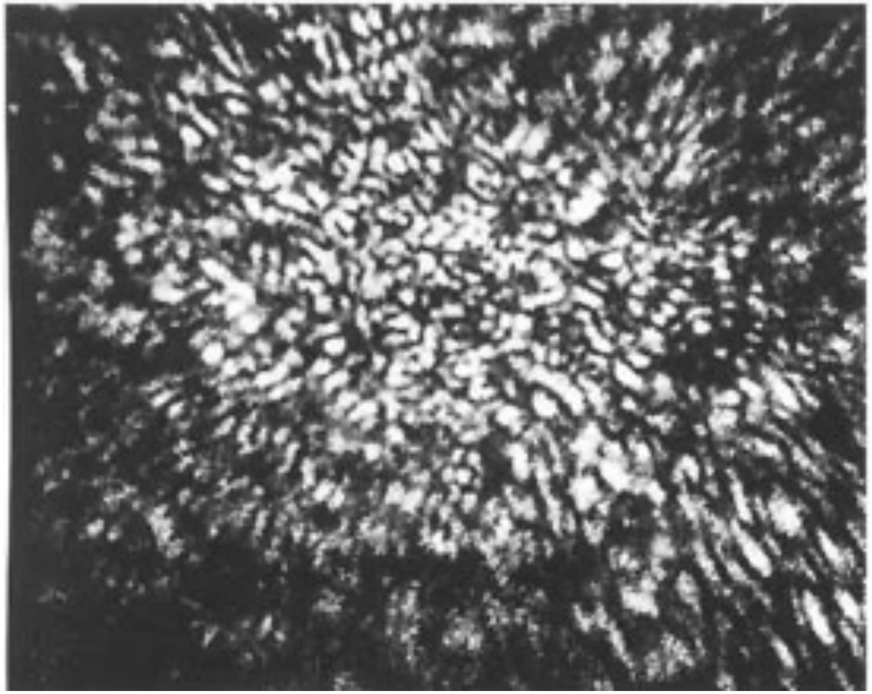
The movable flat mirror moves the image centroid to keep it in a single position in the focal plane; this reduces the excursions required on the actuators of the deformable mirror



Techniques to deal with atmospheric turbulence:
Speckle interferometry

It works by obtaining images of the object sufficiently rapidly (e.g., ~1-10 ms) to freeze the blurring that arises from atmospheric scintillation

The resulting image of a point source then consists of a large number of small dots or speckles, each of which is a diffraction limited image with effective value of d up to the actual diameter of the telescope



Example: speckle images of Vega first obtained in the ‘70s

- Speckle imaging techniques
  - In the *image stacking*, the short exposure images are lined up by the brightest speckle and averaged together to give a single image
  - In the *Lucky Imaging* approach, only the best few short exposures are selected
  - *Speckle interferometry* makes use of Fourier analysis to obtain the high-resolution structure of the object from the speckle patterns
  - Practical procedure

    Record many frames rapidly

    Take the power spectrum of each frame and average

    Divide the power spectrum of the target by the power spectrum of a point source

    Fit a model (e.g. planet around a central star) to the true Fourier transform of the object

Direct imaging of exoplanets
Examples

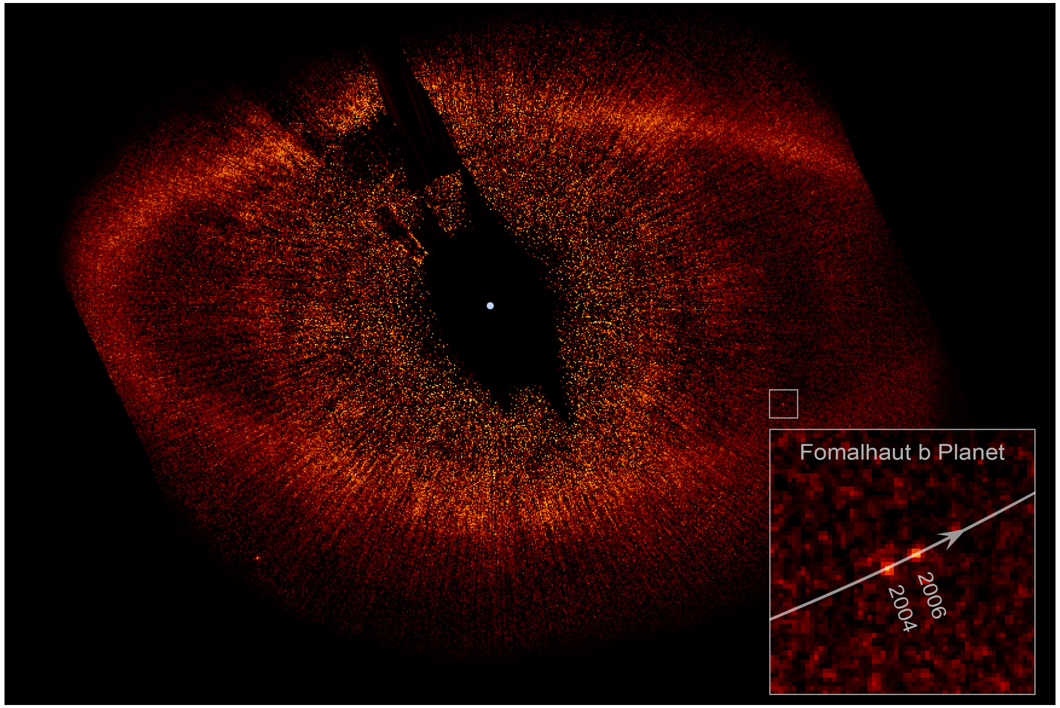
– Fomalhaut b

discovered in 2008 from a re-analysis of previous HST data

a = 119 AU; e ~ 0.11 ; M ~ 3 M_J ; P ~ 870 yr

Formalhaut: d = 8 pc

Kalas et al. (2008)



Direct imaging of exoplanets
Examples

AB Pic b

M = 13 M_J

close to the brown dwarf boundary

a > 80 AU

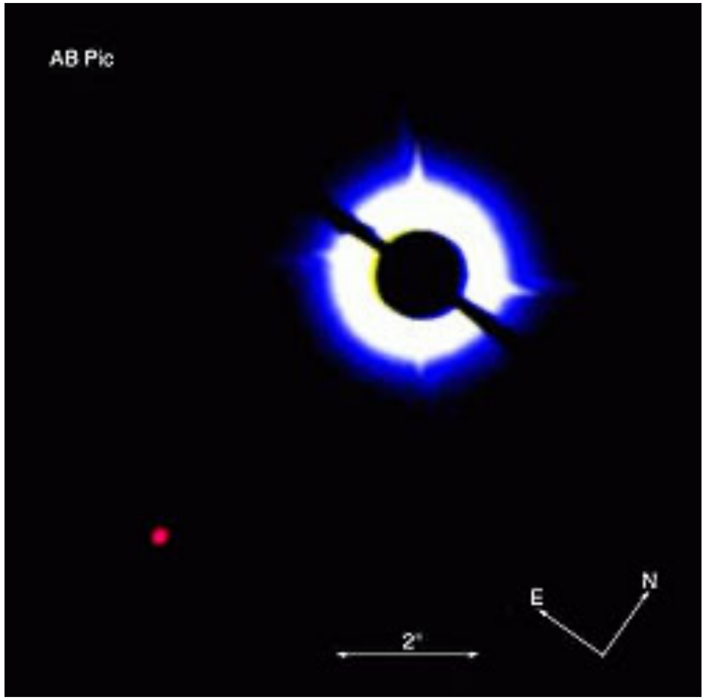
AB Pic, K2 V

d = 47 pc

Discovered using near-infrared Lyot coronagraphic observations

NACO at ESO-VLT

Chauvin et al. (2005)



Direct imaging of exoplanets

Examples

GJ 504 b

$M = 4\ M_J$

$a = 44$ AU

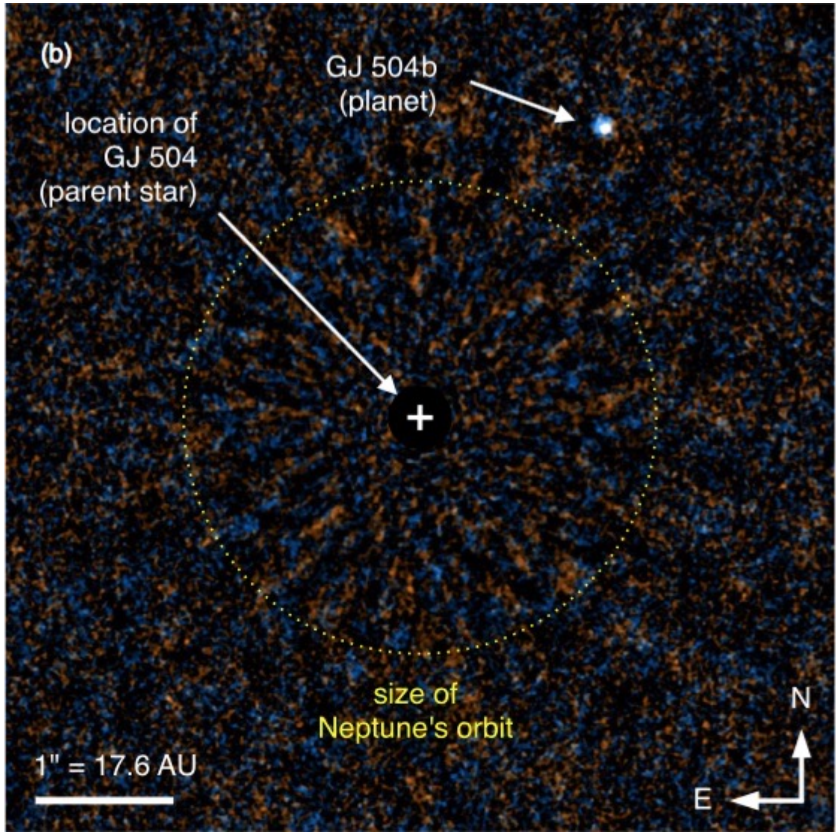
Sun-like star GJ 504

$d = 17.6$ pc

Lowest temperature (510 K) exoplanet observed with direct imaging

Adaptive optics, occulting mask, near infrared

Kuzuhara et al. (2013)



Multiple planetary systems detected with direct imaging

Example:

HR 8799 b, c, d

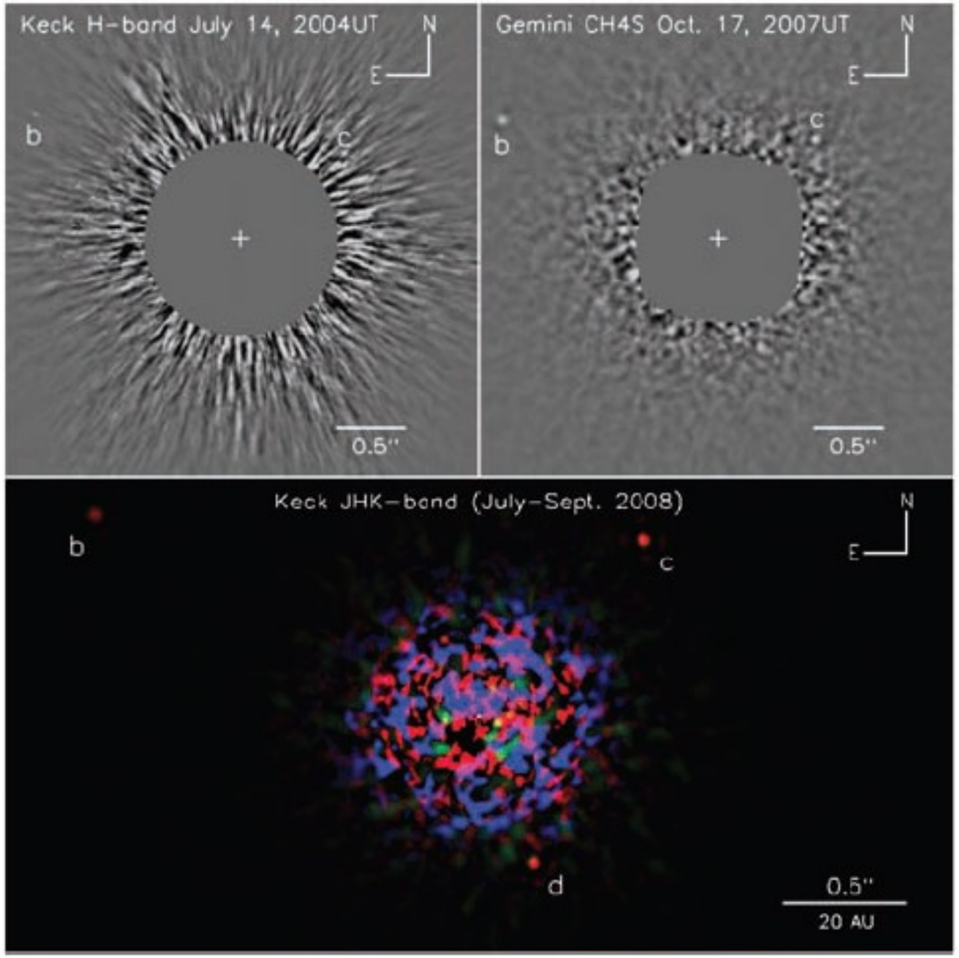
M = 7, 10, 10 M_J

a = 68, 38, 24 AU

d = 39 pc

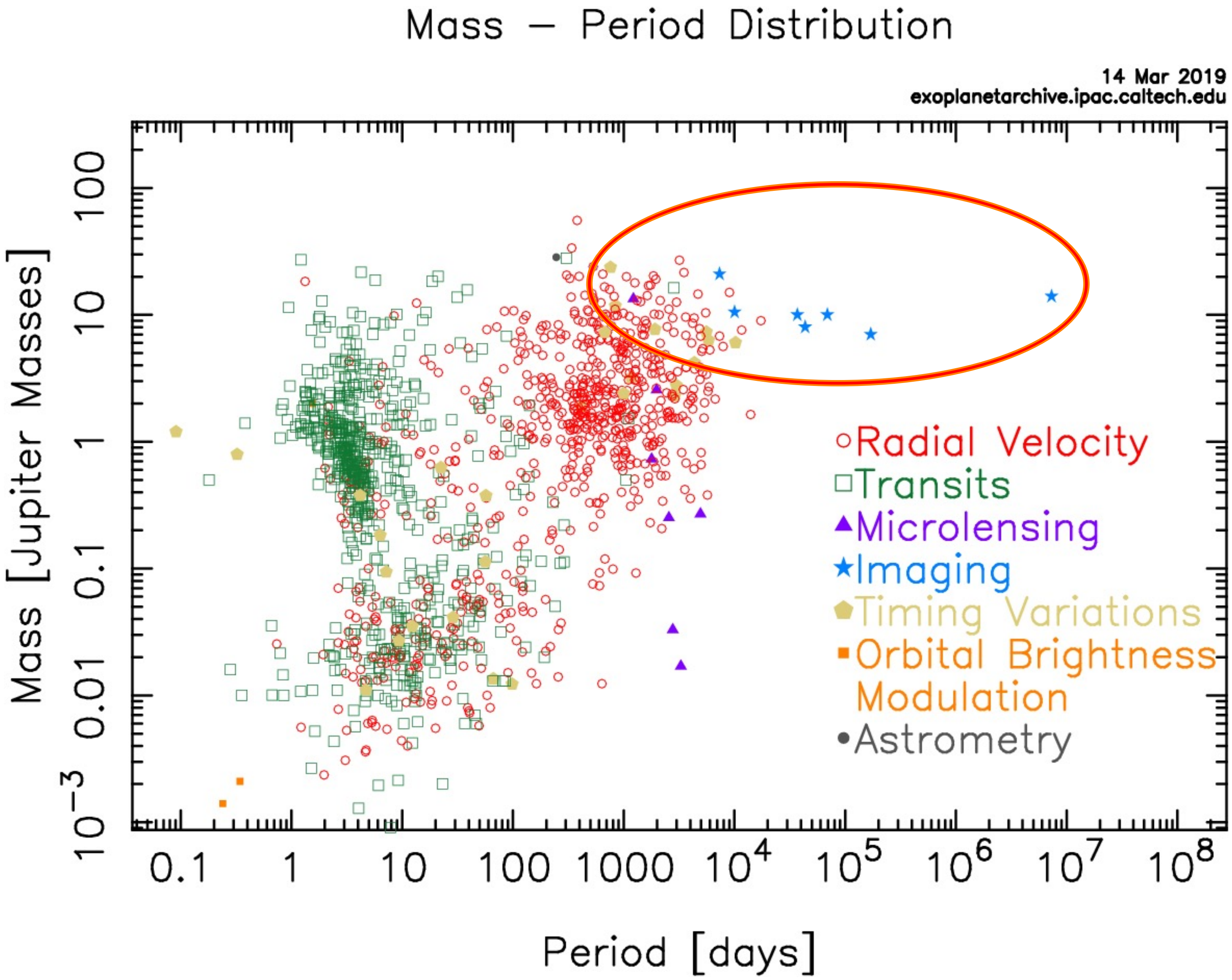
Coronagraphic and speckle imaging techniques in the infrared

(Marois et al. 2008)



Direct imaging: summary of results

About a hundred planets has been detected with the direct imaging method. These planets are quite massive and distant from the central star.



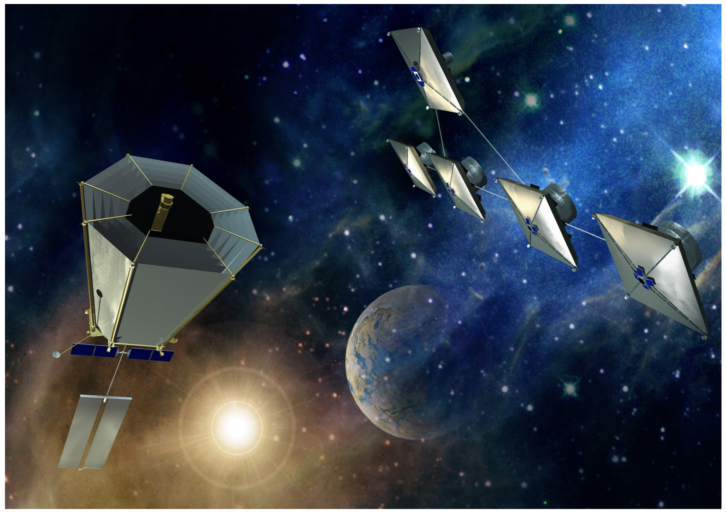
Direct imaging of exoplanets

Future perspectives

- Occulters
- Infrared space interferometers
- Nulling interferometry

- Space projects (suspended)
  – ESA Darwin
  – NASA Terrestrial Planet Finder (TPF)

- Ground based projects
  – examples:
    SPHERE at ESO VLT (active)
    EPICS at ESO E-ELT (future development)



- Nulling interferometry
  - Introduces destructive interference between the pupils of two telescopes for an on-axis star
  - Identical path lengths through the two beams leads to an interference maximum for an on-axis source
  - Introducing a phase difference of π rad in one of the paths suppresses the central maximum
  - By varying the baseline D, a range of constructive interference angles can be examined for the presence of an off-axis source