Chapter 3: Exosolar Planets

Part 1: Clever techniques for detecting extrasolar planets and planetary systems

Brightness of extrasolar planets

What's the problem?

Nearest stars are about 50,000 times further away than Jupiter – i.e. 3×10^9 fainter in brightness.

[In astronomical magnitudes, $m = -2.5 \log f + \text{const.}$]

$m_{\text{Jupiter}} \sim -2 \rightarrow m_{\text{planet}} \sim 21.6$ (easy!)

Angular separation 3.8 arcsec (should also be easy!)

Brightness of extrasolar planets

Planets will shine by both reflected (sun)light and thermal emission. Assuming an albedo of a and radius r of the planet a distance D from a star of radius R_s and temperature T_s, and neglecting non-stellar heat sources:

Reflected sunlight:

$$L_p = a\, 4\pi R_s^2 \sigma T_s^4 \frac{2\pi r^2}{4\pi D^2} = L_s a \frac{r^2}{2D^2}$$

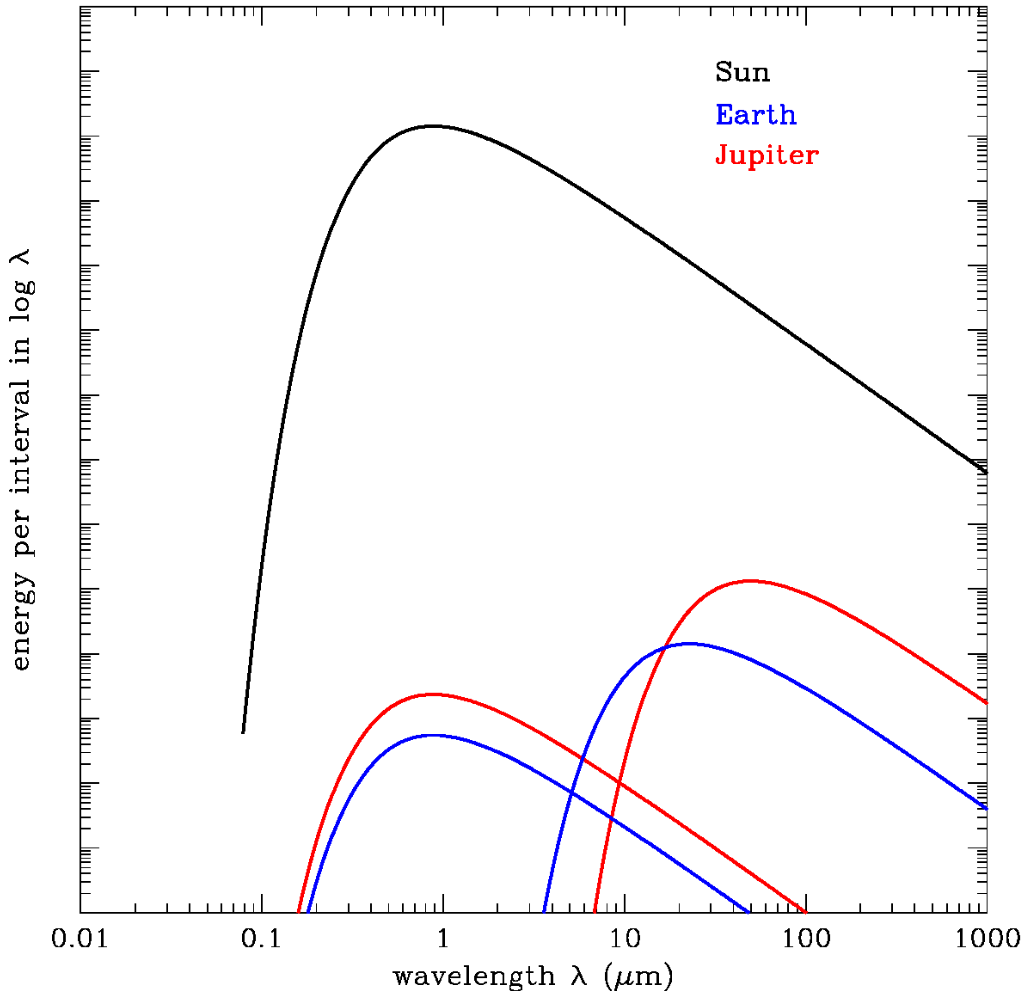
Self-emission:

$$L_p = (1-a)\, L_s \frac{r^2}{2D^2} = (1-a) 4\pi R_s^2 \sigma T_s^4 \frac{r^2}{2D^2}$$

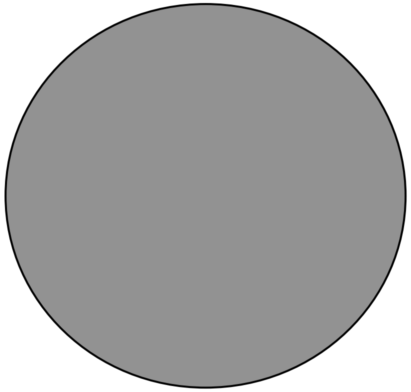
$$T_p = \sqrt[4]{\frac{L_p}{4\pi\sigma r^2}} = T_s (1-a)^{1/4} \sqrt{R_s / 2D}$$

	radius	distance	$r^2/2D^2$
Earth	6.3×10^6 m	1.6×10^{11} m	7.8×10^{-10}
Jupiter	7.1×10^7 m	7.8×10^{11} m	4.1×10^{-9}
Sun	7.0×10^8 m	---	---

- Brightness contrast relative to Sun is ~ **10^9** at $\lambda < 1\mu$m, and still **10^5** at $\lambda \sim 100\ \mu$m
- Note: Earth is brighter than Jupiter at 10 μm!



Sun, Earth and Jupiter



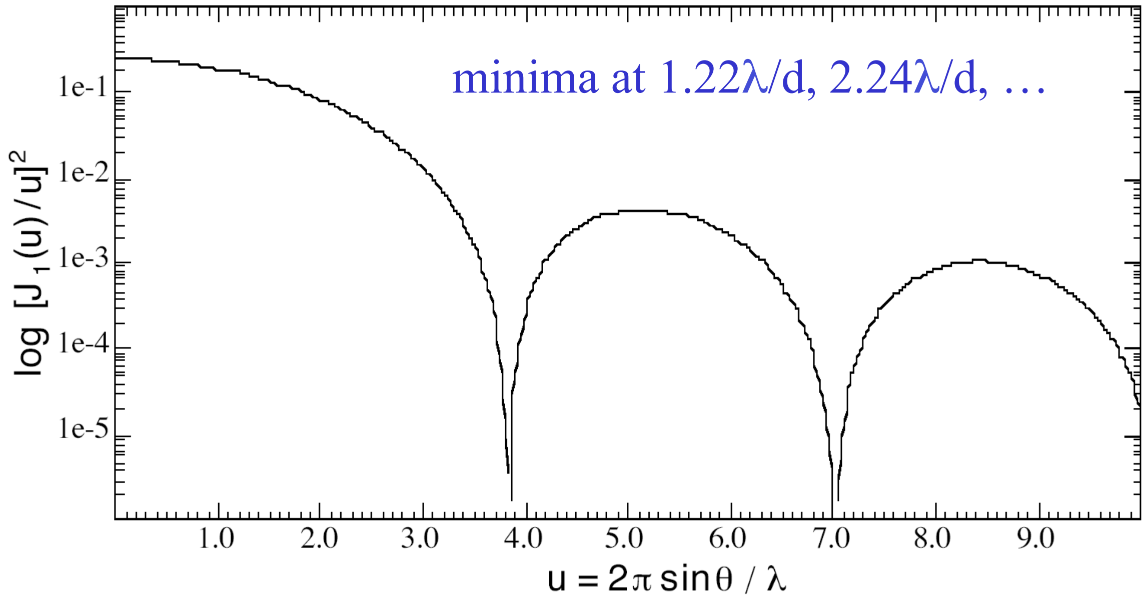
Diffraction from ideal telescope aperture:

Point spread function of telescope (image of point source) is Fourier transform of entrance aperture:

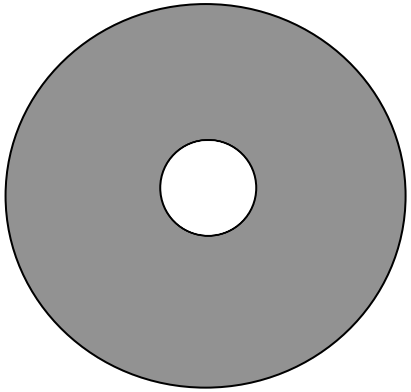
For an idealised perfectly circular aperture:

$$I(\theta) = I_0 \left(\frac{2J_1(u)}{u} \right)^2 \qquad u = 2\pi\theta / \lambda$$

J_1 = 1st order Bessel function of first kind



84% of energy within a diameter of 1.22λ/ d (~ 0.015 arcsec for 8 m telescope at visible wavelengths 550 nm), but scattered light decreases slowly with radius



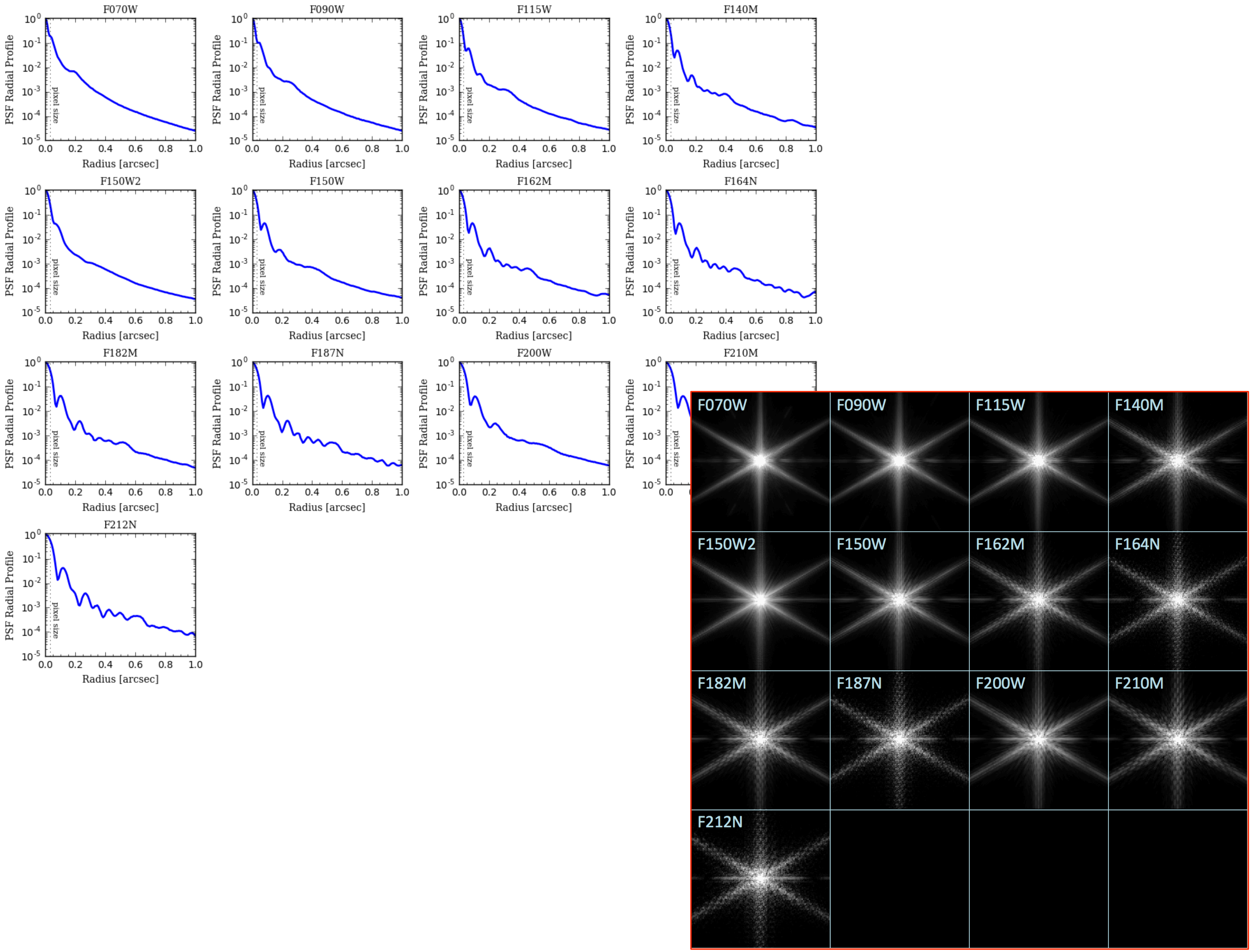
In practice it is even worse

"On-axis" telescopes usually have central obstruction of some kind

Imperfections throw light to large angles

Plus: Phase errors across aperture due to variations in atmospheric refractive index (for ground-based telescope) produce approximately gaussian images of typical FWHM ~ 0.5-1.2 arcsec ~ 30 × diffraction limit

Airy pattern


F070W
F090W
F115W
F140M
F150W2
F150W
F162M
F164N
F182M
F187N
F200W
F210M
F212N
PSF Radial Profile
Radius [arcsec]
pixel size
F070W
F090W
F115W
F140M
F150W2
F150W
F162M
F164N
F182M
F187N
F200W
F210M
F212N

A: Indirect searches (do not detect the light from planet)

1. Radial velocity measurements (and pulsar timing)
2. Astrometric searches
3. Transits
4. Gravitational lensing

B: Direct searches

Use different approaches to subtract the dominant star-light

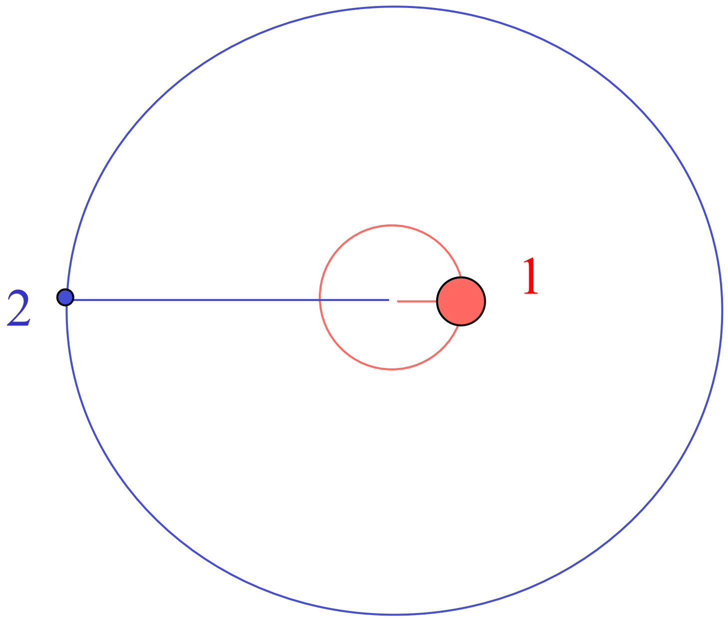
1. Coronagraphy
2. Adaptive optics
3. Polarimetry and/or spectral chopping
4. Interferometry and nulling interferometry

1. Doppler (radial velocity) methods

Simple two-body problem in Newtonian gravity: both bodies orbit their common center of mass → detectable shifts in radial velocity (and/or astrometric position on sky) during orbit.

High stability high resolution spectrographs can measure radial velocities of bright stars at the < 1 m/s level through Doppler shift of wavelengths:

$$\frac{v_r}{c} = \frac{\lambda_{obs} - \lambda_{rest}}{\lambda_{rest}} = \frac{\Delta\lambda}{\lambda}$$



$$\frac{v_1^2}{r_1} = \frac{Gm_2}{(r_1 + r_2)^2}$$

$$m_1 r_1 = m_2 r_2$$

$$2\pi r_1 = v_1 P$$

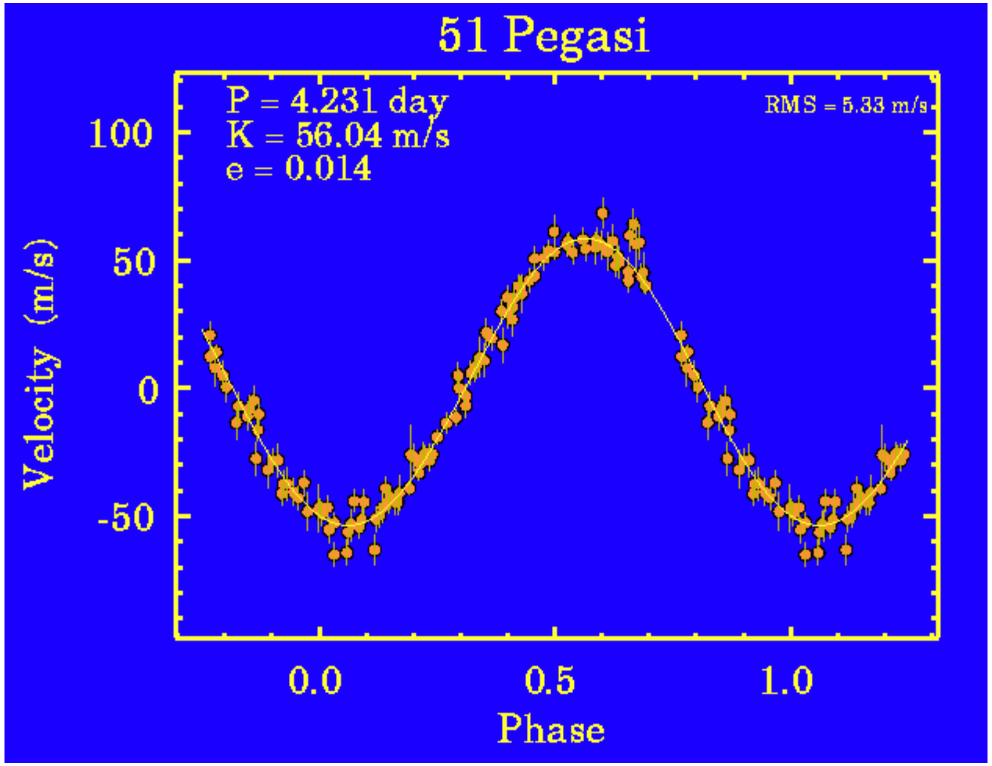
$$\boxed{m_2 = m_1^{2/3} \left(\frac{P}{2\pi G} \right)^{1/3} v_1}$$

We know m_1 from the type of star

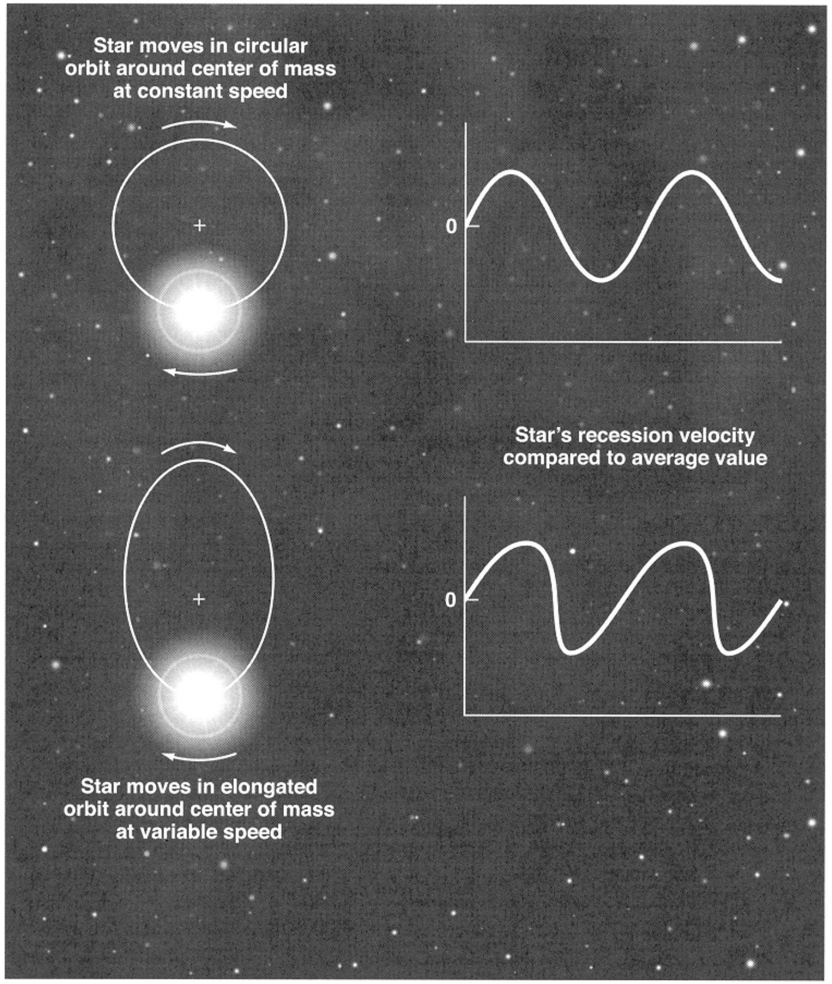
$$v_r = v_1 \sin i$$

We don't a priori know the inclination of the orbit w.r.t. the line of sight, and measure only the radial component v_r (relative to us) of v_1, so the measurement is actually of $m_2 \sin i$. A lower limit on m_2 is obtained with $\sin i = 1$.

51 Peg discovered 1995 by Mayor and Queloz (Geneva)



Circular orbits give sinusoidal wave $v_r(t)$



Eccentric orbits give distorted wave

What about the observability (to others!) of our own Solar System?

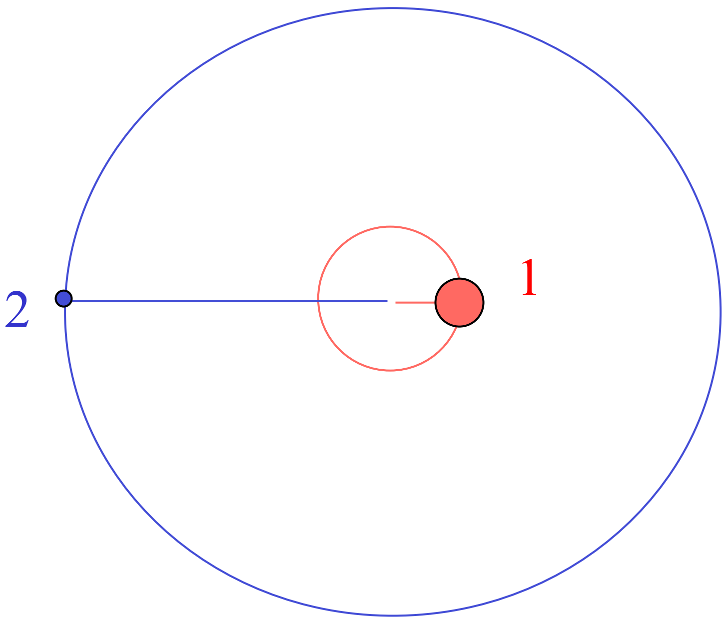
$$v_1 = v_2 \frac{m_2}{m_1}$$

	v_2	m_2/m_{sun}	v_1
Earth	30 kms^{-1}	3.0×10^{-6}	0.1 ms^{-1}
Jupiter	13 kms^{-1}	1.0×10^{-3}	13 ms^{-1}

For a given m_1, easier detection for higher m_2, and smaller r, i.e. smaller P ($\propto r^{-1/2}$).

Note: in principle the signal Δv is independent of the distance to system (but of course star is fainter at larger distances so harder to measure v)

2. Closely related: timing methods



Precise clocks in orbit change speed for distant observers (can think of either as Doppler shift during approach/recession or as light travel time across the orbit)

- Δ(rate)/rate $\sim v_r/c$
- $\Delta t \sim r/c$

Same sin *i* inclination effects as before

> Aside: this is effectively the same method as Römer used to determine speed of light using Jupiter's moons as "clocks" in 1676

Observability for timing methods

$$\Delta t = \frac{r_2}{c} \frac{m_2}{m_{star}}$$

	r_2	m_2/m_{sun}	Δt
Earth	8 light minutes	3.0×10^{-6}	1.4 msec over 1 year
Jupiter	40 light minutes	1.0×10^{-3}	2.4 s over 12 years

Pulsars: rapidly rotating neutron stars ($M \sim 1\ M_{\odot}$, $r \sim 10$ km, $P \sim$ few ms – few s)

PSR 1257+12 (1992): Three roughly one Earth-mass "planets" orbiting a spinning neutron star at 0.2-0.5 AU (plus possible 35 AU Saturn-mass object): Life?

- No light
- Hazardous radiation
- SN explosion few million years ago

2. Astrometric methods

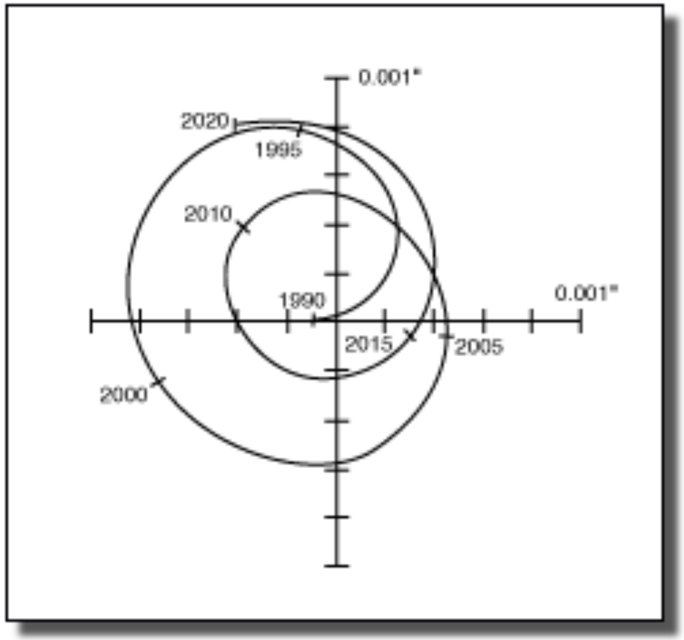
Motion of star around center of mass produces change in position on sky (superimposed on any systematic motion due to stars velocity through space).

(Note center of mass of Sun-Jupiter system is 0.9 R_{sun} from the center of the Sun)

Observability for astrometric methods

Note: Angular displacement decreases with the distance to the star as d^{-1}

$$\Delta\theta = \frac{r_2}{d}\frac{m_2}{m_{star}}$$



Astrometric displacement of the Sun due to Jupiter as seen from 10 parsecs.

Assume d = 10pc	r_2	m_2/m_{Sun}	$\Delta\theta$
Earth	1 A.U.	3.0×10^{-6}	0.3 μarcsec
Jupiter	12 A.U.	1.0×10^{-3}	0.1 marcsec

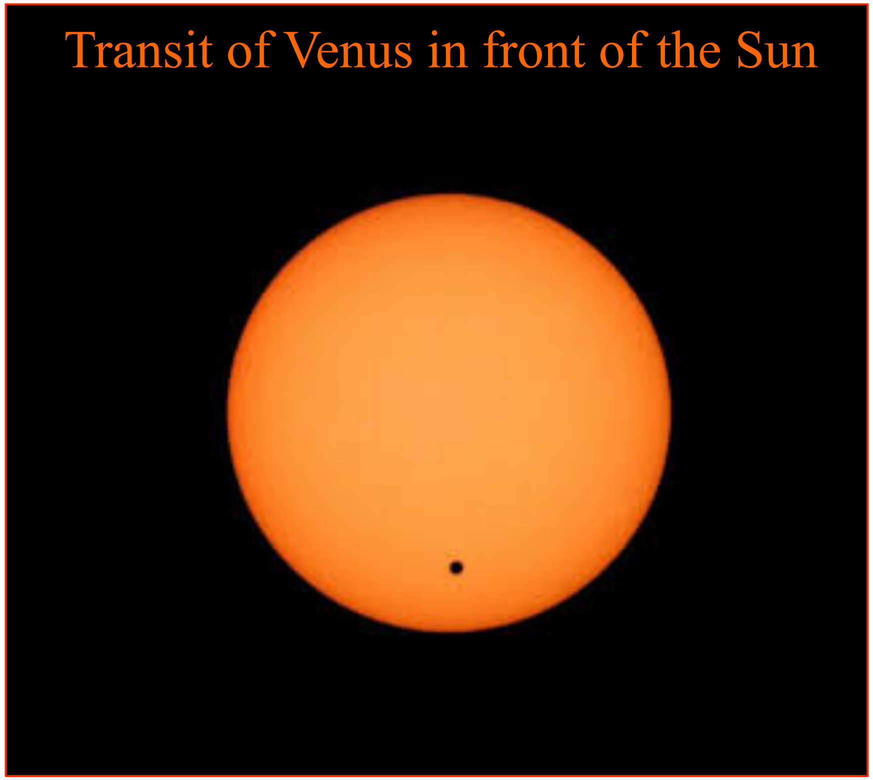
3. Occultations

Jupiter has 0.1 × radius of Sun, i.e. 1% of area. When Jupiter passes in front of Sun (for an extrasolar observer) the brightness of Sun drops by 1% for ~ 15 hours

→ monitor large numbers of stars hoping for occultations

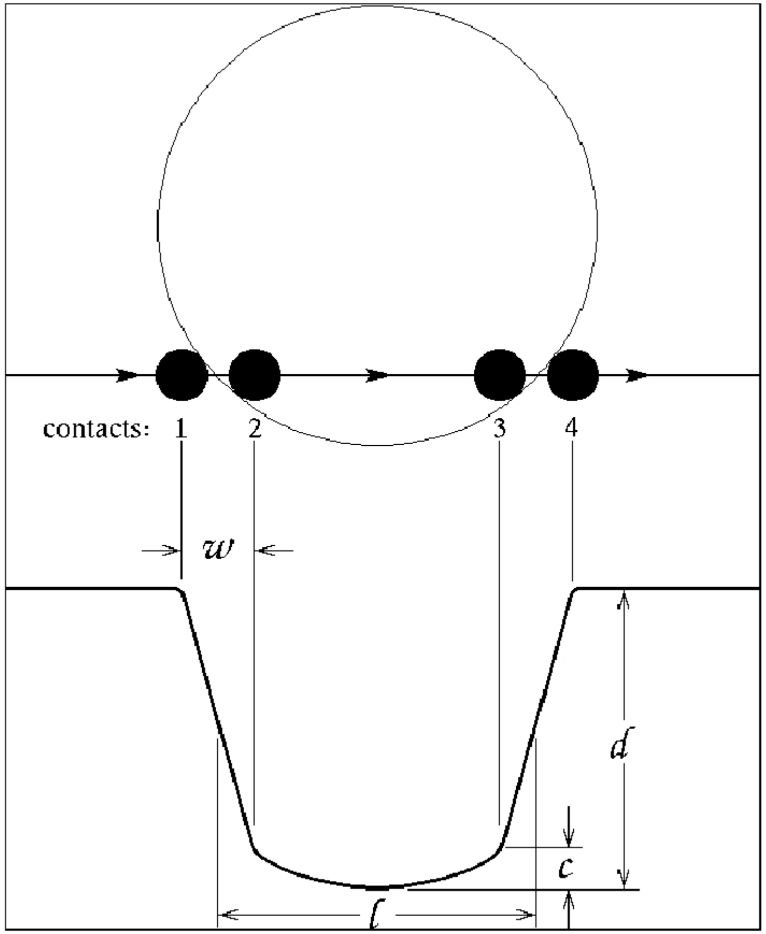
→ or

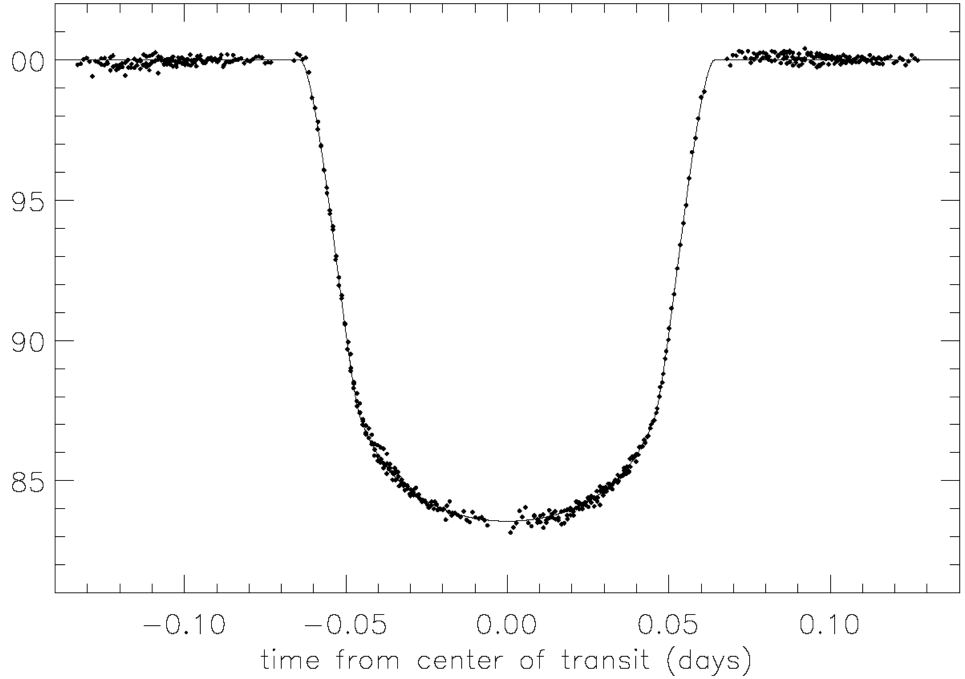
→ focus on known RV systems at the phase when $v_r \sim 0$



Note: occultations will only occur if sin $i \sim 1$ (i.e. $i \sim 90^o$) making a real m_2 measurement out of the $m_2 \sin i$. Also, the occultation gives size of the planet (assuming size of star is known) and therefore can give the density of the planet.

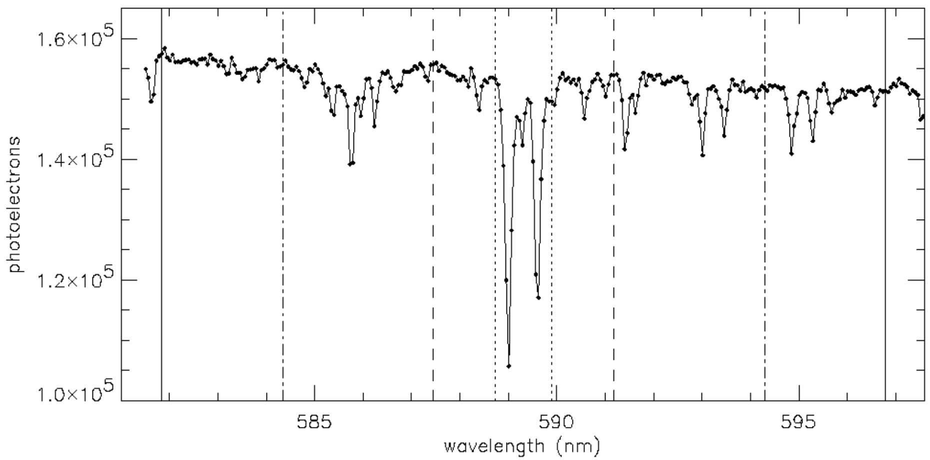
Note: Also, there will be a much smaller drop when the planet passes behind the star and we lose the planets light (best in infrared)

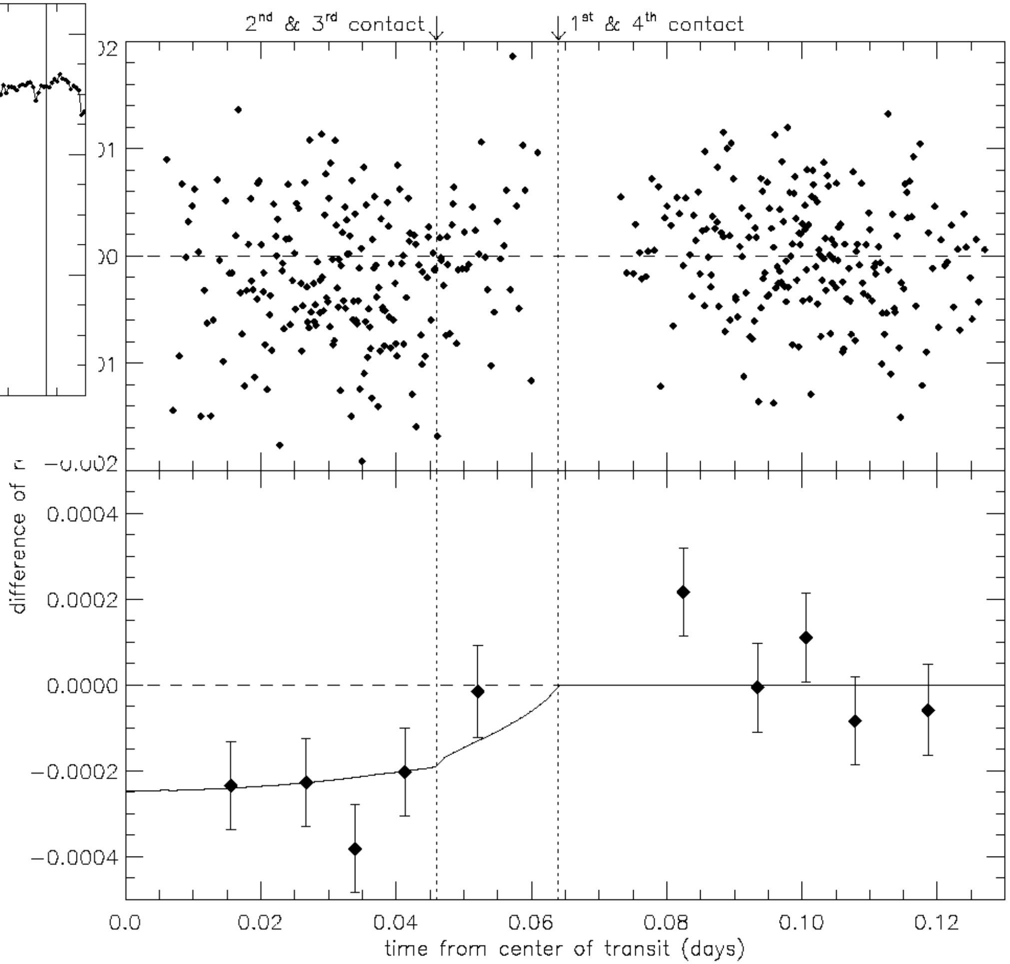

contacts: 1 2 3 4
w
d
c
l


00
95
90
85
−0.10
−0.05
0.00
0.05
0.10
time from center of transit (days)

209458

If the planet has a "transparent" atmosphere with absorption lines, then the planet will be effectively bigger at the wavelengths of the absorption lines, blocking more light → "<u>transit absorption spectroscopy</u>"





First detection of Na absorption in atmosphere of transiting planet

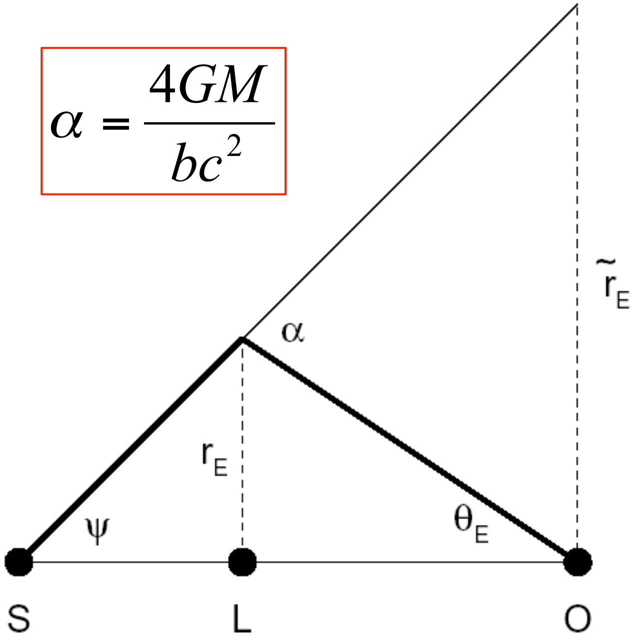
Na in 209458

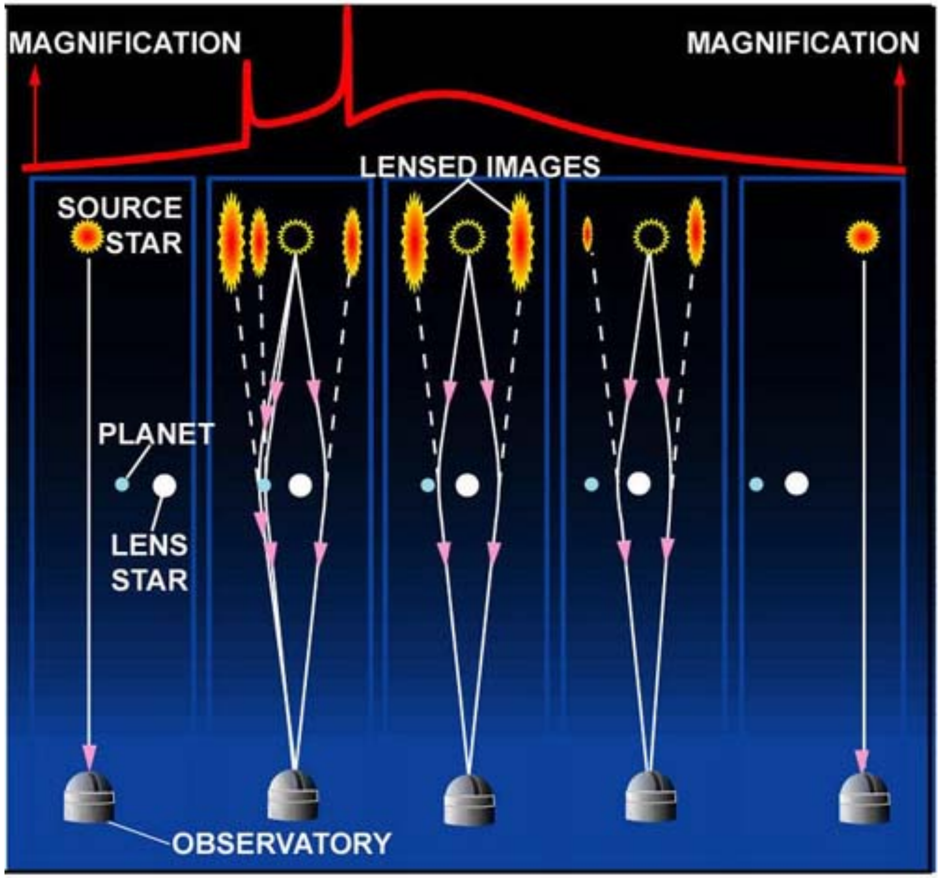
4. Gravitational lensing

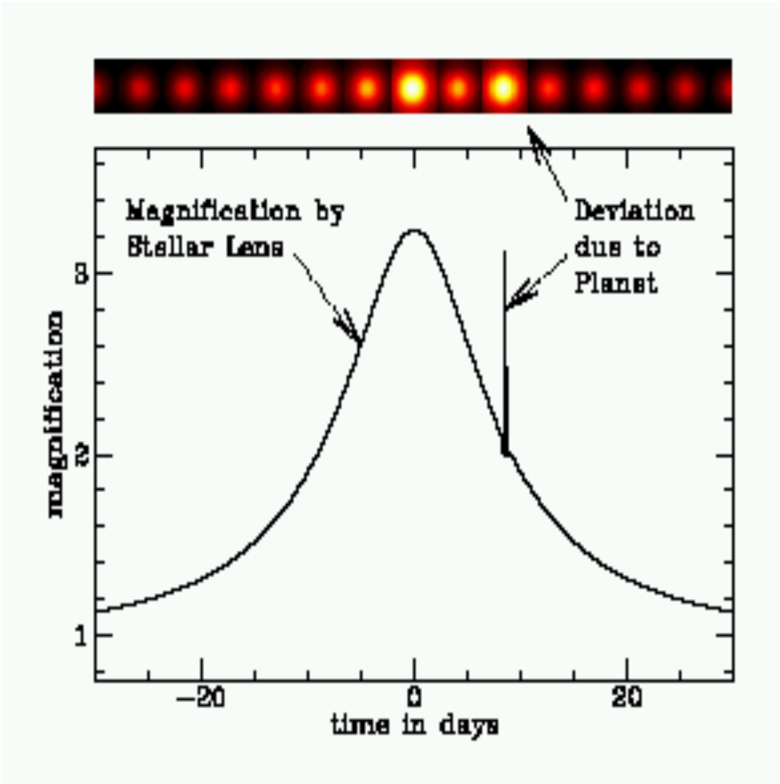
Planets passing in front of background stars can produce gravitational lensing effects, i.e. brightening of the background star.

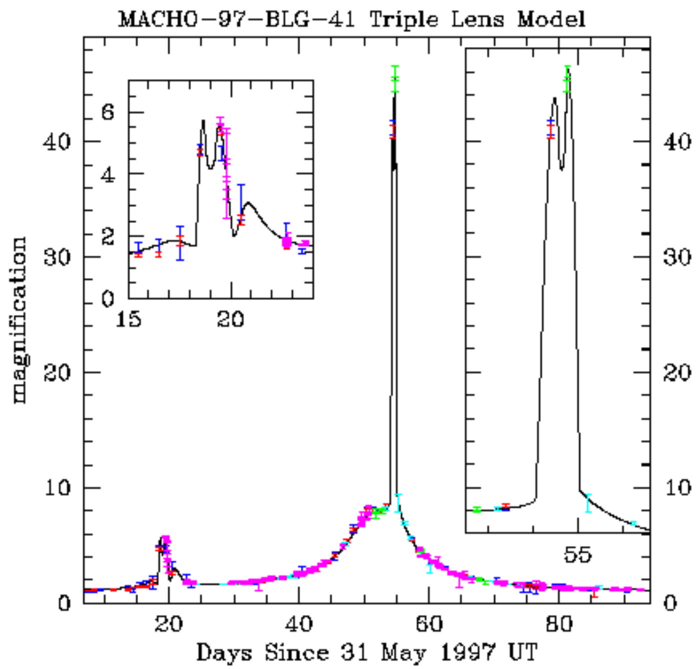
Light passing at distance b from point mass M is deflected through angle α

$$\boxed{\alpha = \frac{4GM}{bc^2}}$$









Again, you must monitor a huge number of stars for a long period of time to see lensing by foreground star, some fraction of which may have planet if you are lucky.

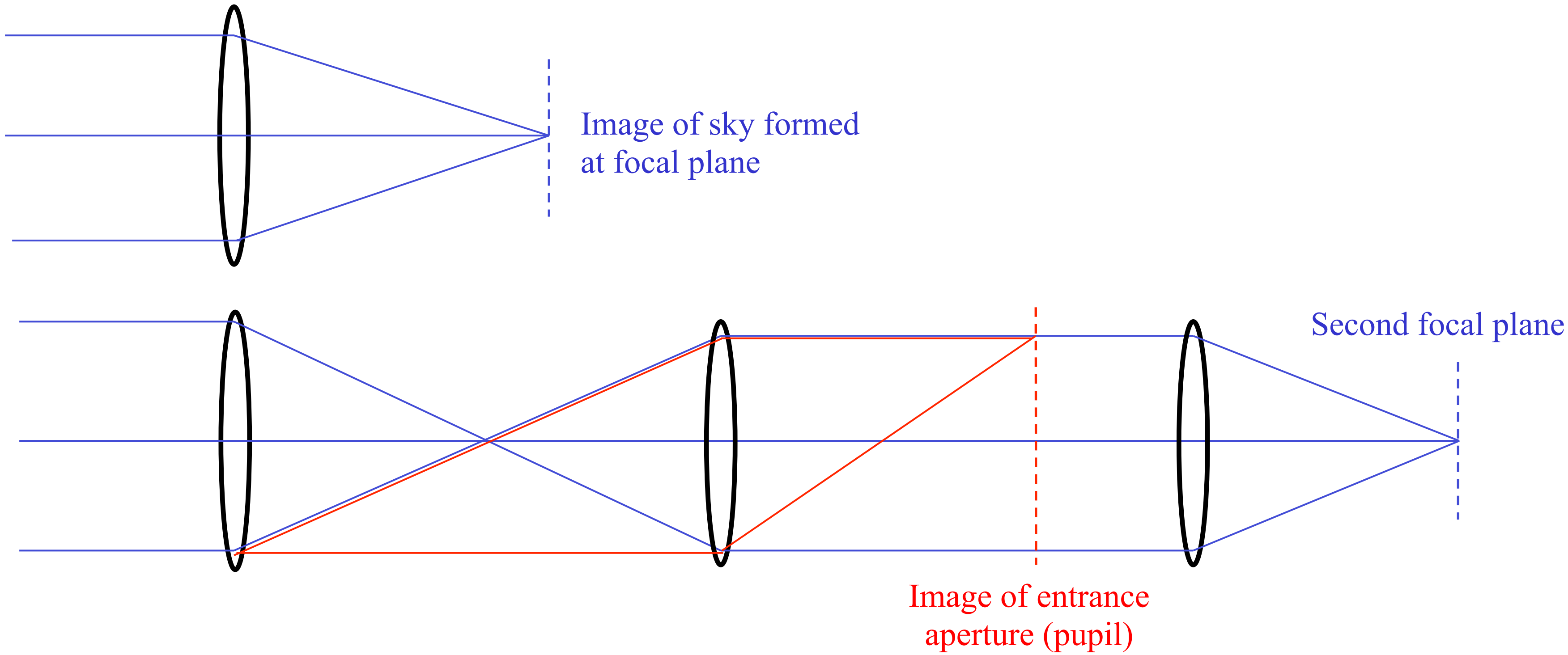
→ Monitor either stars in central region of our Galaxy or nearby system like LMC

B: Direct searches

Potential approaches to try to reduce the dominant star-light so as to detect light from the planet

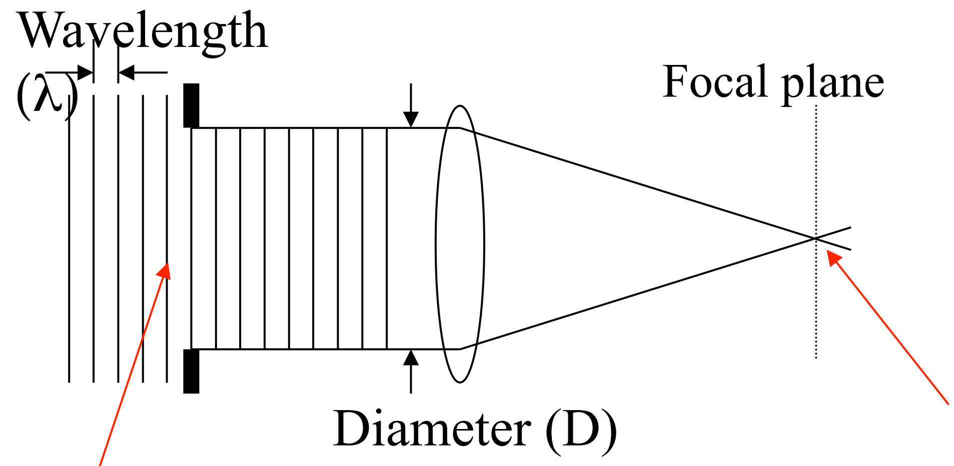
1. Coronagraphy
2. Adaptive optics
3. Polarimetry and/or spectral chopping
4. Interferometry and nulling interferometry

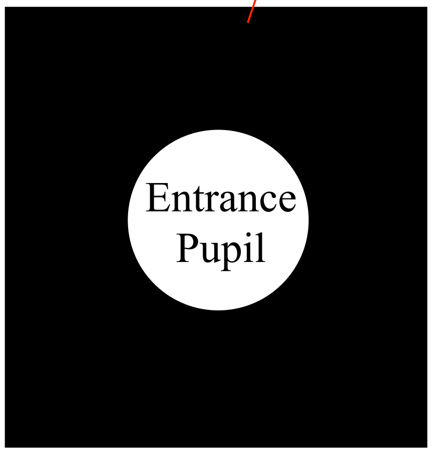
<u>Simple optics</u>: (doesn't matter whether lenses or mirrors)



Key point: at various points through the optical system there are "images" of the different optical elements. This includes "images" of the atmosphere at different altitudes above the telescope

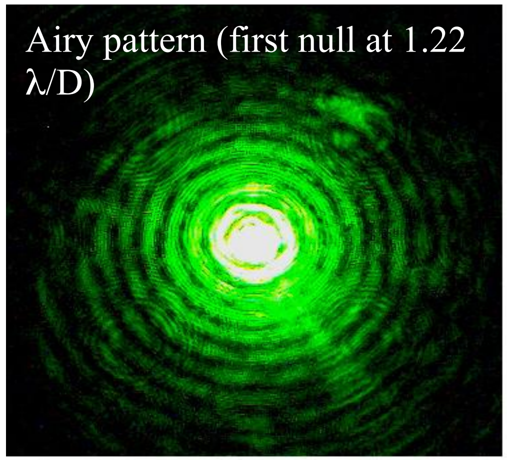
Simple coronagraphics: The classical circular aperture





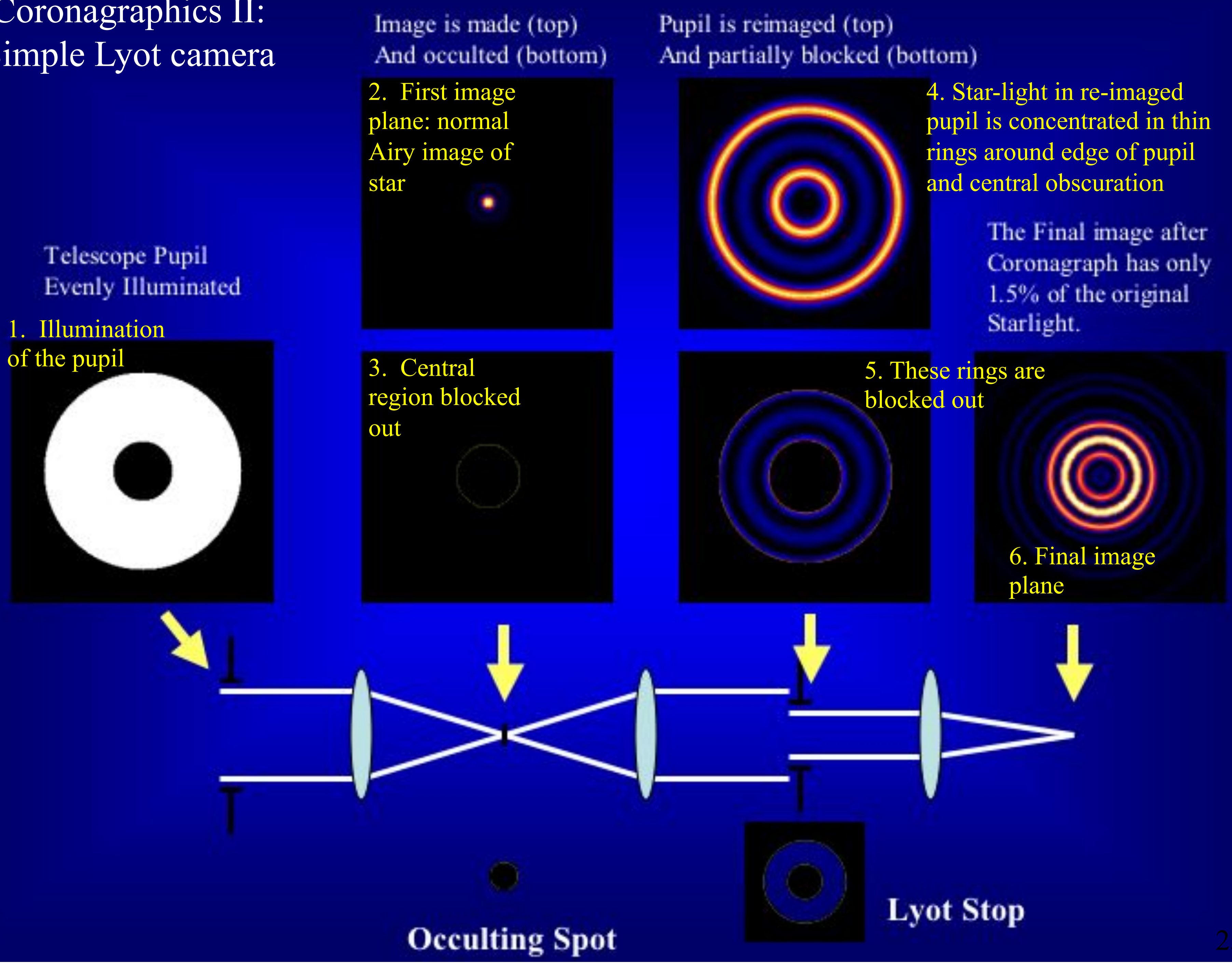
Fourier optics:

The image in the focal plane is the spatial Fourier transform of the entrance field



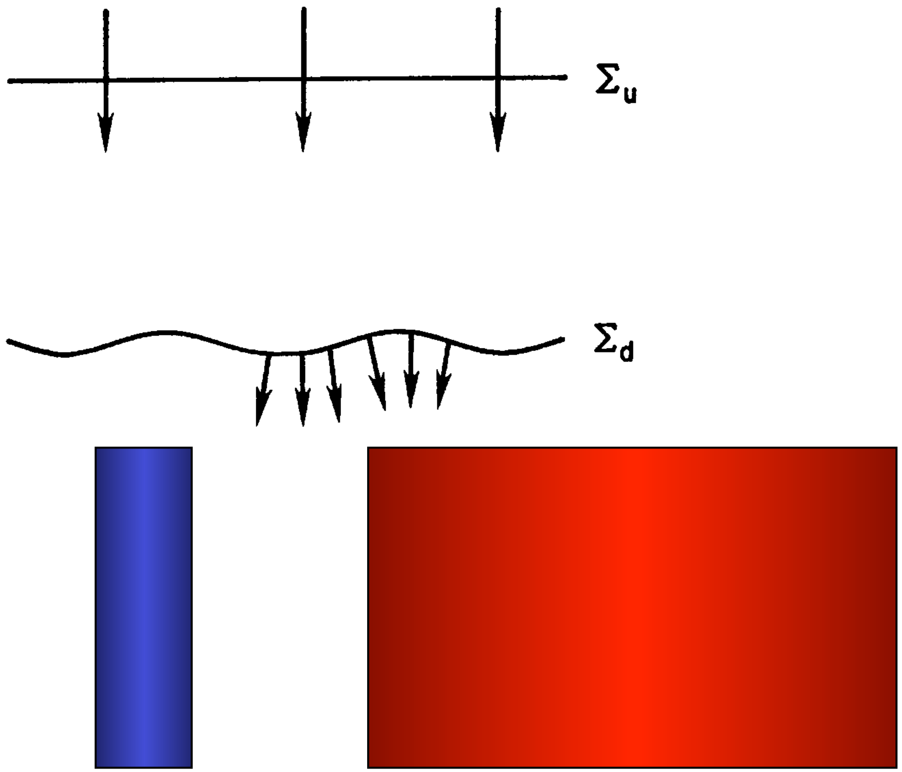
Classical optical system

Coronagraphics II: Simple Lyot camera



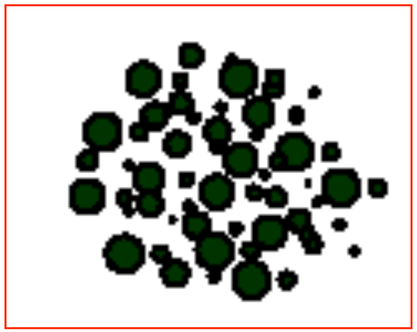
2. Adaptive Optics

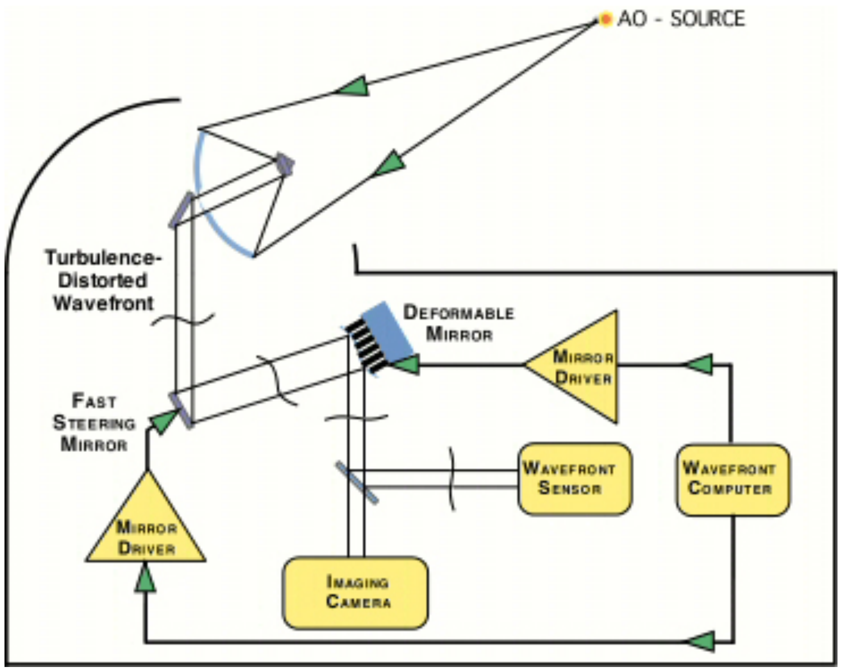
Refractive index variations in atmosphere above telescope introduce wavefront distortions



Small aperture telescope → angled wavefront produces 50 msec image motion and brightness variations

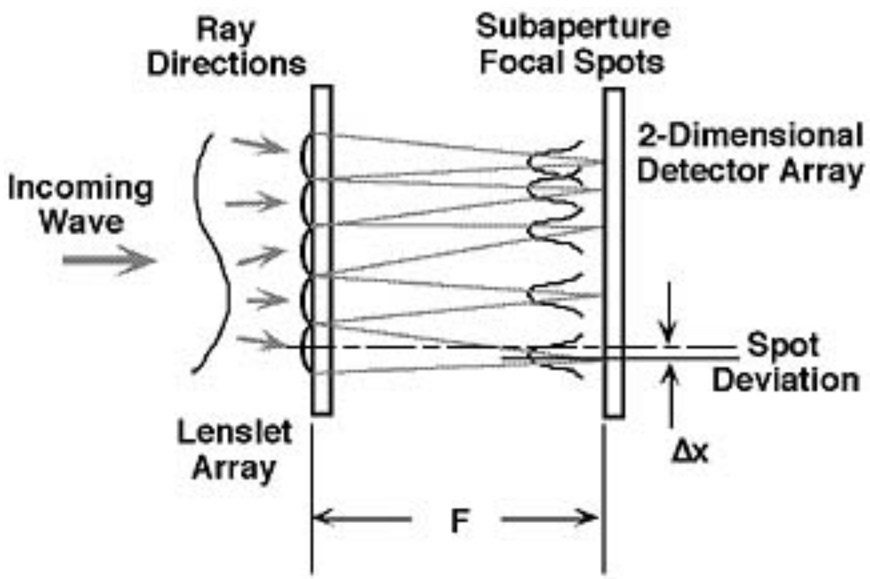
Large aperture telescope → distorted wavefront produces multiple rapidly moving images





Generic adaptive optics system optical layout

How to measure distortions of the wavefront?
Wavefront sensing (e.g. Shack-Hartmann method)



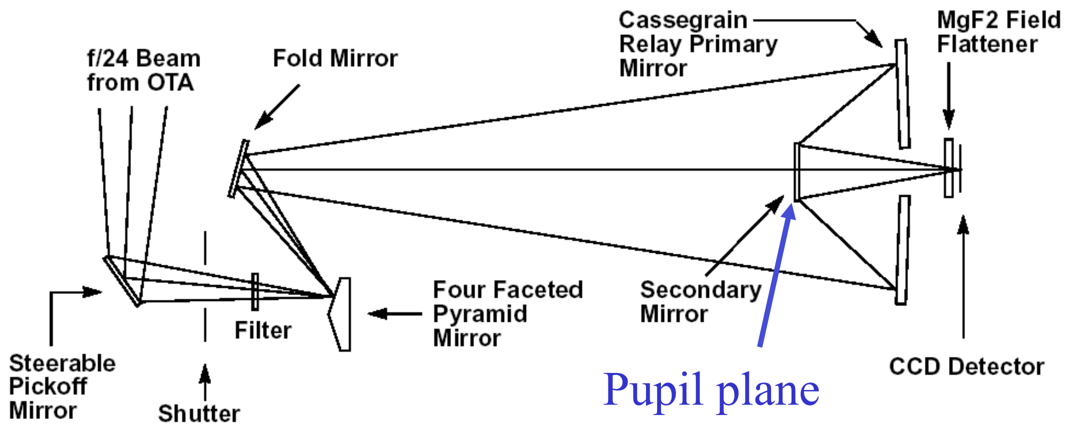
Position of image in sub-pupil gives gradient of wavefront

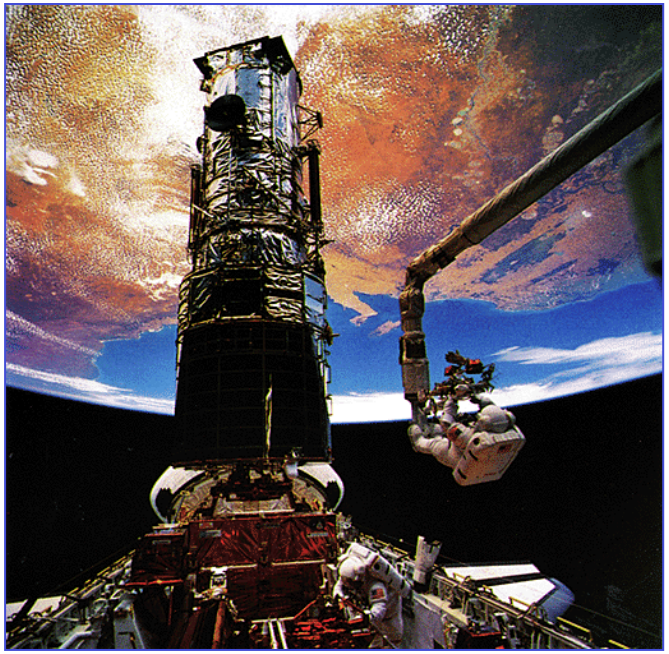
AO system

As an aside: correction of primary mirror aberration on Hubble Space Telescope

HST's primary mirror had gross curvature error: spherical aberration = different radii on mirror have different focal lengths

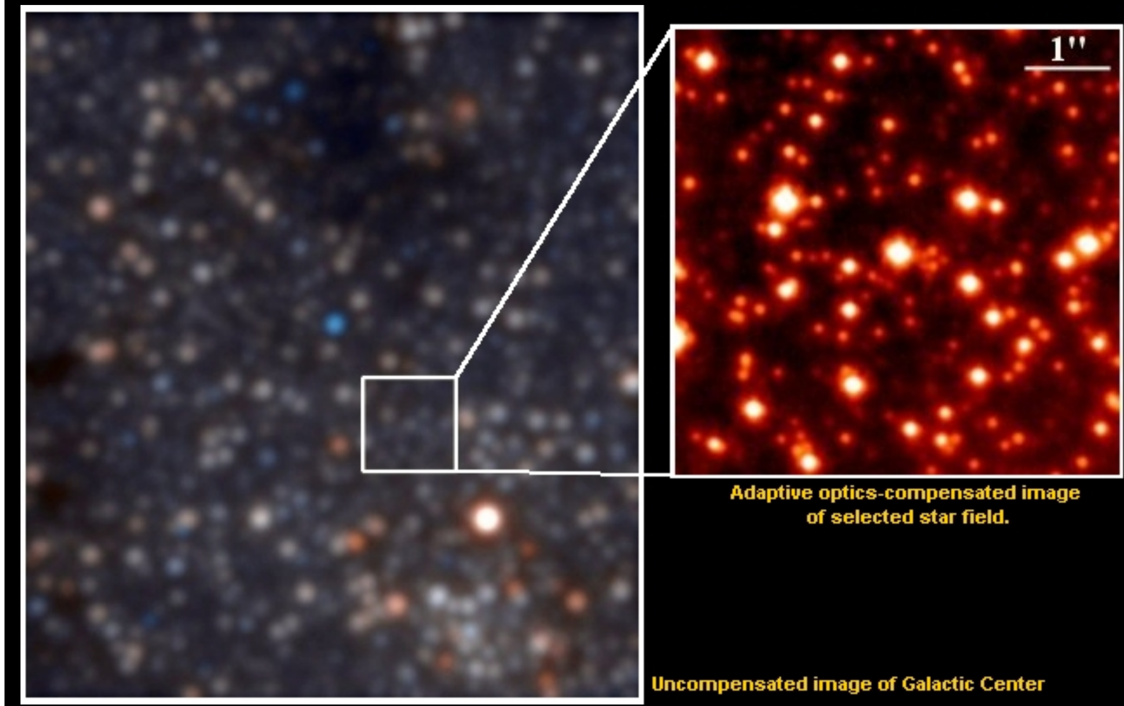
Figure 24.1: WFPC2 Optical Configuration





Wide Field Planetary Camera 1 | Wide Field Planetary Camera 2

HST aberration correction



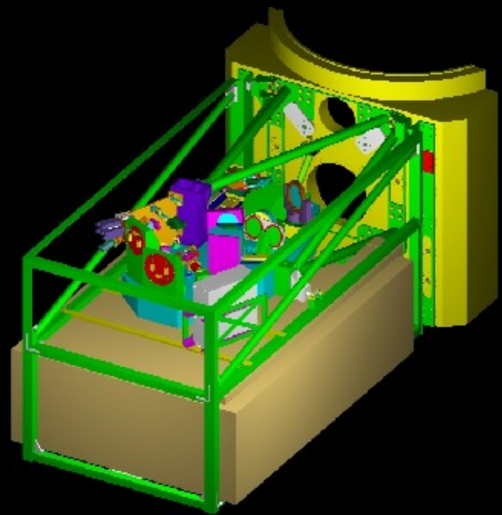
AO image of Galactic Center

65 $M_{Jupiter}$ brown dwarf 0.8 arcsec from 5 mag star

AO systems in practice:

Need bright source to use for wavefront sensing:

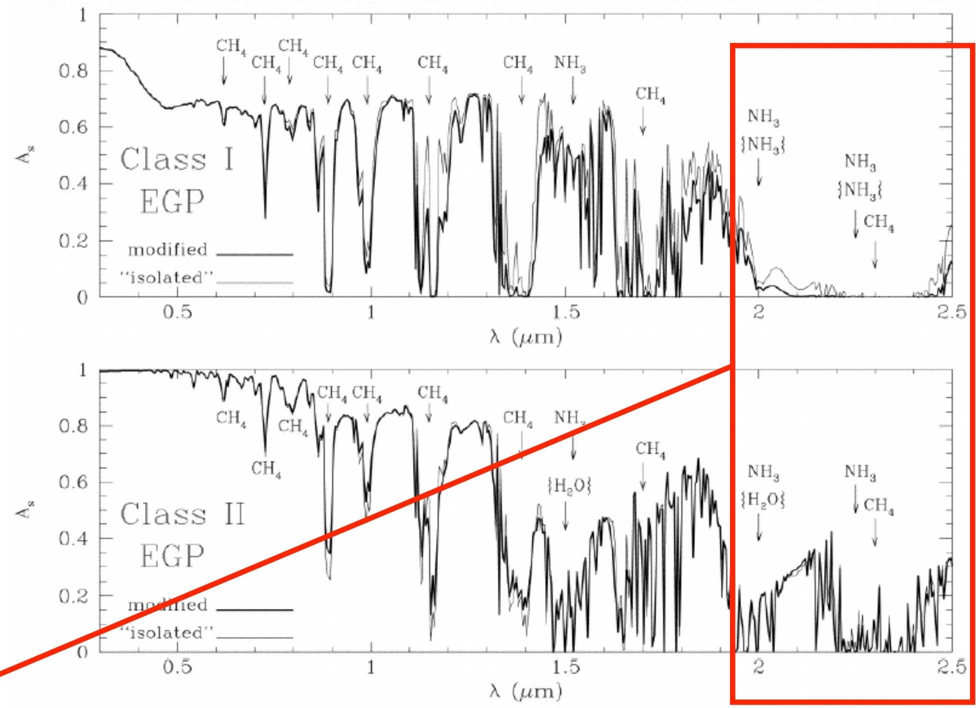
- Self-referencing
- Bright star within "isoplanetic patch"
- Artificial guide stars (e.g. Na laser)

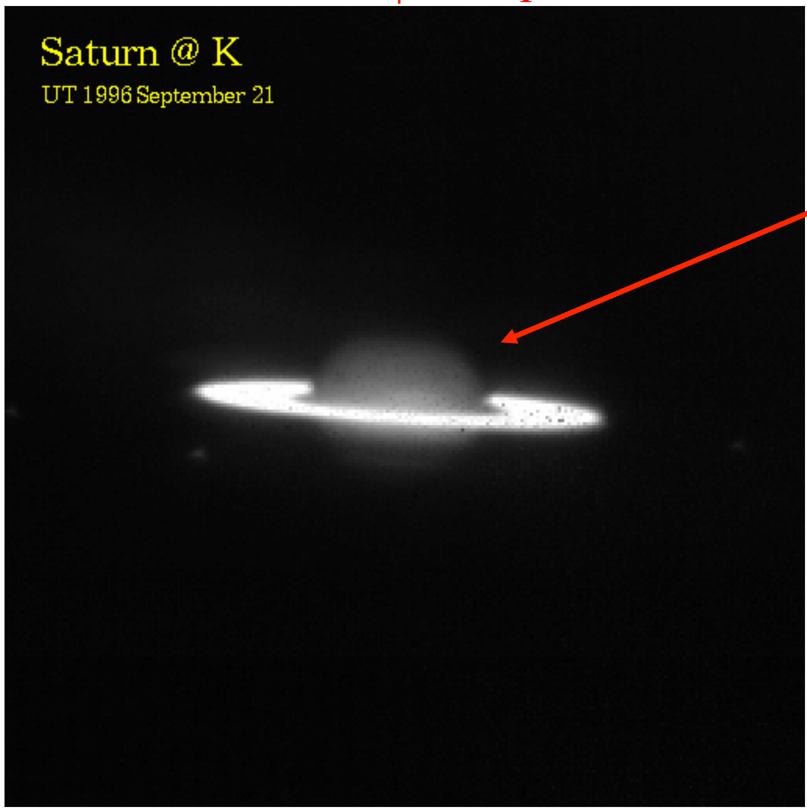


3(a) Spectral subtraction

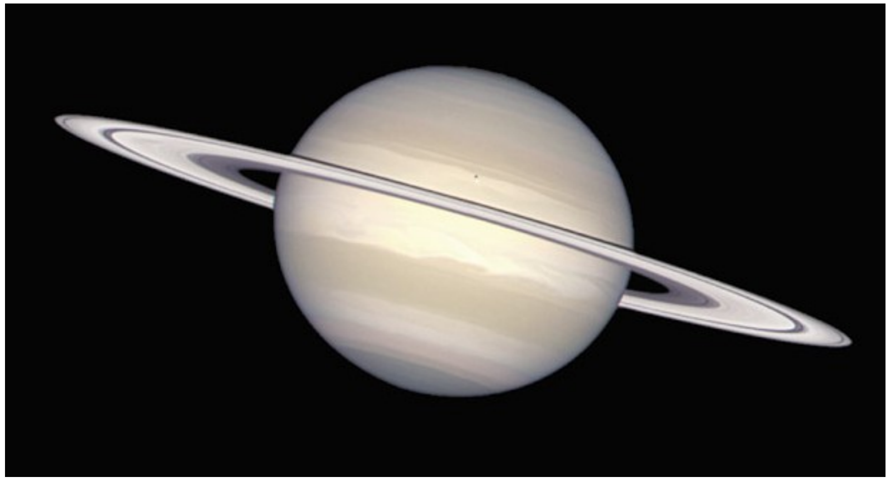
Simultaneous differential “on-off” imaging at two wavelengths at which planet and star are expected to have different relative brightnesses

2 μm: atmospheric albedo very low due to CH_4 absorption





Visible light: uniform albedo

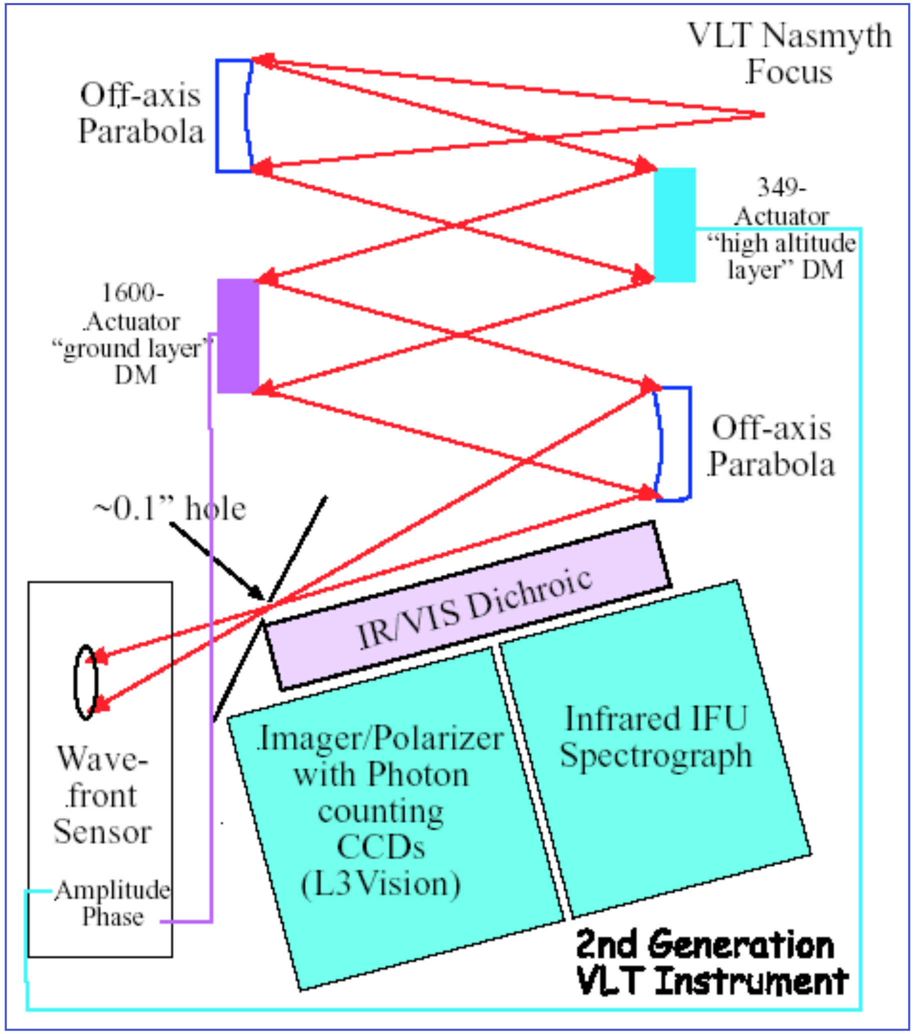


Methane differencing

3(b) Differential polarimetric imaging

SPHERE

If the central star and planet (or dust disk) have different polarizations, then one can effectively remove the star-light

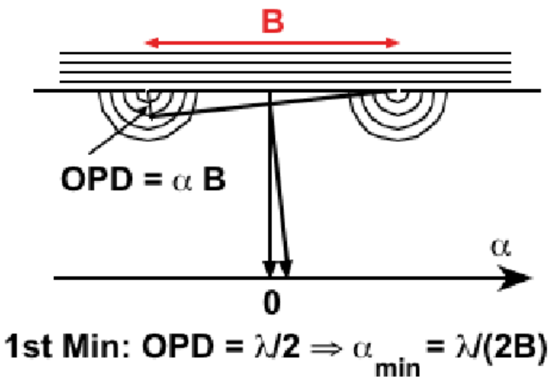


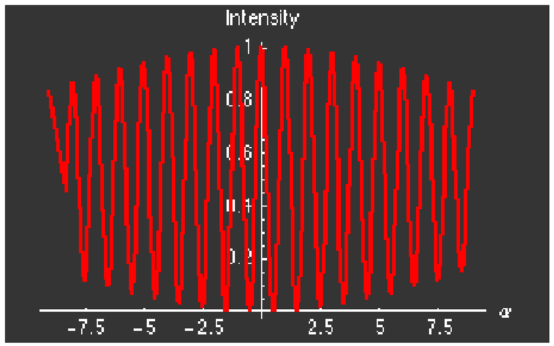
SPHERE "planet-finder" instrument for European VLT combines

- High order multi-layer adaptive optics
- Differential infrared imaging on-off spectral features
- Differential polarimetric imaging

3. Interferometry

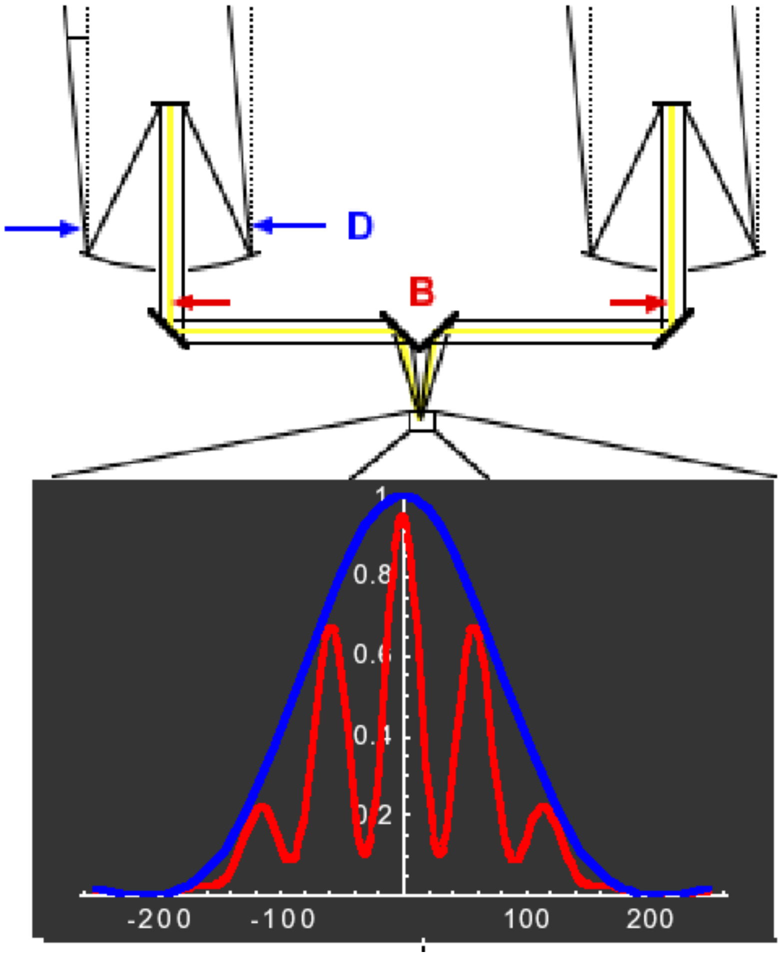
Young's Two-Pinhole Experiment



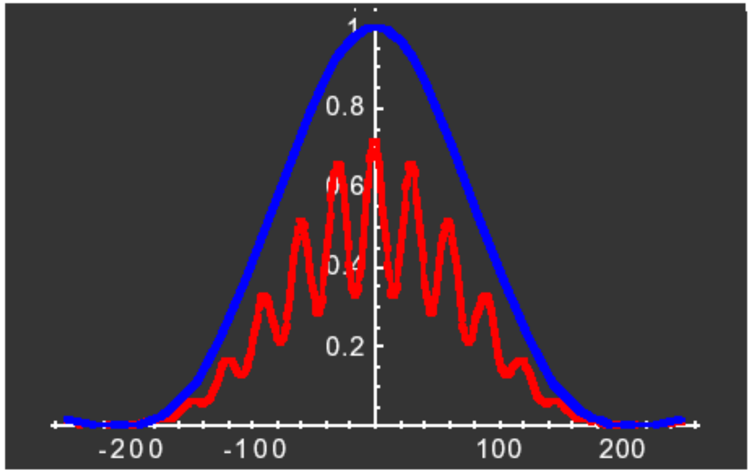


- Light source at infinity
- Intensity pattern = $1 + \cos(2\pi\alpha B/\lambda)$, where αB is the Optical Path Difference (OPD)
- When OPD > coherence length, fringes disappear
- Light source at angle a_0 shifts fringe pattern

Michelson stellar interferometer (1920) used to measure stellar sizes

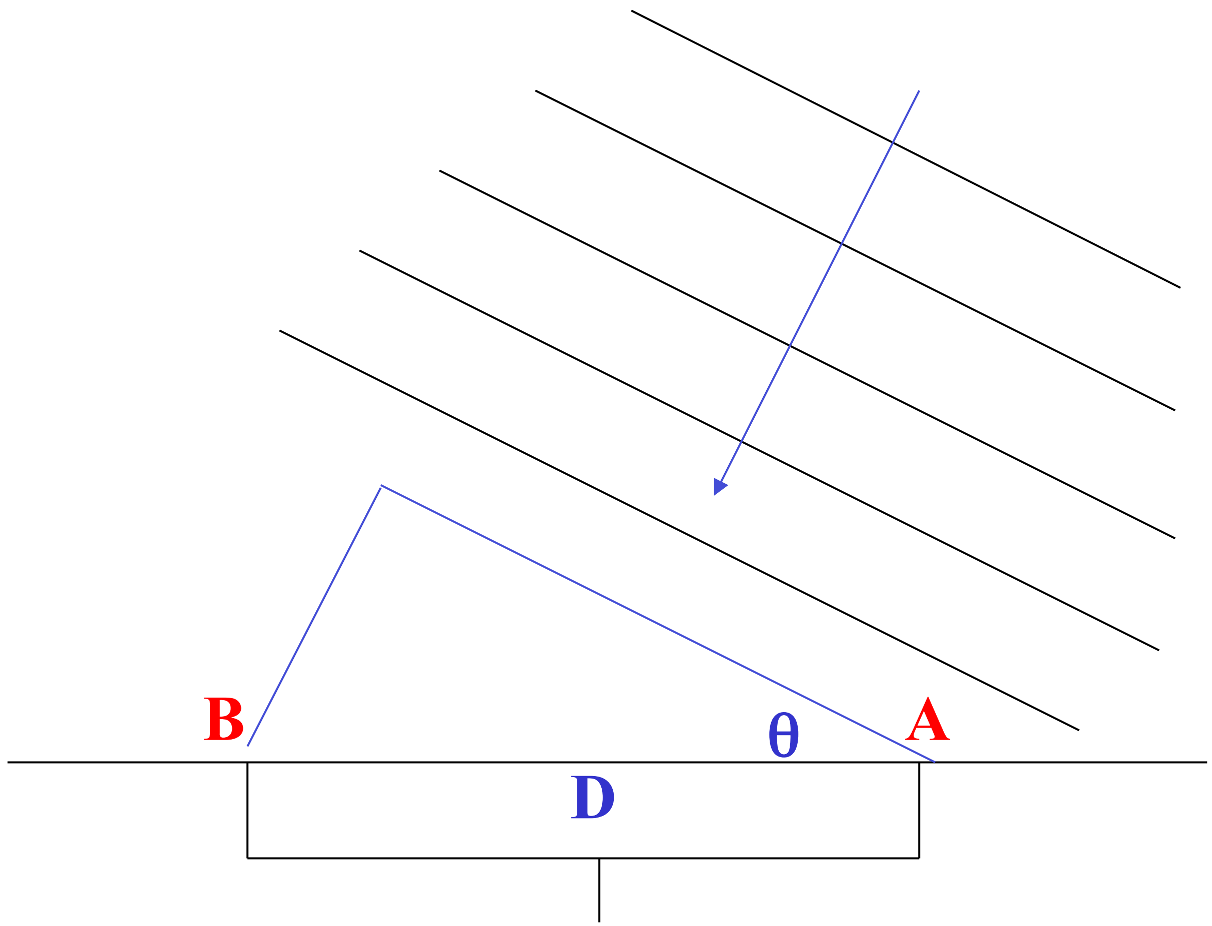


- Stellar source with angular diameter a_0
- Add fringe patterns shifted by 0 to $a_0/2$.
- Fringe pattern reduced in contrast, depending on a_0 and separation B



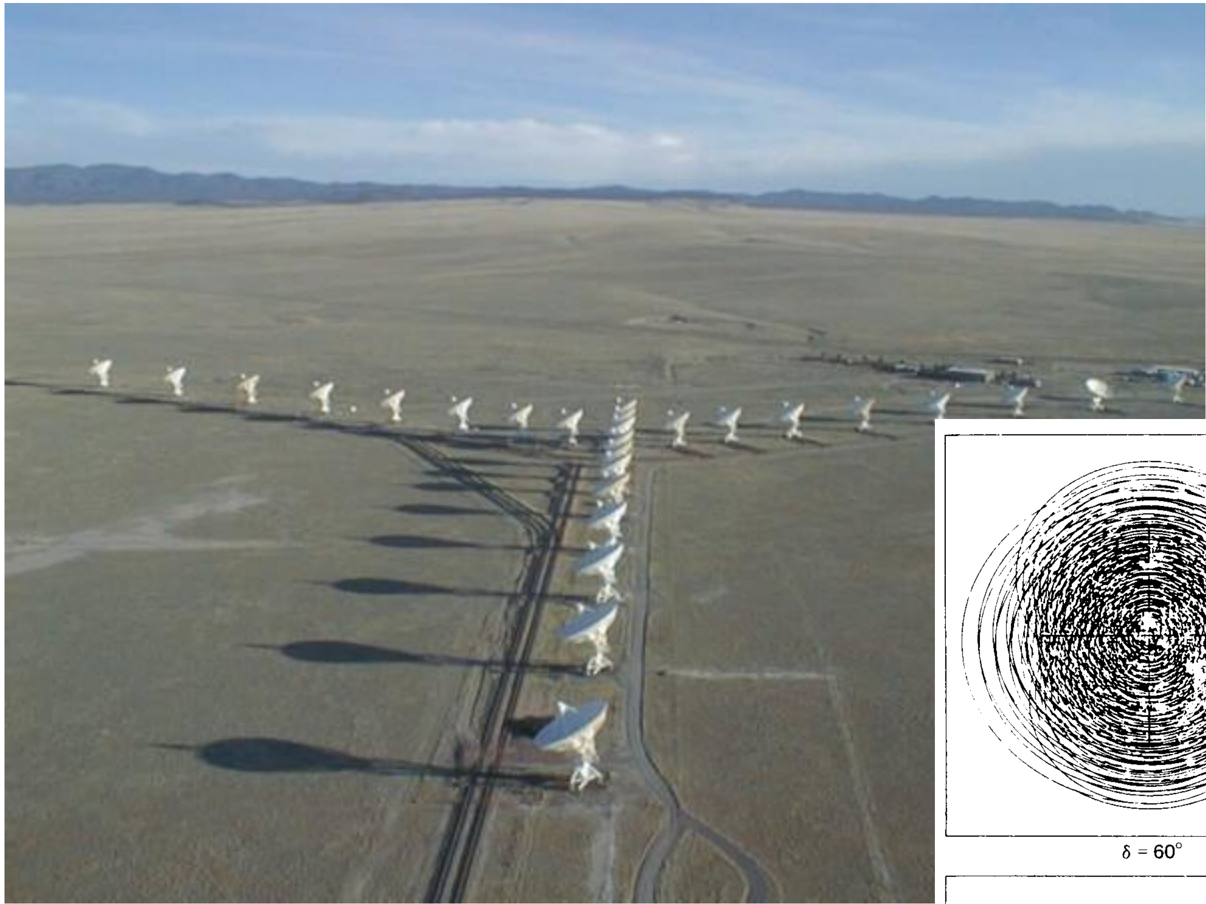
Michelson stellar interferometer

Radio interferometry

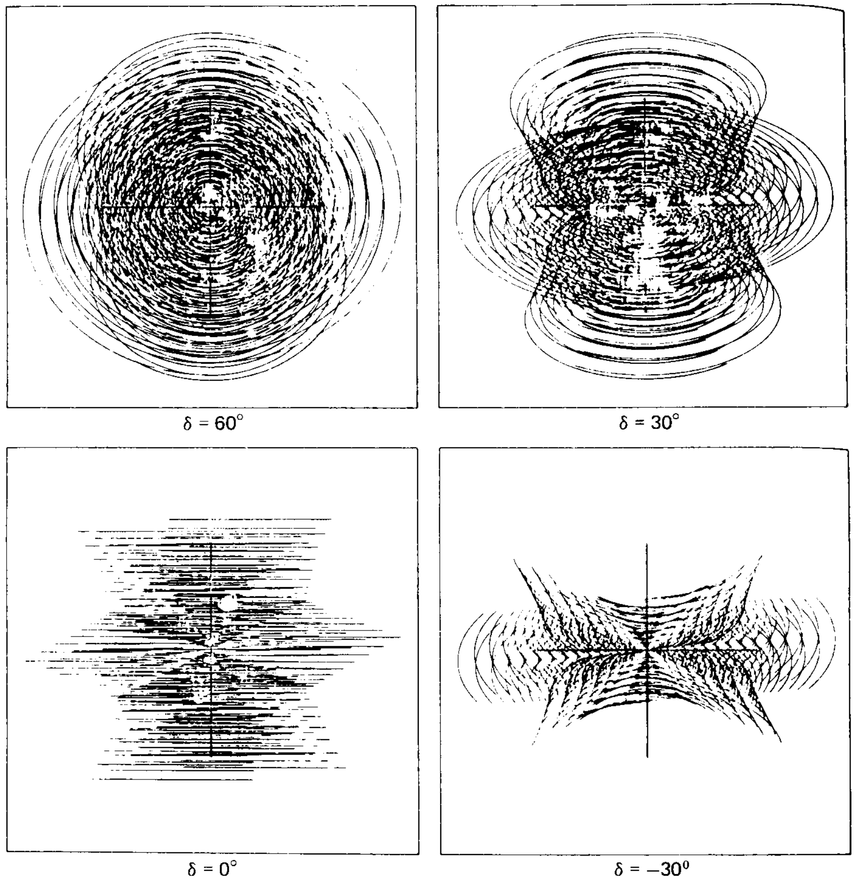


$$V_A \times V_B = \langle V_A \rangle \langle V_B \rangle \cos \phi \; ; \quad \phi = 2\pi D\theta/\lambda$$

Net result: Two radio telescopes measure one Fourier component of of the radio sky brightness



Fourier plane coverage of VLA antennae (as Earth rotates)



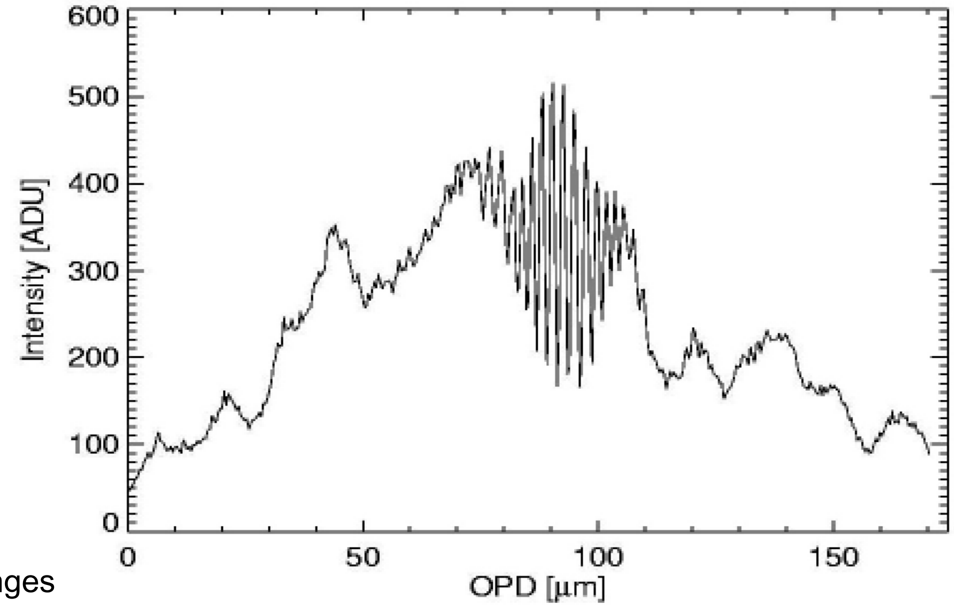
Very Large Array: combining all possible pairs samples the Fourier space quite well. This is the standard technique for radio imaging.

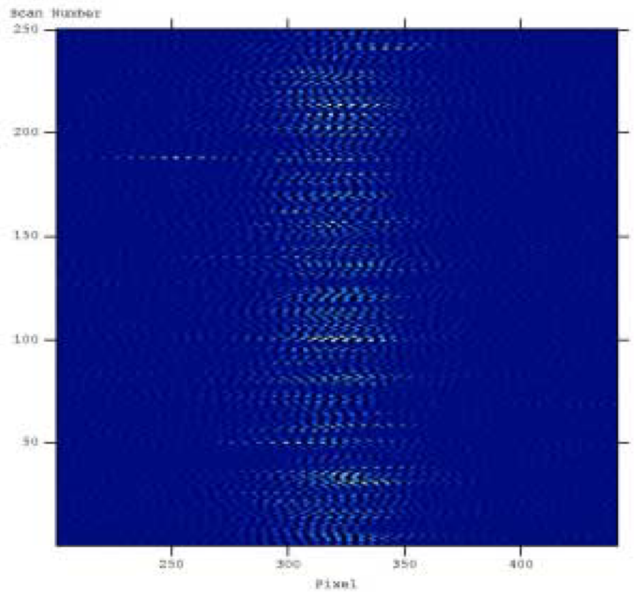
VLA and u-v plane

Much harder at optical wavelengths:

- cannot measure phase of photon like in the radio (must allow the photons themselves to interfere rather than multiply voltage signals)
- short coherence time for short λ photons
- Rapid variation of atmospheric phase effects

Leaders: 4x8m ESO VLT in Chile.

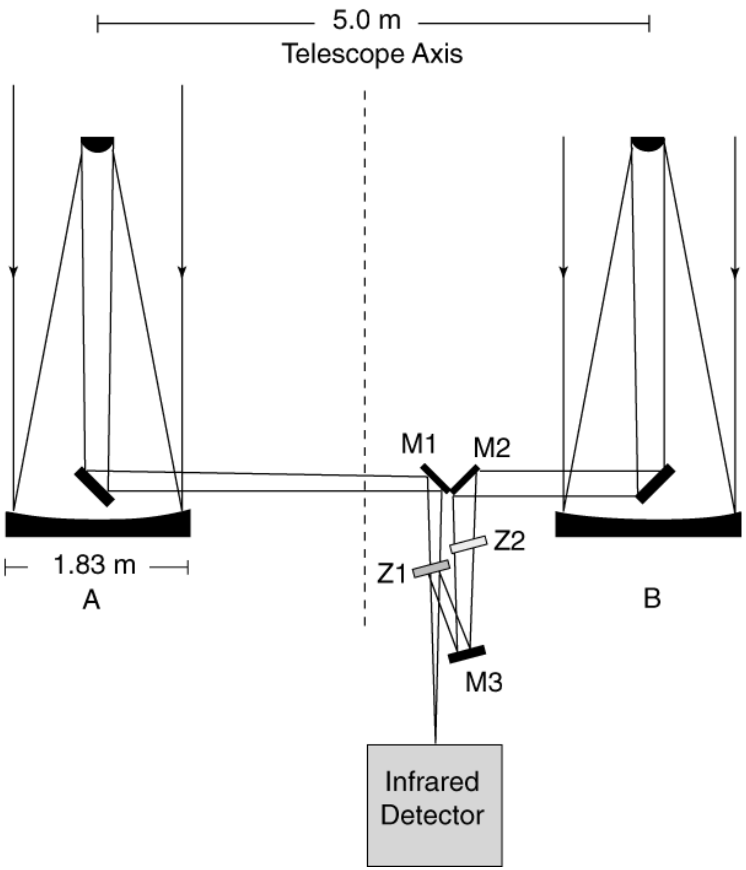


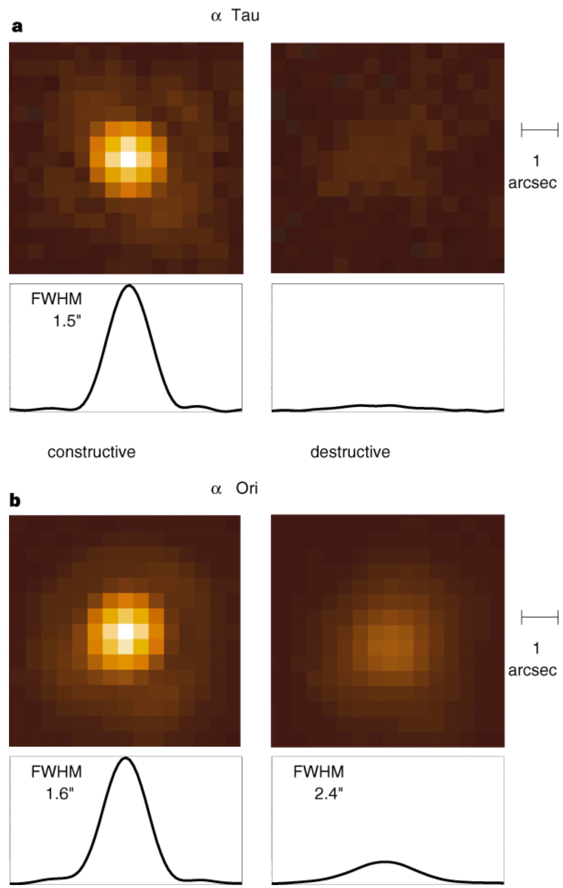


VLT fringes

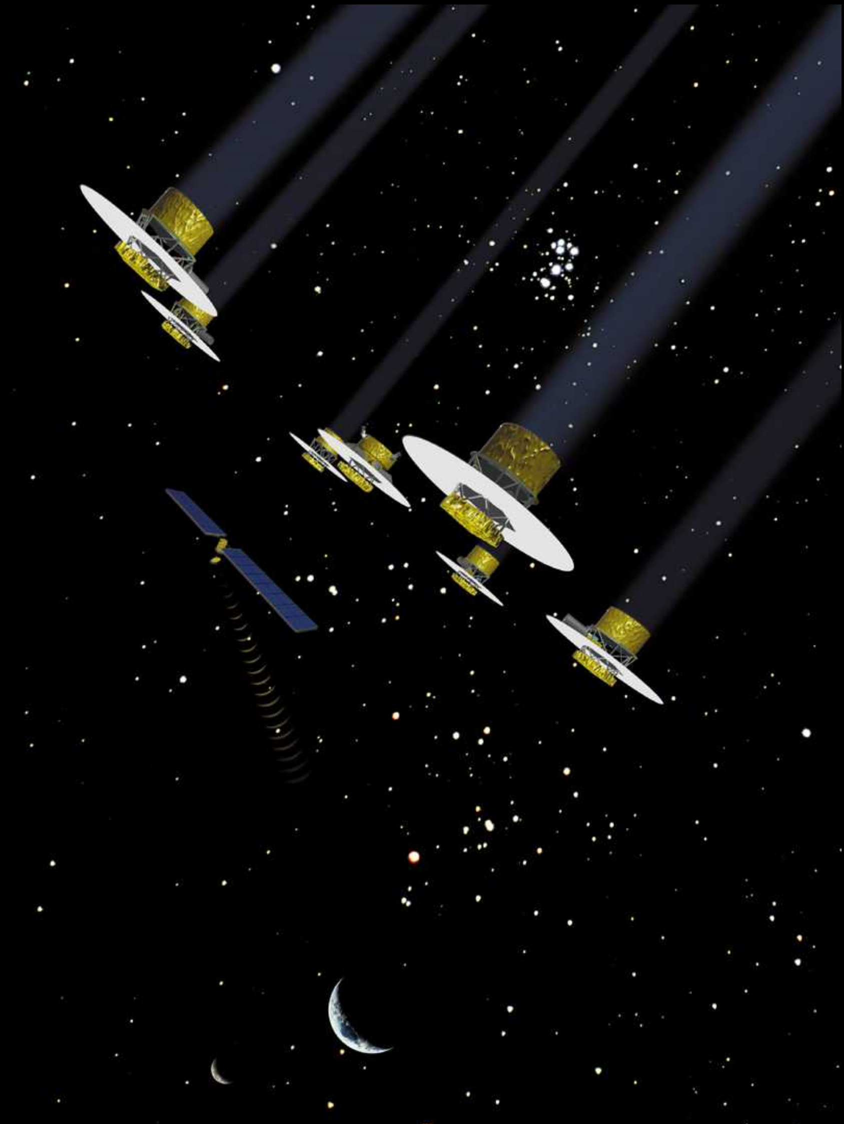
Other techniques: Nulling interferometry

Take half of light and add ± π phase. Central part of Airy disk is now a minimum and first maximum occurs where previously there was the first minimum:

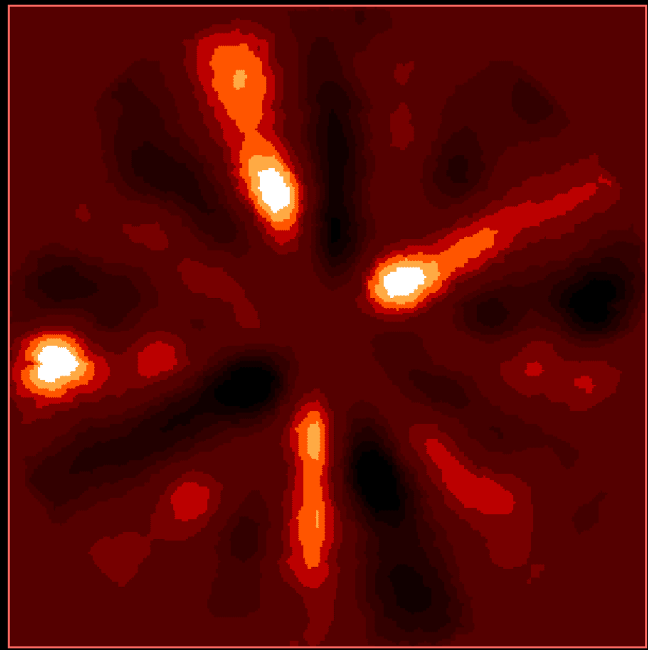




Nulling interferometry

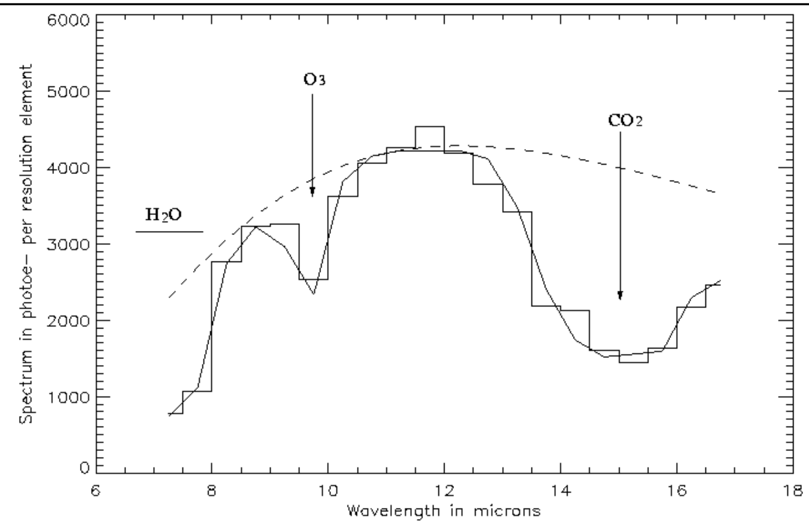


2007 Proposed ESA Darwin mission
(no longer active due to cost)



Simulated Venus, Earth, Mars at 10 pc

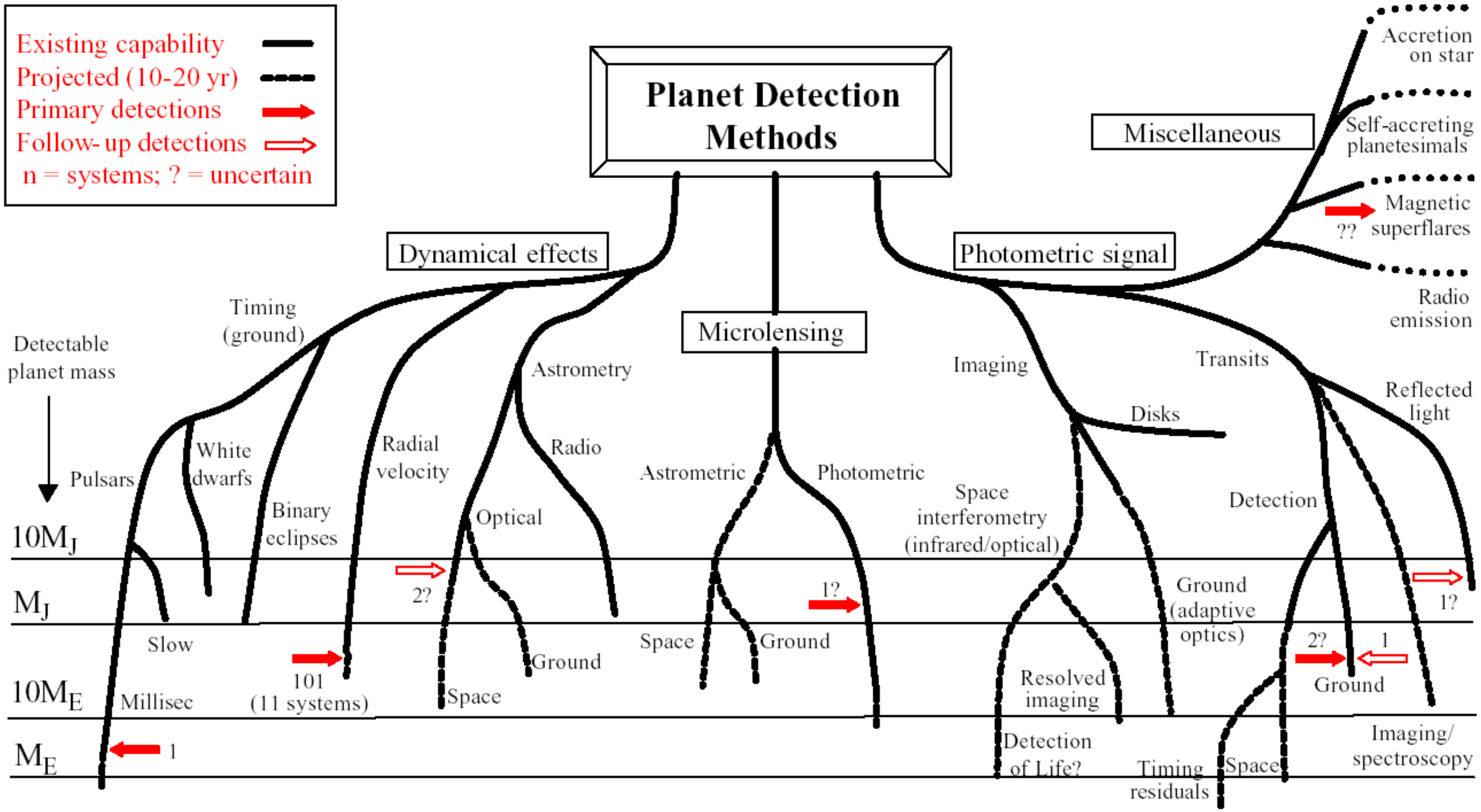
Simulated Earth spectrum



ESO 39m E-ELT artists impression: first light in 2025?

Planet Detection Methods

Michael Perryman: Rep. Prog. Phys, 2000, 63, 1209 (updated Aug 2002)



Summary (Perryman tree)