Chapter 3: Exosolar Planets

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

Detection of extrasolar planets: what's the problem?

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

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

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

Angular separation of Jupiter-Sun at nearest star is about 4 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 a radius r of the planet at an orbital distance D from a star wuth 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:

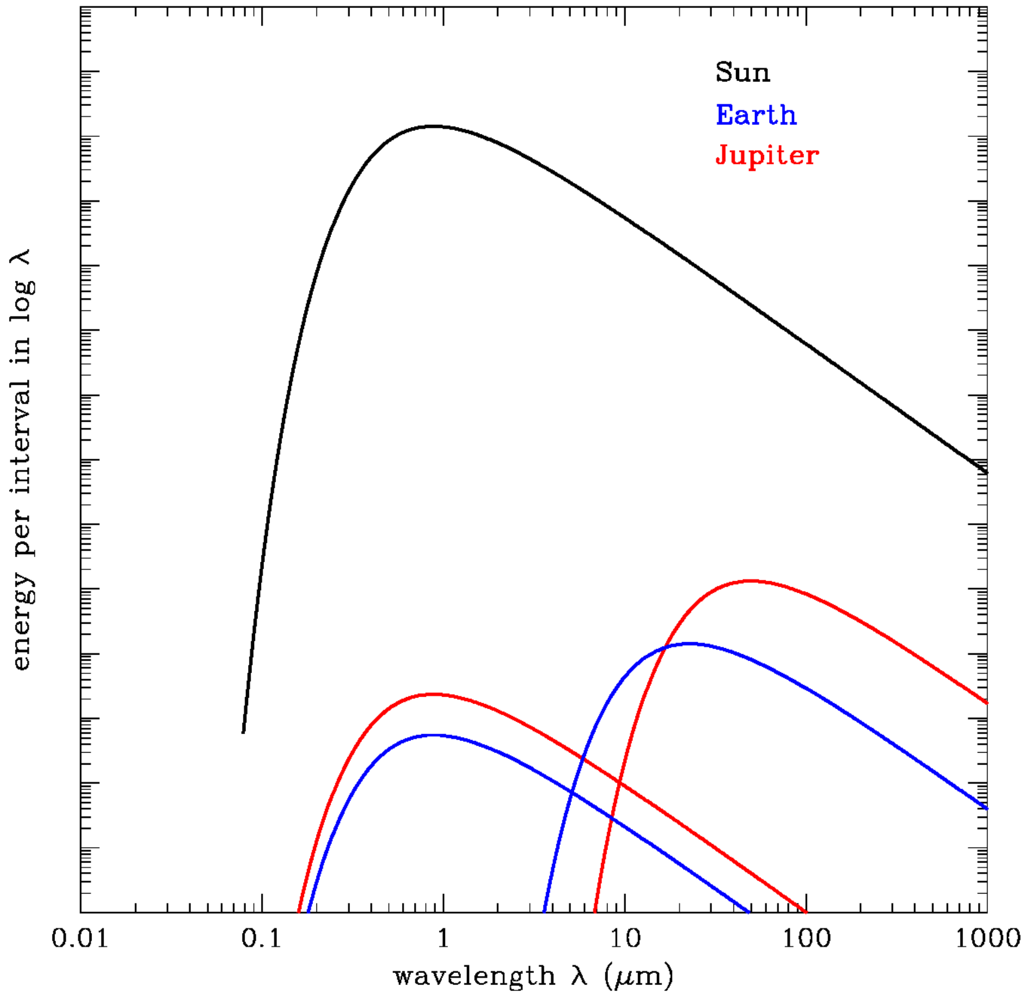
$$L_p = (1-a)\, L_s \frac{r^2}{2D^2} = (1-a) 4\pi R_s^2 \sigma T_s^4 \frac{r^2}{2D^2}$$

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

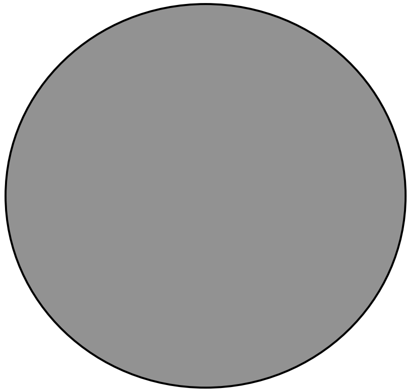
	radius	distance	$r^2/2D^2$
Earth	6.3×10^6 m	1.6×10^{11} m	7.8×10^{-10}
Jupiter	7.1×10^7 m	7.8×10^{11} m	4.1×10^{-9}
Sun	7.0×10^8 m	---	---

Looking at the Earth and Jupiter from far away: The problem is the Sun

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



Sun, Earth and Jupiter



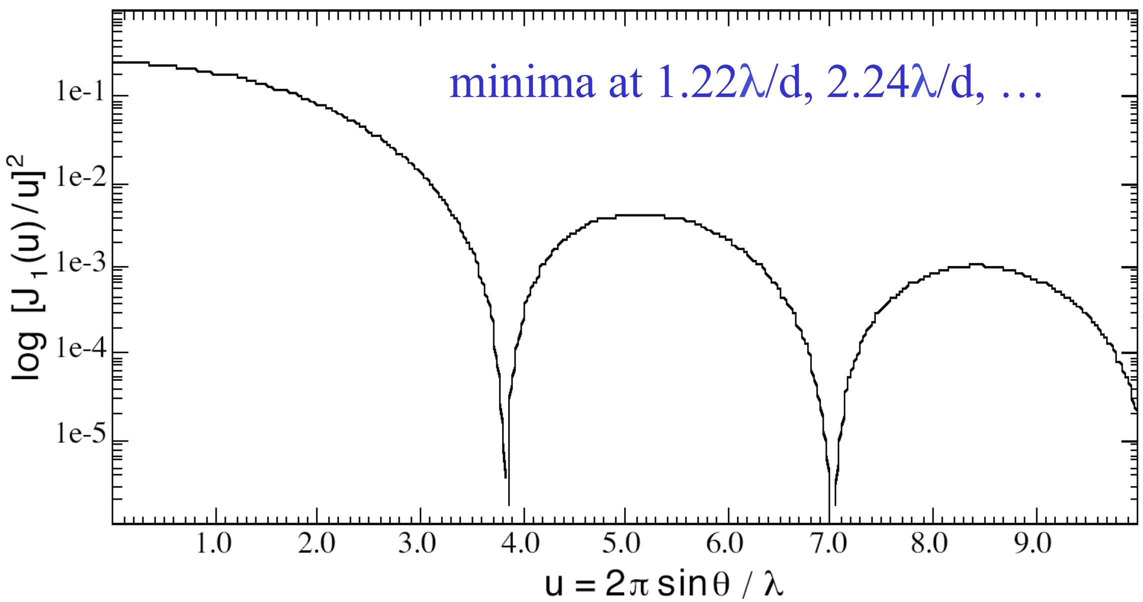
Diffraction from ideal telescope aperture:

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

For an idealised perfectly circular aperture:

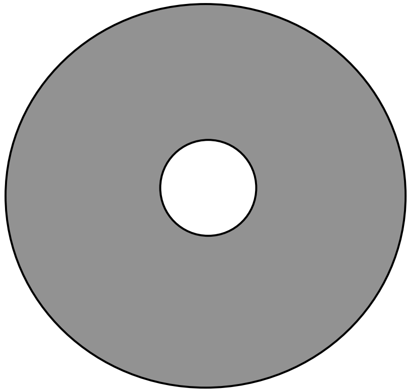
$$I(\theta) = I_0 \left(\frac{2J_1(u)}{u} \right)^2 \qquad u = 2\pi\theta / \lambda$$

J_1 = 1^{st} 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

Airy pattern



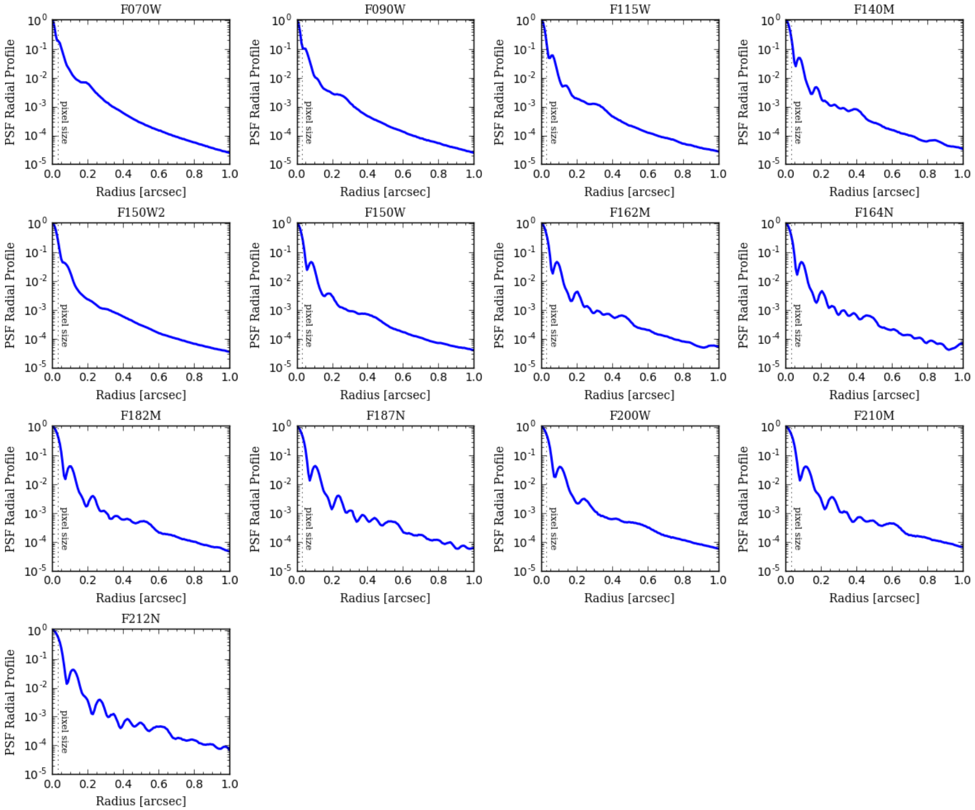
Airy pattern

In practice it is even worse

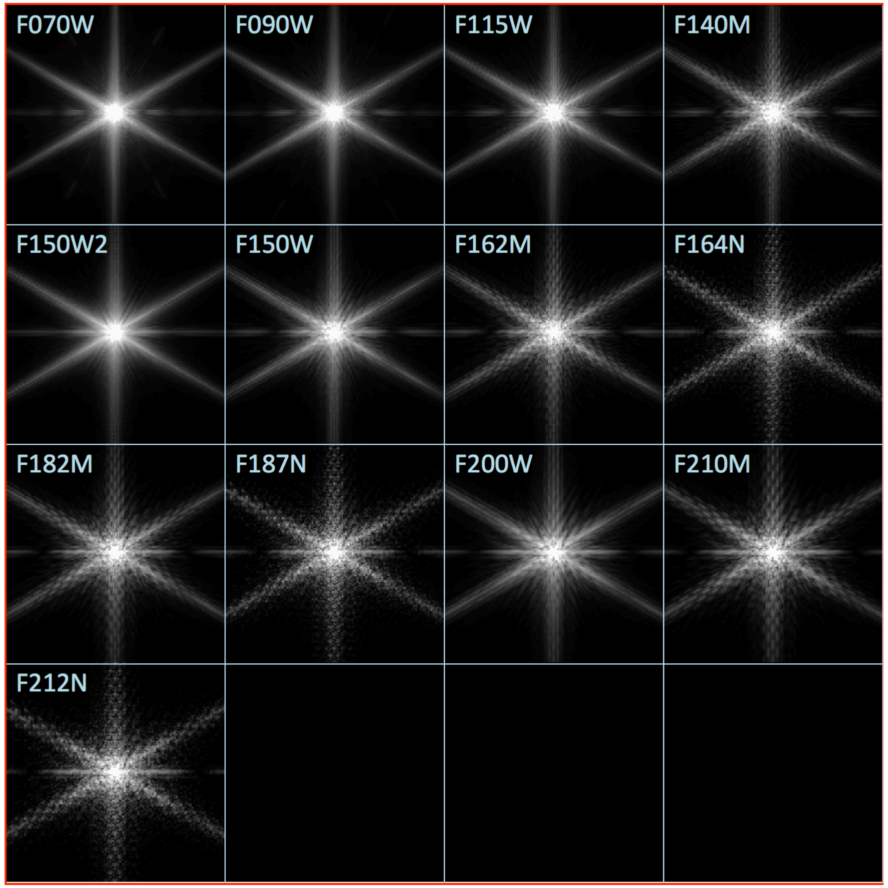
- "On-axis" telescopes usually have central obstruction of some kind for mechanical design reasons
- Imperfections in optics throw light to large angles

Plus:

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



Even telescopes in space have complex point-spread-functions (PSF), e.g. JWST



Exo-solar planet detection: how to do it?

A: Indirect detection (does not detect the light from planet)

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

B: Direct searches (does detect the light from the planet)

Use different approaches to subtract the dominant star-light

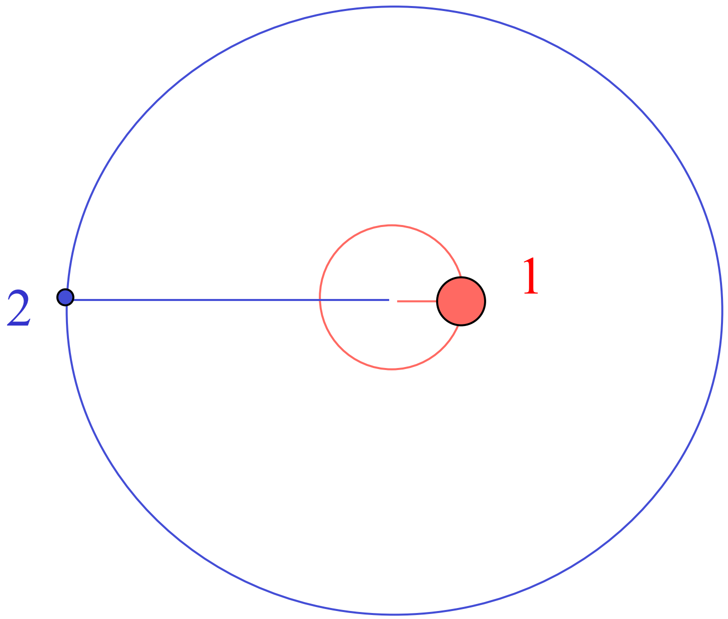
1. Coronagraphy
2. Adaptive optics
3. Polarimetry and/or spectral chopping
4. Interferometry and nulling interferometry

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:

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



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

$$m_1 r_1 = m_2 r_2$$

$$2\pi r_1 = v_1 P$$

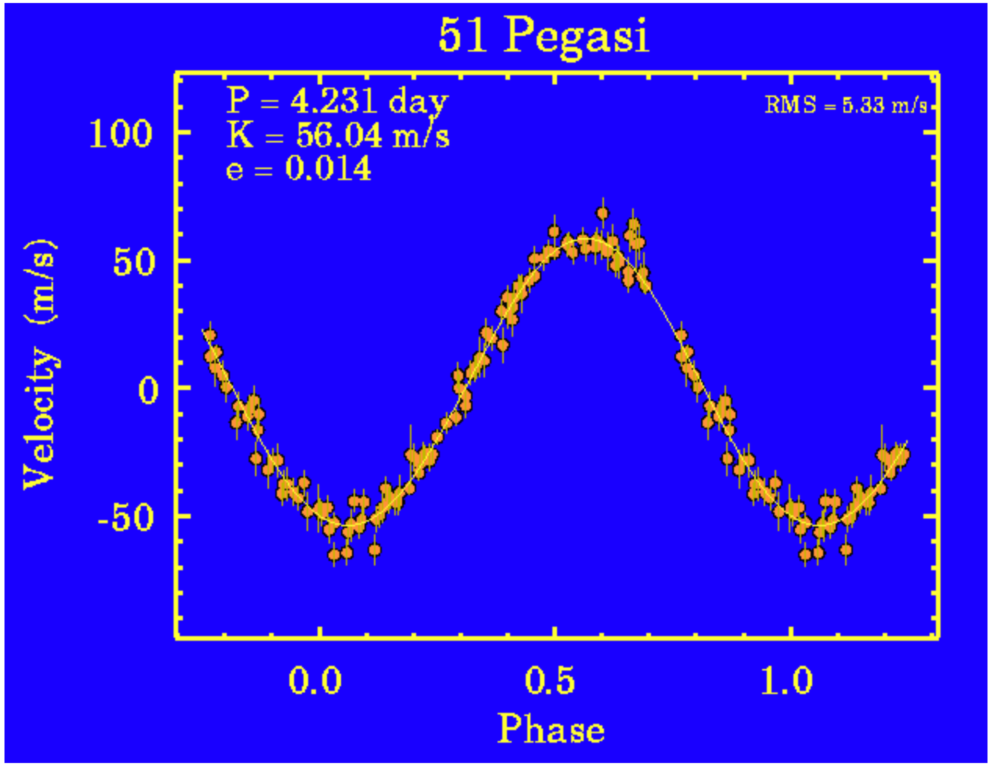
$$\boxed{m_2 = m_1^{2/3} \left(\frac{P}{2\pi G} \right)^{1/3} v_1}$$

We know m_1 from the type of star

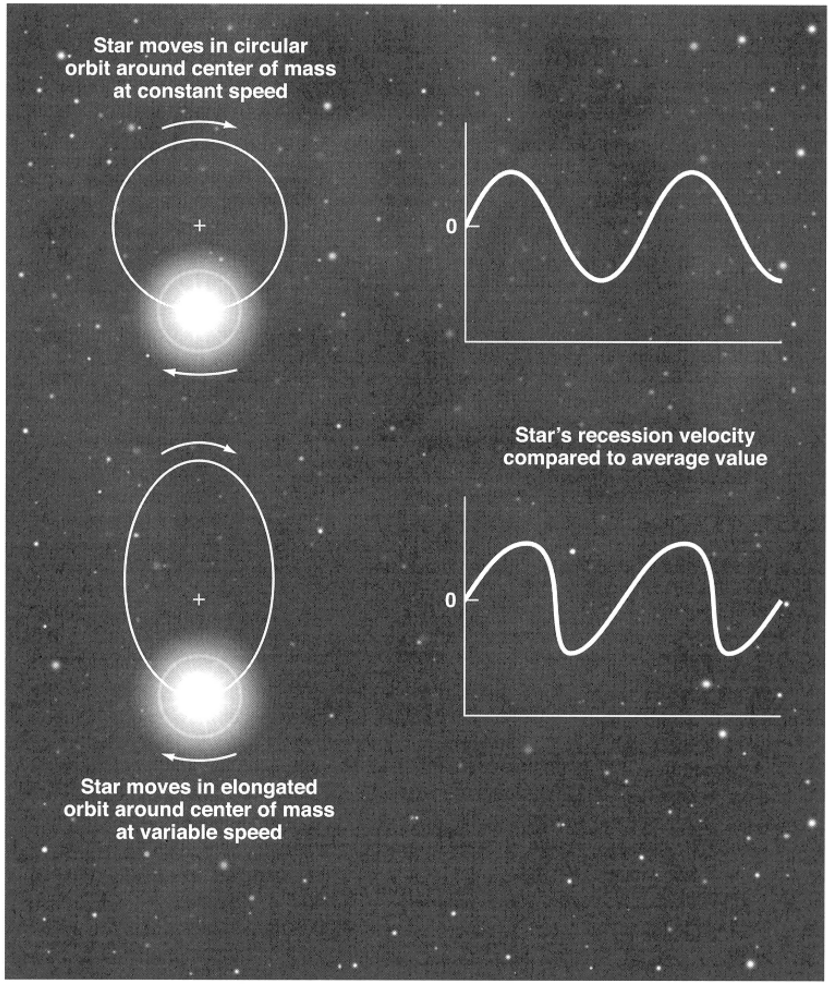
$$v_r = v_1 \sin i$$

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?

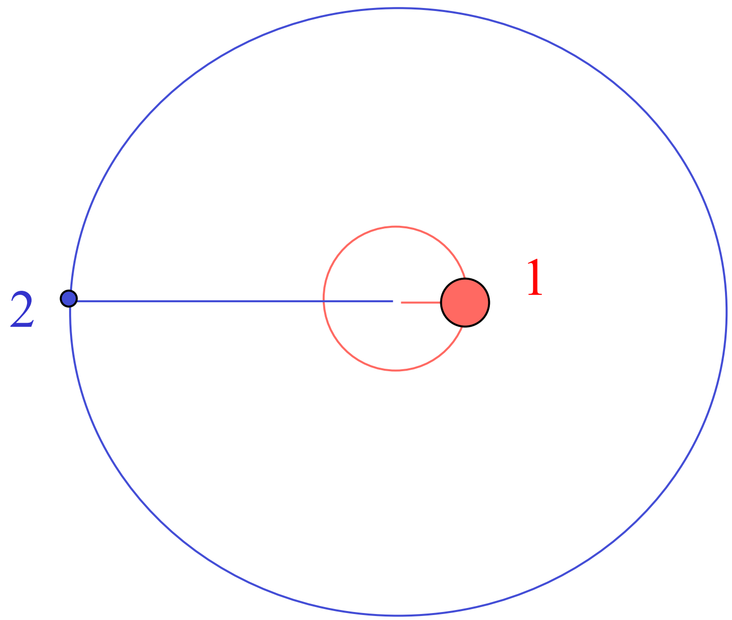
$$\boxed{v_1 = v_2 \frac{m_2}{m_1}}$$

	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 the target star is fainter at larger distances so it is 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)

- $\Delta(\text{rate})/\text{rate} \sim v_r/c$
- $\Delta t \sim r/c$

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 for the central object

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

	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?

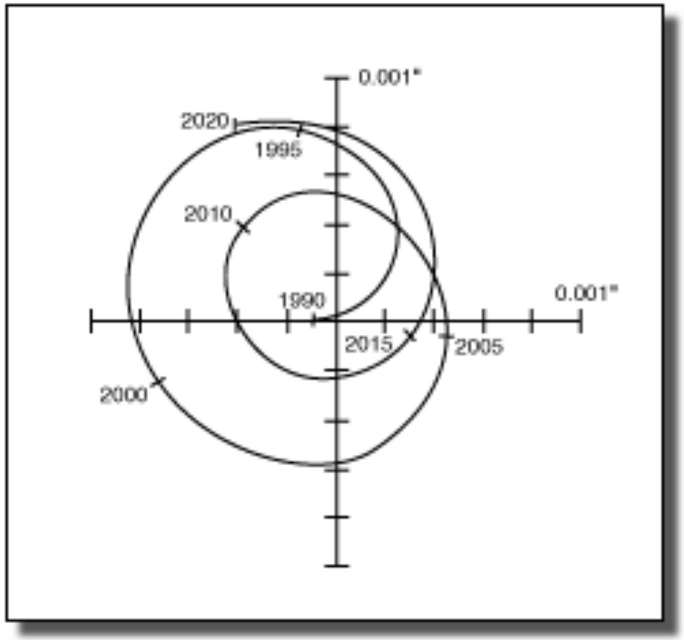
- No light
- Hazardous radiation
- SN explosion few million years ago

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



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

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

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

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

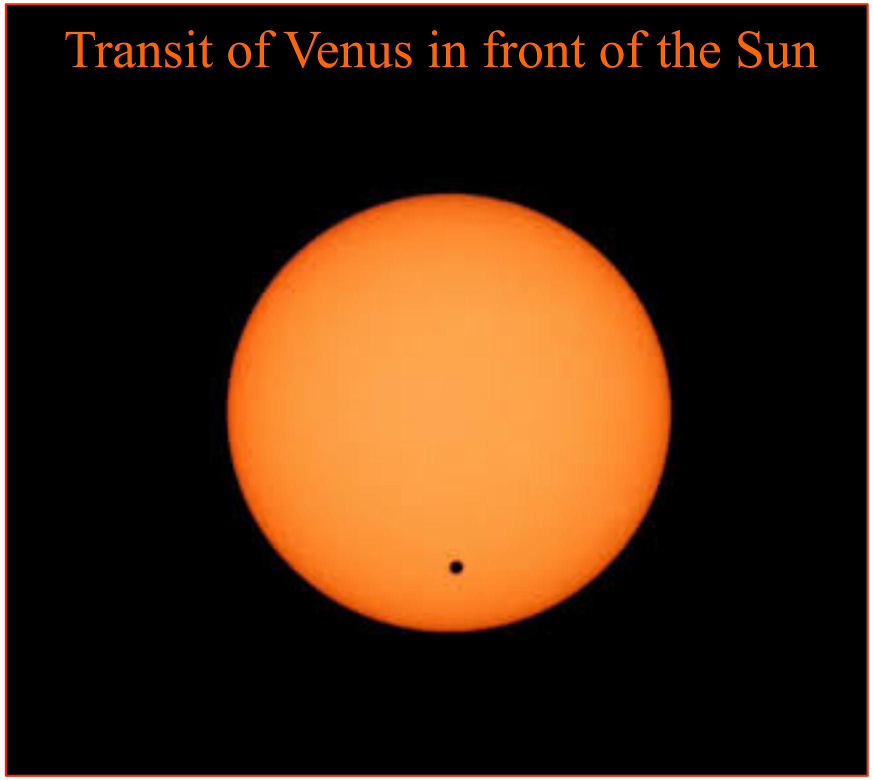
3. Occultations

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

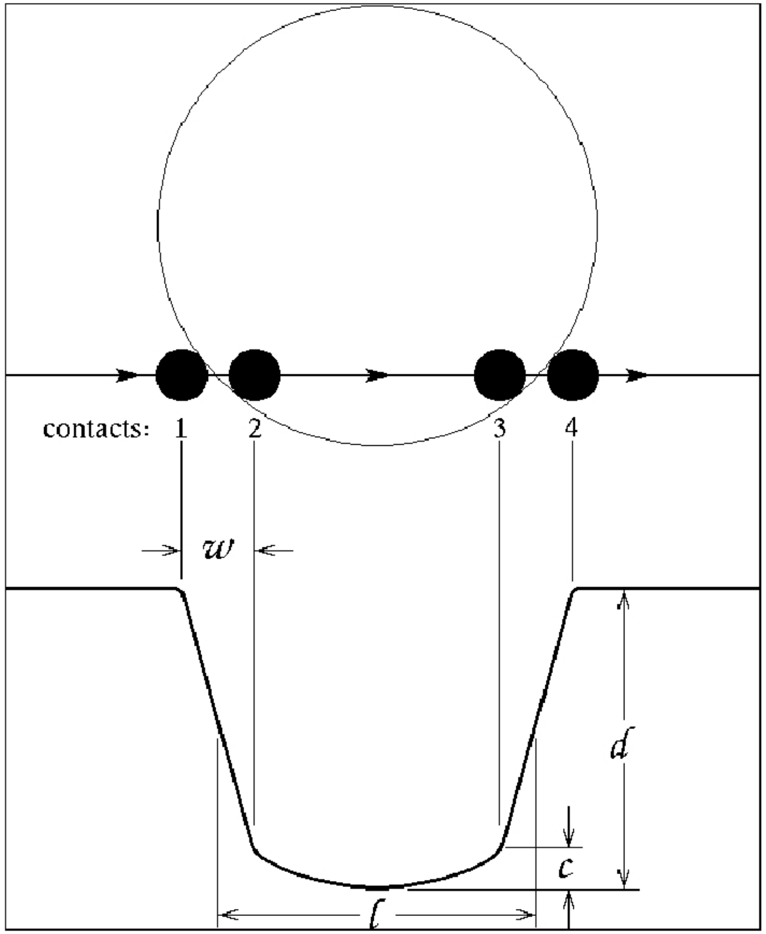
or

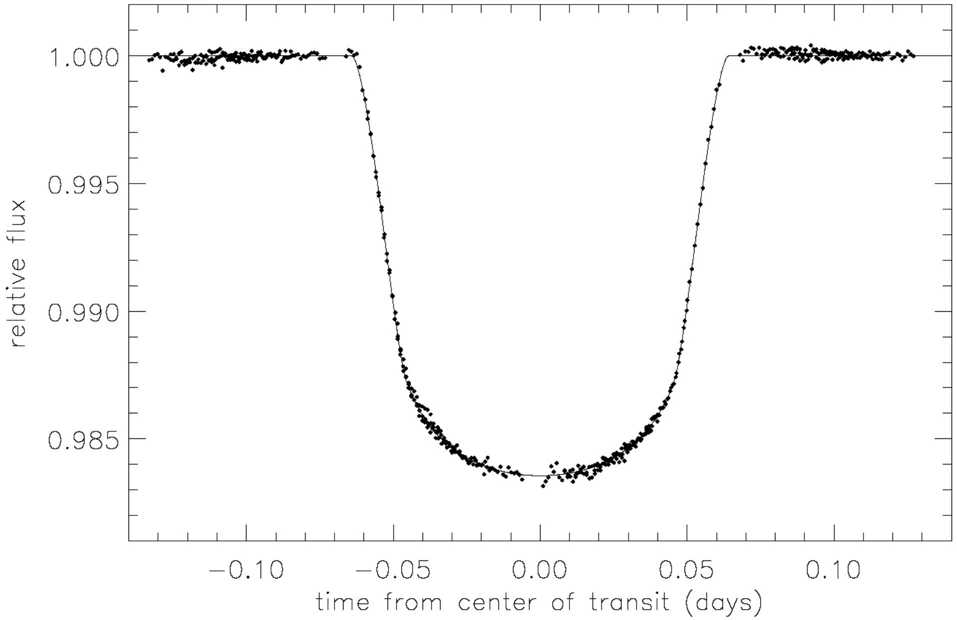
→ focus on known RV systems at the phase when $v_r \sim 0$



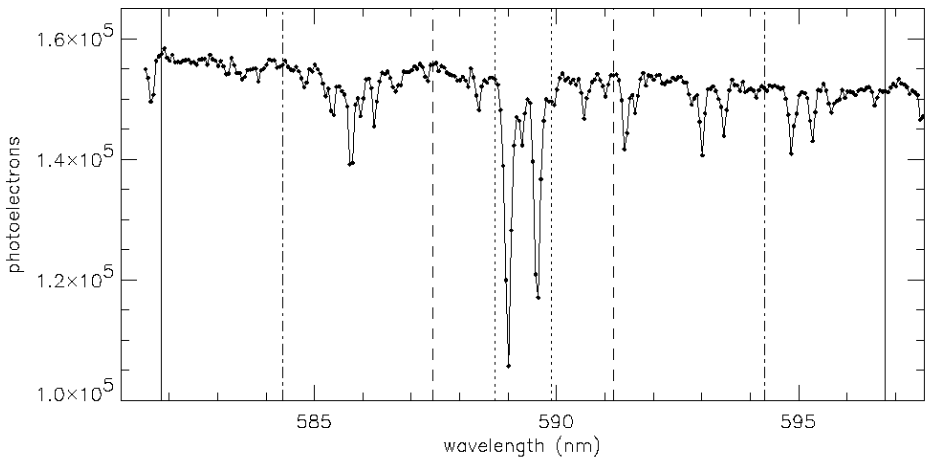
Note: occultations will only occur if sin $i \sim 1$ (i.e. $i \sim 90^o$) making a real m_2 measurement out of the $m_2 \sin i$. Also, the occultation gives size of the planet (assuming size of star is known) and therefore can give the density of the planet.

Note: Also, there will be a much smaller drop when the planet passes behind the star and we lose the planet's own light (therefore best done in infrared where contrast in brightness is smaller)

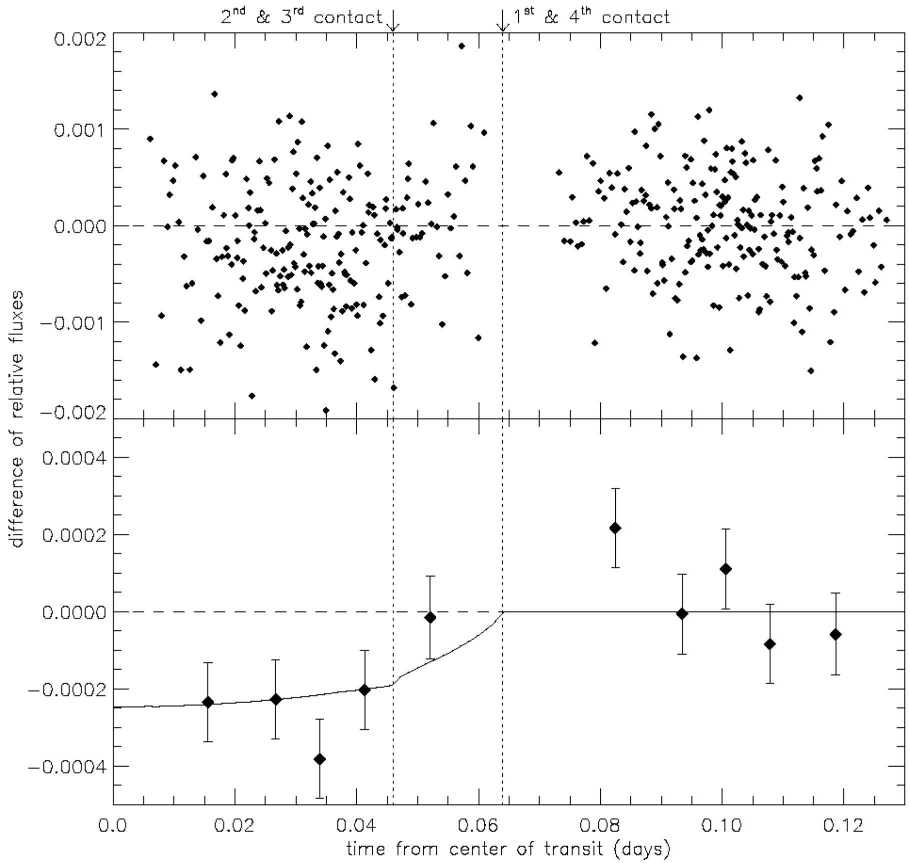

contacts: 1 2 3 4
w
d
c
l


1.000
0.995
0.990
0.985
relative flux
−0.10
−0.05
0.00
0.05
0.10
time from center of transit (days)

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>"



e.g. first detection of Na absorption in atmosphere of a transiting planet



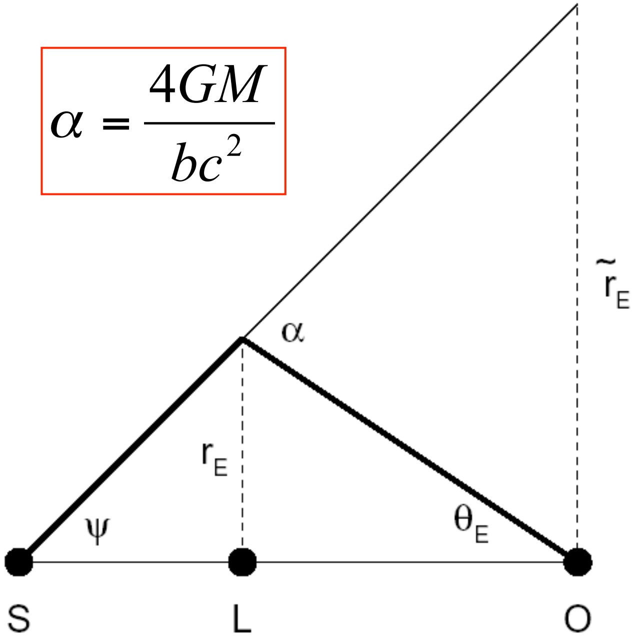
Na in 209458

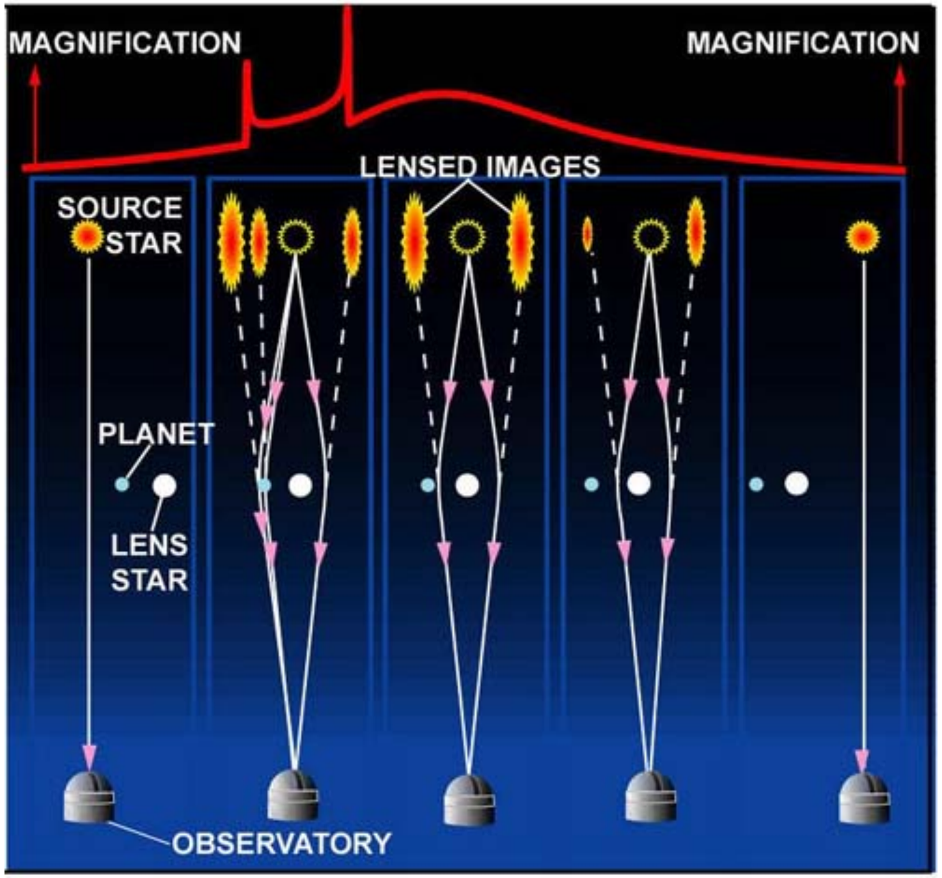
4. Gravitational lensing

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

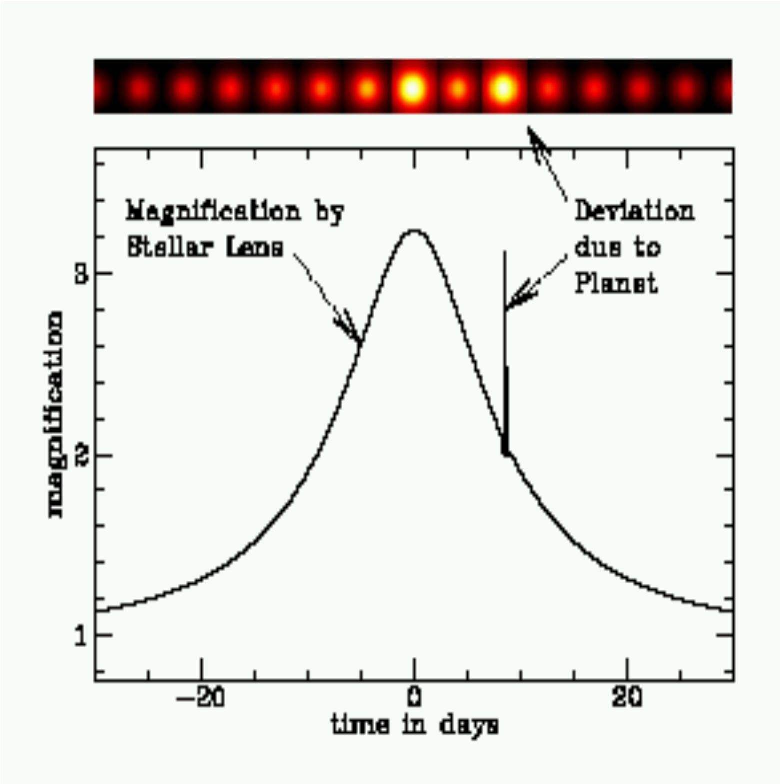
Light passing at distance b from point mass M is deflected through angle α

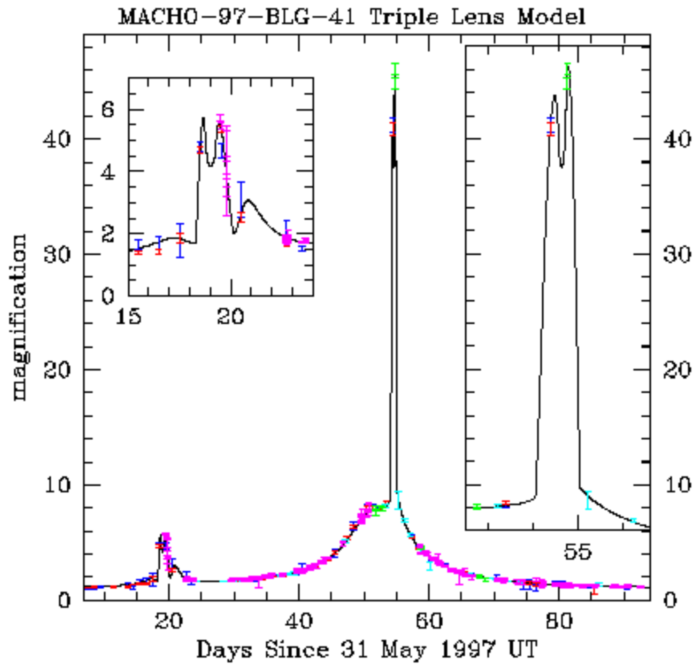
$$\boxed{\alpha = \frac{4GM}{bc^2}}$$





Microlensing theory





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.

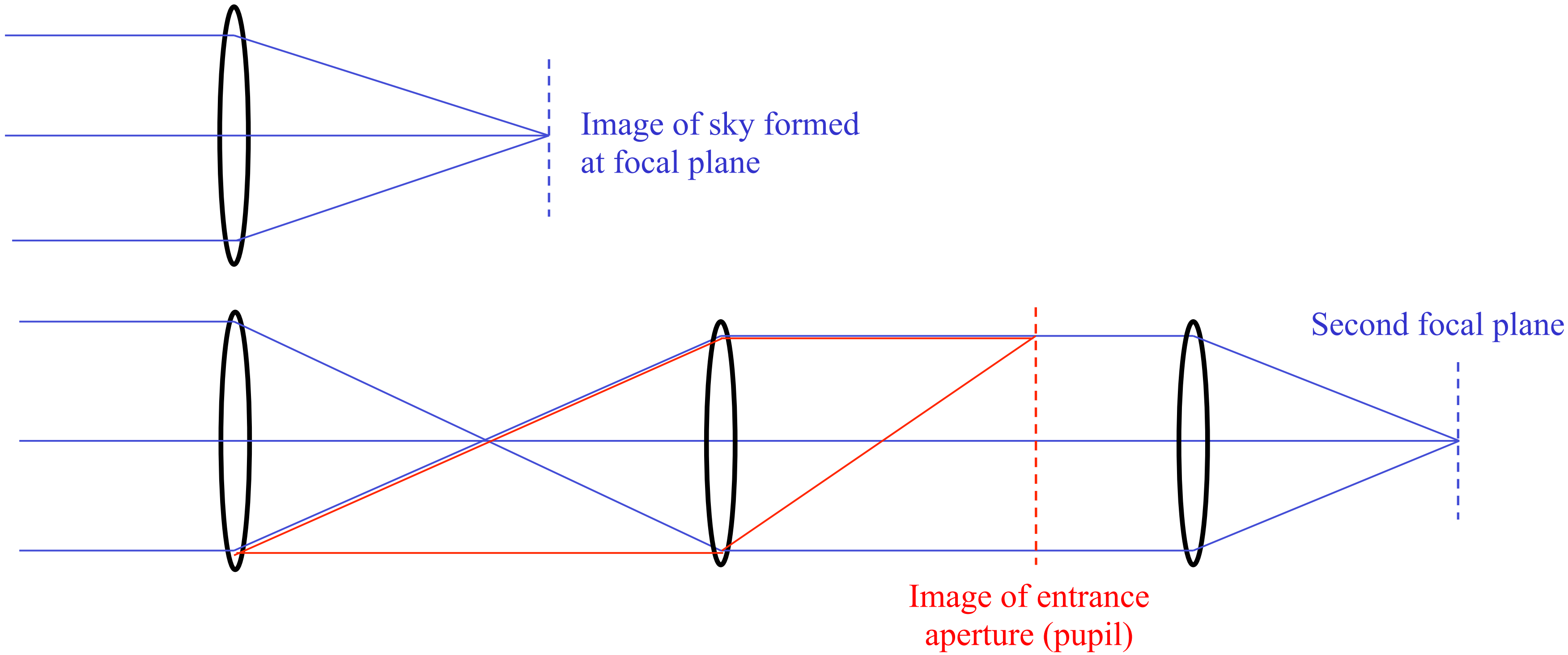
→ Monitor either huge number of stars in central region of our Galaxy or look at a nearby stellar system like the Large Magellanic Cloud (LMC).

B: Direct searches

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

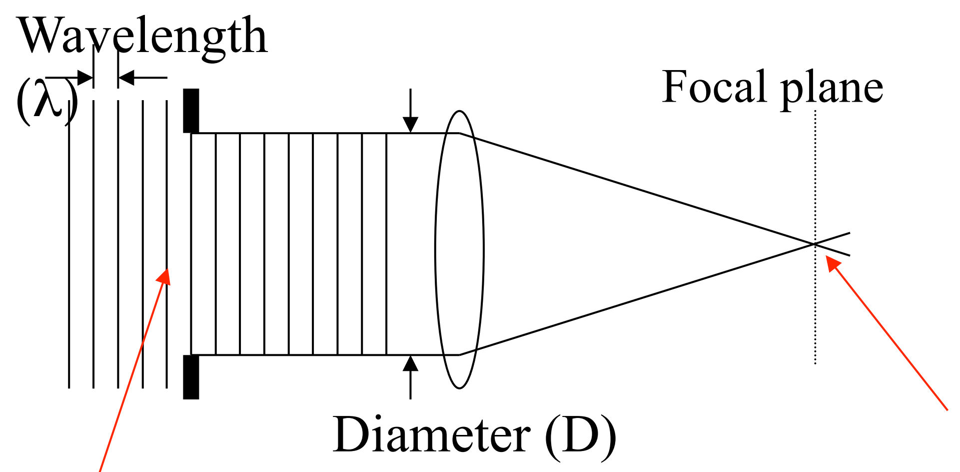
1. Coronagraphy
2. Adaptive optics
3. Polarimetry and/or spectral chopping
4. Interferometry and nulling interferometry

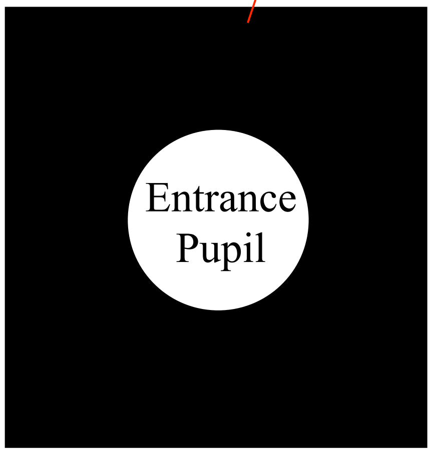
<u>Simple optics</u>: (doesn't matter whether lenses or mirrors)



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

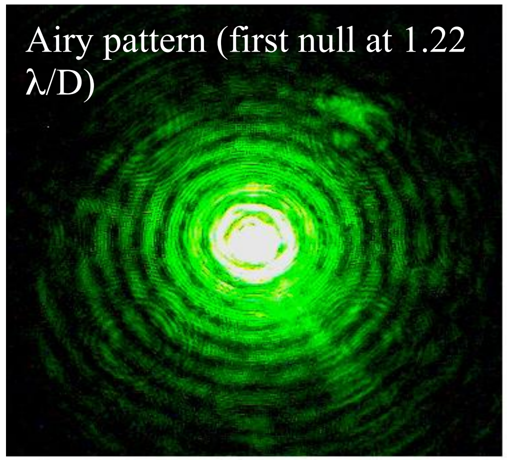
Fourier Optics: The classical circular aperture



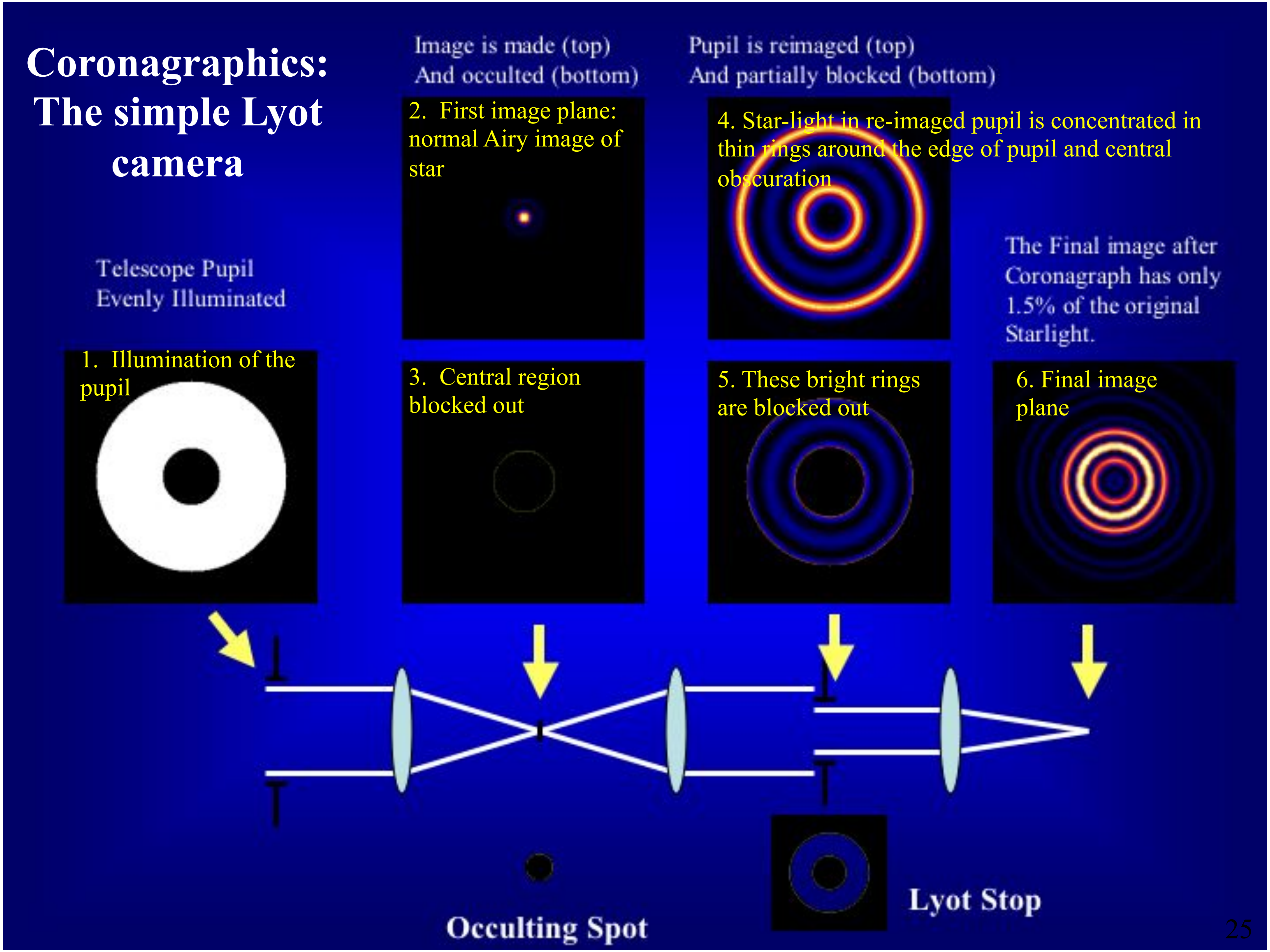


Fourier optics:

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



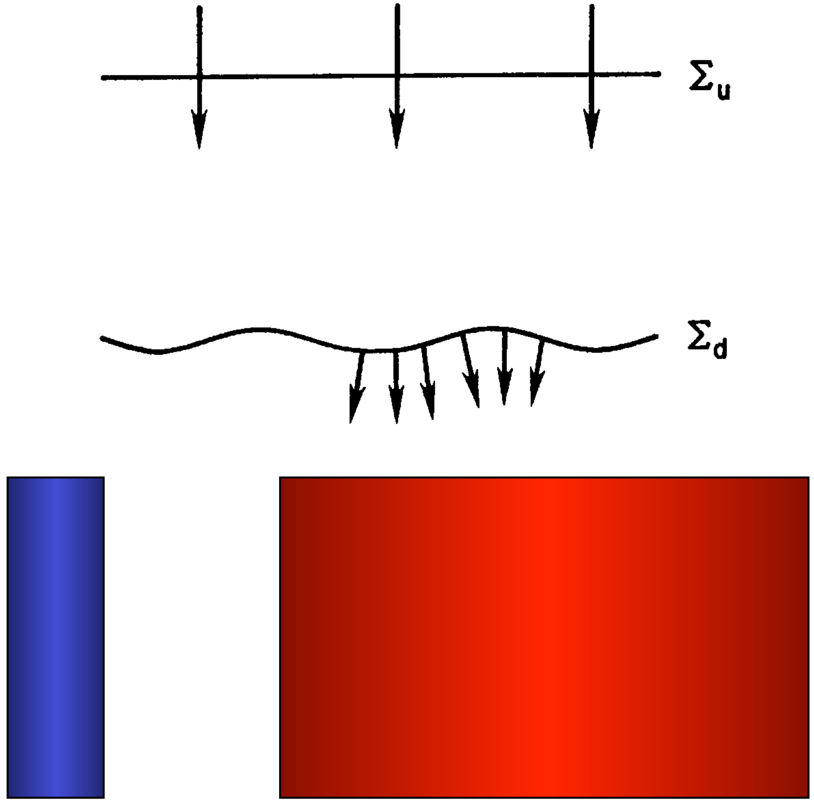
Classical optical system



Coronagraphics: The simple Lyot camera
Image is made (top) And occulted (bottom)
Pupil is reimaged (top) And partially blocked (bottom)
Telescope Pupil Evenly Illuminated
1. Illumination of the pupil
2. First image plane: normal Airy image of star
3. Central region blocked out
4. Star-light in re-imaged pupil is concentrated in thin rings around the edge of pupil and central obscuration
5. These bright rings are blocked out
The Final image after Coronagraph has only 1.5% of the original Starlight.
6. Final image plane
Occulting Spot
Lyot Stop

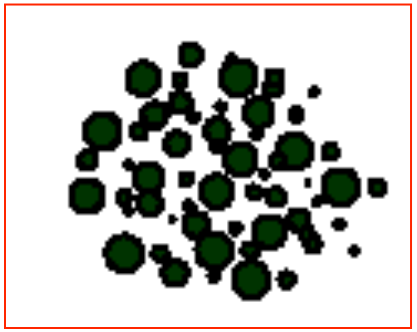
2. Adaptive Optics

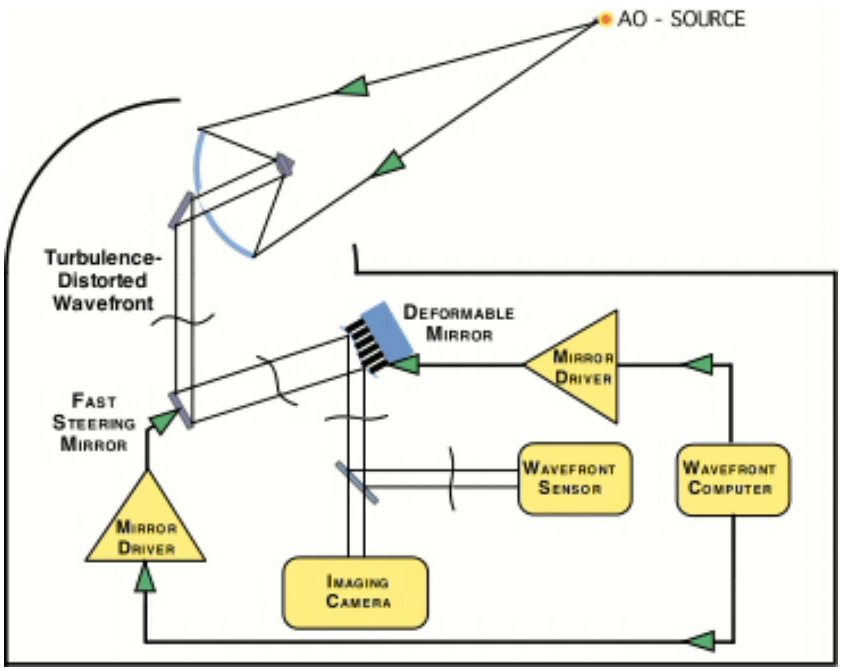
Spatial variations in the refractive index in the atmosphere above the telescope introduce rapidly varying wavefront distortions (phase variations) on a timescale of ~ 10 ms.



Observed with small aperture telescope → angled wavefront produces 10 msec image motion and brightness variations

With large aperture telescope → distorted wavefront produces multiple rapidly moving images ("speckles")

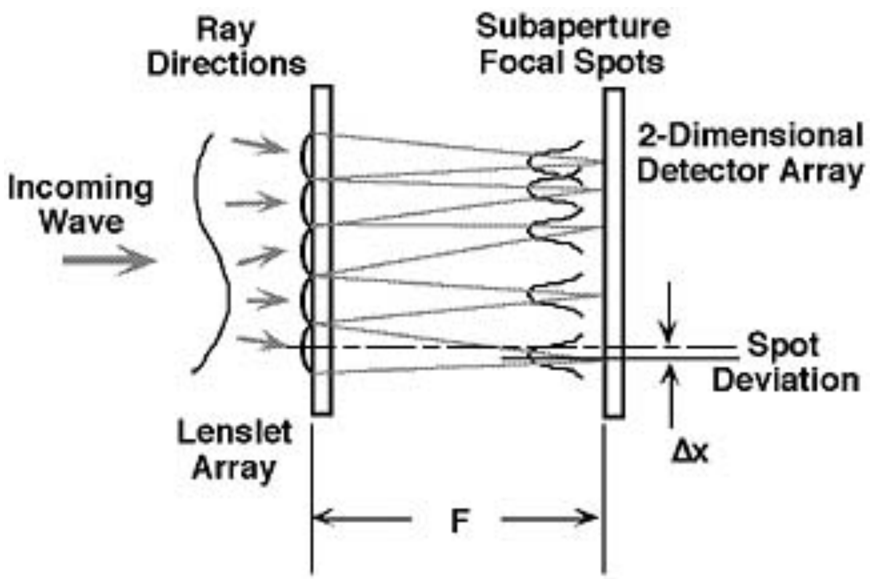




Generic adaptive optics system optical layout: A deformable mirror that is conjugated to the entrance pupil (or better, to the relevant height in the atmosphere) corrects the phase errors.

Must work at kHz rate.

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



Position of image in sub-pupil gives the phase gradient of the 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 annuli on mirror have different focal lengths

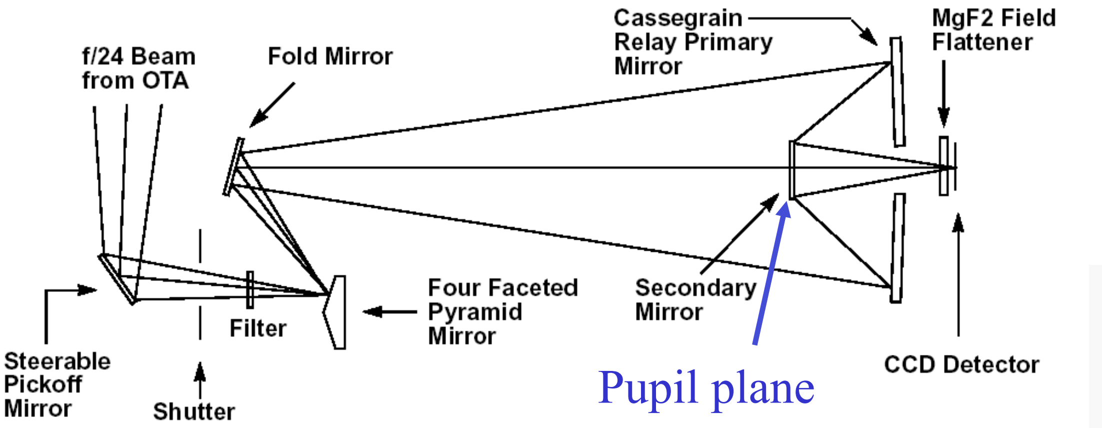
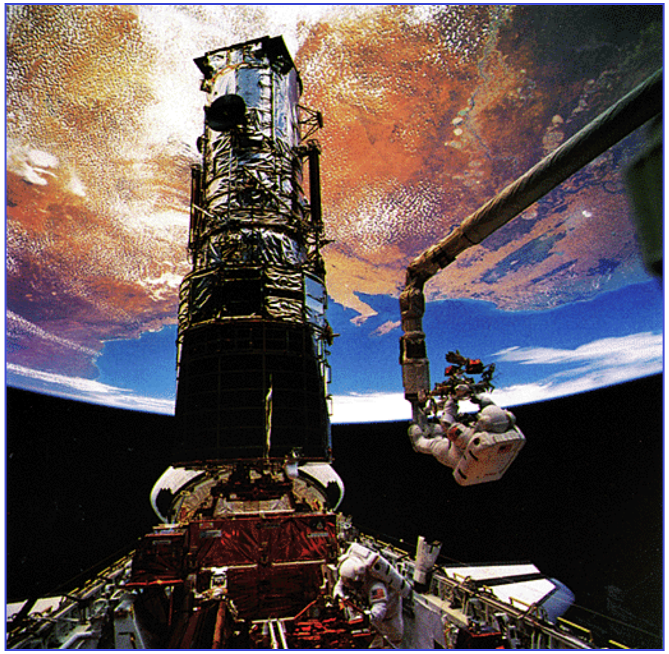
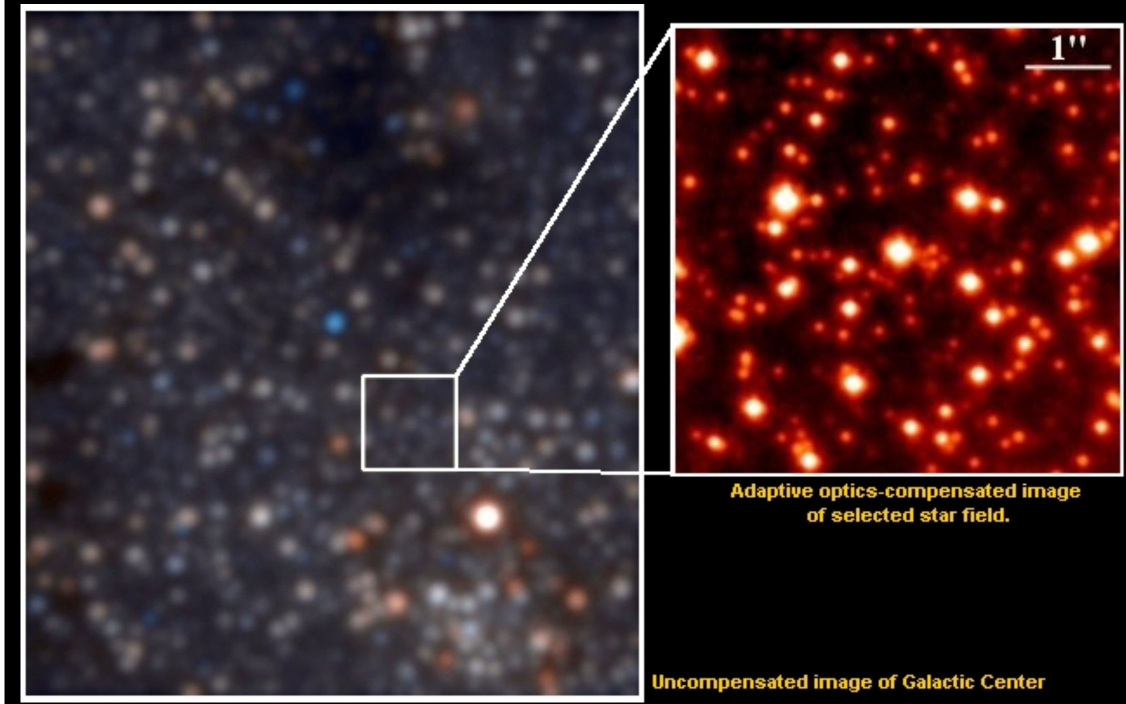


Figure 24.1: WFPC2 Optical Configuration



Wide Field Planetary Camera 1 | Wide Field Planetary Camera 2

HST aberration correction



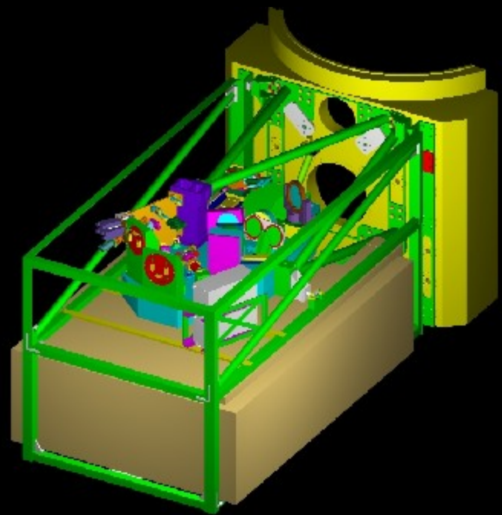
AO image of Galactic Center

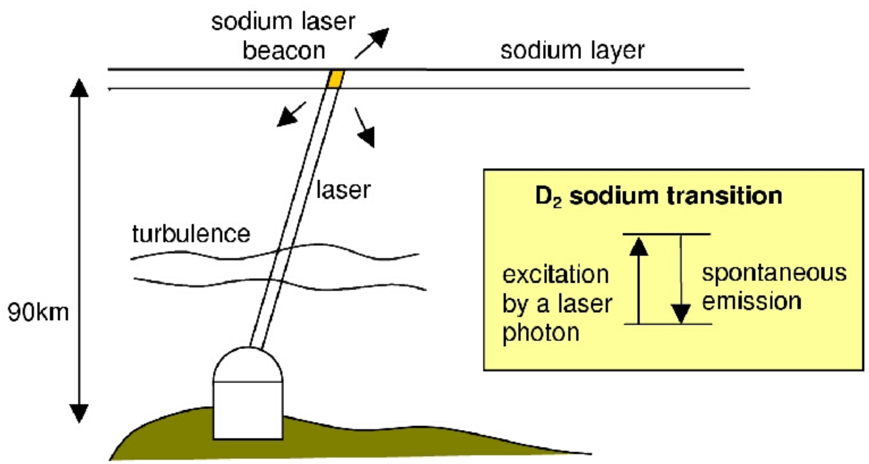
65 $M_{Jupiter}$ brown dwarf 0.8 arcsec from 5 mag star

AO systems in practice:

We need a bright source to use for the kHz wavefront sensing:

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

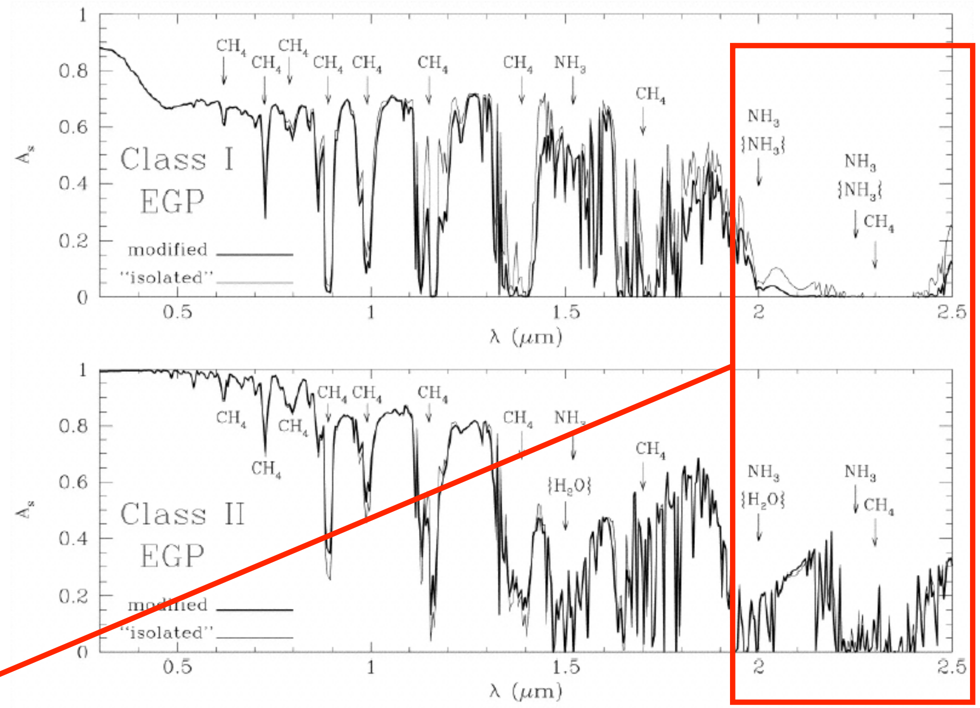




Artificial laser stars for adaptive optics using Na in upper atmosphere to produce artificial “star”

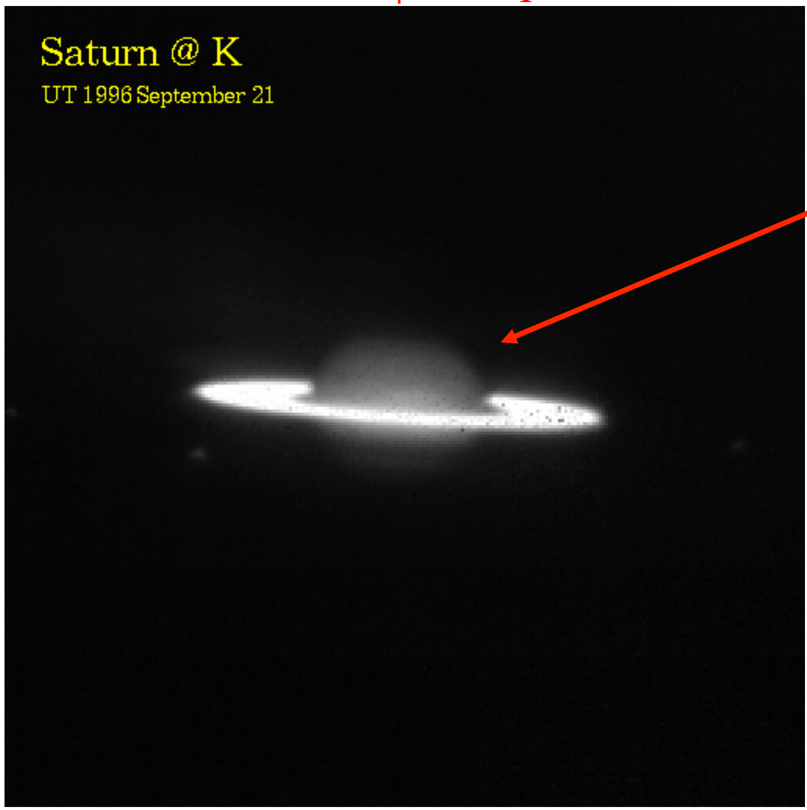
3(a) Spectral subtraction

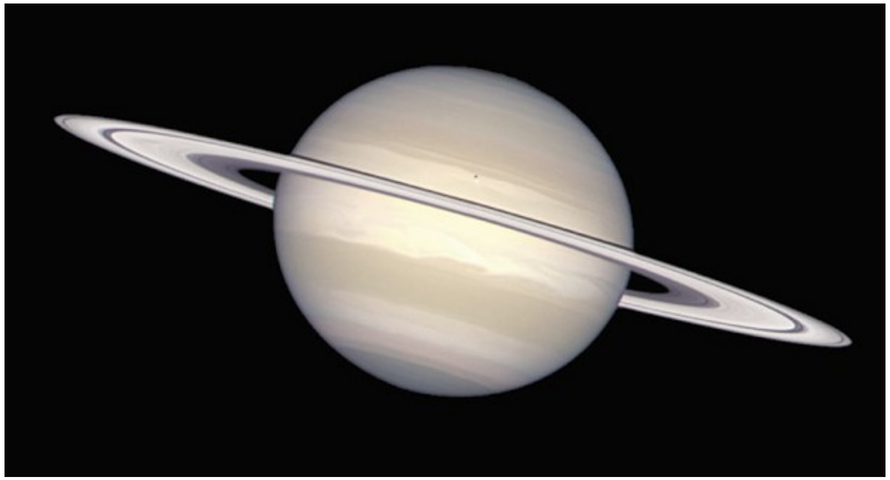
Simultaneous differential “on-off” imaging at two wavelengths at which planet and star are expected to have different relative brightnesses



2 μm: atmospheric albedo very low due to CH_4 absorption

Visible light: uniform albedo





Methane differencing

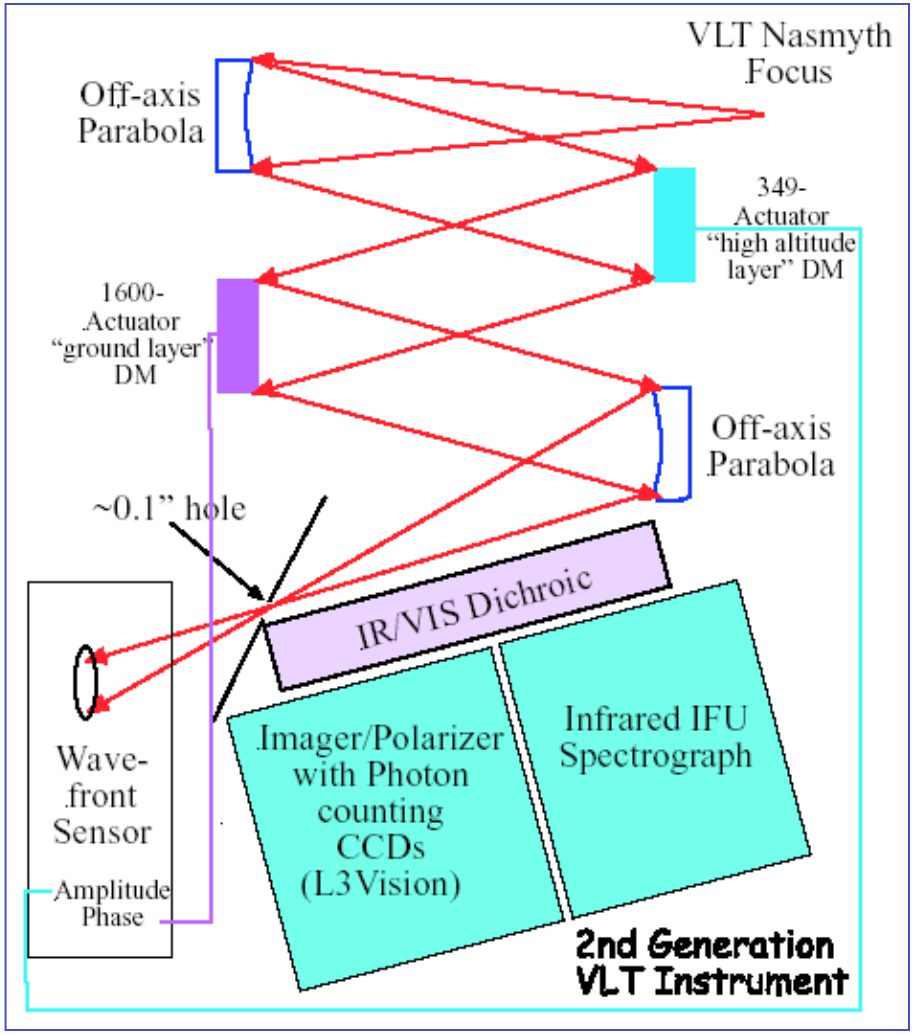
3(b) Differential polarimetric imaging

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

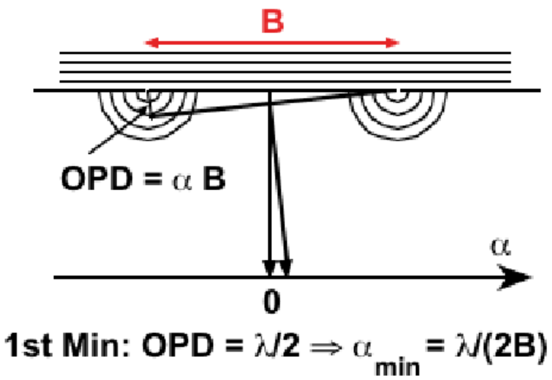
SPHERE

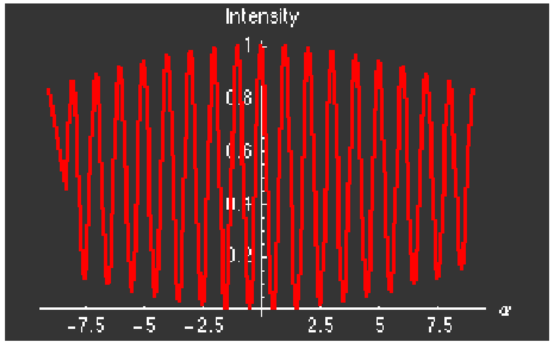


Planet finder

4. Interferometry

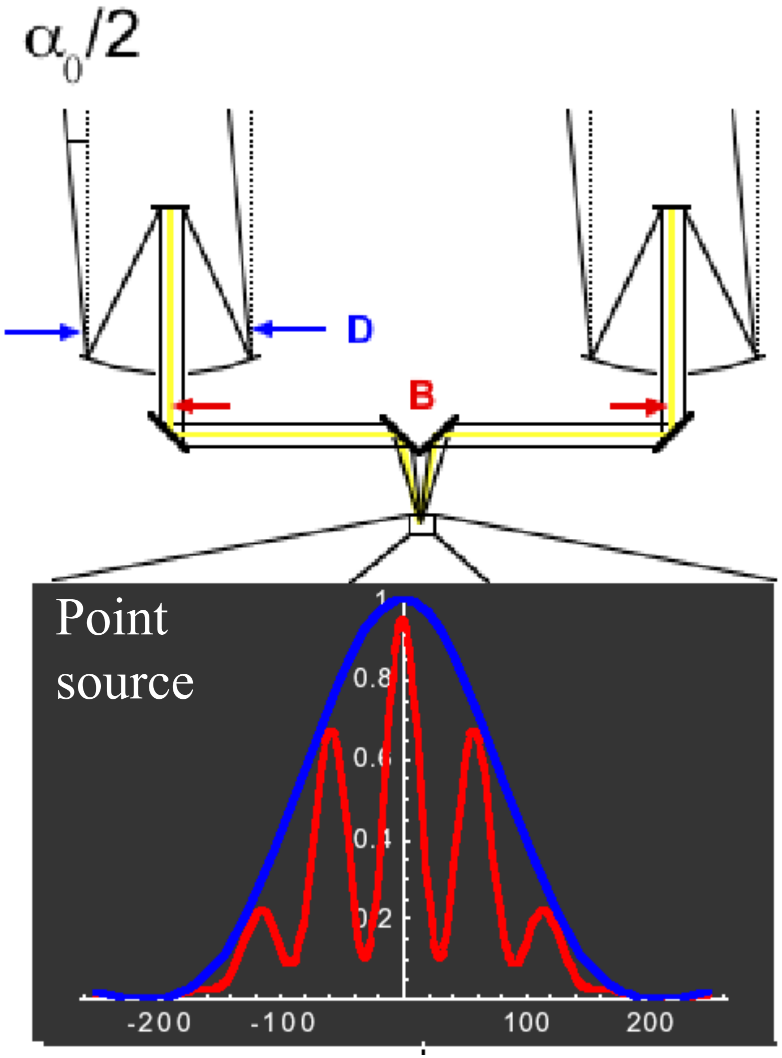
Young's Two-Pinhole Experiment



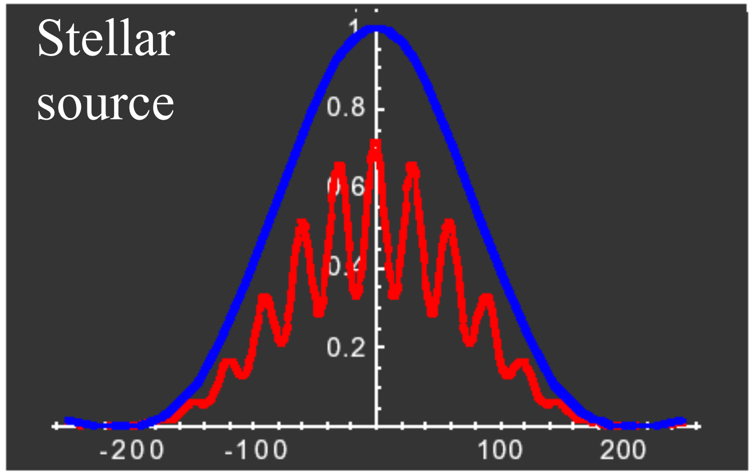


- Light source at infinity
- Intensity pattern = 1 + cos ($2\pi\alpha B/\lambda$), where αB is the Optical Path Difference (OPD)
- When OPD > coherence length, fringes disappear
- Light source at angle a_0 shifts fringe pattern spatially

Aside: The Michelson stellar interferometer (1920) was used to measure stellar angular sizes



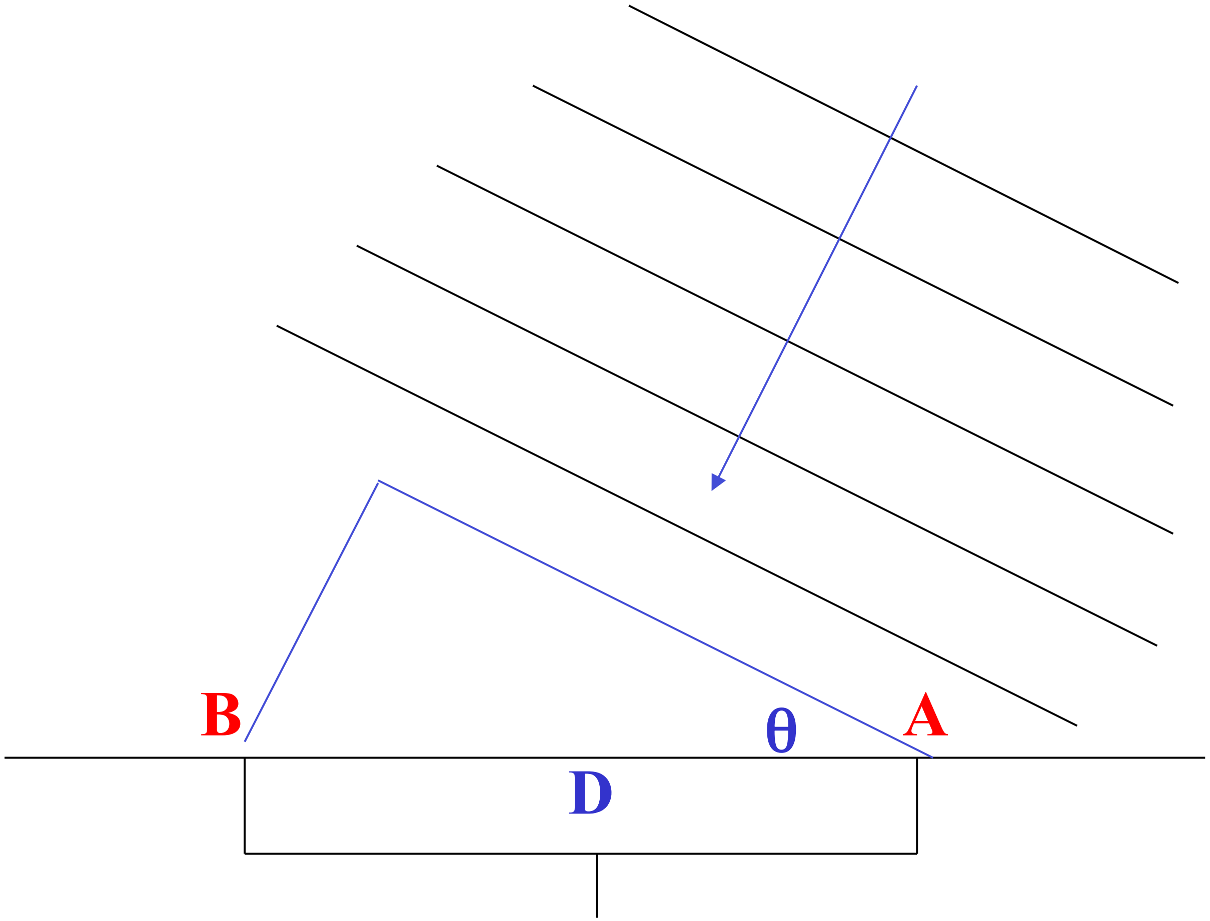
- Stellar source with angular diameter a_0
- Add fringe patterns shifted by 0 to $\pm a_0/2$.
- This reduces the contrast of the fringe pattern depending on a_0 and telescope separation B



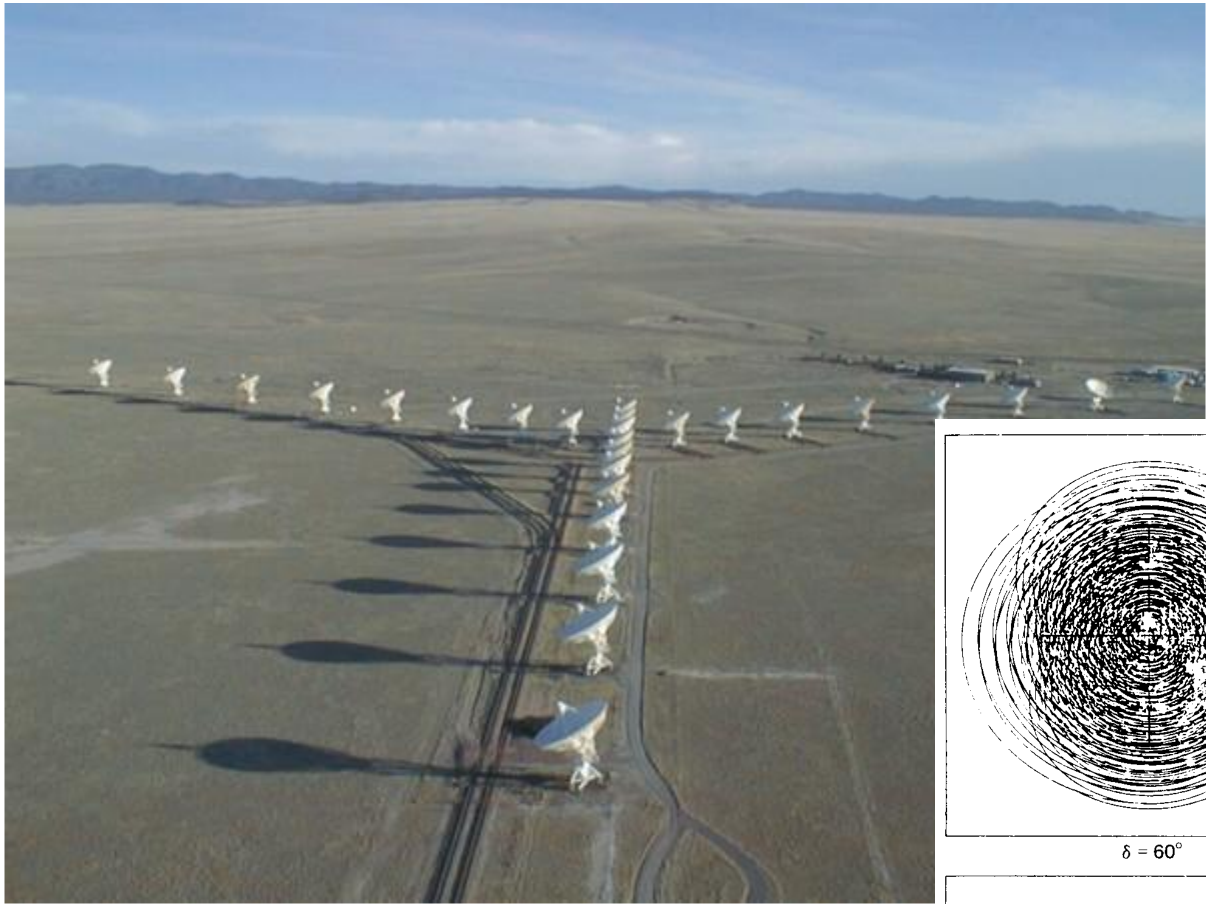
GENIE Workshop, Leiden, June 3-6, 2002

Short aside: radio interferometry

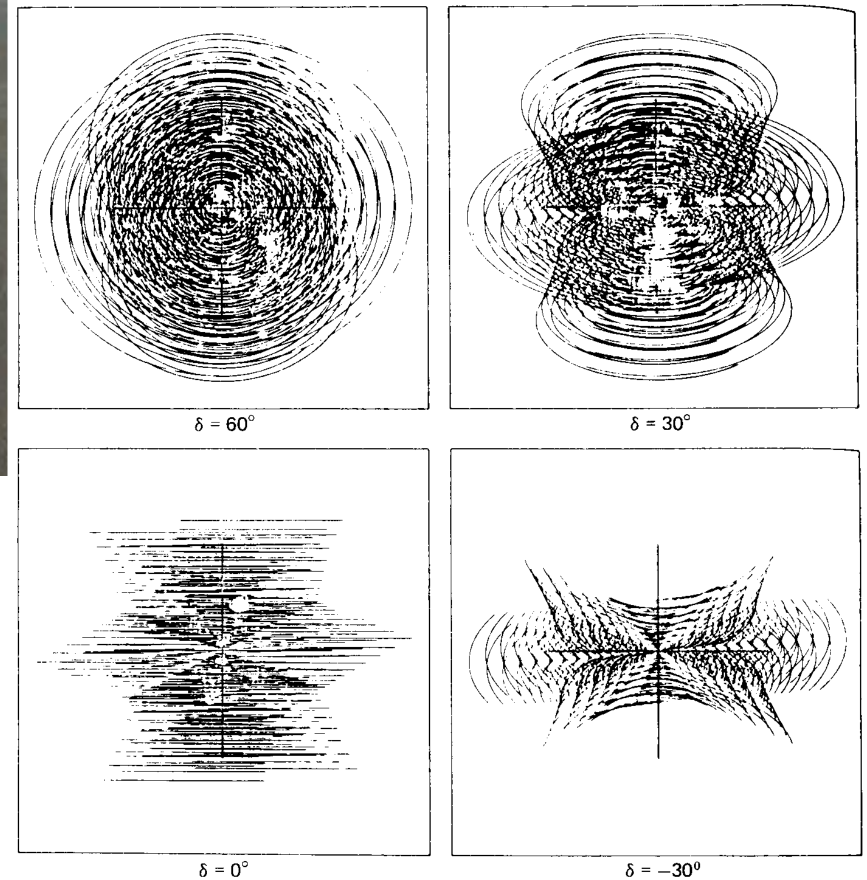
Net result: Two radio telescopes measure one Fourier component of of the radio sky brightness



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



Fourier plane coverage of VLA antennae (as Earth rotates)

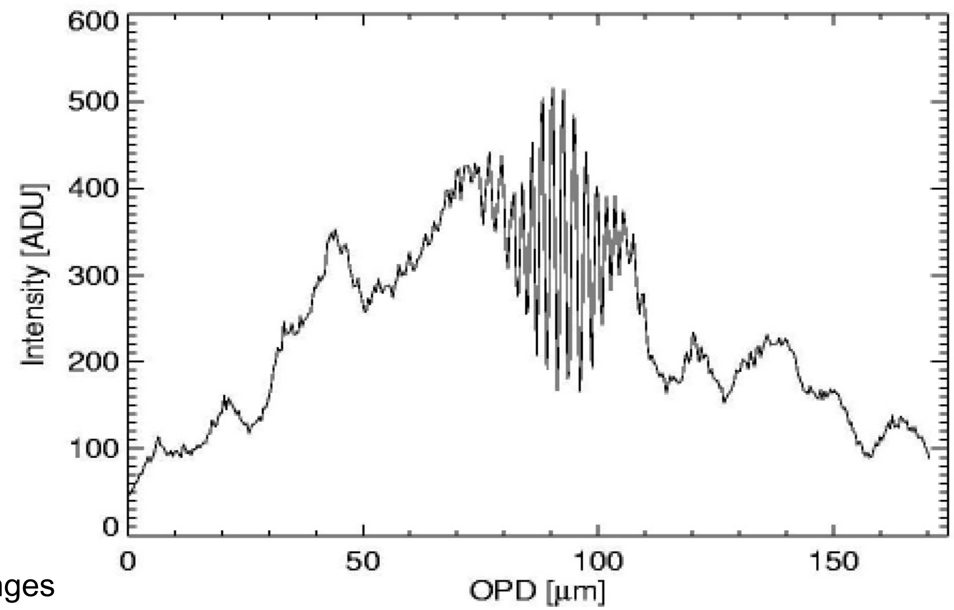


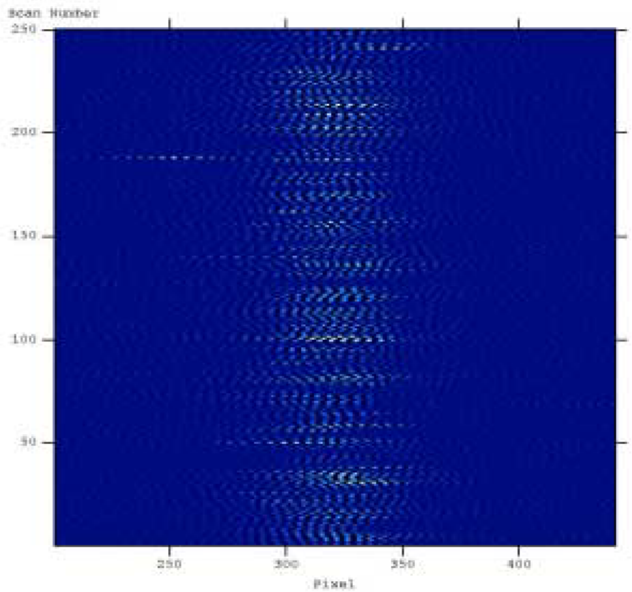
Very Large Array: combining all possible pairs samples the Fourier space quite well. This is the standard technique for making images at radio wavelengths.

This is <u>much harder</u> at optical wavelengths: Why?

- We cannot measure the phase of photons like in the radio (must allow the photons themselves to interfere rather than multiply voltage signals)
- There is a short coherence time for short λ photons
- Effects of rapid variation of atmospheric phase distortions

World leaders: 4x8m ESO VLT in Chile.

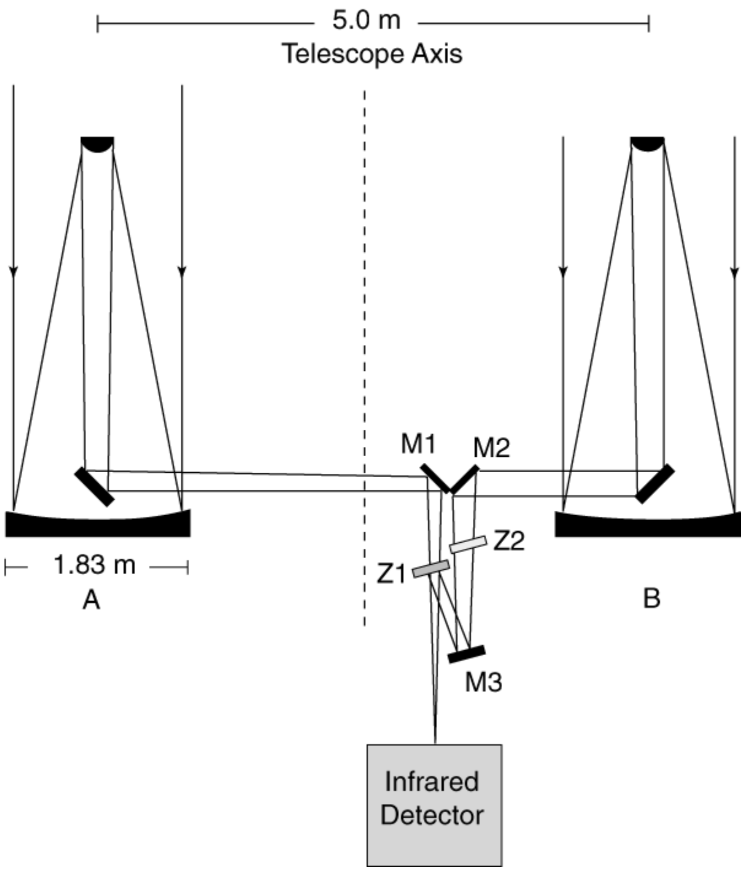


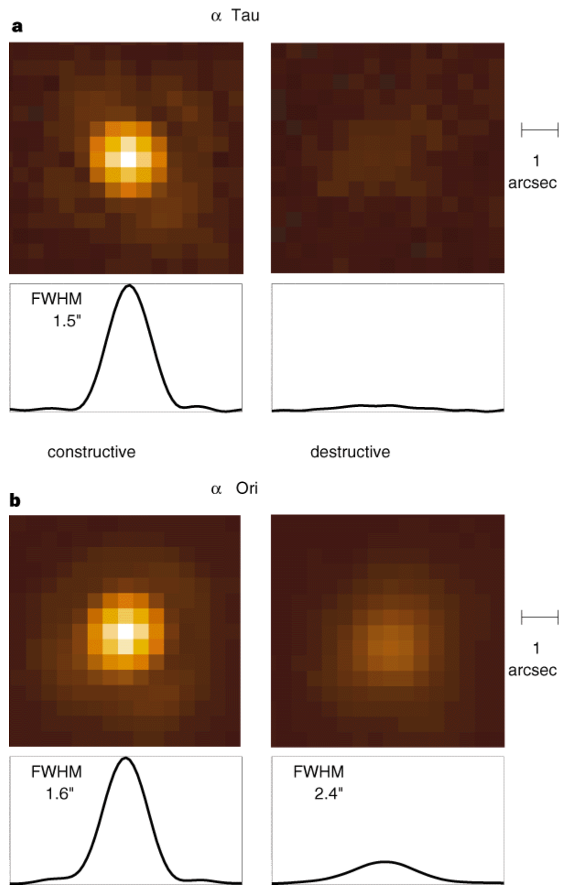


VLT fringes

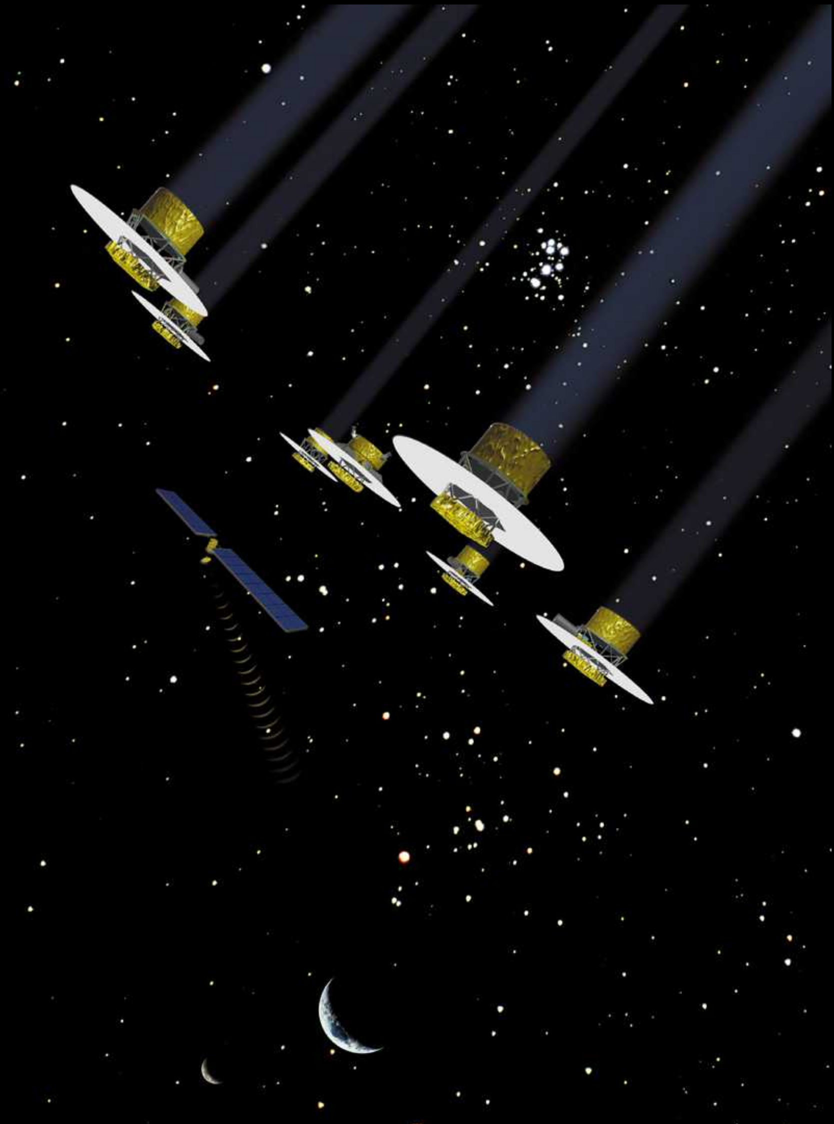
Other clever techniques: Nulling interferometry

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:

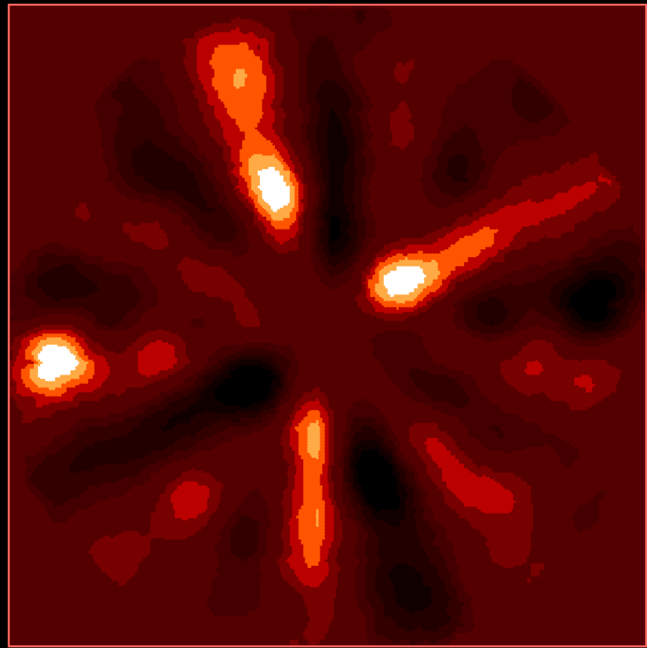




Nulling interferometry

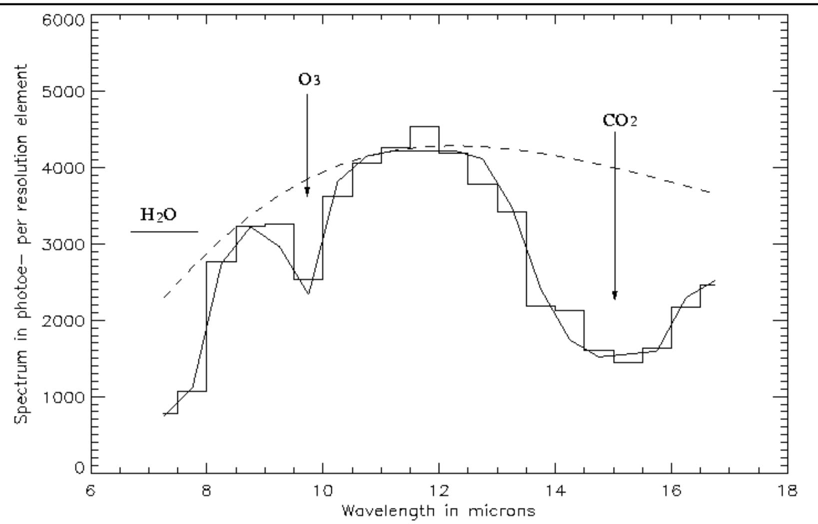


2007 Proposed ESA Darwin mission
(no longer active due to cost)



Simulated Venus, Earth, Mars at 10 pc

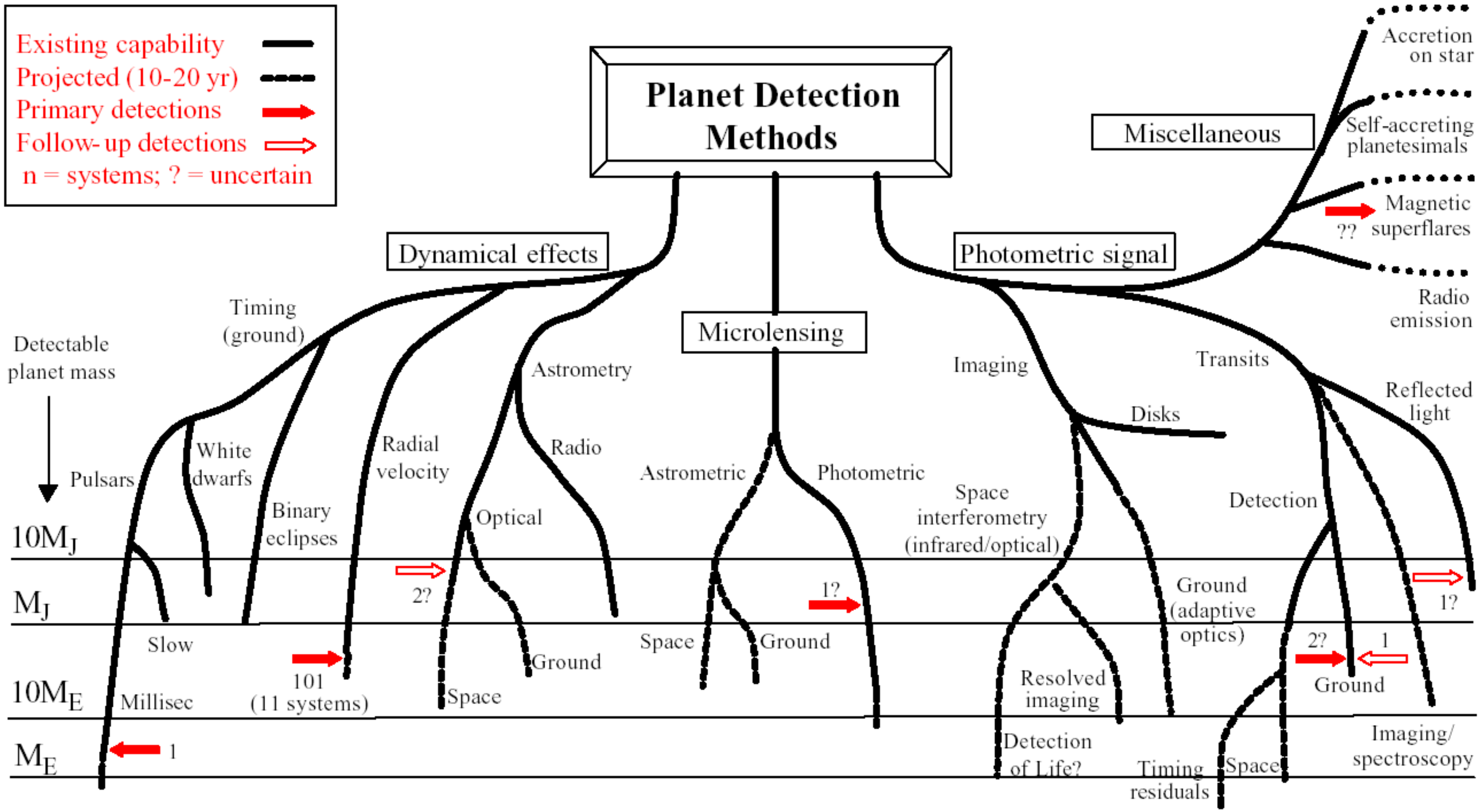
Simulated Earth spectrum




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)