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, $mag = -2.5 \log f + \text{const.}$]

$mag_{\text{Jupiter}} \sim -2 \rightarrow mag_{\text{planet}} \sim 21.6$ This should not be hard!

(the galaxies I study routinely are much fainter than this!)

Angular separation of Jupiter-Sun as seen at the nearest star would be about 4 arcsec. (again, should also be easy!)

Brightness of extrasolar planets compared with their host stars

Planets will shine by both reflected (sun-)light and thermal emission. Assuming an albedo of a (fraction of sunlight reflected) and a radius r of the planet at an orbital distance D from a star with radius R_s and temperature T_s, and neglecting other 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:

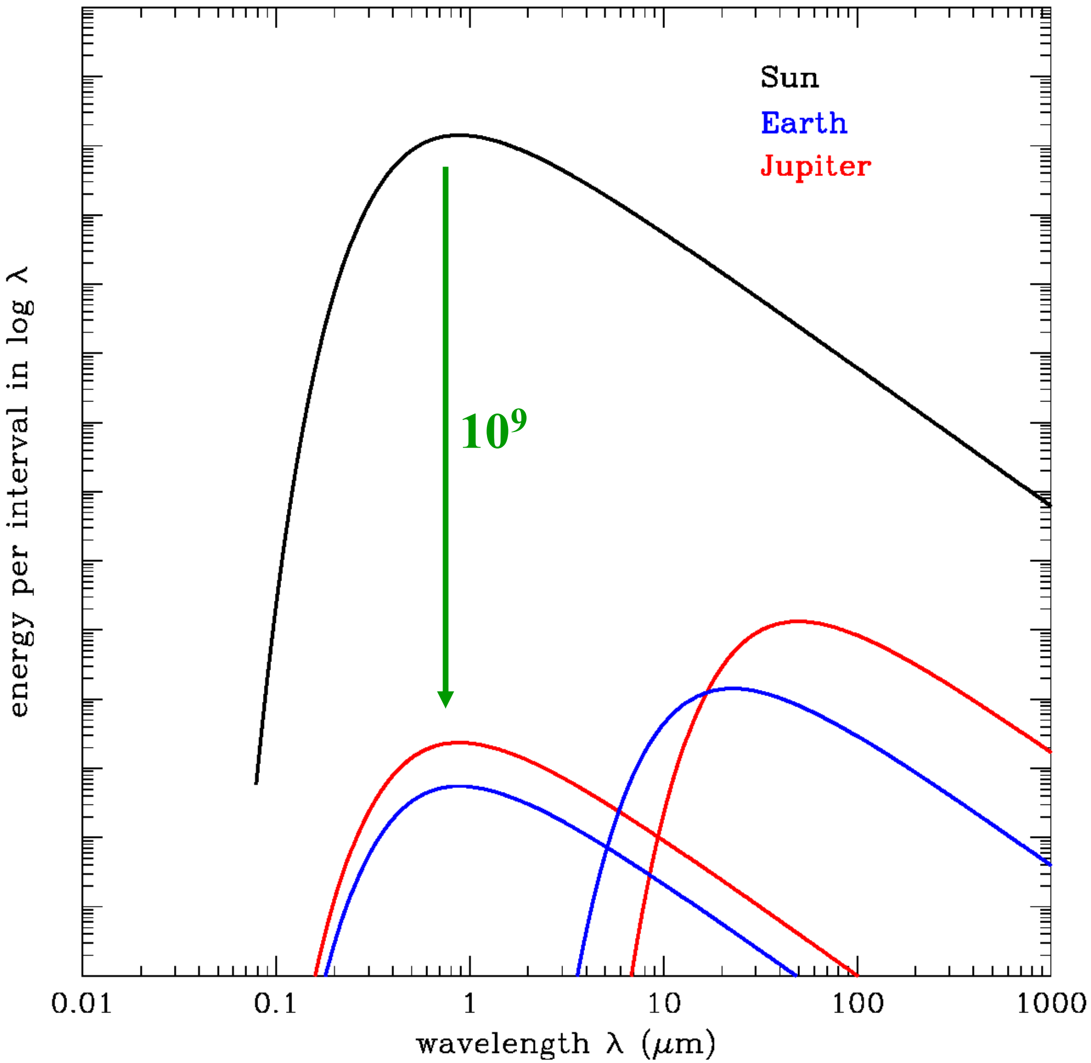
$$L_p = (1-a)\,L_s \frac{r^2}{2D^2} = (1-a) 4\pi R_s^2 \sigma T_s^4 \frac{r^2}{2D^2}$$

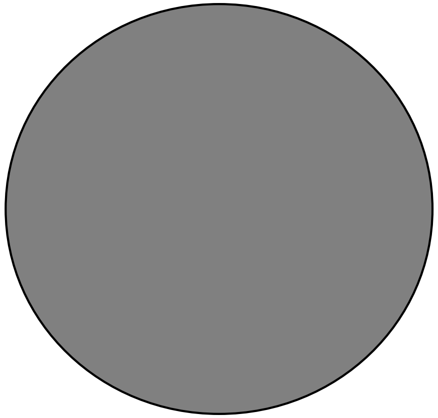
$$T_p = \sqrt[4]{\frac{L_p}{4\pi\sigma r^2}} = T_s (1-a)^{1/4} \sqrt{R_s / 2D}$$

	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 λ ~100 μm**
- Note: The Earth is brighter than Jupiter at 10 μm!





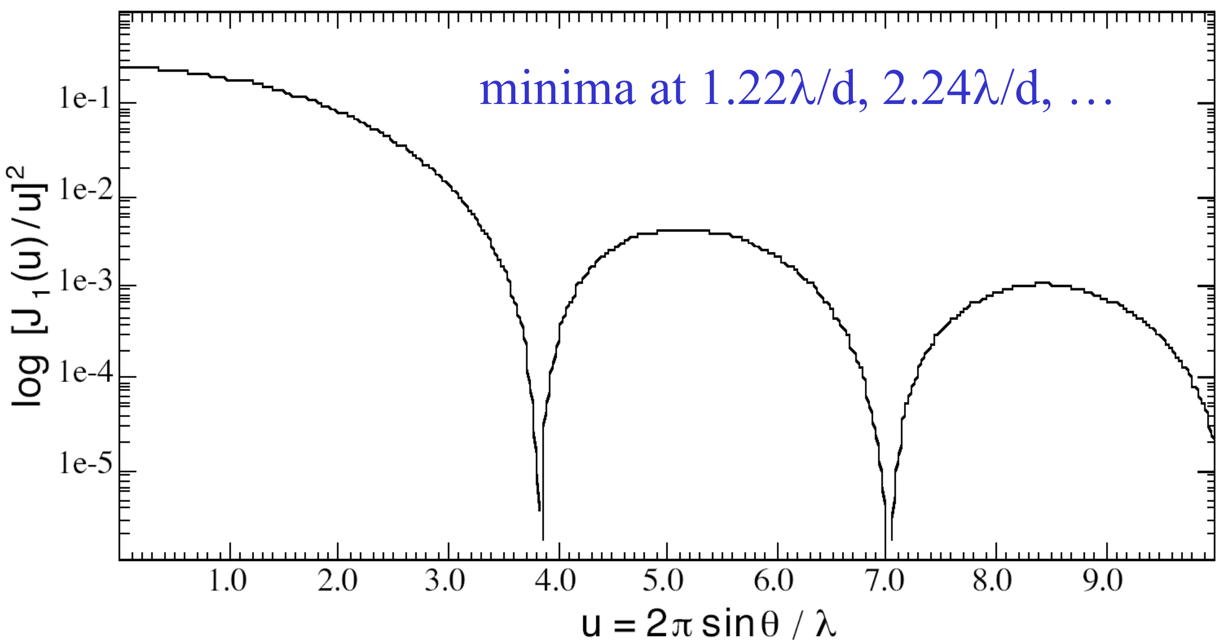
Why is this a problem?

Diffraction from an ideal telescope aperture:

Fourier optics: Point spread function of telescope (image of a distant point source) is the Fourier transform of the entrance aperture/. For an idealized perfectly circular aperture:

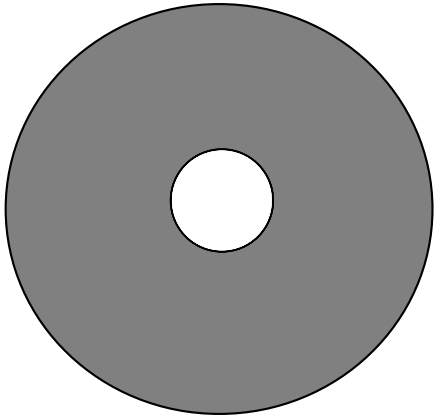
$$I(\theta) = I_0 \left(\frac{2J_1(u)}{u} \right)^2 \qquad u = 2\pi\theta / \lambda$$

J_1 = 1st order Bessel function of first kind



Good: 84% of energy falls within a diameter of 1.22λ/ *d* (~ 0.015 arcsec for 8 m telescope at visible wavelengths 550 nm)

Bad: scattered light decreases only slowly with radius



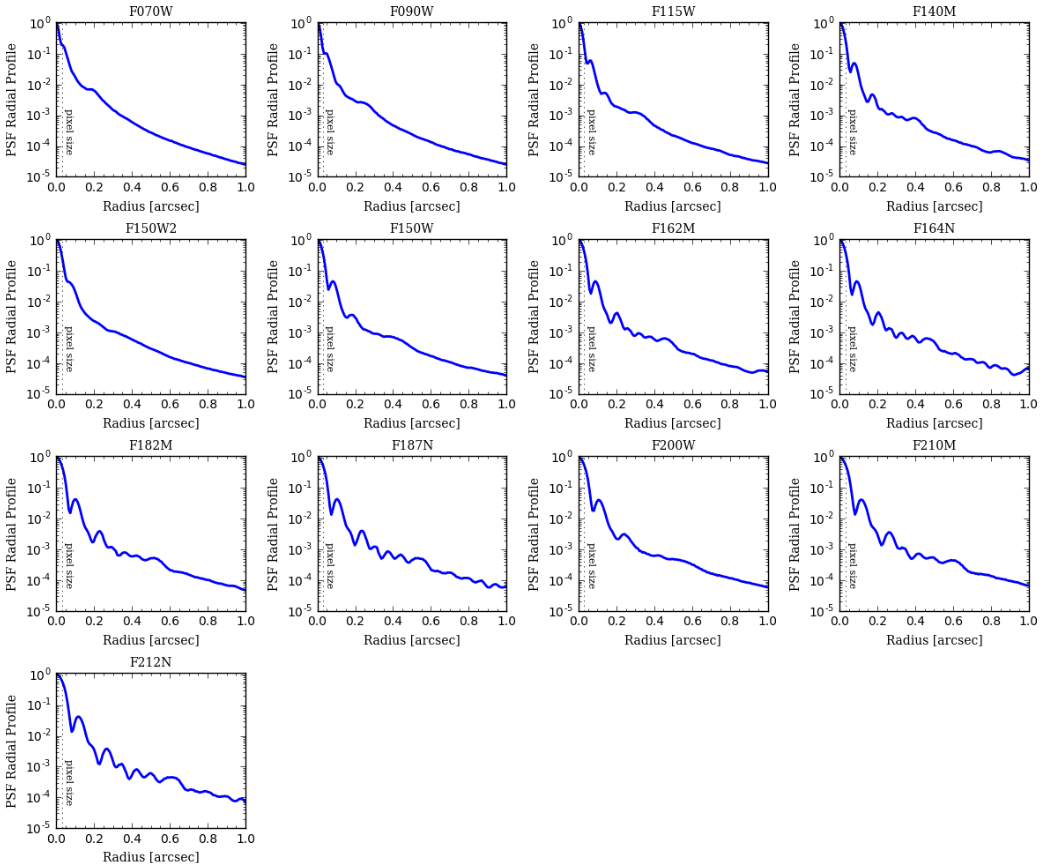
In practical optics it is even worse

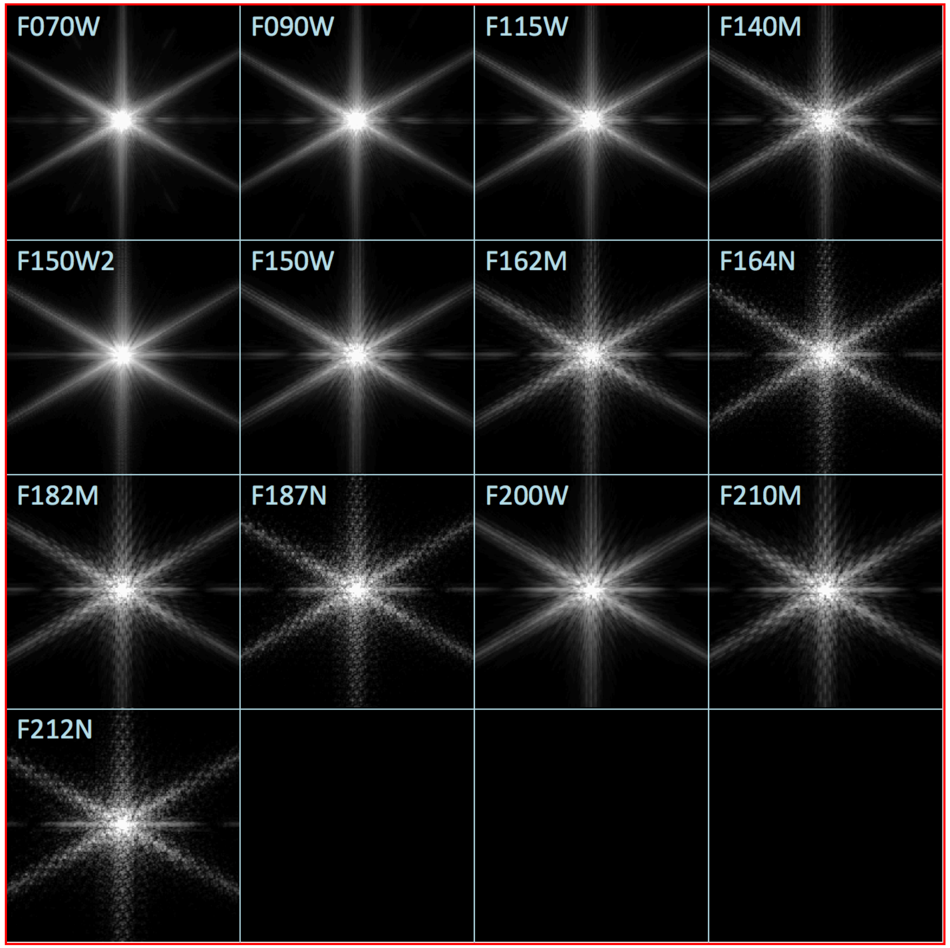
- “On-axis” telescopes usually have central obstruction of some kind for mechanical design reasons
- Other Imperfections in optics also throw light to large angles

Plus:

- Phase errors across the aperture due to variations in atmospheric refractive index (for ground-based telescopes at optical wavelengths) produce approximately gaussian images of typical FWHM ~ 0.5-1.2 arcsec, i.e. about 30 times larger than the diffraction limit of the telescope.

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





Techniques for Exo-solar planet detection

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

Relies on the effect of the planet on the star itself (or something else)

1. Radial velocity measurements (and pulsar timing)
2. Astrometry
3. Transits
4. Gravitational lensing of background sources

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

Use different approaches to subtract the dominant star-light to reveal the planet

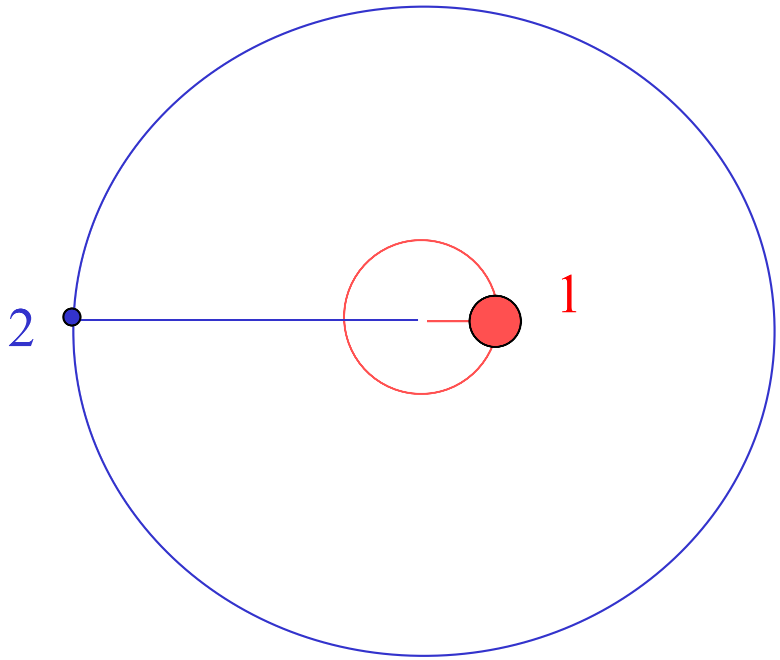
1. Coronagraphy
2. Adaptive optics
3. Polarimetry and/or spectral chopping
4. Interferometry and nulling interferometry

1. Doppler (radial velocity) methods

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

High stability high resolution spectrographs can measure radial velocities (i.e. velocity component along the line of sight) of bright stars at the < 1 m/s level through Doppler shift of wavelengths:

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



$$\frac{v_1^2}{r_1} = \frac{Gm_2}{(r_1 + r_2)^2}$$ Gravitational acceleration on star from planet

$$m_1 r_1 = m_2 r_2$$ Center of mass

$$2\pi r_1 = v_1 P$$ Unknown r_1 in terms of measurable velocity and period

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

We know m_1 from the type of star

Main problem: we don't *a priori* the inclination of the orbit w.r.t. the line of sight, measuring only the radial component v_r (relative to us) of v_1. So the measurement is actually of the product $m_2 \sin i$.

$$\boxed{v_r = v_1 \sin i}$$

A robust <u>lower limit</u> on m_2 is obtained by setting $\sin i = 1$.

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	Period
Earth	30 kms^{-1}	3.0×10^{-6}	**0.1 ms^{-1}**	**1 year**
Jupiter	13 kms^{-1}	1.0×10^{-3}	**13 ms^{-1}**	**12 years**

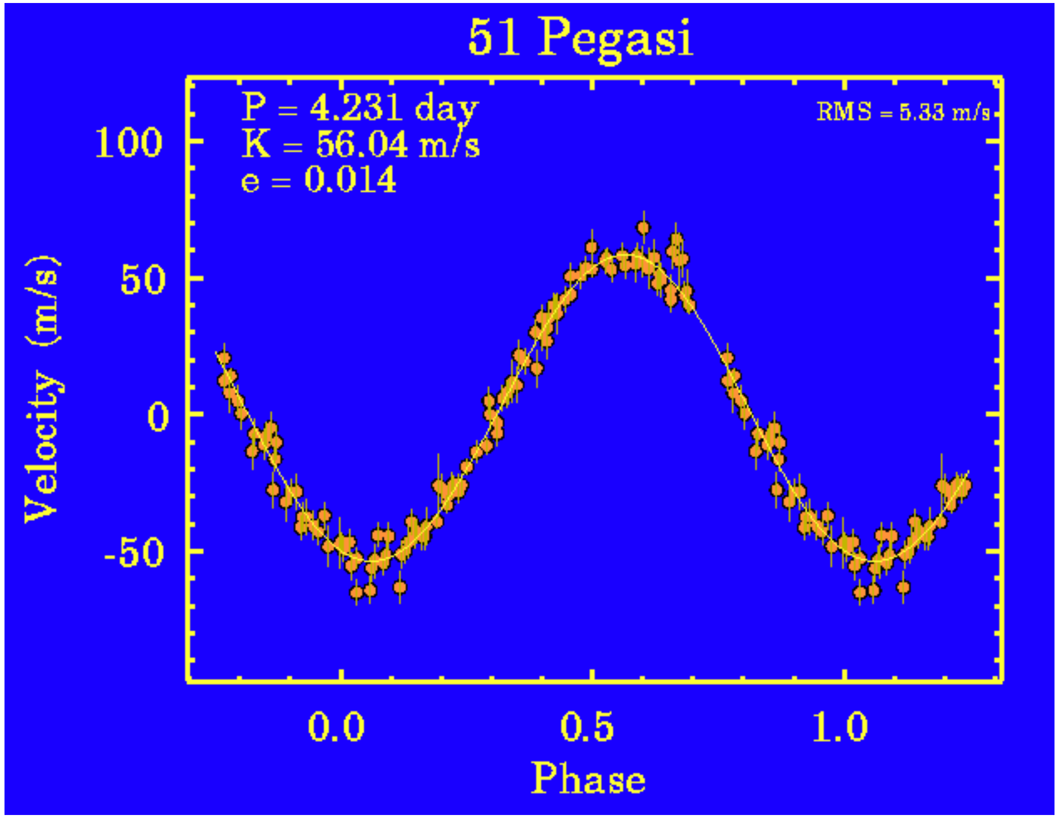
$$m_2 = m_1^{2/3} \left(\frac{P}{2\pi G} \right)^{1/3} v_1$$

Note that for a given stellar m_1, we have larger v_1 for higher m_2, and smaller P (i.e. smaller r, $P \propto r^{3/2}$).

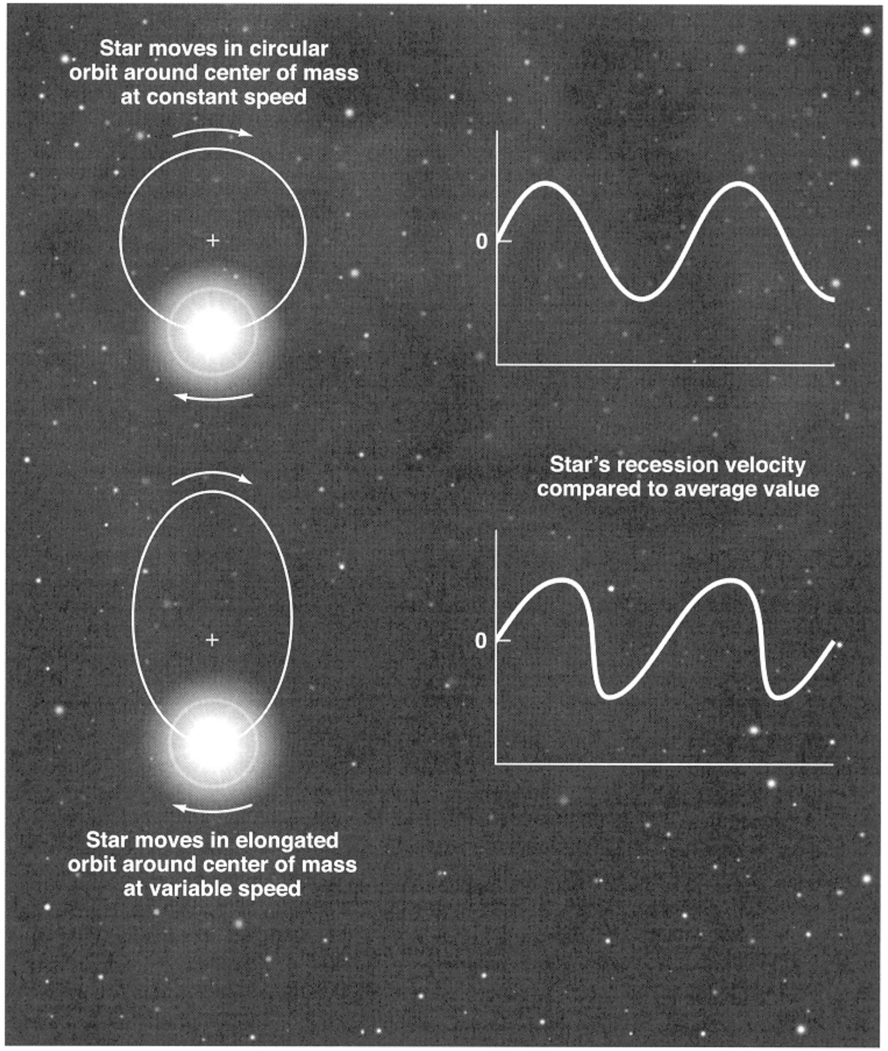
Also note that, in principle, the Δv_1 signal is *independent* of the distance to the system from us. But, in practice, the host star will be fainter with increasing distance, so it will be harder to measure Δv with the same accuracy.

But Δv_1 signal depends on mass of planet m_2, inversely on mass of star $m_1^{-2/3}$ and inversely on orbital radius of planet, $r_1^{-1/2}$. *Quite strong selection effects!*

Exoplanet around 51 Peg discovered 1995 by Mayor and Queloz (Geneva) Nobel prize this year!



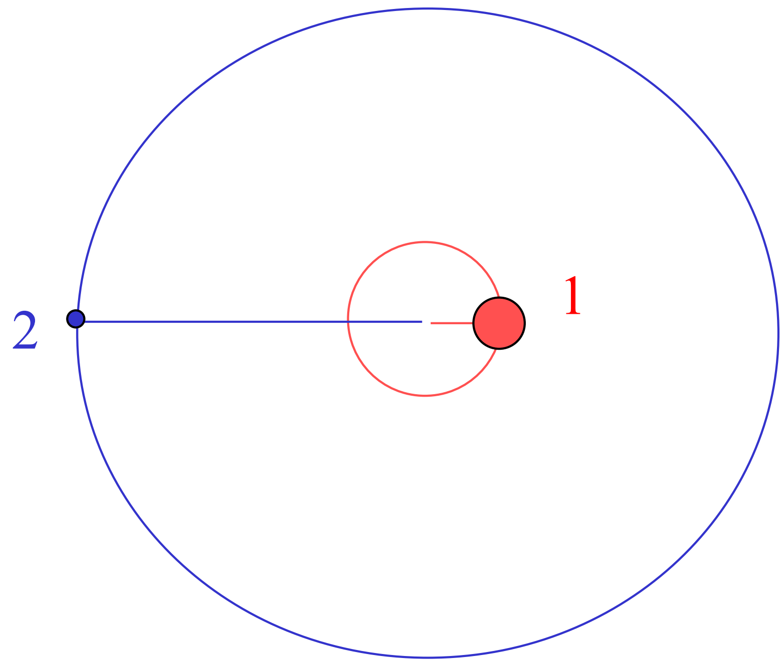
Circular orbits give sinusoidal wave $v_r(t)$



Note: Large amplitude (56 km/s) and an unexpectedly short period

Eccentric orbits give distorted wave depending on azimuthal orientation

Closely related to Δv method, and usually quite impractical: "timing methods"



Precise clocks in an orbit will change their "tick-rate" for distant observers as they orbit – you can think of this either as a Doppler shift during the approach/recession or as an integrated effect due to light travel time across the orbit at furthest/nearest approach

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

Same sin i inclination effects as before

Historical aside: this is effectively the same method that Römer used in 1676 to determine the speed of light using Jupiter's moons as "clocks", and measuring the 22 minute time delay in eclipses of Jupiter's moons as the Earth orbits the Sun.

Observability for Δt for the central (massive) object: e.g. our Solar System

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

	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**

Sounds hopeless, but we do have Pulsars, rapidly and very precisely spinning neutron stars ($M \sim 1\ M_\odot$, $r \sim 10$ km, $P \sim$ few ms – few s) that flash due to beamed radio emission.

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

What about Life?

- No light from the central "star"
- Very hazardous radiation environment
- System went through a violent SN explosion few million years ago with giant star phase before that (planets likely "re-formed" after SN).

2. Astrometric methods

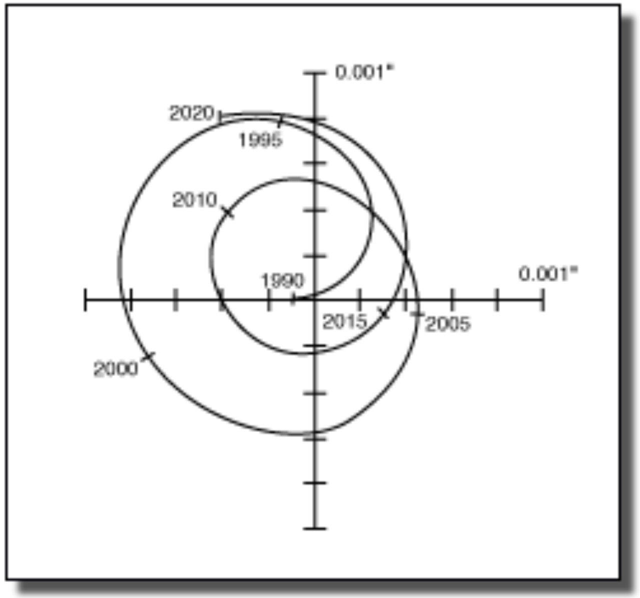
The motion of the star around the common center of mass also produces a small change in position in the sky, superimposed on any systematic uniform motion due to the star's velocity through space (plus the yearly variation due to Earth's orbit around the Sun, called parallax).

Note, as an aside that the center of mass of Sun-Jupiter system is 0.9 R_{sun} from the center of the Sun, i.e. you'd need in this example to know the "position" of the star to within its radius.

Observability of astrometric displacement

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**

** 1 μarcsec ~ 5×10^{-12} radian, i.e. 0.1 mm at 20,000 km.



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

Note: The observed angular displacement decreases as the distance^{-1} from us to the system, but increases with m^2 and r^2.

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

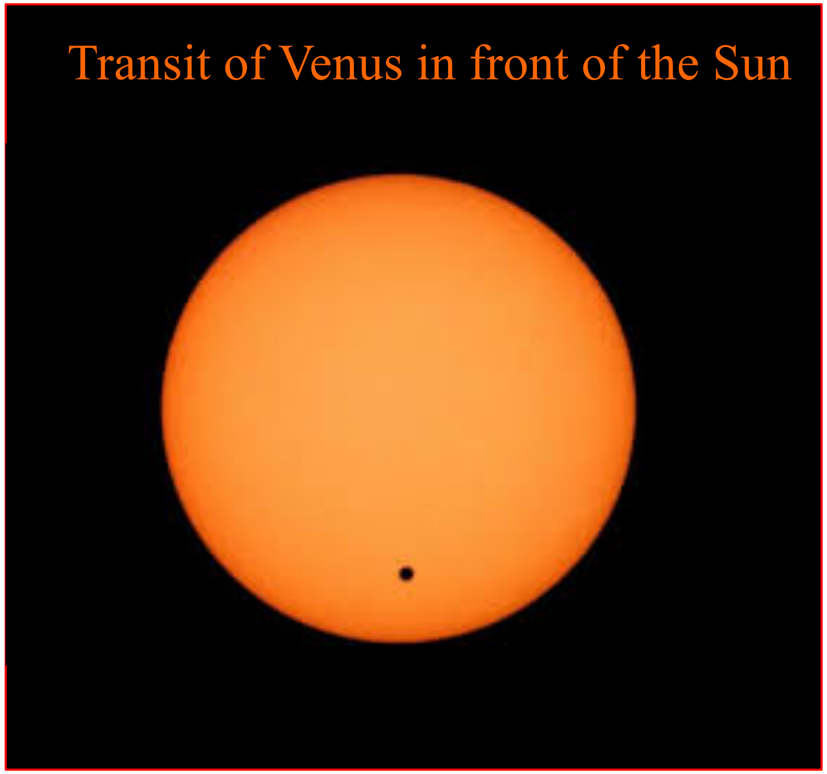
State of the art: GAIA ESA Astrometry mission (2013+):
7 μarcsec accuracy on brightest stars (V ~ 10), ~ 25 μarcsec at V ~ 15 and ~ 300 μarcsec at V ~ 20.

3. Occultations (transits)

Jupiter has 0.1 × radius of Sun, i.e. 1% of area. When Jupiter passes in front of the Sun (for an external observer!) the brightness of Sun would drop by 1% for ~ 15 hours, once every 12 years!

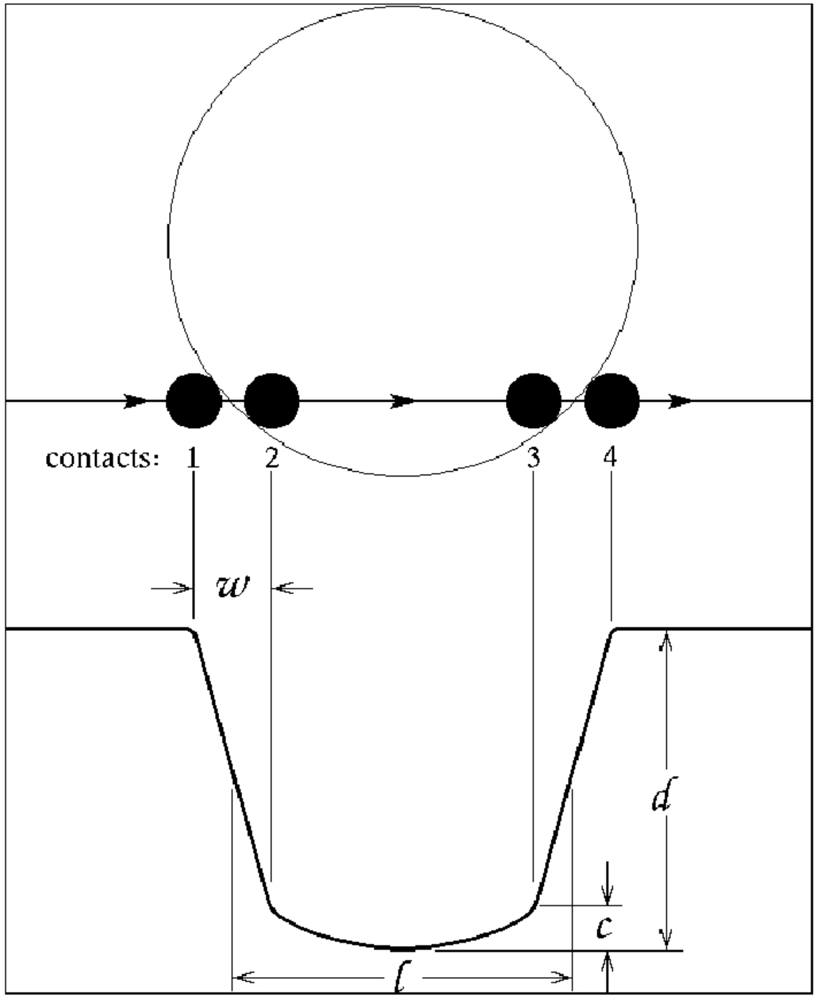
Not too difficult to detect, but

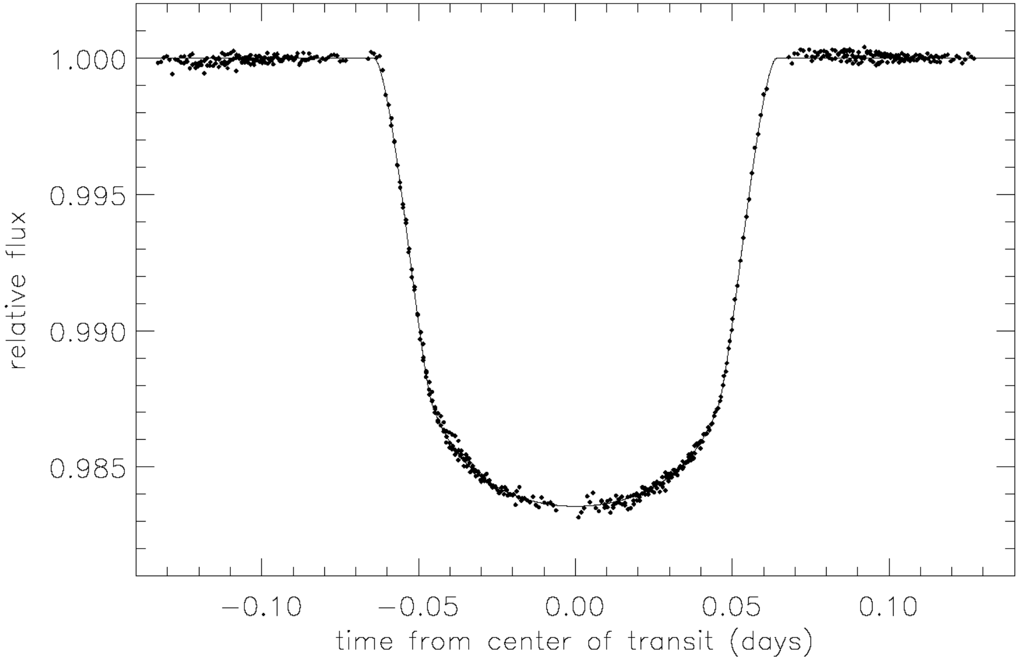
- must monitor large numbers of stars hoping for occultations
- can focus on known RV systems at the orbital phases when $v_r \sim 0$



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 $m_2 \sin i$ from the RV. Also, the occultation gives size of the planet (assuming size of star is known) and therefore can give the density of the planet.
- there will be a much smaller drop when the planet passes *behind* the star and we lose the planet's own light (therefore this is best done in the infrared where contrast in brightness is smaller).





The *detailed* shape of light curve gives a lot of information, especially if you have (theoretical) information on the surface brightness distribution of the star across its disk.

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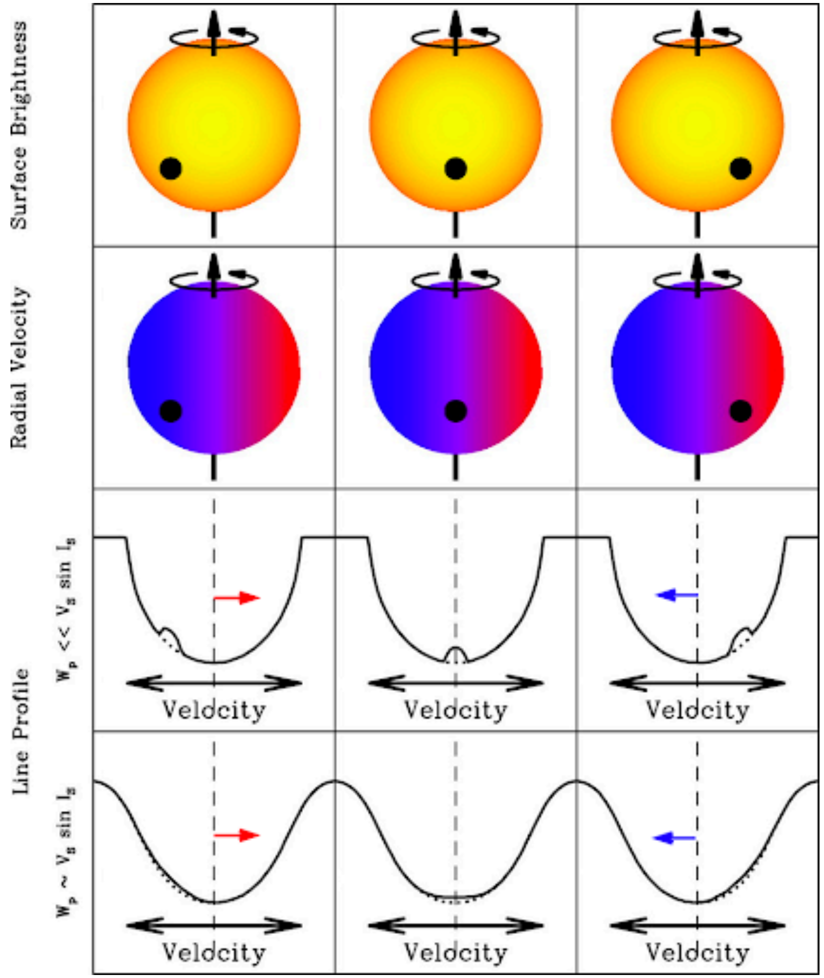
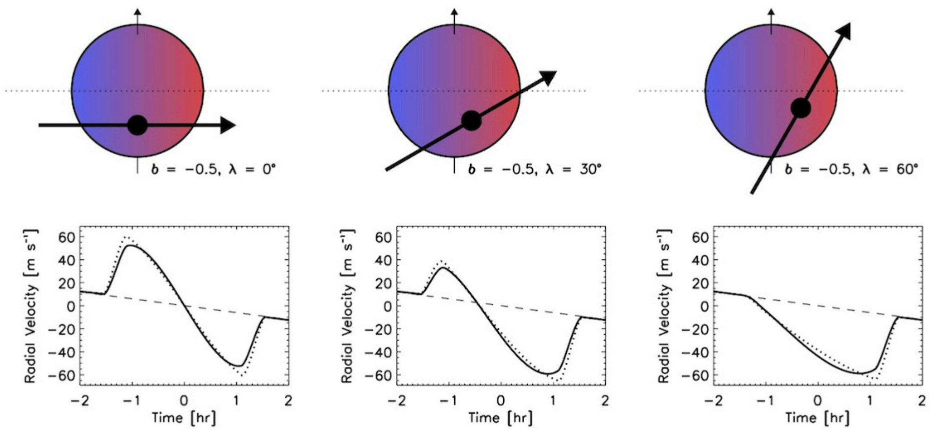
Can also determine if planetary orbit is aligned with the stellar spin:

The Rossiter-McLaughlin effect

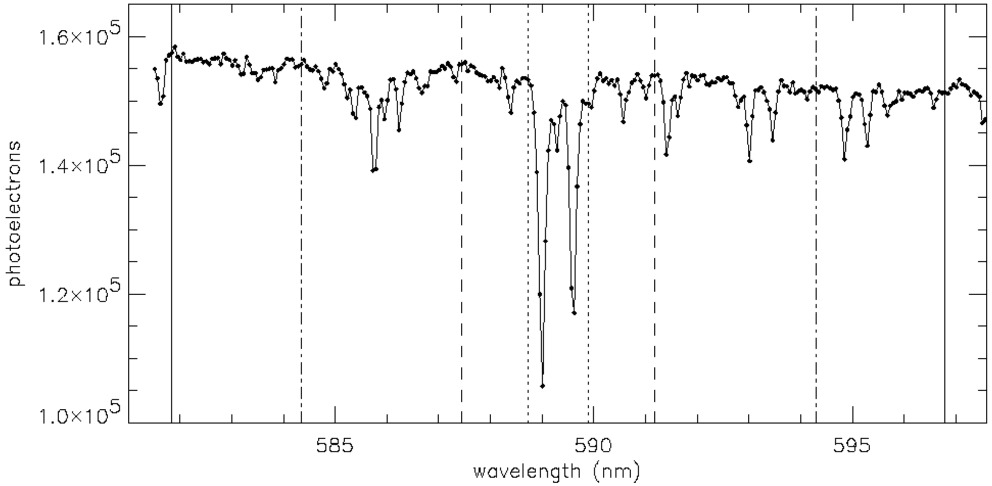
If planetary orbit and stellar spin are aligned, then the occultation will first cover a part of the star that is approaching us (stellar light Doppler shifted to shorter wavelengths) and then cover part that is moving away from us (shifted to longer wavelengths). If there is an absorption line, this specral range will be less absorbed, leading to shift in wavelength of line.

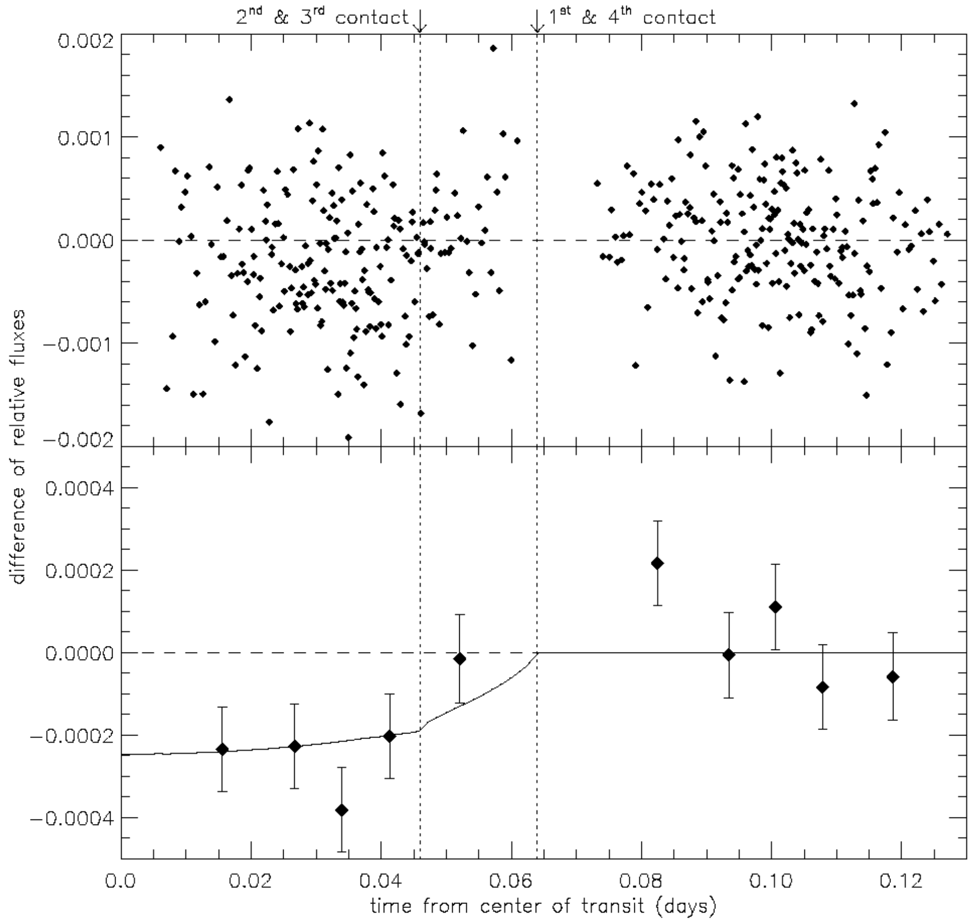




In principle, information on both angle and inclination.

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





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

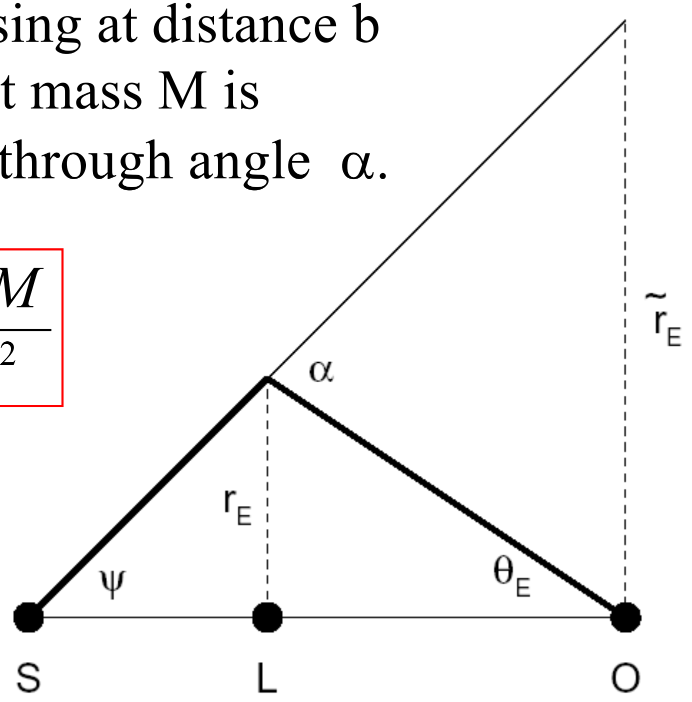
Now applied for many otheratmpsheric species.

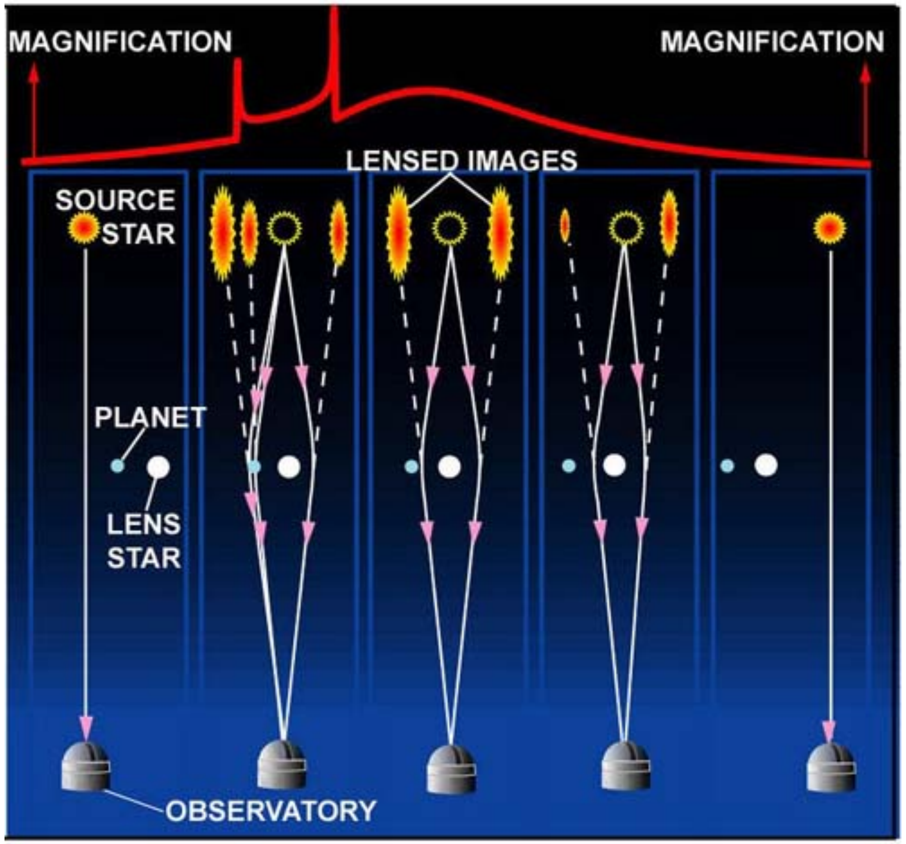
4. Gravitational lensing

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.

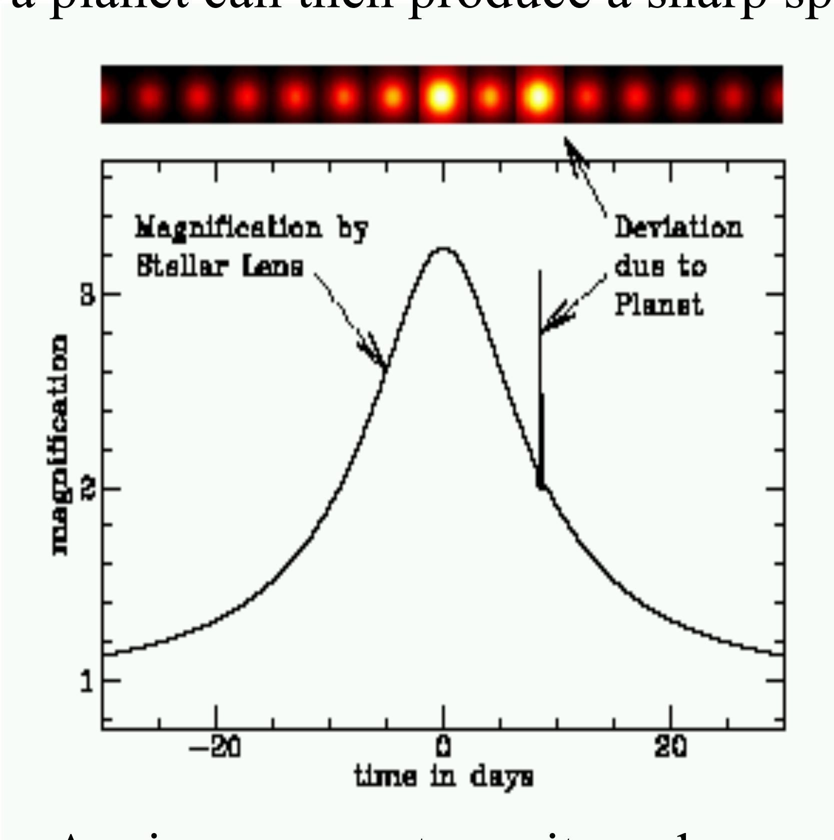
$$\boxed{\alpha = \frac{4GM}{bc^2}}$$

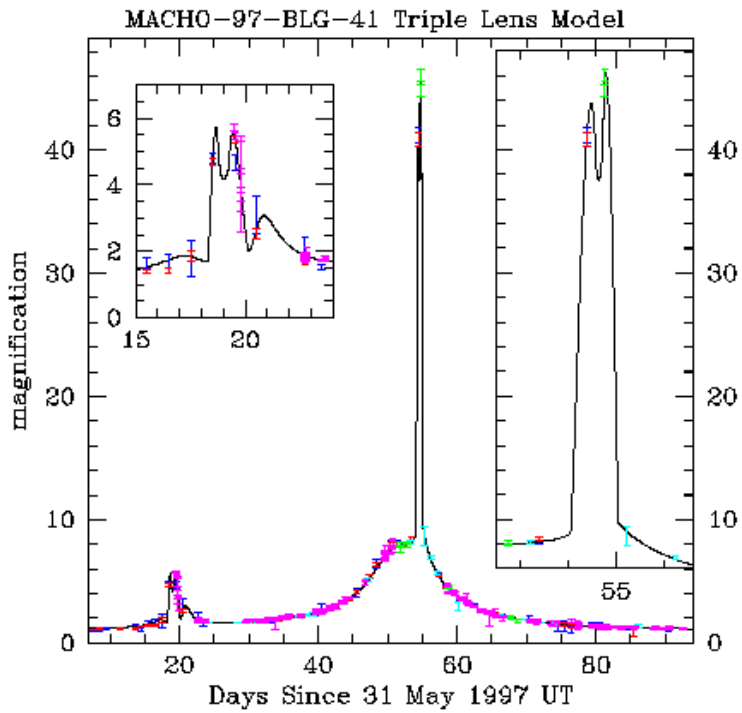




Can act as a magnifying lens, often producing multiple images. Even if these are not resolved, the overall brightness of the background object will be enhanced, depending on its position relative to the foreground lensing system.

Now imagine a (possibly very faint) star with a planetary system passes in front of a (detectable) background star. As the background star effectively moves through regions of different magnification/amplification, its apparent brightness will change – first slowly increasing then decreasing. Presence of a planet can then produce a sharp spike in this light-curve.





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

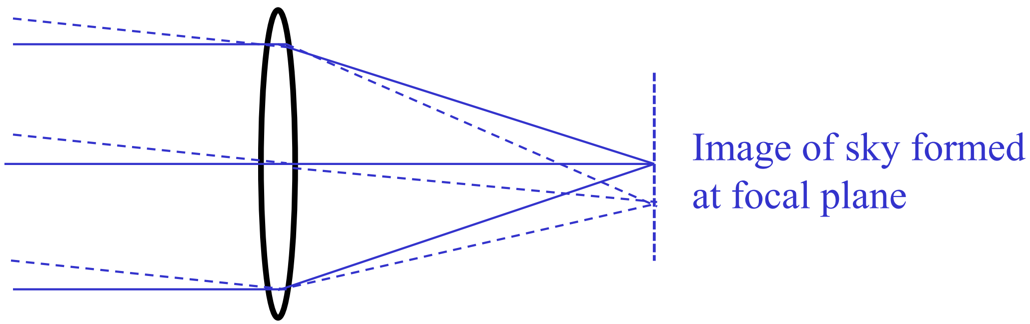
→ Monitor either huge number of stars in central region of our Galaxy or look at a nearby stellar system like the Large Magellanic Cloud (LMC).

B: Direct searches

Focus here on four clever approaches to try to reduce the dominant star-light so as to detect light from the planet itsef:

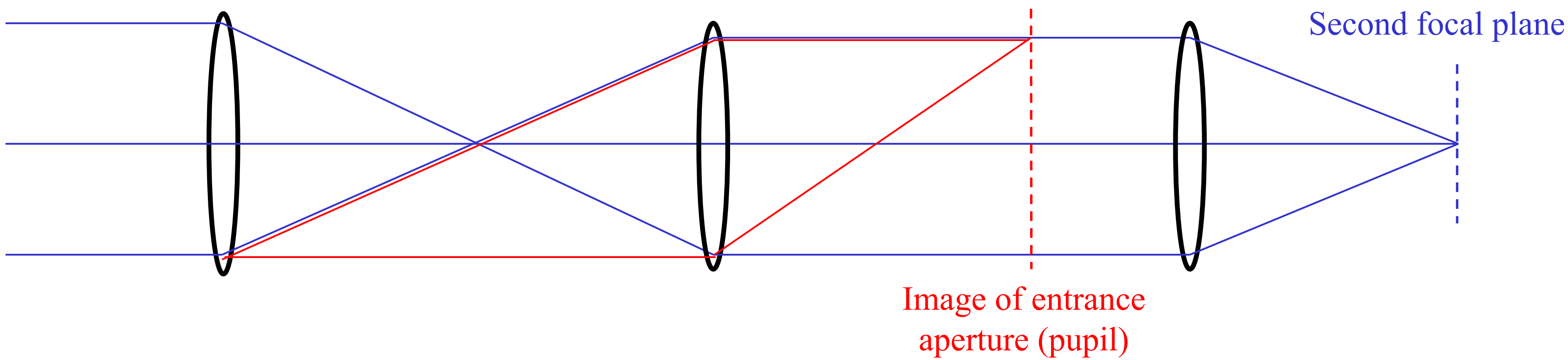
1. Coronagraphy
2. Adaptive optics
3. Polarimetry and/or spectral chopping
4. Interferometry and nulling interferometry

First, some simple optics (doesn't matter whether lenses or mirrors).



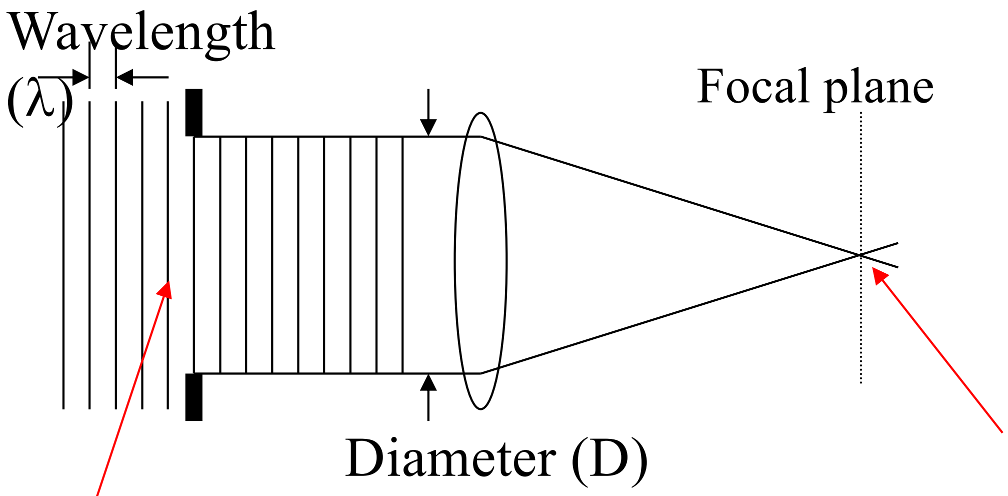
Simplest imaging system (e.g. our eyes or an SLR camera). Light from distant object is brought to a focus where an image is formed.

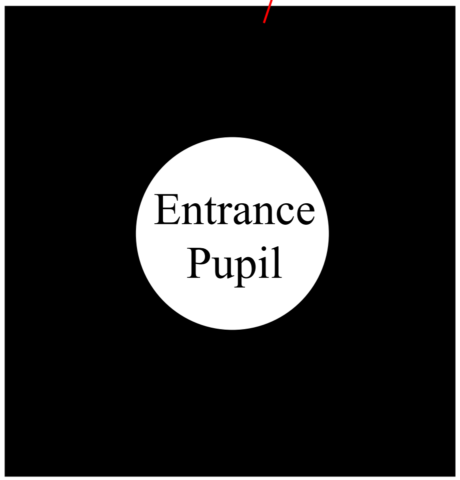
Many optical instruments then "re-image" this first image plane to a second one.



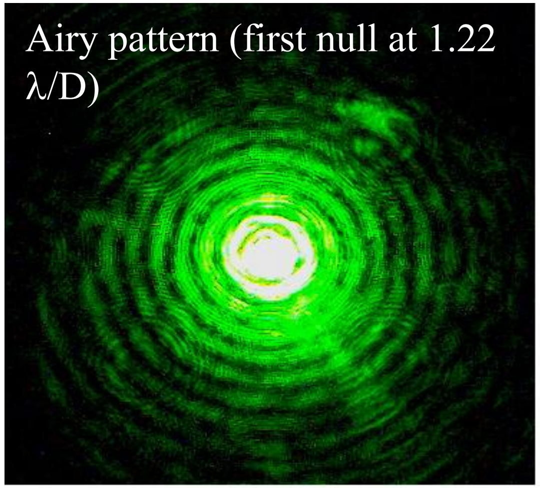
Key point: at various points through the optical system there will be "images" of the different optical elements. This includes "images" of the entrance aperture itself (pupil plane) as well as images of the atmosphere at different altitudes above the telescope

Second: Fourier Optics again, the classical circular aperture



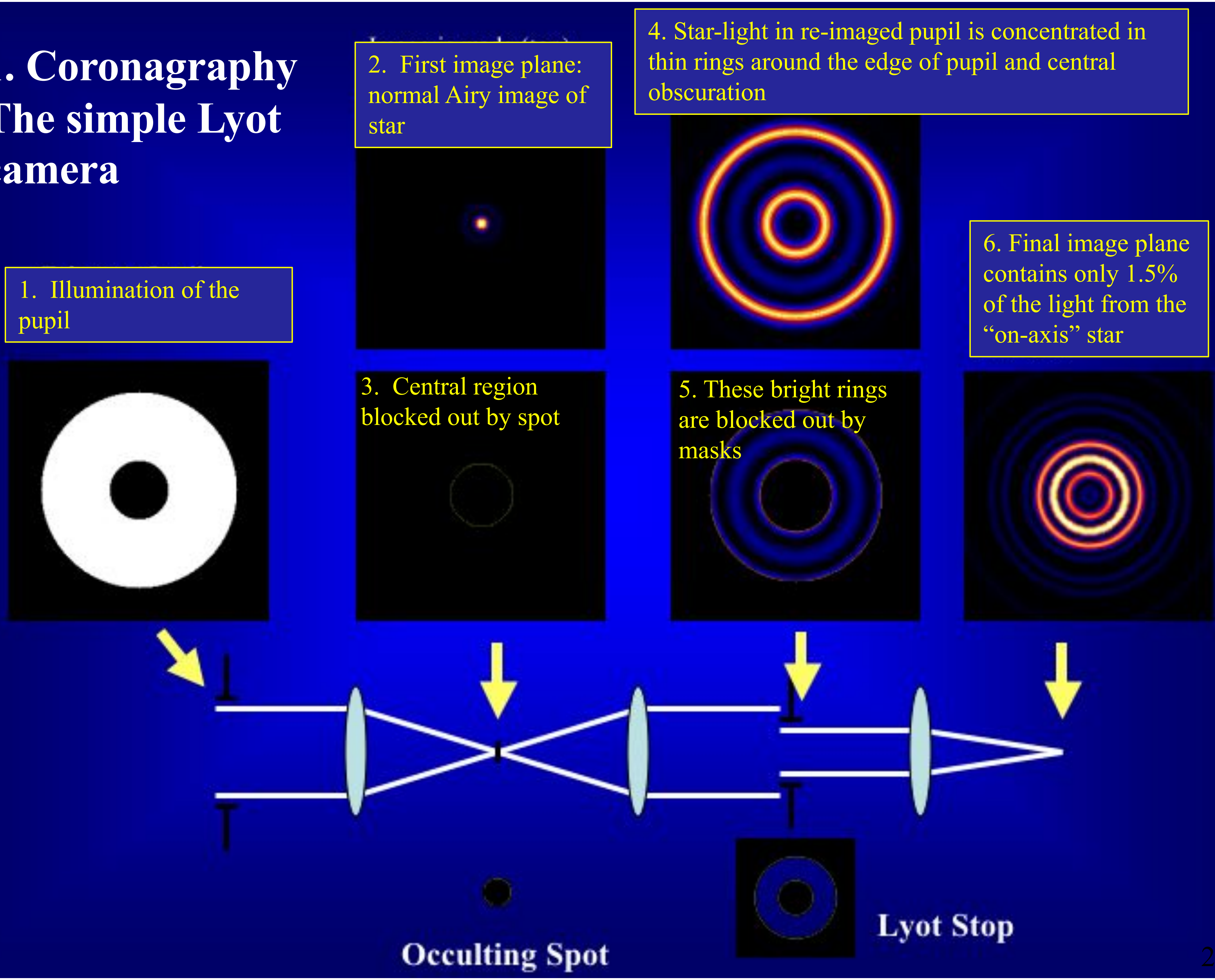


The image of a point source (plane parallel light) in the focal plane is the spatial Fourier transform of the entrance aperture (pupil)



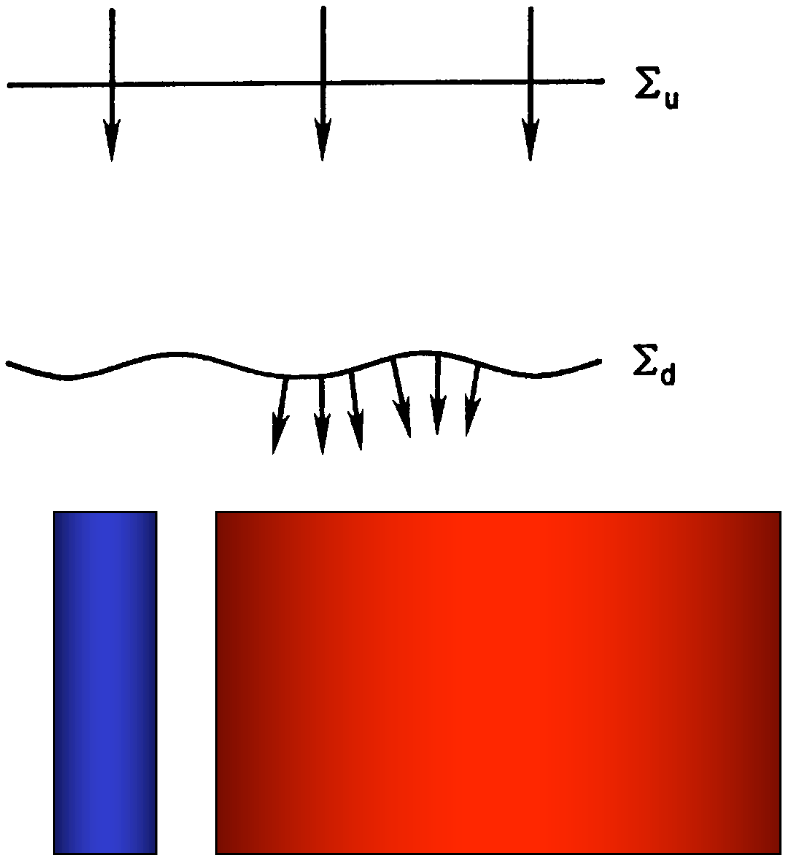
Now let's see how we can use these concepts together!

1. Coronagraphy
The simple Lyot camera



2. Adaptive Optics

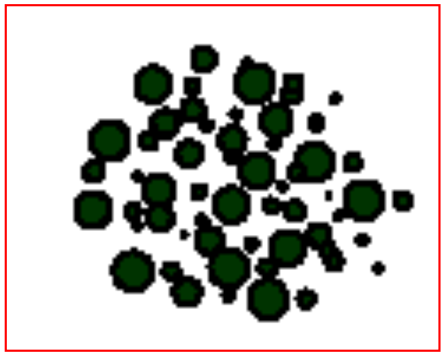
Spatial variations in the refractive index of the atmosphere above the telescope introduce wavefront distortions (phase variations) which rapidly change on a timescale of ~ 10 ms as the atmosphere moves over the telescope



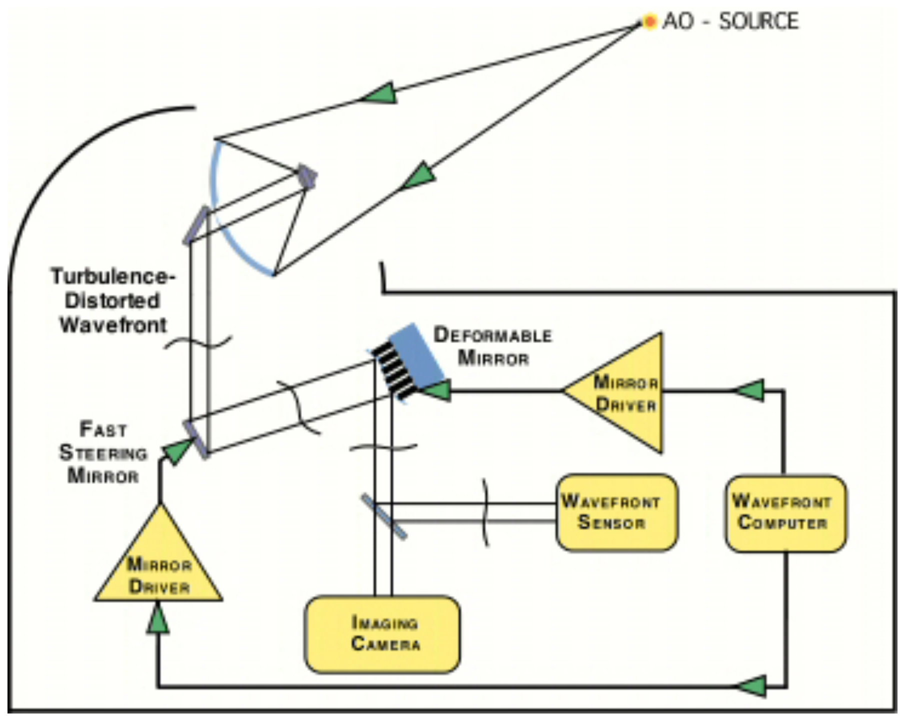
What's the effect of these on what we observe?

Observed with a small aperture (comparable to cell size) telescope → angled wavefront produces image motion and brightness variations

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



A generic adaptive optics system optical layout:

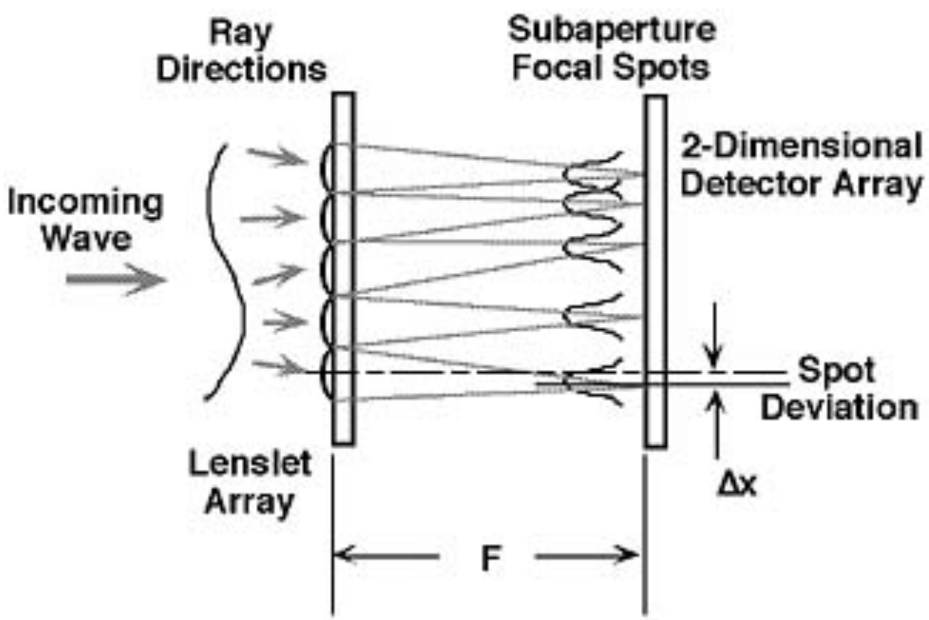


A deformable mirror is conjugated to the entrance pupil (or better, to the relevant height in the atmosphere) and corrects the phase errors, using information on the wavefront distortion.

Must work at kHz rate!

How to measure the phase distortions of the wavefront?

Several approaches, e.g. Shack-Hartmann



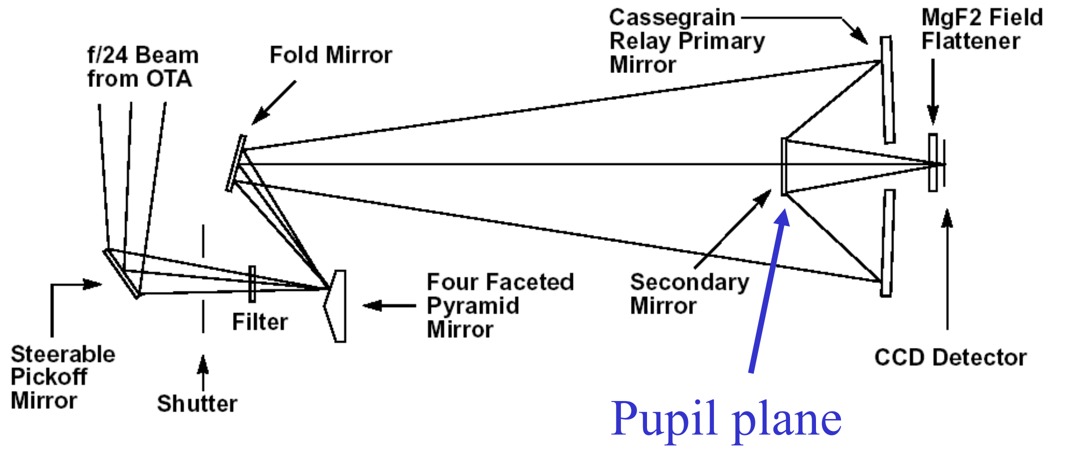
Position of the image in the sub-pupil gives the phase gradient of the wavefront at the position of each lenslet in the lenslet array.

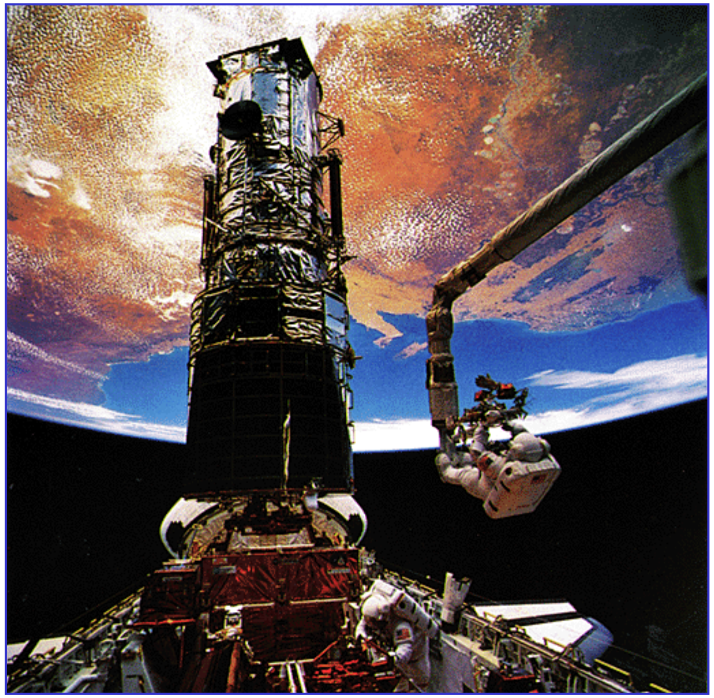
As an aside: correction of primary mirror aberration on Hubble Space Telescope

HST's primary mirror was "perfectly" smooth but had a gross curvature error: spherical aberration = different annuli on mirror have different focal lengths.

Successfully corrected by replacing a flat mirror at the pupil plane.

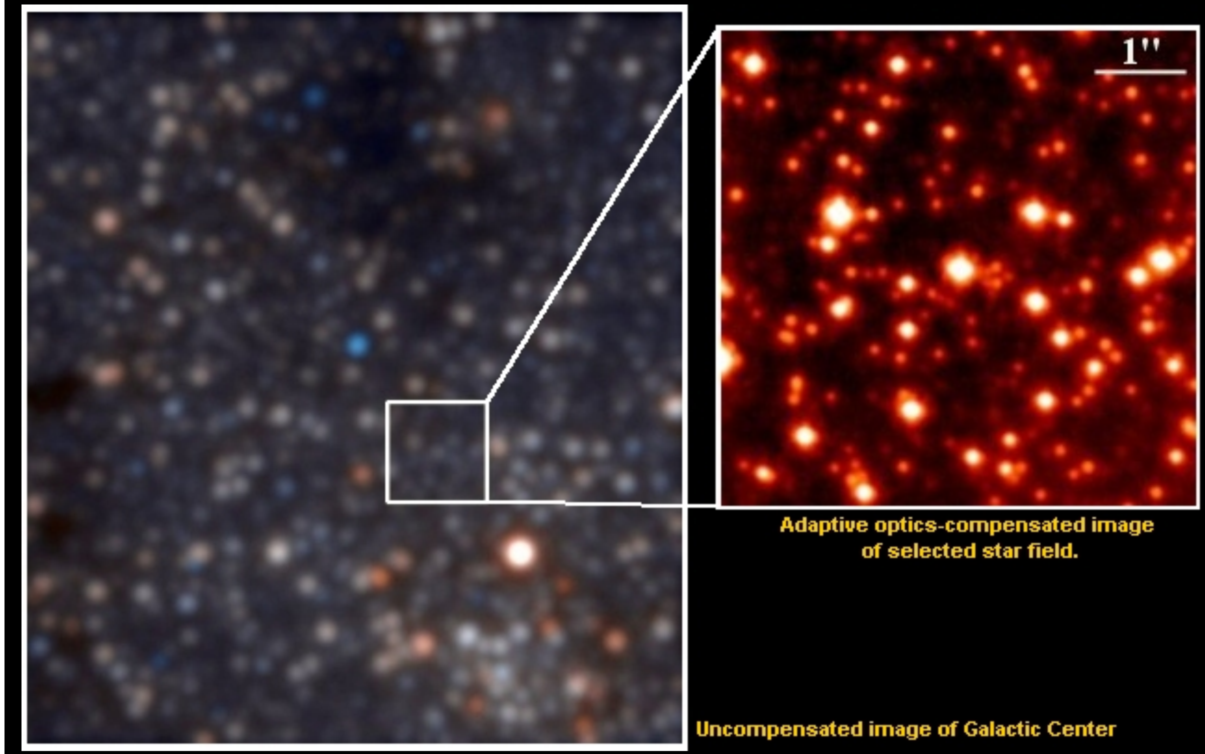
Figure 24.1: WFPC2 Optical Configuration





Wide Field Planetary Camera 1

Wide Field Planetary Camera 2

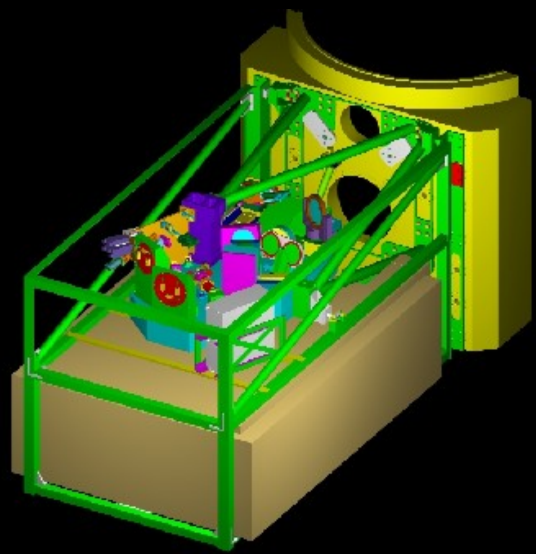


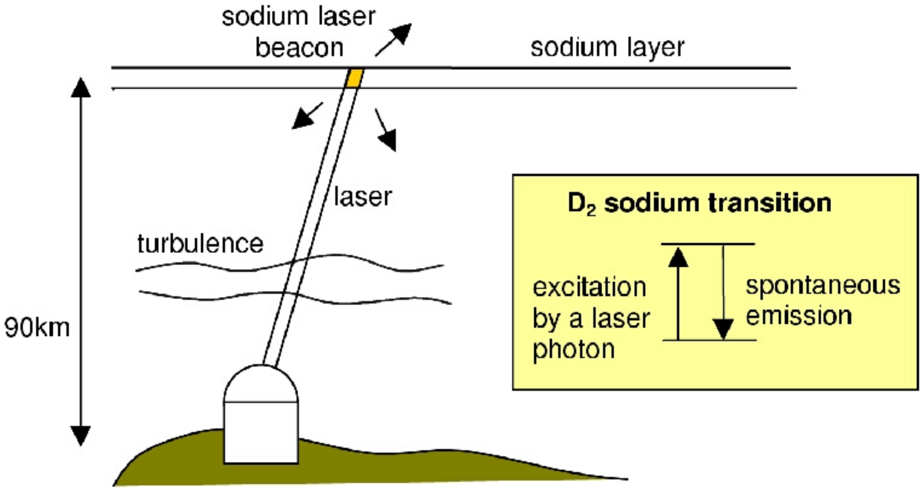
AO image of Galactic Center

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 on bright star (dichroic mirror)
- Bright star within “isoplanetic patch”
- Artificial guide stars (e.g. Na laser) excited in the upper amosphere

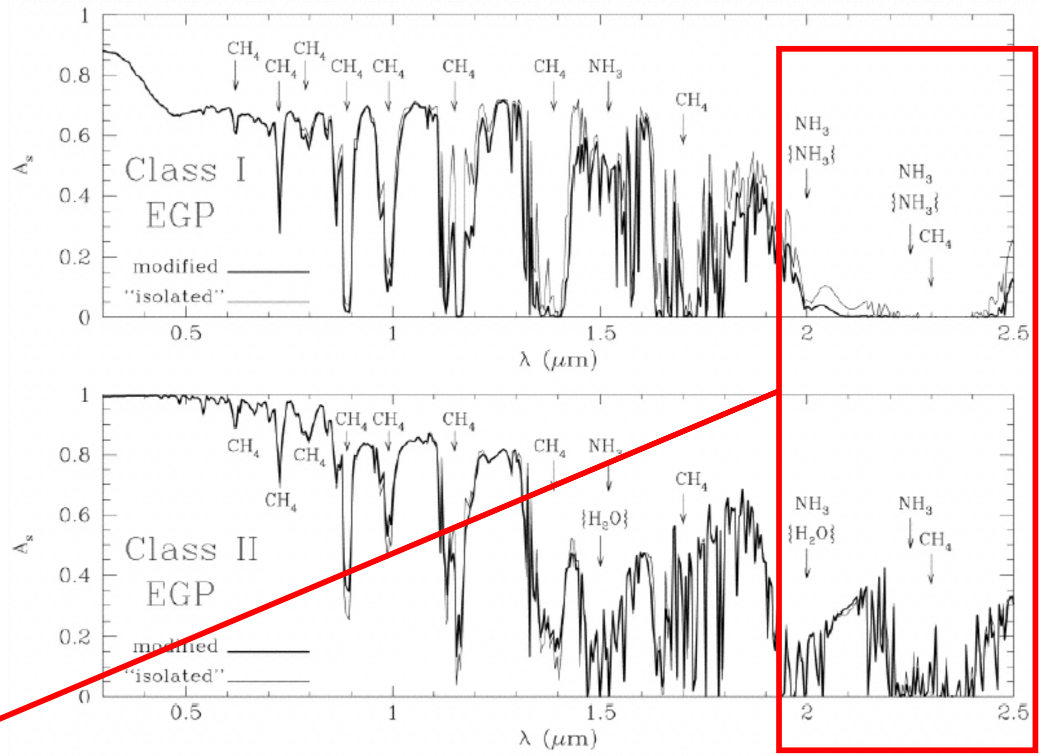


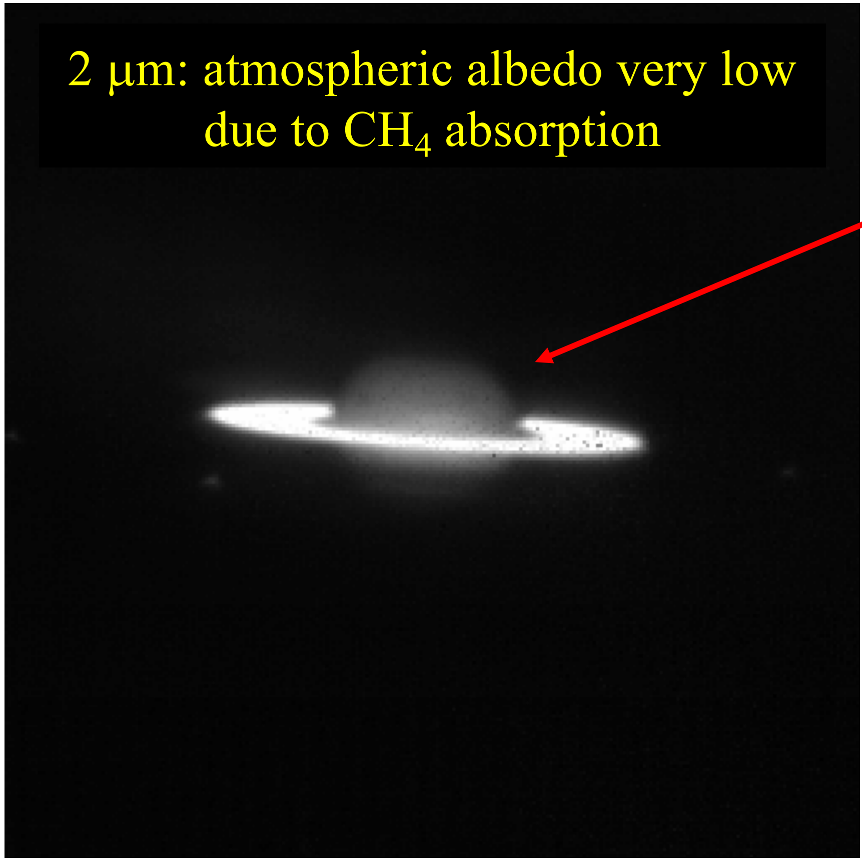


Artificial laser stars for adaptive optics using Na in upper atmosphere to produce artificial "star"

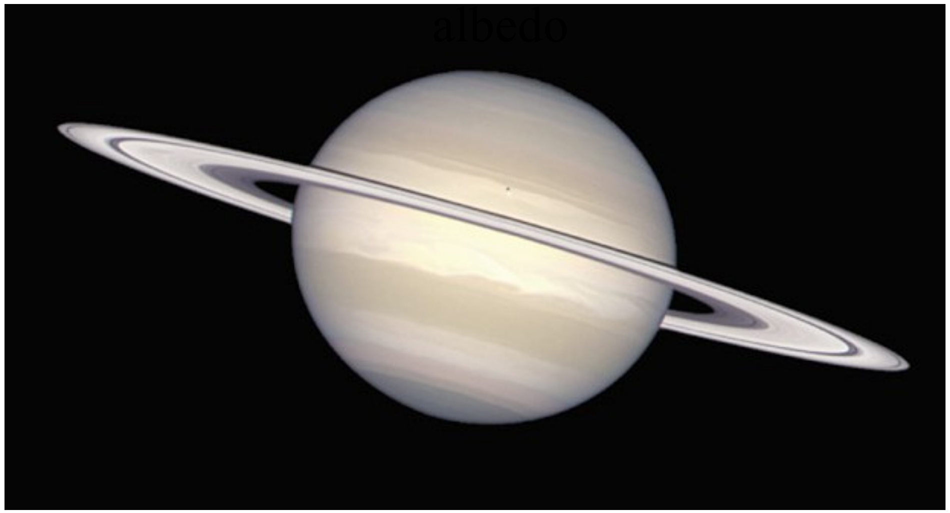
3(a) Spectral subtraction

Simultaneous differential "on-off" imaging at two wavelengths at which the planet and star are expected to have different relative brightnesses. Can remove "all" star-light leaving a residual planet signal.





Saturn in visible light: uniform albedo



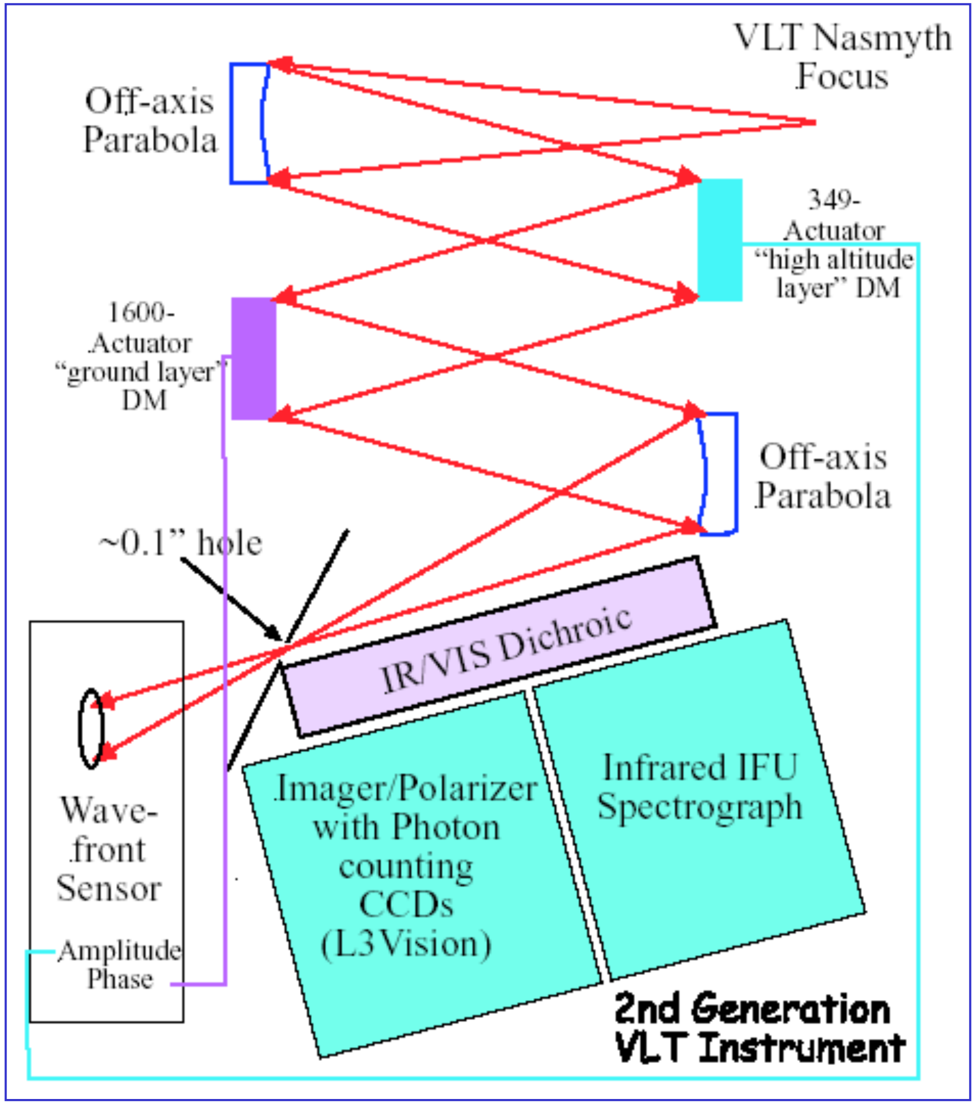
3(b) Differential polarimetric imaging

If the central star and planet (or dust disk) have different *polarizations*, then one can effectively remove the star-light leaving residual planetary signal.

SPHERE "planet-finder" instrument on the European 8-m VLT combines

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

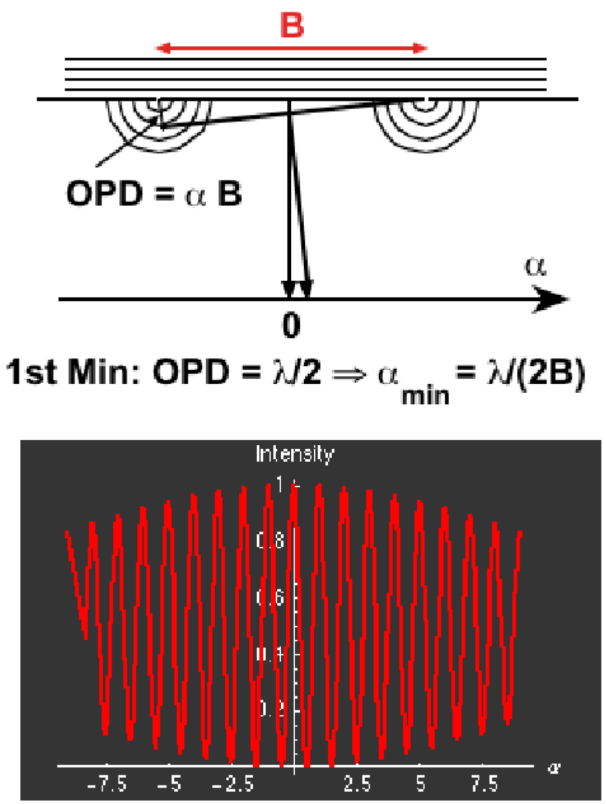
SPHERE



4. Interferometry

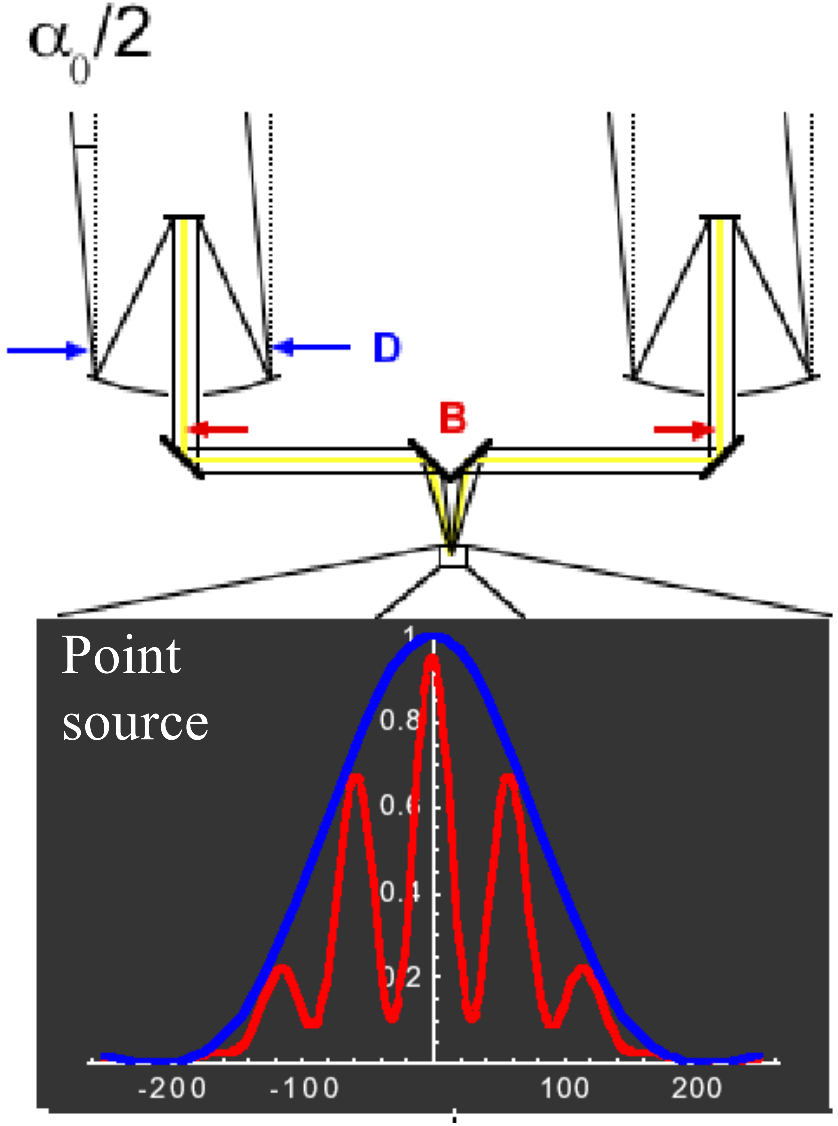
Recall the interference effects of two pinholes

Young's Two-Pinhole Experiment

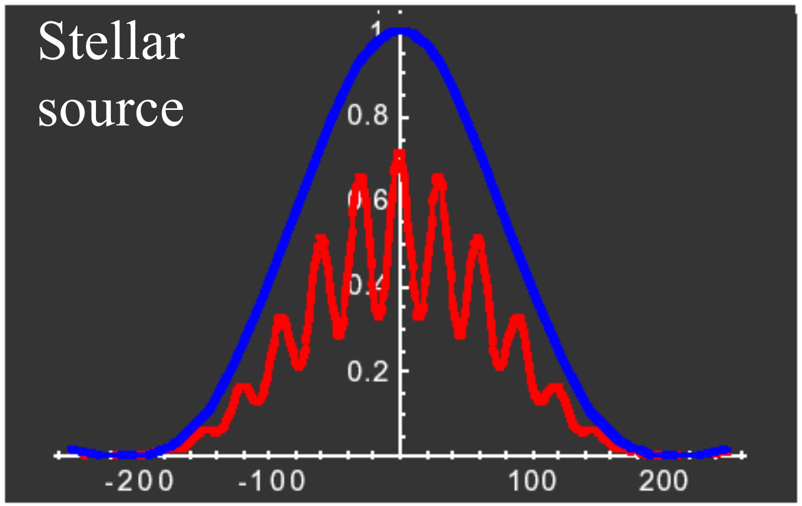


- Light source at infinity
- Intensity pattern = $1 + \cos(2\pi\alpha B/\lambda)$, where αB is the Optical Path Difference (OPD)
- When OPD > coherence length of the photons, the fringes disappear
- Light source at an angle a_0 shifts fringe pattern spatially across the detector.

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

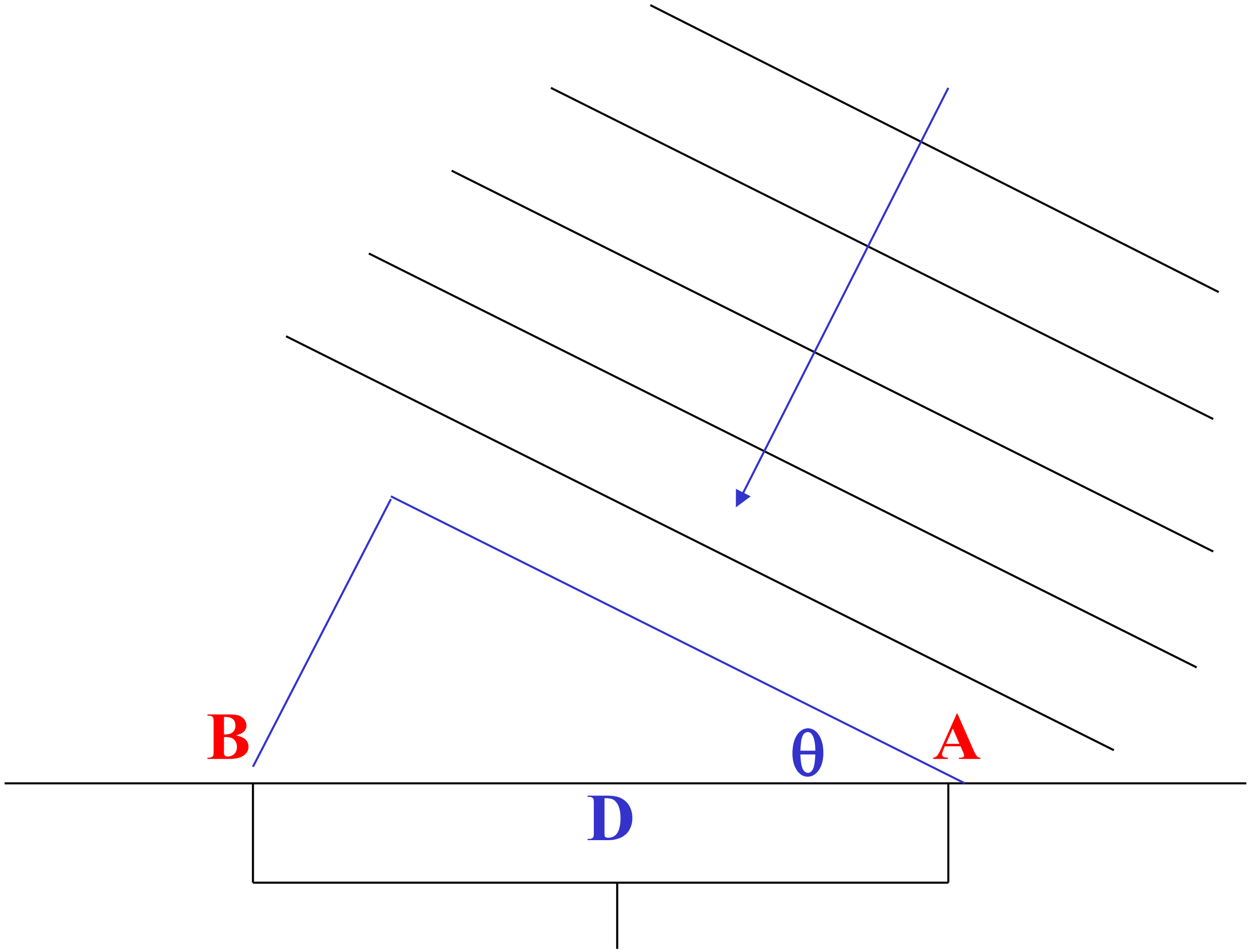


- Stellar source with angular diameter a_0
- Adds fringe patterns shifted by 0 to $\pm a_0/2$.
- This reduces the contrast of the fringe pattern depending on a_0 and telescope separation B



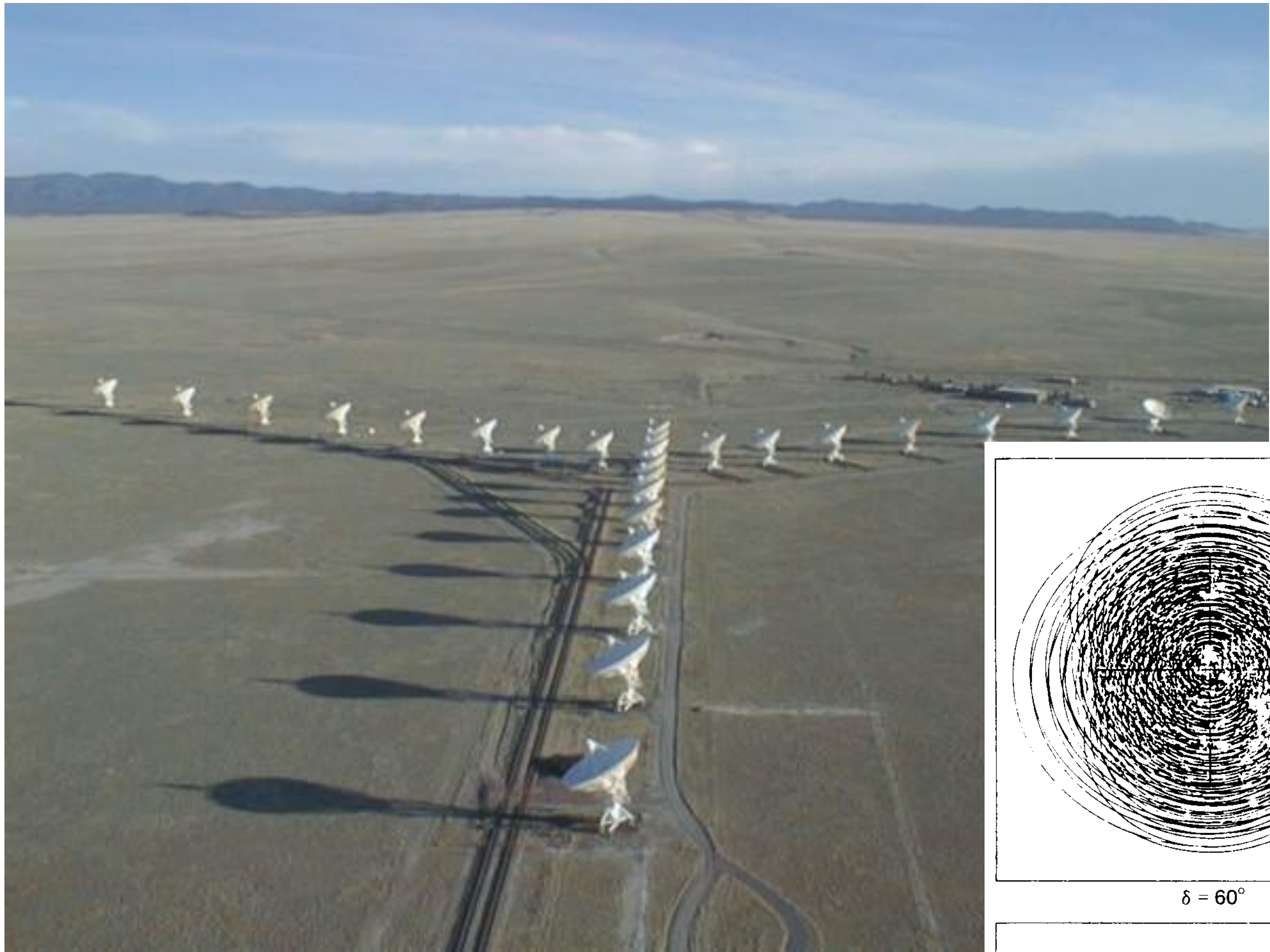
GENIE Workshop, Leiden, June 3-6, 2002

Short aside: radio interferometry

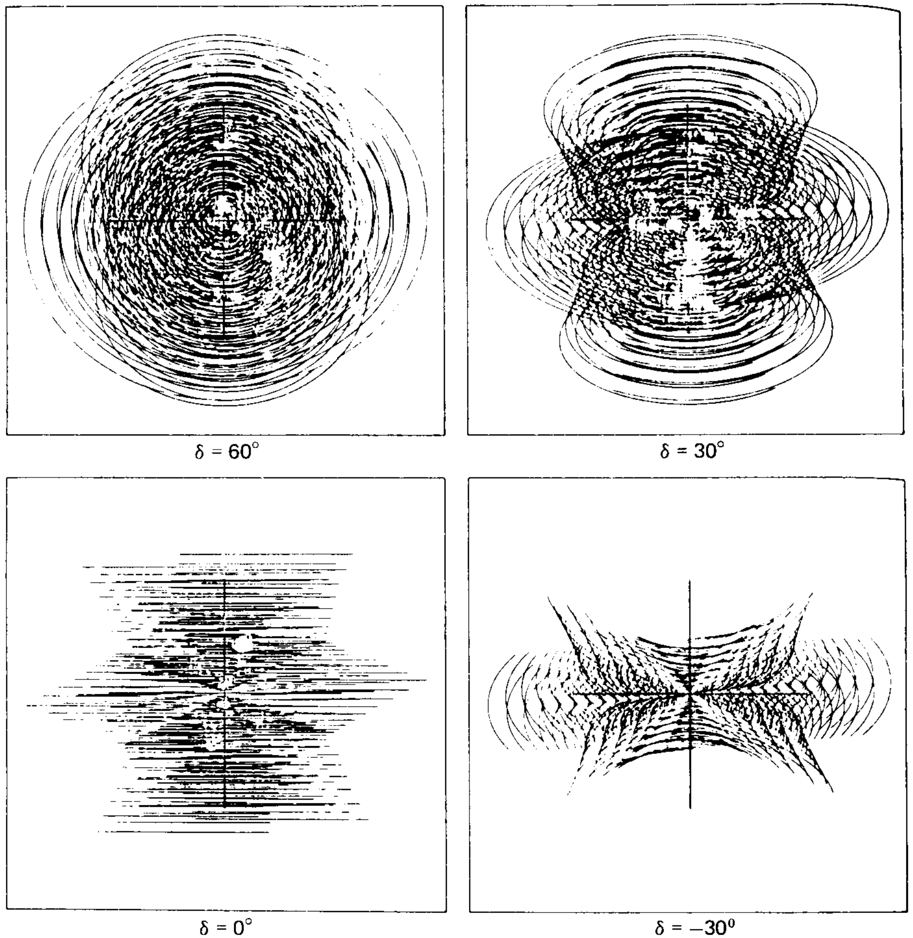


Net result: Two radio telescopes measure one Fourier component of of the radio sky brightness

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



Fourier plane coverage of VLA antennae (as Earth rotates)



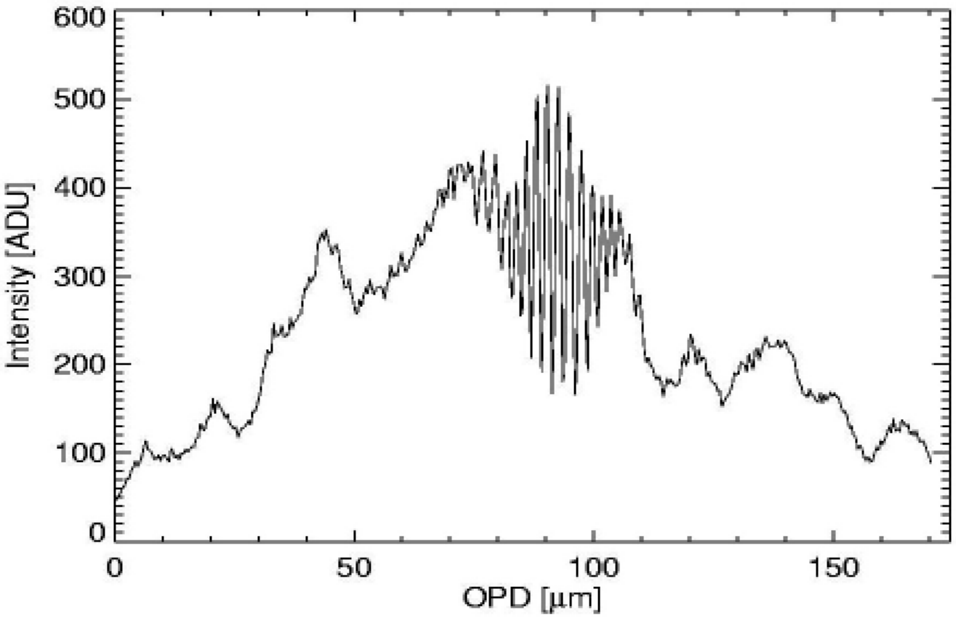
Very Large Array: combining all possible pairs samples the Fourier space quite well. This is the standard technique for making images at radio wavelengths.

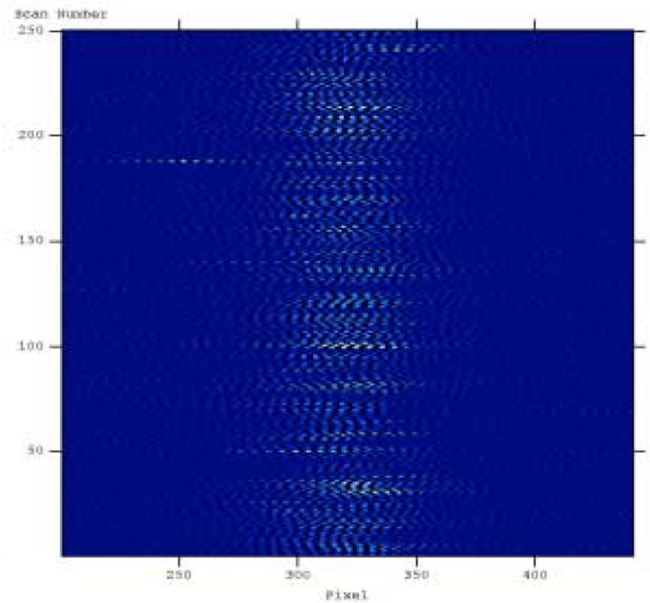
This is <u>much harder</u> at optical wavelengths: Why?

- We cannot measure the *phase* of photons like in the radio (we must allow the photons themselves to interfere rather than multiply voltage signals in a computer)
- There is a short coherence time for short λ photons
- OPDs controlled at 100 μm as against cm.
- Effects of rapid variation of atmospheric phase distortions above the telescope

World leaders: 4x8m ESO VLT in Chile.

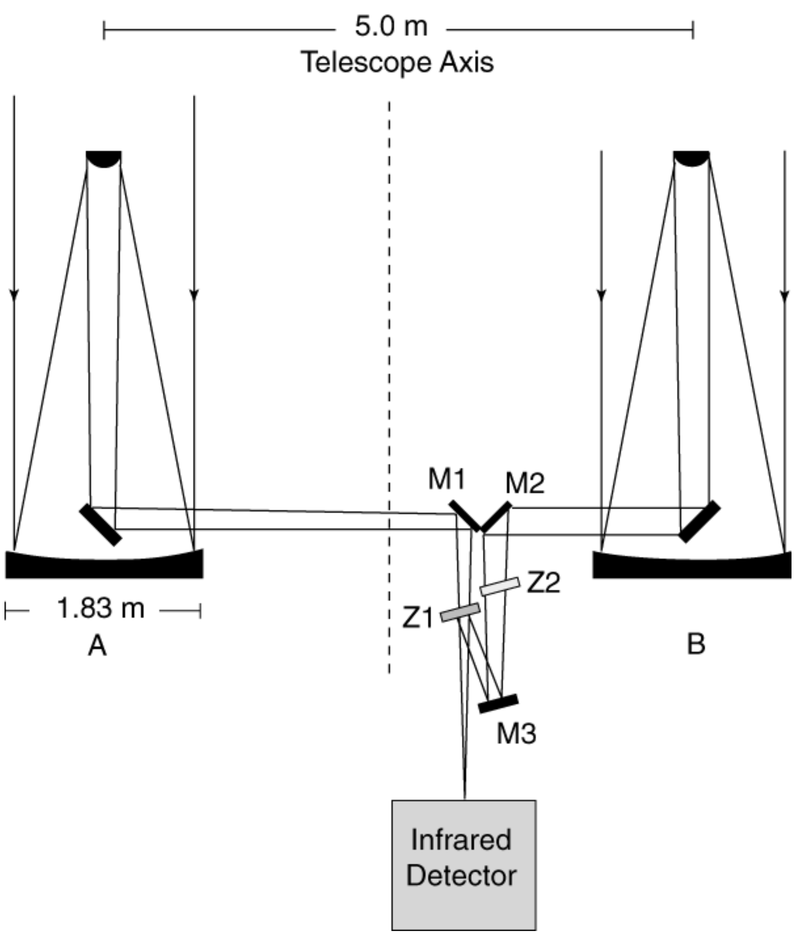
In practice, scan through OPD

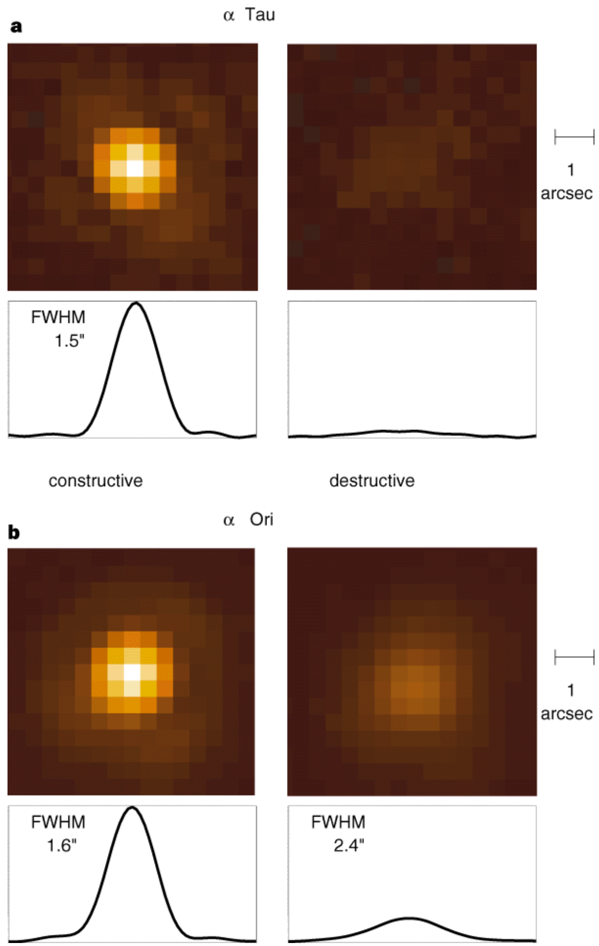




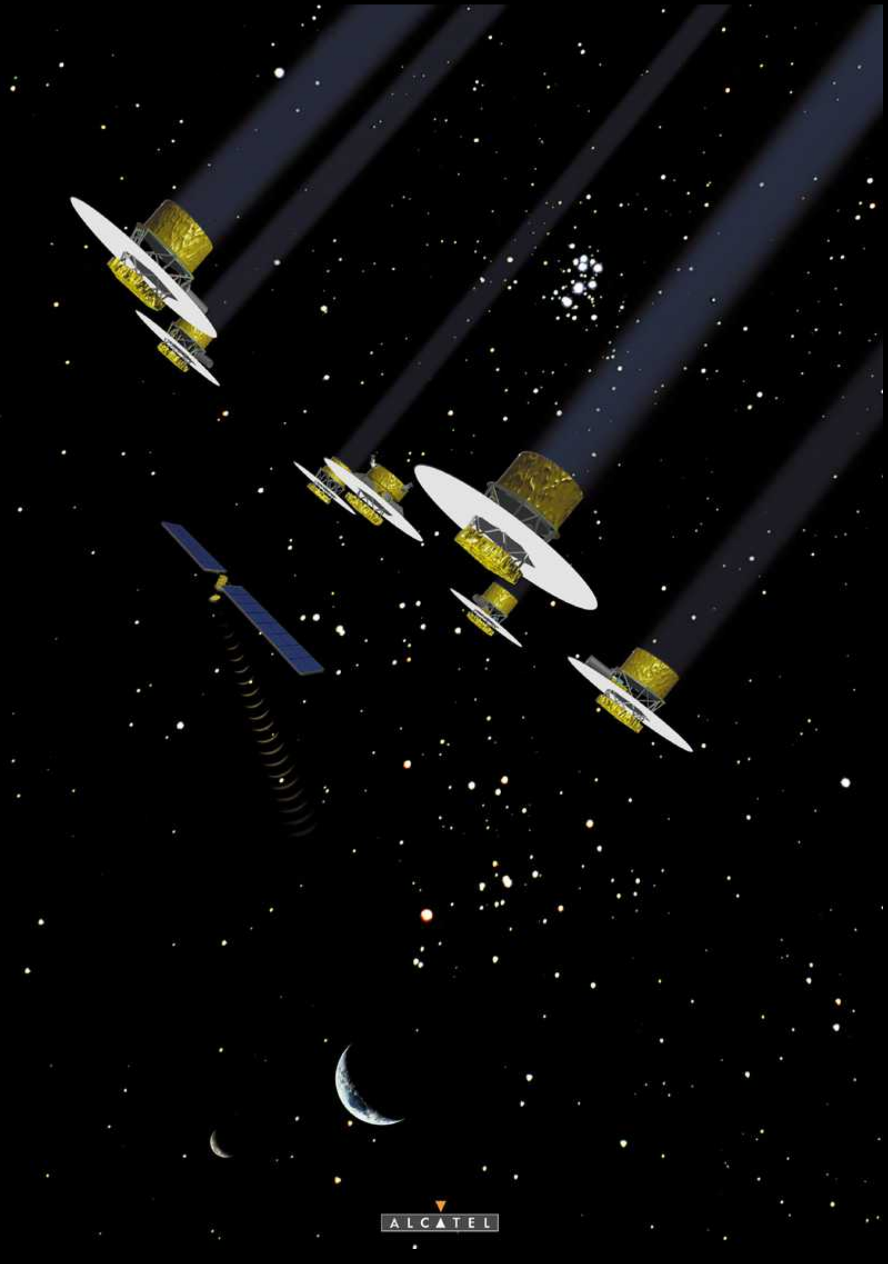
Other clever techniques: Nulling interferometry

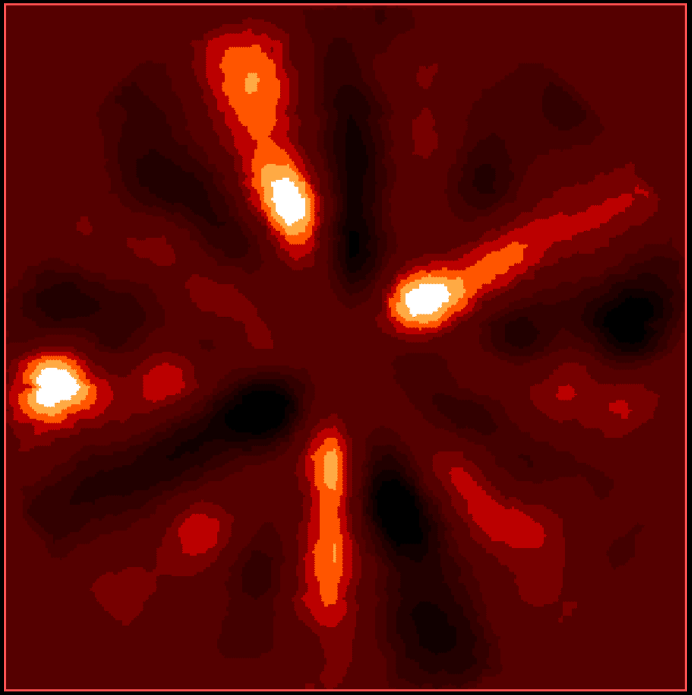
Take half of the light on axis and add $\pm\ \pi$ phase. Central part of Airy disk is now a *minimum* and the first maximum occurs at position where previously there was the first minimum:





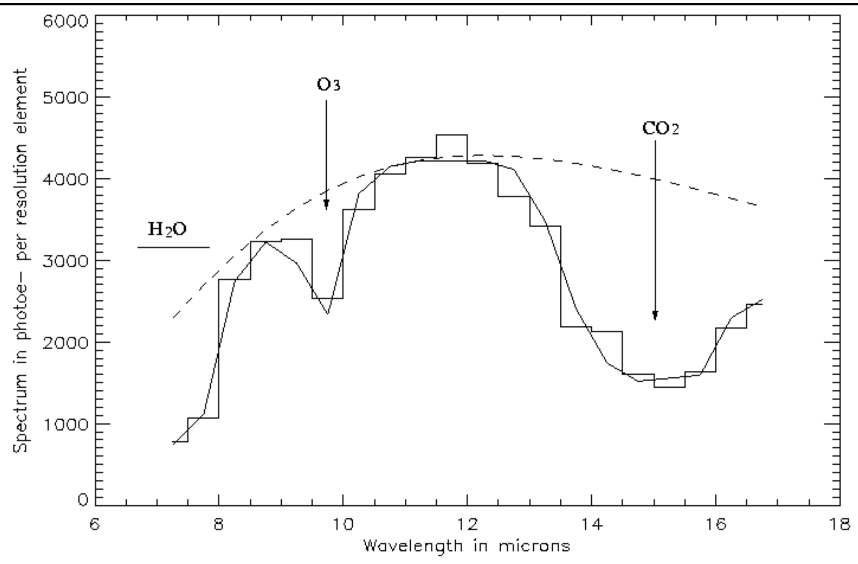
Nulling interferometry





Simulated Venus, Earth, Mars at 10 pc

Simulated Earth spectrum

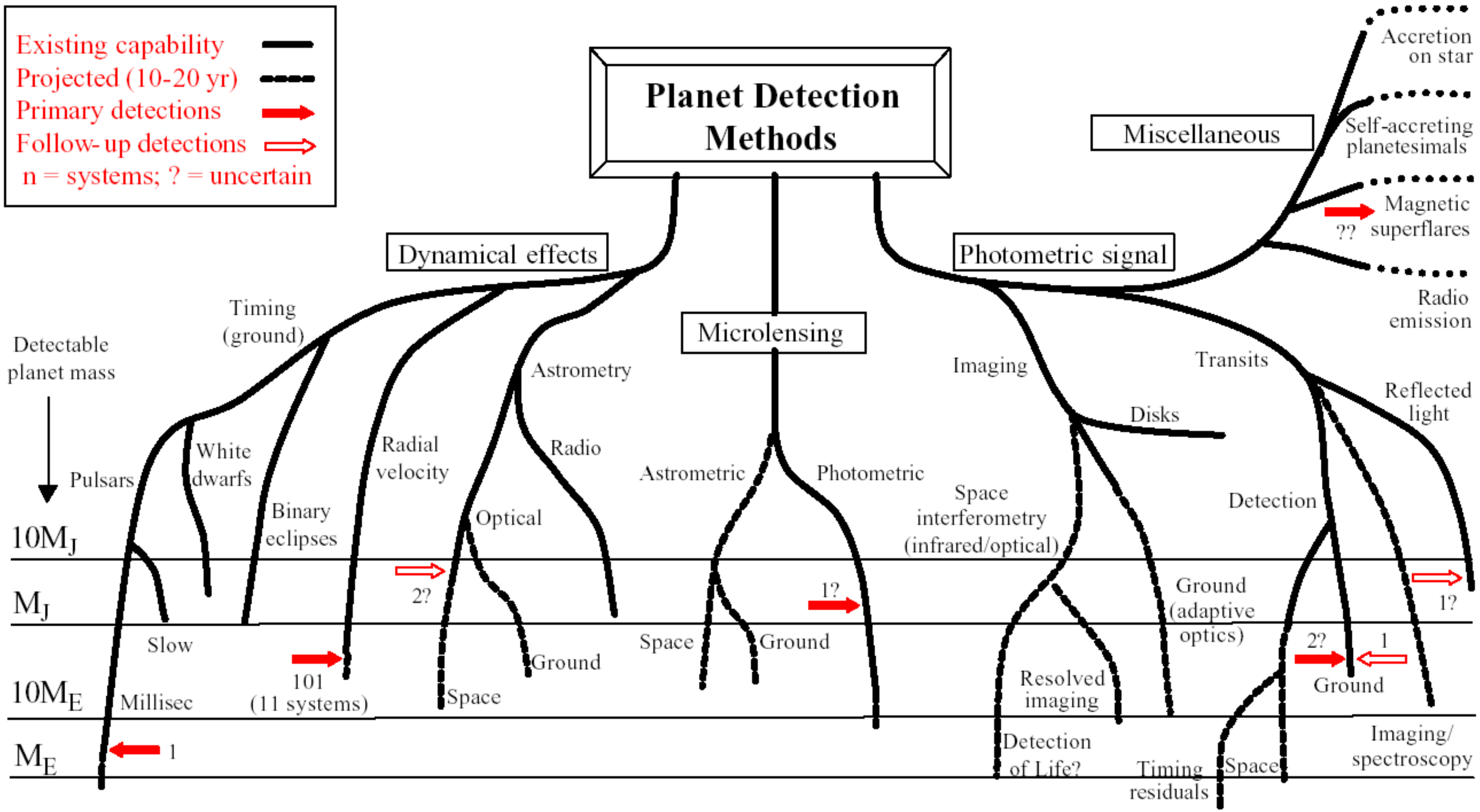


2007 Proposed ESA Darwin mission (no longer in active development due to cost)

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)

Summary:

- Vast majority of exo-planets detected indirectly due to effect on host star (or background object for gravitational lensing).
- Most methods have quite strong selection effects, with planetary properties and/or distance from us, but these are different for the different methods.
- Despite this, quite a lot of information can be gathered from indirect methods, especially if different methods are combined, e.g. radial velocity + transits lead to sizes and densities. Details of transits can give information on atmospheres and orbital inclinations.
- Direct detection relies on different methods to suppress the dominant light from the star. Several different ways are available, often in combination.

Next part: So much for methods, what has actually been found!