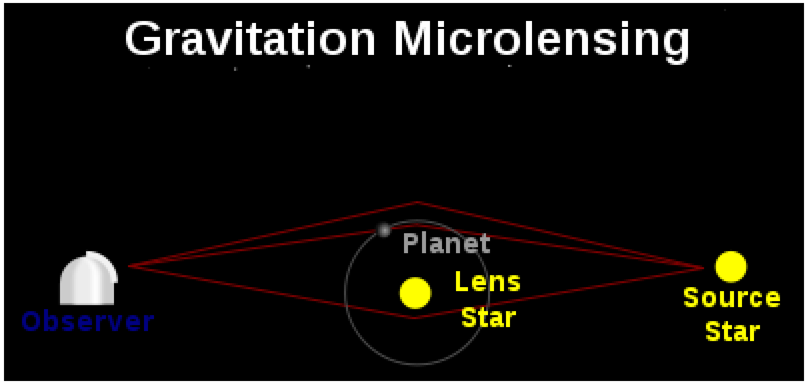
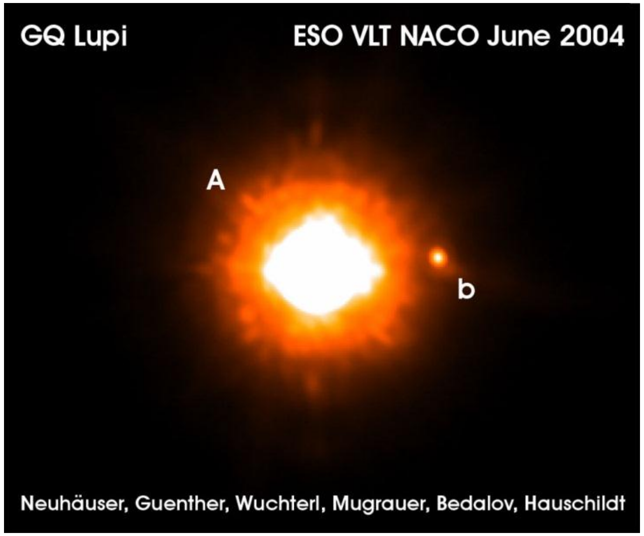
Detection of Extrasolar Planets through Gravitational Microlensing and Direct Imaging





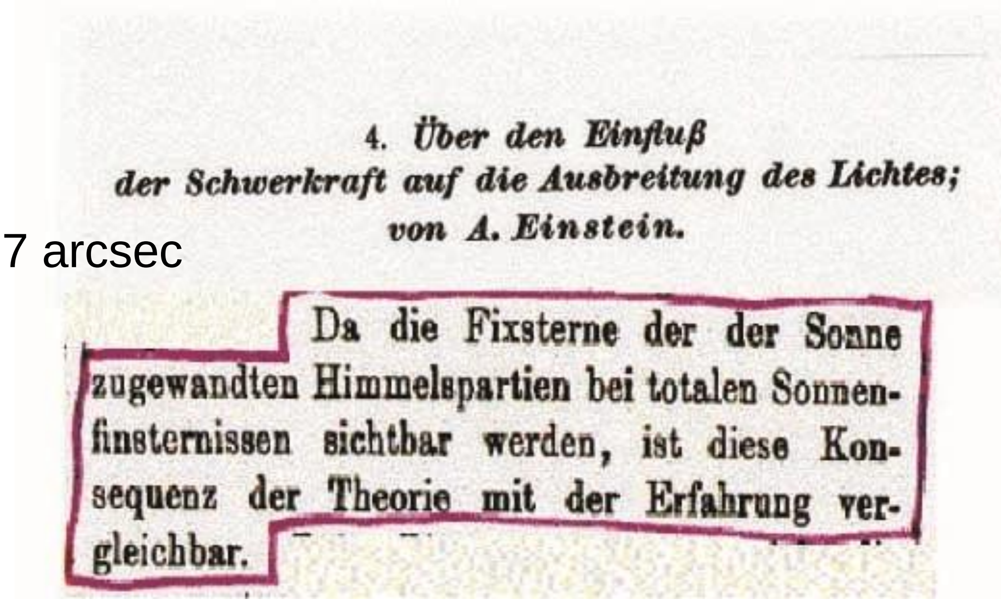
Neuhäuser, Guenther, Wuchterl, Mugrauer, Bedalov, Hauschildt

The Techniques

A Brief History of Light Deflection

In 1911 Einstein derived:

$$\alpha = \frac{2\,GM_\odot}{c^2 R_\odot} = 0.87\ \text{arcsec}$$



4. **Über den Einfluß der Schwerkraft auf die Ausbreitung des Lichtes; von A. Einstein.**

Da die Fixsterne der der Sonne zugewandten Himmelspartien bei totalen Sonnenfinsternissen sichtbar werden, ist diese Konsequenz der Theorie mit der Erfahrung vergleichbar.

Einstein in 1911 was only half right !

In 1916 using General Relativity Einstein derived:

$$\alpha = \frac{4\,GM}{c^2 r}$$

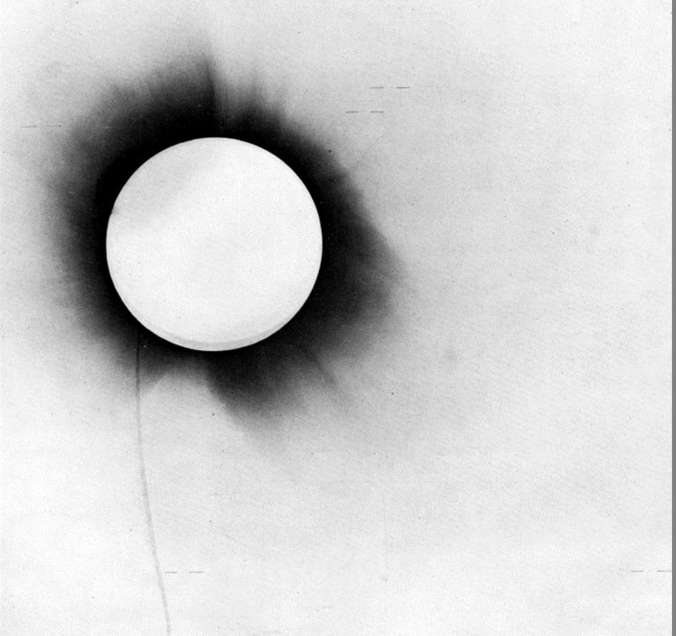
Light passing a distance r from object

$$= 1.74\ \text{arcsec}$$

Factor of 2 due to spatial curvature which is missed if light is treated like particles

Eddington‘s 1919 Eclipse expedition confirmed Einstein‘s result

This image is magnified 281 times, [illegible] with glass plate



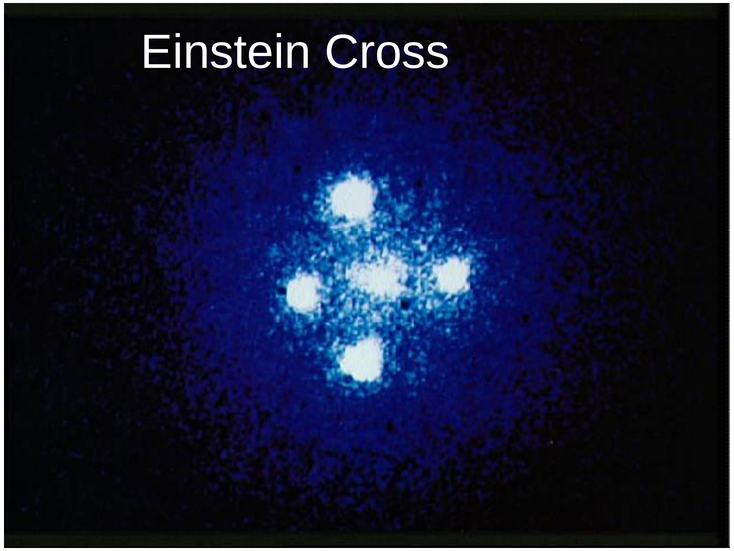
A Brief History of Light Deflection

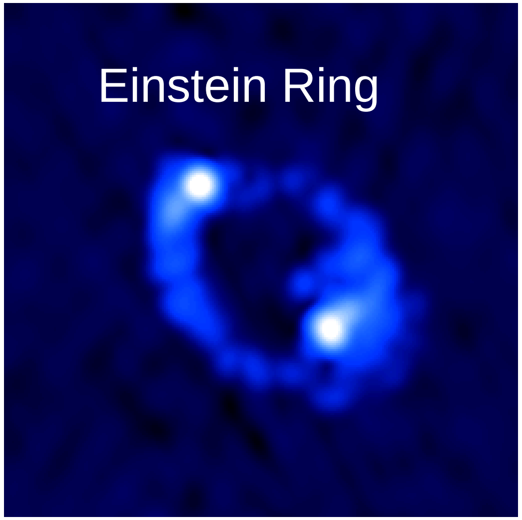
In 1924 Chwolson mentioned the idea of a „factious double star.“ In the symmetric case of a star exactly behind a star a circular image would result

In 1936 Einstein reported about the appearance of a „luminous“ circle of perfect alignment between the source and the lens: „Einstein Ring“

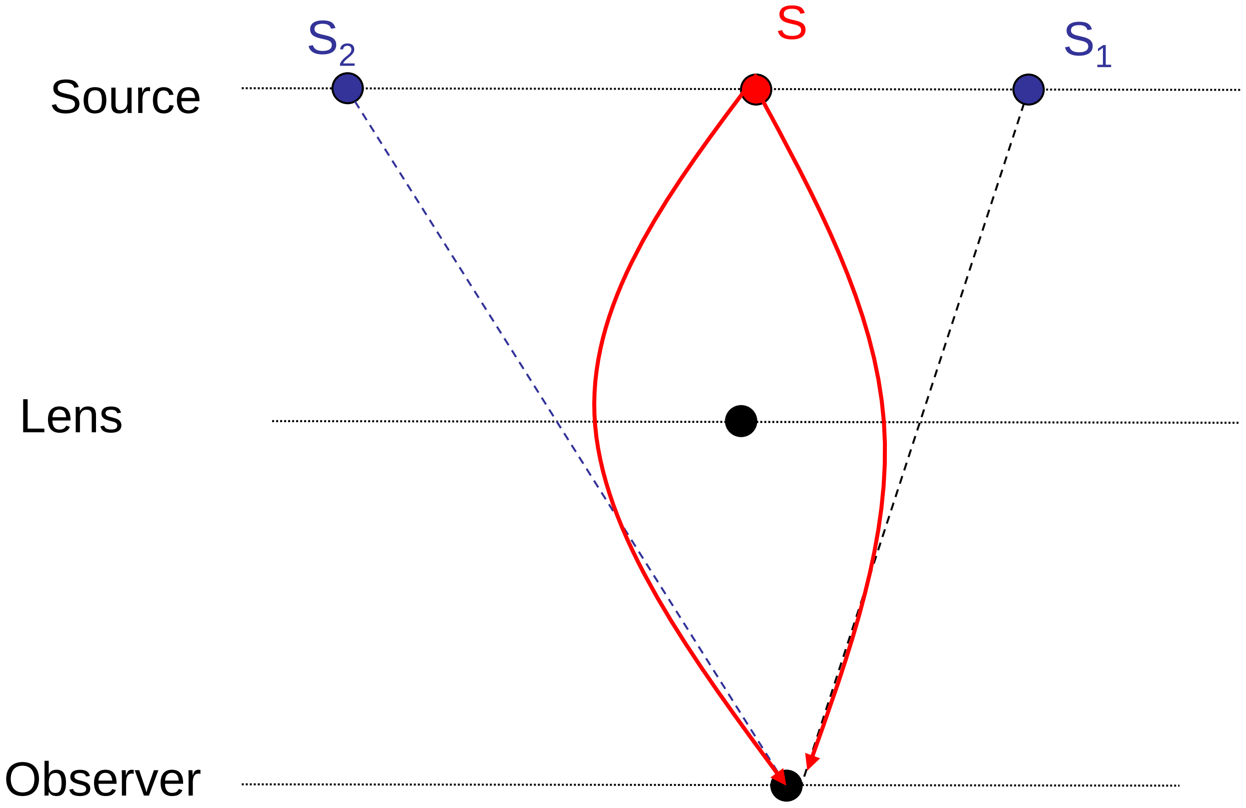
In 1937 Zwicky pointed out that galaxies are more likely to be gravitationally lensed than a star and one can use the gravitational lens as a telescope

Evidence for gravitational lensing first appeared in extragalactic work





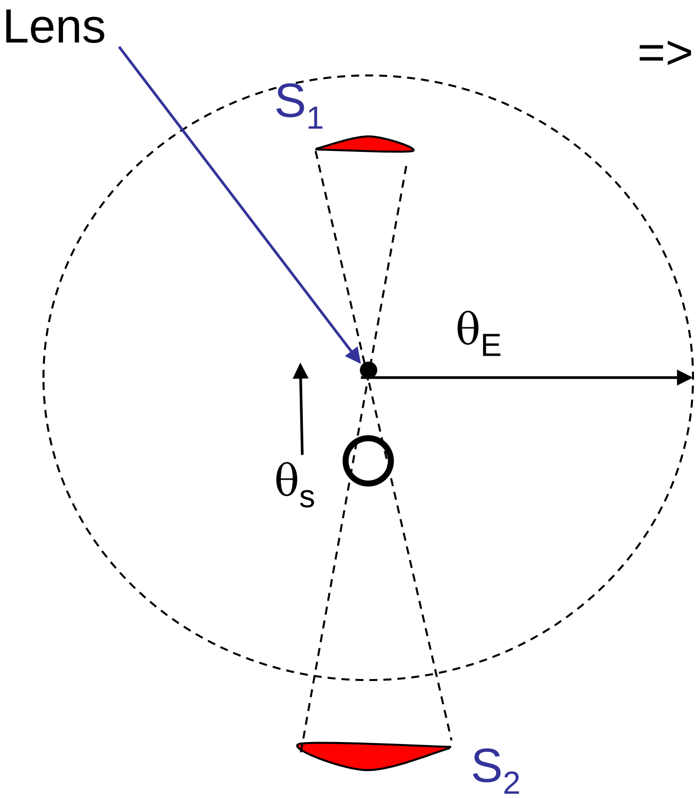
Basics of Lensing:



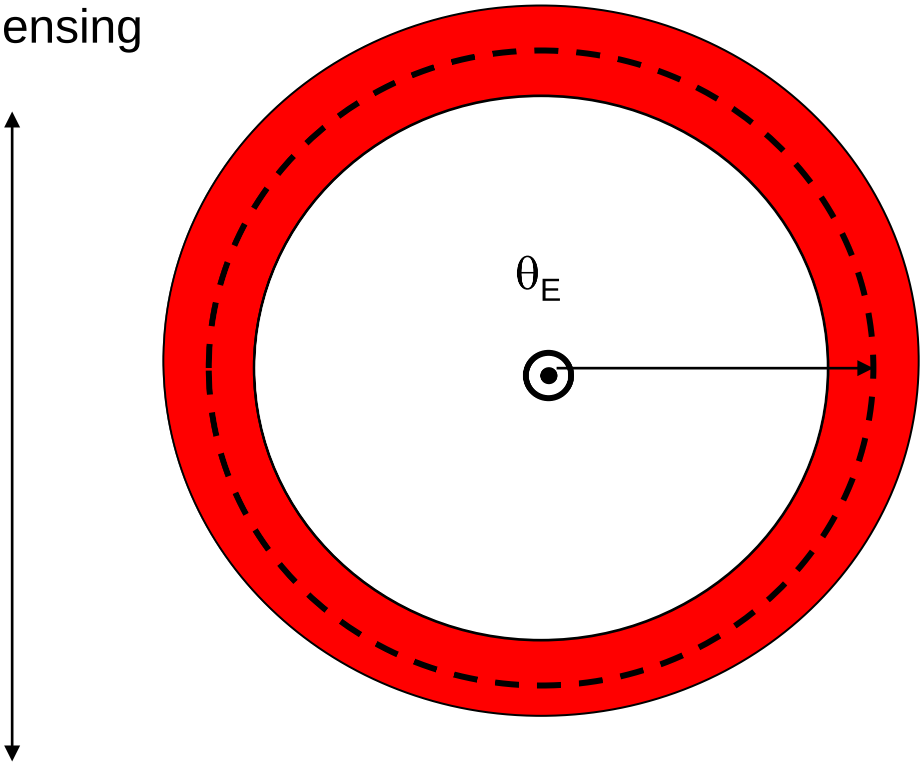
Basics of Lensing: The Einstein Radius

≈ 1 milli-arcsecond

=> Microlensing

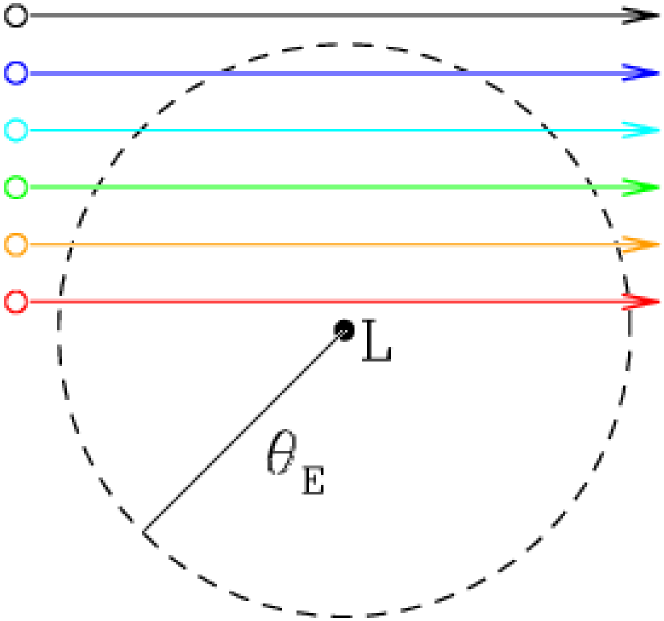


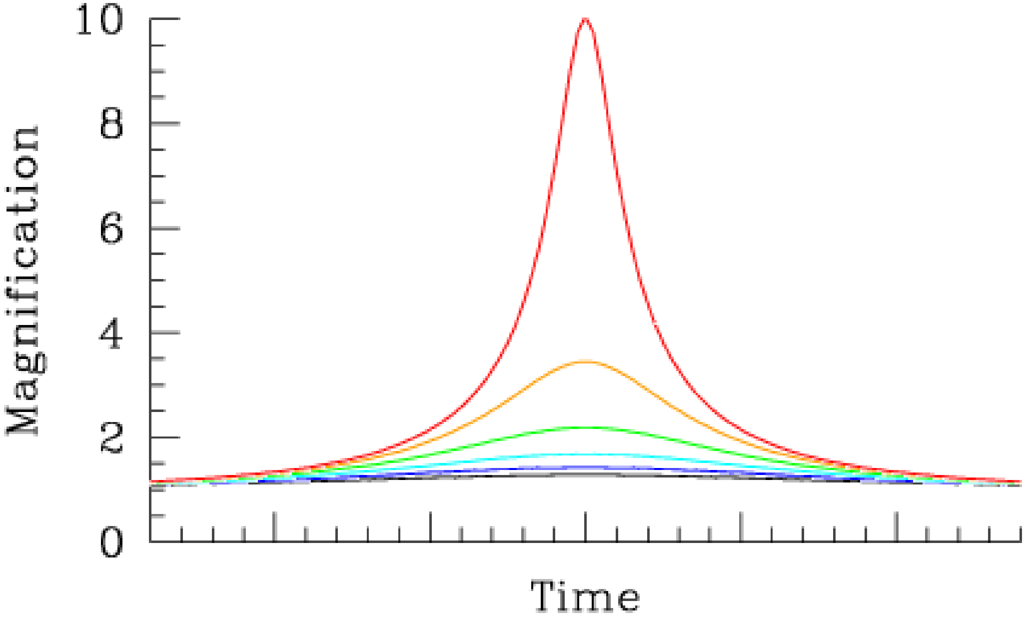
Source off-centered



Source centered

Magnification due to Microlensing:

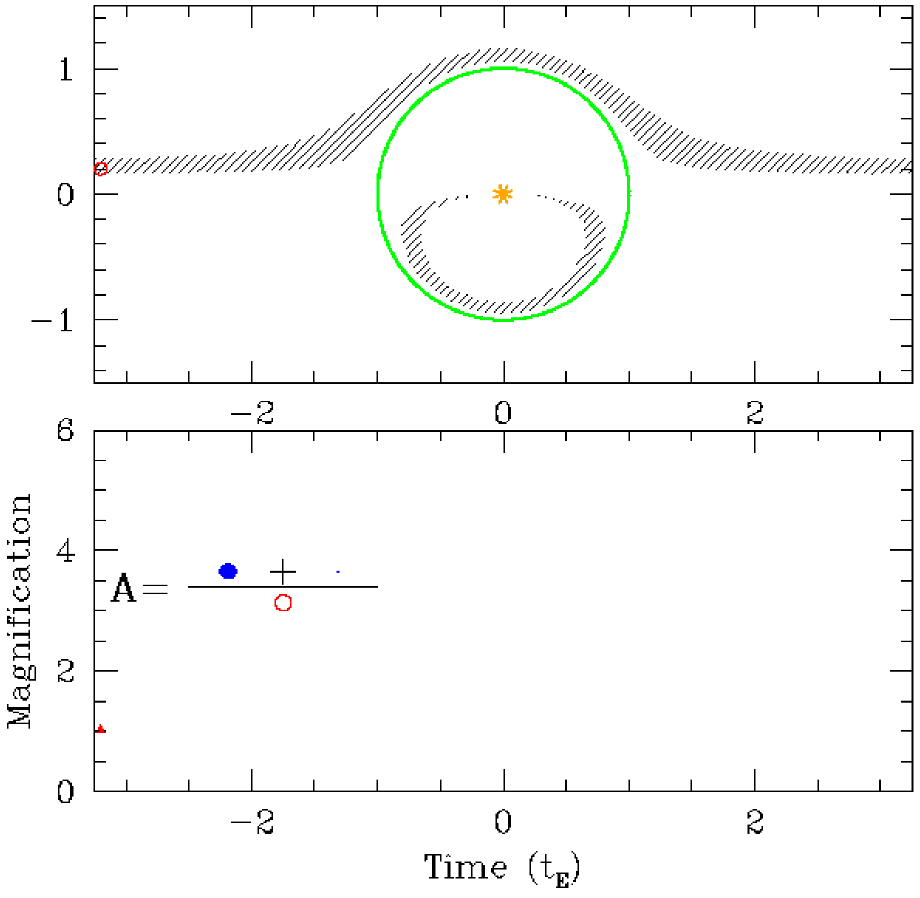




Typical microlensing events last from a few weeks to a few months

Time sequence: single star

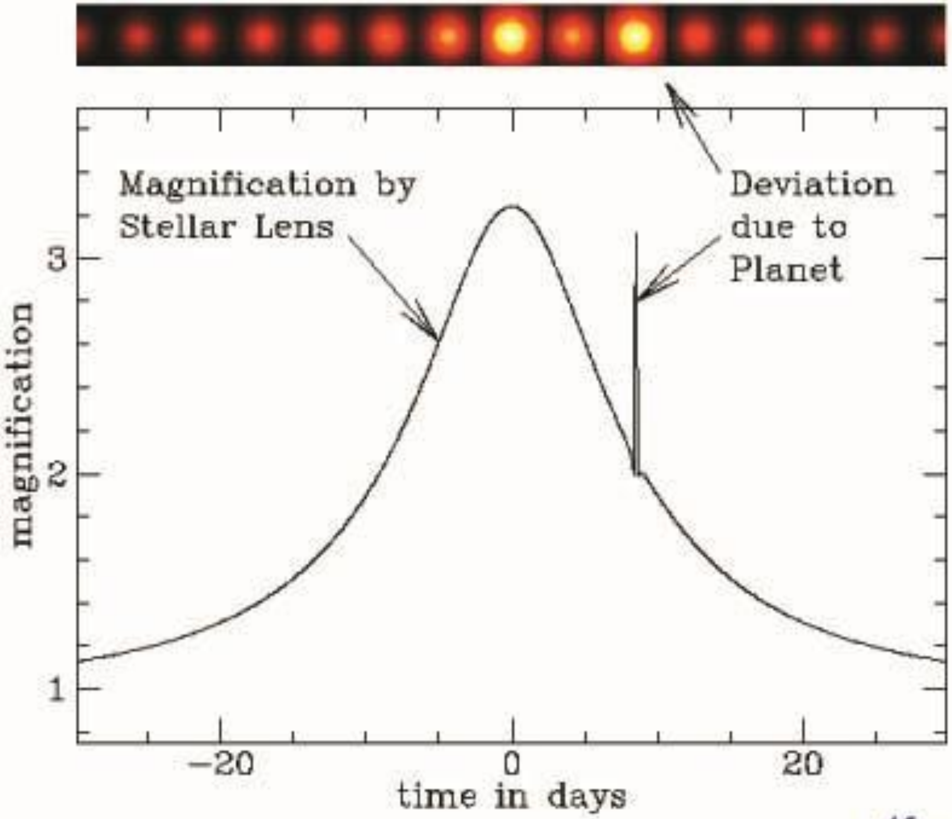
- Top panel shows stellar images at ~1 mas resolution centered on lens star
- Einstein ring in green
- Magnified stellar images shown in blue
- Unmagnified image is red outline
- The observable total magnification is shown in the bottom panel



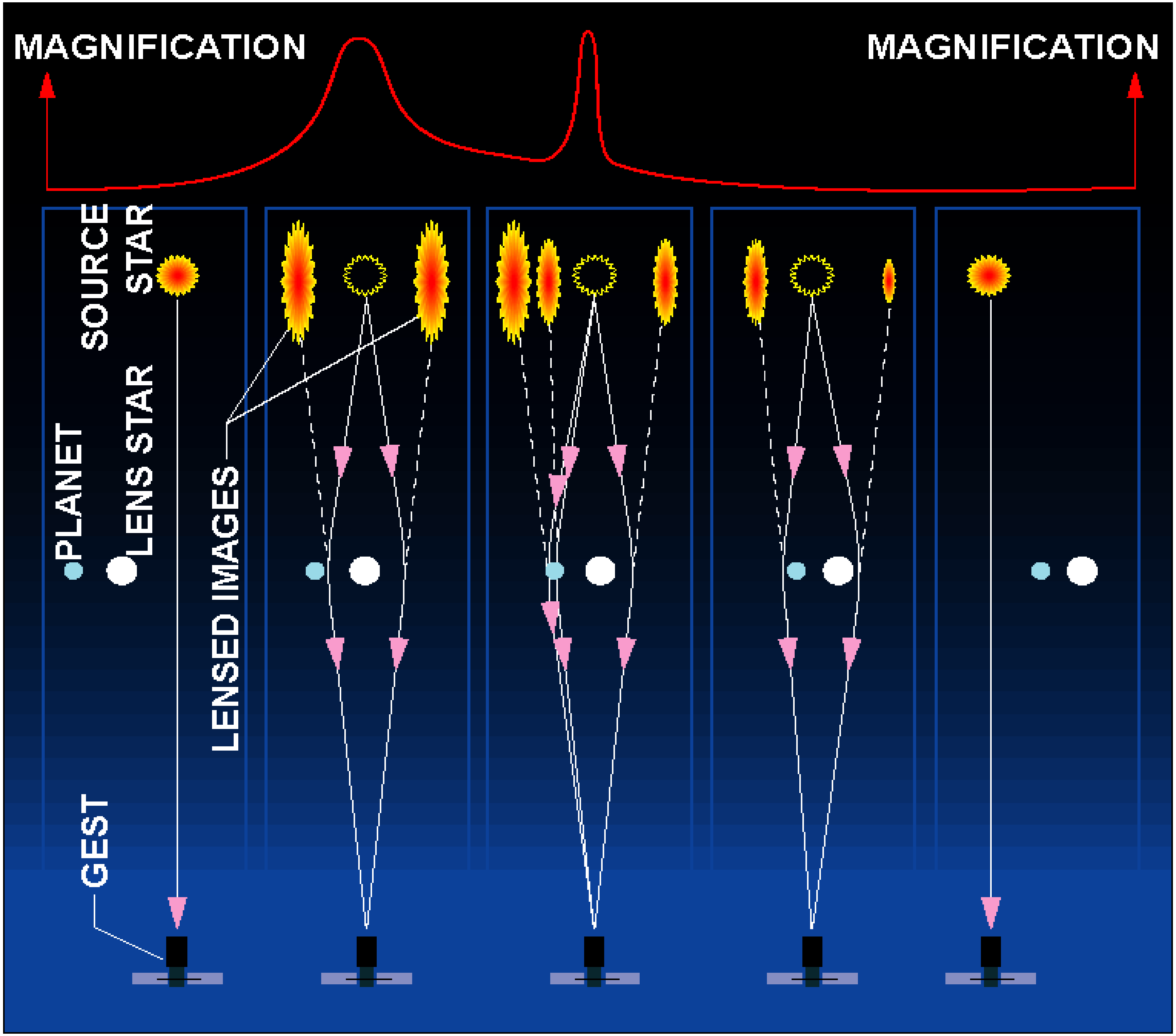
Animation by Scott Gaudi:

http://www.astronomy.ohio-state.edu/~gaudi/movies.html

Microlensing by Planets: The Method



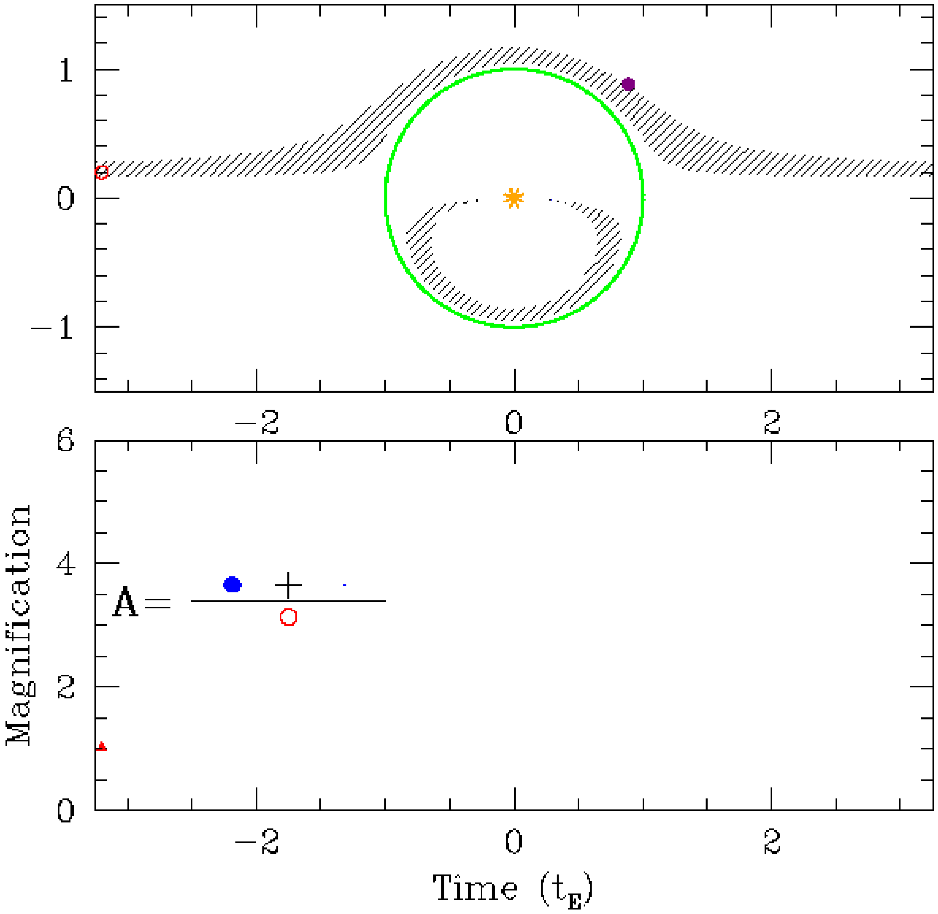
(from D. Bennett)

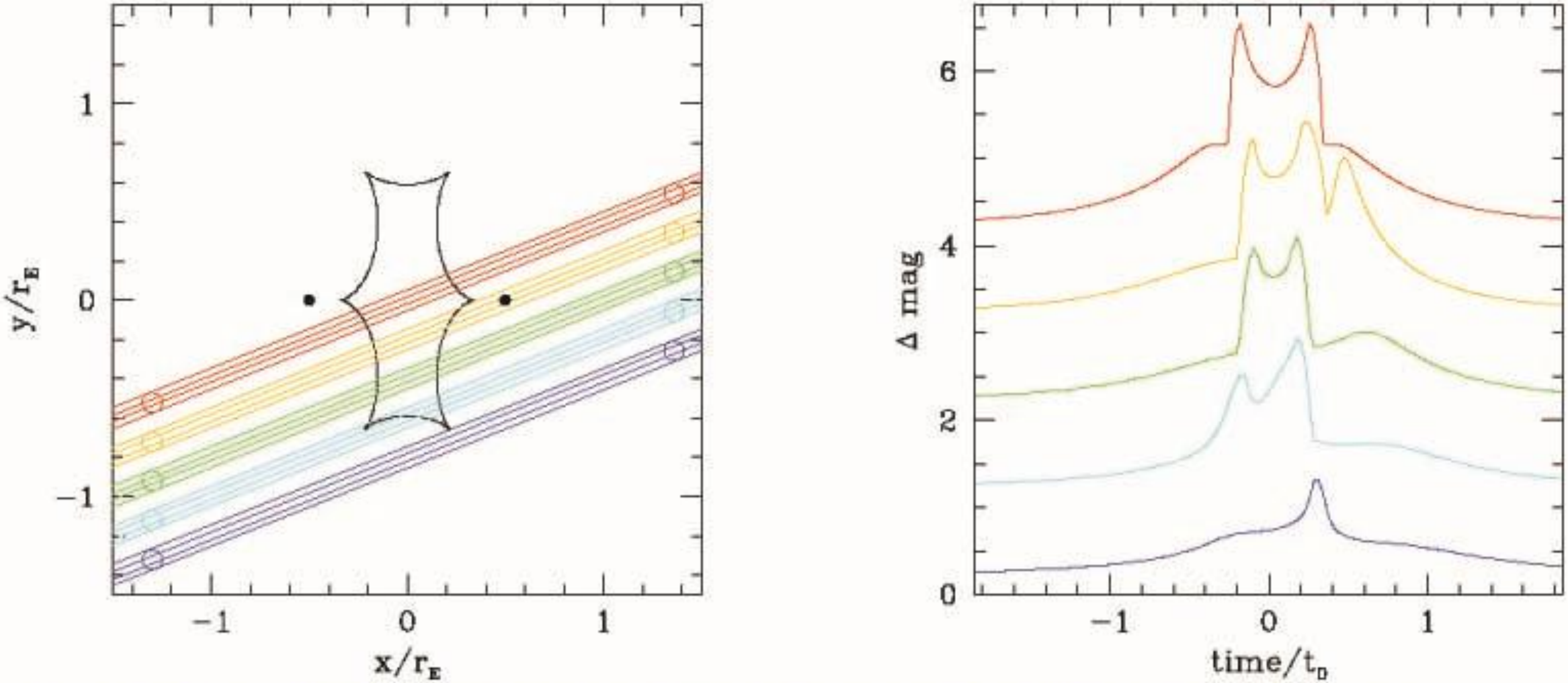

MAGNIFICATION
MAGNIFICATION
SOURCE STAR
PLANET
LENS STAR
LENSED IMAGES
GEST

Time sequence: star + planet

- A planet in the shaded (purple) region gives a detectable deviation

A planet lensing event lasts 10-30 hours





double lens: lightcurves can get very diverse; 3 additional parameters:

- mass ratio: $q = 1 \ldots 10^{-6}$; lensing effect $\propto q^{0.5}$
- projected separation: $d = 1 \ldots 5$ AU
- angle of motion relative to connecting line: φ

Microlensing by Planets: How?

The Method

- Microlensing by stars in the Milky Way (Halo):
  proposed by Paczynski (1986) as a test for compact dark matter
- Idea:
  - monitor (background) stars in LMC or Milky Way bulge;
  - occasionally a random (foreground) star passes in front and magnifies background star in characteristic way
  - about 10% of cases will be binary lenses
  - a (small) fraction of those have small mass ratios: planets!
  - problem: **very** small probability for ML events (of order 10^{-6}), even smaller for planetary companions ...

Mao & Paczynski (1992) propose that star-planet systems will also act as lenses

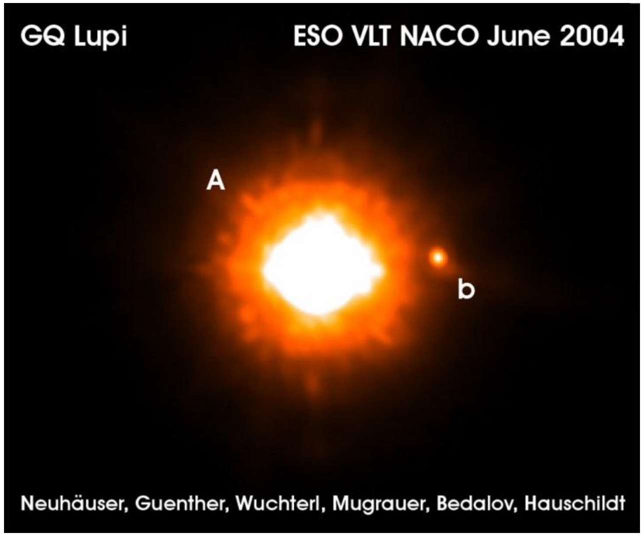
The Advantages of Microlensing Searches

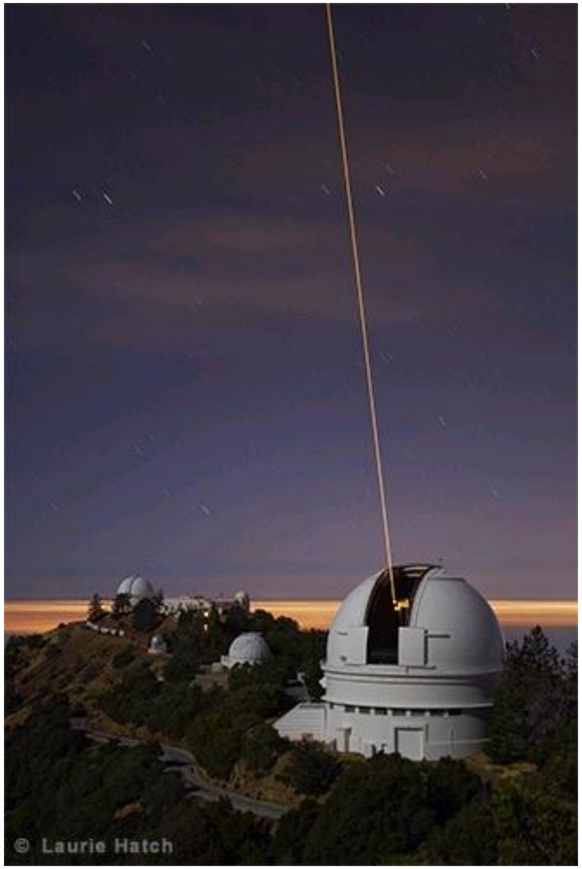
- No bias for nearby stars, planets around solar-type stars
- Sensitive to Earth-mass planets using ground-based observations: one of few methods that can do this
- Most sensitive for planets in the „lensing zone“, $0.6 < a < 2$ AU for stars in the bulge. This is the habitable zone!
- Can get good statistics on Earth mass planets in the habitable zone of stars
- Multiple systems can be detected at the same time
- Detection of free floating planets possible

The Disadvantages of Microlensing Searches

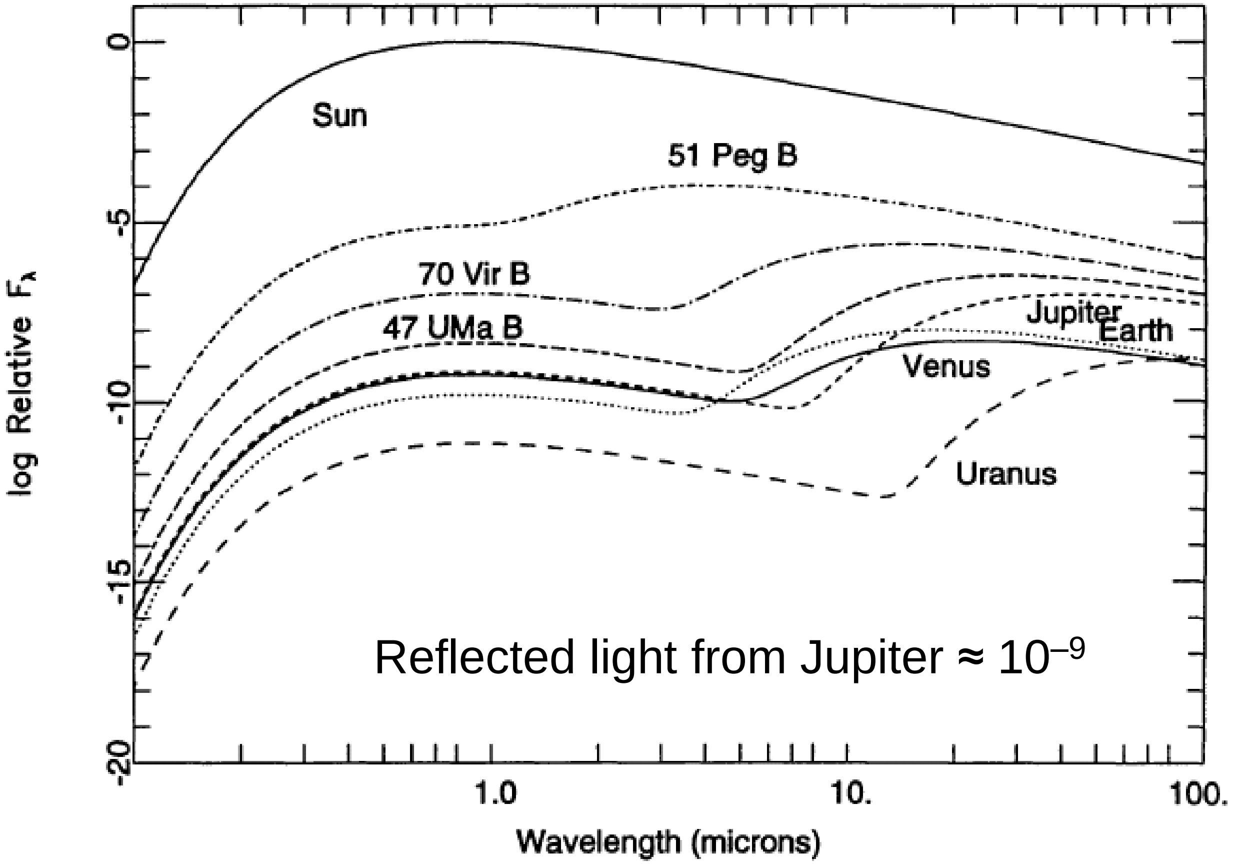
- Probability of lensing events small but overcome by looking at lots of stars
- **One time event, no possibility to confirm, or improve measurements**
- Duration of events is hours to days. Need coordinated observations from many observatories
- **Planet hosting star is distant: Detailed studies of the host star very dfficult**
- **Precise orbital parameters of the planet not possible**
- **Light curves are complex: only one crossing of the caustic. No unique solution and often a non-planet can also model the light curves**
- **Final masses of planet and host stars rely on galactic models and statistics and are poorly known**
- **Future characterization studies of the planet are impossible**

II. Direct Imaging of Exoplanets





Challenge 1: Large ratio between star and planet flux (Star/Planet)



Reflected light from Jupiter ≈ 10^{-9}

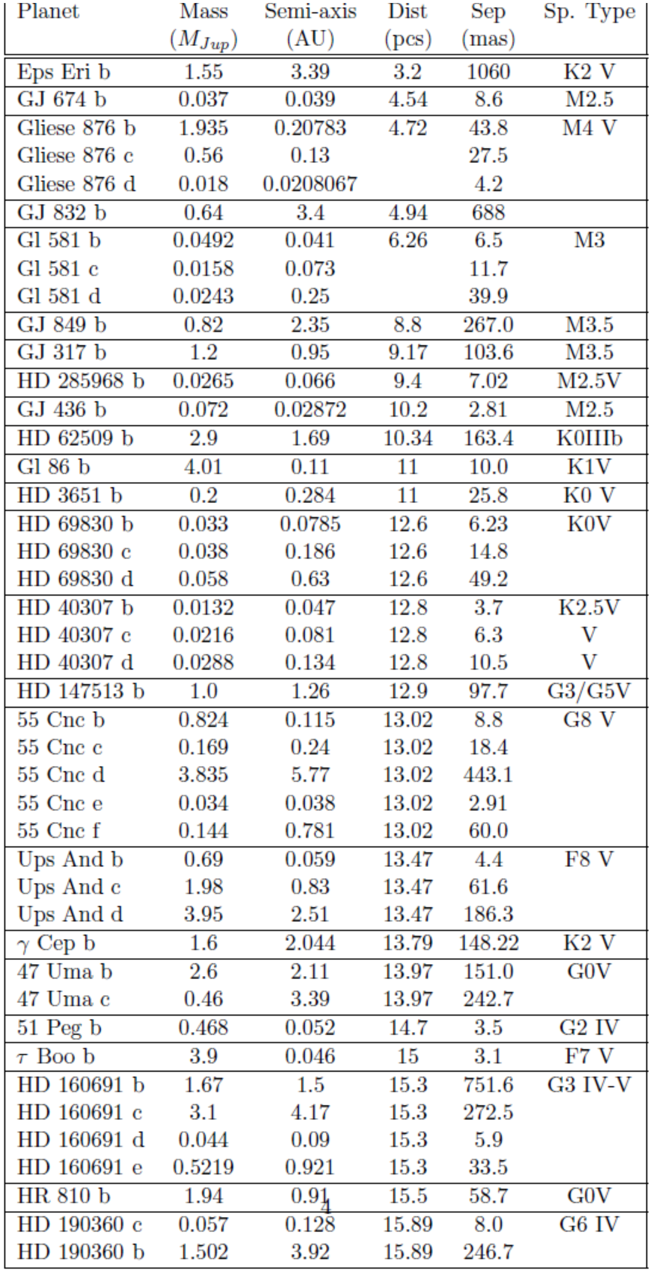
Figure 1. Relative fluxes of the Sun, Venus, Earth, Jupiter, Uranus, and the companion objects to 51 Pegasi, 70 Virginis, and 47 Ursae Majoris from 0.10 μm to 100 μm.

Stars are a billion times brighter…

…than the planet

…hidden
in the glare.

Challenge 2: Close proximity of planet to host star



Planet	Mass (M_{Jup})	Semi-axis (AU)	Dist (pcs)	Sep (mas)	Sp. Type
Eps Eri b	1.55	3.39	3.2	1060	K2 V
GJ 674 b	0.037	0.039	4.54	8.6	M2.5
Gliese 876 b	1.935	0.20783	4.72	43.8	M4 V
Gliese 876 c	0.56	0.13		27.5	
Gliese 876 d	0.018	0.0208067		4.2	
GJ 832 b	0.64	3.4	4.94	688	
Gl 581 b	0.0492	0.041	6.26	6.5	M3
Gl 581 c	0.0158	0.073		11.7	
Gl 581 d	0.0243	0.25		39.9	
GJ 849 b	0.82	2.35	8.8	267.0	M3.5
GJ 317 b	1.2	0.95	9.17	103.6	M3.5
HD 285968 b	0.0265	0.066	9.4	7.02	M2.5V
GJ 436 b	0.072	0.02872	10.2	2.81	M2.5
HD 62509 b	2.9	1.69	10.34	163.4	K0IIIb
Gl 86 b	4.01	0.11	11	10.0	K1V
HD 3651 b	0.2	0.284	11	25.8	K0 V
HD 69830 b	0.033	0.0785	12.6	6.23	K0V
HD 69830 c	0.038	0.186	12.6	14.8	
HD 69830 d	0.058	0.63	12.6	49.2	
HD 40307 b	0.0132	0.047	12.8	3.7	K2.5V
HD 40307 c	0.0216	0.081	12.8	6.3	V
HD 40307 d	0.0288	0.134	12.8	10.5	V
HD 147513 b	1.0	1.26	12.9	97.7	G3/G5V
55 Cnc b	0.824	0.115	13.02	8.8	G8 V
55 Cnc c	0.169	0.24	13.02	18.4	
55 Cnc d	3.835	5.77	13.02	443.1	
55 Cnc e	0.034	0.038	13.02	2.91	
55 Cnc f	0.144	0.781	13.02	60.0	
Ups And b	0.69	0.059	13.47	4.4	F8 V
Ups And c	1.98	0.83	13.47	61.6	
Ups And d	3.95	2.51	13.47	186.3	
γ Cep b	1.6	2.044	13.79	148.22	K2 V
47 Uma b	2.6	2.11	13.97	151.0	G0V
47 Uma c	0.46	3.39	13.97	242.7	
51 Peg b	0.468	0.052	14.7	3.5	G2 IV
τ Boo b	3.9	0.046	15	3.1	F7 V
HD 160691 b	1.67	1.5	15.3	751.6	G3 IV-V
HD 160691 c	3.1	4.17	15.3	272.5	
HD 160691 d	0.044	0.09	15.3	5.9	
HD 160691 e	0.5219	0.921	15.3	33.5	
HR 810 b	1.94	0.91	15.5	58.7	G0V
HD 190360 c	0.057	0.128	15.89	8.0	G6 IV
HD 190360 b	1.502	3.92	15.89	246.7	

Direct Detections need contrast ratios of 10^{-9} to 10^{-10}

At separations of 0.01 to 1 arcseconds

Earth : ~10^{-10} separation = 0.1 arcseconds for a star at 10 parsecs

Jupiter: ~10^{-9} separation = 0.5 arcseconds for a star at 10 parsecs

1 AU = 1 arcsec separation at 1 parsec

Younger planets are hotter and they emit more radiated light. These are easier to detect.

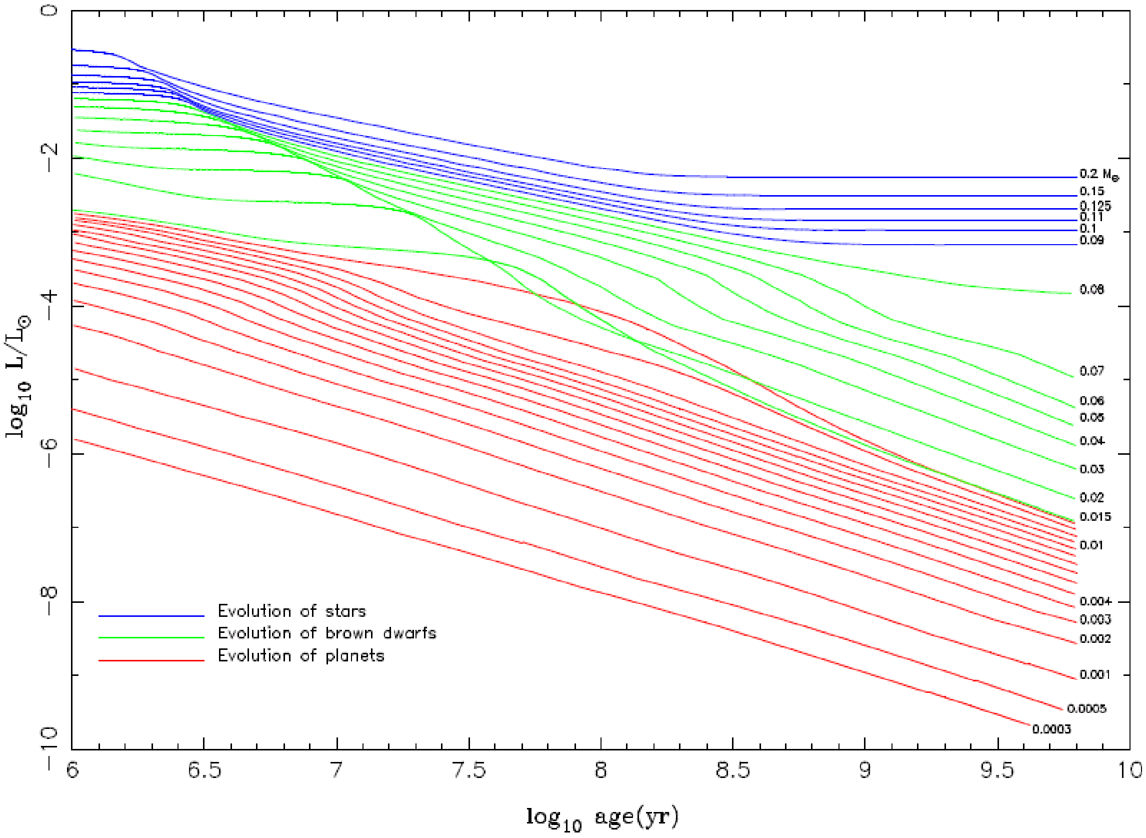
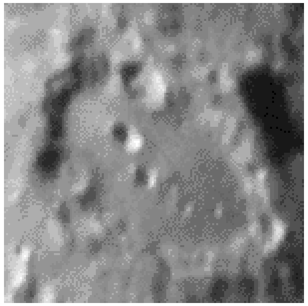
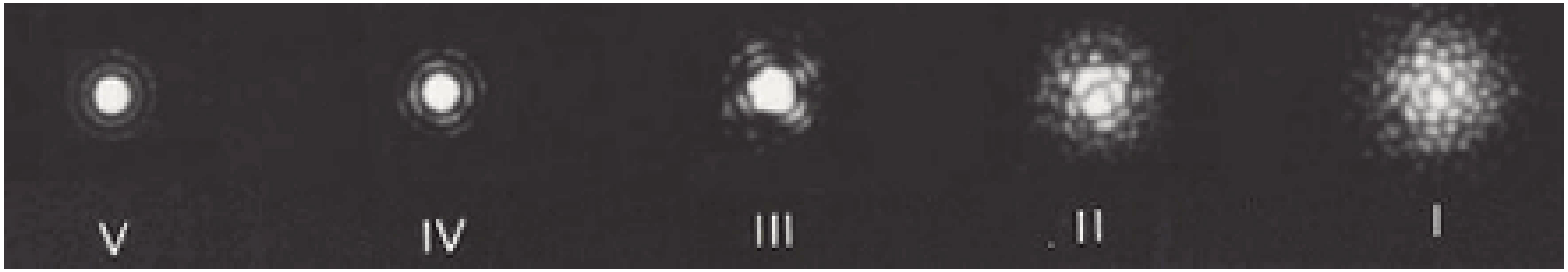


Figure 1. Evolution of the luminosity (in $L_\odot$) of solar–metallicity M dwarfs and substellar objects versus time (in years) after formation. The stars, "brown dwarfs" and "planets" are shown as solid, dashed, and dot–dashed curves, respectively. In this figure, we arbitrarily designate as "brown dwarfs" those objects that burn deuterium, while we designate those that do not as "planets." The masses in $M_\odot$ label most of the curves, with the lowest three corresponding to the mass of Saturn, half the mass of Jupiter, and the mass of Jupiter.

Adaptive Optics : An important component for any imaging instrument





Atmospheric turbulence distorts stellar images making them much larger than point sources. This seeing image makes it impossible to detect nearby faint companions.

Adaptive Optics (AO)

The scientific and engineering discipline whereby the performance of an optical signal is improved by using information about the environment through which it passes

AO Deals with the control of light in a real time closed loop and is a subset of *active optics.*

Adaptive Optics: Systems operating below 1/10 Hz

Active Optics: Systems operating above 1/10 Hz

Example of an Adaptive Optics System: The Eye-Brain

The brain interprets an image, determines its correction, and applies the correction either voluntarily of involuntarily

Lens compression: Focus corrected mode

Tracking an Object: Tilt mode optics system

Iris opening and closing to intensity levels: Intensity control mode

Eyes squinting: An aperture stop, spatial filter, and phase controlling mechanism

The Ideal Telescope

$$P_0(\vec{\alpha}) = \frac{\pi D^2}{4\lambda^2}\left[\frac{2J_1(\pi D|\vec{\alpha}|/\lambda)}{\pi D|\vec{\alpha}|/\lambda}\right]^2,$$

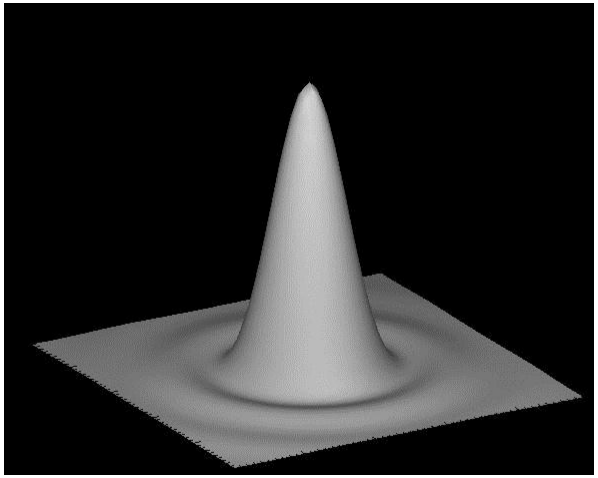


image of a star produced by ideal telescope

where:

- $P(\alpha)$ is the light intensity in the focal plane, as a function of angular coordinates α ;
- λ is the wavelength of light;
- D is the diameter of the telescope aperture;
- J_1 is the so-called Bessel function.

The first dark ring is at an angular distance D_λ of from the center.
This is often taken as a measure of resolution (diffraction limit) in an ideal telescope.

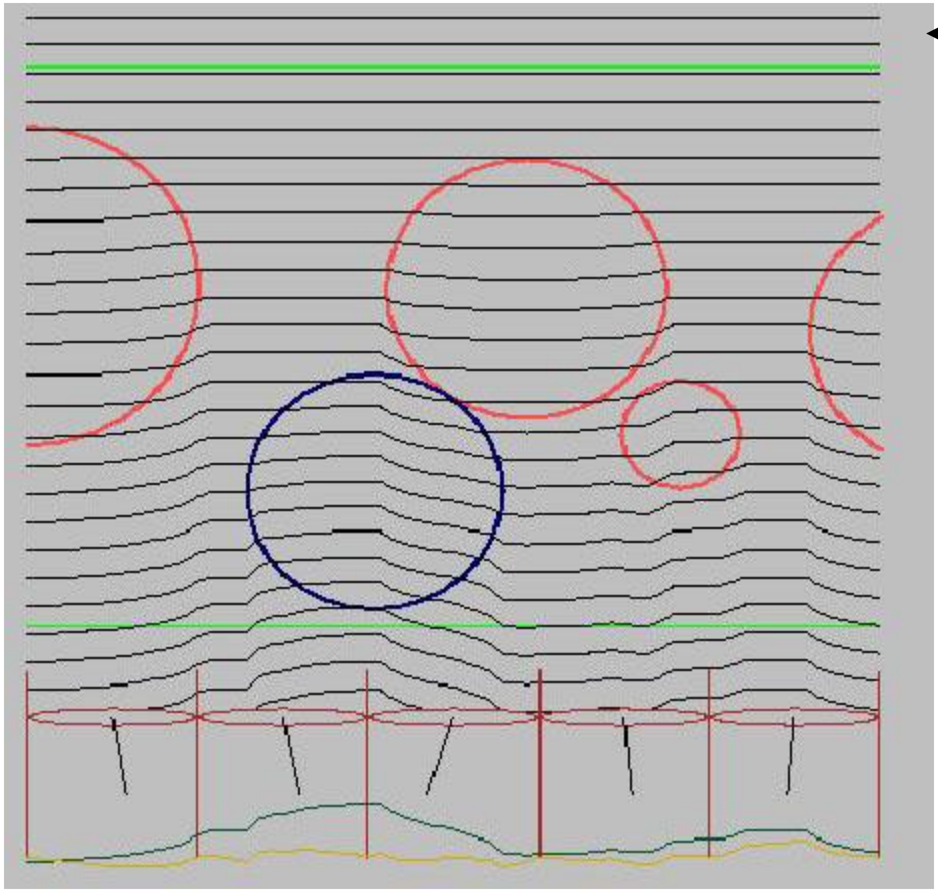
$D_\lambda = 1.22\ \lambda/D = 251643\ \lambda/D$ (arcsecs)

Diffraction Limit

Telescope	5500 Å	2 μm	10 μm	Seeing
TLS 2m	0.06“	0.2“	1.0“	2“
VLT 8m	0.017“	0.06“	0.3“	0.2“
Keck 10m	0.014“	0.05“	0.25“	0.2“
ELT 42m	0.003“	0.01“	0.1“	0.2“

Even at the best sites AO is needed to improve image quality and reach the diffraction limit of the telescope. This is easier to do in the infrared

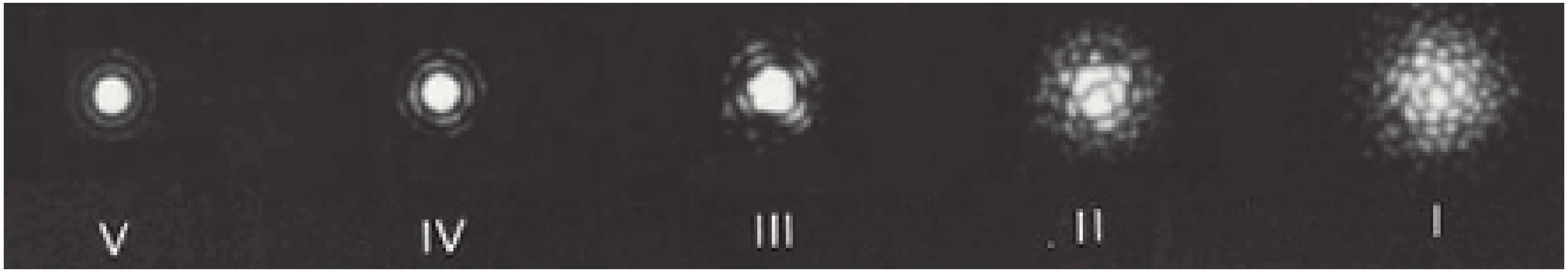
Atmospheric Turbulence



Original wavefront

Distorted wavefront

- Turbulence causes temperature fluctuations
- Temperature fluctuations cause refractive index variations
  - Turbulent eddies are like lenses
- Plane wavefronts are wrinkled and star images are blurred



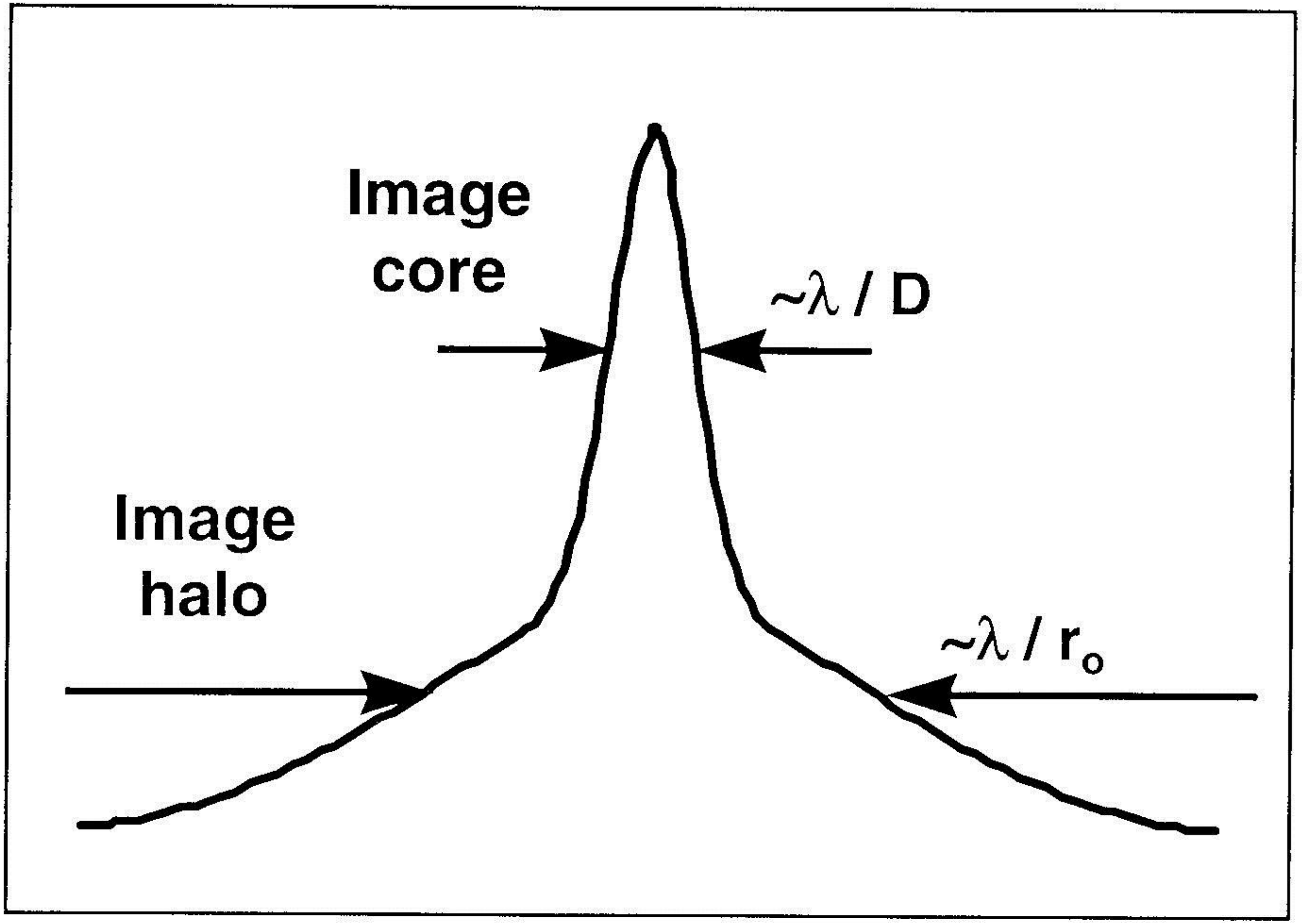
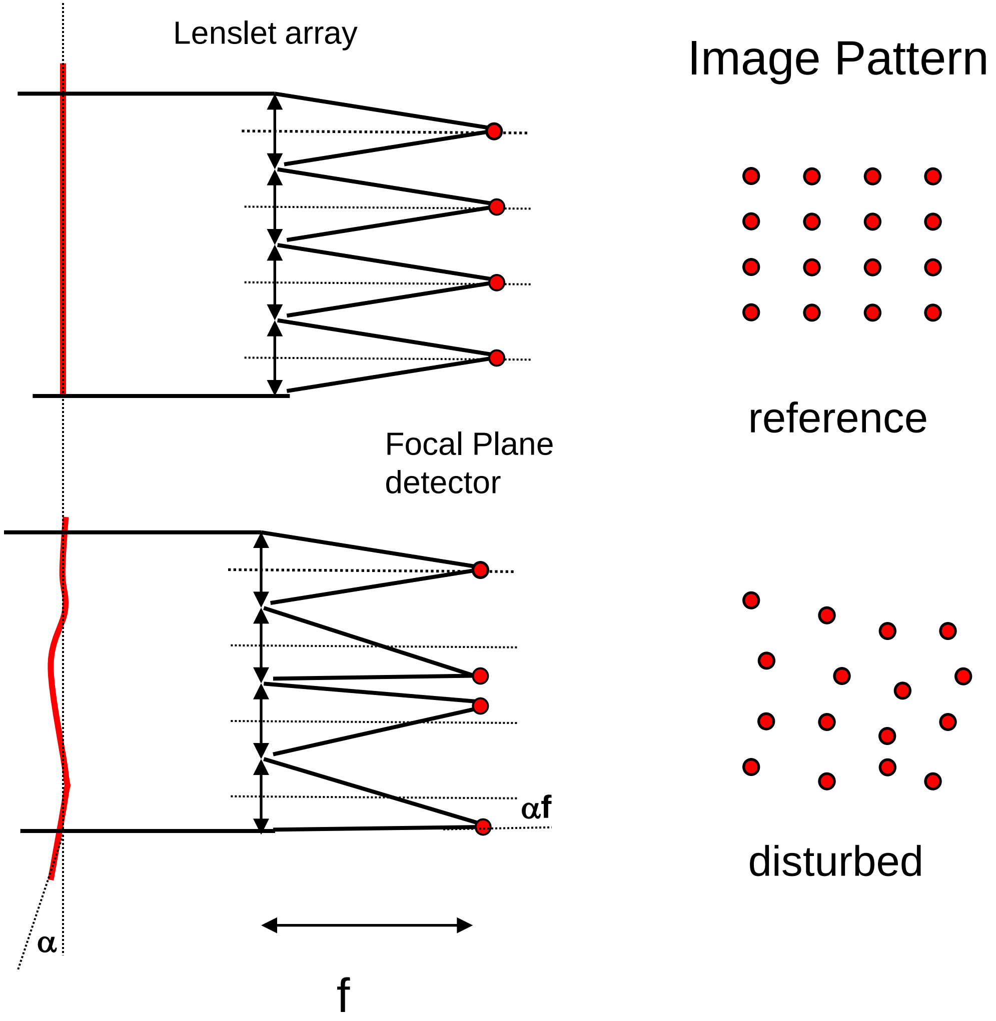


Figure 2.2: The point spread function through the atmosphere exhibits a diffraction-limited central core and a halo.

Basic Components for an AO System

1. You need to have a mathematical model representation of the wavefront
2. You need to **measure the incoming wavefront** with a point source (real or artifical).
3. You need to **correct the wavefront** using a deformable mirror

Shack-Hartmann Wavefront Sensor



Lenslet array

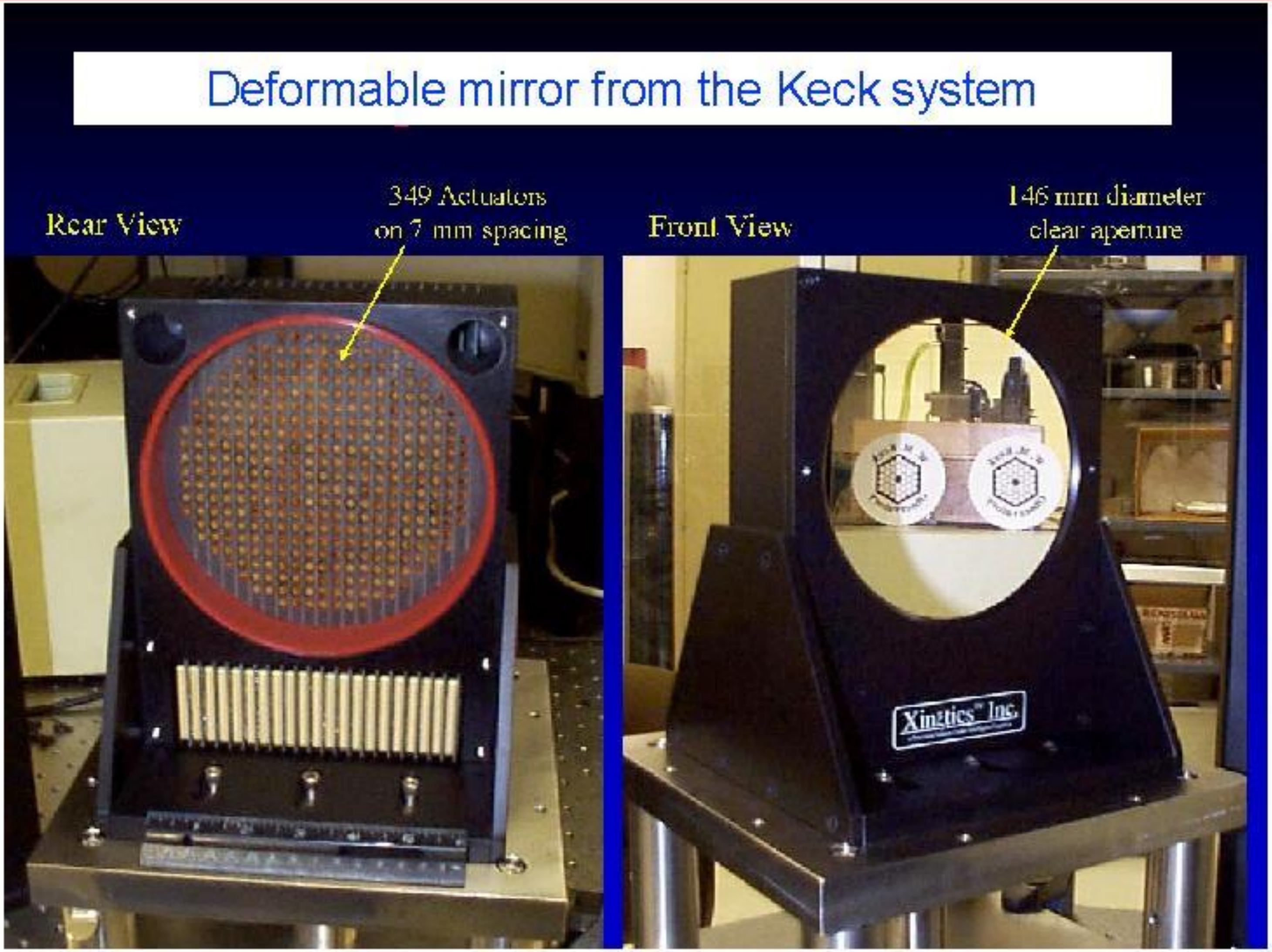
Image Pattern

reference

Focal Plane
detector

disturbed

Deformable mirrors



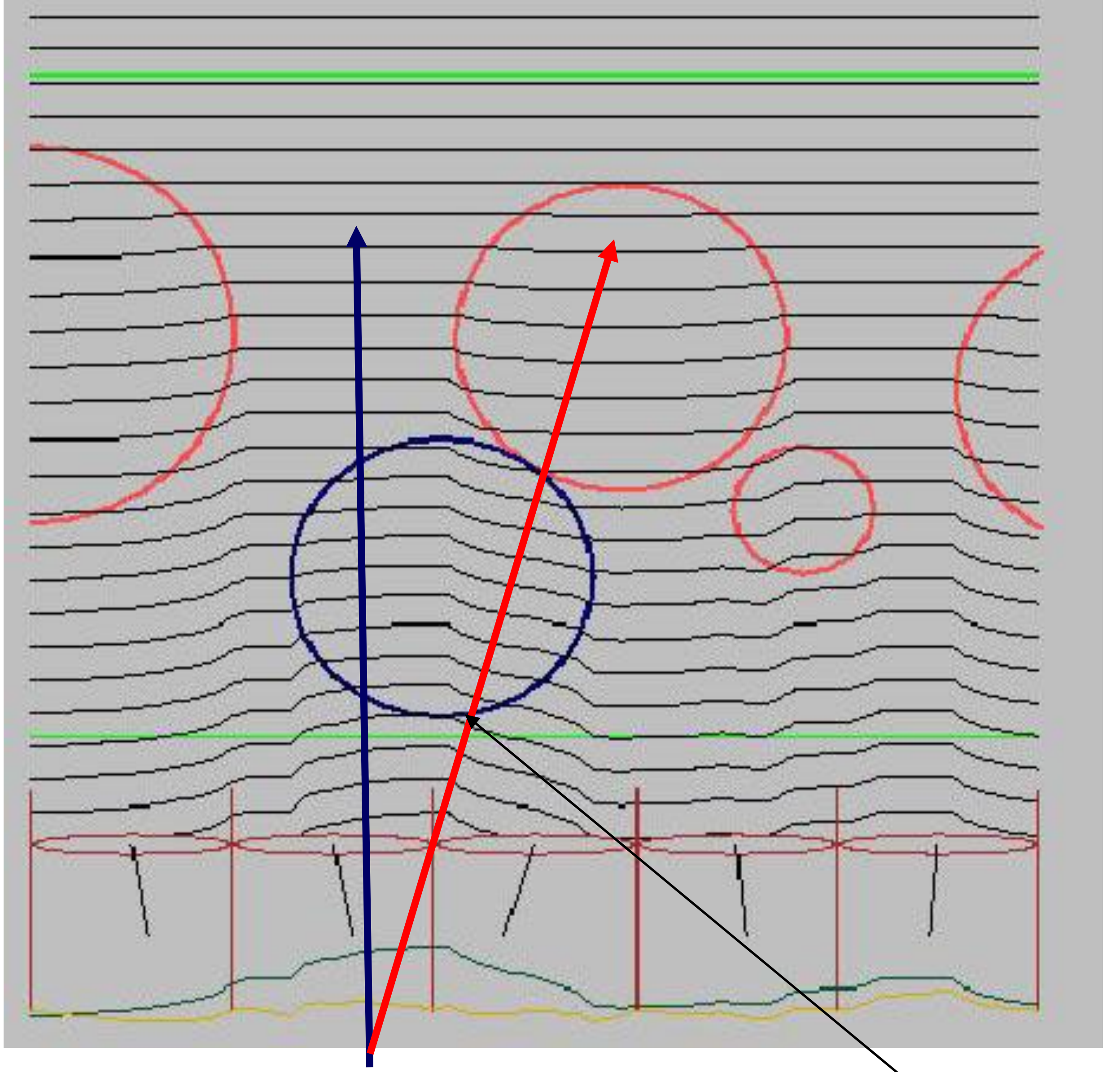
Deformable mirror from the Keck system

Rear View

349 Actuators
on 7 mm spacing

Front View

146 mm diameter
clear aperture



If you are
observing an
object here

You do not want to correct using a
reference star in this direction

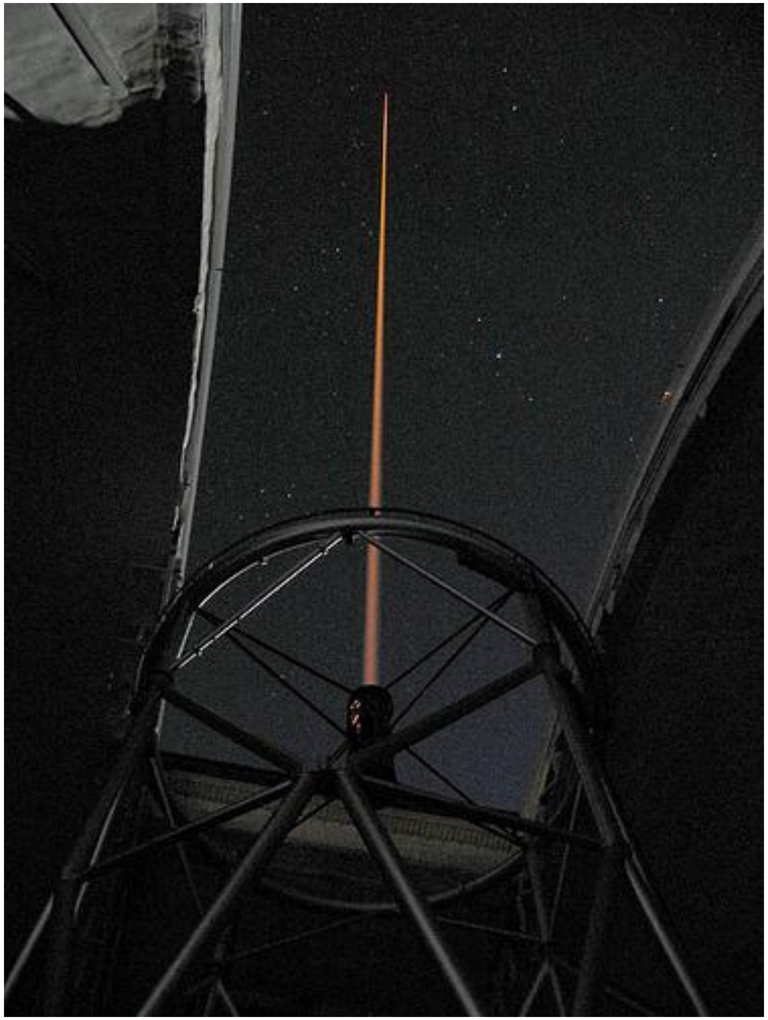
Reference Stars

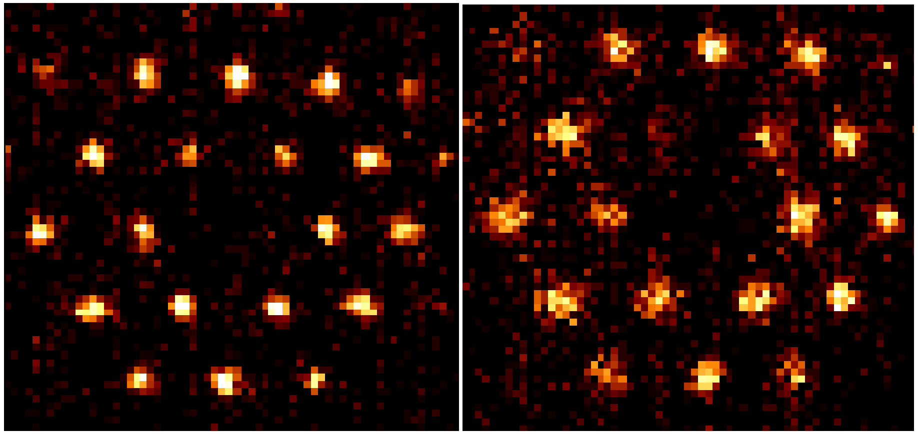
You need a reference point source (star) for the wavefront measurement. The reference star must be within the isoplanatic angle, of about 10-30 arcseconds

If there is no bright (mag ~ 14-15) nearby star then you must use an artificial star or „laser guide star“.

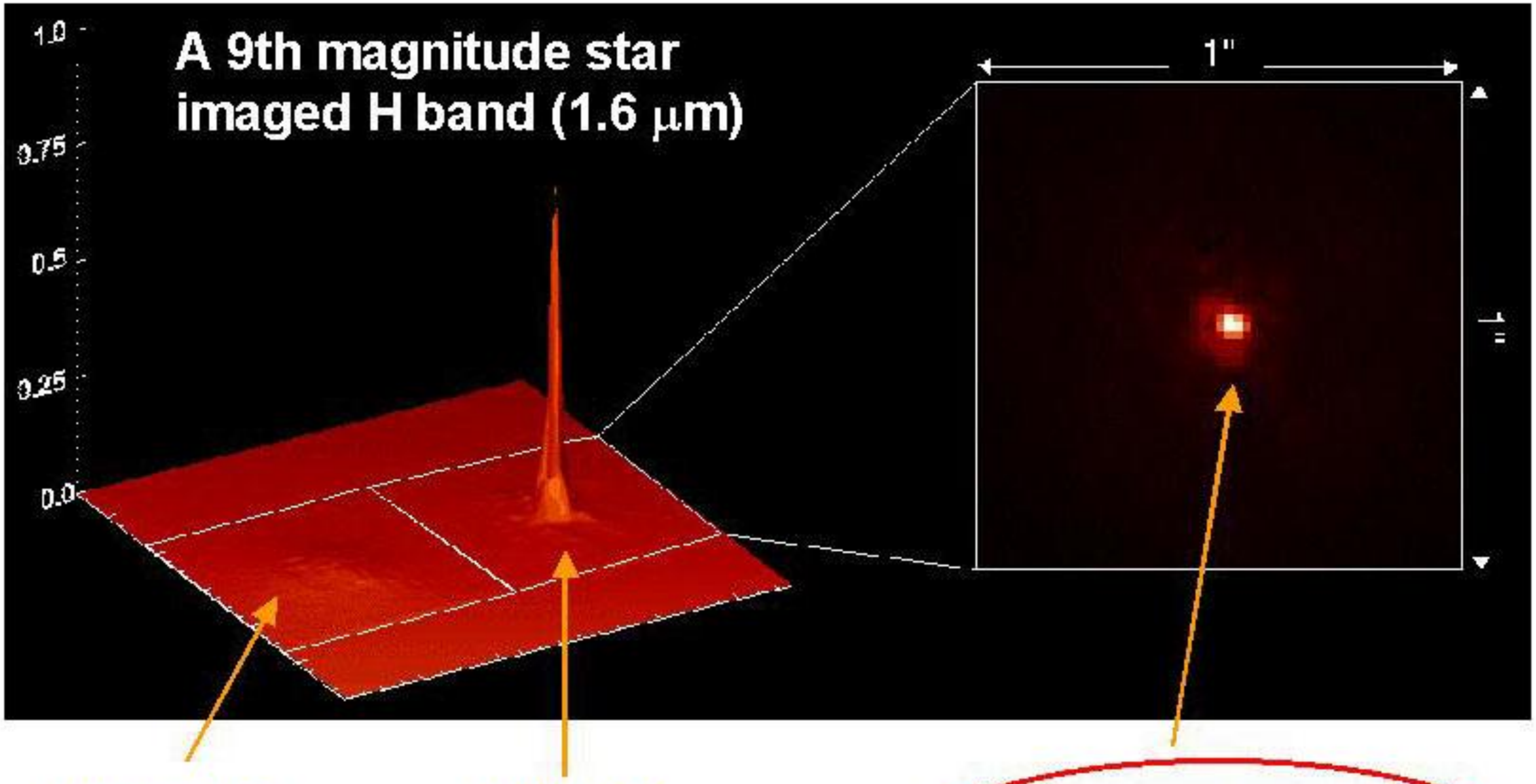
All laser guide AO systems use a sodium laser tuned to Na 5890 Å pointed to the 11.5 km thick layer of enhanced sodium at an altitude of 90 km.

Much of this research was done by the U.S. Air Force and was declassified in the early 1990s.





Images of a natural guide star (left) and the laser guide star (right) on the Shack-Hartmann sensor through the 5×5 lenslet array, and with a sampling rate of 100 Hz giving a disturbance rejection bandwidth of ~10 Hz.



Without AO
FWHM 0.34 arc sec
Strehl = 0.6%

With AO

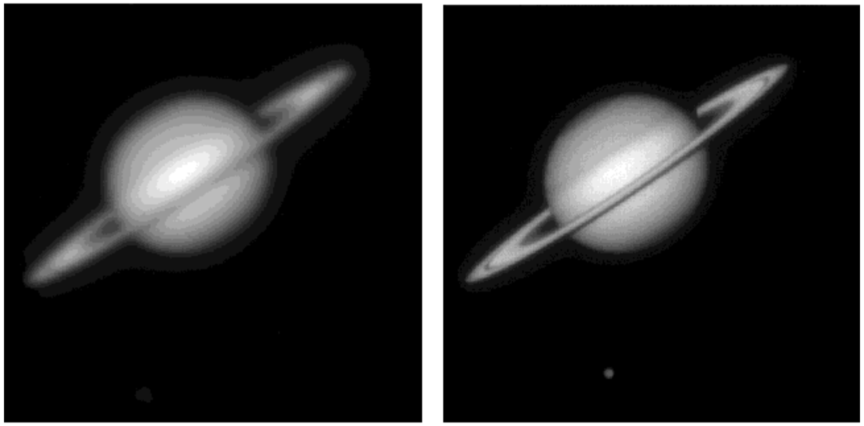
FWHM 0.04 arc sec
Strehl = 34%

Applications of Adaptive Optics

Sun, planets, stellar envelopes and dusty disks, young stellar objects, galaxies, etc. Can get 1/20 arcsecond resolution in the K band, 1/100 in the visible (eventually)

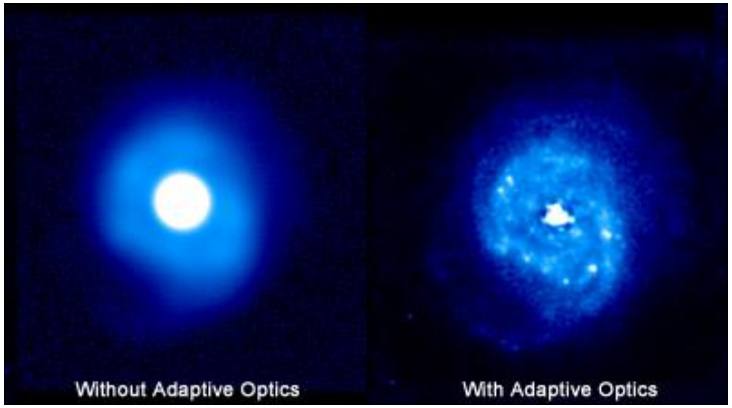
Images of Saturn and Titan

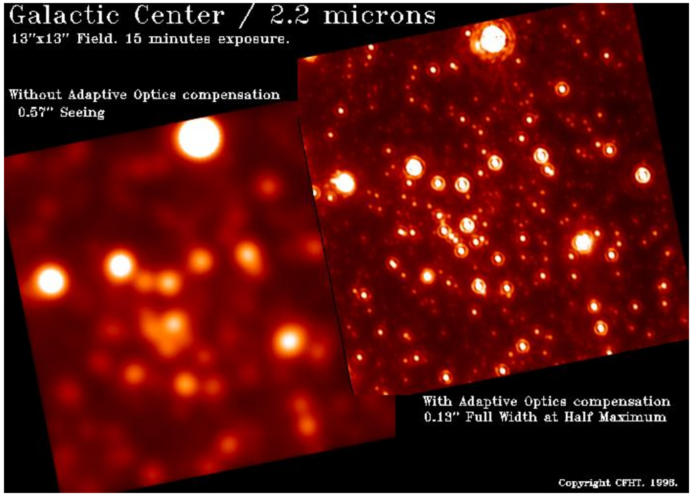
USAF Phillips Laboratory Starfire Optical Range 1.5 m telescope



No tracking, no adaptive optics

Full compensation with laser beacon adaptive optics

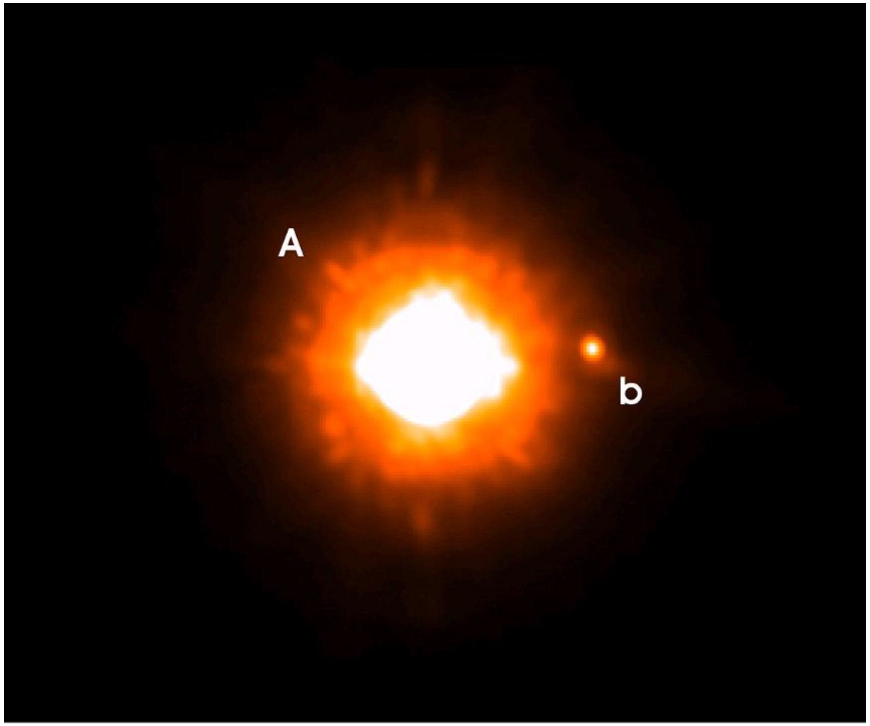




Applications of Adaptive Optics

Faint companions

The seeing disk will normally destroy the image of faint companion. Is needed to detect substellar companions (e.g. GQ Lupi)



The Sub-Stellar Companion to GQ Lupi
(NACO/VLT)

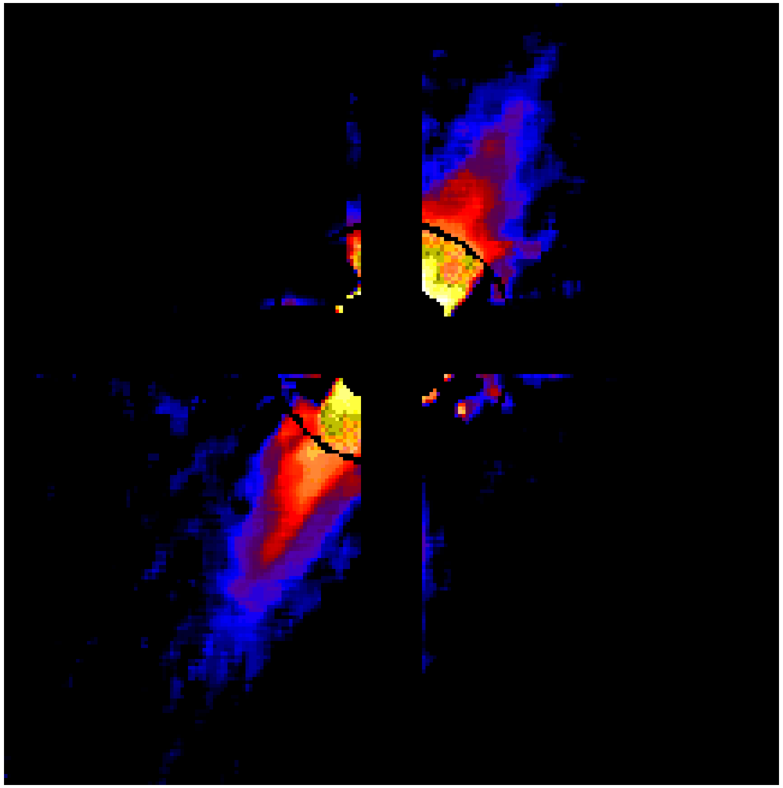
ESO PR Photo 10a/05 (7 April 2005)

© European Southern Observatory

Applications of Adaptive Optics

Coronagraphy

With a smaller image you can better block the light. Needed for planet detection



Coronagraphs

Bernard Lyot, 1939, at Pic du Midi
French Astronomer
Inventor of the Coronagraph

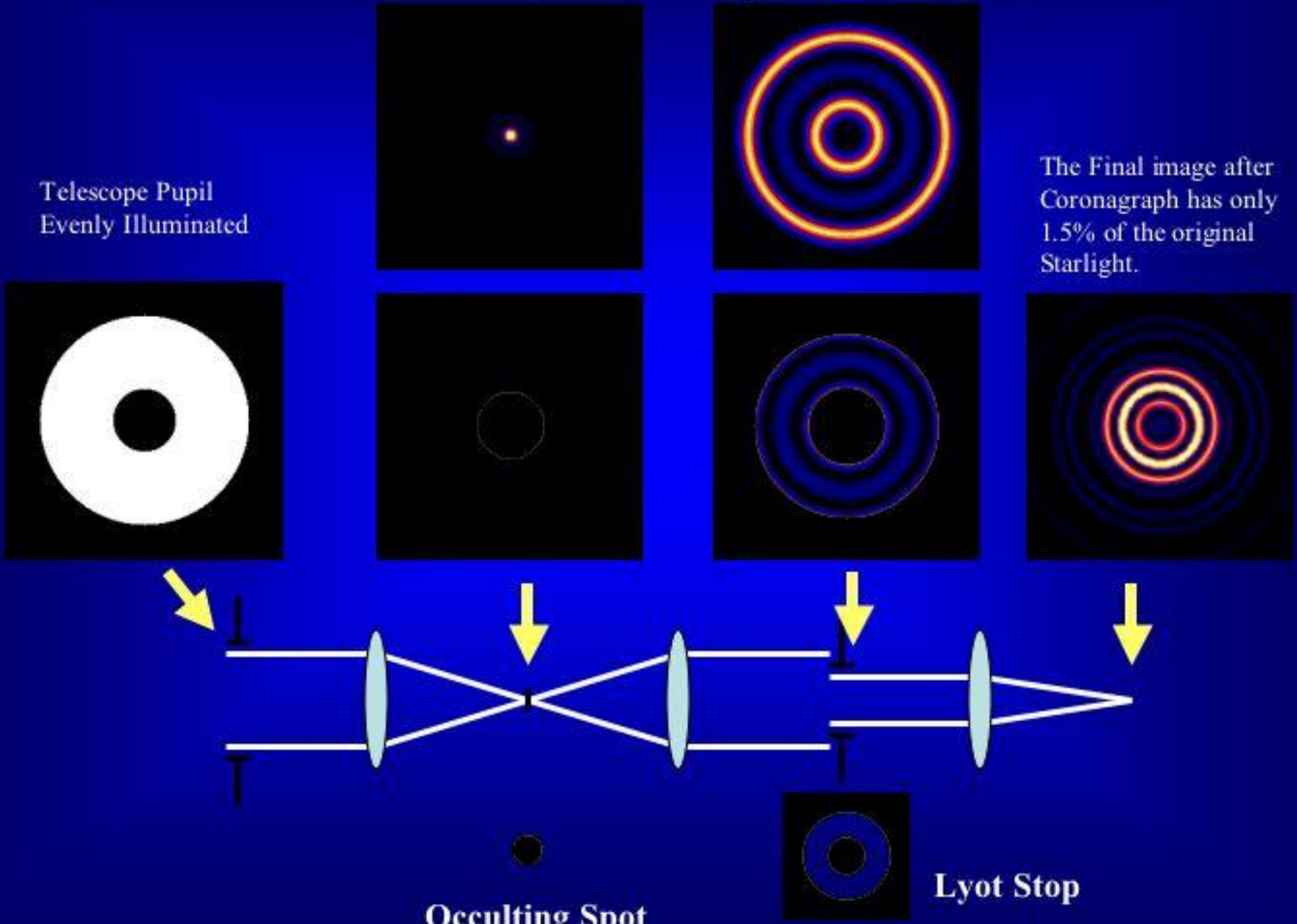


Image is made (top)
And occulted (bottom)

Pupil is reimaged (top)
And partially blocked (bottom)

Telescope Pupil
Evenly Illuminated

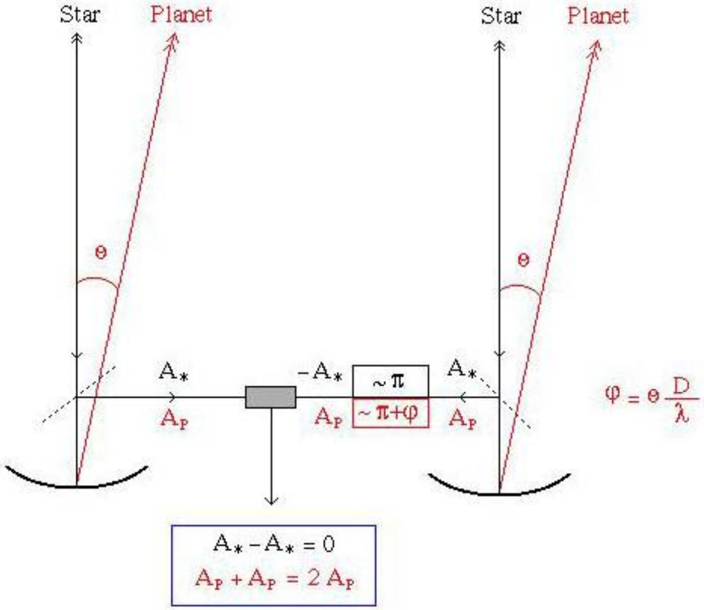
The Final image after
Coronagraph has only
1.5% of the original
Starlight.

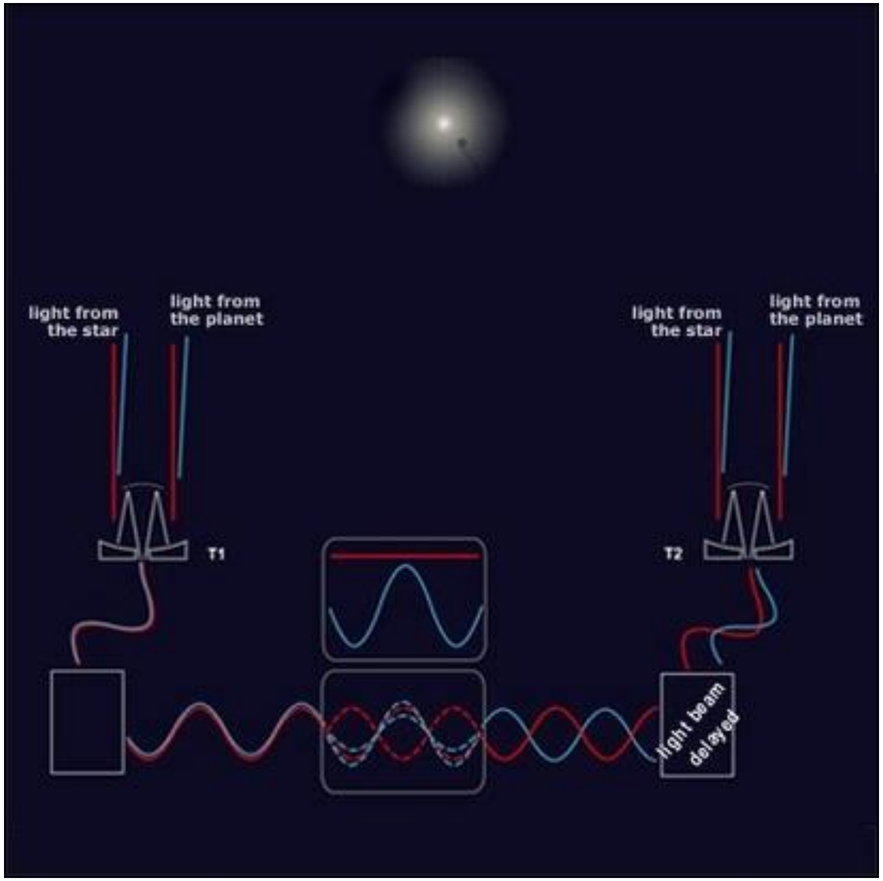
Occulting Spot

Lyot Stop

Nulling Interferometers

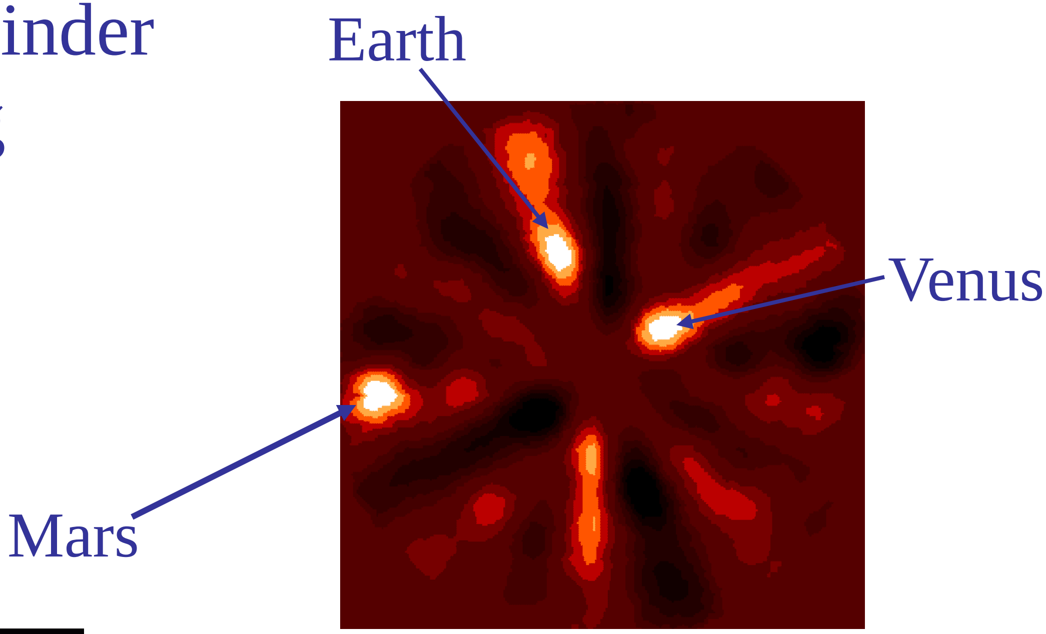
Adjusts the optical path length so that the wavefronts
from both telescope destructively interfere at the position of the star

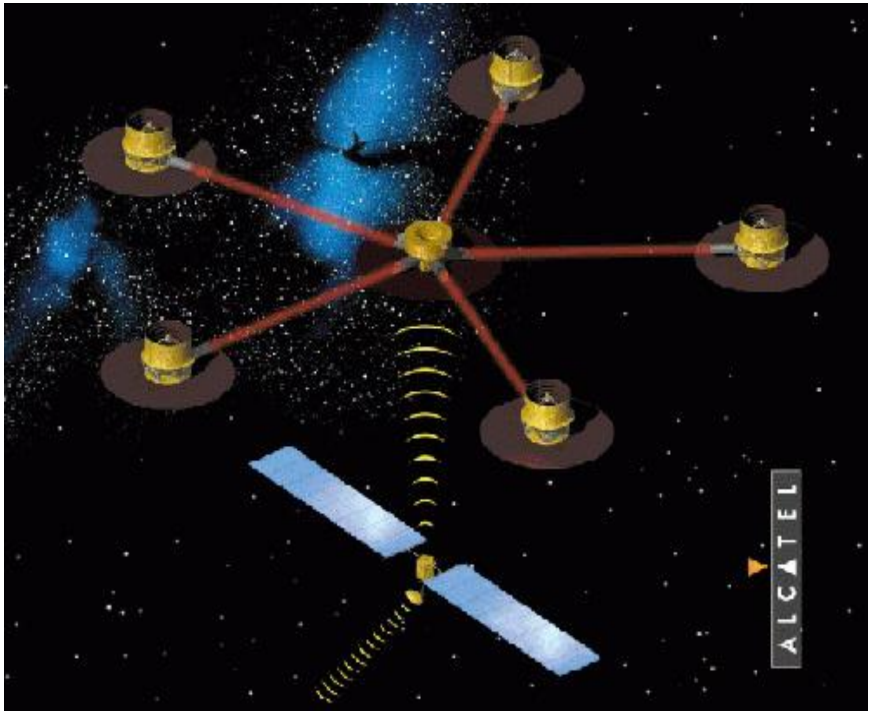




Technological challenges have
prevented nulling interferometry from
being a viable imaging method…for now

Darwin/Terrestrial Path Finder would have used Nulling Interferometry





Ground-based European Nulling Interferometer Experiment will test nulling interferometry on the VLTI