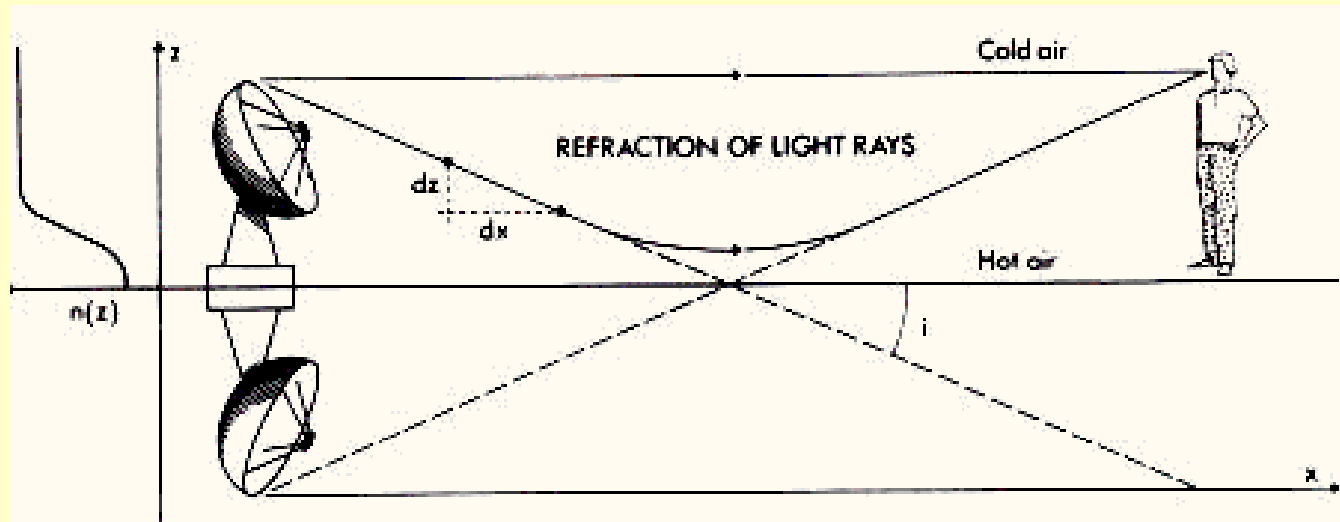


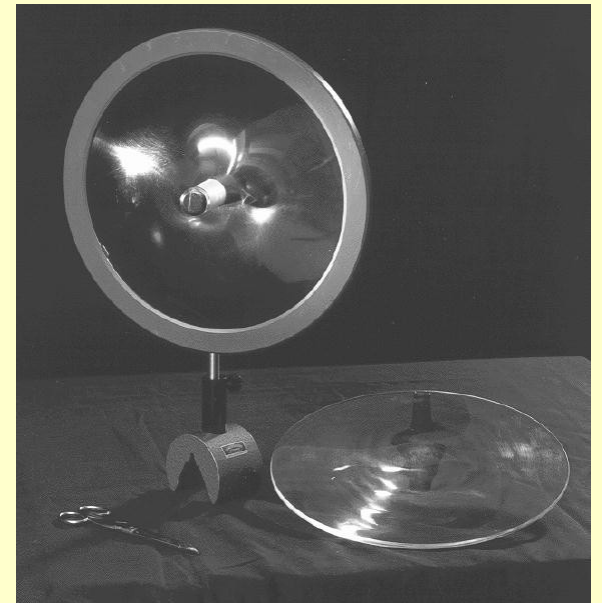
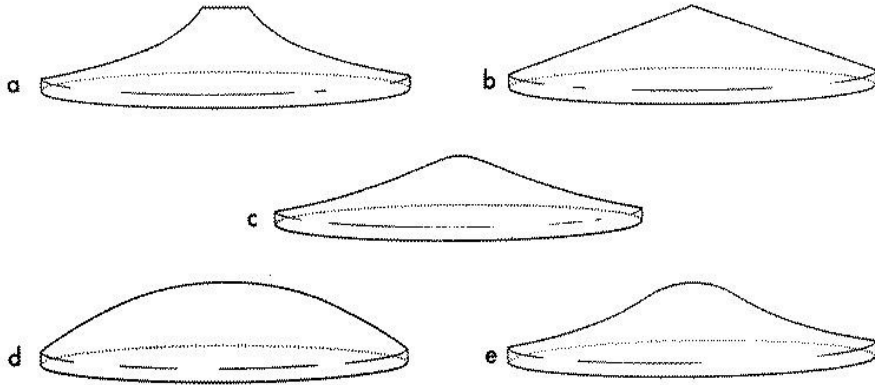
# The Finnish Graduate School in Astronomy and Space Physics Summer School 2007:

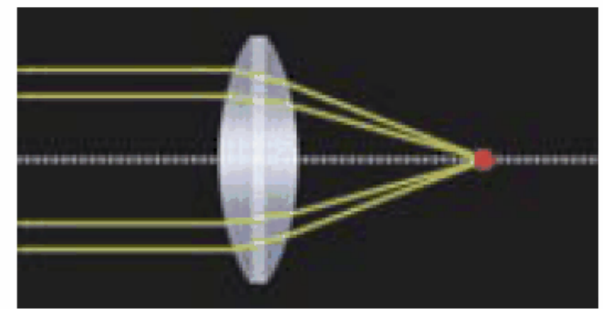
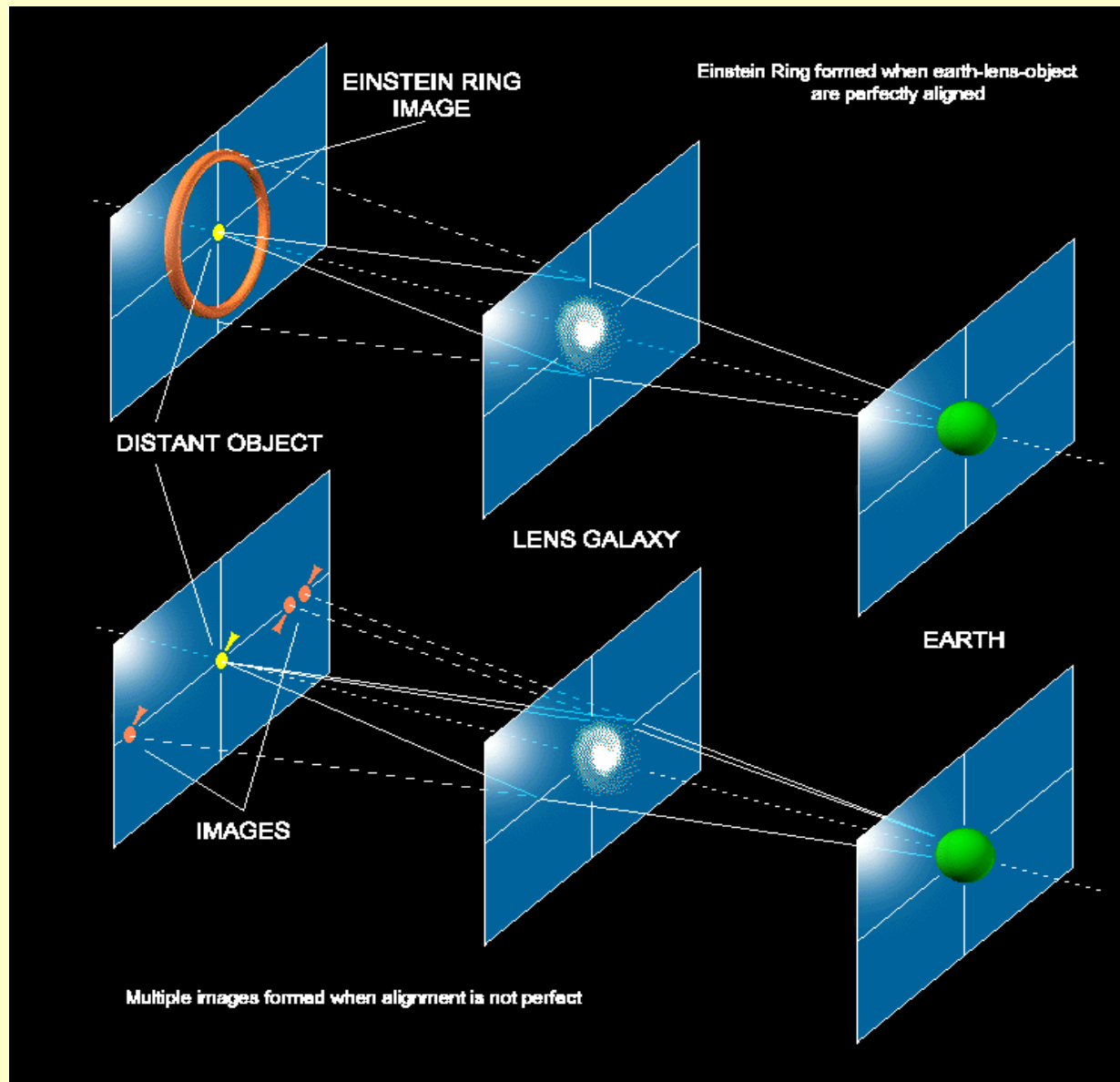
Time Series Analysis  
Part II. Motivation  
Gravitational lenses



Everyday mirages

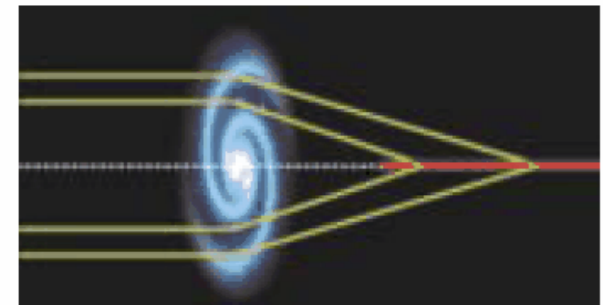
# Optical models of gravitational lenses





### CONVEX GLASS LENS

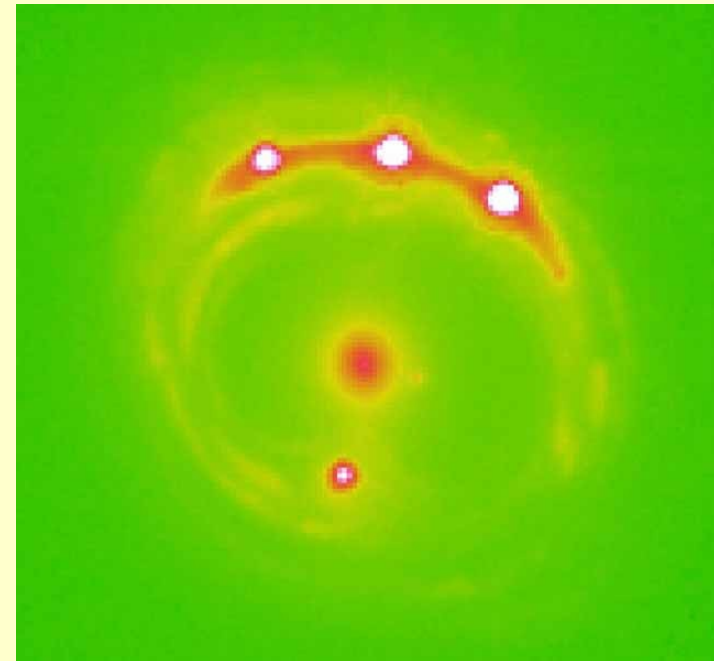
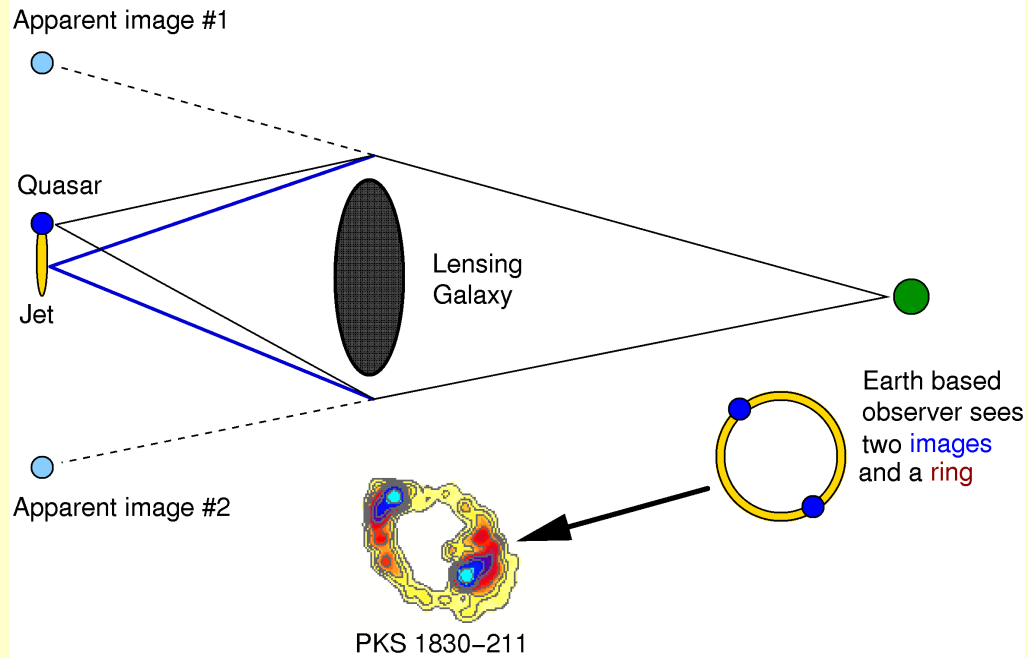
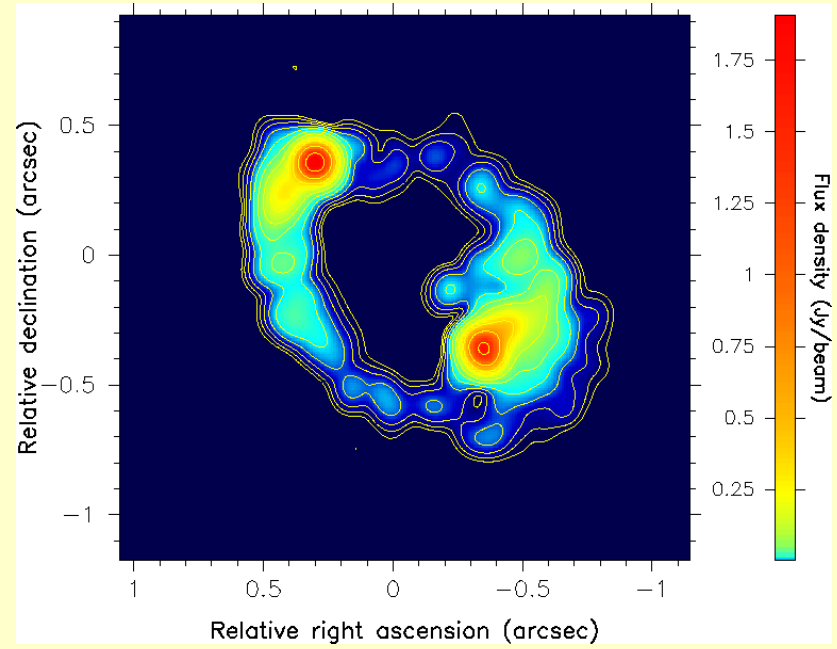
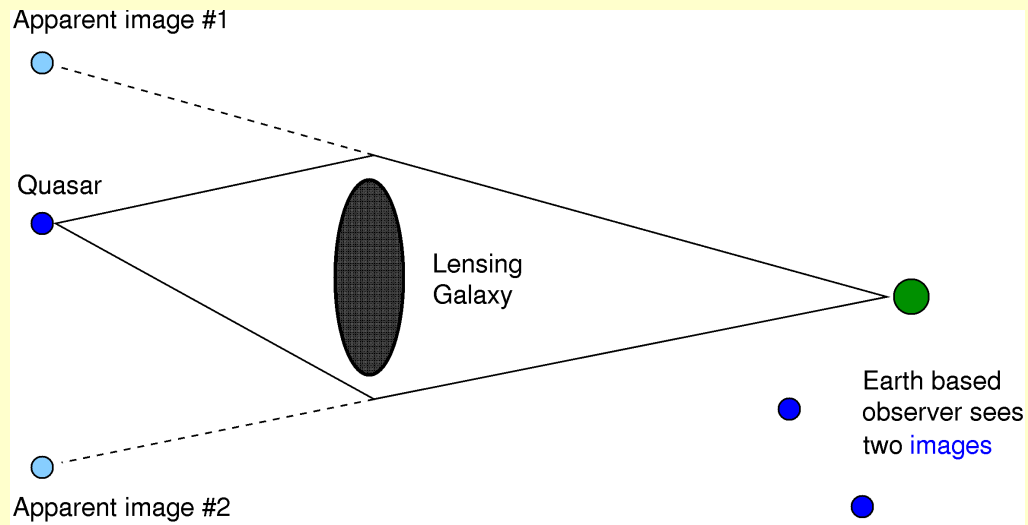
Light near the edge of a glass lens is deflected more than light near the optical axis. Thus, the lens focuses parallel light rays onto a point.



### GRAVITATIONAL LENS

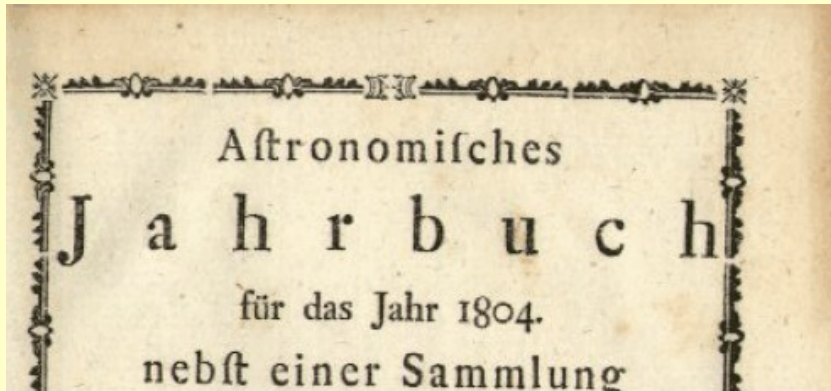
Light near the edge of a gravitational lens is deflected less than light near the center. Thus, the lens focuses light onto a line rather than a point.

# Glass and gravitational lenses



18th Century - John Michell , Laplace and Cavendish - deflection of light by a body, assuming the corpuscular theory of light and Newton's law of gravitation.

# Brief History



Wenn also ein Lichtstral an einem Weltkörper vorbeigeht, so wird er durch die Attraktion desselben genöthiget, anstatt in der geraden Richtung fortzugehen, eine Hyperbel zu beschreiben, deren konkave Seite gegen den anziehenden Körper gerichtet ist.

On the Deflection of a Light Ray from its Straight Motion due to the Attraction of a World Body which it Passes Closely (Johann Soldner 1801)

Ueber die Ablenkung eines Lichtstrals von seiner geradlinigen Bewegung, durch die Attraktion eines Weltkörpers, an welchem er nahe vorbeigeht.

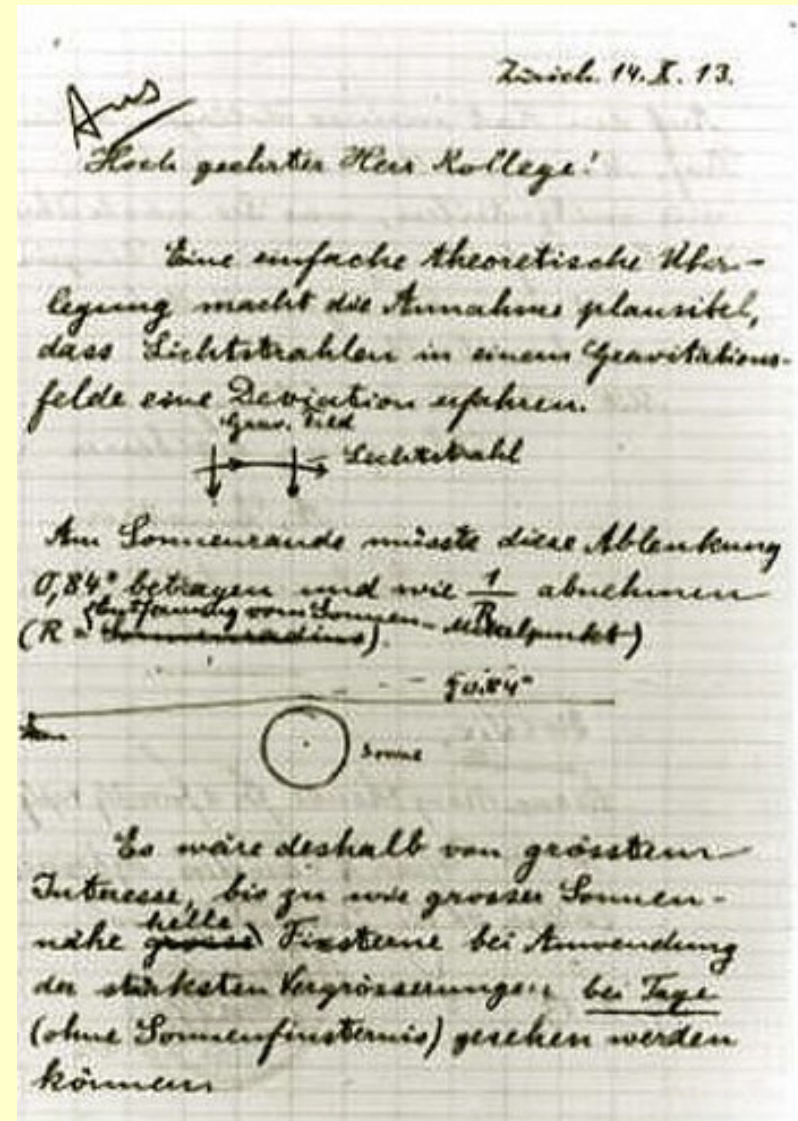
Von Hrn. *Joh. Soldner*.

Berlin, im März 1801.

0.84 arcsec

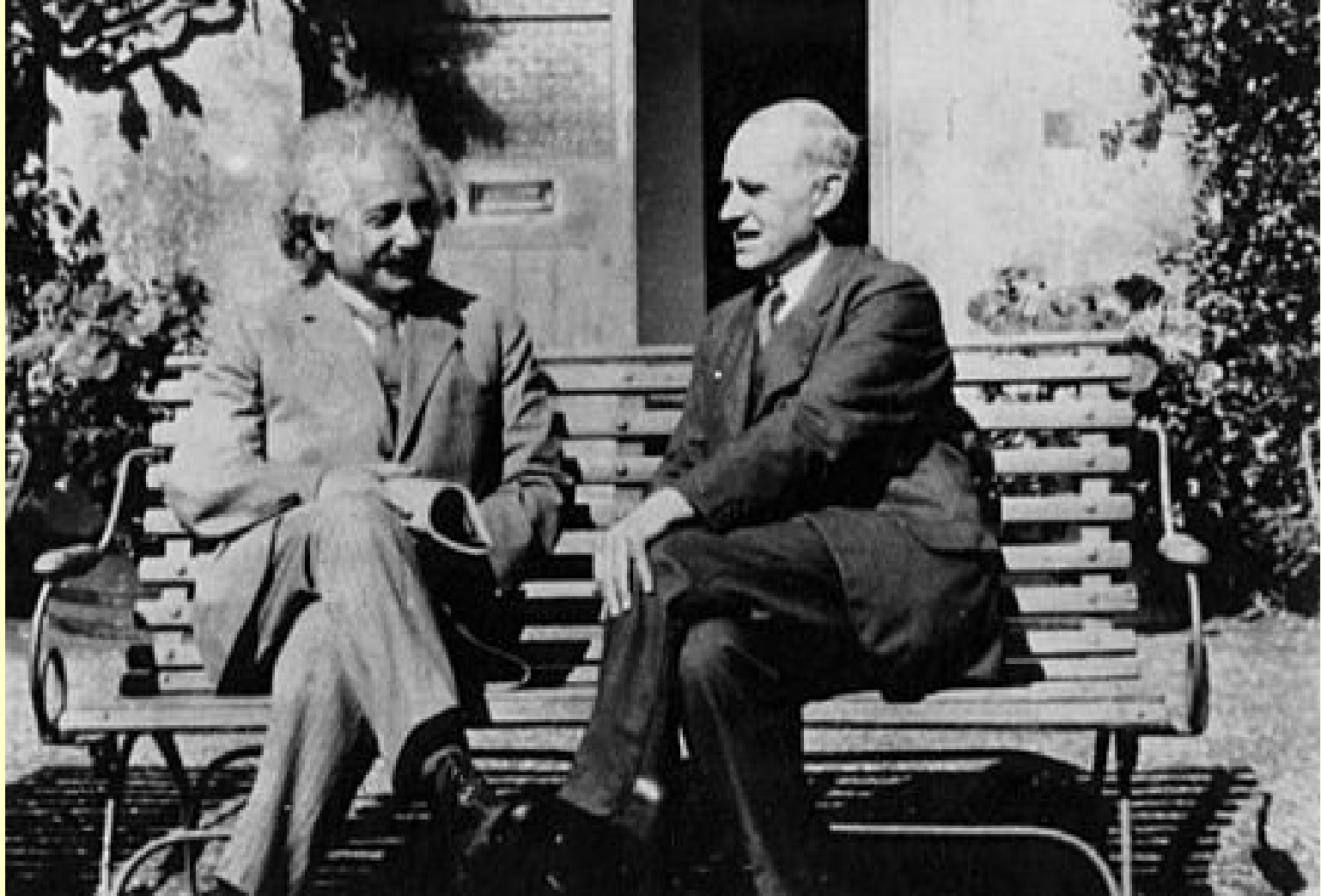


There actually were plans to test Einstein's wrong prediction of the deflection angle during a solar eclipse in 1914 on the Russian Crimea peninsula. However, when the observers were already in Russia, World War I broke out and they were **captured by Russian soldiers**. So, **fortunately for Einstein**, the measurement of the deflection angle at the solar limb had to be postponed for a few years.



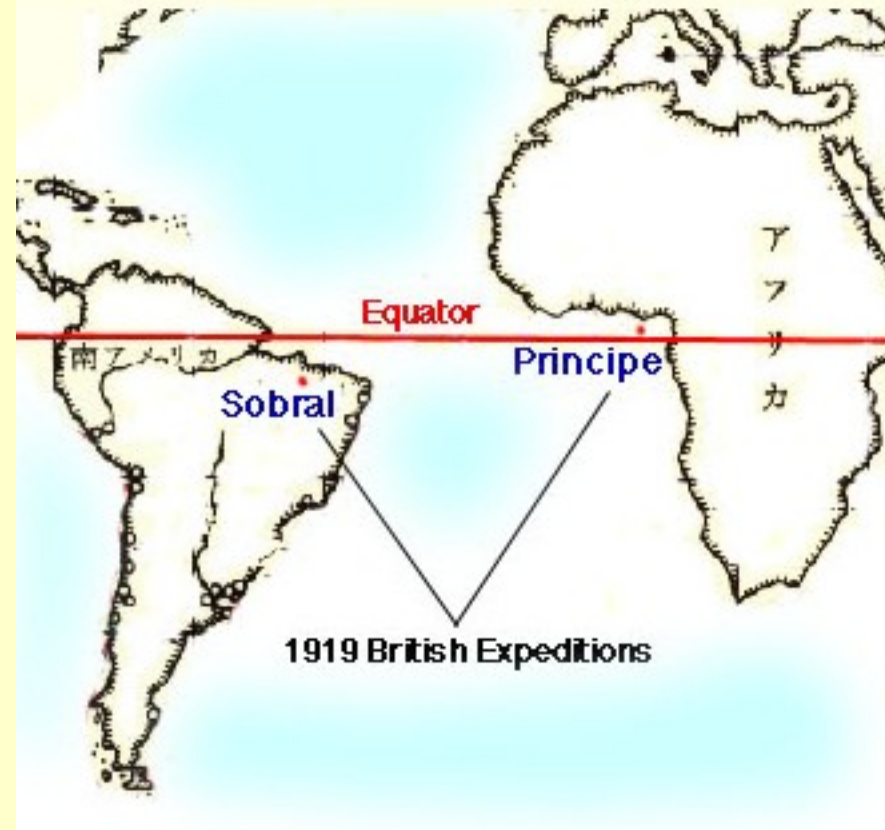
To Georg Hale 1913  
0.84 arcsec

1919 - Sir Oliver Lodge - proposal of gravitational lens,  
similar to optical.



With Arthur Eddington

## Eddington on 1919 Expeditions



In a superstitious age a natural philosopher wishing to perform an important experiment would consult an astrologer to ascertain an auspicious moment for the trial. With better reason, an astronomer today consulting the stars would announce that the most favourable day of the year for weighing light is May 29. The reason is that the sun in its annual journey round the ecliptic goes through fields of stars of varying richness, but on May 29 it is in the midst of a quite exceptional patch of bright stars---part of the Hyades---by far the best star-field encountered. ... by strange good fortune an eclipse did happen on May 29, 1919.

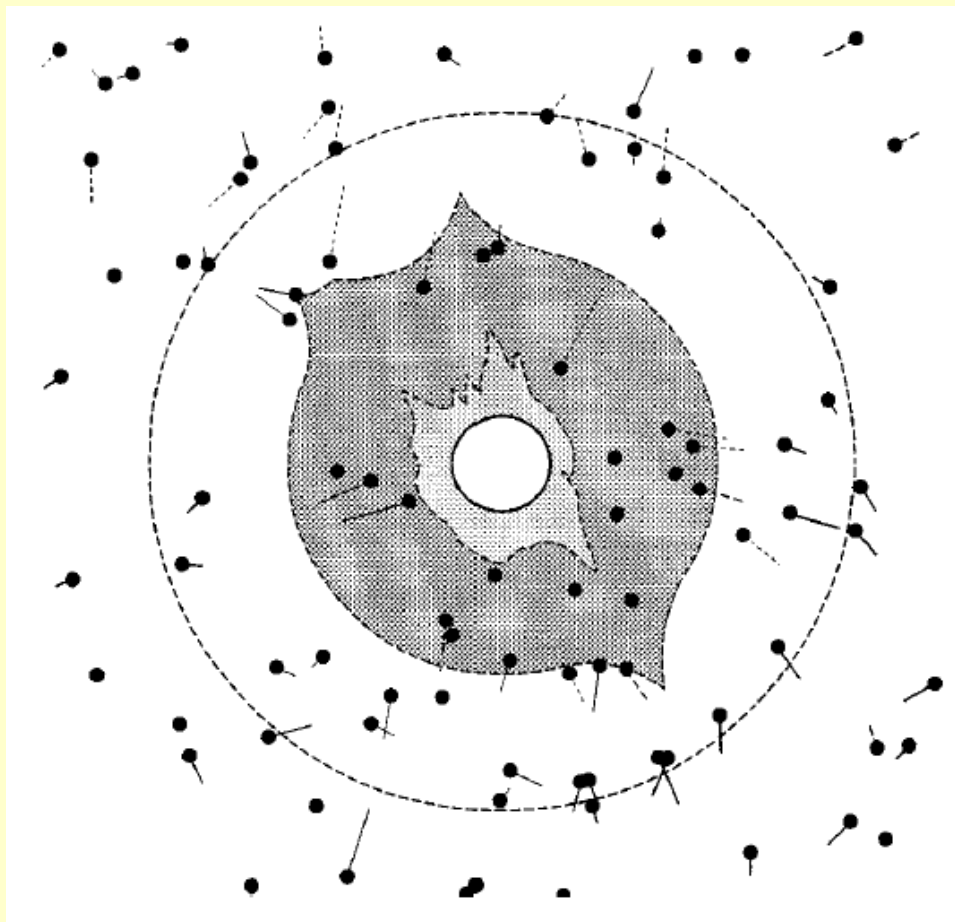


Figure 6. Changes in star positions recorded during the eclipse of 1922 and published in Campbell & Trumper (1923). The eclipsed Sun is represented by the circle in the centre of the diagram, surrounded by a representation of the coronal light. Images too close to the corona cannot be used. The recorded displacements of other stars are represented by lines (not to scale)

A few years later (1924), Chwolson pointed out that if a star, gravitational lens, and observer are in alignment, the observer will see a ring-shaped image of the star centered on the lens.

### COSMIC ILLUSION

The lensing of light by a giant galaxy can make a faraway celestial object appear closer than it really is

Quasar as far as 10 billion light years away

DISTANT OBJECT

Light rays from the quasar are deflected by gravitational distortion of space-time near a giant galaxy

LENS GALAXY

To observers on Earth, the galaxy appears to have a ring of light around it

EARTH

Chwolson-  
Einstein

or

Einstein-  
Chwolson?

Brief an Herrn Mandl.

$$\xi = \frac{\delta \Delta_0}{\Delta} = \frac{\Delta}{b} + \frac{\Delta \cdot x}{a}$$

Gleichung für  $\Delta$

$$\Delta^2 - \frac{x \cdot b}{a+b} \Delta - \frac{\xi_0 \Delta_0 a b}{a+b} = 0 \quad (\text{Wurzeln } \Delta_1 (>0) \quad \Delta_2 (<0))$$

$$\text{für } x=0 \quad \Delta = \sqrt{\frac{\xi_0 \Delta_0 a}{1+\frac{a}{b}}} \quad \text{bezeichnet } \frac{\Delta}{a} = \sqrt{\frac{\xi_0 \Delta_0}{a(1+\frac{a}{b})}}$$

$$\Delta_1 + \Delta_2 = \xi \quad \Delta_1 \Delta_2 = -A$$

$$\Delta_1 + \Delta_2 = \sqrt{\xi^2 + 4A}$$

Verhältnis der Flächen  $\frac{d(\Delta_1^2 - \Delta_2^2)}{d(x^2)}$

$$V = \left(1 + \frac{a}{b}\right) \frac{d(\Delta_1^2 - \Delta_2^2)}{d(x^2)} = \frac{d(\Delta_1^2 - \Delta_2^2)}{d(\xi^2)} = \frac{d}{d(\xi^2)} \sqrt{(\xi^2)^2 + 4A}^2$$

$$= \frac{2 \xi \xi^2 + 2A}{\xi \sqrt{\xi^2 + 4A}} = \frac{\sqrt{A}}{\xi} \frac{1 + \frac{\xi^2}{2A}}{\sqrt{1 + \frac{\xi^2}{4A}}} = \frac{\sqrt{A}}{\xi}$$

Für große  $\xi$

$$V = \frac{\sqrt{A}}{\xi} = \sqrt{\xi_0 \Delta_0 a} \frac{a+b}{b}$$



Calculations on gravitational lensing made by Einstein in 1936 as background for a letter to amateur scientist R. W. Mandl. Einstein here derives the equations published in his note of the same year. The calculations are essentially equivalent to the ones of 1912.

## DISCUSSION

### LENS-LIKE ACTION OF A STAR BY THE DEVIATION OF LIGHT IN THE GRAVITATIONAL FIELD

SOME time ago, R. W. Mandl paid me a visit and asked me to publish the results of a little calculation, which I had made at his request. This note complies with his wish.

The light coming from a star  $A$  traverses the gravitational field of another star  $B$ , whose radius is  $R_0$ . Let there be an observer at a distance  $D$  from  $B$  and at a distance  $x$ , small compared with  $D$ , from the extended central line  $\overline{AB}$ . According to the general theory of relativity, let  $\alpha_0$  be the deviation of the light ray passing the star  $B$  at a distance  $R_0$  from its center.

For the sake of simplicity, let us assume that  $\overline{AB}$  is large, compared with the distance  $D$  of the observer from the deviating star  $B$ . We also neglect the eclipse (geometrical obscuration) by the star  $B$ , which indeed is negligible in all practically important cases. To permit this,  $D$  has to be very large compared to the radius  $R_0$  of the deviating star.

It follows from the law of deviation that an observer situated exactly on the extension of the central line  $\overline{AB}$  will perceive, instead of a point-like star  $A$ , a luminous circle of the angular radius  $\beta$  around the center of  $B$ , where

$$\beta = \sqrt{\alpha_0 \frac{R_0}{D}}.$$

It should be noted that this angular diameter  $\beta$  does

not decrease like  $1/D$ , but like  $1/\sqrt{D}$ , as the distance  $D$  increases.

Of course, there is no hope of observing this phenomenon directly. First, we shall scarcely ever approach closely enough to such a central line. Second, the angle  $\beta$  will defy the resolving power of our instruments. For,  $\alpha_0$  being of the order of magnitude

of one second of arc, the angle  $R_0/D$ , under which the deviating star  $B$  is seen, is much smaller. Therefore, the light coming from the luminous circle can not be distinguished by an observer as geometrically different from that coming from the star  $B$ , but simply will manifest itself as increased apparent brightness of  $B$ .

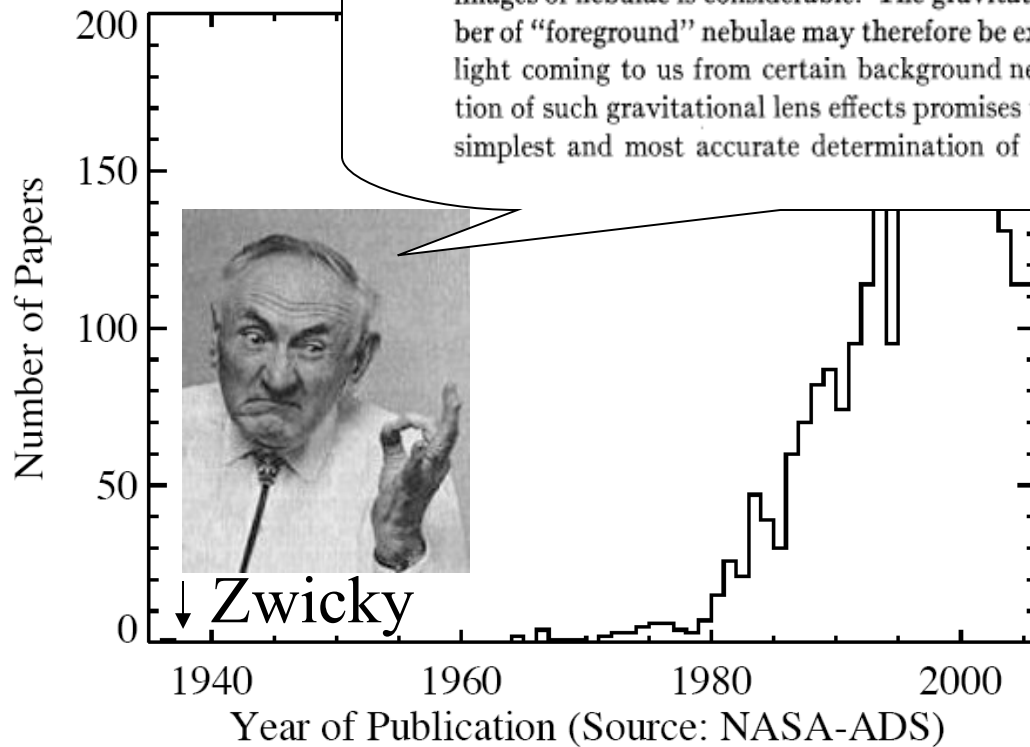
The same will happen, if the observer is situated at a small distance  $x$  from the extended central line  $\overline{AB}$ . But then the observer will see  $A$  as two point-like light-sources, which are deviated from the true geometrical position of  $A$  by the angle  $\beta$ , approximately.

The apparent brightness of  $A$  will be increased by the lens-like action of the gravitational field of  $B$  in the ratio  $q$ . This  $q$  will be considerably larger than unity only if  $x$  is so small that the observed positions of  $A$  and  $B$  coincide, within the resolving power of our instruments. Simple geometric considerations lead to the expression

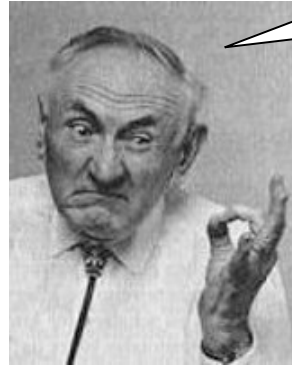
$$q = \frac{l}{x} \cdot \frac{1 + \frac{x^2}{2l^2}}{\sqrt{1 + \frac{x^2}{4l^2}}},$$

where

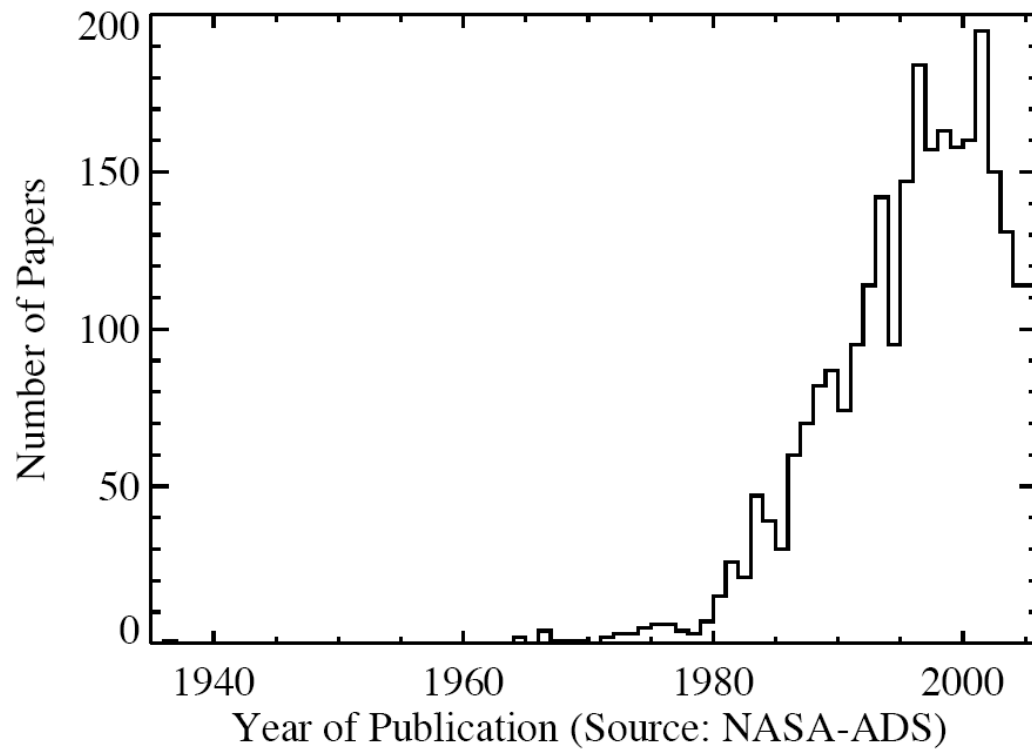
$$l = \sqrt{\alpha_0 D R_0}.$$



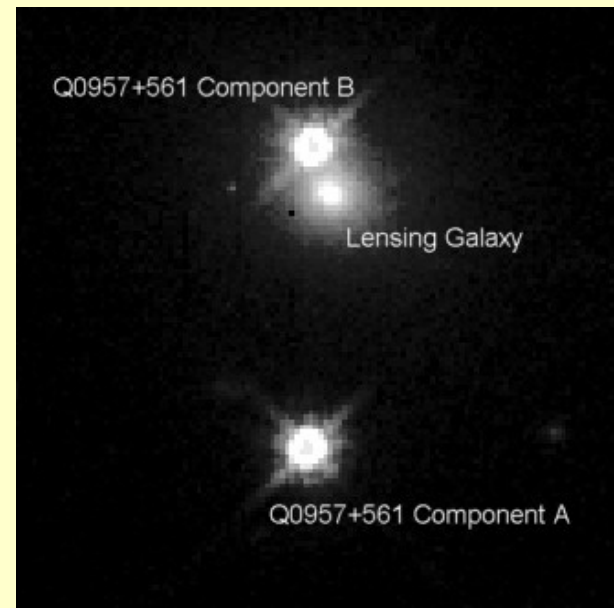
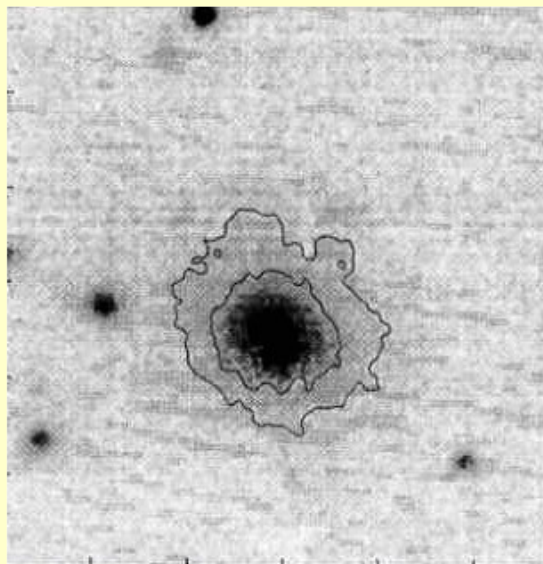
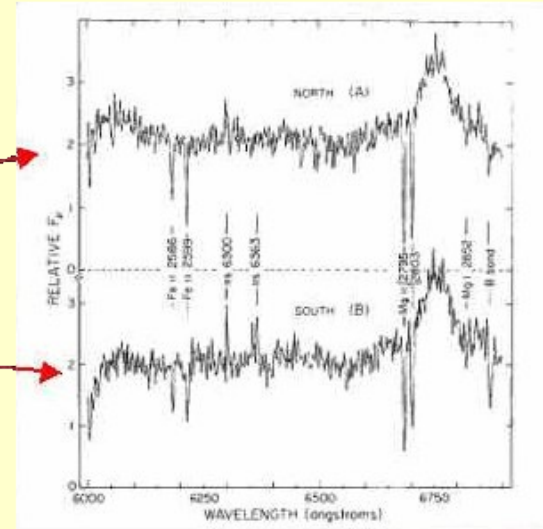
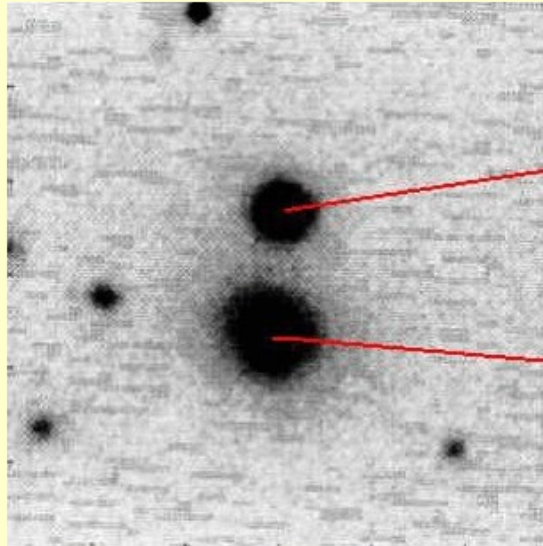
As I have shown previously,<sup>6</sup> the probability of the overlapping of images of nebulae is considerable. The gravitational fields of a number of “foreground” nebulae may therefore be expected to deflect the light coming to us from certain background nebulae. The observation of such gravitational lens effects promises to furnish us with the simplest and most accurate determination of nebular masses

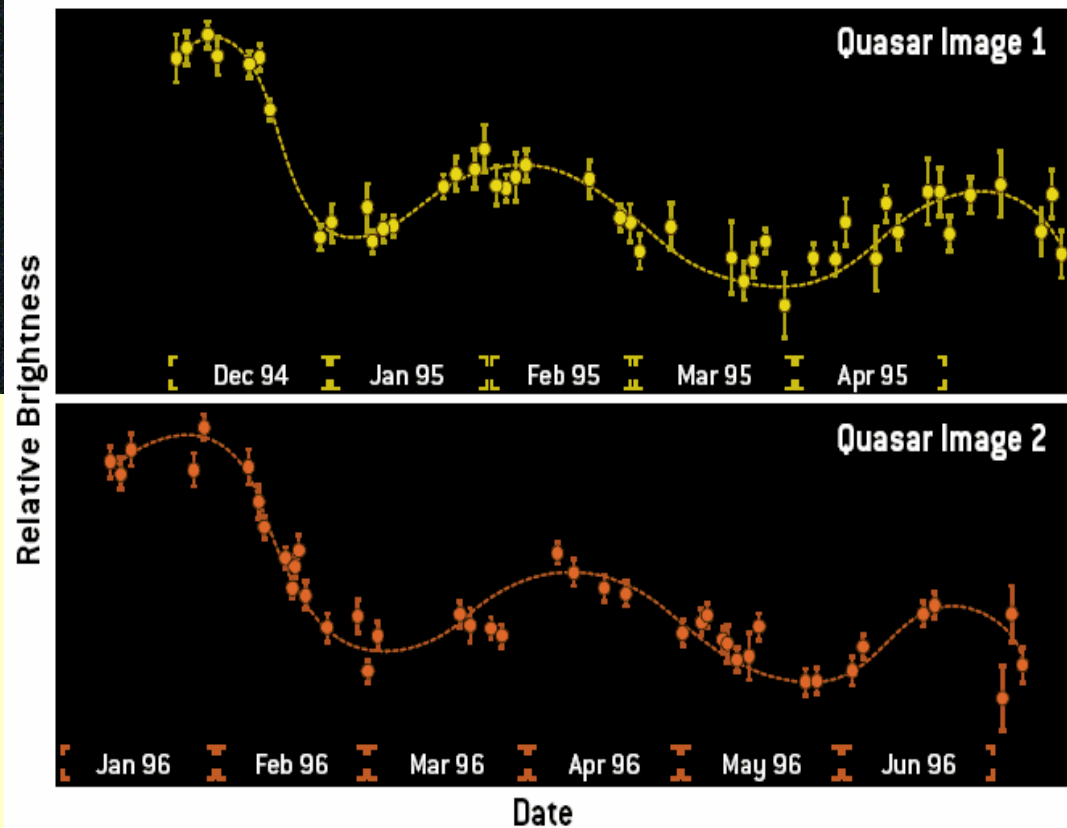
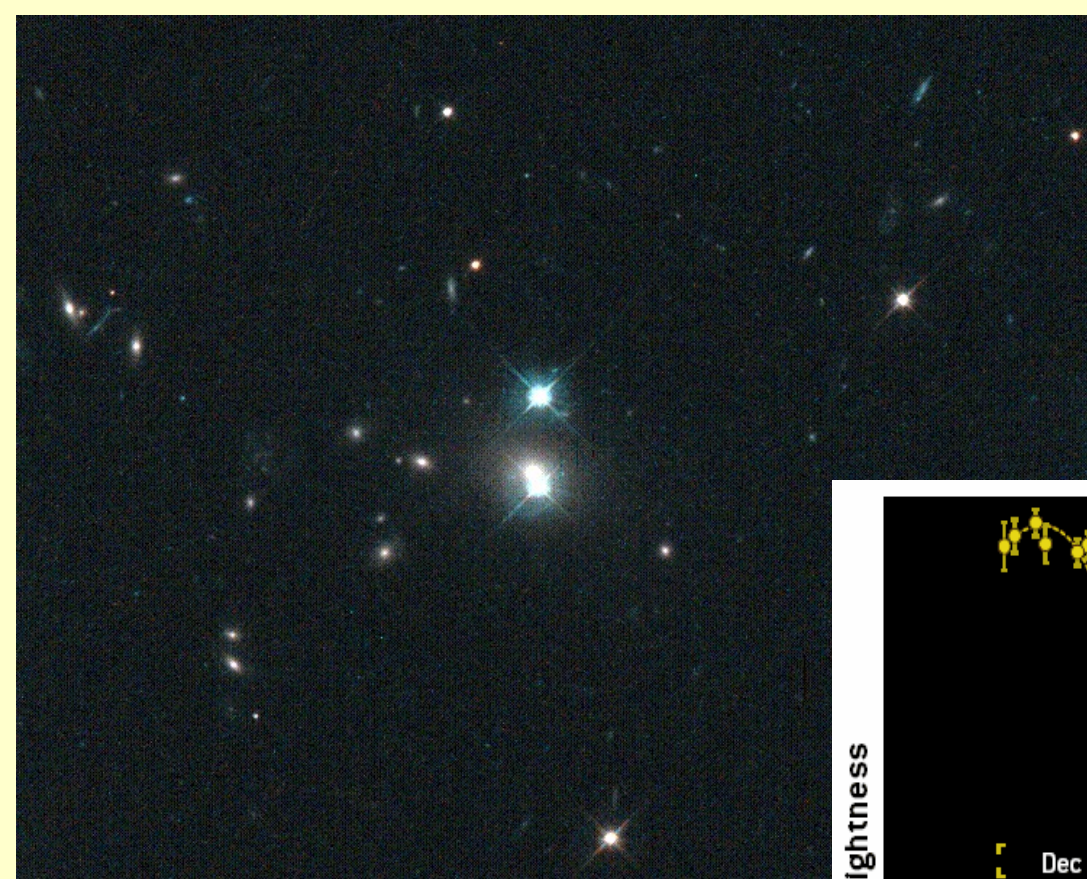


↓ Zwicky



# Q 0957+561 A, B – First observed gravitational lens system





MATCHING BRIGHTNESS VARIATIONS of the double quasar Q0957+561



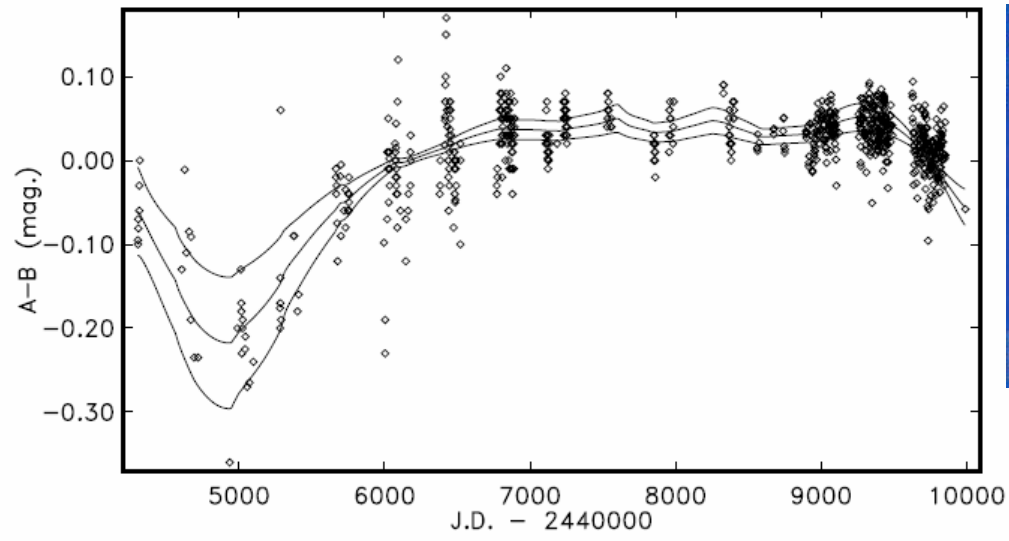


**Centre for Advanced Study**  
at the Norwegian Academy of Science and Letters

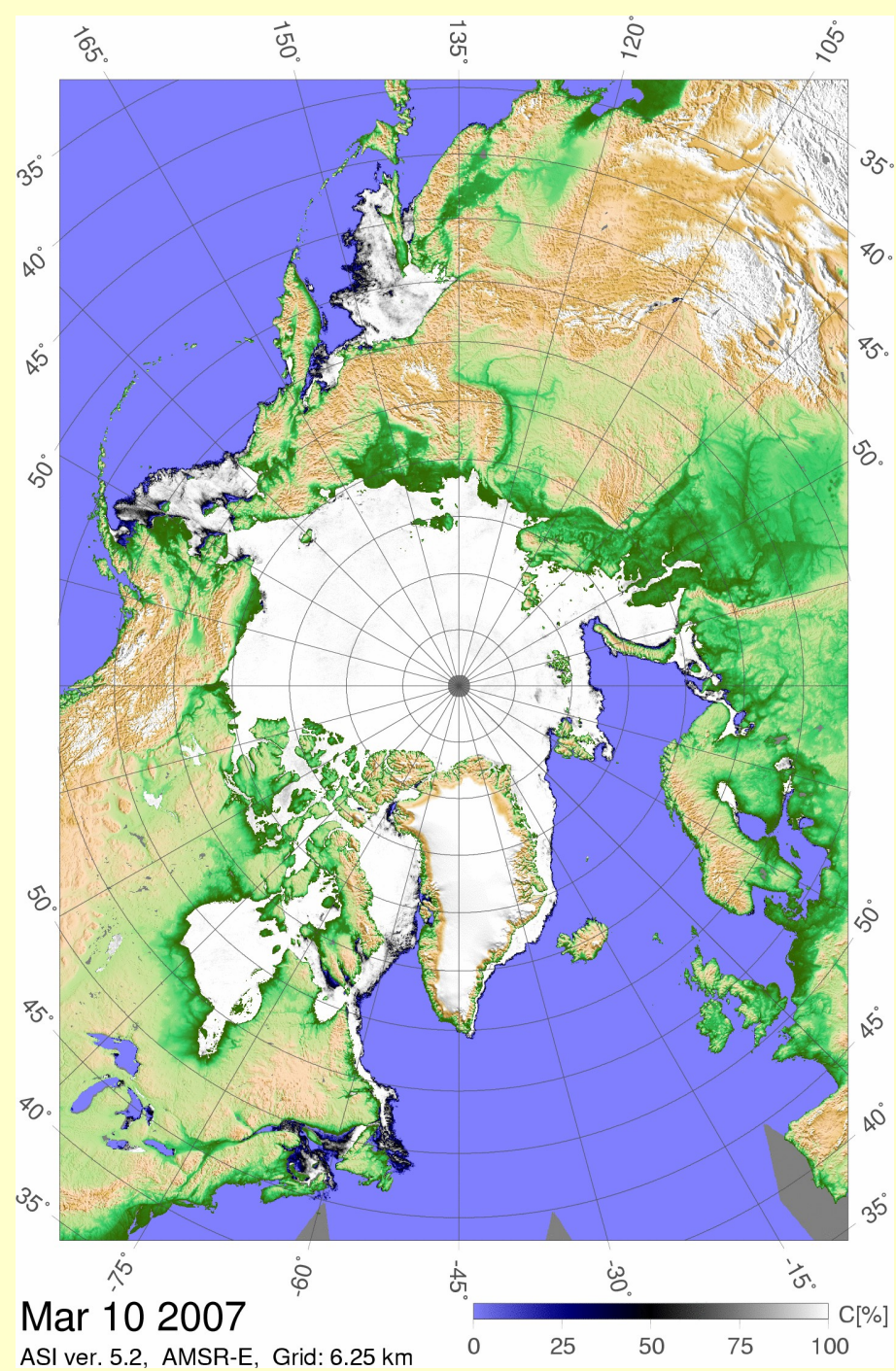


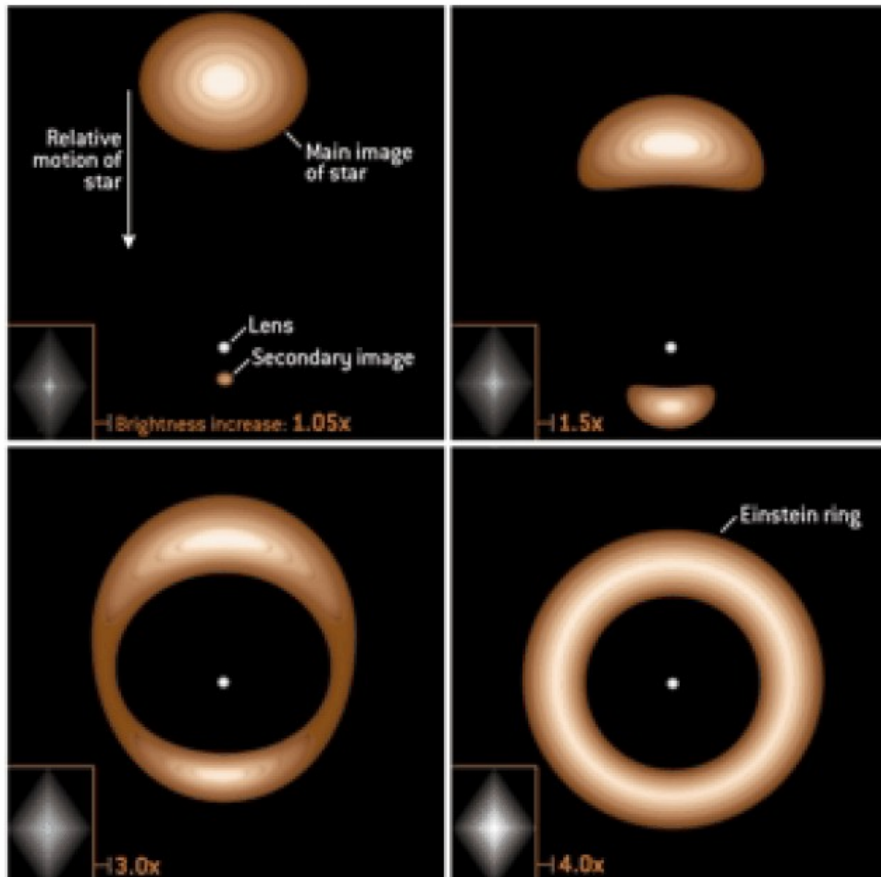
The Centre for Advanced Study (CAS) at the Norwegian Academy of Science and Letters is a basic research institution devoted to ensuring that outstanding, innovative researchers get the resources they need to make further scientific advances. In other words, CAS is intended to serve as a catalyst to enhance the quality of the Norwegian research system, to raise the standards of Norwegian basic and interdisciplinary research to the highest international level.











IF TELESCOPES HAD high enough resolution, a microlensing event would look like this. In practice, observers see only that the star got brighter.

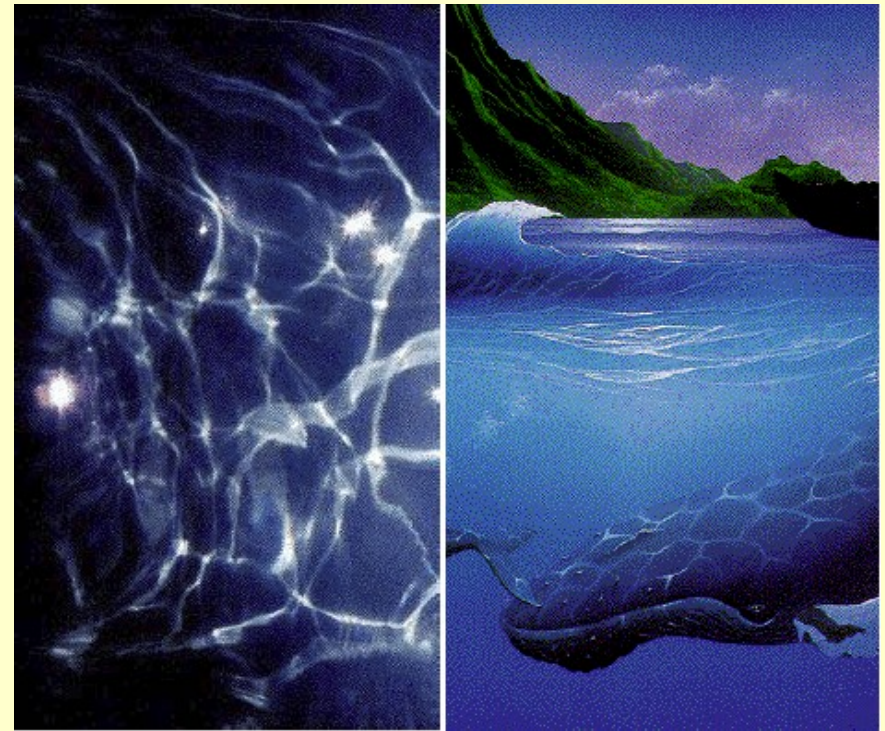
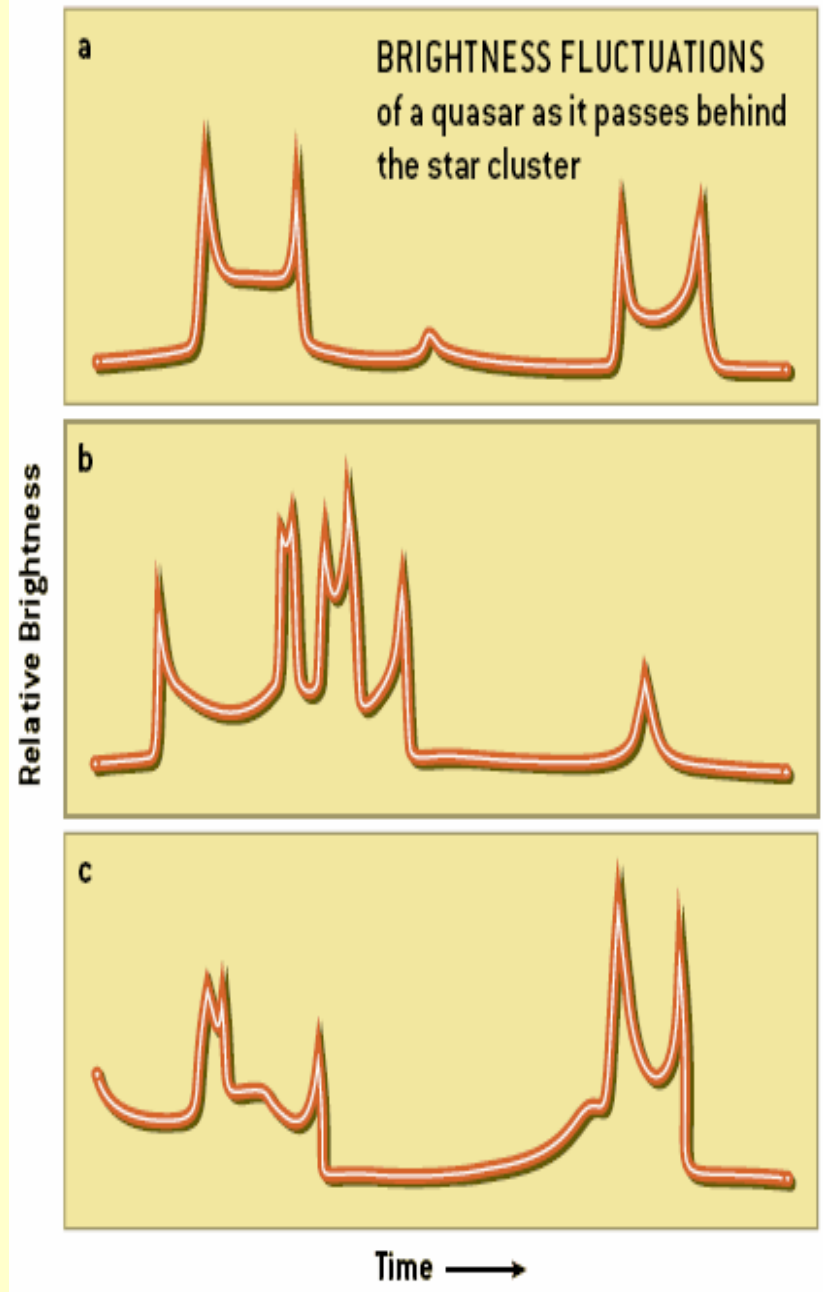
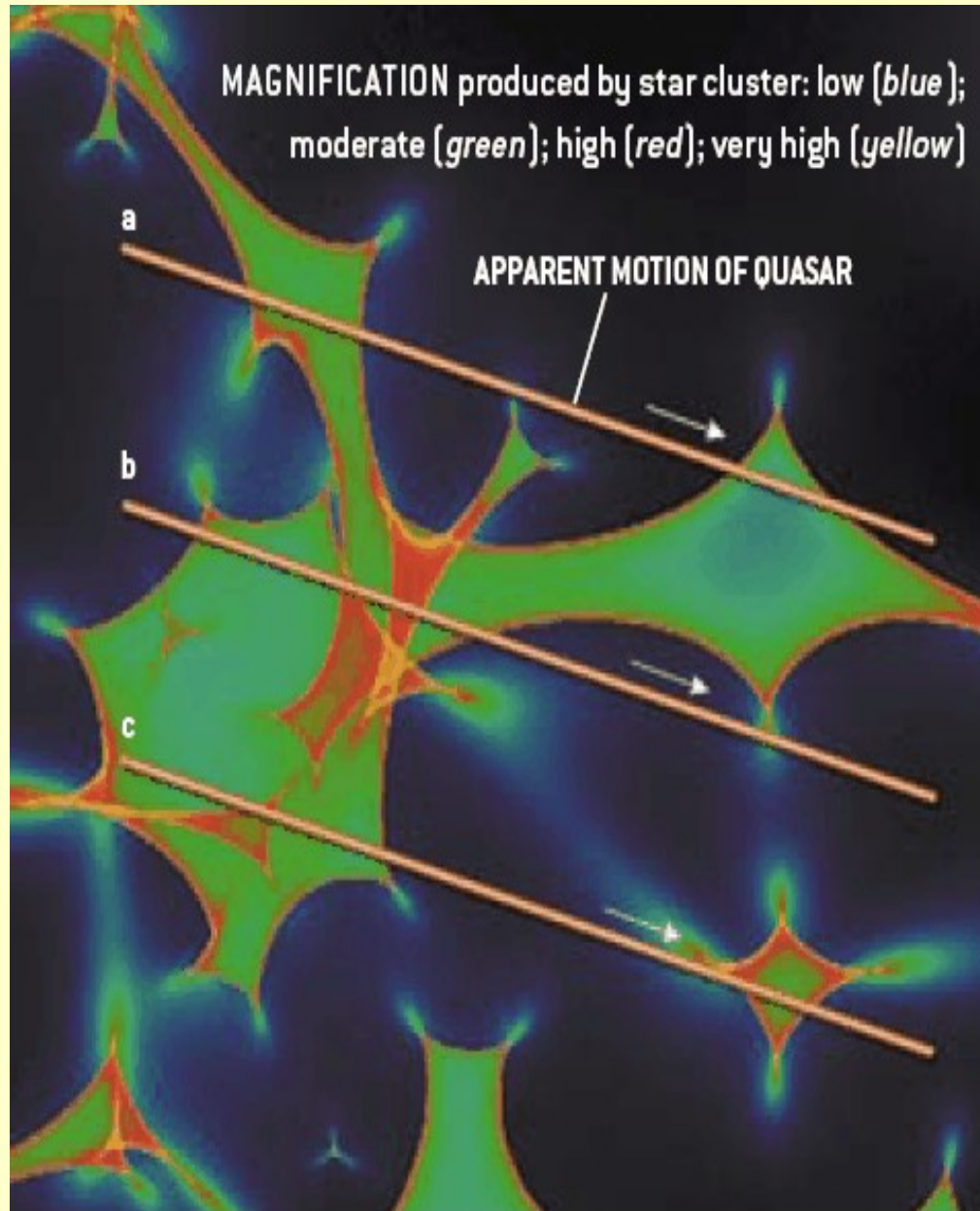


Image shifts

Splitting of images

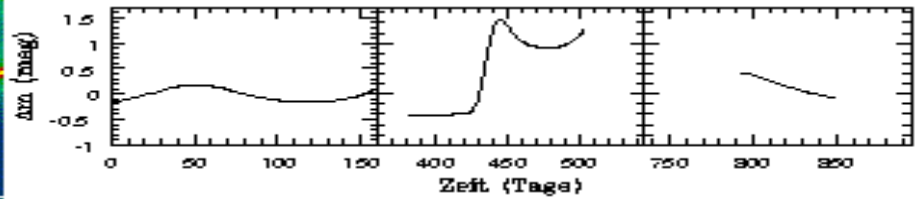
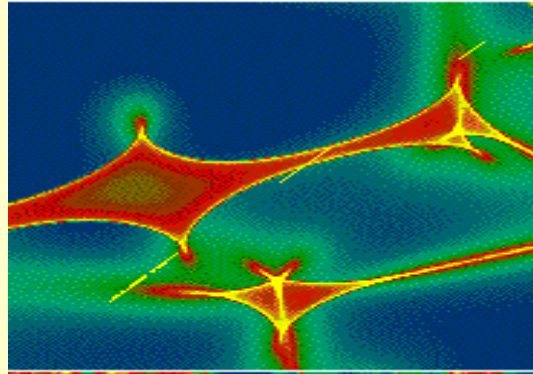
Distortions

Magnification

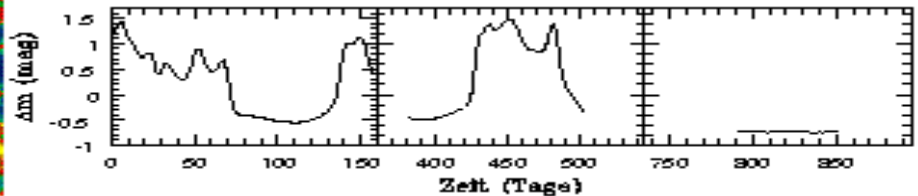
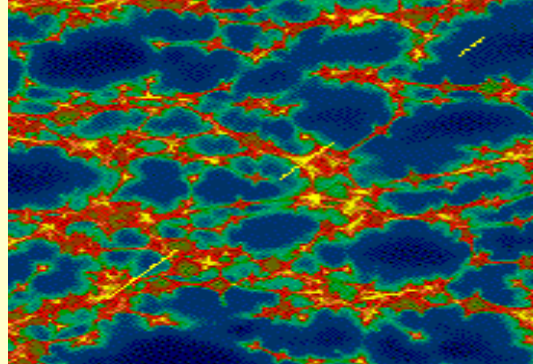


# Time series frequency content depends on masses of halo objects

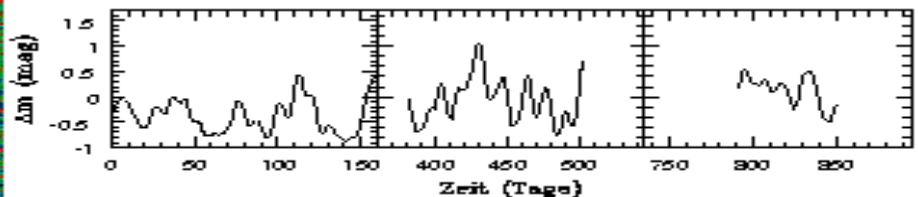
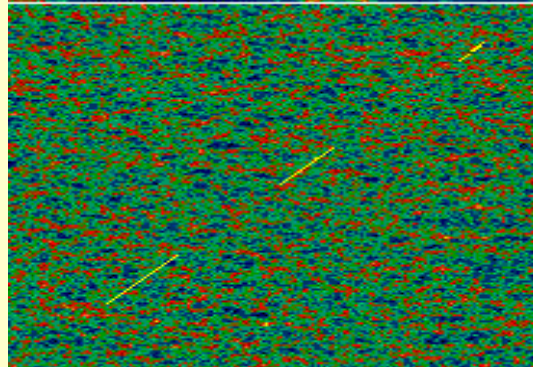
$10^{-1} M_{\odot}$



$10^{-3} M_{\odot}$



$10^{-5} M_{\odot}$



# Another system with strong microlensing : Q2237+0305

C  
A B  
D

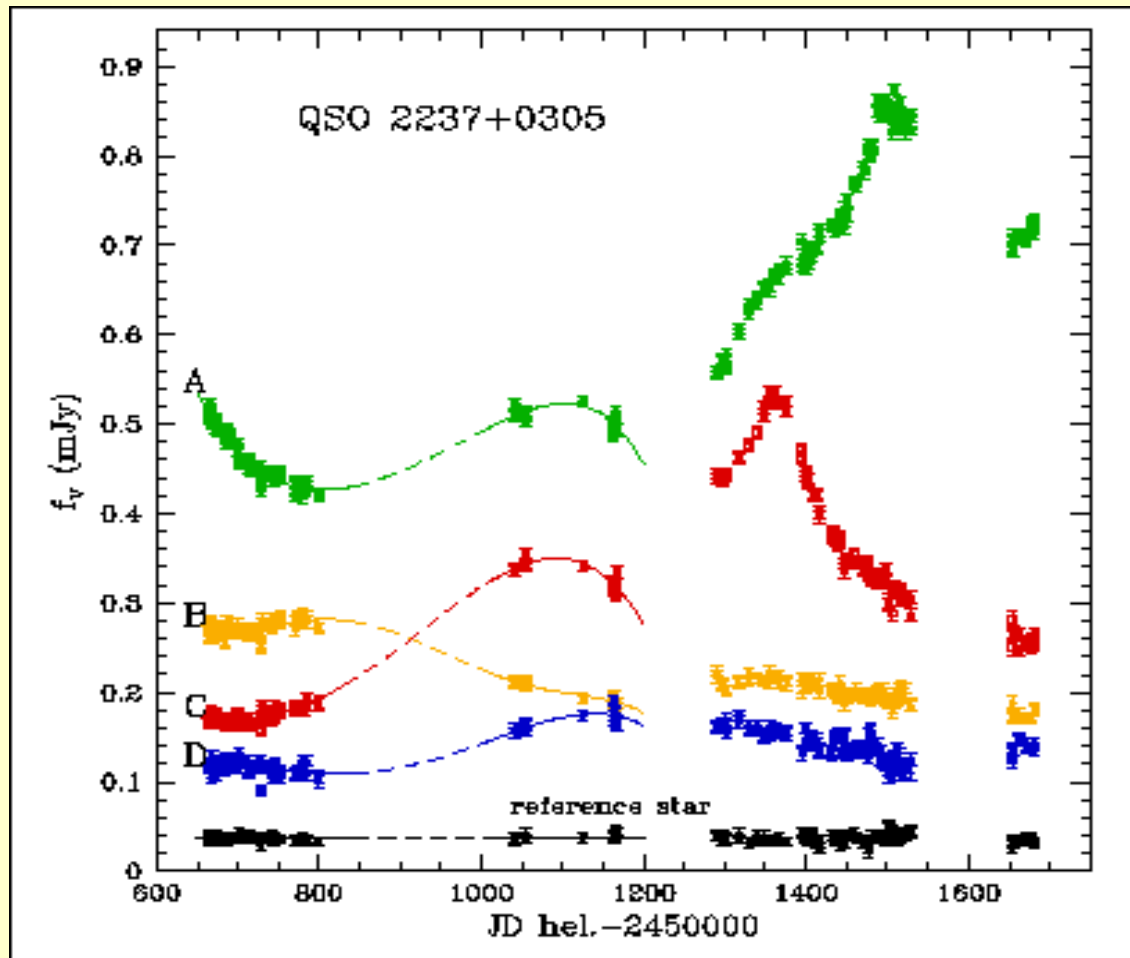
Aug 1990

Aug 1993

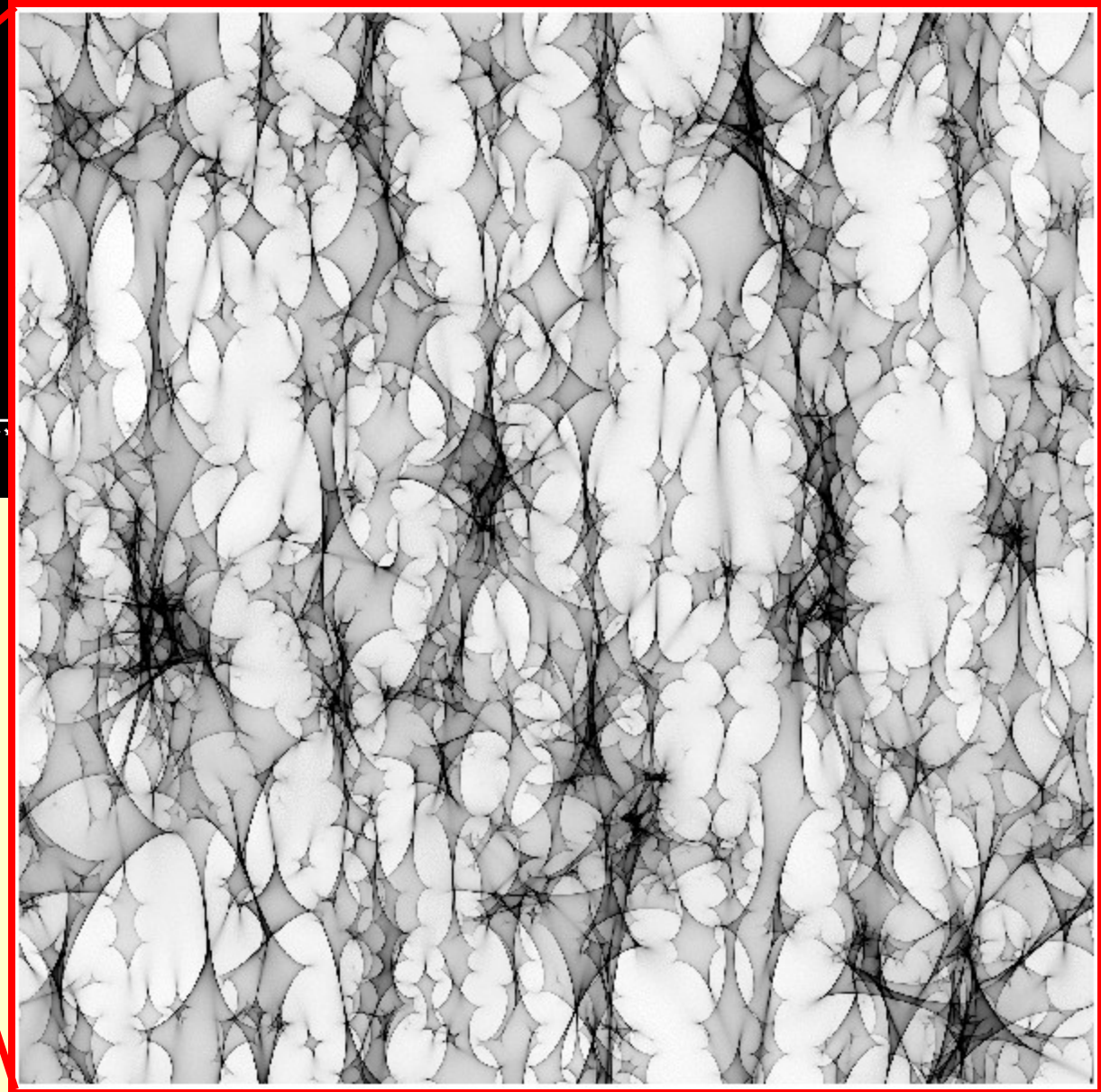
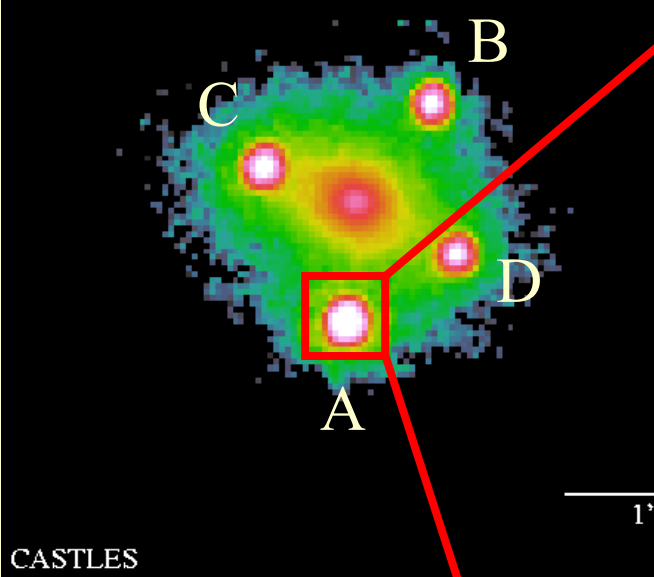
July 1994

Sept 1995

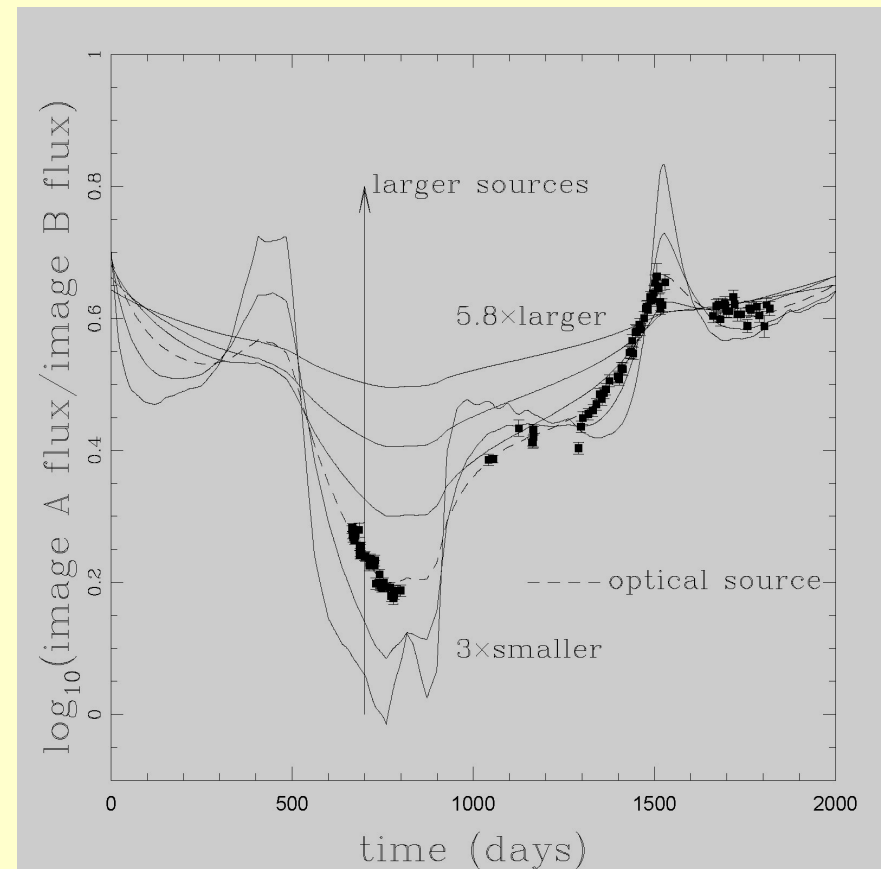
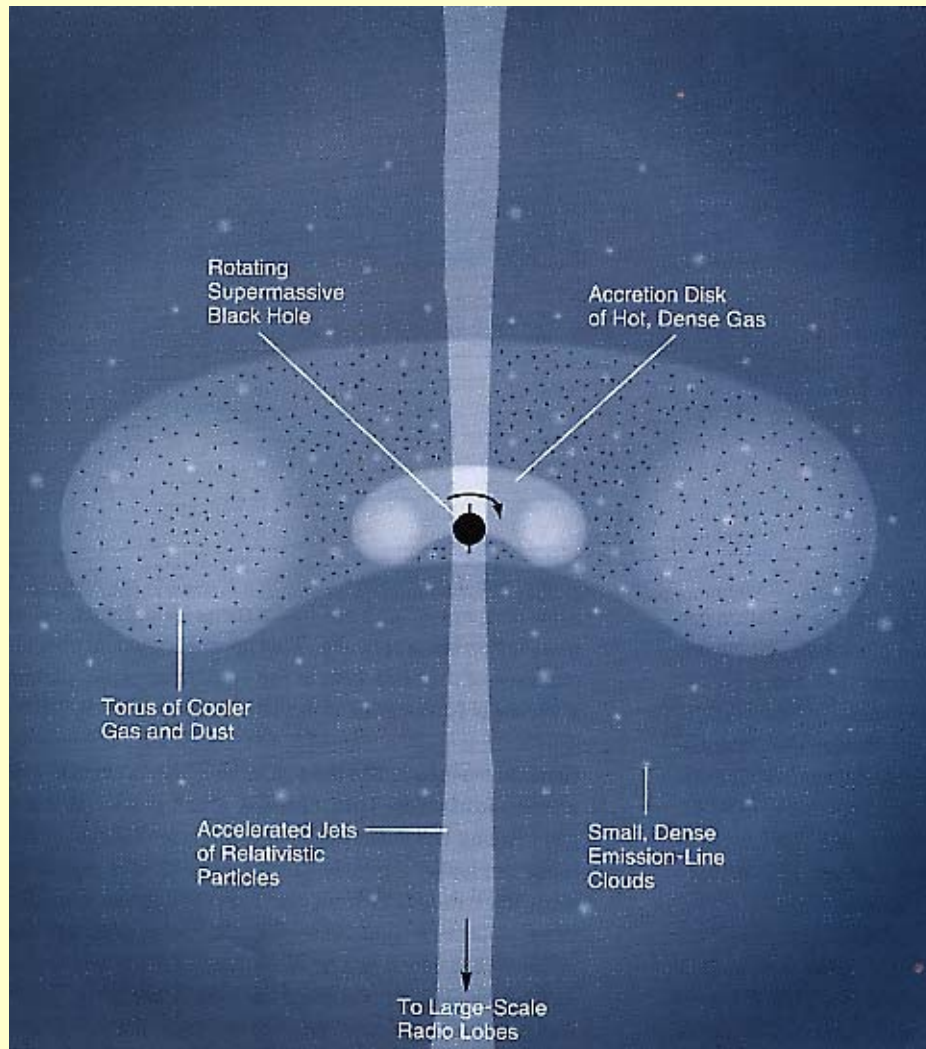
Sept 1996



# I



# Source quasar structure from microlensing?

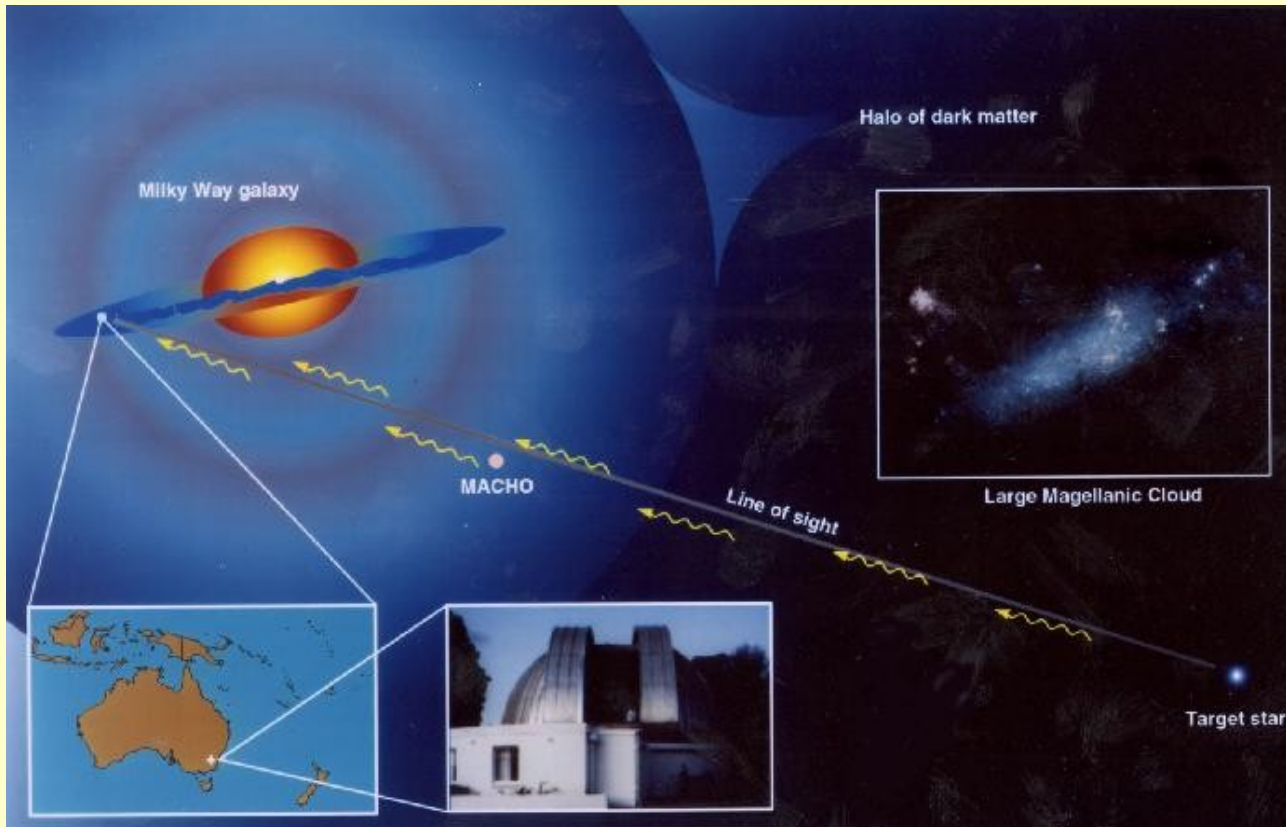


# MACHO – MASSIVE Compact Halo Object



Bohdan Paczyński

Idea in 1985-1986

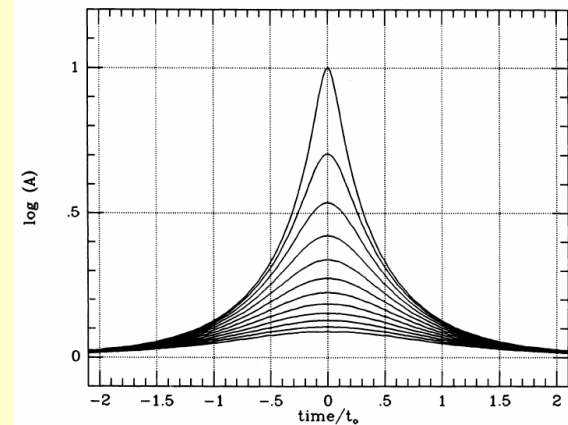


## GRAVITATIONAL MICROLENSING BY THE GALACTIC HALO

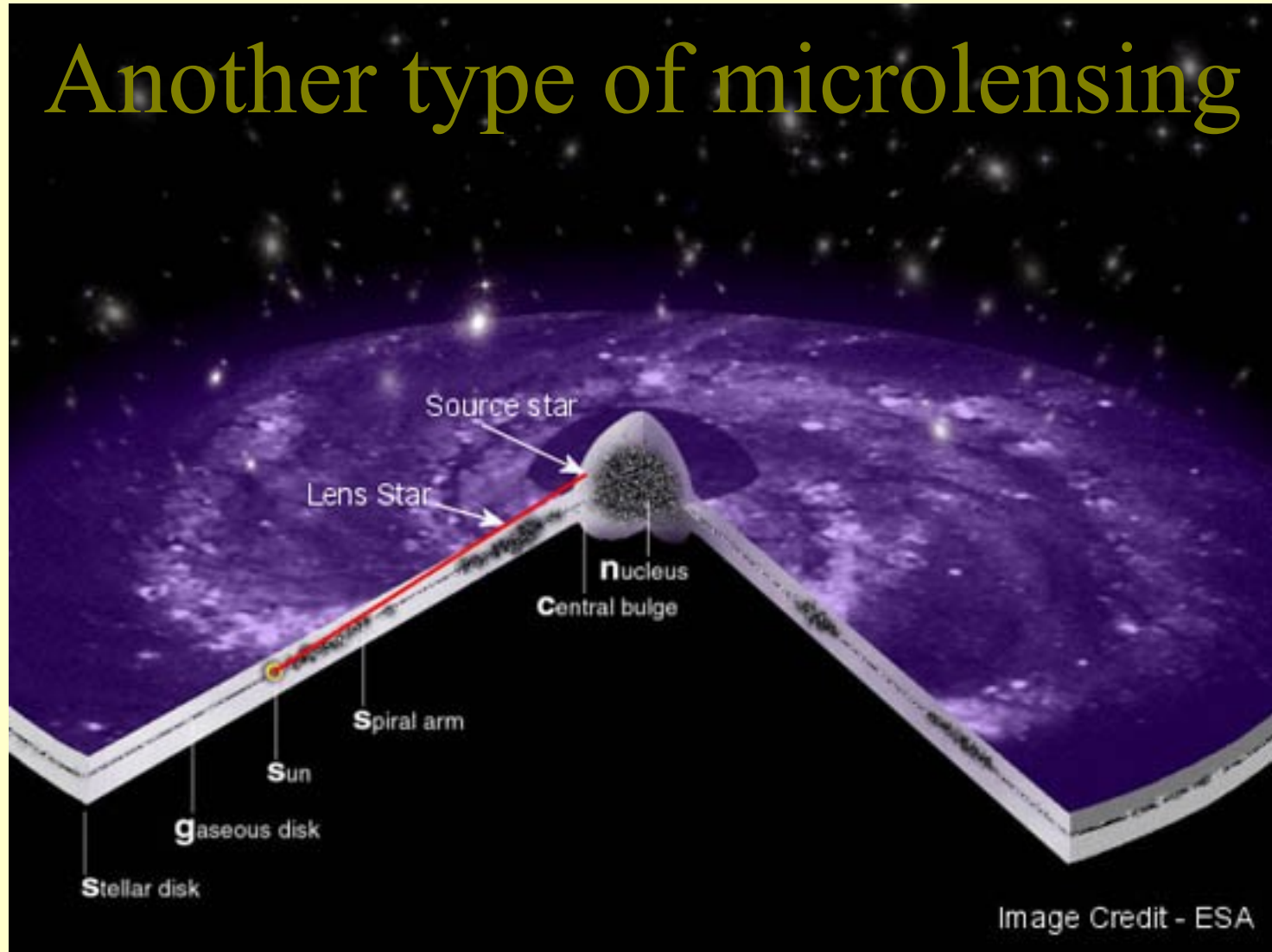
BOHDAN PACZYŃSKI<sup>1</sup>

Princeton University Observatory

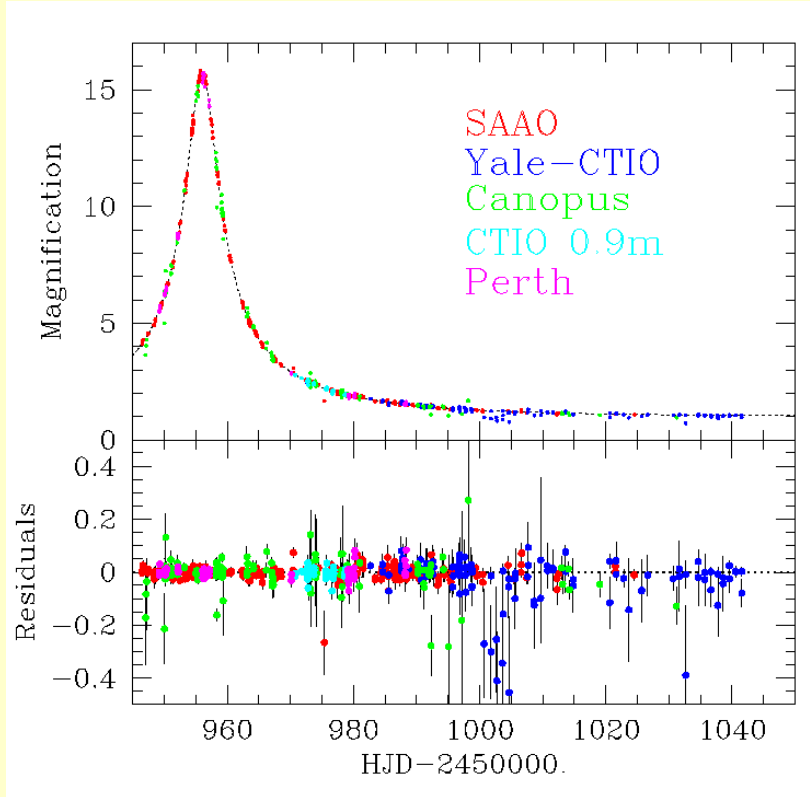
*Received 1985 August 1; accepted 1985 October 23*



# Another type of microlensing



# Microlensing in our Galaxy



Galactic structure (OGLE, MACHO, EROS)

Galactic Halo (MACHO, EROS)

Exoplanets (MPS, MOA, MicroFun)

MACHO - MAssive Compact Halo Objects

EROS - Expérience pour la Recherche d'Objets Sombres

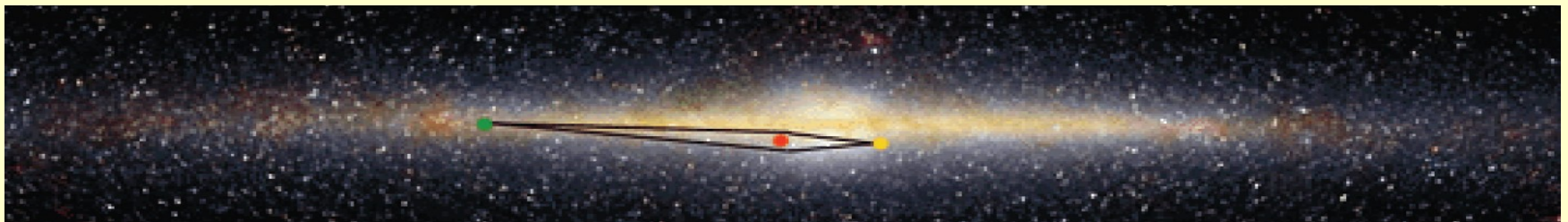
OGLE - the Optical Gravitational Lens Experiment

MOA - Microlensing Observations in Astrophysics

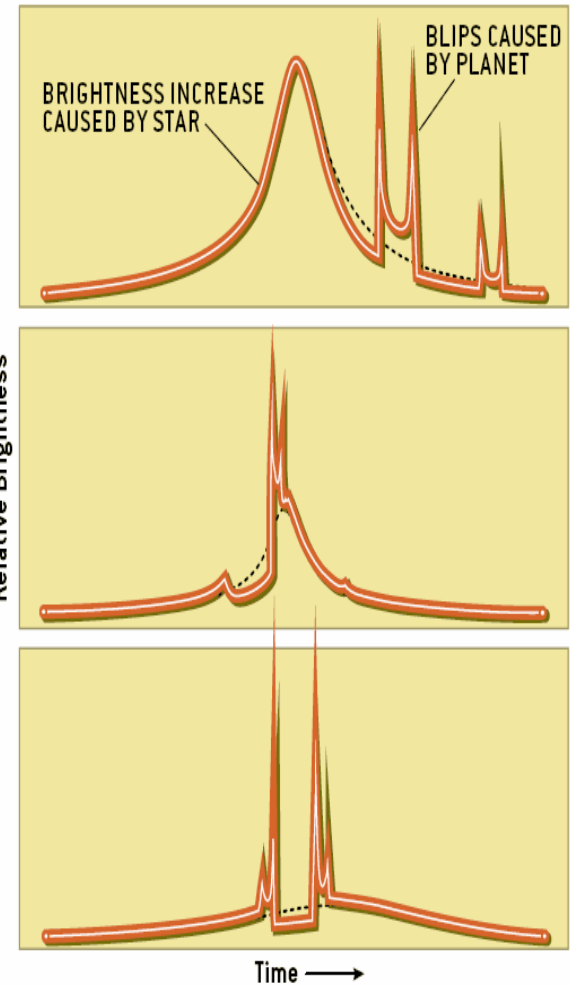
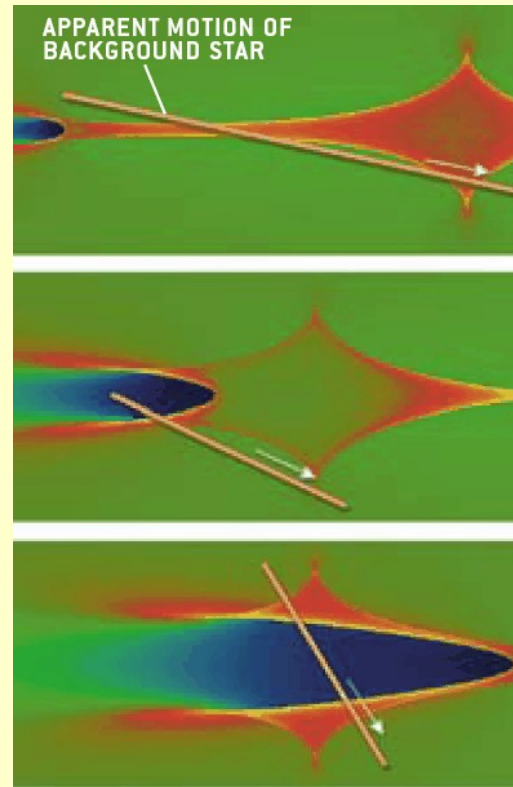
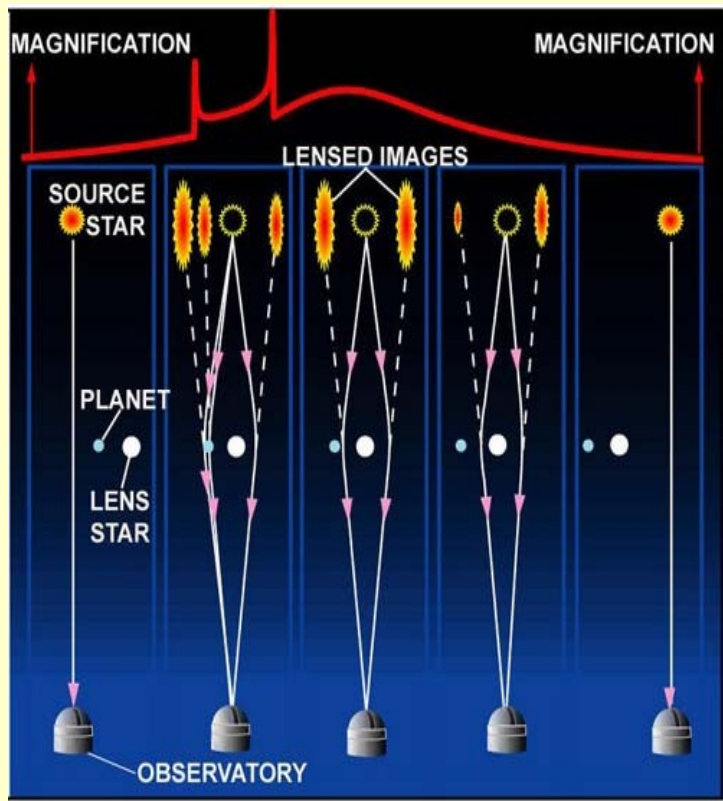
MPS - Microlensing Planet Search Project

MicroFun - Microlensing Follow Up Network

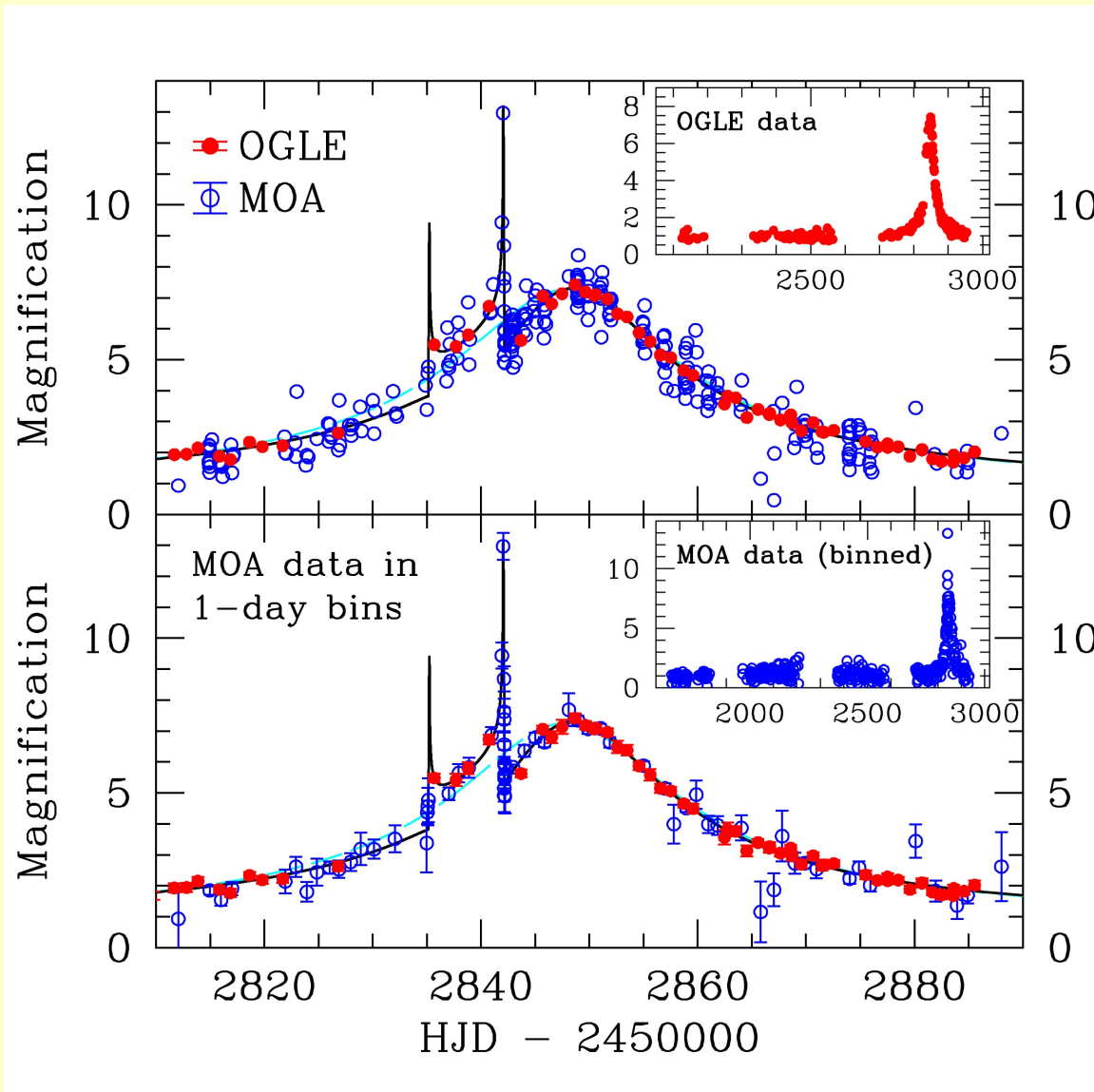
► Magnification of the source



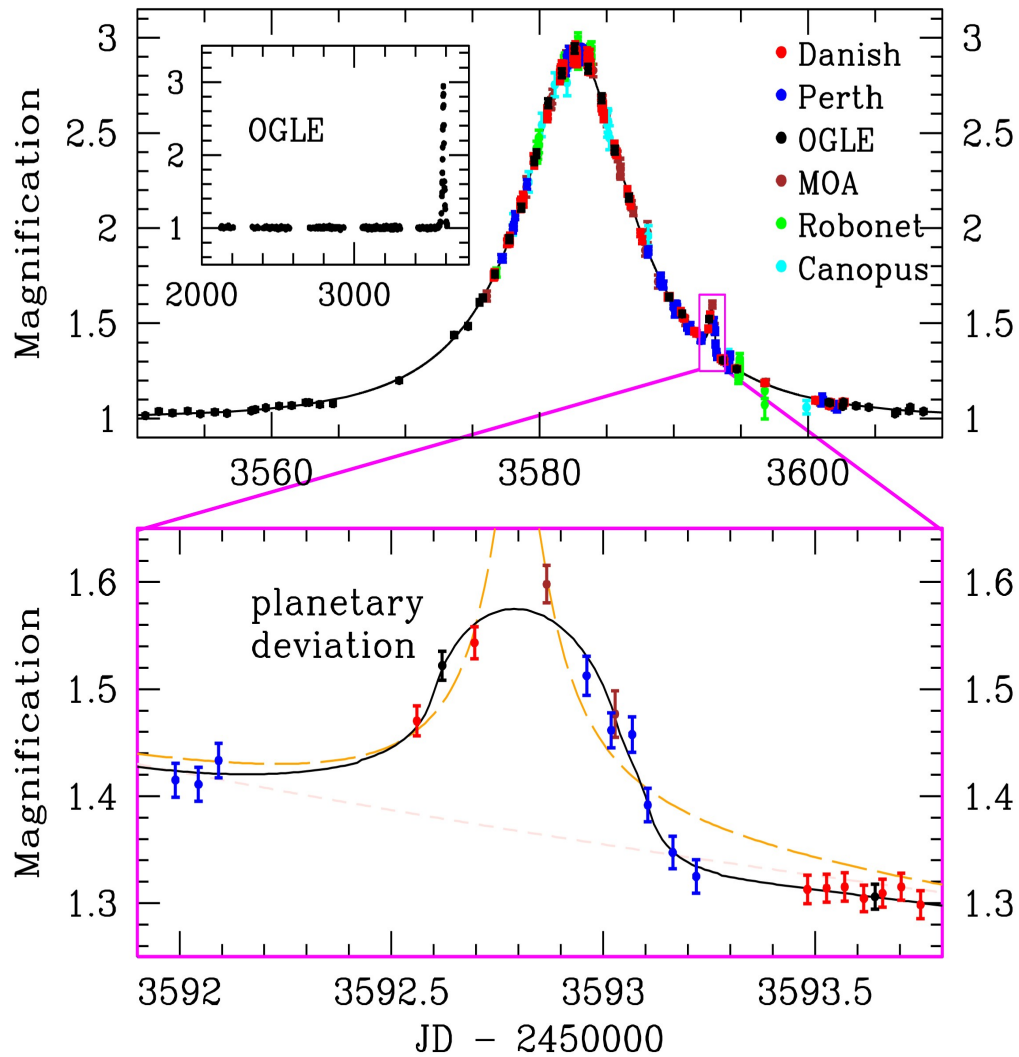
# Search of planets using microlensing



# MOA 2003-BLG-53Lb : Jupiter-like planet

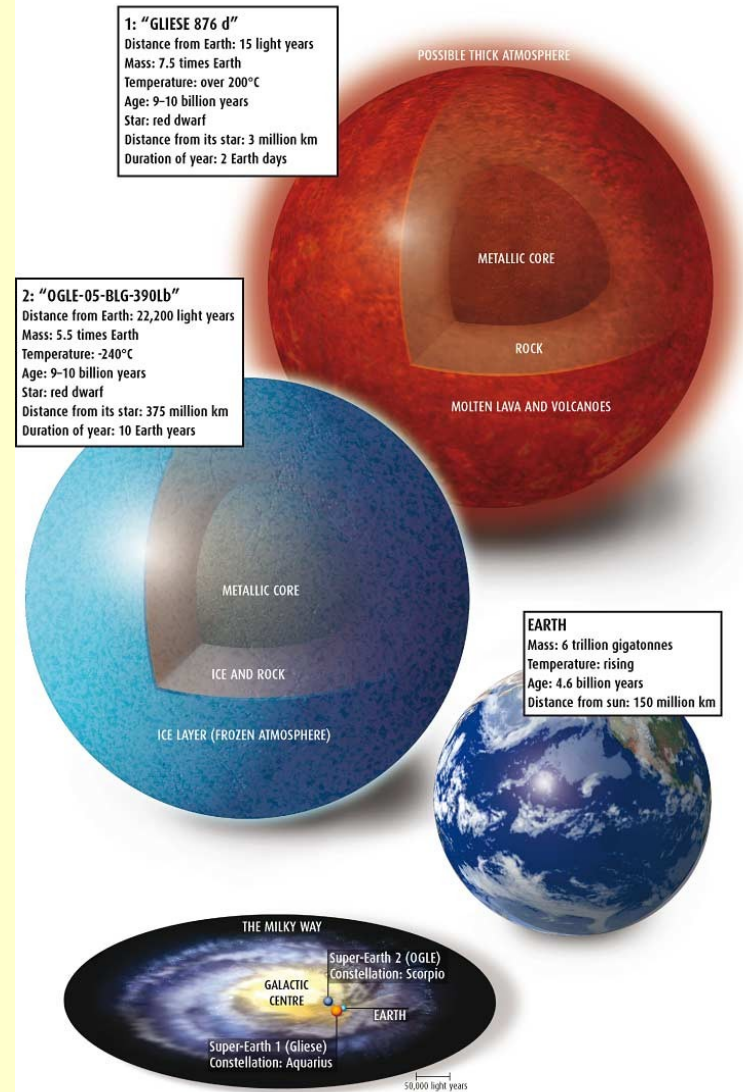


# OGLE-2005-BLG-390Lb 5.5 planet with 5.5 Earth mass



## ANATOMY OF A SUPER-EARTH

A new class of planet has been discovered outside our solar system. In terms of their size and presumed composition, the two known "super-Earths" are the most Earth-like worlds yet seen, but they also have striking differences

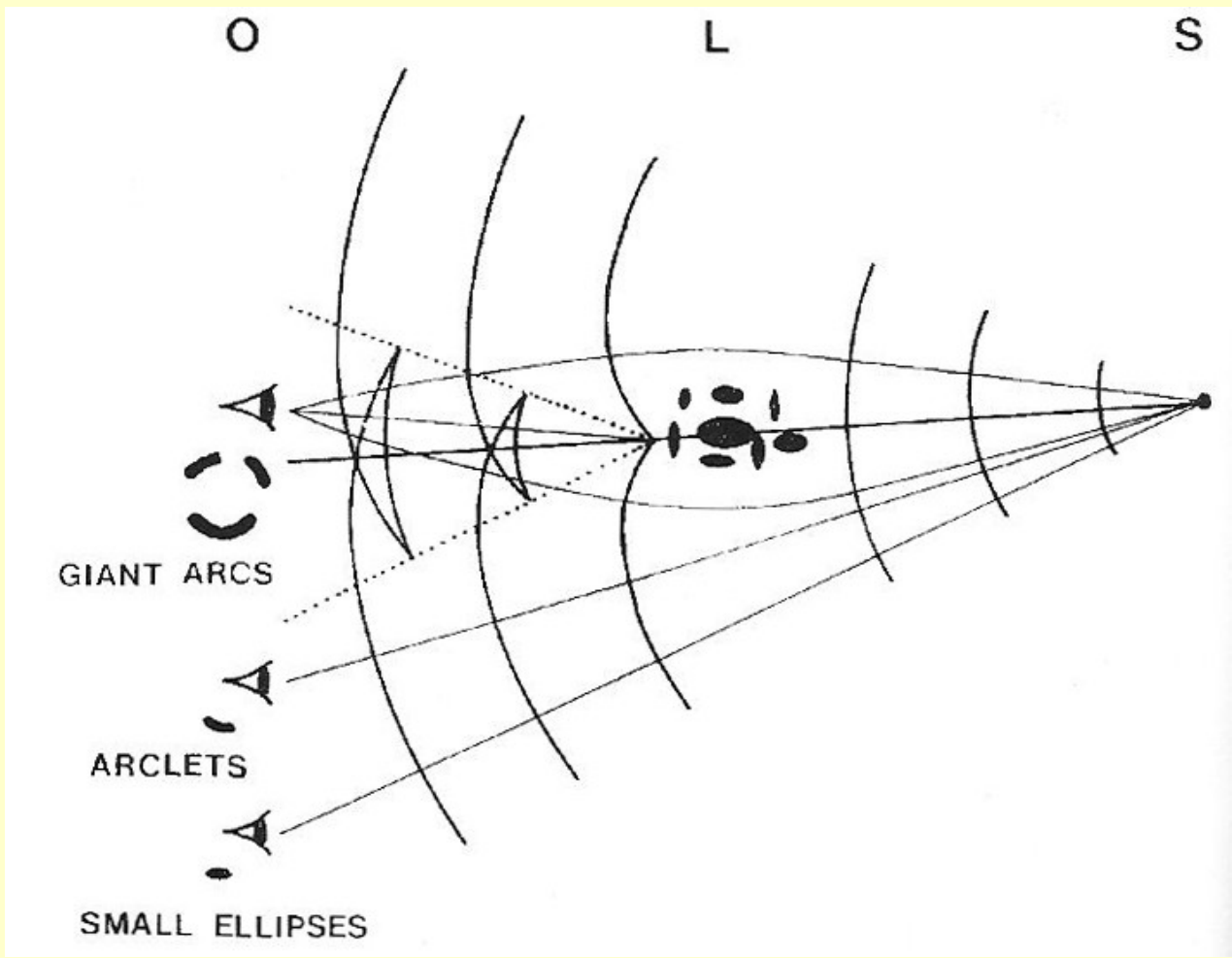


RELATIVE SIZES AND ORBITING DISTANCES FROM THEIR STAR

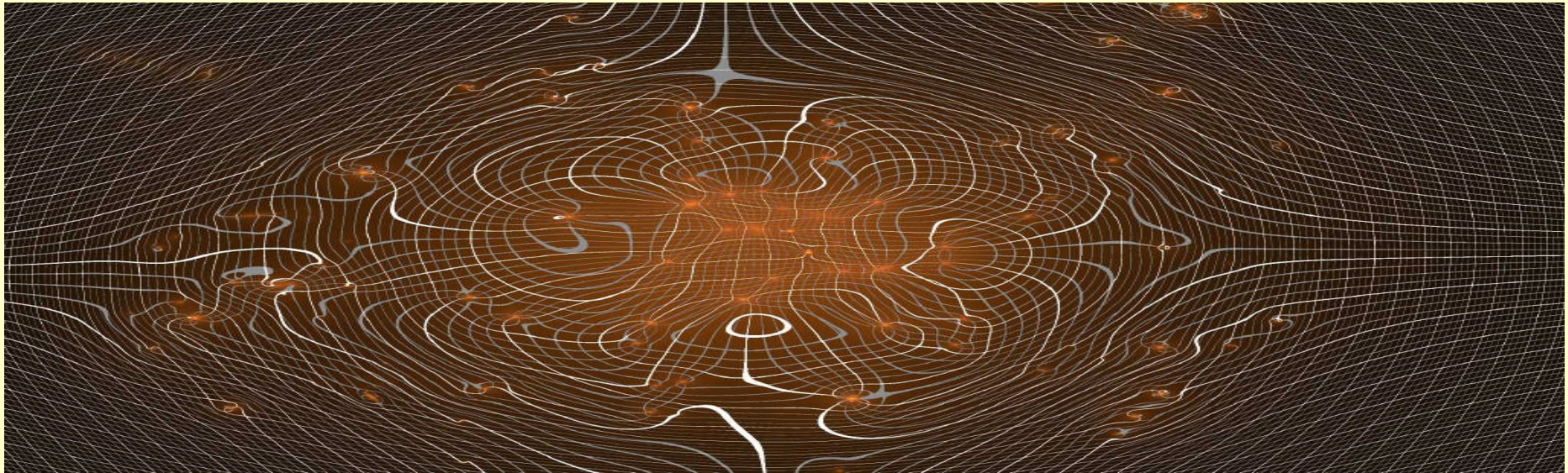
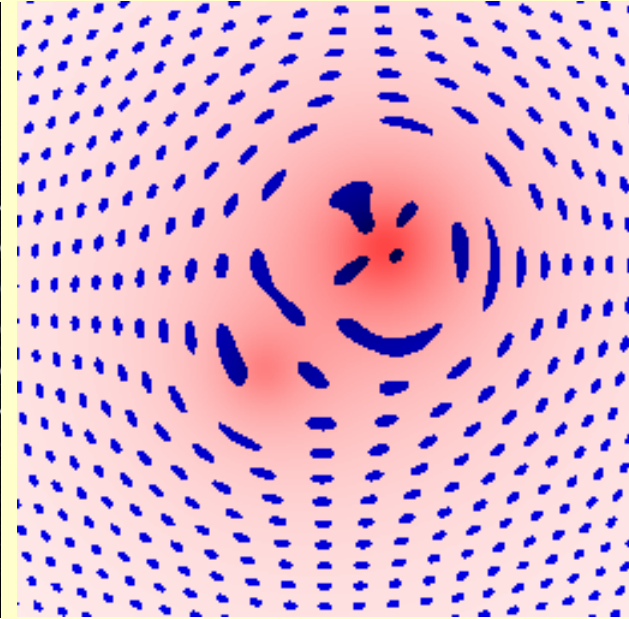
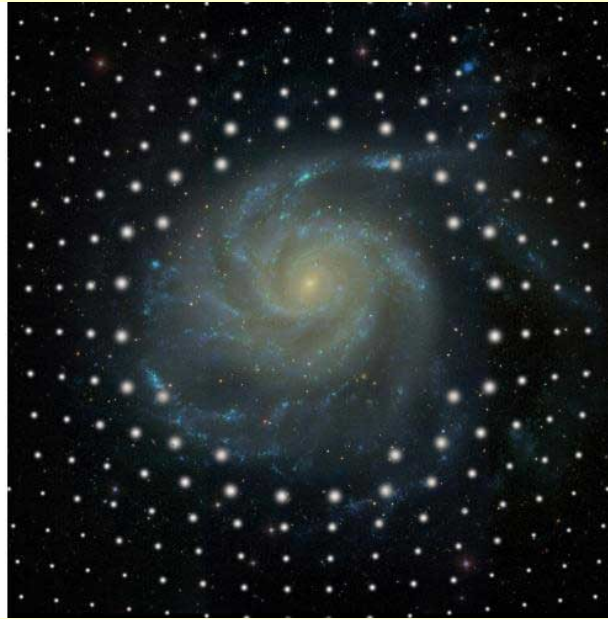
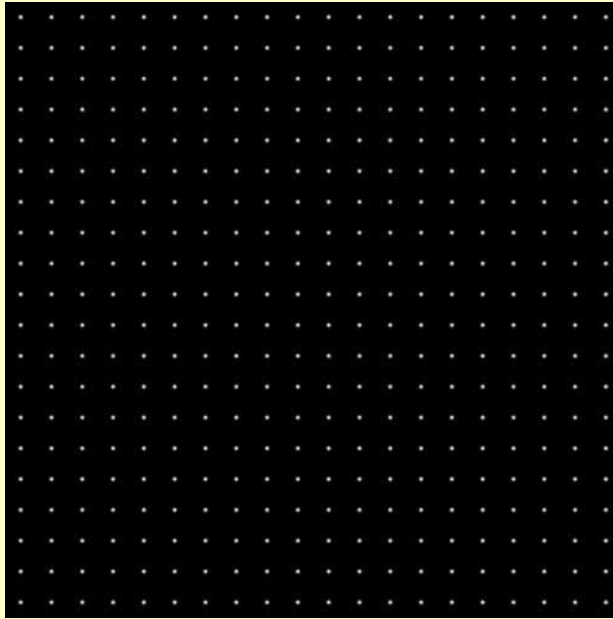




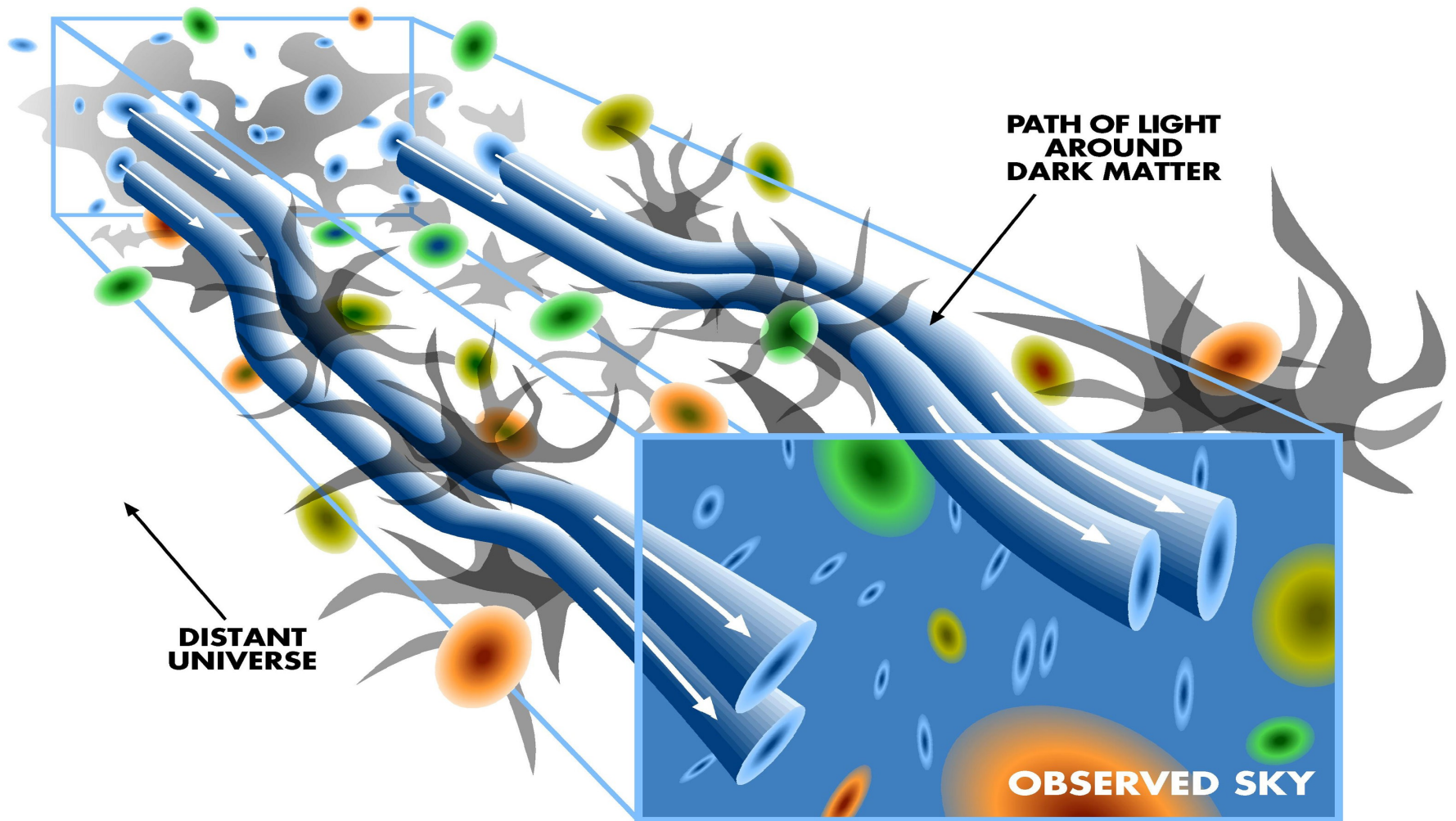
# Splitting and distortions – weak and strong lensing



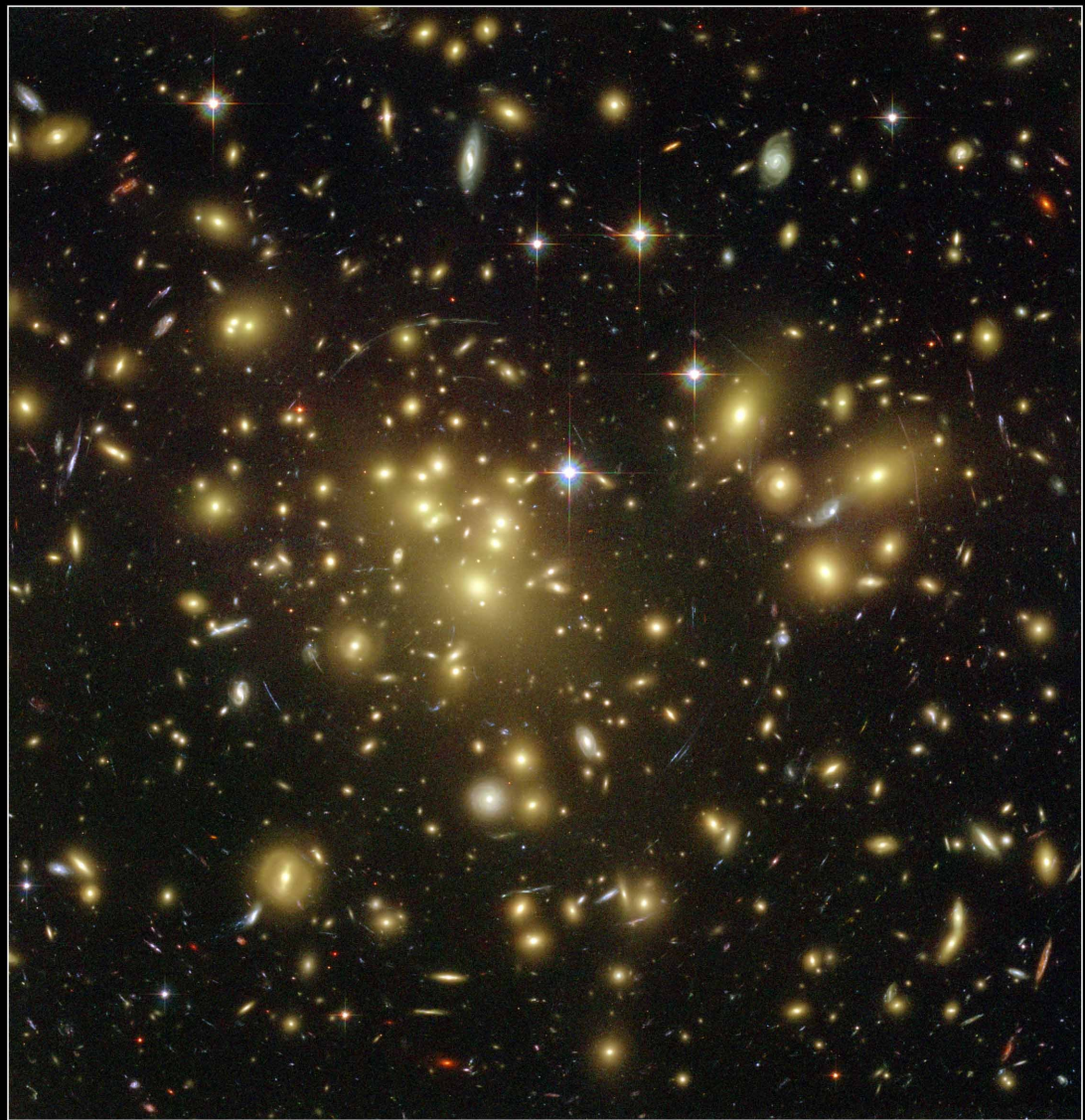
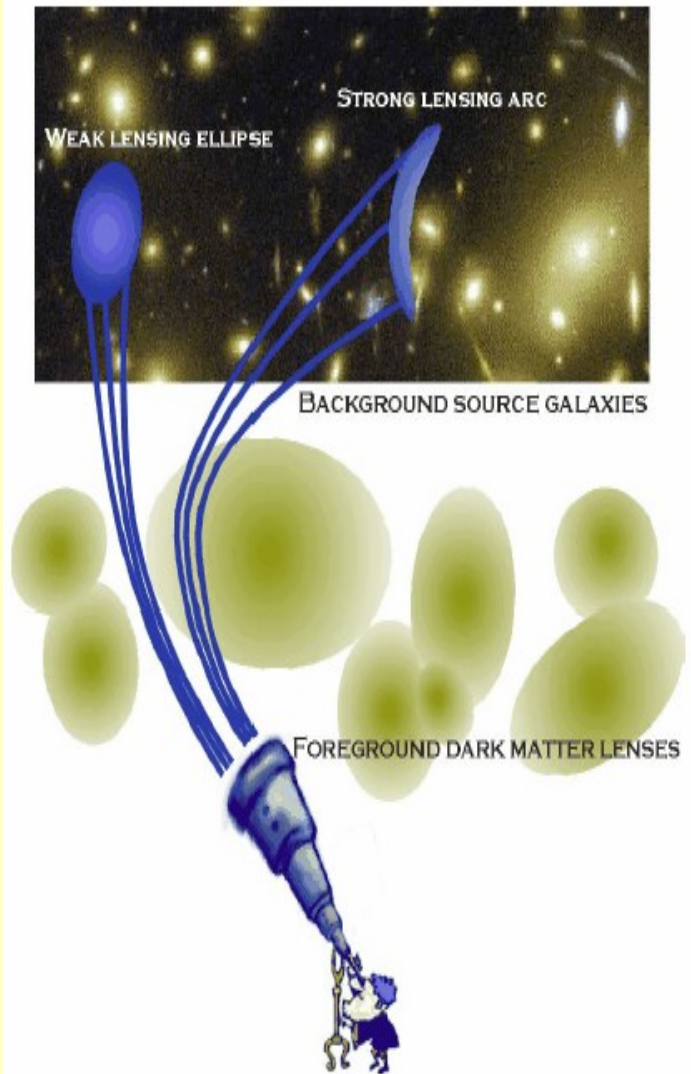
# Galaxy or group of galaxies distorts background images



# Weak lensing – artistic phantasm

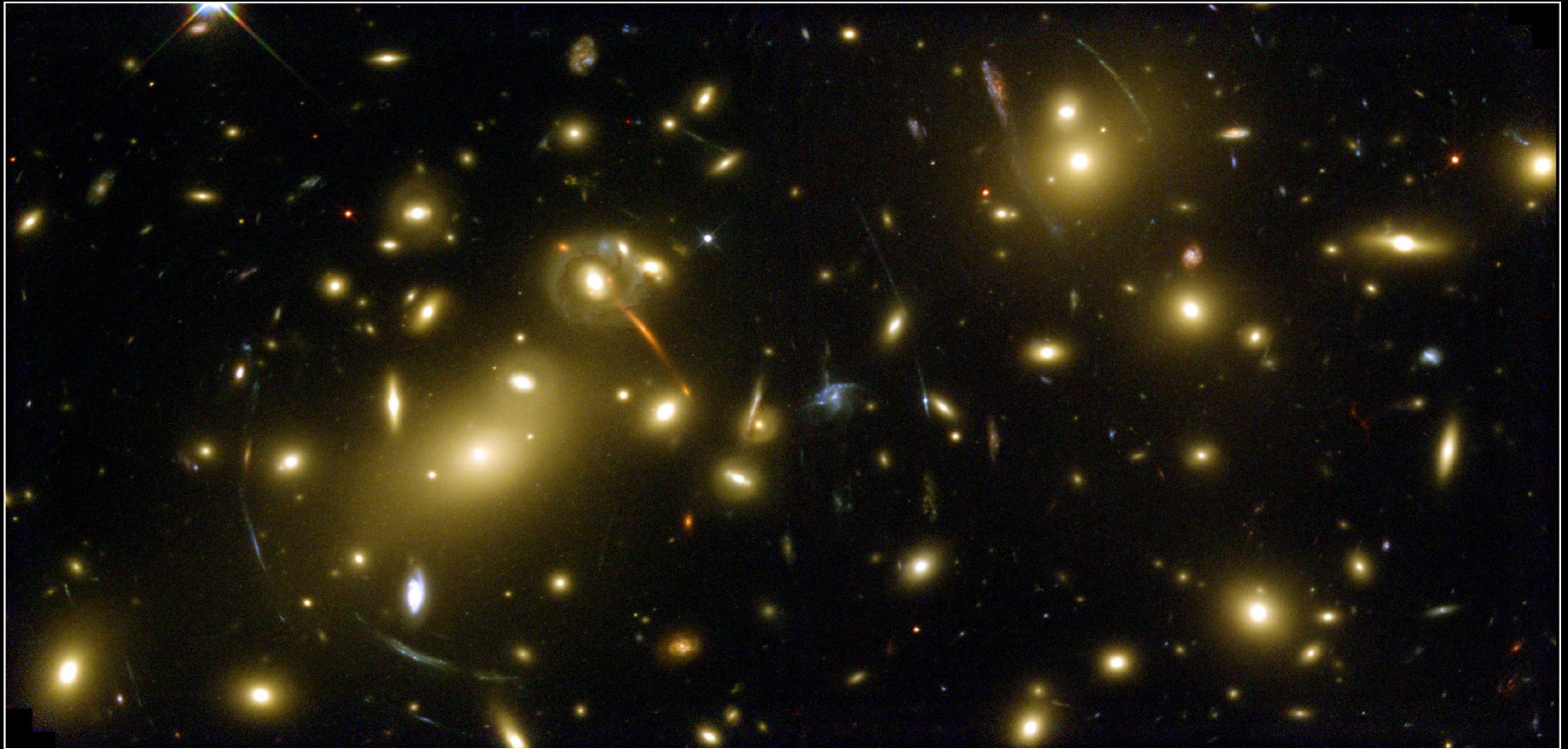


# HST can see it all!



**Galaxy Cluster Abell 1689**  
**Hubble Space Telescope • Advanced Camera for Surveys**

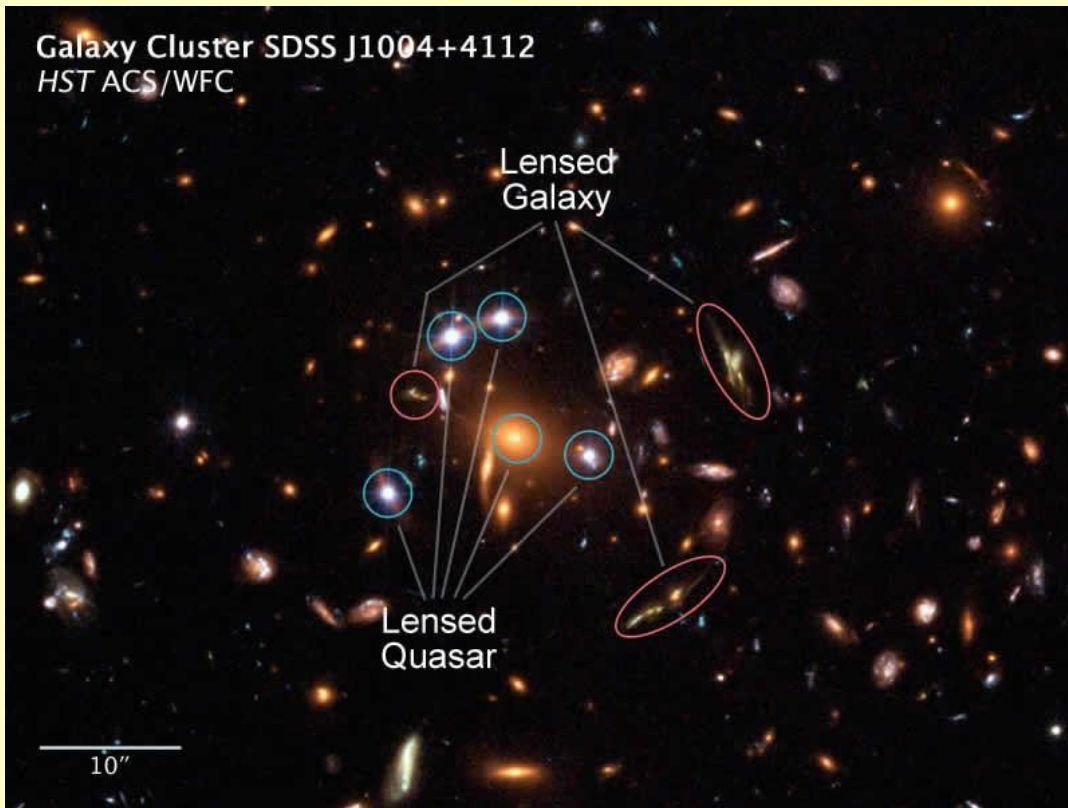
NASA, N. Benitez (JHU), T. Broadhurst (The Hebrew University), H. Ford (JHU), M. Clampin (STScI), G. Hartig (STScI), G. Illingworth (UCO/Lick Observatory), the ACS Science Team and ESA  
STScI-PRC03-01a



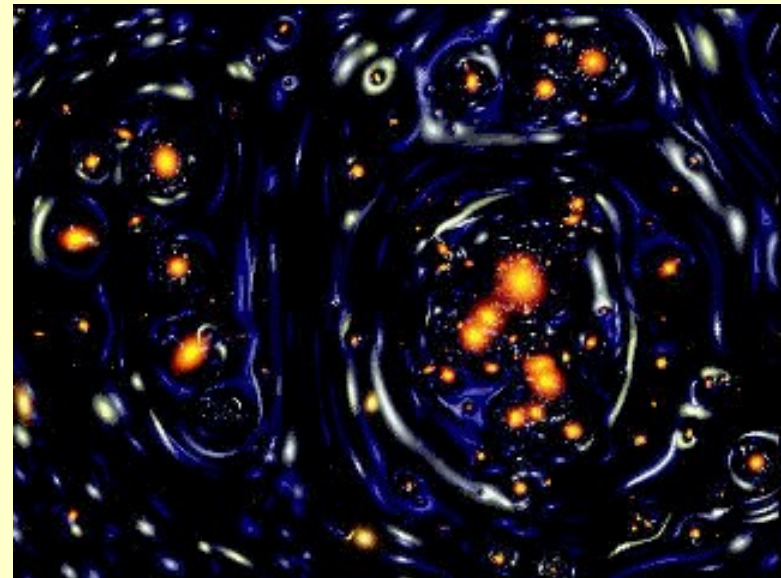
**Galaxy Cluster Abell 2218**  
Hubble Space Telescope • WFPC2

NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08

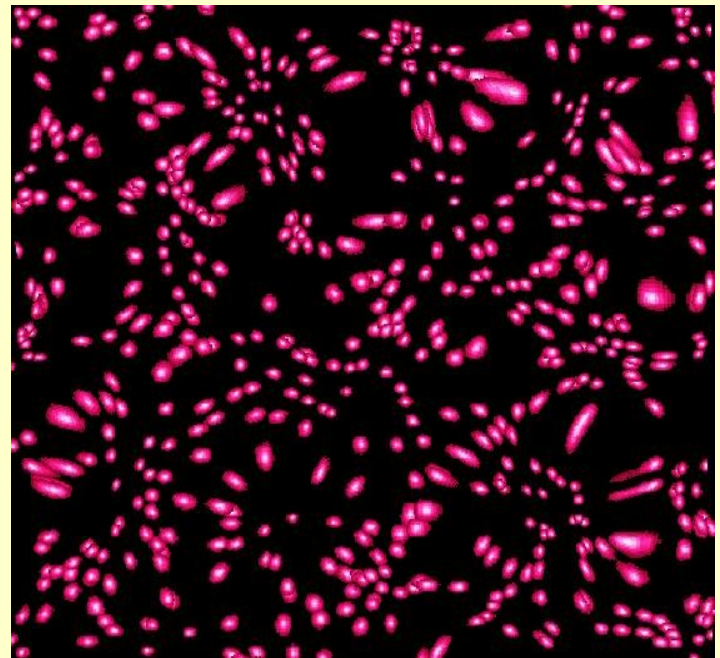
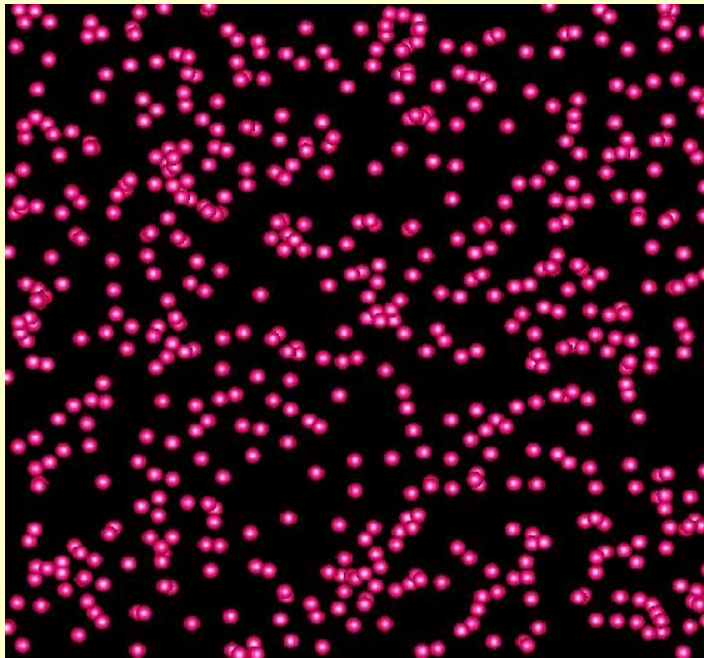
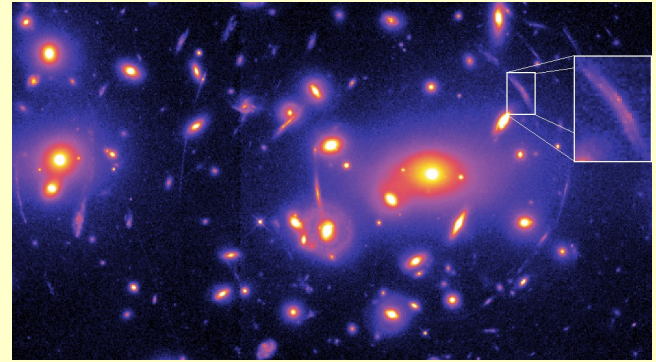
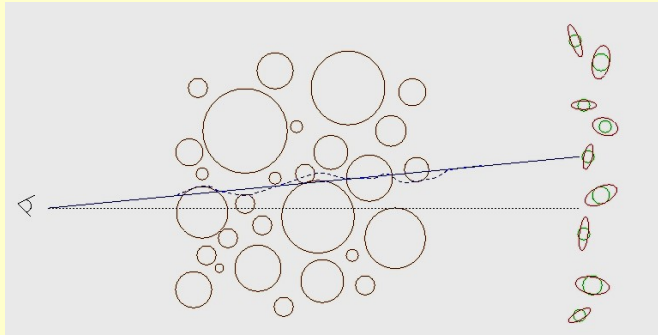
Galaxy Cluster SDSS J1004+4112  
HST ACS/WFC



More fun!

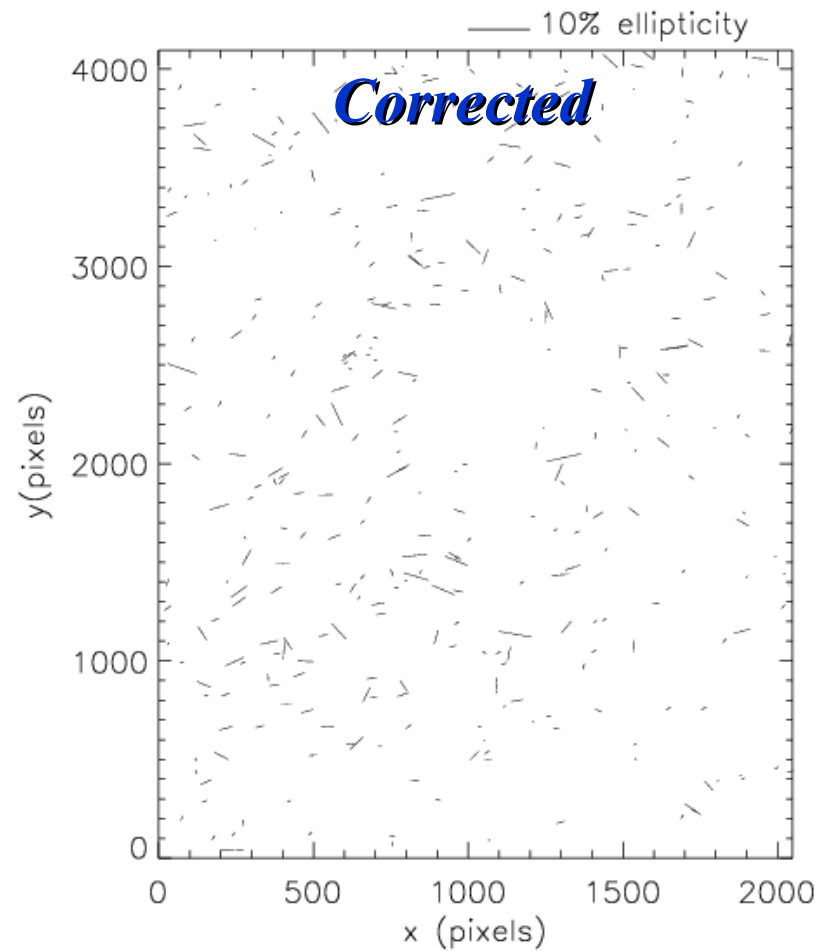
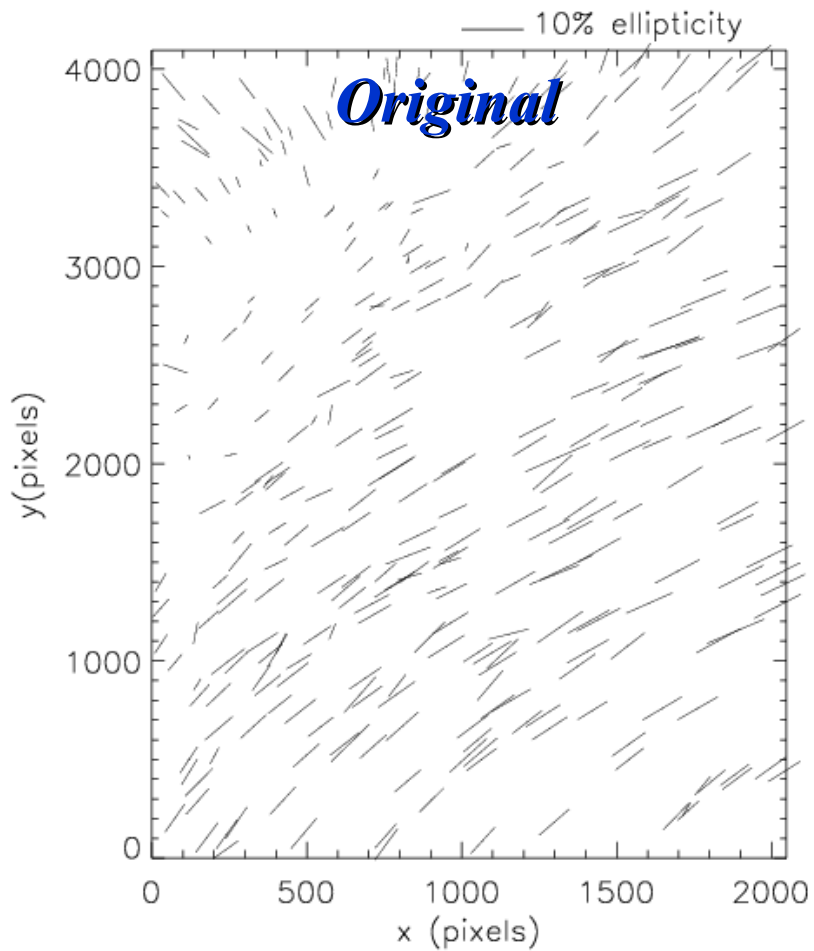
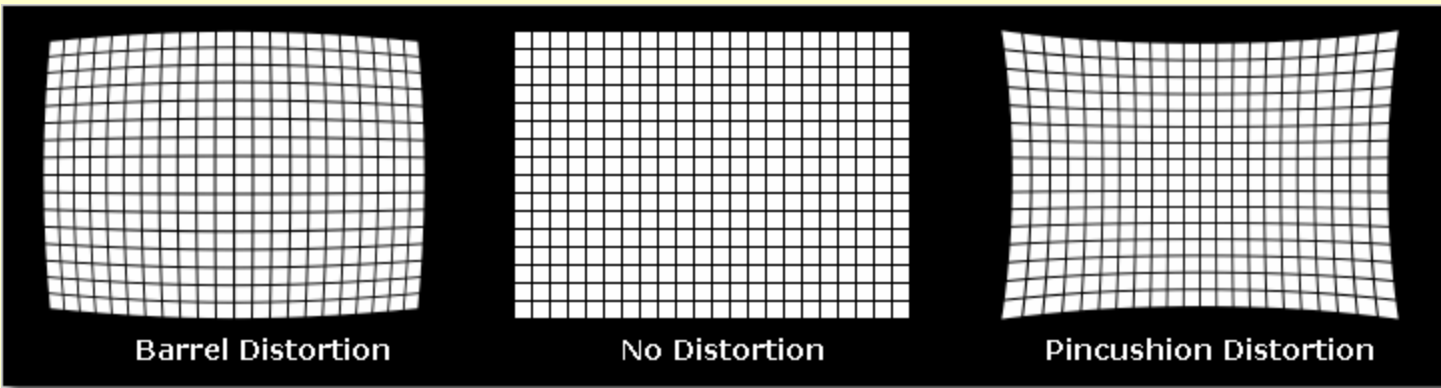


# Weak lensing

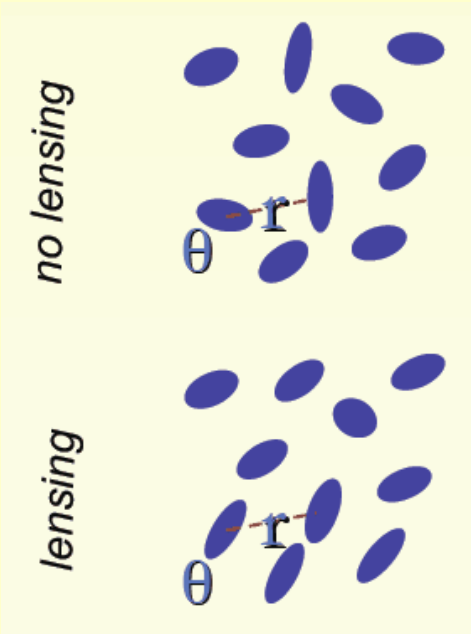
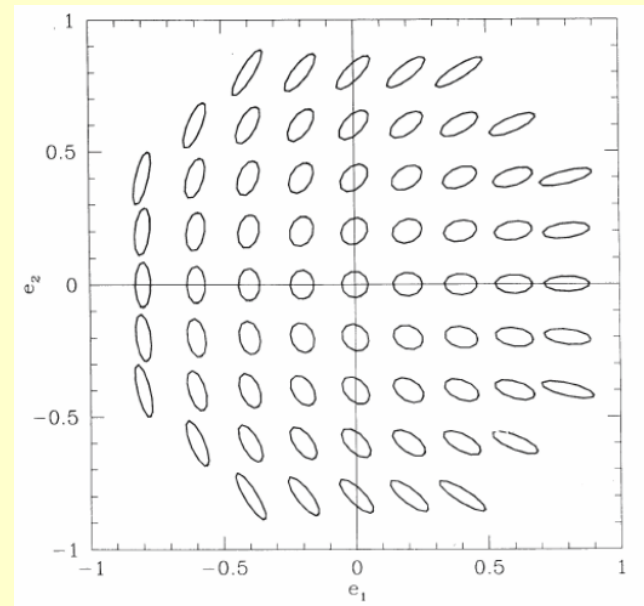
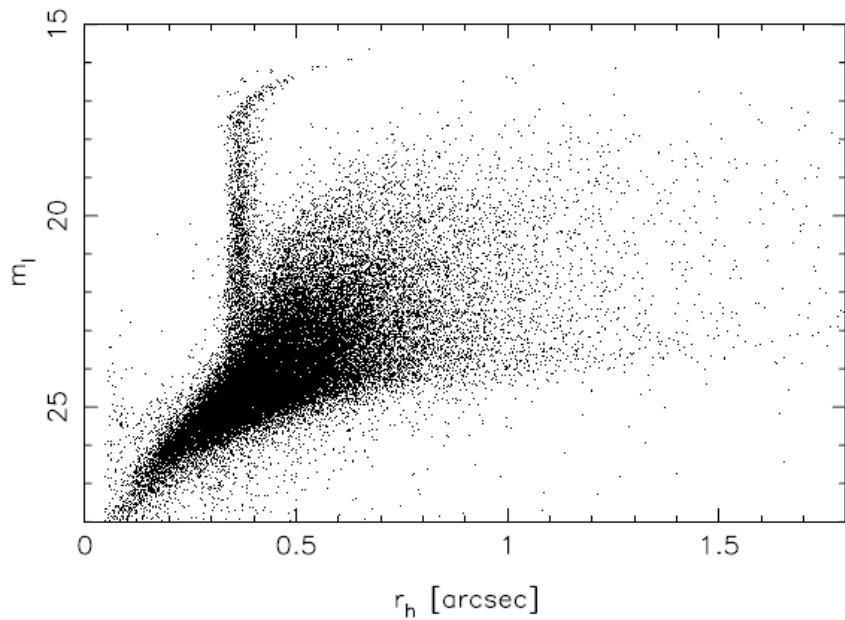


**Originals**

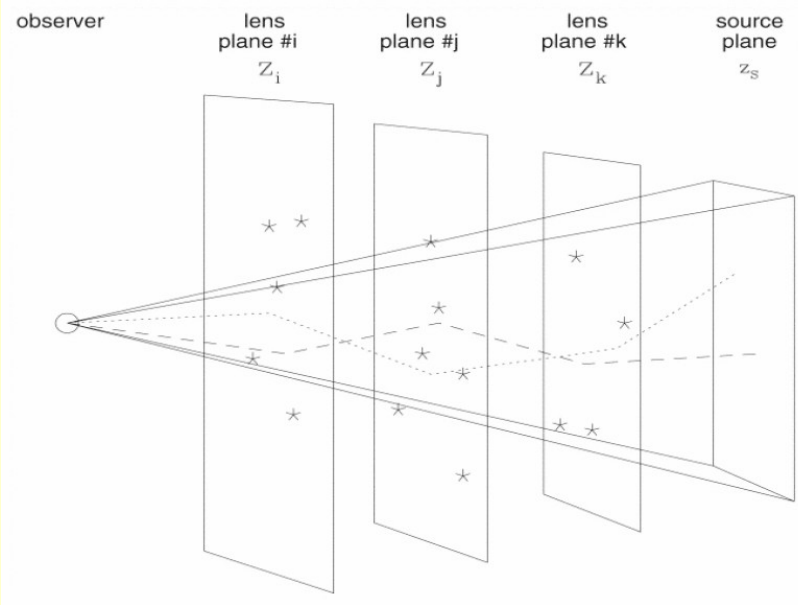
**Images**



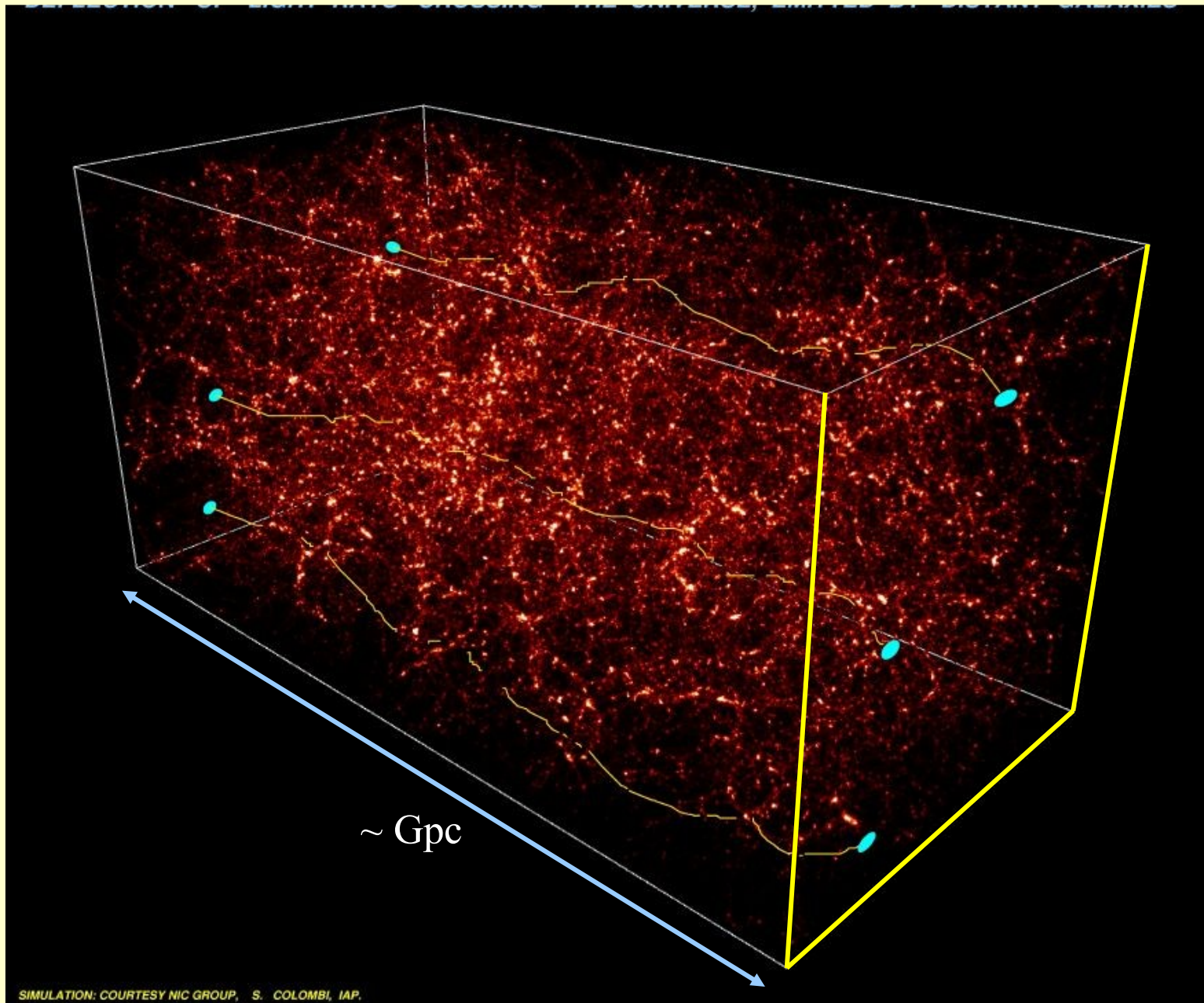
SIZE-MAGNITUDE DIAGRAM



- Stars out
- Search of images
- Averaging of ellipticities
- Sorting by distance
- Inversion



# Path through cosmic mess

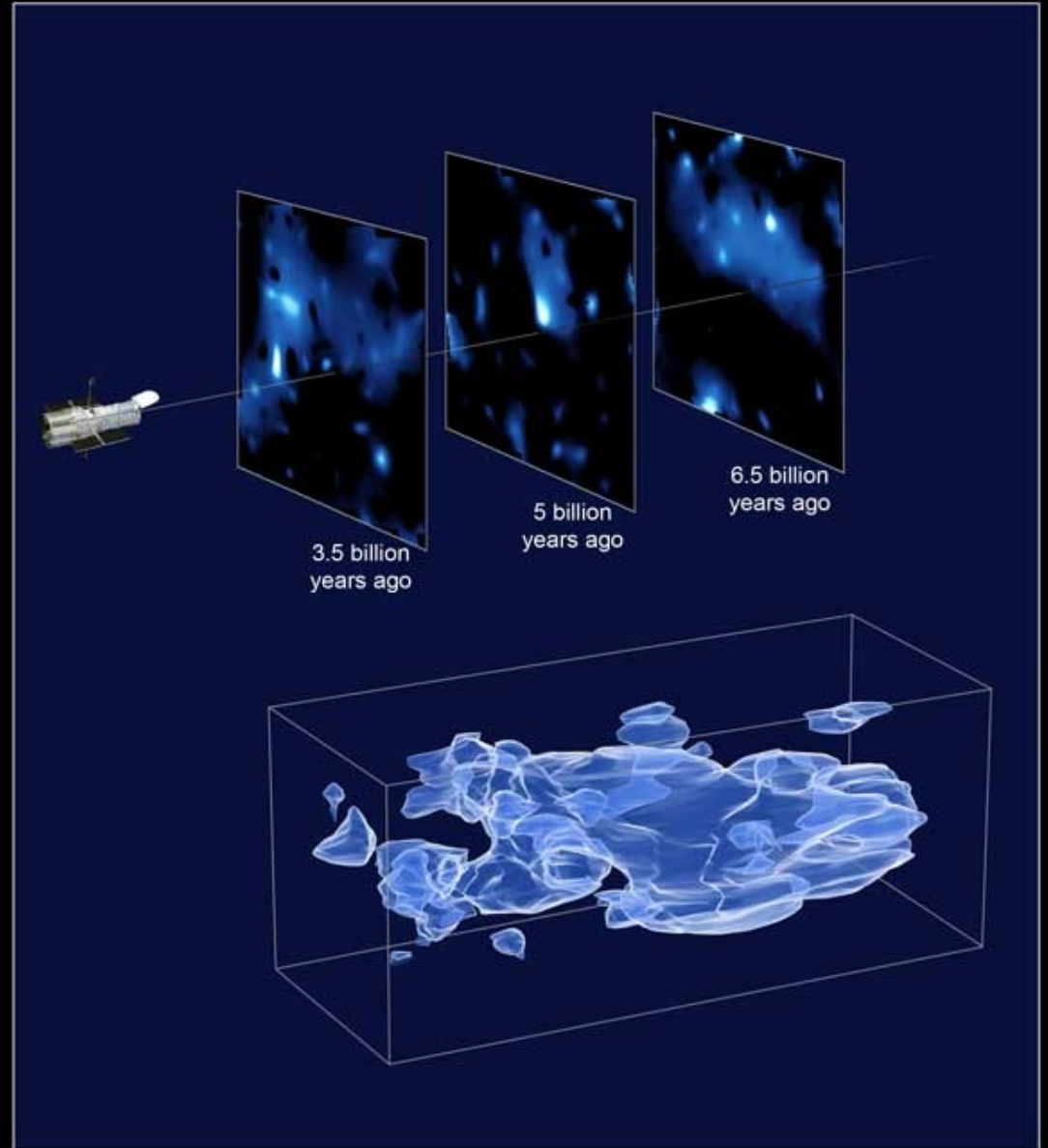




**COSMOS** (*Cosmic  
Evolution Survey*)

Distribution of Dark Matter

HST ■ ACS/WFC



NASA, ESA, and R. Massey (California Institute of Technology)

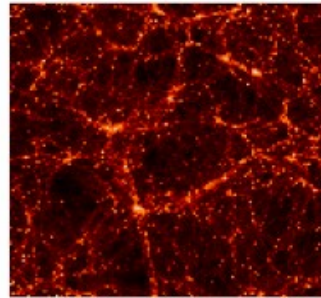
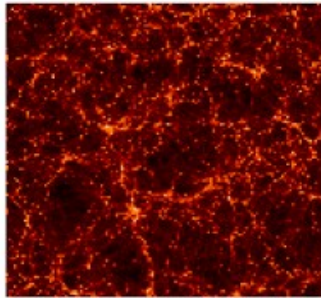
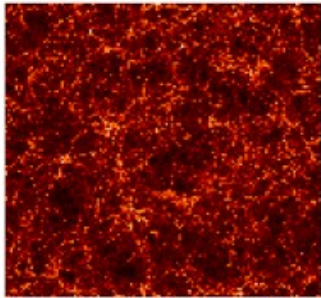
STScI-PRC07-01a

$z=3$

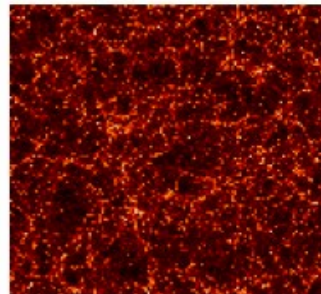
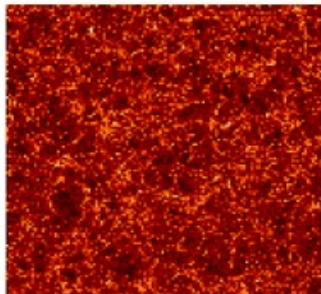
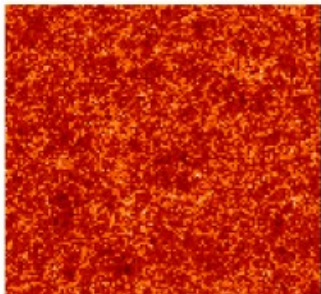
$z=1$

$z=0$

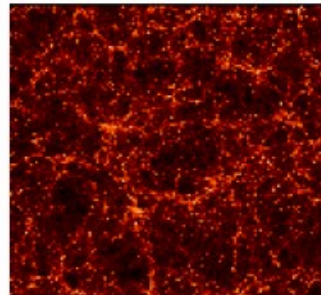
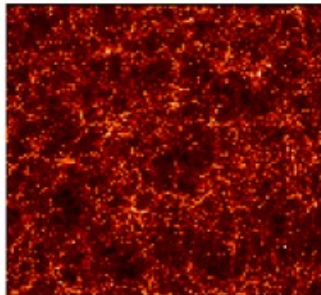
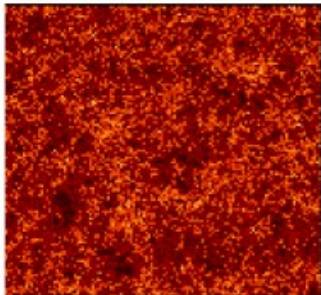
$\Lambda$ CDM



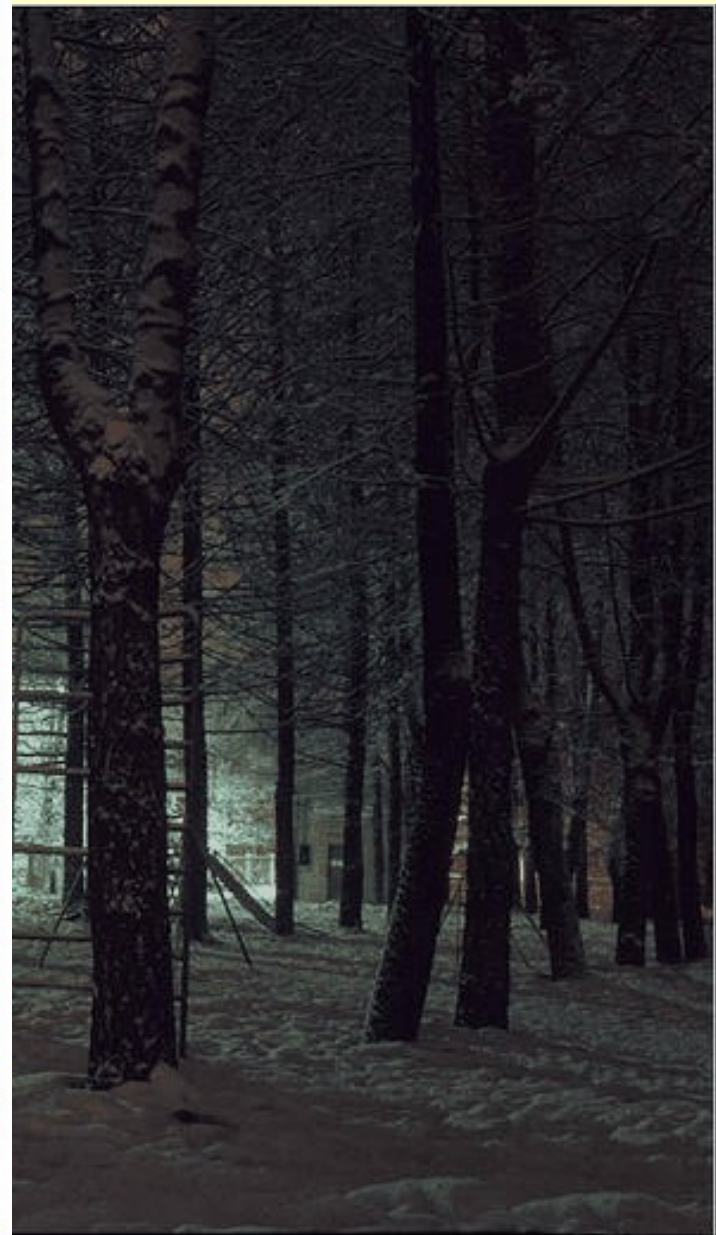
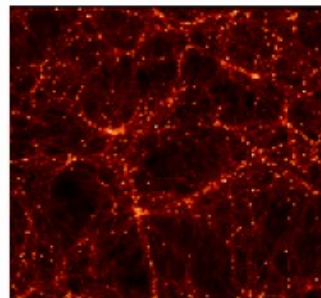
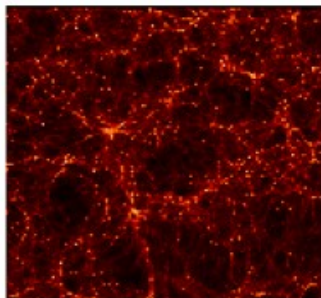
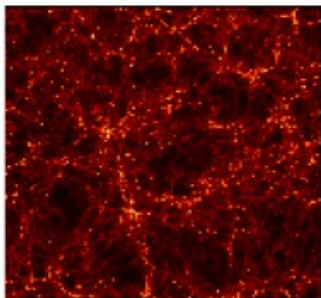
SCDM



$\tau$ CDM



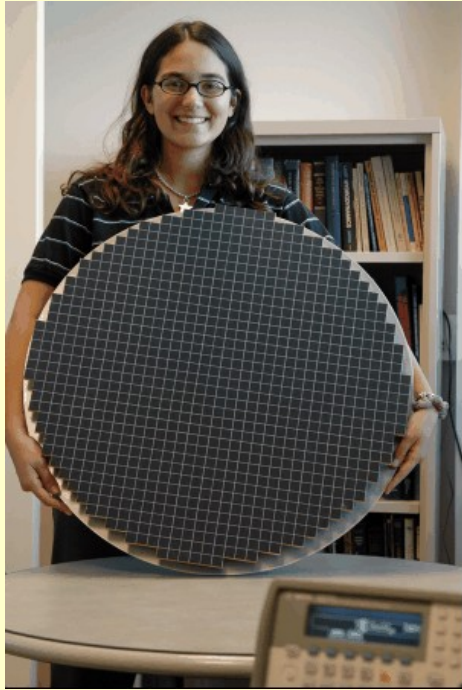
OCDM



Virgo consortium

# LSST

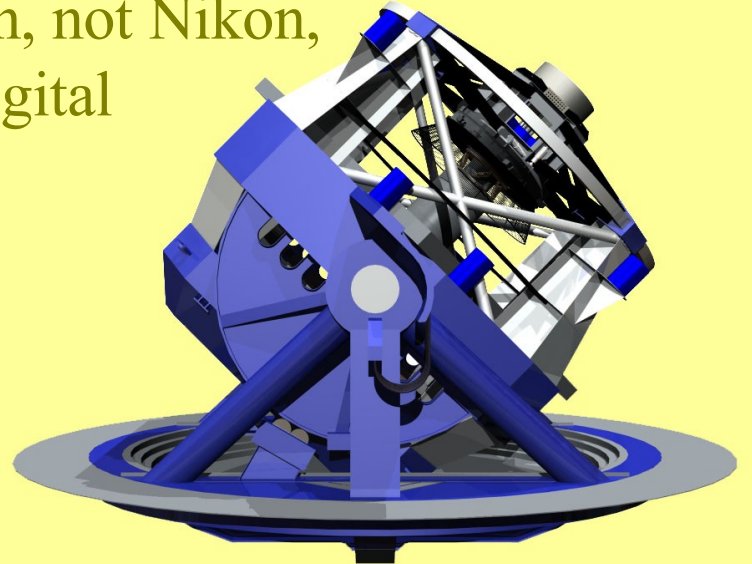
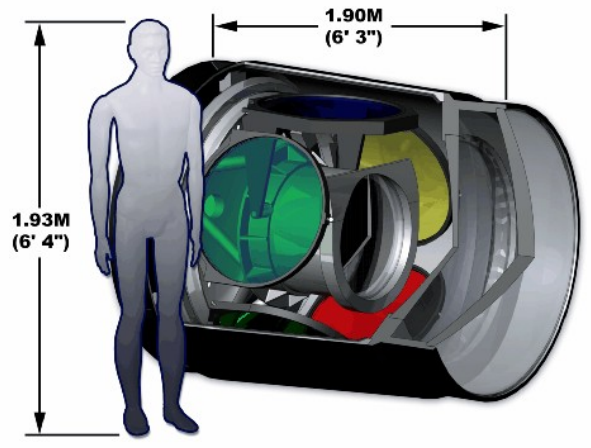
Large Synoptic Survey Telescope



First light 2012?  
Cerro Pachón Chile  
8.4m mirror  
400 Moon images in frame  
4 shots in minute



Not Canon, not Nikon,  
but still digital



# Time series in gravitational lensing context

- Time delay estimation
- Estimation of time delay systems
- Time delays from blended light curves
- Weak transients and their significance
- High precision supernova lightcurves
- Frequency content of the microlensing

# Problems

- Long gaps in data sets
- High noise level
- Crosstalk in photometric channels
- Microlensing
- Low resolution
- Low number of crossing or magnification events