MASS 2023 Course:

Gravitational Lenses

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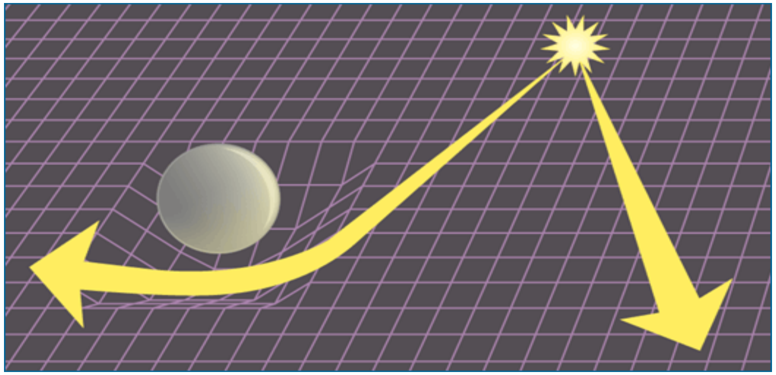
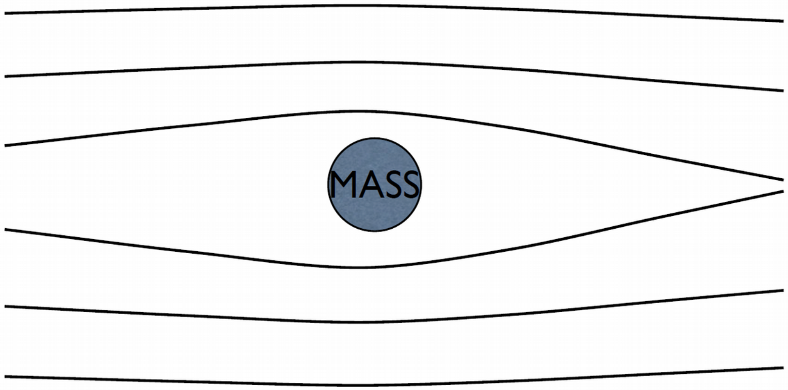
Lecture 01

1. Gravitational lenses:
   - Definition
   - Light bending in the gravitational field
   - Light deflection angle
   - Basic principles
   - Discovery
   - Types: **strong** (macro and micro) and **weak** lensing
   - Applications
2. Exercises

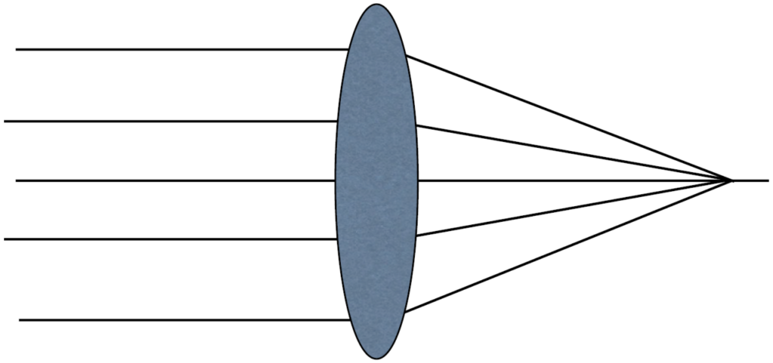
Light bending in the gravitational field

- **Gravitational lens** is a massive celestial object (or a distribution of matter), located between an observer and a distant background source, which gravitational force deflects the light rays from the source, producing the multiple images of the source (macrolensing), amplification of its brightness (microlensing), or distortion of its shape (weak lensing).
- Light "falls" under the gravity
- Newton: gravitational bending of the paths of "corpuscles" (particles from which light is composed)
- General Relativity: light follows geodesics



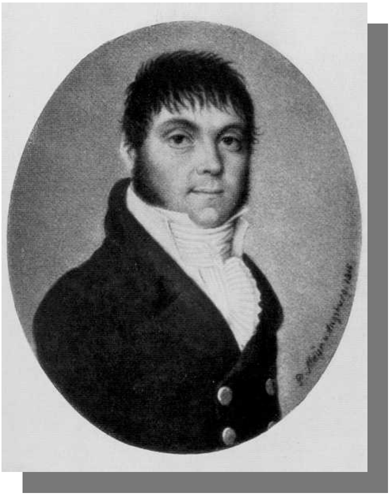


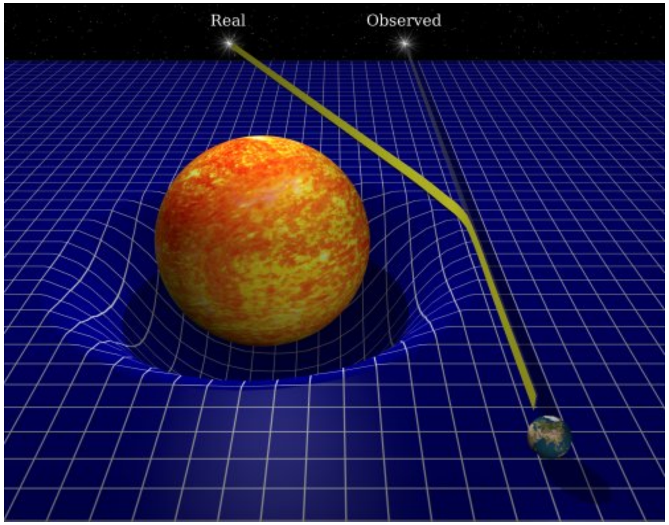
Gravitational lens:
1. deflection is larger closer to the axis
2. focusing to a line

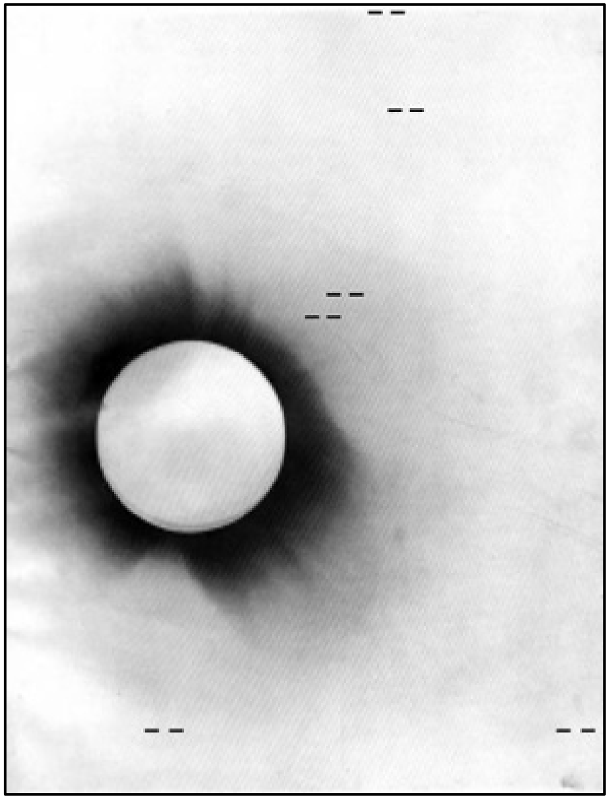


Converging lens in optics:
1. deflection is larger further from the axis
2. focusing to a point

Light deflection angle



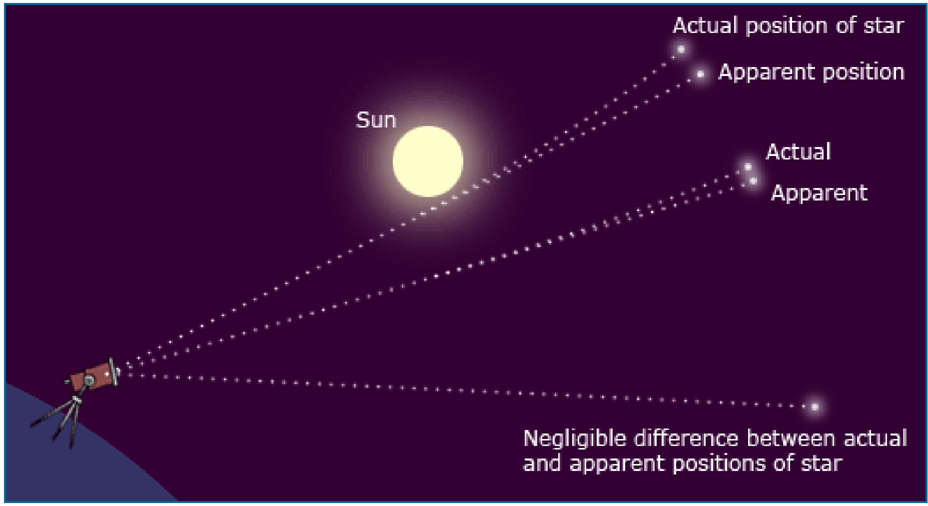


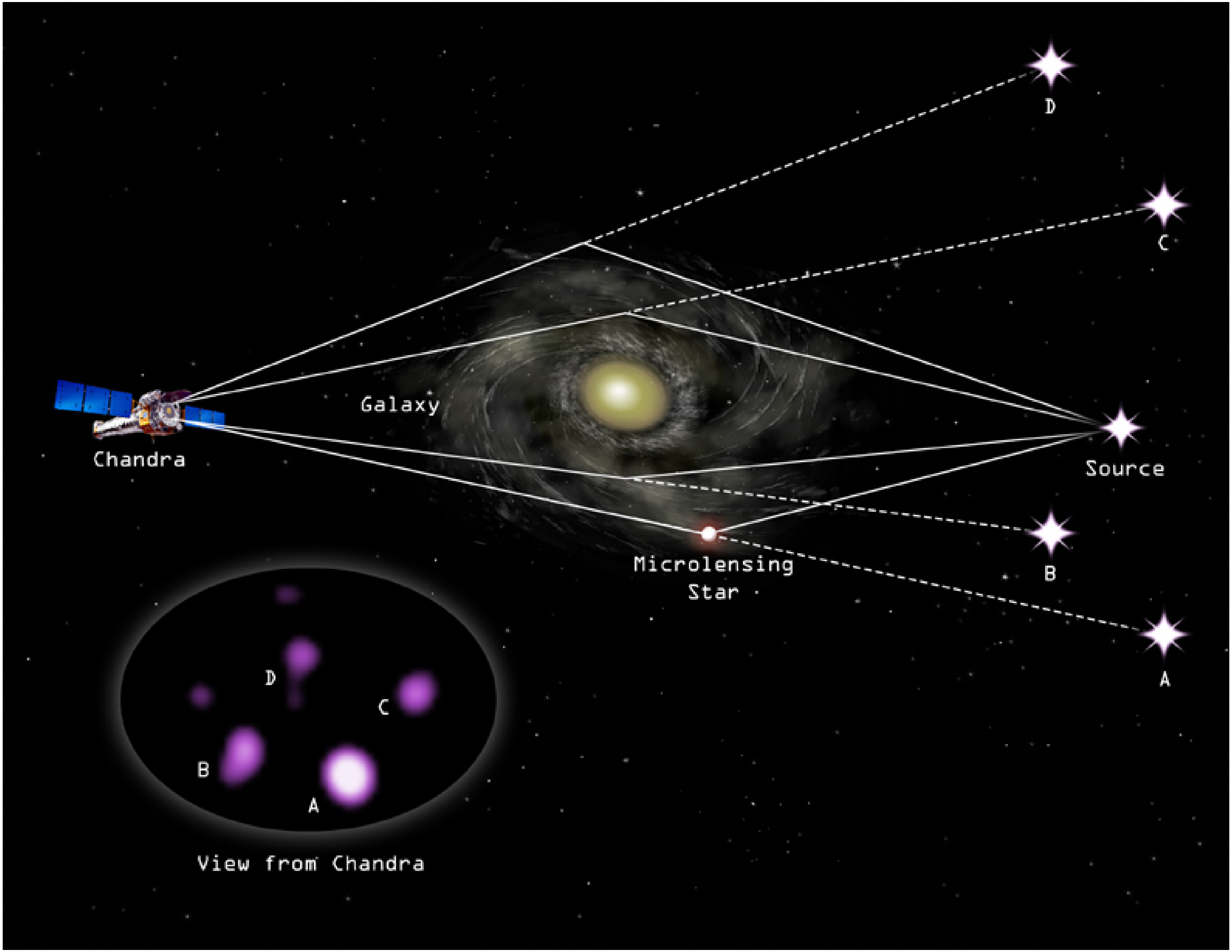


- Johann Georg von Soldner (1804) - trajectory of particle with speed *c*: $\alpha = \frac{2GM}{c^2\xi}$
- Albert Einstein (1915) - General Relativity:

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

- Eddington - total solar eclipse in 1919:
  - No light bending: $\alpha = 0''$
  - Newton's mechanics: $\alpha = 0''.87$
  - GR: $\alpha = 1''.75$
- Confirmation of Einstein's predictions:
  $\alpha_1 = 1''.98 \pm 0''.12 \quad \alpha_2 = 1''.61 \pm 0''.30$

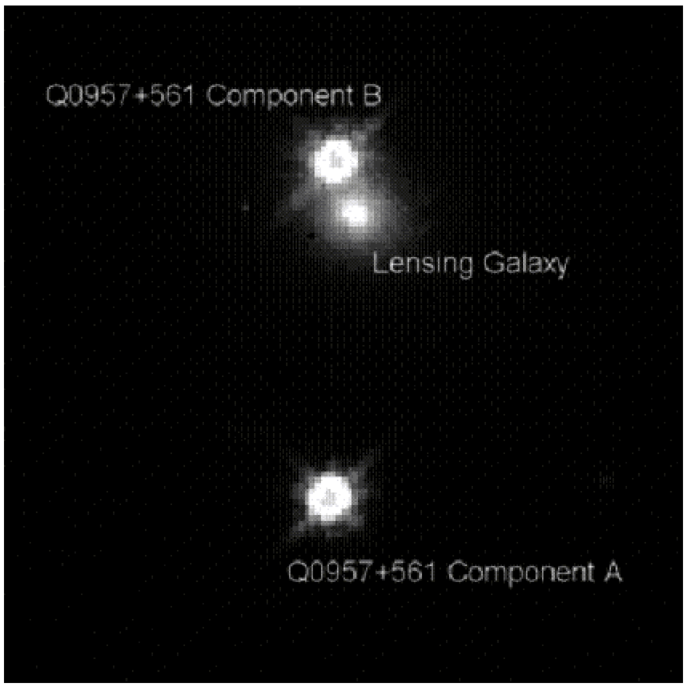


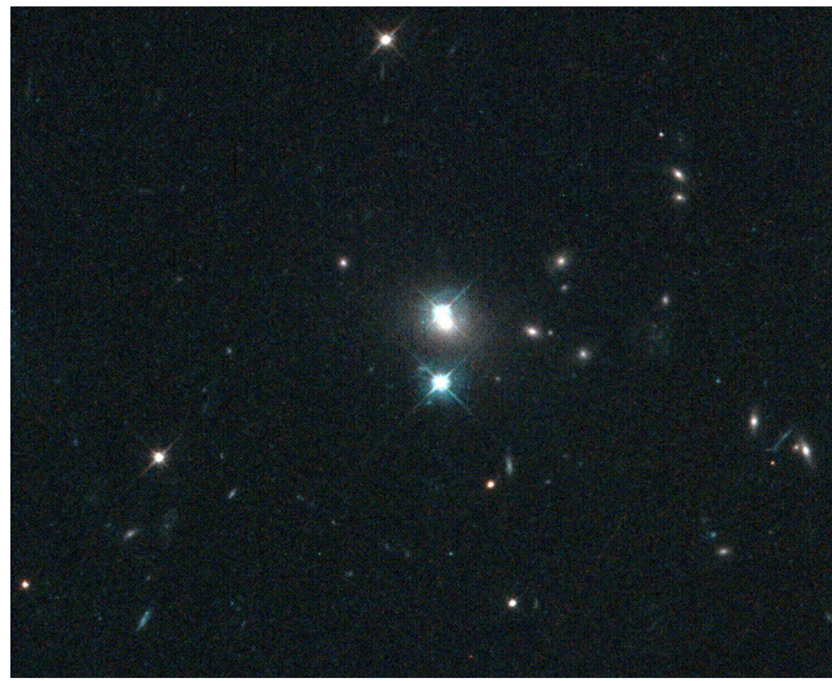


D
C
Galaxy
Chandra
Source
B
Microlensing
Star
A
D
C
B
A
View from Chandra

Discovery of gravitational lenses

- Double-imaged quasar QSO 0957+561: the first identified gravitational lens
- Discovered by Dennis Walsh, Robert Carswell and Ray Weyman in 1979 (Nature 279, 381-384)
- Both components have identical redshifts and spectra



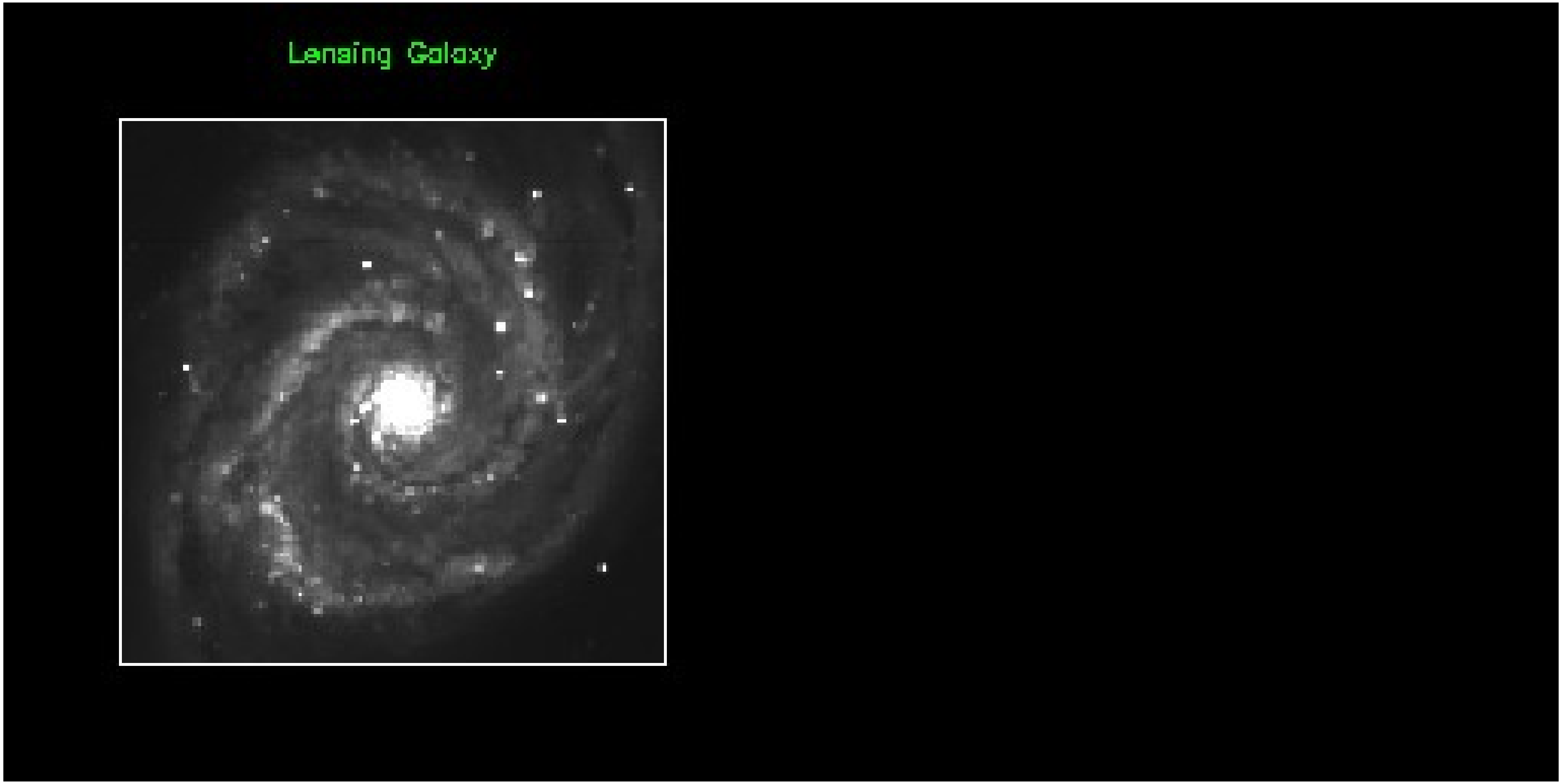


QSO 0957+561: lensing by a luminous galaxy which is almost in front of one of images. A surrounding cluster can also contribute to the lensing.

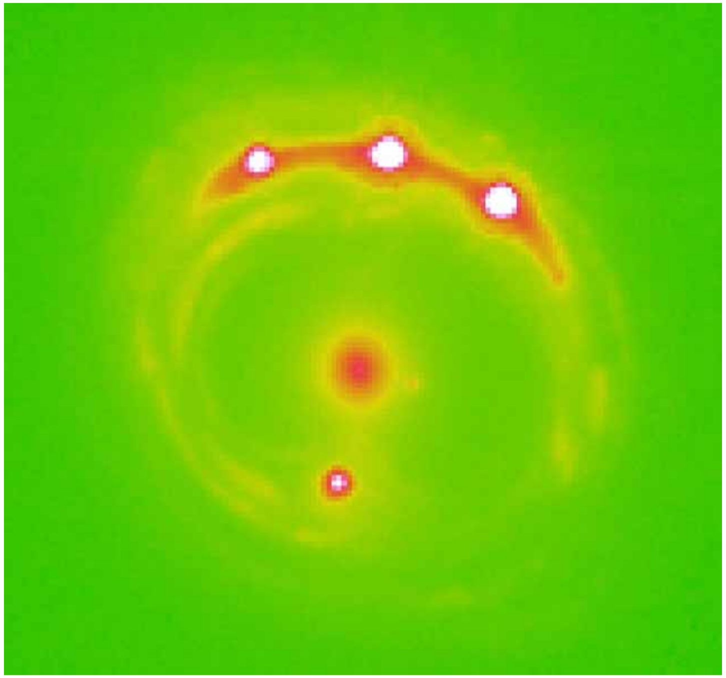
Gravitational lensing applications

1. **Strong lensing:**
   - by galaxies (**macrolensing**) - multiple images of the background sources: determination of cosmological parameters (H_0 from time delays, Ω_M, Ω_Λ, Ω_k from lensing statistics)
   - by stars (**microlensing**) - amplification (magnification) of the background sources: detection of extrasolar planets, studying the innermost regions of active galaxies around their central supermassive black holes, constraining cosmological parameters
   - by clusters of galaxies - giant arcs as images of distant background galaxies: finding the most distant galaxies in the Universe (natural telescopes)
2. **Weak lensing:**
   - by foreground matter with lower density distribution - shape distortions of the background sources: the only direct mean to detect the dark matter, studying the distribution of visible and dark matter in the Universe

Strong lensing by galaxies - macrolensing

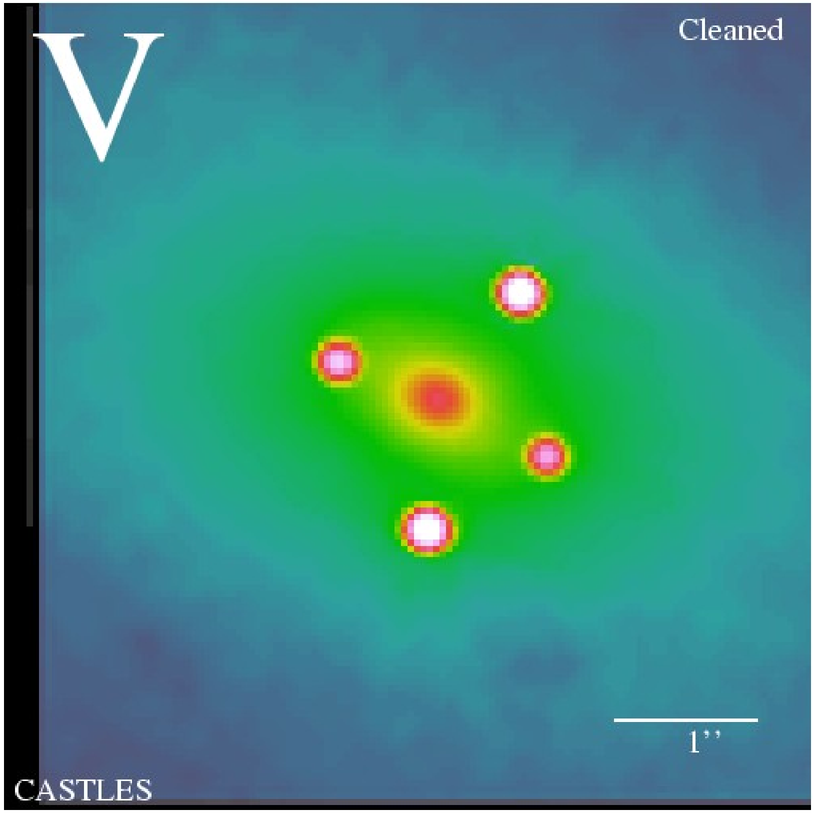


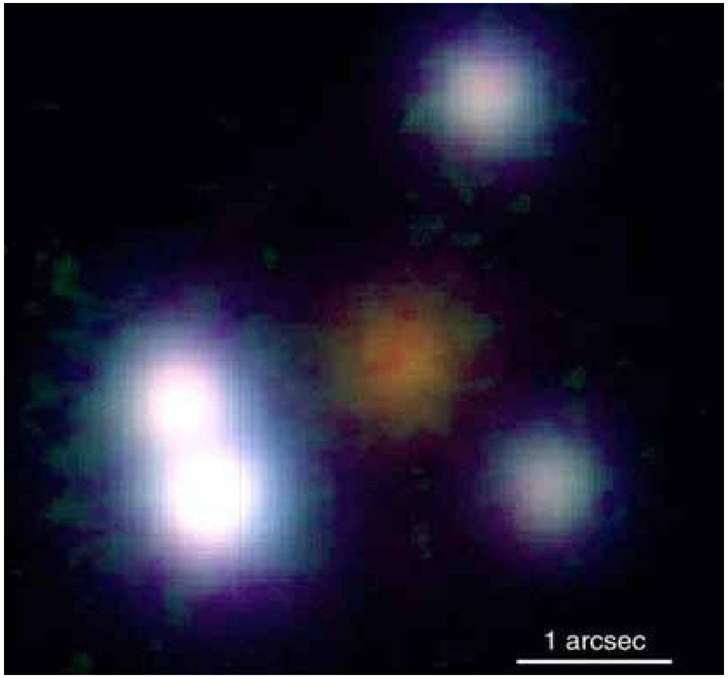
Quasar RXJ1131-1231



- CASTLES Gravitational Lens Data Base: http://www.cfa.harvard.edu/castles/

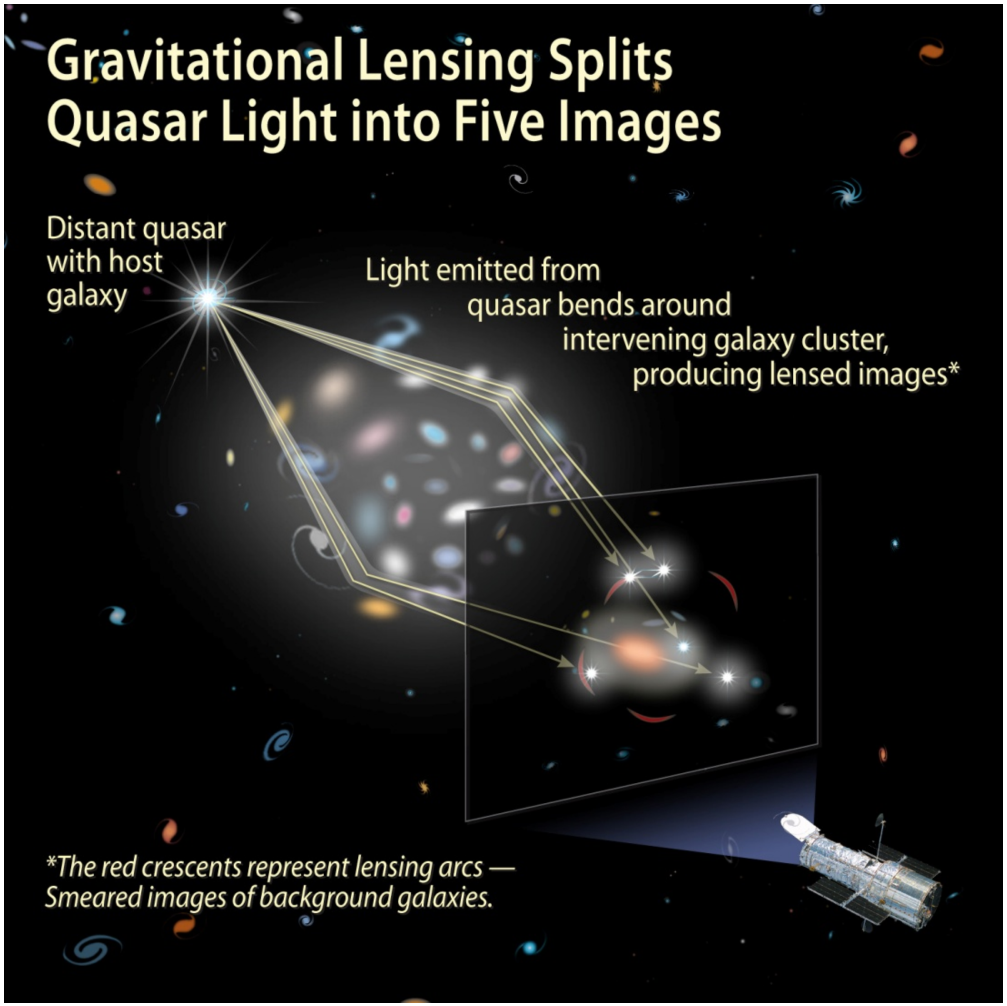
Quasar Q2237+030 at z=1.695 (Einstein cross) and lensing galaxy ZW2237+030 at z=0.0394

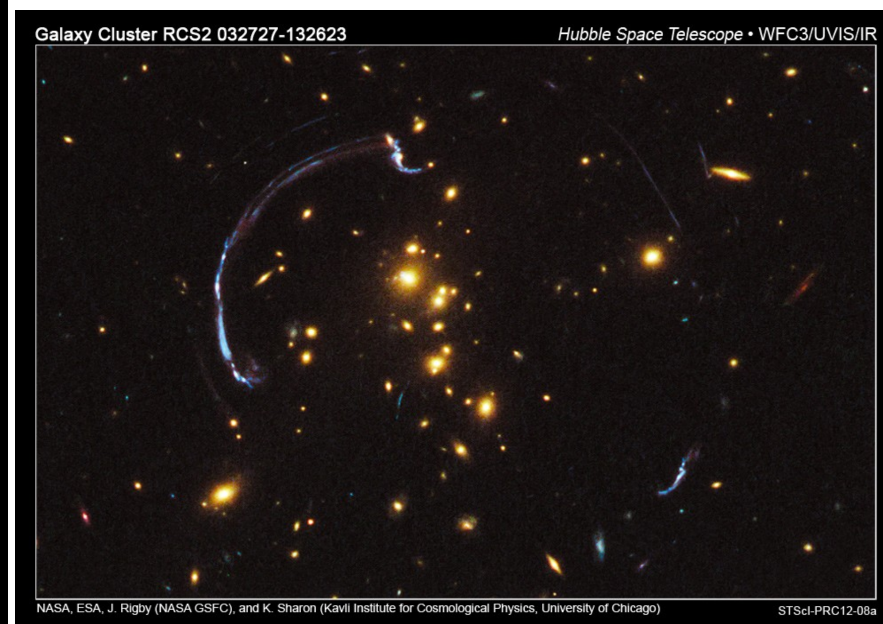




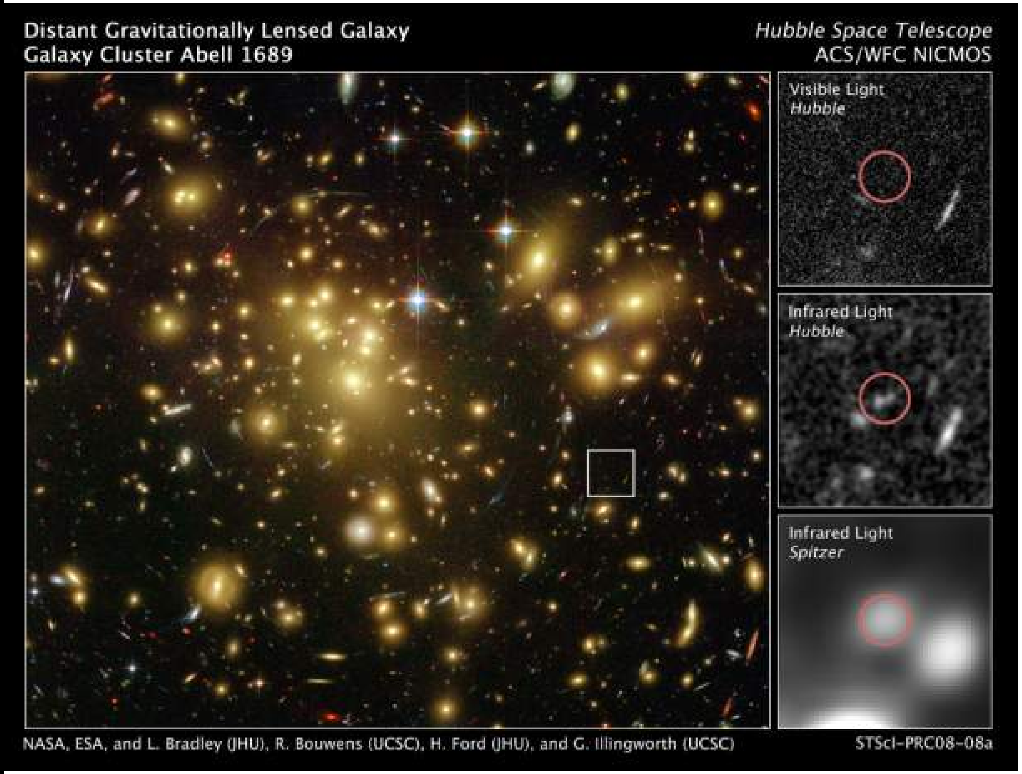
Quasar PG 1115+080

Strong lensing by galaxy clusters (natural telescopes): finding the most distant galaxies



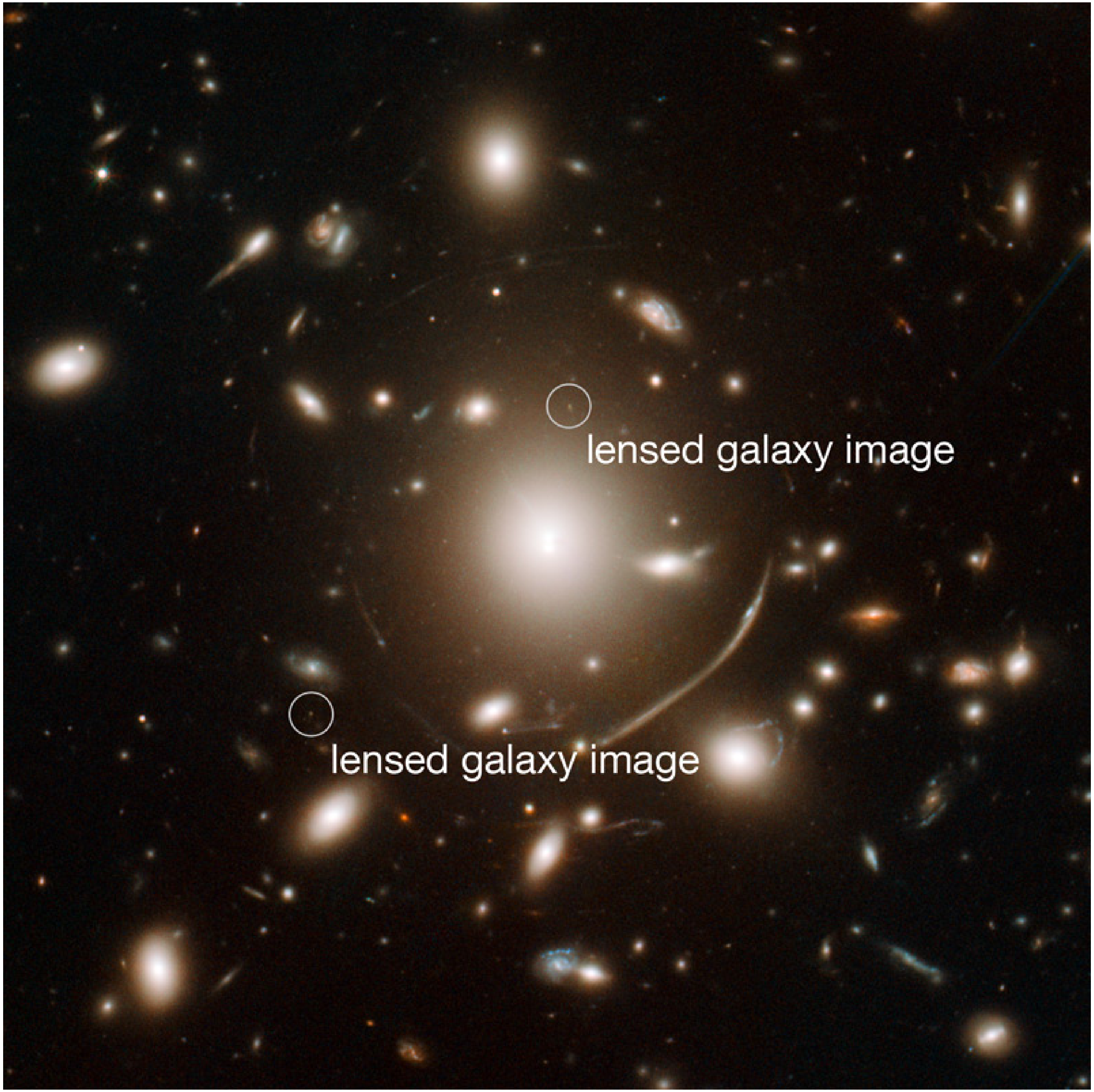


Finding the most distant galaxies

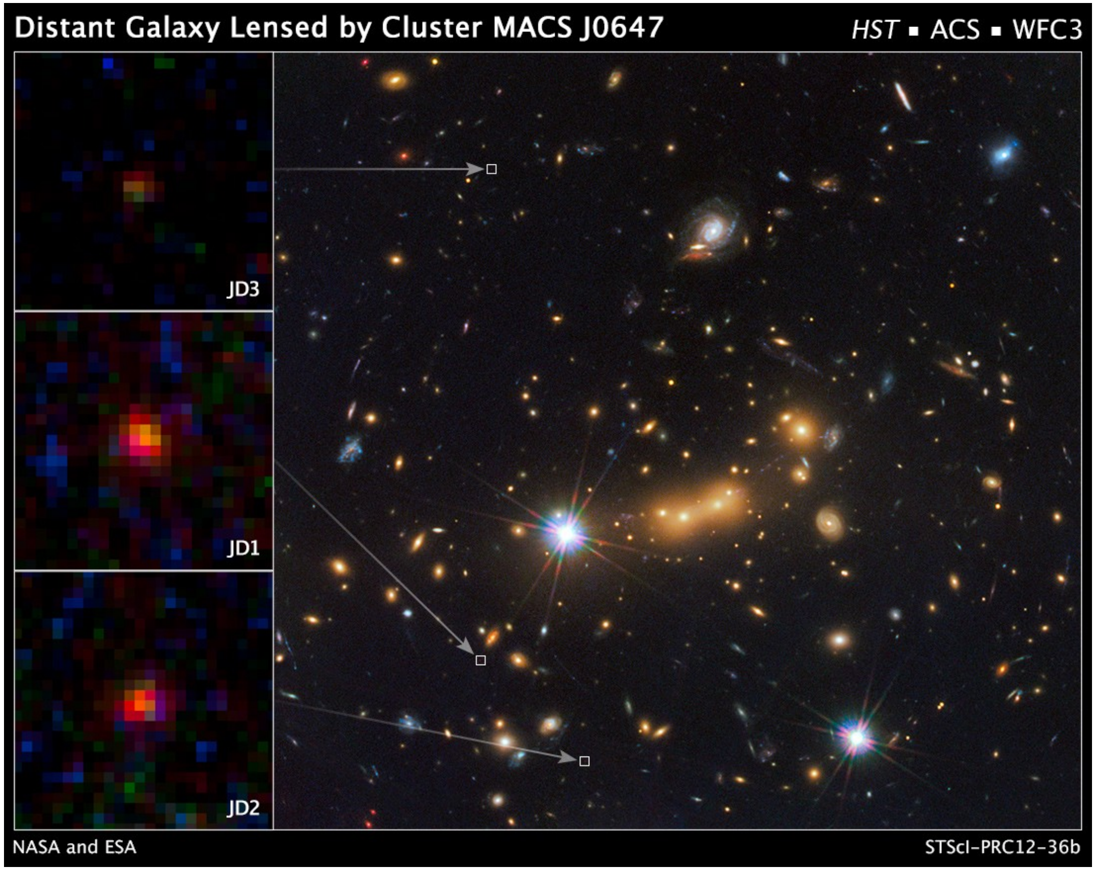


The most distant galaxy known until 2008, located at z~7.6 (≈13×10^9 ly)

Red arc and point: the most distant galaxy known until 2004, located at z~7 (≈13×10^9 ly)

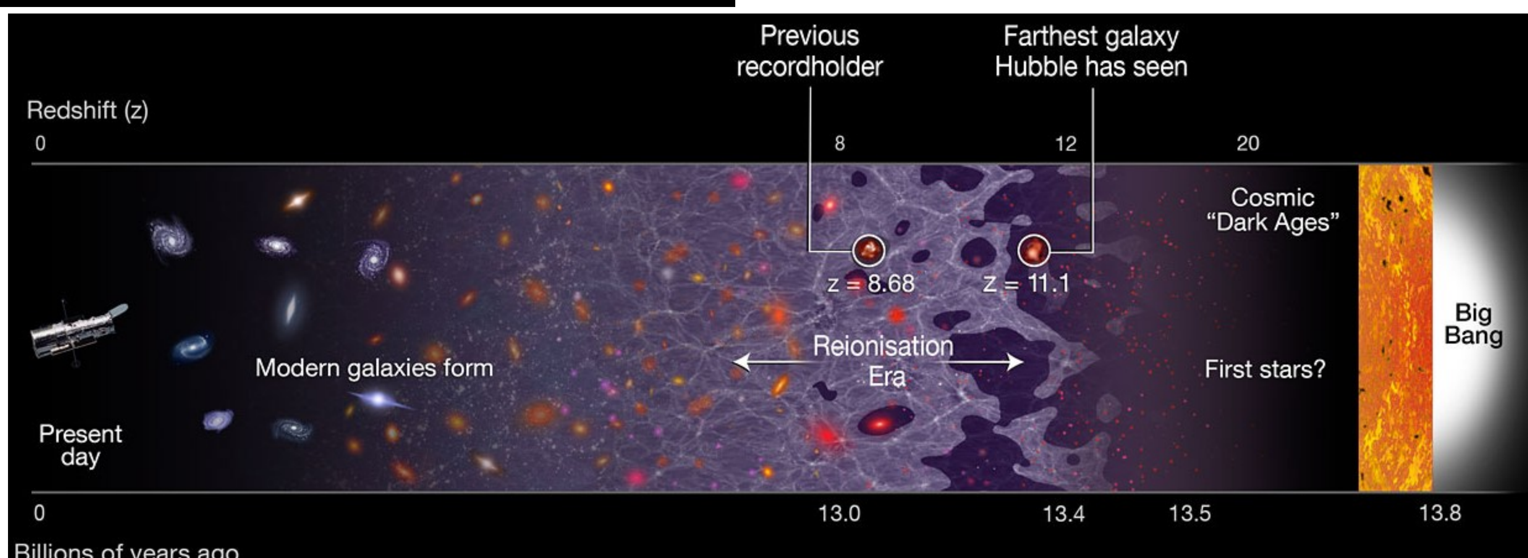


The most distant galaxy known until 2011, formed 13.5 billion years ago, discovered by lensing effect by galactic cluster Abell 383

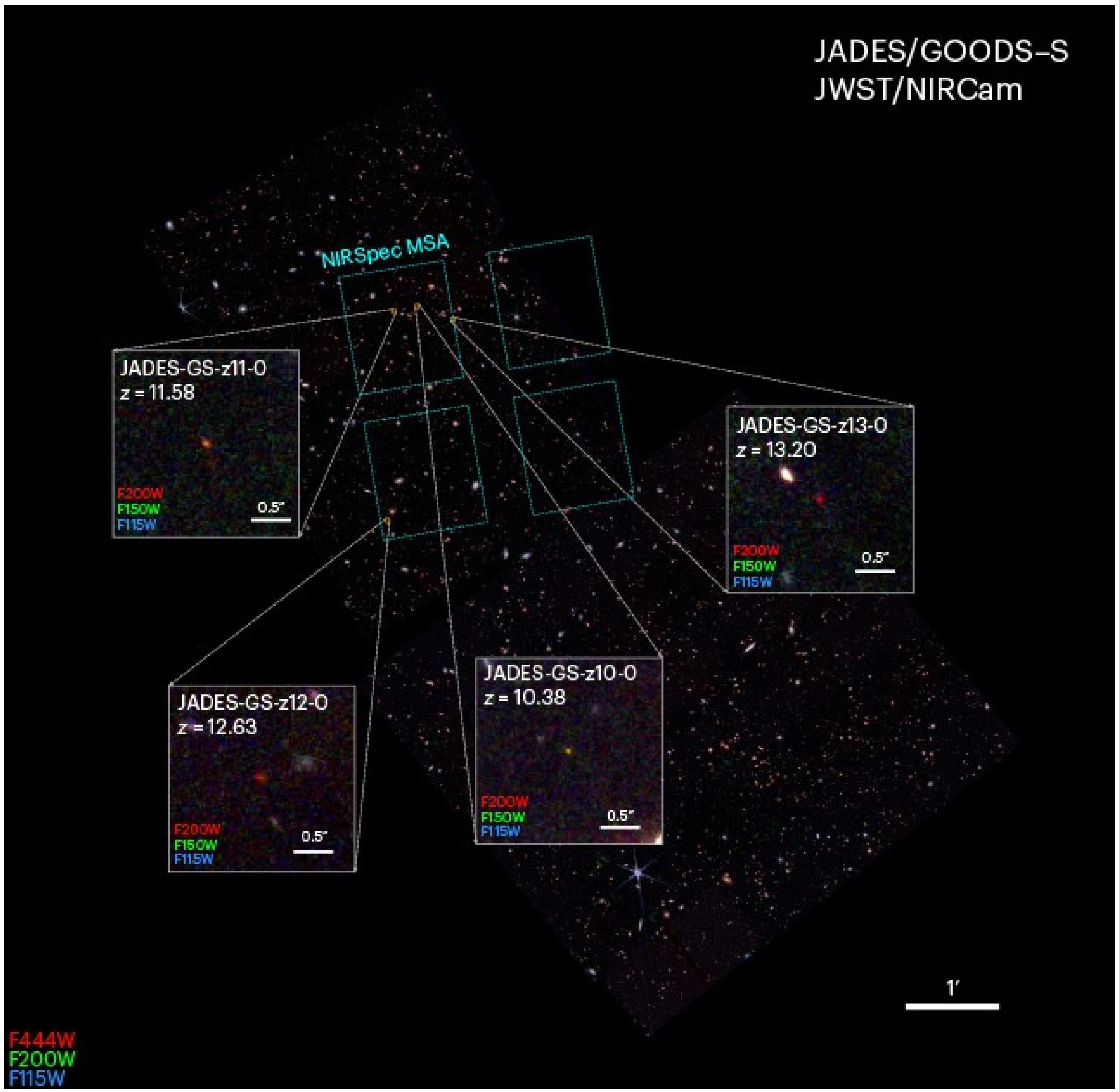


MACS0647-JD: the most distant galaxy discovered in 2012: the distance to the cluster is 5.6 billion ly (z = 0.591) and to the lensed galaxy is 13.3 billion ly (z = 11)

- Current record from 2016: galaxy GN-z11 at z = 11.1



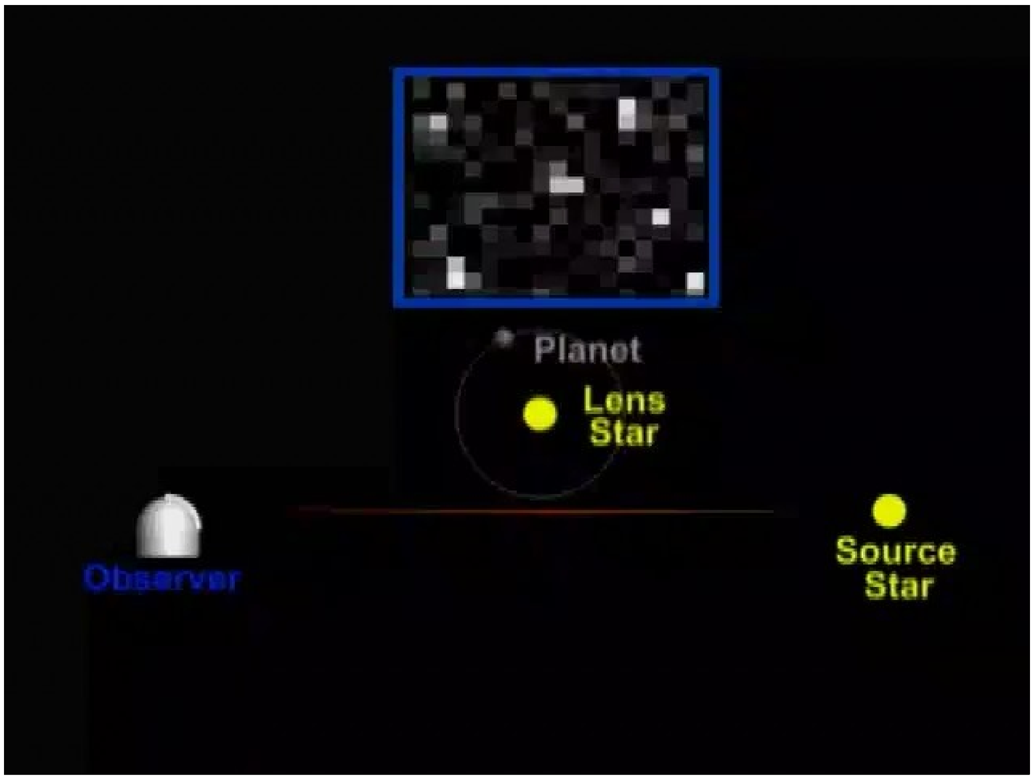
Four most distant galaxies ever seen detected by JWST in 2023

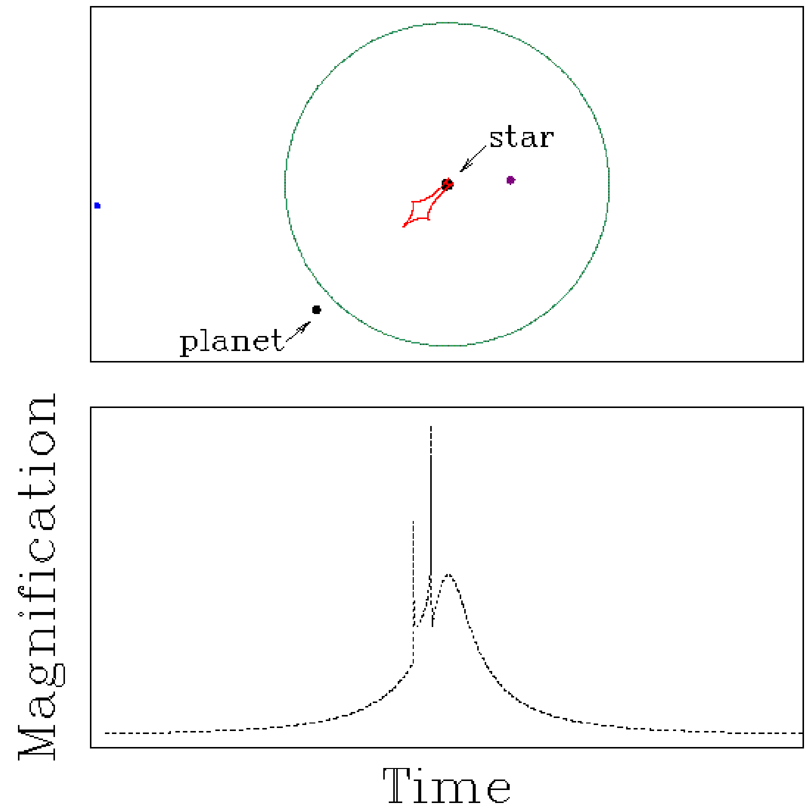


Gravitational lensing by galaxy cluster Abell 2744 (Pandora's Cluster)

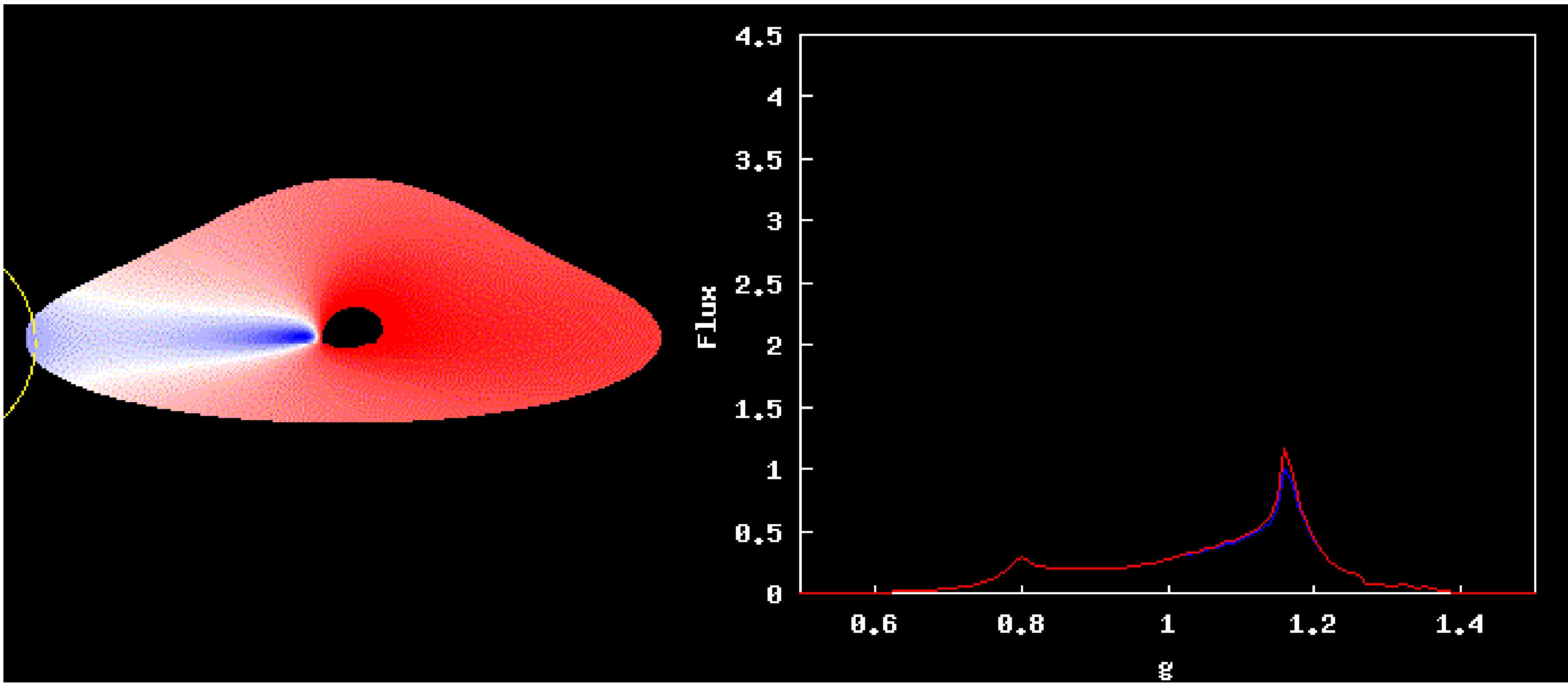
Robertson et al. 2023, Nature Astronomy, 7, 611.

Microlensing (strong lensing by stars): detection of extrasolar planets



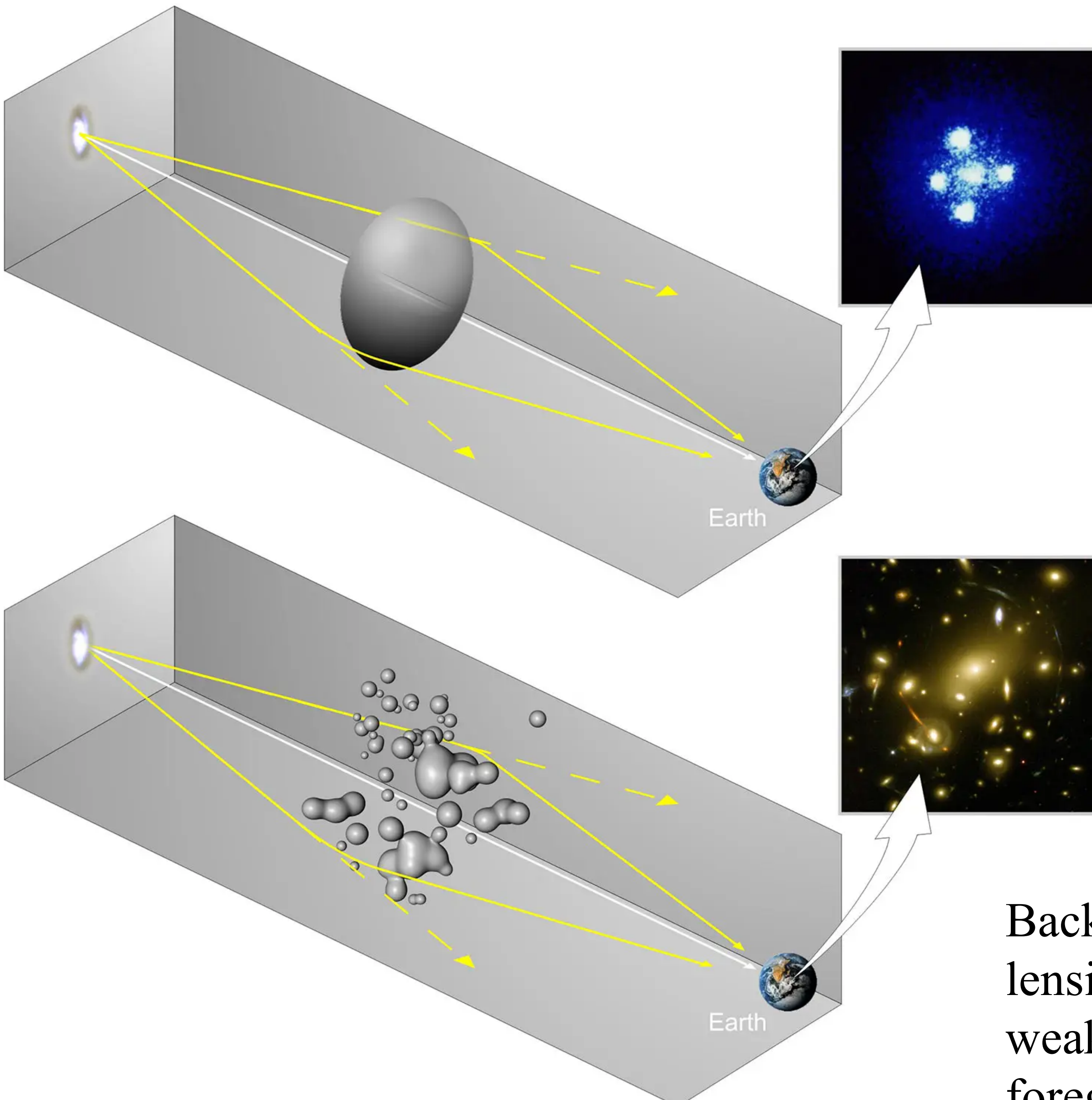


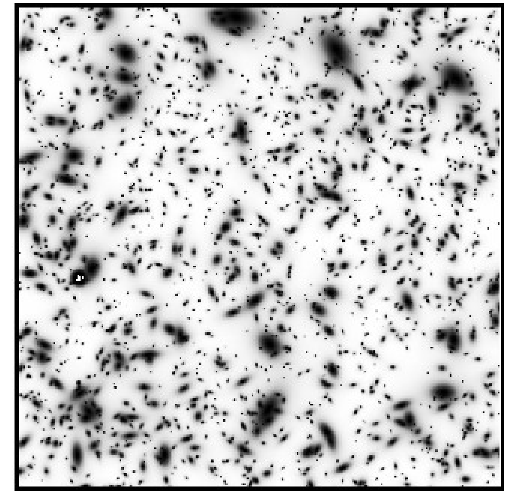
Microlensing applications for studying the physics and space-time geometry in vicinity of supermassive black holes

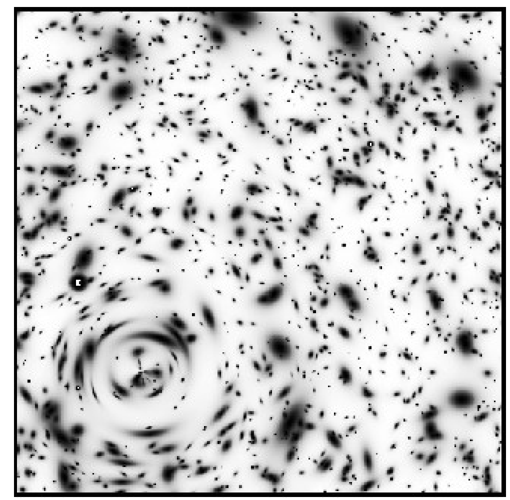


Influence of a point-like microlens on X-ray radiation from a relativistic accretion disk around a SMBH

Weak lensing: shape distortions of the background sources by foreground matter

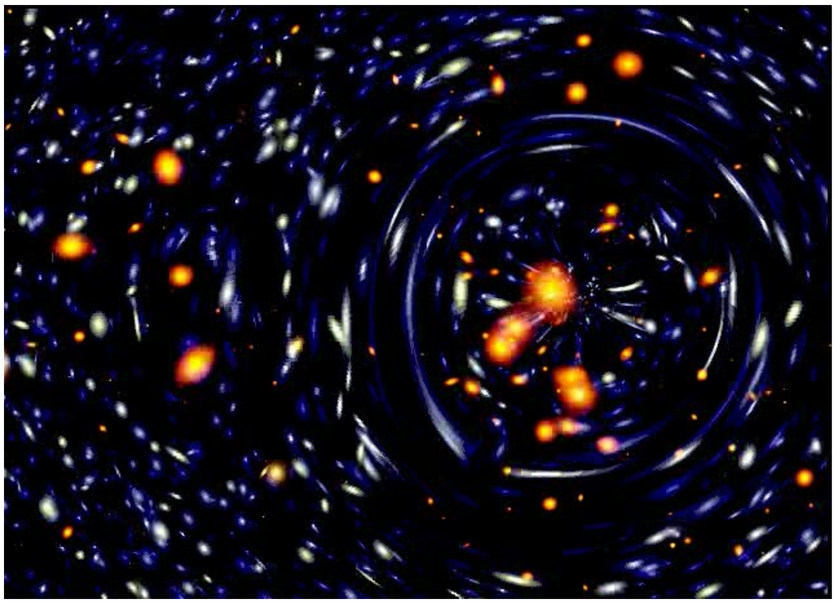


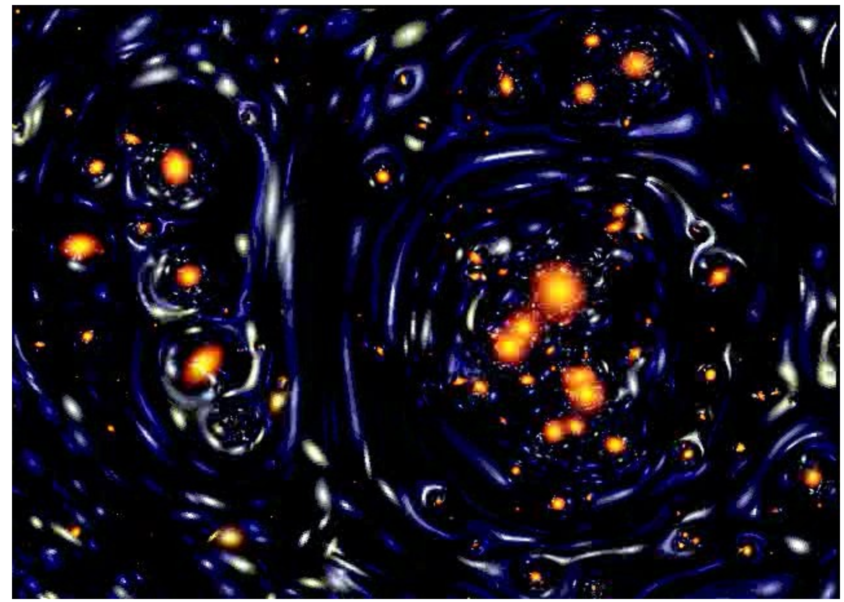




Background galaxies in absence of lensing (top), and in the case of weak lensing by invisible foreground galaxy cluster (bottom)

Weak lensing: the only direct mean to detect the dark matter

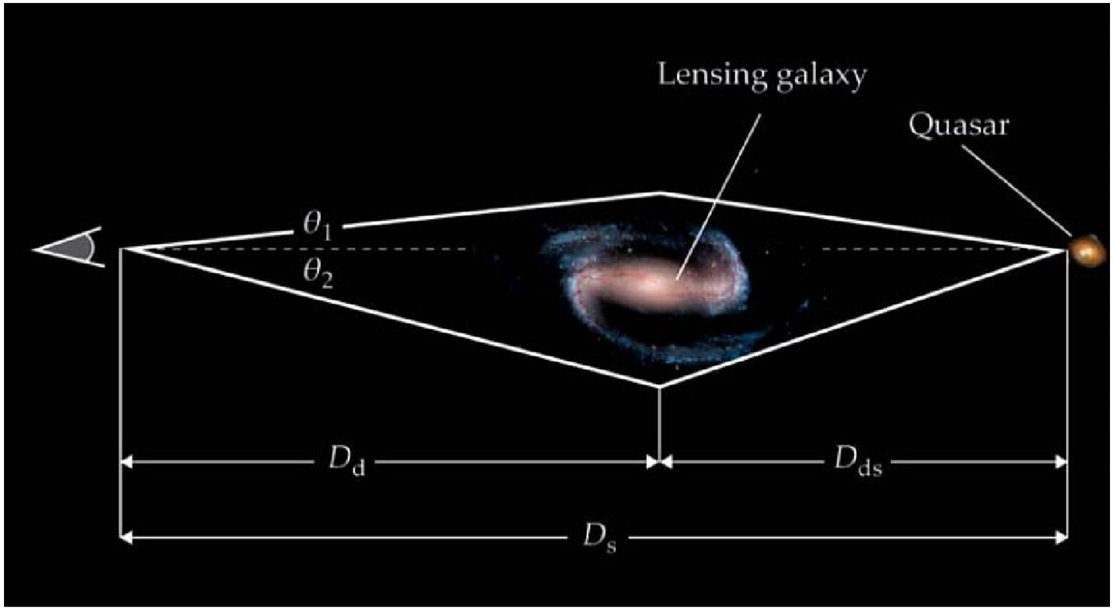


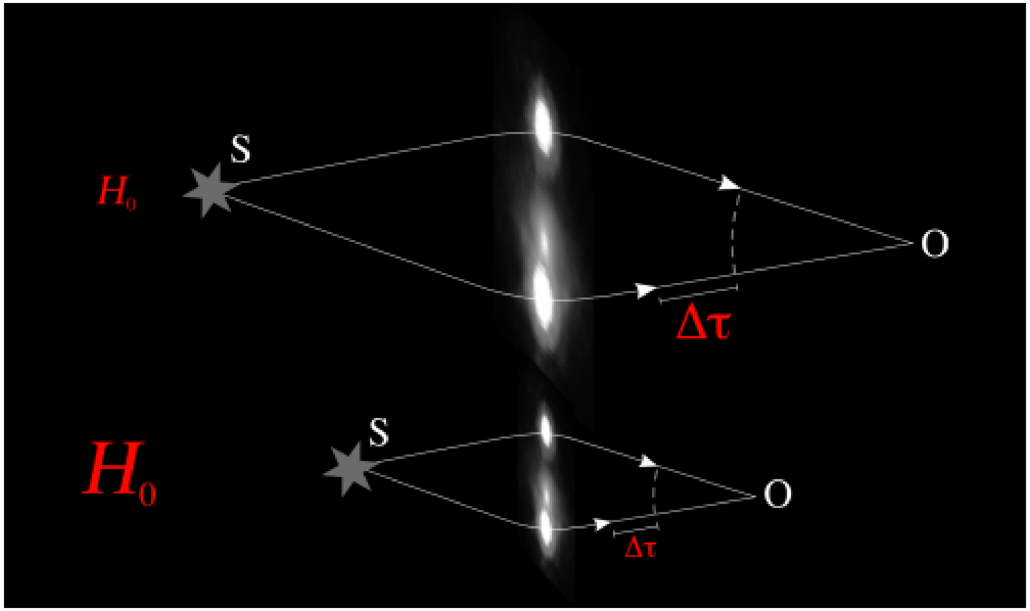


Gravitational lensing by a massive cluster of galaxies with two different distributions of the same amount of the dark matter over the cluster (orange), causing a particular distortion of the background galaxies (white and blue).

Cosmological applications of gravitational lensing

- D_d, D_s, D_{ds} - cosmological distances between the observer and lens, observer and source, and lens and source, respectively
- Angular diameter distances depending on the cosmological parameters: $D_A(z; H_0, \Omega_M, \Omega_\Lambda, \Omega_\kappa)$
- Lensing time-delay: $\Delta t = \tau_2 - \tau_1 \propto H_0^{-1}$





Exam Question

1. Gravitational lenses: basic principles, types and applications.

Literature

Book:

1. *Gravitational Lensing*: Strong, Weak and Micro, Book Series: Saas-Fee Advanced Courses
- P. Schneider - *Introduction to Gravitational Lensing and Cosmology*
- C. S. Kochanek - *Strong Gravitational Lensing*
- P. Schneider - *Weak Gravitational Lensing*
- J. Wambsganss - *Gravitational Microlensing*

Exercise 1

Calculate the angle of light deflection by Sun (i.e. at $1R_\odot$), knowing that gravitational constant, when expressed in convenient units, is:

$$G \approx 190809 \, \frac{\mathrm{km}^2}{\mathrm{s}^2} \frac{R_\odot}{M_\odot}$$

Exercise 2

Calculate the light deflection angle of the quasar J0842+1835 when Jupiter passed within 14 Jovian radii of this quasar on September 8th 2002. Note that Jovian radius is $R \approx 0.1004 \, R_\odot$, while its mass is $M \approx M_\odot/1047$.

Solution 1

$$\alpha = \frac{4GM}{c^2\xi} \quad \overset{\xi=1\,R_\odot}{\Longrightarrow} \quad \alpha_\odot = \frac{4GM_\odot}{c^2R_\odot} = \frac{4\cdot 190809}{9\cdot 10^{10}} = 8.4804\times 10^{-6}\ \mathrm{rad}$$

$$1\ \mathrm{rad} = (648000/\pi)'' \approx 206265'' \quad \Rightarrow$$

$$\alpha_\odot \approx 8.4804\times 10^{-6}\cdot 206265'' \approx 1''.75$$

Solution 2

$$M = \frac{M_\odot}{1047} \wedge \xi = 14\ R \Rightarrow \alpha = \frac{4GM}{c^2\xi} = \frac{\alpha_\odot}{14 \cdot 0.1004 \cdot 1047} \approx 1189\ \mu\text{as}$$