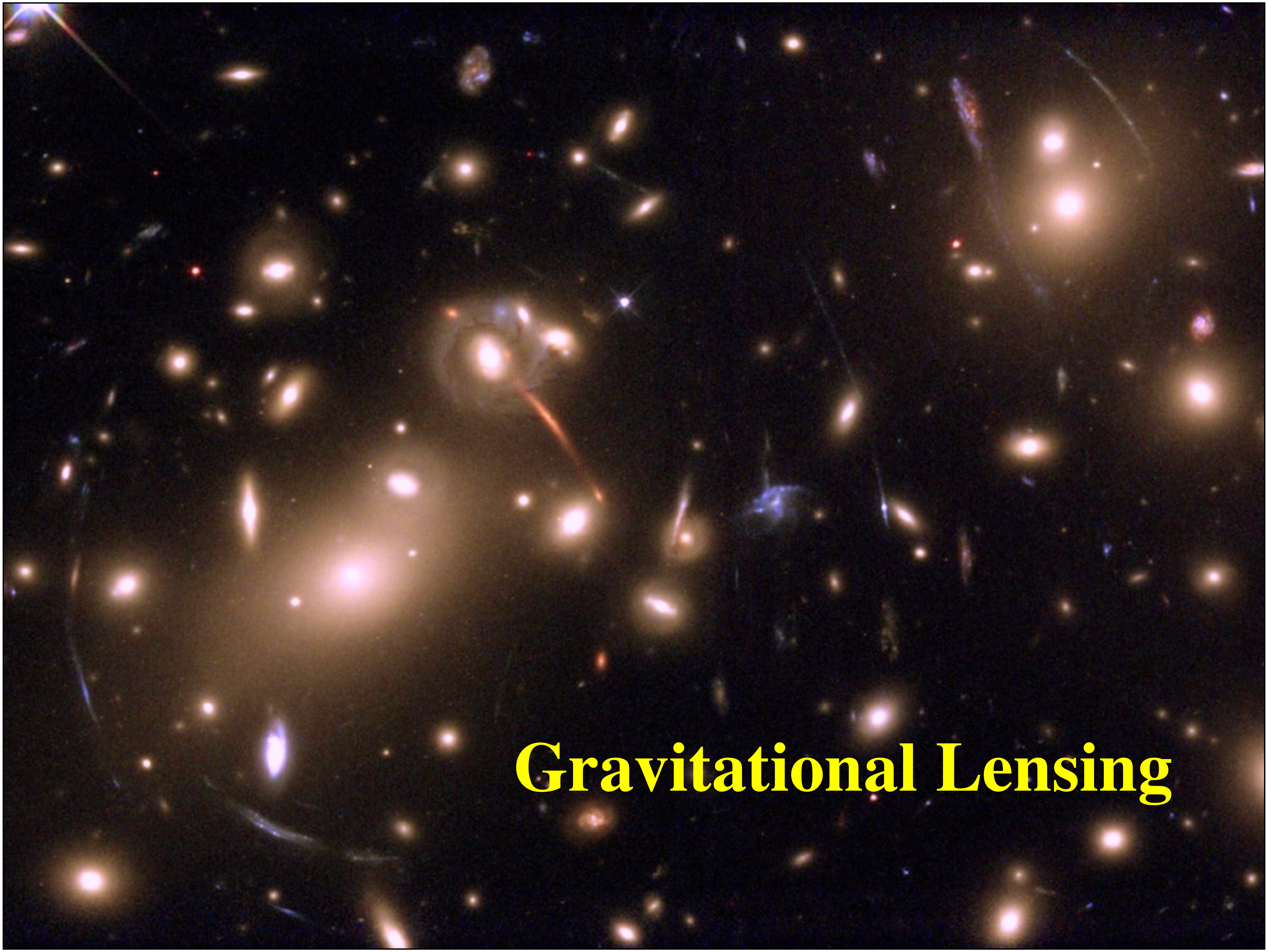
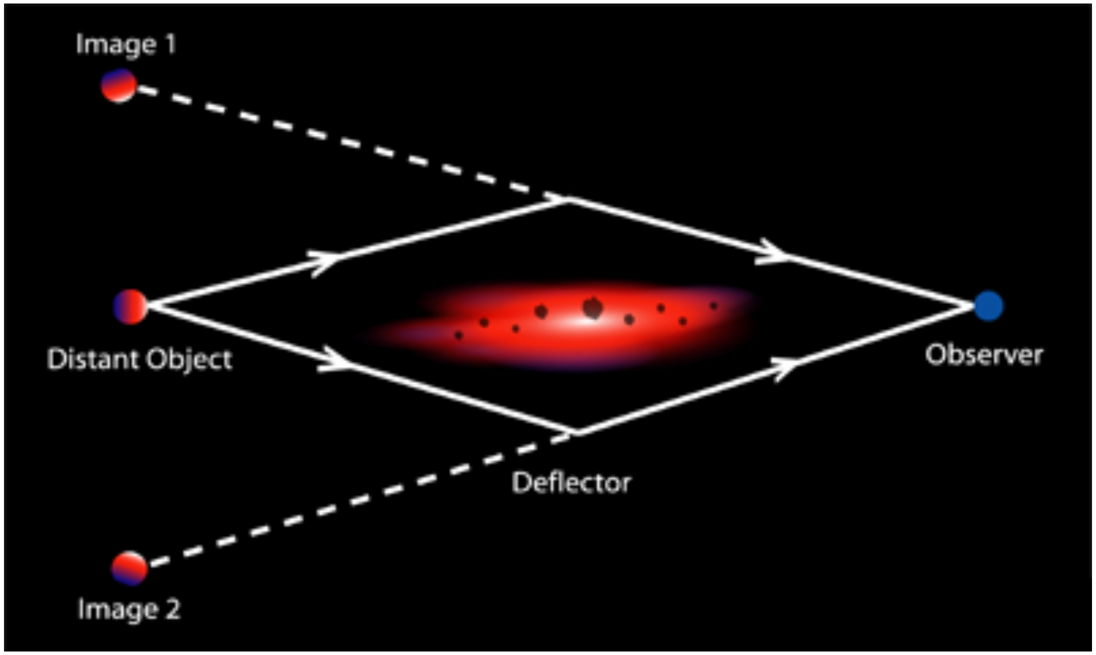
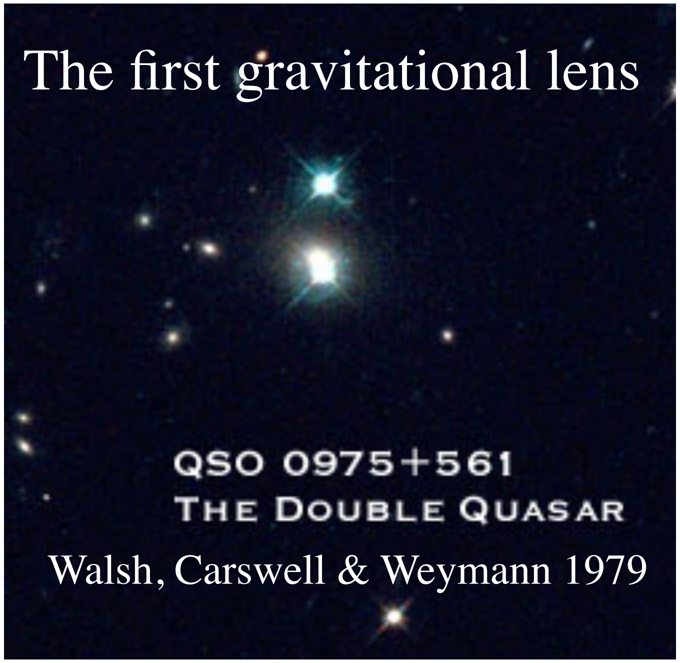

Gravitational Lensing

Gravitational Lensing:
Mapping the Distribution of the Dark Matter

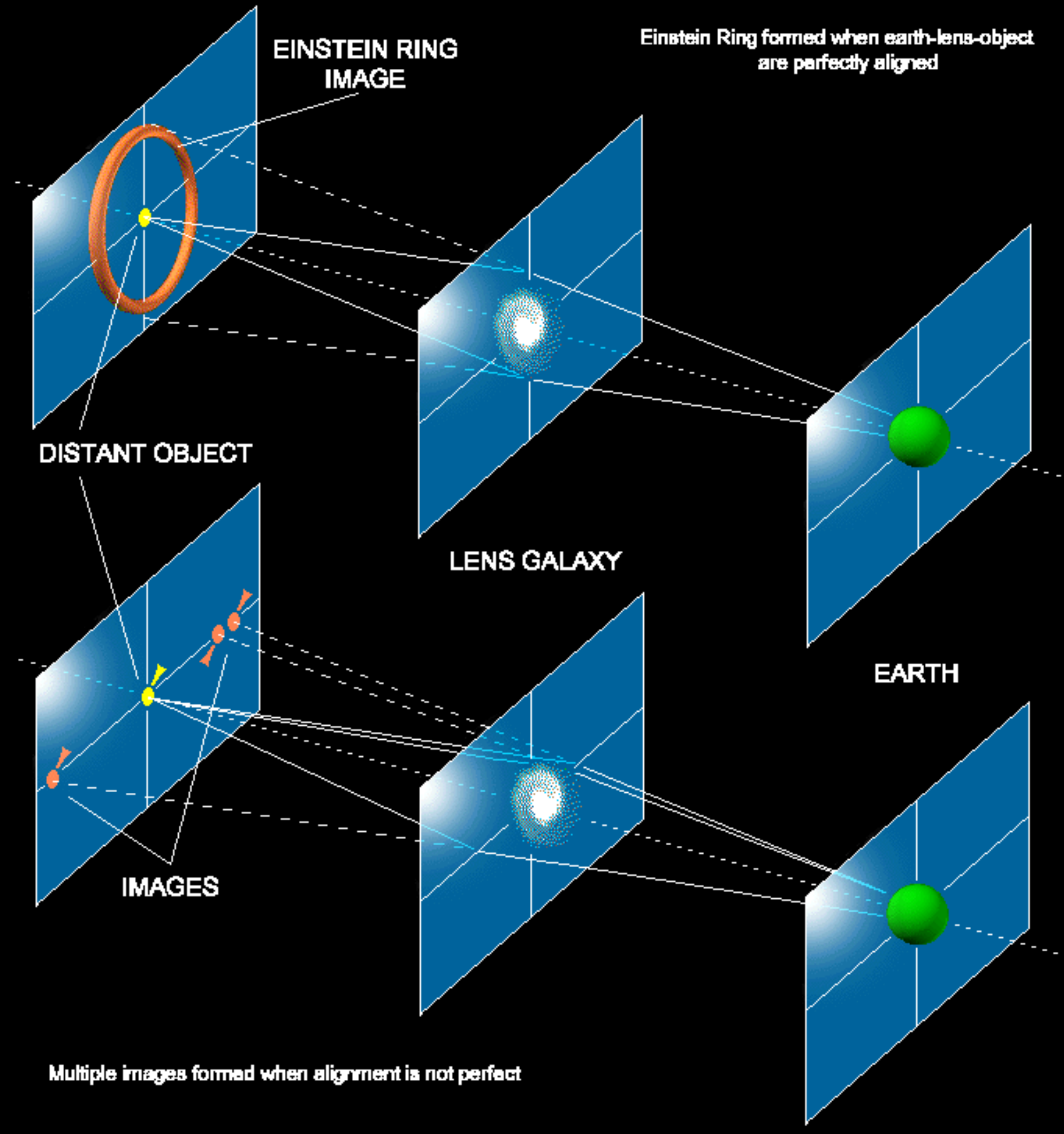
- We know from general relativity that mass - whether it is visible or not - bends light. This opens a possibility of "seeing" the distribution of dark matter
- Chowlson (1924) and Einstein (1936) predicted that if a background object is directly aligned with a point source mass, the light rays will be deflected into an "Einstein Ring"





Gravitational lensing in the strong regime

Misalignment of the line of sight and the center of the lensing mass splits the Einstein ring into multiple images



Gravitationally Lensed Galaxies - "Arcs"

In 1937, Zwicky predicted that one could study the mass distribution (dark matter) in clusters by studying background galaxies that are lensed by the dark matter in the cluster. This was not observationally feasible until the mid-1990's

Galaxy Cluster Abell 1689 Details

Hubble Space Telescope • Advanced Camera for Surveys

Gravitational Lensing

Photons are deflected by gravitational fields - hence images of background objects are distorted if there is a massive foreground object along the line of sight.

Bending of light is similar to deflection of massive particles, except that GR predicts that for **photons** the bending is exactly twice the Newtonian value:

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

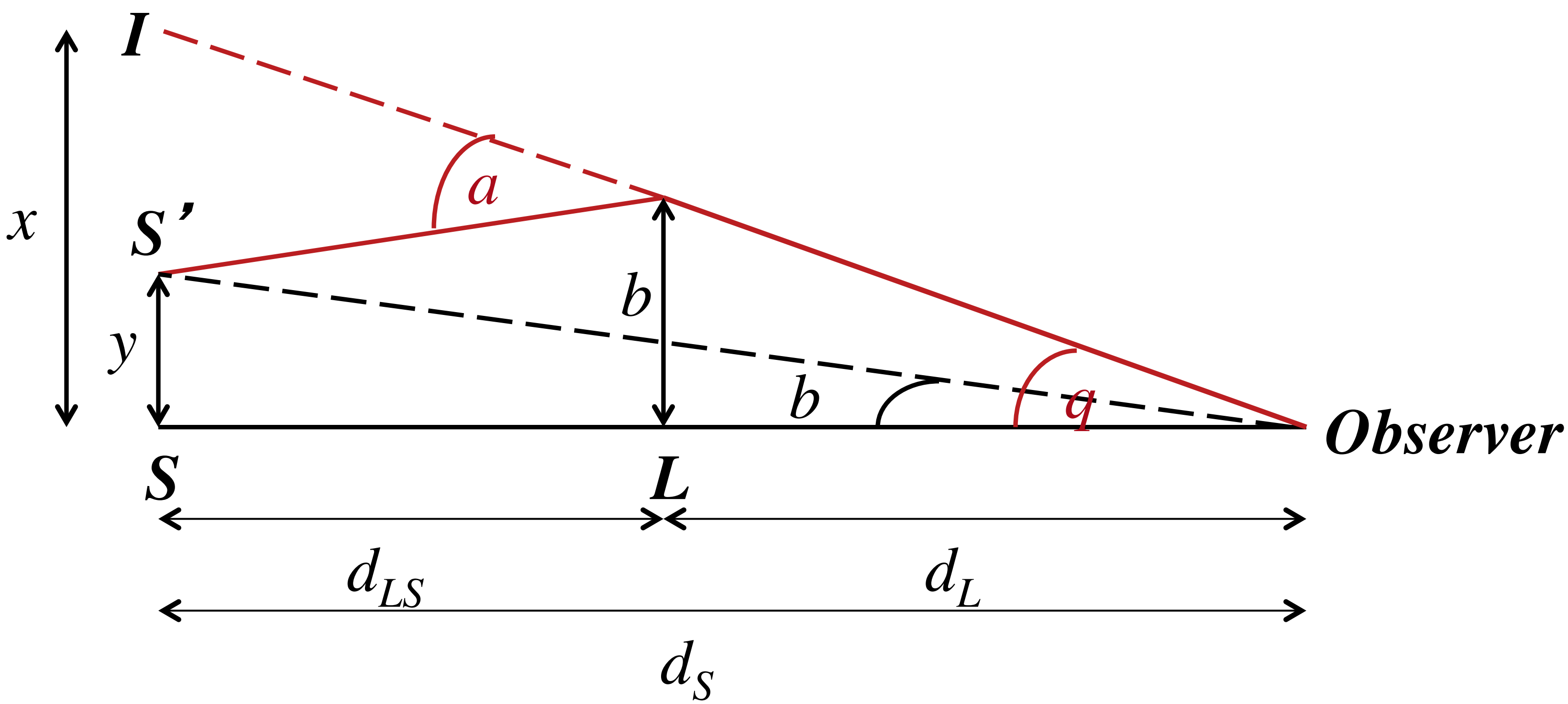
…where $\boldsymbol{R_s}$ is the Schwarzschild radius of a body of mass $\boldsymbol{M}$, and $\boldsymbol{b}$ is the impact parameter. This formula is valid if $\boldsymbol{b} \gg \boldsymbol{R_s}$:

- Not valid very close to a black hole or neutron star
- Valid everywhere else
- Implies that deflection angle a will be small

  e.g., for the stars near the Solar limb, ~ 2 arcsec

Geometry for Gravitational Lensing

Consider sources at distance d_S from the **observer O.**
A point mass **lens *L*** is at distance $\boldsymbol{d_L}$ from the observer:



Observer sees the image I of the source S' at an angle q from line of sight to the lens. In the absence of deflection, would have deduced an angle b.

Recall that all the angles ***a, b, q*** are small, so:

$$\theta = \frac{b}{d_L} = \frac{x}{d_S}, \quad \beta = \frac{y}{d_S}, \quad \alpha = \frac{x-y}{d_{LS}}$$

Substitute these angles into expression for deflection angle:

$$\frac{x-y}{d_{LS}} = \frac{4GM}{bc^2}$$

$$\theta d_S - \beta d_S = \frac{4GM}{bc^2} d_{LS}$$

$$\theta - \beta = \frac{1}{\theta} \underbrace{\frac{4GM}{c^2} \frac{d_{LS}}{d_S d_L}}_{\text{Geometric factors}}$$

Quadratic equation for the apparent position of the image ***q***, given the true position ***b*** and knowledge of the mass of the lens and the various distances

Simplify this equation by defining an angle $\boldsymbol{\theta_E}$, the **Einstein radius** :

$$\theta_E = \frac{2}{c}\sqrt{\frac{GMd_{LS}}{d_L d_S}}$$

Equation for the apparent position then becomes:

$$\theta^2 - \beta\theta - \theta_E^2 = 0$$

Solutions are: $$\theta_\pm = \frac{\beta \pm \sqrt{\beta^2 + 4\theta_E^2}}{2}$$

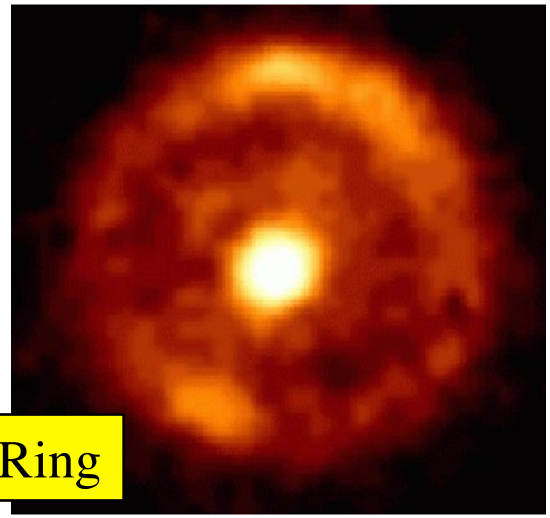
For a source exactly behind the lens, $\boldsymbol{b} = 0$. Source appears as an **Einstein ring** on the sky, with radius $\boldsymbol{\theta_E}$

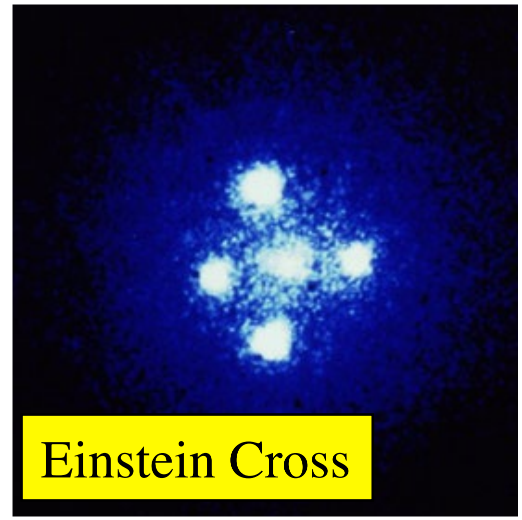
For $\boldsymbol{b} > 0$, get two images, one inside and one outside the Einstein ring radius

Different Lensing Regimes

Conceptually simplest situation for gravitational lensing is when the lens is massive enough to produce a large angle of deflection.

Case where we can resolve multiple images of the background source is called **strong lensing**

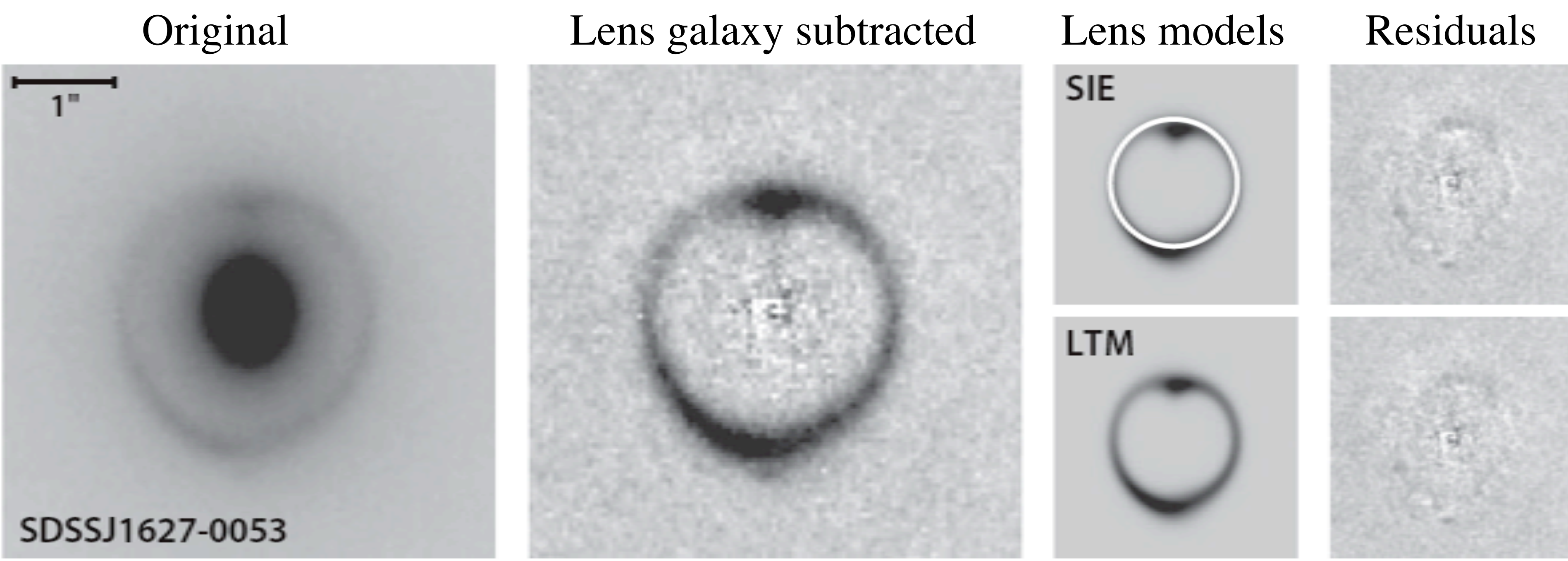

Einstein Ring


Einstein Cross

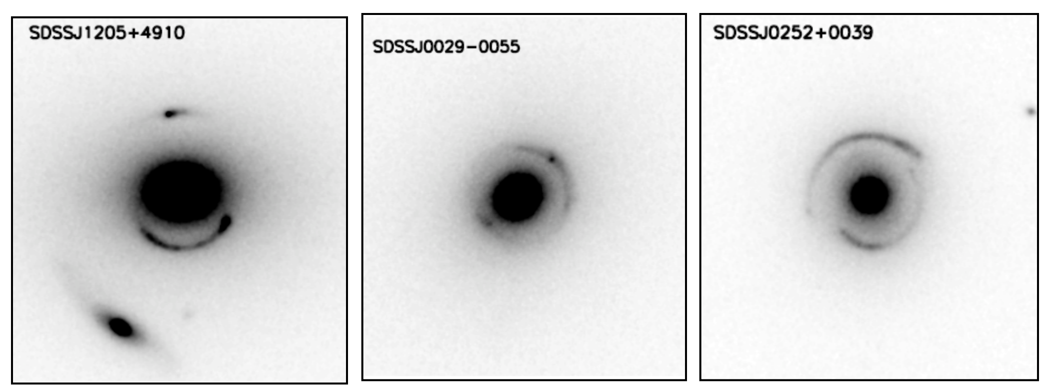
If the lensing is not strong enough to split the images, but it does magnify and distort them, it is called **weak lensing.** This is the effect of the large-scale structure or the outskirts of clusters of galaxies on the background sources (galaxies). ***These image distortions can then be inverted to map the mass distribution.***

Galaxy Masses From Gravitational Lensing

Treu et al. (the SLACS collaboration)

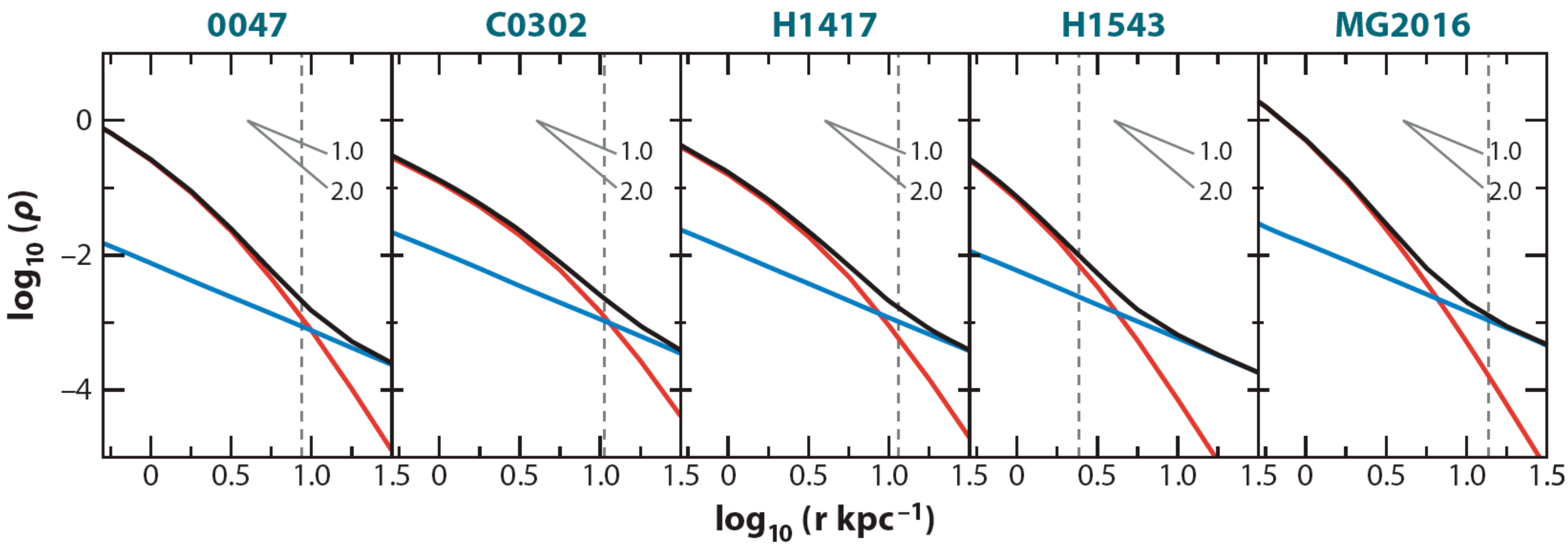


Typically using a Singular Isothermal Ellipsoid (SIE) as a lens mass model



Density Profiles for SLACS Galaxies

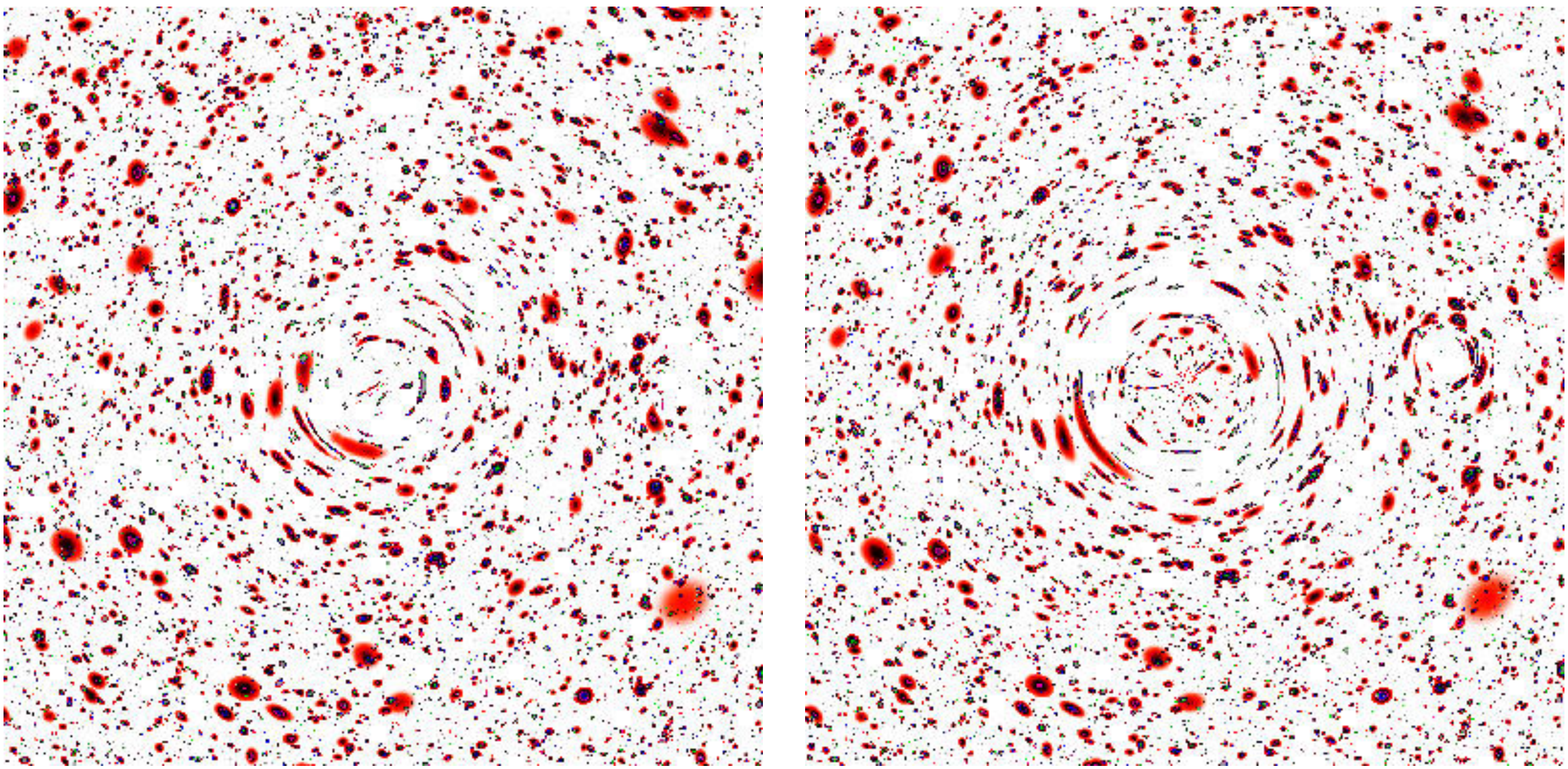
From the best-fit lensing and dynamical models:
red = stars, **blue** = dark matter, **black** = total



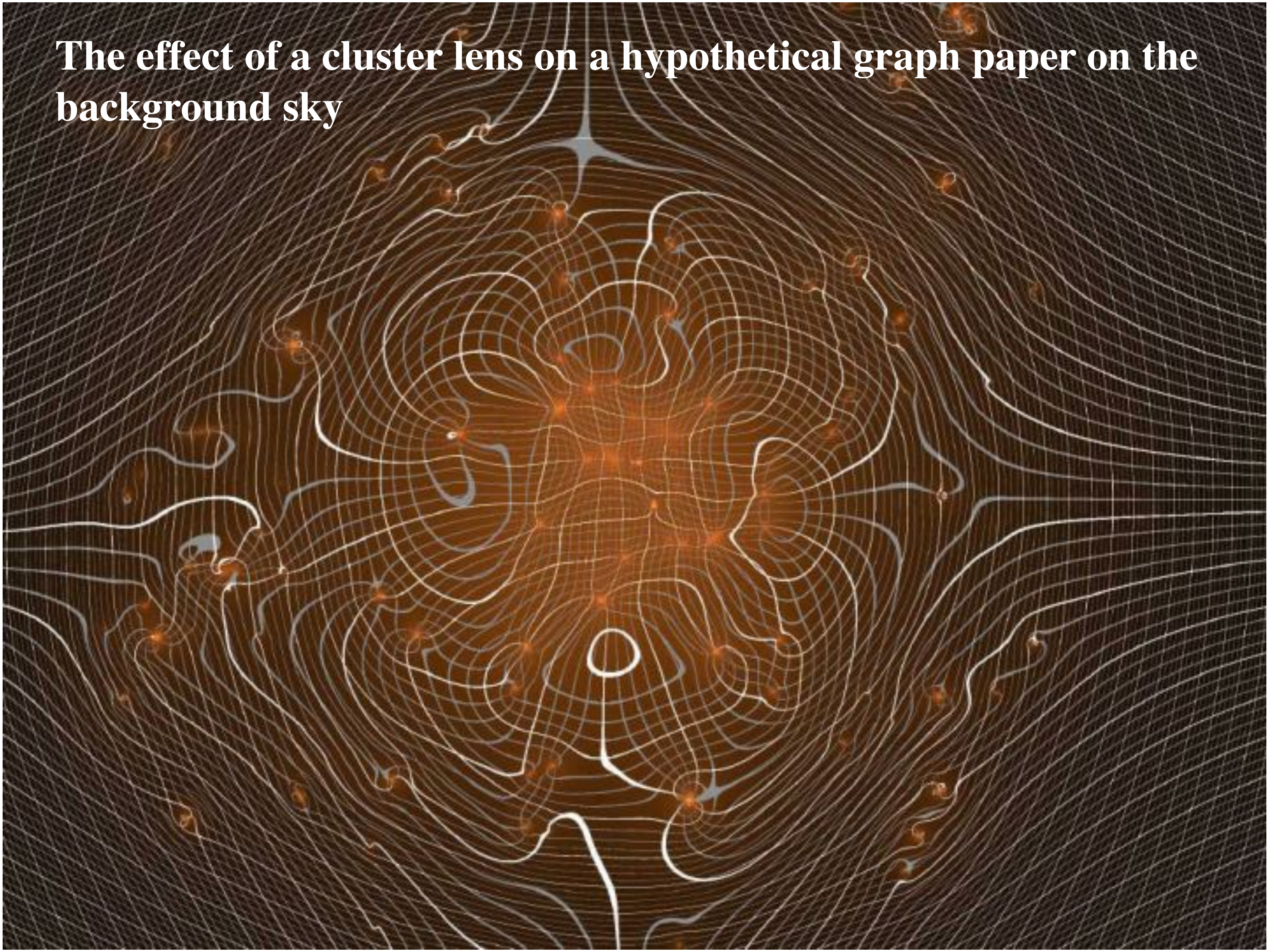
Mass-density profiles of lens galaxies inferred from a strong lensing and dynamical analysis. In addition to the mass associated with the stars (*red line*), the data require a more extended mass component, identified as the dark matter halo (*blue line*). Although neither component is a simple power law, the total mass profile is close to isothermal, i.e., $\gamma' = 2$. The vertical dashed line identifies the location of the Einstein radius. (Figure from Treu & Koopmans 2004, reproduced by permission of the Am. Astron. Soc.)

Weak Lensing Regime

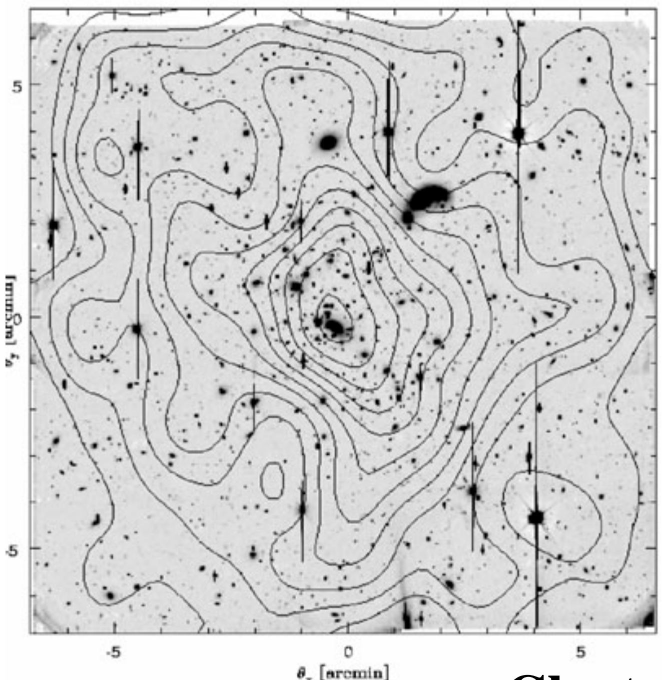
Simulated examples of the appearance of a background field of galaxies, with cluster-type masses in the foreground. Strong lensing is apparent near the center. At larger radii, one has to use statistics of image elongations and orientations



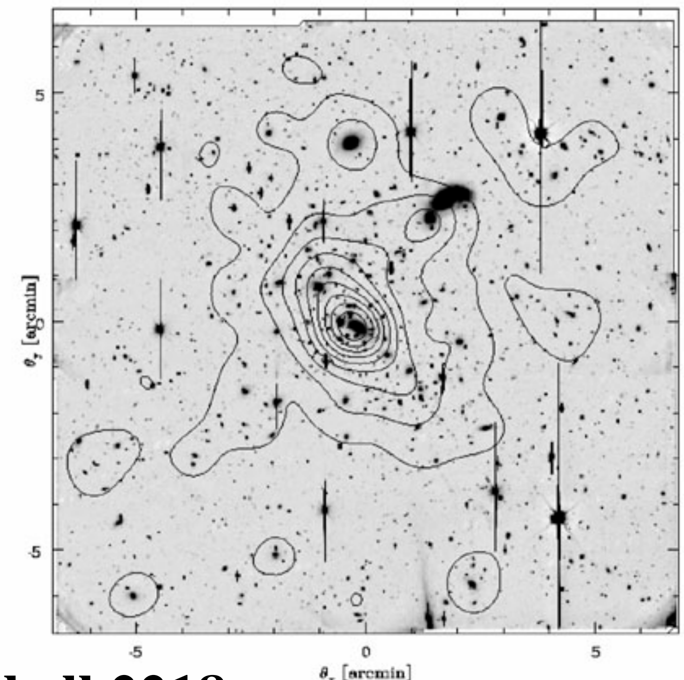
The effect of a cluster lens on a hypothetical graph paper on the background sky



Galaxy number density

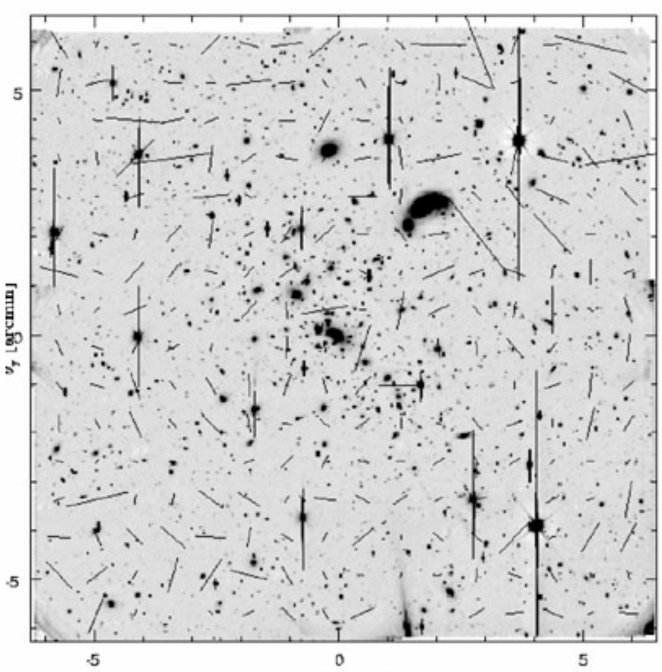


Light

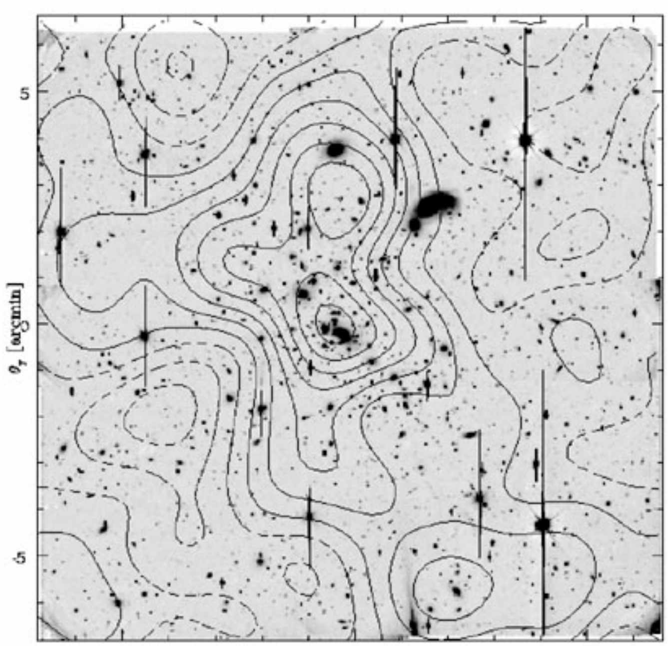


Cluster Abell 2218

Shear map



Mass



Squires et al. 1996

Cluster Masses From Gravitational Lensing

Strong lensing constraints:

A370	$M \sim 5 \times 10^{13} h^{-1} M_\odot$	$M/L \sim 270h$
A2390	$M \sim 8 \times 10^{13} h^{-1} M_\odot$	$M/L \sim 240h$
MS2137	$M \sim 3 \times 10^{13} h^{-1} M_\odot$	$M/L \sim 500h$
A2218	$M \sim 1.4 \times 10^{14} h^{-1} M_\odot$	$M/L \sim 360h$

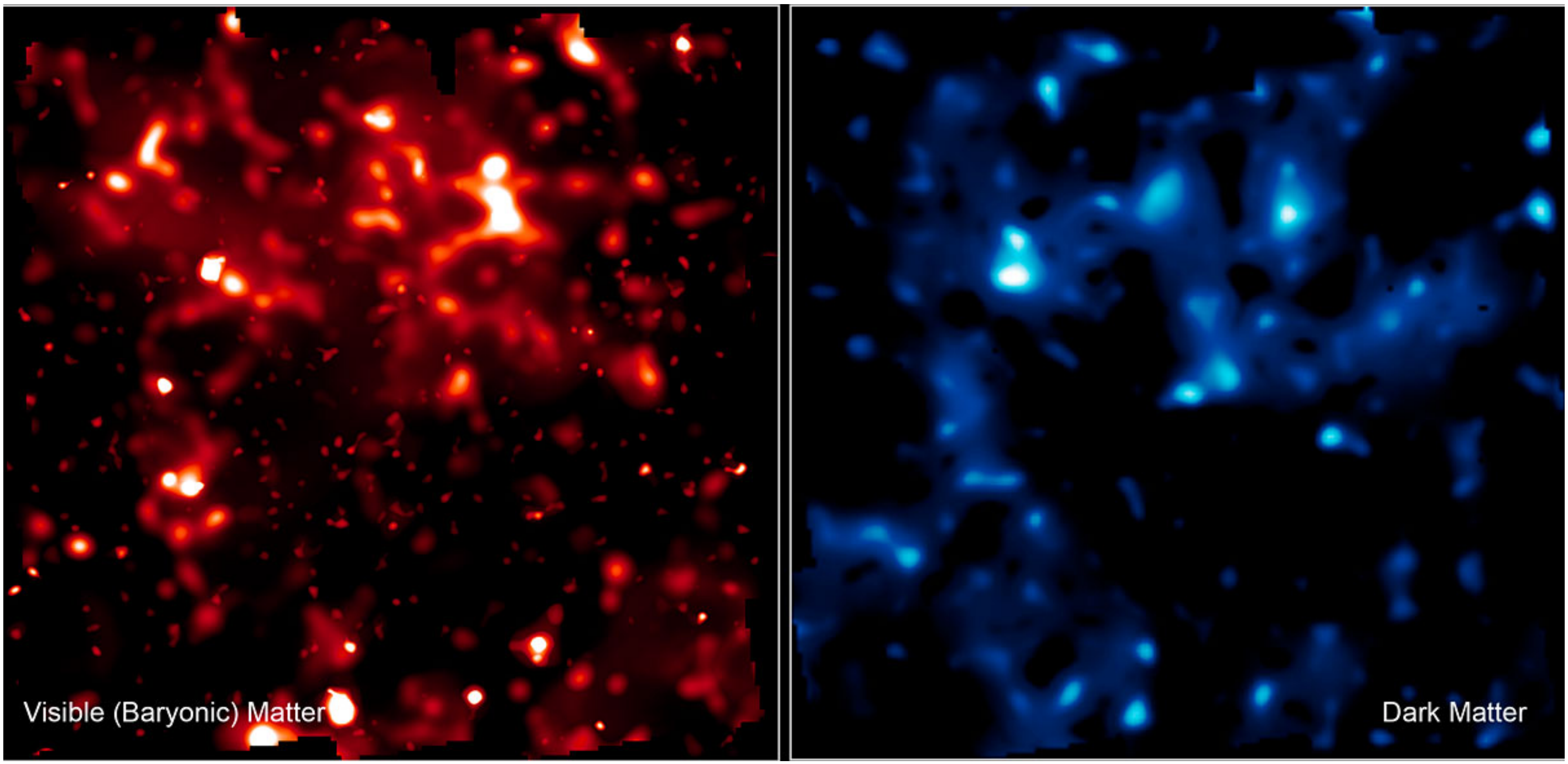
Weak lensing constraints (a subset):

MS1224	$M/L \sim 800h$
A1689	$M/L \sim 400h$
CL1455	$M/L \sim 520h$
A2218	$M/L \sim 310h$
CL0016	$M/L \sim 180h$
A851	$M/L \sim 200h$
A2163	$M/L \sim 300h$

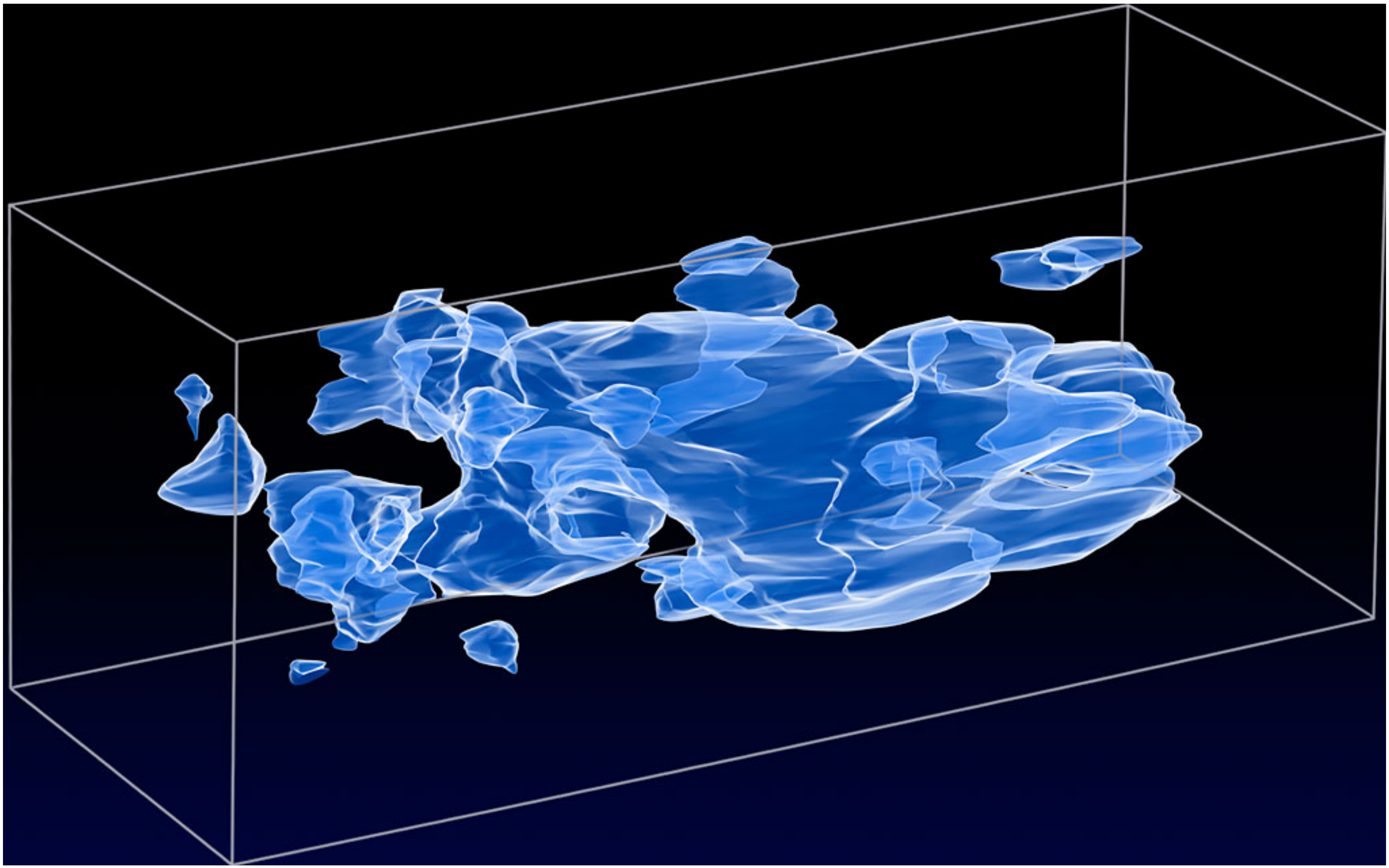
Lots of dark matter in clusters, in a broad agreement with virial mass estimates

Clusters of galaxies imply $\Omega_{dm} \sim 0.1 - 0.3$

Visible and DM Distribution From the COSMOS Survey (Scoville, Massey et al. 2007)



3-D DM Distribution From the COSMOS Survey (Massey et al. 2007)




Next:
Gravitational Microlensing