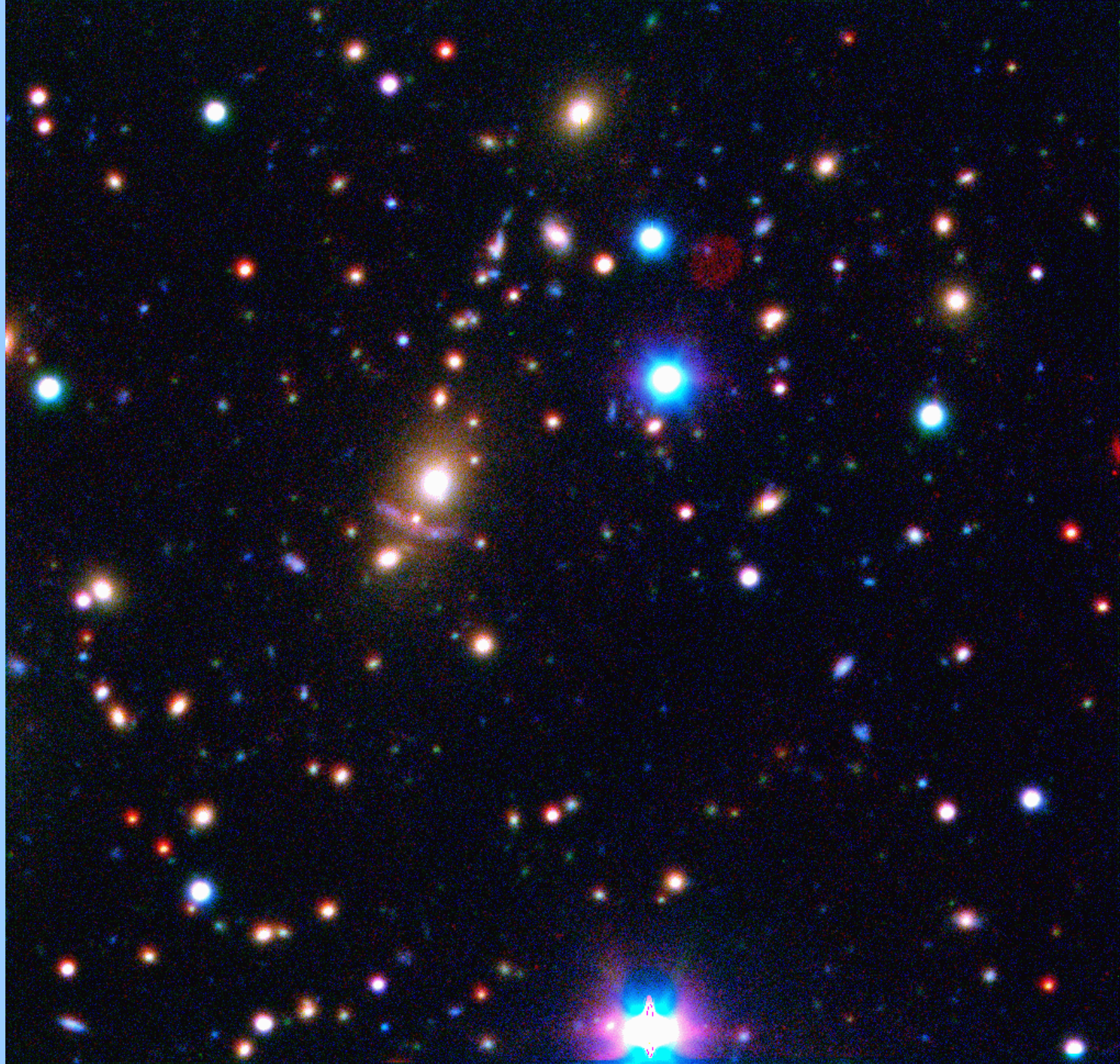


Gravitational lensing and the cluster  
surrounding BL Lac object  
RGB 1745+398

Heidi Lietzen

Seminar on cosmology and astroparticle-physics  
Friday, February 23, 2007

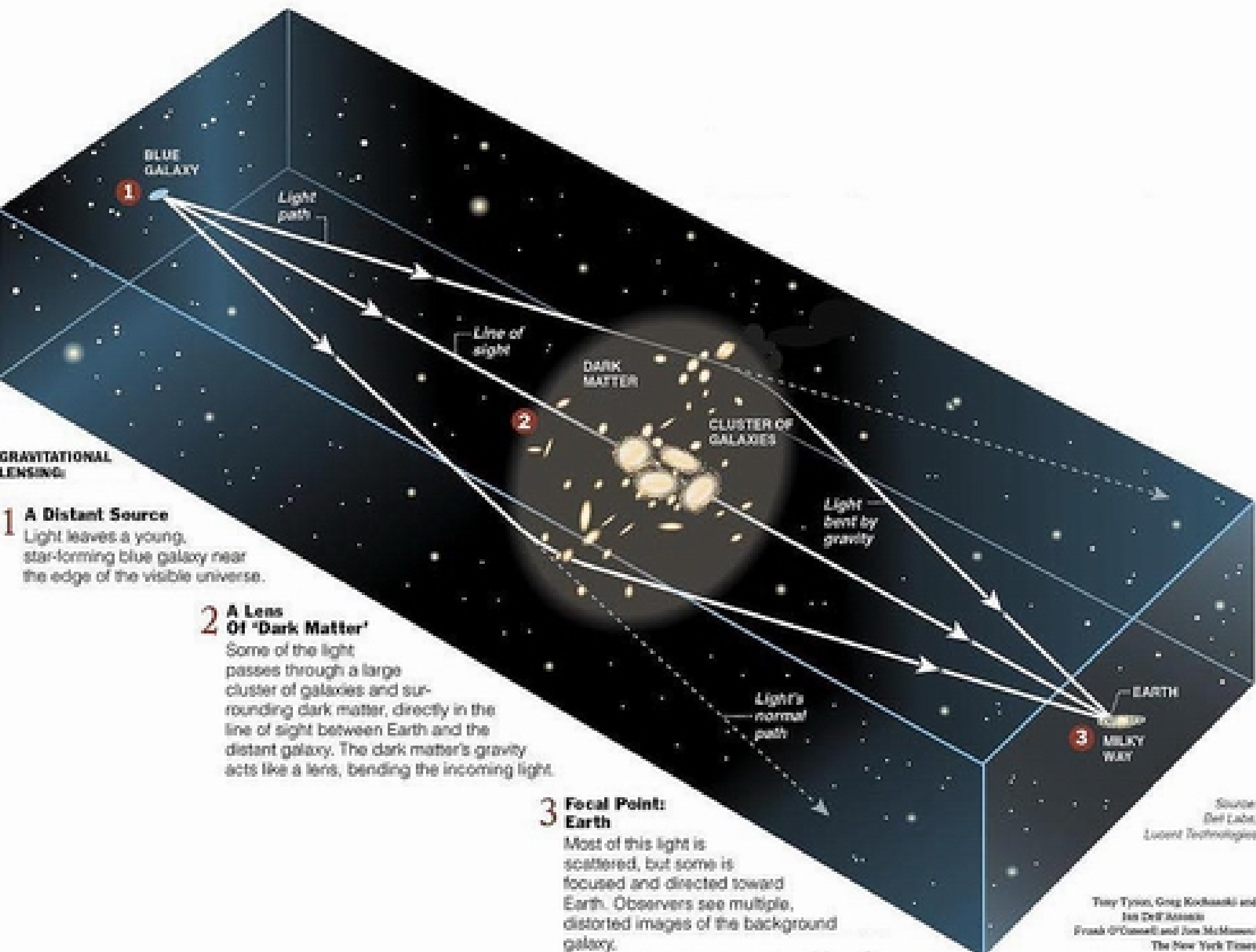


# RGB 1745+398

- BL Lac object
  - Redshift  $z=0.267$
- Elliptical galaxy
  - X-ray luminosity  $1.2 \times 10^{44} \text{ erg/sec}$
- Blue arc
  - Redshift  $z=1.057$
  - Distant from the BL Lac  $8''$
  - Length  $14''$

# Gravitational lensing

- Gravitational field deflects light rays
- A background source can be seen in a different shape when its light passes a massive object
- Makes it possible to “see” some dark matter



## GRAVITATIONAL LENSING:

### 1 A Distant Source

Light leaves a young, star-forming blue galaxy near the edge of the visible universe.

### 2 A Lens Of 'Dark Matter'

Some of the light passes through a large cluster of galaxies and surrounding dark matter, directly in the line of sight between Earth and the distant galaxy. The dark matter's gravity acts like a lens, bending the incoming light.

### 3 Focal Point: Earth

Most of this light is scattered, but some is focused and directed toward Earth. Observers see multiple, distorted images of the background galaxy.

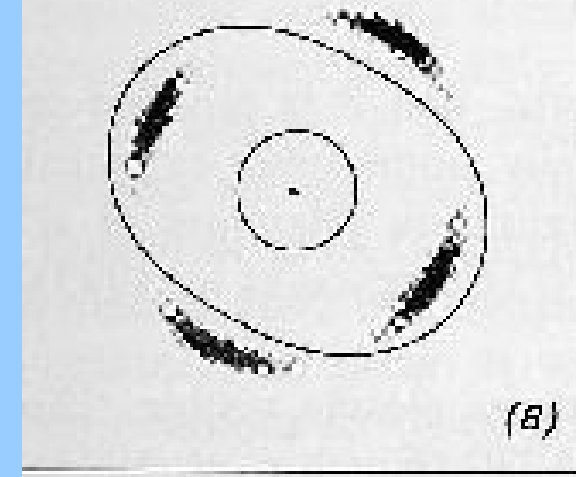
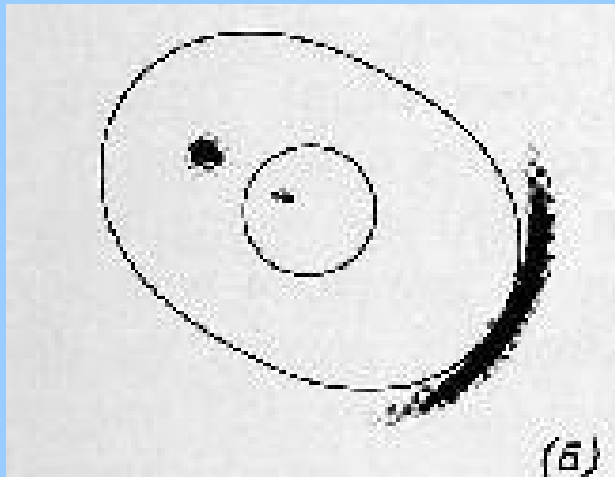
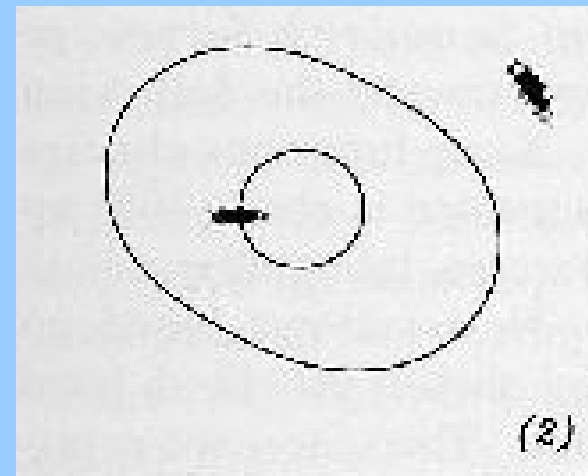
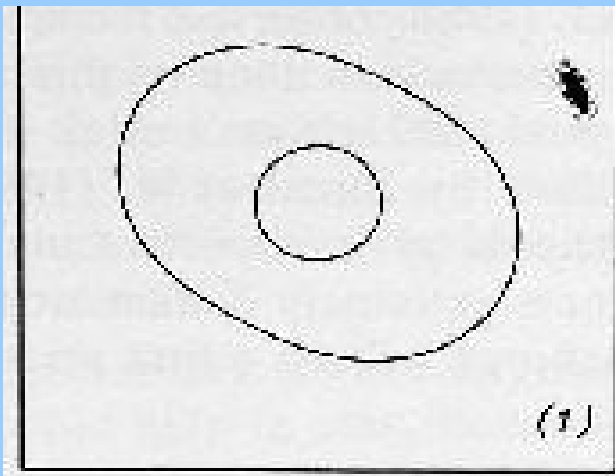
Source:  
Dell Labs,  
Lucient Technologies

Tony Tyson, Greg Kochanski and  
Ian Dell'Antonio  
Frank O'Connell and Tom McManus  
The New York Times

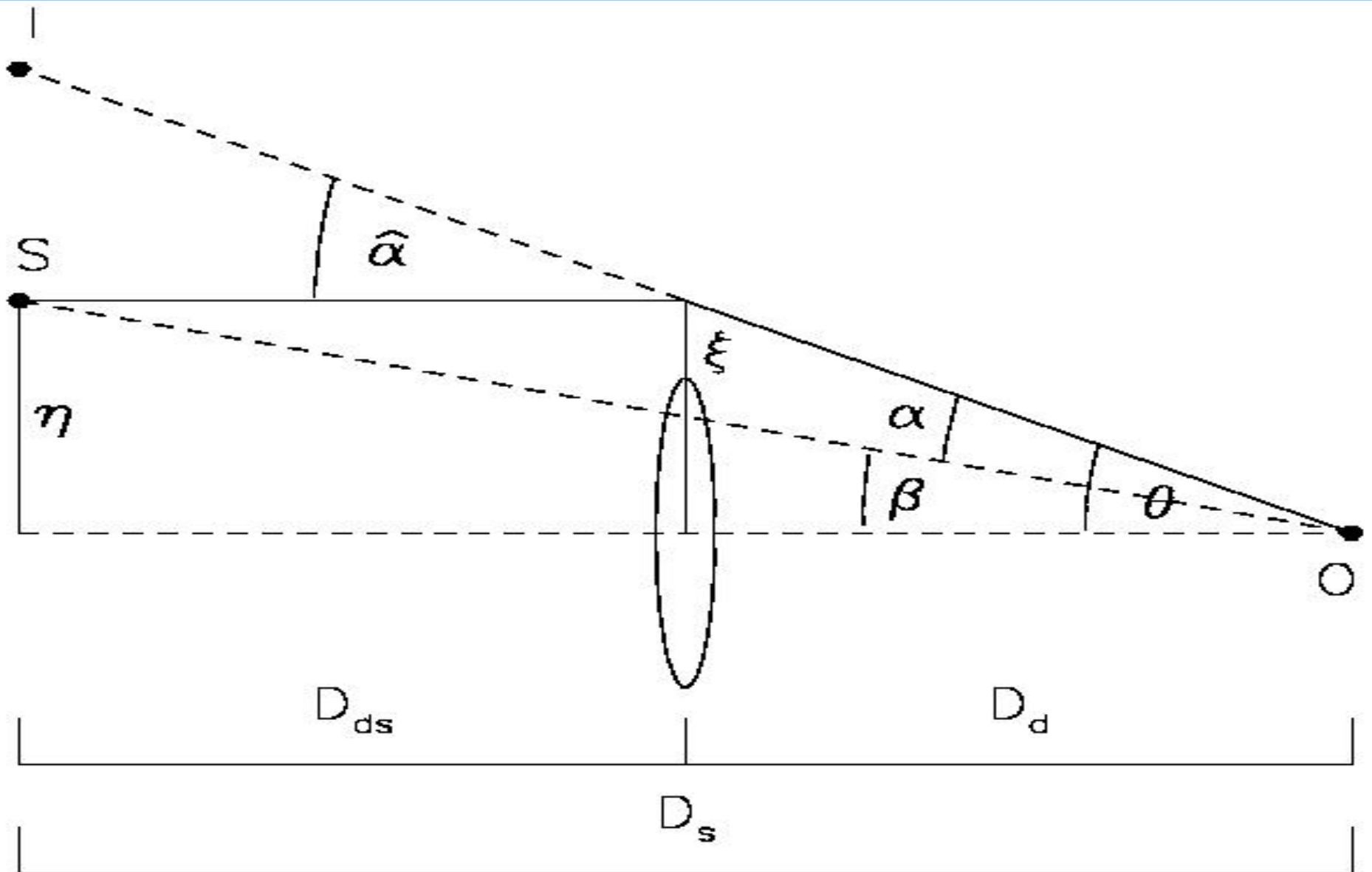
# Strong and weak lensing

- Strong lensing
  - Multiple images
  - Arcs
  - Background source near the lens object line of sight
- Weak lensing
  - Only one image
  - Ellipse
  - Background source far from the lens object line of sight

# Strong and weak lensing



# Distances



# Distances

$$D_{ds} \neq D_s - D_d$$

$$1 + z_s = (1 + z_d)(1 + z_{ds})$$

$$D = \frac{1}{(1+z)} \frac{c}{H_0} \int_0^z \left[ \Omega_\Lambda + \Omega_m (1+z')^3 \right]^{-\left(\frac{1}{2}\right)} dz'$$

# Distances of 1745+398

$$z_d = 0.276$$

$$z_s = 1.057$$

$$z_{ds} = 0.623$$

$$D_d = 840 \text{ Mpc}$$

$$D_s = 1680 \text{ Mpc}$$

$$D_{ds} = 1240 \text{ Mpc}$$

$$\theta = 8'' \Rightarrow \xi = 33 \text{ kpc}$$

# Mass from lensing

Einstein radius

$$\theta_E = \left[ \frac{4GM(\theta_E)}{c^2} \frac{D_{ds}}{D_d D_s} \right]^{1/2}$$

Critical surface density

$$\Sigma_{cr} = \frac{c^2}{4\pi G} \frac{D_s}{D_d D_{ds}} = 5.6 \text{ kg/m}^2$$

# Mass from lensing

Mass inside the arc:

$$M(\theta) = \sum_{cr} \pi (D_d \theta)^2 = \frac{c^2 D_s \xi^2}{4GD_d D_{ds}}$$

$$M(8'') = (9 \pm 4) \times 10^{12} M_{solar}$$

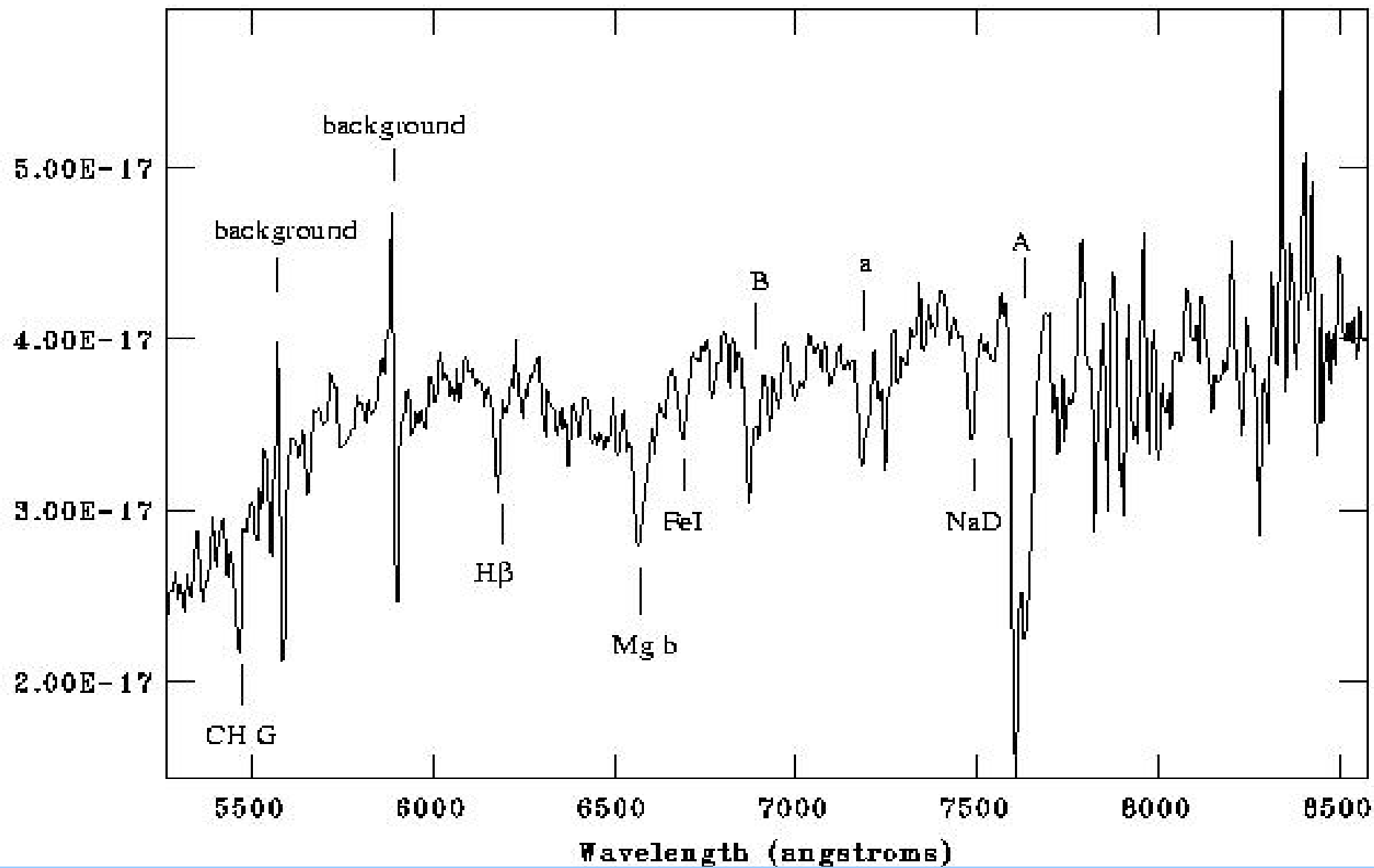
# Purpose of observations

- To find out if there is a cluster around RGB 1745+398
- To measure redshifts of its galaxies
- To calculate the velocity dispersion of the cluster
- To determine the richness of the cluster

# Observations

- Observations were done in July 1998
- Nordic Optical Telescope, ALFOSC
- Long-slit spectroscopy in 5 positions
  - As many targets on one measurement as possible
- Wavelength range from 5000 to 8000 Å
- Absorption lines CH G, H $\beta$ , Mg b, Fe I and Na D were measured if possible

# Spectrum

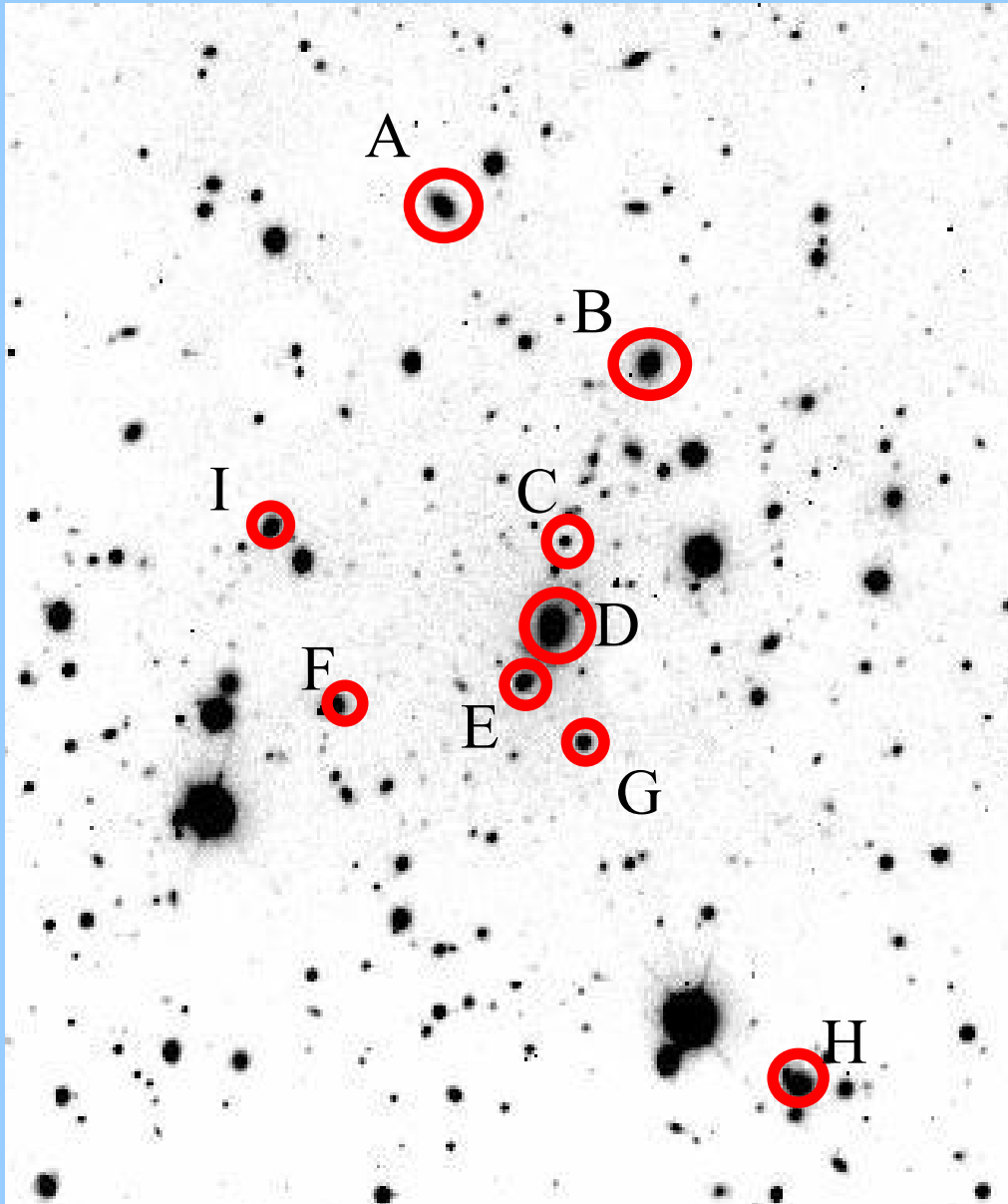


# Measurement results

- Redshifts of nine galaxies were measured
- Result: There is a cluster with average redshift

$$\bar{z} = 0.268 \pm 0.006$$

# Galaxies measured



$$v = \frac{cz - c\bar{z}}{1 + \bar{z}}$$

Object	Redshift	Velocity (km/s)
A	0,266	-400
B	0,271	690
C	0,268	100
D	0,270	500
E	0,270	600
F	0,267	-240
G	0,267	-100
H	0,265	-600
I	0,266	-470

# Velocity dispersion

$$\sigma^2 = \sum_i \frac{v_i^2}{n-1} - \frac{\delta^2}{(1 + \bar{z})^2}$$

Average of errors in velocities  $\delta = 160 \text{ km/s}$

$$\sigma = 471 \begin{matrix} +190 \\ -105 \end{matrix} \text{ km/s}$$

# Isothermal sphere

Singular isothermal sphere:

$$\rho(r) = \frac{\sigma_v^2}{2\pi G r^2} \quad \Sigma(\xi) = \frac{\sigma_v^2}{2G\xi}$$

Softened isothermal sphere:

$$\rho(r) = \frac{\sigma_v^2}{2\pi G (r^2 + r_c^2)} \quad \Sigma(\xi) = \frac{\Sigma_0}{\sqrt{1 + \xi^2/\xi_c^2}} \quad \Sigma_0 = \frac{\sigma_v^2}{2G\xi_c}$$

# Core radius

$$\Sigma_0 \geq \Sigma_{cr} \Rightarrow \xi_c \leq \frac{2\pi\sigma_v^2 D_d D_{ds}}{c^2 D_s} = 10 \text{ kpc}$$

$$\theta_c \leq 2.5''$$

# Surface density

$$M(r) = \int_0^r 2\pi r' \Sigma(r') dr' = 2\pi \Sigma_0 \xi_c^2 \left( \sqrt{1 + \frac{r^2}{\xi_c^2}} - 1 \right)$$

$$\Sigma_0 = \frac{c^6 \xi^2 D_s^3}{32 \pi^3 G D_d^3 D_{ds}^3 \sigma_v^4 \left( \sqrt{1 + \left( \frac{\xi c^2 D_s}{2\pi \sigma_v^2 D_d D_{ds}} \right)^2} - 1 \right)}$$

$$\Sigma_0 = 13 \text{ kg/m}^2 > \Sigma_{cr}$$

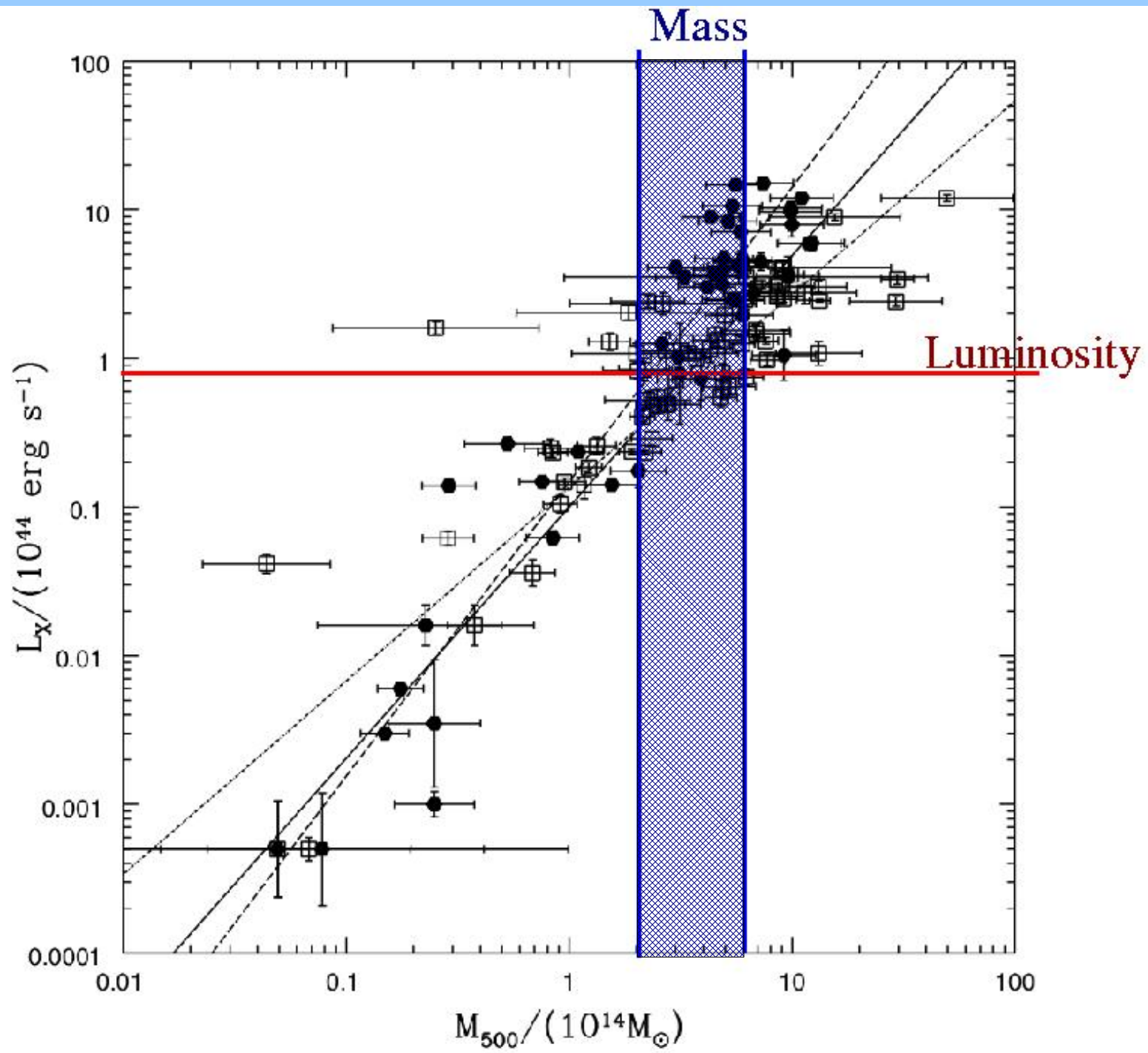
# Mass of the cluster

$$M(r) = \frac{c^2 \xi^2 D_s \left( \sqrt{1 + \left( \frac{rc^2 D_s}{2\pi \sigma_v^2 D_d D_{ds}} \right)^2} - 1 \right)}{4GD_d D_{ds} \left( \sqrt{1 + \left( \frac{\xi c^2 D_s}{2\pi \sigma_v^2 D_d D_{ds}} \right)^2} - 1 \right)}$$

# Mass of the cluster

$$M_{500} = M(r_{500}) = (4 \pm 3) \times 10^{14} M_{solar}$$

$r_{500} \approx 1 \text{ Mpc}$  radius in which the density is larger than 500 times the critical density of the Universe



# Richness

- Determined by counting the galaxies in the cluster and background
- Usual expressions:
  - Galaxy-galaxy spatial covariance function amplitude  $B_{gg}$
  - Abell richness class
- Correlates with mass, luminosity and velocity dispersion

# Determination of $B_{gg}$

- 1 Galaxies at 500 kpc or closer to the center of cluster are counted.
- 2 Background galaxies on a same sized area near the cluster are counted.
- 3 Angular cross-correlation function

$$A_{gg} = \frac{N_{tot} - N_b}{N_b} \frac{3 - \gamma}{2} \theta^{\gamma - 1}$$

# Determination of $B_{gg}$ , continued

- 4 Spatial covariance function is obtained by scaling  $A_{gg}$  with universal luminosity function  $\Phi(m_{limit}, z)$  and average surface density of galaxies  $N_g$

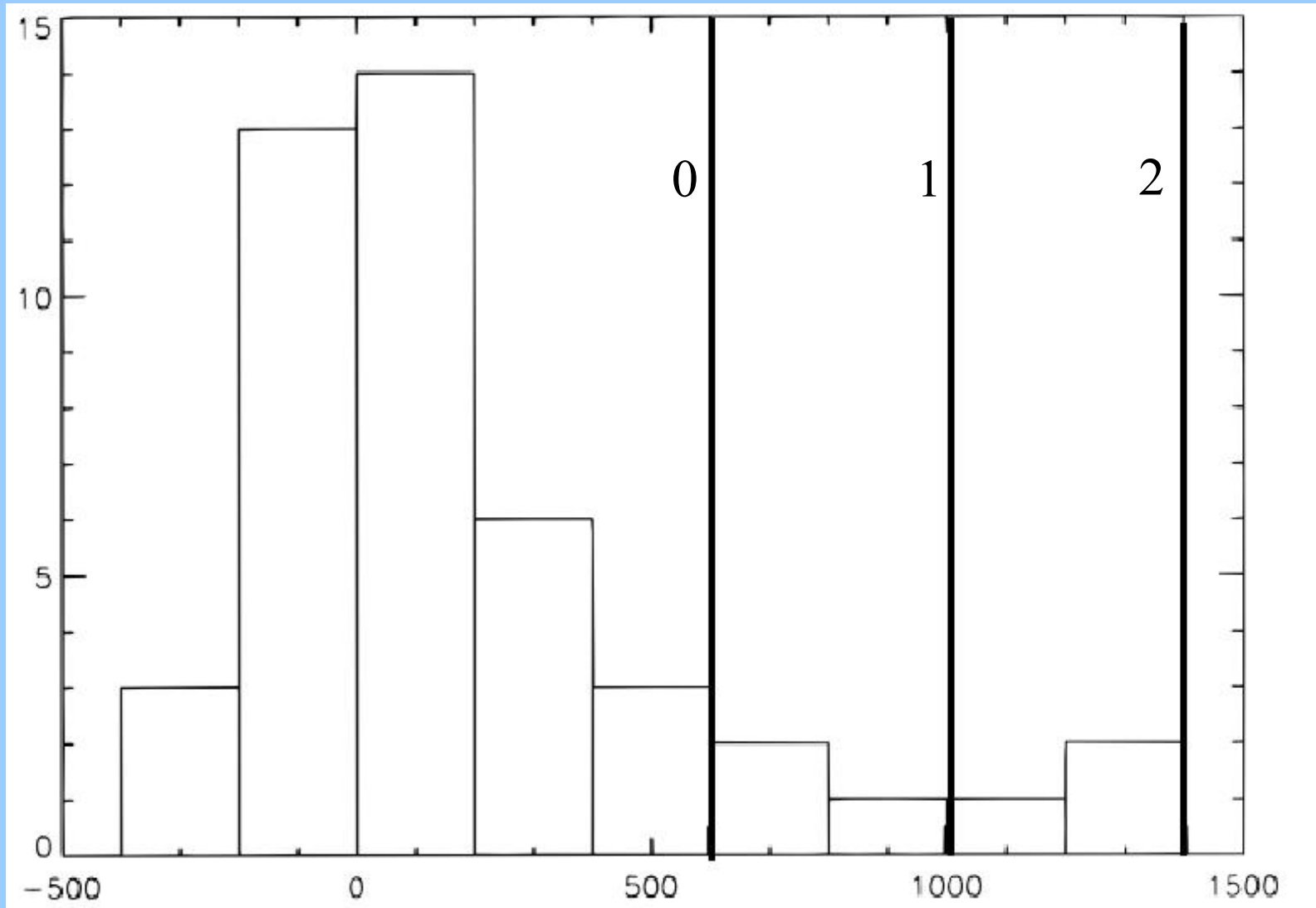
$$B_{gg} = \frac{N_g A_{gg} d_\theta^{\gamma-3}}{\Phi(m_{limit}, z) I_\gamma}$$

# Galaxy counting results

Calar Alto 3.5 m telescope, B band image,  
limiting magnitude 24.5

$$N_{tot} = 96 \quad N_b = 73$$

# Richness of clusters with BL Lac objects



# Future possibilities

- Confirming the results of Wurtz et al. 1997.
- Testing the unification scheme of BL Lacs and FR 1's