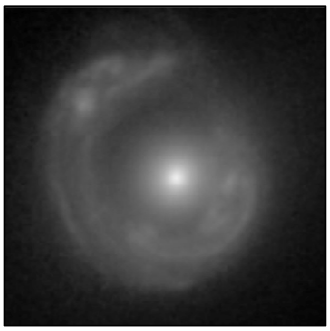
Galaxies AS7007, 2012
Lecture 7: Groups, clusters and lensing



Outline

- Galaxy groups and clusters
  - Basic characteristics
  - Cluster classification
  - Galaxy content
  - The Butcher-Oemler effect
  - Galaxy clusters in our vicinity
  - Compact groups
  - Gas in groups and clusters
  - Mass estimates
  - The Sunyaev-Zeldovich effect

Outline II

- Gravitational lensing
  - General principle
  - Lens equations
  - Strong lensing
    - Rings, arcs and multiple images
  - Microlensing
    - Searching for compact objects
  - Weak lensing
  - Magnification bias
  - Multiply-imaged quasars

Galaxy groups and clusters I

- Around 50% of all galaxies are located in groups and clusters
- The rest are located in “The field”
- Characteristic group/cluster sizes: 1—10 Mpc
- Clusters: More than 30—50 giant galaxies
- Groups: Less than 30—50 giant galaxies

Galaxy groups and clusters II

- Clusters:
  - σ_r~700—1200 km/s
  - Masses 10^{14}—10^{15} solar masses
- Groups:
  - σ_r~100—500 km/s
  - Masses 10^{13} solar masses
- Typical M/L ≈ 100—500
  - 10 times higher than in individual galaxies
  - Most dark matter is located between the galaxies

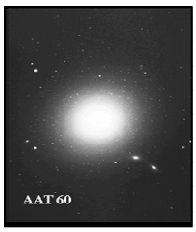
Cluster classification

- Abell richness class:
  - Class 0: 30-49 galaxies
  - Class 1: 50-79
  - Class 2: 80-129
  - Class 3: 130-199
  - Class 4: 200-299
  - Class 5: ≥ 300

Increasing rareness

- Many other schemes in use:
  - Zwicky (Based on compactness)
  - Rood and Sastry (Based on dominant galaxy)
  - Bautz-Morgan (Based on projected distribution of 10 brightest members)

Brightest Cluster Galaxies



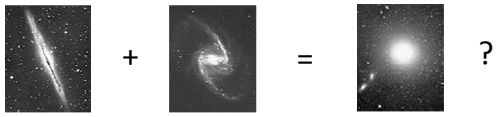
- Limited luminosity range: $M_V \approx -22.8 \pm 0.28$
- Possibly useful as standard candles
- Some, but not all, are cD galaxies

Galaxy content

- Fraction of E/S0 galaxies depends on local galaxy density
- Groups and outskirts of clusters:
  Many S / SB
- Cluster cores:
  Many E / S0
- Mass segregation (in analogy with stars in star clusters):
  - Massive galaxies close to centre
  - Light-weight galaxies further out

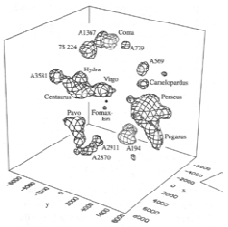
The Butcher-Oemler effect

- More blue galaxies in high-z clusters than in low-z ones
- Blue galaxies: Irr / S / SB
- Red galaxies: E / S0
- Possible interpretation: Mergers
  - Irr / S / SB $\rightarrow$ E / S0 over time



Galaxy groups & clusters in our vicinity

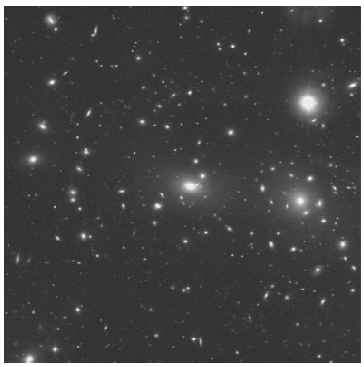
- Groups: Sculptur, Fornax, Centaurus A…
- Clusters: Virgo, Coma, Hydra, Centaurus, Perseus…



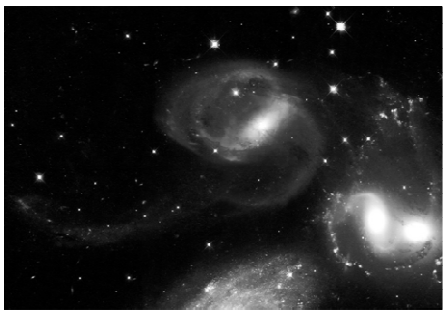
Galaxy groups & clusters in our vicinity II

- Virgo cluster
  - Nearest large galaxy cluster with more than 2000 galaxies brighter than $M_B \approx -14$
  - Extent ~ 3 Mpc
  - Velocity dispersion $\sigma_R \approx 600$ km/s
  - Distance 15—20 Mpc

The Coma cluster



Compact groups



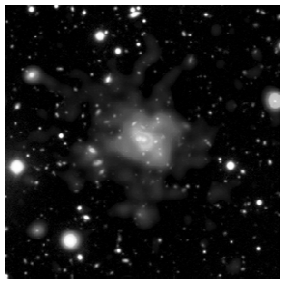
Stephan's Quintet

Compact groups II

- Typically 4—7 galaxies inside few ~100 kpc
- Very often spirals
- Short predicted lifetimes (due to expected merging)
- ≈1/3 discordant redshifts
- Can injection of high-velocity members into these groups prevent mergers?

Gas in groups and clusters

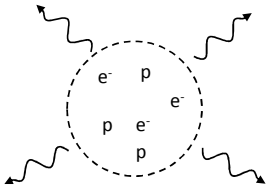
- Most baryonic material in groups and clusters is not stars, but hot gas

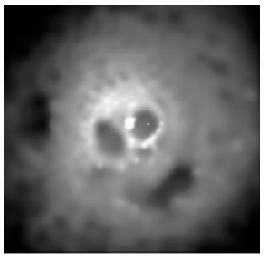


X-ray gas, $T=10^7—10^8$ K

Why does the gas glow?

- Free-free radiation or Brehmsstrahlung (radiation from electrons accelerated by charged particles)





Why is the gas so hot?

- Galaxy motions
  Consider a "gas of galaxies":
  – High cluster mass → High galaxy velocities
  – $kT \sim mv^2$ → High galaxy velocities imply high T
- Winds from supernova explosions inject additional kinetic energy into the gas

Why do the galaxies move so fast?

- Balance between kinetic and potential energy:

$$M \approx \frac{\langle v^2 \rangle R_{\text{grav}}}{G}$$

Gravitational radius

The virial theorem

- Hence, high cluster mass → high v → high T → High X-ray luminosity

Where does the gas come from?

- Mixture of:
  - Gas never captured by galaxies (primordial chemical abundances)
  - Gas (metal-enriched) ejected from galaxies by stellar winds and supernova explosions
- Gas metallicity: Z~10% Solar

Mass estimates

- X-ray spectrum → T(r)
- X-ray luminosity → ρ(r)

Depends on the radiation process

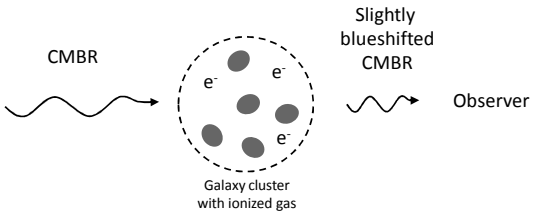
$$L = n_e n_H \Lambda(T)$$

Number densities

- Mass:

$$M(<r) = \frac{k_B}{\mu m_p} \frac{r^2}{G\rho(r)} \frac{d}{dr}(-\rho T)$$

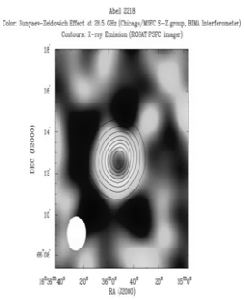
The Sunyaev-Zeldovich effect I



- Compton scattering of CMBR by free electrons in the intercluster medium increases the energy of CMBR photons

The Sunyaev-Zeldovich effect II

- Measure S-Z → thickness of cluster
- Assume thickness=diameter → Linear size of cluster in sky
- Measure angular size of cluster in sky
- Combine angular and linear size → Distance



The S-Z effect is an important tool for cosmology!

Gravitational lensing

Gravitational Lensing

- Strong Lensing
  - Rings
  - Multiple images
  - Arcs
- Microlensing
  - Source magnification (changing over time)
- Weak Lensing
  - Statistical distortion of the shape of galaxies

Gravitational bending of light

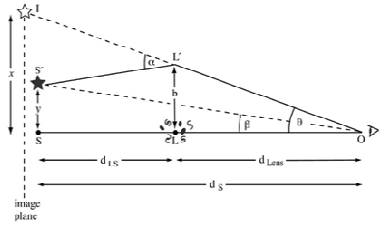


Fig 7.14 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

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

Schwarzschild radius

Impact parameter

Gravitational bending of light II

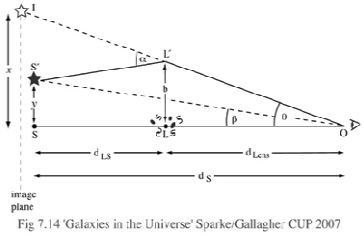


Fig 7.14 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

$$\theta - \beta = \frac{1}{\theta} \cdot \frac{4GM}{c^2} \frac{d_{LS}}{d_L d_S} \equiv \frac{1}{\theta} \cdot \theta_E^2$$

Einstein radius

Angular Size Distances

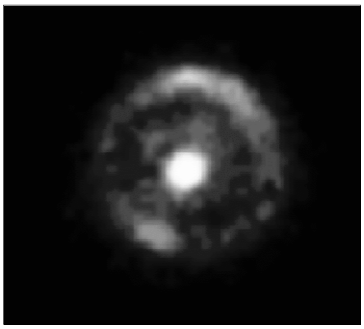
- Luminosity distance: What we get from most distance indicators (e.g. Hubble's law, Tully-Fischer)
- Angular size distances: What is relevant in gravitational lensing
- d_L, d_S, d_{LS} are all angular size distances (d_A)

Angular size distance

$$d_A = \frac{d_L}{(1+z)^2}$$

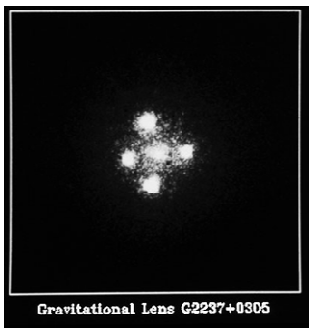
Luminosity distance

The Einstein Ring



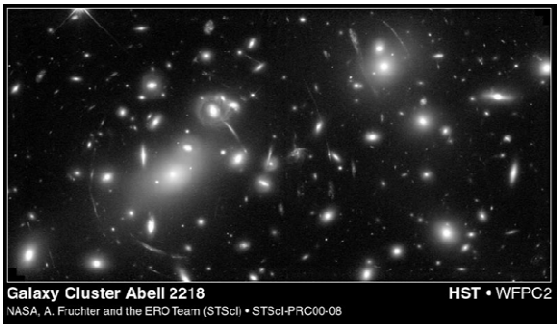
$R=\theta_E$

Multiple Images

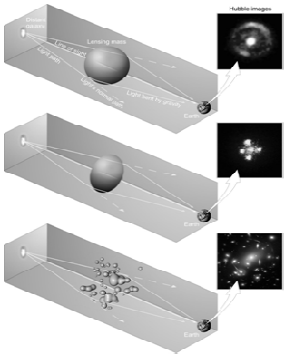


The Einstein Cross

Gravitational Arcs



Lens mass distribution



Perfect alignment / spherical lens / Large source

Not perfect alignment / ellipsoid lens / small source

Complicated mass distribution (e.g. galaxy cluster)

Lens effects gives information on mass distribution in lens

Gravitational magnification

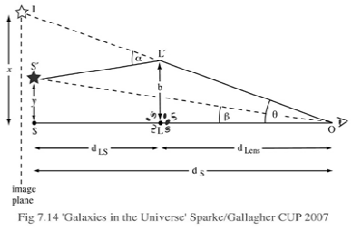


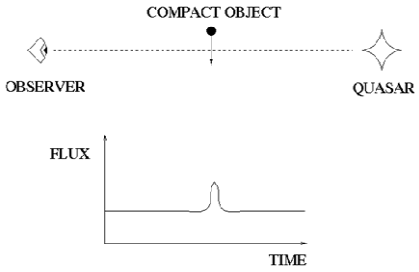
Fig 7.14 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Magnification → $A = \frac{1+x^2/2}{x\sqrt{1+x^2/4}}$ $x = \beta/\theta$

Microlensing

- Image separation too small to be resolved (e.g. microarcseconds) → Microlensing
- Only observable consequence: Source becomes brighter
- Microlensing is achromatic (same magnification at al wavelengths) as long as the light source is small

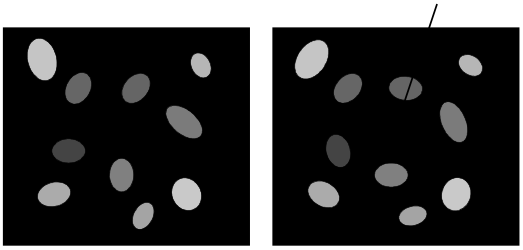
Microlensing II



Same principle for all small light sources
(e.g. stars, supernovae, gamma-ray bursts, quasars, blazars)

Weak Lensing

Invisible mass concentration



Random galaxy orientation

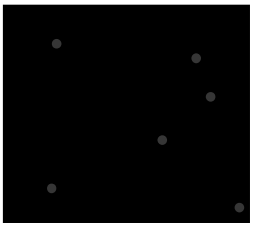
Random galaxy orientation affected by weak lensing

Weak lensing II

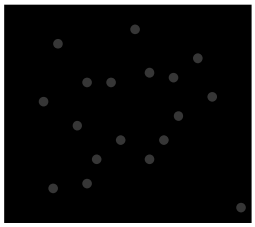
- Two effects:
  - Shear: Image stretching and rotation
  - Convergence: Image magnification
- May e.g. be applied to:
  - Galaxy clusters → Cluster dark halo properties
  - Galaxy surveys → Average dark halo properties
  - Cosmic Microwave Background Radiation
    → Distribution of large scale structure (cosmological parameters)

Magnification bias

A flux-limited survey: Containing objects with fluxes higher than a certain magnitude threshold



True flux-limited distribution around massive foreground object

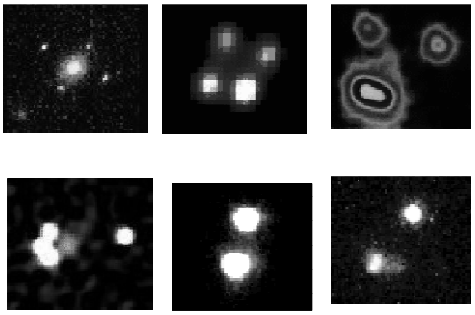


Observed flux-limited distribution around massive foreground object

Multiply-imaged quasars I

- Rare (only ~100 known with galaxy as lens)
- Useful for cosmology:
  - To measure Hubble constant
  - To measure mass and density profile of dark halo around lens galaxy
  - To study microlensing in lens galaxy (or its dark halo)
  - To study dust extinction in the lens galaxy

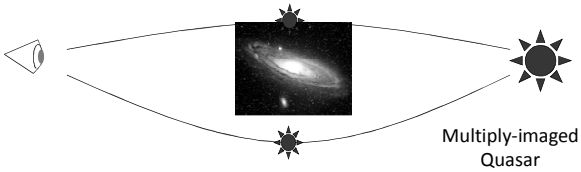
Multiply-imaged quasars II



Typical image separations: A few arcsec

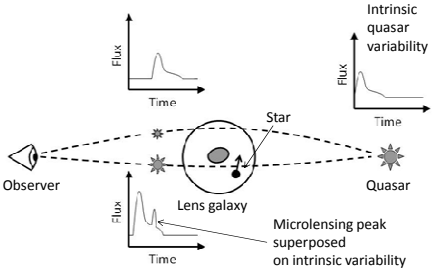
Time delays as a probe of H_0

Different length of light paths for different Images → Quasar variations observed in all Images, but with a certain time-delay

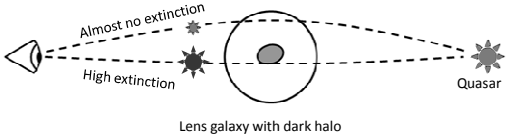


Time-delay → H_0

Microlensing in multiply-imaged quasars as as a probe of stars in the lens galaxy



Multiply-imaged quasars as a probe of dust extinction in the lens galaxy



Lens galaxy with dark halo

Colour differences between images → Extinction law measurement