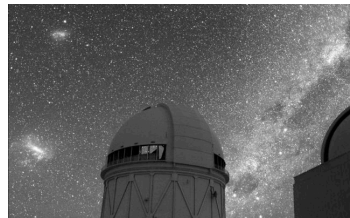


ASTR 303

Galaxy Groups and Clusters

1. Introduction
2. Groups: the home of disk galaxies
3. Rich clusters: the domain of S0 and E galaxies
4. Gravitational Lensing: weighing groups and clusters



Galaxy Groups

- Galaxy aggregations typically numbering 10-50 members.
- Typical “size” of groups is 200kpc-1Mpc
- Masses typically $\sim 10^{13} M_{\text{sun}}$
- Disk galaxies are the prevalent morphological type of galaxy
 - The Local Group is a typical example: the 3 brightest members are spiral galaxies (MW, M31, and M33)
- Groups form as galaxies “detach” from the Hubble flow (the general expansion of the Universe) and collapse under the effects of their mutual gravity



Galaxy Groups

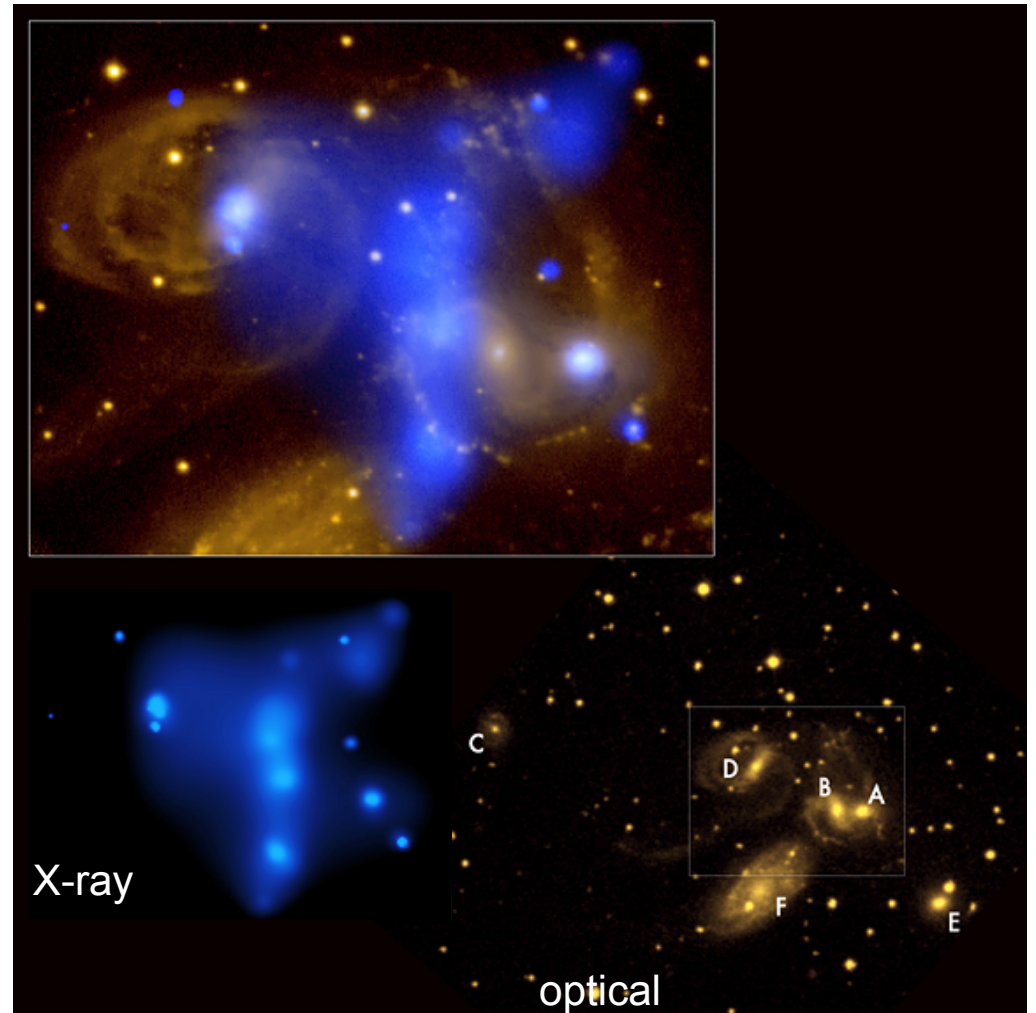
- Some are in very compact configurations
 - Stephan's Quintet: actually a quartet: one galaxy has a "discrepant" redshift
 - Surrounded by an X-ray halo of hot gas



Stephan's Quintet HST • WFPC2
NASA and S. Gallagher (Penn State University)
STScI-PRC01-22

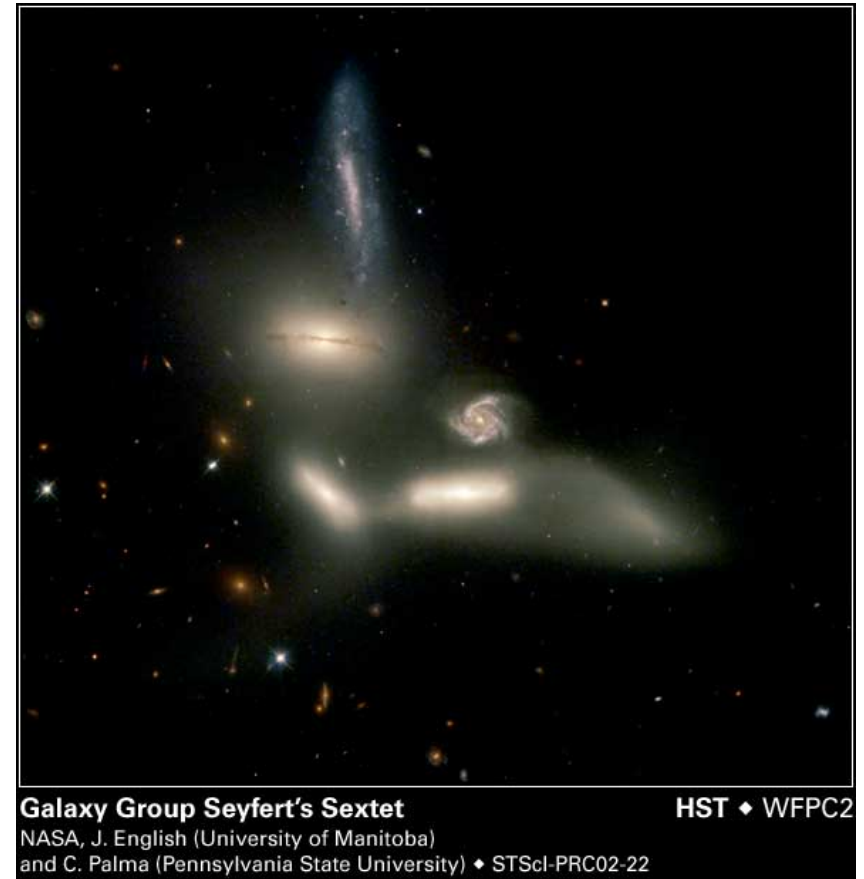
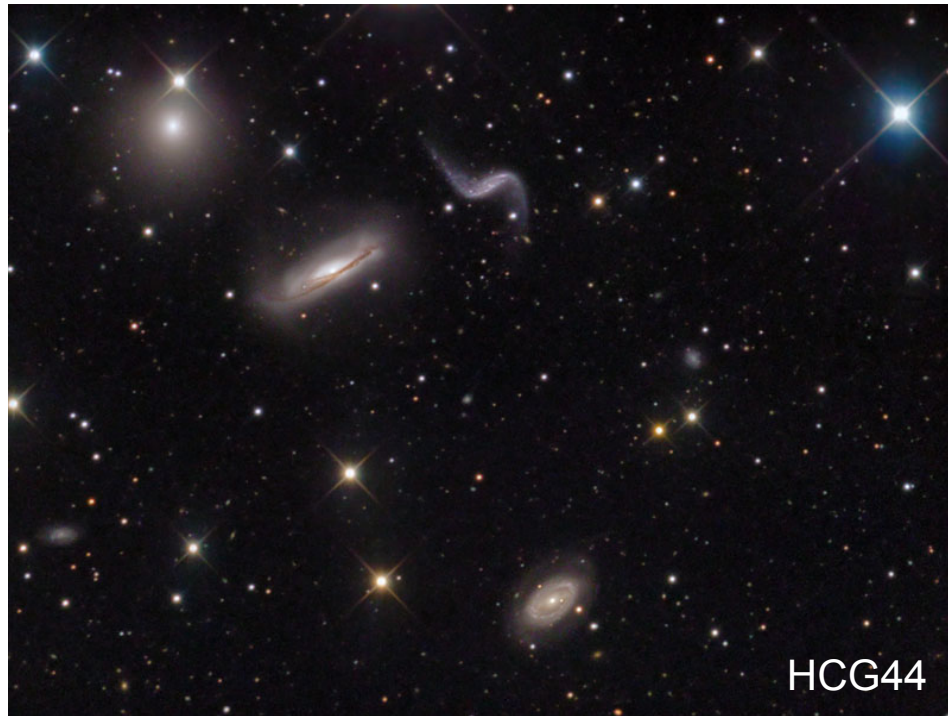
Galaxy Groups

- X-ray emission (in blue) does not come from the galaxies themselves but from their surrounding intergalactic medium
- IGM has been heated to X-ray temperatures ($>\sim 3$ million degrees) by a shock created by the galaxies' collision.
 - The “virial temperature” of a system is that for which the specific kinetic of an atom is comparable to that of the orbital motion of a galaxy
 - $T_{\text{vir}} \sim 5 \times 10^6 (\sigma/300 \text{ km/s})^2 \text{ K}$
 - Emission mechanism is mainly *thermal bremsstrahlung*



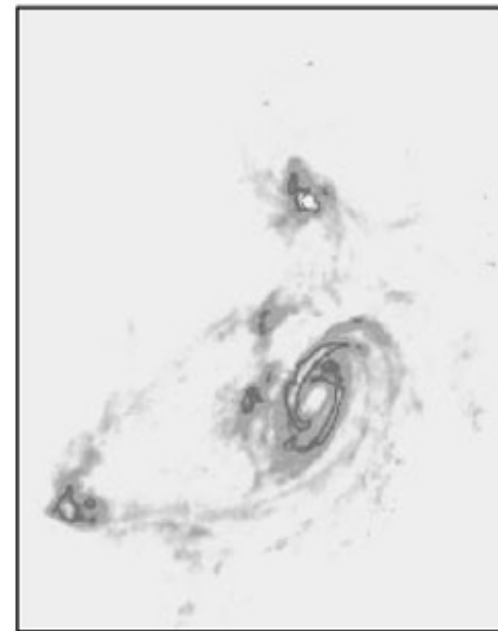
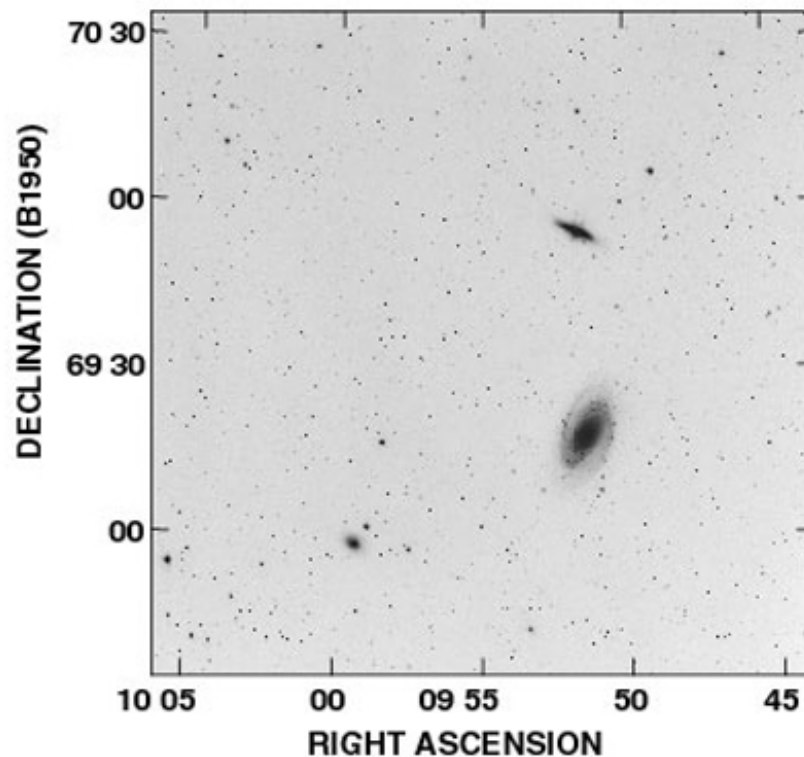
Galaxy Groups

- Often galaxies in groups show signature of ongoing tidal interaction
- Galaxy groups define the “characteristic” mass of equilibrium objects in the universe



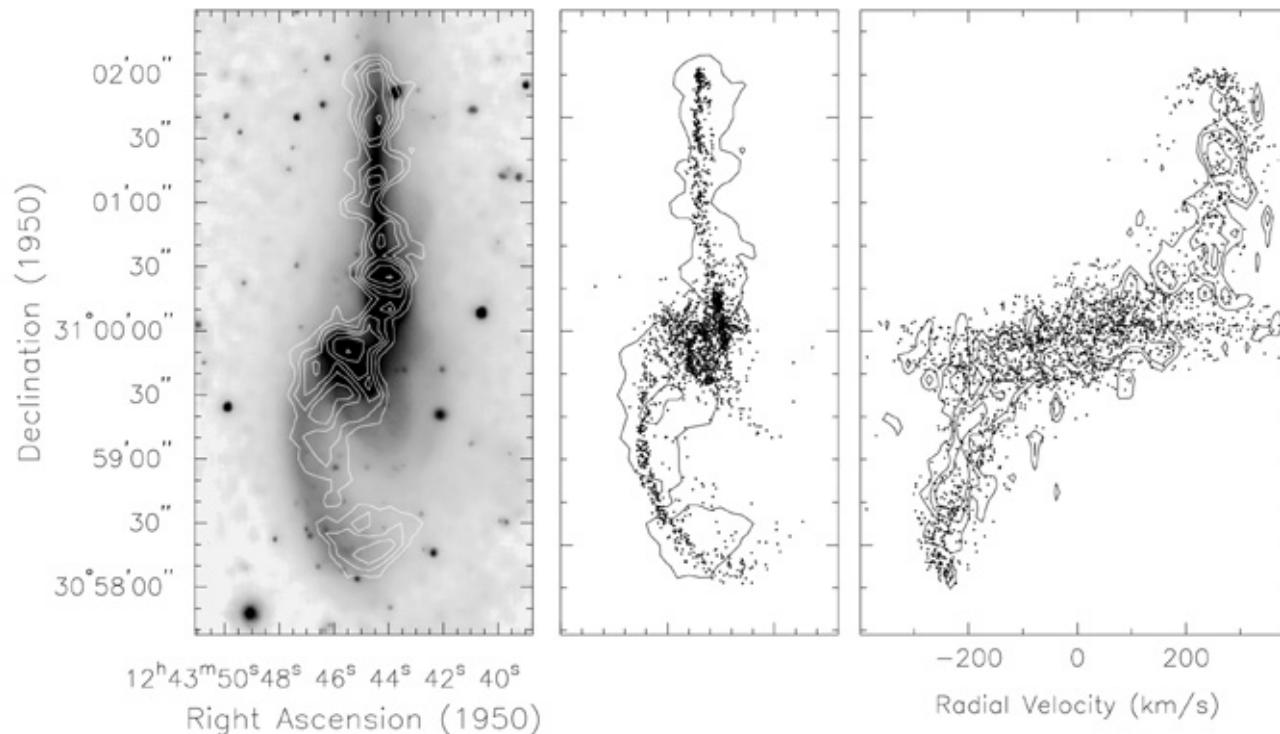
Galaxy Groups

- Sometimes interactions are not easy to detect, unless looking at a tracer that extends very far away from the galaxies
 - The case of the M81 group is illustrated below, in the optical (left) and HI (right)



Galaxy Interactions

- Velocities of galaxies in groups are comparable to internal velocities of stars within the galaxies
 - This implies that collisions are rather inelastic, and the orbital energy of collisions is lost to internal motions of the remnant.
 - Ongoing collisions are common in galaxy groups
 - Because collisions are typically between disks, the results are spectacular → “tidal tails”



Galaxy Interactions

- Interactions are common in regions of high galactic density and lead in general to mergers in groups



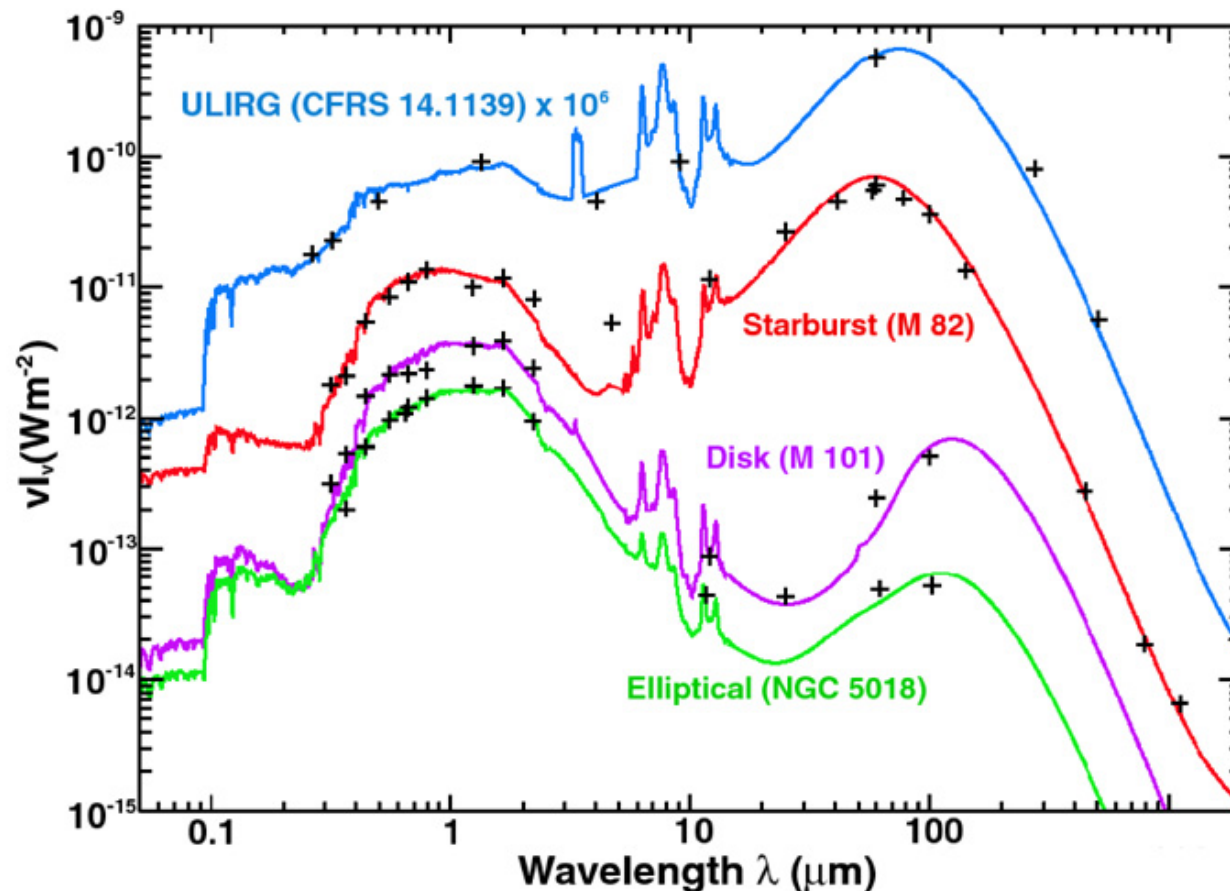
Galaxy Interactions

- Different stages in the interaction lead to different morphologies



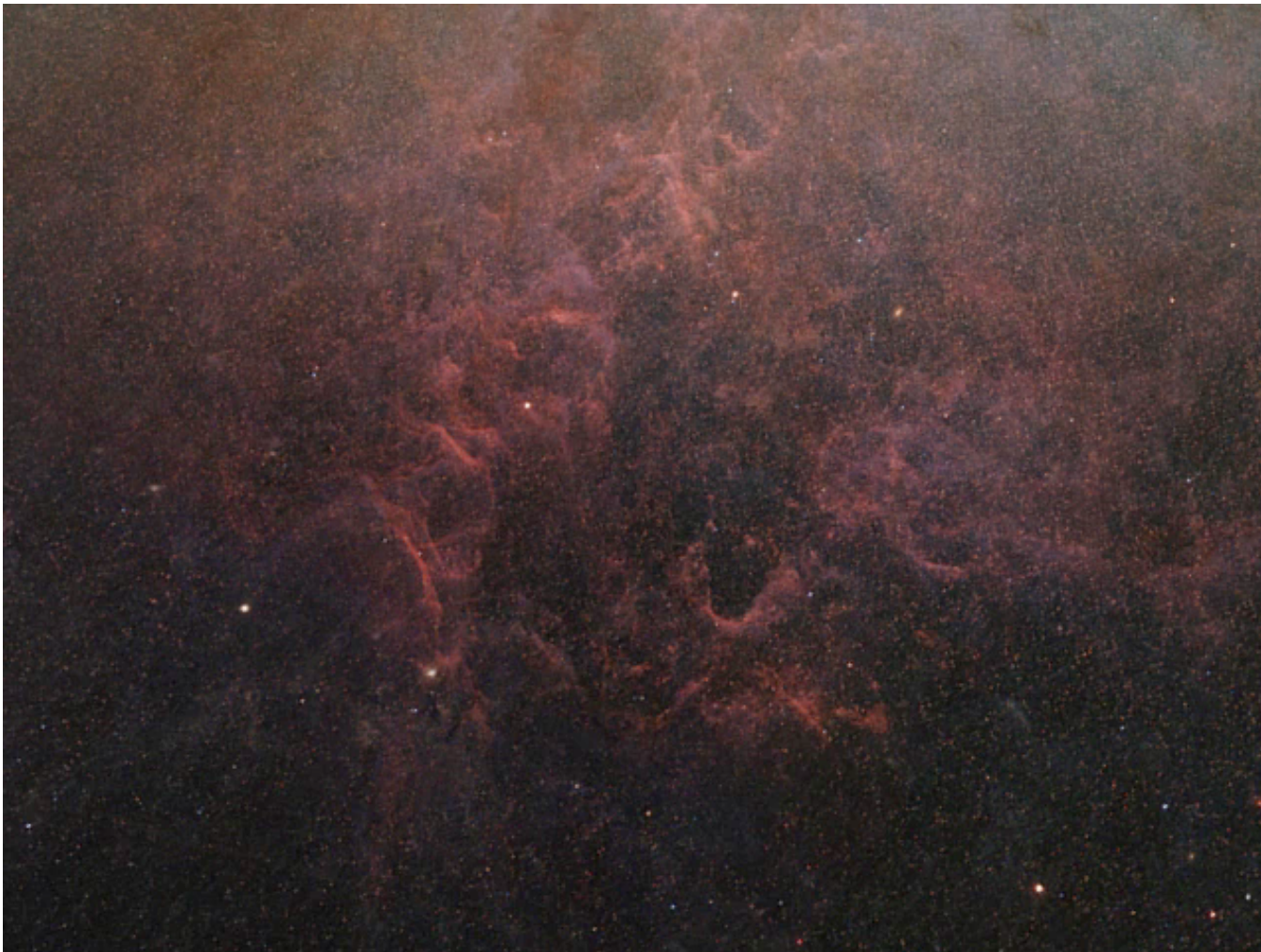
Galaxy Mergers and Starbursts

- Mergers between galaxies typically send the gas to the center of the remnant, where it is transformed violently in stars in a huge *starburst*.
 - The light from starbursts is usually obscured by dust, which re-radiates it in the infrared
 - The brightest infrared galaxies (known as ULIRGs) are all merger remnants



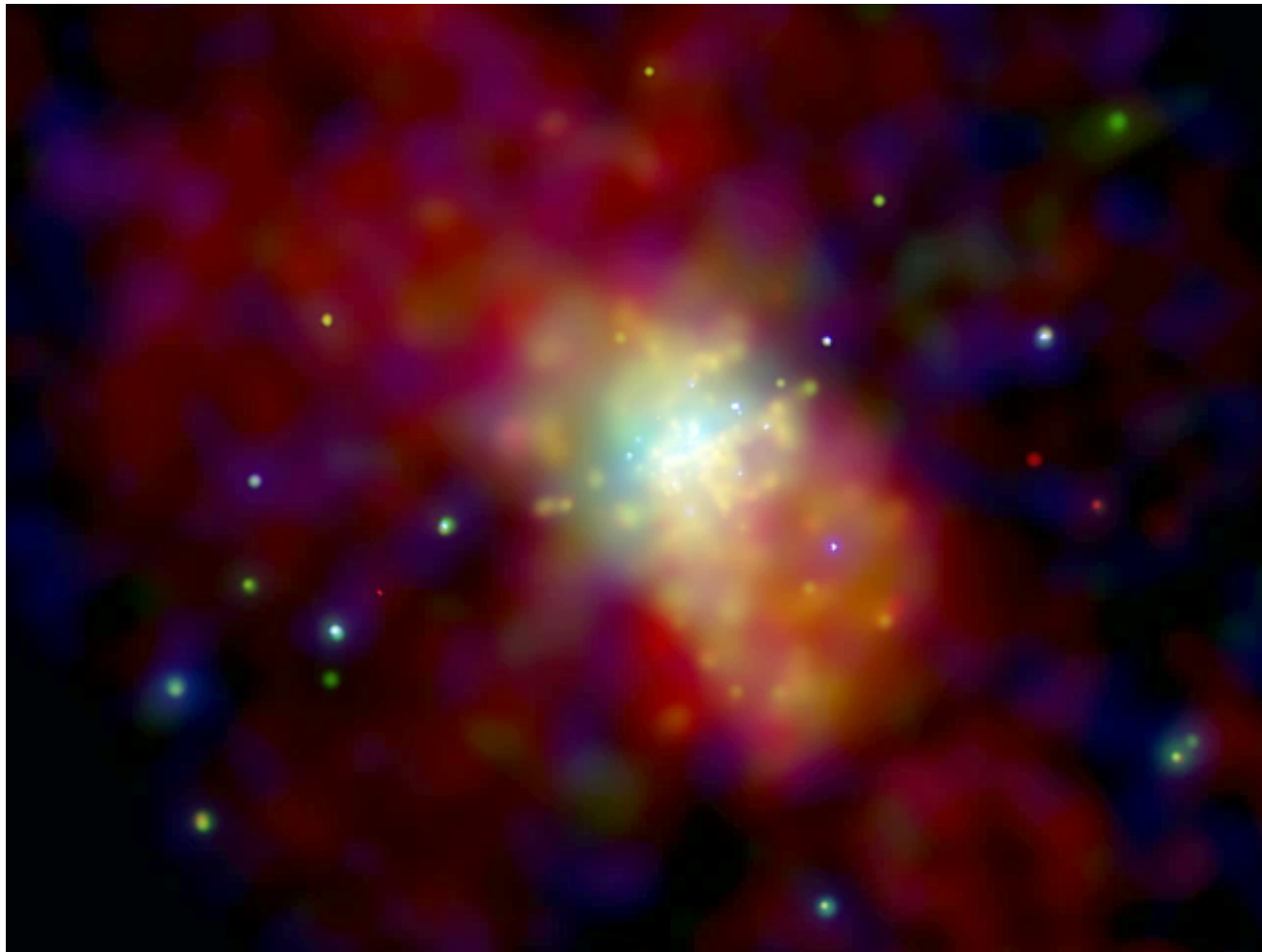
Galaxy Mergers and Starbursts

- Mergers between galaxies typically send the gas to the center of the remnant, where it is transformed violently in stars in a huge *starburst*.
 - The light from starbursts is usually obscured by dust, which re-radiates it in the infrared: M82 is the archetypal example



Galaxy Mergers and Starbursts

- Mergers between galaxies typically send the gas to the center of the remnant, where it is transformed violently in stars in a huge *starburst*.
 - The light from starbursts is usually obscured by dust, which re-radiates it in the infrared



The Masses of Galaxy Groups

- Typically estimated from the **virial theorem**:
 - $M \sim \sigma^2 R$
 - The velocity dispersion of a galaxy group is similar to that of an individual galaxy, but its size is much greater $\rightarrow$ its mass-to-light ratio is much greater than that of a galaxy $\rightarrow$ direct evidence for dark matter
 - Can also be estimated, when there is X-ray gas, assuming **hydrostatic equilibrium** for the gas

$$\frac{dp}{dr} = -\rho(r) \frac{G\mathcal{M}(<r)}{r^2}.$$

$$p = \frac{\rho}{\mu m_p} k_B T, \quad \text{so } \mathcal{M}(<r) = \frac{k_B}{\mu m_p} \frac{r^2}{G\rho(r)} \frac{d}{dr}(-\rho T).$$

The Masses of Galaxy Groups

- Therefore the total mass of the group may be estimated if the **density and temperature** profiles of the gas are known.

$$p = \frac{\rho}{\mu m_p} k_B T, \quad \text{so } \mathcal{M}(< r) = \frac{k_B}{\mu m_p} \frac{r^2}{G \rho(r)} \frac{d}{dr} (-\rho T).$$

- Note that in the equation above the density is that of the gas being supported by the pressure gradient.
- The mass, on the other hand, is the **total mass of the cluster**, including any dark matter component
- The main difficulty is in measuring the temperature profile in the outskirts of the system

Rich Galaxy Clusters

- Rich galaxy clusters can contain hundreds to thousands of reasonably luminous galaxies
 - They are much denser than galaxy groups
 - Evidence for ongoing tidal interaction between cluster members is less obvious. This is due to the high velocity dispersion of clusters, galaxies move relative to each other with velocities approaching a couple of thousand km/s
 - The dominant morphological types are S0 and E galaxies.
 - Rich clusters are filled with X-ray emitting gas

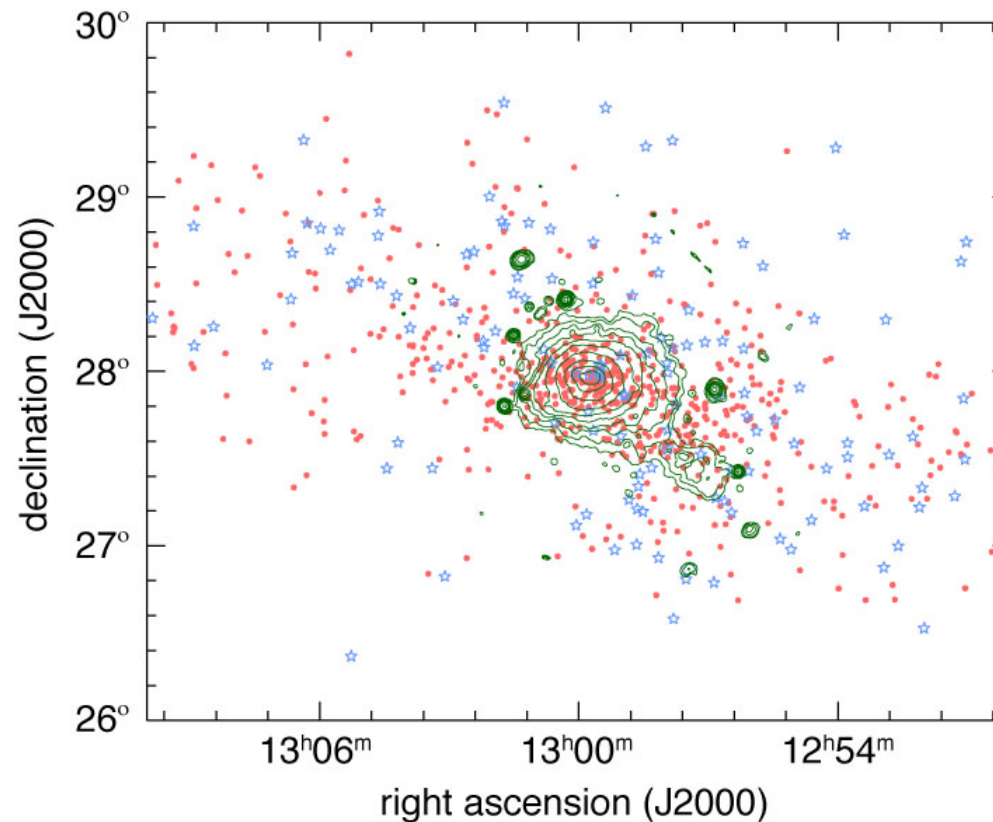


Fig 7.9 (C. Conselice/WIYN, A. Fabian/HST)
'Galaxies in the Universe'
Sparke/Gallagher CUP 2007



Rich Galaxy Clusters

- The Coma cluster is one of the most massive nearby clusters
 - Large fraction of E and S0 galaxies, especially near the center
 - Ellipticals are the orange dots
 - Spirals are the open starred symbols
 - X-ray contours are shown in green



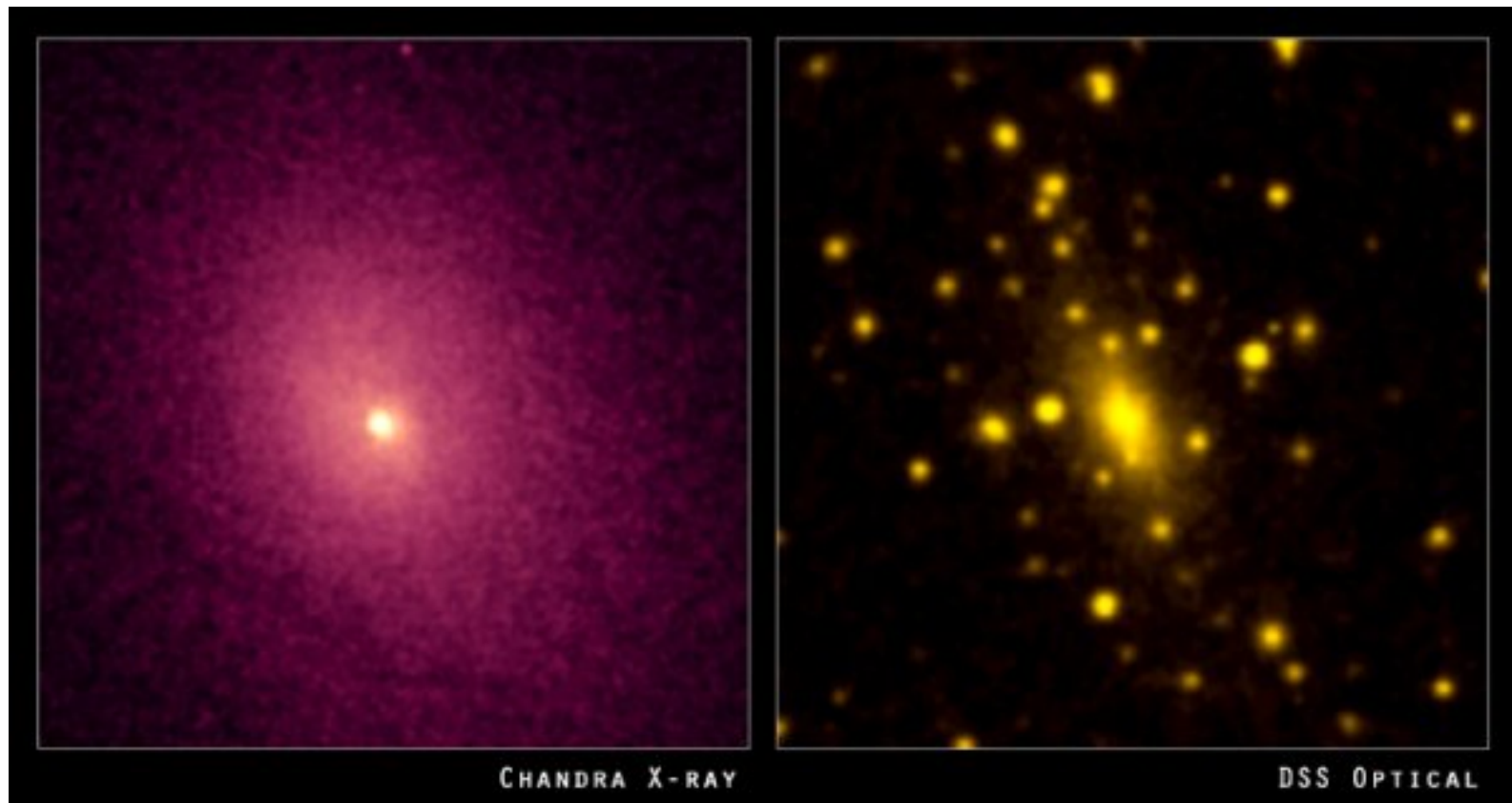
The Coma Cluster

- Animation switches between several different datasets before focussing on the Coma Cluster. Note the two giant ellipticals at the core of the cluster



X-ray Clusters

- Most of the baryons in a galaxy clusters are not in galaxies, but in the X-ray emitting intracluster medium (ICM)
- The ICM fills the cluster and has a mass that can exceed the total combined mass of all cluster galaxies by a factor of 10 or more.
- As in groups, one can use the virial theorem or the hydrostatic equilibrium equation to estimate the total mass of a cluster
 - Very convincing evidence for the presence of dark matter.



Mass Estimates from X-rays or Galaxy Velocities

- The equation of hydrostatic equilibrium may be used to relate the mass to observable quantities for the X-ray emitting gas (temperature and density) or the cluster galaxies (velocities and density)

$$\frac{dp}{dr} = -\rho(r) \frac{GM(<r)}{r^2}.$$

$$p = \frac{\rho}{\mu m_p} k_B T,$$

For X-ray gas; note that it depends on $T(r)$!

$$M(<r) = -\frac{kTr}{G\mu m_p} \left(\frac{d \ln \rho_{\text{gas}}}{d \ln r} + \frac{d \ln T}{d \ln r} \right)$$

For galaxies, temperature is substituted by the velocity dispersion of the galaxies (squared) but

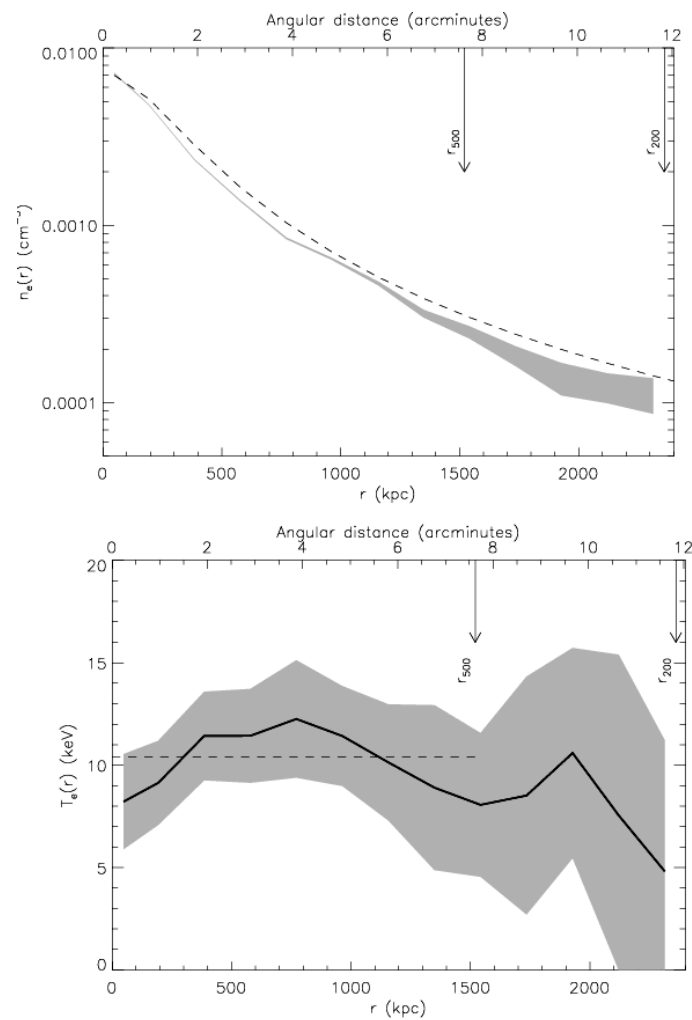
$$M(<r) = -\frac{\langle v_r^2 \rangle r}{G} \left[\frac{d \ln \rho_m}{d \ln r} + \frac{d \ln \langle v_r^2 \rangle}{d \ln r} + 2\beta(r) \right]$$

→ **velocity anisotropy parameter**

$$\beta(r) = 1 - (\langle v_\theta^2 \rangle + \langle v_\phi^2 \rangle) / 2\langle v_r^2 \rangle$$

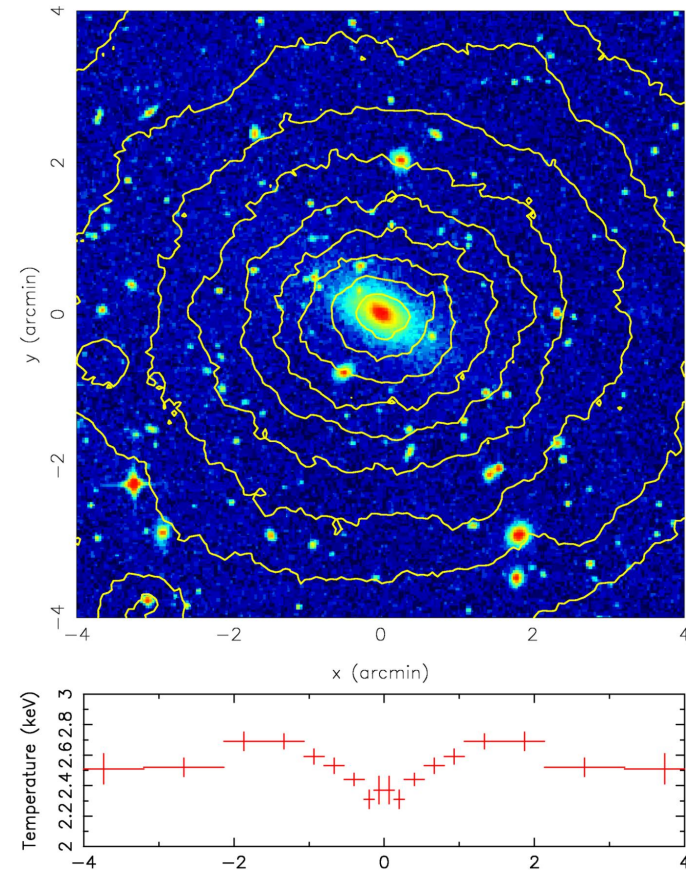
UNKNOWN!

Gas density and temperature profiles from X rays



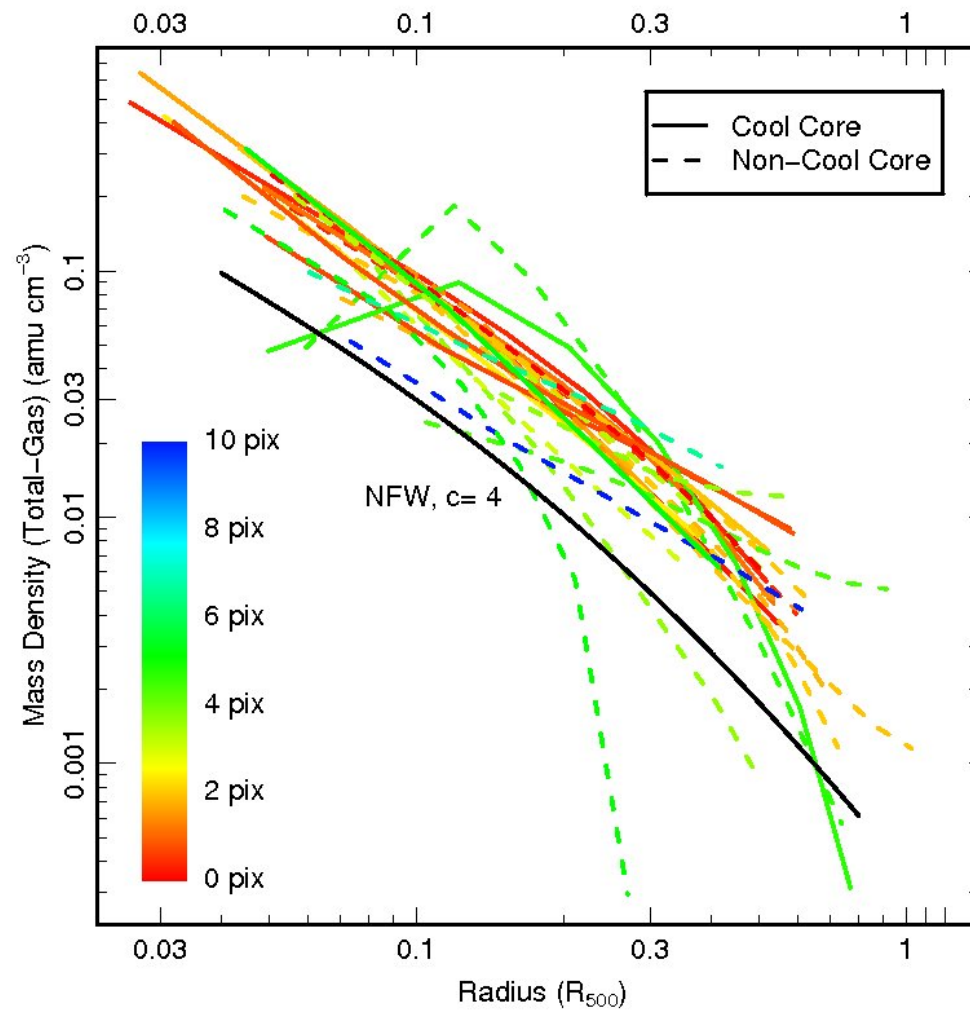
Sérsic 159-03

Contours: XMM-Newton MOS — Image: DSS



Cluster Mass Profiles

- Mass profiles of galaxy clusters require dark matter and in general are in good agreement with what is expected from simulations of cold dark matter



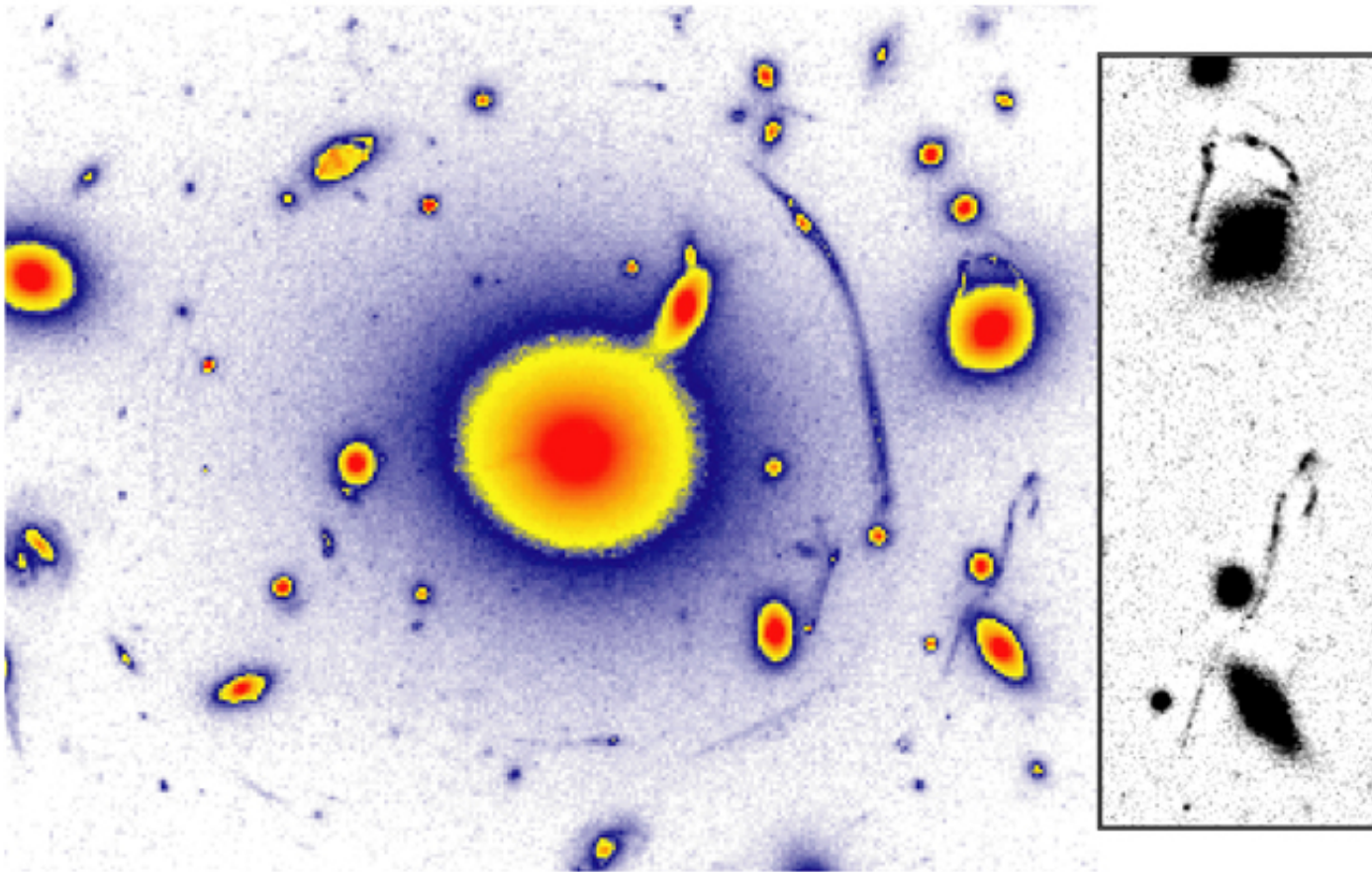
Gravitational Lensing

- Clusters are so massive that they act as “gravitational telescopes”
- The light from background galaxies can be bent by the cluster, creating **multiple images** and distorting their shapes into **arcs**
 - Multiple images+distortion: “strong” gravitational lensing
 - Only distortion: “weak” gravitational lensing.



Gravitational Lensing

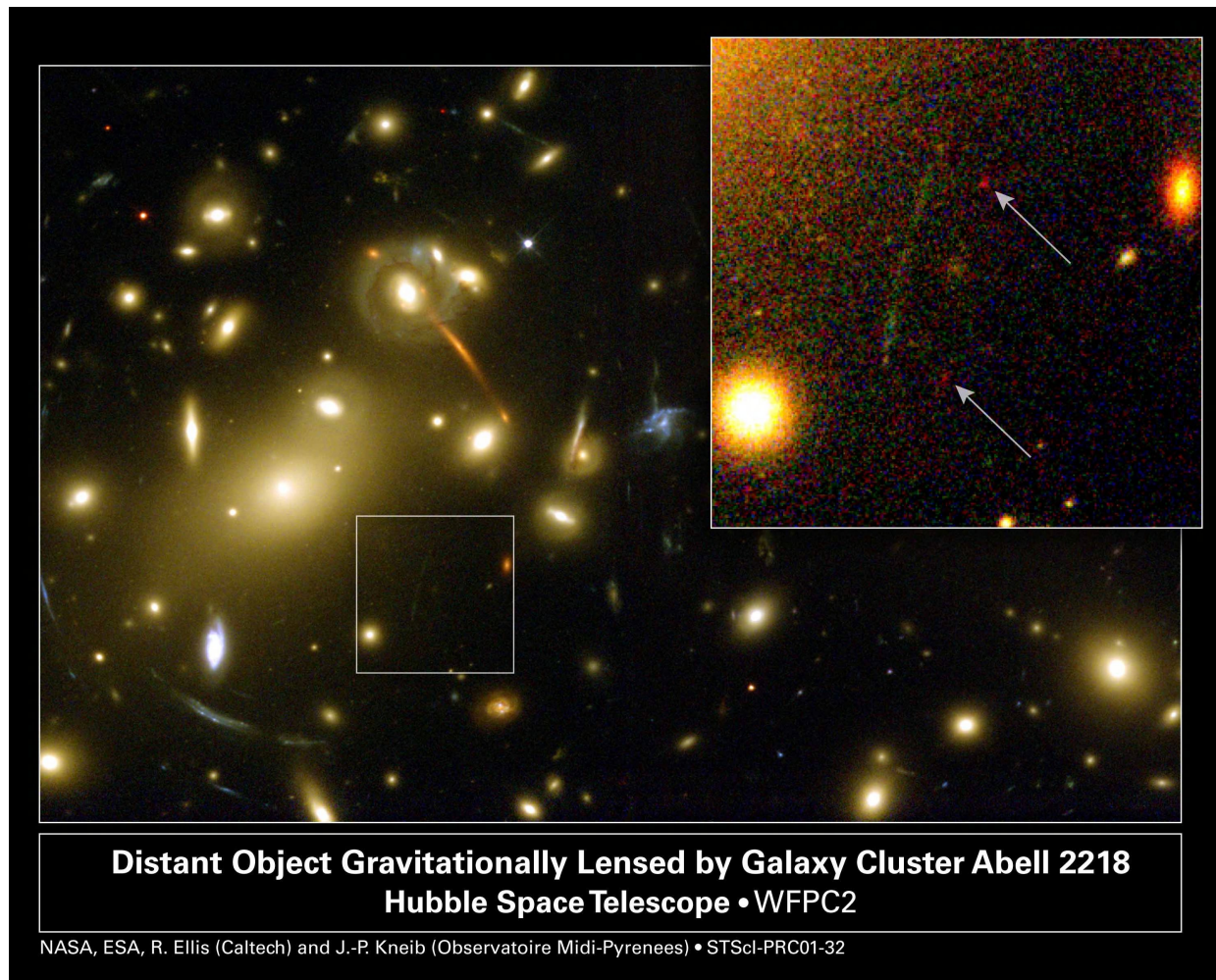
- Both the dark matter in the cluster and the member galaxies participate in the distortion of the light from background galaxies.



Abell 383

Gravitational Lensing

- Because of lensing, we can see and study galaxies that otherwise would be too faint to even consider studying.
 - Observing through a galaxy cluster is sometimes like observing with a 100m telescope!

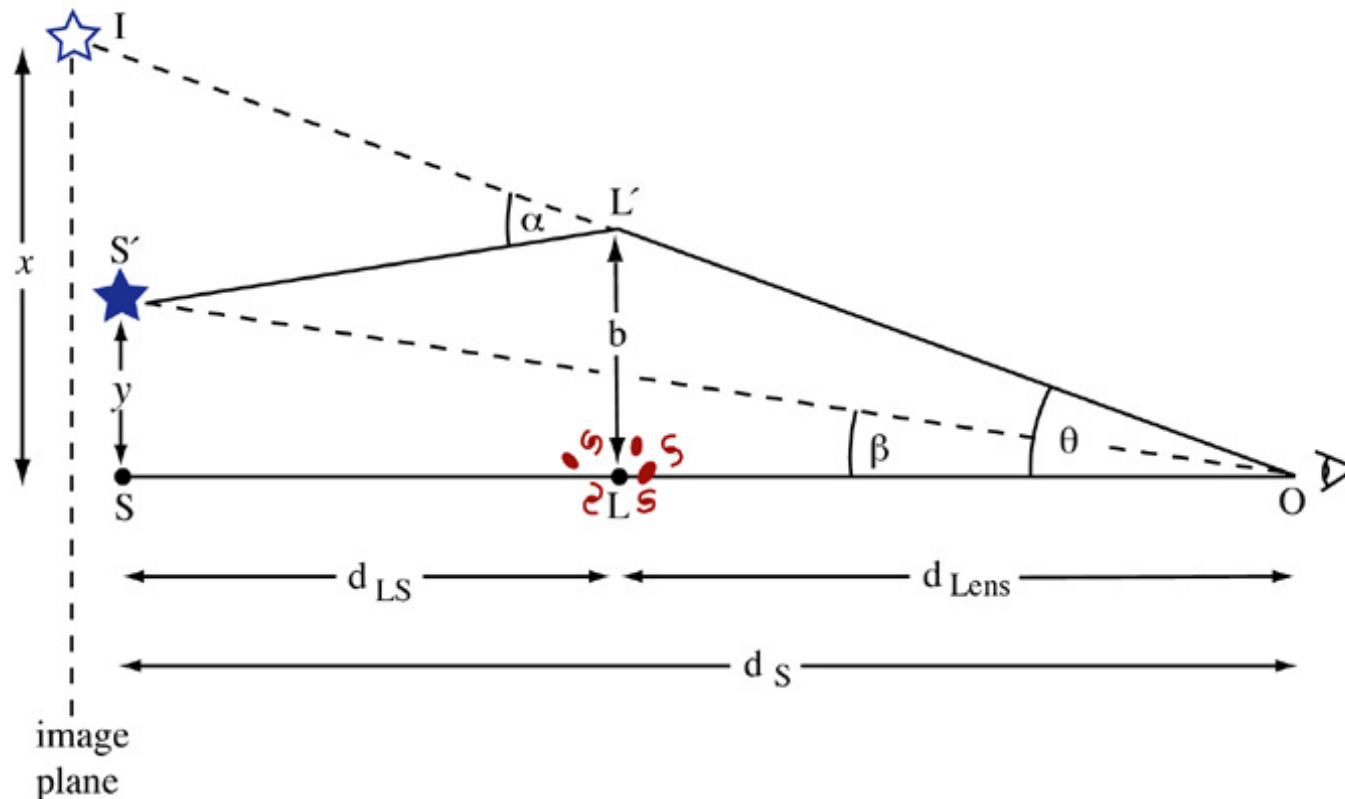


Gravitational Lensing: Theory

- Light rays grazing a massive object bend so that the image of a star (the “source”) would appear displaced from the angle β it would subtend with the line of sight to the lens by α .

$$\alpha \approx \frac{4G\mathcal{M}}{bc^2} = \frac{2R_s}{b}.$$

$R_s = 2GM/c^2$ is the
Schwarzschild radius
corresponding to mass M



Lensing by a compact object

- The image of the background source is displaced from its “true” position by

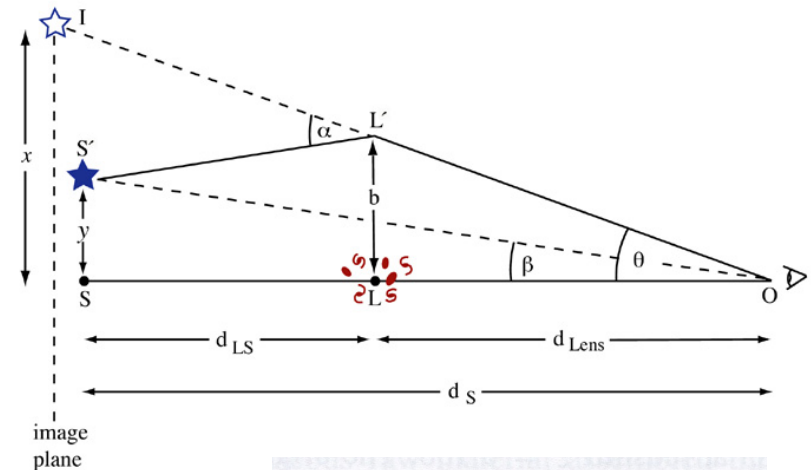
$$\theta - \beta = \frac{\alpha d_{LS}}{d_S} = \frac{1}{\theta} \frac{4GM}{c^2} \frac{d_{LS}}{d_{Lens} d_S} \equiv \frac{1}{\theta} \theta_E^2;$$

- This is a quadratic equation for θ

$$\theta^2 - \beta\theta - \theta_E^2 = 0, \quad \text{so} \quad \theta_{\pm} = \frac{\beta \pm \sqrt{\beta^2 + 4\theta_E^2}}{2}.$$

- Where θ_E is the *Einstein radius*.

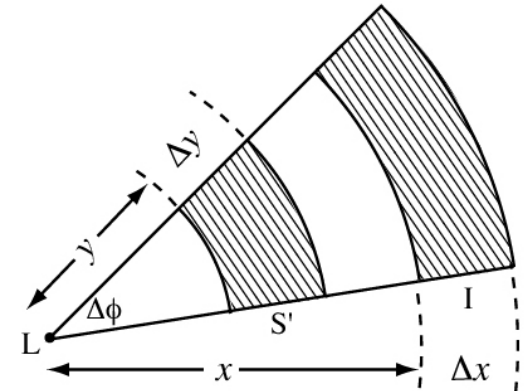
- A source directly behind the lens would be lensed into a *ring* of radius θ_E .
- For $\beta > 0$ one image is shifted away from the lens. A second image (inverted) appears on the other side of the lens.
- When stars lens other stars (a common occurrence) usually the displacements are too small to measure so the images cannot be distinguished as separate in the sky.



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

Microlensing

- Lensing has two other effects:
 - Magnification
 - Shape distortion
- For example, a patch of light S' will be lensed to I .
- The area of the image is larger, and, since gravitational lensing preserves surface brightness, it will be brighter.
 - Note that this is true for *one* of the images (the one pushed away from the lens).
 - The other image is fainter, because it lies closer to the lens than the source
- The ratio of areas is $(x \cdot \Delta x) / (y \cdot \Delta y)$, and, since



$$x/y = \theta/\beta \text{ while } \Delta x/\Delta y = d\theta/d\beta.$$

$$\theta^2 - \beta\theta - \theta_E^2 = 0, \quad \text{so} \quad \theta_{\pm} = \frac{\beta \pm \sqrt{\beta^2 + 4\theta_E^2}}{2}.$$

- We have

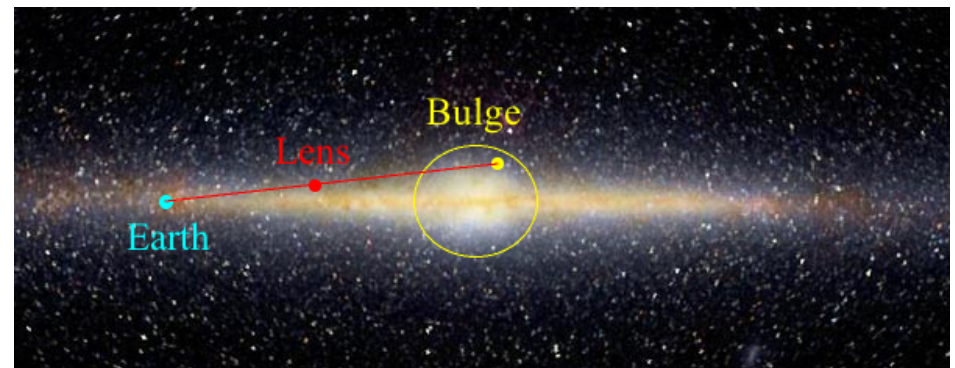
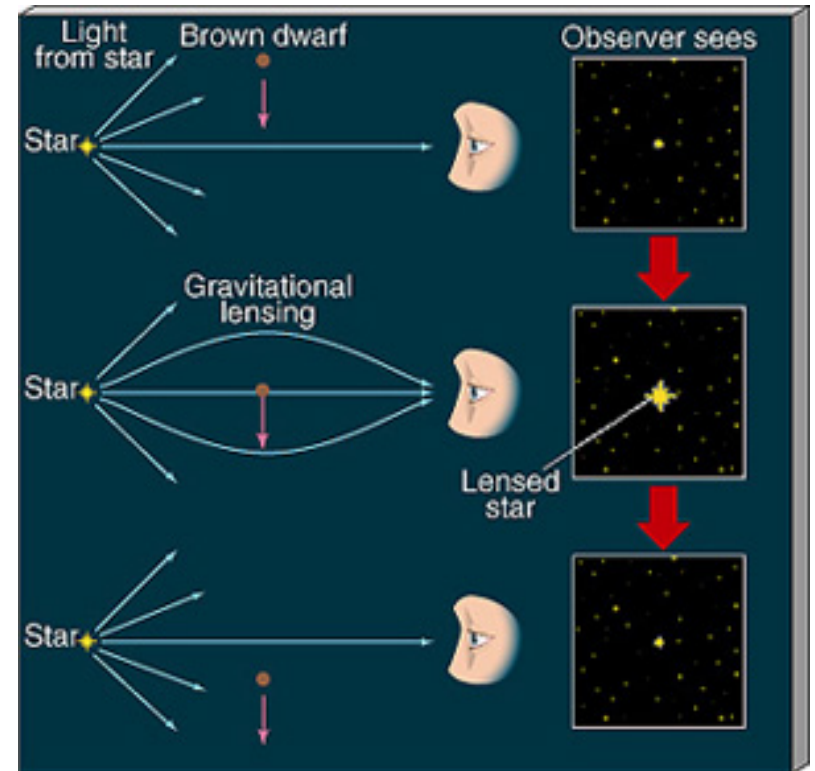
$$\frac{\mathcal{A}_{\pm}(\text{image})}{\mathcal{A}(\text{source})} = \left| \frac{\theta}{\beta} \frac{d\theta}{d\beta} \right| = \frac{1}{4} \left(\frac{\beta}{\sqrt{\beta^2 + 4\theta_E^2}} + \frac{\sqrt{\beta^2 + 4\theta_E^2}}{\beta} \pm 2 \right).$$

- The closer image is dimmer unless

$$\beta^2 < (3 - 2\sqrt{2})\theta_E^2 / \sqrt{2} \text{ or } \beta \lesssim 0.348 \theta_E$$

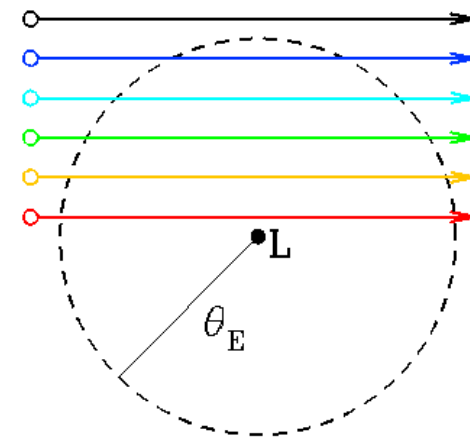
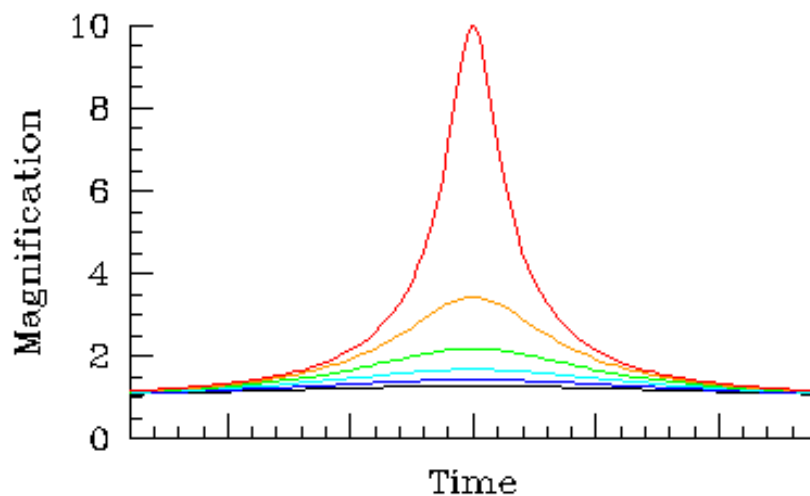
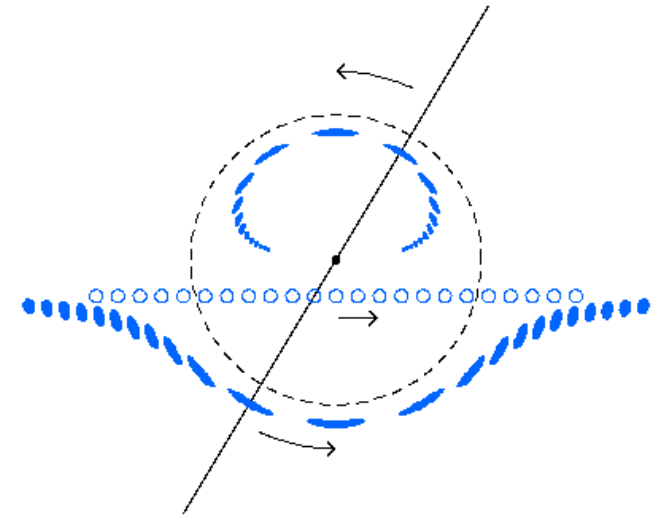
Microlensing

- In general:
 - One image is always brighter than the source would be without lensing
 - Sources are most likely to be brightened by objects midway between observer and source
 - **Microlensing** is usually detected by monitoring the change in brightness of a source, for example a star in the bulge of the galaxy or in a nearby galaxy like the Magellanic Clouds.



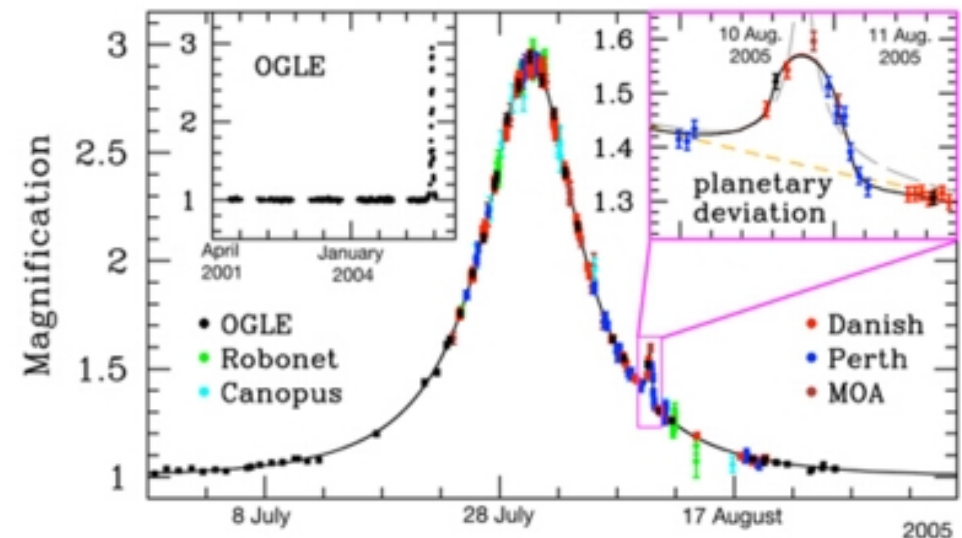
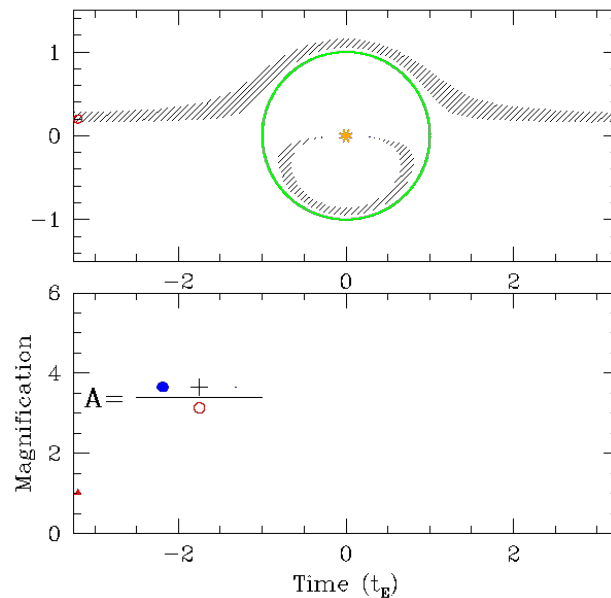
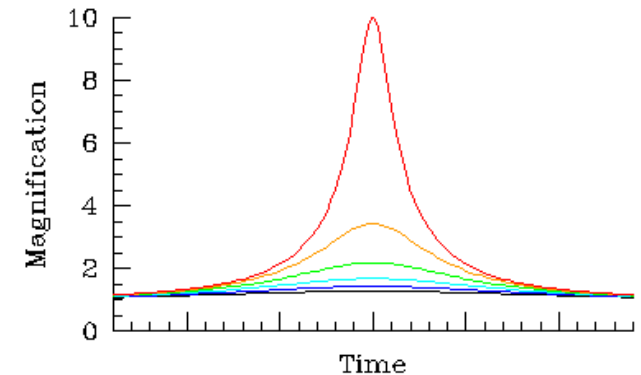
Microlensing Light Curve

- As a compact object transits across the Einstein ring of a background star, its images get brightened.
- Although the images cannot be seen as separate, the magnification has a well defined signature
 - Characteristic shape
 - Achromatic
 - Non-recurrent



Microlensing Light Curve and Planet Searches

- Because the microlensing light curve shapes are so well characterized, one may look at anomalies to search for “structure” in the lens, such as evidence for binarity, presence of small planets, etc



Light Curve of OGLE-2005-BLG-390

Lensing by Galaxies and Clusters

- When lensing is caused by an *extended* object, such as a galaxy or a galaxy cluster, we can think of the effect as caused by a *collection of point masses*.
- It is easiest to compute by writing the displacement angle in terms of a **lensing potential**, ψ_L .

$$\alpha(b) \equiv \frac{d\psi_L}{db}, \quad \text{where} \quad \psi_L = \frac{4G\mathcal{M}}{c^2} \ln b.$$

$$\alpha \approx \frac{4G\mathcal{M}}{bc^2} = \frac{2R_s}{b}.$$

$R_s = 2GM/c^2$ is the *Schwarzschild radius* corresponding to mass M

- When the size of the lens is small compared to the distances to observer and source, then only the surface density, $\Sigma(\mathbf{x})$, matters, and the *vector* deflection $\boldsymbol{\alpha}$ is given by an integral over the cluster

$$\boldsymbol{\alpha}(\mathbf{b}) \equiv \nabla \psi_L(\mathbf{b}), \quad \text{where} \quad \psi_L(\mathbf{b}) = \frac{4G}{c^2} \int \Sigma(\mathbf{b}') \ln |\mathbf{b} - \mathbf{b}'| dS'.$$

Lensing by Galaxies and Clusters

- When the lens is axisymmetric, the bending of a ray passing at a radius b depends only on the mass projected within the circle of radius b

$$\alpha(b) = \frac{4G}{bc^2} \int_0^b \Sigma(R) 2\pi R \, dR = \frac{4G}{c^2} \frac{\mathcal{M}(<b)}{b}.$$

- This is because a ring of uniform density:
 - does not bend light rays passing inside it
 - bends those rays passing outside of it just as a point mass located at the center
- The lensing equation is then:

$$\theta - \beta = \alpha(\theta) \frac{d_{LS}}{d_S} = \frac{1}{\theta} \cdot \frac{4G \mathcal{M}(<b)}{c^2} \frac{d_{LS}}{d_{\text{Lens}} d_S}.$$

- Which is typically written in terms of the critical density for lensing

$$\beta = \theta \left[1 - \frac{1}{\Sigma_{\text{crit}}} \frac{\mathcal{M}(<b)}{\pi b^2} \right], \quad \text{where } \Sigma_{\text{crit}} \equiv \frac{c^2}{4\pi G} \frac{d_S}{d_{\text{Lens}} d_{LS}}.$$

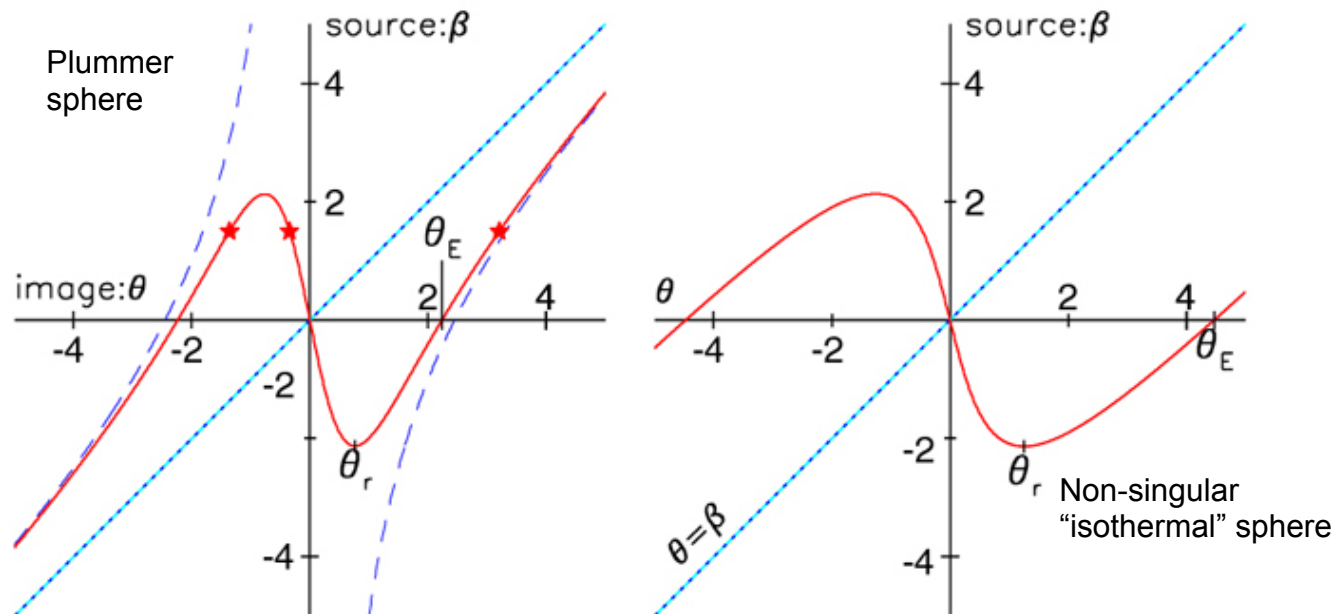
- If the central density exceeds the critical value, then a source placed exactly behind the cluster would be lensed into an Einstein ring of angular size $\theta_E = b_E / d_{\text{Lens}}$

Lensing by Galaxies and Clusters

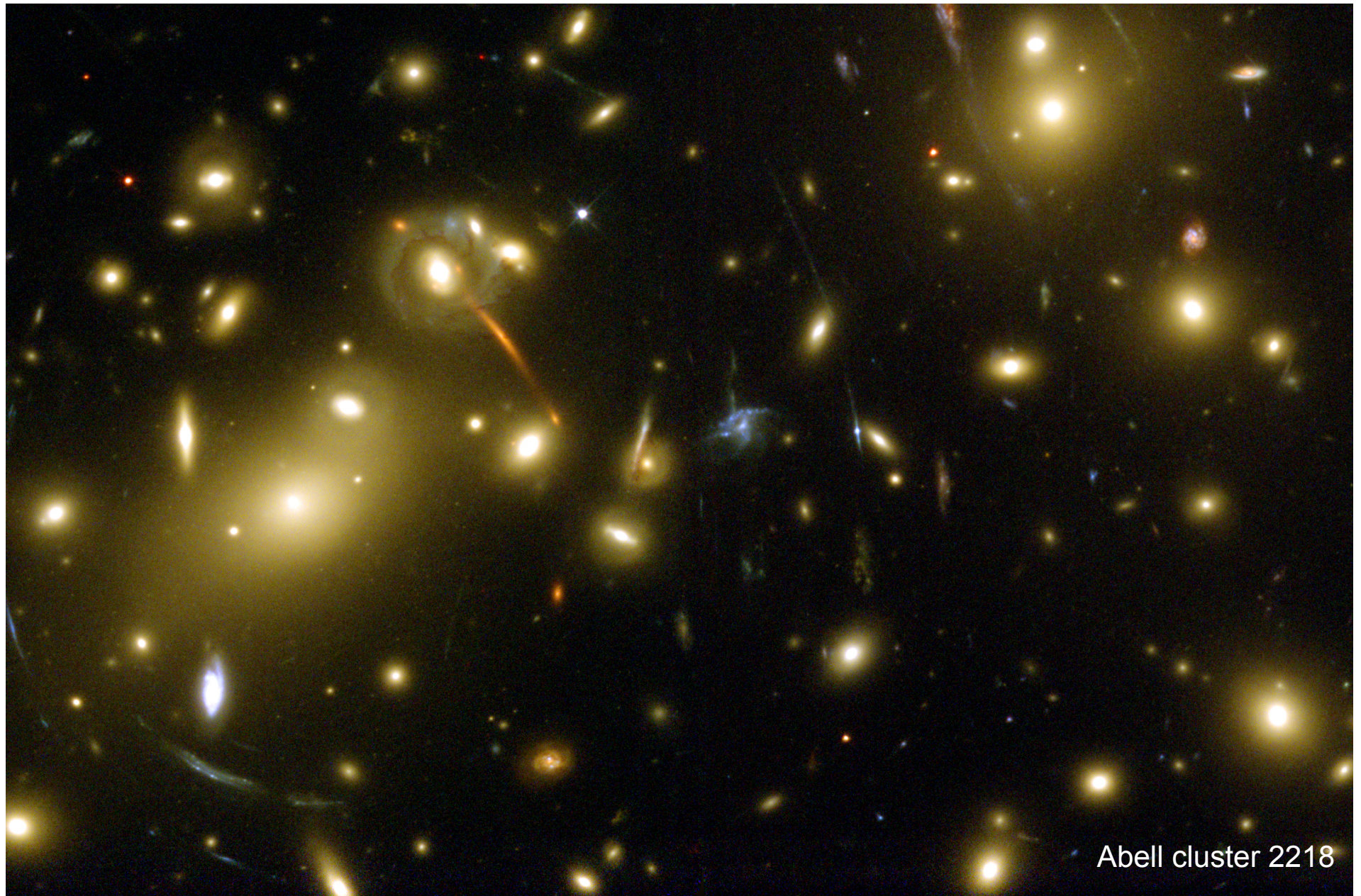
- The Einstein ring radius is where the average enclosed density equals the critical value

$$\frac{\mathcal{M}(<b_E)}{\pi b_E^2} = \Sigma_{\text{crit}}.$$

- Lenses where the density does not exceed the critical value *cannot* produce *multiple images* of sources behind it
- When multiple images exist, there are an odd number of them. In the examples below, there are either one or three images.

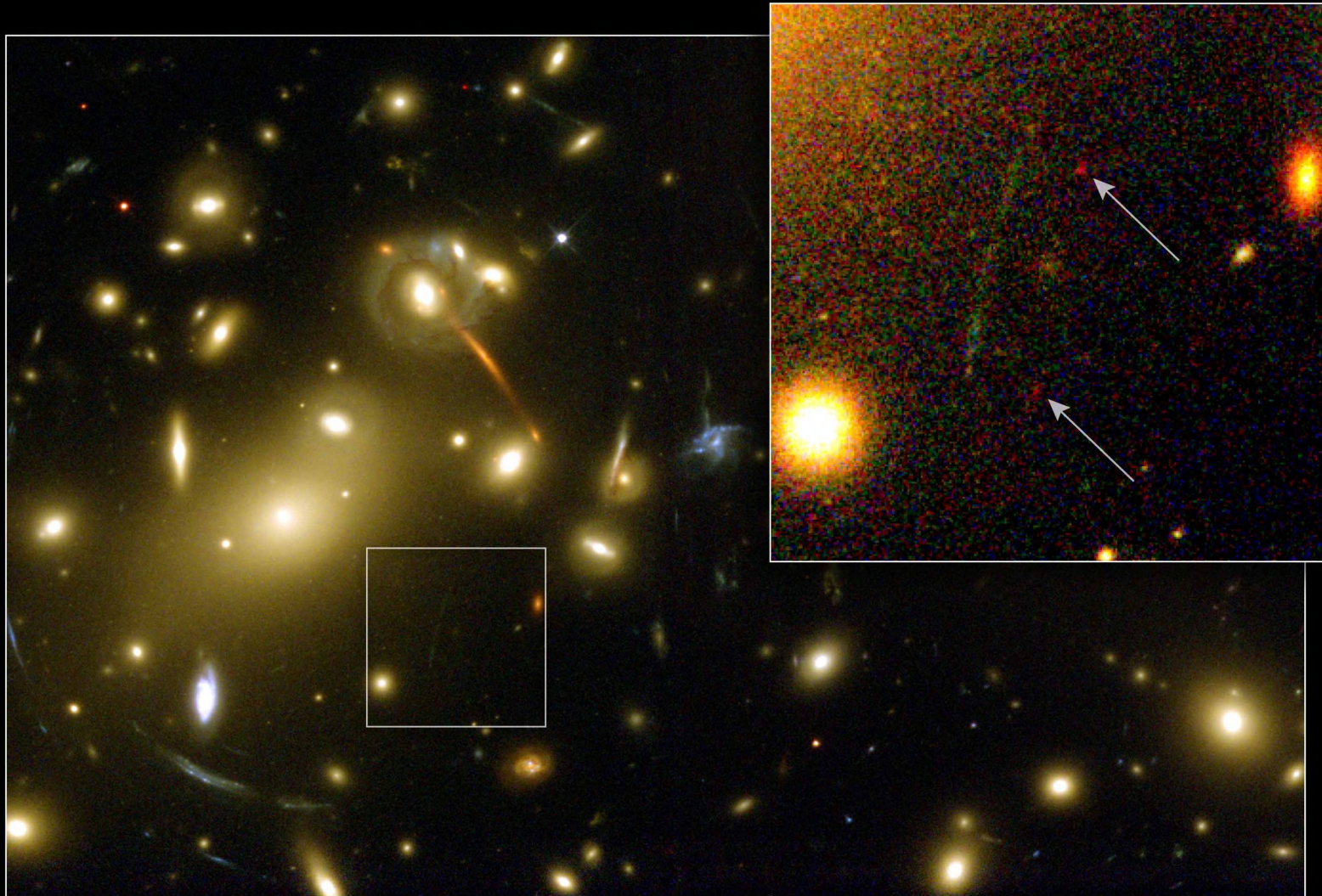


Examples of Multiple Images



Abell cluster 2218

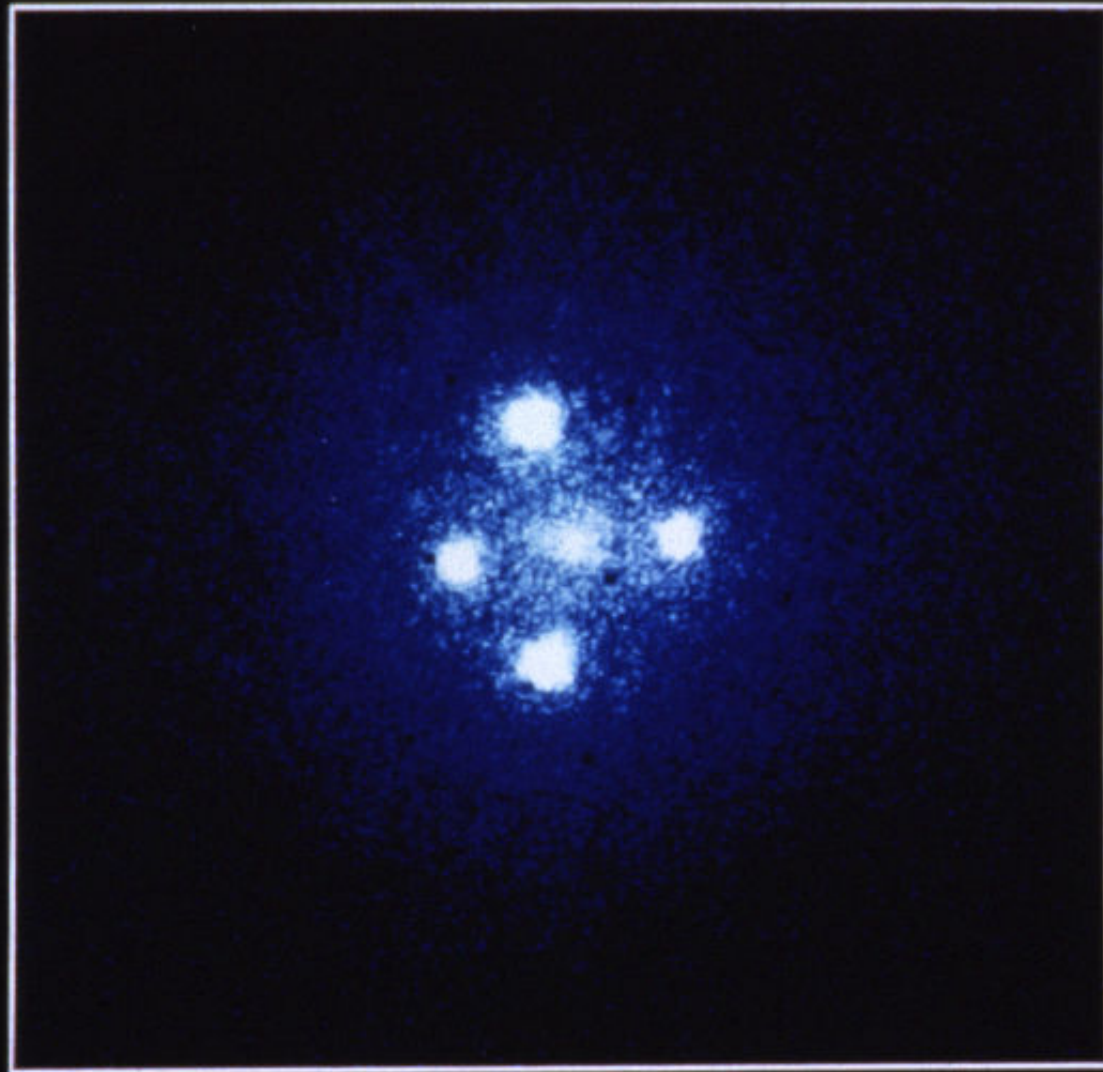
Examples of Multiple Images



Distant Object Gravitationally Lensed by Galaxy Cluster Abell 2218
Hubble Space Telescope • WFPC2

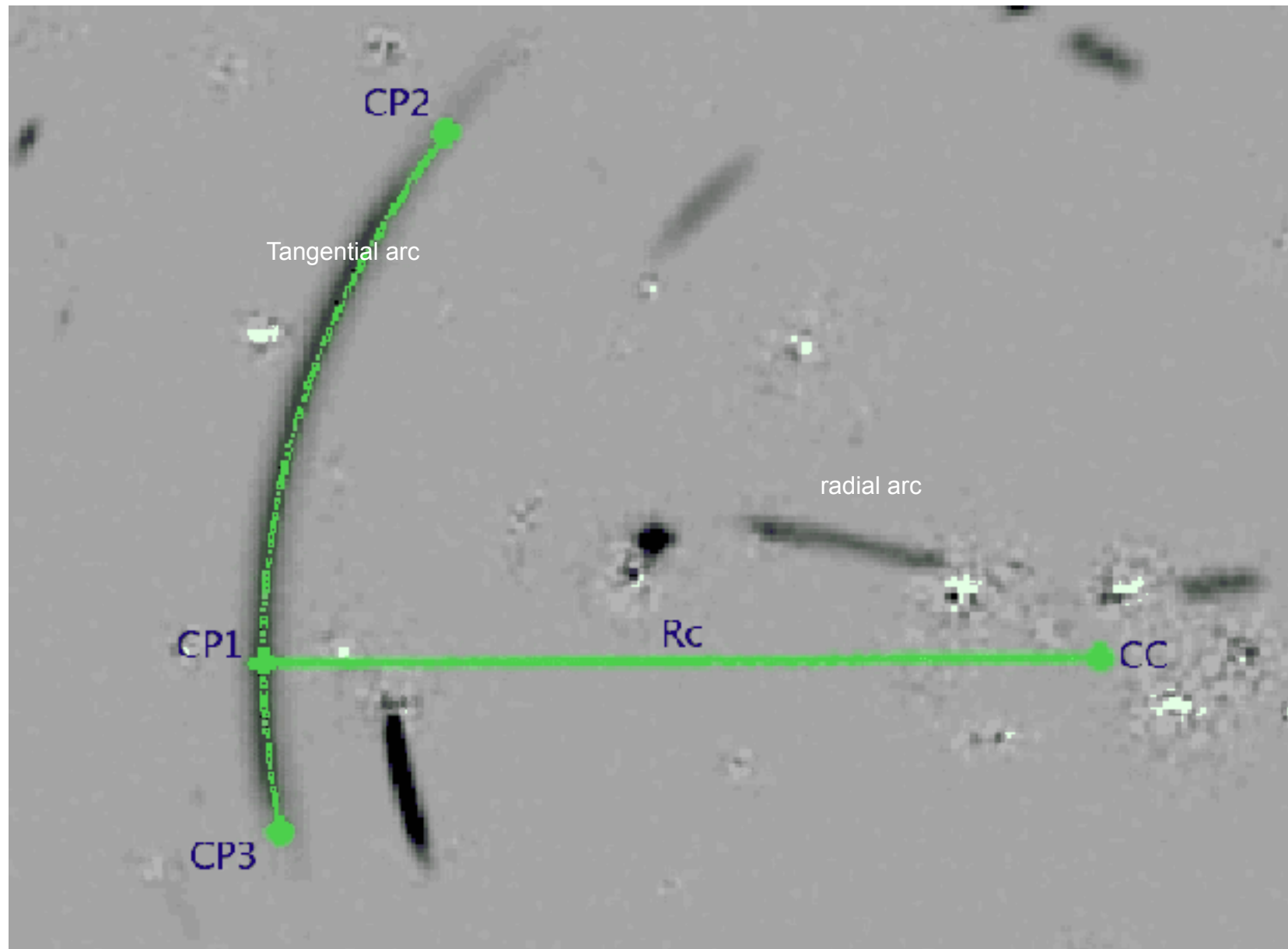
NASA, ESA, R. Ellis (Caltech) and J.-P. Kneib (Observatoire Midi-Pyrenees) • STScI-PRC01-32

Examples of Multiple Images



Gravitational Lens G2237+0305

Examples of Multiple Images



Weak Gravitational Lensing

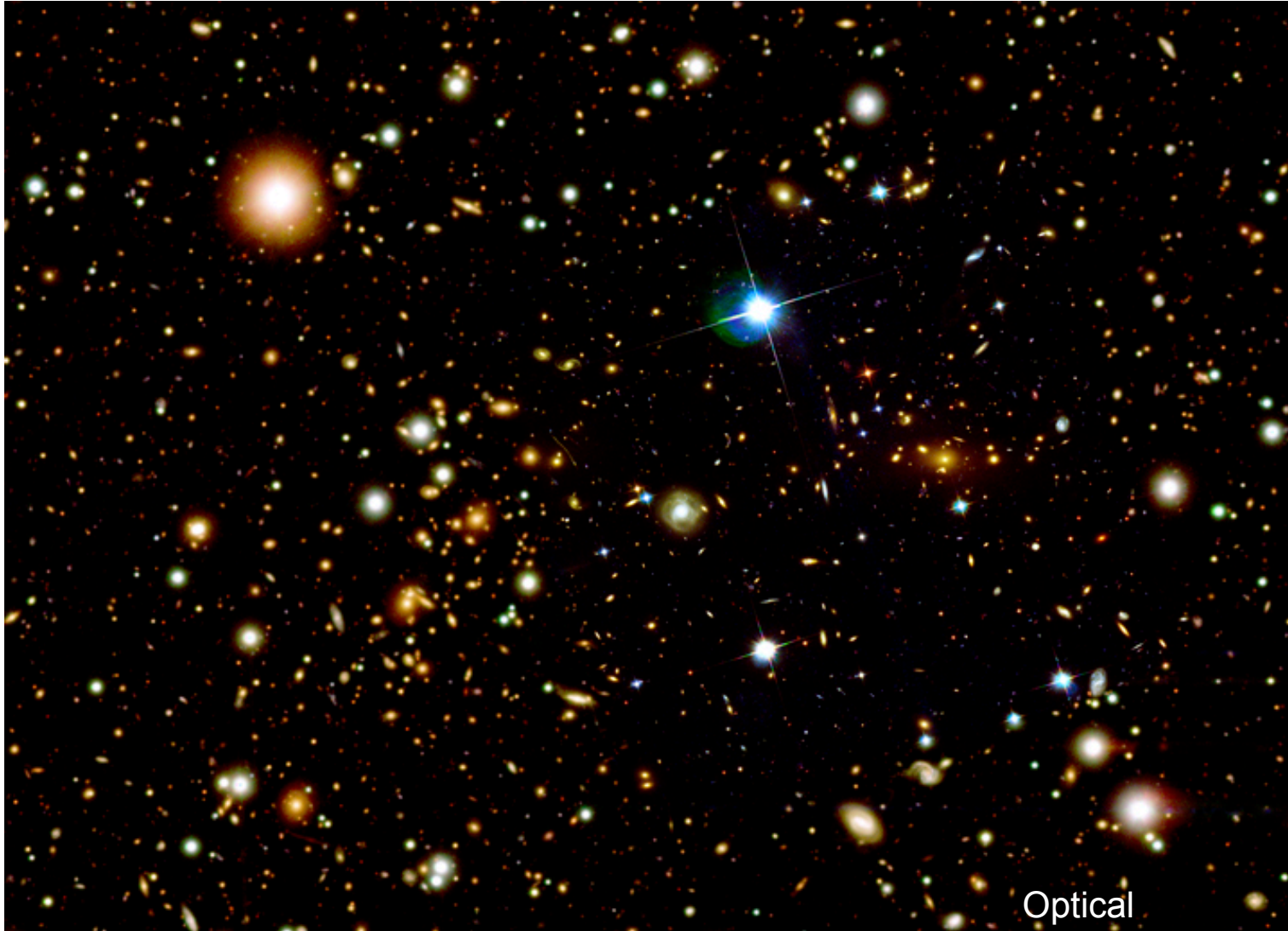
- In regions where the density falls well below the critical value images are all slightly but coherently distorted. This is measured by the “shear”: the difference in the amount an image is compressed in the radial and tangential directions is given by

$$\gamma \equiv \frac{1}{2} \left(\frac{d\beta}{d\theta} - \frac{\beta}{\theta} \right) = \frac{\bar{\Sigma}(<b) - \Sigma(b)}{\Sigma_{\text{crit}}}.$$

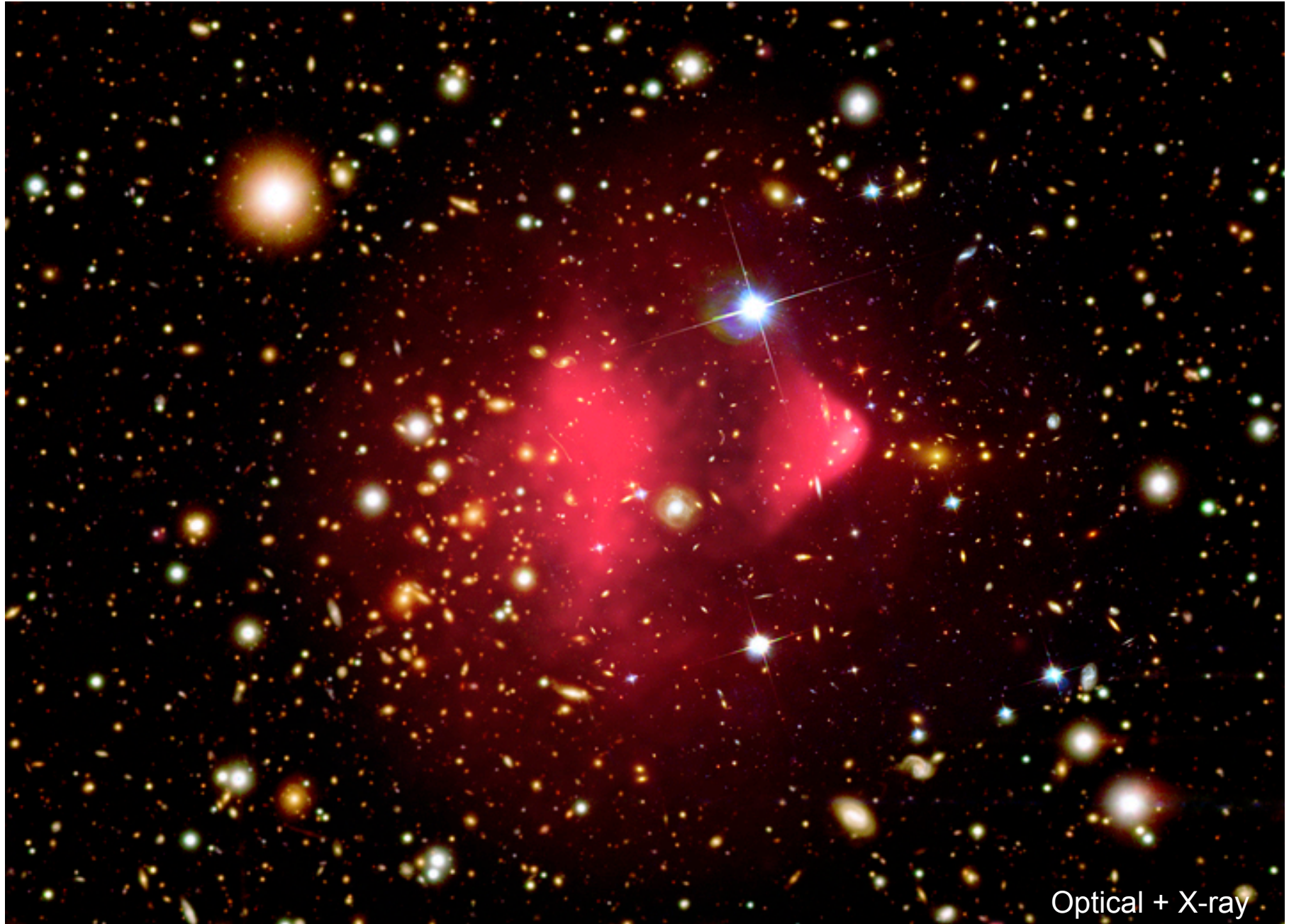
- This effect can be measured by averaging the shape of background galaxies in different regions of the outskirts of the cluster
- This effect allows measurements of the mass distribution well outside the region where the cluster is “critical”
 - Strong lensing → measures mass within the tangential arc (Einstein ring)
 - Weak lensing → measures mass in the outskirts

The “Bullet Cluster”

- A cluster undergoing a collision with another one provides spectacular evidence for dark matter



The “Bullet Cluster”

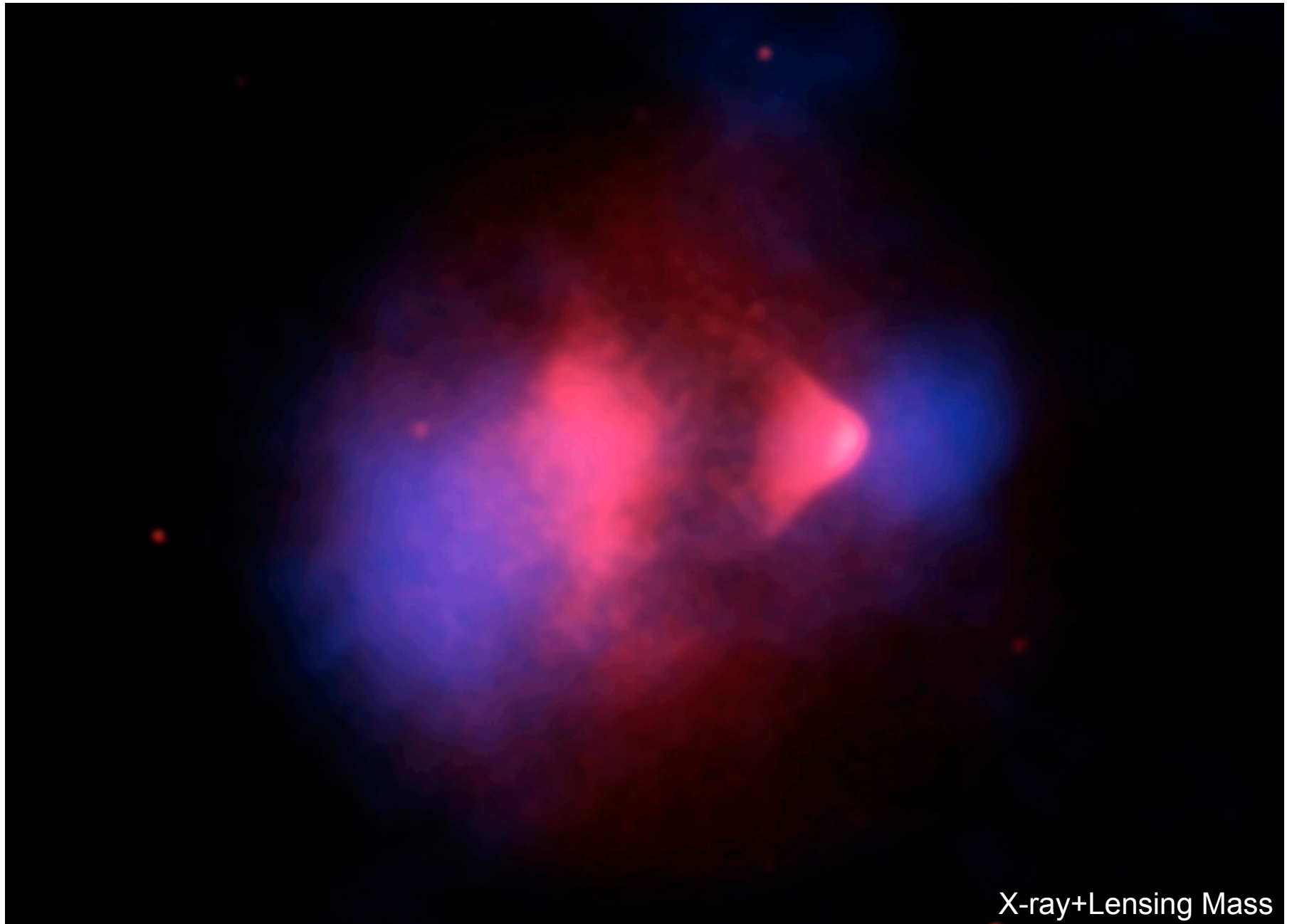


Optical + X-ray

The “Bullet Cluster”



The “Bullet Cluster”



- Mass from lensing traces galaxies
- “Baryonic” mass traces X-ray gas
- Dark matter coincides with galaxies
- Dark matter must be a “collisionless” fluid

