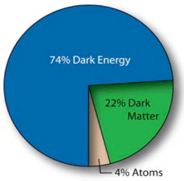
AS1001:Extra-Galactic Astronomy

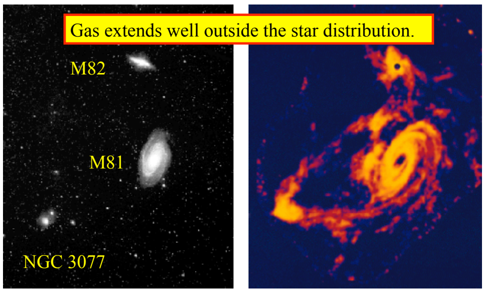
Lecture 5: Dark Matter



Stars and Gas in Galaxies

- Stars are born from gas in high-density regions.
- Compressing gas (e.g. in collisions, or spiral arms) triggers gravitational collapse to form stars.
  - Ellipticals: very little gas => $\frac{\mathbf{M}_{GAS}}{\mathbf{M}_{STARS}} \sim 0.01 - 0.1$
    - ~ all gas converted into stars
  - Spirals: some gas => $\frac{\mathbf{M}_{GAS}}{\mathbf{M}_{STARS}} \sim 0.1 - 1.0$
    - most gas converted
  - Irregulars: lots of gas => $\frac{\mathbf{M}_{GAS}}{\mathbf{M}_{STARS}} > 1.0$
    - little gas converted

Distribution of Gas and Stars



Starlight

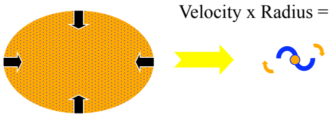
Gas (H I)
λ = 21 cm radio emission
(spin-flip of electron in H I atoms)

Dark Matter

- STARS + GAS account for only ~10% of a galaxy's total mass.
- The rest is DARK MATTER.
- The orbit velocity of the STARS + GAS is too large - they should fly away!
- Not enough gravity to hold the galaxy together, unless there is DARK MATTER (or unless our theory of gravity is wrong).
- Lets examine the evidence …

Spiral Galaxy Rotation

- Galaxies form via **collapse due to gravity.**
- During collapse, **rotation increases:**
  Conservation of angular momentum :
  Velocity x Radius = constant



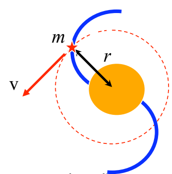
- In Spiral Galaxies, rotation halts the collapse:

GRAVITATIONAL FORCE (inward) = **CENTRIFUGAL FORCE (outward)**

Rotational Equilibrium

- Gravity force:

$$F_{IN} = \frac{G\,M\,m}{r^2}$$



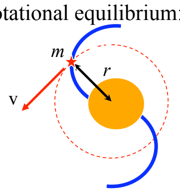
  - M = mass *interior* to radius r
  - m = mass of the orbiting star (or gas cloud)
- Centrifugal force:

$$F_{OUT} = \frac{m\,v^2}{r}$$

Virial Theorem

- **The "Virial Theorem"** (generalised Kepler's Law) applies when a galaxy is in rotational equilibrium:

$$F_{IN} = F_{OUT}$$
$$\frac{G\,M\,m}{r^2} = \frac{m\,v^2}{r}$$
$$v = \sqrt{\frac{G\,M}{r}}$$



- Observe: v = velocity of rotation at radius *r*.
  Calculate: M = mass *interior* to *r*.

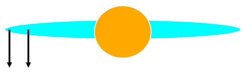
"Virial Mass" of a Galaxy

A star at the edge of a distant galaxy has a velocity about the galaxy's centre of 200 km/s. Its distance from the centre of the galaxy is 15 kpc. What is the mass of the galaxy ?

$$v = \sqrt{\frac{G\,M}{r}}$$
$$M = \frac{v^2 r}{G} = \frac{\left(2\times10^5\,\text{m/s}\right)^2 \times \left(1.5\times10^4\,\text{pc}\right)\times\left(3\times10^{16}\,\text{m/pc}\right)}{\left(6.67\times10^{-11}\,\text{m}^3\text{kg}^{-1}\text{s}^{-2}\right)}$$
$$= \frac{2.7\times10^{41}\,\text{kg}}{2.0\times10^{10}\,\text{kg}/M_{\otimes}} = 1.2\times10^{11}\,M_{\otimes}$$

The Mass Distribution M(r)

- Stars are centrally concentrated.
- Do stars trace the mass ?
- If so, then stars at the edge should "feel" almost all the mass :



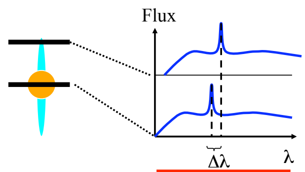
$$v = \sqrt{\frac{G\,M}{r}}$$

- If stars trace mass: $M_A \approx M_B$, so $r_A > r_B \Rightarrow v_A < v_B$

Test: Measure v as a function of *r* => "Rotation curve"

Measuring Rotation Curves

Take spectra at different locations in the galaxy



Doppler shift gives the **velocity difference** between the centre and the edge of the galaxy.

$$v(r) = \frac{\Delta\lambda}{\lambda_{BULGE}}c$$

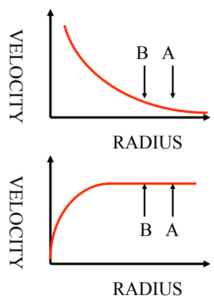
λ = 21 cm radio emission line from H I (neutral Hydrogen) is used to measure velocity of gas outside the star distribution.

Rotation Curves

- Stars (hence mass?) centrally concentrated, so expect: $v \sim r^{-0.5}$

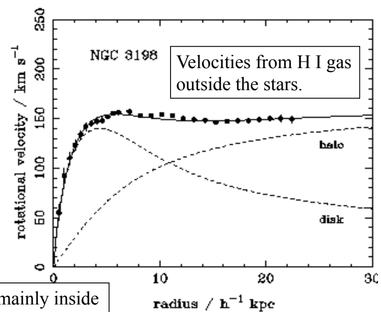
$$v = \sqrt{\frac{G\,M}{r}}$$

- **Measured rotation curves are flat** (outside the stellar distribution).



=> Additional Mass Component

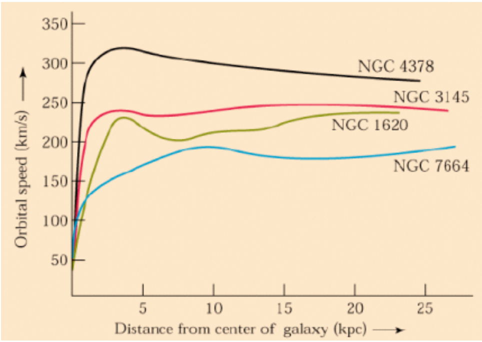
Galaxy Rotation Curves are Flat



Velocities from H I gas outside the stars.

Stars mainly inside 10 kpc

Flat Rotation Curves



Implication for Dark Matter

- At large radii: $v^2 = \frac{GM}{r} = \text{constant}$
- Hence mass is proportional to radius:

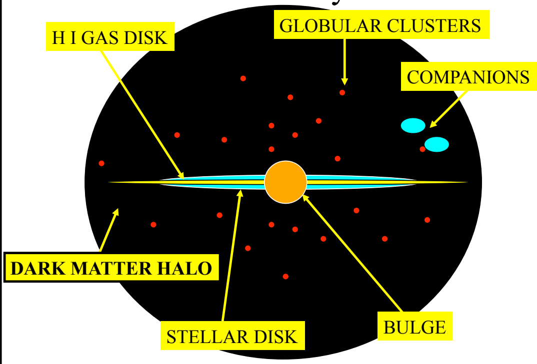
$$M = \frac{v^2 r}{G} \propto r$$

- Density proportional to $1/r^2$

$$\rho = \frac{M}{Volume} \propto \frac{r}{r^3} \propto \frac{1}{r^2}$$

- => a large spherical "halo" of Dark Matter.

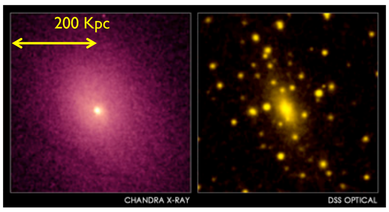
Revised Galaxy Model



Dark Matter in Galaxy Clusters

- Found by Fritz Zwicky (1930s).
- Pre-dates rotation curve observations and analysis (1975).
- Galaxies in clusters have very large observed velocities (**v ~ 1000 km/s**).
- Galaxy clusters should be unbound!
- But clusters ARE bound, so more mass must be present than the luminous matter.
- **Dark Matter needed to bind galaxy clusters**.

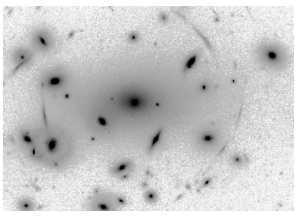
Dark Matter in Galaxy Clusters

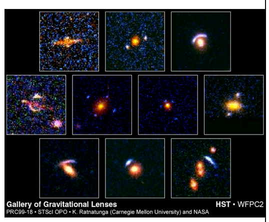


Chandra X-ray Image of Abell 2029
The galaxy cluster Abell 2029: thousands of galaxies enveloped in a gigantic cloud of hot T~10^7 K gas.
Bound by **Dark Matter** equivalent to **10^{14} Suns**.
The enormous elliptical galaxy at the center has formed by mergers of many smaller galaxies.

Gravitational Lensing

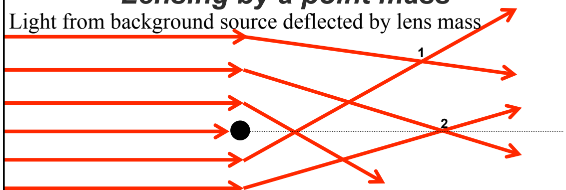
- **Luminous arcs** seen in galaxy clusters.
- **Multiple images** of some quasars.
- Background sources are magnified and distorted by **gravitational lensing** as the light passes through an intervening galaxy or cluster of galaxies.





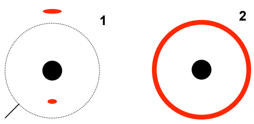
Lensing by a point mass

Light from background source deflected by lens mass



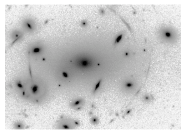
Two distorted/magnified images of background source

Observer's view:



Einstein ring

Masses from Gravitational Lensing



Perfect alignment gives an Einstein Ring.

Imperfect alignment = Luminous arc

Angular size of the Einstein Ring:

$$\theta_E = \left(\frac{4\,G\,M}{c^2} \frac{D_S - D_L}{D_L D_S} \right)^{1/2}$$

Mass of the Lens: $\frac{M}{10^{11} M_{SUN}} = \left(\frac{\theta_E}{1 \text{ arcsec}} \right)^2 \left(\frac{D_L D_S}{(1 \text{ Gpc})\,(D_S - D_L)} \right)$

D_L = Distance to the Lens

D_S = Distance to the background Source

Summary:

- Large spiral galaxies have **flat rotation curves.**
- Stars do not trace the mass.
- Stars are a minor mass component, about 10%.
- DARK MATTER is needed to hold galaxies (and clusters of galaxies) together.
- Dark Matter forms a large halo with density falling as $1/(\text{radius})^2$
- Alternatively, our theory of Gravity may be wrong.

DARK MATTER candidates

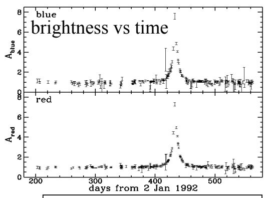
- Normal (i.e., Baryonic)
  - Ionised gas
  - Cold dust
  - Planets
  - White dwarfs
  - Black Holes
  - **MACHOS** (**M**assive **C**ompact **H**alo **O**bjects)
- Exotic (i.e., non-Baryonic)
  - **WIMPS** (**W**eakly **I**nteracting **M**assive **P**articles)
  - Neutrinos

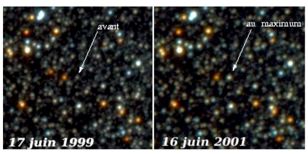
Ruled out by observations.

The Large Hadron Collider is hunting for WIMPS.

MACHO survey using LMC stars

LMC stars would be lensed by MACHOs in the Milky Way's Dark Matter Halo.





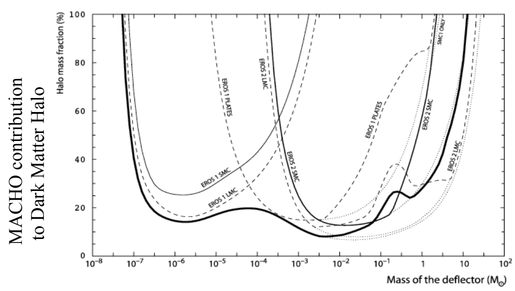
MACHOs predicted to magnify dozens of LMC stars each year.
Only a 1 or 2 are seen.

Slow events -> high mass

Fast events -> low mass

Microlens Surveys rule out MACHOs

MACHO contribution < 5-10 %



MACHO mass

Alternative Gravity Theory ?

- Is our theory of gravity wrong ?
- Newtonian gravity failed to explain all solar system observations (e.g., Mercury's orbit precesses too fast).
- Einstein's General Relativity improved on Newton, but is now failing to explain how galaxies rotate …
- Will an observational breakthrough "discover" Dark Matter?
- Or will a convincing alternative theory of gravity emerge?