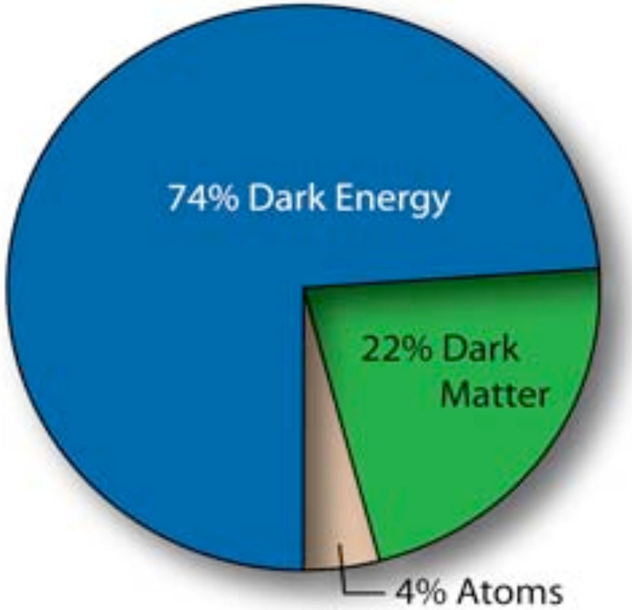
# AS1001:Extra-Galactic Astronomy

## 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.

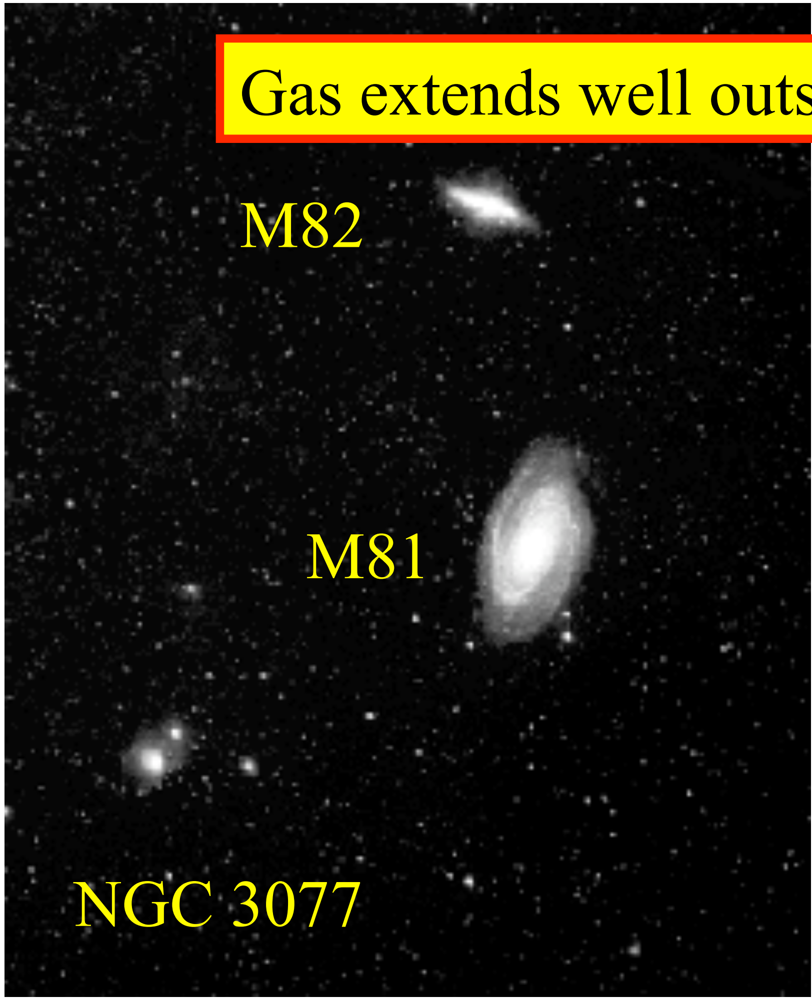
  – Ellipticals: very little gas => $\frac{M_{GAS}}{M_{STARS}} \sim 0.01 - 0.1$
    - ~ all gas converted into stars

  – Spirals: some gas => $\frac{M_{GAS}}{M_{STARS}} \sim 0.1 - 1.0$
    - most gas converted

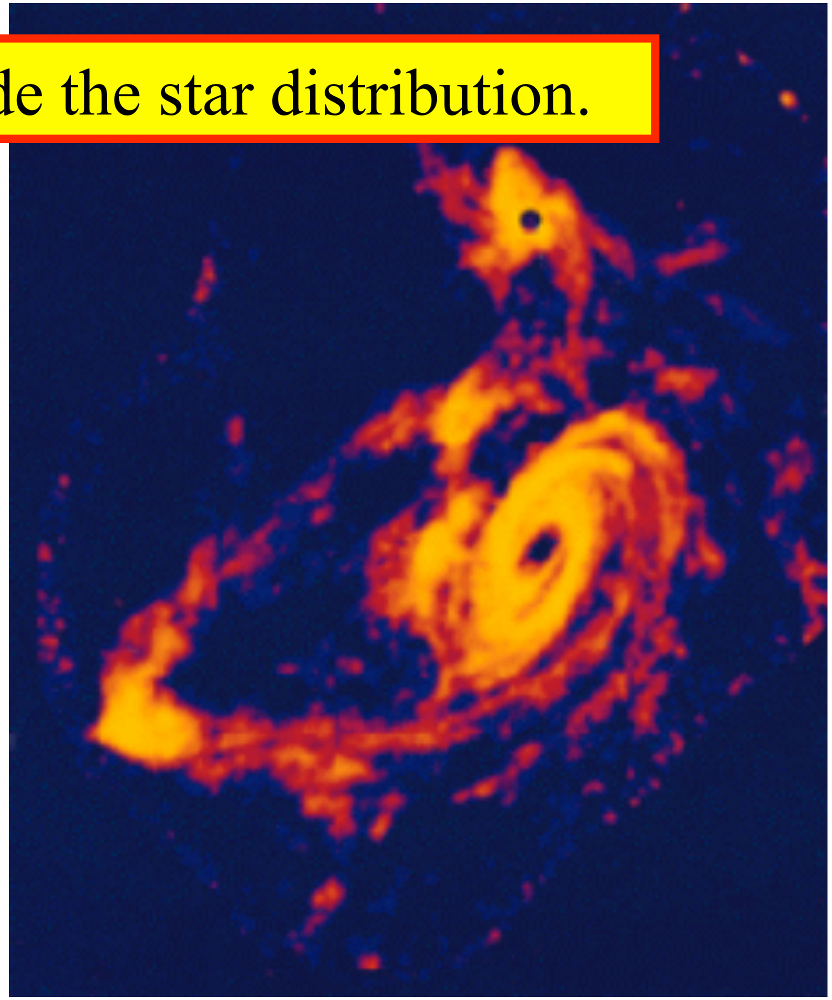
  – Irregulars: lots of gas => $\frac{M_{GAS}}{M_{STARS}} > 1.0$
    - little gas converted

# Distribution of Gas and Stars

Gas extends well outside the star distribution.




Starlight



Gas (H I)

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

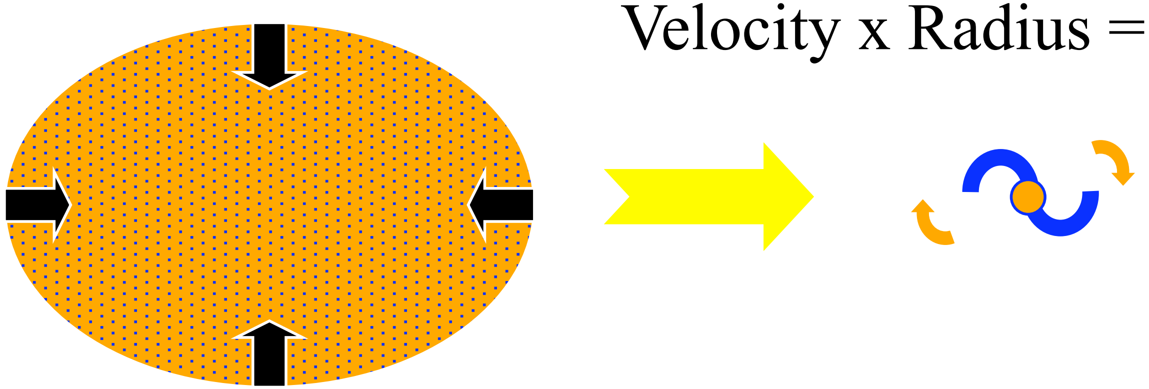
# Dark Matter

- 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



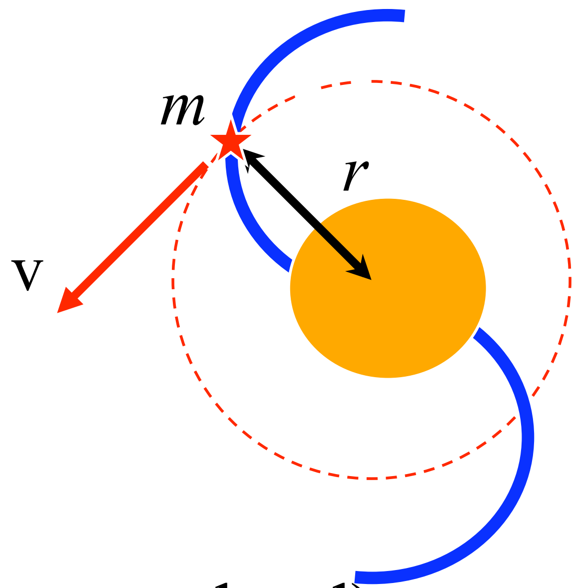
- In Spiral Galaxies, rotation halts the collapse:

**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:

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

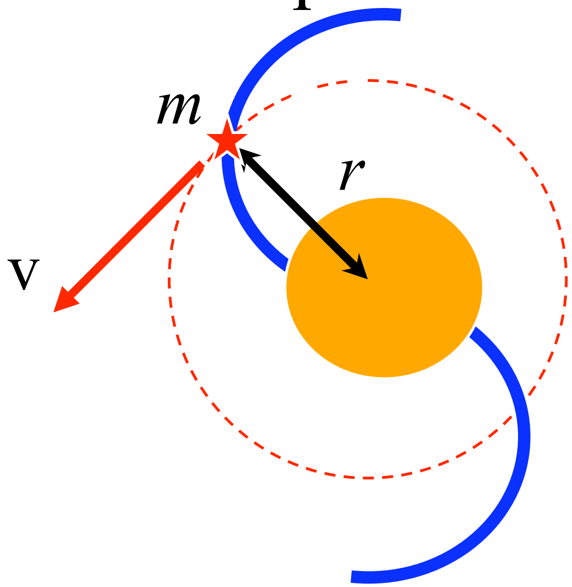
# Virial Theorem

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

$$F_{IN} = F_{OUT}$$

$$\frac{G\,M\,m}{r^2} = \frac{m\,\mathrm{v}^2}{r}$$

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




- 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 ?

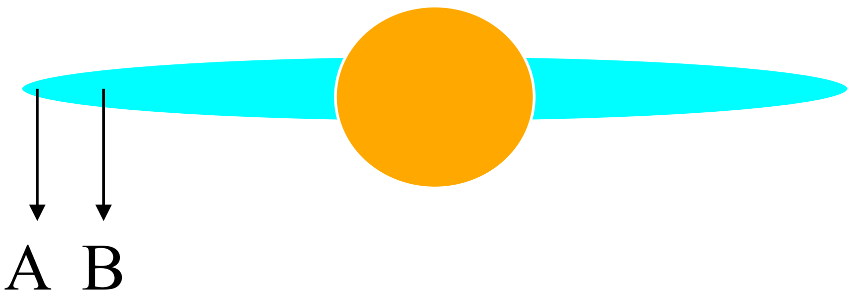
$$\mathrm{v} = \sqrt{\frac{G\,M}{r}}$$

$$M = \frac{\mathrm{v}^2 r}{G} = \frac{\left(2\times10^5\,\mathrm{m/s}\right)^2 \times \left(1.5\times10^4\,\mathrm{pc}\right) \times \left(3\times10^{16}\,\mathrm{m/pc}\right)}{\left(6.67\times10^{-11}\,\mathrm{m^3kg^{-1}s^{-2}}\right)}$$

$$= \frac{2.7\times10^{41}\,\mathrm{kg}}{2.0\times10^{10}\,\mathrm{kg/M_\otimes}} = 1.2\times10^{11}\,\mathrm{M_\otimes}$$

# 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 :



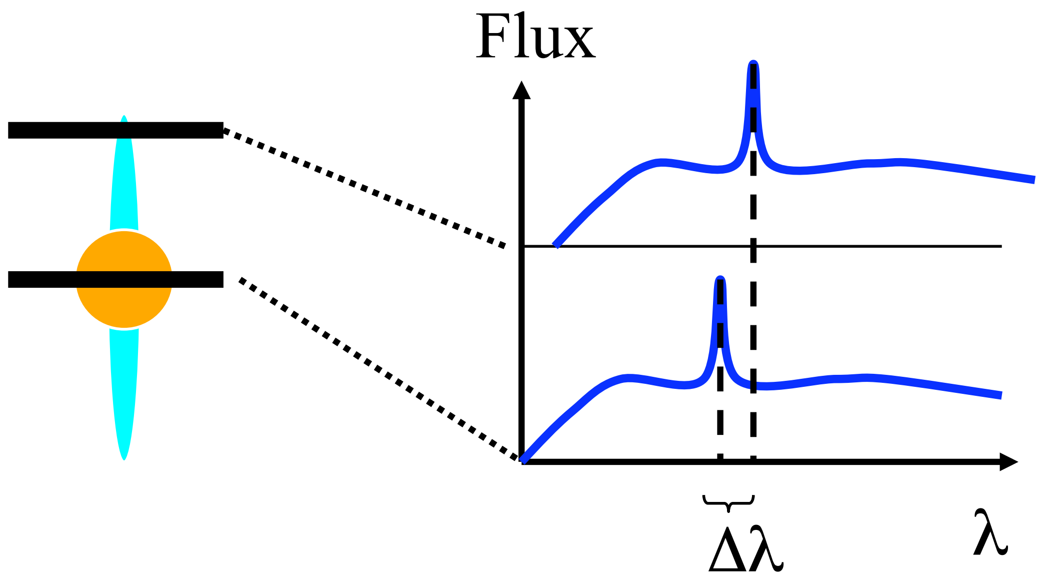

$$v = \sqrt{\frac{G\,M}{r}}$$

- 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.

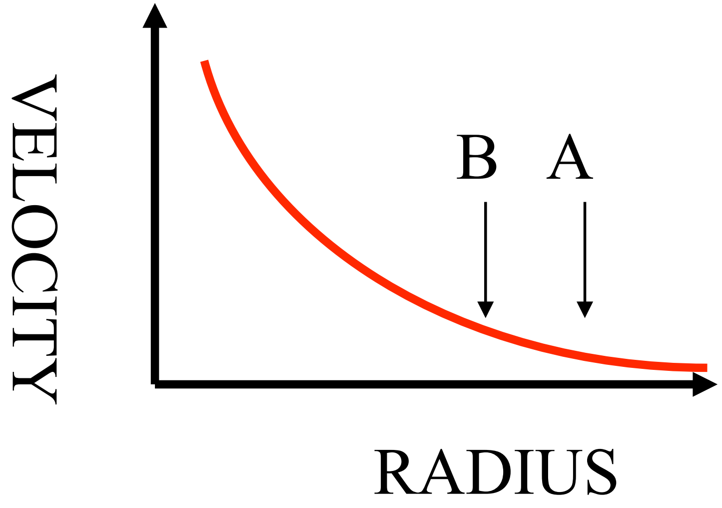
$$v(r) = \frac{\Delta\lambda}{\lambda_{BULGE}} c$$

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

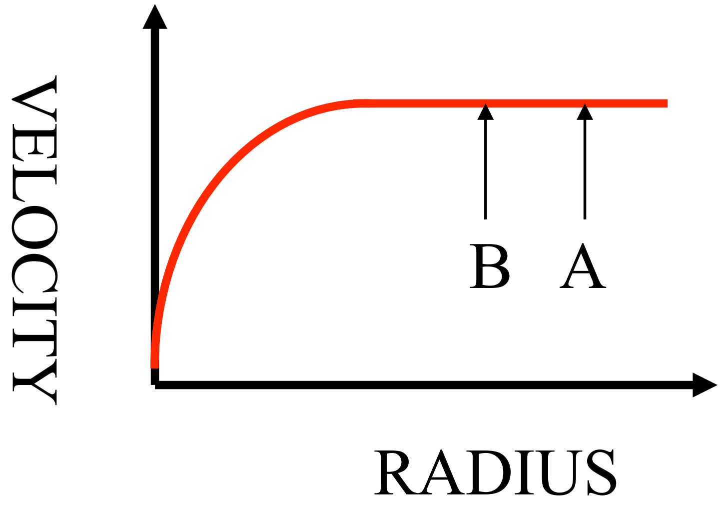
# Rotation Curves

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

$$v = \sqrt{\frac{GM}{r}}$$

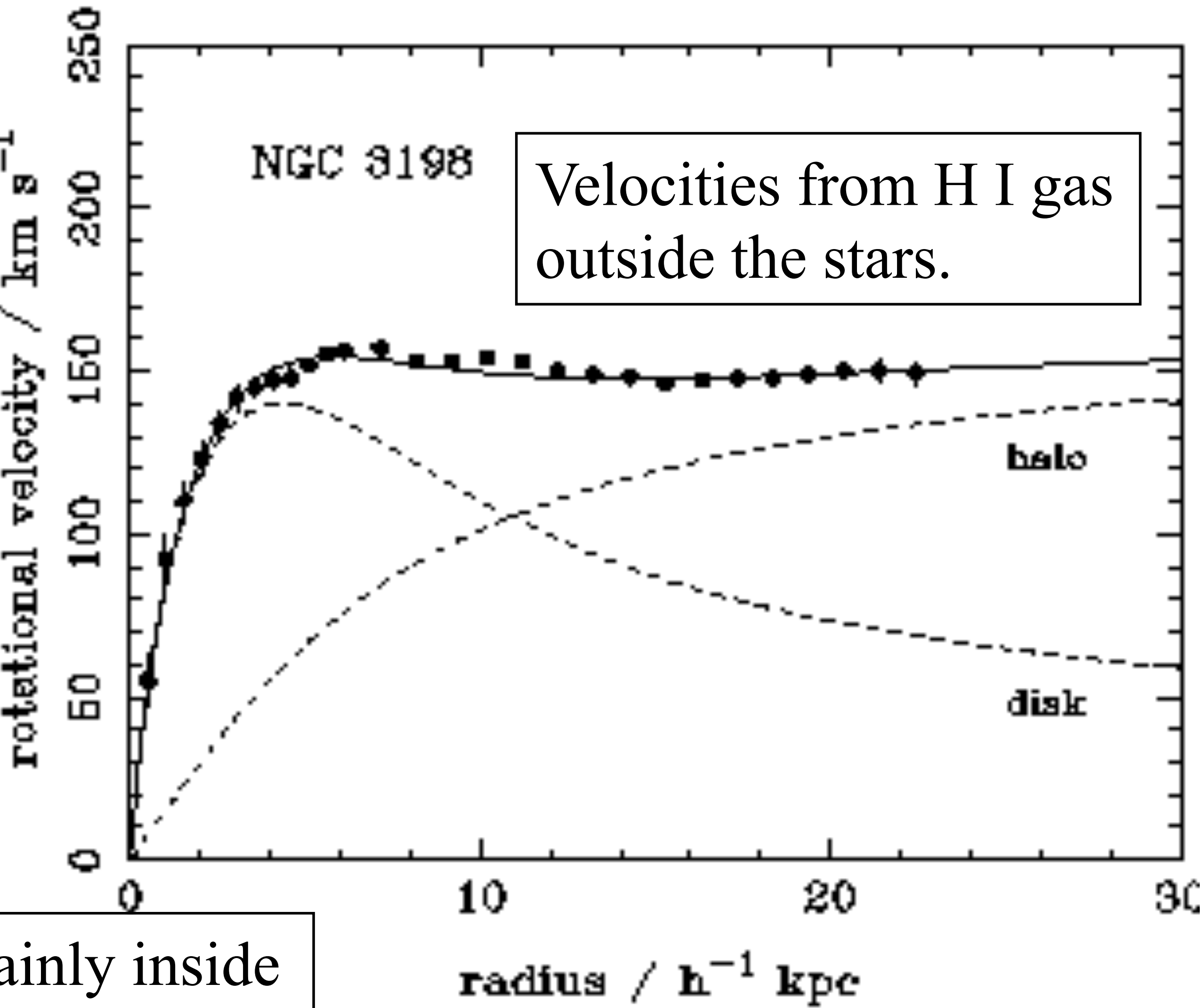



- **Measured rotation curves are flat** (outside the stellar distribution).




**=> Additional Mass Component**

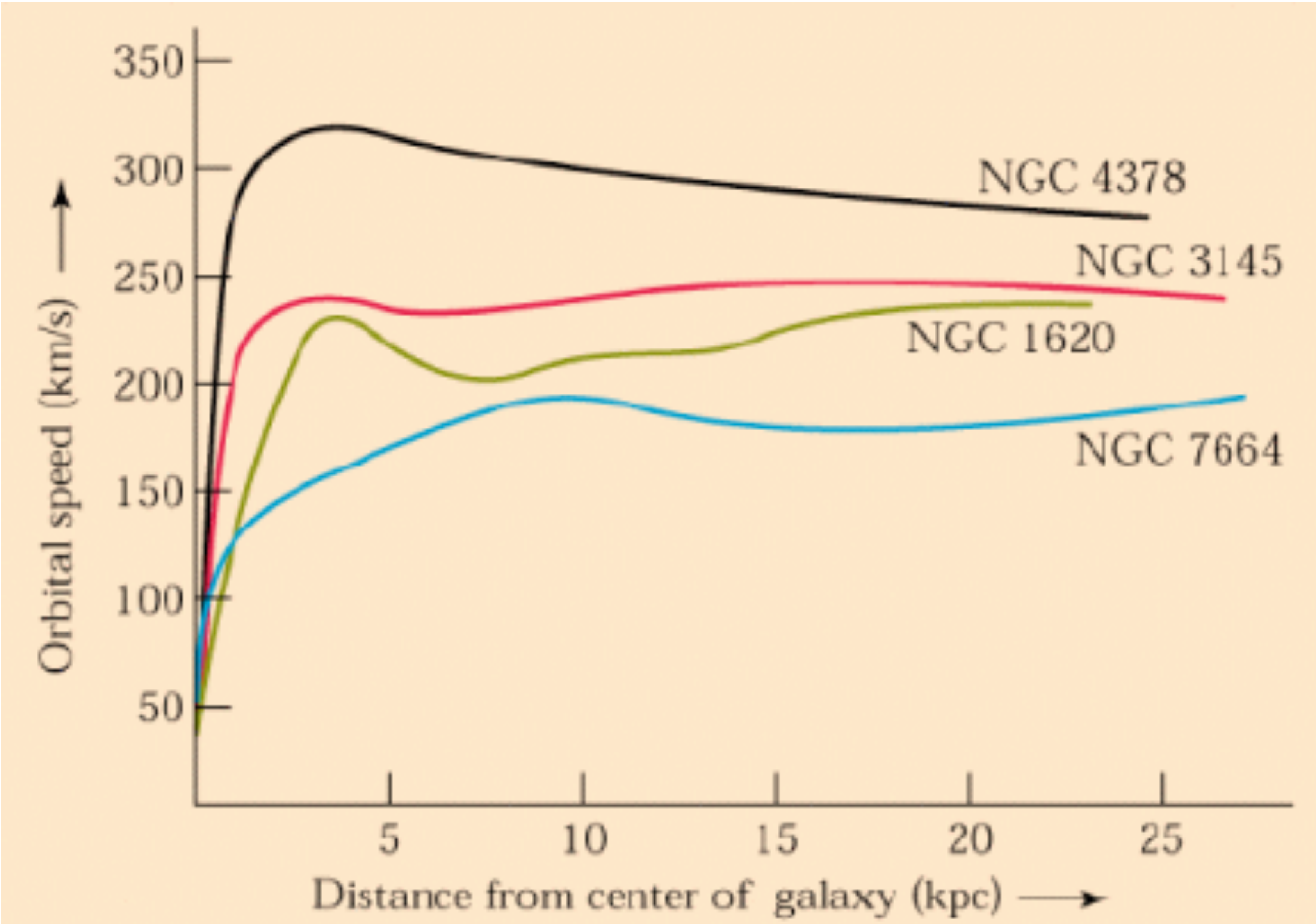
# Galaxy Rotation Curves are Flat




Velocities from H I gas outside the stars.

Stars mainly inside 10 kpc

# Flat Rotation Curves



# Implication for Dark Matter

- At large radii: $$\mathrm{v}^2 = \frac{G\,M}{r} = \text{constant}$$

- Hence mass is proportional to radius:

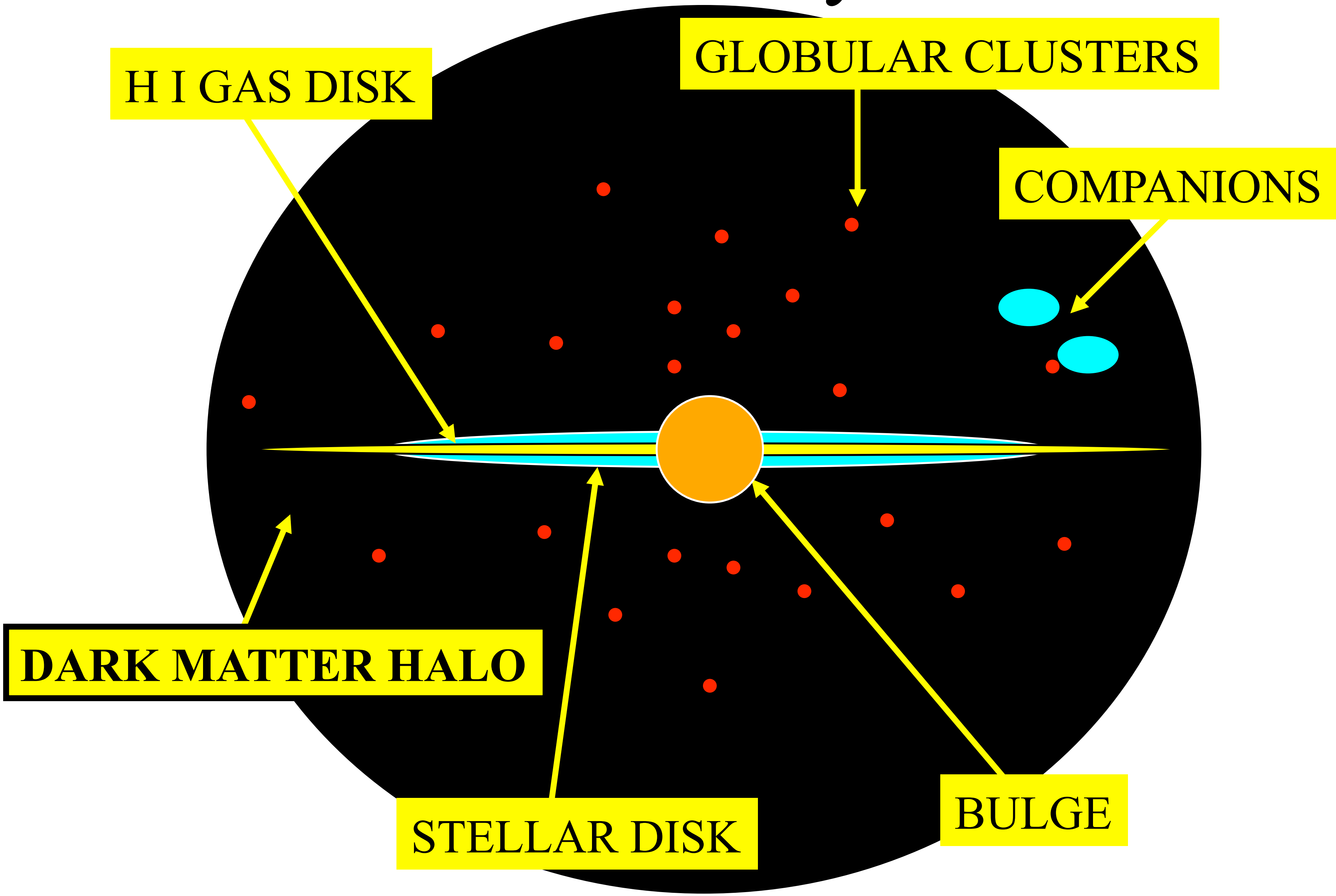
$$M = \frac{\mathrm{v}^2 r}{G} \propto r$$

- 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.

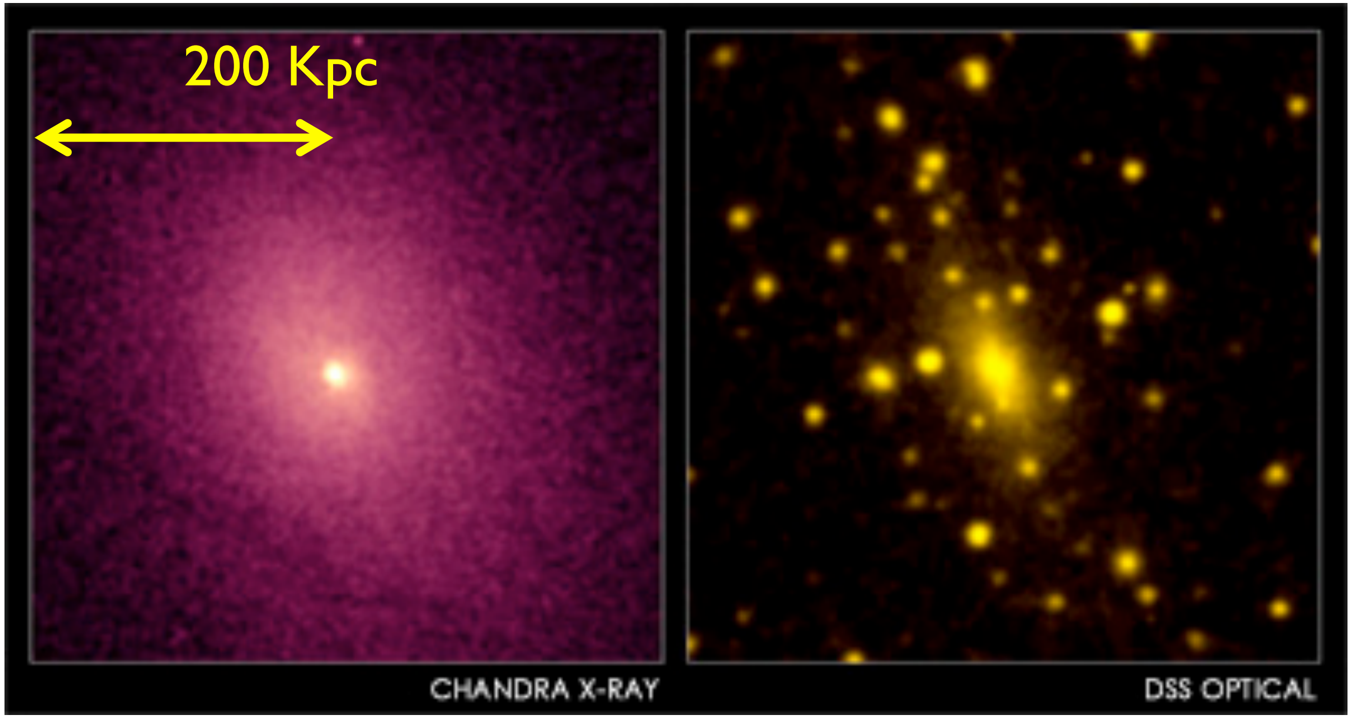
# Revised Galaxy Model



# 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**

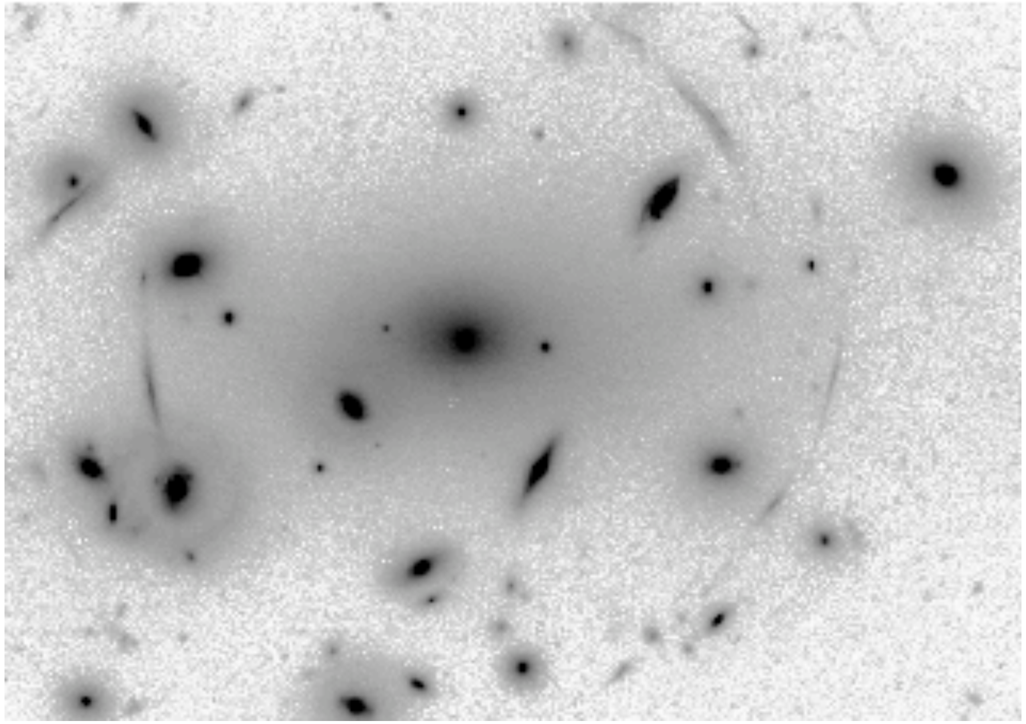
The galaxy cluster Abell 2029: thousands of galaxies enveloped in a gigantic cloud of hot $T \sim 10^7$ K gas.

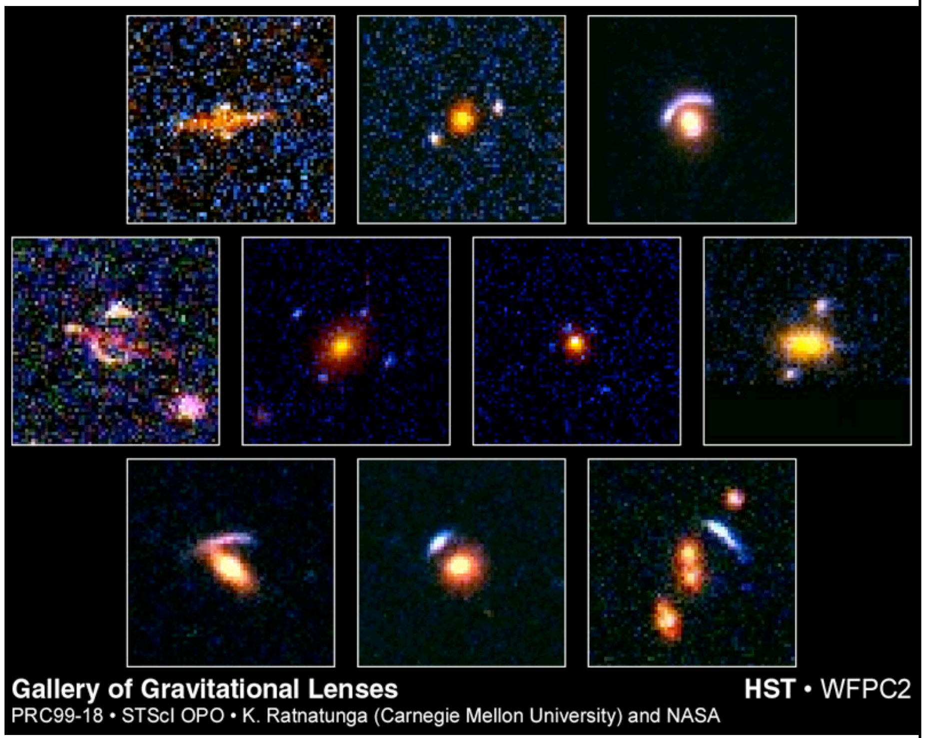
Bound by **Dark Matter** equivalent to **$10^{14}$ Suns**.

The enormous elliptical galaxy at the center has formed by mergers of many smaller galaxies.

# Gravitational Lensing

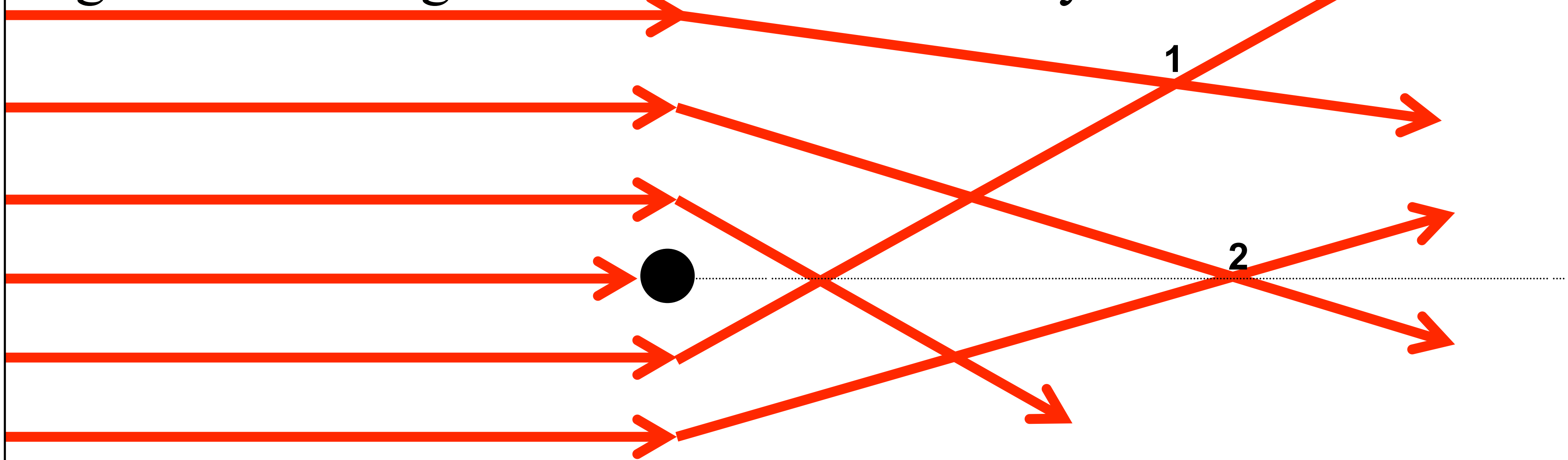
- **Luminous arcs** seen in galaxy clusters.
- **Multiple images** of some quasars.
- Background sources are magnified and distorted by **gravitational lensing** as the light passes through an intervening galaxy or cluster of galaxies.





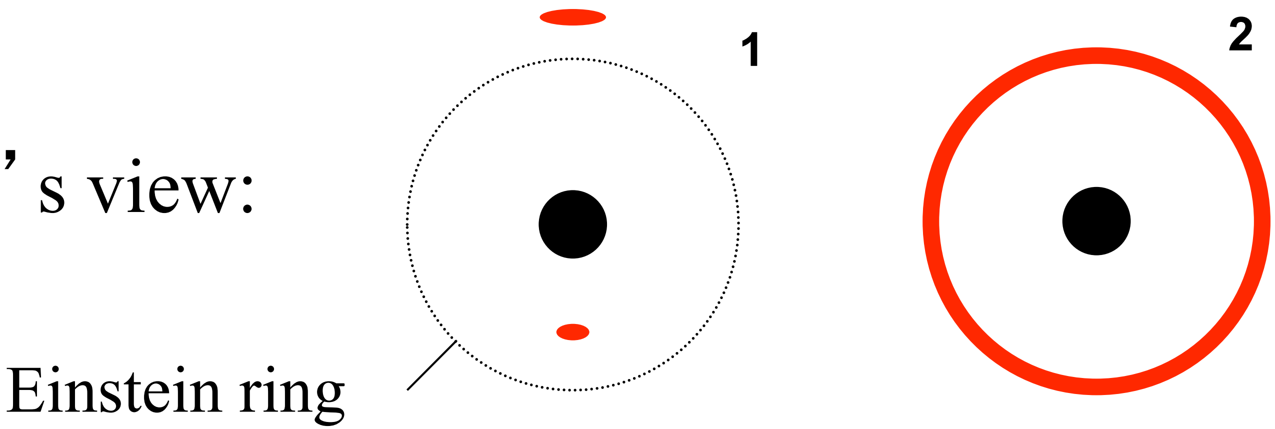
# *Lensing by a point mass*

Light from background source deflected by lens mass

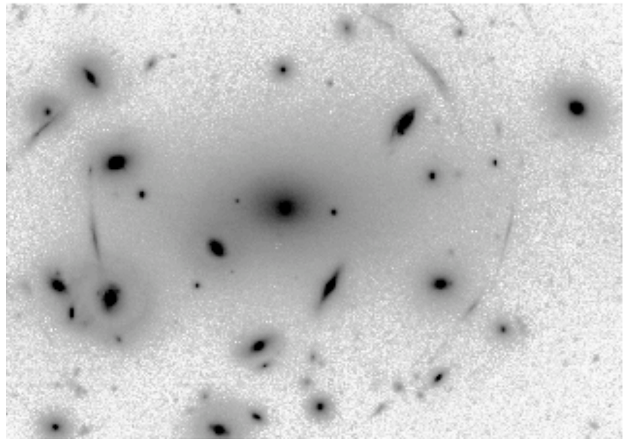



Two distorted/magnified images of background source

Observer's view:



# 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

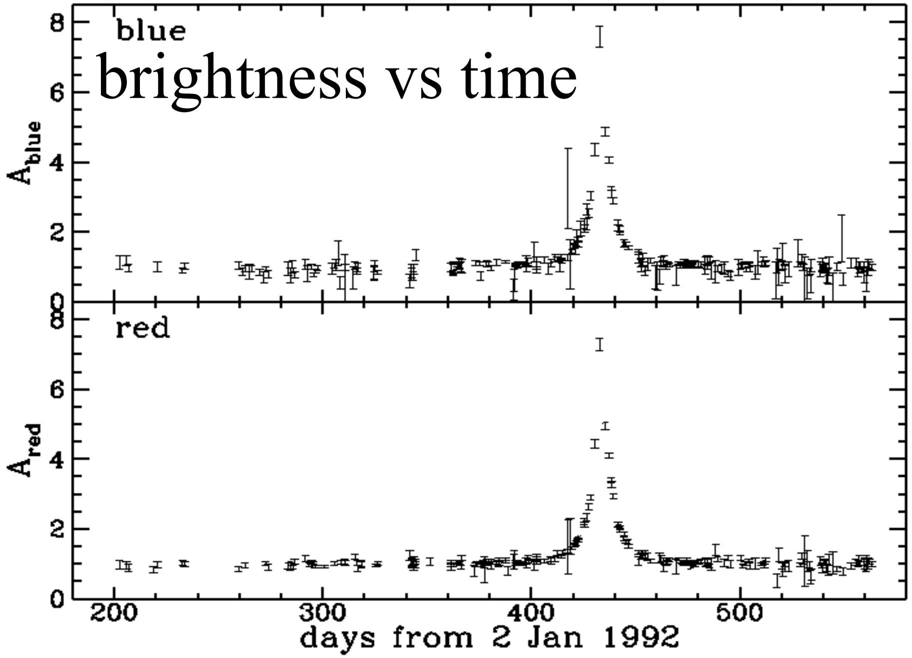
- Normal (i.e., Baryonic)
  - Ionised gas
  - Cold dust
  - Planets
  - White dwarfs
  - Black Holes
  - **MACHOS** (**M**assive **C**ompact **H**alo **O**bjects)
- Exotic (i.e., non-Baryonic)
  - **WIMPS** (**W**eakly **I**nteracting **M**assive **P**articles)
  - Neutrinos

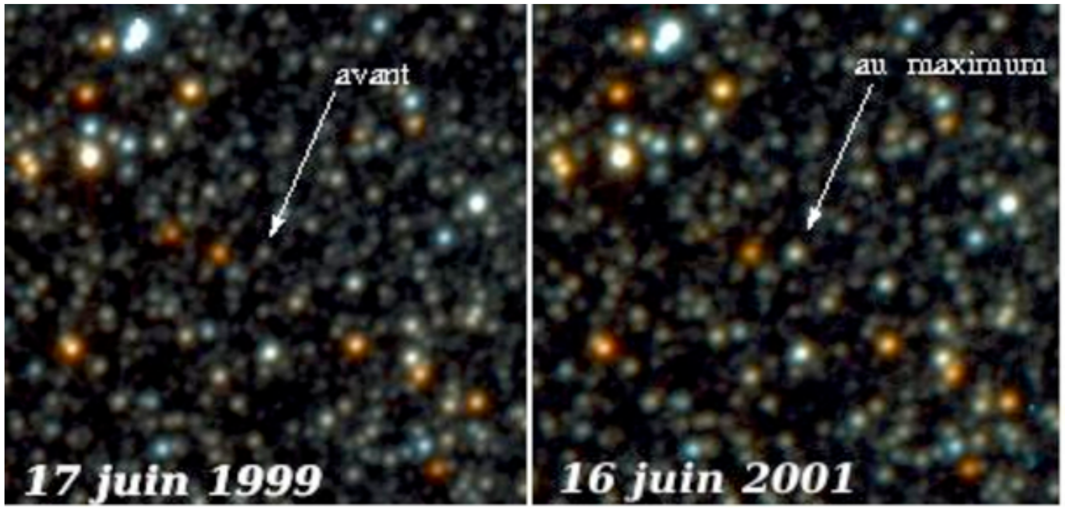
Ruled out by observations.

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.

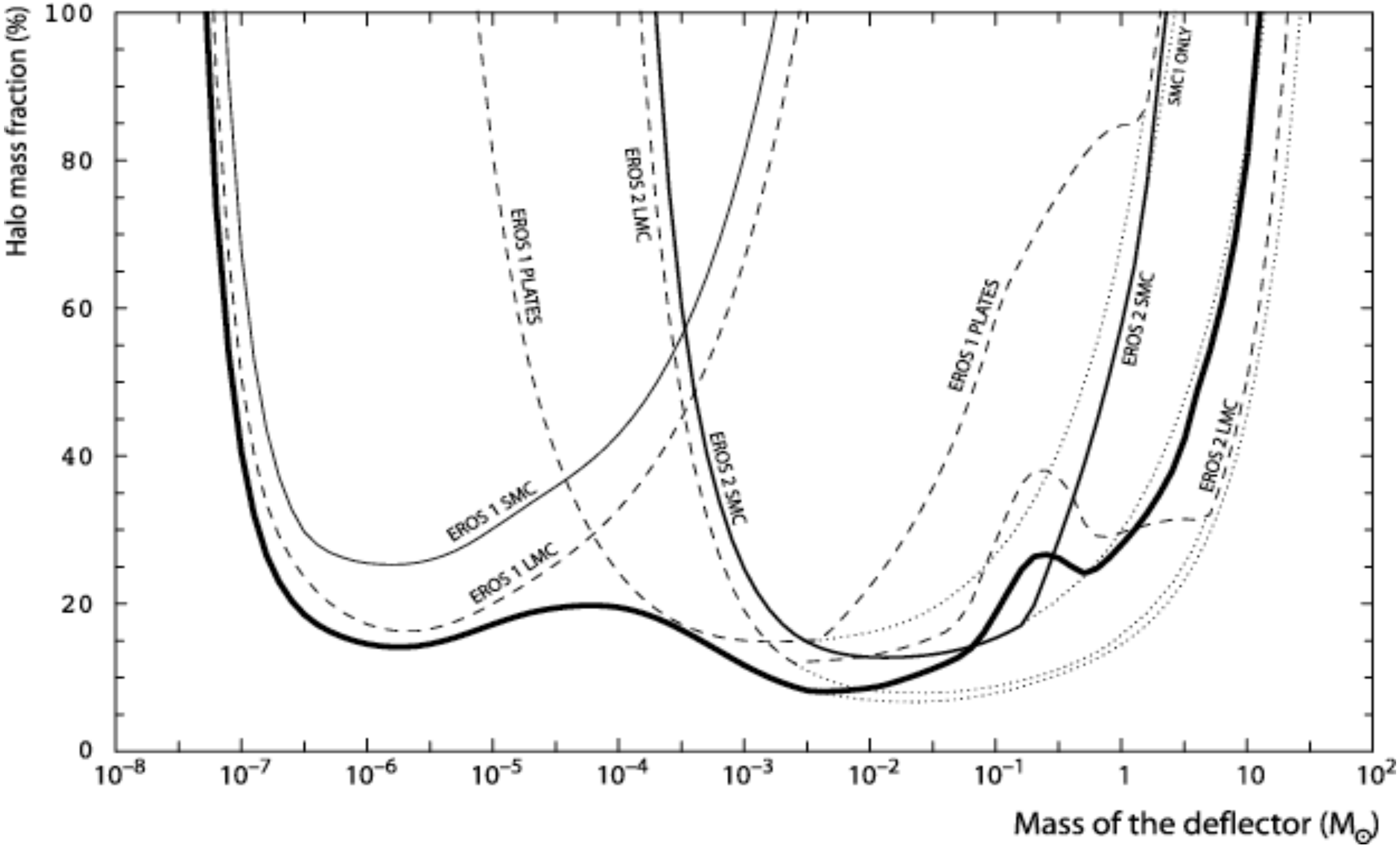
Slow events -> high mass

Fast events -> low mass

# *Microlens Surveys rule out MACHOs*

MACHO contribution < 5-10 %

MACHO contribution
to Dark Matter Halo




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?