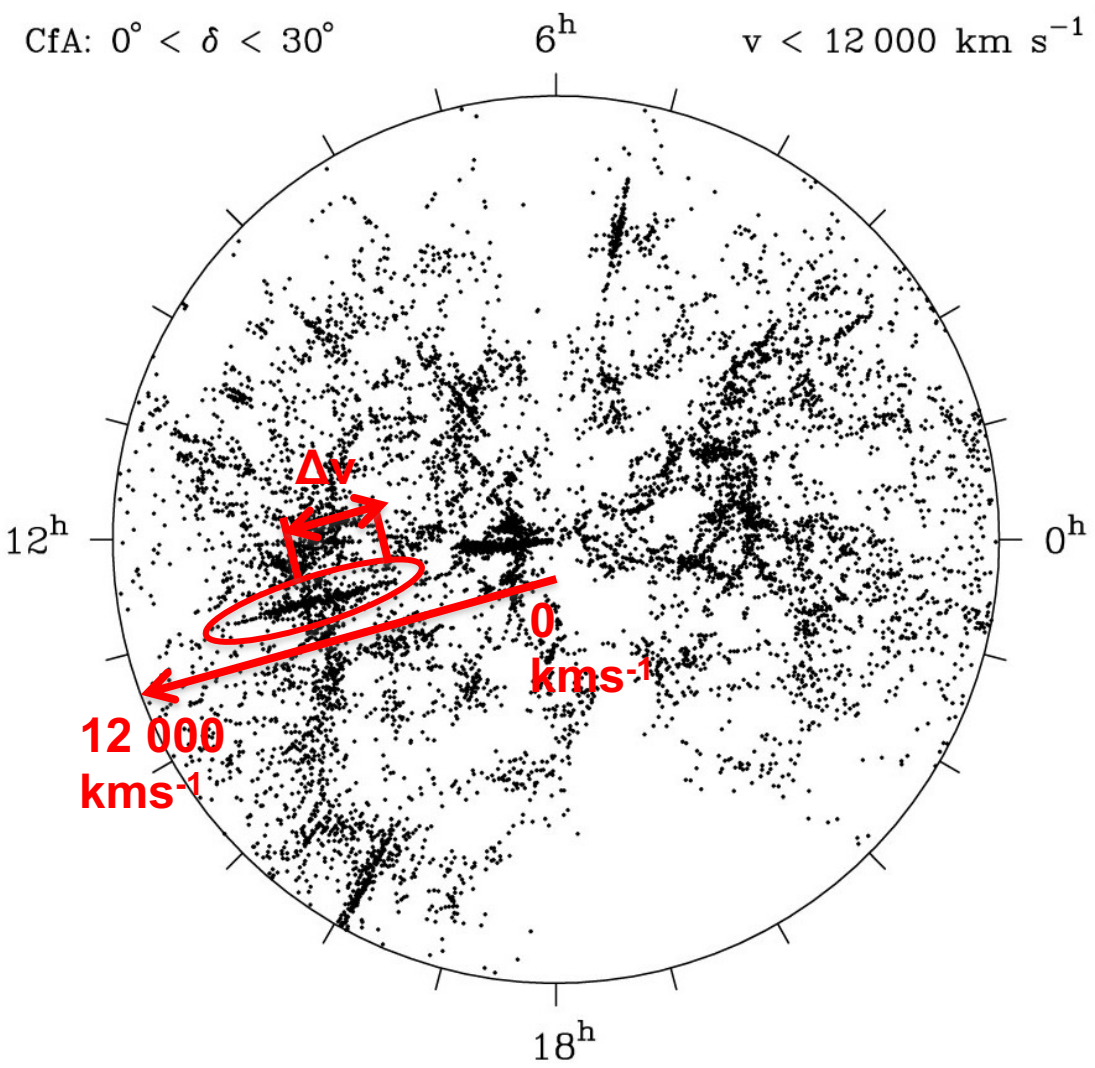


$\Delta v \approx 2500$ kms^{-1}

$v \approx 6700$ kms^{-1}

$v = H_0 d$

$$\frac{\Delta d}{d} = \frac{\Delta v}{v} = \frac{2500}{6700}$$

≈ 0.4 i.e. 40% error

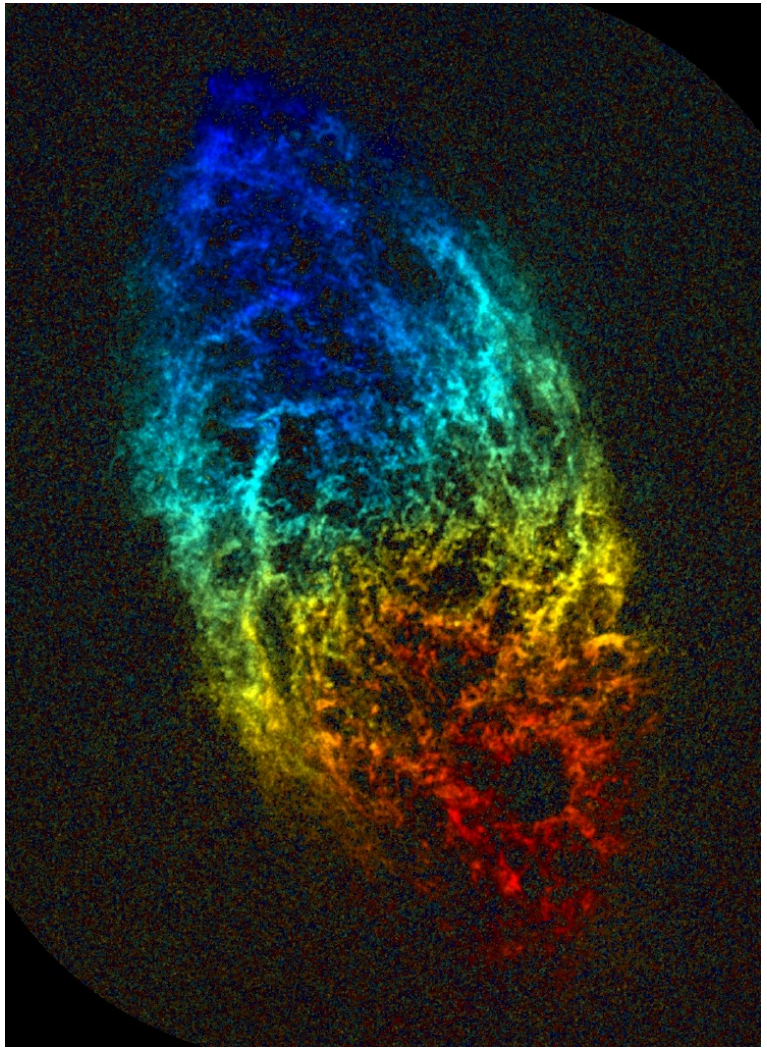
Dark Matter

- Rotation Curves of Galaxies
- Missing Mass in Clusters
- Gravitational Lensing

Galactic Rotation

- The mass of the stars in galaxies is mostly concentrated towards the central regions
- This means the rotation speed of the galaxy should fall off with increasing radius in the outer parts

M33 Optical with H I overlaid in blue



Colour-coded doppler shift showing rotation

Keplerian Rotation

- Equating centripetal force to gravitational force gives

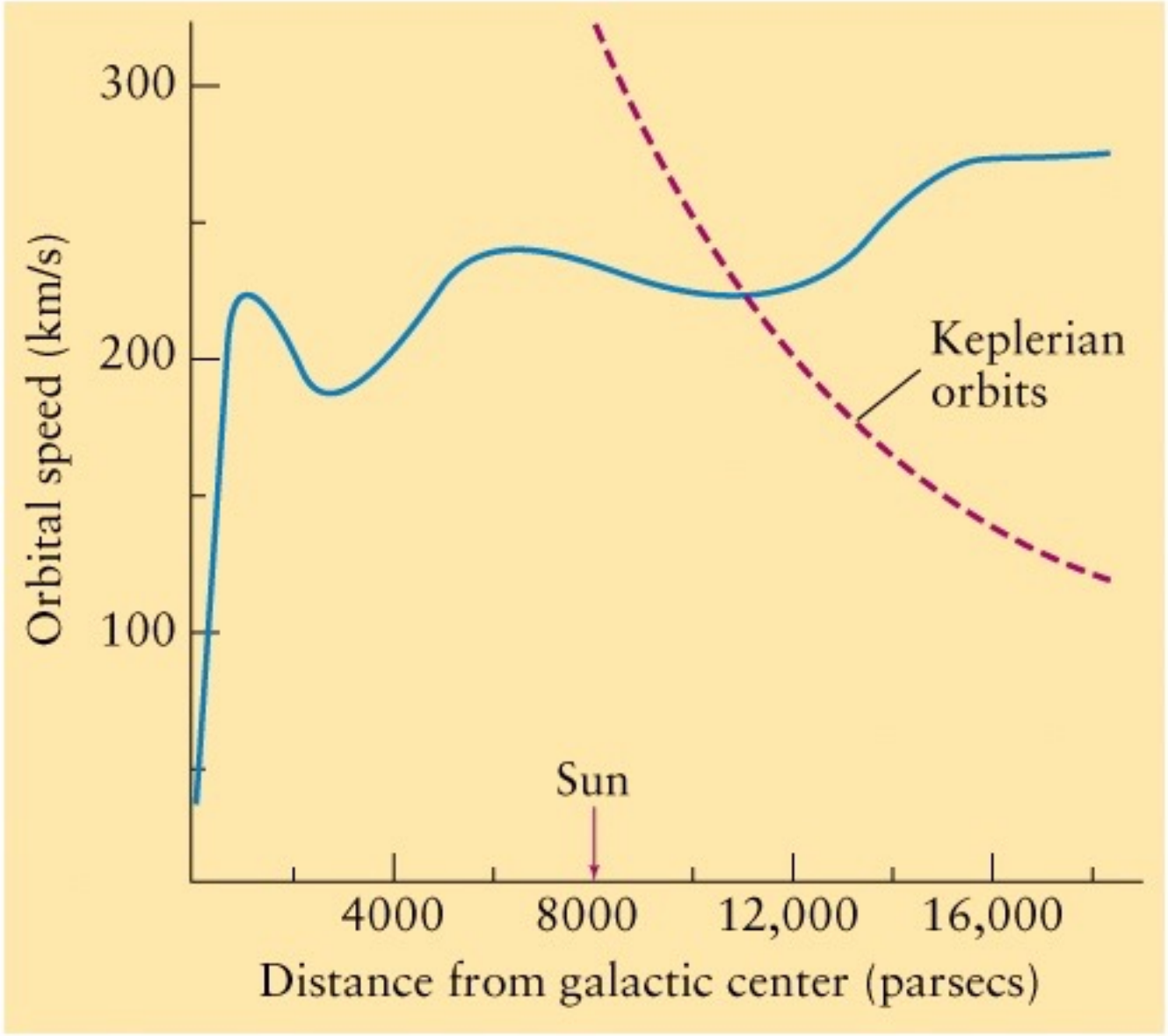
$$\frac{mv^2}{r} = \frac{GMm}{r^2}$$

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

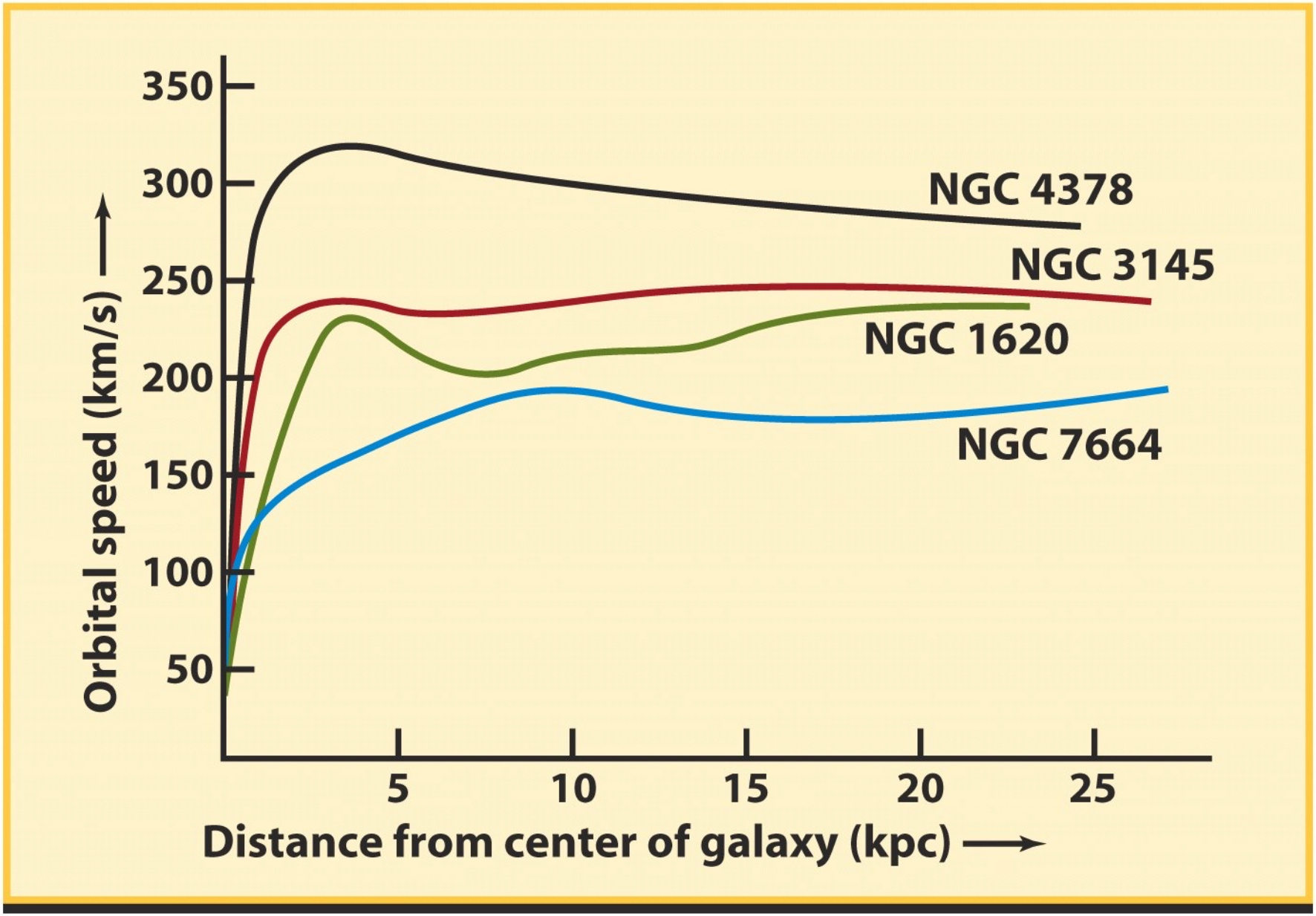
$$v \propto r^{-\frac{1}{2}}$$

Flat Rotation Curves

- Observed rotation curves are flat out to as far as they can be observed
- H I rotation curves extend significantly beyond the starlight and are still flat
- Must be some extended distribution of matter that is not seen to emit at any wavelength – dark matter



From Universe textbook



From Universe textbook

Missing Mass in Clusters

- The speeds that galaxies move around under gravity in clusters is a measure of the mass contained within them
- We can equate the kinetic energy of the galaxies with the gravitational potential energy of the cluster
- (A more accurate description differs by factors of a few)

$$KE \approx PE$$

$$\frac{1}{2}mv^2 \approx \frac{GMm}{r}$$

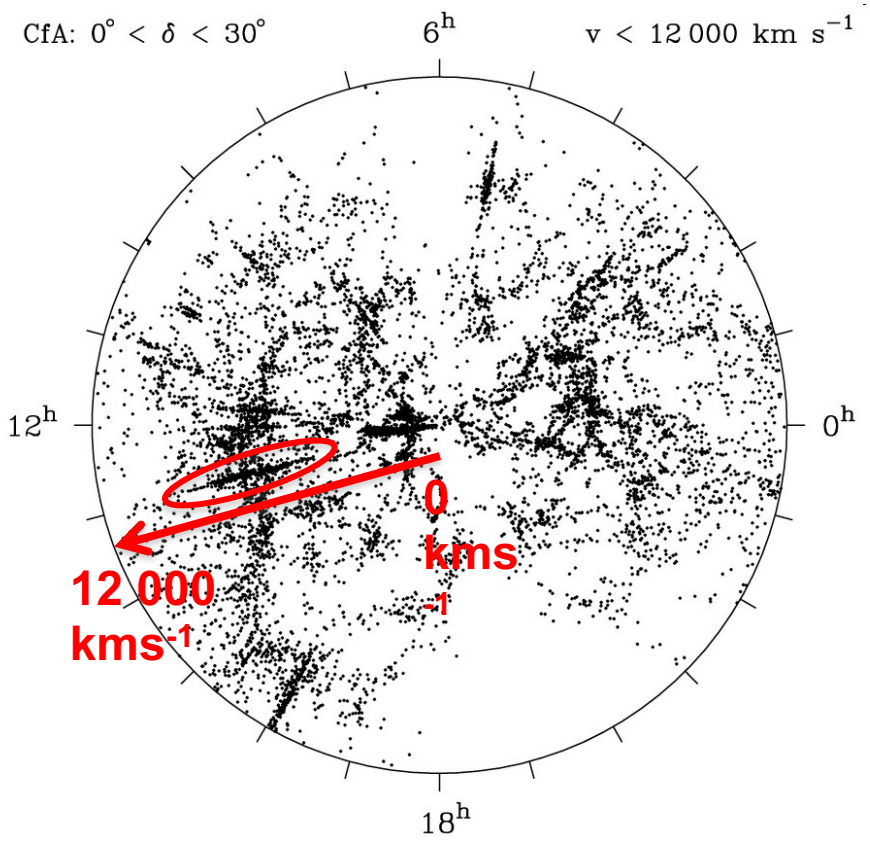
$$v \approx \sqrt{\frac{2GM}{r}}$$

with M the mass of the cluster
and r the size of the cluster

- The observed speeds of galaxies in clusters (the peculiar motions) are much larger than the visible mass in the galaxies can explain
- The cluster would fly apart if there was not more mass present than the visible mass
- The amount of dark matter required is much more than in individual galaxies

Class Example

- Estimate the mass of the galaxy cluster from its peculiar motion seen on the redshift slice at the beginning of the lecture assuming its radius is 1 Mpc



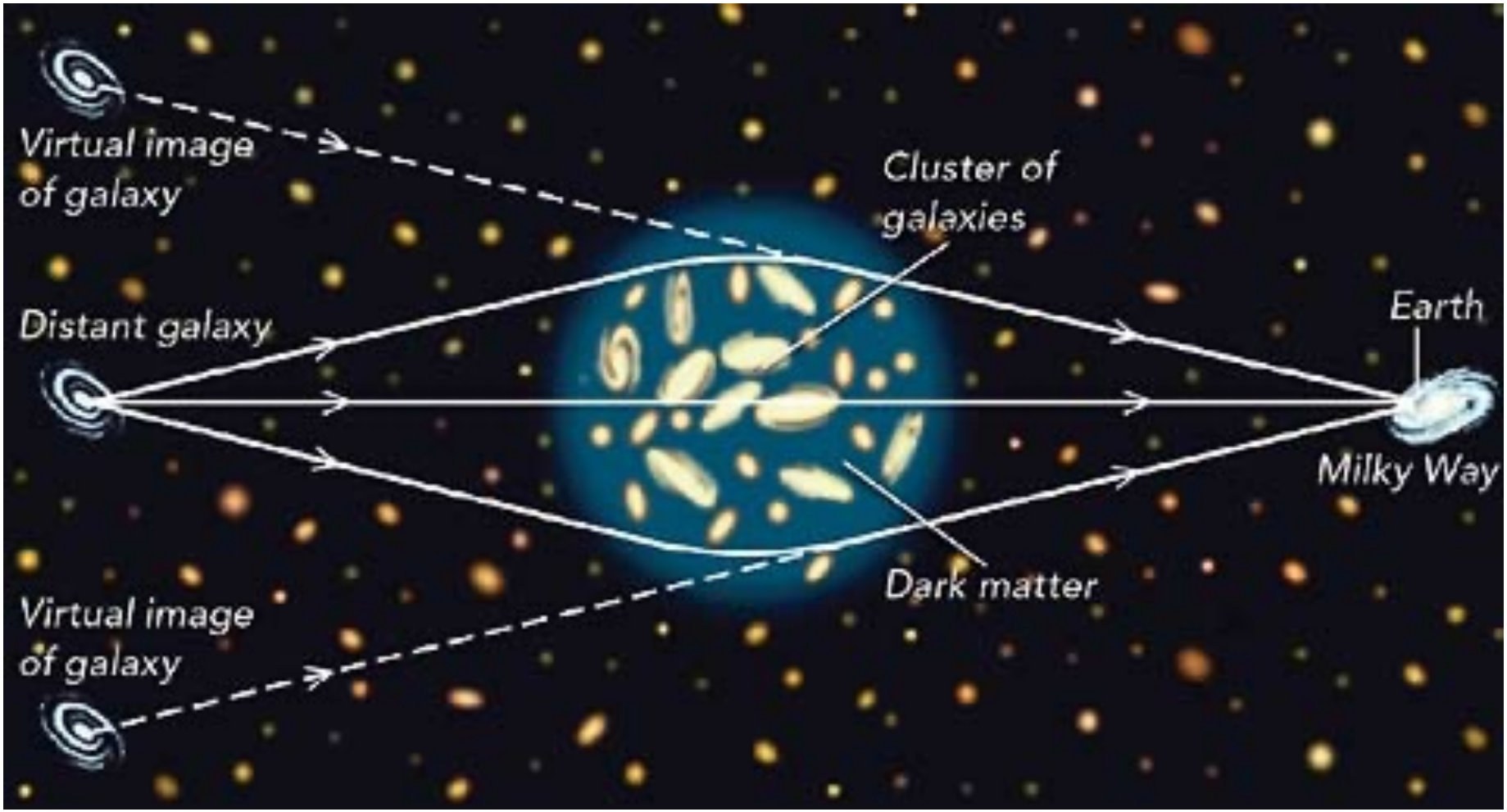
$$M \approx \frac{rv^2}{2G} \approx \frac{3\times10^{22}\left(2500\times10^{3}\right)^2}{2\times7\times10^{-11}} \approx 1\times10^{45}\ \text{kg}$$

$$\approx 7\times10^{14}\ \text{solar masses}$$

Coma Cluster - http://bf-astro.com/abell1656.htm

Gravitational Lensing

- When light from a distant galaxy or quasar passes through a foreground galaxy or cluster of galaxies the light is bent by gravity
- This lensing effect produces distorted or multiple images of the background source



D_L

Einstein Rings

- The source, lens and observer must be aligned to a small angle given by

$$\theta_E \approx \sqrt{\frac{4GM}{D_L c^2}}$$

  called the Einstein ring radius
- If the alignment is perfect the image becomes a ring

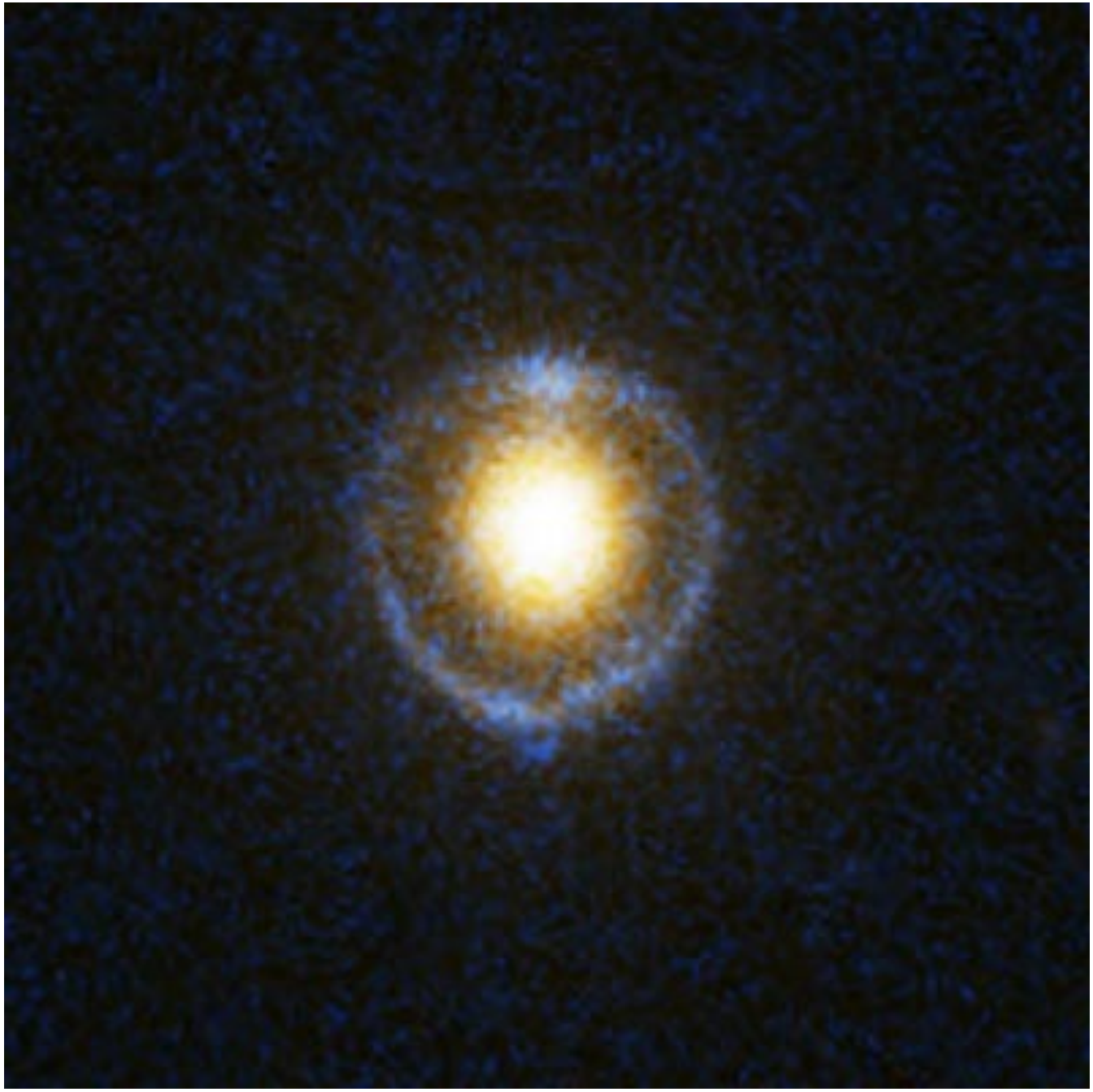
Class Example

- Calculate the Einstein ring radius caused by a typical galaxy 1000 Mpc away

$$\theta_E \approx \sqrt{\frac{4\times 7\times 10^{-11}\times 10^{11}\times 2\times 10^{30}}{1000\times 3\times 10^{22}\times (3\times 10^{8})^{2}}}$$

$$= 4\times 10^{-6} \text{ radians}$$

$$= 1 \text{ arcsecond}$$



Einstein Ring Gravitational Lens (SDSS J162746.44-005357.5)

8 arcsec

Credit: NASA, ESA, A. Bolton (Harvard-Smithsonian CfA) and the SLACS Team

Dark Matter in Clusters

- Clusters of galaxies bend the light even more
- The amount of bending depends on the mass
- The amount of mass required is about 10 times that seen in the visible galaxies

Galaxy Cluster Abell 2218's "Gravitational Lens"

Credit: NASA, ESA, Richard Ellis (Caltech) and Jean-Paul Kneib (Observatoire Midi-Pyrenees, France)
Acknowledgment: NASA, A. Fruchter and the ERO Team (STScI and ST-ECF)

What is the Dark Matter?

- We do not know
- It is not
  - dust
  - failed stars
  - black holes
- It is likely to be made of an as yet undiscovered fundamental particle

Summary

- Rotation curves provide evidence for dark matter in galaxies
- Member velocities and gravitational lensing show there is even more dark matter in clusters
- The nature of dark matter is one of the great unsolved problems in astrophysics