PHAS 1102/1423, Part 2:

‘Cosmology and the Universe’

Ian Howarth idh@star.ucl.ac.uk

http://www.star.ucl.ac.uk/~idh/PHAS1102
=http://www.star.ucl.ac.uk/~idh/PHAS1423

What is the universe made of?

On a *microscopic* (atomic) scale, we appeal to the ‘Standard Model’ of particle physics

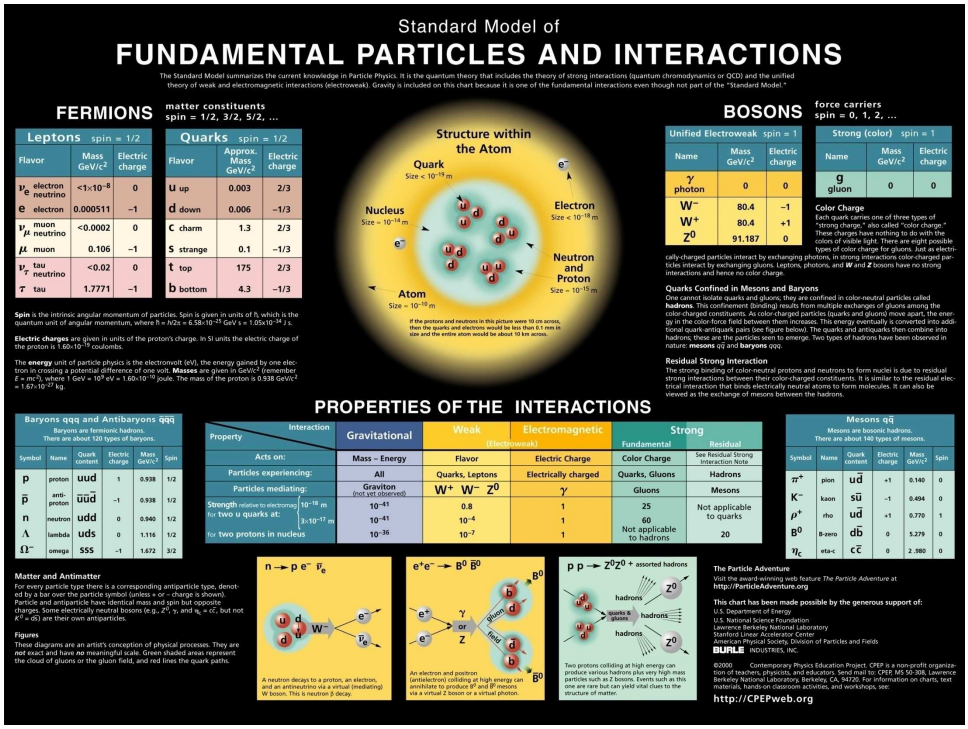
The Standard Model describes more than 200 ‘elementary’ particles, and their interactions, using as ingredients:

- 6 quarks [flavours: up, down, strange, charm, top, bottom]
- 6 leptons [electron, muon, tauon, and their associated neutrinos]

(fermions; half-integer spin), and a few force-carrying particles:

- gluon [strong nuclear]
- photon [electromagnetic]
- W+Z [weak nuclear]
- graviton? [gravity]

(examples of bosons; integer spin)



N.B. The Standard Model is not complete!! (GUTs; TOEs)

What is the universe made of for our purposes?

On a microscopic scale: "Baryonic matter"
3 quarks: protons & neutrons (+Delta, Lambda, Sigma, Xi)

⇒ *Essentially all recognizable mass in the universe consists of baryonic matter in the form of neutrons and protons*

(electrons [muon, tau leptons], neutrinos, etc., are negligible in terms of the mass budget of the universe)

Examples of baryonic matter on a *macroscopic* scale:

Examples of objects whose mass is dominated by BARYONIC MATTER

'Large Hadron Collider' (LHC)

Not our problem, but fyi:

Hadrons are made from quarks and gluons. [Both baryons (odd nos. of quarks) and mesons (even nos.) are hadrons.]

Protons are baryons (and also hadrons)

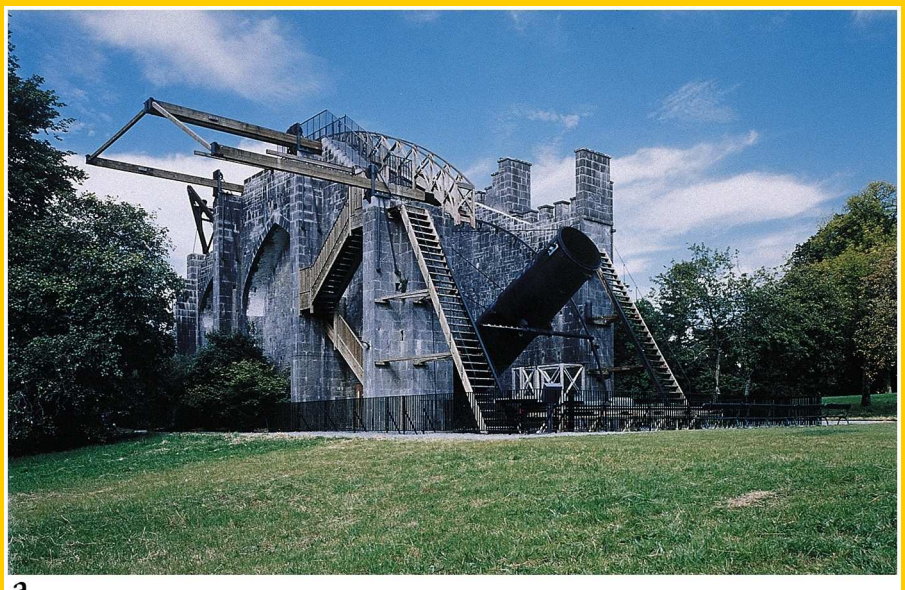
The LHC collides (will collide…) protons

[Why? Heavier particles allow greater collision energies]

WHAT *WE* NEED TO KNOW:

MOST OBSERVABLE MASS IS BARYONIC

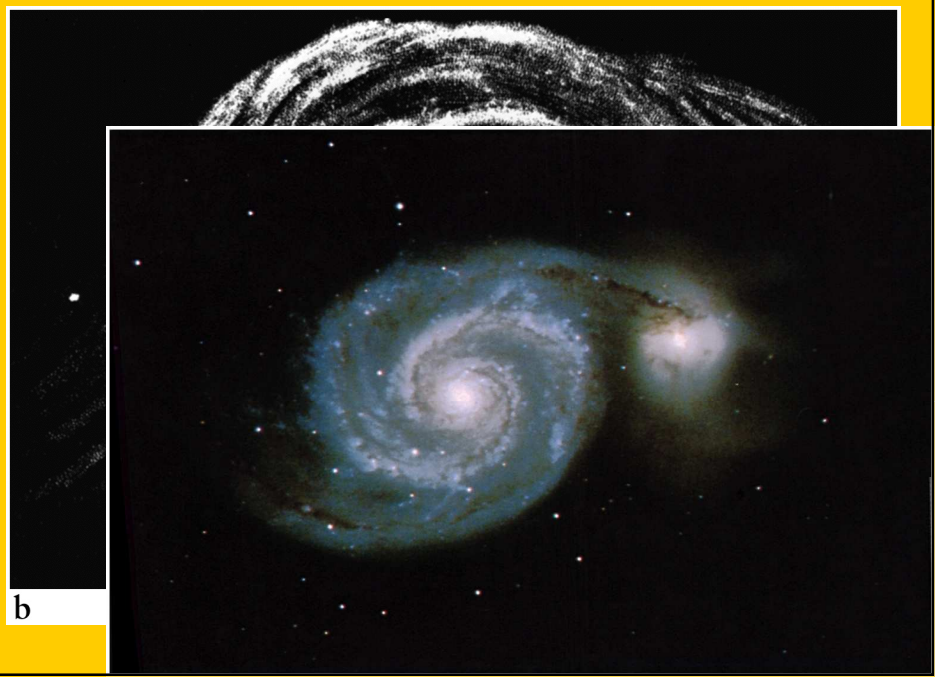
Galaxies



a

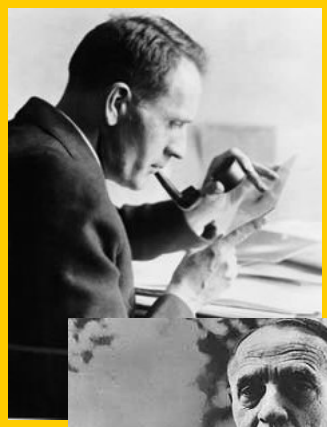
Rosse 70″ 1.8-m telescope (Parsonstown, 1845)

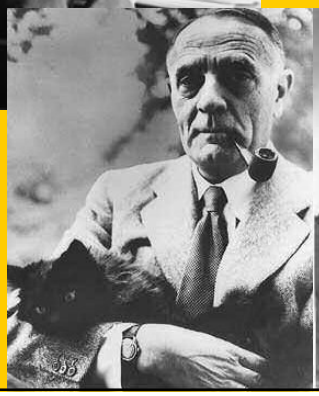
M51 – the first galaxy recognized as having spiral structure



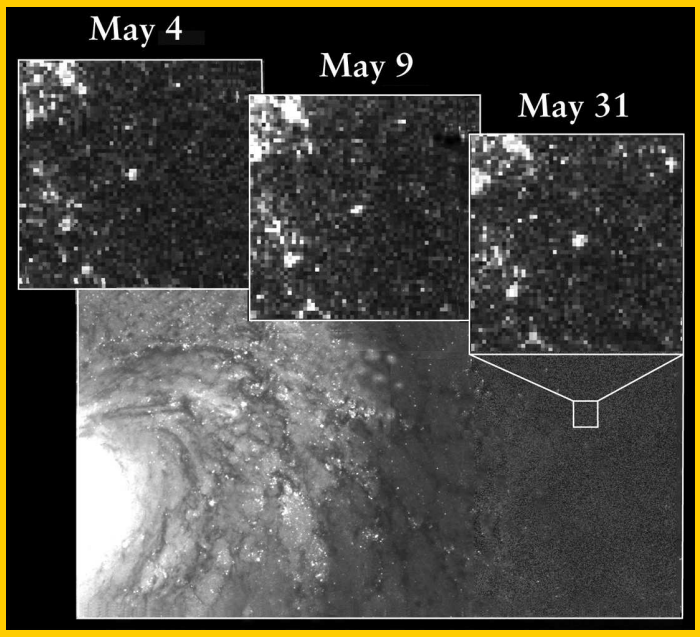
Edwin Hubble

Edwin Hubble (2)

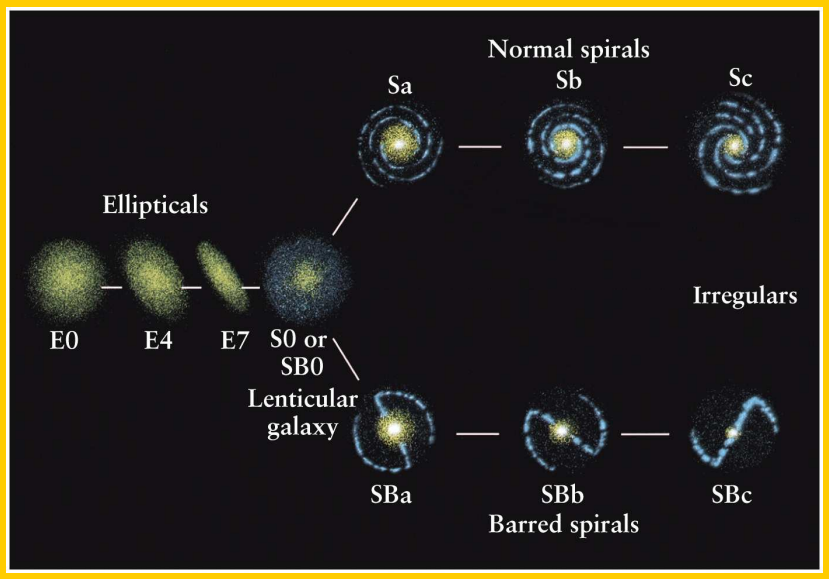


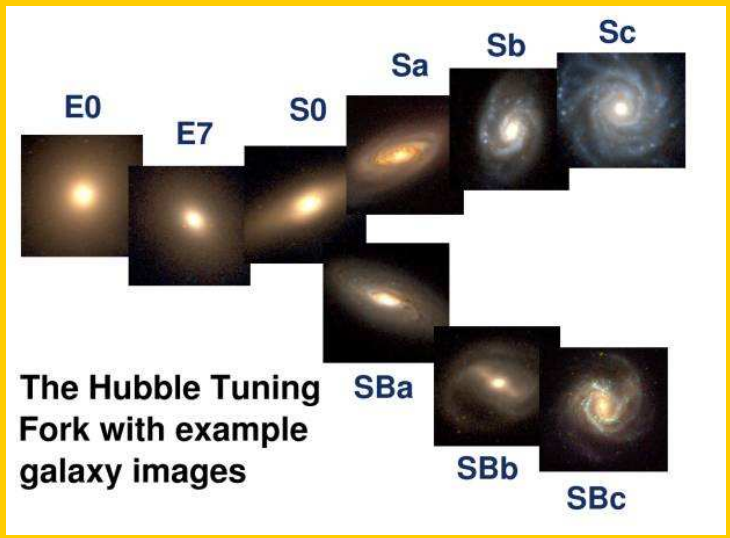


Cepheid variables in the galaxy M100

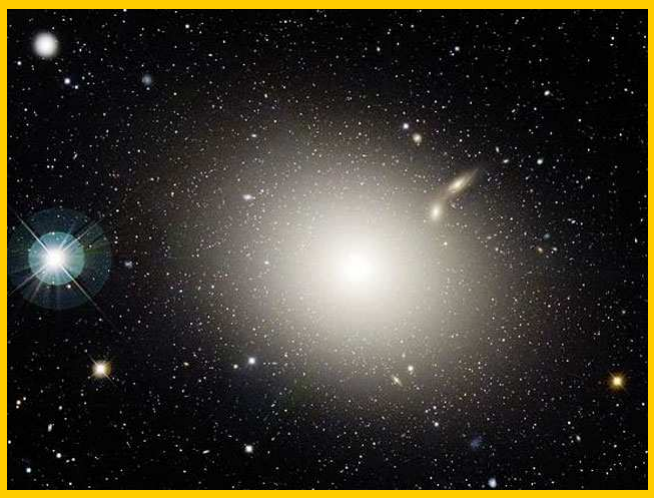


The Hubble ‘tuning fork’ diagram





An Elliptical Galaxy (with globular clusters)



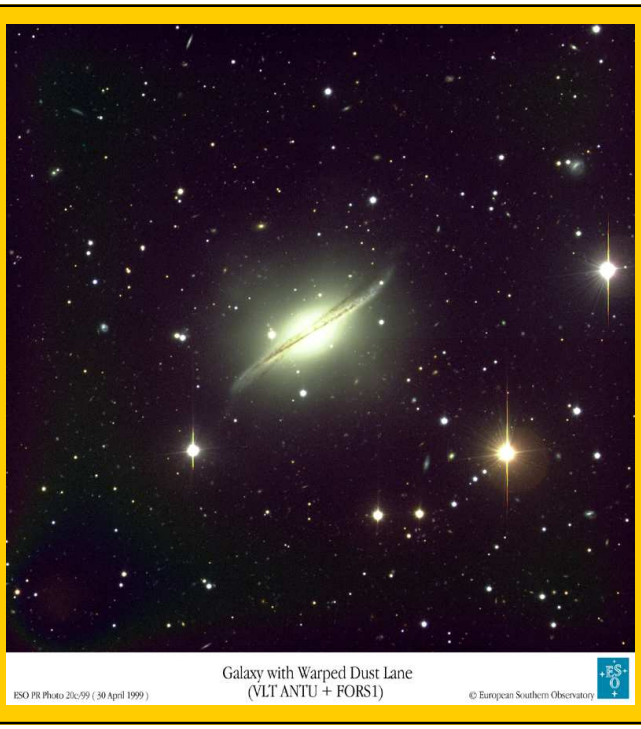
Virgo Cluster (with two giant ellipticals)

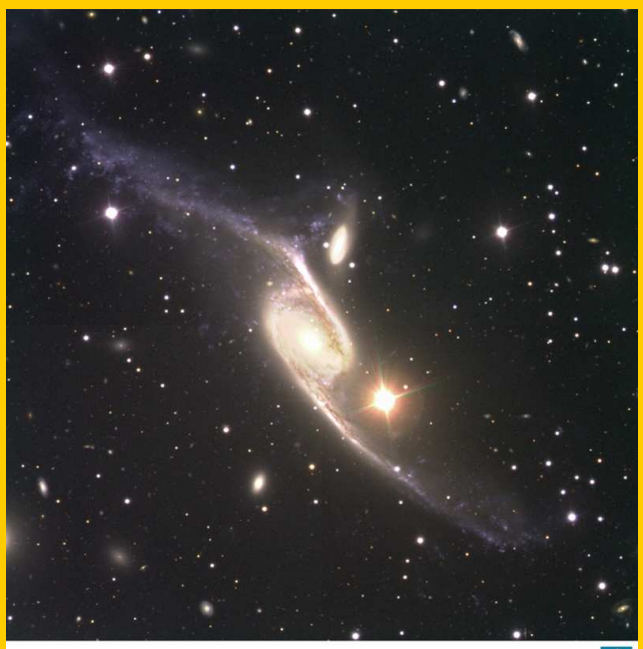
Elliptical and two spirals

b SBb (M83)

c SBc (NGC 1365)

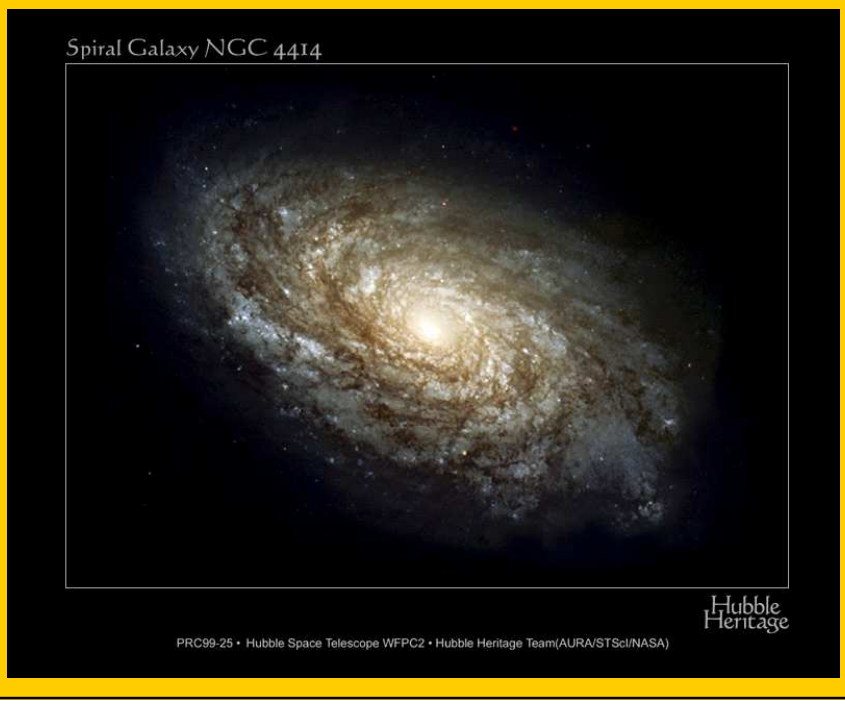

Polar-Ring
Galaxy
NGC 4650A
PRC99-12
Space Telescope
Science Institute
Hubble Heritage Team
(AURA/STScI/NASA)
Hubble
Heritage


Galaxy with Warped Dust Lane
(VLT ANTU + FORS1)
ESO PR Photo 20c/99 (30 April 1999)
© European Southern Observatory

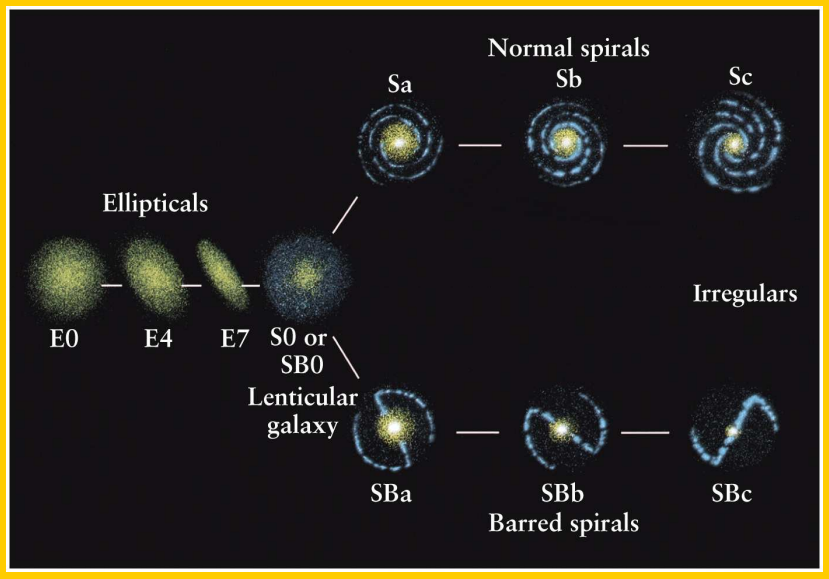


Giant Interacting Galaxies NGC 6872 / IC 4970
(VLT ANTU + FORS1)

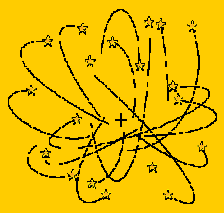
ESO PR Photo 20b/99 (30 April 1999)



The Large Magellanic Cloud (LMC) – an irregular galaxy



Normal Galaxies:



Hubble `Tuning Fork' diagram for classification:

Elliptical galaxies (E0➔E7) –

red, structureless, old stars (Population II)

dwarf & giant ellipticals

Spiral galaxies (`normal' S or SA + barred, SB; Sa➔Sc or Sd) –

discs with spiral structure picked out by young, blue stars (Population I)

+intermediate SO types – spiral galaxies with spiral arms

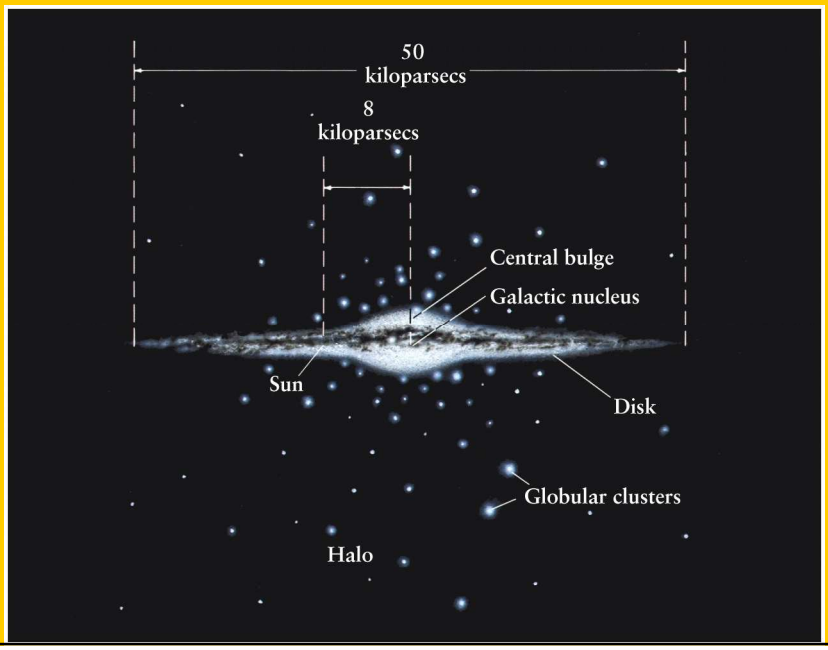
+irregular galaxies

…our Galaxy:

The Milky Way Galaxy

For comparison, an edge-on spiral galaxy

The structure of the Galaxy



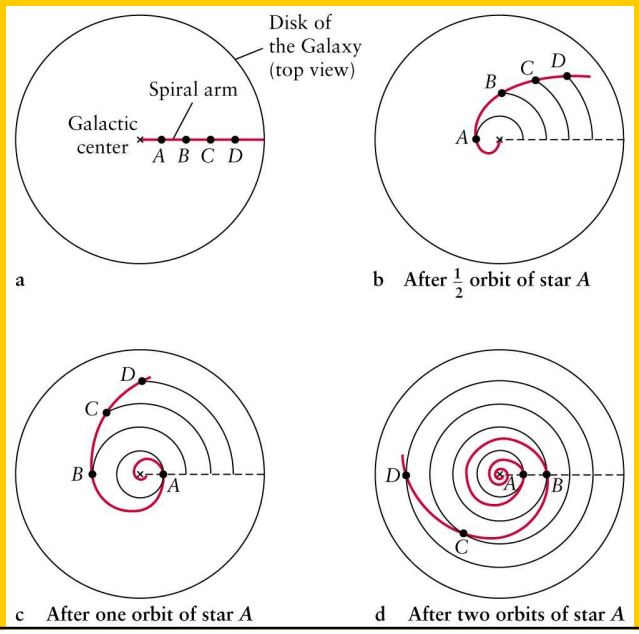
The Galaxy according to Spitzer Space Telescope: an SBc spiral

SPIRAL ARMS:

Which way do galaxies rotate?

What is the nature of spiral arms?

Spiral arms can't be fixed, permanent structures ('windmills')

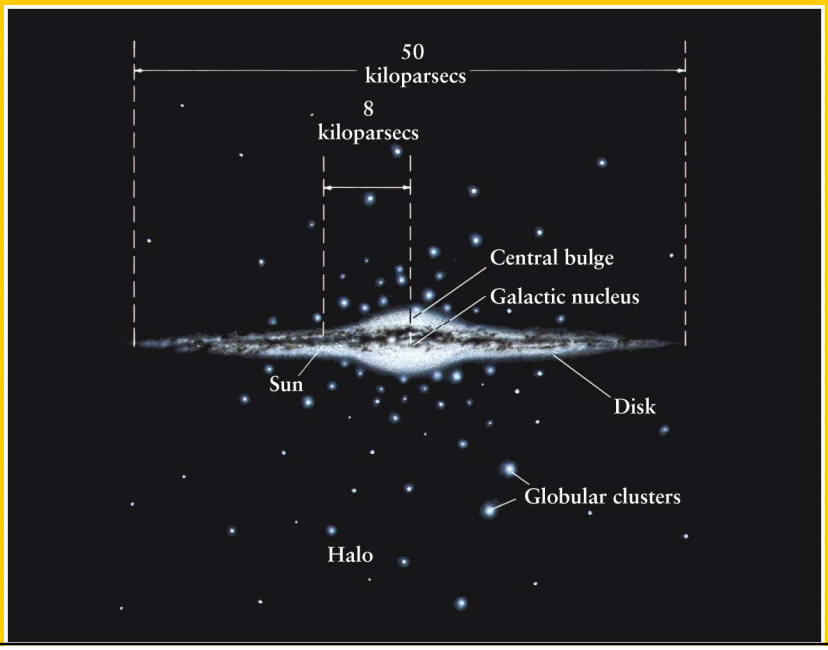


Our Galaxy:

A typical SBc spiral galaxy:

A central 'bulge' (Pop II), a disk (Pop I), embedded in a halo, totalling about 10^{11} to 10^{12} M_o

The structure of the Galaxy



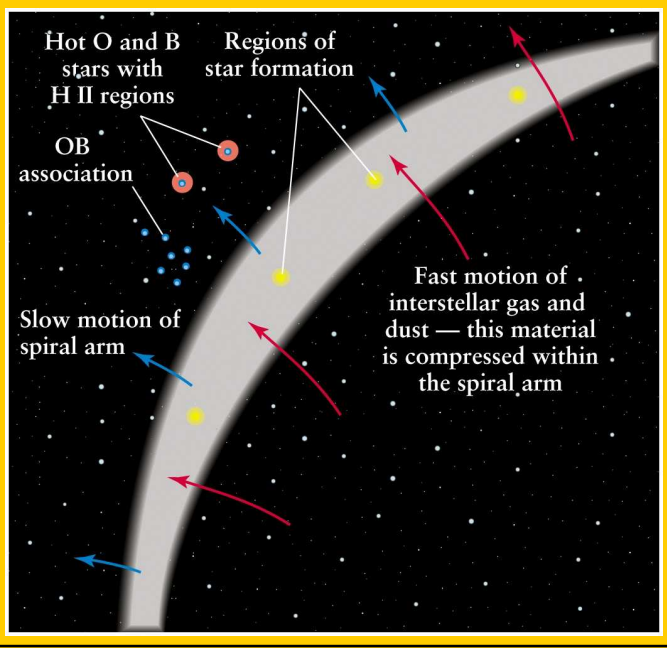
Our Galaxy:

A typical SBc spiral galaxy:

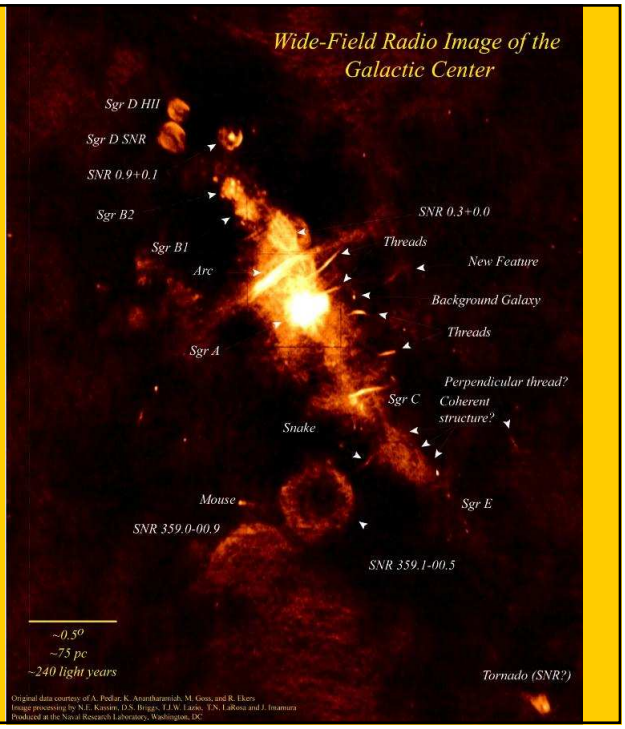
A central 'bulge' (Pop II), a disk (Pop I), embedded in a halo, totalling about 10^{11} to 10^{12} M_o

The spiral arms are not permanent features, but represent density waves, which propagate in the same direction as, but more slowly than, stellar orbits. They represent sites of star formation (and so are picked out by young blue stars).

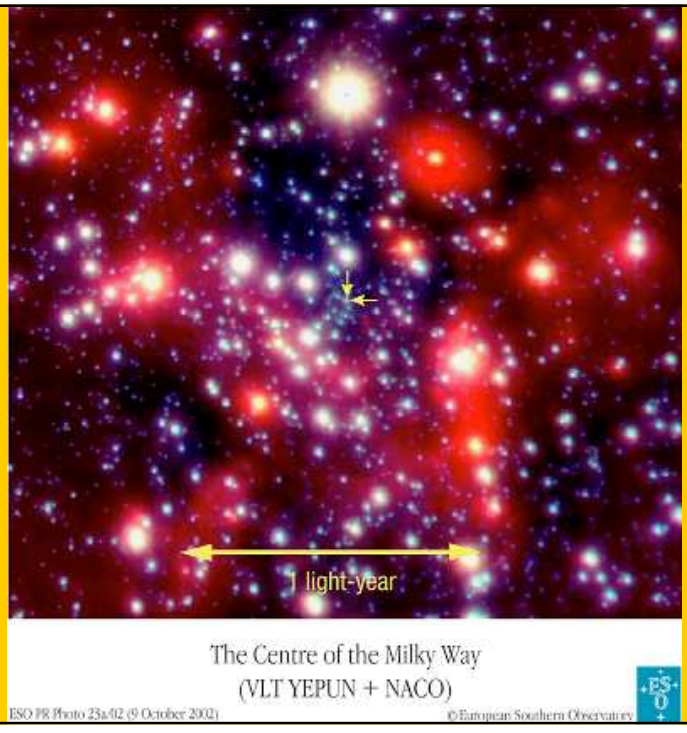
Spiral arms are a manifestation of *density waves*



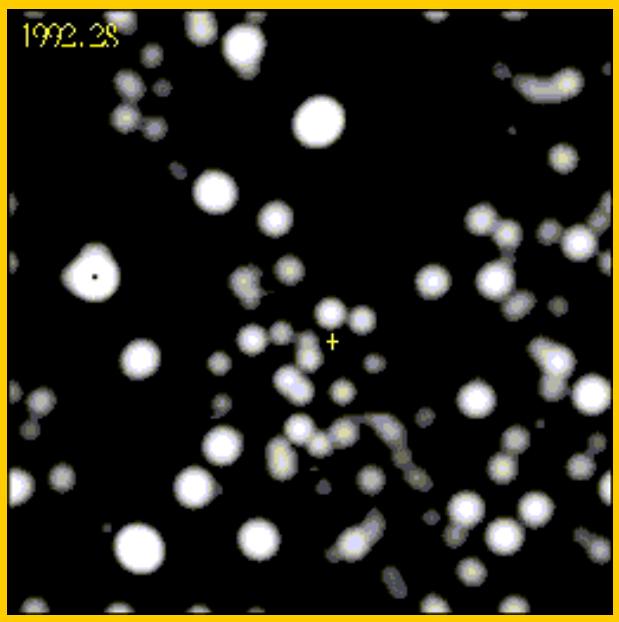
The centre of the Galaxy – a radio view (gas) showing Sgr A



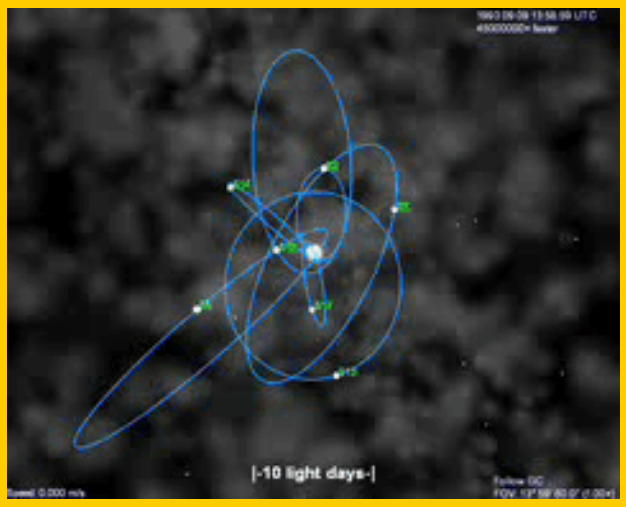
Infrared view



Stars at the core of the Galaxy



Stars at the Galactic Centre, 1993-2008



Review:

Infrared observations allow us to study the centre of our Galaxy, penetrating interstellar dust. *Very* precise positional and radial-velocity measurements determine the orbits of stars, revealing a supermassive black hole.

We measure the motion of stars through 'proper motions' (orbits projected onto the plane of the sky), and radial velocities (orbits projected along the line of sight).

Implied mass: $4 \times 10^6 M_o$!

There is a black hole with a mass of 4 million suns at the centre of our Galaxy ….and many (all??) other galaxies. These can "announce" themselves as Active Galactic Nuclei (AGN)

Characteristic: strong emission (at some wavelength) not due to stars

Seyferts, quasars, radio galaxies….blazars, liners, BL Lacs, etc

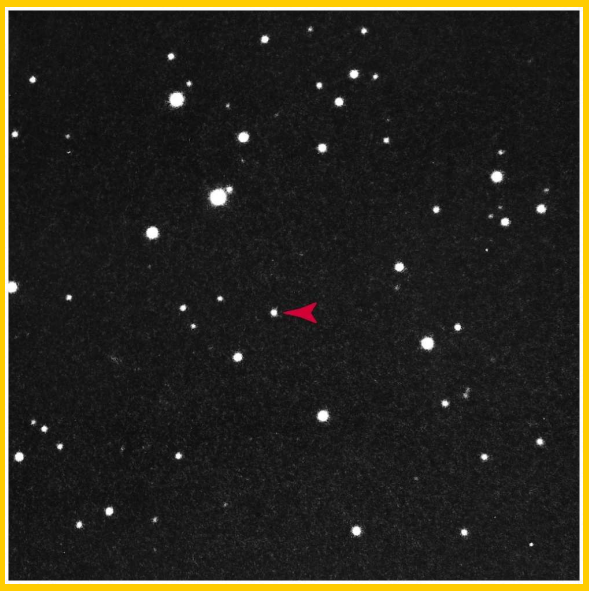
Most, perhaps all, other galaxies also host supermassive black holes at their centres. If these are accompanied by an accretion disk, they reveal themselves as 'Active Galactic Nuclei' (AGN) – such as Seyfert Galaxies, or Quasars.

AGN shows nonthermal continua, and emission-line spectra

Seyfert galaxies (1943)

Nearly all have spiral galaxy 'hosts'

Starlike nuclei, emission-line spectra



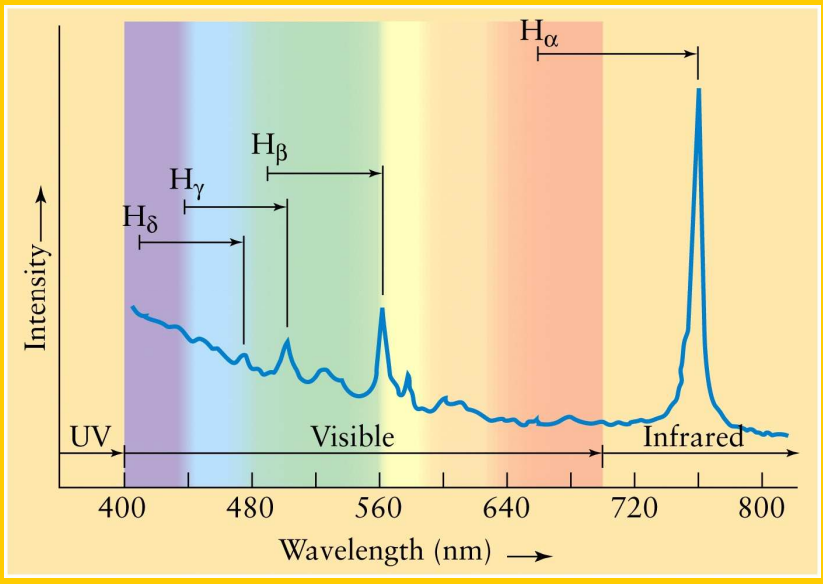
3C48

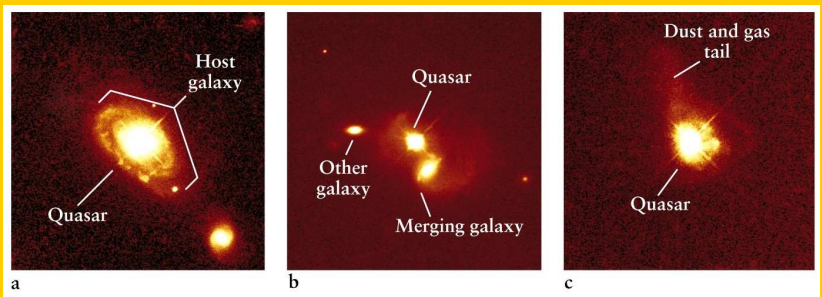
Quasars (QSOs)

Discovered in the 1960s – star-like (Quasi Stellar Radio Sources)

Also show emission spectra -- large redshifts imply large distances and large intrinsic luminosities

Quasars show large *redshifts* of emission lines





Quasars show ‘fuzz’ – they are AGN whose luminosity exceeds of the host galaxy

What can produce this large luminosity in a small volume?

ACCRETION (10% efficiency, cp. <1% for fusion)

Clusters of Galaxies

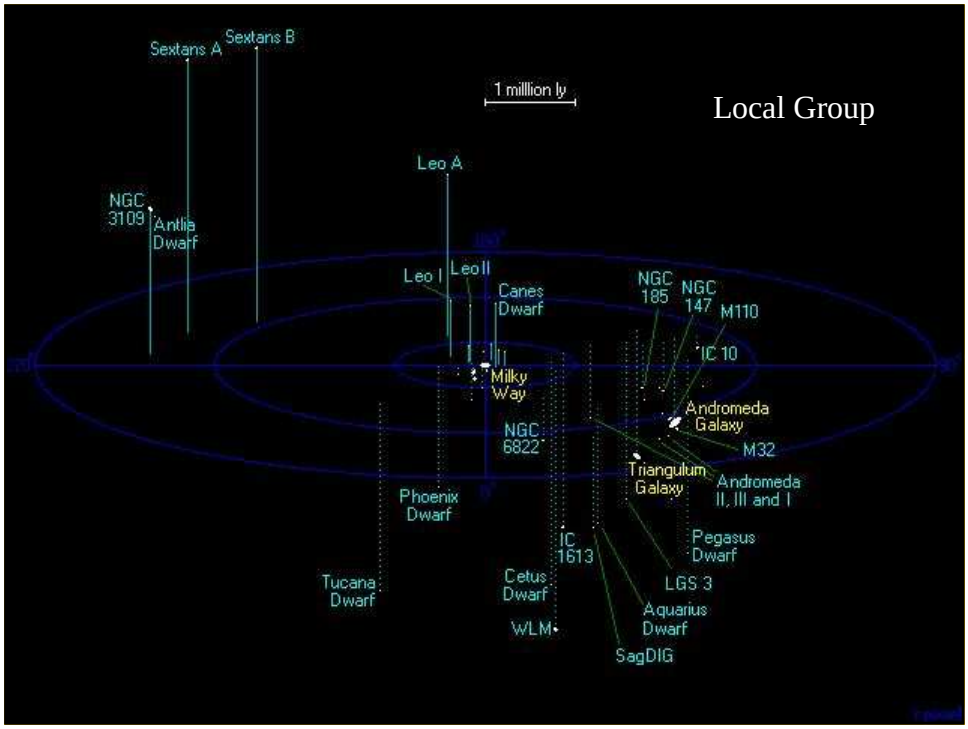
Galaxies are mostly found in groups, clusters, or superclusters

The Coma Cluster

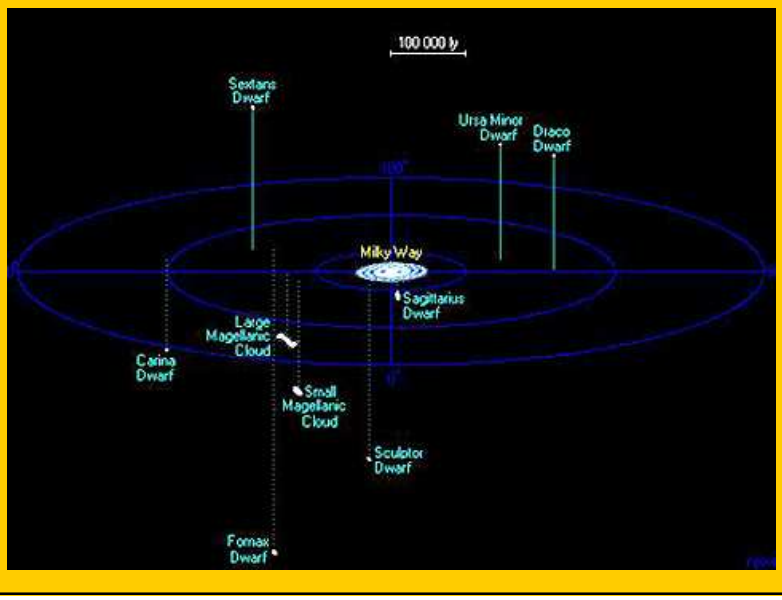
Clusters of Galaxies

Galaxies are rarely isolated, but tend to collect in gravitationally bound ensembles, from small 'groups' (few dozen galaxies) to large 'clusters' (thousands of galaxies).

The environment evidently influences galaxy evolution; clusters contain fewer spiral galaxies than does the 'field', and often have a giant elliptical (cD) galaxy at the centre



The immediate environs of our own Galaxy

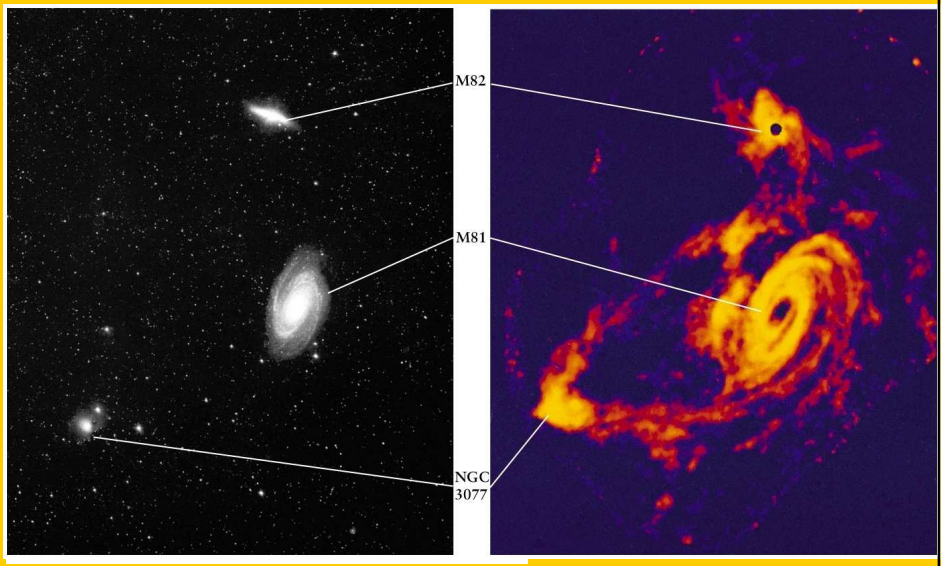


The centre of the Virgo cluster

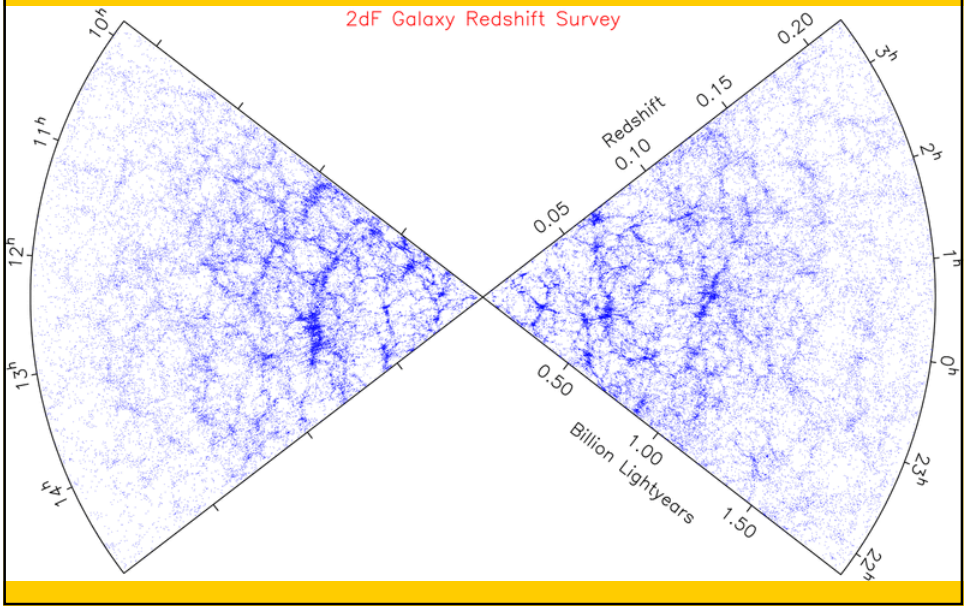
The Coma Cluster

The Hercules Cluster – with interacting spiral galaxies

Galaxies interact more than you might think at first – as traced by gas

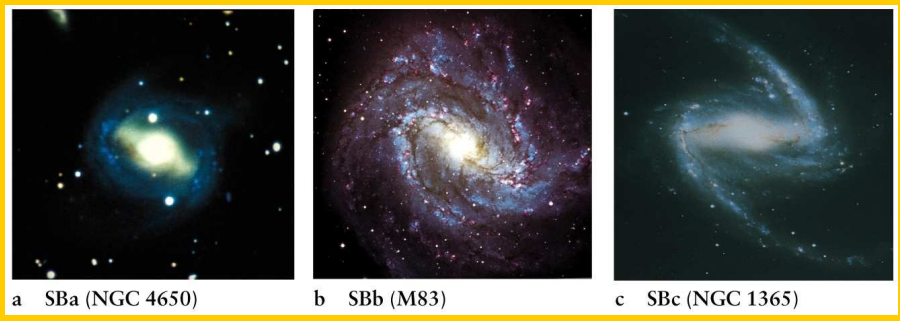


Large-scale structure: ‘superclusters’

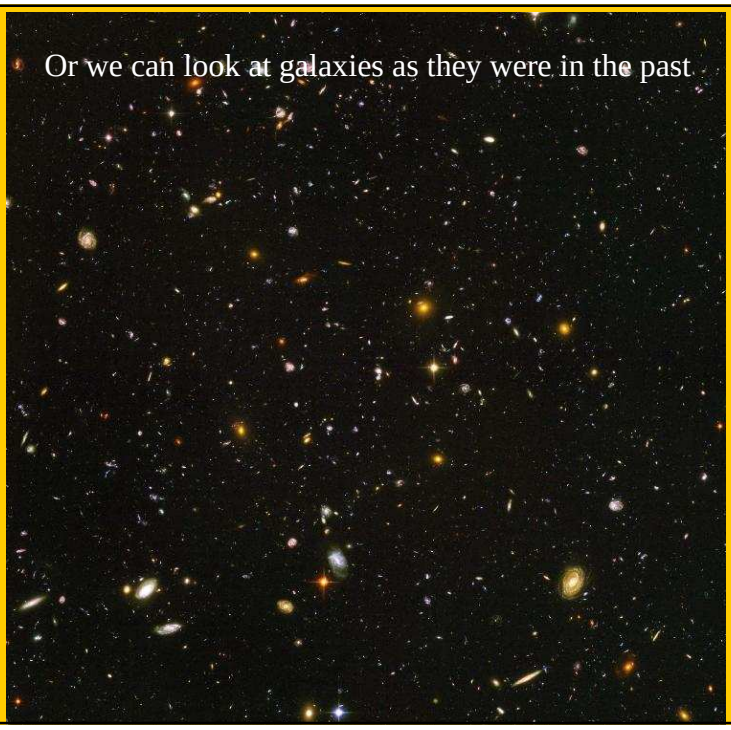


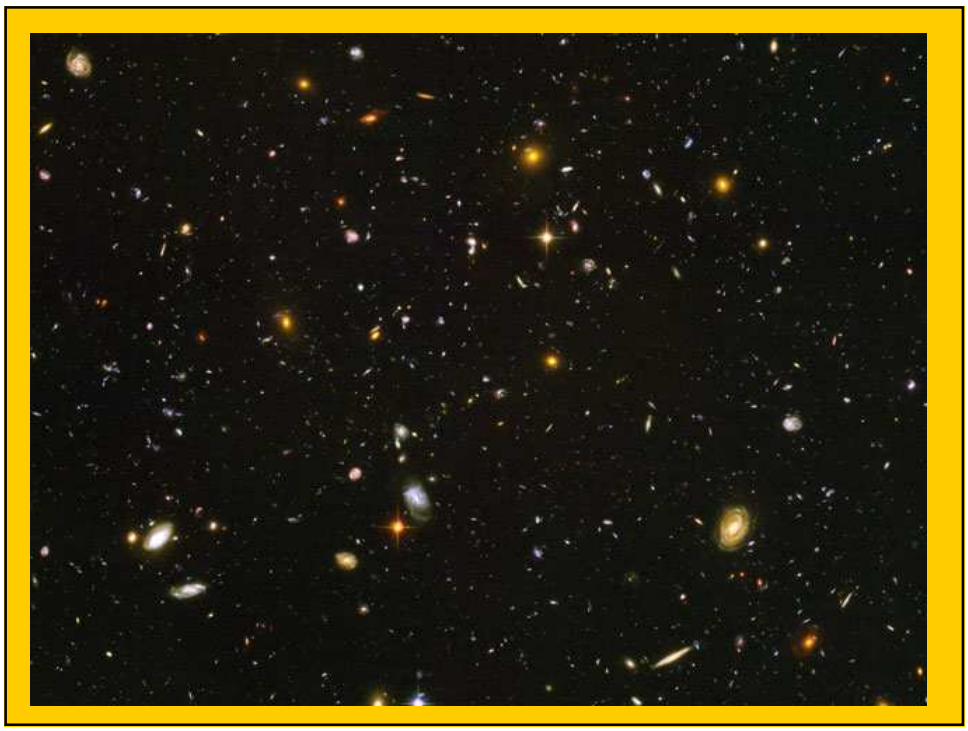
Evolution of Galaxies

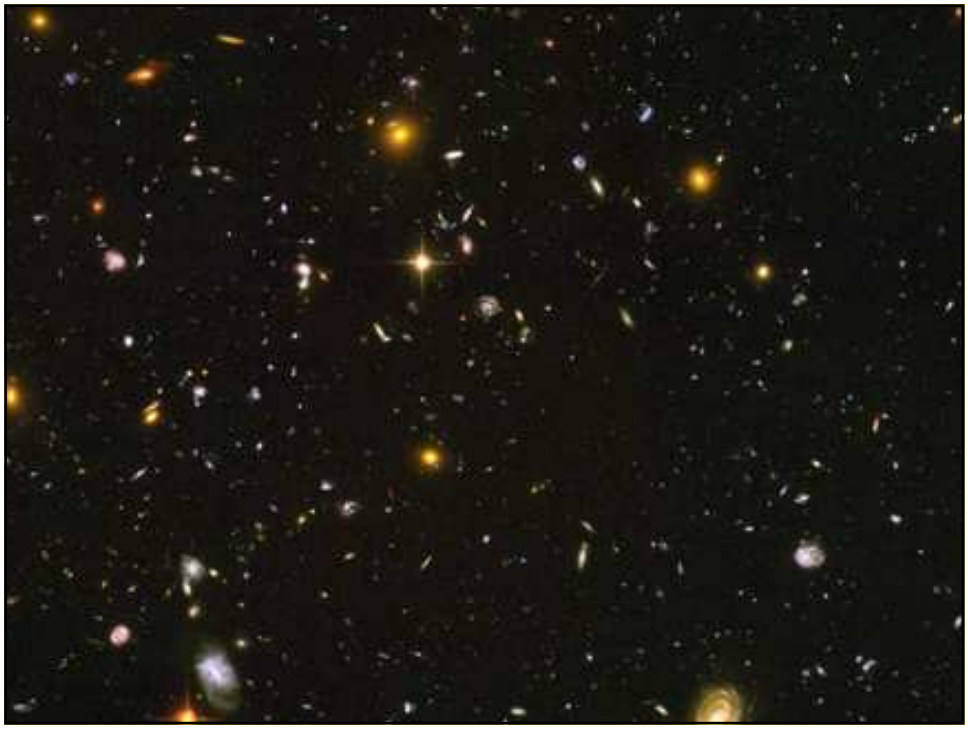
We can look at nearby galaxies and figure how they got that way...



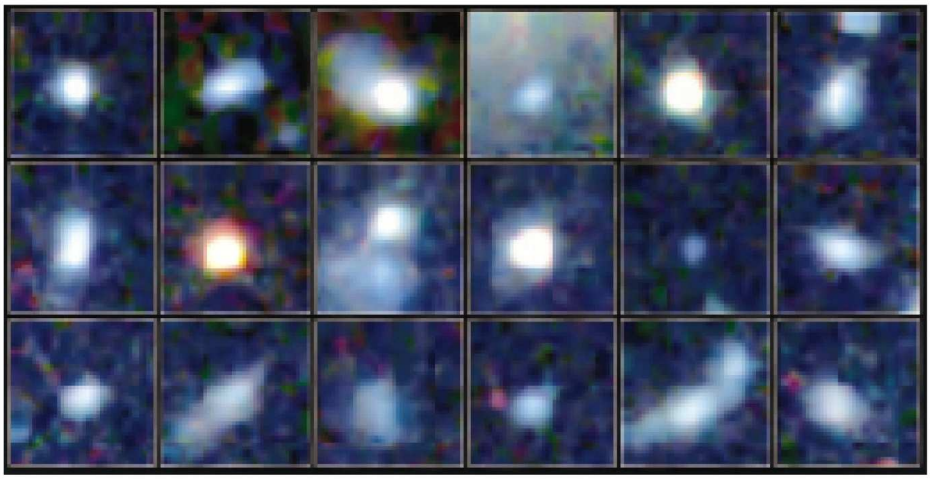
a SBa (NGC 4650) b SBb (M83) c SBc (NGC 1365)





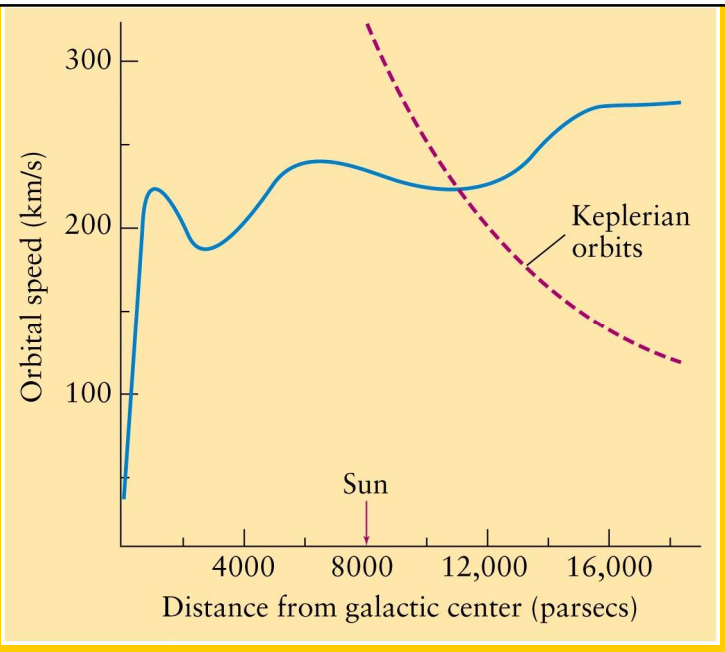


Galaxies in the distant universe (the past!) don't look like galaxies now

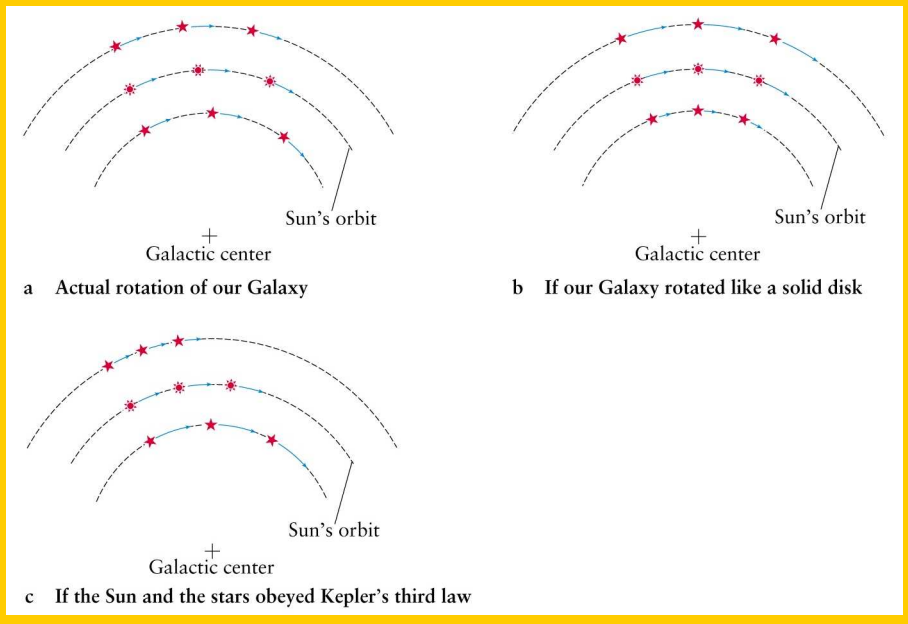


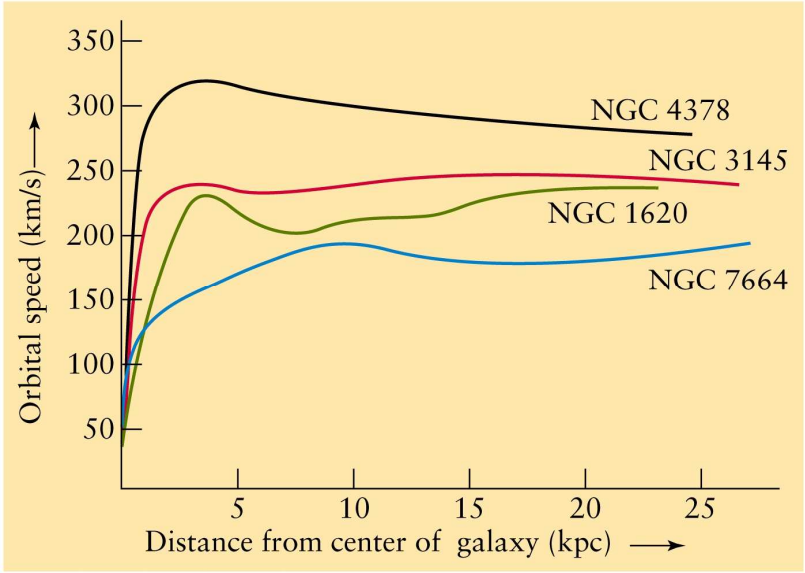
b

Masses of Galaxies: Observational Evidence for Dark Matter



The *rotation curve* of our Galaxy





Dark matter is common in galaxies!!

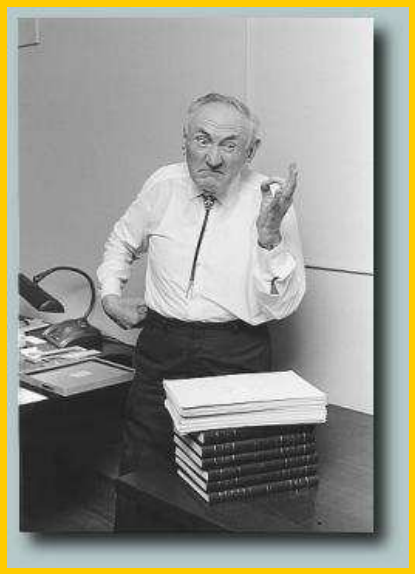
Galaxy clusters ➔ masses

Dynamics (‘virial masses’)

X-ray observations

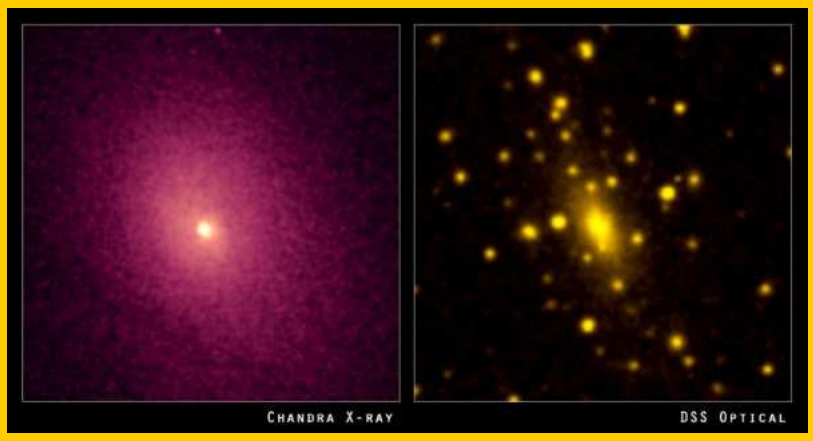
Gravitational lensing

Virial Masses



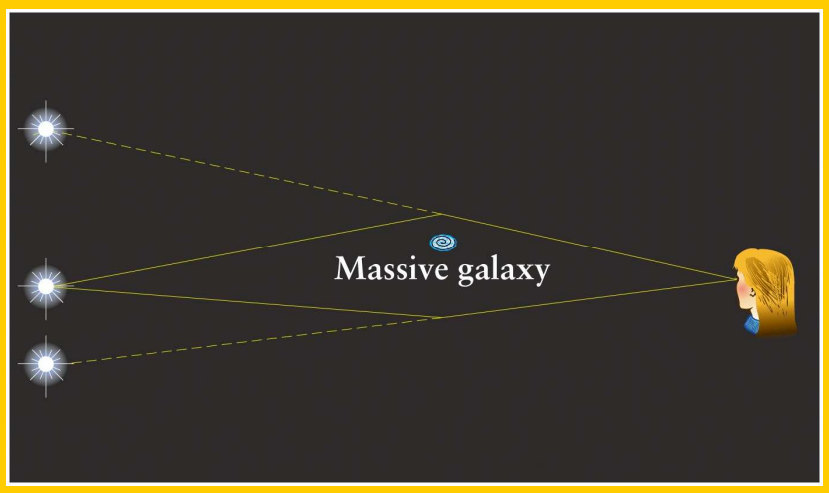
Fritz Zwicky

X-ray observations



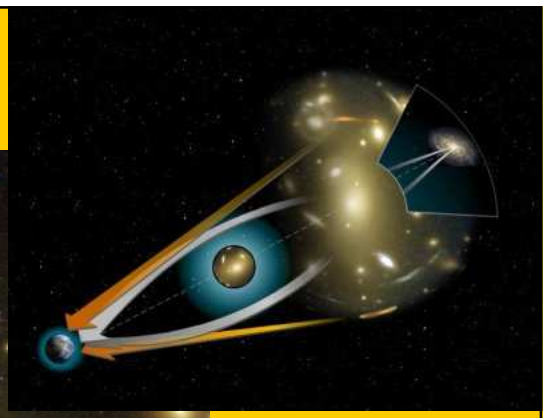
(Abell 2029)

Gravitational Lensing



0024+1654

Abell 2218



So, there is a *lot* of non-baryonic 'dark matter'!

The gravitational effect of dark (and 'ordinary') matter affects the way the universe expands.

But we haven't yet talked about the expansion of the universe....