PHAS 1102 Part 2:

‘Cosmology and the Universe’

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(or via moodle)

What is the universe made of?

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

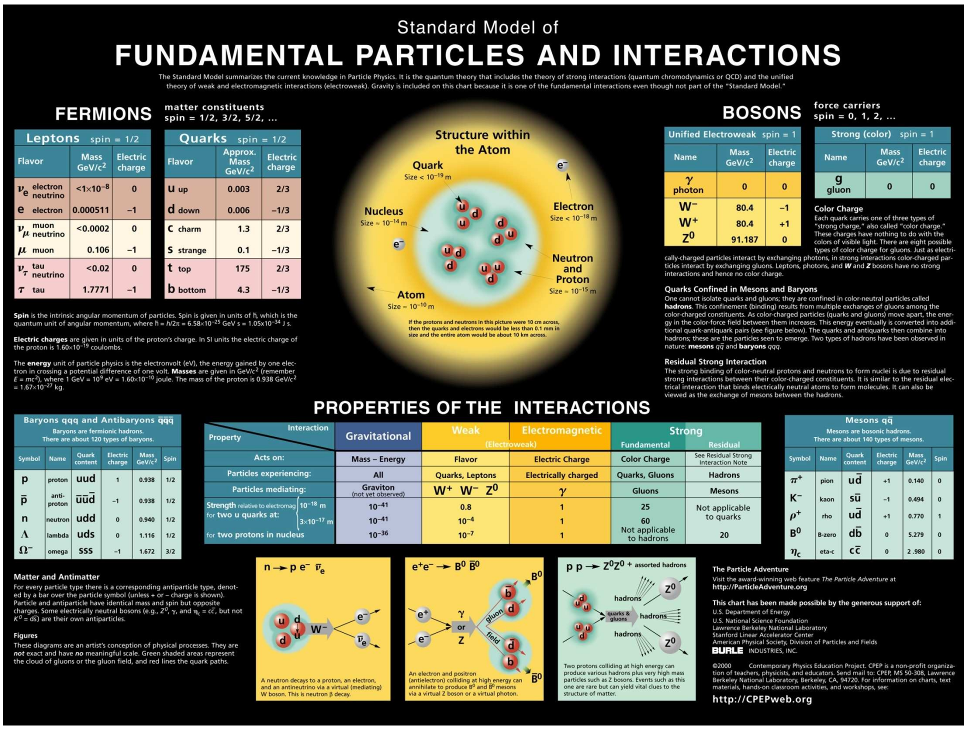
The Standard Model describes more than 200 ‘elementary’ particles, and their interactions, using as ingredients:

- 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?

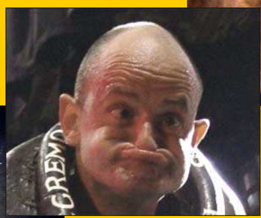
On a microscopic scale: “Baryonic matter”
3 quarks: protons & neutrons (+Delta, Lambda, Sigma, Xi)

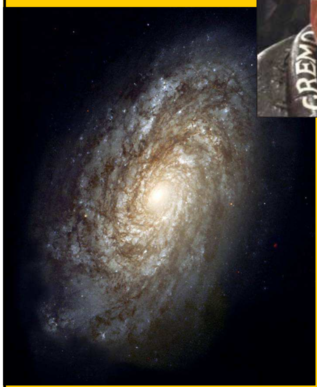
$\Rightarrow$ *Essentially all recognizable mass in the universe consists of baryonic matter in the form of neutrons and protons*

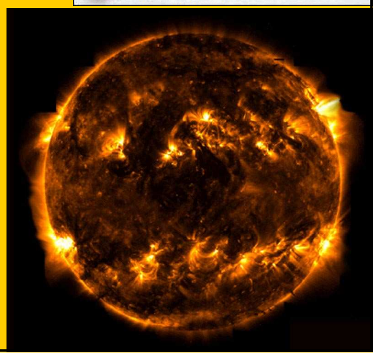
(electrons [muon, tau leptons], neutrinos, etc., are negligible in terms of the mass budget of the universe)

Examples of baryonic matter on a *macroscopic* scale:

Examples of objects whose mass is dominated by BARYONIC MATTER







<u>'Large Hadron Collider' (LHC)</u>

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)

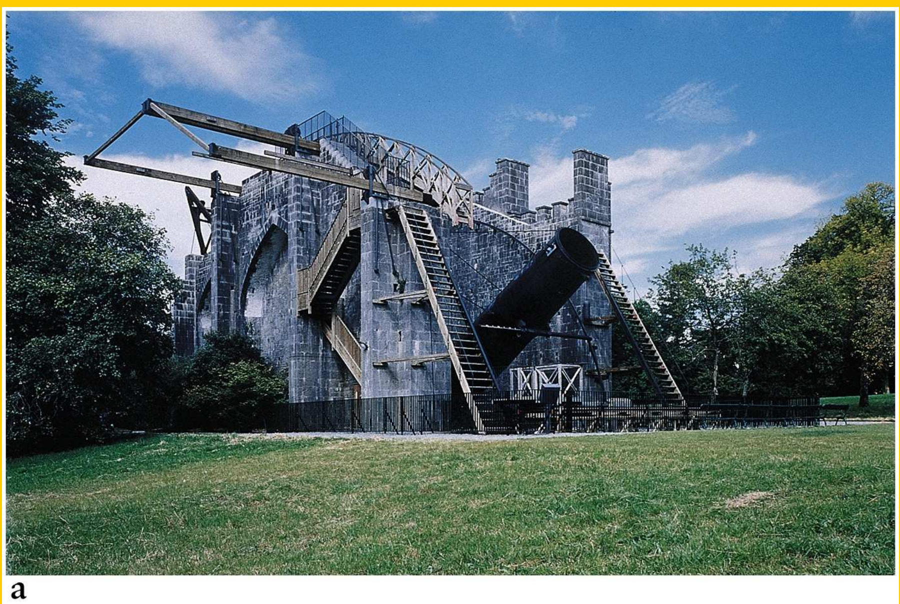
The LHC collides (will collide…) protons

[Why? Heavier particles allow greater collision energies]

WHAT *WE* NEED TO KNOW:

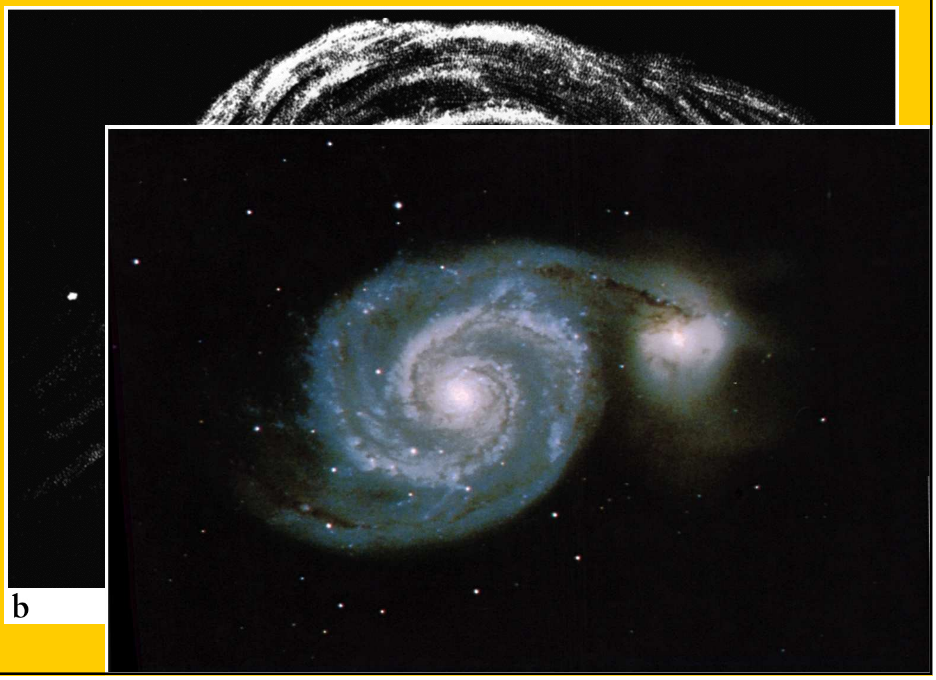
<u>MOST OBSERVABLE MASS IS BARYONIC</u>

Galaxies



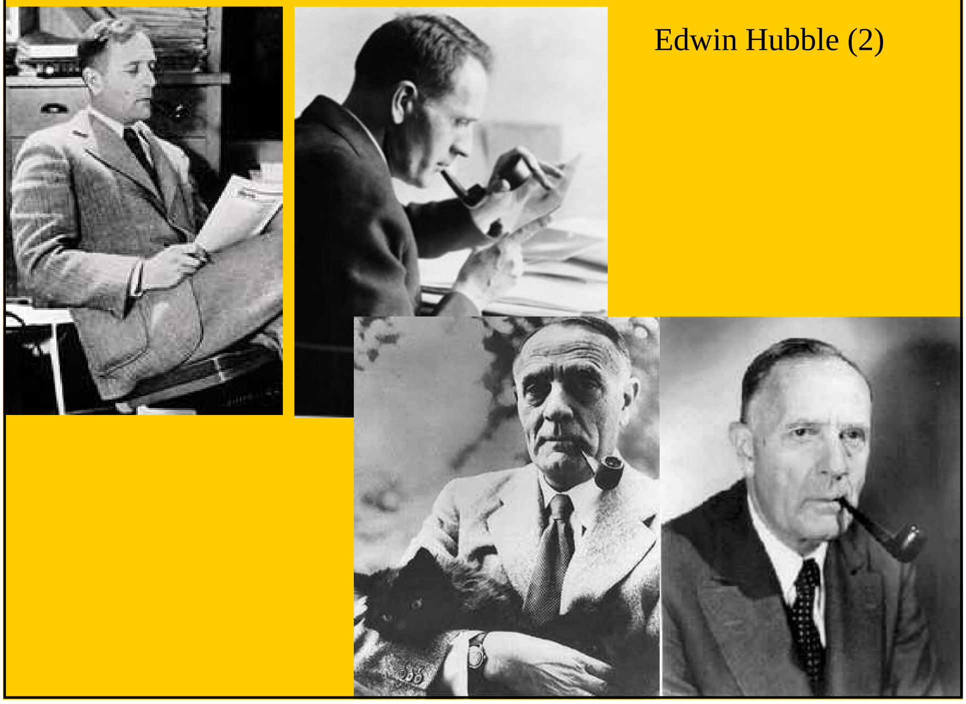
Rosse 70″ 1.8-m telescope (Parsonstown, 1845)

M51 – the first galaxy recognized as having spiral structure

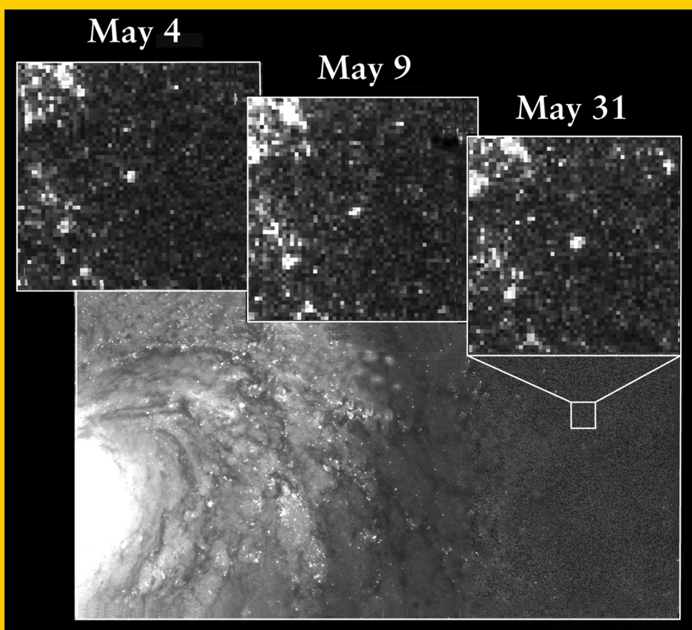


Edwin Hubble

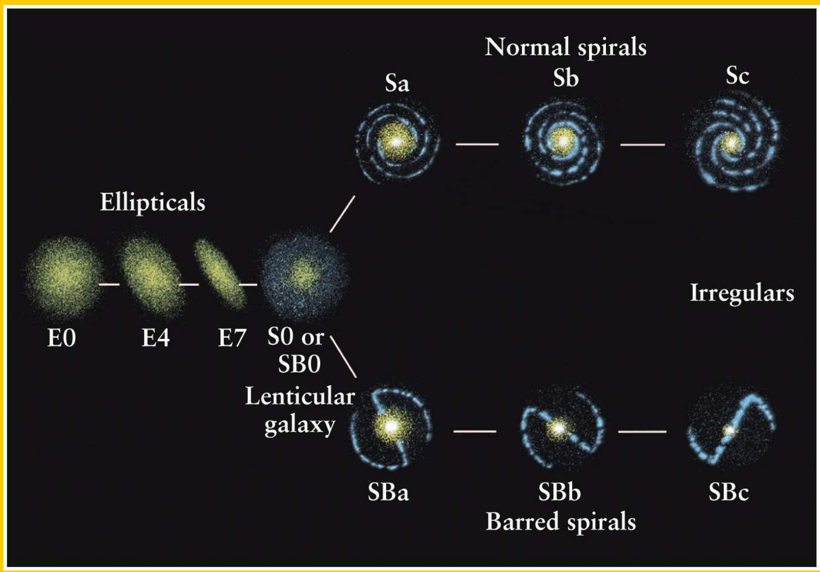
Edwin Hubble (2)

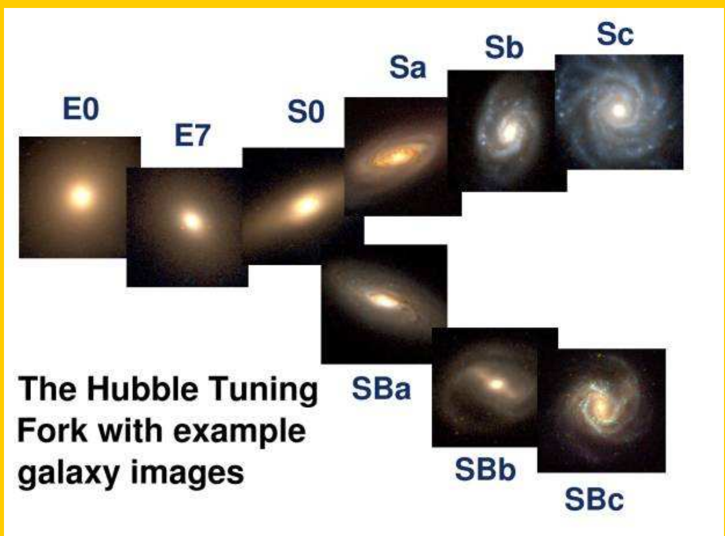


Cepheid variables in the galaxy M100

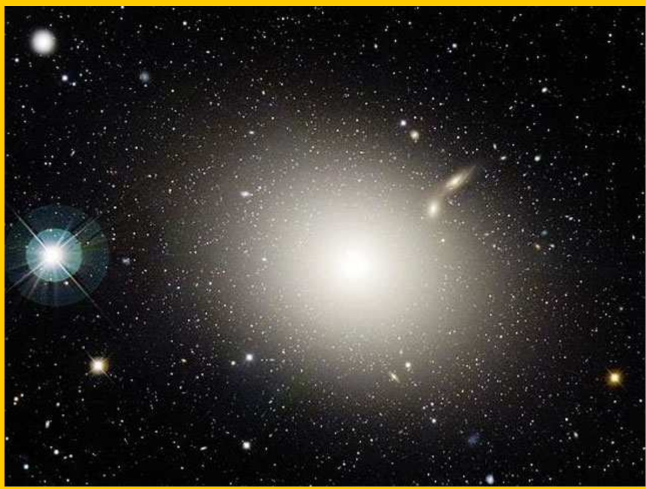


The Hubble ‘tuning fork’ diagram

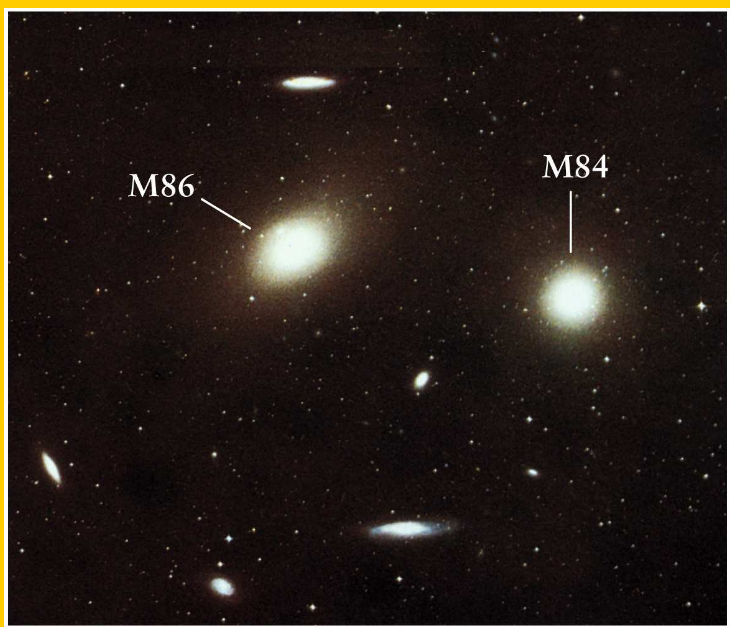




An Elliptical Galaxy (with globular clusters)



Virgo Cluster (with two giant ellipticals)



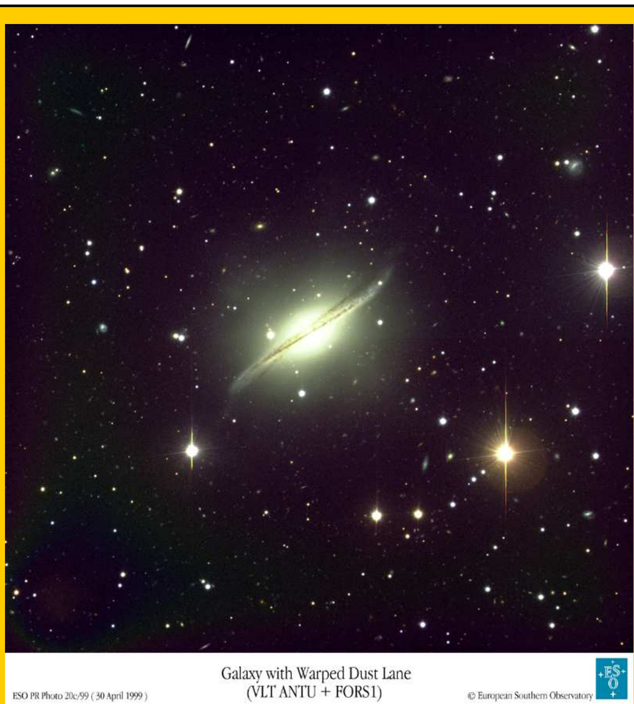
Elliptical and two spirals

b SBb (M83)

c SBc (NGC 1365)

ESO PR Photo 02a/99 (15 January 1999) Spiral Galaxy NGC 253 MPG/ESO 2.2-m + WFI (Full Field)


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
ESO


Giant Interacting Galaxies NGC 6872 / IC 4970
(VLT ANTU + FORS1)
ESO PR Photo 20b/99 (30 April 1999)
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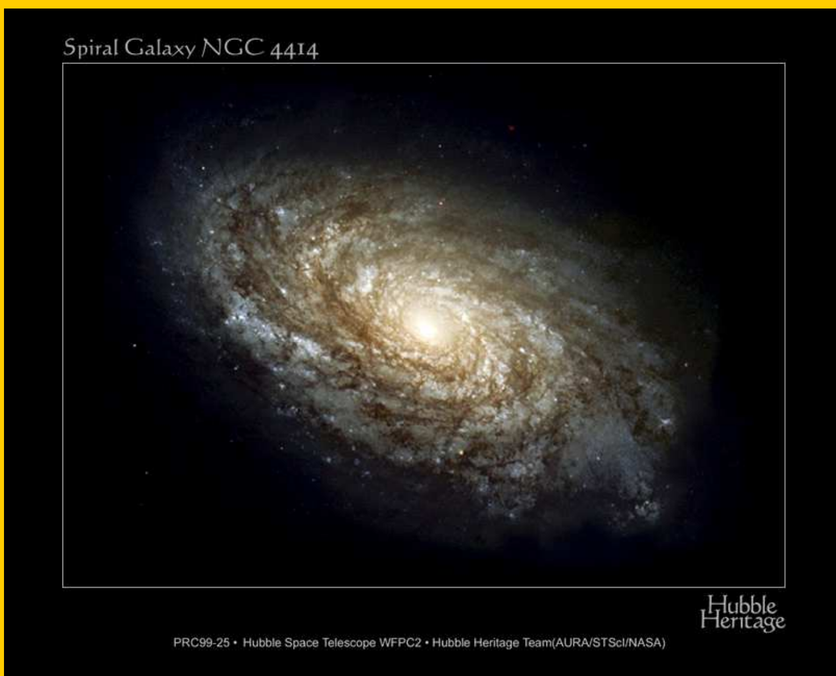
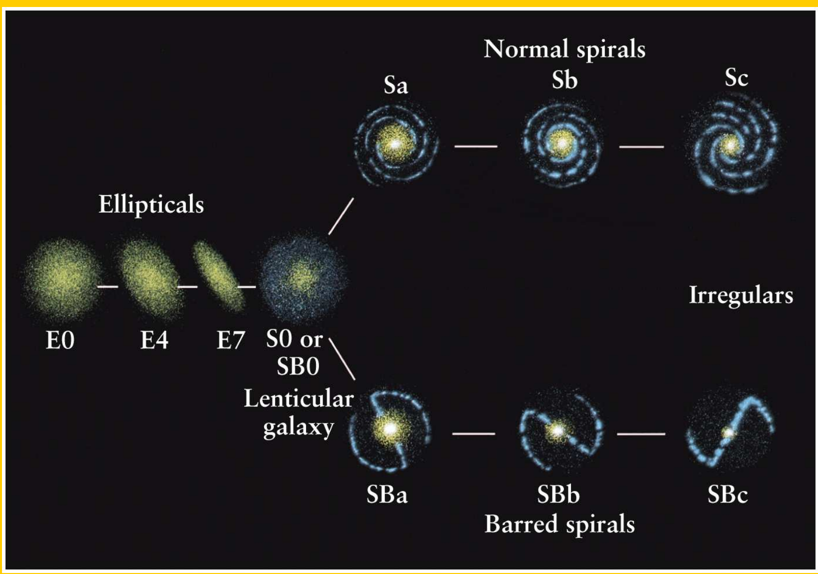
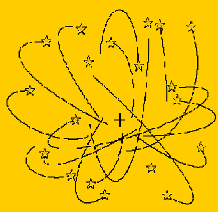

Spiral Galaxy NGC 4414
Hubble Heritage
PRC99-25 • Hubble Space Telescope WFPC2 • Hubble Heritage Team(AURA/STScI/NASA)

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)

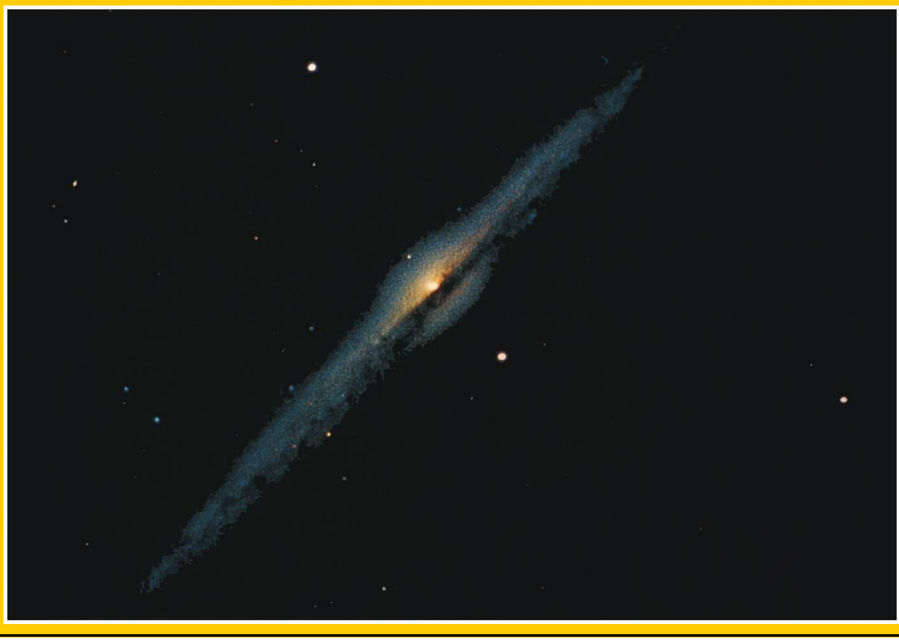
+intermediate SO types – spiral galaxies with spiral arms

+irregular galaxies

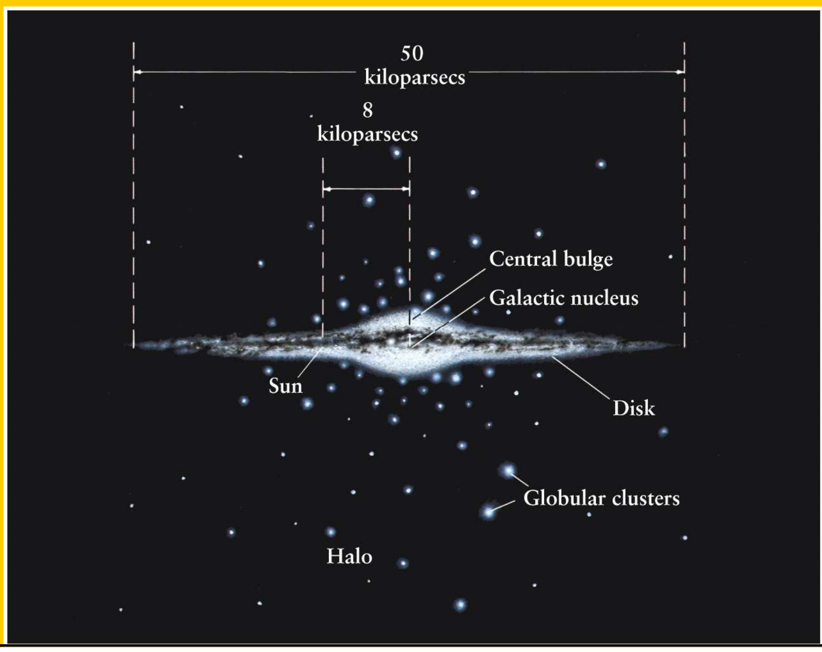
…our Galaxy:

The Milky Way Galaxy

For comparison, an edge-on spiral galaxy



The structure of the Galaxy

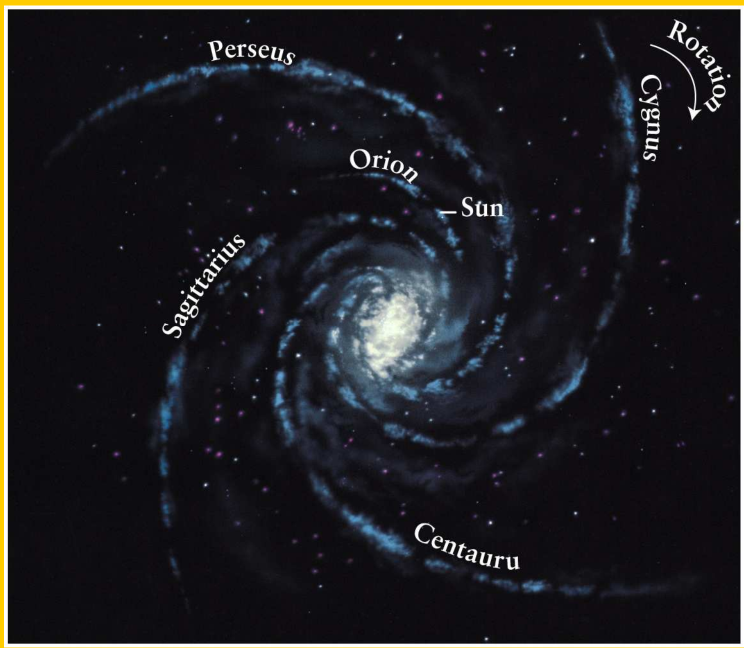


The Galaxy according to Spitzer Space Telescope: an SBc spiral

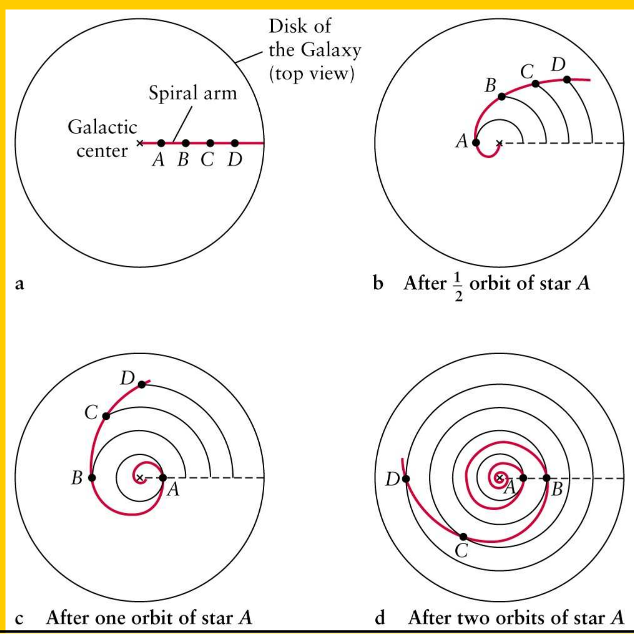
SPIRAL ARMS:

Which way do galaxies rotate?

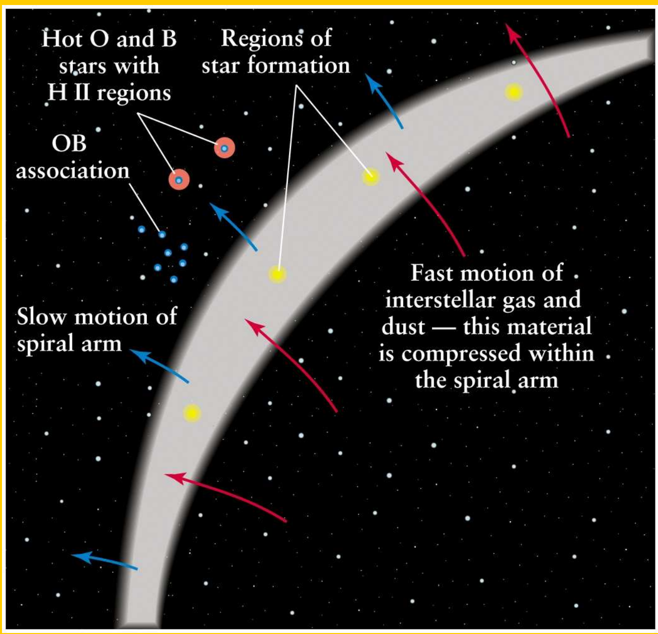
What is the nature of spiral arms?



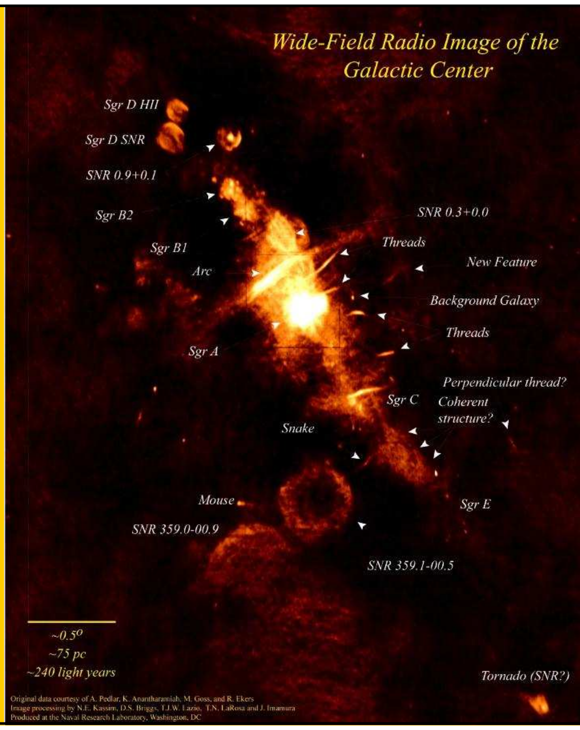
Spiral arms can’t be fixed, permanent structures (‘windmills’)



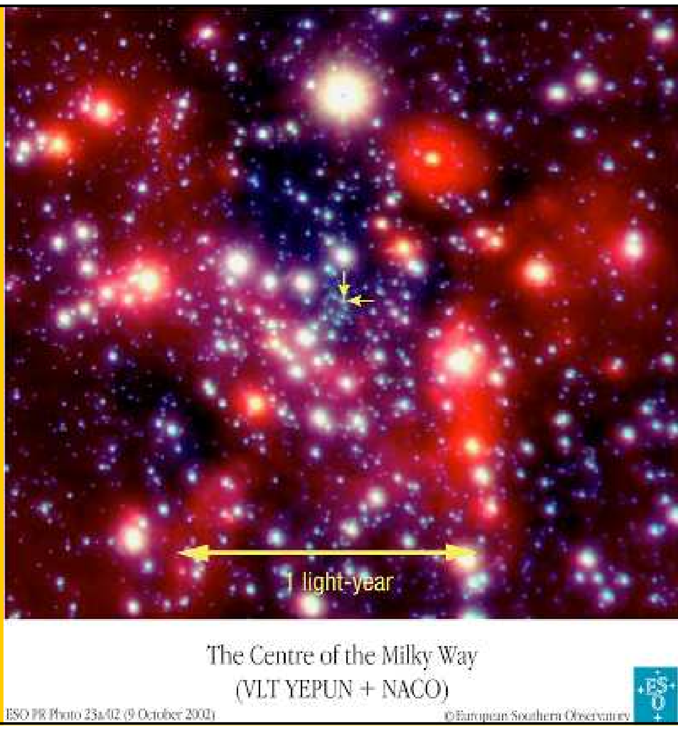
Spiral arms are a manifestation of *density waves*



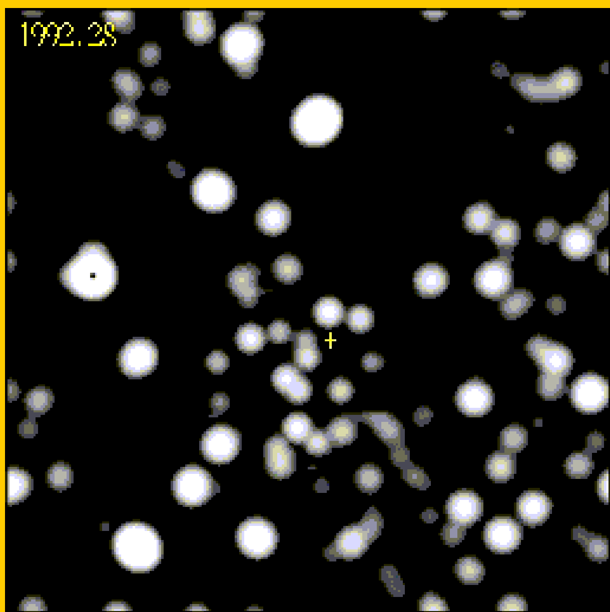
The centre of the Galaxy – a radio view (gas) showing Sgr A

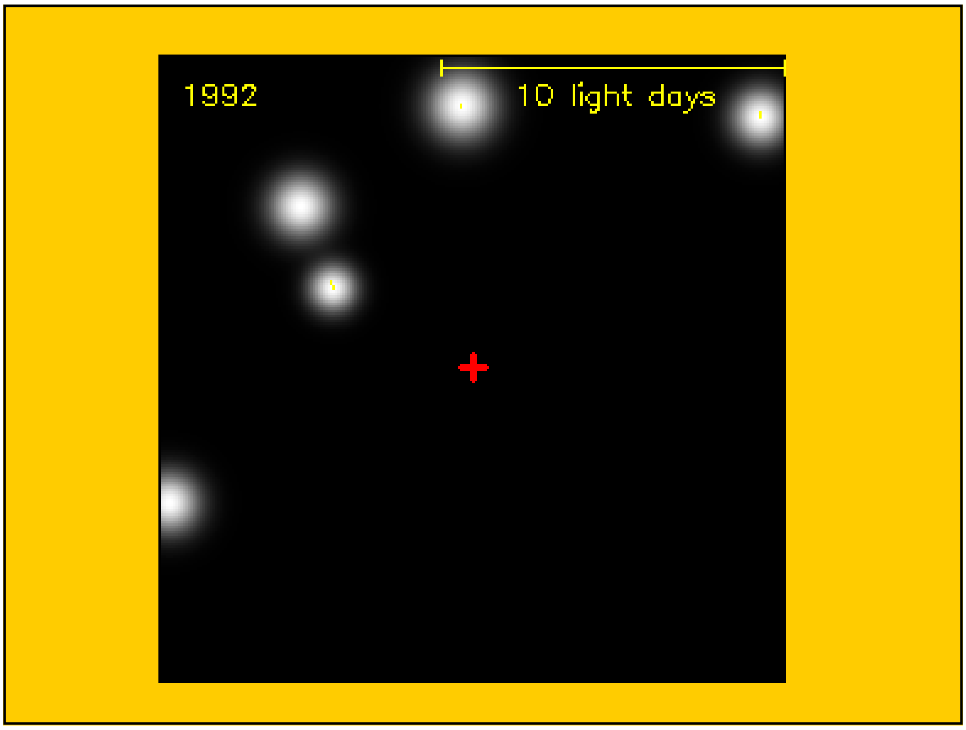


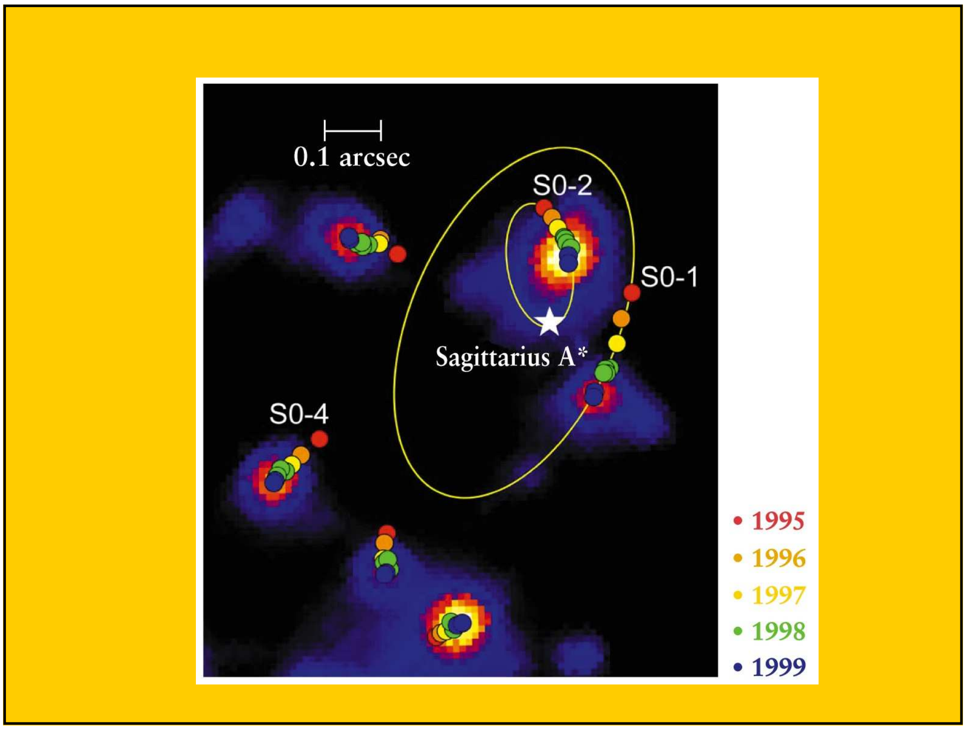
Infrared view

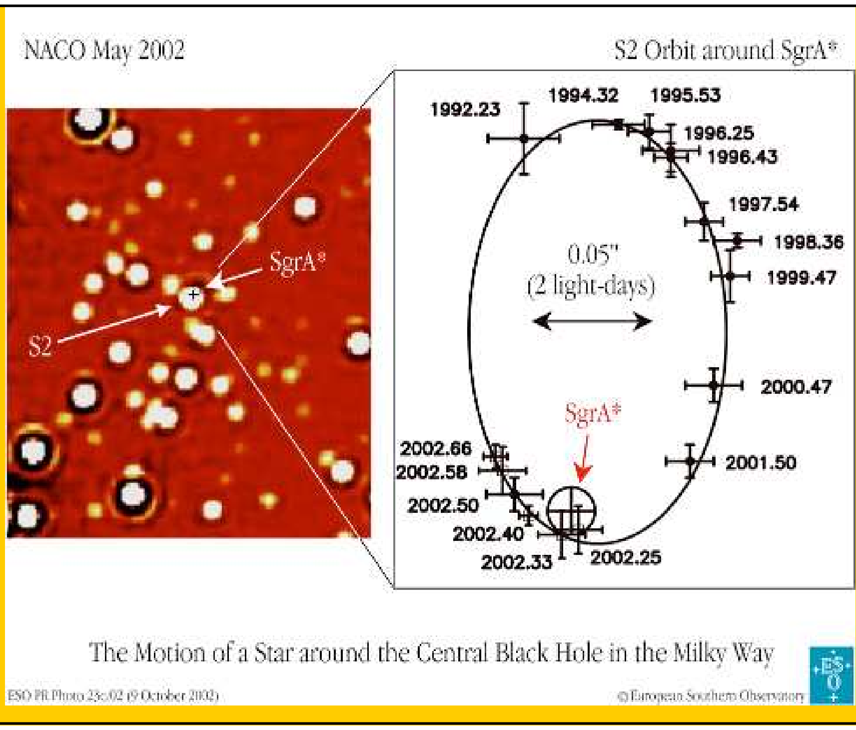


Stars at the core of the Galaxy




1992
10 light days


0.1 arcsec
S0-2
S0-1
Sagittarius A*
S0-4
1995
1996
1997
1998
1999



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

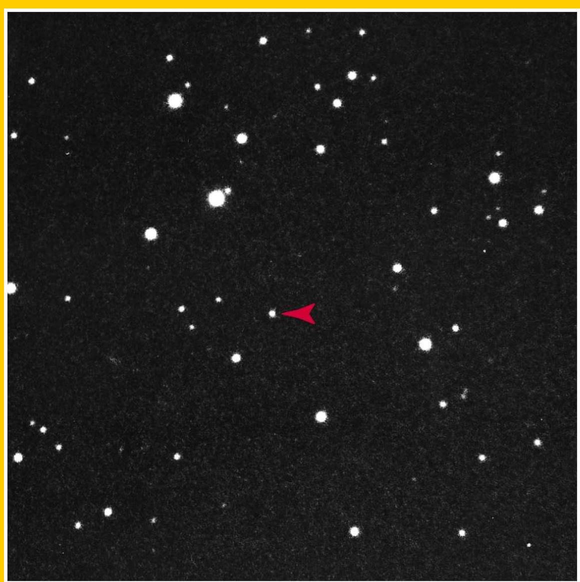
Characteristic: strong emission (at some wavelength) not due to stars

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

Seyfert galaxies (1943)

Nearly all have spiral galaxy ‘hosts’

Starlike nuclei, emission-line spectra



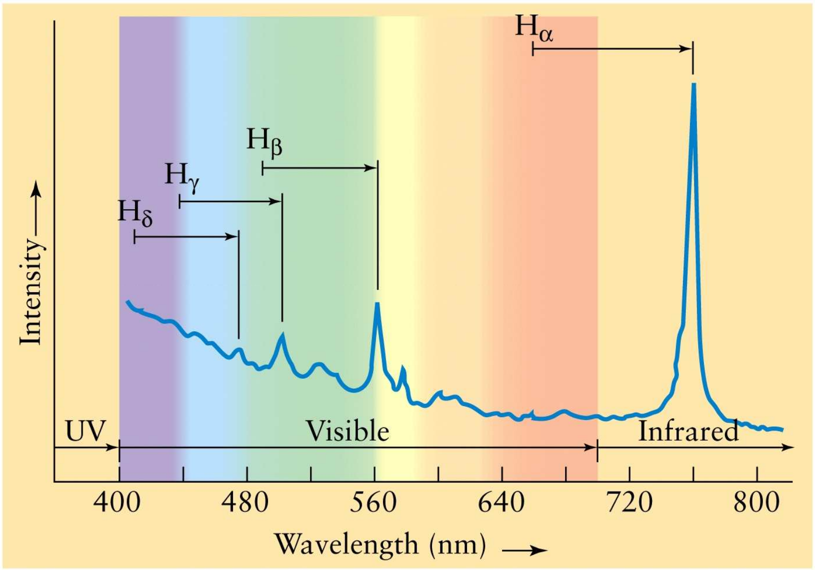
3C48

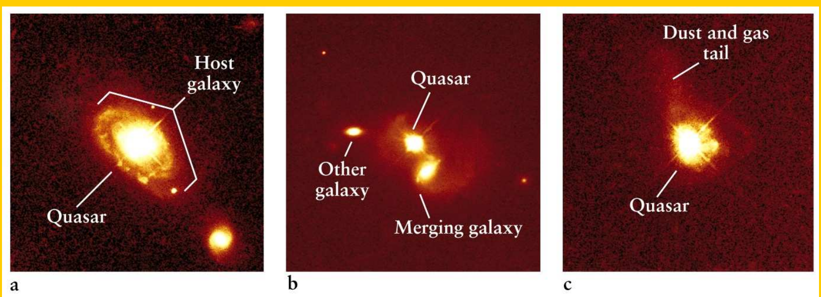
Quasars (QSOs)

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



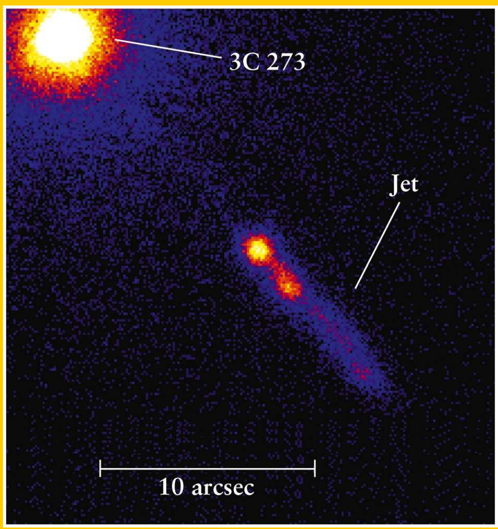


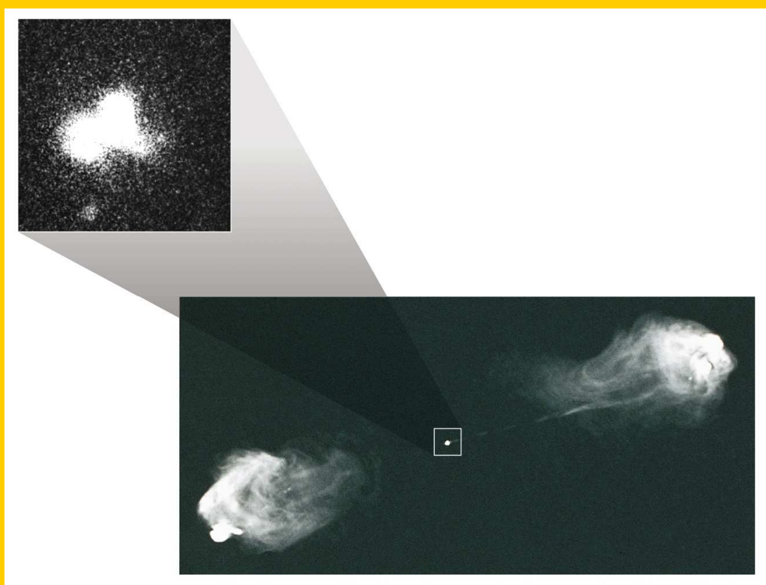
Quasars show 'fuzz' – they are AGN whose luminosity exceeds of the host galaxy

What can produce this large luminosity in a small volume?

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

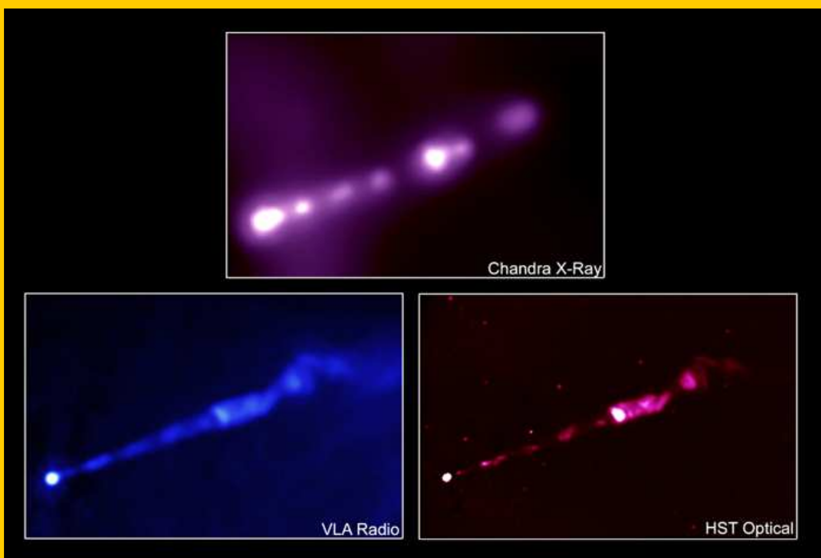
Active galaxies often show ‘jets’

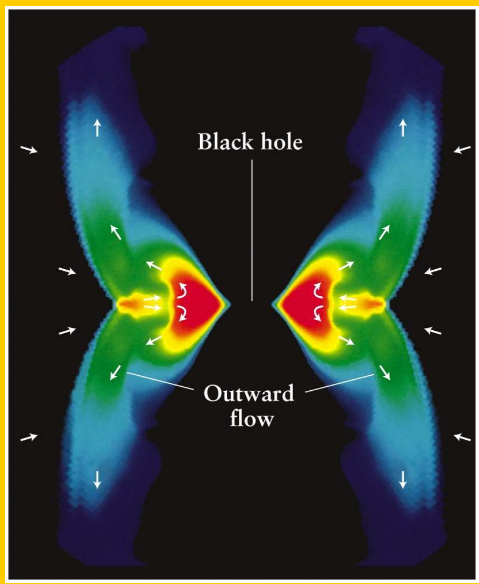


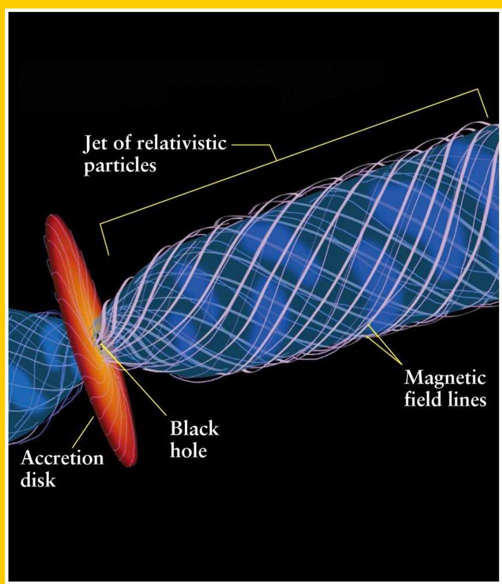


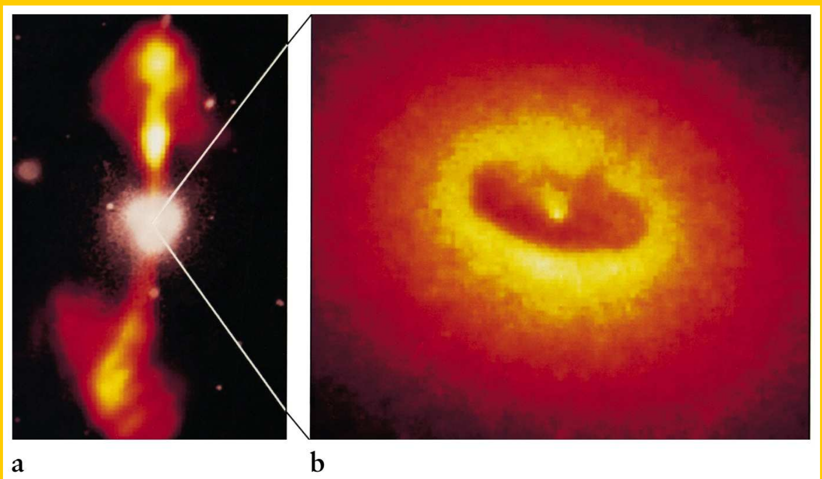
Cygnus A – radio galaxy


1 arcmin
a


Chandra X-Ray
VLA Radio
HST Optical


Black hole
Outward flow

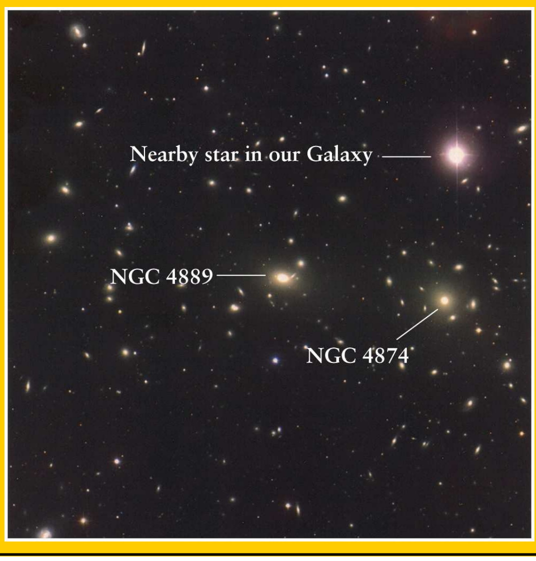

Jet of relativistic particles
Magnetic field lines
Black hole
Accretion disk



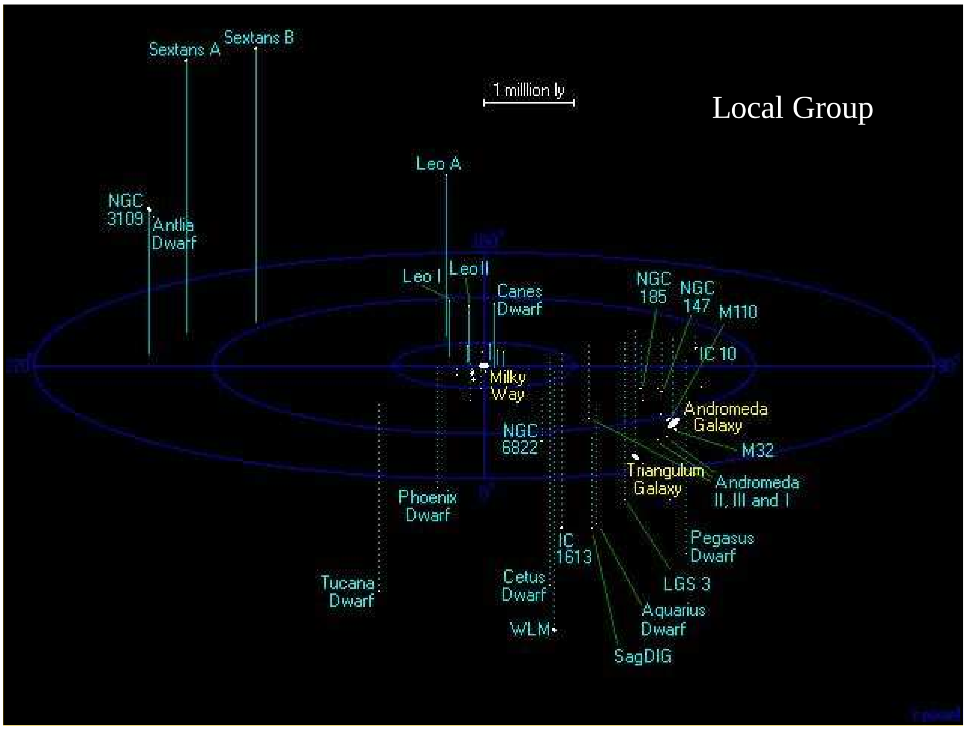
NGC 4261 left: optical+radio right: HST

Clusters of Galaxies

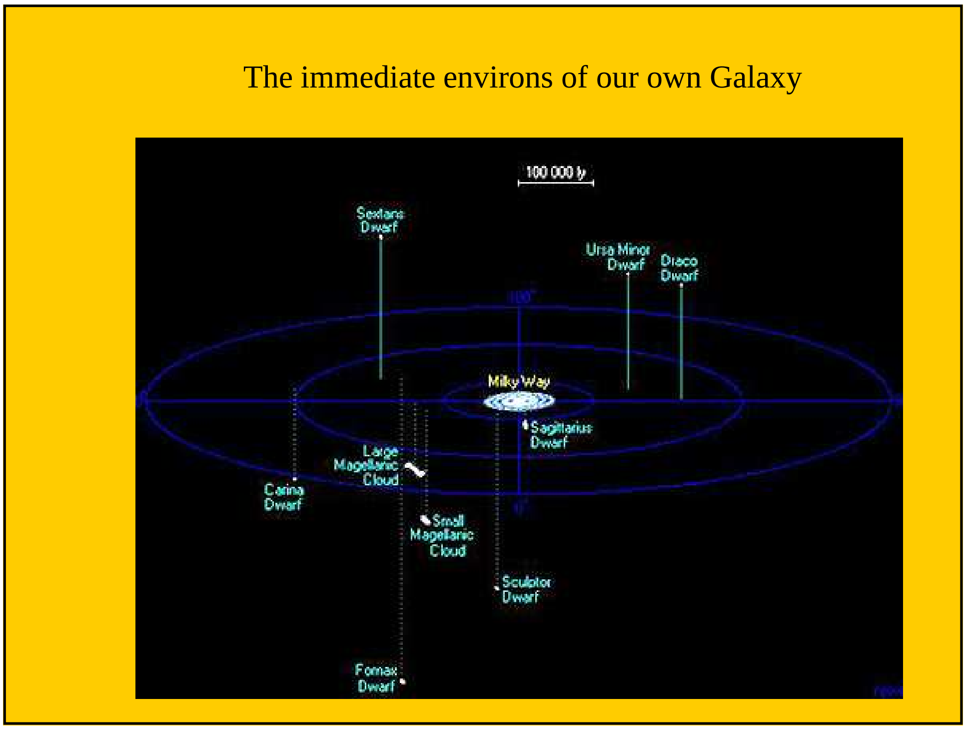
Galaxies are mostly found in groups, clusters, or superclusters



The Coma Cluster



Local Group
1 milllion ly
Sextans A
Sextans B
NGC 3109
Antlia Dwarf
Leo A
Leo I
Leo II
Canes Dwarf
Milky Way
NGC 6822
Phoenix Dwarf
Tucana Dwarf
NGC 185
NGC 147
M110
IC 10
Andromeda Galaxy
M32
Triangulum Galaxy
Andromeda II, III and I
Pegasus Dwarf
IC 1613
Cetus Dwarf
WLM
LGS 3
Aquarius Dwarf
SagDIG

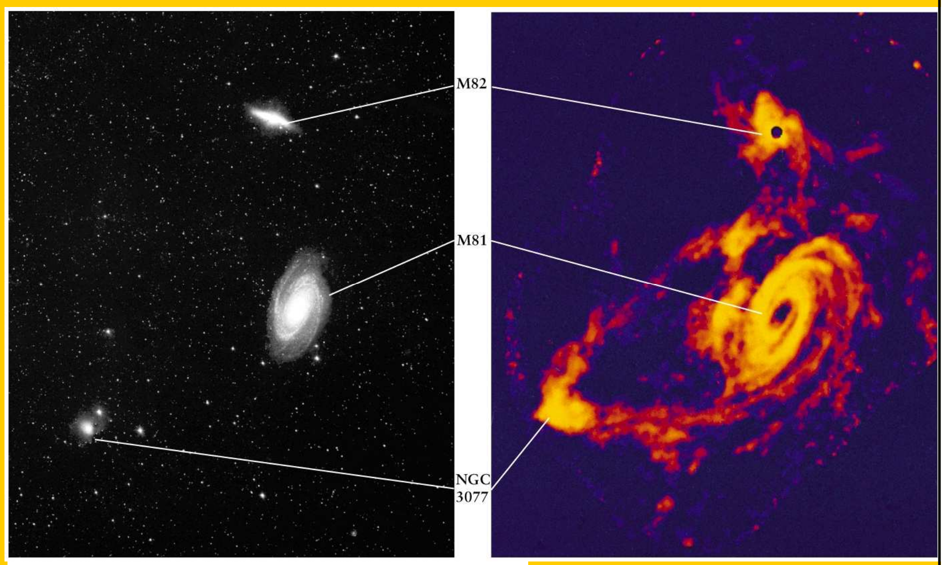


The immediate environs of our own Galaxy
100 000 ly
Sextans Dwarf
Ursa Minor Dwarf
Draco Dwarf
Milky Way
Sagittarius Dwarf
Large Magellanic Cloud
Carina Dwarf
Small Magellanic Cloud
Sculptor Dwarf
Fornax Dwarf

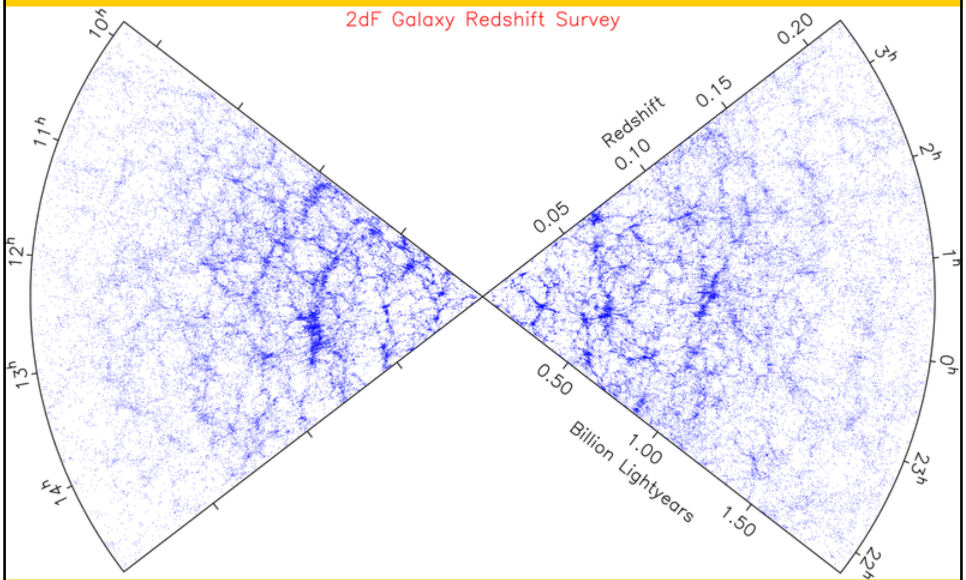
The centre of the Virgo cluster

The Hercules Cluster – with interacting spiral galaxies

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



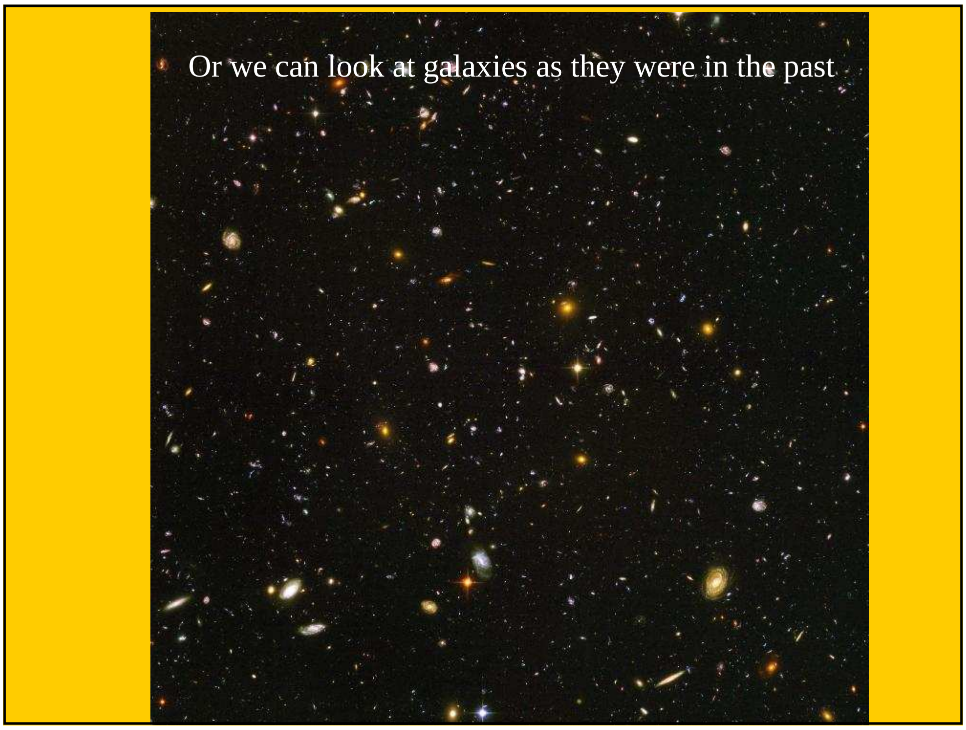
Large-scale structure: ‘superclusters’

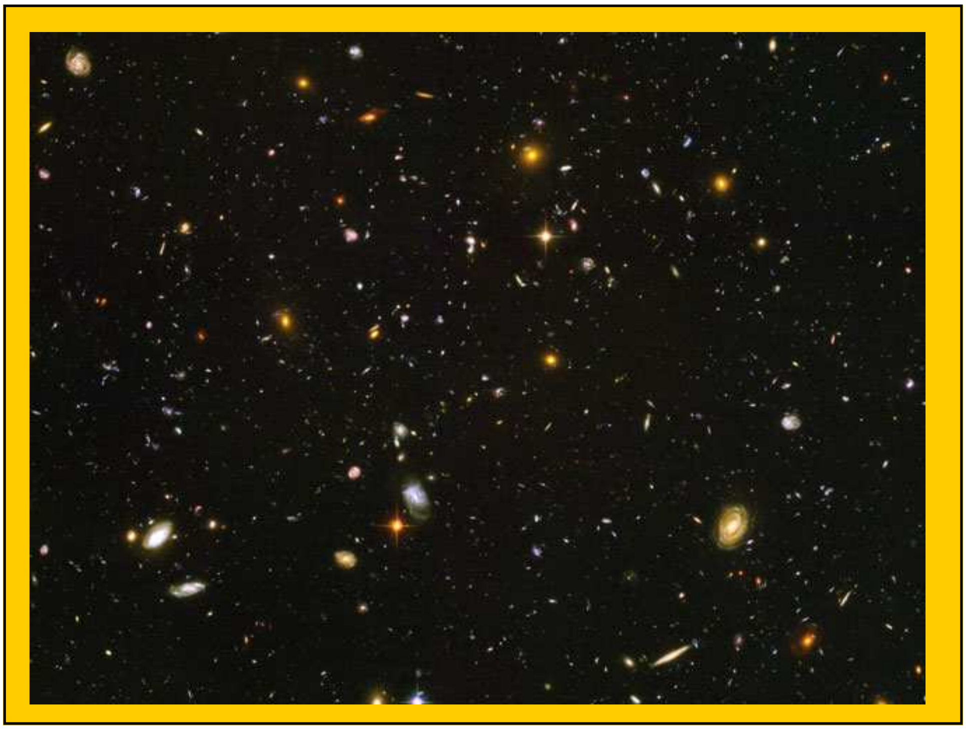


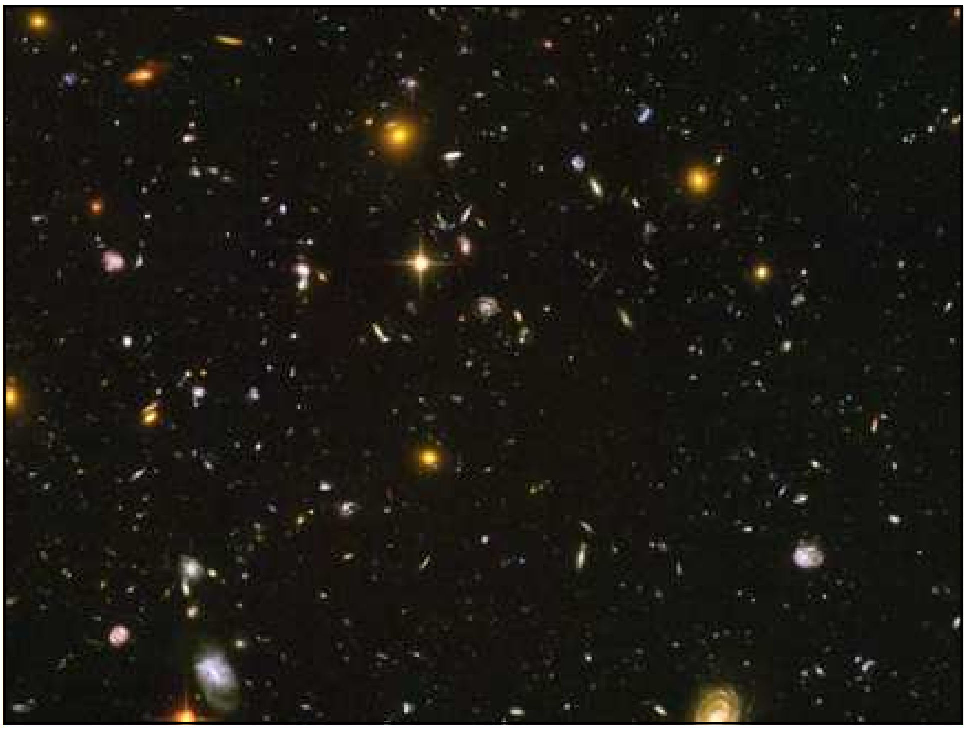
Evolution of Galaxies

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

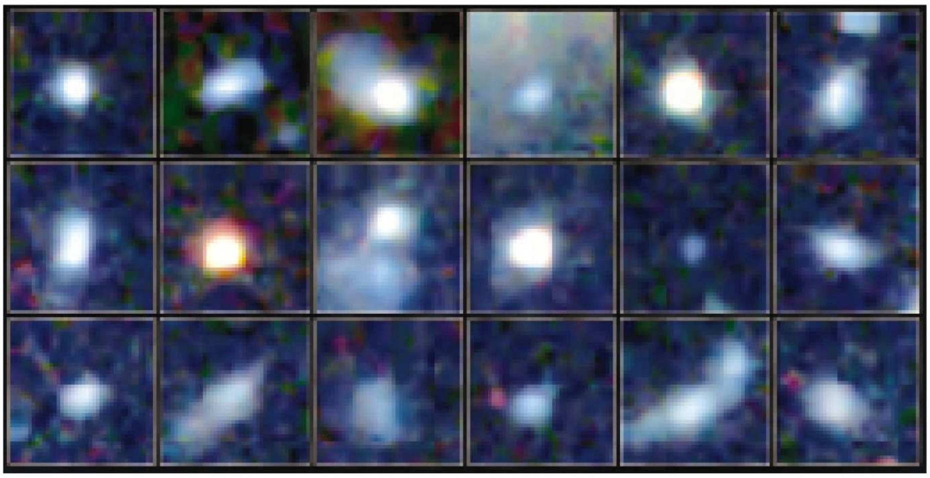
a SBa (NGC 4650) b SBb (M83) c SBc (NGC 1365)


Or we can look at galaxies as they were in the past

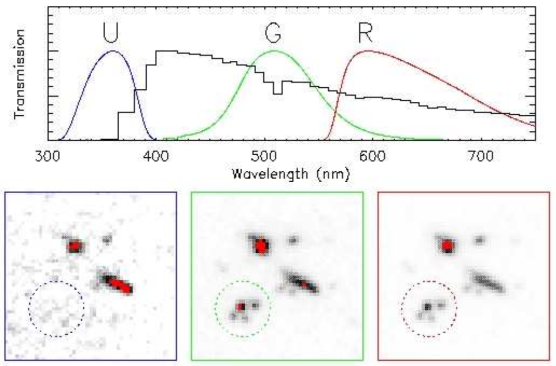




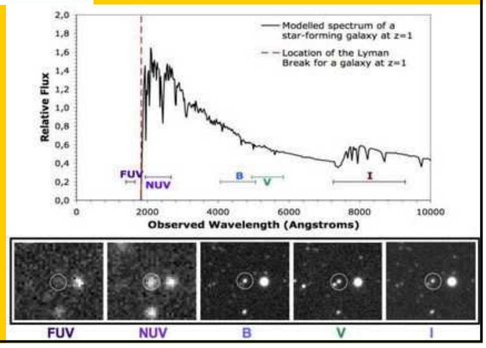
Galaxies in the distant universe (the past!) don't look like galaxies now



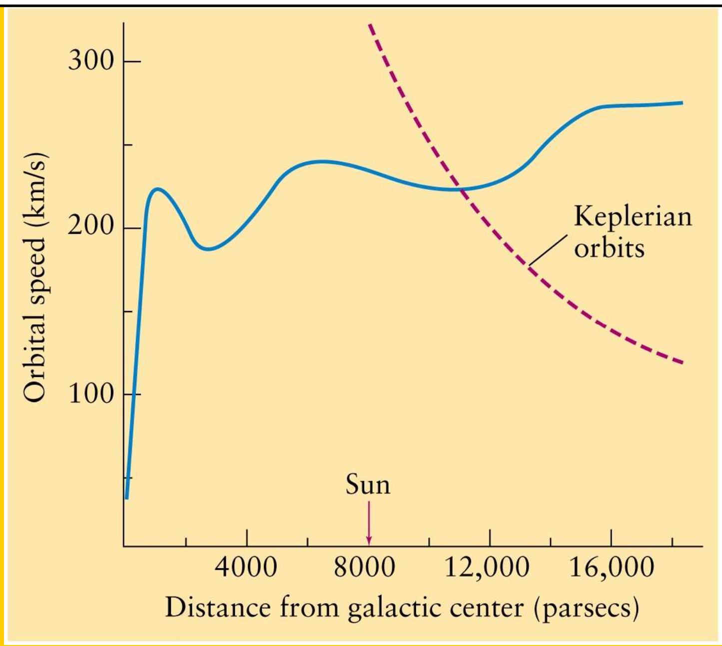
b



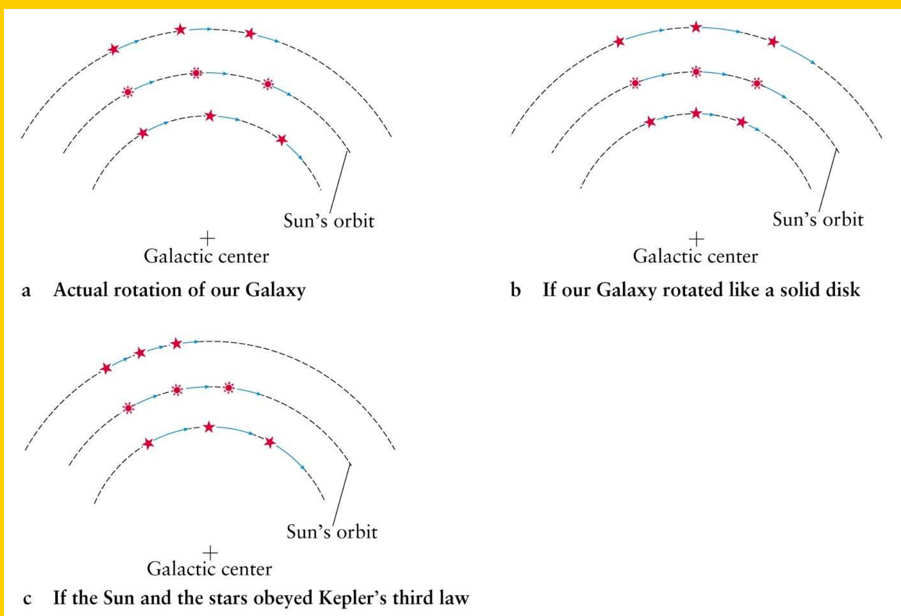
Lyman-Break Galaxies

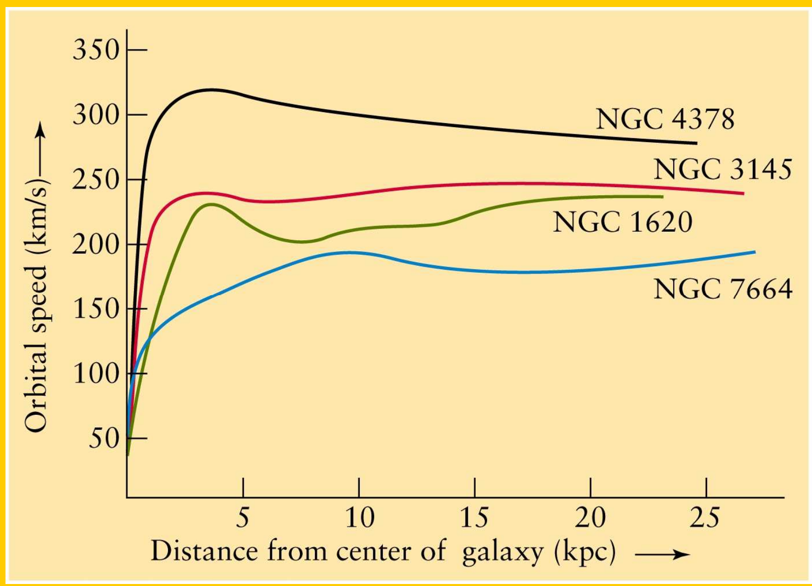


Masses of Galaxies: Observational Evidence for Dark Matter



The *rotation curve* of our Galaxy





Dark matter is common in galaxies!!

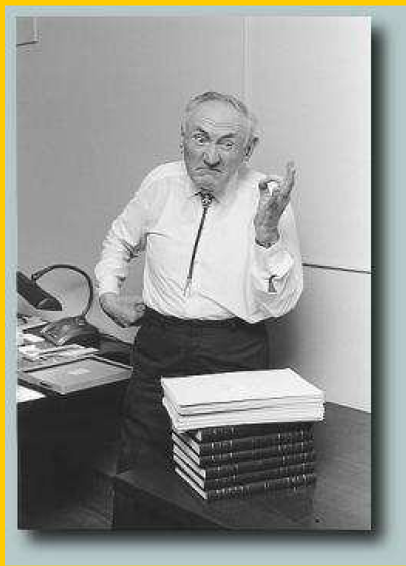
Galaxy clusters ➔ masses

Dynamics (`virial masses')

X-ray observations

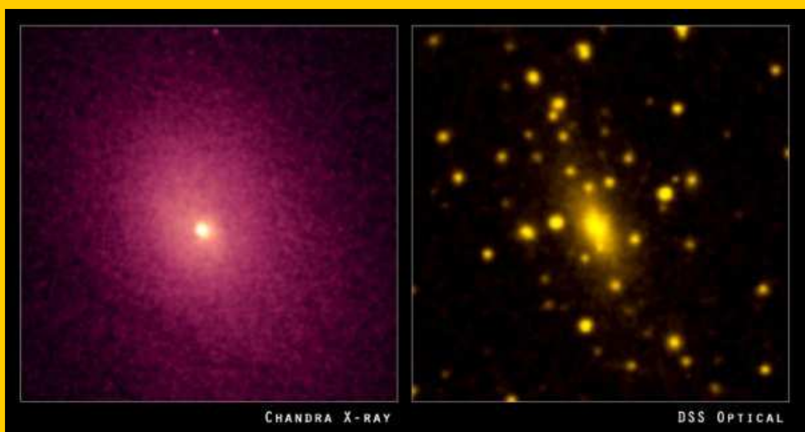
Gravitational lensing

Virial Masses



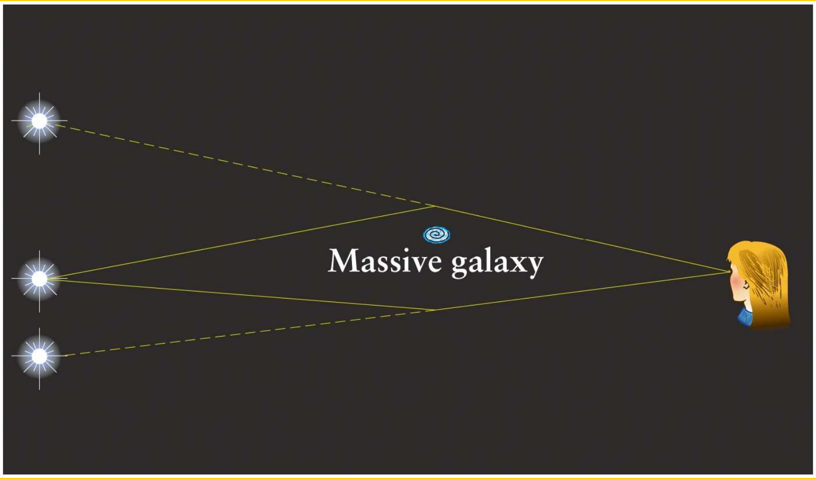
Fritz Zwicky

X-ray observations



(Abell 2029)

Gravitational Lensing



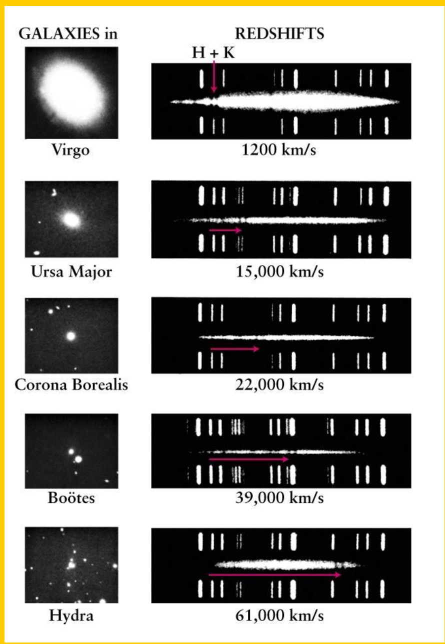
0024+1654

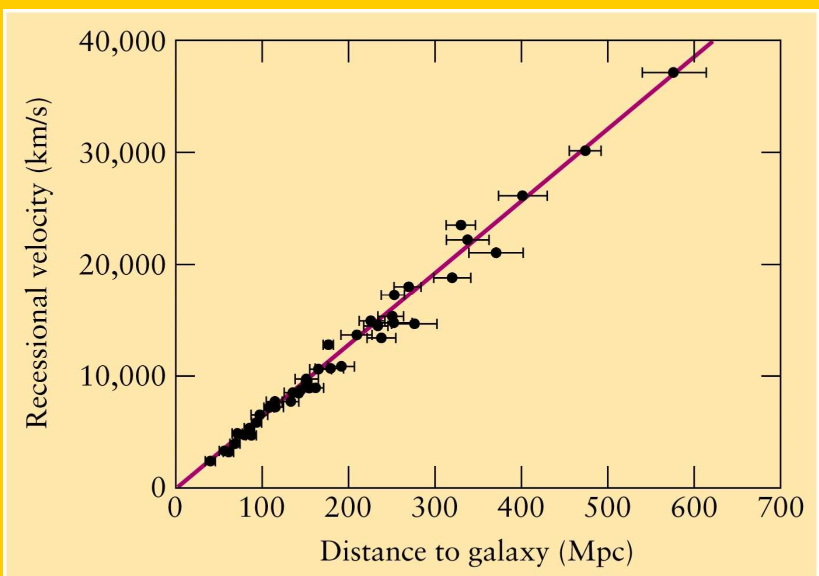
Abell 2218

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....





H_0 = 72 (+/-5) km/s per Mpc