

PHAS 1102 Part 2:  
'Cosmology and the Universe'



Ian Howarth idh@star.ucl.ac.uk

<http://www.star.ucl.ac.uk/~idh/PHAS1102>  
=<http://www.homepages.ucl.ac.uk/~ucapidh/PHAS1102>  
(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)

# Standard Model of FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

## FERMIONS

**Leptons** spin = 1/2

Flavor	Mass, GeV/c <sup>2</sup>	Electric charge
$\nu_e$ electron neutrino	<1×10 <sup>-8</sup>	0
$e^-$ electron	0.000511	-1
$\nu_\mu$ muon neutrino	<0.0002	0
$\mu^-$ muon	0.106	-1
$\nu_\tau$ tau neutrino	<0.02	0
$\tau^-$ tau	1.7771	-1

**Quarks** spin = 1/2

Flavor	Approx. Mass, GeV/c <sup>2</sup>	Electric charge
$u$ up	0.003	2/3
$d$ down	0.006	-1/3
$c$ charm	1.3	2/3
$s$ strange	0.1	-1/3
$t$ top	175	2/3
$b$ bottom	4.3	-1/3

## BOSONS

**Strong (color)** spin = 1

Name	Mass, GeV/c <sup>2</sup>	Electric charge
$g$ gluon	0	0

**Unified Electroweak** spin = 1

Name	Mass, GeV/c <sup>2</sup>	Electric charge
$\gamma$ photon	0	0
$W^\pm$	80.4	-1
$Z^0$	80.4	+1
$Z^0$	91.187	0

**Structure within the Atom**

Quark Size ~ 10<sup>-19</sup> m

Nucleus Size ~ 10<sup>-14</sup> m

Atom Size ~ 10<sup>-10</sup> m

Electron Size ~ 10<sup>-16</sup> m

Neutron and Proton Size ~ 10<sup>-15</sup> m

**Spin** is the intrinsic angular momentum of particles. Spin is given in units of  $\hbar$ , which is the quantum unit of angular momentum, where  $\hbar = h/2\pi = 6.58 \times 10^{-27}$  GeV s =  $1.05 \times 10^{-34}$  J s.

**Electric charges** are given in units of the proton's charge. In SI units the electric charge of the proton is  $1.60 \times 10^{-19}$  coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c<sup>2</sup> (remember  $E = mc^2$ , where  $1 \text{ GeV} = 10^9 \text{ eV} = 1.60 \times 10^{-10}$  joules). The mass of the proton is  $0.938 \text{ GeV}/c^2 = 1.67 \times 10^{-27} \text{ kg}$ .

## PROPERTIES OF THE INTERACTIONS

Property	Interaction	Gravitational		Weak		Electromagnetic		Strong	
		Mass - Energy	Flavor	Electric Charge	Color Charge	Hadrons	Mesons		
Acts on:		All	Quarks, Leptons	Electrically charged	Quarks, Gluons				
Particles experiencing:		All	Quarks, Leptons	Electrically charged	Quarks, Gluons				
Particles mediating:		Graviton (not yet observed)	$W^\pm$ , $Z^0$	$\gamma$	Gluons				
Strength relative to electromagnetism for two u quarks at:		10 <sup>-41</sup>	10 <sup>-4</sup>	1	25				
		10 <sup>-36</sup>	10 <sup>-7</sup>	1	60				
					Not applicable to quarks				
					20				

### Baryons qq<sub>q</sub> and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons. There are about 100 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass, GeV/c <sup>2</sup>	Spin
$p$	proton	$uud$	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	-1	0.938	1/2
$n$	neutron	$udd$	0	0.940	1/2
$\Lambda$	lambda	$uds$	0	1.116	1/2
$\Omega^-$	omega	$sss$	-1	1.672	3/2

### Mesons $q\bar{q}$

Mesons are bosonic hadrons. There are about 160 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass, GeV/c <sup>2</sup>	Spin
$\pi^+$	pion	$u\bar{d}$	+1	0.140	0
$K^-$	kaon	$s\bar{u}$	-1	0.494	0
$\rho^+$	rho	$u\bar{d}$	+1	0.770	1
$B^0$	B-meson	$d\bar{b}$	0	5.279	0
$\eta_c$	eta-c	$c\bar{c}$	0	2.980	0

### Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless a  $\pm$  or  $\bar{c}$  charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g.  $Z^0$ ,  $\gamma$ , and  $g$ ,  $c$ ,  $\bar{c}$ , but not  $p$  or  $\bar{p}$ ) are their own antiparticles.

### Figures

These diagrams are an artist's conception of physical processes. They are not exact and have no meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

A neutron decays to a proton, an electron, and an antineutrino via a virtual  $W^-$  boson.

An electron and positron (antilepton) colliding at high energy can annihilate to produce  $q$  and  $\bar{q}$  mesons via a virtual  $Z$  boson or a virtual photon.

Two protons colliding at high energy can produce various baryons plus very high mass particles such as  $Z$  bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

### The Particle Adventure

Visit the award-winning web feature The Particle Adventure at <http://Particle-Adventure.org>

This chart has been made possible by the generous support of:

- U.S. Department of Energy
- U.S. National Science Foundation
- Lawrence Berkeley National Laboratory
- Stanford Linear Accelerator Center
- American Physical Society, Division of Particles and Fields
- BNFL, INC.

©2000 Contemporary Physics Education Project. CPEP is a non-profit organization of teachers, physicists, and educators. Send mail to: CPEP, MS 50-308, Lawrence Berkeley National Laboratory, Berkeley, CA, 94720. For information on charts, test materials, hands-on classroom activities, and workshops, see: <http://CPEPweb.org>

**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**

***'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**

***'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**

***'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**

***'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**

***'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**

***'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**

***'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

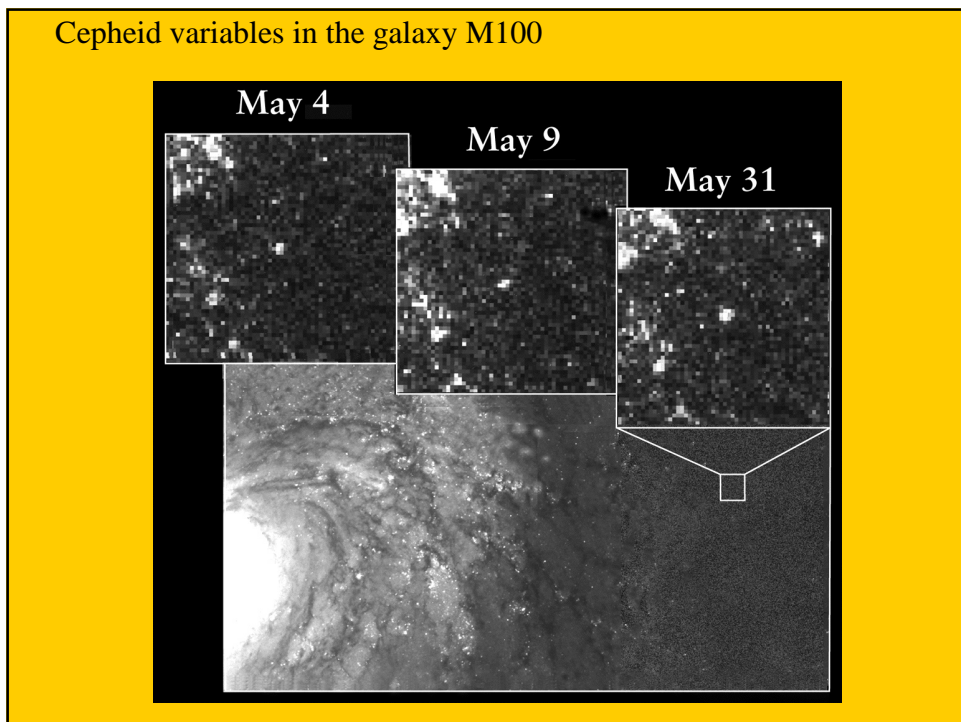
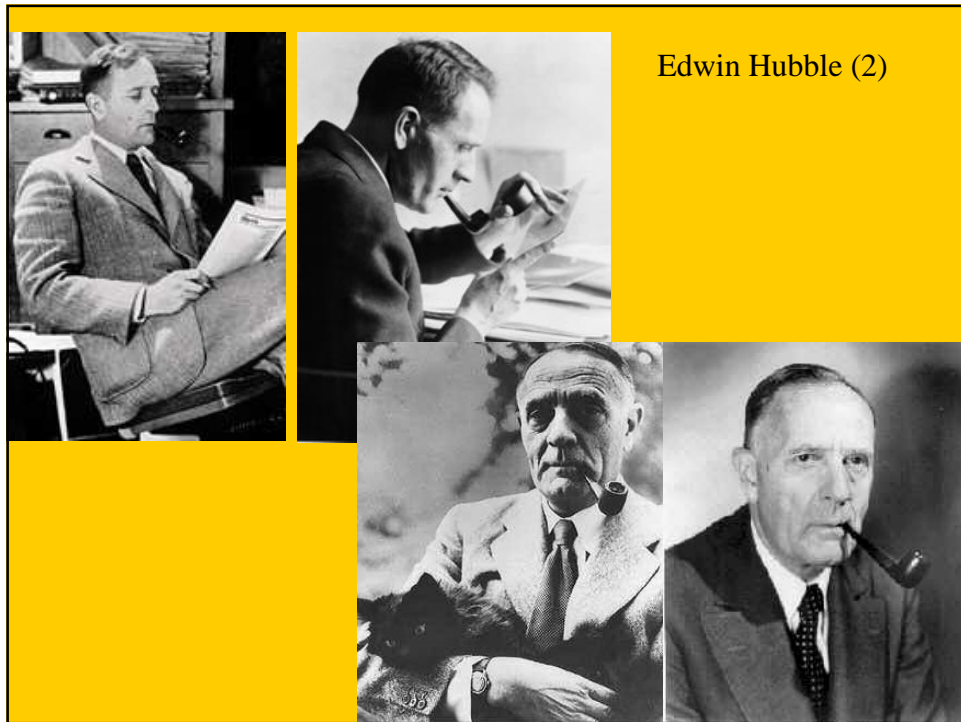
Rosse 70" 1.8-m telescope (Parsonstown, 1845)

M51 – the first galaxy recognized as having spiral structure

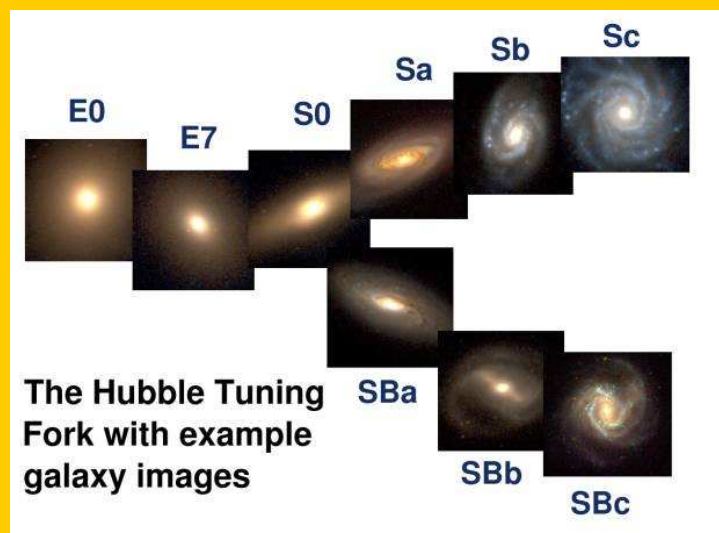
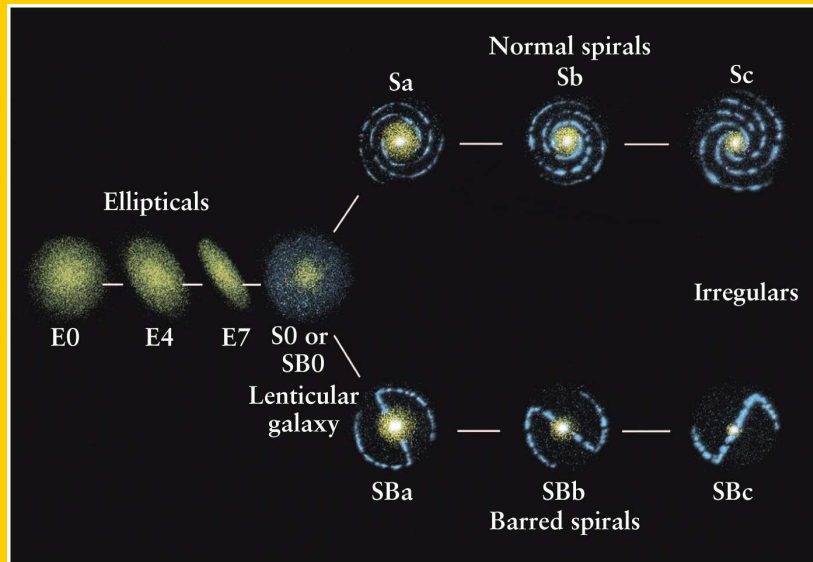


Edwin Hubble

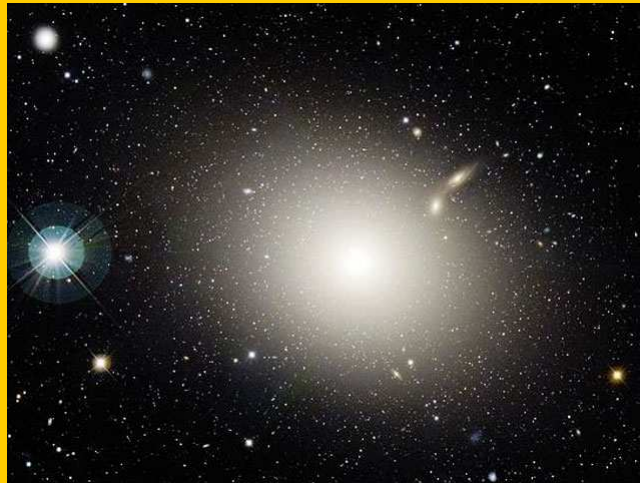




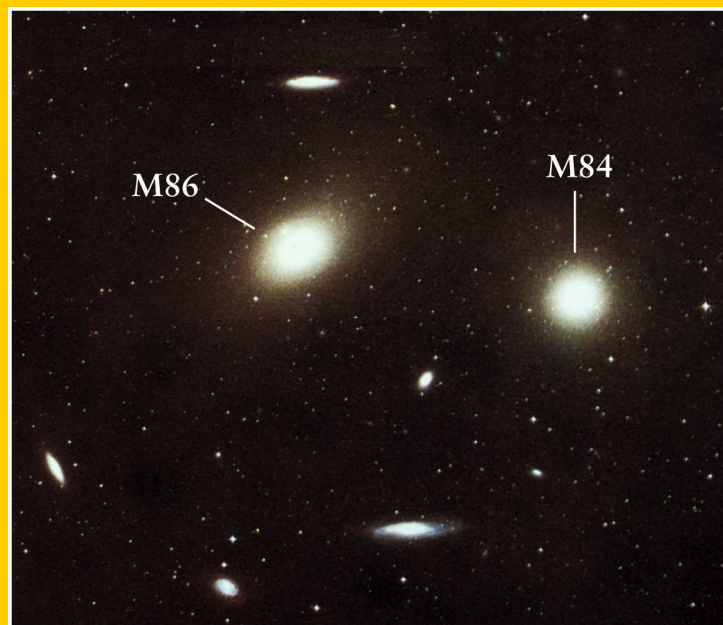
The Hubble 'tuning fork' diagram



An Elliptical Galaxy (with globular clusters)



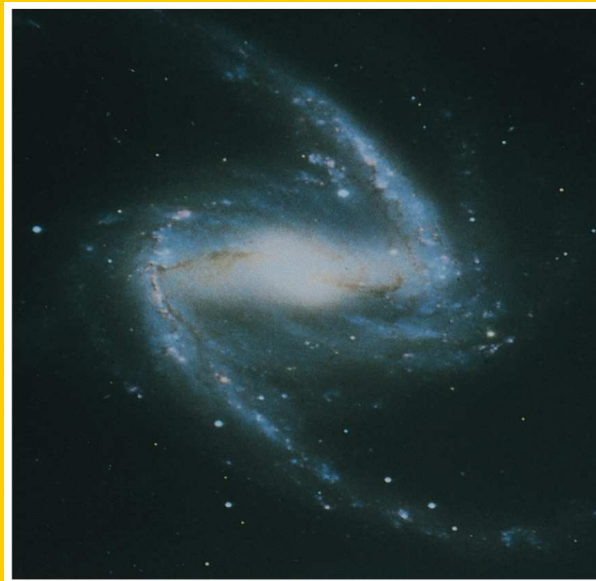
Virgo Cluster (with two giant ellipticals)



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 )

© European Southern Observatory







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

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

© European Southern Observatory



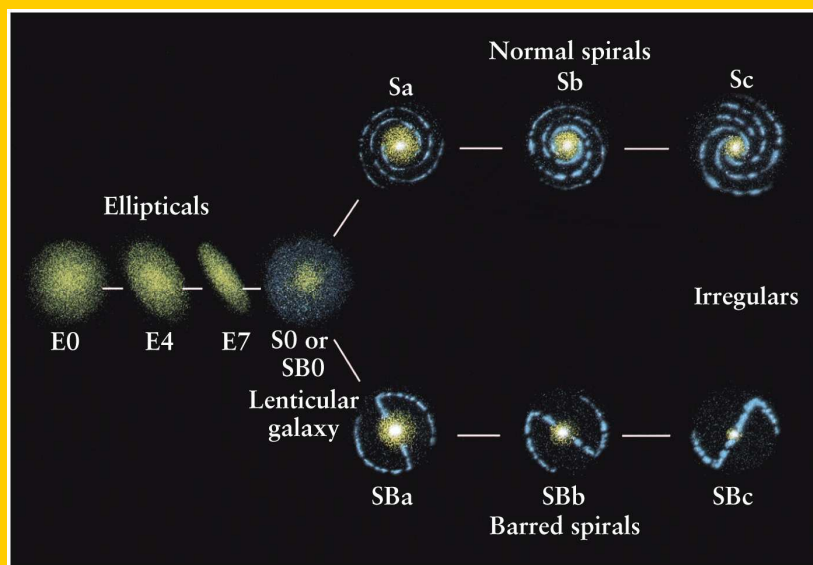
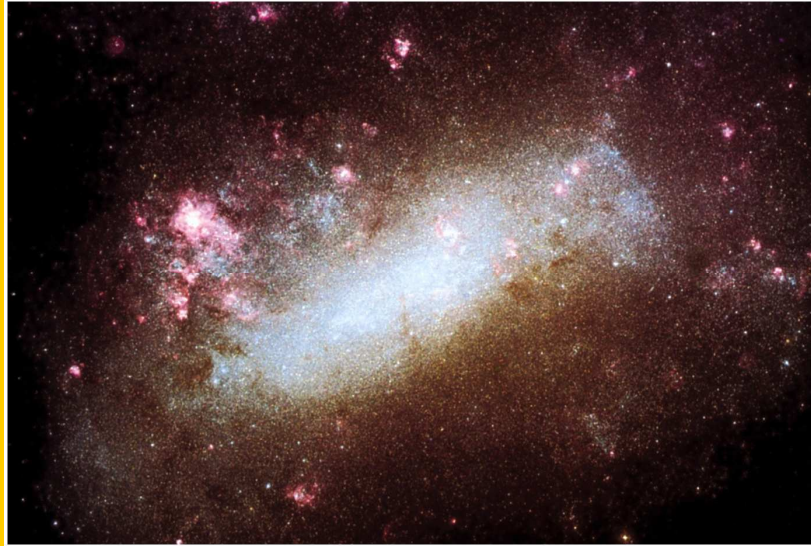
Spiral Galaxy NGC 4414



Hubble  
Heritage

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

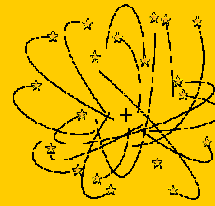
The Large Magellanic Cloud (LMC) – an irregular galaxy



## Normal Galaxies:

Hubble 'Tuning Fork' diagram for classification:

Elliptical galaxies (E0→E7) –  
red, structureless, old stars (Population II)  
dwarf & giant ellipticals

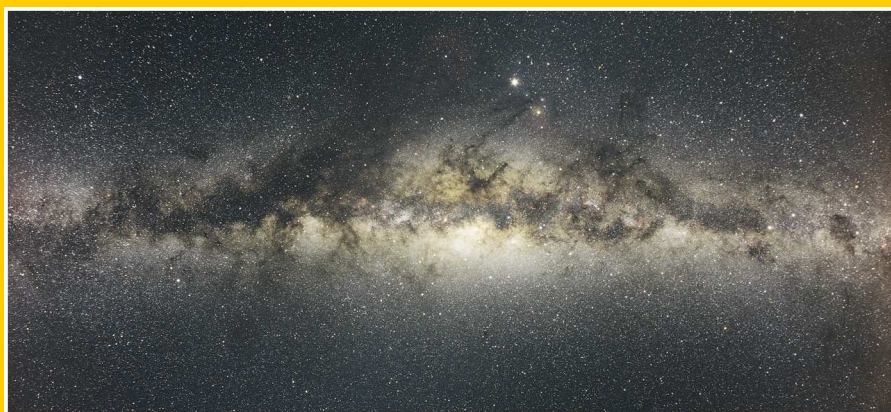


Spiral galaxies ('normal' S or SA + barred, SB; Sa→Sc or Sd) –  
discs with spiral structure picked out by young, blue stars  
(Population I)

+intermediate SO types – spiral galaxies with spiral arms  
+irregular galaxies

...our Galaxy:

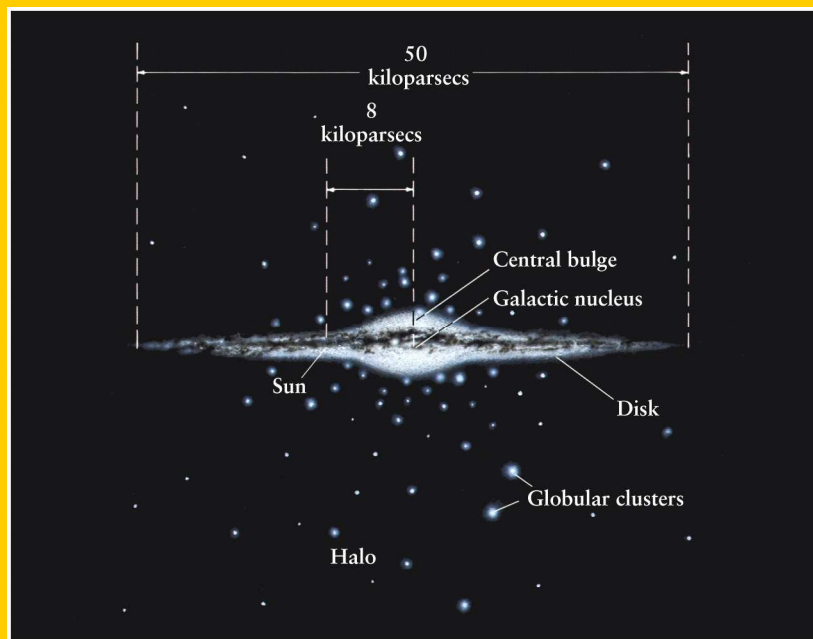
## The Milky Way Galaxy



For comparison, an edge-on spiral galaxy

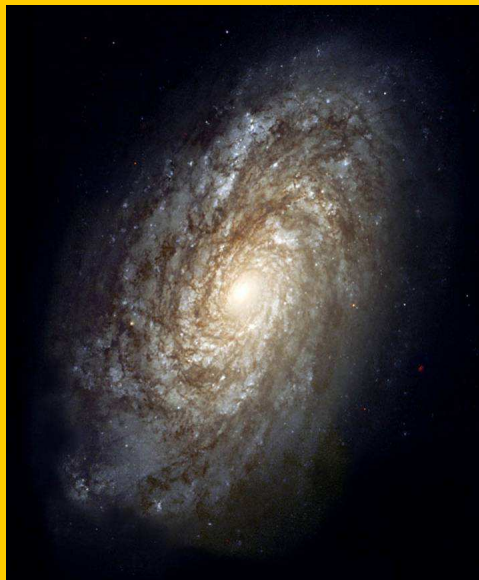


The structure of the Galaxy





The Galaxy according to Spitzer Space Telescope: an SBc spiral



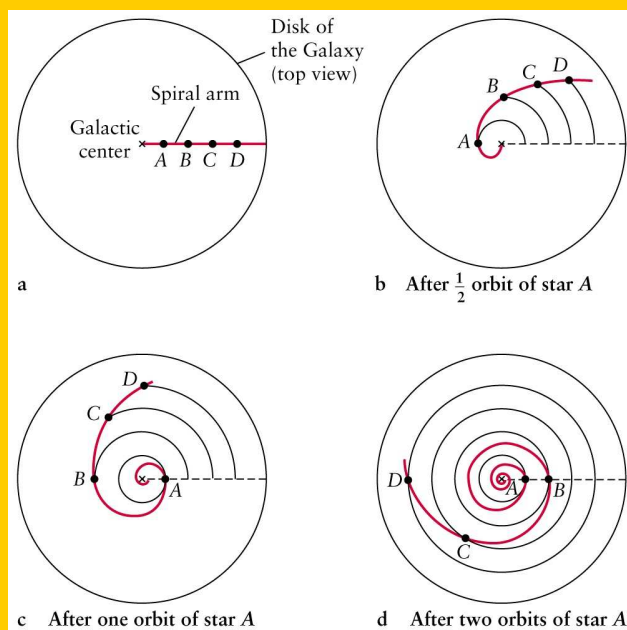
#### SPIRAL ARMS:

Which way do galaxies rotate?

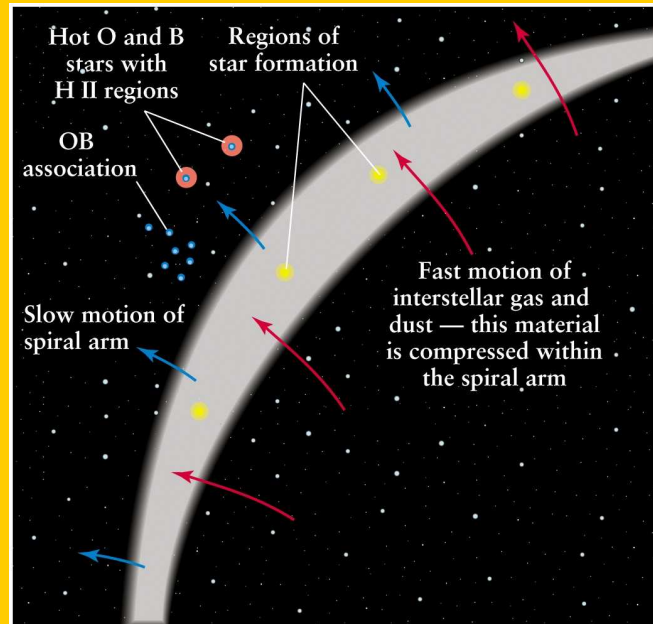
What is the nature of spiral arms?



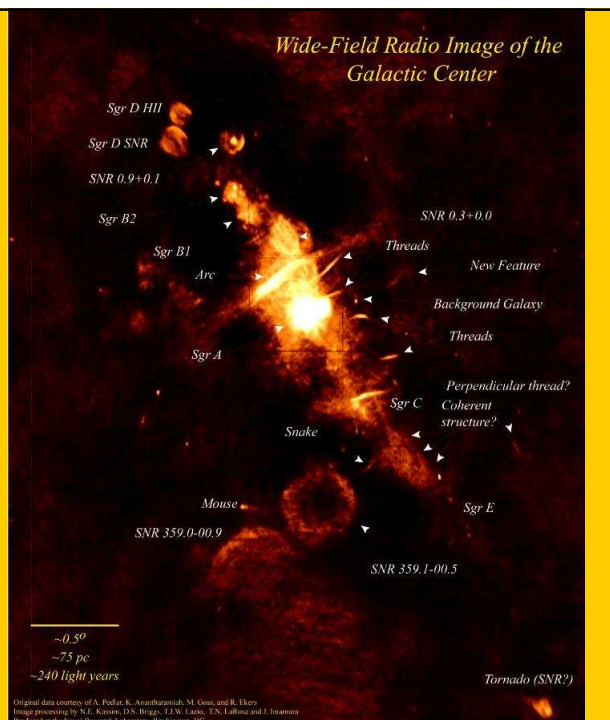
Spiral arms can't be fixed, permanent structures ('windmills')



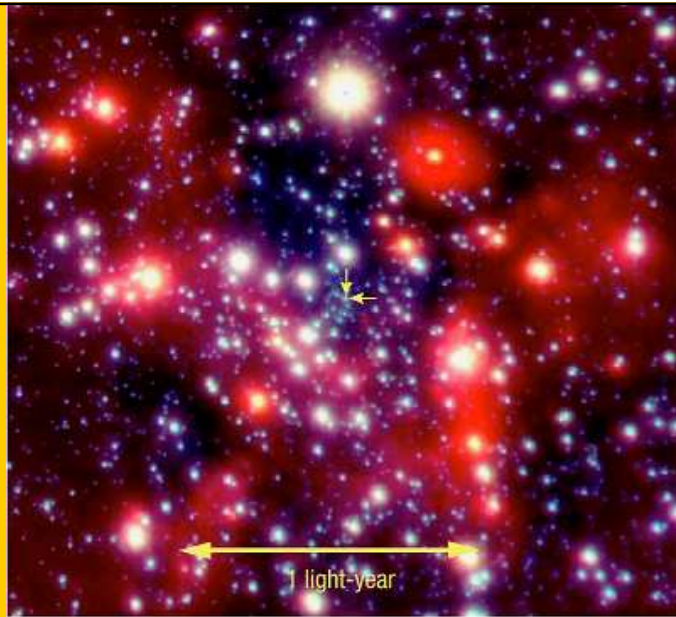
Spiral arms are a manifestation of *density waves*



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



Infrared  
view



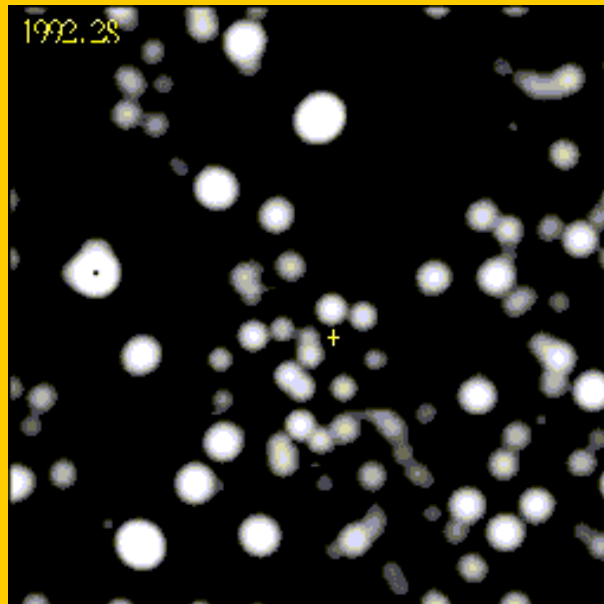
The Centre of the Milky Way  
(VLT YEPUN + NACO)

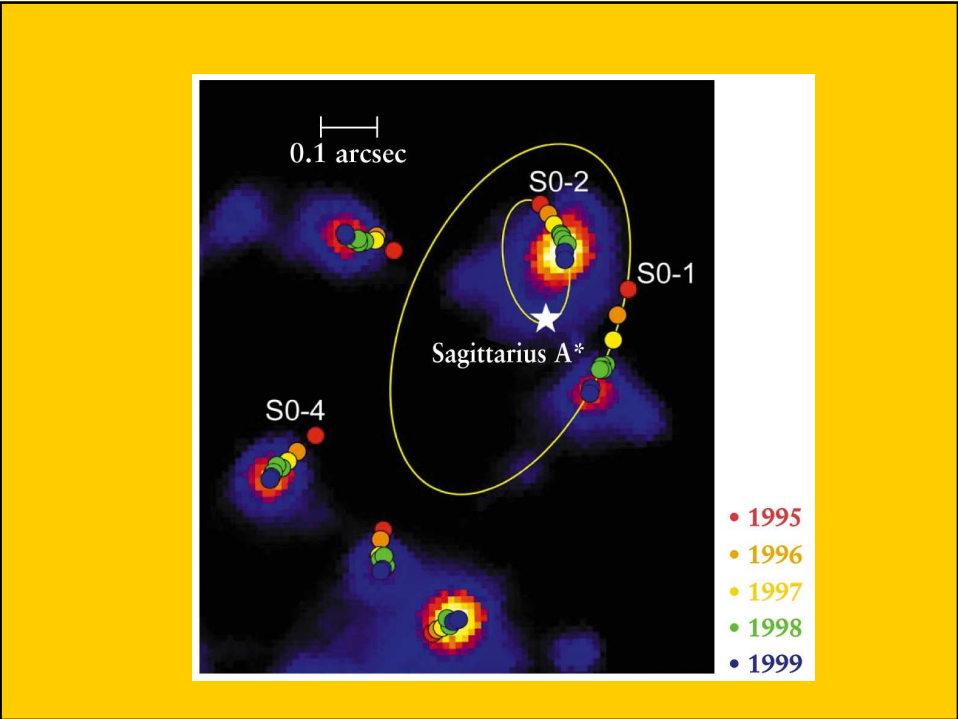
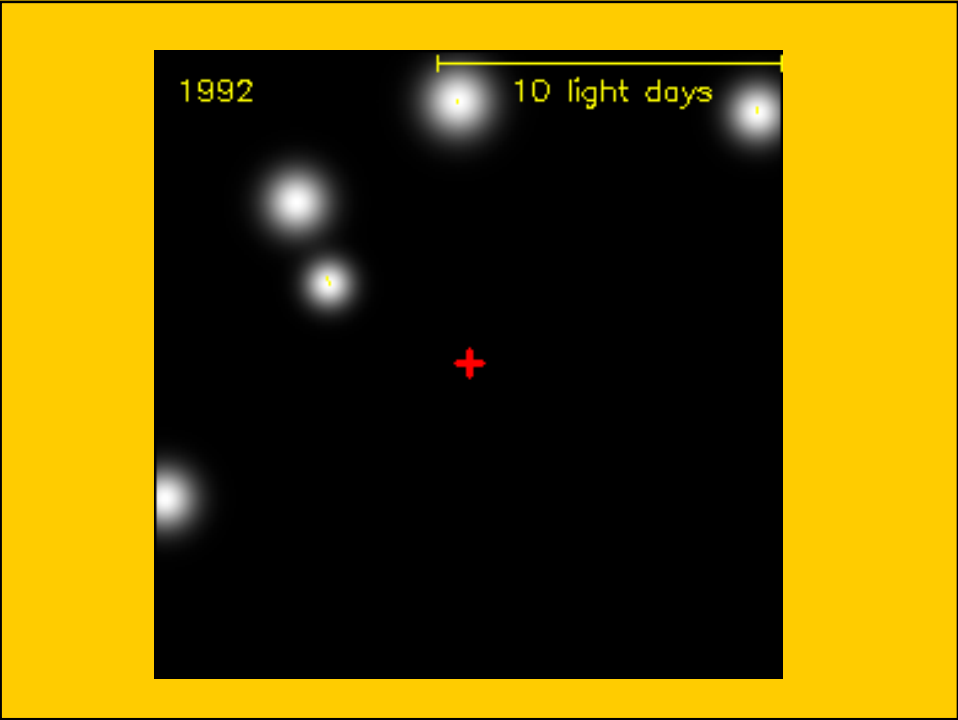
ESO PR Photo 23a/02 (9 October 2002)

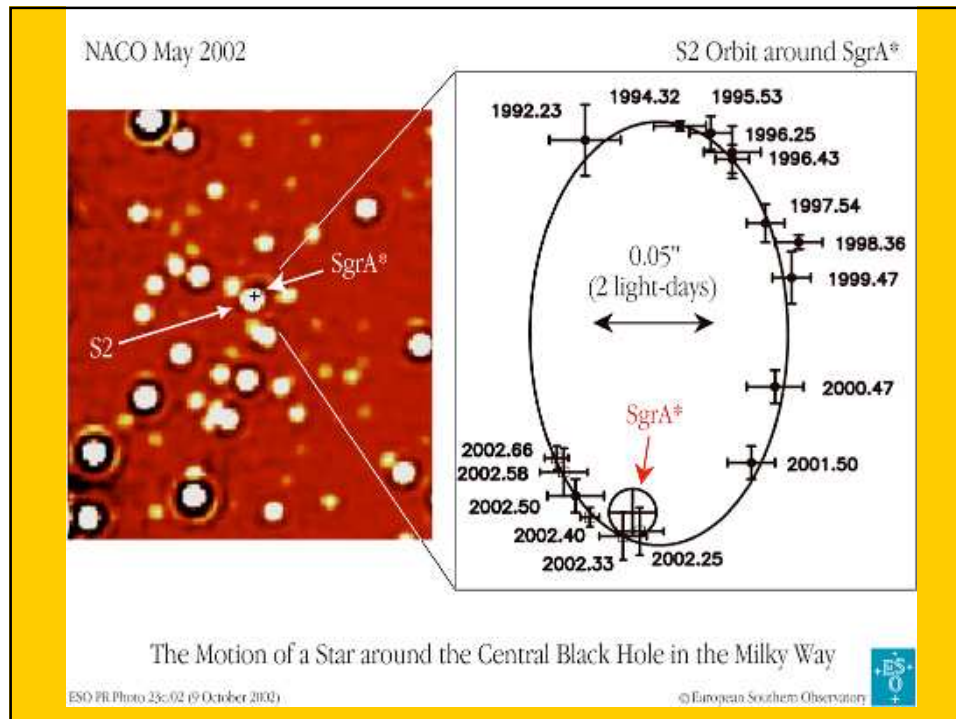
© European Southern Observatory



Stars at the core  
of the Galaxy







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

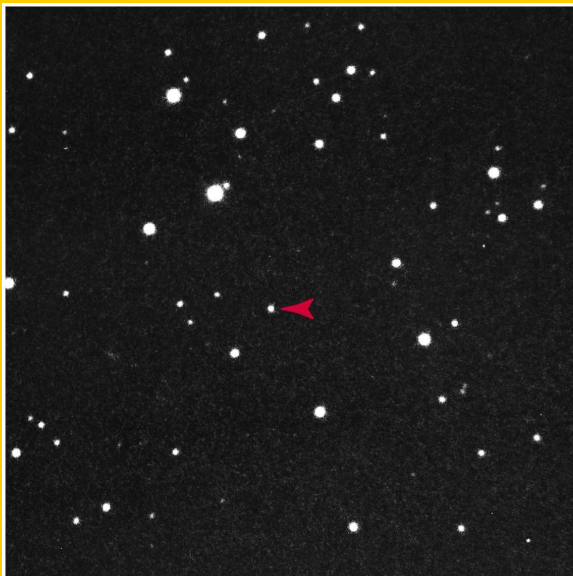
Seyferts, quasars, radio galaxies....blazars,  
liners, BL Lacs, etc



Seyfert galaxies  
(1943)

Nearly all have spiral  
galaxy 'hosts'

Starlike nuclei,  
emission-line  
spectra



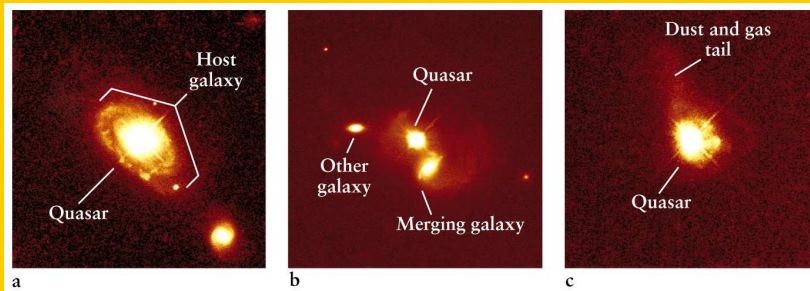
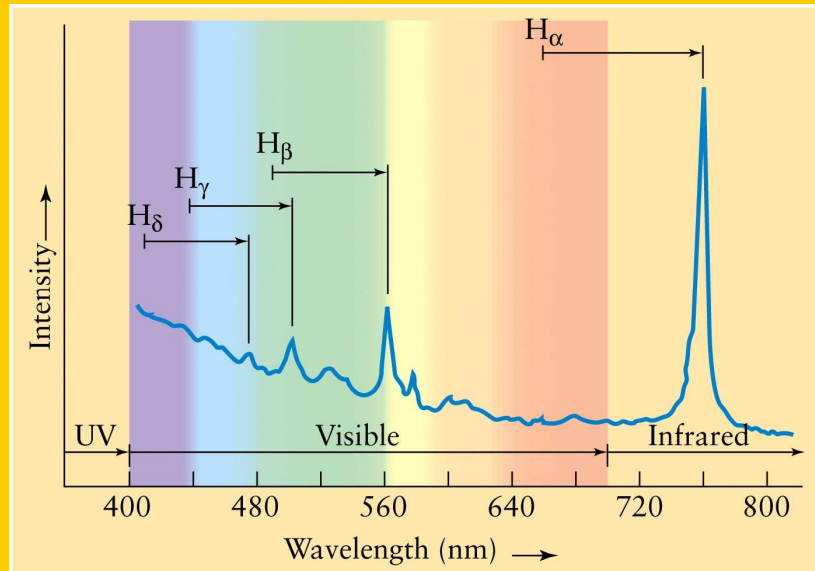
Quasars (QSOs)

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

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

3C48

Quasars show large *redshifts* of emission lines

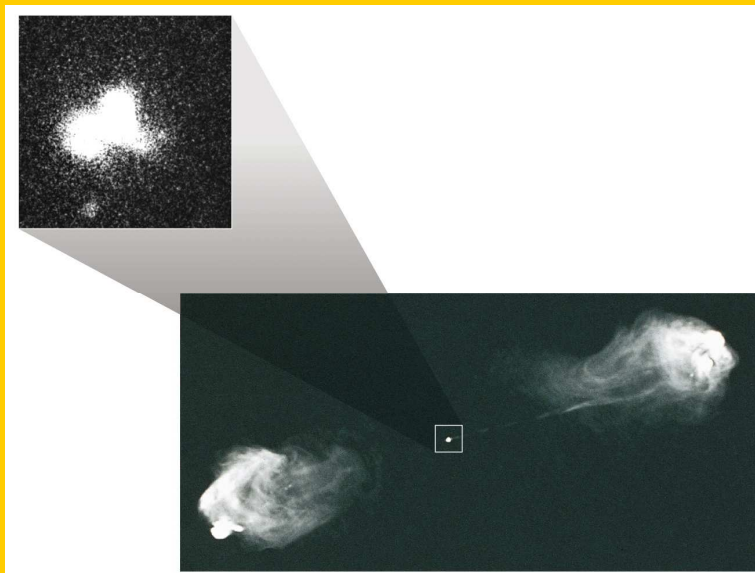
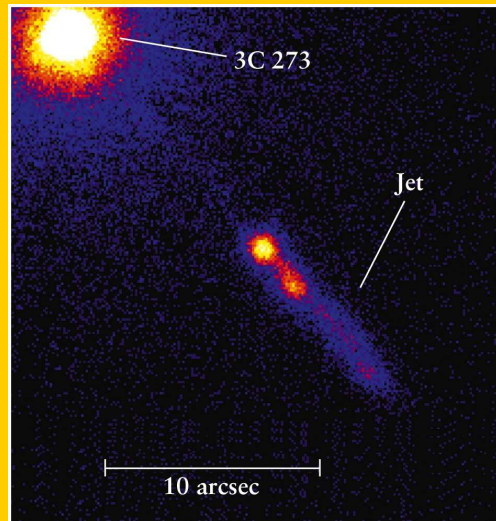


Quasars show ‘fuzz’ – they are AGN whose luminosity exceeds of the host galaxy

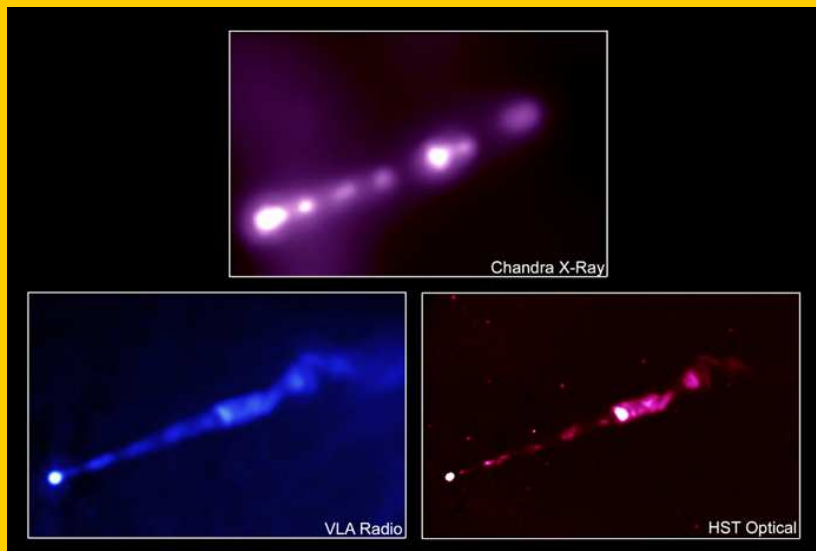
What can produce this large luminosity in a small volume?

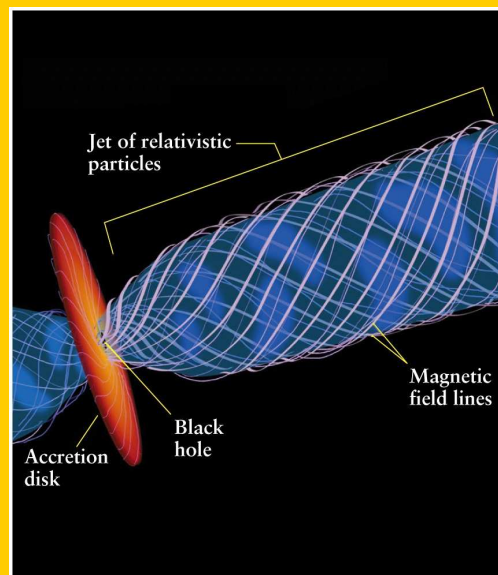
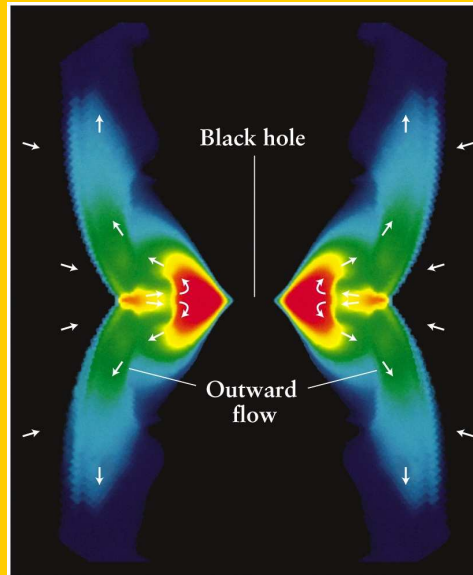
ACCRETION (10% efficiency, cp. <1% for fusion)

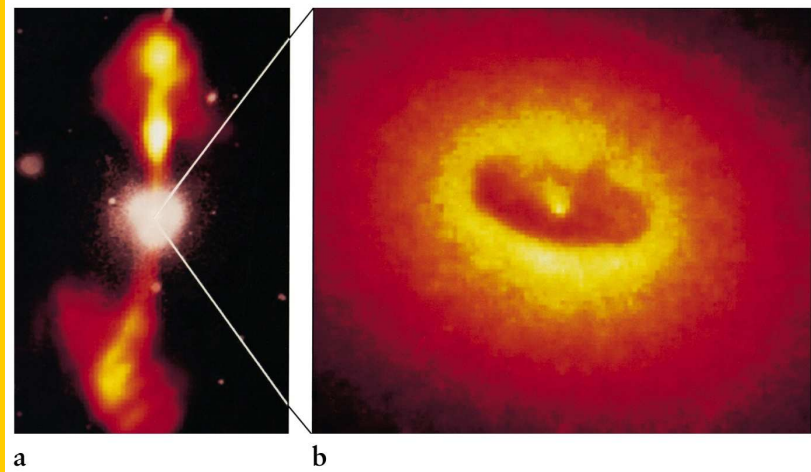
Active galaxies often show 'jets'



Cygnus A – radio galaxy



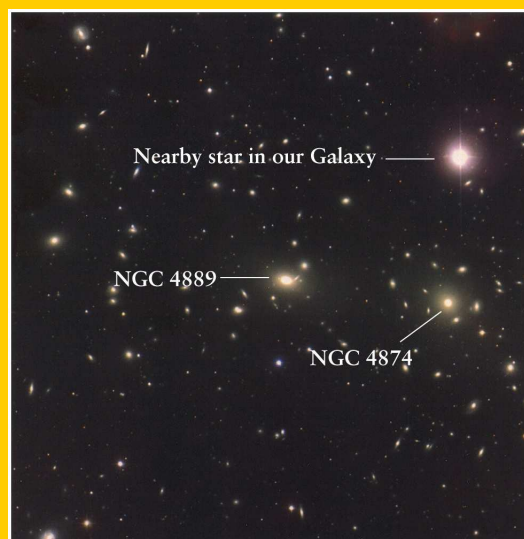




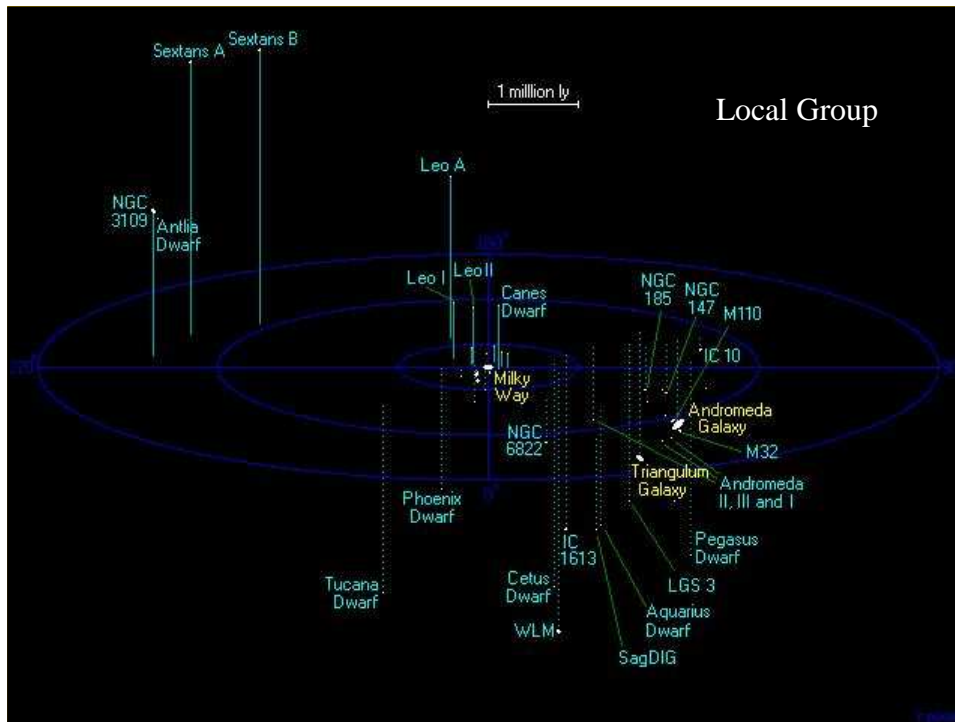
NGC 4261 left: optical+radio right: HST

## Clusters of Galaxies

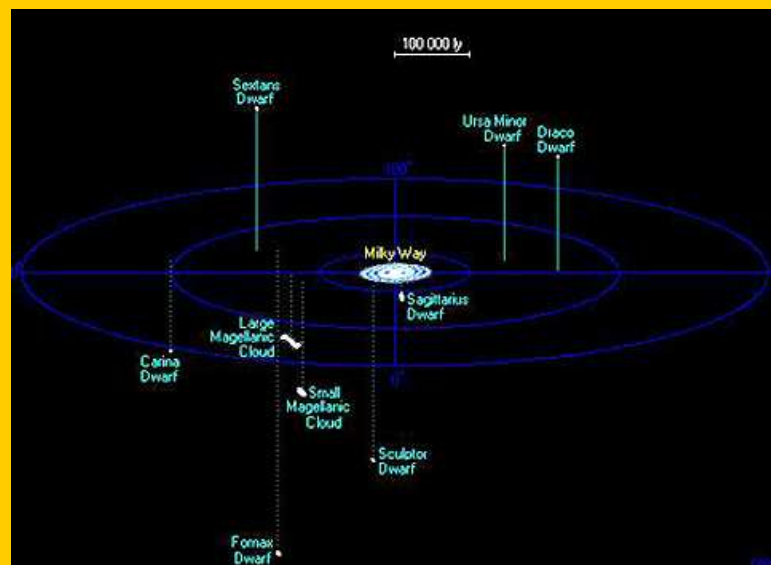
Galaxies are mostly found in groups, clusters, or superclusters



The Coma Cluster

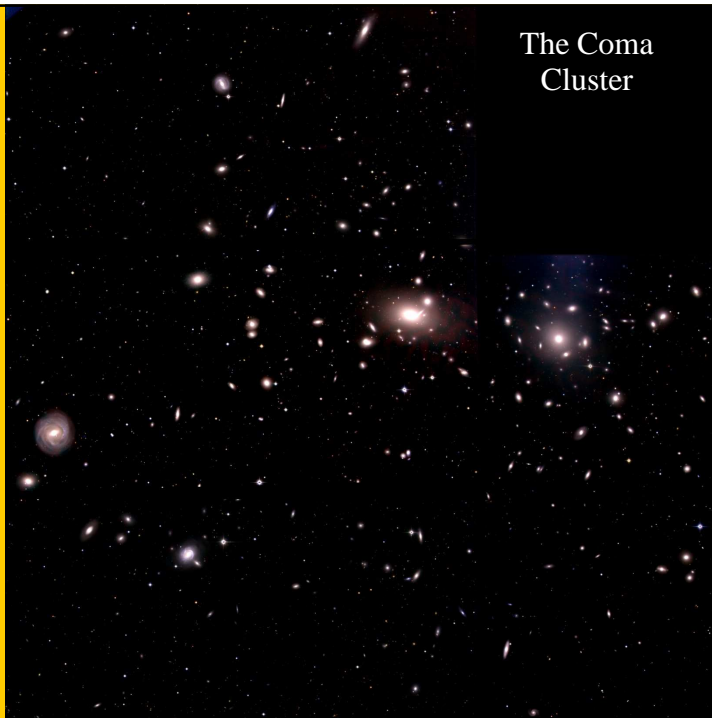


### The immediate environs of our own Galaxy





The centre of the Virgo cluster

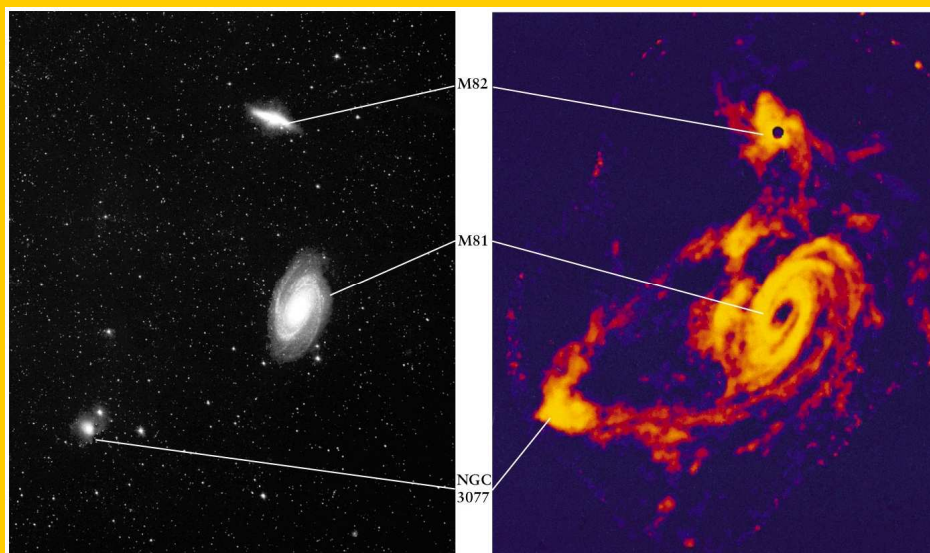


The Coma  
Cluster

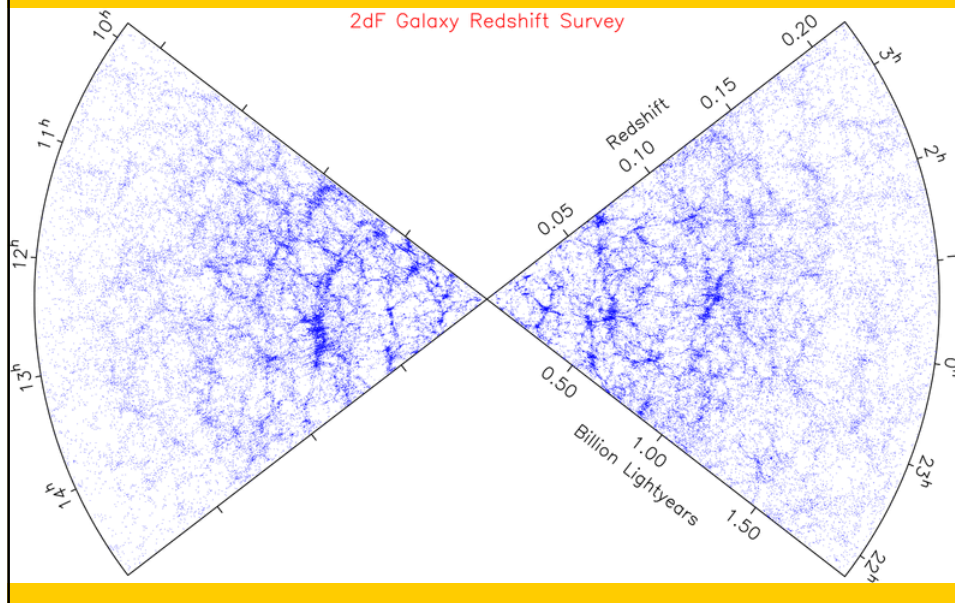


The Hercules Cluster – with interacting spiral galaxies

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

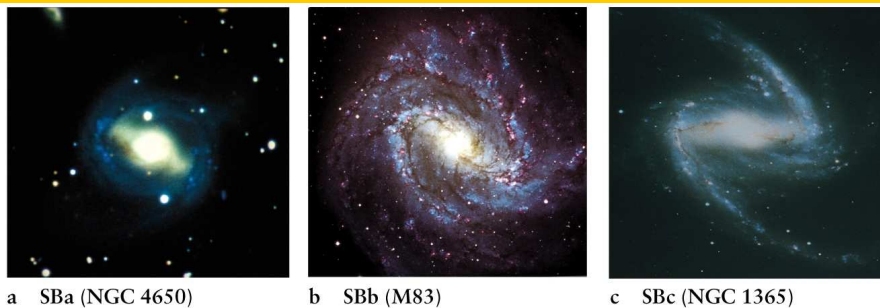


## Large-scale structure: ‘superclusters’

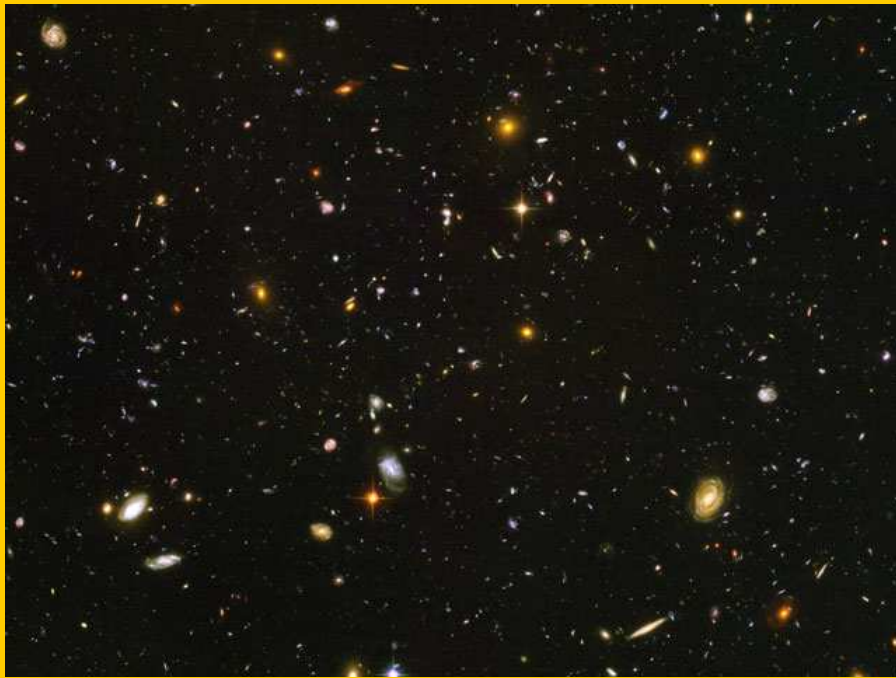


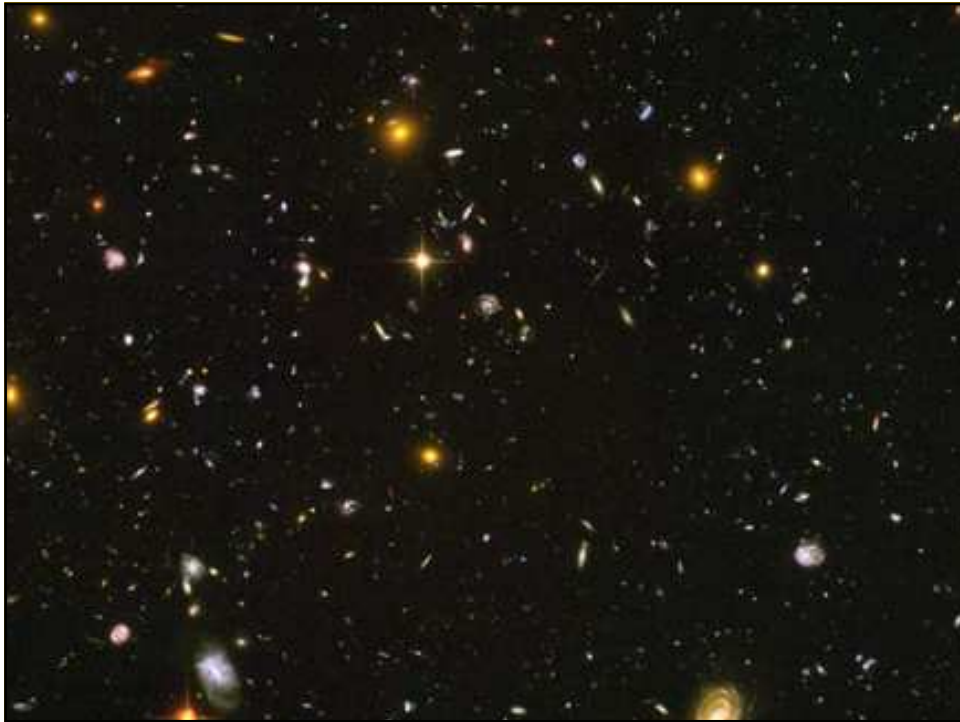
## Evolution of Galaxies

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

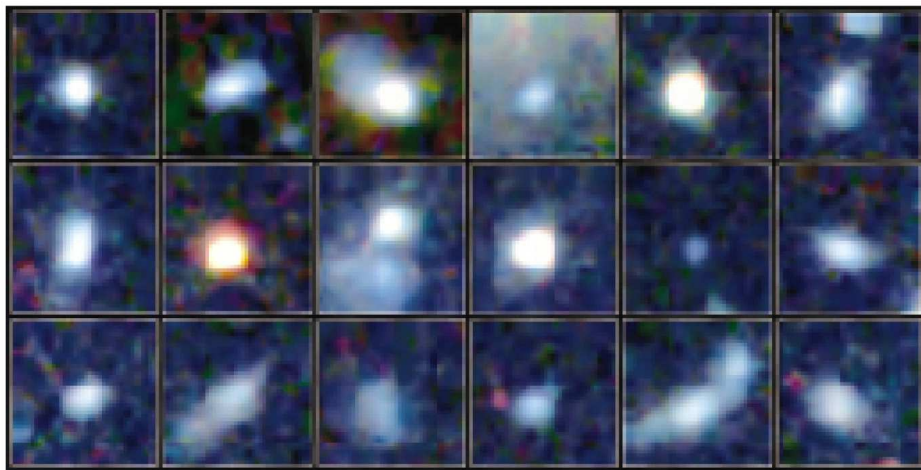


Or we can look at galaxies as they were in the past

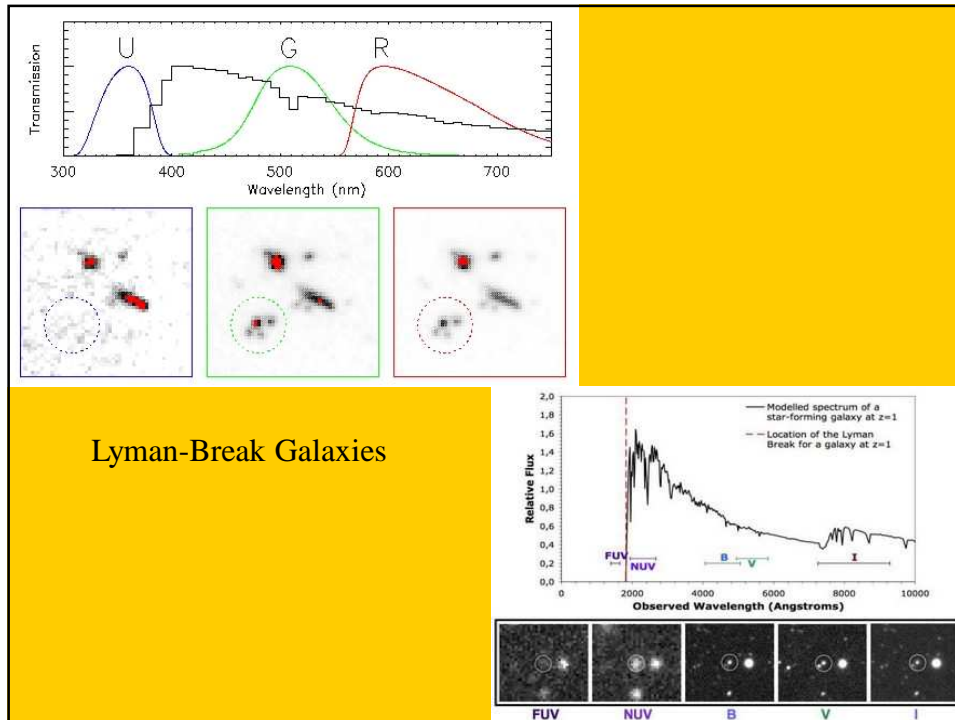




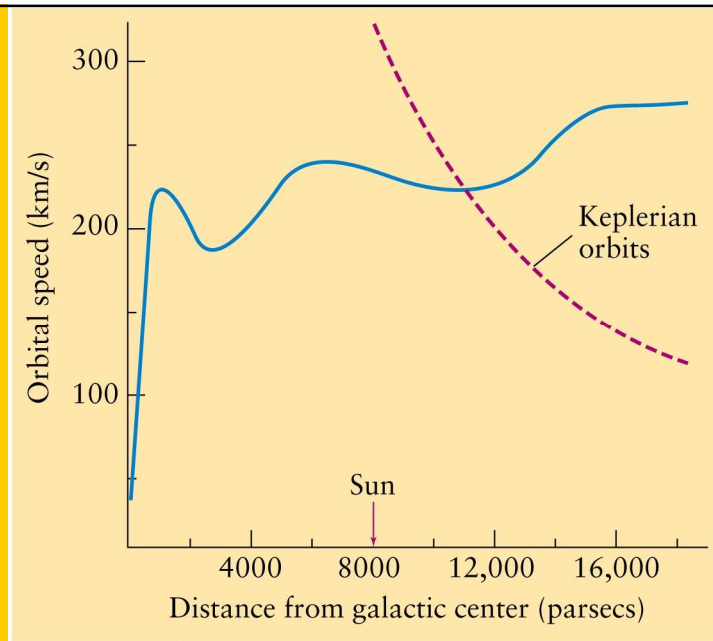
Galaxies in the distant universe (the past!) don't look like galaxies now



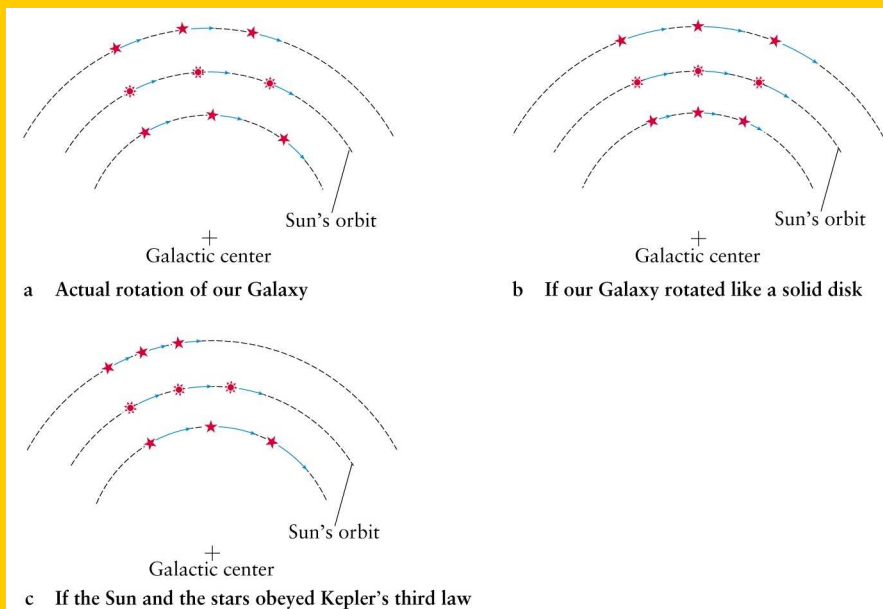
b

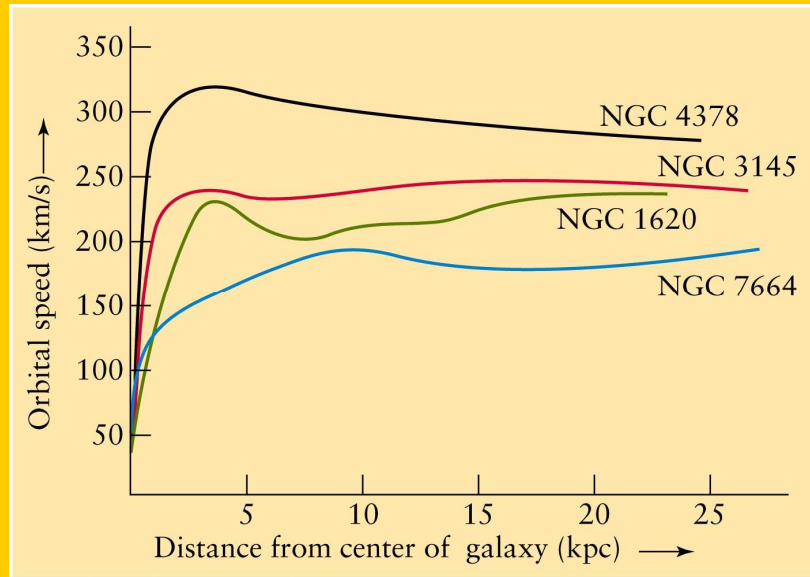


## Masses of Galaxies: Observational Evidence for Dark Matter



The *rotation curve* of our Galaxy





Dark matter is common in galaxies!!

Galaxy clusters → masses

Dynamics ('virial masses')

X-ray observations

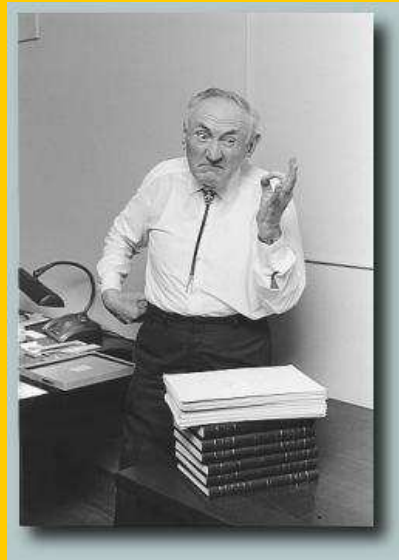
Gravitational lensing

## Virial Masses

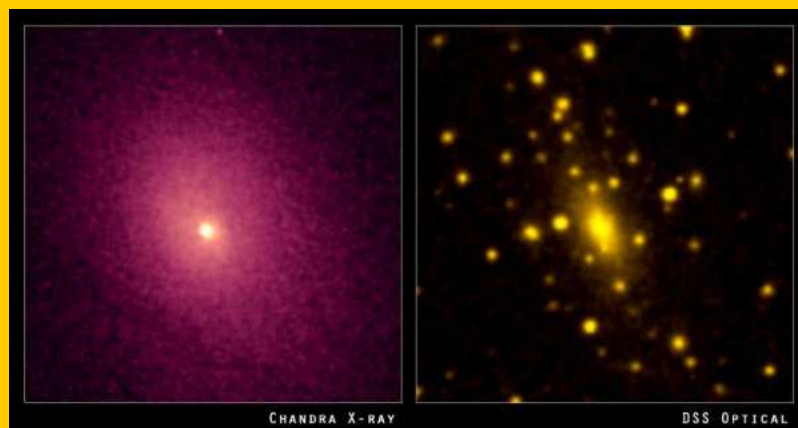


Scanned at the American  
Institute of Physics

Fritz Zwicky

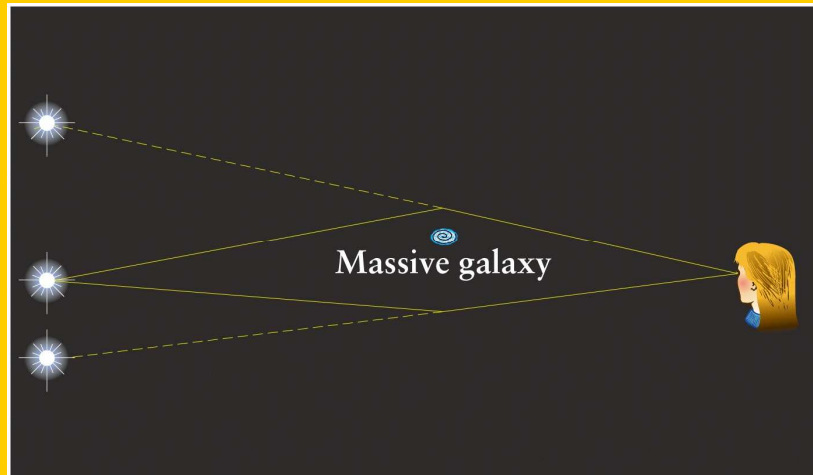


## X-ray observations



(Abell 2029)

## Gravitational Lensing



0024+1654

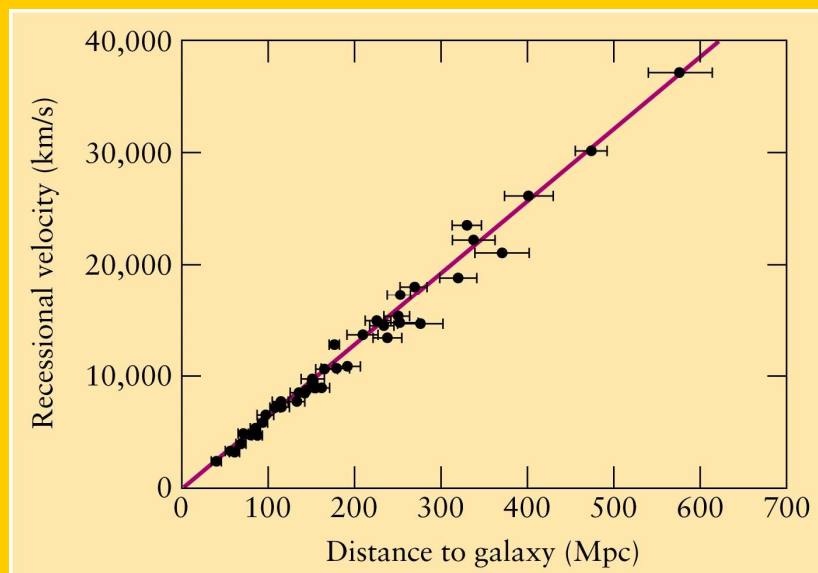
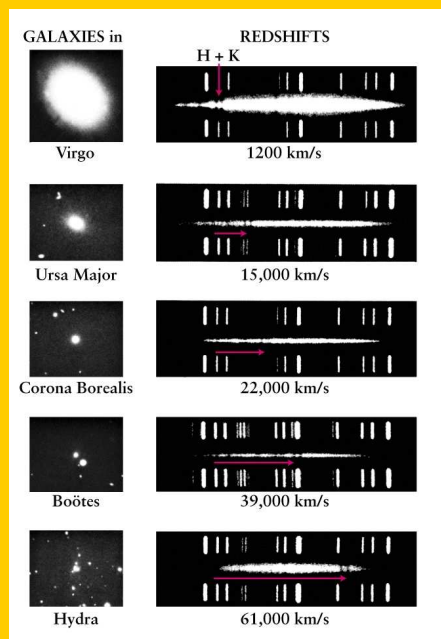


Abell 2218

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....



$$H_0 = 72 (\pm 5) \text{ km/s per Mpc}$$