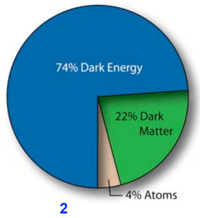
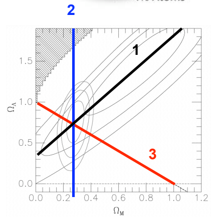
Dark Matter

Galaxy Counts
Redshift Surveys
Galaxy Rotation Curves
Cluster Dynamics
Gravitational Lenses

$$\Omega_M \sim 0.3$$

$$\Omega_b \approx 0.04$$





Mass Density by Direct Counting

- Add up the mass of all the galaxies per unit volume
  - Volume calculation as in Tutorial problem.
- Need representative volume > 100 Mpc.
- Can't see faintest galaxies at large distance.
  Use local Luminosity Functions to include fainter ones.
- Mass/Light ratio depends on type of galaxy.
- Dark Matter needed to bind Galaxies and Galaxy Clusters dominates the normal matter (baryons).
- Hot x-ray gas dominates the baryon mass of Galaxy Clusters.

Galaxy Redshift Surveys

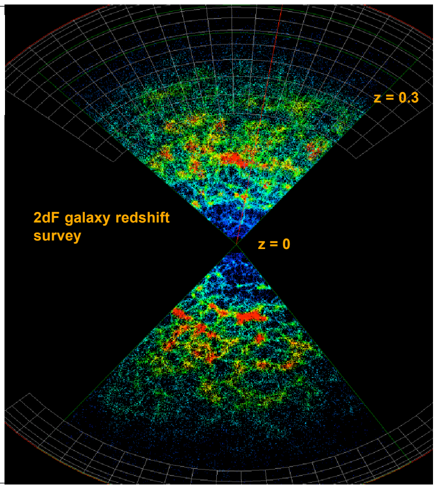
Large Scale Structure:

Empty **voids**

~50Mpc.

Galaxies are in
1. **Walls** between voids.
2. **Filaments** where walls intersect.
3. **Clusters** where filaments intersect.

Like Soap Bubbles !

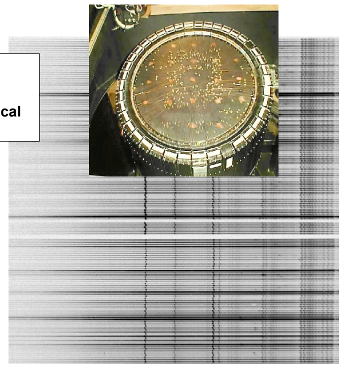


2dF fibre-fed spectrograph for the 4m Anglo-Australian Telescope

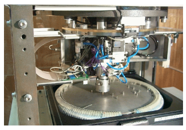
2dF = 2 degree Field

400 spectra in parallel

robotic positioner places magnetic buttons holding optical fibres at galaxy positions



6dF under construction



Galaxy Counts

Galaxies per mag per square degree

Reference models:
$\Omega_M = 1 \quad \Omega_\Lambda = 0$
no galaxy evoloution

Butcher-Oemler effect: Faint blue galaxies: more than expected.

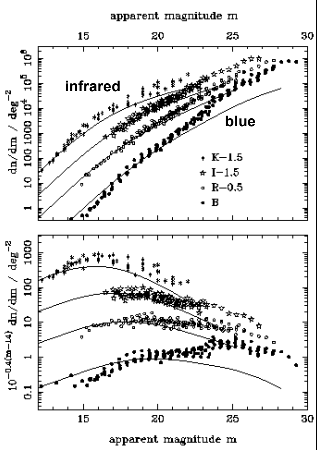
Young galaxies are blue.

so

More young galaxies in the past.

and / or

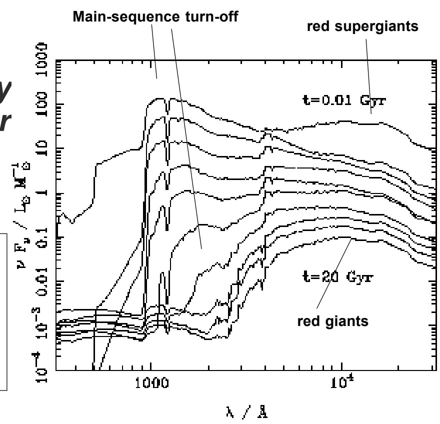
Young galaxies are small.



Galaxy Luminosity and Colour Evolves

Charlot & Bruzual models.

Add up star spectra using stellar evolution models and stellar IMF.



Schechter Luminosity Function

3 Schechter parameters:

$\alpha \quad L^* \quad \Phi^*$

luminosity of a typical big galaxy

$L^* \approx 10^{11}\ \mathrm{L_{sun}}$

luminosity of any galaxy:

$L = x\,L^* \qquad x = \dfrac{L}{L^*}$

number of galaxies per unit luminosity

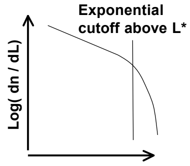
$\Phi(x) = \dfrac{dn}{dx} = \Phi^*\,x^\alpha\,e^{-x}$

add up the luminosities

$\rho_L = \int_0^\infty L\,\dfrac{dn}{dx}\,dx = L^*\Phi^*\int_0^\infty x^{\alpha+1}\,e^{-x}\,dx$

add up the mass (need mass/light ratio)

$\rho_M = \int_0^\infty \dfrac{M}{L}\,L\,\dfrac{dn}{dx}\,dx = \left\langle \dfrac{M}{L} \right\rangle \rho_L$



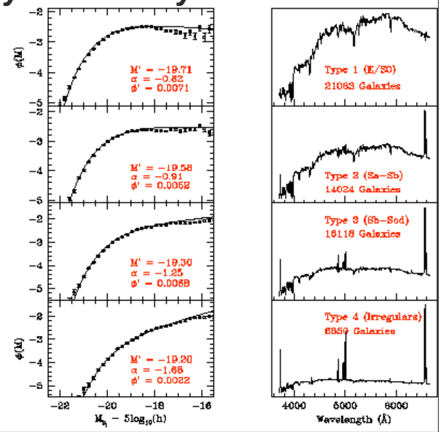
Measure Schechter parameters using:
- galaxy clusters
- galaxy redshift surveys

Measure M/L for :

Nearby galaxies, galaxy clusters

Galaxy Luminosity Function

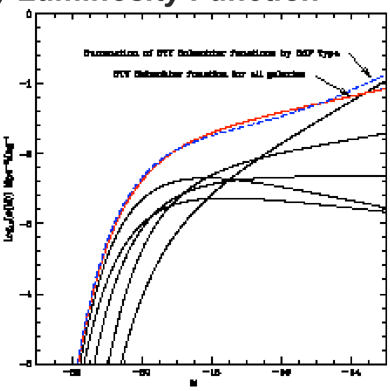
Schechter parameters depend on galaxy type.



Galaxy Luminosity Function

Schechter function also fits sum of all galaxy types.

But each type has a different M/L.



Galaxy Rotation Curves

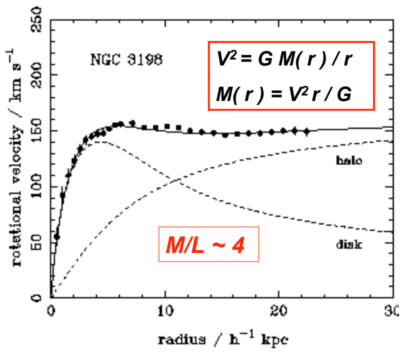
HI velocities

Flat rotation curves

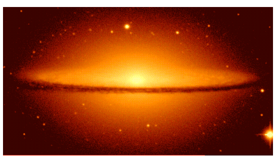
Dark Matter Halos

Spirals, Ellipticals: **M/L~4-10**

Some dwarf galaxies: **M/L ~ 100.**

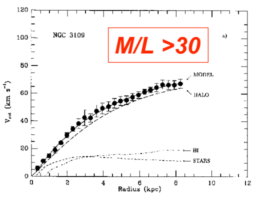


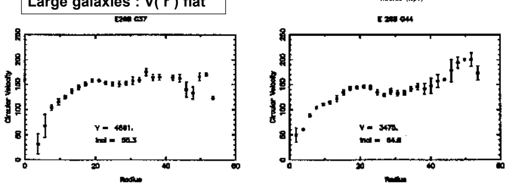
Galaxy Rotation Curves



Small galaxies : V(r) rises

Large galaxies : V(r) flat





Mass / Light ratios

galaxy luminosity distribution

$$\frac{dn}{dL} = \Phi(L) = \Phi^*\left(\frac{L}{L^*}\right)^\alpha \exp\left(-\frac{L}{L^*}\right)$$

luminosity density $\rho_L = \int L\,\Phi(L)\,dL$

e.g. blue light $\approx 2 \pm 0.7\times 10^8\,h\,L_{sun}\ \mathrm{Mpc}^{-3}$

mass density $\rho_M = \int \left(\dfrac{M}{L}\right) L\,\Phi(L)\,dL$

$$= \Omega_M\,\rho_{crit} = 2.8\times 10^{11}\,\Omega_M\,h^2\,M_{sun}\ \mathrm{Mpc}^{-3}$$

Universe:	$M/L = 1400\,\Omega_M\,h^2 \sim 200\,(\Omega_M/0.3)(h/0.7)^2$
Sun:	$M/L = 1$ (by definition)
main sequence stars:	$M/L \propto M^{-3}$ (since $L \propto M^4$)
comets, planets:	$M/L \sim 10^{9-12}$

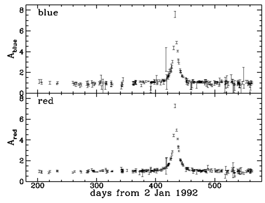
Is our Dark Matter halo filled with MACHOs ?

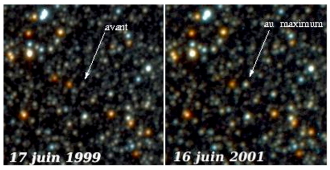
NO. Gravitational Lensing results rule them out.

Dark Matter Candidates

- **MACHOS = Massive Compact Halo Objects**
  - Black holes
  - Brown Dwarfs
  - Loose planets
  - Ruled out by gravitational lensing experiments.
- **WIMPS = Weakly Interacting Massive Particles**
  - Massive neutrinos
  - Supersymmetry partners
  - Might be found soon by Large Hadron Collider in CERN

Microlensing in the LMC

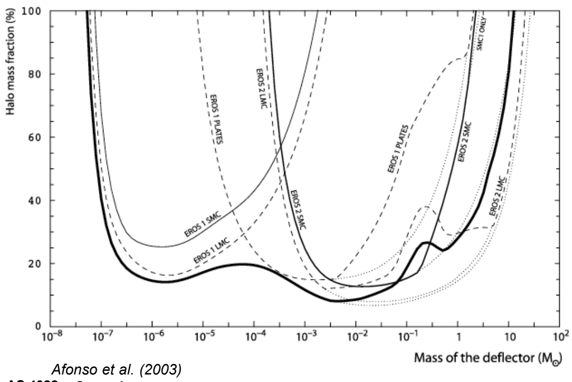




Massive Compace Halo Objects (MACHOS) would magnify LMC stars dozens of times each year. Only a few are seen.

Long events -> high mass
Short events -> low mass

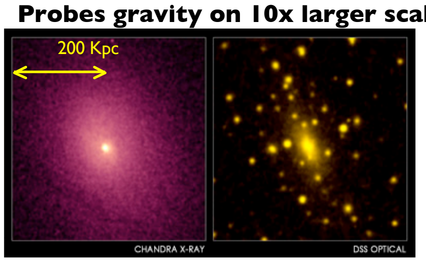
LMC Microlensing says NO to MACHOs



Afonso et al. (2003)

Dark Matter in Galaxy Clusters

Probes gravity on 10x larger scales



$$z = 0.0767$$

$$d \approx \frac{c\,z}{H_0} = 320 \text{ Mpc}$$

Chandra X-ray Image of Abell 2029

The galaxy cluster Abell 2029 is composed of thousands of galaxies enveloped in a gigantic cloud of hot gas, and an amount of **dark matter** equivalent to more than **a hundred trillion Suns**. At the center of this cluster is an enormous, elliptically shaped galaxy that is thought to have been formed from the mergers of many smaller galaxies.

Cluster Masses from X-ray Gas

hydrostatic equilibrium:

$$\frac{dP}{dr} = -\rho\, g = -\rho\, \frac{G\, M(<r)}{r^2}$$

gas law:

$$P = \frac{\rho\, k\, T}{\mu\, m_H}$$

X-ray emission from gas gives: $T(r),\ n_e(r) \rightarrow \rho(r), P(r)$

$$M(<r) = -\frac{r^2}{G\,\rho(r)}\frac{dP}{dr}$$

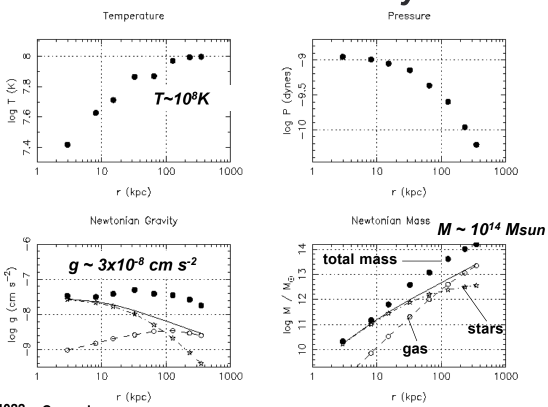
Coma Cluster:

M(gas)~M(stars)~3x10^{13} Msun

often M(gas) > M(stars)

M/L~100-200

Cluster Masses from X-ray Gas

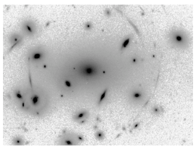


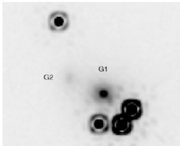
Masses from Gravitational Lensing

$$\theta_E = \frac{R_E}{D_L} = \left(\frac{4\,G\,M}{c^2} \frac{D_{LS}}{D_L D_S} \right)^{1/2}$$

$$\frac{M}{10^{11} M_{sun}} = \frac{D_L D_S / D_{LS}}{\mathrm{Gpc}} \left(\frac{\theta_E}{\mathrm{arcsec}} \right)^2$$

Use redshifts, z_L, z_S,
for the angular diameter distances.





General agreement with Virial Masses.

Evidence for Dark Matter ?

Galaxies: *(r ~ 20 Kpc)*

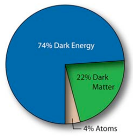
Flat Rotation Curves *V* ~ 200 km/s

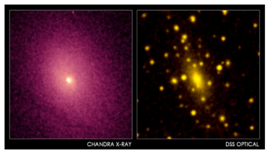
Galaxy Clusters: *(r ~ 200 Kpc)*

Galaxy velocities *V* ~ 1000 km/s

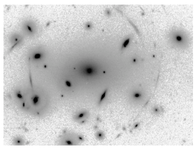
X-ray Gas *T* ~ 10^8 K

Giant Arcs



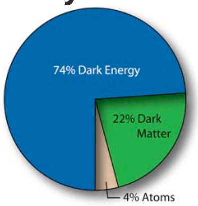


X-ray **Optical**



Or …. Has General Relativity Failed ?

~4% Normal Matter
~22% "Dark Matter" ?
~74% "Dark Energy" ?



Can *Alternative Gravity* Models
fit all the data without 2 miracles ?
(Dark Matter, Dark Energy)

MOND and TeVeS

MOdified **N**ewtonian **D**ynamics:

MOND acceleration parameter:
$a_0 \sim 2 \times 10^{-8}\,\mathrm{cm\ s^{-2}}$

Milgrom 1983 …

$$g \Rightarrow \begin{cases} g_N & g_N > a_0 \\ (g_N\, a_0)^{1/2} & g_N < a_0 \end{cases} \qquad V^2 = g\,r \Rightarrow \begin{cases} GM/r & g_N > a_0 \\ (G\,M\,a_0)^{1/2} & g_N < a_0 \end{cases}$$

Tensor **V**ector **S**calar:

MOND gives flat rotation curves V(r) ~ const and Tully-Fischer : $V^4 \sim M$

Bekenstein 2004 …

Covariant metric gravity theory that
reduces to MOND in weak-field low-velocity limit.