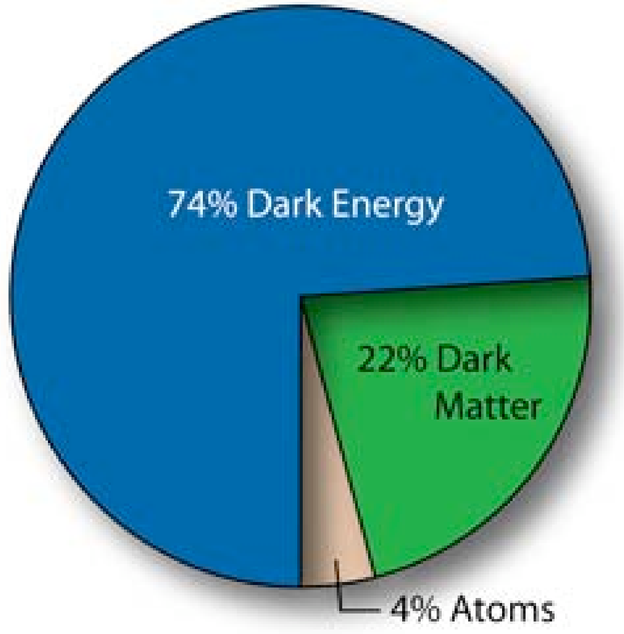
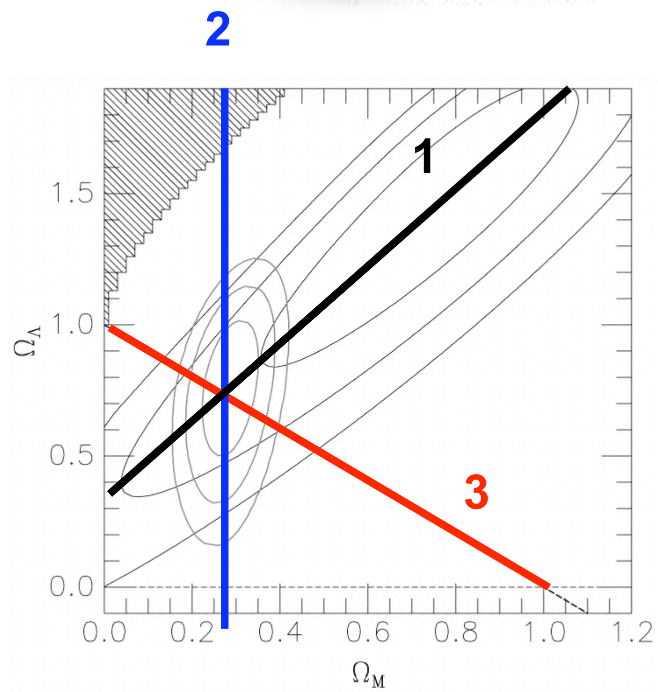
Dark Matter

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**

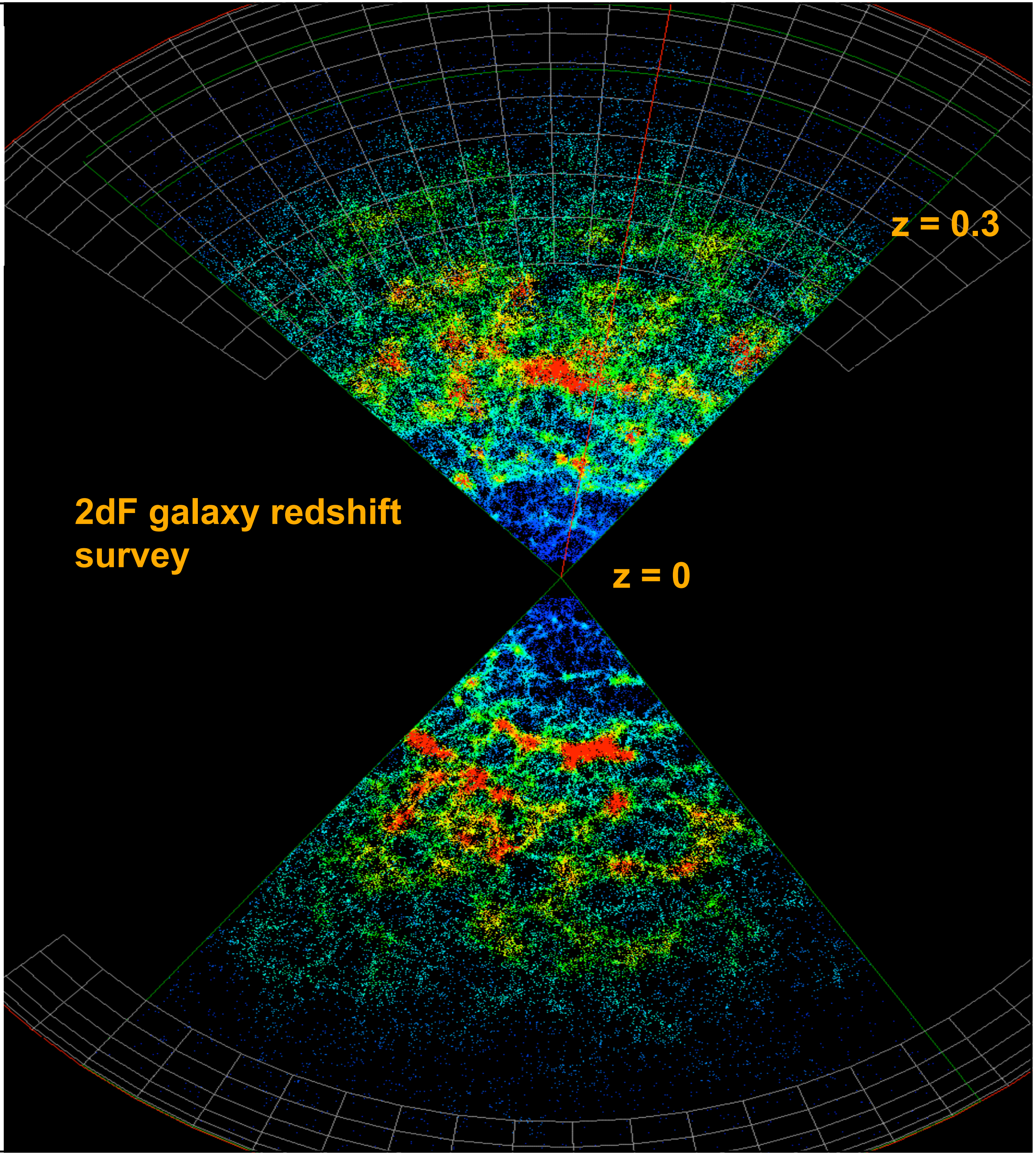
~50Mpc.

Galaxies are in
1. **Walls** between voids.

2. **Filaments** where walls intersect.

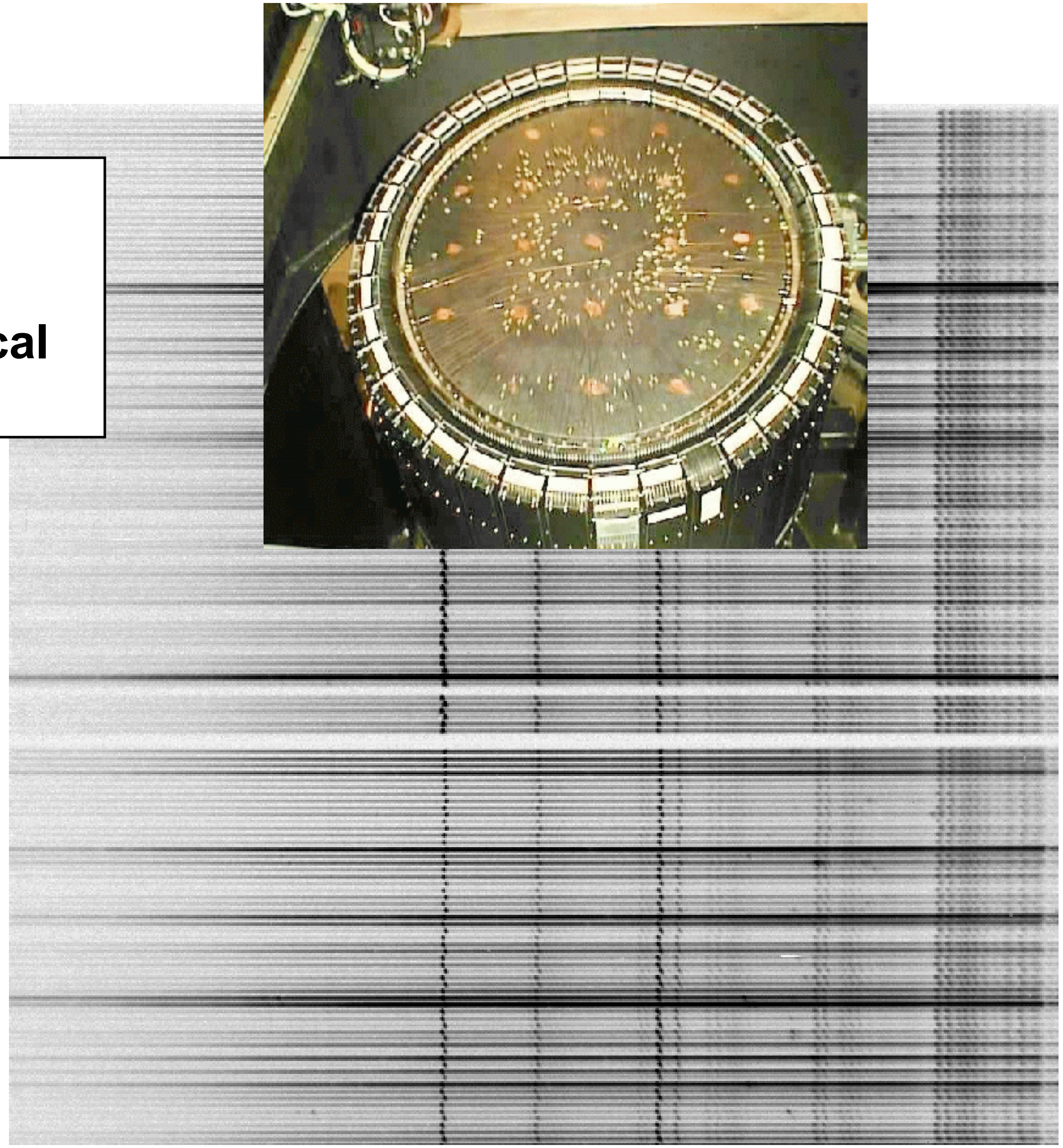
3. **Clusters** where filaments intersect.

Like Soap Bubbles !



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

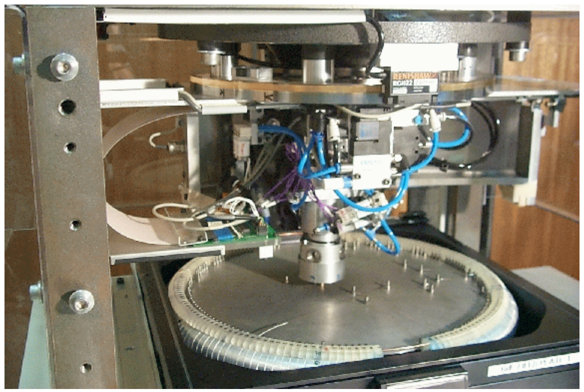
2dF = 2 degree Field



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*.**

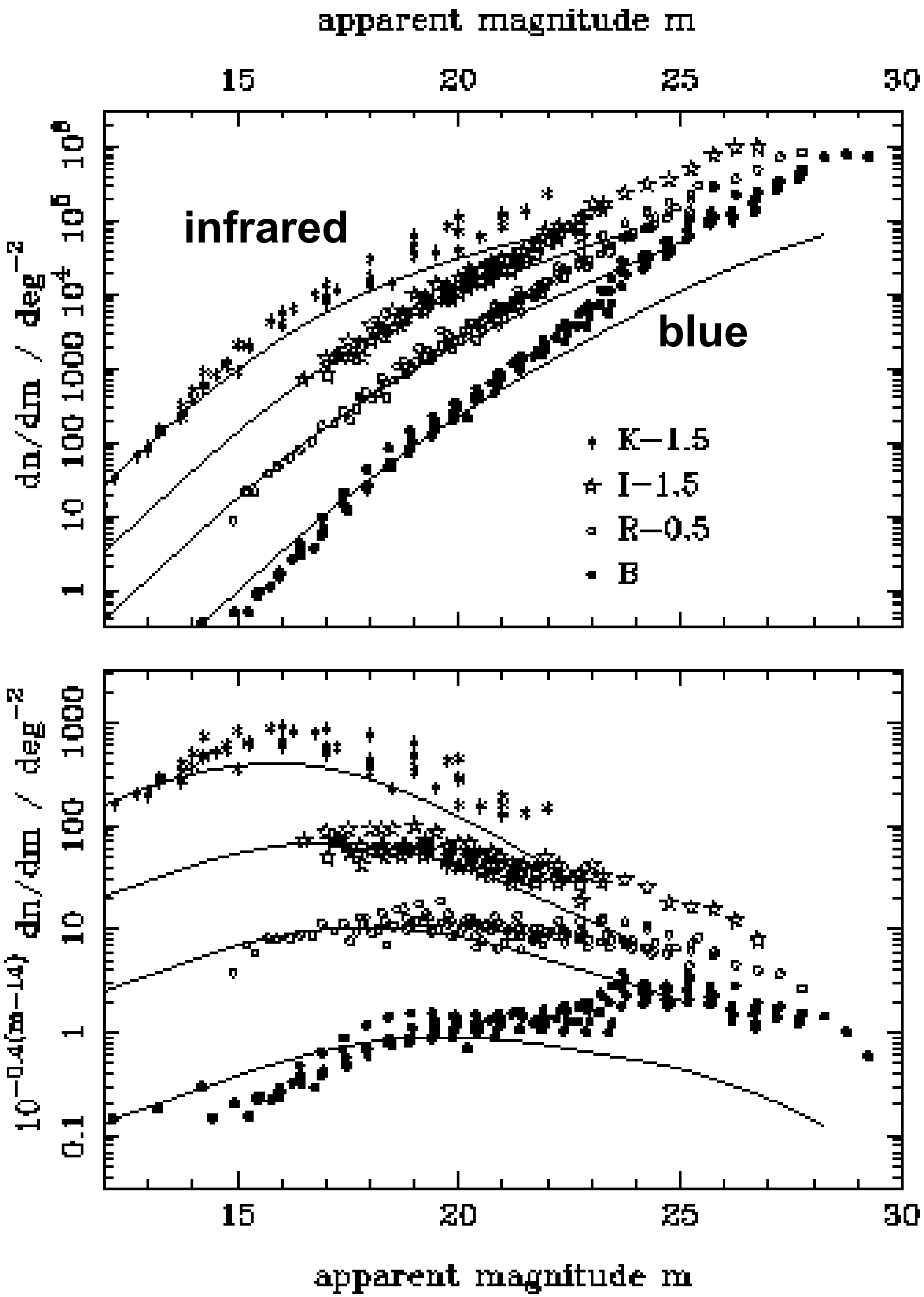
Young galaxies are blue.

so

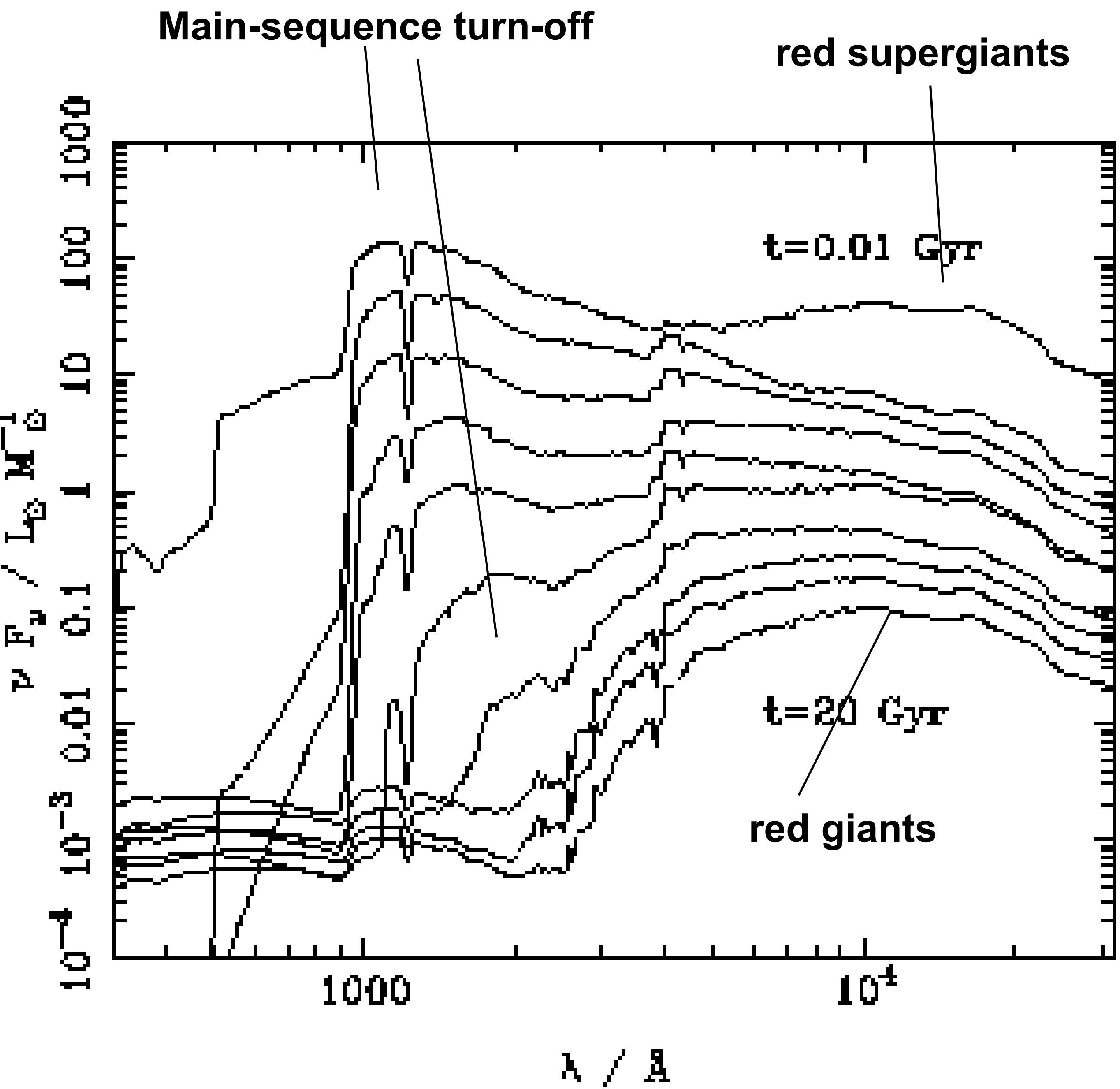
More young galaxies in the past.

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:

$$L = x\,L^* \qquad x \equiv \frac{L}{L^*}$$

number of galaxies per unit luminosity

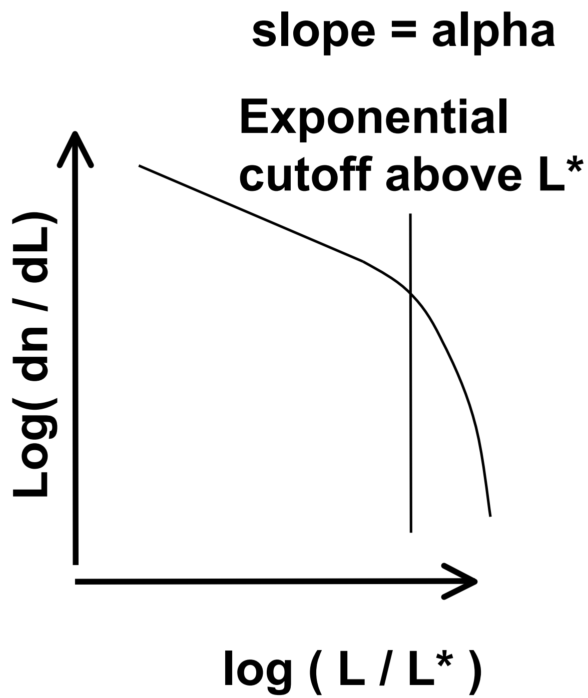
$$\Phi(x) \equiv \frac{dn}{dx} = \Phi^*\ x^{\alpha}\ e^{-x}$$

add up the luminosities

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

add up the mass (need mass/light ratio)

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



Measure Schechter parameters using:

galaxy clusters

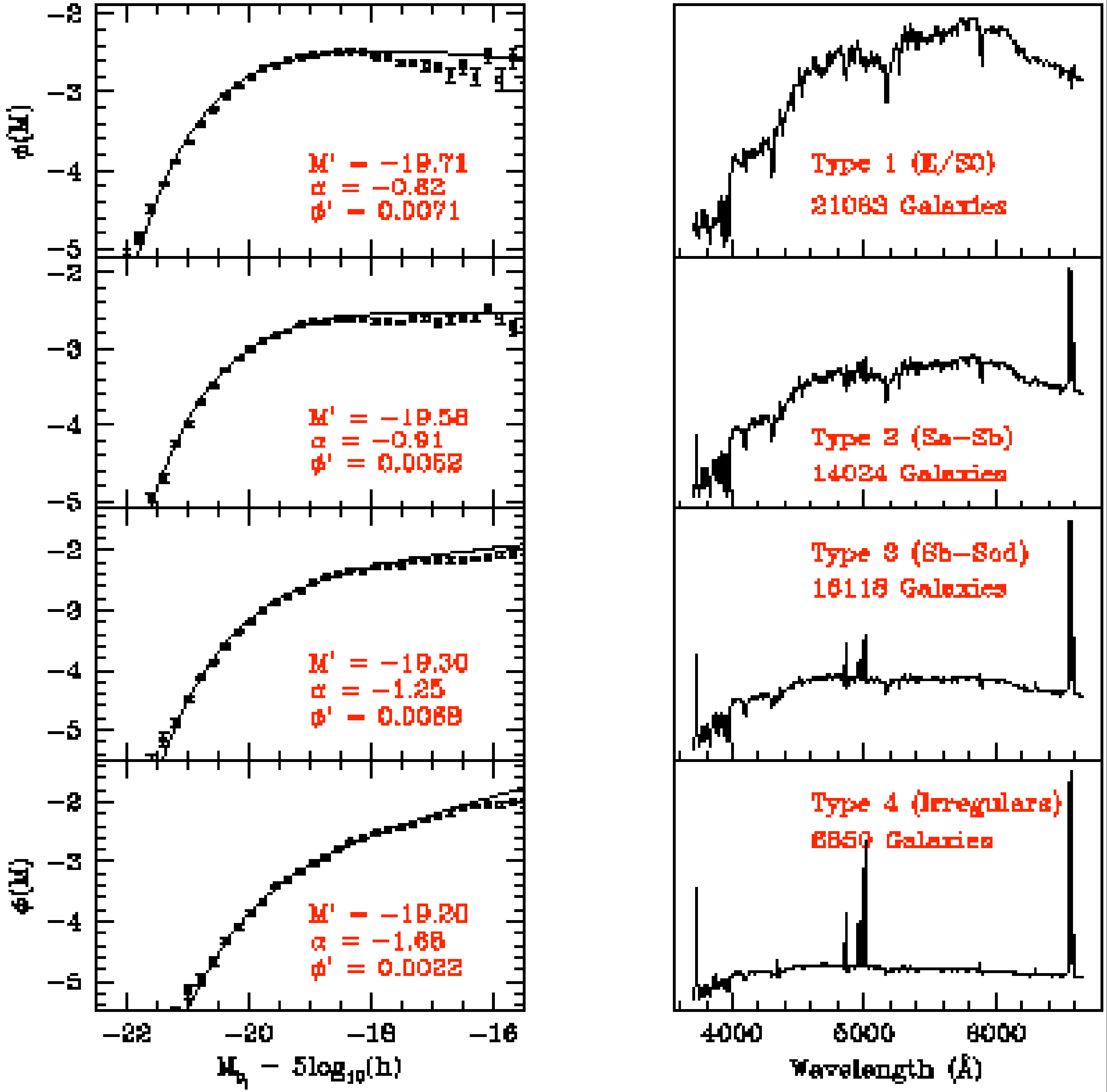
galaxy redshift surveys

Measure M/L for :

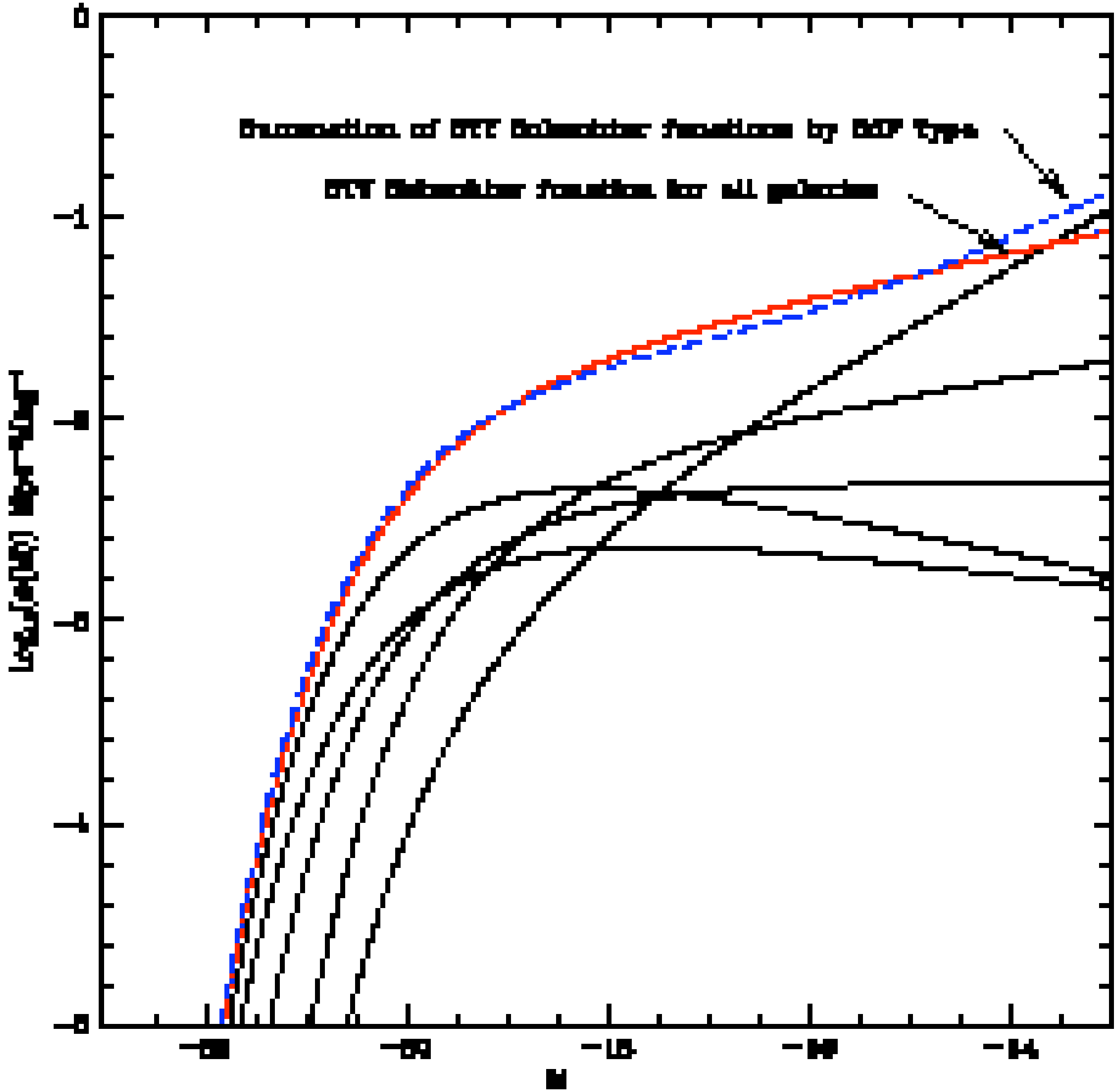
Nearby galaxies, galaxy clusters

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

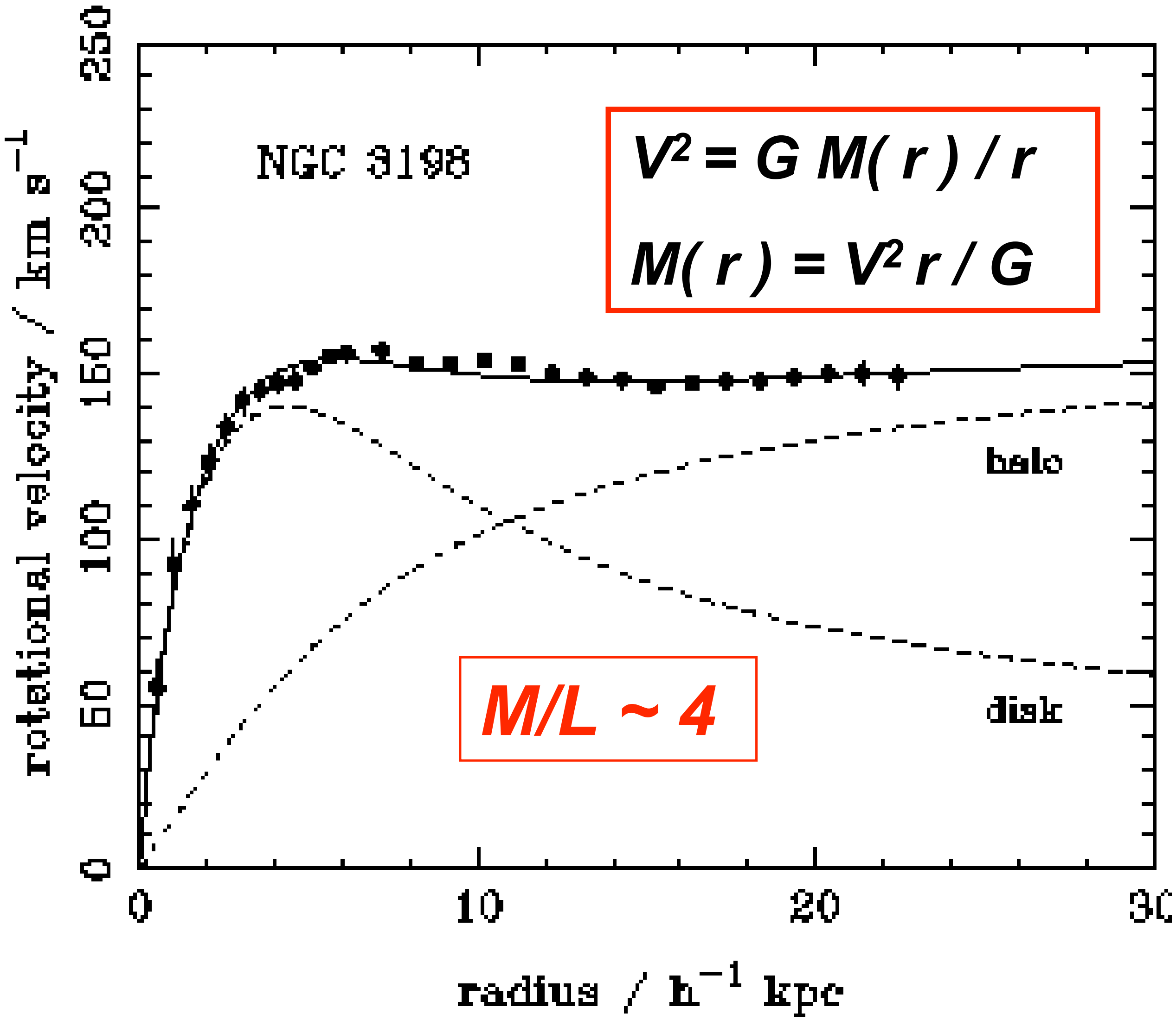
HI velocities

Flat rotation curves

Dark Matter Halos

Spirals, Ellipticals:
M/L~4-10

Some dwarf galaxies:
M/L ~ 100.

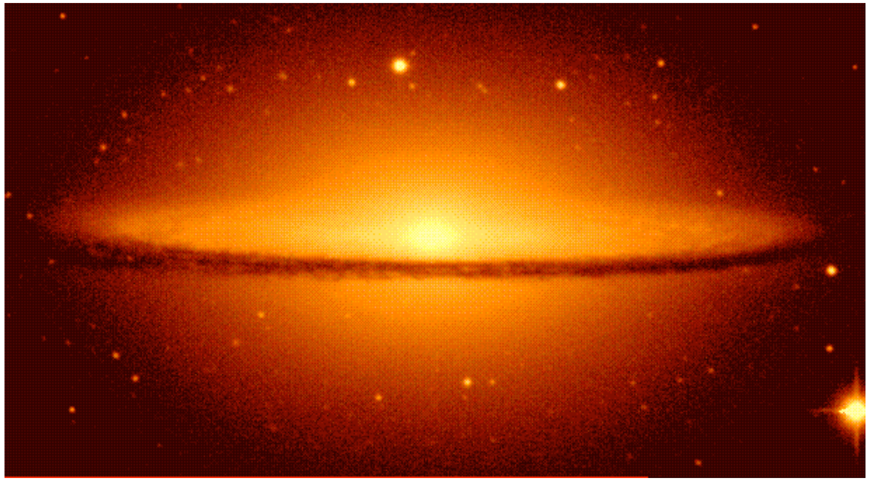


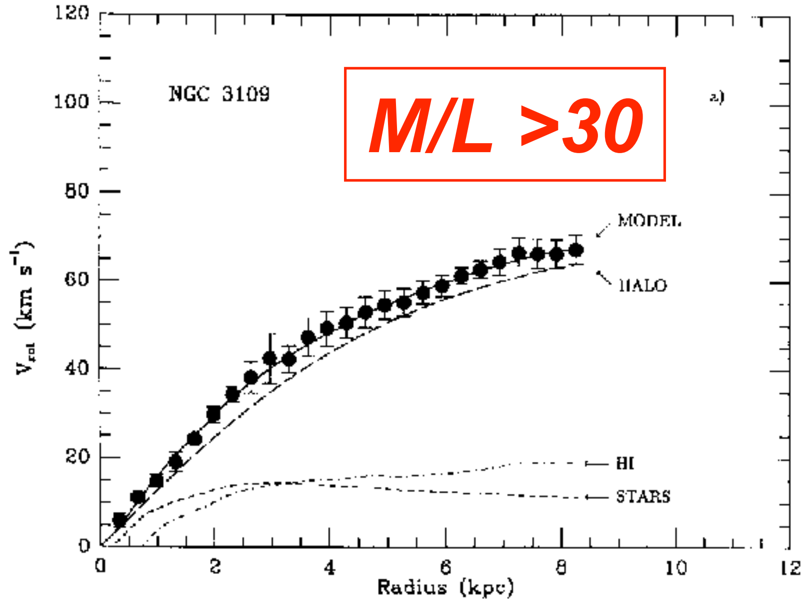
$$V^2 = G\,M(r)\,/\,r$$

$$M(r) = V^2\,r\,/\,G$$

M/L ~ 4

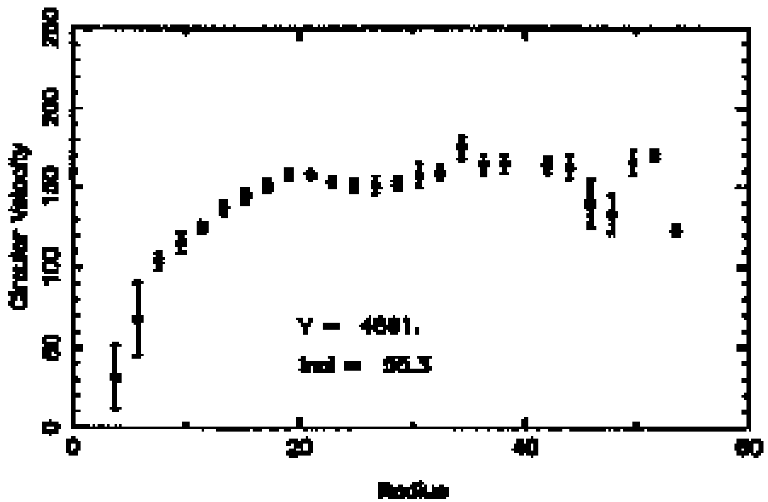
Galaxy Rotation Curves

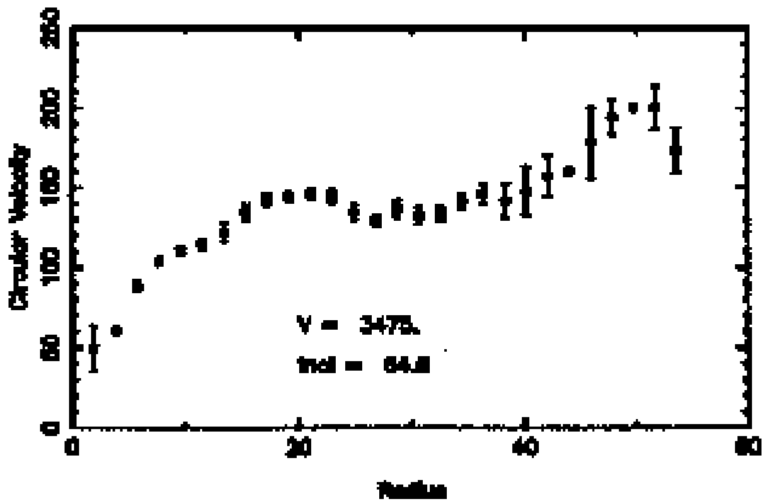




Small galaxies : V(r) rises

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

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

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 $L \propto M^4$)

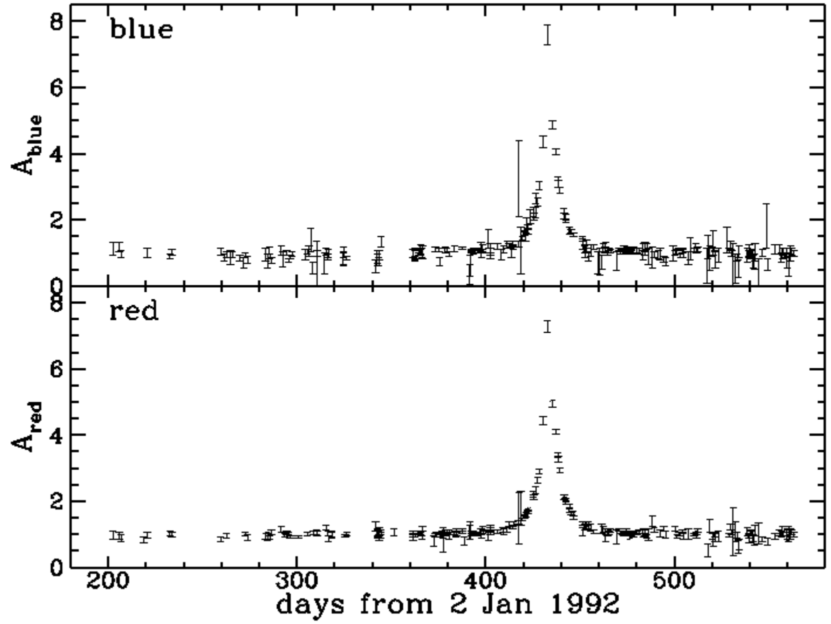
comets, planets: $M/L \sim 10^{9-12}$

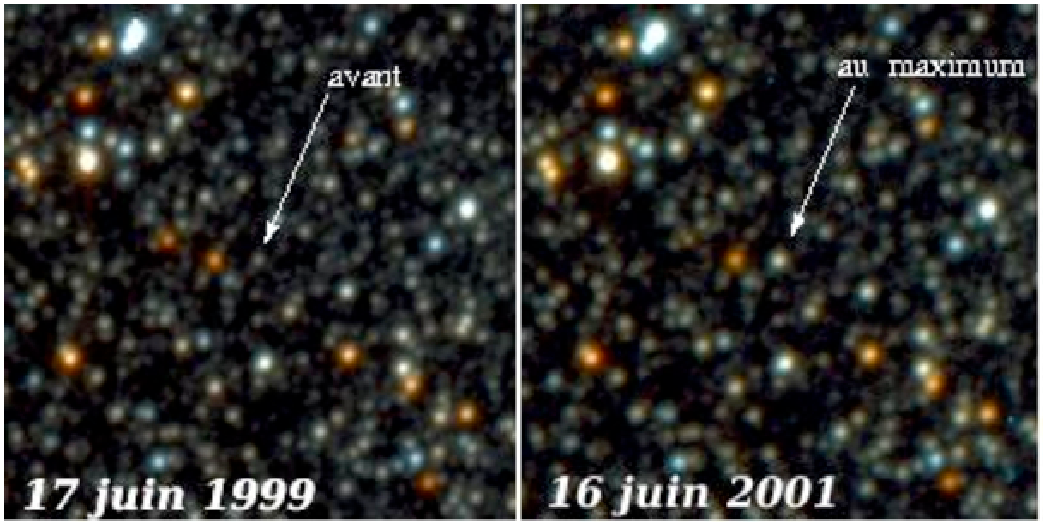
Is our Dark Matter halo filled with MACHOs ?
NO. Gravitational Lensing results rule them out.

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



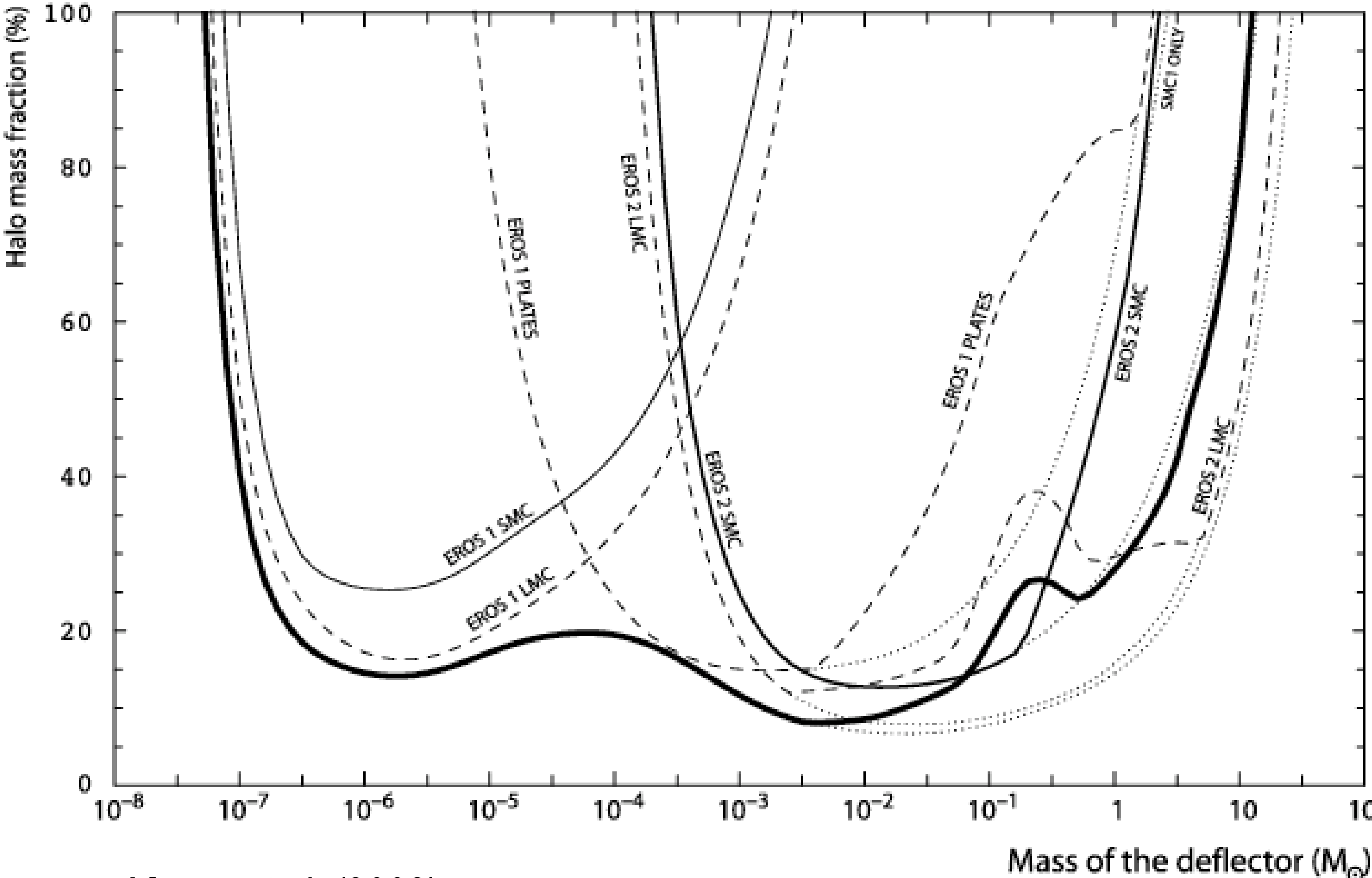


Massive Compace Halo Objects (MACHOS) would magnify LMC stars dozens of times each year. Only a few are seen.

Long events -> high mass

Short events -> low mass

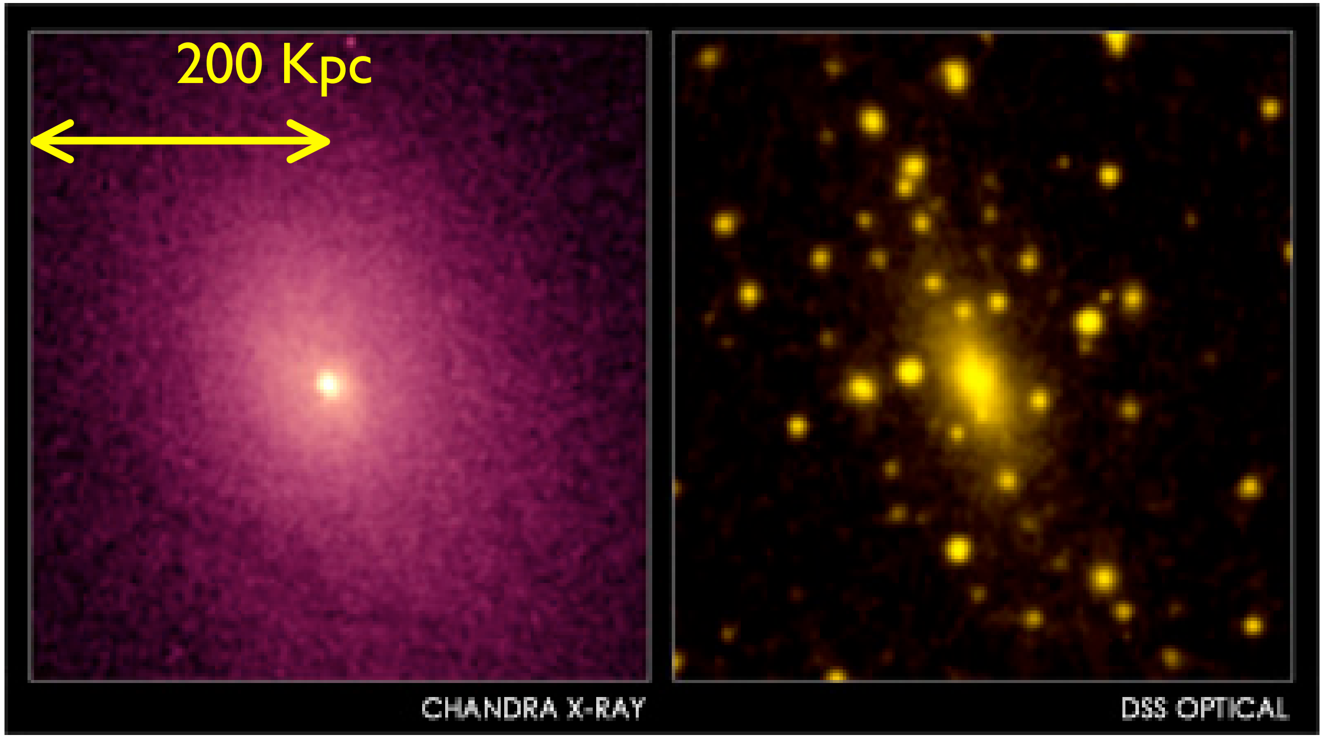
LMC Microlensing says NO to MACHOs



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: $T(r),\ n_e(r) \rightarrow \rho(r), P(r)$

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

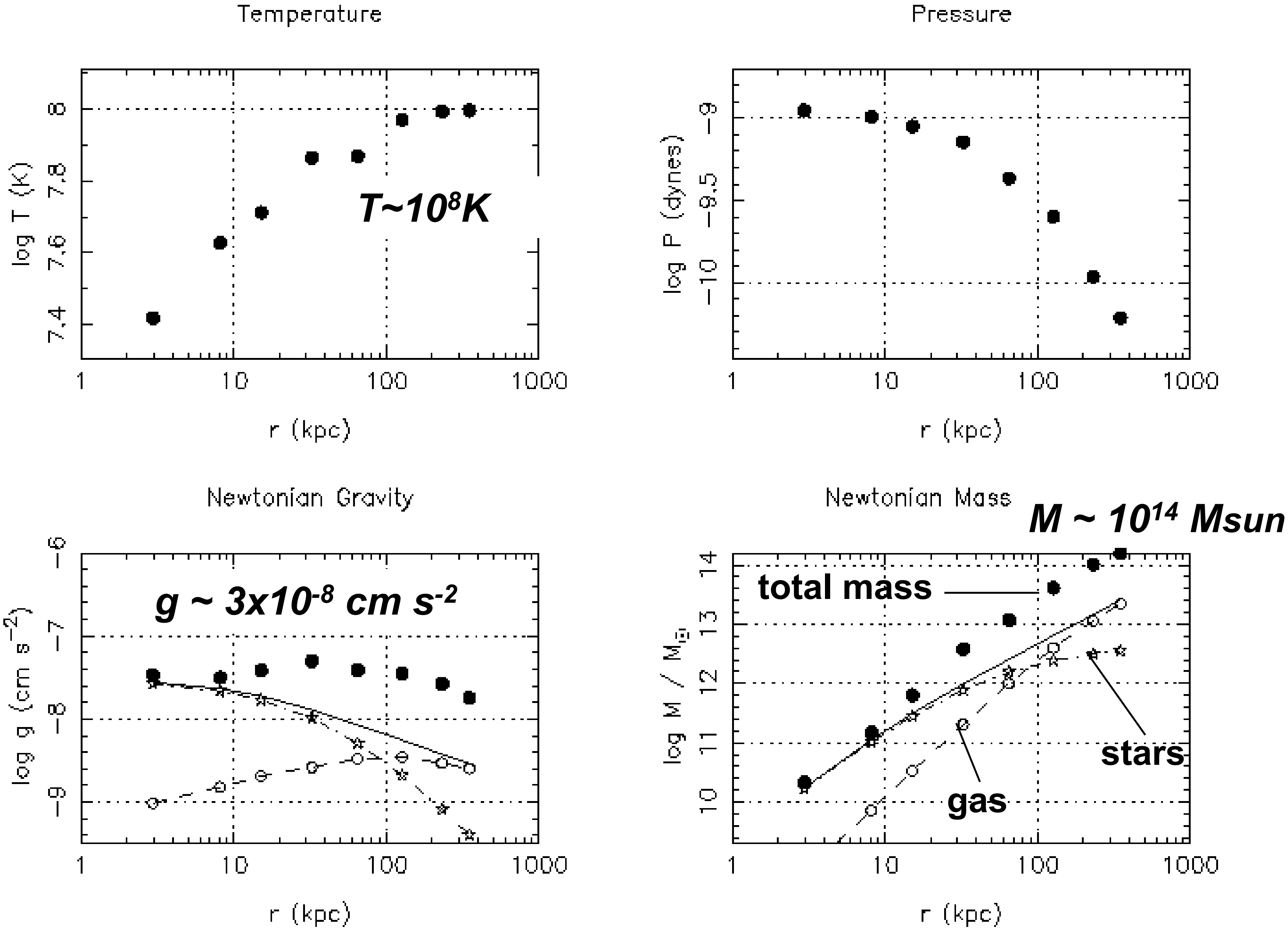
Coma Cluster:

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

often M(gas) > M(stars)

M/L~100-200

Cluster Masses from X-ray Gas



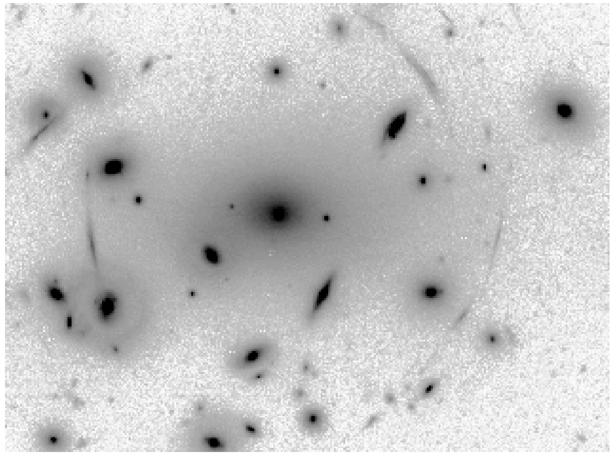
Masses from Gravitational Lensing

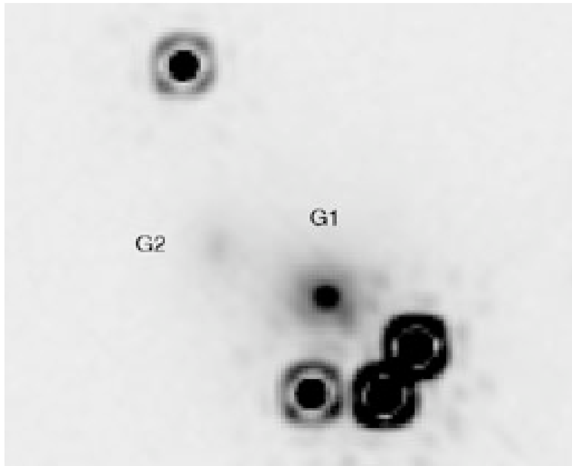
$$\theta_E = \frac{R_E}{D_L} = \left(\frac{4\,G\,M}{c^2} \frac{D_{LS}}{D_L D_S} \right)^{1/2}$$

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

Use redshifts, z_L, z_S,

for the angular diameter distances.





General agreement with Virial Masses.

Evidence for Dark Matter ?

Galaxies: ($r \sim 20$ Kpc)

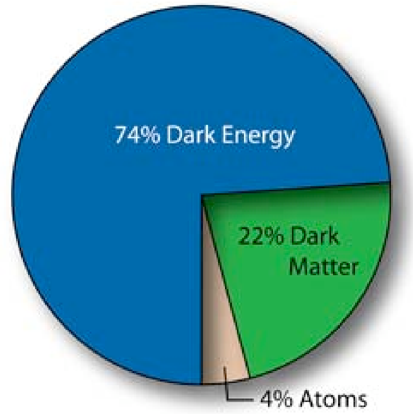
Flat Rotation Curves $V \sim 200$ km/s

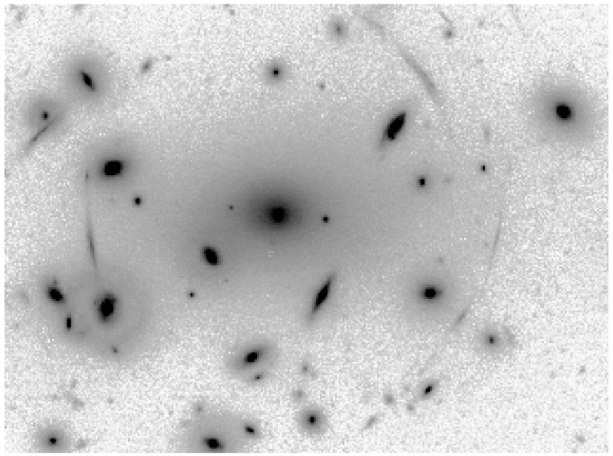
Galaxy Clusters: ($r \sim 200$ Kpc)

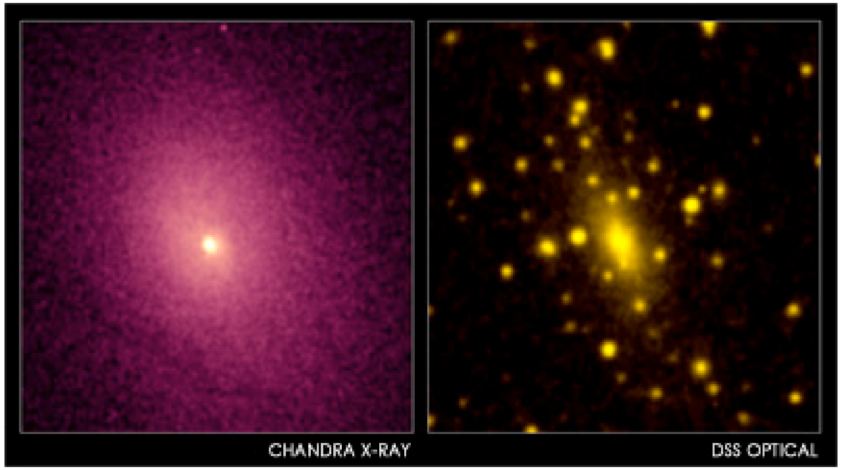
Galaxy velocities $V \sim 1000$ km/s

X-ray Gas $T \sim 10^8$ K

Giant Arcs



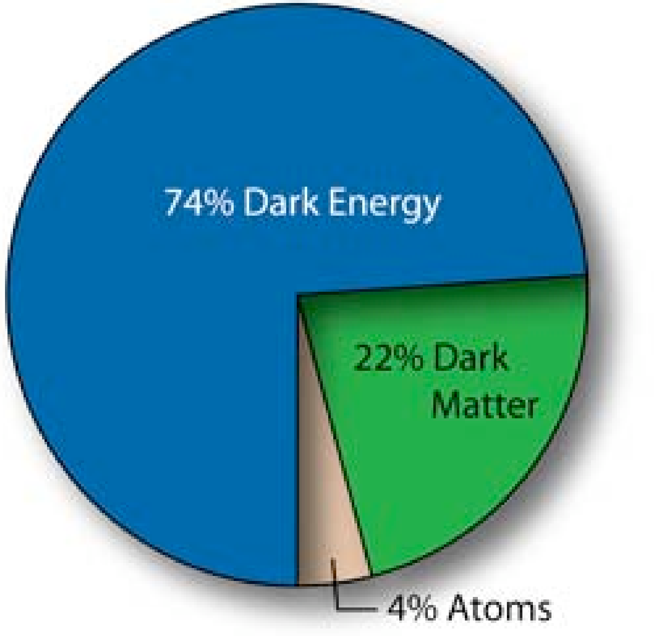




X-ray **Optical**

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:

$$a_0 \sim 2 \times 10^{-8} \text{cm s}^{-2}$$

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 **Ve**ctor **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.