## The Syllabus:

Nov 9,11,13	**The Structure of the Universe & Evolution of Galaxies**
	    [27.3] Clusters of galaxies
	    [28.4] Using quasars to probe the universe (gravitational lenses)

Nov 16,18,20	*What is dark matter?* [30.2] The origin of structure; WMAP measurements.
Nov 23,25	[26.1] Interaction of galaxies
Fri Nov 27	**Thanksgiving Holiday**
Nov 30, Dec 2,4	[26.2] The formation of galaxies
Dec 7,9,11	Quasars & Active galactic Nuclei (AGN) [28.2] Unified model of AGN … *(Skip [28.1], [28.3])* [18.2] Accretion Disk description pp. 661-666 [24.4] The Galactic Center

The agenda:

- Present-day structure.
- Evidence for Dark Matter.
  - Gravitational lenses.
- What is Dark Matter?
  - Hot vs. cold DM
- The growth of structure.
  - Initial fluctuations.
  - WMAP.
  - Bottom-up structure formation.

(turkey break)
  - The Quasar Era.
  - Evolution to modern-day galaxies.
 - Chemical enrichment revisited.
  - The first stars.

The Structure of the Universe

- The Local Group
  - 2 main mass concentrations
    - MW + satellites
      – LMC
      – SMC

    - M31 + satellites
      – M32
      – M33
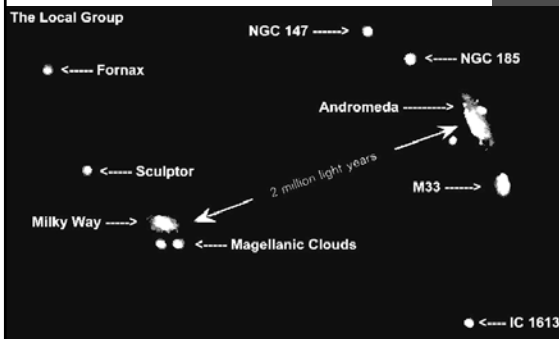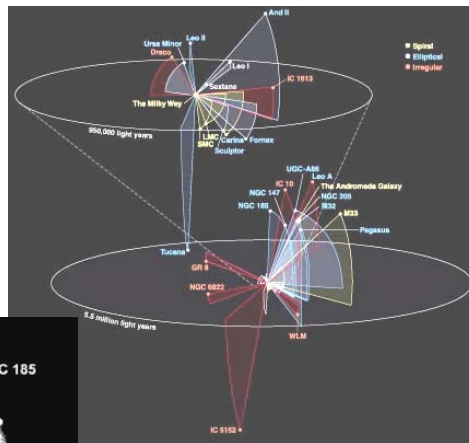
The Brightest Members of the Local Group (an old list)

Galaxy	Type	Distance (1000 LY)	Absolute Magnitude	Apparent Magnitude	Diameter (1000 LY)
Milky Way	S(B)bc	26	−20.6	—	130
Andromeda (M31, NGC224)	Sb	2500	−21.2	3.4	200
M33 (NGC598)	Sc	2600	−18.9	5.1	45
Large Magellanic Cloud	Irr	160	−18.5	0.4	20
Small Magellanic Cloud	Irr	192	−17.1	2.0	15
IC10	Irr	2700	−16.7	10.4	6
NGC205	ESpec	2500	−16.4	8.1	10
M32 (NGC221)	E2	2500	−16.5	8.1	5
NGC6822	Irr	1630	−16.0	8.5	8
WLM	Irr	3000	−14.4	10.4	7
NGC185	E3pec	2150	−15.6	9.1	6
IC1613	Irr	2360	−15.3	9.1	12
NGC147	E5	2150	−15.1	9.5	10
Leo A	Irr	2250	−11.5	12.7	7
Pegasus	Irr	2500	−12.3	12.6	8
Fornax	E3	450	−13.1	7.3	3
DDO210	Irr	3350	−11.3	13.9	4
Sagittarius Dwarf [4]	DwE	80	−13.8	?	25
Sagittarius	Irr	4250	−10.7	14.2	5
Sculptor	E3	285	−9.8	8.8	1
Andromeda I	E3	2650	−11.8	12.8	2
Andromeda III	E5	2500	−10.2	14.2	3
Andromeda II	E2	1900	−11.8	12.7	2.3
Pisces (LGS3)	Irr	2640	−10.4	14.3	0.5
Leo I	E3	800	−11.9	10.2	1
Leo II	E0	695	−10.1	11.6	0.5
Ursa Minor	E5	205	−8.5	10.6	1
Draco	E3	260	−8.6	11.0	0.5
Carina	E4	325	−9.4	10.6	0.5
Andromeda V	DwE	2640	−10.5	15.5	—
Phoenix	Irr	1300	−9.8	—	—
Sextans	DwE	280	−9.5	10.3	—
Tucana	DwE	2850	−9.6	15.2	—
Cassiopeia	DwE	2525	—	15.2	—
Andromeda VI	DwE	2300	—	13.9	—
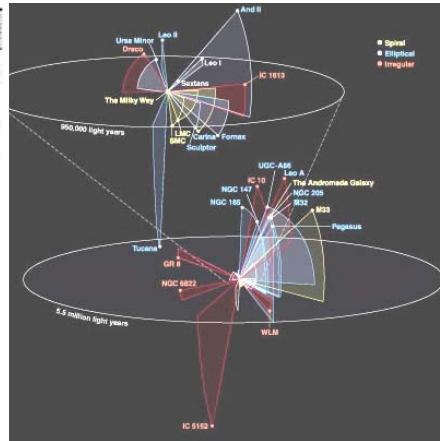
Galaxy Clusters
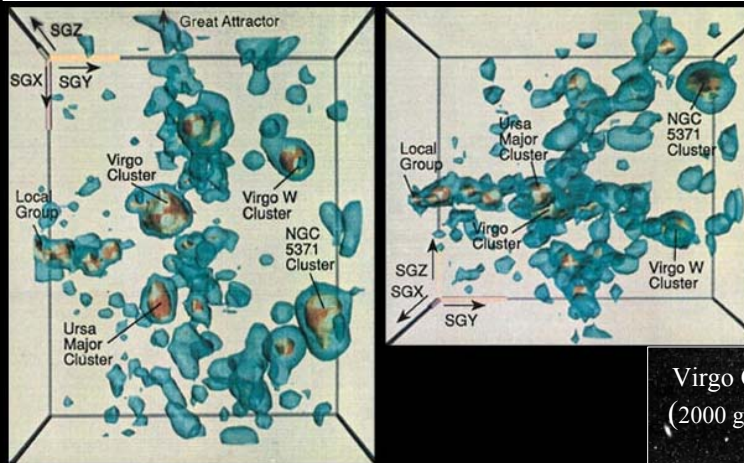### 1000's of galaxies

Hercules Cluster

NGC 4881
Coma Cluster
HST · WFPC2
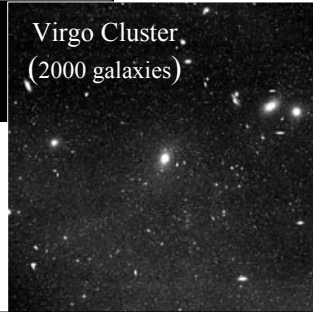
The Local Supercluster

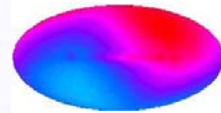
Virgo Cluster
(2000 galaxies)

- Biggest component: Virgo Cluster (10^{14} $M_\odot$).
- Local Supercluster (10^{15} $M_\odot$)
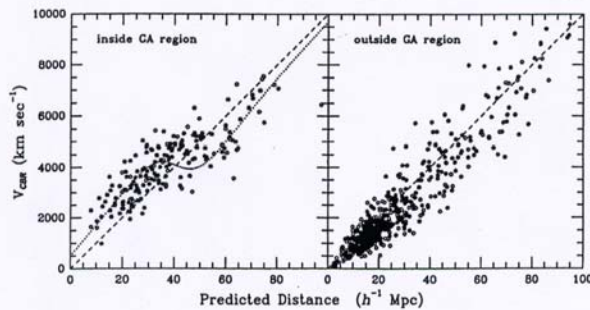

Peculiar motions of galaxies

- Local group within Local Supercluster
  - Virgocentric infall   168 km/s
  - ==> Local Supercluster mass ~ $8\ 10^{14}h^{-1}$ M_{sun}
- Great Attractor
  - flow of 1000s of galaxies over 80 Mpc
  - ~600 km/s
  - seems centered on point 45Mpc from MW
  - involves ~$5\ 10^{16}$ M_{sun}

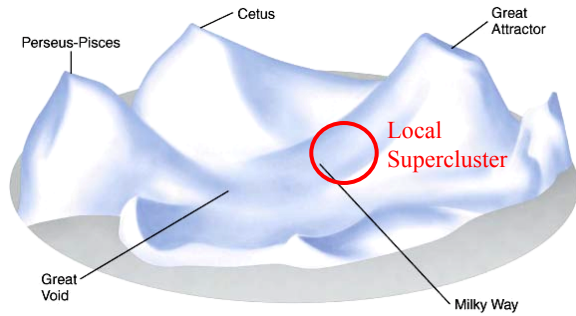Blue = 0^oK
Red = 4^oK
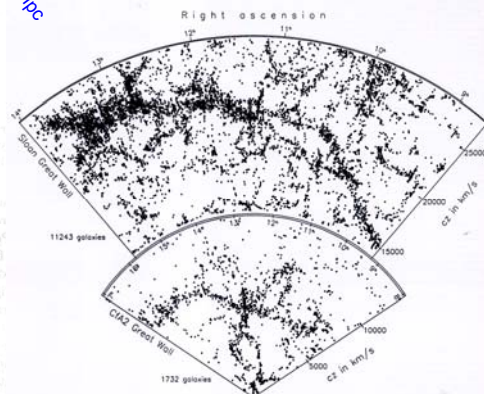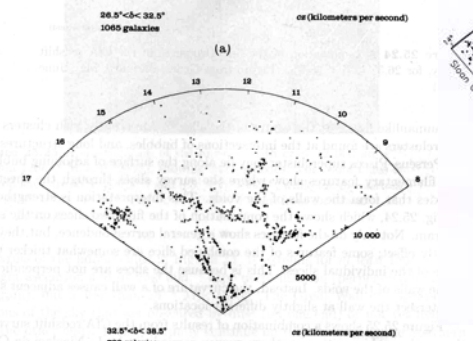
Blue = 2.724^oK
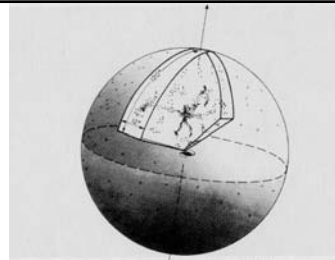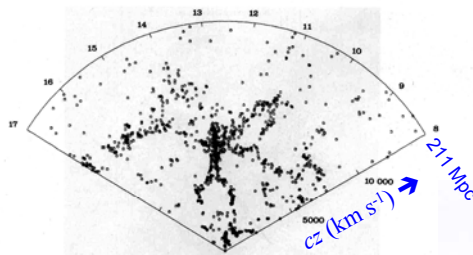Red = 2.732^oK
Dipole Anistropy
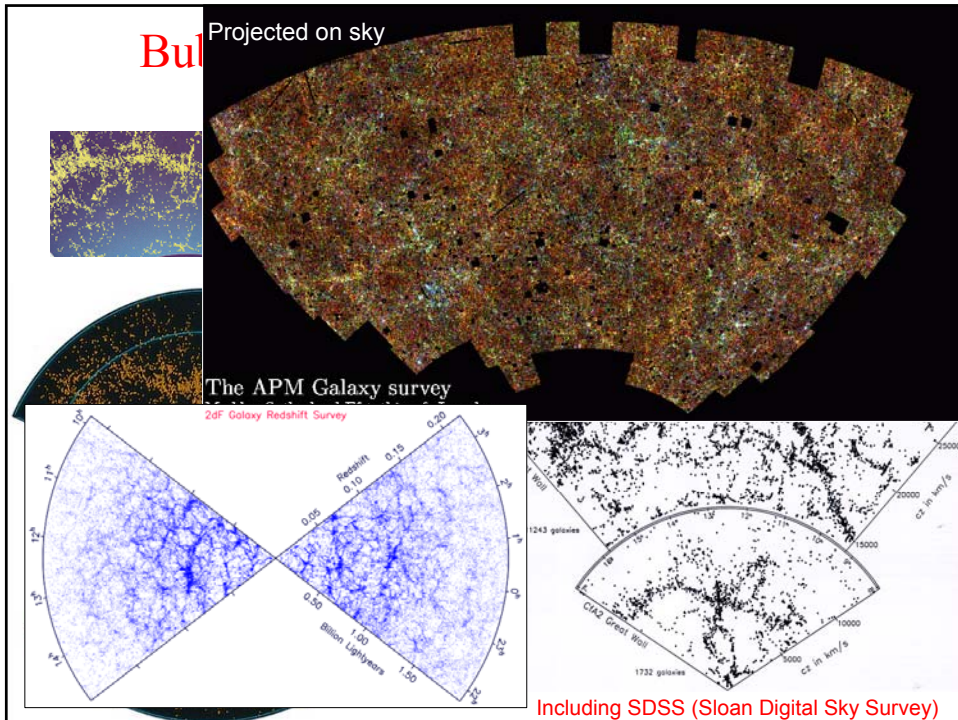
Structure upon structure

- Local Group
- Virgo Cluster (10^{14} M$_\odot$).
- All part of Local Supercluster (10^{15} M$_\odot$)
- Local Supercluster is part of streaming motion towards "Great Attractor"
  - $10^{16\text{-}17}$ M$_\odot$
  - located 45 Mpc away.
- Detected by extra motions superimposed on "Hubble Flow".

Bubbles and Voids

Harvard Center for Astrophysics (CfA) survey (1985)

211 Mpc

cz (km s^{-1})

Right ascension

Sloan Great Wall

CfA2 Great Wall

Including SDSS (Sloan Digital Sky Survey)

Bu[...]

Projected on sky

The APM Galaxy survey

2dF Galaxy Redshift Survey

Including SDSS (Sloan Digital Sky Survey)

The Evidence for Dark Matter

Mass/Luminosity Ratio

- Local stellar luminosity function: $M/L = 0.67$
- Our Galaxy, at larger scales:
  - Local motions $\perp$ disk (Oort limit): $M/L \sim 3\text{-}5$
  - Flat rotation curve > 30
  - Escape speed > 30
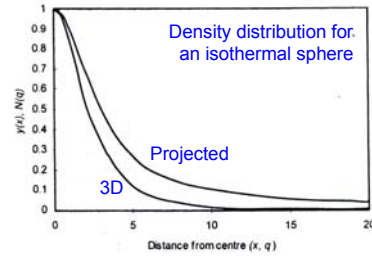 - Pop II dynamics (glob. clusters, etc.) ~ 27

Dark matter in nearby galaxies

- Flat rotation curves in other spiral galaxies
  - ==> dark halos
  - typically *M/L > 28h > 20*

- Central regions of Elliptical Galaxies
  - Virial theorem:

$$\sigma_r^2 = \frac{GM}{5R}$$

Density distribution for an isothermal sphere

Projected

3D

  - or… compare surface brightness, velocity dispersions to isothermal sphere model
  - *M/L ~ 12h ~ 9*

E galaxy X-ray halos

M(r)

- Hot x-ray emitting gas in E galaxies is in hydrostatic equilibrium

P+dP

Density = ρ

P

Hydrostatic equilibrium:

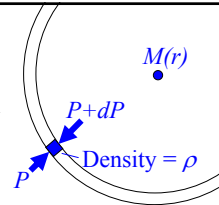pressure

density

$$\frac{dP}{dr} = -\frac{GM(r)}{r^2}\rho$$

[CO 27.17]

Ideal gas law:

$$P = \frac{\rho k_B T}{\mu m_p}$$

$$M(r) = \frac{k_B T r}{G \mu m_p}\left[-\frac{\partial \ln \rho}{\partial \ln r} - \frac{\partial \ln T}{\partial \ln r}\right]$$

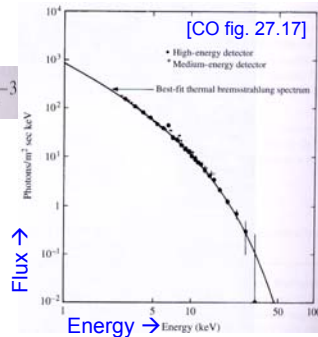- $\rho(r)$, $T(r)$ measured from X-ray bremsstrahlung emission:

Volume emissivity:

amplitude

freq. distr.

[CO fig. 27.17]

$$\ell_\nu \, d\nu = 5.44 \times 10^{-52} \left(4\pi n_e^2\right) T^{-1/2} e^{-h\nu/kT} \, d\nu \ \mathrm{W \ m^{-3}}$$

[CO 27.18, pg. 1066]

M87 is best case
Giant E1 at center of Virgo cluster
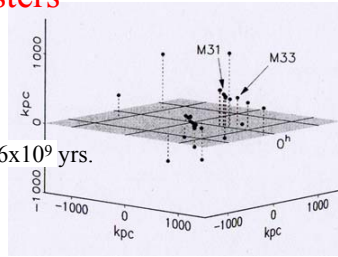➔ *M/L ~ 750*

Flux →

Energy → Energy (keV)

Galaxy Groups & Clusters

- Local Group Dynamics –
  The Impending MW – M31 Collision

  - Approaching each other at 119 km/s
  - Current separation: $r = 770$ kpc ➔ collision in $r/v \sim 6\times10^9$ yrs.
  - Rough mass estimate from Kepler's laws
  - P = PERIOD = age of Universe with $r = 0$ at $t = 0$

$$v^2 = GM\left(\frac{2}{r} - \frac{1}{a}\right)$$ (kinetic energy) = -(potential energy) + (total energy)

$$P^2 = \frac{4\pi^2}{GM} a^3$$ Kepler's 3rd law. a = semi-major axis

$$\Rightarrow v^2 - \frac{2GM}{r} + \left(\frac{2\pi GM}{P}\right)^{2/3} = 0$$ [CO 27.16]

use $P \sim t_H + r/v$ $\Rightarrow M_{total} \sim 5\times10^{12} M_\odot$

  - Binney & Tremaine:
    - more exact analysis,
      same answer ($M = 3\text{-}5\times10^{12}$ M$_\odot$)
  - M/L ~ 100

Dark Matter
so far

Mass/Luminosity

• Local stellar luminosity function:	$M/L = 0.67$
• Our Galaxy, at larger scales:	
• Local motions ⊥ disk (Oort limit):	$M/L \sim 3\text{-}5$
• MW Rotation curve	> 30
• Escape speed	> 30
• Pop II dynamics (glob. clusters, etc.)	~ 27
• Flat rotation curves in other spirals	> 20
• E galaxy virial theorem	9
• X-ray halo of M87	> 750
• Local Group dynamics	100