Homework for next ~~Wed. Nov. 14~~:
CO 30.4, 27.10, 27.12
(= 28.10, 25.10, 25.12 1st ed.)
In 30.4, use $T_{end\ of\ GUT\ epoch} = 10^{28}$ K

Due Friday Nov. 16

The actual agenda:
- Inflation

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- Present-day structure
- The case for dark matter
  - Gravitational lenses
- The nature of dark matter
- The growth of structure
  - Galactic evolution

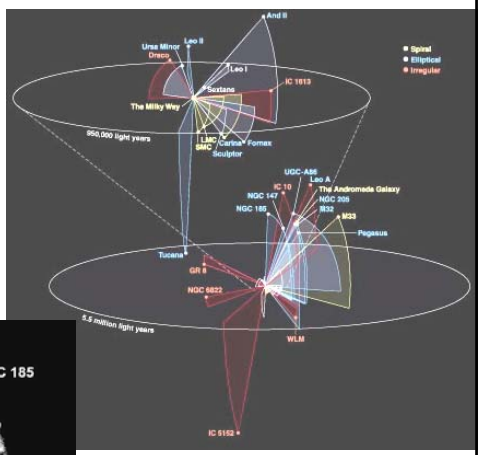
Midterm 2 scores
98
96
95
95
94
92
89
87
84
84
83
81
76
75
73
73
72
71
70
65
60

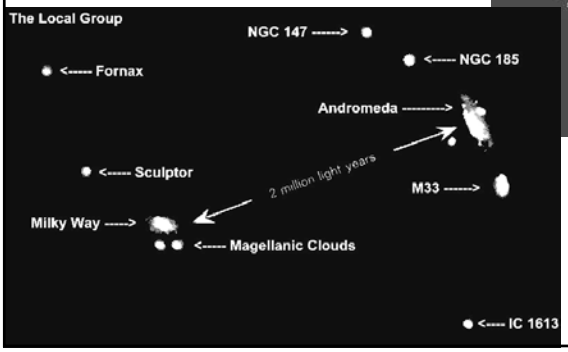
## The Syllabus:

| | |
|---|---|
| **Wednesday 11/7** | **Midterm 2** |
| Week 11: 11/9 | [30.1] The very early universe and inflation |
| Week 12: 11/12–11/16 | **The Structure of the Universe & Evolution of Galaxies**<br>[27.3] Clusters of galaxies<br>[28.4] Using quasars to probe the universe (grav. lenses)<br>*What is dark matter?* |
| Week 13: 11/19+11/21 | [30.2] The origin of structure; WMAP measurements. |
| **Friday 11/23** | **Thanksgiving Holiday** |
| Week 14: 11/26–11/30 | [26.1] Interaction of galaxies<br>[26.2] The formation of galaxies<br>*Steller Population Synthesis* |
| Week 15: 12/3–12/7 | Quasars & Active galactic Nuclei (AGN) *We may not get to here.*<br>[28.2] Unified model of AGN … *(Skip [28.1], [28.3])*<br>[18.2] Accretion Disk description pp. 661-666<br>[24.4] The Galactic Center |
| **Tuesday 12/11** | **Final Exam 3–5PM** |

# The Structure of the Universe

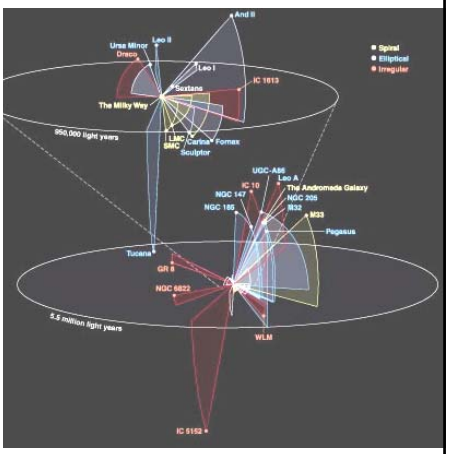
- The Local Group
  - 2 main mass concentrations
    - MW + satellites
      - LMC
      - SMC
    - M31 + satellites
      - M32
      - M33



## The Brightest Members of the Local Group (an old list)

| Galaxy | Type | Distance[3] (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 | E5pec | 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 | — |

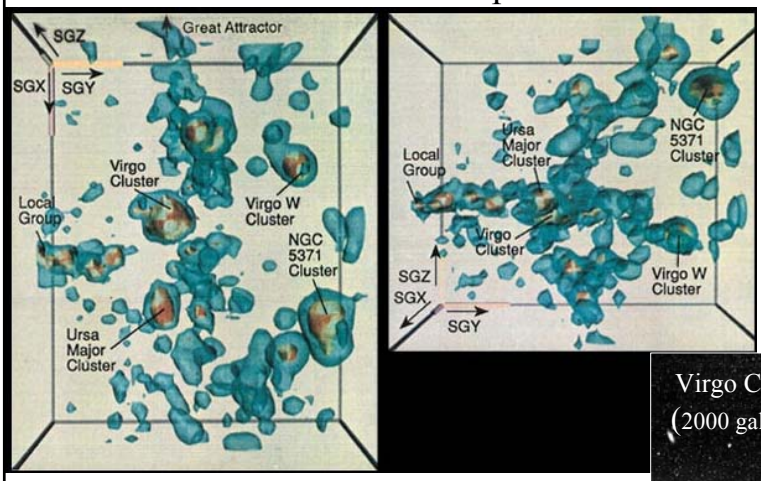


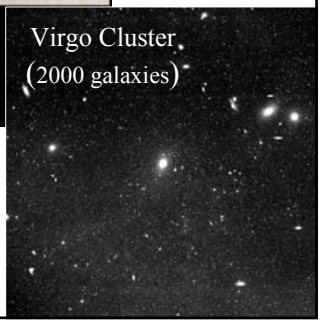

## Galaxy Clusters

1000's of galaxies



# The Local Supercluster



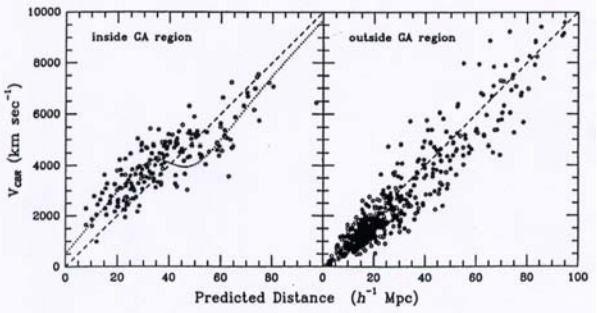




- Biggest component: Virgo Cluster ($10^{14}$ $M_{\odot}$).
- Local Supercluster ($10^{15}$ $M_{\odot}$)

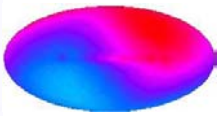
# Peculiar motions of galaxies

- 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 $10^{16}$ $M_{sun}$

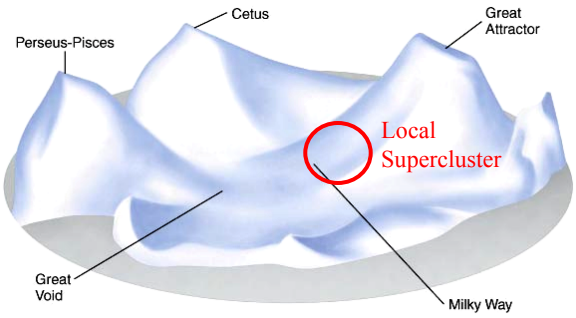



Blue = 0°K
Red = 4°K



Blue = 2.724°K
Red = 2.732°K
Dipole Anistropy

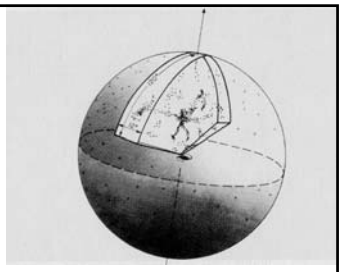
# Structure upon structure

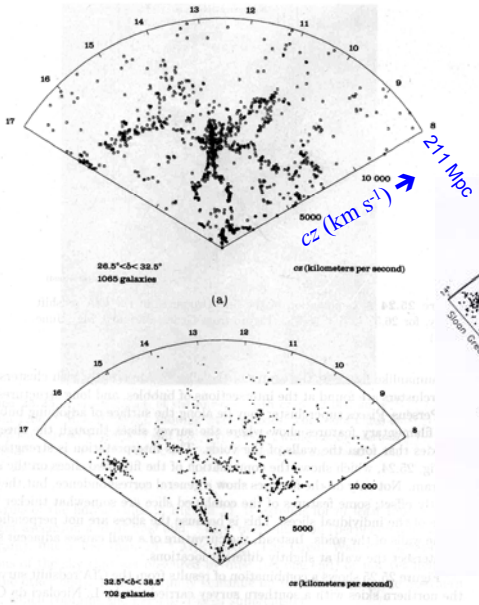


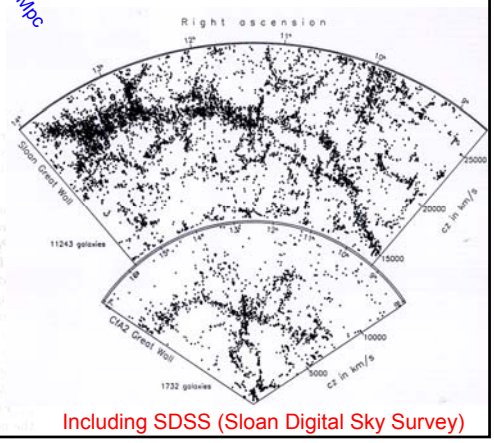

- Local Group
- Virgo Cluster ($10^{14}$ $M_\odot$).
- All part of Local Supercluster ($10^{15}$ $M_\odot$)
- Local Supercluster is part of streaming motion towards "Great Attractor"
  - $10^{16\text{-}17}$ $M_\odot$
  - located 45 Mpc away.
- Detected by extra motions superimposed on "Hubble Flow".

# Bubbles and Voids

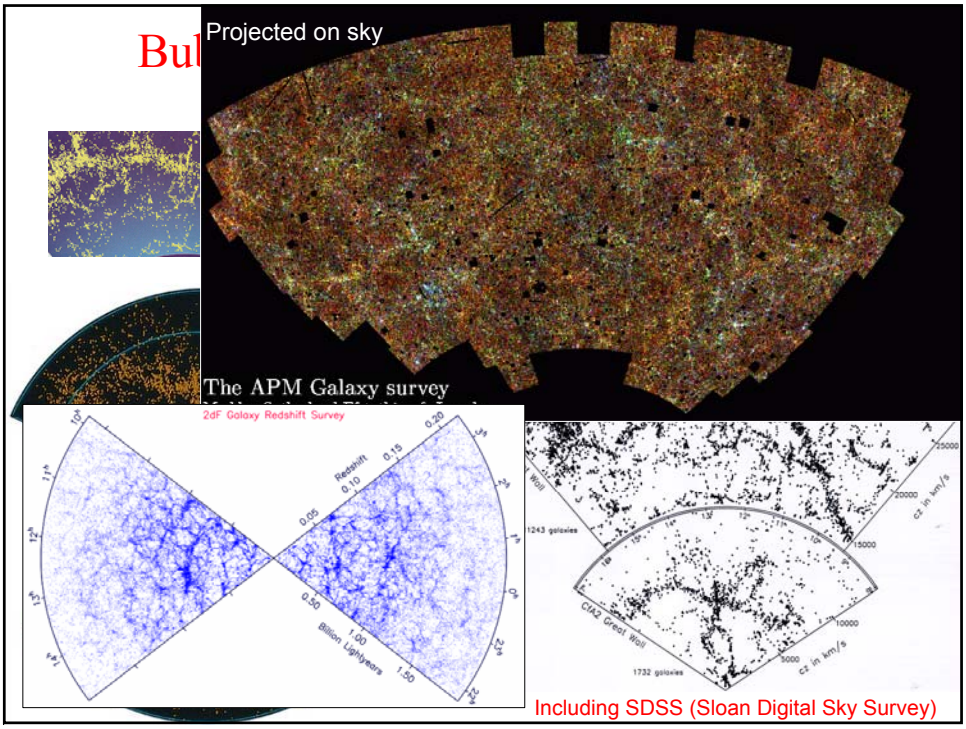
Harvard Center for Astrophysics (CfA) survey (1985)






Including SDSS (Sloan Digital Sky Survey)




## Dark Matter

- About 85% of gravitationally interacting matter is invisible.
  - Detected solely by its gravitational effects.
  - Line of evidence reaching back to Zwicky (1933)
  - Baryonic matter constrained by BBN (Big Bang Nucleosynthesis), WMAP
    - $\Omega_B = .04$
    - This includes large component of invisible Baryons
  - But $\Omega_{Matter} = 0.27$

## Mass/Luminosity

- Local stellar luminosity function: $M/L = 0.67$
- Our Galaxy, at larger scales:
  - Oort limit: $M/L \sim 2.7$
  - Slice through disk (Bahcall & Soniera) $\sim 5$
  - Rotation curve $> 30$
  - Escape speed $> 30$
  - Pop II dynamics (glob. clusters, etc.) $\sim 27$
  - Magellanic stream $> 80$

# Dark matter in nearby galaxies

- Rotation curves of spiral galaxies
  - expect Keplerian $r^{-1/2}$ curve once outside of mass distribution
  - but rotation curves are flat as far out as they can be traced
  - ==> dark halos
  - typically $M/L > 28h$

- Central regions of Elliptical Galaxies
  - Virial theorem:

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

  - or… compare surface brightness, velocity dispersions to isothermal sphere model
  - $M/L \sim 12h$

# E galaxy X-ray halos

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

$$\frac{dP}{dr} = -\frac{GM(r)}{r^2}\rho \qquad P = \frac{\rho k_B T}{\mu m_p}$$

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

[CO 27.17]

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

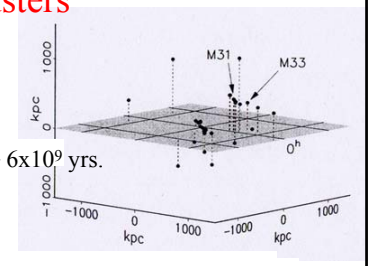
Volume emissivity:

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

[CO 27.18, pg. 1066]

- M87 is best case for study
  - Giant E1 at center of Virgo cluster
  - Linear increase in M out to r = 300 kpc
  - $M(<300\ \mathrm{kpc}) \sim 10^{13}\ M_\odot$
    - 99% dark matter
  - ==> $M/L \sim 750$

# 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 $r/v \sim 6\text{x}10^9$ yrs.
  - Rough mass estimate from Kepler's laws
  - P = 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.

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

use $P \sim t_H + r/v$ $\Rightarrow M_{total} \sim 5\text{x}10^{12} M_\odot$

  - Binney & Tremaine:
    - more exact analysis, same answer ($M = 3\text{-}5\text{x}10^{12}\ M_\odot$)
  - M/L ~ 100 (V-band)