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

The Syllabus:

<table>
<thead>
<tr>
<th>Wednesday 11/7</th>
<th>Midterm 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Week 11: 11/9</td>
<td>[30.1] The very early universe and inflation</td>
</tr>
<tr>
<td>Week 12: 11/12–11/16</td>
<td>The Structure of the Universe &amp; Evolution of Galaxies</td>
</tr>
<tr>
<td>[27.3] Clusters of galaxies</td>
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<tr>
<td>[28.4] Using quasars to probe the universe (grey lenses)</td>
<td></td>
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<tr>
<td>What is dark matter?</td>
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</tbody>
</table>

Midterm 2 scores
98
96
95
94
92
90
89
87
86
84
83
82
81
76
75
74
73
72
71
70
65
60

Due Friday Nov. 16
Homework for next Wed. Nov. 14:
in 30.4, use $T_{\text{end of GUT epoch}} = 10^{28}$ K

The Structure of the Universe

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

The Structure of the Universe

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

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Distance (kpc)</th>
<th>Absolute Magnitude</th>
<th>Apparent Magnitude</th>
<th>Diameter (1000 LY)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Milky Way</td>
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<td></td>
<td></td>
<td>130</td>
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<tr>
<td>Andromeda</td>
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<td>100</td>
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</tbody>
</table>

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
  - $\Rightarrow$ Local Supercluster mass $\sim 8 \times 10^{14} h^{-1} M_{\odot}$
- Great Attractor
  - flow of 1000s of galaxies over 80 Mpc
  - $\sim 600$ km/s
  - seems centered on point 45Mpc from MW
  - involves $\sim 5 \times 10^{16} M_{\odot}$

Dipole Anisotropy

Blue = 2.724$^\circ$K
Red = 2.732$^\circ$K

Blue = 0$^\circ$K
Red = 4$^\circ$K
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”
  - $10^{16-17} \ M_\odot$
  - 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 $\Omega_{\text{Matter}} = 0.27$

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
  - $\Rightarrow$ dark halos
  - typically $M/L > 28h$

- Central regions of Elliptical Galaxies
  - Virial theorem:
    \[ \sigma^2 = \frac{GM}{5R} \]
  - 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

\[ \rho(r), T(r) \text{ measured from X-ray bremsstrahlung emission:} \]

\[ \ell_e \, d\nu = 5.44 \times 10^{-32} \left( 4\pi n_e^2 \right) T^{-1/2} e^{-h\nu/kT} \, d\nu \, W \, m^{-3} \]

- $\rho(r)$, $T(r)$ measured from X-ray bremsstrahlung emission:
  - $\ell_e \, d\nu$ = [CO 27.17]
  - $\ell_e \, d\nu$ = [CO 27.18, pg. 1066]

- $M(\leq 300 \text{ kpc}) \sim 10^{13} M_{\odot}$
  - 99% dark matter

- $\Rightarrow$ $M/L \sim 750$
Galaxy Groups & Clusters

- Local Group Dynamics –
  - The Impending MW – M31 Collision
  - Approaching each other at 119 km/s
  - Current separation: \( r = 770 \text{kpc} \) ➔ collision in \( r/v \sim 6\times10^9 \text{ yrs.} \)
  - Rough mass estimate from Kepler’s laws
  - \( P = \text{age of Universe with } r = 0 \text{ at } t = 0 \)
  - Binney & Tremaine:
    - more exact analysis, same answer (\( M = 3-5\times10^{12} M_\odot \))
    - \( M/L \sim 100 \) (V-band)

\[
\frac{v^2}{r} = \frac{GM}{r} \left( \frac{r}{r} - \frac{1}{r^2} \right) \\
\frac{v^2}{r} = \frac{4\pi^2}{GP} \cdot \frac{r^3}{M} \\
\Rightarrow \left( \frac{v^2}{r} \right)_v \text{ } + \left( \frac{GM}{r} \right)_{V3} = 0 \\
\Rightarrow v \approx \frac{v}{r} + \frac{v}{r} \\
\Rightarrow M_{\text{tot}} \sim 5 \times 10^{12} M_\odot
\]