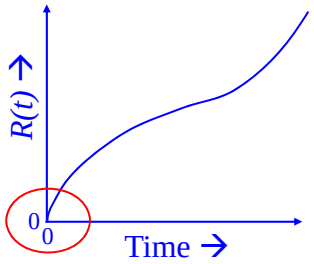
[CO 30.1]

Problems at $t = 0$

when extrapolating current U. back to earliest times using Friedman eqn. and R-W metric.



The Horizon Problem

- Cosmic Microwave Background is smooth to about 1 part in 10^5
- How do regions 180^o apart know about each other?

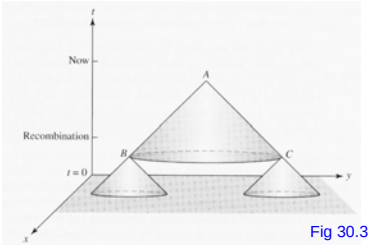
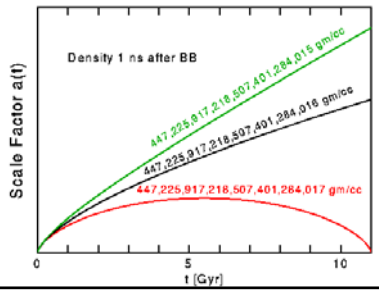


Fig 30.3

The Flatness Problem

- Why does K.E. = Grav. Potential E. to such high precision?



The solution: Inflation

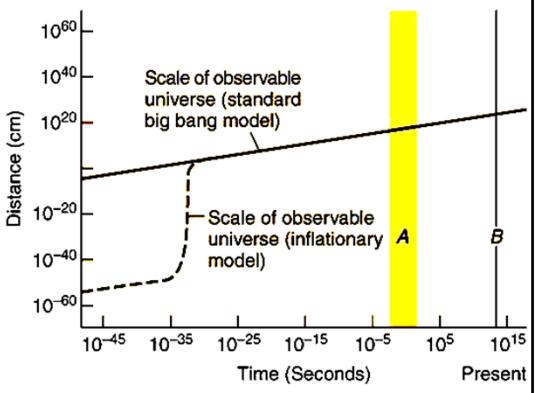
(probably)

(maybe)

Extremely rapid expansion of universe

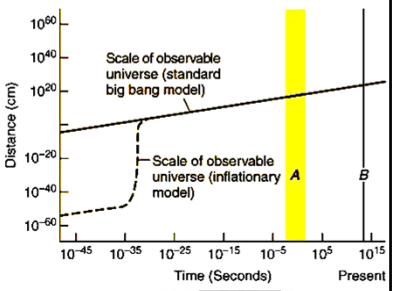
- due to release of energy in "phase change".

Universe became ~ e^{100} ~ 10^{43} times larger within 10^{-34} seconds.



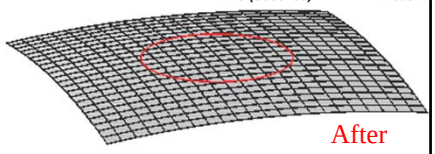
What does inflation predict for geometry of present universe?

Universe became
$\sim e^{100} \sim 10^{43}$ times larger
within 10^{-34} seconds.



- Predicts a flat universe
  - $\Omega_0 = 1.000000\ldots$.
  - As far out as we can see
    - red circle = horizon

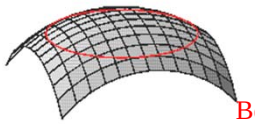
    = most distant place from which light has had time to travel.
- Solves flatness and horizon problems.



After Inflation

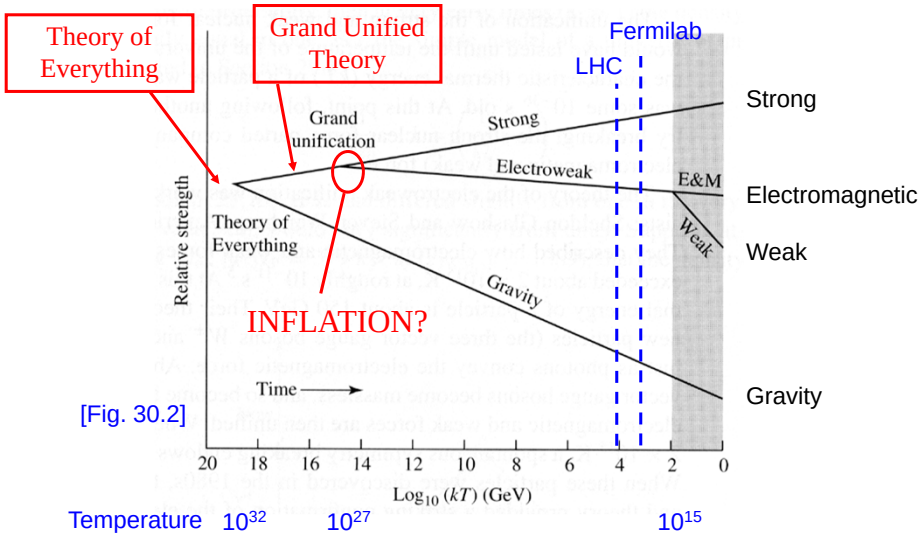
Inflation of universe = 10^{43}

$$\frac{\text{Milky Way Disk}}{\text{electron}} = 10^{36}$$



Before Inflation

Freezing out the forces.

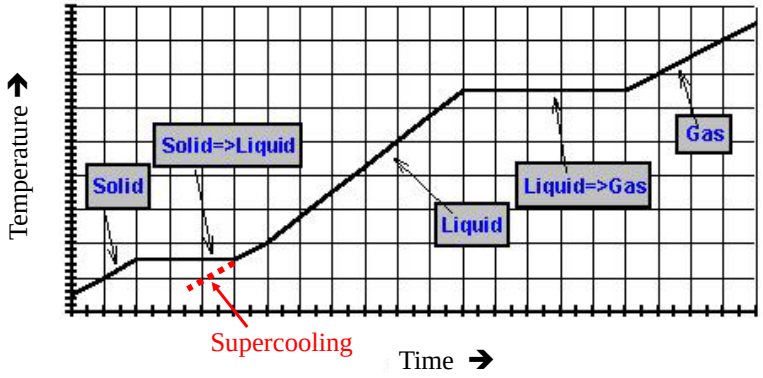


[Fig. 30.2]

Temperature	10^{32}	10^{27}	10^{15}
Age of U	10^{-44}	$10^{-36} - 10^{-34}$	10^{-11}

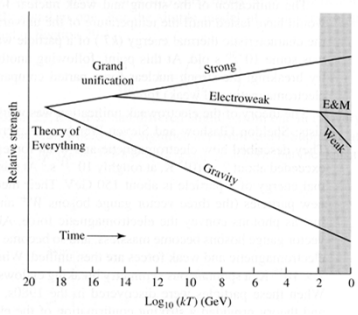
Phase changes and latent heat

- Apply heat energy at a steady rate to a fixed quantity of H_2O
- How does the temperature change?



Inflation

- At *extremely* early stage of universe:
  - $t \sim 10^{-36}$ s
  - $T \sim 10^{28}$ K
  - $r = ct \sim 3 \times 10^{-28}$ m
  - No baryons yet
  - Gravity is a separate force, but E&M, strong, weak forces still joined (GUT)



- Expansion ➔ cooling ➔ "false vacuum"
  - Quasi-stable energy state above true ground state

False Vacuum ➔ Inflation

meaning "ground state"

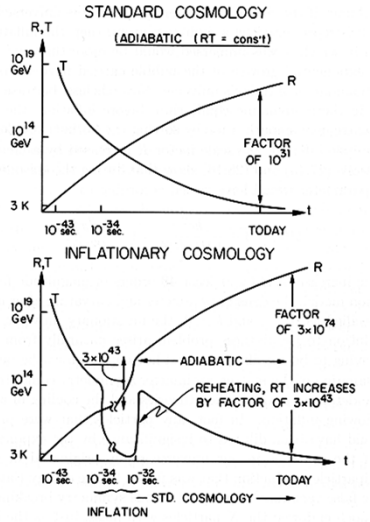
[CO Fig 30.4]

- Fixed energy density.
- Same effect as *large* value of cosmological constant.

$$\left[\left(\frac{1}{R}\frac{dR}{dt}\right)^2 - \frac{1}{3}\Lambda c^2\right]R^2 = -kc^2 = 0$$

$$R(t) = R_i\, e^{(t-t_i)\sqrt{\frac{\Lambda c^2}{3}}}$$ (~0)

- Exponential expansion until universe falls into true lowest energy state.



False vacuum: $u = 10^{98}$ J m^{-3}

Vacuum Energy ≠ Λ

Predict $u_{vac} \sim 2c^7/\hbar G^2 = 10^{\overset{111}{\nearrow}}$ J m^{-3}

vs. Observed $u_\Lambda = 6 \times 10^{-10}$ J m^{-3}

Reheating

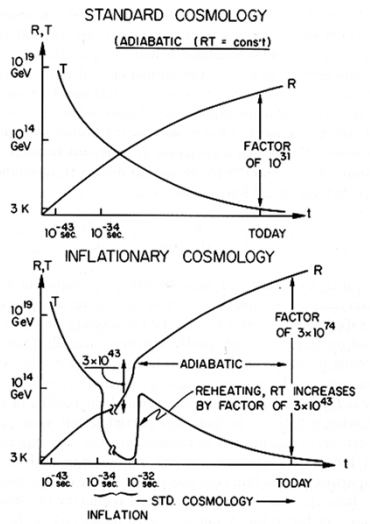
[CO Fig 30.4]

- Then, *reheating*.
  - Vacuum energy density (latent heat) gets converted back to radiation energy.
- Current energy density of CMB radiation (T = 2.725K) :

  $u = aT^4 = 4\times10^{-14}$ J m^{-3}
- GUT epoch ended when T ~ 10^{28}K

  u ~ 8×10^{96} J m^{-3}

same



False vacuum: $u = 10^{98}$ J m^{-3}

Vacuum Energy ≠ Λ

Predict $u_{vac} \sim 2c^7/\hbar G^2 = 10^{\overset{111}{\nearrow}}$ J m^{-3}

vs. Observed $u_\Lambda = 6 \times 10^{-10}$ J m^{-3}

The Syllabus:

Nov 8,10	**The Structure of the Universe & Evolution of Galaxies** [27.3] Clusters of galaxies [28.4] Using quasars to probe the universe (gravitational lenses) *What is dark matter?*
Nov 15,17	[30.2] The origin of structure; WMAP measurements.
Nov 22	[26.1] Interaction of galaxies
Thu Nov 24	**Thanksgiving Holiday**
Nov 29, Dec 1	[26.2] The formation of galaxies
Dec 6,8	Quasars & Active galactic Nuclei (AGN) [28.2] Unified model of AGN … *(Skip [28.1], [28.3])* [18.2] Accretion Disk pp. 661-666 [24.4] The Galactic Center

The agenda:

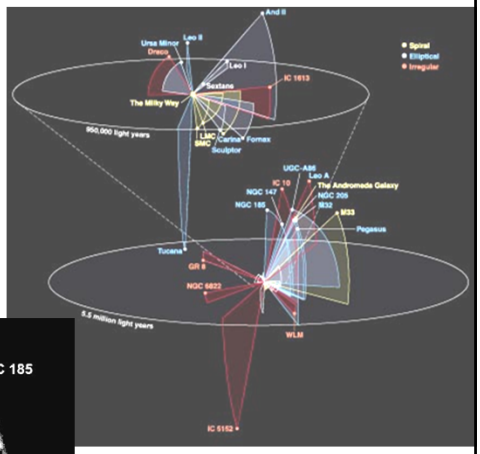
- Present-day structure.
- Evidence for Dark Matter.
  - Gravitational lenses.
- What is Dark Matter?
  - Hot vs. cold DM
- The growth of structure.
  - Initial fluctuations.
  - WMAP.
  - Bottom-up structure formation.

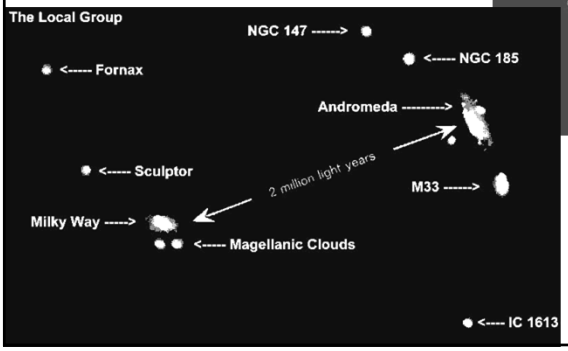
(turkey break)

  - The Quasar Era.
  - Evolution to modern-day galaxies.
  - Chemical enrichment revisited.
  - The first stars.

The Structure of the Universe

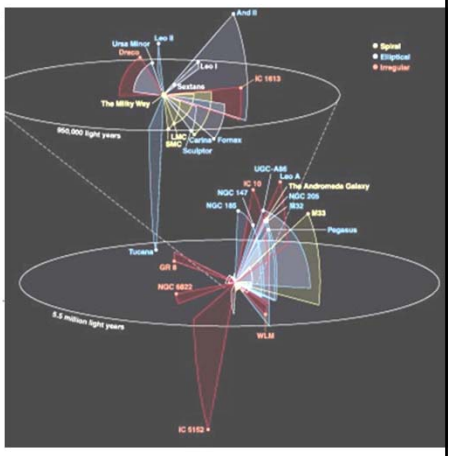
- The Local Group
  - 2 main mass concentrations
    - MW + satellites
      - LMC
      - SMC
    - M31 + satellites
      - M32
      - M33





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

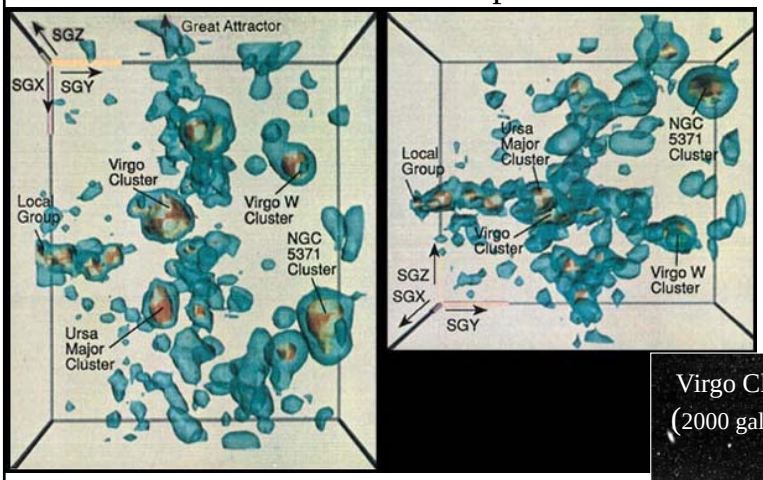
Galaxy	Type	Distance[2] (1000 LY)	Absolute Magnitude	Apparent Magnitude	Diameter (1000 LY)
Milky Way	S(B)bc	26	−20.6	—	130
Andromeda (M31, NGC224)	Sb	2500	−21.2	3.4	200
M33 (NGC598)	Sc	2600	−18.9	5.1	45
Large Magellanic Cloud	Irr	160	−18.5	0.4	20
Small Magellanic Cloud	Irr	192	−17.1	2.0	15
IC10	Irr	2700	−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	—

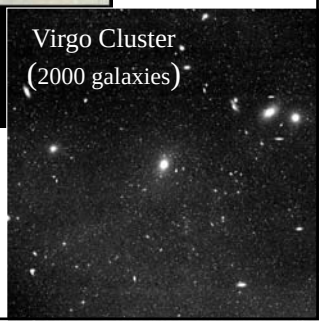


Galaxy Clusters

1000's of galaxies

The Local Supercluster



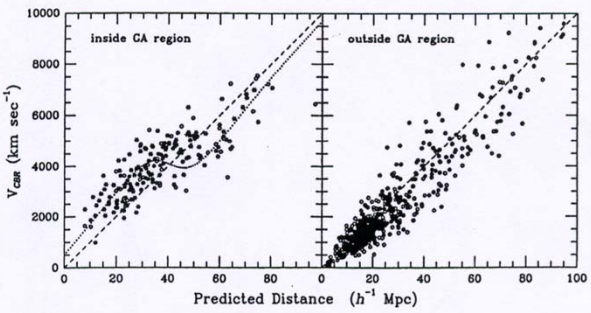


- Biggest component: Virgo Cluster (10^{14} $M_{\odot}$).
- Local Supercluster (10^{15} $M_{\odot}$)

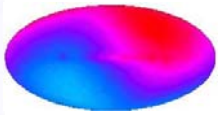
Peculiar motions of galaxies

- Local group within Local Supercluster
  - Virgocentric infall 168 km/s

  ==> Local Supercluster mass ~ $8\times10^{14}h^{-1}$ 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}

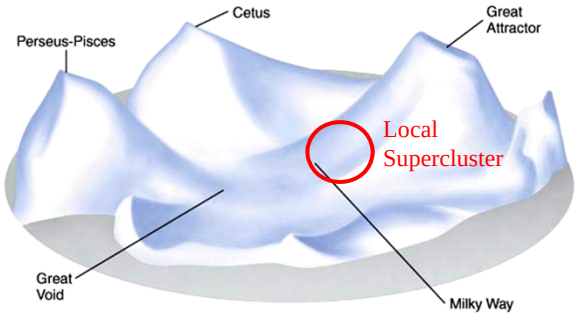


Blue = 0°K
Red = 4°K



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

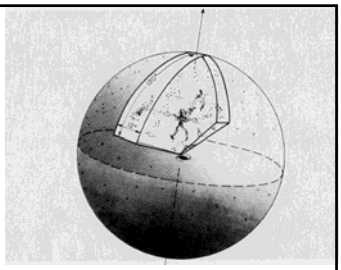
Structure upon structure

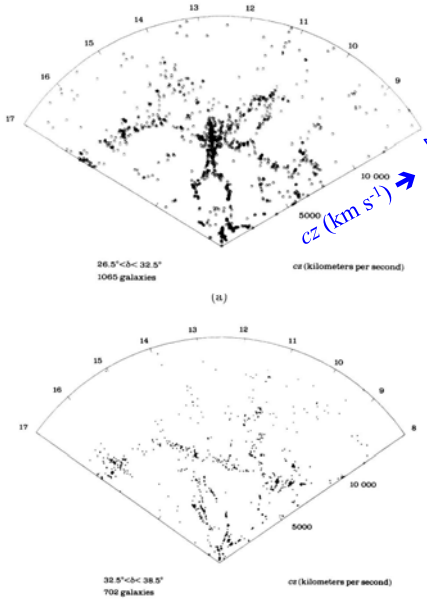


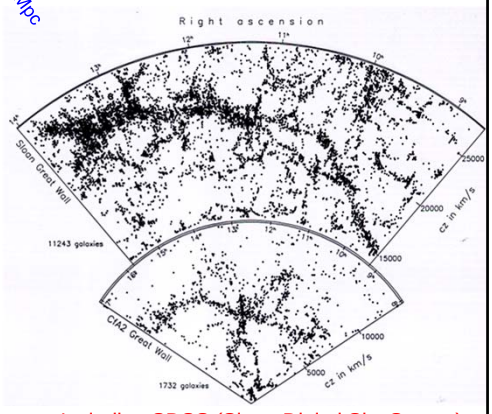
- Local Group
- Virgo Cluster (10^{14} $M_\odot$).
- All part of Local Supercluster (10^{15} $M_\odot$)
- Local Supercluster is part of streaming motion towards "Great Attractor"
  - $10^{16\text{-}17}$ $M_\odot$
  - located 45 Mpc away.
- Detected by extra motions superimposed on "Hubble Flow".

Bubbles and Voids

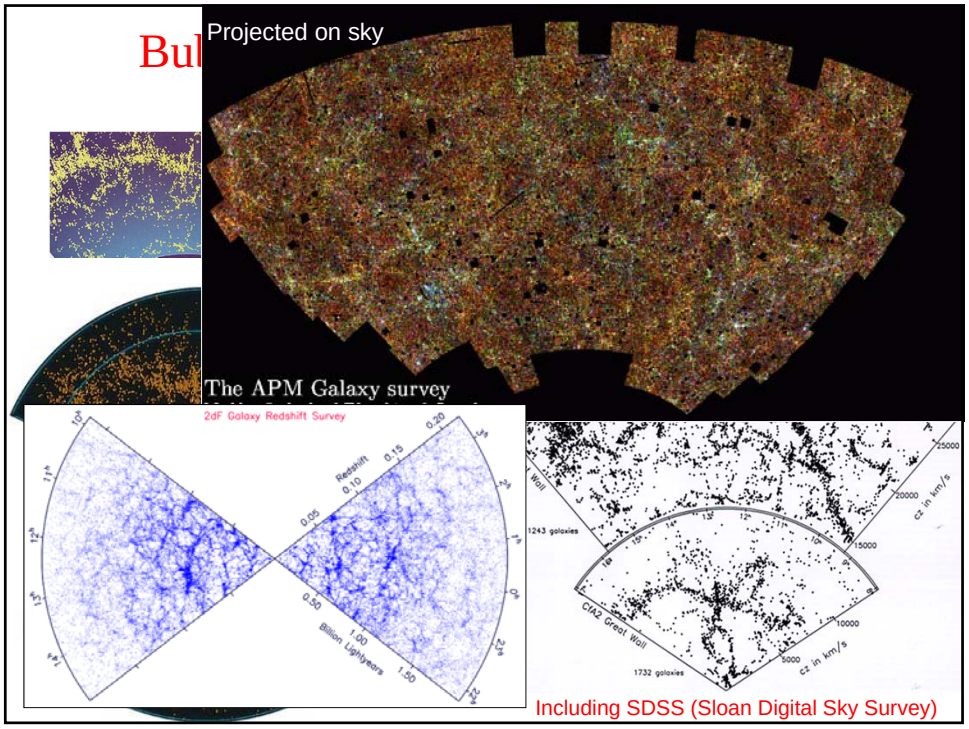
Harvard Center for Astrophysics (CfA) survey (1985)







Including SDSS (Sloan Digital Sky Survey)



The Evidence for Dark Matter

Mass/Luminosity Ratio

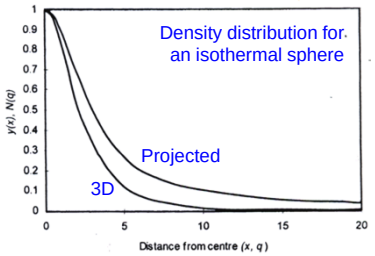
- Local stellar luminosity function: $M/L = 0.67$
- Our Galaxy, at larger scales:
  - Local motions ⊥ disk (Oort limit): $M/L \sim 3\text{-}5$
  - Flat rotation curve > 30
  - Escape speed > 30
  - Pop II dynamics (glob. clusters, etc.) ~ 27

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:

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



  - or… compare surface brightness, velocity dispersions to isothermal sphere model
  - $M/L \sim 12h \sim 9$