Previously:

• How do we measure cosmological parameters?
  – The Hubble constant
    • Measuring v (peculiar velocities)
    • Measuring D (the cosmic distance ladder)
  – Cosmography
    • Luminosity distance and standard candles
  – Cosmic time
    • Ages of the oldest stars
  – Testing the expansion
    • Tolman’s test
Outline:

• Luminous and Dark Matters:
  – Luminous and baryonic matter
  – Dark matter in galaxies
Luminous matter in galaxies

- How much in stars?
  - Luminosity density
  - $M/L$
  - $\Omega^* = 0.004$

- How much gas?
  - In galaxies a similar amount
Intracluster medium

X-ray (plasma at $T \sim 10^8$K) Brehmsstrahlung Emission

$M_{stars} \sim 15\% \ M_{gas}$
Intergalactic medium

- Not hot enough to be seen in X-ray but abundant
- Can be seen in absorption in front of a luminous background source, e.g. quasar or gamma ray burst
Inventory of baryons

How do we know it’s 4% and not more?
Galaxy rotation curves

Circular Orbits
Example: The Milky Way

Stellar mass to light ratio \( \sim 5 \); total mass to light ratio up to 150!
Implications

• There is dark matter, making up 40 times the stellar component: \[ \Omega = 0.004 \times 40 = 0.16 > 0.04 = \Omega_b \]
  – Non baryonic dark matter

• Gravity is wrong at small accelerations (modified newtonian dynamics) [blackboard]
Dark matter in clusters. Virial Theorem

- First evidence for dark matter was actually discovered in clusters
- In the 1930s Zwicky used the virial theorem to derive the mass of the Coma cluster, finding it much higher than that of stars (he didn’t know about ICM)
- Virial Theorem [Blackboard]
Dark matter in clusters.
Hydrostatic Equilibrium

• A second method to determine cluster mass treats the X-ray emitting plasma as a fluid in hydrostatic equilibrium
• Pressure gradients vs gravity
• [Blackboard]
Dark matter in clusters. Implications for cosmology

• If clusters are fair samples of the Universe
• \( \frac{m(\text{baryons})}{m(\text{total})} = \frac{\Omega_b}{\Omega_m} \)
• Baryon density is known from primordial nucleosynthesis 0.04 \( \rightarrow \) \( \Omega_m \approx 0.2-0.3 \)
The End

See you on Wednesday!
(Monday is Presidents Day)