History—27 Apr

• Rate your course
  • And then get 3 clicker pts on angel
• Final Exam
  • Thurs, May 5th, 8:00-10:00pm, VMC E100 (SE corner of Wilson & Bogue)
  • About 70 questions
  • Half on topics covered on previous tests; half on new topics.
  • On Mon., May 9th, you will be able to look at the final on www.loncapa.msu.edu.
• Course grade
  • Final counts 35% of course grade
  • Curved so that class average is about 2.9
  • Study guide is ready (sample questions not ready)
  • See announcement on angel
  • Or go to syllabus and click on “Study Guide” next to Final Exam.
  • Missouri Club (Show me) on Friday during class.
  • No clicker questions.

History—27 Apr

• How and when did galaxies and stars form?
  • 3 min: Helium formed from loose neutrons
  • 300,000 yr: Universe became transparent
  • First stars and galaxies formed at R=1/30-1/11 (80-300Myr)
    • Evidence from computer simulations
    • Evidence from quasars
    • Evidence from WMAP
  • 13.7 Byr: present. Stars and galaxies abound
  • Milky Way
    • Large & Small Magellanic Clouds
    • Many smaller galaxies
  • Andromeda
    • Its satellites

Structure in the Present Universe: Local Group

• Milky Way
  • Large & Small Magellanic Clouds
  • Many smaller galaxies
• Andromeda
  • Its satellites

Structure in the Present Universe: Galaxy Clusters

• Hercules
• Abell 2218
Structure in the Present Universe: Galaxy Clusters

- Virgo Cluster ($10^{14} \, M_\odot$) is nearest big cluster
- Local Super Cluster ($10^{15} \, M_\odot$)

Structure on Larger Scales

- Clusters
- Voids

Before Decoupling

- Forming a star or galaxy
  - By chance there is a denser than average clump of matter.
  - Gravity pulls clump together
  - Gravity of even denser clump grows
  - Clump collapses
- Stars and galaxies cannot form before decoupling
  - Gravity tries to pull a dense clump
  - Radiation & matter are coupled
  - Pressure of radiation resists gravity. Formation fails.

Computer Simulations

- Ingredients of computer simulation
  - Dark matter point masses
    - Does not interact with light
    - Does not hit other dark matter
    - Only interaction is gravity
  - Universe expands
  - Start with random nonuniformity
  - Clustering does reproduce reality
  - Simulation cannot “compute” galaxy formation
    - Requires more complicated physics
      - Gas radiates
      - Interaction between gas & stars: supernovae
Clues from Quasars

- Quasars are black holes fed by gas.
- Quasars formed in dense regions; they must have been first objects to collapse.
- Most distant quasar discovered is at $R=1/5$.

Number of Quasars vs Time

- Number of quasars per unit volume.
- Rate at which stars are formed in galaxies.

Clues from WMAP

- WMAP detected small polarization in cosmic background radiation.
- Scattered light is polarized:
  - Look at reflection off road with your polaroid sunglasses. Then turn sunglasses 90°.
  - Look at sky 90° from sun on clear day with your polaroid sunglasses. Then turn sunglasses 90°.

Clues from WMAP

- WMAP detected small polarization in cosmic background radiation.
- Scattered light is polarized:
  - Look at reflection off road with your polaroid sunglasses. Then turn sunglasses 90°.
  - Look at sky 90° from sun on clear day with your polaroid sunglasses. Then turn sunglasses 90°.

Scattering reduces electric field in paper.

Scattering does not reduce electric field perpendicular to paper.
Clues from WMAP

- WMAP detected small polarization in cosmic background radiation. Polarization is caused by scattering the radiation.
- Un-ionized matter does not scatter light.
- After decoupling, first stars and quasars must have re-ionized the matter.
- First stars & quasars formed at R=1/11+30

- Scattered light can only come from distance
  \[ D = c \times \text{age of universe} \]
- At small angles (large \(l\)), polarization is same b/c light comes from same region of space.

1. If scattering occurs immediately after decoupling (R=1000),
   \[ D= 300,000 \text{lyr} \] & \( l=180 \)

- If scattering occurs at R=100, then peak in polarization occurs at a) \( l=180 \), b) \( l=18 \), c) \( l=4 \), d) very large \( l \).