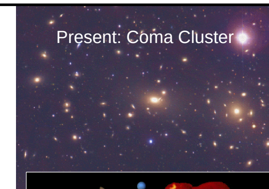
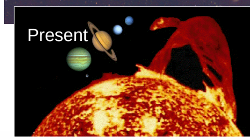
History—27 Apr

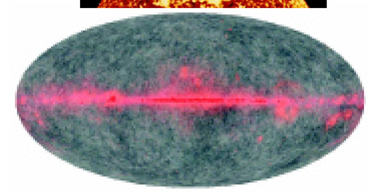
- Rate your course
  - And then get 3 clicker pts on angel
- Final Exam
  - Thurs, May 5^{th}, 8:00-10:00pm, VMC E100 (SE corner of Wilson & Bogue)
  - About 70 questions
  - Half on topics covered on previous tests; half on new topics.
  - On Mon, May 9^{th}, you will be able to look at the final on 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





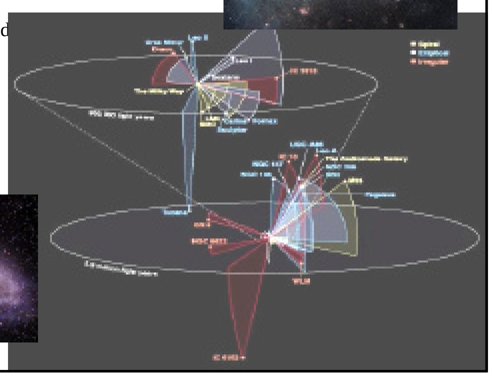
- How and when did galaxies and stars form?
- 3 min: Helium formed from loose neutrons
- 300,000 yr: Universe became transparent
- First stars and galaxies formed at R=1/30-1/11 (80-300Myr)
  - Evidence from computer simulations
  - Evidence from quasars
  - Evidence from WMAP
- 13.7 Byr: present. Stars and galaxies abound

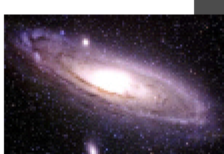


Decoupling: Smooth to 1/100,000

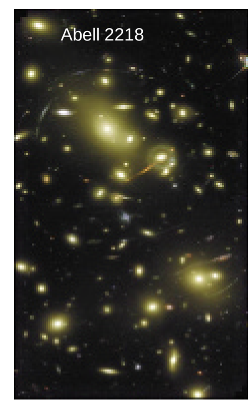
Structure in the Present Universe: Local Group

- Milky Way
  - Large & Small Magellanic Cloud
  - Many smaller galaxies
- Andromeda
  - Its satellites



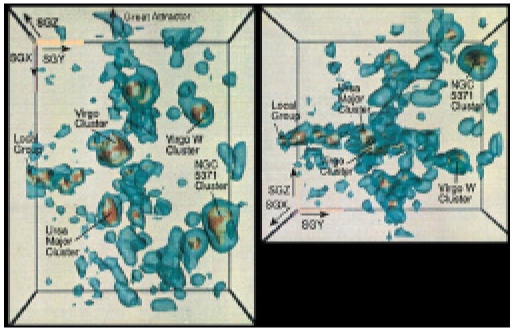


Structure in the Present Universe: Galaxy Clusters



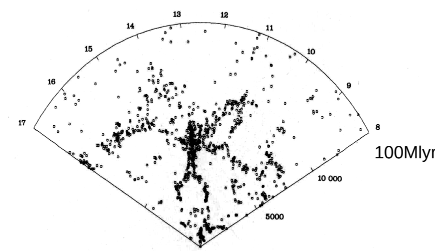
Structure in the Present Universe: Galaxy Clusters

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



Structure on Larger Scales

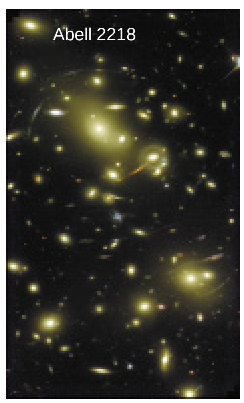
- Clusters
- Voids



100Mlyr

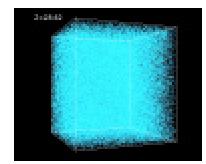
Before Decoupling

- 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



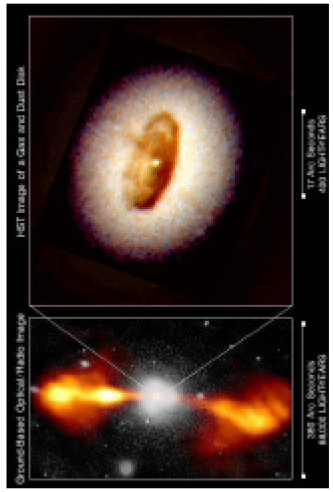
Start with random nonuniformity

End at present time NSCA

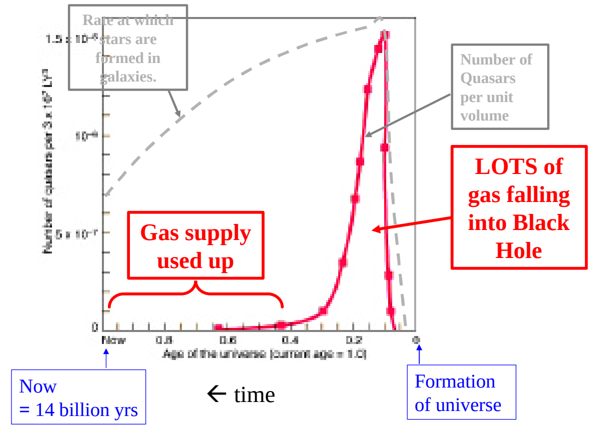
Growth of structure in a box that expands with the universe NCSA

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.

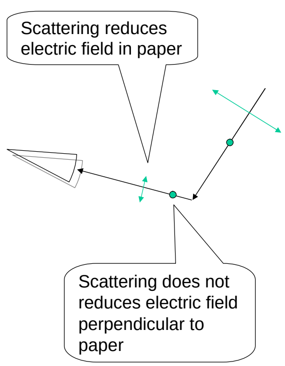


Number of Quasars vs Time



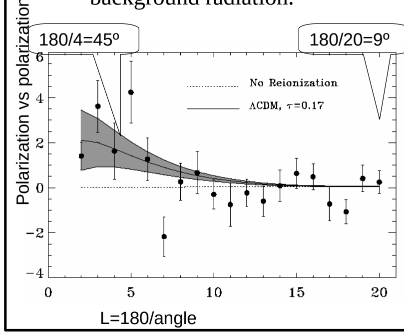
Clues from WMAP

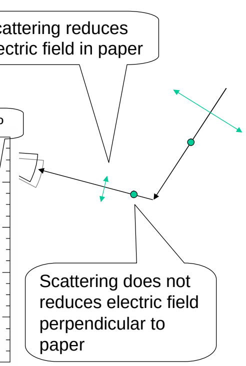
- WMAP detected small polarization in cosmic background radiation.
- Scattered light is polarized
  - Look at reflection off road with your polaroid sunglasses. Then turn sunglasses 90º.
  - Look at sky 90º from sun on clear day with your polaroid sunglasses. Then turn sunglasses 90º.



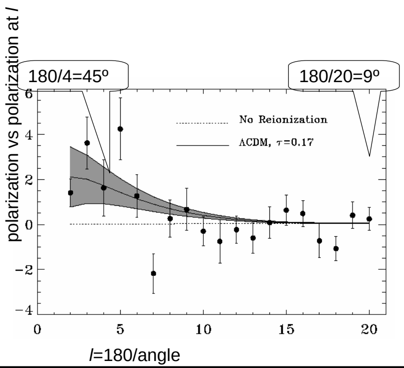
Clues from WMAP

- WMAP detected small polarization in cosmic background radiation.



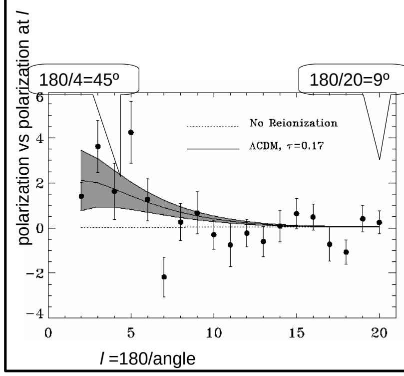


Clues from WMAP



- 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

Clues from WMAP



- Scattered light can only come from distance
  D = c × age of universe
- At small angles (large *l*), polarization is same b/c light comes from same region of space.
- If scattering occurs immediately after decoupling (R=1000),
  D= 300,000lyr & *l*=180

1. 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*.