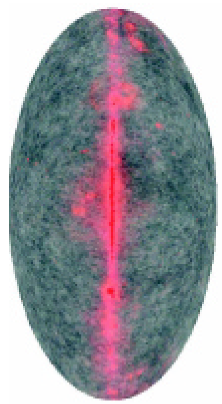
Weighing the Universe with the Cosmic Background Radiation—25 Apr

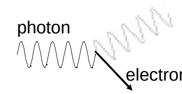
- Decoupling is when universe changed from ionized to neutral and opaque to transparent
- CBR is snapshot of universe at 300,000yr.
- WMAP satellite measured fluctuations in CBR
- Ripples show sound waves at scale of 300,000lyr.
- Angle subtended by "yardstick" => distance => weighing



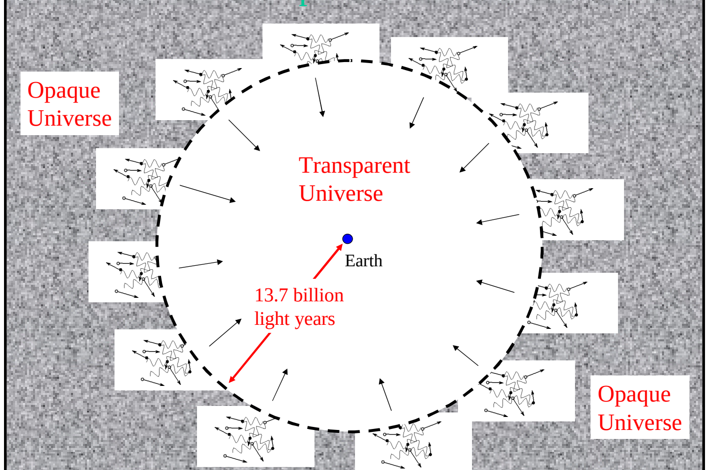
WMAP: Temperature of CBR

Matter and Radiation Become Decoupled

- In early, hot universe, hydrogen is ionized.
  - Protons and electrons are free
- Universe is opaque.
  - Photons travel only short distances.
  - Scattered by free electrons.
  - If earth's atmosphere were ionized, like a fog
- Decoupling: $p + e^- \rightarrow$ H atom
  - T = 3000 K; universe 300,000 yr old.
- Universe is transparent
  - Photons decouple from matter, continue in whatever direction they were moving.

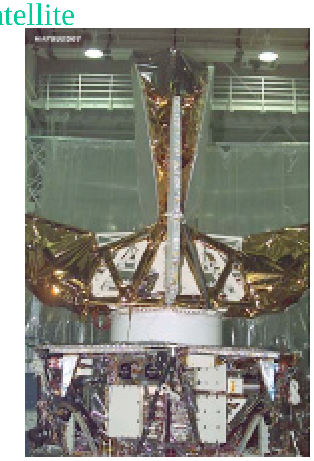


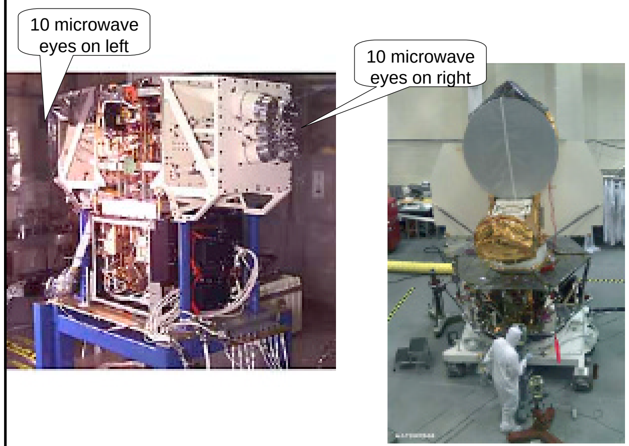
A Snapshot in Time



Wilkinson Microwave Anisotropy Probe (WMAP) Satellite

- Measure spatial variations in temperature of the CBR
- Sensitivity is a part in 100,000. (35/1,000,000 K)
- Anything in the instrument even 0.0001K warmer is fatal.
- Symmetric design
  - Compare temperature between left & right channels



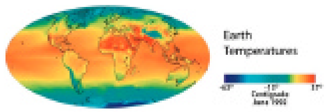


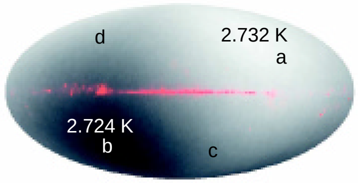
WMAP Results

- WMAP: Temperature of CBR across whole sky
- Notice Milky Way (pink)
- Motion of the earth, sun, MW

1. The earth, sun, and Milky Way are moving toward which direction? In which direction is wavelength compressed

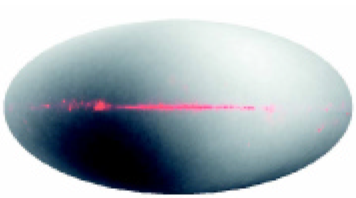
- Speed is 400 km/s

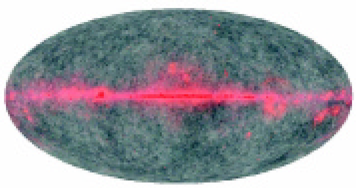




Remove motion

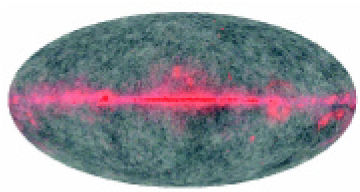
- Remove motion and show with increased contrast
- Largest fluctuations are at an angular scale of 1º.
  - If I look at two points in the sky separated by 0.1º, their temperatures are likely to be the same.
  - If I look at two points in the sky separated by 1º, their temperatures are likely to be different.
  - If I look at two points in the sky separated by 10º, their temperatures are likely to be the same.
- This is a method to weigh the universe.





Angular scale ⇒Weighing the Universe

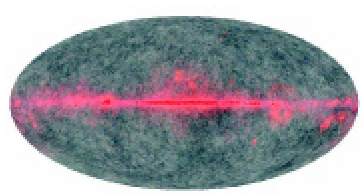
- Largest fluctuations are at an angular scale of 1º.
- This is a method to weigh the universe.
- A “yardstick” is like a standard candle.
  - Flux = Luminosity/D^2.
  - Angle = Length/D.
- Yardstick is size of fluctuations at 300,000yr
- L=1/3 speed of light * 300,000 yr



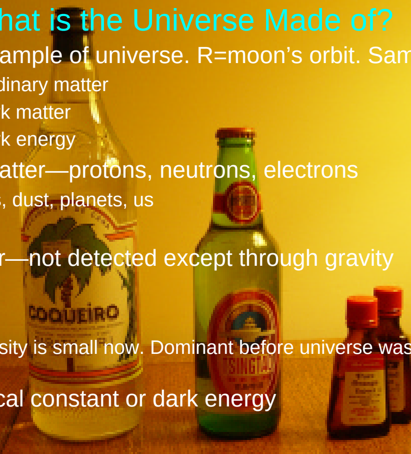
Angular scale ⇒Weighing the Universe

- Largest fluctuations are at an angular scale of 1º.
- This is a method to weigh the universe.
- A “yardstick” is like a standard candle.
  - Flux = Luminosity/D^2.
  - Angle = Length/D.
- Yardstick is size of fluctuations
- If a supernova is faint, the expansion took longer, and the universe has less mass.

2. In which case does the universe have the most mass? The fluctuations occur at an angular scale of a) 0.5º, b) 1º, c) 2º, d) 10º.



What is the Universe Made of?



- Spherical sample of universe. R=moon’s orbit. Sample has
  - 3 oz of ordinary matter
  - 1 lb of dark matter
  - 3 lb of dark energy
- Ordinary matter—protons, neutrons, electrons
  - Stars, gas, dust, planets, us
  - 4%
- Dark matter—not detected except through gravity
  - 23%
- Light
  - Mass density is small now. Dominant before universe was 1 Million years old
- Cosmological constant or dark energy
  - Repulsive
  - 73%