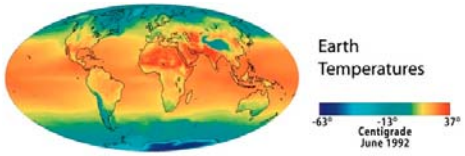
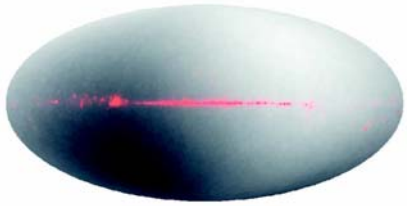
Universe at 400,000yr—30 Nov

- Hwk 9 & many hwk8 grades have not been recorded on angel.
- Cosmic background radiation is a snapshot of U at 400,000 yr.
  - Radiation from the Big Bang separated from matter when universe became neutral (not ionized) at a=0.001.
- What is in the snapshot?
  - Examine snapshot to a very fine accuracy (1part in 10^5)
  - History of MW & local group: motion of 300km/s
  - Fluctuations at an angular scale of 1°.
  - Growing clumps of mass ⇒ mass density of the universe
  - Evidence of first stars



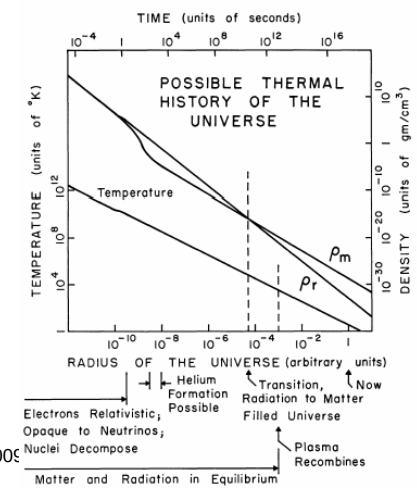


Temperature of radiation from Big Bang, measured by WMAP satellite

What of the universe's history can be observed?

Bob Dicke
1916-1999

- Penzias & Wilson, 1965, "A measurement of the excess antenna temperature at 4080Mc/s," ApJ 142, 419
  - "The excess temperature is … isotropic, unpolarized, and free from seasonal variation."
- Dicke, Peebles, Roll, & Wilkinson, 1965, "Cosmic Black-body Radiation," ApJ 142, 414.
  - "Could the universe have been filled with black-body radiation from this possible high-temperature state?"
- Time line of observable events (from Dicke's paper)
  - Before 3min, nothing is observable, because universe is opaque.
  - Formation of helium, ^{2}H, ^{3}He, & ^{7}Li at 3min.
  - Plasma recombines at 0.5Myr. Matter becomes un ionized. Universe becomes transparent.
  - Stars & galaxies form at 200Myr. (from Dicke's paper)



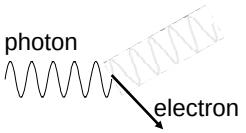
Ionized/un-ionized gas

- Ionization is the loss of an electron.

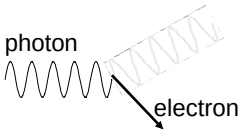
  H atom $\rightarrow$ p + e^-
- Recombination is when electron and nucleus combine.

  p + e^- $\rightarrow$ H atom
- Ionization occurs if the temperature is hot enough.
- Name one thing in this room that is/has ionized gas.
  - Fluorescent light
  - Air
  - Air in my lungs

- Light scatters poorly off of electrons bound in an atom or molecule.
- Light scatters readily off of free electrons.



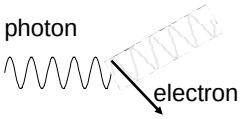
- If the air were ionized, light would travel 500m before it is scattered. Light scatters nearly equally in all directions.
- If the air were ionized, could you, sitting in Spartan Stadium, watch the Spartans beating Michigan? Could you see stars at night?
  - YY
  - YN
  - NY
  - NN



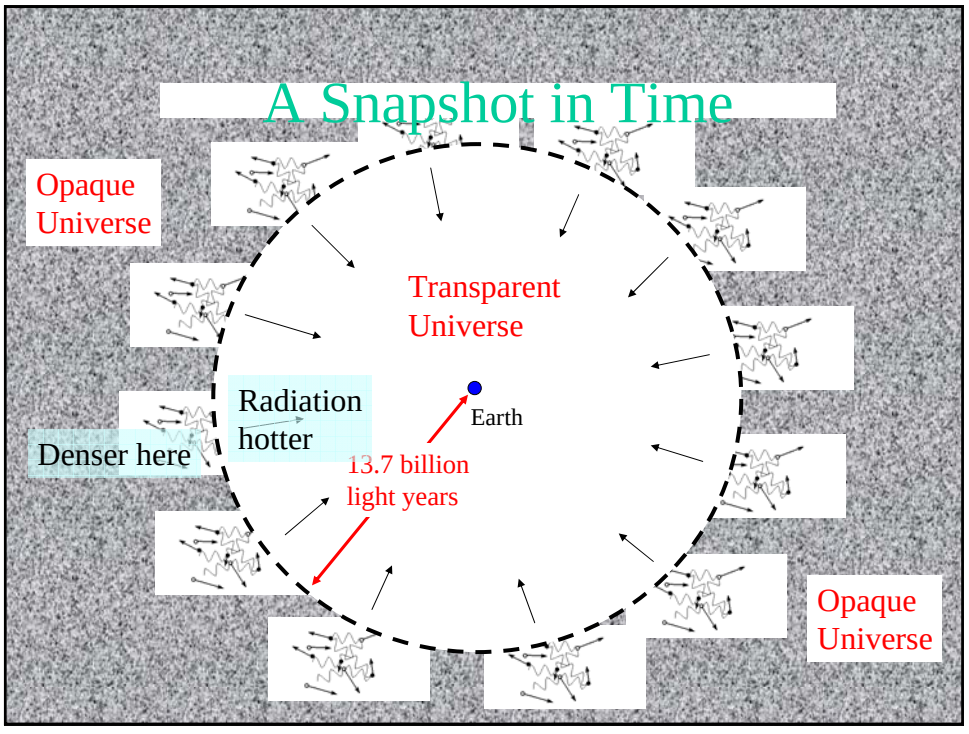
- If the air were ionized, the air would be a fog.

Matter and Radiation Decoupled

- Early, hot universe
  - Hydrogen is ionized.
    - Protons and electrons are free
  - Universe is opaque.
    - Photons travel only short distances.
    - Scattered by free electrons.

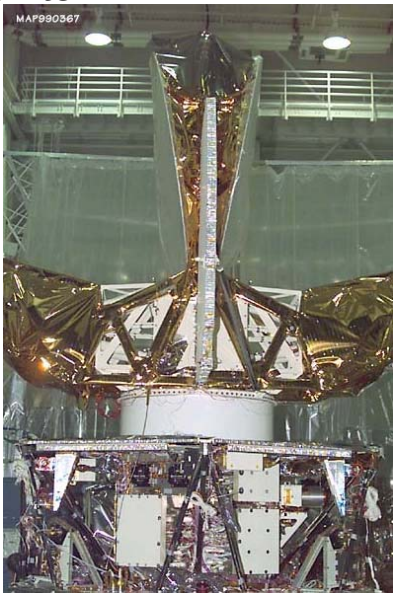


- Decoupling: $p + e^- \rightarrow H$ atom
  - T = 3000 K; universe 400,000 yr old.
  - Universe becomes transparent
    - Photons decouple from matter, continue in whatever direction they were moving.
- After decoupling
  - Photons travel in same direction. Preserves information about the matter at decoupling.
  - In certain directions, matter & light were slightly more dense. Light preserves that information.

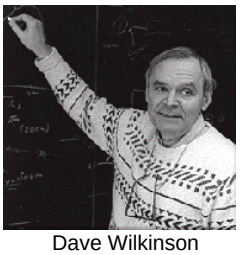


Wilkinson Microwave Anisotropy Probe (WMAP) Satellite

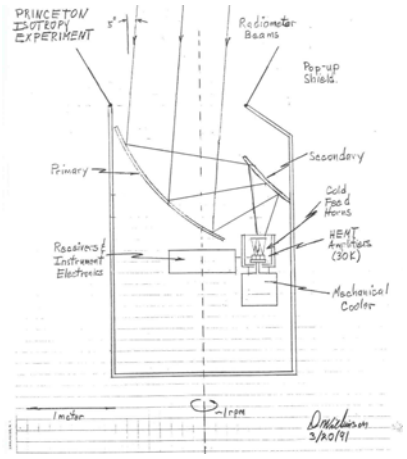
- Measure spatial variations in temperature of the CBR
- Sensitivity is 0.000035K (a part in 100,000).
- Anything in the instrument even 0.0001K warmer is fatal.
- Symmetric design
  - Record temperature difference between left & right channels. Temperature difference is small.
  - Rotate entire instrument.
    - Instrumental problems do not change; radiation from the sky does change.



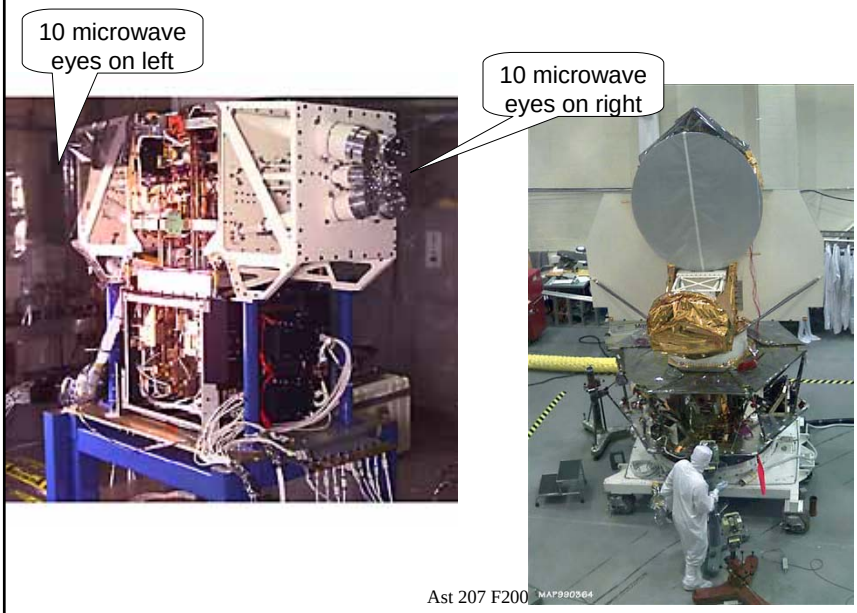
Wilkinson Microwave Anisotropy Probe (WMAP) Satellite



Dave Wilkinson
1935-2002, b. Hillsdale MI



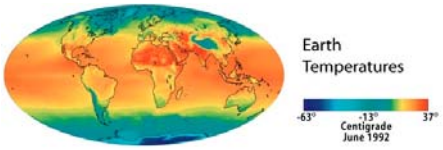
Dave's notebook 3/20/1991, Greg Tucker

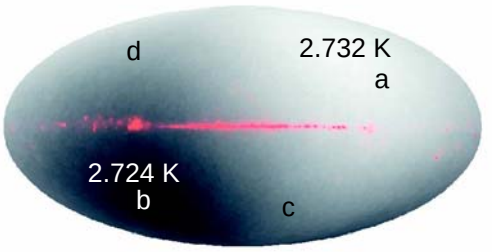


Local Motion

- WMAP: Temperature of CBR across whole sky
- Notice Milky Way (pink)
- Earth, sun, MW, & local group of galaxies move at 300 km/s with respect to whole universe.

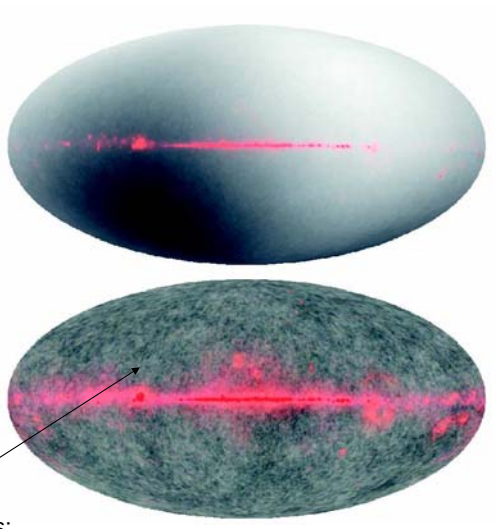
1. The earth, sun, and Mil Way are moving toward which direction? In which direction is wavelength compressed





Remove motion

- Remove motion and show with increased contrast
- Largest fluctuations are at an angular scale of 1º.



Temperature fluctuations:
Light & dark mottling