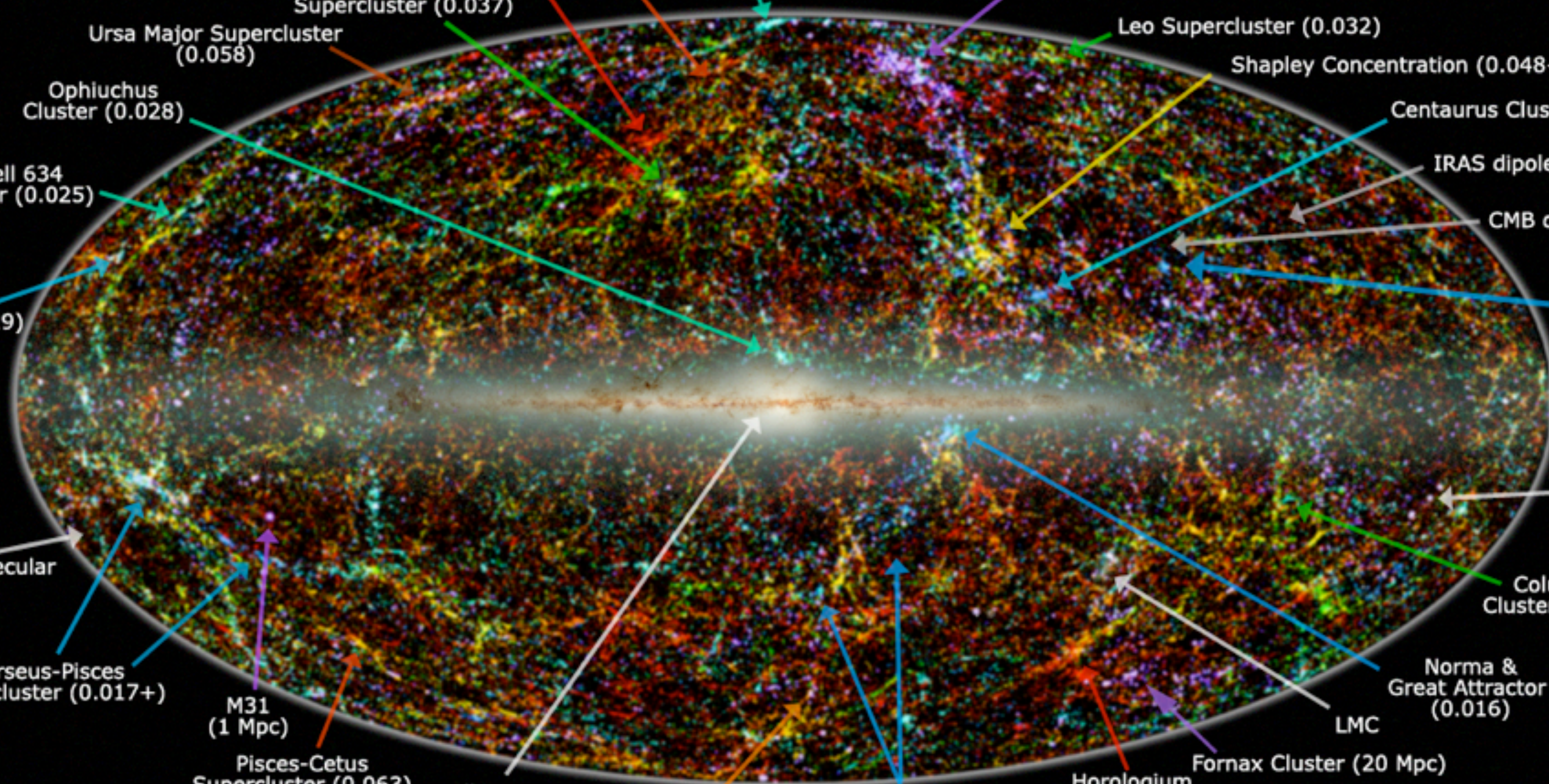
Large Scale Structure in the Local Universe



Legend: image shows 2MASS galaxies color coded by redshift (Jarrett 2004);
familiar galaxy clusters/superclusters are labeled (numbers in parenthesis represent redshift).
Graphic created by T. Jarrett (IPAC/Caltech)

ASTR 1120
Stars and Galaxies
Week 5: Cosmology
The CMB and the Big Bang

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August 2nd, 2010

Outline

- What is a “cosmology” and what competing theories are there?
- History of the CMB
- Where did it come from?
- What does it tell us?

Cosmology

- “Theory of the Universe”
- Historically, has included “creation stories” and gods
  - Geocentric theories
  - Infinite universe with finite or infinite matter
- Modern scientific theories included a Steady State theory and the Big Bang theory
  - Steady State: The universe is constant and unchanging, possibly infinite but with a fixed amount of matter (OR: expanding, with matter constantly being created)

Cosmologies

What distinguishes ancient cosmologies from modern cosmologies?

A) Only modern physical cosmology is consistent with the best observations of the time

B) The prevailing cosmological theory was only culturally influential in ancient times

C) Modern physical cosmology is based off of rigorous scientific experimentation

D) Modern physical cosmology has resolved all unsolved questions about the universe

The Big Bang Theory

- The universe is probably infinite, but started at a point in time so only a finite portion is observable
- Pretty much everything formed in the first second of the universe
    - The chemical composition of the universe was determined at this time
- The universe is expanding and changing

Theory

What distinguishes a good (useful) scientific theory from an unscientific one?

A) A good theory is one that is right

B) A good theory makes testable predictions that allow it to be proved wrong

C) A good theory can be adapted within its own framework to explain any evidence

D) A bad theory will include strong statements about the way things work given an initial set of assumptions

The Story

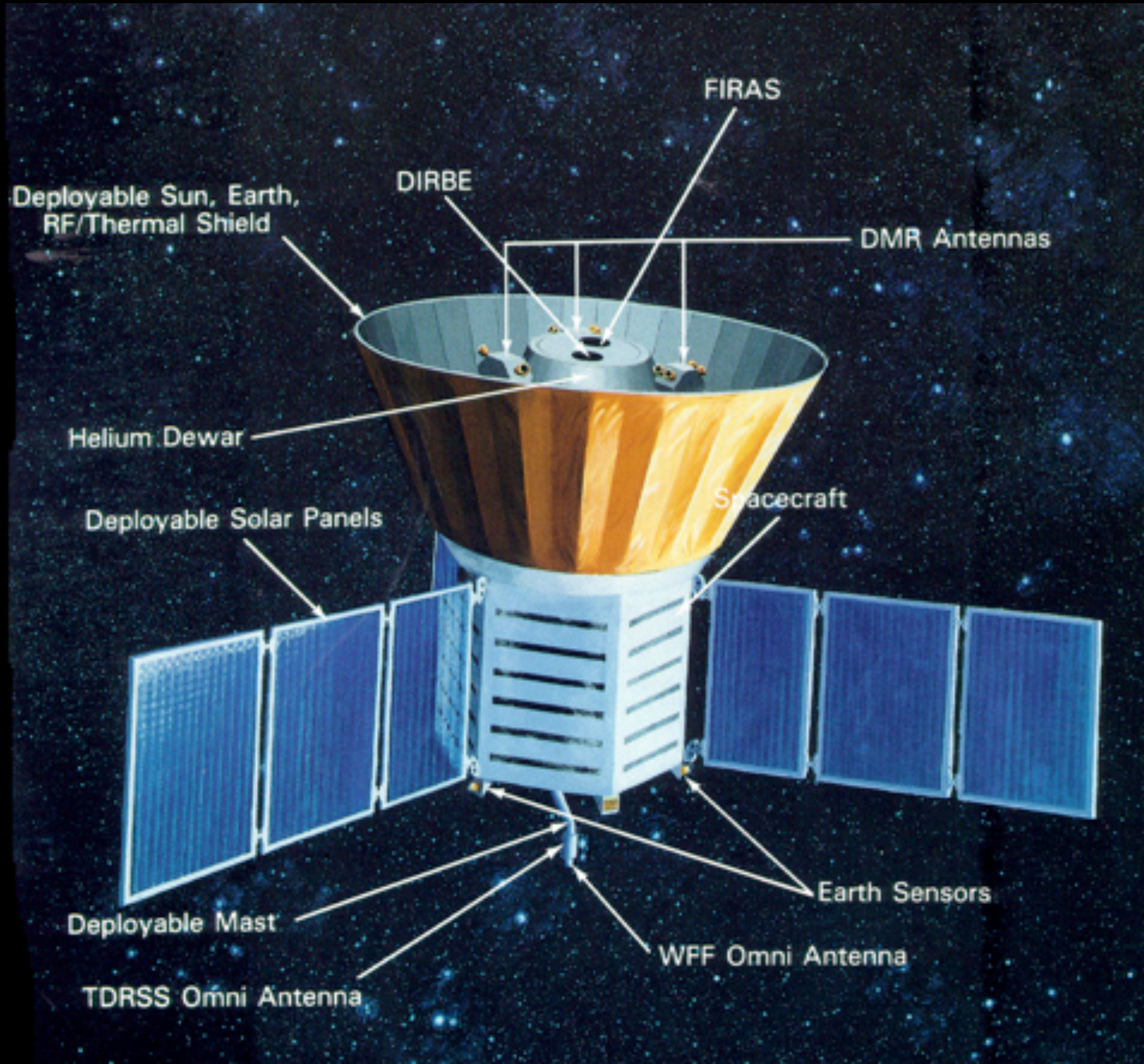
- Arno Penzias and Robert Wilson discovered the CMB with the 7m horn at Bell Labs
- Detected an "excess noise" that corresponded to a 2.73 K blackbody that filled the sky
- Won the 1978 Nobel Prize

Science Research

- The CMB was discovered at AT&T’s Bell Laboratory using a telescope intended for communications research
    - AT&T was a monopoly, and therefore willing to commit a lot of money to “pure research” without promise of sellable results
- Today, that doesn’t happen - nearly all astronomy is publicly funded via the National Science Foundation (NSF) or NASA

Discovery, then follow-up

- The COsmic Background Explorer (COBE) was developed by Mather & Smoot (also won a Nobel)
- Contained detectors to measure the spectrum of the CMB and to measure subtle differences in the CMB radiation across the sky



CMB spectrum

What kind of spectrum would you expect to see from the CMB?

A) Absorption

B) Emission

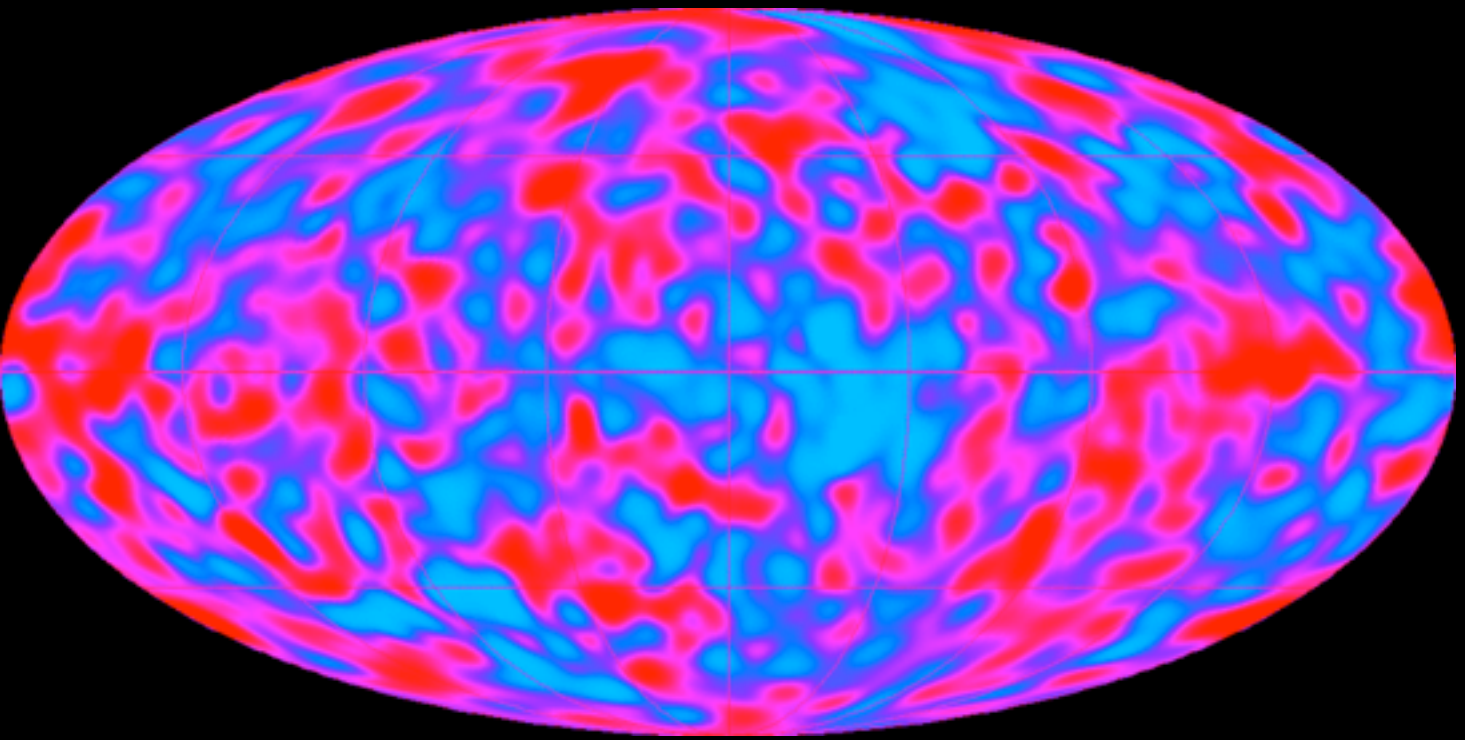
C) Continuum

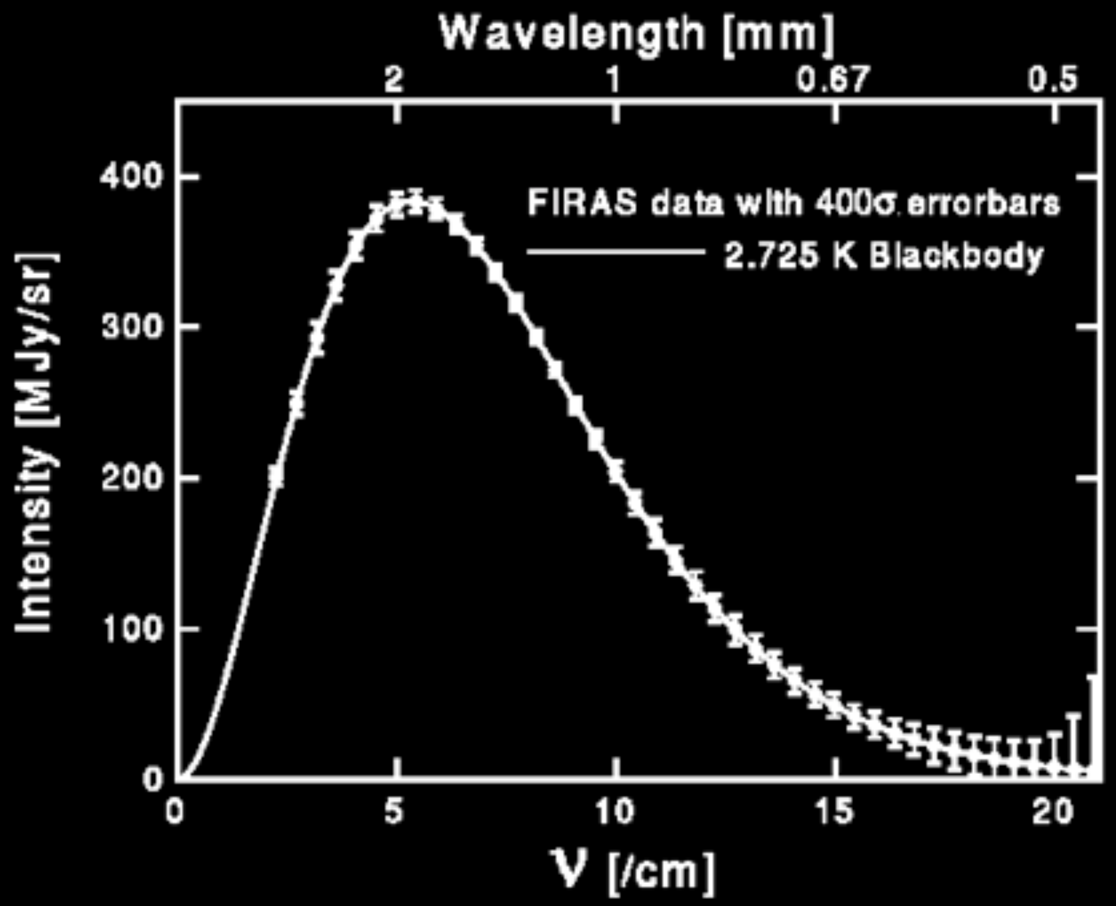
D) Emission + Continuum

E) Something else?

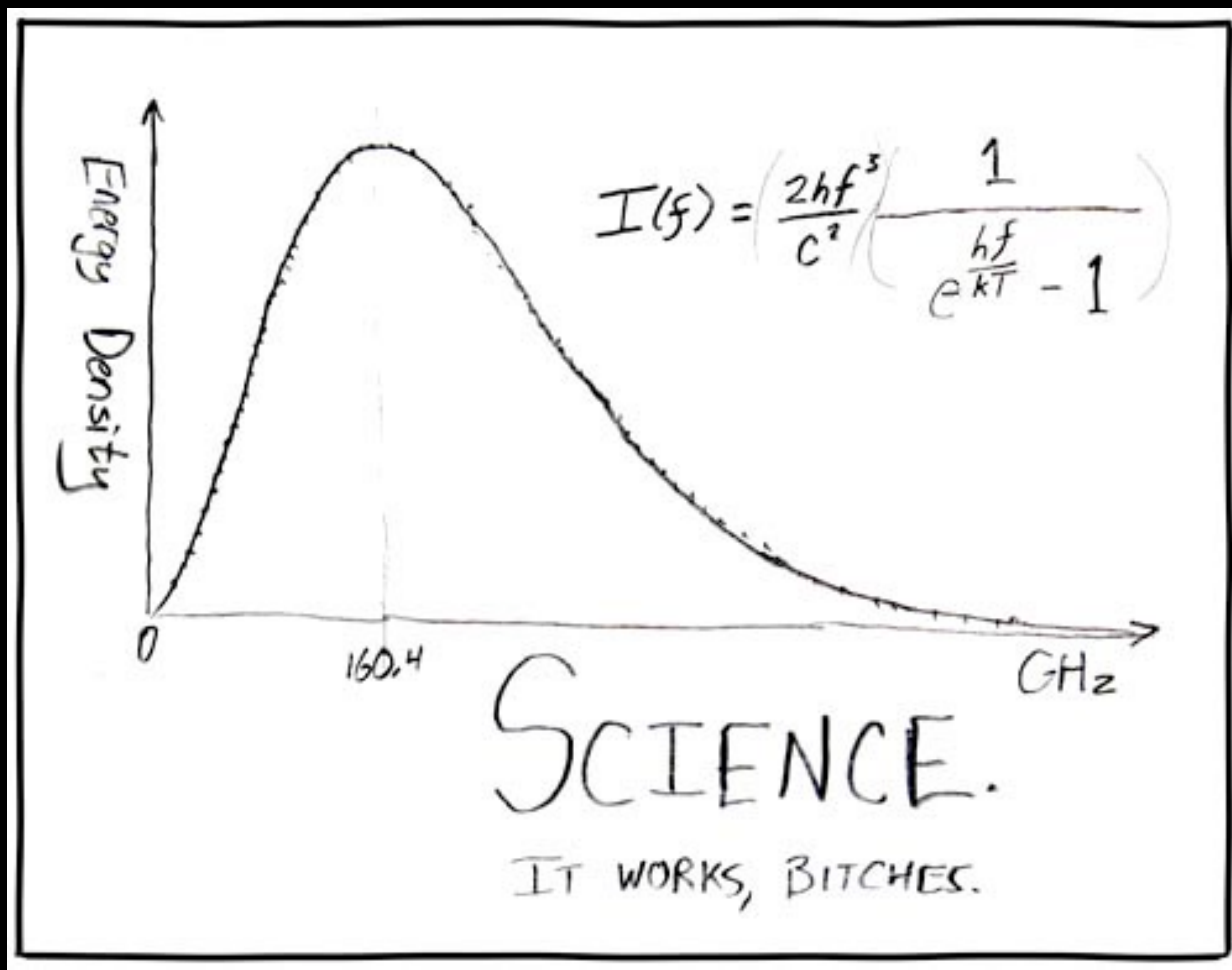
COBE discoveries

- The spectrometer, FIRAS, discovered that the CMB is the most perfect blackbody in nature, with only 0.1% deviations from theory
- Small deviations in the CMB proved that there are things called “CMB anisotropies” that reveal many details about the universe’s early history



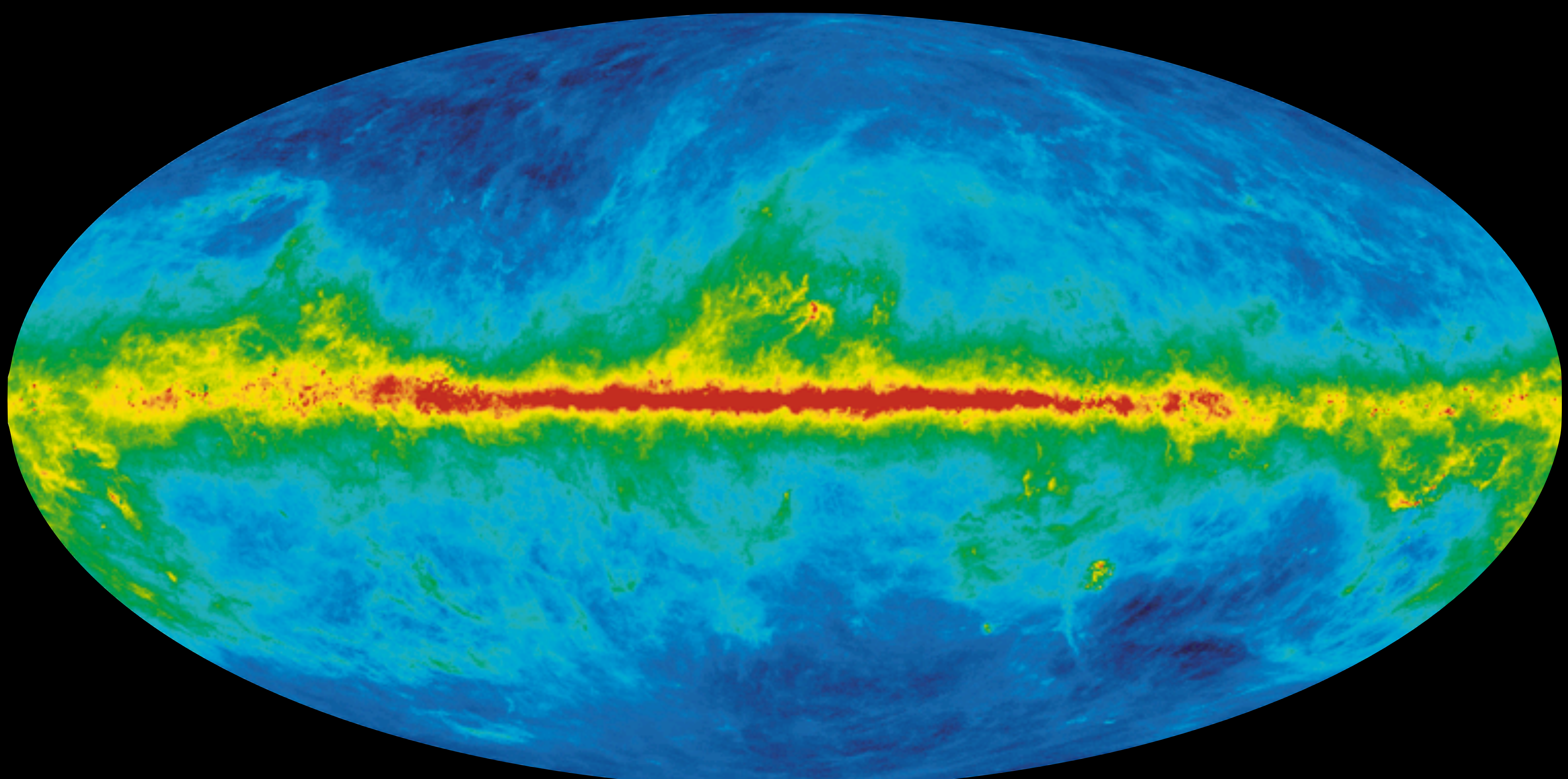


Just for emphasis...



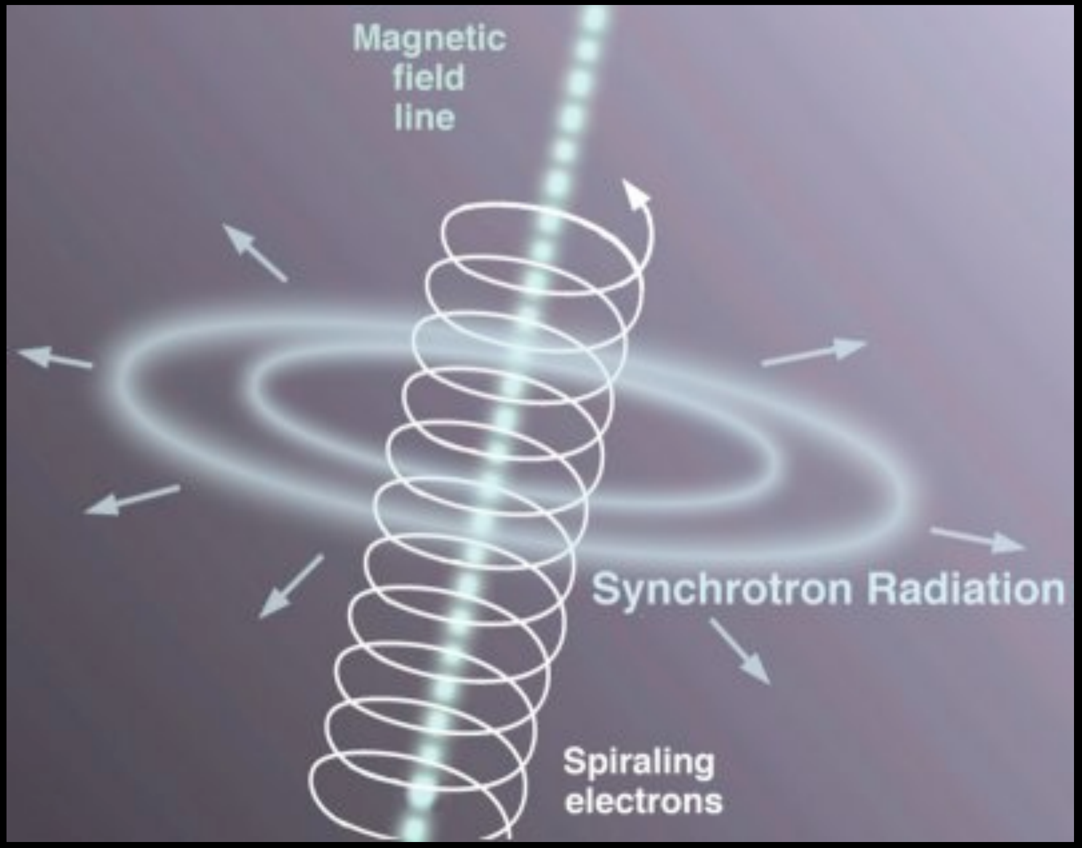
Problems....

- CMB is in the background... what's in the foreground?



Gas, Dust, and...

- Synchrotron Radiation
  - Electrons moving around magnetic field lines at “relativistic speeds” (~99% the speed of light) generate continuum radiation
  - It looks different from a blackbody: it *increases* at longer wavelengths



CMB spectrum again

What kind of spectrum would you expect to see from the CMB plus the foregrounds?

A) Absorption

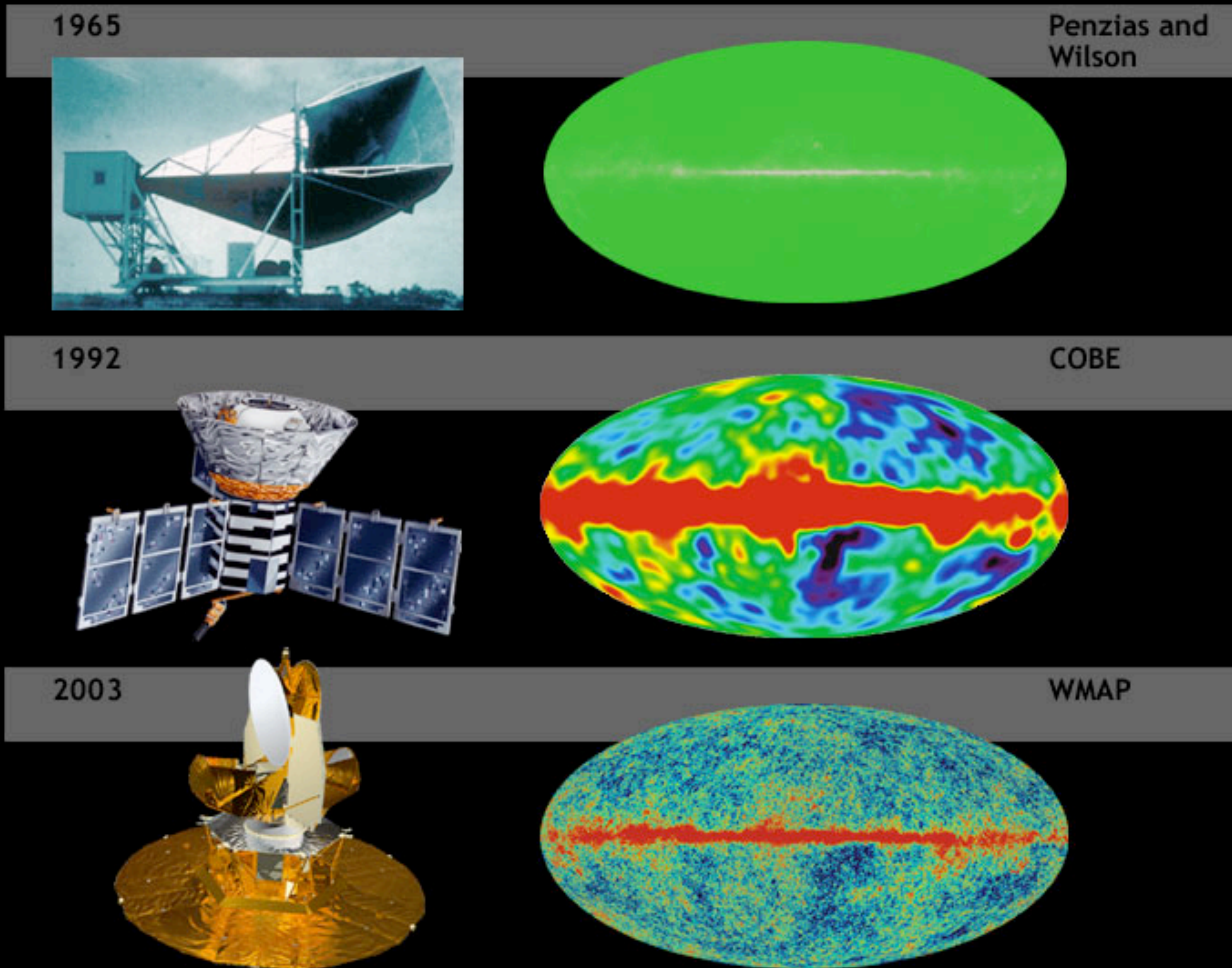
B) Emission

C) Continuum

D) Emission + Continuum

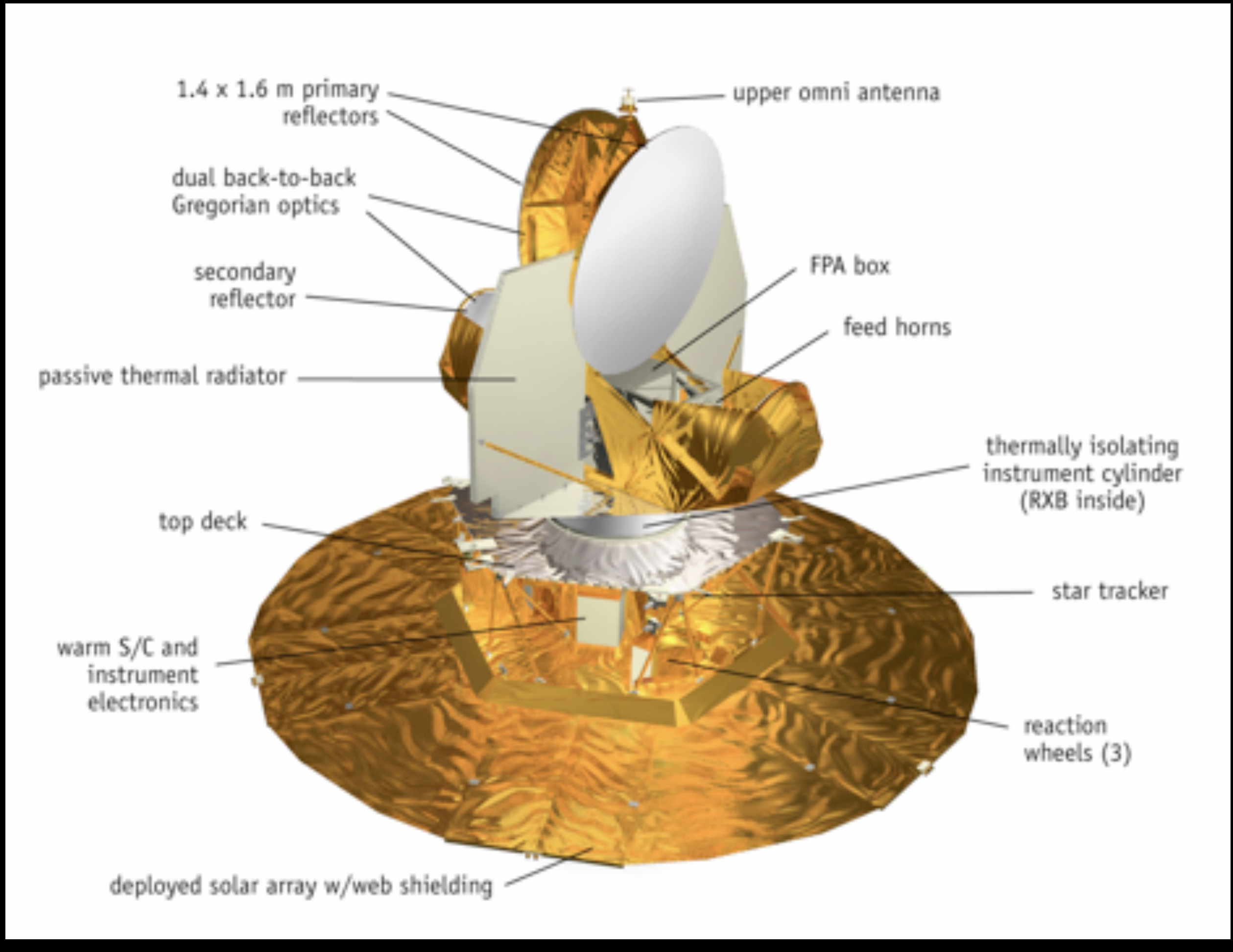
E) Something else?

Next stop... WMAP



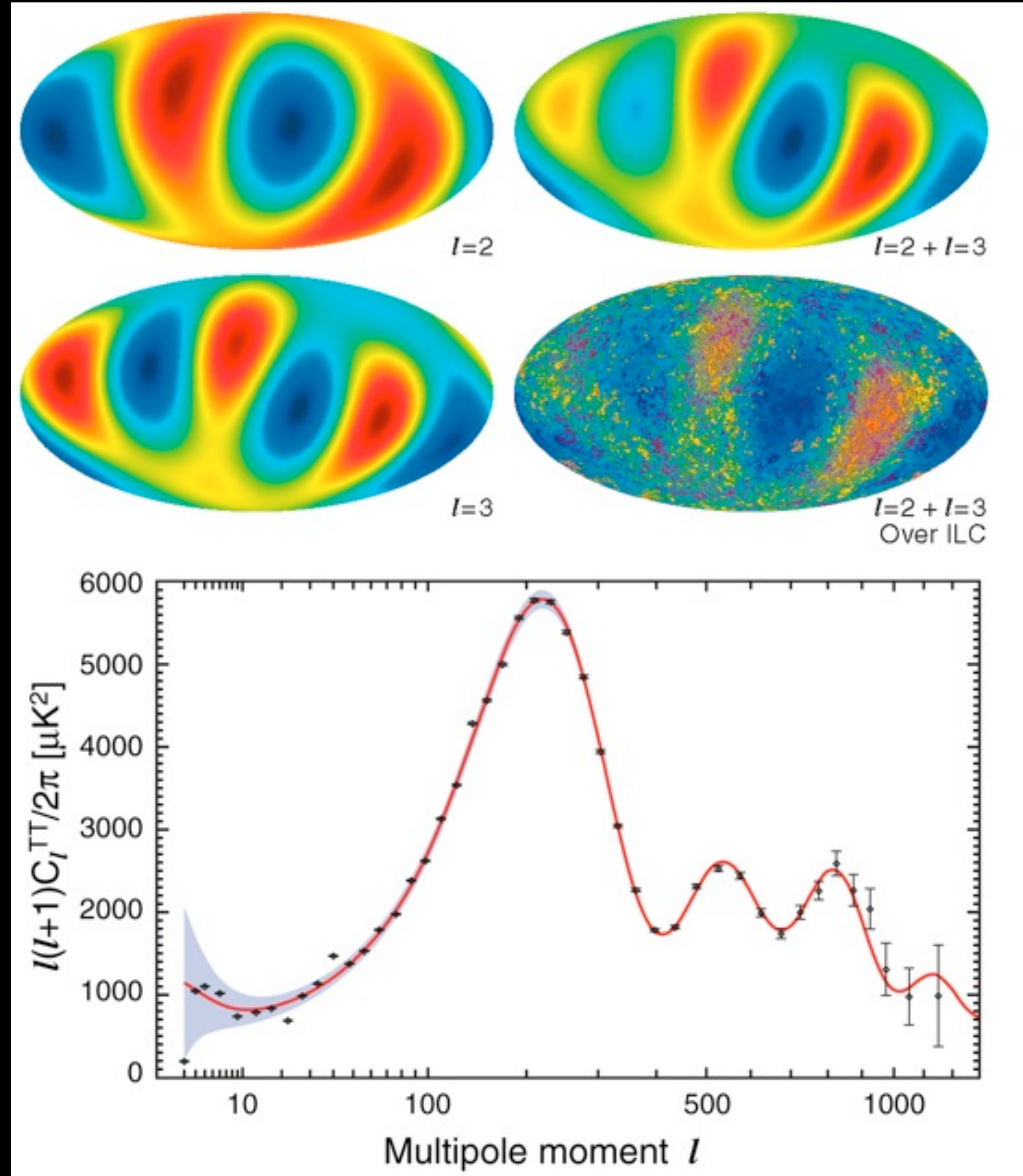
WMAP

- Mission: Obtain precise measurements of "cosmological parameters" by measuring CMB anisotropies
  - Accurate determination of the Age of the Universe (1/Hubble's Constant), the amount of dark vs baryonic matter in the universe, and the total density of the universe

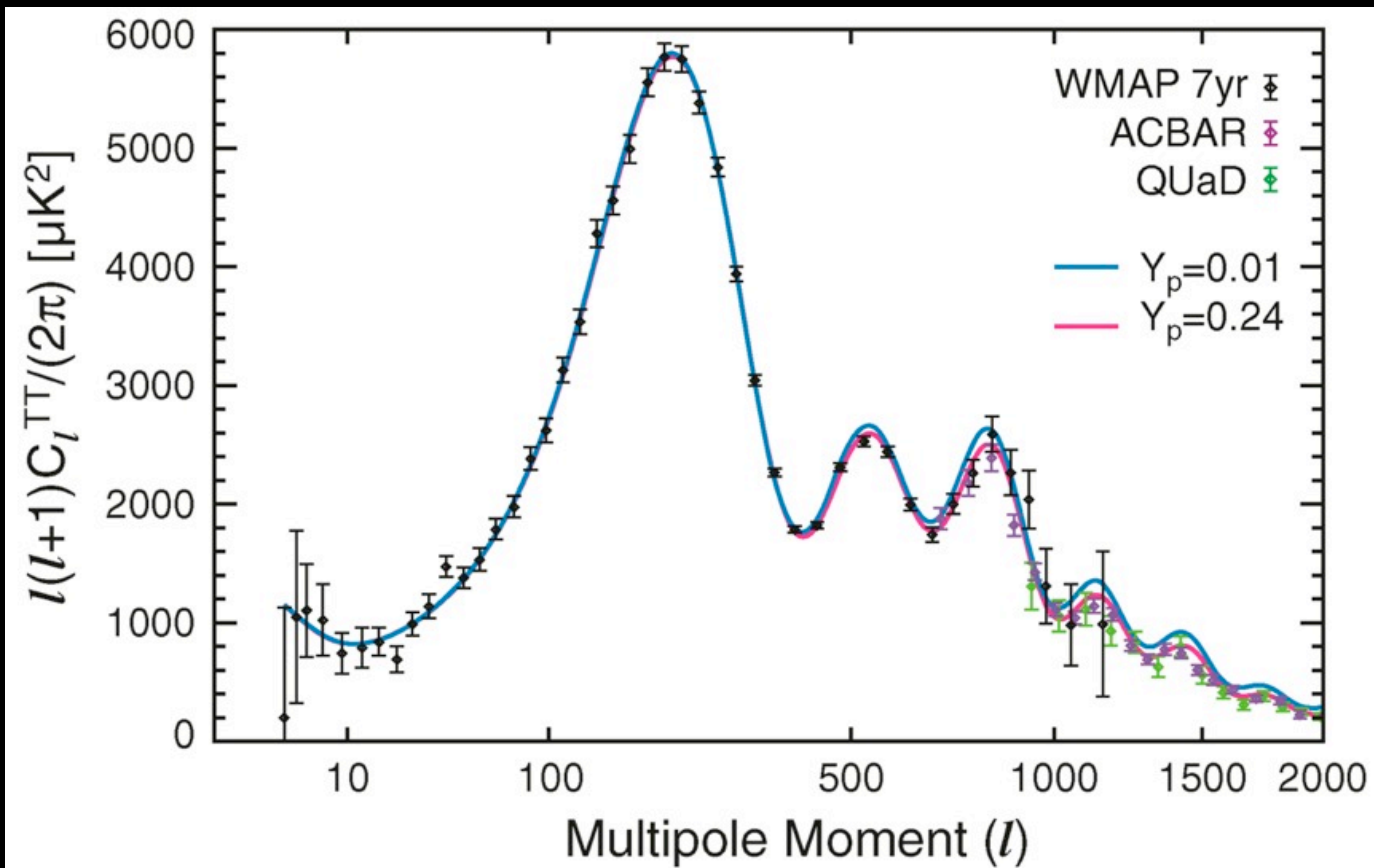


Anisotropies

- There are large-scale correlations of “anisotropies” (small temperature differences) in the CMB
  - Different theories predict different “power spectra” - the one we measure is very consistent with the Big Bang

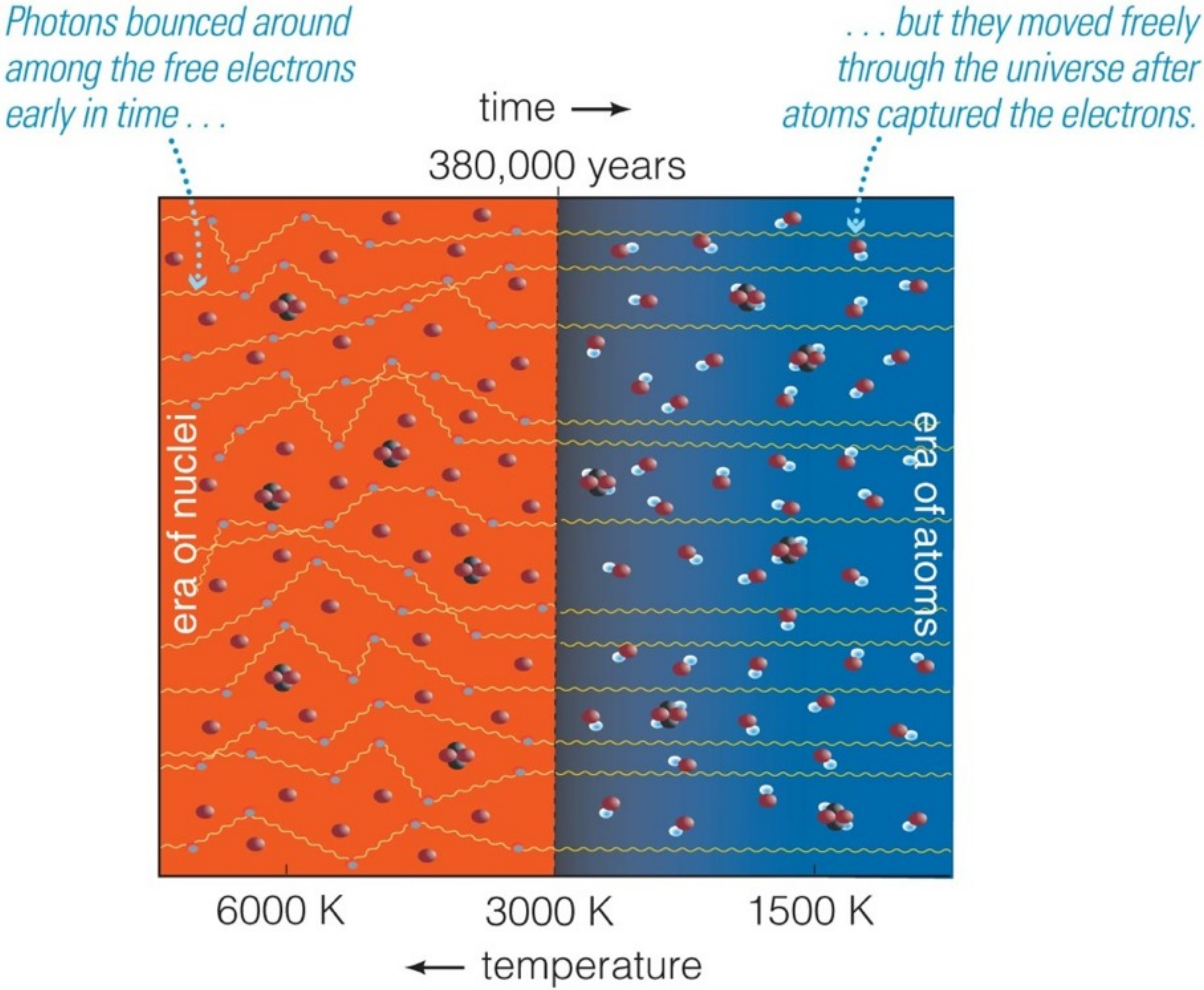


Example: Primordial Helium Abundance



What *is* the CMB?

- The "Surface of Last Scattering" in the universe
  - Like in a stellar photosphere, ionized gas is opaque
  - Neutral gas is transparent at most wavelengths
  - Around 3000K (380,000 years after the Big Bang), hydrogen starts to "recombine" from protons + electrons into atoms


Photons bounced around among the free electrons early in time . . .
. . . but they moved freely through the universe after atoms captured the electrons.
time →
380,000 years
era of nuclei
era of atoms
6000 K
3000 K
1500 K
← temperature

REVIEW: What causes the structures we see on the sun's surface?

A) Continents and oceans like on Earth

B) Convection Cells bringing hot gas up and cold gas down

C) Magnetic field structures creating round hot-spots bordered by cold spots

D) Aliens

What are the slight fluctuations seen in maps of the cosmic background radiation?

A. uncertainties in the map

B. variations in the instrument’s sensitivity

C. dust patches blocking background light

D. dark matter convection cells

E. none of the above

CMB Anisotropies

- CMB anisotropies are small variations in the density of matter when the universe was 380,000 years old
    - therefore they represent the very first phase in the formation of Large Scale Structure

What is the furthest back in time we can see, using telescopes at any wavelength?

A. To the beginning of the era of galaxies (1 billion years after the Big Bang)

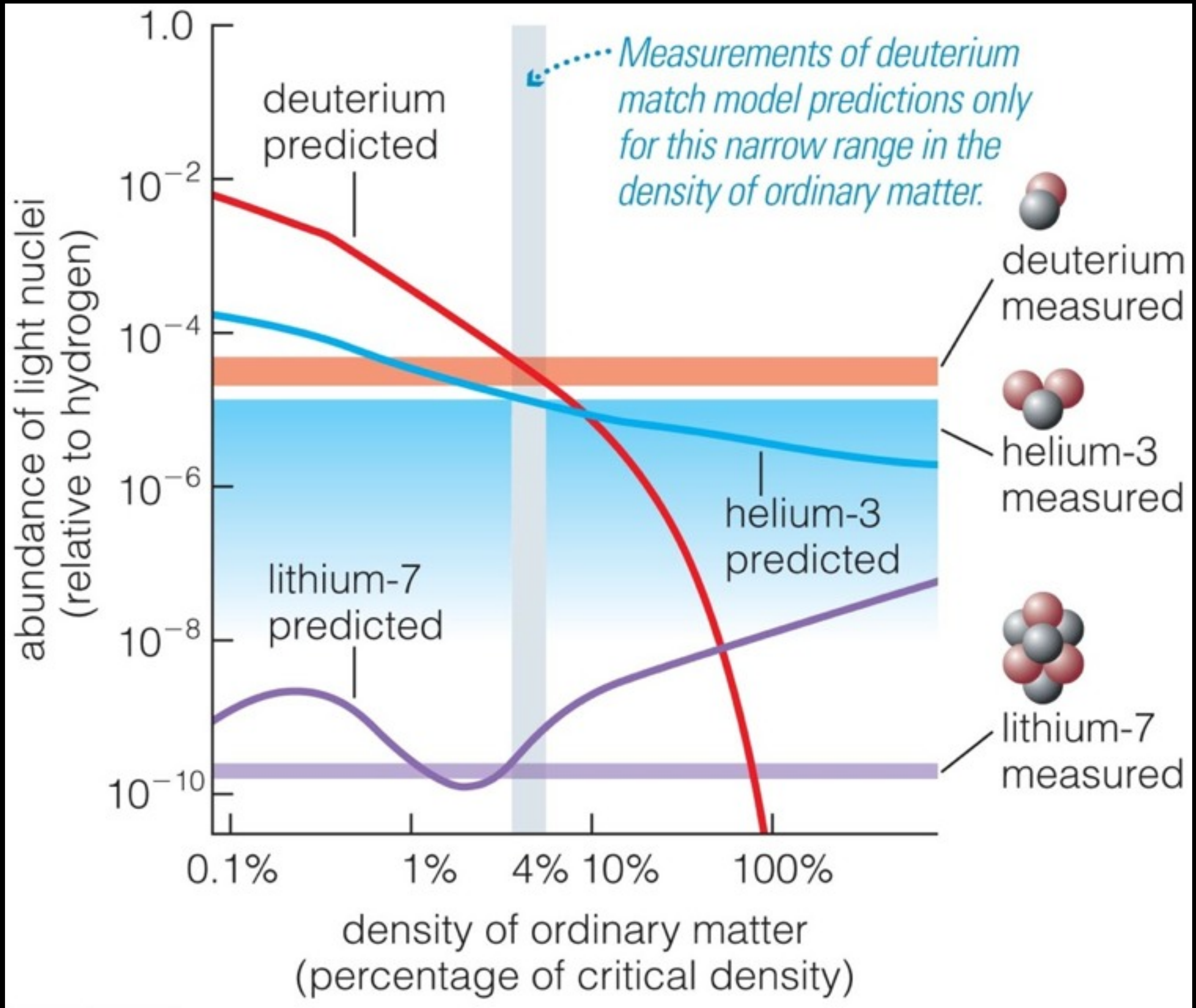
B. To the beginning of the era of atoms (380,000 years after the Big Bang)

C. To the beginning of the era of nuclei (3 minutes after the Big Bang)

D. To the era of Inflation ($\sim 10^{-38}$ seconds after the Big Bang)

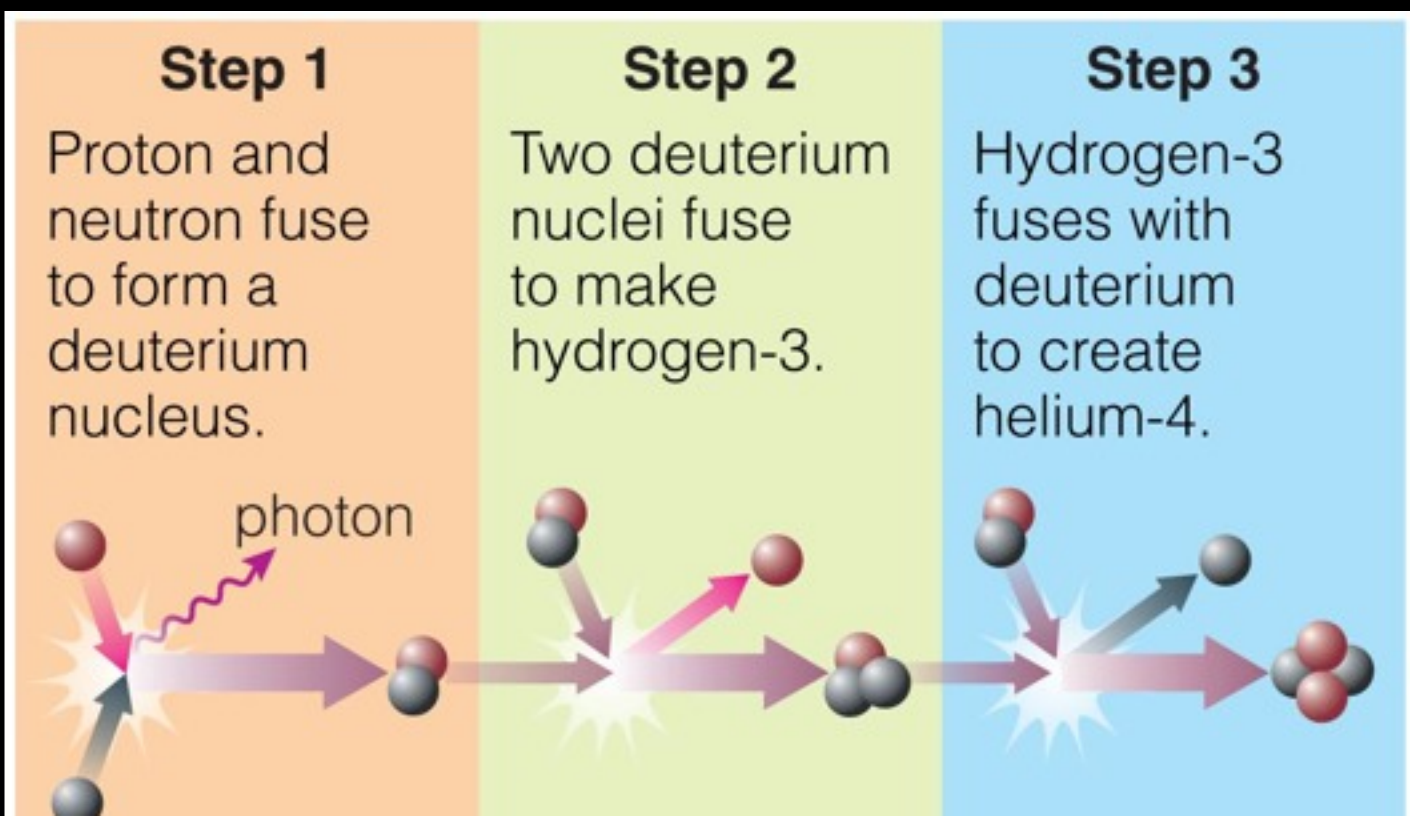
E. To the Big Bang itself ($t = 0$ sec)

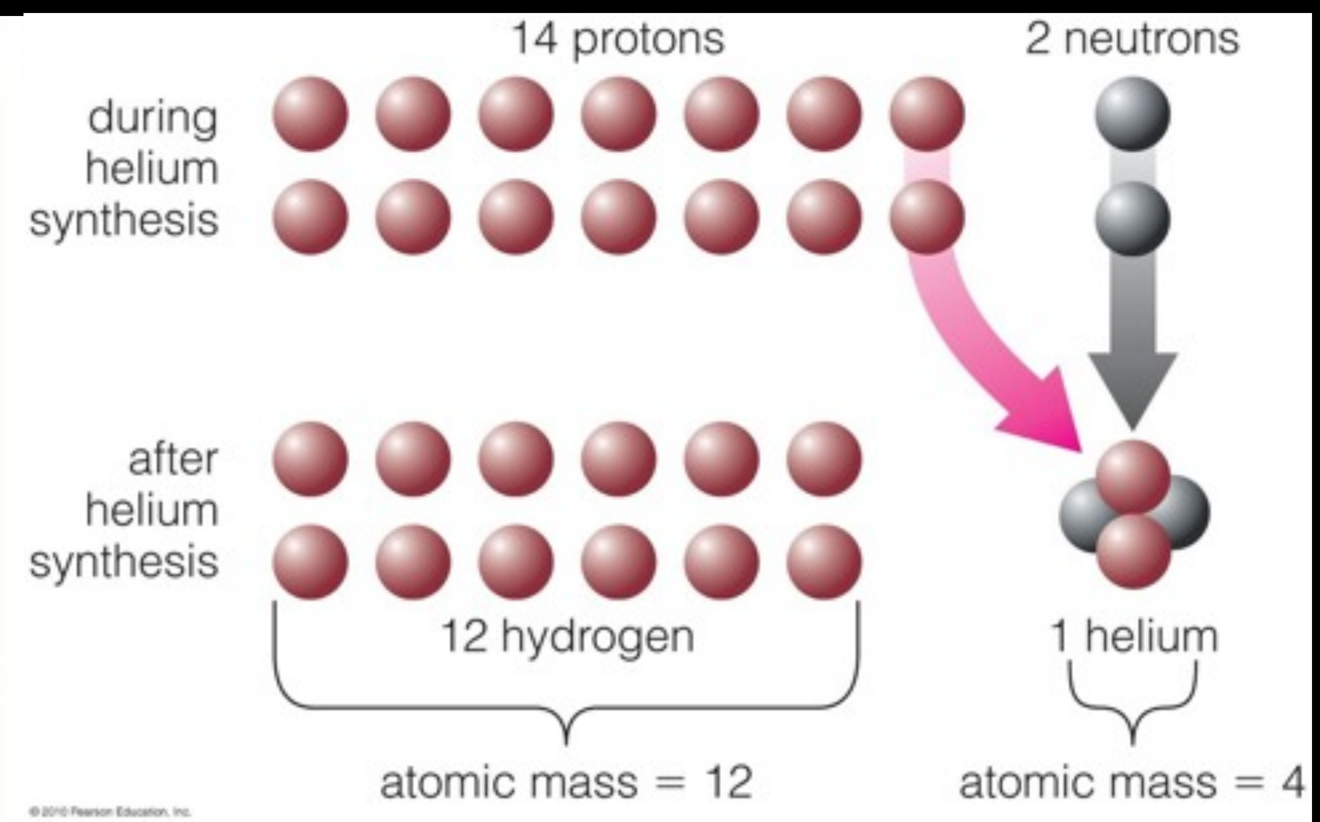
We can measure the abundances of elements and compare to models of Big Bang Nucleosynthesis



What happened to matter in the Big Bang?

- Similar to stellar nucleosynthesis: Hydrogen fuses into Helium at high temperatures and densities





Which of these abundance patterns is an unrealistic chemical composition for a star?

A. ~70% H, ~28% He, ~2% other

B. ~78% H, ~22% He, less than 0.02% other

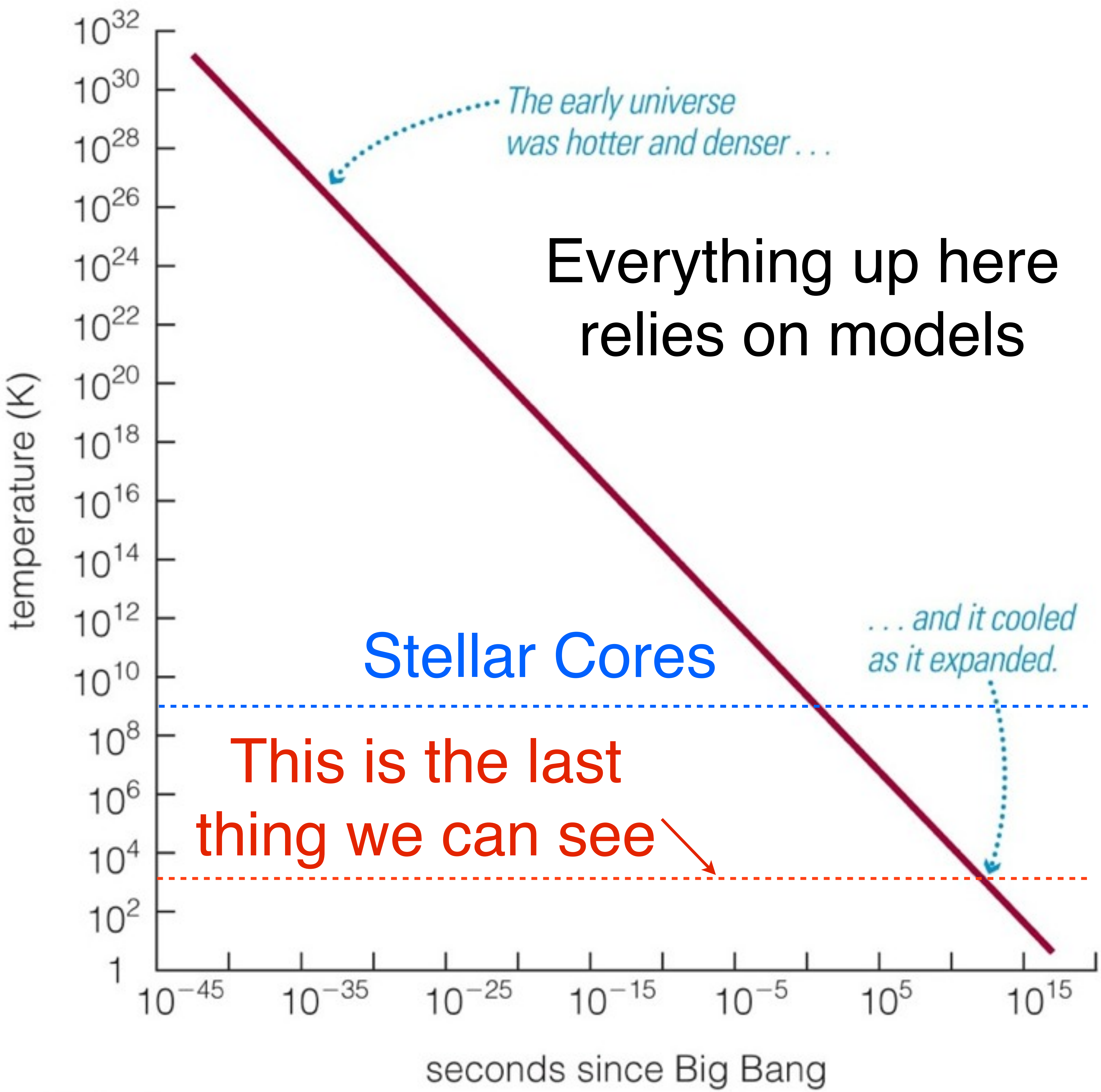
C. ~75% H, ~25% He, less than 0.02% other

D. ~72% H, ~27% He, ~1% other

E. They are all realistic values

Points for the Big Bang

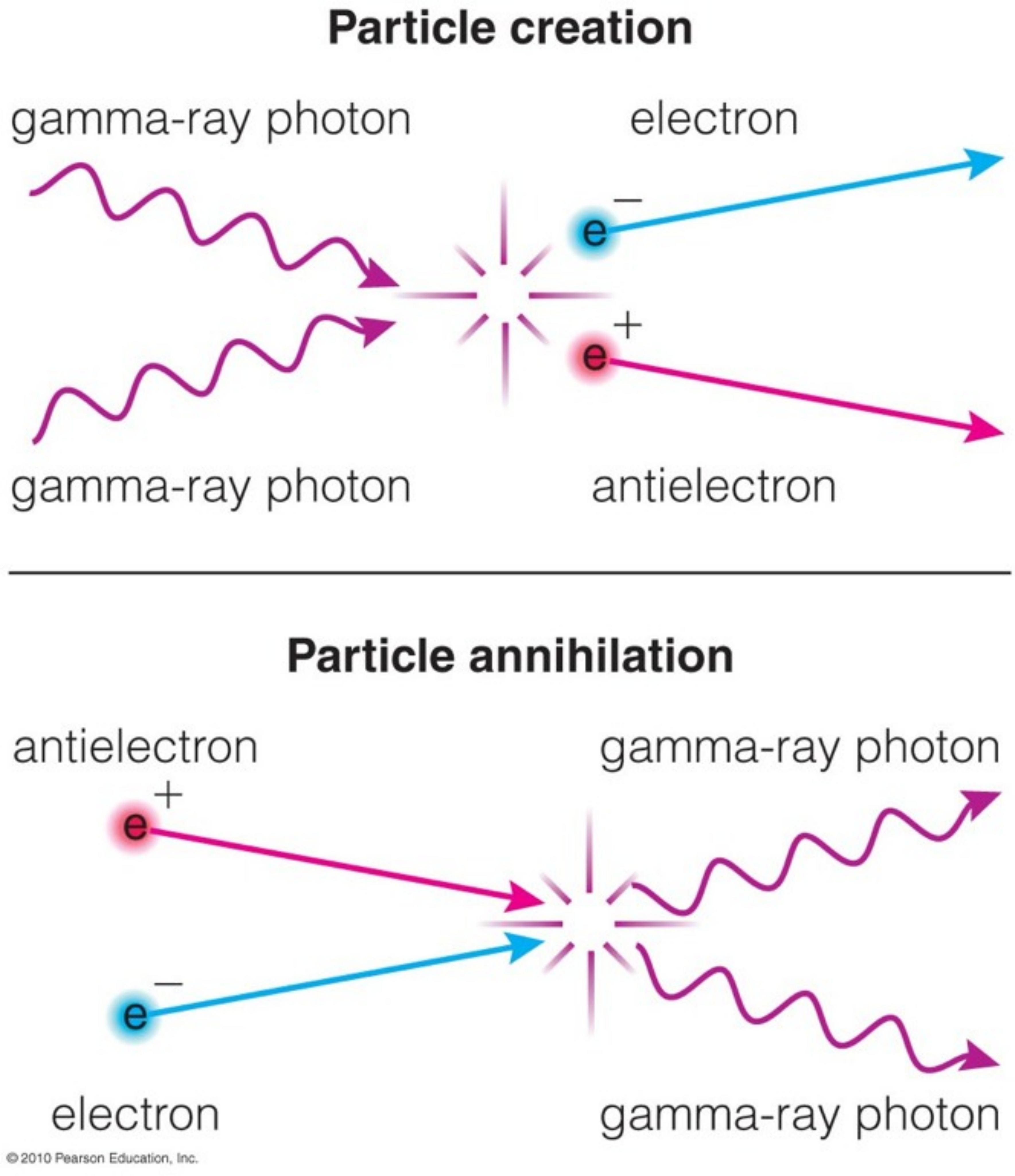
- The Big Bang directly predicts the observed abundance of elements
- The Steady State model requires that, in an expanding universe, matter has to be constantly created - it has no explanation for why 25% of matter would be Helium



The early universe was hotter and denser . . .
Everything up here relies on models
Stellar Cores
. . . and it cooled as it expanded.
This is the last thing we can see
temperature (K)
10^{32}
10^{30}
10^{28}
10^{26}
10^{24}
10^{22}
10^{20}
10^{18}
10^{16}
10^{14}
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
1
10^{-45}
10^{-35}
10^{-25}
10^{-15}
10^{-5}
10^{5}
10^{15}
seconds since Big Bang

Back in time...

- UP in density and temperature (energy)
  - “Energy” means the average energy of interactions between particles
- Way beyond “standard” physics and impossible to test first-hand



- When the universe was hot enough (>10^{15}K), there were high-energy gamma-rays zooming around and spontaneously creating matter and antimatter
- Energy was in equilibrium with matter

Matter and Antimatter

- Every particle has an accompanying anti-particle with opposite properties
  - the “positron” has the same mass as the electron, but opposite charge
- They are attracted to each other. When they meet, they annihilate and release energy in the form of photons

At the end of the particle era, temperatures are low enough that photons can not collide to create matter/anti-matter anymore. Nearly all the matter and antimatter that is in the universe at that time annihilates and forms photons. But if there is a little bit more of some type of matter/anti-matter it would remain… Was one type of matter more numerous?

A. Yes, regular matter

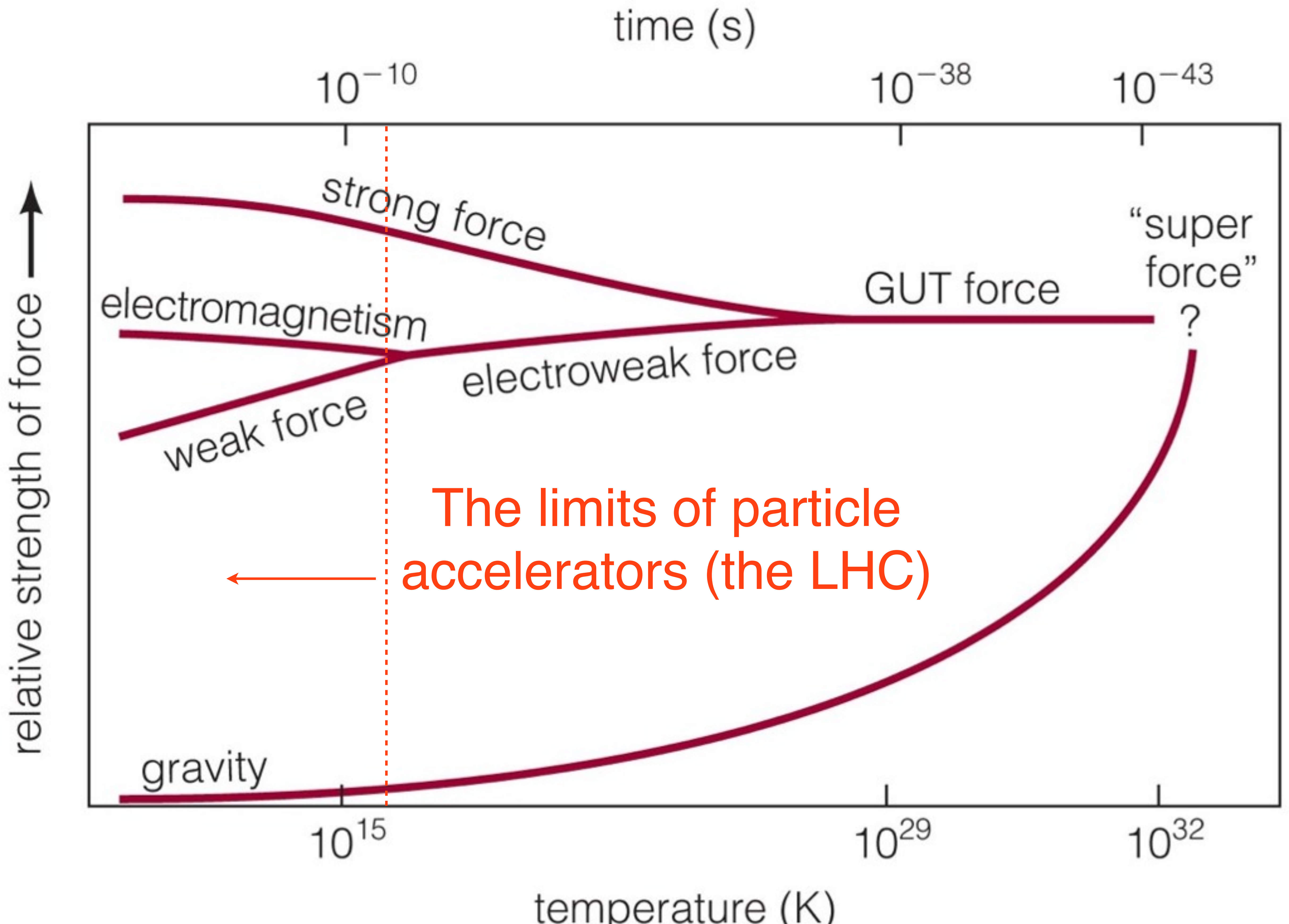
B. Yes, anti-matter

C. No, equal amounts of both

D. We can’t generate those kinds of temperatures so there’s no way we can tell!

Matter and Antimatter

- When temperatures were above 10^{15} K, photons, matter, and antimatter were in equilibrium (~same number of each)
- Between 10^{12} and 10^{15} K, photons were no longer energetic enough to make matter/antimatter pairs and particles started to stick around
  - For unknown reasons, there was a slight excess of matter particles. There are no known deposits of antimatter in the universe
  - photon/proton ratio = 1 billion today


time (s)
10^{-10}
10^{-38}
10^{-43}
strong force
"super force"
GUT force
?
electromagnetism
electroweak force
weak force
The limits of particle accelerators (the LHC)
relative strength of force
gravity
10^{15}
10^{29}
10^{32}
temperature (K)

- These detectors can explore "symmetry breaking" and search for new particles up to a very limited energy
- The peak energies at the beginning of the universe were *15 orders of magnitude* greater.
- The LHC is a 10x improvement on the Tevatron, and cost about 10 billion dollars to build

LHC

Tevatron

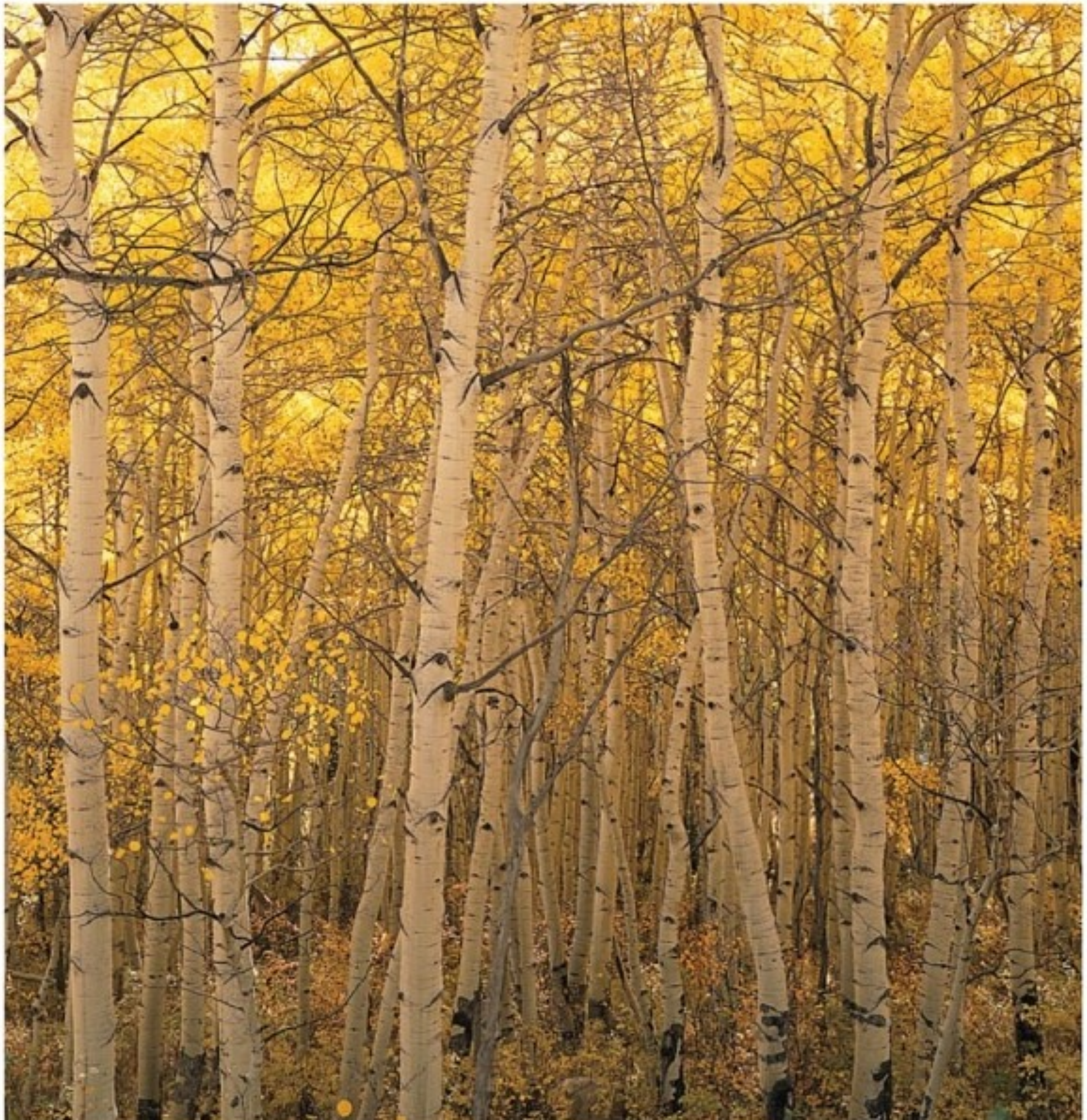
Motivation

- Since the CMB is the only tie we have to those early times in the universe, cosmology is closely tied to particle physics
  - it will probably never be possible to reproduce early-universe conditions on Earth

Olber’s Paradox

- We discussed that the CMB fills the sky with microwave radiation
- Olber’s Paradox raises the question: If the universe is infinite and there are an infinite number of stars, why isn’t the whole sky lit by visible light from stars?

Analogy



Olber's Paradox: Resolution

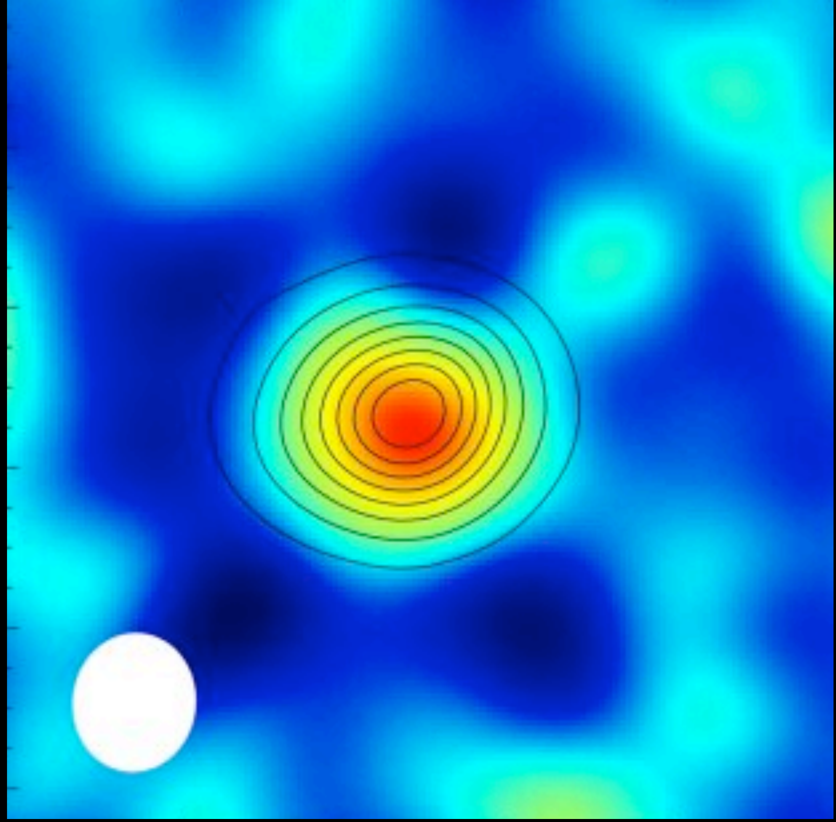
- A few possibilities:
  - The universe is not infinite
  - There is finite matter in the universe
  - Something about the universe prevents us from seeing starlight everywhere (but the universe, and matter, are still infinite)

Big Bang

- The Big Bang presents a natural resolution to the paradox
  - The universe is infinite, but had a starting time, so we can only see a finite amount of it
  - Also, expansion redshifts stars so that we no longer see visible photons from them

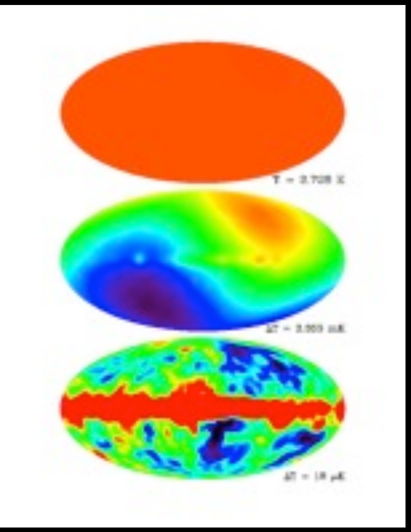
The future of CMB measurement: the Planck Satellite

SZ effect

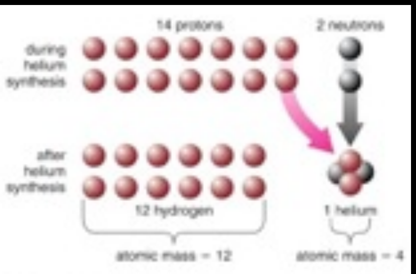


- Photons traveling through hot intracluster gas get "upscattered" to higher energies
- Good method to detect X-ray faint, hard-to-see galaxy clusters!

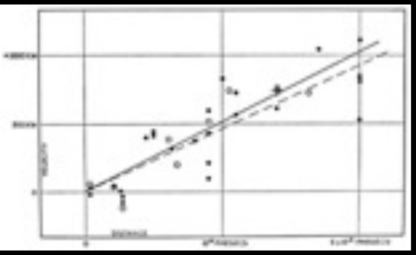
The "Observational Pillars" of the Big Bang Theory



1. The universe is aglow with thermal radiation, which we call the Cosmic Microwave Background (CMB)



2. The observed abundances of light elements agree with Big Bang predictions



3. The universe is expanding

4. The night sky is dark

Summary

- What is a “cosmology” and what competing theories are there?
  - Theory of the Universe
  - Steady State, Big Bang, others
- History of the CMB
  - Discovery + satellite missions
- Where did it come from?
  - Photosphere of the universe
- What does it tell us?
  - Lots!!