Was due Today - L20

- Reading:
  - (BBBHNM Unit 3)
  - Unit 4: Assigned today, due before class Wednesday
- Pre-Lecture Reading Questions Quiz:
  - (Unit 3 Quiz)
  - Unit 4 Quiz: Assigned today, due before class Wednesday
- End-of-Chapter Quizzes:
  - Chapter 11
- Papers (All items due at 11:55PM in Peerceptiv)
  - Paper 1:
    - Revision grades mostly done
  - Paper 2:
    - Text: Was due Wednesday Oct 23rd (Grace period with late penalties)
    - Reviews: Was due Monday Oct 28th (Grace period with late penalties)
    - Back Evaluations: Closes tonight, Monday Nov 4th
  - Paper 3: (Best guesses)
    - Rough Draft (if desired): Friday Nov 8th
    - Text: Due Wednesday Nov 13th (Grace period with late penalties)
    - Reviews: Open Saturday Nov 16th, due Monday Nov 18th (Grace period with late penalties)
    - Back Evaluations: Open Thursday Nov 21st, Closes Monday Nov 25th

Big Bang, Black Holes, No Math

Evidence for the Big Bang

Topic 3: Photons and Hydrogen in the Universe
Paper 3: The Assignment

• Abbreviated Description: What is the evidence for the Big Bang?

  - Explain it to someone who isn’t taking the class (no jargon)

• Make sure you read ALL the instructions in Peerceptiv
Overview

Evidence for the Big Bang?

• Finished Evidence 1:
  - The Exploding Universe
  - Expanding Space-Time

• This Time:
  - More evidence for a hot early Universe?
  - Photons and Hydrogen in the Universe today
Two Different Pieces of Evidence

When we look at the atoms and photons in the Universe we see that

1. ~90% of the atoms are hydrogen, ~10% are helium and there is very little of everything else
   - The Earth is very different than the rest of the Universe in many ways

2. Lots of photons with a Temperature of 2.7 Kelvin coming from all directions
   - Cosmic Background Radiation
Evidence for the Big Bang

Outline

• A ridiculously brief history of time

• The Early Universe and its Particles

• Nuclei and atoms and their reactions in the Early Universe

• The stuff in the Early Universe

• What happens to the “stuff” in the Universe as it “cools”
Ridiculously Brief History of Time with 3 Time Steps

1. It all started with a Big Bang
2. The Universe gets Bigger, Older and Colder
3. We observe the evidence today
The Early Universe

If there was a Big Bang, what would the Universe look like a single second after the Big Bang?

1) Very small
2) All the particles would have high energies
3) Lots of free particles

Will address each of these issues one at a time
If we hypothesize that the universe was small with lots of high energy free particles, how did it become what we observe today?

Early Universe
- Electron
- Proton
- Photon
- Neutron

How did the universe get from to?

Today
- Hydrogen
- $^4$He
- Photon
- Deuterium
Why Small?

If the universe has been expanding for billions of years, it would have been smaller billions of years ago.
Why **High Energy Particles**?

- If the universe has been expanding, then (according to General Relativity) it has been stretching the wavelengths of all the particles since then.
- Back then, when they were less-stretched, they must have been higher energy.
  - Long wavelength $\rightarrow$ Low energy (today)
  - Short wavelength $\rightarrow$ High energy (then)
Why **Free Particles in The Early Universe** instead of Composite Particles like Atoms?

- This one is harder to understand
- Need to learn more about what happens when particles interact
- Need to explain how we got from lots of free particles then to lots of composite particles today
Free Particles in the Early Universe

Many things COULD happen if we just had lots of free particles

Focus on describing how they combine

• Quarks could combine to form protons and neutrons
• Protons/neutrons could combine to form nuclei
• Nuclei and electrons could combine to form atoms
Forming Protons from Quarks

\[ \text{Quark} \rightarrow \text{Proton} \]

Nuclear Reaction

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Evidence for the Big Bang

Topic 3: Photons and Hydrogen in the Universe
Forming Heavy Nuclei from Protons

Proton + Proton $\rightarrow$ Deuterium + Anti-Electron + Neutrino

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Evidence for the Big Bang
Forming Atoms from Nuclei and Electrons

Proton + electron \rightarrow \text{Hydrogen Atom} + \text{photon}

Proton

ElectroMagnetic Reaction

Hydrogen Atom

Electron

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Evidence for the Big Bang

Topic 3: Photons and Hydrogen in the Universe
The Story

This is great... you can see that IF there were lots of free particles in the early Universe, they could combine to create the things we see today, like stars and galaxies.

Universe could just slowly assemble over time.

Lots of atoms combine to form stars, then galaxies, then us!

(more on this in later chapters, since it's not that simple)
But Why **Only** Free Particles in the Early Universe?

Since the Universe is hot, composite things get broken up in high energy collisions (like at particle accelerators)

Examples:
Atoms in the Early Universe

High Energy Photon Breaks up Atoms quickly → Free electrons and protons

Electromagnetic Reaction → Hydrogen Atom

Proton

Electron

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Evidence for the Big Bang
Nuclei in the Early Universe

Photon Breaks up Nucleus before it can find an electron to create an Atom or find another nucleon to form a bigger nucleus.

- Deuterium
- Free protons and neutrons
**Bottom line:**
*Early Universe has Free Particles with Really High Energies*

- In the early Universe we had many different types of free particles because high energy collisions can create all the different types.

- Composite particles could get formed, but other high energy particles would bust them apart → we end up with only free particles.
What else happens in collisions in the Early Universe?

High energy photons

→ lower energy photons

Low energy photons

→ higher energy photons
The Same Temperature

- All these high energy particles are quickly colliding in a small space
- Eventually all the particles will (roughly) have the same energy
  - Said better: The same Temperature
Particles in a Hot Small Universe

Because of the way particles interact at high energies, at just a single second after the bank we would have lots of photons, protons, neutrons and electrons.

Even if the universe didn’t start with lots of each of these particles, eventually there would be lots of them

- Produced in collisions or in the decay of other particles
Electron-Photon Soup in the Early Universe

Electron pairs and photon pairs interact and annihilate \(\rightarrow\) electron and photon Soup
Then what happens?

What will happen later?

The Universe Expands and stretches the wavelengths of the particles

Universe cools... energies drop
Expanding Space Part 1

Photons in the Universe

Early Times $\rightarrow$ High Temperature, high energy particles
Expanding Space Part 2

Later Time $\Rightarrow$ Space gets Bigger $\Rightarrow$ Wavelength gets Longer $\Rightarrow$ Temperature is Cooler, lower energy particles
Evidence for the Big Bang

Expanding Space Part 3

Even later ➞ Even more red Shifted

Even cooler, even lower energies
Bottom Line

• As time progresses all the particles, including the photons, will have lower energies
  - Lower temperatures
  - Bigger, older and colder...

• The interactions between the particles are very different at different energies
Later Times: Atoms and Low Energy Photons

Low energy photons typically only "bump" atoms or excite them.

ElectroMagnetic Reaction ➔ Hydrogen Atom

Proton

Electron

Low Energy Photon

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Evidence for the Big Bang

Topic 3: Photons and Hydrogen in the Universe
Nuclei and Low Energy Photons

Low energy photons only "bump" nuclei

Deuterium

Low Energy Photon
Can Now Build Up Heavier Heavy Nuclei

Proton + Deuterium $\rightarrow$ Helium$_3$ + Photon

Evidence for the Big Bang

Big Bang, Black Holes, No Math

Topic 3: Photons and Hydrogen in the Universe
Creating Stable Helium

\[ \text{Helium}_3 + \text{Helium}_3 \rightarrow \text{Helium}_4 + 2 \text{ Protons} \]

This is why we have \( \sim 90\% \) hydrogen and \( \sim 10\% \) helium. More on this later…
Particles in the Universe

• Early times: Protons, Neutrons, Electrons, Positrons and Photons

• Later times: Photons and atoms

• Much later: Atoms combine to form stars and galaxies

• More on this later
Evidence for a Hot Early Universe

The high-energy particles in a hot, small Universe would break apart heavy atoms and nuclei, and explains two pieces of experimental data.

Evidence? (Reminder)

1. Movement of distant galaxies
2. So much hydrogen and so little of other types of atoms except Helium
3. Lots of photons with the same temperature in all directions
Evidence 2: Mostly Hydrogen and Helium in the Universe Today

- We can see how to build up heavier nuclei… Should have lots of each. No?

- Observed facts:
  - 91% of all the atoms in the universe are hydrogen
  - Most of the rest are helium
  - In comparison, almost nothing of heavier types

- Why is this?
Why so few atoms Heavier than Helium?

Nuclear Physics

Can build up Hydrogen and Helium one at a time

→ Next possibility, $^5$He or $^5$Li, isn't stable

So What? Since $^5$He and $^5$Li decay quickly they don't have enough time to find another proton to become $^6$Li and be stable

→ Almost no elements heavier than helium are produced in the early Universe (if you can't produce them, they can't exist)

• Will happen much later, and in stars

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Evidence for Topic 3: Photons and Hydrogen in the Universe
The Helium Story

- Able to predict the fraction of the atoms in the Universe that are Helium
  - 75% of atomic mass in hydrogen
  - 25% of observed mass in helium
    - Same as saying about 91% of the atoms are hydrogen
- Helium is the same in every direction because it was created everywhere
  - Entire Universe had the same temperature everywhere
  - If it was created mostly in stellar cooking we’d see it coming from the directions where there are more stars
    - I.e., the direction of galaxies
    - More on this in Chapter 16
Evidence 3: Photons in the Universe

- If a photon is high enough energy to break an atom apart, it will do so
- Any photon that isn’t high energy enough won’t interact again and will thus just travel forever
- Thus, the last thing a typical photon in the universe interacts with is an atom/electron
- Why does that matter? Essentially, most photons are unchanged since the time of “last interaction” except to be stretched by expanding space
  - Tells us about the Universe when they last interacted
Evidence for the Big Bang

What happens to the Photons?

The temperature simply “cools” as space expands → Longer Wavelengths → Lower energy → Lower Temperature

What
happens to
the Photons?

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What happens to the Photons?

Then
Now

What happens to the Photons?

What happens to the Photons?

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What happens to the Photons?
Why should we believe this Story?

Should be able to observe this “remnant” of the Big Bang

Any evidence for photons with energies that look like a low temperature?
Arno Penzias and Robert Wilson in 1964 were doing high precision measurements of photons for radio waves. Noticed “noise” in their system that turned out to be photons with a temperature of about 3 degrees above absolute zero. Not looking for these photons... but won the Nobel Prize anyway.
The same Temperature in all directions?

Look at the full sky in a single map

Temperature Map (i.e., different colors correspond to different temperatures)

Stretch out a sphere onto a flat page

Incredibly Uniform! 2.78 Kelvin
Conclusion from the data?

• Data is exactly consistent with a Universe that was small and hot a long time ago... what we would expect with a Big Bang!

• No other reasonable explanation for where lots of photons with a specific temperature would come from, and be the same in all directions
Full Set of Evidence

1. We observe galaxies moving away from us in a manner that is consistent with an expansion of space-time.

2. Most of the atoms in the universe are hydrogen and helium and not much else.

3. We observe photons (the cosmic background radiation) uniformly distributed in all directions that have a temperature consistent with cooling for \( \sim 13.7 \) billion years.
Fun Way to think about things

- Look at things “far away” in space ➔ Backward in time
- Can see stars from millions of years ago
  - Look like stars today
- Look at galaxies from billions of years ago
  - Look like galaxies today
- Look at galaxies from about 13 billion years ago
  - Look like baby galaxies forming
- Look even “farther back”
  - No galaxies! Why? Because they haven’t even formed!
- Look further still… See the “white noise” of the cosmic background radiation and no evidence of any galaxies
  - Looking back at the earliest times we can “see” without the photons going through the “fog” of the early universe… Can’t see through the fog to earlier times… Then again, there isn’t much time before that anyway
How far can we look back in time?

All we can see is back a certain distance in time. We can’t see anything “past” the background radiation.
Lecture on Chapter 12 now complete
What’s Next?

Unit 4: Evolution of the Universe

More details about:

- The Early Universe
- After the First Three Minutes
Paper 3: The Assignment

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Evidence for the Big Bang

Big Bang, Black Holes, No Math

Topic 3: Photons and Hydrogen in the Universe