Evidence for the Big Bang

Photons and Hydrogen in the Universe
Was due Today - L16

- Reading:
  - (BBBHNH Unit 3)
  - Unit 4: Will assign today

- Pre-Lecture Reading Questions (PLRQ)
  - Unit 3:
    - Let us know if you think you were misgraded
    - Revision open now: Due before class Wednesday
  - Unit 4: Will assign today

- End-of-Chapter Quizzes:
  - Chapter 11

- Papers:
  - Paper 1:
    - Let us know if you think you were misgraded
    - Revisions of the text (if desired): Due in TurnItIn by tonight (Monday) before 11:55PM
  - Paper 2:
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  - Paper 3: Will assign today. Due next Wednesday

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:
  - The Exploding Universe
  - Expanding Space-Time

• This Time:
  - More evidence for a hot early Universe?
  - Photons and Hydrogen in the Universe today
Before we begin...

- The Cosmic Background Radiation provides, perhaps, the most compelling piece of evidence for the story of the Big Bang
- Unfortunately, it’s the hardest to explain to the non-scientist
  - Radiation = Photons
Two Different Pieces of Evidence

When we look at the atoms 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
Prelude to the Story

To understand why the photons and amount of hydrogen in the universe are important, we need to understand a little about the way the Universe changed over time (the evolution of the Universe).
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
• As the Universe expands and cools
How the Universe Changes

• If the Big Bang theory is correct, that means that over time the universe has been getting

  - Bigger,
  - Older, and
  - Colder
Why Colder?

Space-time is stretching

→ The wavelengths of the particles are stretching

→ Longer wavelength particles

→ Lower energy particles

→ Temperature is dropping!
Why Colder?

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

- Photon Wavelength
  - $10^3$ m: Radio Waves, not yet
  - $10^{-2}$ m: Microwaves, ~2.5 billion years
  - $10^{-5}$ m: Infrared Light, ~15 million years
  - $10^{-6}$ m: Visible Light, ~5 million years
  - $10^{-7}$ m: Ultraviolet Light, ~20,000 years
  - $10^{-8}$ m: X-rays, ~200 years
  - $10^{-10}$ m: Gamma Rays, ~0 years
  - $10^{-12}$ m: Photons and Hydrogen in the Universe
Ridiculously Brief History of Time with 3 Time Steps

1. It all started with a Big Bang
2. Then the Universe got Bigger, Older and Colder
3. We observe the evidence today
Setting up to Tell the History

• Tell you the hypothesis of what the Universe would look like a short time after the Big Bang
• Say a little bit about how the Universe changed from “how-it-was-back-then” to “how-it-is-today”
• Then explain WHY we think it looked that “back-then”
The Early Universe

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

**Visualize**

How did the universe get from to?

- **Early Universe**
  - Electron
  - Proton
  - Photon
  - Neutron

- **Today**
  - Hydrogen
  - Deuterium
  - $^4$He
  - Photon

Big Bang, Black Holes, No Math

Topic 3: Photons and Hydrogen in the Universe
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 high-energy particles interact
Free Particles in the Early Universe

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

Start by 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

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

Big Bang, Black Holes, No Math

Evidence for the Big Bang
Forming Heavy Nuclei

Proton + Proton → Deuterium + Anti-Electron + Neutrino

Evidence for the Big Bang
Forming Atoms

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

Proton

ElectroMagnetic Reaction

\rightarrow \text{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 just slowly assembled 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?

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

Big Bang, Black Holes, No Math

Topic 3: Photons and Hydrogen in the Universe
Nuclei in the Early Universe

**Evidence for the Big Bang**

**Topic 3: Photons and Hydrogen in the Universe**

- **Big Bang, Black Holes, No Math**

- Photon Breaks up Nucleus before it can find an electron to create an Atom or find another nucleon to form a bigger nucleus → Free protons and neutrons

- Nuclear Reaction
  - Photon
  - Proton
  - Deuterium
  - High Energy Photon

- \( \text{Nucleus} \rightarrow \text{Deuterium} \)
  - Photon breaks up nucleus before it can find an electron to create an atom or find another nucleon to form a bigger nucleus
  - \( \text{Nuclear Reaction} \)
  - Proton
  - Deuterium
  - High Energy Photon
**Bottom line:**
Early Universe has Free Particles with Really High Energies

- In the early Universe we have 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 we get 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 → 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
<table>
<thead>
<tr>
<th>Expanding Space Part 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Even later ➔ Even more red Shifted</td>
</tr>
<tr>
<td>Even cooler, even lower energies</td>
</tr>
</tbody>
</table>
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

Holes, No Math
Topic 3: Photons and Hydrogen in the Universe
Later Times: Atoms and **Low Energy** Photons

**Low energy photons** typically only “bump” atoms or excite them.

- Proton
- Electron
- Hydrogen Atom
- Low Energy Photon
- Electromagnetic Reaction

Evidence for the Big Bang
Nuclei and Low Energy Photons

Low energy photons only "bump" nuclei

Deuterium

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Evidence for the Big Bang

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

Can Now Build Up Heavier Heavy Nuclei
Creating Stable Helium

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

This is why we have ~90% hydrogen and ~10% helium. More on this later…
Evidence Today: Hydrogen

- 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

• Will happen much later, and in stars
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
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:

1. So much hydrogen and so little of other types of atoms except Helium

2. Lots of photons with the same temperature in all directions

Holes, No Math

Topic 3: Photons and Hydrogen in the Universe
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

What happens to the photons?
Life as a Photon in the Universe

• If a photon is high enough energy to break a part an atom, 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, they are unchanged since the time of “last interaction” except to be stretched by expanding space
  - Tells us about the Universe when they last interacted
What happens to the Photons?

The photons simply “cool” as space expands → Lower Temperature → Longer Wavelengths

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Evidence for the Big Bang

To picture 3: Photons and Hydrogen in the Universe
Full set of Readings So Far

• Required:
  - BBBHNM: Chaps. 1–13

• Recommended:
  - TFTM: Chaps. 1–5
  - BHOT: Chaps. 1–7, 8 (68–76), 9 and 11 (117–122)
  - SHU: Chaps. 1–3, 4 (77–86), 5 (95–114), 6, 7 (up-to-page 159)
  - TOE: Chaps. 1 & 2