Evidence for the Big Bang

Topic 3: Photons and Hydrogen in the Universe
Was due Today – L19

- **Reading:**
  - Unit 4: Was due before class Today
- **Pre-Lecture Reading Questions (PLRQ):**
  - Unit 3: Let us know if you think you were misgraded
  - Unit 3 Revision (if desired): Was due before class Today
  - Unit 4: Was due before class Today

- **End-of-Chapter Quizzes:**
  - (Chapter 11)

- **Papers:**
  - Apologies for the grades flopping
  - Send mail to 109help if:
    - If your score doesn’t look right
    - If your grade dropped because of back-evaluations
    - If you didn’t/couldn’t get something in on time
  - Paper 2 Revision (if desired): Due Thursday Nov 1st 11:59PM
  - Paper 3:
    - Text due Tuesday Nov 6th

Bi Holes, Ño Math

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
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
Why so few atoms Heavier than Helium?

Nuclear Physics
Can build up Hydrogen and Helium one at a time

⇒ Next possibility, $^5\text{He}$ or $^5\text{Li}$, isn't stable

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

Evidence for the Big Bang
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 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, 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 temperature simply “cools” as space expands → Longer Wavelengths → Lower energy → Lower Temperature

What Big Bang?

Photons and Hydrogen in the Universe

What happens to the Photons?

Radio Waves

Microwaves

Infrared Light

Visible Light

Ultraviolet Light

X-rays

Gamma Rays

Photon Wavelength

$10^3$ m

$10^{-2}$ m

$10^{-5}$ m

$10^{-6}$ m

$10^{-7}$ m

$10^{-8}$ m

$10^{-10}$ m

$10^{-12}$ m

Photon Type

Time After Big Bang

not yet

~2.5 billion years

~15 million years

~5 million years

~20,000 years

~200 years

~0 years

Big Bang in the Universe

50
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?
A Great Experiment

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

Stretch out a sphere onto a flat page

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

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.
Summary

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 ~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

• The Early Universe
• After the First Three Minutes
Unit 4: Evolution of the Universe

• Big Picture of the Evolution of the Universe:
  - Temperature and Time
• Collisions and how they explain what we see
• Photons as “Bullies of the Universe” and “Bathtubs” of particles
• The First Three Minutes
• After the First Three Minutes
Getting Started

We now have a basic understanding of the evidence for the Big Bang.

Let's look at the Evolution of the Universe after the Big Bang in more detail.
The Big Bang

• Ideally we’d start telling the story at the Big Bang itself and then move forward

• Maybe even talk about what came BEFORE the Big Bang

• Unfortunately, we don’t REALLY understand the Bang part or if there even was a bang
The best we can do with confidence is start describing the Universe a short time AFTER its beginning.

Start there, then work our way forward and backward in time.

What happened RIGHT AFTER the Big Bang?

Then what happened after that?

Then what? Etc.
The Big Bang Theory

- A Big Bang occurs and the early Universe has the same temperature everywhere and has lots of high energy particles
- Then the Universe gets
  - Bigger
  - Older and
  - Colder
- As time goes by it changes over time
  - Often we use the word **evolves**
The History of the Universe

Universe expands as time passes

Universe cools down as time passes

- Bigger wavelengths → Smaller energies
- Smaller Temperature

10 billion years

1 degree

1 second

10 billion degrees
What happens at Different Times?

Particles, nuclei and atoms interact in different ways at early times and later times

- Early Times
  - High Temperature
  - High-energy collisions

- Later Times
  - Low Temperature
  - Low-energy collisions
Various Times

Explain what happens during each of a number of different periods in time:
- The VERY early universe
- The first three Minutes
- The next 300,000 years
- The next billion years
- ~13 billion years later (now)
- The ultimate fate of the universe?

- The first four will take a couple of lectures

Chap 13
Chap 14
Chaps 15-17
Unit 6
What Happening?

What happens to the particles at each of these times?

Collisions!
Collisions

In each collision a number of things can happen

- Can create new particles
  - Only in high-energy collisions
- Particles can combine to form composite objects
  - Protons, neutrons, atoms etc.
- Composite particles can get broken up
- Collisions can transfer energy

Thus, the energy of the particles and what particles CAN exist in nature has a HUGE impact on the evolution of the early universe

Should also say that particles can decay
### A Brief History of Time

<table>
<thead>
<tr>
<th>Time Event</th>
<th>Timeline</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero</td>
<td>Zero</td>
<td></td>
</tr>
<tr>
<td>Well before a trillionth of a second</td>
<td>Well before a trillionth of a second</td>
<td></td>
</tr>
<tr>
<td>One millionth of one second</td>
<td>One millionth of one second</td>
<td></td>
</tr>
<tr>
<td>A few minutes</td>
<td>A few minutes</td>
<td></td>
</tr>
<tr>
<td>A few hundred thousand years</td>
<td>A few hundred thousand years</td>
<td></td>
</tr>
<tr>
<td>100 million to 1 billion years</td>
<td>100 million to 1 billion years</td>
<td></td>
</tr>
<tr>
<td>9 billion years</td>
<td>9 billion years</td>
<td></td>
</tr>
<tr>
<td>~13.5 billion years</td>
<td>~13.5 billion years</td>
<td></td>
</tr>
<tr>
<td>The Big Bang (?)</td>
<td>The Big Bang (?)</td>
<td>All parts of the visible universe come to have the same temperature everywhere</td>
</tr>
<tr>
<td>Quarks and gluons combine to form protons and neutrons</td>
<td>Quarks and gluons combine to form protons and neutrons</td>
<td></td>
</tr>
<tr>
<td>Protons and Neutrons combine to form deuterium and helium nuclei</td>
<td>Protons and Neutrons combine to form deuterium and helium nuclei</td>
<td></td>
</tr>
<tr>
<td>Protons and electrons combine to form hydrogen atoms</td>
<td>Protons and electrons combine to form hydrogen atoms</td>
<td></td>
</tr>
<tr>
<td>Stars and galaxies begin to form</td>
<td>Stars and galaxies begin to form</td>
<td></td>
</tr>
<tr>
<td>Our solar system forms</td>
<td>Our solar system forms</td>
<td></td>
</tr>
<tr>
<td>You take ASTR/PHYS 109</td>
<td>You take ASTR/PHYS 109</td>
<td></td>
</tr>
</tbody>
</table>
Photons: The Bullies of the Universe

• In many ways, the history of the universe is the history of the energy of the photons

• Early Days: Energetic photons break apart anything formed (Bullies!)

• Later Days: They lose their ability to break things apart (no longer bullies!)
The Evolution of the Universe

Topic 1: The Early Universe

Big Bang, Black Holes, No Math

- Photons no longer energetic enough to bust apart protons
- Photons no longer energetic enough to bust apart nuclei
- Photons no longer energetic enough to bust apart atoms

More detail

- 10^{-6} Seconds: Protons and Neutrons form
- A Few Minutes: Nuclei form
- \sim 10^5 Years: Hydrogen atoms form
- \sim 10^8 Years: Stars and Galaxies form
- \sim 10^9 Years: Our Solar System forms
- \sim 10^{10} Years: You Read This Book

Time

Temperature (K)

- 10^{-6}s
- 10^{-4}s
- 10^{-2}s
- 1s
- 1min
- 1h
- 1day
- 1y
- 10^2y
- 10^4y
- 10^6y
- 10^8y
- 10^{10}y

16
Confidence in this Story?

- Why do we think it happened this way?
- Will walk through the reasons next... It’s all about the energy of the collisions...
The Evolution of the Universe

Overview
1. The Early Universe
2. The First Three Minutes
3. The next 300,000 years
4. The next billion years
5. The next ~13 billion years, until today

The particles have the same temperature everywhere

- Once the Universe has the same temperature everywhere, only the details really depend on what came before it.
Not exactly sure how it all starts... Call it a Big Bang

Artists conception...
Well before a Trillionth of a Second

- Particles at VERY high energies
  - Small wavelengths
- What is now the visible universe was so small back then that it had the same temperature everywhere
  - Which is why we see it having the same temperature everywhere now
Before a Millionth of a Second

• All particles will be **FREE**
  - Composite particles would be broken apart
    • No protons, neutrons or heavy nuclei
    • No atoms
  • Only **FUNDAMENTAL** particles
    - Quarks
    - Photons
    - Electrons
    - Muons
    - Other from Chapter 3, plus others
Before a millionth of a Second

Lots of free particles, same temperature everywhere
Quarks can combine in the Early Universe to make a proton, but are quickly broken apart by high-energy photons in the Universe.

\[
\begin{align*}
\text{Quark} & \rightarrow \text{Proton} \\
\text{Nuclear Reaction} & \rightarrow \text{Proton} \\
\text{High Energy Photon} & \rightarrow \text{Proton}
\end{align*}
\]
Before a millionth of a second → very high energy collisions

• Lots of free quarks to make protons
• Not many protons in the Universe because they are quickly busted apart
Time passes

- The Universe Expands and Cools
- Easier to tell the story after a millionth of a second after the Big Bang
- Cool enough that when quarks combine to form a proton or neutron they stay together
  - Said differently, other particles aren’t energetic enough to bust them apart anymore
A Millionth of a Second after the Big Bang

The quarks have combined to form Protons and Neutrons
The Evolving Universe

Early Universe

- Up Quark
- Down Quark
- Photon
- Electron

Later Times

- Electron
- Neutron
- Proton
- Photon

The Universe changes from this to this
Protons after a Millionth of a Second

After a millionth of a second

• No more free quarks to make more protons
• Number of protons doesn’t decrease because they aren’t getting busted apart by high energy photons
  - High enough energy photons don’t exist anymore

All the free quarks have combined to form protons or neutrons

Lots of water in the tub = Lots of protons in the universe

Very few high energy photons: Can’t break apart protons
The Evolution of the Universe

Topic 1: The Early Universe

• The other fundamental and composite particles also have a big impact.

• One example is a Muon which is (for our purposes) just a heavier version of an electron.

  - Discuss them more in Chapter 19.
Photons and Muons

At very high energies photons can also turn into Muon pairs.

Muon pairs can turn into Photons.
Muons are an Important Part of the Early Universe

Muon pairs can always produce photon pairs. If the photons are energetic enough they can interact and create muon pairs (or vice versa). μ mesons, electrons and photons all have the same temperature.
Why Aren’t They Around anymore?

- Most particles, except protons, electrons and photons decay REALLY quickly
  - Some at $10^{-24}$ sec, some $10^{-10}$ sec
  - Muons can live for $10^{-6}$ sec
- Can study lots of different types of particles here in experiments on Earth
- Need an accelerator to produce most new ones if you want to study them
- The photons in Today’s Universe aren’t energetic enough to produce new ones
Muon decay

Muon → Electron + Neutrino

Muon → Neutrino + Neutrino
Muons in the Universe

Early Universe
- Lots of high energy collisions: Can create lots of muons
- Some water in the tub = Muons in the Universe
- Muons are decaying and interacting to produce other particles

Later Times
- Very few high energy collisions: Very few muons being produced
- Very little water in the tub = Very few muons in the universe
- Muons decay away very quickly

Big Bang, Black Holes, No Math
Very Early Universe is Very Complicated

What particles CAN exist determine what’s going on in the Very Early Universe

Problem:

We don’t know if we have discovered all the fundamental particles yet!

• Good reasons to believe there are new ones out that we just haven’t found yet
  - Need bigger accelerators and/or Other tools
  - More on this later also
Nuclei in the Early Universe

Proton + Proton $\rightarrow$ Deuterium

Deuterium + Photon $\rightarrow$ Proton + Neutron

A high energy photon can break apart a nucleus before it can find an electron to create an atom or find another nucleon to form a bigger nucleus.

High Energy Photon

Proton

The Evolution of the Universe
Topic 1: The Early Universe
What's happening at about a millionth of a second after the Bang?

- Lots of protons
  - Photons can't break them apart any more
- Not many heavy nuclei
  - Every one formed gets quickly busted apart
- Not many neutral atoms
  - Every one formed quickly gets busted apart
- Very few other fundamental particles
  - Old ones would have decayed already, new ones not being produced
Moving towards later times...

- Universe gets bigger, older and colder
- By one hundredth of a second after the Big Bang there are basically no unstable fundamental particles left and the story is simpler to tell
- Protons, Neutrons, Electrons, Photons etc.
The Evolution of the Universe

Topic 1: The Early Universe

Big Bang, Black Holes, No Math

One hundredth of a second

$10^{-6}$ Seconds
Protons and Neutrons form

$\sim 10^5$ Years
Hydrogen atoms form

$\sim 10^8$ Years
Stars and Galaxies form

$\sim 10^9$ Years
Our Solar System forms

$\sim 10^{10}$ Years
You Read This Book

Fancy particles gone by this time
Photons can break up nuclei and neutral atoms, but not protons

Big Holes, No Math

Topic 1: The Early Universe
Electron pairs interact and annihilate but photon pairs no longer turn into particle pairs.

No easy way to produce more positrons.
Approaching the Three Minute Mark

• By three minutes after the bang the Universe is cool enough for Helium nuclei to form ($^4$He) even though it doesn’t happen too much...

• Complicated to produce $^4$He, lots of intermediate steps that are easier to break apart
At these lower energies the photon can’t often break apart the nucleus

⇒ Amount of Deuterium in the Universe rises
Lecture on Chapter 13 now complete
Chapter 13 and 14 worksheet

- One of the most important things to understand is how much of each type of “stuff” is found in the universe during its History (and why).
- Since many people struggle with this (especially for the EOC quizzes) we have made a handout and an Excel worksheet to help you.
  - On the main 109 page
    http://people.physics.tamu.edu/toback/109/ under “Chapter 13 and 14 Materials”
  - Make sure you enter in “Negligible” or “Abundant” in all boxes.
  - There is feedback for you if you didn’t enter in things correctly.
Big Bang, Black Holes, No Math  The Evolution of the Universe  Topic 1: The Early Universe
Full set of Readings So Far

- **Required:**
  - BBBHNM: Chaps. 1–14

- **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