Lecture 2: From the Big Bang to Today—
Puzzles Unsolved

& Neutrino Relics from the Big Bang

Brian Odom

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THE UNIVERSITY OF CHICAGO
“As we know, 
There are known knowns. 
There are things we know we know. 
We also know 
There are known unknowns. 
That is to say 
We know there are some things 
We do not know. 
But there are also unknown unknowns, 
The ones we don't know 
We don't know.”

- Donald Rumsfeld, Secretary of Defense, 
February 12, 2002, Department of Defense news briefing 
(emphasis added)
Known Unknowns

These are unsolved problems, where we at least know how to articulate the questions and have some solid ideas for possible answers.

• **What is the origin of particle masses?** The Higgs boson?
• **Why are masses of the known particles so small?** Supersymmetry?
• **What is the cold dark matter (the “CDM” of $\Lambda$CDM)?**
• **Why is our universe dominated by matter and not antimatter?**
• **What are the masses of the neutrinos?**
• **What is the nature of neutrinos?** Dirac or Majorana?
Every particle has an antimatter counterpart. Experiments show that some properties like mass are exactly the same for particles and antiparticles, and other properties like charge are exactly opposite. (There is some deep physics—the CPT theorem—which predicts this).
Unknown Unknowns

These are unsolved problems, where we can sometimes barely articulate questions and where we are grasping in the dark for answers. Solutions might require dramatic paradigm shifts in our understanding of nature.

- Why are there so many free parameters in the Standard Model?
- Why are there so many particles? Why are the particle masses so different from one another?
- Why are there so many forces?
- What is the dark energy (the $\Lambda$ of $\Lambda$CDM)?
- What caused the brief inflationary epoch?
- Why do we live in the narrow age when the dark matter and dark energy contributions are comparable?
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If only two decay products, conservation of momentum dictates they go in opposite directions. Conservation of energy then insists that the electron flies off with a well-defined speed. But experiments disagree…

Expect spike here—not a continuous spectrum
Pauli’s Solution, Fermi’s Naming

If we add a 3rd particle, the “neutrino” (actually antineutrino here), then the electron speed can have a range of values, as observed. We get to keep conservation of energy, at the expense of adding a new particle to the zoo.

Fermi’s play on words:
- *neutrone* (Italian for neutron) means big and neutral
- *neutrino* means small neutral

![Diagram of beta-decay process]
Neutrino Poetry

"Cosmic Gall" by John Updike:

Neutrinos, they are very small
They have no charge and have no mass
And do not interact at all.
The earth is just a salty ball
To them, through which they simply pass,
Like dust maids down a drafty hall
Or photons through a sheet of glass...
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Well, the spirit of it is right. Let’s leave the poetry intact, but these details actually have measurable effects on the cosmos...
Feynman diagrams are tools for performing Quantum Field Theory calculations. One use is simply figuring out which processes are possible. Here, we’ll use them to figure out ways to detect antineutrinos.

Feynman diagram for beta-decay

(Input on left) (Output on right)

Read: neutron decays to antineutrino + proton + electron

\[ n \rightarrow \bar{\nu}_e + p + e \]
How Not to Detect Antineutrinos

Original process:

\[ n \rightarrow \bar{\nu}_e + p + e \]

Manipulate Feynman diagram to get other allowed processes:

\[ \nu_e + p + \bar{e} \rightarrow \bar{n} \]

\[ \bar{\nu}_e + p + e \rightarrow n \]

In principle OK, but:
1. Neutrino, not antineutrino, detector
2. Antiprotons hard to come by
3. Three particles on input

In principle OK, and better, but:
1. Three particles on input (hard to arrange for collision of p & e at exact time of antineutrino arrival)
How to Detect Antineutrinos

Clyde Cowan and Fred Reines used this process to make the first direct observation of reactor antineutrinos in 1956 (26 years after Pauli’s proposal). 1995 Nobel prize to Reines.
For those interested…

Fission reactions in nuclear reactors break up heavy nuclei into lighter ones. Fusion reactions, like in the sun, combine light elements into heavier ones. Fusion reactions in the sun produce neutrinos, in contrast to nuclear fission reactors which produce antineutrinos. Find a process which allows detection of solar neutrinos.

Homework (optional, of course):

Fission reactions in nuclear reactors break up heavy nuclei into lighter ones. Fusion reactions, like in the sun, combine light elements into heavier ones. Fusion reactions in the sun produce neutrinos, in contrast to nuclear fission reactors which produce antineutrinos.
Why a Nobel Prize?

Fusion reactions in the sun give off neutrinos.

Question: If a neutrino passes through some lead bricks, what are the chances that it bounces off a lead atom?
Why a Nobel Prize?

Answer: Only 50% for 1 light year ($10^{16}$ meters) of lead... for a single bounce!

The weak force is... really weak! Since the process is so rare, you must be very clever or else false signals (such as from naturally occurring gamma rays) will fool you.
The “solar neutrino problem” had physicists stumped for decades. SNO showed that electron neutrinos were not going missing, but were just changing flavor. Other experiments also observed flavor change in reactor and atmospheric neutrinos.
Wave Interference—Beat Notes

This graph shows what happens when two waves of different frequencies are combined—they interfere.

At some times they enhance each other, at other times they cancel each other.

The slow beat occurs at the difference frequency. If the difference is zero, the beat goes away.
Quantum mechanics introduces a wave-particle duality. Particles have behavior which must be described by a wave equation. So, it’s not surprising that something like the acoustic beat notes also appear in neutrino physics.

Emitted electron neutrinos can later become muon neutrinos.
Neutrino Oscillation

Acoustic beat intensity:

\[ \sin^2 \left[ \left( f_1 - f_2 \right) \pi t \right] \]

Probability for a \( \nu_e \) to flavor-transform into a \( \nu_\mu \) (slightly simplified):

\[ \sin^2 \left[ \left( \frac{m_1^2 - m_2^2}{E} \right) \frac{ct}{4} \right] \]

• The \textbf{difference in mass (squared)} takes on a role in neutrino flavor oscillations just like that of frequency difference in acoustic beats.

• As in the case of matched acoustic frequencies, \textbf{if the neutrino masses are equal, there is no oscillation}.

• \textbf{So, oscillation requires one of the neutrinos to have non-zero mass.}
Strange Mass Units: eV

The electron-Volt (eV) is an energy unit. It is the energy required to push an electron from the positive end of a 1-V battery to the negative end.

(AA batteries are 1.5 V, so moving an electron from one end to the other requires 1.5 eV)

Special relativity allows us to interchange mass and energy, by the famous $E=mc^2$. This is often convenient, and particle physicists almost always use energy units for mass. A proton weighs 938,000,000 eV (or 938 MeV), and an electron weighs 511,000 eV (or 0.511 MeV).
Oscillation experiments are only sensitive to mass differences.

\[
\sin^2 \left[ \left( \frac{m_1^2 - m_2^2}{E} \right) \frac{ct}{4} \right]
\]

They tell us that one of the neutrinos must weigh at least 0.05 eV (corresponding to the measured mass difference). But if that neutrino pair weighed 0.00 and 0.05 eV, or 10.00 and 10.05 eV, we wouldn’t know the difference. To determine what the mass actually is, we look to the big bang...
Cosmic Neutrino Background

• The big bang was hot enough to produce particles of every known kind. For particles which are stable and do not decay, such as protons, neutrons, electrons, photons, and neutrinos, our universe is still filled with these big bang relics.

• Believe it or not, there are about 10,000,000 relic neutrinos from the big bang sharing the space that your body takes up!

• We have not yet figured out any way to directly detect these relics—that’s a little shocking considering how many there are!

• But, we have a chance at indirectly detect through their effect on structure formation.
Structure Formation

The universe started out as a very smooth place.

But, today, we have planets, solar systems, galaxies, galaxy clusters, etc.—the universe is not smooth but somewhat clumpy! Clumpiness, or “structure”, grew from small inhomogeneous seeds, probably quantum fluctuations.
This video shows cluster formation, beginning one billion years after the big bang. If density = wealth, 

*the rich get richer and the poor get poorer*
Watching Neutrinos through a Window

Through my window, I watch a neutrino in the Andromeda galaxy as the universe expands a little bit.

Today

Tomorrow—it’s gone!

Can gravitational attraction between us and those neutrinos create a density pileup? No. The neutrinos are long gone before clumpiness can start to develop.
Watching Neutrinos through a Window

Today Tomorrow—about the same

Can gravitational attraction between us and those neutrinos create a density pileup? Yes. Compared to the distance between us, even neutrinos don’t go far.
Effect of Neutrinos on Structure Growth

• The cosmic neutrino background is incredibly difficult to detect directly, but it has important implications for structure formation.

• On small scales, neutrinos are moving too quickly to participate in gravitational clustering (because of their fast speeds, they are classified as hot dark matter).

• But on larger scales, they can cluster just like heavy matter.

• The transition occurs somewhere around the size of clusters of galaxies (∼10 MPc).
Effect of Neutrinos on Structure Growth

- Detailed understanding of the big bang tells us the relic neutrino number density ($\# / \text{cm}^3$)
- We can turn this into a mass density ($\text{grams} / \text{cm}^3$) by assuming some neutrino mass
- What happens if a big portion of the dark matter mass comes from relic neutrinos?
  - Nothing changes on large scales, where neutrinos can cluster
  - But on short scales, clustering is suppressed
  - Heavier neutrinos $\rightarrow$ fewer galaxy clusters
CMB Fluctuation Power Spectrum

WMAP full-sky image of the tiny fluctuations in cosmic microwave background (CMB), where false color indicates microwave intensity. By eye, you see that the most obvious clumps are on a ~ 1 degree scale.

CMB fluctuation power spectrum. On each angular scale (1 degree, 10 degrees, etc.), how much does the image fluctuate? Notice that this careful mathematical analysis confirms what our eye told us—the strongest fluctuations are on a ~ 1 degree scale.
Matter Power Spectrum

How clumpy is the distribution of matter in the universe?

This is the same idea as the CMB power spectrum plot. But here, the x-axis is distance rather than angle (those are obviously related—the larger the observed angle between two galaxies, the further apart they are).

This plot combines several survey techniques to find the clumpiness of matter on various length scales.

To set the scale, 1 Mpc = 3,300,000 light years. Since $h=0.7$, and the distance to the Andromeda galaxy is 0.77 Mpc, the distance between us and Andromeda has a value $\lambda = 0.77 \text{ Mpc} / 0.7 = 1.1 \text{ Mpc}$
You can see by eye that a neutrino mass as small as 1 eV makes a measurable change in the mass power spectrum for shorter distances. Mathematical analysis shows that this mass is far too large to be allowed by the data.
Neutrino Mass: What We Know

The oscillation experiments show that the heaviest neutrino must weigh more than 0.05 eV. The oscillation limit will not change, but hopefully soon better clustering data will actually see an effect from neutrino mass.

The big bang/clustering results place an upper limit on the mass of the heaviest neutrino at 0.14 eV. This is the best limit physicists have!

The oscillation experiments show that the heaviest neutrino must weigh more than 0.05 eV. The oscillation limit will not change, but hopefully soon better clustering data will actually see an effect from neutrino mass.
Neutrinos have important consequences, but must be a small piece of the pie... So, this is why it’s called \( \Lambda \text{CDM} \), and not \( \Lambda \text{HDM} \)!
A Great Clue from a Surprising Place

• The neutrinos we have succeeded in detecting come from:
  • Natural radioactivity
  • Nuclear reactors
  • Fusion reactions in the sun
  • Cosmic ray collisions with the atmosphere

• But our best information of neutrino mass comes from understanding the relic production in the big bang—an event that happened 13.7 billion years ago!

• Physicists had to look in a surprising place to fill a gap in our knowledge of the Standard Model, and they came back with impressive results!