

The 64th Compton Lecture Series

Unsolved Mysteries of the Universe:
Looking for Clues in Surprising Places

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**Lecture 2: From the Big Bang to Today—Puzzles Unsolved
& Neutrino Relics from the Big Bang**

Known unknowns (terminology ala D. Rumsfeld)

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 Λ CDM)?** A surprising claim of Λ CDM is that we are not made of the same stuff as most of the mass in the universe. So, if not the protons, neutrons, and electrons which make up normal matter, what type of particles make up the dark matter?
- **Why is our universe dominated by matter and not antimatter?** Matter-antimatter particle pairs can be created from energy and can annihilate one another to become energy. Why are there any particles at all left over after the big bang? The mass of our universe (at least the non-dark-matter component) is known to be almost entirely matter. Why isn't it antimatter instead?
- **What are the masses of the neutrinos?**
- **What is the nature of neutrinos?** Only recently we discovered that these elusive particles actually have a tiny mass. Given this fact, it is now possible that they might provide a mechanism to explain one puzzle of the universe—why we ended up getting electrons out of the big bang (the problem of “leptogenesis”). However, to account for leptogenesis, the neutrinos must have a particular characteristic—they must be “Majorana” particles rather than “Dirac” particles. Is this the case?

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?** Sure, the Standard Model explains all present data, but it is ugly. There are at least 19 parameters (numbers) which we cannot predict—they must be measured. On historical and aesthetic grounds, this is taken as evidence that there is a better model waiting to be discovered.
 - **Why are there so many particles?** We now know that all the elements of the periodic table (hydrogen, carbon, oxygen, etc.) are composed of the same fundamental particles—protons, neutrons, and electrons. But, there are many more particles than these in the “zoo” (muons, charm quarks, Z bosons, etc.). Are there reasons to expect the fundamental particle zoo to be filled with so many denizens? Or is there a similar story as with the elements—are the particles we think of as fundamental actually just made from smaller building blocks?
 - **Why are the particle masses so different from one another?**
 - **Why are there so many forces?** Maxwell showed that electricity and magnetism, at first glance very different forces, are actually different manifestations of the same underlying physics—the electromagnetic force. The standard model then combines electromagnetism with the weak force. Can the electroweak force be combined with the strong force and with gravity?
- **What is the dark energy (the Λ of Λ CDM)?** Einstein’s discarded cosmological constant? Quantum energy inherent in empty space?
- **What caused the brief inflationary epoch?** To explain cosmological observations without resorting to doubtful fine-tuning of the initial conditions, it is proposed that the big bang was followed by a brief epoch of extremely rapid expansion, called inflation. Inflation is consistent with observations, but what caused it to happen?
- **Why do we live in the narrow age when the dark matter and dark energy contributions are comparable?** In the days since Copernicus, we are highly suspicious of coincidences that place us (humans) at a favored location. Nevertheless, we seem to be living at a highly special time in the history of the universe—this is described by the phrase “our preposterous universe”. Just a coincidence?

Meet the Neutrino

- Neutrinos were first postulated by Wolfgang Pauli in 1930 to explain energy that seemed to have gone missing in **beta decays** (where a neutron decays to a proton and

an electron). A third decay product (the neutrino) would allow energy conservation to remain in place in this process.

- The first direct detection of neutrinos occurred **26 years later** by Fred Reines and Clyde Cowan. 1995 Nobel prize to Reines.
- **Feynman diagrams** are tools for performing quantum field theory calculations. One application is to find allowed particle interactions. Incoming particles/antiparticles are on the left, outgoing on the right. A right-pointing arrow denotes a particle; an left-pointing arrow denotes an antiparticle. We can start with the beta-decay diagram and end up with the diagram for the process used by Reines and Cowan to detect reactor antineutrinos.
- **Neutrinos are really hard to detect!** A neutrino coming from the sun would need to travel through 1 light-year of lead before it had a 50% chance of scattering once!

Neutrino Oscillations and Mass

- There is a neutrino “**flavor**” to match each of the three heavier leptons (electron, muon, tau)
- **Neutrinos were originally believed to be massless, like photons.**
- The “**solar neutrino problem**” had physicists stumped for decades. Too few electron neutrinos got to the earth, given our understanding of solar fusion. One proposed solution was that electron neutrinos were changing to muon or tau neutrinos on their way here—“**flavor oscillation**”.
- In 2001, Sudbury Neutrino Observatory (SNO) in Canada detected both the electron neutrino component and the total flux of solar neutrinos. The “missing” electron neutrinos from the sun had not disappeared; they had undergone flavor oscillation. The solar neutrino problem was solved.
- Other experiments also detected oscillations of reactor antineutrinos and of atmospheric neutrinos.
- **Neutrino flavor oscillations are allowed by quantum mechanics, but only if neutrinos have mass.**
 - We can get an intuition for this by listening to acoustic beat notes, which happen when two sound waves are mixed. When the two component frequencies are different, there is a beat note in the resulting intensity. If the component frequencies are the same, the beat oscillation goes away.
 - For neutrinos, the story is similar. For an electron neutrino to be described by quantum mechanical waves of two different component frequencies, neutrinos must have non-zero mass. You also need different types of neutrinos to have different masses. If the masses of all three neutrino types are the same, the flavor oscillations go away.
- Oscillation experiments tell us that the heaviest neutrino must weigh more than 0.05 eV. Oscillation experiments are only sensitive to mass differences, not to the actual

value of the mass. Whether neutrinos are very light or very heavy, oscillation experiments cannot say. **To set limits on how heavy neutrinos might actually be, we look to the big bang...**

Neutrino Relics from the Big Bang

- 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.**
- **Right now, there are about 10,000,000 relic neutrinos from the big bang sharing the space that your body takes up!** Solar neutrinos are hard enough to detect, but these relic neutrinos have much lower energies—making detection even more difficult. We have not yet figured out any way to detect these relics—that’s a little shocking considering how many there are!
- Direct detection of the relic neutrinos eludes us, but indirect detection, through their gravitational interaction might not prove as tricky.
- Since neutrinos are so light, they usually move at near the speed of light. Therefore, relic neutrinos are classified as called **“hot dark matter”** rather than “cold dark matter”.

Clustering

- Right after the big bang, the universe was a fairly smooth place. **Today, the matter distribution is clumpy**—we have planets, solar systems, galaxies, clusters of galaxies, and lots of mostly empty space in between.
- **The clumpiness, or clustering, grew from small initial seeds. Gravitational attraction caused the clumps to grow with time,** as matter is gathered and the surrounding space is emptied. This process of gravitational clustering eventually lead to clumpiness on huge length scales.
- The high speeds of neutrinos prevent them from participating in clustering on small length scales—they are moving too fast to get caught up in the process. However, on larger length scales, their high speeds are not important, and they contribute to clustering just like heavier matter. Here, the “small”-“large” distinction is somewhere around the size of galaxy clusters (~10 Mpc).
- The degree of clumpiness on different length scales is described in a plot called the **matter power spectrum.**

Constraints on Neutrino Mass from the Big Bang

- Big bang physics tells us the relic neutrino **number density**—how many neutrinos there are per cubic centimeter.

- Given a number density, the **mass density** (how many grams/cubic centimeter) depends on the neutrino mass.
- The heavier the neutrinos, the more of the dark matter budget they take up. This causes no problem for the clustering of matter on very large length scales. But at shorter distances, clumpiness is suppressed as you turn up the neutrino mass—the universe is predicted to be smoother and smoother. **Heavier neutrinos -> fewer clusters of galaxies.**
- By looking at the clumpiness on small length scales, we can tell what fraction of the dark matter might be hot. From there, we can say how massive neutrinos might be.
- **We have not yet observed a clustering suppression from neutrinos.** Neutrinos are evidently too light for the effect to be observed.
- The best upper limit on neutrino mass comes from this. **How heavy are neutrinos? We don't know. But big bang physics tells us that the heaviest neutrino is lighter than some value: 0.14 eV.**
- **Notice that we're closing in:** experiments on mundane neutrinos (solar, reactor, atmospheric) tell us that the mass of the heaviest neutrino is greater than 0.05 eV. So, improved clustering observations might actually see the effects of neutrino mass (from the exotic relic neutrinos) in the near future.

Conclusions

- **Not much of the dark matter is hot!** That's why the model is called Λ CDM and not Λ HDM.
- Neutrinos are important in fission power plants, the fusion powered stars, and in natural radioactivity occurring all around us.
- It is amazing that big bang physics, where we look back to an explosion that happened 13.7 billion years ago, gives us the best information about neutrino mass, one of the unknowns of Standard Model physics
- **Here, physicists have looked for a clue in a surprising place, and we have done quite well!**