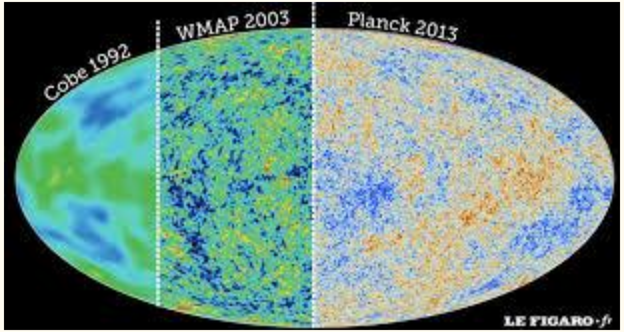
Sterile Neutrinos as Dark Matter Candidates

Hector Moya Freire

Cosmic neutrino background

A relic from the big bang, the CνB is a consequence of the low rate of interactions of the neutrinos

- As the universe started cooling off, the rate of interaction of weak reactions dropped, “freezing” these neutrinos



A natural candidate for DM

- Neutrinos are weakly interacting, long lived and electrically neutral, a good candidate for DM
  - However:
    - The matter density of neutrinos when we drop to non-relativistic energies is determined by the sum of all flavor masses
    - This value is below 2 eV (a conservative estimation. There are lower ones). In order to represent 100% of the DM, it would have to be around 11.5 eV
      - Besides the mass: active neutrinos only become non-relativistic late into the history of universe. If they were what makes up DM, the universe would look different structurally

What is dark matter then?

- A heavier particle with the same desirable characteristics as a SM neutrino and less coupled to other particles could be an ideal candidate, solving all problems we have with active neutrinos.
- Sterile and heavy neutrinos, however, aren’t a new idea

What do we know about neutrinos?

- We know there are 3 active neutrinos (more active neutrinos would mean more lepton families, something, as far as we know, absurd)
- We know they oscillate, which means that they have a non-zero mass (The probability of oscillation is dependent of the mass difference between the two states)

A quick intermission

- How do we express the oscillation mathematically?

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}.$$

- Two bases of three eigenstates: the mass eigenstates and the flavor eigenstates
- The U matrix is the Pontecorvo–Maki–Nakagawa–Sakata matrix (or PMNS for short)

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$
$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{bmatrix},$$

Reading the PMNS matrix

- We can look at the mass eigenstates the same way we look at an spatial matrix
  - In this case, c's and s's are the angles between two mass eigenstates
  - The delta phase is the CP violation phase
- A special characteristic of the matrix is the consequences of it being unitary or not
  - If the matrix is unitary, all probabilities sum up to 1, meaning all possible oscillations are included. If it isn't, then we have more possible oscillations, which means more neutrinos
    - But it isn't enough to just have new neutrinos. They have to be heavy. How do we justify that?

Where the neutrino mass comes from?

- One of the recent topics in neutrino research is whether neutrinos are Dirac or Majorana particles
    - Dirac: The neutrino isn't the same as the antineutrino, and its mass is solely generated by the Higgs mechanism
        - Among other arguments against it, we have that the Yukawa coupling (i.e. the parameter that encodes the interaction of the particle with the Higgs field) would be unnaturally low in this case, thanks to the vanishing mass of the neutrino
    - Majorana: neutrino and antineutrino are the same, and their mass is not solely generated by the Higgs mechanism
        - Taken the arguments against the neutrinos being Dirac particles, the behavior and other considerations about the DM candidates are made considering neutrinos as Majorana particles

The seesaw mechanism

- As we know, neutrinos have non-zero mass, but they are still extremely low
- This is useful: The seesaw model of type 1 tells us that it means there have to be heavy neutrinos in order to counterbalance the seesaw, our sterile neutrinos (at least two of them)
- If all mass eigenstates are non-zero * then this number jumps to an N greater or equal to the number of flavor states
  - All active neutrinos we have seen so far left handed. In the seesaw mechanism, our sterile neutrinos are the right handed ones.

How much heavier?

- Theoretically, no constraints. Maybe we haven’t found them yet simply because the energy of the current experiments isn’t enough for these neutrinos to propagate as real particles.
- There are even articles that suggest that a good place to look for these heavy sterile neutrinos would be in supernovas
- However, as we’re focusing on DM, we need candidates with appropriate masses (few keV)

What about oscillations?

- A natural concern is how these sterile neutrinos oscillate, because if all of them had high rates of turning into active neutrinos, they couldn't be DM candidates
- They do need to be able to oscillate. Otherwise, it doesn't even make sense to call them neutrinos
- We define, then, two mixing matrices: One for the active neutrinos and one for the sterile neutrinos. Mixing between both groups is given by a third matrix. In order for the sterile neutrinos to be DM, the mixing rates between groups have to be lower.

Consequences of their existence

- We know there would be at least 2 sterile neutrinos, but the existence of one for each neutrino mass brings forth some interesting consequences of the seesaw
  - If one of these neutrinos is the DM, then the lightest neutrino mass would be approximately zero, because it needs to have a very weak mixing to the rest
  - If the lightest neutrino mass however, is bigger than a meV, then these neutrinos cannot be DM. In this case, the mixing angles are too big and the oscillation between them and the active neutrinos would be too great, resulting in shorter lives for them
- These consequences, however, are easily avoided if we have more than three sterile neutrinos
  - As their existence gives mass to the light neutrinos, the author considers the scenario with one sterile neutrino for DM and two others that give mass to the light neutrinos, with bigger masses

And the consequences for DM

- In order to be our DM candidate, one of the sterile neutrinos need to have a mass in the KeV range
  - We consider this for the case where these particles are created through weak interactions. As the mass of the sterile neutrinos grows, they are less likely to oscillate, so while you could have heavier dark matter, their mixing with other neutrinos would be so small it escapes our definition here.
- They will be unstable, but this is not a problem. Depending on the mixing angles, their life expectancy may be longer than the age of the universe
- Their interaction strength is really small. One consequence of this is that they can’t stay in thermodynamic equilibrium with the rest of the universe.
  - This brings us the matter of how they were produced, to begin with

Their origin

- While they can be created by the oscillation of active neutrinos, as said before, this limits their mass. This makes for a very small production, however
- There are other possibilities:
    - Maybe they appear sterile at low energies. New physics might appear at bigger energies that bring new interactions capable of producing them.
    - Maybe they are produced by the decay of heavier particles
- These alternatives are the ones take away the limits from the sterile neutrino masses

And how do we find them?

- Being sterile means that they don't have a lepton associated to them, not that it won't give origin to anything
- An strategy when looking for new particles is to look for their decay signature
- For these neutrinos, the decay product changes depending on the mass.
  - For sterile neutrinos below twice the mass of the electron, our decay products will be mainly 3 neutrinos (one neutrino of flavor alpha and a neutrino and antineutrino of flavor beta)
  - One very important alternative, less frequent, but possible: a neutrino and a photon of energy half the mass of the sterile neutrino
- Why is it important?
  - A very definite light signal is a good way of detecting them.

The 3.5 keV line

- An emission line inconsistent with atomic transition limes, candidate for dark matter decay
- It could be correspondig to the alternative decay channel in the previous slide, coming from the decay of a 7 keV sterile neutrino
- The mass would be consistent with the few keV requirement we estabilished earlier

In conclusion

- Neutrinos are prime dark matter candidates for their low reaction rate
- Standard model neutrinos, however, are too light for the task
- Heavy sterile neutrinos are not only good substitutes, but an alternative that is easily implemented in our current understanding of physics without the need for the introduction of a whole dark sector
- Their detection would also be relatively simple
- This model is also a good example to show how intricately different subjects of particle physics are tied together

References

- Calculating the probability of neutrino oscillations: https://physicsx.erau.edu/Office/oscillations.pdf
- Sterile Neutrino Dark Matter : https://arxiv.org/abs/1807.07938