PROCEEDINGS OF SCIENCE

The H_0 tension and the physics of the neutrino sector

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The mismatch between direct measurements of the current expansion rate of the Universe and the ΛCDM prediction based on early Universe observables (the so-called *Hubble tension*) has motivated the search for new physics that can accommodate these measurements. Here we discuss a possible modification of standard cosmology at energies between Big Bang Nucleosynthesis and recombination that does not spoil the fit to Cosmic Microwave Background measurements in a significant way, while injecting energy to boost the expansion rate. The mechanism is based on the existence on a scalar field, the majoron, which is motivated by particle physics models attempting to explain the origin of neutrino masses, and has been proposed as a possible solution of the Hubble tension. Here we expand that model to make this majoron an axion-like particle, linking the production of this particle to the primordial magnetic field.

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1. Introduction

Recent high-precision direct measurements of the local expansion rate of the Universe [1] have raised the significance of the discrepancy with the present-day extrapolated value from Cosmic Microwave Background (CMB) observations [2] using the standard cosmological model (ΛCDM) to more than 5 sigma. This is known as the *Hubble tension*, and the significance of this mismatch requires an explanation from the revision of these measurements, the use of complementary cosmological probes, as well as a modification or extension of current theoretical models describing the expansion history of the Universe.

On the theoretical side, a plethora of models have attempted to alleviate this tension to more acceptable levels [3, 4]. Among those, the models that involve modifications of the Early Universe (i.e. before recombination) seem to be favored [5], but are forced to pass strong constraints from current high-precision CMB measurements.

In a recent paper, Escudero & Witte [6] have proposed a solution based on a particle physics model that includes a neutrophilic scalar known as the *majoron*. This particle is a pseudo-Goldstone boson arising from the spontaneous symmetry breaking of a global $U(1)$ lepton number symmetry. We will focus on this model due to its relatively high performance in the comparisons carried out in the recent reviews [3, 4], making it particularly promising.

This particle is motivated in the context of the unknown origin of neutrino masses. The reasoning goes as follows: If right-handed neutrinos are included, then we can write a Majorana mass term (hence the name), which can be used to explain the small mass of the active neutrinos through the see-saw mechanism. This mass term can be justified with the breaking of a global symmetry, which is the lepton number. When a global symmetry is spontaneously broken, a Goldstone boson appears (if it is a local symmetry, this boson is eaten by the gauge bosons, becoming massive), which has a small but non-zero mass due to quantum gravity effects. This new particle is the majoron.

Hence this framework provides a dynamical mechanism to explain: 1) the small mass of neutrinos due to the existence of much heavier right-handed neutrinos (see-saw); 2) lepton number violating processes (such as baryogenesis); 3) as a by-product, the appearance of a light scalar particle (pseudo-Goldstone boson) which couples to neutrinos, becoming dark radiation.

Our proposal of an Axion-Like Majoron (ALM) [7] adds extra phenomenology to this model: if we make the majoron an axion-like particle, we can transfer energy from photons to this dark radiation. This is due to resonant production in the presence of a primordial magnetic field (in coherent domains of size $\sim$ Mpc and field strength $B \lesssim 1$nG). Our majoron has tiny couplings to charged leptons. Therefore, the Primakoff and Compton production of majorons is very inefficient. However, a primordial magnetic field can mediate resonant production of majorons in the primordial plasma. This resonance occurs at a very specific temperature, which is not arbitrary due to observational constraints.

PoS(CORFU2022)236

2. Phenomenology

In order to study the cosmological implications of our model, which is largely based upon [6] we need to discuss the parametrization we are using. Besides the standard ΛCDM cosmological parameters, the majoron model has the following parameters [8]: its mass m_ϕ, its interaction rate $\Gamma_{\rm eff}$, and the effective number of relativistic species $\Delta N_{\rm eff}$, which measures the extra energy density in the neutrino-majoron fluid with respect to the standard model value of 3.044.

However, when applied to our context, the majoron parameters are very constrained. For instance, $m_\phi \sim$ eV since we want to modify expansion rate before (but close to) recombination (T=0.26eV). This implies that any majorons produced earlier will decay around that temperature (into neutrinos). Besides, $\Gamma_{\rm eff} \equiv \Gamma/H$ must be $\gtrsim 1$ so that the interaction rate keeps up with the expansion rate of the Universe. This forces a thermal equilibrium between the majoron and the neutrinos. More importantly, it reduces the neutrino free streaming which is necessary to fit the CMB observations, despite the extra energy density injected by the majorons with respect to the standard cosmology. Finally, the amount of energy density in the form of dark radiation, which is parametrized by $\Delta N_{\rm eff}$, must be $\simeq 1$ in order to reduce the Hubble tension significantly: $H_0 \simeq (67.5 + 6.2\Delta N_{\rm eff})$ km s^{-1} Mpc^{-1} [9].

The background evolution of the average energy density is as follows:

1. A primordial population of majorons decouple at temperatures around 500 GeV, so Big Bang Nucleosynthesis (BBN) is not affected. This population barely contributes to $\Delta N_{\rm eff}$.

2. A primordial magnetic field mixes photons and majorons, resulting in resonant oscillations $\gamma \leftrightarrow \phi$. This resonant production of majorons occurs at the end of BBN (T = 26 keV), reducing the number of photons and cooling their temperature. This increases the effective number of relativistic species by $\Delta N_{\rm eff}$ =0.58 (individually $\Delta N_{\rm eff}^{\nu} \simeq 0.26$ and $\Delta N_{\rm eff}^{\phi} \simeq 0.32$).

3. When the temperature of the plasma is $T \lesssim m_\phi$, the majorons are in thermal contact with the neutrinos $\phi \leftrightarrow \nu\bar{\nu}$, damping their free-streaming.

4. At temperatures $T \lesssim m_\phi/3$ majorons increase their energy density with respect to photons ($\Delta N_{\rm eff} \simeq 0.27$), because non-relativistic matter in an expanding Universe cools down slower than radiation.

5. Shortly after that, majorons decay into active neutrinos, dumping their energy into the neutrino sector (the dominant branching ratio is into neutrinos, not photons), as shown in Figure 1.

6. The net injection of energy after all these steps corresponds to $\Delta N_{\rm eff} = 0.85$, increasing the derived value of H_0 when interpreting the data in the context of this model.

As a side effect, since the resonant production of majorons reduced the number of photons after BBN, this implies that the actual baryon-to-photon ratio at BBN was smaller than what is measured at recombination, in a way that is consistent with the latest primordial Deuterium observations [10].

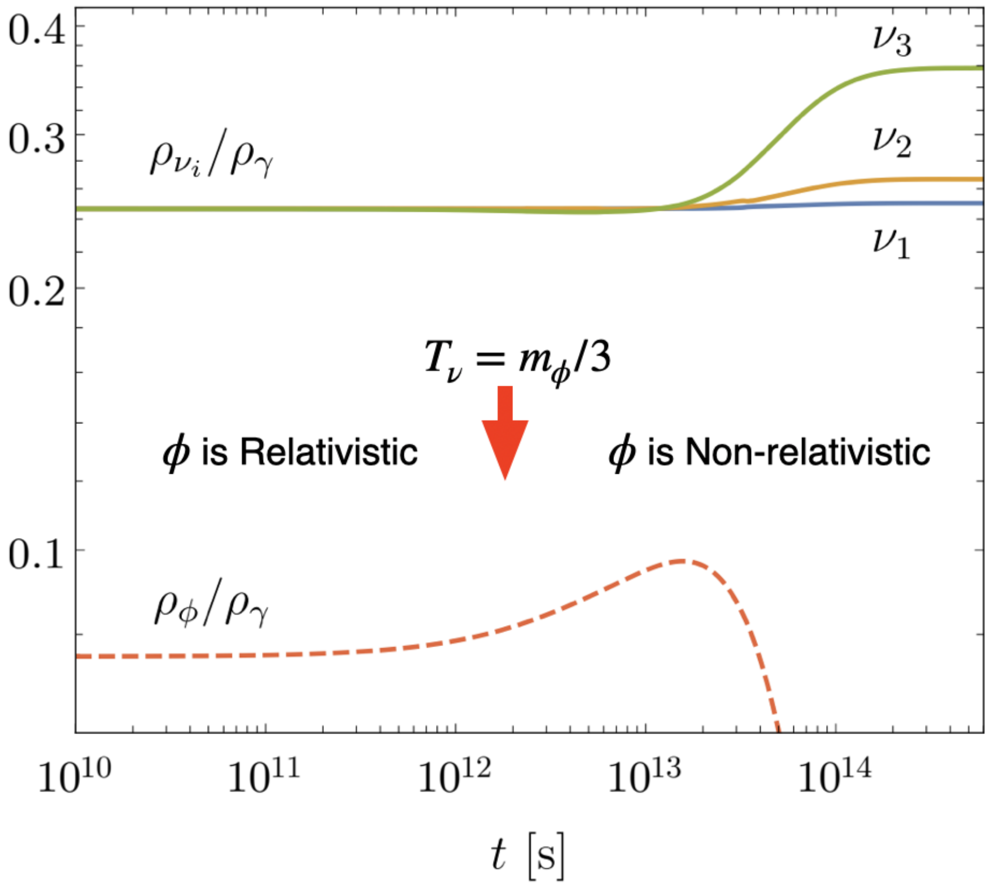

Figure 1: Evolution of the energy density of the majoron-neutrino fluid. The solid lines correspond to the energy density for each of the neutrino mass states, whereas the dashed lines correspond to the energy density in majorons. This shows the non-relativistic transition of majorons before their decay preferentially into the heaviest neutrino mass state.

3. Results

In Table 1 we show the results of a Markov Chain Monte Carlo analysis of the ALM model through the use of the numerical code `MontePython` and a modified version of `CLASS`. This is a global fit to cosmological data including the power spectrum of temperature and polarization CMB anisotropies (Planck), CMB lensing (Planck), and Baryon Acoustic Oscillations (BAO) distance measurements from different surveys (6dF, SDSS MGS, BOSS). The results show (see [7]):

1. A larger value of the Hubble constant H_0 consistent with late-Universe measurements, hence reducing the H_0 tension.

2. An increase in the baryon density (actually in the baryon-to-photon ratio), thus helping reconcile Deuterium observations and BBN predictions.

3. The χ^2 values show that the ALM model provides a similar fit to ΛCDM, providing an alternative interpretation of cosmological data.

Parameter	ΛCDM	ALM (m_ϕ = 0.5eV, τ_ϕ = 3.5 × 10^{12}s)
$100\Omega_b h^2$	2.242±0.015	2.295±0.014
$\Omega_{\rm cdm} h^2$	0.119±0.001	0.129±0.001
$100\theta_s$	1.0420±0.0003	1.0407±0.0003
$\ln\left(10^{10}A_s\right)$	3.046±0.015	3.062±0.016
n_s	0.967±0.004	0.991±0.004
$\tau_{\rm reio}$	0.055±0.008	0.056±0.008
H_0 (km s^{-1} Mpc^{-1})	67.71±0.44	71.4±0.5
$\chi^2_{\rm TOT}$	2785	2790

Table 1: Results of the global fit of cosmological data, assuming a standard ΛCDM cosmology (left column), or an Axion-Like Majoron cosmological model (right column).

In Figure 2 (taken from [7]) we show how the modified background (increase of $N_{\rm eff}$, gold line) and perturbations (green line) in the majoron-neutrino fluid affect the temperature power spectrum of cosmic microwave background (CMB) fluctuations. The damping of the number of free streaming neutrinos is necessary to preserve the position of the peaks of the CMB acoustic oscillations. Given the value of m_ϕ, and since these interactions are only effective between $10m_\phi \gtrsim T \gtrsim m_\phi/10$, the interactions will only alter CMB multipoles $\ell \lesssim 1000$. Adding both contributions together (red line), the fit to the data (blue points with error bars) is recovered, as previously shown in [6].

4. Conclusions

Our proposal of an *Axion-Like Majoron* model, and its global fit to cosmological data results in the following conclusions:

- The neutrino sector has the potential to provide hints to unsolved problems in Cosmology and Particle Physics.

- Extensions to the Standard Model such as the majoron can be viable models to explain the origin of neutrino masses, while reducing the H_0 tension.

- An axion-like majoron has the advantage that the value of $\Delta N_{\rm eff}$ can be $\simeq 1$, due to photon-to-majoron resonant production, and decay while non-relativistic.

- The majoron parameters can be chosen so that they can reduce the H_0 tension without spoiling the fit to CMB or BBN observations.

- A global fit including CMB and LSS observables is mandatory in order to better constrain the physics of such extensions.

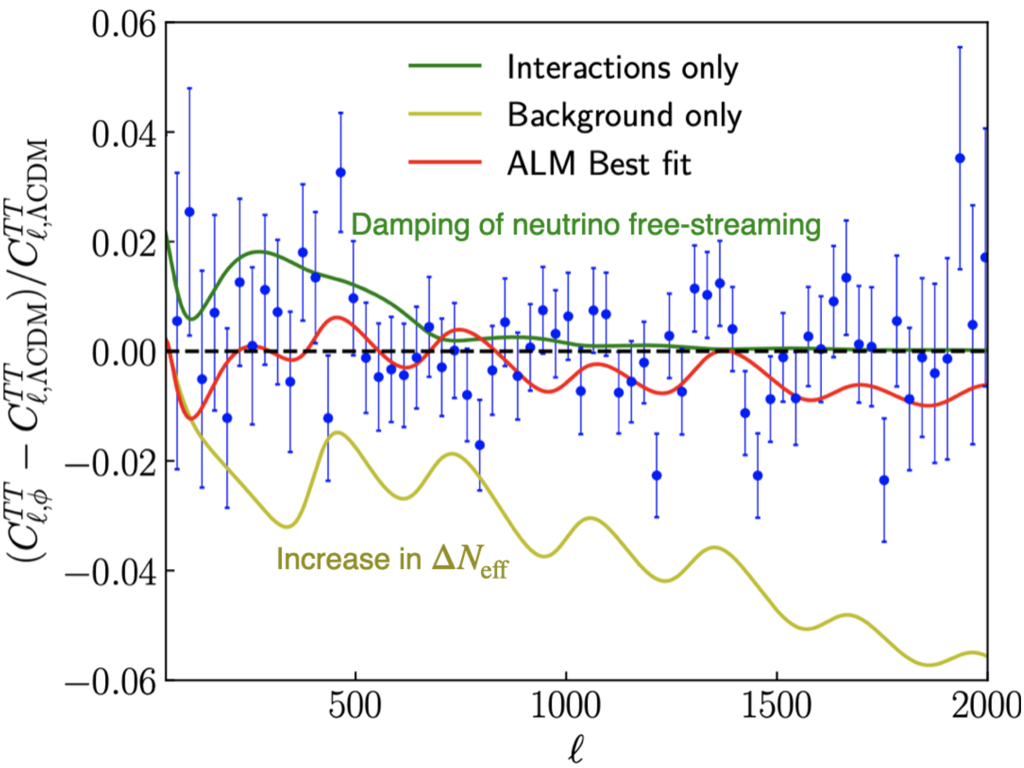

Figure 2: Residuals of the CMB temperature power spectrum (with respect of the best fitting ΛCDM model) of the ALM model (red solid line) and Planck observations (blue data points). Also shown is the separate effect of the damping of neutrino free-streaming (green line), and the effect of the increase in the effective number of relativistic species (gold line).

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