Extremes in Mixing Angle Space: Sterile Neutrino Sensitivity in the Next Generation of Searches

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Sterile neutrinos represent a clear extension of the Standard Model with multiple potential cosmological signatures. We numerically follow the cosmic production of sterile neutrino dark matter to constrain the mass-mixing angle parameter space, leading to a better understanding of the models which remain viable for further study in future experimental probes. In the small mixing angle regime, we study Shi-Fuller-based production or models with enhanced active sector self-interaction, which furthers the possibility that sterile neutrinos comprise the majority of the dark matter. In the high mixing angle regime, we explore possible mechanisms of suppressing production of keV scale sterile neutrinos, within the HUNTER experiment parameter space.

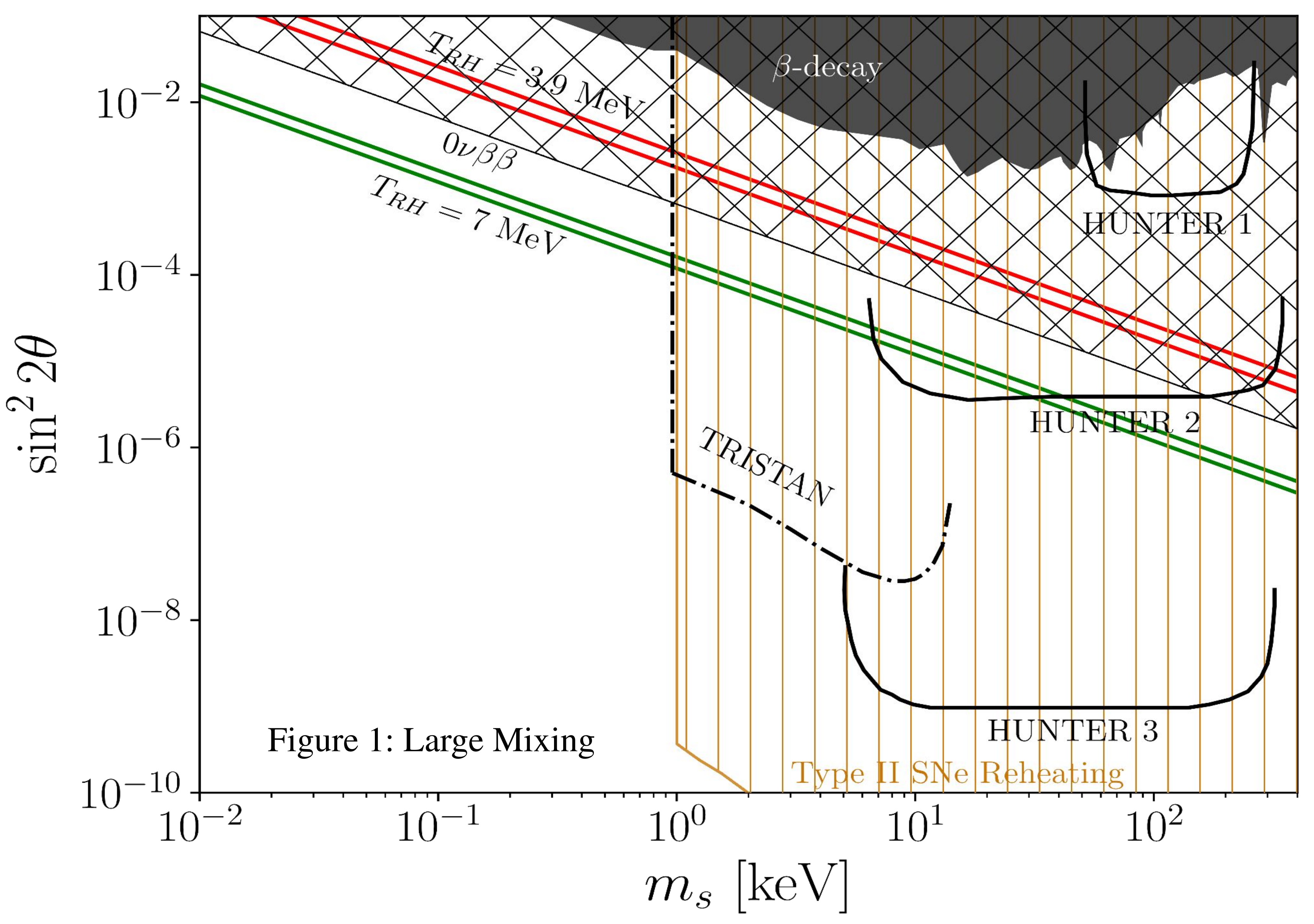

Figure 1: Large Mixing

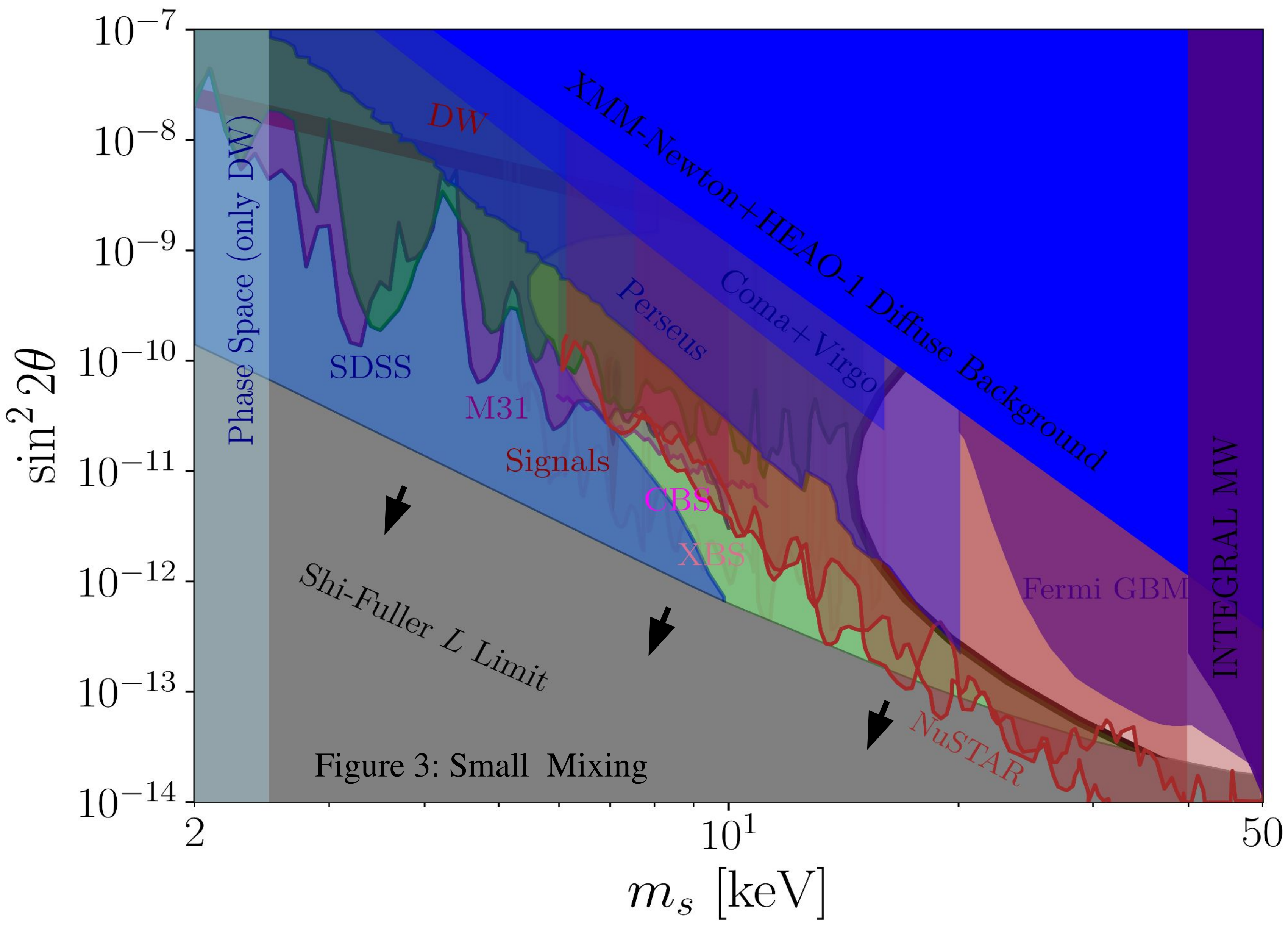

Figure 3: Small Mixing

Very Large Mixing Angle, Visible Sterile Neutrinos

We study the decay of keV-scale sterile neutrinos to a dark sector, which can allow for their presence at large mixing angles and could even be responsible for the existence of the Hubble tension in low-reheating temperature universes. The invisible decay mechanism could be $\nu_s \rightarrow \nu_{s'} \bar{\nu}_{s'} \nu_{s'}$, which needs an effective four-fermion interaction of sterile neutrinos, or a two body decay to a (pseudo)scalar and $\nu_{s'}$. Within this scenario, the relativistic nature of the sterile neutrino makes its mass not important in the first radiation-dominated part of the evolution of the Universe, as shown in Fig. 2. Eventually, the massive sterile neutrino redshifts as matter, with its energy density becoming comparable to that of the photon and the standard neutrino background. With a sterile neutrino decay to light or massless particles at such a time, it will contribute a non-trivial amount of radiation energy density to the Universe.

Low Reheating Temperature Universes

A low reheating temperature $T_{\mathrm{RH}} \ll 100$ MeV at the end of inflation has been proposed as a scenario that could make sterile neutrinos visible in future experiments. The coupling between the active neutrinos and steriles could be as large as experimental and cosmological bounds permit. The abundance in this scenario depends on the precise reheating temperature.

We combine the decay mechanism in a low reheating Universe to explore the suppression production of keV-scale sterile neutrinos. In particular we study the parameter space of an upcoming experiments that will probe the possible presence of keV-scale sterile neutrinos. HUNTER (Heavy Unseen Neutrinos from Total Energy-momentum Reconstruction) is a future experiment that will search for additional "sterile" neutrinos beyond the Standard Model (BSM) using an instrument for radioactive atom trapping and high-resolution decay-product spectrometry. HUNTER will be a precise experimental test for the existence of a sterile neutrino with masses between a 10-100 keV range, at a level beyond current laboratory experimental constraints. If a signal is detected in this parameter space, it would indicate new physics in the early Universe that could be explained within this scenario, explaining the first detected remnant from the untested pre-BBN era in the Universe.

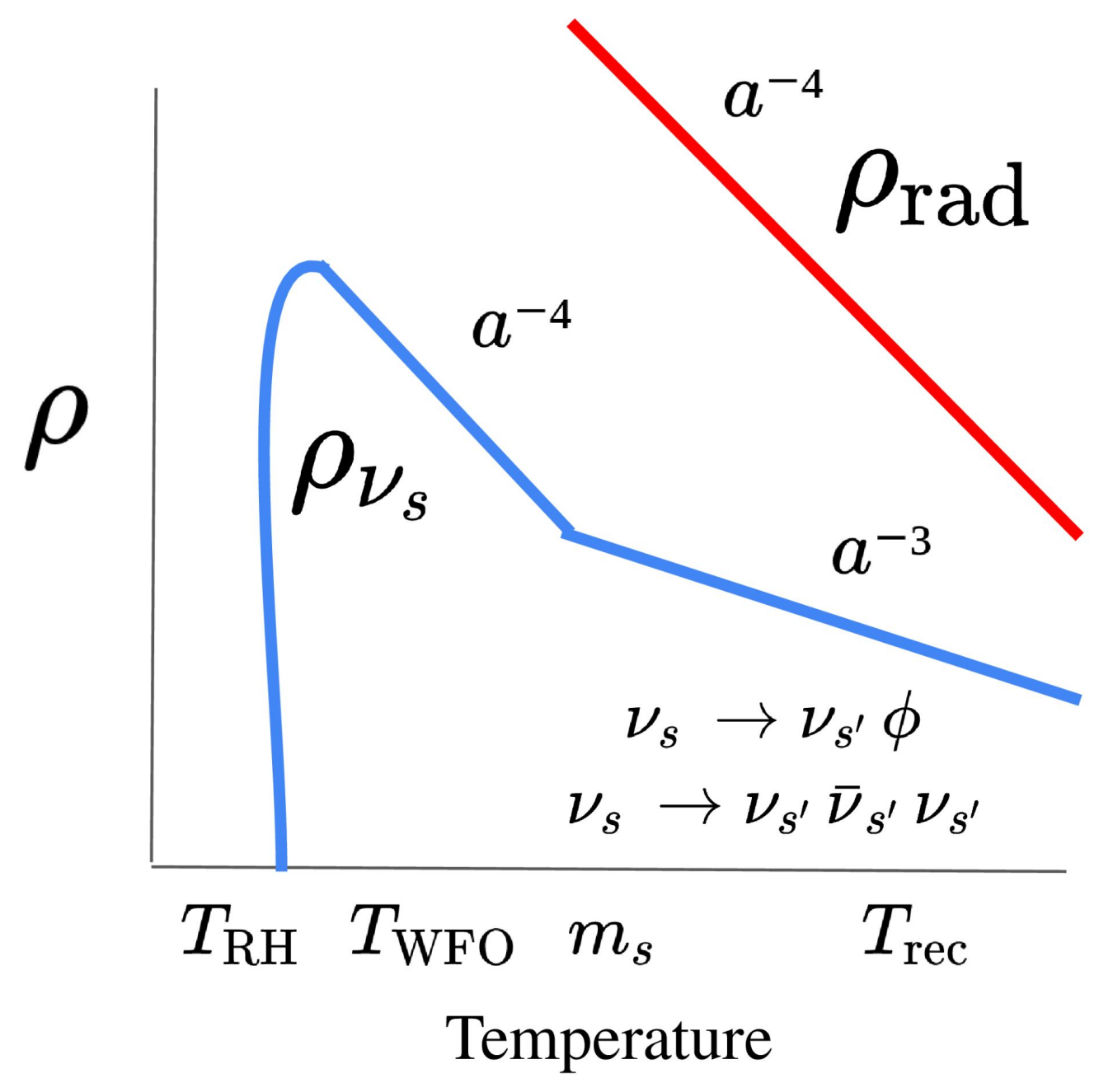

Figure 2

Large Mixing Angle Parameter Space

In Fig. 1, we present two different T_{RH}: 3.9 MeV (red solid lines), the lowest allowed by BBN, and 7 MeV (green solid lines), where the active neutrinos are nearly fully thermalized. The two lines represent the number of relativistic species that is considered in the standard scenario and in the case where an additional contribution to the number of relativistic species is present in order to resolve the Hubble tension. Anywhere above the lower line of a given reheating temperature can accommodate a standard N_{eff}, while anywhere above the upper line can accommodate N_{eff} that resolves the Hubble tension. We also show the experimental constraints present within this parameter space. This graph proves there is room for future experiments to detect sterile neutrino signals for the first time in scenarios without any cosmological constraints.

Very Small Mixing Angle Parameter Space

We focus here on the standard Shi-Fuller model, which normally allows for sterile neutrino production into the small mixing-angle region via lepton-number-driven resonant conversion of active neutrinos. This conversion mechanism is well constrained by modern indirect and direct searches; however, current bounds have yet to be examined concurrently until this work. The small mixing angle region of the parameter space is given in Fig. 3. Our work also includes further study in expanding pre-existing sterile neutrino production codes to include additional active sector interactions, which are present in a variety of models under current development. These enhanced interactions lead to increased production, which lowers the Shi-Fuller L limit given in Fig. 3, allowing for mixing angles well below the current lower-bounds between 10^{-10}-10^{-14}. Due to the diversity of models and limited space, the current results focus on bounds in standard Shi-Fuller models.

Updated Lepton Asymmetry Constraints

In addition to the use of enhanced active sector models, a careful study of the lepton asymmetry relationship between neutrino flavors allows for a relaxed bound in small mixing angles for the standard Shi-Fuller model. In particular, the electron neutrino chemical potential, ξ_e, must be mapped to any potential initial ξ_μ from the synchronized oscillation reset of lepton number as shown in Abazajian, Beacom, Bell (2002). The resulting ξ_μ limit is then calculated to be 0.069. This limit can be mapped to the mass-mixing angle space via production code produced lepton asymmetry requirements.

Constraints from Thermal WDM

Recent combinations of cosmological and astrophysical bounds have further pushed the constraints on allowed thermal warm dark matter (WDM). Zelko et al. (2022) have demonstrated that the strongest current bounds on thermal relics can be produced via a combination of satellite counts and strong lensing. The current constraint from this method is $m_{\mathrm{th\ WDM}} > 9.7$ keV, which is stronger than previous Lyman-*a* forest values at > 5.3 keV (both at 95% CL). These thermal relic constraints can be applied to sterile neutrino parameter space by carefully following the cosmic history of sterile neutrino production. Specifically, by following the methods of Venumadhav et al. (2015) the production processes can be computed, allowing for the generation and evolution of phase space densities (PSDs) which are non-trivial, as these particles are not thermal. The late-time PSDs, taken at $T = 10$ MeV when primary production has ceased, are then used as a dark matter distribution input into CLASS in the place of cold dark matter over a large range of sterile neutrino masses and mixing angles. With the remaining inputs specified by Planck 2018 best fit values, the Boltzmann equation is then integrated to produce a matter power spectrum, which can be compared to the fitting function of thermal WDM found in Vogel and Abazajian (2022).

This gives a constraint matching method, allowing for a new exclusion in the parameter space, as seen in Fig. 3. Notably, the black curve produced by the thermal constraints provides for a region which excludes the majority of the small-mass space, and, when taken with the updated NuSTAR limits, fully excludes Shi-Fuller production at 95% CL. Ongoing analysis consists of more precise bounds in this region of interest via a detailed study following the above pipeline. The current result is the exclusion of standard Shi-Fuller models in the entire parameter space. However, enhanced active sector-based sterile neutrino production relaxes many of these constraints, providing for the potential for a new generation of direct and indirect searches calibrated for the specific allowances given under promising sets of models. Future work will further analyze these systems and the relationship between their resonant production values in relation to conditions arising from precision astrophysical and cosmological experiments.

Acknowledgements

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