Flavor Oscillations and Sterile Neutrino Production in the Early Universe

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Goal: describing the production of sterile neutrinos via flavor oscillations in the early Universe

Background

Past experiments in neutrino physics (notably MiniBooNE) have observed oscillation results incongruous with theory, and the existence of **sterile neutrinos** is one possible explanation that could resolve the discrepancy and reveal new physics. **Flavor oscillations** between active and sterile neutrino species then depends on the specific mixing parameters.

One constraint on these mixing parameters comes from cosmology: the evolution of the early universe is dependent on the **effective number of neutrino species (N_{eff})**, which is currently measured as N_{eff}=2.99±0.17 [4]. Since $N_{eff} < 4$, the thermalisation of a sterile state must be limited, which can be used to reduce the allowed range of parameters.

Polarization vector formalism used in the two-flavor case:

$$\varrho = f_0 \begin{pmatrix} f_\alpha & f_{\alpha s} \\ f_{s\alpha} & f_s \end{pmatrix} = \frac{1}{2} f_0 \left[P_0 \mathbb{I} + \mathbf{P} \cdot \boldsymbol{\sigma} \right]$$

The equations that determine the evolution of neutrinos in the early universe are known as the **Quantum Kinetic Equations (QKEs)**. These equations are given as (2.2) from Hannestad et al. 2015 [1]:

$$\dot{\mathbf{P}} = \mathbf{V} \times \mathbf{P} + \frac{R}{f_0} \hat{\mathbf{z}} - D\, \mathbf{P}_\perp$$

$$\dot{P}_0 = \frac{R}{f_0}$$

In these equations, f_0 is the Fermi-Dirac equilibrium distribution of neutrinos.

The term **V×P** corresponds to flavor oscillations under the total Hamiltonian **V**, which contains:

- the matter term, due to interactions with electrons;
- the vacuum term, characterized by the **mass-squared difference** Δm^2 and the **mixing angle** θ_0.

The matter term dominates at high temperatures, with a transition to vacuum domination at a few MeV.

R and D are the repopulation and damping terms, respectively, and are defined as follows, with $\Gamma_\alpha \propto G_F^{2} p T^4$ the collision rate:

$$R = \Gamma_\alpha (1 - f_\alpha)$$

$$D = \Gamma_\alpha / 2$$

Many approximate solutions also exist, which helps to reduce the computational complexity of solving the differential equations posed by the full QKEs. Results are compared with the **Dodelson-Widrow approximation**:

$$\dot{f}_s \simeq \frac{\Gamma_\alpha}{2} \langle \mathbb{P}(\nu_\alpha \to \nu_s) \rangle \left[f_\alpha - f_s \right] = \frac{\Gamma_\alpha}{4} \sin^2(2\theta_{\mathrm{eff}}) \left[f_\alpha - f_s \right]$$

which is based on a mechanism of only conversion and repopulation, averaging over the oscillatory behavior present in the QKEs.

Methods

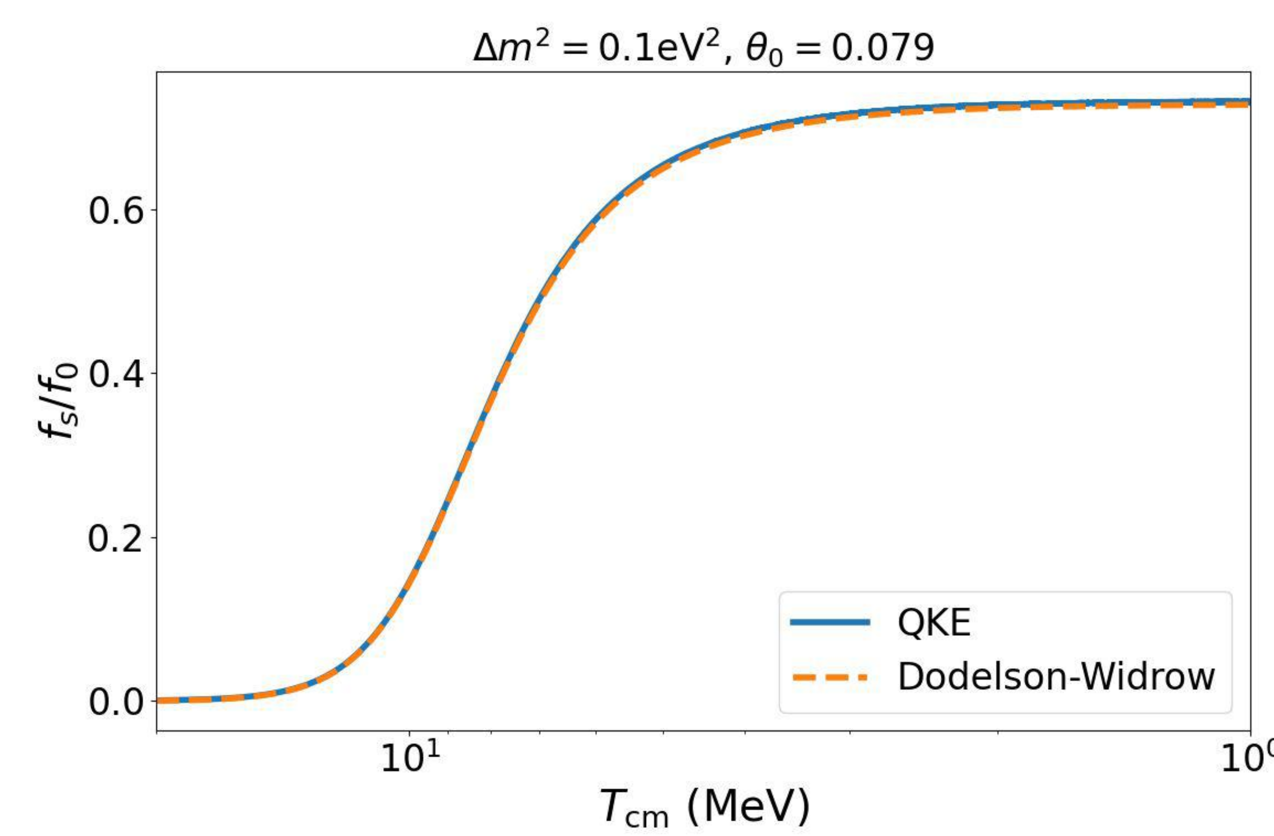
The QKEs and the Dodelson-Widrow approximation are solved at various mixing angles and mass-squared differences between one active (electron flavor) and one sterile species.

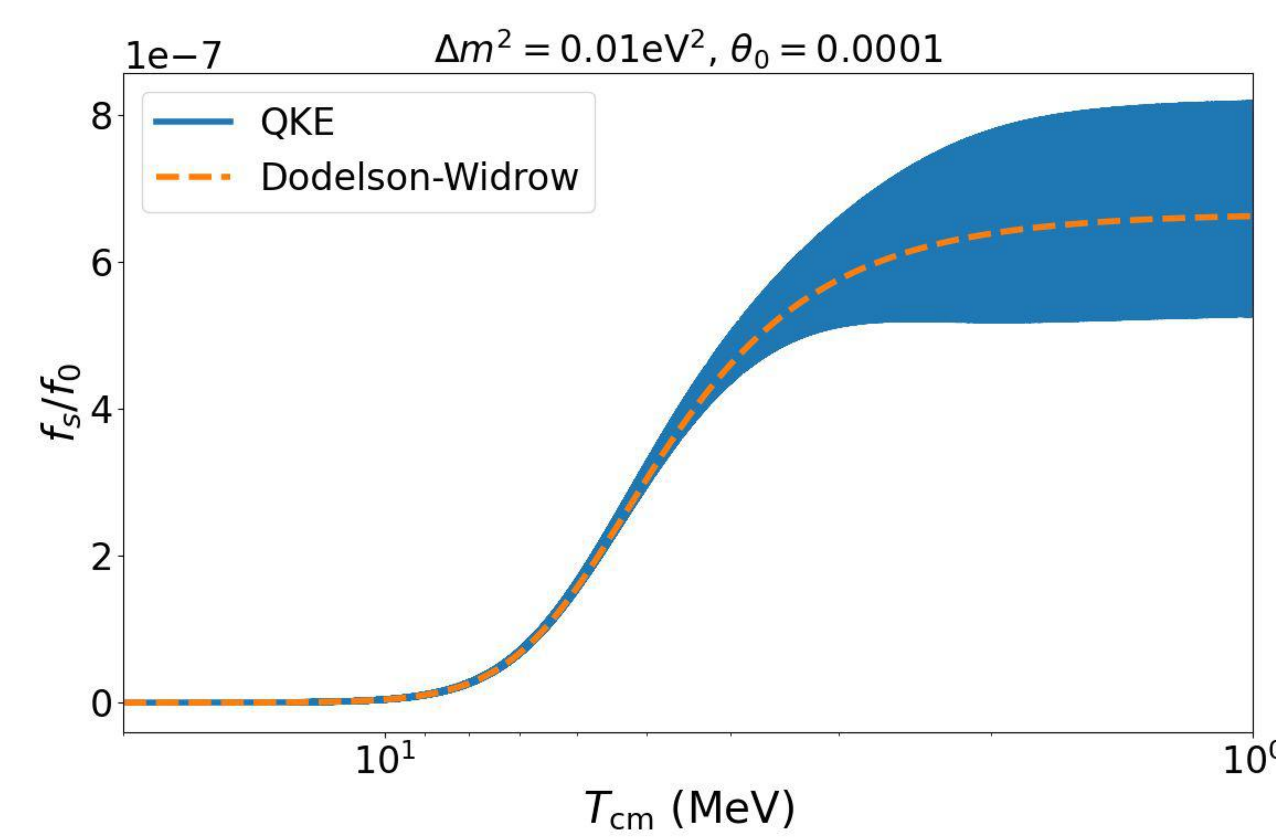
Simplifying assumptions:

- one momentum bin $p \approx 3.15 T_{cm}$
- damping approximation for collisions

T_{cm}: comoving temperature, a reference temperature which is inversely proportional to the scale factor.
Temperature range: [20 MeV, 1 MeV]

Results

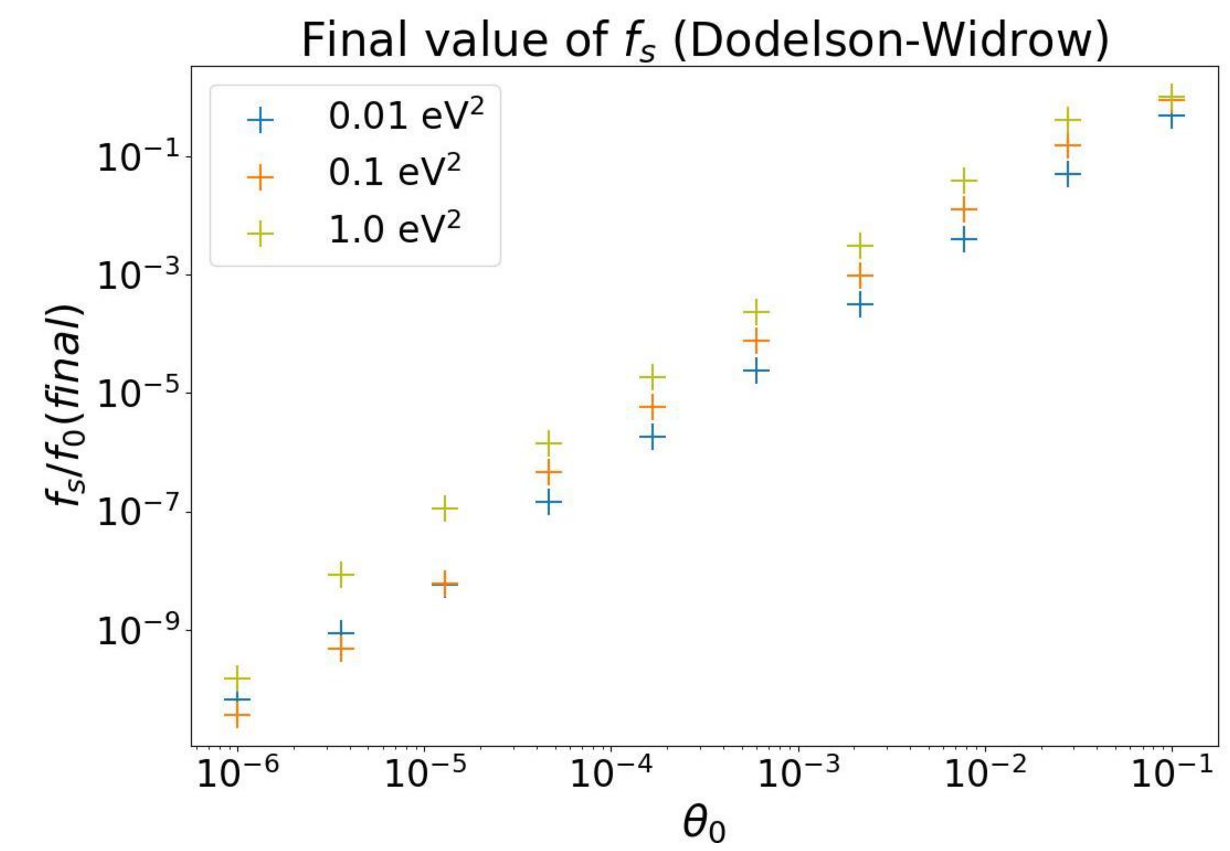




At a reference value of **Δm^2 = 0.01 eV² and θ_0 = 0.079**, the average value of f_s around T = 1 MeV obtained by solving the exact QKEs is equal to **0.73 f_0**, in agreement with [1].

The exact QKE solution and the approximation are also in close agreement throughout the evolution. The approximation effectively presents an average value of the QKE solution.

Results



To quantify the relationship between mixing parameters and the resulting evolution, a range of mixing angles were tested at fixed Δm^2 using the Dodelson-Widrow approximation. On a double-log scale, the behavior matches the expectation from the sine-squared scaling for mixing angle in neutrino oscillations.

Conclusion

The results obtained so far are in agreement with other sources, which brings confidence that the method design is robust.

Prospects for future work:

- Further testing of the parameter space to identify quantitative relationships in the evolution of the active and sterile species, and to evaluate which sections of the parameter space are in agreement with both experimental and cosmological results.
- Increasing the *number of momentum bins* to simulate a more realistic energy distribution for neutrinos, which would also allow for a more nuanced model of neutrino interactions.
- *Lepton asymmetry*, which suppresses the conversion of active to sterile [2].
- *Increasing number of flavors*: 3 active + 1 sterile flavor model or additional sterile species, which would allow for additional properties which could resolve experimental discrepancies [2].

Acknowledgements

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References

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