# Flavor Oscillations and Sterile Neutrino Production in the Early Universe

David Yang, Julien Froustey

N3AS, University of California Berkeley

N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries PHYSICS FRONTIER CENTER

NSF 2020275

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

## Background

Past experiments in neutrino physics observed results which could imply the existence of **sterile neutrinos**, which undergo **flavor oscillations** with active species depending on their mixing parameters. One constraint on mixing parameters comes from cosmology: the evolution of the early universe is dependent on the **effective number of neutrino species ($N_{eff}$)**, $N_{eff}$=2.99±0.17 [4].

In a two flavor (one active, one sterile) model, the eigenstates are related with the transformation:

$$\nu_a = cos(\theta_0)\nu_1 - sin(\theta_0)\nu_2$$

$$\nu_s = sin(\theta_0)\nu_1 + cos(\theta_0)\nu_2$$

*Polarization vector formalism* used in the two-flavor case:

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

**Quantum Kinetic Equations (QKEs)** determine the neutrino evolution, given as (2.2) from Hannestad et al. 2015 [1]:

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

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

$f_0$ is the Fermi-Dirac equilibrium distribution of neutrinos.

**V** is the total Hamiltonian, which contains:

- the matter term, due to interactions with electrons;
- the vacuum term, characterized by the **mass-squared difference** $\Delta m^2 \stackrel{\text{def}}{=} m_2^2 - m_1^2$ and the **mixing angle** $\theta_0$.

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

Repopulation and damping terms, with $\Gamma_\alpha \propto G_F^2 * p * T^4$ the collision rate:

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

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

$N_{eff}$ can be calculated from the neutrino population using

$$\delta N_{\text{eff}} = \frac{\int dy y^3 f_0 (P_0 - 1)}{\int dy y^3 f_0} \propto$$ Extra energy density from sterile species

The **Dodelson-Widrow approximation**:

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

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

**Adiabaticity** quantifies the relative rate of change of the Hamiltonian.

Two possible mass orderings:

- Normal hierarchy when $\Delta m^2 > 0$
- Inverted hierarchy $\Delta m^2 < 0$: resonance which can cause additional conversion into sterile neutrinos.

## Methods

ODEs for QKEs and Dodelson-Widrow solved with scipy.

Simplifying assumptions:

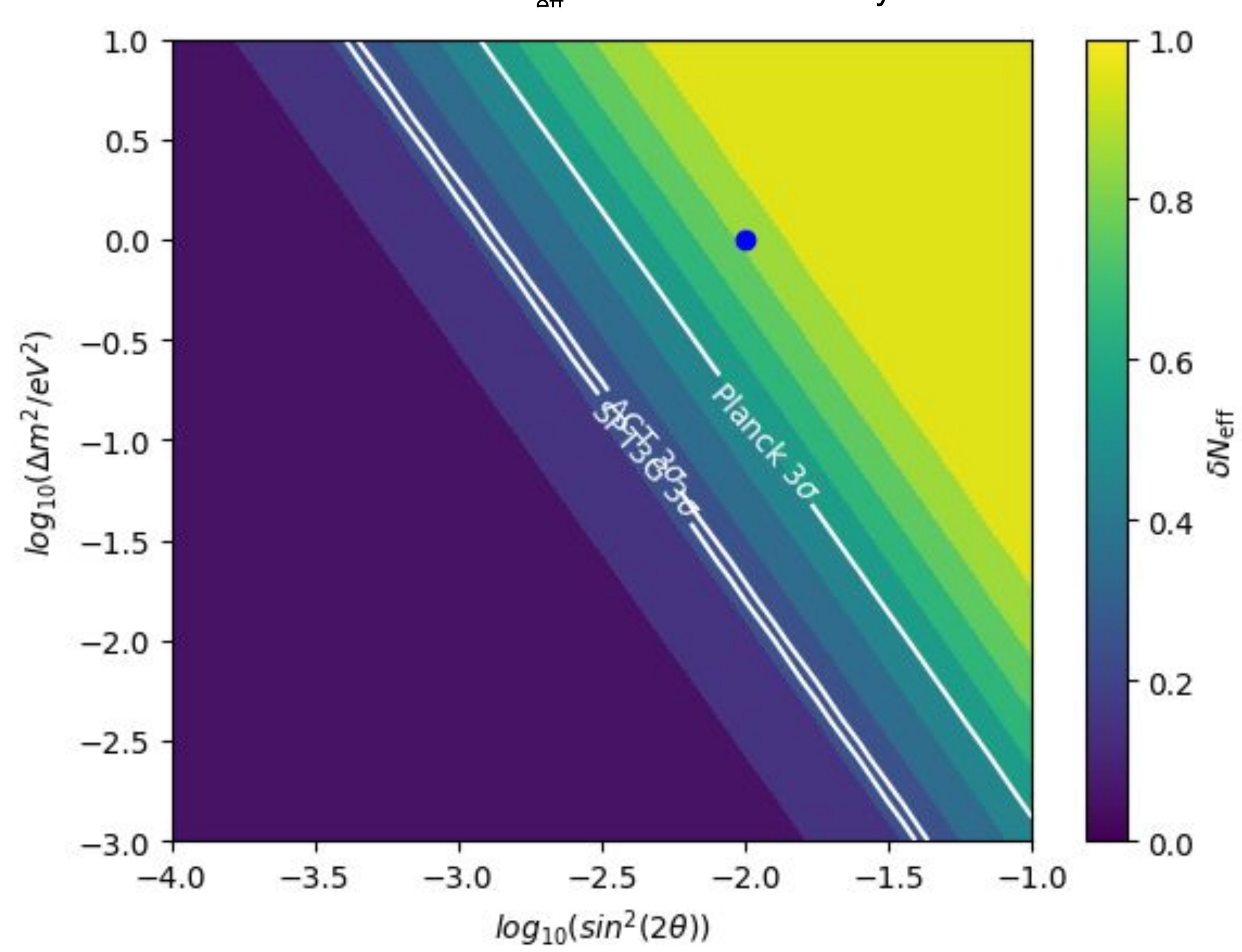
- 20 momentum bins linearly spaced from $p = 0.1 T_{cm}$ to $25\ T_{cm}$
- damping approximation for collisions

$T_{cm}$: comoving temperature, a reference temperature which is inversely proportional to the scale factor.

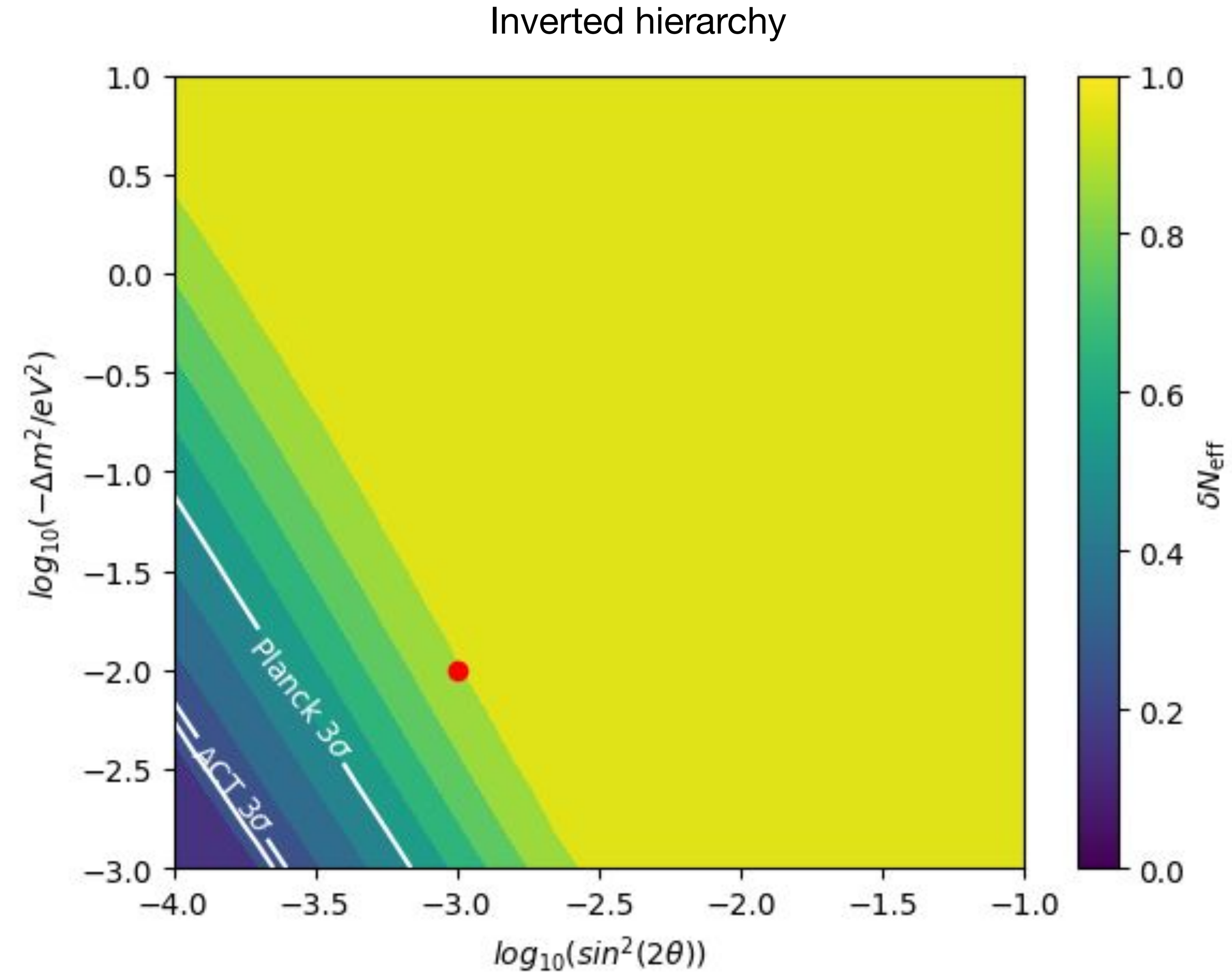
Temperature range: [40 MeV, 0.1 MeV]

## Results

Final $\delta N_{eff}$ in normal hierarchy



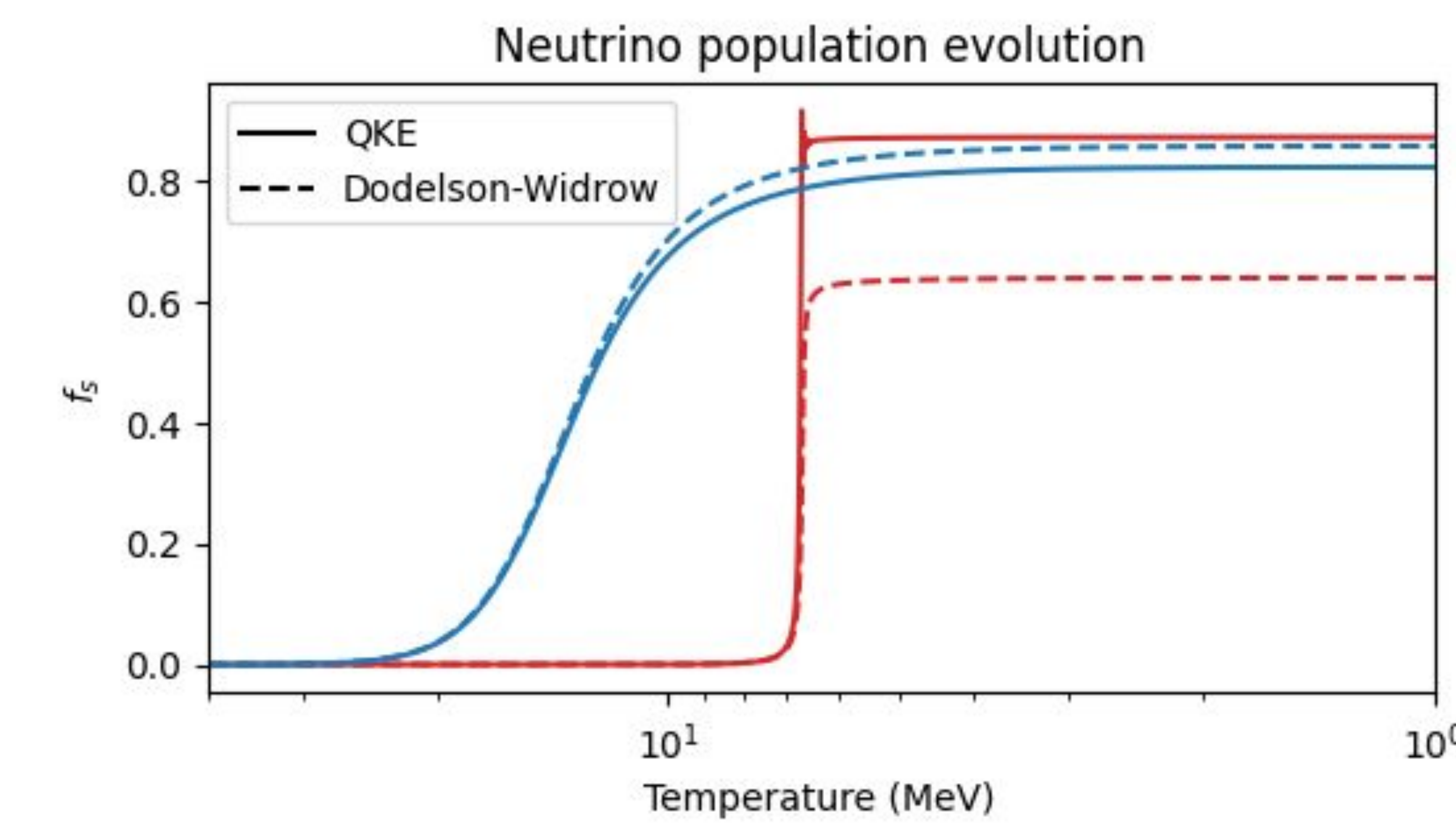

Inverted hierarchy

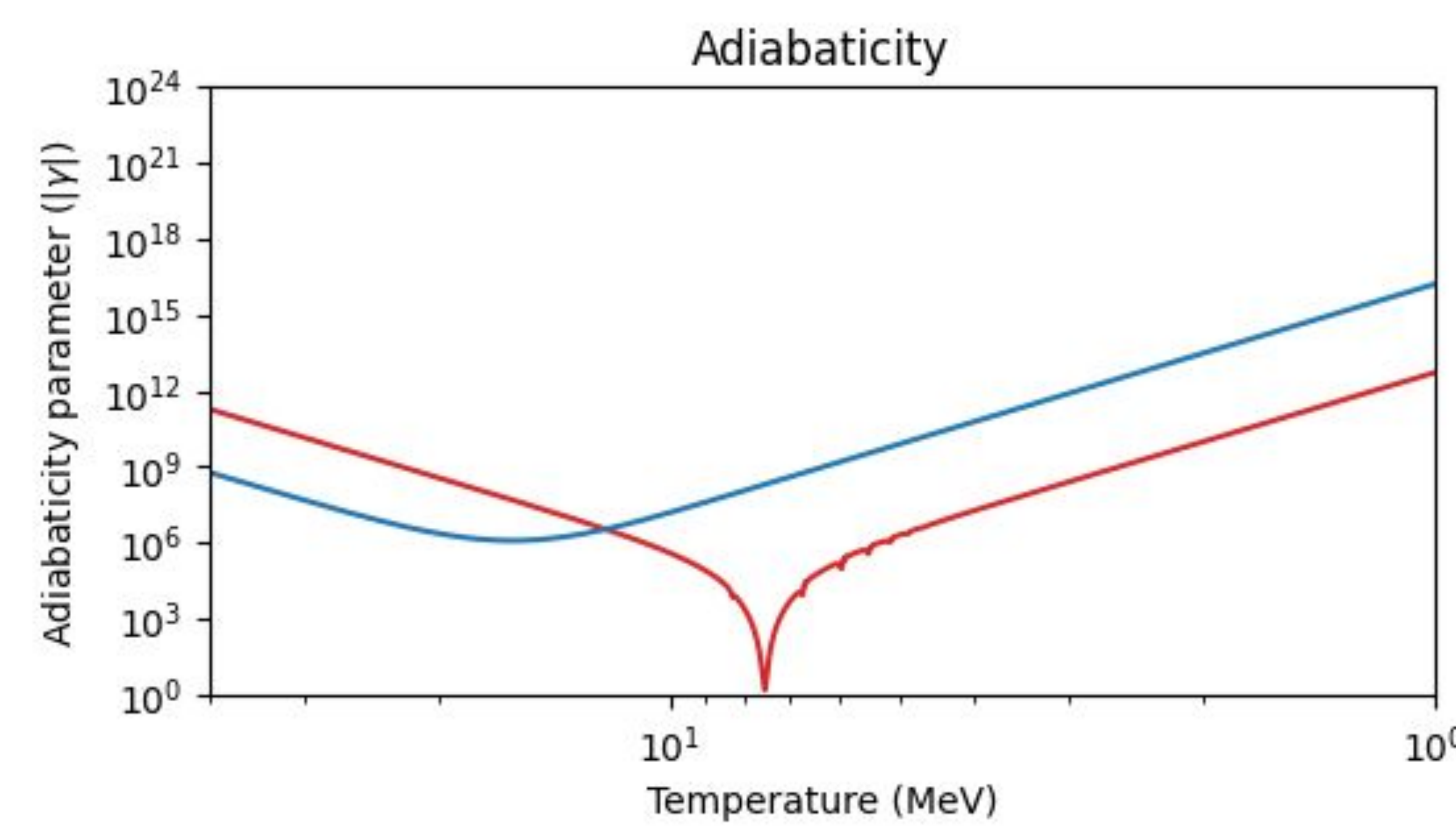



## Example cases

$\Delta m^2 = 1eV^2$, $sin^2(2\theta_0) = 0.01$ and $\Delta m^2 = -0.01 eV^2$, $sin^2(2\theta_0) = 0.001$

Plotting only the bin with momentum y=2.72:




## Conclusion

For one sterile species, the parameters favored by short baseline experiments result in large thermalisation, which is cosmologically forbidden. Comparison of the results obtained show the applicability of the Dodelson-Widrow approximation in different cases, which can improve the computational efficiency in further work.

Prospects for future work:

- *Lepton asymmetry*, which suppresses active-sterile conversion [2].
- *Increasing number of flavors*: 3 active + 1 sterile flavor model or additional sterile species [2].

## Acknowledgements

This research was supported by NSF Physics Frontier Center, award No. PHYS-2020275.

## References

1. S. Hannestad, I. Tamborra, and T. Tram, *Journal of Cosmology and Astroparticle Physics* 07, 025 (2012).
2. S. Hannestad, R.S. Hansen, T. Tram, and Y.Y.Y. Wong, *Journal of Cosmology and Astroparticle Physics* 08, 019 (2015).
3. K. Abazajian, G.M. Fuller, and M. Patel, *Physical Review D* 64, (2001).
4. N. Aghanim et al., *Astronomy & Astrophysics* 641, (2020).