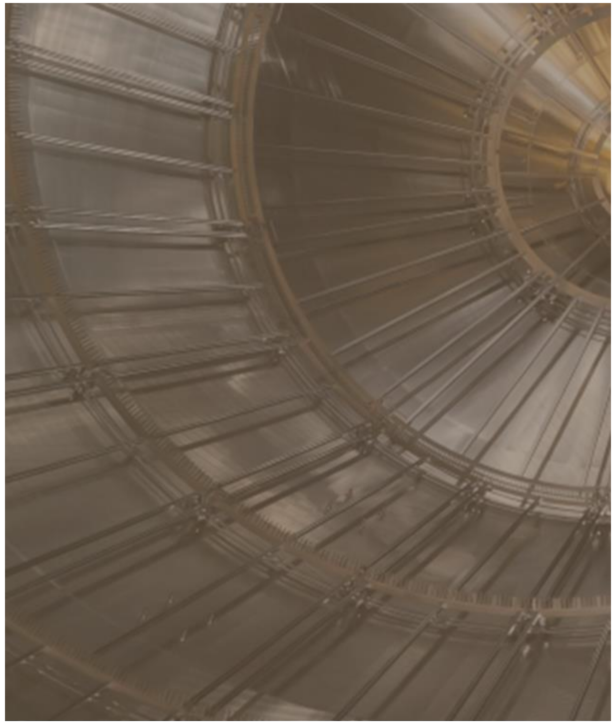
COSMOLOGY-FRIENDLY TIME-VARYING NEUTRINO MASSES and beta decay experiments

Pablo Martínez-Miravé, IFIC (Univ. Valencia – CSIC)
in collaboration with G.Huang, M. Lindner and M. Sen

FLASY2022 - 9th Workshop on Flavour Symmetries and Consequences in Accelerators and Cosmology



Neutrinos can acquire a time-varying mass via the sterile neutrino portal and its coupling to ultralight dark matter.

Various cosmological bounds on sterile neutrinos can be evaded and several experimental signatures are expected, including in beta decay experiments.

ULTRALIGHT DARK MATTER

- An ultralight scalar with mass $m_\phi > O(10^{-22}$ eV) can alliviate some discrepancies between cosmological observations and simulations at small scales.

(Fuzzy Dark Matter)

- An ultralight scalar field produced coherently, behaves like a classical field

$$\phi(t) = \phi \sin m_\phi t \quad \text{with} \quad \phi = \sqrt{2\rho}/m_\phi$$

and the modulation period is related to the scalar mass

$$\tau_\phi \equiv \frac{2\pi}{m_\phi} = 0.41 \left(\frac{10^{-14}\text{eV}}{m_\phi}\right) \text{s}$$

Rich phenomenology expected in case it couples to neturinos

ULTRALIGHT DARK MATTER and NEUTRINOS

A feasible way to couple light neutrinos to the scalar field is by mixing with right-handed sterile neutrinos,

$$
\begin{aligned}
-\mathcal{L} \supset\; & y_D \bar{l}_L \tilde{h} N + \frac{1}{2}(m_N + g\boldsymbol{\phi})\overline{N^c}N \\
& + \frac{1}{2}\kappa \bar{l}_L \tilde{h}\tilde{h}^T l_L^c + \frac{1}{2}\frac{y}{\Lambda}\boldsymbol{\phi}^2\overline{N^c}N + h.c. + \ldots
\end{aligned}
$$

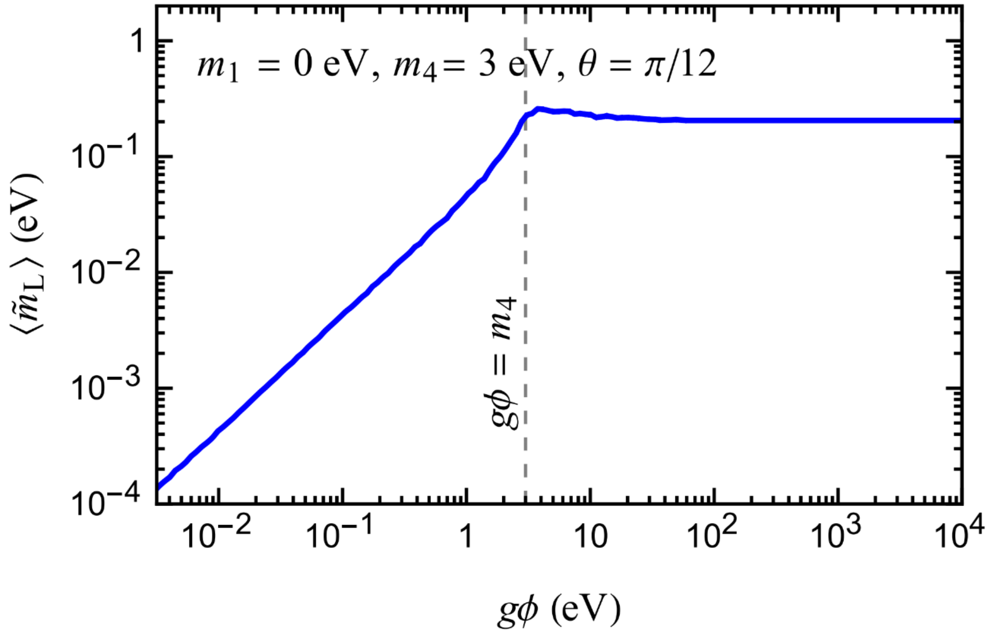
DISCLAIMER:
For simpliciy and aiming to have a deeper understanding of the phenomenological implications, we work in a two neutrino framework (with one active and one sterile).

ULTRALIGHT DARK MATTER and NEUTRINOS

Then,

$$\widetilde{M_\nu} = U^\dagger \begin{pmatrix} m_1 & 0 \\ 0 & m_4 \end{pmatrix} U^* + \begin{pmatrix} 0 & 0 \\ 0 & g\phi \end{pmatrix}$$

$$= \tilde{U}^\dagger \begin{pmatrix} \tilde{m}_1 & 0 \\ 0 & \tilde{m}_4 \end{pmatrix} \tilde{U}^*$$



**In the case of a very heavy sterile,

$$\tilde{m}_1 \simeq m_1 + \sin^2\theta_{14} \cdot g\phi \qquad \tilde{m}_4 \simeq m_4 + \cos^2\theta_{14} \cdot g\phi$$

which could manifest as time-dependent signals or distortions in oscillations experiments.

[A.Berlin *PRL* 117 (2016) 23, 231801] [G.Krnjaic et al. *PRD* 97 (2018) 7, 075017] [A.Dev et al. *JHEP* 01 (2021) 094]

COSMOLOGICAL CONSEQUENCES

Neutrino decoupling and Big Bang Nuclenthesosyis (BBN)
Cosmic Microwave Background (CMB) and Large Scale Structure (LSS)

BBN and NEUTRINO DECOUPLING

Light sterile neutrinos have an additional risk of thermalisation, contributing as radiation in the early Universe (and also leading to a larger N_{eff})

The number of relativistic neutrinos is defined from the radiation density

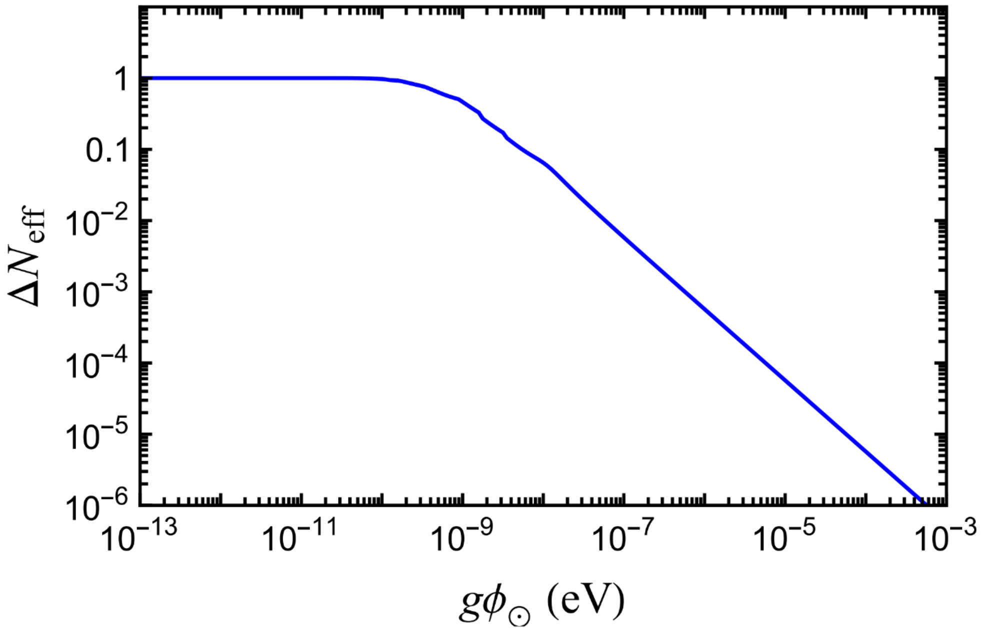
$$\rho_{\mathrm{rad}} = \rho_\gamma \left[1 + \frac{7}{8} \left(\frac{4}{11} \right)^{4/3} (N_{\mathrm{eff}} + \Delta N_{\mathrm{eff}}) \right]$$

with N_{eff} = 3.044 0.0002
[J.Froustey et al. JCAP 12 (2020) 015]
[J.J Bennett et al. JCAP 04 (2021) 073]

The idea in this scenario is that the effective dark matter potential suppresses active-sterile mixing.

BBN and NEUTRINO DECOUPLING

The idea in this scenario is that **the effective dark matter potential suppresses active-sterile mixing**.



$\Delta m^2_{41} = 10\ \mathrm{eV}^2$

$\sin^2 2\theta = 0.25$

What if the ultraligth scalar acts itself as extra radiation?

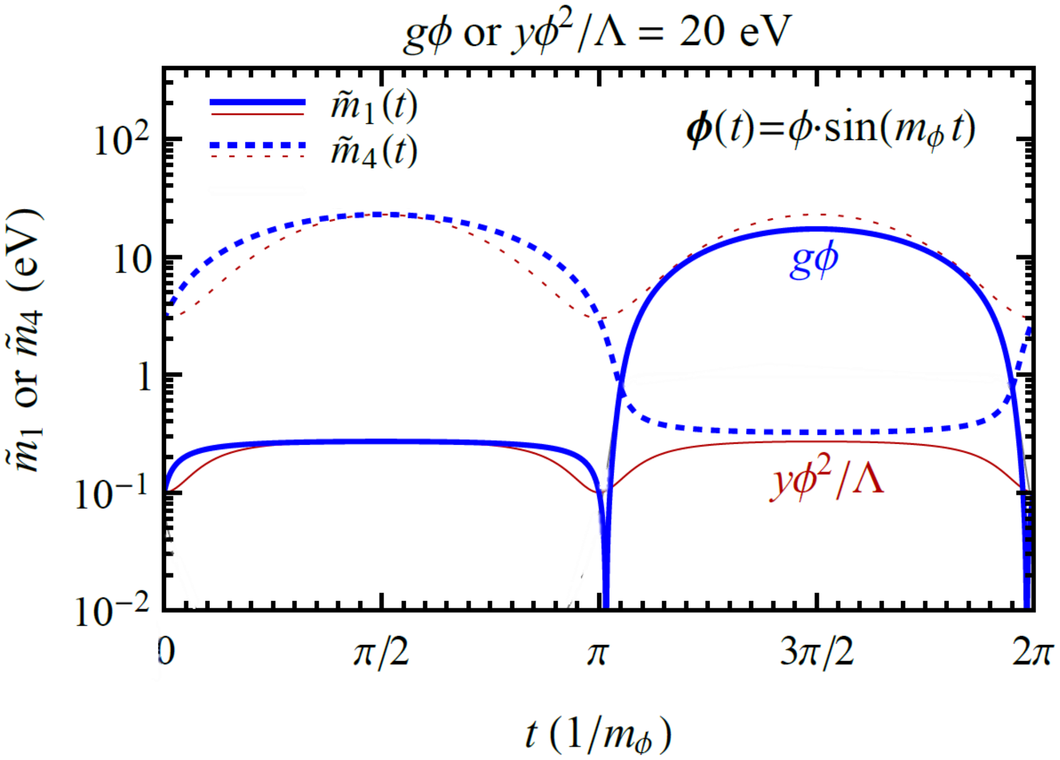
In this scenario, this is prevented due to the tiny coupling considered.

$$g\phi_\odot \approx 2.15 \times 10^{-7}\mathrm{eV} \cdot \left(\frac{g}{10^{-22}}\right) \cdot \left(\frac{10^{-18}\mathrm{eV}}{m_\phi}\right)$$

TWO KEY IDEAS:

- After decoupling, neutrino masses keep varying with the background scalar field.

- Free-streaming neutrinos during recombination damp all the perturbation modes for small scales.



We expect neutrinos to be relativistic half of the time

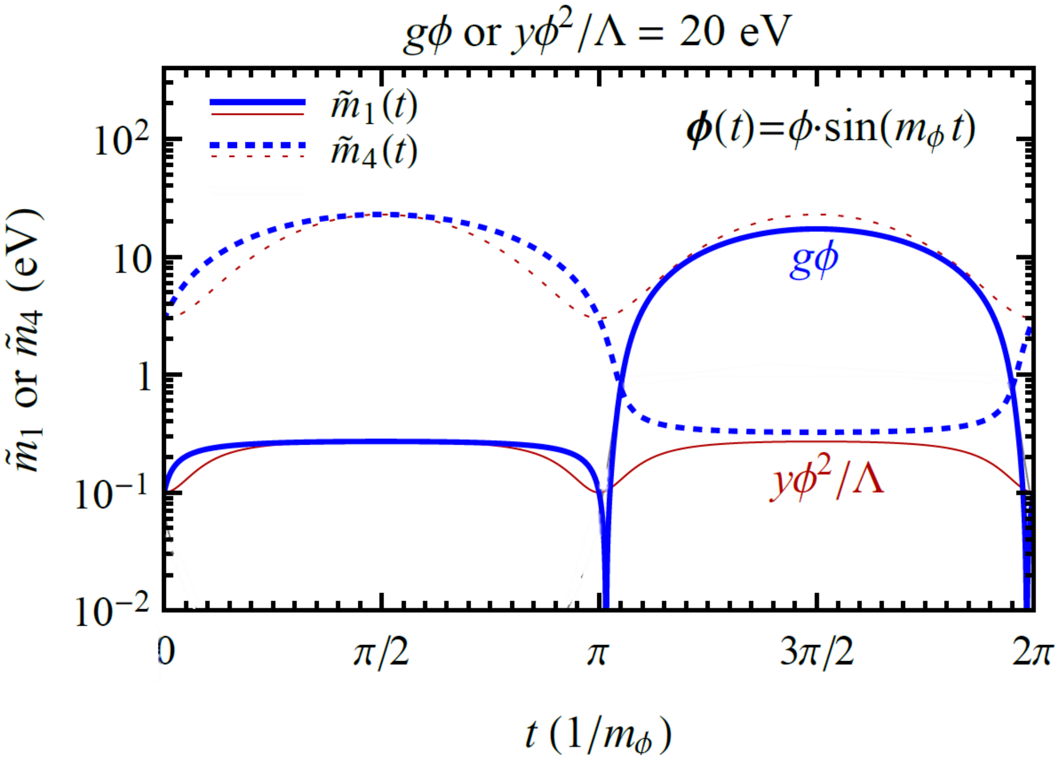
Considerable reduction of the free streaming length

If the higher dimensional term in the Lagrangian dominates,

$$-\mathcal{L} \supset \frac{1}{2}(m_N + g\phi)\overline{N^c}N + \frac{1}{2}\frac{y}{\Lambda}\phi^2\overline{N^c}N + h.c. + \ldots$$

this would no longer be an issue…

A. Anisimov, P. Di Bari *PRD* 80 (2009) 073017
Y. Zhao, PRD 95 (2017) 11, 115002



WHY?
This term could be large during recombination and negligible in present times, since it scales as

$$\phi(z) = \phi(0)(1+z)^3$$

SIGNATURES IN BETA DECAY EXPERIMENTS

TAKING KATRIN AS AN EXAMPLE

HEAVY STERILE NEUTRINO

The standard beta decay spectrum depends on the effective neutrino mass,

$$m_\beta^2 \equiv \sum_{i=1}^{3} |U_{ei}|^2 m_i^2$$

In our case, in the limit in which sterile neutrino masses are much larger than the $g\phi$ term, then the effective neutrino mass is approximately,

$$\tilde{m}_\beta \approx m_\beta + g_\nu \phi \sin m_\phi t$$

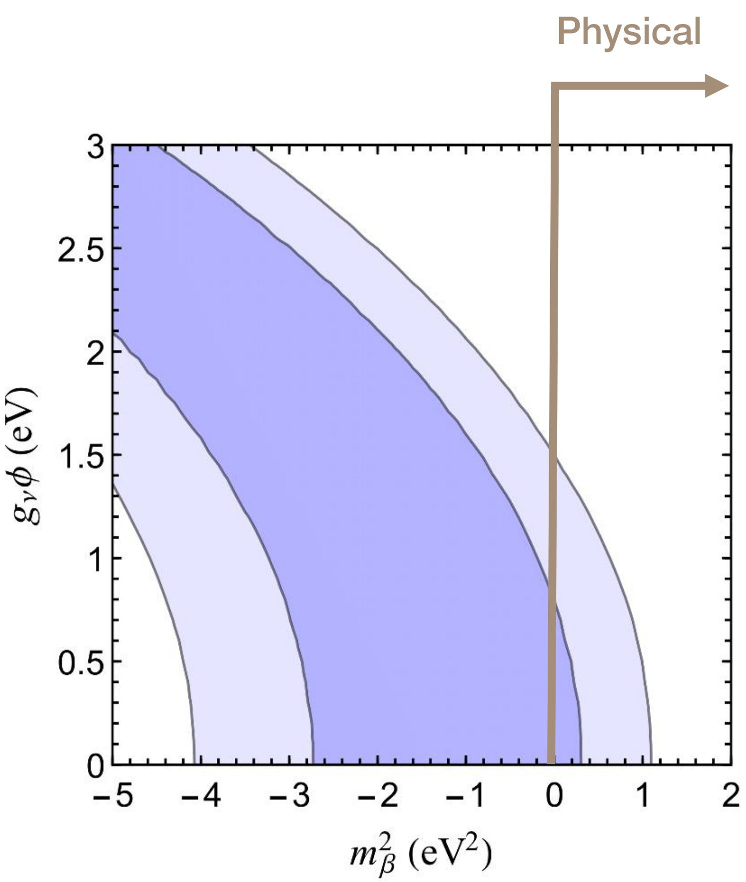
Then, for a fast-oscillating DM field (i.e. after averaging over a modulation cycle)

$$\langle \tilde{m}_\beta^2 \rangle = m_\beta^2 + \frac{(g_\nu \phi)^2}{2}$$

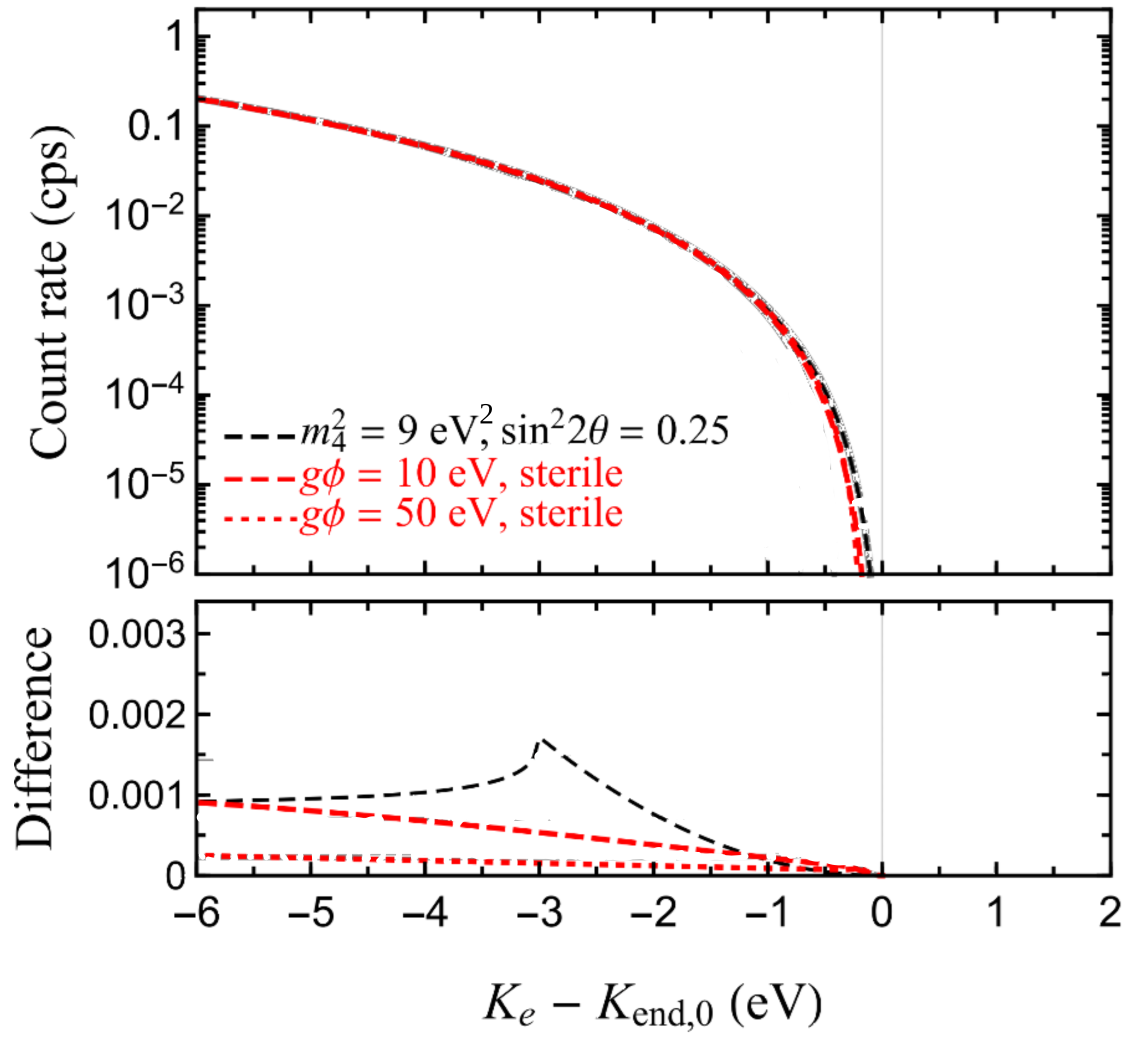
HEAVY STERILE NEUTRINO

- The averaged effect of the scalar is degenerated with the effective neutrino mass.
- The limits derived when assuming $g\phi = 0$ are conservative.

Taking KATRIN's first campaign as an example…



LIGHT (eV) STERILE NEUTRINO



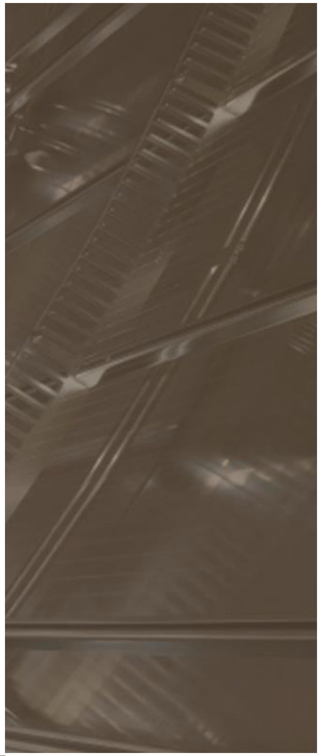
In the presence of a light sterile neutrino, the beta decay gets an additional kink.

In the presence of an ultralight scalar, its averaged effect results in a distortion of that kink and of the overall spectrum.

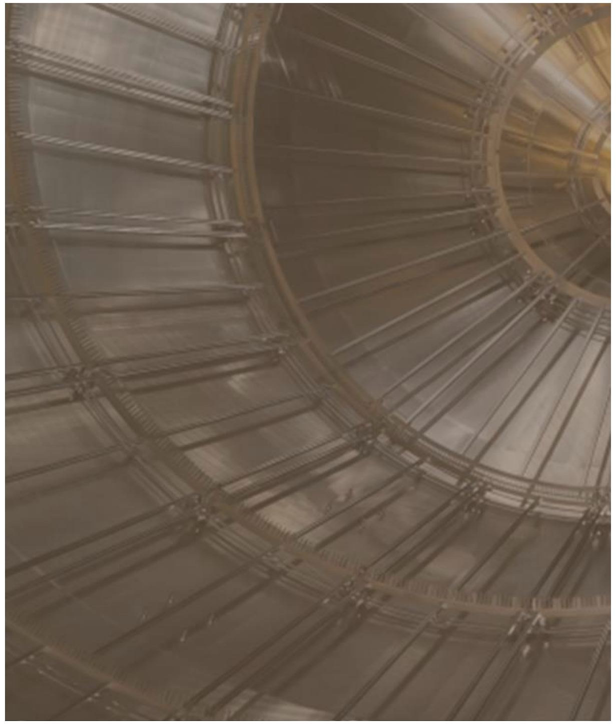
In this scenario, some of the existing limits on eV and keV sterile neutrinos can be relaxed.

Also the sterile neutrino interpretation of the Gallium anomaly and the reactor antineutrino anomaly would be altered.

This could also lead to interesting phenomenology in other oscillation experiments in which a full 3+1 neutrino treatment is required.



TAKE-HOME MESSAGE

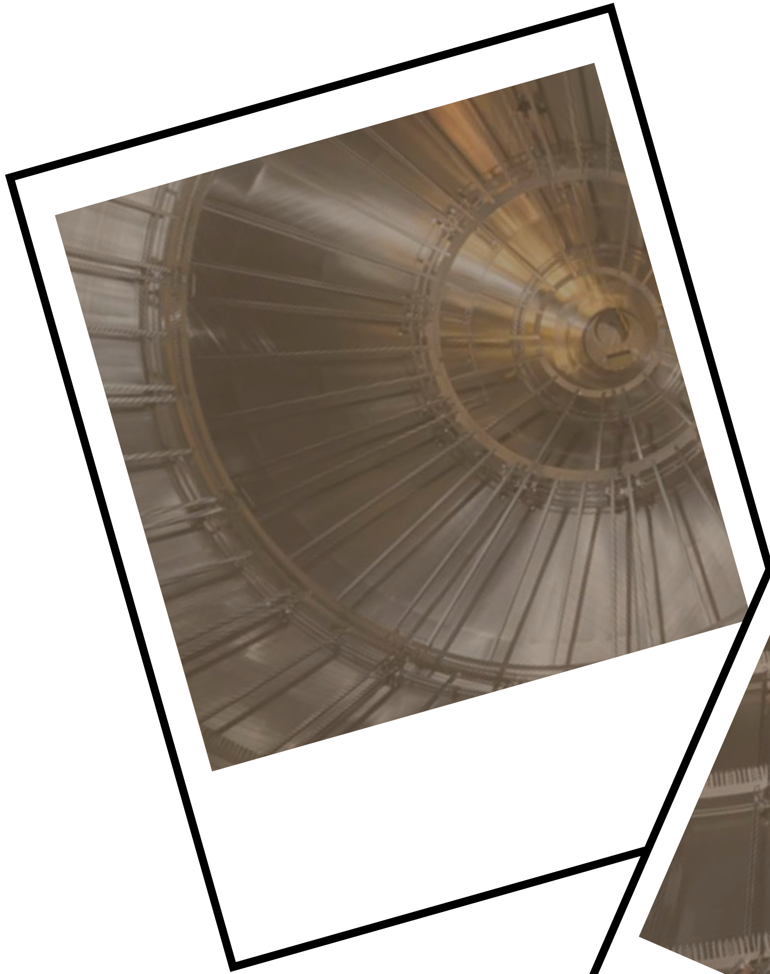


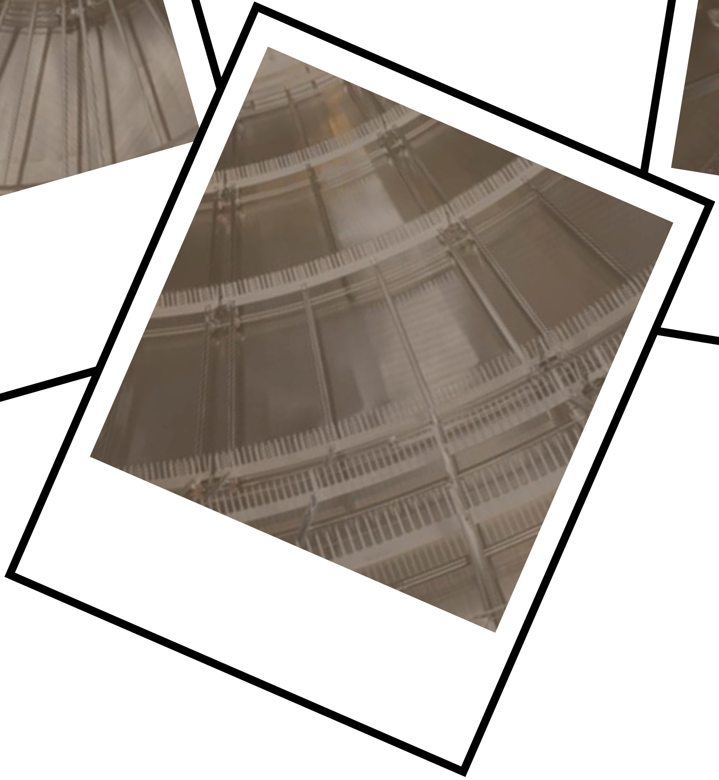
Neutrinos can acquire a time-varying mass via the sterile neutrino portal and its coupling to ultralight dark matter.

Various cosmological bounds on sterile neutrinos can be evaded and several experimental signatures are expected, including in beta decay experiments.

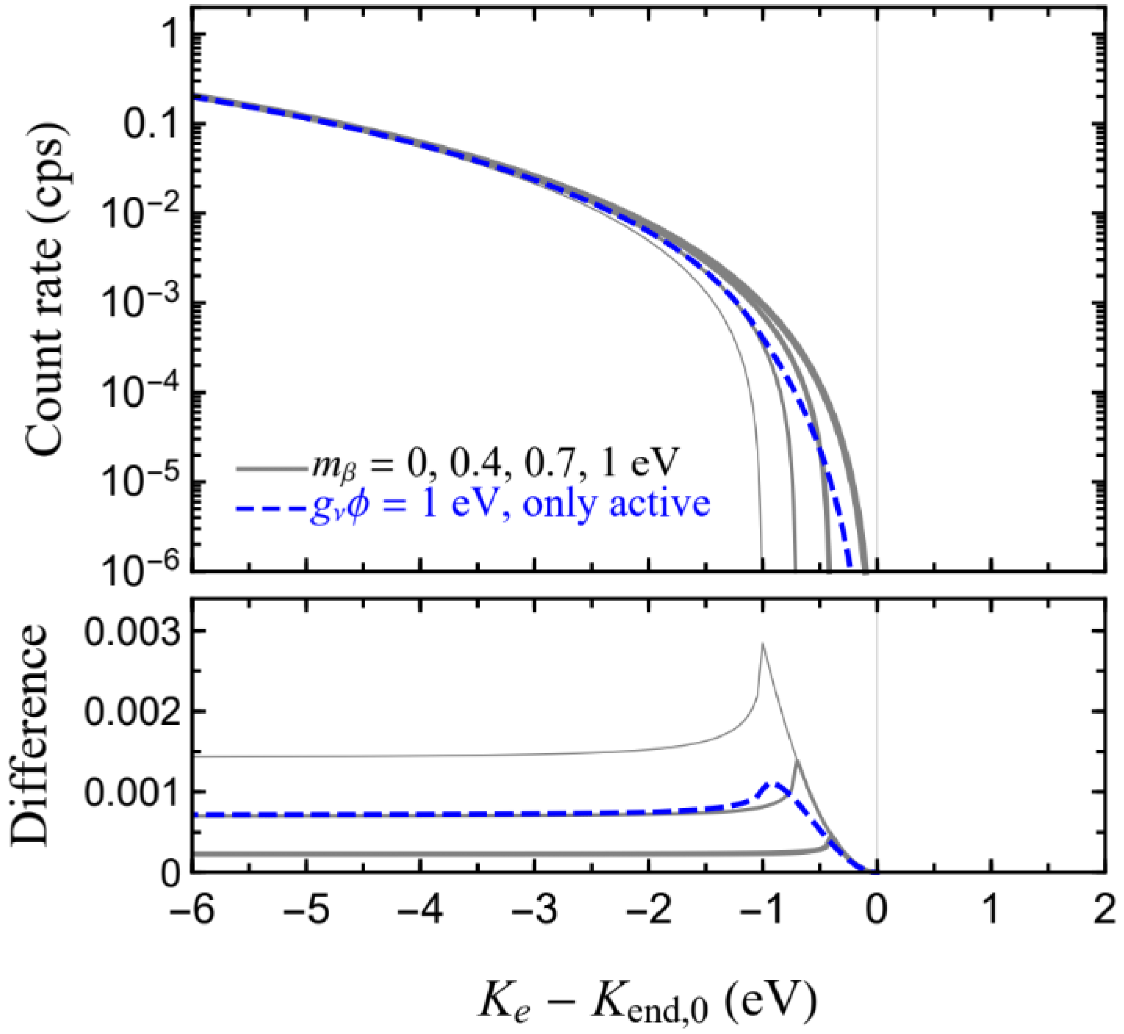

arXiv:2205.08431 [hep-ph]
ν_e
ν_μ
ν_τ

SPARE SLIDES





ON BETA DECAY EXPERIMENTS

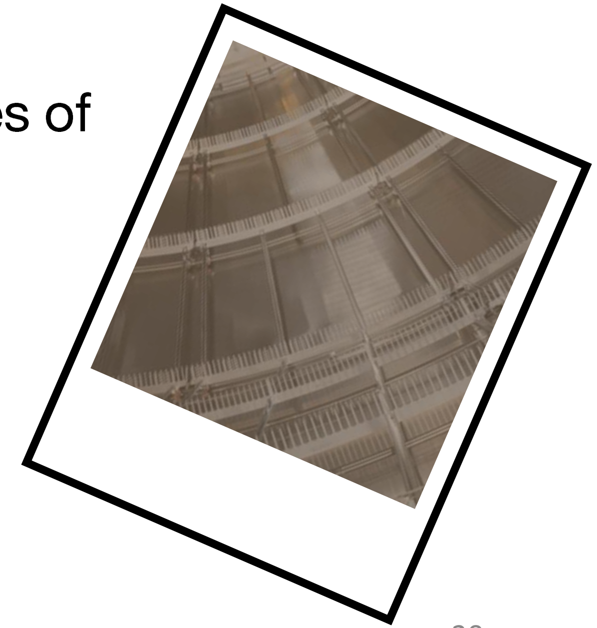


OTHER LIMITS ON TIME-VARYING NEUTRINO MASSES

- Strong constraints from direct coupling of the ultralight scalar to the leptón doublet from the non-observation of a time-dependent electron mass.

- There are some limits from black hole superradiance for particular values of the scalar mass

- Limits from the non-observation of a solar flux periodicity.



SIGNATURES IN OSCILLATION EXPERIMENTS (like DUNE)

[A.Dev et al. *JHEP* 01 (2021) 094]

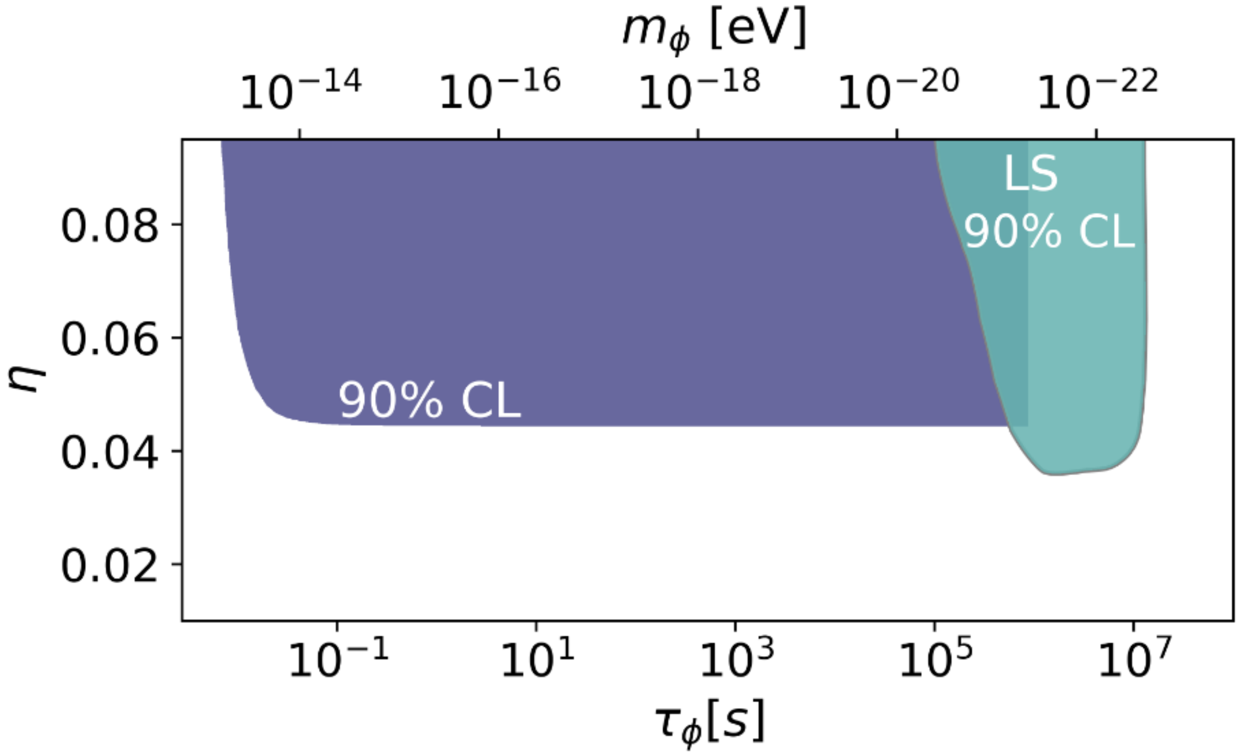
Search for:

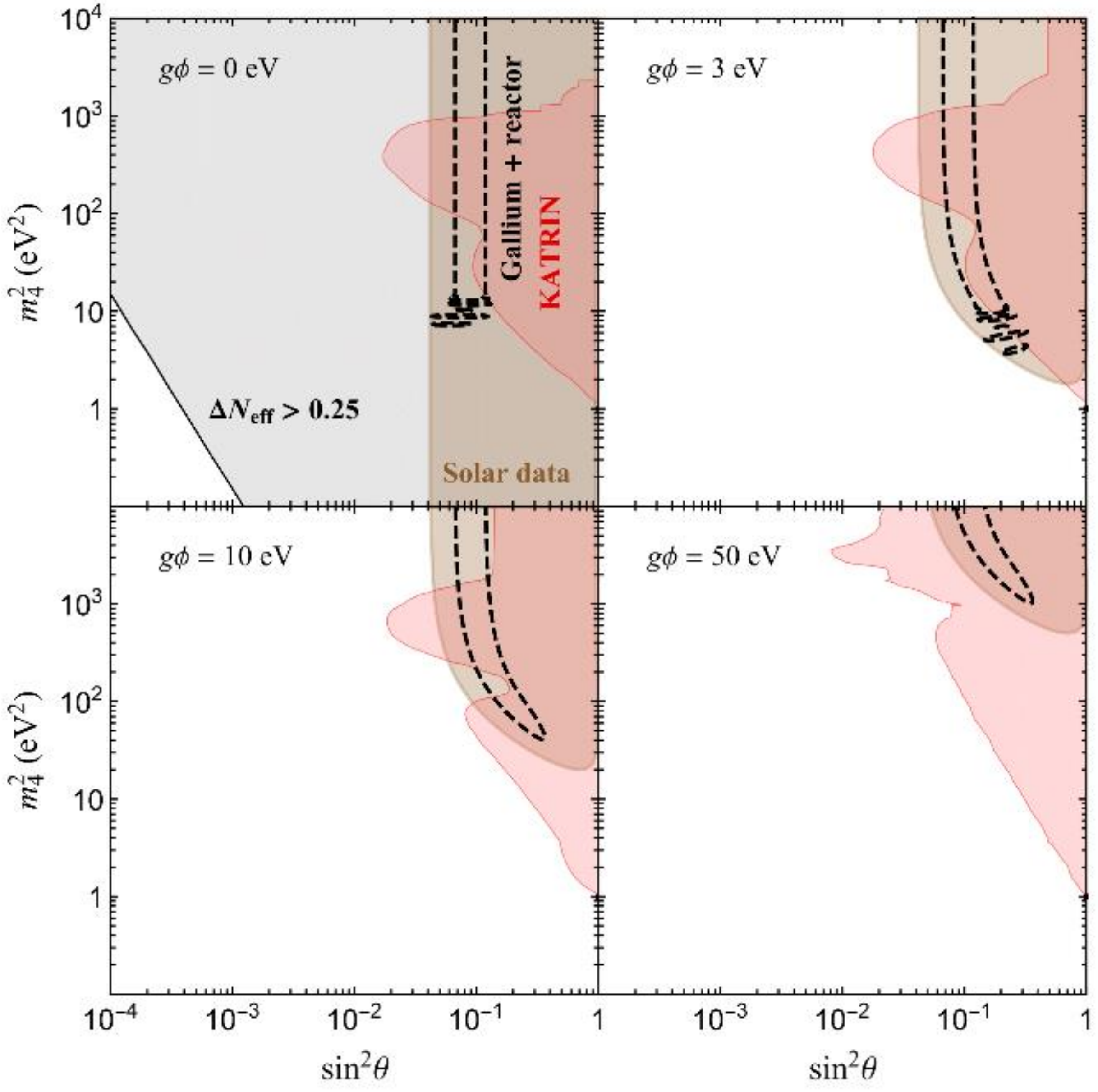
- Time –varying signals

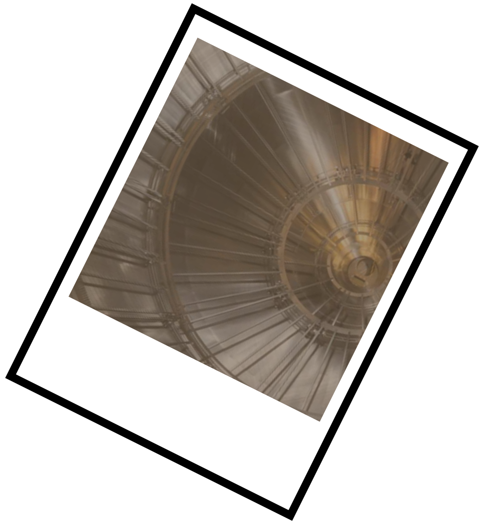
  Lomb-Scargle method

- Distorted neutrino oscillations

  Effect is not averaged out and leads to a distortion in probabilities which is partially degenerate with oscillation parameters

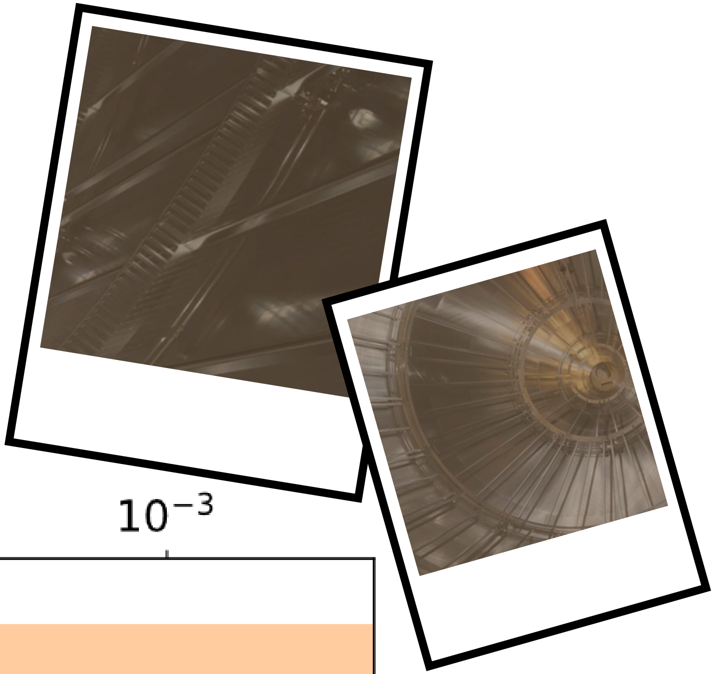


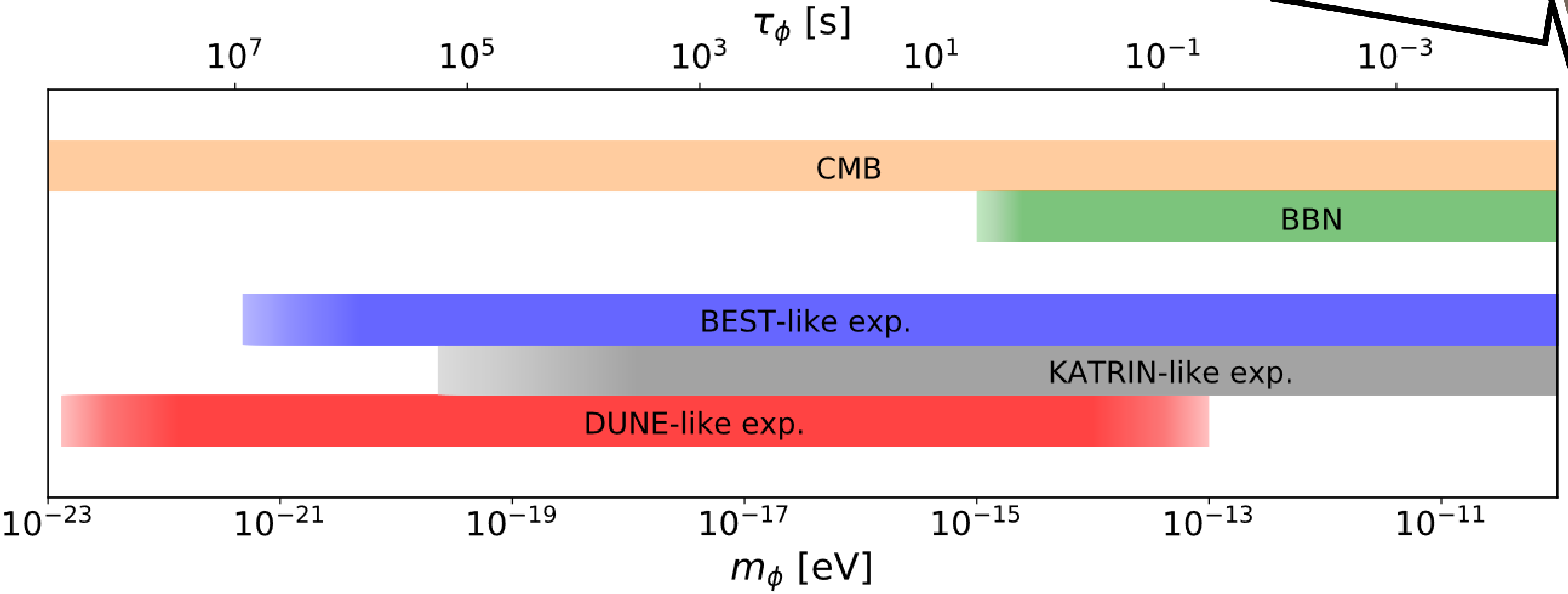




REINTERPRETING BOUNDS ON STERILE NEUTRINOS

ULTRALIGHT SCALAR MASS AND TIME SCALES





For BBN and CMB estimates we require the scalar mass to be larger than the Hubble rate at T ~ 1MeV and T ~0.3 eV respectively.