NEUTRINOS *meet* ULTRALIGH DARK MATTER *(in the lab)*

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YOUNGST@RS - Interacting dark sectors in astrophysics, cosmology, and the lab

A very **rich phenomenology** would result from neutrinos **coupling** to ultralight dark matter.

Such signatures are within the **reach** of **current** and **next-generation** neutrino **experiments**.

I. ULTRALIGHT DARK MATTER and its coupling to neutrinos

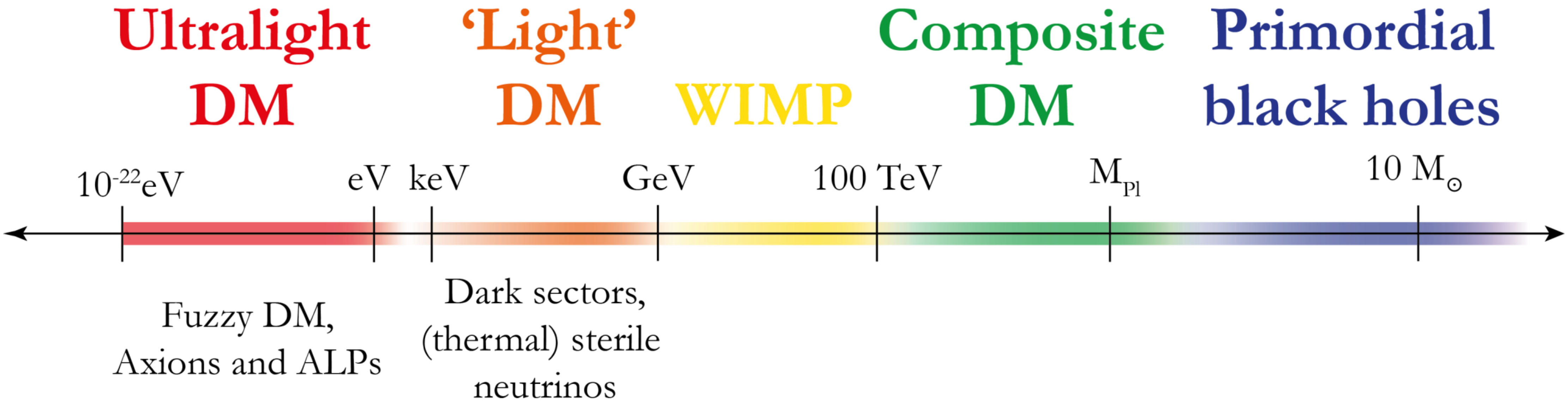
II. Signatures in NEUTRINO OSCILLATIONS

III. Signatures in BETA DECAY SPECTRUM

IV. OTHER signatures and OPEN QUESTIONS

DARK MATTER CANDIDATES

(not to scale)



ULTRALIGHT DARK MATTER

- Axions and ALPS
- Dark Photons
- Pseudo Majorons
- Spin-2 Dark Matter
- Fuzzy Dark Matter

ULTRALIGHT SCALARS
IN A NUTSHELL

Due to the large occupation number, such dark matter candidate effectively behaves as a classical field.

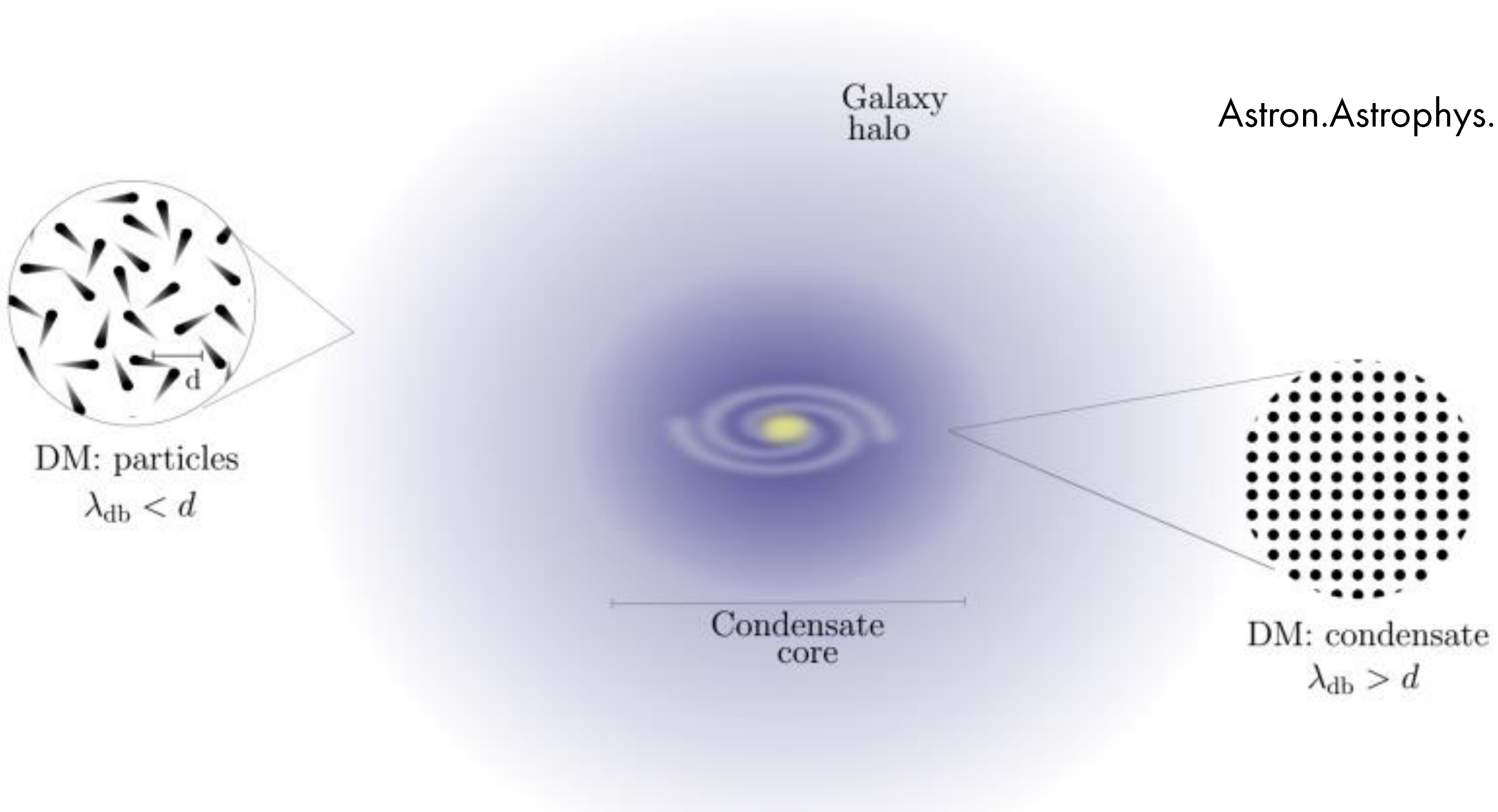
$$\Phi(\vec{x}, t) \simeq \frac{\sqrt{2\rho_\phi}}{m_\phi} \sin\left[m_\phi(t - \vec{v}_\phi \cdot \vec{x})\right]$$

The modulation period of the ultralight scalar is related to its mass:

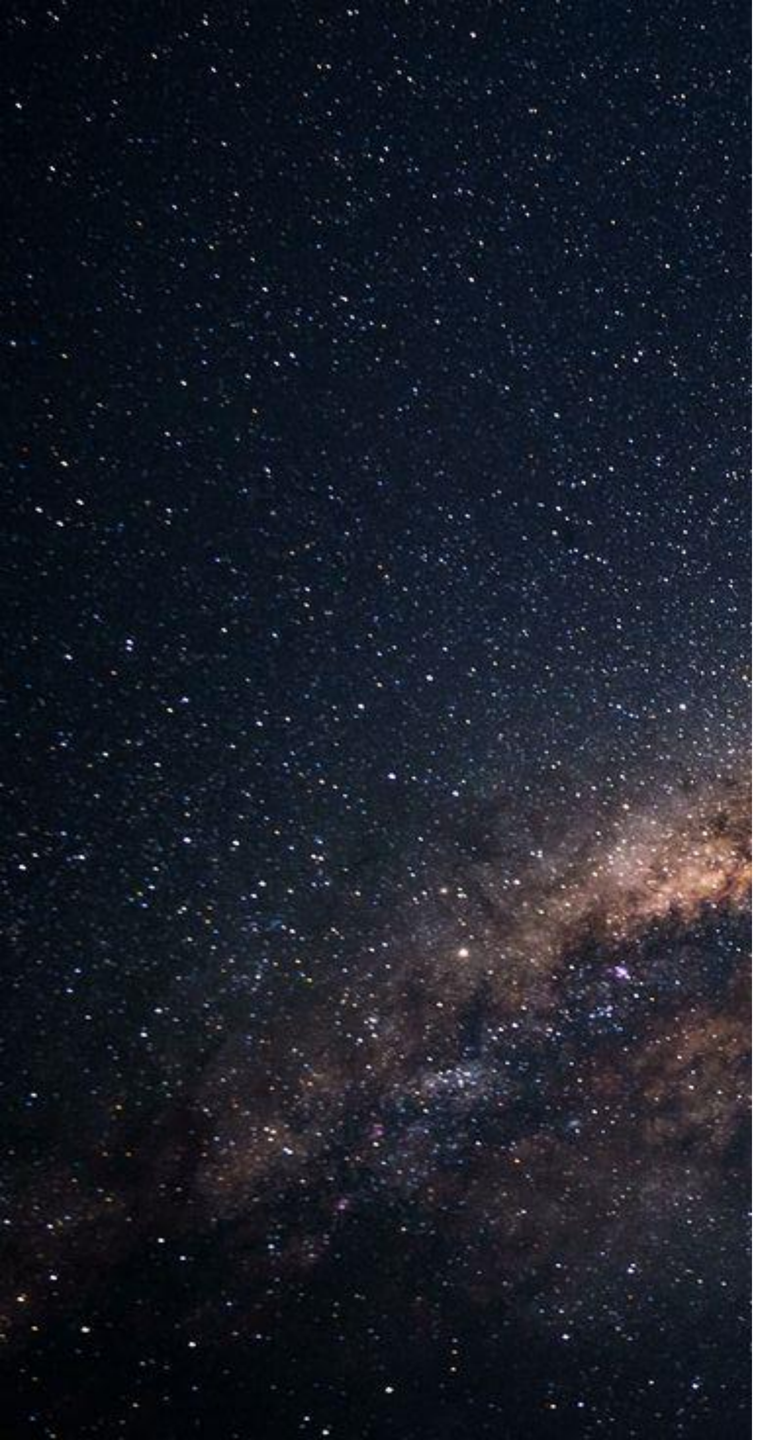
$$\tau_\phi \equiv \frac{2\pi\hbar}{m_\phi} = 0.41 \left(\frac{10^{-14}\ \mathrm{eV}}{m_\phi}\right)\ \mathrm{s}$$

ULTRALIGHT DARK MATTER

Elisa G.M. Ferreira
Astron.Astrophys.Rev. 29 (2021) 1, 7



Small scale discrepancies between observations and cosmological simulations would be alleviated if dark matter was ultralight (cusp vs core, too-big-to fail problem, Missing satellite...)



NEUTRINOPHILIC
ULTRALIGHT SCALARS

If such an ultralight scalar was effectively coupled to active neutrinos, for instance through

$$\mathscr{L} \supset -y_\nu HLN - (\Lambda - y\phi)NN$$

$$\mathscr{L}_{\text{eff}} = -m_\nu \left(1 + y\frac{\phi}{\Lambda}\right) \nu\nu + h.c.$$

then, the neutrino mass matrix will get an additional contribution

$$\delta m_\nu = y\,\frac{\sqrt{2\rho_\phi^\odot}}{\Lambda m_\phi}\,\sin(m_\phi t)$$


Signatures in
OSCILLATION
EXPERIMENTS

NEUTRINOPHILIC
ultralight scalars

A. Berlin
Phys.Rev.Lett. 117 (2016) 23, 231801

A rich phenomenology is expected if the ultralight field were coupled to neutrinos.

Comparison between the modulation period and the relevant time-scale of the neutrino experiment

Time-of-flight

$\tau_\phi \sim \tau_\nu \sim 10^{-2}$ - 10^{-3} s

m_ϕ ~10^{-13} –10^{-14} eV

Time between two events (inverse of the event rate)

$\tau_\phi \sim \tau_{\rm evt} \sim 1$ day

m_ϕ ~10^{-20} eV

Running time

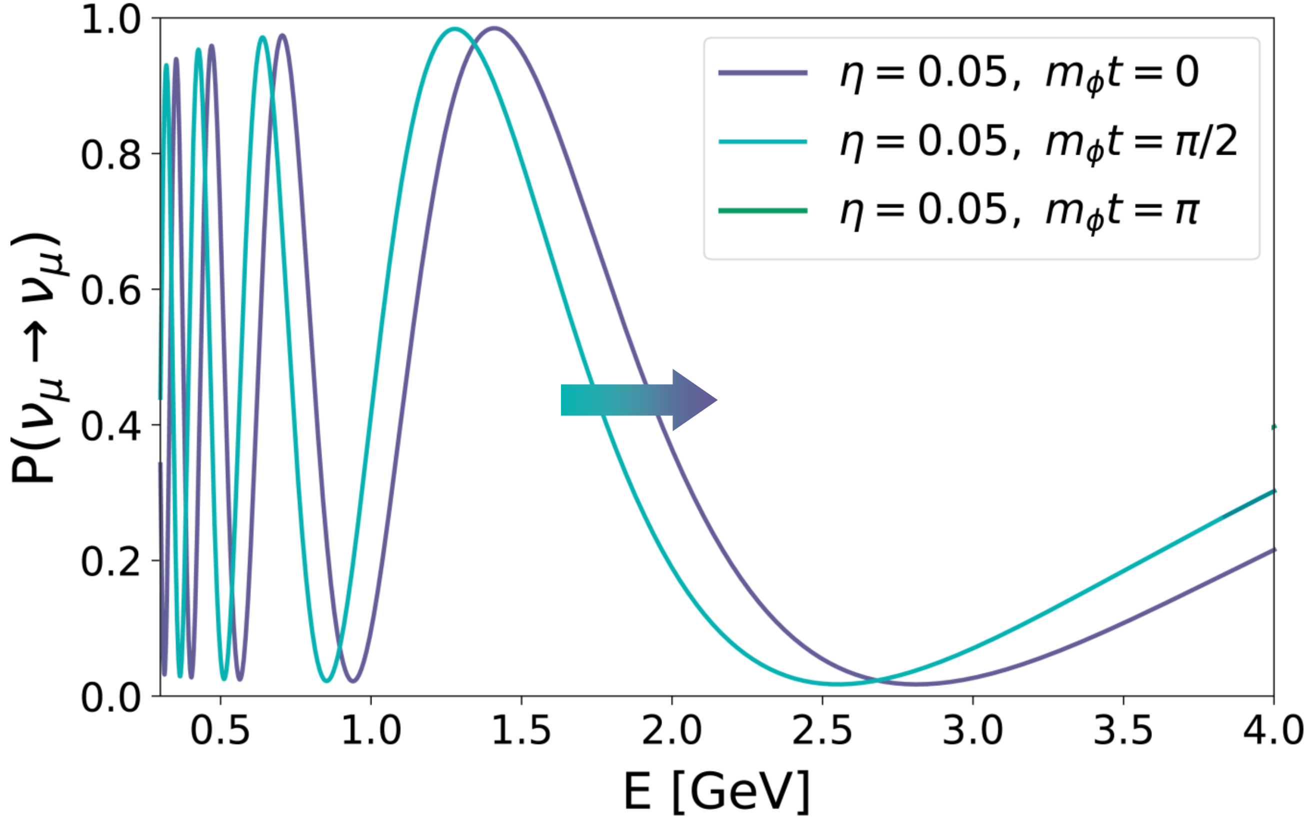
$\tau_\phi \sim \tau_{\rm exp} \sim 10$ years

m_ϕ ~10^{-23} eV

NEUTRINOPHILIC
ultralight scalars

In oscillation experiments, one can search for time-varying signals and distortions in the oscillatory pattern.

In DUNE, for a modulating mass splitting only, Δm^2_{31}



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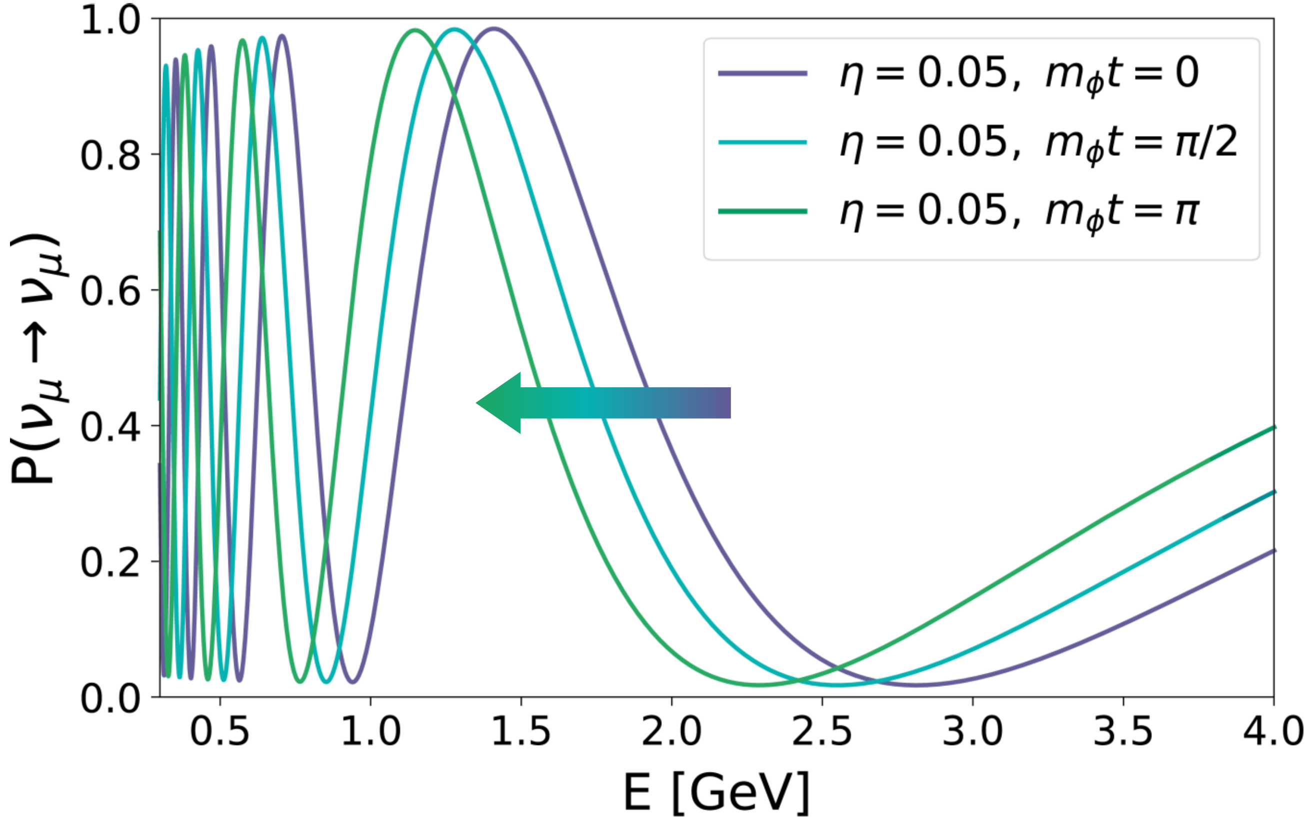

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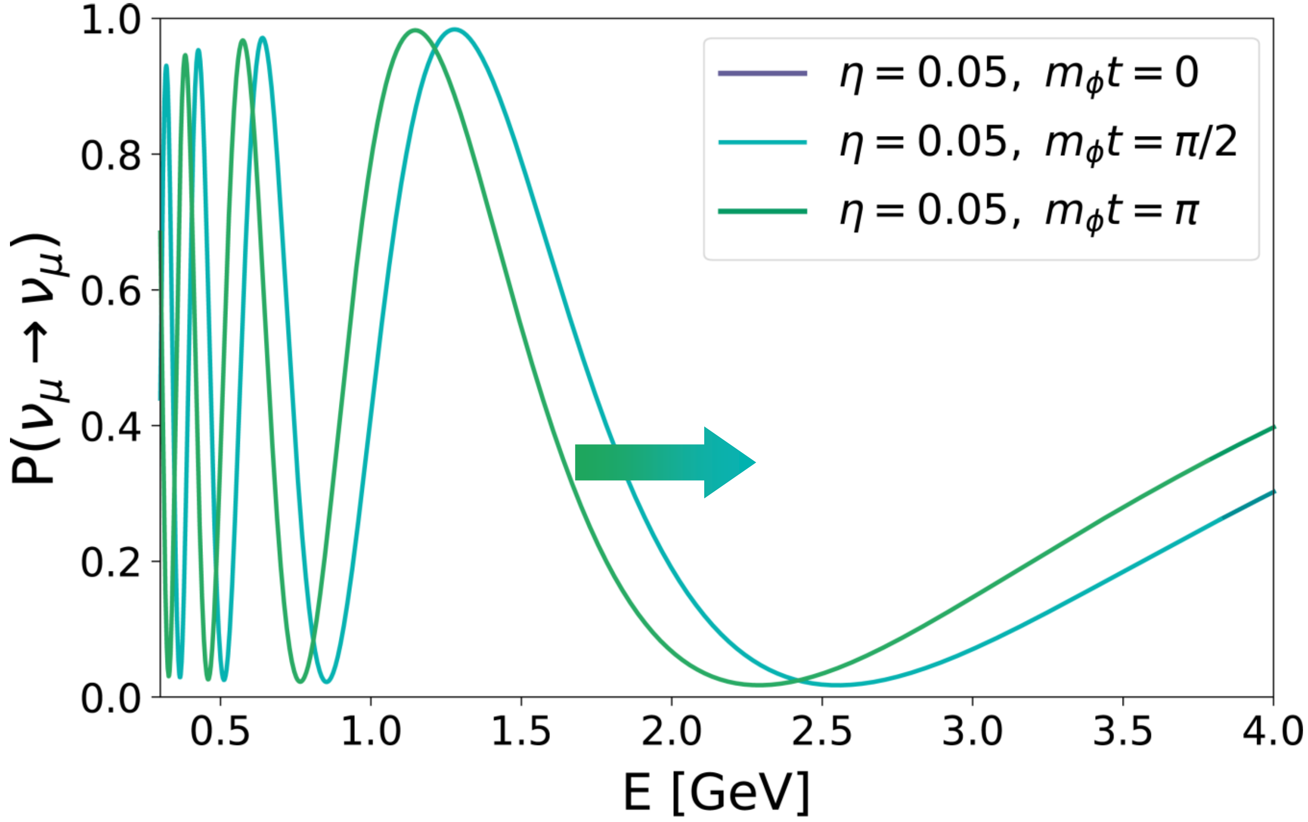

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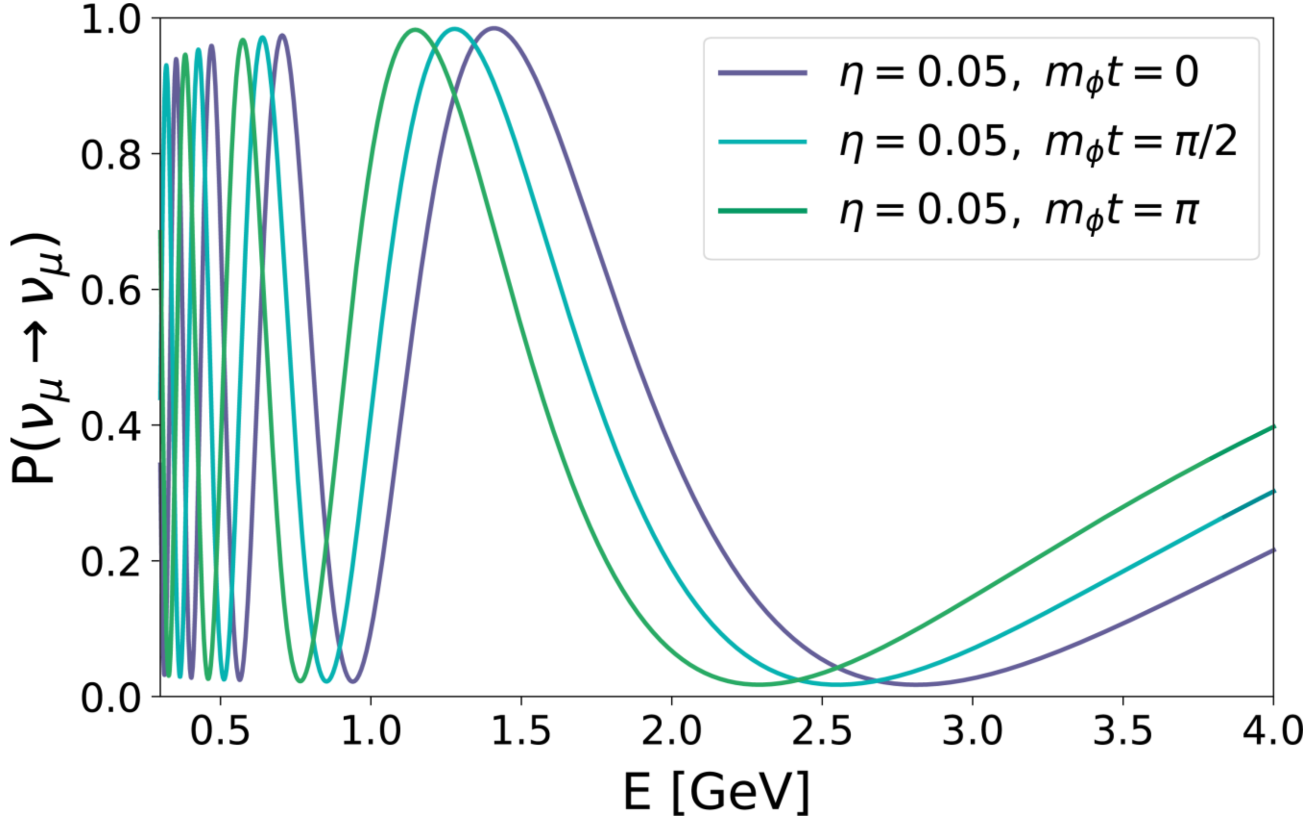

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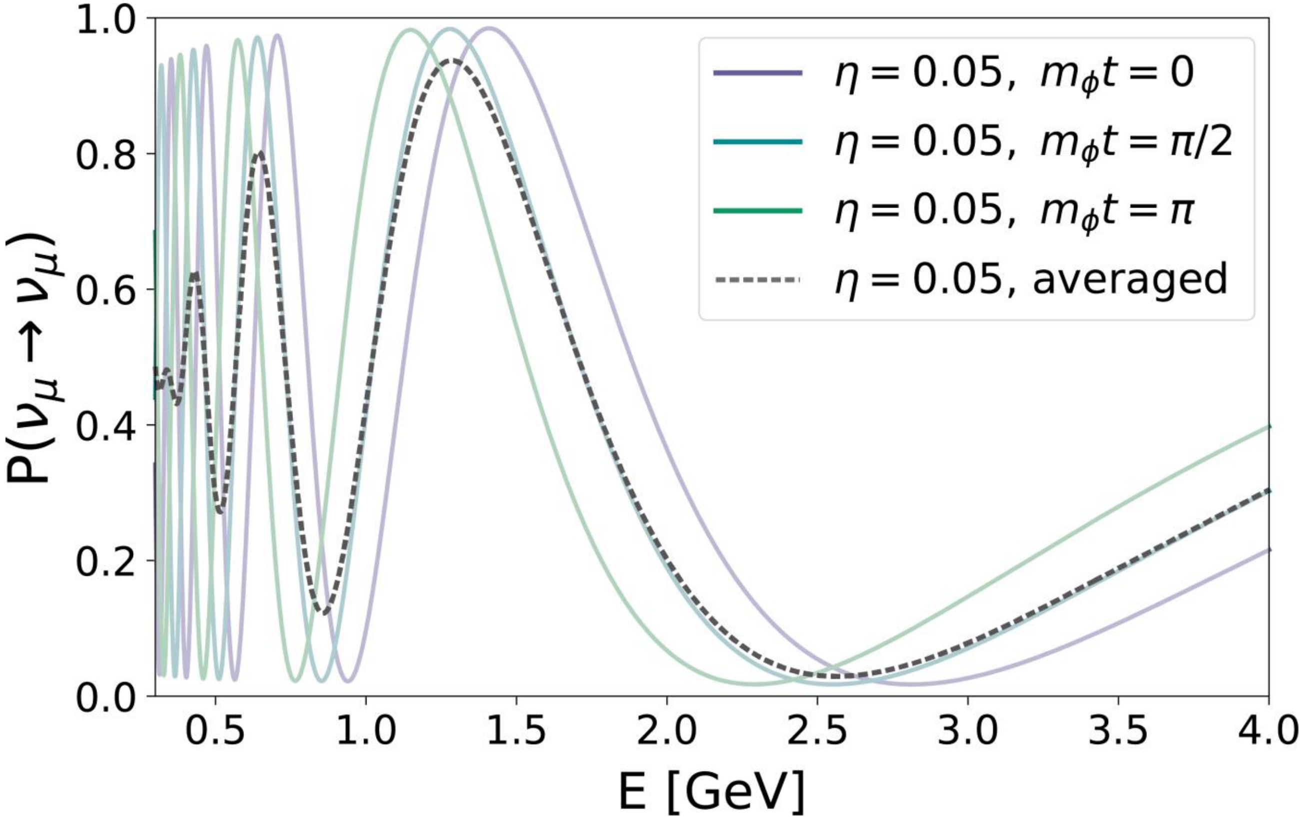


Signatures in
OSCILLATION experiments

Time-varying signal

Suitable methods: Lomb-Scargle periodogram

Similar searches exist and on-going (SK solar data, Daya Bay reactor data)

Daya Bay Collab., *Phys.Rev.D* 98 (2018) 9, 0920;
SK Collab., 2311.01159

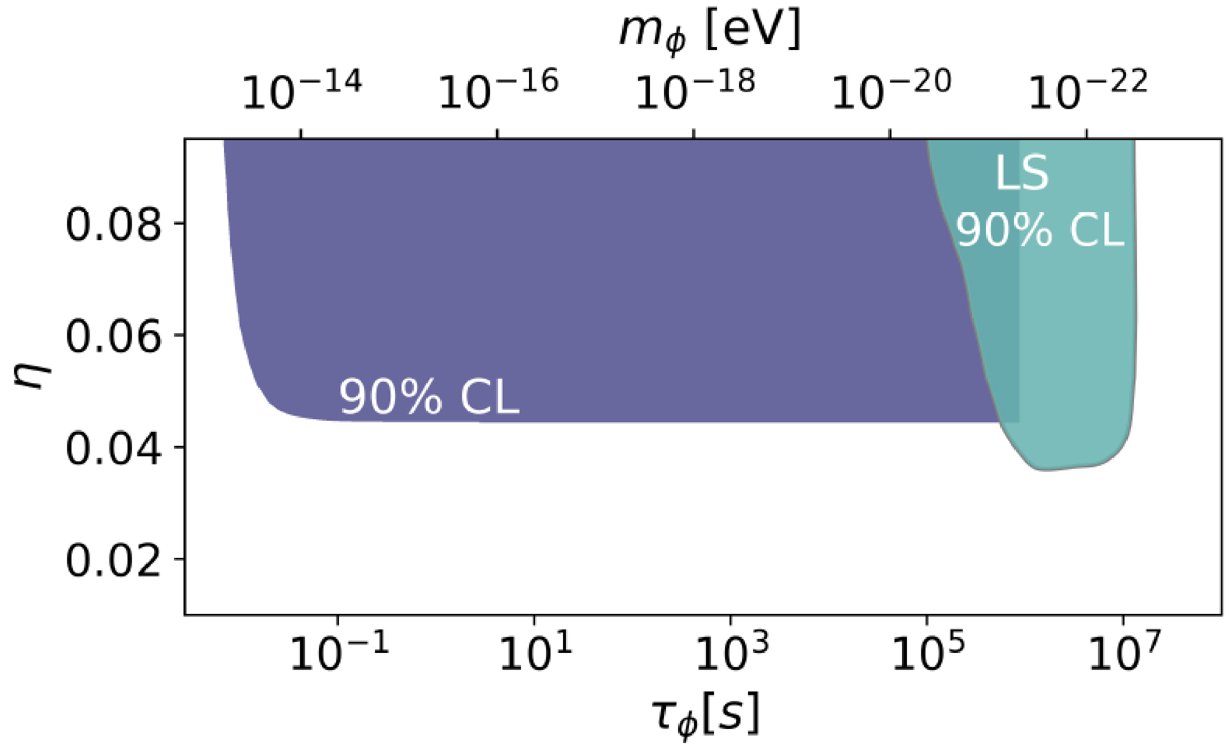
Distortion in the oscillation probability

Non-trivial and non-degenerate with other detector systematics

G. Krnjaic et al. *Phys.Rev.D* 97 (2018) 7, 075017; V. Brdar et al. *Phys.Rev.D* 97 (2018) 4, 043001;
A. Dev, **PMM**, P. Machado *JHEP* 01 (2021) 094

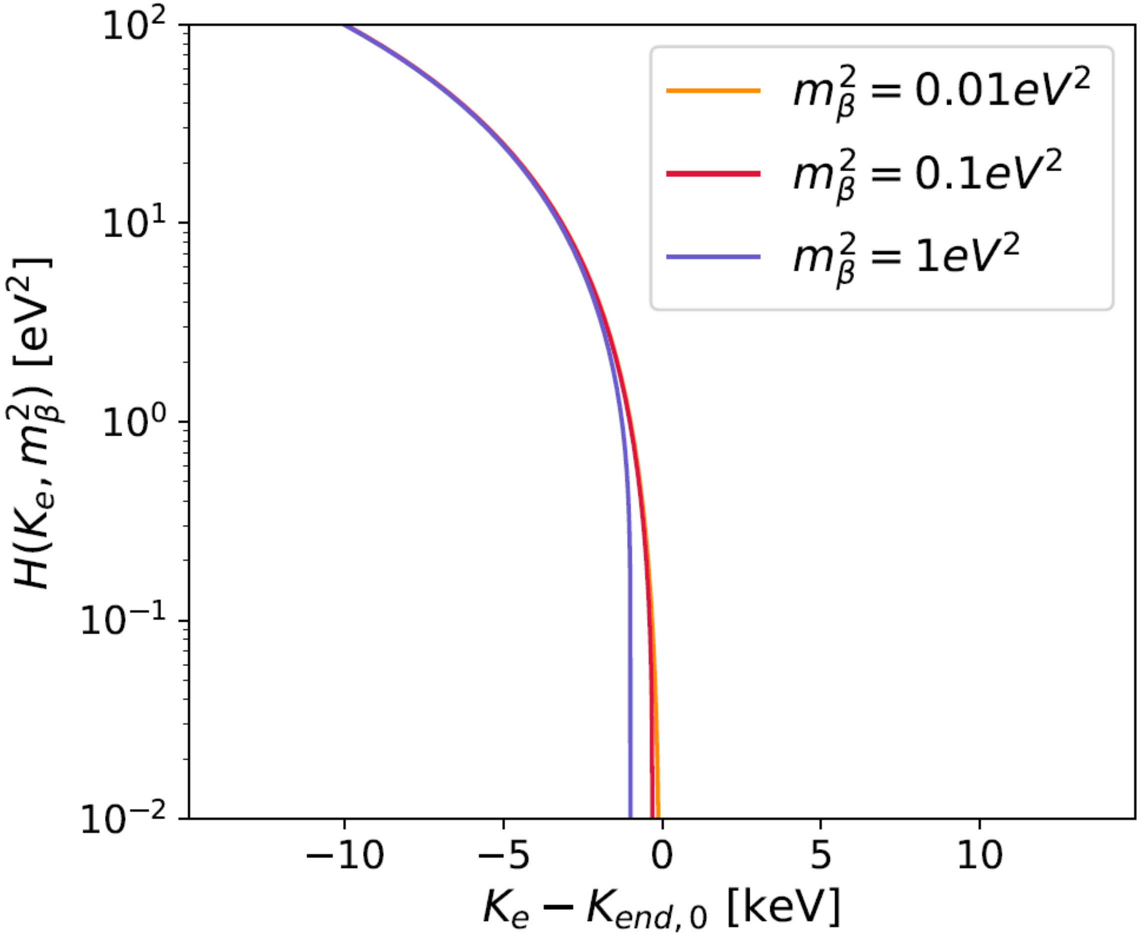
Signatures in

OSCILLATION experiments



A. Dev, **PMM**, P. Machado *JHEP* 01 (2021) 094


Signatures in
BETA-DECAY
SPECTRUM



If neutrino masses are non-zero, the electron/positron energy spectrum in a beta-decay is shifted. For instance, in tritium

$$^3\text{H} \rightarrow ^3\text{He} + e^- + \bar{\nu}_e$$

Given current sensitivity, experiments are sensitive to the effective neutrino mass:

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

NEUTRINOPHILIC
ultralight scalars

If active neutrinos were effectively coupled to an ultralight scalar, the effective neutrino mass is approximately,

$$\tilde{m}_\beta \approx m_\beta + y\phi \sin(m_\phi t)$$

One can look for:

- **Time varying signal** (limited statistics)
- Averaged effect (non trivial **spectral distortion**)

G. Huang, M. Lindner, **PMM**, M. Sen,
Phys.Rev.D 106 (2022) 3, 033004

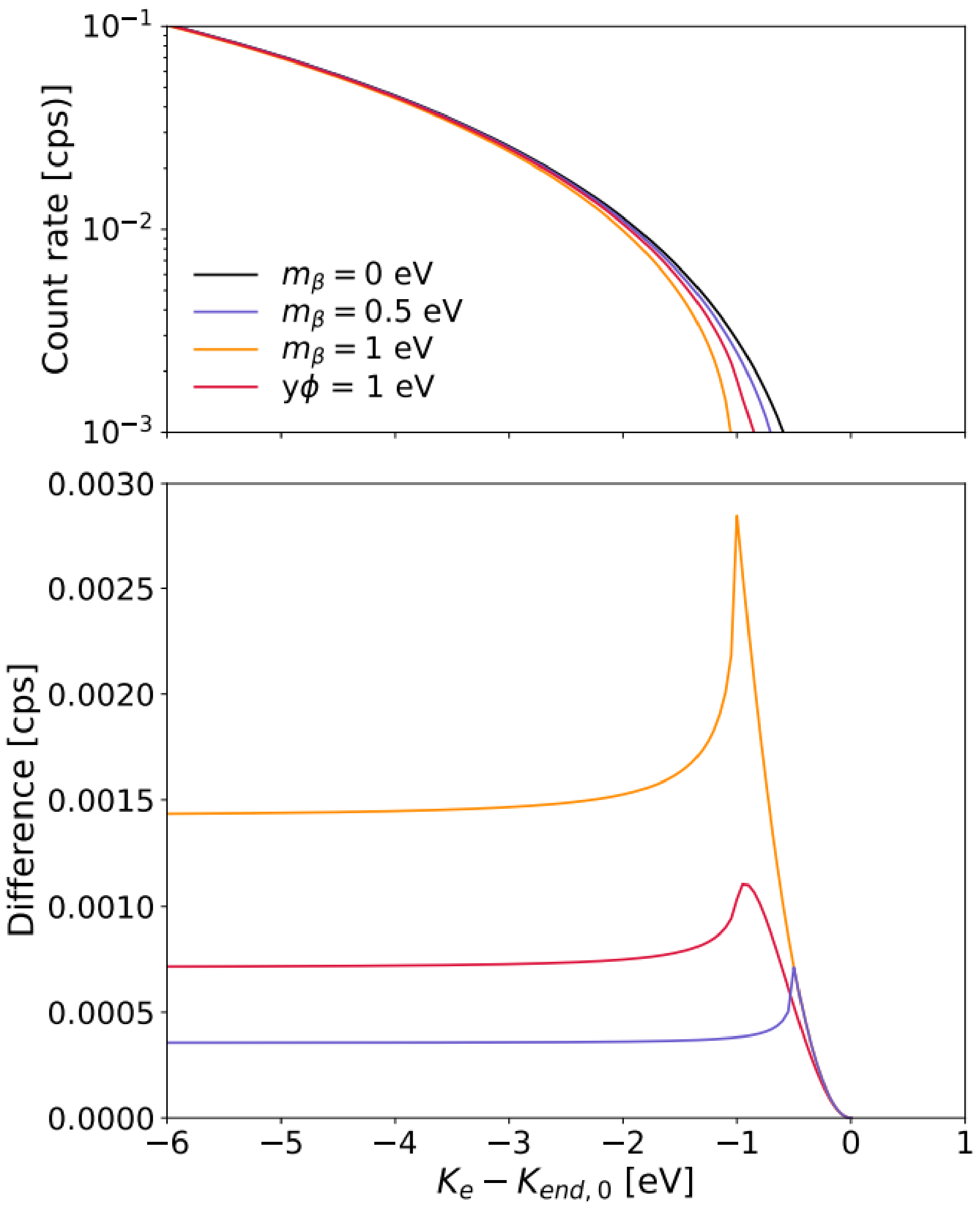
NEUTRINOPHILIC

ultralight scalars

The averaged effect of the scalar is degenerated with the effective neutrino mass.

$$\langle \widetilde{m}_\beta^2 \rangle = m_\beta^2 + \frac{(y\phi)^2}{2}$$

G. Huang, M. Lindner, **PMM**, M. Sen,
Phys.Rev.D 106 (2022) 3, 033004



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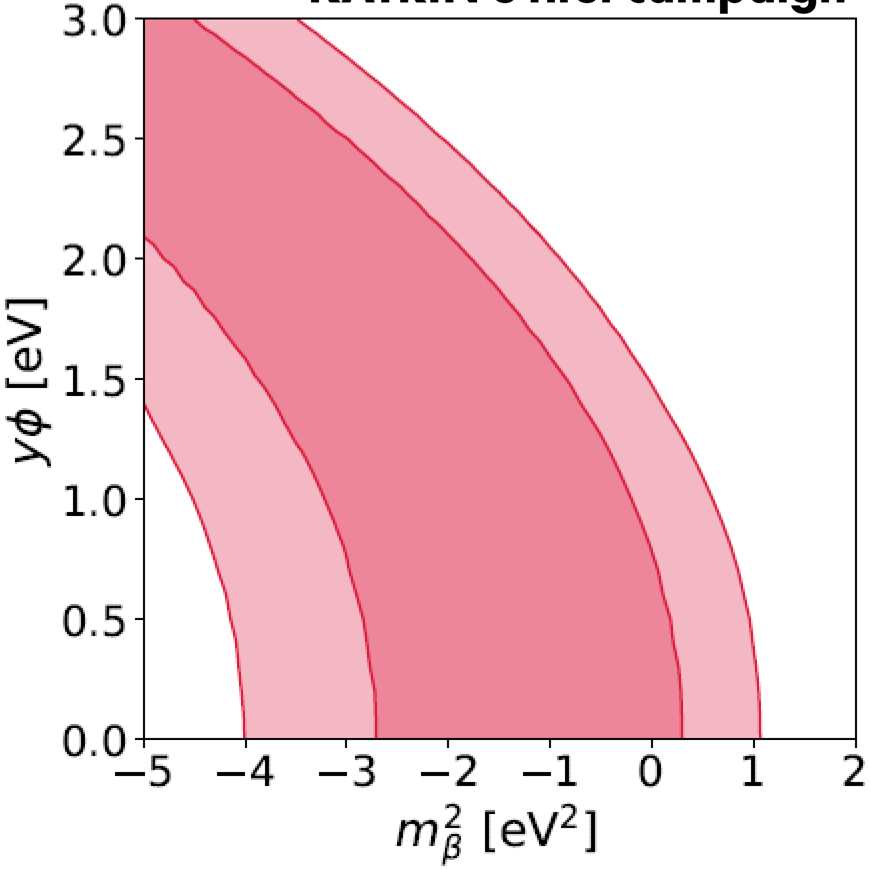
KATRIN's first campaign



DATA: KATRIN Collab.
Phys.Rev.Lett. 123 (2019) 22, 221802

NEUTRINOPHILIC
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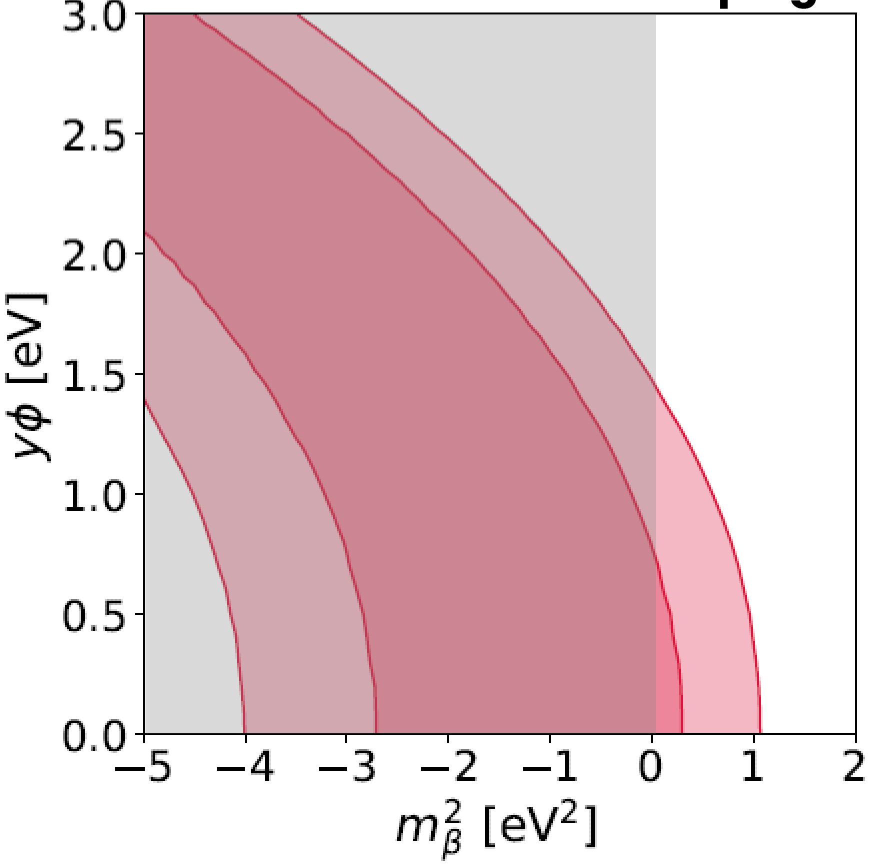


DATA: KATRIN Collab. Phys.Rev.Lett. 123 (2019) 22, 221802

Signatures in
BETA DECAY experiments

Time-varying signal

Similar searches exist and on-going by KATRIN in the context of Lorentz Invariance Violation

KATRIN Collab. Phys.Rev.D 107 (2023) 8, 082005

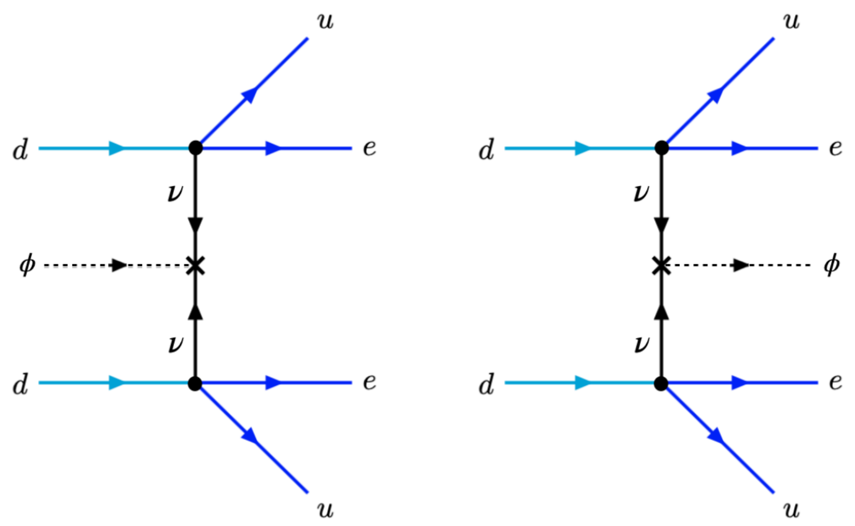
Distortion in the spectrum

Potential to alliviate limits on the neutrino mass scale

G. Huang, M. Lindner, **PMM**, M. Sen, Phys.Rev.D 106 (2022) 3, 033004

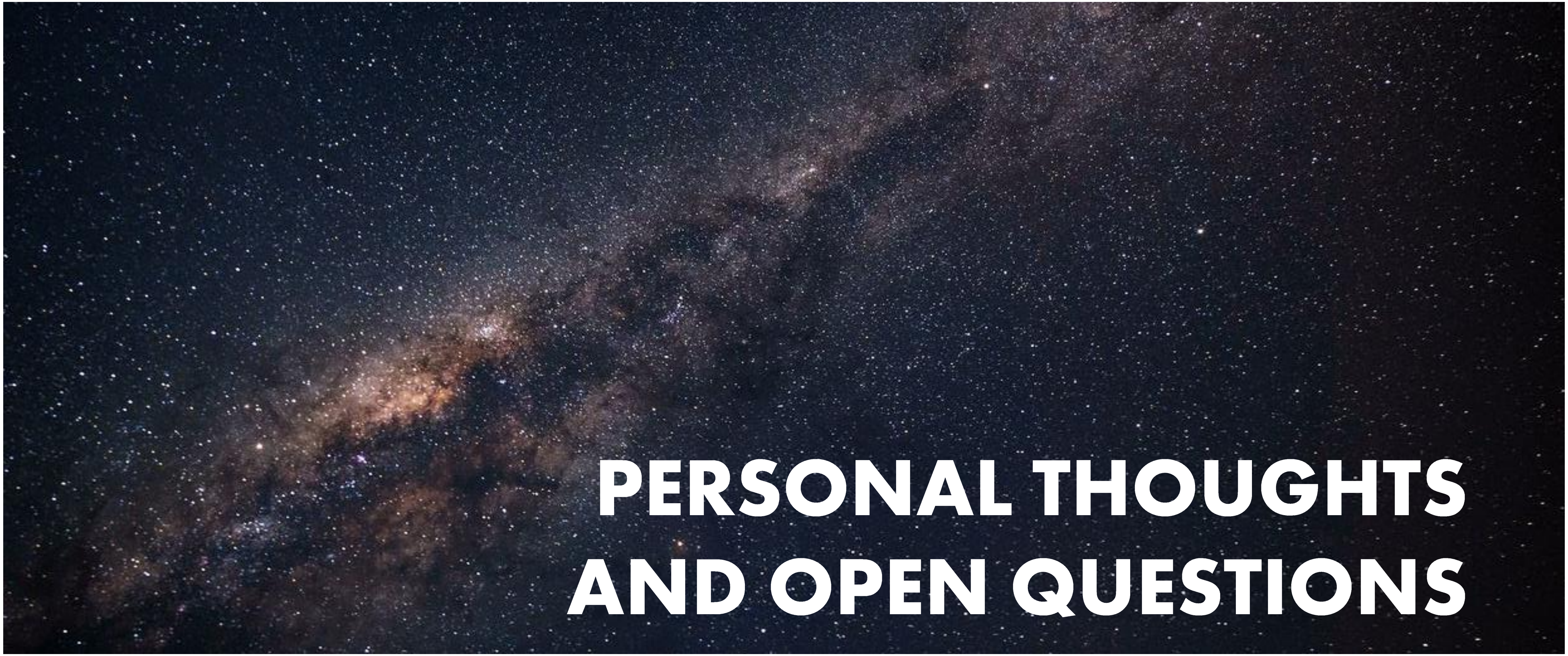

OTHER SIGNATURES

Coupling between neutrinos and an ultralight scalar could also modify the predictions for **neutrinoless double beta decay**



The coupling between neutrinos and ultralight scalars can also be tested from **cosmological obsevations** (CMB, BBN, structure formation...)

M. Sen and A. Smirnov 2306.15718
G.Huang and N. Nath JCAP 05 (2022) 05, 034
G. Huang et al. Phys.Rev.D 106 (2022) 3, 033004



PERSONAL THOUGHTS AND OPEN QUESTIONS

A ROADMAP

Do different **ultralight dark matter candidates** give different signatures? Can we discriminate?

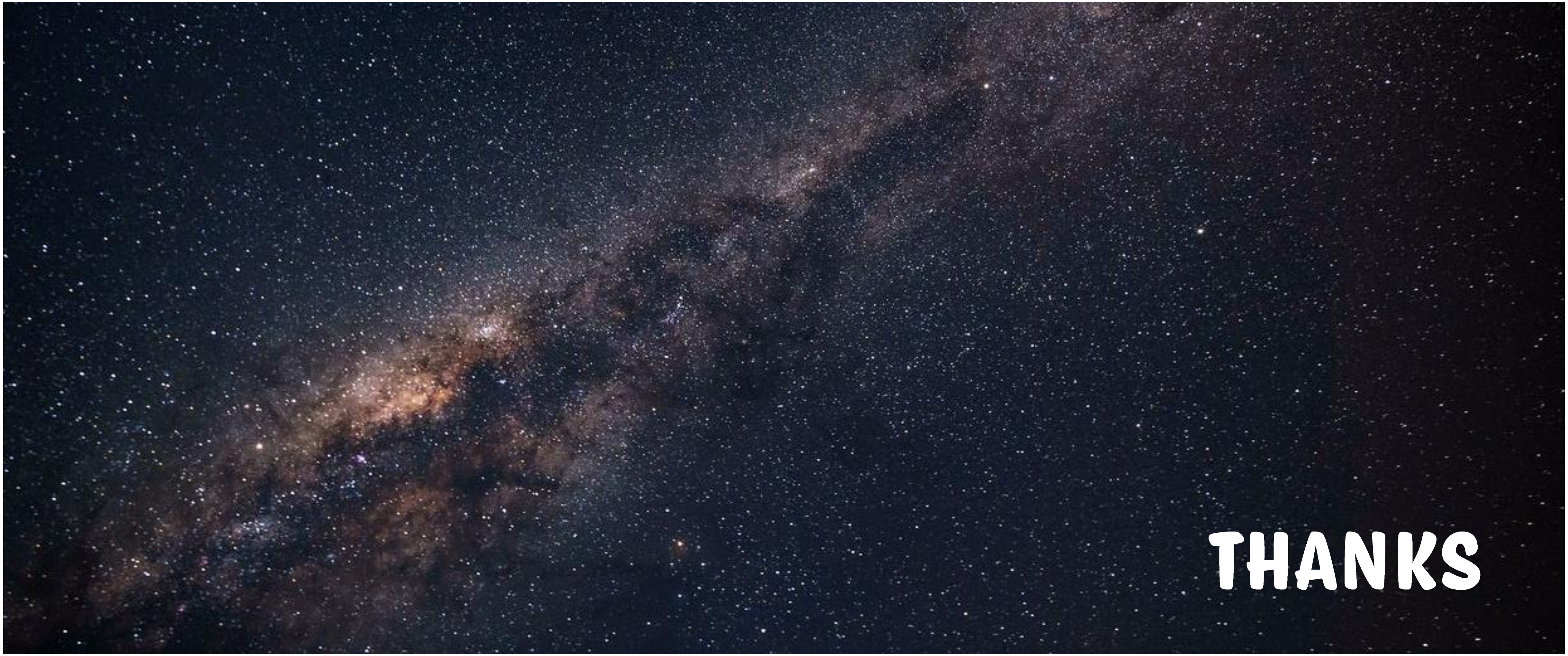
What happens in the presence of **additional neutrino species**?

UV **completions** of such couplings

Is the picture consistent with **cosmological observations**?

A very **rich phenomenology** would result from neutrinos **coupling** to ultralight dark matter.

Such signatures are within the **reach** of **current** and **next-generation** neutrino **experiments**.


THANKS