Phenomenolgy of time-varying neutrino masses

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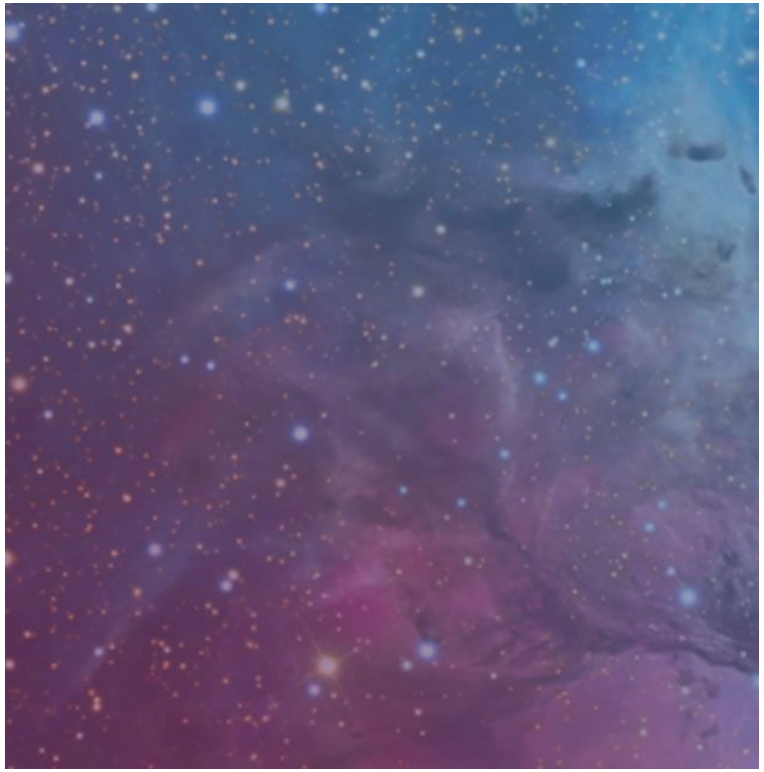


Time-varying neutrino masses can arise from interactions with ultralight dark matter.

Experimental searches for the signatures of these scenarios are of potential interest for Lorentz Invariance Violation tests.

ULTRALIGHT DARK MATTER

- An ultralight scalar with mass $m_\phi > O(10^{-22}$ eV) can alleviate 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,

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

which has been shown to be compatible with cosmological observations. [2205.08431]

DISCLAIMER: This talk will be limited to the case of heavy sterile neutrinos such that effectively the ultralight scalar **couples directly to active neutrinos**, i.e

$$-\mathcal{L} \supset g_\nu^{ij}\phi\bar{\nu}_i\nu_j$$

Active neutrinos get time-dependent masses and mixing

Signatures in terrestrial experiments

OSCILLATION EXPERIMENTS
AND BETA DECAYS

SIGNATURES IN NEUTRINO OSCILLATIONS

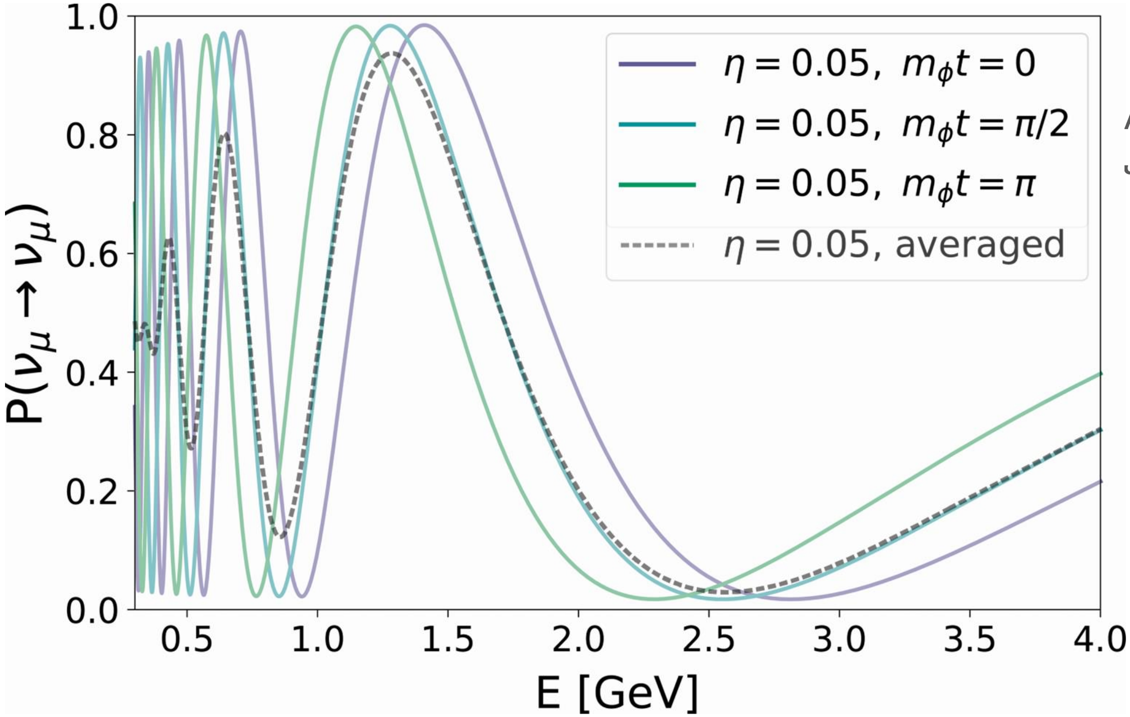
Two main type of signatures can be searched for:

- Time-dependent signals
- Distorted neutrino oscillation probabilities

A.Berlin, *PRL 117* (2016) 23, 231801
G.Krnjaic et al, *PRD* 97 (2018) 7, 075017
V. Brdar et al, *PRD* 97 (2018) 4, 043001
A.Dev et al, *JHEP* 01 (2021) 094

Let us take DUNE as an example and a time dependent mass splitting parameterised as

$$\Delta m^2_{ij}(t) \simeq \Delta m^2_{ij}\left[1 + 2\eta \sin(m_\phi t)\right]$$



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

SIGNATURES IN BETA DECAY EXPERIMENTS

Time varying neutrino masses also alter the beta decay spectrum near the end-point, where neutrino masses become relevant.

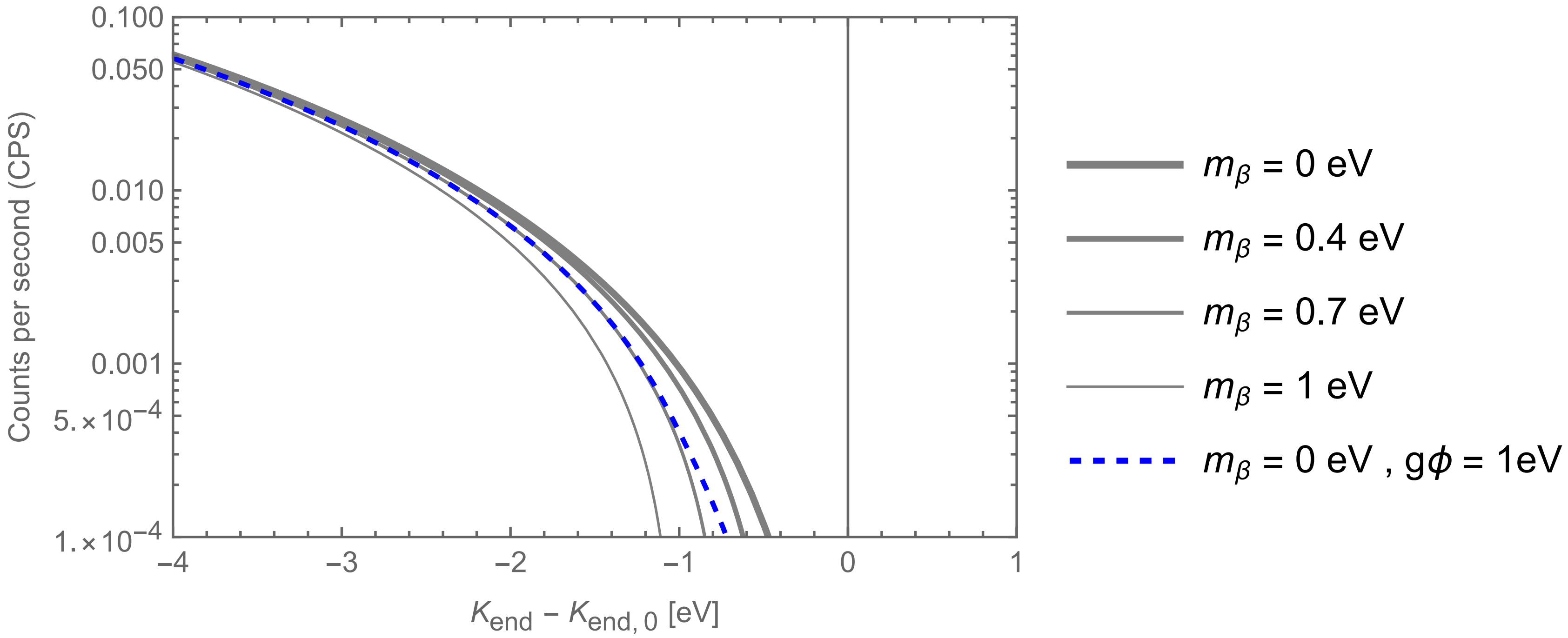
If sterile neutrinos are heavy (for instance of order keV), then

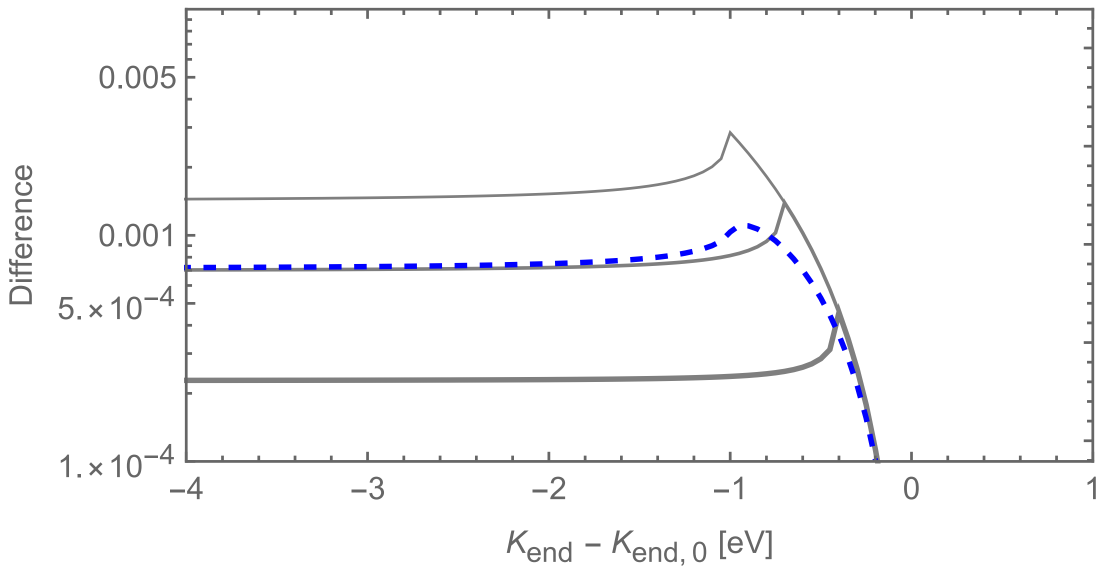
$$\widetilde{m}_\beta(\phi) \approx m_\beta + g_\nu \phi \sin m_\phi t$$

In principle, time variations in the signal could be searched for.

The averaging of the time modulation leads to a non-trivial distortion of the spectrum.

SIGNATURES IN BETA DECAY EXPERIMENTS





The amplitude of the modulation is strongly degenerated with the ‘standard’ parameters.

However, the upper limits on the mass are robust.

BOUNDS ON THE
STANDARD MODEL EXTENSION

Synergies with Lorentz Invariance Violation tests

STANDARD MODEL EXTENSION (SME)

Extension of the SM which respects its symmetries while allowing for CPT and Lorentz Invariance violating terms.

In the minimal SME, only operators with dimension 4 or smaller are allowed.

Current limits on the SME coefficients can be found in e-Print: 0801.0287 [hep-ph] (V. Alan Kostelecký and Neil Russell)

Data Tables for Lorentz and CPT Violation

V. Alan Kostelecký[a] and Neil Russell[b]
[a] *Physics Department, Indiana University, Bloomington, IN 47405*
[b] *Physics Department, Northern Michigan University, Marquette, MI 49855*

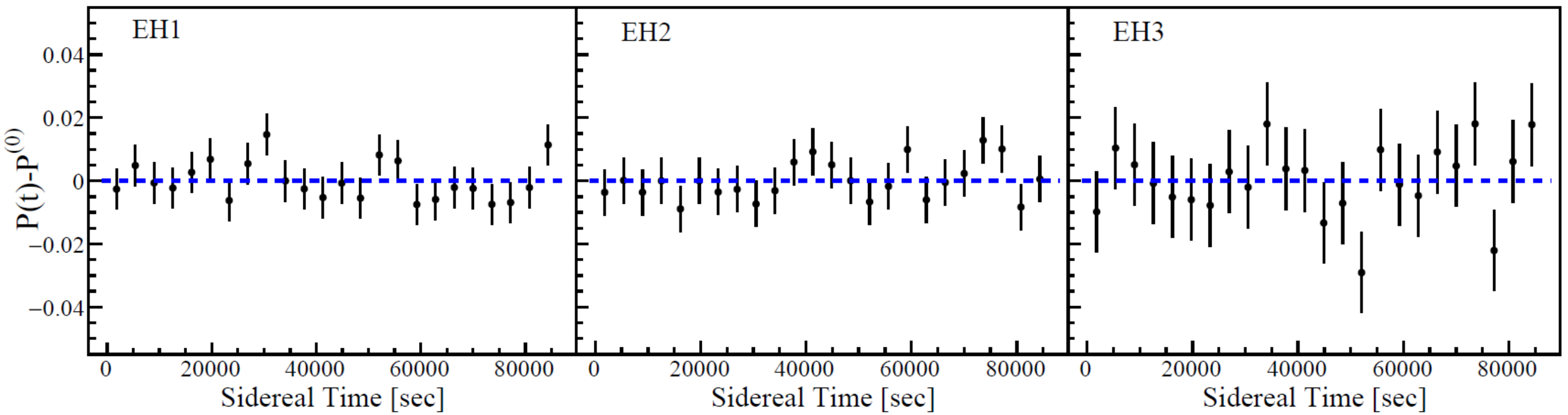
January 2022 update of *Reviews of Modern Physics* **83**, 11 (2011) [arXiv:0801.0287]

SYNERGIES WITH LIV SEARCHES IN OSCILLATIONS

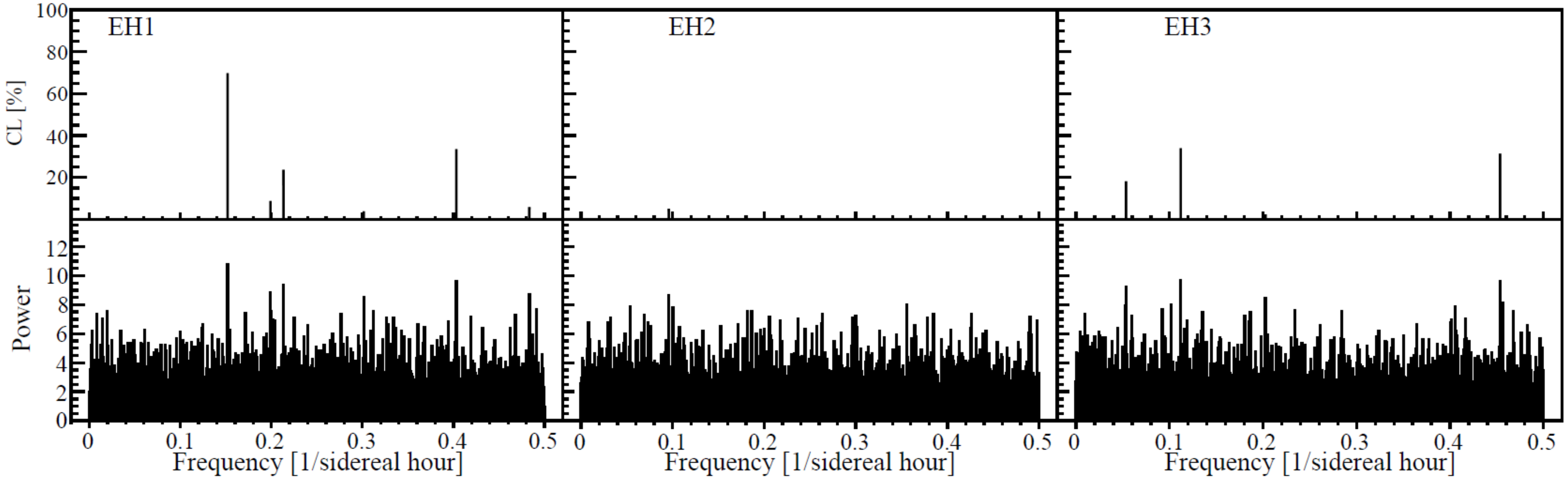
Several SME coefficients can give rise to a modulation of the signal with sidereal time. The experimental signature can be degenerate with that expected from an ultralight scalar – neutrino coupling.

Similar analysis techniques can be used.

CASE STUDY: Daya Bay used the Lomb Scargle method to look for periodicity in their data.



SYNERGIES WITH
LIV SEARCHES IN OSCILLATIONS



A similar search was proposed for DUNE

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

Other oscillation experiments, like MINOS and IceCube, have placed bound on the SME coeffcients.

SYNERGIES WITH
LIV SEARCHES IN BETA DECAYS

Several signatures are also expected in beta decays. Actually some of the best limits on SME coefficients come from Mainz and Troitsk experiments.
An improvement from KATRIN is then expected.

What effects are we talking about?
- Spectral distortions
- Shifts and time dependences of the effective mass
- …

Combination	Result	System
$\left(c_{\text{eff}}^{(2)}\right)_{10}^{ee}$	$> -1 \times 10^{-17}$ GeV^2	Troitsk tritium decay
"	$> -2 \times 10^{-17}$ GeV^2	Mainz tritium decay
$\left(c_{\text{eff}}^{(2)}\right)_{10}^{\mu\mu}$	$> -2 \times 10^{-17}$ GeV^2	Troitsk tritium decay
"	$> -4 \times 10^{-17}$ GeV^2	Mainz tritium decay
$\left(c_{\text{eff}}^{(2)}\right)_{10}^{\tau\tau}$	$> -2 \times 10^{-17}$ GeV^2	Troitsk tritium decay
"	$> -5 \times 10^{-17}$ GeV^2	Mainz tritium decay
$\text{Re}\left(c_{\text{eff}}^{(2)}\right)_{10}^{e\mu}$	$< 1 \times 10^{-17}$ GeV^2	Troitsk tritium decay
"	$< 3 \times 10^{-17}$ GeV^2	Mainz tritium decay

SYNERGIES WITH
LIV SEARCHES IN BETA DECAYS

For instance, some coeffcients modify the effective mass parameter which is measured in beta decays

J.S.Diaz,
Adv.High Energy Phys. (2014) 305298

$$m_\nu^2 \to m_\nu^2 + \delta m^2$$

$$\delta m^2 = m_{\mathcal{C}}^2 + m_{\mathcal{A}_s}^2 \sin \omega_\oplus T_\oplus + m_{\mathcal{A}_c}^2 \cos \omega_\oplus T_\oplus$$

Shift in the value. Interesting in case of a disagreement with other mass measurement.

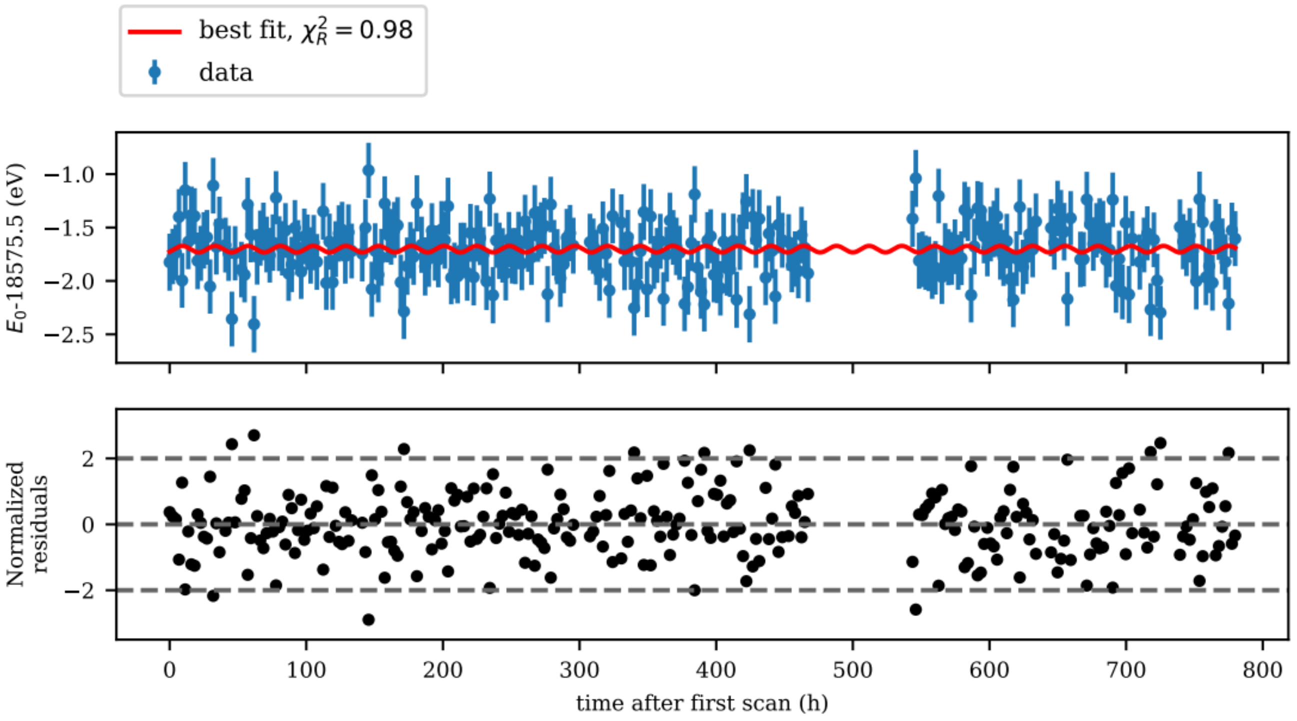
Modulation dependent on the sidereal time. Analysis strategy shared with ULDM scenario.

SYNERGIES WITH LIV SEARCHES IN BETA DECAYS

NEW!

2207.06326

KATRIN has performed a LIV analysis of their data from the first campaign from a distortion of the endpoint energy!

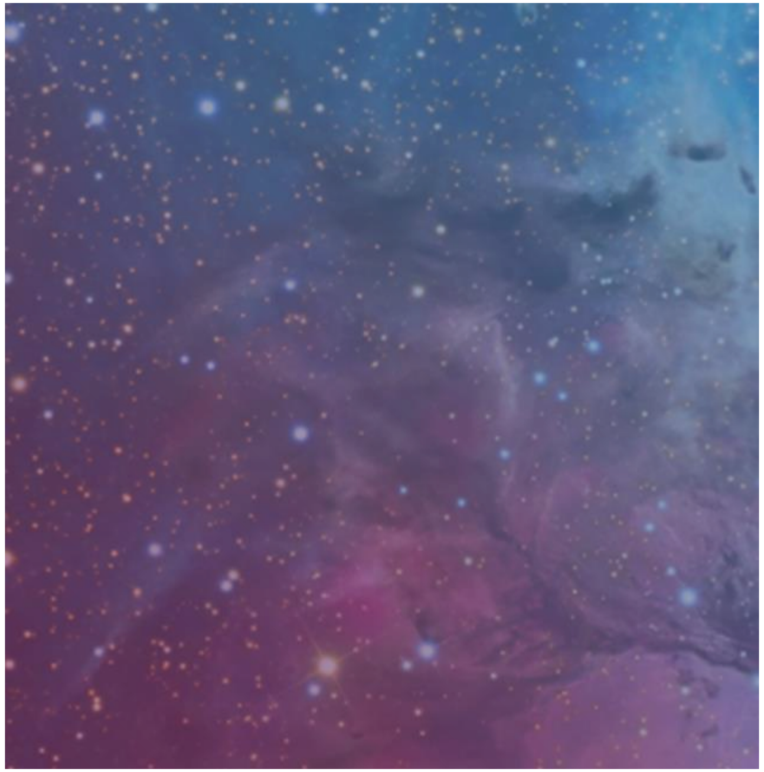


$$L^a_{SME} = -\bar{\psi}_w a^\mu \gamma_\mu \psi_w$$

At 90% C.L,

$$\left|(a^{(3)}_{\text{of}})_{00}\right| < 3.0 \cdot 10^{-8}\,\text{GeV}$$

$$\left|(a^{(3)}_{\text{of}})_{10}\right| < 6.4 \cdot 10^{-4}\,\text{GeV}$$



Time-varying neutrino masses can arise from interactions with ultralight dark matter.

Experimental searches for the signatures of these scenarios are of potential interest for Lorentz Invariance Violation tests.

Grazie!

QUANTUM · GRAVITY · MULTI · MESSENGER

Spare slides

SME coefficients teastables in beta decays

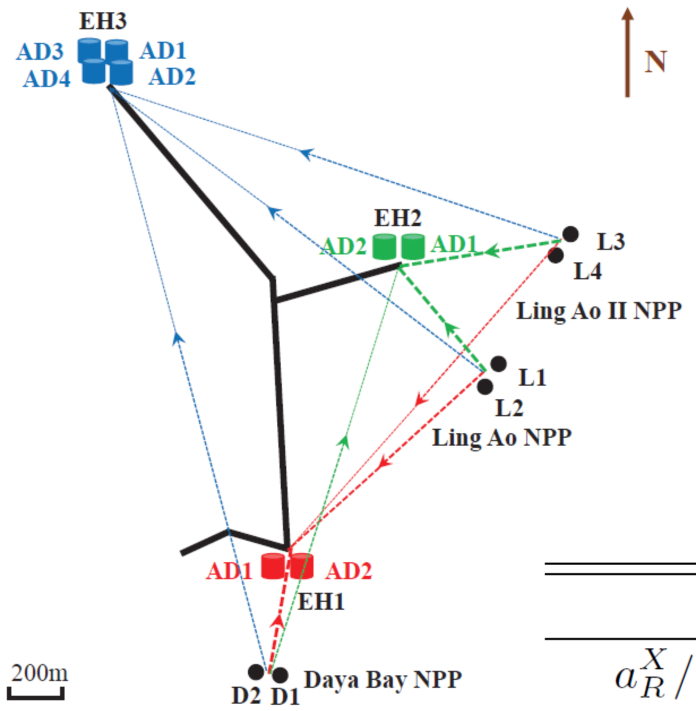
$$m_\nu^2 \to m_\nu^2 + \delta m^2$$

$$\delta m^2 = m_{\mathcal{C}}^2 + m_{\mathcal{A}_s}^2 \sin\omega_\oplus T_\oplus + m_{\mathcal{A}_c}^2 \cos\omega_\oplus T_\oplus$$

$$m_{\mathcal{C}}^2 = \sqrt{\frac{3}{\pi}} \cos^2\frac{\theta_0}{2} \sin\chi \cos\xi \, (c_{\text{eff}}^{(2)})_{10},$$

$$m_{\mathcal{A}_s}^2 = \sqrt{\frac{6}{\pi}} \cos^2\frac{\theta_0}{2} \left[\sin\xi \, \mathrm{Re}\,(c_{\text{eff}}^{(2)})_{11} - \cos\chi \cos\xi \, \mathrm{Im}\,(c_{\text{eff}}^{(2)})_{11}\right]$$

$$m_{\mathcal{A}_c}^2 = \sqrt{\frac{6}{\pi}} \cos^2\frac{\theta_0}{2} \left[\sin\xi \, \mathrm{Im}\,(c_{\text{eff}}^{(2)})_{11} + \cos\chi \cos\xi \, \mathrm{Re}\,(c_{\text{eff}}^{(2)})_{11}\right]$$



DayaBay limits on SME

Coefficient	$\bar{e}\bar{e}$	$\bar{\mu}\bar{\mu}$	$\bar{\tau}\bar{\tau}$	$\bar{e}\bar{\mu}$	$\bar{e}\bar{\tau}$	$\bar{\mu}\bar{\tau}$
$a_R^X/10^{-20}$ (GeV)	-5 ± 25	9 ± 45	13 ± 58	-3.4 ± 5.5	-5.6 ± 8.0	10 ± 51
$c_R^{TX}/10^{-18}$	-15 ± 55	26 ± 99	34 ± 122	-4.5 ± 7.1	-6.9 ± 9.7	29 ± 109
$c_R^{XZ}/10^{-18}$	-20 ± 70	36 ± 128	43 ± 153	-2.1 ± 6.8	-2.7 ± 8.4	39 ± 139
$a_R^Y/10^{-20}$ (GeV)	5 ± 25	-9 ± 45	-10 ± 58	-0.3 ± 5.5	-0.9 ± 8.0	-9 ± 51
$c_R^{TY}/10^{-18}$	2 ± 55	-3 ± 99	-4 ± 122	-0.9 ± 7.1	-1.6 ± 9.7	-4 ± 109
$c_R^{YZ}/10^{-18}$	-10 ± 70	19 ± 128	22 ± 152	-1.4 ± 6.8	-1.9 ± 8.4	21 ± 139
$(c_R^{XX} - c_R^{YY})/10^{-18}$	13 ± 46	-24 ± 84	-29 ± 103	1.0 ± 8.2	0.9 ± 10.5	-26 ± 92
$c_R^{XY}/10^{-18}$	6 ± 23	-11 ± 42	-14 ± 51	1.0 ± 4.1	1.3 ± 5.3	-12 ± 46

MINOS ND & FD limits on SME

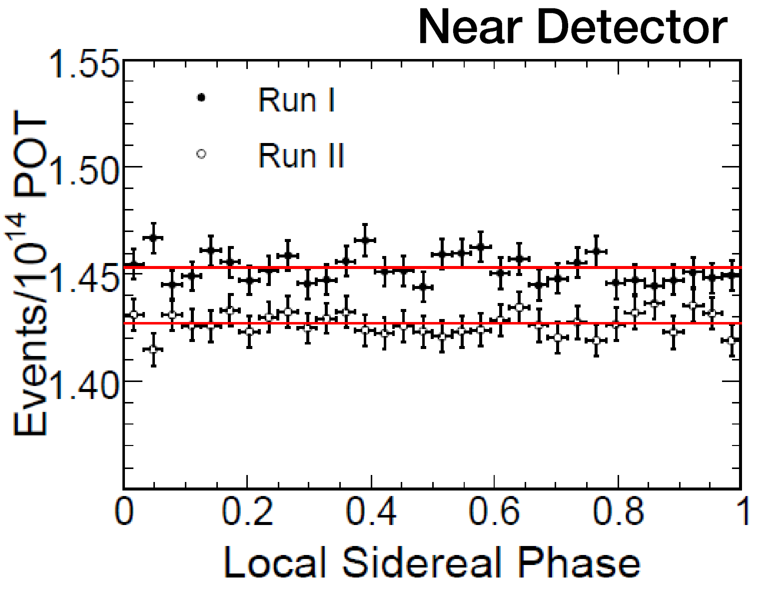


FIG. 1: The local sidereal phase histograms for Run I and Run II. Superposed are fits to a constant sidereal rate.

Improvement

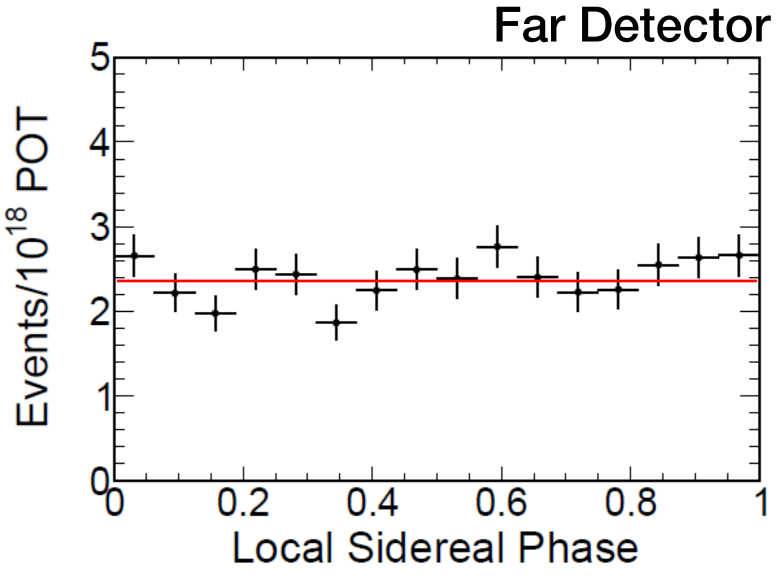


FIG. 1: Event rate as a function of LSP for the total data set.

Coeff.	Limit	$\mathcal{I}$	Coeff.	Limit	$\mathcal{I}$
$(a_L)^X_{\mu\tau}$	5.9×10^{-23}	510	$(a_L)^Y_{\mu\tau}$	6.1×10^{-23}	490
$(c_L)^{TX}_{\mu\tau}$	0.5×10^{-23}	20	$(c_L)^{TY}_{\mu\tau}$	0.5×10^{-23}	20
$(c_L)^{XX}_{\mu\tau}$	2.5×10^{-23}	220	$(c_L)^{YY}_{\mu\tau}$	2.4×10^{-23}	230
$(c_L)^{XY}_{\mu\tau}$	1.2×10^{-23}	230	$(c_L)^{YZ}_{\mu\tau}$	0.7×10^{-23}	170
$(c_L)^{XZ}_{\mu\tau}$	0.7×10^{-23}	190	—	—	—

PRL 101 (2008) 151601
PRL 105 (2010) 151601

IceCube limits on SME

PRD 82 (2010) 112003

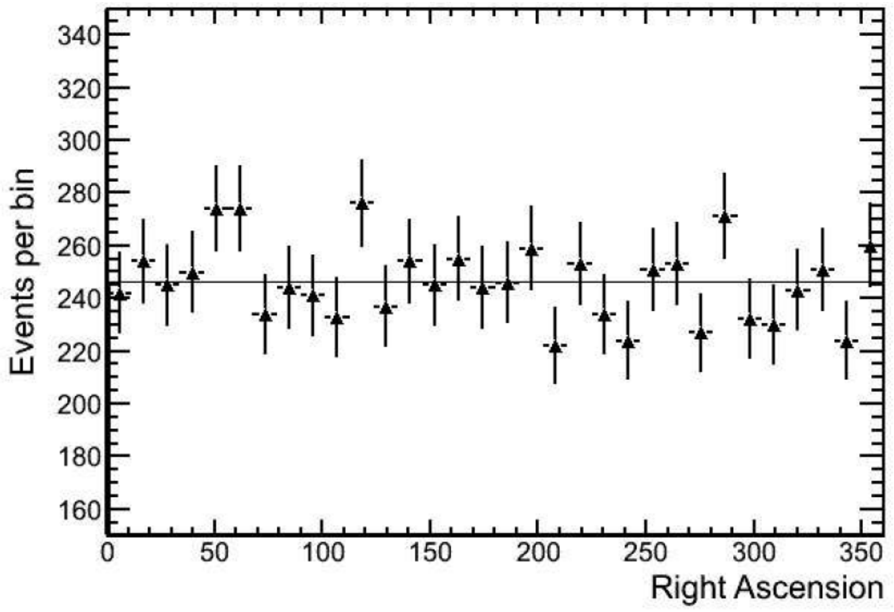


FIG. 2. RA distribution of events in data. Vertical error bars are statistical uncertainty only. Fluctuations in the data, above and below the mean (horizontal line), are consistent with statistical variations. χ^2 per bin for a straight-line fit to the mean is 0.9.

At 3 sigma,

$$a_L^X, a_L^Y < 1.8 \times 10^{-23} \quad \text{GeV}$$

$$c_L^{TX}, c_L^{TY} < 3.7 \times 10^{-27}$$

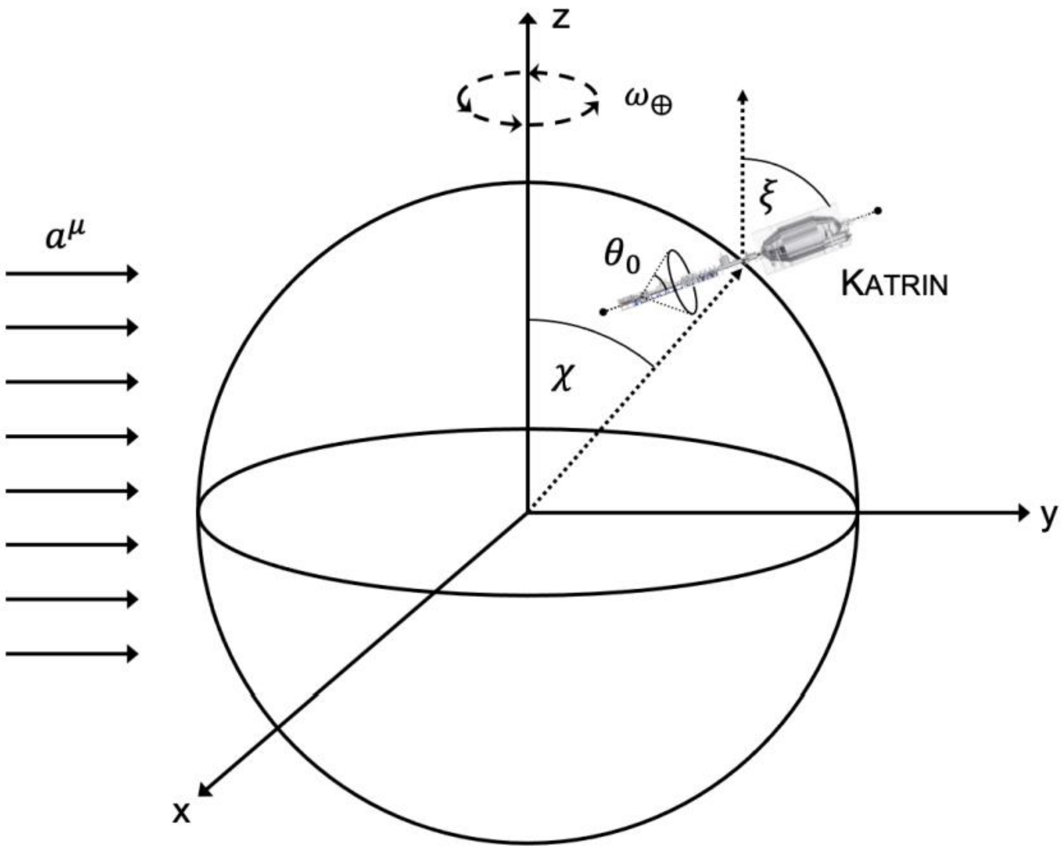
More details on the LIV analysis from KATRIN

2207.06326 [nucl-ex]

$$
\begin{aligned}
\Delta E_0 =& (\gamma - \beta_{rot} B \sin\xi) \frac{1}{\sqrt{4\pi}} a_{00}^{(3)} + \sqrt{\frac{3}{4\pi}} B \sin\chi \cos\xi \, a_{10}^{(3)} \\
&+ \sqrt{\frac{3}{2\pi}} \cos(\omega_\oplus T_\oplus) \Big[(\beta_{\rm rot} - B\sin\xi) \, \mathrm{Im}(a_{11}^{(3)}) \\
&- B \cos\xi \cos\chi \, \mathrm{Re}(a_{11}^{(3)}) \Big] \\
&+ \sqrt{\frac{3}{2\pi}} \sin(\omega_\oplus T_\oplus) \Big[(\beta_{\rm rot} - B\sin\xi) \, \mathrm{Re}(a_{11}^{(3)}) \\
&+ B \cos\xi \cos\chi \, \mathrm{Im}(a_{11}^{(3)}) \Big] ,
\end{aligned}
$$

$$\Delta E_0 = A \cos(\omega_\oplus t - \phi)$$

The amplitude gets all the dependence on the SME coefficients



More details on the LIV analysis from KATRIN

2207.06326 [nucl-ex]

$$L^a_{SME} = -\bar{\psi}_w a^\mu \gamma_\mu \psi_w$$

SME coefficeints (a BONUS) *PRD* 85 (2012) 096005

$$\mathcal{L} = \tfrac{1}{2}\overline{\Psi}_A(\gamma^\mu i\partial_\mu\delta_{AB} - M_{AB} + \widehat{\mathcal{Q}}_{AB})\Psi_B + \text{h.c.}$$

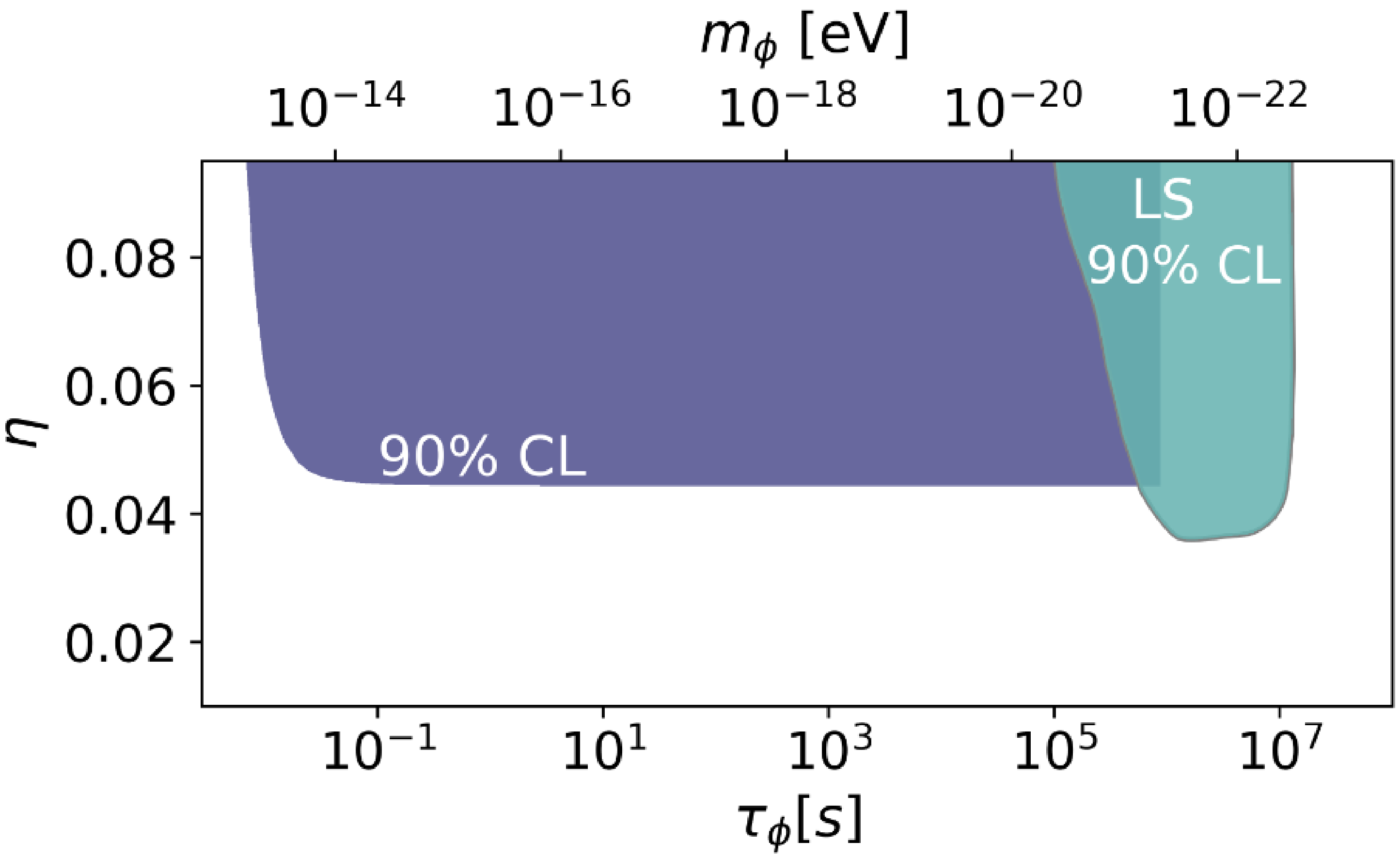
$$\gamma^\nu p_\nu\delta_{AB} - M_{AB} + \widehat{\mathcal{Q}}_{AB} = \widehat{\Gamma}^\nu_{AB}p_\nu - \widehat{M}_{AB}$$

$$\widehat{\mathcal{Q}}^I_{AB} = \sum_{d=3}^{\infty}\mathcal{Q}^{(d)I\alpha_1\alpha_2\ldots\alpha_{d-3}}_{AB}\,p_{\alpha_1}p_{\alpha_2}\cdots p_{\alpha_{d-3}}$$

spherical	cartesian	j	number
$(a^{(3)}_{\rm eff})_{jm}$	$a_L^{(3)\mu},\ e_l^{(4)\mu},\ g_l^{(4)\mu\nu\rho}$	$0,1,2$	81
$(c^{(2)}_{\rm eff})_{jm}$	$H_l^{(3)\mu\nu}$	1	27
$(c^{(4)}_{\rm eff})_{jm}$	$c_L^{(4)\mu\nu}$	$0,1,2$	81
$(g^{(2)}_{\rm eff})_{jm}$	$a_l^{(3)\mu}$	1	36
$(g^{(4)}_{\rm eff})_{jm}$	$g_{M+}^{(4)\mu\nu\rho}$	$1,2$	96
$(H^{(3)}_{\rm eff})_{jm}$	$H_{M+}^{(3)\mu\nu},\ c_l^{(4)\mu\nu}$	$1,2$	48

These coefficients can lead to a modification of the effective neutrino mass measured in beta decay (and in some cases, also to the endpoint energy)

DUNE limits on ultralight scalar DM



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

TIME-VARYING SIGNAL

AVERAGED EFFECT

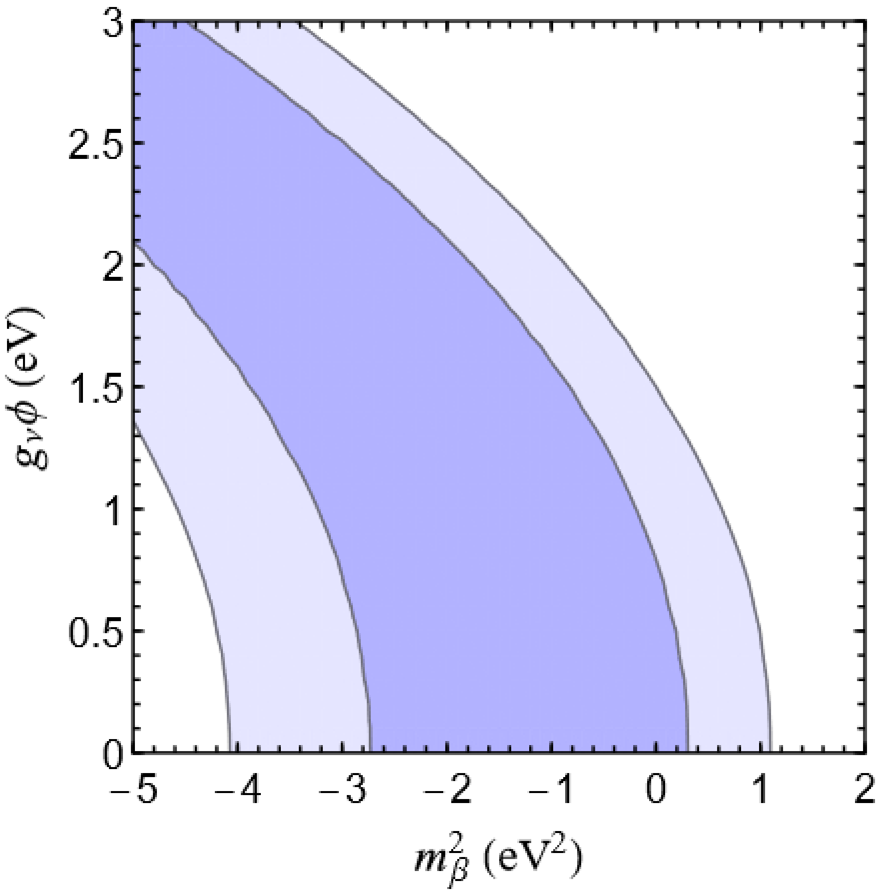
KATRIN limits on ultralight scalar DM

Huang, Lindner, PMM, Sen
2205.08431

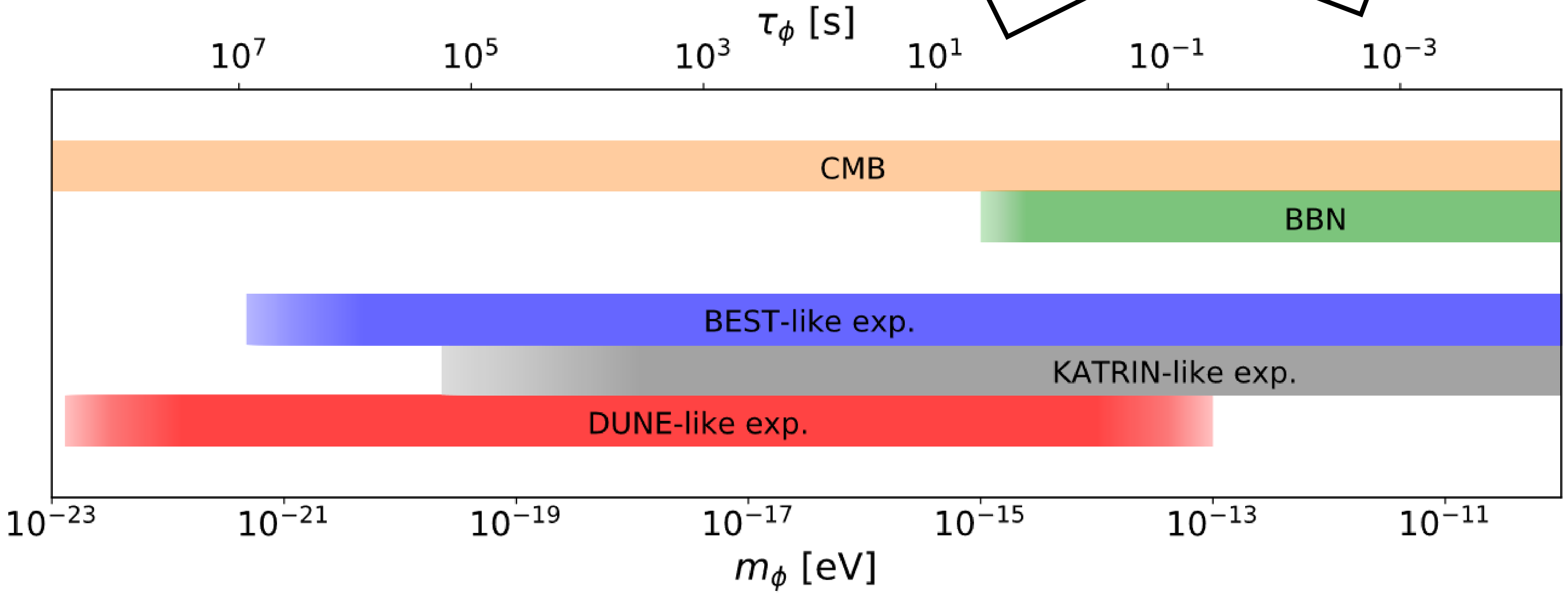
- The infered upper limits on the effective neutrino mass are conservative

- The interaction can lead to negative values of the effective mass (just like LIV)

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



Ultraligh 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.