Snowmass2021 - Letter of Interest

Ultralight dark matter and neutrinos

NF Topical Groups: (check all that apply □/■)

■ (NF1) Neutrino oscillations
■ (NF2) Sterile neutrinos
■ (NF3) Beyond the Standard Model
■ (NF4) Neutrinos from natural sources
■ (NF5) Neutrino properties
■ (TF11) Theory of neutrino physics
■ (NF10) Neutrino detectors
■ (CF2) Dark Matter: Wave-like

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NF/SNOWMASS21-NF3_NF1-CF2_CF0-TF11_TF0_Pedro_Machado-203.pdf (link here)

Ultralight dark matter

If DM is very light, it behaves like a classical field, with a de Broglie wavelength given by $\lambda = 1/m_\varphi \sim 2\text{km} * (10^{-10}\ \text{eV}/m_\varphi)$

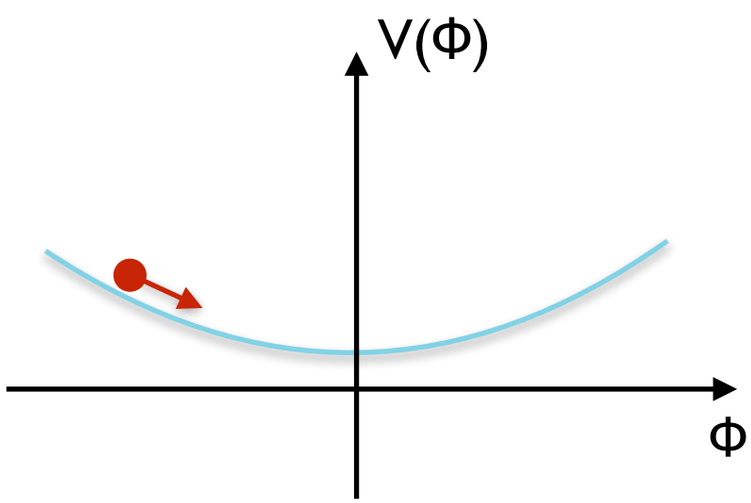
In the very low mass region ($m_\varphi \sim 10^{-22}$ eV, or $\lambda \sim 0.4$ parsec) this is typically called Fuzzy DM and may offer a solution to too-big-to-fail, missing satellites and cusp-vs-core problems

Hu Barkana Gruzinov 2000
Marsh Silk 2013
Hui et al 2016
...

DM is "spread out:"
Flatter profiles (cusp-vs-core)
High change of tidal disruption (missing satellite and TBTF)

Ultralight dark matter and neutrinos

Berlin 2017
Krnjaic Machado Necib 2017
Brdar et al 2017
Capozzi Shoemaker Vecchi 2017
Farzan Palomares-Ruiz 2019
Liao Marfatia Whisnant 2018
Ge Parke 2019
Dev Machado Martinez-Mirave 2020
…



Very light scalar DM (<< eV):

- very high occupation number
- classical field

$$(\partial_t^2 + \underbrace{3H\partial_t}_{\text{friction}} + m_\phi^2)\phi = 0$$

Klein-Gordon

Damped harmonic oscillator

Coherent oscillations

$$\phi(x,t) \simeq \frac{\sqrt{2\rho_\phi^\odot}}{m_\phi}\cos[m_\phi(t - \vec{v}\cdot\vec{x})]$$

What if this field couples to neutrinos?

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

Bottom-up approach

Modulation amplitude (set y = 1):

$$\eta_\phi \equiv \frac{\sqrt{2\rho_\phi^\odot}}{\Lambda m_\phi} = 2.2\left(\frac{\rho_\phi^\odot}{0.3\ \text{GeV/cm}^3}\right)\left(\frac{\text{TeV}}{\Lambda}\right)\left(\frac{10^{-15}\ \text{eV}}{m_\phi}\right)$$

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Ultralight dark matter and neutrinos

$m_\nu = m_\nu(t)$
Δm^2 and θ_{ij} modulate!

$$\Delta m^2_{ij}(x,t) \equiv m_i^2 - m_j^2 \simeq \Delta m^2_{ij,0}\left(1 + 2\frac{\phi(x,t)}{\Lambda}\right) \qquad \theta_{ij}(x,t) = \theta_{ij,0} + \frac{\phi(x,t)}{\Lambda}$$

Modulation period $\tau_\phi \equiv \frac{2\pi}{m_\phi} \sim 10 \text{ min}\left(\frac{7\times 10^{-18}\text{ eV}}{m_\phi}\right)$

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~ 10^{-12} eV — interesting region — ~ 10^{-23} eV

2.7 msec — ~ 10 years

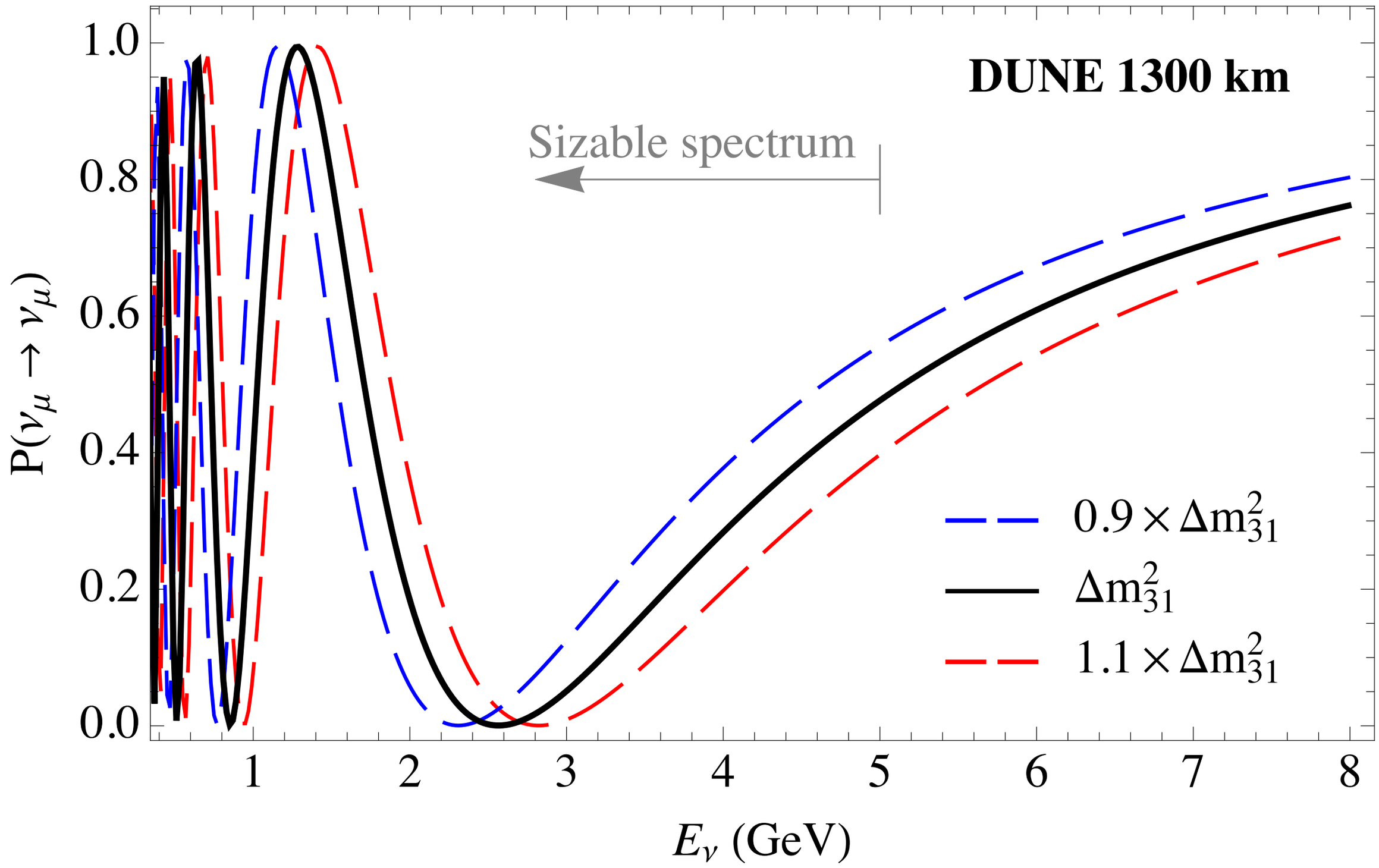
(L = 800 km)

11 orders of magnitude!!!

Regimes

Signal periodicity: temporal modulation of the neutrino oscillation probability
Averaged distorted neutrino oscillations (average DiNO): time averaged of the above (non-trivial)
Dynamical distorted neutrino oscillations (dynamical DiNO): time dependent matter effect

Ultralight dark matter and neutrinos - signal periodicity



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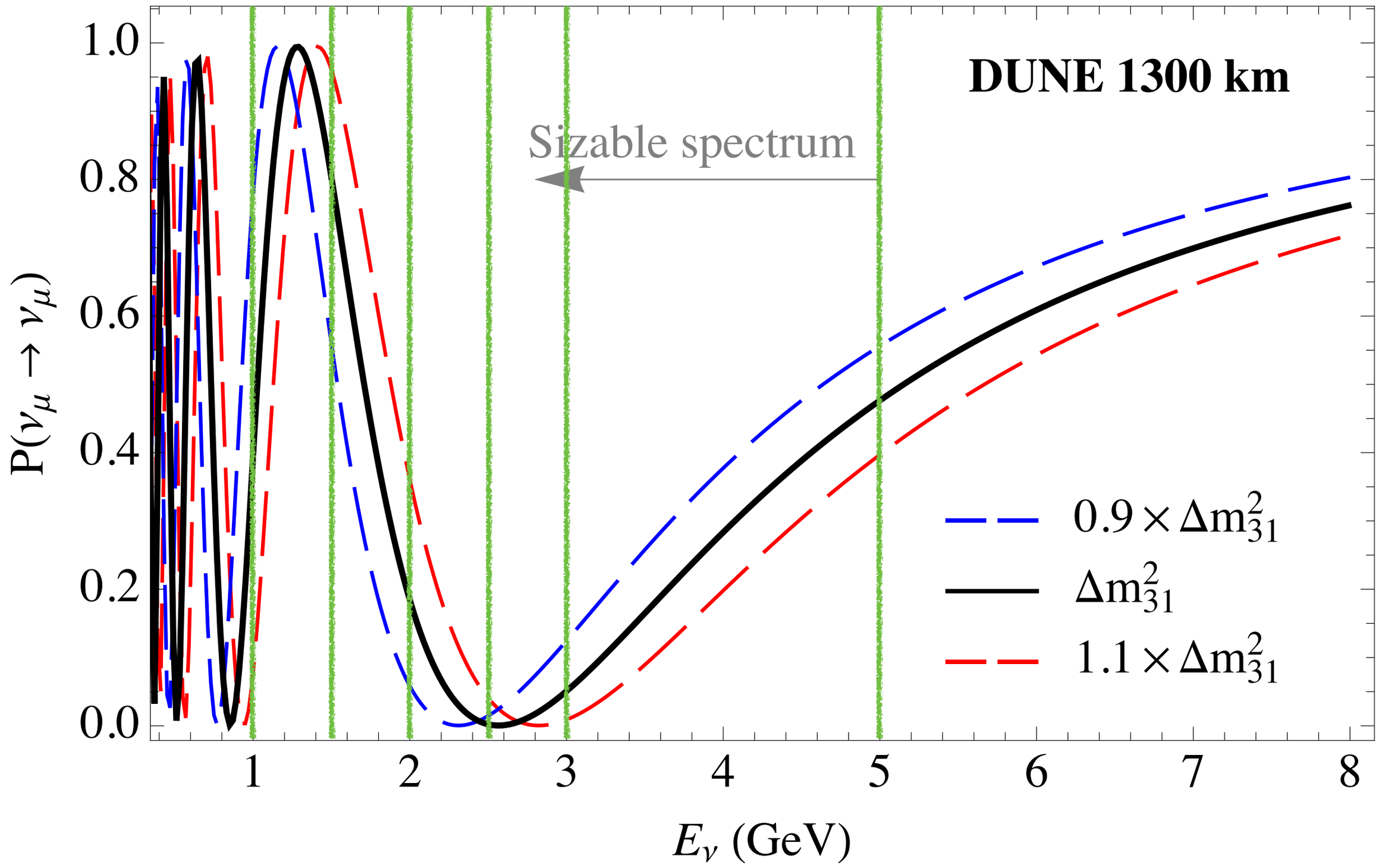
Ultralight dark matter and neutrinos - signal periodicity



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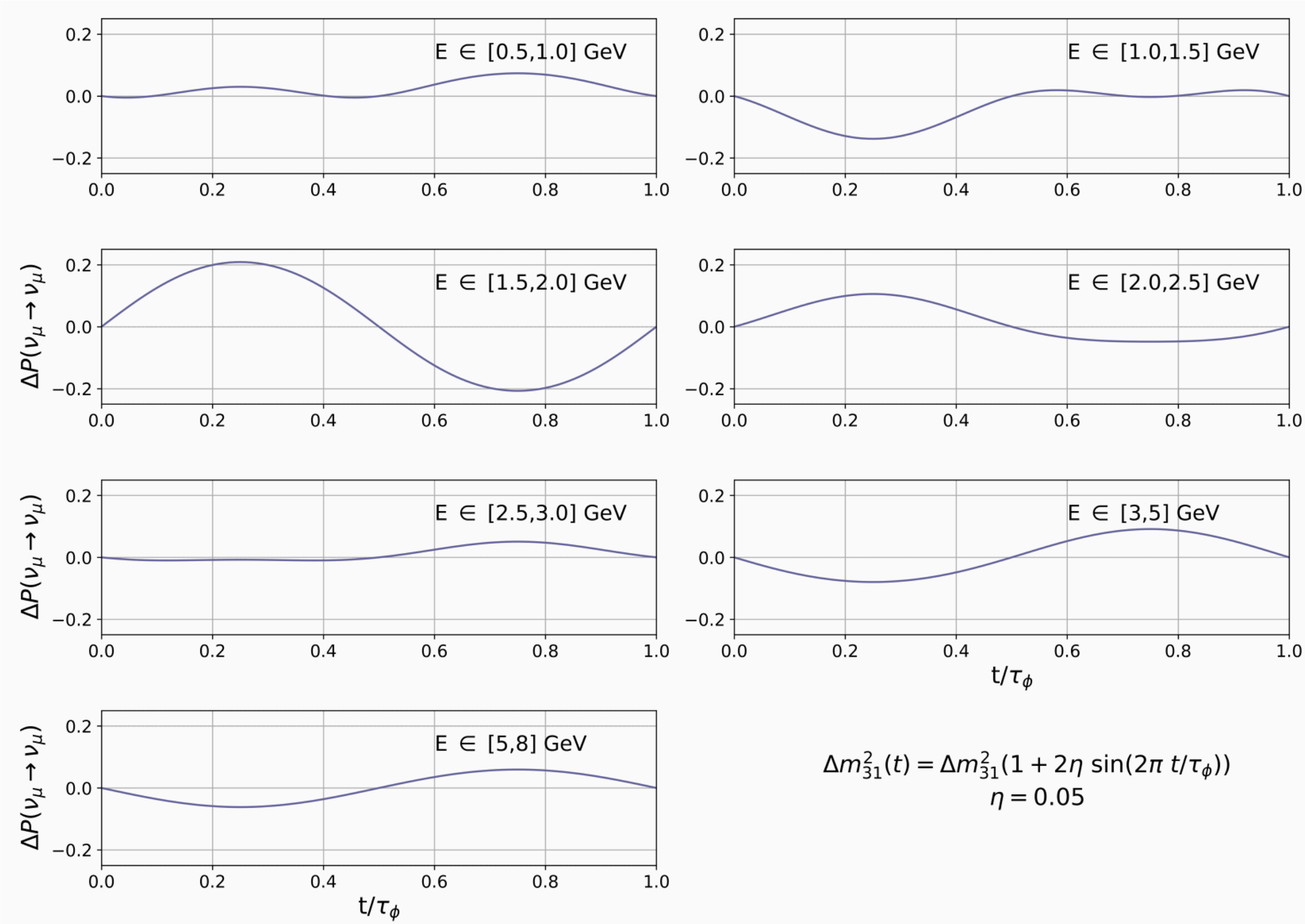

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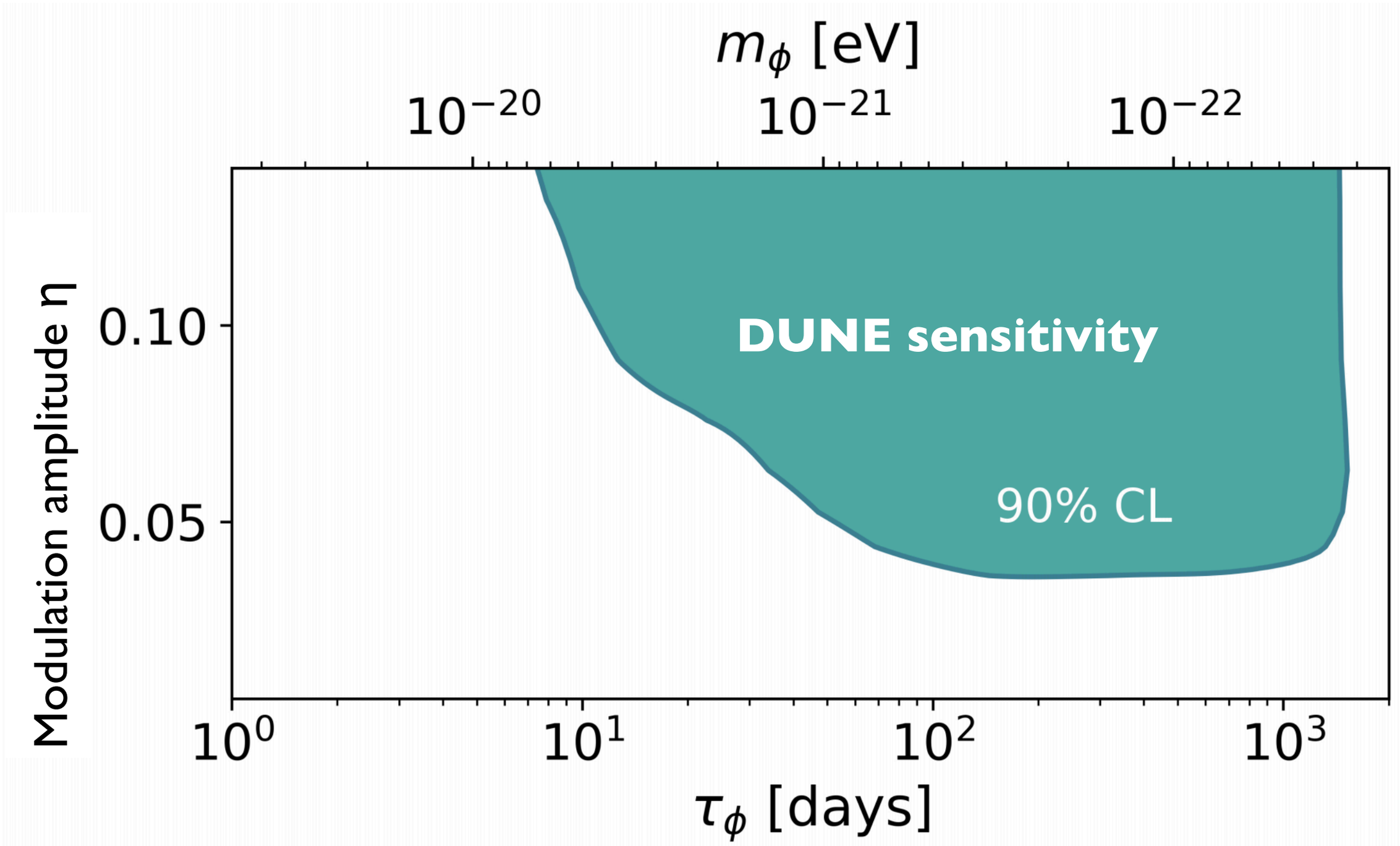
Ultralight dark matter and neutrinos - signal periodicity

How to look for this: Lomb-Scargle Periodogram

see Dev Machado Martinez-Mirave 2007.03590 for a details



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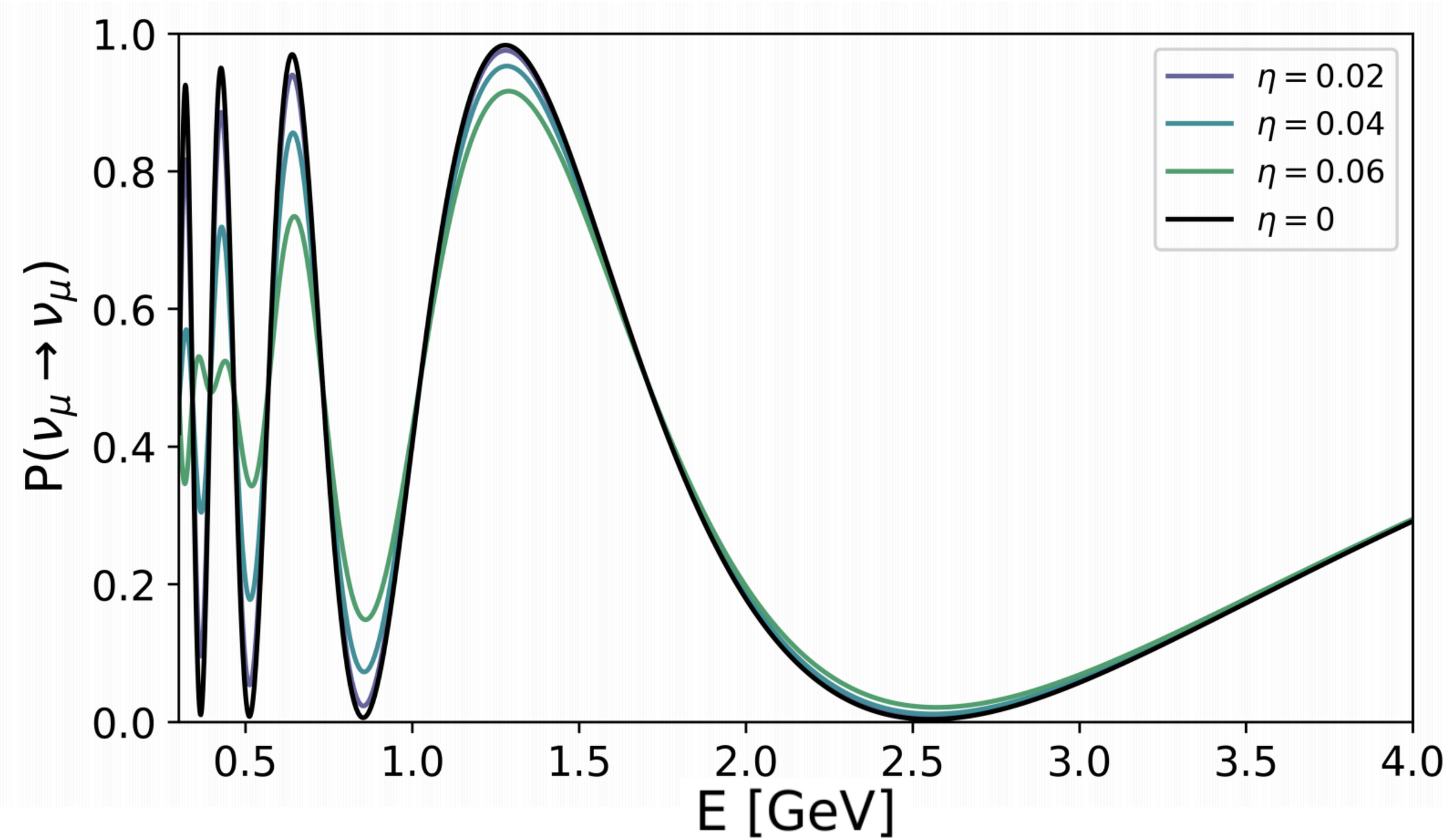
Ultralight dark matter and neutrinos - average DiNO



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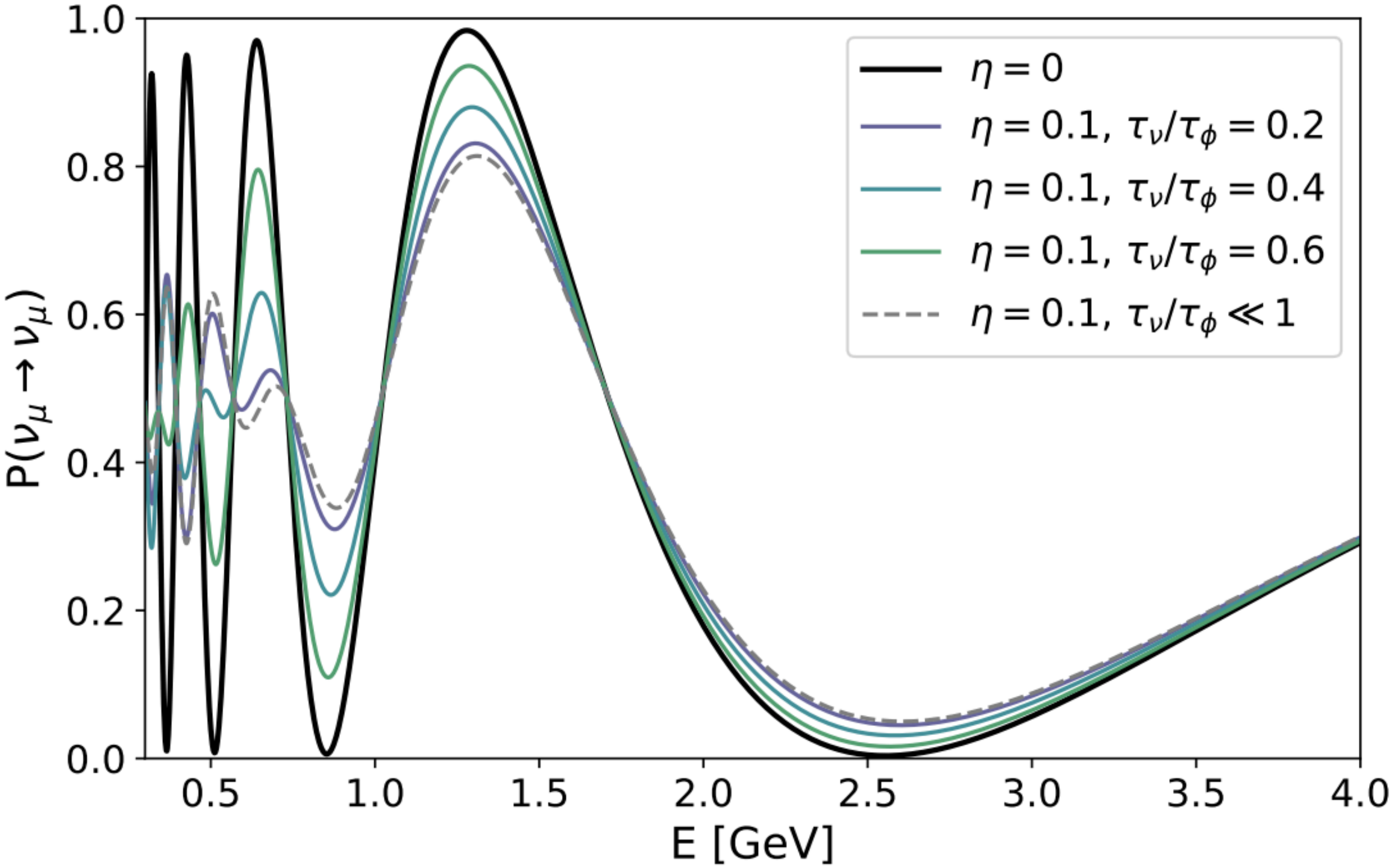
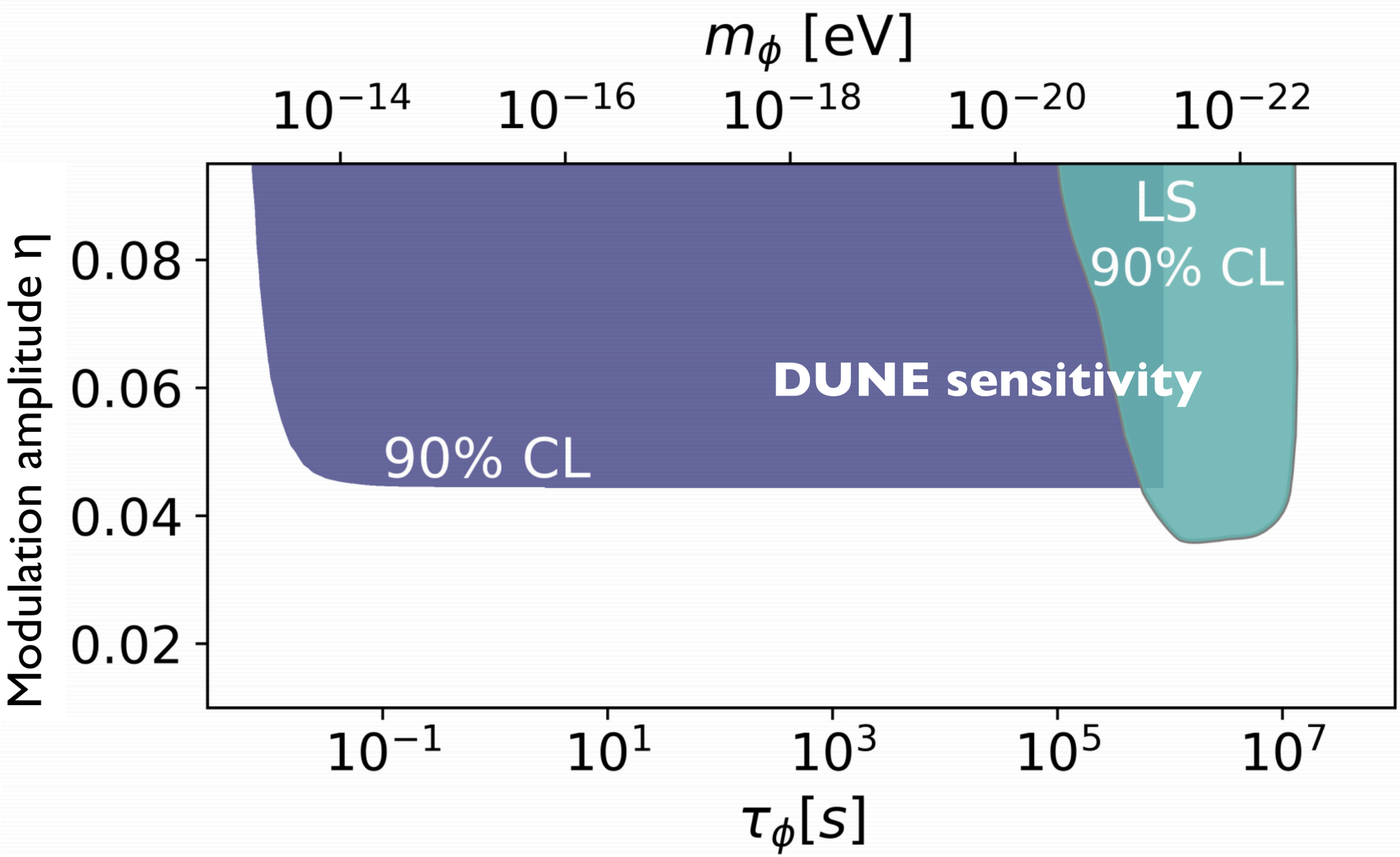
Ultralight dark matter and neutrinos - dynamical DiNO



Ultralight dark matter and neutrinos - average and dynamical DiNO

How to look for this: modified oscillation probability

see Dev Machado Martinez-Mirave 2007.03590 for a details



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Ultralight dark matter and neutrinos - conclusions

Exciting phenomenology and interesting question:
Are constants of Nature constant?
What if neutrino masses and mixings change in time?

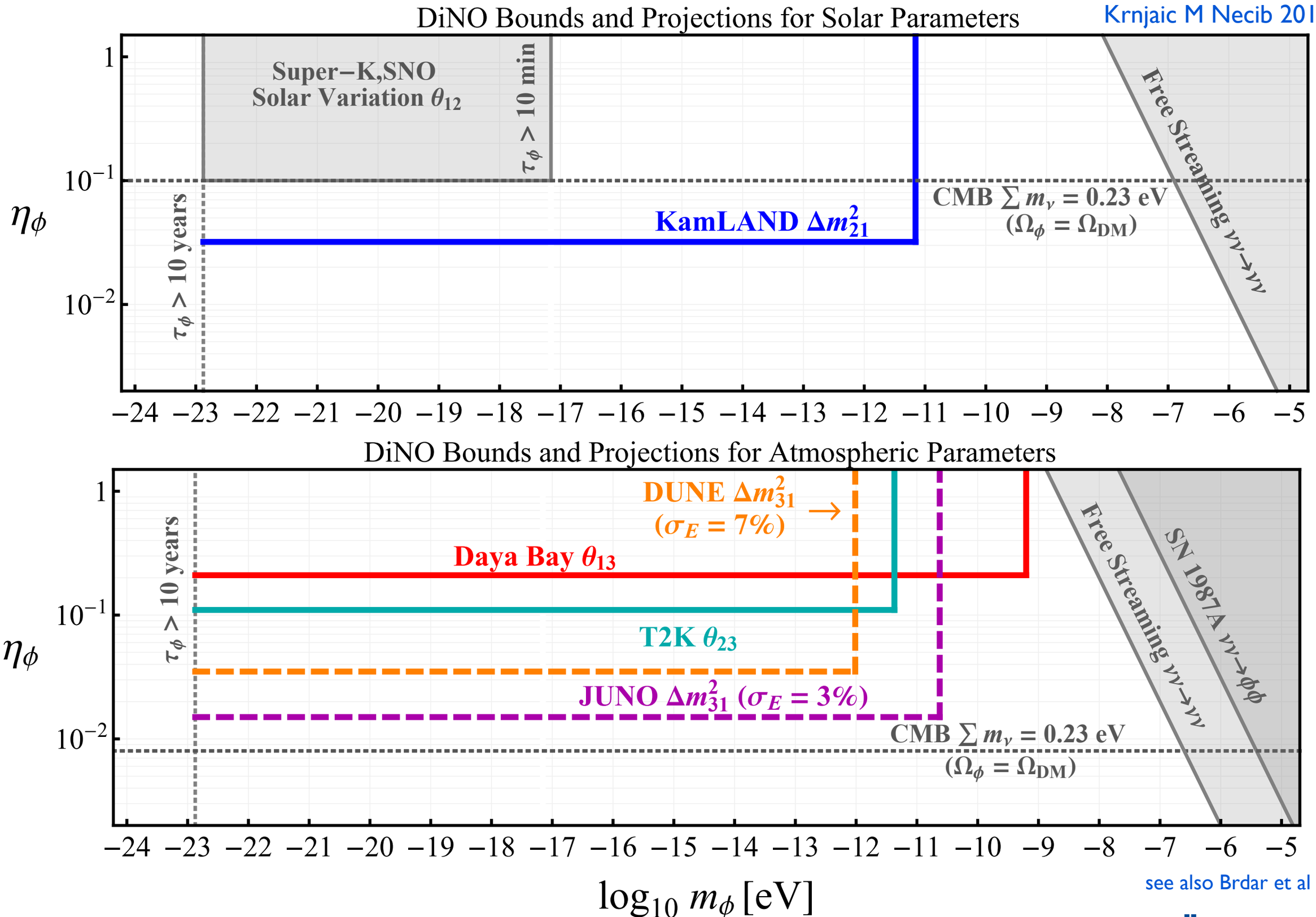
Bottom-up approach allows for model independent analysis

Good novel test of three neutrino paradigm:
Lomb-Scargle technique is appropriate to other searches
(e.g. Lorentz symmetry violation)
Oscillation probability modified in unique way

Non-trivial connections to other fields:
Black hole spin measurements
CMB and BBN
Astrophysical neutrinos
...

Neutrinos and ultralight dark matter

Krnjaic M Necib 2017



see also Brdar et al 2017

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Ultralight dark matter

How to look for such scenario?

If it is axion-like, it couples to photons and so it

1) Disrupts magnetic fields - resonant cavity searches (ADMX)
2) Converts to γ in B field - CAST
3) Sources E field in B field - LC circuits Sikivie Sullivan Tanner 2013
4) Induces oscillation in fine structure constant - Atomic spectroscopy Tilburg et al 2015

If it couples to fermions it

Derevianko Pospelov 2013
Arvanitaki Huang Tilburg 2014

5) Changes the effective electron/proton mass ratio - Atomic clocks
6) Changes the rest mass of atoms - Atom interferometry Geraci Derevianko 2016
7) Generates equivalence-principle violating force - accelerometers Graham et al 2015
Arvanitaki Dimopoulos Tilburg 2015

What if it couples to neutrinos?

- Modulation of solar neutrino flux Berlin 2016
- Striking signatures at oscillation experiments Krnjaic M Necib 2017
Brdar et al 2017

Other constraints

CMB

Cosmological density of Φ redshifts

$\rho_\Phi(z) \sim (1 + z)^3 \rho_\Phi(0)$

Contributions to sum of ν masses!

If Φ couples to heavy states:

$$\eta_\phi(z_{\rm rec}) = \frac{\sqrt{2\rho_\phi(z=0)}}{\Lambda m_\phi}(1+z_{\rm rec})^{3/2} \lesssim 1$$

$$\eta_\phi(z=0) \equiv \frac{\sqrt{2\rho_\phi^\odot}}{\Lambda m_\phi} \lesssim 9\times 10^{-3}$$

with $\rho_\phi^\odot \sim 10^5 \rho_\phi(z=0)$.

If Φ couples to light states:

$$\eta_\phi(z=0) \equiv \frac{\sqrt{2\rho_\phi^\odot}}{\Lambda m_\phi} \lesssim 0.1$$

These bounds are weakened if Φ constitutes a subdominant fraction of the DM density.

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Supernova 1987A

ν ν > Φ Φ can lead to anomalous energy loss, which is estimated to be

$$\Delta E_\phi \sim 4\times 10^{50}\,{\rm erg}\left(\frac{50\,{\rm keV}}{\Lambda}\right)^4\left(\frac{\Delta t}{10\ {\rm sec}}\right)$$

translating into Λ > 50 keV.
That translates into

$$m_\phi \lesssim 3\times 10^{-7}\,{\rm eV}\left(\frac{0.1}{\eta_\phi}\right)\left(\frac{0.1\,{\rm eV}}{m_{\nu,i}}\right)^2\left(\frac{\Omega_\phi}{\Omega_{\rm DM}}\right)^{1/2}$$

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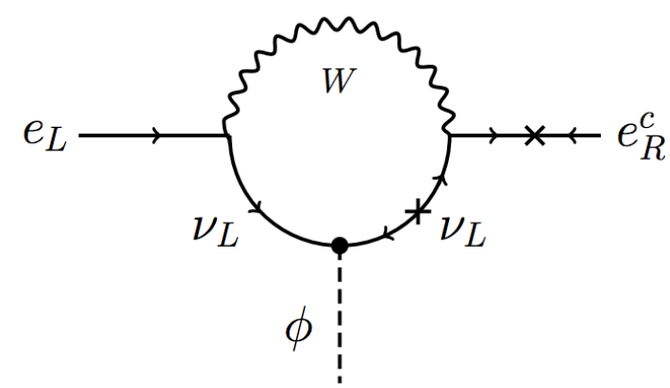
Charged lepton mass variation



$$\frac{\delta m_e}{m_e} \sim \frac{G_F m_\nu^2}{16\pi^2} \sim 10^{-28}\left(\frac{\eta_\phi}{0.1}\right) \lesssim 10^{-16}$$

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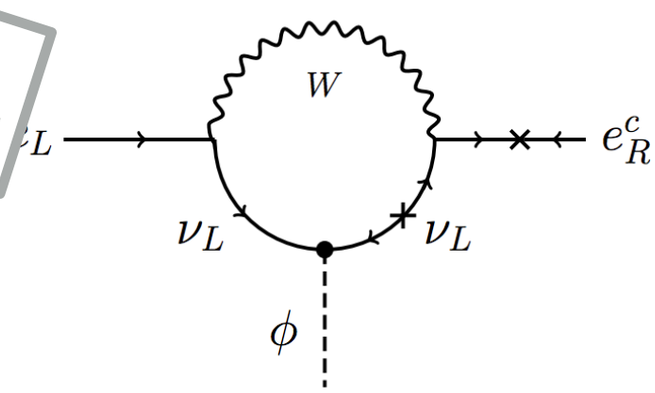

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