GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

GENERALITAT VALENCIANA

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Signatures of ULTRALIGHT DARK MATTER in DUNE

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17th MultiDark Consolider Workshop

Presentation based on arXiv:2007.03590

MultiDark
Multimessenger Approach for Dark Matter Detection

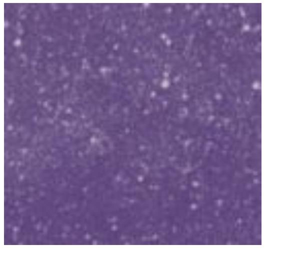
IFIC Institut de Física Corpuscular

Vniversitat de València

CSIC Consejo Superior de Investigaciones Científicas

ASTROPARTICLES Astroparticles and High Energy Physics Group

DUNE* could detect **ultralight scalars** via **signal time modulations** and **distorted neutrino oscillations.**



*Other neutrino oscillation experiments too.

Neutrino oscillations in a nutshell

Quantum phenomena with a **L/E** dependence.

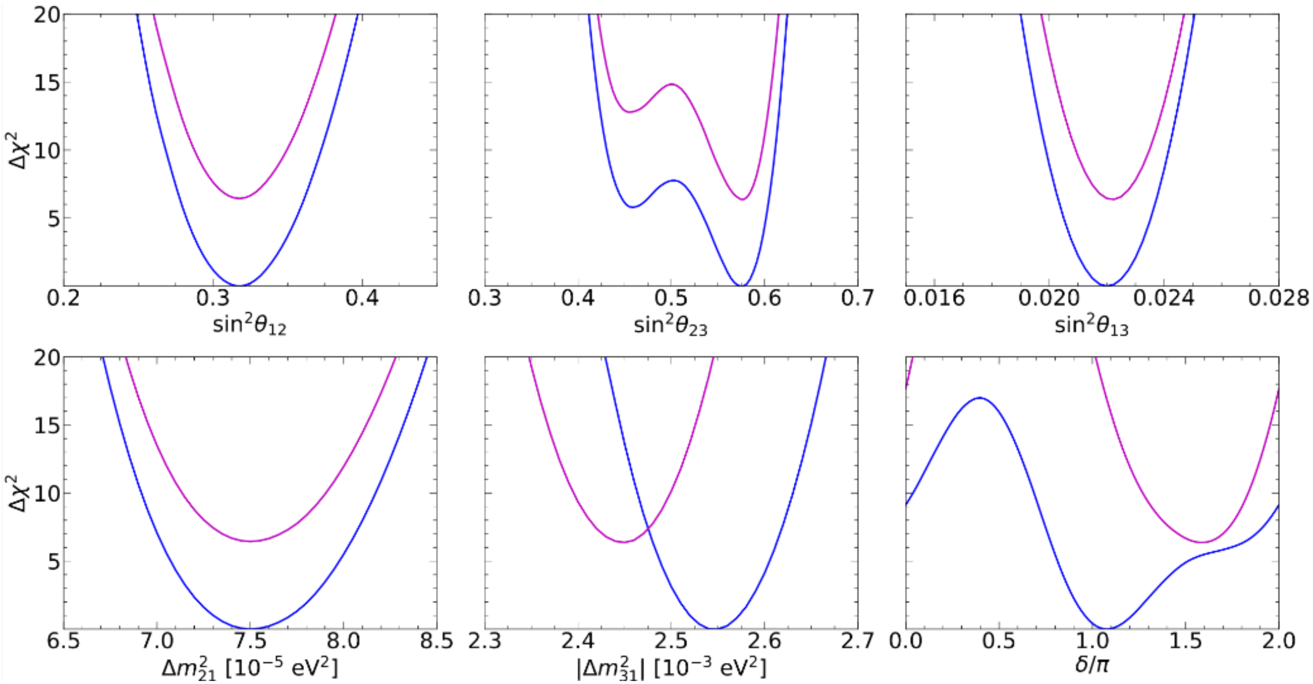
Parametrised in terms of **3 angles**, **1 phase** and **2 mass splittings**.

Tested against different **sources**, **baselines** and **energies** for **neutrinos** and **antineutrinos**.

Neutrino **interactions with matter** can significantly alter the picture.

See Christoph's talk

Neutrino oscillation experiments have reached the precision era.



de Salas *et al*. JHEP XX (2021) XXX (2006.11237)
https://globalfit.astroparticles.es

See also:
Esteban *et al.* JHEP 09 (2020) 178,
Capozzi *et al.* PRD 101 (2020) 11, 116013 (addendum)

ULTRALIGHT DM*

Ultralight dark matter seems to offer a solution to three **small-scale cosmological puzzles**:

- Cups-vs-core,
- Missing satellite,
- And too-big-to-fail problem.

*Ultralight refers to a mass scale much smaller than the eV scale.

Ultralight scalars and neutrinos

See G.Krnjaic et al
Phys.Rev.D 97 (2018) 7, 075017

An **ultralight scalar field**

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

coupling (effectively) to **neutrinos** as

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

induces **time dependencies** on the mass splittings and also on the mixing angles (depending on the flavour structure of the coupling)

$$\Delta m_{ij}^2(t) \equiv m_i^2(t) - m_j^2(t) \simeq \Delta m_{ij}^2 \left[1 + 2\eta \sin(m_\phi t)\right]$$

$$\theta_{ij}(t) = \theta_{ij} + \eta \sin(m_\phi t),$$

The **mass** of the ultralight scalar is related to the **modulation period**

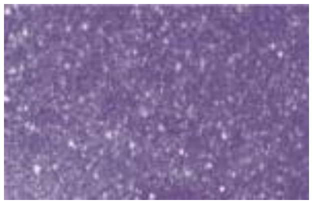
$$\tau_\phi \equiv \frac{2\pi\hbar}{m_\phi} = 0.41 \left(\frac{10^{-14}\ \mathrm{eV}}{m_\phi} \right) \ \mathrm{seconds.}$$

There are **three** characteristic time scales in the experimental set up:

- **Time of flight,** τ_ν.
- Time between two events (inverse of the **event rate**), τ_{evt}.
- **Lifetime** of the experiment, τ_{exp}.

Mass range: ~10^{-13} -10^{-23} eV

Three regimes can be identified.



Signal time modulation ($\tau_{\rm evt} \lesssim \tau_\phi \ll \tau_{\rm exp}$).

A temporal variation could be measured in experiments with large statistics and high event rates.

Averaged Distorted Neutrino Oscillations (DiNOs) ($\tau_\nu \ll \tau_\phi \ll \tau_{\rm evt}$).

Modulation is too fast but its averaging leads to deviations from the standard picture.

Dynamical Distorted Neutrino Oscillations ($\tau_\phi \sim \tau_\nu$).

Propagation modelled by a modified (time-dependent) matter potential. If matter variations are too fast, one recovers standard oscillations.

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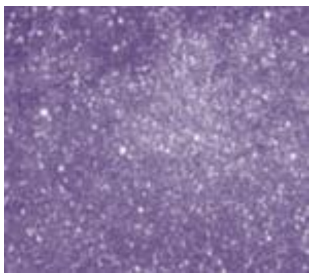

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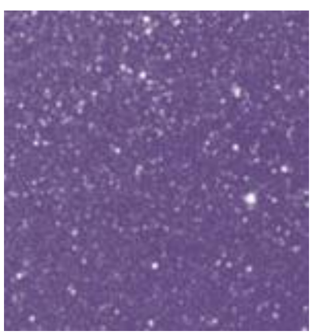

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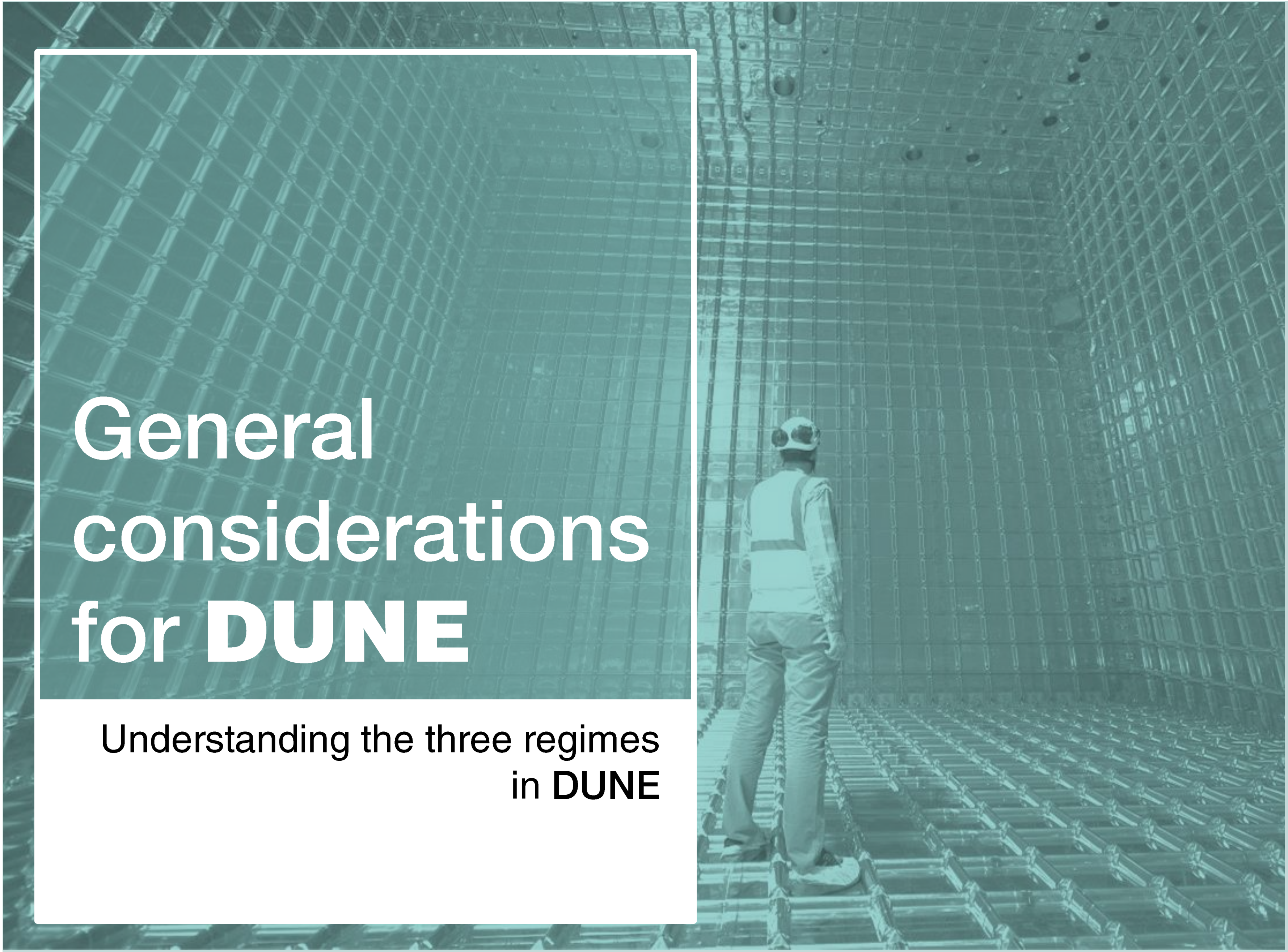


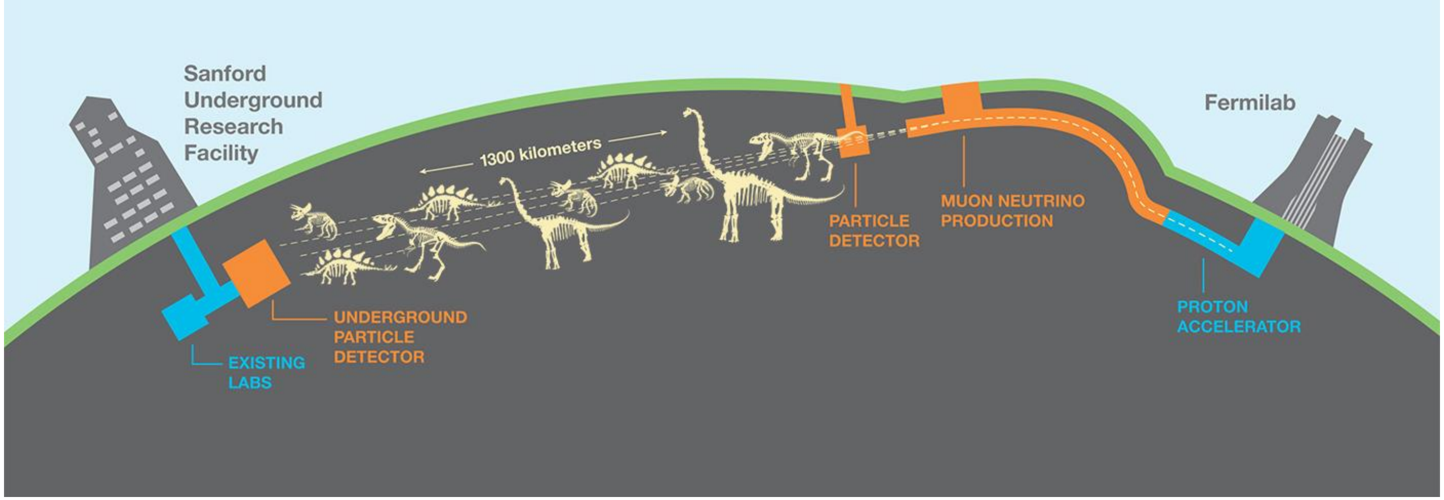
General considerations for **DUNE**

Understanding the three regimes in **DUNE**

DUNE

Deep Underground Neutrino Experiment

Next-generation neutrino experiment.
High-energy neutrino beam.
Far detector 1300km away from source.
Large statistics expected.
Good **energy reconstruction**.

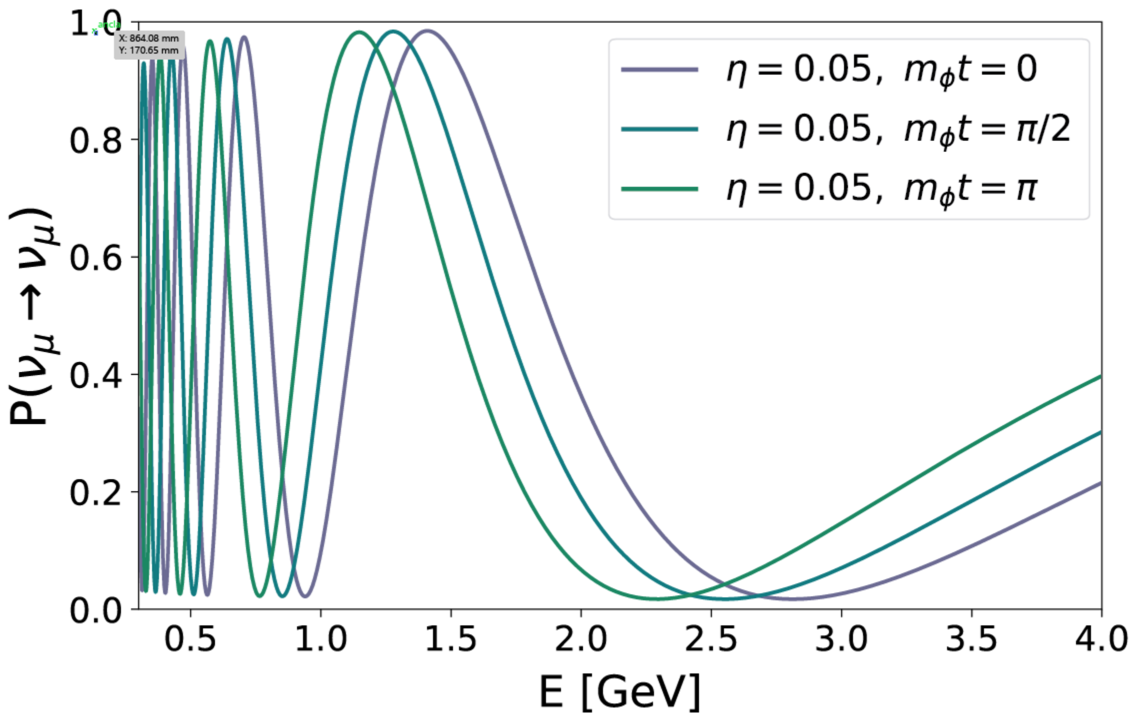


For $\Delta m^2_{31}(t)$

Signal time modulation

Maxima and minima shift with time, leading to changes in the average disappearance probability.

$$P^{\text{mass}}_{\mu\mu} \simeq 1 - \sin^2(2\theta)\sin^2\left\{\left(\frac{\Delta m^2 L}{4E}\right)[1 + 2\eta\sin(m_\phi t)]\right\}$$

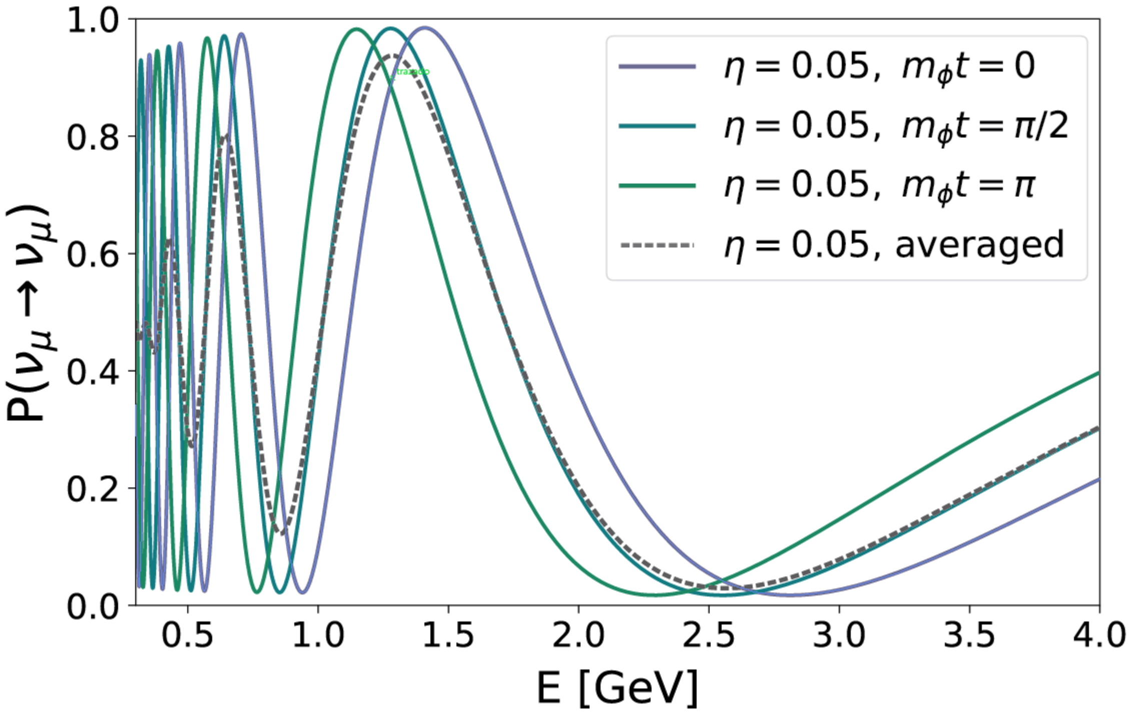


For $\Delta m^2_{31}(t)$

Average DiNOs

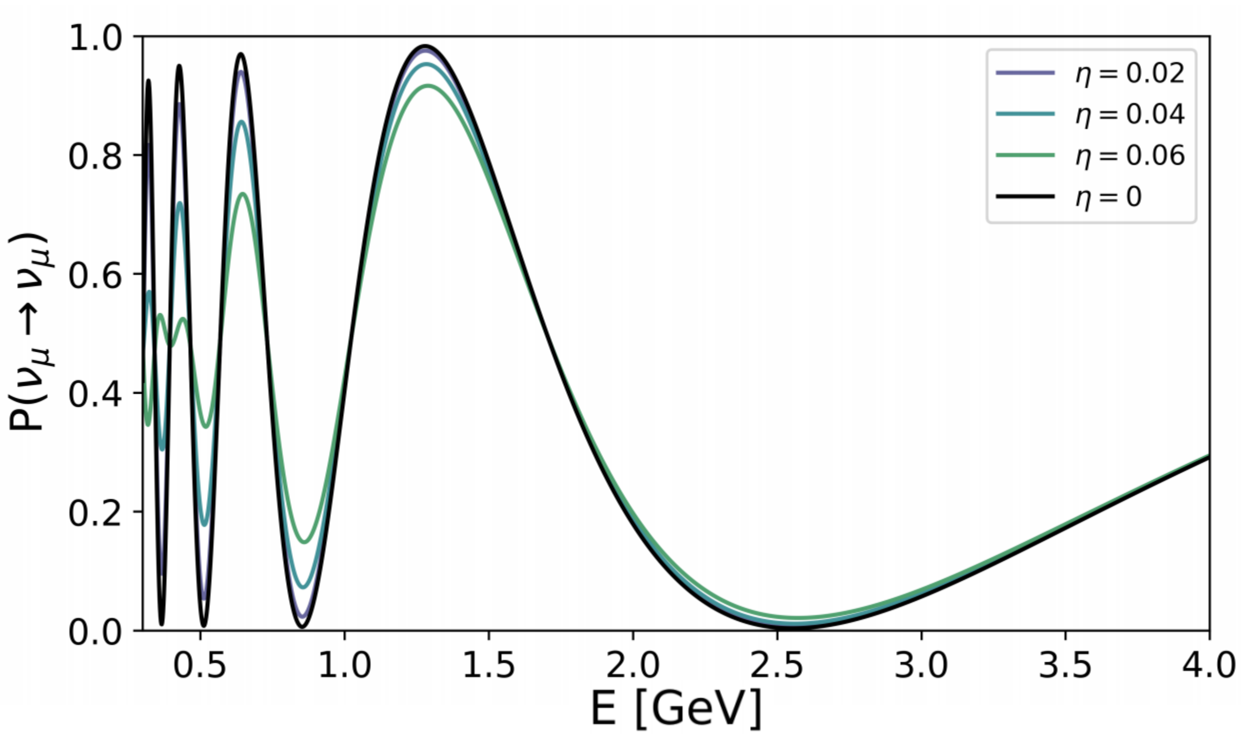
Very fast modulations get averaged and lead to a distortion in the disappearance probability.
Maxima and minima are not shifted so its determination is not expected to be affected.

$$\langle P_{\alpha\beta}\rangle = \frac{1}{\tau_\phi}\int_0^{\tau_\phi} dt\, P_{\alpha\beta}(t)$$



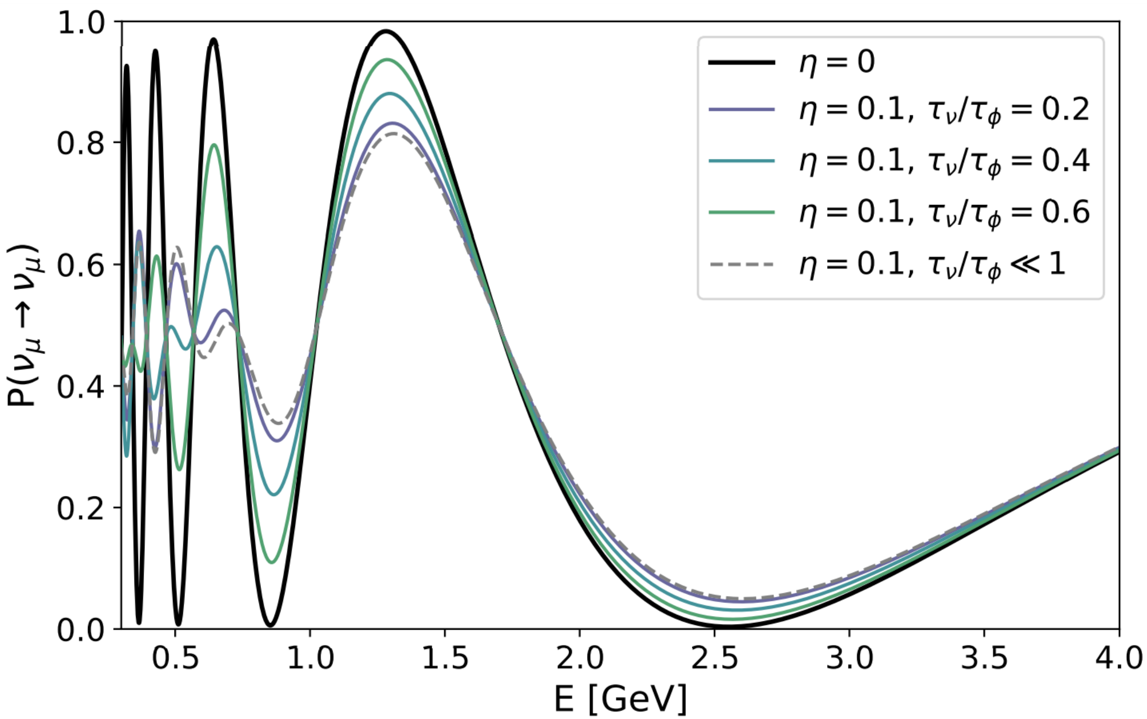
For $\Delta m^2_{31}(t)$
Average DiNOs

For different values of η , different smearing of the oscillation probability.



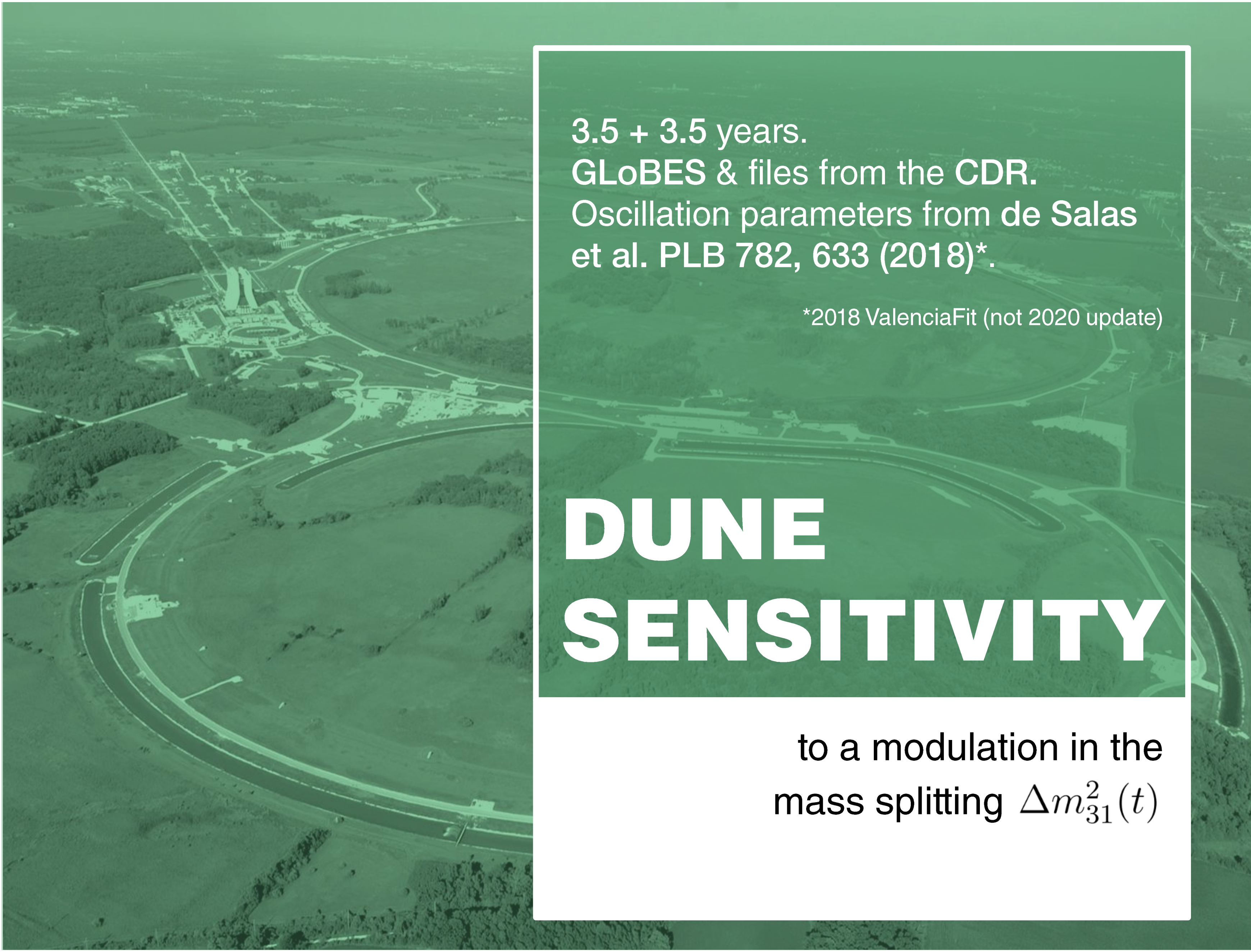
For $\Delta m^2_{31}(t)$
Dynamical DiNOs

- As the value of τ_ν/τ_Φ gets larger, the effect shrinks.
- As the value of τ_ν/τ_Φ gets smaller, one recovers the averaged regime.



DUNE SENSITIVITY

to a modulation in the mass splitting $\Delta m^2_{31}(t)$



3.5 + 3.5 years.
GLoBES & files from the **CDR.**
Oscillation parameters from **de Salas et al. PLB 782, 633 (2018)*.**

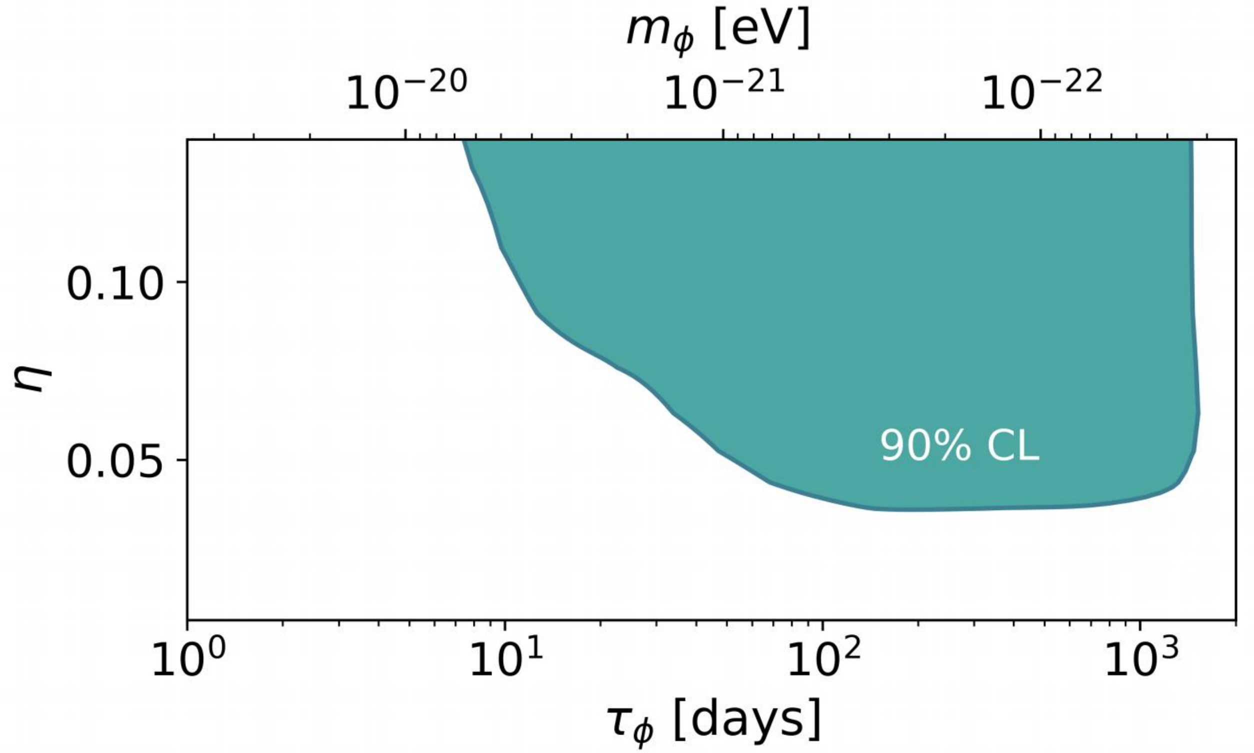
*2018 ValenciaFit (not 2020 update)

DUNE SENSITIVITY

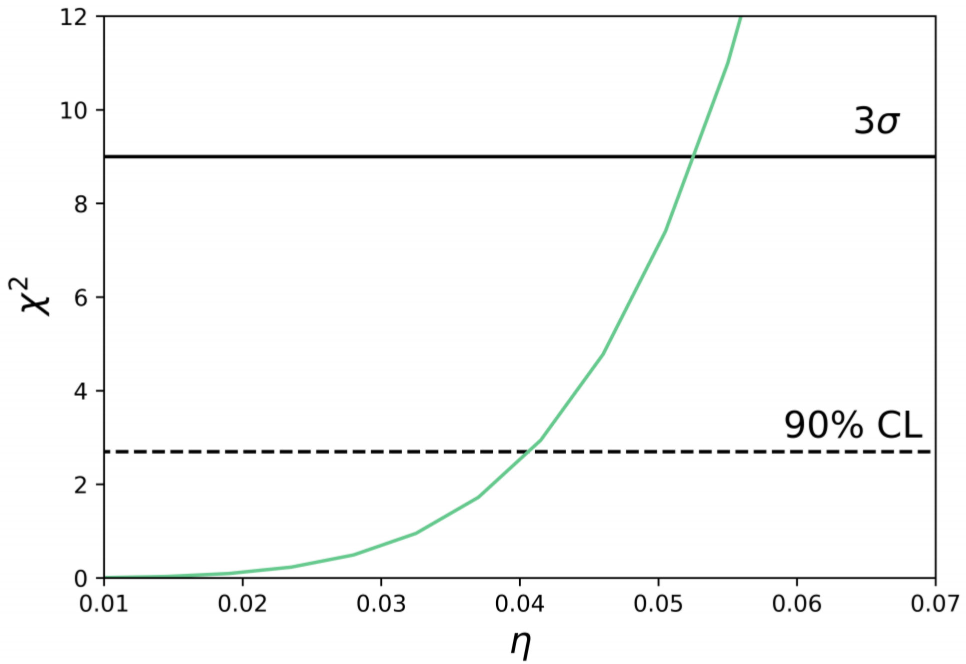
to a modulation in the mass splitting $\Delta m^2_{31}(t)$

Lomb Scargle periodogram and **signal time modulation**

Lomb Scargle (LS) analysis using different binning in time allows to cover a wide range of modulation periods (from ~ 3 years to ~ week).



Average DiNOs

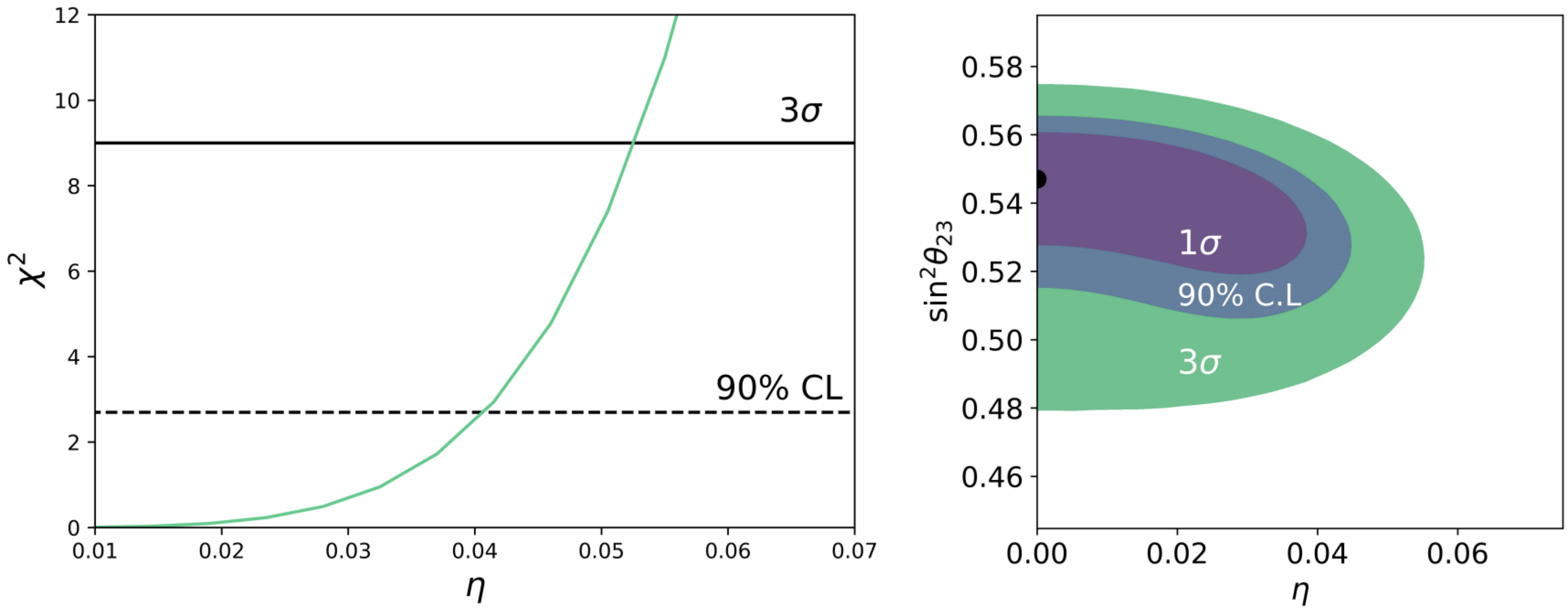


$$\langle P_{\alpha\beta} \rangle = \frac{1}{\tau_\phi} \int_0^{\tau_\phi} dt\, P_{\alpha\beta}(t)$$

DUNE could find **evidence** for such distortions (3σ for 2η~0.1).

Only a **small degeneracy** with θ_{23} is found.

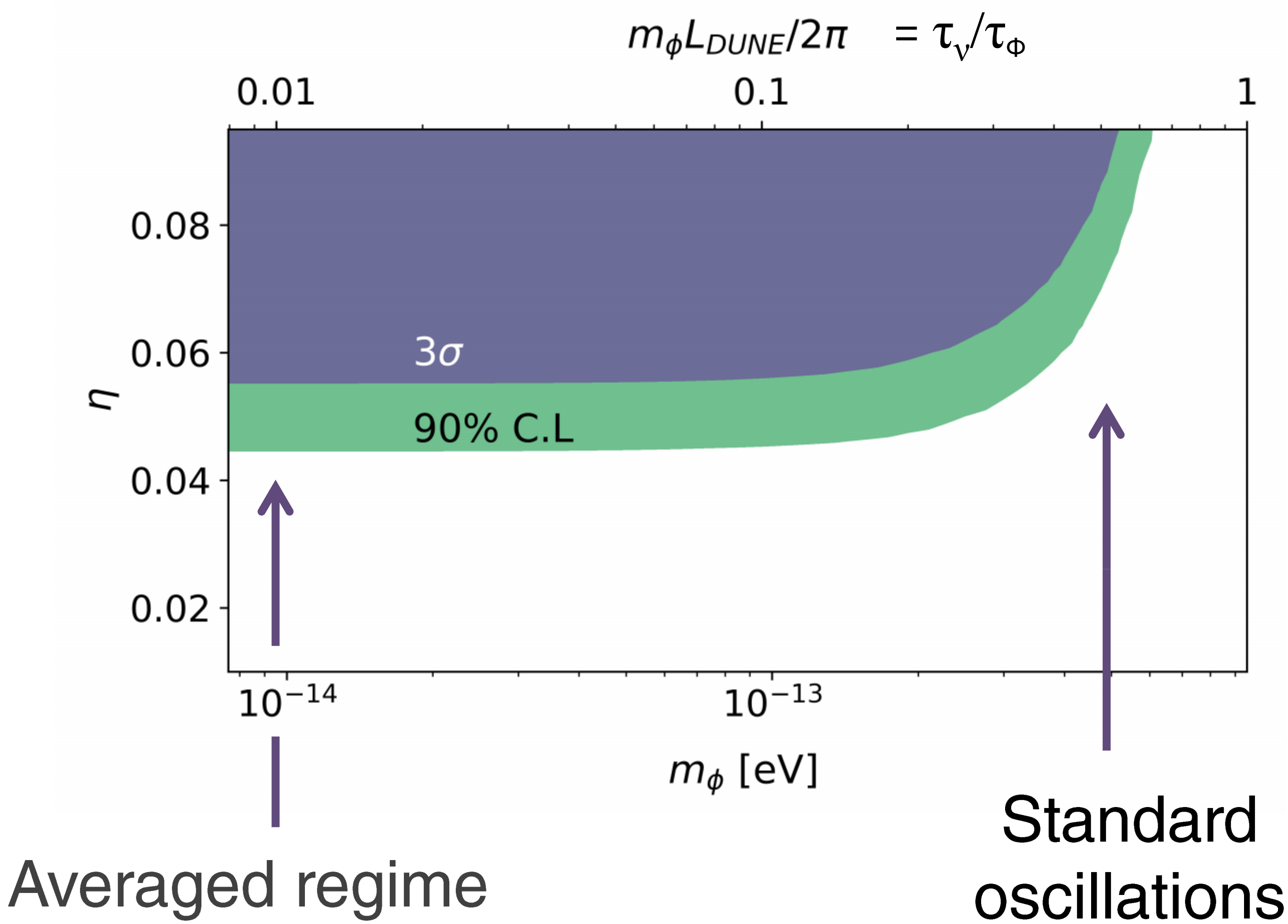
Average DiNOs



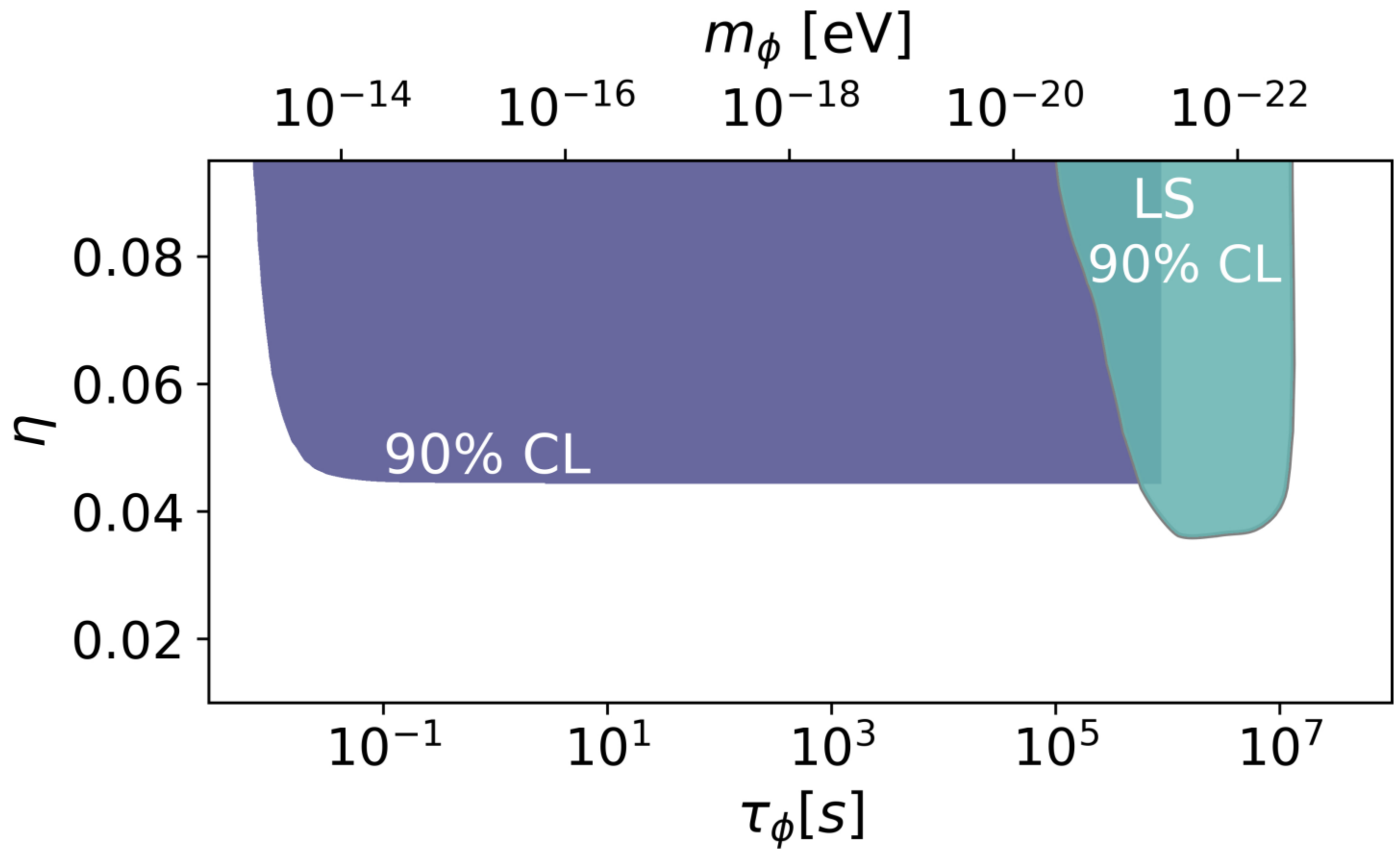
DUNE could **evidence** for such distortions (3σ for $2\eta \sim 0.1$).

Only a **small degeneracy** with θ_{23} is found.

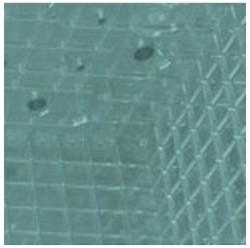
Dynamical DiNOs



Combining the **Lomb Scargle approach** (LS) with searches for **Distorted Neutrino Oscillations** allows to cover almost **ten orders of magnitude in masses** and a large range of modulation amplitudes.



Take-home message**:**



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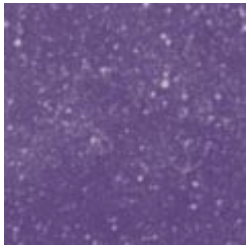

Thank you.