

Probing the Local Dark Matter Halo with Neutrino Oscillations

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Motivation

- Dark matter exists.

Ultra-light scalar or vector bosons are well-motivated dark matter candidates.

These include QCD axion and dark photon.

Particle Data Group, Prog. Theor. Exp. Phys. 2022, 083C01 (2022)

They can form a coherently oscillating background.

astro-ph/0003365, 1105.2812, 1610.08297, 1907.06243

Interaction of this background with Standard Model fields leads, e.g., to the variation of fundamental constants of Nature.

New possibilities for dark matter searches, e.g., in atomic clock experiments.

1710.01833

- The particles can form dense compact objects, with $\rho_{\text{local}} \gg \rho_{\text{average}}$.

These objects are bound by self-gravity; also self-interaction may play an important role.

hep-ph/9303313, 1406.6586, 1610.08297, 1804.05857, 1804.09647, 1809.07673, 1809.09241, 1906.01348

Boson / Axion / Proca stars — coherent / solitonic / classical configurations

- They can also be trapped in a background potential of some astrophysical body, such as the Earth or the Sun, and form a “local halo”.

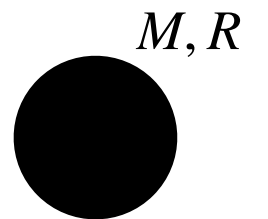
This is intriguing: the presence of such a halo could greatly enhance the sensitivity of terrestrial experiments to new physics.

1902.08212, 1912.04295

Setup

- Assume a local, **nonrelativistic** ($E \ll mc^2$, where E is the bound state energy and m is a dark matter particle mass) halo sustained by the **gravitational** potential of the host body.

Here we do not consider how to form such a halo \Rightarrow the **halo mass** M_{halo} is a free parameter (subject to experimental constraints).



0808.0899

On the other hand, the **halo size** ℓ is fixed by m and the parameters of the host body. We take it to be the solid ball of mass M and radius R .

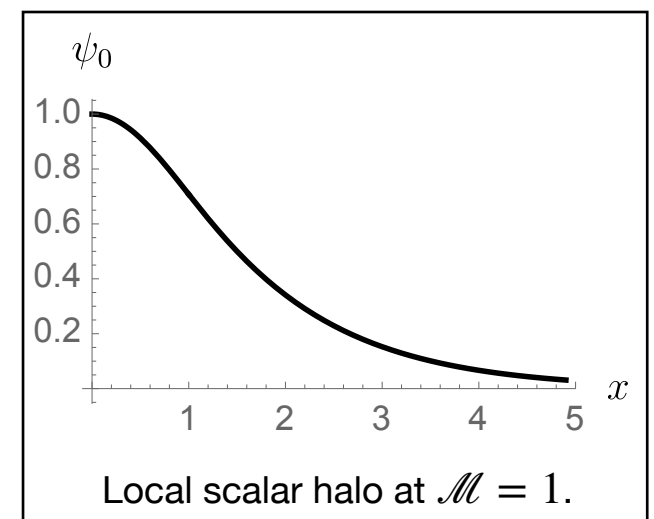
- The problem of finding the **scalar** halo profile reduces to solving the Schroedinger equation:

$$\varphi(r, t) = \sqrt{\frac{2c}{m}} \left(\Psi(r, t) e^{-imc^2 t} + c.c. \right), \quad \Psi(r, t) = \psi(r) e^{-iEt} \quad \text{— nonrel. ansatz}$$

$$x = r/R, \quad \mathcal{M} = Gm^2 MR, \quad \mathcal{E} = EmR^2 \quad \text{— dimensionless units}$$

$$-\frac{1}{x^2} \frac{d}{dx} \left(x^2 \frac{d\psi}{dx} \right) + 2(\mathcal{M}\tilde{\Phi} - \mathcal{E})\psi = 0 \quad \text{— } \tilde{\Phi} \text{ is the (rescaled) grav. potential}$$

The solution can be found analytically. We are interested in the ground state $\psi_0(x)$.



► The only parameter characterising the halo is \mathcal{M} .

- For concreteness, take the Earth as the host body.

$$\ell \sim R_{\oplus} \left(\frac{10^{-9} \text{ eV}}{m} \right)^2 \quad m \ll 10^{-9} \text{ eV}$$

If $\ell > R_{\oplus}$, the halo extends beyond the Earth's surface \Rightarrow can be probed in terrestrial and near-orbit experiments.

$$\ell \sim R_{\oplus} \left(\frac{10^{-9} \text{ eV}}{m} \right)^{1/2} \quad m \gg 10^{-9} \text{ eV}$$

If $\ell < R_{\oplus}$, the halo is in the Earth's interior \Rightarrow much harder to probe.

1902.08212

Neutrino oscillations as a probe of the local halo

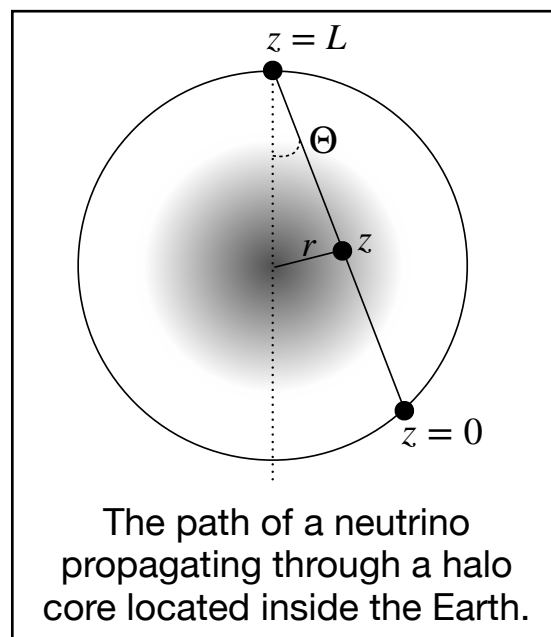
- Assume that the particles comprising the halo couple to neutrinos.
Then one can look for the halo in the neutrino oscillation data.

Observational consequences of possible interactions between ultra light dark matter and neutrinos have been extensively studied in various terrestrial, astrophysical and cosmological setups.

1608.01307, 1705.06740, 1705.09455, 1804.05117, 1803.01773, 1809.01111,
1908.02278, 2007.03590, 2107.10865, 2205.03749, 2212.05073, 2301.04152

What can we add?

- If $\ell \gtrsim R_{\oplus} \Rightarrow$ Enhanced homogeneous oscillating background \Rightarrow Stronger constraints on the couplings
 $m \sim 10^{-10} - 10^{-9}$ eV, “**big halo**”
In reactor / accelerator neutrino experiments
- If $\ell \ll R_{\oplus} \Rightarrow$ Probe the small-size, interior halo inaccessible by other means; resolve its spatial profile
 $m \gg 10^{-9}$, “**small (interior) halo**”
With atmospheric neutrinos flying through the Earth



- This is at the cost of the hypothesis that the halo exists; the constraints are functions of M_{halo} .
- For $m \gtrsim 10^{-10}$ eV, we cannot rely on the non-observation of time-modulation of neutrino parameters.

Dark matter - neutrino interaction

- Adopt the plane-wave treatment of neutrino oscillations.

Neglect effects of decoherence and dispersion.

The evolution equation for the (ultrarelativistic) neutrino wavefunction then takes the form:

$$i \frac{d\nu_a}{dz} = H_{ab} \nu_b$$

$$H = \frac{1}{2E} U_0 \text{diag}(0, \Delta m_{0,21}^2, \dots) U_0^\dagger + \Delta H = \frac{1}{2E} U \text{diag}(0, \Delta m_{21}^2, \dots) U^\dagger$$

vacuum mass-squared differences

z-dependent eigenvalues

vacuum neutrino mixing matrix

diagonalises the full Hamiltonian

- For example, consider the following scalar-neutrino interaction terms:

complex, symmetric

$$\mathcal{L}_{4,\text{int}} = -y h_{ab} \varphi \bar{\psi}_{La} \psi_{Lb}^C + h.c.$$

shifts the neutrino mass

$$\Delta H_4 = \frac{y}{E} \varphi (h^\dagger m_\nu + m_\nu^\dagger h) + \frac{2y^2}{E} \varphi^2 h^\dagger h$$

See, e.g., R. Mohapatra, G. Senjanovic, Z. Phys. C 17, 53 (1983)

Hermitian

$$\mathcal{L}_{5,\text{int}} = -\frac{g_{ab}}{\Lambda_5} \partial_\mu \varphi \bar{\psi}_{La} \gamma^\mu \psi_{Lb}$$

shifts the neutrino momentum

$|\dot{\varphi}| \gg |\nabla \varphi|$

$$\Delta H_5 = \frac{m}{\Lambda_5} g \varphi$$

See, e.g., 2107.14018

$$\varphi(r, t) = f(r) \cos(mt + \delta) \quad - \text{background halo configuration}$$

Big halo

• Adiabatic regime

$$P_{ab}(L) = \left| \sum_i U_{ai}(0) e^{-\frac{i}{2E} \int_0^L dz m_i^2(z)} U_{bi}^*(L) \right|^2, \quad \langle P_{aa} \rangle_\delta = \frac{1}{2\pi} \int_0^{2\pi} d\delta P_{aa} \quad \text{— Survival probability}$$

• Perturbation theory

Introduce the following parameters: $\beta_4 = \frac{y \sum m_\nu}{2E}$, $\beta_5 = \frac{m}{2\Lambda_5}$, $\beta = \beta_4$ or β_5

$$\epsilon \equiv \frac{\beta f_0}{m} \sim \left(\frac{\beta}{10^{-22}} \right) \left(\frac{m}{10^{-10} \text{ eV}} \right) \left(\frac{M_{\text{halo}}}{10^{15} \text{ kg}} \right)^{1/2} \quad \text{— Expansion parameter, depends on the halo mass}$$

$$\eta \equiv \frac{mE}{\Delta m_0^2} = \left(\frac{2.5 \times 10^{-3} \text{ eV}^2}{\Delta m_0^2} \right) \left(\frac{m}{10^{-10} \text{ eV}} \right) \left(\frac{E}{25 \text{ MeV}} \right) \quad \text{— Number of halo oscillations per one neutrino oscillation}$$

$$\text{Then } \langle P_{aa} \rangle = P_{0,aa} + (\epsilon\eta)^2 \langle P_{2,aa} \rangle_\delta$$

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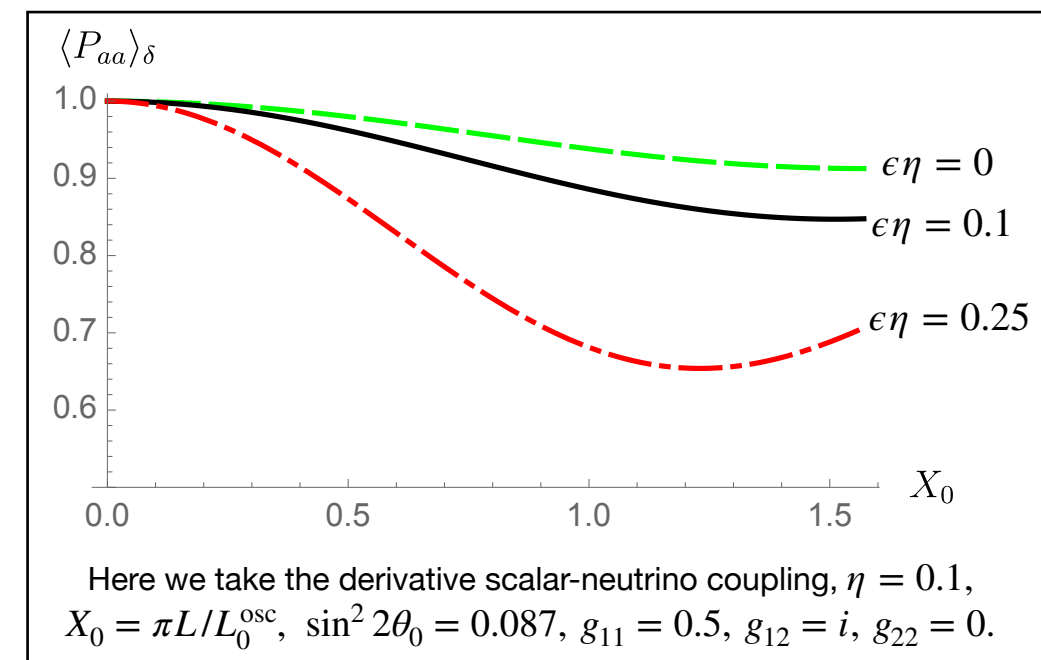
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► If $\eta \ll 1$, this is like the usual MSW effect; P.T. works until $\epsilon \sim \eta^{-1} \gg 1$.

► If $\eta \gg 1$, the neutrino propagates in the wildly oscillating background; P.T. works until $\epsilon \sim \eta^{-1}$?

Not really: **the adiabatic approximation breaks down** at $\epsilon \sim \eta^{-2} \ll \eta^{-1}$.



Big halo

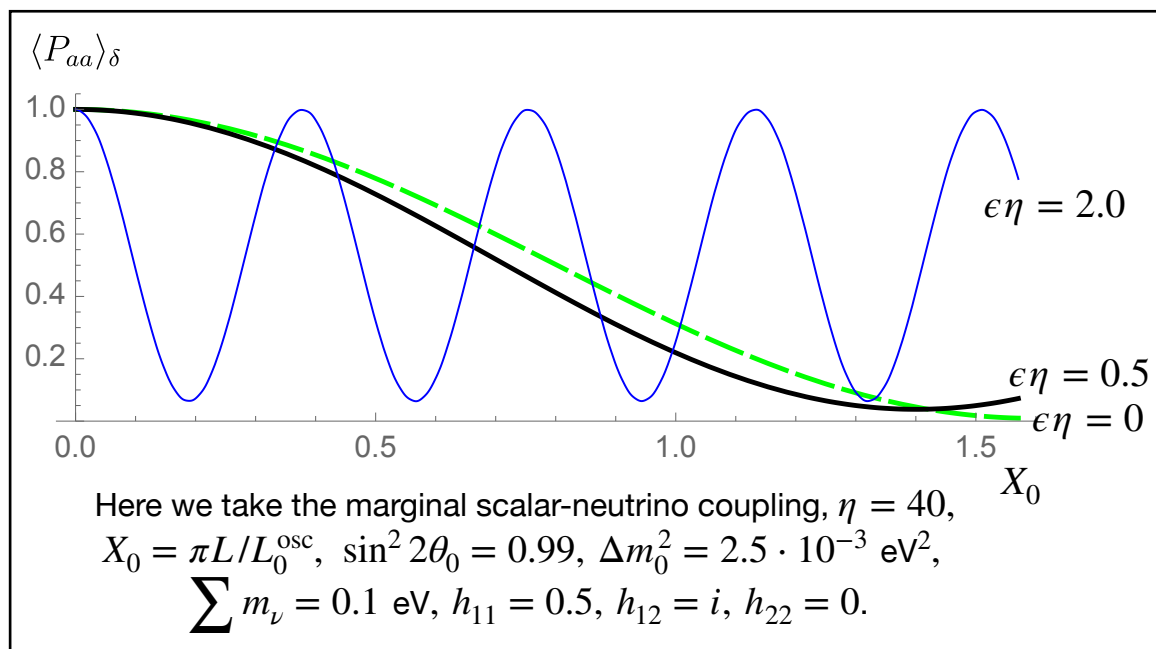
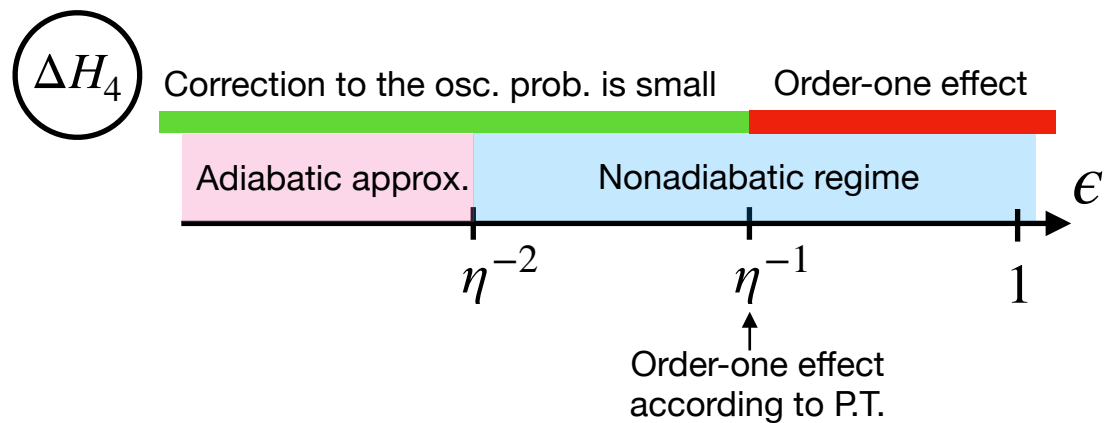
- **Nonadiabatic regime at $\eta \gg 1$** (that is, at $E \gg 25$ MeV for $m = 10^{-10}$ eV)

The situation is different for the different types of scalar-neutrino interaction.

Big halo

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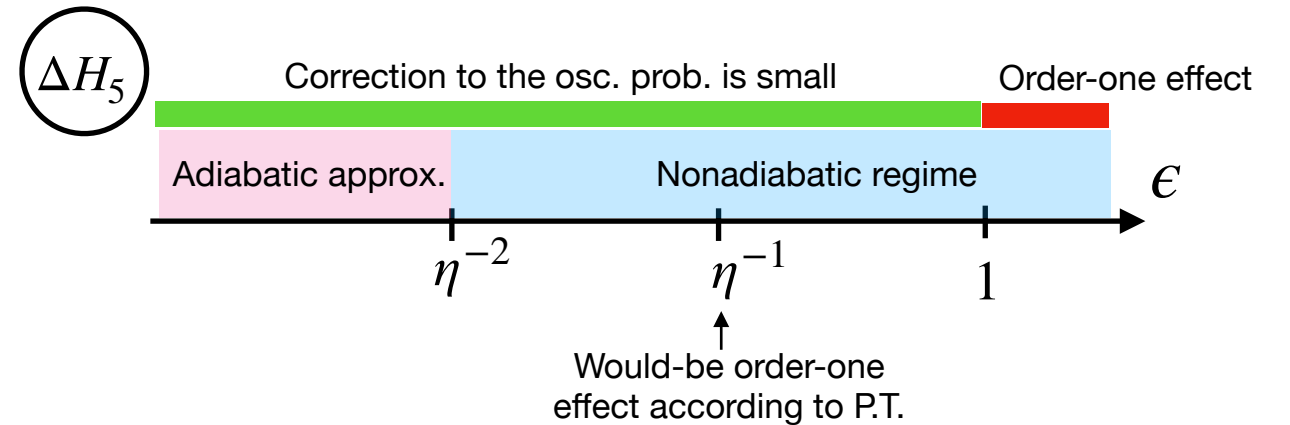
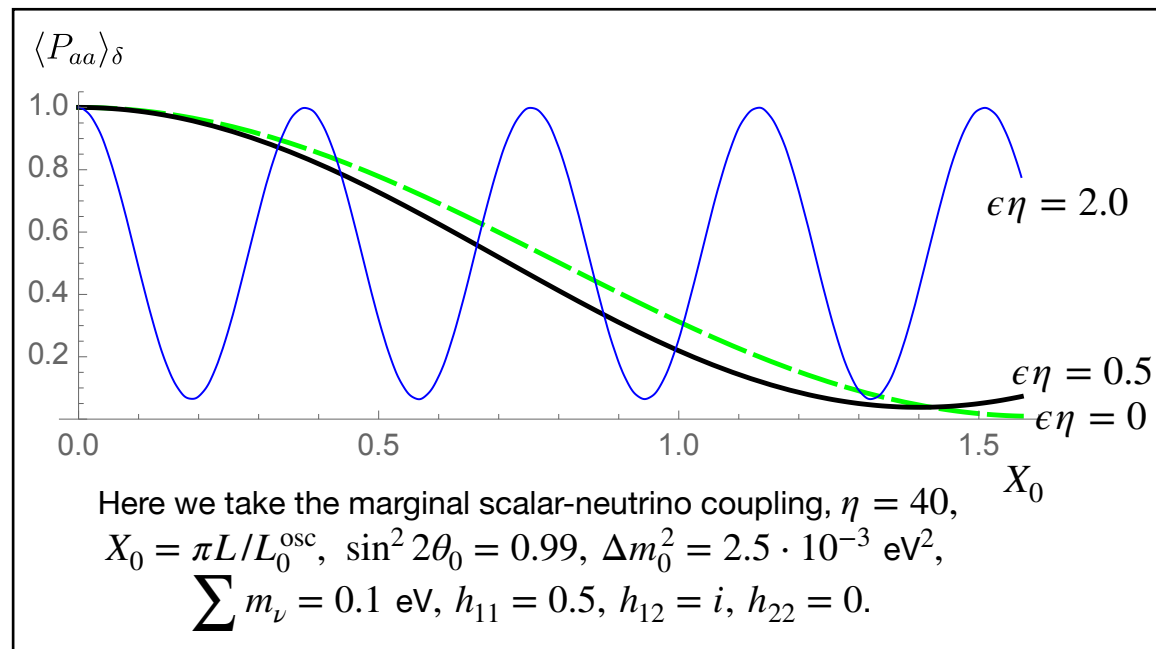
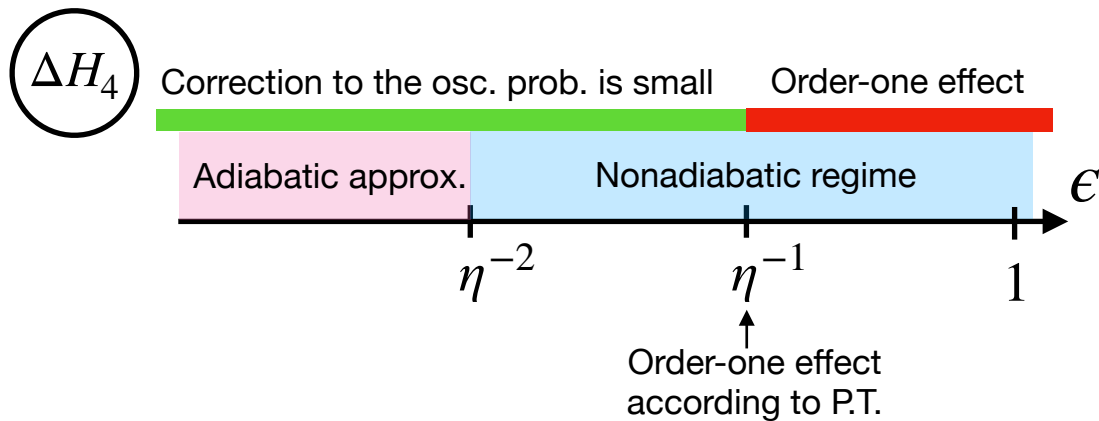
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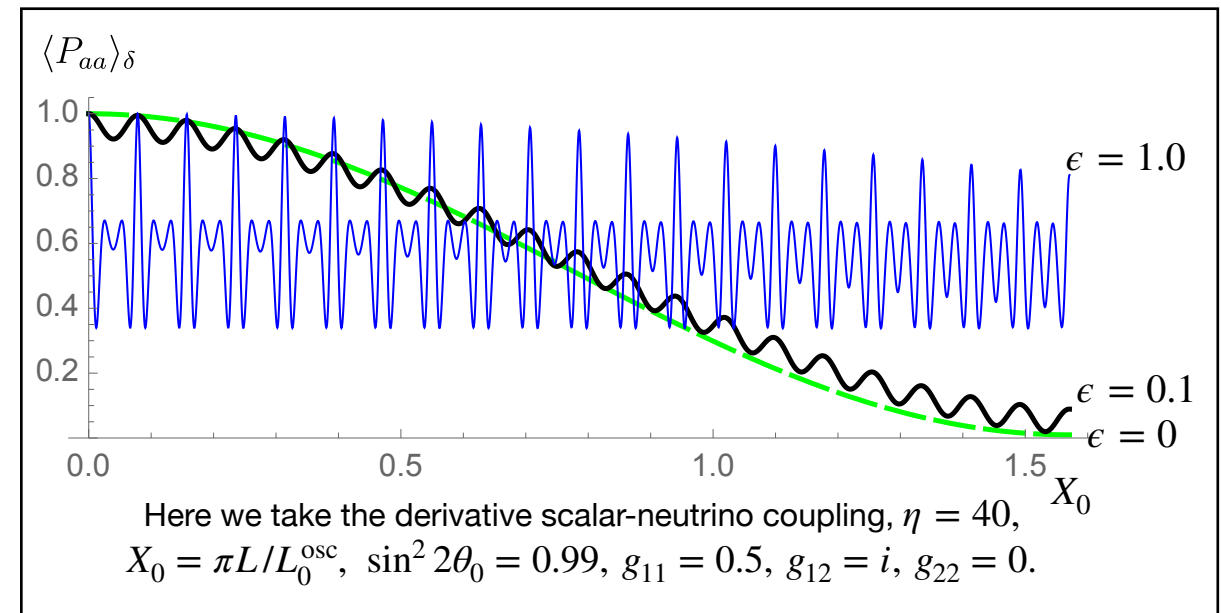
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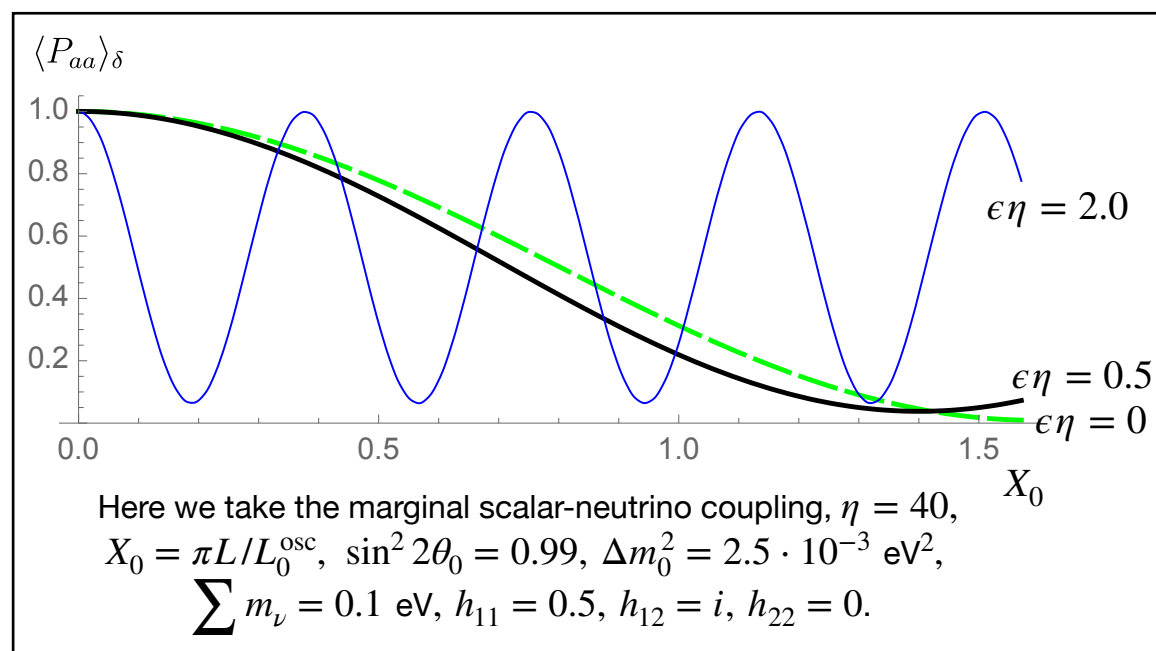
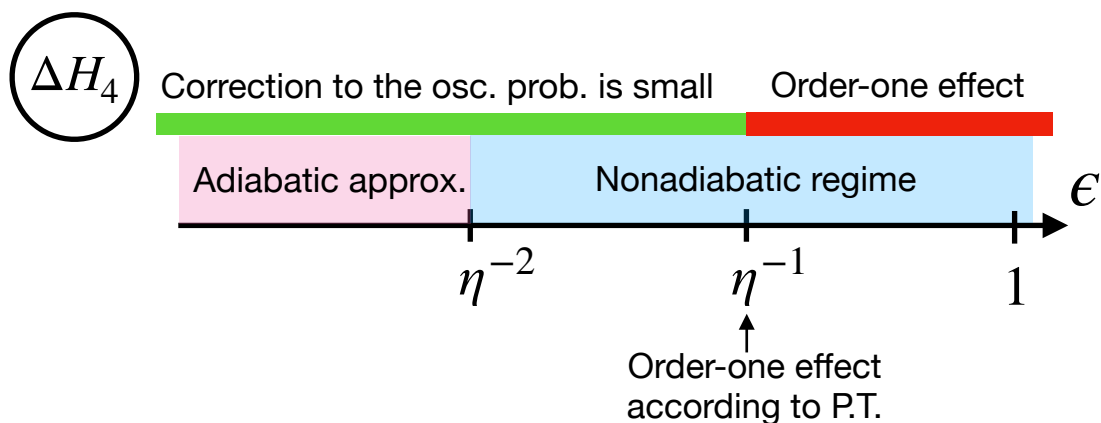
► Resonance effects can **suppress** the deviation from vacuum oscillations.



Big halo

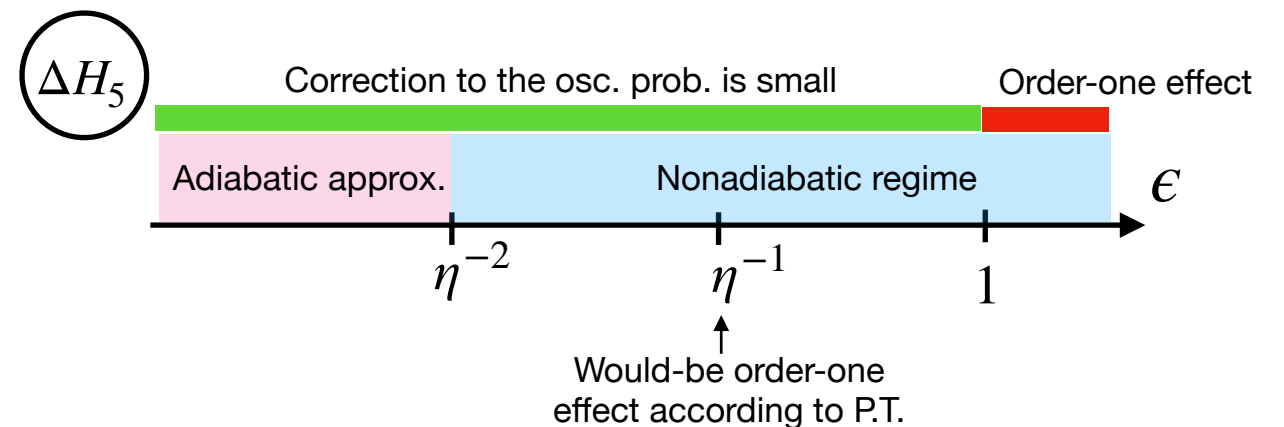
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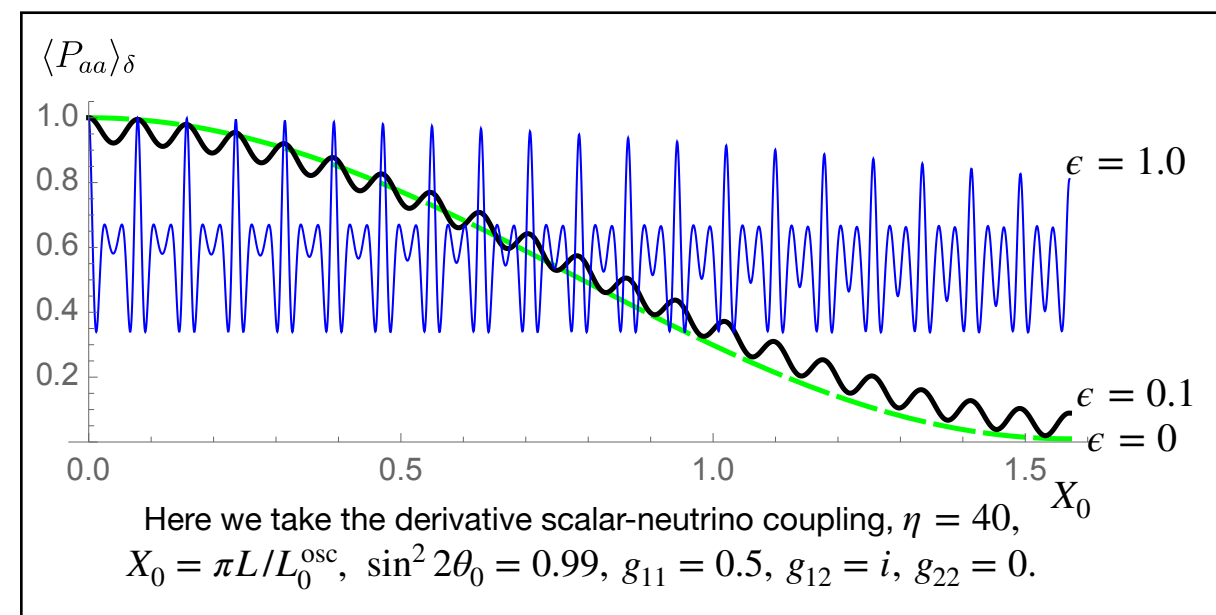


Thus:

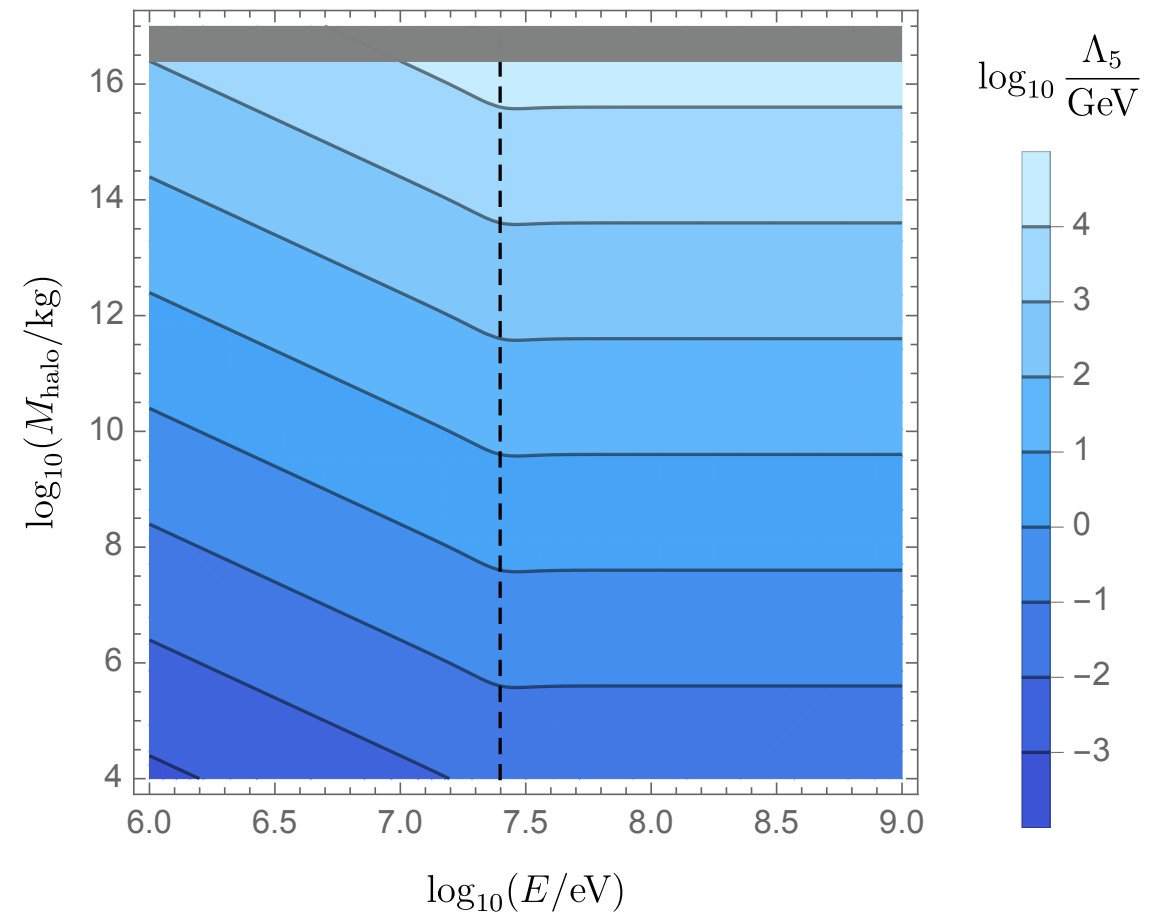
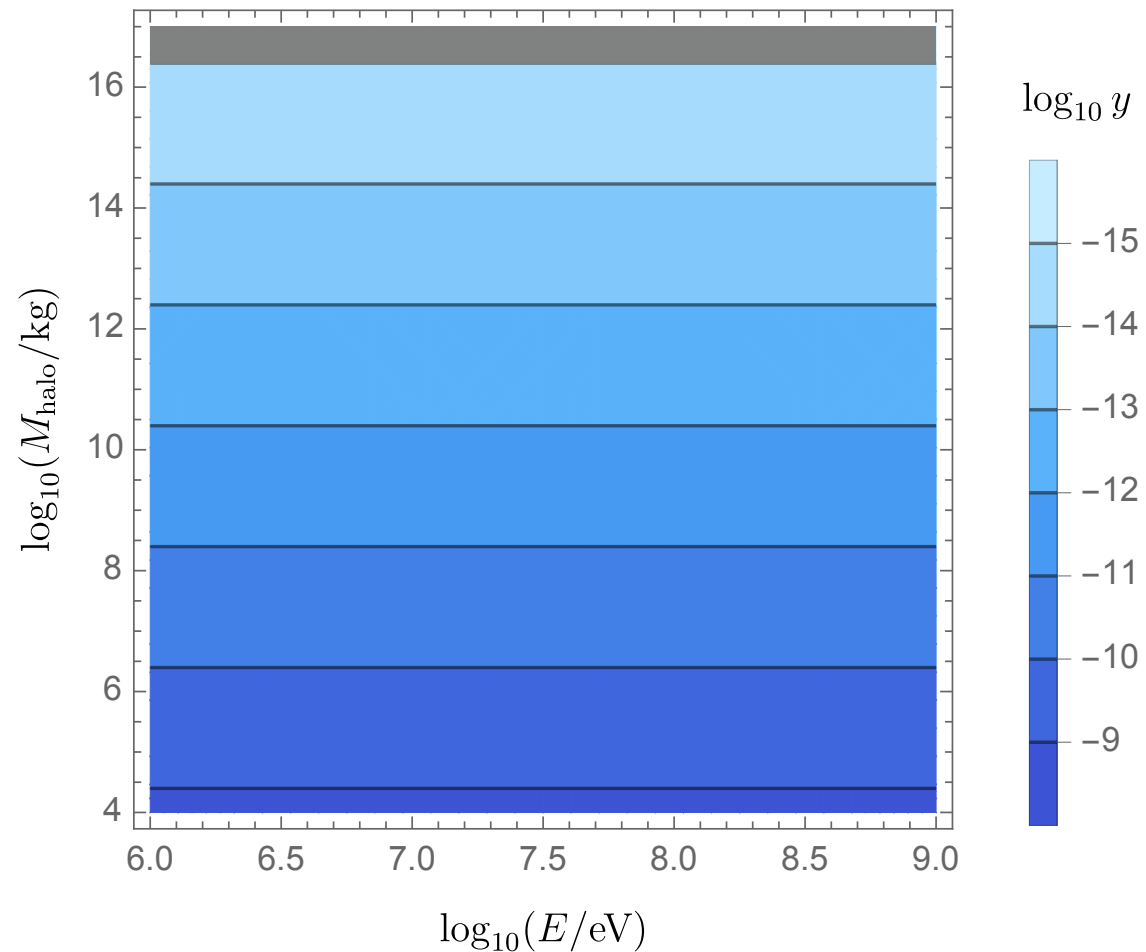
- The correction due to the halo can be small and at the same time be dominated by nonadiabatic effects.
- The correction gives rise to interesting features in the oscillation curve.
- The magnitude of the correction is essentially energy-independent.



► Resonance effects can **suppress** the deviation from vacuum oscillations.



Big halo: results



Values of the parameters at which the relative deviation from the vacuum oscillation probability reaches 0.1.

The grey shaded region depicts the experimentally excluded values of M_{halo} , the dashed line is $\eta = 1$.

We take $m = 10^{-10} \text{ eV}$ and $\Delta m_0^2 = 3.5 \cdot 10^{-3} \text{ eV}^2$.

Probing the interior halo

- The previous analysis gives us the qualitative understanding of what happens in the case of small halo ($m \gtrsim 10^{-9}$ eV).

We have in mind atmospheric neutrinos of $E \gtrsim 1$ GeV traversing the Earth.

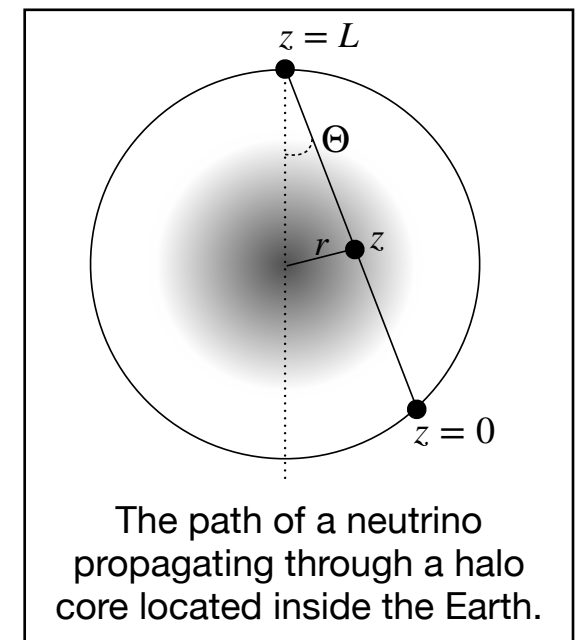
Our parameters become

$$\epsilon \sim \left(\frac{\beta}{10^{-23}} \right) \left(\frac{10^{-9} \text{ eV}}{m} \right)^{5/4} \left(\frac{M_{\text{halo}}}{10^{15} \text{ kg}} \right)^{1/2}$$

$$\eta = 400 \left(\frac{2.5 \times 10^{-3} \text{ eV}^2}{\Delta m_0^2} \right) \left(\frac{m}{10^{-9} \text{ eV}} \right) \left(\frac{E}{1 \text{ GeV}} \right)$$

where now $\beta \sim f(0)$ — the amplitude of the halo at its centre.

Clearly, $\eta \gg 1$.



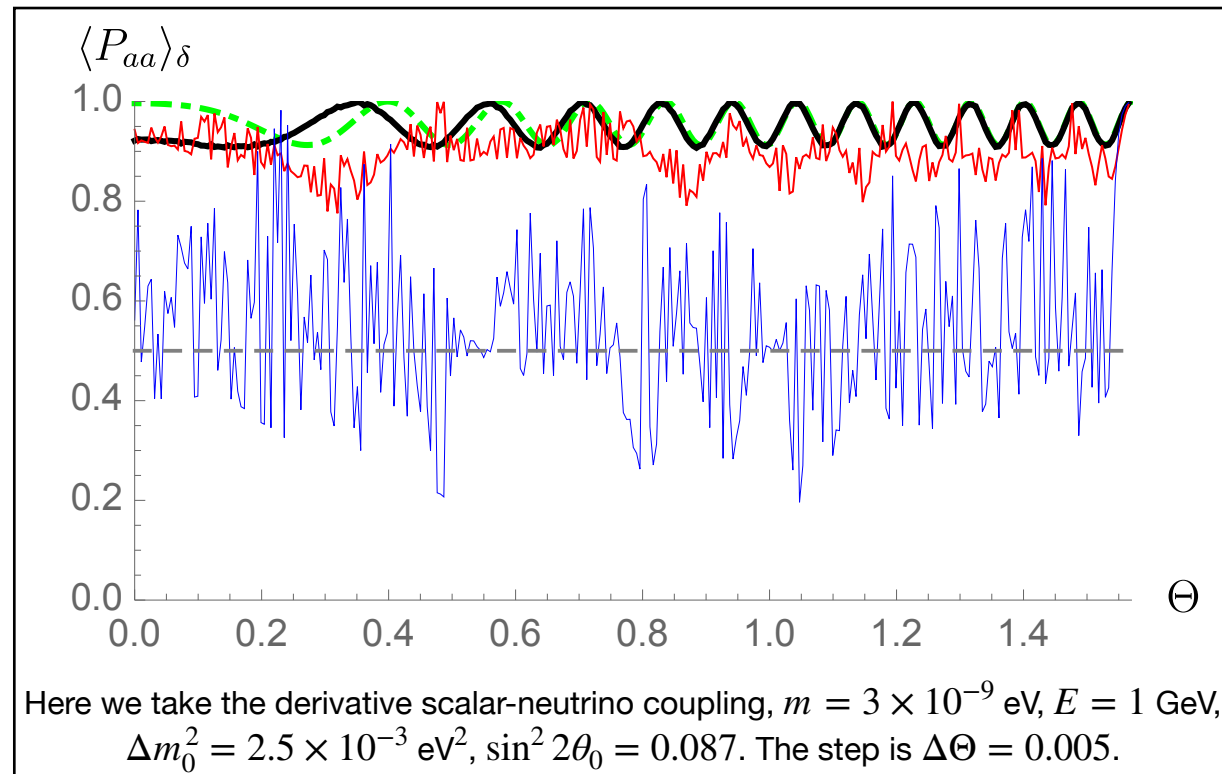
- Perturbation theory is straightforward, but is limited to $\epsilon \lesssim \eta^{-2}$.

⇒ Visible distortions in neutrino oscillations are from the nonadiabatic effects.

Probing the interior halo

- One computes numerically the neutrino wavefunction as it travels through the halo.

Here is the typical result for the survival probability after traversing the Earth (neglecting the MSW effect):

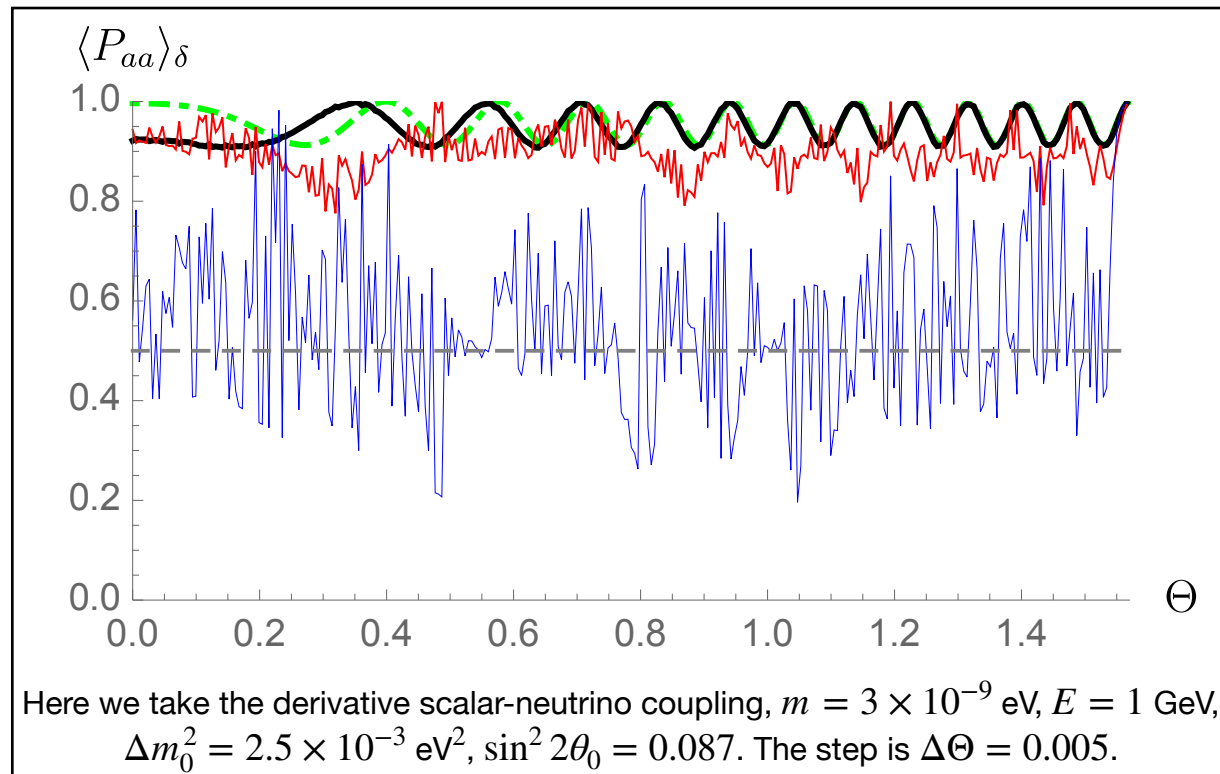


- vacuum oscillations
- $\epsilon = 0.1$ — the effect is only visible at small Θ , due to the fact that $\ell/L_0^{\text{osc}} \sim 10$ at this value of m .
- $\epsilon = 0.5$ — the effect is visible at all Θ .
- $\epsilon = 2.0$ — the survival probability tends to 1/2 (grey dashed line).

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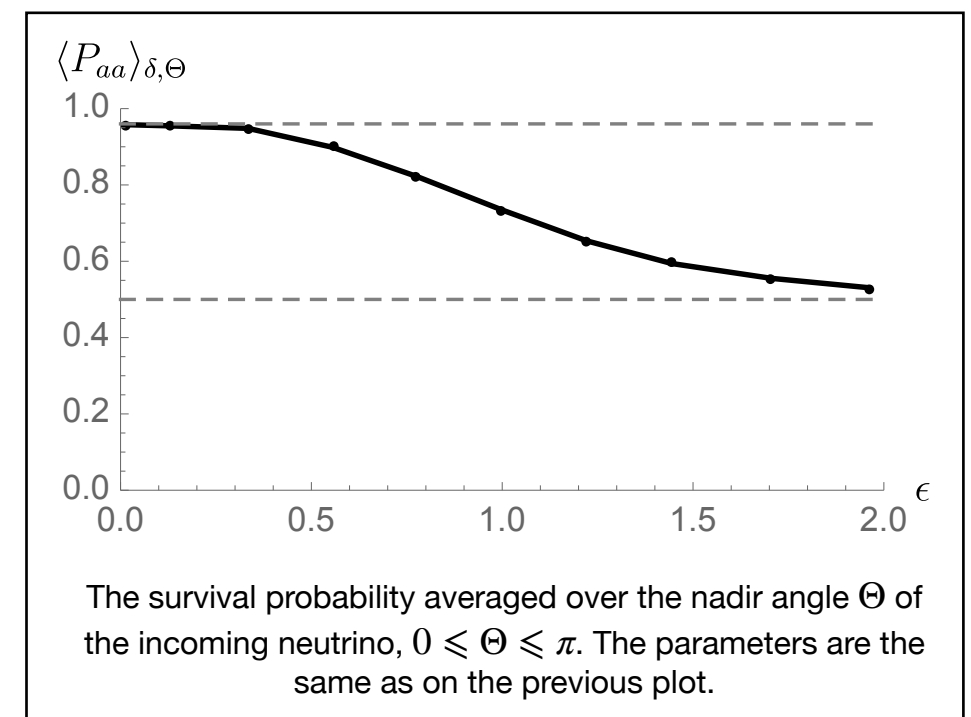
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- $\epsilon = 2.0$ — the survival probability tends to 1/2 (grey dashed line).

- What happens at $m \gg 10^{-9}$ eV corresponding to $\ell \ll R_\oplus$?

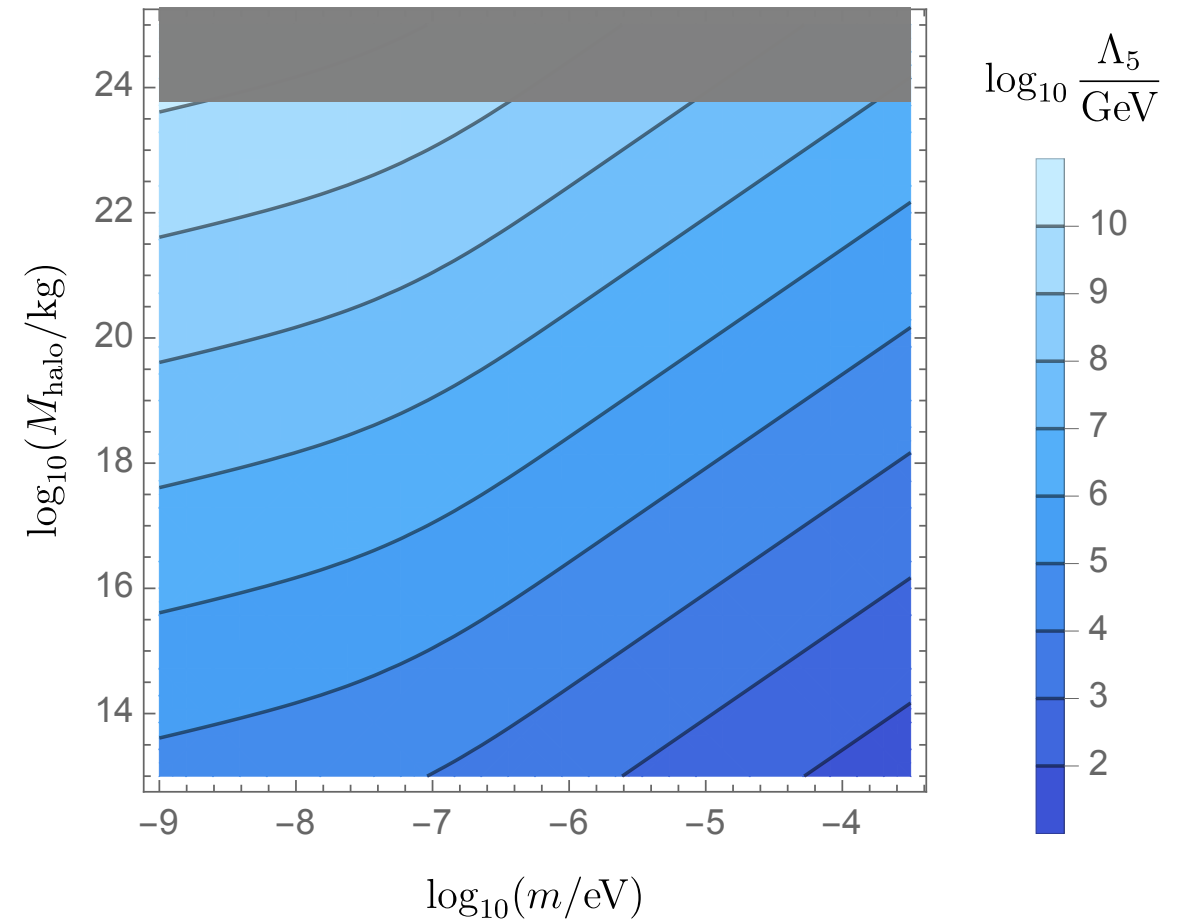
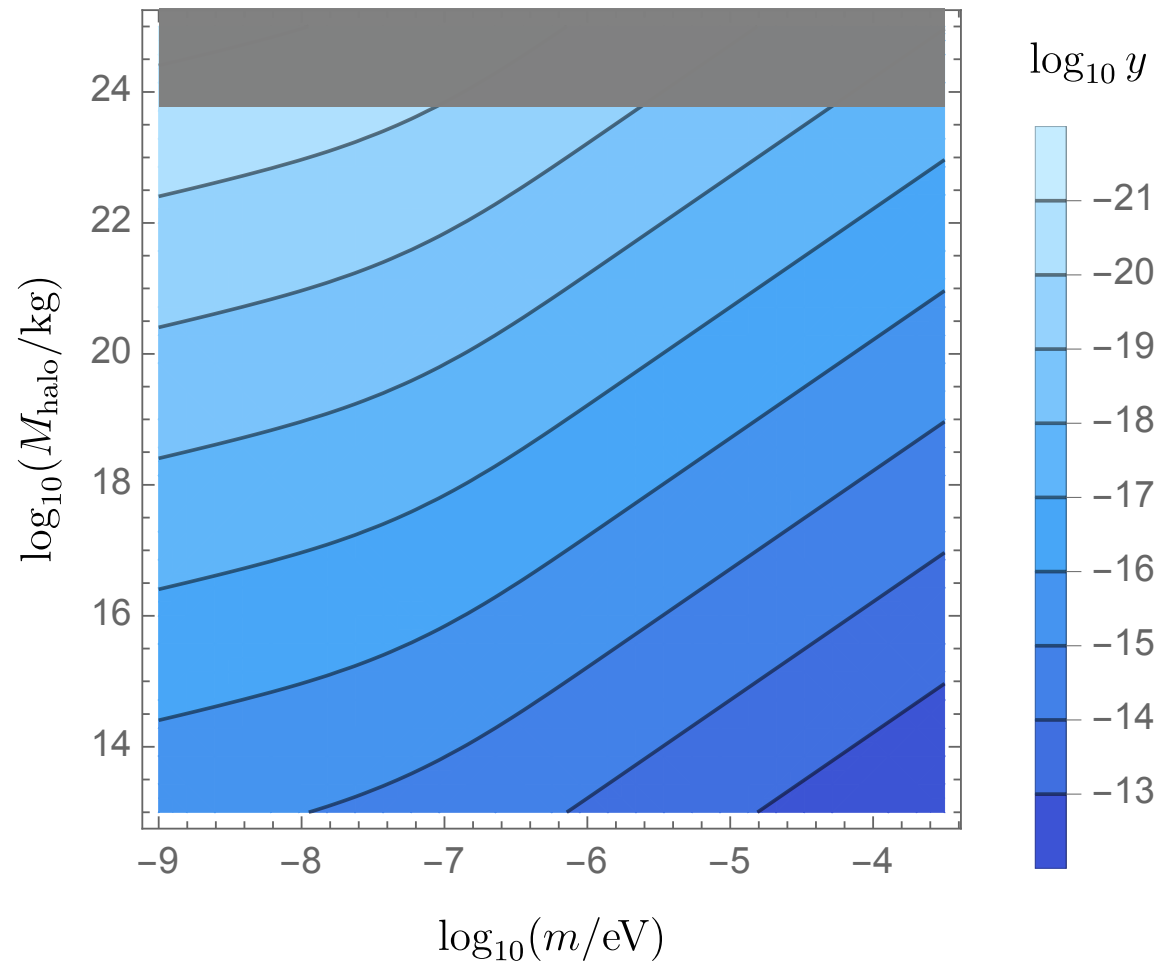
The sensitivity goes down due to the limited angular resolution Θ_{res} of a detector. Formally, one should replace:

$$\epsilon \mapsto \epsilon_{\text{eff}} = \Theta_{\text{res}}^{-1} \int_0^{\Theta_{\text{res}}} d\Theta \epsilon(\Theta), \quad \epsilon(\Theta) = \frac{\beta}{m} f(R_\oplus \sin \Theta)$$

But the effect is still there.



Probing the interior halo: results



Values of the parameters at which the relative deviation from the vacuum oscillation probability reaches 0.1, for $m \gtrsim 10^{-9}$ eV. The grey shaded region depicts the values of $M_{\text{halo}} > 0.1 M_{\oplus}$. We take $\Delta m_0^2 = 3.5 \cdot 10^{-3} \text{ eV}^2$, $E = 1 \text{ GeV}$, and $\Theta_{\text{res}} = 30^\circ$.

Discussion

- It is intriguing that a local dark matter halo could exist surrounding the Earth.

Possible interactions with neutrinos provide a novel way to search for the dark matter particle in neutrino oscillation experiments.
- We repeated the analysis for the (radially-polarised) local vector halo coupled to the neutrino current.
- We worked in the approximate 2-flavour scheme. It is interesting to do 3-flavour oscillations.
- It would be interesting to understand better the local halo formation.