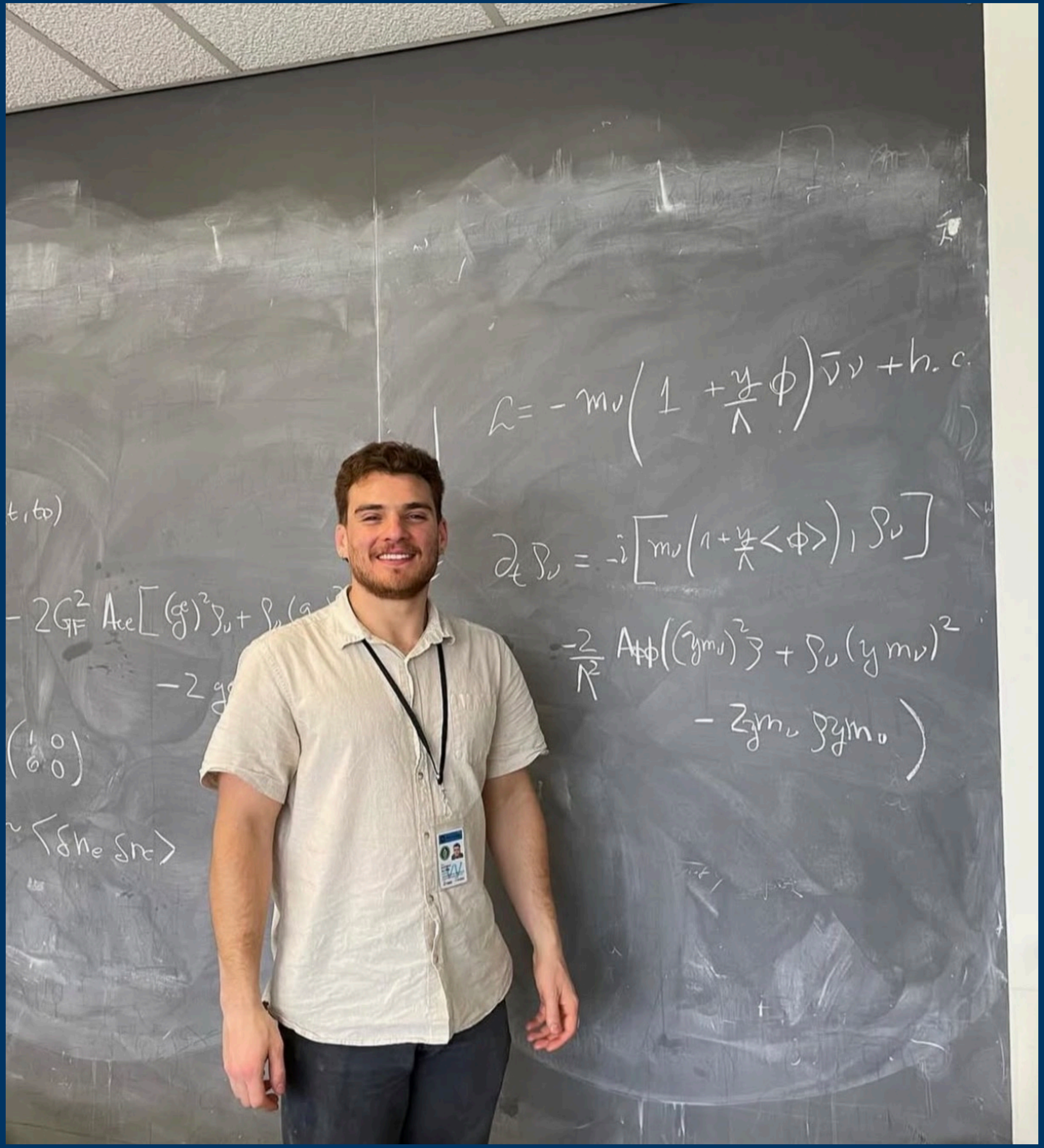
If neutrino masses are clocks, can we hear them tick?

Gustavo F. S. Alves

Fermilab

NORTHWESTERN UNIVERSITY

Back to 2023



Ultralight scalars are compelling dark matter candidates

Hui, et al., Phys. Rev. D 95, 043541
Hu, et al., Phys. Rev. Lett. 85, 1158
Ferreira, Astron.Astrophys.Rev. 29 (2021) 1, 7.
Chadha-Day et al., Sci. Adv. 8, sciadv.abj3618
Arvanitaki, Phys. Rev. D 81, 123530
...

Neutrinos interacting with a new scalar

$$-\mathscr{L} \supset g_{\phi,1}\phi\bar{\nu}_1\nu_1 + g_{\phi,2}\phi\bar{\nu}_2\nu_2 + g_{\phi,3}\phi\bar{\nu}_3\nu_3$$

Neutrinos interacting with a new scalar

$$-\mathscr{L} \supset g_{\phi,1}\phi\bar{\nu}_1\nu_1 + g_{\phi,2}\phi\bar{\nu}_2\nu_2 + g_{\phi,3}\phi\bar{\nu}_3\nu_3$$

Neutrino masses get modified

$$m_{\nu_i} = m_{\nu_i}(g_\phi = 0) + g_{\phi,i}\phi$$

We will show that

$$\phi \sim \phi_0 \cos(m_\phi t + \theta) \quad \phi_0 = \frac{\sqrt{2\rho_\phi}}{m_\phi}$$

Neutrino masses become time dependent

$$m_{\nu_i}(t) = m_{\nu_i}^0 + g_{\phi,i}\phi_0 \cos(m_\phi t + \theta)$$

Neutrino oscillation frequency is modified

$$\Delta m_{ij}^2(t) \approx \Delta m_{ij}^2(\phi_0 = 0) + 2((g_\phi m)_i - (g_\phi m)_j)\phi_0 \cos(m_\phi t + \theta)$$

Theory Background

Ultralight scalars have interesting properties

$$\frac{N}{V} = \frac{\rho_\phi}{m_\phi}$$

For ultralight scalar dark matter

$$[a, a^\dagger] = 1 \rightarrow aa^\dagger = \underbrace{a^\dagger a}_{N} + 1 \approx N$$

Ultralight scalars have interesting properties

$$\frac{N}{V} = \frac{\rho_\phi}{m_\phi}$$

For ultralight scalar dark matter

$$[a, a^\dagger] = 1 \rightarrow aa^\dagger = \underbrace{a^\dagger a}_{N} + 1 \approx N$$

It's convenient to describe it as a coherent state

Quick review of coherent states

A coherent state is a superposition of states of the harmonic oscillator

$$|\alpha\rangle = e^{-|\alpha|^2/2} \sum_{n=0}^{\infty} \frac{\alpha^n}{\sqrt{n!}} |n\rangle$$

R. J. Glauber, Phys. Rev. 131, 2766 (1963).
C. G. Sudarshan, Phys. Rev. Lett. 10, 277 (1963).

Quick review of coherent states

It is an eigenstate of the annihilation operator

$$a\,|\alpha\rangle = e^{-|\alpha|^2/2}\sum_{n=0}^{\infty}\frac{\alpha^n}{\sqrt{n!}}\sqrt{n}\,|n-1\rangle$$

R. J. Glauber, Phys. Rev. 131, 2766 (1963).
C. G. Sudarshan, Phys. Rev. Lett. 10, 277 (1963).

Quick review of coherent states

It is an eigenstate of the annihilation operator

$$a|\alpha\rangle = e^{-|\alpha|^2/2}\sum_{n=0}^{\infty}\frac{\alpha^n}{\sqrt{n!}}\sqrt{n}|n-1\rangle$$

$$= e^{-|\alpha|^2/2}\sum_{n=0}^{\infty}\frac{\alpha^n}{\sqrt{(n-1)!}}\sqrt{n}|n-1\rangle = \alpha|\alpha\rangle$$

R. J. Glauber, Phys. Rev. 131, 2766 (1963).
C. G. Sudarshan, Phys. Rev. Lett. 10, 277 (1963).

Quick review of coherent states

Summary

$$a|\alpha\rangle = \alpha|\alpha\rangle$$

$$\alpha = |\alpha| e^{i\theta}$$

R. J. Glauber, Phys. Rev. 131, 2766 (1963).
C. G. Sudarshan, Phys. Rev. Lett. 10, 277 (1963).

Quick review of coherent states

Summary

$$a|\alpha\rangle = \alpha|\alpha\rangle$$

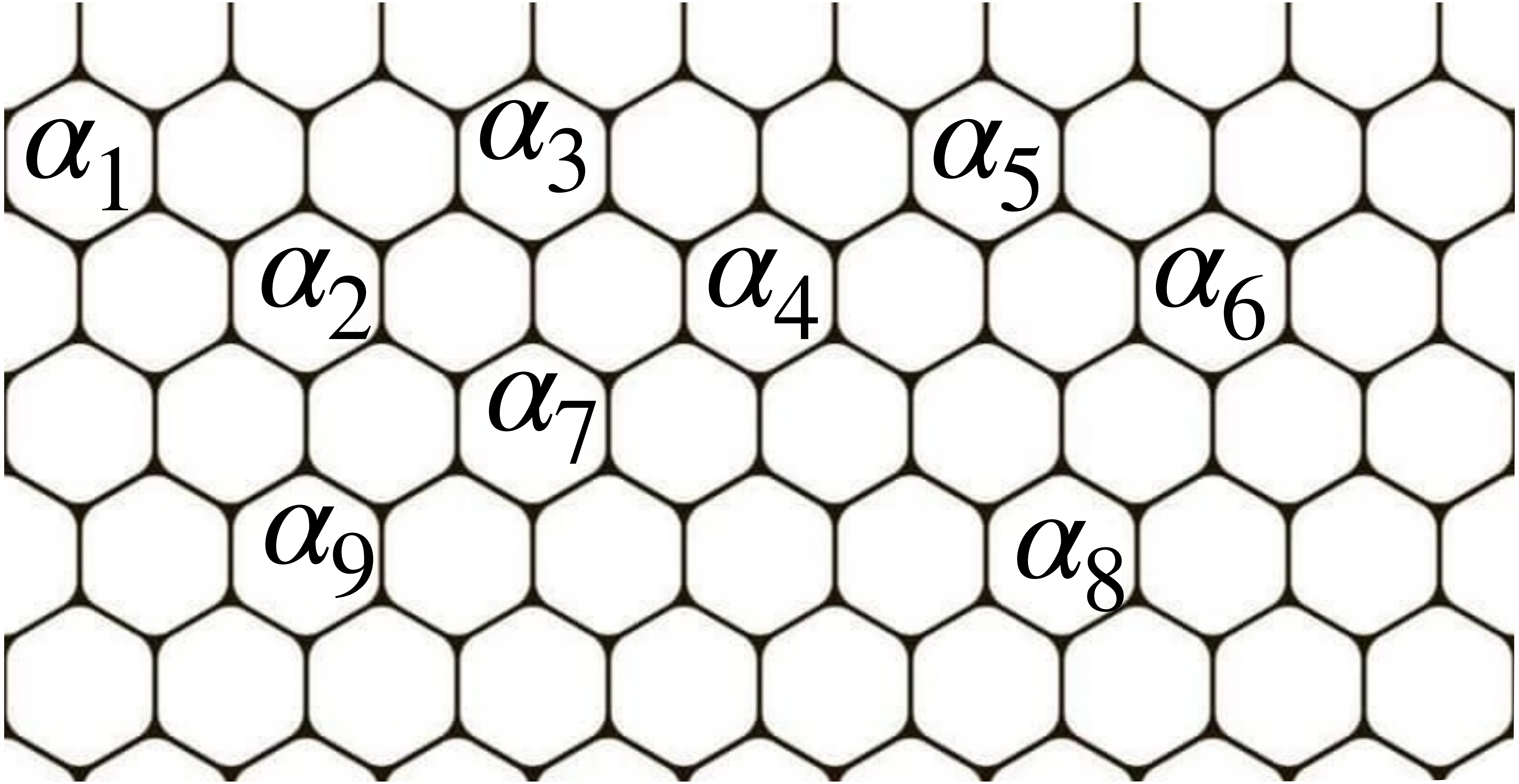
$$\alpha = |\alpha|e^{i\theta}$$

Effectively

$$a \to \alpha \qquad a^\dagger \to \alpha^*$$

R. J. Glauber, Phys. Rev. 131, 2766 (1963).
C. G. Sudarshan, Phys. Rev. Lett. 10, 277 (1963).

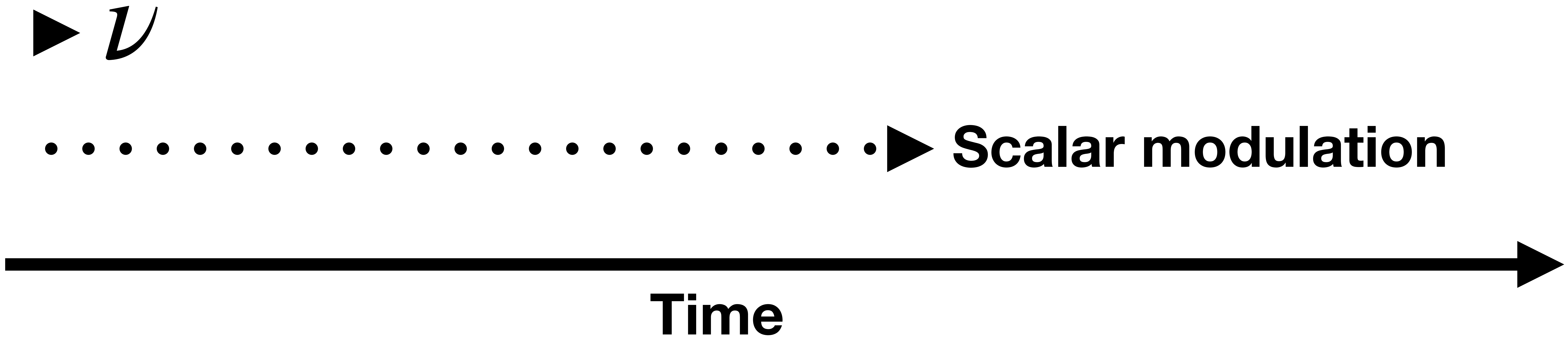
The scalar field can be seen as



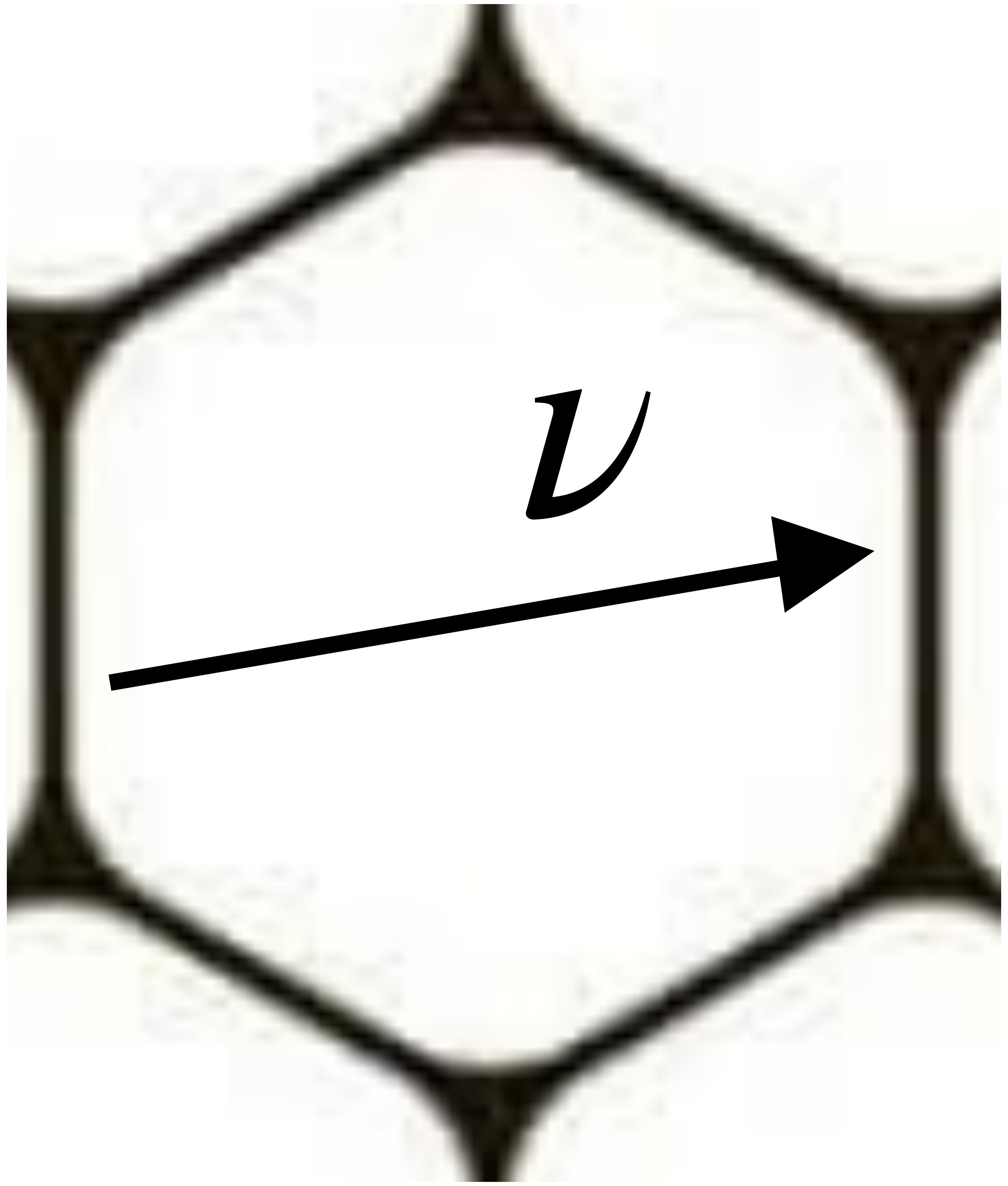
Time hierarchy

- ν

Time hierarchy



The scales determine the scalar state



Field state

$|\alpha\rangle$

The scales determine the scalar state

$$\phi(x,t) = \sum_k \frac{1}{\sqrt{2VE_k}}(a_k e^{-ikx} + a_k^\dagger e^{ikx})$$

The scales determine the scalar state

$$\phi(x,t) = \sum_k \frac{1}{\sqrt{2VE_k}}(a_k e^{-ikx} + a_k^\dagger e^{ikx})$$

Coherent states

$$\phi(x,t) = \sum_k \frac{1}{\sqrt{2VE_k}}(\alpha_k e^{-ikx} + \alpha_k^\dagger e^{ikx})$$

The scales determine the scalar state

$$\phi(x,t) = \sum_k \frac{1}{\sqrt{2VE_k}}(a_k e^{-ikx} + a_k^\dagger e^{ikx})$$

Coherent states

$$\phi(x,t) = \sum_k \frac{1}{\sqrt{2VE_k}}(\alpha_k e^{-ikx} + \alpha_k^\dagger e^{ikx})$$

Non relativistic

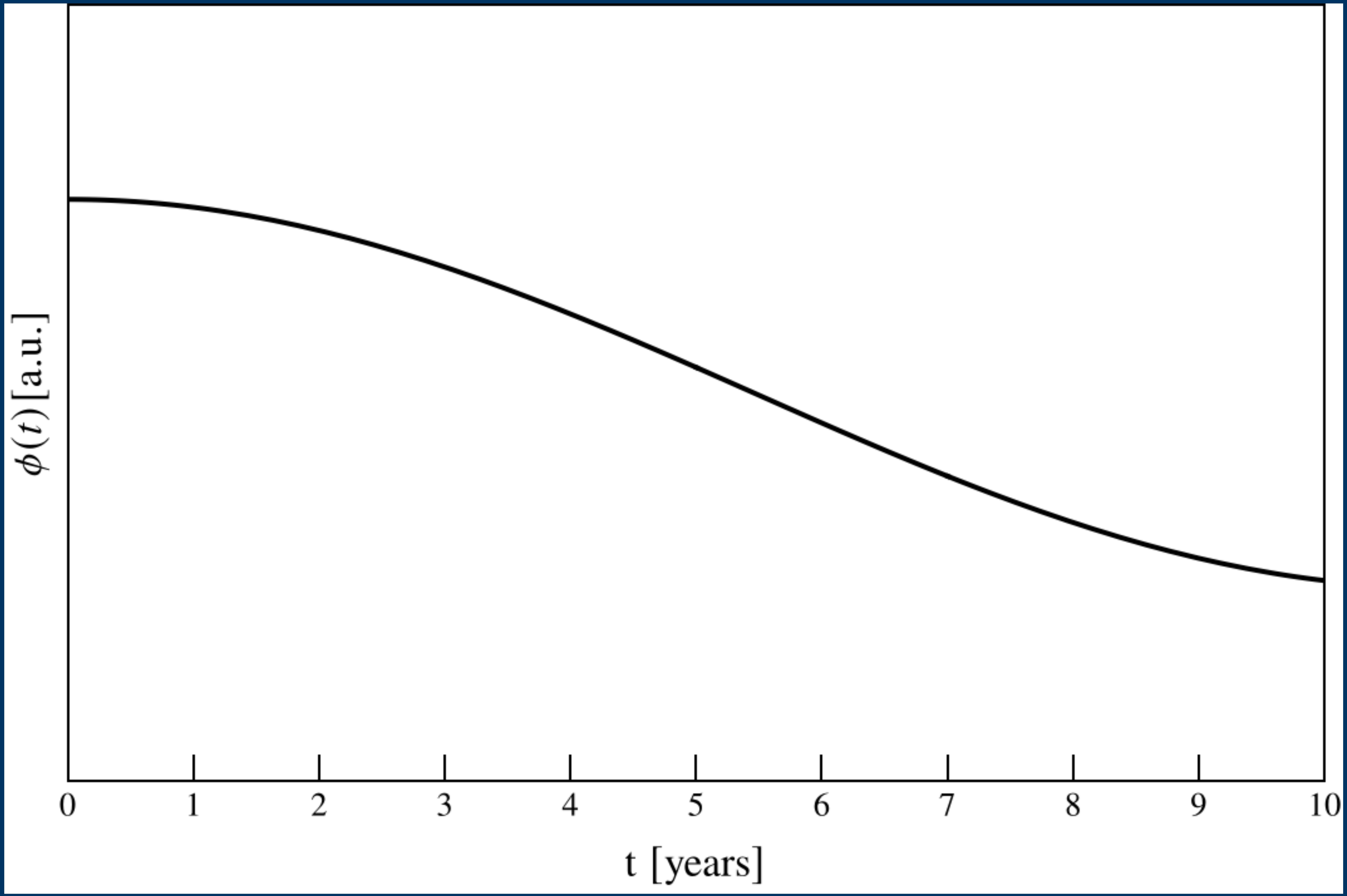
$$\phi(x,t) \approx \frac{\sqrt{2\rho_\phi}}{m_\phi}\cos(m_\phi t + \theta)$$

Neutrino masses become time dependent

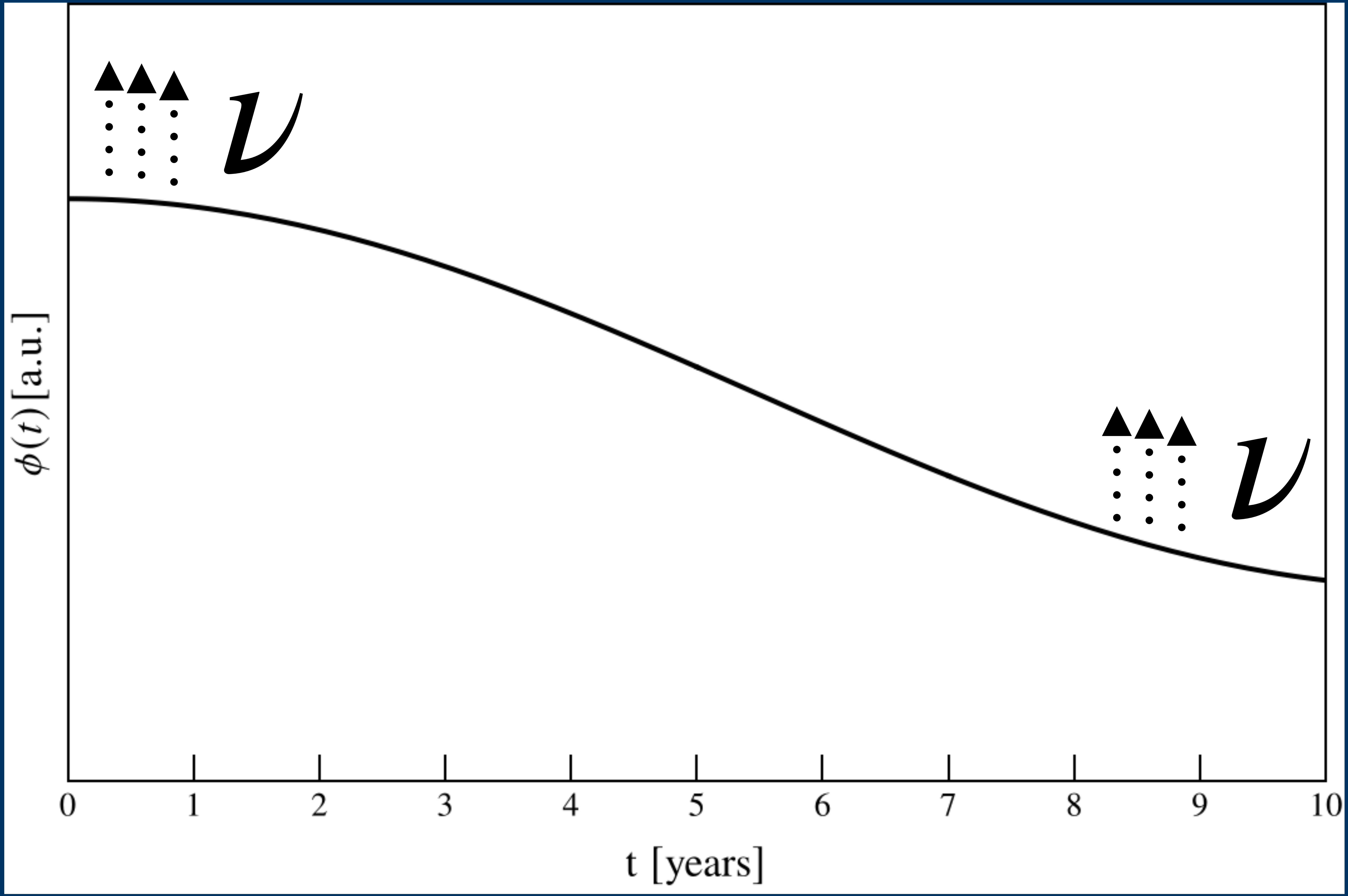
$$m_{\nu_i}(t) = m_{\nu_i}^0 + g_{\phi,i}\phi_0 \cos(m_\phi t + \theta)$$

First scenario

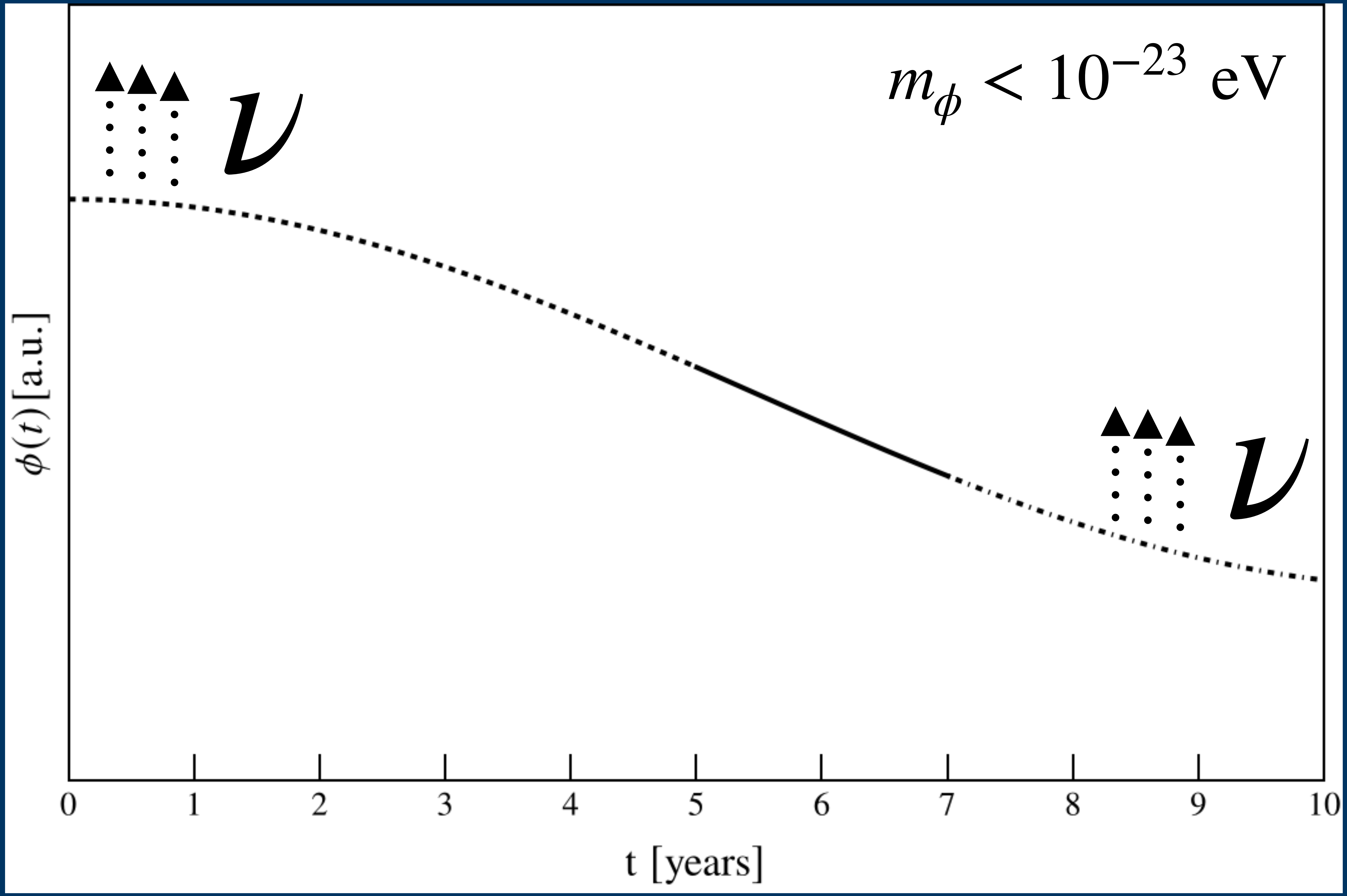
First: Very slow scalar modulations



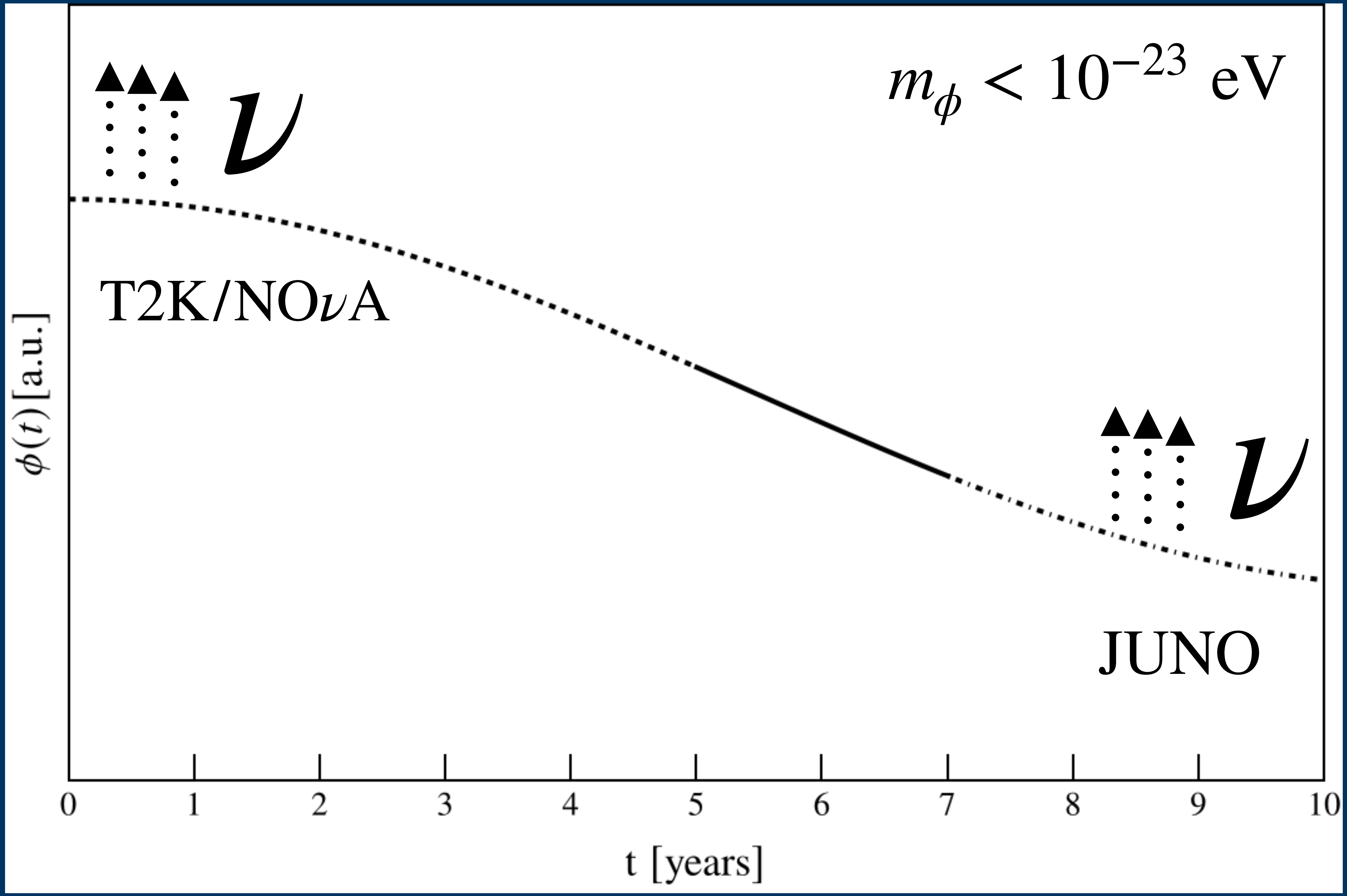
Very slow scalar modulations



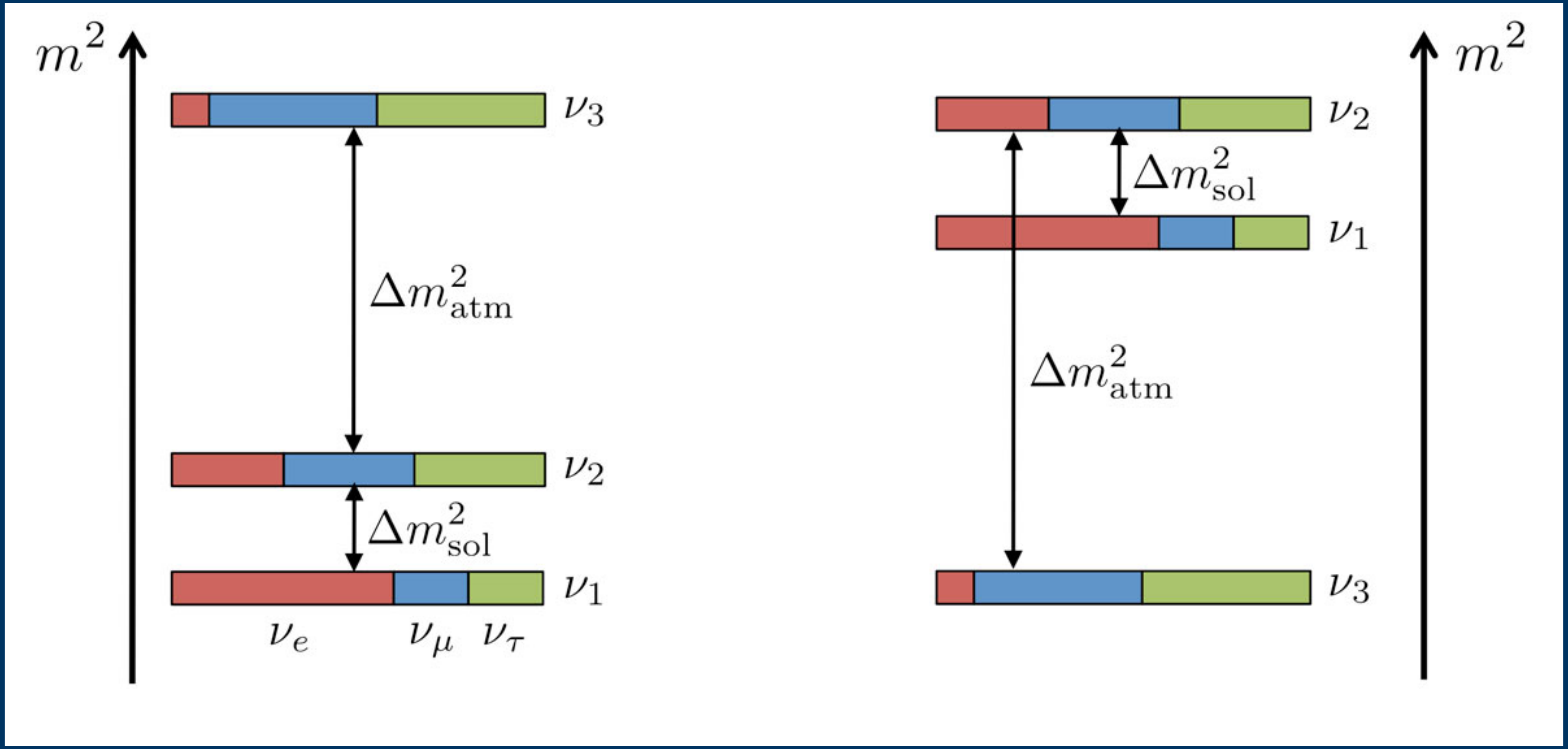
Very slow scalar modulations



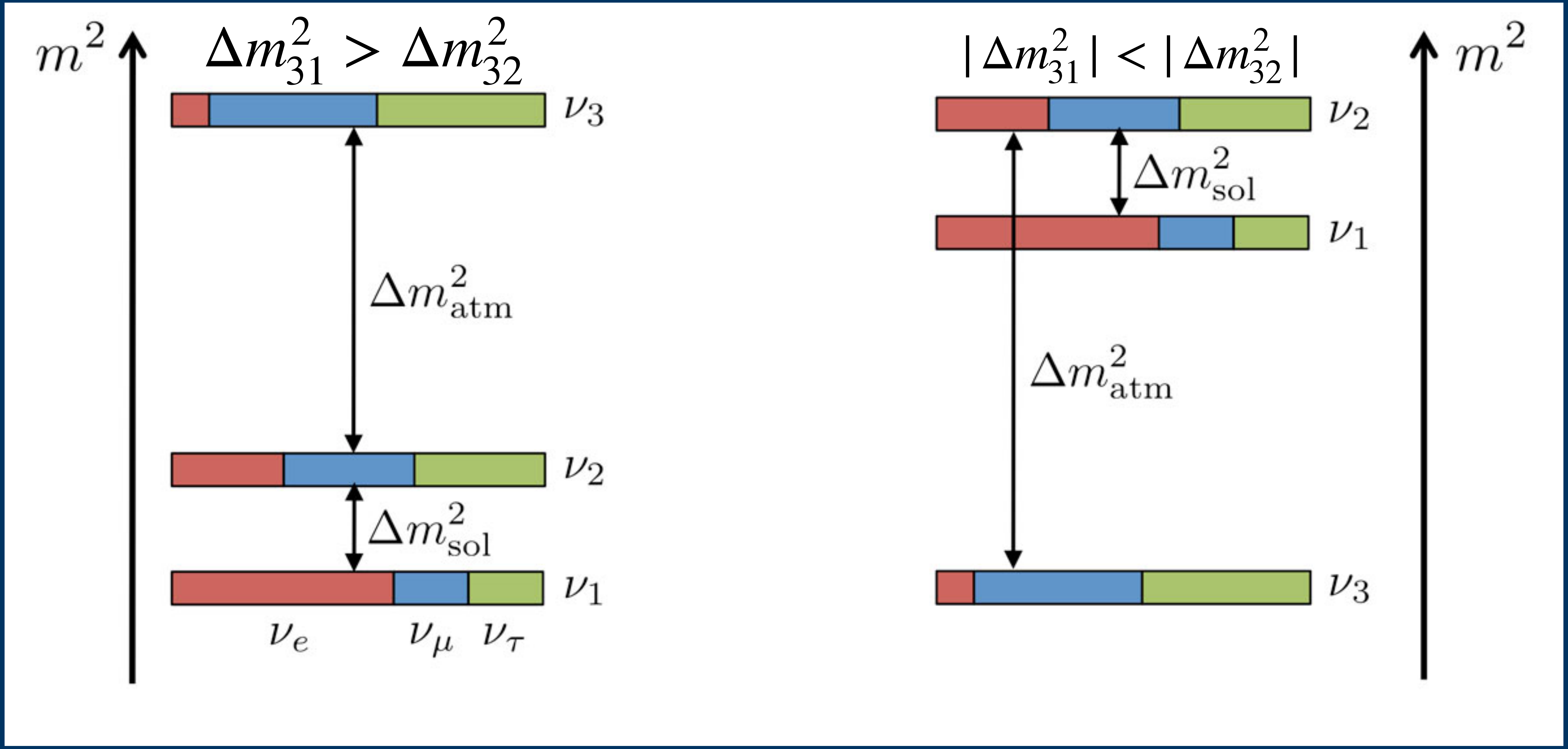
Very slow scalar modulations



What might happen?



What might happen?



One way to determine the ordering

T2K/NOνA
(LBL)

Nunokawa, Parke, Zukanovich Phys. Rev. D 72, 013009

One way to determine the ordering

T2K/NOνA
(LBL)

$$P(\nu_\mu \to \nu_\mu)$$
$$P(\overline{\nu}_\mu \to \overline{\nu}_\mu)$$

Nunokawa, Parke, Zukanovich Phys. Rev. D 72, 013009

One way to determine the ordering

T2K/NOνA
(LBL)

$$P(\nu_\mu \rightarrow \nu_\mu)$$
$$P(\overline{\nu}_\mu \rightarrow \overline{\nu}_\mu)$$

JUNO

Nunokawa, Parke, Zukanovich Phys. Rev. D 72, 013009

One way to determine the ordering

T2K/NOνA (LBL)

$$P(\nu_\mu \to \nu_\mu)$$
$$P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$$

JUNO

$$P(\bar{\nu}_e \to \bar{\nu}_e)$$

Nunokawa, Parke, Zukanovich Phys. Rev. D 72, 013009

One way to determine the ordering

T2K/NOνA (LBL)

$$P(\nu_\mu \rightarrow \nu_\mu)$$

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$$

$$\Delta m^2_{31}?$$

$$\Delta m^2_{32}?$$

JUNO

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$$

Nunokawa, Parke, Zukanovich Phys. Rev. D 72, 013009

What is actually measured

T2K/NOνA (LBL) $\Delta m^2_{\mu\mu}$

JUNO Δm^2_{ee}

Nunokawa, Parke, Zukanovich Phys. Rev. D 72, 013009

What is actually measured

T2K/NOνA (LBL)

$$\Delta m^2_{\mu\mu} \approx \Delta m^2_{31} \sin^2\theta_{12} + \Delta m^2_{32} \cos^2\theta_{12} + \Delta m^2_{21} \sin\theta_{13} \cos\delta$$

JUNO

$$\Delta m^2_{ee} = \Delta m^2_{31} \cos^2\theta_{12} + \Delta m^2_{32} \sin^2\theta_{21}$$

Nunokawa, Parke, Zukanovich Phys. Rev. D 72, 013009

Rephrasing the mass ordering question

NO

$$|\Delta m^2_{ee}| > |\Delta m^2_{\mu\mu}|$$

IO

$$|\Delta m^2_{ee}| < |\Delta m^2_{\mu\mu}|$$

Nunokawa, Parke, Zukanovich Phys. Rev. D 72, 013009

Rephrasing the mass ordering question

NO

$$|\Delta m^2_{ee}| > |\Delta m^2_{\mu\mu}|$$

IO

$$|\Delta m^2_{ee}| < |\Delta m^2_{\mu\mu}|$$

This naturally requires precise measurements

Nunokawa, Parke, Zukanovich Phys. Rev. D 72, 013009

Fortunately

another. JUNO claims that after 100 days of data taking they will be able to determine $|\Delta m^2_{\rm atm}|$ at 0.8% precision and will continue to improve ultimately reaching 0.2%

Parke, Zukanovich, Phys. Rev. D 111, 013008
JUNO, Chin. Phys. C 46, 123001

Fortunately

another. JUNO claims that after 100 days of data taking they will be able to determine $|\Delta m^2_{\rm atm}|$ at 0.8% precision and will continue to improve ultimately reaching 0.2%

how many units of $\Delta\chi^2$. In this manner it is conceivable, if JUNO measures $|\Delta m^2_{\rm atm}|$ close to the one given by combining Daya Bay and RENO data, that NO could be soon (in a year or so) determined, by the combined (T2K, NOvA and JUNO) disappearance measurements alone, to better than 3 σ i.e. a confidence level of 99.73%.

Parke, Zukanovich, Phys. Rev. D 111, 013008

The actual question

If nature's choice is $|\Delta m^2_{ee}| > |\Delta m^2_{\mu\mu}|$ **NO**

The actual question

If nature's choice is $|\Delta m^2_{ee}| > |\Delta m^2_{\mu\mu}|$ **NO**

But neutrinos couple to ULDM

The actual question

If nature's choice is $|\Delta m^2_{ee}| > |\Delta m^2_{\mu\mu}|$ **NO**

But neutrinos couple to ULDM

Could we get confused? $|\Delta m^2_{ee}| < |\Delta m^2_{\mu\mu}|$

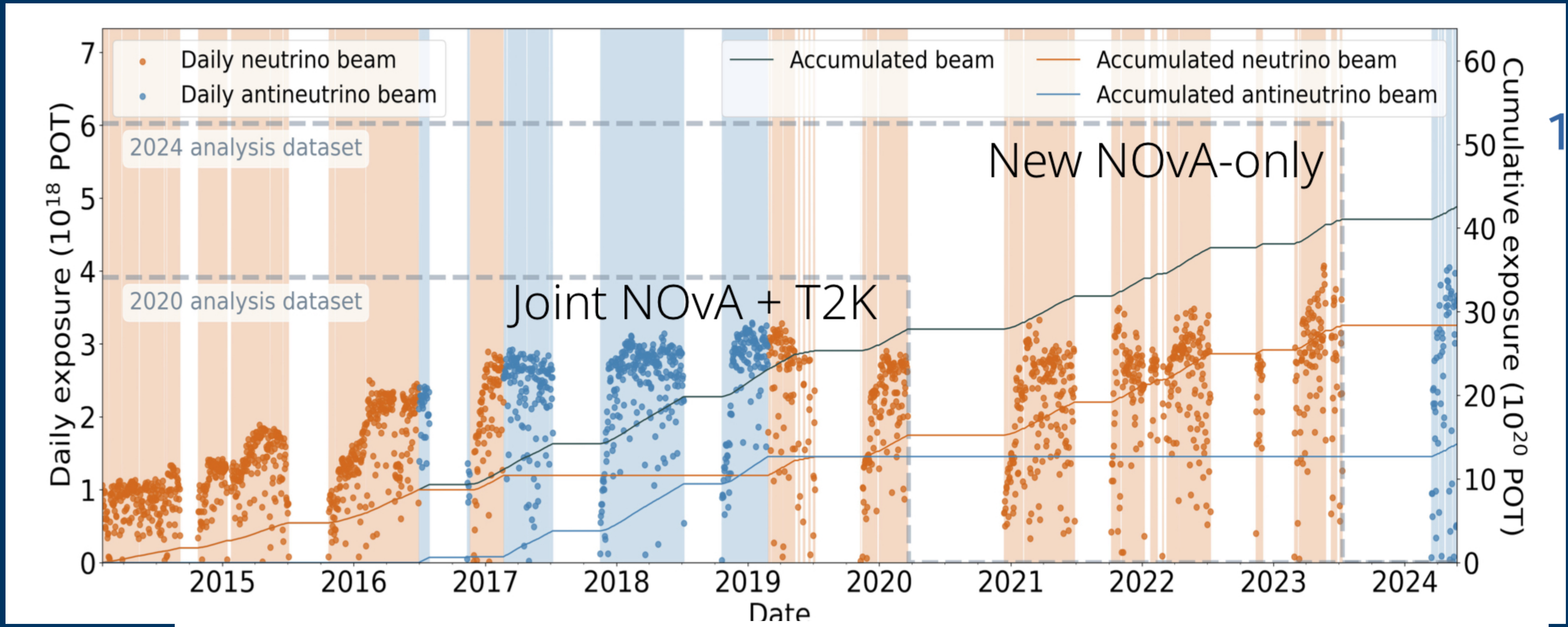
The actual question

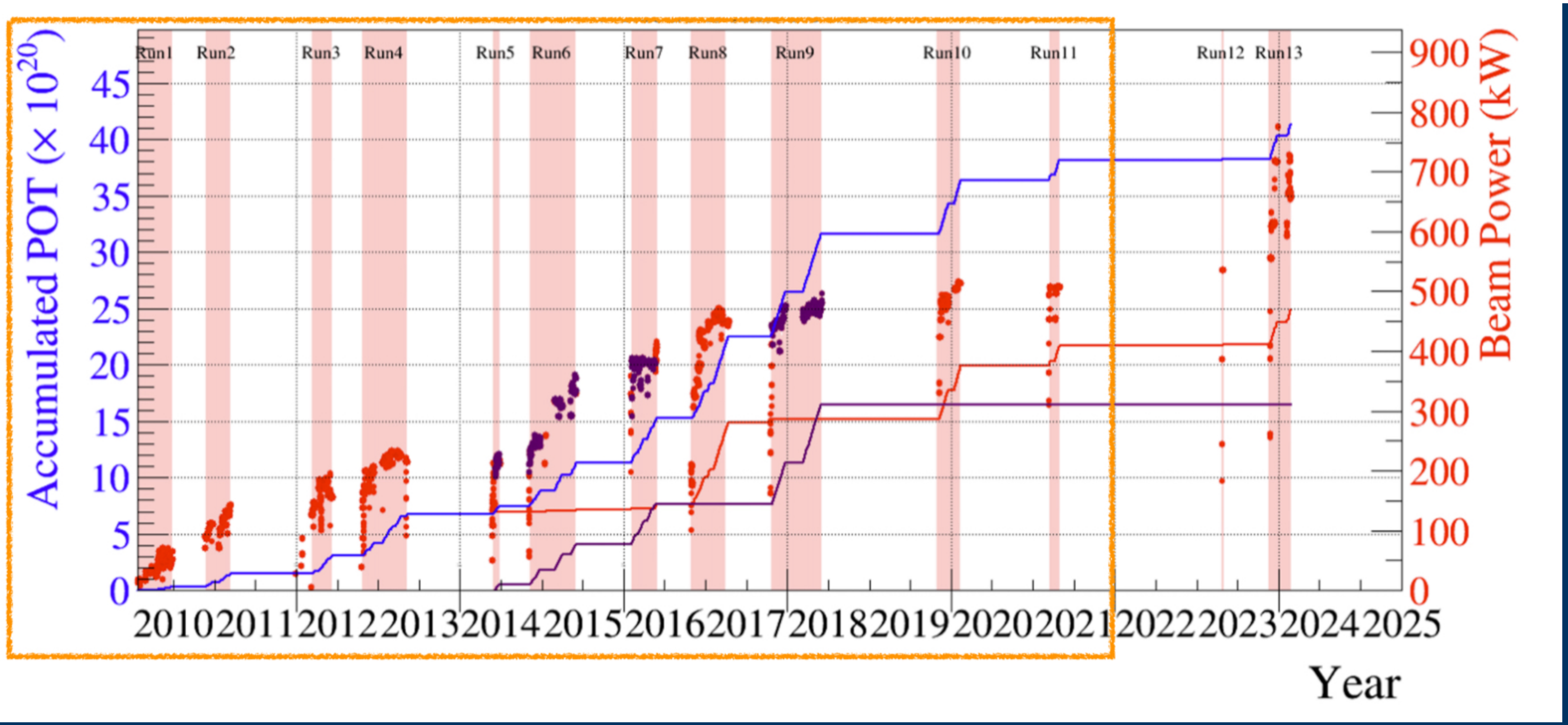
Can New Physics Spoil the JUNO–Long-Baseline Synergy in the Neutrino Mass Ordering Determination?

Gustavo F. S. Alves,[1,2,3,*] Hiroshi Nunokawa,[4,†] and Renata Zukanovich Funchal[3,‡]

LBL data taking periods

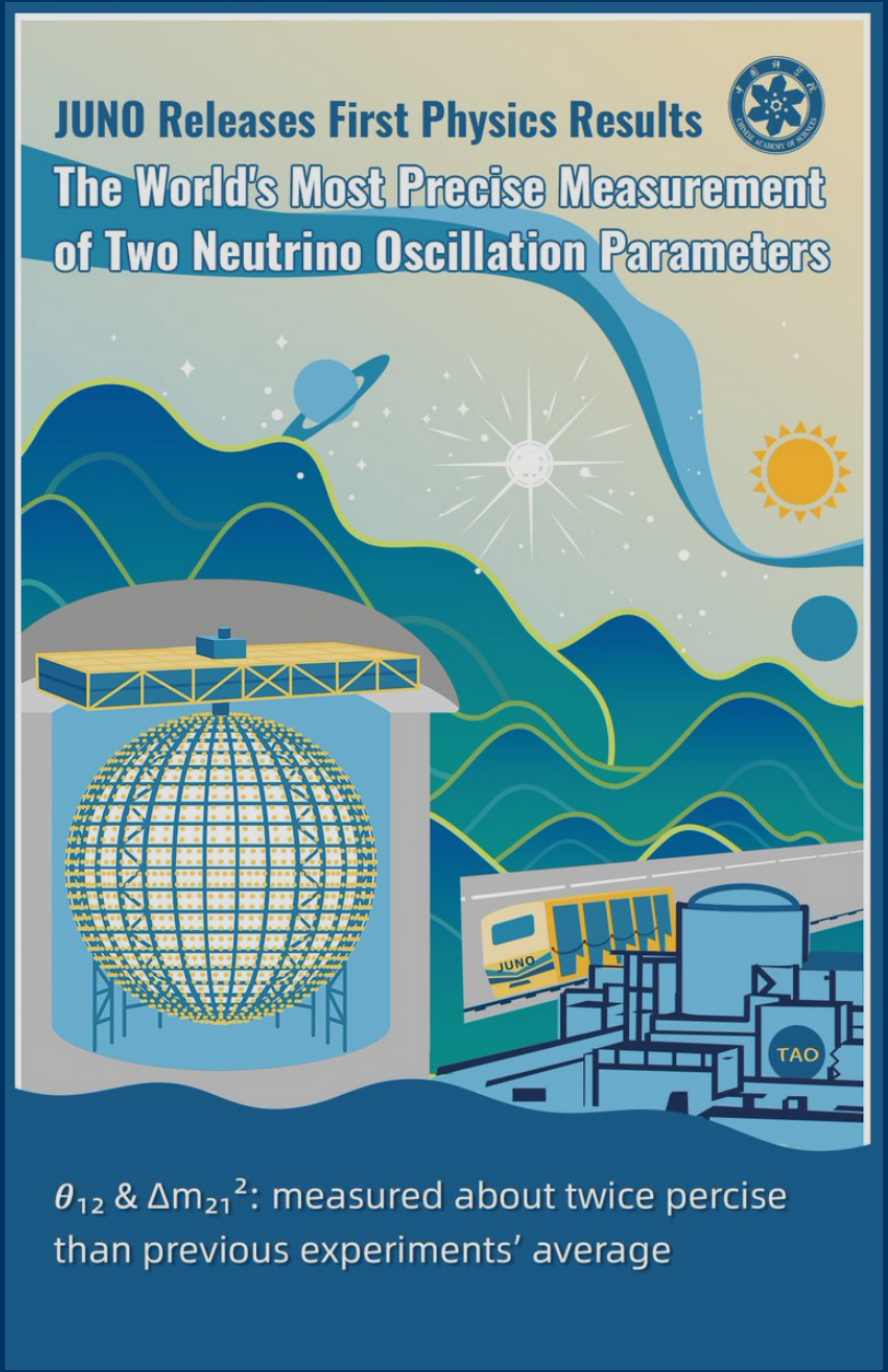
Wolcott, New neutrino oscillation results from NOvA with 10 years of data (talk-neutrino 2024)





Giganti, T2K experiment status and plans (talk-neutrino 2024)

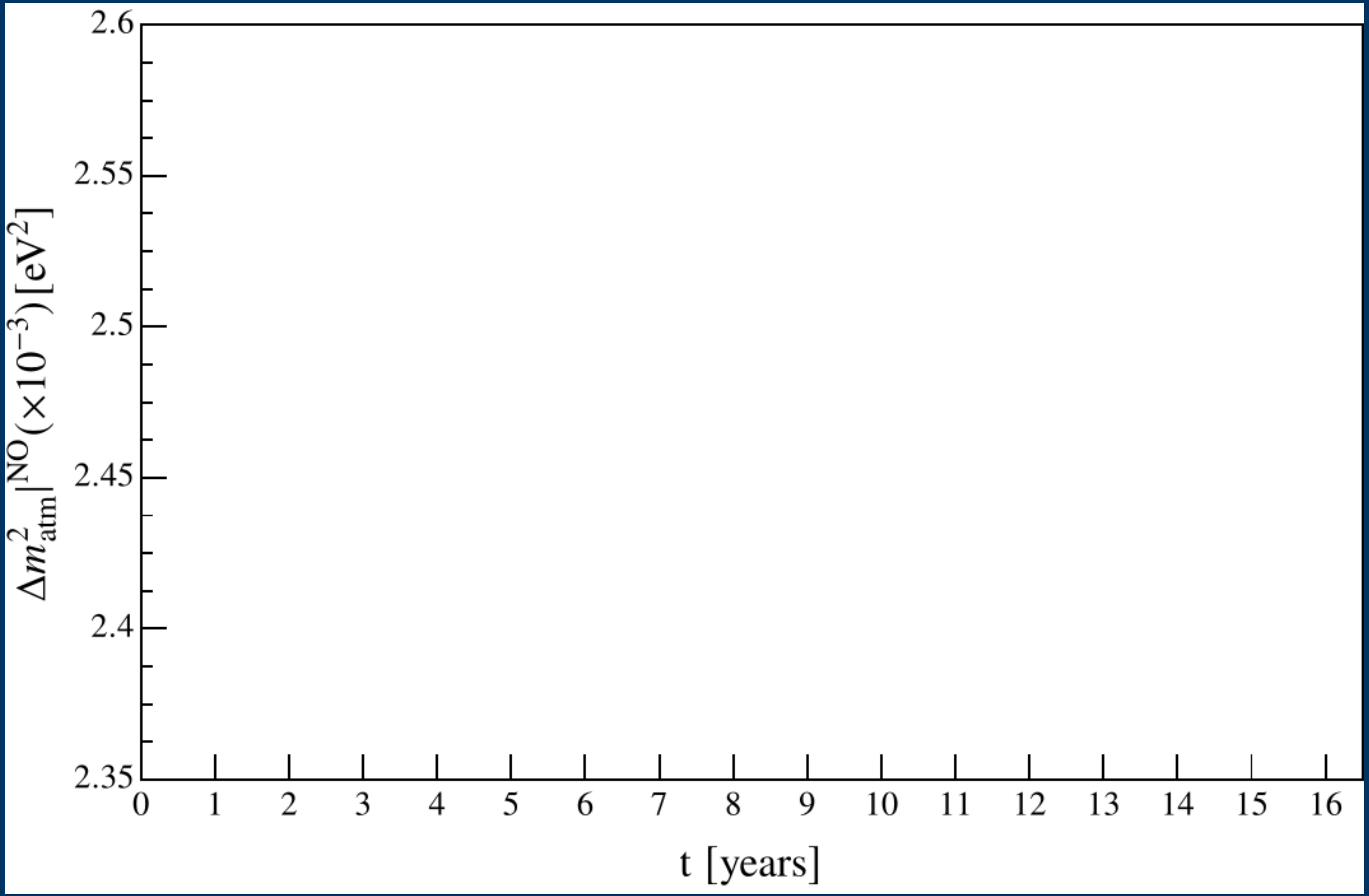
JUNO has just started!



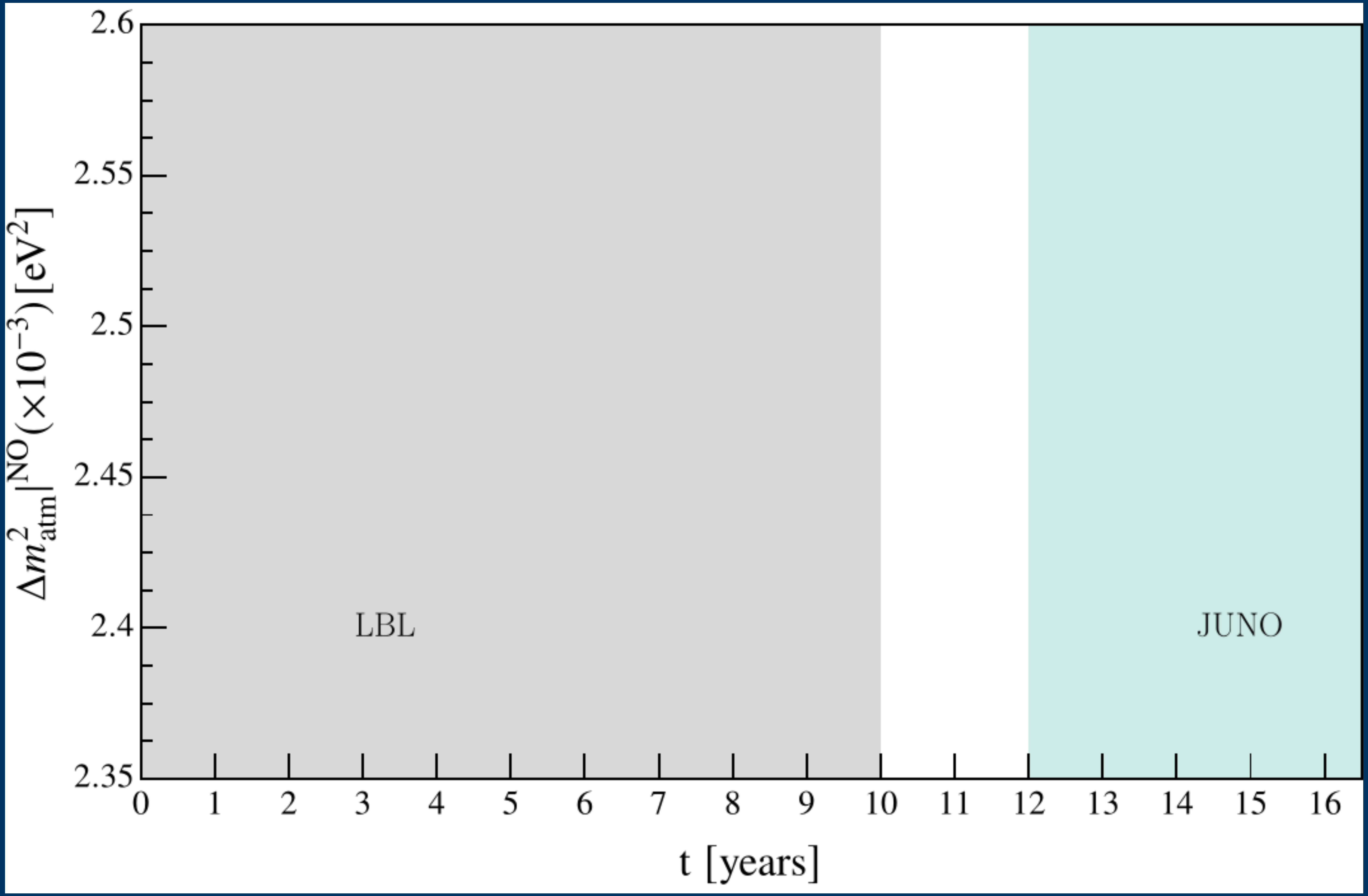
Setup

We will assume the scalar only couples to the third mass eigenstate

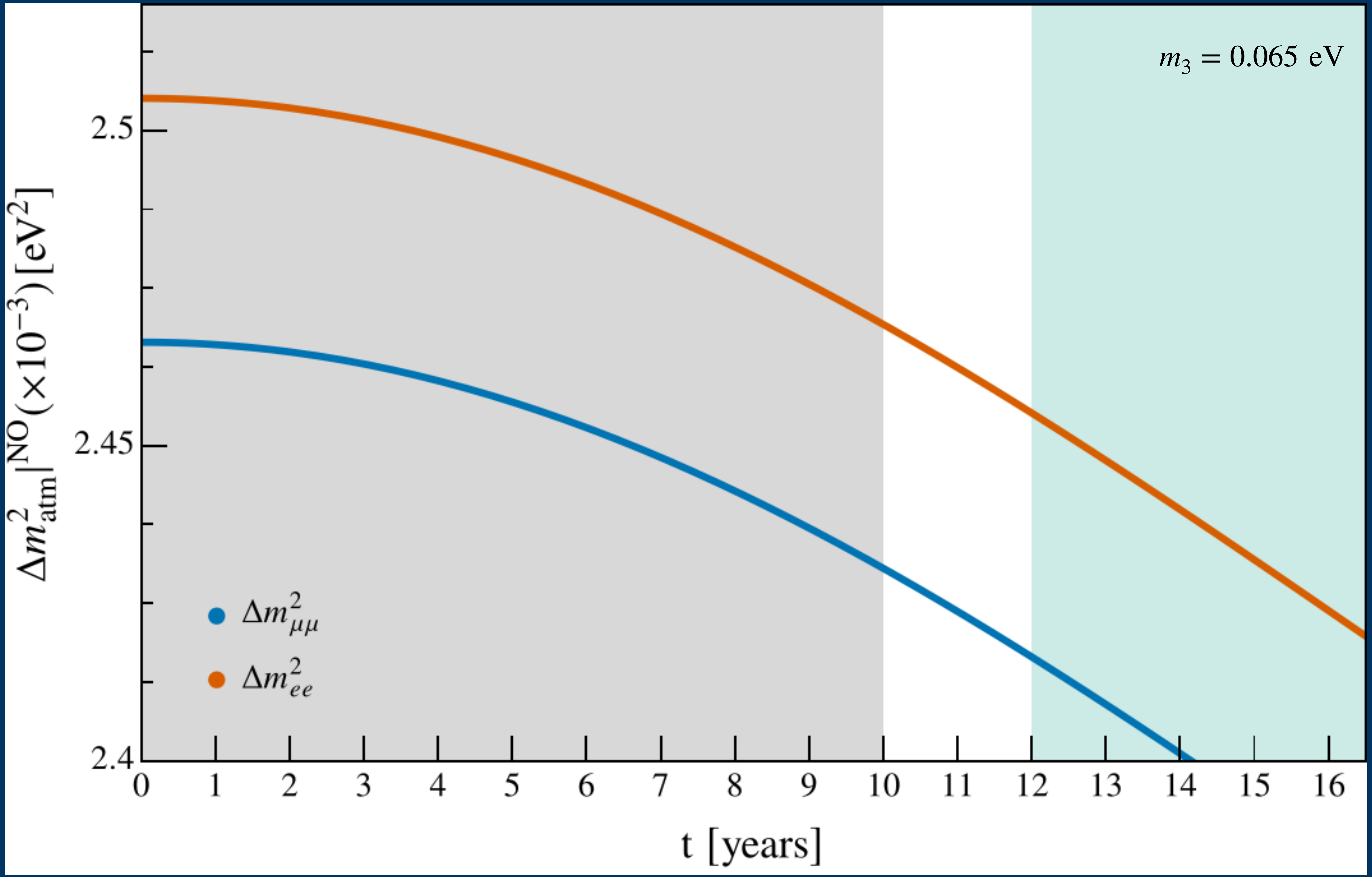
$$\Delta m_{31}^2(t) \approx \Delta m_{31}^2(g_\phi = 0) + 2m_3 g_{\phi,3}\phi_0 \cos(m_\phi t)$$


2.6
2.55
2.5
2.45
2.4
2.35
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
t [years]
$\Delta m^2_{atm}|^{NO}(\times 10^{-3})\,[eV^2]$

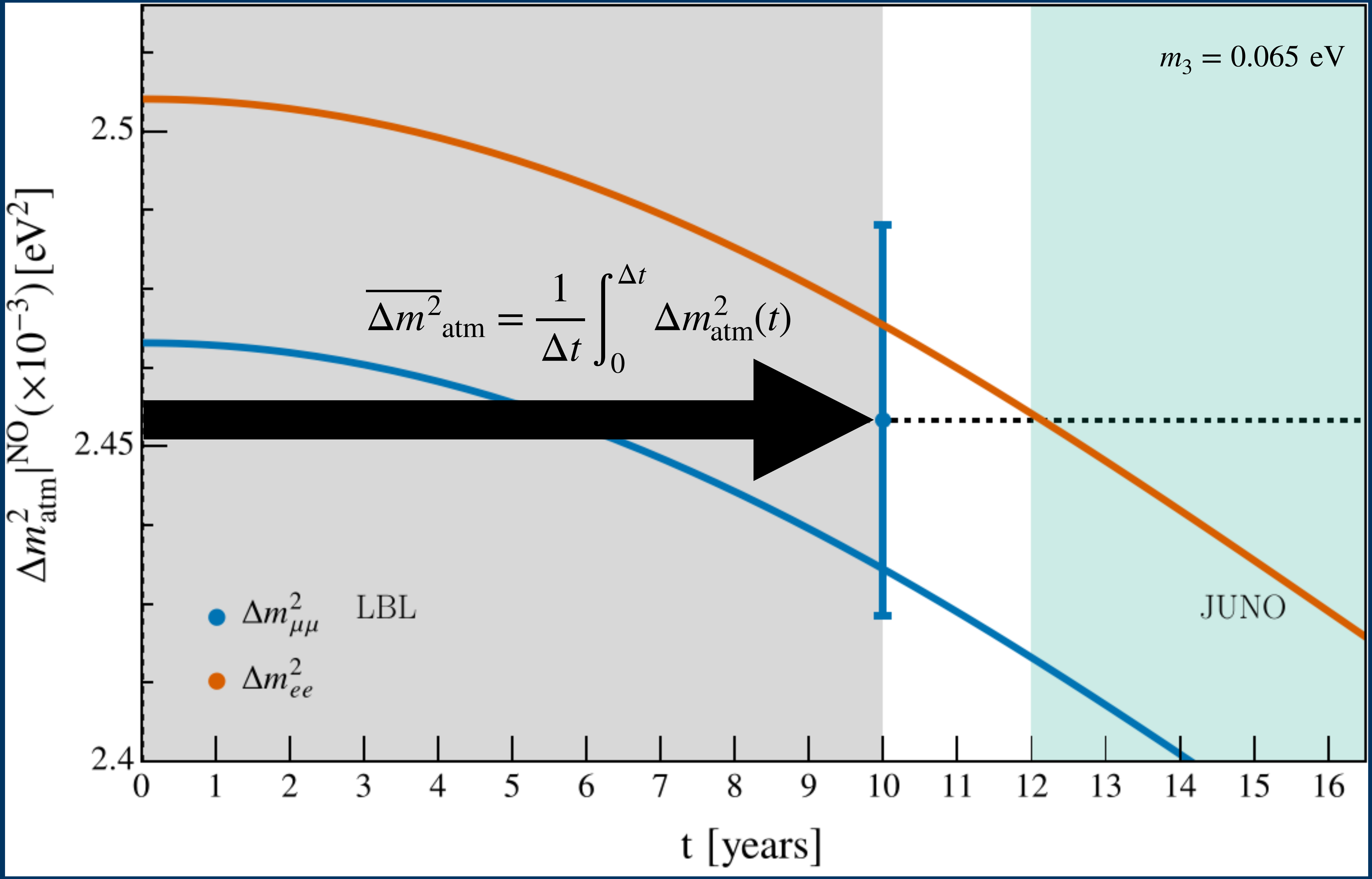
LBL and JUNO are asynchronous



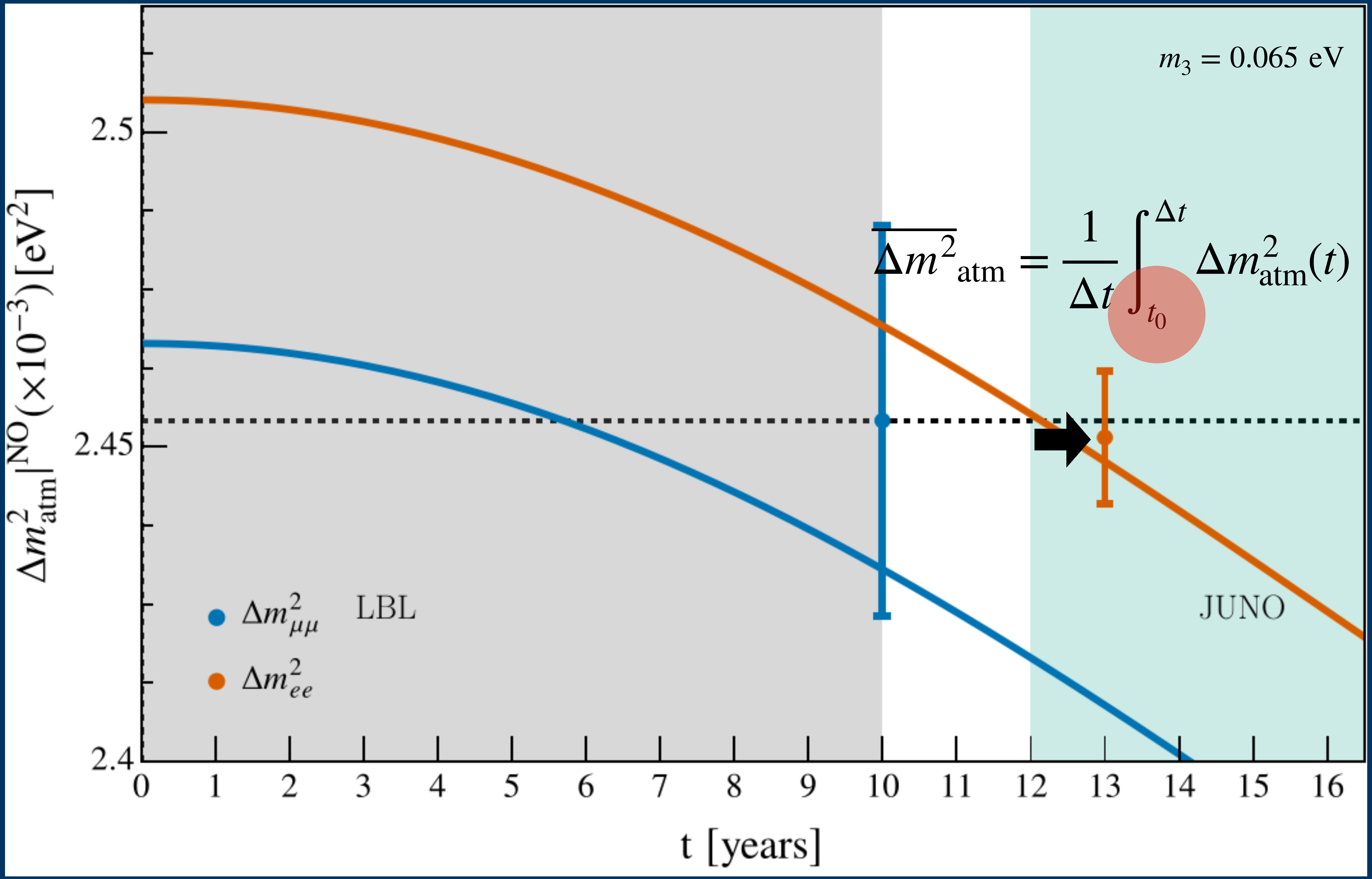
Instantaneous mass splittings



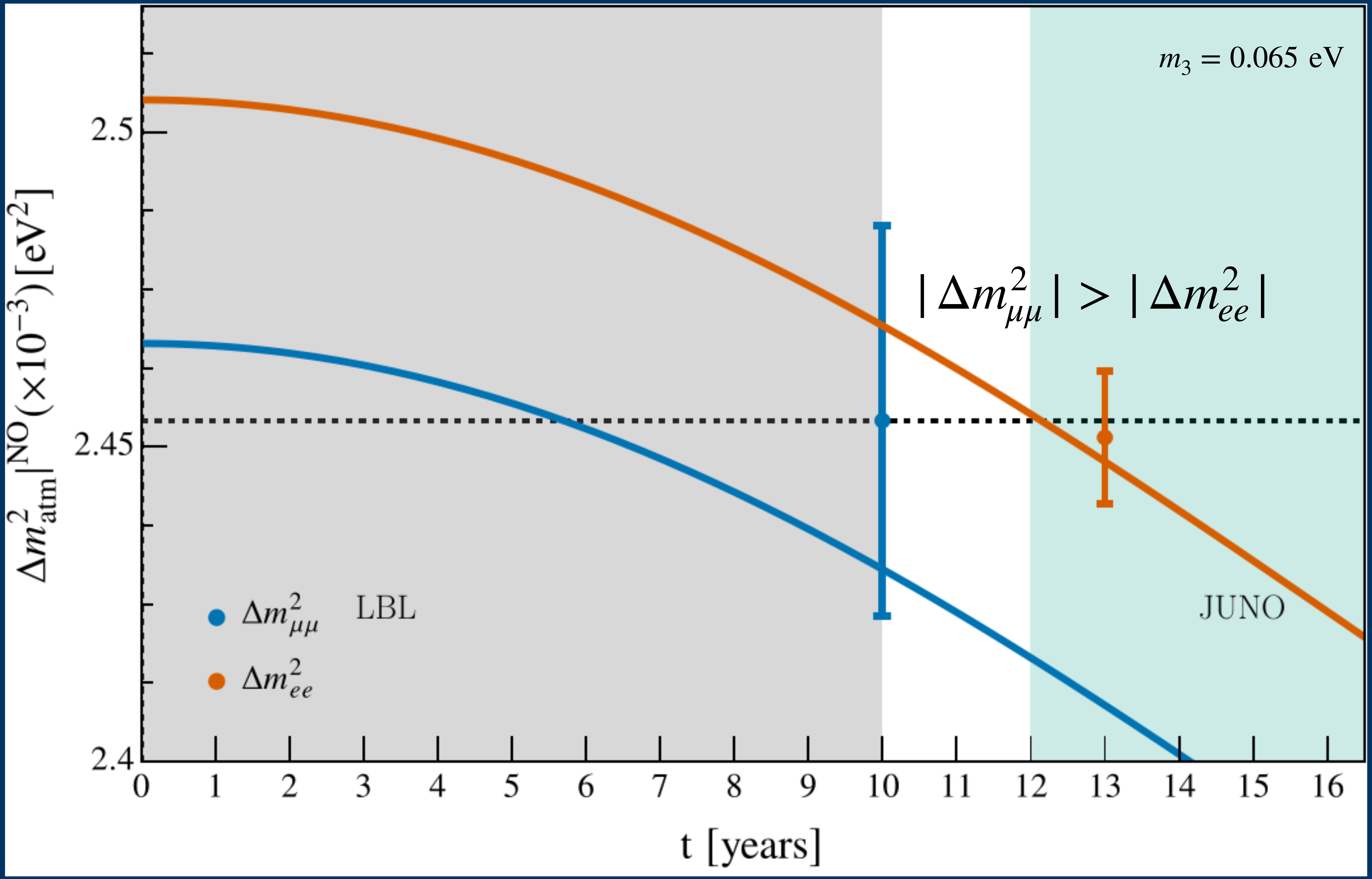
Experimental result LBL



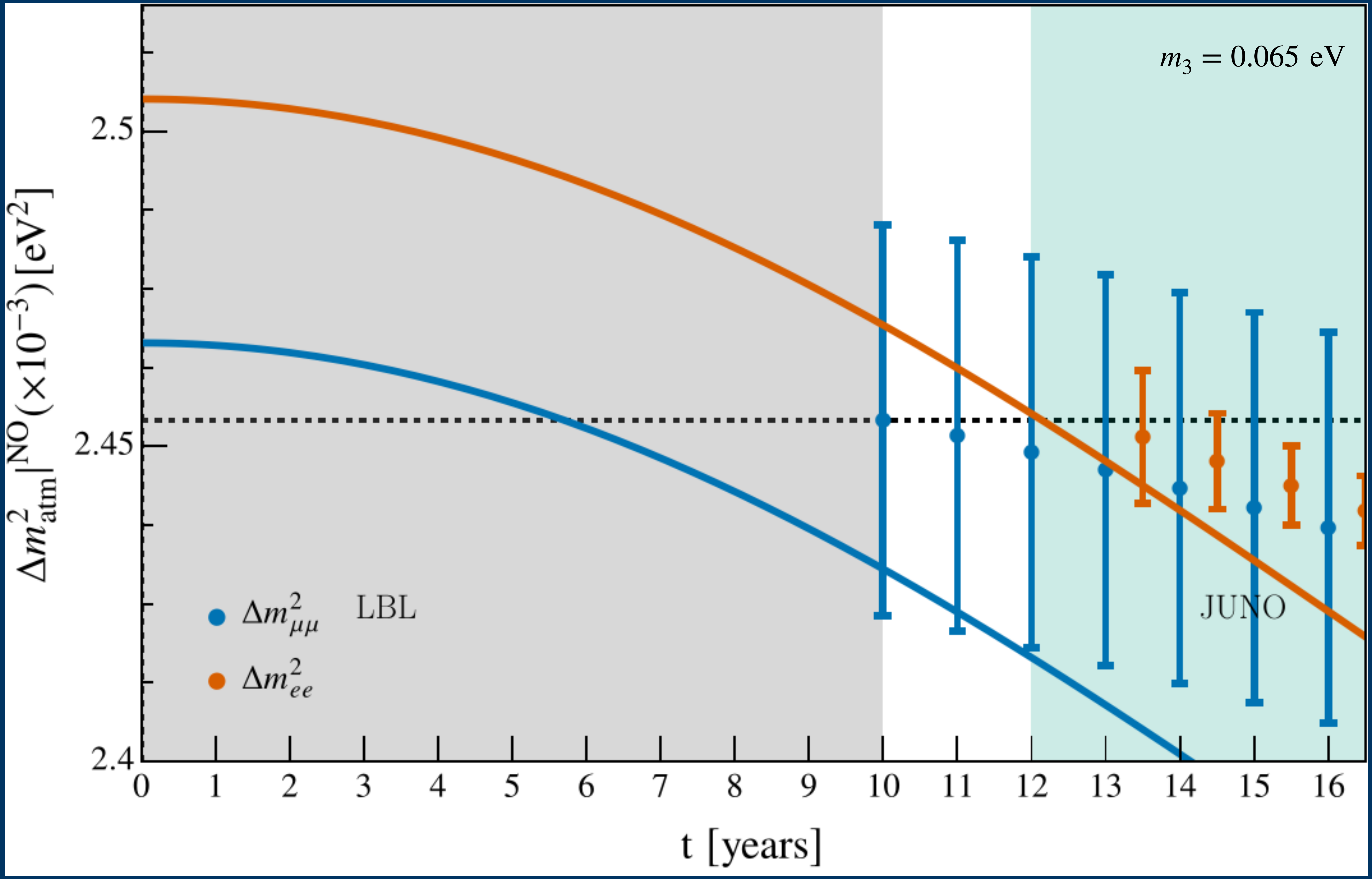
Experimental result JUNO



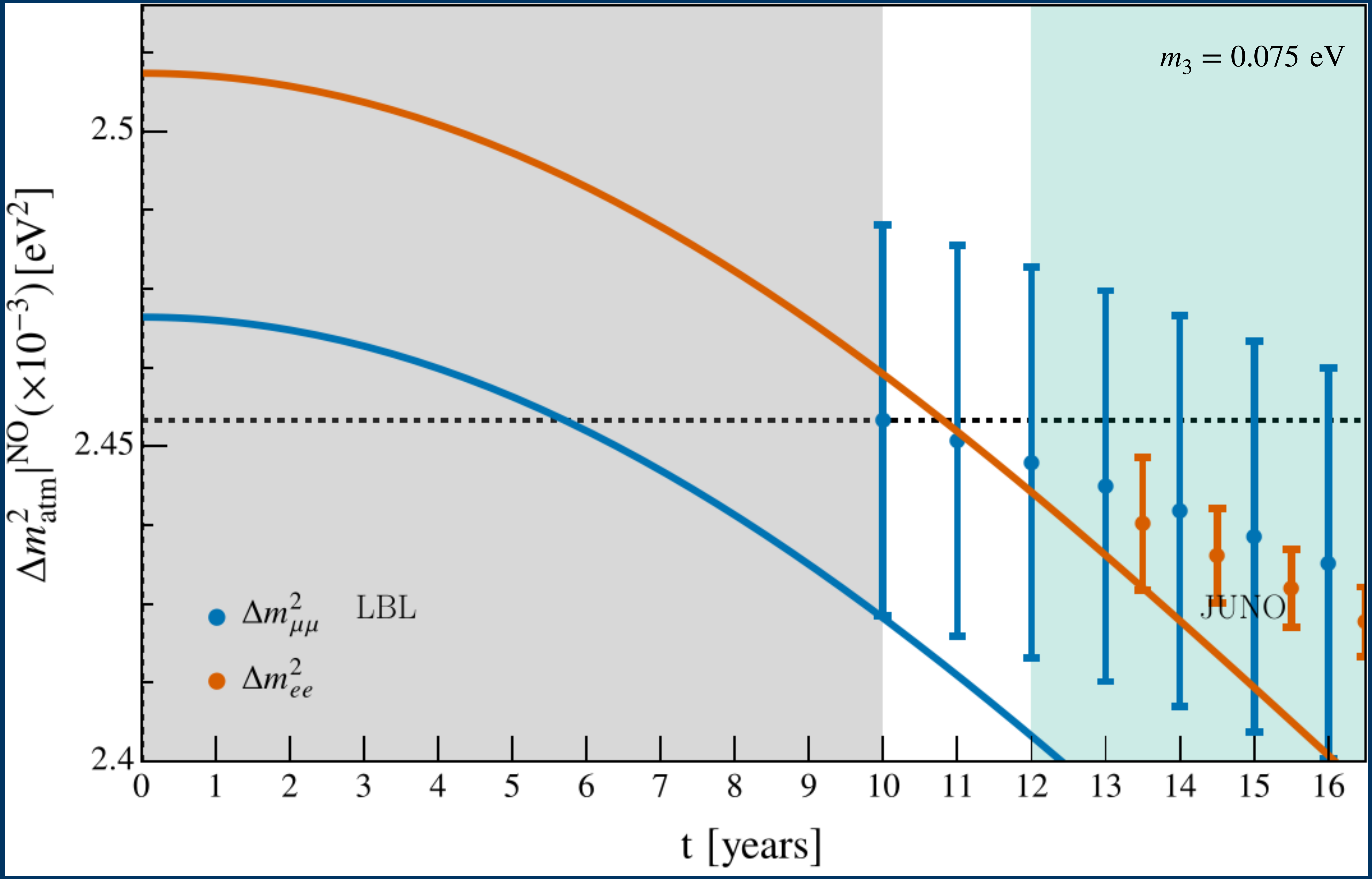
Apparent mass ordering confusion



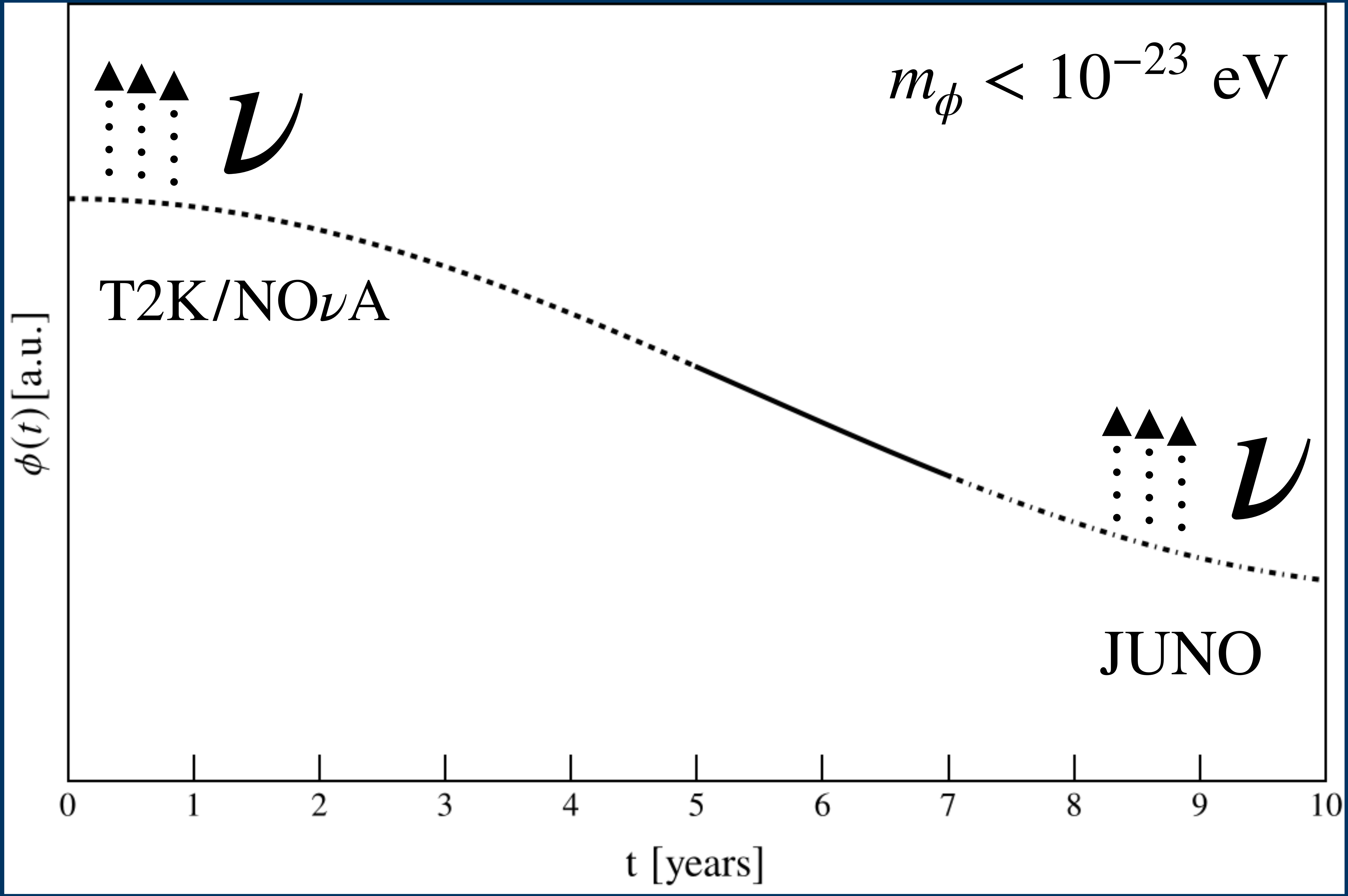
Conclusions are time dependent



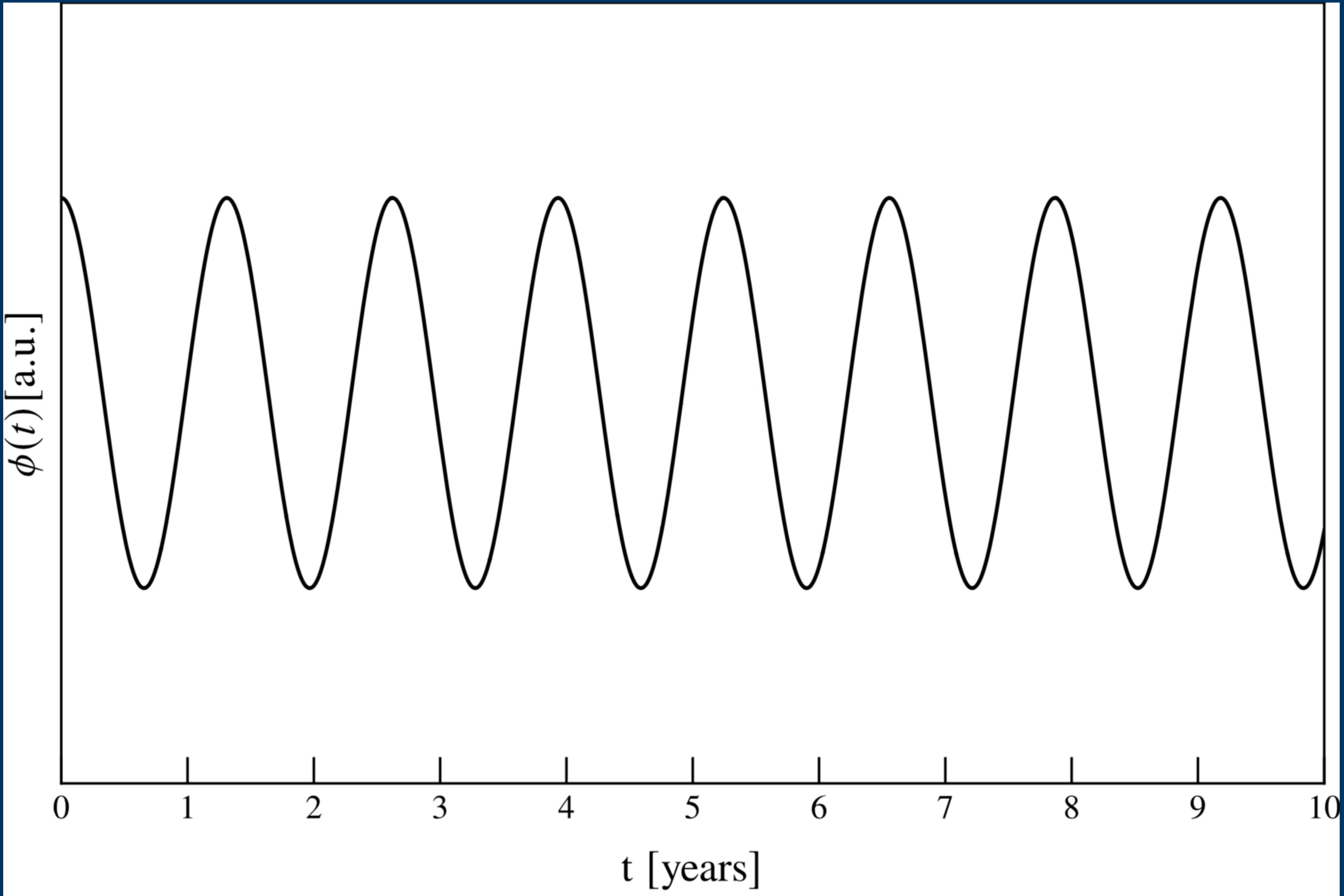
Conclusions are time dependent



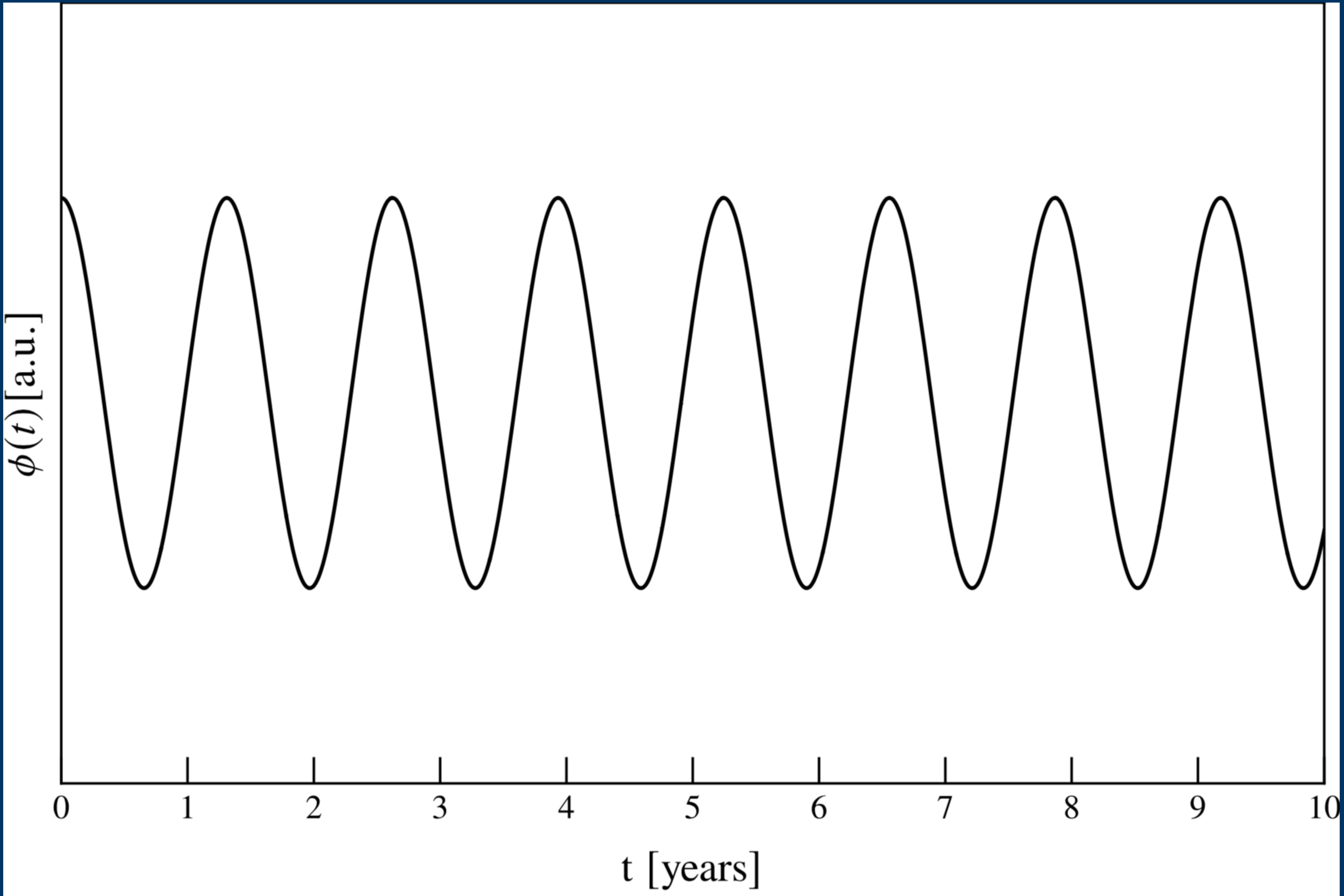
Done with the first scenario



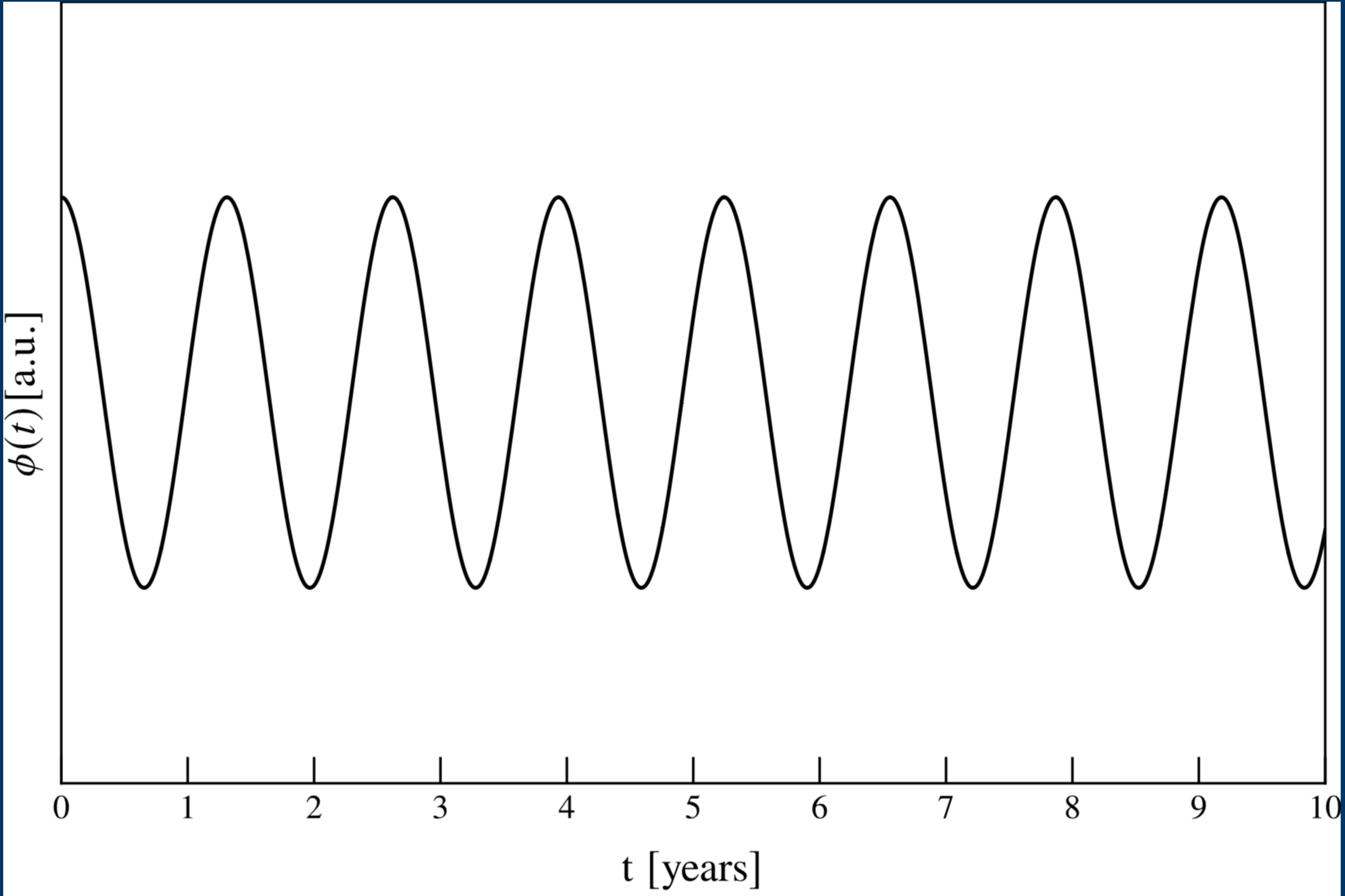
Second scenario



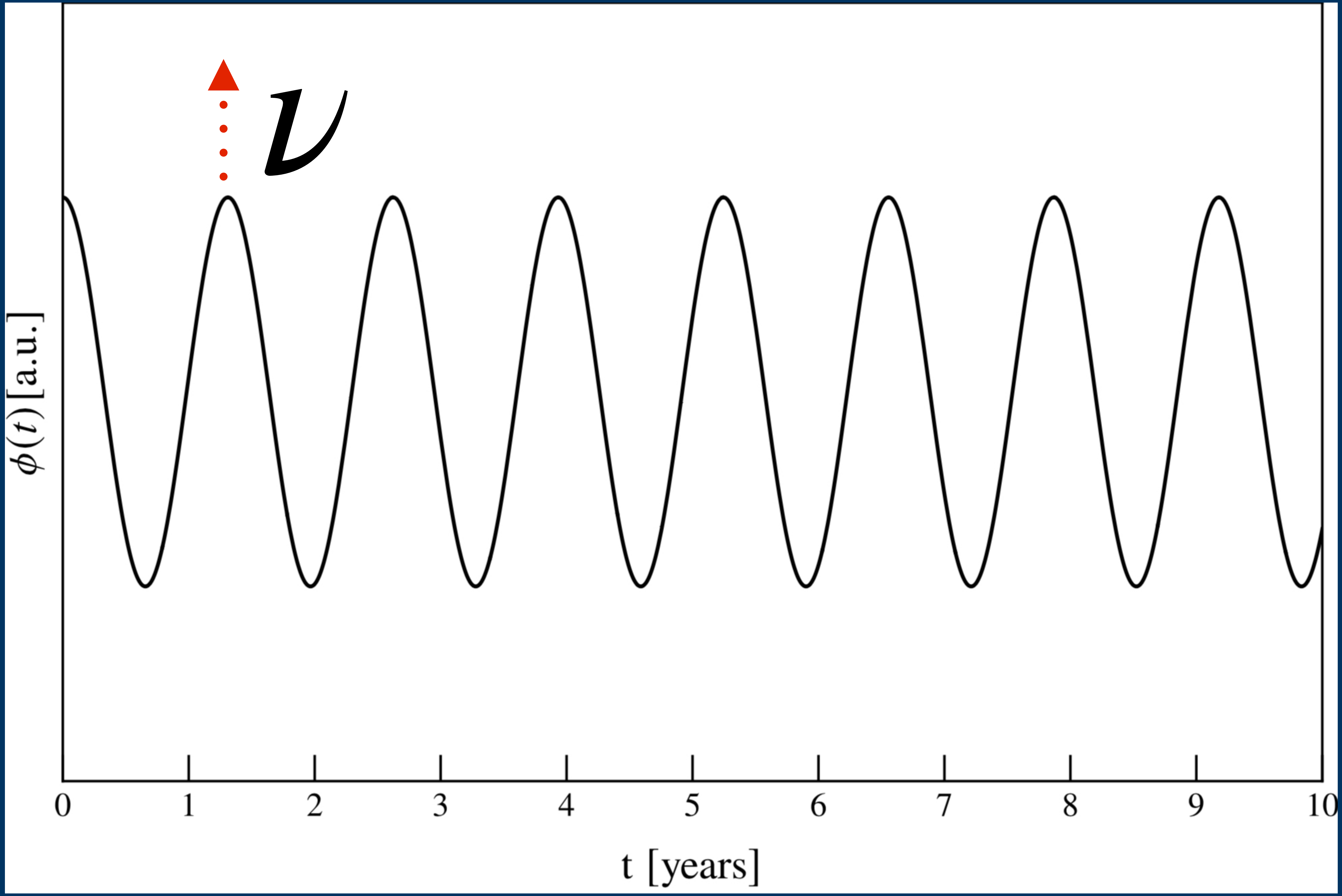
Several cycles over the experimental livetime



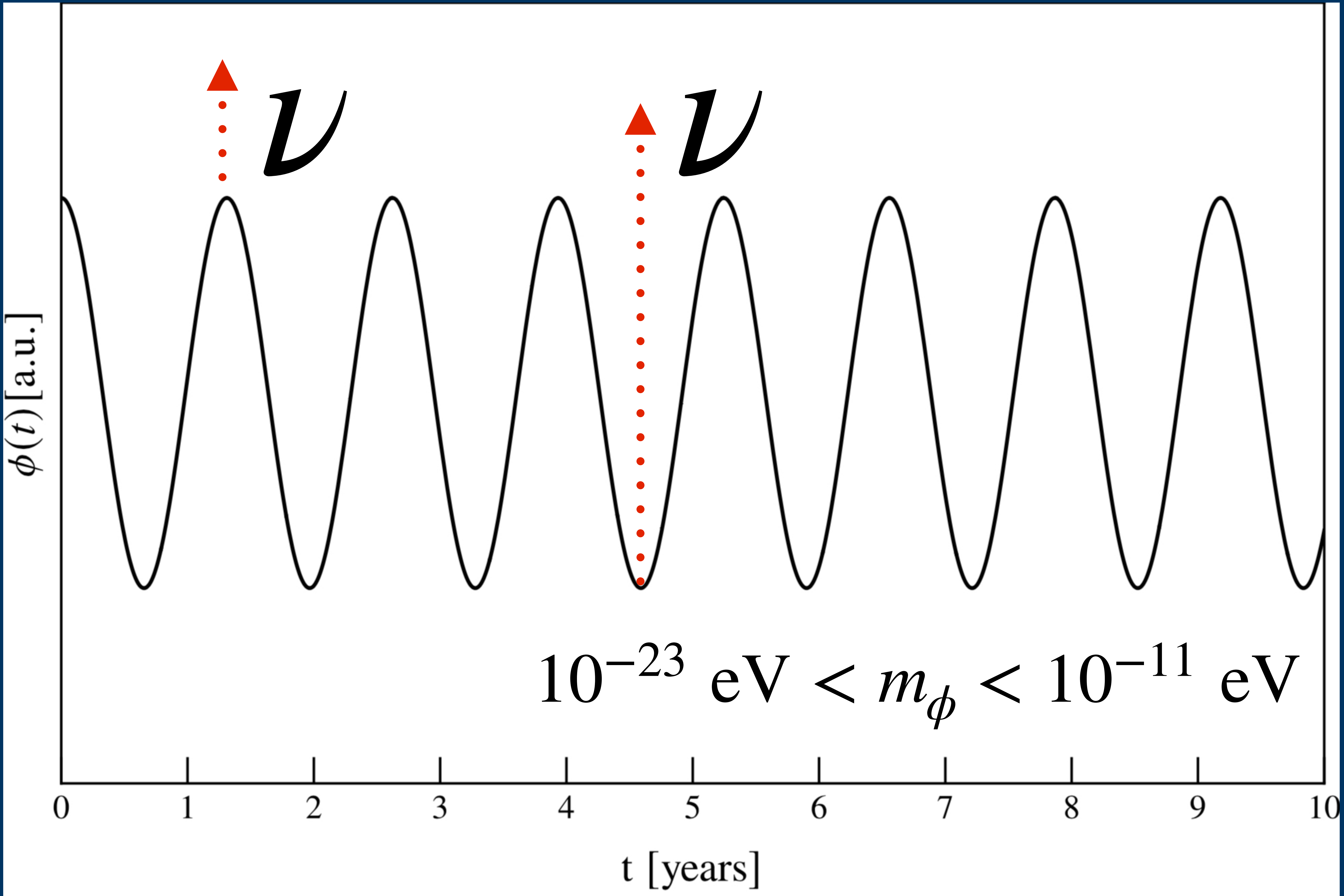
Neutrinos start with different initial conditions



Neutrinos start with different initial conditions



Neutrinos start with different initial conditions



Most explored scenario

$$10^{-23}\ \mathrm{eV} \leq m_\phi \leq 10^{-11}\ \mathrm{eV}$$

Neutrino Oscillations as a Probe of Light Scalar Dark Matter

Asher Berlin

Show more

Phys. Rev. Lett. **117**, 231801 – **Published 30 November, 2016**

DOI: https://doi.org/10.1103/PhysRevLett.117.231801

OPEN ACCESS

Distorted neutrino oscillations from time varying cosmic fields

Gordan Krnjaic[1,*], Pedro A. N. Machado[1,†], and Lina Necib[2,‡]

Show more

Phys. Rev. D **97**, 075017 – **Published 16 April, 2018**

Expo

DOI: https://doi.org/10.1103/PhysRevD.97.075017

[Submitted on 20 Dec 2025]

Ultralight dark matter search in a large liquid scintillator detector

Luis A. Delgadillo, O. G. Miranda, Hiroshi Nunokawa

Home › Journal of High Energy Physics › Article

Signatures of ultralight dark matter in neutrino oscillation experiments

Regular Article – Theoretical Physics | Open access | Published: 18 January 2021

Volume 2021, article number 94, (2021) Cite this article

You have full access to this open access article

Download PDF

Abhish Dev, Pedro A. N. Machado & Pablo Martínez-Miravé

Most explored scenario

I will show that we can also approach the problem from an open systems perspective

Most explored scenario

I will show that we can also approach the problem from an open systems perspective

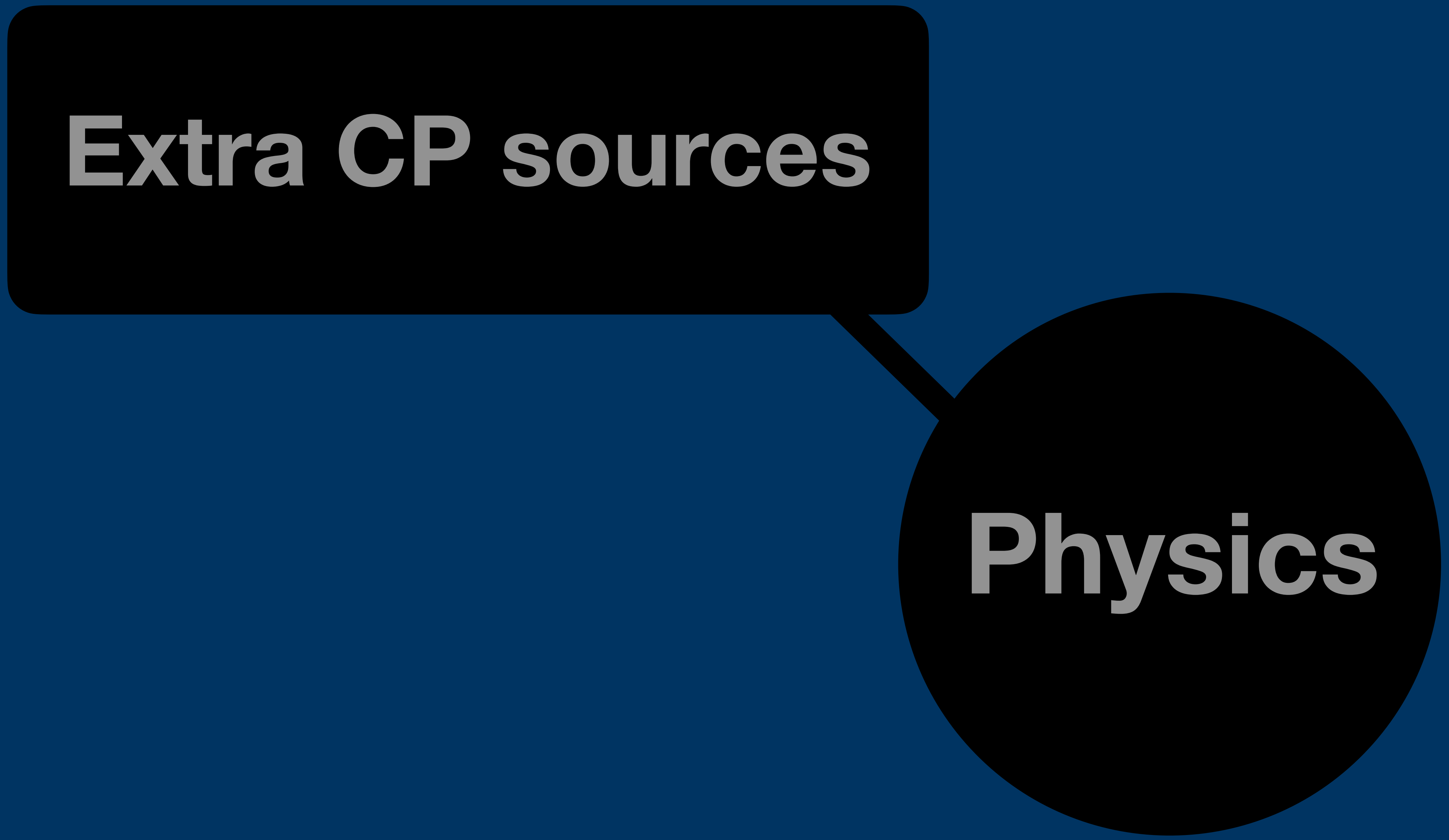
But why would one like to do that?

Neutrinos as open systems

Physics

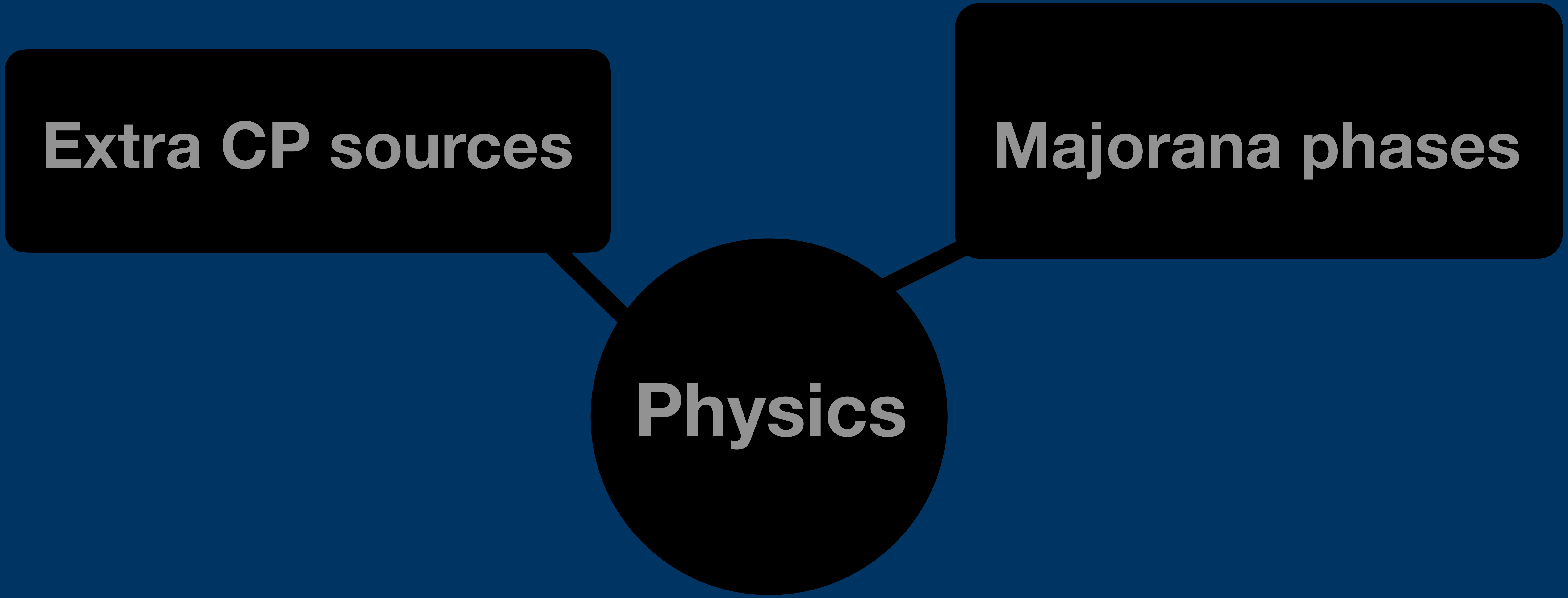
Benatti, et. al., JHEP 10.1088
Gago, et. al., Phys. Rev. D.,10.1103
Guzzo, et. al., EPJ C 10.1140
Lisi, et. al., PRL. 85.1166
Guzzo, et. al., Phys. Rev. D., 89.053002
Schwetz, et. al, JHEP JHEP05 (2015) 007
……..

Neutrinos as open systems



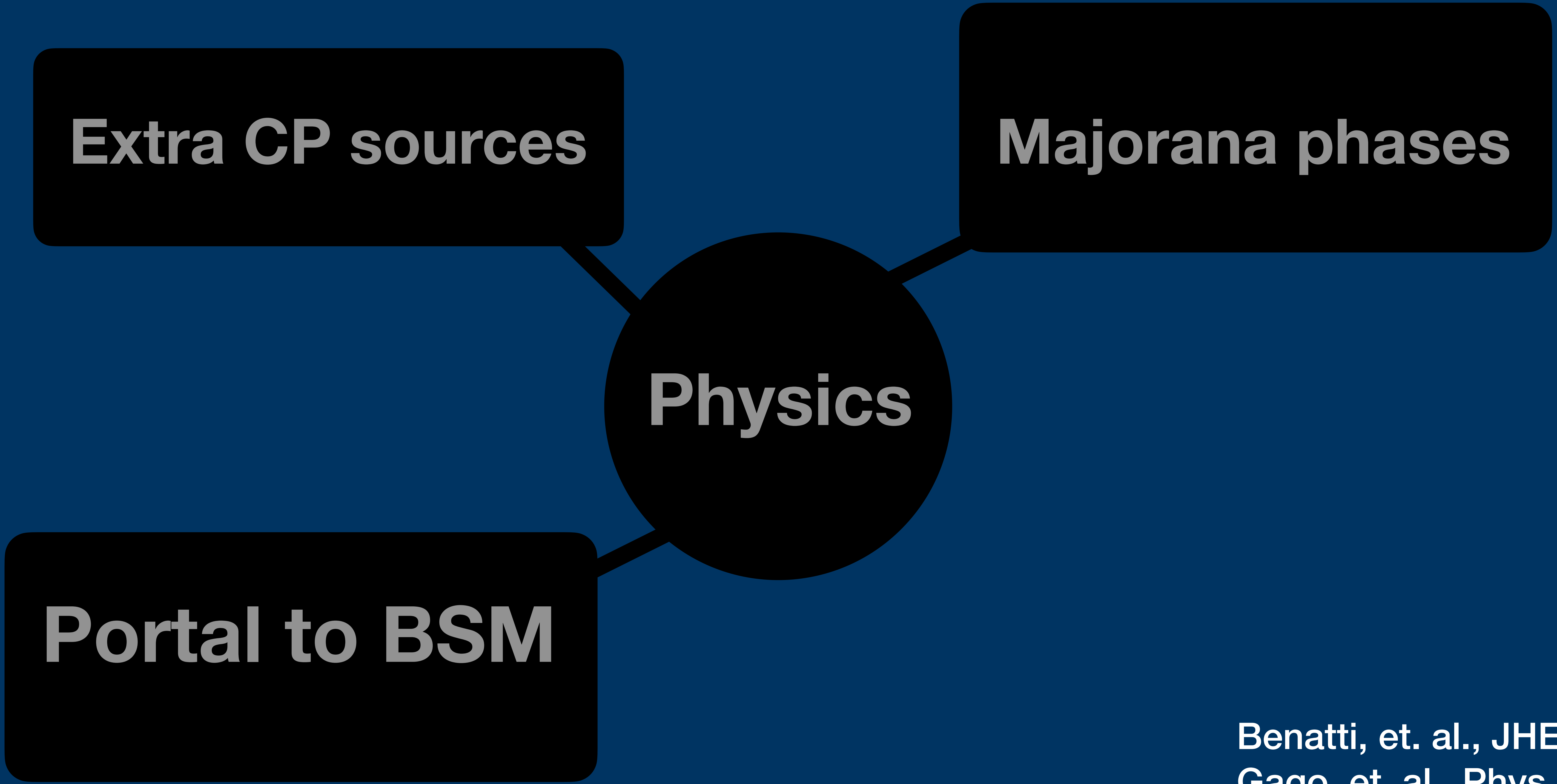
Benatti, et. al., JHEP 10.1088
Gago, et. al., Phys. Rev. D.,10.1103
Guzzo, et. al., EPJ C 10.1140
Lisi, et. al., PRL. 85.1166
Guzzo, et. al., Phys. Rev. D., 89.053002
Schwetz, et. al, JHEP JHEP05 (2015) 007
……..

Neutrinos as open systems



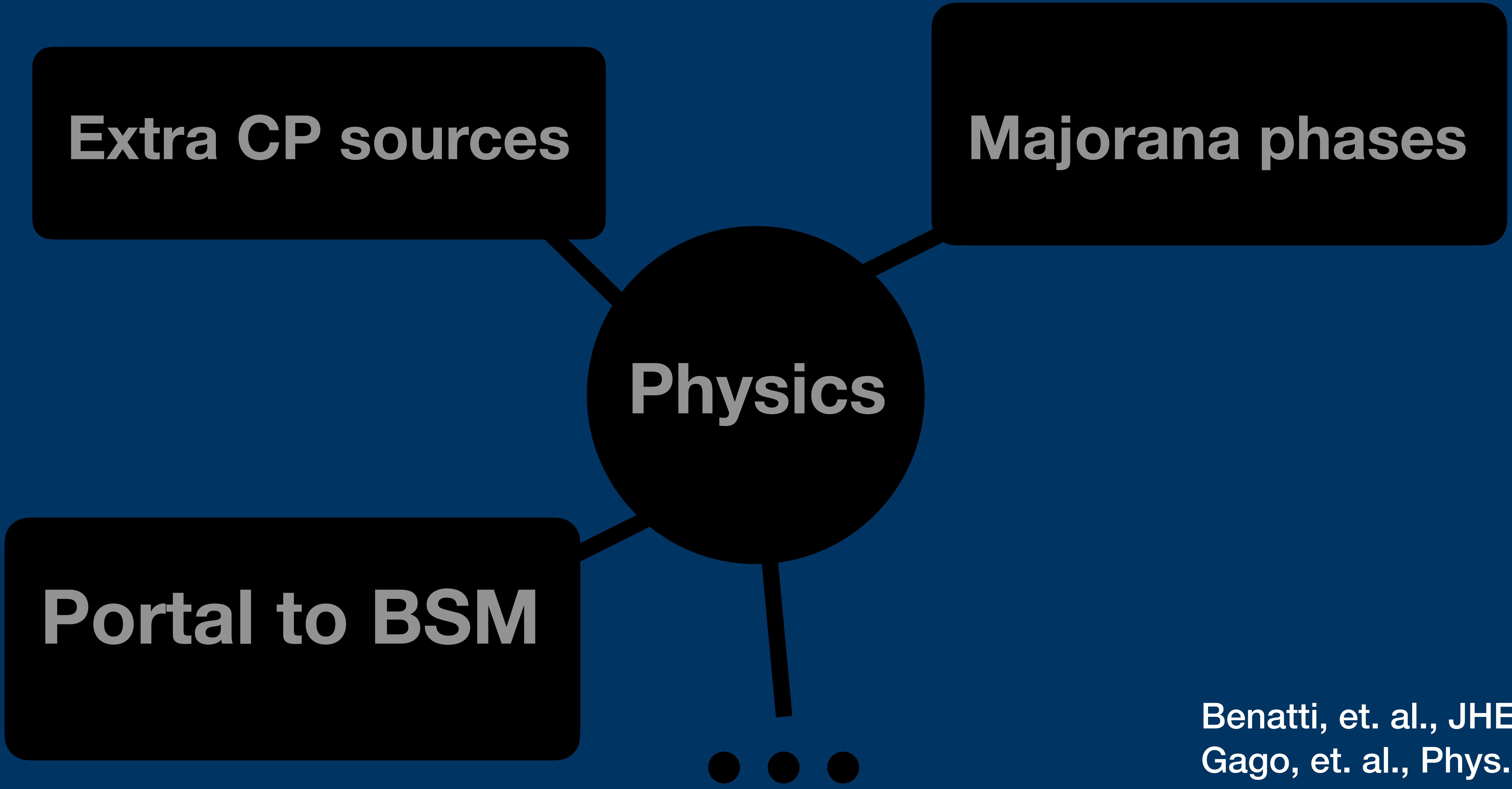
Benatti, et. al., JHEP 10.1088
Gago, et. al., Phys. Rev. D.,10.1103
Guzzo, et. al., EPJ C 10.1140
Lisi, et. al., PRL. 85.1166
Guzzo, et. al., Phys. Rev. D., 89.053002
Schwetz, et. al, JHEP JHEP05 (2015) 007
……..

Neutrinos as open systems



Benatti, et. al., JHEP 10.1088
Gago, et. al., Phys. Rev. D.,10.1103
Guzzo, et. al., EPJ C 10.1140
Lisi, et. al., PRL. 85.1166
Guzzo, et. al., Phys. Rev. D., 89.053002
Schwetz, et. al, JHEP JHEP05 (2015) 007
……..

Neutrinos as open systems



Benatti, et. al., JHEP 10.1088
Gago, et. al., Phys. Rev. D.,10.1103
Guzzo, et. al., EPJ C 10.1140
Lisi, et. al., PRL. 85.1166
Guzzo, et. al., Phys. Rev. D., 89.053002
Schwetz, et. al, JHEP JHEP05 (2015) 007
……..

How the framework has been applied to neutrino physics?

Open systems, open possibilities

Article | Published: 26 March 2024

Search for decoherence from quantum gravity with atmospheric neutrinos

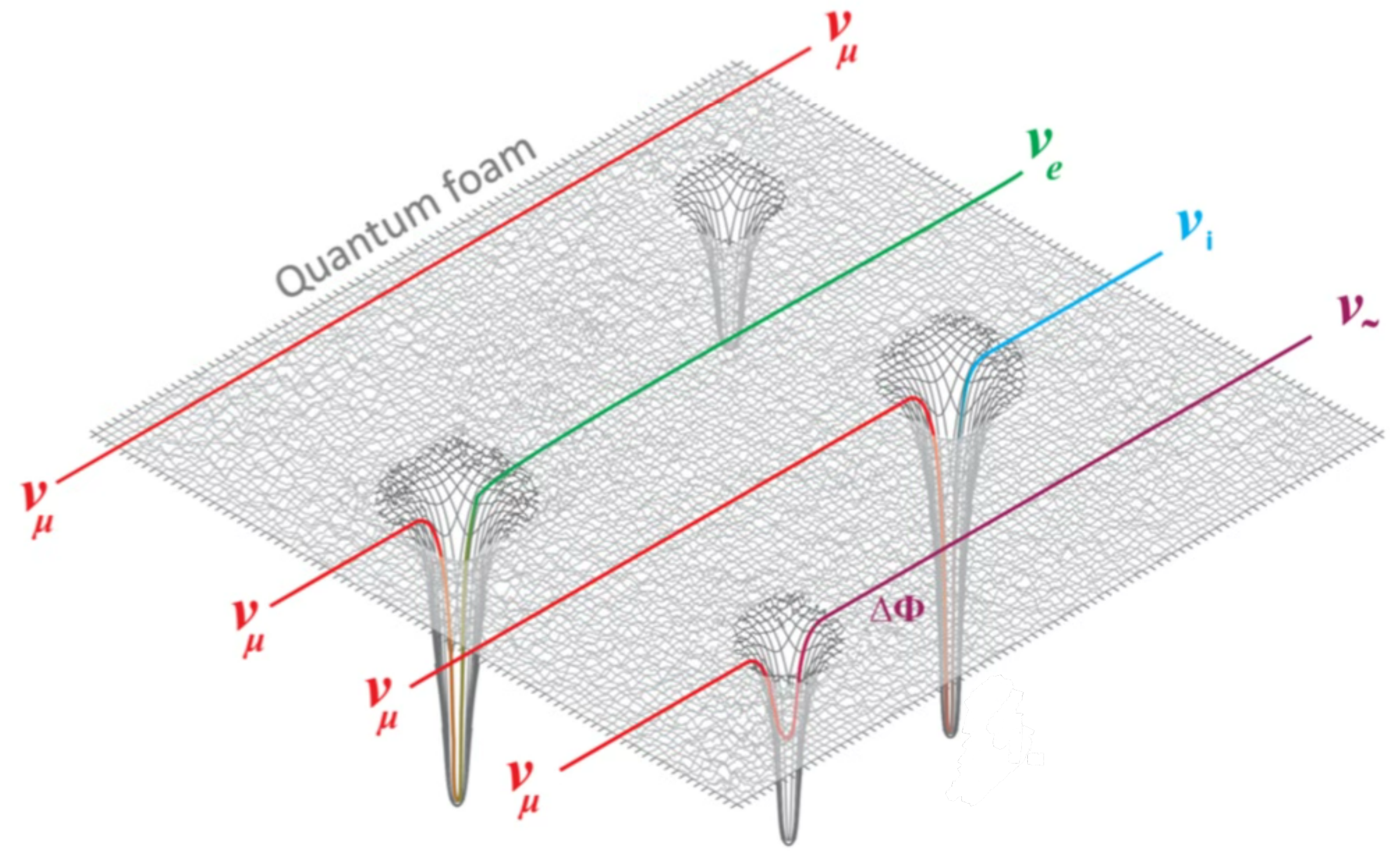
The IceCube Collaboration

Nature Physics **20**, 913–920 (2024) | Cite this article

3483 Accesses | **4** Citations | **315** Altmetric | Metrics

How the framework is applied to neutrino physics

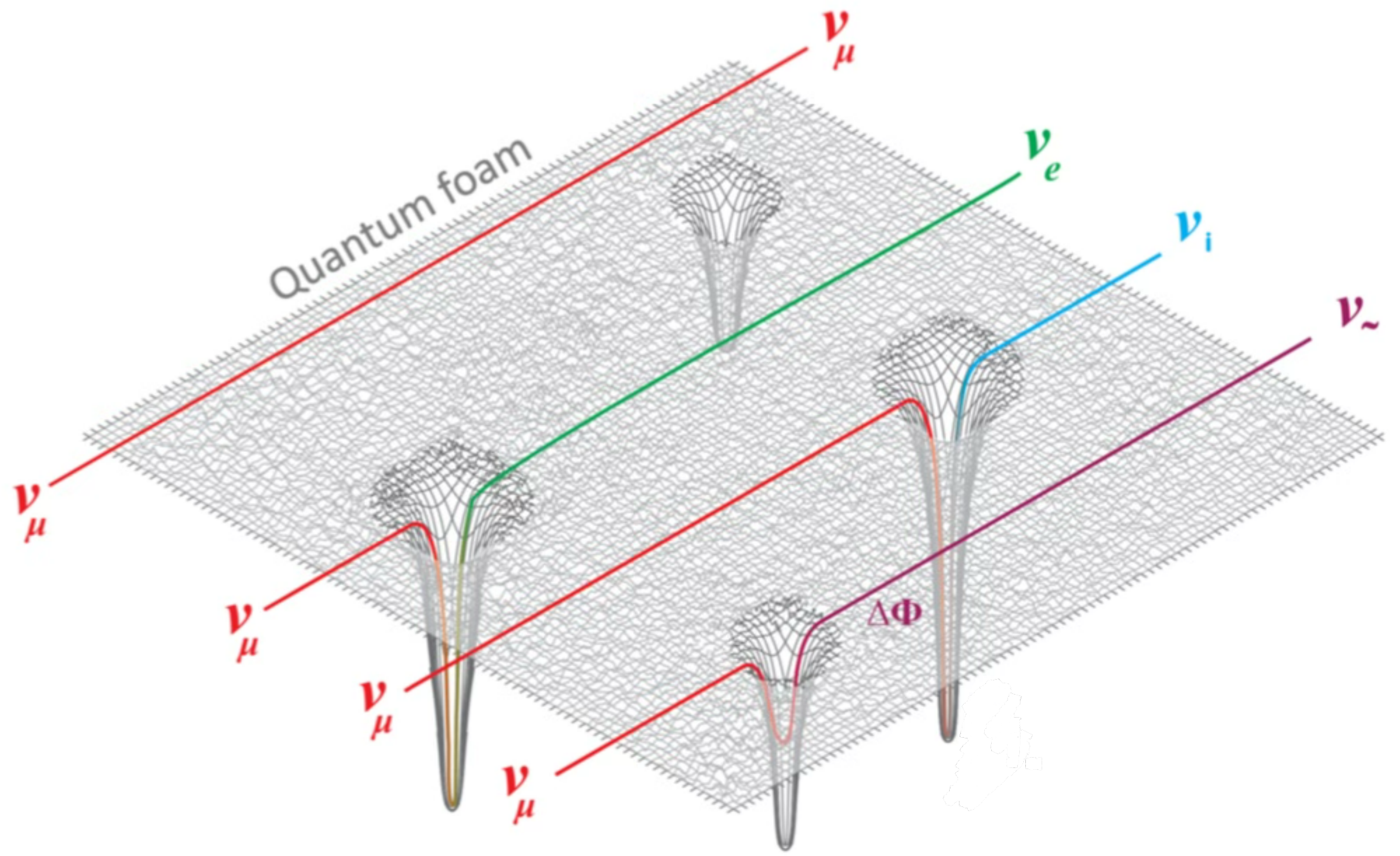
Motivation:



From: The IceCube collaboration, Nature Physics 20, 913-920

How the framework is applied to neutrino physics

Motivation:



From: The IceCube collaboration, Nature Physics 20, 913-920

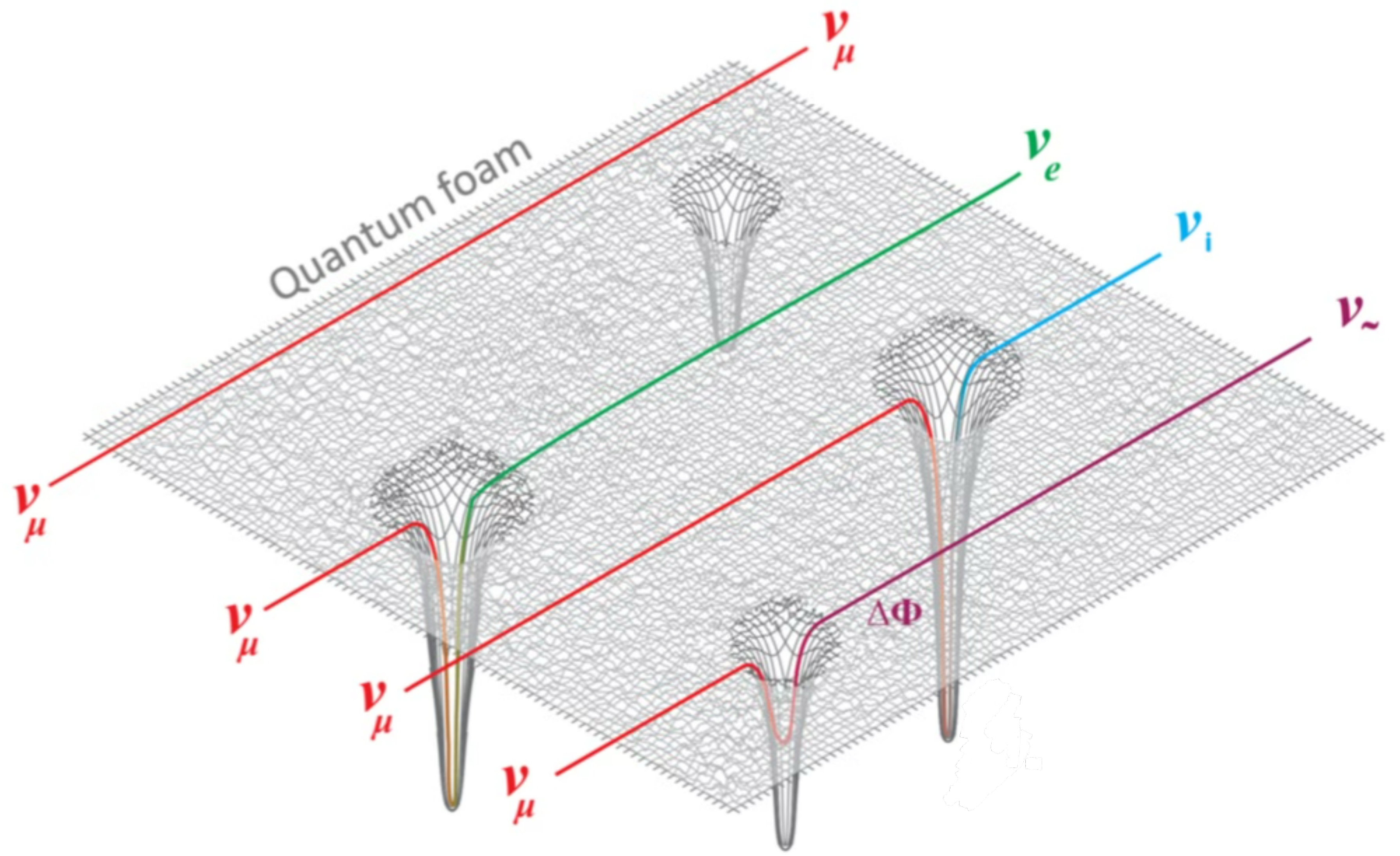
Method:

$$\dot{\rho} = -i[H, \rho] - \mathcal{D}[\rho]$$

$$D_{\text{phase perturbation}} = \text{diag}(0, \Gamma, \Gamma, 0, \Gamma, \Gamma, \Gamma, \Gamma, 0)$$

How the framework is applied to neutrino physics

Motivation:



From: The IceCube collaboration, Nature Physics 20, 913-920

Method:

$$\dot{\rho} = -i[H, \rho] - \mathcal{D}[\rho]$$

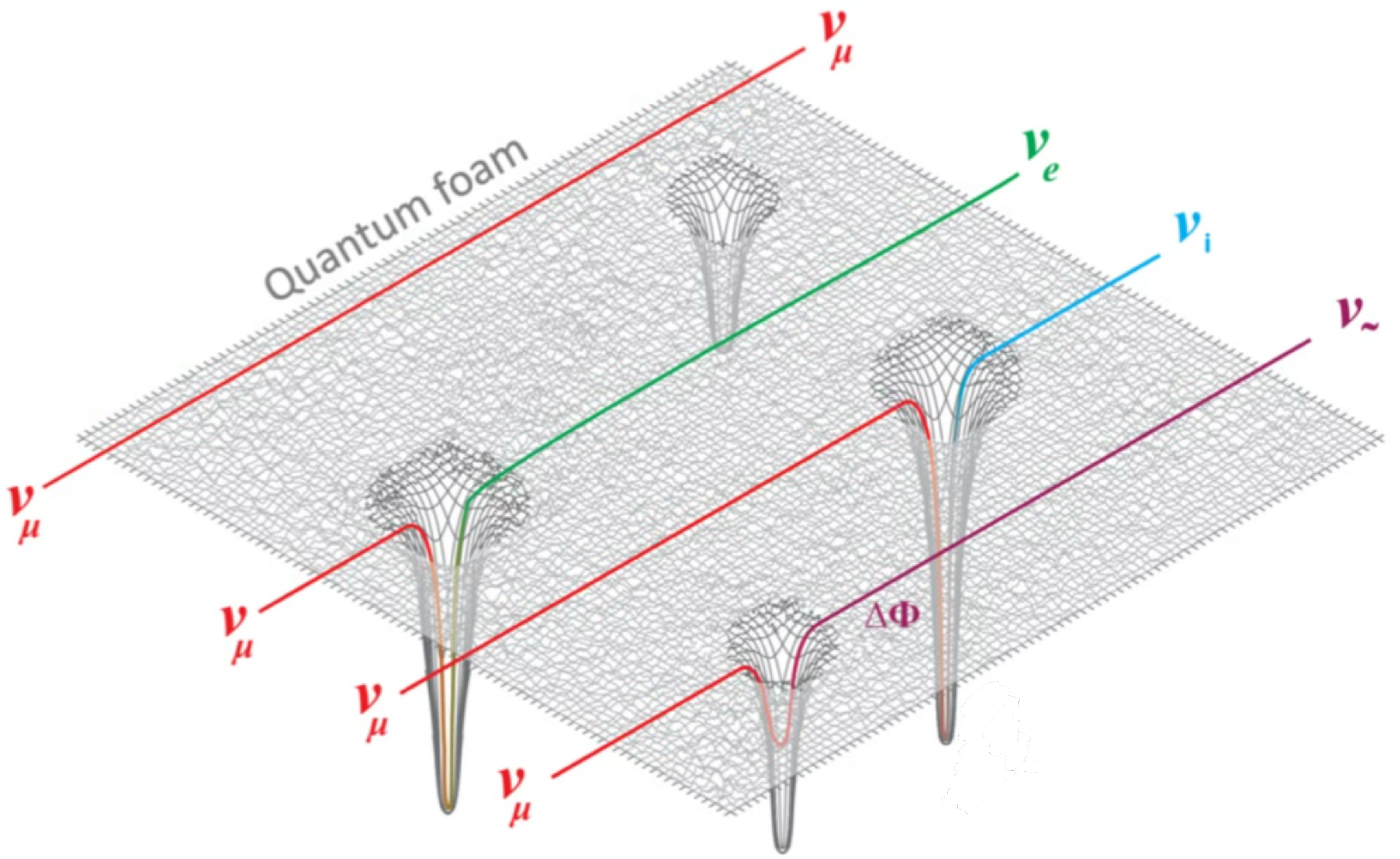
$$D_{\text{phase perturbation}} = \text{diag}(0, \Gamma, \Gamma, 0, \Gamma, \Gamma, \Gamma, \Gamma, 0)$$

Pheno:

$$\Gamma(E_\nu) = \Gamma_0 \left(\frac{E_\nu}{E_0} \right)^n$$

How the framework is applied to neutrino physics

Motivation:



From: The IceCube collaboration, Nature Physics 20, 913-920

Method:

$$\dot{\rho} = -i[H,\rho] - \mathcal{D}[\rho]$$

$$D_{\text{phase perturbation}} = \text{diag}(0,\Gamma,\Gamma,0,\Gamma,\Gamma,\Gamma,\Gamma,0)$$

Pheno:

$$\Gamma(E_\nu) = \Gamma_0 \left(\frac{E_\nu}{E_0}\right)^n$$

What is Γ?

Where does it come from? How?

Complete framework?

I will give you one concrete example

An open system approach to neutrino propagating through a ultralight scalar background

Lua F. T. Airoldi,[1,2,*] Gustavo F. S. Alves,[1,2,3,†] Pedro A. N. Machado,[2,‡] and Peter Vander Griend[2,4,§]

I will give you one concrete example

An open system approach to neutrino propagating through a ultralight scalar background

Lua F. T. Airoldi,[1,2,*] Gustavo F. S. Alves,[1,2,3,†] Pedro A. N. Machado,[2,‡] and Peter Vander Griend[2,4,§]

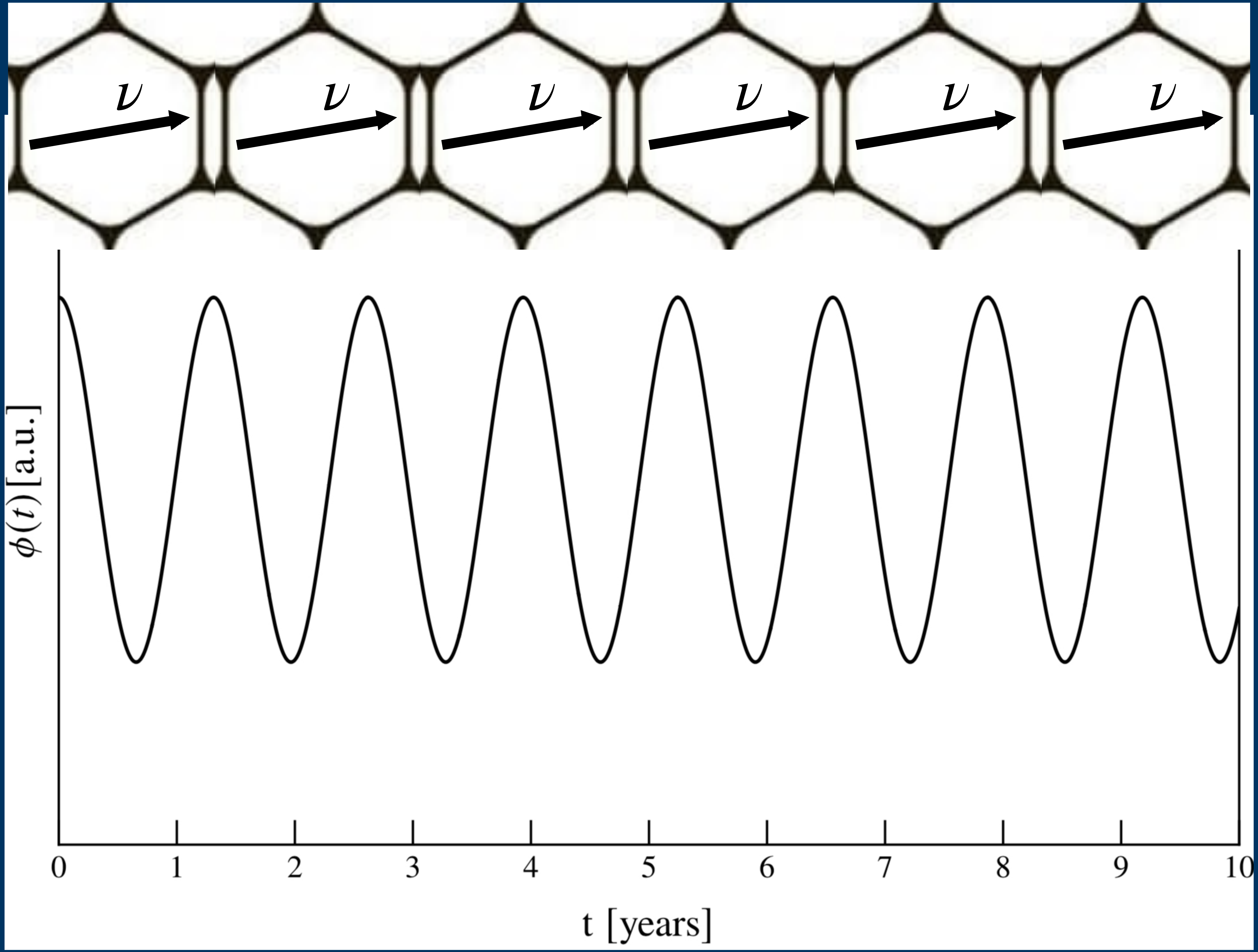
1. Mapping between model parameters and open systems framework

I will give you one concrete example

An open system approach to neutrino propagating through a ultralight scalar background

Lua F. T. Airoldi,[1,2,*] Gustavo F. S. Alves,[1,2,3,†] Pedro A. N. Machado,[2,‡] and Peter Vander Griend[2,4,§]

1. Mapping between model parameters and open system framework
2. This simple model eludes previous analyses


ν
$\phi(t)$ [a.u.]
0
1
2
3
4
5
6
7
8
9
10
t [years]

The field can be effectively described as

$$\phi(x, t) = \phi_0 \cos(\xi)$$

$$\xi \in [0,2\pi]$$

Setup

We will assume the scalar couples with all mass eigenstates with the same coupling constant

Impact on neutrino propagation

Neutrino Hamiltonian

$$H_\nu = H_0 + H_\phi$$

Impact on neutrino propagation

Neutrino Hamiltonian

$$H_\nu = H_0 + H_\phi$$

$$H_0 = \frac{1}{2E}\text{diag}(m_1^2, m_2^2, m_3^2)$$

Impact on neutrino propagation

Neutrino Hamiltonian

$$H_\nu = H_0 + H_\phi$$

$$H_0 = \frac{1}{2E}\mathrm{diag}(m_1^2, m_2^2, m_3^2)$$

$$H_\phi = g_\phi \frac{\phi_0}{E}\mathrm{diag}(m_1, m_2, m_3)\cos\xi$$

How to approach the problem?

Typically:

1. **Compute the time evolution for one neutrino.**

$$U(t,\xi) = \exp\left(-iH_\nu(\xi)t\right)$$

How to approach the problem?

Typically:

1. Compute the time evolution for one neutrino.
2. Compute the oscillation probability. It will be a function of an unknown phase.

How to approach the problem?

Typically:

1. **Compute the time evolution for one neutrino.**
2. **Compute the oscillation probability. It will be a function of an unknown phase.**
3. **Average over the phase.**

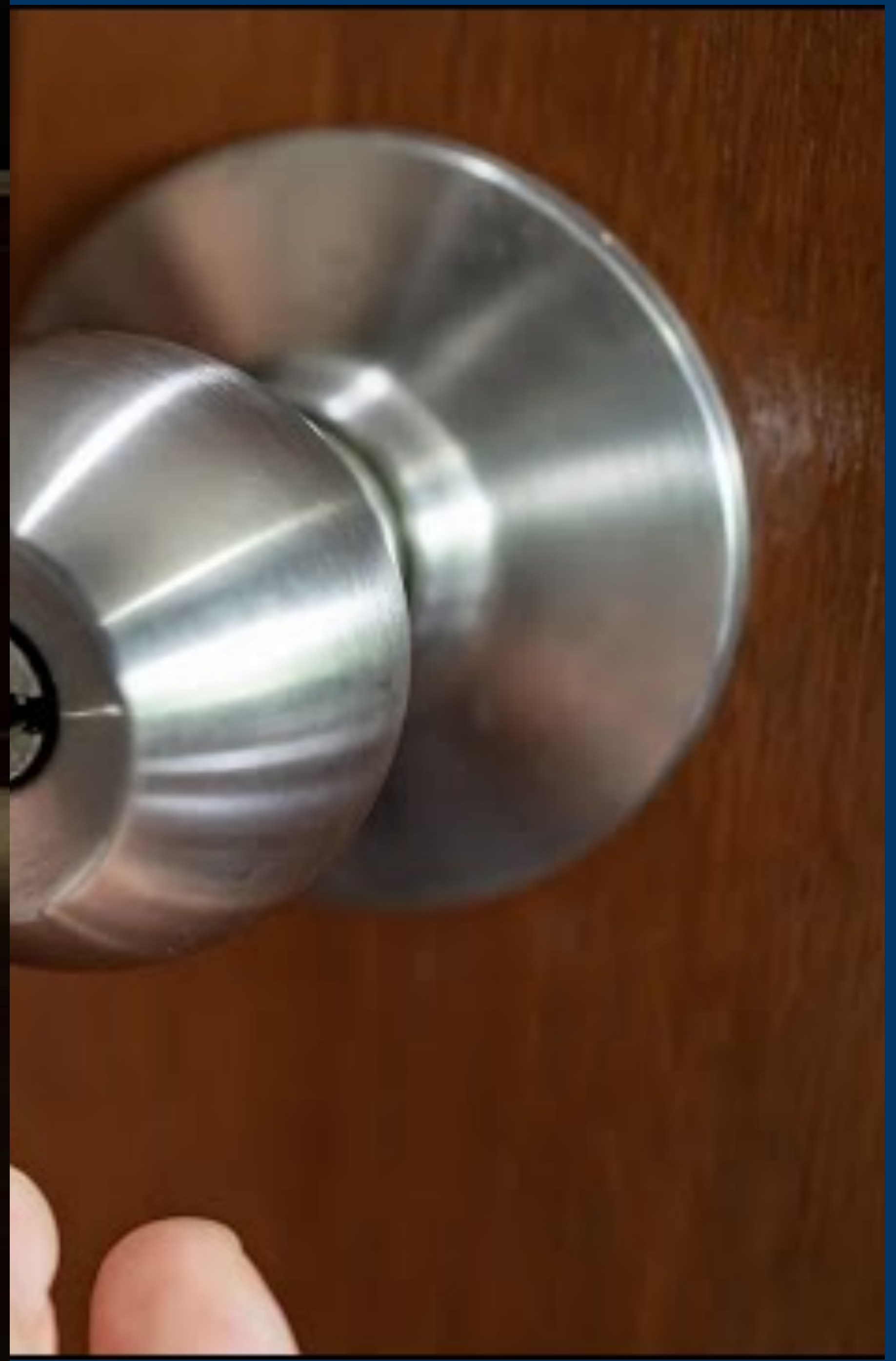
$$\overline{P} = \frac{1}{2\pi}\int_0^{2\pi} d\xi P(\xi)$$

This particular example is easy enough to treat analytically

Think of this problem as a door with a key

We will explore other methods





Density Operators

Quick review of density operators

Quick review of density operators

The density operator satisfies

$$\rho = \rho^\dagger \quad \mathrm{Tr}(\rho) = 1 \quad \rho \geq 0$$

Quick review of density operators

The density operator satisfies

$$\rho = \rho^\dagger \quad \mathrm{Tr}(\rho) = 1 \quad \rho \geq 0$$

Given a ket $|\psi\rangle$ **the density operator for the state is**

$$\rho = |\psi\rangle\langle\psi|$$

Quick review of density operators

The density operator satisfies

$$\rho = \rho^\dagger \quad \mathrm{Tr}(\rho) = 1 \quad \rho \geq 0$$

Given a ket $|\psi\rangle$ the density operator for the state is

$$\rho = |\psi\rangle\langle\psi|$$

This is a <u>pure state</u>.

Quick review of density operators

The density operator satisfies

$$\rho = \rho^{\dagger} \quad \mathrm{Tr}(\rho) = 1 \quad \rho \geq 0$$

Given a ket $|\psi\rangle$ the density operator for the state is

$$\rho = |\psi\rangle\langle\psi|$$

This is a <u>pure state</u>.

Any pure state satisfies $\mathrm{Tr}(\rho^2) = 1$

Quick review of density operators

Simple example

$$|\nu_e\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$

$$\rho_e = |\nu_e\rangle\langle\nu_e| = \begin{pmatrix} \cos^2\theta & \cos\theta\sin\theta \\ \cos\theta\sin\theta & \sin^2\theta \end{pmatrix}$$

Quick review of density operators

Mixed states have the form

$$\rho = \sum_i p_i |\psi_i\rangle\langle\psi_i|$$

With $\mathrm{Tr}(\rho^2) < 1$

Quick review of density operators

Simple example

$$\rho = \cos\theta^2 \,|\nu_1\rangle\langle\nu_1| + \sin\theta^2 \,|\nu_2\rangle\langle\nu_2|$$

$$\rho = \begin{pmatrix} \cos^2\theta & 0 \\ 0 & \sin^2\theta \end{pmatrix}$$

$$\mathrm{Tr}(\rho^2) < 1$$

Quick review of density operators

Time evolution

$$\partial_t \rho(t) = -i[H, \rho(t)]$$

$$\rho(t) = U(t)\rho(0)U^\dagger(t)$$

Quick review of density operators

Time evolved neutrino state

$$|\nu_e\rangle = \cos\theta e^{-iE_1 t}|\nu_1\rangle + \sin\theta e^{-iE_2 t}|\nu_2\rangle$$

$$\rho_e = |\nu_e\rangle\langle\nu_e| = \begin{pmatrix} \cos^2\theta & \cos\theta\sin\theta e^{-i\Delta E_{12} t} \\ \cos\theta\sin\theta e^{i\Delta E_{12} t} & \sin^2\theta \end{pmatrix}$$

Quick review of density operators

Time evolution with open systems

$$\partial_t \rho(t) = -i[H, \rho(t)] - L^\dagger L \rho(t) - \rho(t) L^\dagger L + 2L\rho(t)L^\dagger$$

A taste of open systems effects

Time evolved neutrino state

$$\rho_e = |\nu_e\rangle\langle\nu_e| = \begin{pmatrix} \cos^2\theta & \cos\theta\sin\theta e^{-i\Delta E_{12}t-\Gamma L} \\ \cos\theta\sin\theta e^{i\Delta E_{12}t-\Gamma L} & \sin^2\theta \end{pmatrix}$$

A taste of open systems effects

Time evolved neutrino state

$$\rho_e = |\nu_e\rangle\langle\nu_e| = \begin{pmatrix} \cos^2\theta & \cos\theta\sin\theta e^{-i\Delta E_{12}t-\Gamma L} \\ \cos\theta\sin\theta e^{i\Delta E_{12}t-\Gamma L} & \sin^2\theta \end{pmatrix}$$

For large L

$$\rho_e = |\nu_e\rangle\langle\nu_e| = \begin{pmatrix} \cos^2\theta & 0 \\ 0 & \sin^2\theta \end{pmatrix}$$

How to find the master equation

How to find the master equation

This is not a AI generated output*

How to get the master equation?

Recall

$$\rho(t,\xi) = U(t,\xi)\rho(0)U^\dagger(t,\xi)$$

How to get the master equation?

Recall

$$\rho(t,\xi) = U(t,\xi)\rho(0)U^\dagger(t,\xi)$$

Average

$$\overline{\rho}(t) = \frac{1}{2\pi}\int_0^{2\pi} d\xi U(t,\xi)\rho(0)U^\dagger(t,\xi)$$

How to get the master equation?

Define

$$\Delta U = U(t,\xi) - \overline{U}(t) \qquad \overline{U}(t) = \frac{1}{2\pi}\int_0^{2\pi} d\xi U(t,\xi)$$

How to get the master equation?

Define

$$\Delta U = U(t,\xi) - \overline{U}(t) \qquad \overline{U}(t) = \frac{1}{2\pi}\int_0^{2\pi} d\xi U(t,\xi)$$

We can rewrite

$$\overline{\rho}(t) = \overline{U}(t)\rho(0)\overline{U}^\dagger(t) + \frac{1}{2\pi}\int_0^{2\pi} d\xi \Delta U(t,\xi)\rho(0)\Delta U^\dagger(t,\xi)$$

How to get the master equation?

Define an effective hamiltonian

$$\partial_t \overline{U}(t) = -\, iV(t)\overline{U}(t)$$

Burgess, et al., Annals of Physics
Volume 256, Issue 1, 1

How to get the master equation?

Define an effective hamiltonian

$$\partial_t \overline{U}(t) = -iV(t)\overline{U}(t)$$

Burgess, et al., Annals of Physics Volume 256, Issue 1, 1

We find the time evolution equation

$$\partial_t \overline{\rho}(t) = -i[V(t), \overline{\rho}(t)] + \partial_t \left(\frac{1}{2\pi} \int_0^{2\pi} d\xi \Delta U(t,\xi) \rho(0) \Delta U^\dagger(t,\xi) \right)$$

How to get the master equation?

To second order in perturbation theory

$$U(t,\xi) \approx \mathbf{1} - i\int_0^t d\tau H(\tau,\xi) - \int_0^t d\tau \int_0^\tau d\tau' H(\tau,\xi)H(\tau',\xi)$$

We can determine $V(t)$ and $\Delta U(t,\xi)$

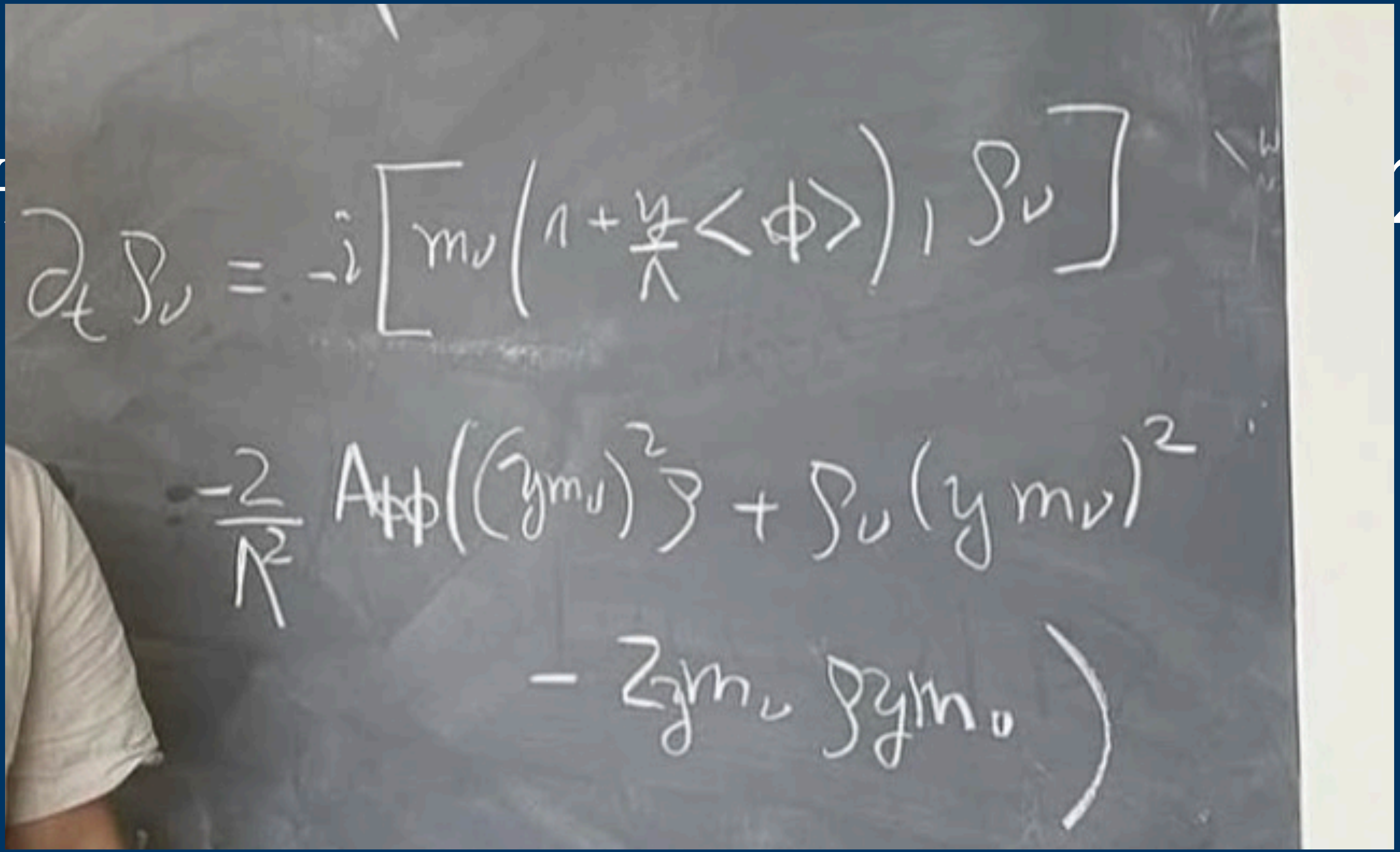
The master equation

$$\partial_t \overline{\rho}(t) = -\, i[H_0, \overline{\rho}(t)] - \frac{g_\phi^2 \phi_0^2 t}{2E^2}(\hat{m}_\nu^2 \overline{\rho}(t) + \overline{\rho}(t)\hat{m}_\nu^2 - 2\hat{m}_\nu \overline{\rho}(t)\hat{m}_\nu)$$

$$\hat{m}_\nu = \mathrm{diag}(m_1, m_2, m_3)$$

The master equation

$\partial_t \overline{\rho}(t) = -\, i[H$ … $2\hat{m}_\nu \overline{\rho}(t)\hat{m}_\nu)$



The master equation

$$\partial_t \overline{\rho}(t) = -i[H_0, \overline{\rho}(t)] - \frac{g_\phi^2 \phi_0^2 t}{2E^2}\left(\hat{m}_\nu^2 \overline{\rho}(t) + \overline{\rho}(t)\hat{m}_\nu^2 - 2\hat{m}_\nu \overline{\rho}(t)\hat{m}_\nu\right)$$

JUNO is the best candidate to search for these effects.

The master equation

$$\partial_t \overline{\rho}(t) = -i[H_0, \overline{\rho}(t)] - \frac{g_\phi^2 \phi_0^2 t}{2E^2}\left(\hat{m}_\nu^2 \overline{\rho}(t) + \overline{\rho}(t)\hat{m}_\nu^2 - 2\hat{m}_\nu \overline{\rho}(t)\hat{m}_\nu\right)$$

Let's have a look at the probability

How does the probability change?

$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) \approx 1 - \frac{1}{2}\left(\sin^2(2\theta_{13}) + \sin^2(2\theta_{12})\right)$$

$$-\exp\left(-\frac{(\Delta_{21}^{\phi})^2}{4}\right)P_{\odot}$$

$$+\exp\left(-\frac{(\Delta_{atm}^{\phi})^2}{4}\right)\frac{\sin^2(2\theta_{13})}{2}\sqrt{1 - \sin^2(2\theta_{12})\sin^2\Delta_{21}}\cos(2|\Delta_{ee}| \pm \Phi_{\odot})$$

How does the probability change?

$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) \approx 1 - \frac{1}{2}\left(\sin^2(2\theta_{13}) + \sin^2(2\theta_{12})\right)$$
$$-\exp\left(-\frac{(\Delta_{21}^{\phi})^2}{4}\right)P_{\odot}$$
$$+\exp\left(-\frac{(\Delta_{atm}^{\phi})^2}{4}\right)\frac{\sin^2(2\theta_{13})}{2}\sqrt{1 - \sin^2(2\theta_{12})\sin^2\Delta_{21}}\cos(2|\Delta_{ee}| \pm \Phi_{\odot})$$

$$\Delta_{ee} = \cos^2\theta_{12}\Delta_{31} + \sin^2\theta_{12}\Delta_{32}$$

$$\Phi_{\odot} = \arctan(\cos 2\theta_{12}\tan\Delta_{21}) - \Delta_{21}\cos 2\theta_{12}$$

$$\cos^4\theta_{13} \approx 1$$

How does the probability change?

$$P(\overline{\nu}_e \to \overline{\nu}_e) \approx 1 - \frac{1}{2}\left(\sin^2(2\theta_{13}) + \sin^2(2\theta_{12})\right)$$
$$-\exp\left(-\frac{(\Delta_{21}^{\phi})^2}{4}\right) P_\odot$$
$$+\exp\left(-\frac{(\Delta_{atm}^{\phi})^2}{4}\right) \frac{\sin^2(2\theta_{13})}{2} \sqrt{1 - \sin^2(2\theta_{12})\sin^2\Delta_{21}} \cos(2|\Delta_{ee}| \pm \Phi_\odot)$$

$$P_\odot \approx \sin^2 2\theta_{12} \sin^2 \Delta_{21}$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2}{4E} L$$

How does the probability change?

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \frac{1}{2}\left(\sin^2(2\theta_{13}) + \sin^2(2\theta_{12})\right)$$
$$-\exp\left(-\frac{(\Delta^{\phi}_{21})^2}{4}\right)P_{\odot}$$
$$+\exp\left(-\frac{(\Delta^{\phi}_{atm})^2}{4}\right)\frac{\sin^2(2\theta_{13})}{2}\sqrt{1-\sin^2(2\theta_{12})\sin^2\Delta_{21}}\cos(2|\Delta_{ee}| \pm \Phi_{\odot})$$

$$\Delta^{\phi}_{ij} = g_{\phi}\phi_0\frac{(m_i - m_j)}{E}L$$

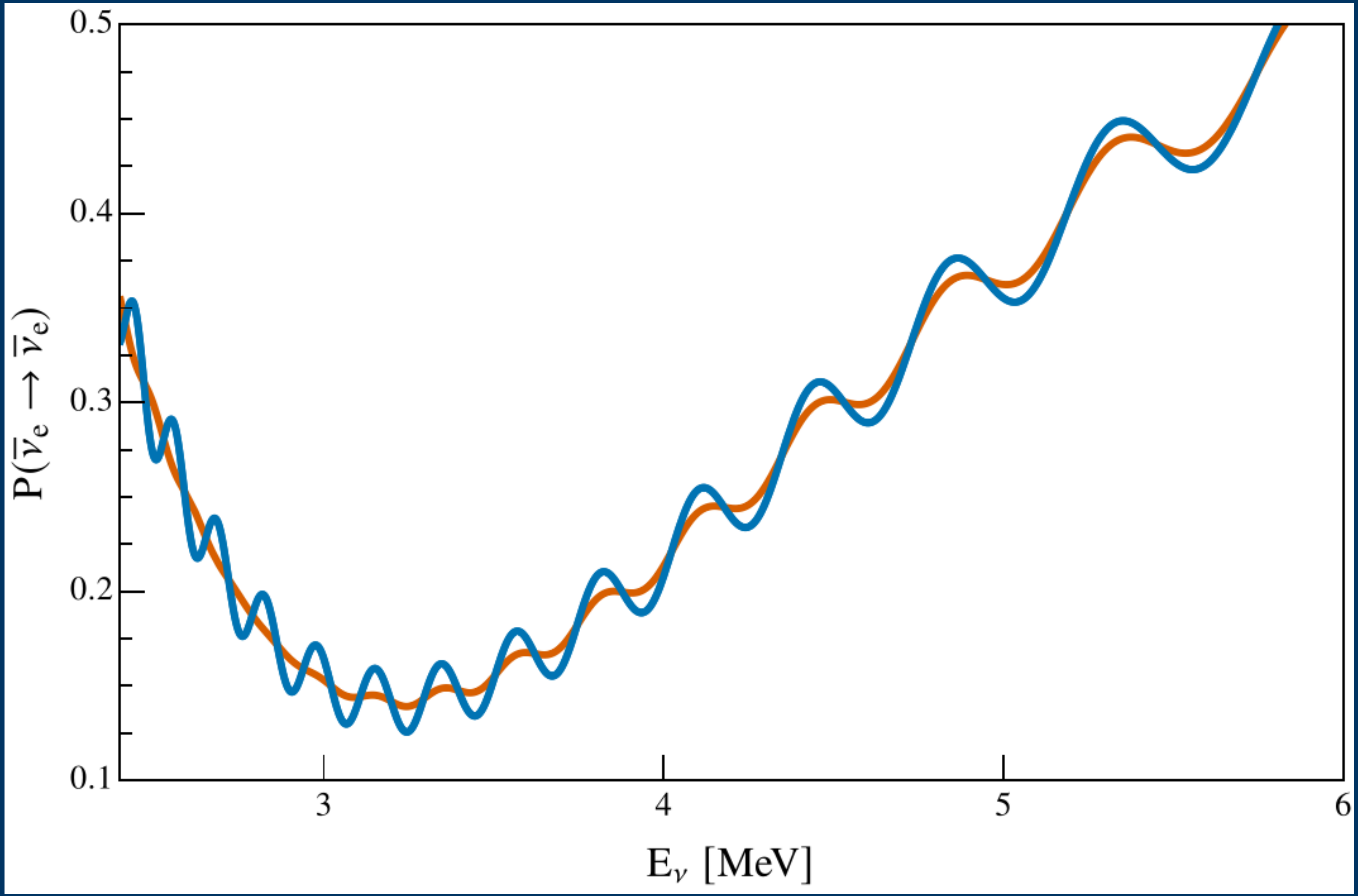
How does the probability change?

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \frac{1}{2}\left(\sin^2(2\theta_{13}) + \sin^2(2\theta_{12})\right)$$
$$-\exp\left(-\frac{(\Delta_{21}^{\phi})^2}{4}\right) P_{\odot}$$
$$+\exp\left(-\frac{(\Delta_{atm}^{\phi})^2}{4}\right) \frac{\sin^2(2\theta_{13})}{2}\sqrt{1 - \sin^2(2\theta_{12})\sin^2\Delta_{21}}\cos(2|\Delta_{ee}| \pm \Phi_{\odot})$$

$$\Delta_{ij}^{\phi} = g_{\phi}\phi_0 \frac{(m_i - m_j)}{E} L$$

Scaling as L^2/E^2

Consequences



Consequences

For large L

$$P(\bar{\nu}_e \to \bar{\nu}_e) \to 1 - \frac{1}{2}\left(\sin^2(2\theta_{13}) + \sin^2(2\theta_{12})\right)$$

The exact solution

$$P(\overline{\nu}_e \to \overline{\nu}_e) \approx 1 - \frac{1}{2}\left(\sin^2(2\theta_{13}) + \sin^2(2\theta_{12})\right)$$

$$-J_0(\Delta_{21}^{\phi})P_{\odot}$$

$$+J_0(\Delta_{\text{atm}}^{\phi})\frac{\sin^2(2\theta_{13})}{2}\sqrt{1 - \sin^2(2\theta_{12})\sin^2\Delta_{21}}\cos(2\,|\,\Delta_{ee}\,|\pm\Phi_{\odot})$$

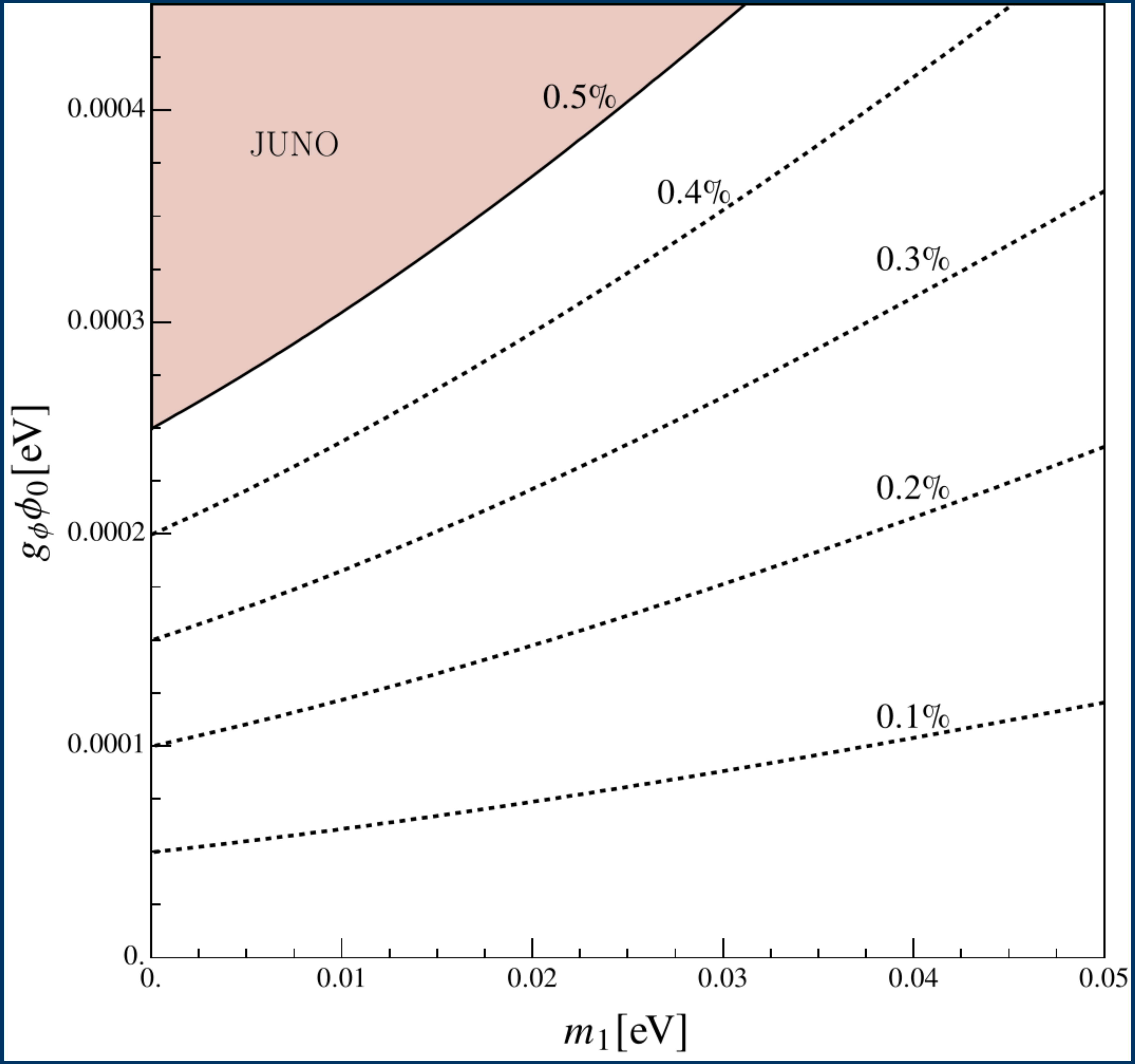
To leading order they coincide

$$J_0(x) = 1 - \frac{x^2}{4} + \mathcal{O}(x^4)$$

$$\exp\left(-\frac{x^2}{4}\right) = 1 - \frac{x^2}{4} + \mathcal{O}(x^4)$$

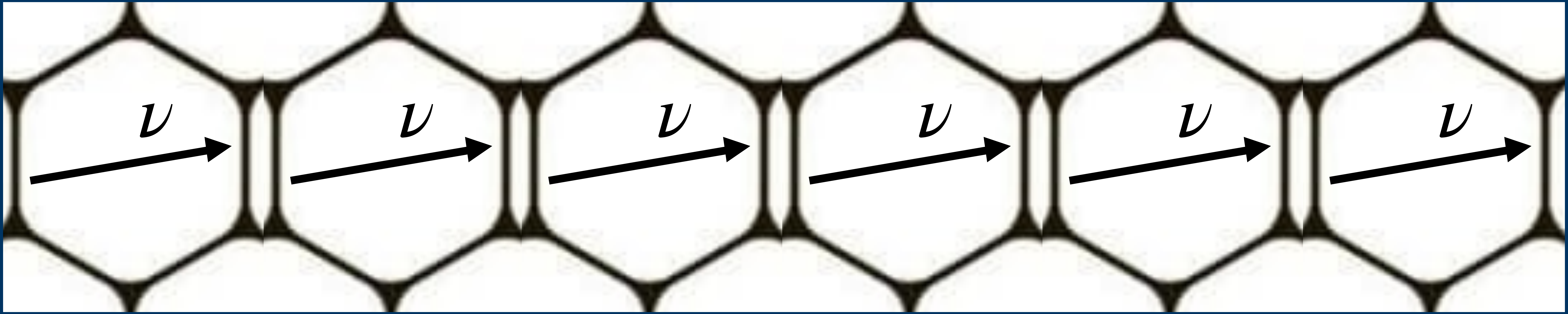
Open system can be mapped to model parameters

$$g_\phi \phi_0 (m_i - m_j) = \Delta m^2_{ij} (\eta_\phi)_{ij}$$



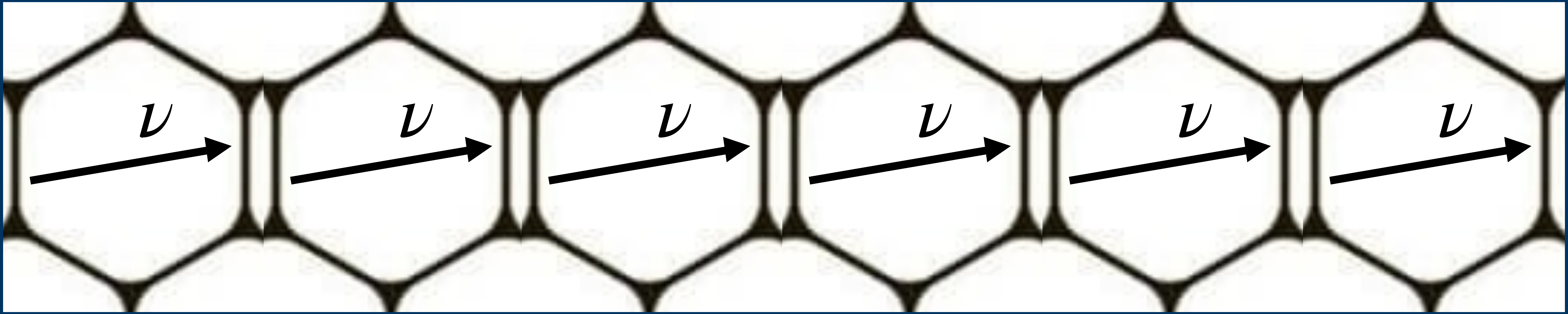
For JUNO: Delgadillo, arXiv:2512.18186

Statistical decoherence, not quantum



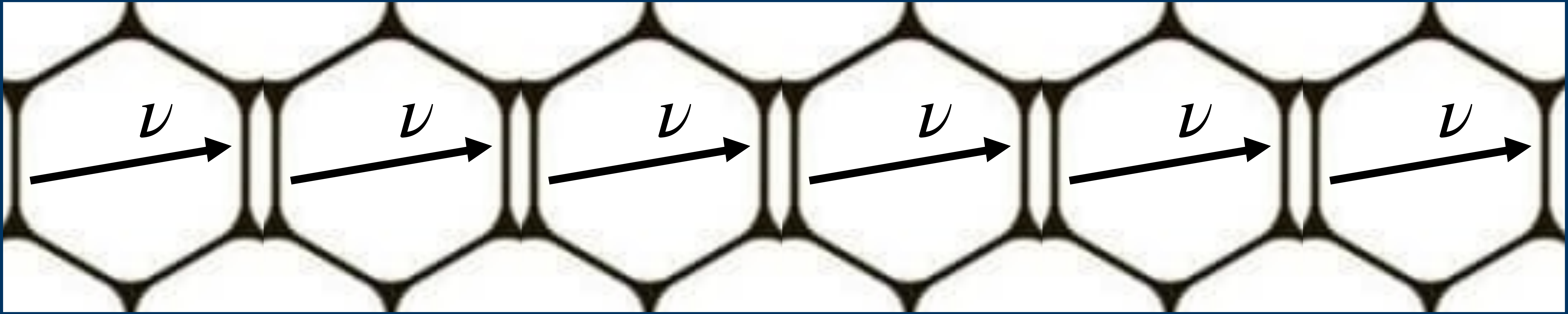
Statistical decoherence, not quantum

$\rho(t, \xi_1)$



Statistical decoherence, not quantum

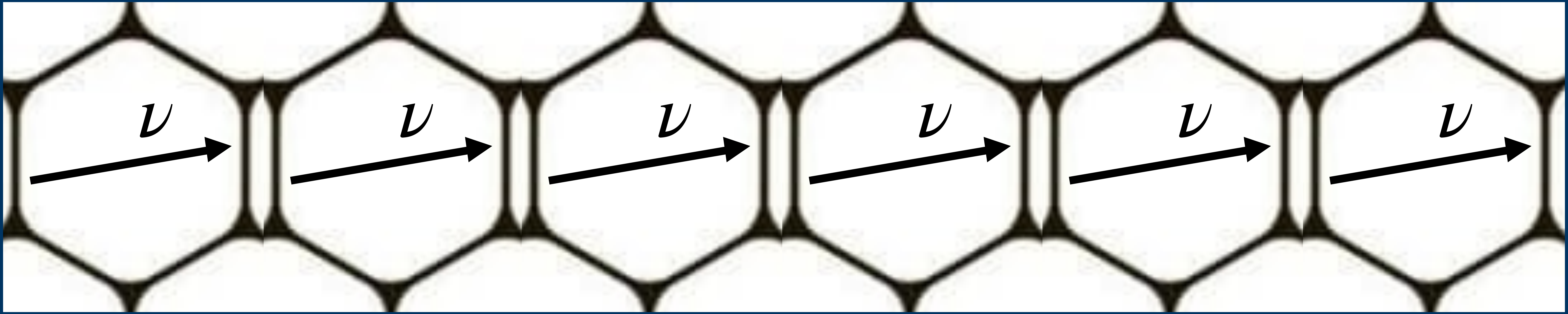
$\rho(t, \xi_1)$ $\rho(t, \xi_2)$ $\rho(t, \xi_3)$ $\rho(t, \xi_4)$ $\rho(t, \xi_5)$ $\rho(t, \xi_6)$



$$\mathrm{Tr}(\rho^2) = 1$$

Statistical decoherence, not quantum

$\rho(t, \xi_1)$ $\rho(t, \xi_2)$ $\rho(t, \xi_3)$ $\rho(t, \xi_4)$ $\rho(t, \xi_5)$ $\rho(t, \xi_6)$



$$\bar{\rho}(t) = \frac{1}{2\pi}\int_0^{2\pi} d\xi U(t,\xi)\rho(0)U^\dagger(t,\xi)$$

$$\mathrm{Tr}(\bar{\rho}^2) < 1$$

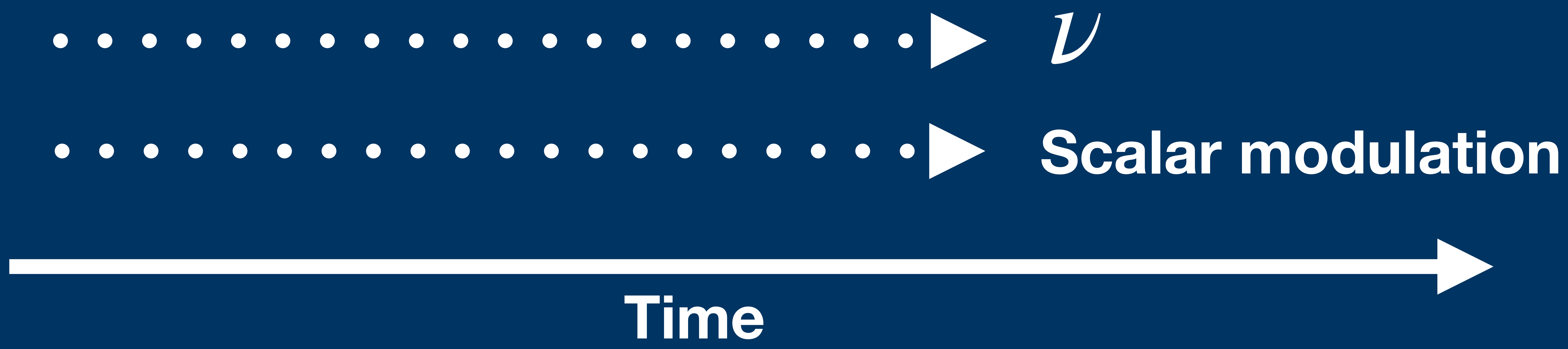
Routes to pursue

“The end of a story is like the end of a good meal. We’re sated but it doesn’t mean that we will never be hungry again.”

— Kate Tellers

Can we have an observable quantum decoherence effect?

Dynamical field regime



How the master equation should look

$$\partial_t \rho(t) = -i[H_0 + H_\phi(t), \rho(t)]$$

$$-\int d\tau \int d\tau' \frac{\mathrm{Tr}(\Delta\phi(\tau)\Delta\phi(\tau')\rho_\phi)}{2E^2}(\hat{m}_\nu^2 \rho(t) + \rho(t)\hat{m}_\nu^2 - 2\hat{m}_\nu \rho(t) \hat{m}_\nu)$$

$$\Delta\phi = \phi - \mathrm{Tr}(\phi\rho_\phi) \qquad \rho_\phi = \int d\alpha P(\alpha) |\alpha\rangle\langle\alpha|$$

Requirements

1. **We must fix the scalar state ρ_ϕ.**

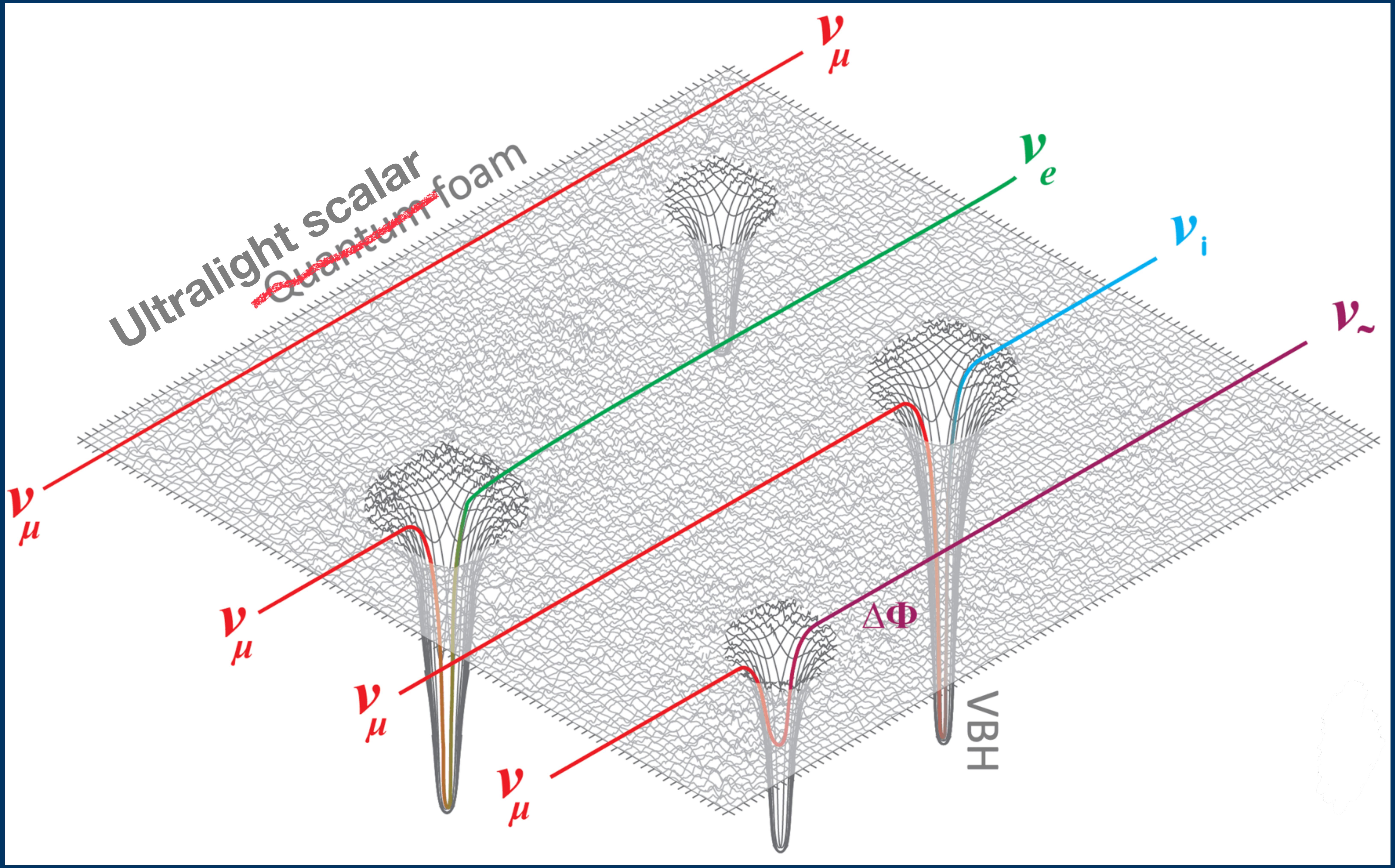
Requirements

1. We must fix the scalar state ρ_ϕ.
2. The field must have a nontrivial variance $\langle \Delta\phi \Delta\phi \rangle$

Requirements

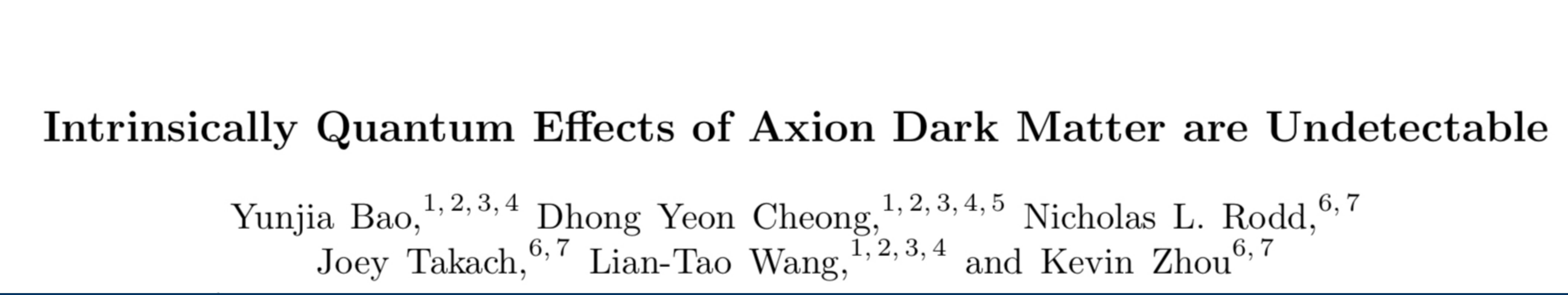
1. We must fix the scalar state ρ_ϕ.
2. The field must have a nontrivial variance $\langle \Delta\phi \Delta\phi \rangle$
3. The field must not oscillate too fast

Routes to pursue



Can we probe true quantum decoherence instead of statistical decoherence?

Routes to pursue


Intrinsically Quantum Effects of Axion Dark Matter are Undetectable

Yunjia Bao,[1,2,3,4] Dhong Yeon Cheong,[1,2,3,4,5] Nicholas L. Rodd,[6,7]
Joey Takach,[6,7] Lian-Tao Wang,[1,2,3,4] and Kevin Zhou[6,7]

$$\rho_\phi = \int d\alpha P(\alpha) \, |\alpha\rangle\langle\alpha|$$

Routes to pursue

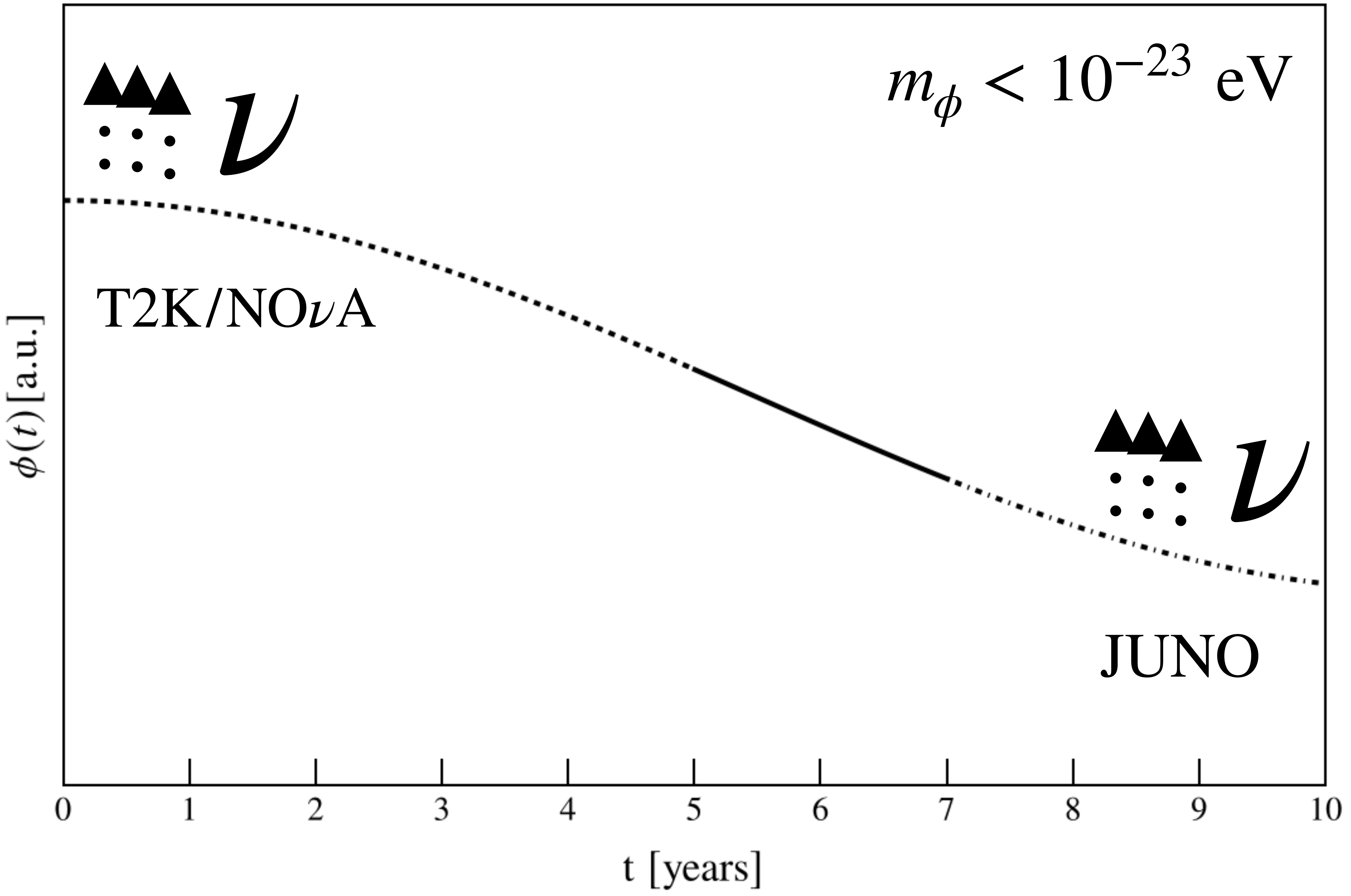
Intrinsically Quantum Effects of Axion Dark Matter are Undetectable

Yunjia Bao,[1,2,3,4] Dhong Yeon Cheong,[1,2,3,4,5] Nicholas L. Rodd,[6,7]
Joey Takach,[6,7] Lian-Tao Wang,[1,2,3,4] and Kevin Zhou[6,7]

Any hope from the neutrino side?

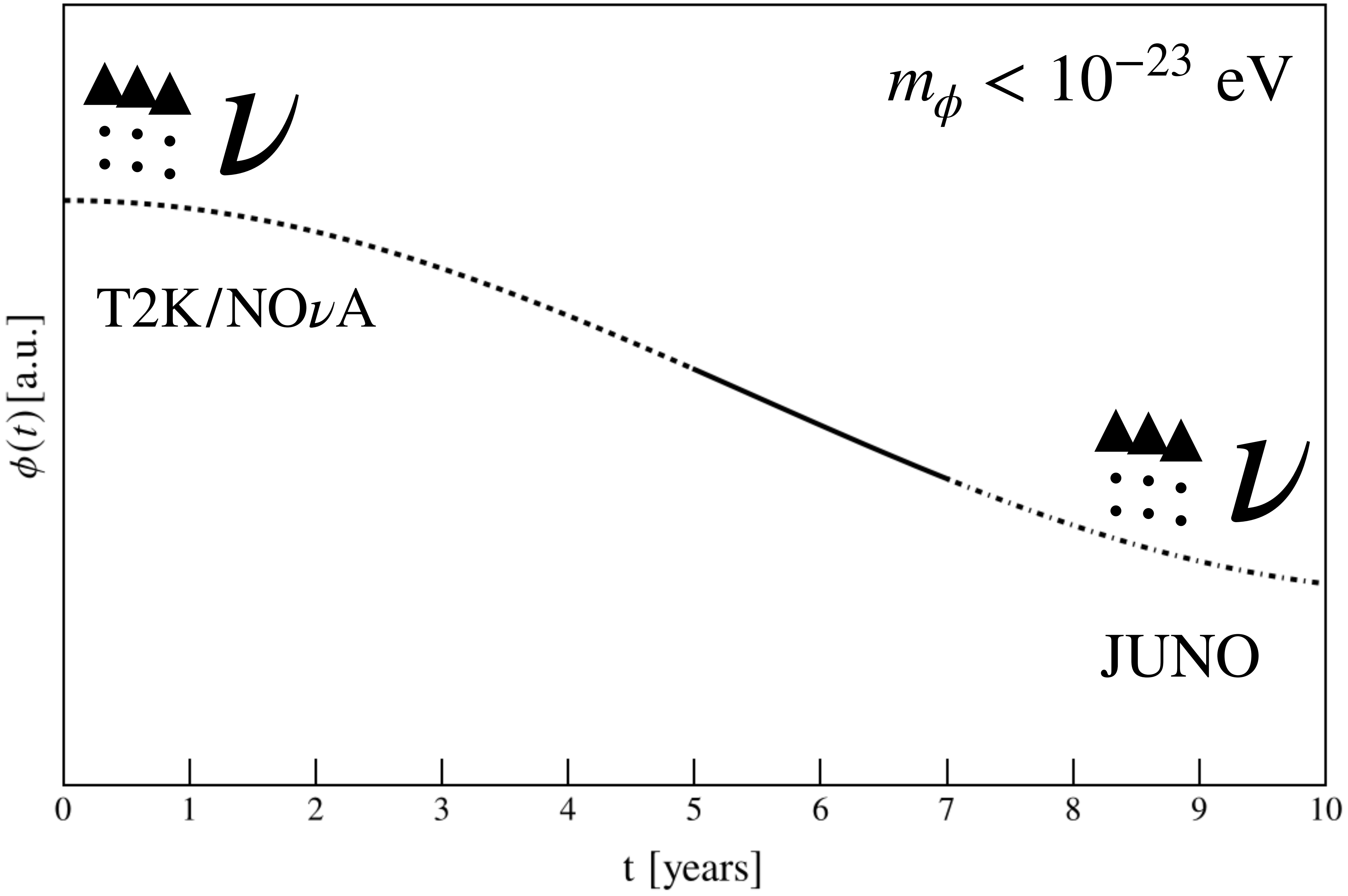
Summary

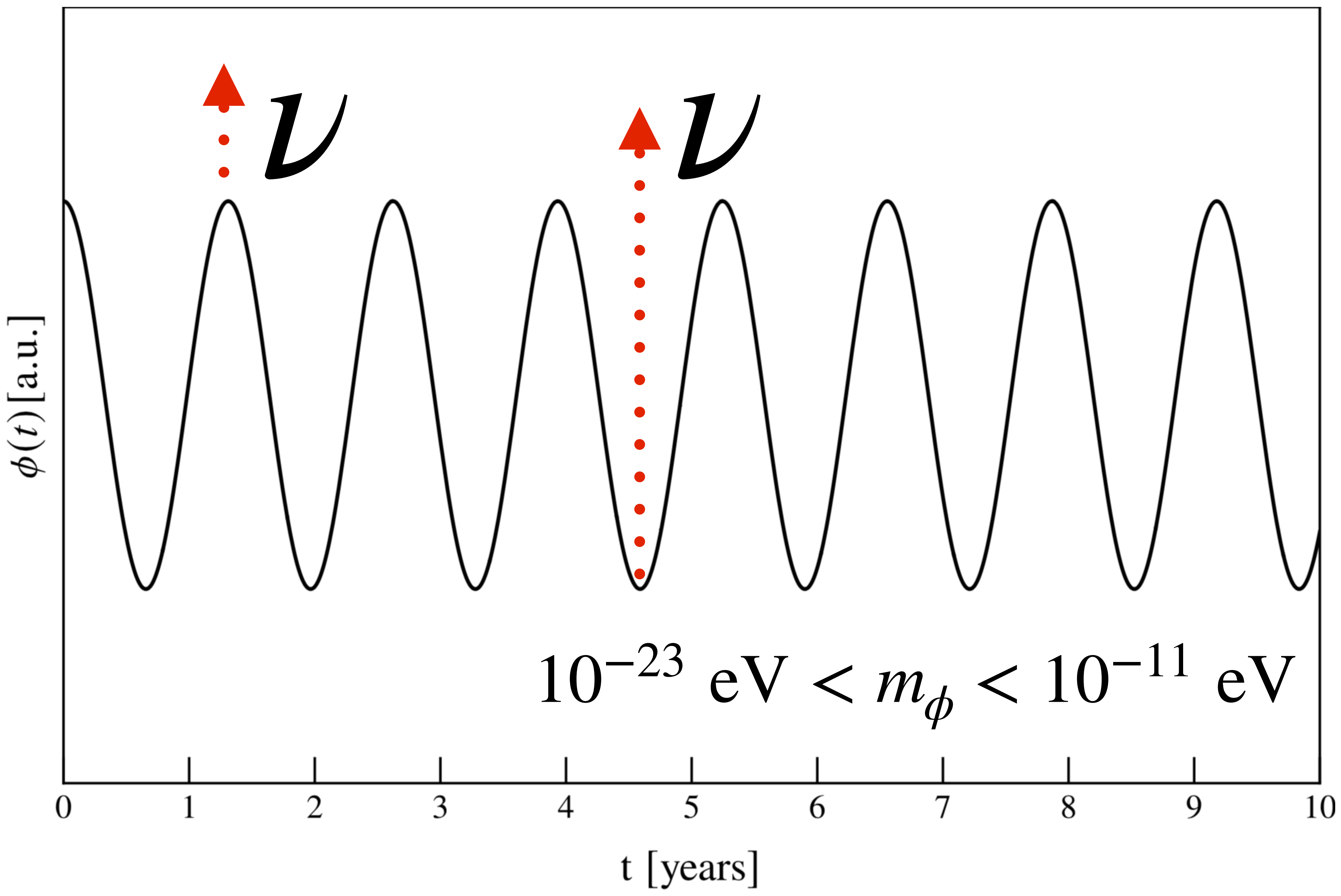
Quick recap



$m_\phi < 10^{-23}$ eV
ν
T2K/NOνA
ν
JUNO
$\phi(t)$ [a.u.]
0
1
2
3
4
5
6
7
8
9
10
t [years]

Quick recap


$m_\phi < 10^{-23}$ eV
T2K/NOνA
JUNO
ν
ν
$\phi(t)$ [a.u.]
t [years]
0 1 2 3 4 5 6 7 8 9 10


ν
ν
10^{-23} eV $< m_\phi < 10^{-11}$ eV
$\phi(t)$ [a.u.]
t [years]
0 1 2 3 4 5 6 7 8 9 10

If neutrino masses are clocks, can we hear them tick?

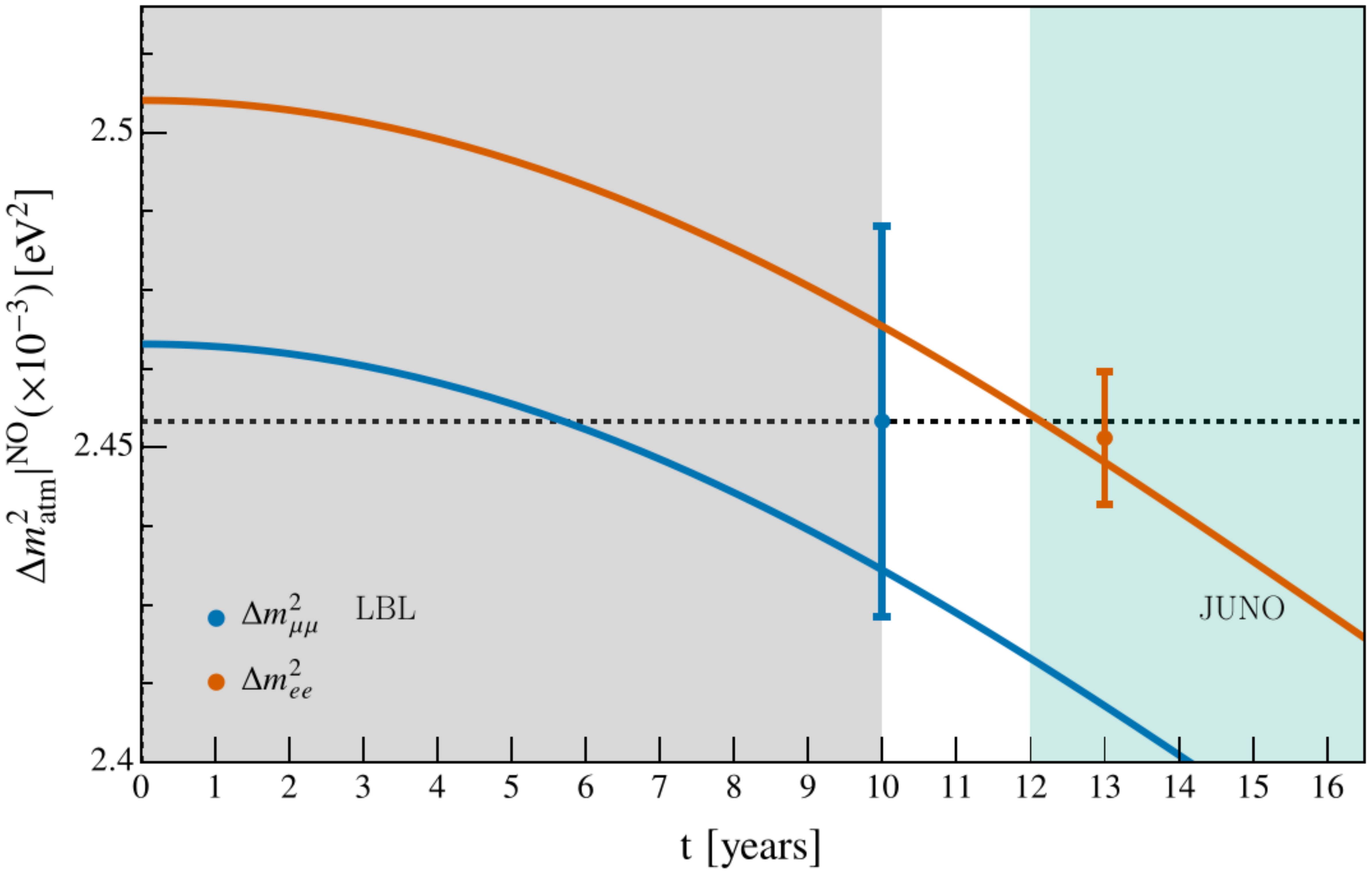
If neutrino masses are clocks, can we hear them tick?

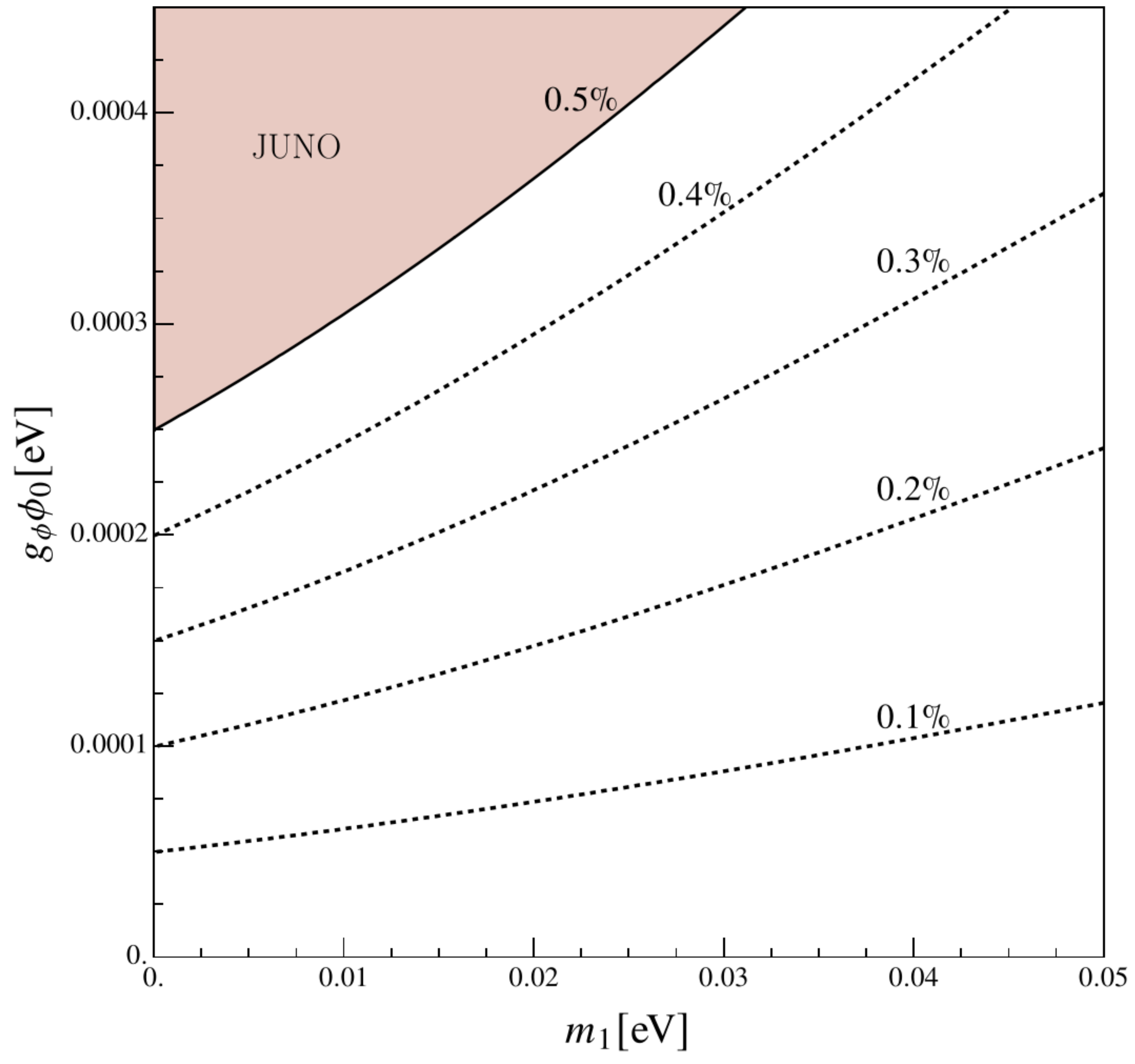
Yes.

And even if we listen only to the sound of silence…

And even if we listen only to the sound of silence…

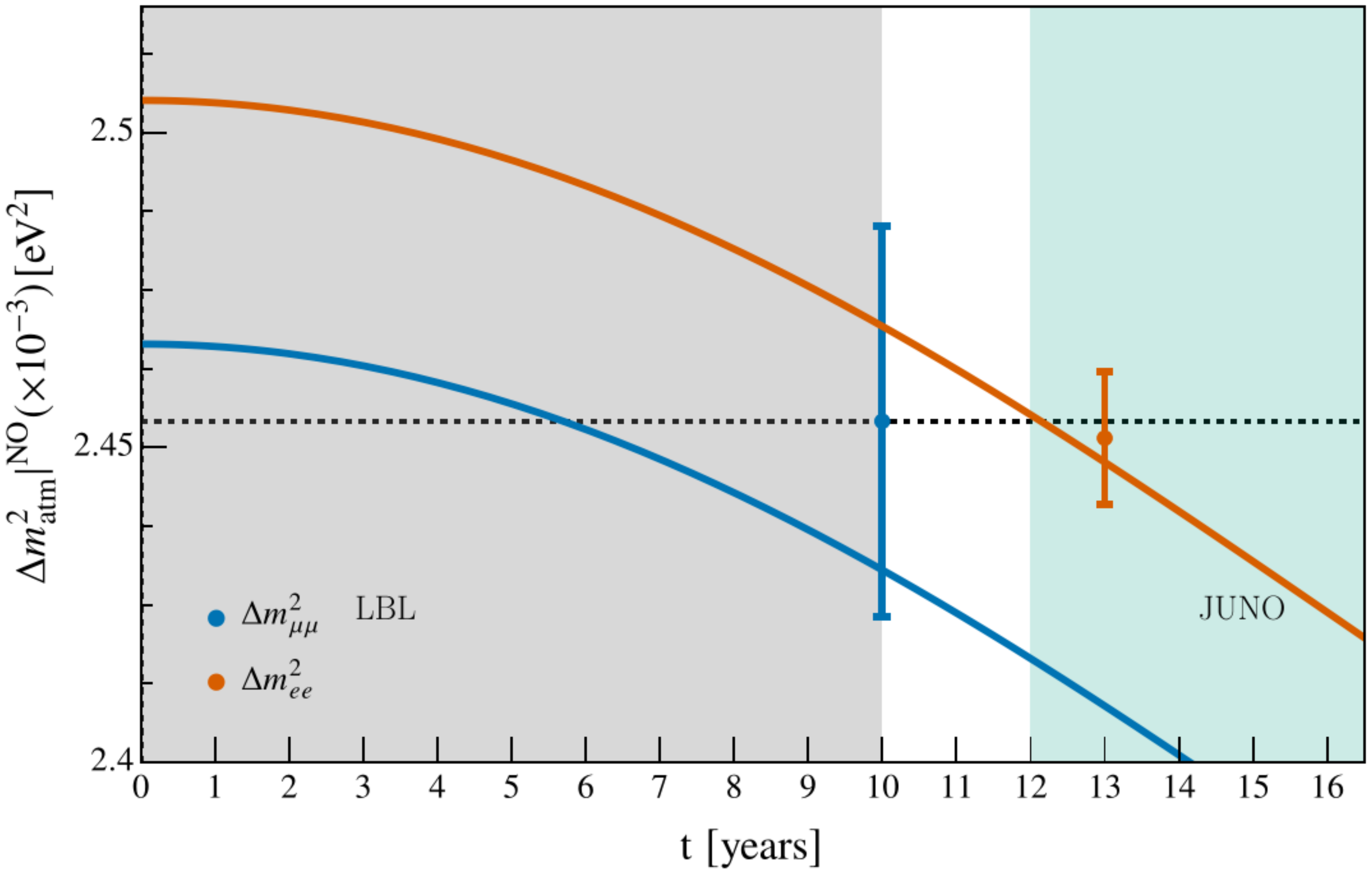
We can still learn something new!

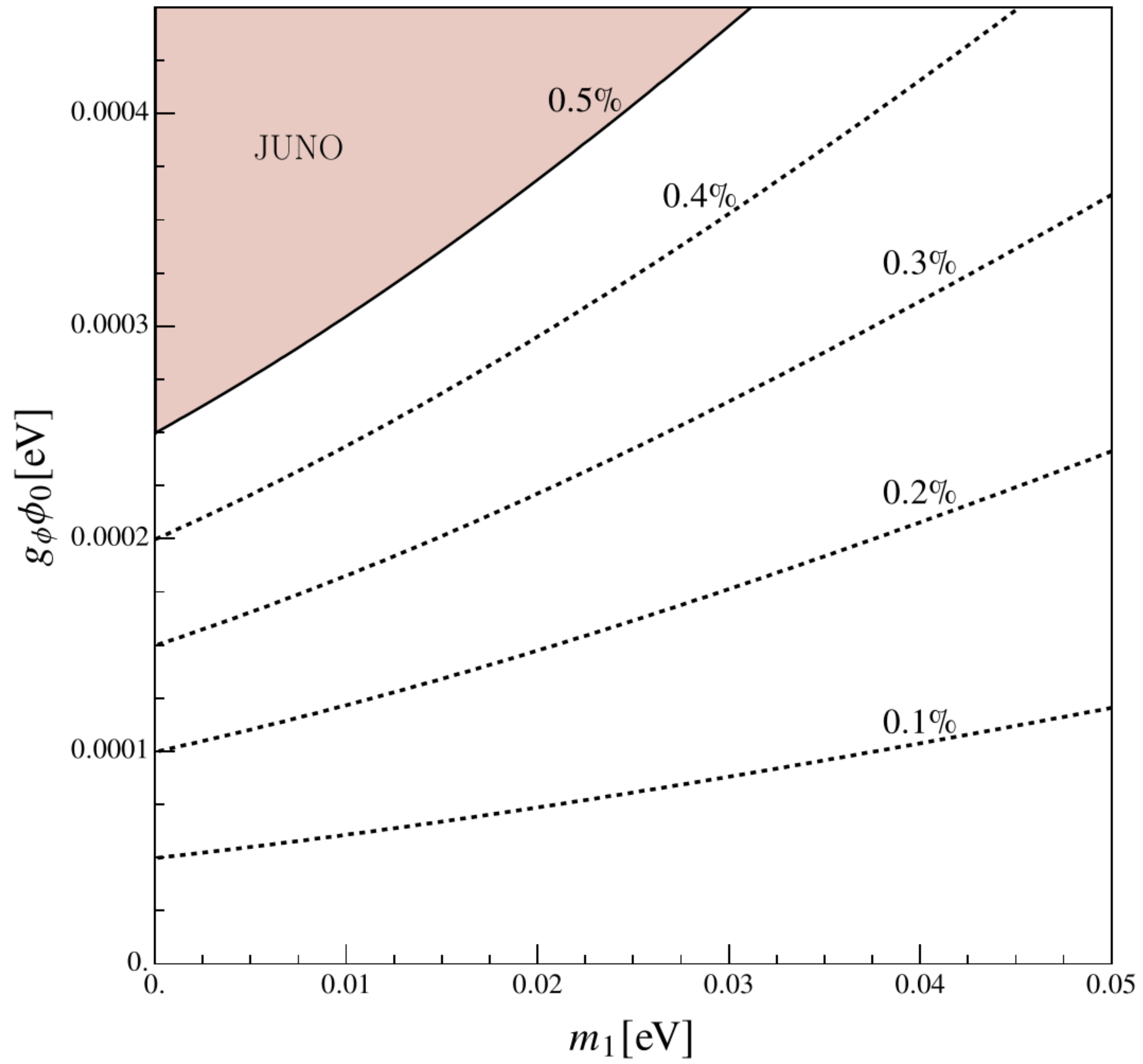




And even if we listen only to the sound of silence…

We can still learn something new!





Thank you!

BACKUP

"Vectorizing" the time evolution

$$\rho(t,\xi) = \sum_{\mu=0}^{8} \rho^{\mu}\lambda_{\mu} = \begin{pmatrix} \frac{\rho_0}{\sqrt{3}} + \frac{\rho_3}{\sqrt{2}} + \frac{\rho_8}{\sqrt{6}} & \frac{\rho_1}{\sqrt{2}} - \frac{i\,\rho_2}{\sqrt{2}} & \frac{\rho_4}{\sqrt{2}} - \frac{i\,\rho_5}{\sqrt{2}} \\ \frac{\rho_1}{\sqrt{2}} + \frac{i\,\rho_2}{\sqrt{2}} & \frac{\rho_0}{\sqrt{3}} - \frac{\rho_3}{\sqrt{2}} + \frac{\rho_8}{\sqrt{6}} & \frac{\rho_6}{\sqrt{2}} - \frac{i\,\rho_7}{\sqrt{2}} \\ \frac{\rho_4}{\sqrt{2}} + \frac{i\,\rho_5}{\sqrt{2}} & \frac{\rho_6}{\sqrt{2}} + \frac{i\,\rho_7}{\sqrt{2}} & \frac{\rho_0}{\sqrt{3}} - \sqrt{\frac{2}{3}}\,\rho_8 \end{pmatrix}$$

$$H(\xi) = \sum_{\mu=0}^{8} h^{\mu}\lambda_{\mu}, \quad \lambda_{\mu} = \{\frac{\mathbf{1}_{3\times 3}}{\sqrt{3}}, \lambda_i\}, \quad \mathrm{Tr}(\lambda^{\mu}\lambda^{\nu}) = \delta_{\mu\nu}$$

"Vectorizing" the time evolution

Defining

$$|\rho(t,\xi)\rangle = \begin{pmatrix} \rho_0 \\ \rho_1 \\ \vdots \\ \rho_8 \end{pmatrix}$$

Expanding both sides

$$\partial_t \rho_\mu \lambda^\mu = -\, i h_\nu \rho_\theta [\lambda^\nu, \lambda^\theta]$$

Collect coefficients

$$\partial_t |\rho(t,\xi)\rangle = \mathscr{H}(\xi)\,|\rho(t)\rangle$$

This can be treated analytically

$$\mathcal{U}(t,\xi) = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \cos\Delta_{21}^{\text{eff}} & \sin\Delta_{21}^{\text{eff}} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -\sin\Delta_{21}^{\text{eff}} & \cos\Delta_{21}^{\text{eff}} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \cos\Delta_{31}^{\text{eff}} & \sin\Delta_{31}^{\text{eff}} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\sin\Delta_{31}^{\text{eff}} & \cos\Delta_{31}^{\text{eff}} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \cos\Delta_{32}^{\text{eff}} & \sin\Delta_{32}^{\text{eff}} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -\sin\Delta_{32}^{\text{eff}} & \cos\Delta_{32}^{\text{eff}} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\Delta_{ij}^{\text{eff}} = \frac{\Delta m_{ij}^2}{2E_\nu}L + g_\phi \phi_0 \frac{(m_i - m_j)}{E_\nu}L \equiv \Delta_{ij} + \Delta_{ij}^{\phi}$$

The averaged evolution

$$\overline{\cos(\Delta_{ij}^{\text{eff}})} = J_0(\Delta_{ij}^{\phi})\cos(\Delta_{ij})$$

Oscillation probability

$$P(\overline{\nu}_e \to \overline{\nu}_e) = P^{\text{SM}}(\overline{\nu}_e \to \overline{\nu}_e) + \frac{\cos^4\theta_{13}\sin^2(2\theta_{12})}{2}\left(J_0(\Delta_{21}^{\phi}) - 1\right)\cos(\Delta_{21})$$
$$+\frac{\sin^2(2\theta_{13})}{2}\left(\cos^2\theta_{12}\left(J_0(\Delta_{31}^{\phi}) - 1\right)\cos(\Delta_{31}) + \sin^2\theta_{12}\left(J_0(\Delta_{32}^{\phi}) - 1\right)\cos(\Delta_{32})\right)$$