

Emergent Large Lepton Mixing from Neutrino Refraction in Dark Matter

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The quark lepton mixing puzzle

- Quark mixings are small.
- Lepton mixing is strikingly large.
- Maybe a complementarity:

$$\theta_{12}^{\text{CKM}} + \theta_{12}^{\text{PMNS}} \approx 45^\circ$$

Could be indicative of a possible symmetry between quarks and leptons.

- Are the large PMNS angles fundamental - or can they emerge dynamically from neutrino interactions in a medium?

$$V_{\text{CKM}} = \begin{bmatrix} \text{large red} & \text{small yellow} & \text{tiny pink} \\ \text{small yellow} & \text{large green} & \text{small orange} \\ \text{tiny pink} & \text{small orange} & \text{large red} \end{bmatrix}$$

$$V_{\text{PMNS}} = \begin{bmatrix} \text{large red} & \text{large green} & \text{small orange} \\ \text{small yellow} & \text{large green} & \text{large pink} \\ \text{small yellow} & \text{large green} & \text{large pink} \end{bmatrix}$$

The basic observation

- What we know: neutrino oscillations imply neutrino mass!
- Oscillation experiments probe $H = \sqrt{p^2 + |m|^2} \approx p + \frac{|m|^2}{2E}$
- Oscillations probe m^2 and not m directly. This gives energy dependence of oscillation probabilities.
- Any contribution to the Hamiltonian of evolution with a $\frac{\text{const}}{E}$ form can reproduce oscillations.

A forward scattering potential?

The Wolfenstein potential

- In the medium, neutrinos “feel” a potential due to scattering with the particles.
- Potential is proportional to the number density (n) of background scatters, $V_n = \sqrt{2}G_F n_n$, where $G_F \propto g^2/M_W^2$.

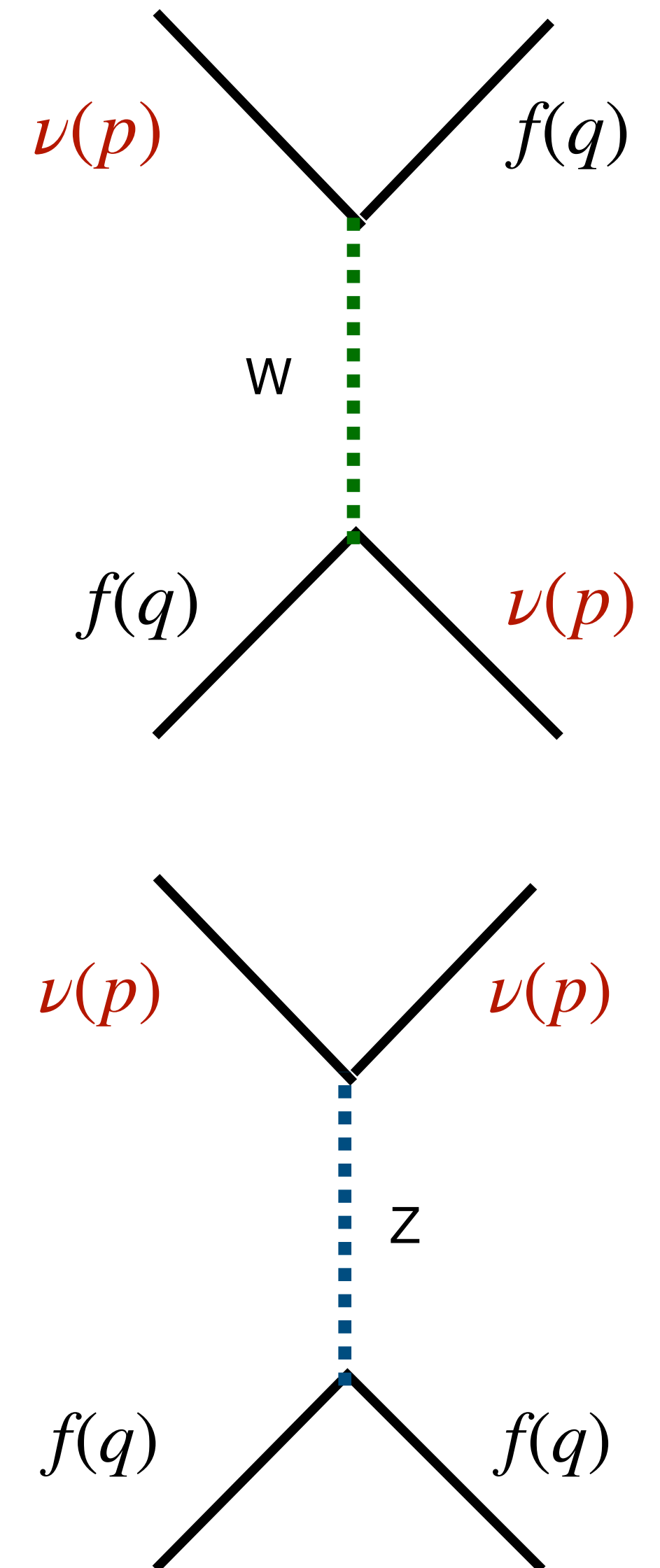
- This potential has an energy dependence at $\sqrt{s} \gg m_W$

$$V \propto \begin{cases} \frac{1}{m_W^2} & \text{if } \sqrt{s} < m_W \\ \frac{1}{2m_W E} & \text{if } \sqrt{s} > m_W \end{cases}$$

Lunardini, Smirnov (NPB 00)

- Indeed can be of the form (1/E) for high energy or light mediator!

Refraction in a uniform background can mimic a neutrino mass!



ULDM as classical field

- Large occupation number $\equiv$ classical field.
- de-Broglie wavelength $\lambda_{\text{dB}} = (m_\phi v_\phi)^{-1} \simeq 600 \text{ pc} \left(\frac{10^{-22} \text{ eV}}{m_\phi} \right) \left(\frac{10^{-3}}{v_\phi} \right)$
- In a given vol λ_{dB}^3 , occupation number $N = 10^{91} \left(\frac{10^{-22} \text{ eV}}{m_\phi} \right)^4$. Justifies use as a classical field since the fluctuations are N^{-1} .

$$\phi_c = \langle \Phi_c | \hat{\phi} | \Phi_c \rangle = \int \frac{d^3 k}{(2\pi)^3} \frac{1}{\sqrt{2E_k}} \left[f_a^{\text{tot}}(k) e^{-ikx} + f_b^{\text{tot}}(k) e^{ikx} \right] = F(x, t) e^{i\Phi}$$

Refractive Neutrino Mass

- Neutrinos scattering off ultralight scalar DM ϕ through a fermionic mediator χ .

$$\mathcal{L} \supset \sum_{\substack{\alpha = e, \mu, \tau \\ k = 1, 2}} -\frac{1}{2} \left(g_{\alpha k} \bar{\nu}_\alpha \chi_k \phi^\star + m_{\chi_k} \bar{\chi}_k \chi_k \right),$$

Smirnov, **MS** (JCAP 2024, PRD 2025)

- **Refractive masses** arise from the term: $g_{\alpha k} \bar{\nu}_\alpha \chi_k \phi^\star$. Assume $M_{\text{vac}} = 0$.
- The mass matrix in the basis $(\nu_f, \chi_L) = (\nu_e, \nu_\mu, \nu_\tau, \chi_1, \chi_2)$ is

$$M_{\text{ref}} = \begin{pmatrix} 0_{3 \times 3} & [g]_{\alpha k} \langle \phi \rangle_{\text{coh}}^\star \\ [g^T]_{k\alpha} \langle \phi \rangle_{\text{coh}}^\star & [m_{\chi_k}]_D \end{pmatrix}, \quad \alpha = e, \mu, \tau, \quad k = 1, 2.$$

- Exactly analogous to **matter effect** for neutrinos. Can be explained as $m_{\text{ref}}^2 \equiv (2E) V$.

Can it mimic neutrino “vacuum” masses?

- ULDM classical field: $\langle \phi \rangle_{\text{coh}}^* = F(x) e^{-i\Phi(x)}$

- The refractive term contributes a mass term to the Hamiltonian

$$H_{\text{ref}} \approx \frac{1}{2E} M_{\text{ref}} M_{\text{ref}}^\dagger = \frac{1}{2E} \begin{bmatrix} F^2[g] \cdot [g^\dagger] & F[g] \cdot [m_{\chi_k}]_D \\ F[m_{\chi_k}]_D \cdot [g^\dagger] & F^2[g^T] \cdot [g^\star] + [m_{\chi_k}^2 + 2E\dot{\Phi}]_D \end{bmatrix}$$

Therefore, $m_{\text{ref}} \approx 0.01 \text{ eV} \left(\frac{g}{10^{-8}} \right) \left(\frac{10^{-9} \text{ eV}}{m_\phi} \right) \rho_{\text{MW}}.$

Smirnov, **MS** (JCAP 2024, PRD 2025)

- Generate an effective mixing matrix in a dark matter background.

The key idea: CKM to PMNS

- Previously, $m_{\text{ref}} \approx 0.01 \text{ eV} \left(\frac{g}{10^{-8}} \right) \left(\frac{10^{-9} \text{ eV}}{m_\phi} \right) \rho_{\text{MW}}$ and $M_{\text{vac}} = 0$.
- Assume tiny vacuum masses with **CKM mixing**:
$$M_{\text{vac}} = V_{\text{CKM}} \cdot \text{diag}(m_1, m_2, m_3) \cdot V_{\text{CKM}}^\dagger$$
- Net Hamiltonian :
$$H_{\text{eff}} = \frac{1}{2E} V_{\text{CKM}} \cdot \text{diag}(m_1^2, m_2^2, m_3^2) \cdot V_{\text{CKM}}^\dagger + H_{\text{ref}}.$$
- If H_{ref} dominates, then effective mass eigenstates are not vacuum eigenstates.

Vacuum Mixing $\neq$ Observed Mixing

Emergent Leptonic Mixing in Dark Matter

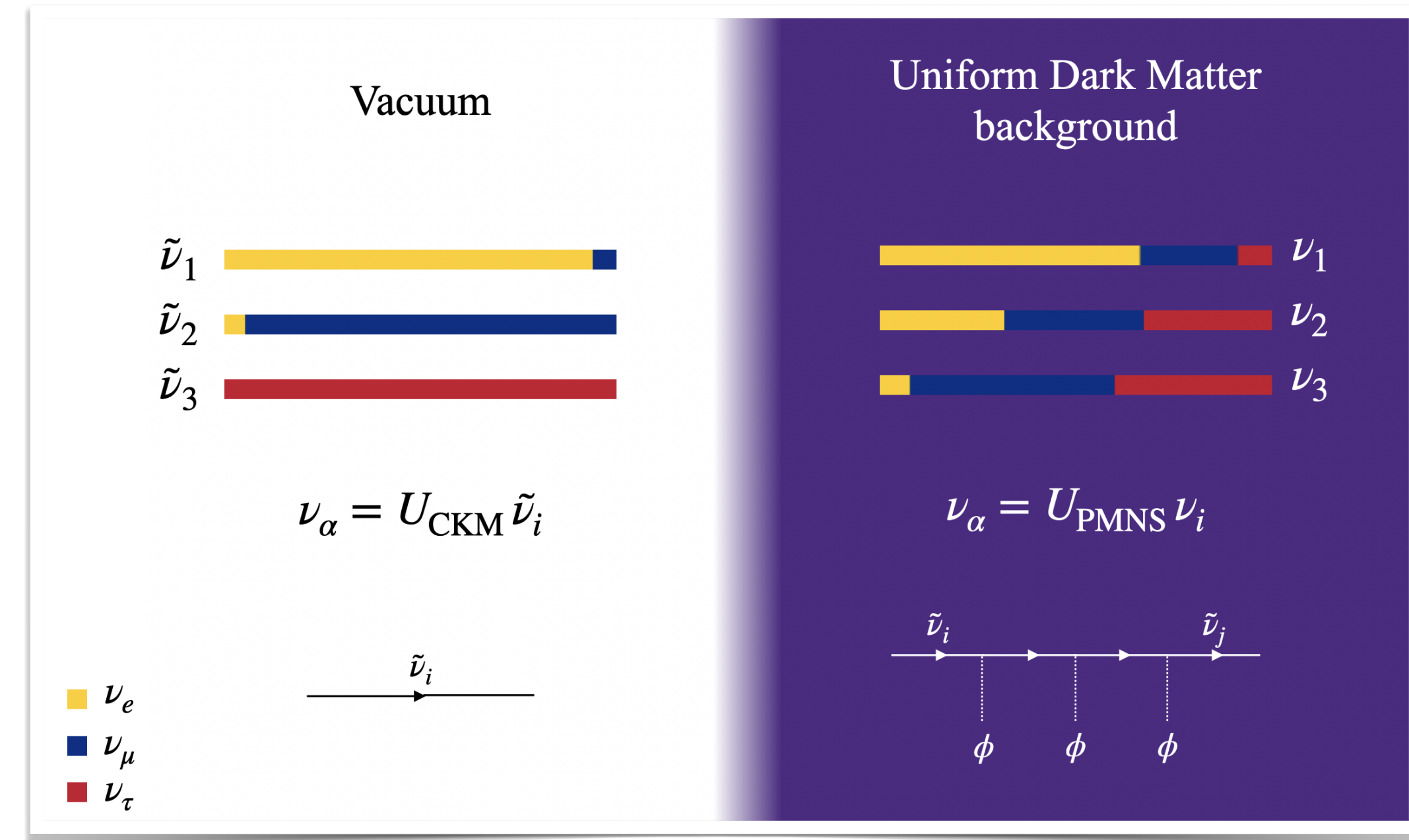
- Effective mass matrix in (ν_α, χ_k) basis

$$\mathbb{M} = \begin{pmatrix} 0_{3 \times 3} & [g]_{\alpha k} \langle \phi \rangle_{\text{coh}}^* \\ [g^T]_{k\alpha} \langle \phi \rangle_{\text{coh}}^* & [m_{\chi_k}]_D \end{pmatrix} + \begin{pmatrix} M_{\text{vac}} & 0 \\ 0 & 0 \end{pmatrix},$$

- Choose g and vacuum m^2 such that

$$\mathbb{M} = V_{\text{PMNS}} \cdot \text{diag}(0, \Delta m_{\text{sol}}^2, \Delta m_{\text{atm}}^2) \cdot V_{\text{PMNS}}^\dagger$$

- Possible if $M_{\text{vac}} \ll g |\langle \phi \rangle_{\text{coh}}|$, the $V_{\text{eff}} \approx V_{\text{PMNS}}$.

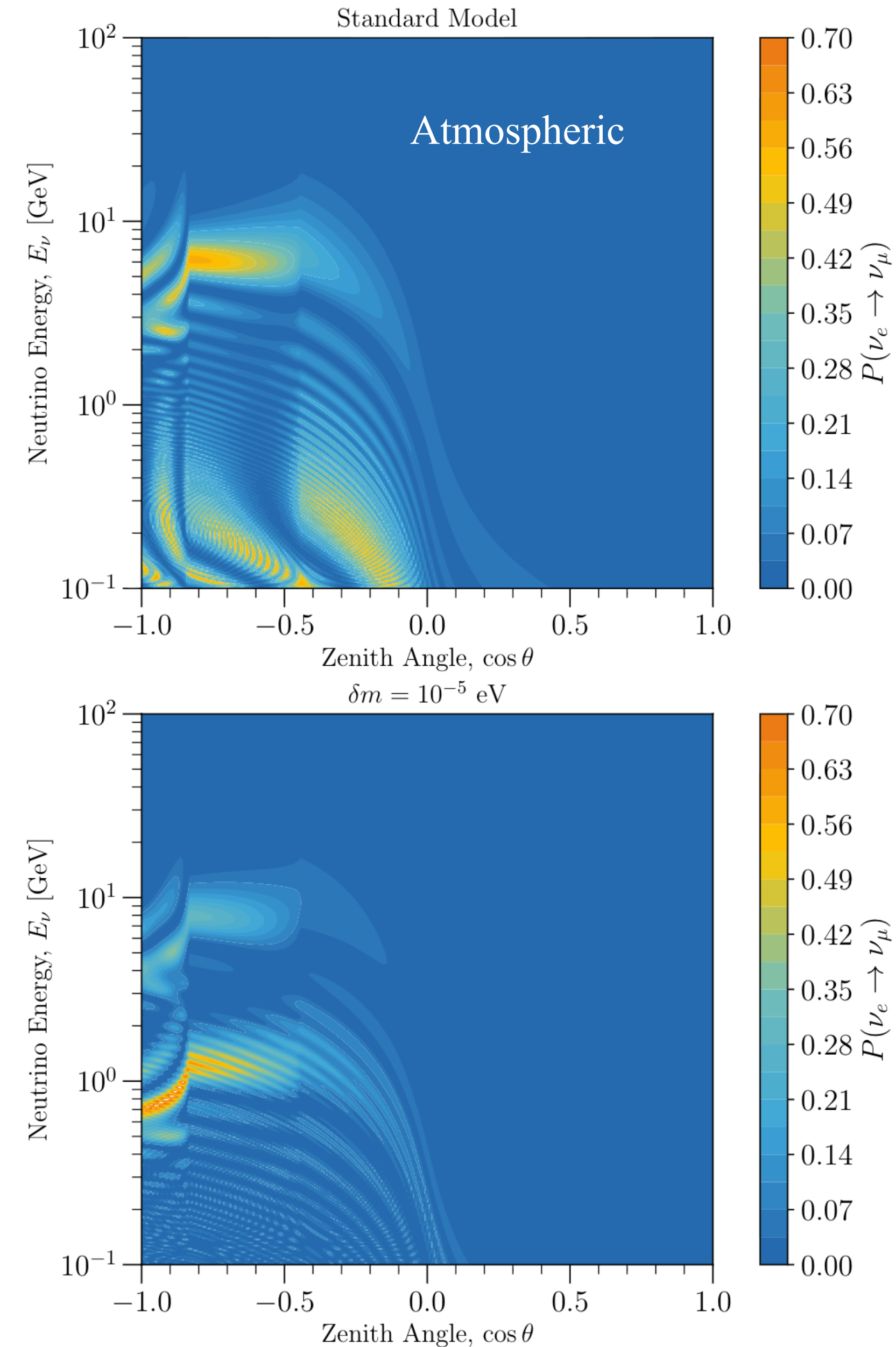
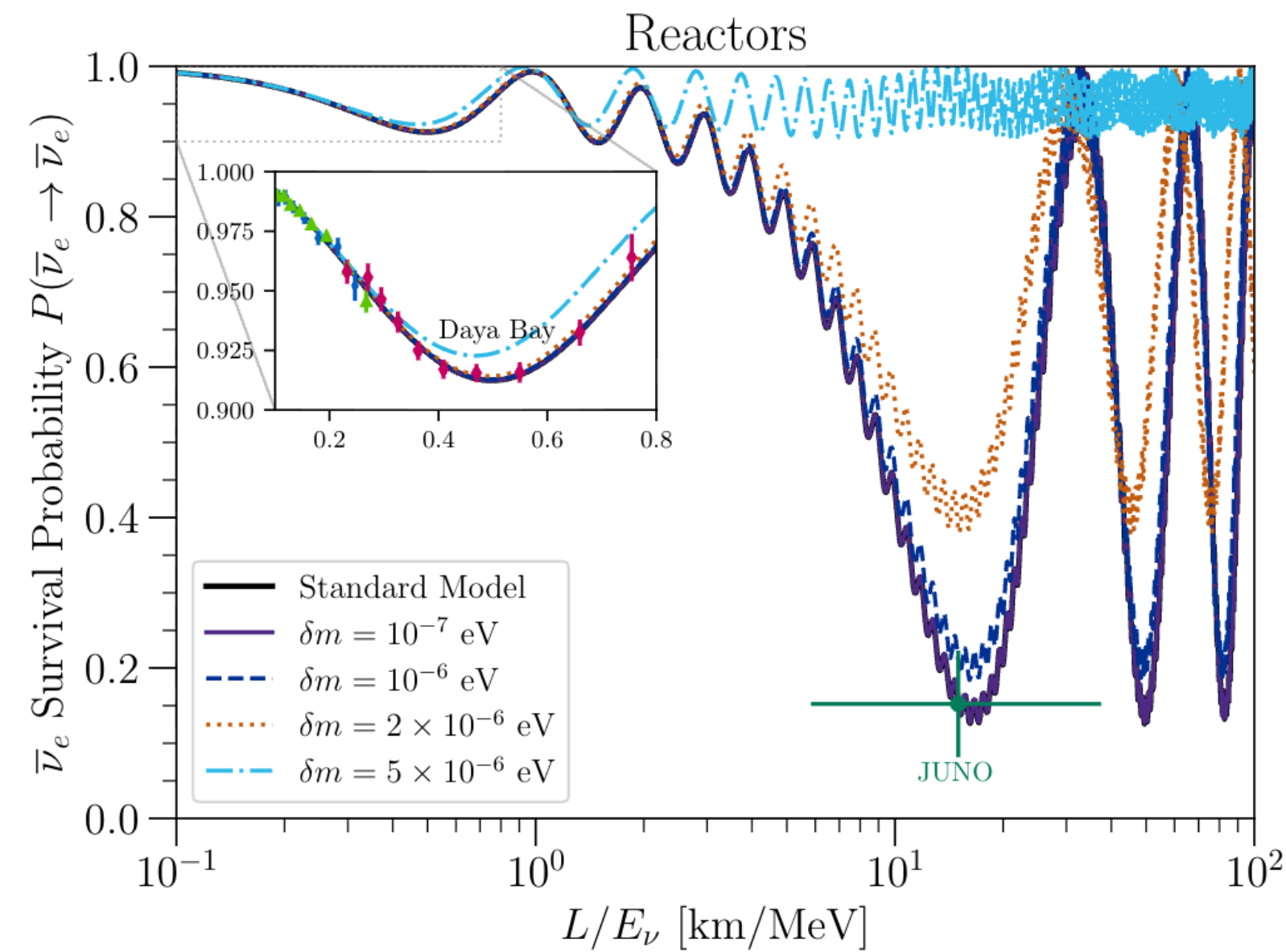
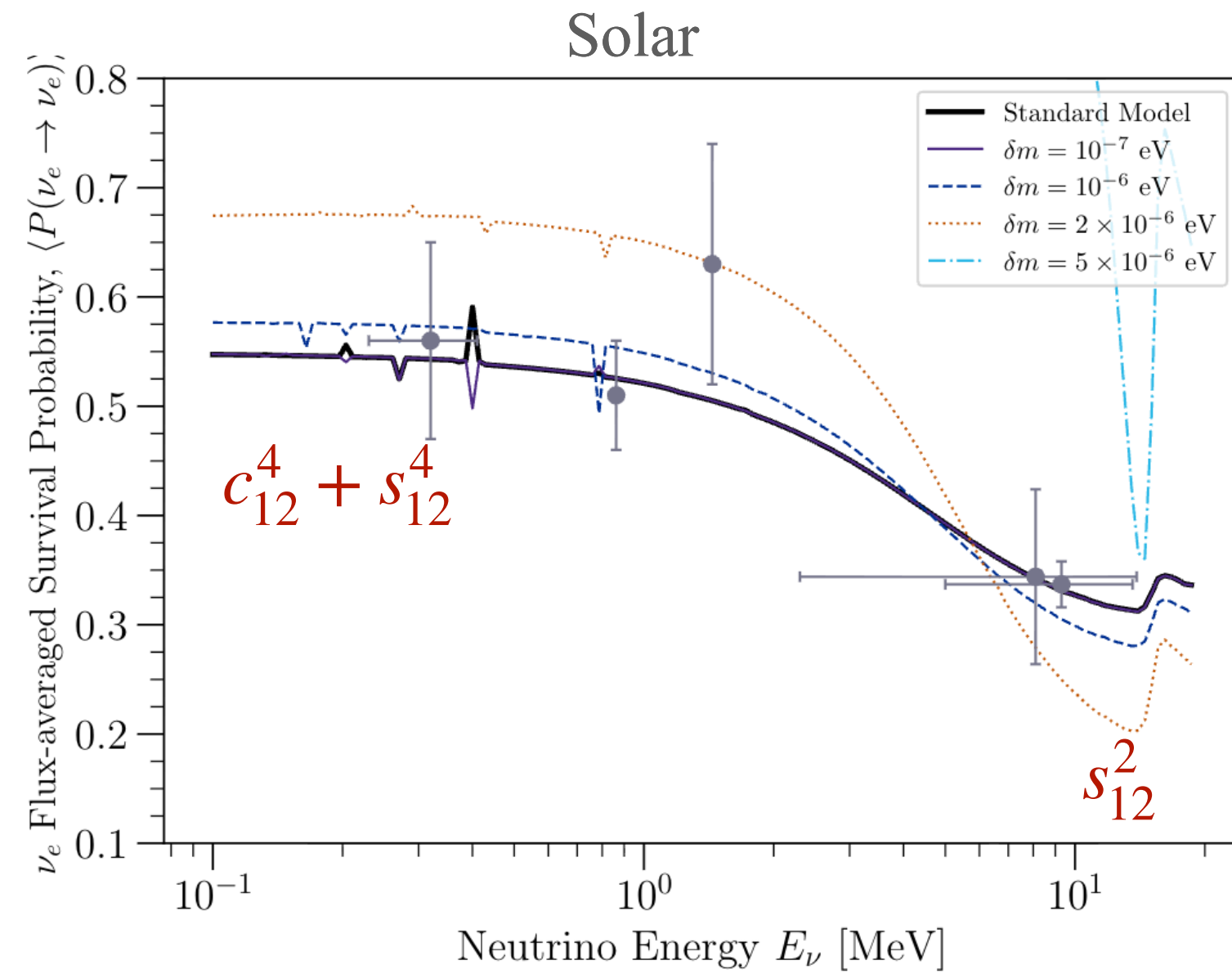


- Large lepton mixing becomes an environmental effect.

The smoking gun: environment-dependent mixing!

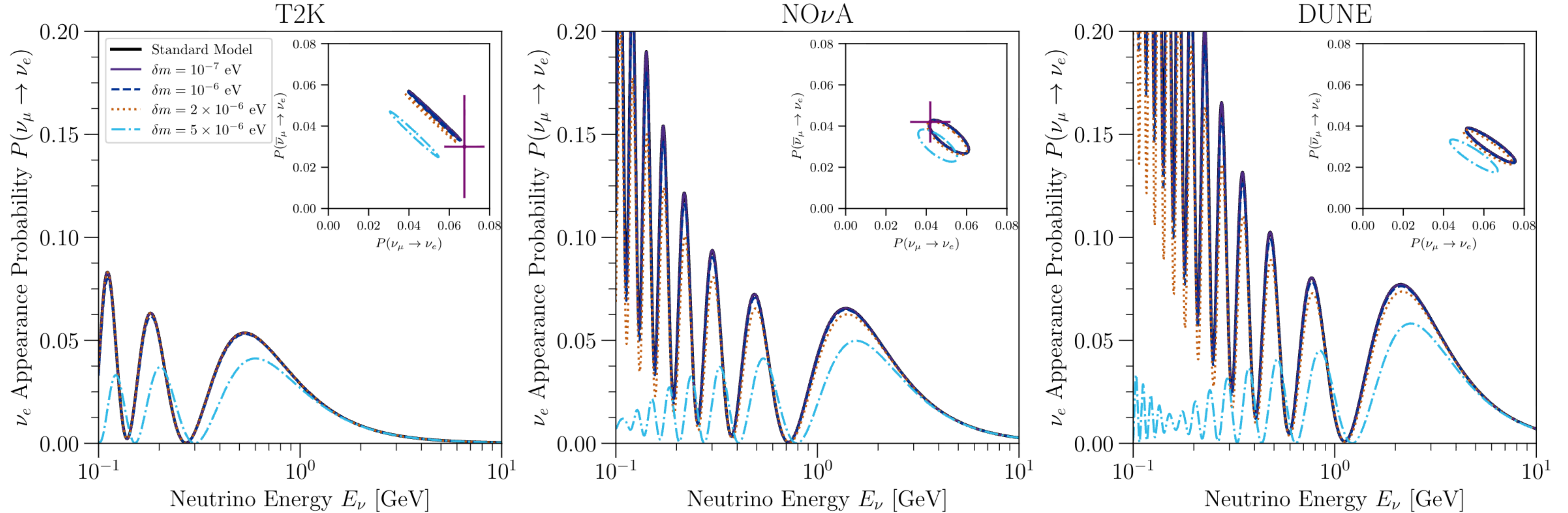
- Neutrino mass and mixing is a function of DM density ρ_{DM} , mass m_{DM} and coupling g , as well as mass-squared difference in vacuum, δm^2 .
- Oscillation probabilities will be modified.
- Solar, atmospheric, reactor vs SN/ cosmological, high energy astrophysical neutrinos need not probe exactly the same effective Hamiltonian.
- Different neutrino sources can therefore probe different effective Hamiltonians.
- Direct experimental handle on the origin of mixing.

What do neutrino experiments tell us?



Existing oscillation data already force the CKM-like vacuum contribution: $m < 10^{-6}$ eV.

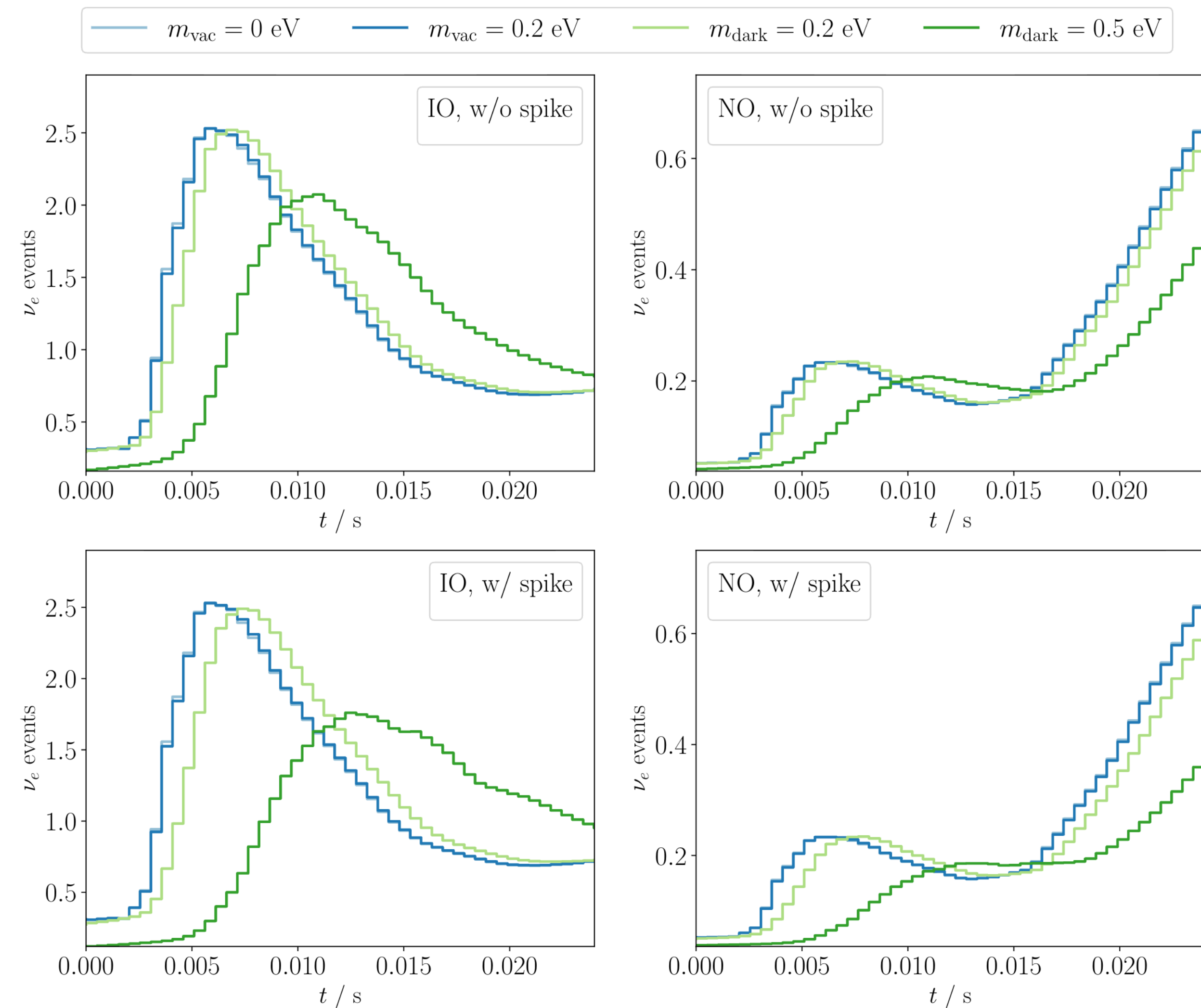
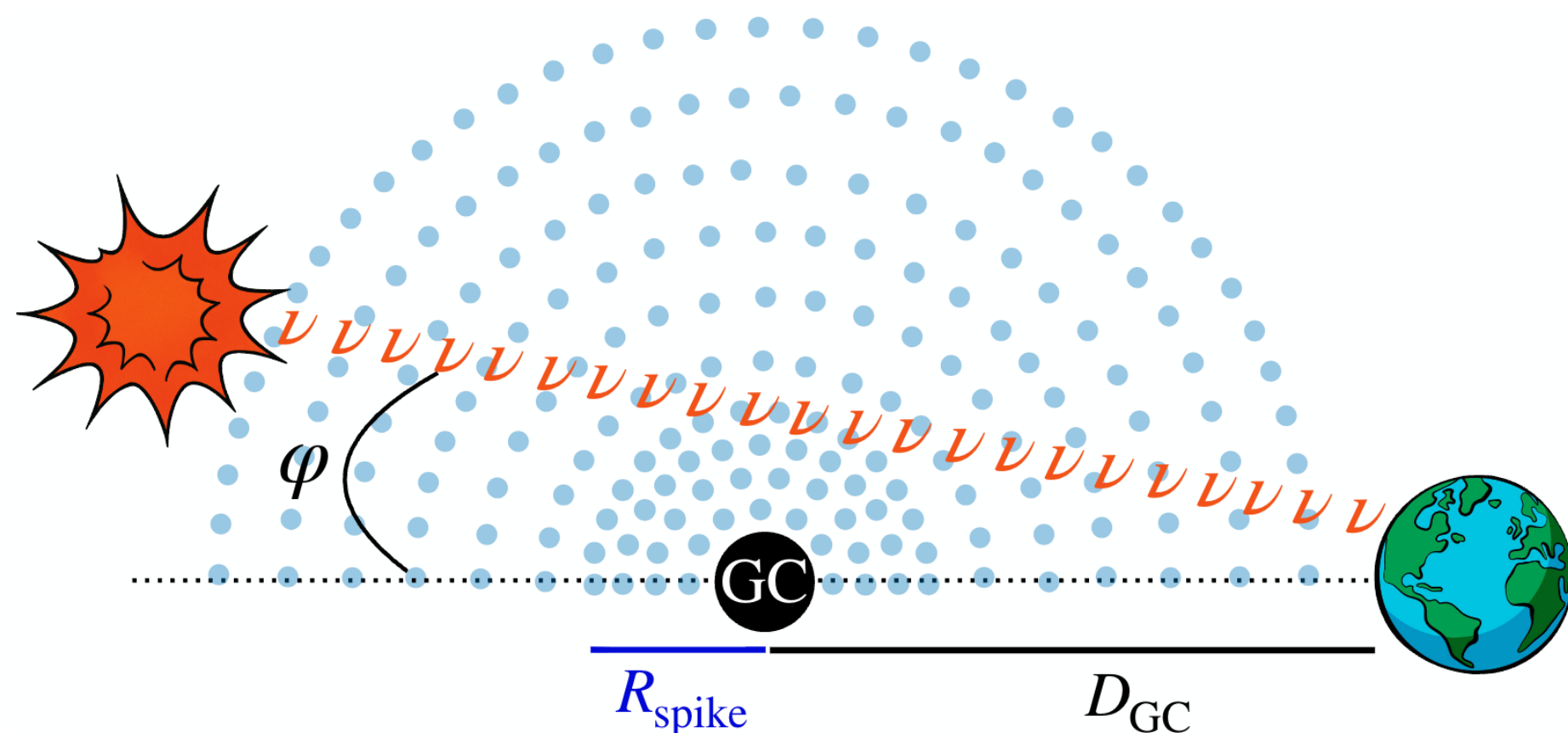
What do neutrino experiments tell us?



If the PMNS matrix is emergent, then comparing measurements of the mixing parameters in different environments becomes a test of its origin

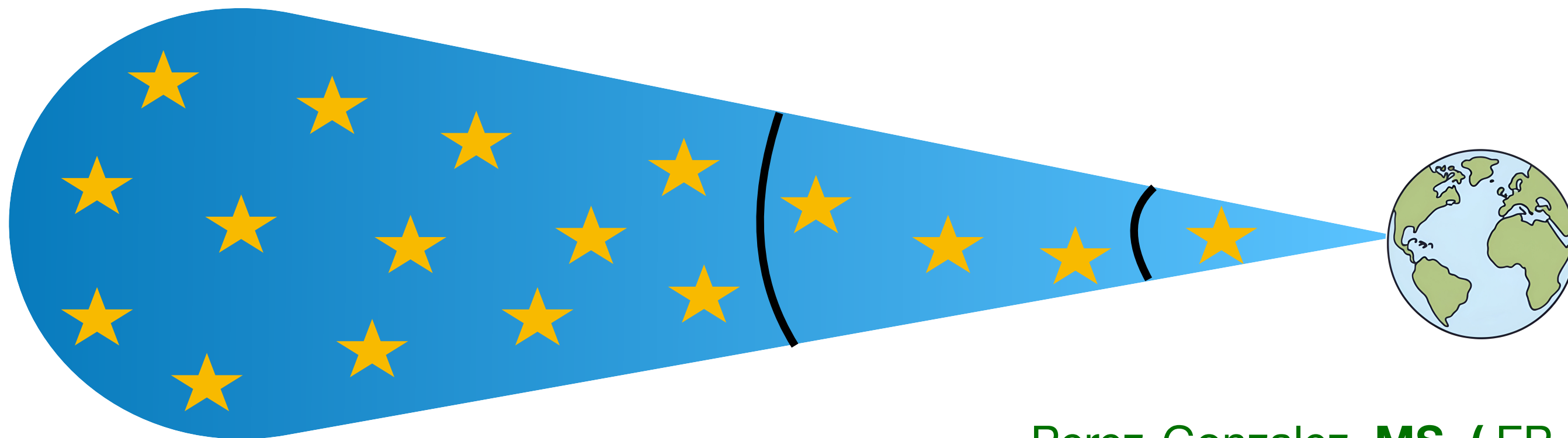
Time of flight delays of supernova neutrinos

- Refractive neutrino mass is dependent on the local DM density $m^2 \propto n_{\text{DM}}$.
- Therefore, it can be different in DM rich/poor regions. Time-of-flight delay of neutrinos from SNe.
- Results can be sensitive to DM spikes.

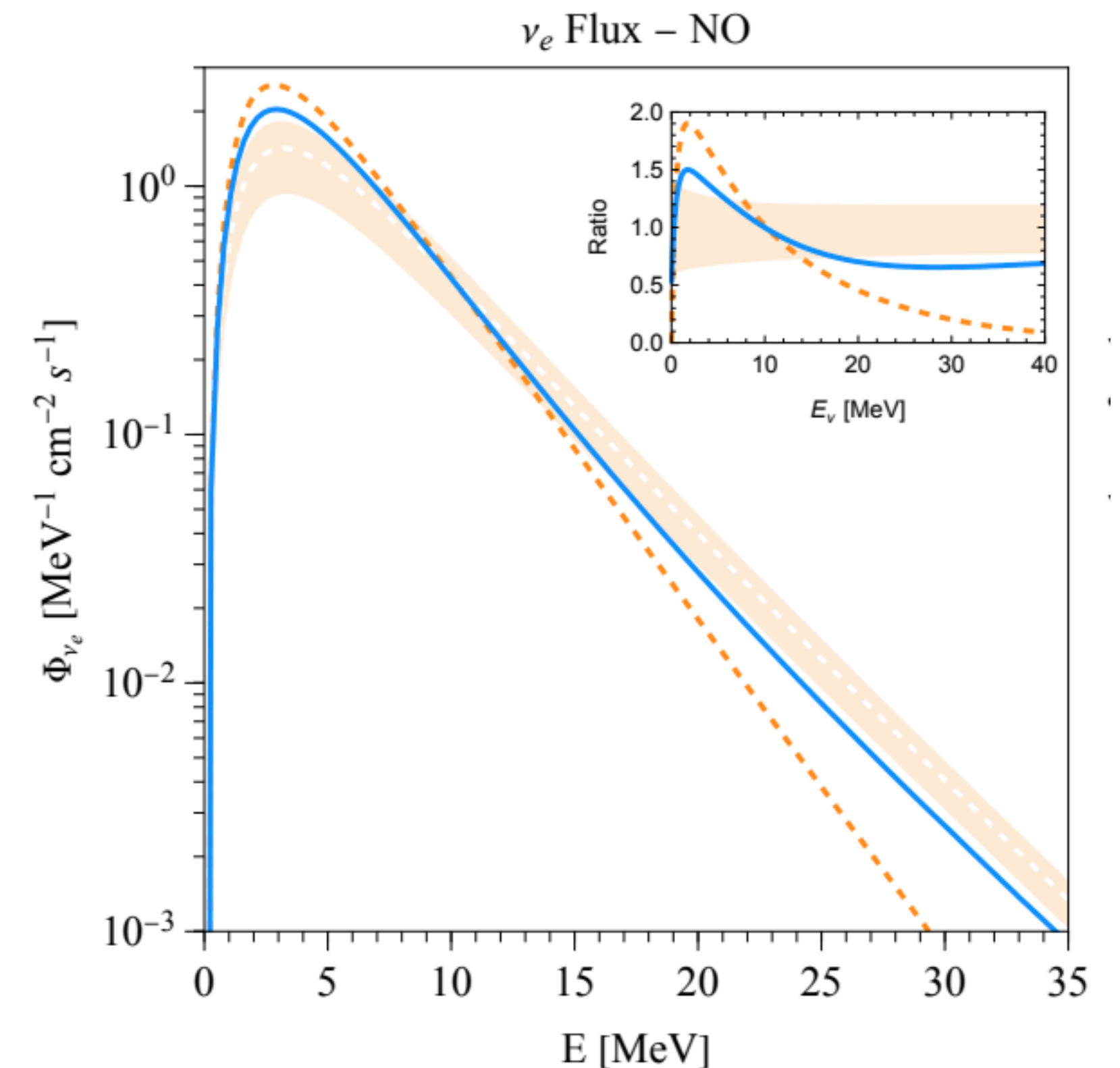
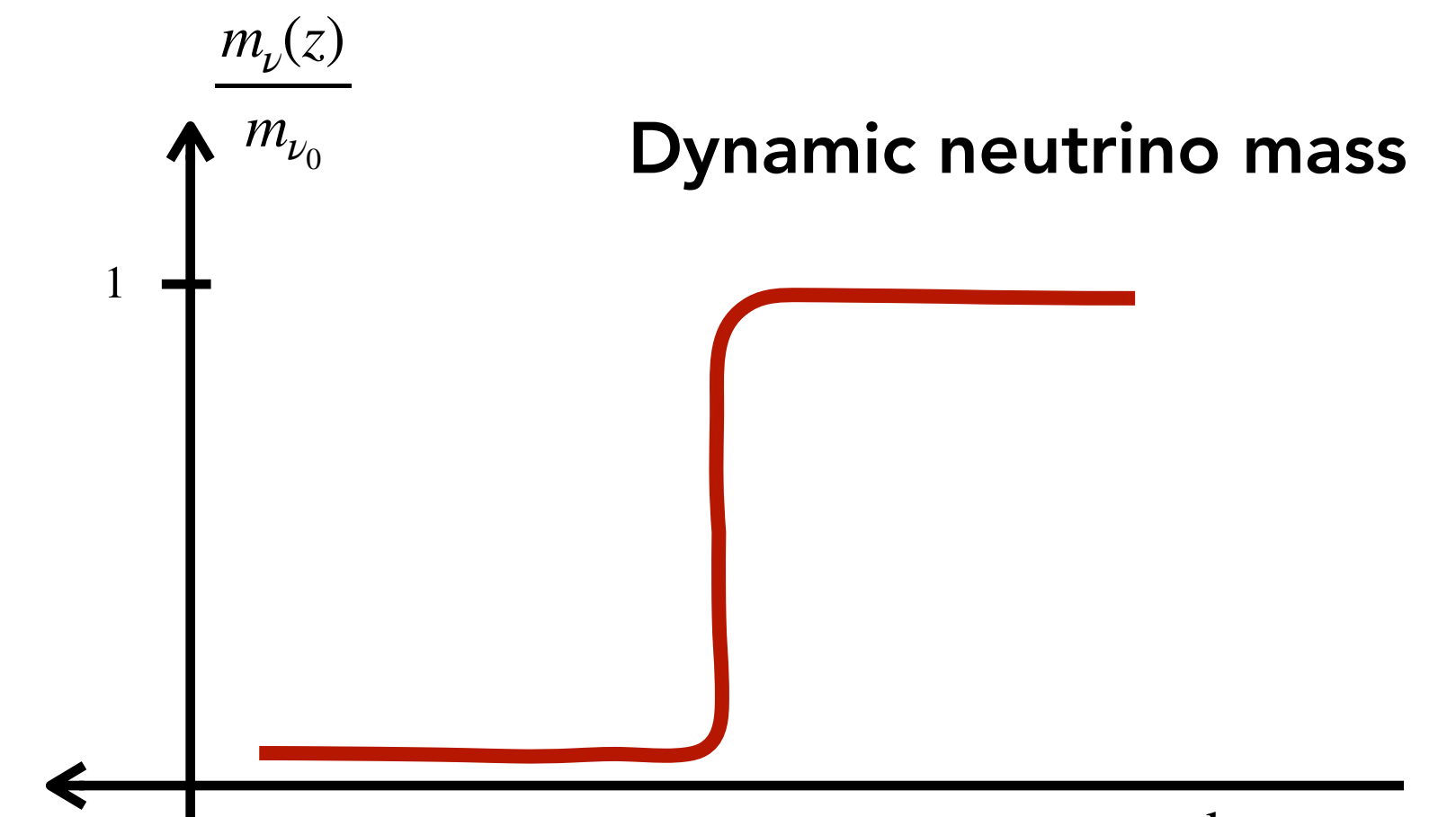


Diffuse SN neutrino background

- Refractive neutrino mass is redshift dependent.
- Neutrinos in the past had lower mass.
- Can show up through different neutrino propagation in core-collapse SN in the past (MSW resonance, adiabaticity, etc.). Changes in the DSNB!



Perez-Gonzalez, **MS** (EPJC 2026)



Concluding...

- Neutrino mass can be predominantly refractive.
- Large lepton mixing can be environmental!
- Vacuum mixing can be CKM-like, whereas PMNS mixing is environment generated.

$$\begin{array}{ccccc}
 \nu_e & \nu_\mu & \nu_\tau & \chi_1 & \chi_2 \\
 \left(\begin{array}{cc}
 \boxed{U_{CKM}{}_{3 \times 3}} & U_{\nu\chi}{}_{3 \times 2} \\
 U_{\nu\chi}{}^\dagger{}_{2 \times 3} & I_{\chi\chi}{}_{2 \times 2}
 \end{array} \right) & \xRightarrow[\text{interaction}]{\text{DM-}\nu} & \left(\begin{array}{cc}
 \boxed{U_{PMNS}} & U'_{\nu\chi} \\
 U'_{\nu\chi} & I_{\chi\chi}
 \end{array} \right)
 \end{array}$$

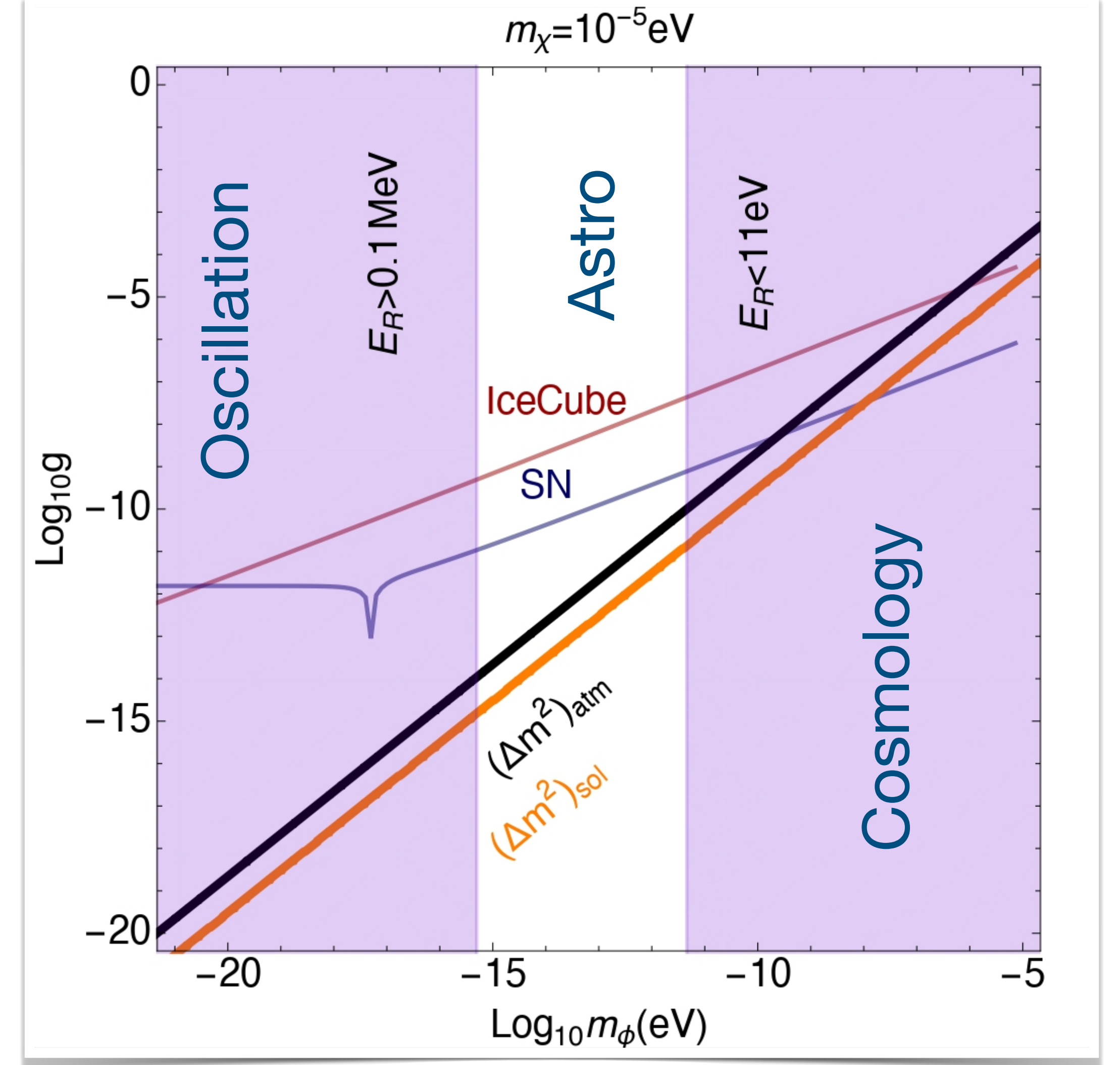
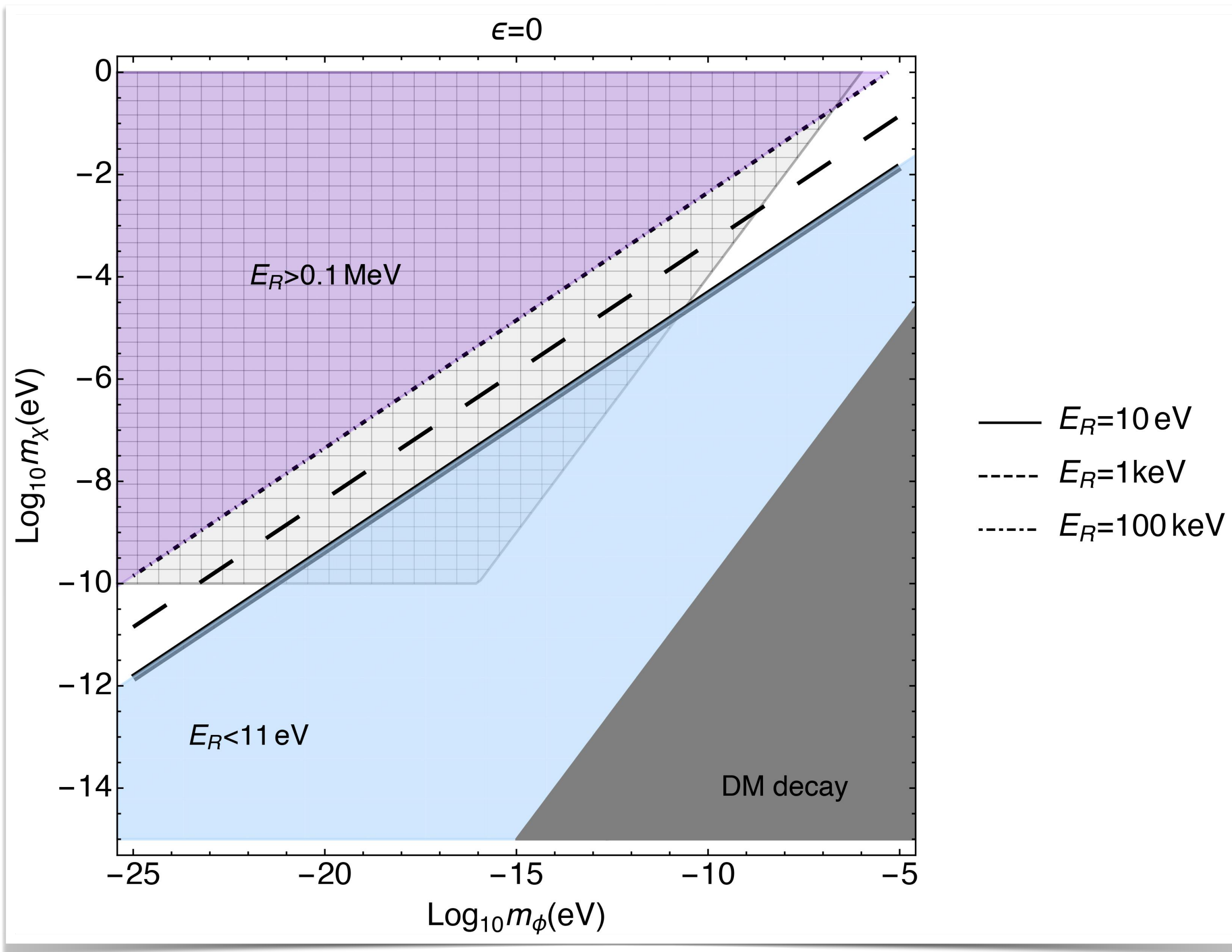
- Energy, density and redshift dependence make the scenario testable.

THANK YOU



BACKUP

Different constraints



- Bounds on parameters required for explaining observation.

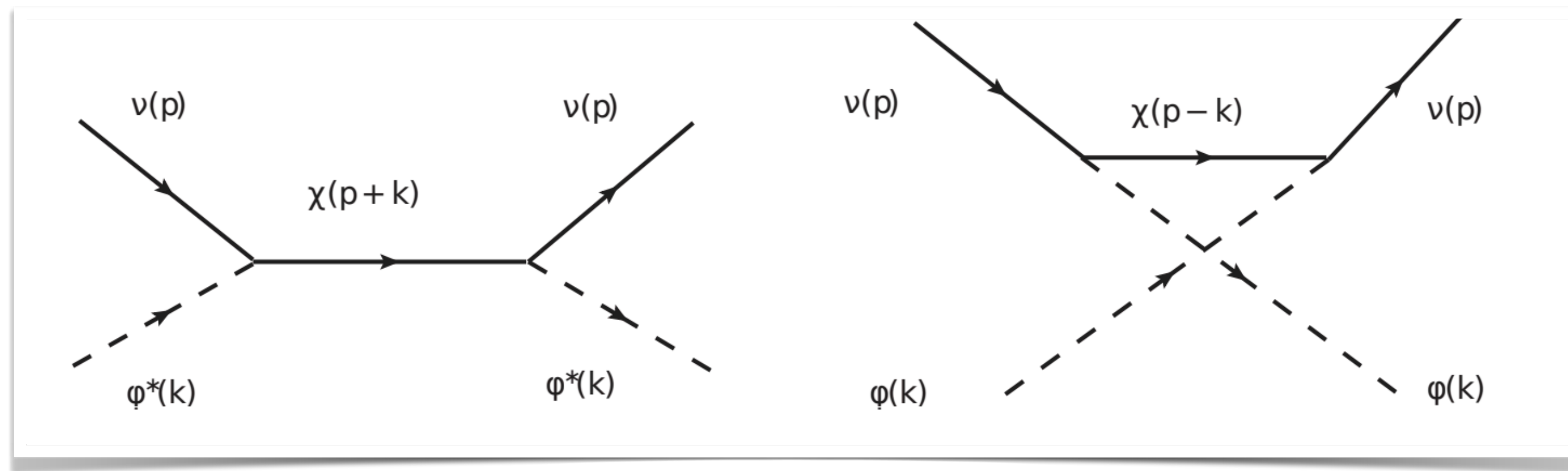
Smirnov, **MS** (JCAP 2024)

- Additional bounds on ultralight DM.

How is this implemented?

- Neutrinos scattering off ultralight scalar DM ϕ through a fermionic mediator χ .

$$\mathcal{L} \supset \sum_{\substack{\alpha = e, \mu, \tau \\ k = 1, 2}} -\frac{1}{2} \left((M_{\text{vac}})_{\alpha\beta} \bar{\nu}_\alpha \nu_\beta + g_{\alpha k} \bar{\nu}_\alpha \chi_k \phi^\star + m_{\chi_k} \bar{\chi}_k \chi_k \right),$$



Smirnov, **MS** (JCAP 2024)

The effective potential

$$V_{\alpha\beta} = \sum_k g_{\alpha k} g_{\beta k}^* \left[\frac{\bar{n}_\phi (2Em_\phi - m_{\chi k}^2)}{(2Em_\phi - m_{\chi k}^2)^2 + (m_\chi \Gamma_{\chi k})^2} + \frac{n_\phi}{2Em_\phi + m_{\chi k}^2} \right], \quad E_R = \frac{m_\chi^2}{2m_\phi}$$

Define the refractive mass $\tilde{m}^2 \equiv (2E) V$

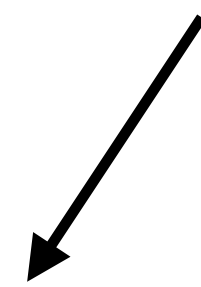
The refractive mass

- In terms of $y \equiv E/E_R$, we can write

$$\tilde{m}_{\alpha\beta}^2 = 2y E_R \sum_k \frac{g_{\alpha k} g_{\beta k}^*}{2m_\chi^2} (n_\phi + \bar{n}_\phi) \left[\frac{(1 - \epsilon)(y - 1)}{(y - 1)^2 + \frac{\Gamma_{\chi^k}^2}{m_\chi^2}} + \frac{1 + \epsilon}{1 + y} \right]$$

where $\epsilon \equiv \frac{n_\phi - \bar{n}_\phi}{n_\phi + \bar{n}_\phi}$ is the DM asymmetry

- We can write this as $\tilde{m}^2 = \tilde{m}_{\text{asy}}^2 \frac{y(y - \epsilon)}{y^2 - 1}$ where $\tilde{m}_{\text{asy}}^2 = \left(\frac{n_\phi + \bar{n}_\phi}{m_\phi} \sum_k g_{\alpha k} g_{\beta k}^* \right)$



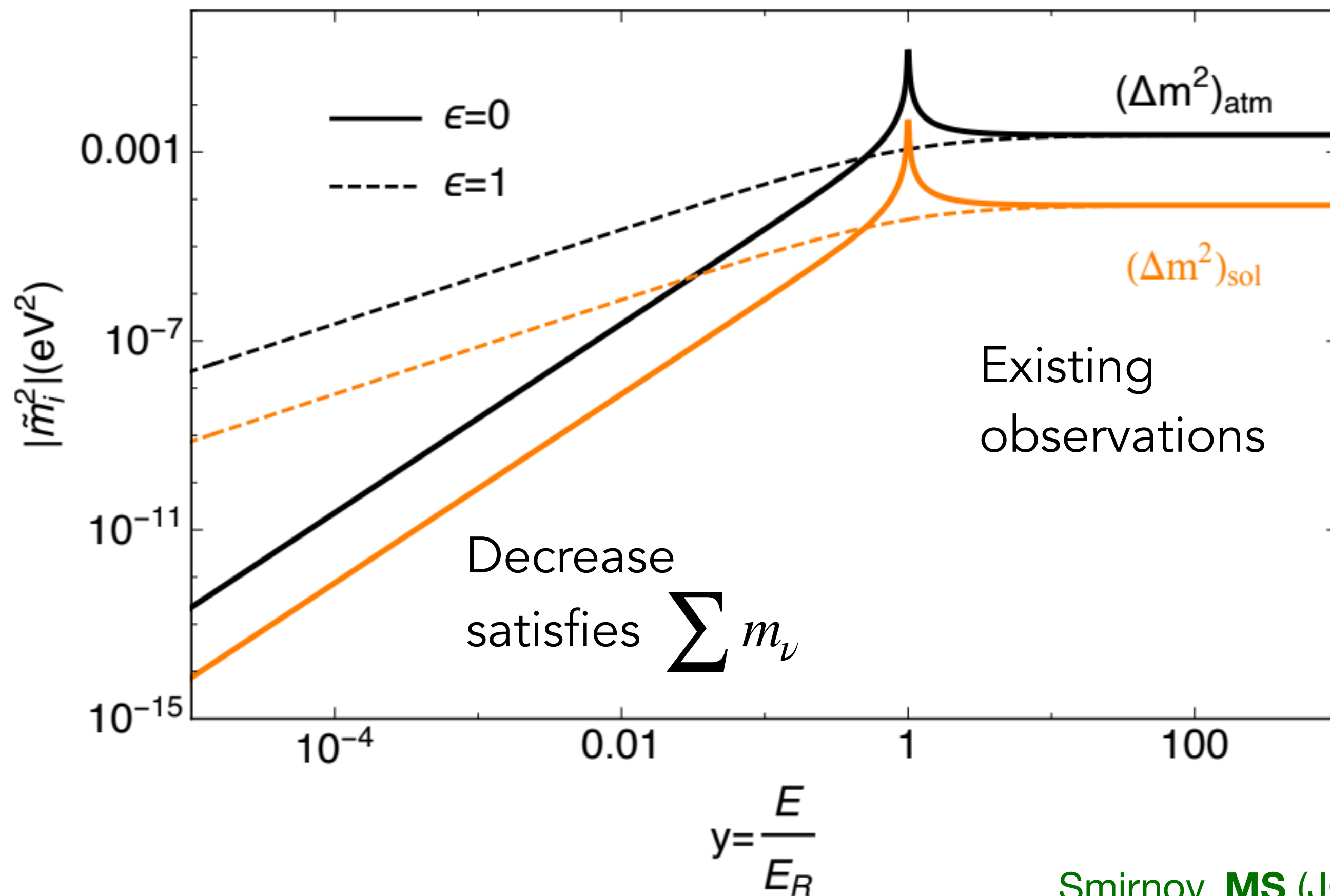
Energy independent



Energy dependent

Fitting the neutrino oscillation data

$$\tilde{m}^2 = \tilde{m}_{\text{asy}}^2 \frac{y(y - \epsilon)}{y^2 - 1}$$



Smirnov, **MS** (JCAP 2024)

- For high energies, $y \gg 1$,

$$\tilde{m}^2 / \tilde{m}_{\text{asy}}^2 = \begin{cases} 1 - \frac{\epsilon}{y}, & \epsilon \neq 0. \\ 1 + y^{-2}, & \epsilon = 0. \end{cases}$$

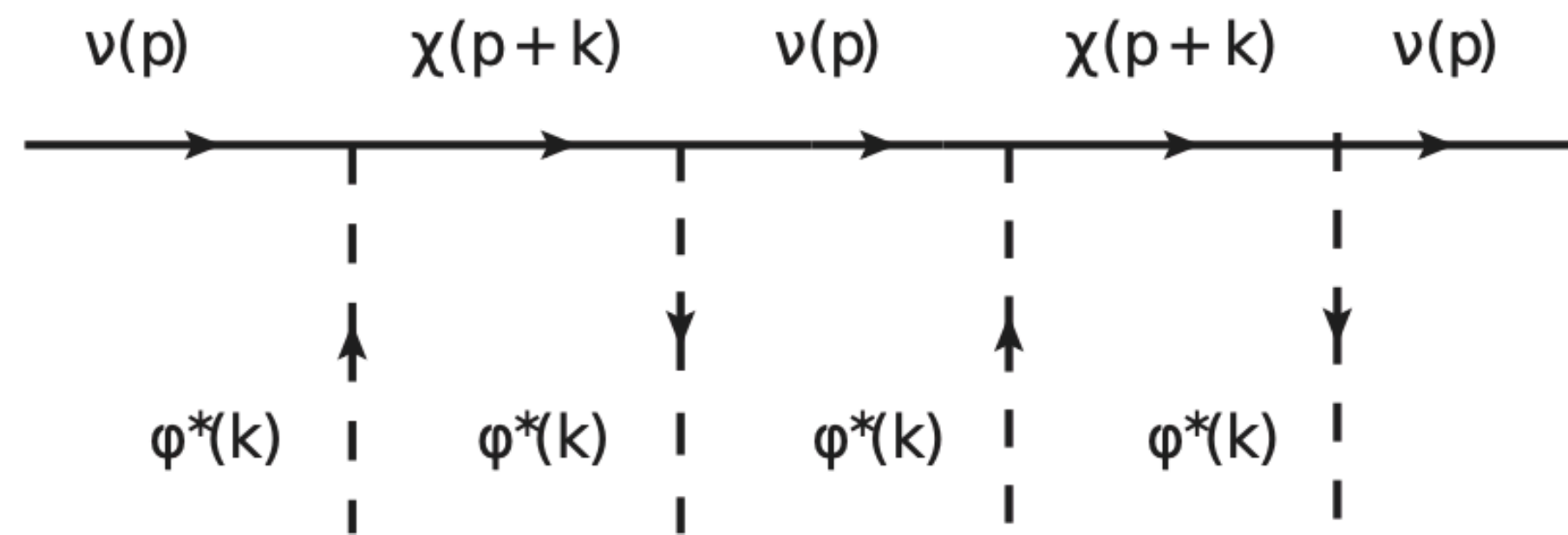
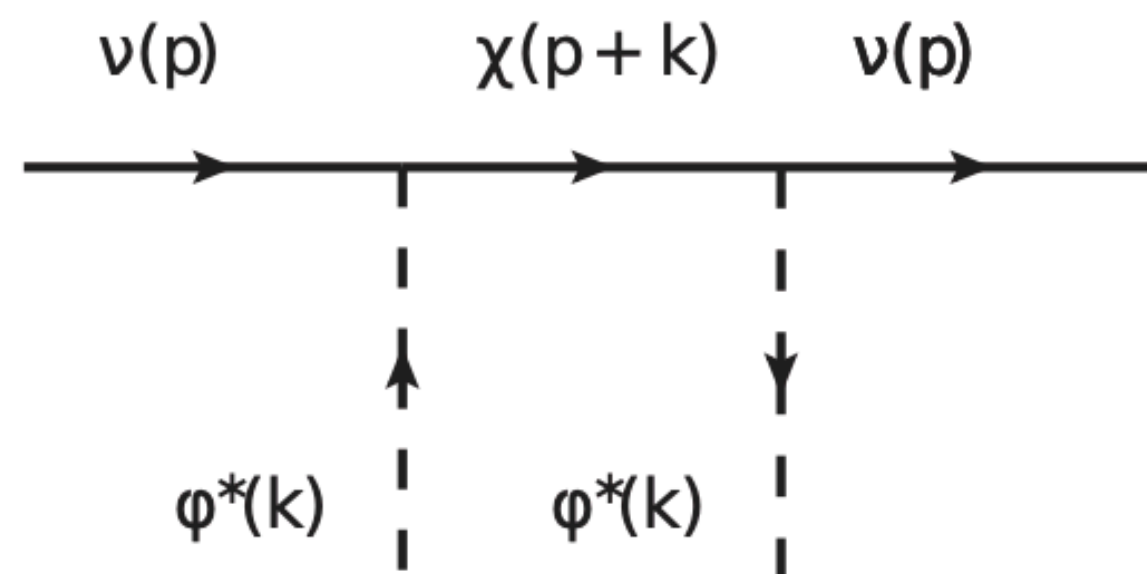
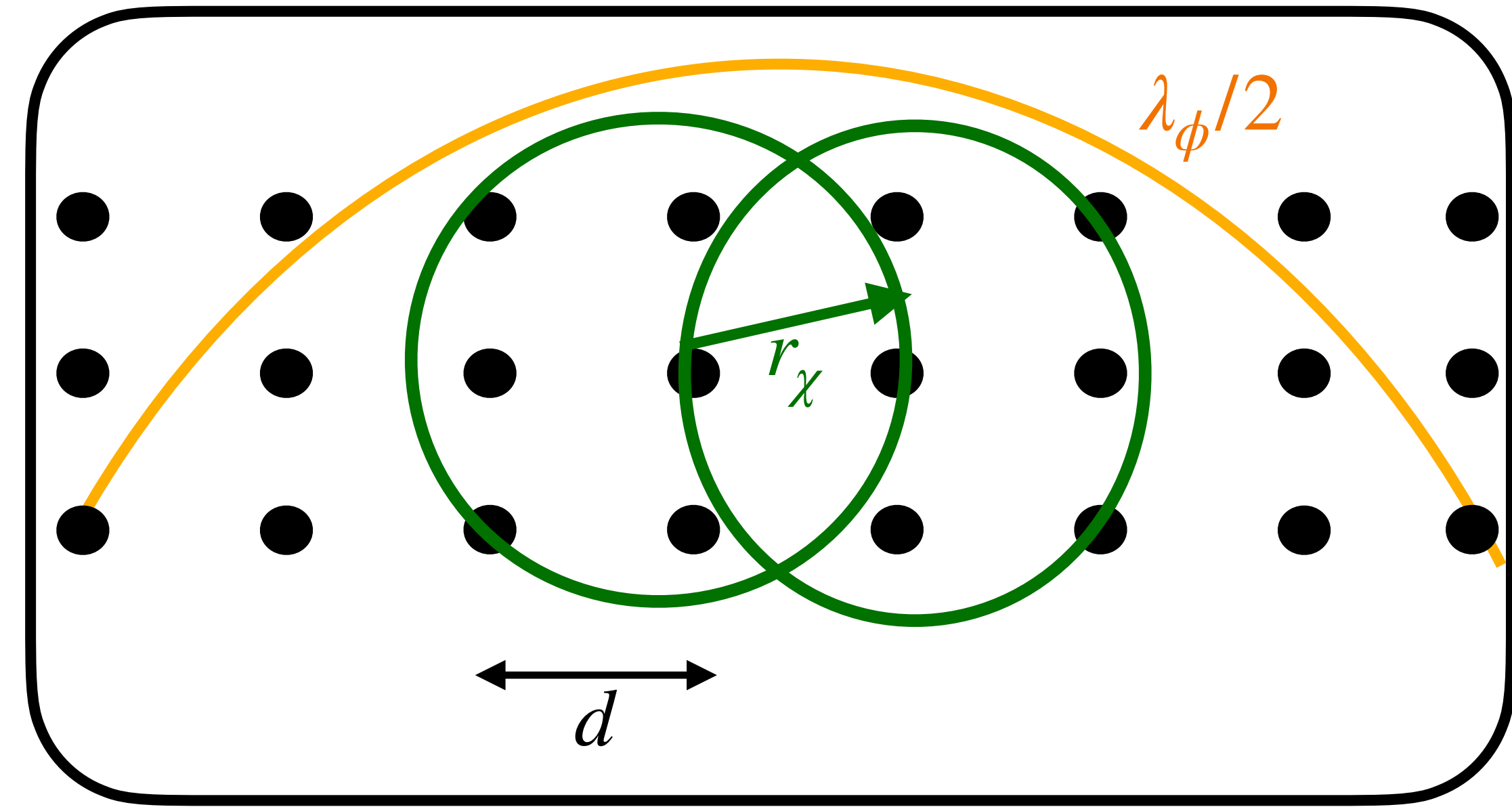
$\tilde{m}^2$ independent of energy! Can be used to fit oscillation data!

- For low energies $y \ll 1$,
 $\tilde{m}^2 / \tilde{m}_{\text{asy}}^2 = y(\epsilon - y).$

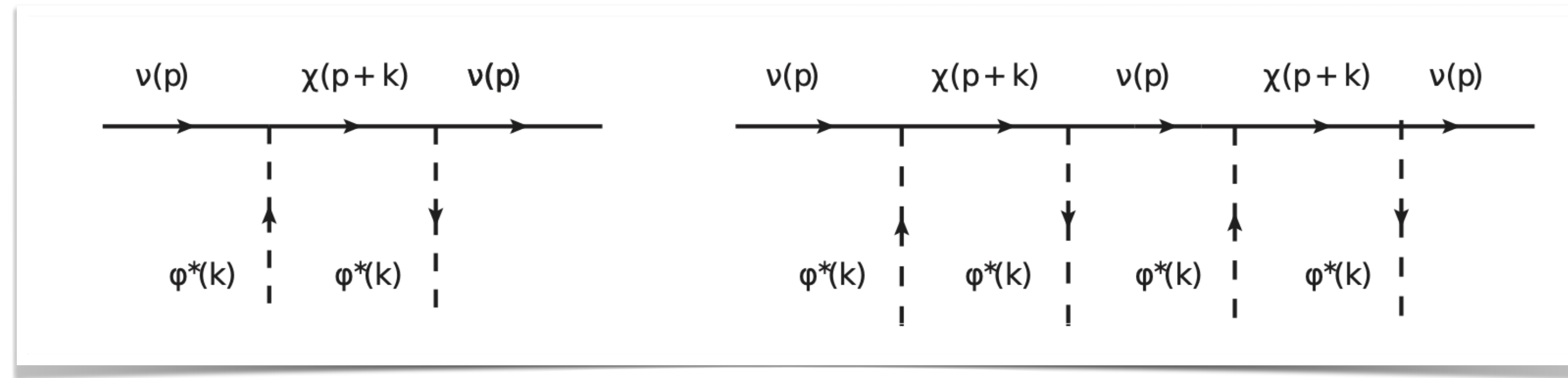
Can satisfy cosmological bounds

Caution: Perturbativity and resummation

- Typically $d < r_\chi < \lambda_{dB}$, where distance between scatterers $d \sim n_\phi^{-1/3}$, radius of interaction $r_\chi \sim 1/m_\chi$ & de-Broglie wavelength $\lambda_{dB} \sim 1/m_\phi v_\phi$
- Need to resum the series of diagrams. Can lead to perturbativity violation.
- Leads to additional constraints.



Caution: Perturbativity and resummation



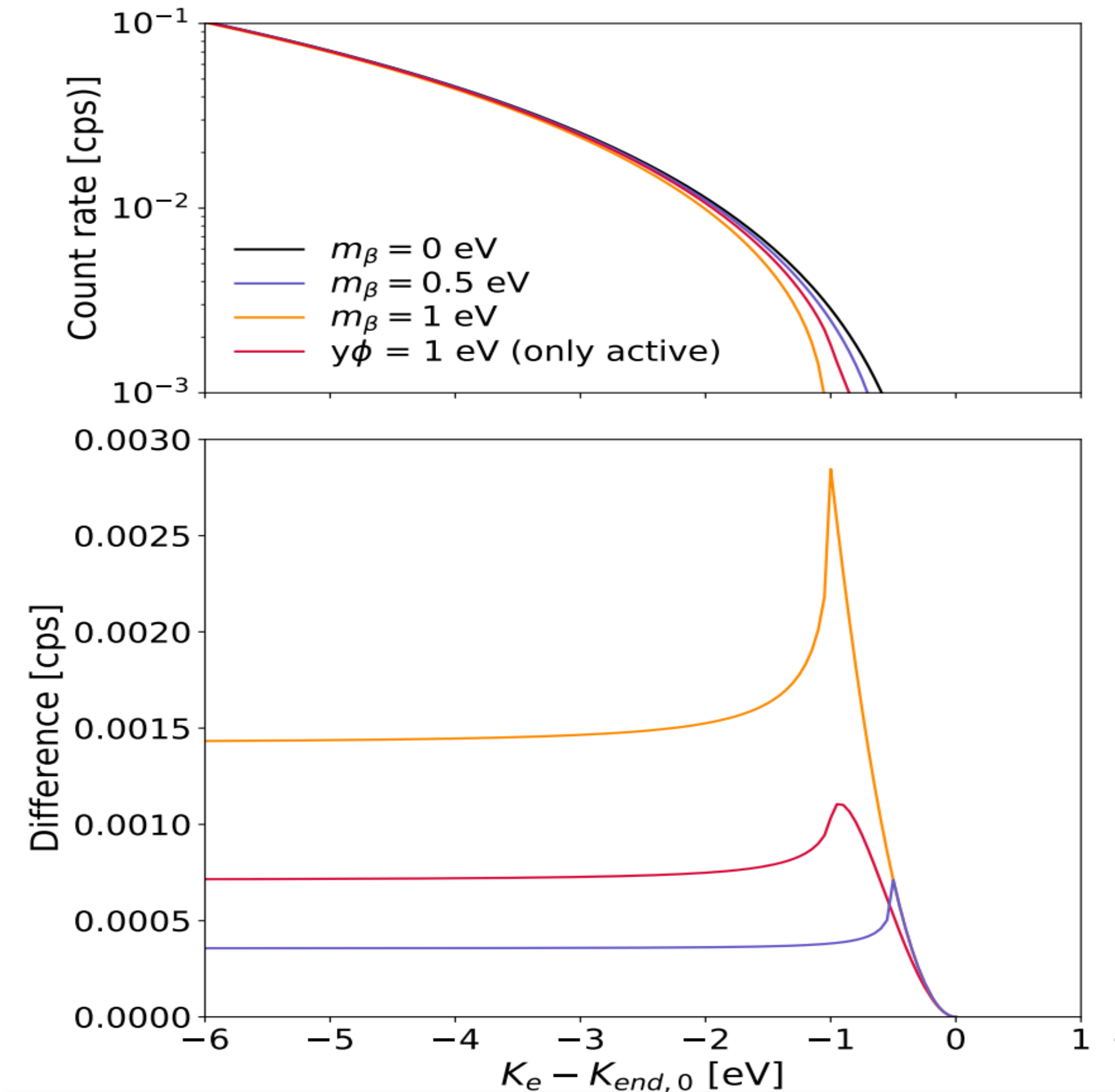
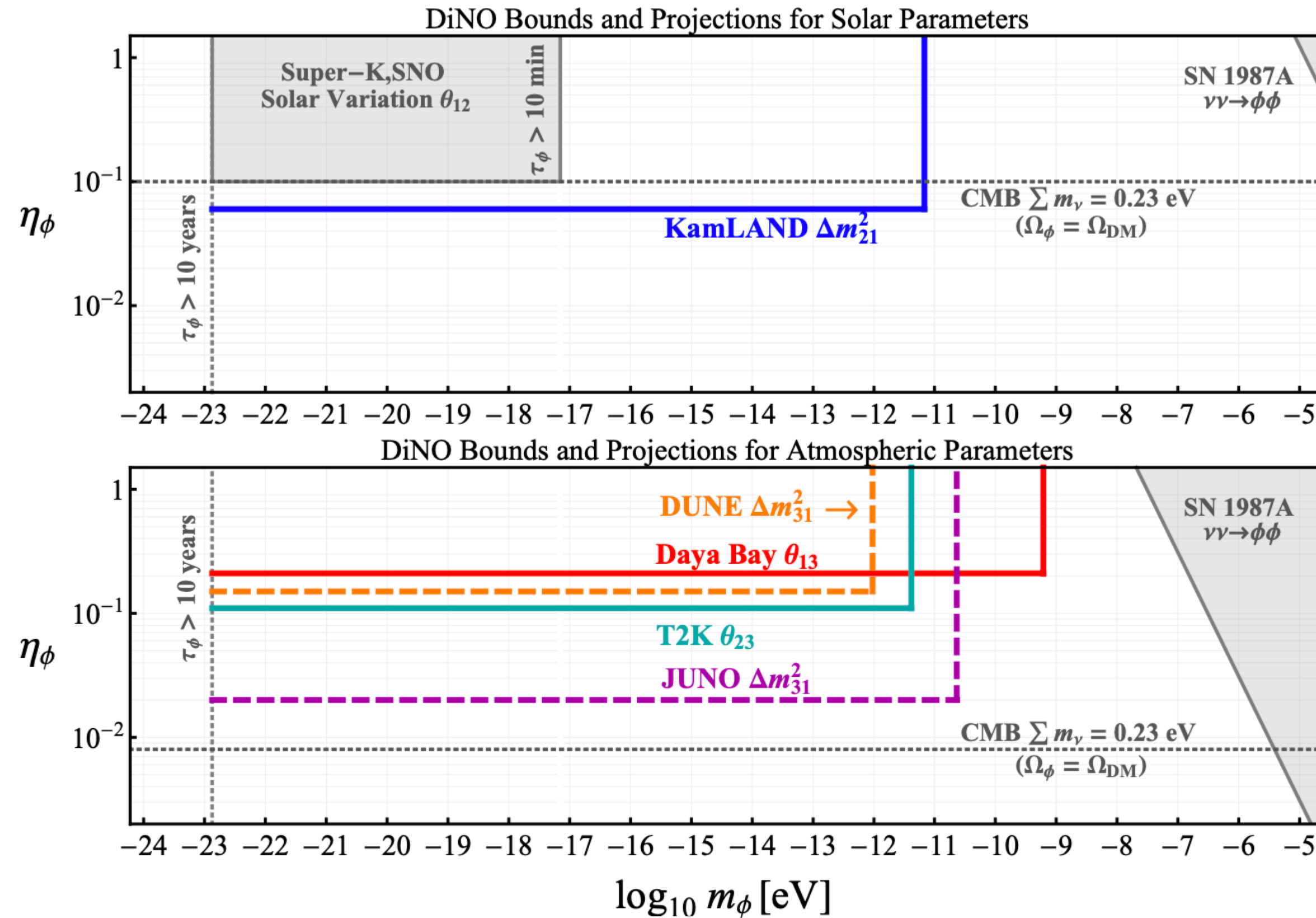
- Radius of interaction $r_\chi \ll \lambda_{\text{dB}}$. Hence multiple scatterings with DM.

- Formal resummation : $\tilde{V} = \frac{V}{1 + \zeta}$, where

$$\zeta \approx \begin{cases} \frac{\Delta m_{\text{atm}}^2}{2Em_\phi - m_\chi^2} = \frac{V}{m_\phi} & \text{for } \epsilon = -1, \\ \frac{V}{m_\phi} \frac{E_R}{E} & \text{for } \epsilon = 0. \end{cases}$$

- Perturbativity might be broken below E_R , however, qualitative conclusions remain same.

Other ways of probing refractive masses



- Ultralight DM can induce time-dependence in neutrino masses. Can show up in oscillation experiments or beta decay experiments

Dev, Machado, Martinez-Mirave (JHEP 2020)
 Krnjaic, Machado, Necib (PRD 2018),
 Huang, Lindner, Martinez-Mirave, **MS**, (PRD 2022)