Exploring the origins of neutrino mass in dark alleys

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MPIK, Heidelberg

Neutrino Frontiers @ GGI, 2024

MAX-PLANCK-INSTITUT
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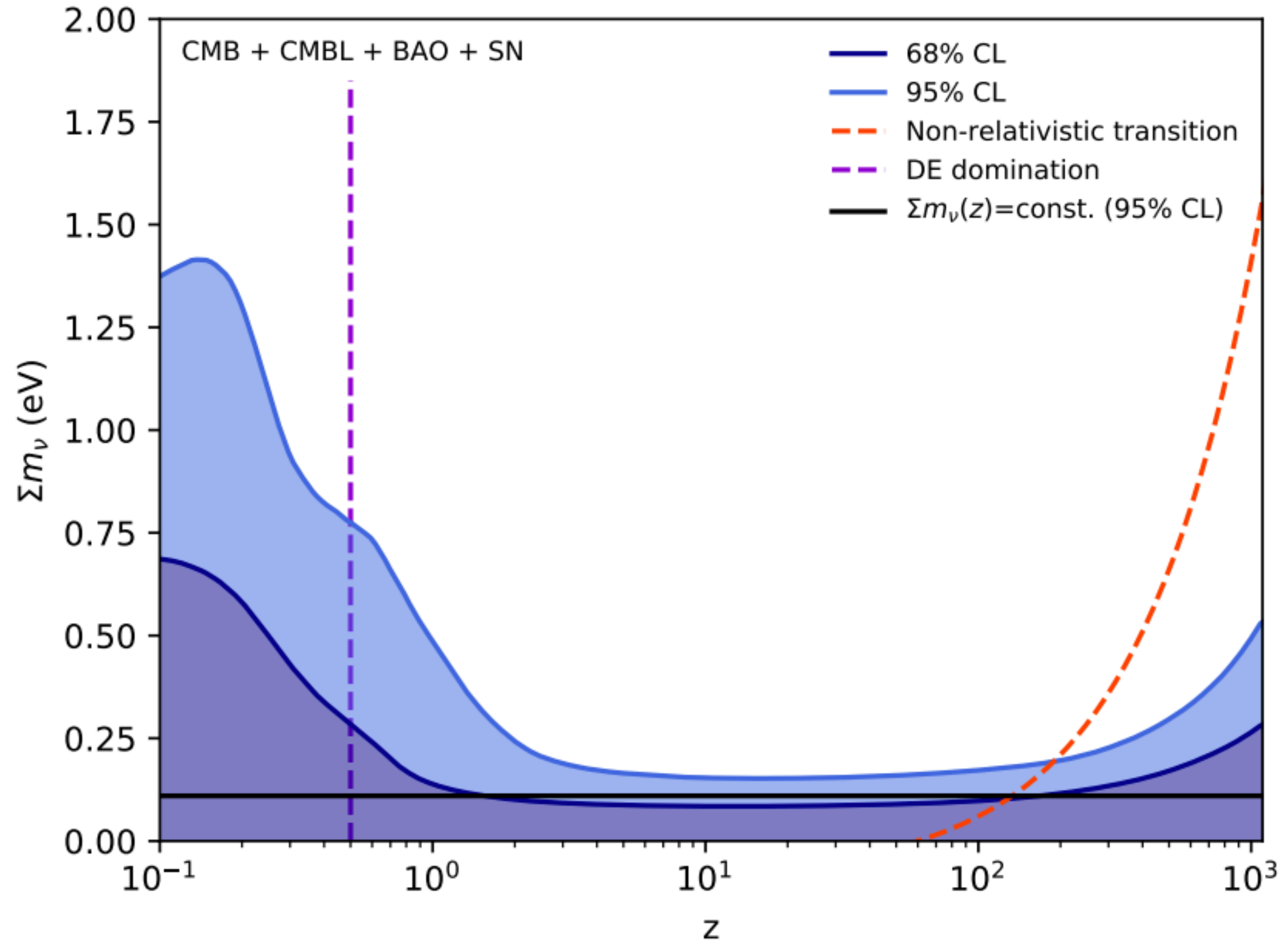
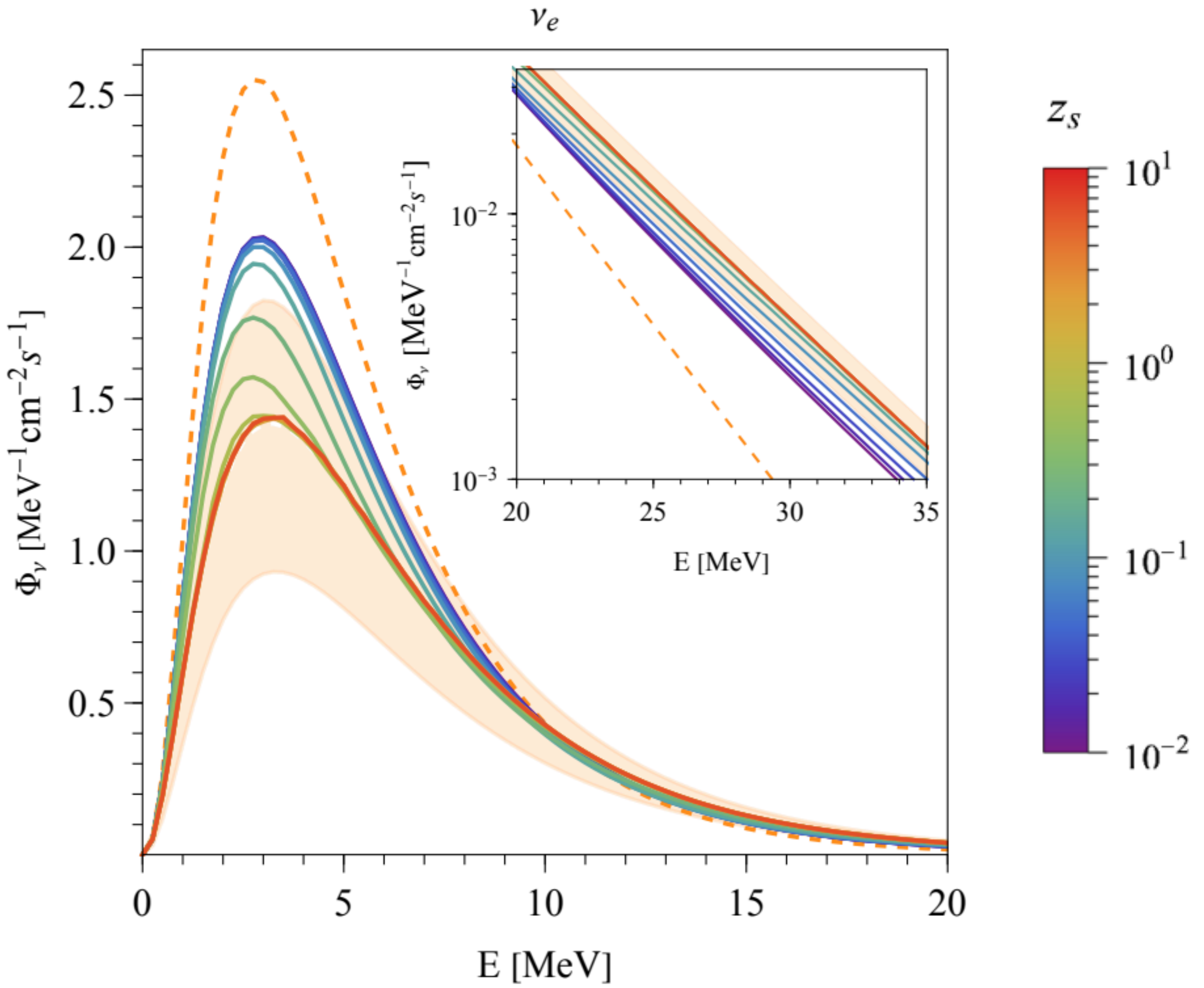
The basic question?

- Can the neutrino mass vary as a function of redshift?

- Consider bounds from
  1. CMB temperature, polarization and lensing data from Planck.
  2. BAO from 6dF, SDSS, BOSS,…
  3. Type Ia SN from Pantheon.
  4. Diffuse SN neutrino background





Dvali, Funcke, PRD 2016
Lorenz,Funcke,Löffler, Calabrese, PRD 2021
Lorenz,Funcke,Calabrese,Hannestad PRD 2019
de Gouvea, Martinez-Soler, Perez-Gonzalez, **MS**, PRD 2022

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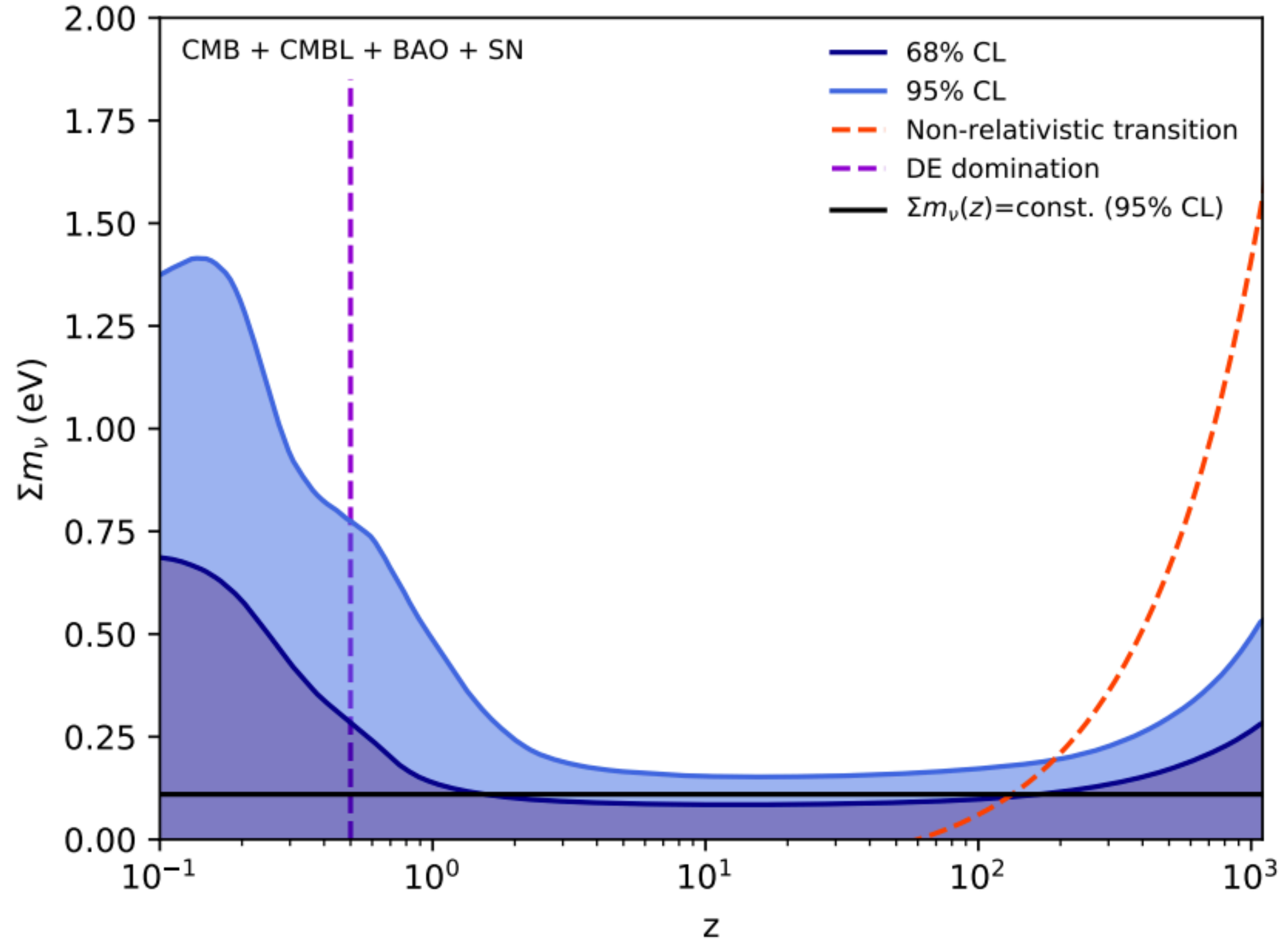
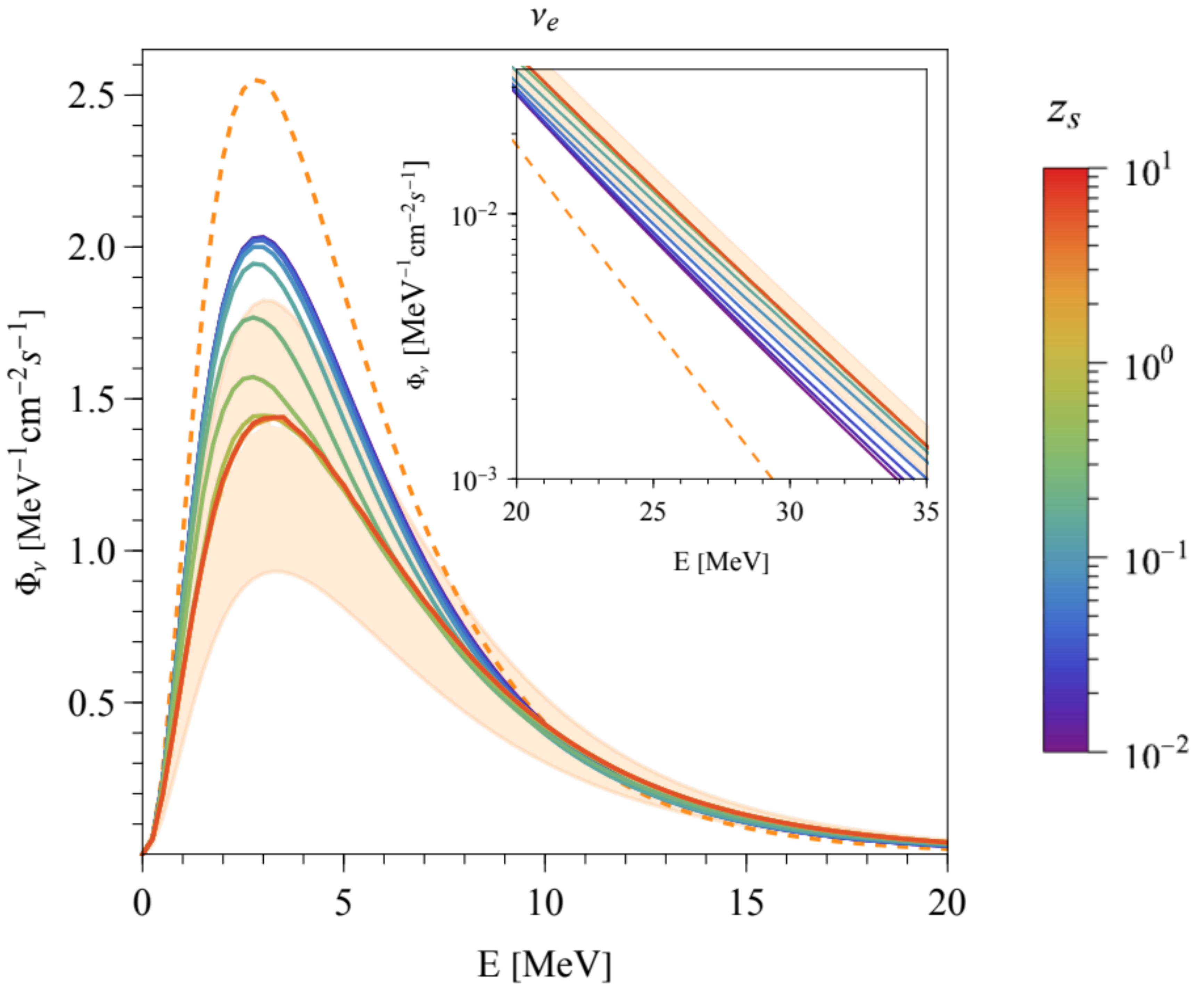
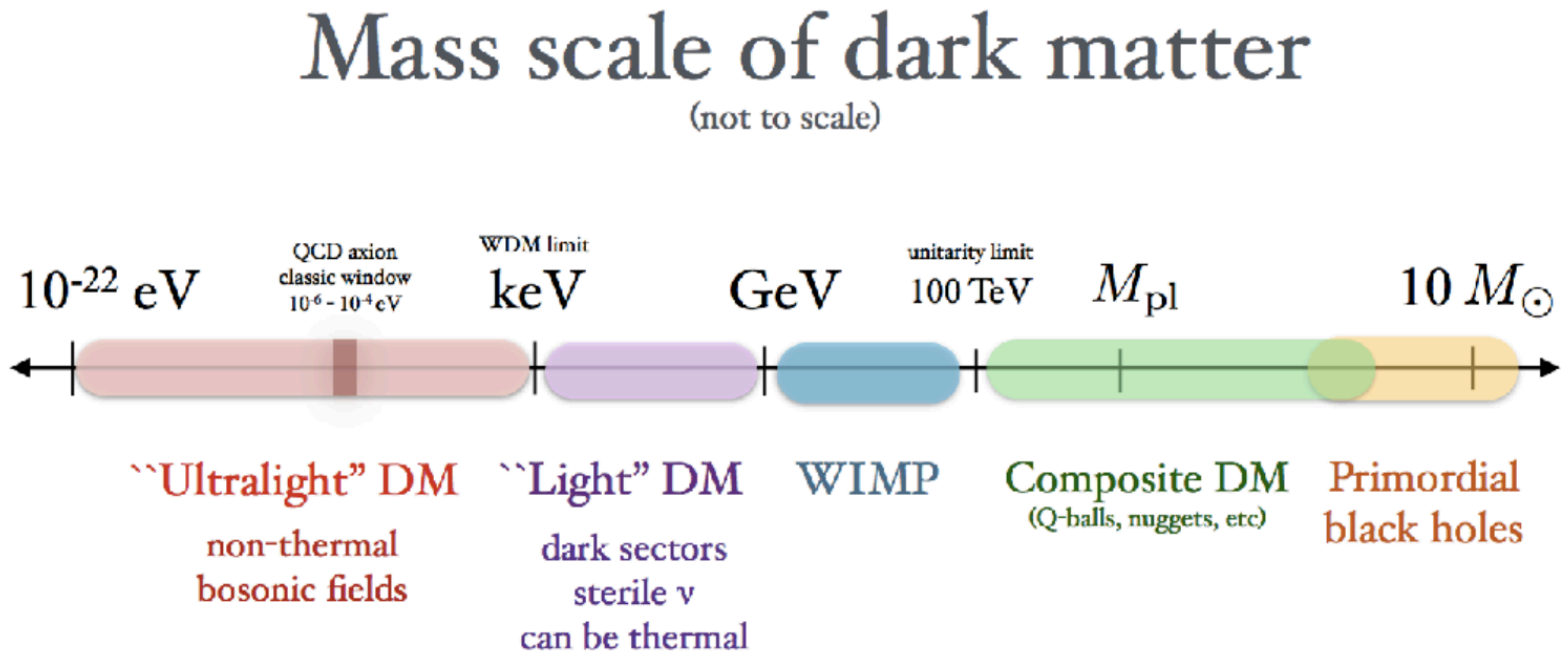
- This can arise due to neutrino coupling with ultralight dark matter.





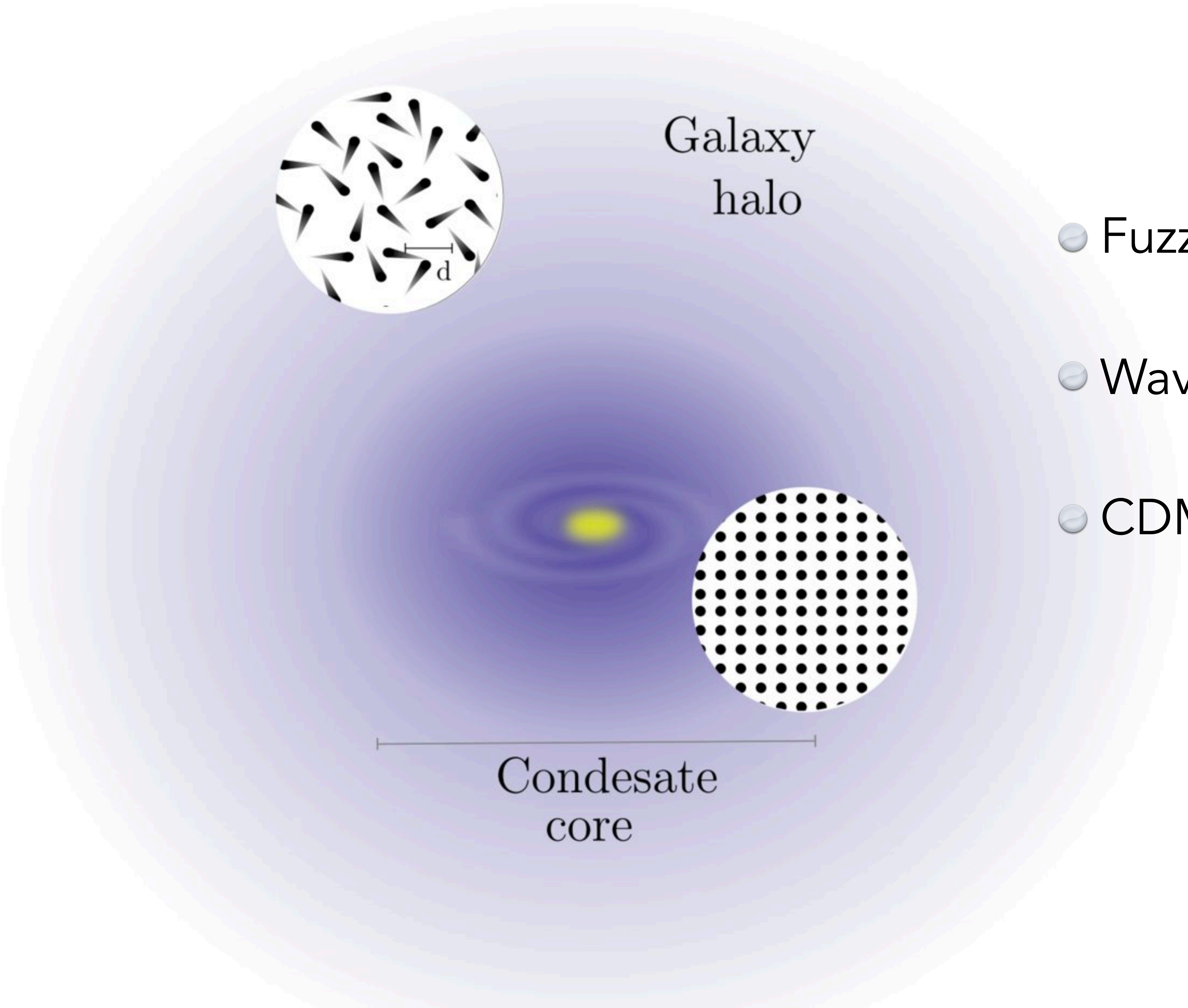
What is ultralight dark matter?



Dark Sector Searches, Snowmass 2020

A phenomenological overview

E. Ferreira, Astronomy Review 2021



- Fuzzy Dark matter
- Wave DM for $\lambda_{dB} \gg r_{\rm sep}$
- CDM in the outskirts of galaxies

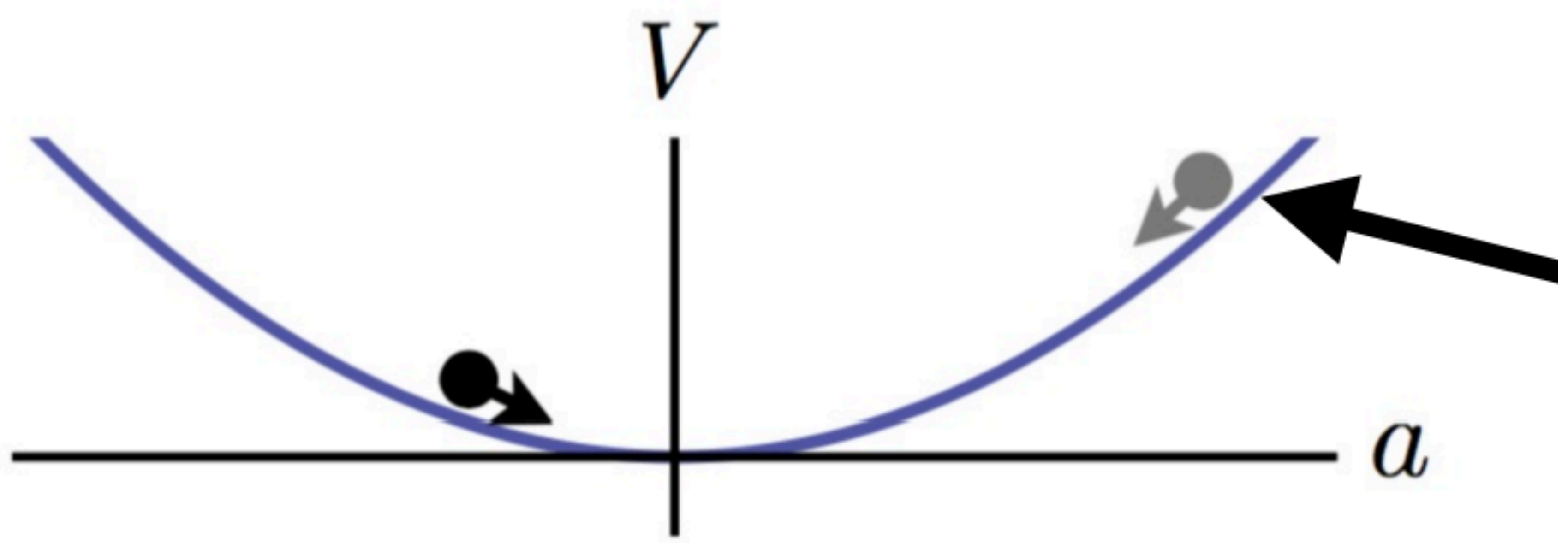
Hu, Barakana, Gruzinov (PRL 2000)
Hui, Ostrikar, Tremaine, Witten (PRD 2017)

What is ultralight dark matter?

E. Ferreira, Astronomy Review 2021

- Ultralight scalar field produced **coherently.**

$$\ddot{\phi} + 3H\dot{\phi} + m_\phi^2 \phi = 0$$



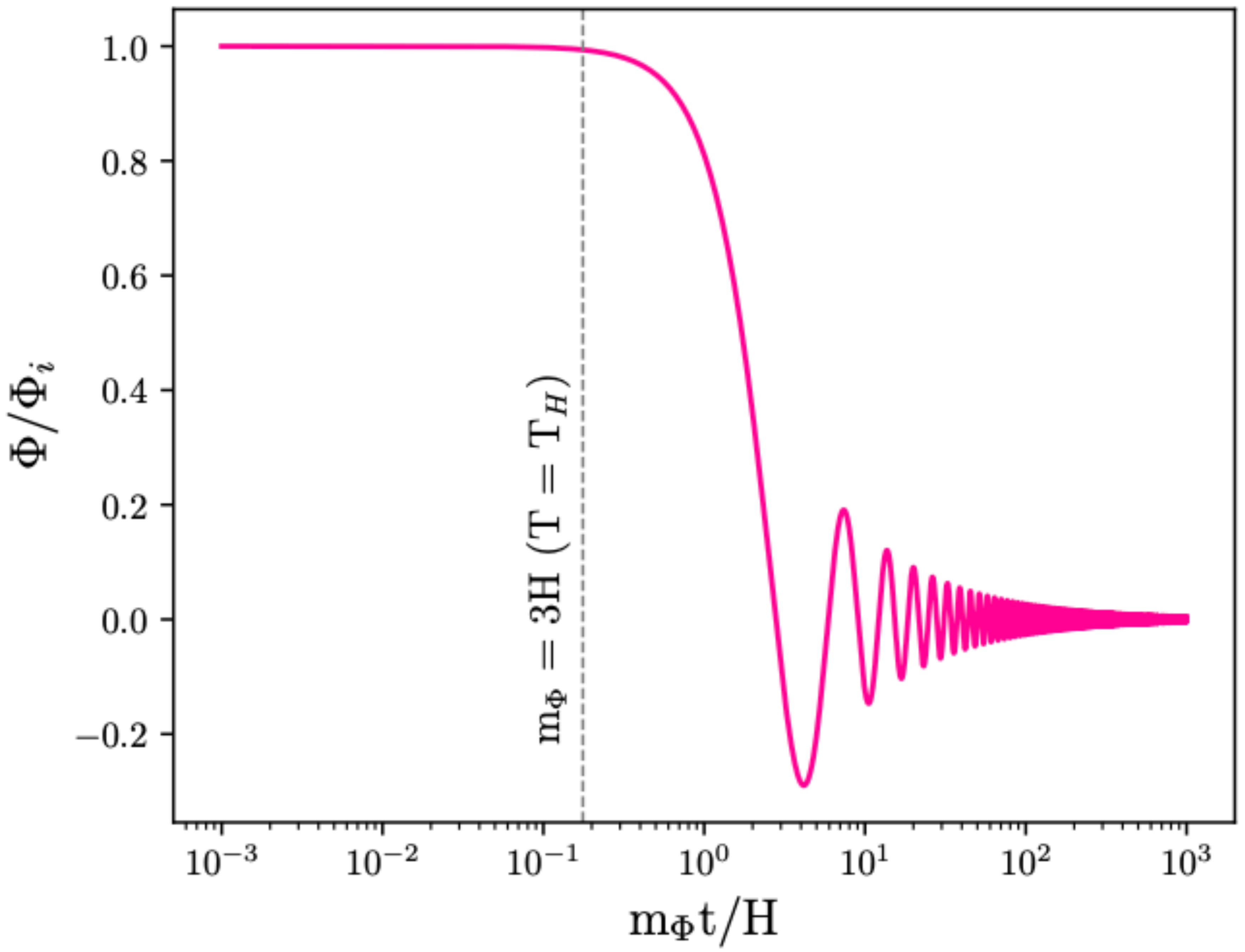
- Can be produced in the early Universe through the misalignment mechanism.

- Consider a Glauber-Sudarshan state

$$|\Phi_c\rangle \propto \exp\left(-\int \frac{d^3k}{(2\pi)^3}\phi(k)\, a_k^\dagger\right)|0\rangle.$$

- Expand $\langle \Phi_c | \hat{\phi} | \Phi_c \rangle = \phi_0 \cos(m_\phi t - \mathbf{kx})$.

Here $\phi_0 = \dfrac{\sqrt{2\rho}}{m_\phi}$.



Talk by A. Smirnov

Some back-of-the-envelope estimates

- de-Broglie wavelength $\lambda_{\rm dB} = (m_\phi v_\phi)^{-1} \simeq 600\,{\rm pc}\left(\frac{10^{-22}{\rm eV}}{m_\phi}\right)\left(\frac{10^{-3}}{v_\phi}\right)$

- In a given vol $\lambda_{\rm dB}^3$, occupation number $N = 10^{91}\left(\frac{10^{-22}{\rm eV}}{m_\phi}\right)^4$. Justifies use as a classical field since the fluctuations are N^{-1}.

$$\langle \Phi_c | \hat{\phi} | \Phi_c \rangle = \phi_0 \cos(m_\phi t - \mathbf{kx}) + \mathcal{O}(N^{-1})$$

- Modulation period $\tau_\phi = 2\pi/m_\phi \simeq 1\,{\rm yr}\left(\frac{10^{-22}\,{\rm eV}}{m_\phi}\right)$.

What if this ULDM is neutrinophilic?

- Consider a term $\mathscr{L} \supset g\,\bar{\nu}\,\nu\,\phi(t) = \dfrac{\sqrt{2\rho}}{m_\phi}\,g\cos(m_\phi t)\,\bar{\nu}\,\nu$

- For local DM density $\rho_\odot \sim 0.3\,\mathrm{g/cc}$, $\mathscr{L} \supset\ 10^{15}\,\mathrm{eV}\left(\dfrac{10^{-18}\,\mathrm{eV}}{m_\phi}\right) g\ \cos(m_\phi t)\ \bar{\nu}\,\nu$

- For $g \lesssim 10^{-15}$, this gives an $\mathscr{O}(1)$ eV contribution to neutrino mass.

- Rich phenomenology expected from oscillation experiments, solar neutrinos, and atmospheric neutrinos

Berlin (PRL 2016),
Krnjaic, Machado, Necib (PRD 2018),
Brdar, Kopp, Liu, et al (PRD 2018),
Liao, Marfatia, Whisnant (JHEP 2018),
Dev, Machado, Martınez-Mirave (JHEP 2020) + ……

But cosmology spoils the party…

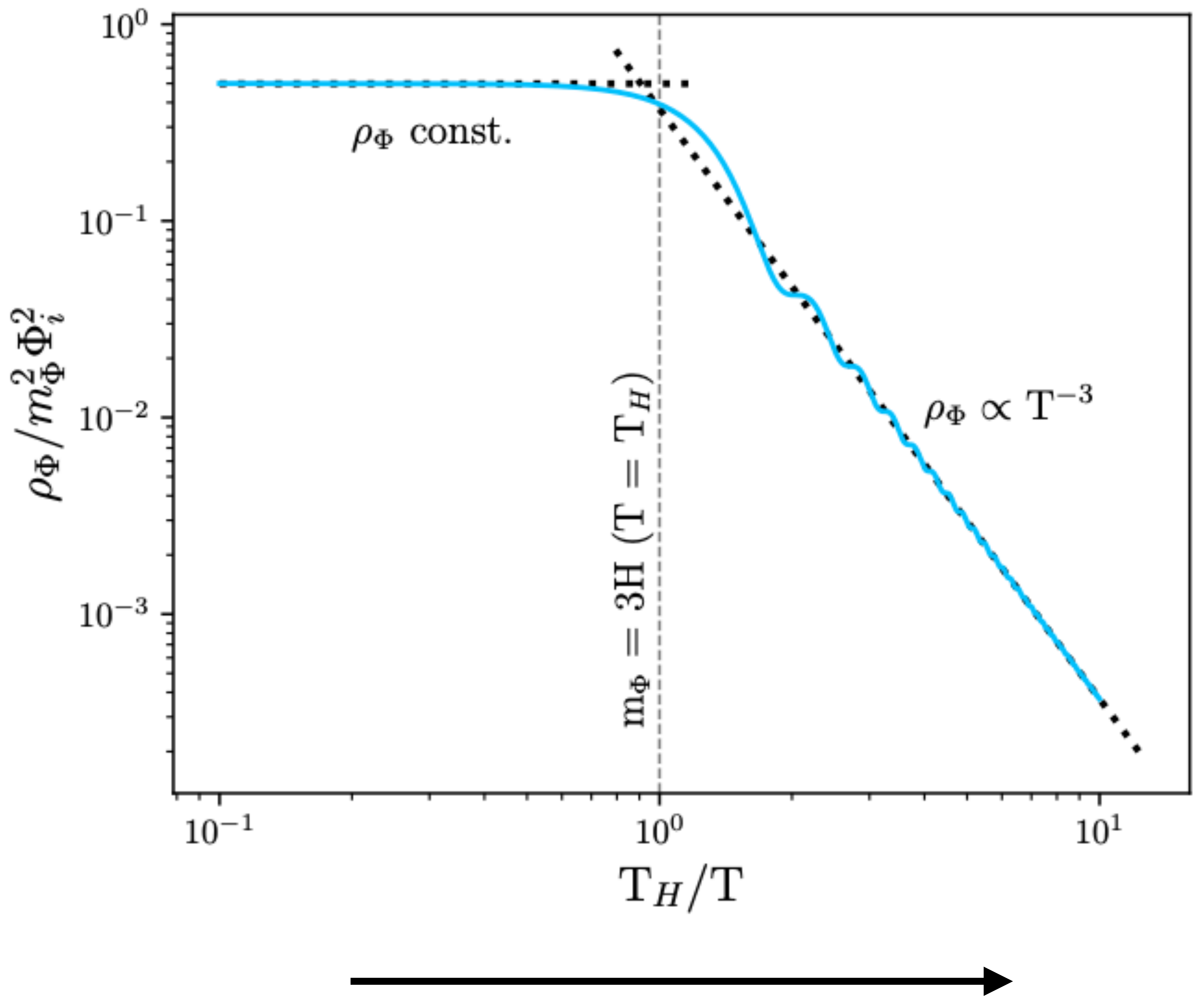
- Major issues with cosmology. Remember $|\phi| = \sqrt{2\rho}/m_\phi$.
  DM redshifts as $|\phi| \propto (1+z)^{3/2}$.

- Neutrino mass from ϕ also redshifts.

- If $g\phi(0) = \sqrt{\Delta m^2_{\rm atm}}$, then $g\phi(z \sim 3000) \simeq 10\,\mathrm{eV}$.
  Large contribution to neutrino mass at matter-radiation equality.

- Spoils observation of $\sum m_\nu$ from CMB and structure formation.

- How to make this **cosmology-friendly** ?



Universe expands

Cosmology-friendly mass-varying neutrinos

- Avoid direct coupling between ν and ULDM .

- Couple the ULDM ϕ to sterile neutrinos N.

- Consider , $$\mathscr{L} \supset y_{\rm D} \overline{L}\, h^{\rm c} N + \frac{1}{2}(m_N + g\phi(t))\, \overline{N^{\rm c}} N$$

- 2 flavour: in the flavour basis,

$$\tilde{M}_\nu = U^\dagger \begin{pmatrix} m_1 & 0 \\ 0 & m_4 \end{pmatrix} U + \begin{pmatrix} 0 & 0 \\ 0 & g\phi(t) \end{pmatrix}$$

- What happens to the light neutrino mass after diagonalisation?

G. Huang. M. Lindner, P. Martinez-Mirave, **MS,** (PRD 2022)
P. Martinez-Mirave, Y. Perez-Gonzalez ,**MS,** (arXiv: 2406.01682)

Cosmology-friendly mass-varying neutrinos

- Limit 1: when $g\phi$ is small, i.e., $|g\phi| \ll m_4$,

$$\widetilde{m}_1 \simeq m_1 + \sin^2\theta_{14} \cdot g\phi \ , \qquad \widetilde{m}_4 \simeq m_4 + \cos^2\theta_{14} \cdot g\phi$$

This can lead to time-modulation in oscillation experiments!

- Limit 2: when $g\phi$ is large, i.e., $|g\phi| \gg m_4 > 0$,

$$\widetilde{m}_4 \simeq \frac{m_1 + m_4 + (m_4 - m_1)\cos 2\theta_{14}}{2} + g\phi$$

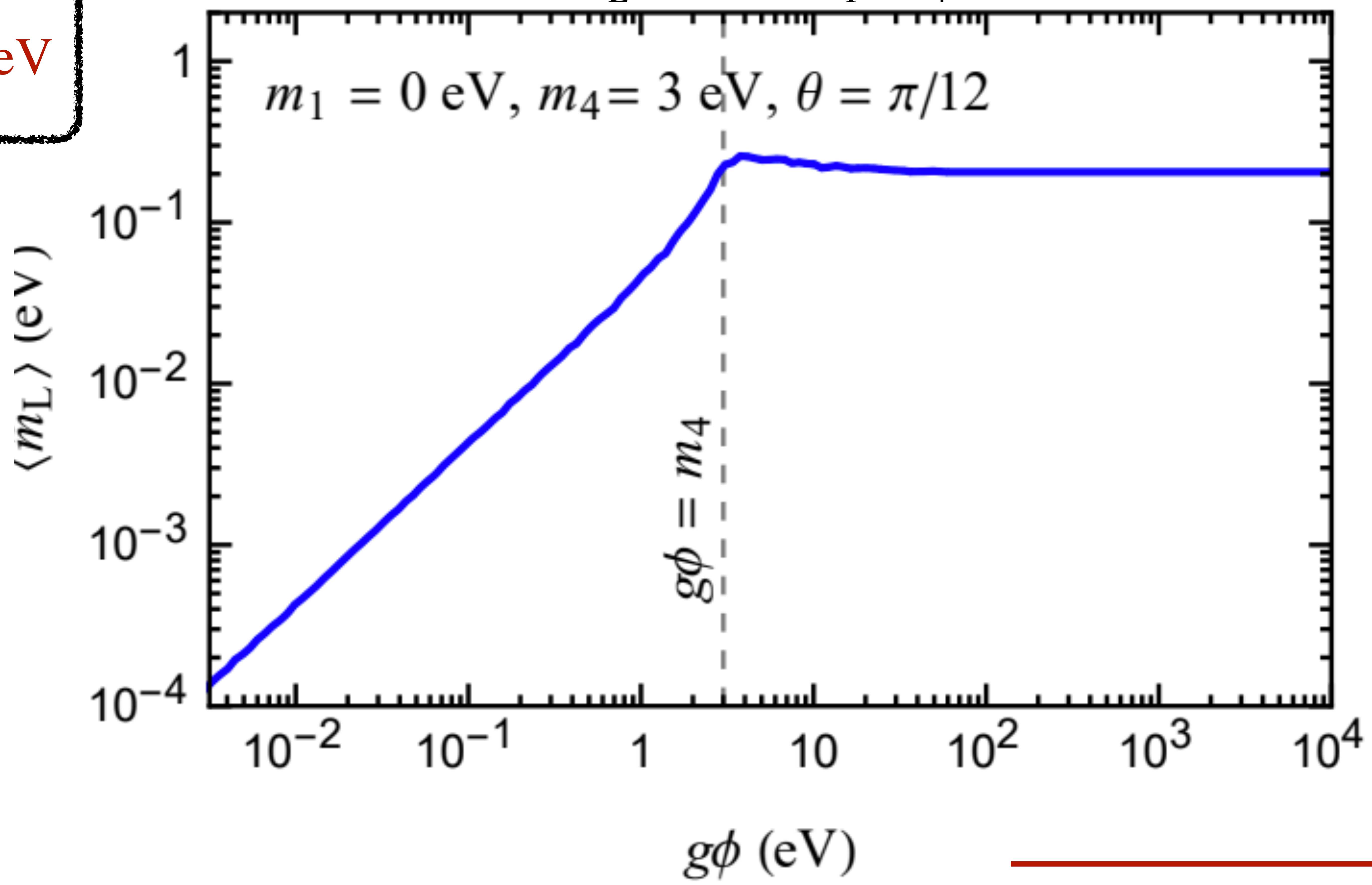
$$\widetilde{m}_1 \simeq \frac{m_1 + m_4 - (m_4 - m_1)\cos 2\theta_{14}}{2} - \frac{(m_4 - m_1)^2 \sin^2 2\theta_{14}}{4\, g\phi}$$

G. Huang. M. Lindner, P. Martinez-Mirave, **MS,** (PRD 2022)

Cosmology-friendly mass-varying neutrinos

$m_1 = 0, m_4 = 3\,\mathrm{eV}$

$m_L = \mathrm{Min}(\widetilde{m}_1, \widetilde{m}_4)$



$|\phi| \propto (1+z)^{3/2}$

early Universe

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Cosmology-friendly mass-varying neutrinos

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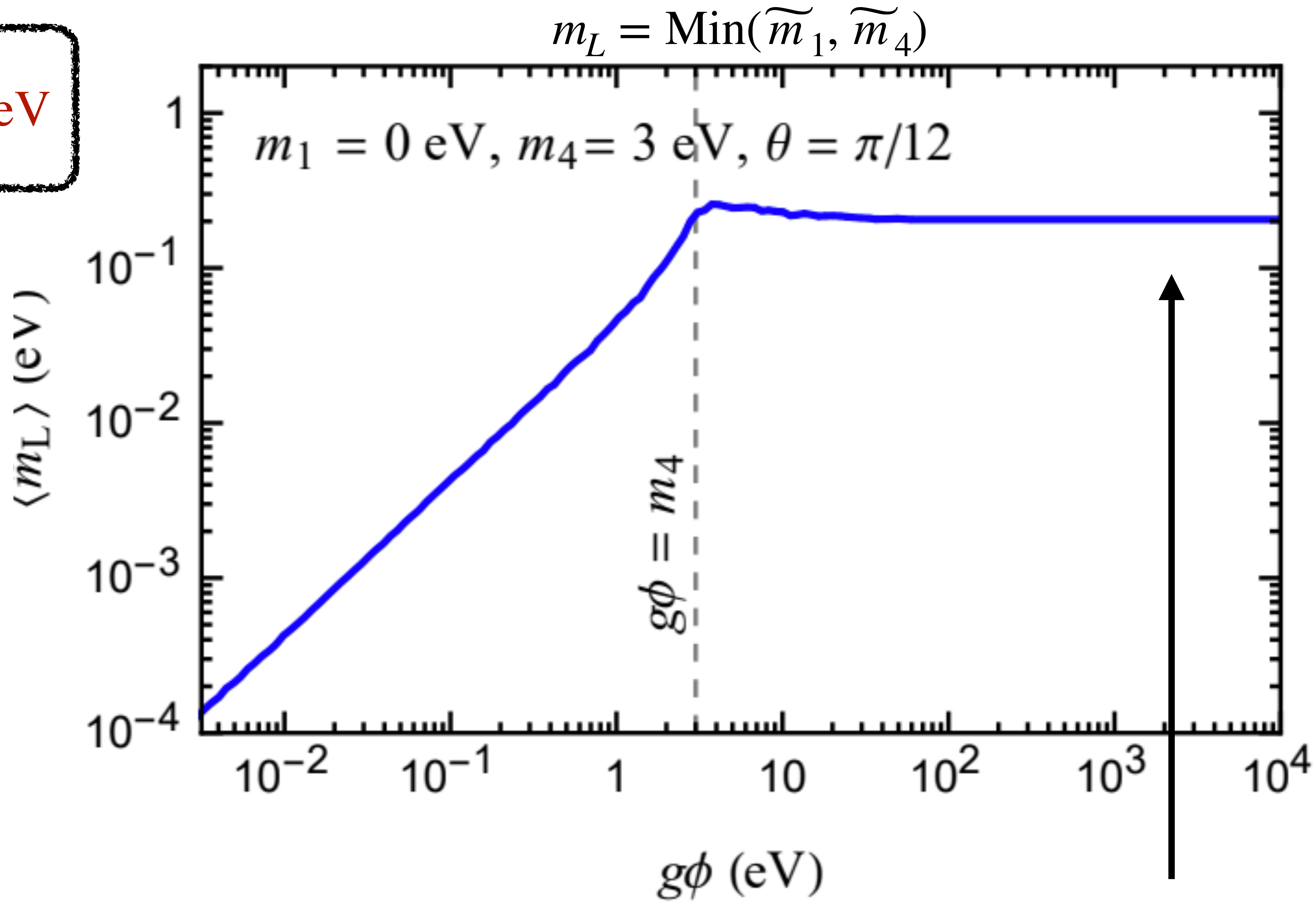


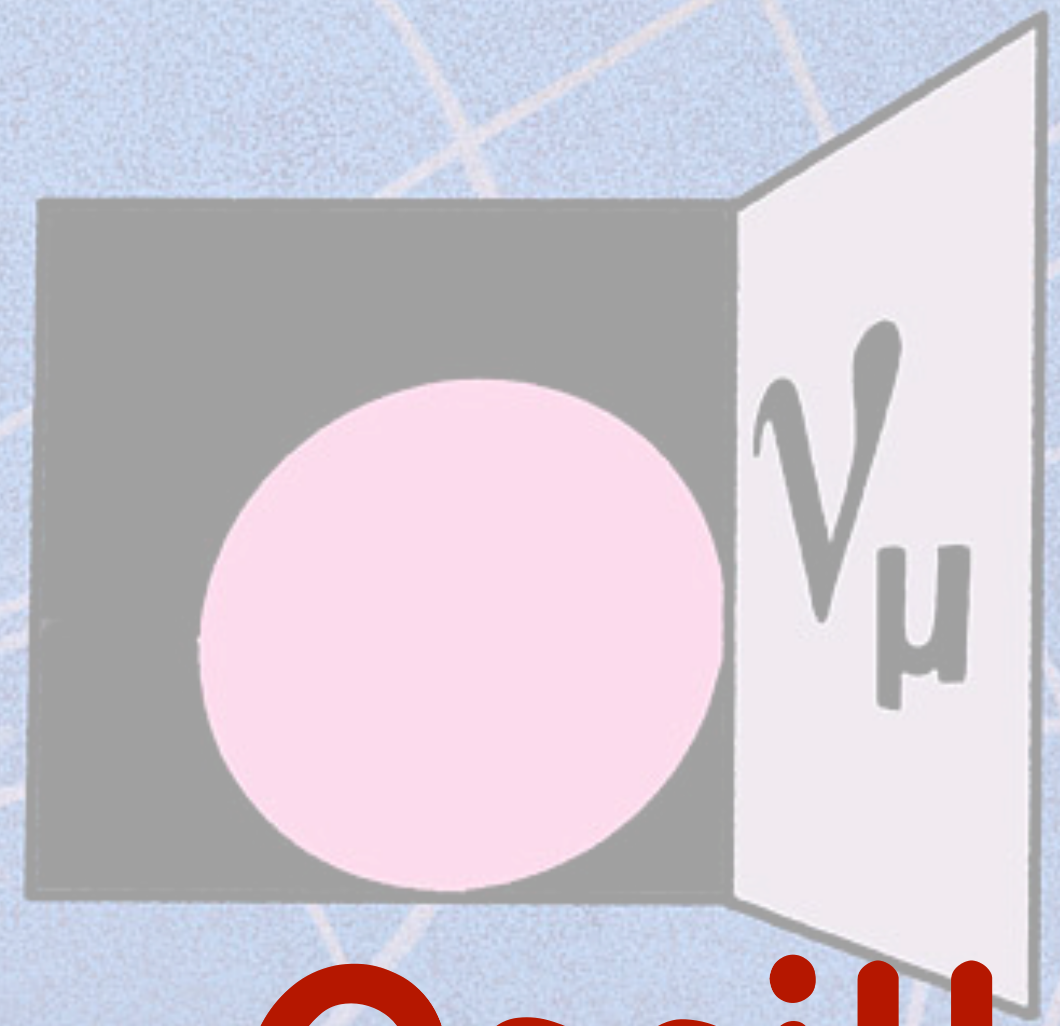
cosmology friendly for eV scale N

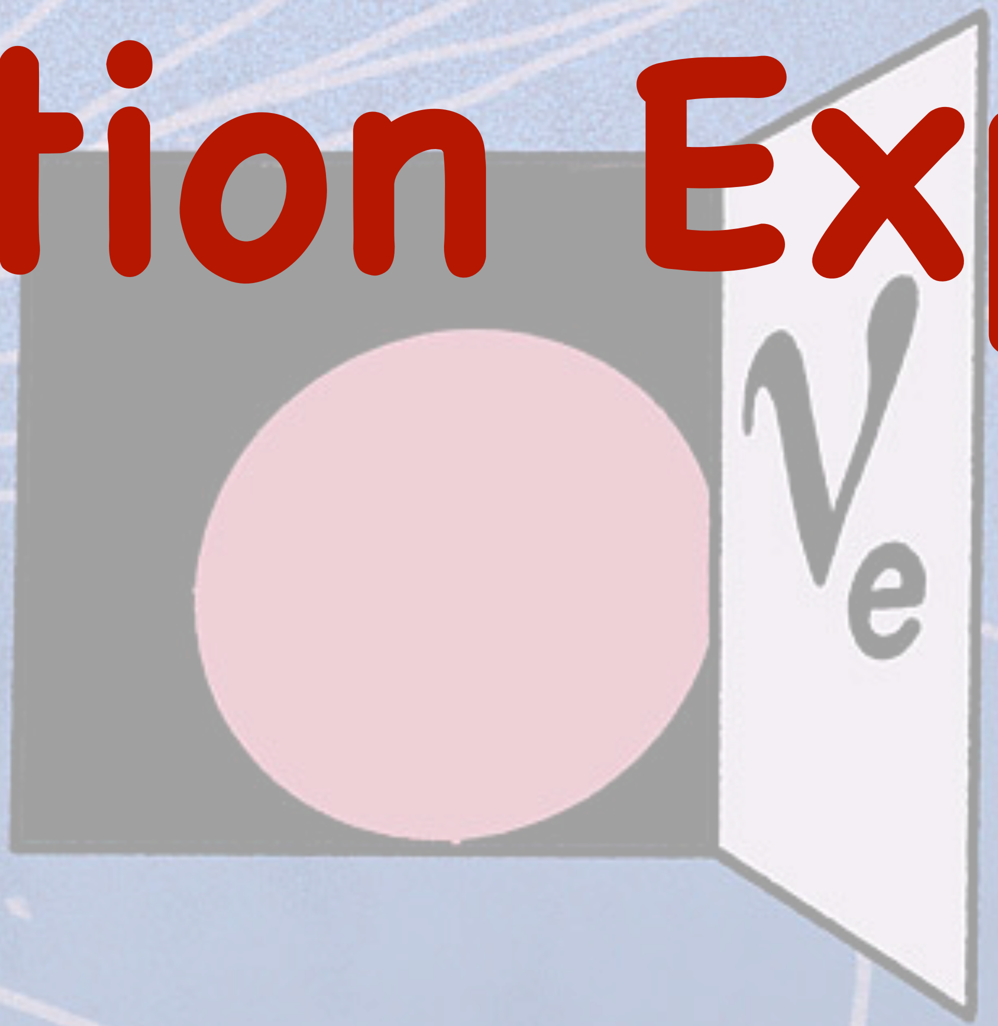
early Universe

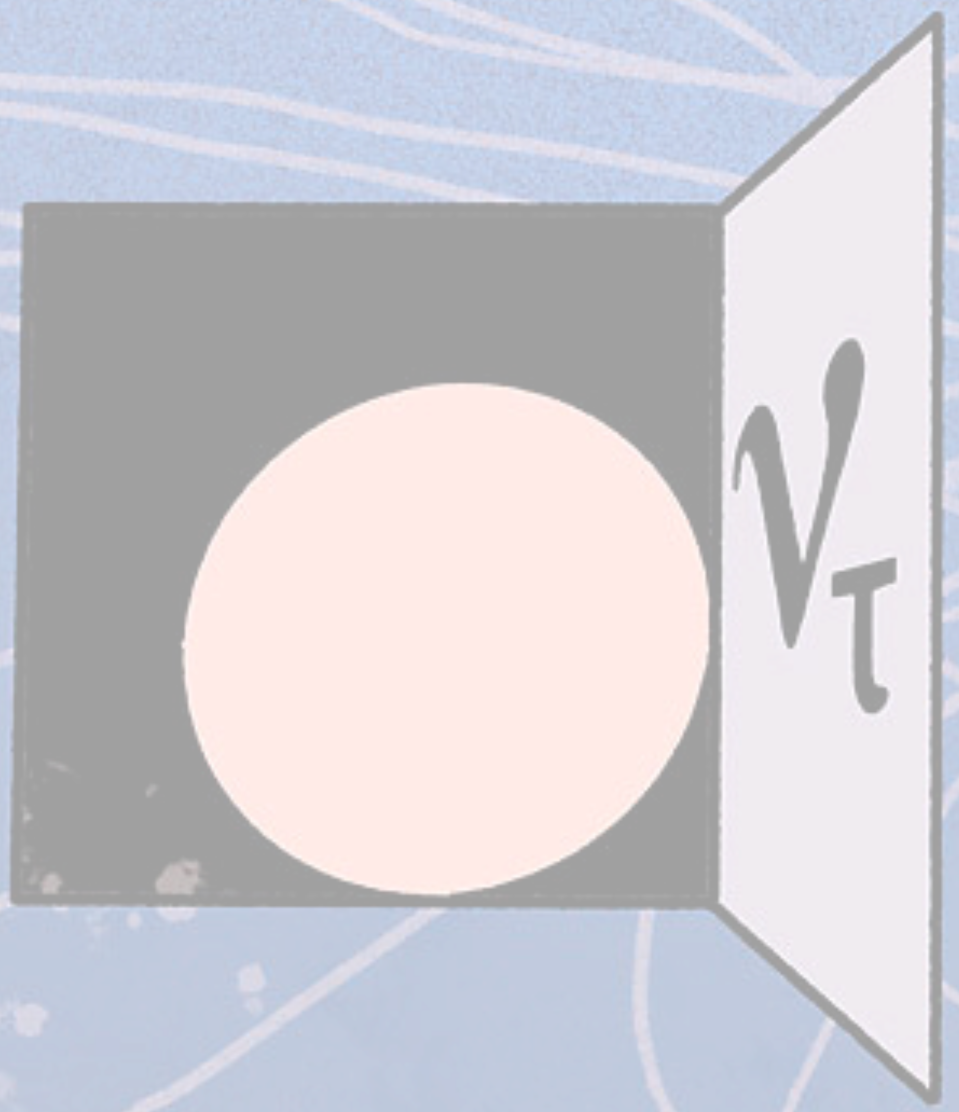
Implications for neutrino experiments

- Neutrino oscillations experiments
- Beta decay experiments.
- Short baseline oscillations.
- Relic neutrino capture
- Solar neutrinos, atmospheric neutrinos, cosmology

Neutrino Oscillation Experiments







Neutrino Oscillation Experiments

- Rich phenomenology for neutrinophilic ULDM.

- When $g\phi$ is small, i.e., $|g\phi| \ll m_4$,

$$\widetilde{m}_1 \simeq m_1 + \sin^2\theta_{14} \cdot g\phi(t)$$

Timescales

$$\tau_\phi = \frac{2\pi}{m_\phi}$$

$$\tau_\nu \sim \frac{L}{c}$$

$$\tau_{\rm exp}$$

This can lead to time-modulation in oscillation experiments!

$\tau_\phi \sim \tau_\nu = \frac{L}{c}$	$\tau_\nu \ll \tau_\phi \ll \tau_{\rm exp}$	$\tau_\phi \sim \tau_{\rm exp} \sim 10\,{\rm yrs}$
$m_\phi \sim 10^{-13} \div 10^{-14}\,{\rm eV}$	$m_\phi \sim 10^{-20}\,{\rm eV}$	$m_\phi \sim 10^{-23}\,{\rm eV}$
Dyn Distorted Neutrino Osc.	Avg Distorted Neutrino Osc.	Time Modulation

Krnjaic, Machado, Necib (PRD 2018)
A. Dev, P. Machado, P. Martınez-Mirave (JHEP 2020)

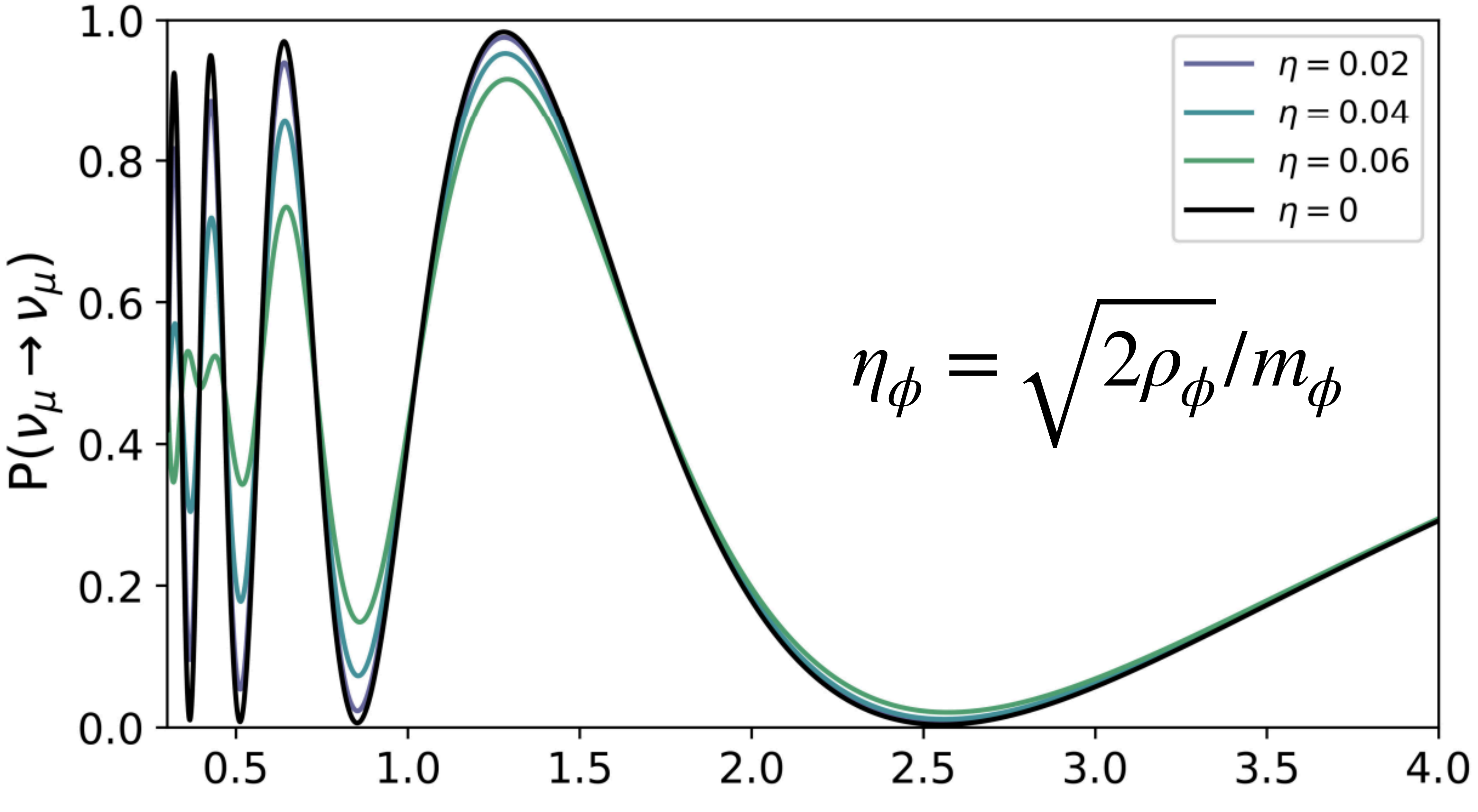
Distorted Neutrino Oscillations

Average

$\tau_\nu \ll \tau_\phi \ll \tau_{\rm exp}$

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

Smearing



$$\eta_\phi = \sqrt{2\rho_\phi}/m_\phi$$

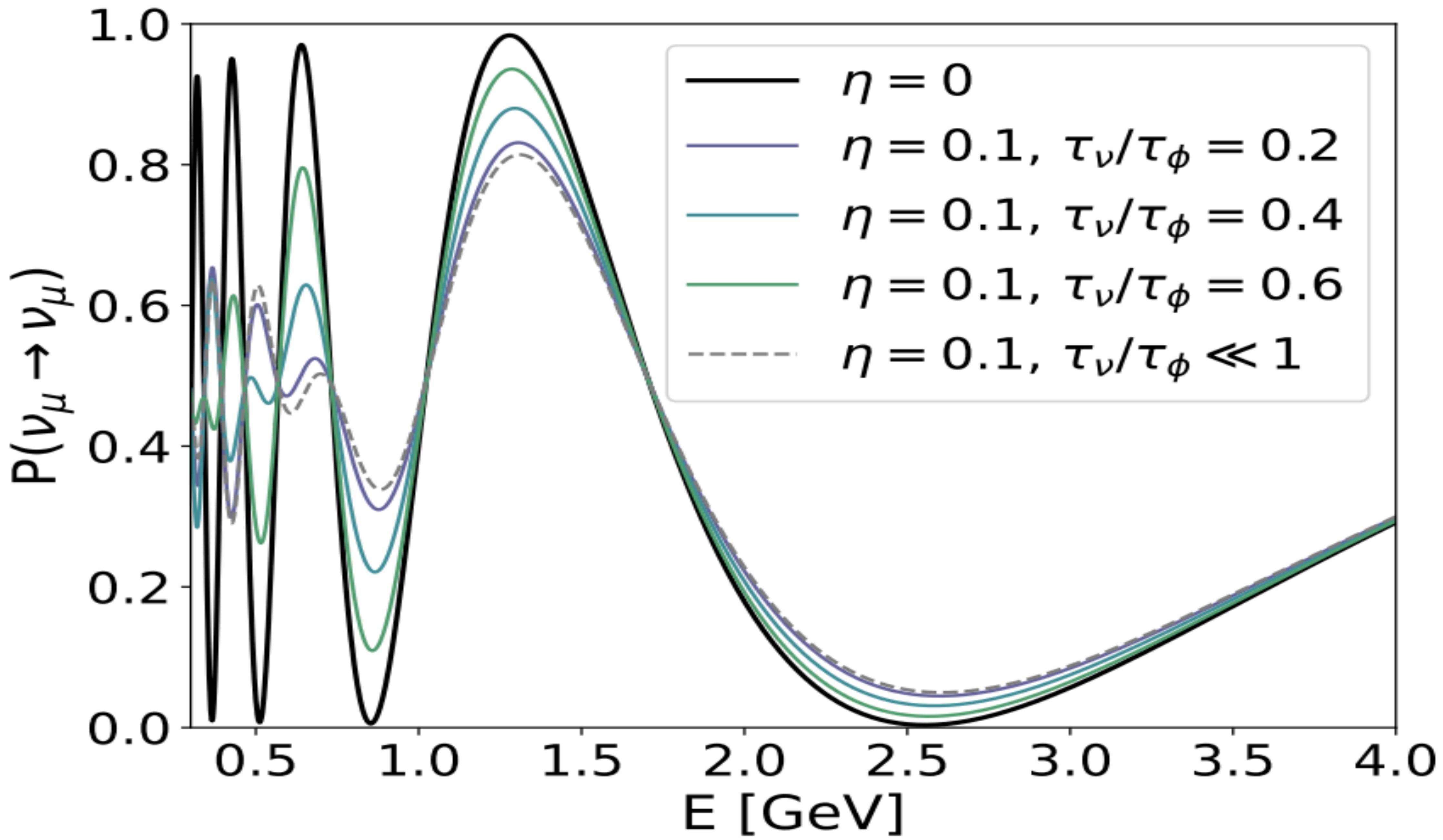
Dynamic

$\tau_\phi \sim \tau_\nu = \frac{L}{c}$

$$H(t) = H_{\rm vac} + H_{\rm mat} + V(t)$$

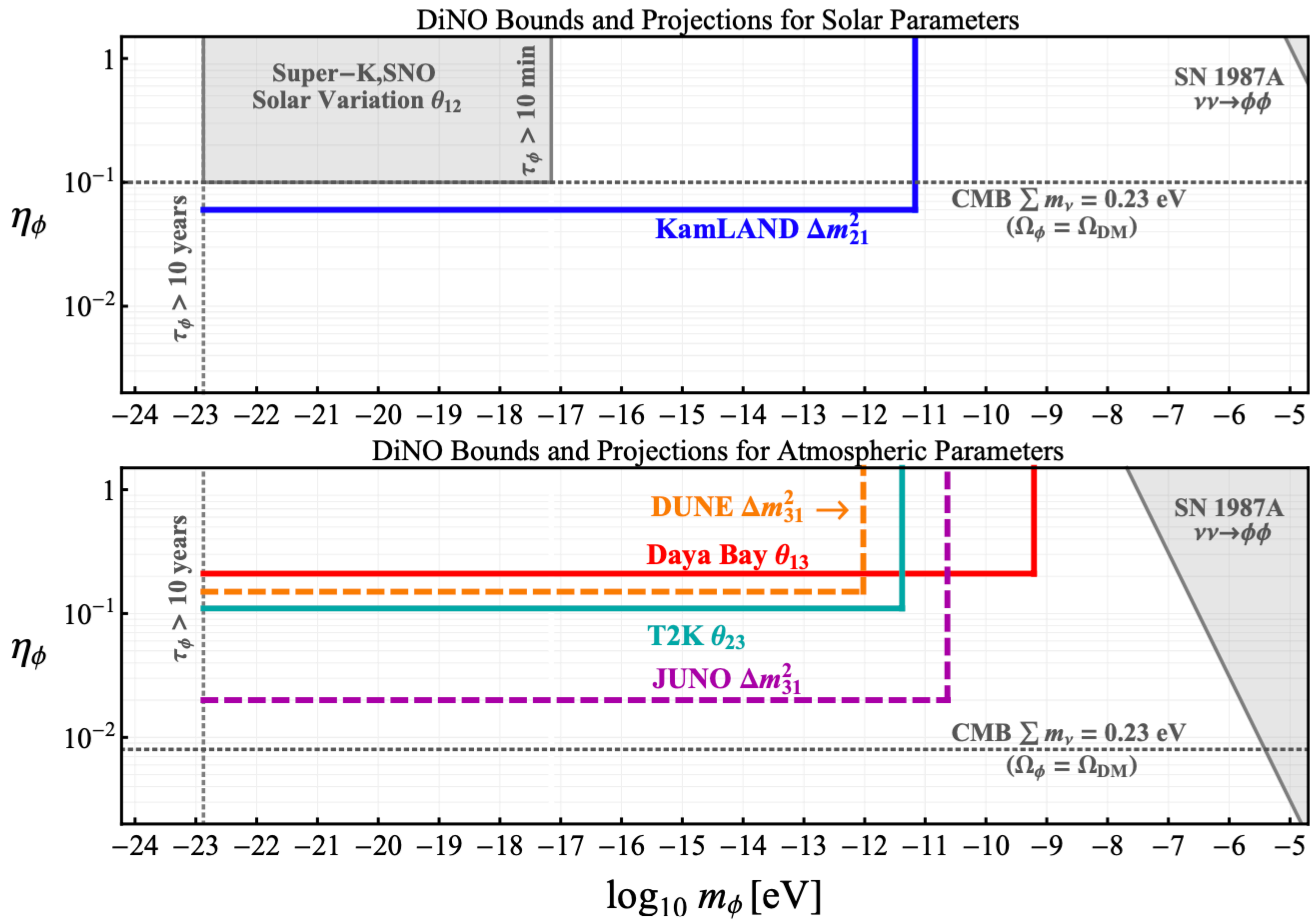
$$P_{\mu\mu}(t) = |\langle \nu_\mu | U \prod_n \exp\left[iH(t_n)L\right] U^\dagger | \nu_\mu\rangle|^2$$

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

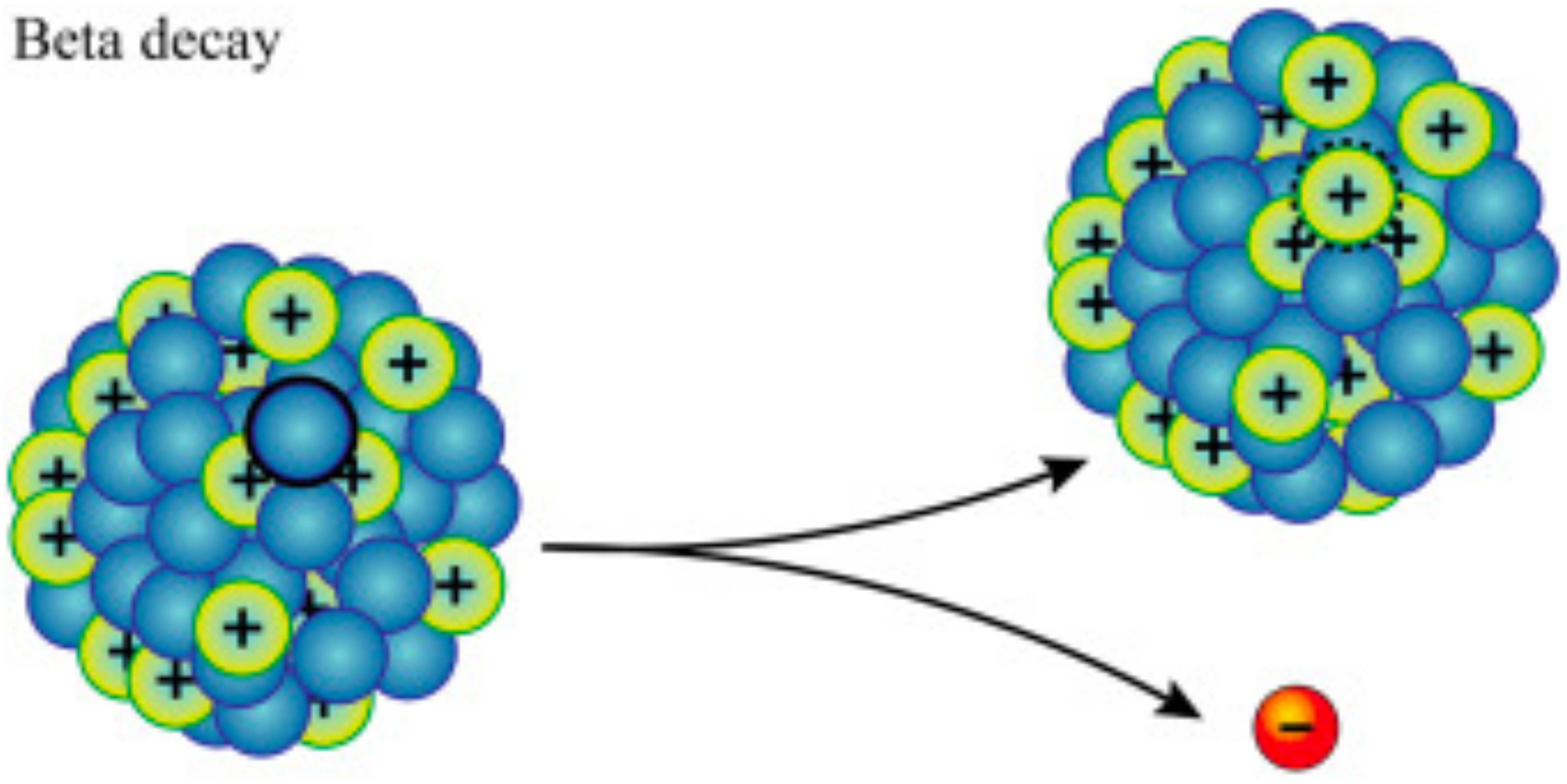


Implications for neutrino experiments

$$\eta_\phi = \sqrt{2\rho_\phi}/m_\phi$$



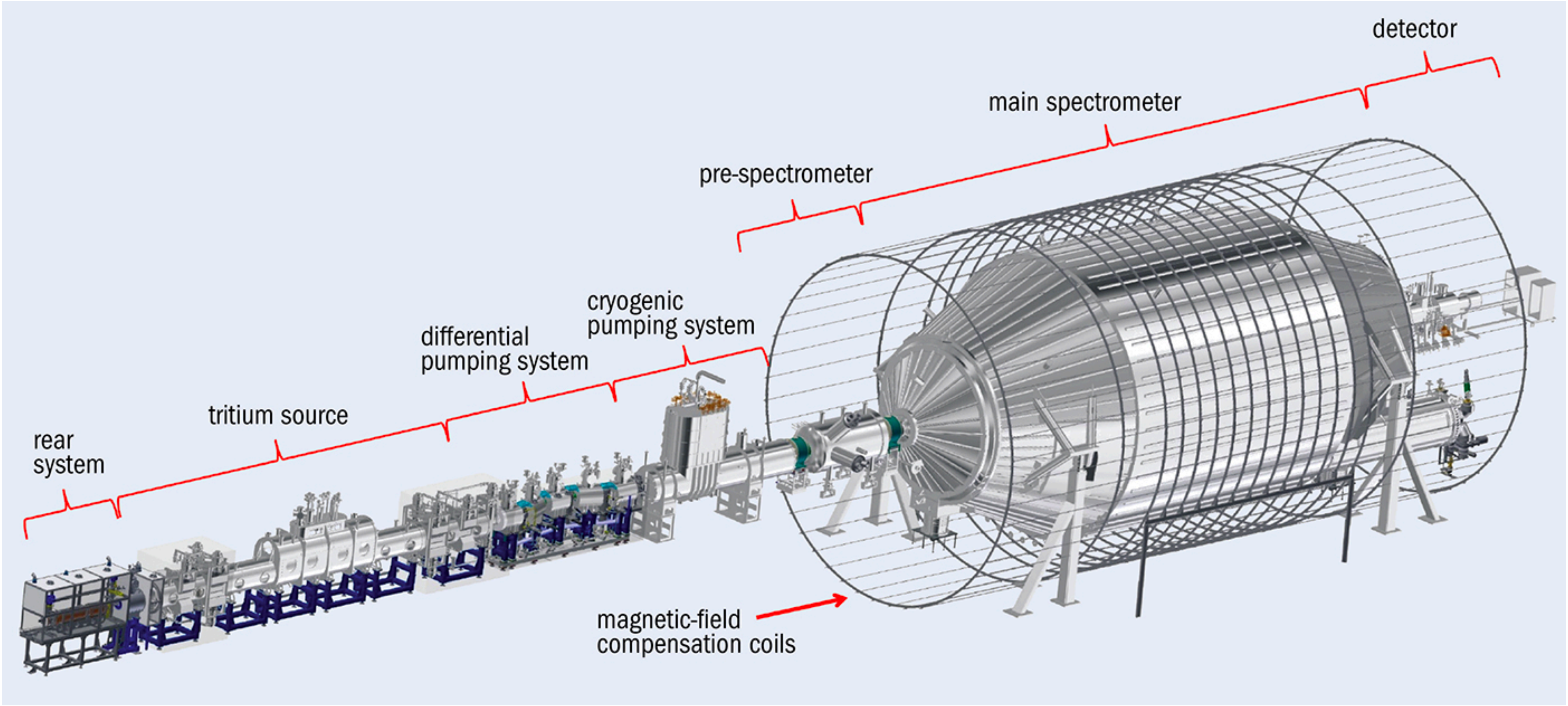
G. Krnjaic, P. Machado, L. Necib (PRD 2018),
A. Dev, P. Machado, P. Martınez-Mirave (JHEP 2020)

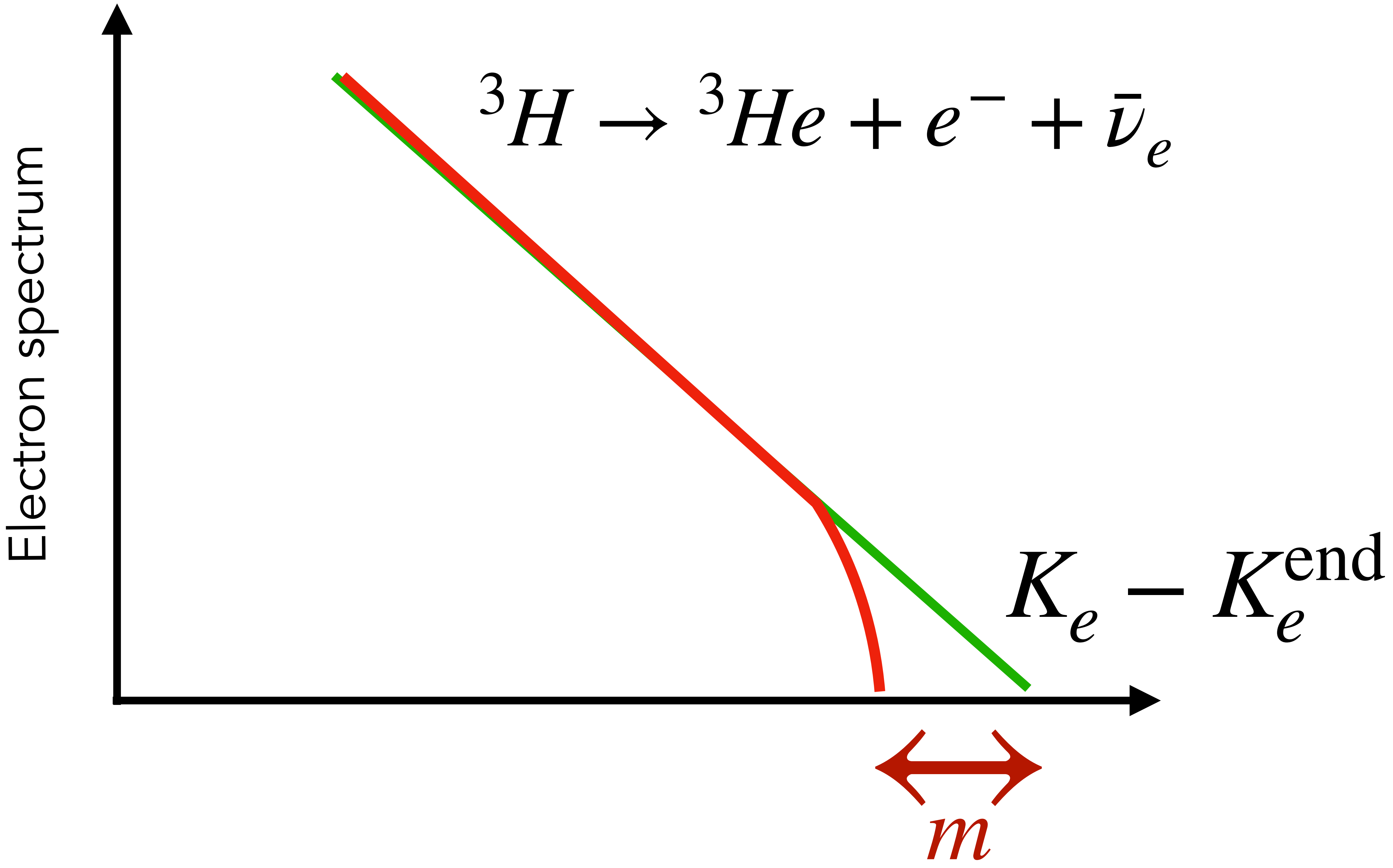


$$^{A}_{Z}X \longrightarrow \, ^{0}_{-1}e + \, ^{A}_{Z+1}Y$$

Beta Decay Experiments

KATRIN





- Potentially observable imprints in beta-decay experiments like KATRIN
- Spectral shape $R_\beta \propto \sqrt{(K_{\mathrm{end},0} - K_e)^2 - \widetilde{m}_\beta^2} \times \left(K_{\mathrm{end},0} - K_e\right)$
- Extract effective neutrino mass $\widetilde{m}_\beta^2 = \sum_i |U_{ei}|^2 m_i^2$ from spectral shape near endpoint.

Signatures in KATRIN for heavy sterile neutrinos

- Effective neutrino mass:

$$\widetilde{m}_\beta^2 = \sum_i |U_{ei}|^2 m_i^2$$

- Kink and constant shift.

- Time modulated mass ($|g\phi| \ll m_4$):

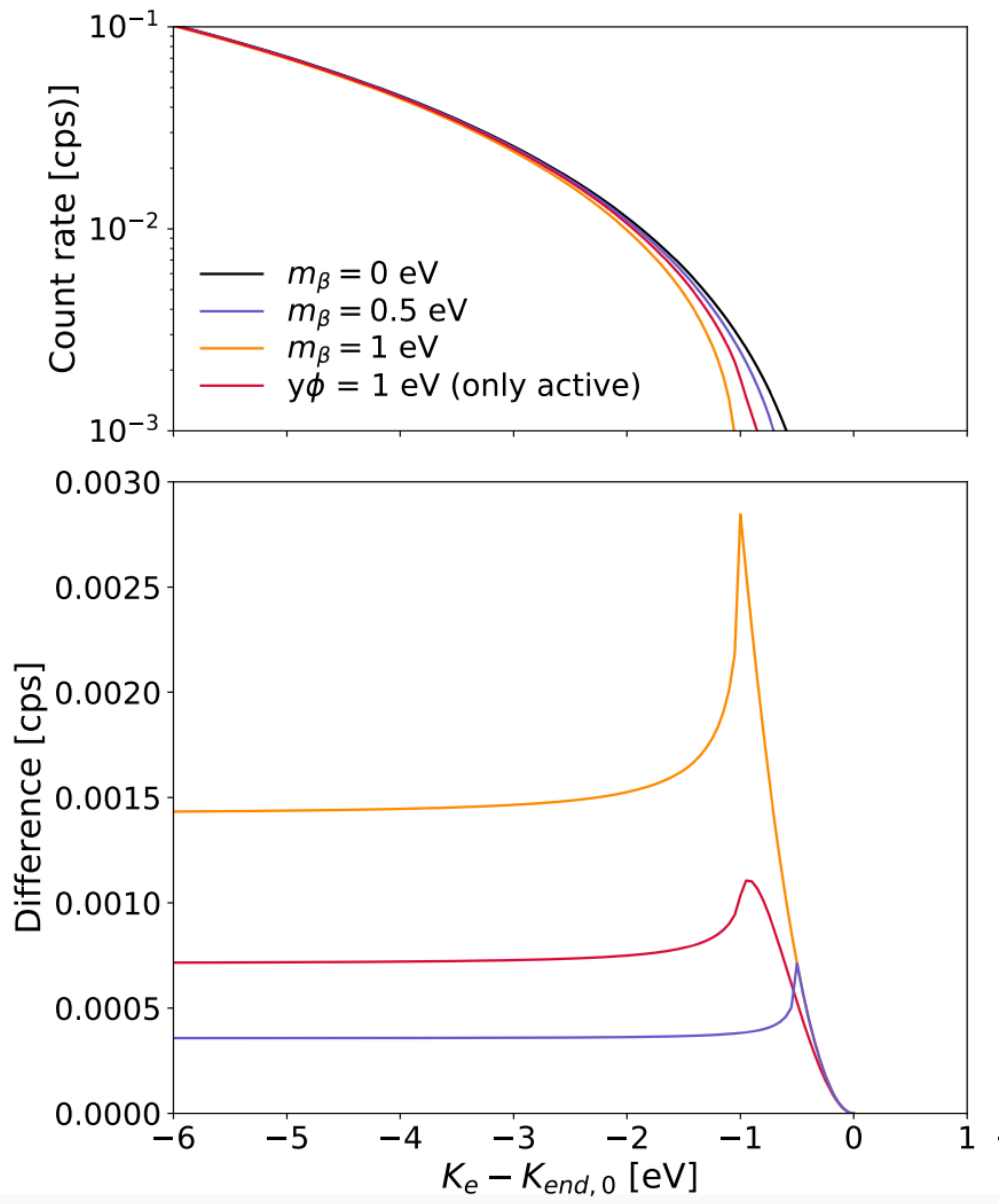
$$\widetilde{m}_1 \simeq m_1 + \sin^2\theta_{14} \cdot g\phi(t)$$

- Degeneracy: $\langle m_\beta^2 \rangle = m_\beta^2 + \frac{(g\phi)^2}{2}$

- Resolution with cosmology?

Talk last week by M. Archidiacono

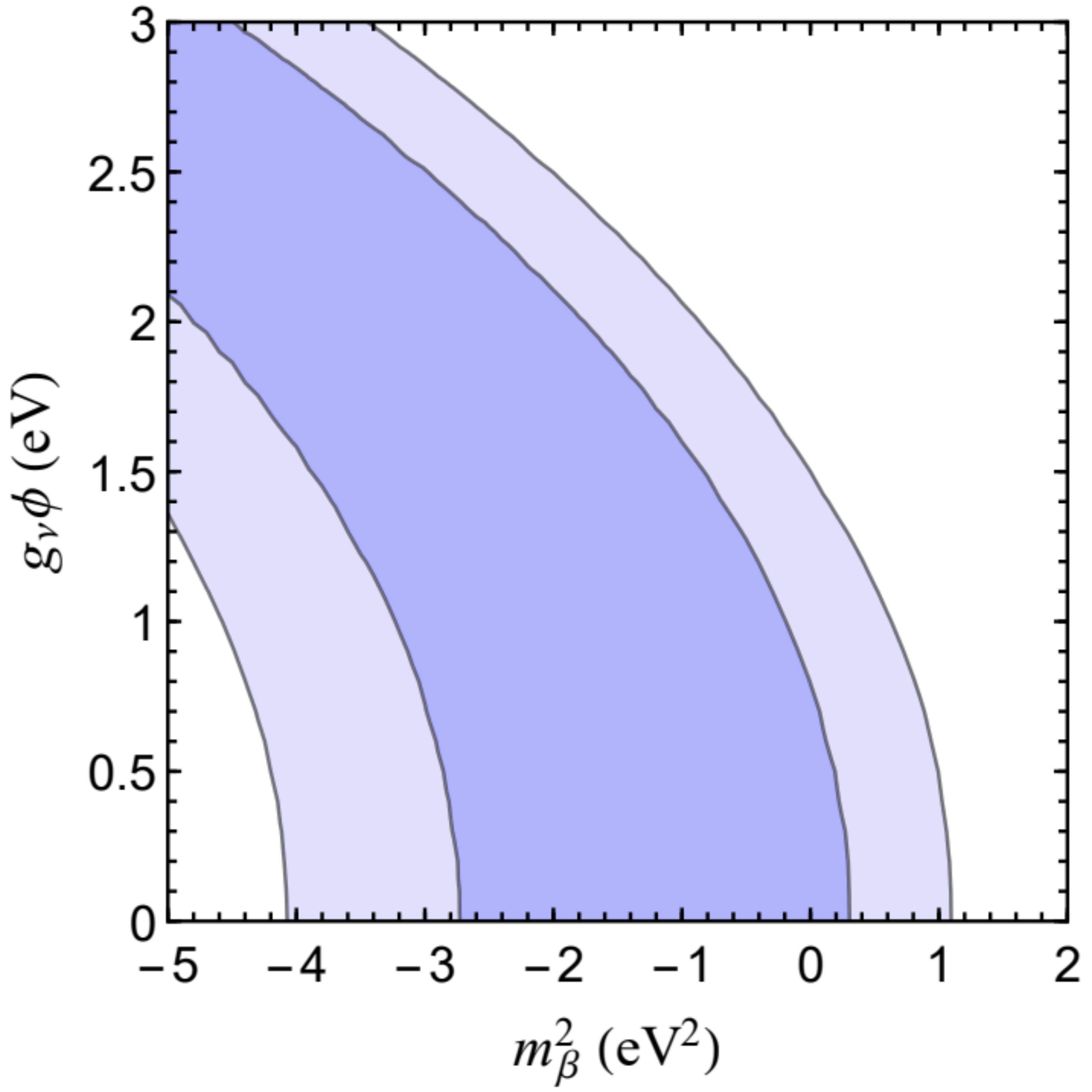
G. Huang. M. Lindner, P. Martinez-Mirave, **MS**, (PRD 2022)

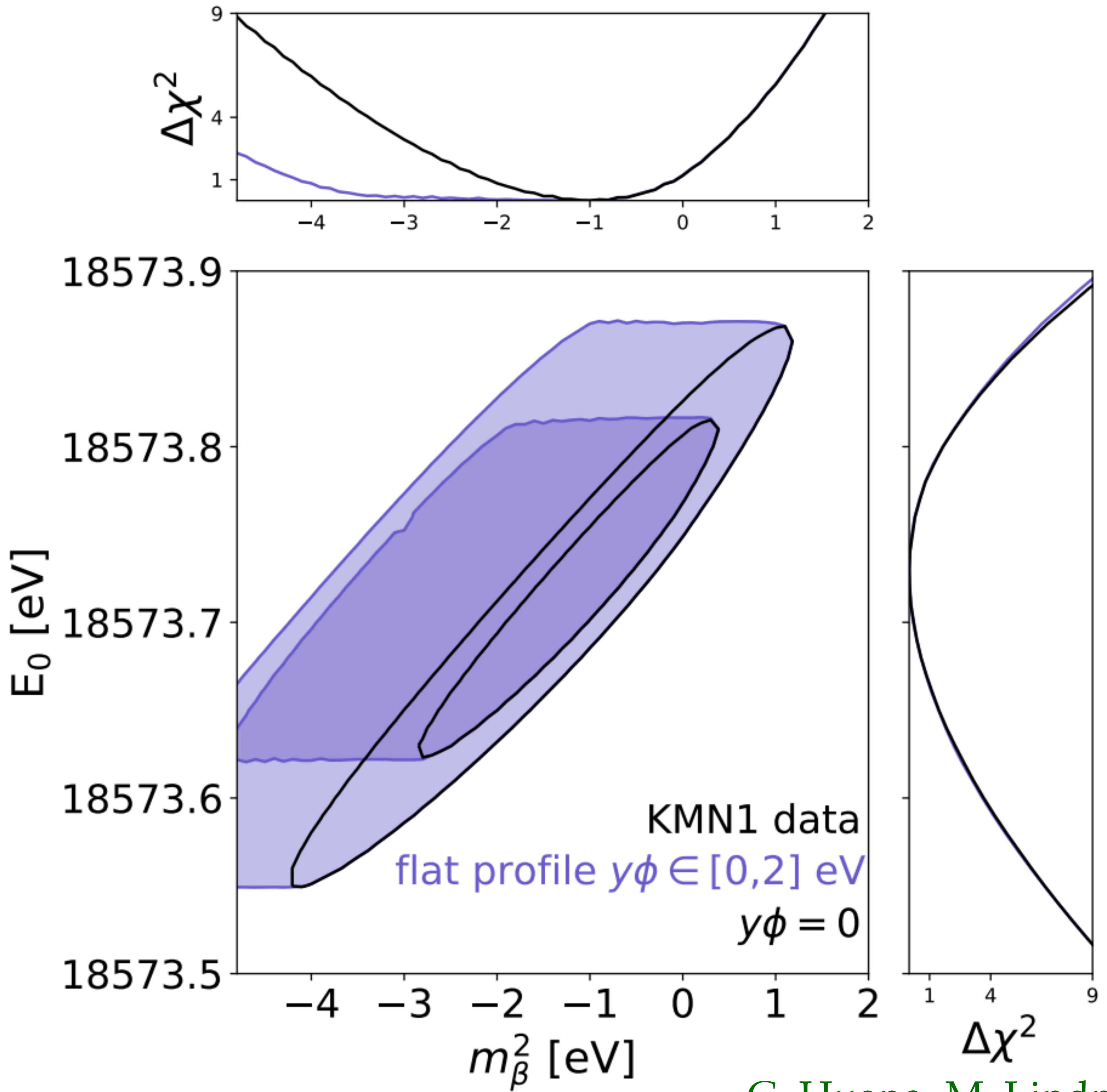


Effect of degeneracy

- Limit of heavy sterile neutrinos: $\widetilde{m}_1 \simeq m_1 + g\phi \sin(m_\phi t)$

- Look for time-variation and/or average distortion. Degeneracy: $\langle m_\beta^2 \rangle = m_\beta^2 + \frac{(g\phi)^2}{2}$





G. Huang. M. Lindner, P. Martinez-Mirave, **MS**, (PRD 2022)

eV scale sterile neutrinos in KATRIN

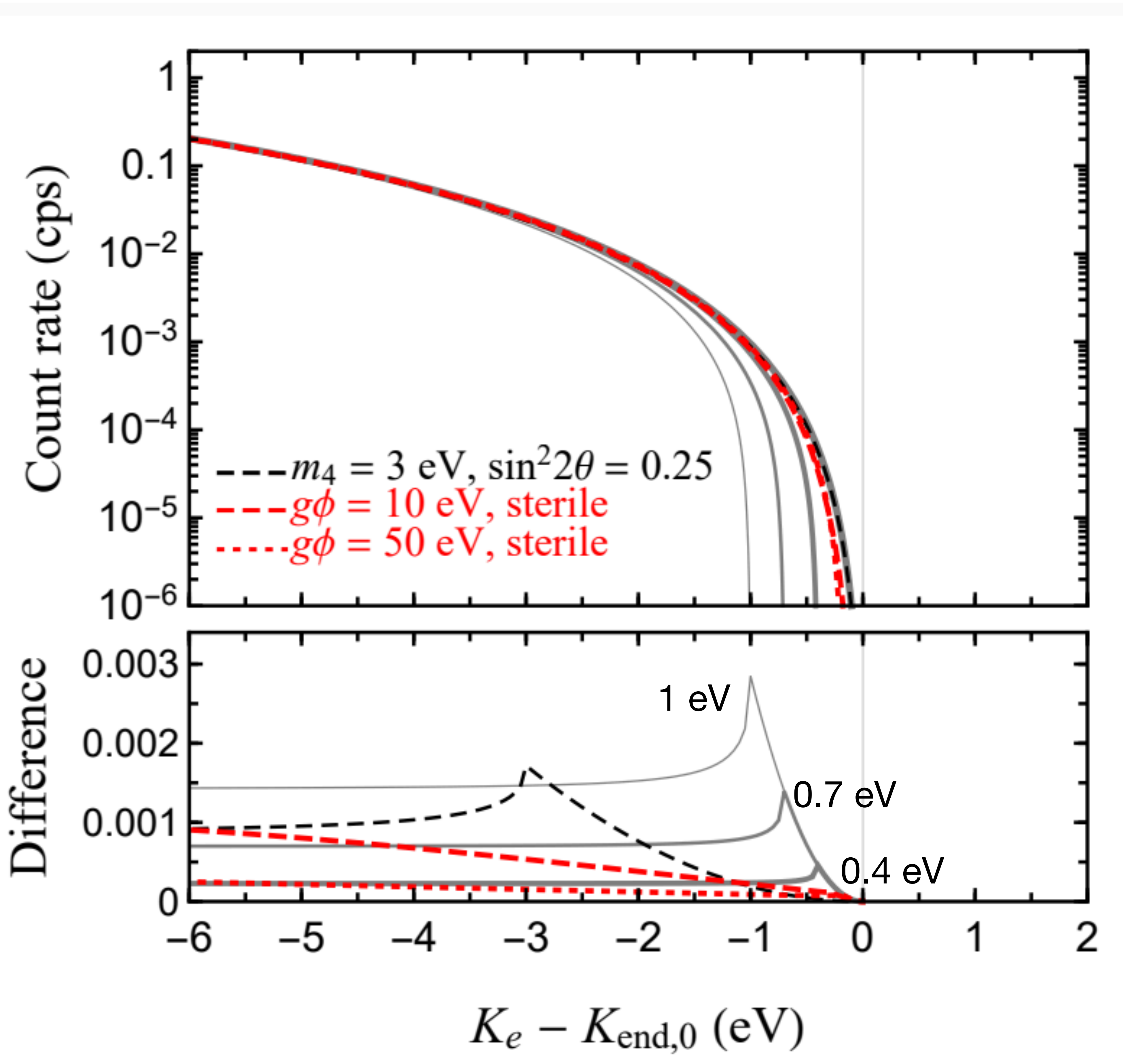
- For additional light sterile neutrinos,

$$R_\beta^{(3+1)\nu}(E_e) = \left(1 - \left|U_{e4}\right|^2\right) R_\beta(E_e, \widetilde{m}_\beta) + \left|U_{e4}\right|^2 R_\beta(E_e, \widetilde{m}_4$$

- Suppression of mixing due to large scalar potentials.

$$\tan 2\widetilde{\theta}_{14} = \frac{(m_4 - m_1)\sin 2\theta_{14}}{(m_4 - m_1)\cos 2\theta_{14} + g\phi}$$

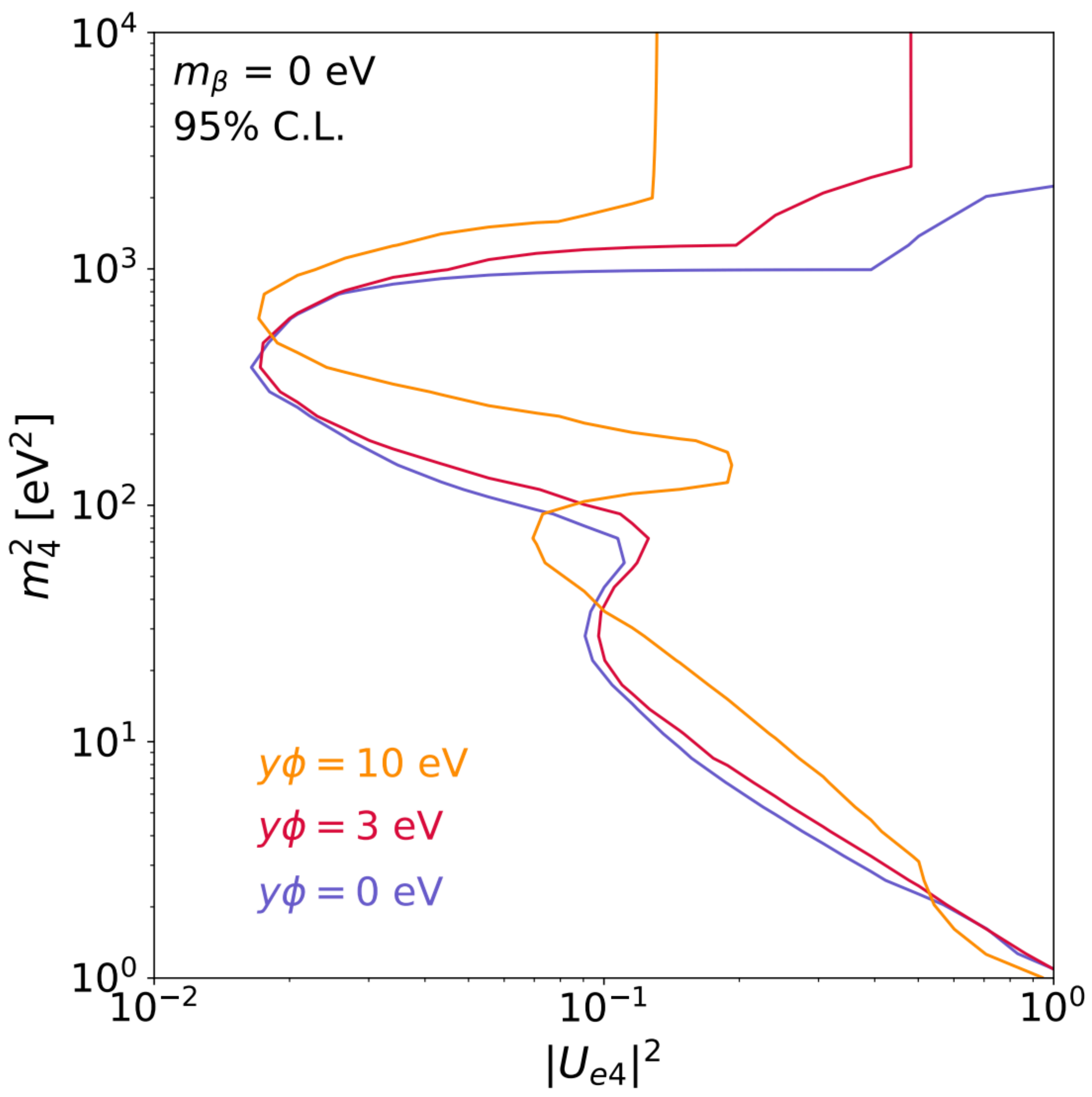
- For ULDM-sterile neutrino interaction, the time variation causes an averaged distortion of the kink. Loss in sensitivity.



G. Huang. M. Lindner, P. Martinez-Mirave, **MS,** (PRD 2022)

eV scale sterile neutrinos in KATRIN

- Larger values of mixing allowed.
- Does this open up sterile neutrino paramater space in SBL experiments?



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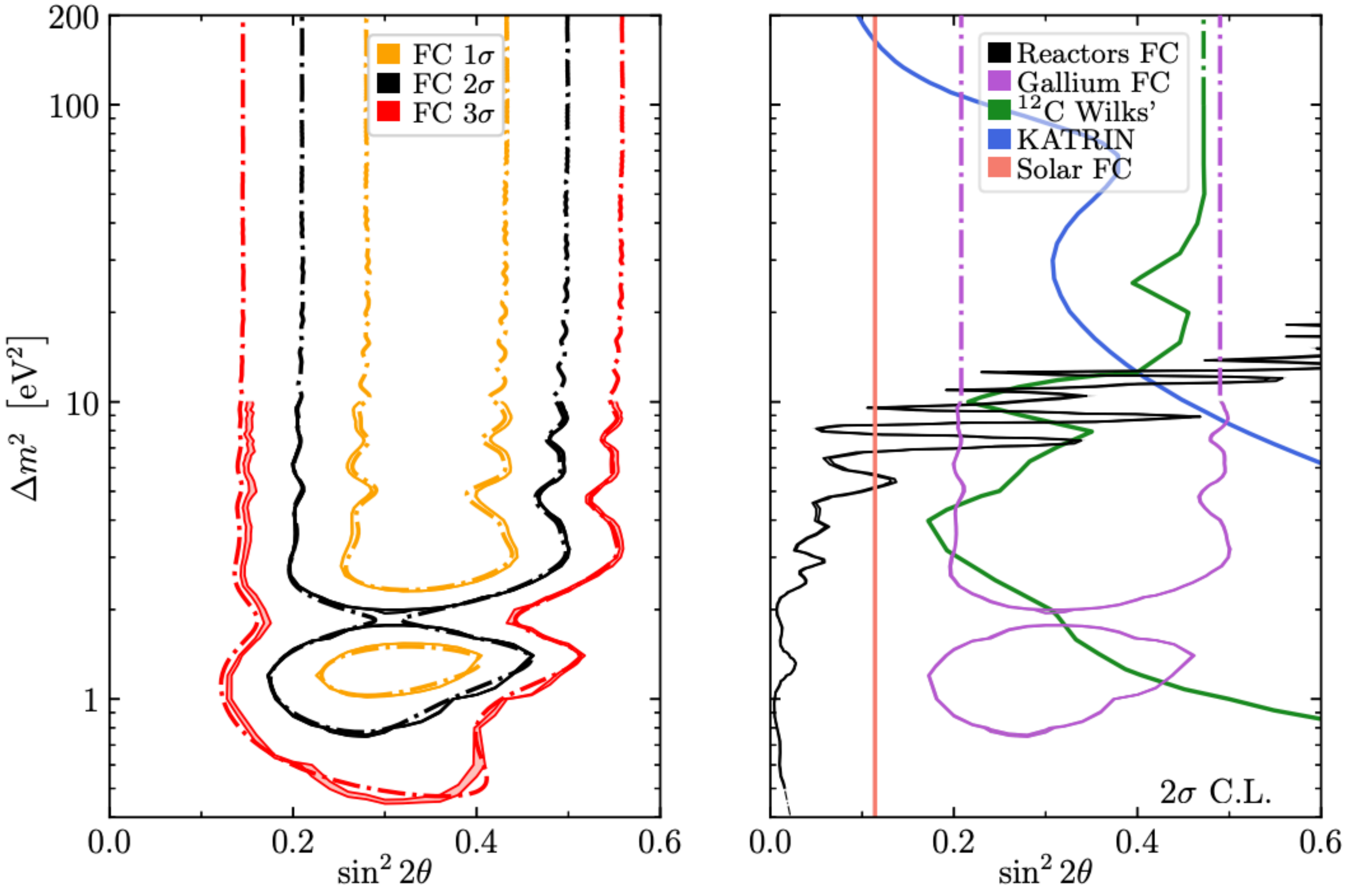
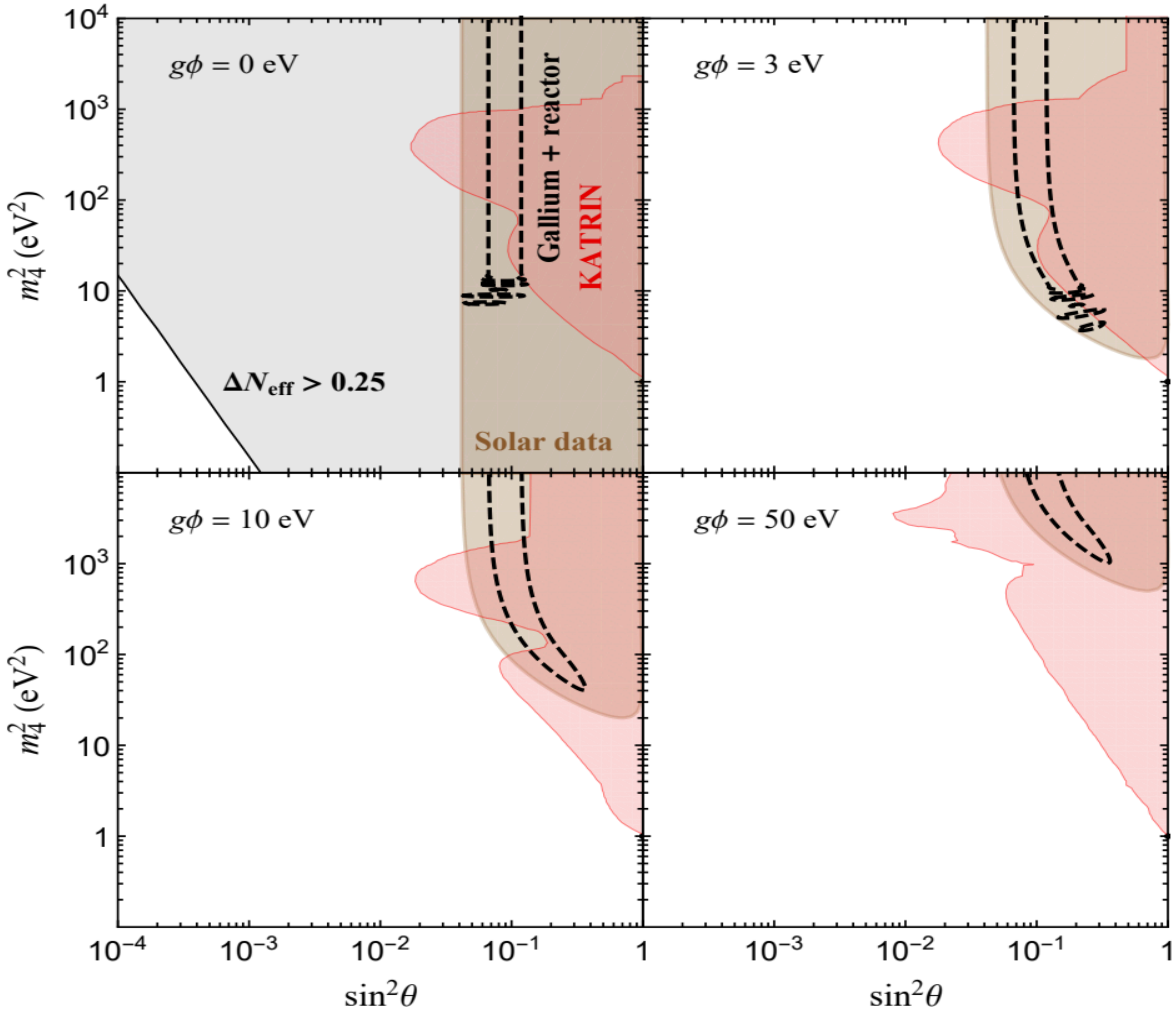


Short baseline oscillation

Talk last week by B. Littlejohn
Talk by I. Martinez-Soler

Sterile neutrino parameter space in presence of ULDM



- Reinterpret paramater space for neutrinos in a DM halo.
- For large values of $g\phi$, mixing is suppressed.

$$\tan 2\tilde{\theta}_{14} = \frac{(m_4 - m_1)\sin 2\theta_{14}}{(m_4 - m_1)\cos 2\theta_{14} + g\phi}$$

- Need larger values of vacuum mixing angle θ to satisfy same bounds!
- More work needed.

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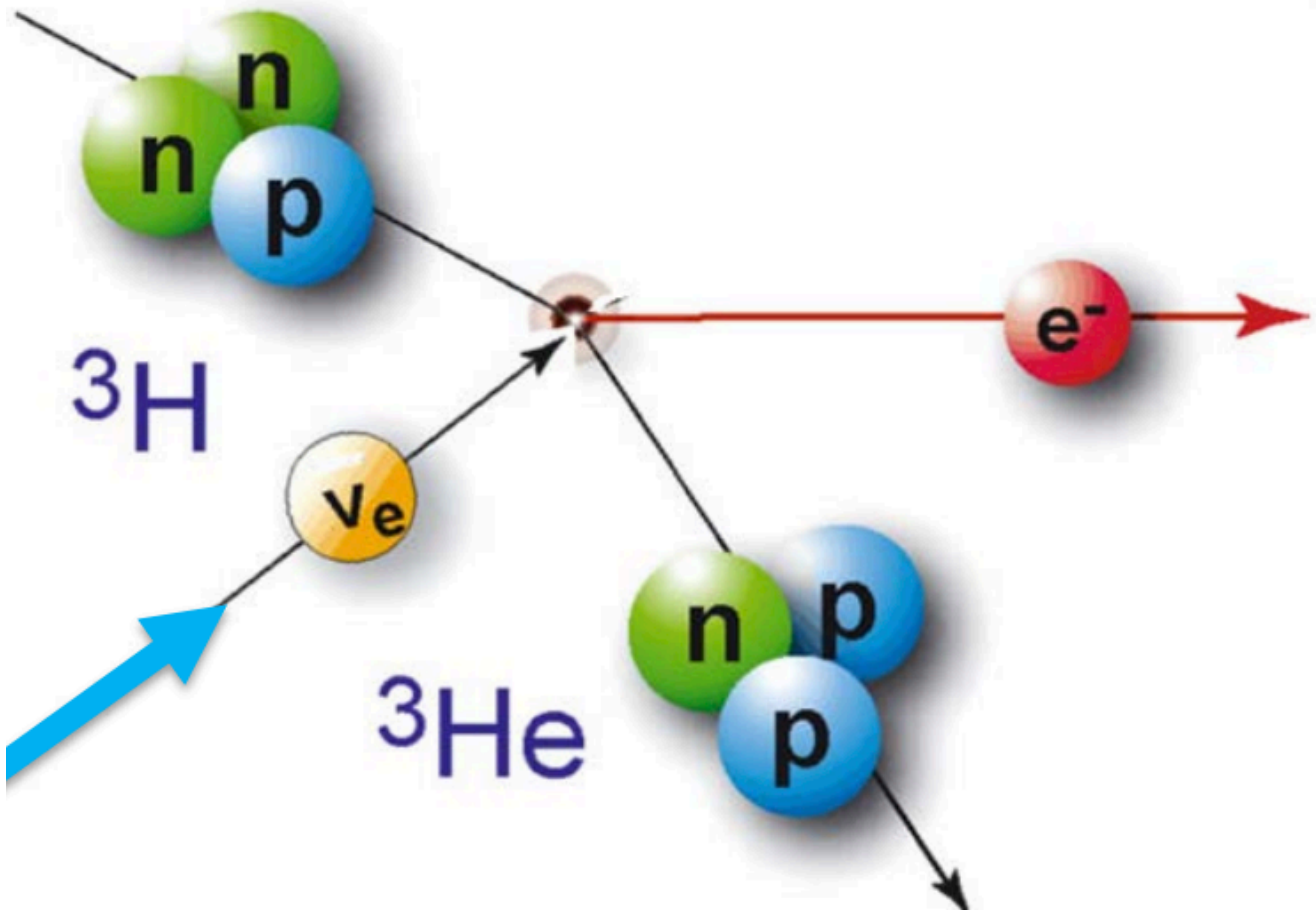
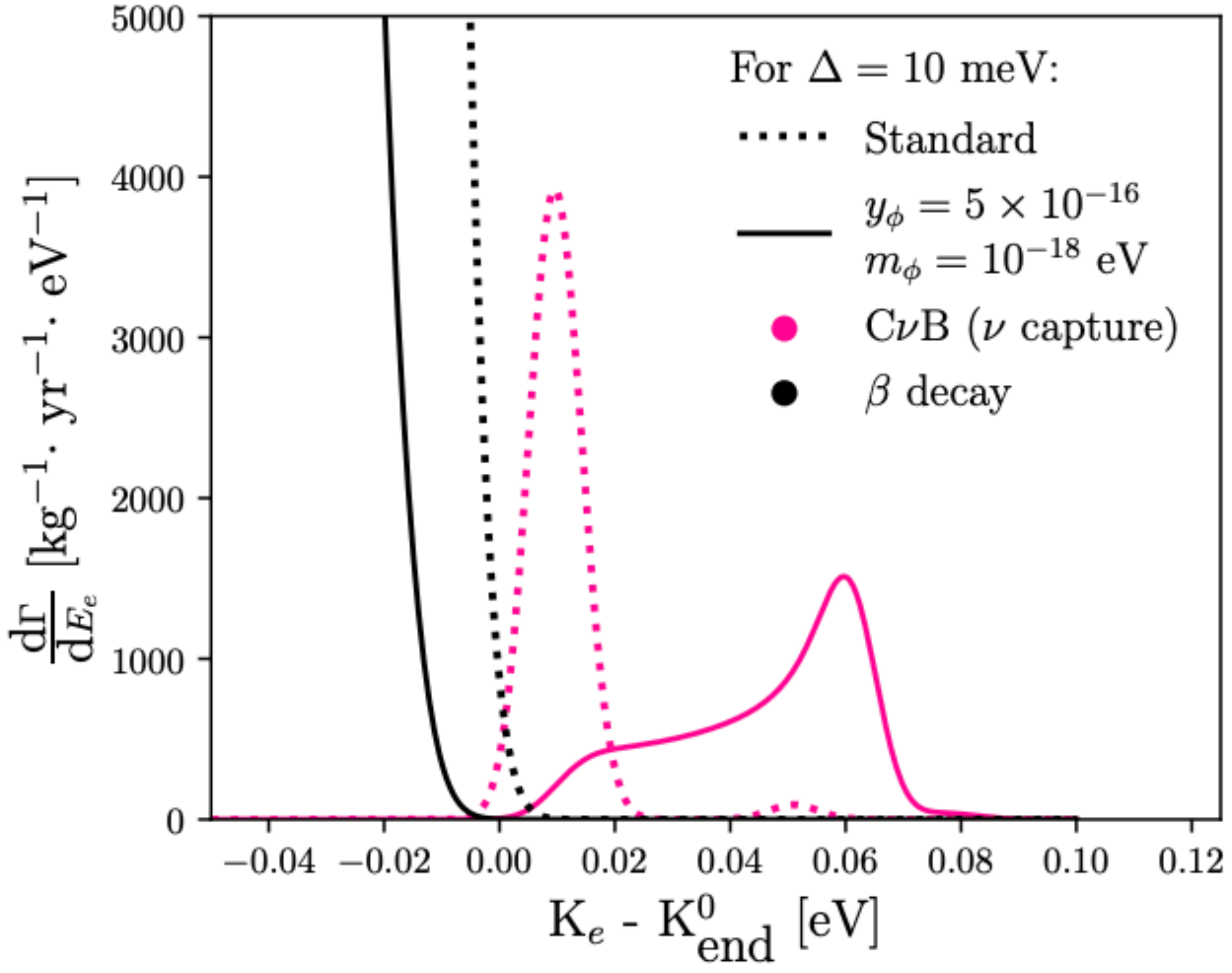
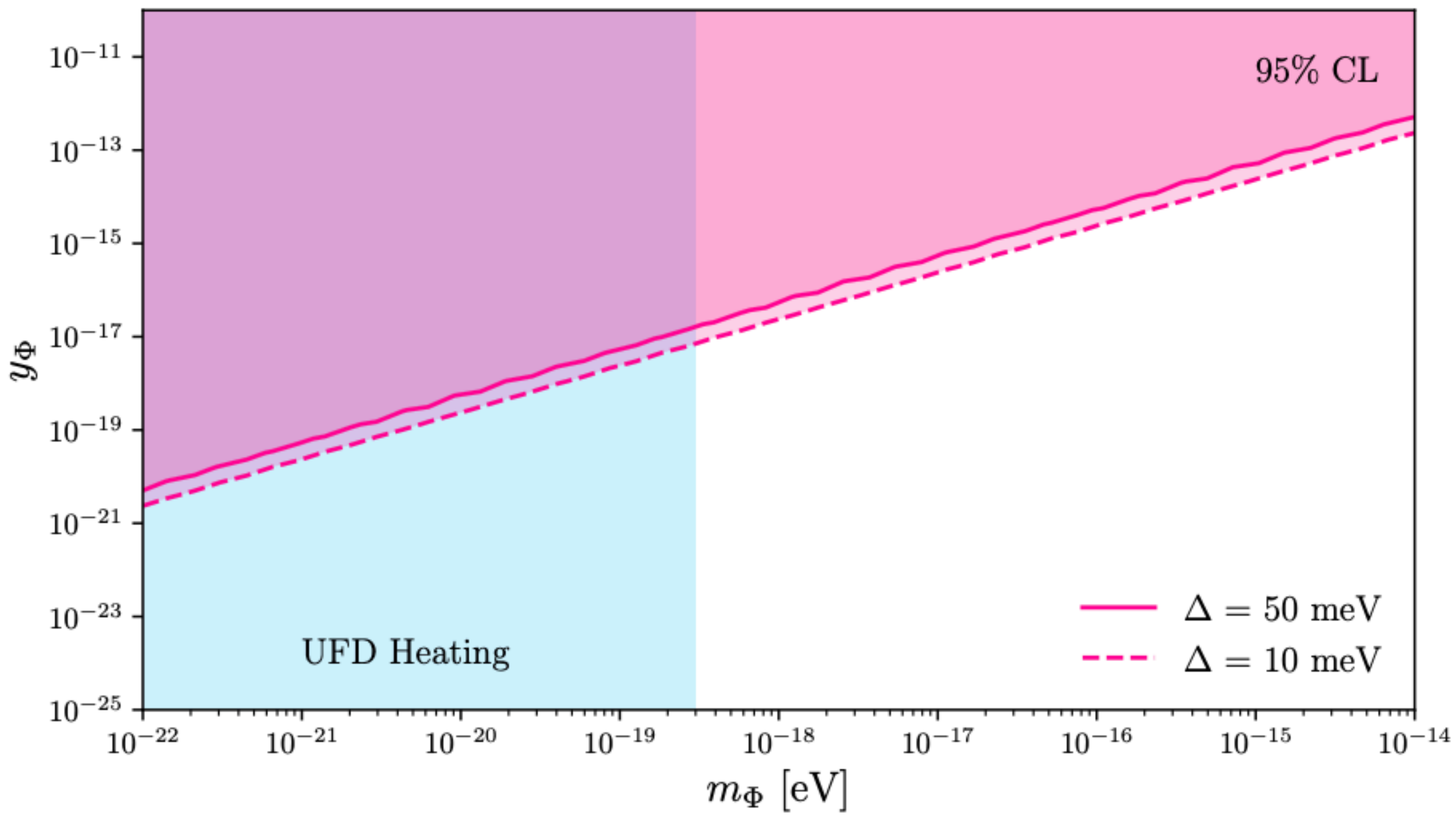


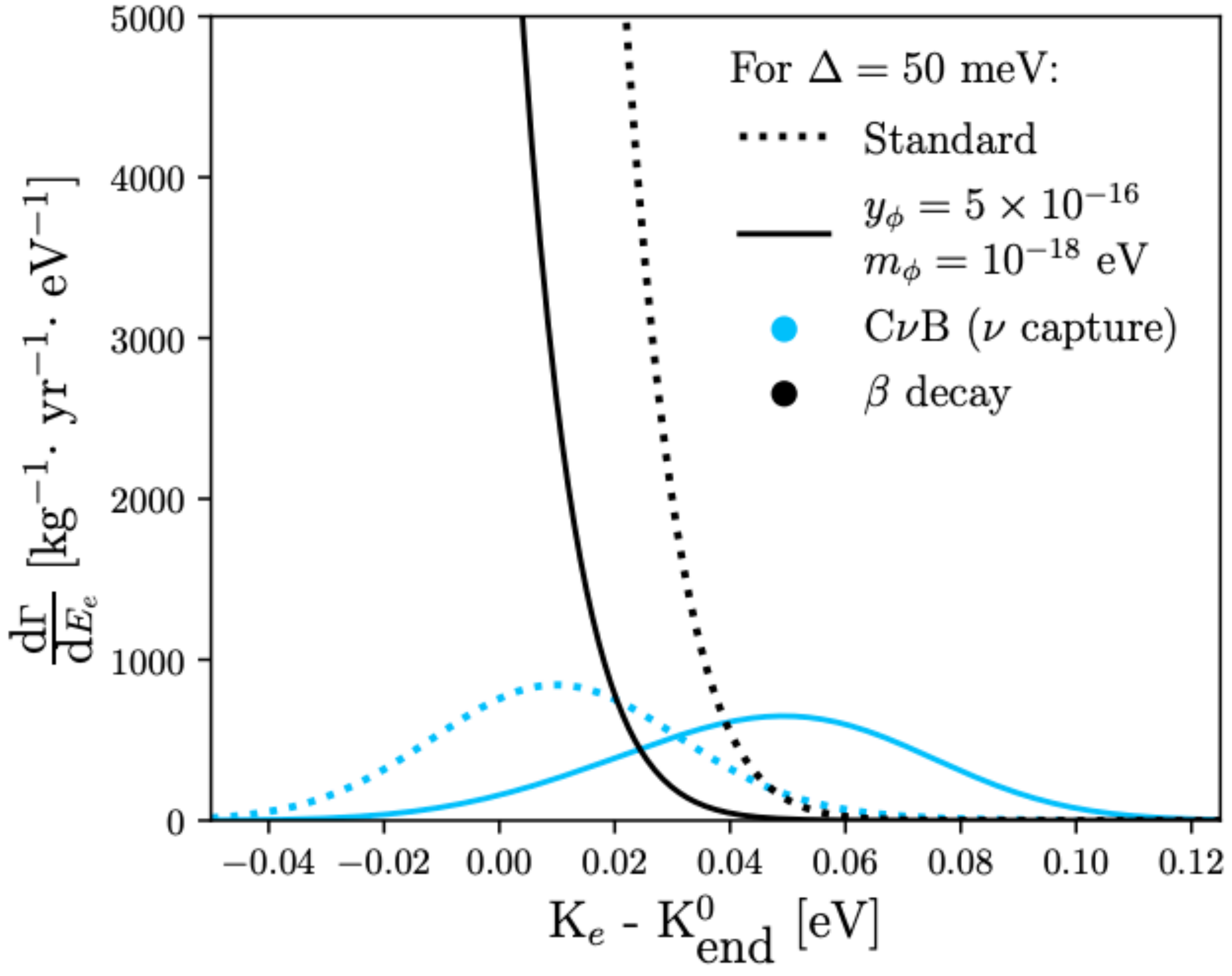
Relic neutrino capture:PTOLEMY

Talk last week by S. Gariazzo

Predicted constraints from PTOLEMY

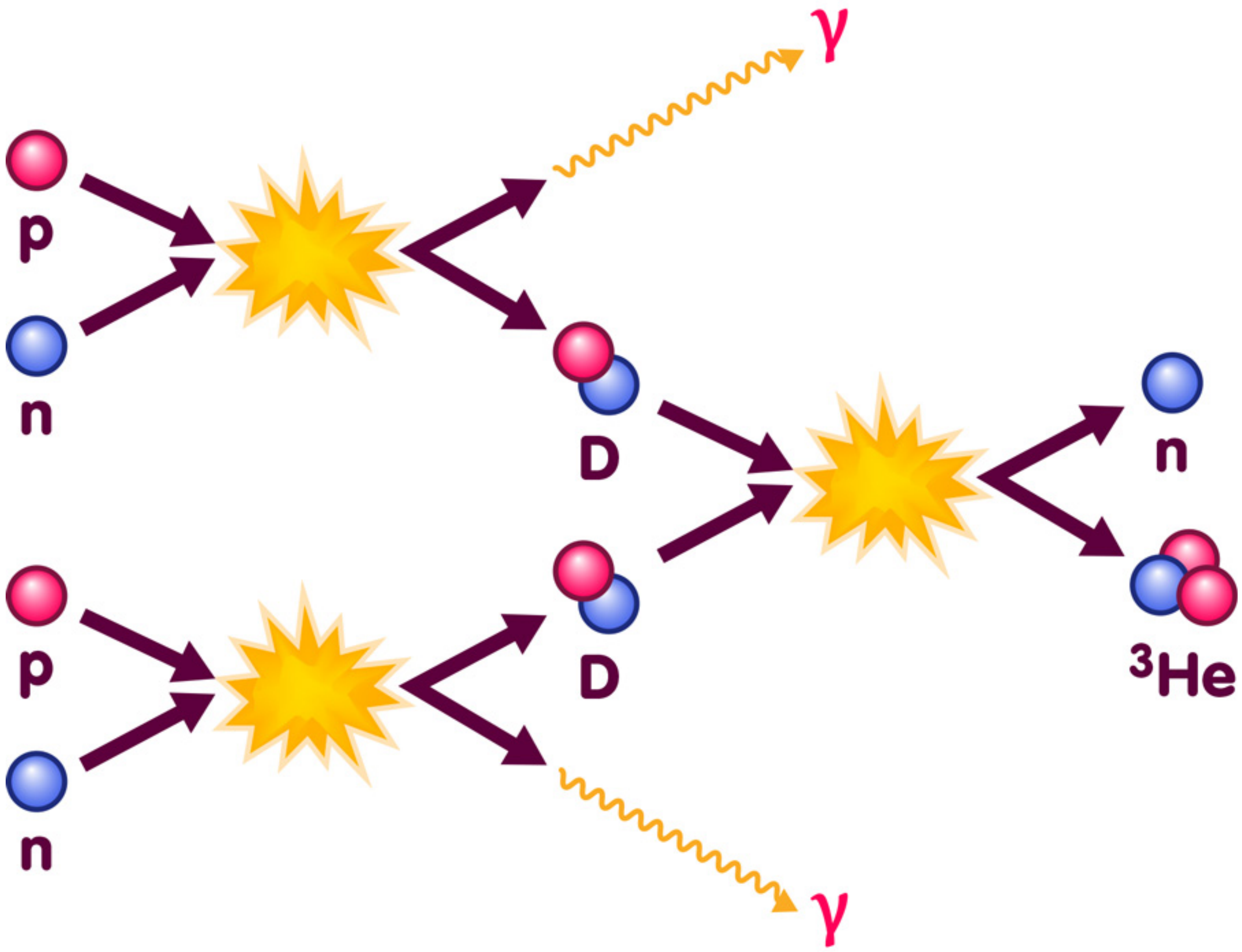






Distortion of signal and background in PTOLEMY

P. Martinez-Mirave, Y. Perez-Gonzalez ,**MS,** (arXiv: 2406.01682)



BBN constraints

Extra radiation in the early Universe?

- Light sterile neutrinos can thermalize around BBN and ruin $\Delta N_{\rm eff}$ bounds.

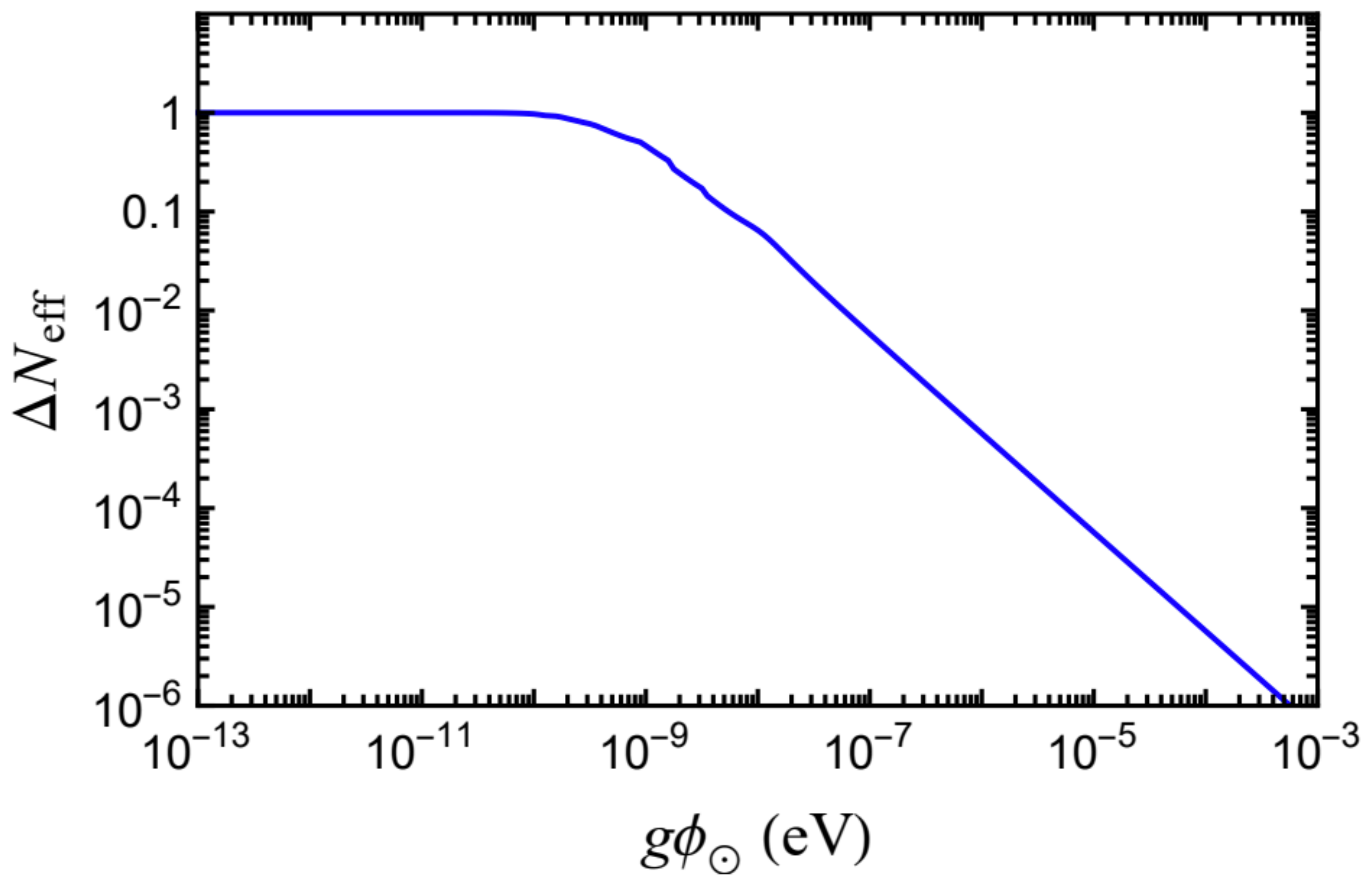
Talk last week by S. Pastor

- The mixing angle is suppressed

$$\tan 2\widetilde{\theta}_{14} = \frac{(m_4 - m_1)\sin 2\theta_{14}}{(m_4 - m_1)\cos 2\theta_{14} + g\phi}$$

- Thermalisation of ϕ is also inhibited due to tiny g.

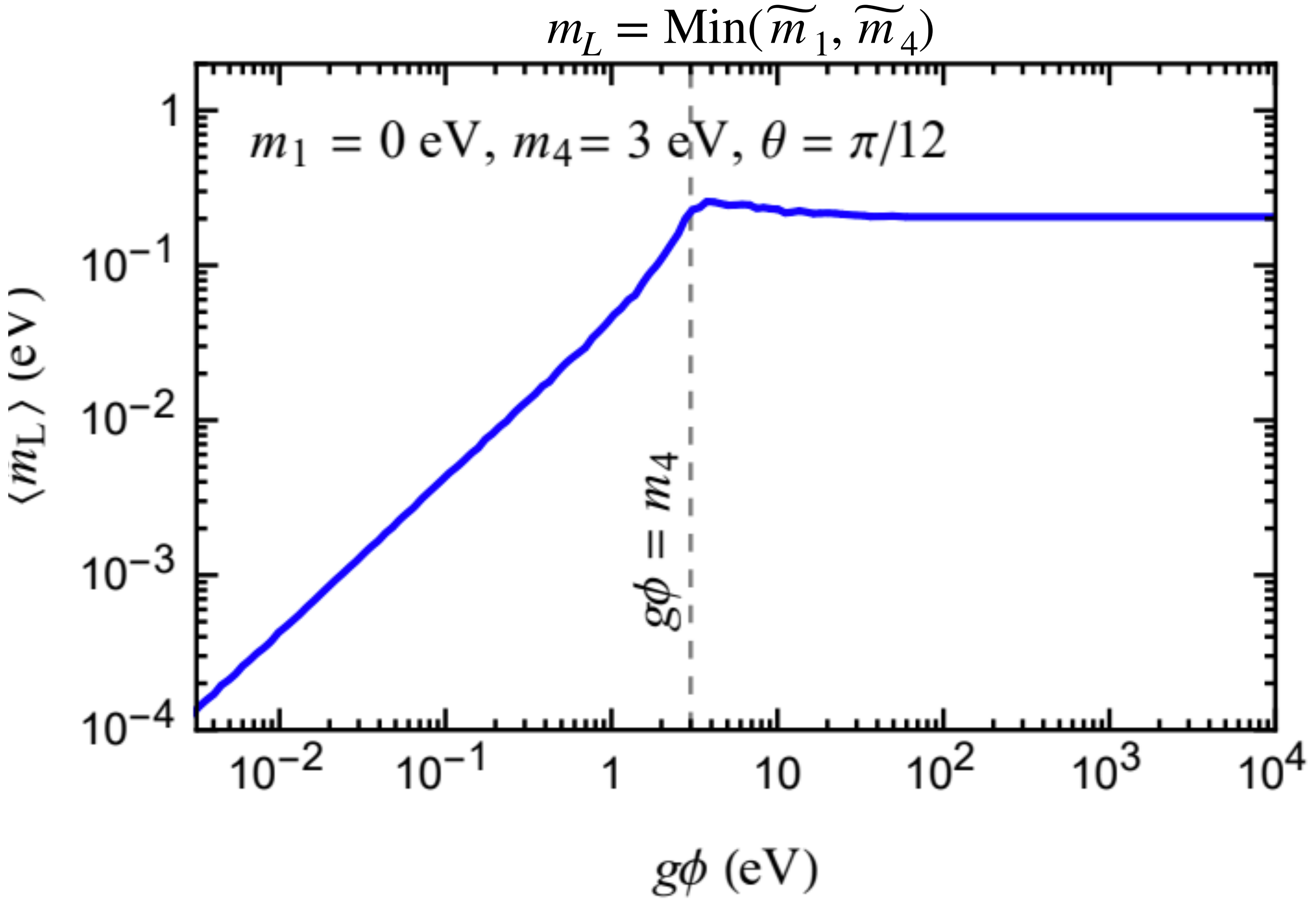
$$g\phi_\odot \sim 10^{-7}\,\mathrm{eV}\left(\frac{g}{10^{-22}}\right)\left(\frac{10^{-18}\,\mathrm{eV}}{m_\phi}\right)$$



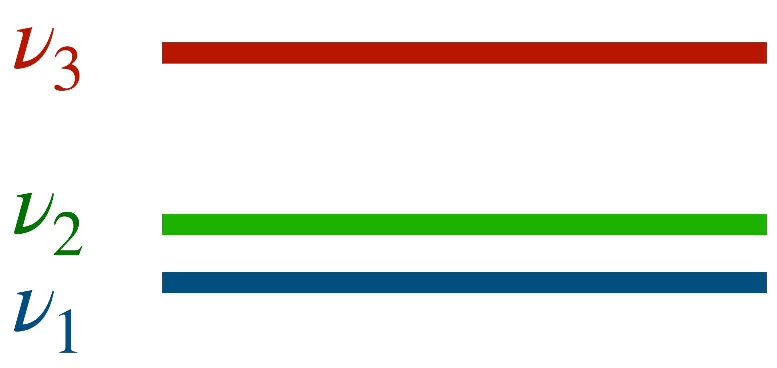
G. Huang. M. Lindner, P. Martinez-Mirave, **MS**, (PRD 2022)

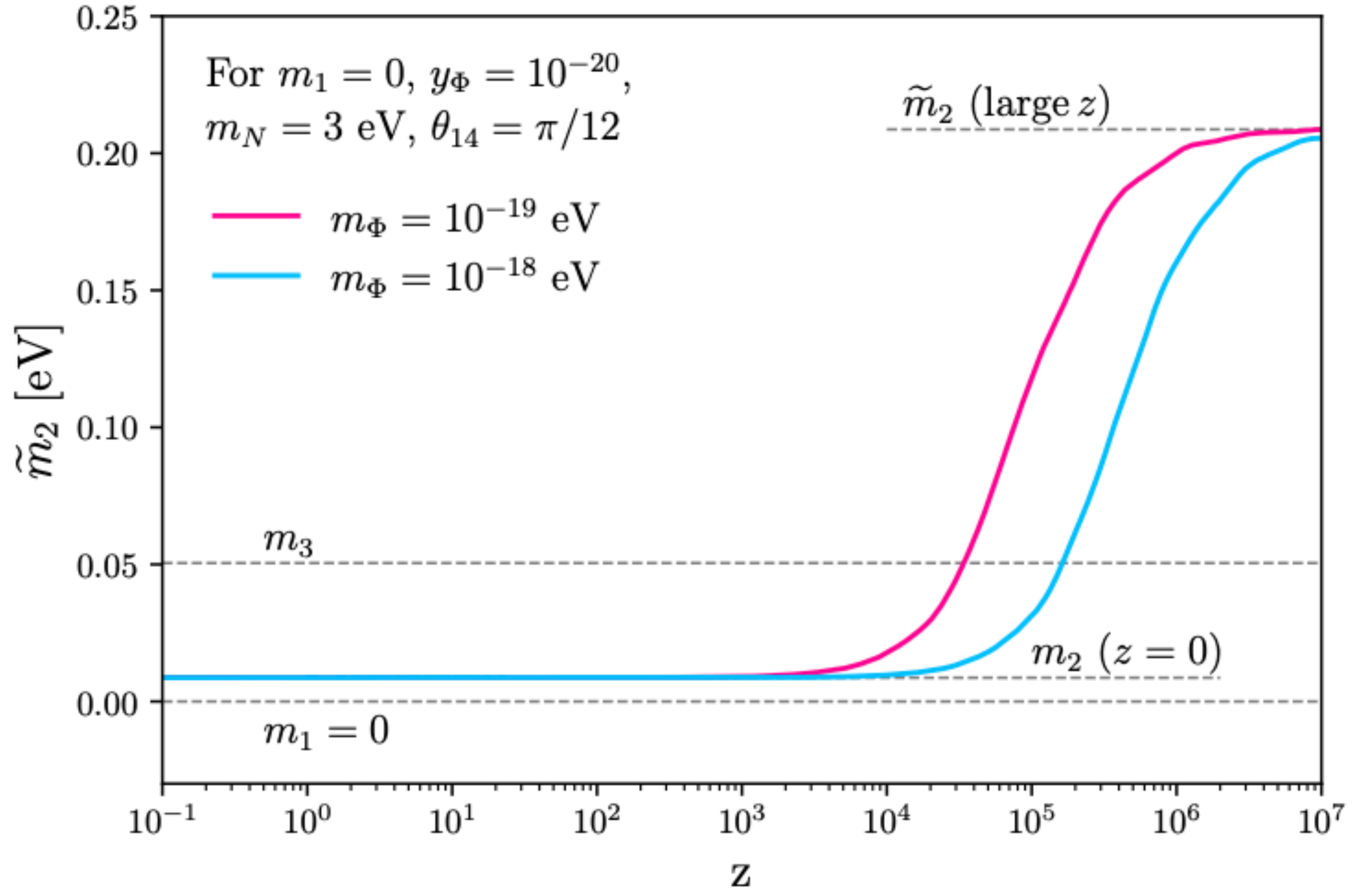
Open question?

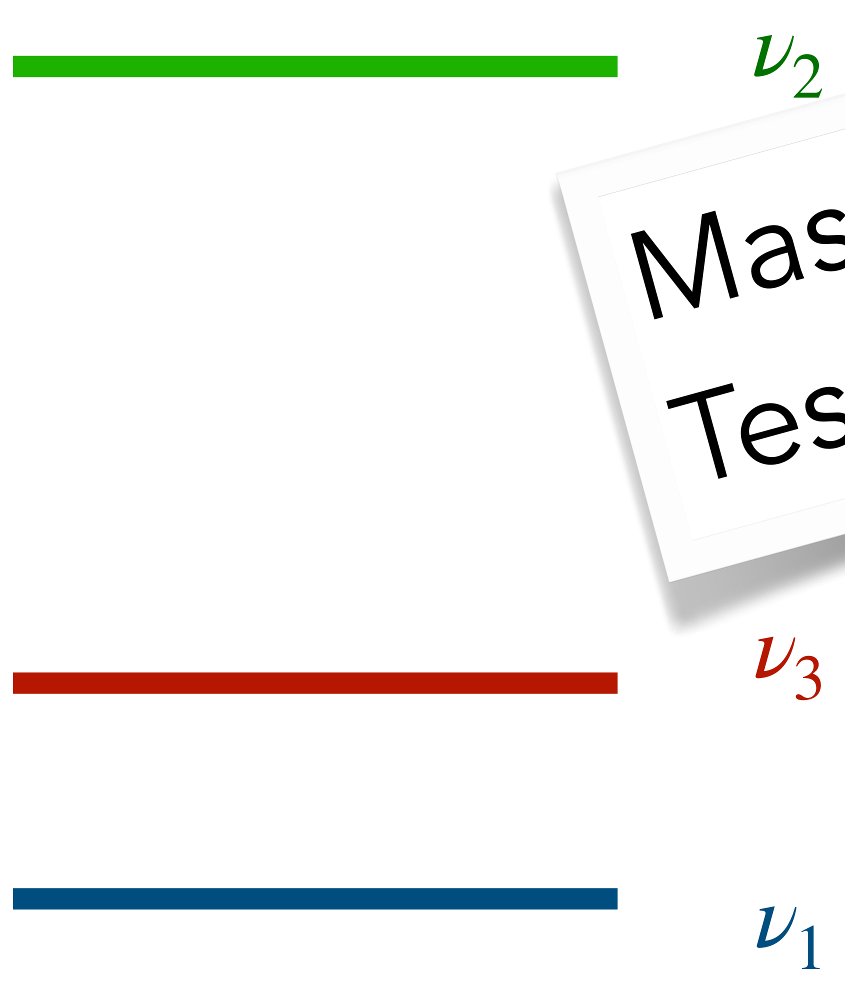
Changing the mass-ordering



- Neutrino mass grows with redshift, upto present constraints.
- Say, only one mass eigenstate picks up this dynamic mass - a bit stretched but not impossible.







Mass ordering scrambled.
Testable in cosmology?

P. Martinez-Mirave, Y. Perez-Gonzalez ,**MS**, (arXiv: 2406.01682)

Take-away message

- Active neutrinos coupled to ULDM leads to rich phenomenology. Cosmologically difficult to accomodate.
- One way out is to couple ULDM to sterile neutrinos.
- Active neutrinos acquire a mass variation due to mixing with sterile neutrinos.
- Suppresses the large contribution to neutrino mass during CMB. Cosmologically friendly!
- Fascinating probes in early Universe, beta decay experiments as well as SBL experiments.
- Interesting open questions - can we probe them with upcoming surveys?

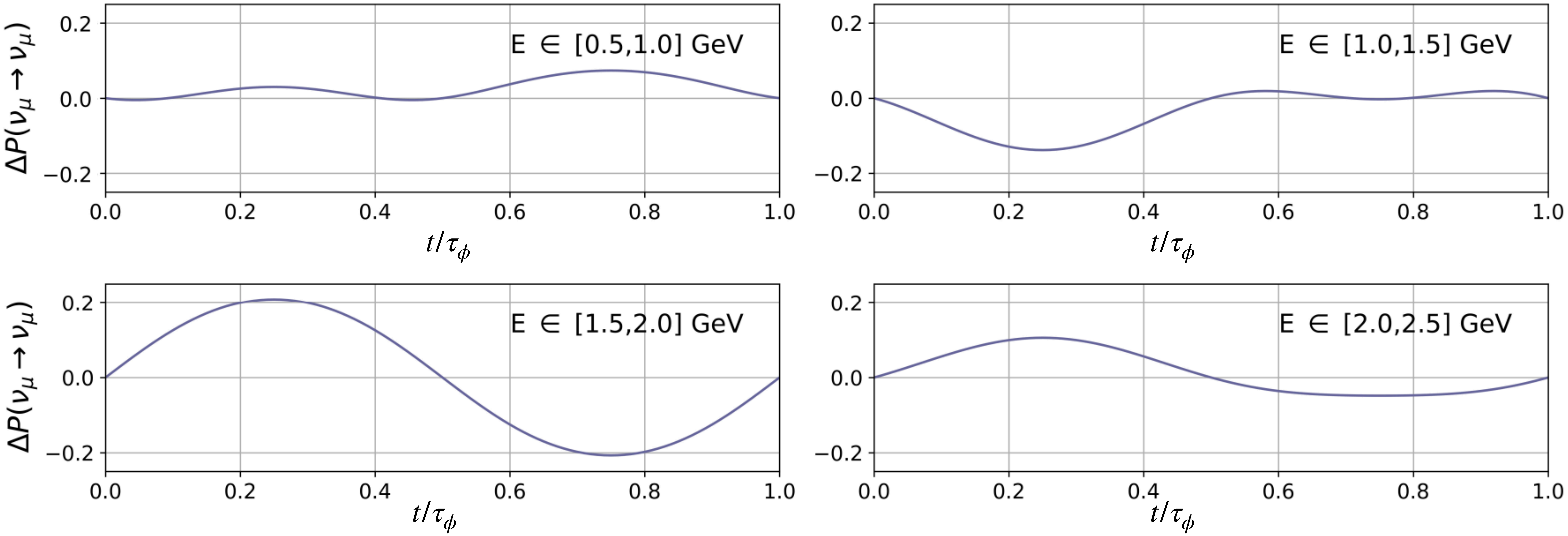
Thank you!

Time modulation

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

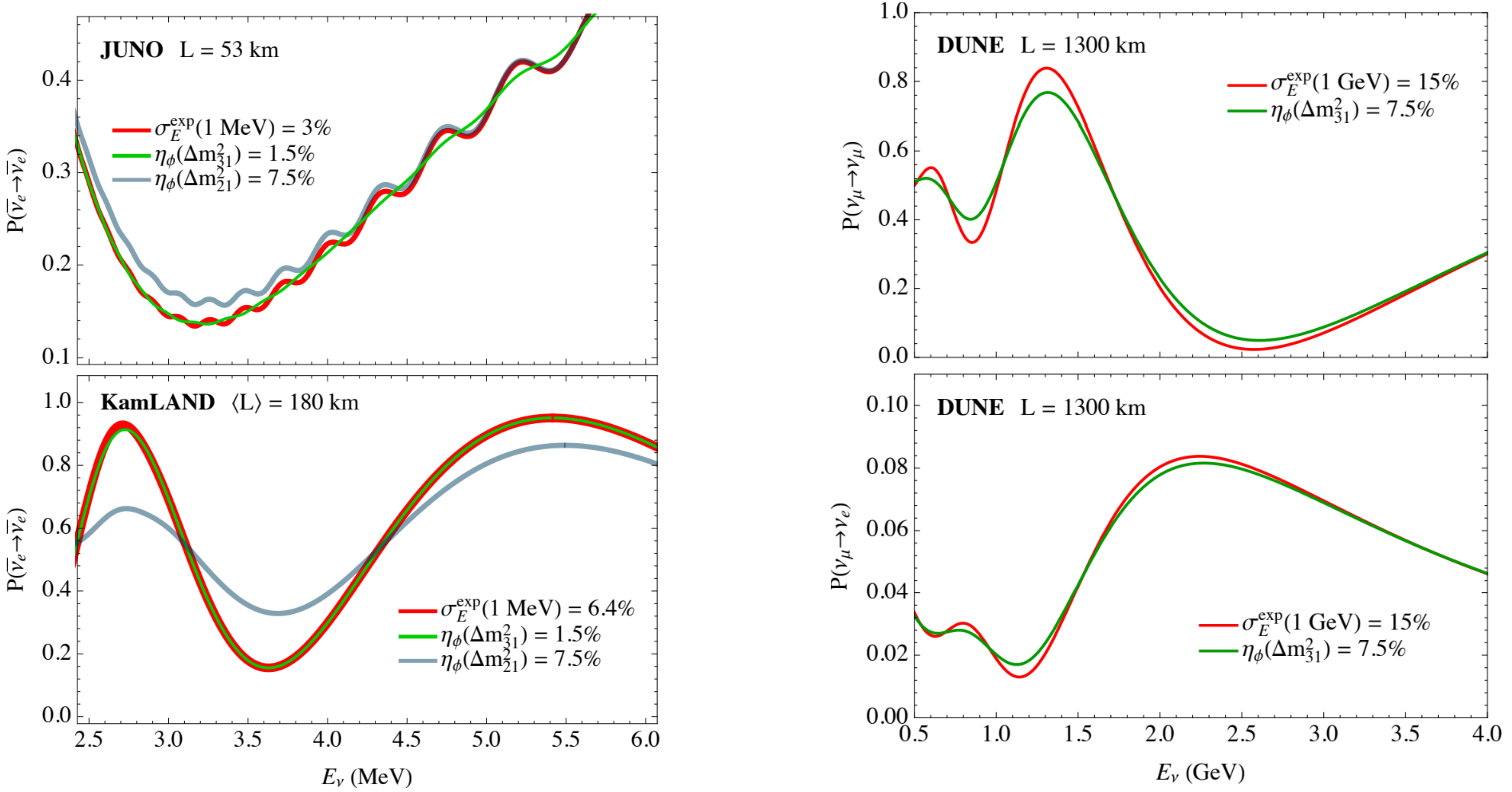
Modulates the maxima and minima!

$\tau_\phi \sim \tau_{\rm exp} \sim 10\,{\rm yrs}$



A. Dev, P. Machado, P. Martınez-Mirave (JHEP 2020)

Time modulation



Krnjaic, Machado, Necib (PRD 2018)

Neutrino mass variations with time

- Consider $\mathscr{L} \supset y_D \overline{L} h^c N + \frac{1}{2}(m_N + g\phi(t)) \overline{N^c} N + \frac{1}{2}\kappa \overline{L} \tilde{h}\tilde{h}^T L^c + \frac{1}{2}\frac{y}{\Lambda}\phi(t)^2 \overline{N^c} N$

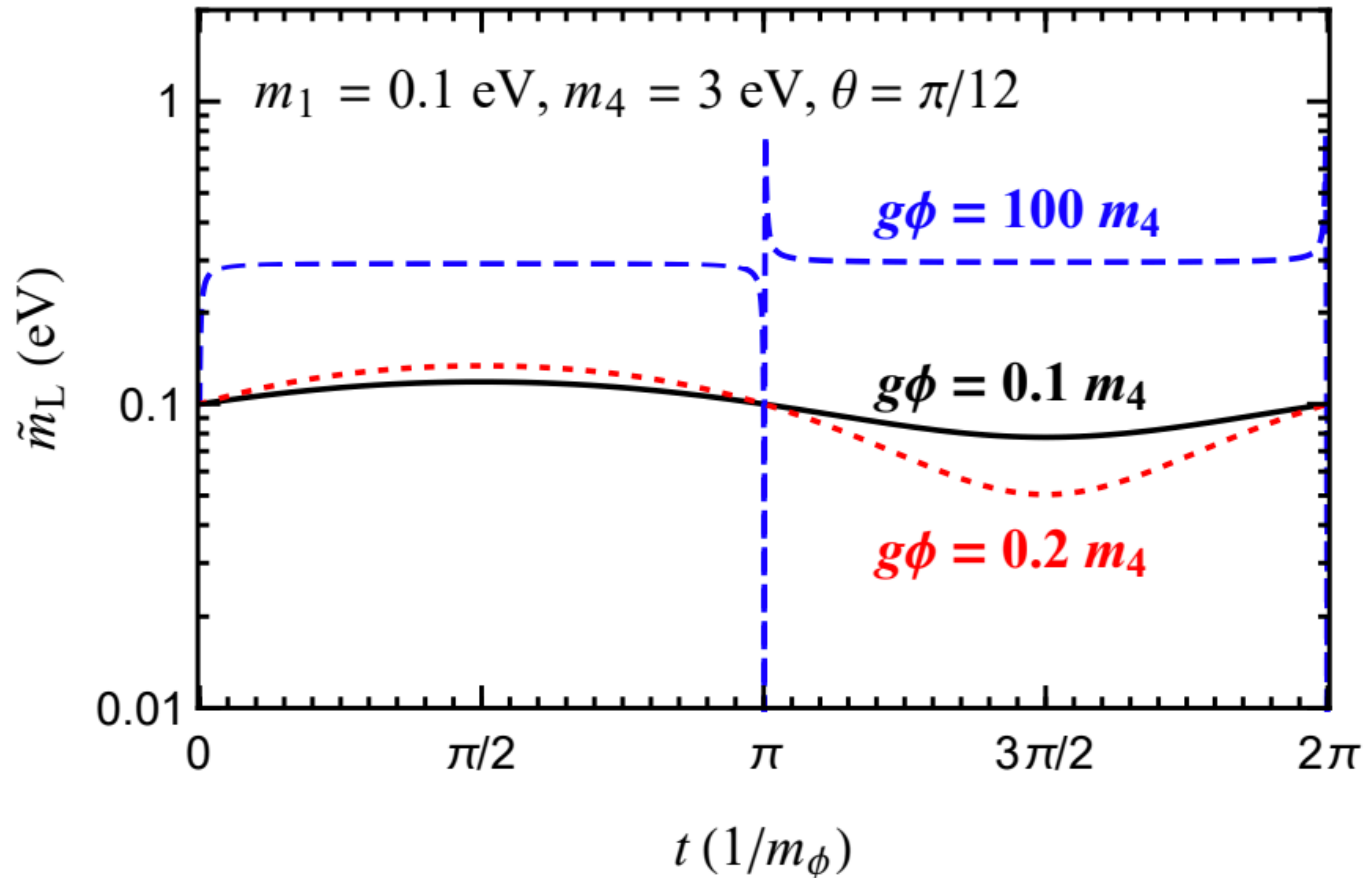
- 2 flavour: mass matrix can be written in the flavour basis as

$$\tilde{M}_\nu = U^\dagger \begin{pmatrix} m_1 & 0 \\ 0 & m_4 \end{pmatrix} U + \begin{pmatrix} 0 & 0 \\ 0 & g\phi(t) \end{pmatrix} = U^\dagger \begin{pmatrix} \tilde{m}_1 & 0 \\ 0 & \tilde{m}_4 \end{pmatrix} U$$

- Lightest mass $\tilde{m}_L = \min(\tilde{m}_1, \tilde{m}_2)$.

- Can hit a resonance if

$$g\phi(t) \sim -(m_4 - m_1)$$



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Swapping of states

- Velocity of active neutrinos can be reduced. Affect free-streaming.
- Can be saved by higher dimensional terms. Needs detailed study.

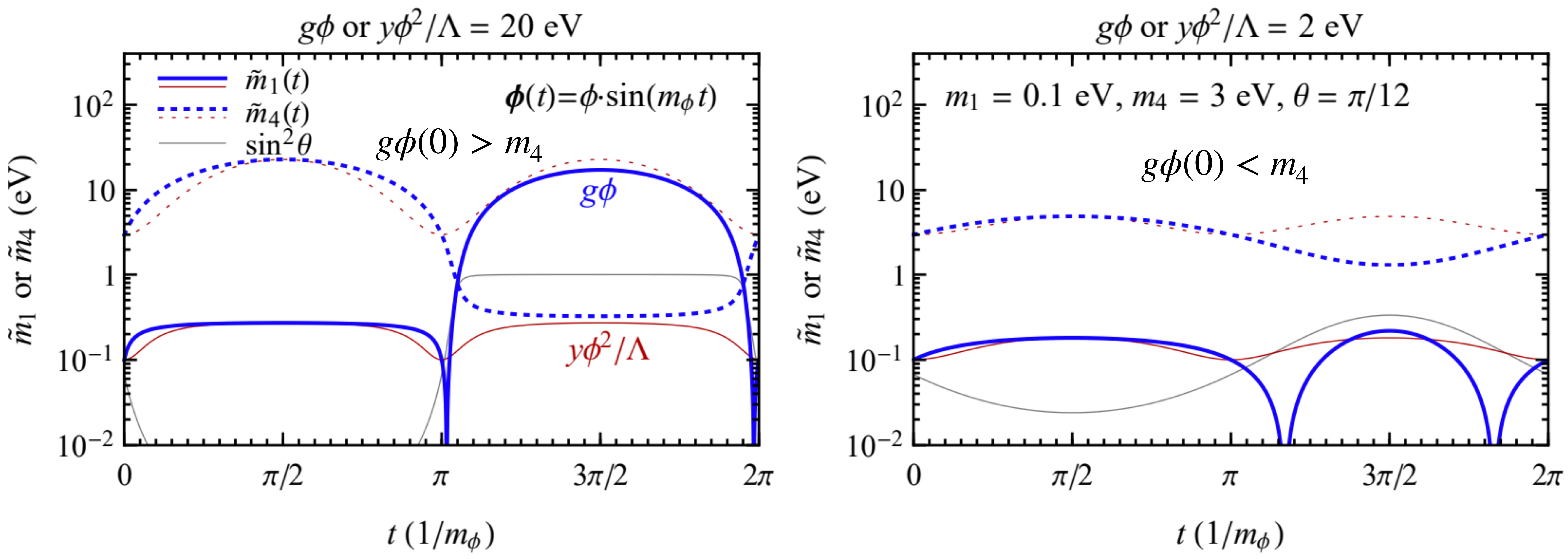

FIG. 5. The evolution of $\widetilde{m}_1$ (solid curves) and $\widetilde{m}_4$ (dotted curves) as functions of time, within one DM cycle. The DM potential is taken to be $g\phi = 20$ eV (blue curves) or $y\phi^2/\Lambda = 20$ eV (red curves) for the left panel. Vacuum neutrino parameters are fixed as $m_1 = 0.1$ eV, $m_4 = 3$ eV and $\theta = \pi/12$. Conventions are the same for the right panel except that we take $g\phi = 2$ eV or $y\phi^2/\Lambda = 2$ eV.

G. Huang. M. Lindner, P. Martinez-Mirave, **MS,** (PRD 2022)