Cosmology-friendly time-varying neutrino mass and implications

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MAX-PLANCK-INSTITUT
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The basic question?

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

- Consider bounds from

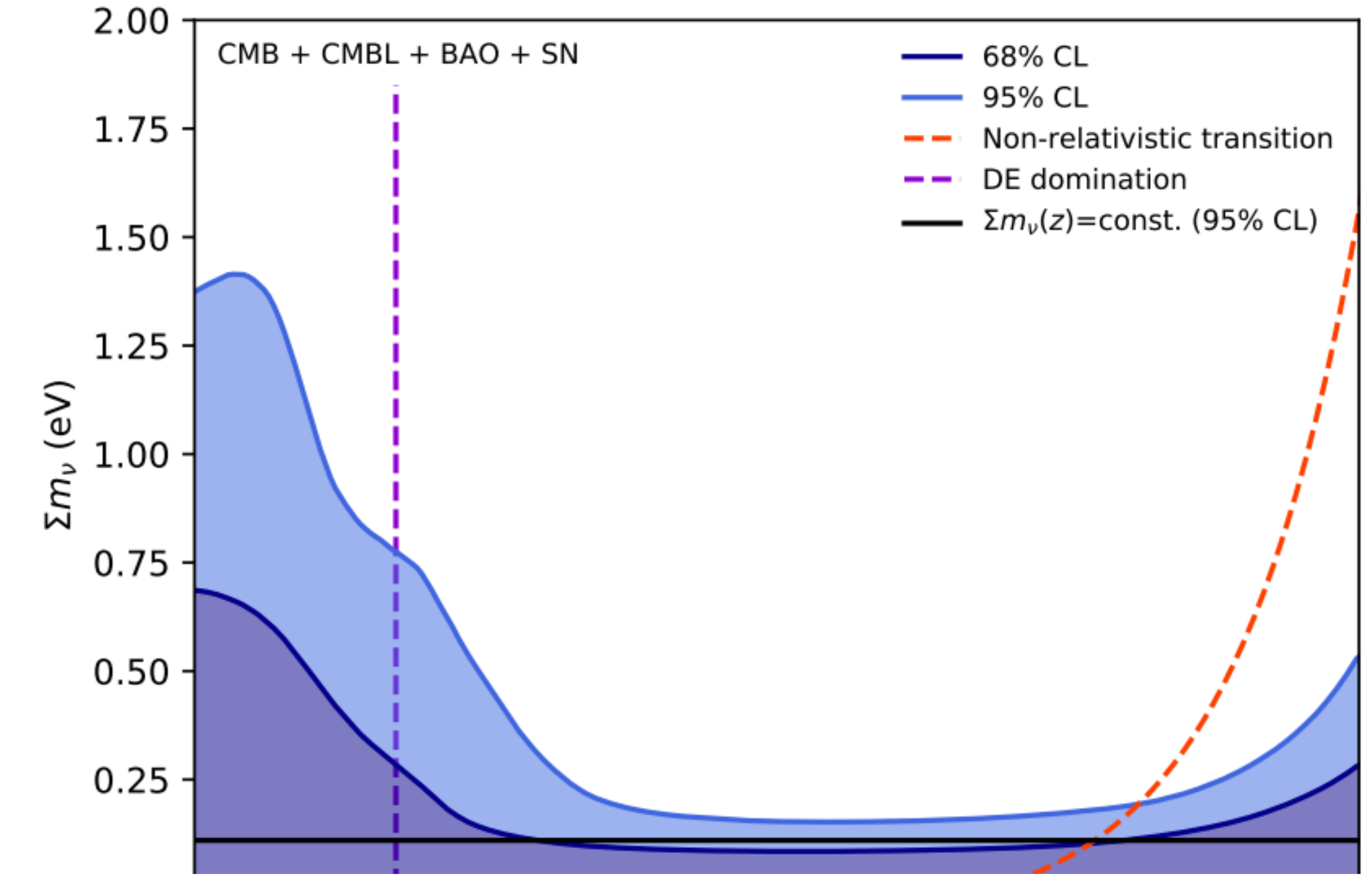
1. CMB temperature, polarization and lensing data from Planck.

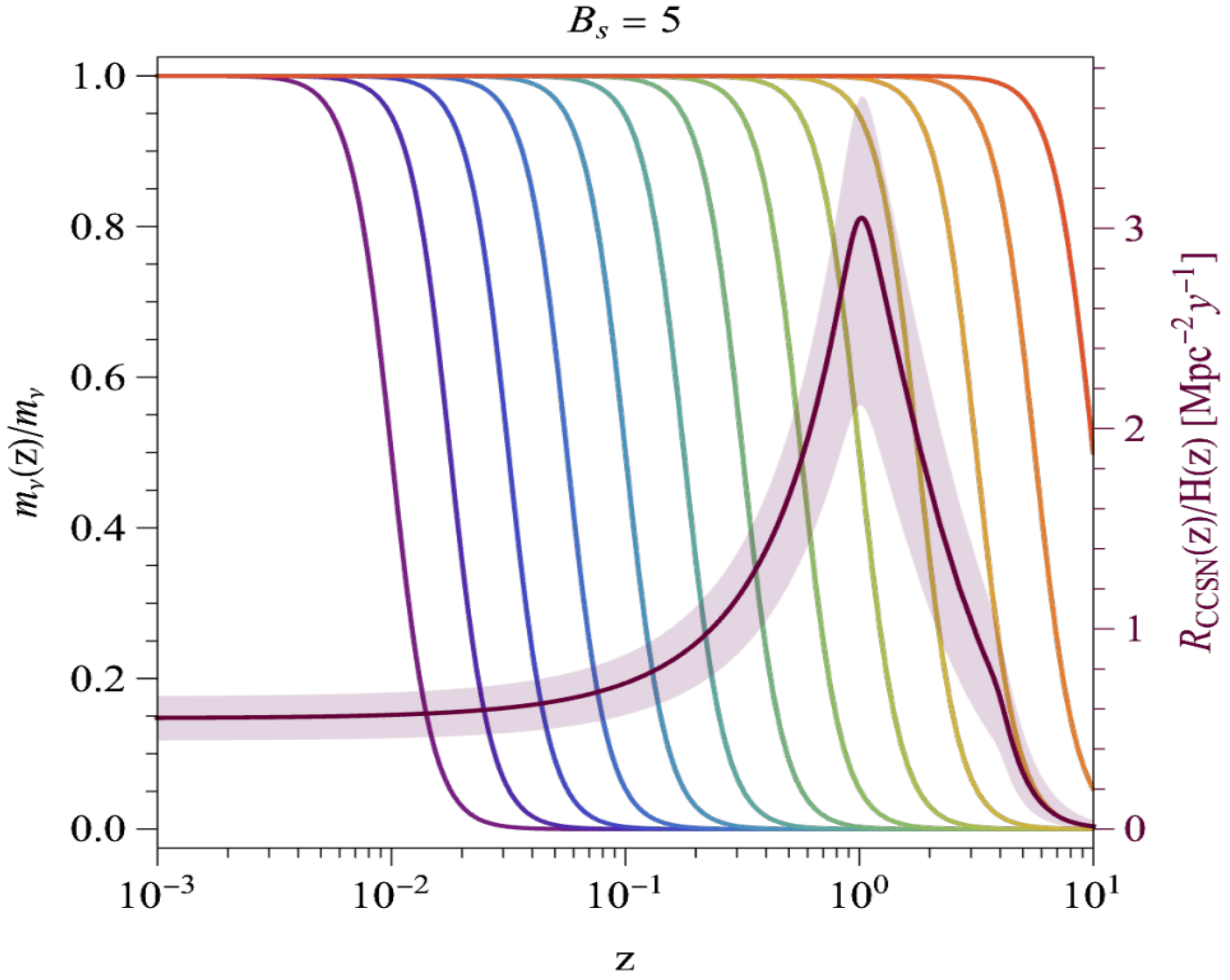
2. BAO from 6dF, SDSS, BOSS,…

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





See talk by Yuber Perez-Gonzalez

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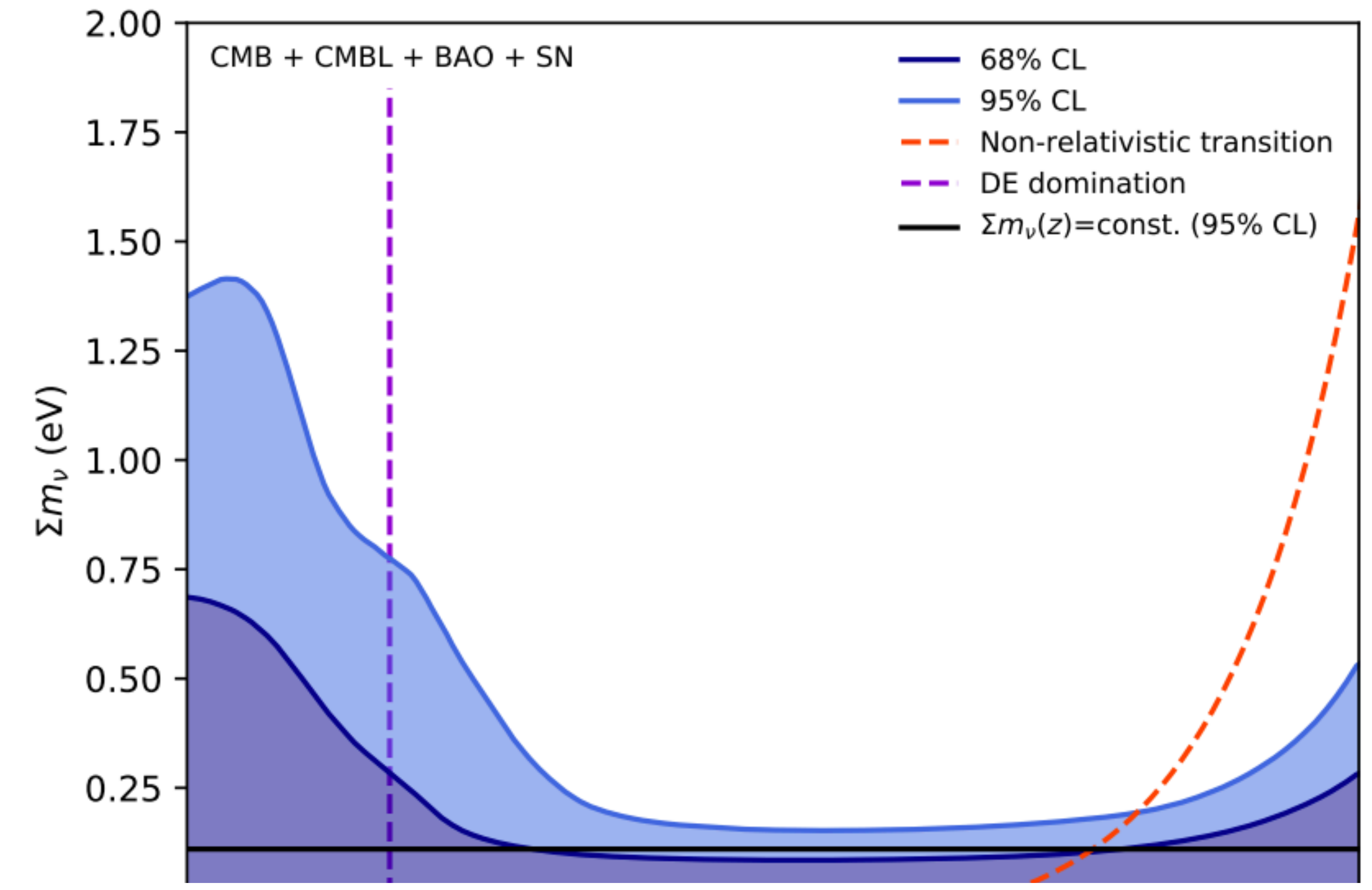
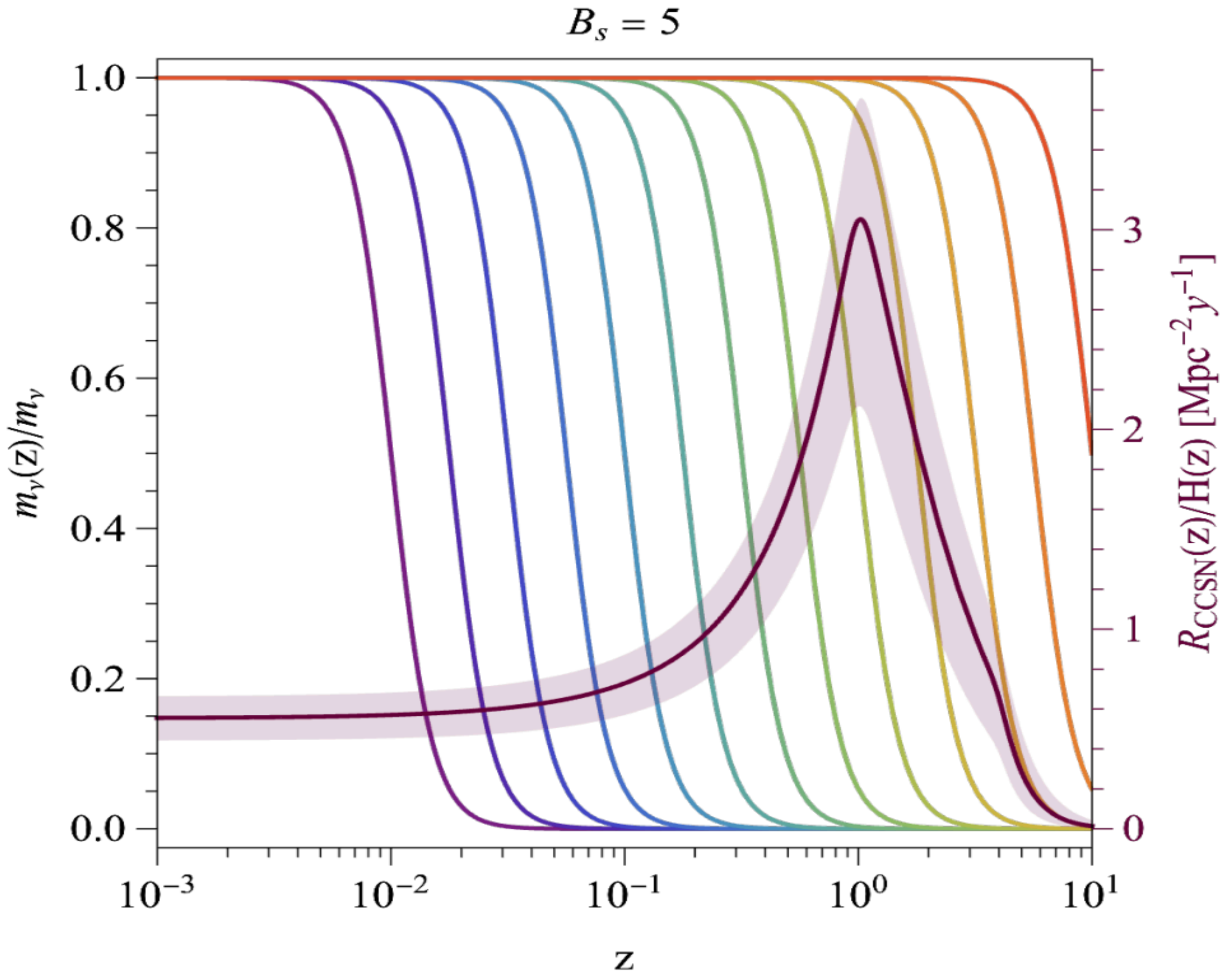
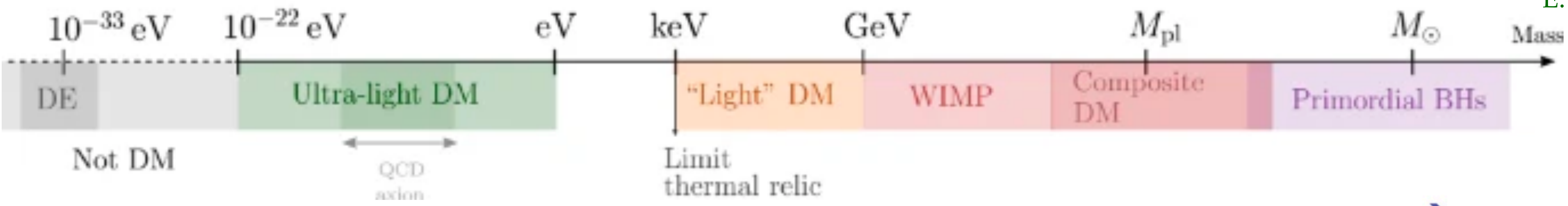
- This can arise due to neutrino coupling with ultralight dark matter.

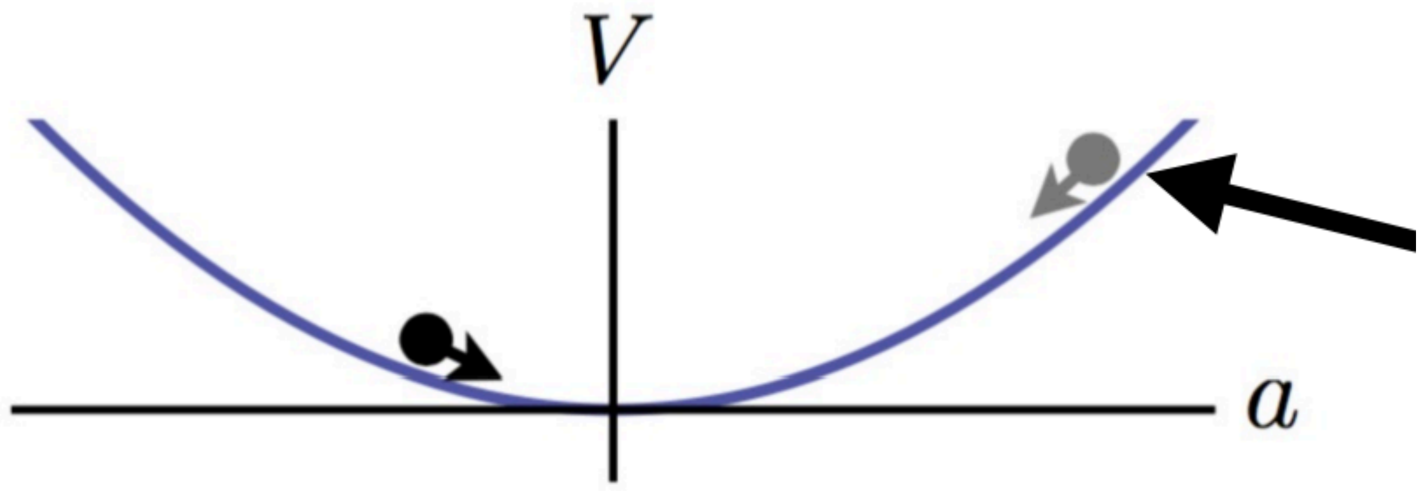




What is ultralight dark matter?



E. Ferreira, Astronomy Review 2021



- Ultralight scalar field produced **coherently.**
- 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 $\langle\Phi_c|\hat{\phi}|\Phi_c\rangle = \phi_0 \cos(m_\phi t - \mathbf{k}\mathbf{x}).$ Here $\phi_0 = \sqrt{2\rho}/m_\phi$.
- Eg. fuzzy dark matter

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

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 time modulation in 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 $g\phi(z \sim 3000) \simeq 10\,{\rm eV}$. 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** ?

Cosmology-friendly mass-varying neutrinos

- Avoid direct coupling between ν and ULDM .

  Couple the ULDM ϕ to sterile neutrinos N.

- Consider

$$\mathscr{L} \supset y_{\mathrm{D}} \overline{L}\, h^{\mathrm{c}} N + \frac{1}{2}(m_N + g\phi(t))\, \overline{N^{\mathrm{c}}} N + \frac{1}{2}\kappa \overline{L}\, \tilde{h}\tilde{h}^{\mathrm{T}} L^{\mathrm{c}} + \underbrace{\frac{1}{2}\frac{y}{\Lambda}}_{\text{higher dimension: neglect for this talk!}} \phi(t)^2 \overline{N^{\mathrm{c}}} N$$

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

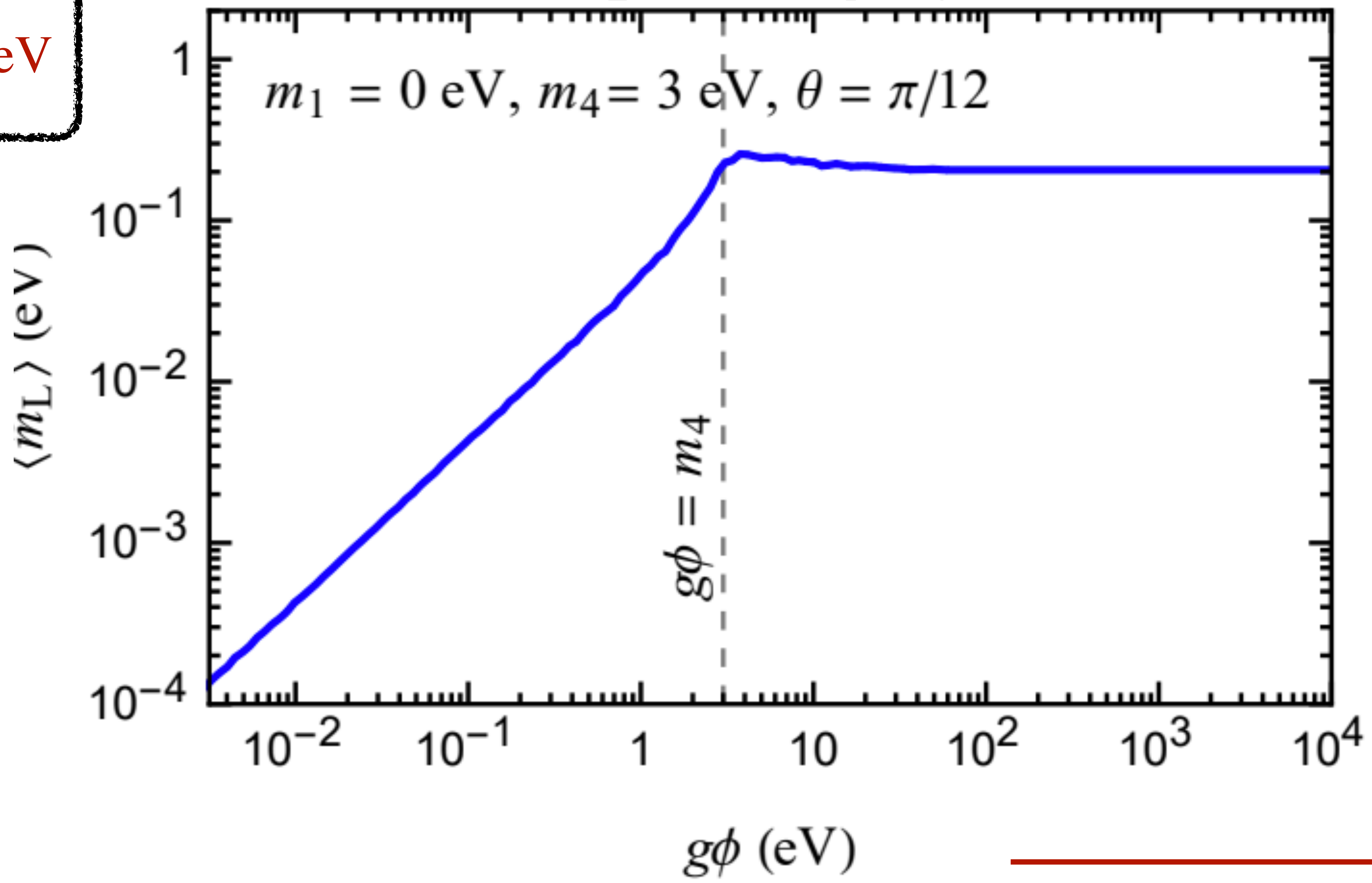
$$\tilde{M}_\nu = U^\dagger \begin{pmatrix} m_1 & 0 \\ 0 & m_4 \end{pmatrix} U + \begin{pmatrix} 0 & 0 \\ 0 & g\phi(t) \end{pmatrix}$$

- What happens to the light neutrino mass after diagonalisation?

Cosmology-friendly mass-varying neutrinos

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

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



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

$\longrightarrow$

early Universe

Cosmology-friendly mass-varying neutrinos

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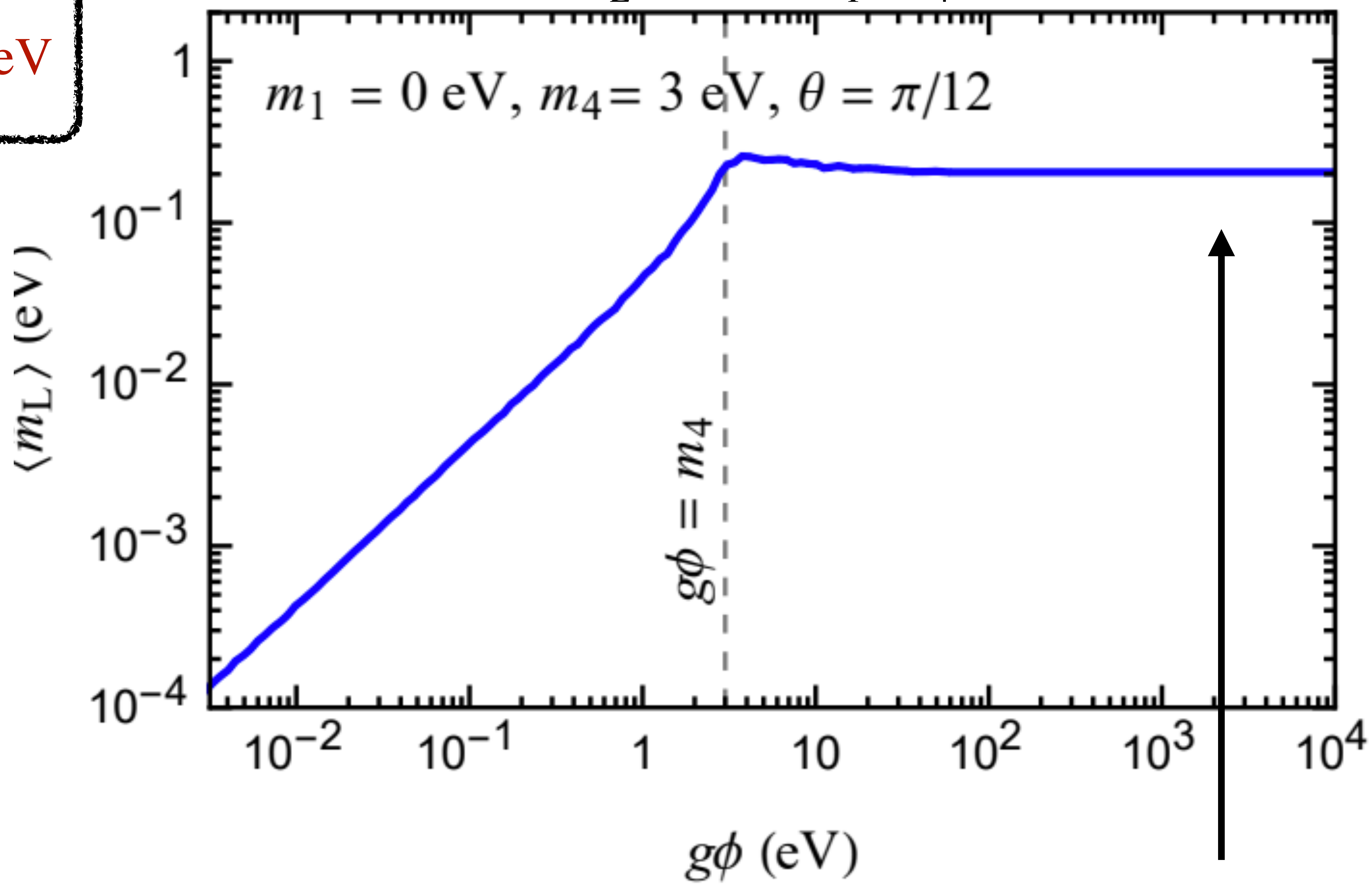
$m_L = \mathrm{Min}(\widetilde{m}_1, \widetilde{m}_4)$



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

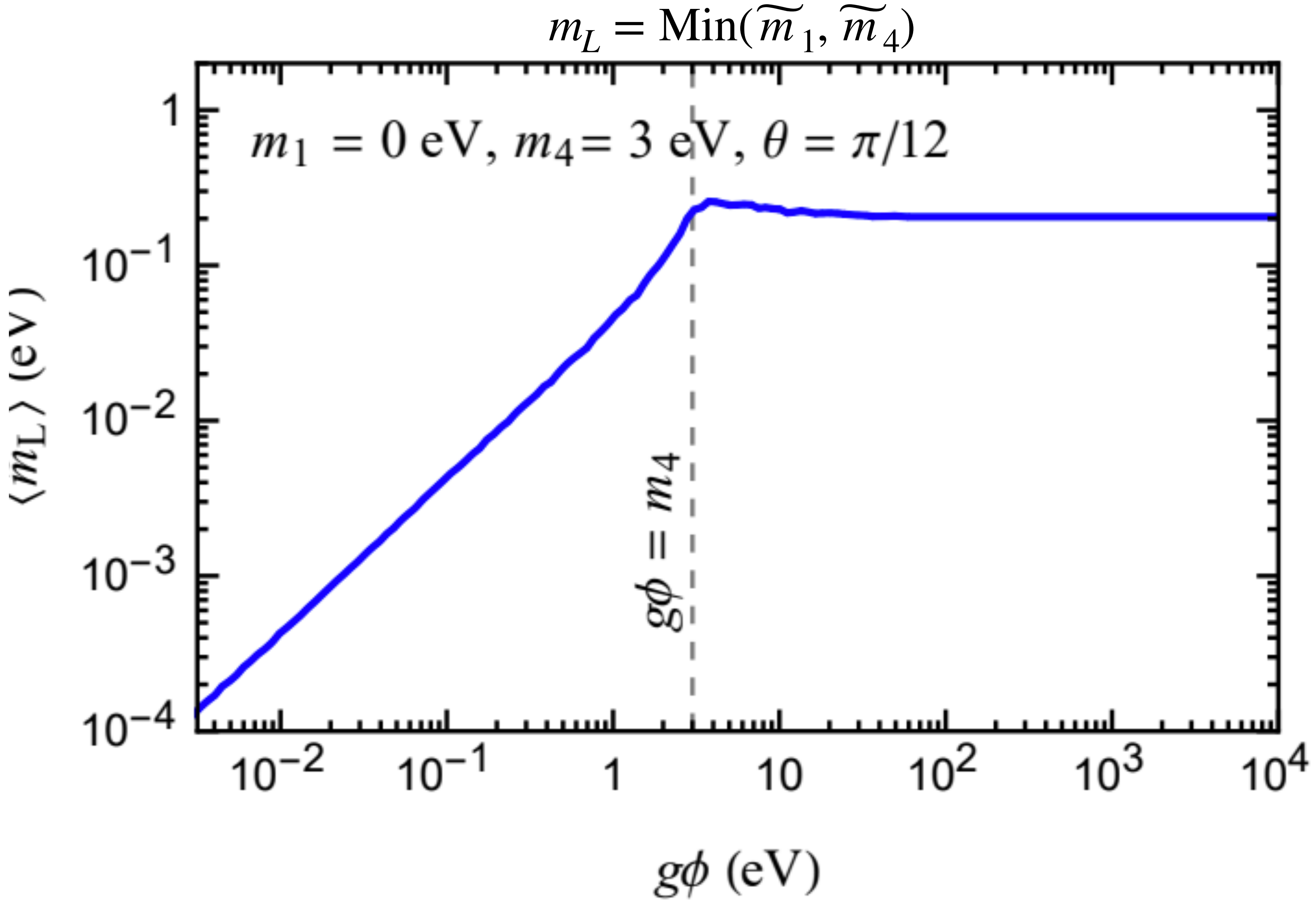
cosmology friendly for eV scale N

Cosmology-friendly mass-varying neutrinos

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

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

This can lead to time-modulation in oscillation experiments!



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

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

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

Extra radiation in the early Universe?

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

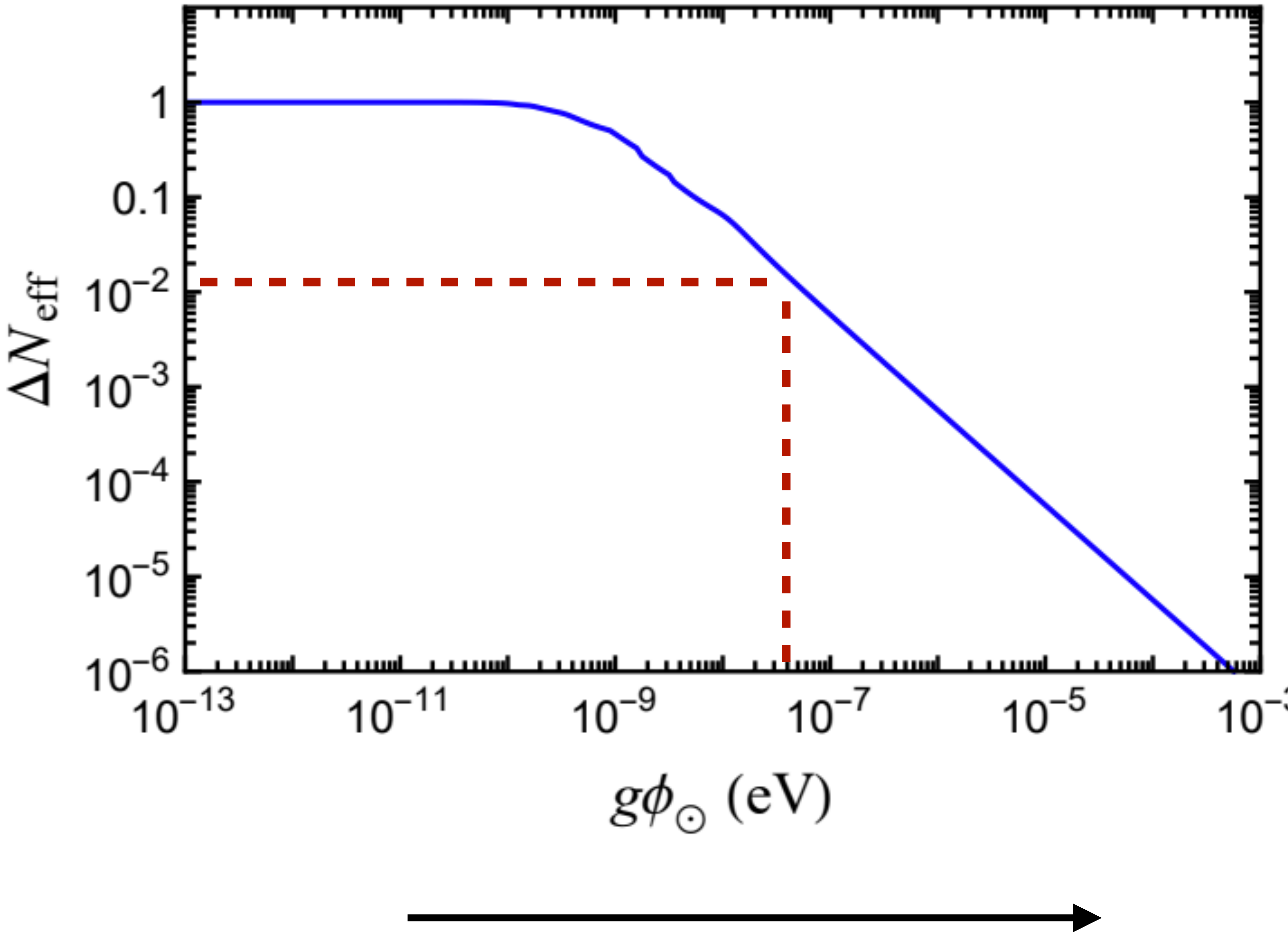
- The mixing angle is suppressed

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

- This protects the model from $\Delta N_{\rm eff}$ bounds.

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

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



early Universe

Implications for neutrino experiments

- Neutrino oscillations experiments - neutrino probability time-modulated. ✓
- Solar neutrinos, atmospheric neutrinos. ✓

Berlin (PRL 2016),
Krnjaic, Machado, Necib (PRD 2018),
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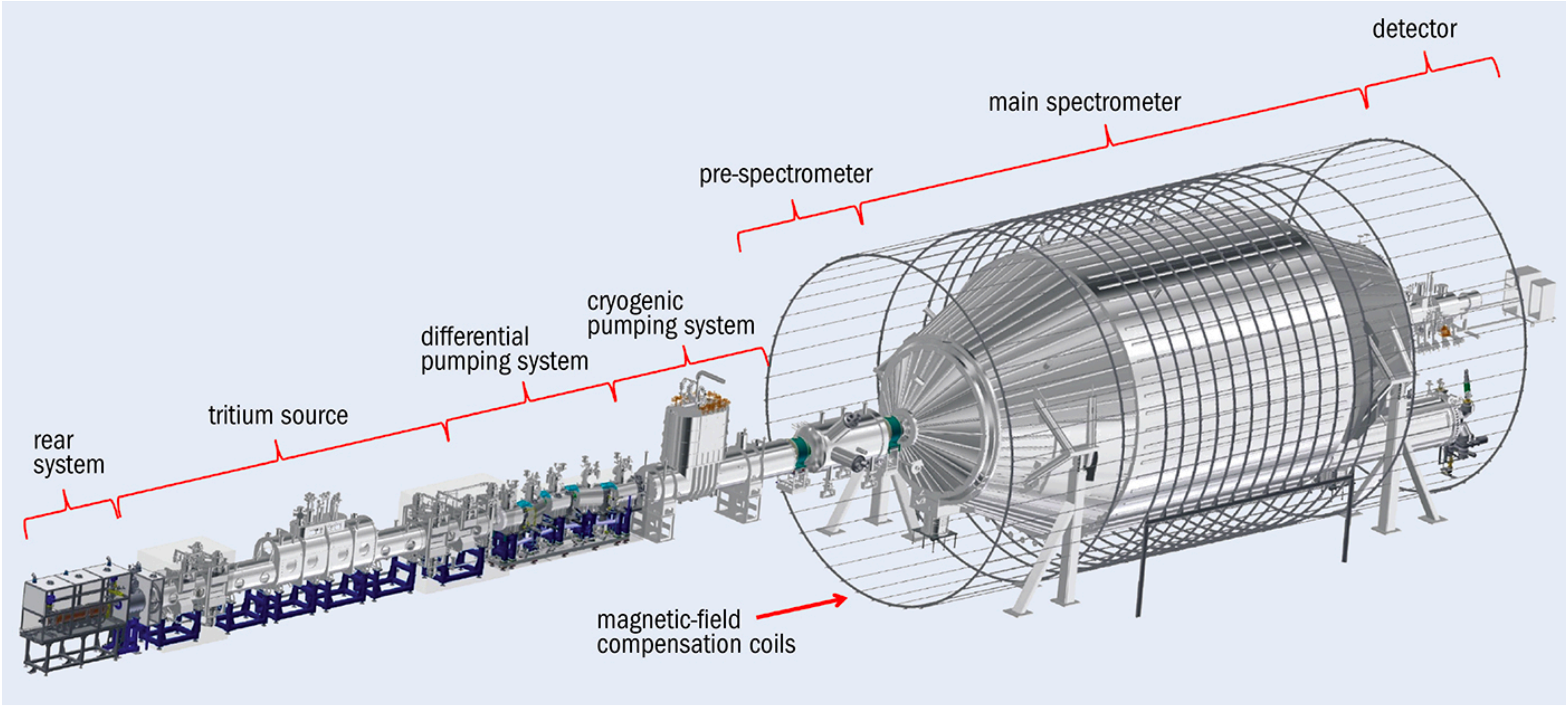
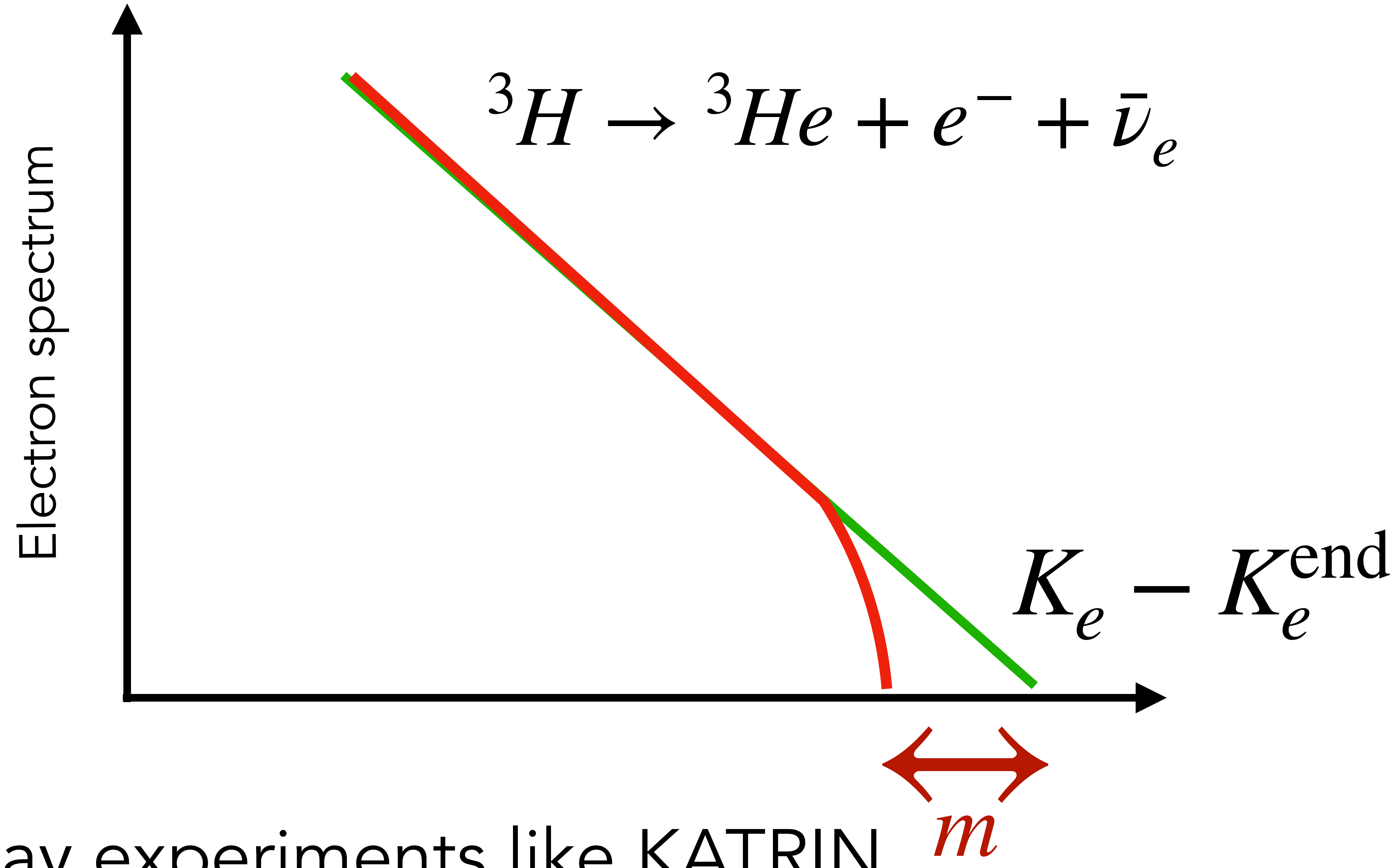
- Beta decay experiments.
- Short baseline oscillations.

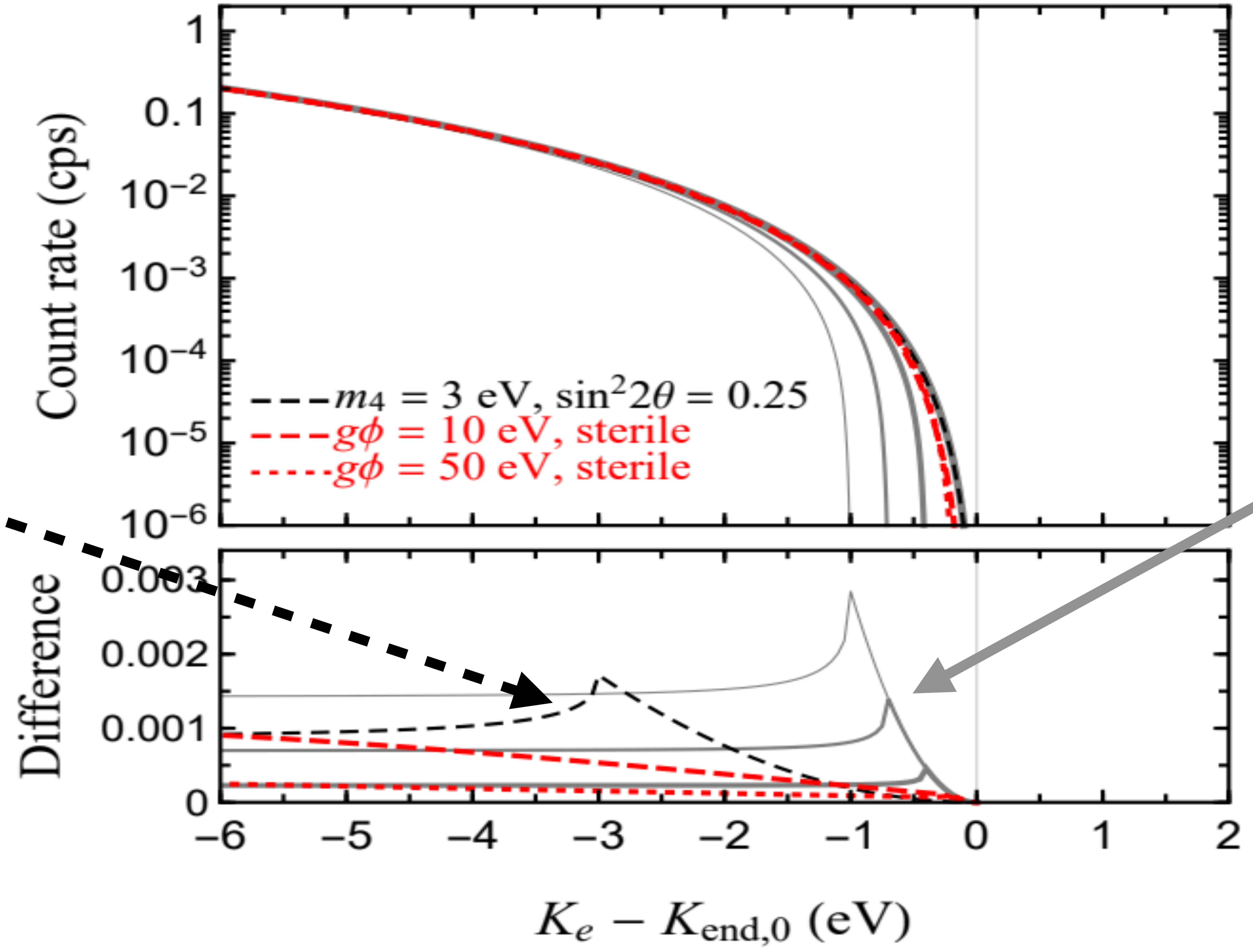
Signatures in beta decay experiment-KATRIN





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

eV scale sterile neutrinos in KATRIN



sterile neutrinos produce
an additional kink and a shift

Active neutrinos
of different masses
produce a kink

$m_\beta = 0.4\,\mathrm{eV}, 0.7\,\mathrm{eV}, 1\,\mathrm{eV}$

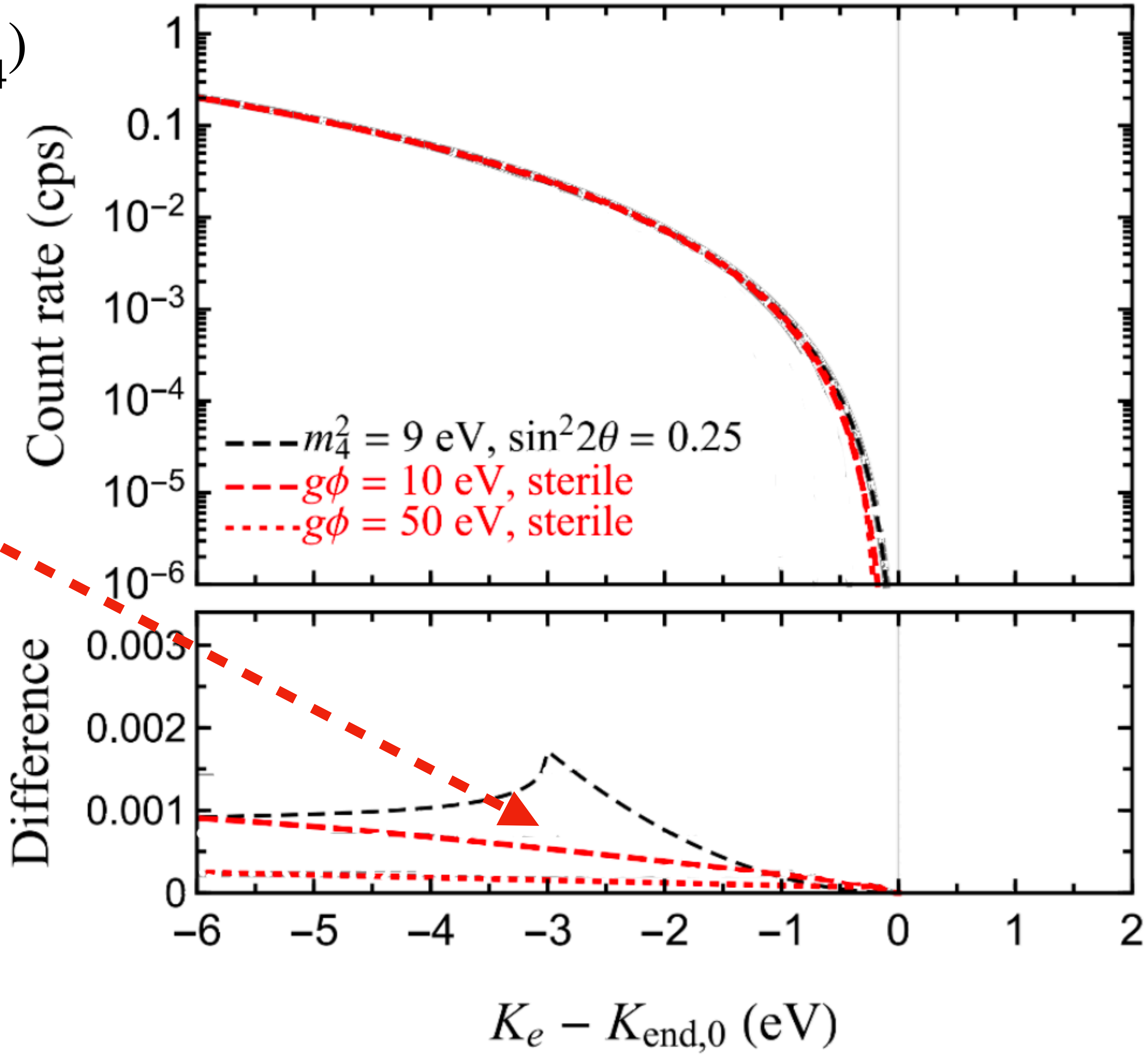
- For additional light sterile neutrinos,

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

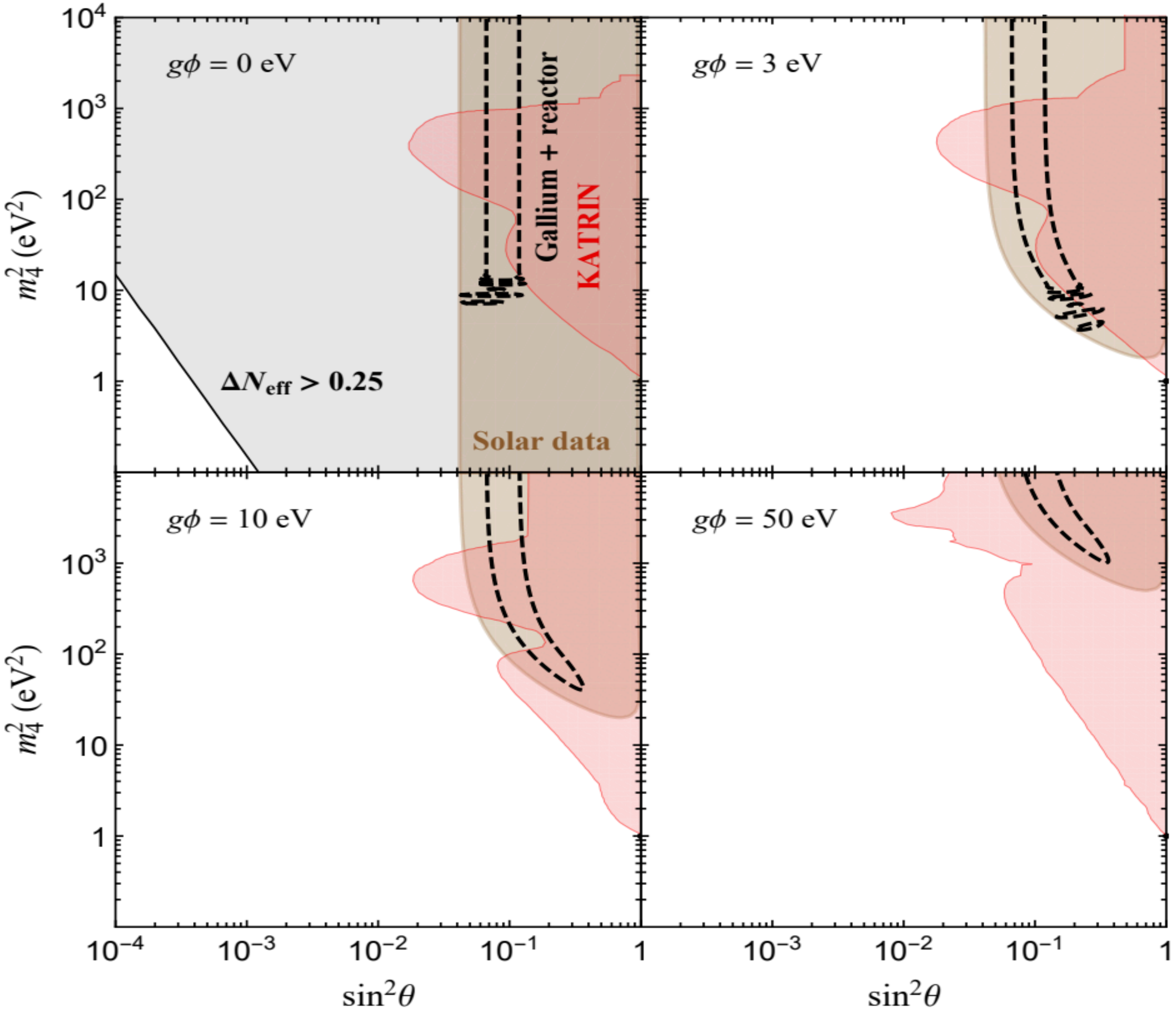
Signatures of ULDM in KATRIN

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

- For ULDM-sterile neutrino interaction, the time variation causes an averaged distortion of the kink.
- Primarily due to suppression of mixing due to large scalar potentials.
- Does this open up sterile neutrino paramater space in SBL experiments?



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.

Take-away message

- Coupling of active neutrinos 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.
- This suppresses the large contribution to neutrino mass during CMB. Cosmologically friendly!
- Number of fascinating probes in the early Universe, beta decay experiments as well as SBL experiments.

Neutrino PLATFORM

Thank you!

Questions and comments:
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Other constraints

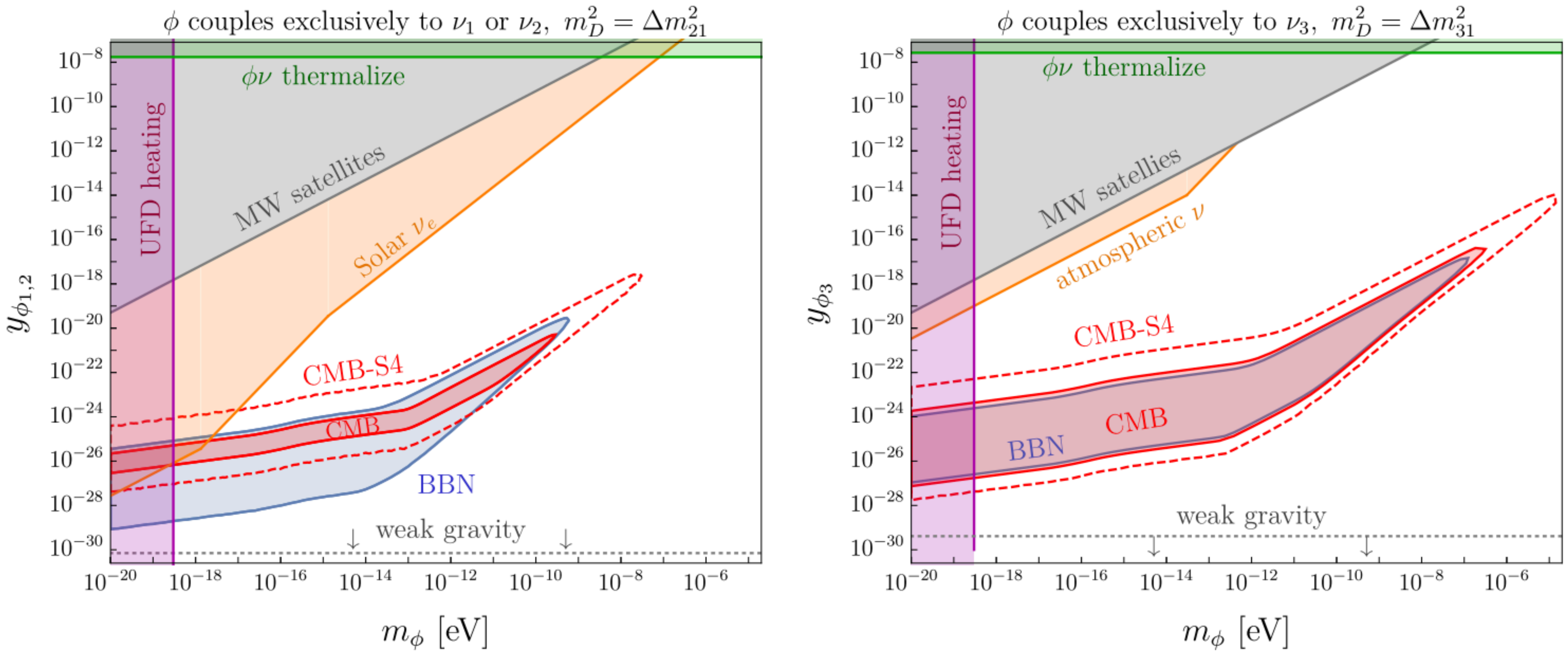
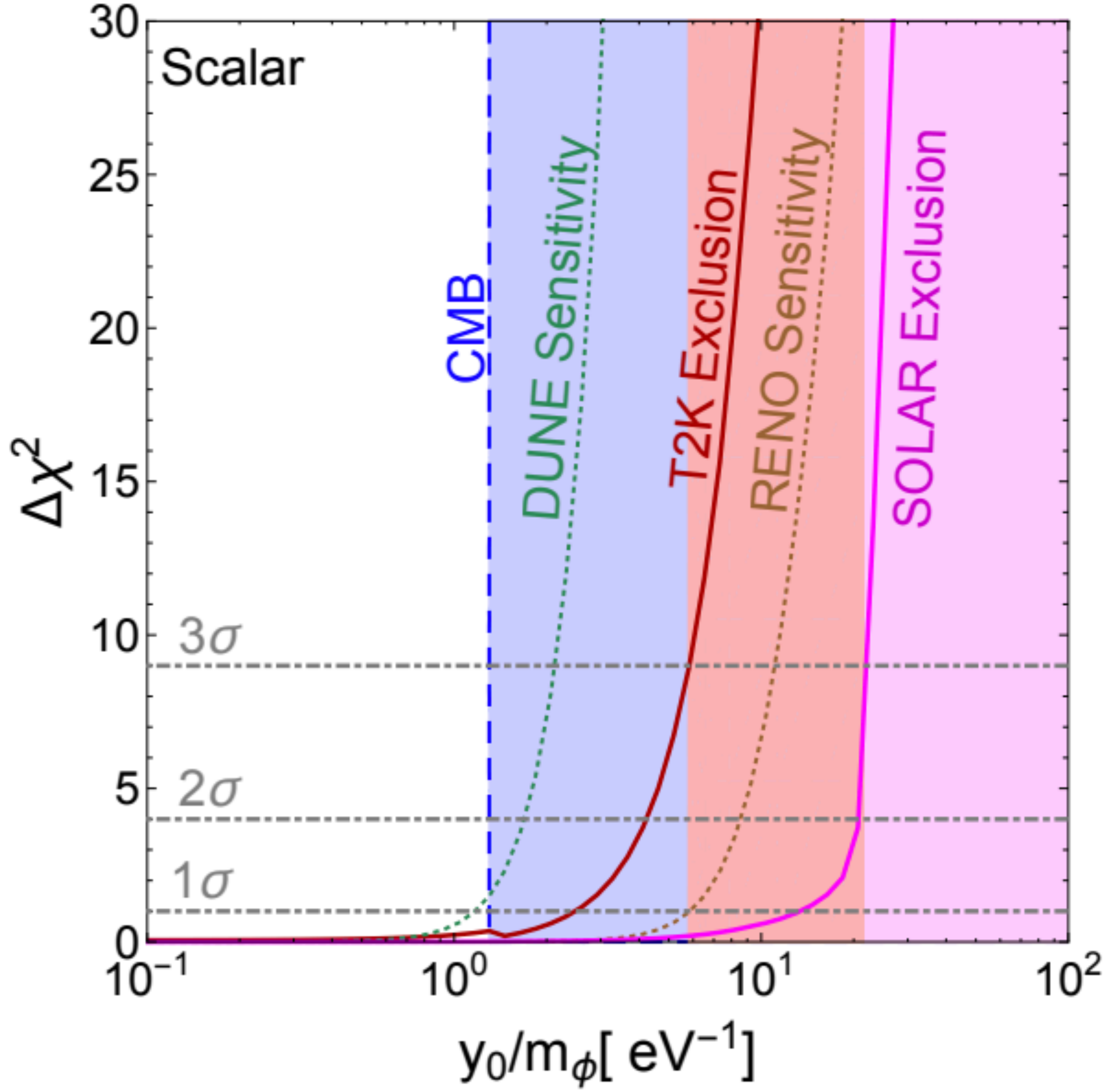


FIG. 1: **Left**: Parameter space for ϕ coupled only to ν_1 or ν_2 mass eigenstates, which is predominantly constrained ν_e oscillation bounds. Here we show bounds from CMB and BBN from Sec. V, Milky Way satellites from Sec. V B, scalar thermalization with neutrinos from Sec. V C, solar neutrino oscillations from Sec. IV A, and model independent limits on light DM from ultra faint dwarf (UFD) heating [17]. For points below the gray dotted line, the ϕ mediated force between right handed neutrinos is weaker than gravity, which is theoretically disfavored by the weak gravity conjecture [18] **Right:** same as the left panel, only ϕ now couples only to ν_3, so the limits are driven by $\nu_{\mu,\tau}$ oscillations for which the solar bound is subdominant to the atmospheric bound described in Sec. IV B.

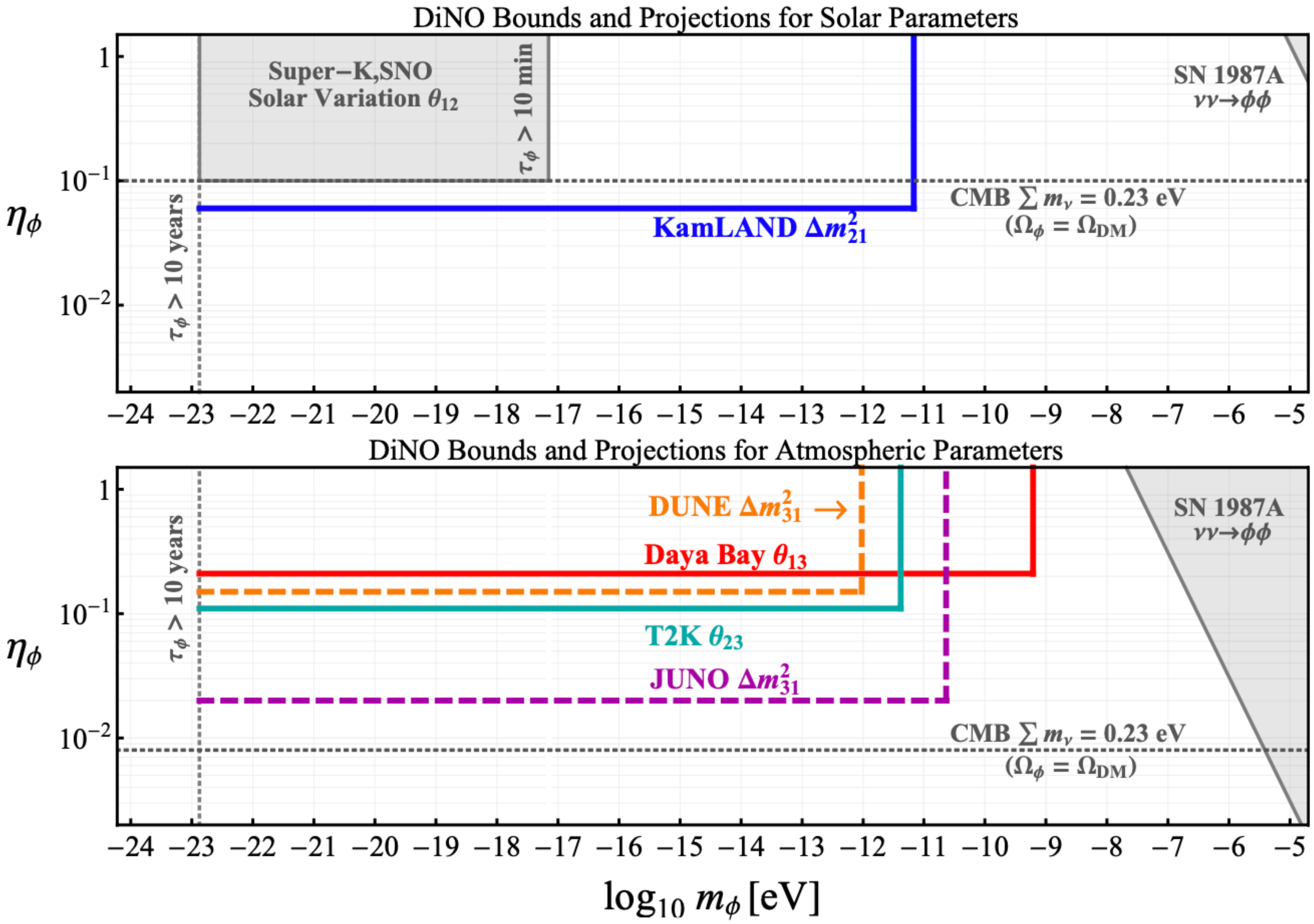
Dev, Krnjaic, Machado, Ramani , arXiv: 2205.06821

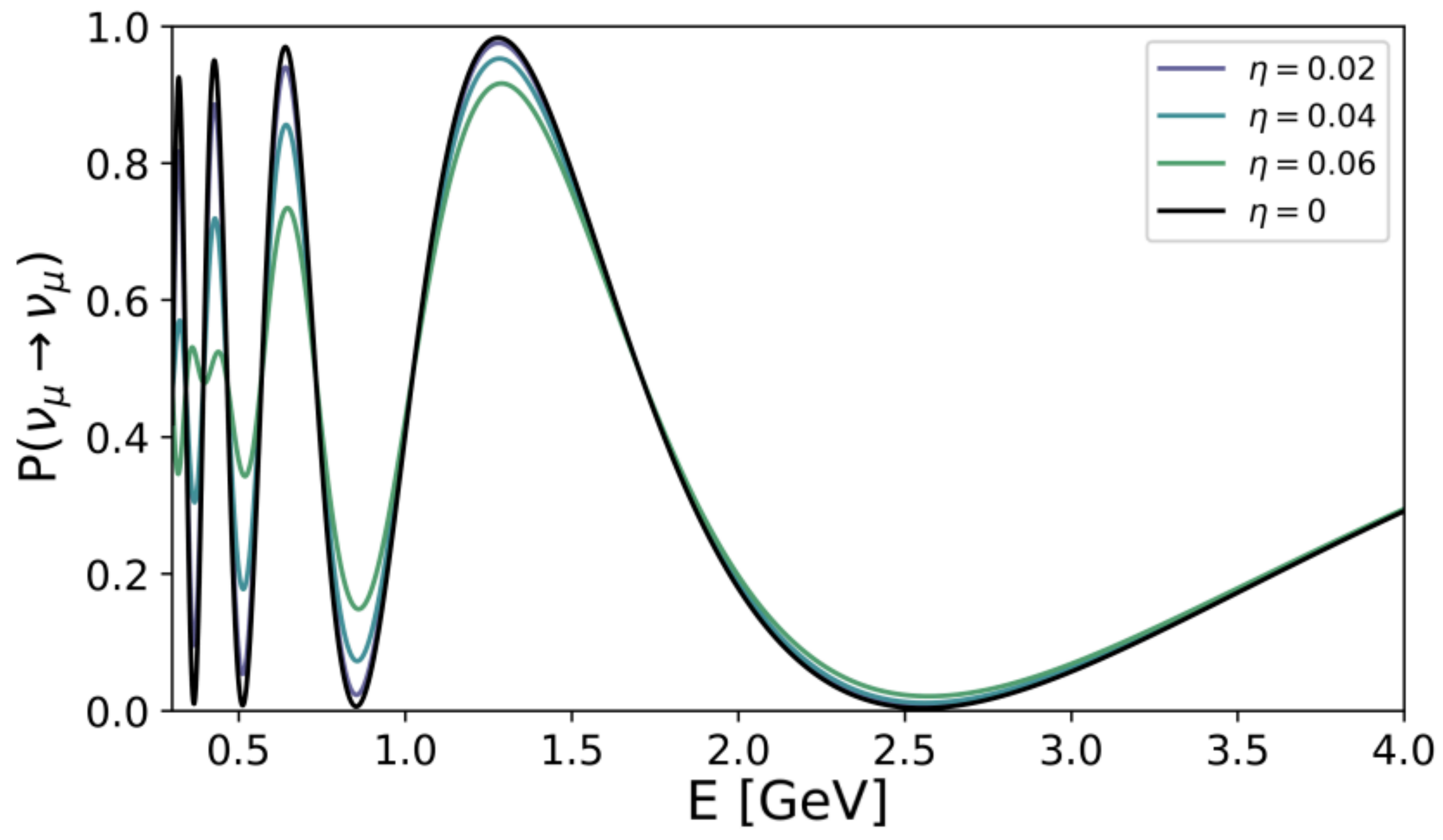
Oscillation constraints



Brdar, Kopp, Liu, et al (PRD 2018)

Oscillation constraints





Krnjaic, Machado, Necib (PRD 2018),

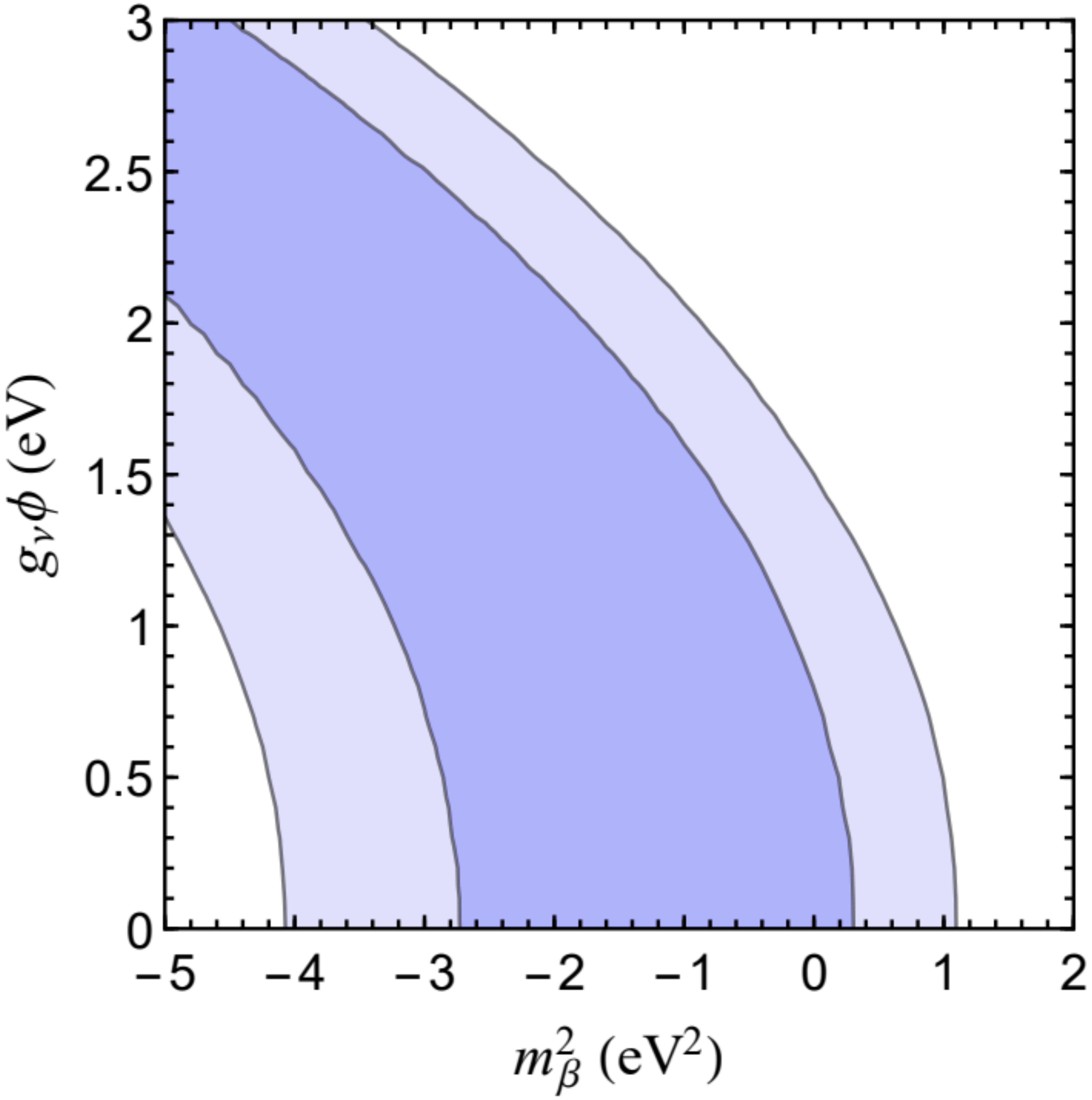
KATRIN degeneracy for large sterile mass

In the limit $m_4 > g\phi$, averaged

$$\langle \tilde{m}_\beta^2 \rangle = m_\beta^2 + \frac{(g\phi)^2}{2}$$

leads to a degeneracy.

Time modulation also possible if the DM cycle is comparable to KATRIN cycle.



Neutrino mass variations with time

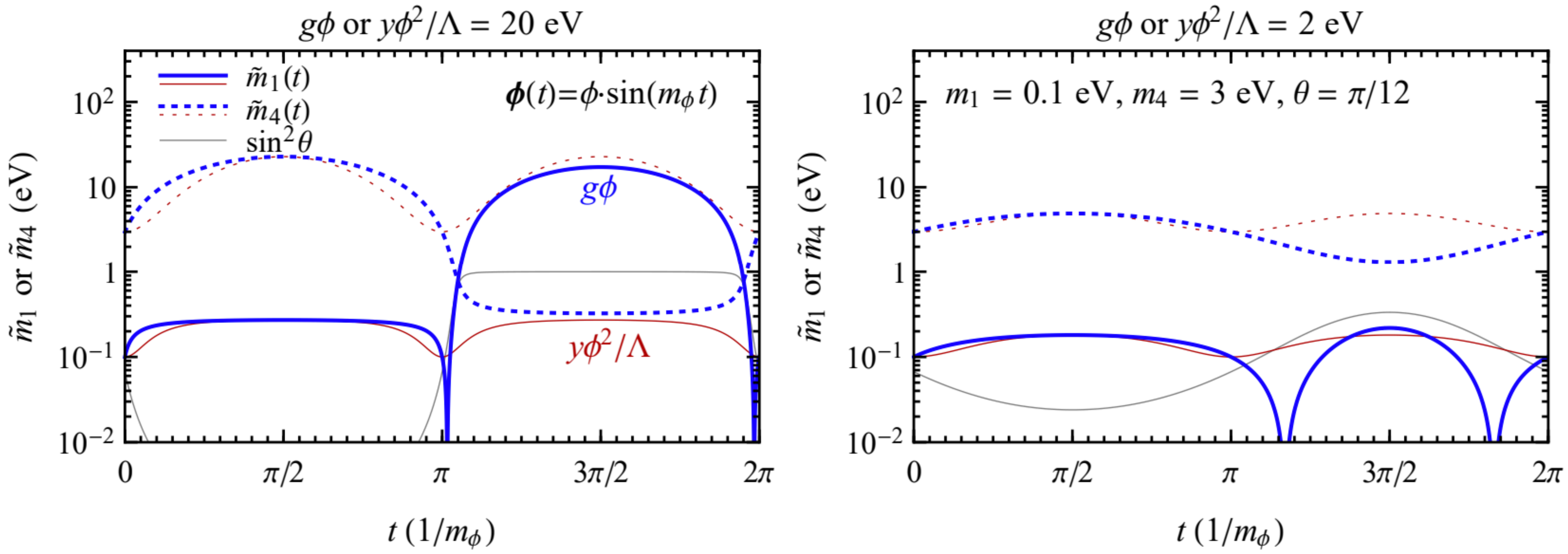


FIG. 5. The evolution of $\tilde{m}_1$ (solid curves) and $\tilde{m}_4$ (dotted curves) as functions of time, within one DM cycle. The DM potential is taken to be $g\phi = 20$ eV (blue curves) or $y\phi^2/\Lambda = 20$ eV (red curves) for the left panel. Vacuum neutrino parameters are fixed as $m_1 =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

States swapped
for large $g\phi$

BEST experiment