DYNAMIC NEUTRINO MASSES - WHAT, HOW AND WHERE?

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Dark Matter and Neutrinos

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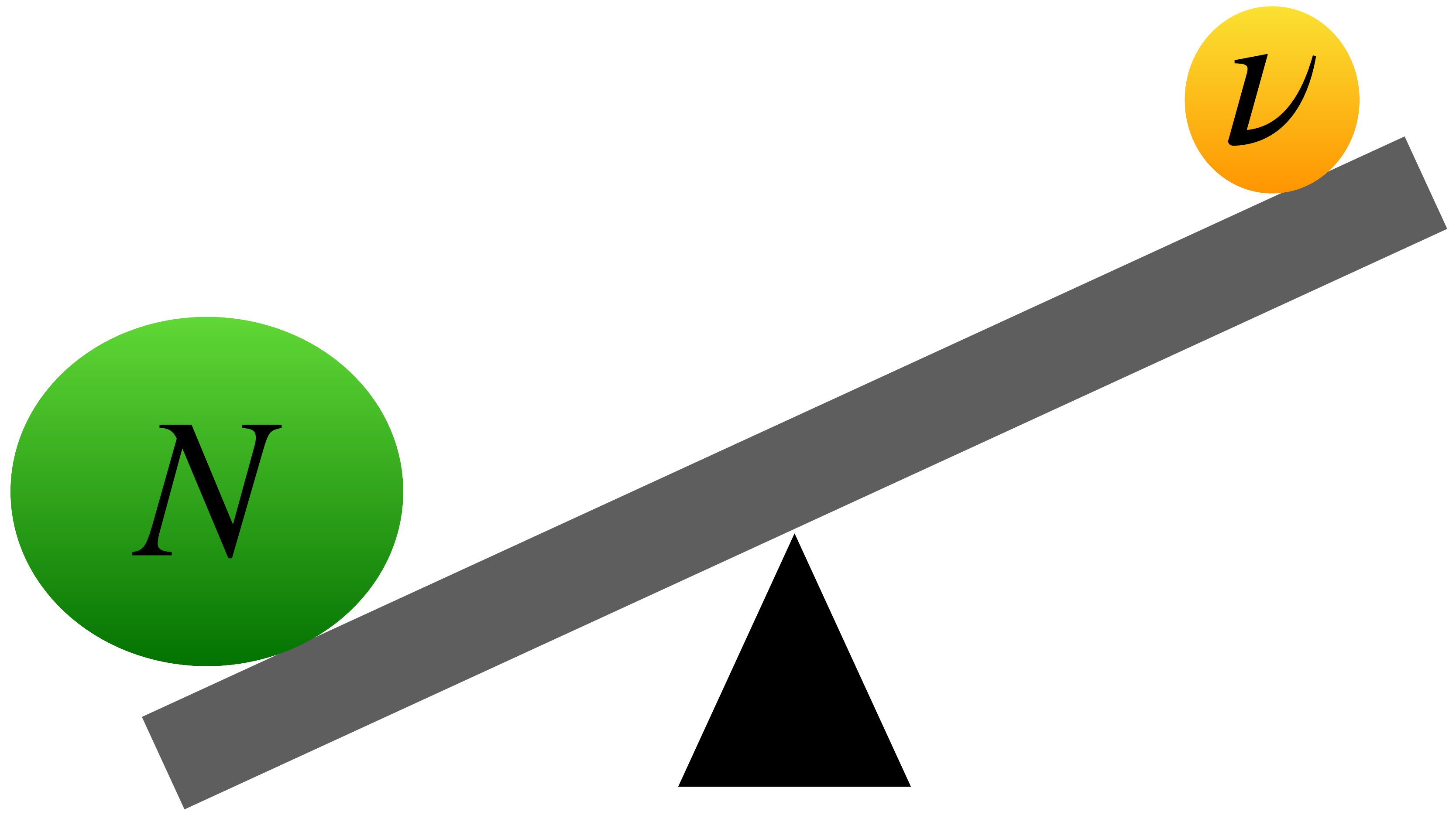
Origin of neutrino mass

- Neutrino mass can be Dirac: add a RH neutrino N and no lepton number violation.
  $\mathscr{L} \supset y\, LH^c N = m_D\, \nu N$
- Majorana neutrinos-lepton number violated. Generate the Weinberg operator at dim=5:
  $\mathscr{L} \supset y\,(LH)^2/\Lambda$.
- Seesaw mechanism.

  $\mathscr{L} = m_D\, \nu N + m_N\, NN$
- Diagonalise and if $m_N \gg m_D$, then $m_{\text{light}} \sim m_D^2/m_N$ and $m_{\text{heavy}} \sim m_N$.
- Neutrino mass from vacuum expectation values of scalars.



Seesaw mechanism

But neutrinos are special...

- Neutrinos stand out from the rest of the SM particles. Can offer a gateway to beyond the SM physics.
- We can speculate that neutrino mass can have a different origin from the rest of the SM particles
- Neutrino mass can be generated through some "dark" interactions.
- Or through some unknown phase transition in the early Universe.

Dark, dynamic origin of neutrino mass

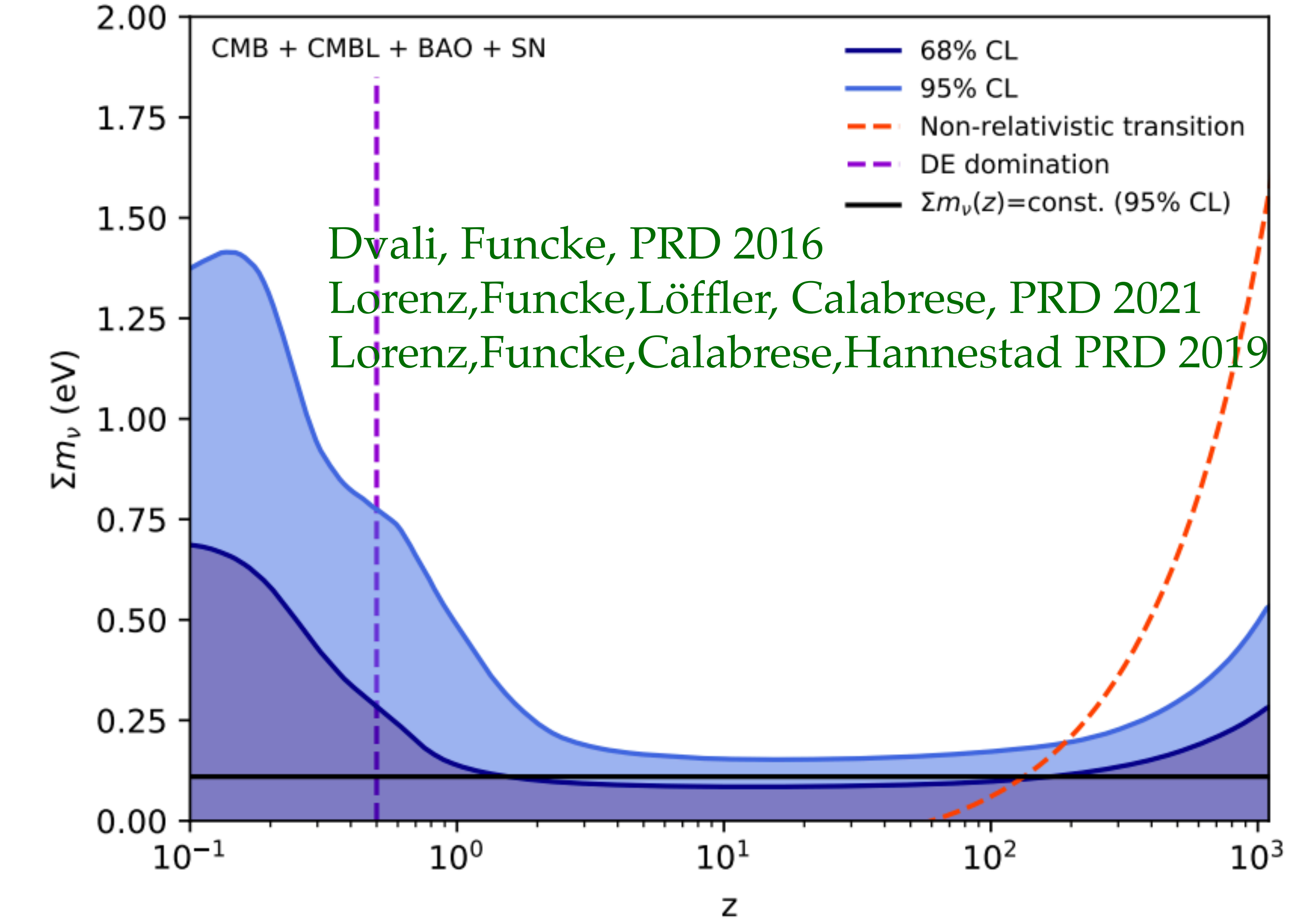
Do we have any reasons to think like this?

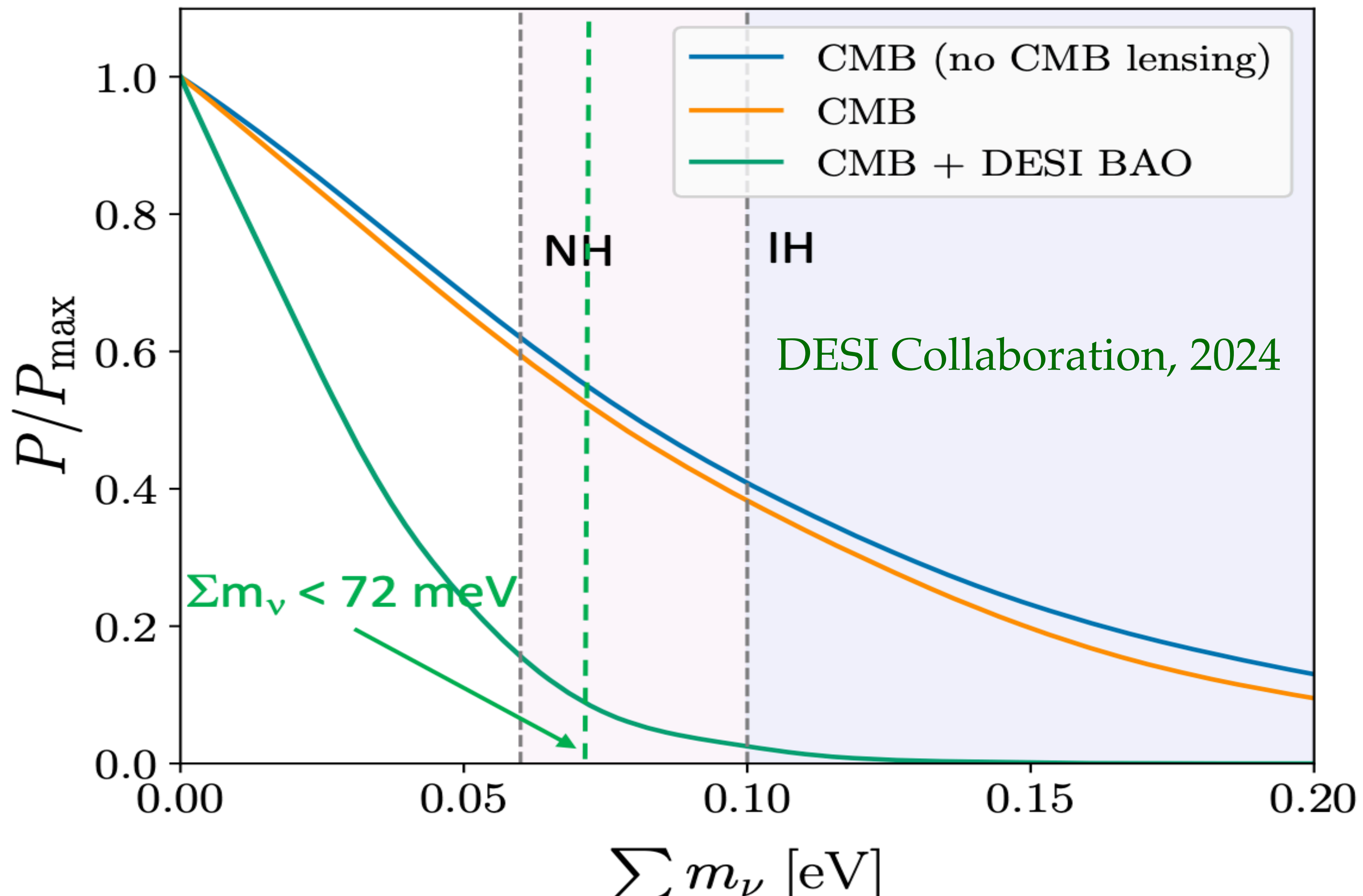
- Nothing concrete, to be honest. The Higgs mechanism works just fine.
  However, some scattered hints, maybe?

- Redshift dependent bounds on $\sum m_\nu$ from CMB (TT, polarisation, lensing), BAO, SNIA.

- Loosening of bounds at low redshift can be explained by a redshift dependent mass - dynamic masses.

- Recent DESI results indicate some tension in $\sum m_\nu$ with oscillation results.





Dynamic Neutrino Masses - What?

The basic observation

- Neutrino oscillations imply neutrino mass!

- Oscillation experiments probe mass-squared $H = \sqrt{p^2 + |m|^2} \approx p + \frac{|m|^2}{2E}$

- 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.

Wolfenstein (PRD 1978)

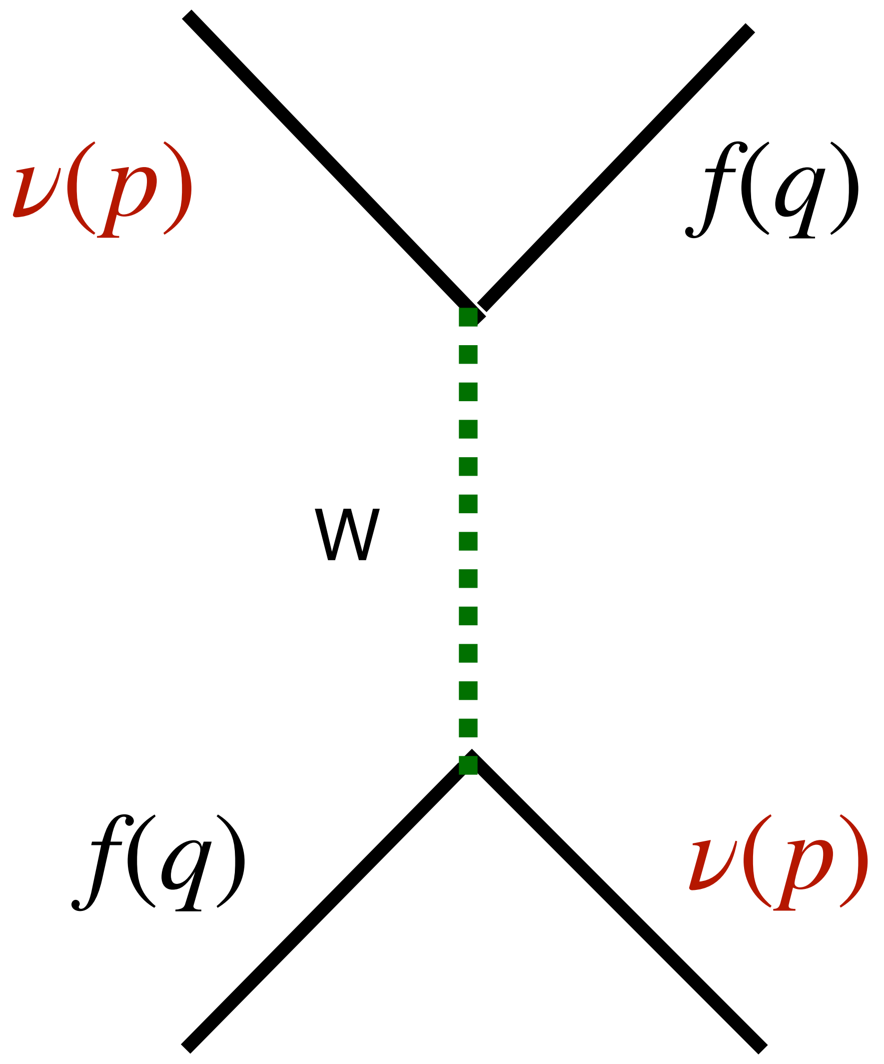
- Potential is proportional to the number density (n) of background scatters, $V_n = \sqrt{2} G_F n_n$, where $G_F \propto g^2/M_W^2$.

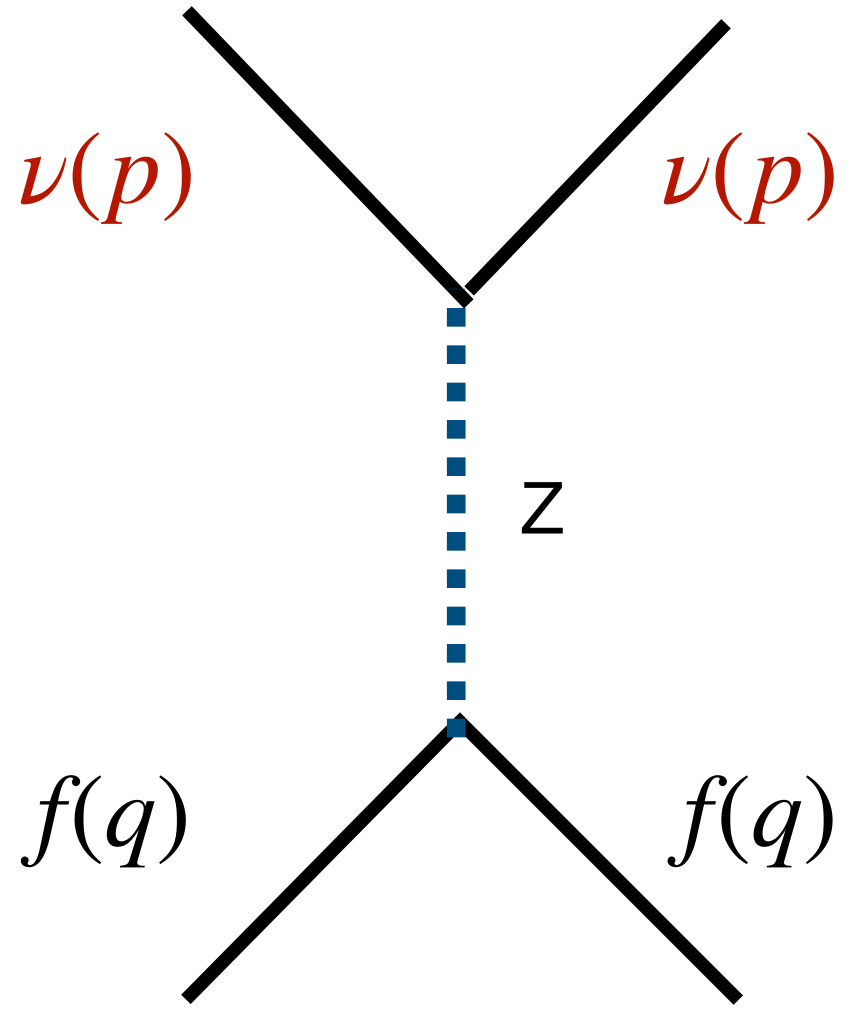
- This potential has an energy dependence at $\sqrt{s} \gg m_W$

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

Lunardini, Smirnov (NPB 00)

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





The basic observation...revisited

- Any contribution to the Hamiltonian of evolution with a $\frac{\mathrm{const}}{E}$ form can reproduce oscillation data.

- Forward scattering of neutrinos on light targets through a light mediator can have a (1/E) form at experimentally accessible energies.

- Can the potential with 1/E dependence substitute the mass completely? In this case, neutrinos can be "massless" in "vacuum".

Refractive neutrino mass

- Neutrinos are massless in vacuum.

- Space is filled with light dark matter particles. DM fills up vacuum, somewhat like a uniform coherent field.

- Forward scattering on DM generates "refractive neutrino masses" such that $m^2 \propto n_{\mathrm{DM}}$.

- Problem with cosmology: $m(z) \propto (1+z)^{3/2}\, m(0)$.

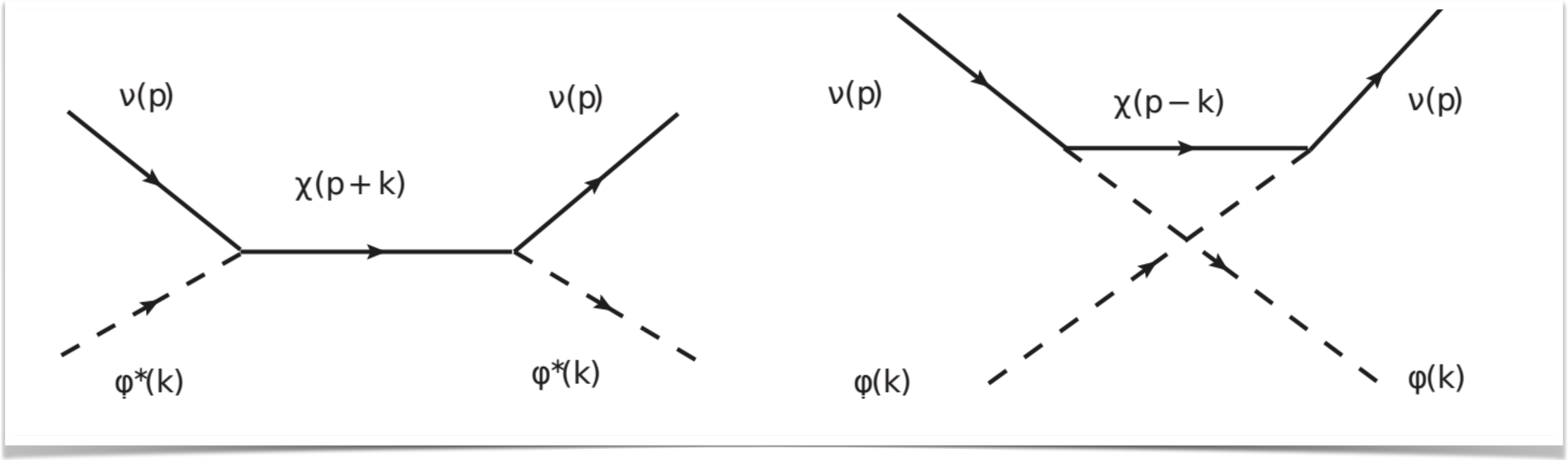
- If $m(0) = \sqrt{\Delta m^2_{\mathrm{atm}}}$, then $m(z \sim 1000) \simeq \mathcal{O}(10\,\mathrm{eV})$.
  Spoils observation of $\sum m_\nu$ from CMB and structure formation. Need to evade!

Dynamic neutrino masses - how?

A model of dark neutrino mass

- Consider massless neutrinos scattering off ultralight scalar DM ϕ through a fermionic mediator χ.

$$\mathscr{L} \supset \sum_{\alpha=e,\mu,\tau} \sum_k g_{\alpha k} \bar{\chi}_{kR} \nu_{\alpha L} \phi^* + m_{\chi k} \bar{\chi}_{kR} \chi_{kL} + \mathrm{h.c.}$$



Choi, Chun, Kim (PDU 2020)
Chun (2021)
Smirnov, Valera (JHEP 2021)
Smirnov, **MS** (JCAP 2024)

The effective potential

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

$$E_R = \frac{m_\chi^2}{2 m_\phi}$$

The refractive mass

- Define the refractive mass $\tilde{m}^2 \equiv (2E)\, V$
- In terms of $y \equiv E/E_R$, we can write

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

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

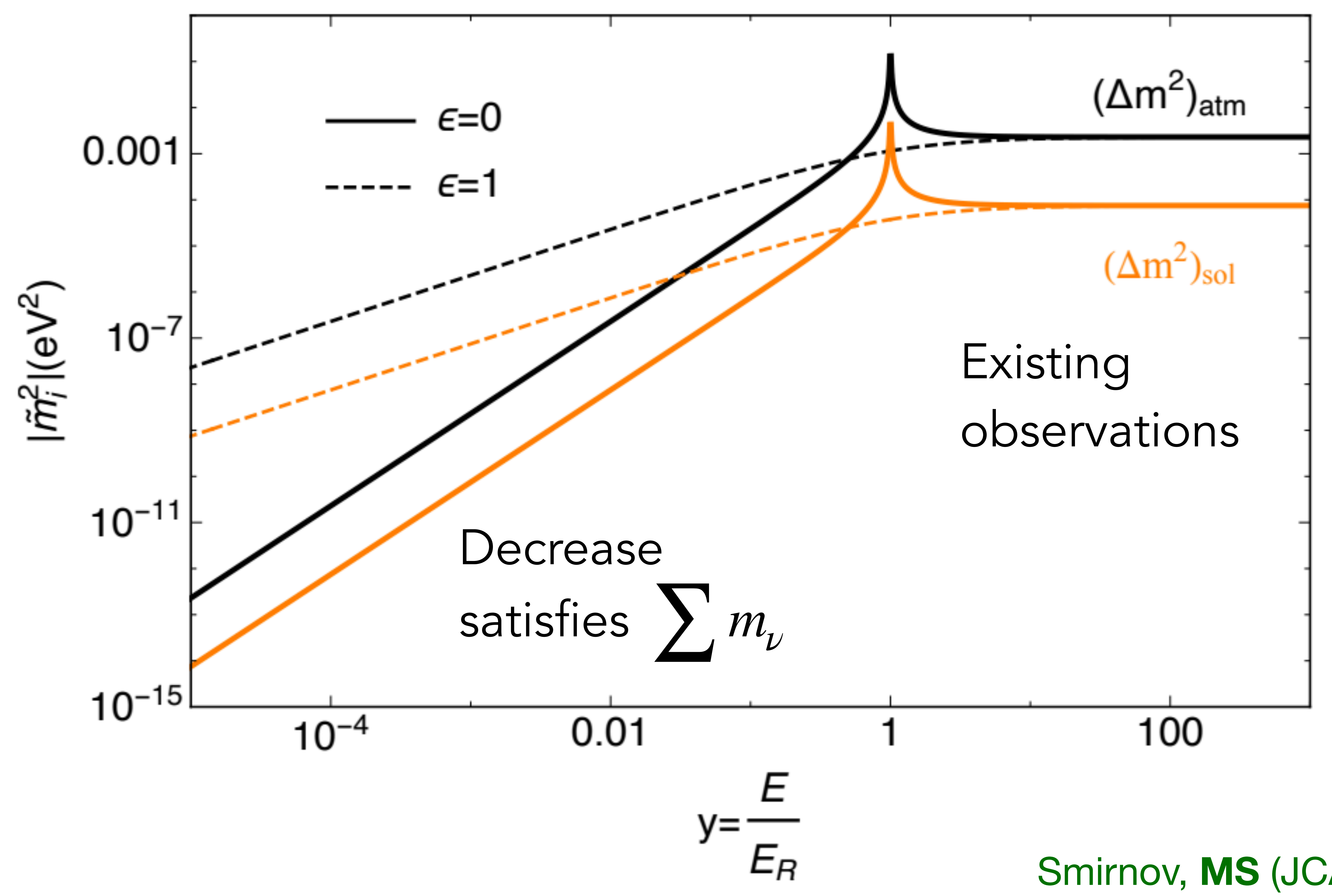
- We can write this as $\tilde{m}^2 = \tilde{m}^2_{\text{asy}} \dfrac{y(y-\epsilon)}{y^2 - 1}$ where $\tilde{m}^2_{\text{asy}} = \left(\dfrac{n_\phi + \bar{n}_\phi}{m_\phi} \sum_k g_{\alpha k} g^*_{\beta k} \right)$

Energy independent ($\tilde{m}^2_{\text{asy}}$) — Energy dependent ($\frac{y(y-\epsilon)}{y^2-1}$)

Smirnov, **MS** (JCAP 2024)

Fitting the neutrino oscillation data

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



Smirnov, **MS** (JCAP 2024)

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

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

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

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

Can satisfy cosmological bounds

Fitting the neutrino oscillation data

- To explain 3ν data, we need at least 2 mediators $\chi_{1,2}$.

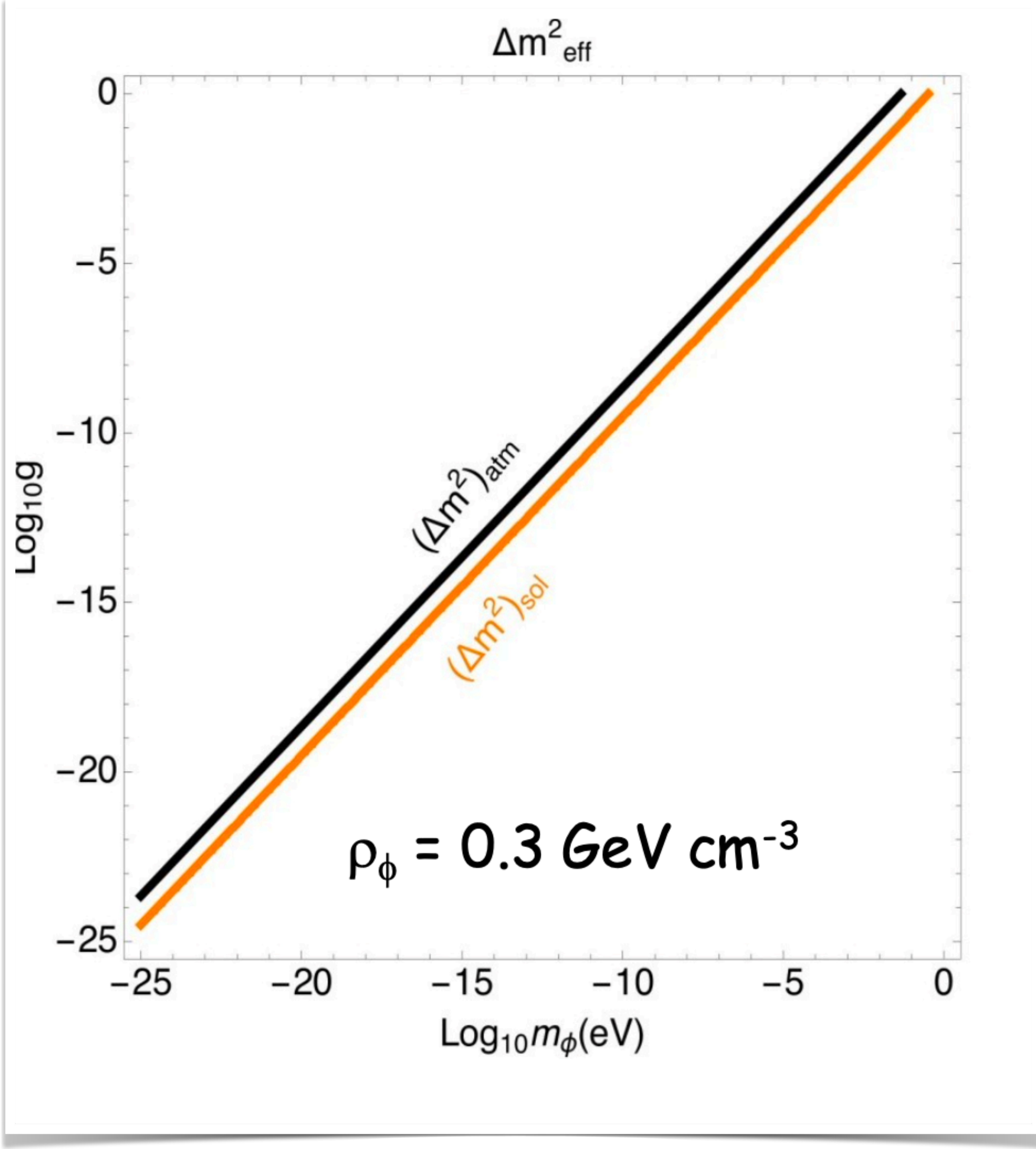
- In the $(\nu_e, \nu_\mu, \nu_\tau, \chi_1, \chi_2)$ basis, a nearly TBM form:

$$g_{e1} = g_{\mu 1} = g_{\tau 1} = g_1, \quad g_{e2} = 0, \quad g_{\mu 2} = -g_{\tau 2} = g_2$$

- Under NMO $(m_1 = 0)$,

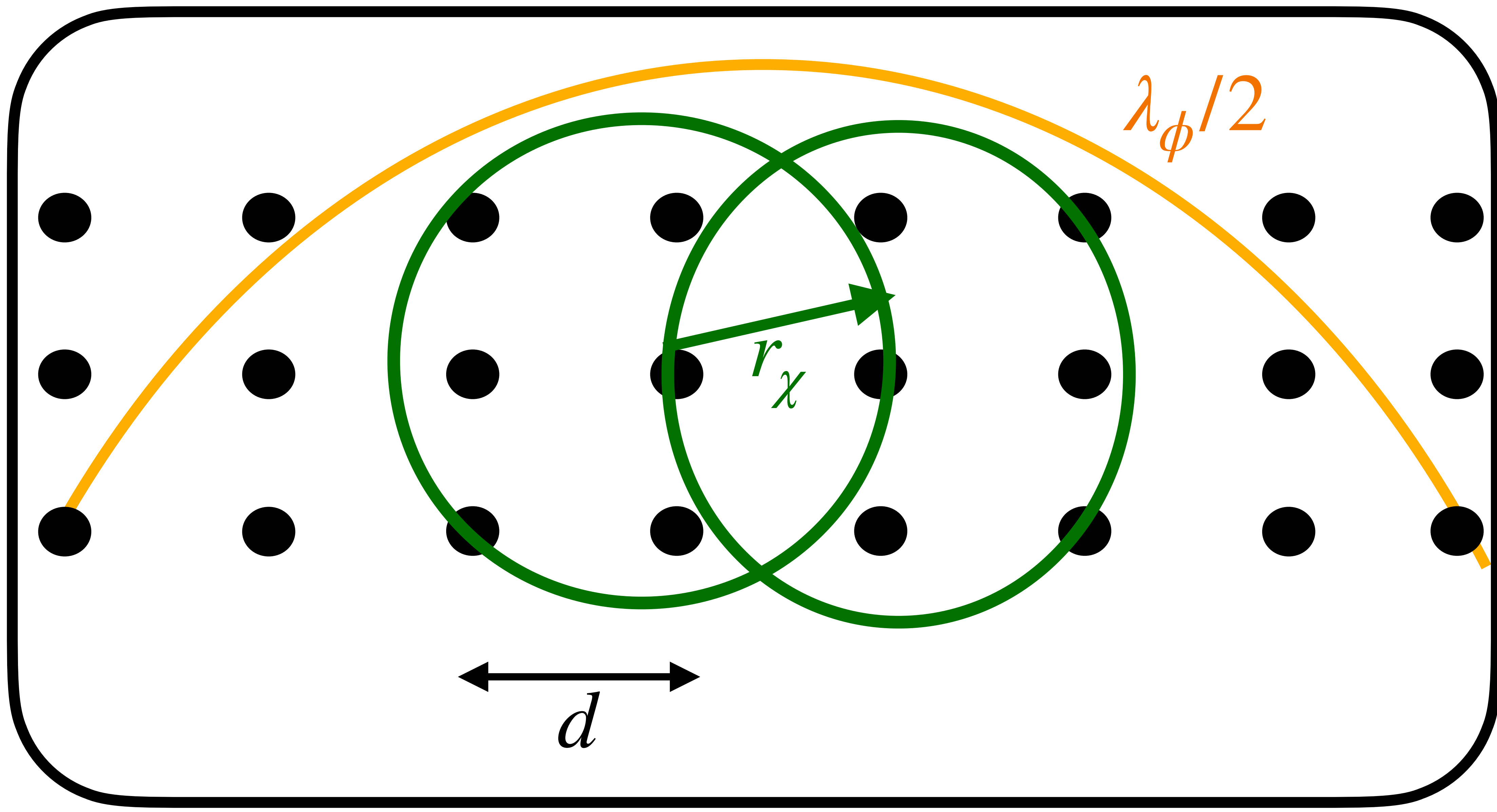
$$\left(\frac{g_1}{m_\phi}\right)^2 = \frac{\Delta m^2_{\rm sol}}{3\rho_\phi}, \qquad \left(\frac{g_2}{m_\phi}\right)^2 = \frac{\Delta m^2_{\rm atm}}{2\rho_\phi}$$

- This does not depend on m_χ, which is computed from $m_\chi = \sqrt{2 E_R m_\phi}$



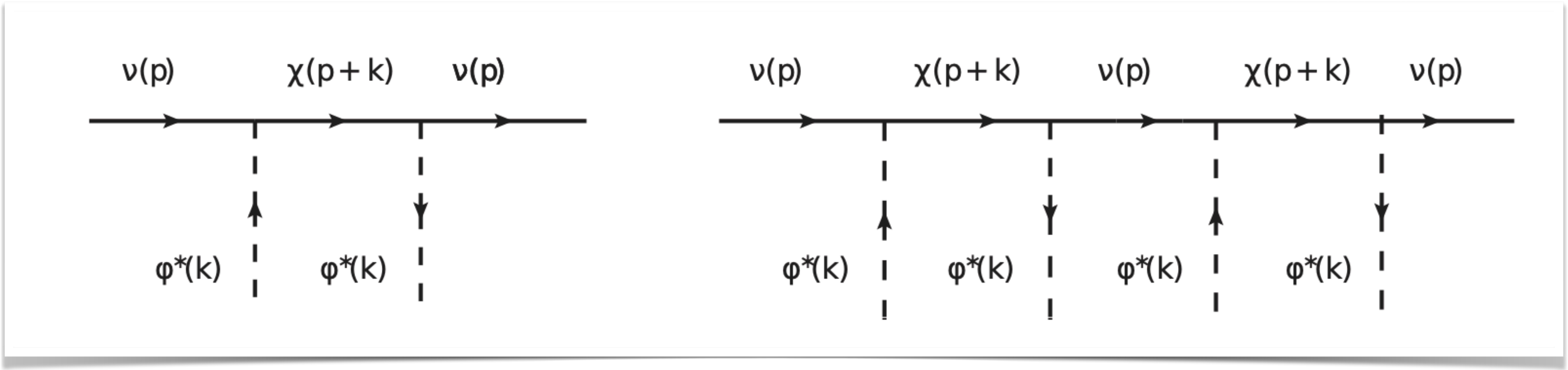
A word of caution

- 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 $\lambda_{dB} \sim 1/m_\phi v_\phi$

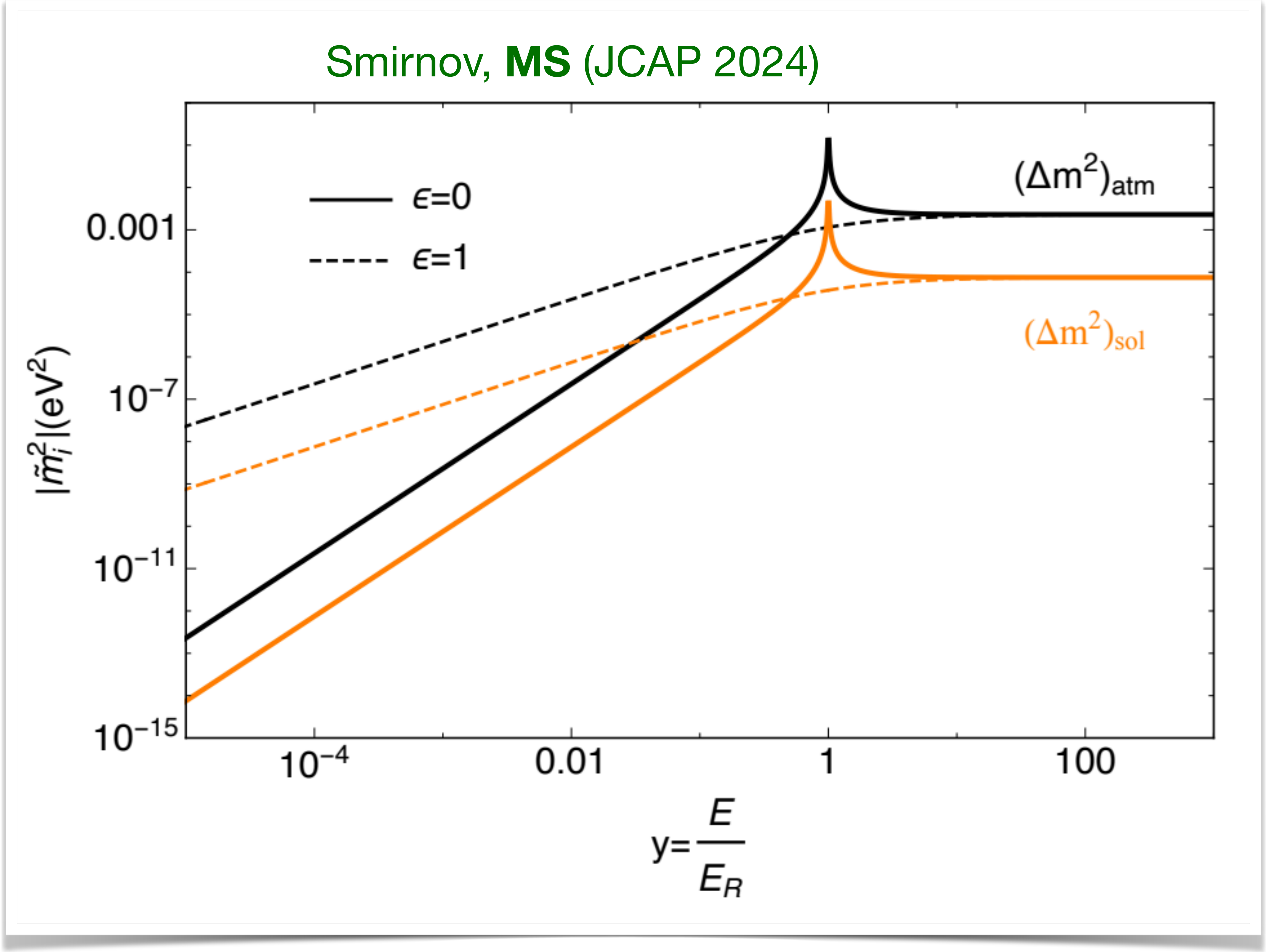


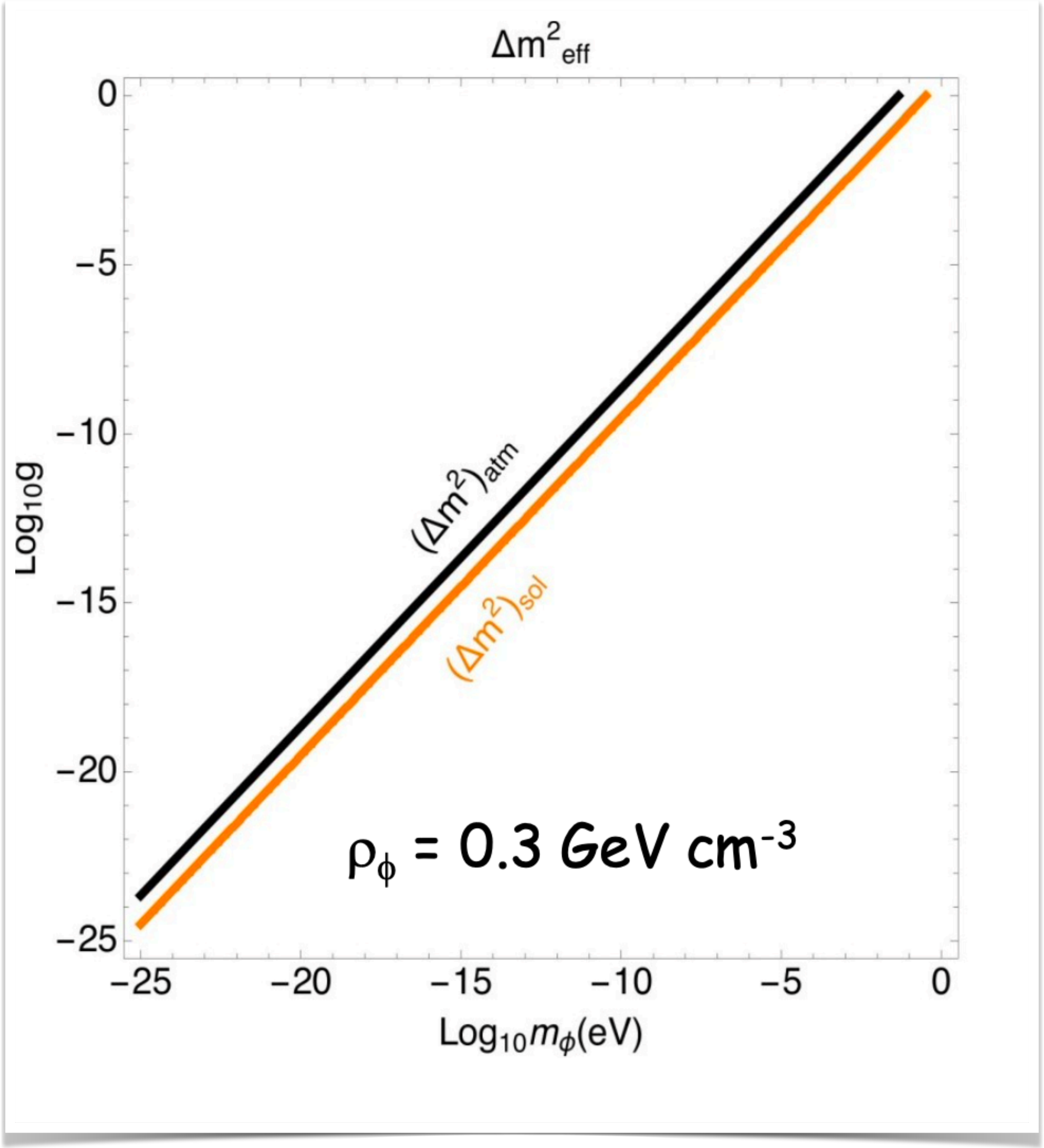
- Need to resum the series of diagrams.
  Can lead to perturbativity violation.

- Leads to additional constraints.



What are the major roadblocks?





Neutrino constraints

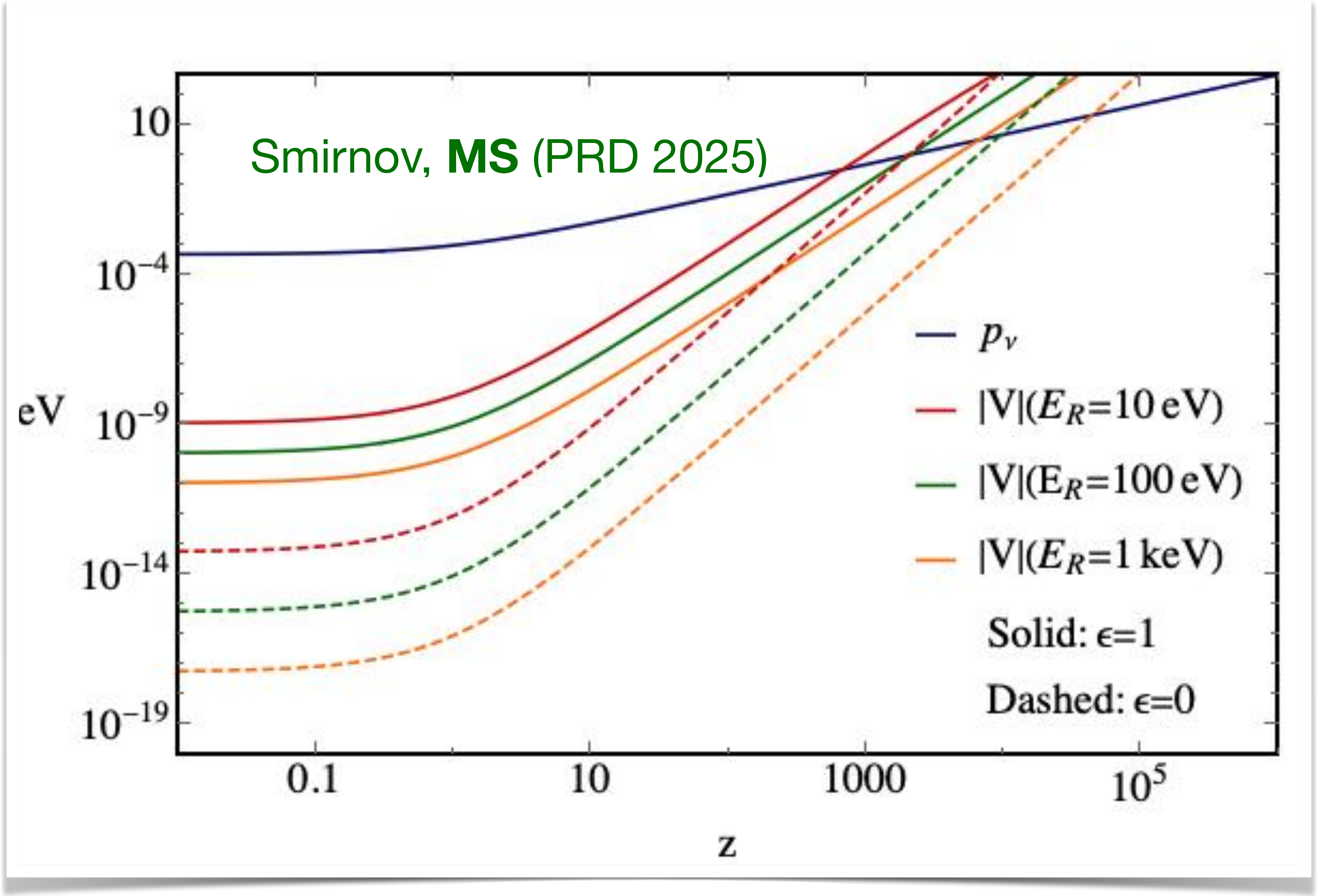
- Δm^2 should not vary with energy for $E > 0.1\,\mathrm{MeV}$. Therefore, E_R cannot be bigger than lowest energy neutrinos observed - solar pp neutrinos $\sim 0.1\,\mathrm{MeV}$.

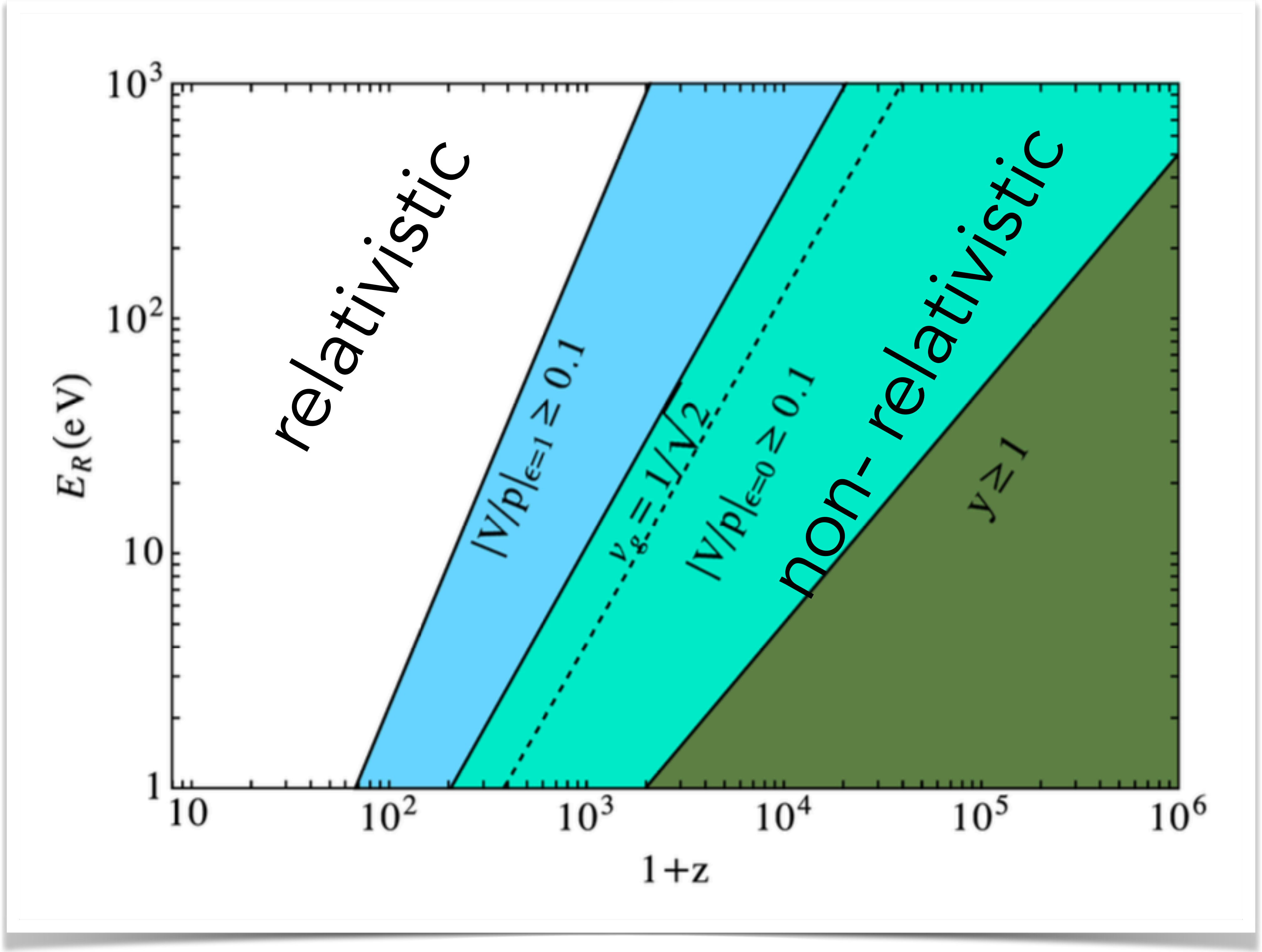
- Astrophysical neutrinos interact with DM, leading to energy loss of the neutrinos and a suppression of their flux. Can be translated to a bound on $\sigma_{\nu\phi}(g, m_\phi, m_\chi)/m_\phi$.

- Consider two sources:
  1. Observation of O(10) MeV neutrinos from SN1987A at roughly 50 kpc.
  2. Observation of O(100) TeV neutrino by IceCube.

- Oscillations of $\nu \to \chi$. Strong constraints from solar neutrinos and BBN.

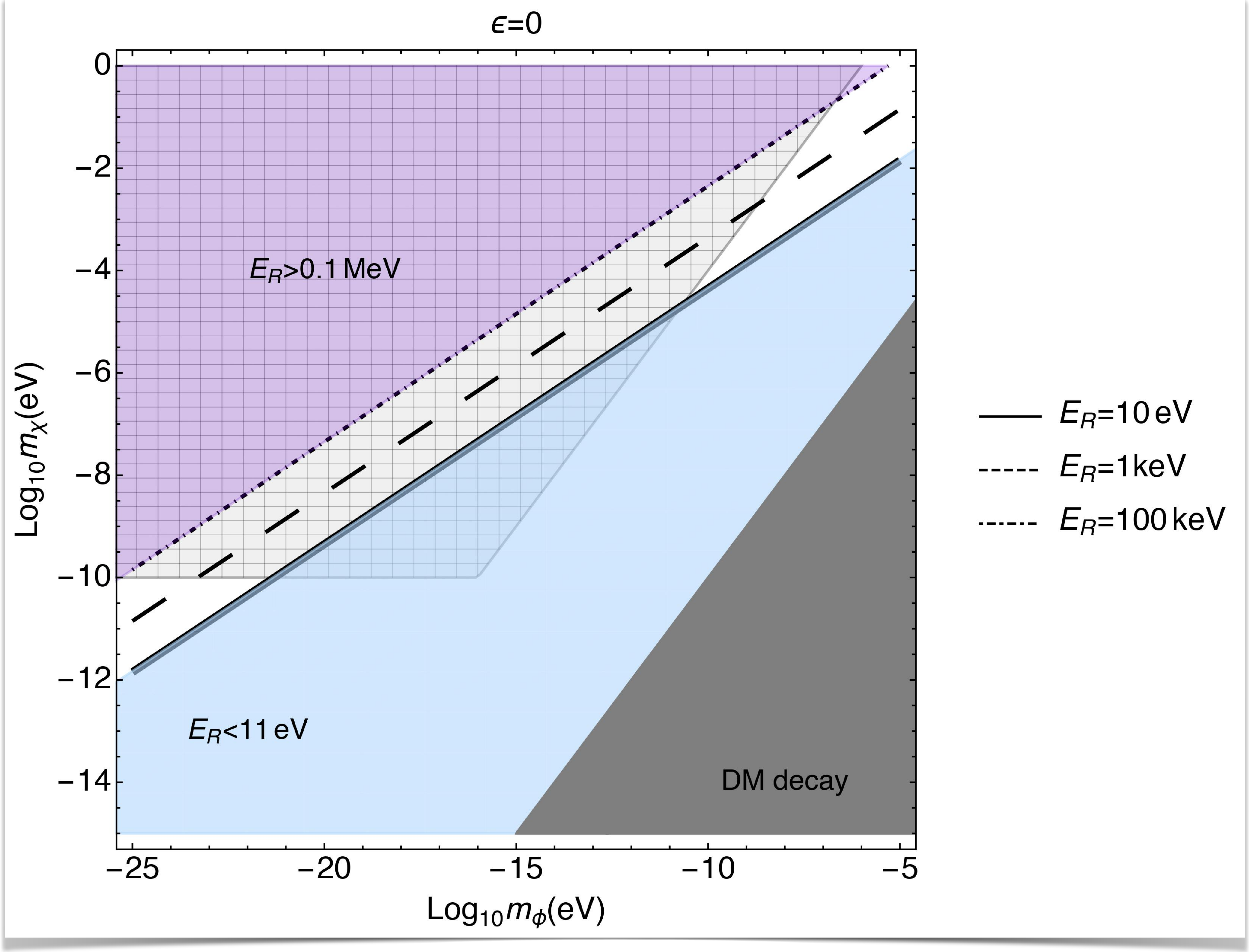
Cosmological probes of neutrino masses

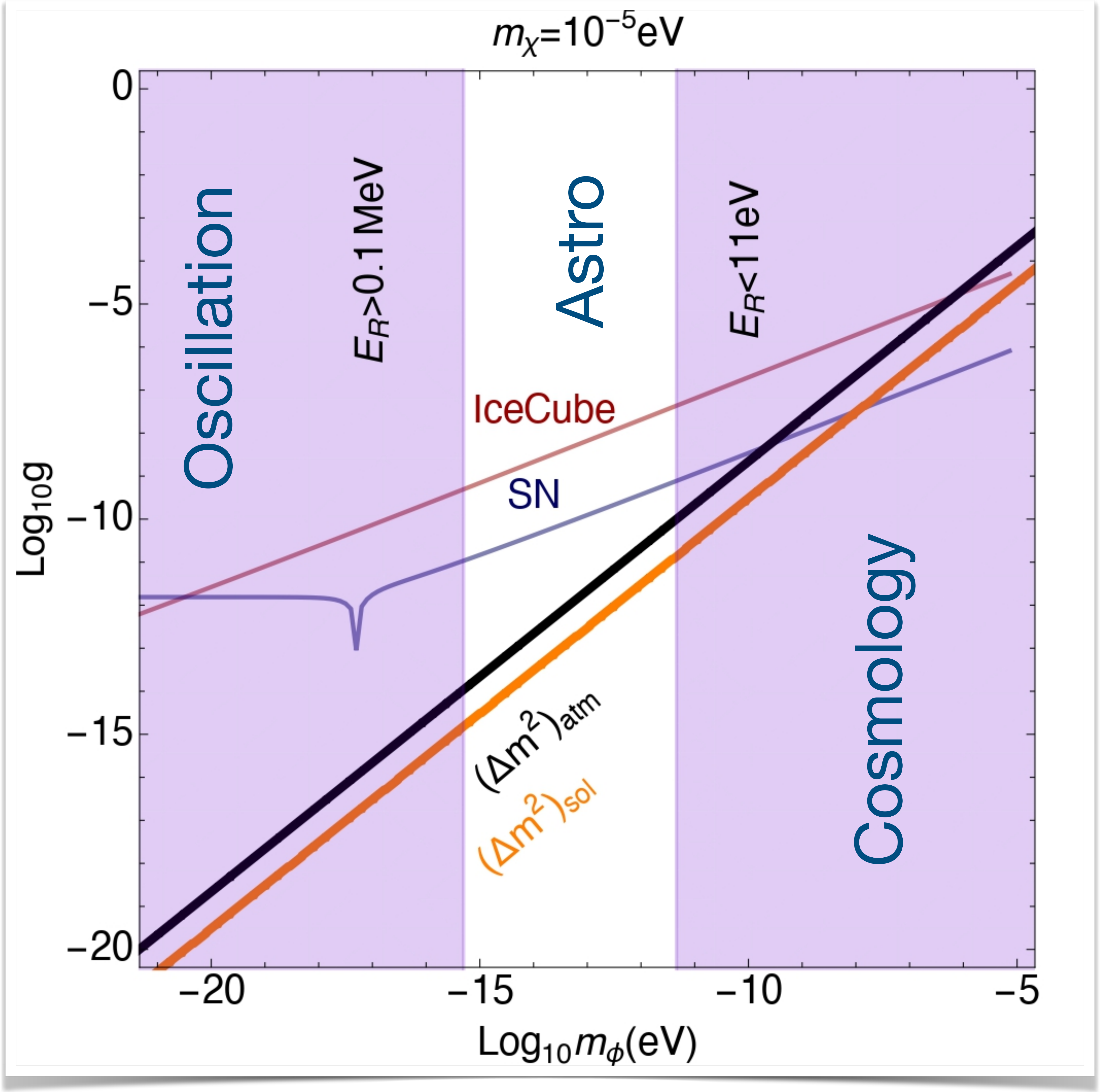




- Dispersion for massless neutrinos: E= p(z) + V(z) and group velocity $v_g = \frac{dE}{dp} = 1 + \frac{dV}{dp}$
- Satisfying constraints on $\sum m_\nu$ requires $E_R > 11\,\mathrm{eV}$.
- Below z=1000, neutrinos effectively massless. Can also resolve the DESI tension!

Different constraints





- Bounds on parameters required for explaining observation.

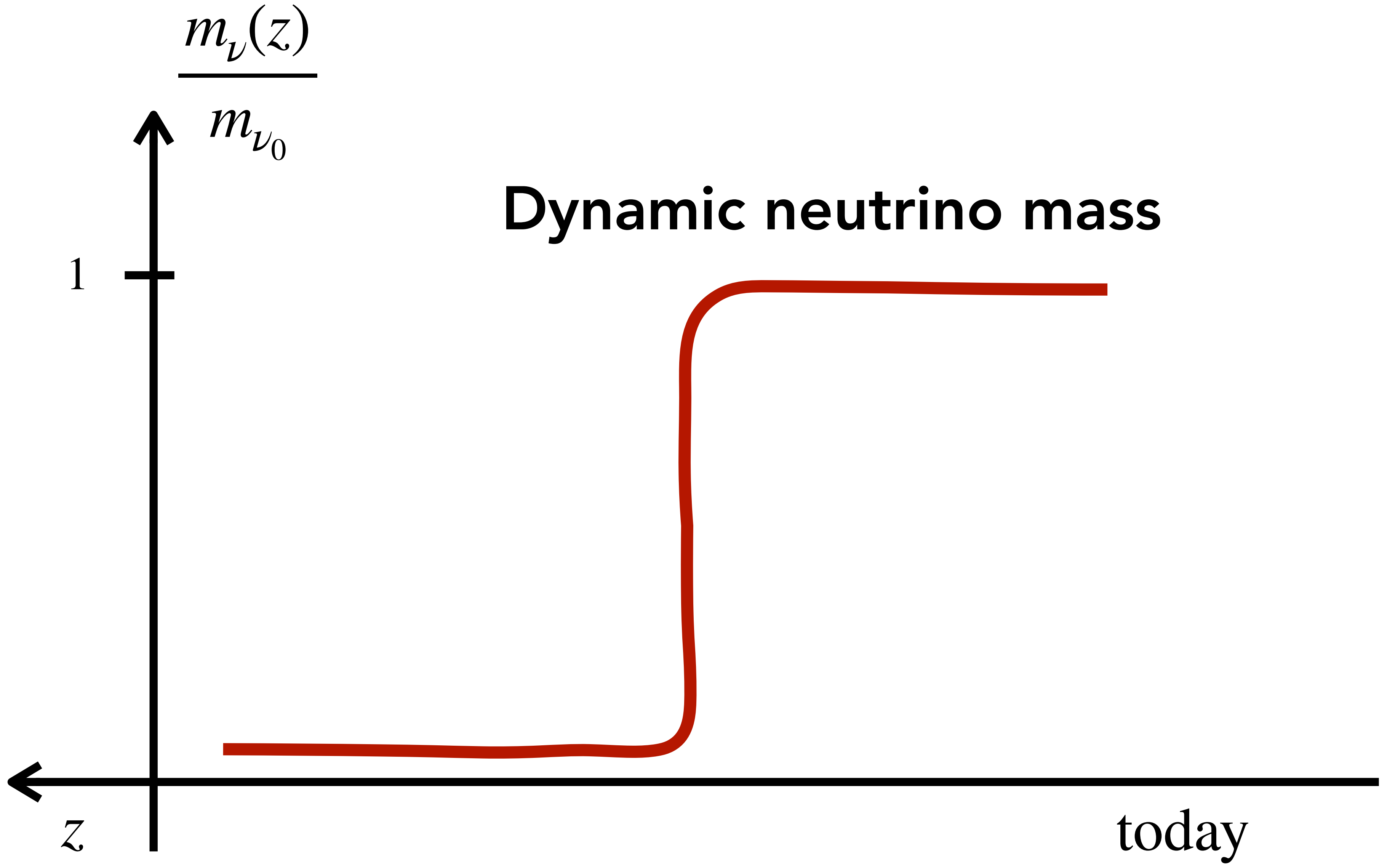
Smirnov, **MS** (JCAP 2024)

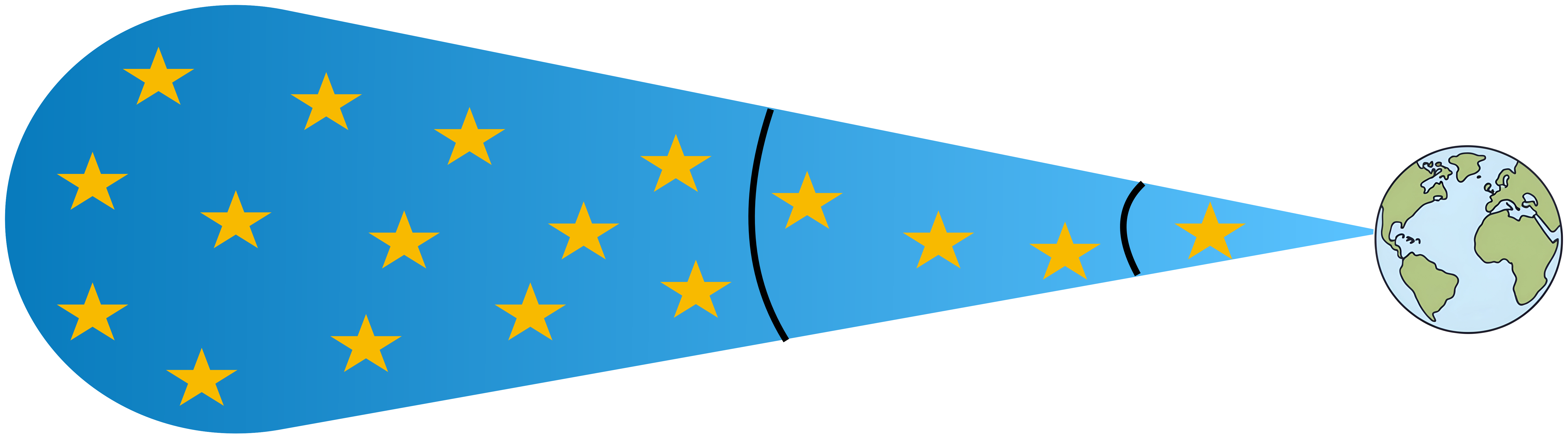
- Additional bounds on ultralight DM.

Dynamic Neutrino Masses - Where?

Redshift dependent neutrino masses

- 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** (PRD 25)

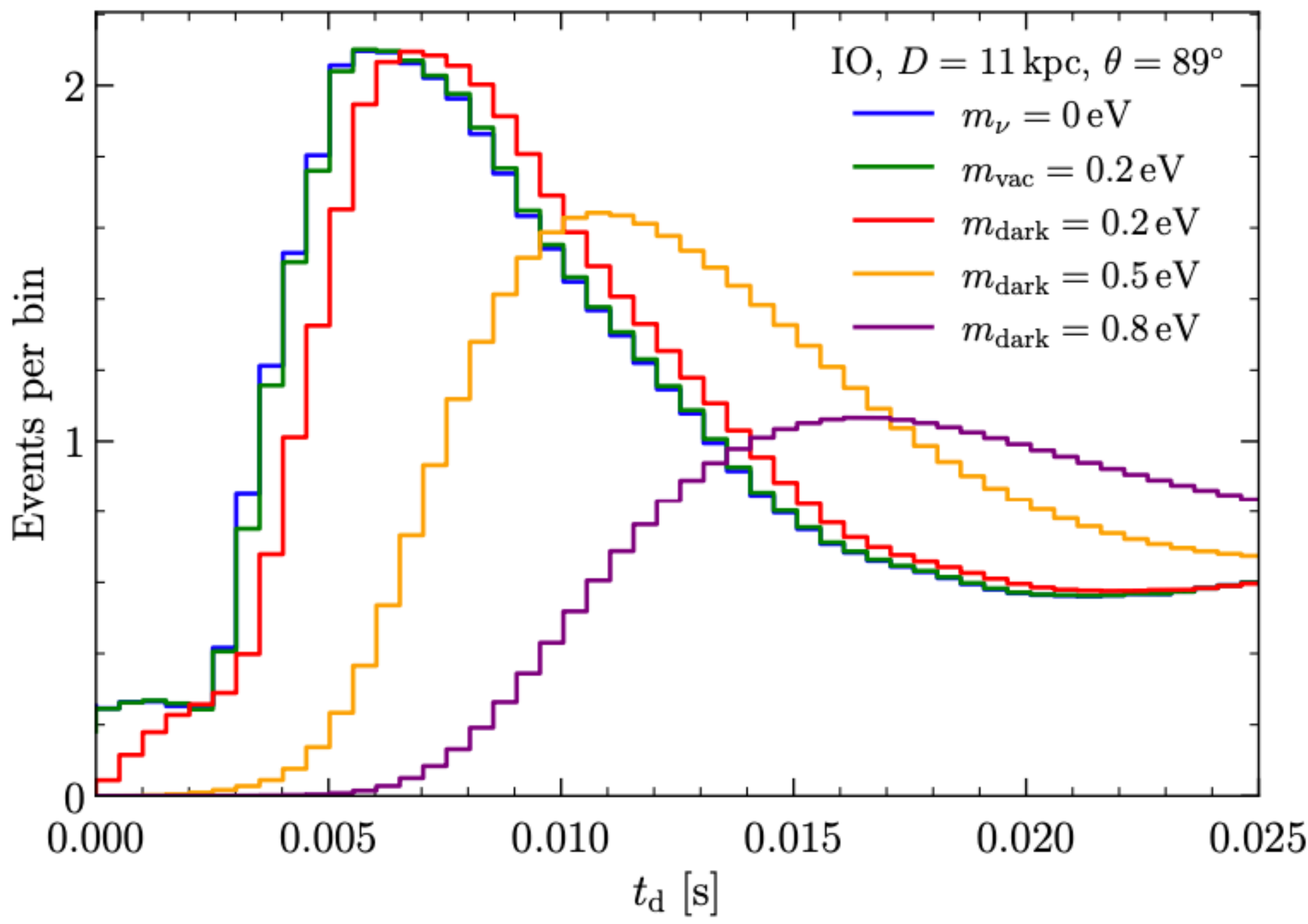
Time of flight delays of neutrinos

- Refractive neutrino mass is dependent on the local DM density $m^2 \propto n_{\mathrm{DM}}$.

- Therefore, it can be different in DM rich/poor regions.

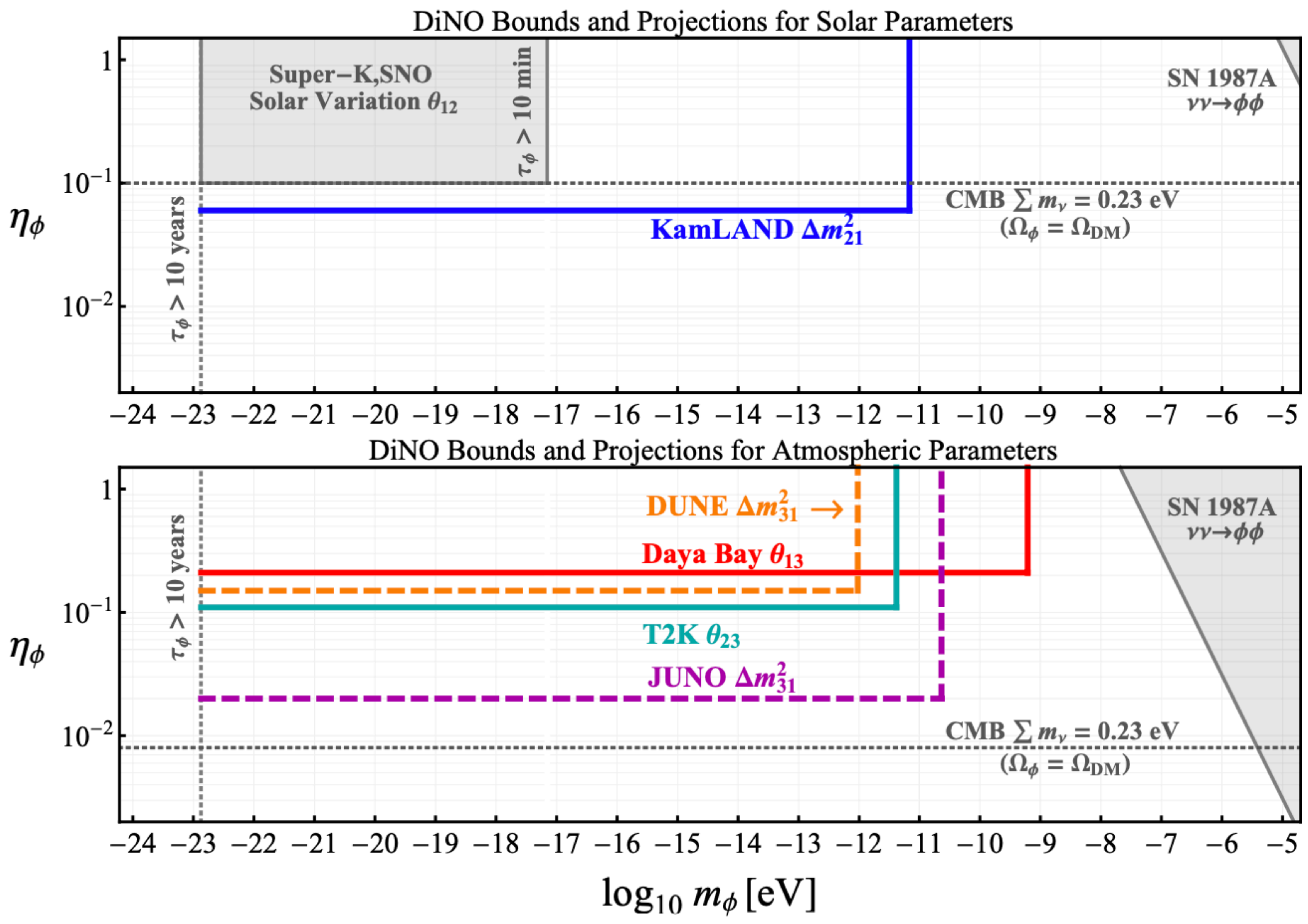
- Look for time-of-flight delay of neutrinos from SNe neutronisation burst.

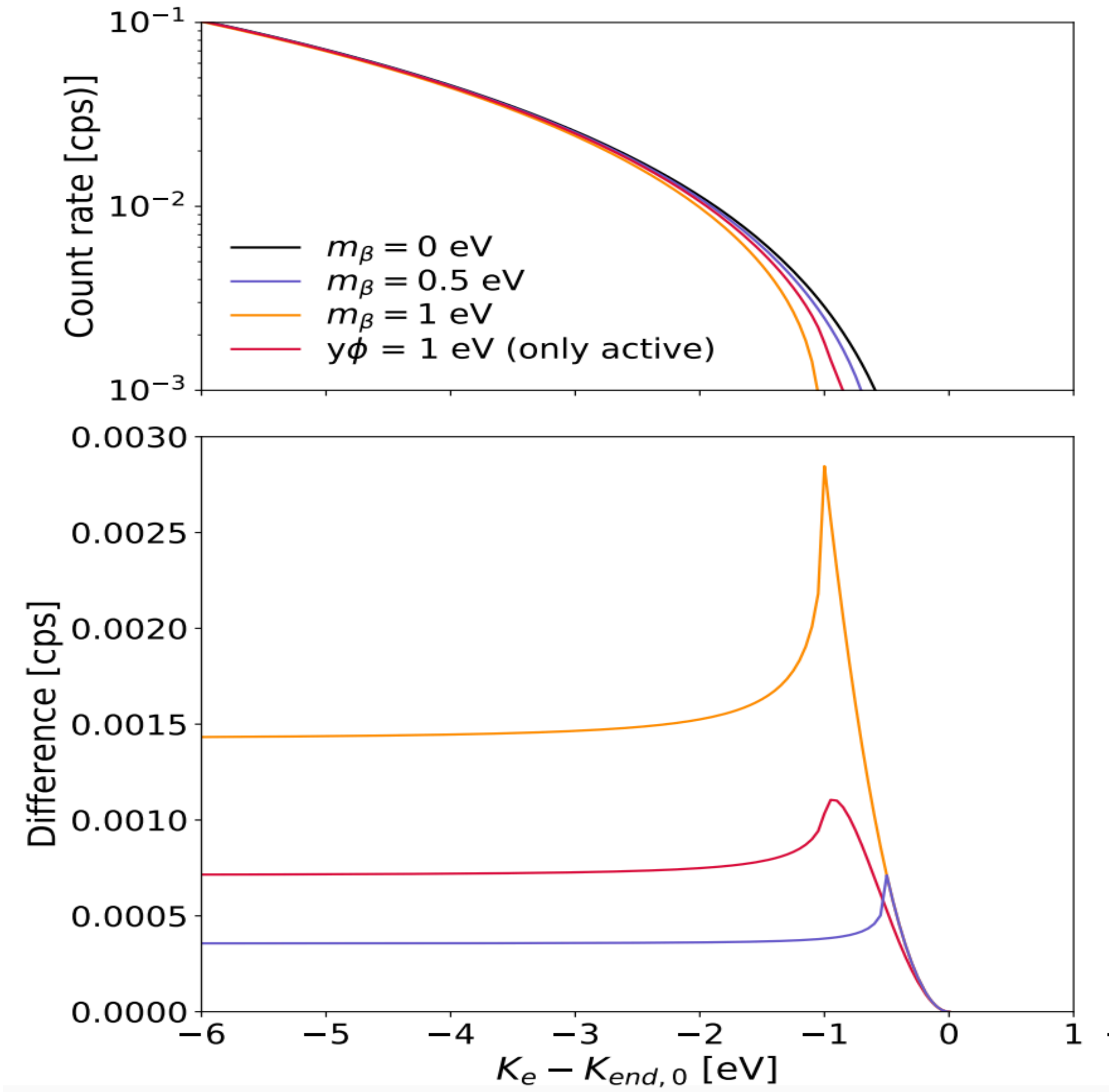
- Results can be sensitive to DM spikes.



Ge, Kong, Smirnov (PRL 2024)
Pompa, **MS** (in prep)

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

Talk by Hong-Yi Zhang

Revisiting Quark-Lepton complementarity

$$\begin{array}{ccccc} \nu_e & \nu_\mu & \nu_\tau & \chi_1 & \chi_2 \end{array}$$

$$\begin{pmatrix} U_{CKM\,3\times3} & U_{\nu\chi\,3\times2} \\ U^{\dagger}_{\nu\chi\,2\times3} & I_{\chi\chi\,2\times2} \end{pmatrix} \xrightarrow[\text{interaction}]{\text{DM-}\nu} \begin{pmatrix} U_{PMNS} & U'_{\nu\chi} \\ U'_{\nu\chi} & I_{\chi\chi} \end{pmatrix}$$

- We can postulate that neutrinos have a tiny non-zero mass in vacuum and a mixing consistent with the CKM mixing.
- Interaction with DM provides a "matter effect" and rotates the mixing angle to the observed PMNS mixing. Generates a "dark" PMNS.

Perez-Gonzalez, Chattopadhyay , **MS** (in prep)

Final thoughts

- Neutrinos present a definite clue of existence of non-standard physics.

- The origin of neutrino mass holds the key to this unexplored chamber of secrets.

- Neutrino oscillation results can be explained by interactions of massless neutrinos with ultralight dark matter through a light fermionic mediator. Need at least 2 mediators.

- Refraction gives energy dependent mass at low energies, and allows to avoid the cosmological bound on sum of neutrino masses from structure formation. Viable parameter space from observations.

- Might give us a clue about the nature of dark matter - another unanswered avenue in the Standard Model.

Thank you!

BACKUP

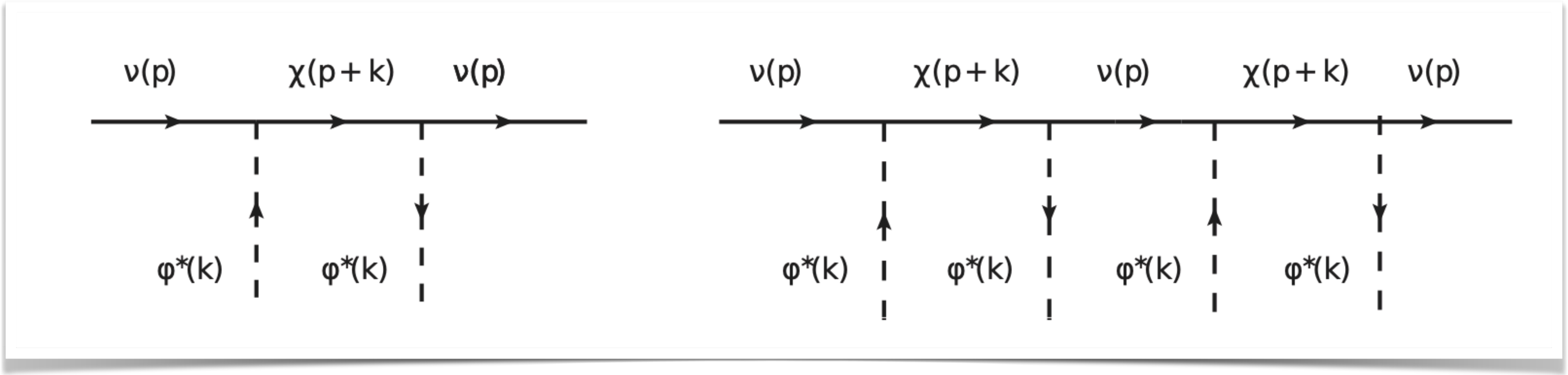
Caution 1: Perturbativity and resummation

Some back-of-the-envelope estimates:

- de-Broglie wavelength $\lambda_{dB} = \frac{1}{m_\phi v_{\rm vir}} = 4 \cdot 10^7\,{\rm cm}\left(\frac{5 \cdot 10^{-10}\,{\rm eV}}{m_\phi}\right).$
- Number density $n_\phi = \frac{\rho_\phi}{m_\phi} = 6 \cdot 10^{17}\,{\rm cm}^{-3}\left(\frac{5 \cdot 10^{-10}\,{\rm eV}}{m_\phi}\right).$
- Distance between scatteres: $d \simeq n_\phi^{-1/3} = 1.2 \cdot 10^{-6}\,{\rm cm}\left(\frac{m_\phi}{5 \cdot 10^{-10}\,{\rm eV}}\right)^{1/3}.$
- Radius of interaction: $r_\chi = \frac{1}{m_\chi} = 6 \cdot 10^{-4}\,{\rm cm}\left(\frac{0.03\,{\rm eV}}{m_\chi}\right)$

$$\lambda_{dB} \gg r_\chi \gg d$$

Caution 1: Perturbativity and resummation



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

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

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

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

ULDM as classical field

- System of ϕ with large occupation number can condense to a classical field.
- 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}.

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

ULDM as classical field

- The Lagrangian $\mathscr{L} \supset g_{\alpha k}\, \phi_c^*\, \bar{\nu}_{\alpha L}\, \chi_{kR}$ contributes to neutrino mass.

- The mass matrix in the basis $(\nu_f, \chi_L) = (\nu_e, \nu_\mu, \nu_\tau, \chi_1, \chi_2)$ is

$$\mathbf{M} = \begin{bmatrix} 0 & g_{\alpha k}\phi_c^{\text{tot}\,\dagger} \\ g_{\alpha k}\phi_c^{\text{tot}\,\dagger} & \text{diag}(m_{\chi k}) \end{bmatrix}, \quad \alpha = e, \mu, \tau, \quad k = 1{,}2.$$

- The Hamiltonian

$$\mathbf{H} \approx \frac{1}{2E}\mathbf{M}\mathbf{M}^\dagger = \frac{1}{2E}\begin{bmatrix} \bar{F}^2 \sum_k g_{\alpha k} g_{\beta k}^* & g_{\alpha k}\bar{F} m_{\chi k} e^{-i\bar{\Phi}} \\ g_{\alpha k}^* \bar{F}^* m_{\chi k} e^{i\bar{\Phi}} & \bar{M}_\chi^2 \end{bmatrix}$$

- 3X3 block of active neutrinos has the same form as m_{asy}^2.

ULDM as classical field

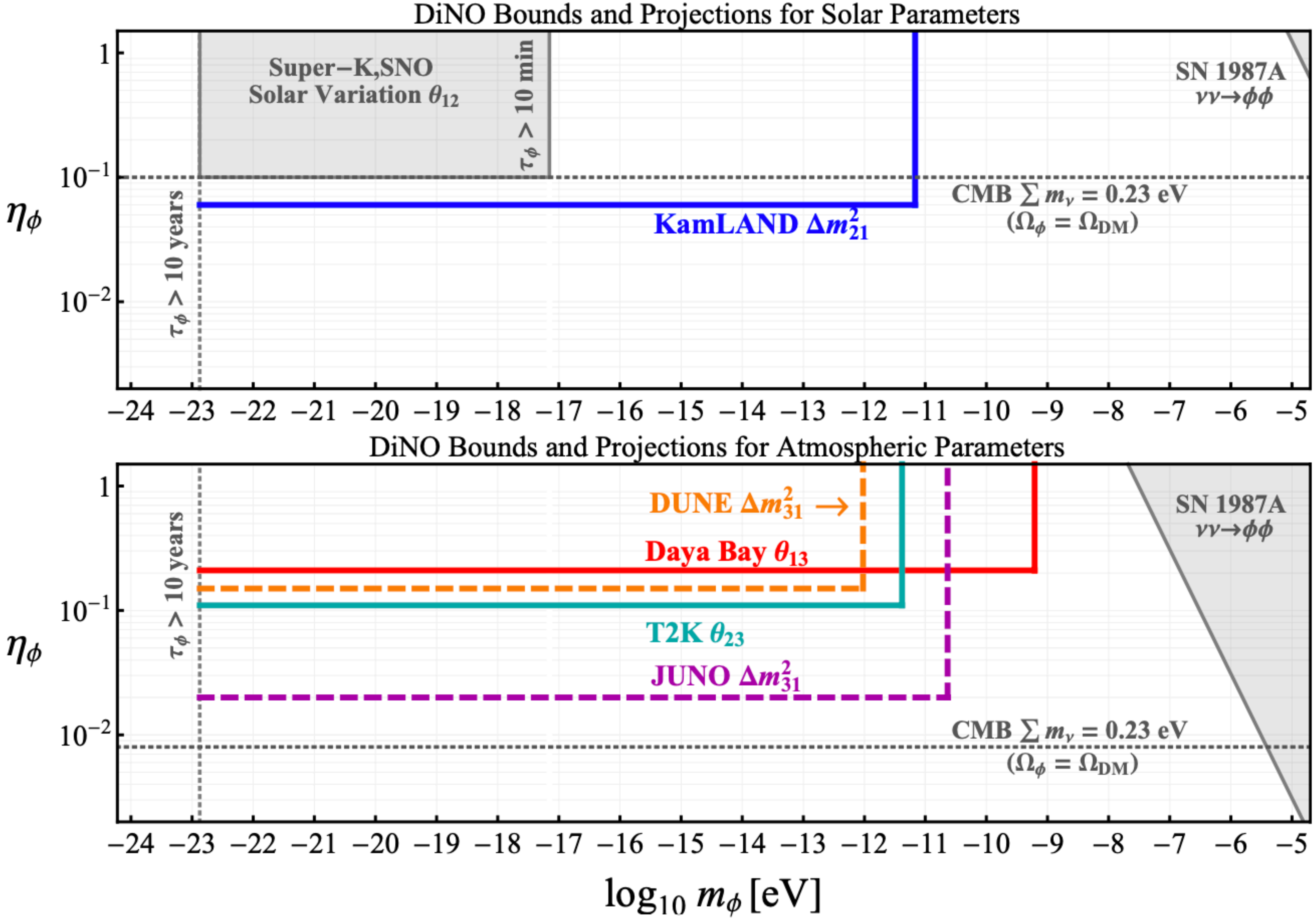
- We get an addditional time dependence due to $F(x,t)$. For a real field,
  $$|F(x,t)|^2 = \frac{\rho_\phi}{m_\phi^2}\cos^2(m_\phi t)$$
- Resonance can arise due to periodic time dependence of F.

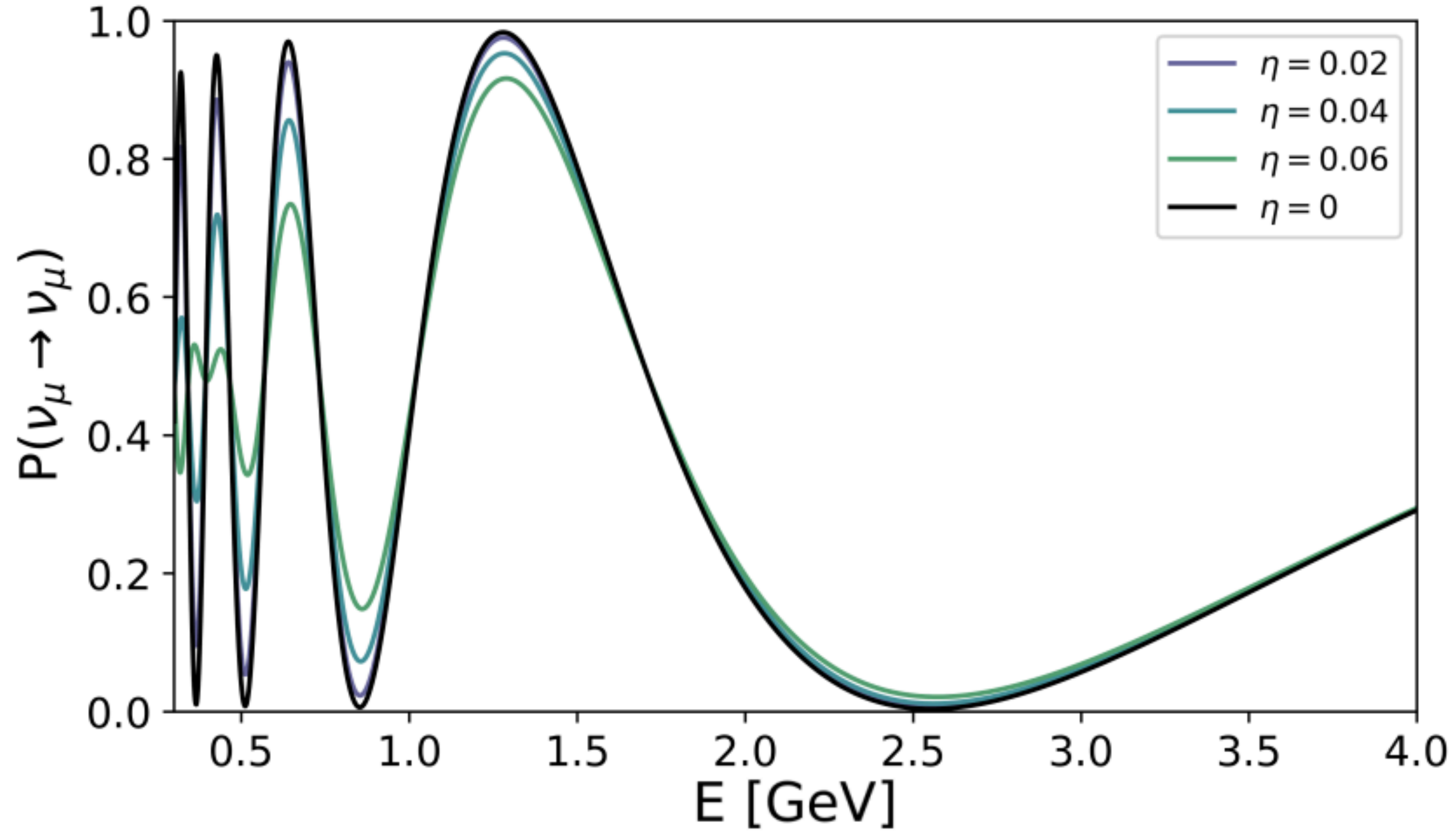
- After a TBM rotation,
  - one massless state decouples.
  - other 4 states evolve as two pairs independently with
  $$\mathbf{M}_{a1} = \begin{bmatrix} 0 & m_{ak}e^{-i\bar{\Phi}} \\ m_{ak}e^{-i\bar{\Phi}} & m_{\chi k} \end{bmatrix}$$

- Bounds from $\nu - \chi$ oscillations. Can be avoided with small δm^2 or small mixings.

- Require this component to be sub-dominant.

Oscillation constraints





Krnjaic, Machado, Necib (PRD 2018),