# TESTING NEUTRINO NON-STANDARD PROPERTIES


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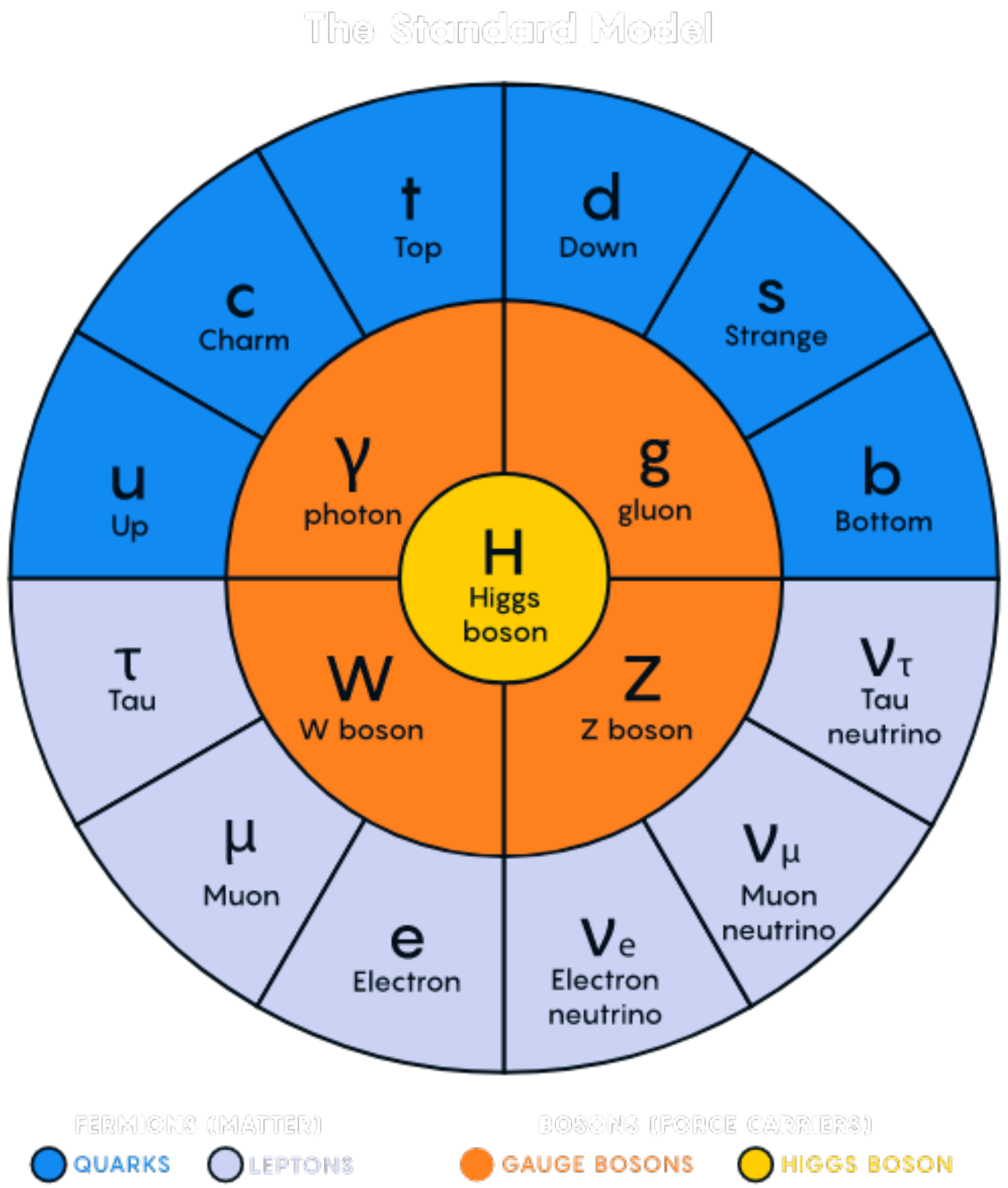
MPIK, Heidelberg


Neutrino Oscillation Workshop

04.09.24


MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

# Sensitive to new physics

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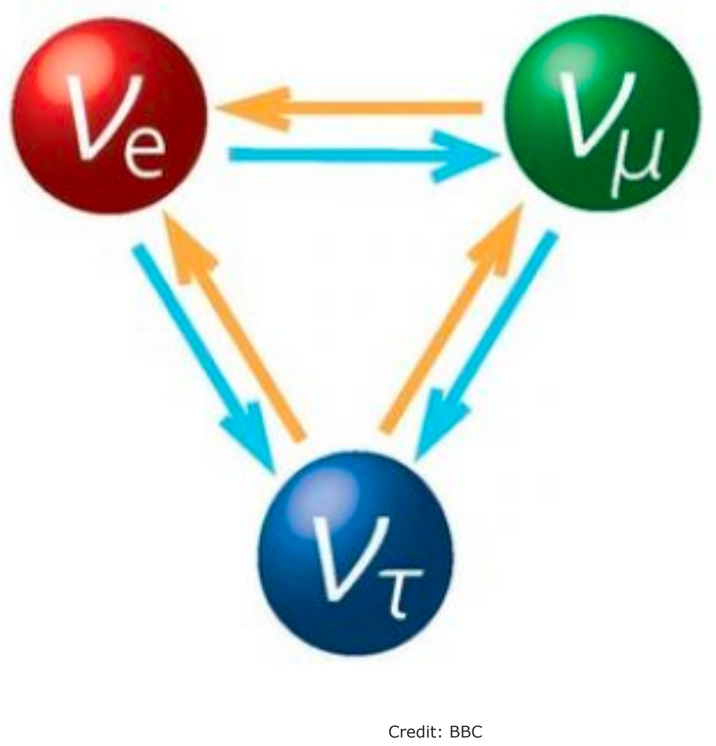
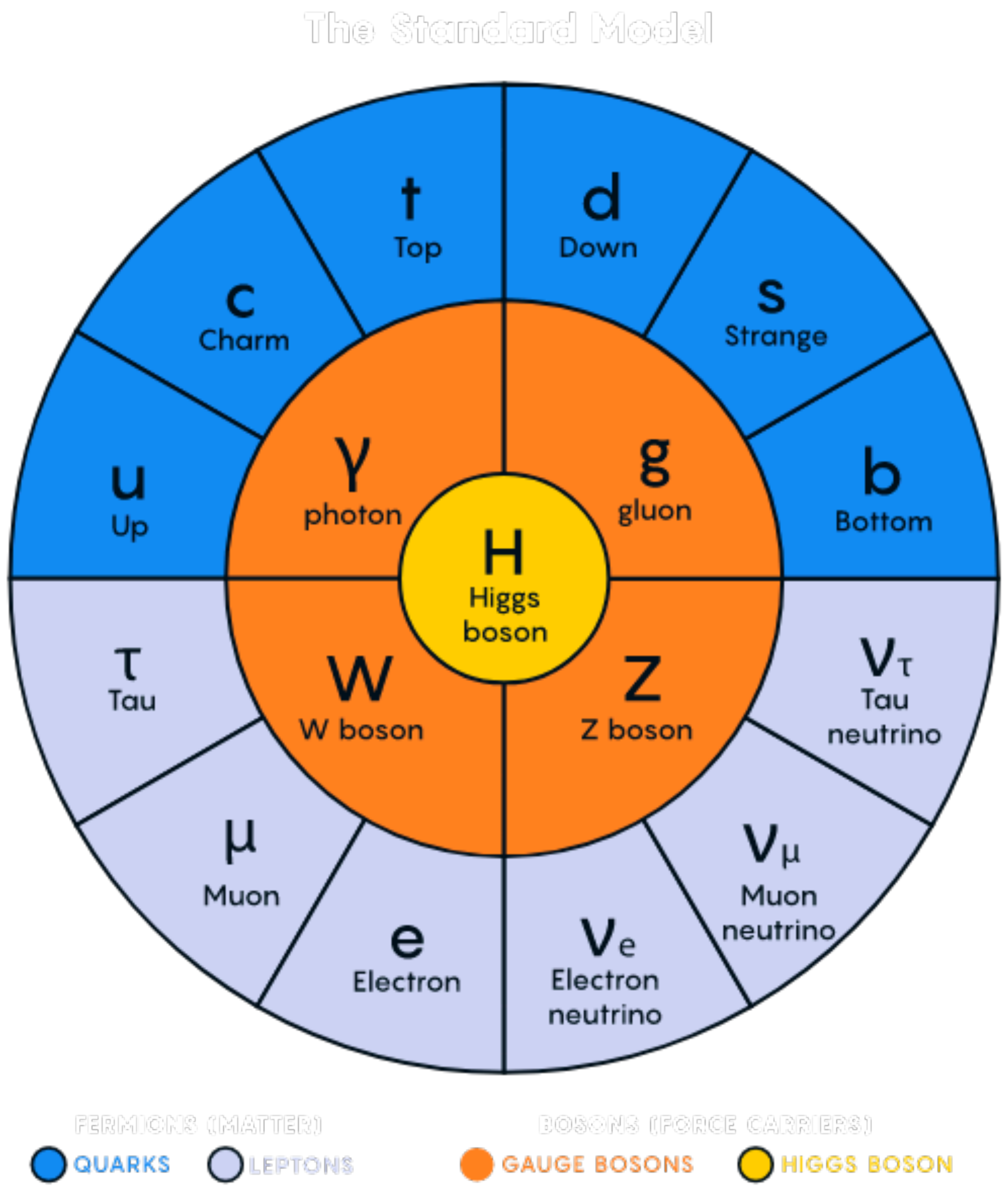
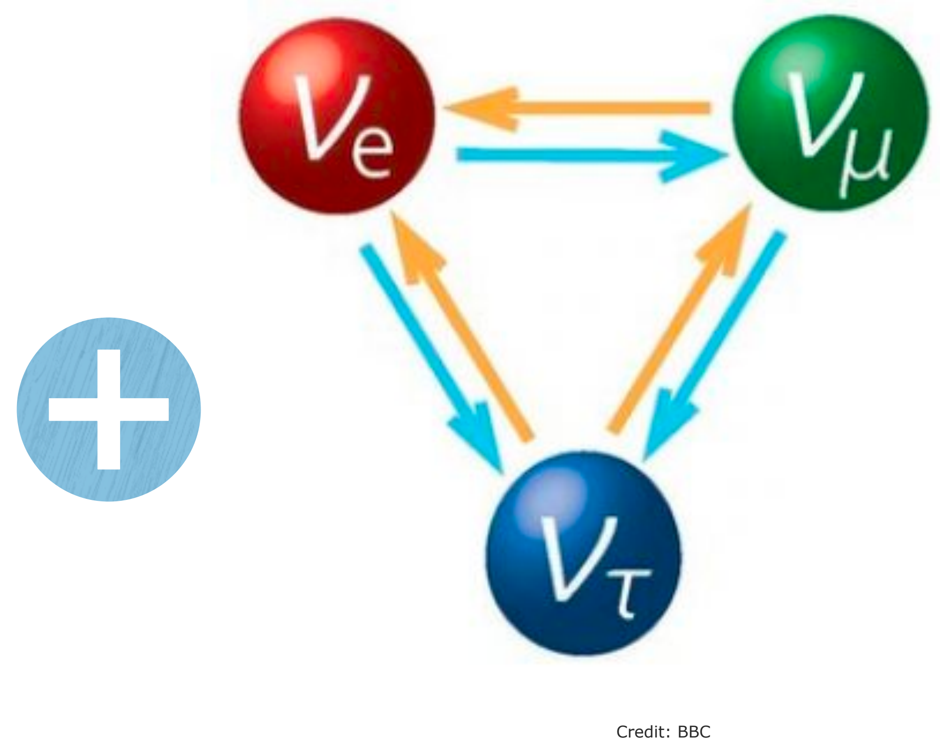
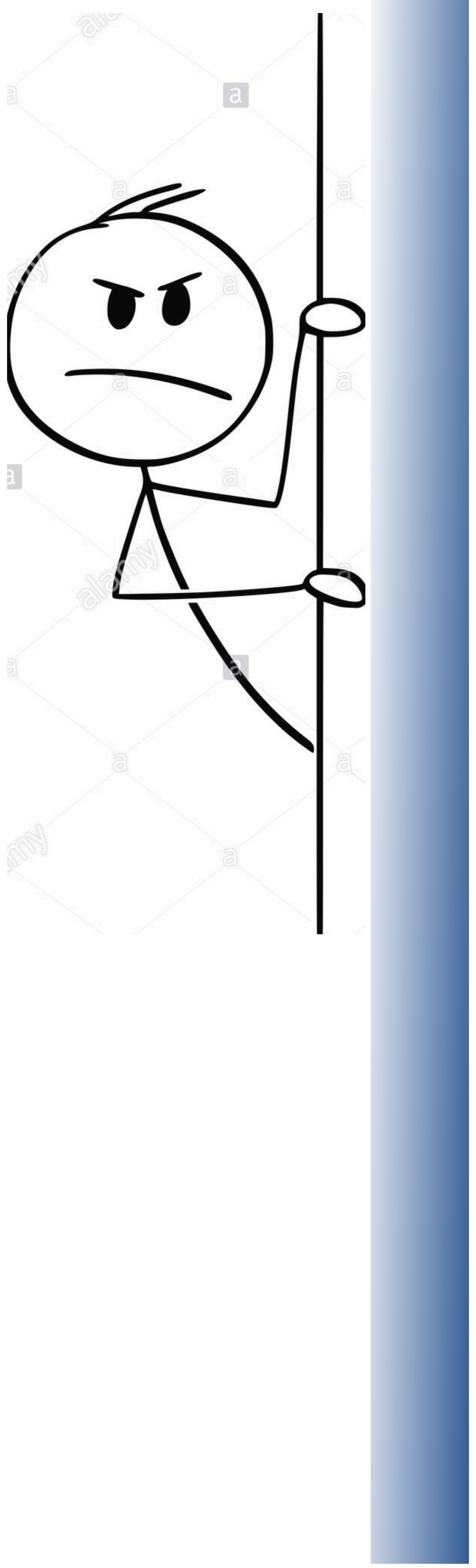



The Standard Model

# Sensitive to new physics



Beyond

The Standard Model

# How can new physics affect neutrinos?

A brief list of non-standard neutrino physics:

Mass and Mixing, Decay,

Dirac or Majorana nature (L-violation),

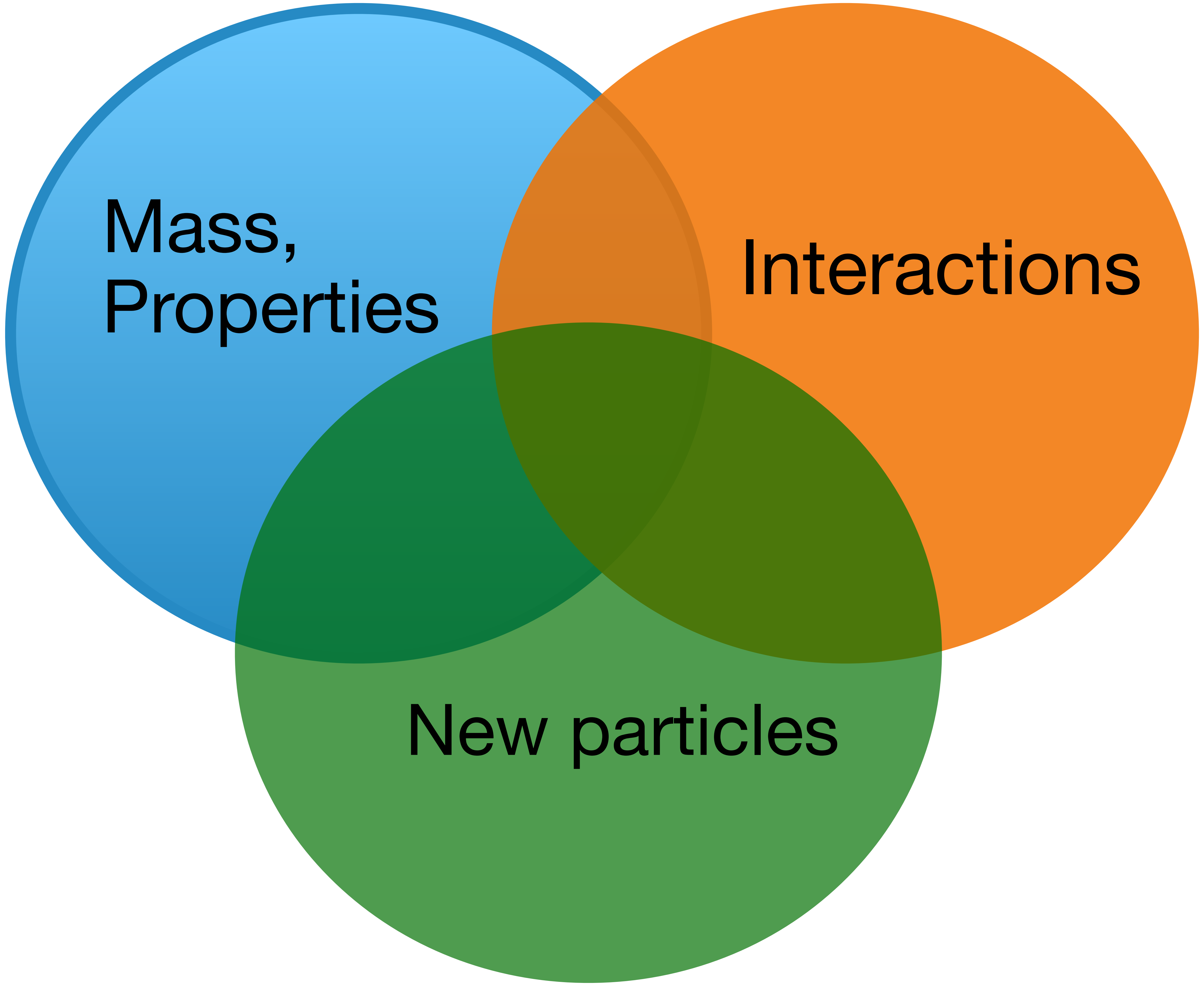
Sterile Neutrinos,

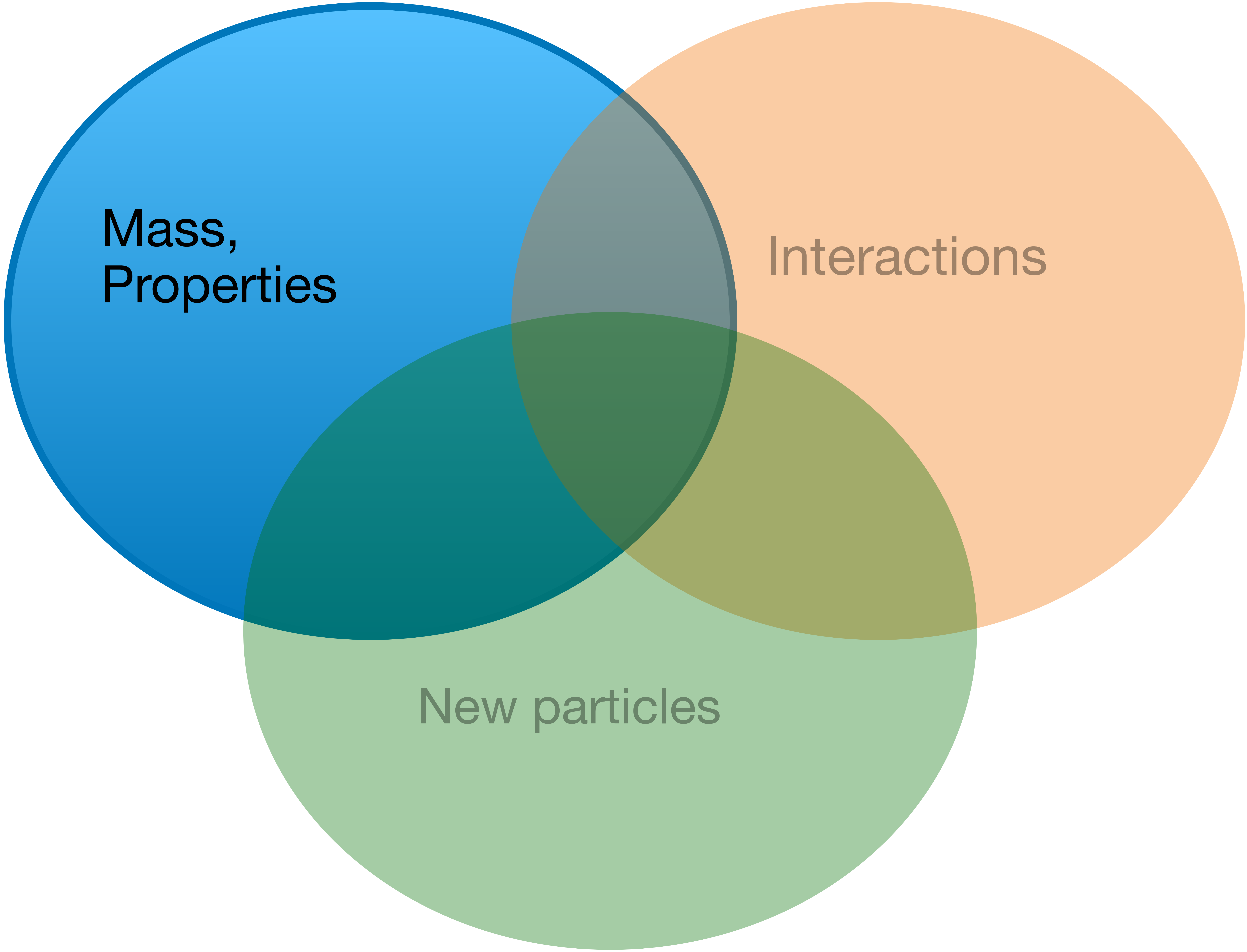
Non-SM interactions,

Electromagnetic properties, CPT-properties and Lorenz invariance,

Quantum Decoherence,

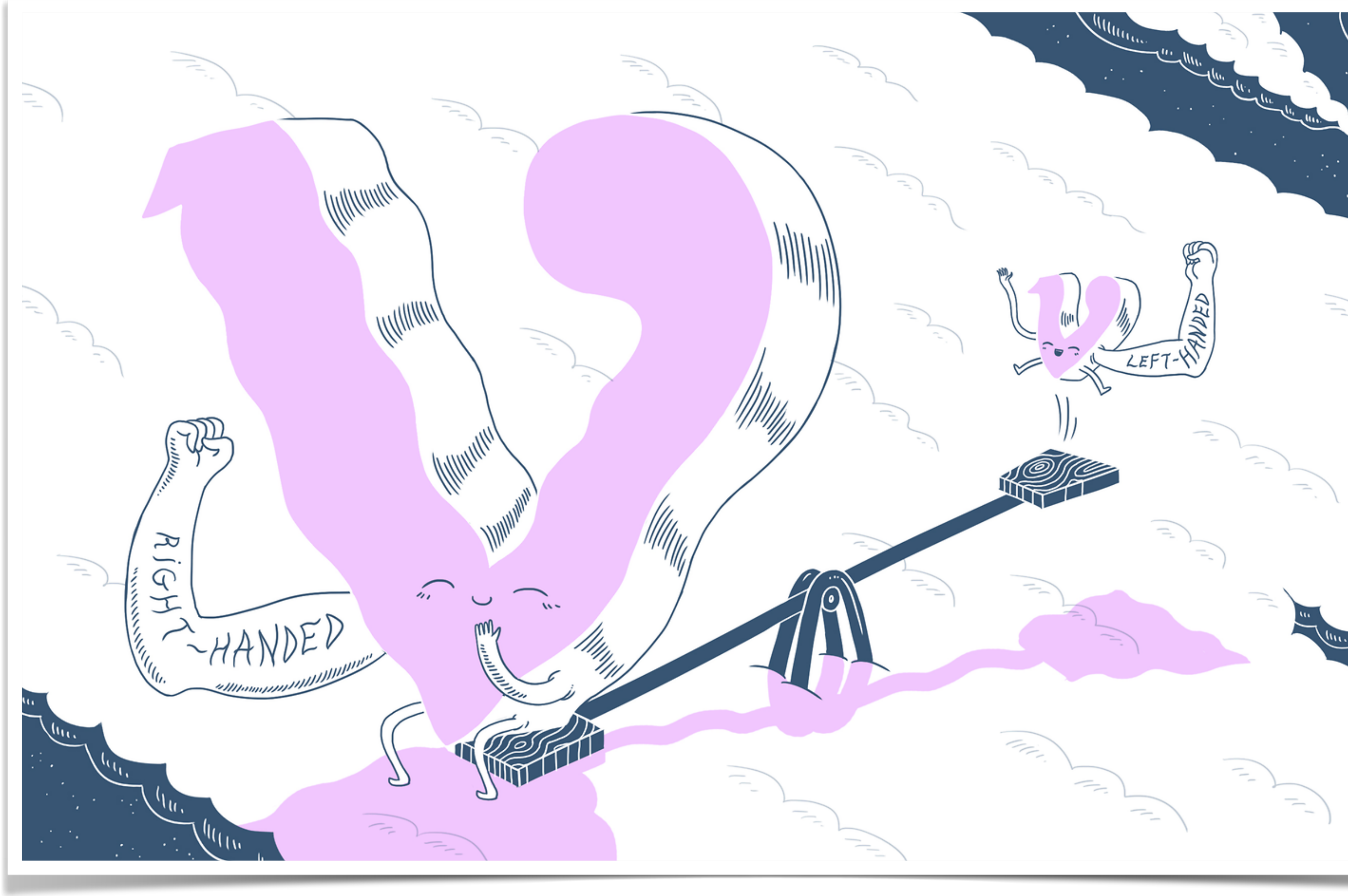
.......




Mass,
Properties
Interactions
New particles

# Origin of neutrino mass

- Neutrino mass can be of Dirac type - no lepton number violation.
- Majorana neutrinos-lepton number violated.
  Generate the Weinberg operator at dim=5:
  $\mathscr{L} \supset y\,(LH)^2/\Lambda$ .
- Seesaw mechanism - introduce SM singlet neutrinos N.




$$\mathscr{L} = m_D\,\nu N + m_N\,NN$$

- 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.

Talk by E. Fernandez-Martinez

- Other sources?

# Dark origin of neutrino mass

$\nu_i$

$\nu_i$

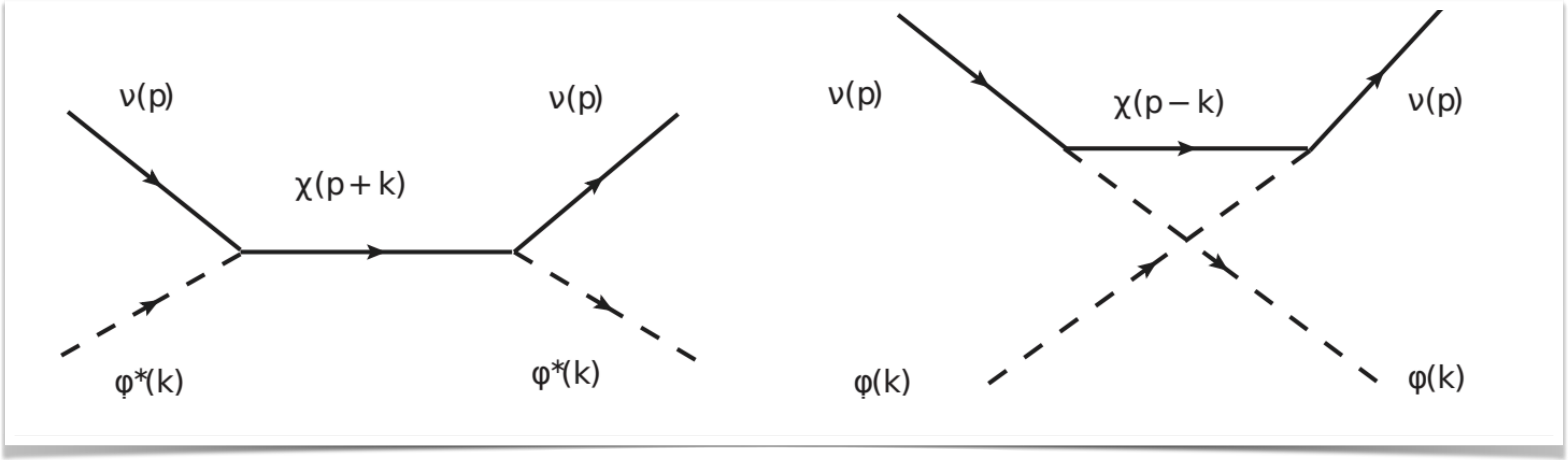
# The basic observation

- How do we know that the vacuum neutrino mass is behind neutrino oscillations?
- Oscillation experiments probe mass-squared $H \sim \sqrt{p^2 + |m|^2} \approx p + \frac{|m|^2}{2E}$
- Any contribution to the Hamiltonian of evolution with a $\frac{\text{const}}{E}$ form can reproduce oscillation data. A forward scattering potential?
- Wolfenstein's potential in the SM also has an energy dependence above the mediator masses.
- Therefore, we need a light mediator.

# A model of dark neutrino mass

- Consider massless neutrinos scattering off ultralight scalar DM $\phi$ through a fermionic mediator $\chi$.

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




The effective potential

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

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

# The refractive mass

- Define the refractive mass $\tilde{m}^2_{\alpha\beta} \equiv 2EV_{\alpha\beta}$

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

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

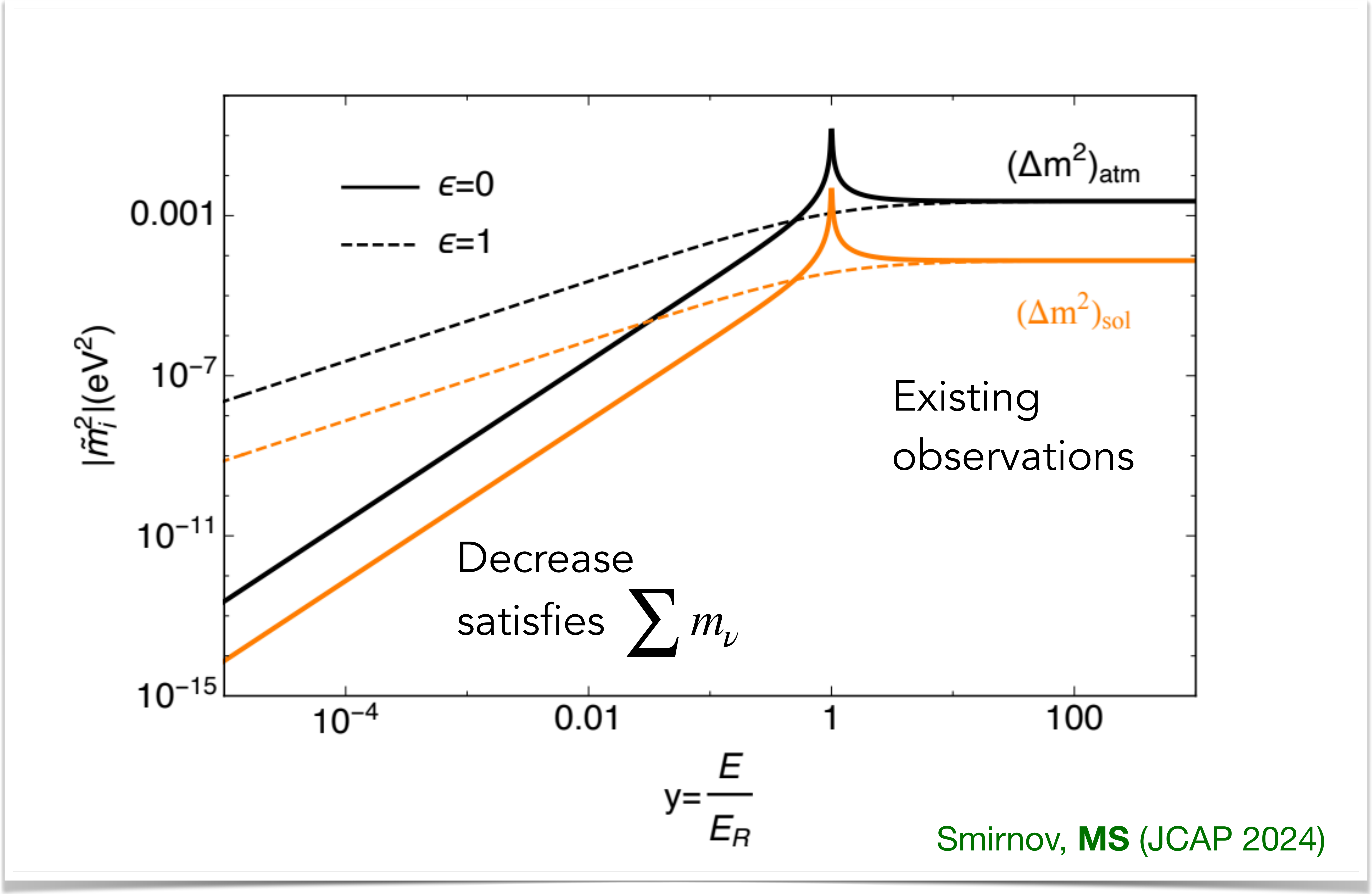
where $\epsilon \equiv \dfrac{n_\phi - \bar{n}_\phi}{n_\phi + \bar{n}_\phi}, \quad (\epsilon = -1 \div 1),$

- Neglecting $\Gamma_{\chi k}$, we can write this as

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

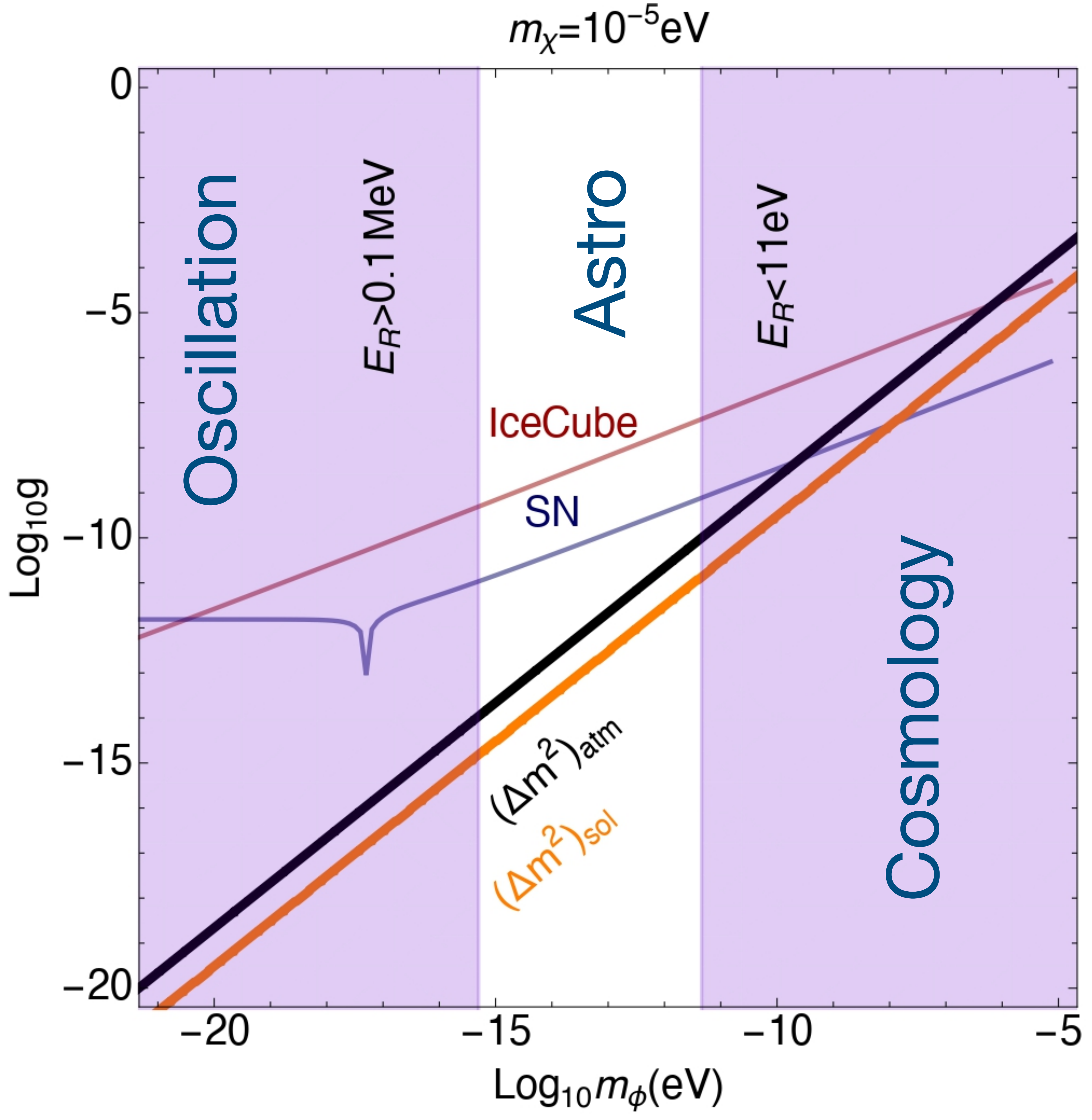
# Fitting the neutrino oscillation data

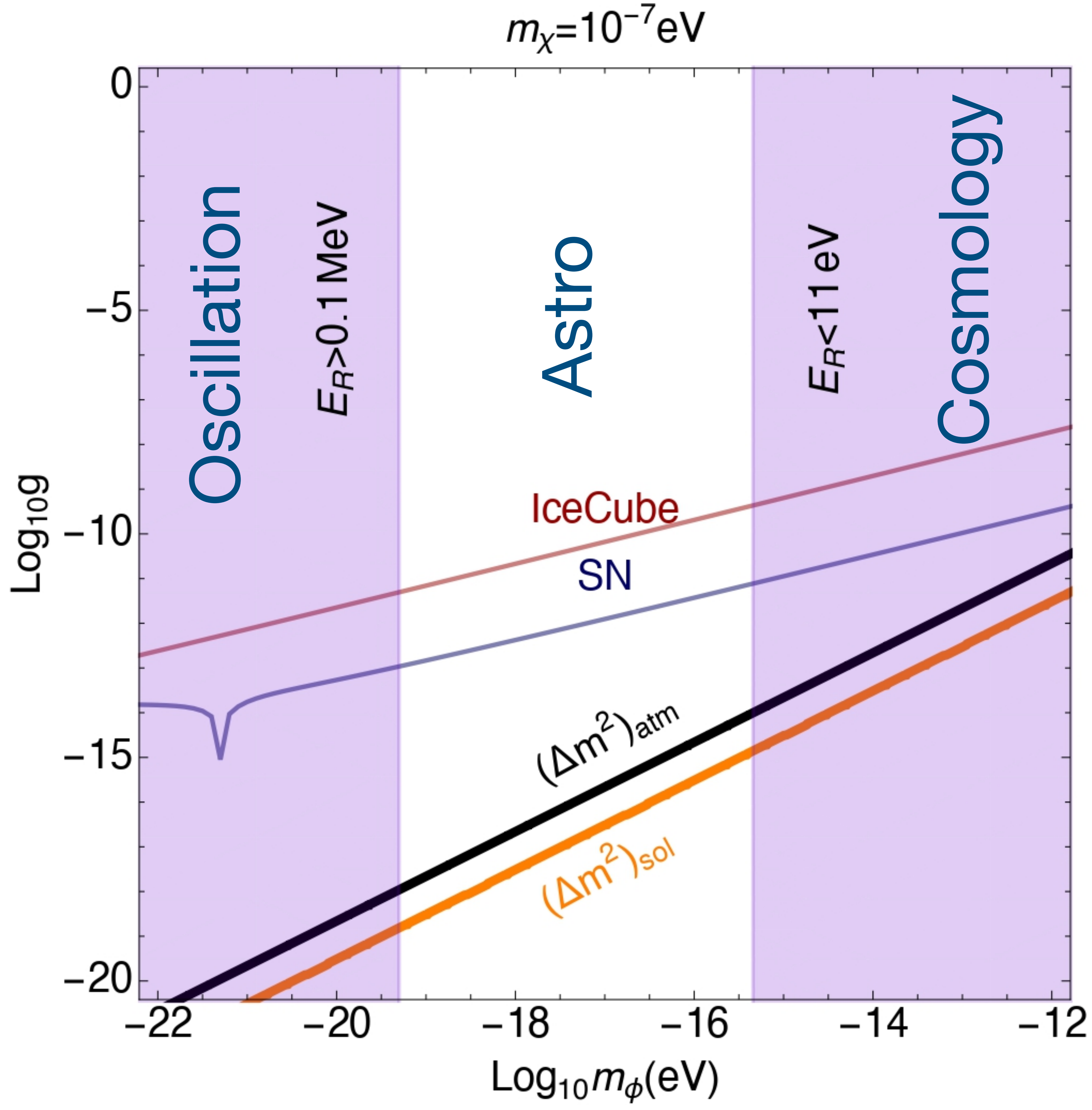
$$\tilde{m}^2 = \tilde{m}^2_{asy} \frac{y(y-\epsilon)}{y^2-1}$$




- $\Delta m^2$ does not vary with energy for $E > 0.1\,\mathrm{MeV}$
- $E_R$ cannot be bigger than lowest energy neutrinos observed - pp neutrinos from the Sun $\sim 0.1\,\mathrm{MeV}$.
- $m^2_{asy} \propto n_\phi$, hence it redshifts and grows. Need to satisy bounds on $\sum m_\nu$.

# Different constraints



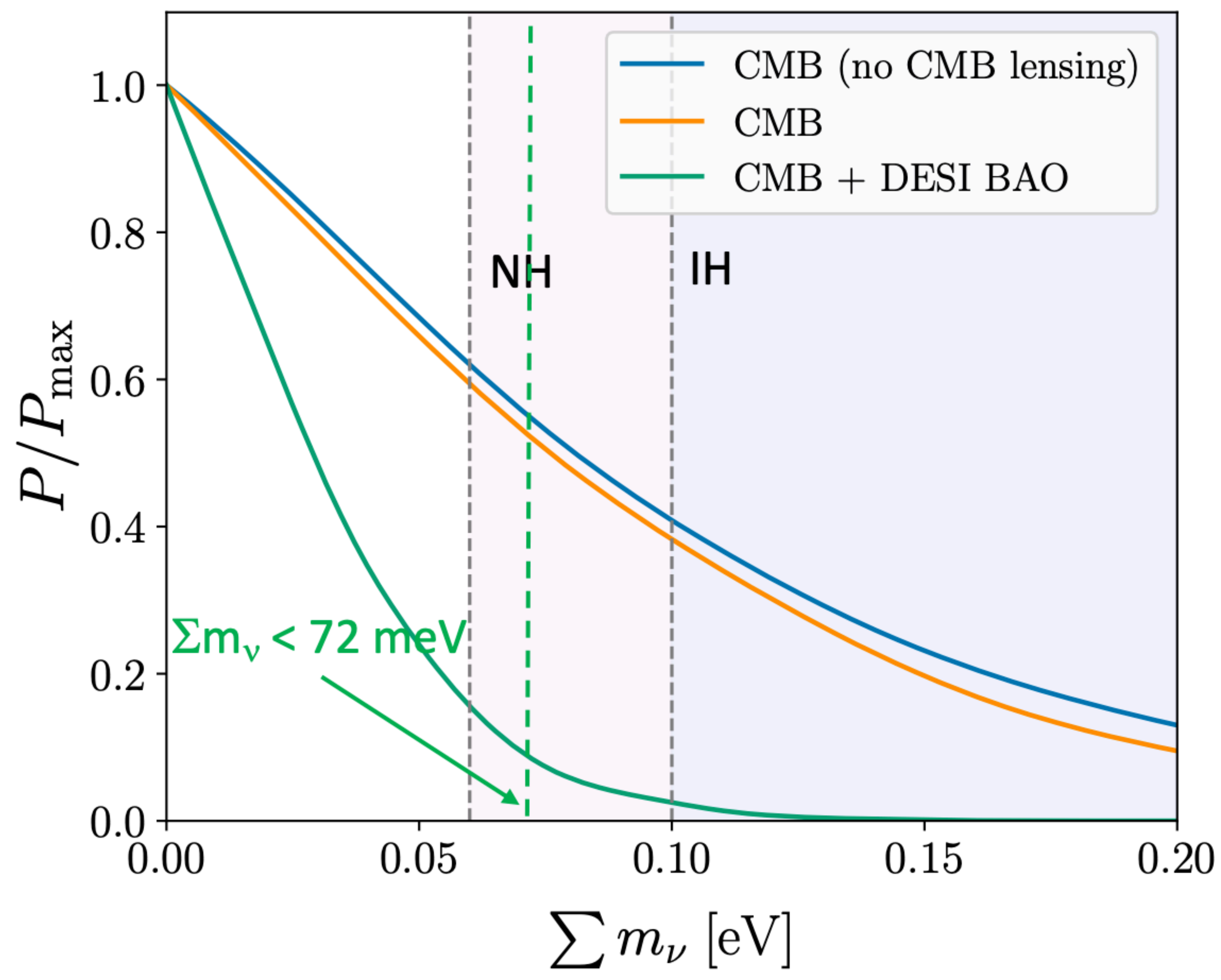




Smirnov, **MS** (JCAP 2024)

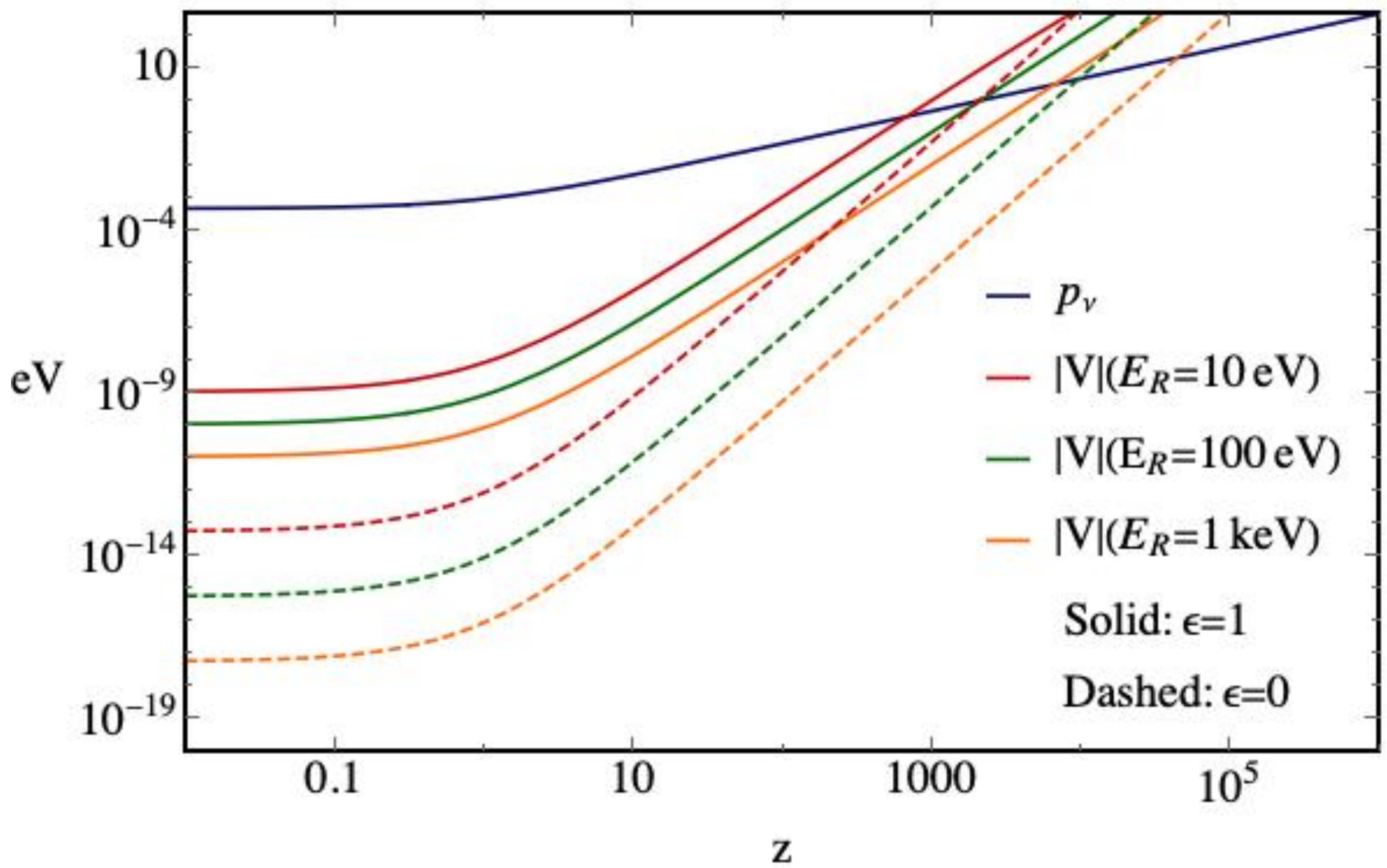
Bounds on parameters required for explaining observation.

# Cosmological probes

Talk by M. Lattanzi




Smirnov, **MS** (2024)




CMB+DESI-BAO :

$$\sum m_\nu < 72\,\mathrm{meV}$$

Redshift < 1000

Dispersion for massless neutrinos: E= p(z) + V(z)

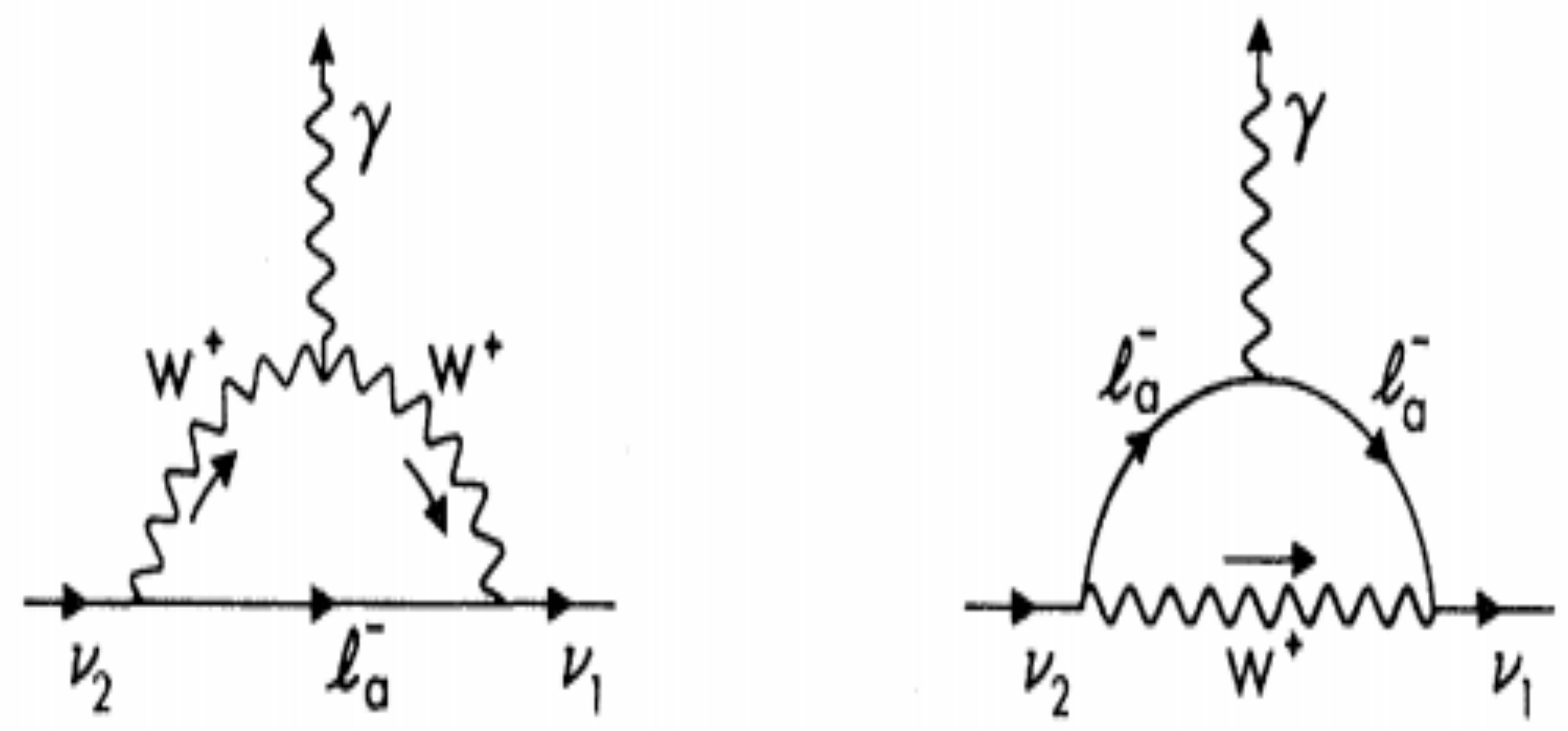
Below z=1000, neutrinos effectively massless.

Can explain DESI results.

# Neutrino Decay

# Neutrino Decay

- Massive neutrinos can decay to lighter ones even within the SM. Age longer than universe.



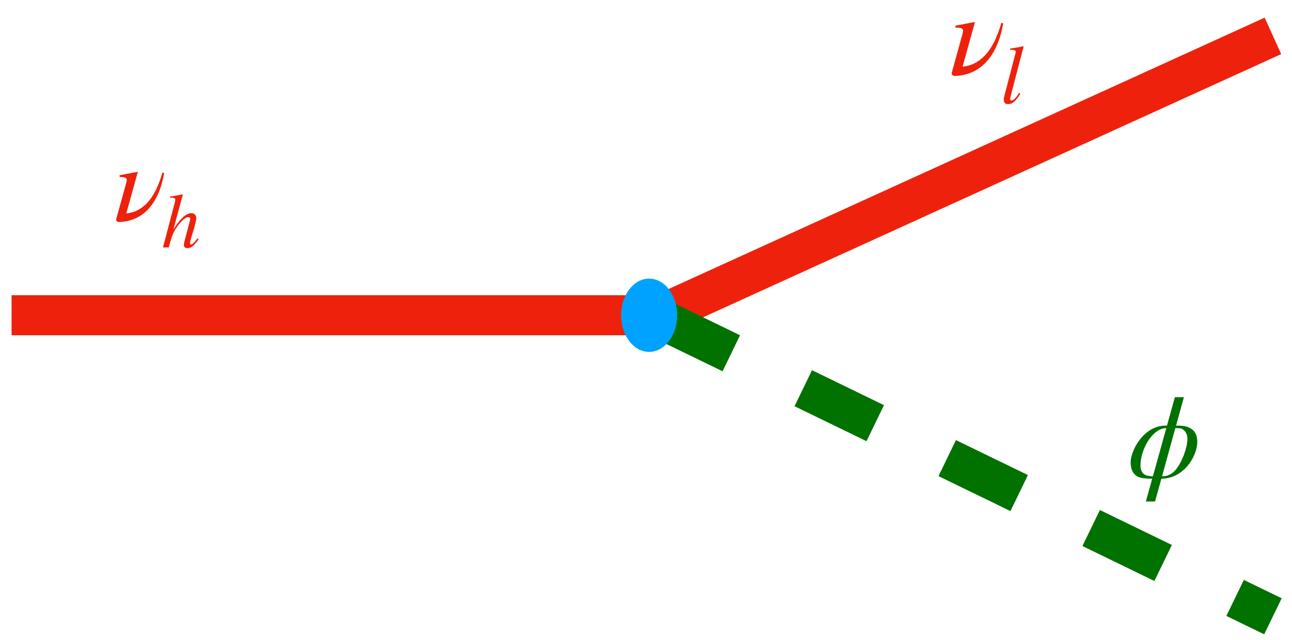
Pal and Wolfenstein (PRD1982)

- New physics can mediate faster decay.

$$\mathscr{L} \supset \bar{\nu}_l \nu_h \, \varphi + \mathrm{H.c.}$$

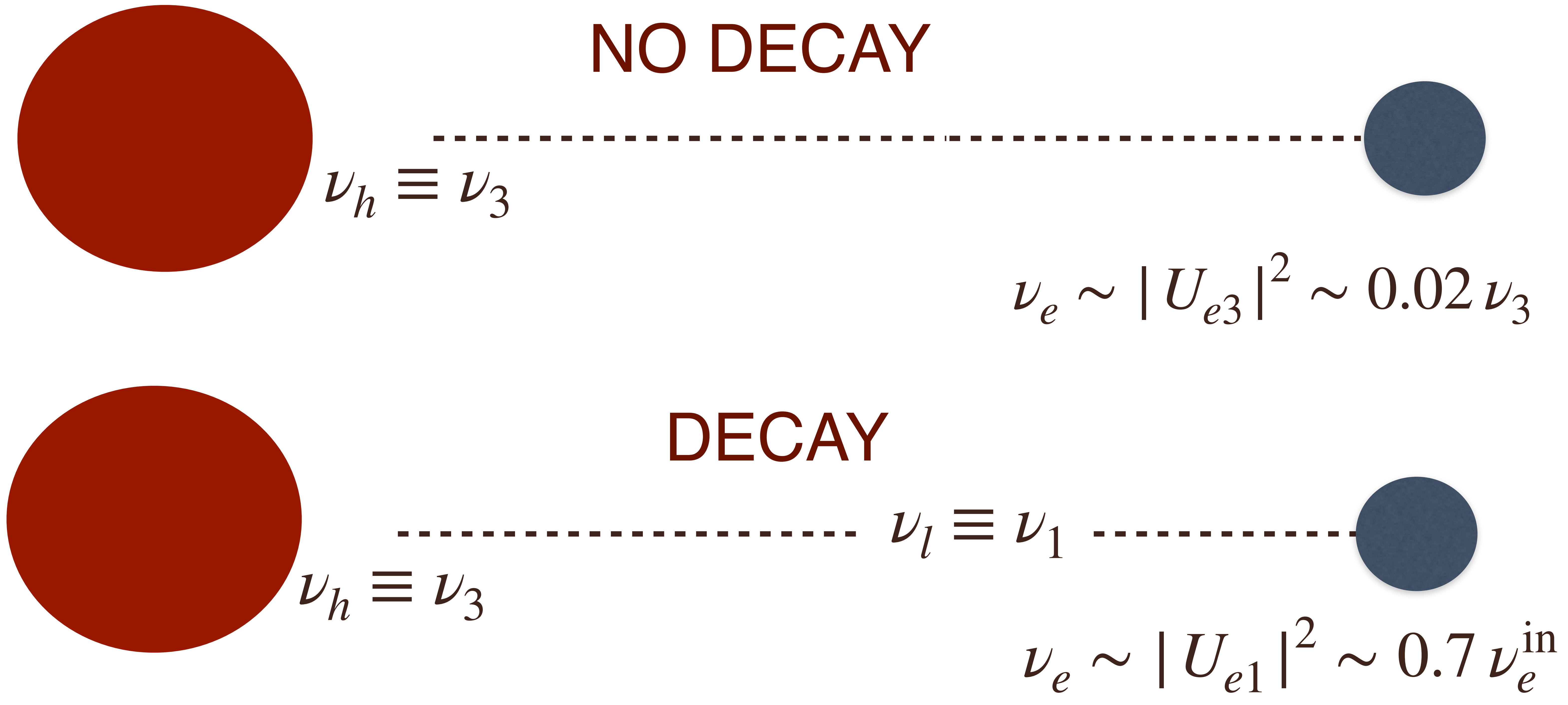
- $\nu_{hL} \to \nu_{lL} + \varphi$ .... Helicity cons. (h.c.)

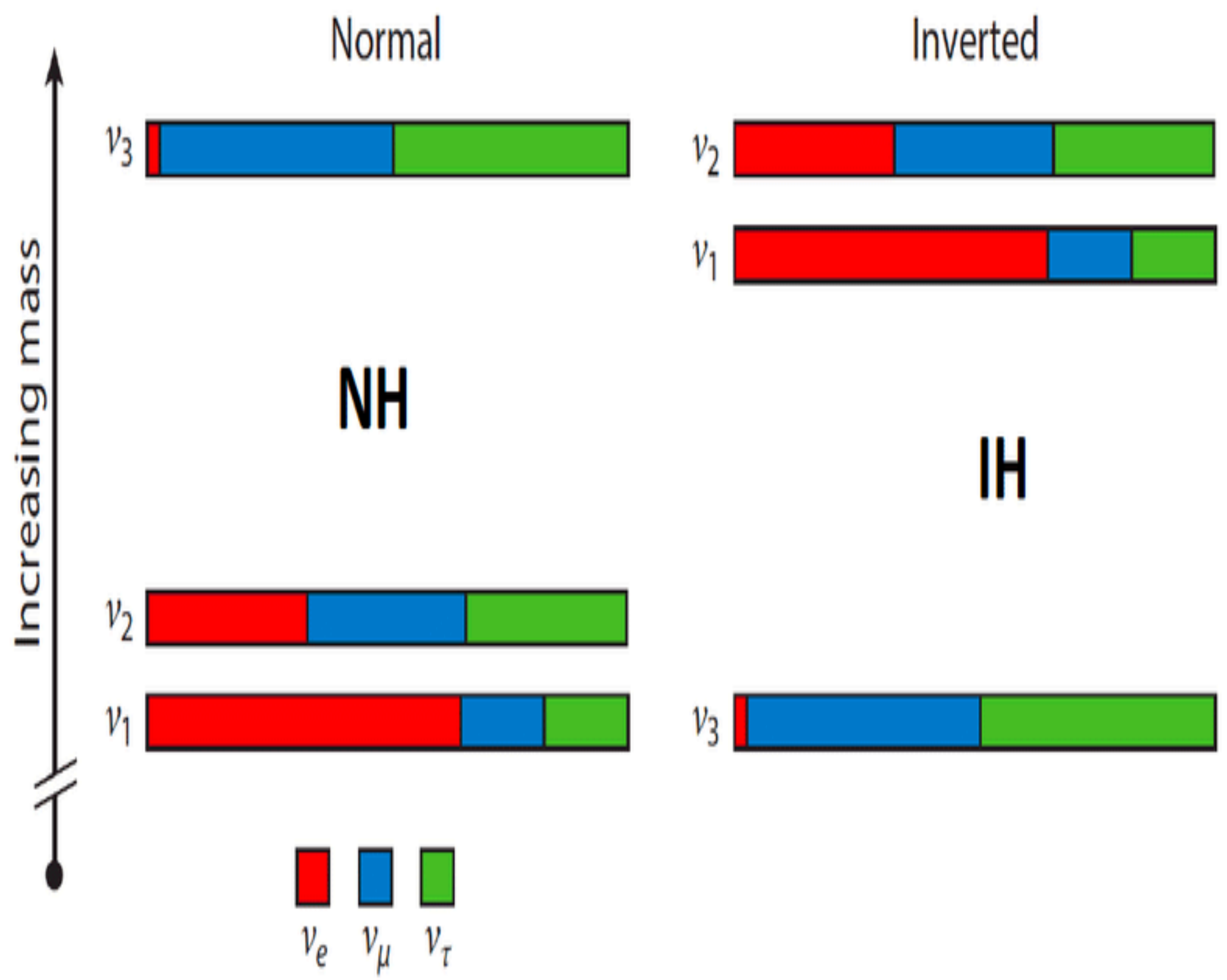
  $\nu_{hL} \to \nu_{lR} + \varphi$ .... Helicity flip. (h.f.)




- Visible vs Invisible decay

# How does neutrino decay work?




Normal Ordering

$\nu_3 \rightarrow \nu_1 \varphi$

Enhancement in spectra

# Constraints from neutrino decay

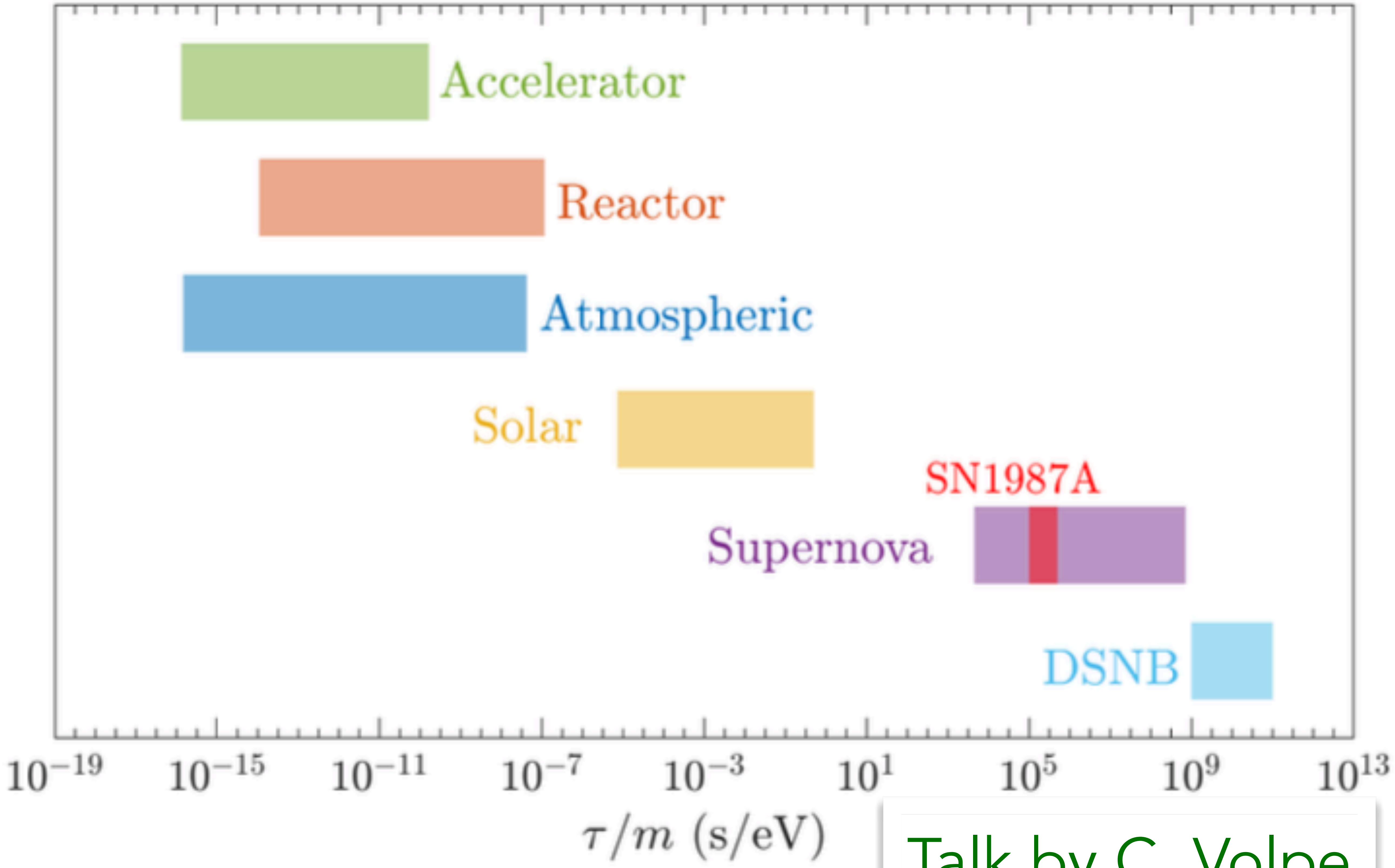
- Solar bounds: $\tau_2/m_2 > 10^{-3}\,\mathrm{s/eV}$.
  $\tau_3/m_3 > 10^{-5}\,\mathrm{s/eV}$.

- Long baseline: $\tau_3/m_3 \sim 10^{-14} - 10^{-10}\,\mathrm{s/eV}$

- IceCube: $\tau_3/m_3 \sim 10^{2-3}\,\mathrm{s/eV}$.

- SN1987A: $\tau/m \sim 10^5\,\mathrm{s/eV}$

- CMB: $\tau/m \sim 10^6\,\mathrm{s/eV}$

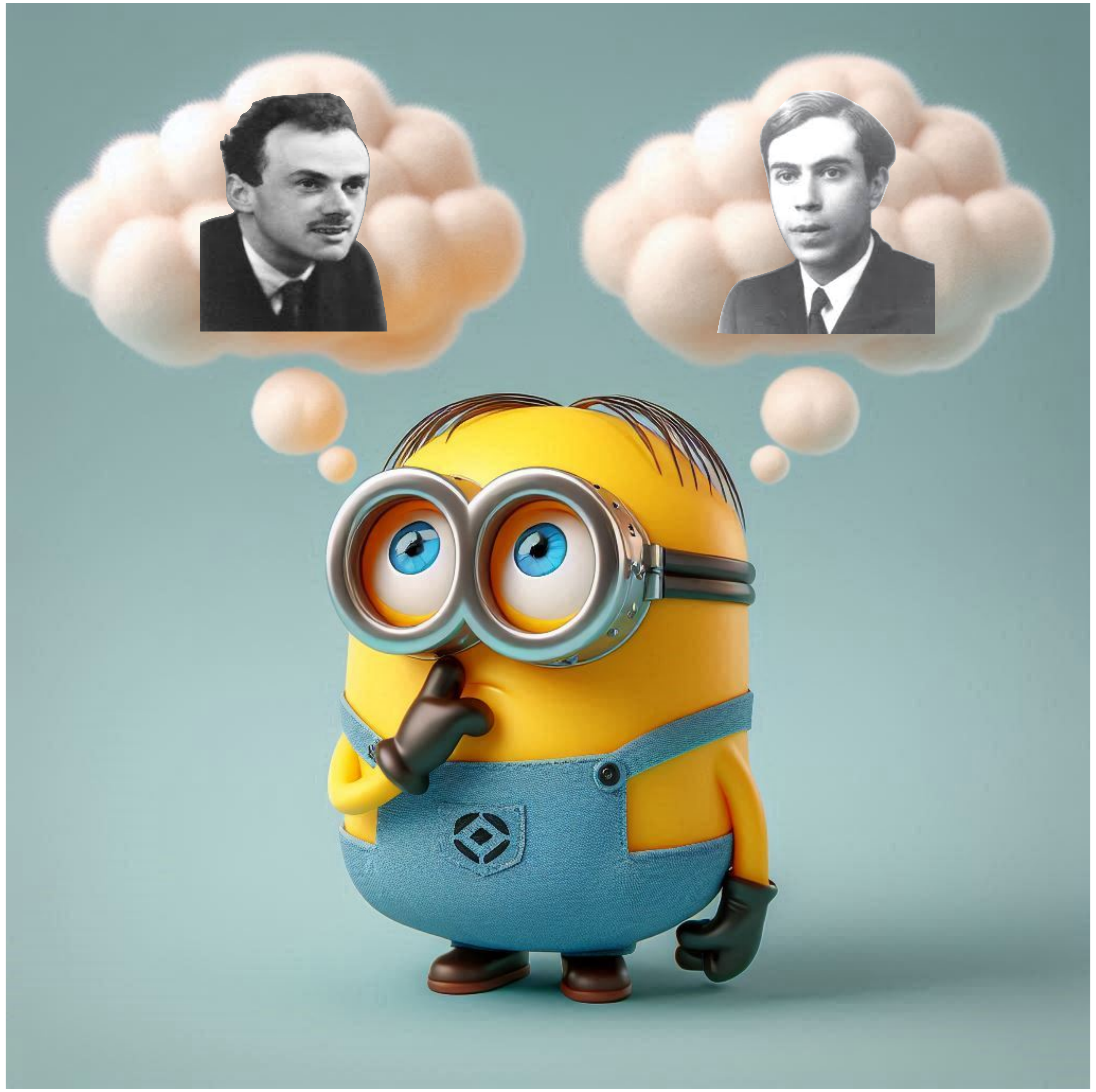



Talk by C. Volpe

Ivanez-Ballesteros, Volpe (PLB 2023)

Longer baselines provide stronger constraints $\frac{L}{\tau} \cdot \frac{m}{E} \sim 1$

# Dirac vs Majorana+ Non-standard physics



Talk by E. Akhmedov

# Decaying Dirac vs Decaying Majorana

$$\mathscr{L}_{\rm Dir} \supset \nu_h \nu_l^c \phi + {\rm H.c.}$$

$\nu_{hL} \to \nu_{lL} + \phi$

$\nu_{hR} \to \nu_{lR} + \phi$

acts as an "inert" neutrino and cannot be observed.

$$\mathscr{L}_{\rm Maj} \supset \nu_h \nu_l \phi + {\rm H.c.}$$

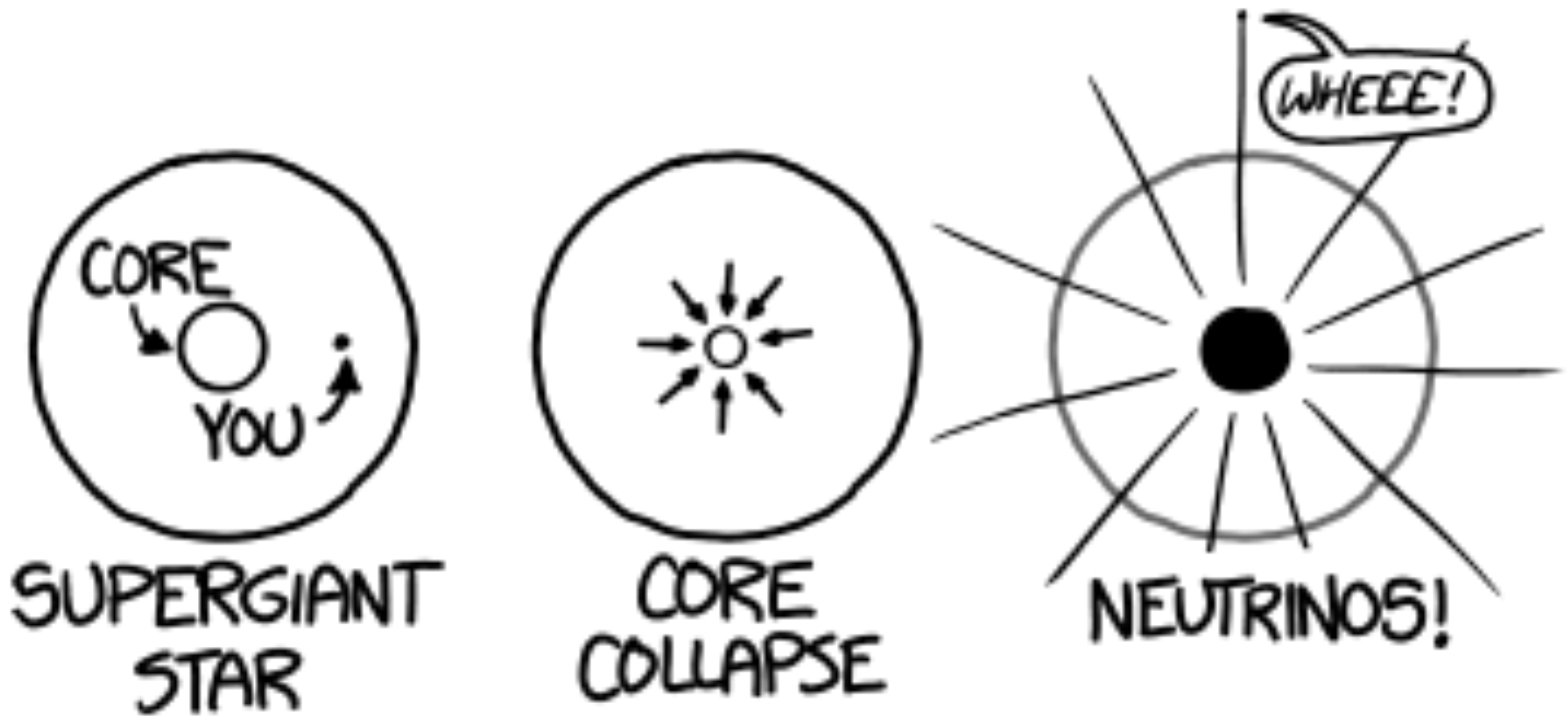
$\nu_{hL} \to \nu_{lL} + \phi$

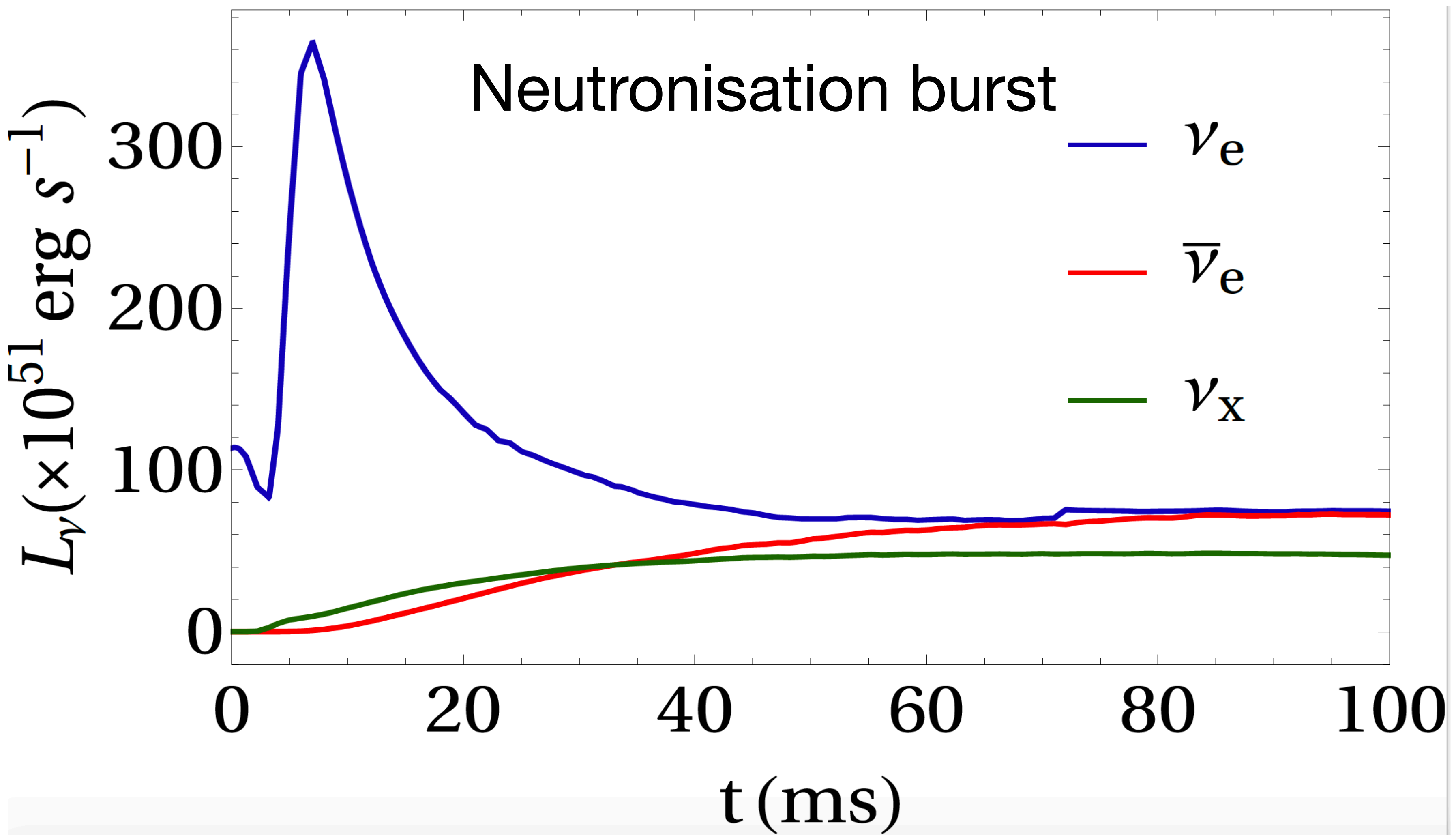
$\nu_{hL} \to \nu_{lR} + \phi$

acts as the "antineutrino" - produces an $e^+$ on interaction—observable

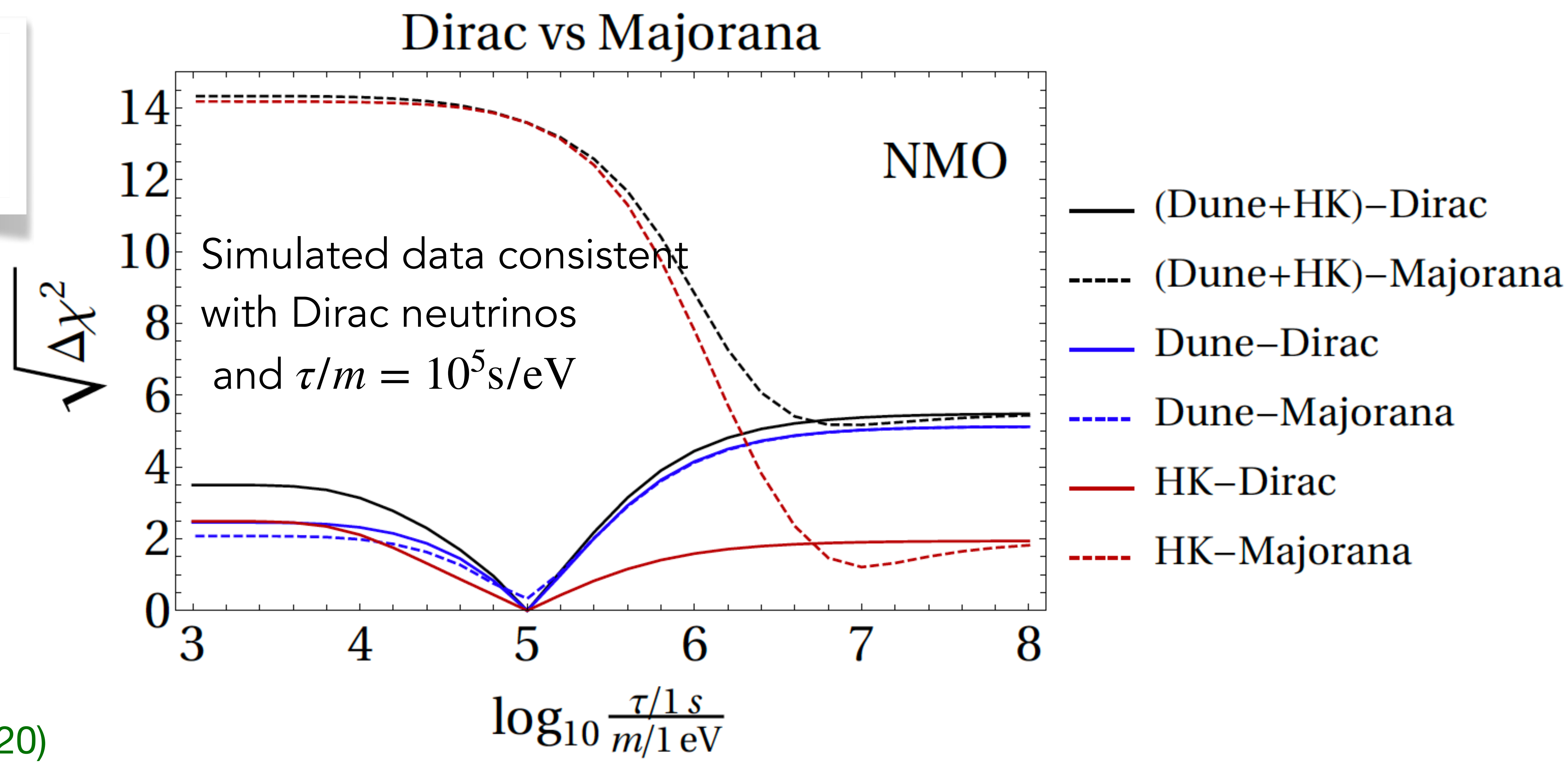
Martinez-Soler, de Gouvea, **MS** (PRD 2020)

# Decaying Dirac vs Decaying Majorana




Talks by C. Volpe, S. Abbar, H. Nagakura, L. Johns,…




Martinez-Soler, de Gouvea, **MS** (PRD 2020)

# Pseudo-Dirac Neutrinos

# Pseudo-Dirac neutrinos

- Neutrinos have sub-dominant Majorana mass terms.

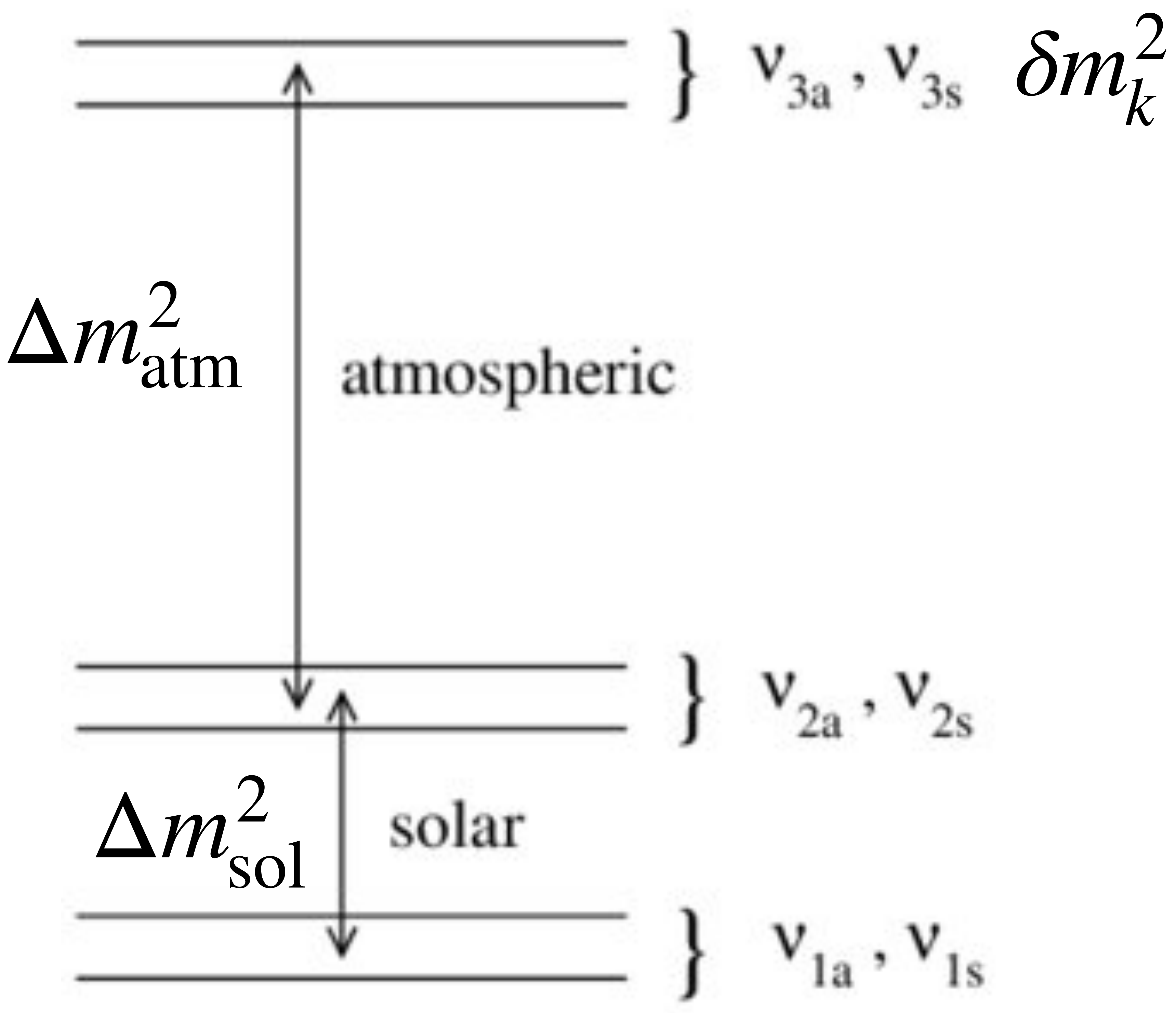
  Generic Majorana mass matrix $\begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix}$.

  Pseudo-Dirac limit : $m_{L,R} \ll m_D$

- 3 pairs of quasi-degenerate states, separated by $\delta m_k^2$, which is much smaller than the usual $\Delta m^2_{\rm sol}$ and $\Delta m^2_{\rm atm}$.

$$\nu_{\alpha L} = \frac{1}{\sqrt{2}} U_{\alpha j} (\nu_{js} + i\, \nu_{ja})$$

- Oscillations driven by this tiny $\delta m_k^2$ at large distances.

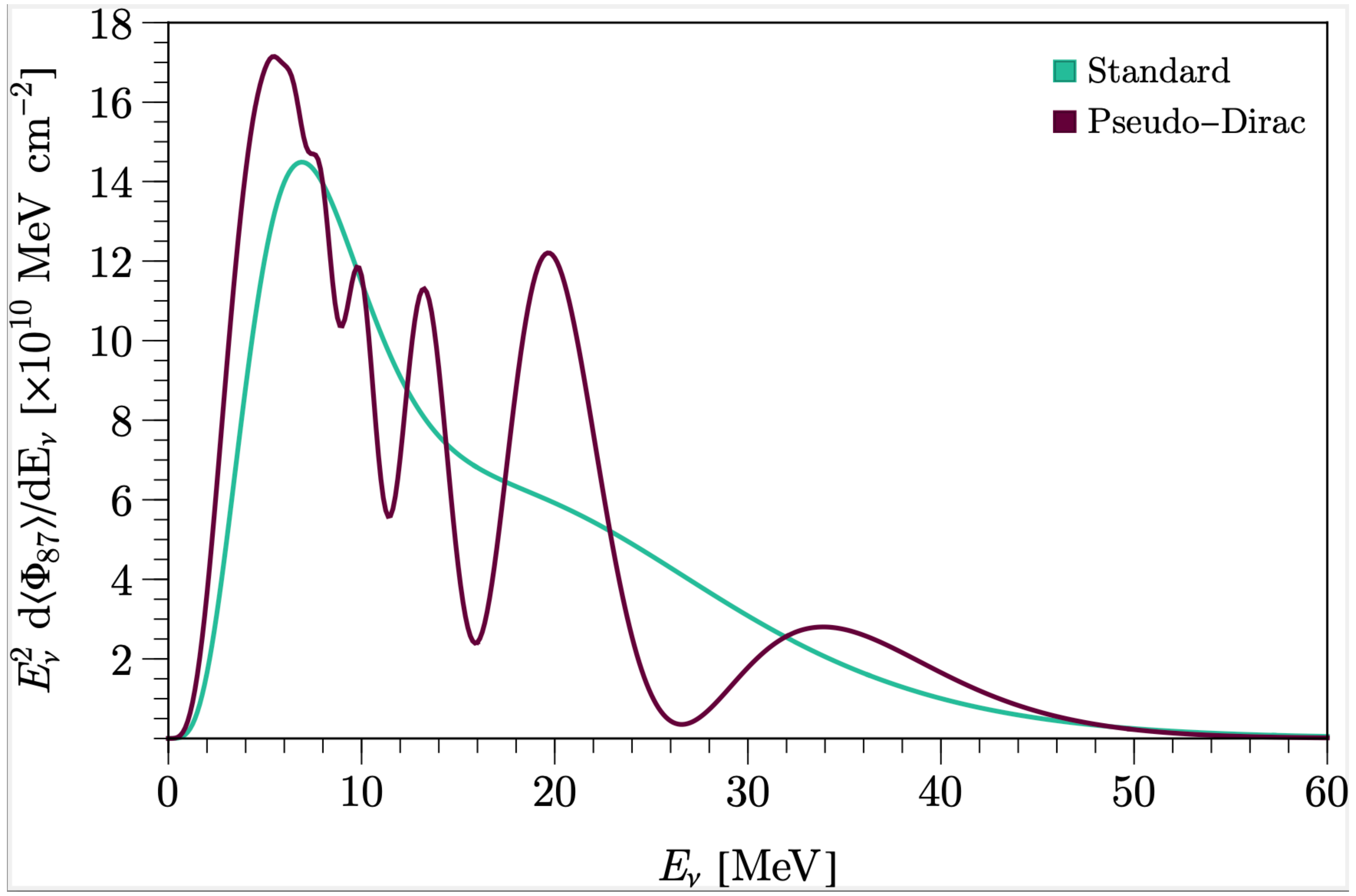



Martinez-Soler, Perez-Gonzalez, **MS** (PRD 2022)

# Active-sterile oscillations

- Flavor oscillation probability induced by $\Delta m^2_{\rm sol}$ and $\Delta m^2_{\rm atm}$ over a large distance gets averaged.

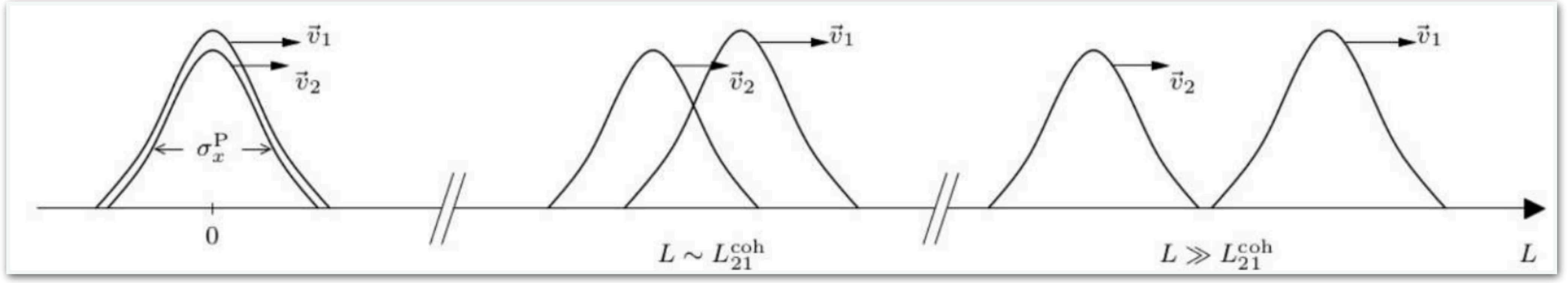
$$P(\nu_\beta \to \nu_\gamma) = P_{aa}(z,E)\left|U_{\beta k}\right|^2\left|U_{\gamma k}\right|^2$$




- The active-sterile probability, driven by $\delta m_k^2$ is

$$P_{aa}(z,E) = \frac{1}{2}\left(1 + e^{-\left(\frac{L(z)}{L_{\rm coh}}\right)^2}\cos\left(2\pi\frac{L(z)}{L_{\rm osc}}\right)\right)$$

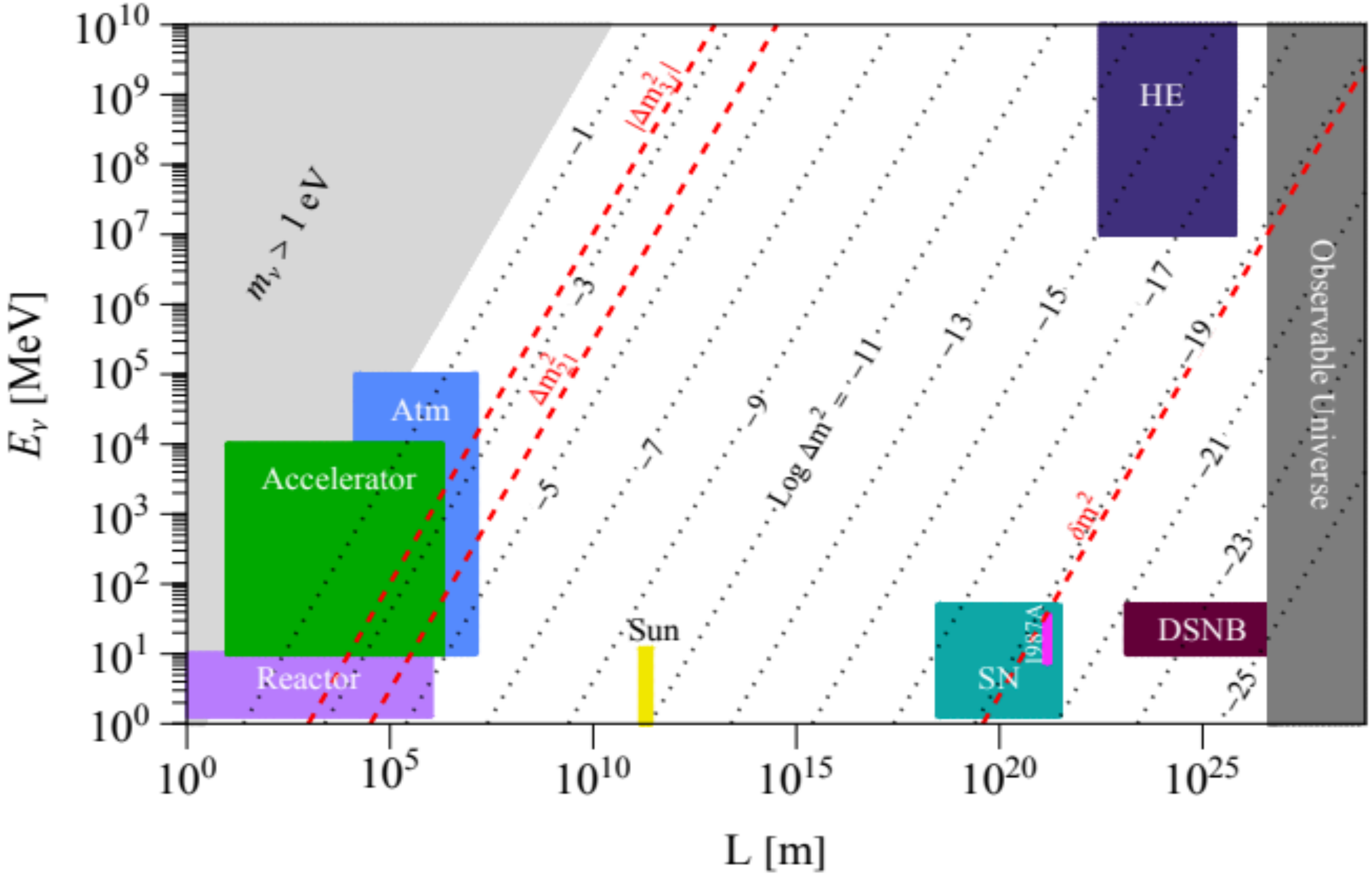
- Wave-packet separation decoherence also becomes important.



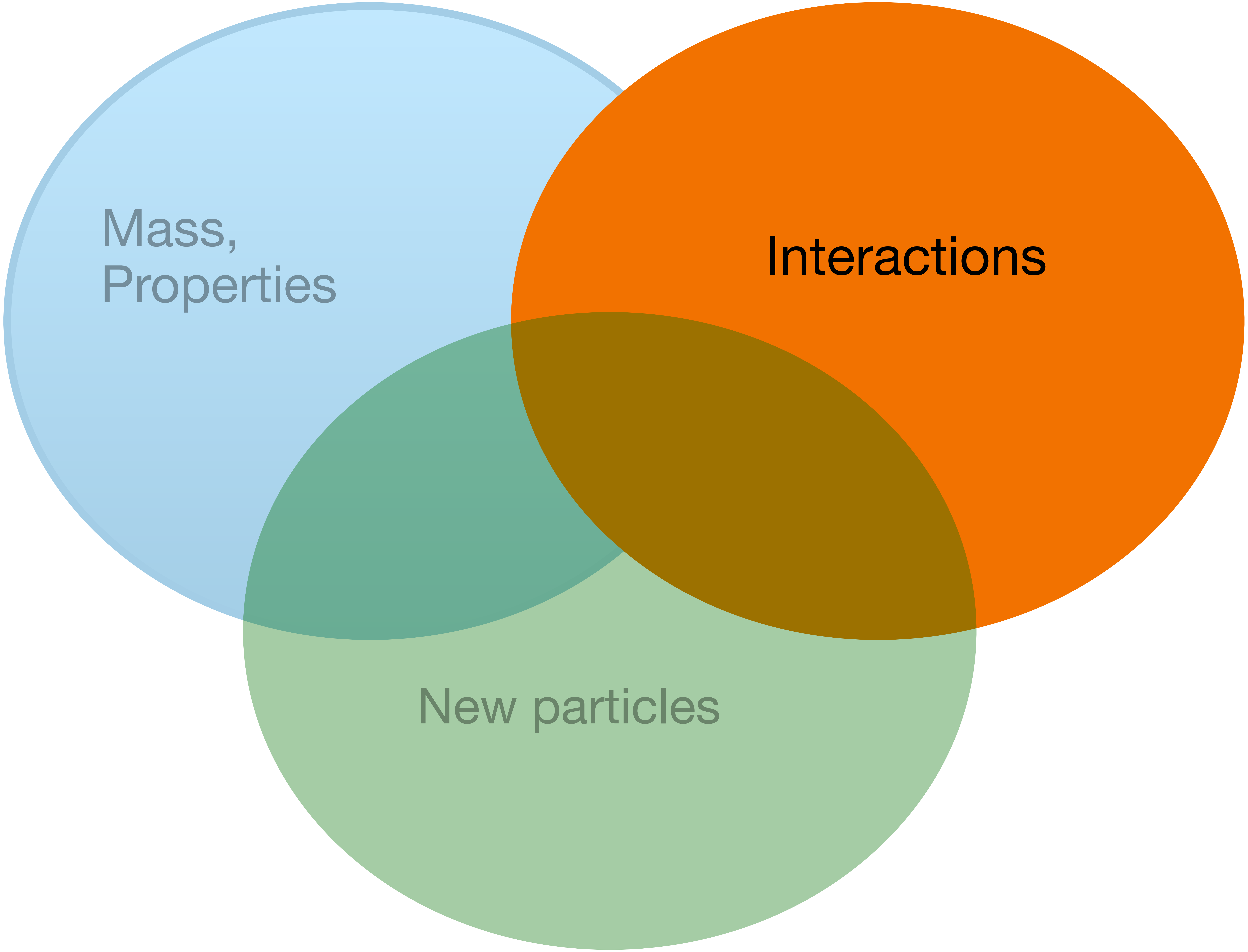

$$L_{\rm osc} = \frac{4\pi E_\nu}{\delta m^2} \sim 20\,{\rm kpc}\left(\frac{E_\nu}{25{\rm MeV}}\right)\left(\frac{10^{-19}{\rm eV}^2}{\delta m^2}\right)$$

$$L_{\rm coh} = \frac{4\sqrt{2}E_\nu}{|\delta m^2|}(E_\nu\sigma_x) \sim 114\,{\rm kpc}\left(\frac{E_\nu}{25{\rm MeV}}\right)^2\left(\frac{10^{-19}{\rm eV}^2}{\delta m^2}\right)\left(\frac{\sigma_x}{10^{-13}{\rm m}}\right),$$

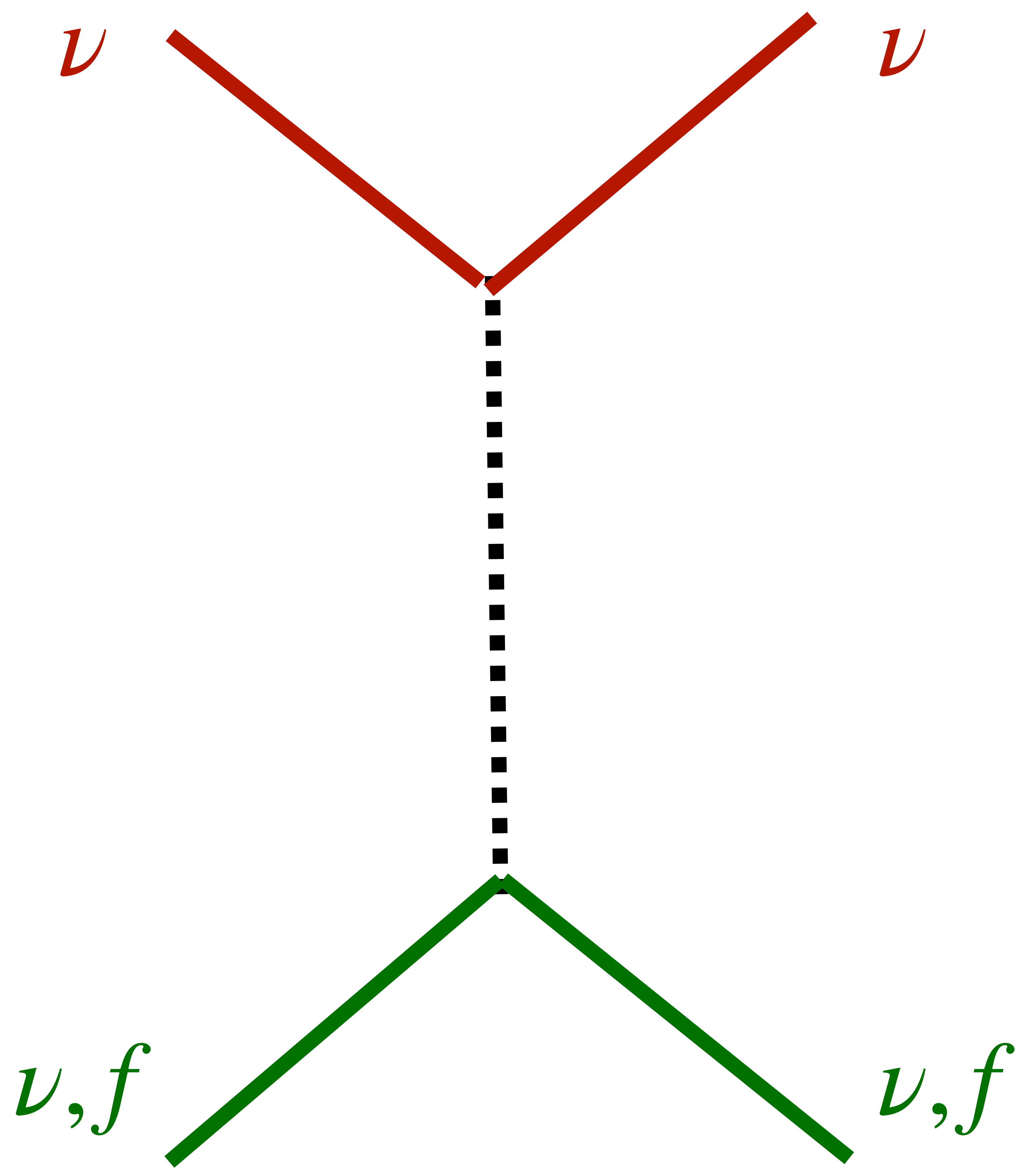
# Pseudo-Dirac neutrinos: Landscape




Martinez-Soler, Perez-Gonzalez, **MS** (PRD 2022)


Mass,
Properties
Interactions
New particles

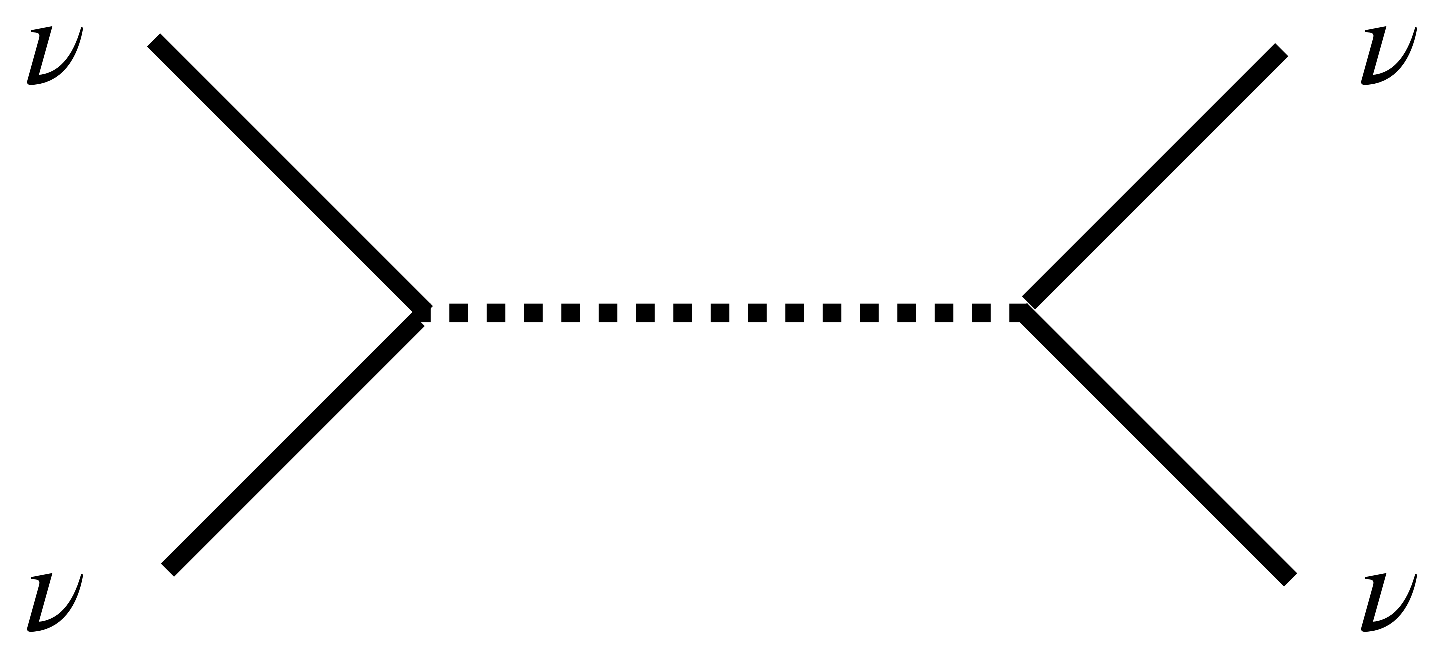
# Neutrino non-standard interactions



# Neutrino secret self-interactions

- Active neutrino secret self-interactions. Can be much stronger than ordinary weak interactions.

- Model building aspect?
  Consider
  $$\mathscr{L}_\nu = \frac{y}{\Lambda^2}(LH)^2\varphi^* \xrightarrow{\text{EWSB}} \lambda_\varphi \nu_a \nu_a \varphi^* \,,$$
  $\varphi$ can have lepton number




- Constraints from terrestrial experiments are loose: $G \sim (10^7 - 10^9) G_F$ cannot always be ruled out.

- However, can have strong impact in the early Universe or compact objects.

# What are the different constraints?

- Invisible Higgs decays, Z decays : $H, Z \to \nu\nu\phi$. Tau decays.
- Meson decays: $K^- \to \mu^- \nu_\mu \varphi, \quad \varphi \to \nu\nu$ . Bounds from $\mathrm{Br}(K^- \to \mu^- 3\nu) < 10^{-6}$ .
- Neutrinoless double beta decay. $(Z, A) \to (Z+2, A)\ e^- e^- \phi$
- BBN: extra radiation

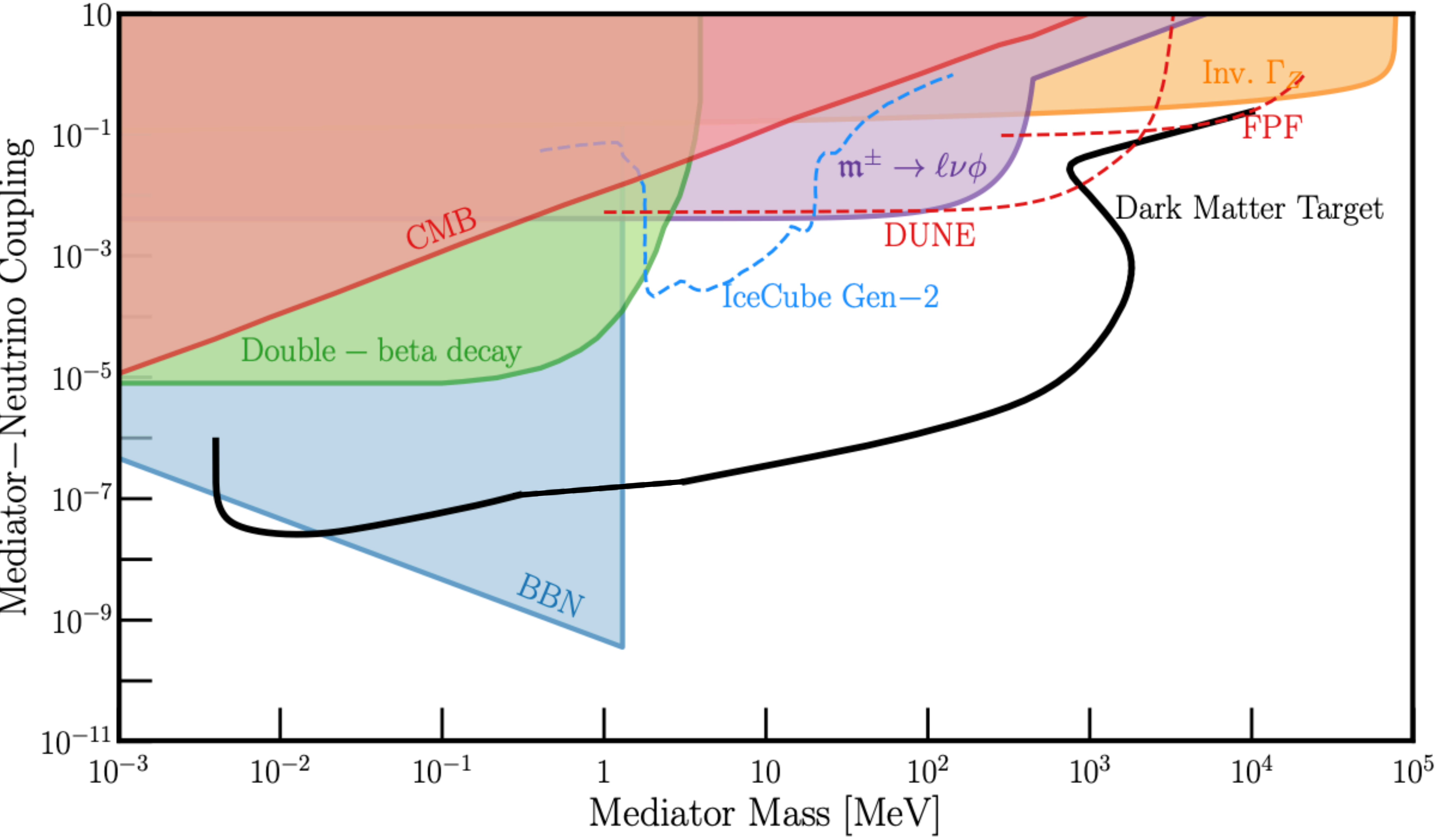
- SN1987A: cooling bounds, scattering on dense environments.
- High energy neutrinos scattering off the Cosmic Neutrino Background.
- Look for "wrong sign muon" in $\nu_\mu N \to \mu^+ N' \varphi$.

**Neutrino Self-Interactions: A White Paper**

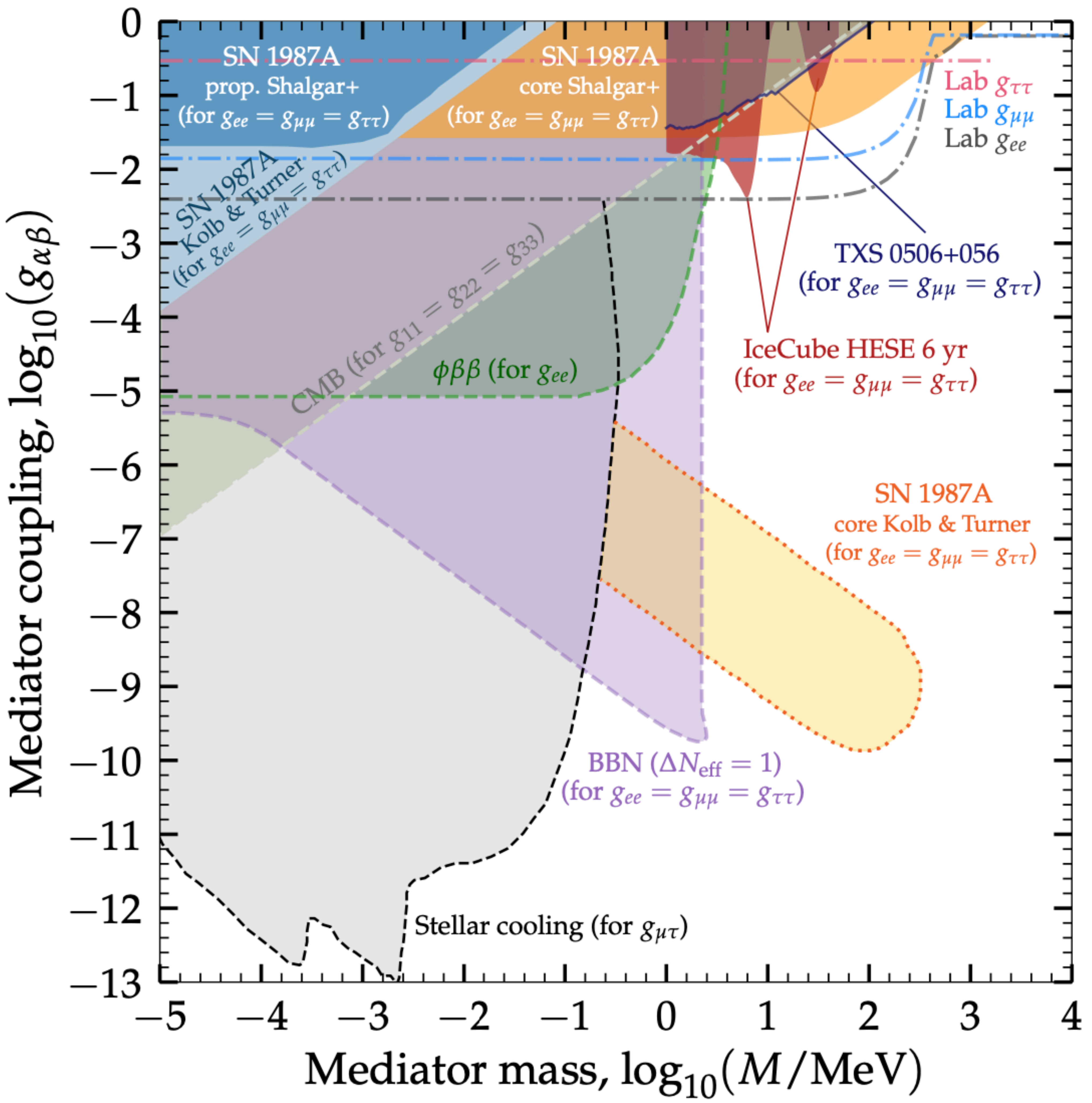
Jeffrey M. Berryman, Nikita Blinov, Vedran Brdar, Thejs Brinckmann, Mauricio Bustamante, Francis-Yan Cyr-Racine, Anirban Das, André de Gouvêa, Peter B. Denton, P.S. Bhupal Dev, Bhaskar Dutta, Ivan Esteban, Damiano F.G. Fiorillo, Martina Gerbino, Subhajit Ghosh, Tathagata Ghosh, Evan Grohs, Tao Han, Steen Hannestad, Matheus Hostert, Patrick Huber, Jeffrey Hyde, Kevin J. Kelly, Felix Kling, Zhen Liu, Massimiliano Lattanzi, Marilena Loverde, Sujata Pandey, Ninetta Saviano, Manibrata Sen, Ian M. Shoemaker, Walter Tangarife, Yongchao Zhang, Yue Zhang

Snowmass report (Phys. Dark. Uni., 2023)

# Neutrino self-interaction bounds




Zhang, Kelly, **MS**, (PRL 2021)




Snowmass report (Phys. Dark. Uni., 2023)

# Neutrino non-standard interactions

- Neutrinos give the first indication of physics beyond the SM. Hence it is not unusual to expect NSI of neutrinos.

$$\mathscr{L}_{\rm NSI} = \frac{\epsilon^f_{\alpha\beta}}{\Lambda^2}\left(\bar{\nu}_\alpha \Gamma \nu_\beta\right)\left(\bar{f}\,\Gamma f\right)$$

- Reasonably strong constraints exists from solar, atmospheric, reactor and long-baseline accelerator neutrinos.

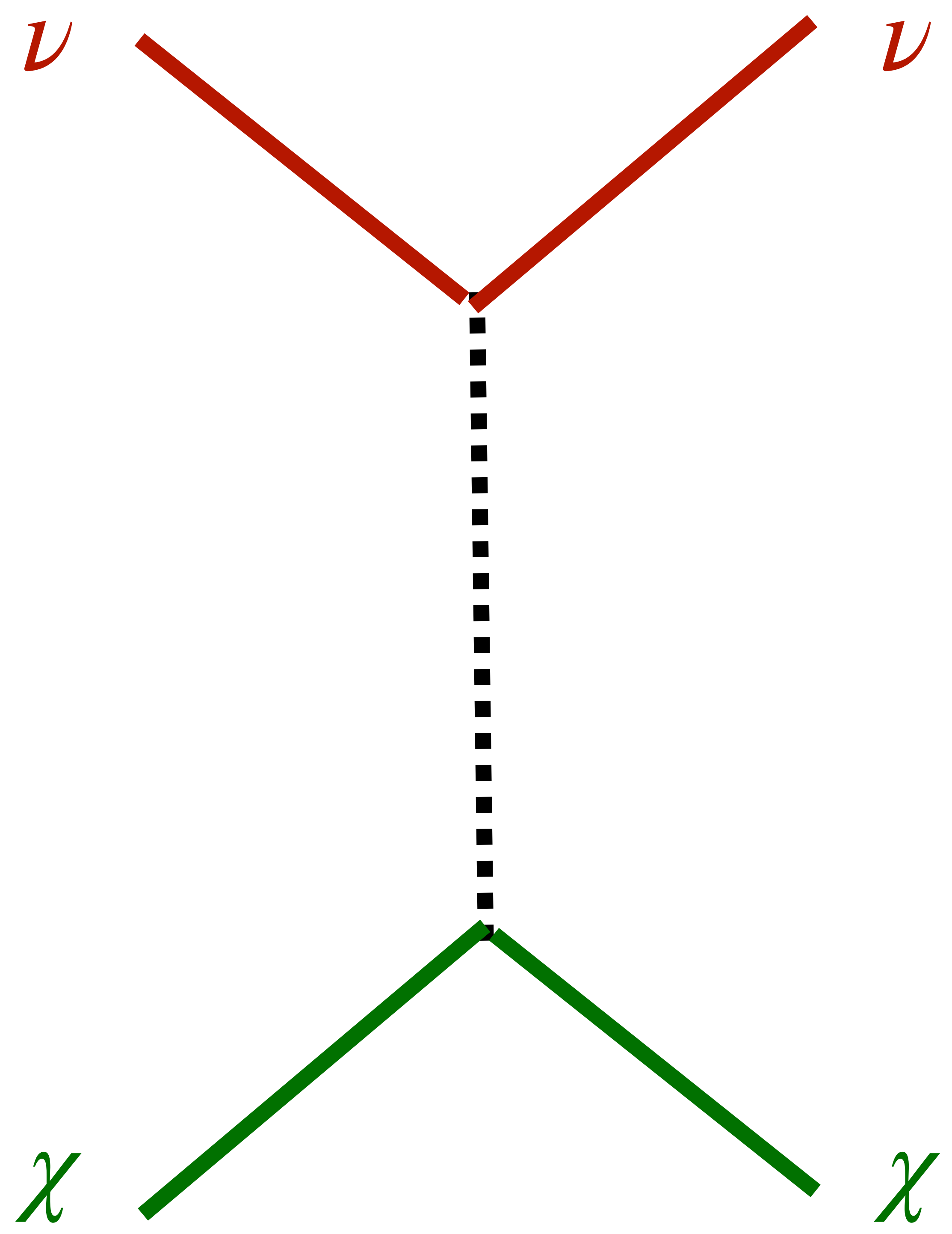
- Global fit analyses exists.

**Neutrino Non-Standard Interactions: A Status Report**

P. S. Bhupal Dev, K. S. Babu, Peter B. Denton, Pedro A. N. Machado, Carlos A. Argüelles, Joshua L. Barrow, Sabya Sachi Chatterjee, Mu-Chun Chen, André de Gouvêa, Bhaskar Dutta, Dorival Gonçalves, Tao Han, Matheus Hostert, Sudip Jana, Kevin J. Kelly, Shirley Weishi Li, Ivan Martinez-Soler, Poonam Mehta, Irina Mocioiu, Yuber F. Perez-Gonzalez, Jordi Salvado, Ian M. Shoemaker, Michele Tammaro, Anil Thapa, Jessica Turner, Xun-Jie Xu

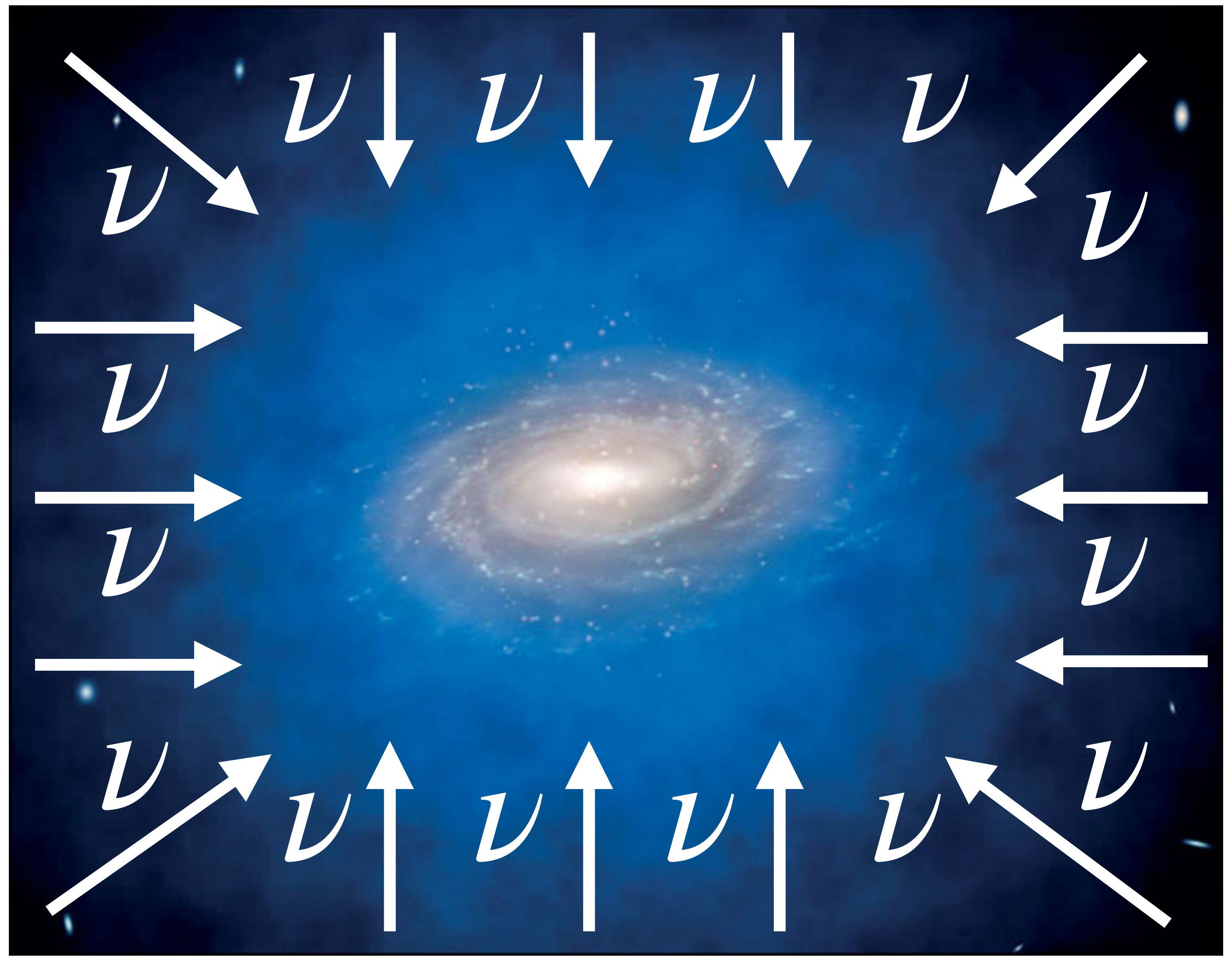
This report summarizes the present status of neutrino non-standard interactions (NSI). After a brief overview, several aspects of NSIs are discussed, including connection to neutrino mass models, model-building and phenomenology of large NSI with both light and heavy mediators, NSI phenomenology in both short- and long-baseline neutrino oscillation experiments, neutrino cross-sections, complementarity of NSI with other low- and high-energy experiments, fits with neutrino oscillation and scattering data, DUNE sensitivity to NSI, effective field theory of NSI, as well as the relevance of NSI to dark matter and cosmology. We also discuss the open questions and interesting future directions that can be pursued by the community at large. This report is based on talks and discussions during the Neutrino Theory Network NSI workshop held at Washington University in St. Louis from May 29-31, 2019 (this https URL)

# Neutrino Dark Matter Interactions

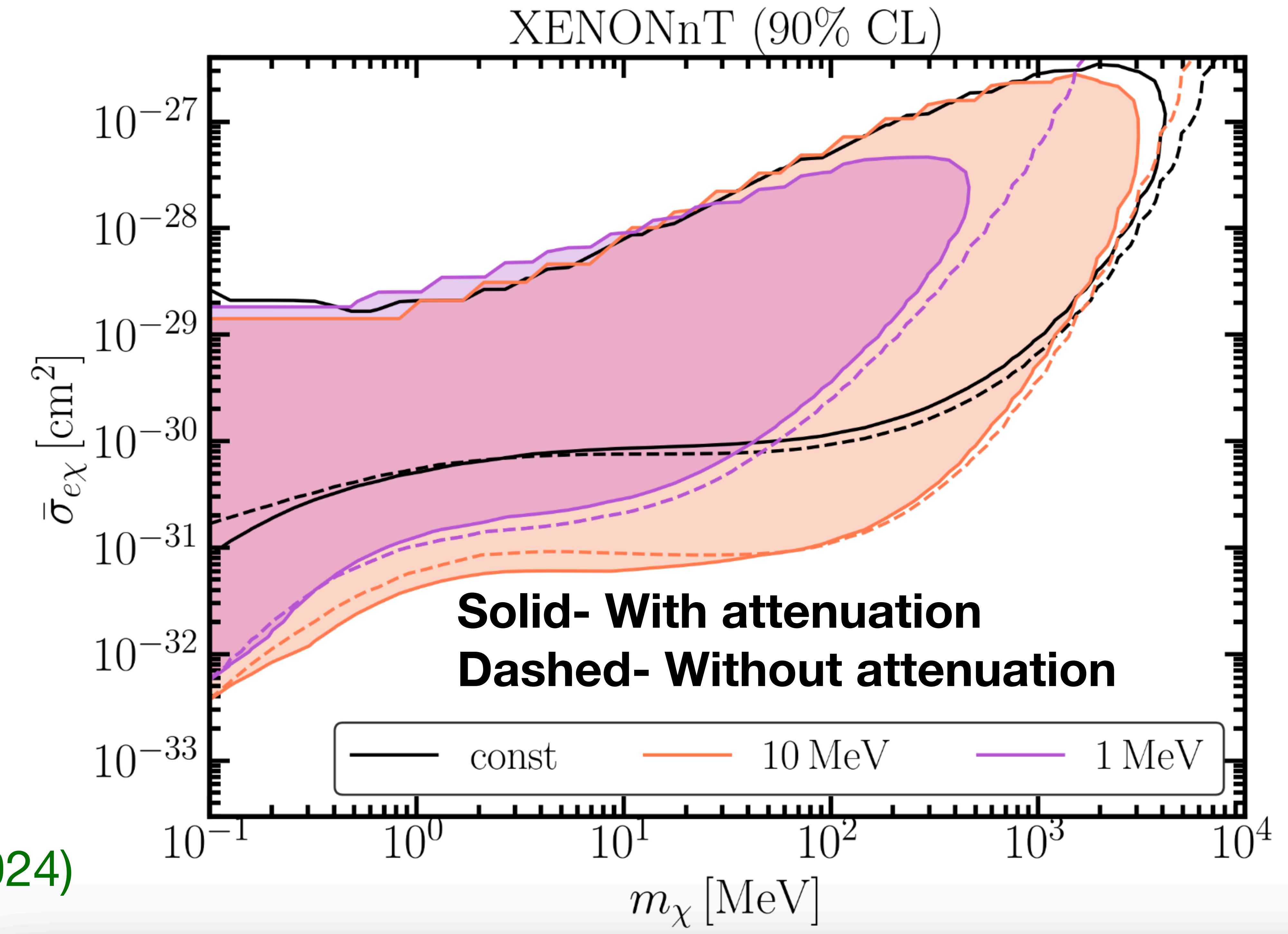


# Boosted Dark Matter interactions

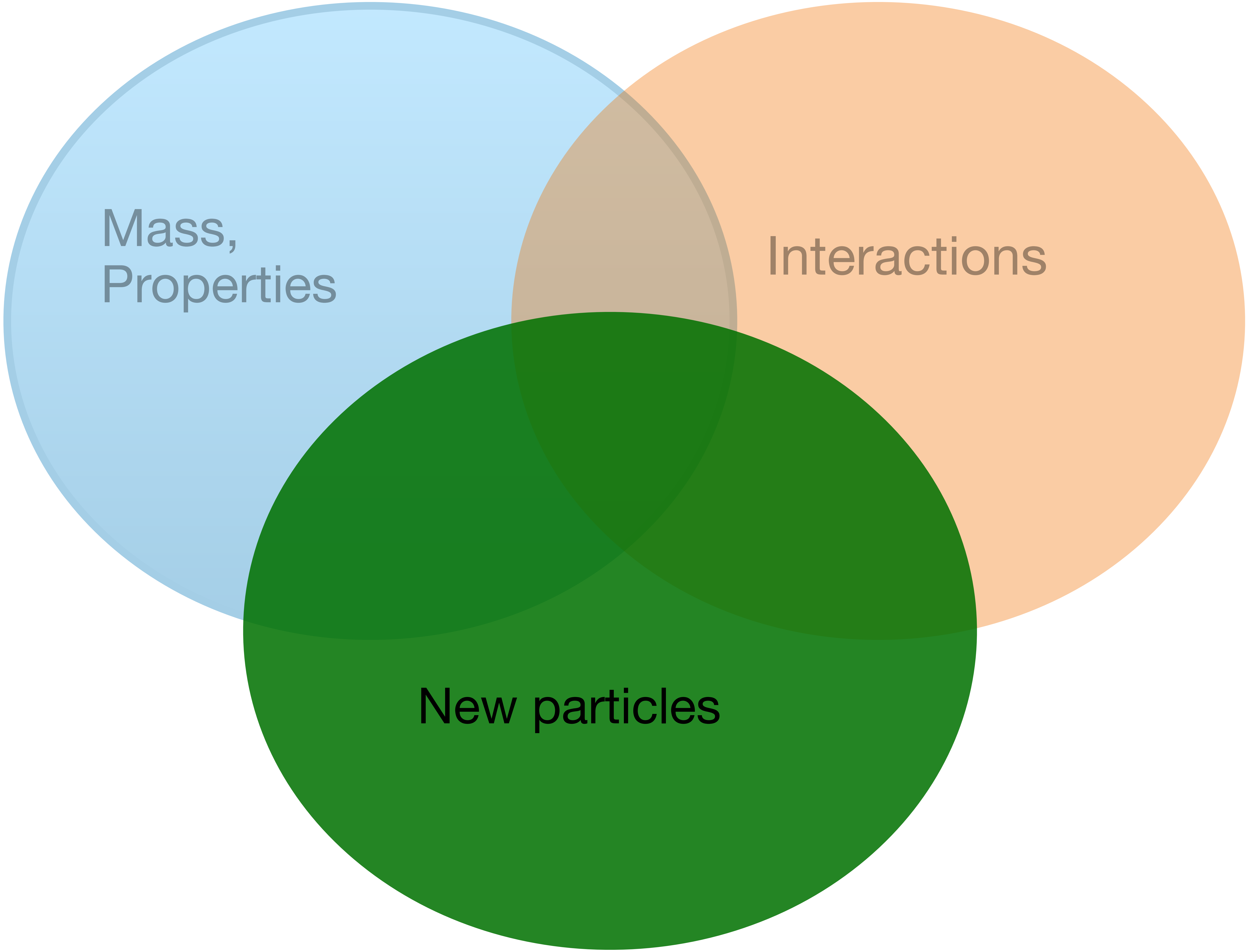
- Neutrino-Dark Matter interactions can allow neutrinos to scatter off DM.
- Upscatter a fraction of cold DM to neutrino-like energies.
- Can leave observable signature in DM direct detection experiments.
- Example: DM scattering off the DSNB.




Talk by T. Herbermann




Das, Herbermann, **MS**, Takhistov (JCAP 2024)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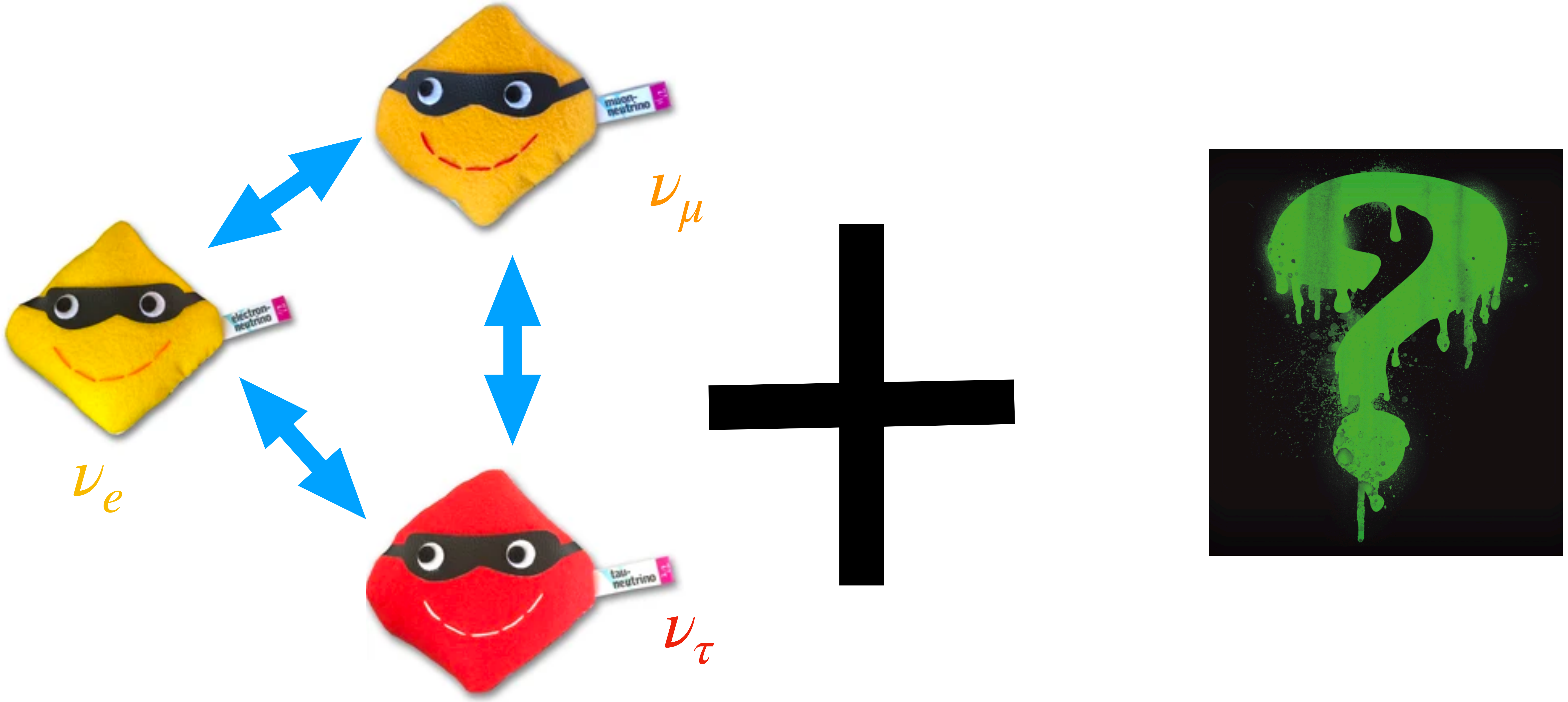
# Sterile neutrinos



# The sterile neutrino

Three directions:

1. Neutrino masses (TeV onwards)
2. Cosmology. ( mostly keV onwards )
3. Short baseline anomalies. ( eV masses)

Talks by E. Fernandez-Martinez, C. Farnese, A. Granelli, S. Rosauro-Alcaraz, A. Nava,…

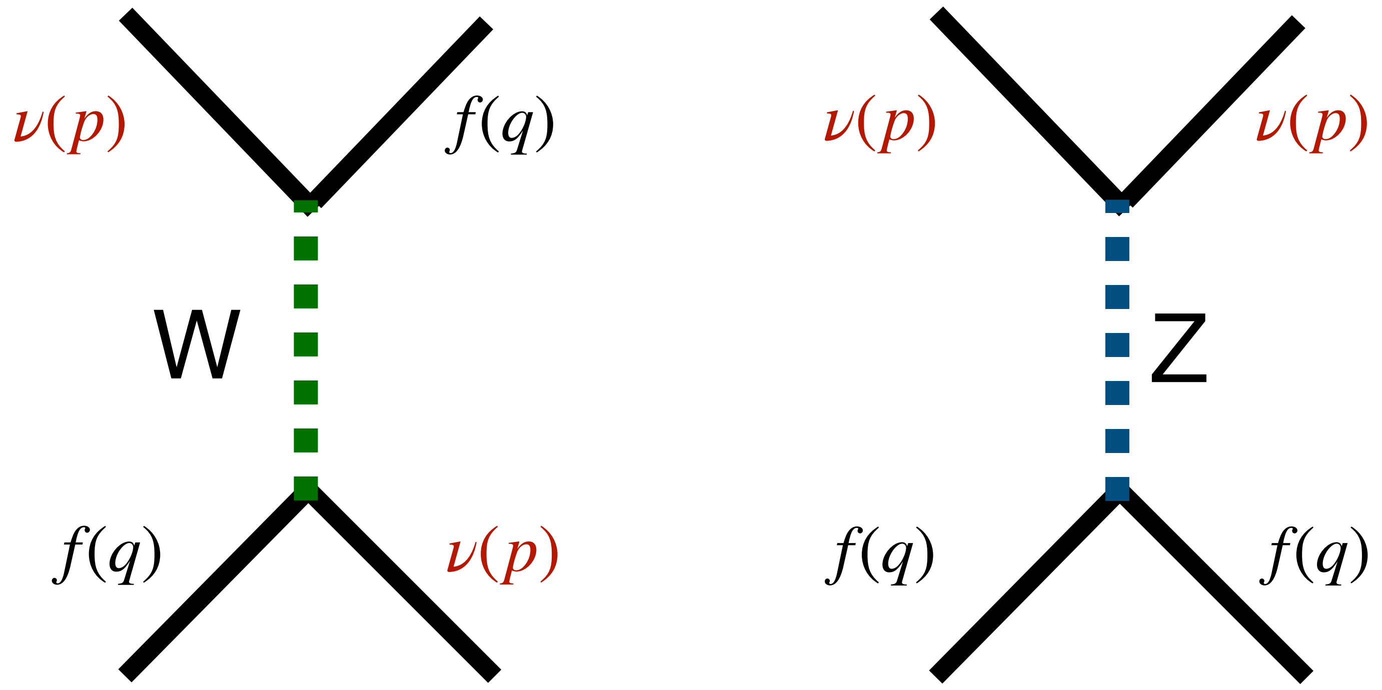
**Sterile neutrino mass range**

# Production: the Dodelson-Widrow mechanism

Extra keV mass eigenstate $\nu_4 = \cos\theta\,\nu_s + \sin\theta\,\nu_a$.

$\nu_a$ oscillates into $\nu_s$ before decoupling.

Creates a non-thermal population of $\nu_s$. Dodelson and Widrow, PRL1994




$$T\frac{\partial}{\partial T} f_{\nu_s}|_{p/T} = \frac{\Gamma_a}{2H}\ \langle P(\nu_a \to \nu_s)\rangle\ f_{\nu_a}\ ,$$

$$\langle P(\nu_a \to \nu_s)\rangle = \frac{1}{2}\frac{\Delta^2 \sin^2 2\theta}{\Delta^2 \sin^2 2\theta + \frac{\Gamma_a^2}{4} + (\Delta\cos 2\theta - V)^2}$$

Averaged over one mean free path

$\Delta = m_s^2/2E$

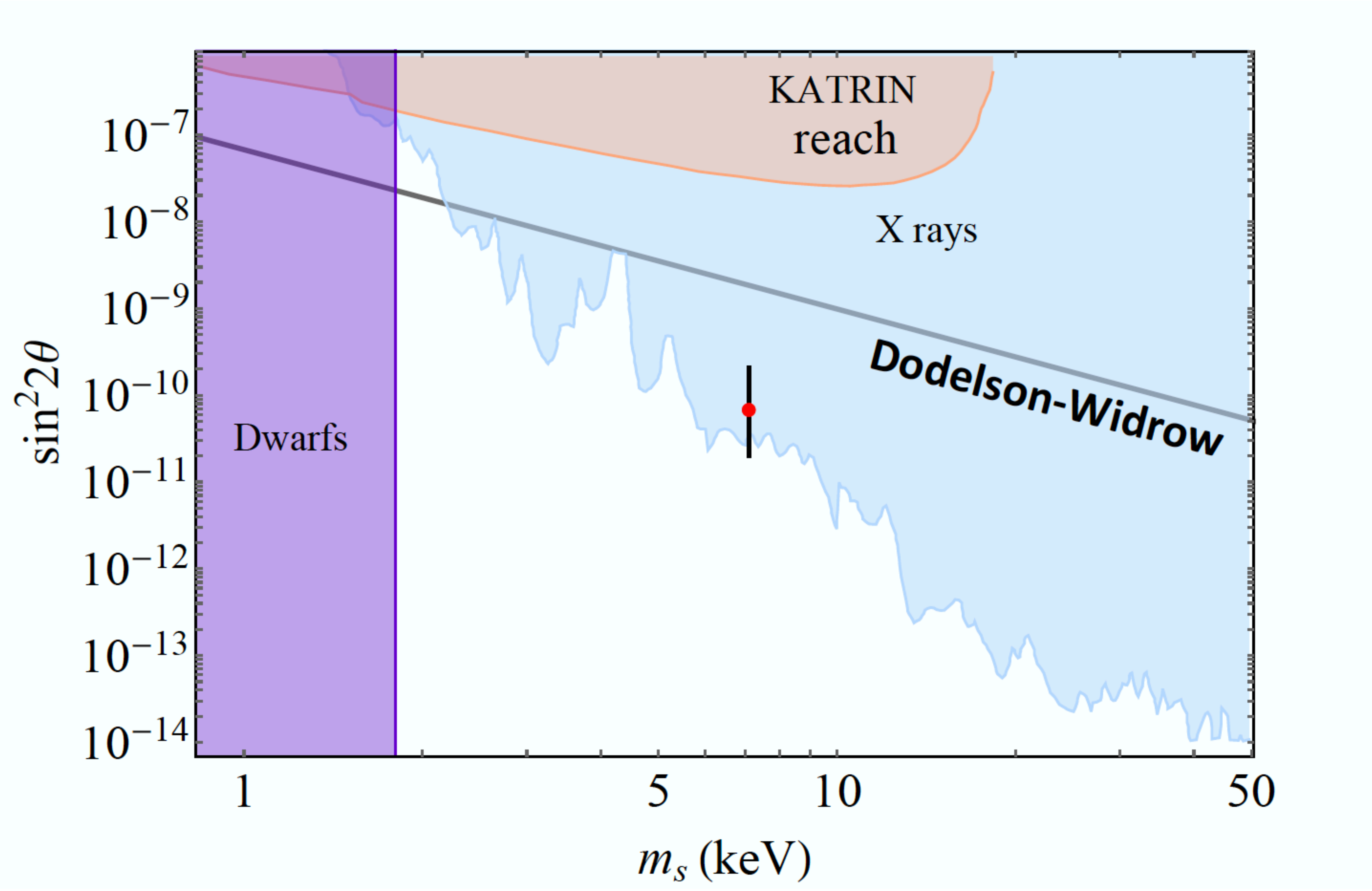
Damping

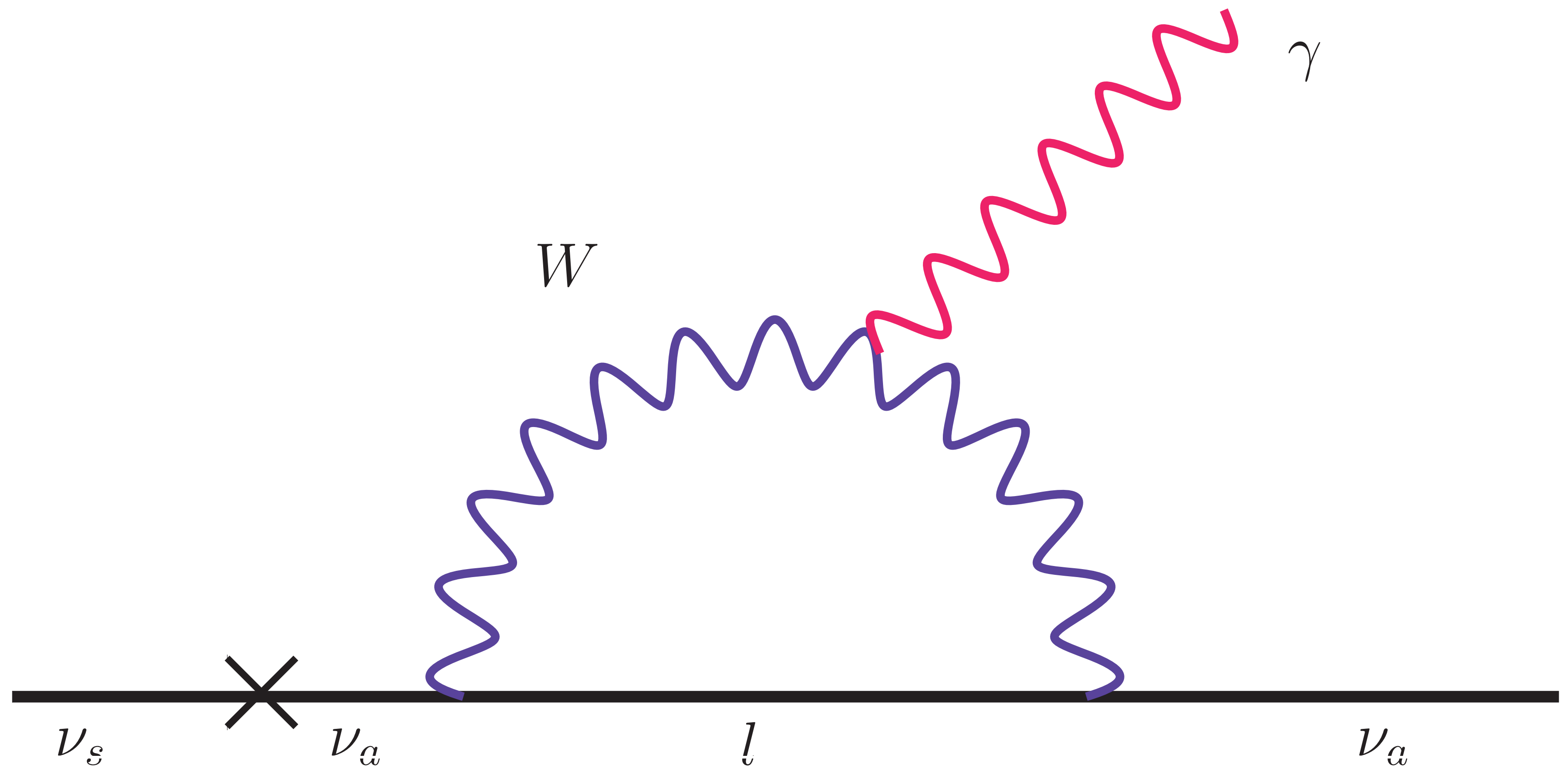
Matter potential $V = V_T + V_D$

Finite temperature: $V_T \propto T$

Finite density: $V_D \propto n_f$

# Sterile neutrino dark matter




Ruled out by X-ray bounds and phase-space considerations (galaxy counts, Lyman alpha, strong lensing, etc.).

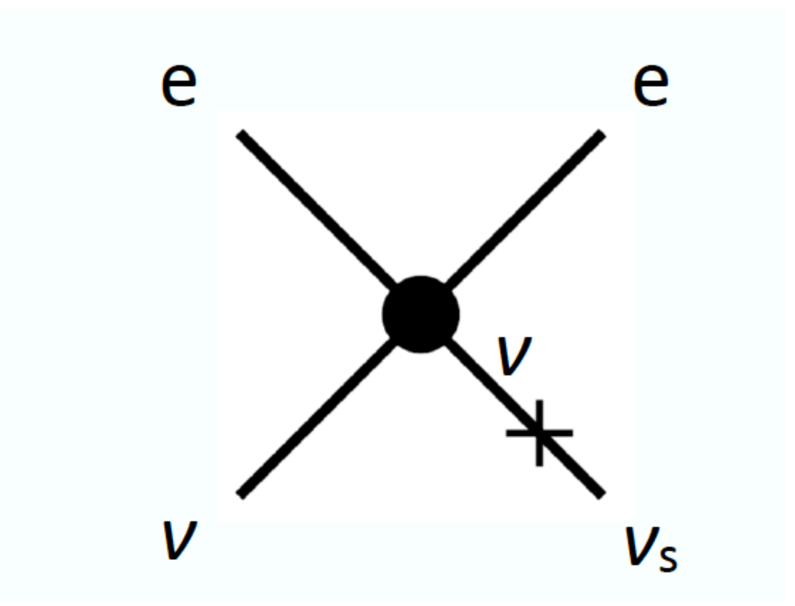
de Gouvêa, **MS**, Tangarife and Zhang (PRL 2020)

# The Dodelson-Widrow mechanism in the presence of NSSI

Relic ~ (interaction rate) X (mixing angle)

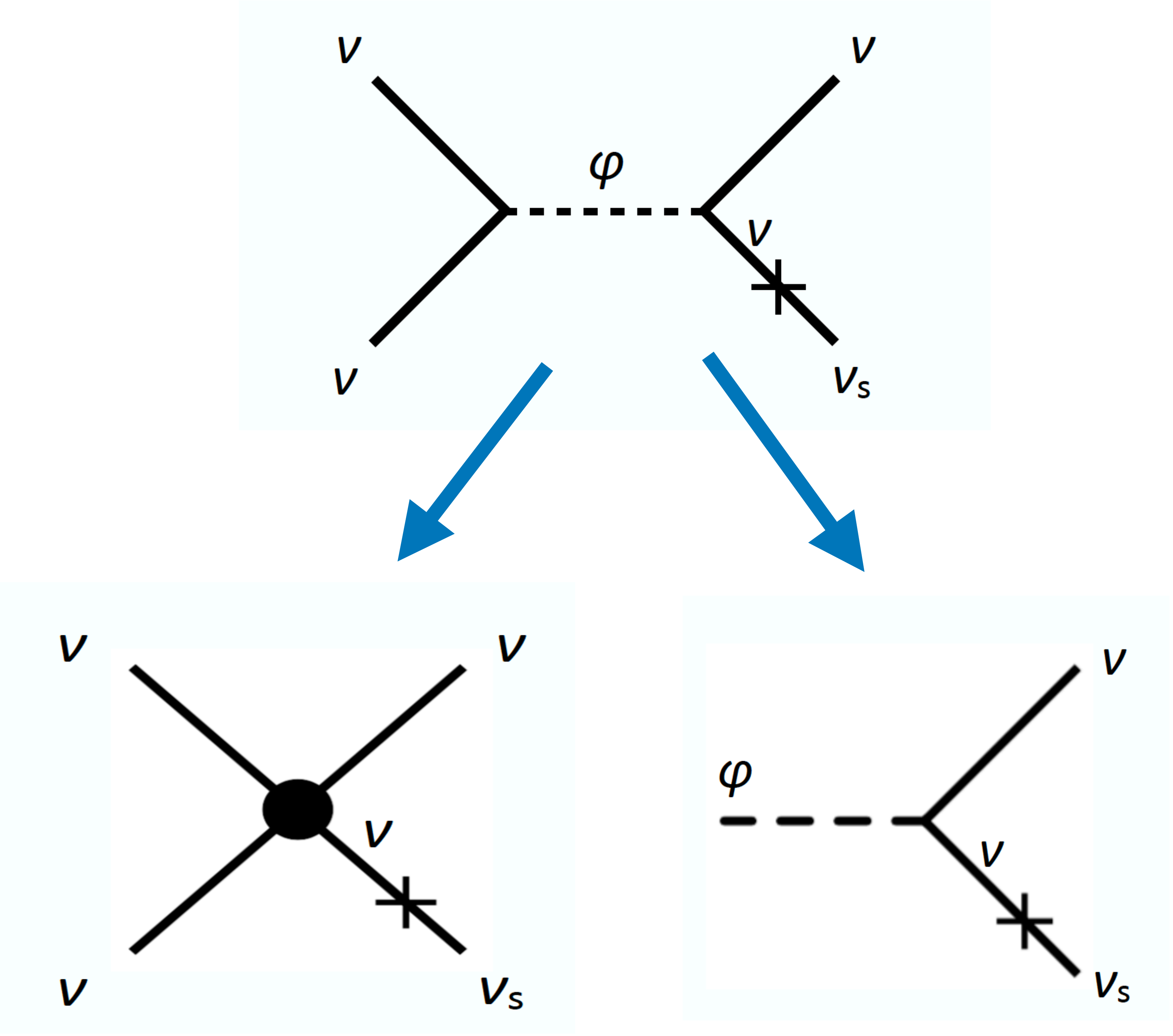
$$\mathscr{L}_\nu \supset \mathscr{L}_{SM} + \lambda_\varphi \nu_a \nu_a \varphi^*$$

S.M



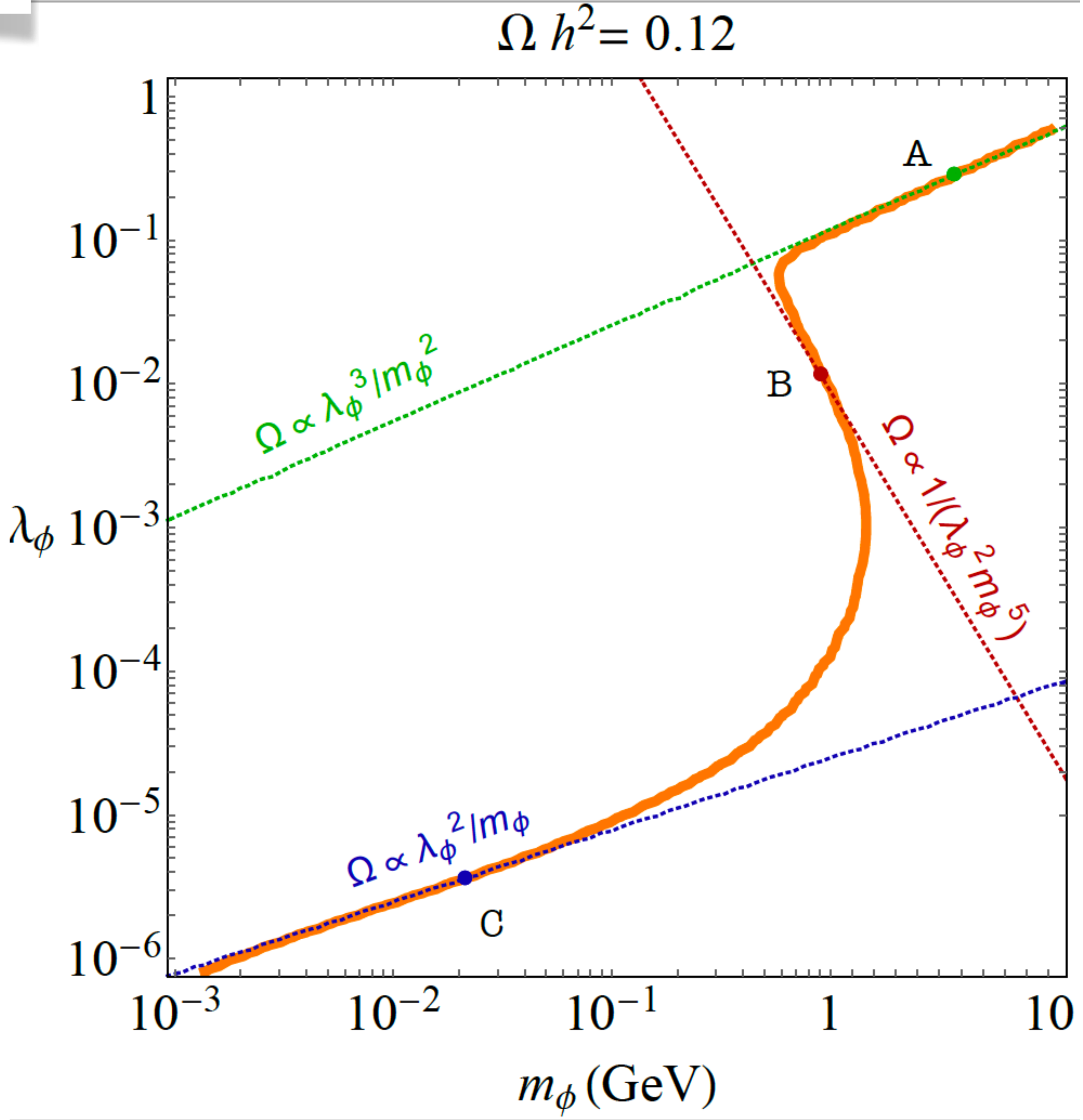

$M_{W,Z} \geq T_{peak}$

S.M + Self-Interactions



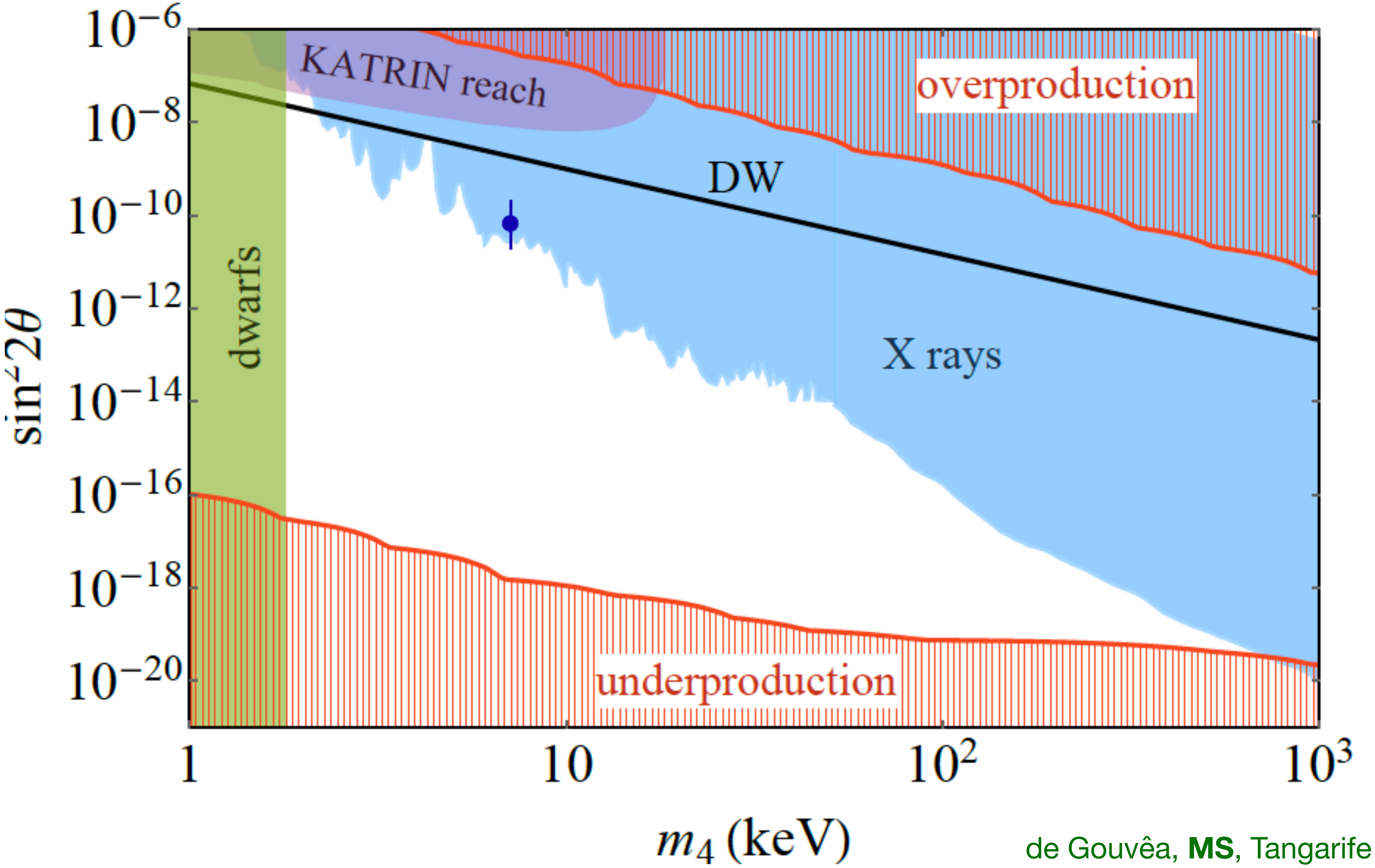

$M_\varphi > T_{peak}$

$M_\varphi \lesssim T_{peak}$




de Gouvêa, **MS**, Tangarife and Zhang (PRL 2020)

# The Dodelson-Widrow mechanism: revived




de Gouvêa, **MS**, Tangarife and Zhang (PRL 2020)

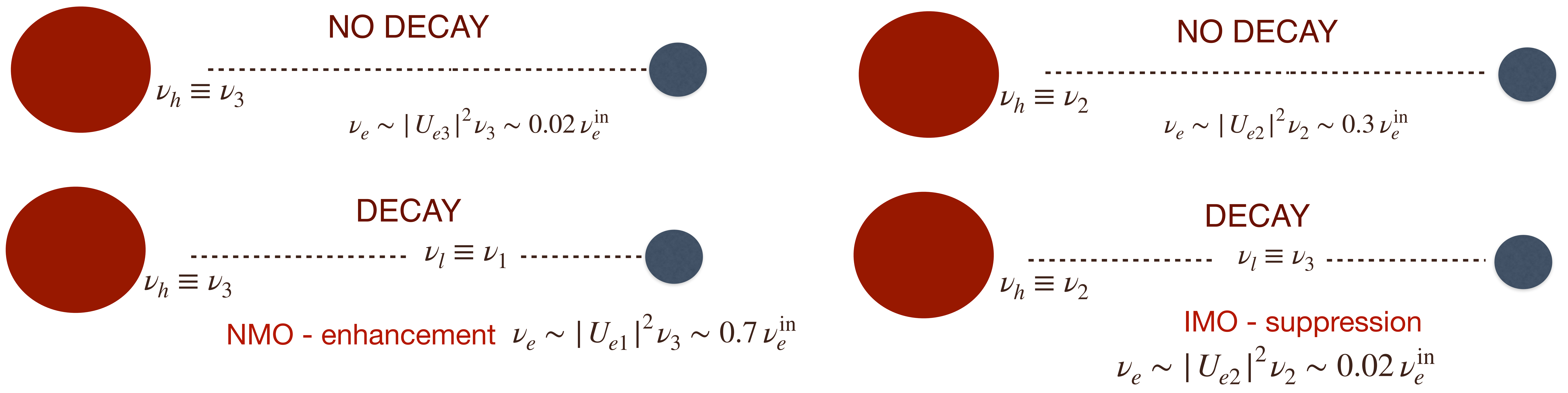
# Final thoughts

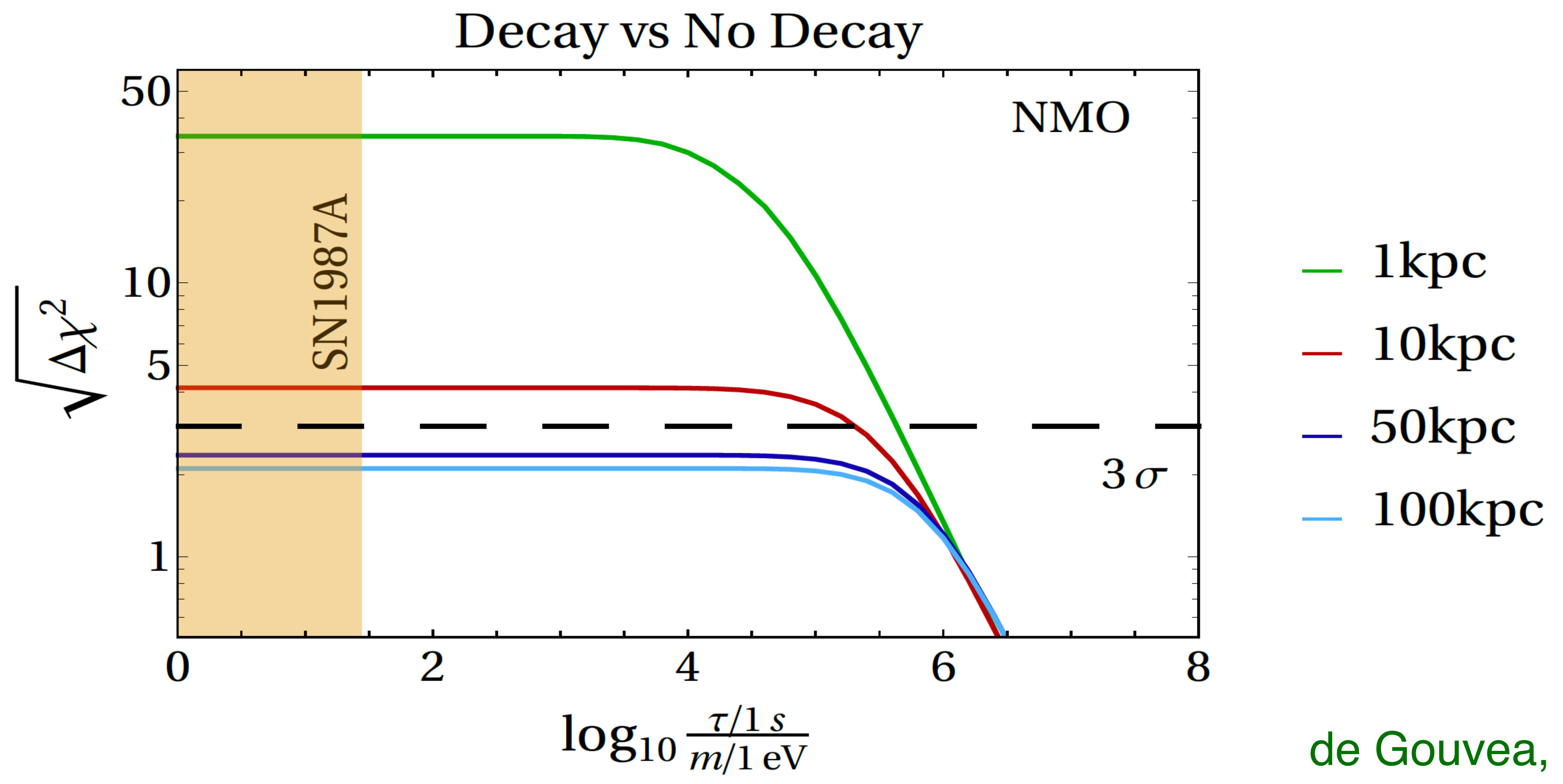
- Neutrinos present a definite clue of existence of non-standard physics - beyond the Standard Model.
- The origin of neutrino mass holds the key to this unexplored chamber of secrets.
- Ongoing terrestrial efforts aimed at testing non-standard properties of neutrinos.
- Extreme properties can only be tested with astrophysical and cosmological sources, due to the long baseline offered.
- Might give us a clue about the nature of dark matter - another unanswered avenue in the Standard Model.


NEUTRINO OSCILLATION WORKSHOP
STANDARD THREE-NEUTRINO OSCILLATIONS
BEYOND STANDARD NEUTRINO FRAMEWORK
NOW MMXXIV II-VIII · SEPTER HYDRUNTUM LECCE – ITALY
NEUTRINO MASSES STATES AND INTERACTIONS
PARTICLE PHYSICS FROM SKY AND COSMOS

# THANK YOU

# Neutrino decay

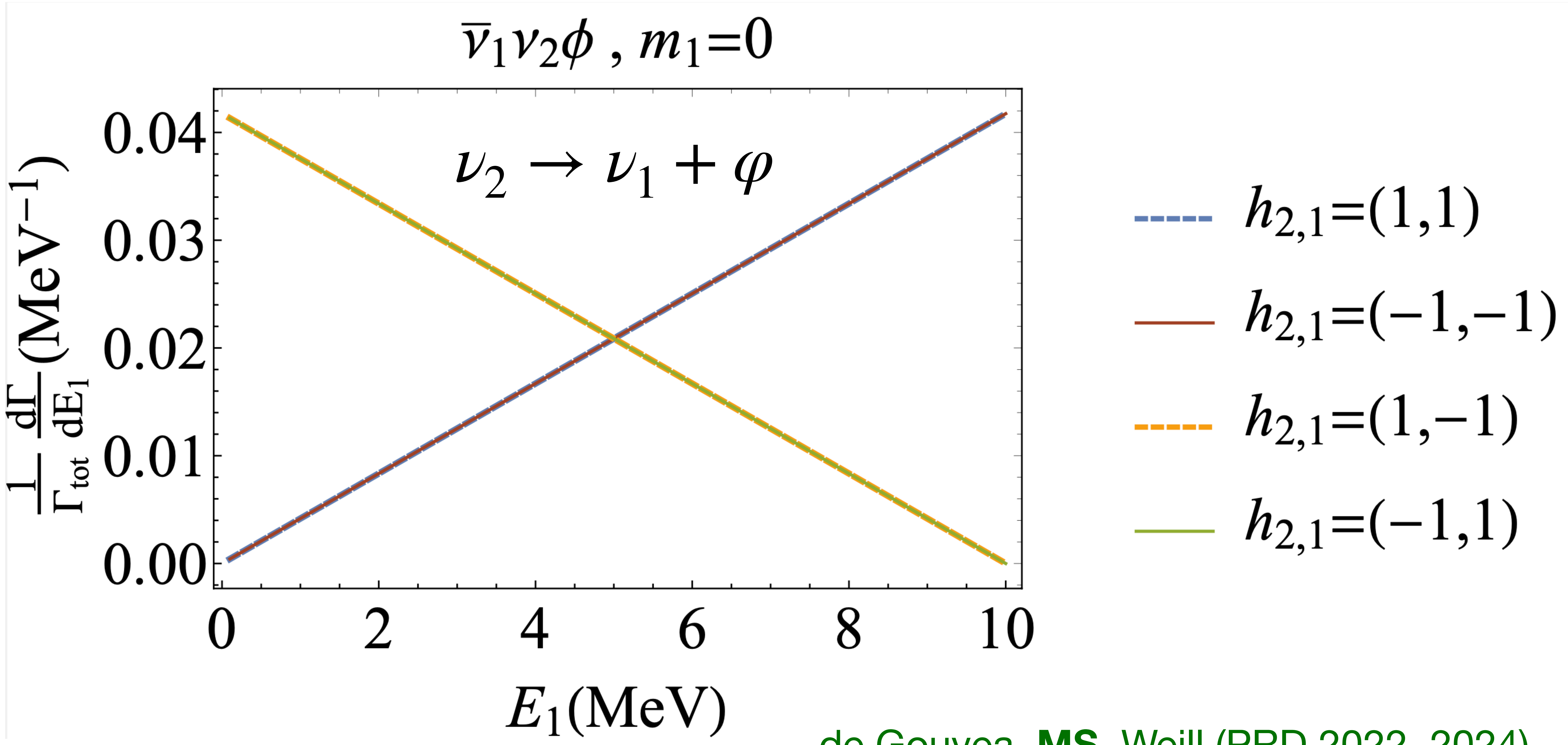


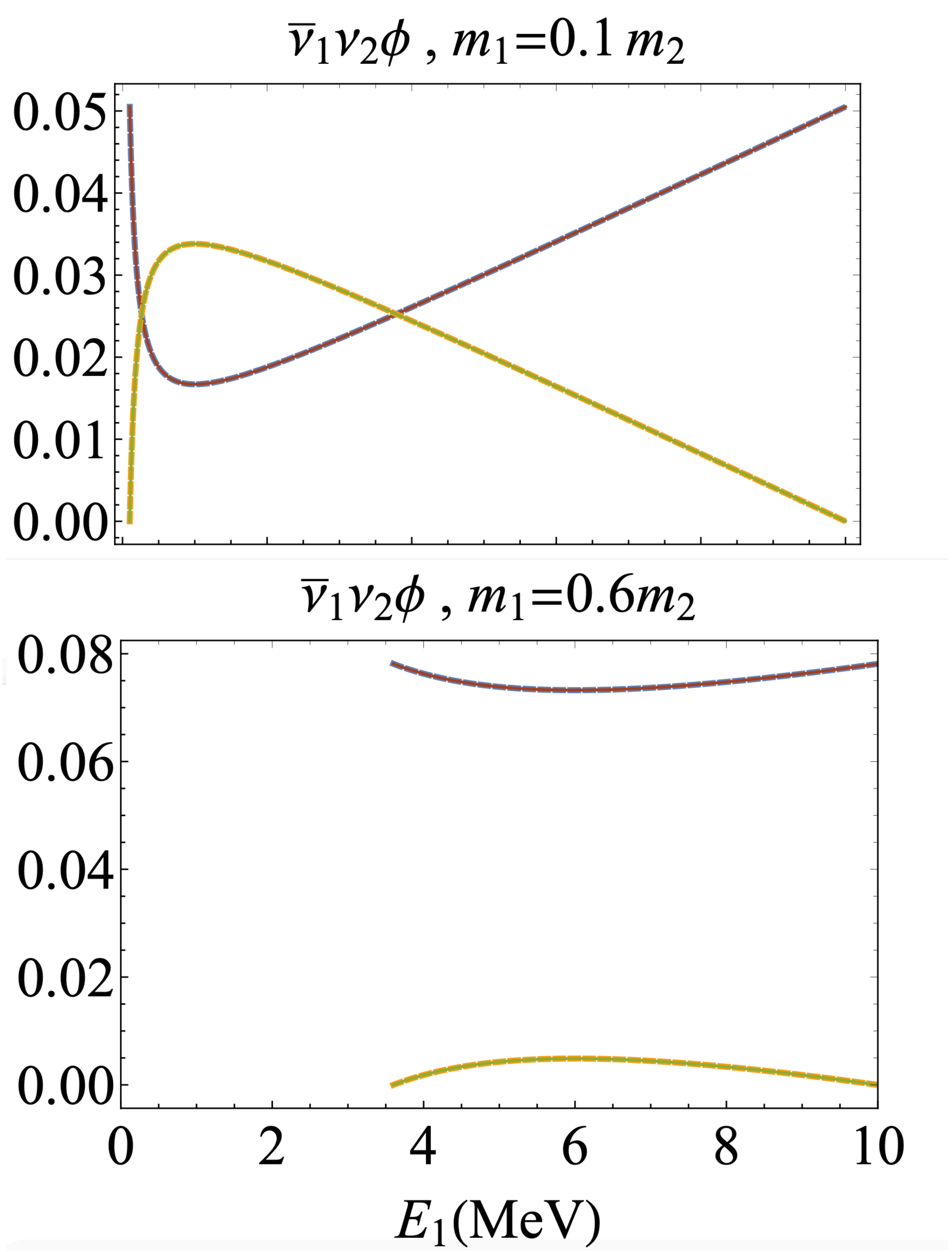

- Strongest bounds on non-standard neutrino decay $\nu_h \to \nu_l + \phi$
- Confuse mass ordering determination

de Gouvea, Martinez-Soler, **MS** (PRD 2019)

# Energy distribution of daughter particles



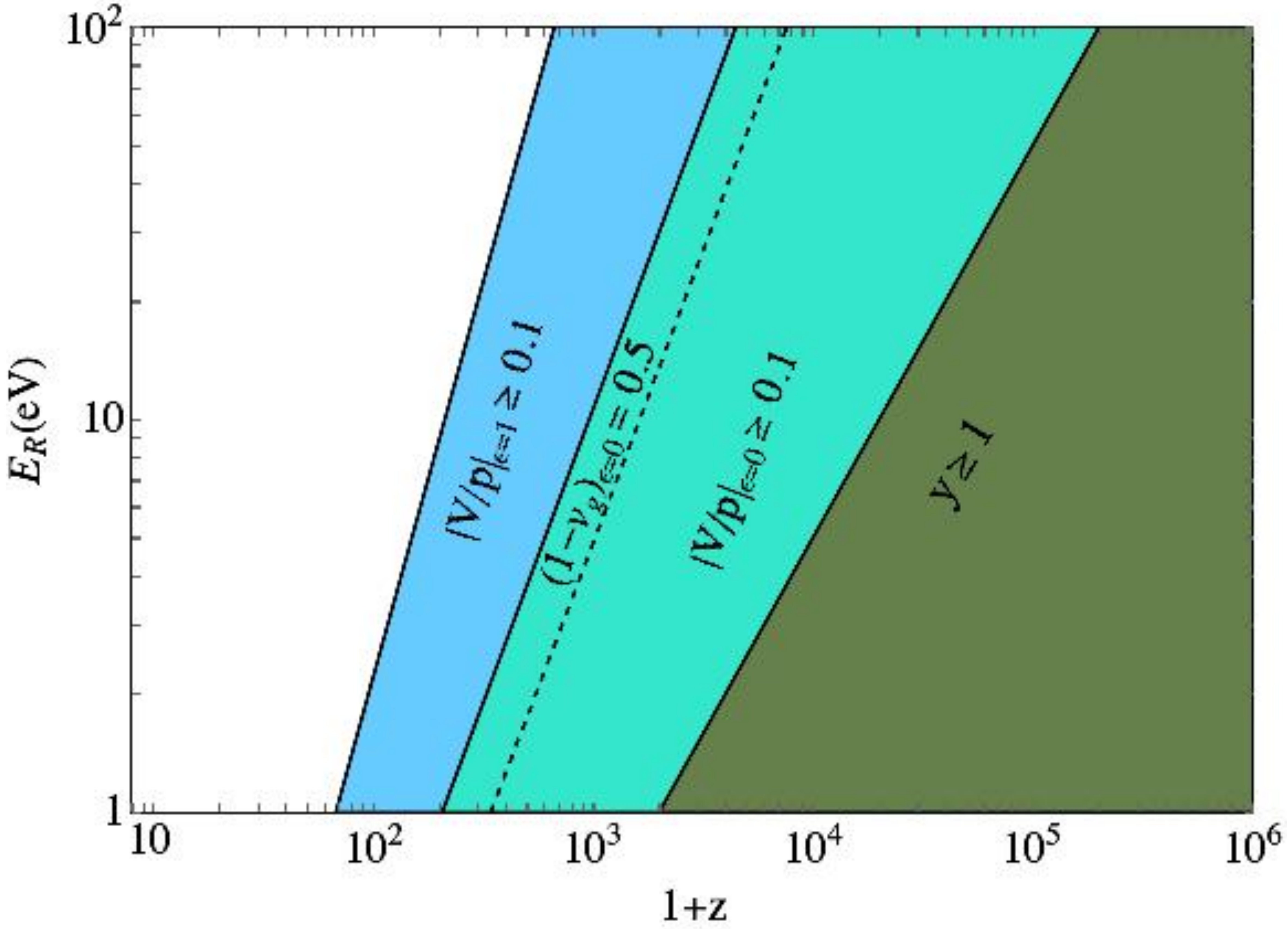

de Gouvea, **MS,** Weill (PRD 2022, 2024)

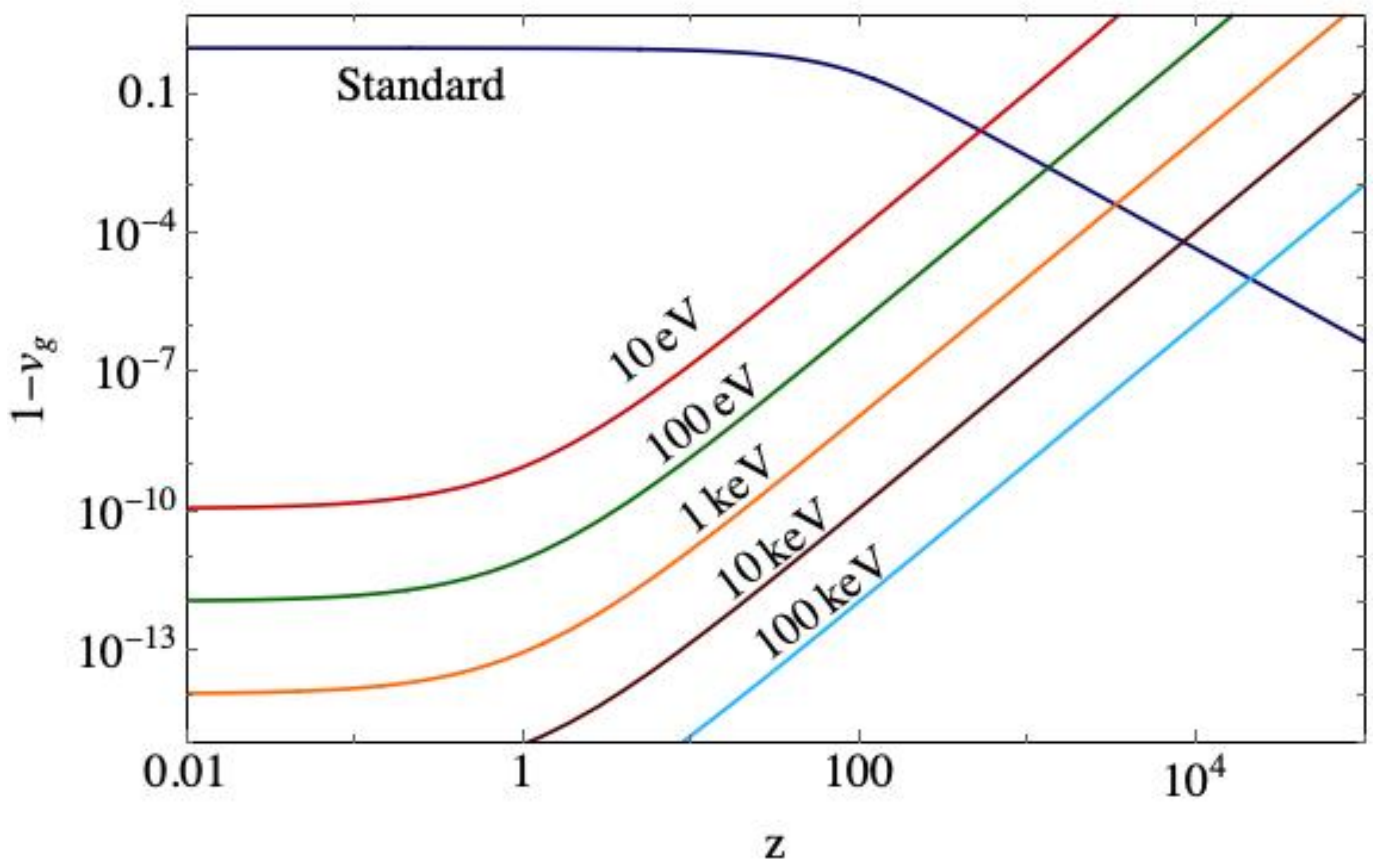



In $\nu_h$ rest frame, the daughter that shares the same helicity as the parent is emitted preferrentially along the parent helicity direction.

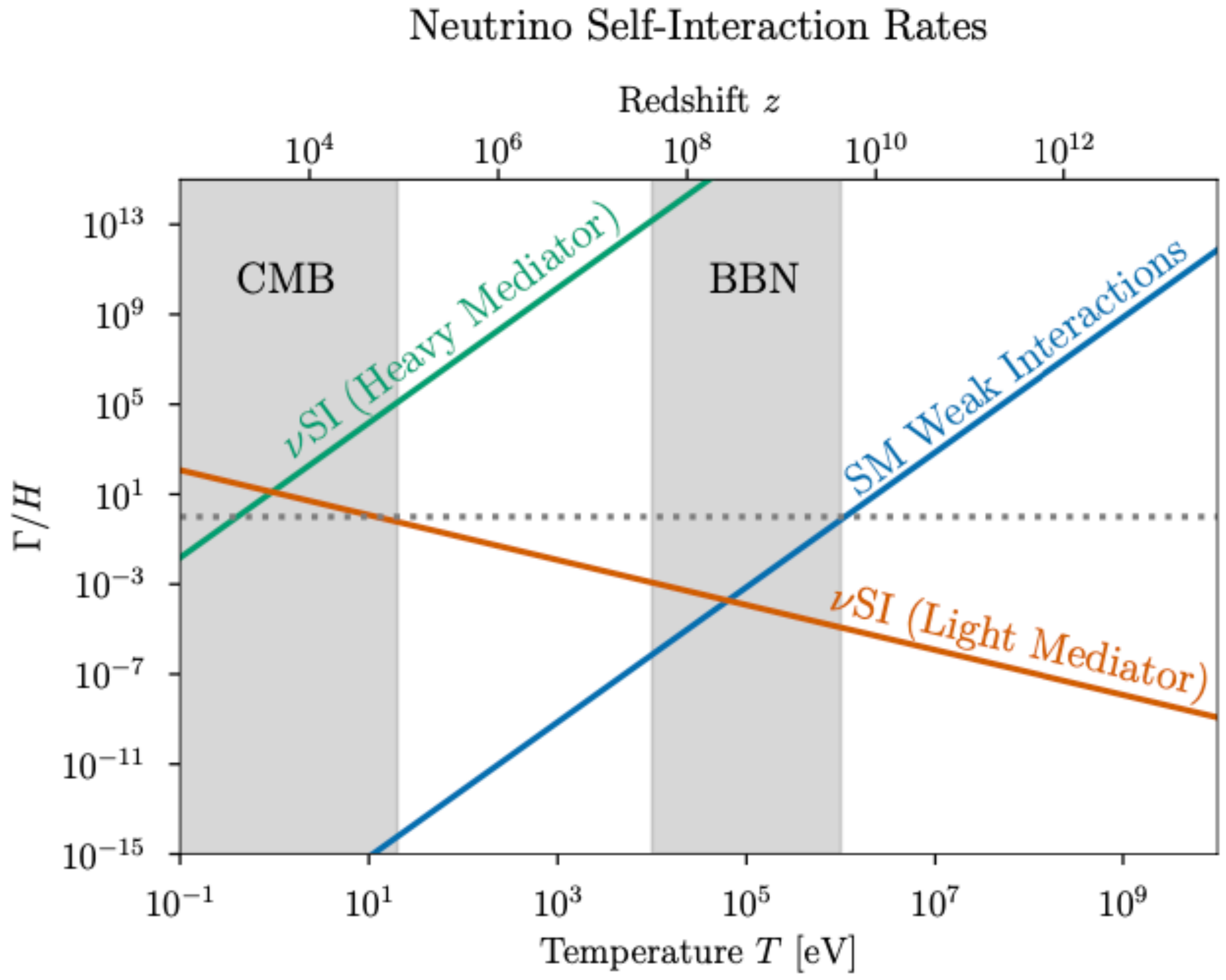
Effect of daughter mass

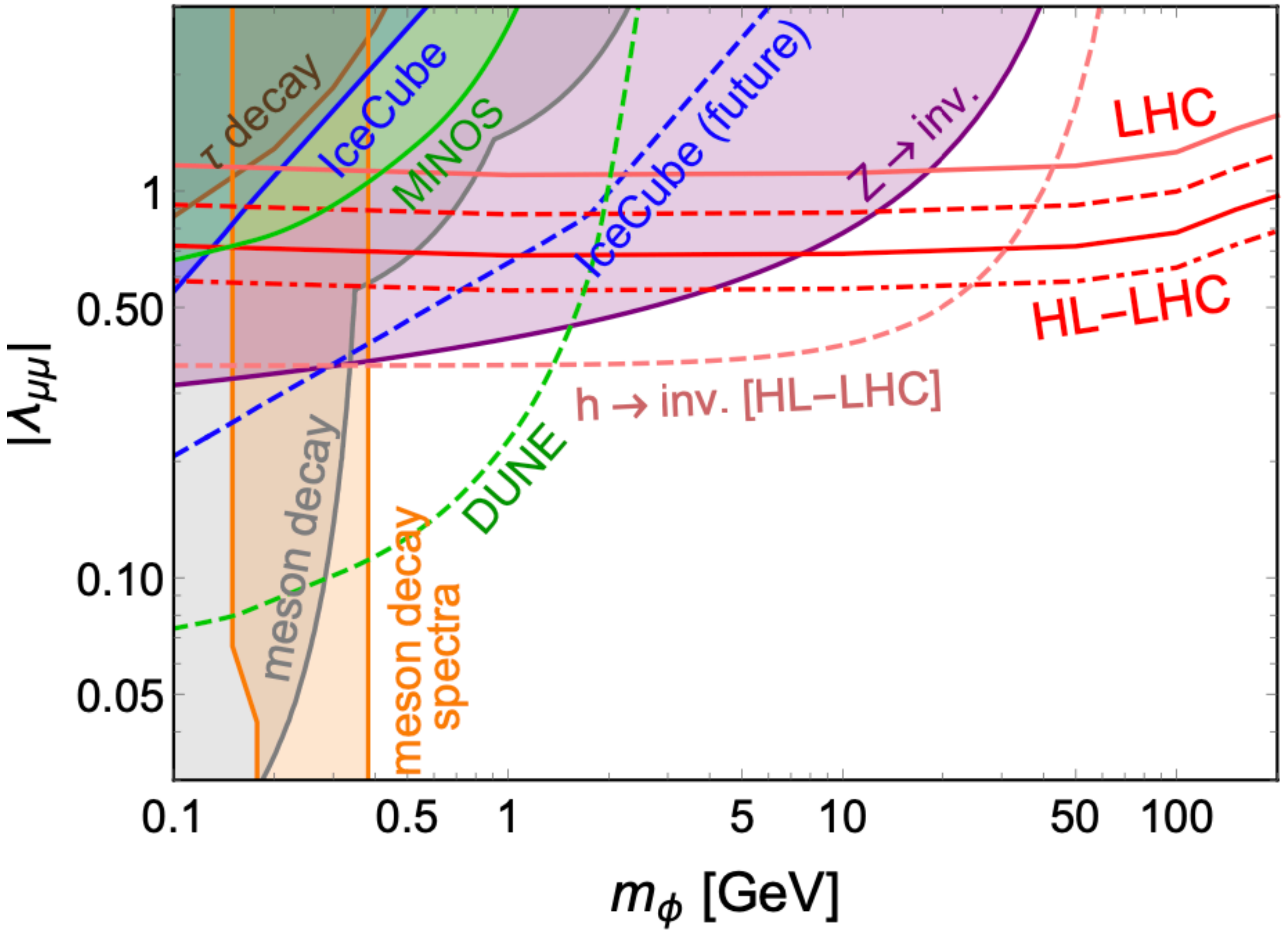
# DESI results



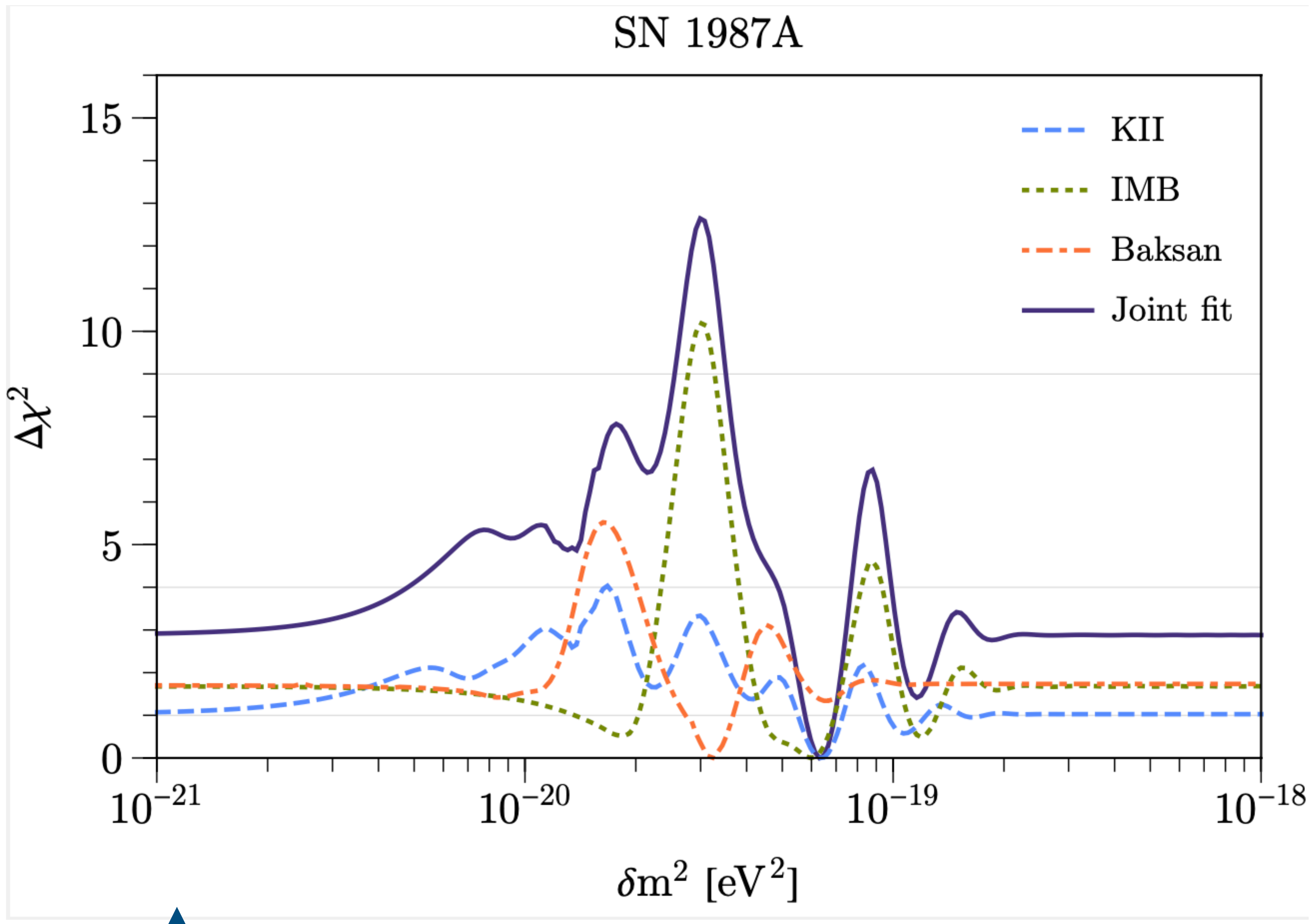



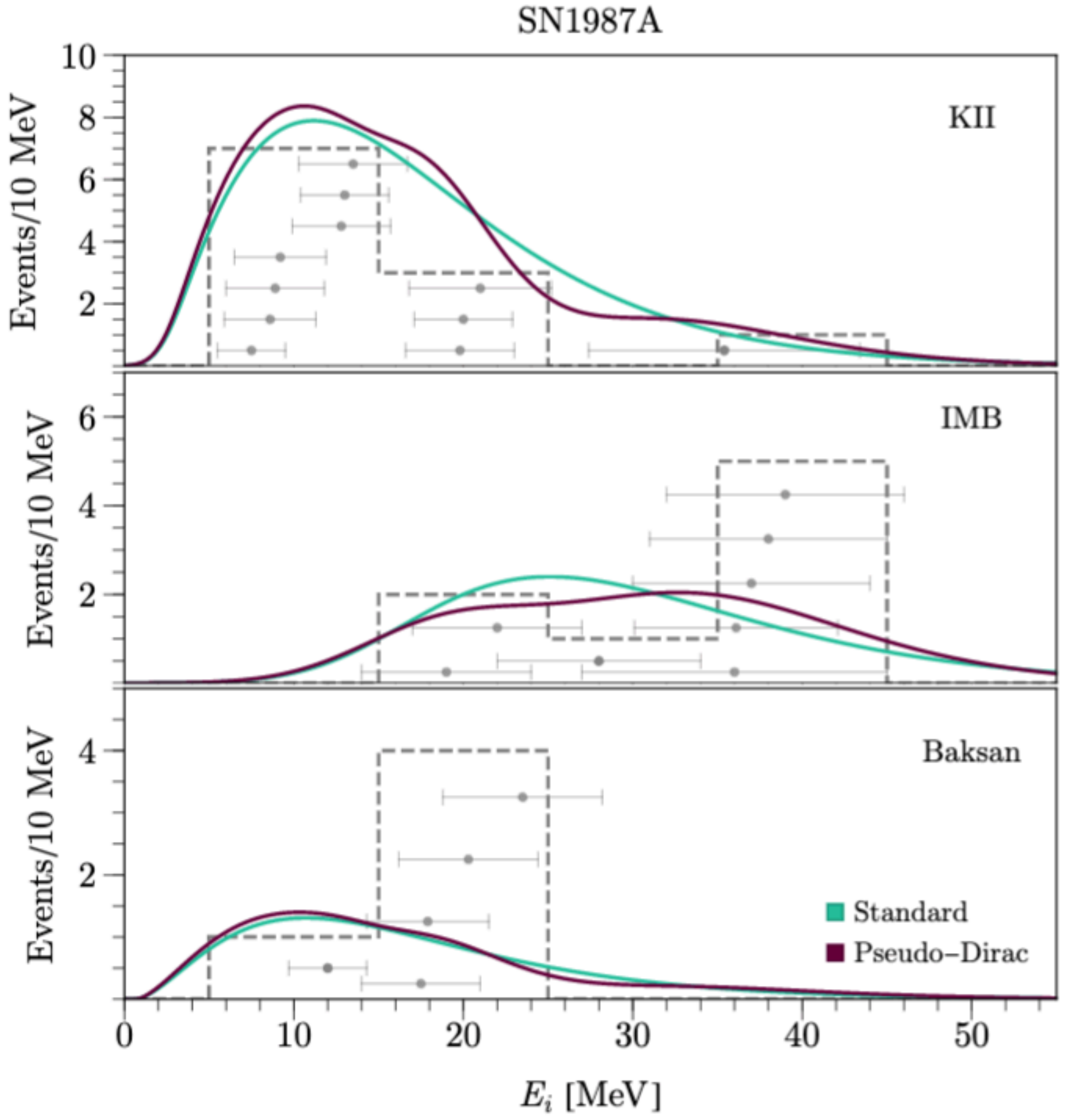
# Neutrino self-interactions



# SN1987A data and comparison



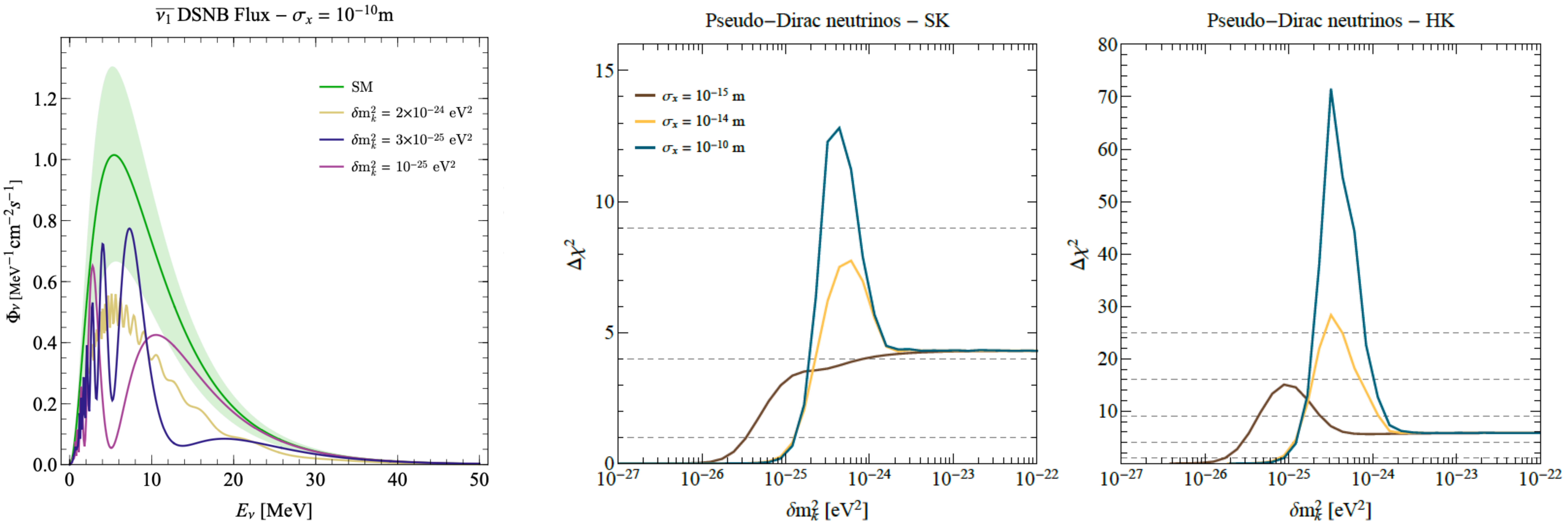




No Oscillations

Martinez-Soler, Perez-Gonzalez, **MS**, (PRD 2021)

- Slight preference for the PD possibility, $\Delta\chi^2 \sim 3$!
- Exclude $\delta m^2 \sim [2.5, 3.] \times 10^{-20}\text{eV}^2$ with $\Delta\chi^2 > 9$

# DSNB sensitivity to pseudo-Dirac neutrinos

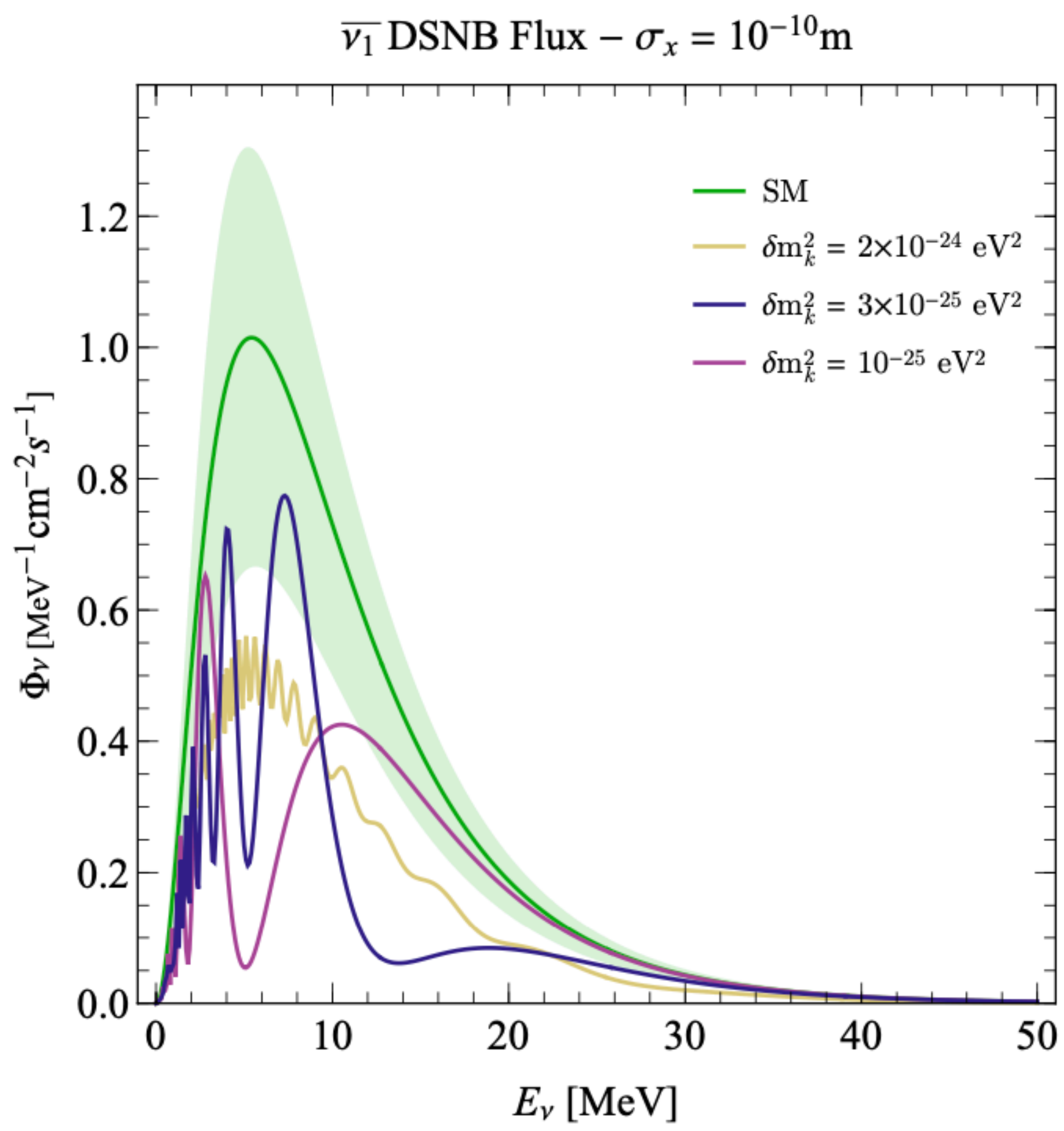


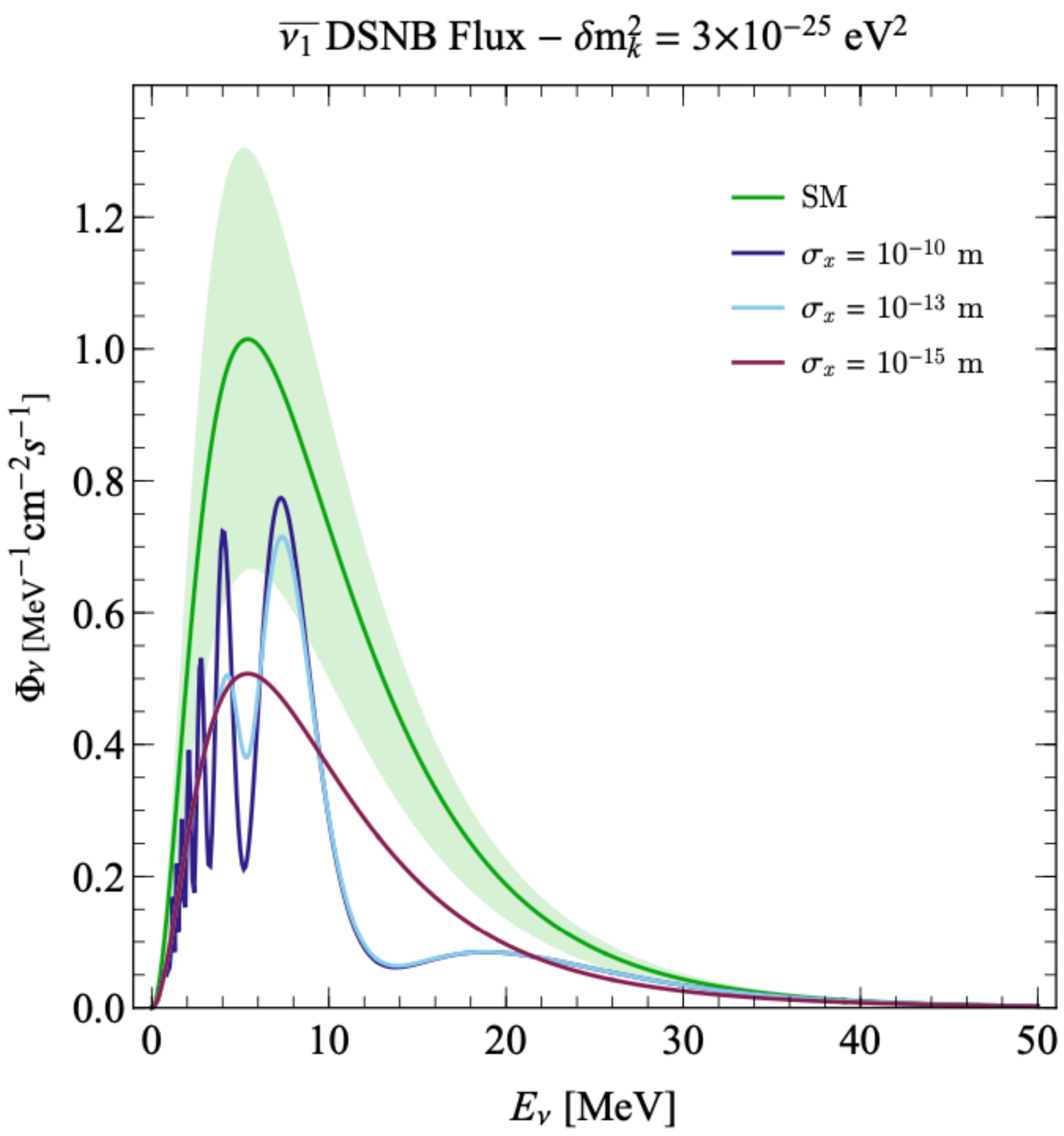

$$L_{\text{osc}} = \sim 16\,\text{Gpc}\left(\frac{E_\nu}{20\text{MeV}}\right)\left(\frac{10^{-25}\text{eV}^2}{\delta m^2}\right)$$

de Gouvea, Martinez-Soler, Perez-Gonzalez, **MS** (PRD 2020)

DSNB sensitive to $\delta m^2 \sim \mathcal{O}(10^{-25}\,\text{eV}^2)$ with a high significance.

# DSNB: Oscillations due to pseudo-Dirac nature

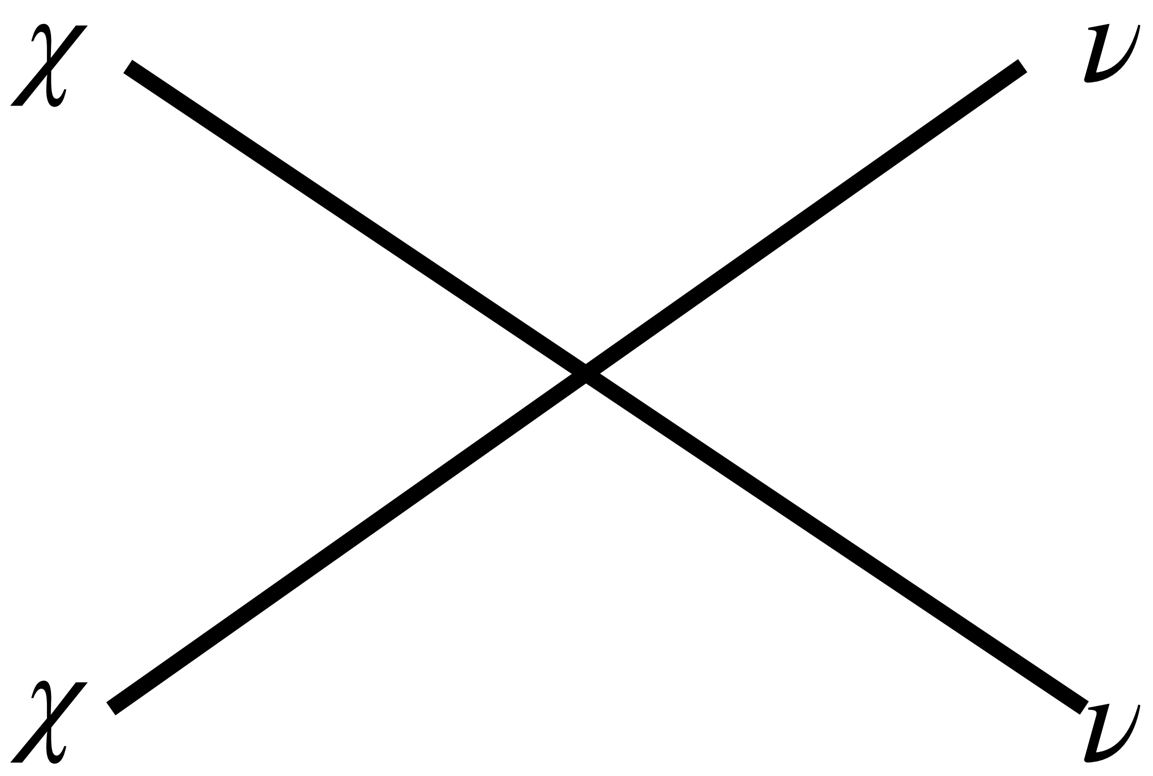


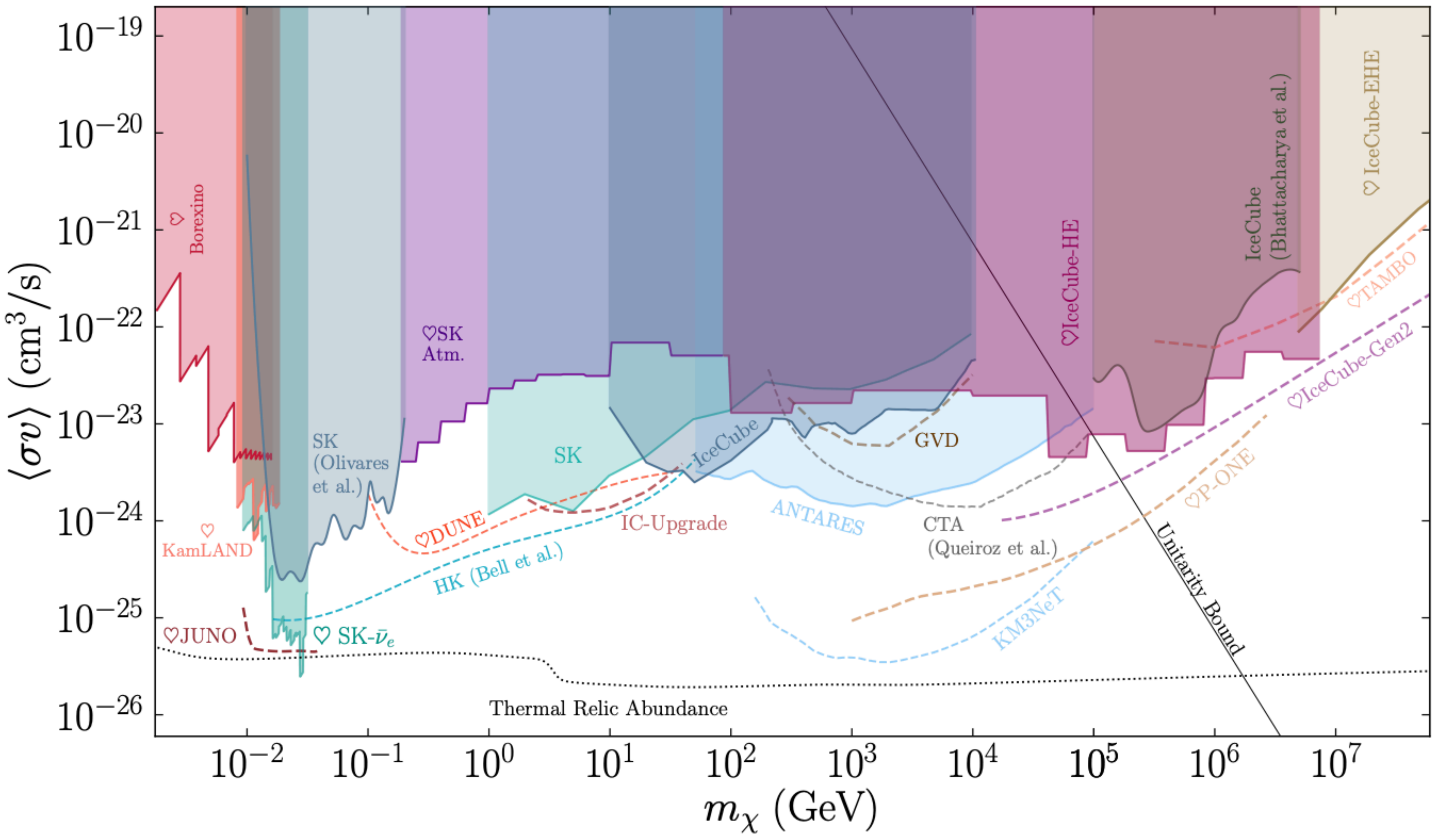




Increasing $\delta m^2$ reduces $L_{\rm osc}$ and $L_{\rm coh}$, and causes more oscillations

Decreasing $\sigma_x$ reduces $L_{\rm coh}$ , and causes more decoherence

# Dark Matter annihilations to neutrinos




Arguelles et al. (Rev. Mod. Phys, 2021)