

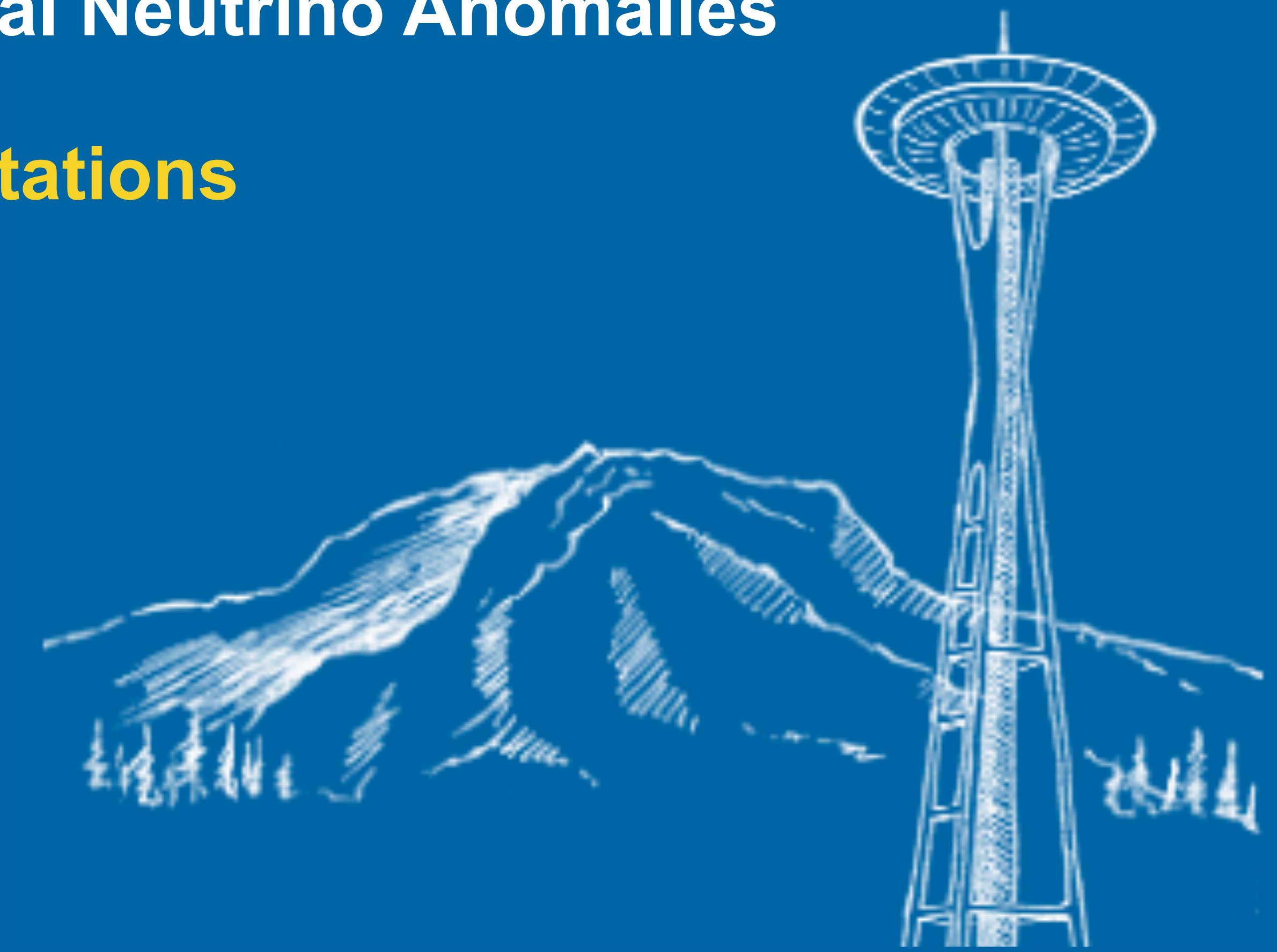
Neutrino Frontier 2022 — Experimental Neutrino Anomalies

Recent Theory Progress and Interpretations

Matheus Hostert

Perimeter Institute and University of Minnesota

For more details, see: NF02 WP arxiv.org/abs/2203.07323



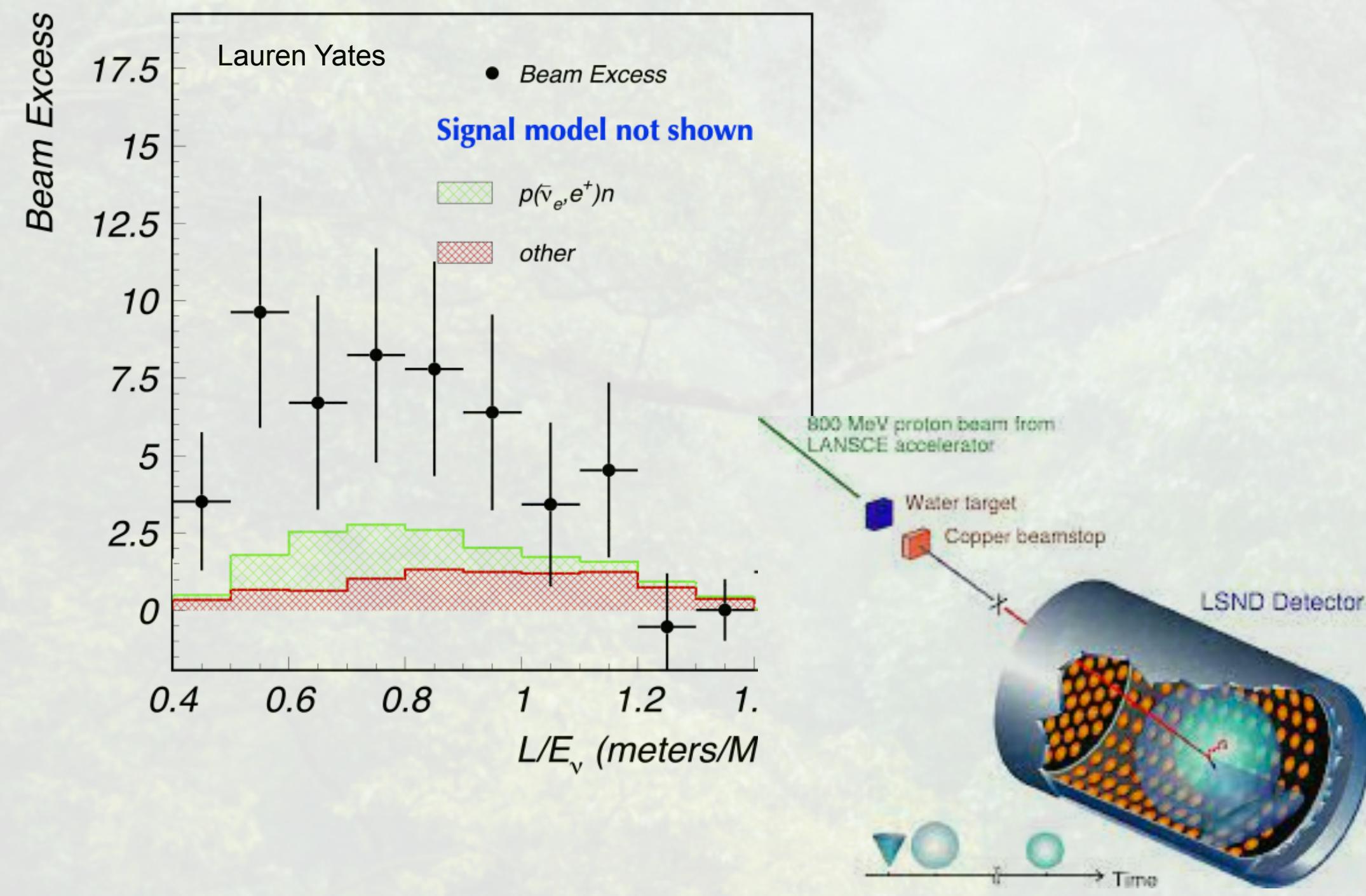
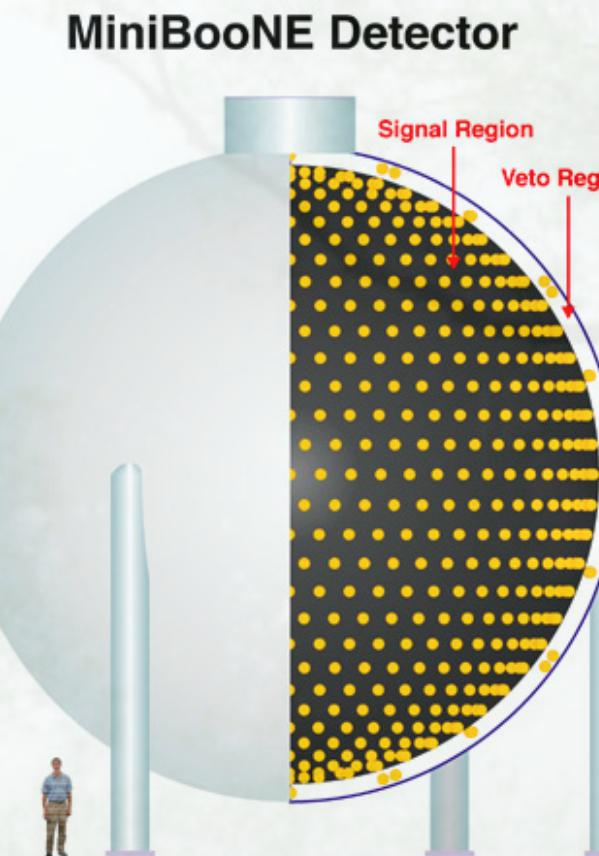
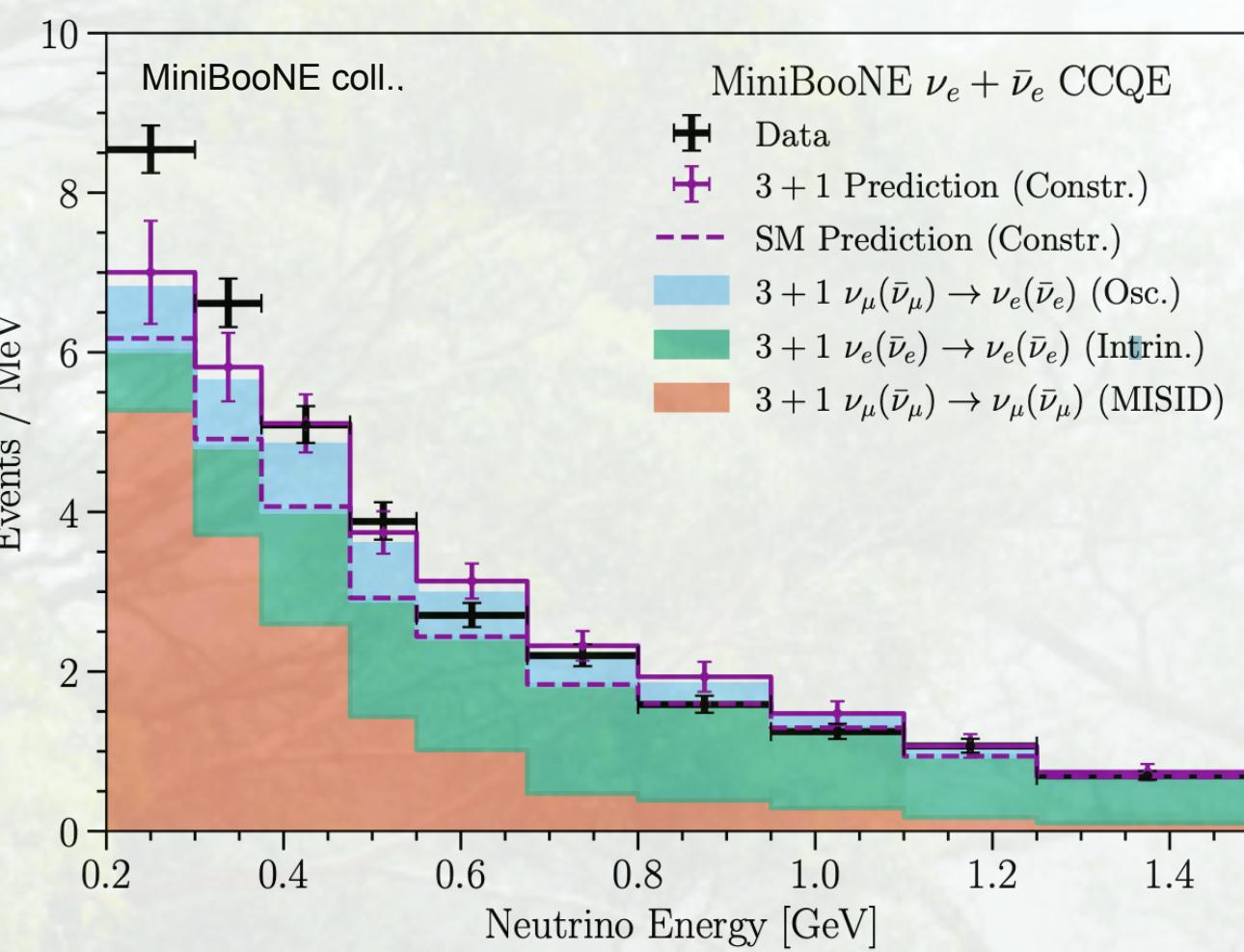
**Community Summer Study
Snowmass 2022
Seattle
July 21st**

The Outline

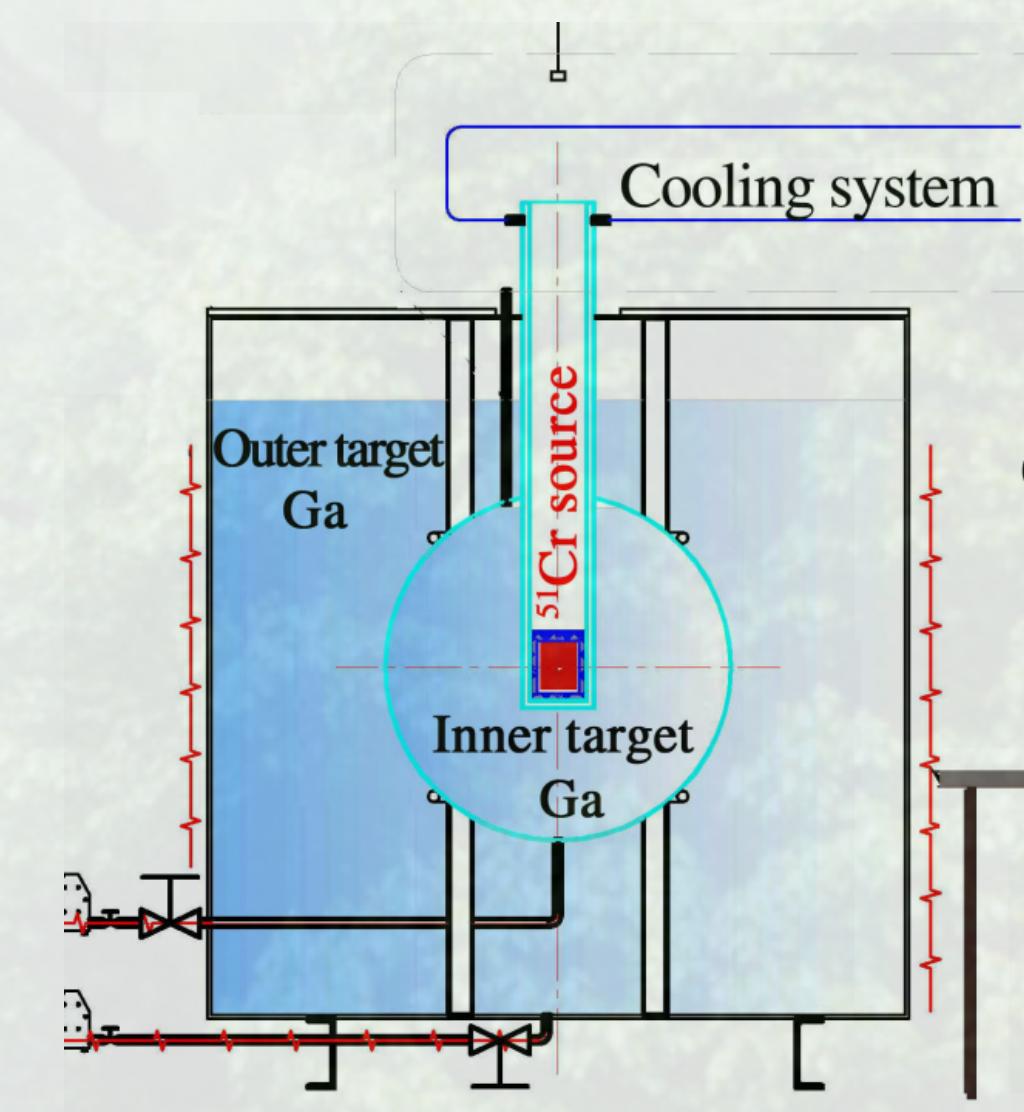
Short-baseline anomalies and the broader theory context.

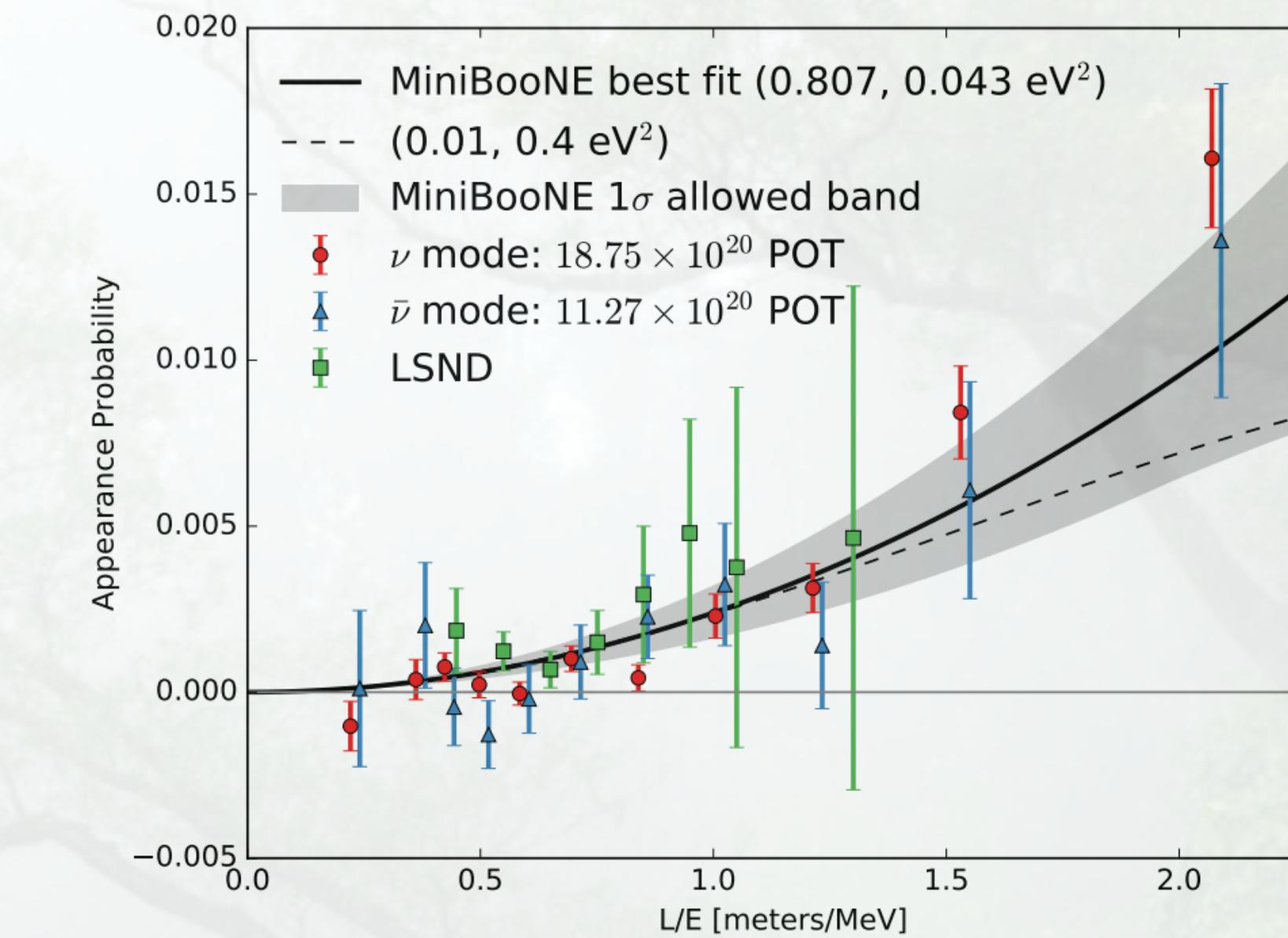
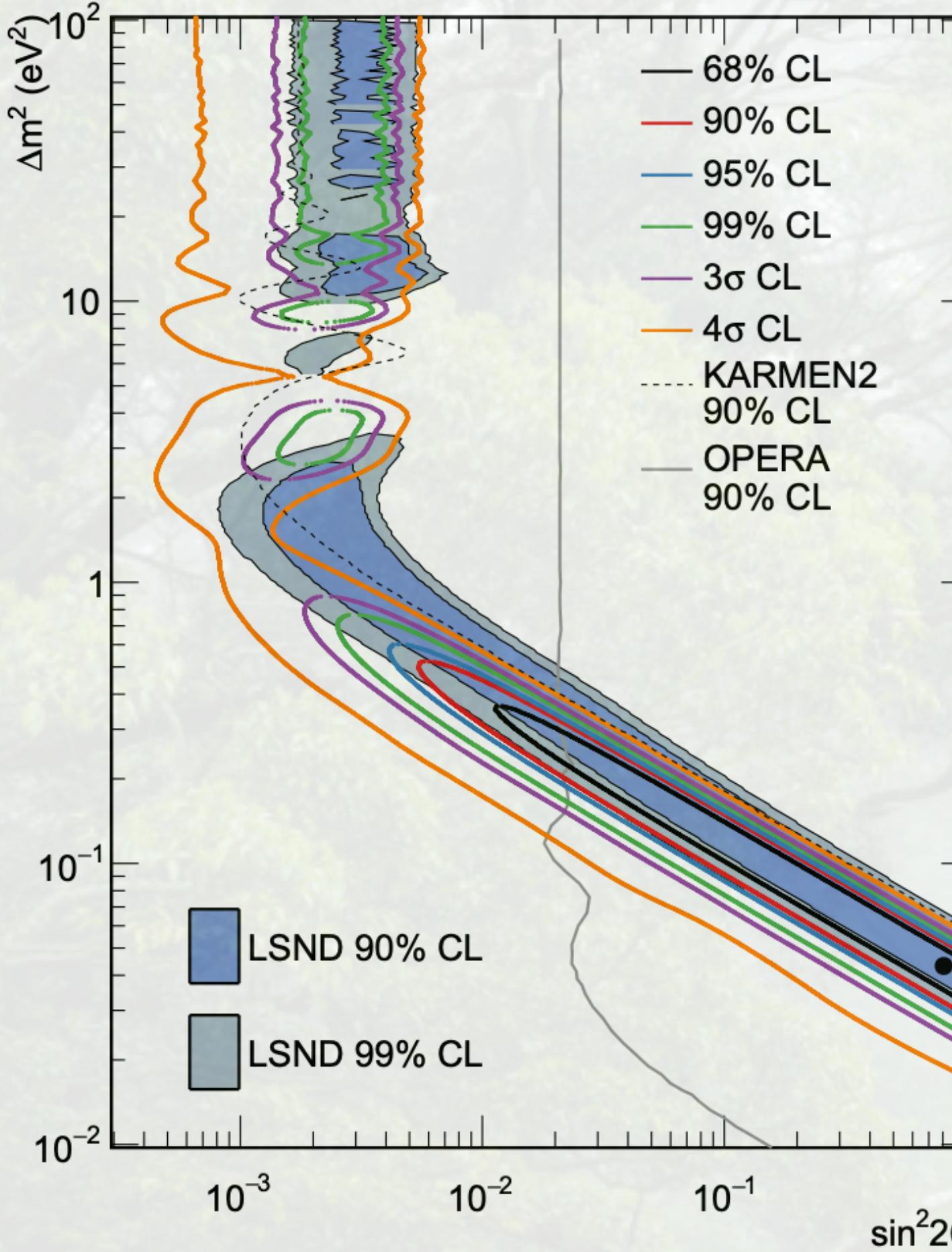
Some new ideas that have been proposed in the past decade.

New complementarity between experiments.

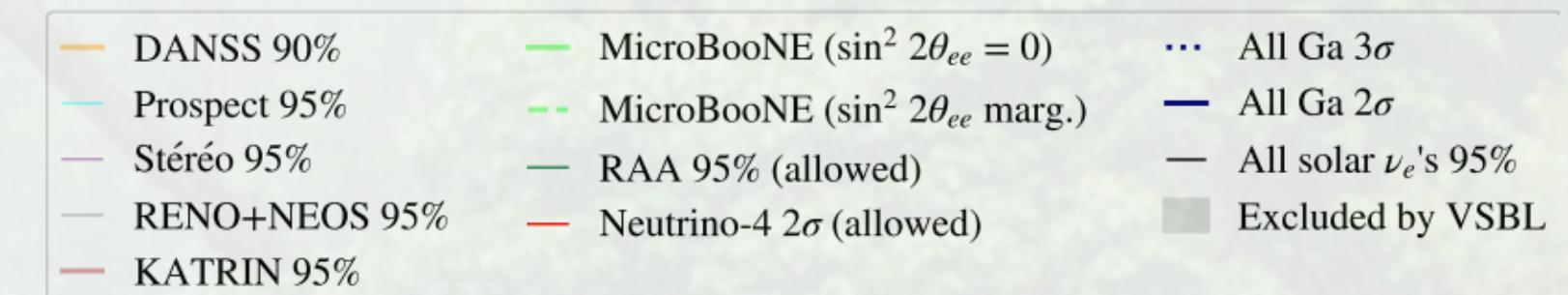


Global Picture?



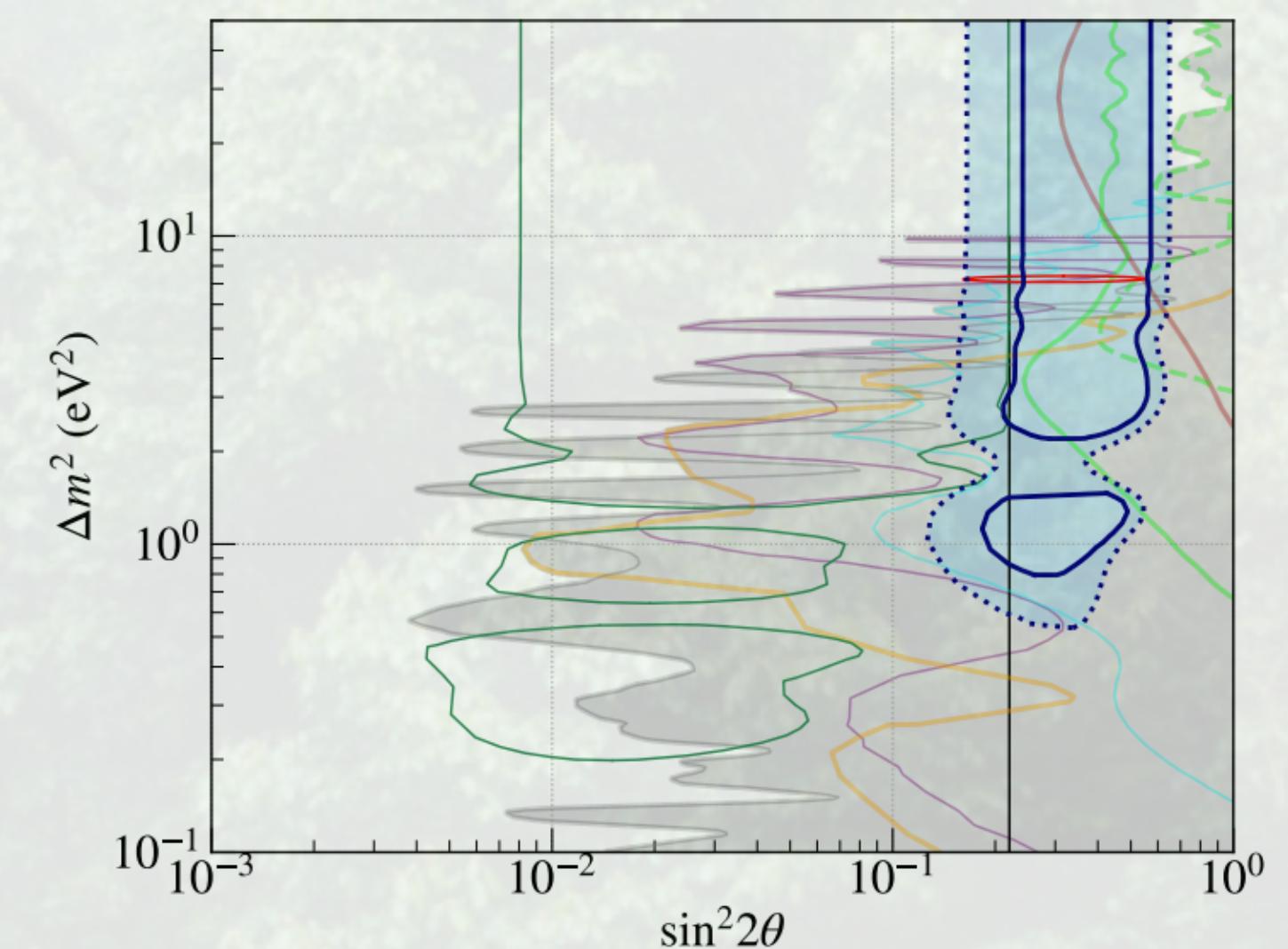


Are oscillations the right picture?



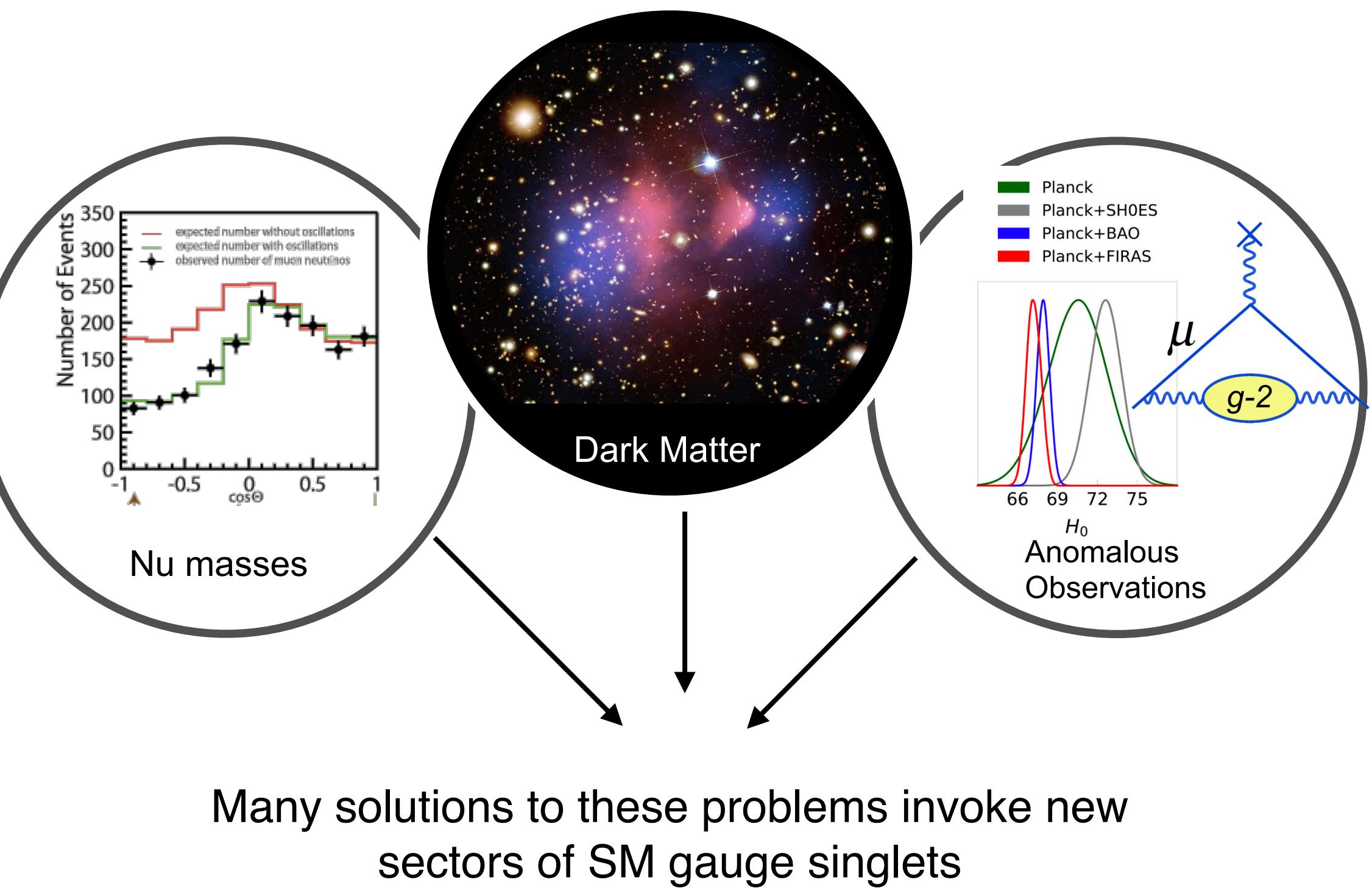
A lot of effort has been put into interpretations that connect all SBL anomalies with similar L/E, but no coherent picture has emerged.

In the past decade, the community has looked at the broader landscape in HEP and suggested new interpretations.

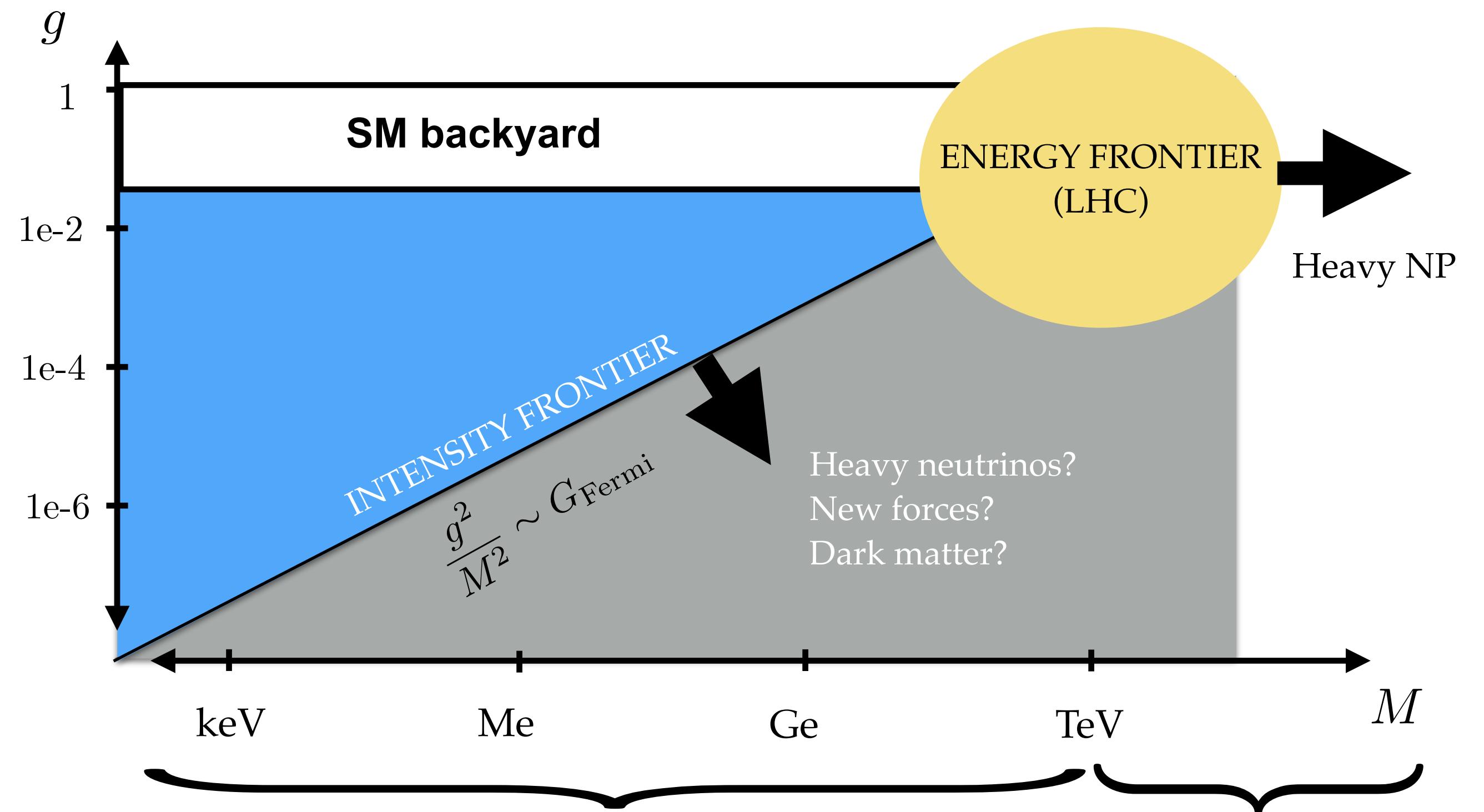


Novel approaches to new physics searches.

Dark sectors and light particles



New light states **feebly coupled to the SM**:
Makes sense if new sector is “secluded”.



Growing interest in low-scale extensions:
Lee-Weinberg argument for light mediators in dark sectors, testability, naturalness, pNG bosons.

Indirect tests:
EFT and complementary probes

Multi-prong approach

If new physics is secluded and weakly coupled to SM, it would make sense that it would take us a long time to find it.

It would also make sense that even with the first indications of BSM, we would take our time to claim any discoveries — extraordinary claim.

The plan of attack has been multi-pronged:

Theory: lay out “reasonable” theory landscape.

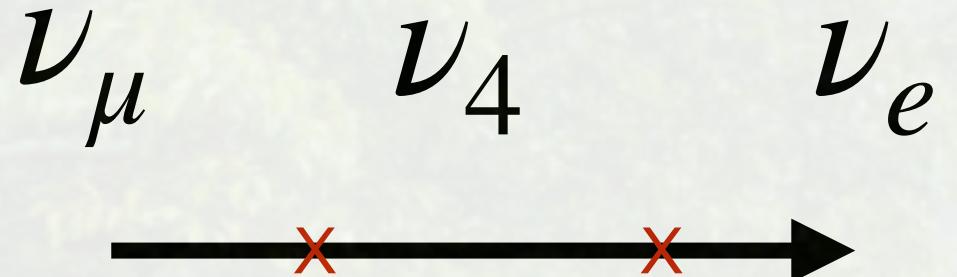
Experiment: combine existing data from oscillations and direct searches to cover it.

SBL anomaly interpretations

Model landscape evolved significantly over the years.

Category	Model	Signature	Anomalies				References
			LSND	MiniBooNE	Reactors	Sources	
Flavor transitions Secs. 3.1.1-3.1.3, 3.1.5	(3+1) oscillations	oscillations	✓	✓	✓	✓	Reviews and global fits [93, 103, 105, 106]
	(3+1) w/ invisible sterile decay	oscillations w/ ν_4 invisible decay	✓	✓	✓	✓	[151, 155]
	(3+1) w/ sterile decay	$\nu_4 \rightarrow \phi \nu_e$	✓	✓	✗	✗	[159–162, 270]
Matter effects Secs. 3.1.4, 3.1.7	(3+1) w/ anomalous matter effects	$\nu_\mu \rightarrow \nu_e$ via matter effects	✓	✓	✗	✗	[143, 147, 271–273]
	(3+1) w/ quasi-sterile neutrinos	$\nu_\mu \rightarrow \nu_e$ w/ resonant ν_s matter effects	✓	✓	✓	✓	[148]
Flavor violation Sec. 3.1.6	Lepton-flavor-violating μ decays	$\mu^+ \rightarrow e^+ \nu_\alpha \bar{\nu}_e$	✓	✗	✗	✗	[174, 175, 274]
	neutrino-flavor-changing bremsstrahlung	$\nu_\mu A \rightarrow e \phi A$	✓	✓	✗	✗	[275]
Decays in flight Sec. 3.2.3	Transition magnetic mom., heavy ν decay	$N \rightarrow \nu \gamma$	✗	✓	✗	✗	[207]
	Dark sector heavy neutrino decay	$N \rightarrow \nu (X \rightarrow e^+ e^-)$ or $N \rightarrow \nu (X \rightarrow \gamma\gamma)$	✗	✓	✗	✗	[208]
Neutrino Scattering Secs. 3.2.1, 3.2.2	neutrino-induced upscattering	$\nu A \rightarrow N A$, $N \rightarrow \nu e^+ e^-$ or $N \rightarrow \nu \gamma \gamma$	✗	✓	✗	✗	[205, 206, 209–216]
	neutrino dipole upscattering	$\nu A \rightarrow N A$, $N \rightarrow \nu \gamma$	✗	✓	✗	✗	[40, 185, 187, 188, 190, 193, 233, 276]
Dark Matter Scattering Sec. 3.2.4	dark particle-induced upscattering	γ or $e^+ e^-$	✗	✓	✗	✗	[217]
	dark particle-induced inverse Primakoff	γ	✓	✓	✗	✗	[217]

Flavor Transitions



Category	Model	Signature	Anomalies				References
			LSND	MiniBooNE	Reactors	Sources	
Flavor transitions Secs. 3.1.1-3.1.3, 3.1.5	(3+1) oscillations	oscillations	✓	✓	✓	✓	Reviews and global fits [93, 103, 105, 106]
	(3+1) w/ invisible sterile decay	oscillations w/ ν_4 invisible decay	✓	✓	✓	✓	[151, 155]
	(3+1) w/ sterile decay	$\nu_4 \rightarrow \phi \nu_e$	✓	✓	✗	✗	[159–162, 270]
Matter effects Secs. 3.1.4, 3.1.7	(3+1) w/ anomalous matter effects	$\nu_\mu \rightarrow \nu_e$ via matter effects	✓	✓	✗	✗	[143, 147, 271–273]
	(3+1) w/ quasi-sterile neutrinos	$\nu_\mu \rightarrow \nu_e$ w/ resonant ν_s matter effects	✓	✓	✓	✓	[148]
Flavor violation Sec. 3.1.6	Lepton-flavor-violating μ decays	$\mu^+ \rightarrow e^+ \nu_\alpha \bar{\nu}_e$	✓	✗	✗	✗	[174, 175, 274]
	neutrino-flavor-changing bremsstrahlung	$\nu_\mu A \rightarrow e \phi A$	✓	✓	✗	✗	[275]
Decays in flight Sec. 3.2.3	Transition magnetic mom., heavy ν decay	$N \rightarrow \nu \gamma$	✗	✓	✗	✗	[207]
	Dark sector heavy neutrino decay	$N \rightarrow \nu (X \rightarrow e^+ e^-)$ or $N \rightarrow \nu (X \rightarrow \gamma\gamma)$	✗	✓	✗	✗	[208]
Neutrino Scattering Secs. 3.2.1, 3.2.2	neutrino-induced upscattering	$\nu A \rightarrow N A$, $N \rightarrow \nu e^+ e^-$ or $N \rightarrow \nu \gamma \gamma$	✗	✓	✗	✗	[205, 206, 209–216]
	neutrino dipole upscattering	$\nu A \rightarrow N A$, $N \rightarrow \nu \gamma$	✗	✓	✗	✗	[40, 185, 187, 188, 190, 193, 233, 276]
Dark Matter Scattering Sec. 3.2.4	dark particle-induced upscattering	γ or $e^+ e^-$	✗	✓	✗	✗	[217]
	dark particle-induced inverse Primakoff	γ	✓	✓	✗	✗	[217]

3+1 neutrino oscillations

Appearance versus disappearance data

Effectively a 2-neutrino oscillation system: $\Delta \equiv 1.27 \frac{\Delta m^2 [\text{eV}^2] L [\text{m}]}{E [\text{MeV}]}$

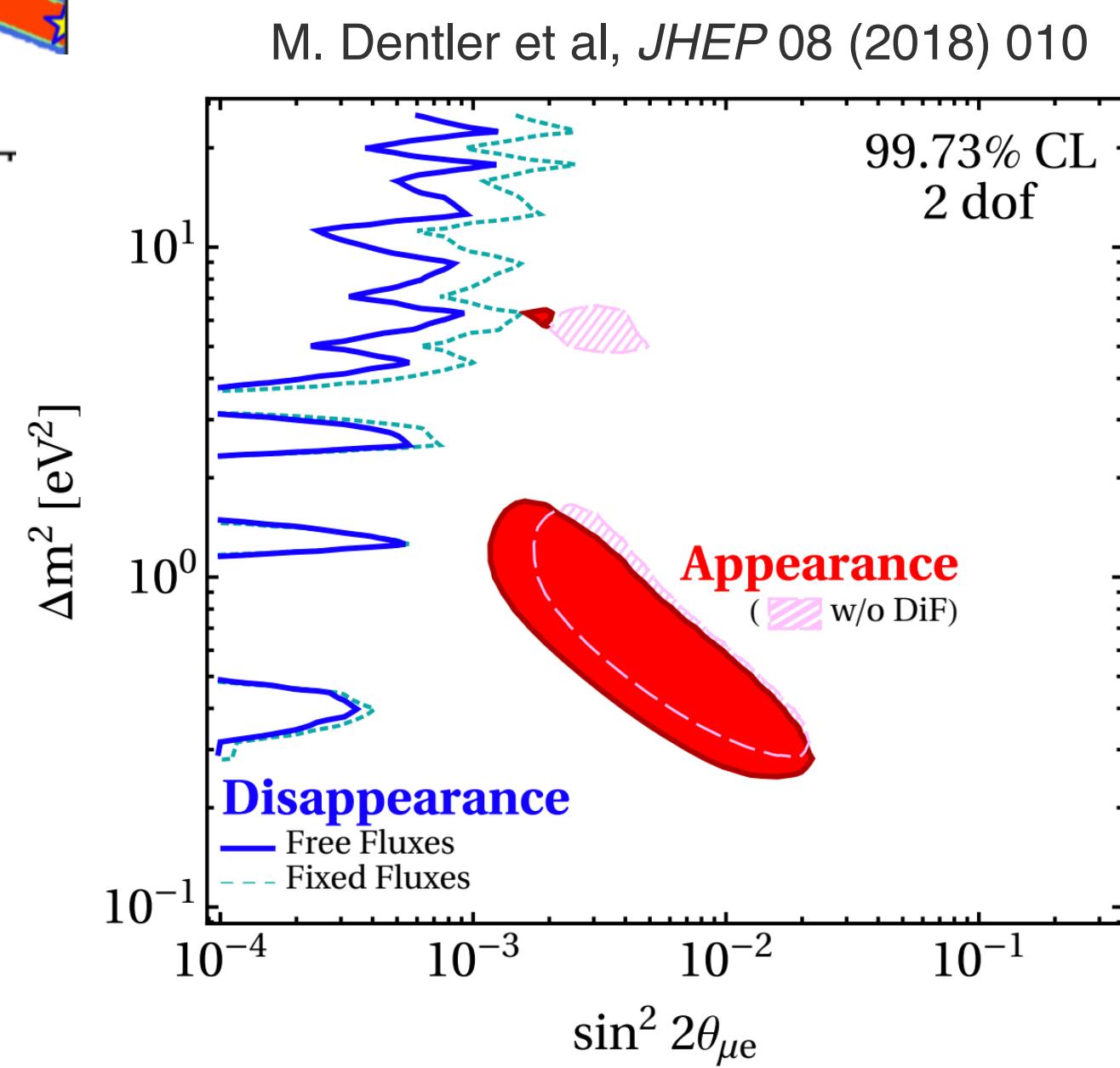
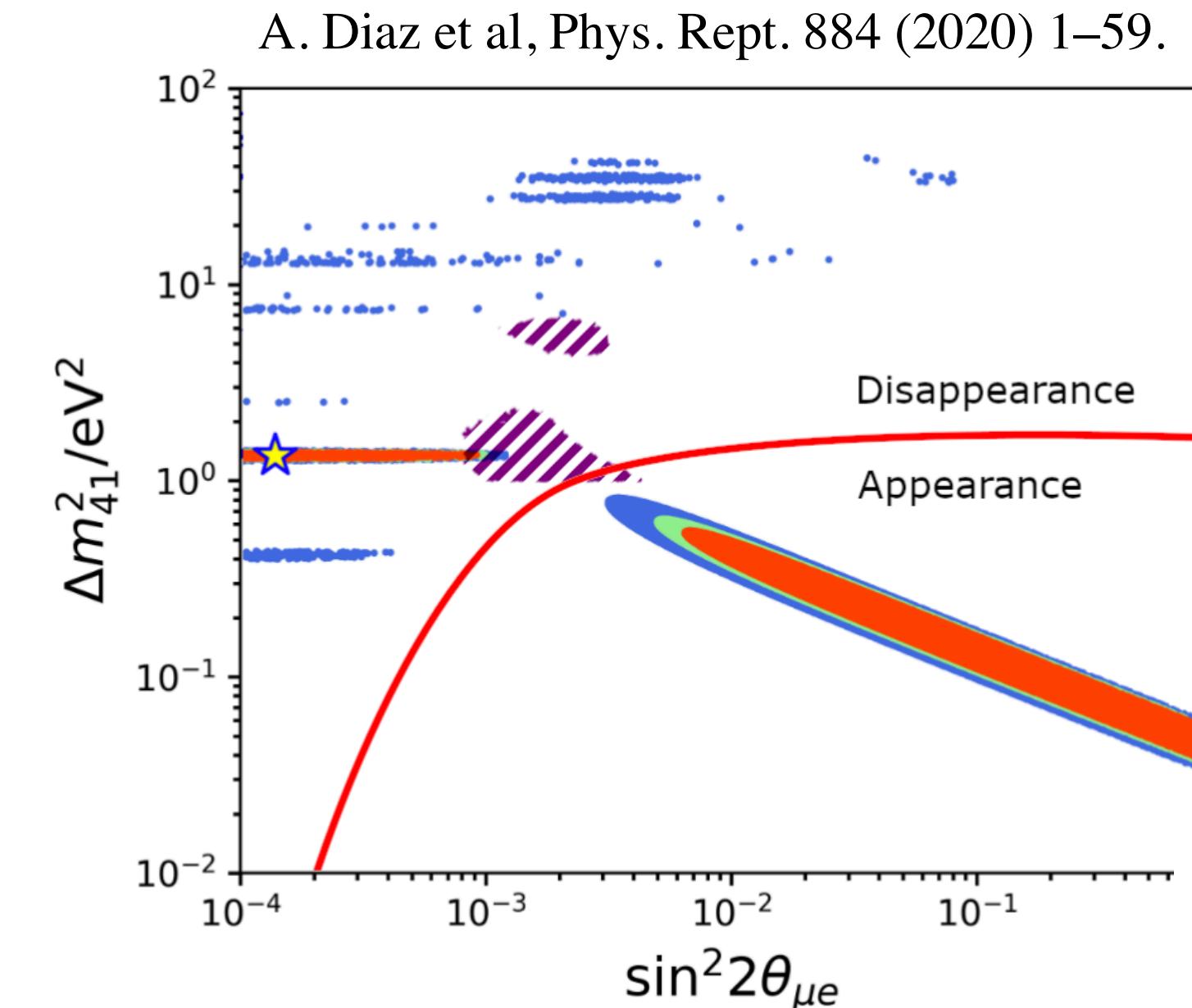
$$P_{\nu_\mu \rightarrow \nu_\mu} = 1 - \sin^2 2\theta_{\mu\mu} \sin^2 \Delta = 1 - 4 |U_{\mu 4}|^2 (1 - |U_{\mu 4}|^2) \sin^2 \Delta$$

$$P_{\nu_\mu \rightarrow \nu_e} = \sin^2 2\theta_{e\mu} \sin^2 \Delta = 4 |U_{e 4}|^2 |U_{\mu 4}|^2 \sin^2 \Delta$$

New oscillation frequency at SBL:

$$\Delta m^2 \sim 1 \text{ eV}^2$$

Standard assumption for many years, but appearance and disappearance data in strong tension!



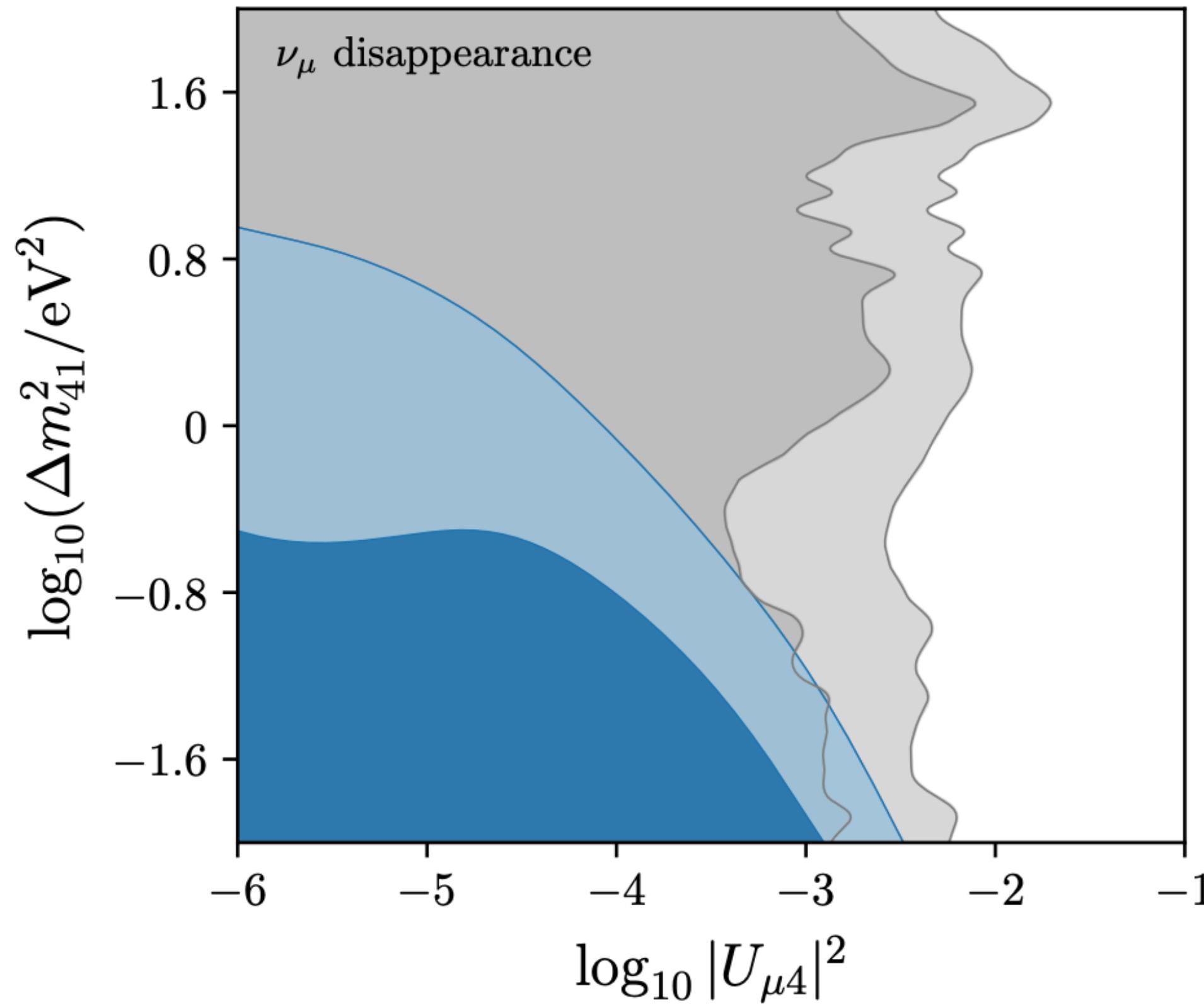
3+1 neutrino oscillations

Cosmological discord

Dasgupta & Kopp 2014
 Chu, Dasgupta & Kopp 2015
 Saviano et al. 2014
 Mirrizi et al. 2015
 Cherry, Friedland & Shoemaker 2016
 Chu et al. 2018

Light sterile neutrinos would thermalize in the early Universe and contribute to N_{eff} .

S. Hagstotz et al, Phys. Rev. D 104 no. 12, (2021) 123524, arXiv:2003.02289.



Several ideas in the literature to reconcile eV-steriles with this picture:

A large matter potential for heavy neutrinos can suppress mixing angles in the early Universe ...

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta_0}{\left(\cos^2 2\theta_0 + \frac{2EV_{\text{eff}}}{\Delta m^2} \right)^2 + \sin^2 2\theta_0}$$

$$V_{\text{eff}} \simeq \begin{cases} -\frac{7\pi^2 e_s^2 E T_s^4}{45 M^4} & \text{for } T_s \ll M \\ +\frac{e_s^2 T_s^2}{8E} & \text{for } T_s \gg M \end{cases}$$

Dark Sectors!

... but suppression cannot be guaranteed at all times. Late production is also constrained (N. Song et al 2018).

Other proposals consider matter potential sourced by ultra-light DM.
(Y. Farzan 2019 and J. M. Cline 2020.)

3+1 neutrino oscillations

Theory interpretation

Very surprising, not the seesaw partners we are used to discussing, but $M \sim \mathcal{O}(1)$ eV is possible (*de Gouvea, 2005*),

$$\mathcal{L} \supset y \bar{L} \tilde{H} N + M \bar{N}^c N + \dots$$

Alternatively, this could be part of a “hidden” structure in Type-I seesaw (*Barry et al 2011, Zhang 2011, + others*). For instance,

$$M_\nu \sim M_D \cancel{M_N^{-1}} M_D^T$$

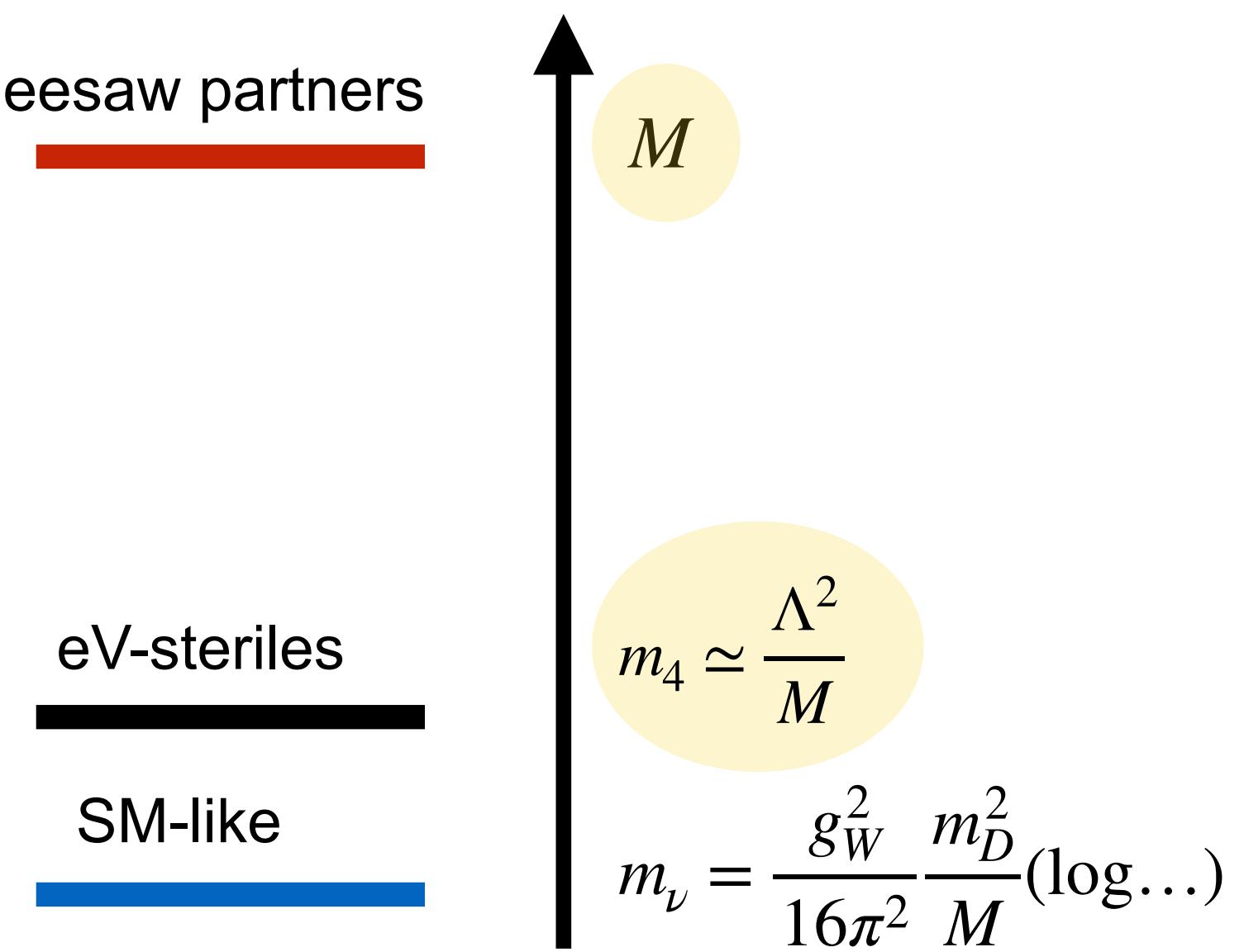
(3x3) (3x?) (?x?) (?)x3

$$\cancel{M_N} \rightarrow \frac{1}{2} \begin{pmatrix} 0 & m_D & 0 \\ m_D & M & \Lambda \\ 0 & \Lambda & 0 \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N^c \\ S^c \end{pmatrix}$$

Easy to see when integrating out N ($\mu' \rightarrow \infty$):

$$\frac{1}{2M} \begin{pmatrix} m_D^2 & m_D \Lambda \\ m_D \Lambda & \Lambda^2 \end{pmatrix} \begin{pmatrix} \nu_L^c \\ S^c \end{pmatrix}$$

All light neutrinos, including a sterile states, can be “seesawed”

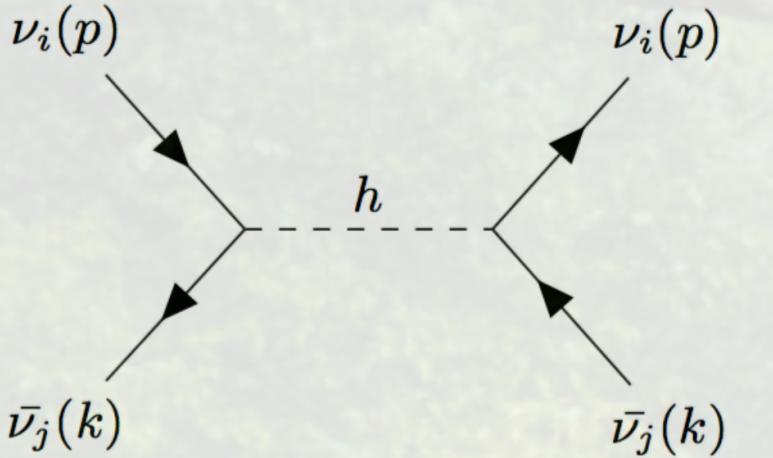


Matter Effects

NSI's or light mediators

$$\mathcal{L}_{NC} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \varepsilon_{\alpha\beta}^{f,P} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta) (\bar{f} \gamma_\mu P f)$$

Resonance from neutrino over-densities

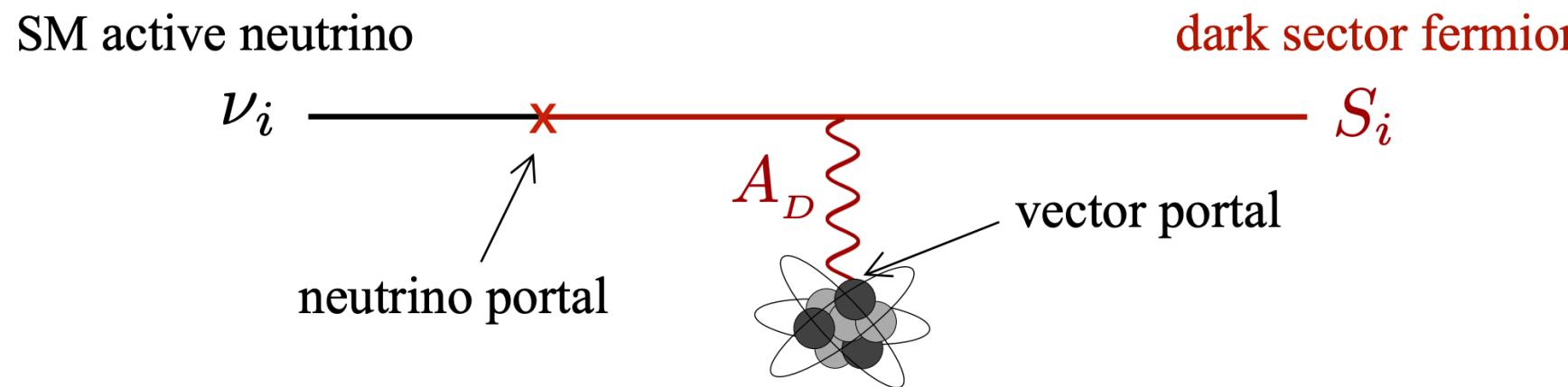


Category	Model	Signature	Anomalies				References
			LSND	MiniBooNE	Reactors	Sources	
Flavor transitions Secs. 3.1.1-3.1.3, 3.1.5	(3+1) oscillations	oscillations	✓	✓	✓	✓	Reviews and global fits [93, 103, 105, 106]
	(3+1) w/ invisible sterile decay	oscillations w/ ν_4 invisible decay	✓	✓	✓	✓	[151, 155]
	(3+1) w/ sterile decay	$\nu_4 \rightarrow \phi \nu_e$	✓	✓	✗	✗	[159–162, 270]
Matter effects Secs. 3.1.4, 3.1.7	(3+1) w/ anomalous matter effects	$\nu_\mu \rightarrow \nu_e$ via matter effects	✓	✓	✗	✗	[143, 147, 271–273]
	(3+1) w/ quasi-sterile neutrinos	$\nu_\mu \rightarrow \nu_e$ w/ resonant ν_s matter effects	✓	✓	✓	✓	[148]
Flavor violation Sec. 3.1.6	Lepton-flavor-violating μ decays	$\mu^+ \rightarrow e^+ \nu_\alpha \bar{\nu}_e$	✓	✗	✗	✗	[174, 175, 274]
	neutrino-flavor-changing bremsstrahlung	$\nu_\mu A \rightarrow e \phi A$	✓	✓	✗	✗	[275]
Decays in flight Sec. 3.2.3	Transition magnetic mom., heavy ν decay	$N \rightarrow \nu \gamma$	✗	✓	✗	✗	[207]
	Dark sector heavy neutrino decay	$N \rightarrow \nu (X \rightarrow e^+ e^-)$ or $N \rightarrow \nu (X \rightarrow \gamma \gamma)$	✗	✓	✗	✗	[208]
Neutrino Scattering Secs. 3.2.1, 3.2.2	neutrino-induced upscattering	$\nu A \rightarrow N A$, $N \rightarrow \nu e^+ e^-$ or $N \rightarrow \nu \gamma \gamma$	✗	✓	✗	✗	[205, 206, 209–216]
	neutrino dipole upscattering	$\nu A \rightarrow N A$, $N \rightarrow \nu \gamma$	✗	✓	✗	✗	[40, 185, 187, 188, 190, 193, 233, 276]
Dark Matter Scattering Sec. 3.2.4	dark particle-induced upscattering	γ or $e^+ e^-$	✗	✓	✗	✗	[217]
	dark particle-induced inverse Primakoff	γ	✓	✓	✗	✗	[217]

Resonant matter effects

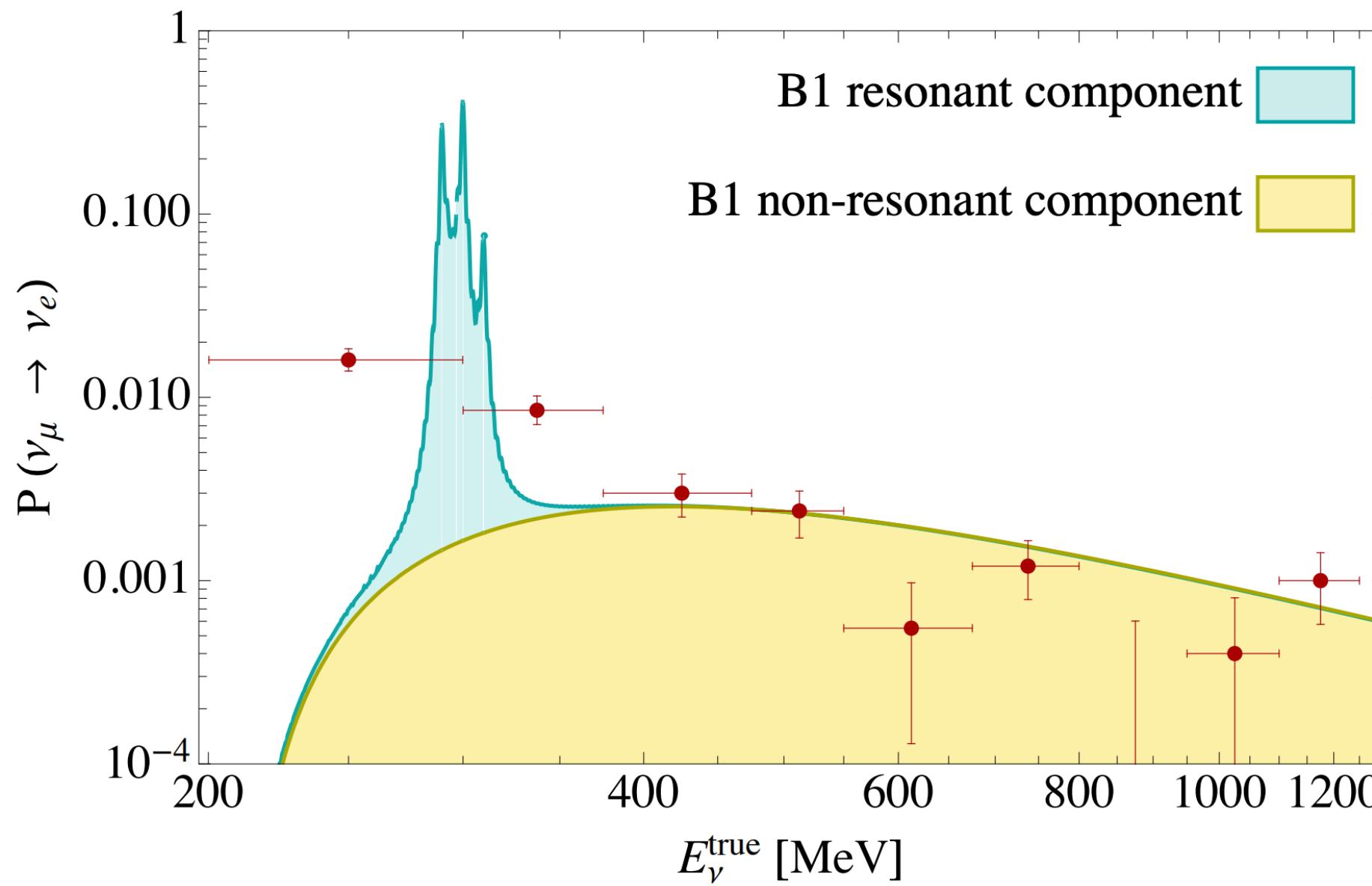
Example: Quasi-sterile neutrinos

D.S. M. Alves et al arXiv: [2201.00876](https://arxiv.org/abs/2201.00876)



Quasi-sterile neutrinos with large interactions with matter.

$$\Delta V|_{\text{matter}} = (V_{S_3} - V_{\nu_i})|_{\text{matter}} = - \frac{(g_s - g_\nu)}{2 m_{A_D}^2} \sum_{f=e, p, n} g_f n_f$$



$$E_{\nu_3}^{\text{res}} = \frac{\delta M_3^2 \cos 2\theta_{S_3}}{2 |\Delta V|}$$

Resonance depends on matter density — 200 MeV is a challenging region for other oscillation experiments, but T2K and NoVA data are available.

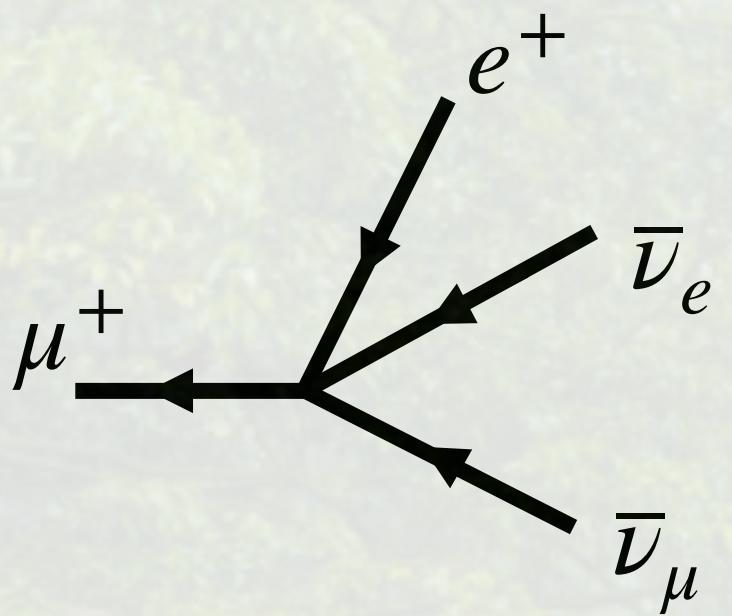
Challenging to find a UV model yet with such large potential, but interesting phenomenological avenue.

Flavor Violation

LNV or LFV muon decays

$$\mathcal{L}_1 \rightarrow [(\bar{\mu}_R \nu_{eL})(\nu_{aL}^T C e_L) - (\bar{\mu}_R \nu_{eL})(\ell_{aL}^T C \nu_{eL})] \langle |H^0| \rangle ,$$

$$\mathcal{L}_2 \rightarrow (e_L^T C \nu_{eL})(\mu_R^T C \nu_R)^* \langle |H^0| \rangle^2 .$$



At LSND, this mimics the appearance signal.
Does not impact π -decay experiments, so
oscillations may still need to be considered.

S. Bergmann, Grossman 1998, Babu et al 2016.

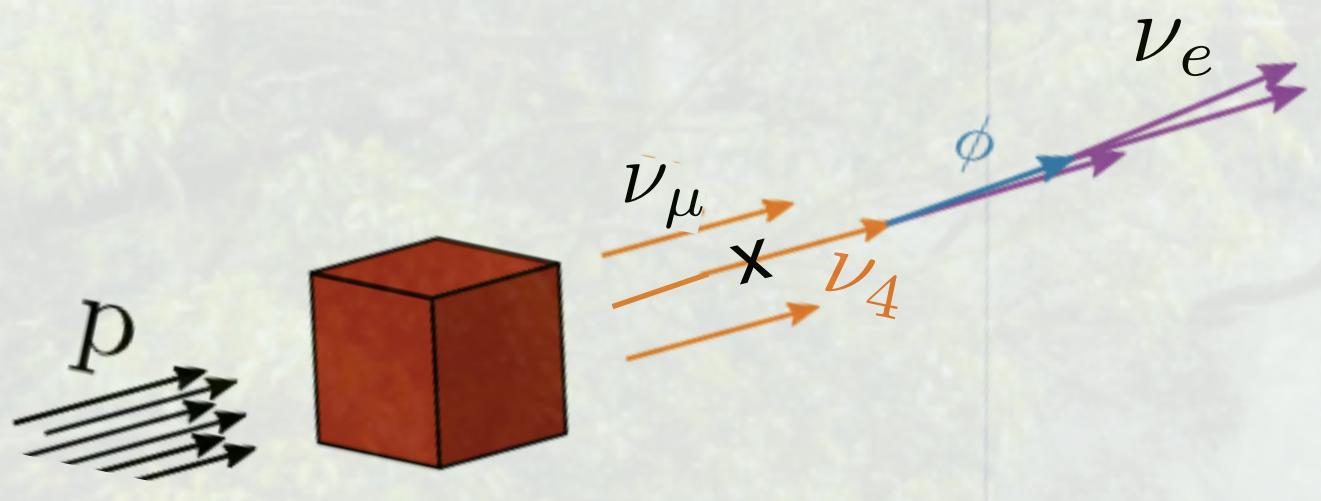
Similar ideas can also be applied to scattering.

Usually, these scenarios are strongly constrained
by flavor physics observables ← intensity frontier.

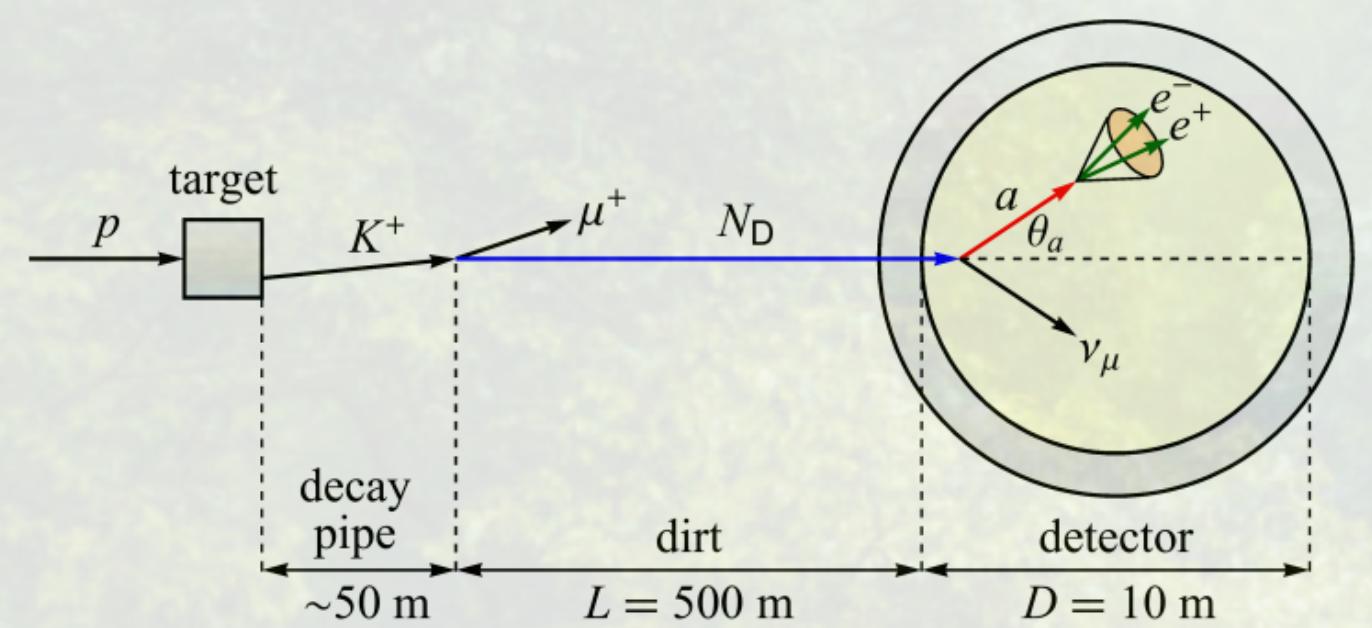
Category	Model	Signature	Anomalies				References
			LSND	MiniBooNE	Reactors	Sources	
Flavor transitions Secs. 3.1.1-3.1.3, 3.1.5	(3+1) oscillations	oscillations	✓	✓	✓	✓	Reviews and global fits [93, 103, 105, 106]
	(3+1) w/ invisible sterile decay	oscillations w/ ν_4 invisible decay	✓	✓	✓	✓	[151, 155]
	(3+1) w/ sterile decay	$\nu_4 \rightarrow \phi \nu_e$	✓	✓	✗	✗	
Matter effects Secs. 3.1.4, 3.1.7	(3+1) w/ anomalous matter effects	$\nu_\mu \rightarrow \nu_e$ via matter effects	✓	✓	✗	✗	[143, 147, 271-273]
	(3+1) w/ quasi-sterile neutrinos	$\nu_\mu \rightarrow \nu_e$ w/ resonant ν_s matter effects	✓	✓	✓	✓	[148]
Flavor violation Sec. 3.1.6	Lepton-flavor-violating μ decays	$\mu^+ \rightarrow e^+ \nu_\alpha \bar{\nu}_e$	✓	✗	✗	✗	[174, 175, 274]
	neutrino-flavor-changing bremsstrahlung	$\nu_\mu A \rightarrow e \phi A$	✓	✓	✗	✗	[275]
Decays in flight Sec. 3.2.3	Transition magnetic mom., heavy ν decay	$N \rightarrow \nu \gamma$	✗	✓	✗	✗	[207]
	Dark sector heavy neutrino decay	$N \rightarrow \nu (X \rightarrow e^+ e^-)$ or $N \rightarrow \nu (X \rightarrow \gamma \gamma)$	✗	✓	✗	✗	[208]
Neutrino Scattering Secs. 3.2.1, 3.2.2	neutrino-induced upscattering	$\nu A \rightarrow N A$, $N \rightarrow \nu e^+ e^-$ or $N \rightarrow \nu \gamma \gamma$	✗	✓	✗	✗	[205, 206, 209-216]
	neutrino dipole upscattering	$\nu A \rightarrow N A$, $N \rightarrow \nu \gamma$	✗	✓	✗	✗	[40, 185, 187, 188, 190, 193, 233, 276]
Dark Matter Scattering Sec. 3.2.4	dark particle-induced upscattering	γ or $e^+ e^-$	✗	✓	✗	✗	[217]
	dark particle-induced inverse Primakoff	γ	✓	✓	✗	✗	[217]

Decays in Flight

Effective transition: decay-in-flight to ν_e



Visible decay in flight: ALPs, HNLs, etc.



Category	Model	Signature	Anomalies				References
			LSND	MiniBooNE	Reactors	Sources	
Flavor transitions Secs. 3.1.1-3.1.3, 3.1.5	(3+1) oscillations	oscillations	✓	✓	✓	✓	Reviews and global fits [93, 103, 105, 106]
	(3+1) w/ invisible sterile decay	oscillations w/ ν_4 invisible decay	✓	✓	✓	✓	[151, 155]
	(3+1) w/ sterile decay	$\nu_4 \rightarrow \phi \nu_e$	✓	✓	✗	✗	[159–162, 270]
Matter effects Secs. 3.1.4, 3.1.7	(3+1) w/ anomalous matter effects	$\nu_\mu \rightarrow \nu_e$ via matter effects	✓	✓	✗	✗	[143, 147, 271–273]
	(3+1) w/ quasi-sterile neutrinos	$\nu_\mu \rightarrow \nu_e$ w/ resonant ν_s matter effects	✓	✓	✓	✓	[148]
Flavor violation Sec. 3.1.6	Lepton-flavor-violating μ decays	$\mu^+ \rightarrow e^+ \nu_\alpha \bar{\nu}_e$	✓	✗	✗	✗	[174, 175, 274]
	neutrino-flavor-changing bremsstrahlung	$\nu_\mu A \rightarrow e \phi A$	✓	✓	✗	✗	[275]
Decays in flight Sec. 3.2.3	Transition magnetic mom., heavy ν decay	$N \rightarrow \nu \gamma$	✗	✓	✗	✗	[207]
	Dark sector heavy neutrino decay	$N \rightarrow \nu (X \rightarrow e^+ e^-)$ or $N \rightarrow \nu (X \rightarrow \gamma\gamma)$	✗	✓	✗	✗	[208]
Neutrino Scattering Secs. 3.2.1, 3.2.2	neutrino-induced upscattering	$\nu A \rightarrow N A$, $N \rightarrow \nu e^+ e^-$ or $N \rightarrow \nu \gamma \gamma$	✗	✓	✗	✗	[205, 206, 209–216]
	neutrino dipole upscattering	$\nu A \rightarrow N A$, $N \rightarrow \nu \gamma$	✗	✓	✗	✗	[40, 185, 187, 188, 190, 193, 233, 276]
Dark Matter Scattering Sec. 3.2.4	dark particle-induced upscattering	γ or $e^+ e^-$	✗	✓	✗	✗	[217]
	dark particle-induced inverse Primakoff	γ	✓	✓	✗	✗	[217]

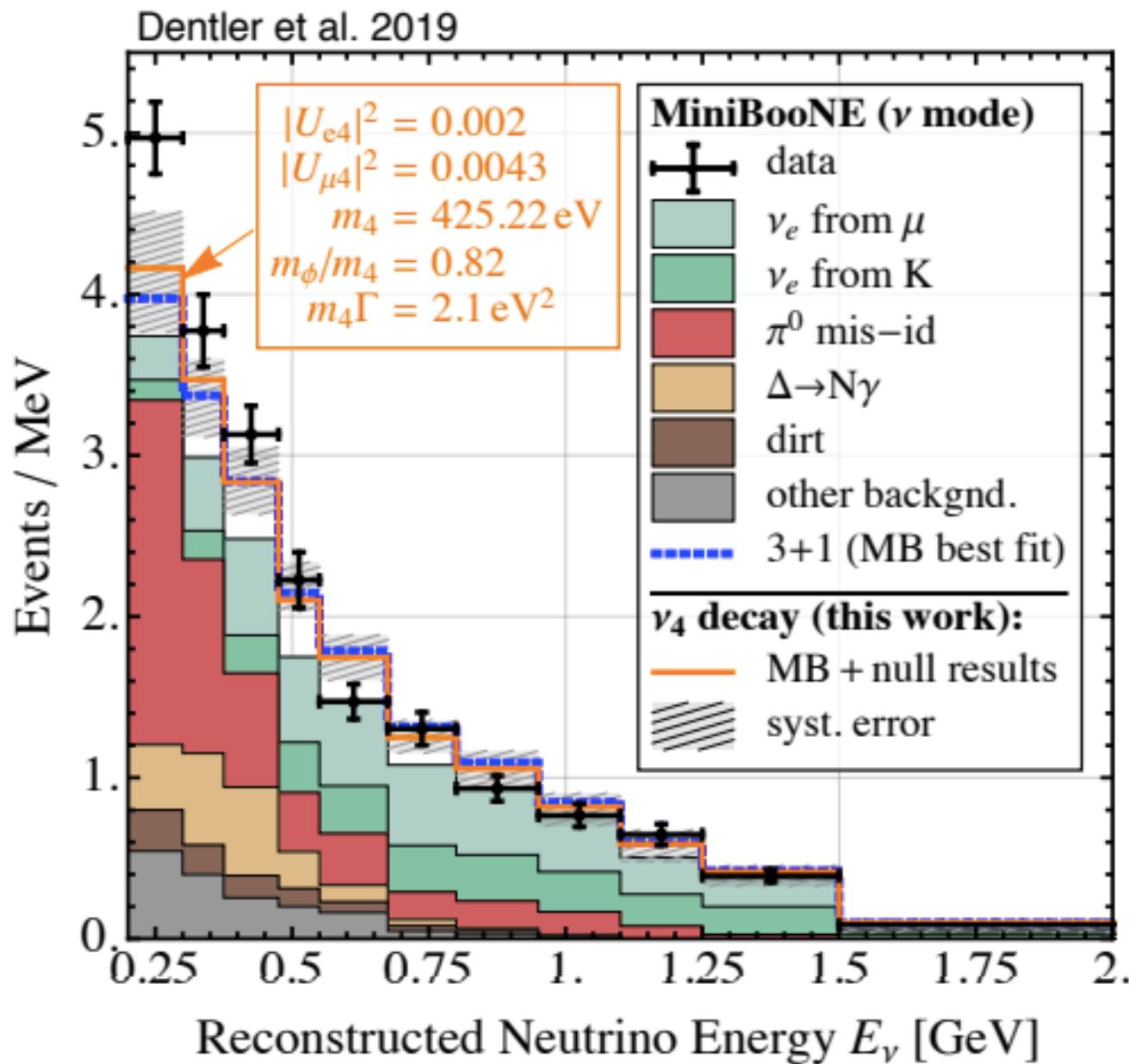
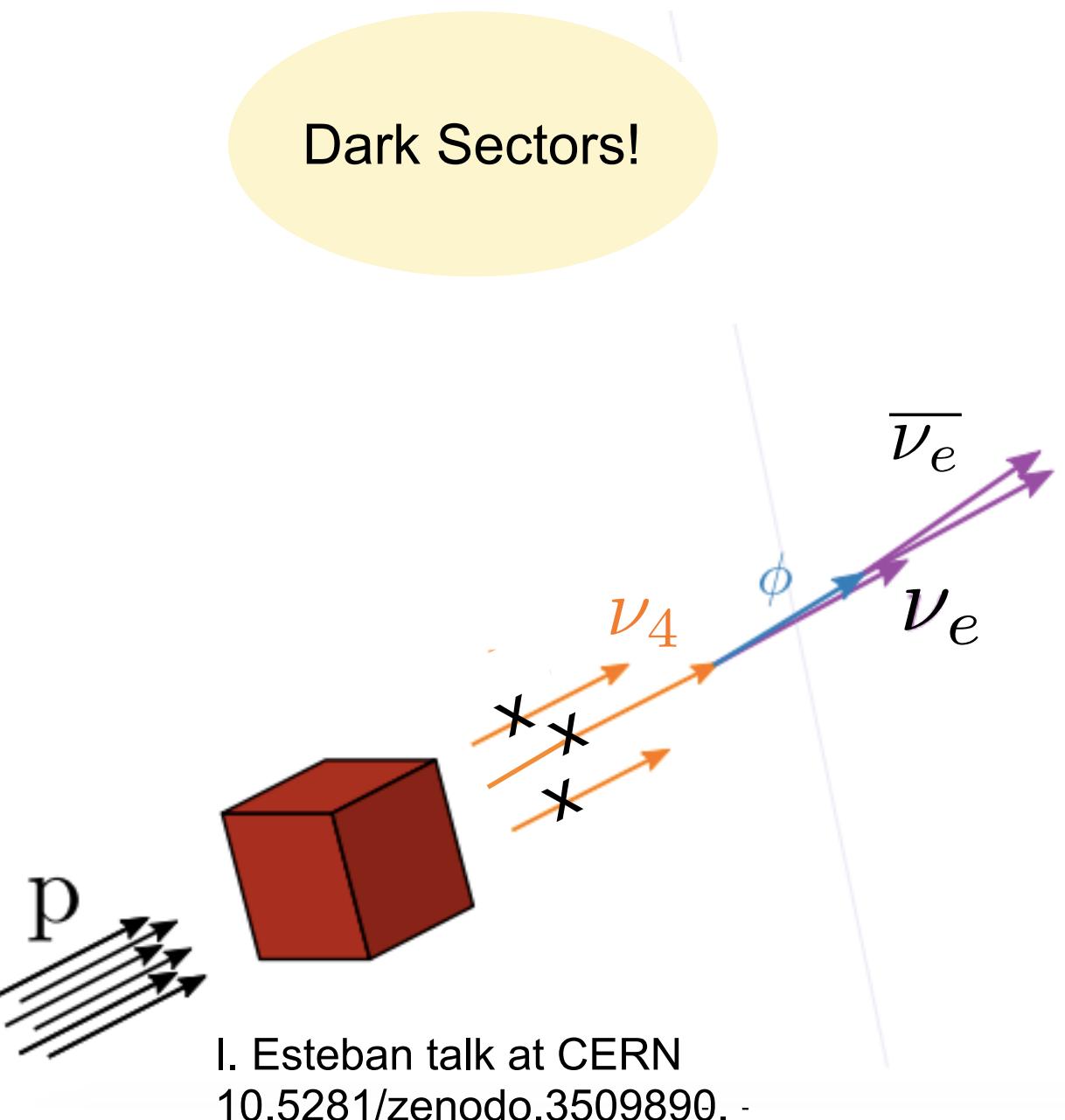
Decaying sterile neutrinos

Effective appearance without disappearance

S. Palomares-Ruiz *et al*, JHEP09(2005)048
 Z. Moss *et al*, PRD 97, 055017 (2018)
 M. Dentler *et al*, PRD101(2020) 115013.
 A. deGouvea *et al*, JHEP07(2020)141

Dirac sterile neutrino visible decays:

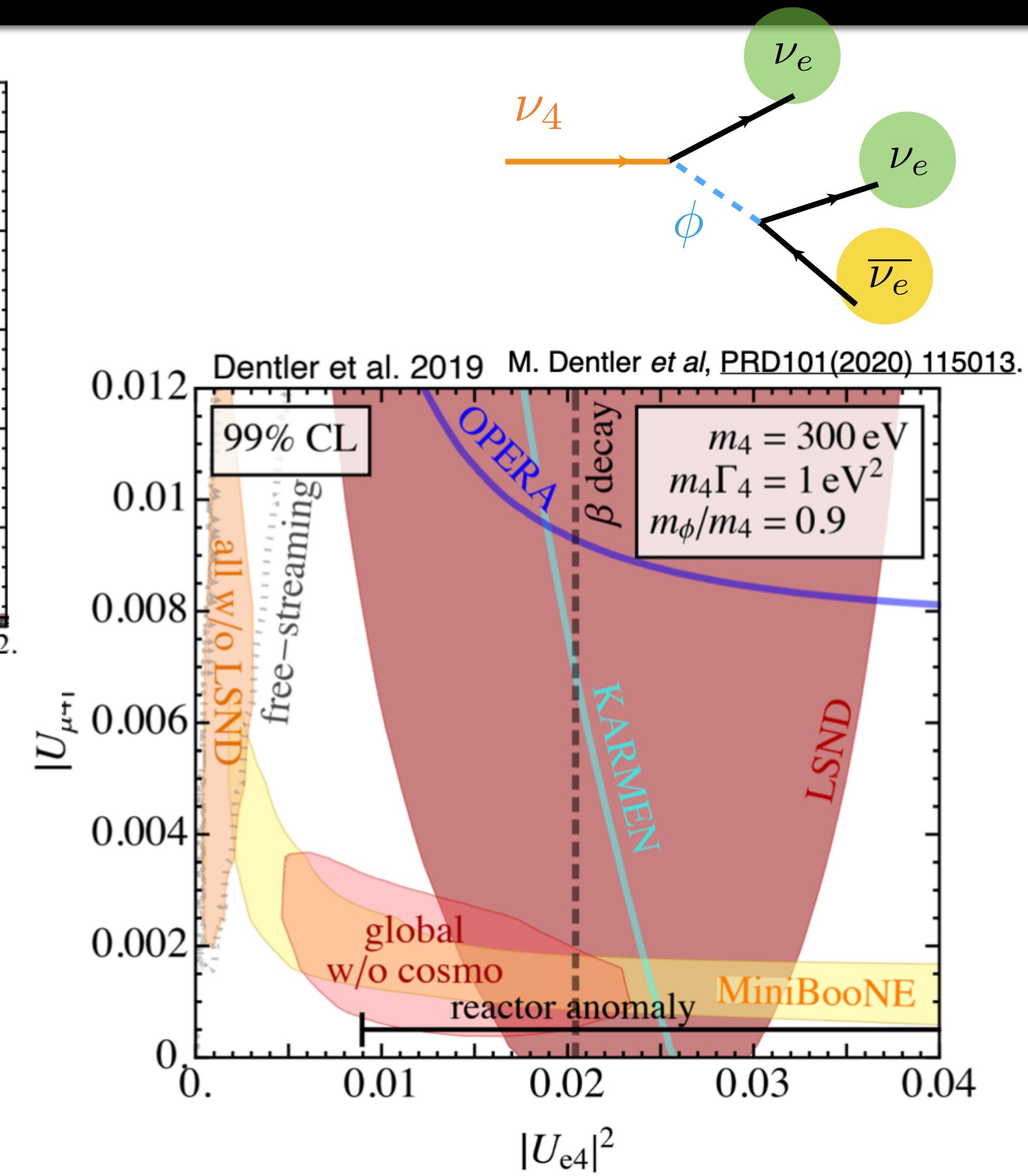
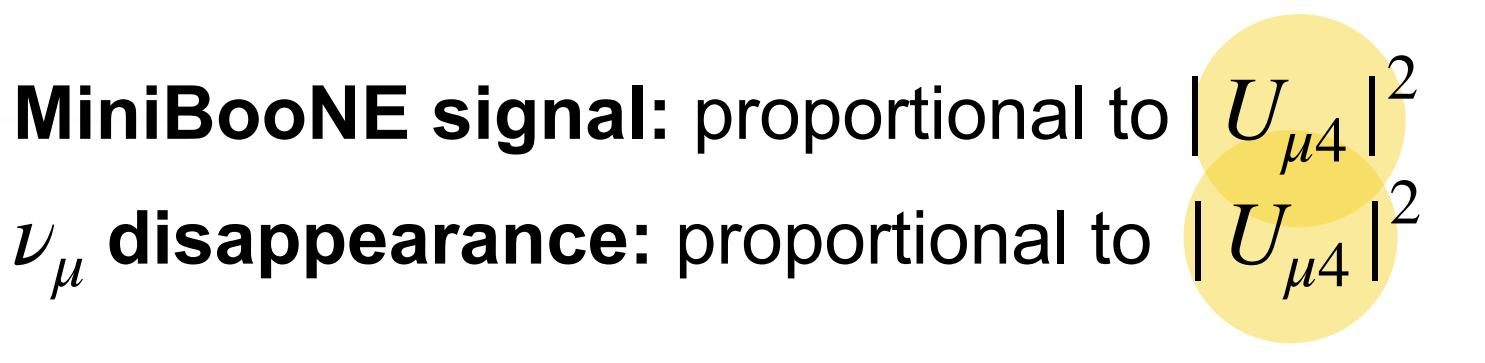
$$-\mathcal{L} \supset g_s \bar{\nu}_s \nu_s \phi + m_{ab} \bar{\nu}_a \nu_b.$$



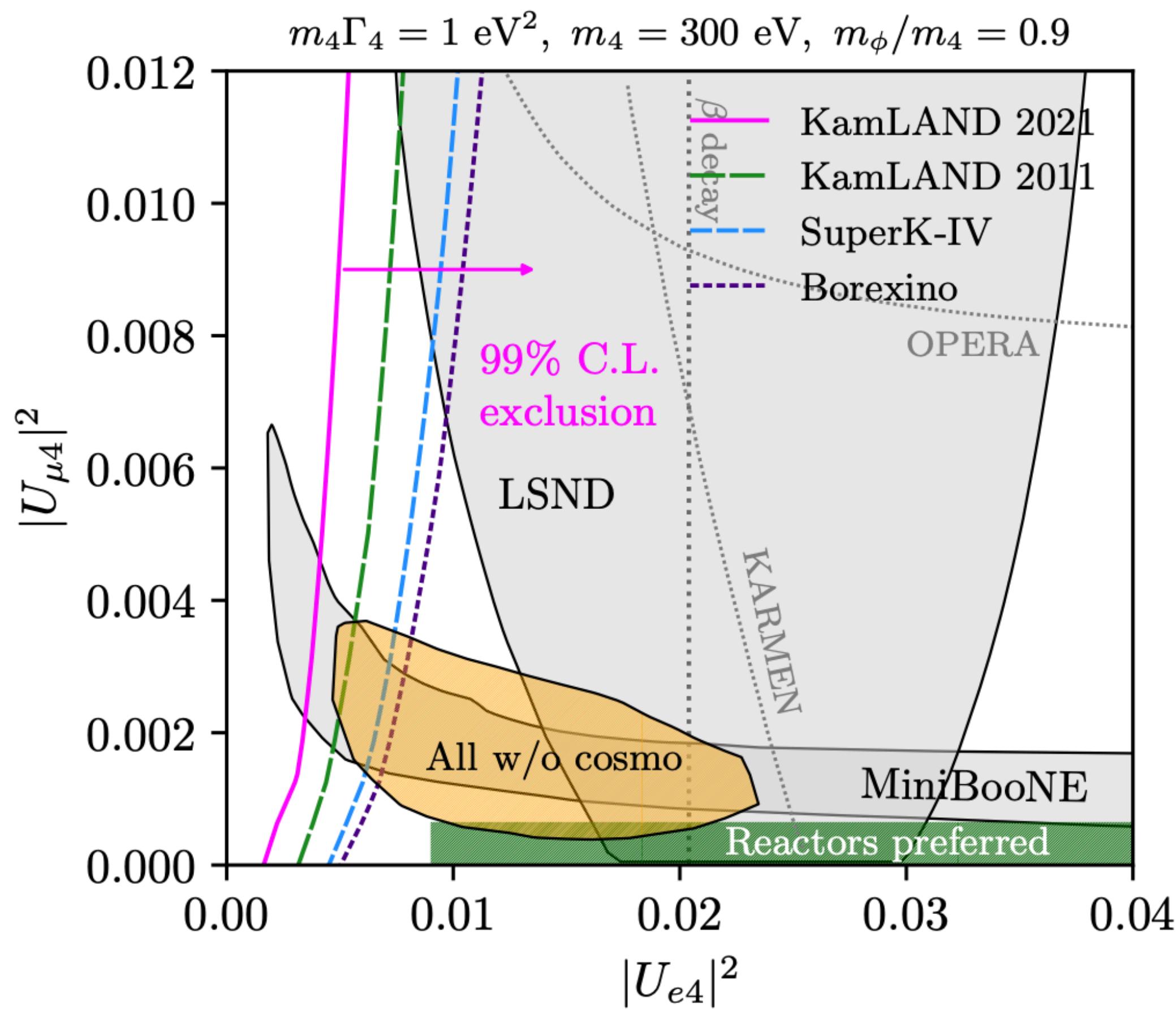
No tension with disappearance:

MiniBooNE signal: proportional to $|U_{μ4}|^2$

ν_μ disappearance: proportional to $|U_{μ4}|^2$



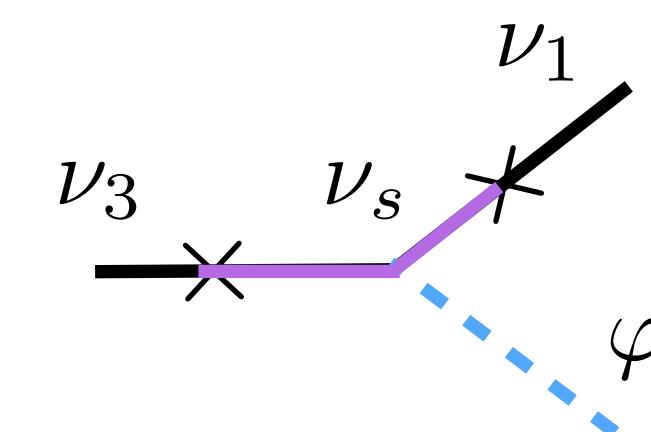
Decaying sterile prediction



A simultaneous explanation of LSND and MiniBooNE is in tension with Solar antineutrino searches.

Improvement expected at JUNO and SK-Gd:
 S.J. Li *et al*, [Nucl.Phys.B 944\(2019\)114661](#)

- Massless scalars would not decay to antineutrinos, but would also predict **light neutrino decays**. For $m_1 = 0$,



$$\begin{aligned} \text{NH: } c\tau_3^{\text{LAB}} &\approx \\ \text{IH: } c\tau_2^{\text{LAB}} &\approx \end{aligned}$$

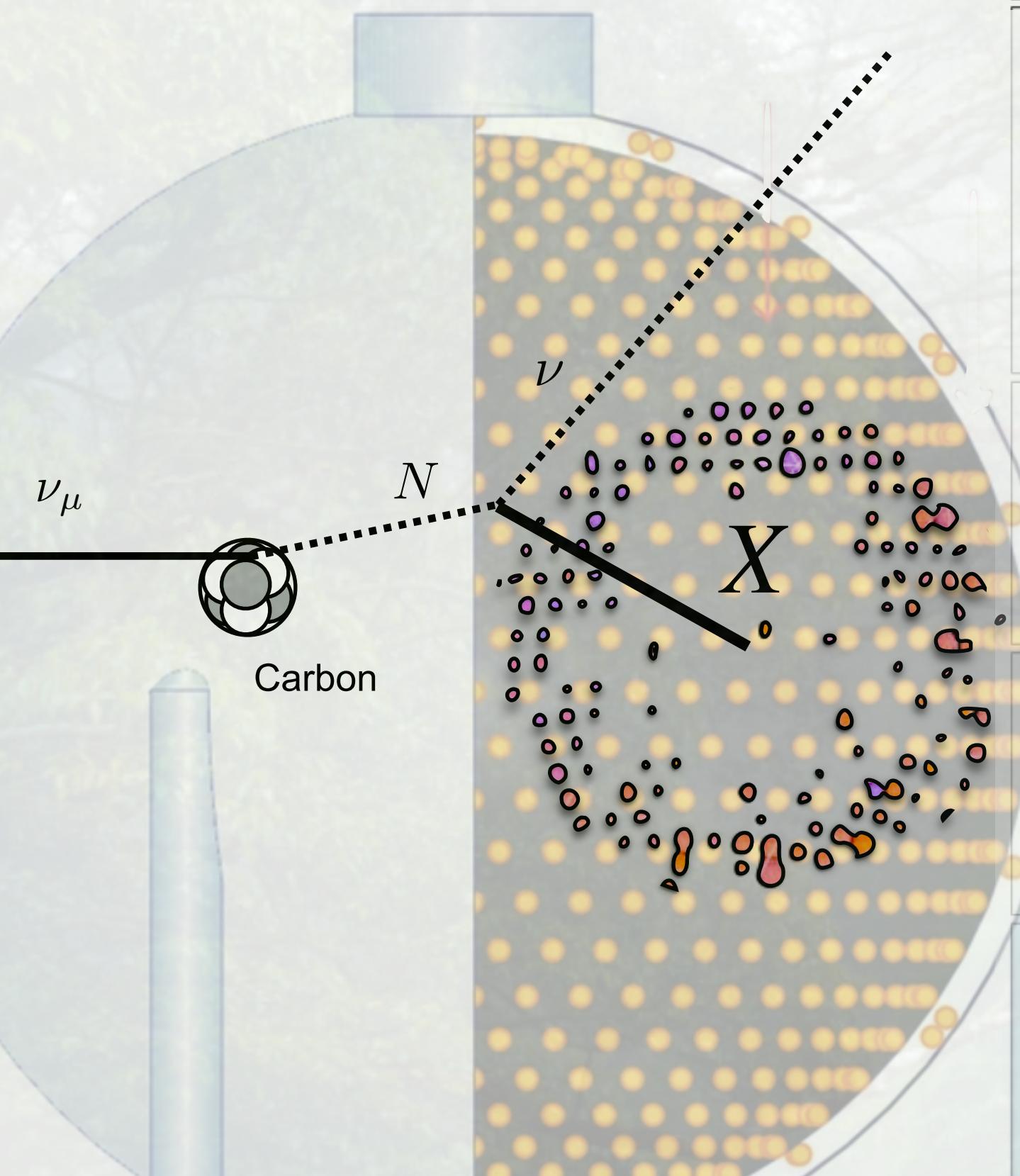
$$0.03 \text{ AU} \left(\frac{10^{-5}}{|U_{s1}U_{s3}|^2} \right) \left(\frac{E_3}{10 \text{ MeV}} \right)$$

- Majorana neutrinos are even more strongly constrained due to $\nu_4 \rightarrow \bar{\nu}_e \phi$ decay.

- Sterile decay may proceed via **higher-dimensional operators**: $\phi(LH)^2$, or $\phi(LH)\nu_s$, which do not necessarily require mixing with electron sector, predicting no production of sterile in the Sun.

S. Palomares-Ruiz *et al*, [JHEP09\(2005\)048](#)
 A. deGouvea *et al*, [JHEP07\(2020\)141](#)

Neutrino Scattering



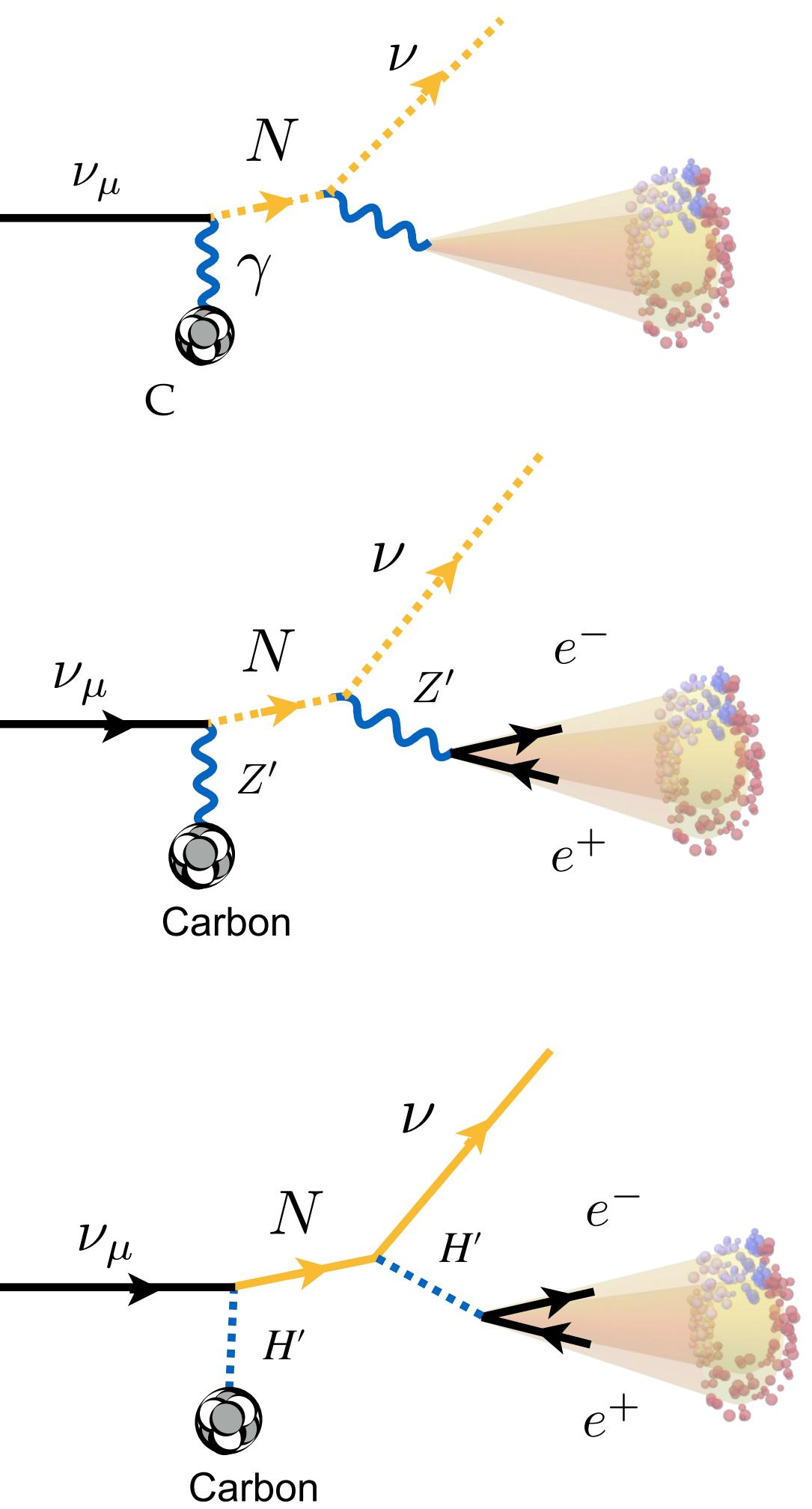
Category	Model	Signature	Anomalies				References
			LSND	MiniBooNE	Reactors	Sources	
Flavor transitions Secs. 3.1.1-3.1.3, 3.1.5	(3+1) oscillations	oscillations	✓	✓	✓	✓	Reviews and global fits [93, 103, 105, 106]
	(3+1) w/ invisible sterile decay	oscillations w/ ν_4 invisible decay	✓	✓	✓	✓	[151, 155]
	(3+1) w/ sterile decay	$\nu_4 \rightarrow \phi \nu_e$	✓	✓	✗	✗	[159–162, 270]
Matter effects Secs. 3.1.4, 3.1.7	(3+1) w/ anomalous matter effects	$\nu_\mu \rightarrow \nu_e$ via matter effects	✓	✓	✗	✗	[143, 147, 271–273]
	(3+1) w/ quasi-sterile neutrinos	$\nu_\mu \rightarrow \nu_e$ w/ resonant ν_s matter effects	✓	✓	✓	✓	[148]
Flavor violation Sec. 3.1.6	Lepton-flavor-violating μ decays	$\mu^+ \rightarrow e^+ \nu_\alpha \bar{\nu}_e$	✓	✗	✗	✗	[174, 175, 274]
	neutrino-flavor-changing bremsstrahlung	$\nu_\mu A \rightarrow e \phi A$	✓	✓	✗	✗	[275]
Decays in flight Sec. 3.2.3	Transition magnetic mom., heavy ν decay	$N \rightarrow \nu \gamma$	✗	✓	✗	✗	[207]
	Dark sector heavy neutrino decay	$N \rightarrow \nu(X \rightarrow e^+ e^-)$ or $N \rightarrow \nu(X \rightarrow \gamma\gamma)$	✗	✓	✗	✗	[208]
Neutrino Scattering Secs. 3.2.1, 3.2.2	neutrino-induced upscattering	$\nu A \rightarrow N A$, $N \rightarrow \nu e^+ e^-$ or $N \rightarrow \nu \gamma \gamma$	✗	✓	✗	✗	[205, 206, 209–216]
	neutrino dipole upscattering	$\nu A \rightarrow N A$, $N \rightarrow \nu \gamma$	✗	✓	✗	✗	[40, 185, 187, 188, 190, 193, 233, 276]
Dark Matter Scattering Sec. 3.2.4	dark particle-induced upscattering	γ or $e^+ e^-$	✗	✓	✗	✗	[217]
	dark particle-induced inverse Primakooff	γ	✓	✓	✗	✗	[217]

Neutrino scattering signatures

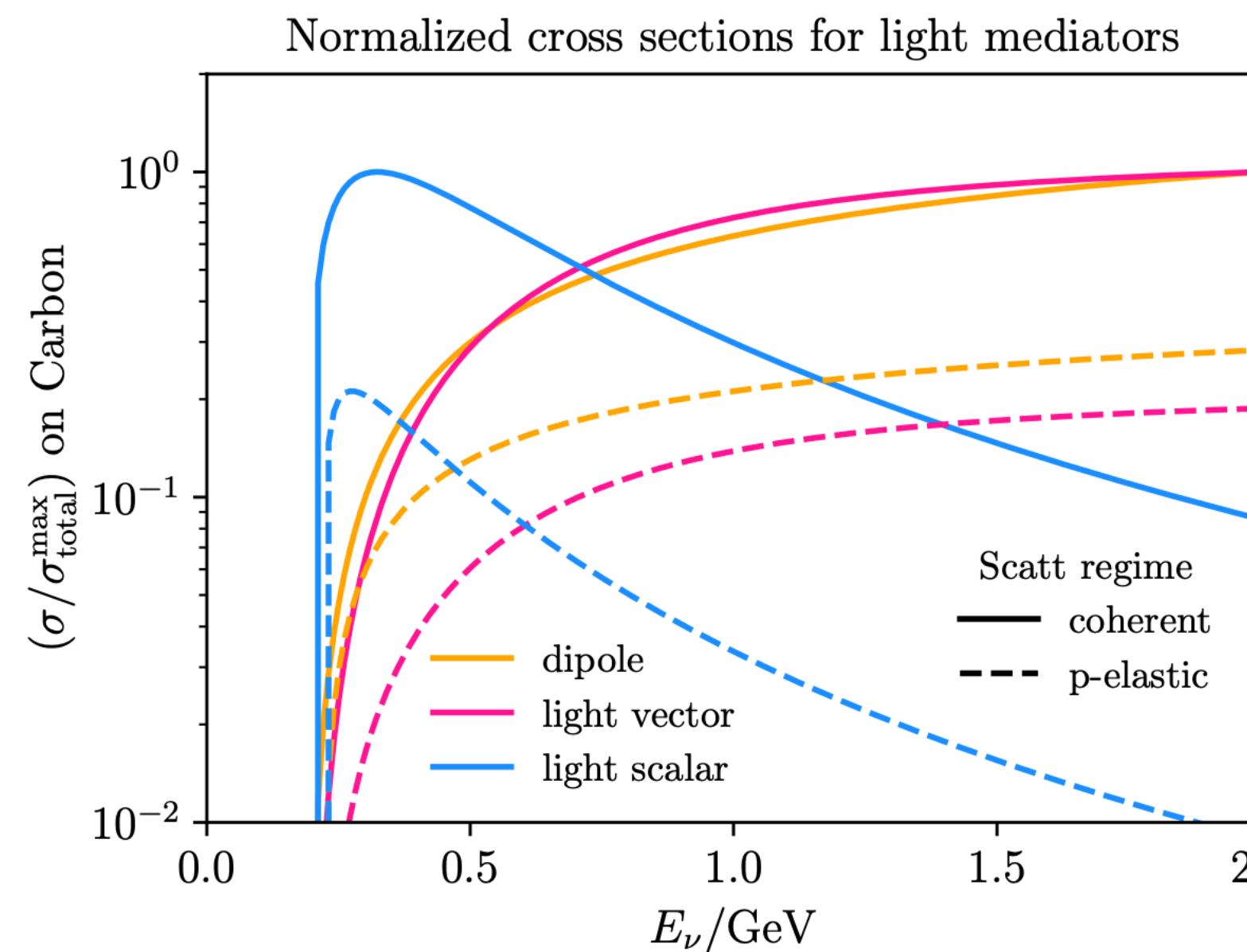
Searches for EM final state

P. Ballett, MH, S. Pascoli [arxiv:1903.07589]
 A. Abdullahi, MH, S. Pascoli, [arXiv:2007.11813]
 E. Bertuzzo et al., [arXiv:1807.09877]
 C. Argüelles et al, [arXiv:1812.08768]
 P. Ballett et al, [arxiv:1808.02915]

B. Dutta et al, [arxiv:2006.01319]
 A. Datta et al, [arXiv:2005.08920]
 B. Dutta et al, [arxiv:2006.01319]
 W. Abdallah et al, arXiv:2202.09373



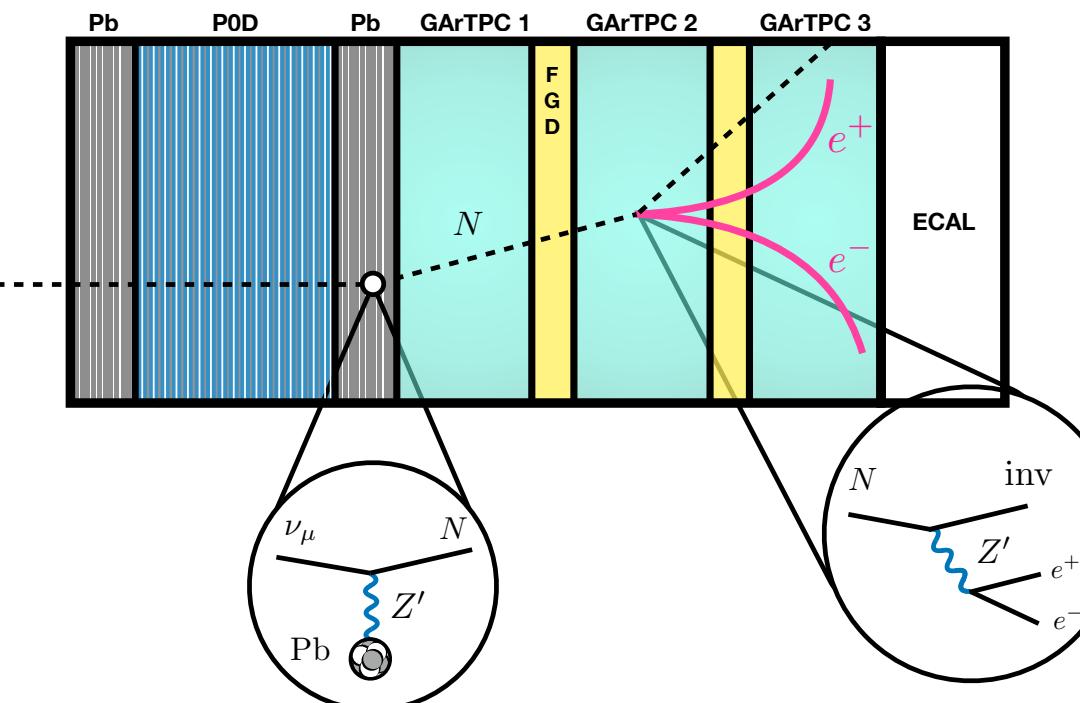
Upscattering cross sections in different models:



Not all neutrino experiments would see the same physics. Importance of complementarity.

Some of the current approaches:

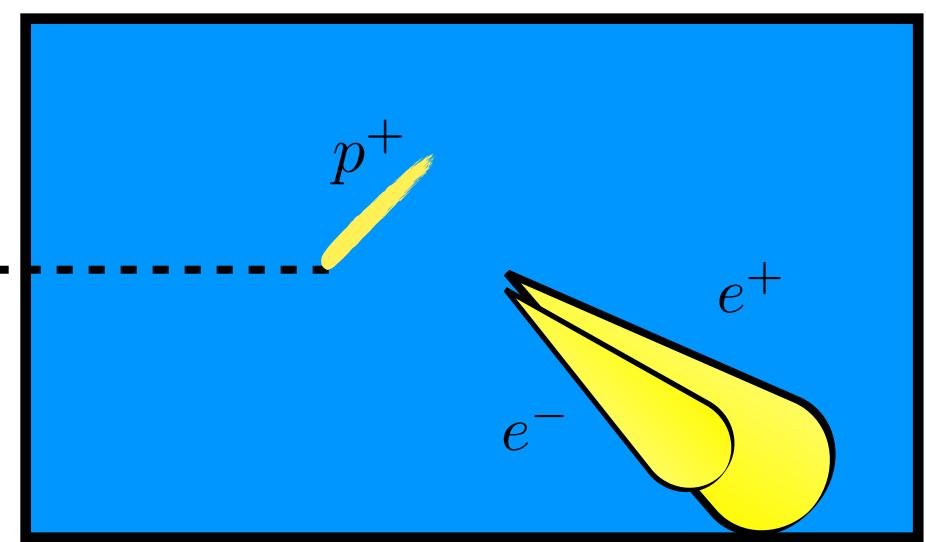
MINERvA $\nu - e$ scattering Phenomenological studies



T2K e^+e^- and γ searches Phenomenological studies



MicroBooNE e^+e^- and γ searches Currently on-going

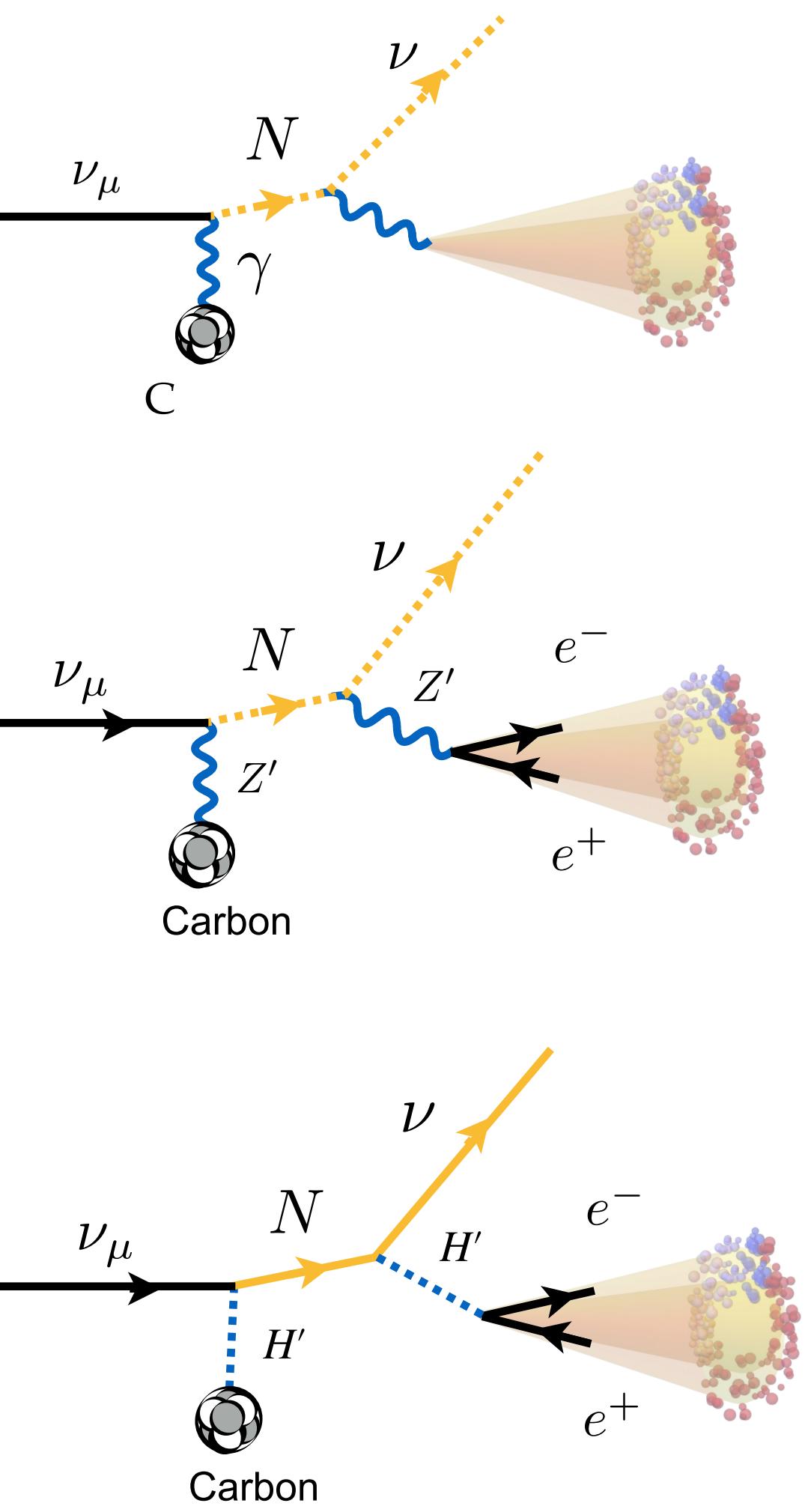


Neutrino scattering signatures

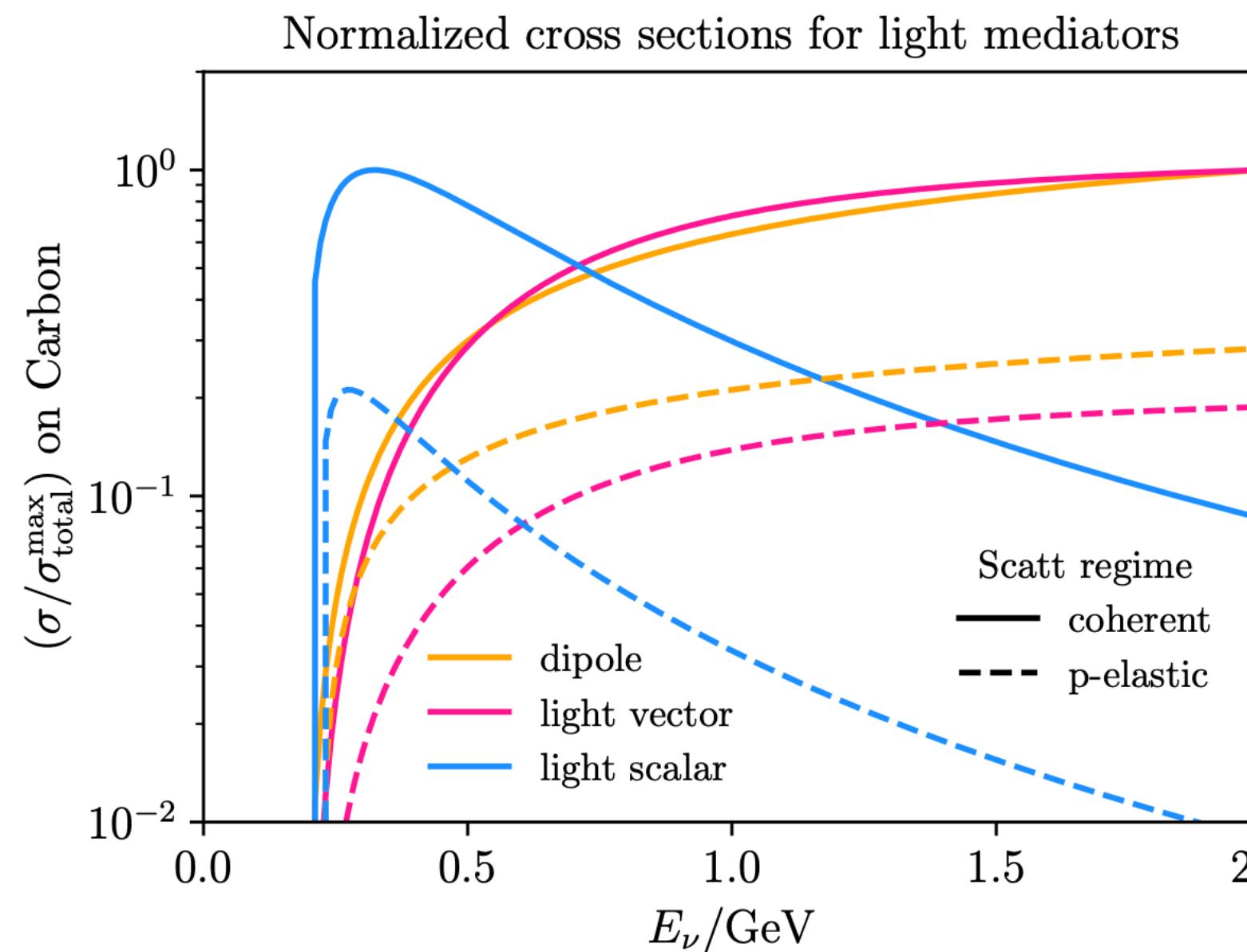
Complementary probes

P. Ballett, MH, S. Pascoli [[arxiv:1903.07589](#)]
 A. Abdullahi, MH, S. Pascoli, [[arXiv:2007.11813](#)]
 E. Bertuzzo et al., [[arXiv:1807.09877](#)]
 C. Argüelles et al, [[arXiv:1812.08768](#)]
 P. Ballett et al, [[arxiv:1808.02915](#)]

B. Dutta et al, [[arxiv:2006.01319](#)]
 A. Datta et al, [[arXiv:2005.08920](#)]
 B. Dutta et al, [[arxiv:2006.01319](#)]
 W. Abdallah et al, [arXiv:2202.09373](#)



Upscattering cross sections in different models:



Not all neutrino experiments would see the same physics. Importance of complementarity.

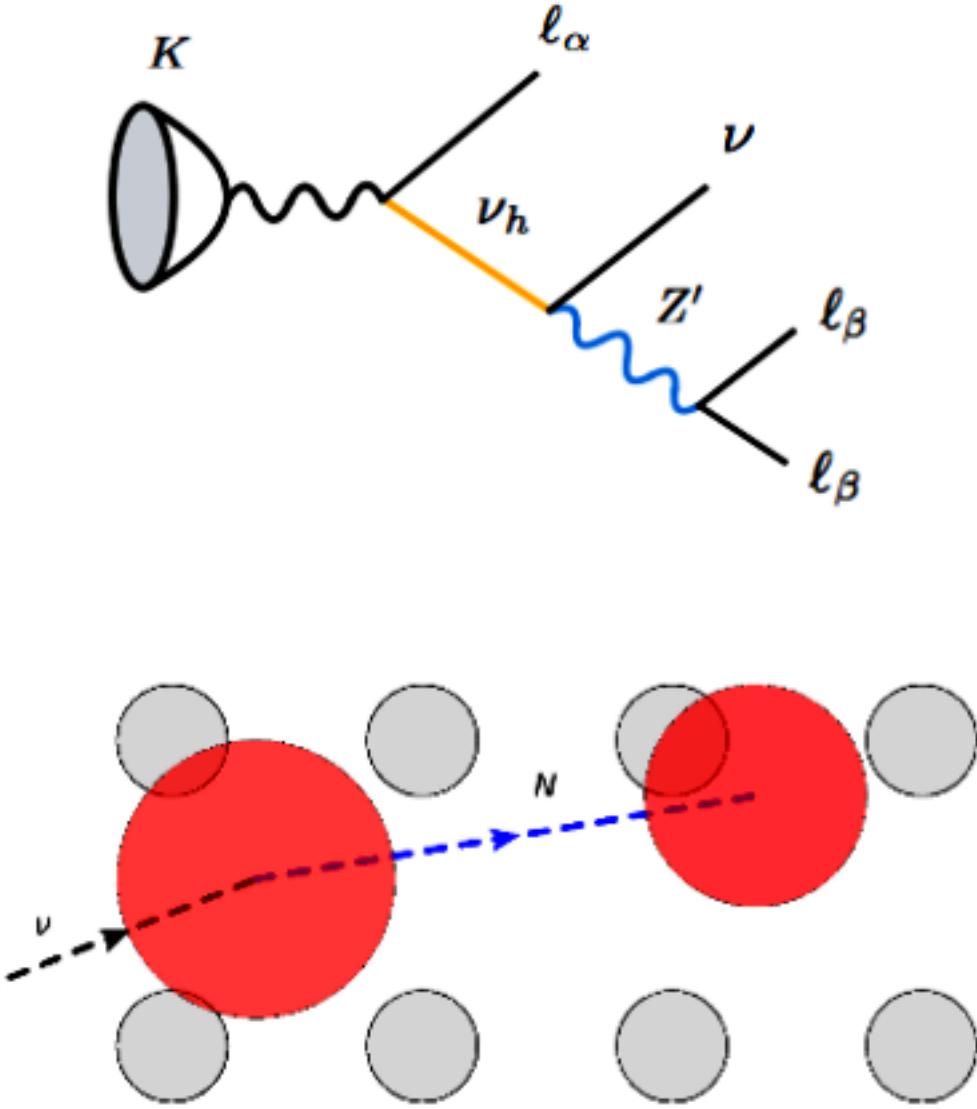
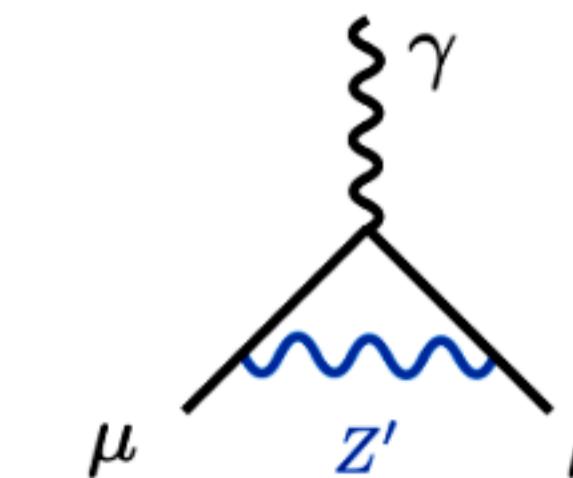
Rare kaon decays at NA62

P. Ballett et al [[arxiv:1903.07589](#)]

Double cascades in IceCube

P. Coloma et al, [[arxiv:1707.08573](#)]
 P. Coloma et al, [[arxiv:2105.09357](#)]

Dark sector may also be related to other anomalies:
 KOTO, muon ($g-2$), dark matter

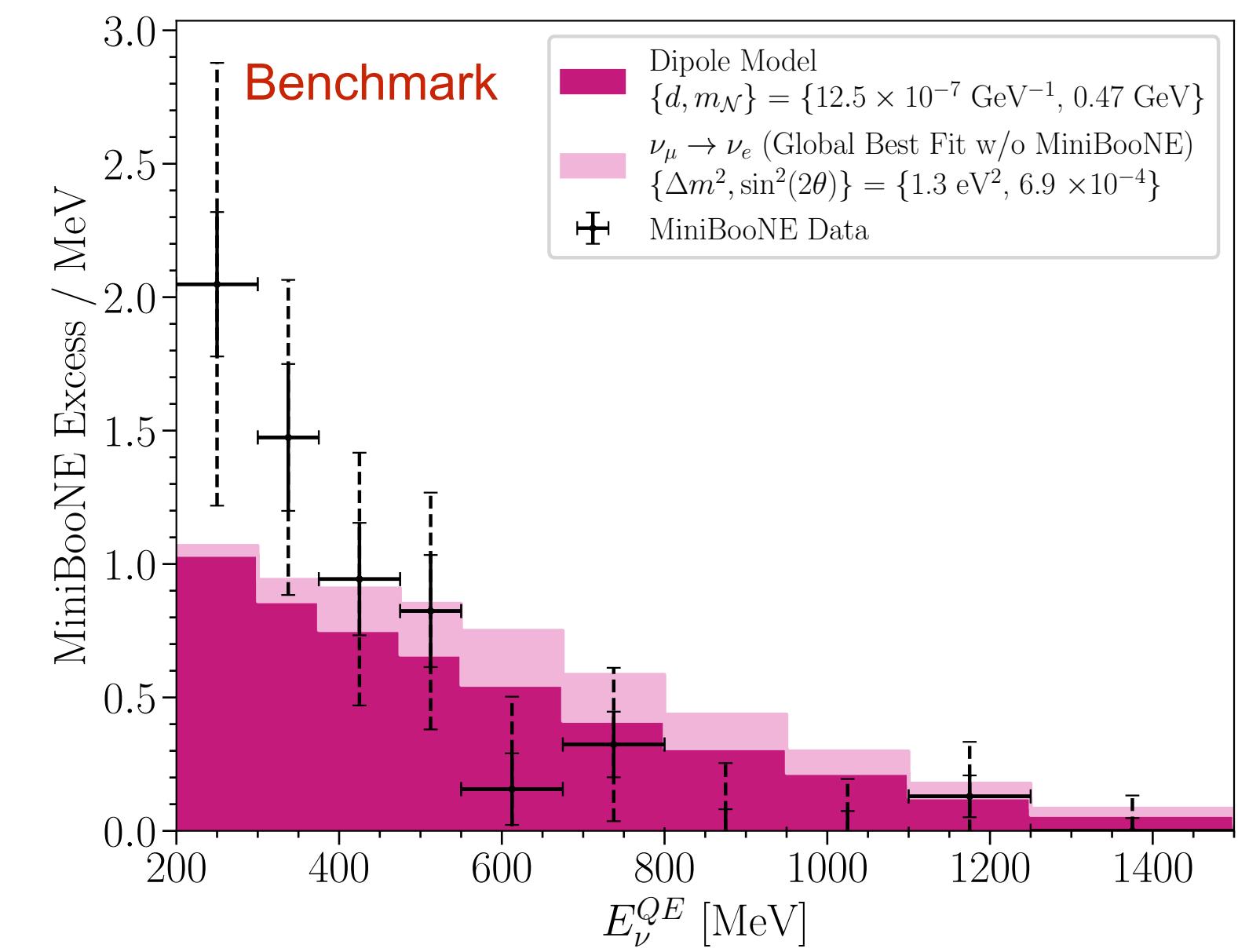
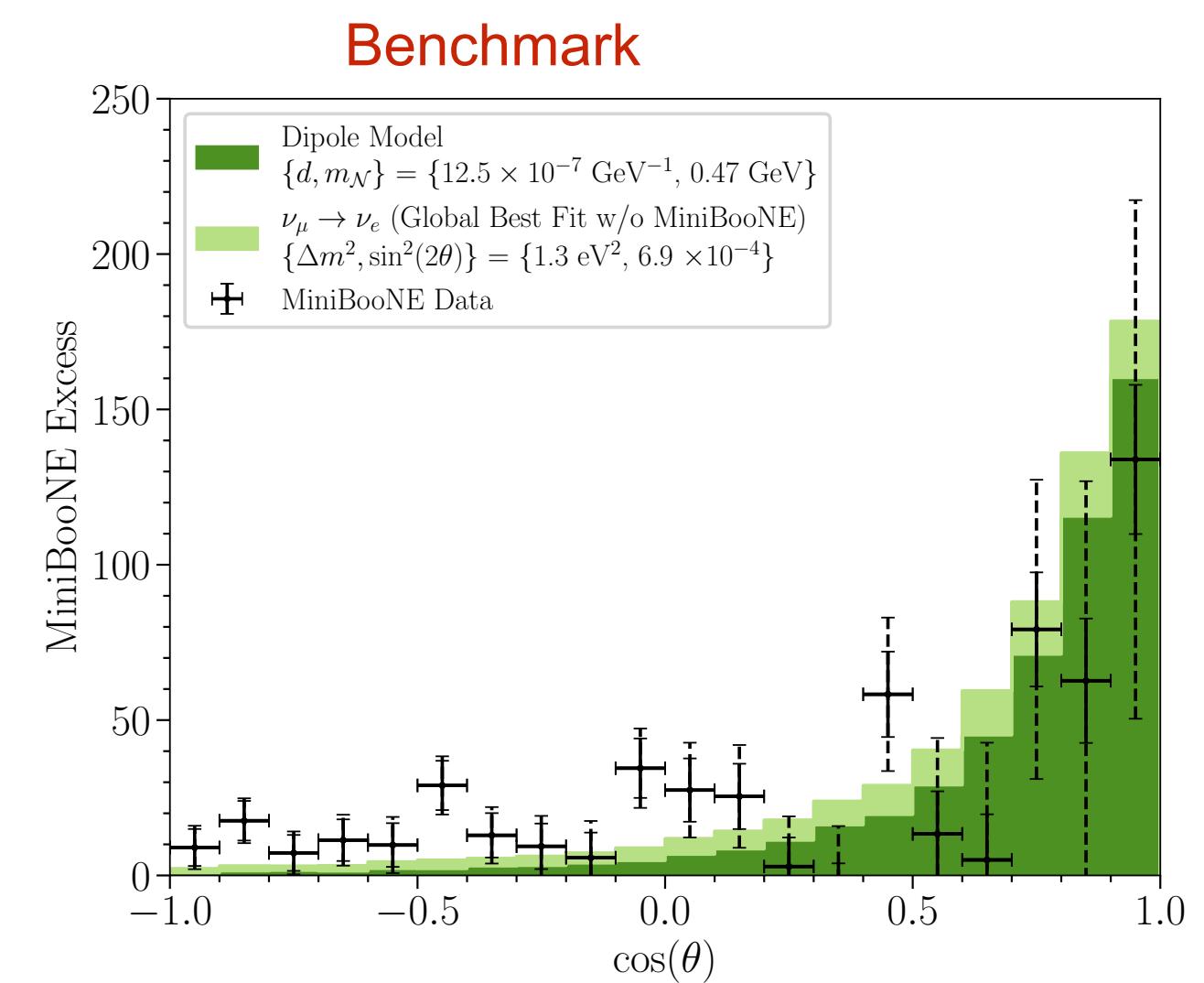
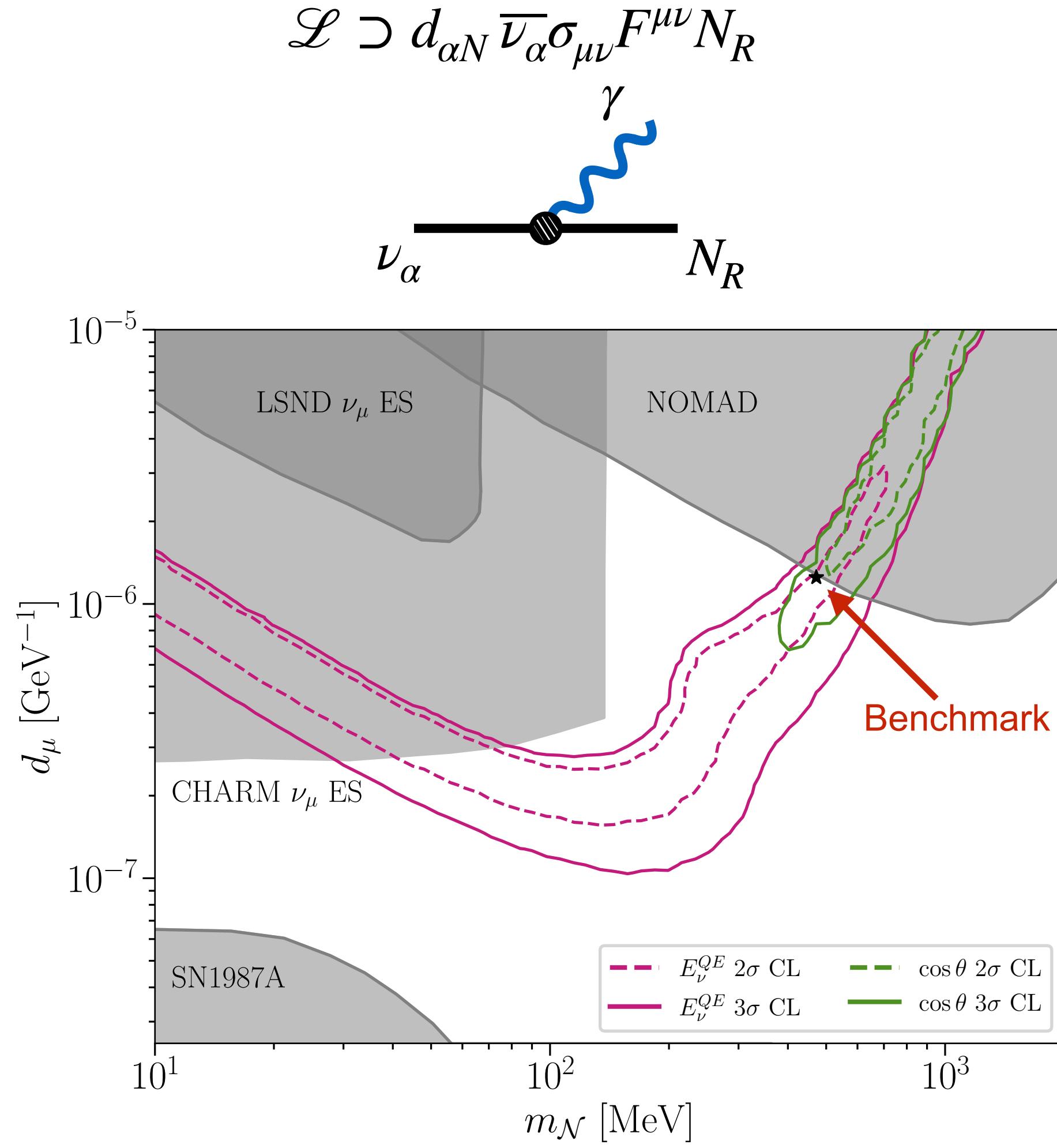


B. Dutta et al, [[arxiv:2006.01319](#)]
 W. Abdallah et al, [[arXiv:2006.01948](#)]
 A. Datta et al, [[arXiv:2005.08920](#)]
 A. Abdullahi et al, [[arXiv:2007.11813](#)]

Transition magnetic moment

MiniBooNE region of interest

N. Kamp, M. Hostert, A. Schneider, S. Vergani, C. A. Argüelles, J. M. Conrad, M. H. Shaevitz, and M. Uchida, arXiv:2206.07100



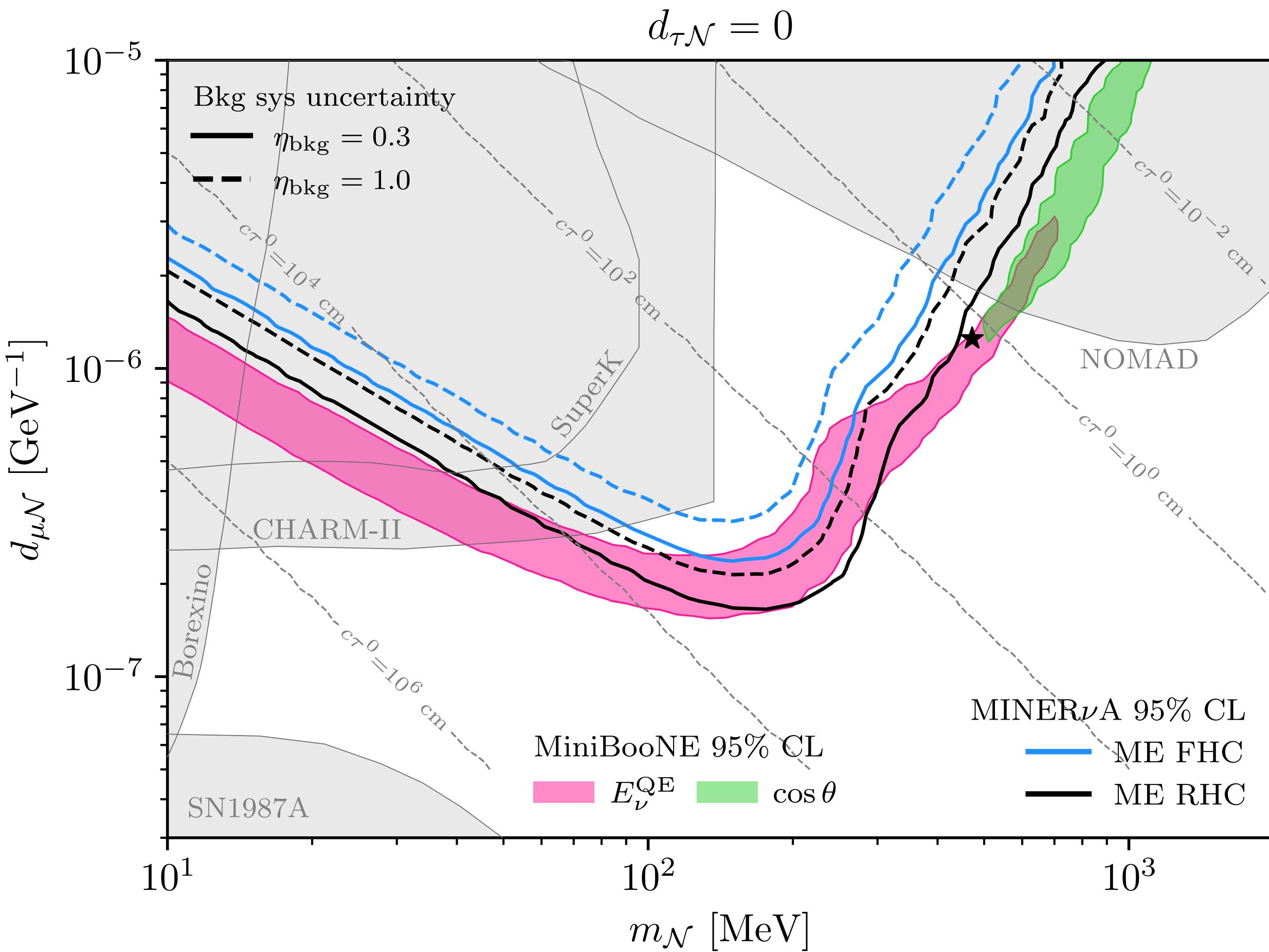
Angular and energy spectrum fits overlap only at the largest m_N values.

Oscillations due to an eV-sterile on top of the dipole using the global best-fit point from Vergani et al. 2021

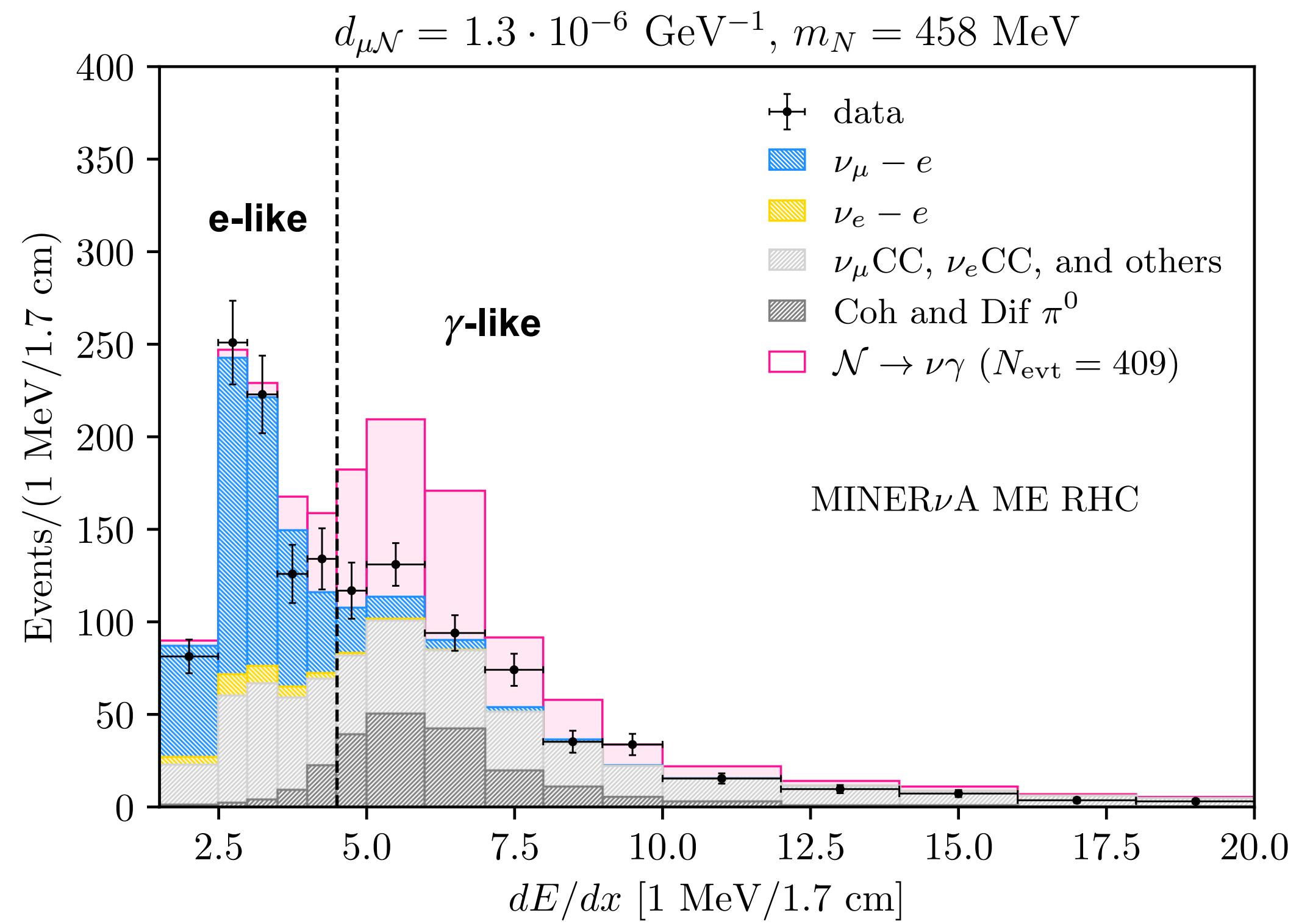
Transition magnetic moment

MINERvA limits from $\nu - e$ scattering measurement

N. Kamp, M. Hostert, A. Schneider, S. Vergani, C. A. Argüelles, J. M. Conrad, M. H. Shaevitz, and M. Uchida, arXiv:2206.07100



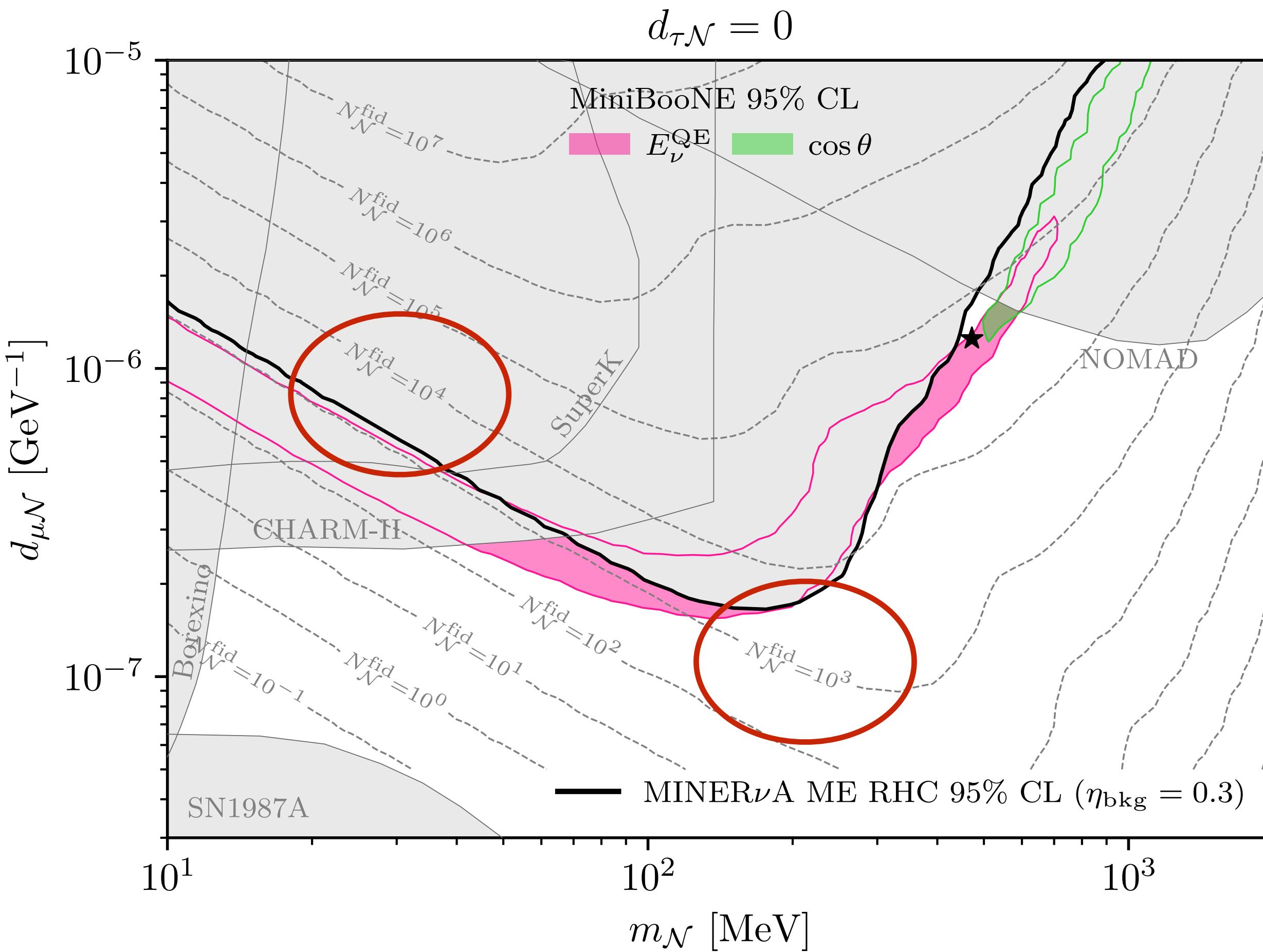
Using photon-like sample of the **MINERvA** antineutrino-electron scattering analysis.



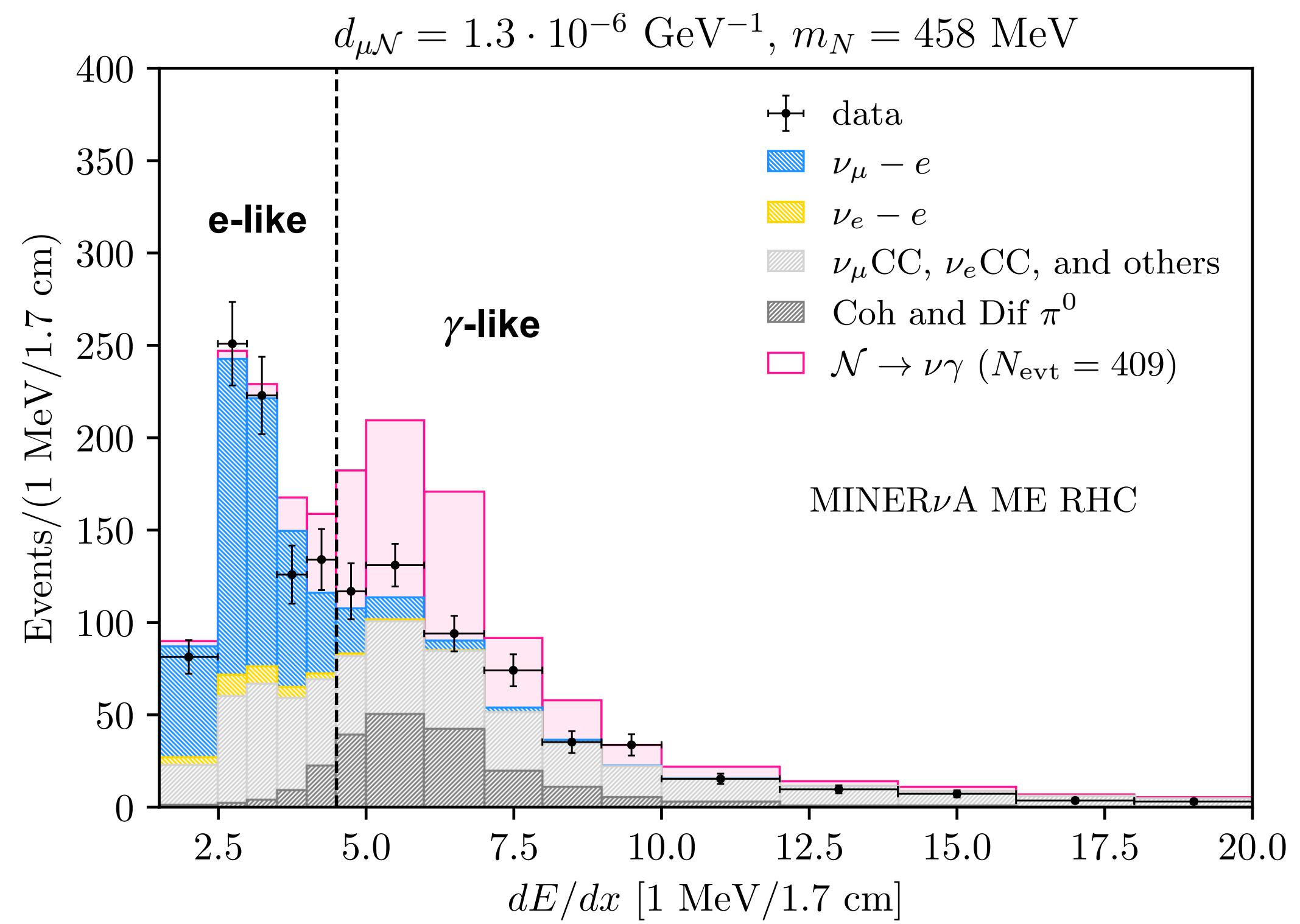
Transition magnetic moment

MINERvA limits from $\nu - e$ scattering measurement

N. Kamp, M. Hostert, A. Schneider, S. Vergani, C. A. Argüelles, J. M. Conrad, M. H. Shaevitz, and M. Uchida, arXiv:2206.07100

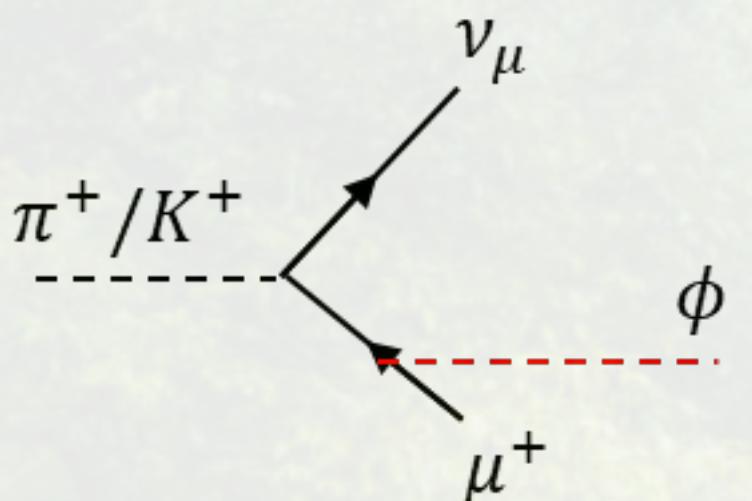
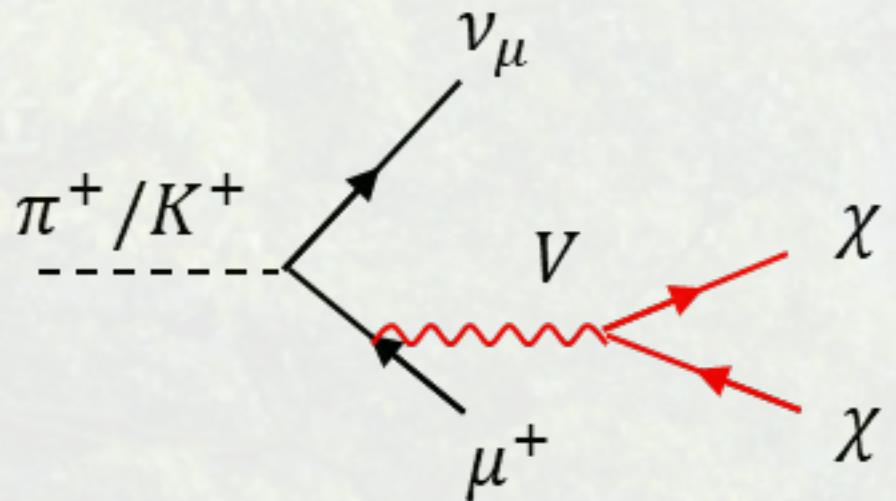


Using photon-like sample of the **MINERvA** antineutrino-electron scattering analysis.



Dark Particle Scattering

Indications that the new physics may be related to charged

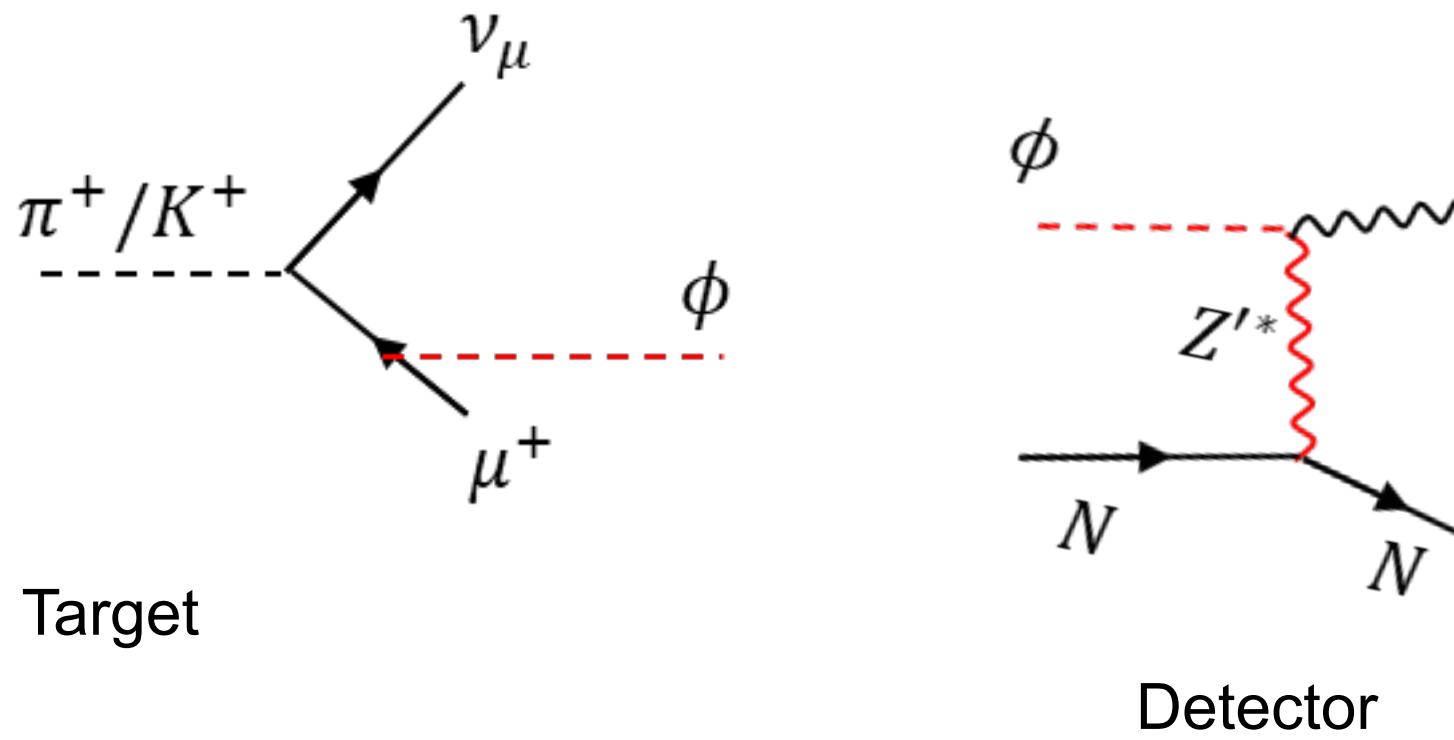


Category	Model	Signature	Anomalies				References
			LSND	MiniBooNE	Reactors	Sources	
Flavor transitions Secs. 3.1.1-3.1.3, 3.1.5	(3+1) oscillations	oscillations	✓	✓	✓	✓	Reviews and global fits [93, 103, 105, 106]
	(3+1) w/ invisible sterile decay	oscillations w/ ν_4 invisible decay	✓	✓	✓	✓	[151, 155]
	(3+1) w/ sterile decay	$\nu_4 \rightarrow \phi \nu_e$	✓	✓	✗	✗	[159–162, 270]
Matter effects Secs. 3.1.4, 3.1.7	(3+1) w/ anomalous matter effects	$\nu_\mu \rightarrow \nu_e$ via matter effects	✓	✓	✗	✗	[143, 147, 271–273]
	(3+1) w/ quasi-sterile neutrinos	$\nu_\mu \rightarrow \nu_e$ w/ resonant ν_s matter effects	✓	✓	✓	✓	[148]
Flavor violation Sec. 3.1.6	Lepton-flavor-violating μ decays	$\mu^+ \rightarrow e^+ \nu_\alpha \bar{\nu}_e$	✓	✗	✗	✗	[174, 175, 274]
	neutrino-flavor-changing bremsstrahlung	$\nu_\mu A \rightarrow e \phi A$	✓	✓	✗	✗	[275]
Decays in flight Sec. 3.2.3	Transition magnetic mom., heavy ν decay	$N \rightarrow \nu \gamma$	✗	✓	✗	✗	[207]
	Dark sector heavy neutrino decay	$N \rightarrow \nu (X \rightarrow e^+ e^-)$ or $N \rightarrow \nu (X \rightarrow \gamma \gamma)$	✗	✓	✗	✗	[208]
Neutrino Scattering Secs. 3.2.1, 3.2.2	neutrino-induced upscattering	$\nu A \rightarrow N A$, $N \rightarrow \nu e^+ e^-$ or $N \rightarrow \nu \gamma \gamma$	✗	✓	✗	✗	[205, 206, 209–216]
	neutrino dipole upscattering	$\nu A \rightarrow N A$, $N \rightarrow \nu \gamma$	✗	✓	✗	✗	[40, 185, 187, 188, 190, 193, 233, 276]
Dark Matter Scattering Sec. 3.2.4	dark particle-induced upscattering	γ or $e^+ e^-$	✗	✓	✗	✗	[217]
	dark particle-induced inverse Primakoff	γ	✓	✓	✗	✗	[217]

Dark particle scattering in MiniBooNE

Inverse primakoff scattering

B. Dutta et al, arXiv:2110.11944

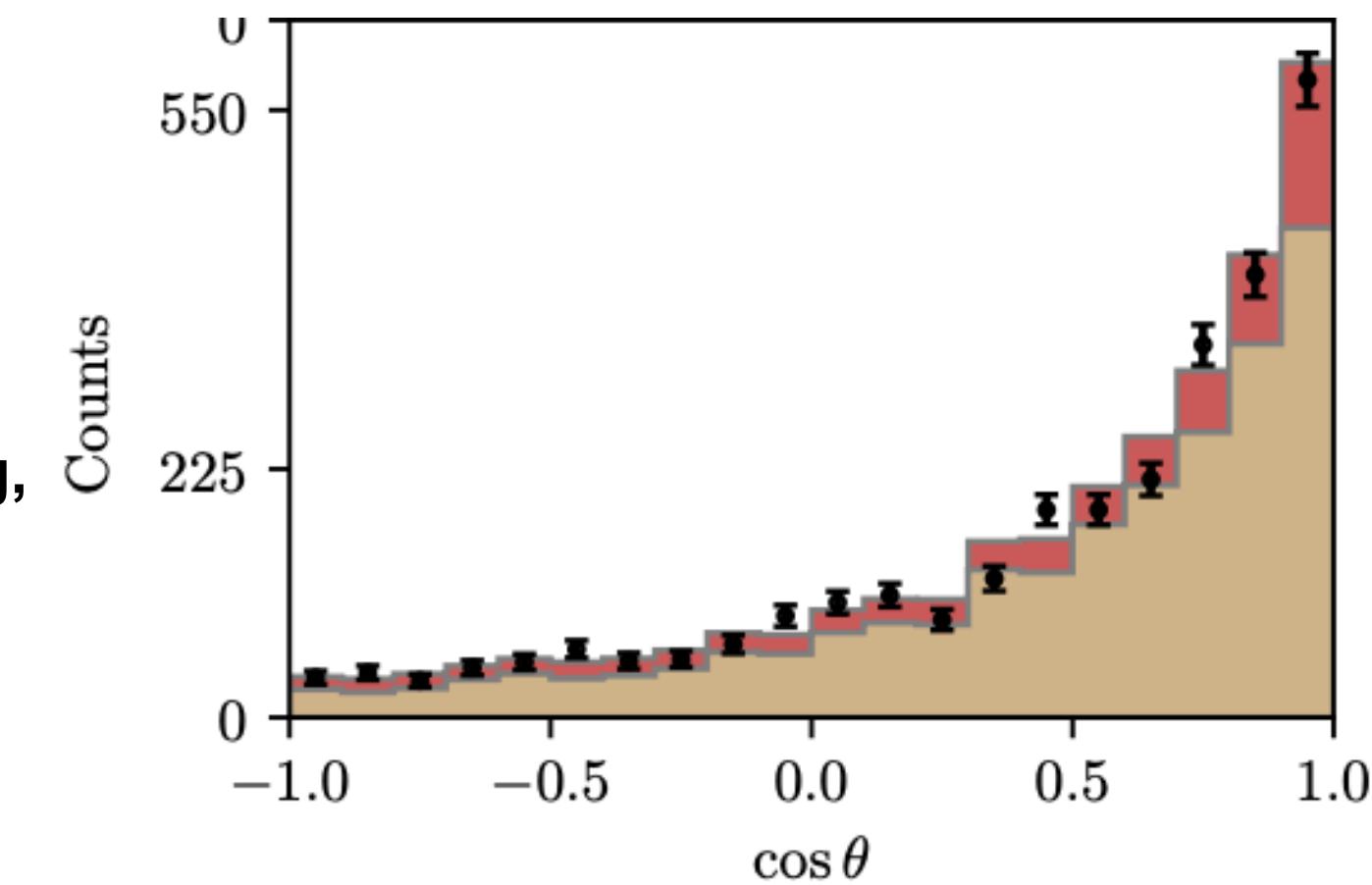
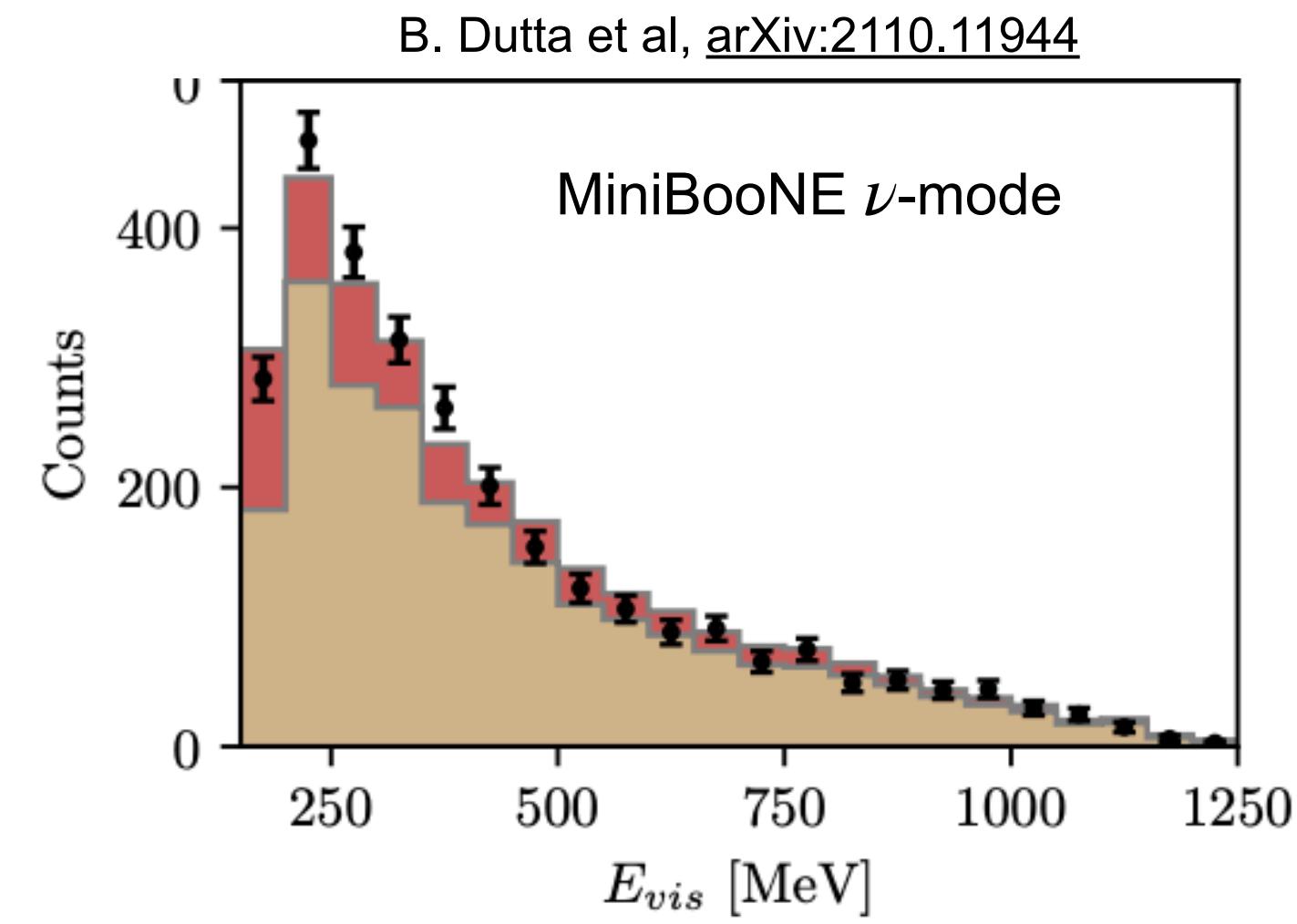


Scalar particle coupled to leptons and dark photon.

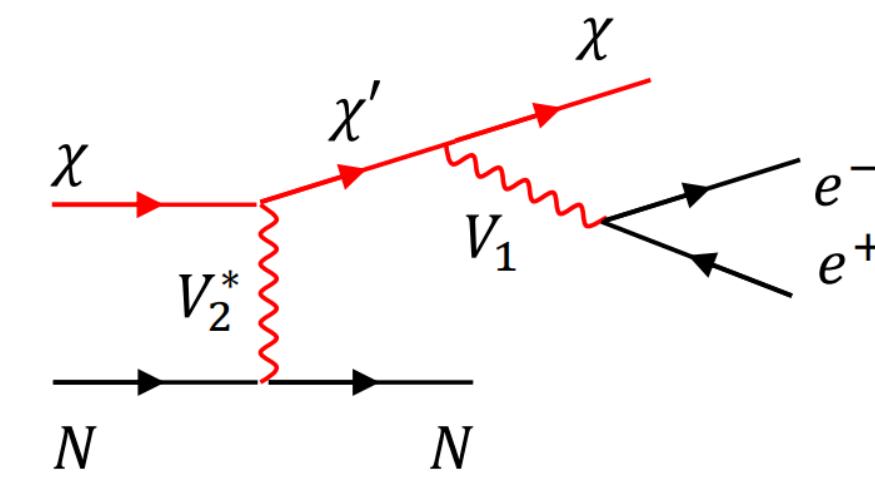
$$\mathcal{L}_S \supset g_\mu \phi \bar{\mu} \mu + g_n Z'_\alpha \bar{u} \gamma^\alpha u + \frac{\lambda}{4} \phi F'_{\mu\nu} F^{\mu\nu} + \text{h.c.}$$

Very similar signatures as discussed in the case of neutrino scattering, except that they are initiated by a dark particle in the beam.

It needs to be light ($\mathcal{O}(10's)$ MeV) so as to avoid time delays.



Also works for vector portal dark matter.



Would be a spectacular way to have found dark matter, but it will take time to prove that it is indeed the case.

SBL anomaly interpretations

Model landscape evolved significantly over the years.

Category	Model	Signature	Anomalies				References
			LSND	MiniBooNE	Reactors	Sources	
Flavor transitions Secs. 3.1.1-3.1.3, 3.1.5	(3+1) oscillations	oscillations	✓	✓	✓	✓	Reviews and global fits [93, 103, 105, 106]
	(3+1) w/ invisible sterile decay	oscillations w/ ν_4 invisible decay	✓	✓	✓	✓	[151, 155]
	(3+1) w/ sterile decay	$\nu_4 \rightarrow \phi \nu_e$	✓	✓	✗	✗	[159–162, 270]
Matter effects Secs. 3.1.4, 3.1.7	(3+1) w/ anomalous matter effects	$\nu_\mu \rightarrow \nu_e$ via matter effects	✓	✓	✗	✗	[143, 147, 271–273]
	(3+1) w/ quasi-sterile neutrinos	$\nu_\mu \rightarrow \nu_e$ w/ resonant ν_s matter effects	✓	✓	✓	✓	[148]
Flavor violation Sec. 3.1.6	Lepton-flavor-violating μ decays	$\mu^+ \rightarrow e^+ \nu_\alpha \bar{\nu}_e$	✓	✗	✗	✗	[174, 175, 274]
	neutrino-flavor-changing bremsstrahlung	$\nu_\mu A \rightarrow e \phi A$	✓	✓	✗	✗	[275]
Decays in flight Sec. 3.2.3	Transition magnetic mom., heavy ν decay	$N \rightarrow \nu \gamma$	✗	✓	✗	✗	[207]
	Dark sector heavy neutrino decay	$N \rightarrow \nu (X \rightarrow e^+ e^-)$ or $N \rightarrow \nu (X \rightarrow \gamma\gamma)$	✗	✓	✗	✗	[208]
Neutrino Scattering Secs. 3.2.1, 3.2.2	neutrino-induced upscattering	$\nu A \rightarrow N A$, $N \rightarrow \nu e^+ e^-$ or $N \rightarrow \nu \gamma \gamma$	✓	✓	✗	✗	[205, 206, 209–216]
	neutrino dipole upscattering	$\nu A \rightarrow N A$, $N \rightarrow \nu \gamma$	✓	✓	✗	✗	[40, 185, 187, 188, 190, 193, 233, 276]
Dark Matter Scattering Sec. 3.2.4	dark particle-induced upscattering	γ or $e^+ e^-$	✗	✓	✗	✗	[217]
	dark particle-induced inverse Primakoff	γ	✓	✓	✗	✗	[217]

Conclusions:

Still no coherent picture for SBL anomalies, but new approaches have appeared.

Testing these will require lots of effort from both neutrino experiments (or otherwise).

Oscillations require some more definitive tests:

SBN program + JSNS² + dedicated future programs (IsoDAR, reactor upgrades, LBL program)?

Covering the huge class of models for light dark sector with existing data — dedicated searches starting to appear.

Model building and pheno being guided by inputs from flavor physics, dark matter, and collider program.