Neutrino Non-Standard Interactions (NSI)

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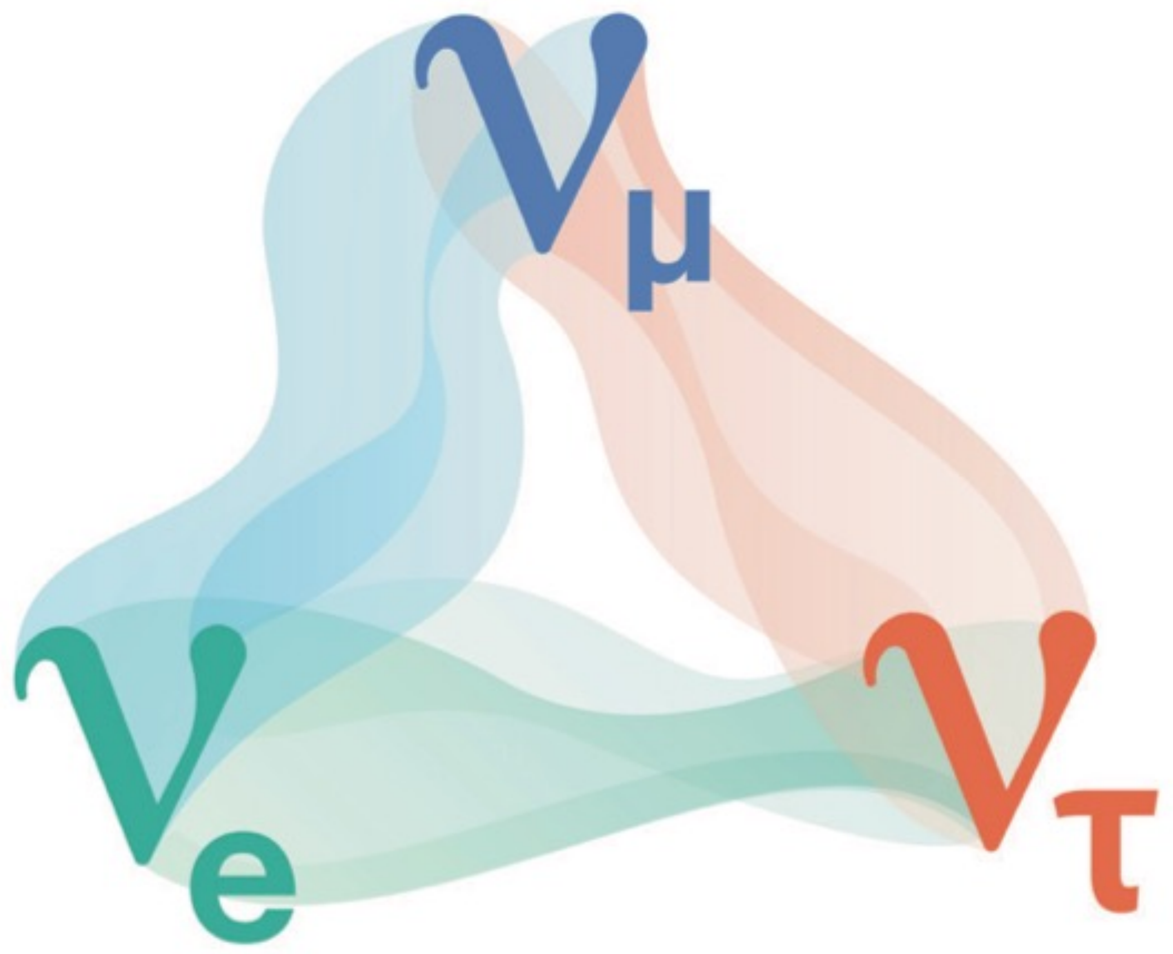
Why NSI?

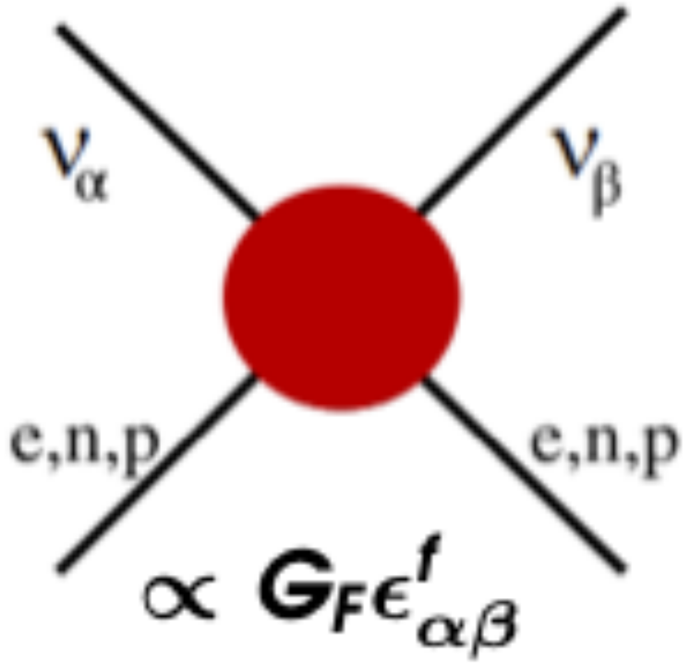


Neutrino Oscillations $\Longrightarrow$ Nonzero Neutrino Mass $\Longrightarrow$ BSM Physics

- Must introduce new fermions, scalars, and/or gauge bosons.
- New couplings involving neutrinos (beyond the standard weak interactions).
- Could affect neutrino propagation in matter, production, and/or detection.
- At the very least, could serve as a foil for the standard 3-neutrino oscillation paradigm.
- Better understanding of NSI is crucial for the correct interpretation of the oscillation data.
- Could open a new window into BSM physics.

- > 500 papers on NSI phenomenology. Apologies if your favorite paper(s) not included here.
- For a more comprehensive review, see e.g. Ohlsson, 1209.2710; Miranda, Nunokawa, 1505.06254; Farzan, Tortola, 1710.09360; BD et al, 1907.00991; Snowmass Whitepaper, 2203.10811

Neutral Current (Matter) NSI



$$\mathcal{L}^{\rm NC}_{\rm NSI} = -2\sqrt{2}G_F \sum_{f,X,\alpha,\beta} \varepsilon^{fX}_{\alpha\beta}(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)(\bar{f}\gamma_\mu P_X f)$$

Wolfenstein (PRD '78)

with $X = L, R$, and $f \in \{e, u, d\}$.

- Only vector part is relevant (axial-vector part is spin-dependent):

$$\varepsilon_{\alpha\beta} = \sum_{f\in\{e,u,d\}} \frac{N_f}{N_e}\varepsilon^{fV}_{\alpha\beta} = \varepsilon^{eV}_{\alpha\beta} + (2+Y_n)\varepsilon^{uV}_{\alpha\beta} + (1+2Y_n)\varepsilon^{dV}_{\alpha\beta}$$

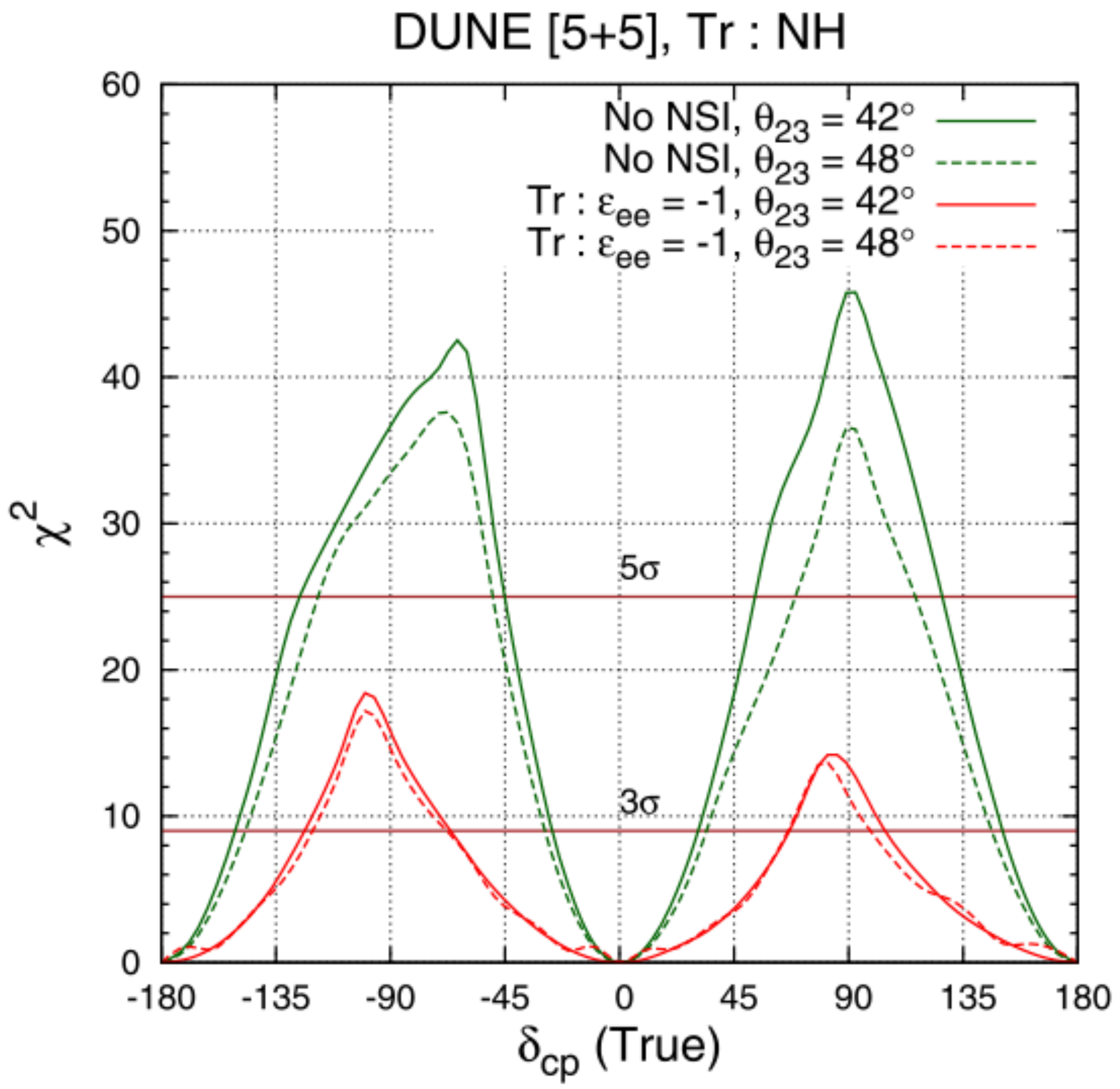
with $\varepsilon^{fV}_{\alpha\beta} = \varepsilon^{fL}_{\alpha\beta} + \varepsilon^{fR}_{\alpha\beta}$ and $Y_n = N_n/N_e \simeq 1$ for Earth.

- Leads to additional matter effect in propagation:

$$P(\nu_\alpha \to \nu_\beta) = \left|\langle\nu_\beta|e^{-i(H+V_{\rm NSI})L}|\nu_\alpha\rangle\right|^2 ,$$

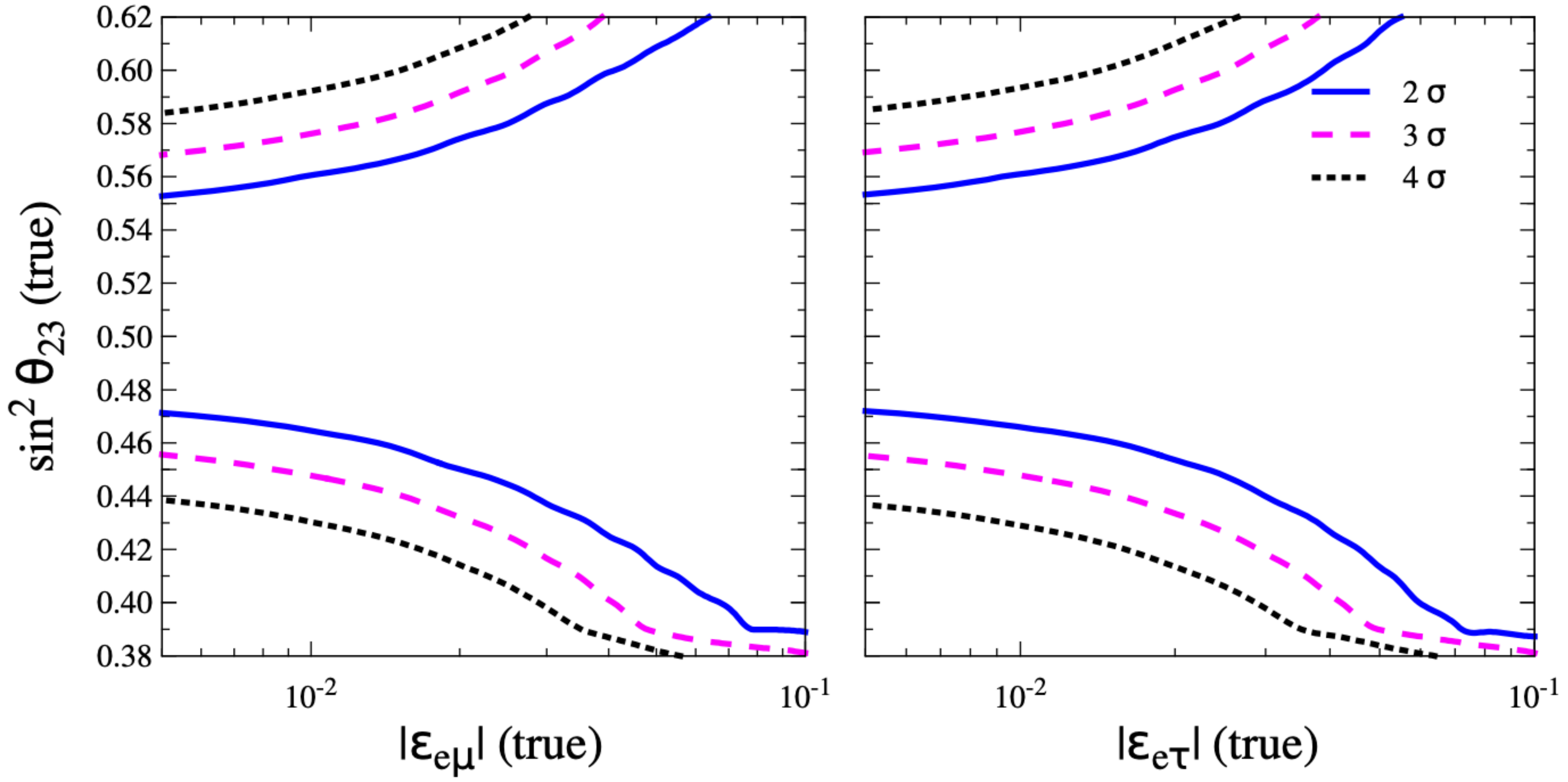
where $V_{\rm NSI} = \sqrt{2}G_F N_e \begin{pmatrix} \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix}$

Can Degrade Discovery Potential of LBNE



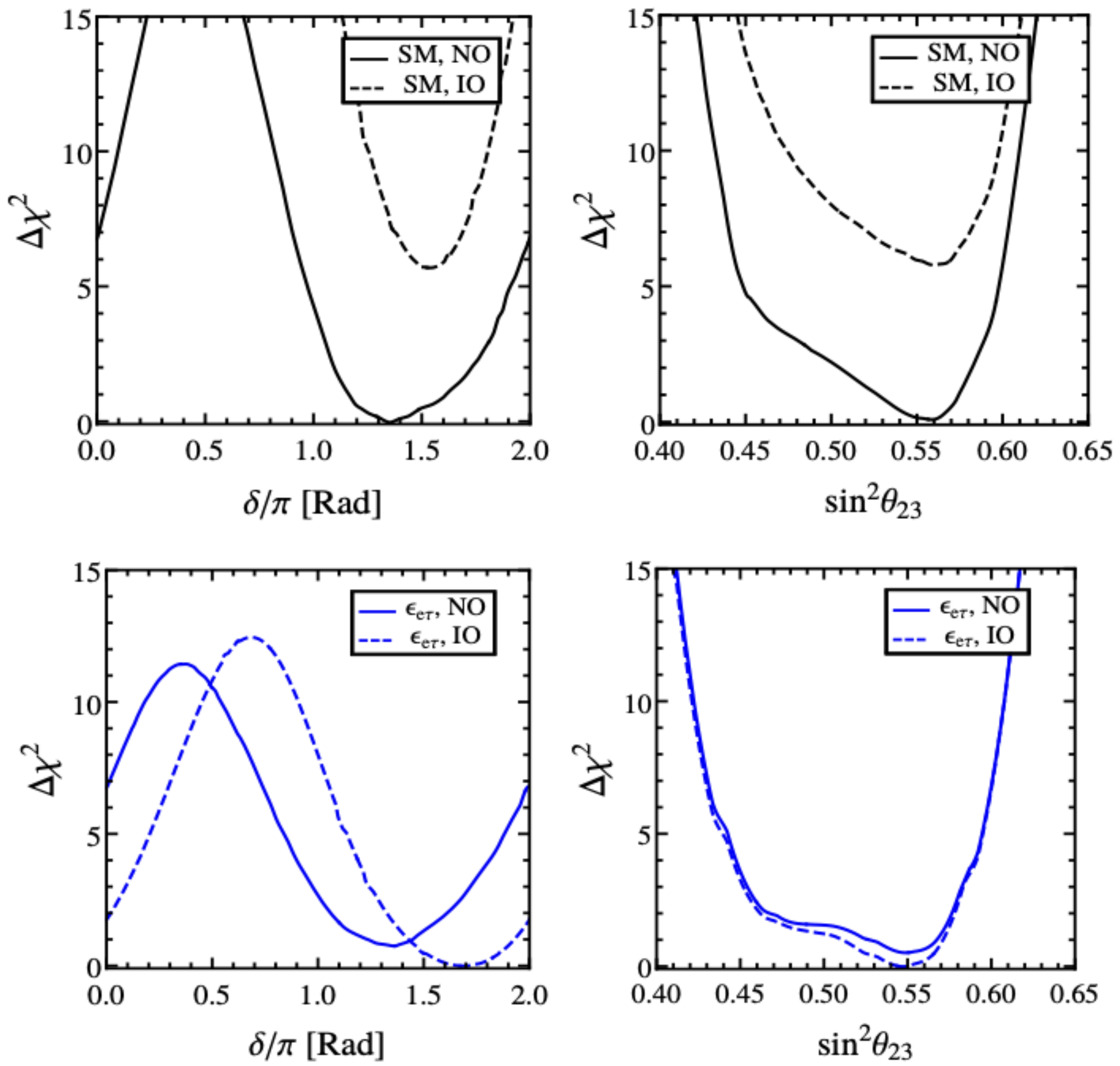
δ_{CP} at DUNE

Deepthi, Goswami, Nath, 1711.04840



Octant at DUNE

Agarwalla, Chatterjeea, Palazzo, 1607.01745



Mass Ordering at T2K+NOvA

Capozzi, Chatterjee, Palazzo, 1908.06992

Information from other oscillation experiments (solar, atmospheric, reactor, MINOS) and COHERENT data can break the degeneracy. Esteban, Gonzalez-Garcia, Maltoni, 2004.04745

Can Solve the T2K-NOvA Tension

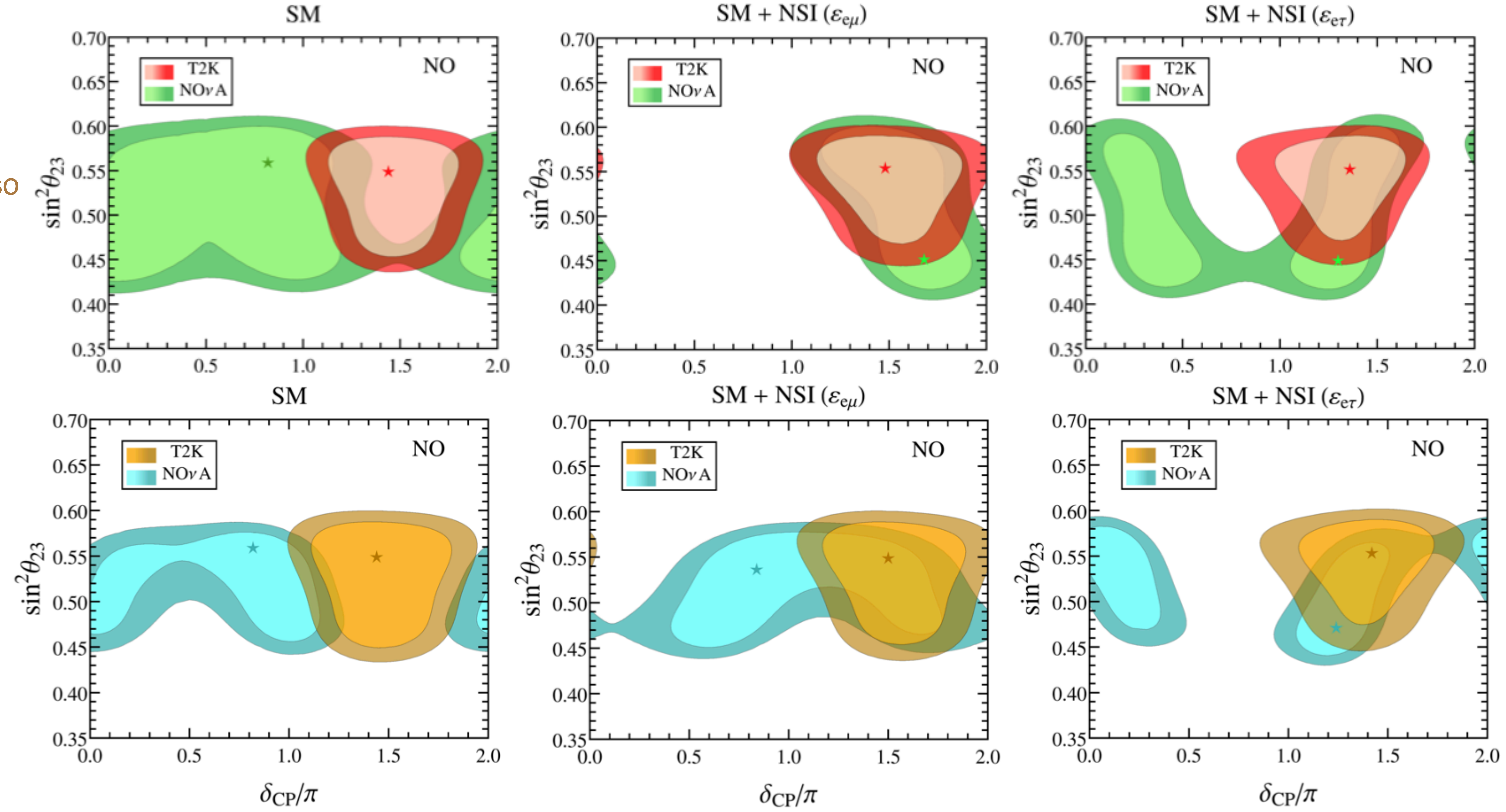
For latest NOvA updates, see posters by M. Acero, G. Davies, X. Huang.

2020 status

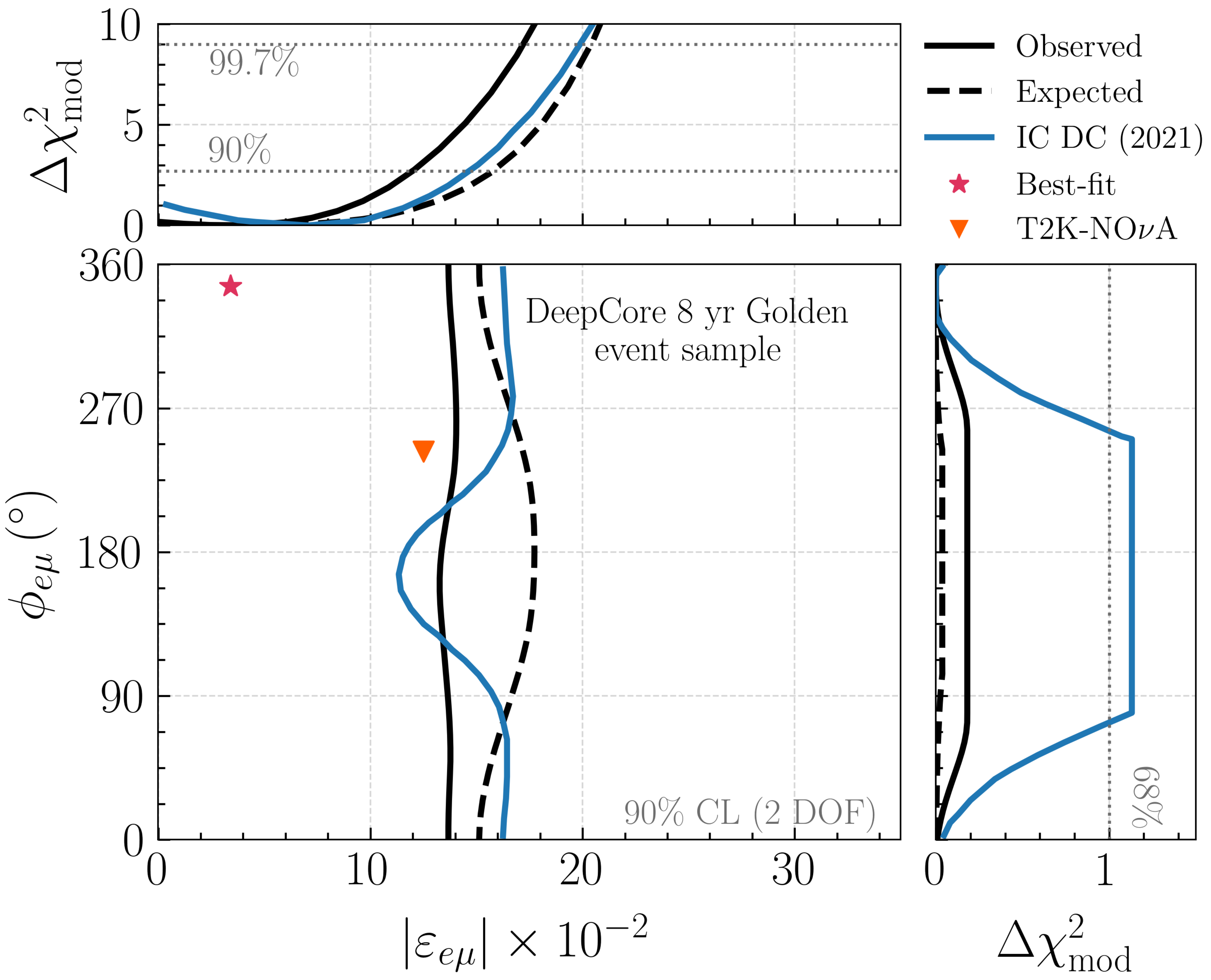
Chatterjee, Palazzo, 2008.04161; see also Denton, Gehrlein, Pestes, 2008.01110

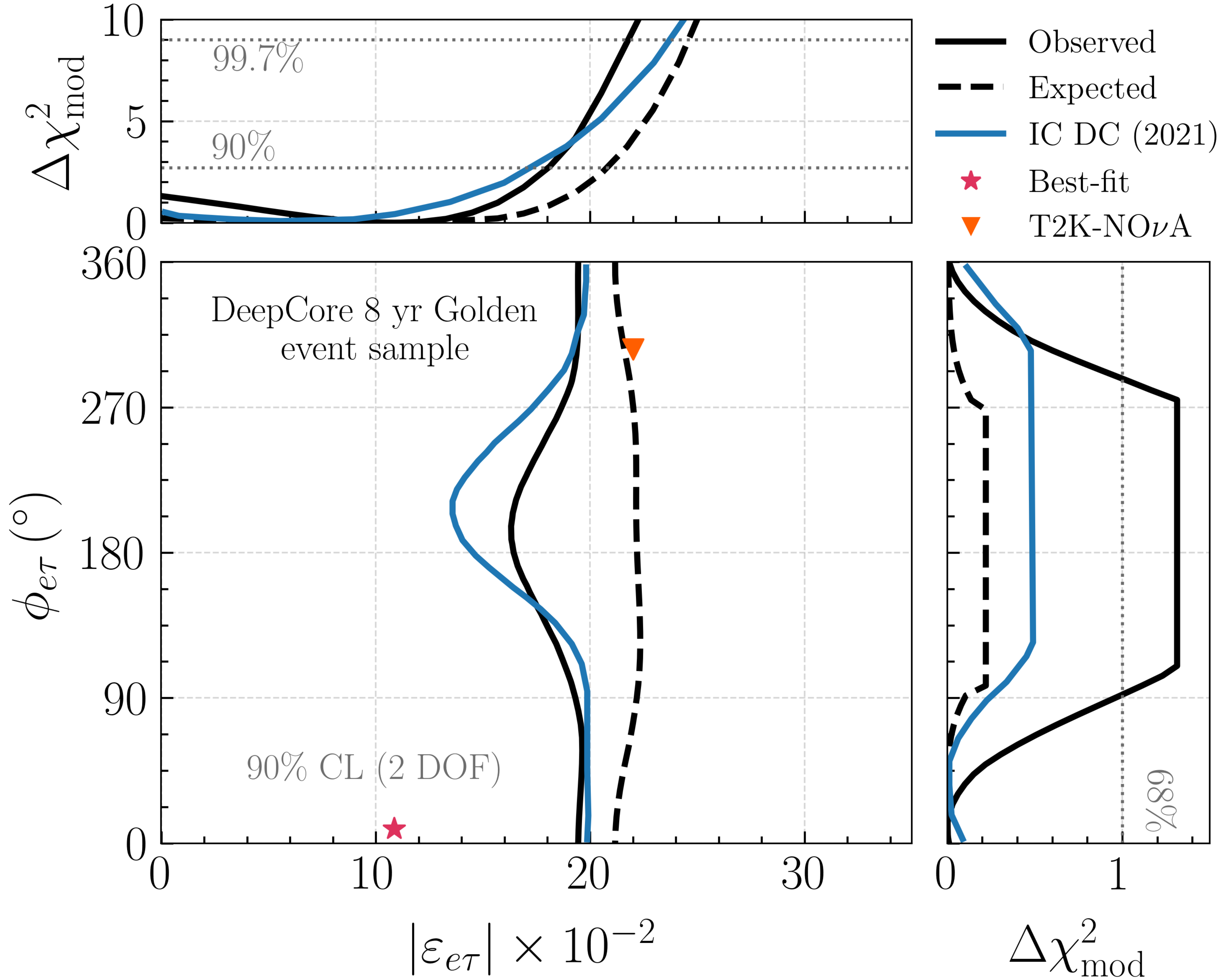
2024 update

Chatterjee, Palazzo, 2409.10599; see also Cherchiglia *et al*, 2310.18401; Goswami et al, 2512.00172



New Constraints from IceCube DeepCore



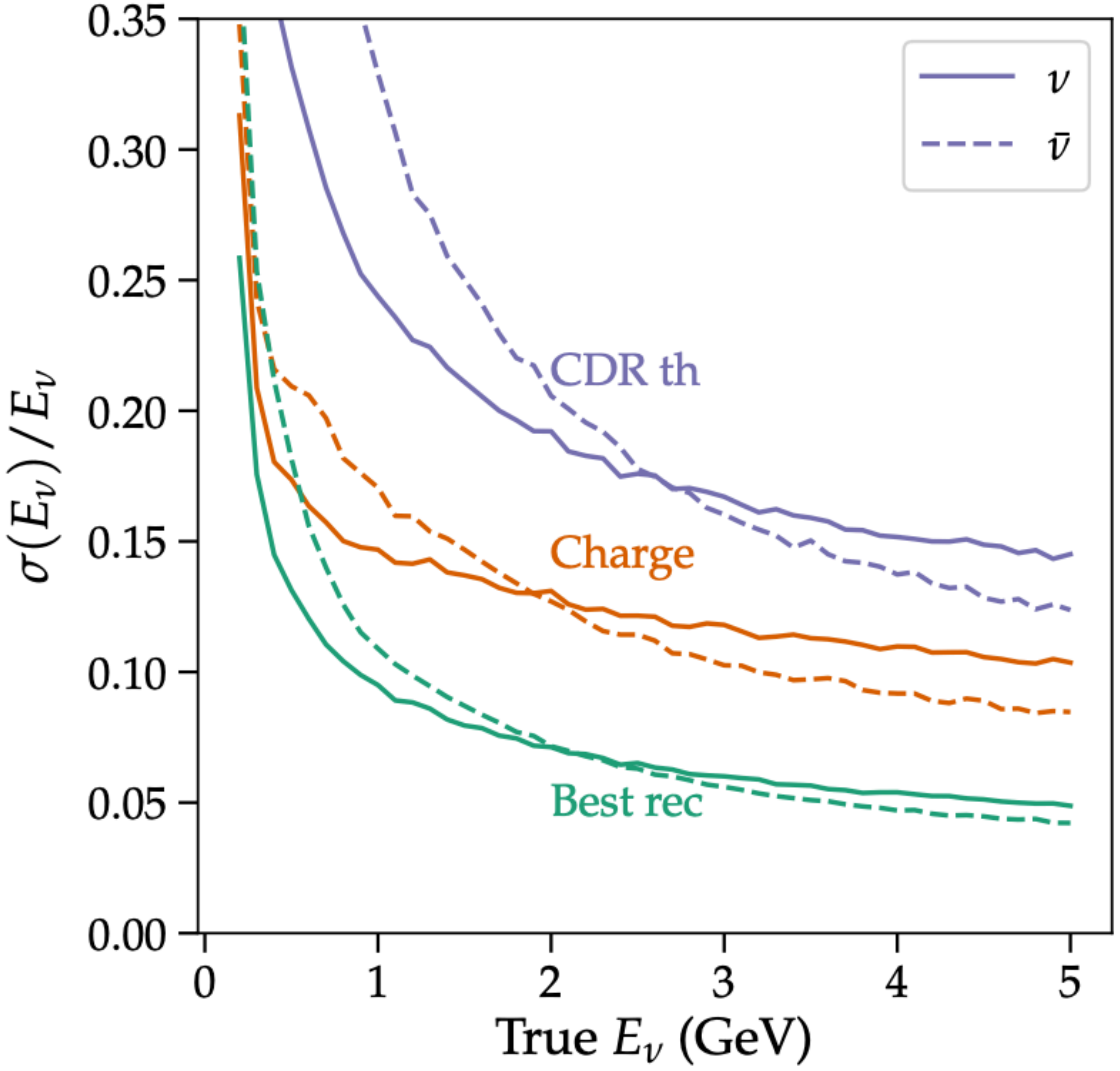


Krishnamoorthi, Kumar, Agarwalla, 2512.22632, 2604.16157; see also 2601.22374

DUNE Sensitivity

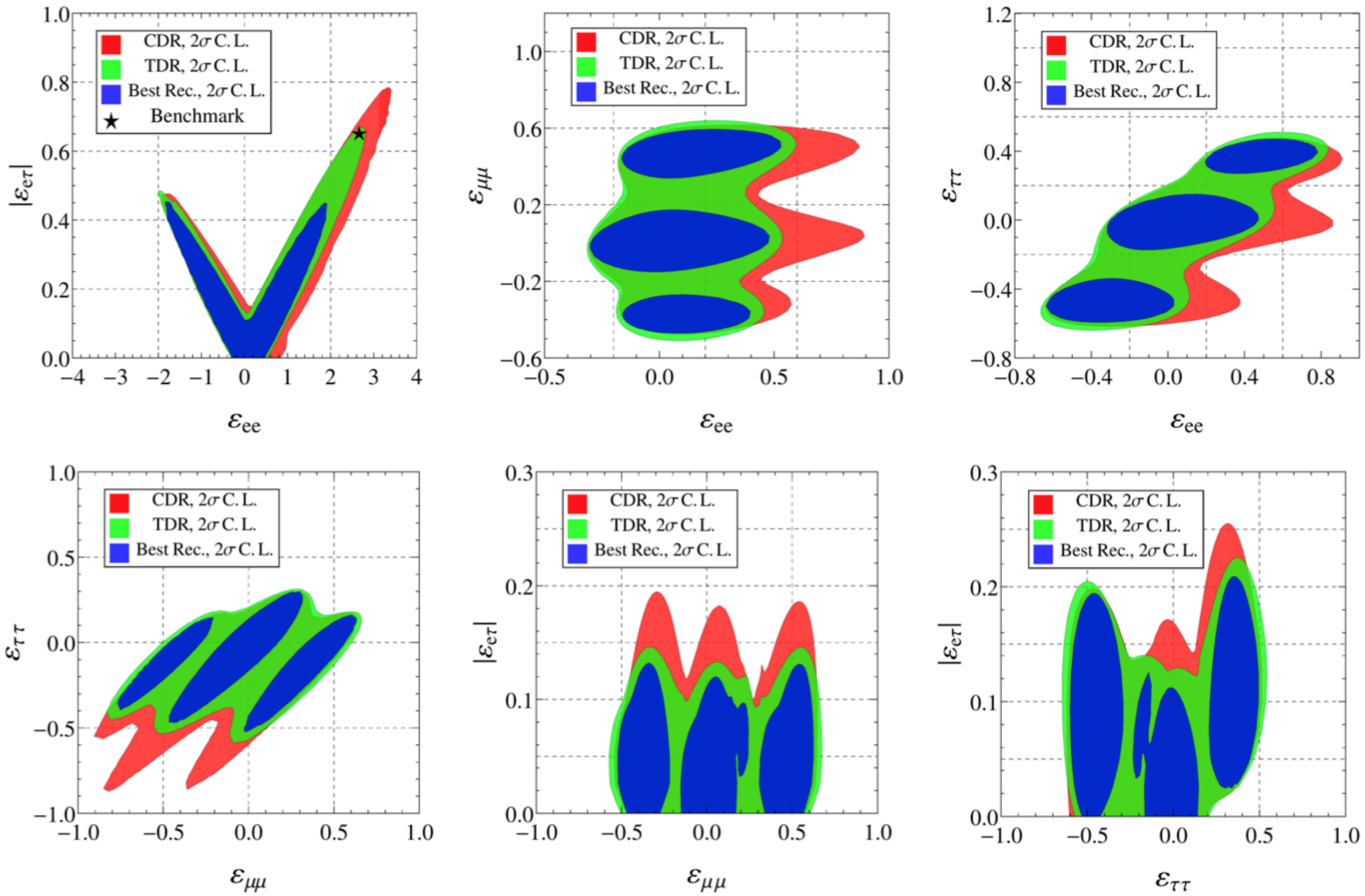
de Gouvea, Kelly, 1511.05562; Coloma, 1511.06357; Blennow *et al*, 1606.08851; Liao, Marfatia, Whisnant, 1612.01443; Chatterjee et al, 1809.09313; Han et al, 1910.03272; …

Poster by L. Prais



With improved energy resolution

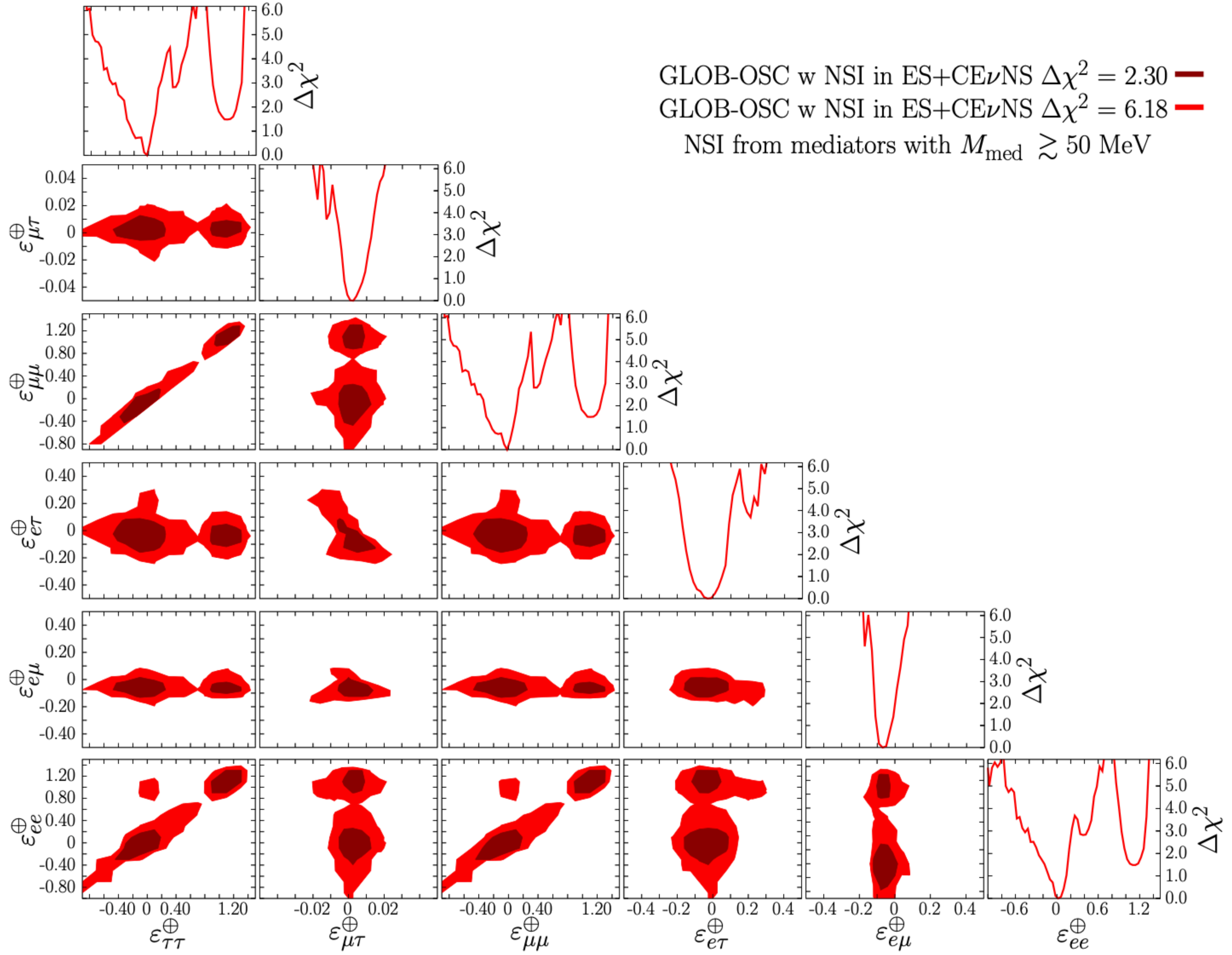
Friedland, Li, 1811.06159



Chatterjee, BD, Machado, 2106.04597

Global Fit Constraints

Coloma, Gonzalez-Garcia, Maltoni, Pinheiro, Urrea, 2305.07698;
See also Coloma *et al*, 2411.00090 for a global SMEFT fit



Charged Current NSI

$$\mathcal{L}_{\rm NSI}^{\rm CC} = -2\sqrt{2}G_F\varepsilon_{\alpha\beta}^{ff'X}(\bar{\nu}_\alpha\gamma^\mu P_L\ell_\beta)(\bar{f}'\gamma_\mu P_X f)$$

- Modifies neutrino flavor at source or detector:

$$|\nu_\alpha^{\rm s}\rangle = |\nu_\alpha\rangle + \sum_{\beta=e,\mu,\tau}\varepsilon_{\alpha\beta}^{\rm s}|\nu_\beta\rangle\,, \quad \text{e.g. } \pi^+ \xrightarrow{\varepsilon_{e\mu}^{\rm s}} \mu^+\nu_e$$

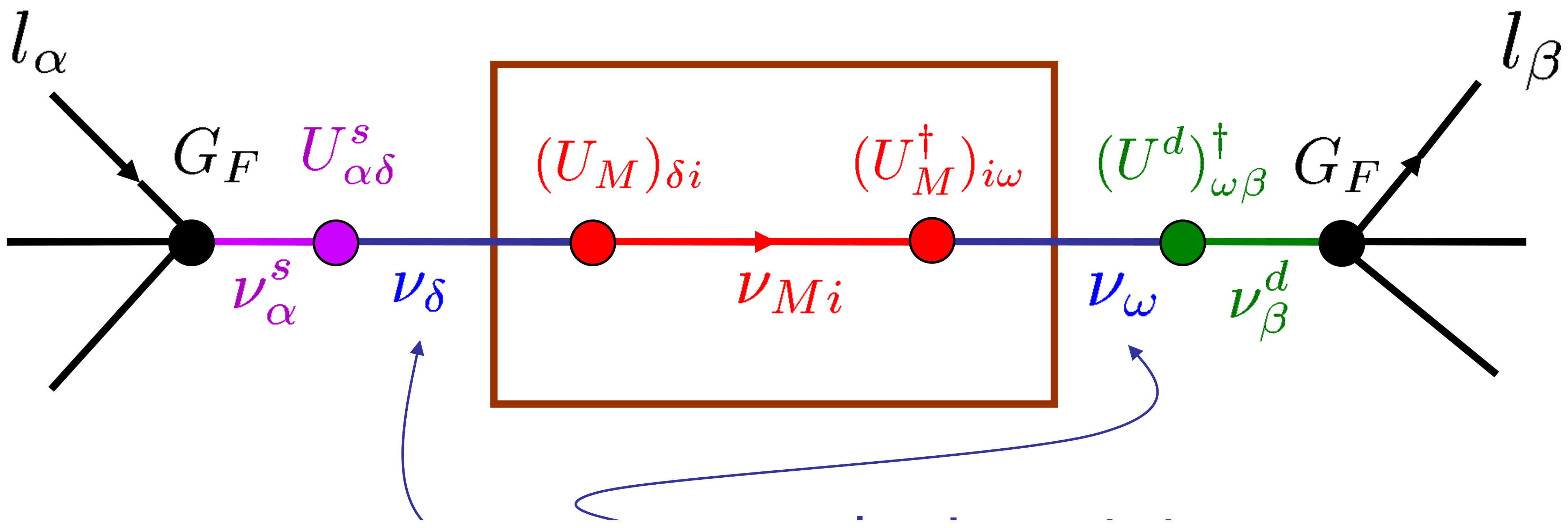
$$\langle\nu_\alpha^{\rm d}| = \langle\nu_\alpha| + \sum_{\beta=e,\mu,\tau}\varepsilon_{\alpha\beta}^{\rm d}\langle\nu_\beta|\,, \quad \text{e.g. } \nu_\tau n \xrightarrow{\varepsilon_{e\tau}^{\rm d}} e^-p$$

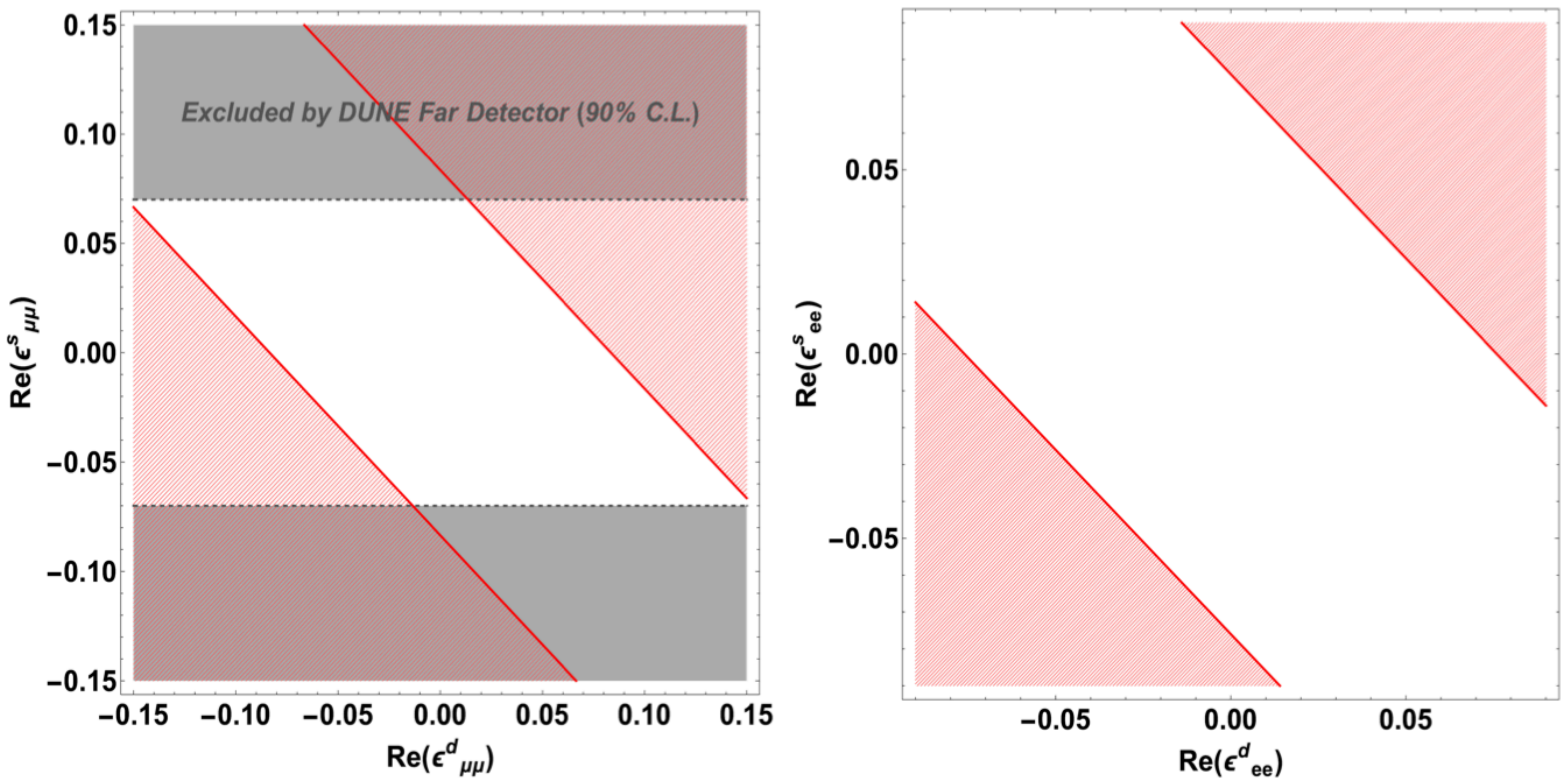
$$P(\nu_\alpha\to\nu_\beta) = \left|\langle\nu_\beta^{\rm d}|e^{-iHL}|\nu_\alpha^{\rm s}\rangle\right|^2$$

- Zero-distance effect: $P_{\alpha\beta}\neq\delta_{\alpha\beta}$ for $L\to 0$.
- Near Detector facilities capable of probing this parameter space down to a few % level.

Blennow *et al*, 1507.02868; Coloma *et al*, 2411.00090

Grossman, hep-ph/9507344

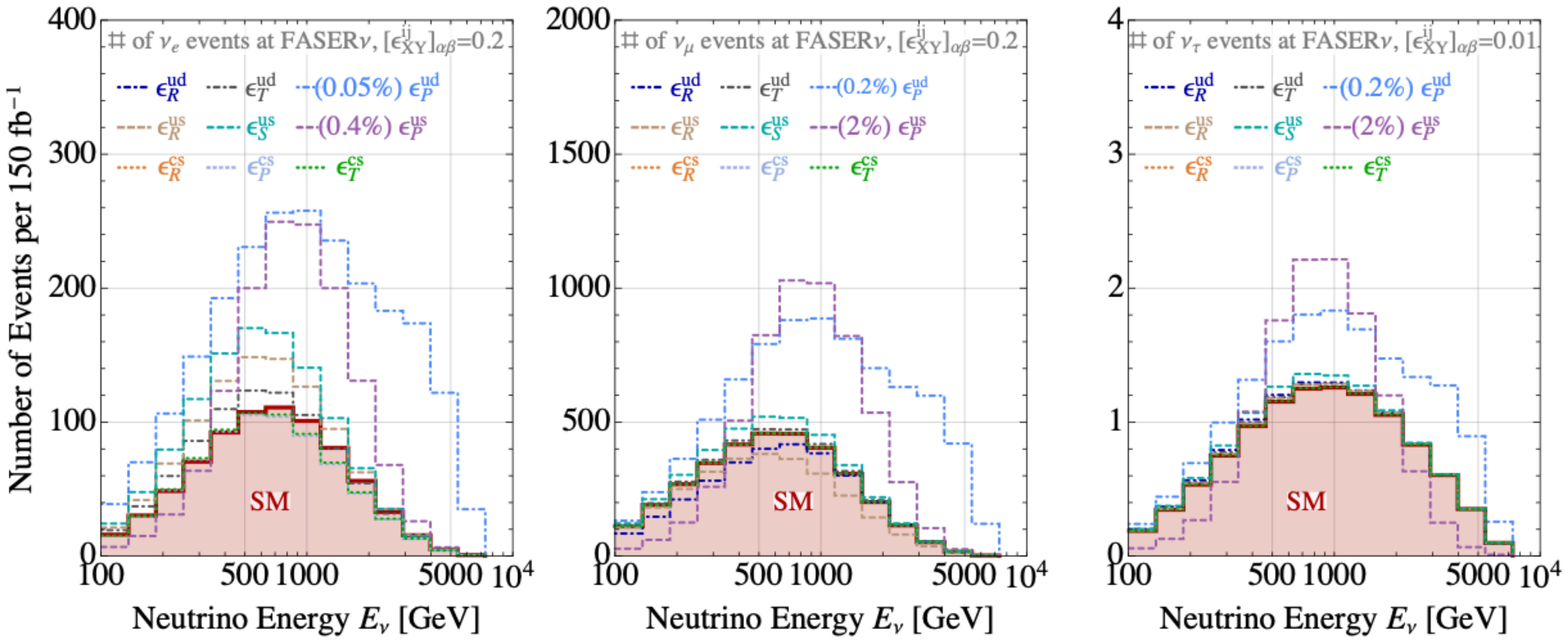


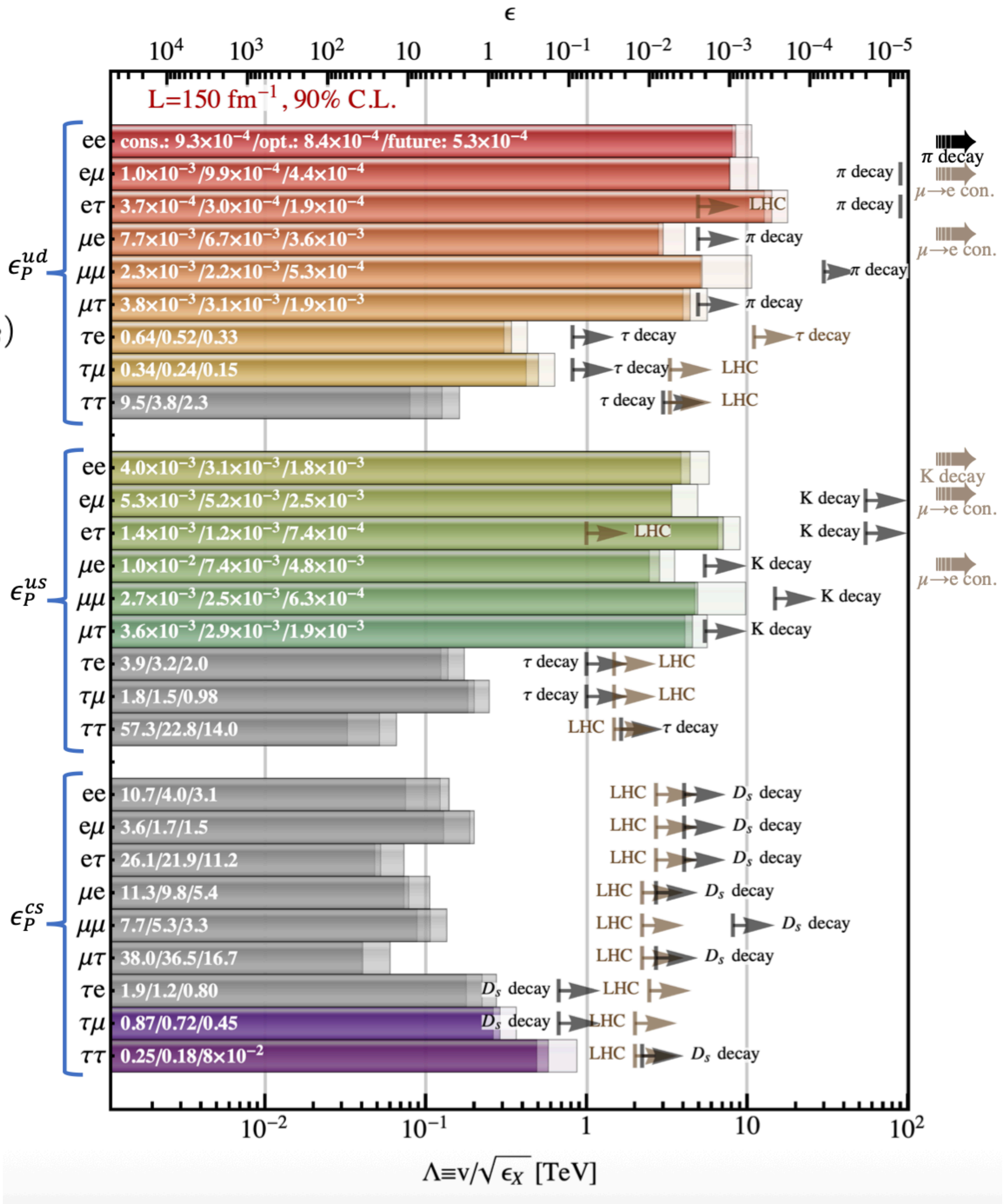


Giarnetti, Meloni, 2005.10272

Collider Constraints

$$\mathcal{L}_{\rm WEFT} \supset -\frac{2V_{jk}}{v^2}\Big\{[\mathbf{1}+\epsilon_L^{jk}]_{\alpha\beta}(\bar u^j\gamma^\mu P_L d^k)(\bar\ell_\alpha\gamma_\mu P_L\nu_\beta) + [\epsilon_R^{jk}]_{\alpha\beta}(\bar u^j\gamma^\mu P_R d^k)(\bar\ell_\alpha\gamma_\mu P_L\nu_\beta) + \frac{1}{2}[\epsilon_S^{jk}]_{\alpha\beta}(\bar u^j d^k)(\bar\ell_\alpha P_L\nu_\beta) - \frac{1}{2}[\epsilon_P^{jk}]_{\alpha\beta}(\bar u^j\gamma_5 d^k)(\bar\ell_\alpha P_L\nu_\beta) + \frac{1}{4}[\epsilon_T^{jk}]_{\alpha\beta}(\bar u^j\sigma^{\mu\nu}P_L d^k)(\bar\ell_\alpha\sigma_{\mu\nu}P_L\nu_\beta) + \text{h.c.}\Big\}.$$





Falkowski, González-Alonso, Kopp, Soreq, Tabrizi, 2105.12136

NSI Model Building

- Can we have 'large' NSI $\varepsilon_{\alpha\beta} \gtrsim \mathcal{O}(0.1)$ in a realistic UV-complete model?
- From EFT, we expect $\varepsilon \sim \dfrac{g_{\rm NP}^2 m_W^2}{\Lambda_{\rm NP}^2}$.
- Two regimes to realize $\varepsilon \sim \mathcal{O}(0.1)$:
  - **Heavy mediator:** $\Lambda_{\rm NP} \gtrsim m_W$ and $g_{\rm NP} \sim \mathcal{O}(1)$.
  - **Light mediator:** $\Lambda_{\rm NP} \ll m_W$ and $g_{\rm NP} \ll 1$, but $\dfrac{g_{\rm NP}^2}{\Lambda_{\rm NP}^2} \sim \mathcal{O}(G_F)$.
- Main challenge is that restoring $SU(2)_L$ gauge invariance in general imposes stringent constraints on NSI. Antusch *et al*, 0807.1003; Gavela *et al*, 0809.3451; Biggio *et al*, 0907.0097
- This is important to understand which kind of new physics the neutrino experiments are probing when model-independent NSI constraints are presented.
- Can then use NSI to probe neutrino mass physics.

NSI in Tree-Level Neutrino Mass Models

3N-SS	Normal Ordering	
	68%CL	95%CL
$\eta_{ee} = \frac{\lvert\theta_e\rvert^2}{2}$	$[0.28, 0.99] \cdot 10^{-3}$	$1.3 \cdot 10^{-3}$
$\eta_{\mu\mu} = \frac{\lvert\theta_\mu\rvert^2}{2}$	$1.3 \cdot 10^{-7}$	$1.1 \cdot 10^{-5}$
$\eta_{\tau\tau} = \frac{\lvert\theta_\tau\rvert^2}{2}$	$[0.3, 3.9] \cdot 10^{-4}$	$1.0 \cdot 10^{-3}$
$\mathrm{Tr}\,[\eta] = \frac{\lvert\theta\rvert^2}{2}$	$[0.35, 1.3] \cdot 10^{-3}$	$1.9 \cdot 10^{-3}$
$\lvert\eta_{e\mu}\rvert = \frac{\lvert\theta_e\theta_\mu^*\rvert}{2}$	$8.5 \cdot 10^{-6}$	$1.2 \cdot 10^{-5}$
$\lvert\eta_{e\tau}\rvert = \frac{\lvert\theta_e\theta_\tau^*\rvert}{2}$	$[1.3, 5.1] \cdot 10^{-4}$	$9.0 \cdot 10^{-4}$
$\lvert\eta_{\mu\tau}\rvert = \frac{\lvert\theta_\mu\theta_\tau^*\rvert}{2}$	$5.0 \cdot 10^{-6}$	$5.7 \cdot 10^{-5}$

Type-I seesaw

NSI is related to non-unitarity.

Blennow *et al*, 2306.01040

Decay	Constraint on	Bound
$\mu^- \to e^- e^+ e^-$	$\lvert\varepsilon_{ee}^{e\mu}\rvert$	3.5×10^{-7}
$\tau^- \to e^- e^+ e^-$	$\lvert\varepsilon_{ee}^{e\tau}\rvert$	1.4×10^{-4}
$\tau^- \to \mu^- \mu^+ \mu^-$	$\lvert\varepsilon_{\mu\mu}^{\mu\tau}\rvert$	1.2×10^{-4}
$\tau^- \to e^- \mu^+ e^-$	$\lvert\varepsilon_{e\mu}^{e\tau}\rvert$	1.0×10^{-4}
$\tau^- \to \mu^- e^+ \mu^-$	$\lvert\varepsilon_{\mu e}^{\mu\tau}\rvert$	1.0×10^{-4}
$\tau^- \to e^- \mu^+ \mu^-$	$\lvert\varepsilon_{\mu\mu}^{e\tau}\rvert$	1.0×10^{-4}
$\tau^- \to e^- e^+ \mu^-$	$\lvert\varepsilon_{\mu e}^{e\tau}\rvert$	9.9×10^{-5}
$\mu^- \to e^- \gamma$	$\lvert\sum_\alpha \varepsilon_{\alpha\alpha}^{e\mu}\rvert$	2.6×10^{-5}
$\tau^- \to e^- \gamma$	$\lvert\sum_\alpha \varepsilon_{\alpha\alpha}^{e\tau}\rvert$	1.8×10^{-2}
$\tau^- \to \mu^- \gamma$	$\lvert\sum_\alpha \varepsilon_{\alpha\alpha}^{\mu\tau}\rvert$	2.0×10^{-4}
$\mu^+ e^- \to \mu^- e^+$	$\lvert\varepsilon_{\mu e}^{\mu e}\rvert$	3.0×10^{-3}

Type-II seesaw

Strongly constrained by CLFV.

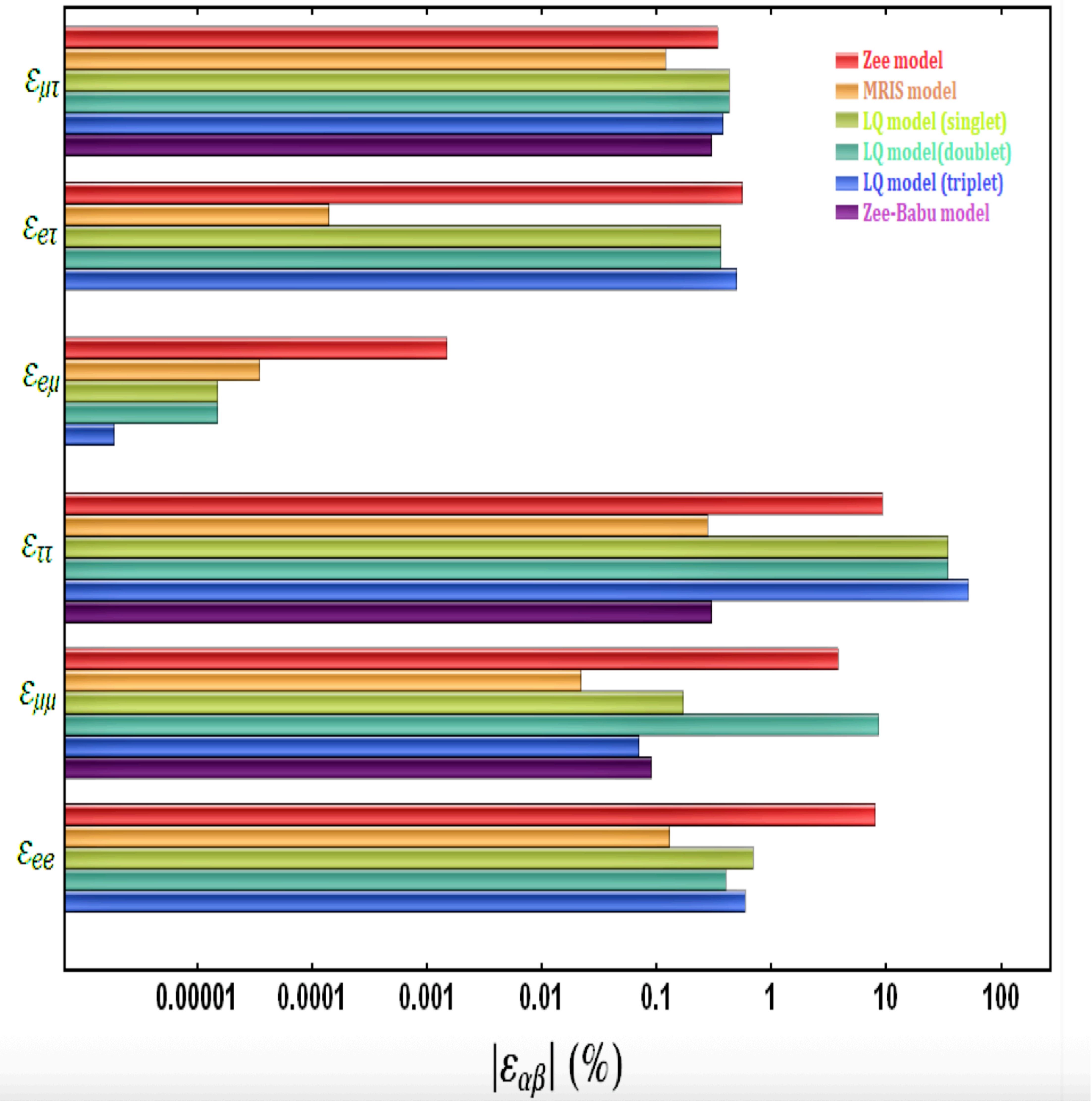
Huitu *et al*, 1711.02971

NSI in Radiative Neutrino Mass Models

Particle Content	Lagrangian term
$\eta^+(\mathbf{1},\mathbf{1},1)$ or $h^+(\mathbf{1},\mathbf{1},1)$	$f_{\alpha\beta}L_\alpha L_\beta\,\eta^+$ or $f_{\alpha\beta}L_\alpha L_\beta\,h^+$
$\Phi\left(\mathbf{1},\mathbf{2},\frac{1}{2}\right)=(\phi^+,\phi^0)$	$Y_{\alpha\beta}L_\alpha\ell^c_\beta\widetilde{\Phi}$
$\Omega\left(\mathbf{3},\mathbf{2},\frac{1}{6}\right)=\left(\omega^{2/3},\omega^{-1/3}\right)$	$\lambda_{\alpha\beta}L_\alpha d^c_\beta\Omega$
$\chi\left(\mathbf{3},\mathbf{1},-\frac{1}{3}\right)$	$\lambda'_{\alpha\beta}L_\alpha Q_\beta\chi^\star$
$\bar{\rho}\left(\bar{\mathbf{3}},\mathbf{3},\frac{1}{3}\right)=\left(\bar{\rho}^{4/3},\bar{\rho}^{1/3},\bar{\rho}^{-2/3}\right)$	$\lambda''_{\alpha\beta}L_\alpha Q_\beta\bar{\rho}$
$\delta\left(\mathbf{3},\mathbf{2},\frac{7}{6}\right)=\left(\delta^{5/3},\delta^{2/3}\right)$	$\lambda'''_{\alpha\beta}L_\alpha u^c_\beta\delta$
$\Delta(\mathbf{1},\mathbf{3},1)=\left(\Delta^{++},\Delta^+,\Delta^0\right)$	$f'_{\alpha\beta}L_\alpha L_\beta\Delta$

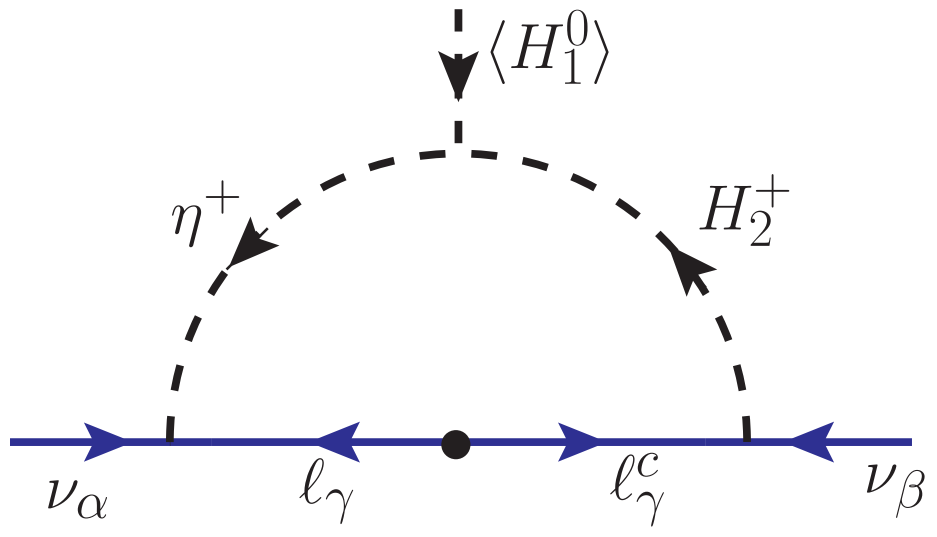
- Essentially covers all NSI possibilities with heavy mediators.
- Possible to get large diagonal NSI, but off-diagonal NSI constrained by CLFV.

Babu, BD, Jana, Thapa, 1907.09498

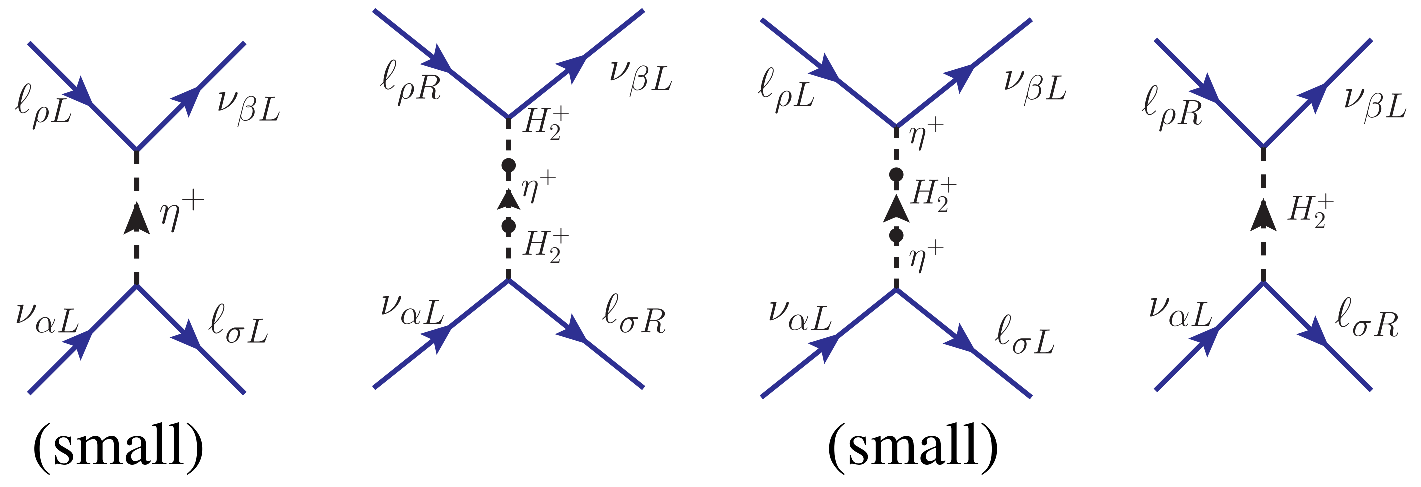


Example: Zee Model

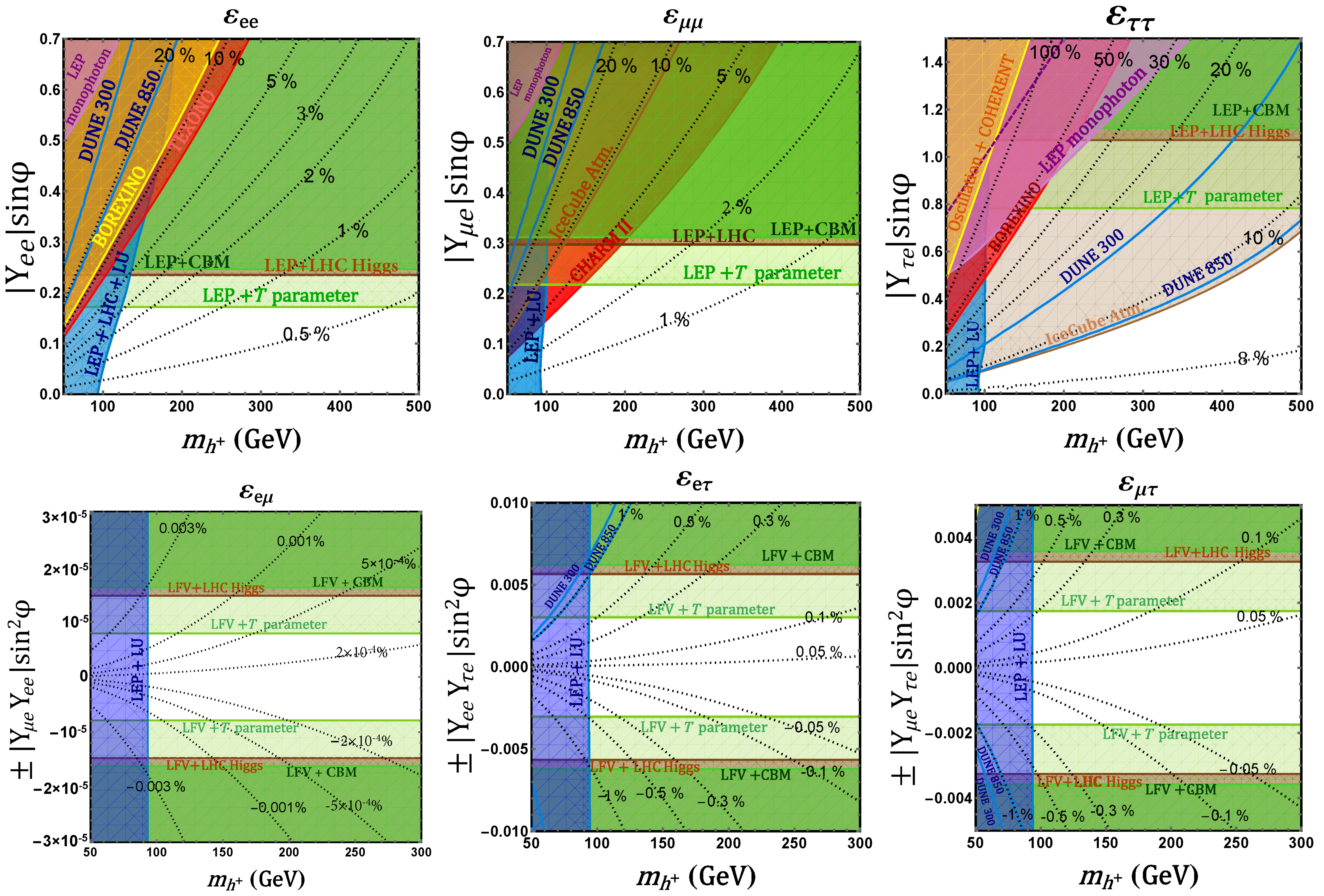
Zee (PLB ’80)



$$M_\nu \;=\; \kappa\left(f M_\ell Y + Y^T M_\ell f^T\right)$$



$$\varepsilon_{\alpha\beta} \;\equiv\; \varepsilon^{(h^+)}_{\alpha\beta} + \varepsilon^{(H^+)}_{\alpha\beta} \;=\; \frac{1}{4\sqrt{2}G_F} Y_{\alpha e} Y^{\star}_{\beta e}\left(\frac{\sin^2\varphi}{m^2_{h^+}} + \frac{\cos^2\varphi}{m^2_{H^+}}\right)$$



Babu, BD, Jana, Thapa, 1907.09498

NSI with Light Mediator

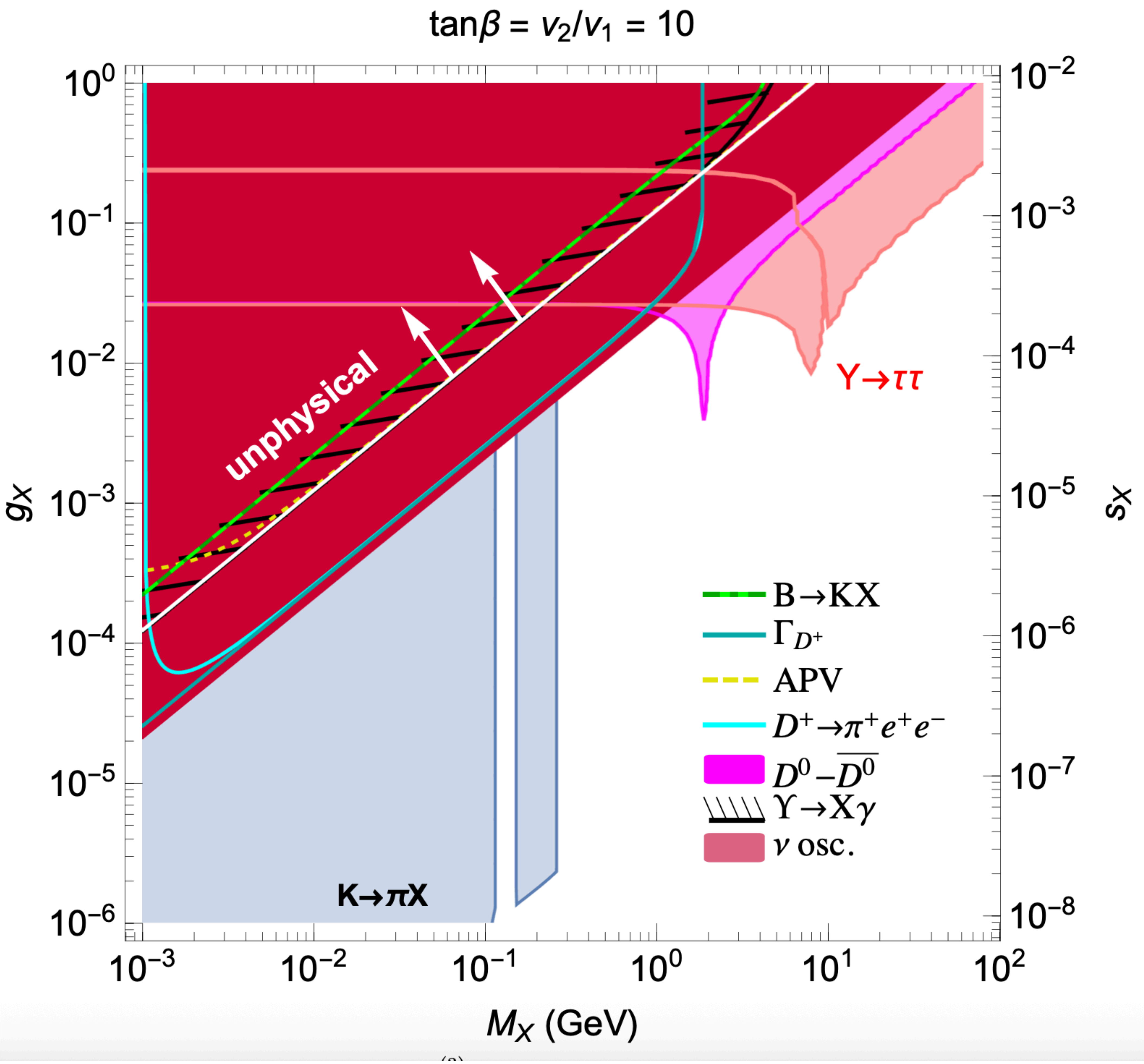
- Possible to avoid CLFV constraints with flavored light mediators.
- In an explicit construction with $U(1)^{(3)}_{B-L'}$, diagonal NSI up to ~50% possible.
- Getting large off-diagonal NSI is much harder.
- Cauchy-Schwarz inequality: $|\varepsilon^f_{\alpha\beta}|^2 \leq |\varepsilon^f_{\alpha\alpha}\varepsilon^f_{\beta\beta}|$

Farzan, Heeck, 1607.07616

- An explicit $U(1)' \times Z_2$ model violating this relation and allowing for large off-diagonal NSI. Farzan, 1912.09408

$$\varepsilon^f_{\alpha\beta} = \frac{g_f (g_\nu)_{\alpha\beta}}{2\sqrt{2} G_F m^2_{Z'}}$$

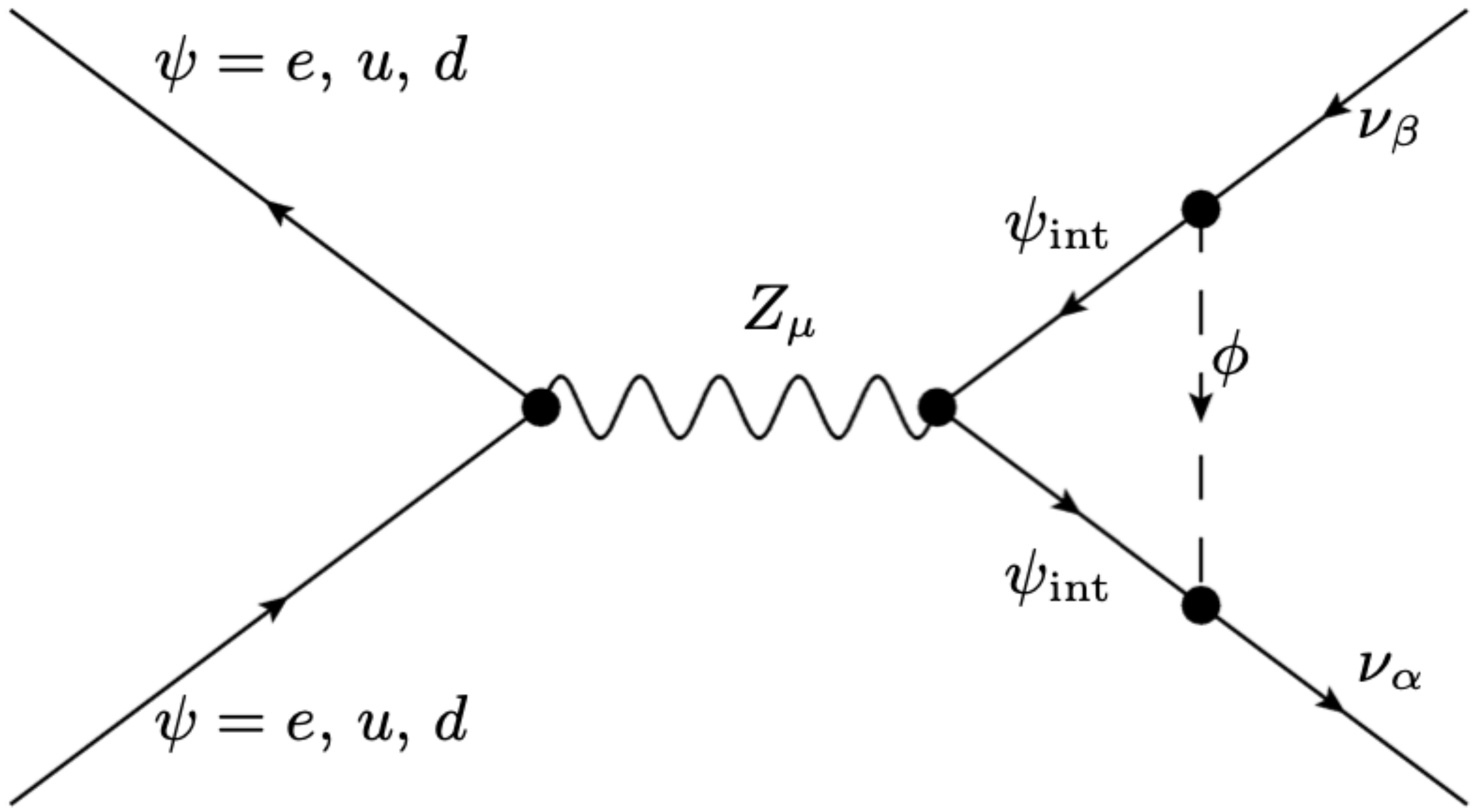
- NSI often gives the leading constraint in electrophobic anomaly-free $U(1)_X$ models. Heeck, Lindner, Rodejohann, Vogl, 1812.04067.

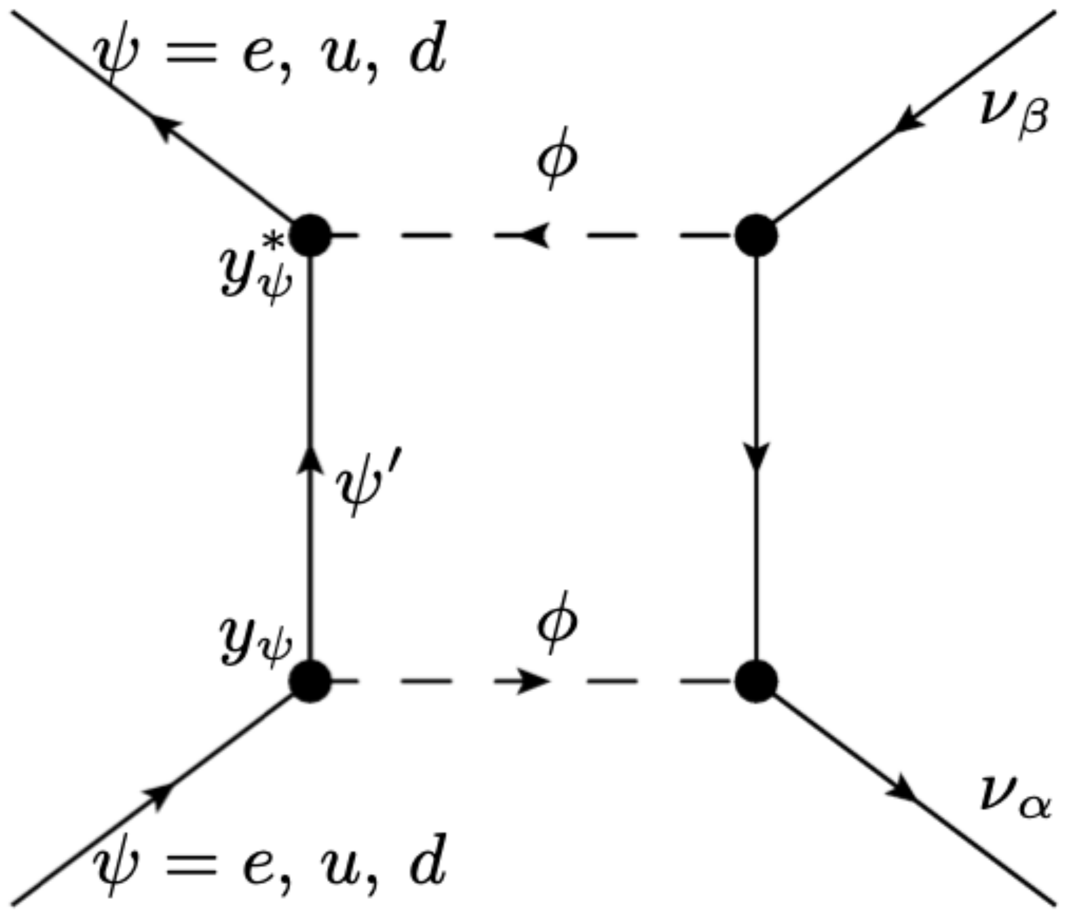


Babu, Friedland, Machado, Mocioiu, 1705.01822

Loop-Induced NSI

Bischer, Rodejohann, Xu, 1807.08102





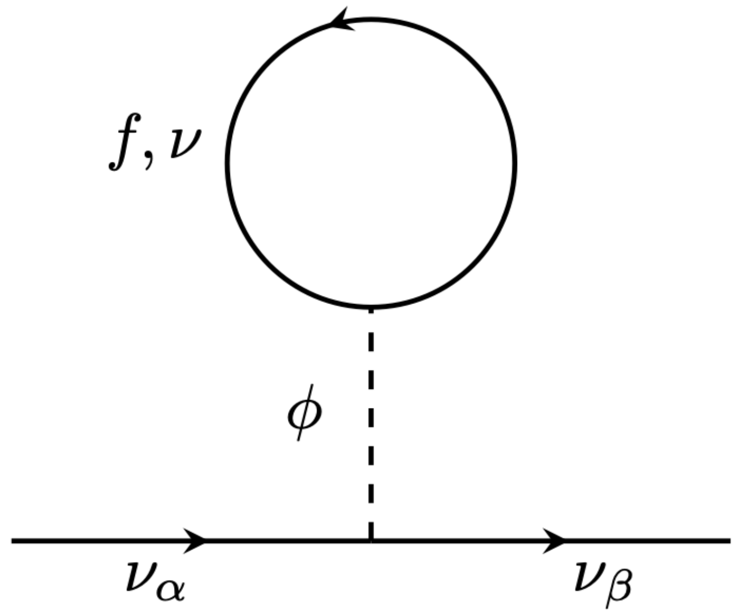
$$\mathcal{L}_{\rm NSI} = \left(\epsilon^{\triangleright}_{\alpha\beta} + \epsilon^{\square}_{\alpha\beta}\right)\frac{G_F}{\sqrt{2}}\overline{\psi}\gamma^\mu\psi\overline{\nu_\alpha}\gamma_\mu P_L\nu_\beta, \quad (\psi = e_L,\ e_R,\ u_L,\ u_R,\cdots),$$

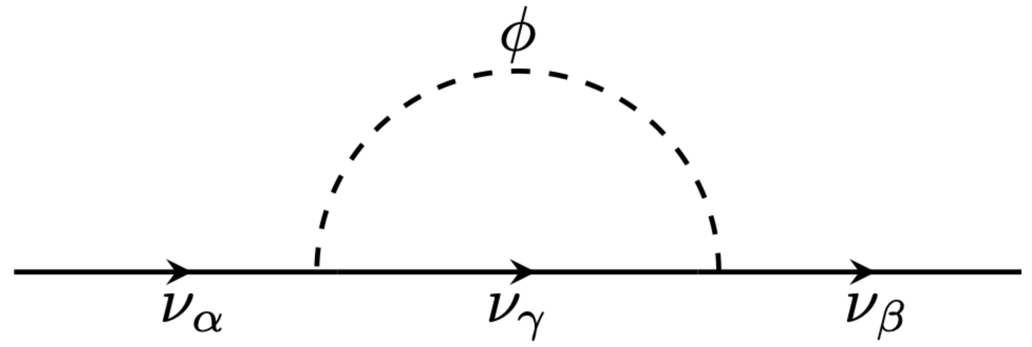
$$\epsilon^{\triangleright}_{\alpha\beta} = -\frac{8g^{(1)}_{\alpha\beta}}{g}Q_Z^{(\psi)}c_W, \qquad \epsilon^{\square}_{\alpha\beta} = \frac{1}{16\pi^2}\frac{\sqrt{2}y_\alpha^* y_\beta |y_\psi|^2}{4m_\phi^2 G_F}.$$

	ϵ_e^F	$\epsilon_e^{\triangleright}$	$\epsilon_n^{\triangleright}$	$\epsilon_p^{\triangleright}$	$\epsilon_e^{\square}$	$\epsilon_n^{\square}$	$\epsilon_p^{\square}$
model A	$\mathcal{O}(10^{-3})$	$\mathcal{O}(10^{-5})$	$\mathcal{O}(10^{-4})$	$\mathcal{O}(10^{-5})$	$\mathcal{O}(10^{-3})$	0	0
model B	0	$\mathcal{O}(10^{-1})$	$\mathcal{O}(1)$	$\mathcal{O}(10^{-1})$	0	0	0
model C	0	0	0	0	$\mathcal{O}(10^{-2})$	$\mathcal{O}(10^{-2})$	$\mathcal{O}(10^{-2})$

Scalar NSI

- For a neutral scalar mediator, $\mathcal{L}_{\rm eff}^{\phi} = \frac{y_f y_{\alpha\beta}}{m_\phi^2}(\bar{\nu}_\alpha \nu_\beta)(\bar{f} f)$
- Cannot be Fierzed into a vector current, so doesn't contribute to matter potential.
- Instead, appears as a medium-dependent correction to the neutrino mass. Ge, Parke, 1812.08376; Smirnov, Xu, 1909.07505; Babu, Chauhan, BD, 1912.13488;…

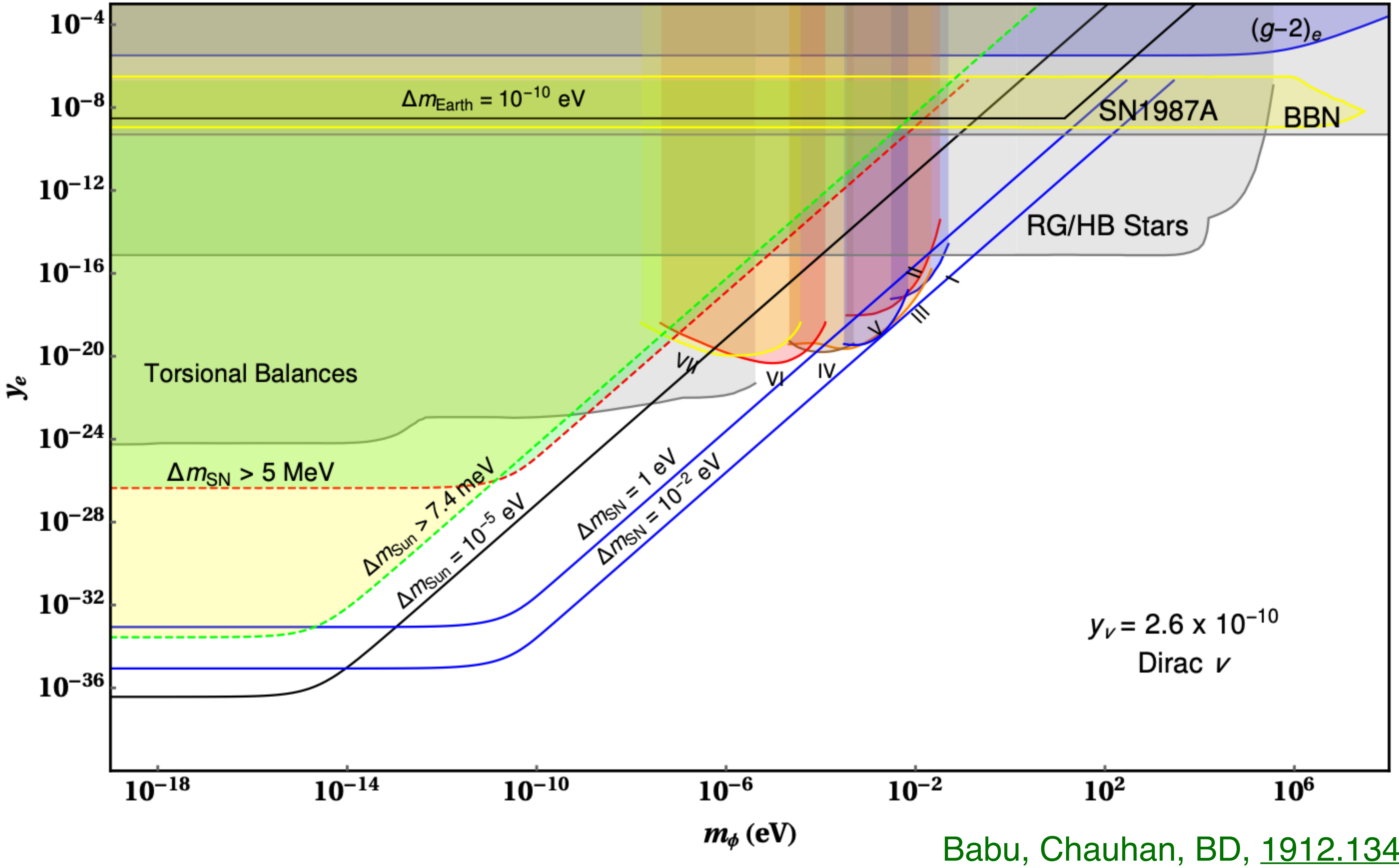




$$\Sigma_{\alpha\beta} = \frac{y_{\alpha\beta} y_f m_f}{\pi^2 m_\phi^2} \int_{m_f}^{\infty} dk_0 \sqrt{k_0^2 - m_f^2}\left[n_f(k_0) + n_{\bar{f}}(k_0)\right] \equiv \Delta m_{\nu,\alpha\beta}$$

$$\Delta m_{\nu,\alpha\beta} = \begin{cases} \frac{y_f y_{\alpha\beta}}{m_\phi^2}\left(N_f + N_{\bar{f}}\right) & (\mu, T \ll m_f) \\ \frac{y_f y_{\alpha\beta}}{m_\phi^2}\frac{m_f}{2}\left(\frac{3}{\pi}\right)^{\frac{2}{3}}\left(N_f^{2/3} + N_{\bar{f}}^{2/3}\right) & (\mu > m_f \gg T) \\ \frac{y_f y_{\alpha\beta} m_f}{3\, m_\phi^2}\left(\frac{\pi^2}{12\,\zeta(3)}\right)^{\frac{2}{3}}\left(N_f^{2/3} + N_{\bar{f}}^{2/3}\right) & (\mu < m_f \ll T)\,. \end{cases}$$

Constraints on Scalar NSI



Babu, Chauhan, BD, 1912.13488

- Need $G_{\rm eff} \sim \frac{y_f y_\nu}{m_\phi^2} \sim 10^{10} G_F$
- Only ultra-light mediators allowed.
- Novel oscillation phenomenology, distinct from vector NSI.

See posters by D. Bezboruah and S. Das

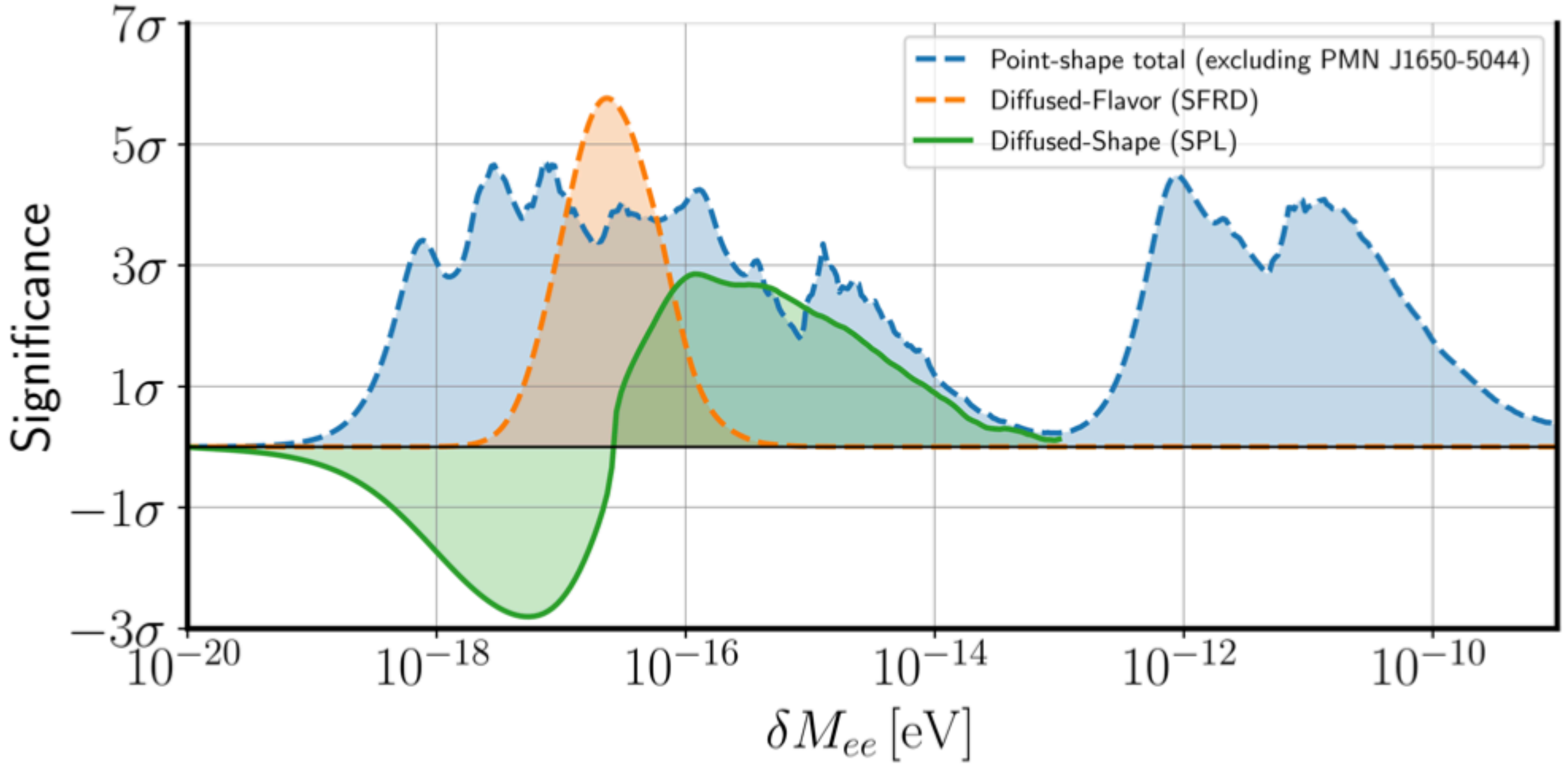
Scalar NSI and Pseudo-Dirac Neutrinos

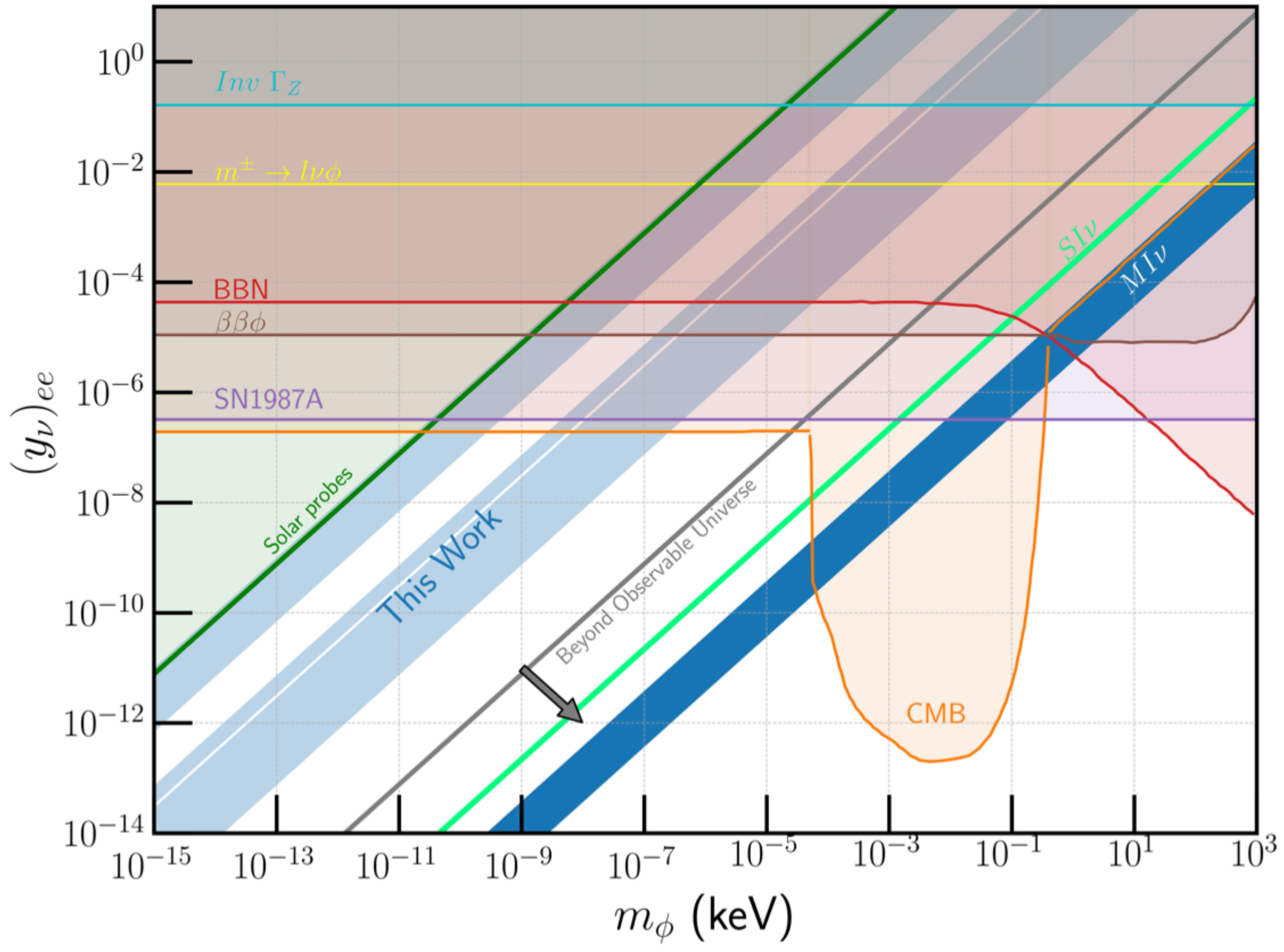
$$\mathcal{L} \supset -M^D_{\alpha\beta}\bar{\nu}_{R\alpha}\nu_{L\beta} + y^D_{\alpha\beta}\phi\bar{\nu}_{R\alpha}\nu_{L\beta} + \frac{1}{2}y^M_{\alpha\beta}\phi\nu^T_{L\alpha}C\nu_{L\beta} - \frac{m^2_\phi}{2}\phi^2 + \text{H.c.}\,,$$

$$\delta M^L_{\alpha\beta} = y^M_{\alpha\beta}\langle\phi\rangle_{\rm bg} \simeq -\frac{y^M_{\alpha\beta}y^D_{\rm eff}}{m^2_\phi}(n_\nu + n_{\bar{\nu}})\,,$$

$$\delta M^D_{\alpha\beta} = y^D_{\alpha\beta}\langle\phi\rangle_{\rm bg} \simeq -\frac{y^D_{\alpha\beta}y^D_{\rm eff}}{m^2_\phi}(n_\nu + n_{\bar{\nu}})\,.$$

$$\mathcal{M}_{\rm eff} = \begin{pmatrix} \delta M^L & M^D + \delta M^D \\ (M^D + \delta M^D)^T & 0 \end{pmatrix}.$$





Verma, Argüelles, BD, Dutta, Martinez-Soler, 2606.25050 (today!)

Neutrino Self-Interaction

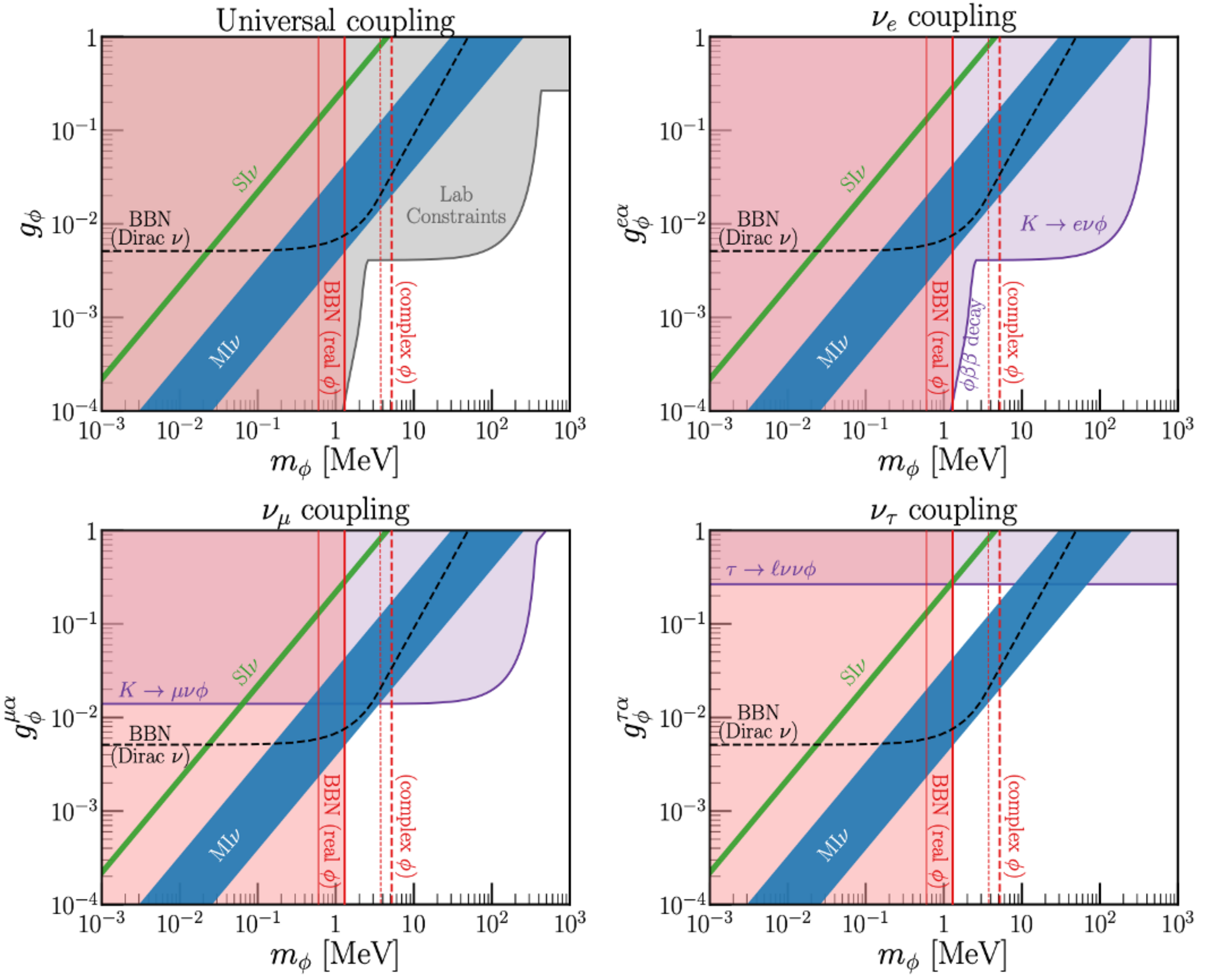
$$\mathcal{L}_{\rm eff} = G_{\rm eff}(\bar{\nu}\nu)(\bar{\nu}\nu)$$

- Alleviates the Hubble tension:

$$G_{\rm eff} = \begin{cases} (4.7^{+0.4}_{-0.6}\ \text{MeV})^{-2} & (\text{SI}\nu) \\ (89^{+171}_{-61}\ \text{MeV})^{-2} & (\text{MI}\nu) \end{cases}$$

Kreisch, Cyr-Racine, Dore, 1902.00534

- Stringent constraints from lab experiments.
- Only flavor-specific scenario survives.
- Is there a realistic model of flavor-specific neutrino self-interactions?

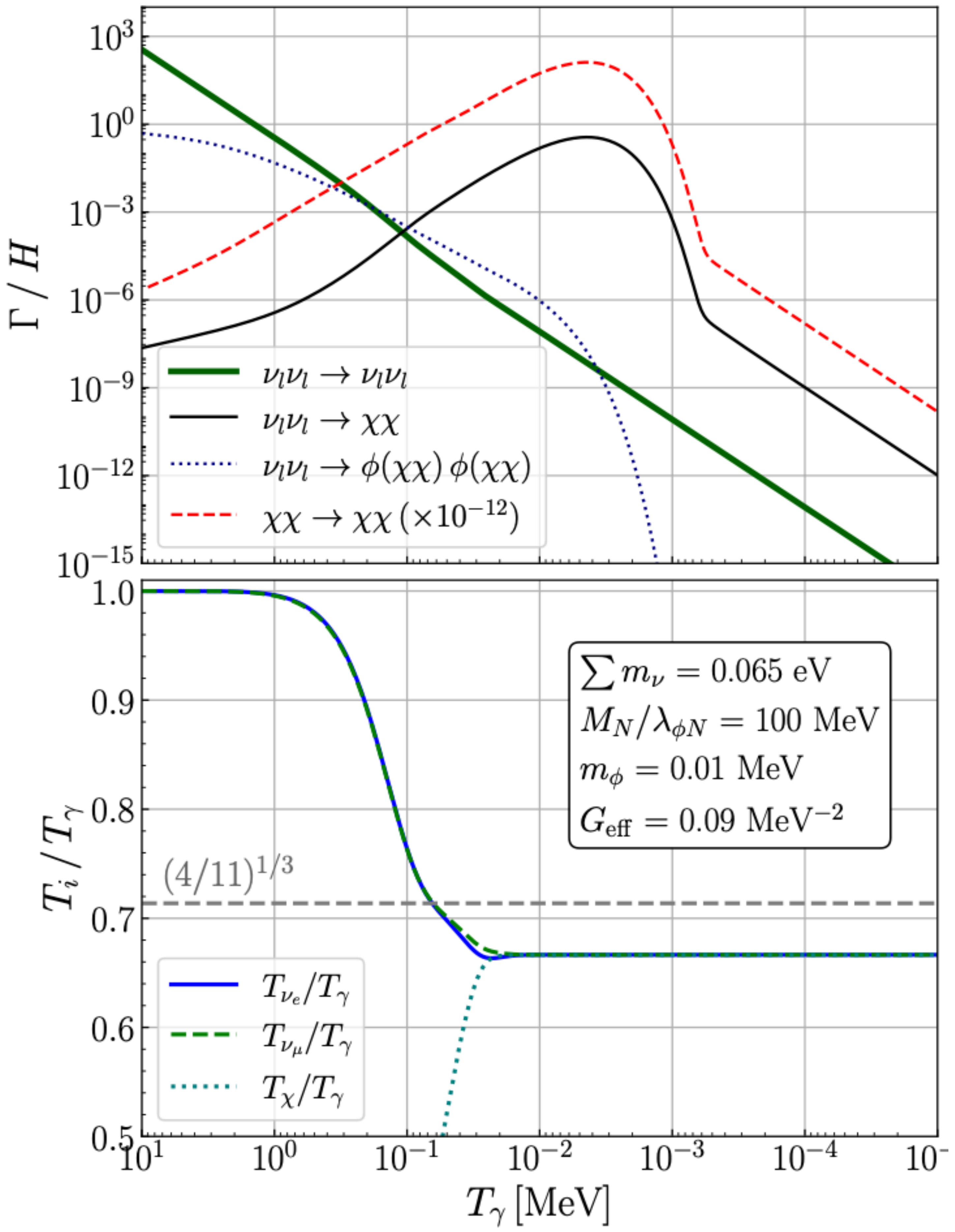


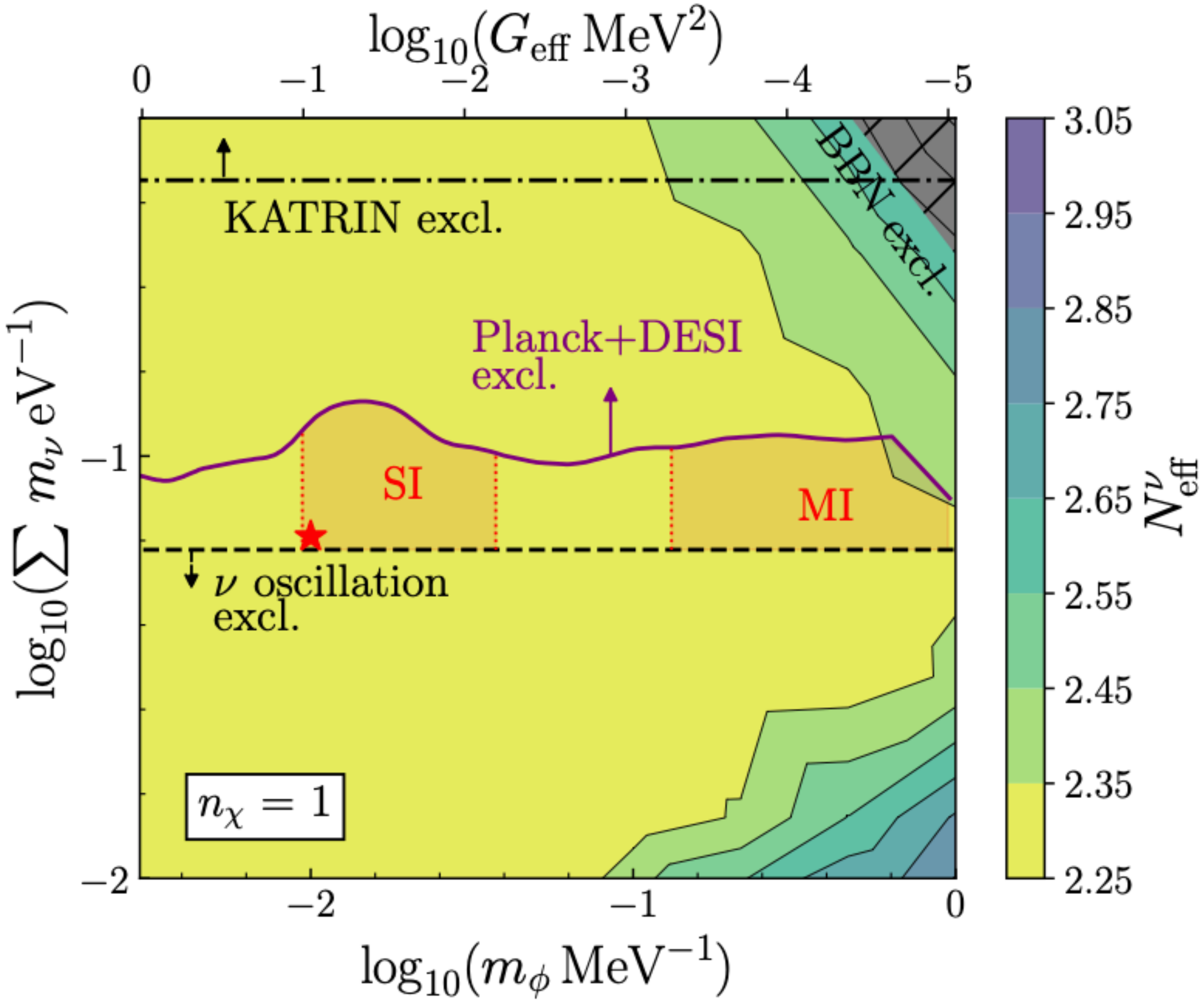
Blinov, Kelly, Krnjaic, McDermott, 1905.02727

A Viable Model Mimicking Self-Interaction

$$\Delta\mathcal{L} = \left(y^{\alpha i} L_\alpha N_i^c H - \frac{1}{2} M_N^{ii} N_i^c N_i^c + h.c. \right) - \frac{1}{2}\lambda_{\phi N}\, \phi\, N^c N^c - \frac{1}{2}\lambda_{\phi\chi}\, \phi\, \chi^2$$

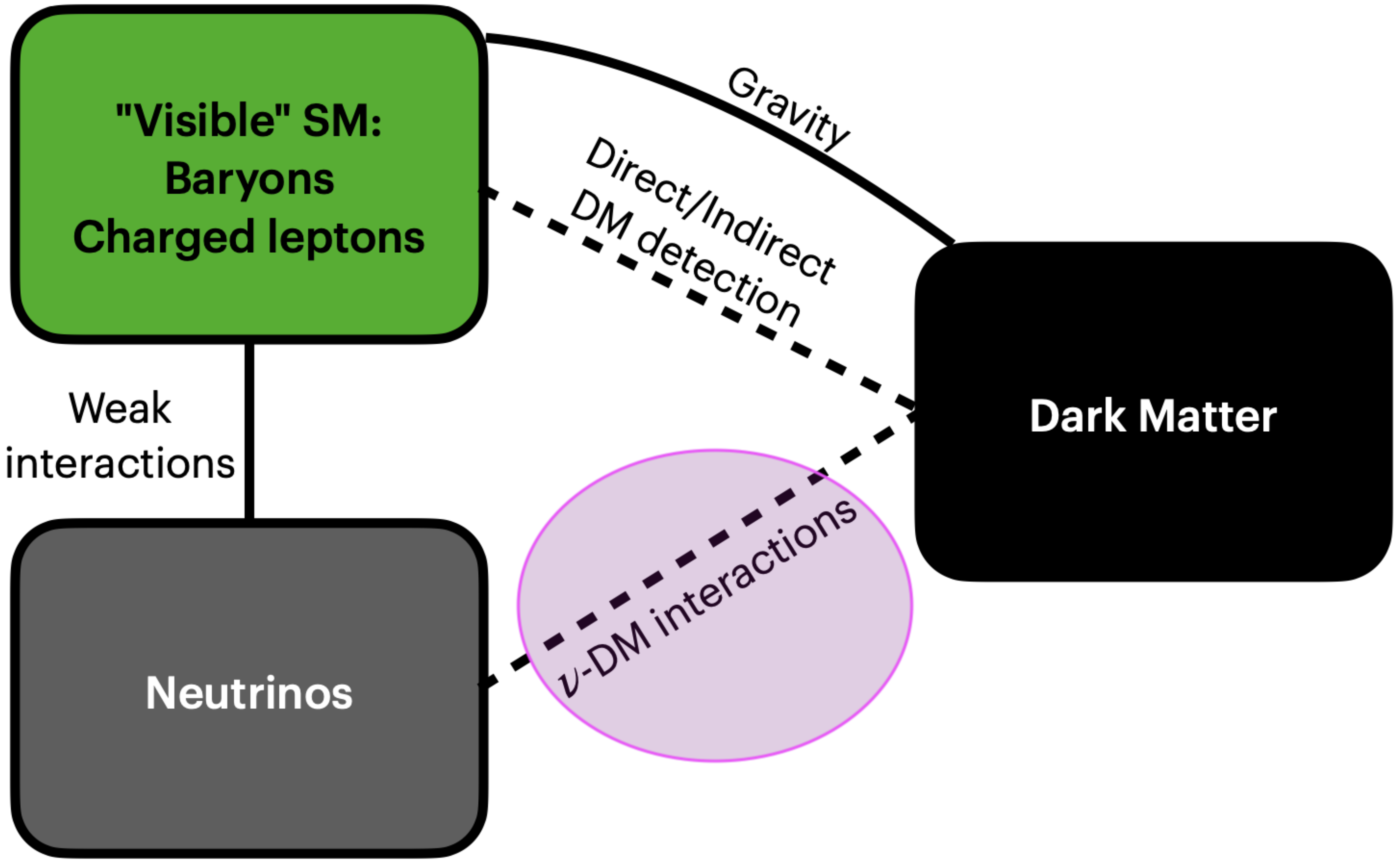
- Strongly self-interacting dark sector.
- Mimics self-interacting neutrinos.
- Flavor-specific or flavor-universal, depending on n_χ.
- Relaxes the tension between cosmology and oscillation experiments.



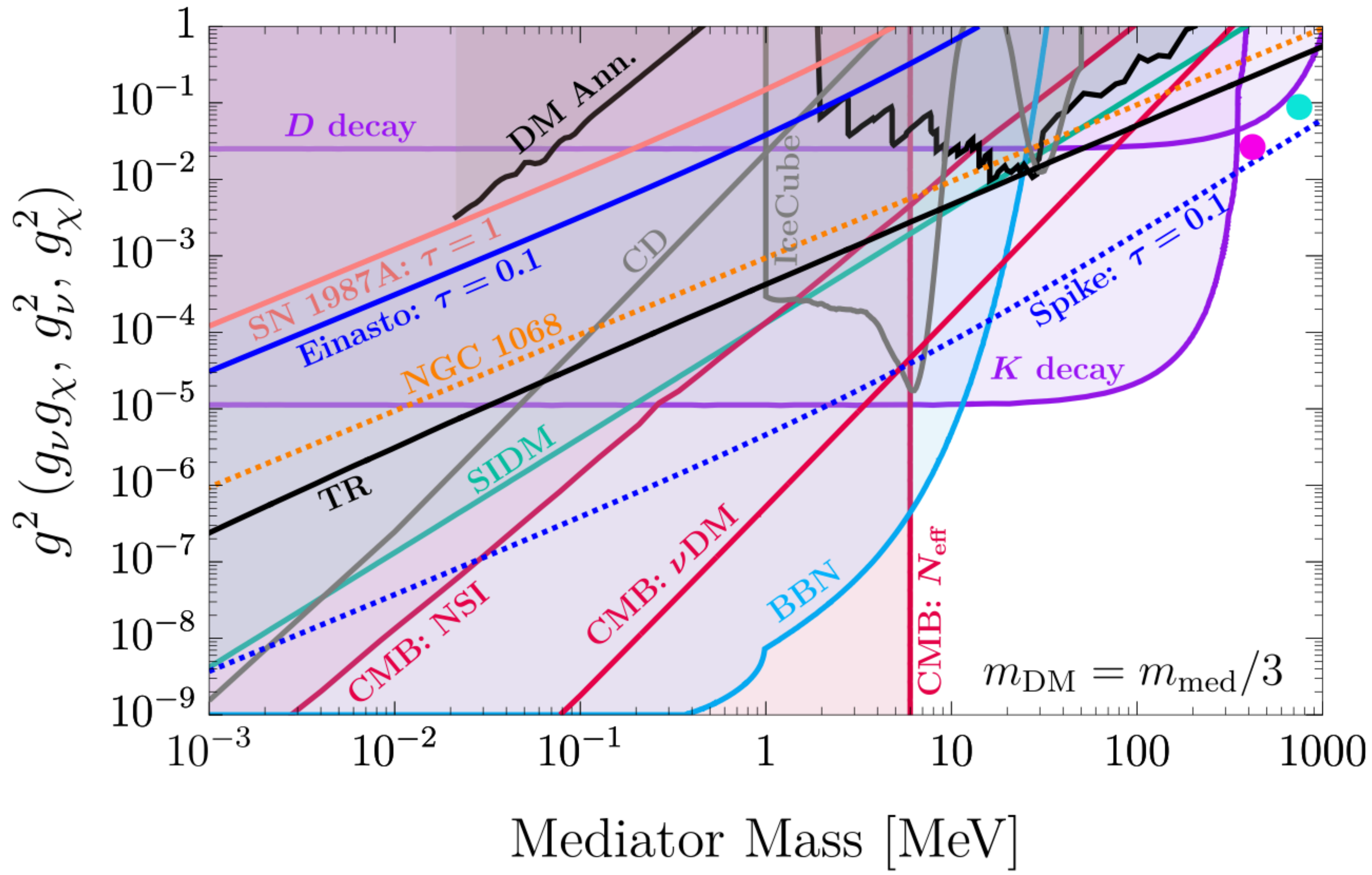


Das, BD, Gao, Ghosh, Kim, 2506.08085

Neutrino-Dark Matter Interaction



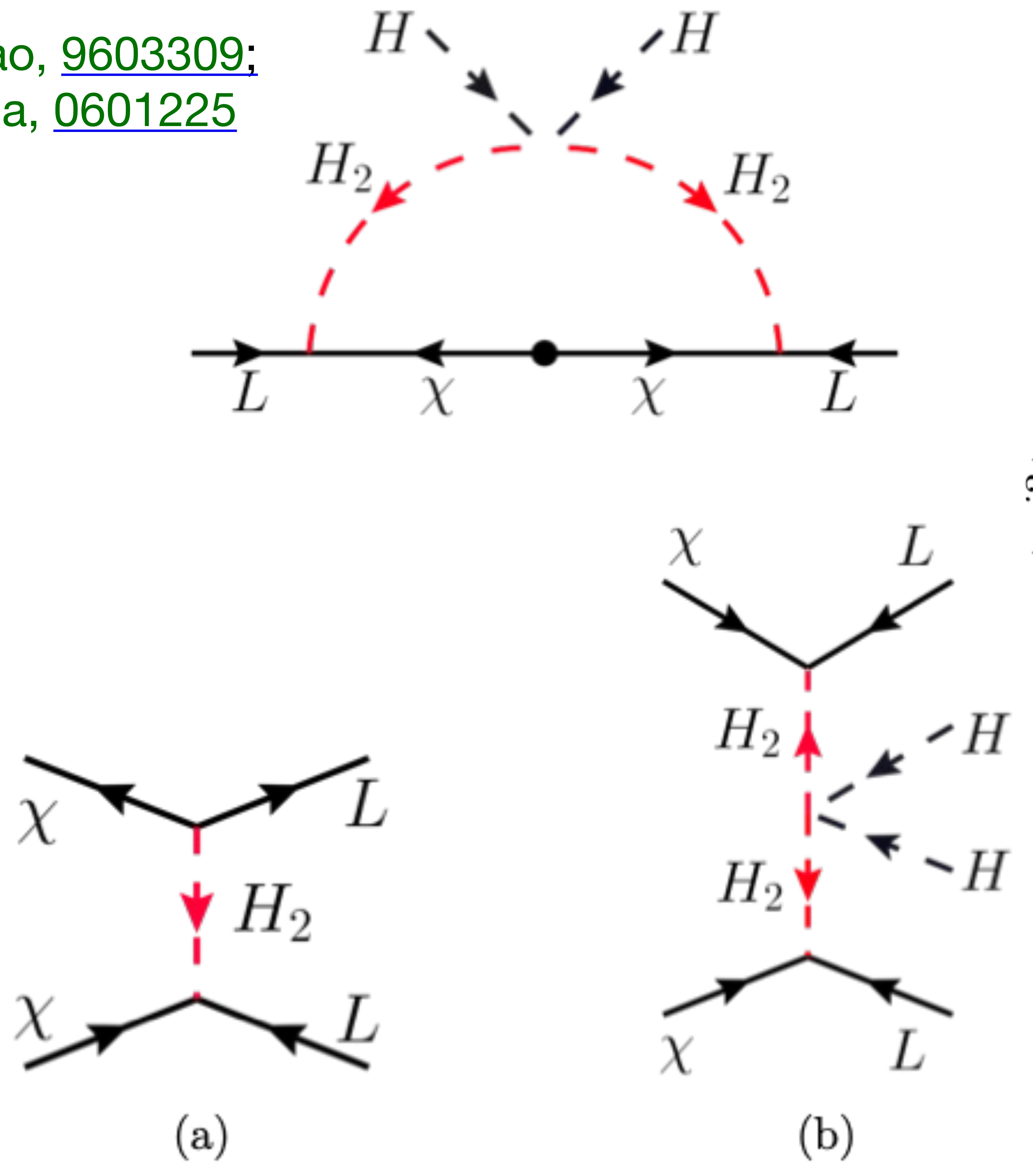
BD, Kim, Sathyan, Sinha, Zhang, 2507.01000

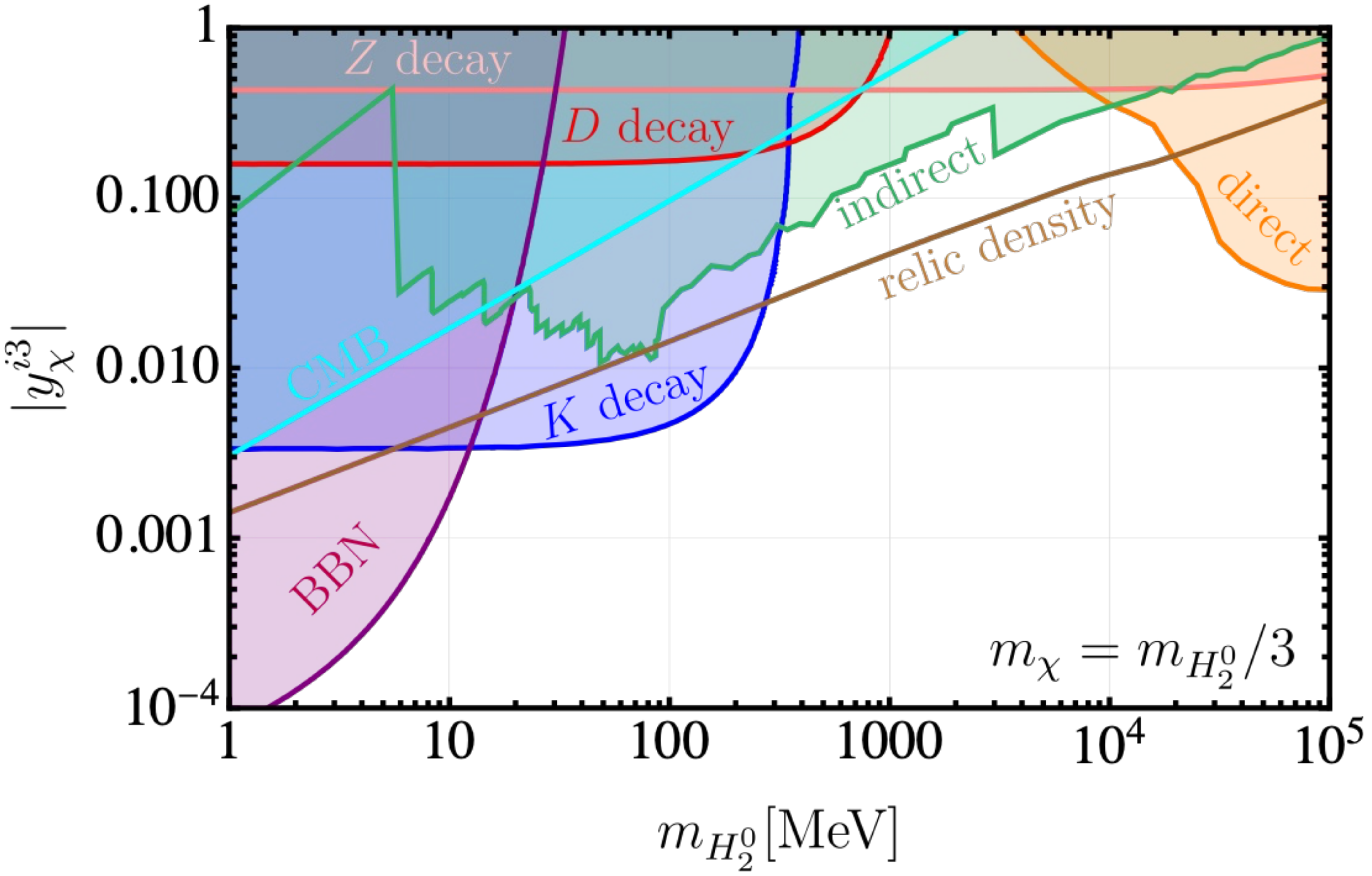


- How to see the 'invisible'?
- Is there a UV-complete model for 'large' neutrino-DM interaction?
- A complete classification up to dimension-8 in DM-SMEFT. Babu, BD, Thapa, 2512.25035

An Example: Pseudo-Dirac DM in Scotogenic Model

Tao, 9603309;
Ma, 0601225

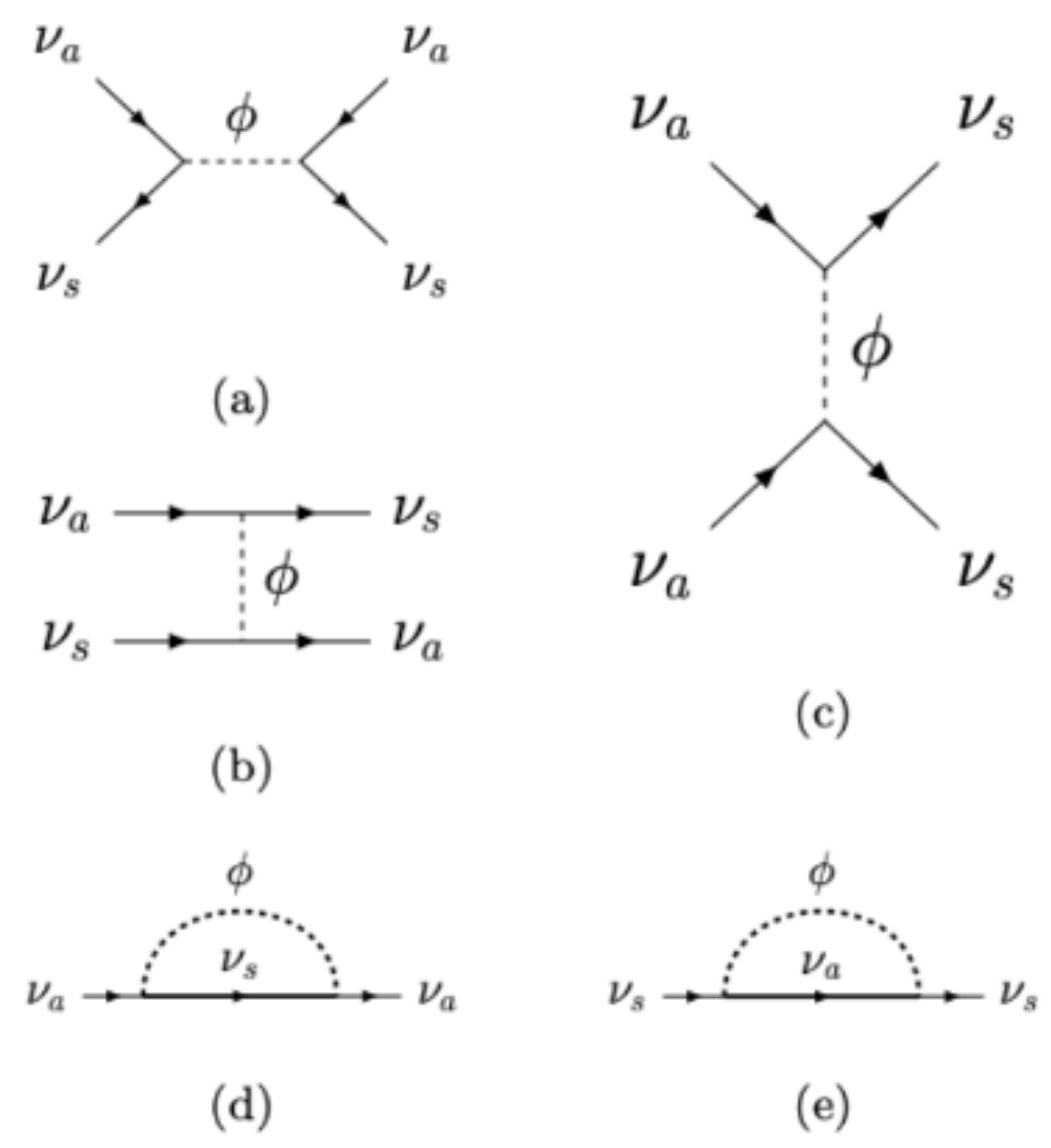


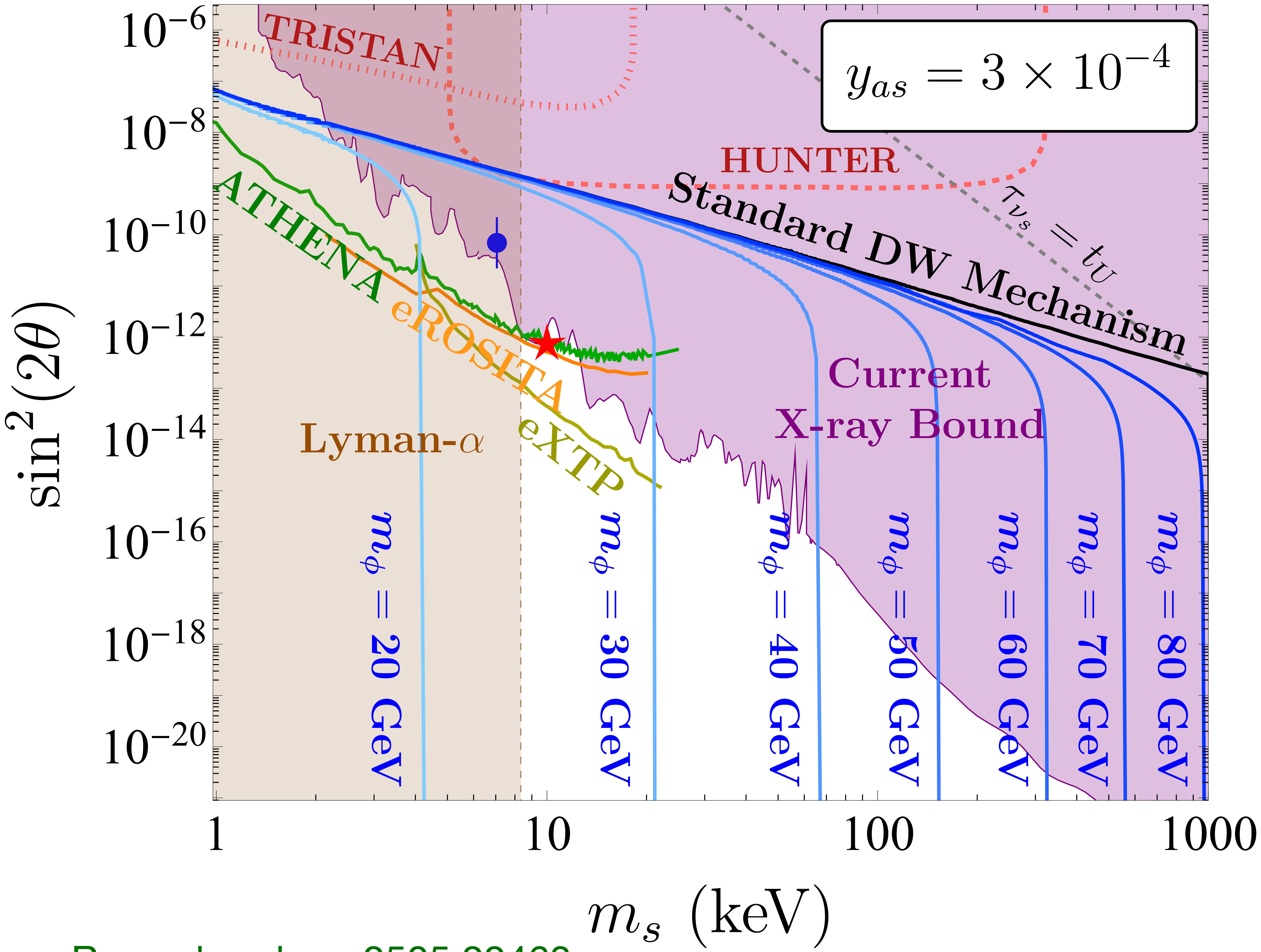


Babu, BD, Thapa, 2512.25035

Another Example: Sterile Neutrino DM with Active-Sterile NSI

$$-\mathcal{L} \supset y_{as}\bar{\nu}_a \nu_s \phi + \text{h.c.}$$





BD, Dutta, Goswami, Tang, Ramachandran, 2505.22463

Conclusions

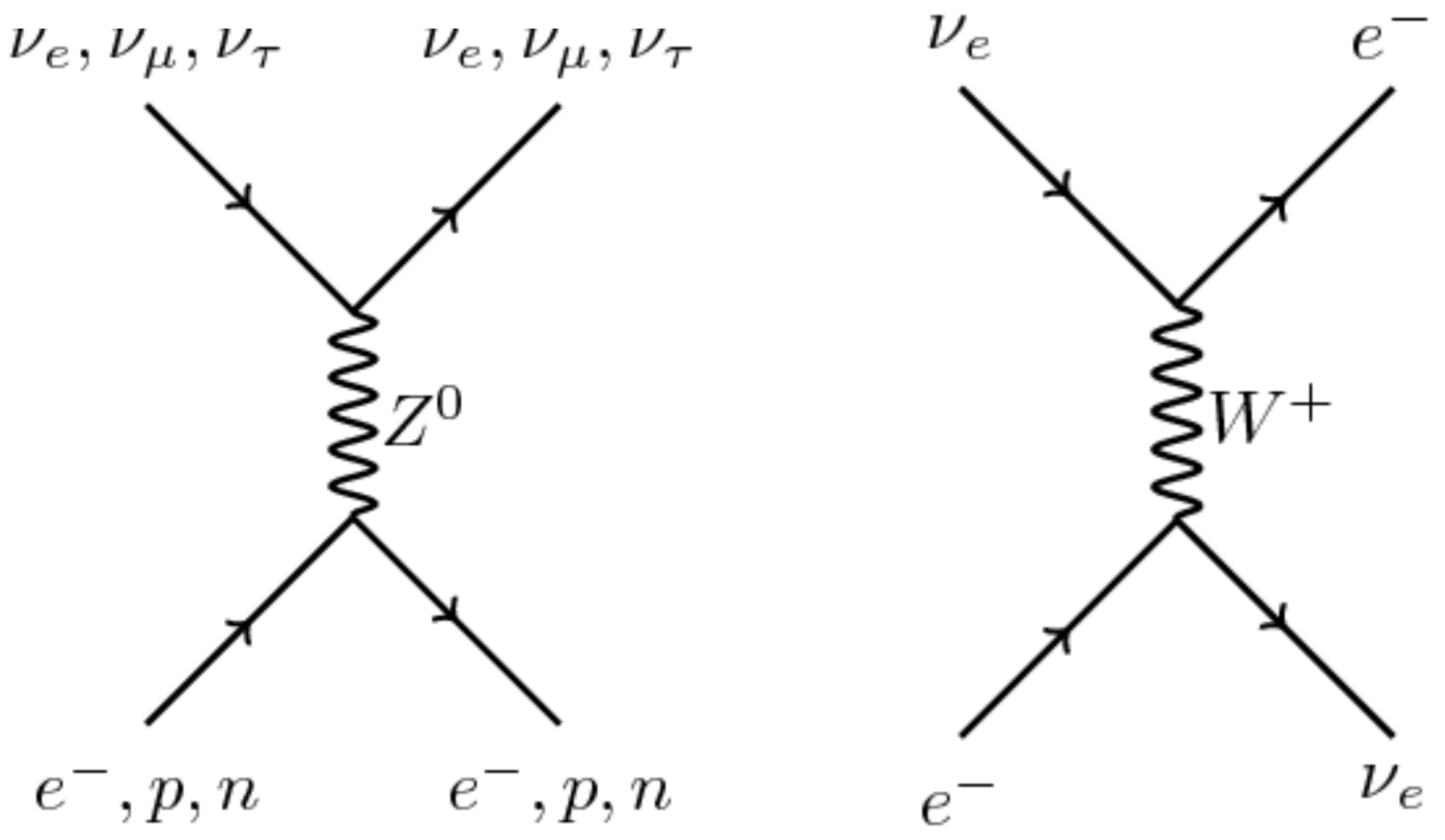
- NSI (at some level) is inevitable. Whether observable is model-dependent.
- Understanding them is necessary for the correct interpretation of the oscillation data.
- Different types: Matter (vector) NSI, source/detector NSI, scalar NSI, self-interactions, and interactions with dark sector.
- Large NSI possible in UV-complete neutrino mass models.
- Rich phenomenology in oscillation, scattering, and collider experiments, as well as in astrophysical and cosmological observations.

Backup Slides

Standard Neutrino Interactions with Matter

Type of reaction	Matter potential
V_Z^n	$\mp G_F N_n/\sqrt{2}$
V_Z^p	$\pm G_F(1-4\sin^2\theta_W)N_p/\sqrt{2}$
V_Z^e	$\mp G_F(1-4\sin^2\theta_W)N_e/\sqrt{2}$
V_W^e	$\pm\sqrt{2}G_F N_e$

[For a derivation, see e.g., J. Linder, hep-ph/0504264]



- In an electrically neutral medium, $V_Z^p + V_Z^e = 0$.
- $V_{\rm NC} = V_Z^n$ is diagonal in neutrino flavor. Doesn't affect oscillations.
- Effective neutrino matter potential: $V_{\rm CC} = V_W^e = \sqrt{2}G_F N_e \simeq 3.8\times 10^{-14}\ {\rm eV}\left(\frac{\rho}{\rm gm/cm^3}\right)\left(\frac{Y_e}{0.5}\right)$

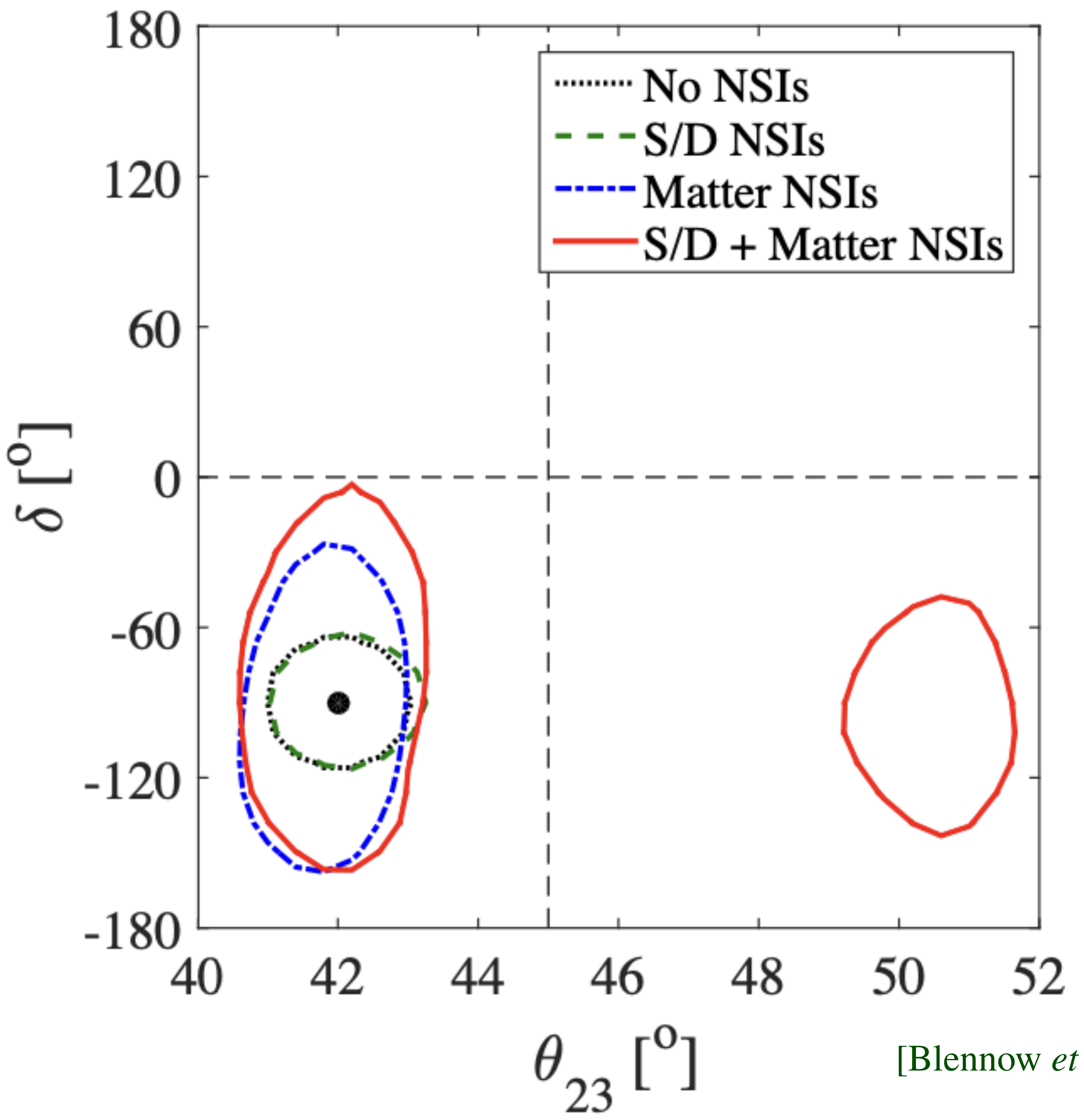
$$H = \frac{1}{2E}\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m_{21}^2 & 0\\ 0 & 0 & \Delta m_{31}^2\end{pmatrix} + N^\dagger \begin{pmatrix}V_{\rm CC}+V_{\rm NC} & 0 & 0\\ 0 & V_{\rm NC} & 0\\ 0 & 0 & V_{\rm NC}\end{pmatrix} N,$$

$$P(\nu_\alpha\to\nu_\beta) = \left|\langle\nu_\beta|e^{-iHL}|\nu_\alpha\rangle\right|^2 \simeq \sin^2 2\theta_M \sin^2\left(\frac{\Delta m_M^2 L}{4E}\right),$$

where $\tan 2\theta_M = \frac{\Delta m^2 \sin 2\theta}{\Delta m^2\cos 2\theta - A}$, $A = 2EV_{\rm CC}$

$$\Delta m_M^2 = \sqrt{(\Delta m^2\cos 2\theta - A)^2 + (\Delta m^2 \sin 2\theta)^2}$$

CC+NC NSI Can Make Things Worse!

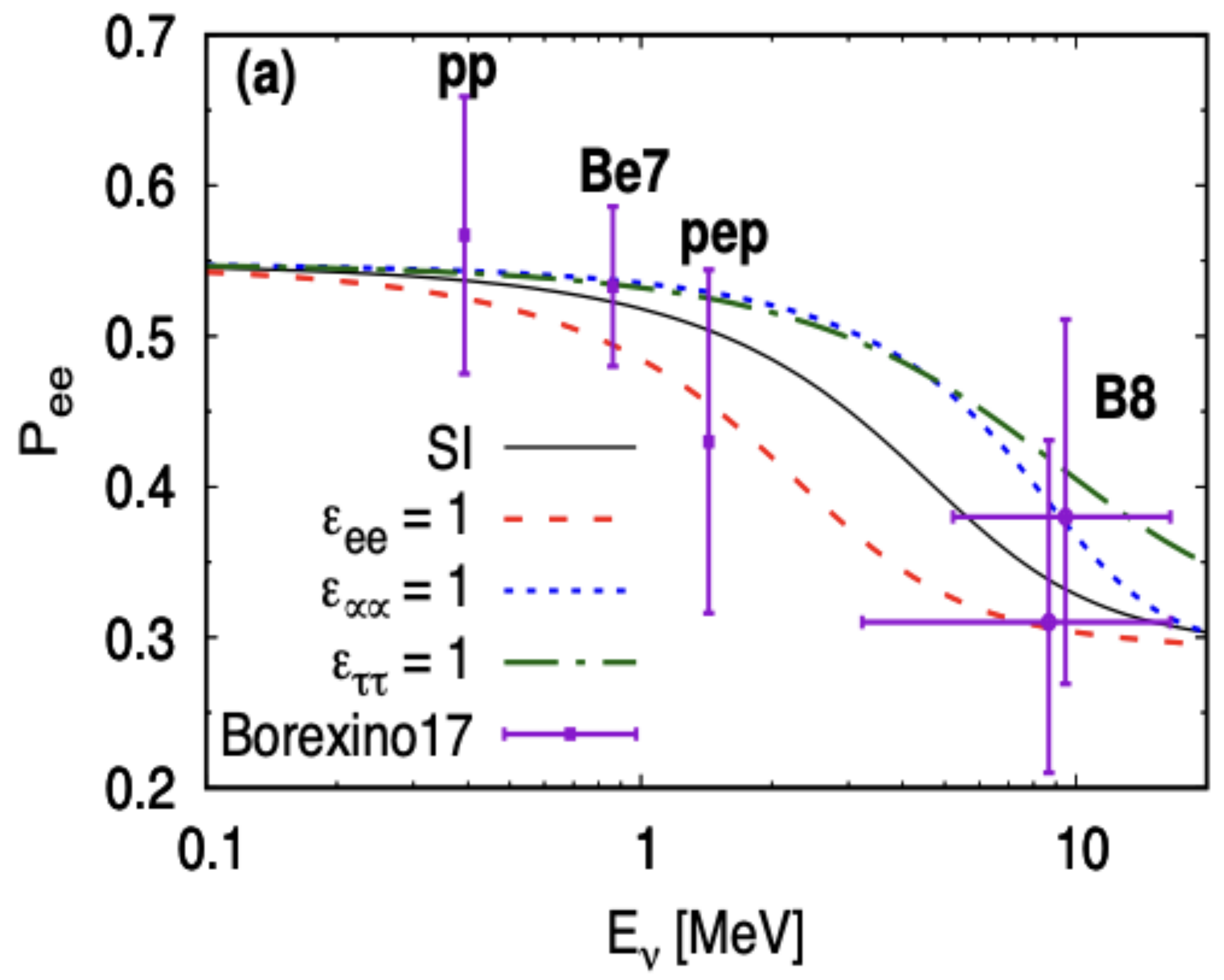


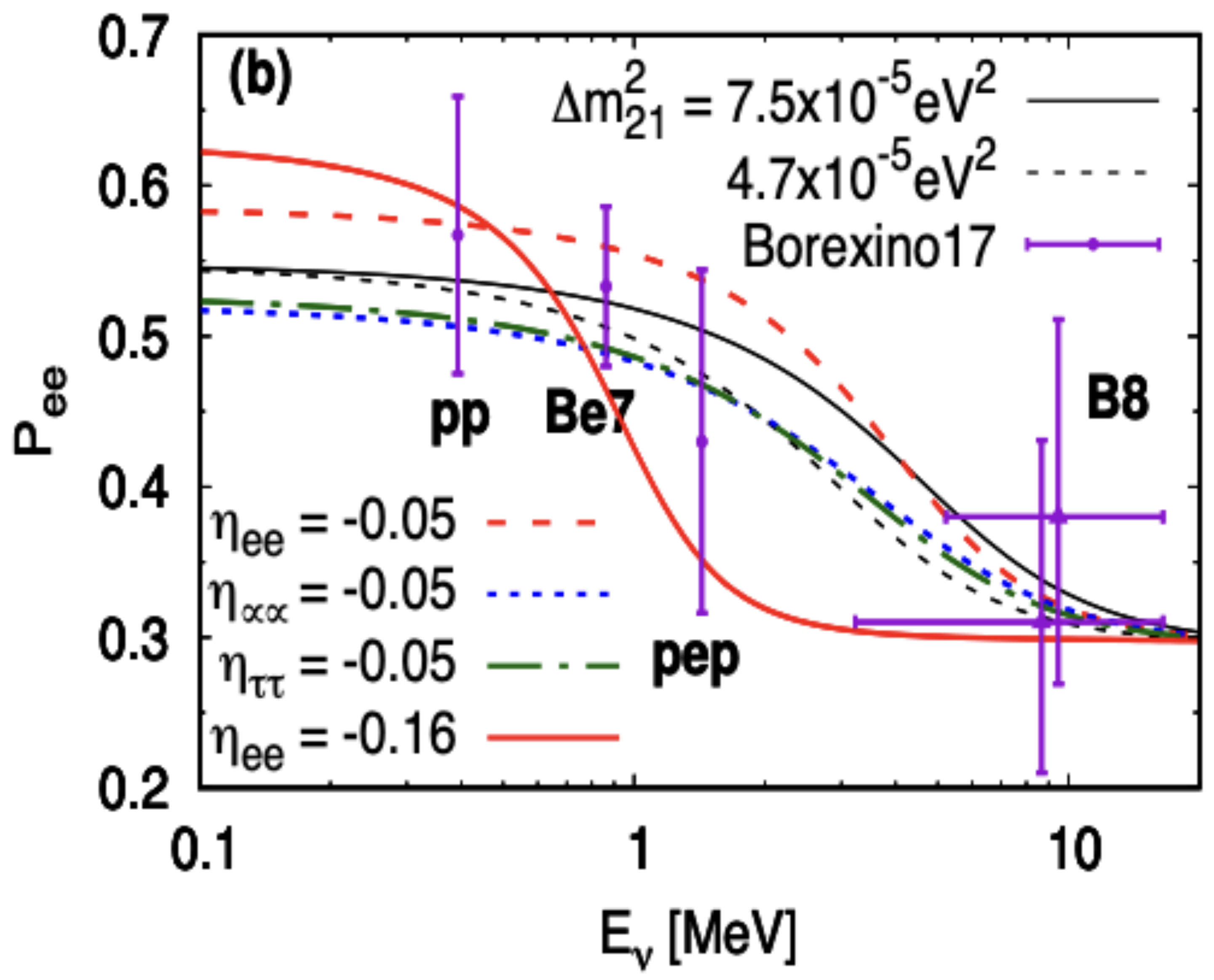
[Blennow *et al*, 1606.08851]

Comparison of Vector and Scalar NSI

$$\delta \mathbb{M}_{\alpha\beta} \equiv \sqrt{|\Delta m^2_{31}|} \begin{pmatrix} \eta_{ee} & \eta_{e\mu} e^{i\phi_{e\mu}} & \eta_{e\tau} e^{i\phi_{e\tau}} \\ \eta_{e\mu} e^{-i\phi_{e\mu}} & \eta_{\mu\mu} & \eta_{\mu\tau} e^{i\phi_{\mu\tau}} \\ \eta_{e\tau} e^{-i\phi_{e\tau}} & \eta_{\mu\tau} e^{-i\phi_{\mu\tau}} & \eta_{\tau\tau} \end{pmatrix}$$

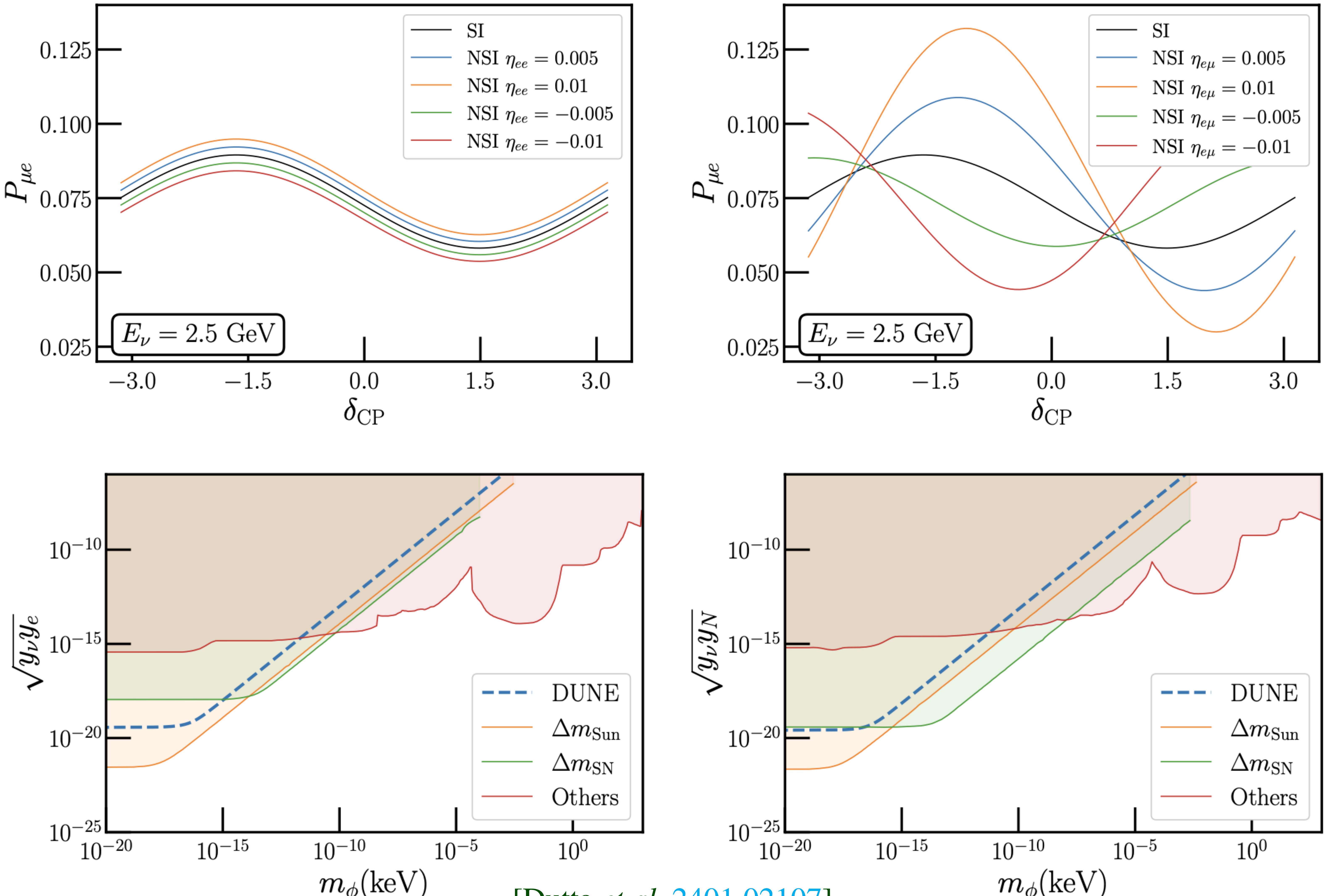
$$\eta_{\alpha\beta} = \frac{n_f y_f y_{\alpha\beta}}{\sqrt{|\Delta m^2_{31}|} m^2_\phi}$$





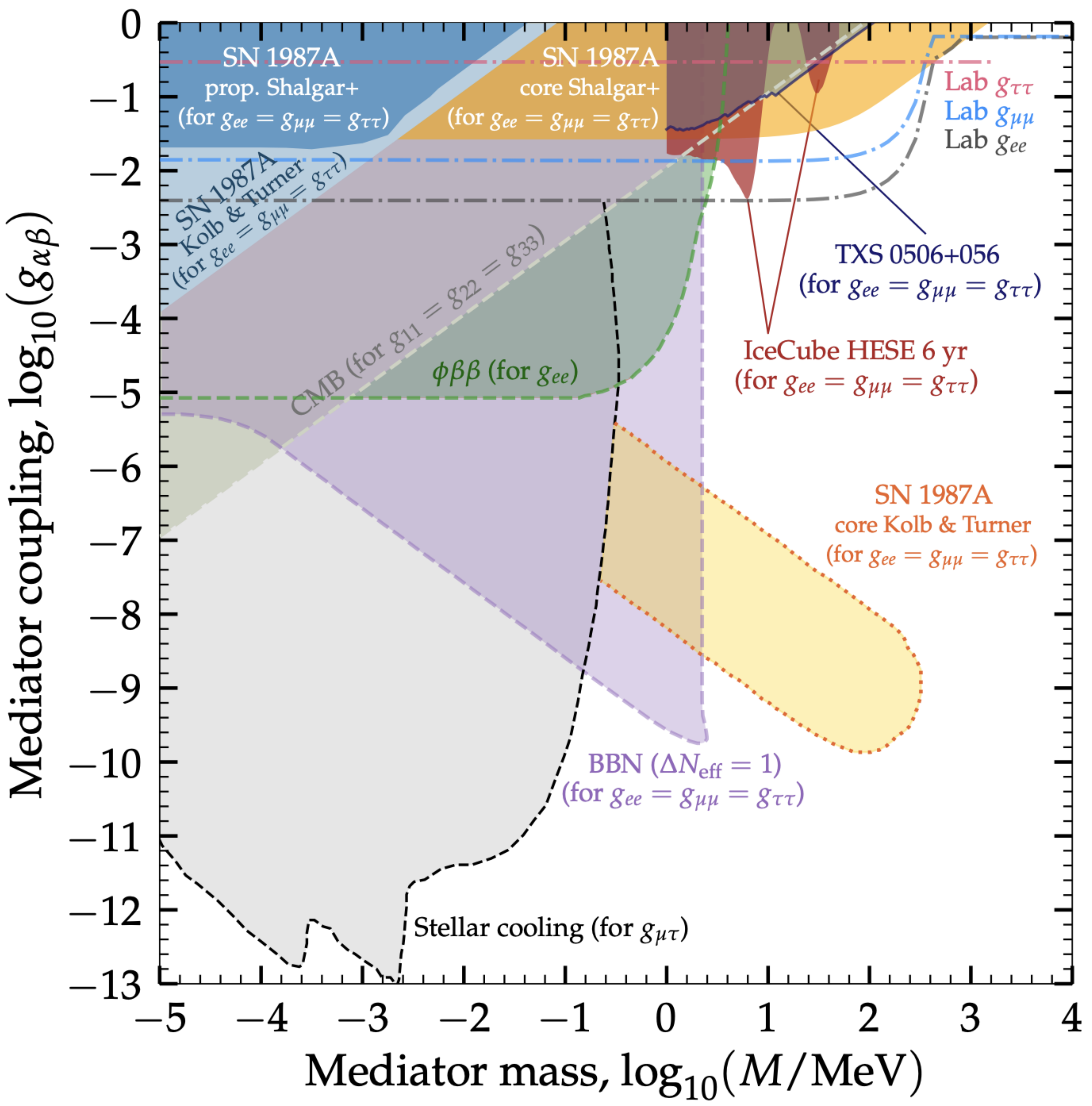
[Ge, Parke, 1812.08376 (PRL)]

Scalar NSI at DUNE



[Dutta *et al*, 2401.02107]

Astrophysical Constraints on NSSI



[Bustamante *et al.*, 2001.04994]

New Supernova Constraints on Neutrino-DM Interaction

Cappiello, BD, Patwardhan, 2503.09691