New physics searches at neutrino experiments

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Sydney-CPPC online seminar (Oct 6th, 2022)

Instituto de Física Teórica UAM-CSIC

HIDDeν
MINISTERIO DE CIENCIA E INNOVACIÓN
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EXCELENCIA SEVERO OCHOA

Why BSM?

Experimental evidence:

Dark matter

Neutrino masses

Matter-antimatter asymmetry

Gravitational interaction

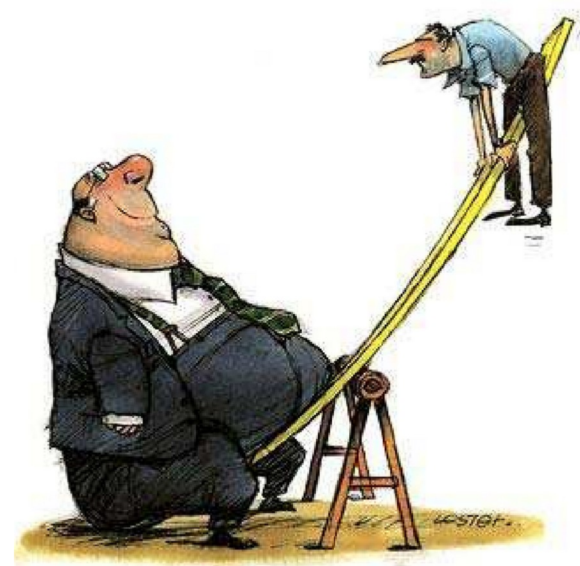
Theoretical indications:

Strong CP problem

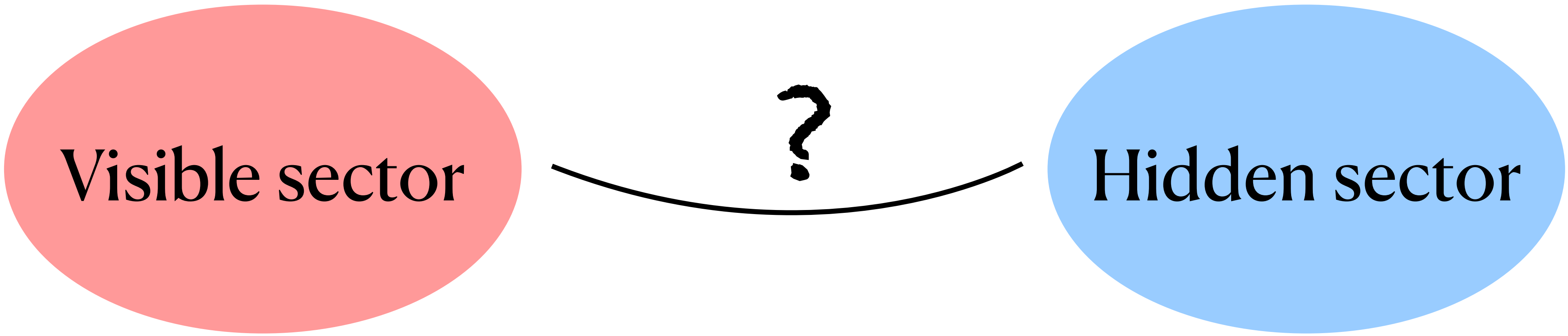
Hierarchy problem

Flavor puzzle

Cosmological constant



ok, so…where is it??



Why neutrino experiments?

$$\nu_\alpha = \sum_i U_{\alpha i} \nu_i$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\theta_{23} \sim 45^\circ$ $\theta_{13} \sim 8.5^\circ$ $\theta_{12} \sim 33^\circ$

$$\Delta m^2_{21} \sim 7.5 \times 10^{-5} \text{ eV}^2$$

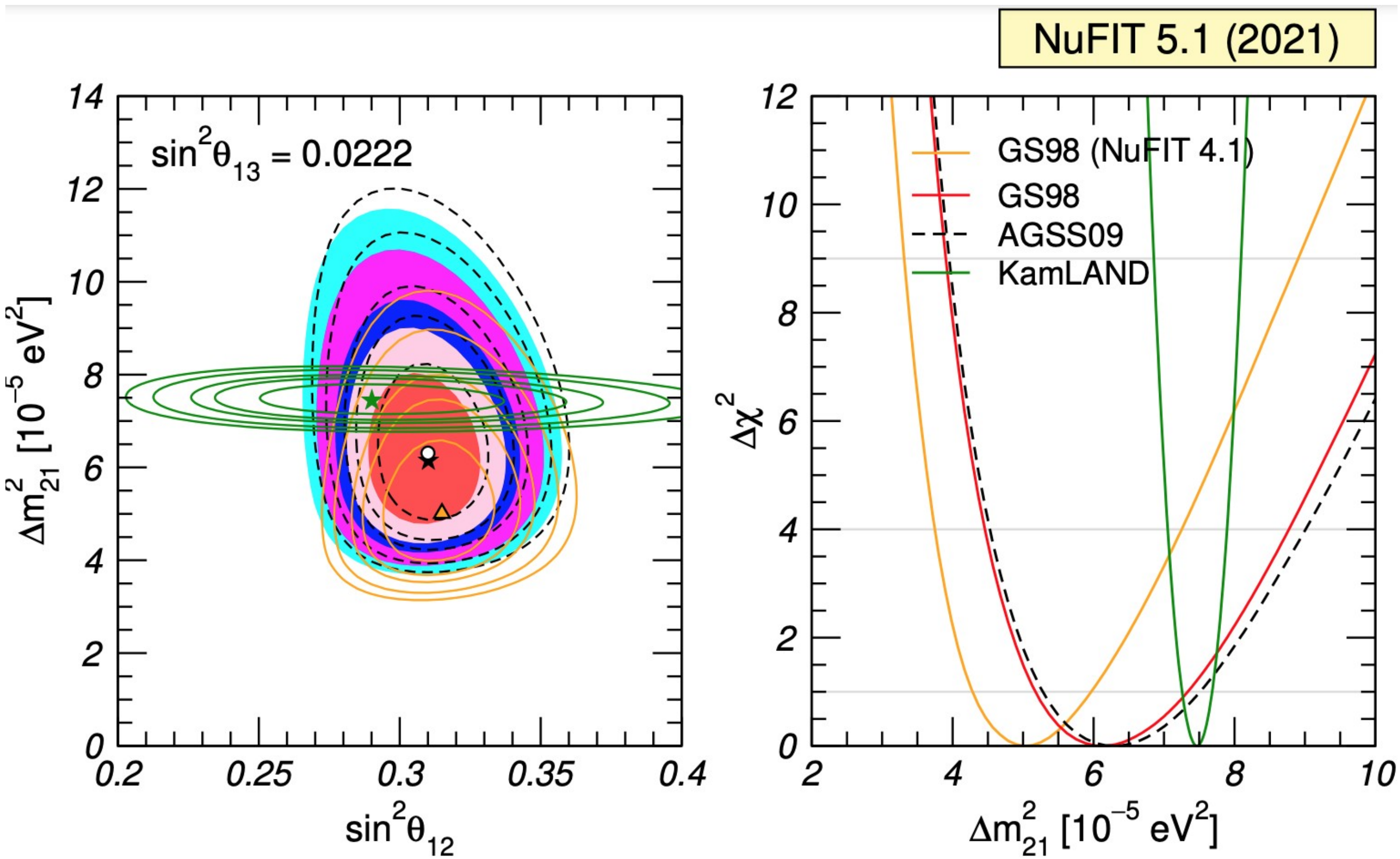
$$\Delta m^2_{31} \sim 2.5 \times 10^{-3} \text{ eV}^2$$

Tiny!

$$c_{ij} = \cos\theta_{ij}$$

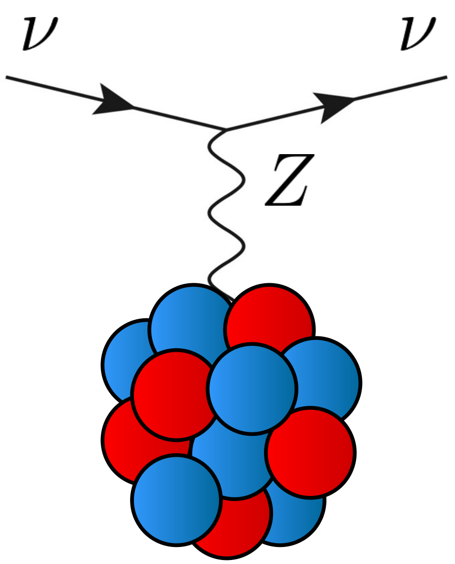
$$s_{ij} = \sin\theta_{ij}$$

Why neutrino experiments?



Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou 2007.14792
http://www.nu-fit.org/

Why neutrino experiments?



Why neutrino experiments?

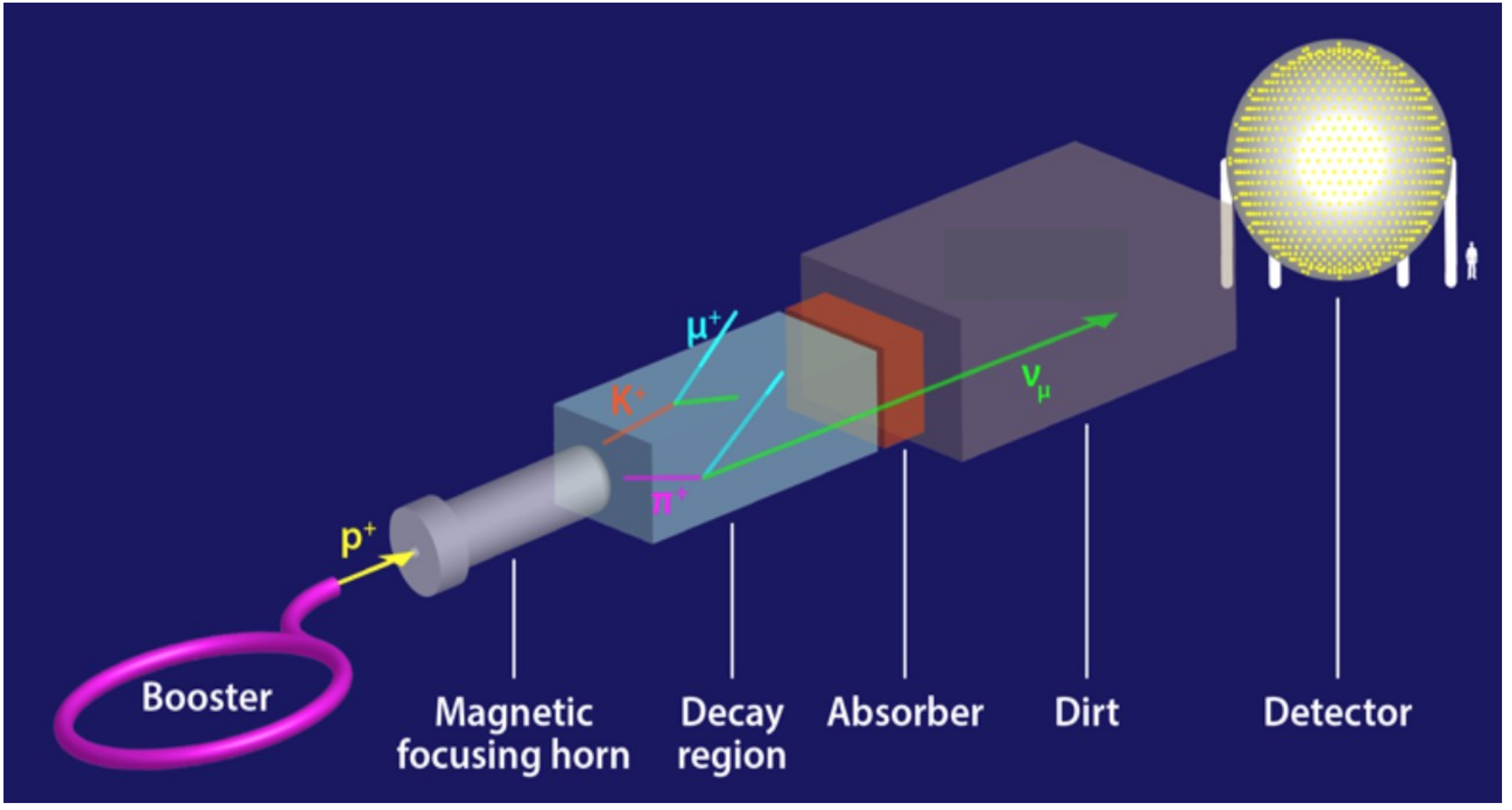
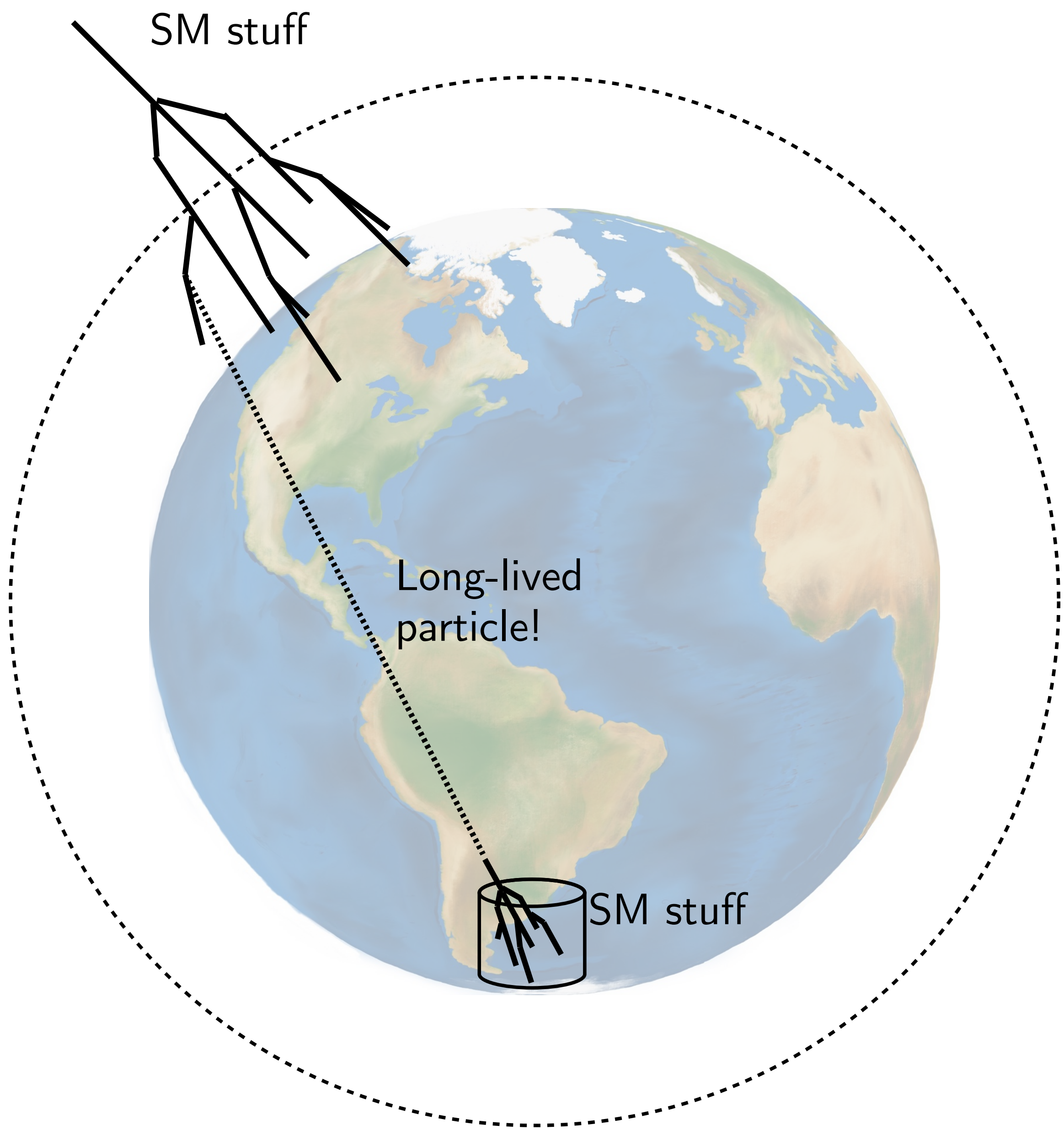


Image credit: APS/Alan Stonebraker

Why neutrino experiments?

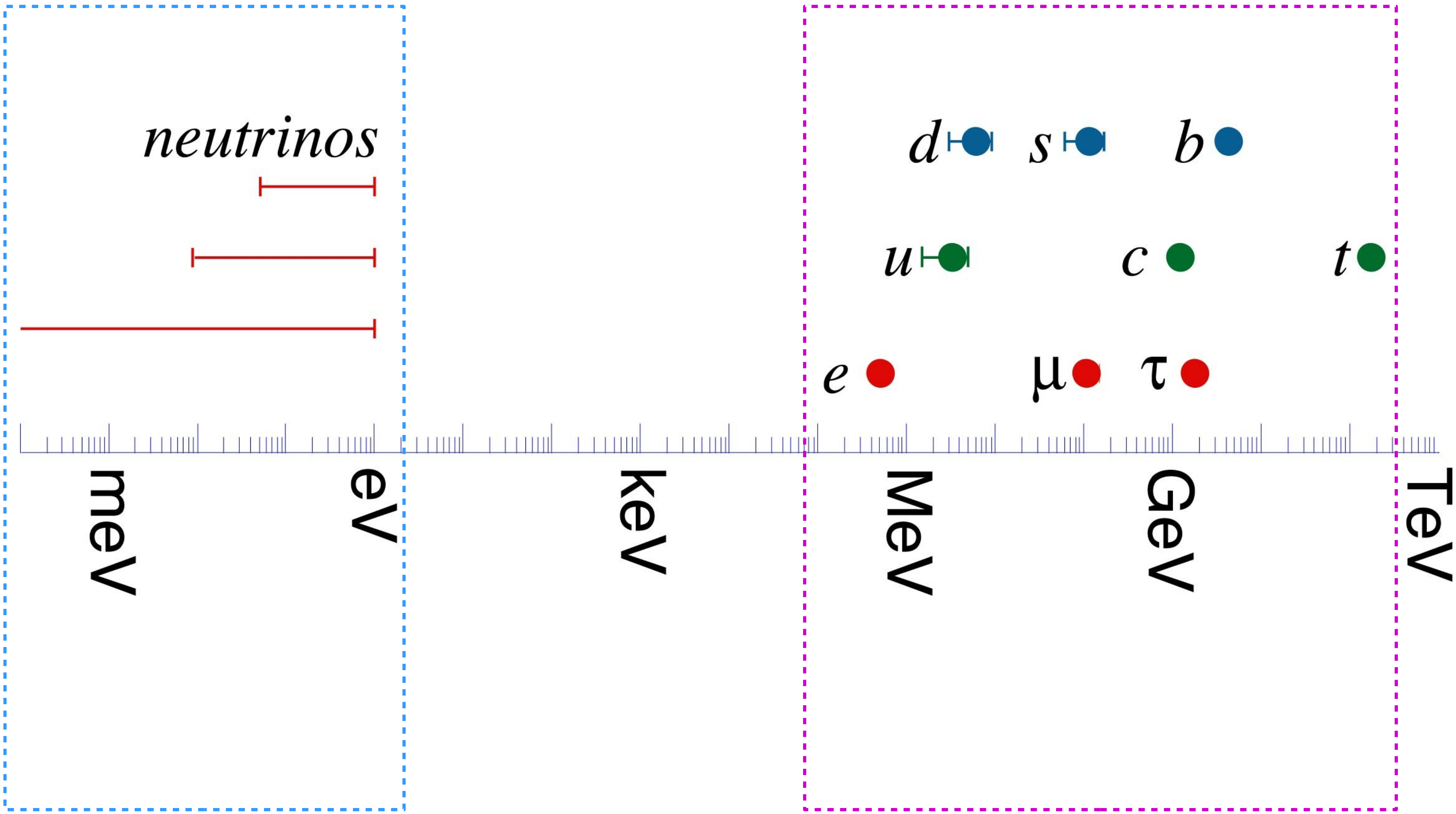


This talk

- Neutrino oscillations + neutrino scattering
  - NSI
  - Light Z'
- Neutrino experiments as fixed target facilities
  - Heavy neutral leptons, axion-like particles, …

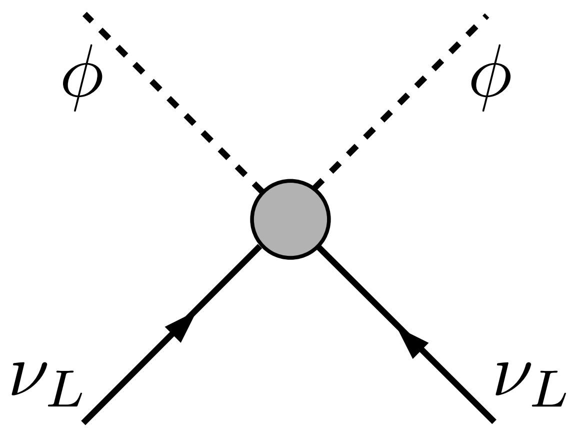
Non-Standard Interactions

Neutrino masses



Neutrino masses

$$\mathcal{L}^{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\delta\mathcal{L}^{d=5} + \ldots$$

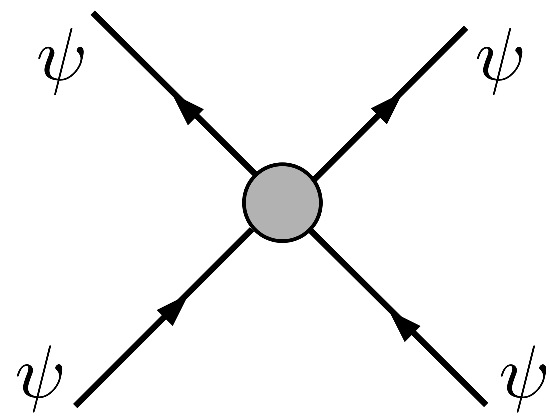


$$\propto \frac{1}{\Lambda}(\overline{L}_L\widetilde{\phi})(\widetilde{\phi}^t L_L^c)$$

Weinberg, 1979

Non-Standard Interactions

$$\mathcal{L}^{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\,\delta\mathcal{L}^{d=5} + \frac{1}{\Lambda^2}\,\delta\mathcal{L}^{d=6} + \ldots$$

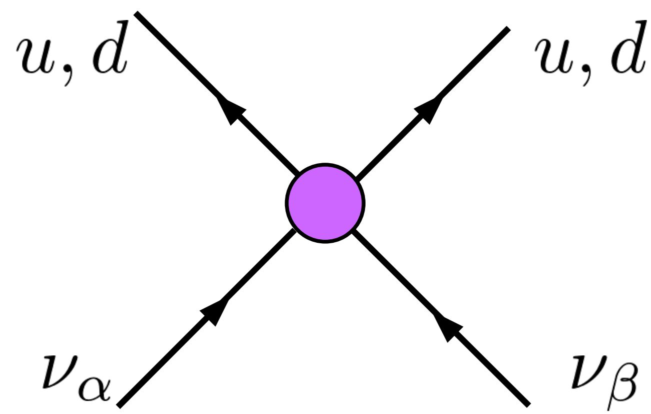


$$G_x \sim \frac{g^2}{\Lambda^2}$$

Non-Standard Interactions

$$\mathcal{L}^{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\delta\mathcal{L}^{d=5} + \frac{1}{\Lambda^2}\delta\mathcal{L}^{d=6} + \ldots$$

NSI affecting
propagation



$$-2\sqrt{2}G_F\varepsilon^{f,P}_{\alpha\beta}\left(\overline{f}\gamma^\rho P f\right)\left(\overline{\nu}_\alpha\gamma_\rho P_L \nu_\beta\right)$$

$$\varepsilon \sim \mathcal{O}(G_x/G_F)$$

NSI in propagation

NSI in propagation will lead to a generalized matter potential affecting neutrino oscillations:

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \left[U\mathcal{H}_0U^\dagger + V_{cc}(x)\begin{pmatrix}1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau}\\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau}\\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

$$V_{cc}(x) \propto G_F n_e(x)$$

Oscillations are only sensitive to vector NSI in the form:

$$\epsilon_{\alpha\beta} \equiv \sum_{f,P}\frac{n_f(x)}{n_e(x)}\varepsilon^{fP}_{\alpha\beta} \quad \text{(f = u,d,e; P = L,R)}$$

NSI in propagation

NSI in propagation will lead to a generalized matter potential affecting neutrino oscillations:

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \left[U\mathcal{H}_0U^\dagger + V_{cc}(x)\begin{pmatrix}1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau}\\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau}\\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

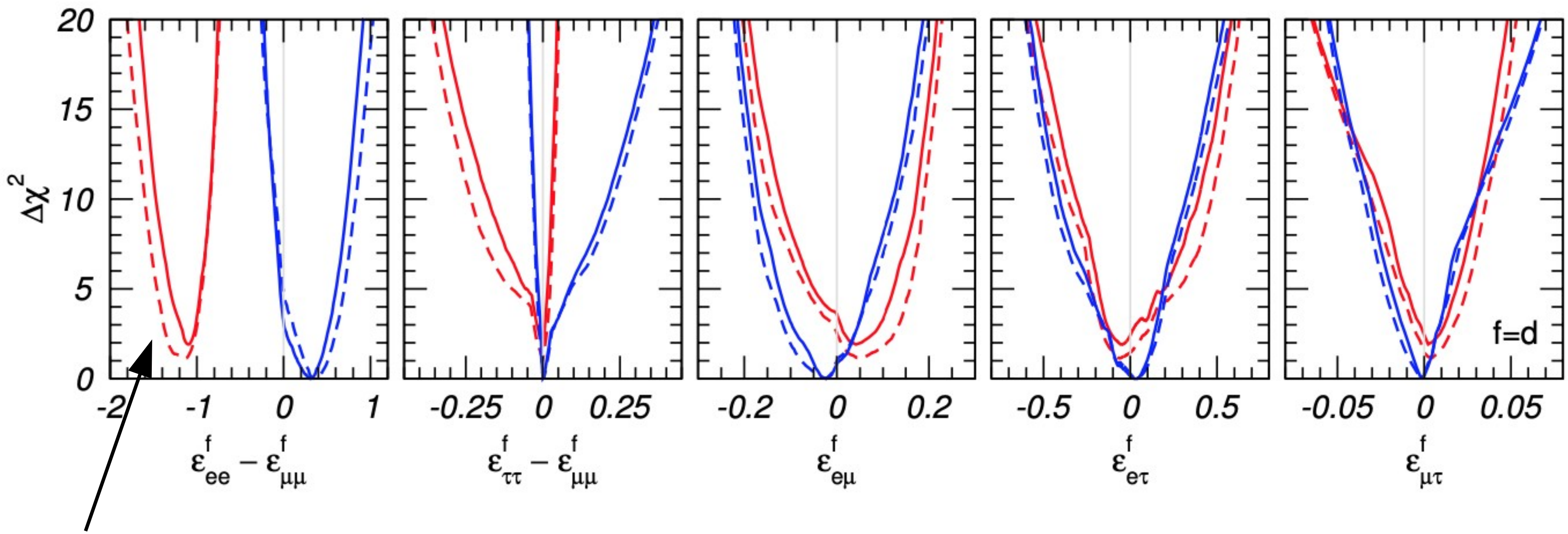
$$V_{cc}(x) \propto G_F n_e(x)$$

$$\downarrow$$

$$\begin{pmatrix}1+(\epsilon_{ee}-\epsilon_{\mu\mu}) & \epsilon_{e\mu} & \epsilon_{e\tau}\\ \epsilon^*_{e\mu} & 0 & \epsilon_{\mu\tau}\\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & (\epsilon_{\tau\tau}-\epsilon_{\mu\mu})\end{pmatrix}$$

Bounds from oscillations

Fig from Gonzalez-Garcia and Maltoni, 1307.3092



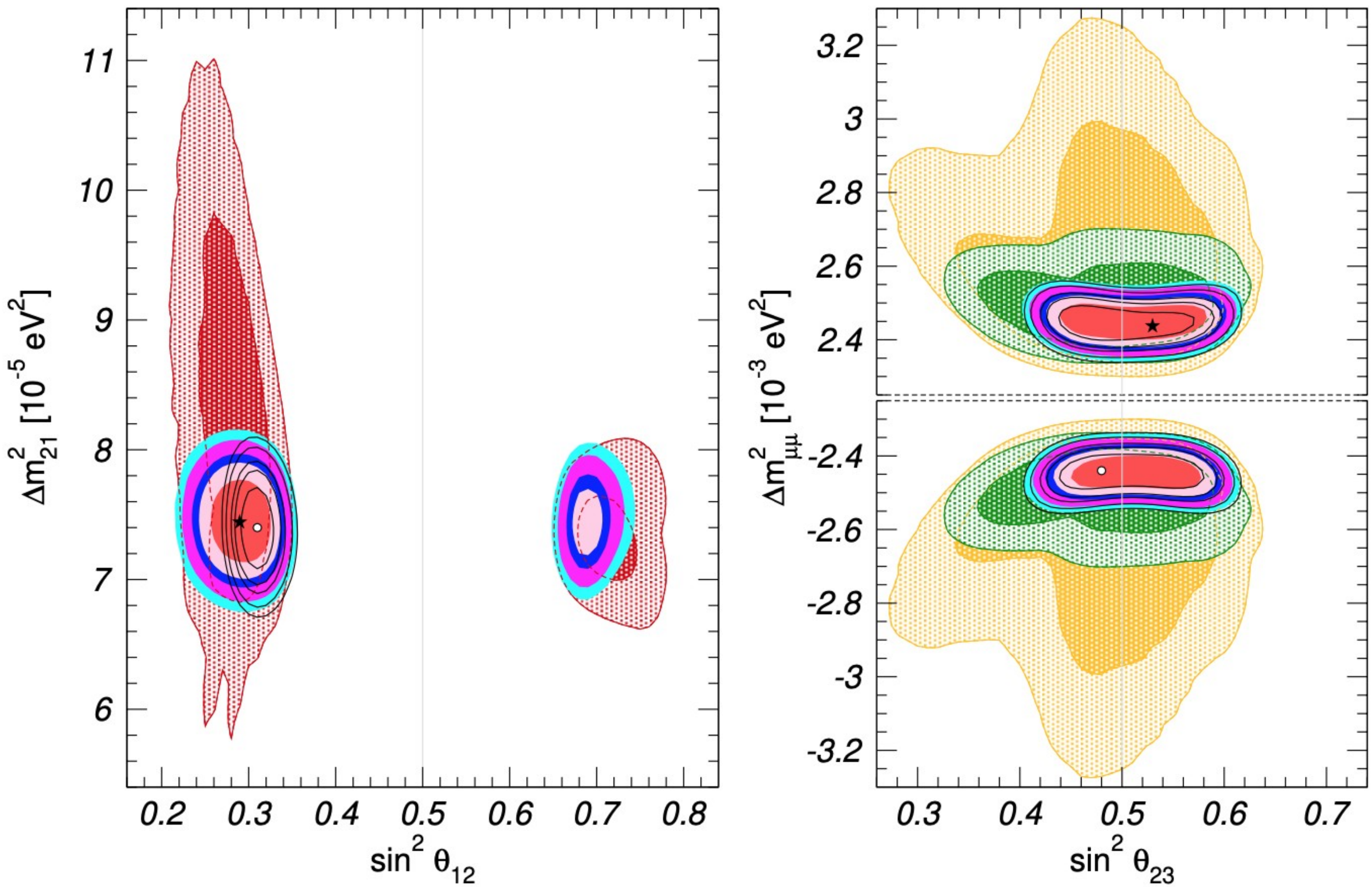
LMA-Dark
solution

Miranda, Tortola, Valle,
hep-ph/0406280

$$\epsilon^{\oplus}_{\alpha\beta} \sim 3\,\varepsilon^u_{\alpha\beta} + 3\,\varepsilon^d_{\alpha\beta} + \varepsilon^e_{\alpha\beta}$$

$$\epsilon^{\odot}_{\alpha\beta} \sim 2\,\varepsilon^u_{\alpha\beta} + \varepsilon^d_{\alpha\beta} + \varepsilon^e_{\alpha\beta}$$

Bounds from oscillations

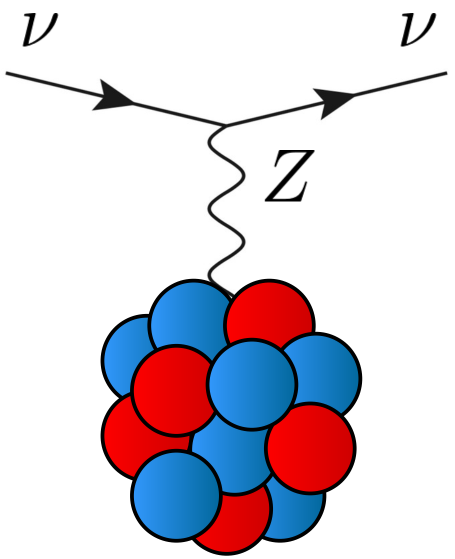


Esteban, Gonzalez-Garcia, Maltoni, Martinez-Soler and Salvado, 1805.04530,
(see also Esteban et al 1905.05203, 2004.04745 and Capozzi et al, 1908.06992)

CEvNS

In the SM:

$$\frac{d\sigma_\alpha}{dE_r} = \frac{G_F^2}{2\pi}\frac{\mathcal{Q}_\alpha^2}{4}F^2(2ME_r)M\left(2-\frac{ME_r}{E_\nu^2}\right)$$



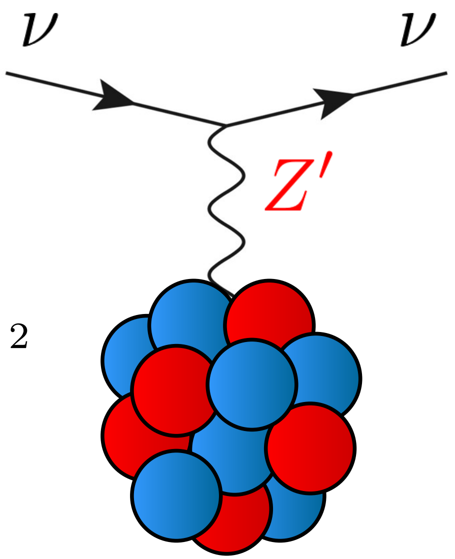
$$\mathcal{Q}^2_{\alpha,\mathrm{SM}} = (Zg_p^V + Ng_n^V)^2$$

Freedman, PRD 9 (1974)

CEνNS

In presence of NSI:

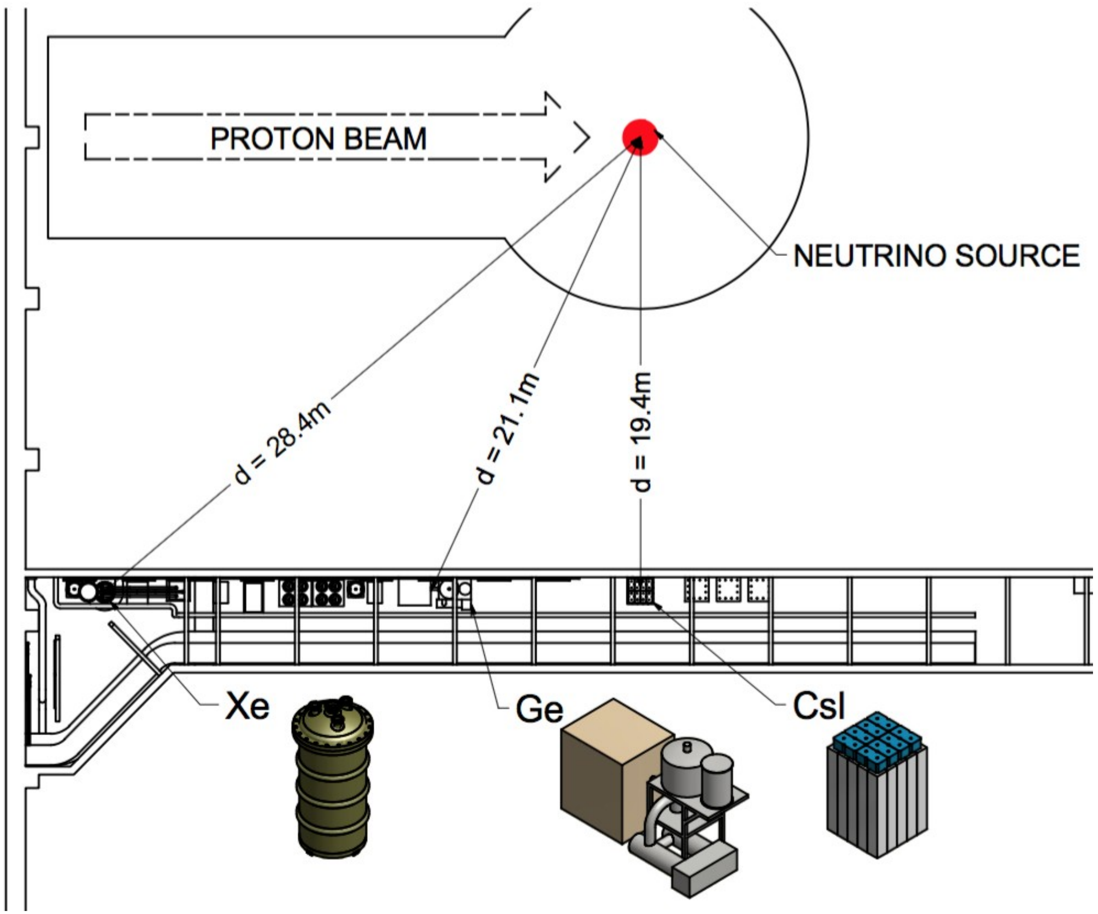
$$\frac{d\sigma_\alpha}{dE_r} = \frac{G_F^2}{2\pi}\frac{\mathcal{Q}_\alpha^2}{4}F^2(2ME_r)M\left(2-\frac{ME_r}{E_\nu^2}\right)$$



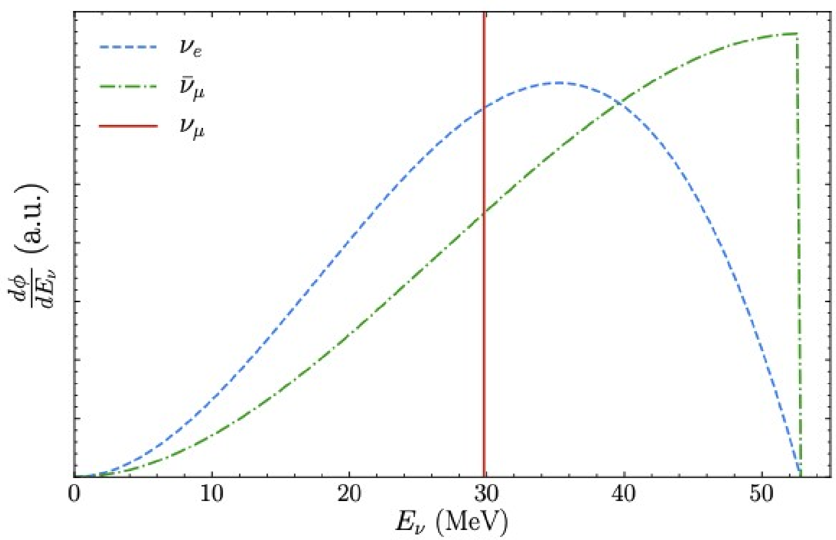
$$\mathcal{Q}_\alpha^2(\vec{\varepsilon}) = \left[Z(g_p^V + 2\varepsilon_{\alpha\alpha}^u + \varepsilon_{\alpha\alpha}^d) + N(g_n^V + \varepsilon_{\alpha\alpha}^u + 2\varepsilon_{\alpha\alpha}^d)\right]^2 + \sum_{\beta\neq\alpha} \mid Z(2\varepsilon_{\alpha\beta}^u + \varepsilon_{\alpha\beta}^d) + N(\varepsilon_{\alpha\beta}^u + 2\varepsilon_{\alpha\beta}^d) \mid^2$$

Barranco, Miranda, Rashba, hep-ph/0508299

COHERENT



$$\pi^+ \to \mu^+ \nu_\mu$$
$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$$



→ For a medium sized nucleus (Cs, I, Ar, etc), coherence condition satisfied below 50 MeV

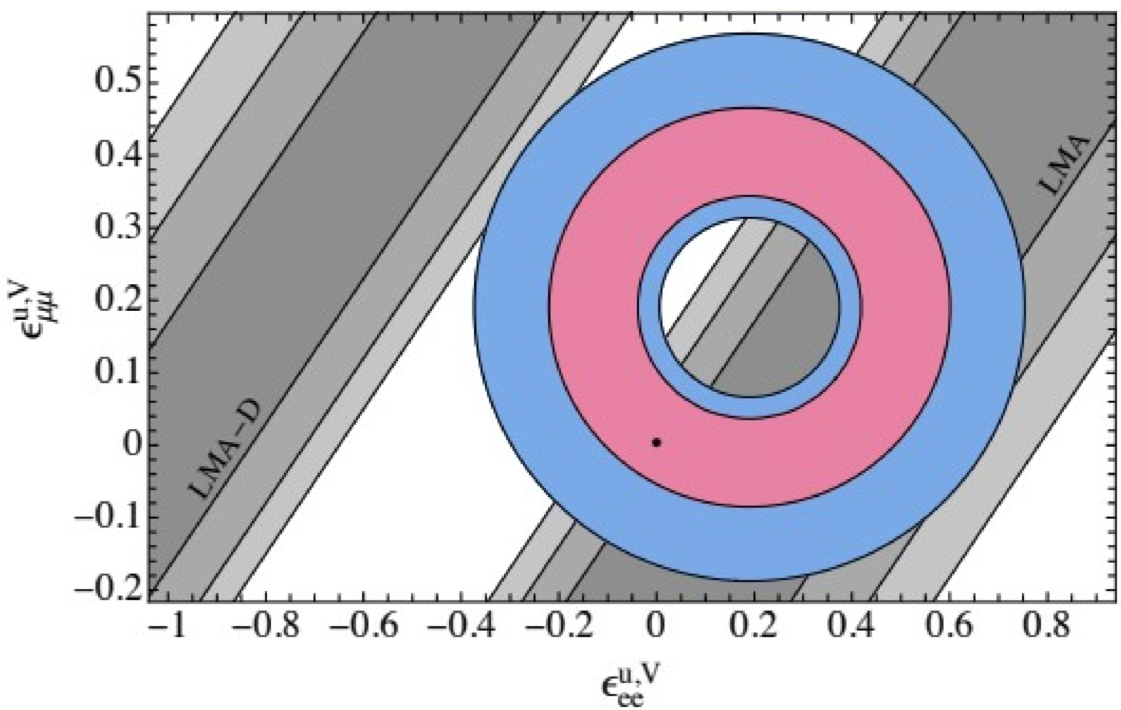
COHERENT coll., 1509.08702

COHERENT

Using only total rate info, the allowed region is an ellipse in NSI space:

$$[\mathcal{Q}_W + (2\,Z + N)\;\varepsilon^u_{ee}]^2 + 2\;\left[\mathcal{Q}_W + (2\,Z + N)\;\varepsilon^u_{\mu\mu}\right]^2 = \text{constant}$$

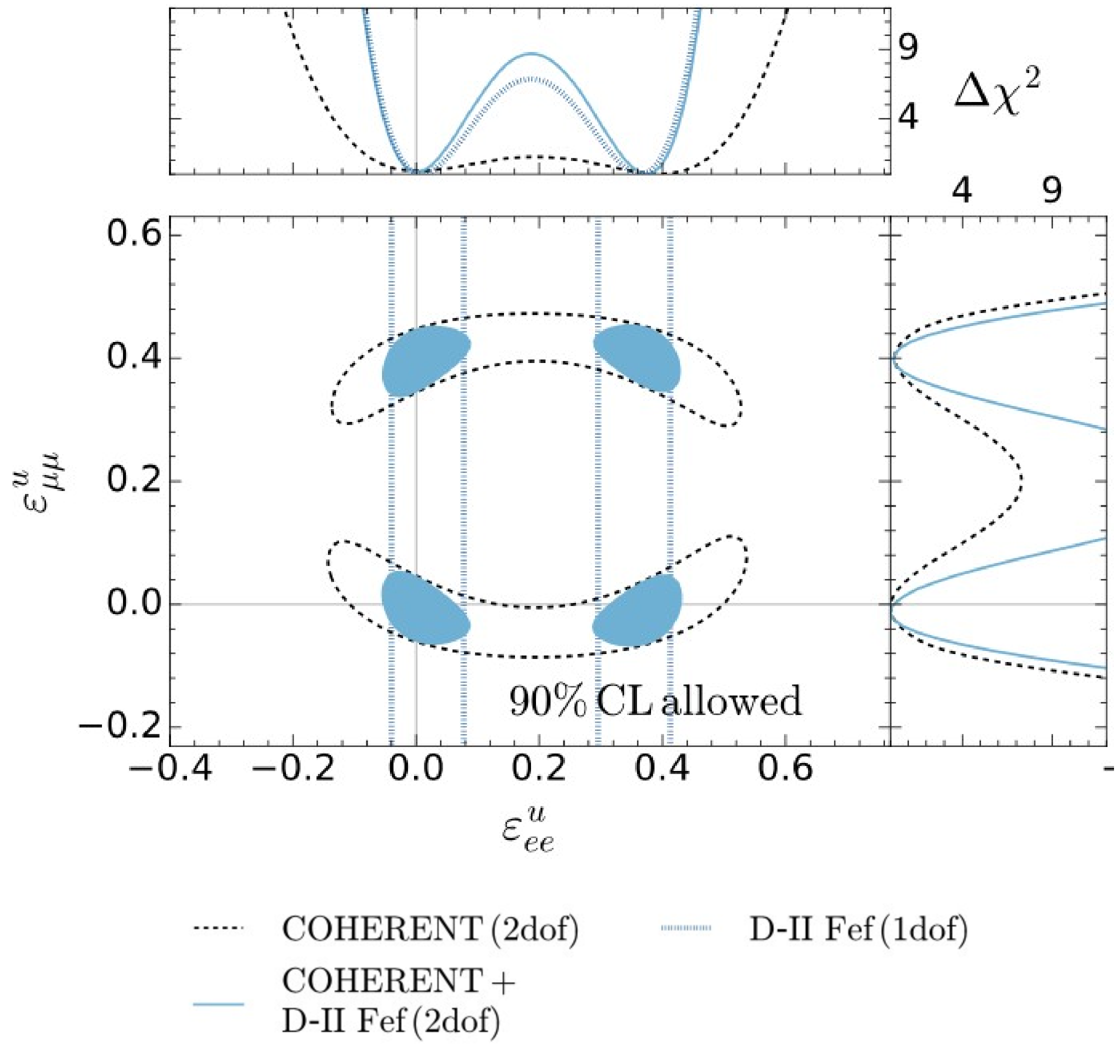
CsI data:



Coloma, Gonzalez-Garcia, Maltoni and Schwetz, 1708.02899
(updated results in Coloma, Esteban, Gonzalez-Garcia, Maltoni, 1911.09109)

CEvNS at reactors – Dresden II

Nice synergies appear with reactor experiments, particularly useful for NSI



Coloma, Esteban, Gonzalez-Garcia, Larizgoitia, Monrabal, Palomares-Ruiz, 2202.10829

Coloma, Esteban, Gonzalez-Garcia, Maltoni, 1911.09109

New (light) vector bosons

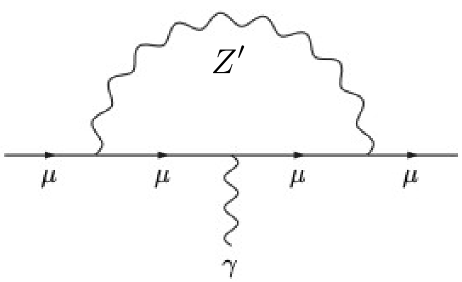
Light flavored Z'

$$\mathcal{L}_{Z'} \supset \sum_f g_{Z'} Q'_f Z'_\mu \bar{f} \gamma^\mu f + \frac{1}{2} M^2_{Z'} Z'^\mu Z'_\mu$$

Anomaly-free for SM + $3N_R$:

$$\mathcal{G} = G_{SM} \times U(1)_{B-L} \times U(1)_{L_\alpha - L_\beta} \times U(1)_{L_\beta - L_\gamma}$$

(see eg Araki, Heeck, Kubo, 1203.4951)



See eg, Ma, Roy, Roy, hep-ph/0110146; Baek, Deshpande, He, Ko, hep-ph/0104141; Heeck, Rodejohann, 1107.5238; Choubey, Rodejohann, hep-ph/0411190

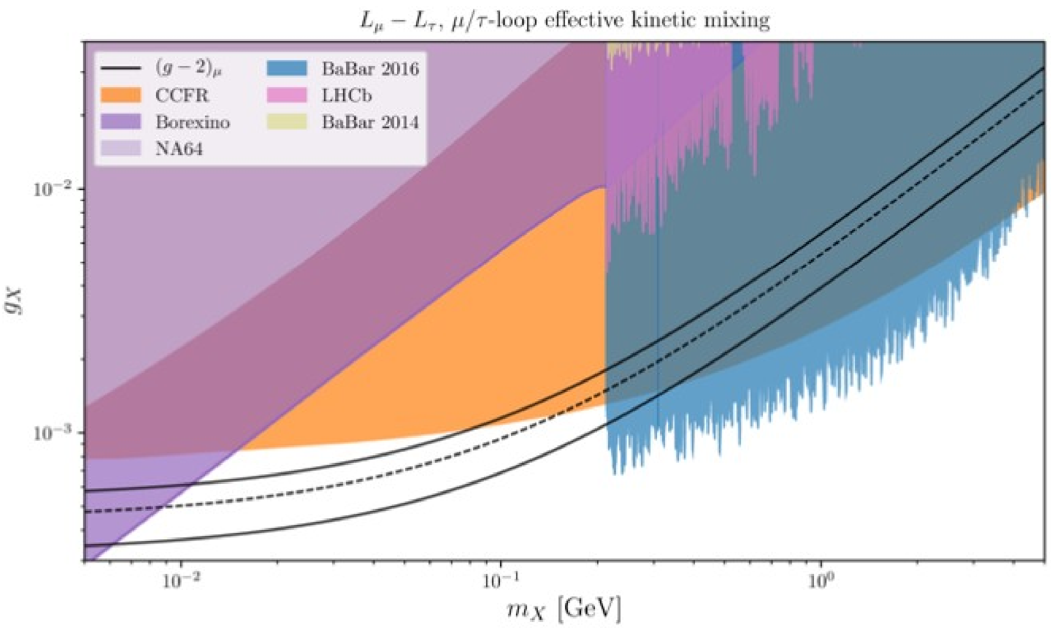
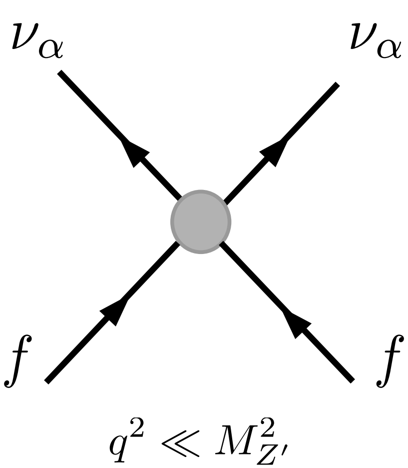


Fig from Greljo, Stangl, Thomsen, Zupan, 2203.13731

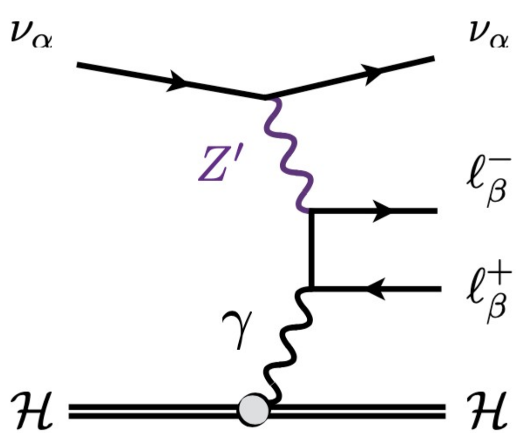
Light flavored Z'

$$\mathcal{L}_{Z'} \supset \sum_f g_{Z'} Q'_f Z'_\mu \bar{f} \gamma^\mu f + \frac{1}{2} M_{Z'}^2 Z'^\mu Z'_\mu$$

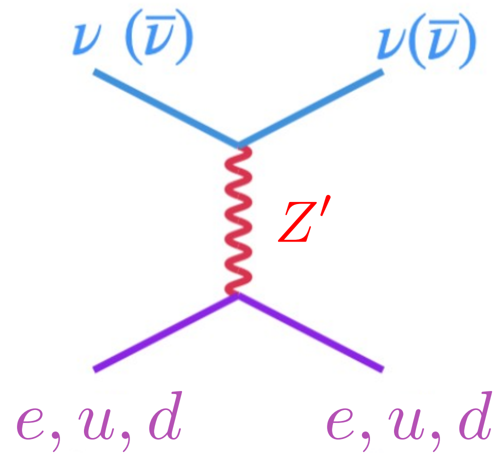
Oscillations



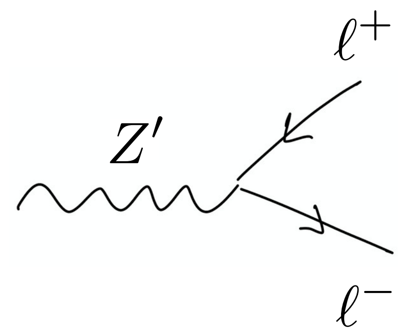
Tridents



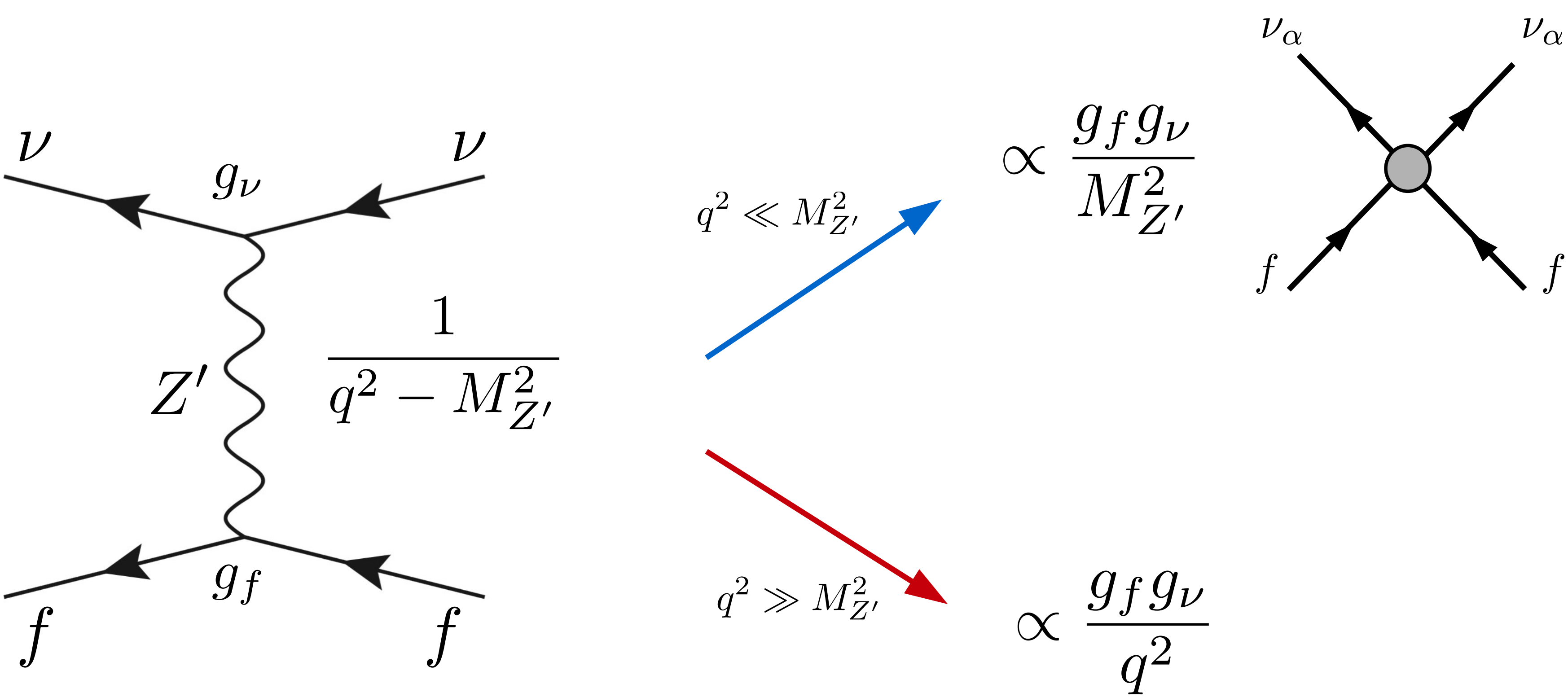
Scattering



Decays

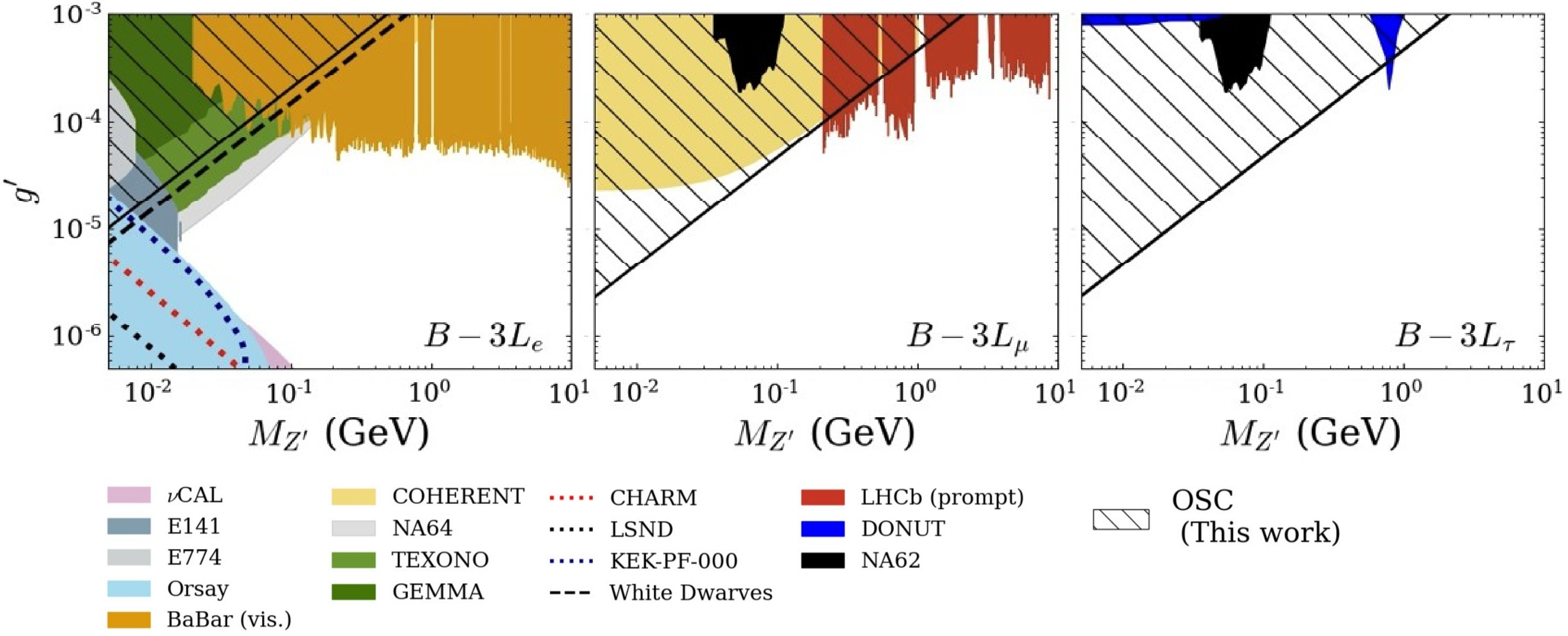


Scattering vs Oscillations



Light flavored Z': present bounds

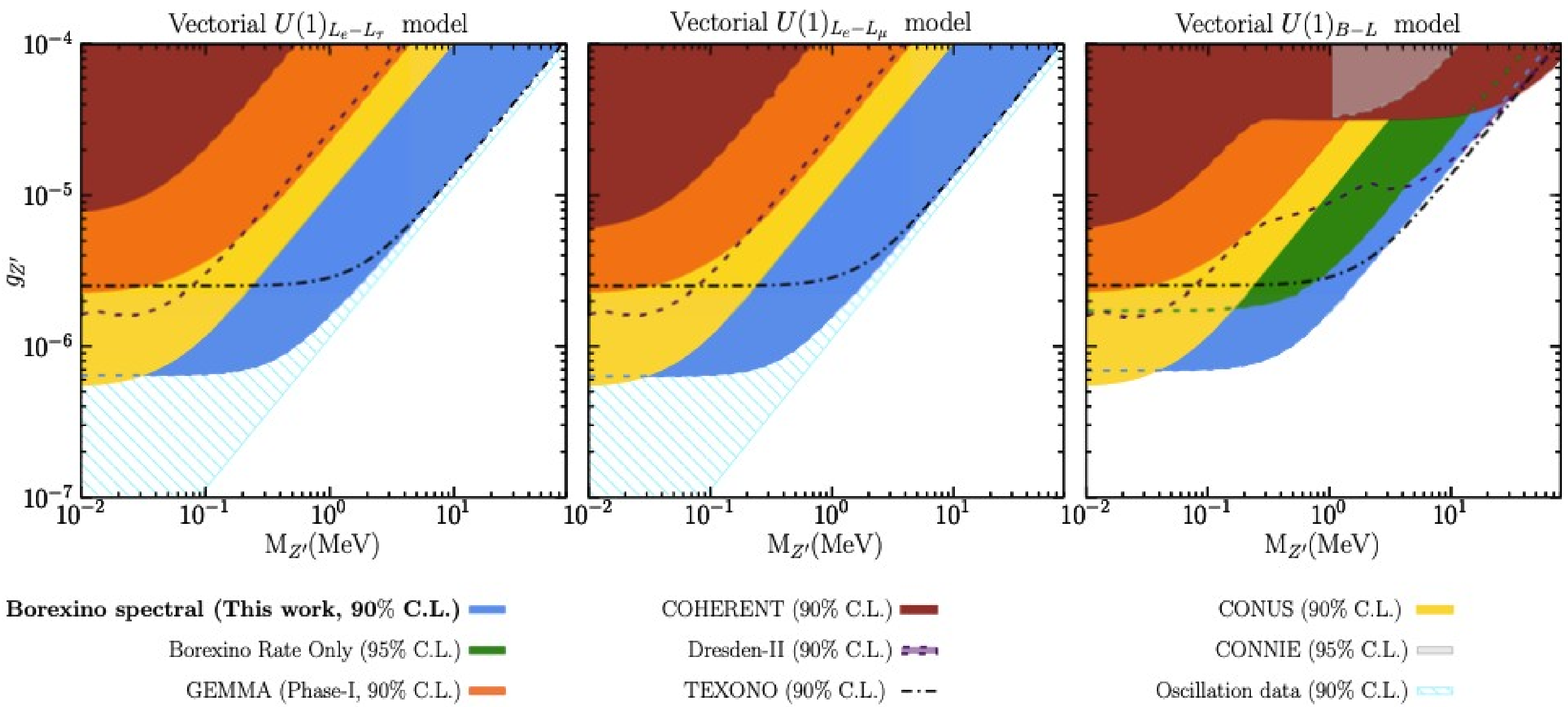
Coloma, Gonzalez-Garcia and Maltoni, 2009.14220



→ Oscillation data rules out many U(1)' explanations of the muon g-2 anomaly!

(see Greljo, Soreq, Stangl, Thomsen, Zupan, 2107.07518; Greljo, Stangl, Thomsen, Zupan, 2203.13731)

Light flavored Z': present bounds



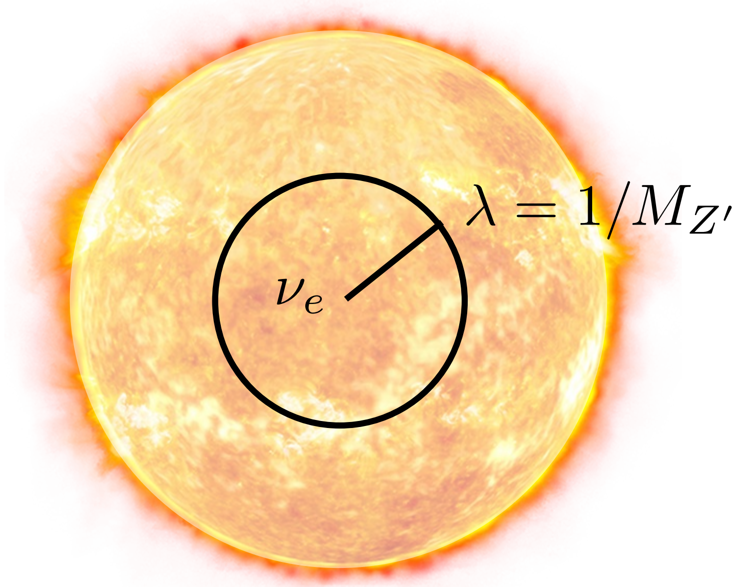
Coloma, Gonzalez-Garcia, Maltoni, Pinheiro, Urrea, 2204.03011

How light can we go...?

Long-range forces

Matter potential depends now on:

$$\int N_f(\vec{\rho})\,\frac{e^{-M_{Z'}|\vec{\rho}-\vec{x}|}}{|\vec{\rho}-\vec{x}|}\,d^3\vec{\rho}$$



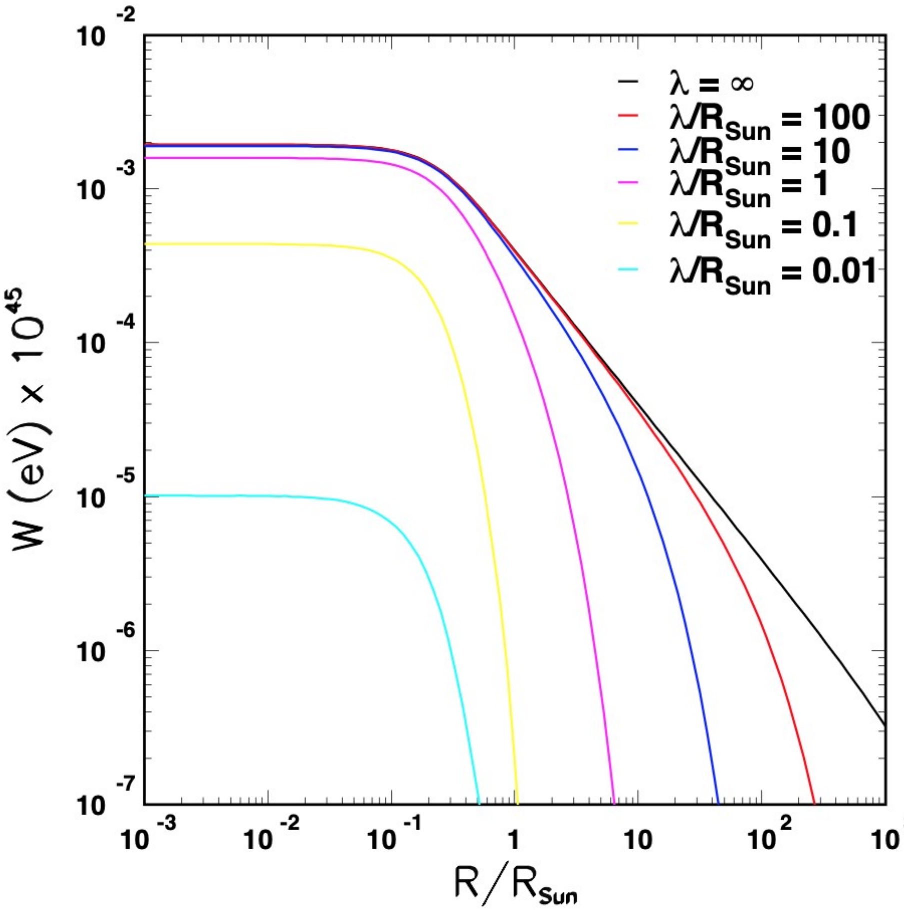
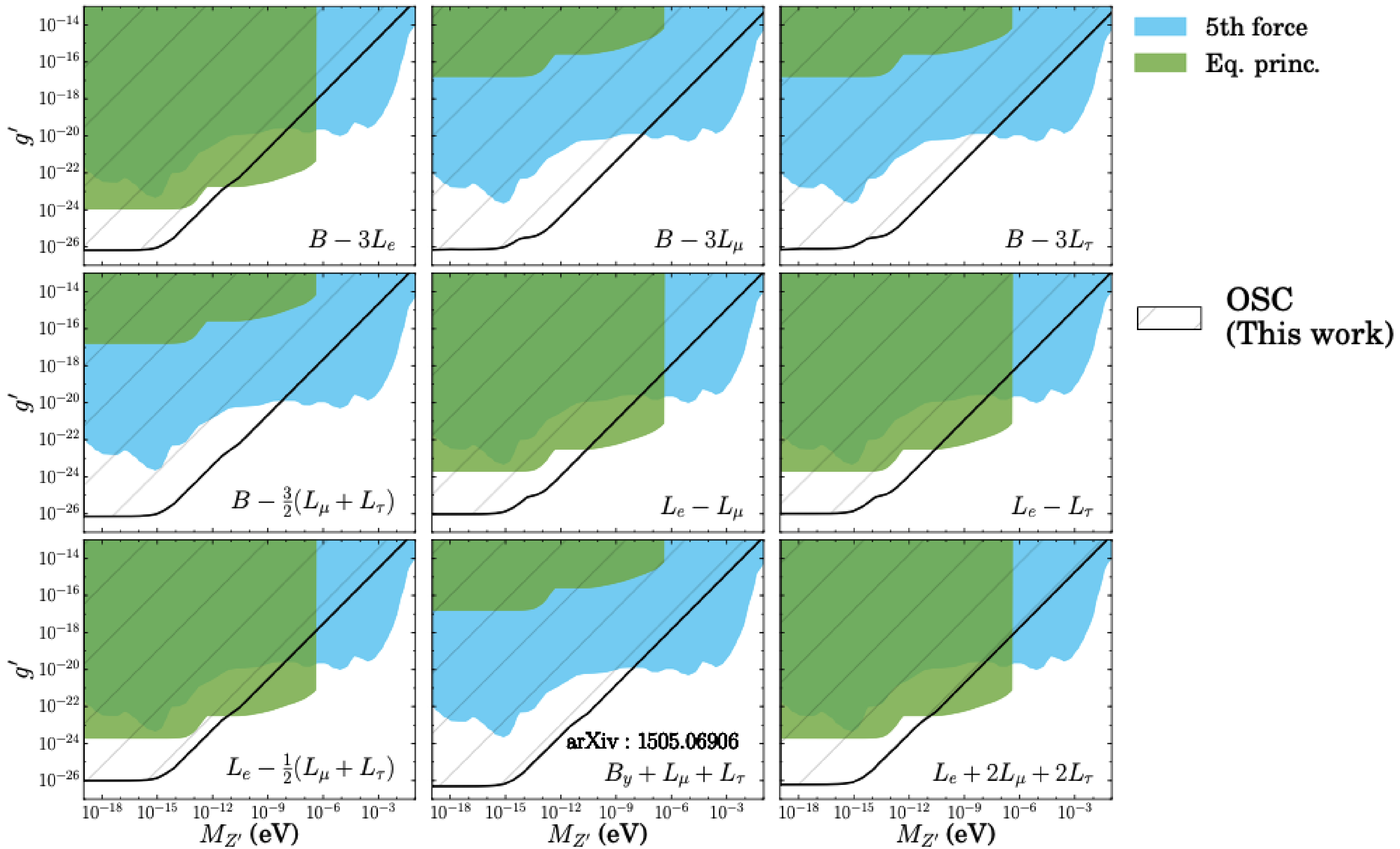


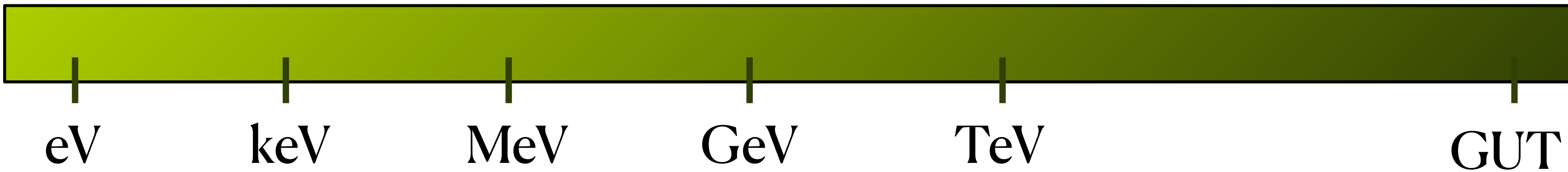
Fig from Gonzalez-Garcia, de Holanda, Masso, Zukanovich Funchal, hep-ph/0609094
(see also Grifols and Masso, hep-ph/0311141
Joshipura and Mohanti, hep-ph/0310210)



Coloma, Gonzalez-Garcia and Maltoni, 2009.14220

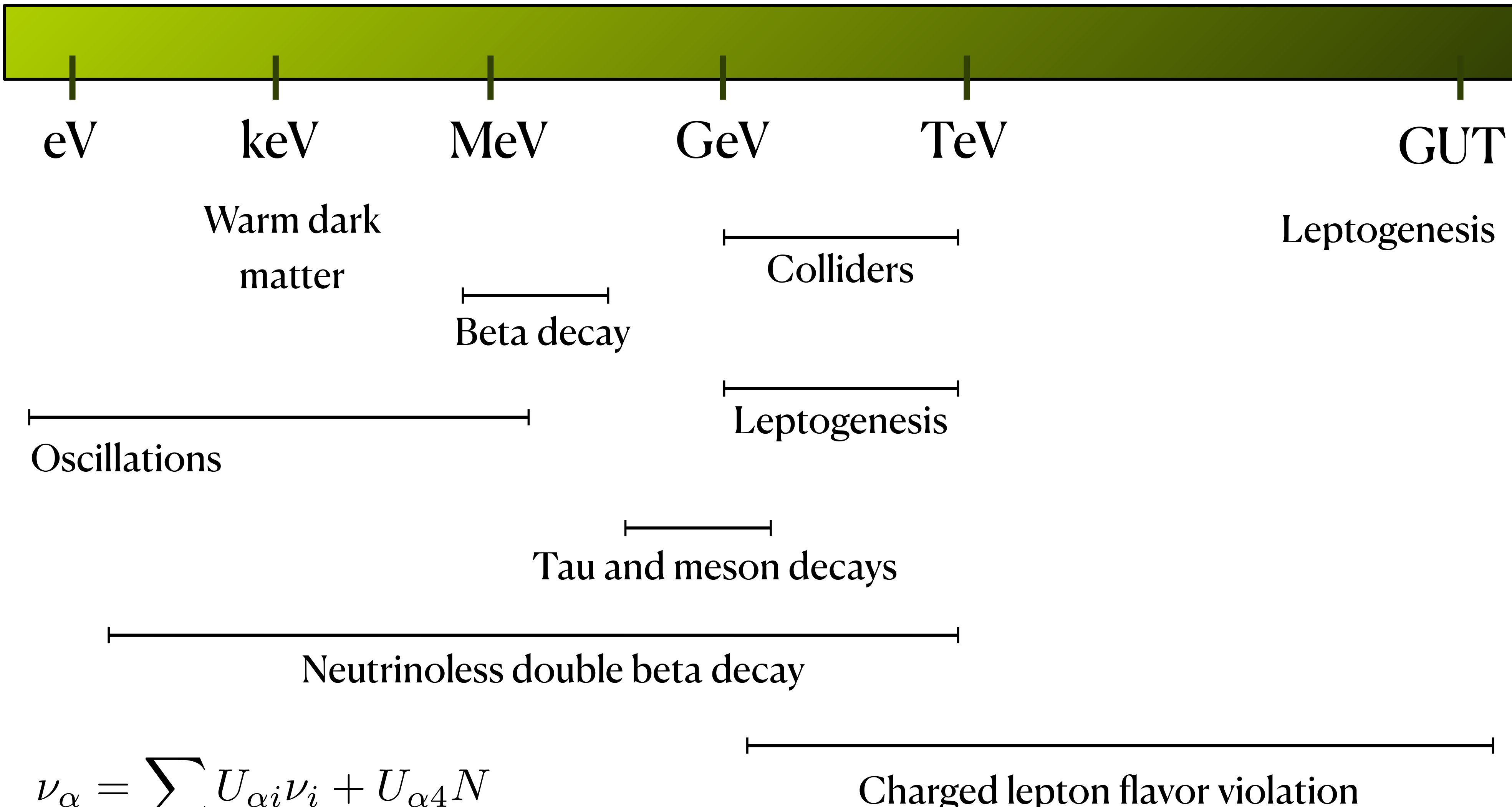
Neutrino experiments as fixed target facilities

Heavy neutrinos



$$\nu_\alpha = \sum_i U_{\alpha i}\nu_i + U_{\alpha 4} N$$

Heavy neutrinos

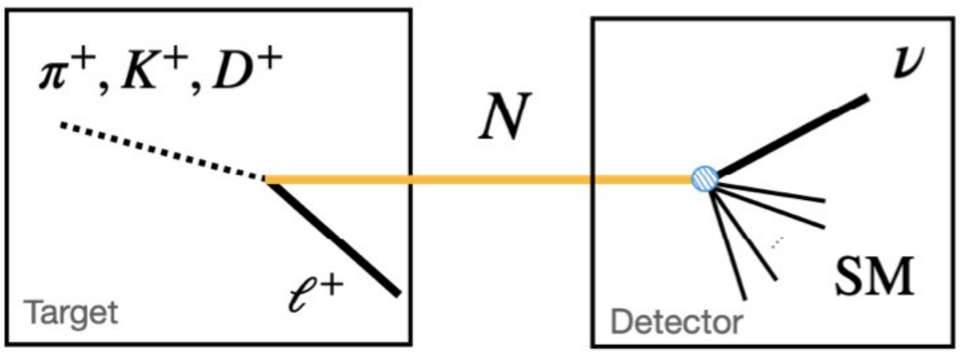


$$\nu_\alpha = \sum_i U_{\alpha i}\nu_i + U_{\alpha 4} N$$

Heavy Neutral Leptons

For HNL masses below a few GeV:

$$\nu_\alpha = \sum_i U_{\alpha i}\nu_i + U_{\alpha 4} N$$



$$c\tau_N \simeq 400 \left(\frac{10^{-6}}{|U|^2}\right) \text{ m}$$

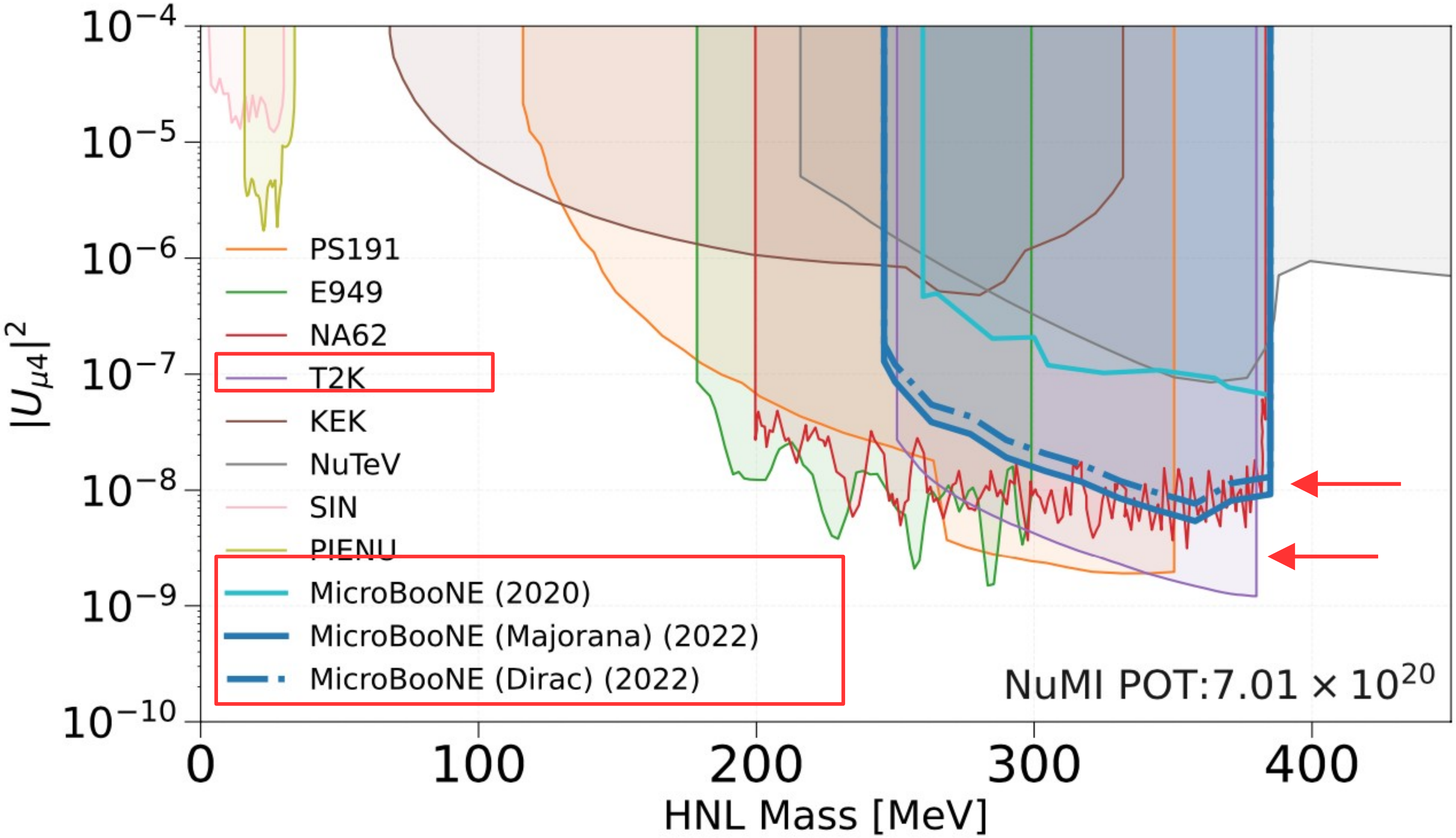
For $\begin{cases} m_N \sim 1 \text{ GeV} \\ |U_{e4}| = |U_{\mu 4}| = |U_{\tau 4}| \end{cases}$

See e.g., Krasnov, 1902.06099; Ballett et al, 1905.00284; Berryman et al, 1912.07622; Coloma et al, 2007.03701; Breitbach et al, 2102.03383; …

Figure from Snowmass'21 WP "Dark sector searches with neutrino beams", 2207.06898

Heavy Neutral Leptons

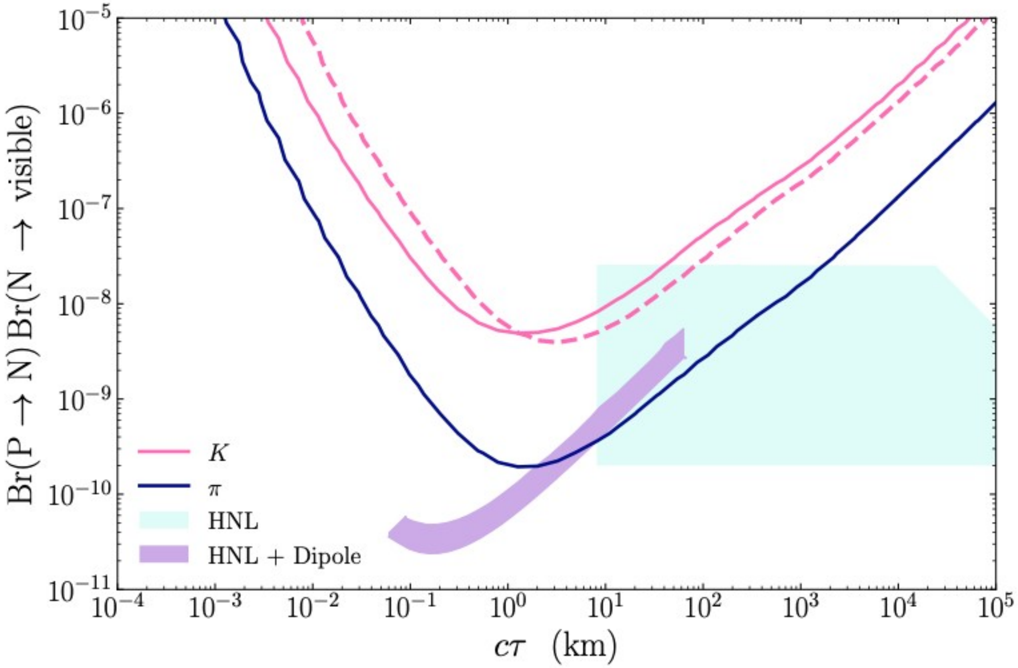
Production in the target:

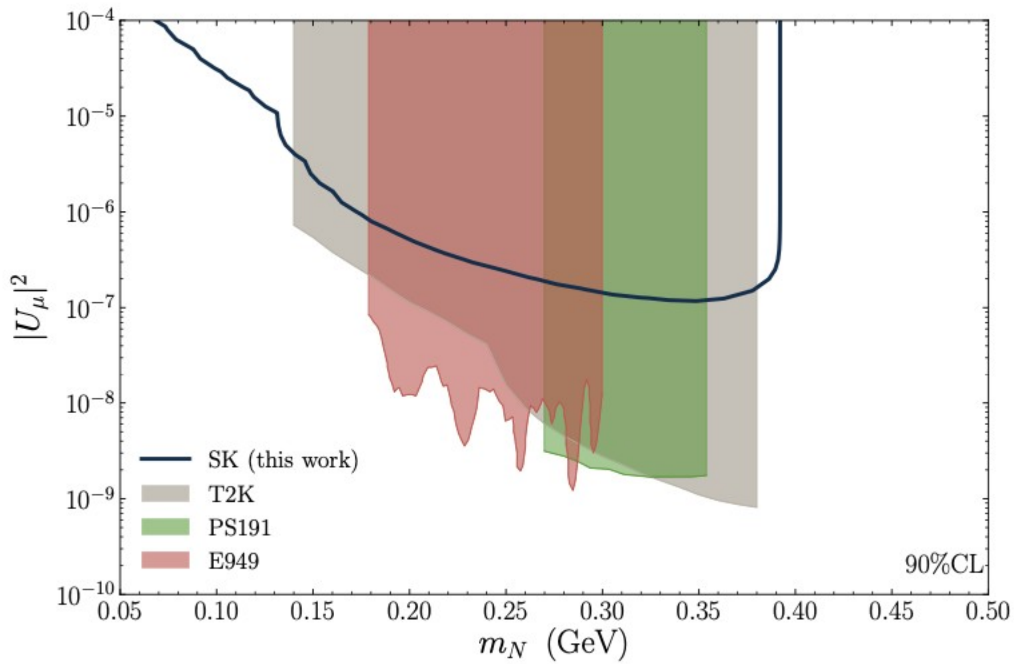


MicroBooNE coll., 2207.03840

Heavy Neutral Leptons

Production in the atmosphere

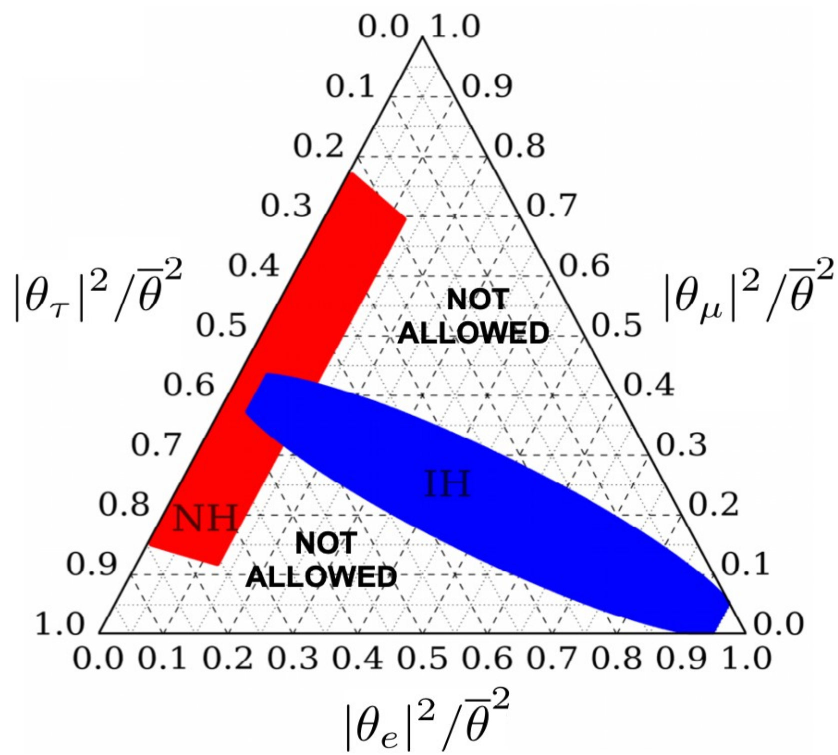




Coloma, Hernandez, Munoz, Shoemaker, 1911.09129
(see also Kusenko, Pascoli, hep-ph/0405198; Asaka, Watanabe, 1202.0725)

Heavy Neutral Leptons

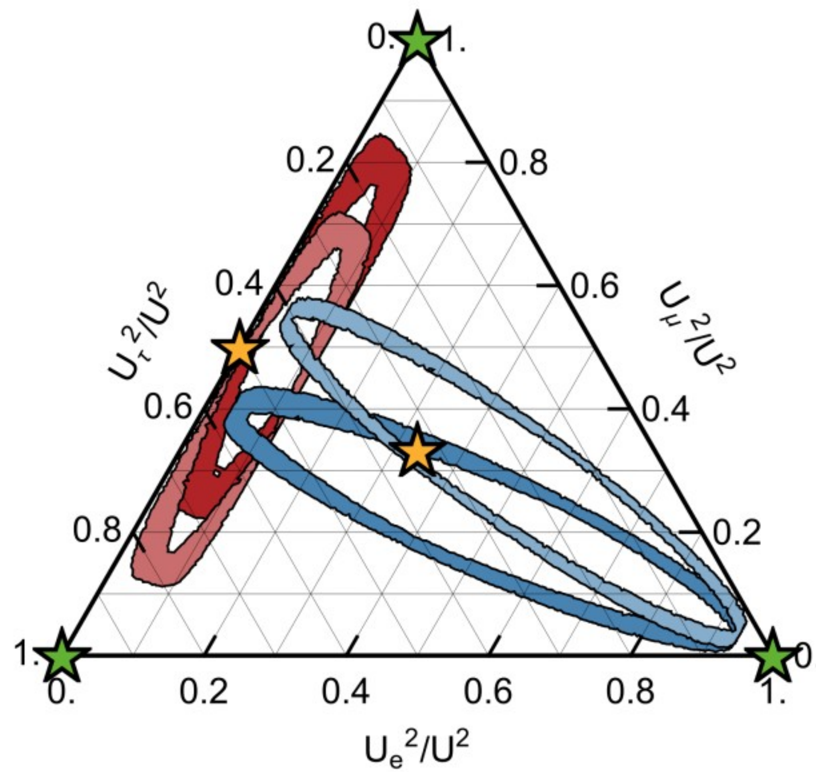
- Minimal scenario: 2 heavy neutral leptons



Caputo, Hernandez, Lopez-Pavon, Salvado, 1704.08721

Heavy Neutral Leptons

- Minimal scenario: 2 heavy neutral leptons



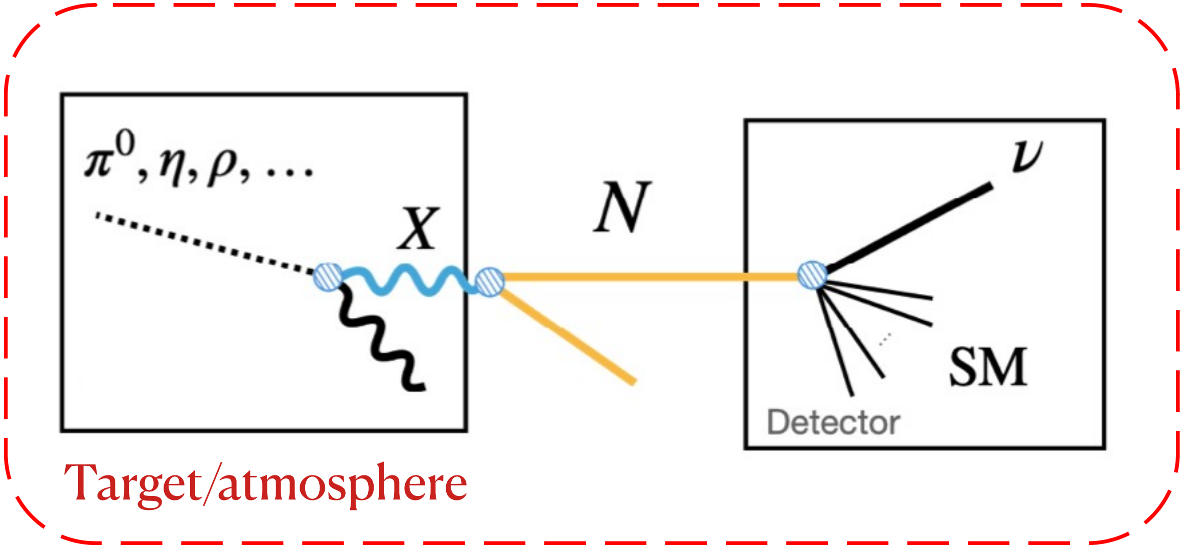
→ Including DUNE input on osc. params.

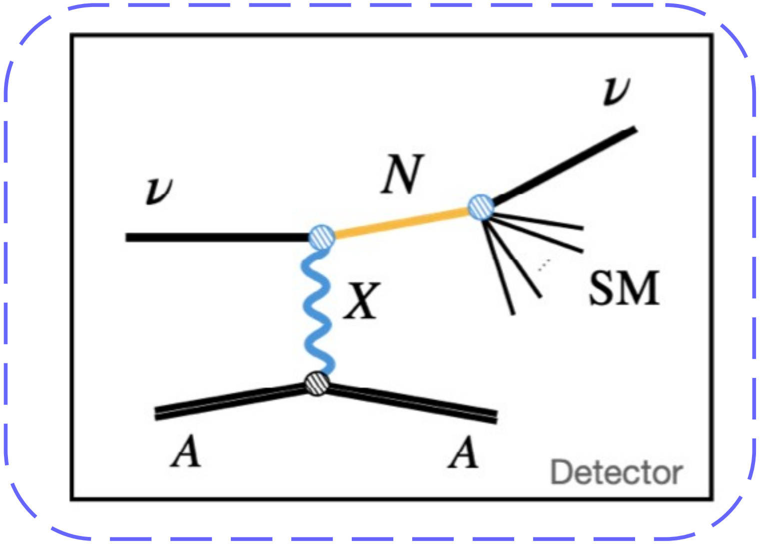
$$\delta = -\pi/2$$
$$s_{23}^2 = 0.42, 0.58$$

Drewes, Klaric, Lopez-Pavon, 2207.02742

Heavy Neutral Leptons

- Minimal scenario: production and decay through mixing
- Non-minimal extensions could lead to new signatures!





See e.g. Batell et al, 1604.06099; Magill et al, 1803.03262; Atkinson et al, 2105.09357; Schwetz et al, 2203.02309; ...

Figure from Snowmass'21 WP "Dark sector searches with neutrino beams", 2207.06898

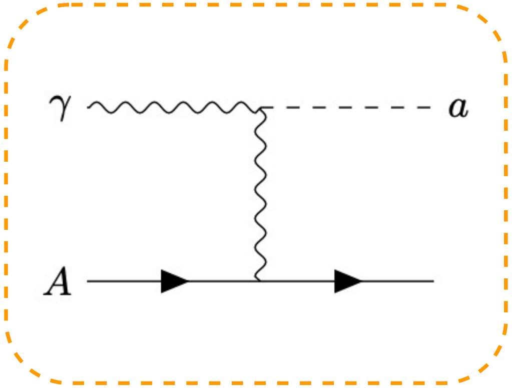
Axion-like particles

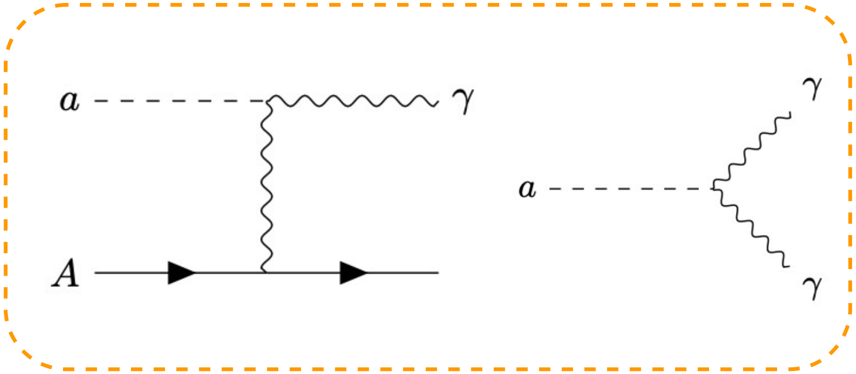
Light (pseudo)scalars

- Is the Higgs the only fundamental scalar?
- Light scalars arise as pseudo-Nambu Goldstone bosons in BSM models with global symmetry breaking
    - The axion solves the strong CP problem and provides a viable DM candidate
    - However, it is not the only possibility → ALPs

ALPs

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

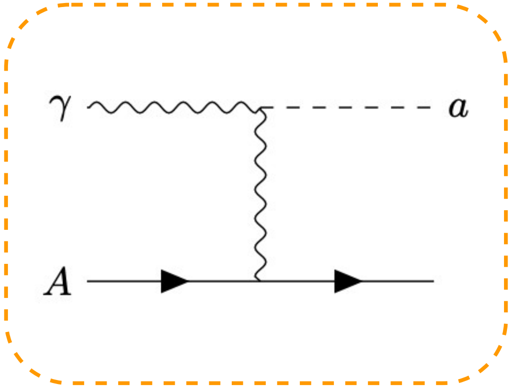


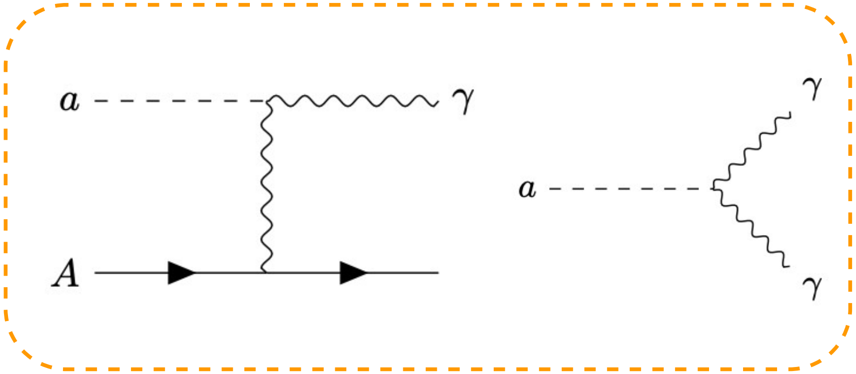


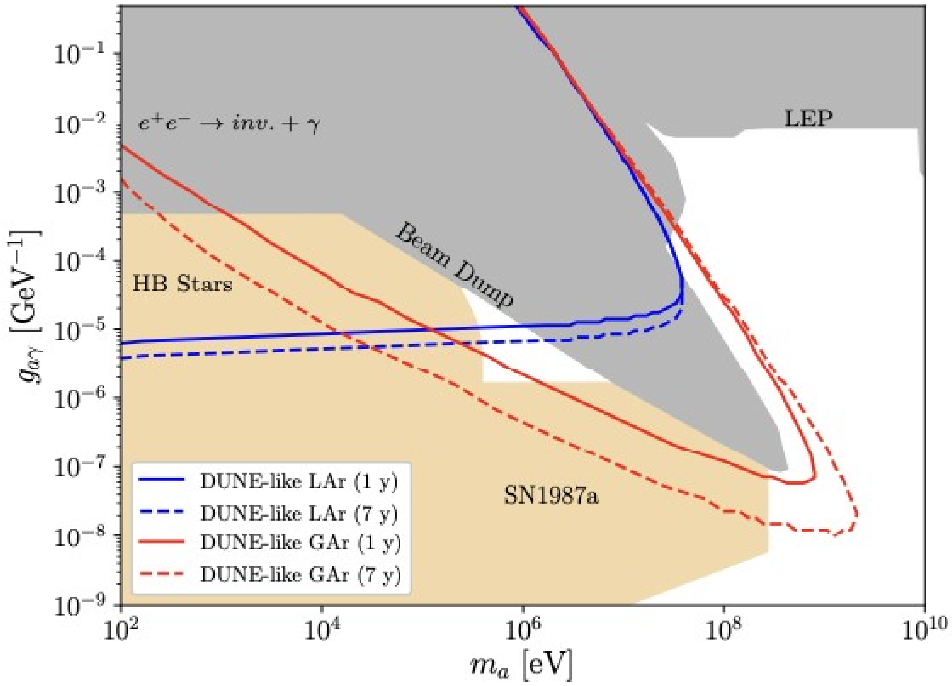
See e.g., Brdar, Dutta, Jang, Kim, et al, 2011.07054; Bhattarai, Brdar, Dutta, et al, 2206.06380; Dent, Dutta, Kim, et al, 1912.05733; Kelly, Kumar, Liu, 2011.05995

ALPs

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$



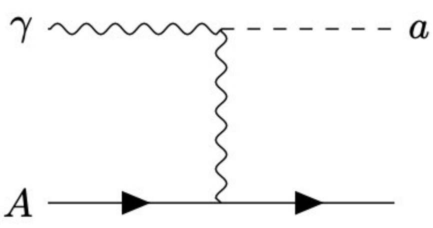


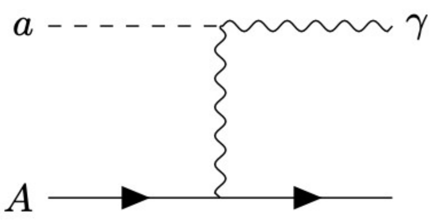


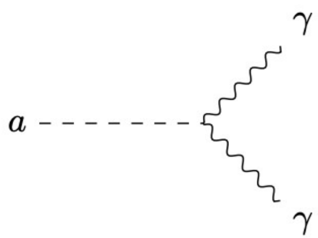
Brdar, Dutta, Jang, Kim, et al, 2011.07054

ALPs

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$







$$g_{ae} \partial_\mu a \bar{e} \gamma^\mu \gamma^5 e$$

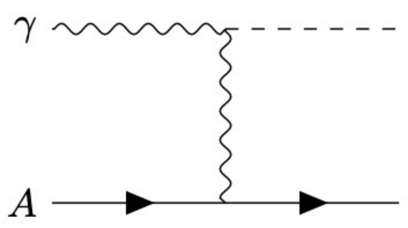
$$\gamma e^- \to e^- a$$
$$e^- \mathcal{N} \to e^- a \, \mathcal{N}$$
$$e^- e^+ \to \gamma a$$

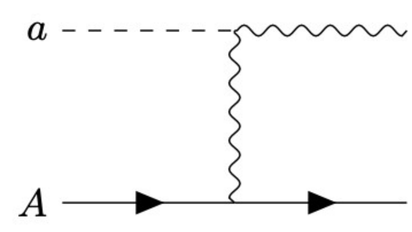
$$a \to e^+ e^-$$

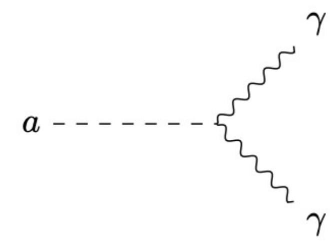
See e.g., Brdar, Dutta, Jang, Kim, et al, 2011.07054; Bhattarai, Brdar, Dutta, et al, 2206.06380; Dent, Dutta, Kim, et al, 1912.05733; Kelly, Kumar, Liu, 2011.05995

ALPs

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$







$$g_{ae} \partial_\mu a \bar{e} \gamma^\mu \gamma^5 e$$

$$\gamma e^- \to e^- a$$
$$e^- \mathcal{N} \to e^- a \, \mathcal{N}$$
$$e^- e^+ \to \gamma a$$

$$a \to e^+ e^-$$

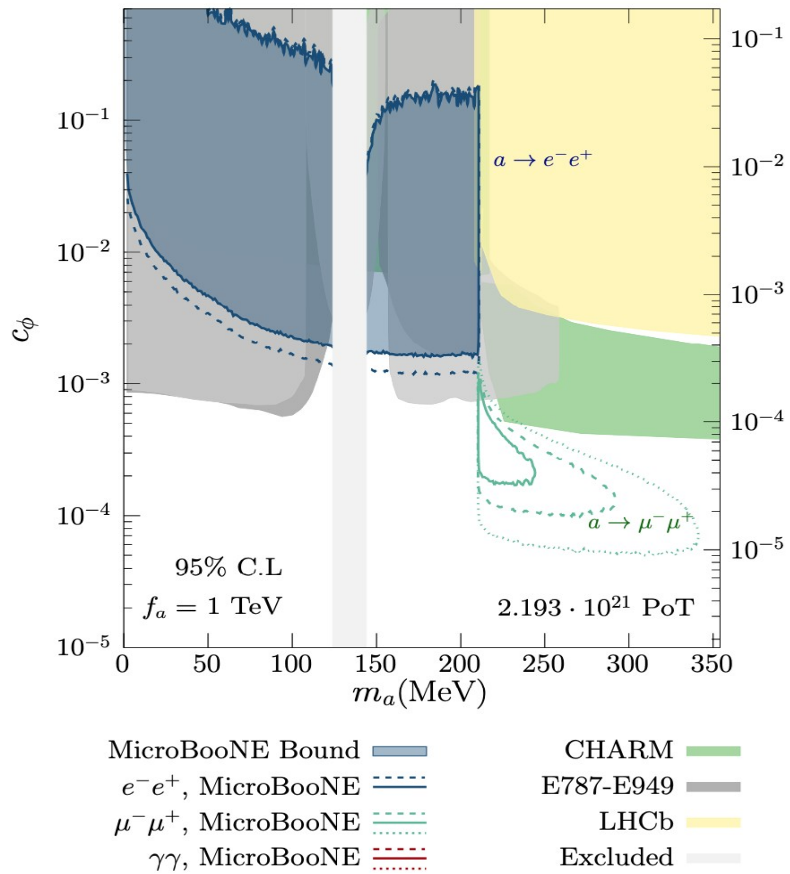
$$\frac{a}{8\pi f_a} \left(c_3 \alpha_3 G\tilde{G} + c_2 \alpha_2 W\tilde{W} + c_1 \alpha_1 B\tilde{B} \right)$$

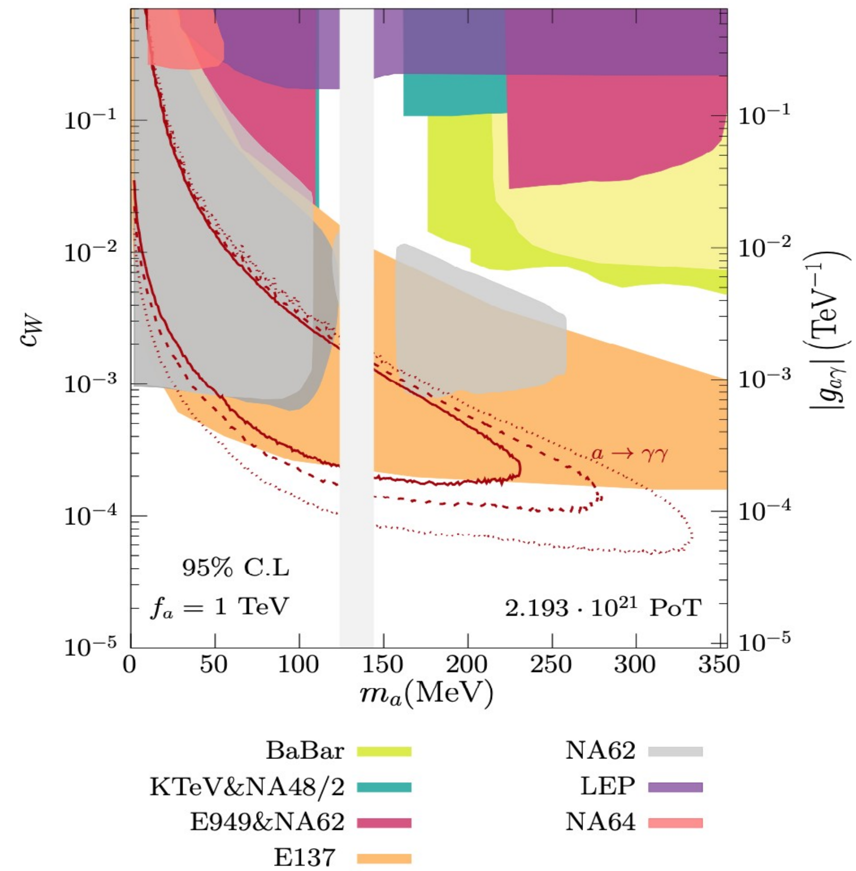
$$\theta_{\pi^0 a}, \theta_{\eta a}, \theta_{\eta' a}$$

$$a \to \gamma\gamma$$
$$a \to \pi\pi\pi, \pi\pi\gamma, \ldots$$

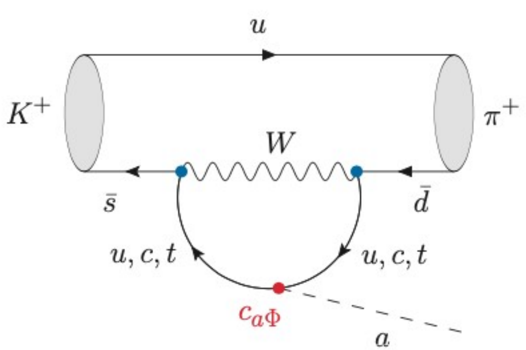
See e.g., Brdar, Dutta, Jang, Kim, et al, 2011.07054; Bhattarai, Brdar, Dutta, et al, 2206.06380; Dent, Dutta, Kim, et al, 1912.05733; Kelly, Kumar, Liu, 2011.05995

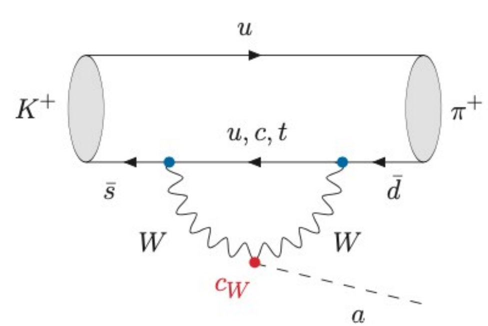
ALPs





Coloma, Hernandez, Urrea, 2202.03447





$$\mathcal{O}_\phi = i\frac{\partial^\mu a}{f_a}\phi^\dagger \overleftrightarrow{D}_\mu \phi\,,$$

$$\mathcal{O}_B = -\frac{a}{f_a} B_{\mu\nu}\widetilde{B}_{\mu\nu}\,,$$

$$\mathcal{O}_W = -\frac{a}{f_a} W^a_{\mu\nu}\widetilde{W}^a_{\mu\nu}\,.$$

Summary

- We have good reasons to believe that BSM physics is out there
- A new Era of precision neutrino experiments is well positioned to search for its signals, not only in oscillations
- CEvNS data is already here!
- I have left out of this talk many exciting topics worth pursuing…

Lorentz Invariance violation, Large Extra Dimensions, light dark matter, neutrino-DM interactions, distorted neutrino oscillations, baryonic neutrinos, neutrino magnetic moments, neutrino charge radii, pseudo-Dirac neutrino oscillations, millicharged particles, dark photons,…

Thanks!

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