Going Beyond the SM

Pilar Coloma – Instituto de Física Teórica UAM-CSIC

Snowmass'22 Community Summer Study, Seattle (July 19th, 2022)

Instituto de Física Teórica UAM-CSIC

HIDDeν

MINISTERIO DE CIENCIA E INNOVACIÓN

European Union
European Social Fund

AGENCIA ESTATAL DE INVESTIGACIÓN

EXCELENCIA SEVERO OCHOA

Why BSM?

Experimental evidence:

Dark matter

Neutrino masses

Matter-antimatter asymmetry

Gravitational interaction

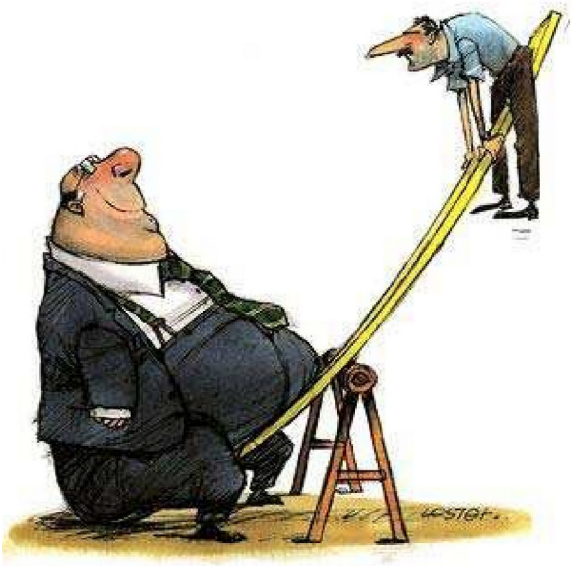
Theoretical indications:

Strong CP problem

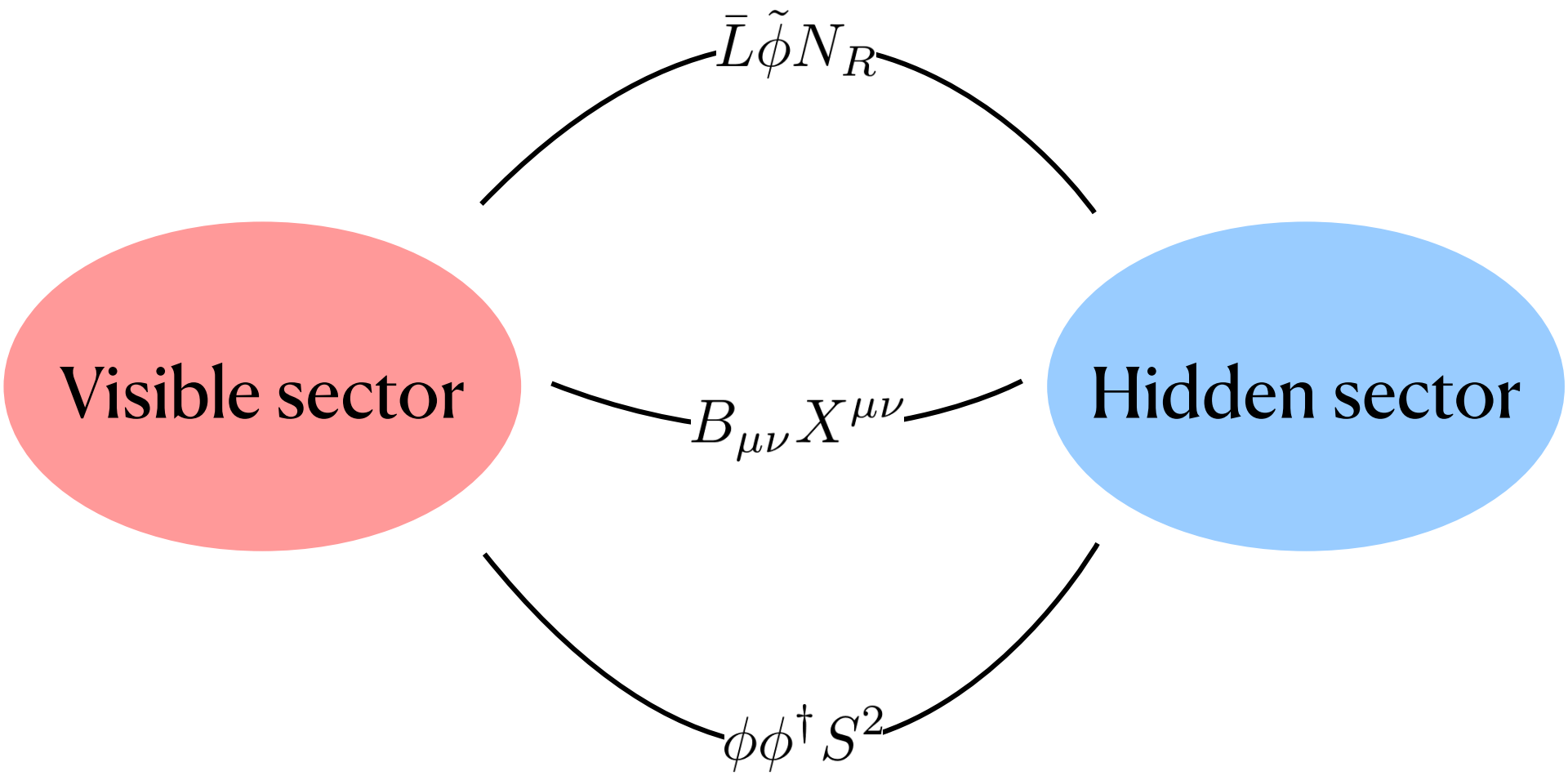
Hierarchy problem

Flavor puzzle

Cosmological constant



ok, so...where is it??



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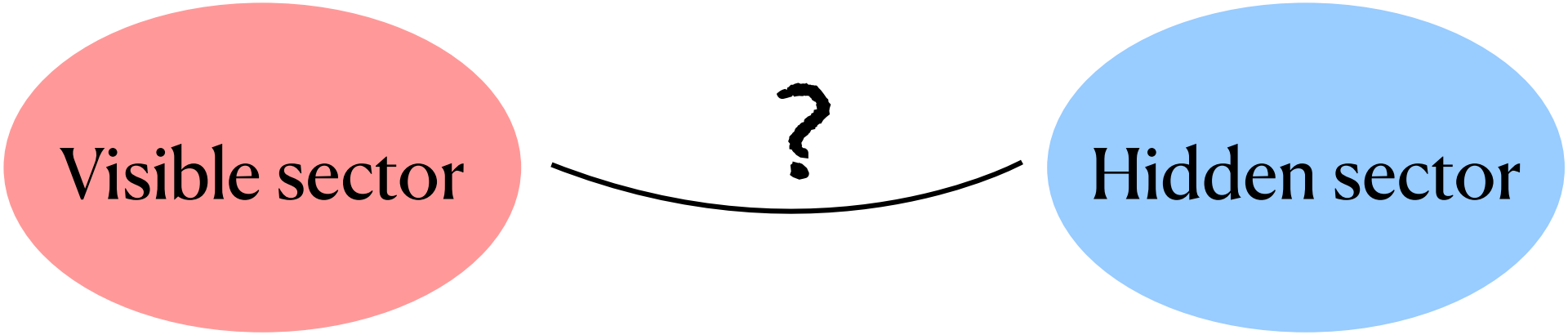


Why neutrino experiments?

- Powerful beam
- Near detectors (ND) available
- Large underground far detector (FD)
    - new physics in neutrino oscillations
    - new particles produced in the beam
    - new particles produced in the atmosphere

Why DUNE?

- The DUNE design has specific advantages:
  - High luminosity
  - Long baseline (matter effects)
  - High neutrino energy
    - D-mesons and τ at the target
    - ν_τ detection?
  - FD/ND: LAr TPC offers great PID, energy and angular resolution
  - Other near detectors or configurations:
    - DUNE Prism! Gas TPC!


DUNE

This talk

- What can we search for at DUNE?
  - New fermions
  - New vector bosons
  - New (pseudo)scalars

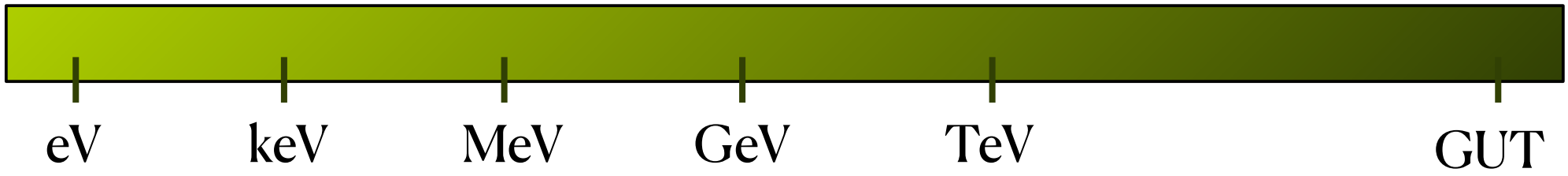
→ Apologies if your favorite model is not included

→ For DUNE prospects, see talks by A. Sousa and J. Yu

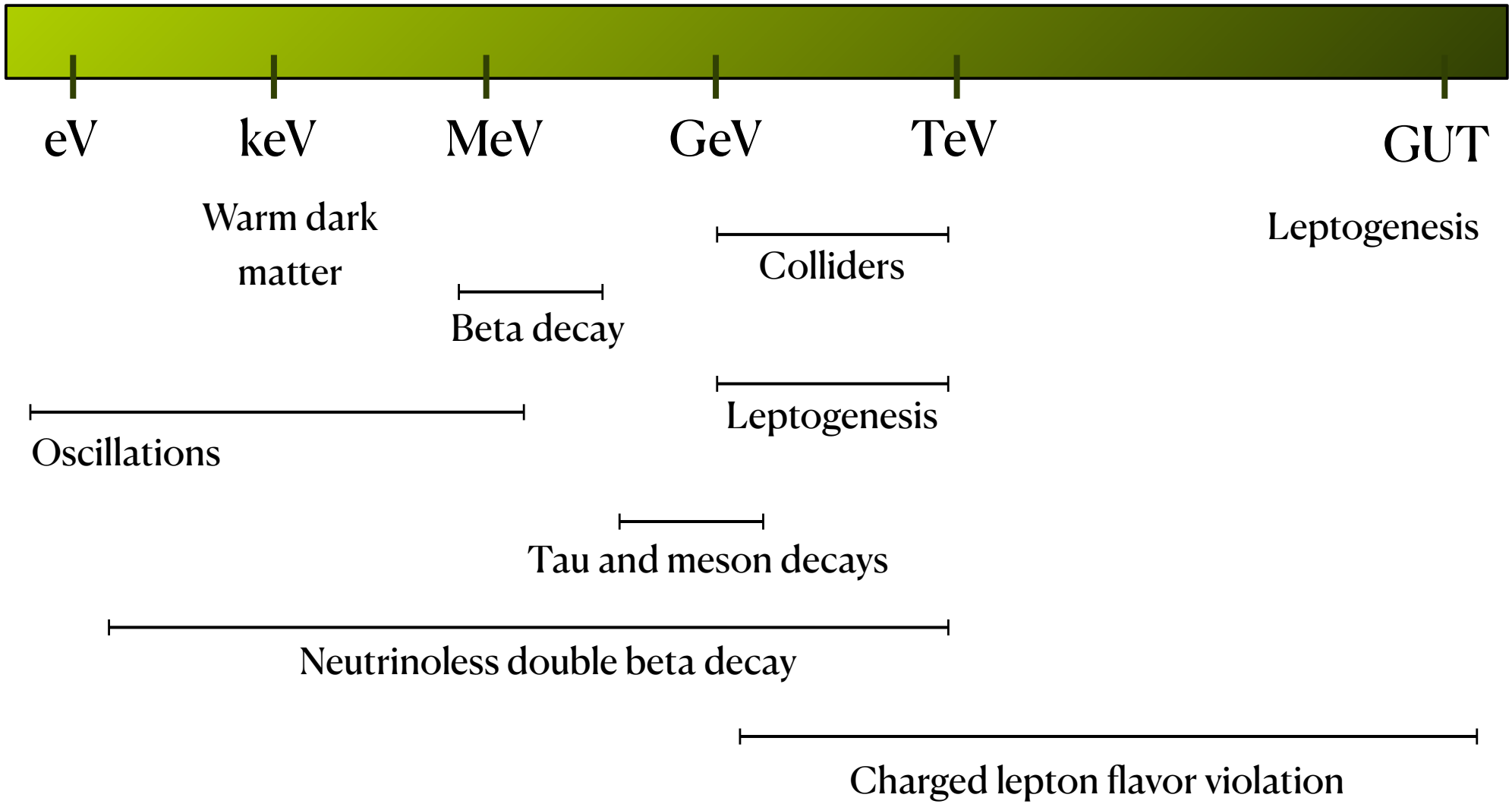
(I) New fermions

→ Heavy neutral leptons, sterile neutrinos, right-handed neutrinos, neutrino portal, ...

Sterile neutrino searches



Sterile neutrino searches



eV-scale sterile neutrinos

A sterile may leave multiple imprints through oscillations:

- Anomalous appearance
- ν_e disappearance
- ν_μ disappearance
- NC measurements

All of them available at DUNE!

$$\sin^2 2\theta_{ee} = 4(1-|U_{e4}|^2)|U_{e4}|^2;$$
$$\sin^2 2\theta_{\mu\mu} = 4(1-|U_{\mu4}|^2)|U_{\mu4}|^2;$$
$$\sin^2 2\theta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2.$$

Both ND and FD could be used for this:

- sensitive to different ranges in mass-squared splitting
- solar neutrinos also provide useful input → See Goldhagen et al, 2109.14898

Heavier steriles and Non-Unitarity

- Heavier steriles can still be produced, but oscillations will be averaged out; at ND, zero-distance effect.
- General (model-independent) parametrization:

$$N = (I - T)U$$

Unitary matrix

$$T = \begin{pmatrix} \alpha_{ee} & 0 & 0 \\ \alpha_{\mu e} & \alpha_{\mu\mu} & 0 \\ \alpha_{\tau e} & \alpha_{\tau\mu} & \alpha_{\tau\tau} \end{pmatrix}$$

Z.-z. Xing 2008, 2012

Escrihuela, Forero, Miranda, Tortola 2015

Heavier steriles and Non-Unitarity

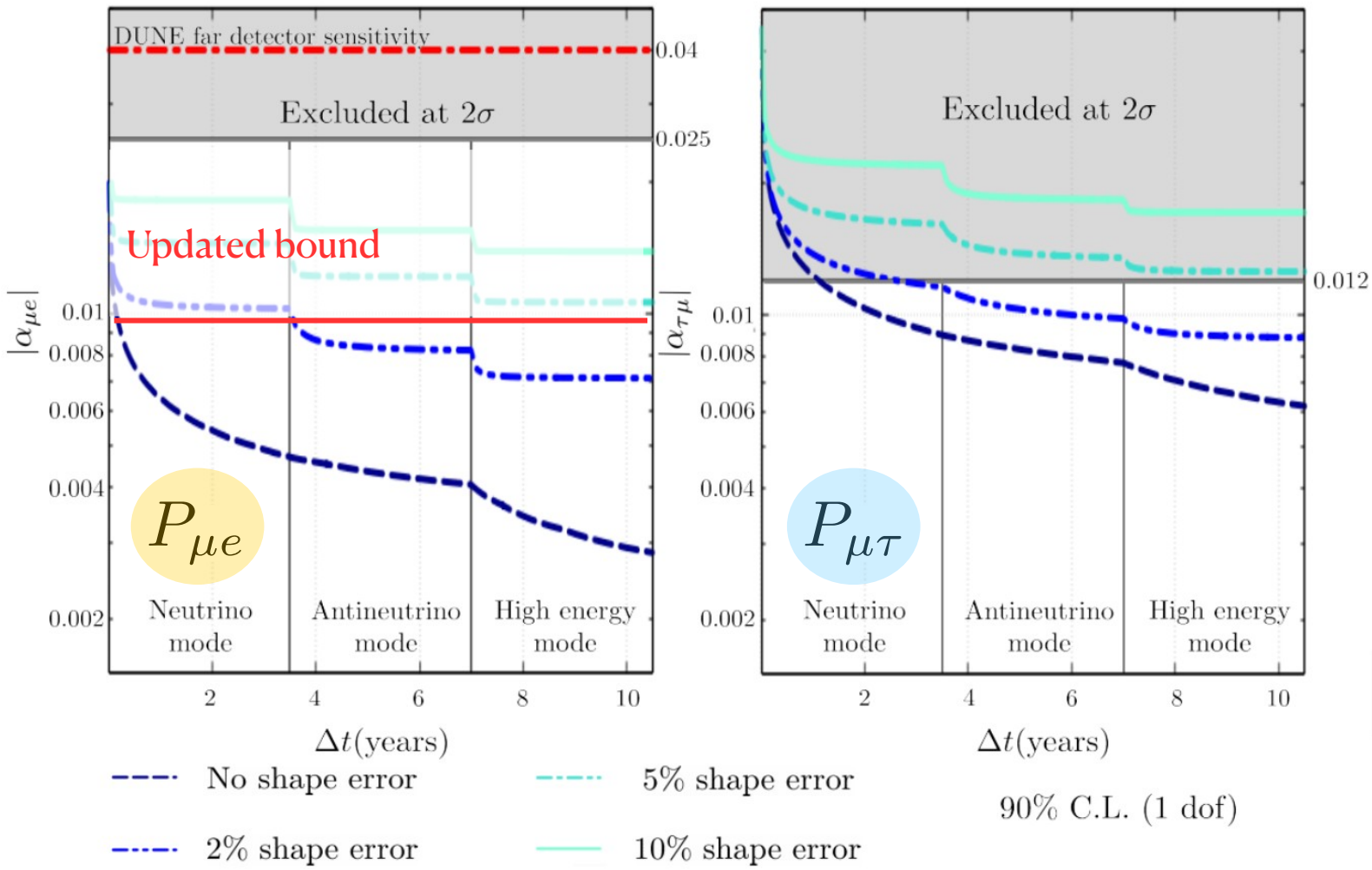
	"flavor+electroweak" $m >$ EW (2σ limit)	"Averaged-out oscillations" $\Delta m^2 \gtrsim 0.1$ eV^2 (90% CL)
α_{ee}	$1.3 \cdot 10^{-3}$ [36]	$8.4 \cdot 10^{-3}$ [55]
$\alpha_{\mu\mu}$	$2.2 \cdot 10^{-4}$ [36]	$5.0 \cdot 10^{-3}$ [15]
$\alpha_{\tau\tau}$	$2.8 \cdot 10^{-3}$ [36]	$6.5 \cdot 10^{-2}$ [56]
$\lvert\alpha_{\mu e}\rvert$	$6.8 \cdot 10^{-4}$ ($2.4 \cdot 10^{-5}$) [36]	$9.2 \cdot 10^{-3}$
$\lvert\alpha_{\tau e}\rvert$	$2.7 \cdot 10^{-3}$ [36]	$1.4 \cdot 10^{-2}$
$\lvert\alpha_{\tau\mu}\rvert$	$1.2 \cdot 10^{-3}$ [36]	$1.1 \cdot 10^{-2}$

$$\alpha_{\beta\gamma} \leq 2\sqrt{\alpha_{\beta\beta}\alpha_{\gamma\gamma}}$$

Snowmass'21 White Paper "BSM effects on Neutrino Flavor", 2203.10811
(see also Blennow et al, 1609.08637)

→ Interesting possibility: use the DUNE ND to test for anomalous tau neutrino appearance?

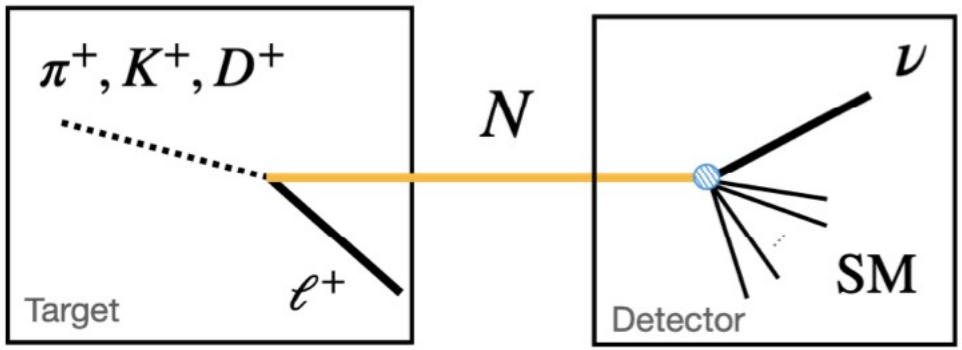
Heavier steriles and Non-Unitarity



Coloma, Lopez-Pavon, Rosauro-Alcaraz, Urrea, 2105.11466
(see also Miranda, Pasquini, Tortola, Valle, 1802.02133)

Heavy Neutral Leptons

- Minimal scenario: production and decay through mixing



@ DUNE ND

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

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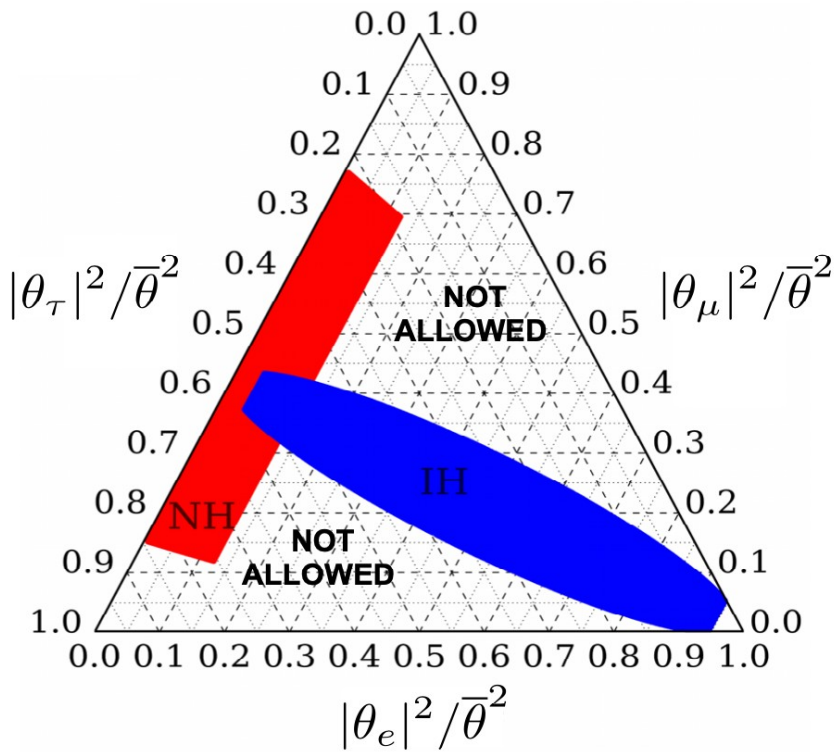

Caputo, Hernandez, Lopez-Pavon, Salvado, 1704.08721

Heavy Neutral Leptons

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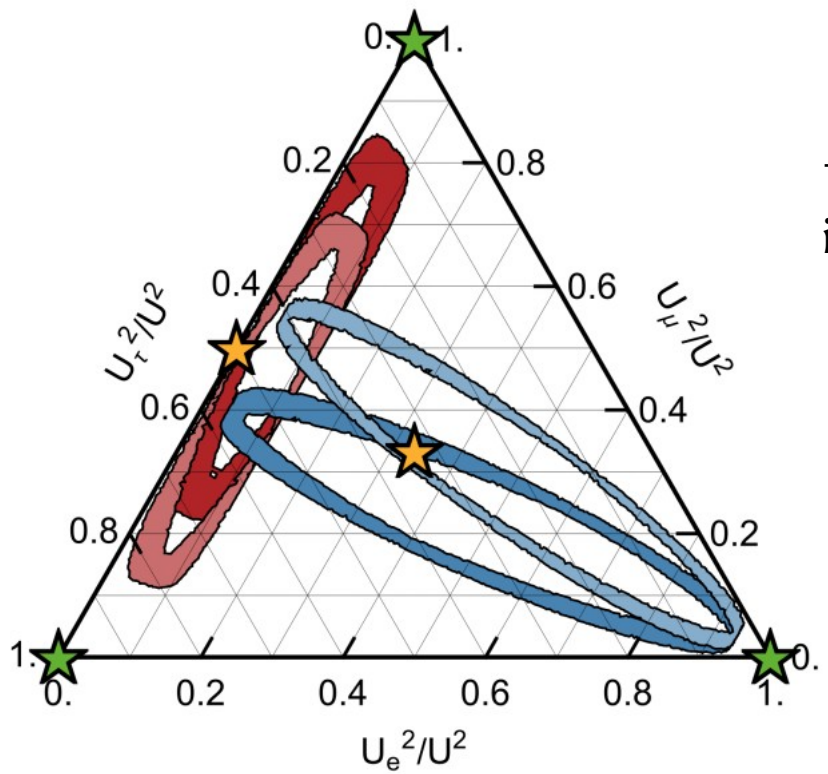


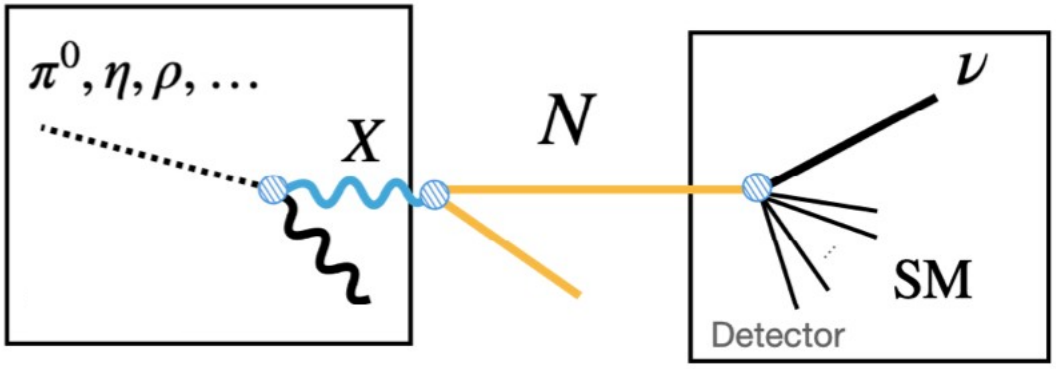
→ Including DUNE input on osc. params.

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

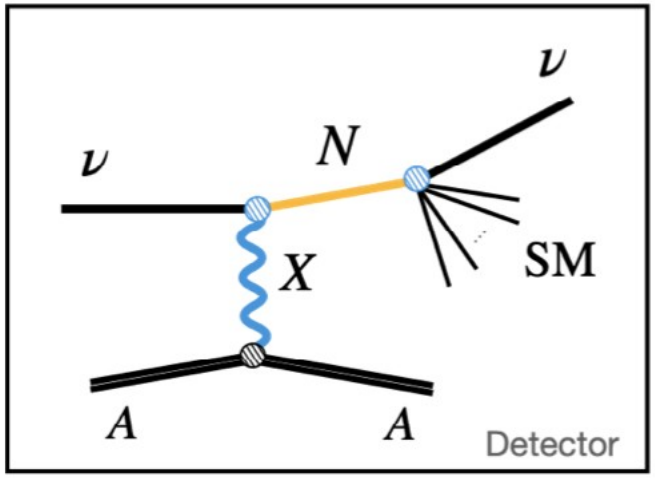
Drewes, Klaric, Lopez-Pavon, 2207.02742

Heavy Neutral Leptons

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



Target/atmosphere



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

(II) New vector bosons

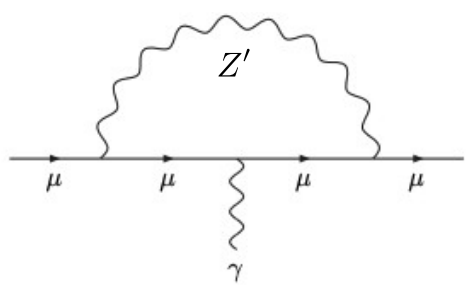
→ vector portal to DM, dark photons, flavored Z', ...

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 within SM particle content: Foot '91; He, Joshi, Lew, Volkas, '91; Foot, He, Lew, Volkas, hep-ph/9401250

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



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

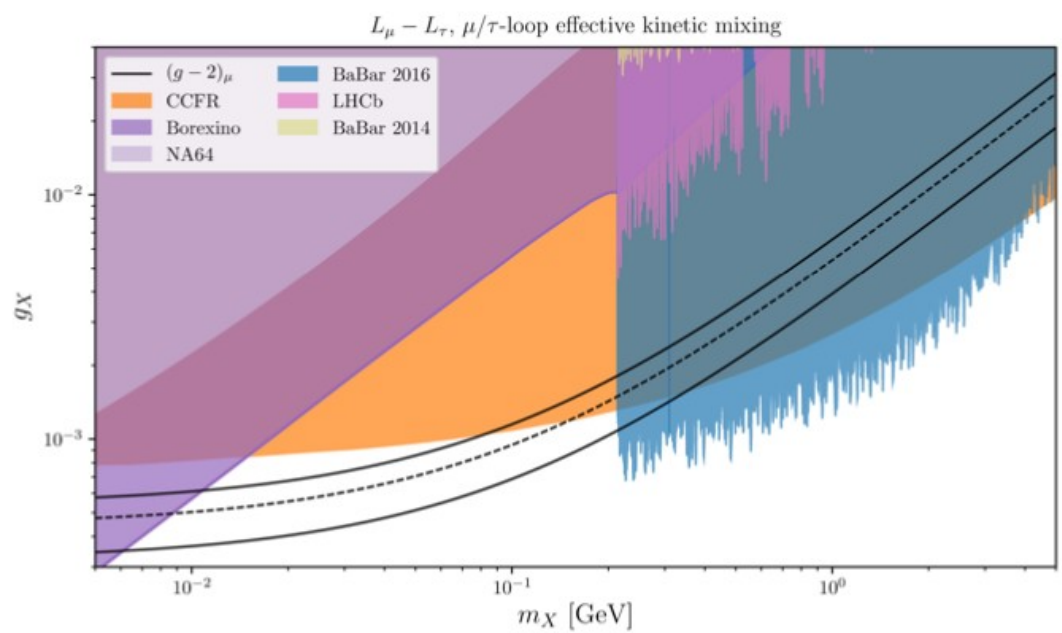
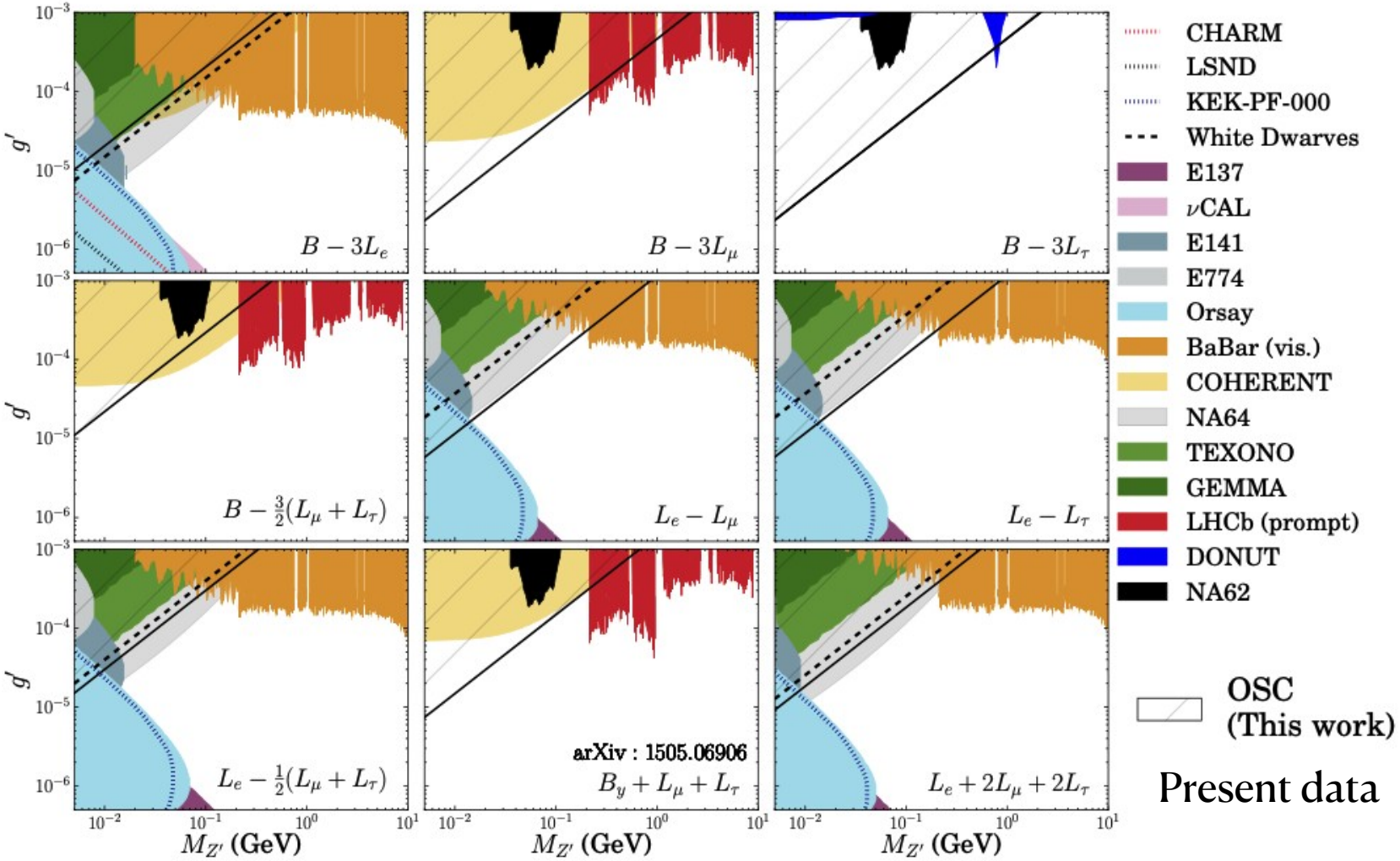


Fig from Greljo, Stangl, Thomsen, Zupan, 2203.13731

Light flavored Z': present bounds

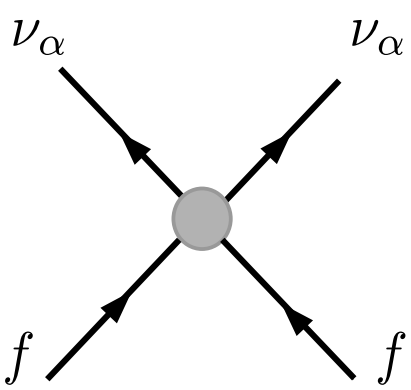


Coloma, Gonzalez-Garcia and Maltoni, 2009.14220

Light flavored Z'

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

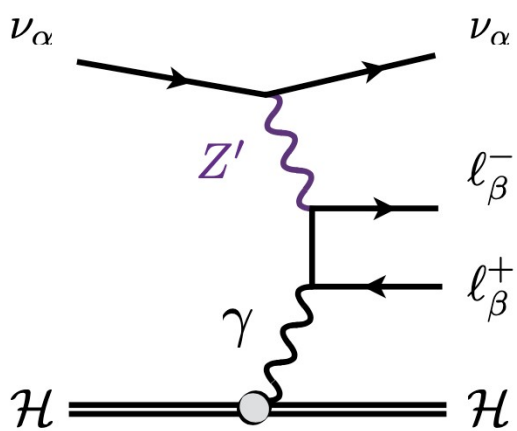
NSI, long-range forces



$q^2 \ll M^2_{Z'}$

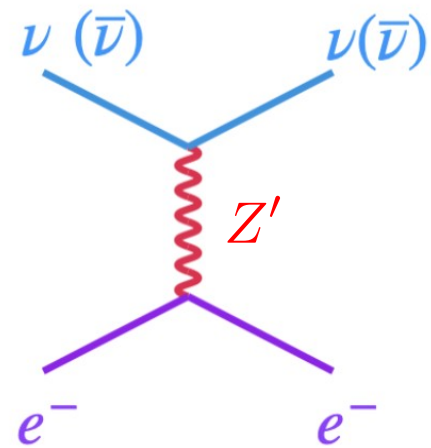
NSI: many references!
LRF: Chatterjee et al, 1509.03517

Tridents



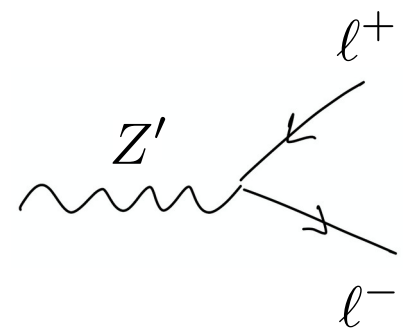
Altmannshofer et al, 1902.06765;
Ballett et al, 1902.08579

ν-e scattering



Ballett et al, 1902.08579;
Chakraborty et al, 2111.08767

Decays



Berryman et al, 1912.07622; Capozzi et al, 2108.03262

Vector portal

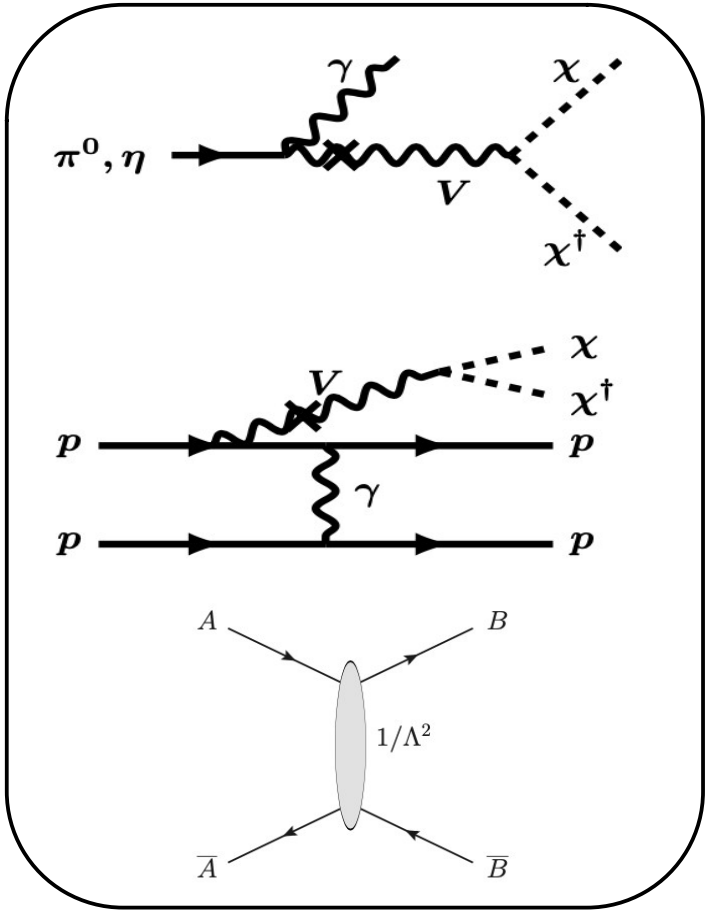
$$\mathcal{L} \supset -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}M_V^2\, V_\mu V^\mu + \frac{\varepsilon}{2}V_{\mu\nu}F^{\mu\nu} \; + \; \begin{cases} \text{Scalar/vector DM} \\ \text{pseudo-Dirac fermions (iDM)} \\ \text{Subset of states (BDM)} \end{cases}$$

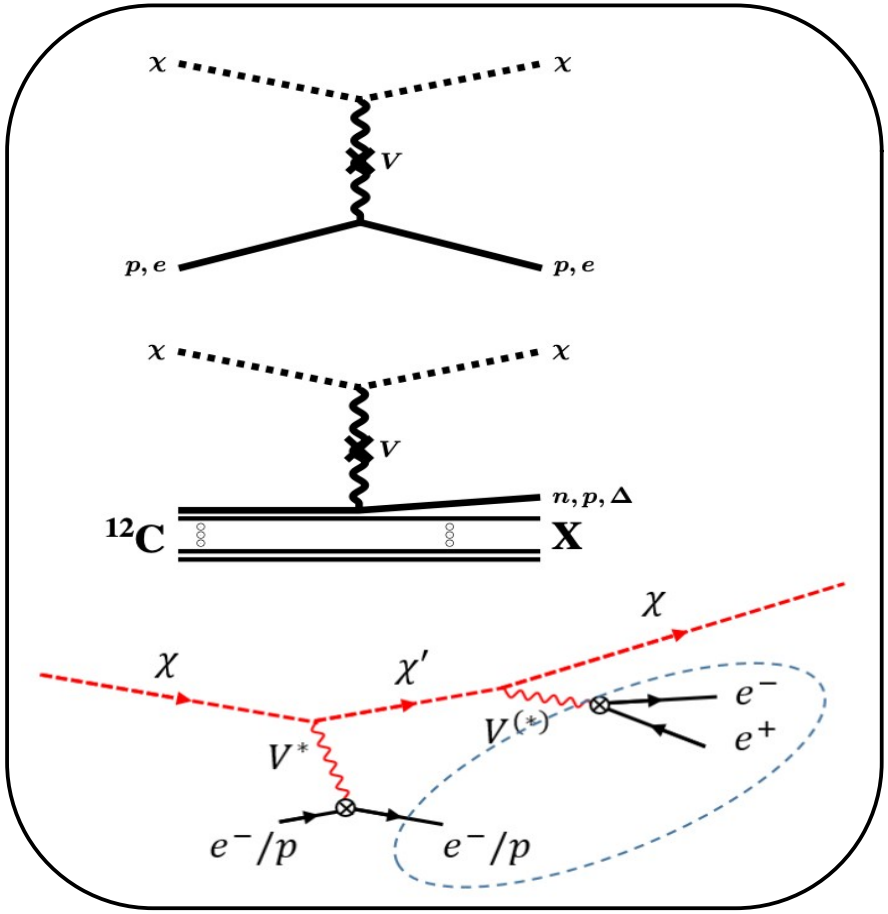
<u>Vector coupling to dark sector:</u>

Vector portal

$$\mathcal{L} \supset -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}M_V^2\, V_\mu V^\mu + \frac{\varepsilon}{2}V_{\mu\nu}F^{\mu\nu} \; + \; \begin{cases} \text{Scalar/vector DM} \\ \text{pseudo-Dirac fermions (iDM)} \\ \text{Subset of states (BDM)} \end{cases}$$

<u>Vector coupling to dark sector:</u>





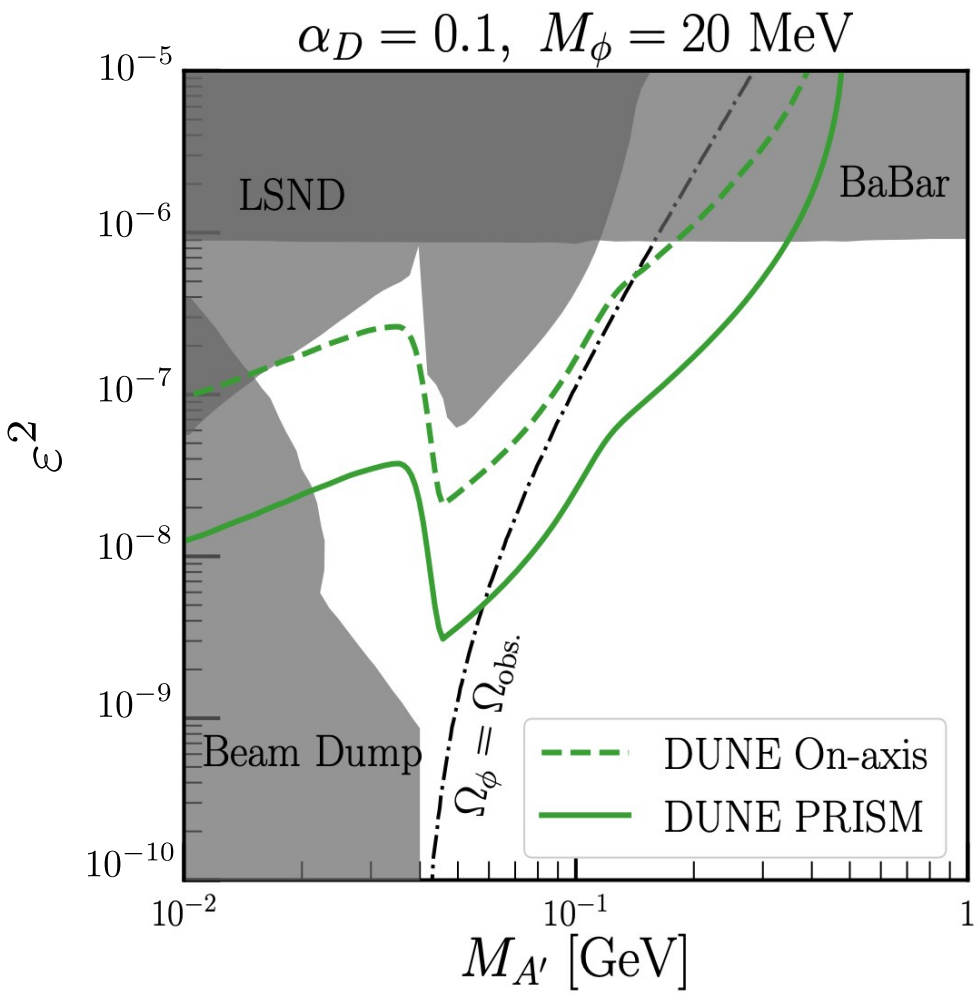
Vector portal

- MiniBooNE: clear example of prior success

Batell, Pospelov, Ritz, 0906.5614; deNiverville, Pospelov, Ritz,1107.4580; deNiverville, McKeen, Ritz, 1205.3499, ...

- Careful with backgrounds:
  - go off-axis Coloma, Dobrescu, Frugiuele, Harnik, 1512.03852
  - beam-dump Bhattarai, Brdar, Dutta, et al, 2206.06380
  - use electron scattering de Romeri, Kelly, Machado, 1903.10505

Vector portal



Scalar DM;

e^- scattering on LArTPC

de Romeri, Kelly, Machado, 1903.10505

(see also e.g. Coloma et al, 1512.03852; Breitbach et al, 2102.03383, Berryman et al, 1912.07622)

(III) New (pseudo)scalars

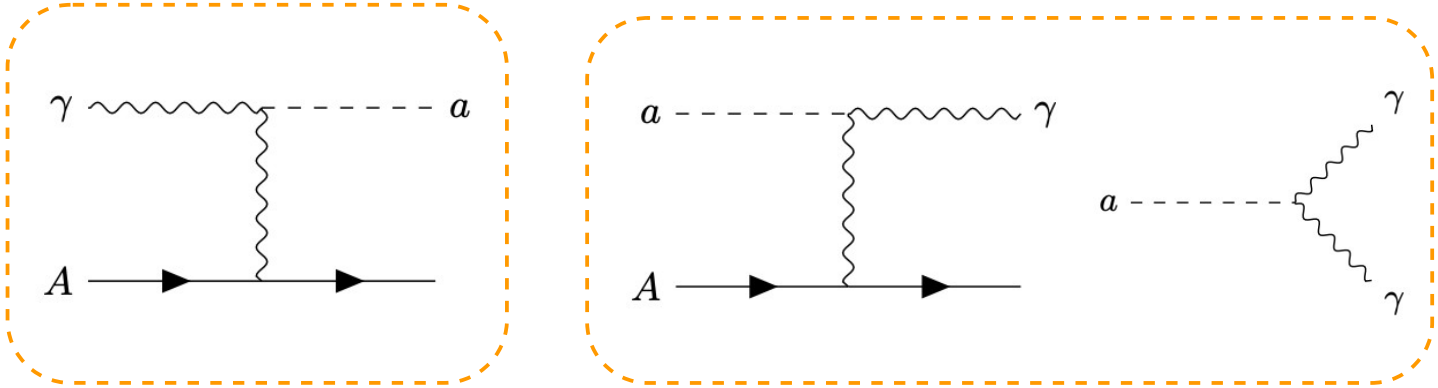
$\rightarrow$ axions, axion-like particles, dark pions, dark Higgs, ...

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

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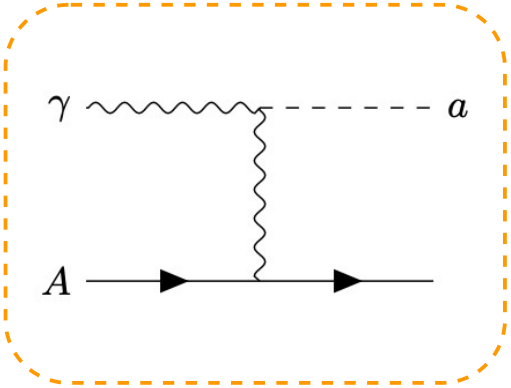
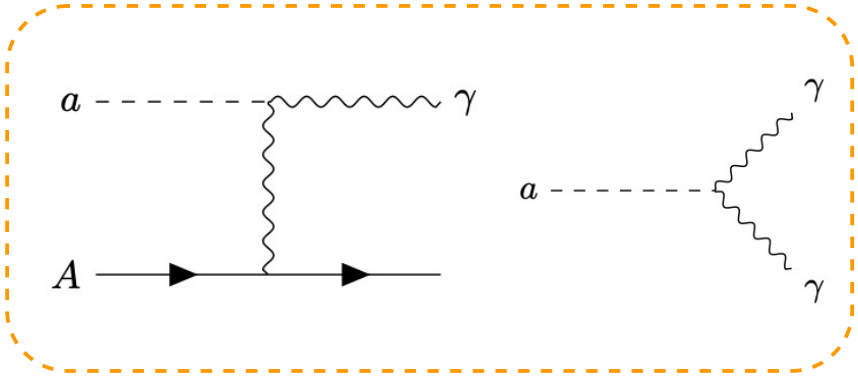




$$g_{ae} \partial_\mu a \bar{e} \gamma^\mu \gamma^5 e$$

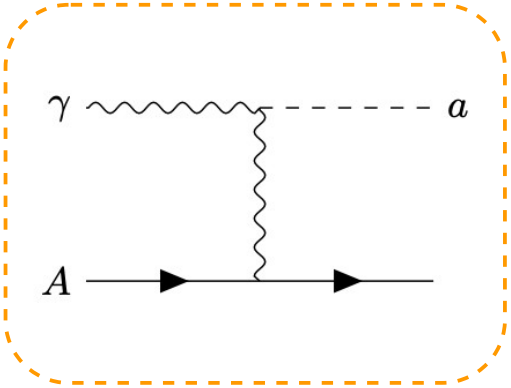
$$\gamma e^- \to e^- a$$
$$e^- \mathcal{N} \to e^- a \, \mathcal{N}$$
$$e^- e^+ \to \gamma a$$

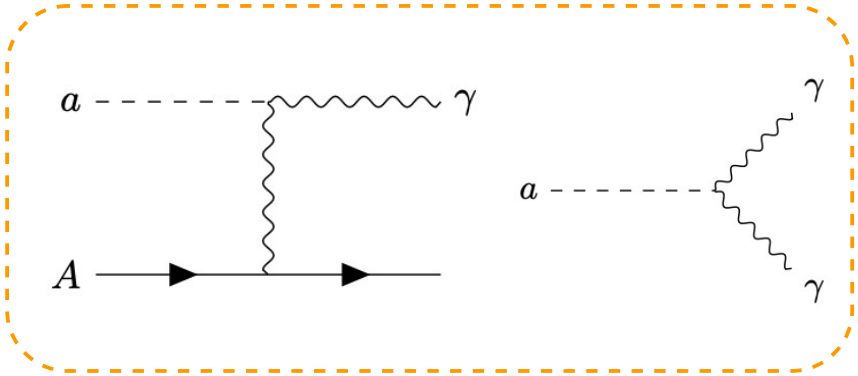
$$a \to e^+ e^-$$

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

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





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

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

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

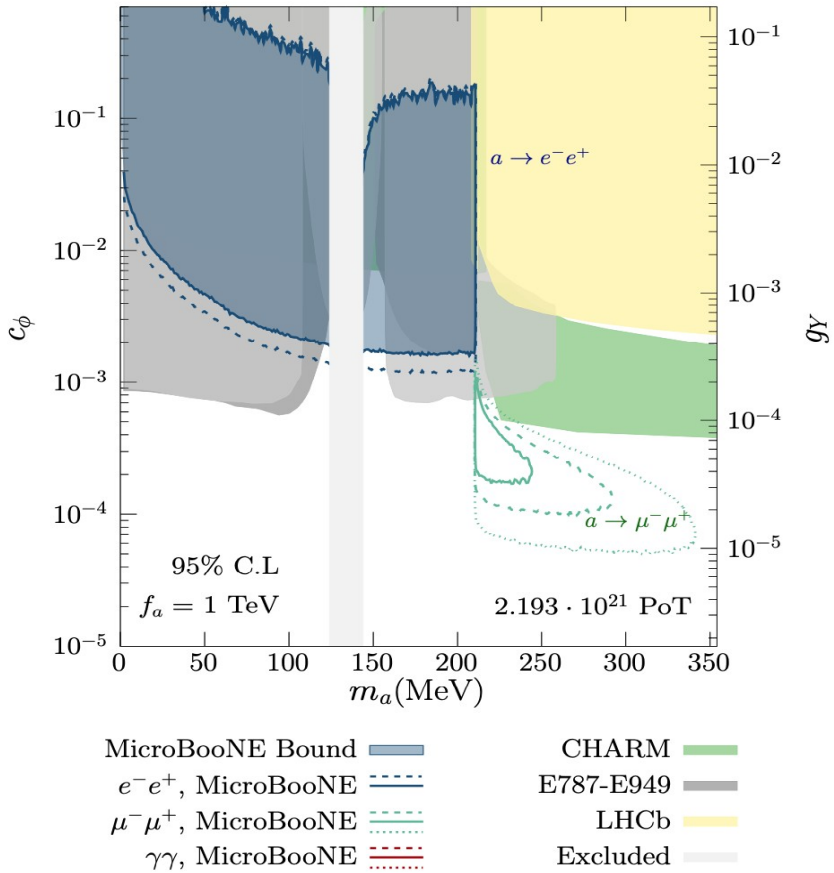
$$\frac{a}{8\pi f_a} \left(c_3 \alpha_3 G\tilde{G} + c_2 \alpha_2 W\tilde{W} + c_1 \alpha_1 B\tilde{B} \right)$$

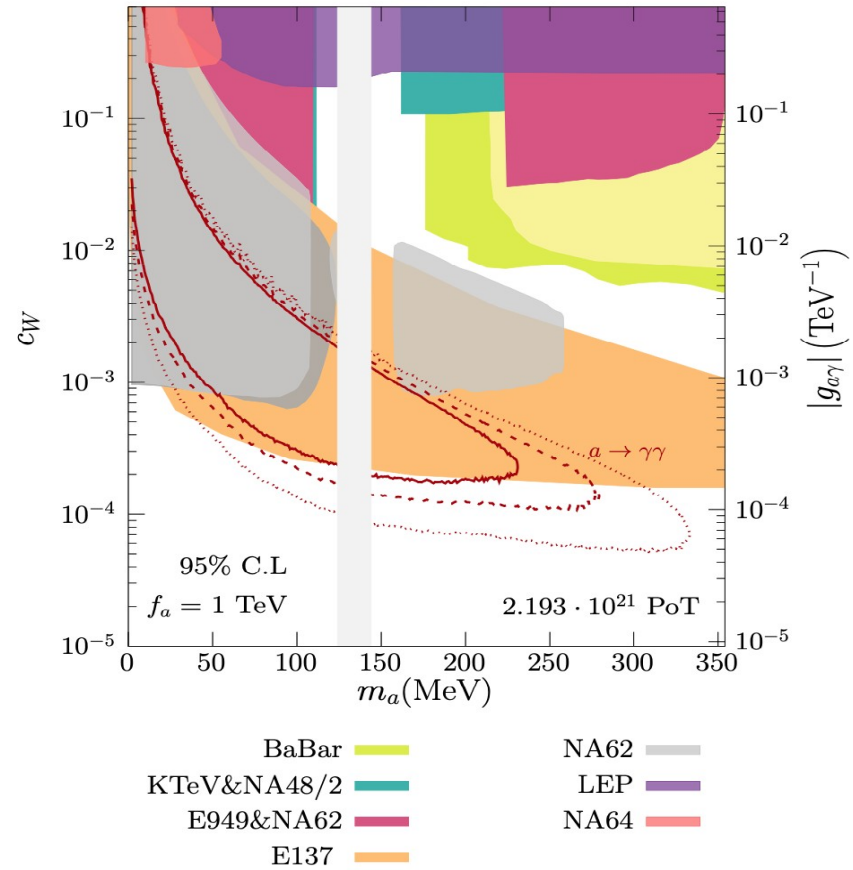
$$\theta_{\pi^0 a}, \theta_{\eta a}, \theta_{\eta' a}$$

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

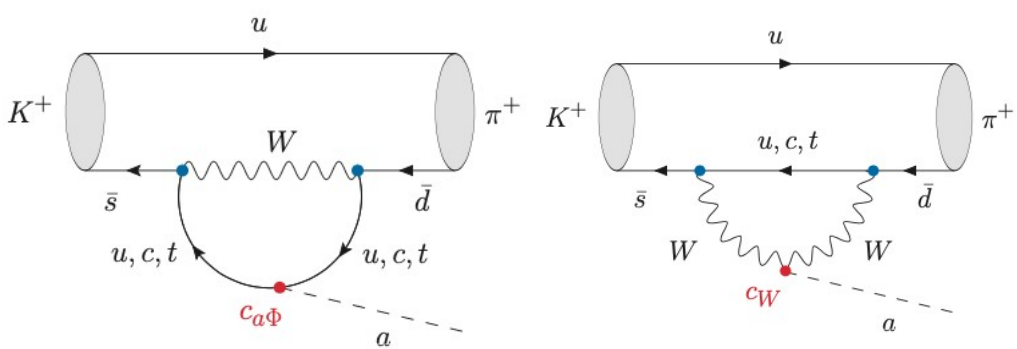
See e.g., Brdar, Dutta, Jang, Kim, et al, 2011.07054; Bhattarai, Brdar, Dutta, et al, 2206.06380; Dent, Dutta, Kim, et al, 1912.05733; Kelly, Kumar, Liu, 2011.05995

ALPs





Coloma, Hernandez, Urrea, 2202.03447



→ See Salvador Urrea's talk on Saturday!

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 deviations from the standard picture
- DUNE offers an appealing design, with key features that define it as a BSM facility

Thanks!

Work supported by Grants RYC2018-024240-I
PID2019-108892RB-I00, CEX2020-001007-S

Backup

Heavier steriles and Non-Unitarity

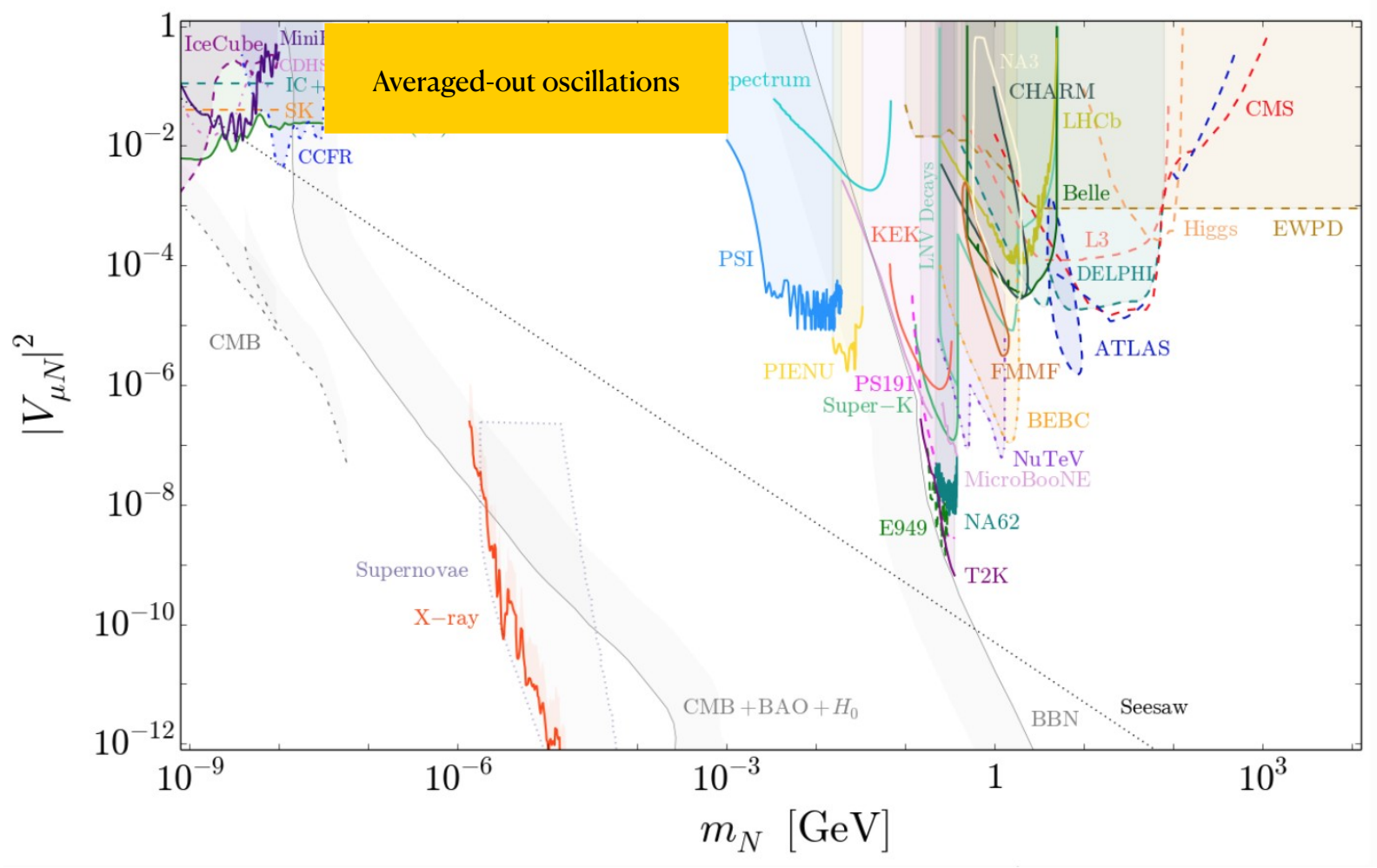
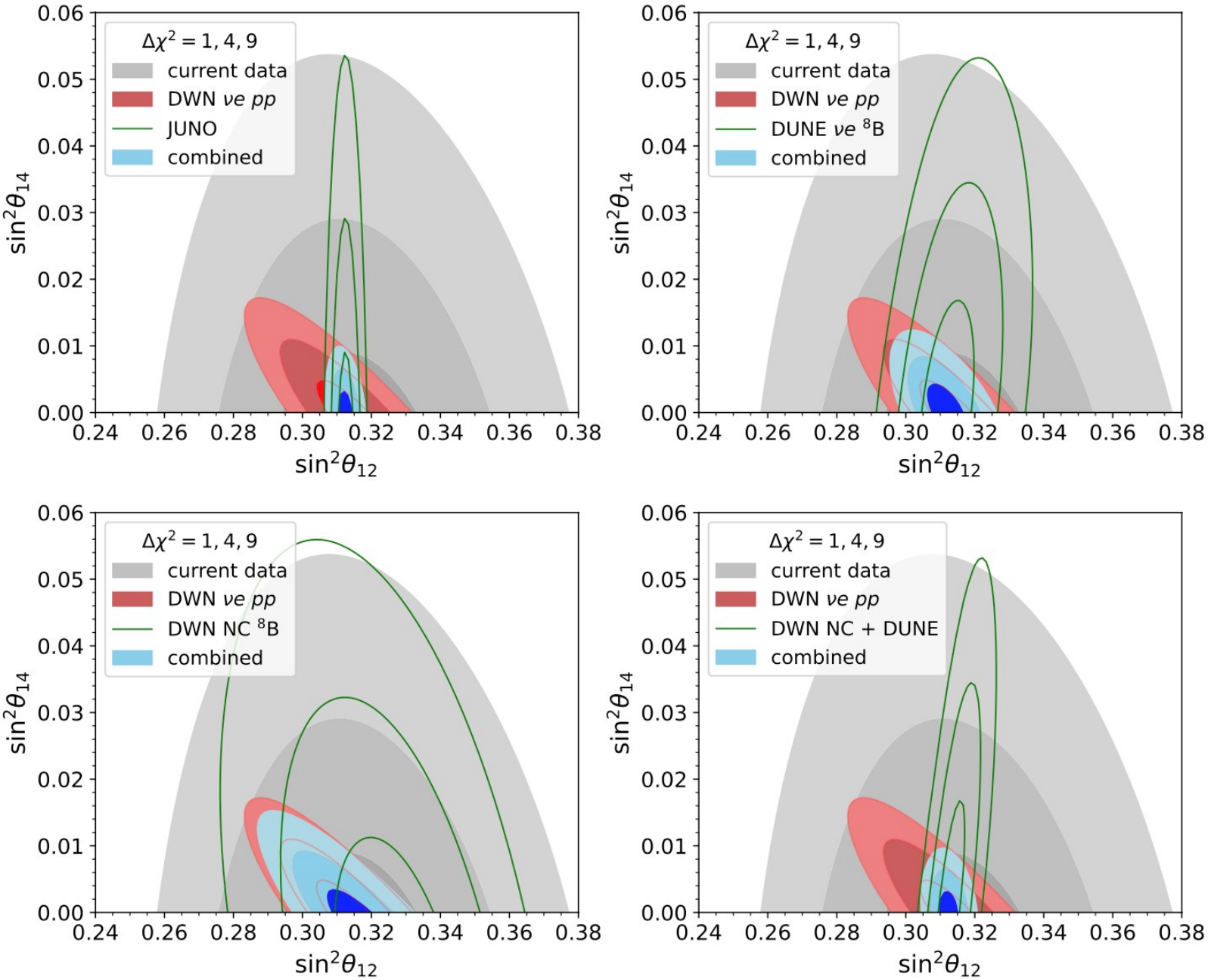


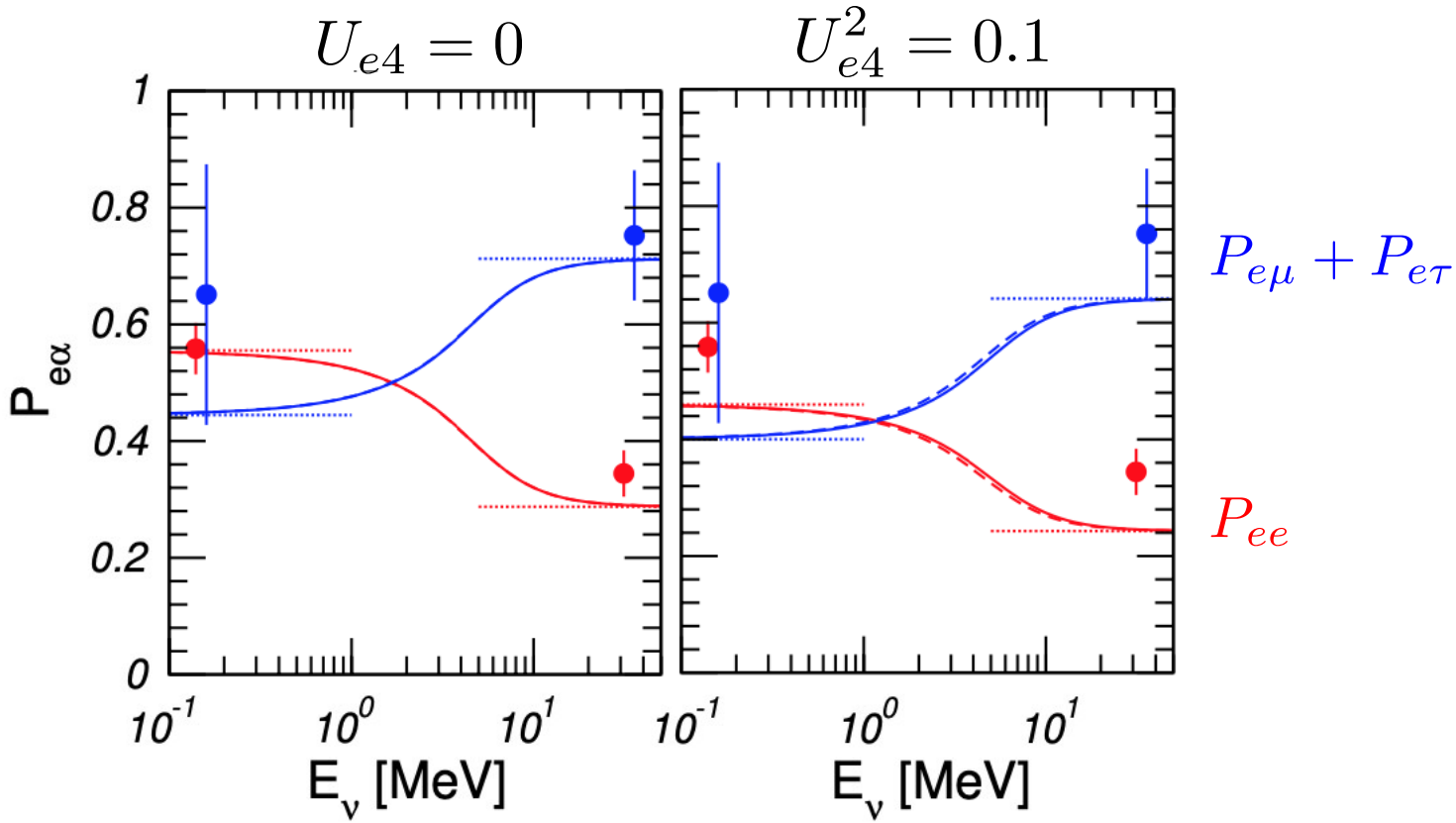
Fig from Bolton, Deppisch, Dev, 1912.03058

www.sterile-neutrino.org



Goldhagen, Maltoni, Reichard, Schwetz, 2109.14898

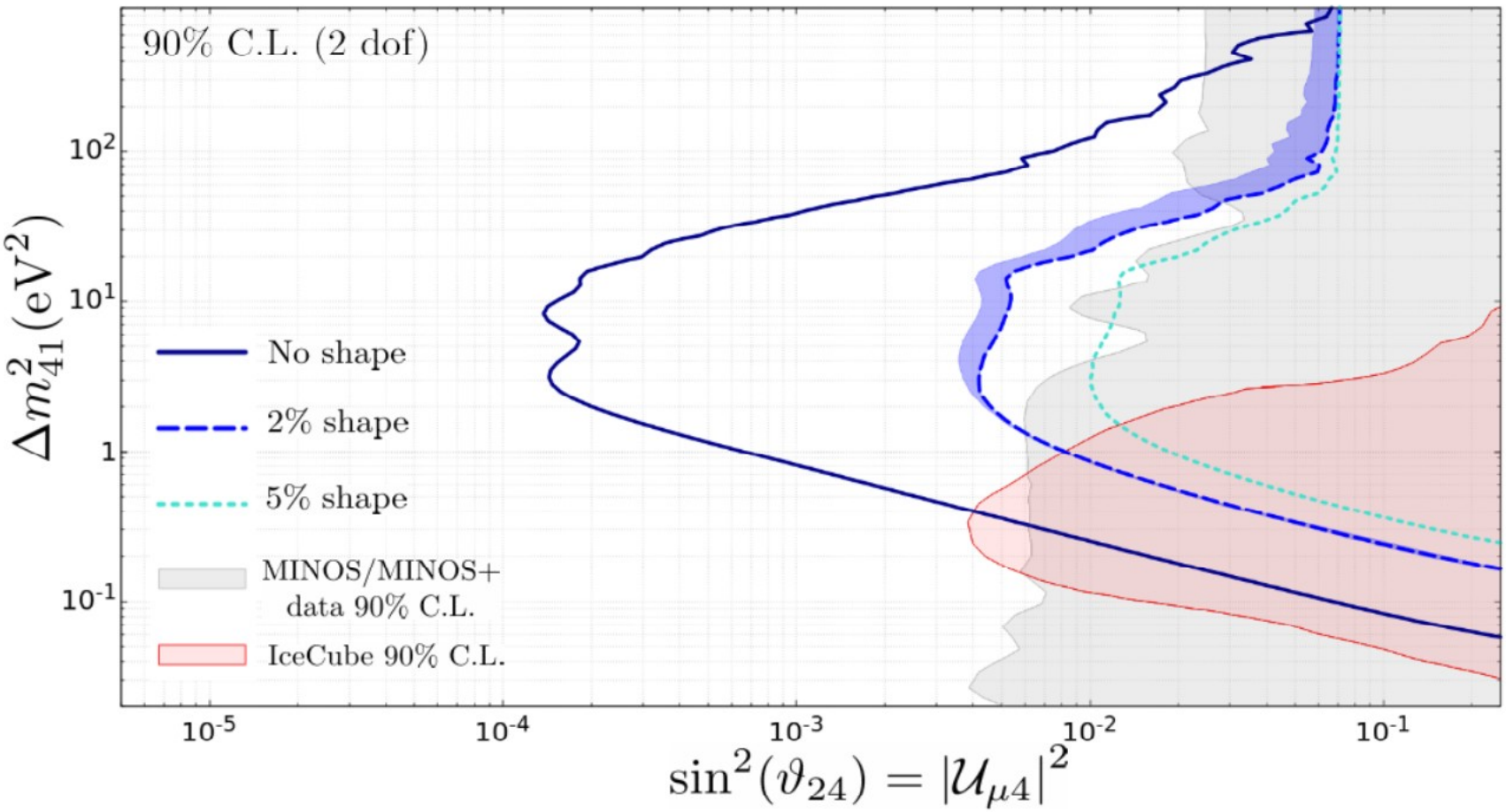
Solar neutrinos



Goldhagen, Maltoni, Reichard, Schwetz, 2109.14898
(solar analysis as in Esteban et al, 2007.14792)

eV-scale sterile neutrinos @ ND

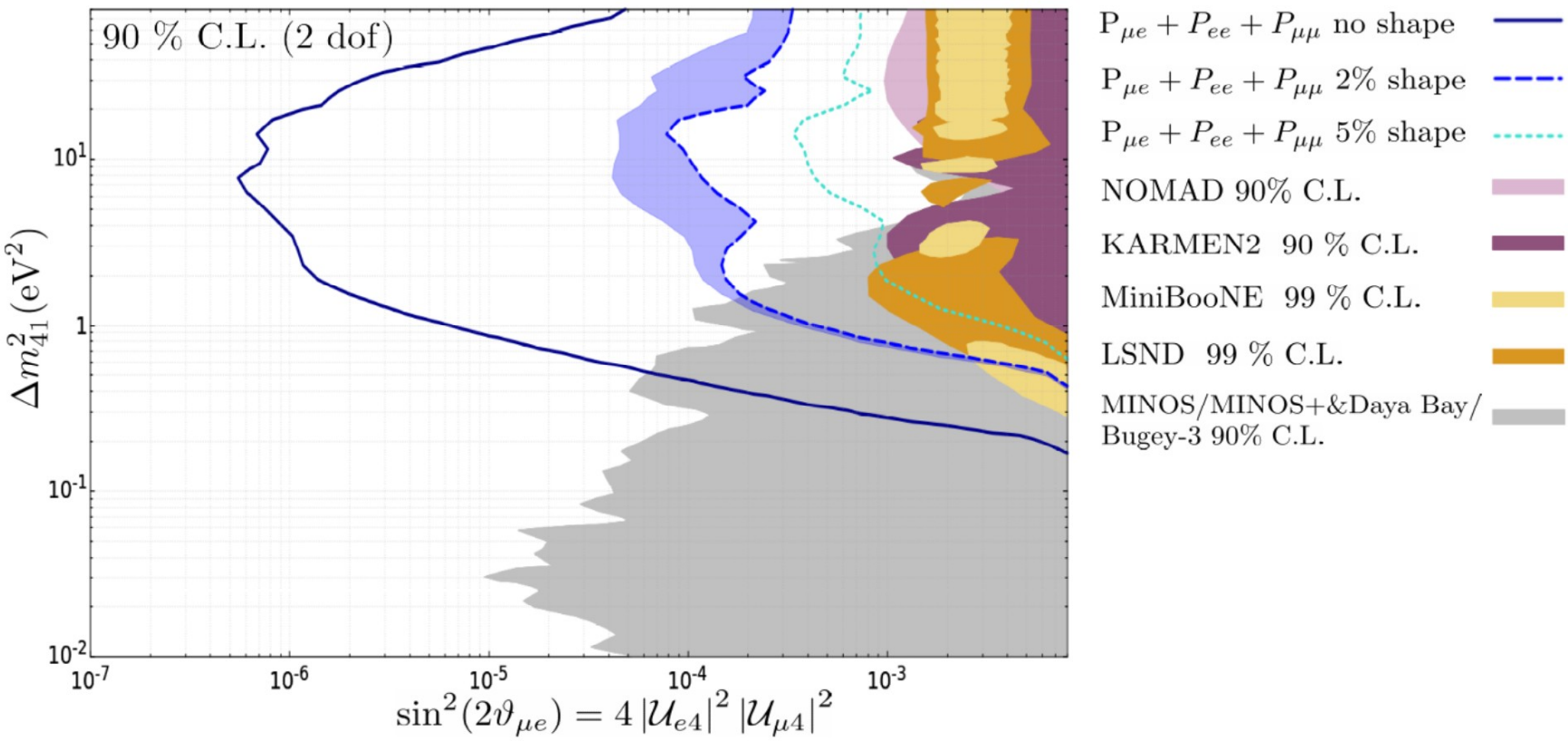
Great potential, but we have to be careful with systematics:



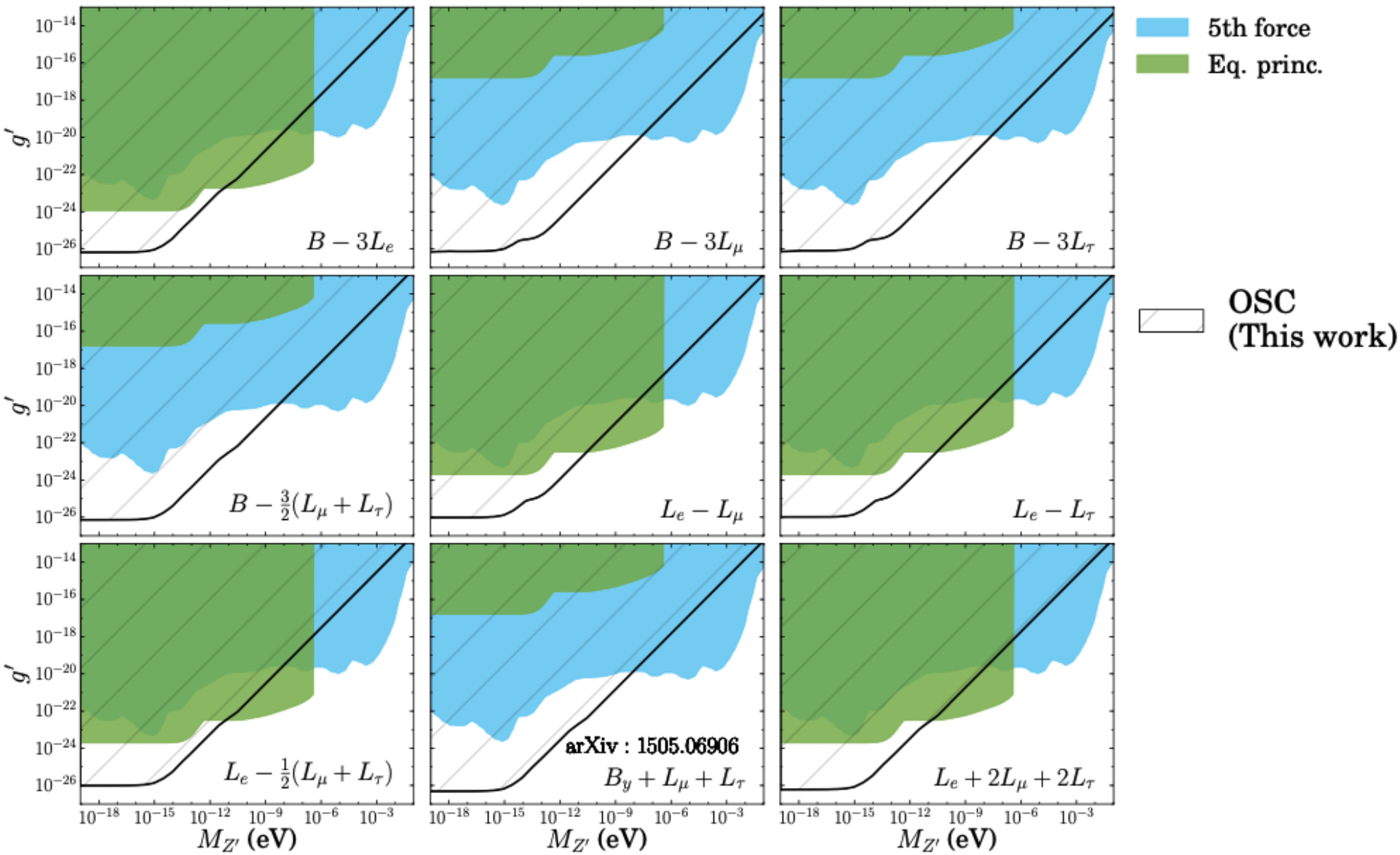
Coloma, Lopez-Pavon, Rosauro-Alcaraz, Urrea, 2105.11466

eV-scale sterile neutrinos @ ND

DUNE offers the possibility to combine multiple samples in the same experiment:



Coloma, Lopez-Pavon, Rosauro-Alcaraz, Urrea, 2105.11466



Coloma, Gonzalez-Garcia and Maltoni, 2009.14220