# Beyond the SM with neutrinos from the lab

Enrique Fernández-Martínez

HIDDeν

Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Asymmetry

Essential Asymmetries of Nature

# $\nu$ and BSM

Adapted from: P. Coloma, L. Koerner, I. Shoemaker and J. Yu Snowmass report
see arXiv:2209.10362 for summary and links to dedicated analyses

# $\nu$ and BSM

$\nu$ masses require BSM physics

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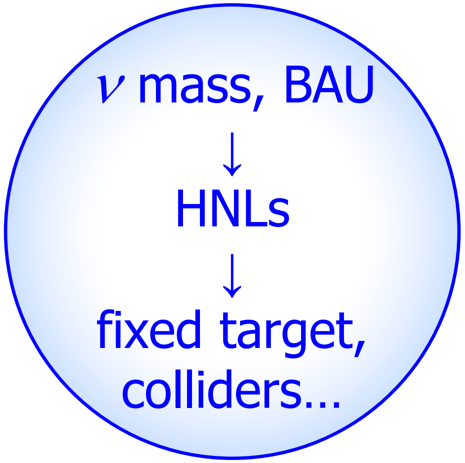


Probed in fixed target including ND of oscillation experiments: NuTeV, T2K, NA62, ProtoDUNE, SHiP, DUNE, ICARUS, SBND, $\mu$BooNE…

Or from atmospheric: SK, IceCube, HK ESS$\nu$SB, INO-ICAL, KM3NeT-ORCA,…

Also in nuclear decay kinematics: KATRIN/Tristan, HUNTER…

Collider searches: ATLAS, CMS, Faser, Belle II…

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$\nu$ mass, BAU
↓
non-Unitarity
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EWPO, flavour oscillations…

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If they are too heavy to be produced: indirect searches from PMNS non-unitarity: electroweak precision and flavour observables

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Also "zero distance" effect in oscillations: solar, reactors, MINOS/MINOS+, NO$\nu$A, T2K, IceCube, HK, ESS$\nu$SB, INO-ICAL, KM3NeT-ORCA, DUNE, JUNO, TAO, SUPERCHOOZ/CLOUD…

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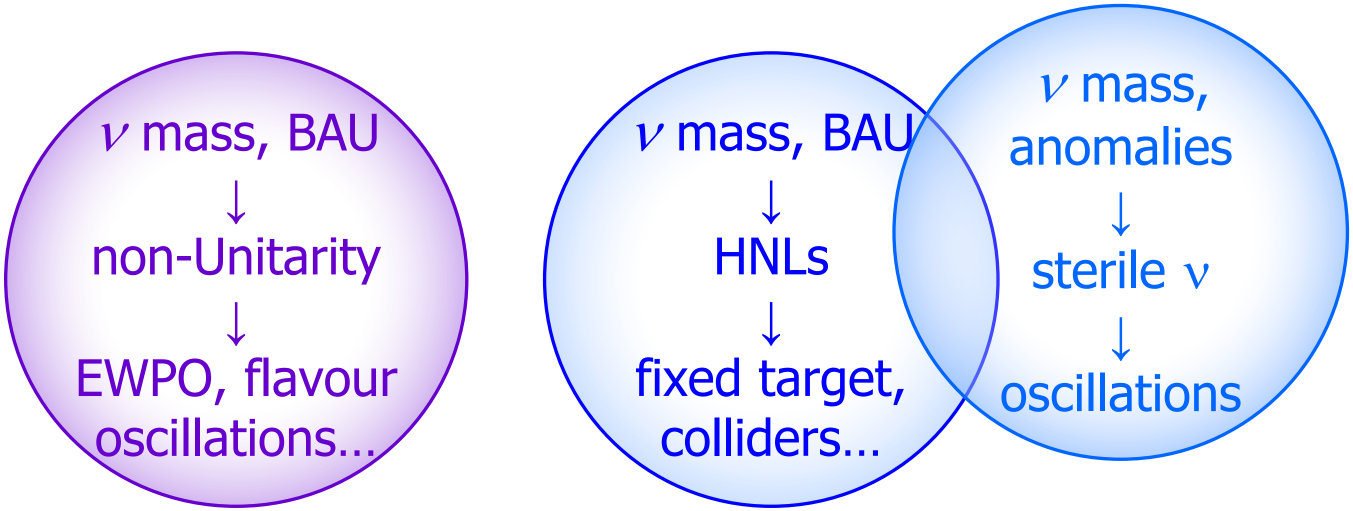


If they are very light they participate in oscillations

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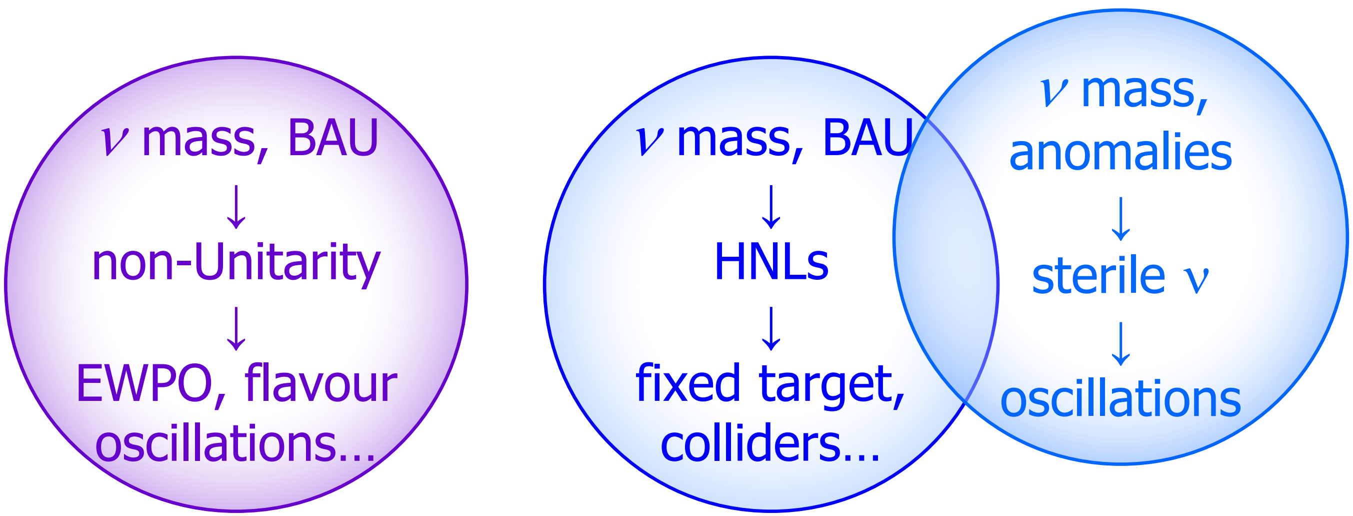


But also "zero distance" effect in averaged-out oscillations: solar, reactors, MINOS/MINOS+, NO$\nu$A, T2K, IceCube, HK, ESS$\nu$SB, INO-ICAL, KM3NeT-ORCA, DUNE, JUNO, TAO, SUPERCHOOZ, CLOUD…

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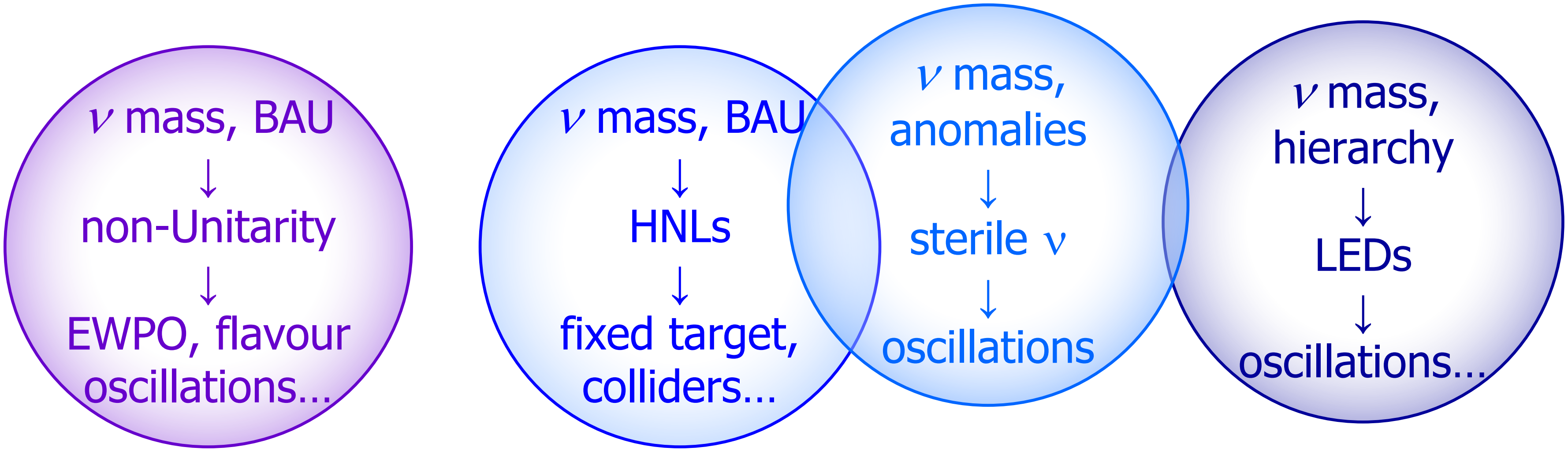
# $\nu$ and BSM

Possible connections to other open problems: LED may address the hierarchy problem and $\nu$ masses




Similar pheno to steriles but with characteristic masses and mixings: solar, reactors, MINOS/MINOS+, NOνA, T2K, IceCube, HK, ESSνSB, INO-ICAL, KM3NeT-ORCA, DUNE, JUNO/TAO, SUPERCHOOZ/CLOUD…

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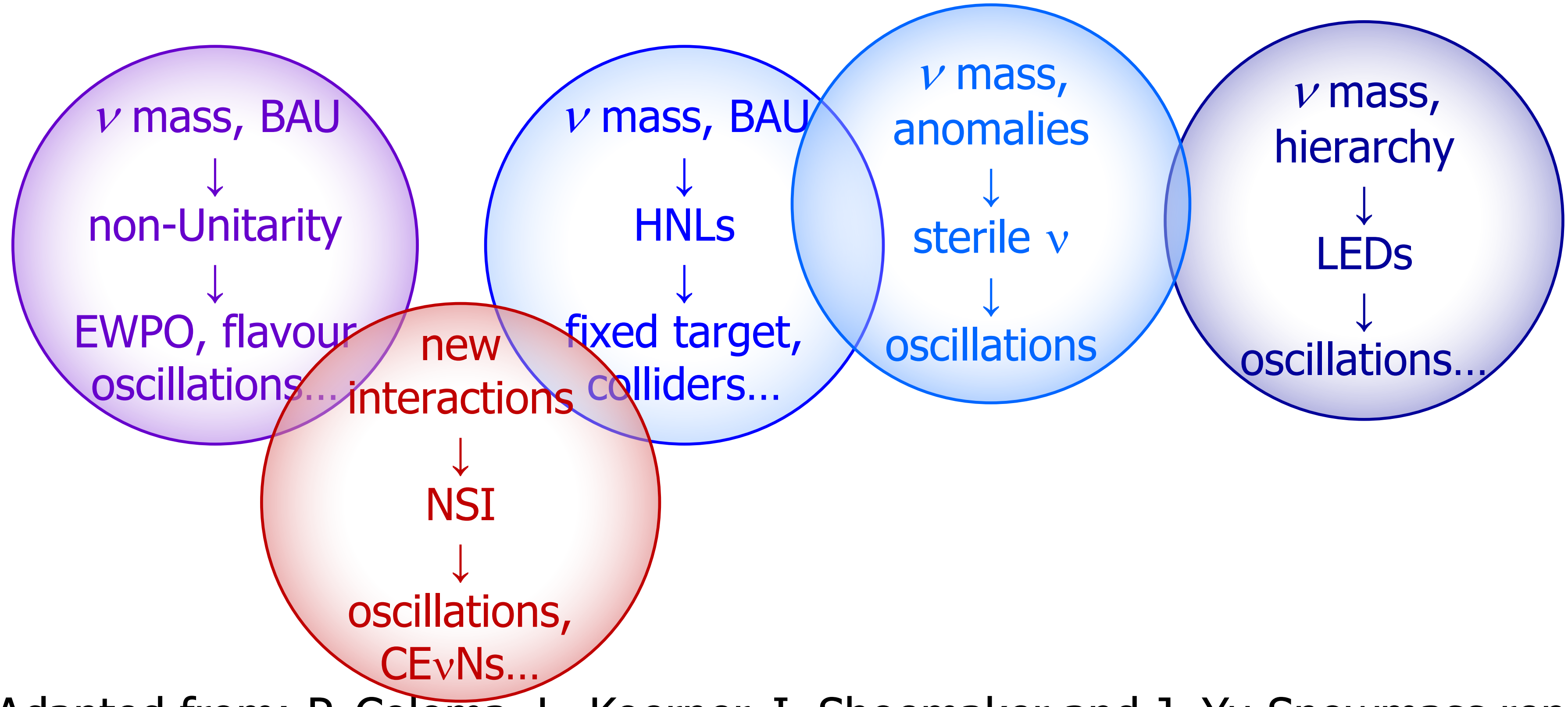
# ν and BSM

Also searches for non-standard ν properties:
NSI: affect oscillations solars, MINOS/MINOS+, NOνA, T2K, IceCube, HK, ESSνSB, INO-ICAL, KM3NeT-ORCA, DUNE IsoDAR…
and directly probed through CEνNs: COHERENT, CONNIE, CONUS…

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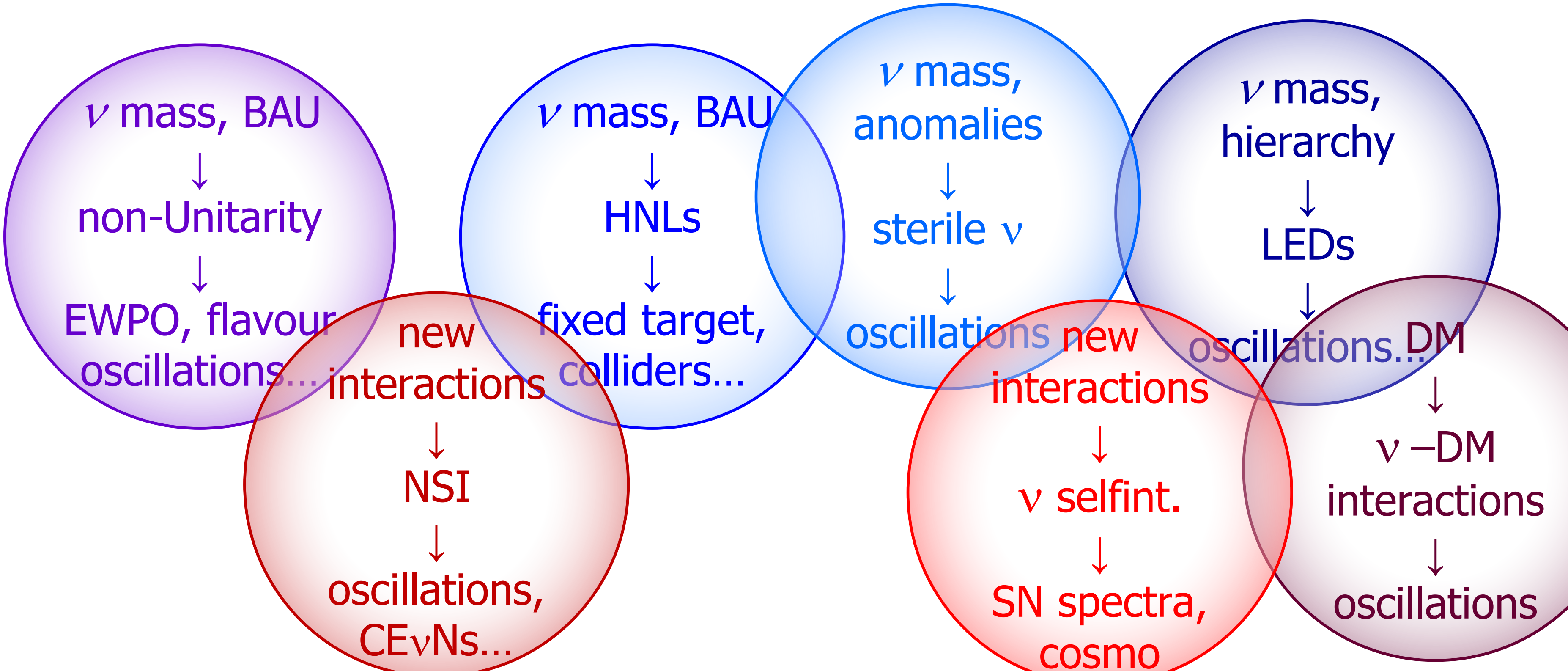
# $\nu$ and BSM

Also searches for non-standard $\nu$ properties:

Longer range forces or interactions with DM → modified matter potentials

Self-interactions → impact cosmological abundance and distort SN fluxes

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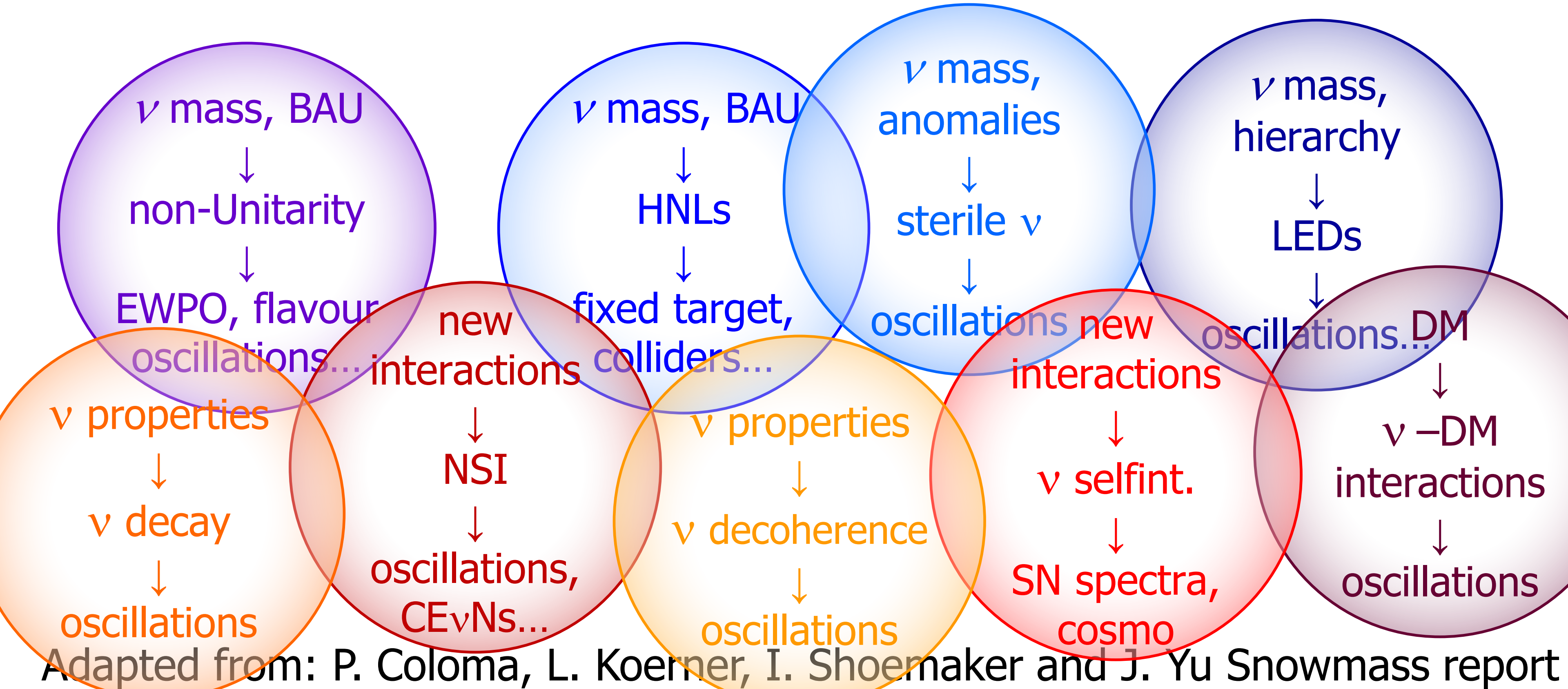
# $\nu$ and BSM

Also searches for non-standard $\nu$ properties:

Neutrino decay or decoherence would also impact oscillations: solar, MINOS/MINOS+, NOνA, T2K, IceCube, HK, ESSνSB, INO-ICAL, KM3NeT-ORCA, DUNE, JUNO,…

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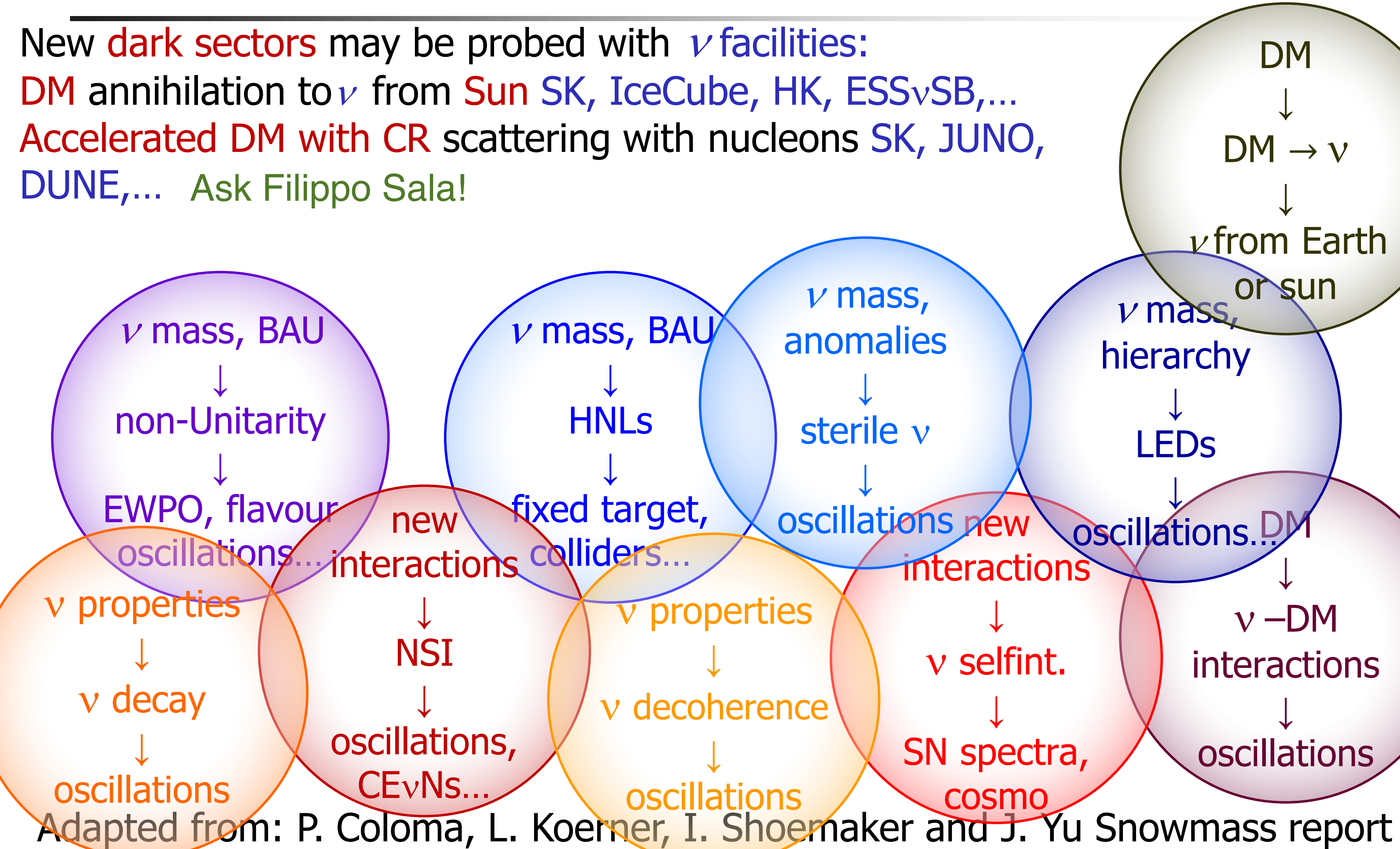
# $\nu$ and BSM

New dark sectors may be probed with $\nu$ facilities:
DM annihilation to $\nu$ from Sun SK, IceCube, HK, ESS$\nu$SB,…
Accelerated DM with CR scattering with nucleons SK, JUNO, DUNE,… Ask Filippo Sala!

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DS like Z′ or millicharged particles produced in fixed target and scattering or decay in ND:
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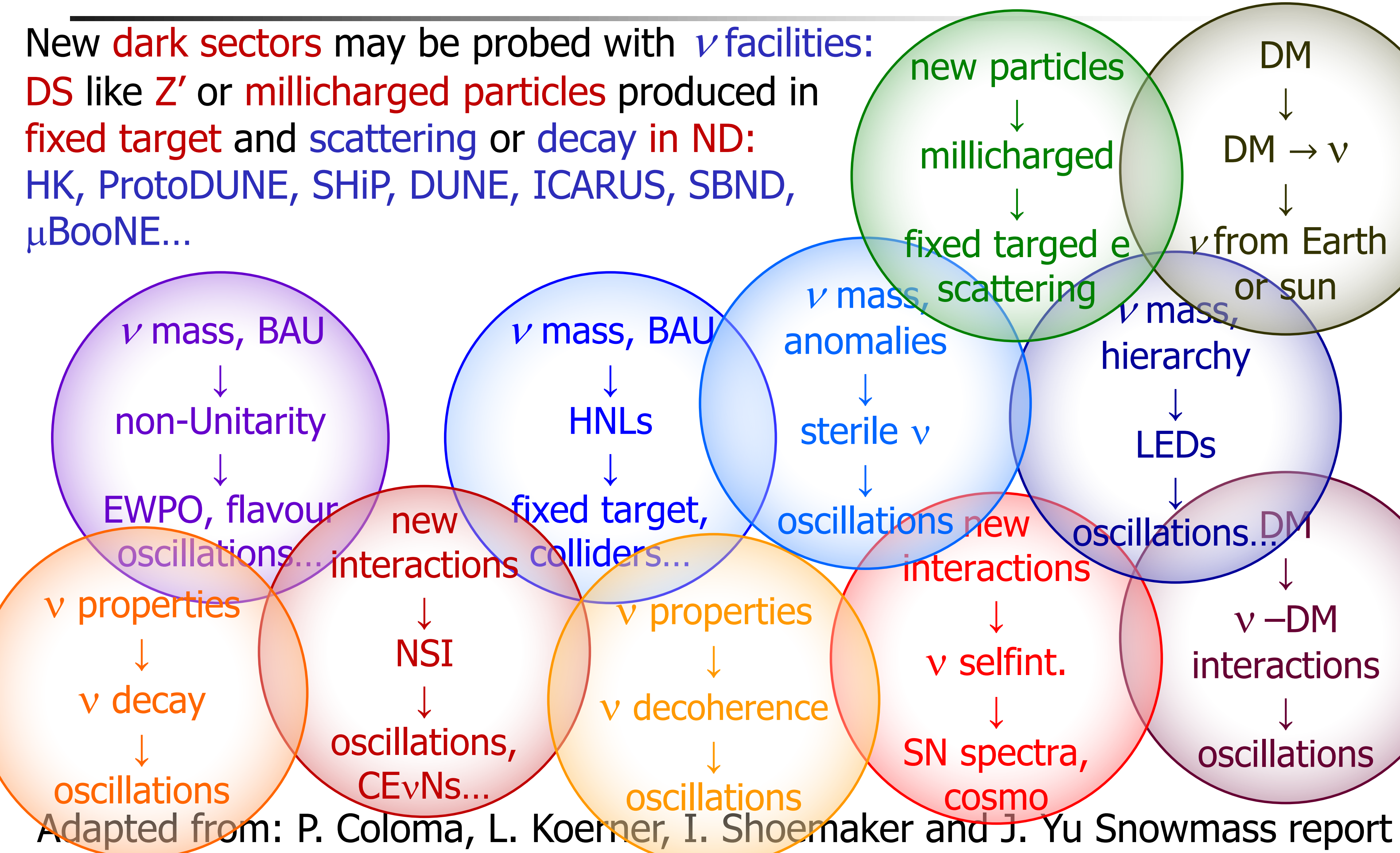


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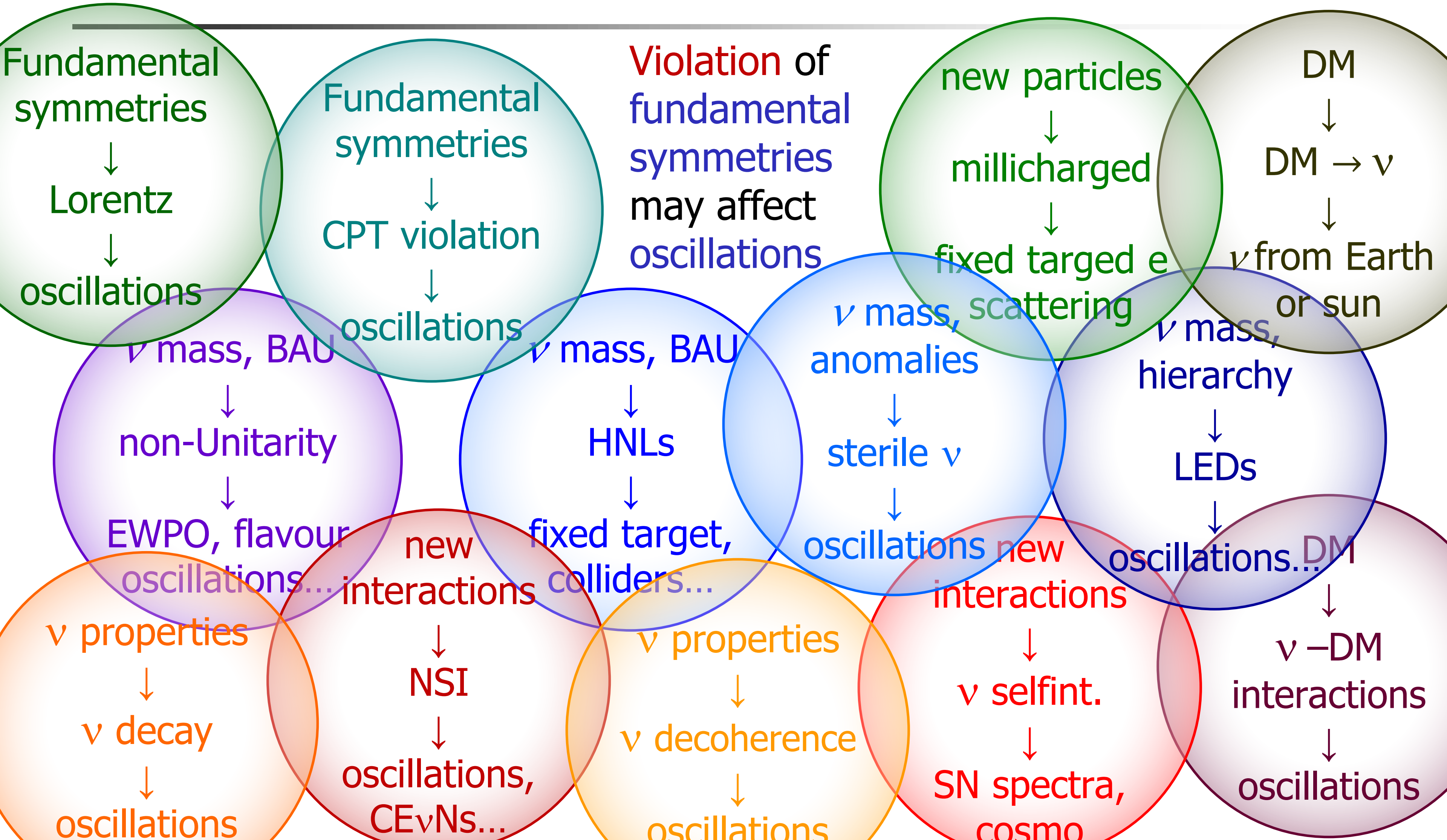


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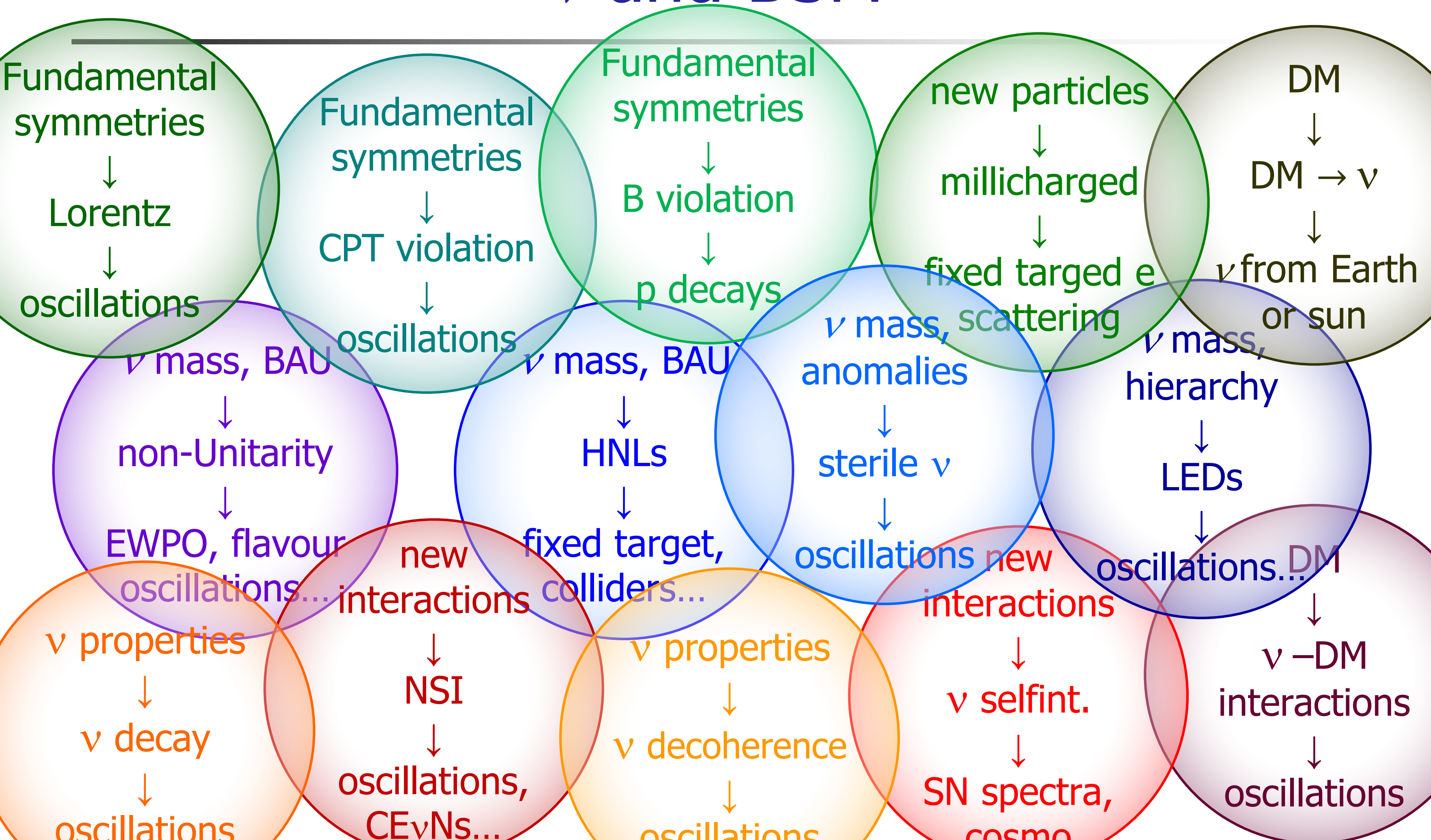


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# $\nu$ mass from right-handed neutrinos

Simplest option add $\nu_R$ and acquire Dirac masses via Yukawas

$$Y_\nu \bar{\nu}_R \phi \nu_L \xrightarrow[\langle \phi \rangle = \frac{Y_f v}{\sqrt{2}}]{\text{SSB}} \frac{Y_\nu v}{\sqrt{2}} \bar{\nu}_R \nu_L \qquad m_D = \frac{Y_\nu v}{\sqrt{2}}$$

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→ To be searched for at experiments!!

# $\nu$ mass from right-handed neutrinos

$$m_\nu = \begin{pmatrix} 0 & m_D^t \\ m_D & M_N \end{pmatrix} \xrightarrow[\text{Seesaw}]{} U^t \begin{pmatrix} 0 & m_D^t \\ m_D & M_N \end{pmatrix} U = \begin{pmatrix} m & 0 \\ 0 & M \end{pmatrix}$$

If $M_N \gg m_D$ then $M \approx M_N$ and $m \approx m_D^t M_N^{-1} m_D \rightarrow$ lightness of $\nu$

small mixing $\Theta \approx m_D^\dagger M_N^{-1}$

# A new physics scale

But a very high $M_N$ leads to the Higgs hierarchy problem

Lightness of $\nu$ masses could also come naturally from an approximate symmetry (B-L)

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$$m_D \overline{N}_R \nu_L + M_N \overline{N}_R N_L$$

$$\begin{pmatrix} 0 & m_D^t & 0 \\ m_D & 0 & M_N^t \\ 0 & M_N & 0 \end{pmatrix}$$

G. C. Branco, W. Grimus, and L. Lavoura 1988
A. Abada, C. Biggio, F. Bonnet, M.B. Gavela, T. Hambye 0707.4058
J. Kersten and A. Y. Smirnov 0705.3221
K. Moffat, S. Pascoli, C. Weiland 1712.07611

Low $M \approx M_N$ and large $\Theta \approx m_D^\dagger M_N^{-1}$ even if vanishing $m_\nu = 0$

# A new physics scale

But a very high $M_N$ leads to the Higgs hierarchy problem

Lightness of $\nu$ masses could also come from an naturally from an approximate symmetry (B-L)

$$m_D \bar{N}_R \nu_L + M_N \, \bar{N}_R N_L + \mu \bar{N}_L^c \, N_L$$

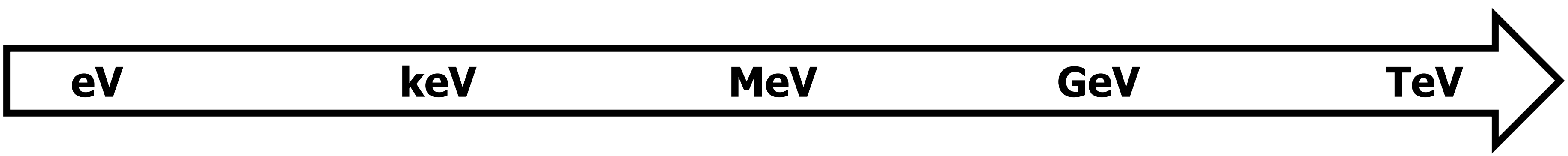
$$\begin{pmatrix} 0 & m_D^t & 0 \\ m_D & 0 & M_N^t \\ 0 & M_N & \mu \end{pmatrix}$$

"inverse Seesaw"

R. Mohapatra and J. Valle 1986

Low $M \approx M_N \pm \frac{\mu}{2}$ and large $\Theta \approx m_D^\dagger M_N^{-1}$ even if small $m_\nu \approx \mu \frac{m_D^2}{M_N^2}$

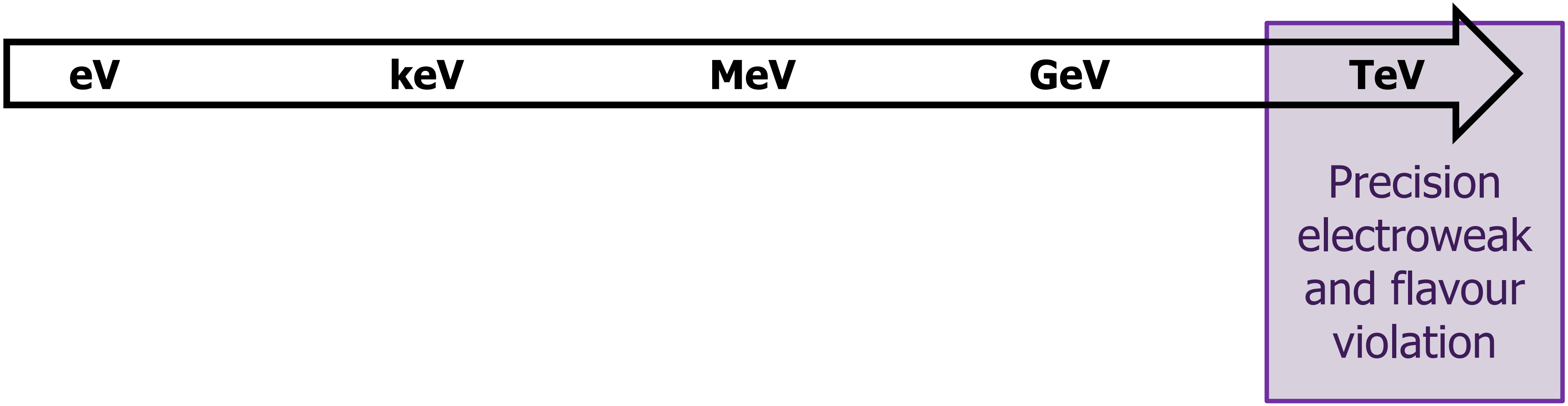
# A new physics scale




$M_N$ could be anywhere...

Very different phenomenology at different scales

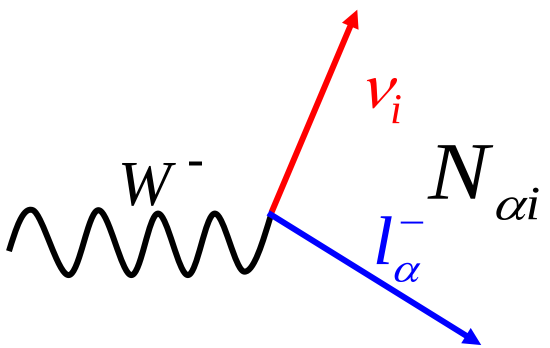
# A new physics scale

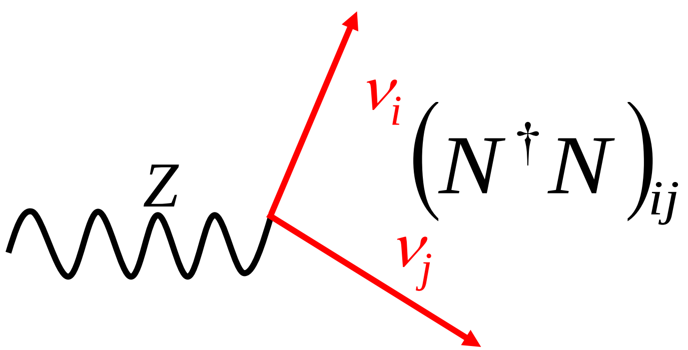


# Looking for $\nu_R$: Non-Unitarity

$$U^t \begin{pmatrix} 0 & m_D^t \\ m_D & M_N \end{pmatrix} U \approx \begin{pmatrix} N^t & -\Theta^* \\ \Theta^t & X^t \end{pmatrix} \begin{pmatrix} 0 & m_D^t \\ m_D & M_N \end{pmatrix} \begin{pmatrix} N & \Theta \\ -\Theta^\dagger & X \end{pmatrix} = \begin{pmatrix} m & 0 \\ 0 & M \end{pmatrix}$$

The 3×3 submatrix $N$ of active neutrinos will not be unitary




Effects in weak interactions…

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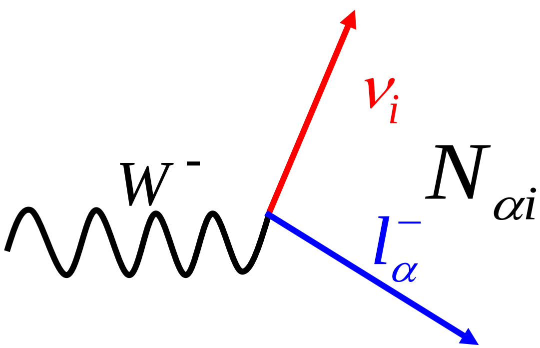
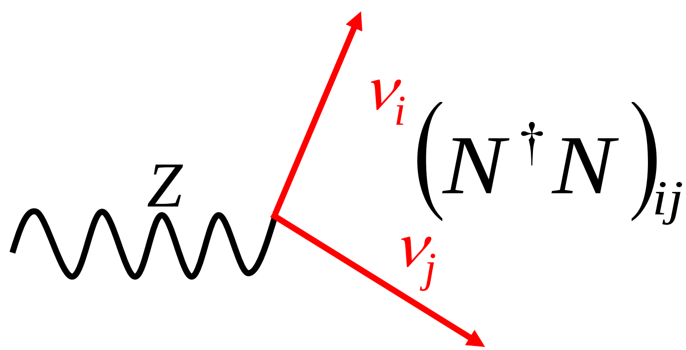


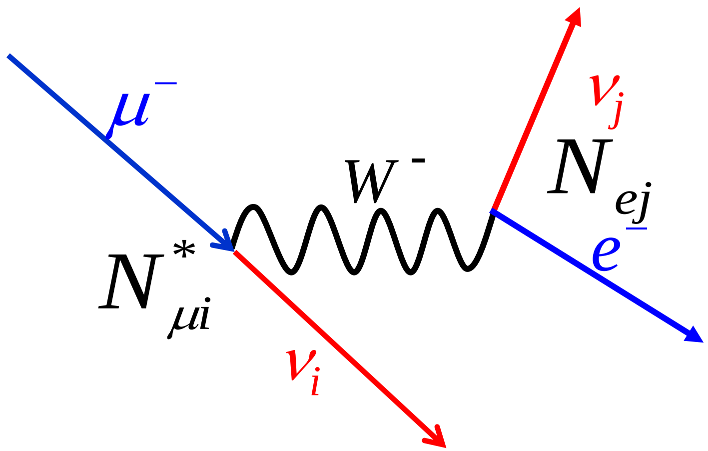

Effects in weak interactions…

When the W and Z are integrated out to obtain the Fermi theory NSI are recovered!

see e.g. M. Blennow, P.Coloma, EFM, J. Hernandez-Garcia and J. Lopez-Pavon arXiv:1609.08637 for the dictionary

# Looking for $N_R$: Non-Unitarity

$G_F$ from $\mu$ decay is affected!




$$G_\mu = G_F \left(NN^\dagger\right)_{ee} \left(NN^\dagger\right)_{\mu\mu}$$

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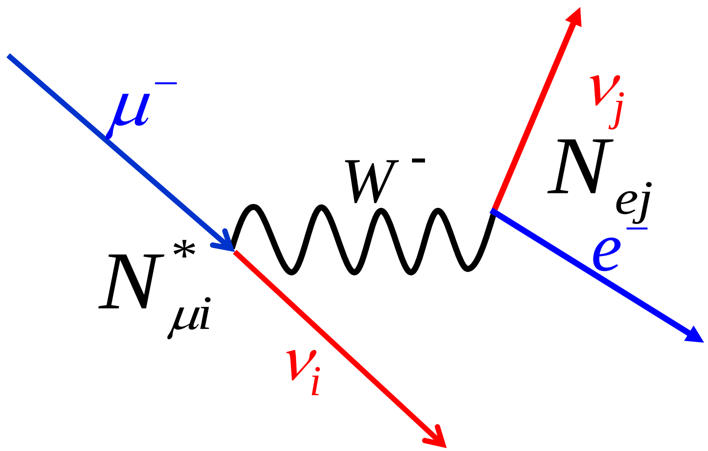


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But this agrees at $\sim 10^{-3}$ with $G_F$ from $M_W$ (modulo CDF), measurents of $\sin\theta_W$ from LEP, Tevatron and LHC and $\beta$ and $K$ decays

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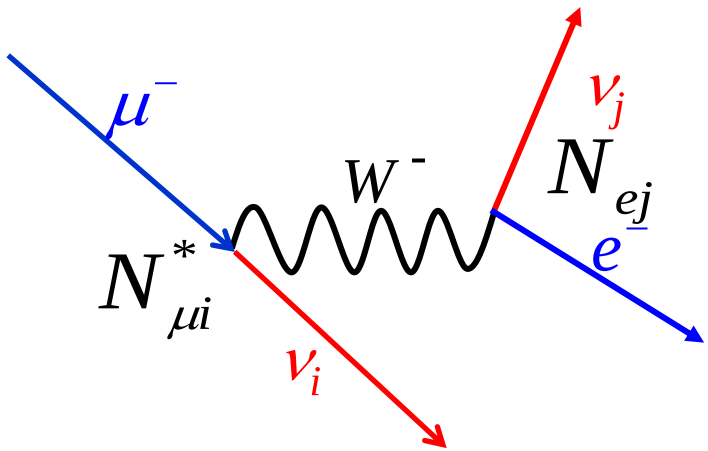


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LFU also strong bounds on ratios:

$$\frac{\left(NN^\dagger\right)_{\alpha\alpha}}{\left(NN^\dagger\right)_{\beta\beta}}$$

From ratios of $\pi$, $K$, and lepton decays

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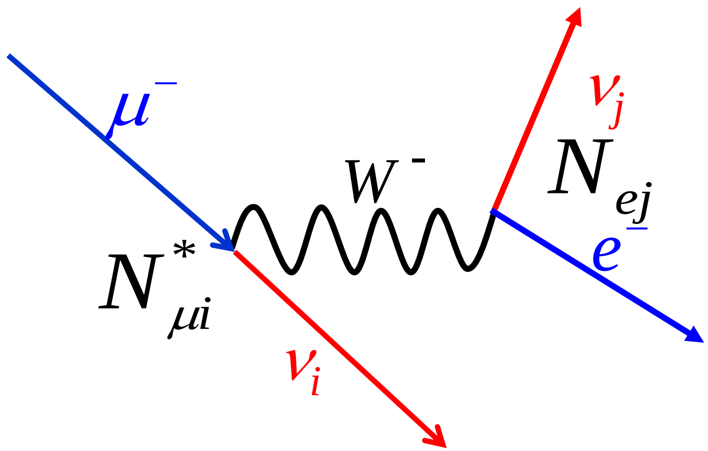


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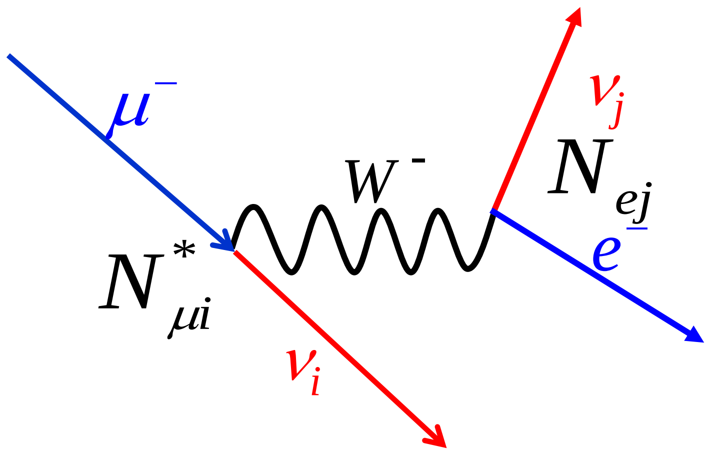


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From ratios of $\pi$, $K$, and lepton decays

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And LFV processes such as $\mu \rightarrow e\,\gamma$ since the GIM cancellation is lost

# Looking for $N_R$: Non-Unitarity

Bounds from a global fit to flavour and Electroweak precision

| 95% CL | LFC | LFV |
|---|---|---|
| $\eta_{ee} = \frac{1}{2}\sum_k \lvert\Theta_{ek}\rvert^2$ | $[0.081, 1.4] \cdot 10^{-3}$ | - |
| $\eta_{\mu\mu}$ | $1.4 \cdot 10^{-4}$ | - |
| $\eta_{\tau\tau}$ | $8.9 \cdot 10^{-4}$ | - |
| $\mathrm{Tr}\,[\eta]$ | $2.1 \cdot 10^{-3}$ | - |
| $\lvert\eta_{e\mu}\rvert$ | $3.4 \cdot 10^{-4}$ | $\mathbf{1.2 \cdot 10^{-5}}$ |
| $\lvert\eta_{e\tau}\rvert$ | $\mathbf{8.8 \cdot 10^{-4}}$ | $8.1 \cdot 10^{-3}$ |
| $\lvert\eta_{\mu\tau}\rvert$ | $\mathbf{1.8 \cdot 10^{-4}}$ | $9.4 \cdot 10^{-3}$ |

$$N = (\mathbb{I} - \eta)U$$

$$\eta = \frac{\Theta\Theta^\dagger}{2} \qquad \Theta \approx m_D^\dagger M_N^{-1}$$

M. Blennow, EFM,
J. Hernandez-Garcia,
J. Lopez-Pavon
X. Marcano and
**D. Naredo-Tuero**
2306.01040

See also P. Langaker and D. London 1988; S. M. Bilenky and C. Giunti hep-ph/9211269 ; E. Nardi, E. Roulet and D. Tommasini hep-ph/9503228; D. Tommasini, G. Barenboim, J. Bernabeu and C. Jarlskog hep-ph/9503228; S. Antusch, C. Biggio, EFM, B. Gavela and J. López Pavón hep-ph/0607020; S. Antusch, J. Baumann and EFM 0807.1003; D. V. Forero, S. Morisi, M. Tortola, and J. W. F. Valle 1107.6009; S. Antusch and O. Fischer 1407.6607; F.J. Escrihuela, D.V. Forero, O.G. Miranda, M. Tórtola, J.W.F. Valle 1612.07377, EFM, J. Hernandez-Garcia and J. Lopez-Pavon 1605.08774, A. M. Coutinho, A. Crivellin, and C. A. Manzari 1912.08823…

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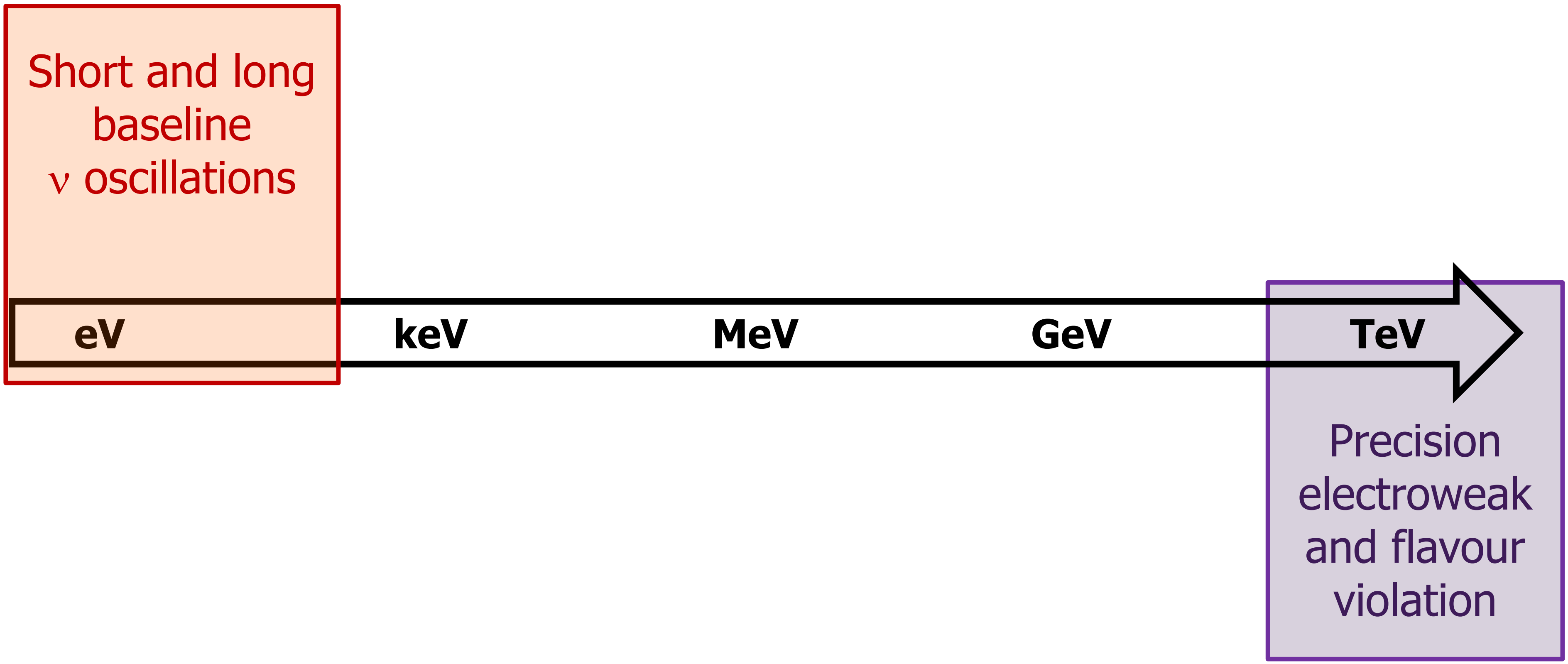
| $\mathrm{Tr}\,[\eta]$ | $2.1 \cdot 10^{-3}$ | - |
| $\lvert\eta_{e\mu}\rvert$ | $3.4 \cdot 10^{-4}$ | $\mathbf{1.2 \cdot 10^{-5}}$ |
| $\lvert\eta_{e\tau}\rvert$ | $\mathbf{8.8 \cdot 10^{-4}}$ | $8.1 \cdot 10^{-3}$ |
| $\lvert\eta_{\mu\tau}\rvert$ | $\mathbf{1.8 \cdot 10^{-4}}$ | $9.4 \cdot 10^{-3}$ |

2 $\sigma$ preference for mixing with electrons ~0.03

M. Blennow, EFM,
J. Hernandez-Garcia,
J. Lopez-Pavon
X. Marcano and
**D. Naredo-Tuero**
2306.01040

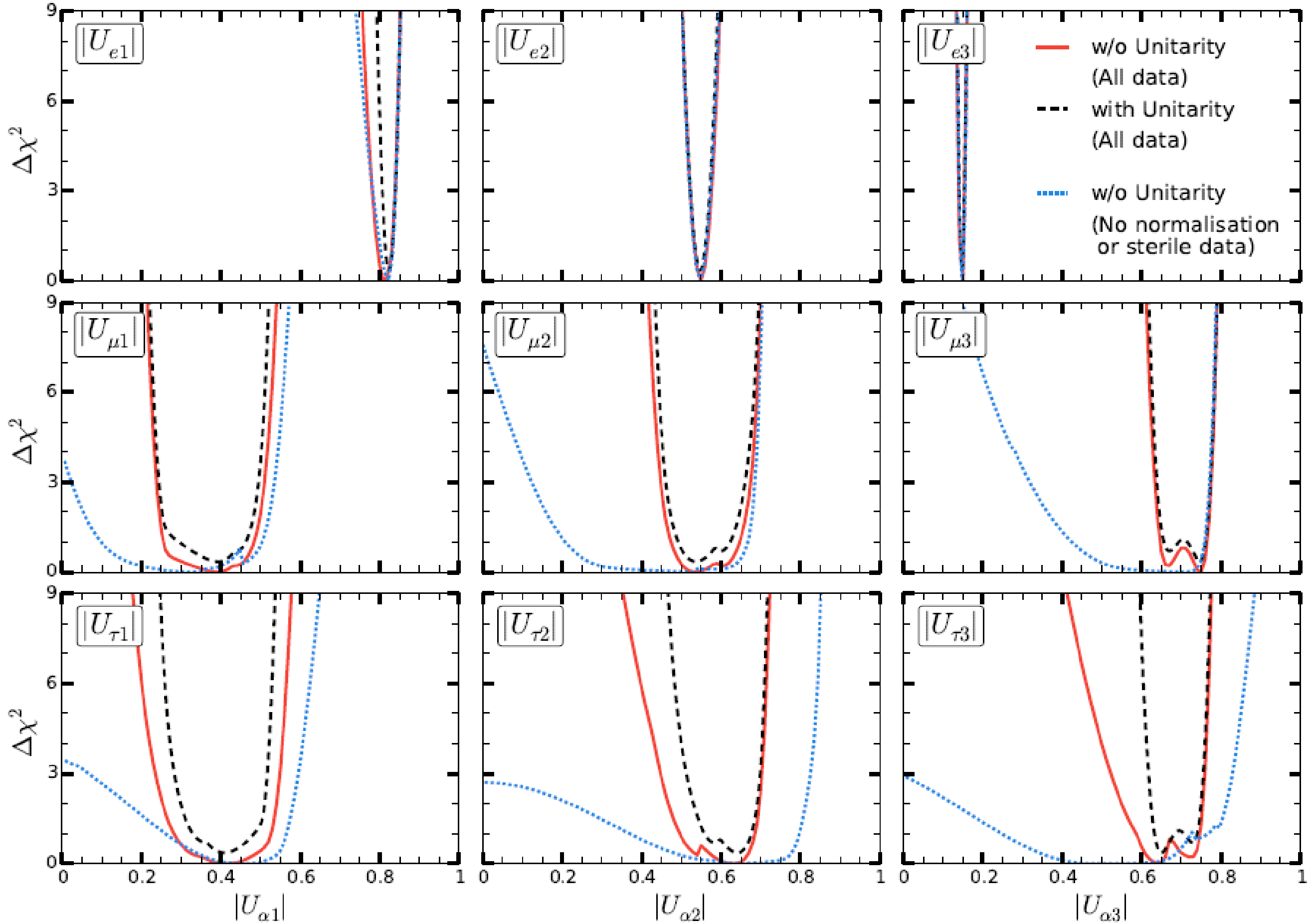
See also P. Langaker and D. London 1988; S. M. Bilenky and C. Giunti hep-ph/9211269 ; E. Nardi, E. Roulet and D. Tommasini hep-ph/9503228; D. Tommasini, G. Barenboim, J. Bernabeu and C. Jarlskog hep-ph/9503228; S. Antusch, C. Biggio, EFM, B. Gavela and J. López Pavón hep-ph/0607020; S. Antusch, J. Baumann and EFM 0807.1003; D. V. Forero, S. Morisi, M. Tortola, and J. W. F. Valle 1107.6009; S. Antusch and O. Fischer 1407.6607; F.J. Escrihuela, D.V. Forero, O.G. Miranda, M. Tórtola, J.W.F. Valle 1612.07377, EFM, J. Hernandez-Garcia and J. Lopez-Pavon 1605.08774, A. M. Coutinho, A. Crivellin, and C. A. Manzari 1912.08823…

# A new physics scale



# The way out: lighter Steriles

For very light (< keV) extra neutrinos the strong constraints from EW and flavour are lost and ν oscillations dominate




S. Parke and M. Ross-Lonergan arXiv:1508.05095

# Steriles vs NU

$$U = \begin{pmatrix} N & \Theta \\ -\Theta^\dagger & X \end{pmatrix}$$

"Heavy ν" Non-Unitarity

$$P_{\alpha\beta} = \sum_{i,j} N_{\beta i} N^*_{\alpha i} N_{\alpha j} N^*_{\beta j} e^{\frac{-i\Delta m^2_{ij} L}{2E}}$$

M. Blennow, P. Coloma, EFM, J. Hernandez-Garcia and J. Lopez-Pavon arXiv:1609.08637
C. S. Fong, H. Minakata and H. Nunokawa arXiv:1609.08623

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"Light ν" Steriles

$$P_{\alpha\beta} = \sum_{i,j} N_{\beta i} N^*_{\alpha i} N_{\alpha j} N^*_{\beta j} e^{\frac{-i\Delta m^2_{ij} L}{2E}} + \sum_{I,J} \Theta_{\beta I} \Theta^*_{\alpha I} \Theta_{\alpha J} \Theta^*_{\beta J} e^{\frac{-i\Delta m^2_{IJ} L}{2E}} + \sum_{i,J} N_{\beta i} N^*_{\alpha i} \Theta_{\alpha J} \Theta^*_{\beta J} e^{\frac{-i\Delta m^2_{iJ} L}{2E}}$$

M. Blennow, P. Coloma, EFM, J. Hernandez-Garcia and J. Lopez-Pavon arXiv:1609.08637
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If $\frac{\Delta m^2_{ij} L}{2E} \gg 1$ oscillations too fast to resolve and only see average effect

M. Blennow, P. Coloma, EFM, J. Hernandez-Garcia and J. Lopez-Pavon 1609.08637
C. S. Fong, H. Minakata and H. Nunokawa 1609.08623

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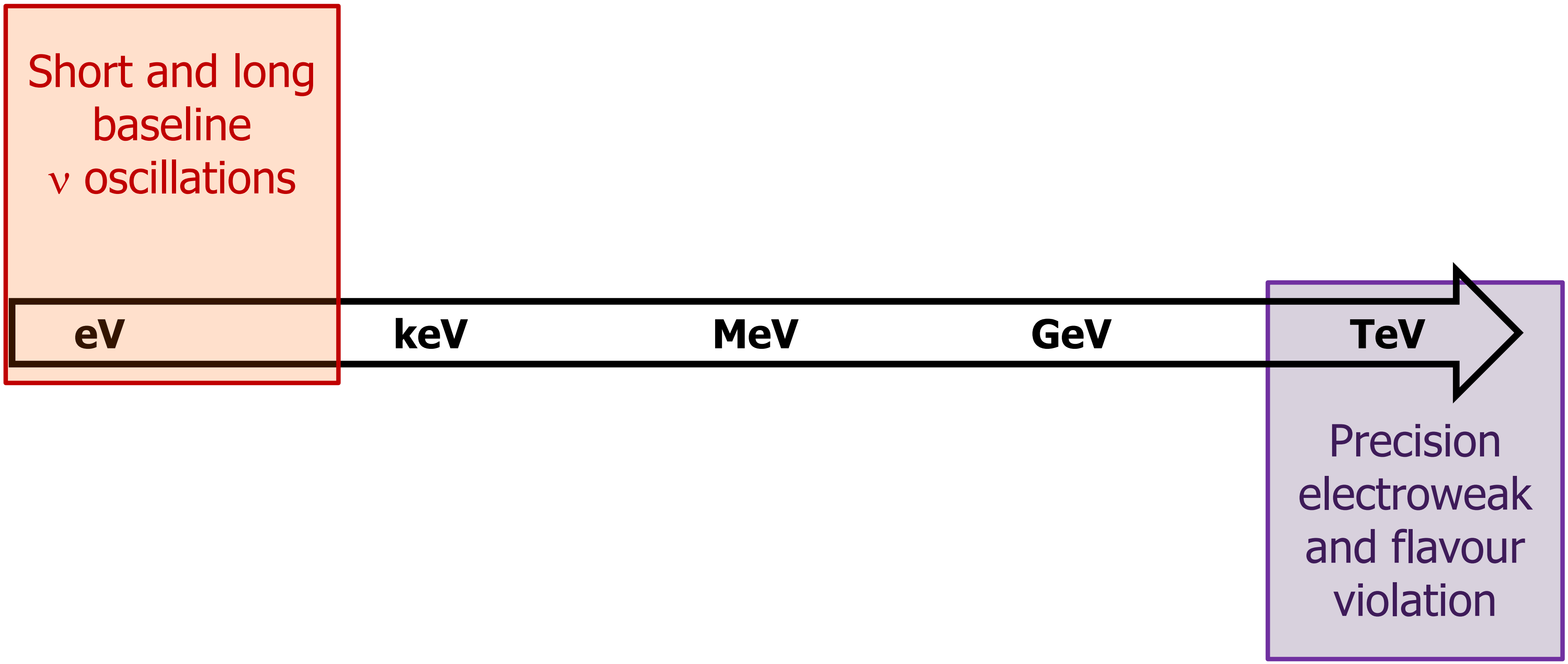
At leading order "heavy" non-unitarity and avergaed-out "light" steriles have the same impact in oscillations

M. Blennow, P. Coloma, EFM, J. Hernandez-Garcia and J. Lopez-Pavon arXiv:1609.08637

# A new physics scale



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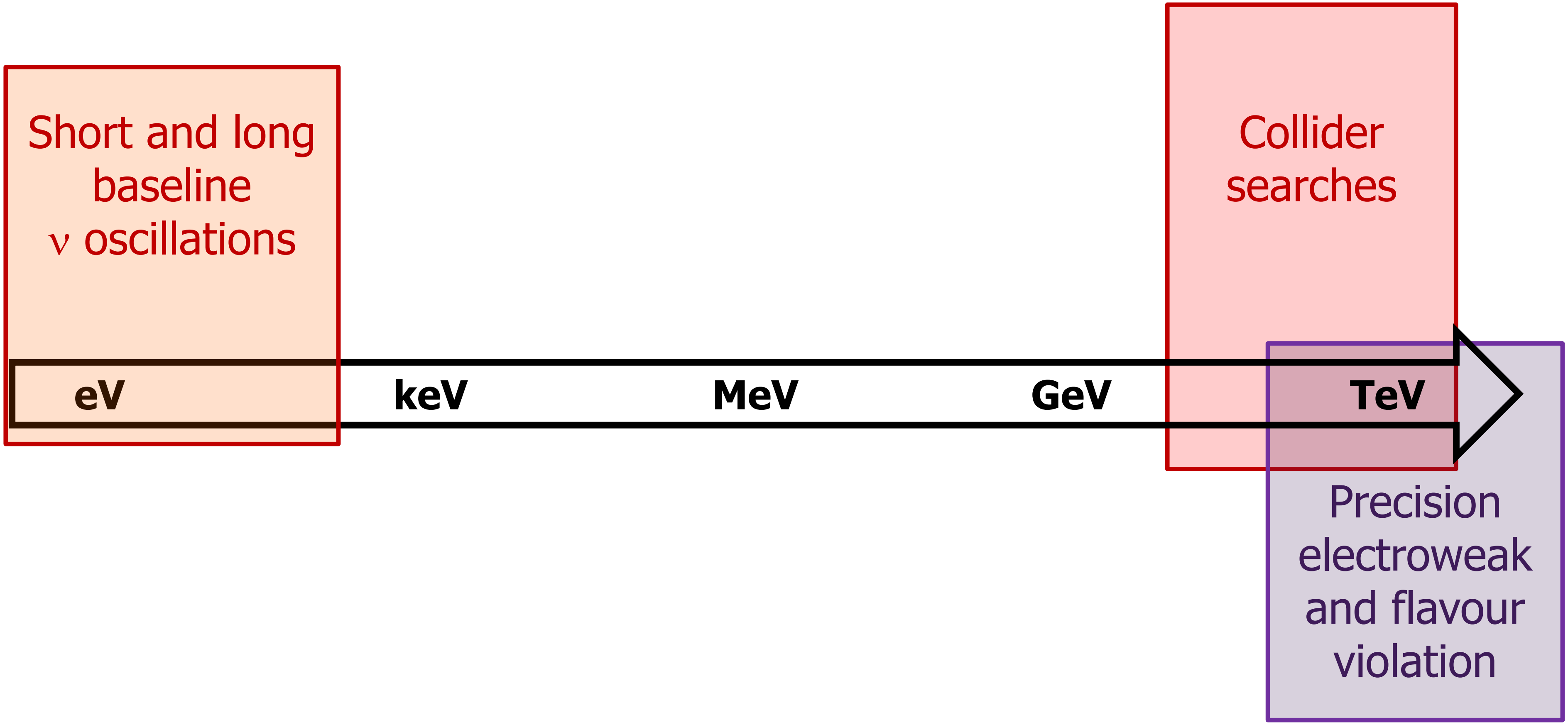

# LNV at colliders

If the HNLs are pseudoDirac, LNV signals should be very supressed

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But, if $\Delta M >> \Gamma$ they will oscillate many times between the two states before decaying, breaking the coherence and the supression of LNV

S. Antusch, E. Cazzato, and O. Fischer 1709.03797; M. Drewes, J. Klarić, and P. Klose 1907.13034; J. Gluza and T. Jeliński 1504.05568; P. S. Bhupal Dev and R. N. Mohapatra 1508.02277; G. Anamiati, M. Hirsch, and E. Nardi 1607.05641; A. Das, P. S. B. Dev, and R. N. Mohapatra 1709.06553

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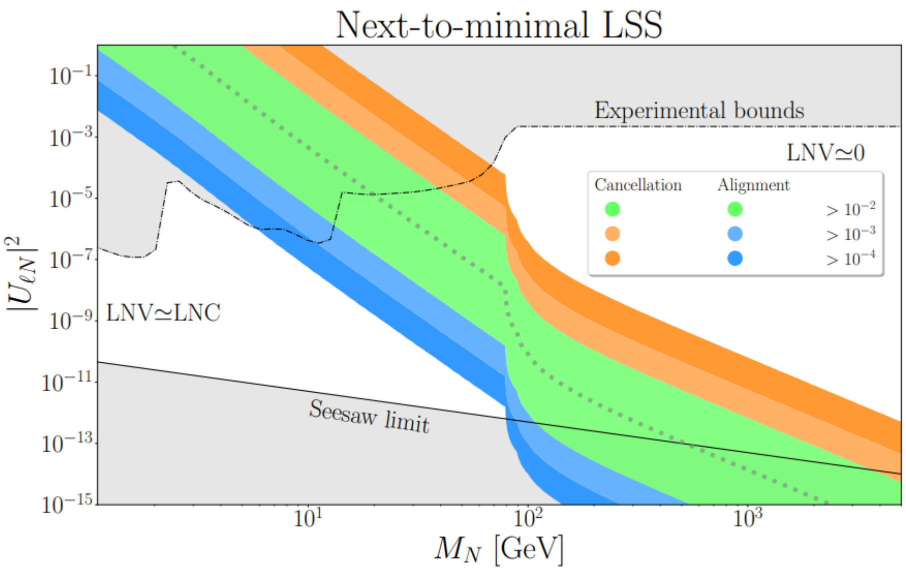


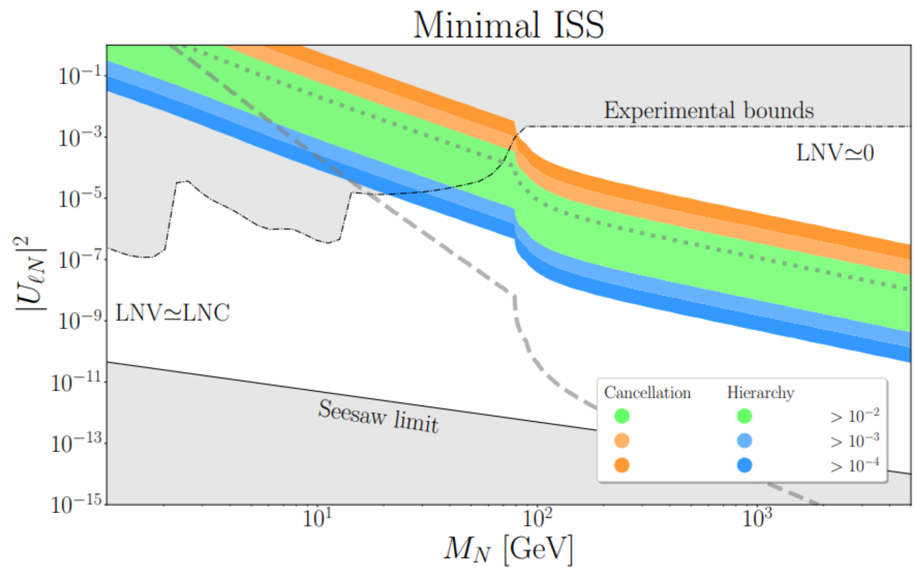


Could allow to distinguish between low scale Seesaw models!

EFM, X. Marcano and D. Naredo-Tuero 2209.04461

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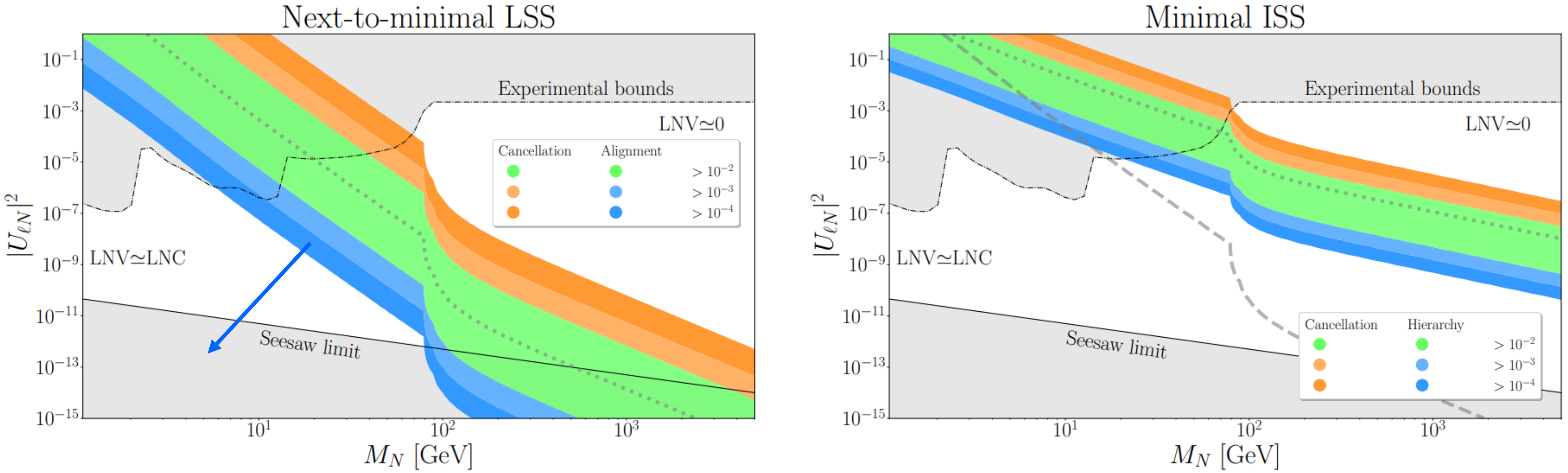


Very small values of $\Delta M$ are related to Yukawas that are almost orthogonal in the LSS.
Maybe a symmetry can explain the $\Delta M \sim 10^{-7}$eV needed for Shi-Fuller?

EFM, X. Marcano and D. Naredo-Tuero 2209.04461

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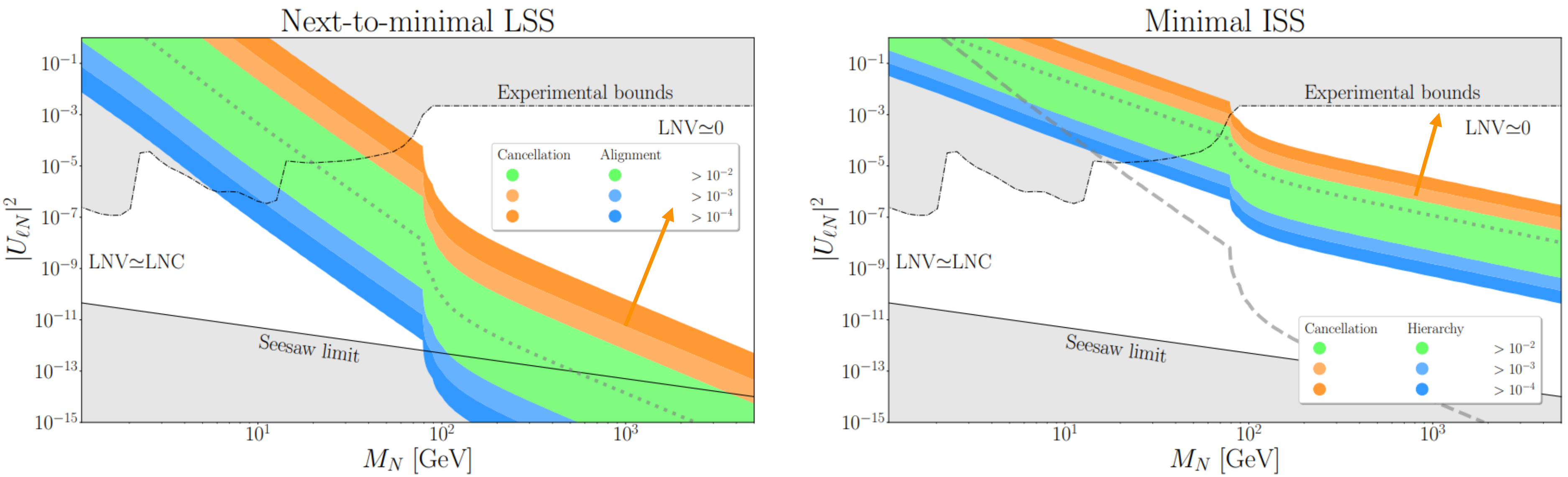
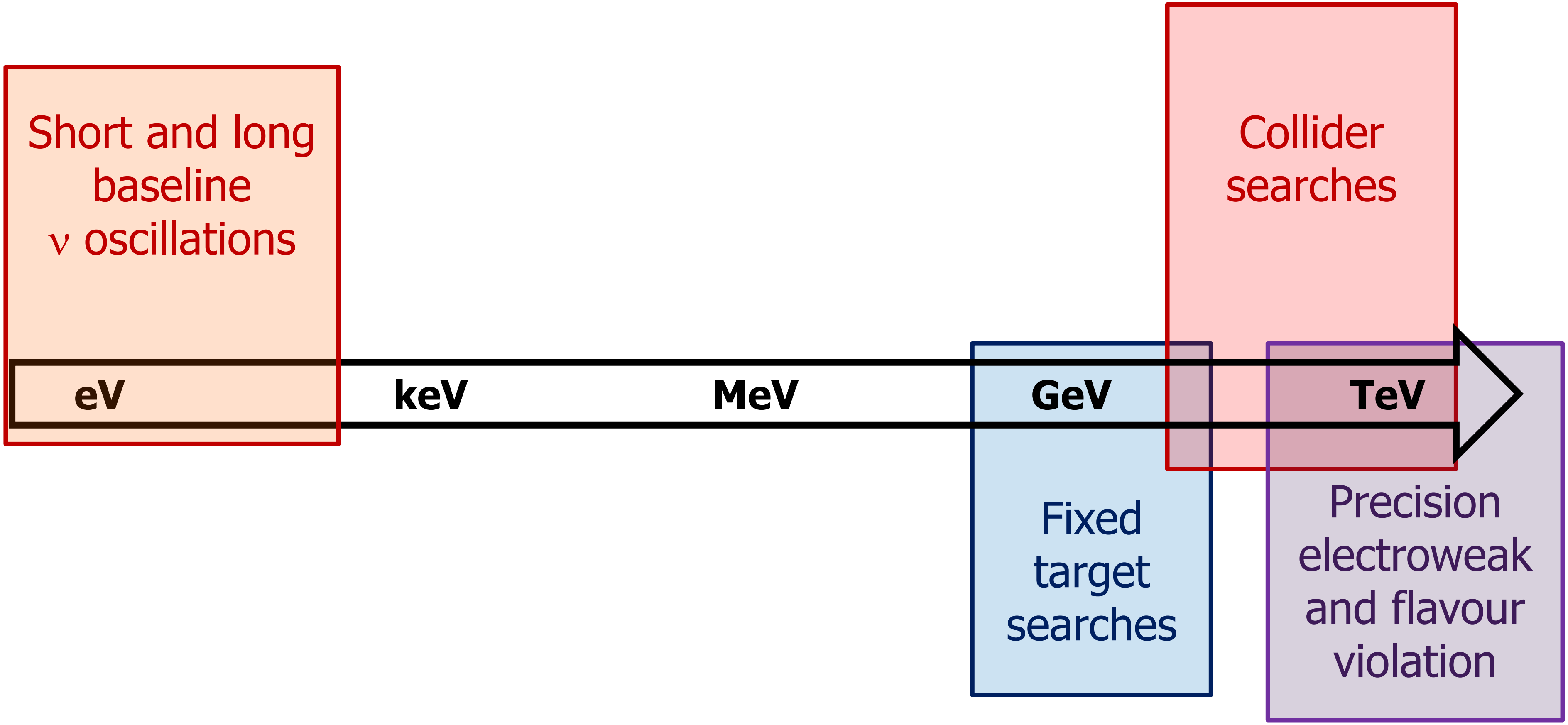


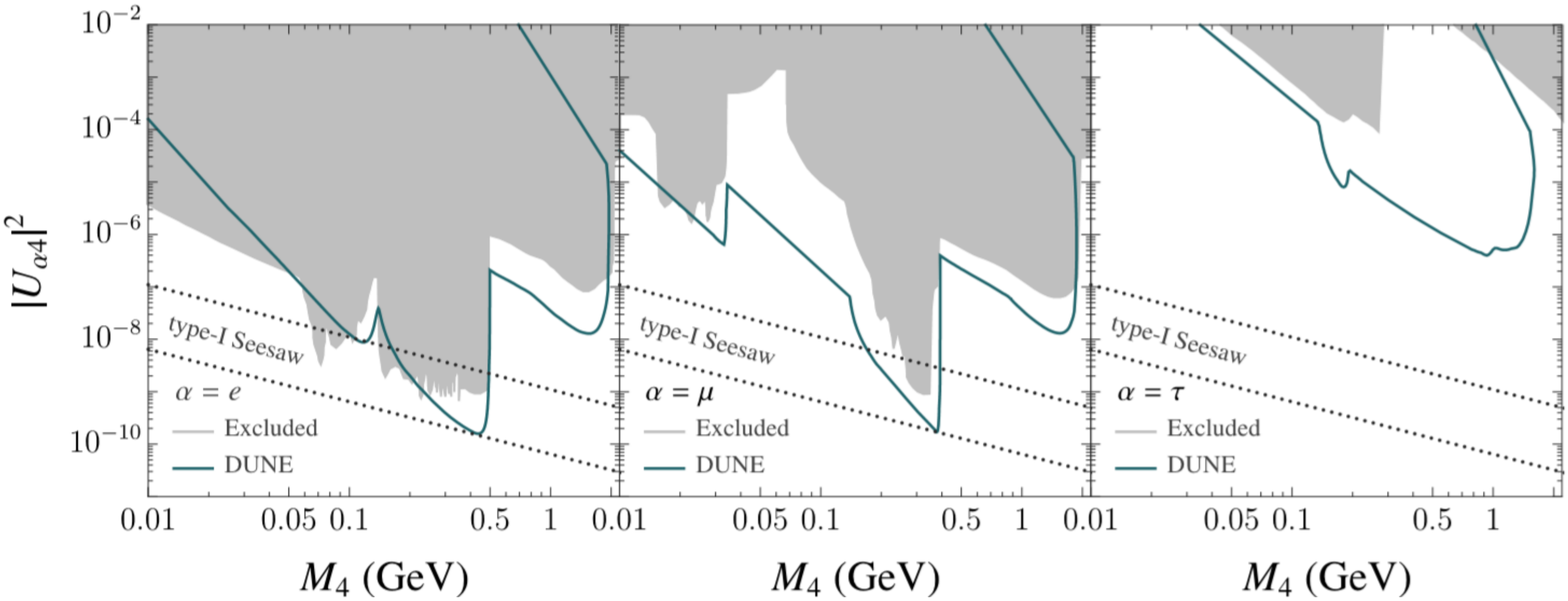

Large values of $\Delta M$ need fine tunned cancellations to keep $\nu$ mass low.

EFM, X. Marcano and D. Naredo-Tuero 2209.04461

# A new physics scale



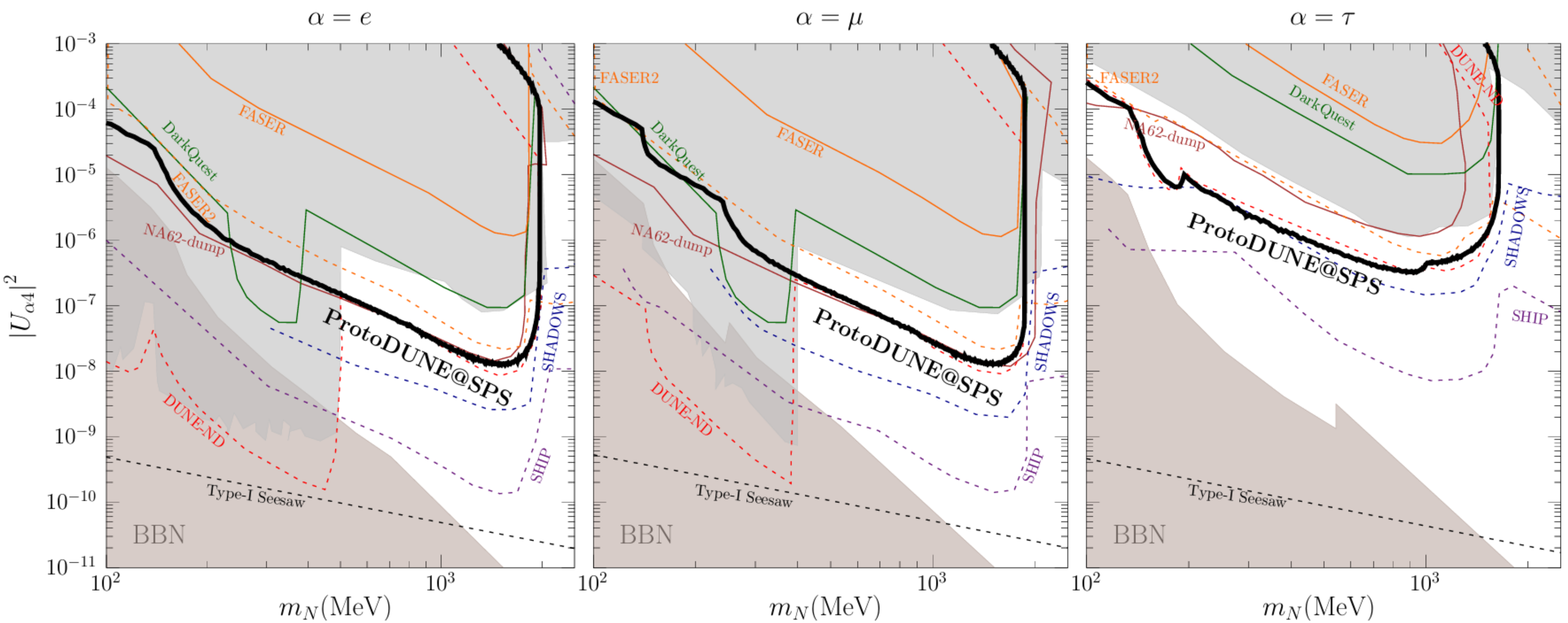
# Looking for $\nu_R$: Beam Dumps




P. Coloma, EFM, M. González-López, J. Hernández-García arXiv:2007.03701 also a FeynRules file with interactions between mesons and $N_R$ (HNLs)

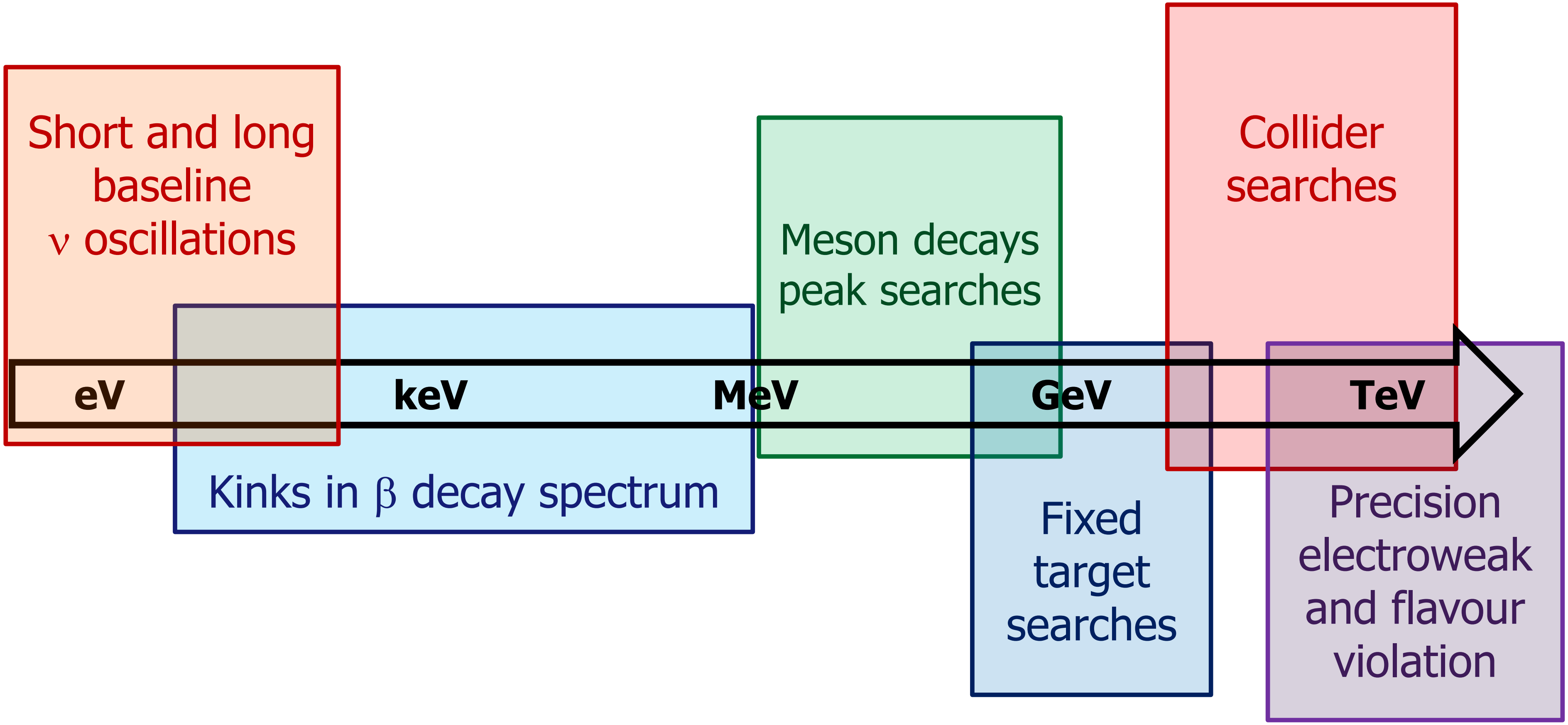
See also J. L. Feng, A. Hewitt, F. Kling and D. La Rocco 2405.07330 for a python library

# Looking for $\nu_R$: Beam Dumps



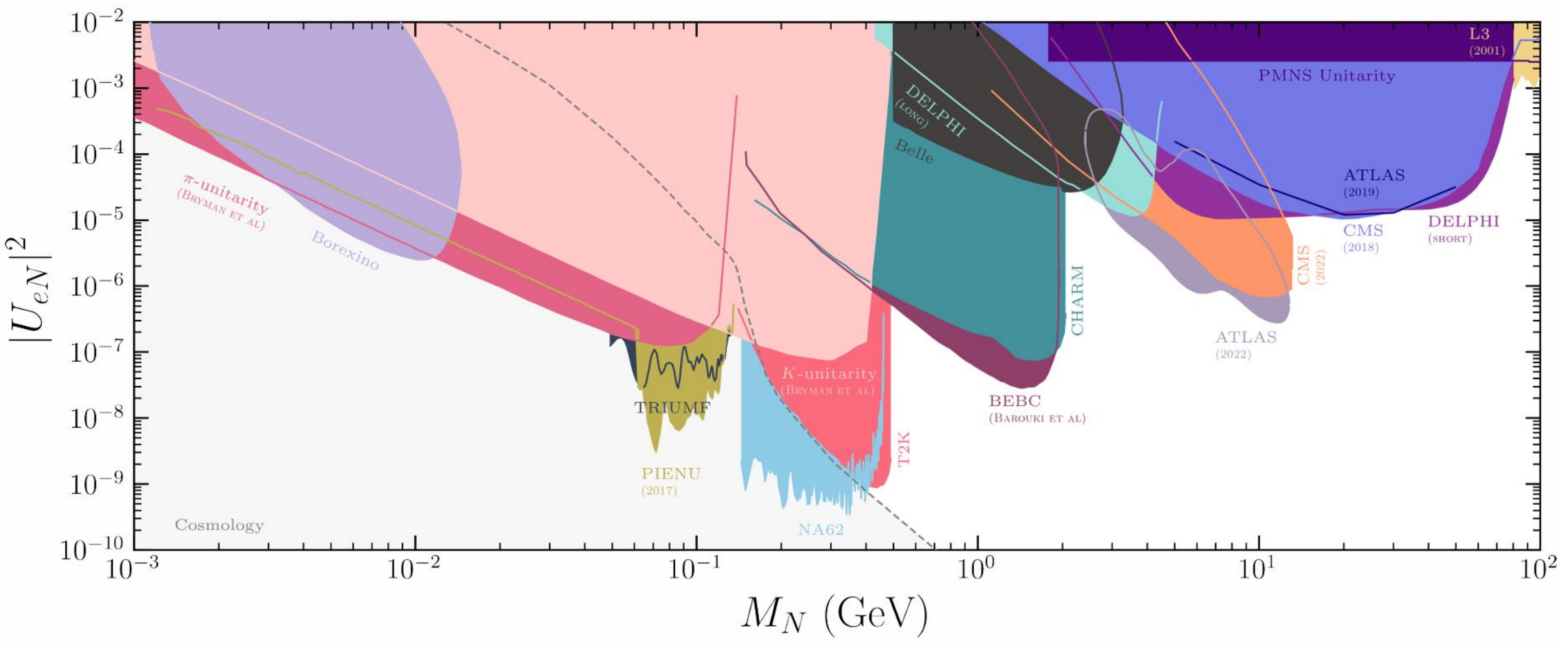

P. Coloma, J. Lopez-Pavon, L. Molina-Bueno and S. Urrea 2304.06765

# A new physics scale



# Looking for $\nu_R$

All together:




EFM, M. González-López, J. Hernández-García, M. Hostert, J. López-Pavón arXiv:2304.06772
https://github.com/mhostert/Heavy-Neutrino-Limits
See also: P. D. Bolton, F. F. Deppisch and P. S. B. Dev arXiv:1912.03058

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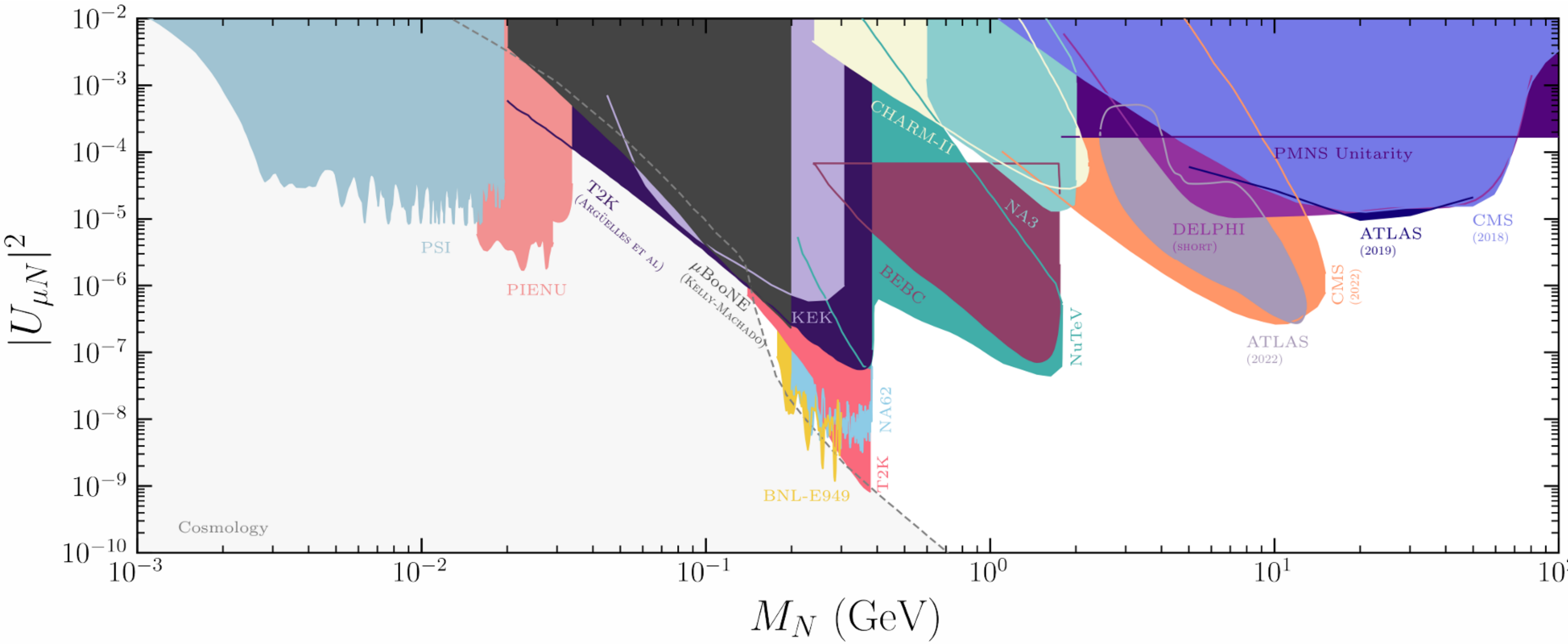


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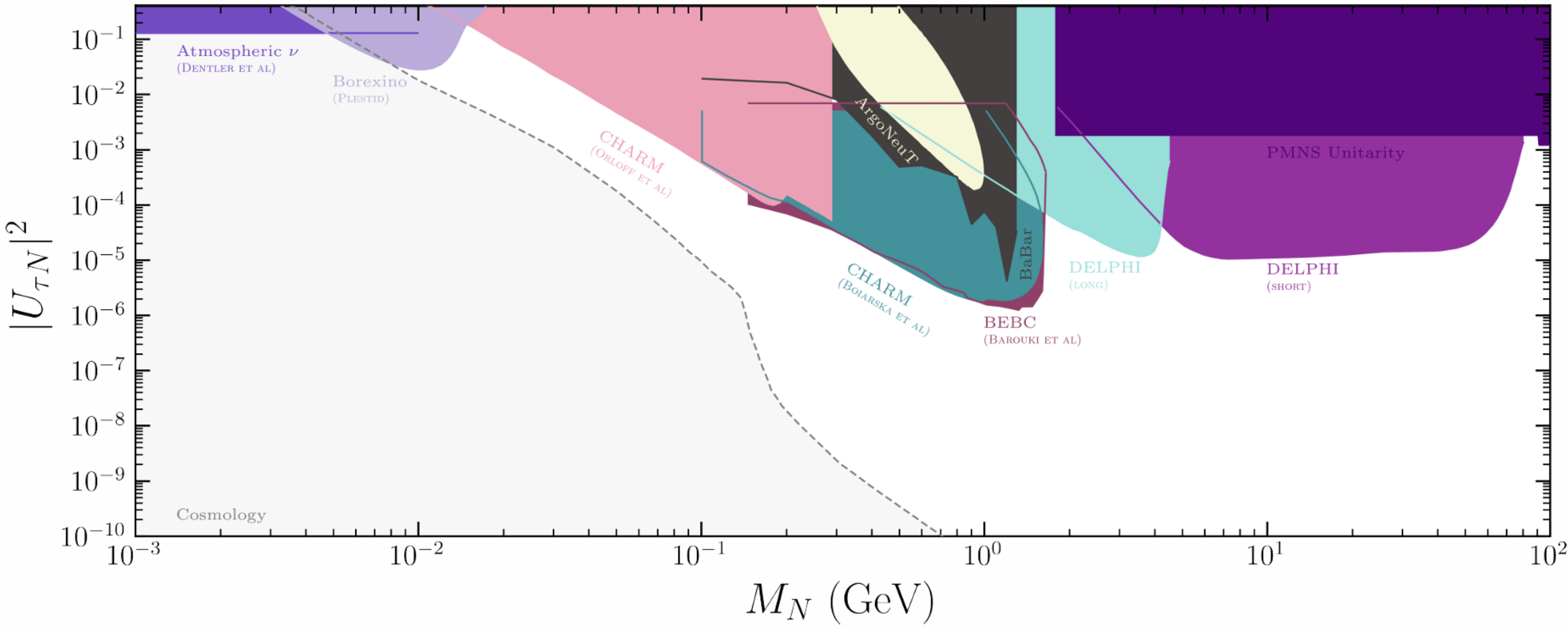


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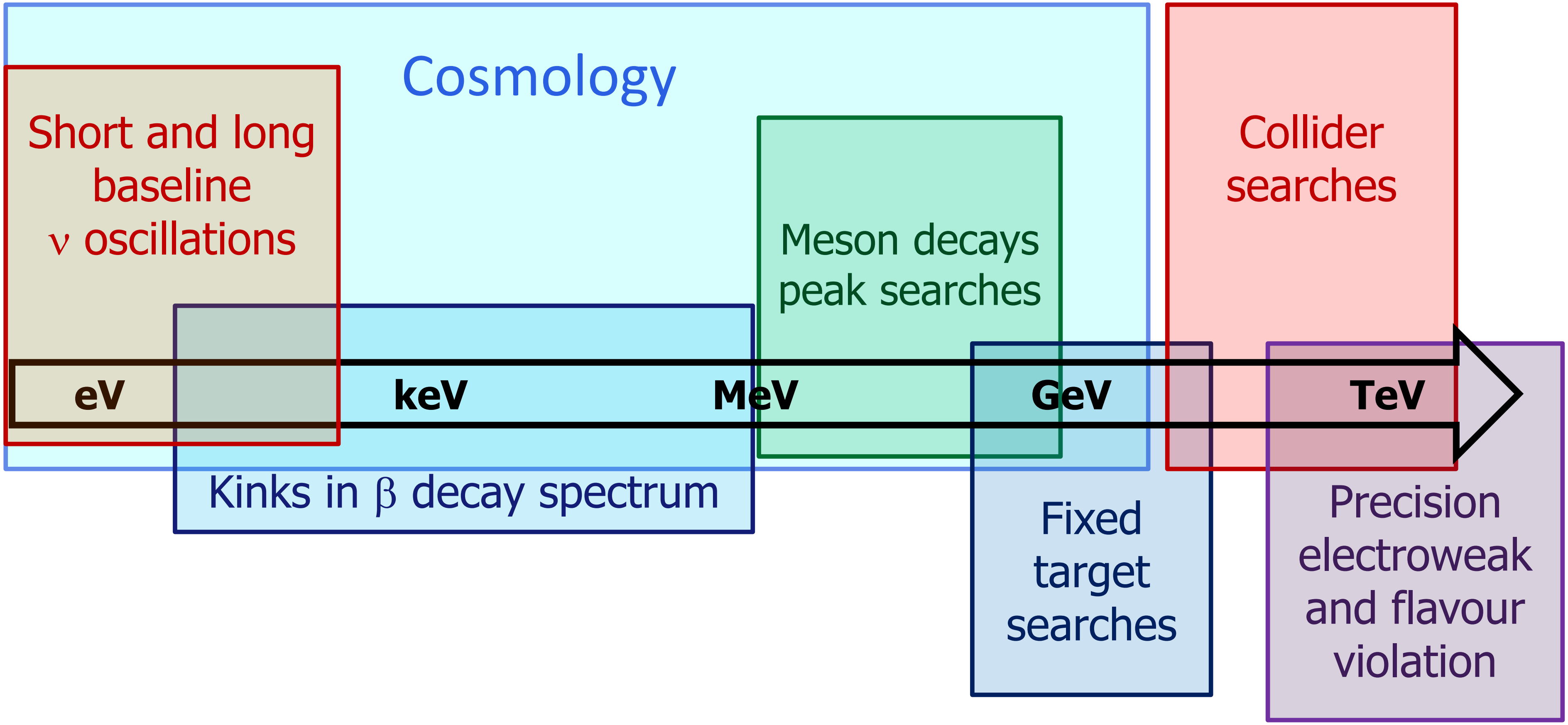
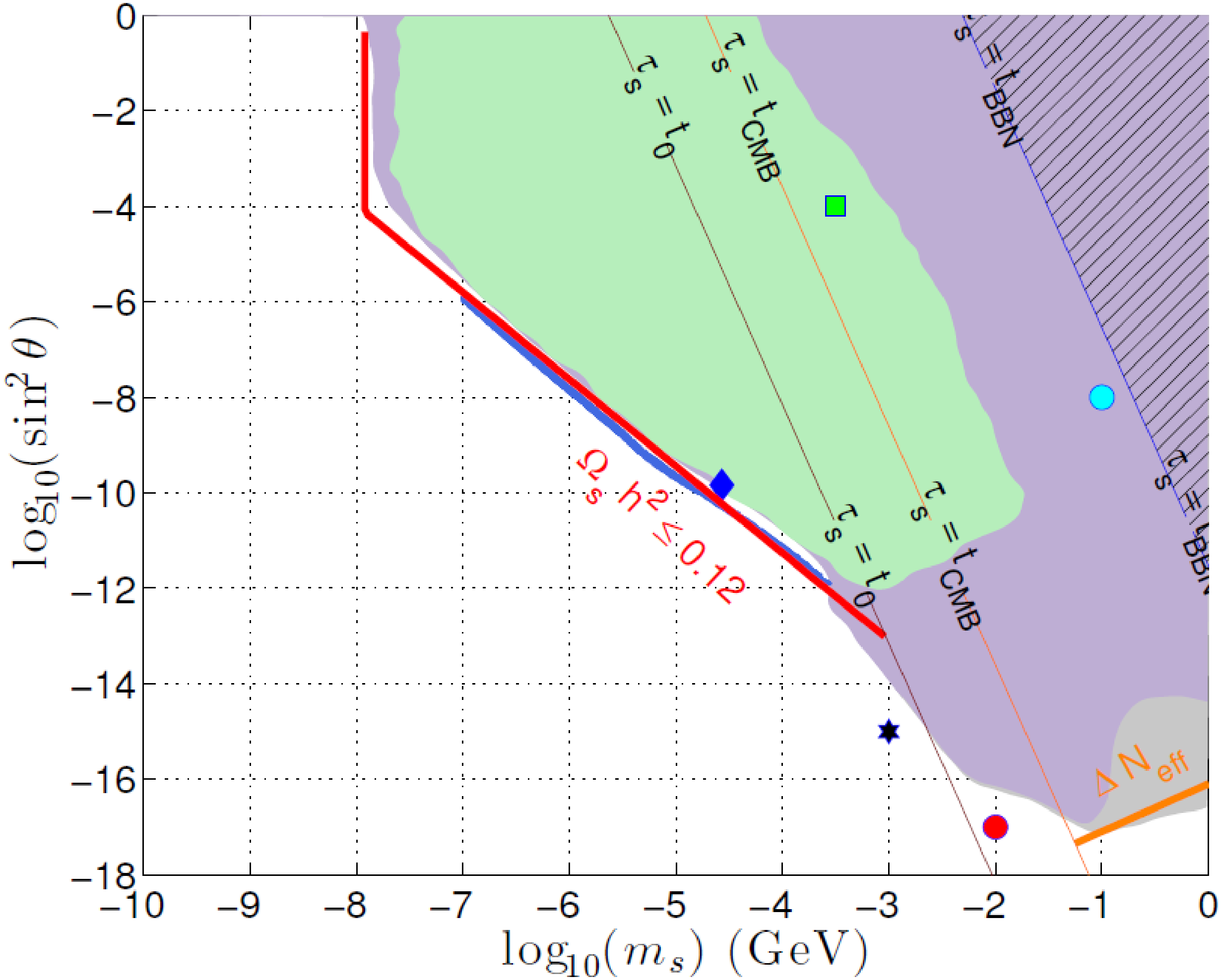


# Cosmology




A. C Vincent, EFM, P. Hernandez, M. Lattanzi and O. Mena arXiv:1408.1956
See also K. Langhoff, N. J. Outmezguine, and N. L. Rodd arXiv:2209.06216

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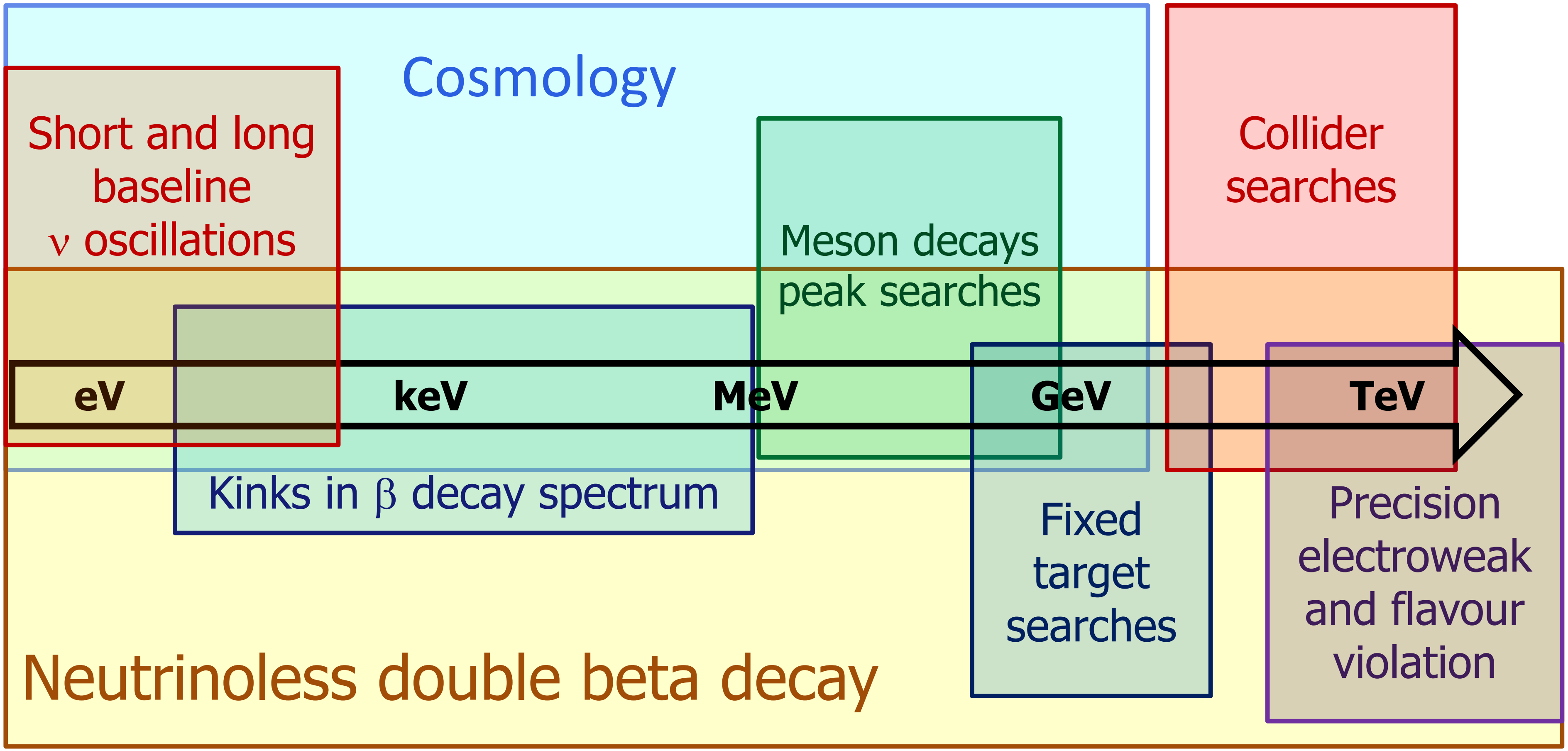
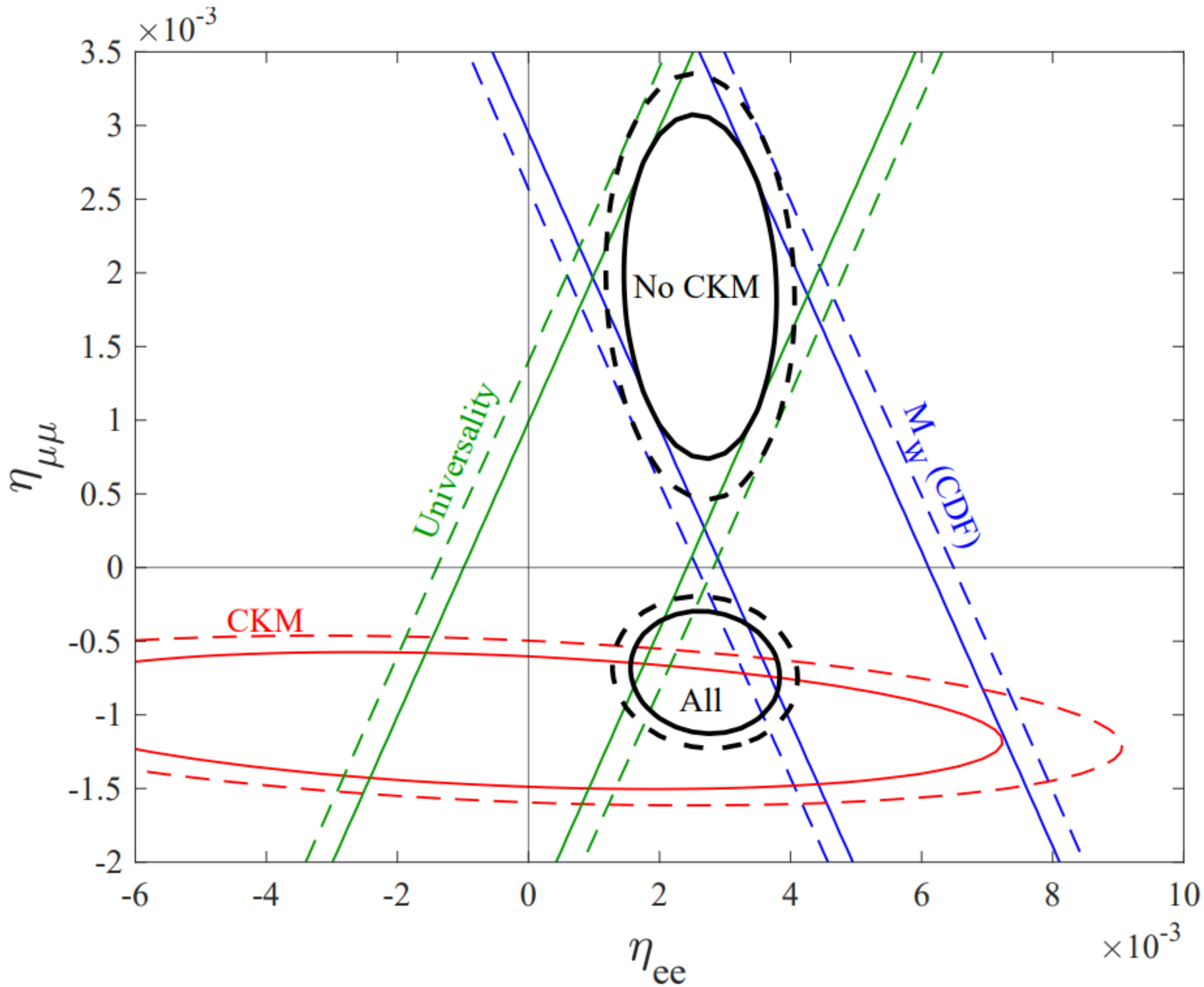


# Conclusions

- Neutrino masses and mixings imply new BSM physics
- The simplest extension, right-handed neutrinos, already imply a lot of new phenomenology to search for:
  - Non-unitarity, searches at colliders, fixed targets, cosmology, $0\nu\beta\beta$,…
- Also offers conexions to other open problems of the SM
  - Baryogenesis, Dark Matter, Flavour puzzle...
- Neutrino detectors can also probe for other BSM physics
- Neutrino physics is an excellent window BSM!!

# Non-unitarity and $M_W$ from CDF




M. Blennow, P. Coloma, EFM, M-González-Lopez 2204.04559
M. Blennow, EFM, J. Hernandez-Garcia, X. Marcano and D. Naredo-Tuero and J. Lopez-Pavon 2306.01040

# Non-unitarity in oscillations

Just replace $U$ by $N$

$$P_{\alpha\beta}(L) = \sum_{i,j} N_{\beta i} N^*_{\alpha i} N_{\alpha j} N^*_{\beta j} e^{\frac{-\Delta m^2_{ij} L}{2E}}$$

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Careful!! The "zero distance effect" will also be present in the data used to estimate the flux and cross section

For instance, if the prediction for $P_{\mu e}$ comes from near detector data on $P_{\mu\mu}$:

$$\hat{P}_{\mu e}(L) = \frac{P_{\mu e}(L)}{P_{\mu\mu}(0)} = \frac{\sum_{i,j} N_{ei} N^*_{\mu i} N_{\mu j} N^*_{ej} e^{\frac{-\Delta m^2_{ij} L}{2E}}}{\left|\left(NN^\dagger\right)_{\mu\mu}\right|^2}$$

M. Blennow, P. Coloma, EFM, J. Hernandez-Garcia and J. Lopez-Pavon arXiv:1609.08637

# Non-unitarity in oscillations

Also, no zero distance effect in disappearance channles!!

$$\hat{P}_{\mu\mu}(L) = \frac{P_{\mu\mu}(L)}{P_{\mu\mu}(0)} = \frac{\sum_{i,j} N_{\mu i} N^*_{\mu i} N_{\mu j} N^*_{\mu j} e^{\frac{-\Delta m^2_{ij} L}{2E}}}{\left|\left(N N^\dagger\right)_{\mu\mu}\right|^2}$$

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These are often thought to be the strongest bounds, but the effect cancels (together with the systematics) when using actual data involving $\nu$ to predict the unoscillated events

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And data involving neutrinos is always necessary:
If I know $\pi$ flux from hadroproduction need $\pi \to \mu\nu$ Br
Even if computing from "first principles" need $G_F$ ($\mu$ decay) and $V_{ud}$ ($\beta$ decay)

M. Blennow, P. Coloma, EFM, J. Hernandez-Garcia and J. Lopez-Pavon arXiv:1609.08637

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At most, if the prediction comes from a different channel, one may constrain the ratio

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D. Aloni,
A Dery
2211.09638

But these are more efficiently constraint from LFU bounds, from instance $\pi$ decay ratios, no need to also detect the $\nu$…

# Non-Unitarity vs oscillations

Bounds from a global fit to flavour and Electroweak precision data

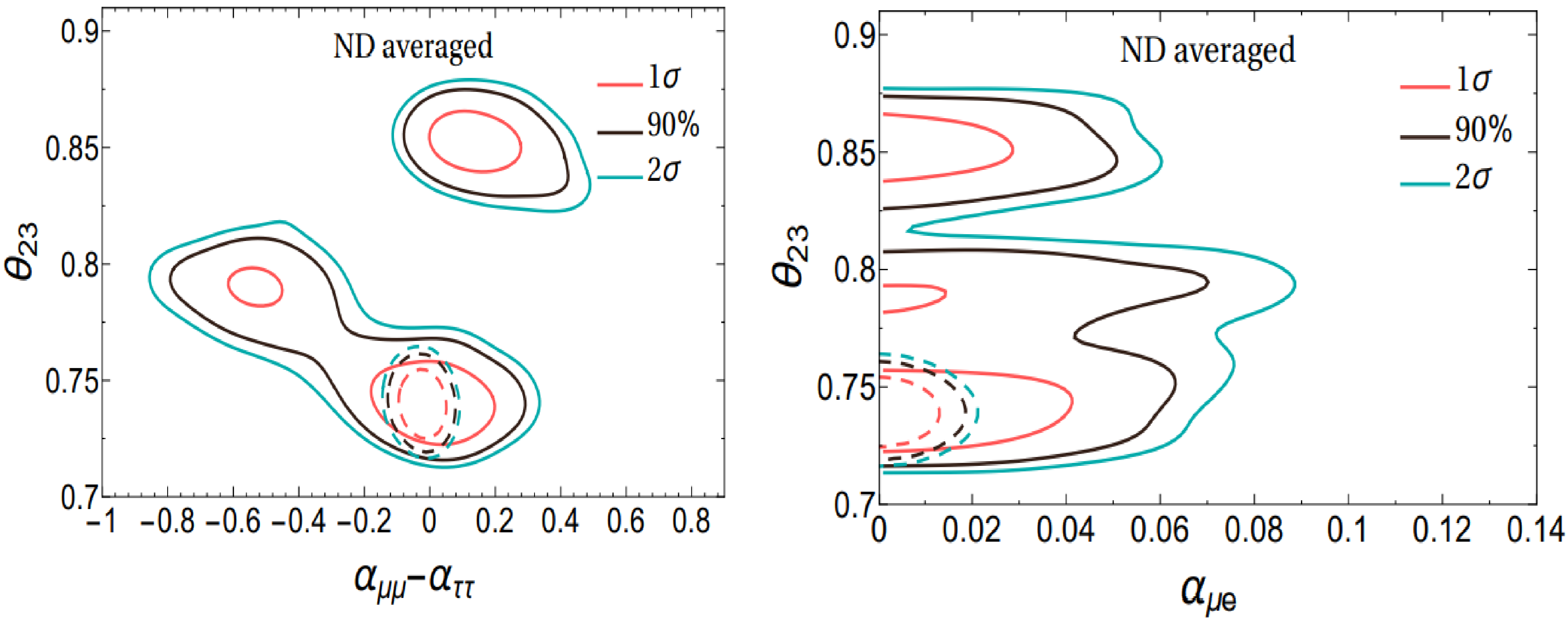
| | "flavor+electroweak" $m >$ EW ($2\sigma$ limit) | Oscillations (from zero distance effects in disappearance, 90%) |
|---|---|---|
| $\alpha_{ee}$ | $1.4 \cdot 10^{-3}$ | $8.4 \cdot 10^{-3}$ |
| $\alpha_{\mu\mu}$ | $1.4 \cdot 10^{-4}$ | $5.0 \cdot 10^{-3}$ |
| $\alpha_{\tau\tau}$ | $8.8 \cdot 10^{-4}$ | $6.5 \cdot 10^{-2}$ |
| $\lvert\alpha_{\mu e}\rvert$ | $7.8 \cdot 10^{-4}$ $(2.4 \cdot 10^{-5})$ | $9.2 \cdot 10^{-3}$ |
| $\lvert\alpha_{\tau e}\rvert$ | $1.8 \cdot 10^{-3}$ | $1.4 \cdot 10^{-2}$ |
| $\lvert\alpha_{\tau\mu}\rvert$ | $3.6 \cdot 10^{-4}$ | $1.1 \cdot 10^{-2}$ |

From C. Argüelles et al Snowmass Whitepaper arXiv:2203.10811 and M. Blennow, EFM, J. Hernandez-Garcia, X. Marcano and D. Naredo-Tuero and J. Lopez-Pavon 2306.01040

with

$$N = \begin{pmatrix} 1-\alpha_{ee} & 0 & 0 \\ -\alpha_{\mu e} & 1-\alpha_{\mu\mu} & 0 \\ -\alpha_{\tau e} & -\alpha_{\tau\mu} & 1-\alpha_{\tau\tau} \end{pmatrix} U$$

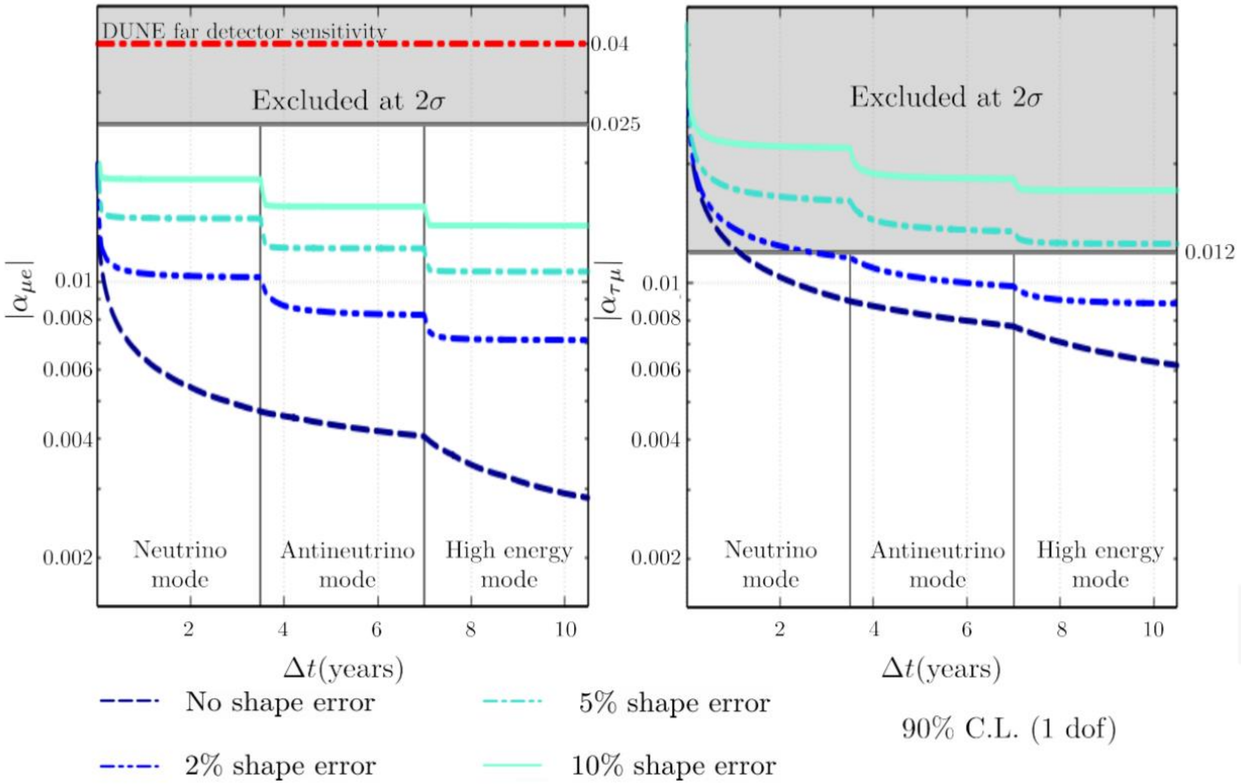
# Non-unitarity at DUNE




The far detector would suffer from degeneracies but they are lifted with present bounds

M. Blennow, P. Coloma, EFM, J. Hernandez-Garcia and J. Lopez-Pavon arXiv:1609.08637

# Non-unitarity at DUNE




The posible improvements by the near detector depend critically on the level of systematic uncertainties, particularly affecting the shape of the spectra

P. Coloma, J. Lopez-Pavon, S. Rosauro-Alcaraz and S. Urrea arXiv:2105.11466

# Looking for $\nu_R$: Non-Unitarity

It has become common to call them:

"Indirect" or "charged leptons" | "Direct" or "neutrinos"

| | "flavor+electroweak" $m >$ EW ($2\sigma$ limit) | Oscillations (from zero distance effects in disappearance, 90%) |
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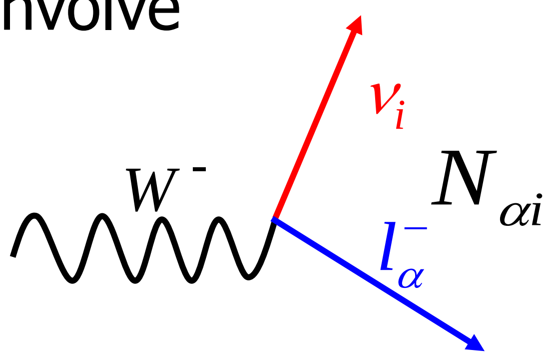
From C. Argüelles et al Snowmass Whitepaper arXiv:2203.10811
and M. Blennow, EFM, J. Hernandez-Garcia, X. Marcano and D. Naredo-Tuero
and J. Lopez-Pavon 2306.01040

# Looking for $\nu_R$: Non-Unitarity

It has become common to call them:

"Indirect" or "charged leptons" "Direct" or "neutrinos"

But they all involve



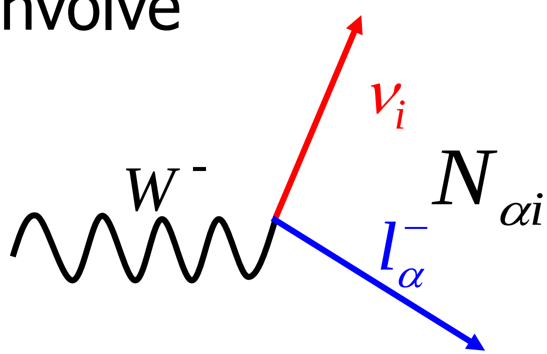
# Looking for $\nu_R$: Non-Unitarity

It has become common to call them:

"Indirect" or "charged leptons"

"Direct" or "neutrinos"

But they all involve




it's where the sensitivity comes from…

So they are all equally "direct" and they all have a neutrino and a charged lepton…

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Which one is more robust/model-independent?

"Indirect" or "charged leptons" "Direct" or "neutrinos"

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$G_F$ from μ decay compared to from $M_W$, measurements of $\sin\theta_w$ at different energies (Moller, colliders) and $\beta$ and $K$ decays. Very different physics! Not easy to cancel all…

"Direct" or "neutrinos"

Introducing an NSI operator with u and d quarks the zero distance effect could be cancelled

They also induce a zero-distance effect…

But the "neutrino" bounds are often assumed to be more robust… why??

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