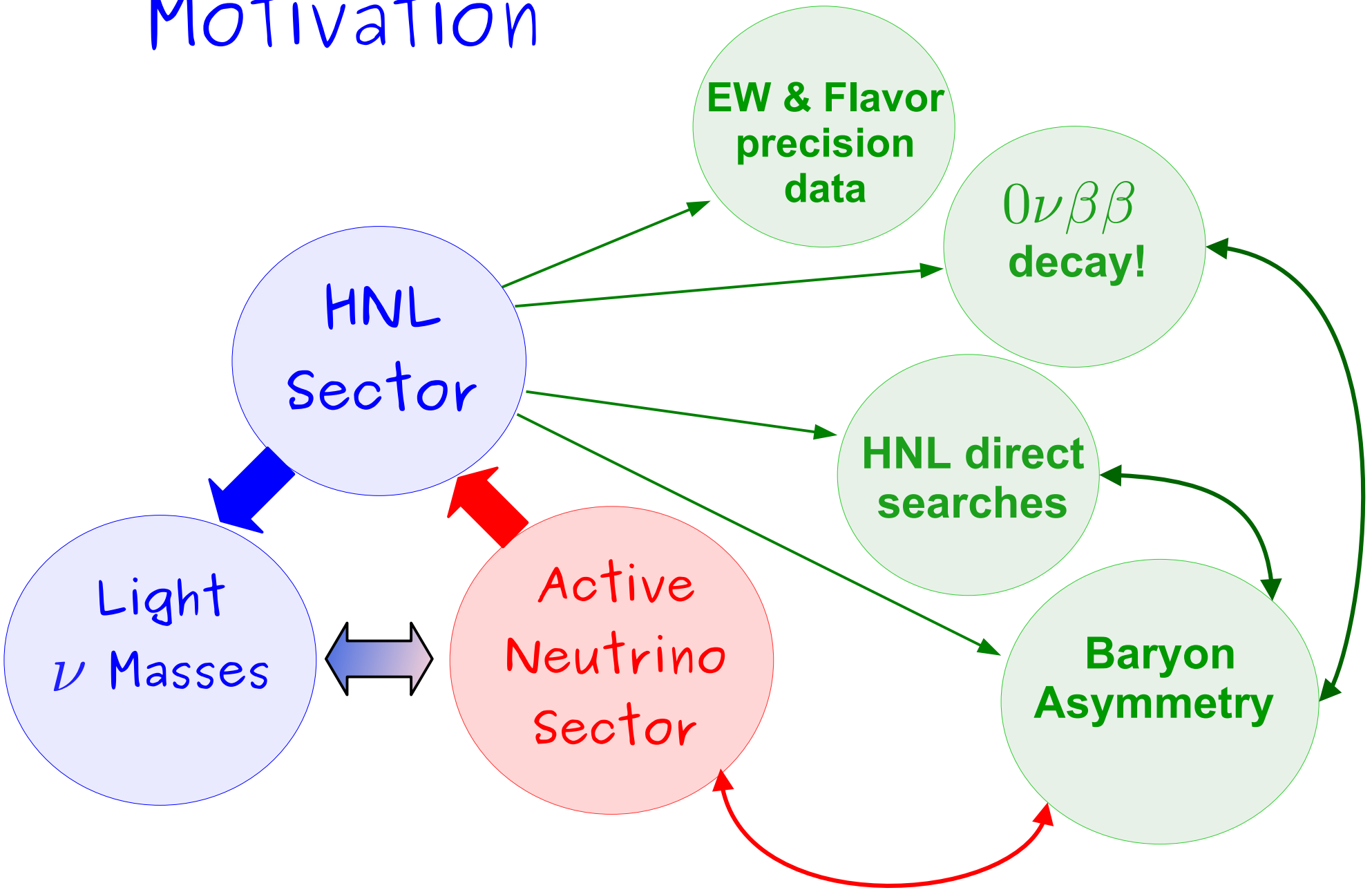
Heavy Neutral Leptons (HNLs)
Phenomenological Overview

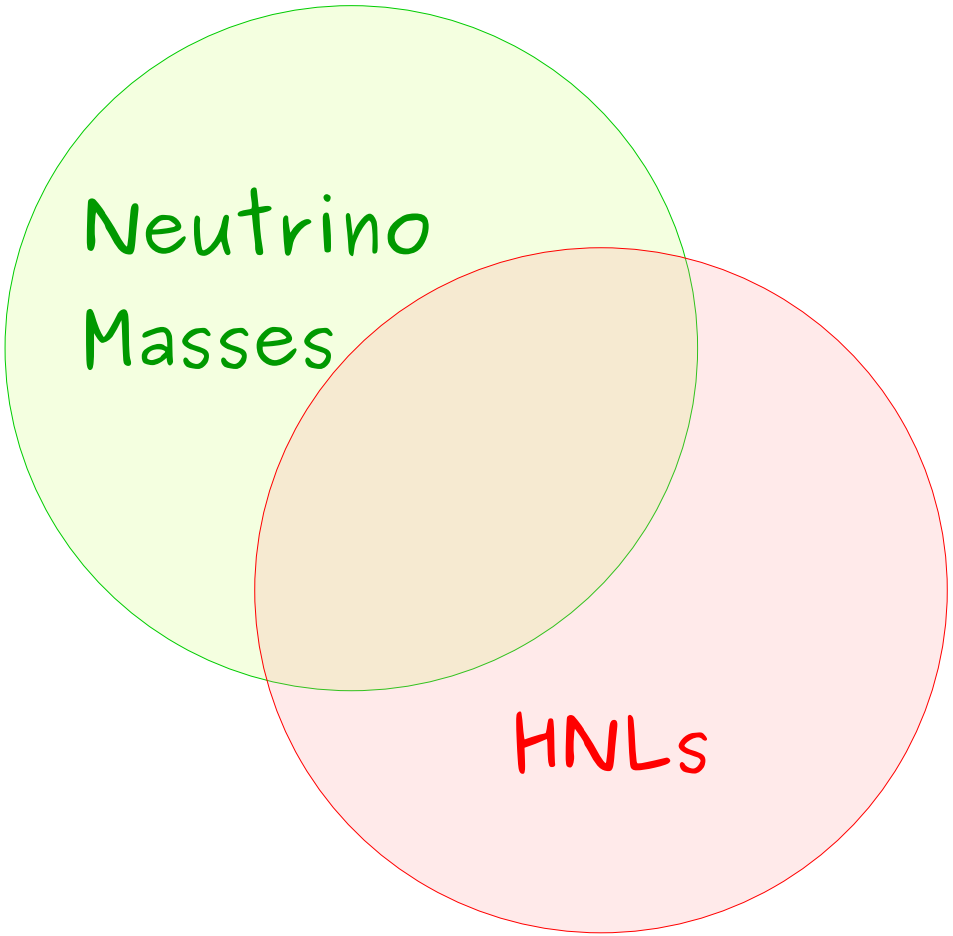
Jacobo López-Pavón

Atmospheric Neutrinos: Experiments and Phenomenology
5 December 2024, Valencia

Project CNS2022-136013 funded by MICIU/AEI/10.13039/501100011033
and the European Union NextGenerationEU/PRTR

Motivation


EW & Flavor precision data
$0\nu\beta\beta$ decay!
HNL Sector
HNL direct searches
Light ν Masses
Active Neutrino Sector
Baryon Asymmetry

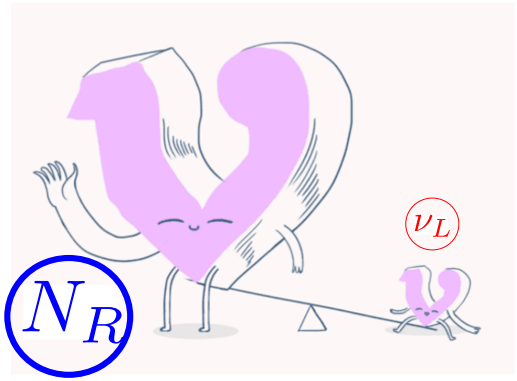

Neutrino
Masses
HNLs

Minimal model: Seesaw Model

- Simplest extension of SM able to account for neutrino masses. Consists in the addition of heavy fermion singlets (N_i) to the SM field content:

$$\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \mathcal{L}_{\mathcal{K}} - \boxed{\frac{1}{2}\overline{N_i^c} M_{ij} N_j - Y_{i\alpha}\overline{N_i}\widetilde{H}^\dagger L_\alpha} + h.c.$$

Light Neutrino Masses



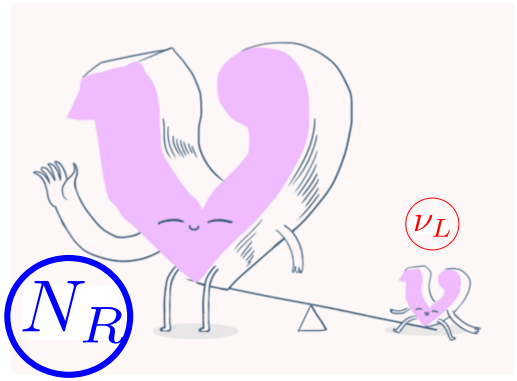
Minkowski 77; Gell-Mann, Ramond, Slansky 79
Yanagida 79; Mohapatra, Senjanovic 80

Minimal model: Mass Matrix

$$M_\nu = \begin{array}{c} \\ \nu \\ N^c \end{array} \begin{array}{c} \begin{array}{cc} \overline{\nu^c} & \overline{N} \end{array} \\ \begin{pmatrix} 0 & Y^T v/\sqrt{2} \\ Y v/\sqrt{2} & M \end{pmatrix} \end{array}$$

Light Neutrino Masses

$$\begin{pmatrix} \frac{v^2}{2} Y^T M^{-1} Y & 0 \\ 0 & M \end{pmatrix}$$



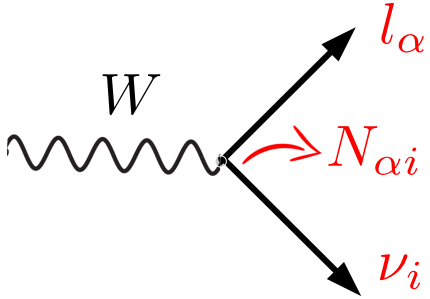
Minkowski 77; Gell-Mann, Ramond, Slansky 79
Yanagida 79; Mohapatra, Senjanovic 80; Schechter, Valle 80

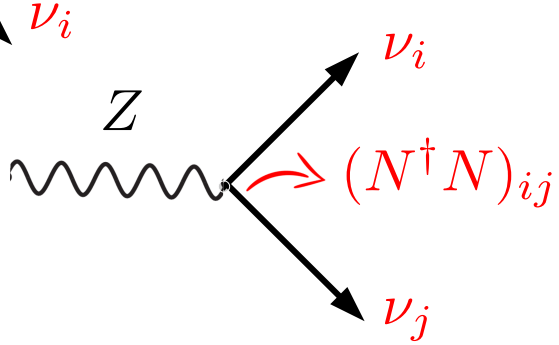
Mixing

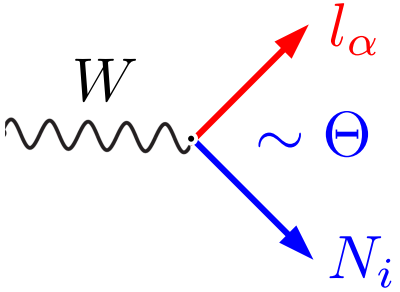
$\nu_i - \nu_\alpha$ mixing

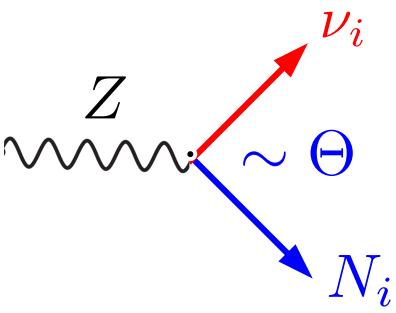
$$U = \begin{pmatrix} N & \Theta \\ R & S \end{pmatrix}$$

$N_i - \nu_\alpha$ mixing









Deviation from unitarity of the PMNS matrix

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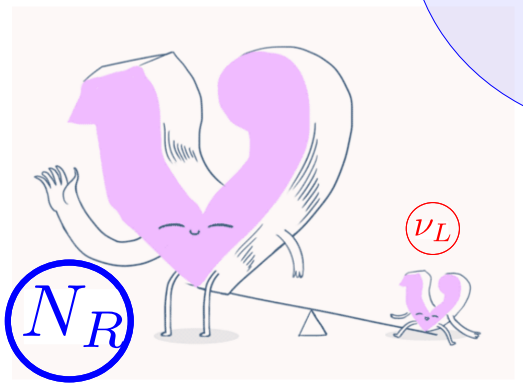
New Physics Scale

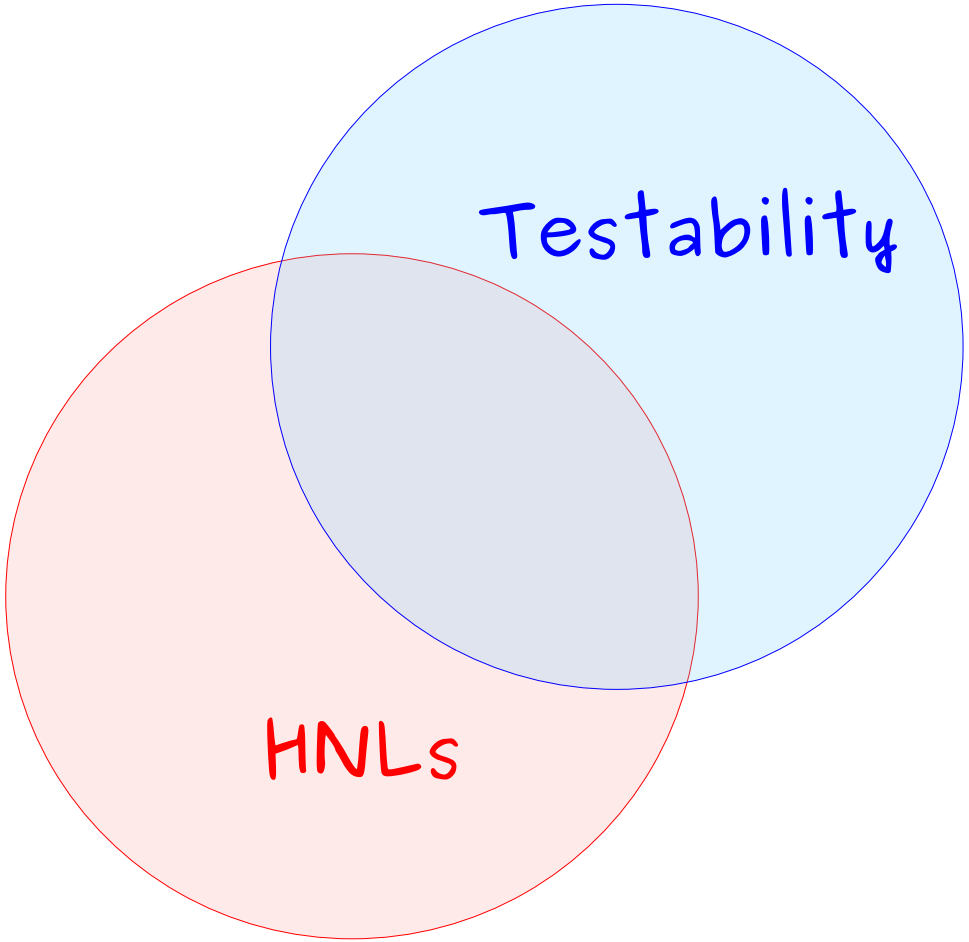
Lepton Number Violation

$0\nu\beta\beta$ **decay!**

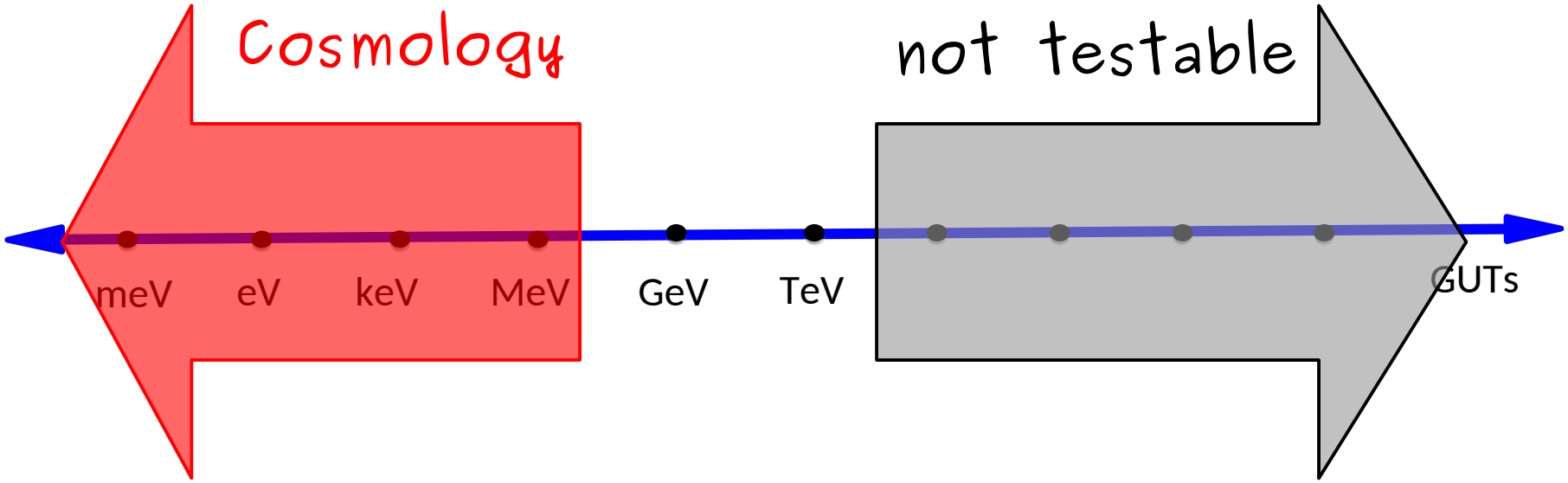
Leptogenesis!



Fukujita, Yanagida 1986

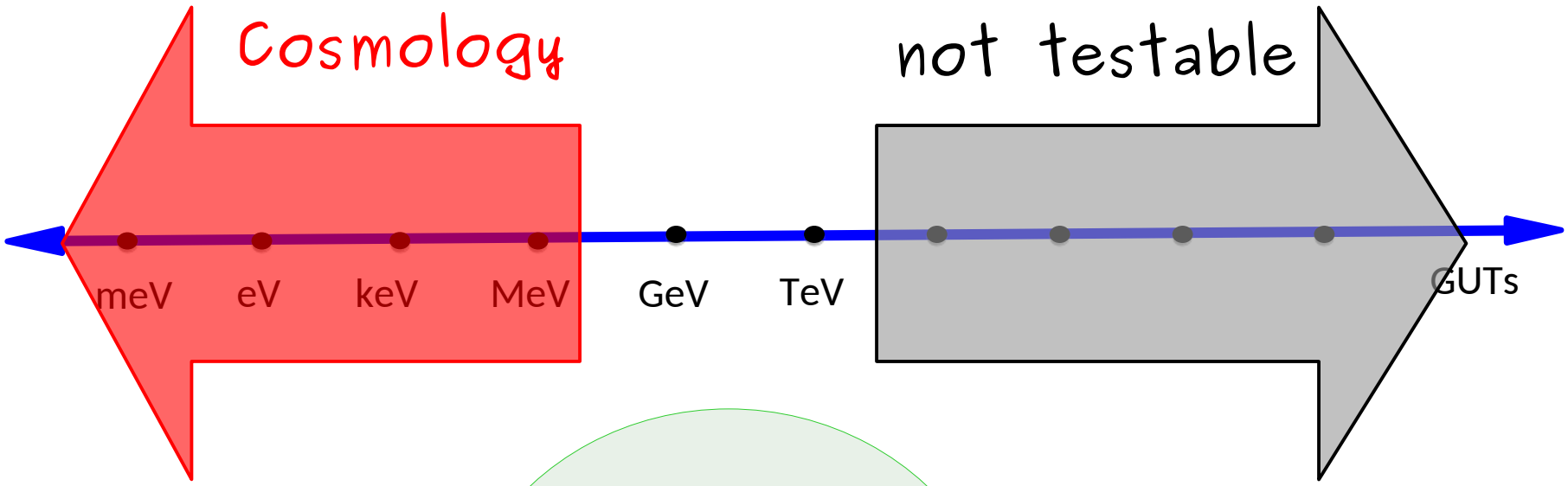

Testability
HNLs

The New Physics Scale



P. Hernandez, M. Kekic, JLP
1311.2614, 1406.2961
Bondarenko, Boyarsky,
Klaric,Mikulenko, Ruchayskiy,
Syvolap, Timiryasov
2101.09255
…

The New Physics Scale



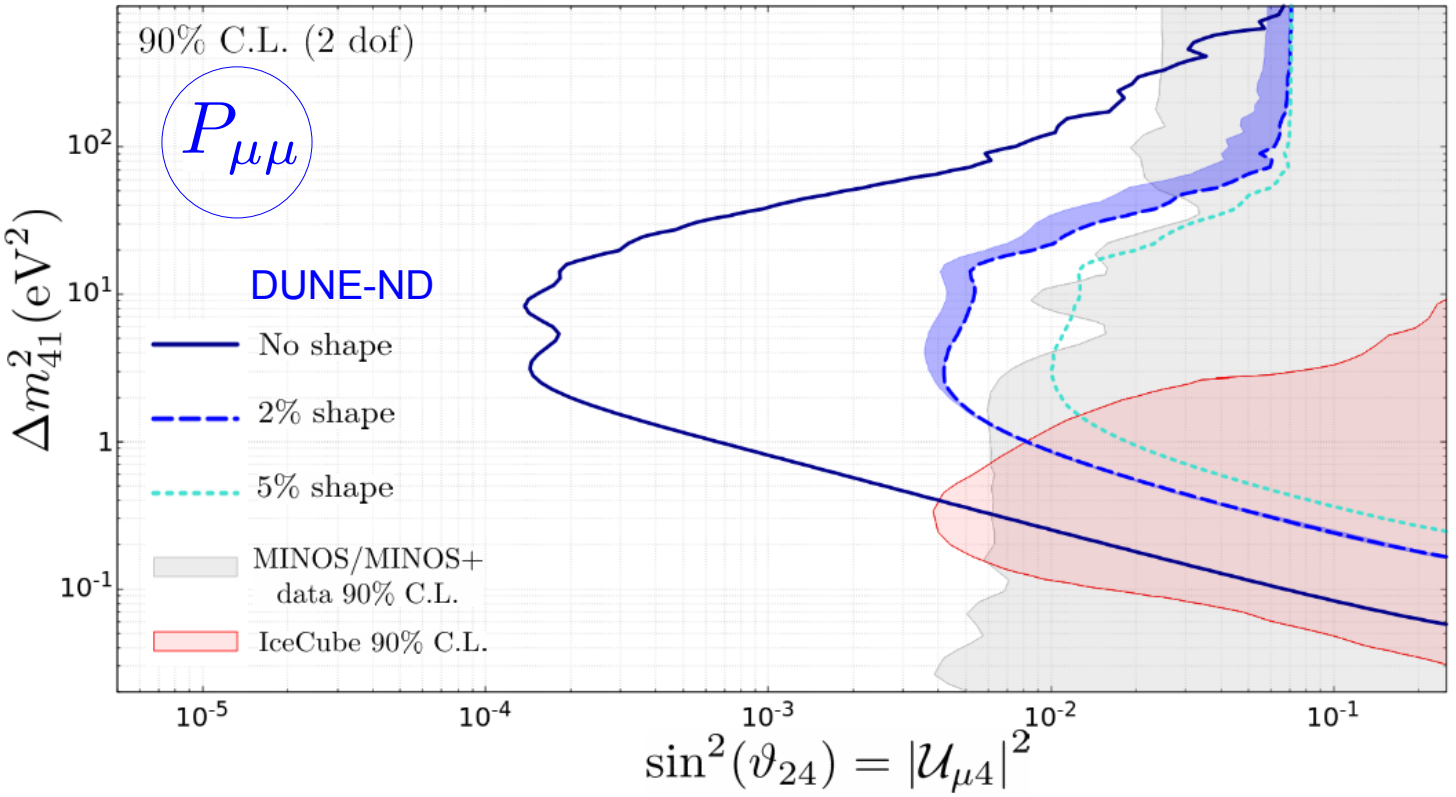
How about
Lab
Measurements?

Neutrino Oscillations

TeV
GeV
MeV
keV
eV

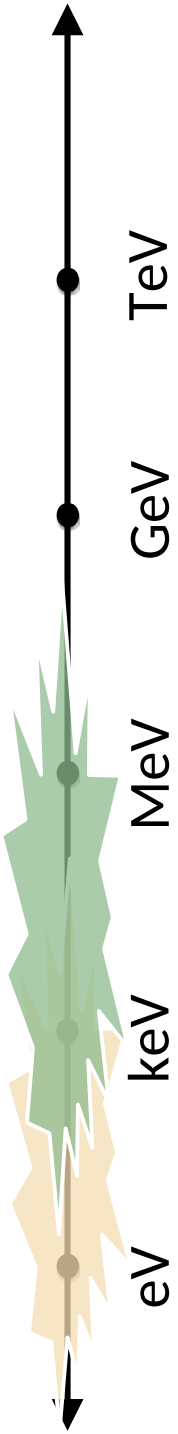
• For very light scales M, HNLs (in this regime usually called sterile neutrinos) participate in neutrino oscillations. In simplified 3+1 scenario:

See talks by Carlos A. Argüelles and Christoph A. Ternes

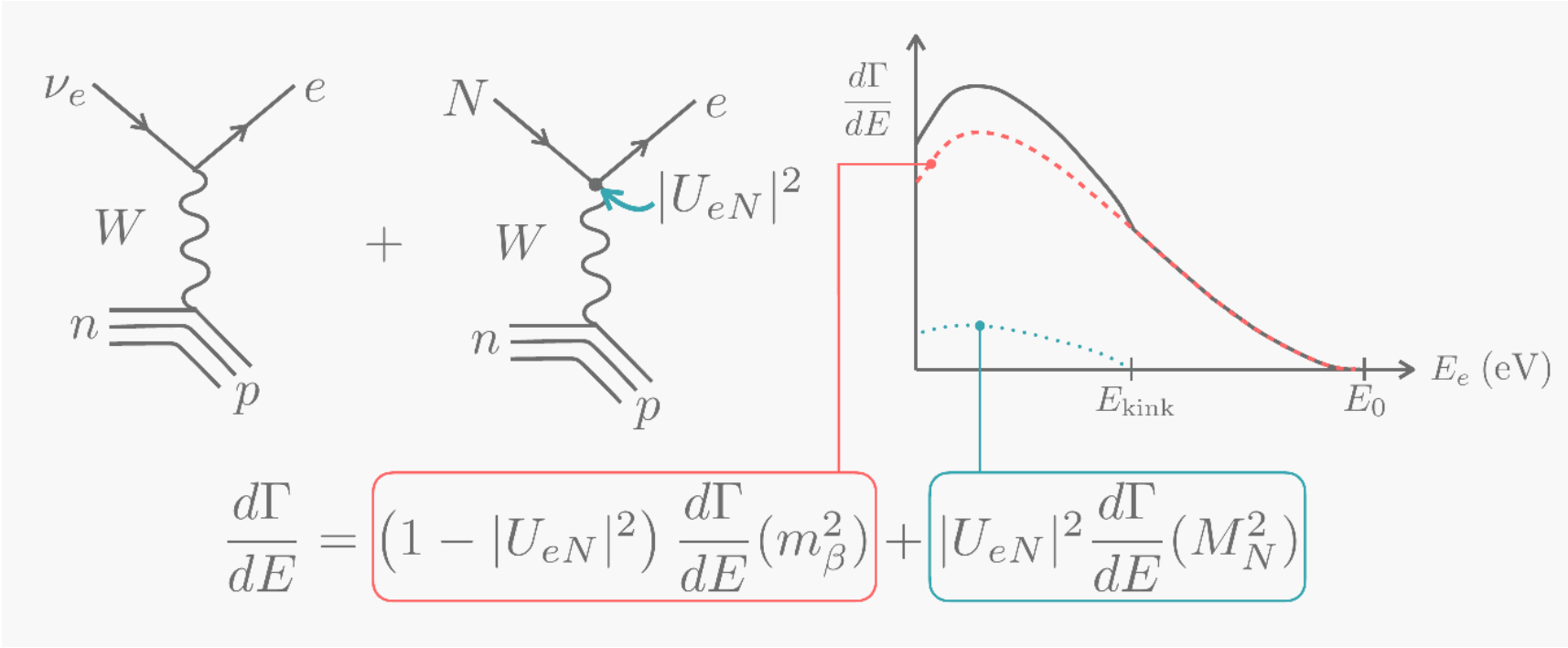


Coloma, JLP, Rosauro-Alcaraz, Urrea 2105.11466

Kinetic Searches

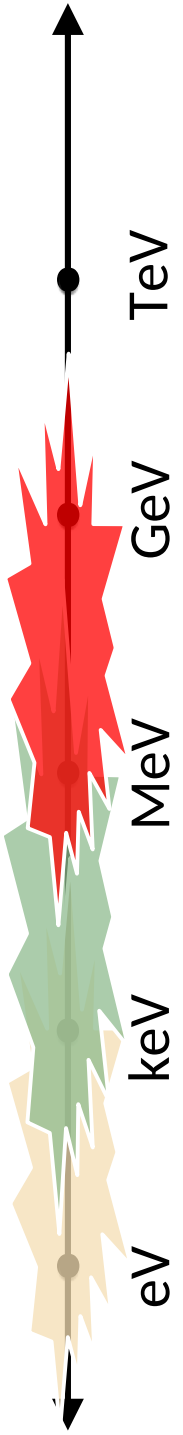


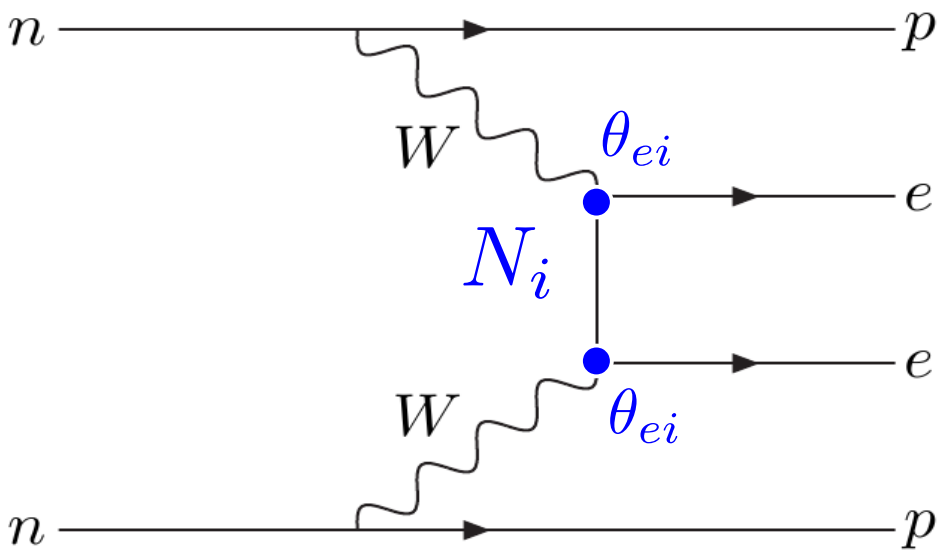
• Search for kinks in beta decays & peak searches in semileptonic meson decays (pion & kaon decays)



Cortesy of J. Hernandez-Garcia

Neutrinoless double beta decay



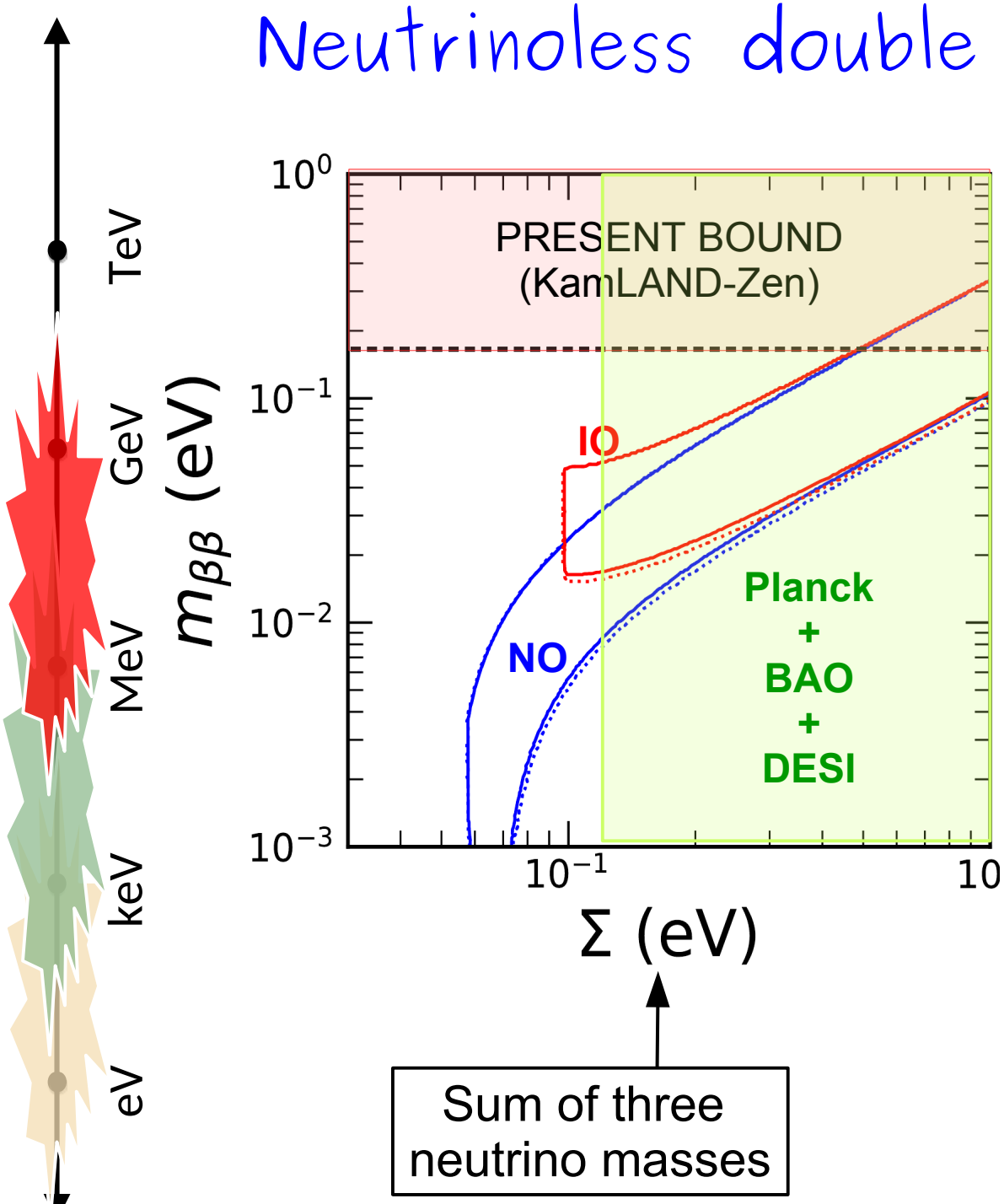


$$m_{\beta\beta} = \sum_{i=light} U_{ei}^2 m_i + \sum_{i=heavy} \overbrace{\frac{\mathcal{M}^{0\nu\beta\beta}(M_i)}{\mathcal{M}^{0\nu\beta\beta}(0)}}^{\text{NMEs}} \theta_{ei}^2 M_i$$

$$M_i \gg 100\,MeV: \quad \sim 1/M_i^2$$

$$M_i \ll 100\,MeV: \quad \sim 1$$

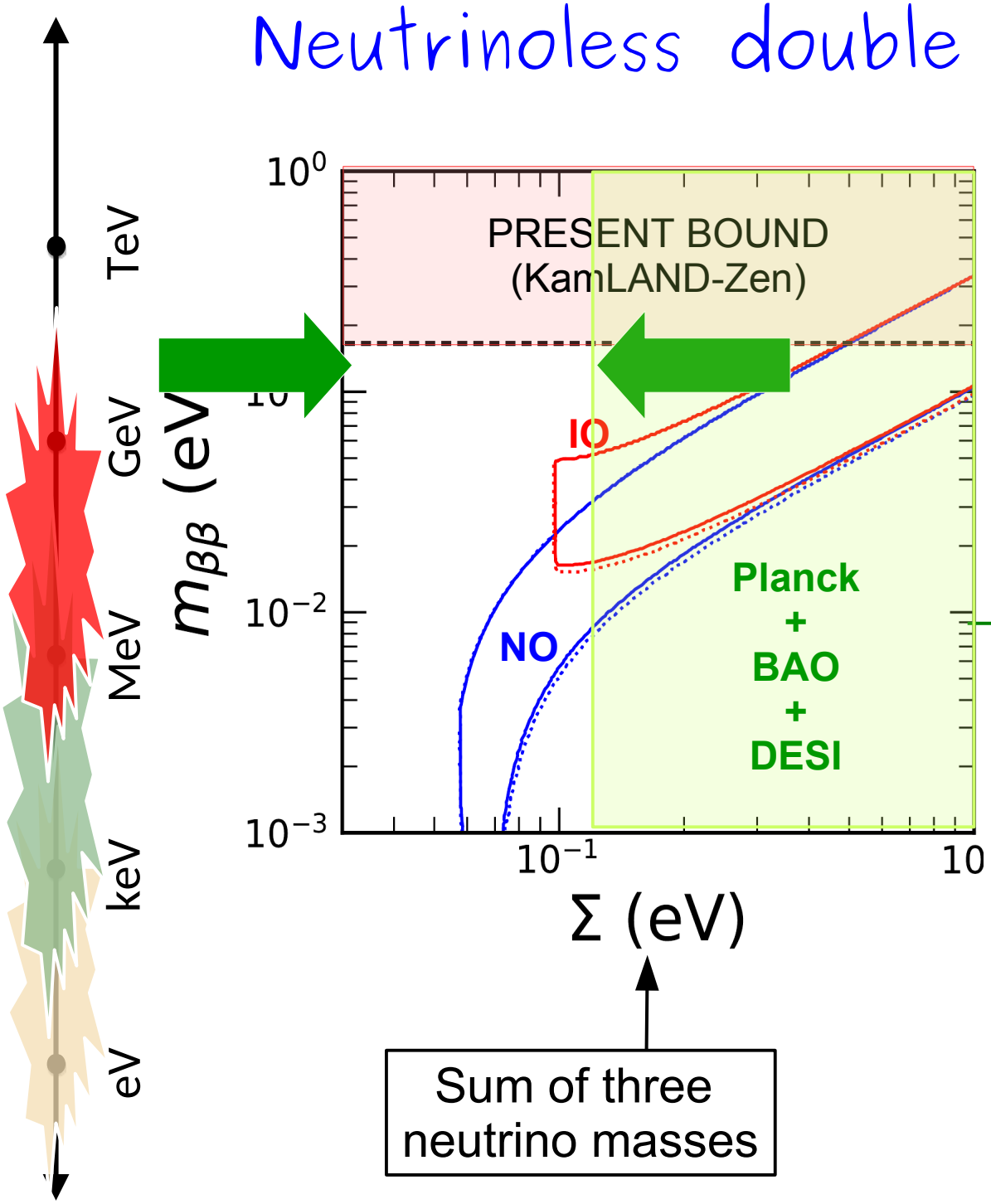
Neutrinoless double beta decay



- Outstanding complementarity among neutrino oscillations, $0\nu\beta\beta$ decay and cosmology.

- *Extremely relevant input in order to probe New Physics models responsible for ν mass generation*.

Neutrinoless double beta decay



- Outstanding complementarity among neutrino oscillations, $0\nu\beta\beta$ decay and cosmology.

- *Extremely relevant input in order to probe New Physics models responsible for ν mass generation*.

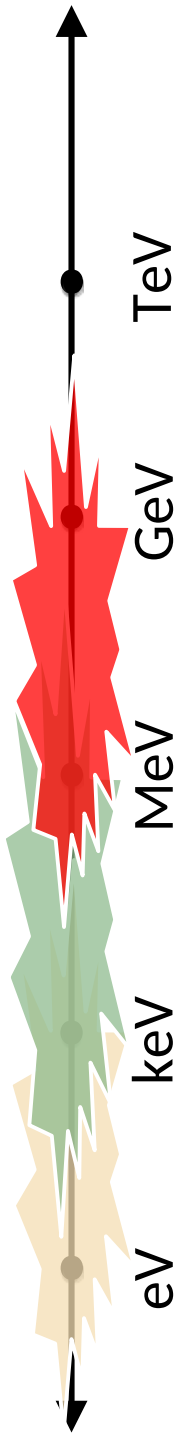
Posibilities:

- Dominated by New Physics as HNL contribution

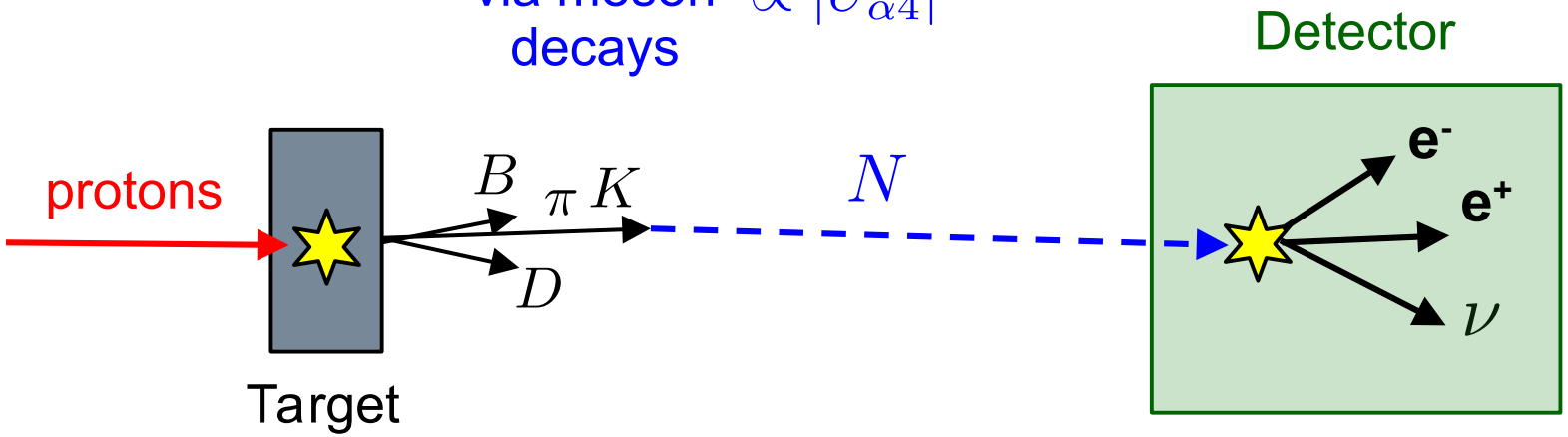
Ibarra, Molinaro, Petcov 2010;Mitra, Senjanovic, Vissani 2011;JLP, Pascoli, Wang 2012;JLP, Molinaro, Petcov 2015;Bolton, Deppisch, Dev 2020

- Cosmological bound could be relaxed. For instance, if neutrinos decay (new interactions required) Escudero, JLP, Rius, **Sandner** 2007.04994

Beam dump experiments

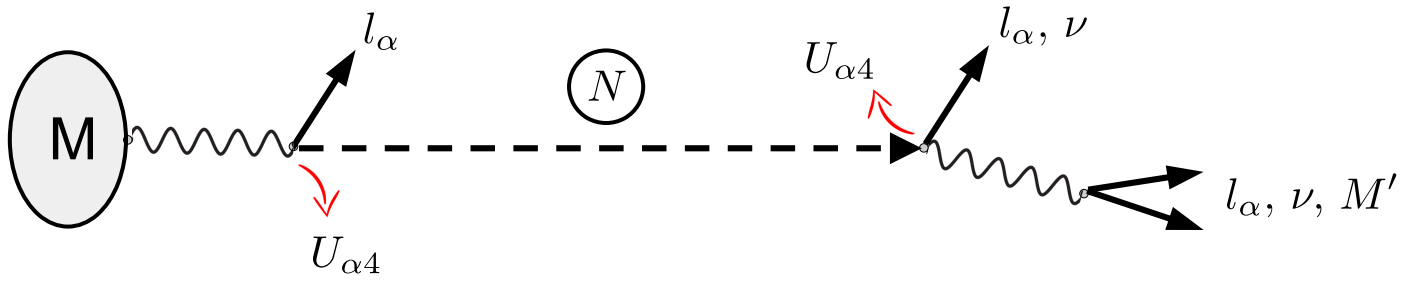


HNL production via meson decays $\propto |U_{\alpha 4}|^2$

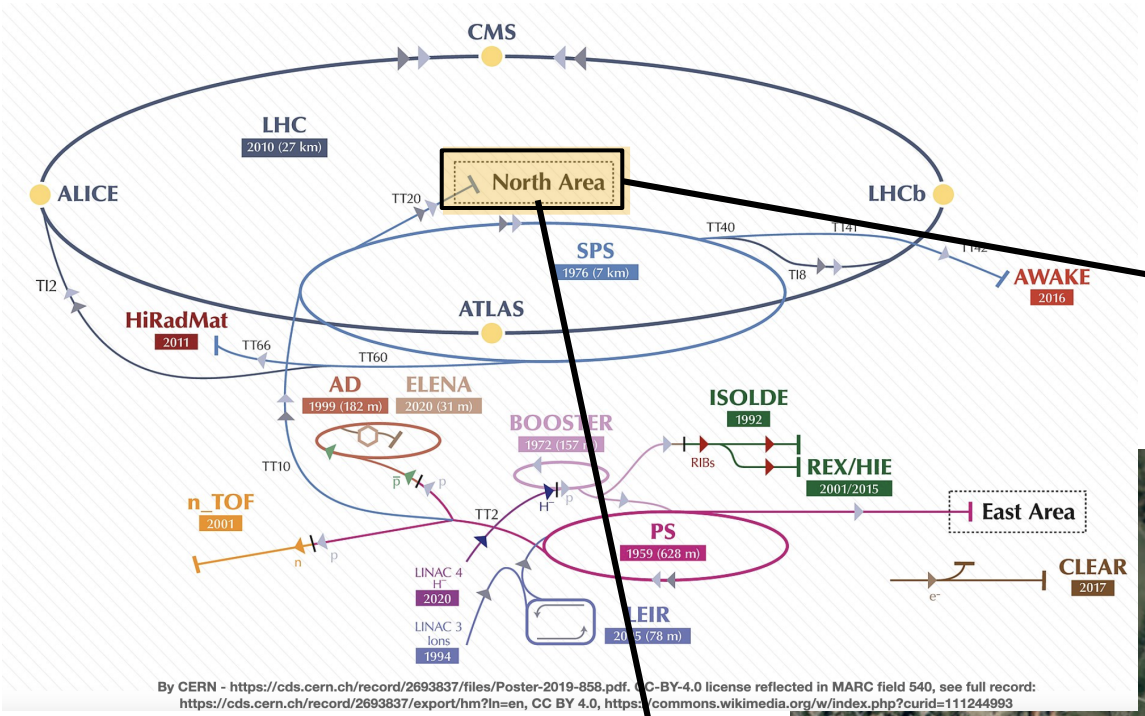


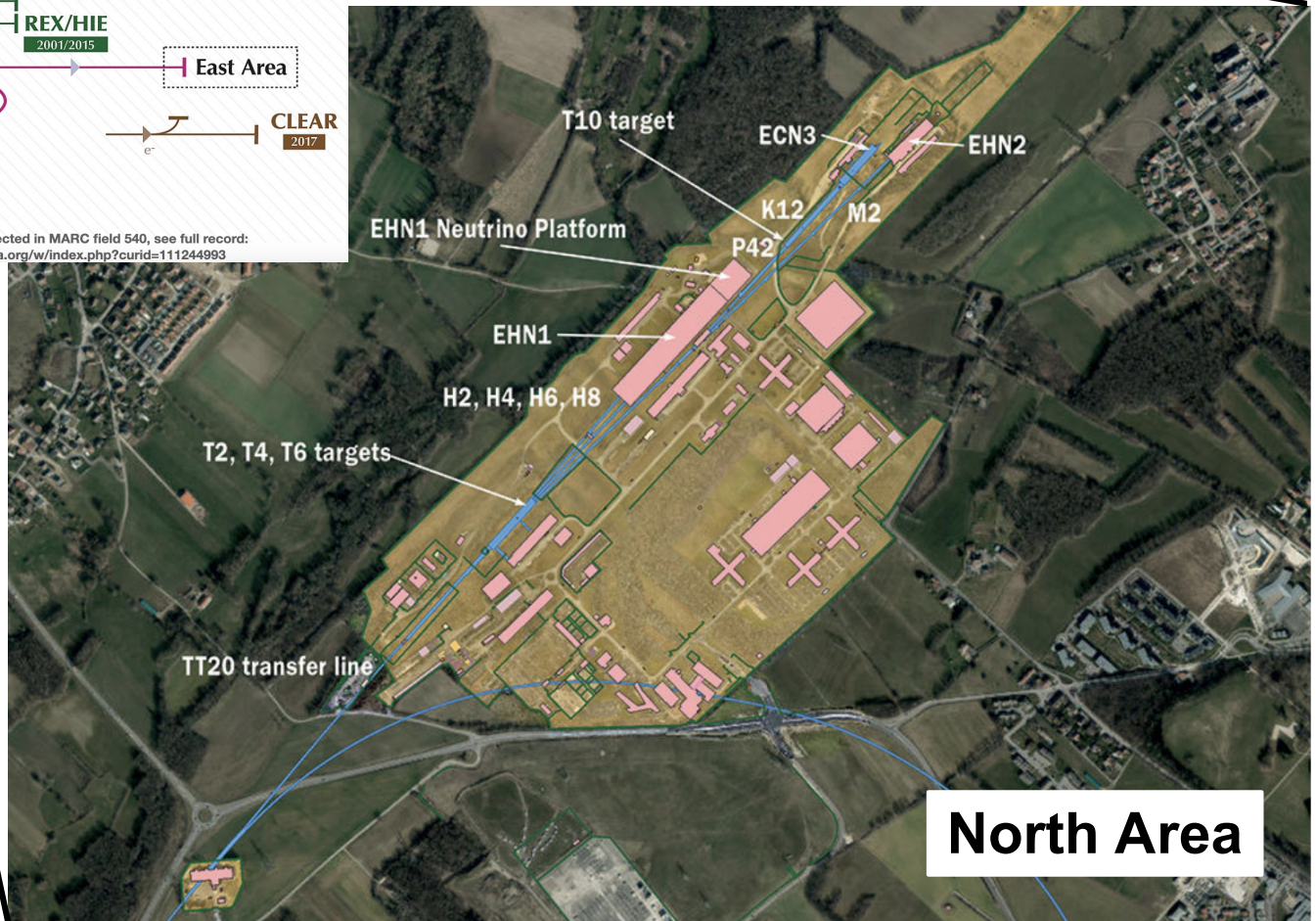
Production of Mesons

HNL decay into SM particles $\propto |U_{\alpha 4}|^2$



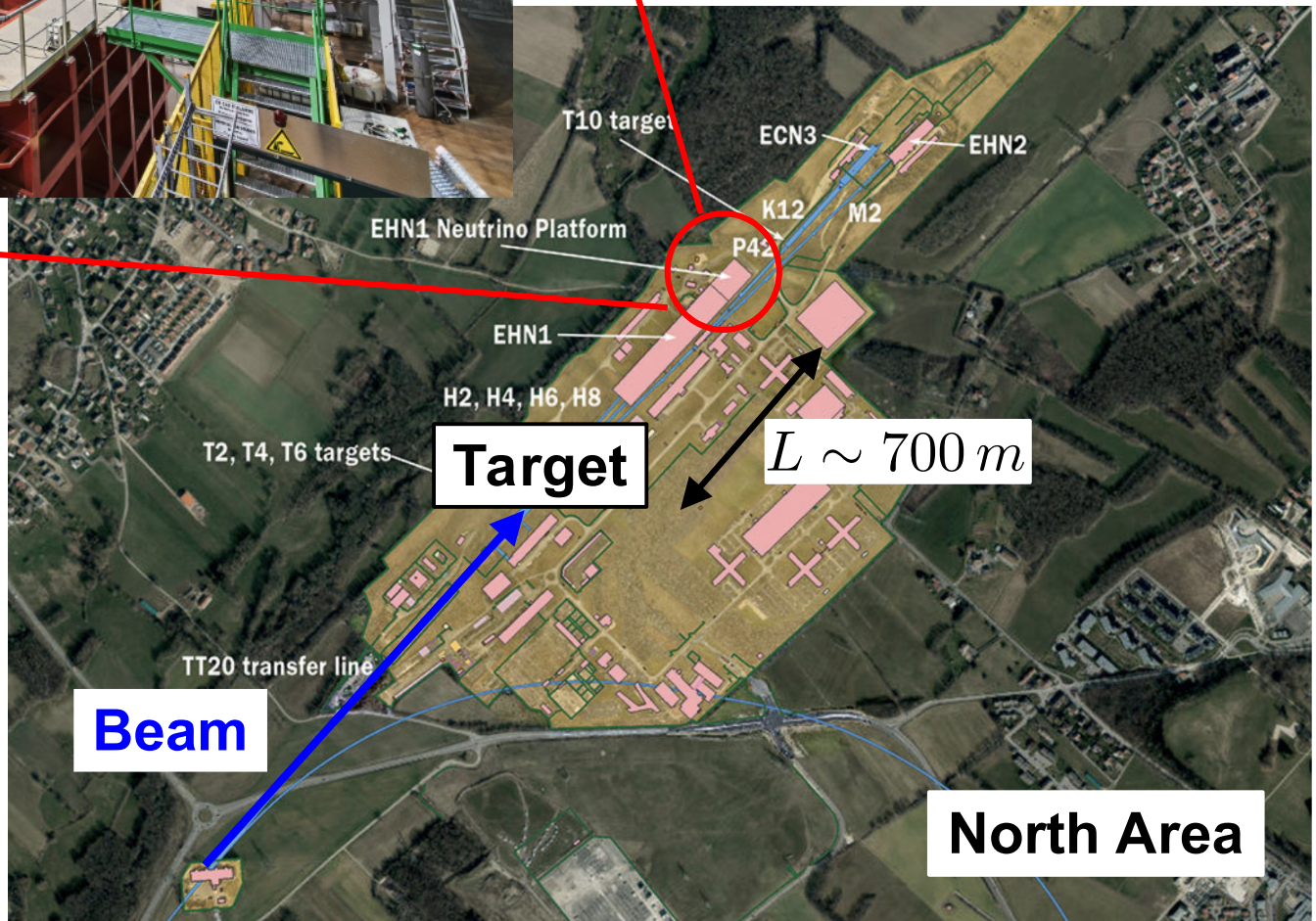
ProtoDUNE in beam dump configuration?



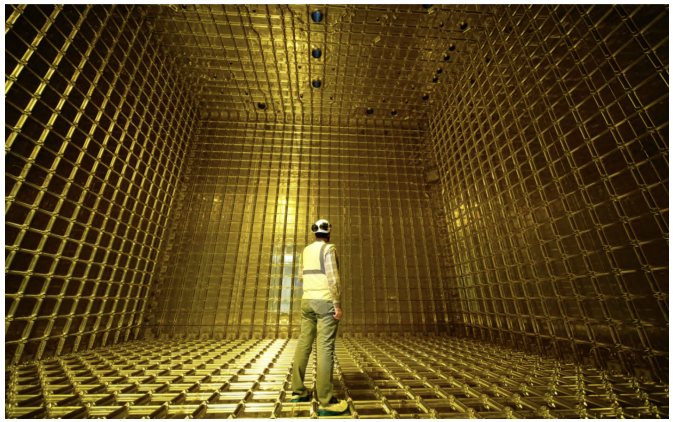


ProtoDUNE in beam dump configuration?

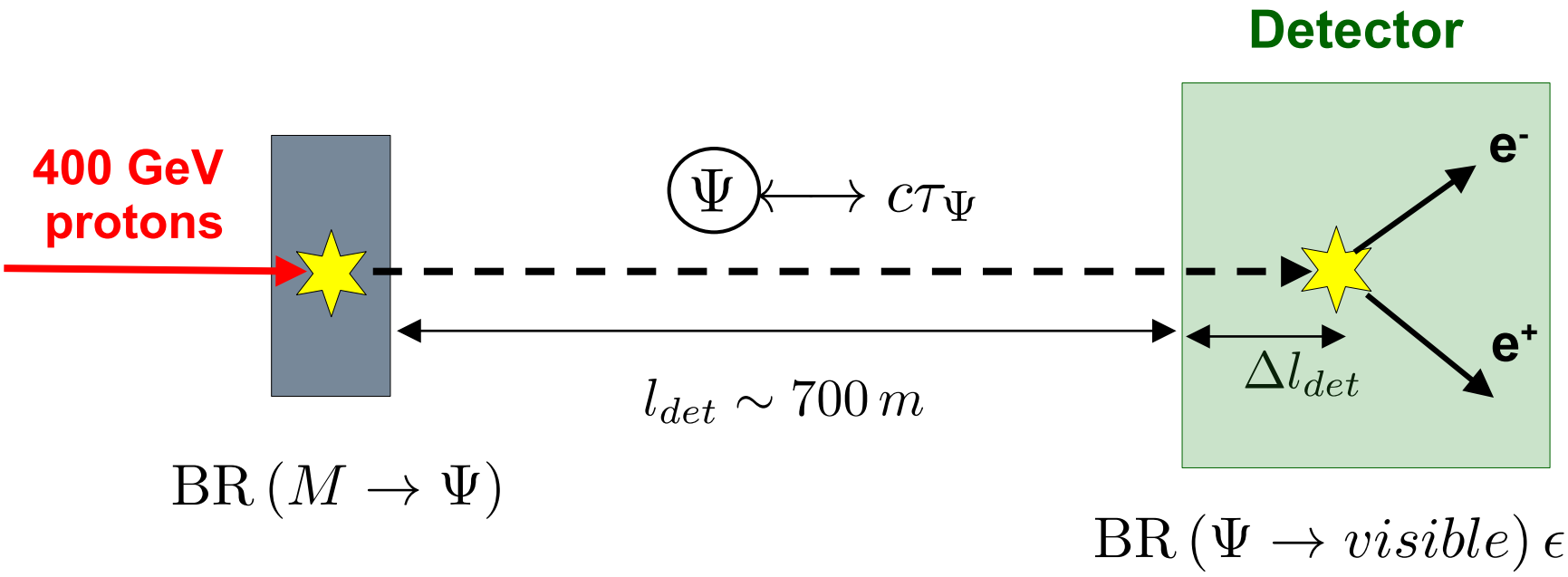
CERN Neutrino Platform
(**ProtoDUNE** detectors)



We consider only one detector



Model independent approach

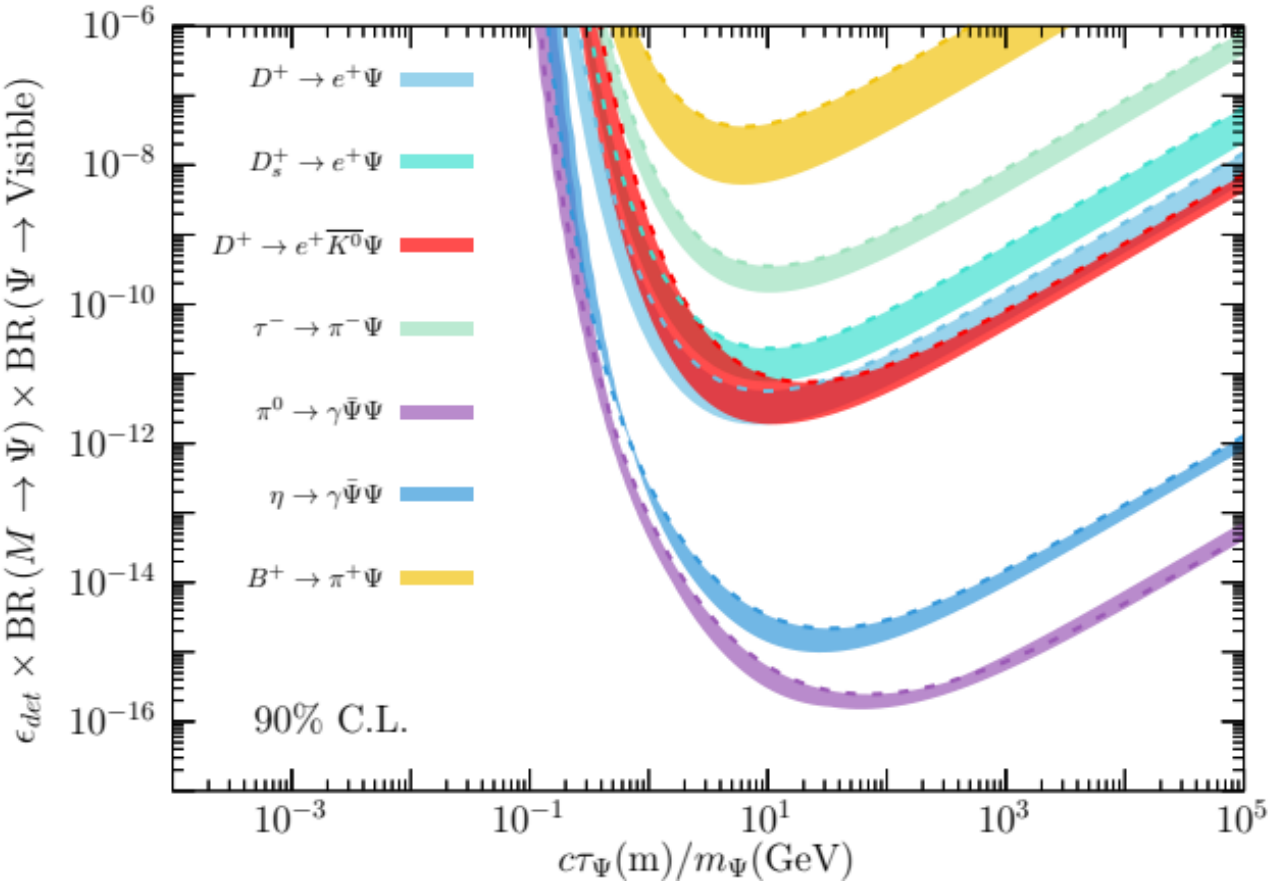


$$N_{ev}^{M} = N_M \mathrm{BR}(M \to \Psi)\mathrm{BR}\,(\Psi \to visible)\,\epsilon_{det} \int dS \int dE_\Psi \mathcal{P}(c\tau_\Psi/m_\Psi E_\Psi, \Omega_\Psi)\frac{dn^{M\to\Psi}}{dE_\Psi dS}$$

Model dependent

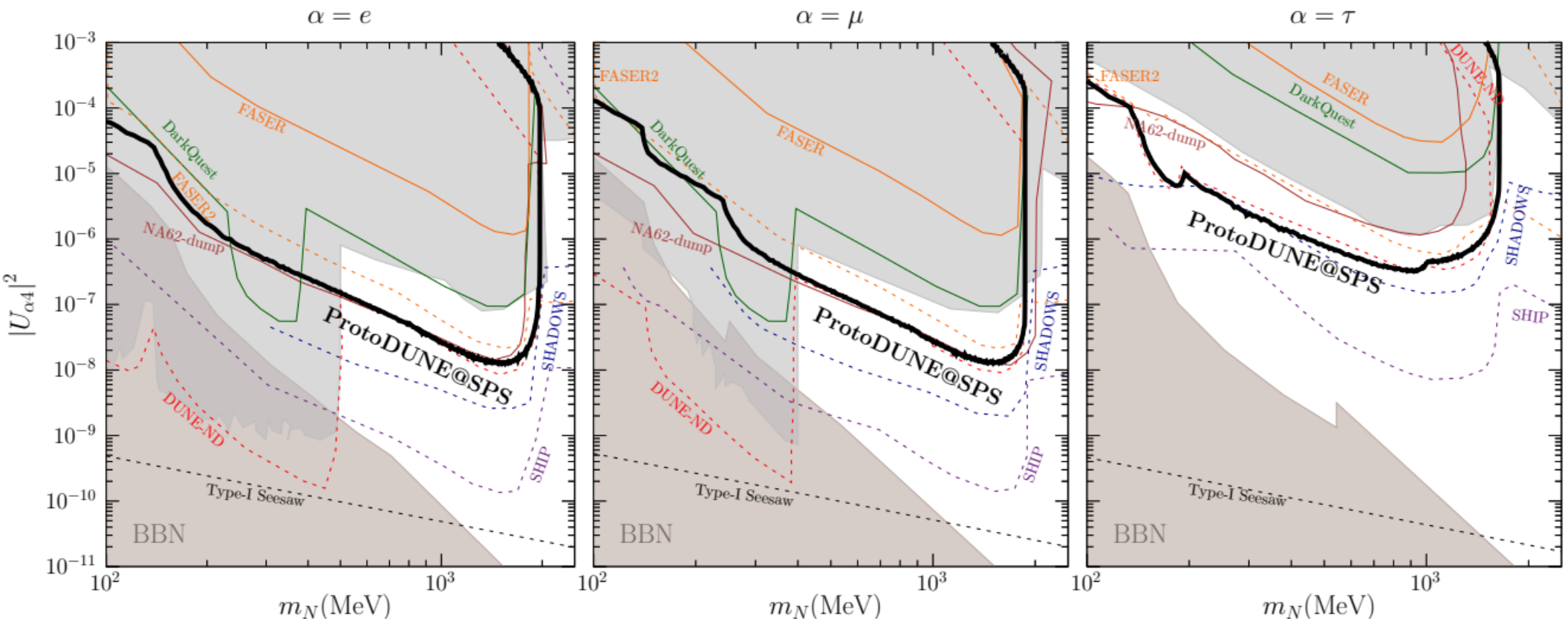
Model independent approach

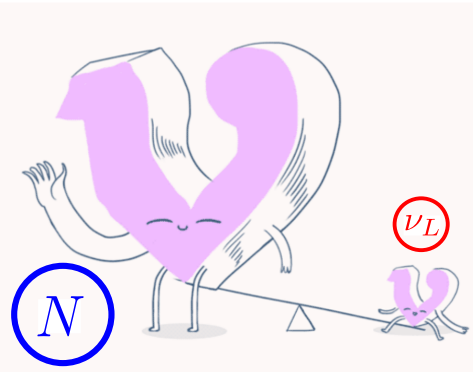
$$N_{ev} = N_{ev}\left(\mathrm{BR}\left(M \to \Psi\right)\mathrm{BR}\left(\Psi \to visible\right)\epsilon_{det}, c\tau_{\Psi}/m_{\Psi}\right)$$



P. Coloma, JLP, L. Molina-Bueno, S. Urrea https://arxiv.org/pdf/2304.06765.pdf

ProtoDUNE BSM searches





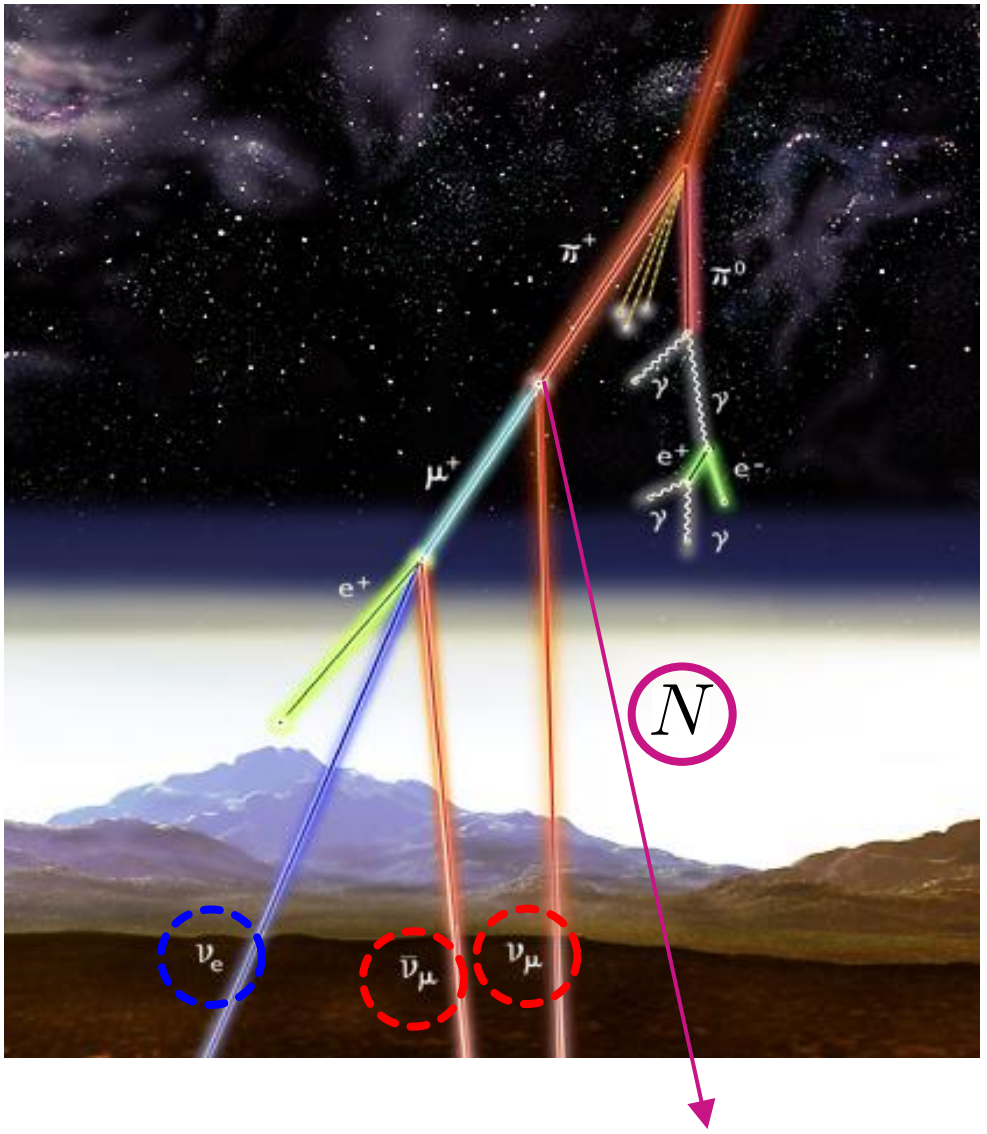
- Ongoing feasibility study in collaboration with CERN neutrino platform.

Coloma, JLP, Molina-Bueno, Urrea 2304.06765

Searches for atmospheric HNLs

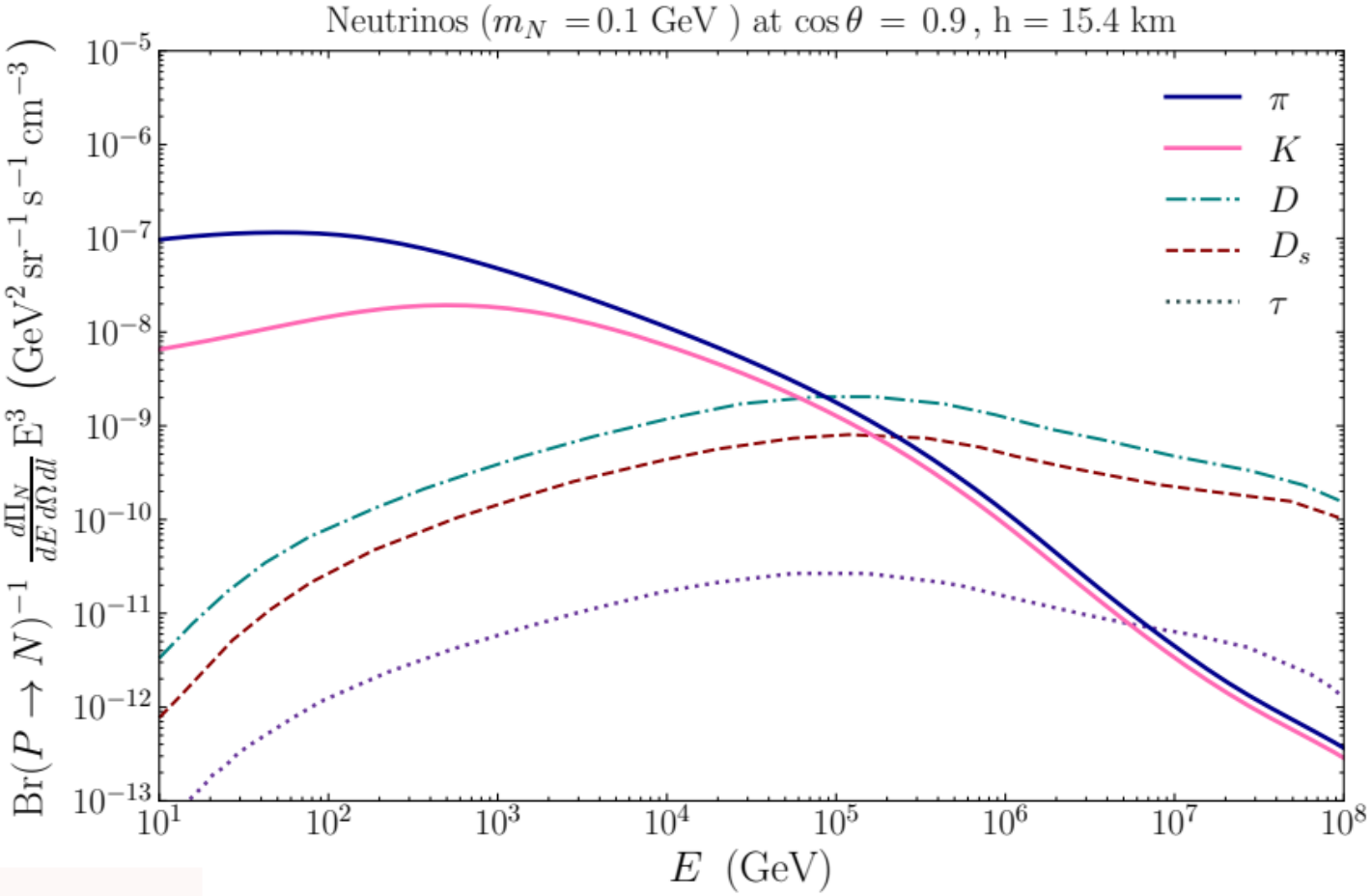
$$c\tau_N \sim (10^{-4} - 50) \times |U_{\alpha 4}|^{-2}\,\mathrm{km}$$

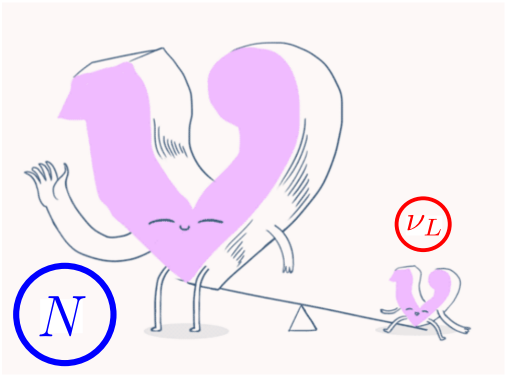
$$\text{for M} \sim 40 - 400\,\mathrm{MeV}$$



Coloma, Hernández, Muñoz, Shoemaker 1911.09129
Argüelles, Coloma, Hernández, Muñoz 1910.12839

Searches for atmospheric HNLs: Production

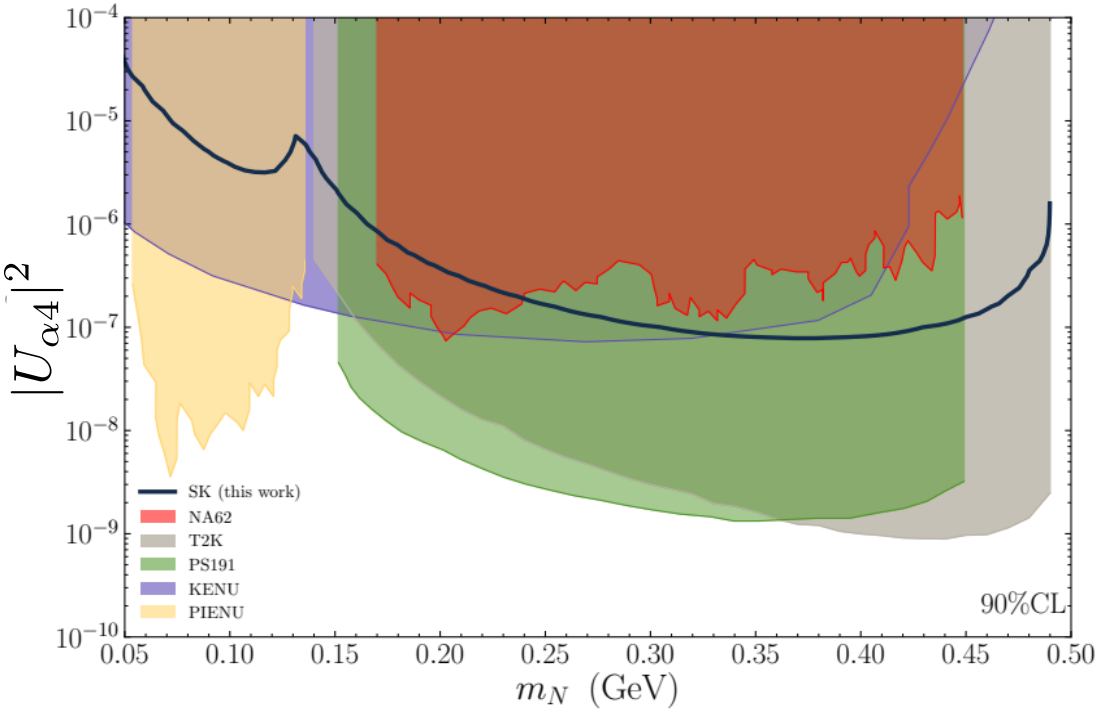




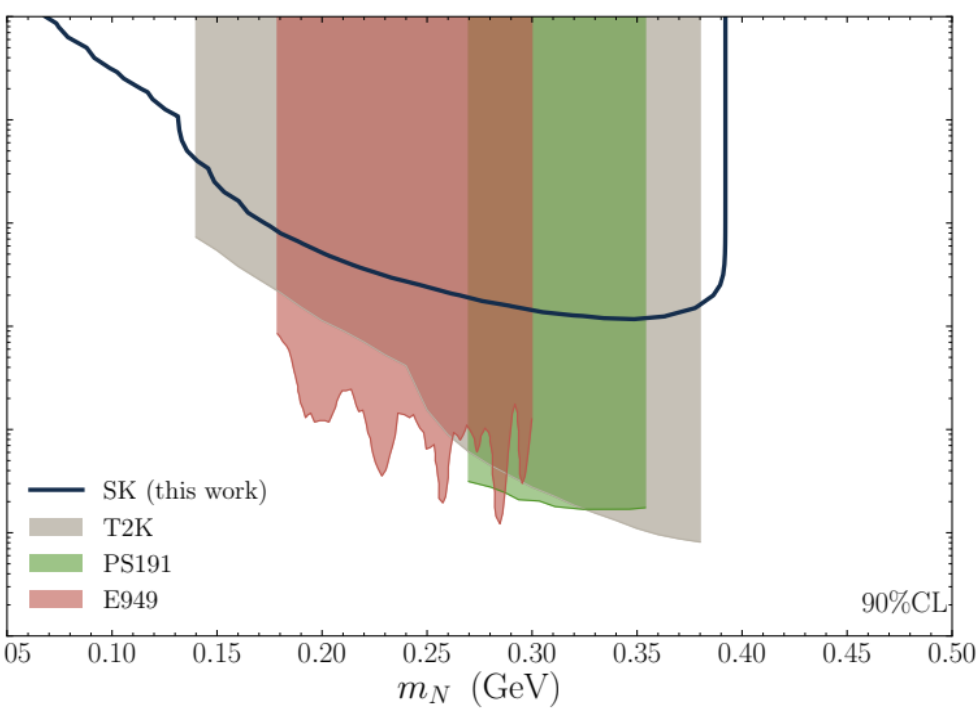
Coloma, Hernández, Muñoz, Shoemaker 1911.09129
Argüelles, Coloma, Hernández, Muñoz 1910.12839

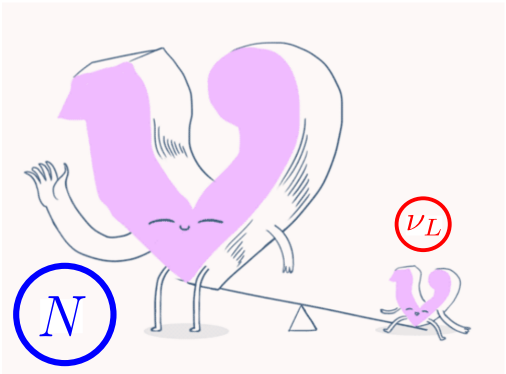
Searches for atmospheric HNLs: bounds

e *(BC6)*



μ *(BC7)*

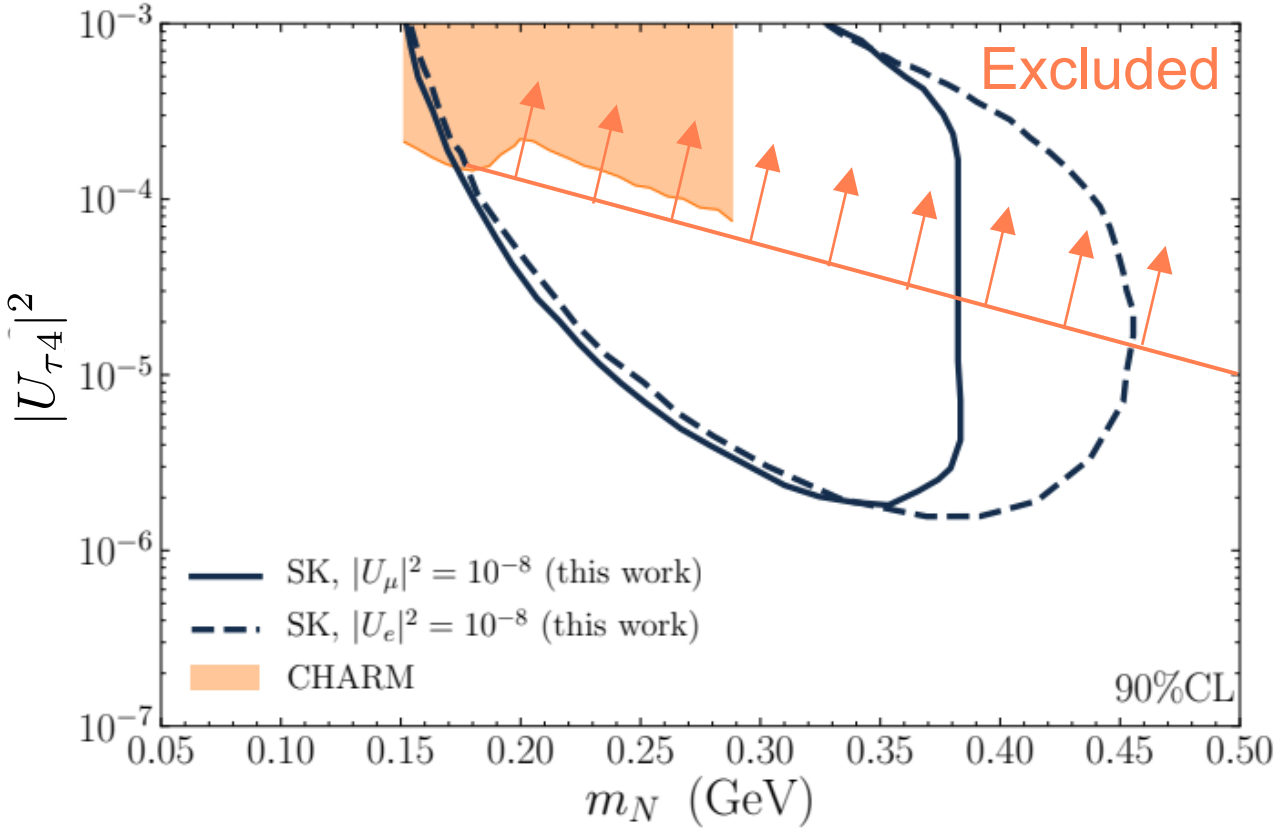




Coloma, Hernández, Muñoz, Shoemaker 1911.09129

Searches for atmospheric HNLs: bounds

$\tau \& \alpha$



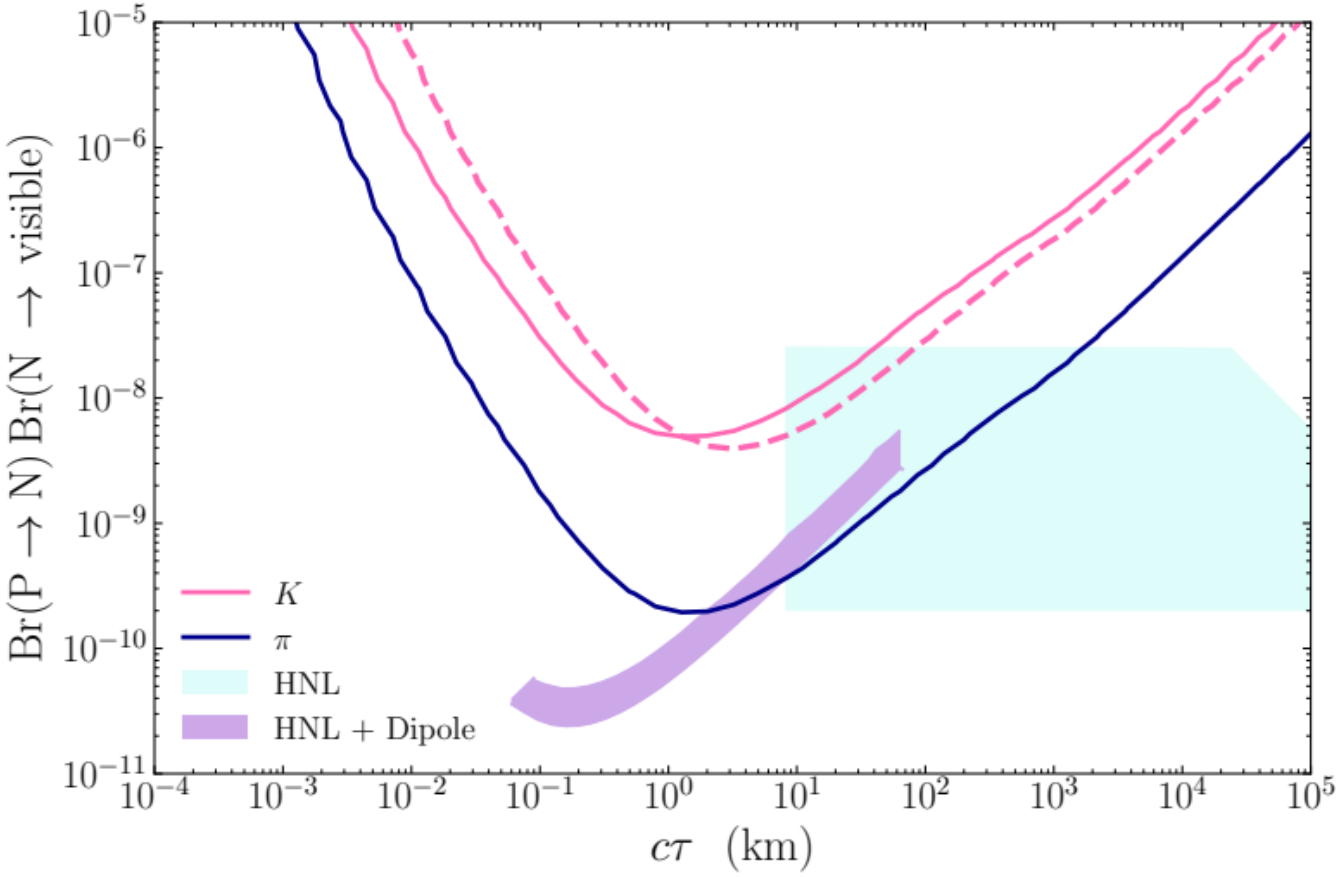
Boiarska, Boyarsky, Mikulenko, Ovchynnikov 2107.14685

Barouki, Marocco, Sarkar 2208.00416

Coloma, Hernández, Muñoz, Shoemaker 1911.09129

Searches for atmospheric LLP

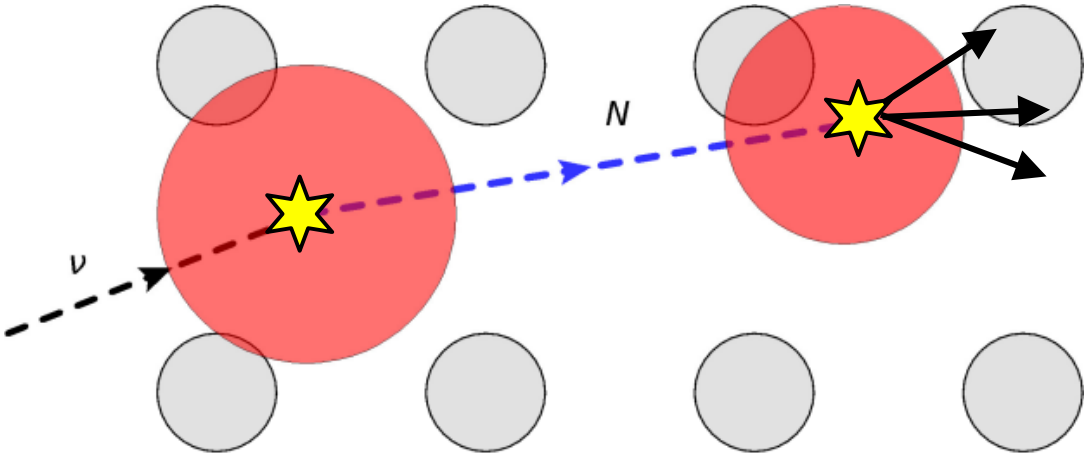
- Model independent bounds:



Solid: $M = 0.1\,\mathrm{GeV}$
Dashed: $M = 0.25\,\mathrm{GeV}$

Coloma, Hernández, Muñoz, Shoemaker 1911.09129

Searches for atmospheric HNLs: double bang



HNL decay into visible particles

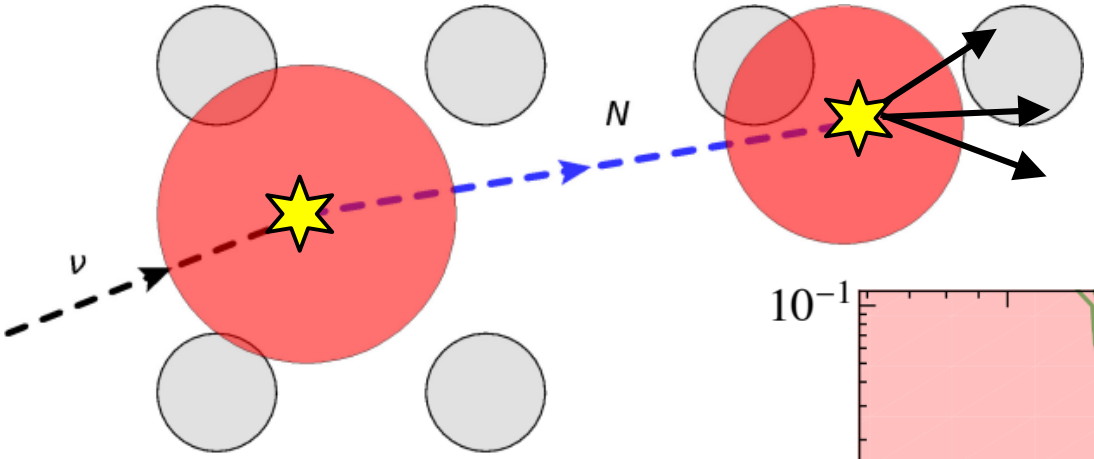
$\propto |U_{\alpha 4}|^2$

Production via neutrino up-scattering along shower

$\propto |U_{\alpha 4}|^2$

Coloma, Machado, Martinez-Soler, Shoemaker 1707.08573

Searches for atmospheric HNLs: double bang



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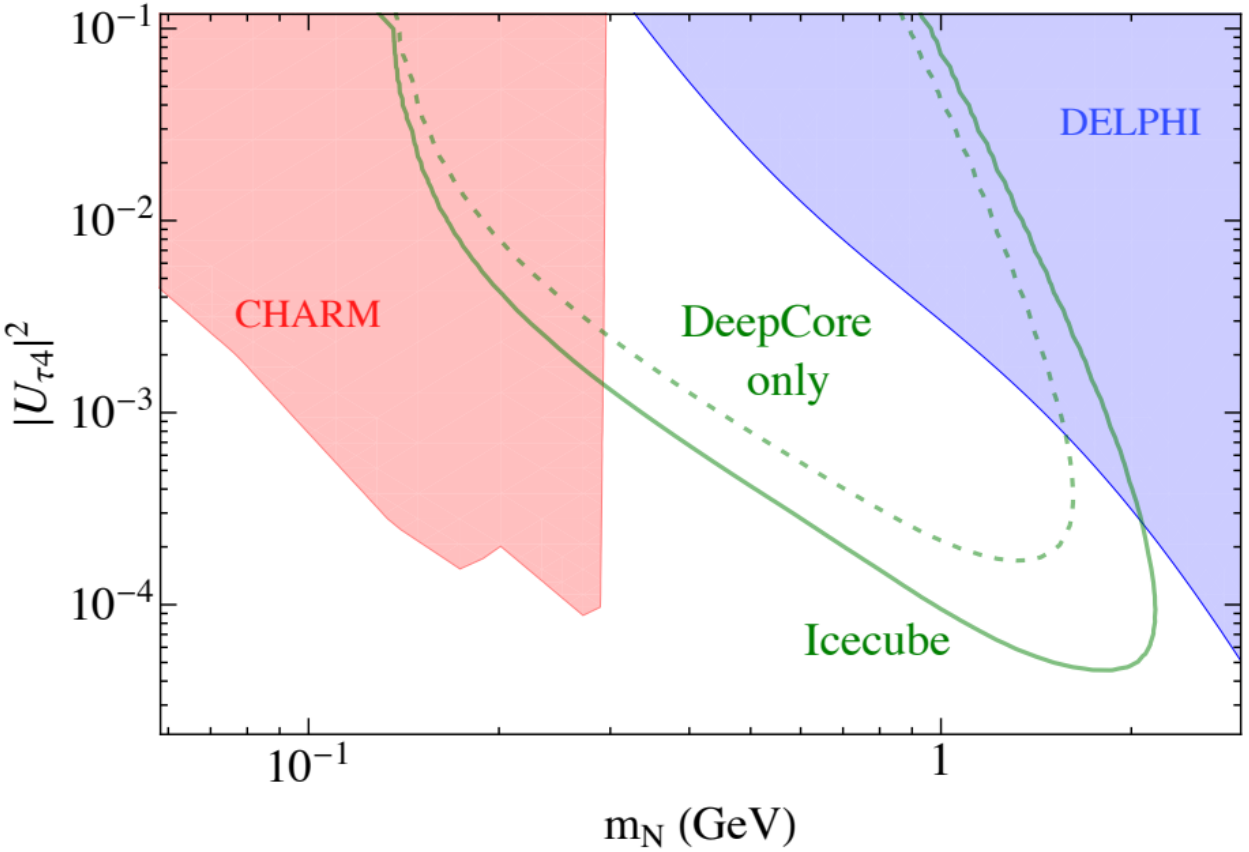
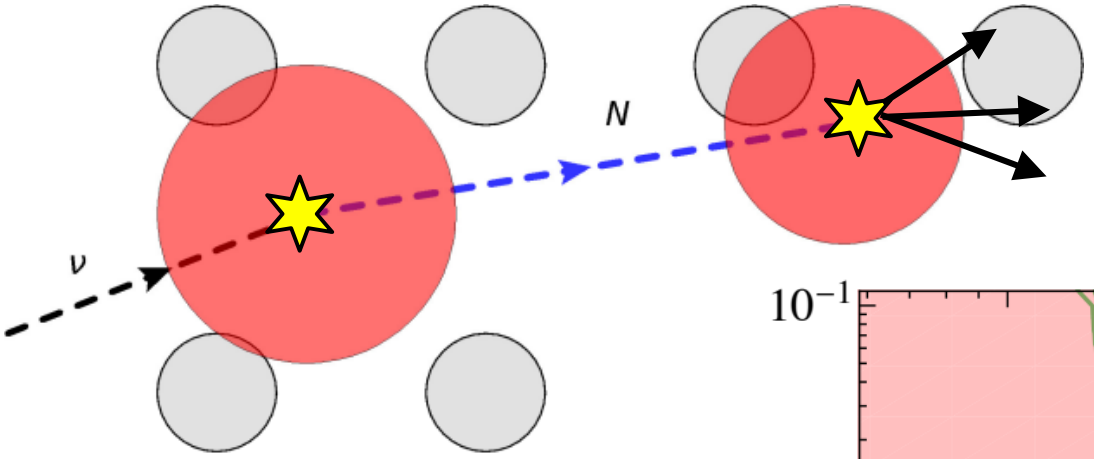


Coloma, Machado, Martinez-Soler, Shoemaker 1707.08573

Searches for atmospheric HNLs: double bang



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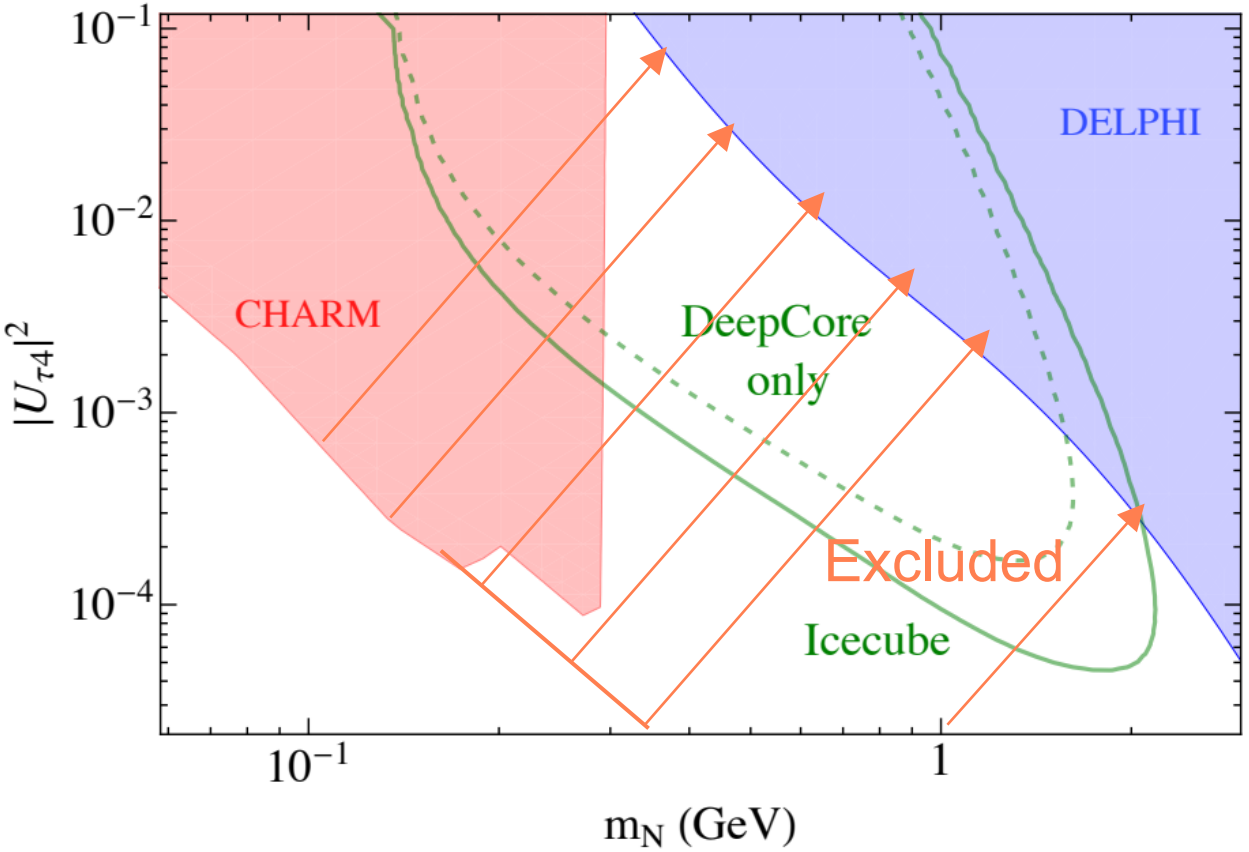

Boiarska, Boyarsky, Mikulenko, Ovchynnikov 2107.14685

Barouki, Marocco, Sarkar 2208.00416

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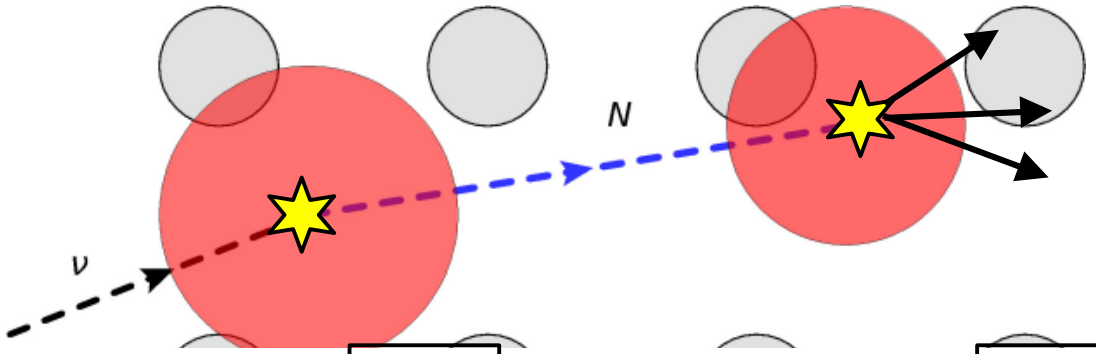
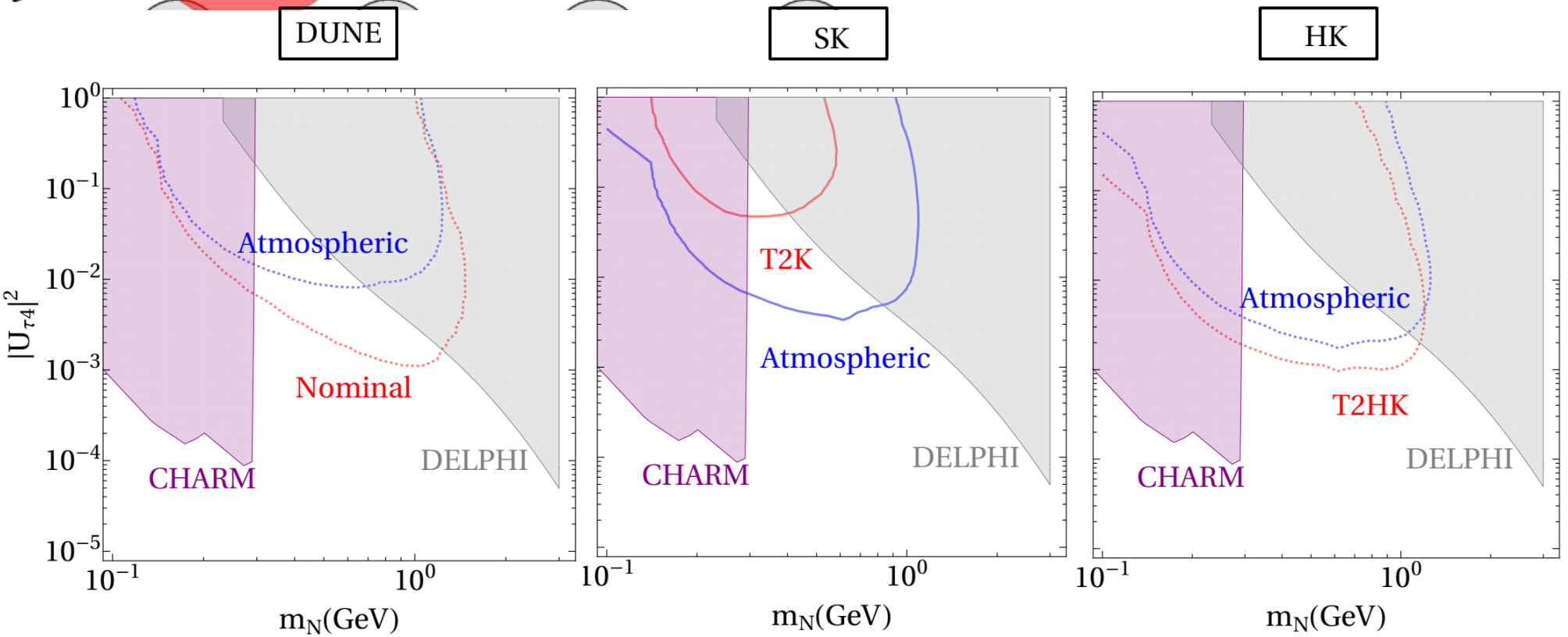


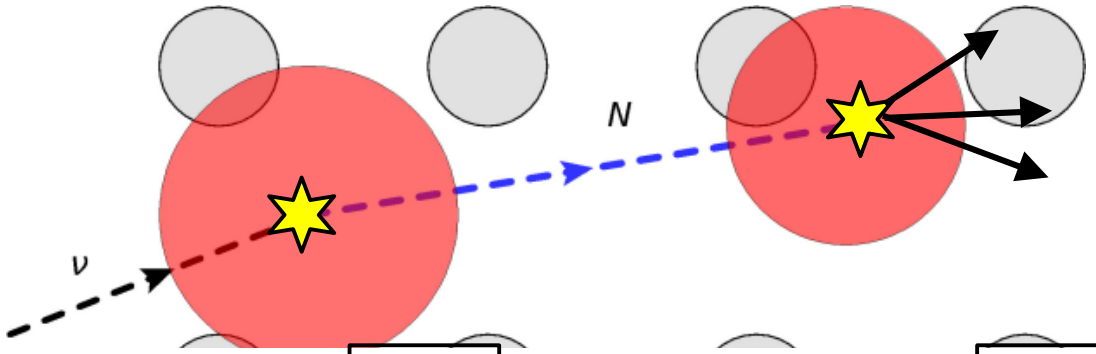
HNL decay into visible particles

$\propto |U_{\alpha 4}|^2$



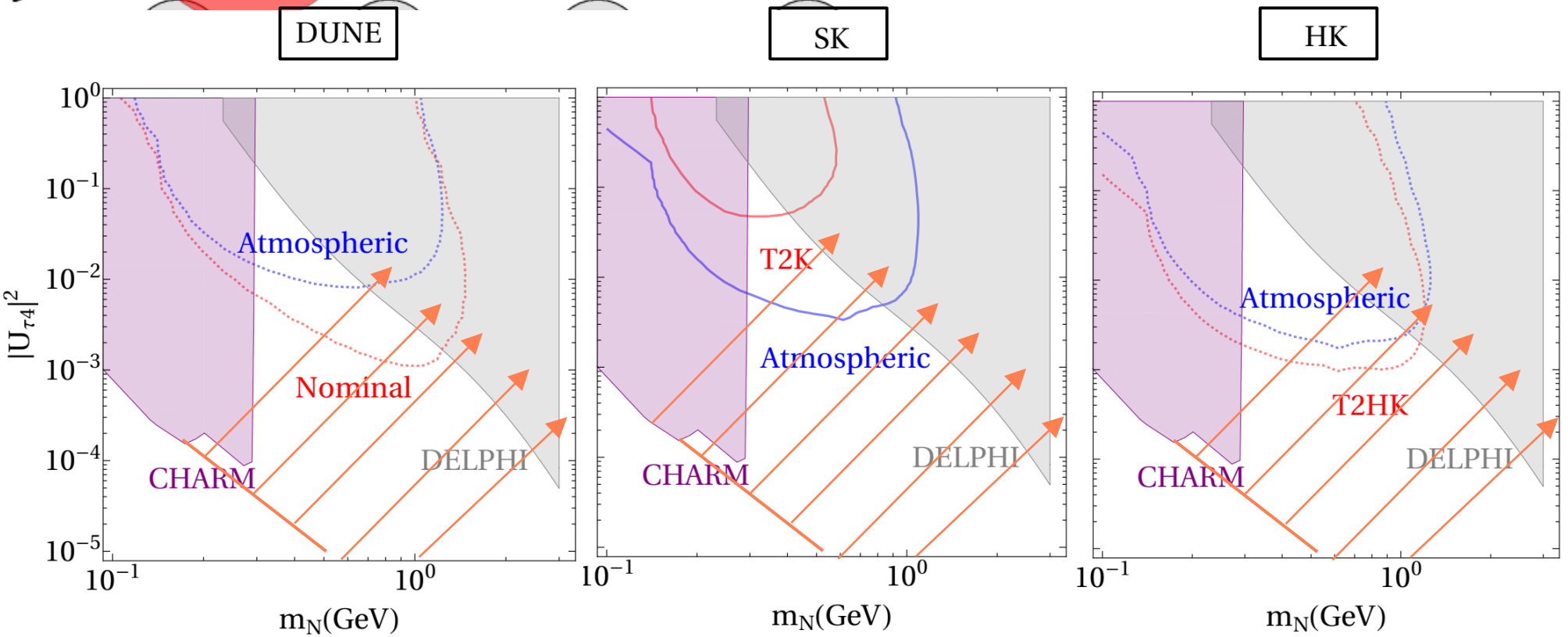
Atkinson, Coloma, Martinez-Soler, Rocco, Shoemaker 2105.09357

Searches for atmospheric HNLs: double bang



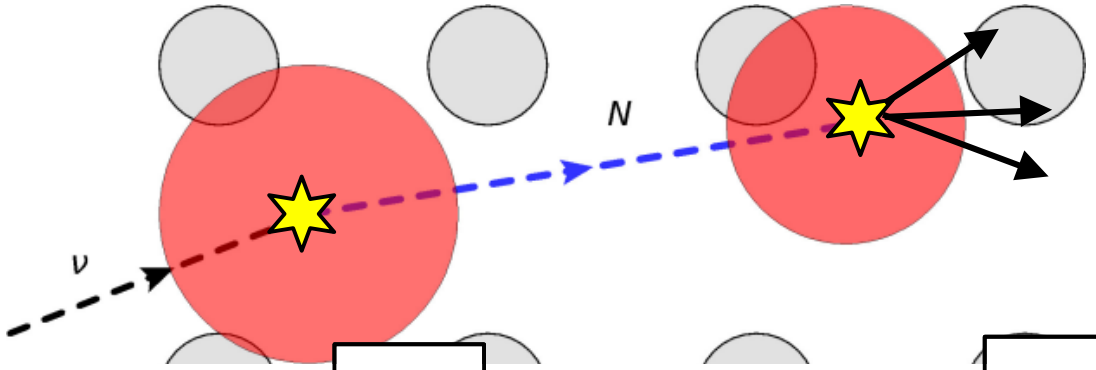
HNL decay into visible particles

$\propto |U_{\alpha 4}|^2$



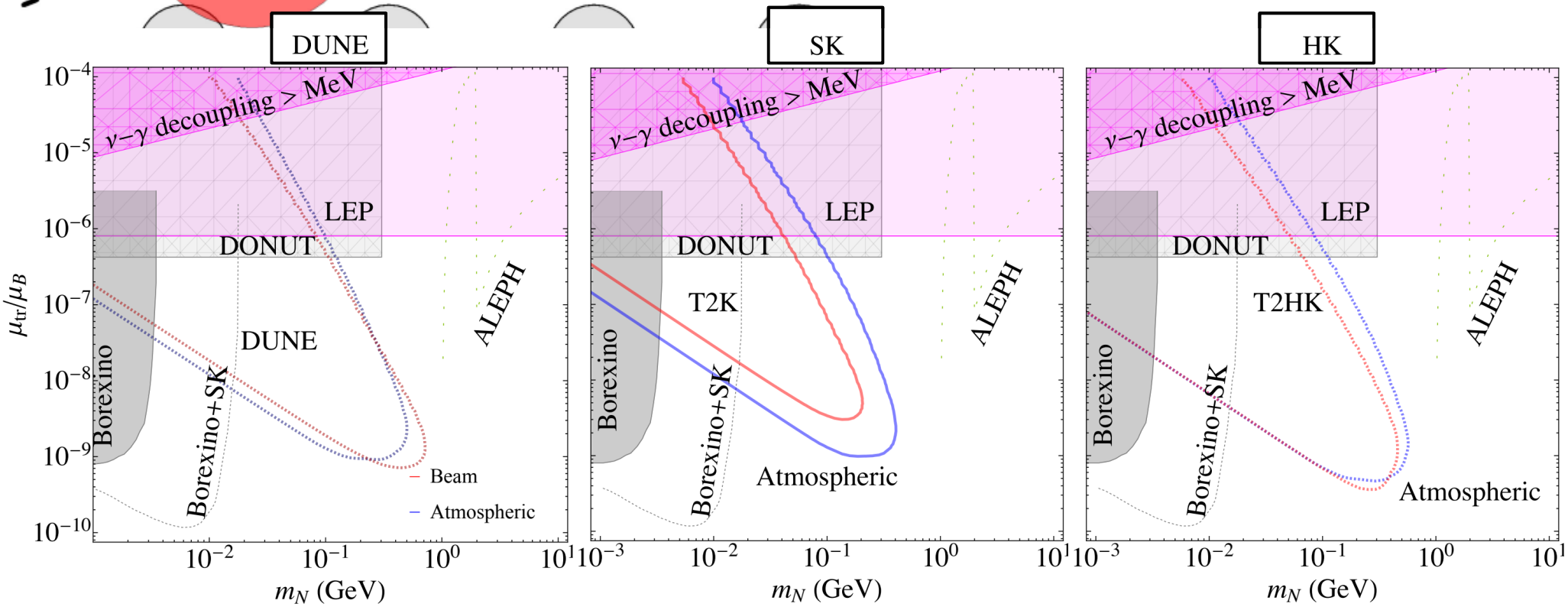
Atkinson, Coloma, Martinez-Soler, Rocco, Shoemaker 2105.09357

Searches for non minimal HNLs: double bang



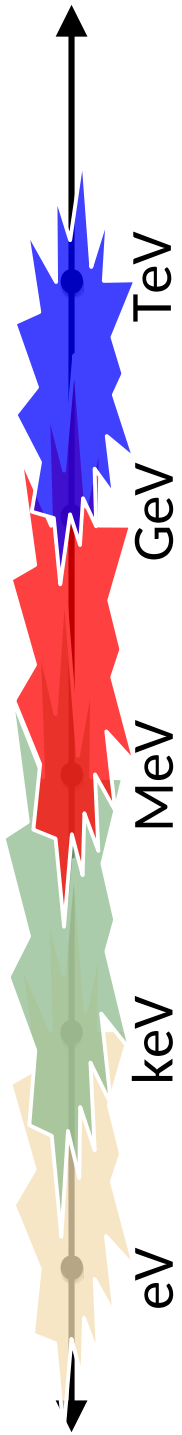
HNL decay into visible particles *via dipole portal*

$$\mu(\bar{\nu}_L \sigma^{\mu\nu} N) F_{\mu\nu}$$



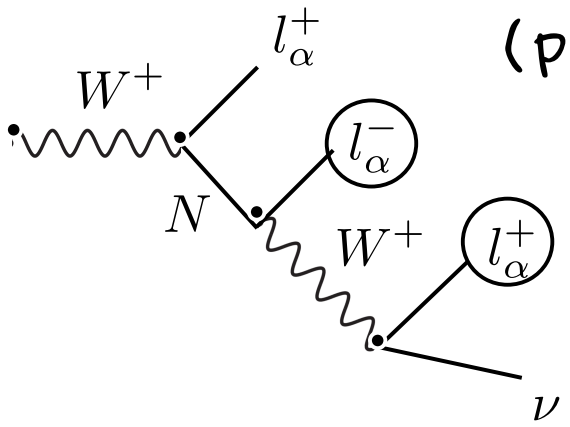
Atkinson, Coloma, Martinez-Soler, Rocco, Shoemaker 2105.09357

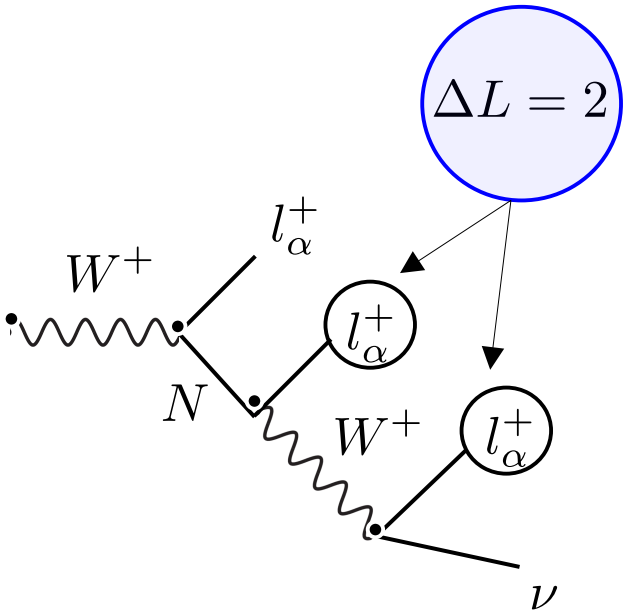
Colliders

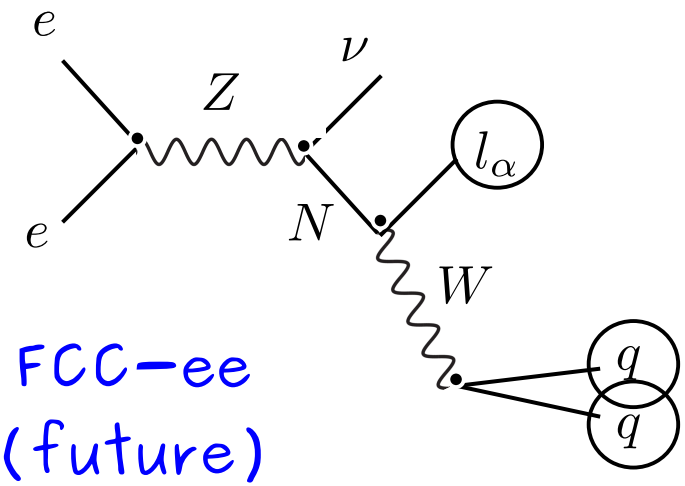


- Colliders

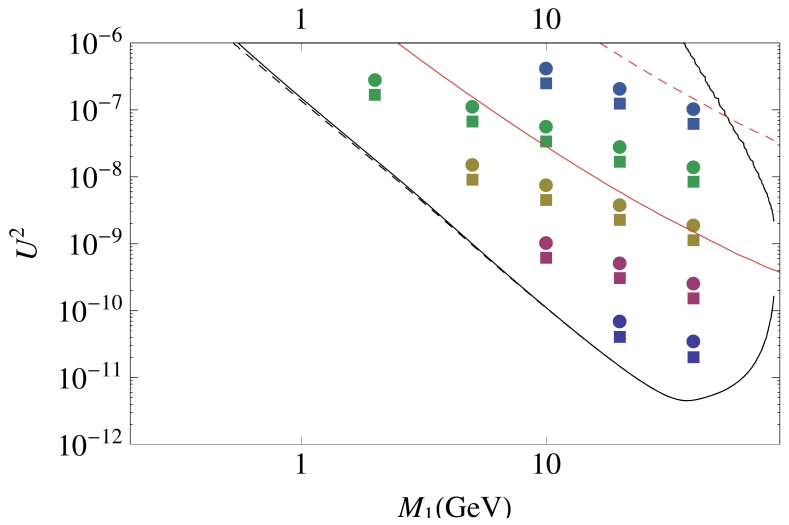
LHC
(present)



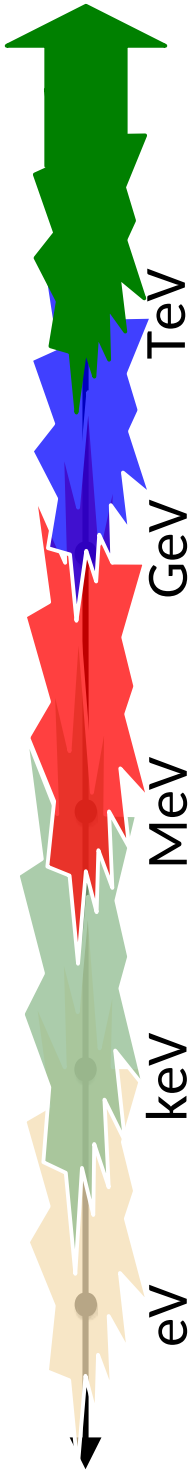




FCC-ee
(future)



Caputo, Hernandez, Kekic, JLP, Salvado arXiv:1611.05000
Blondel, Graverini, Serra, Shaposhnikov 1411.5230



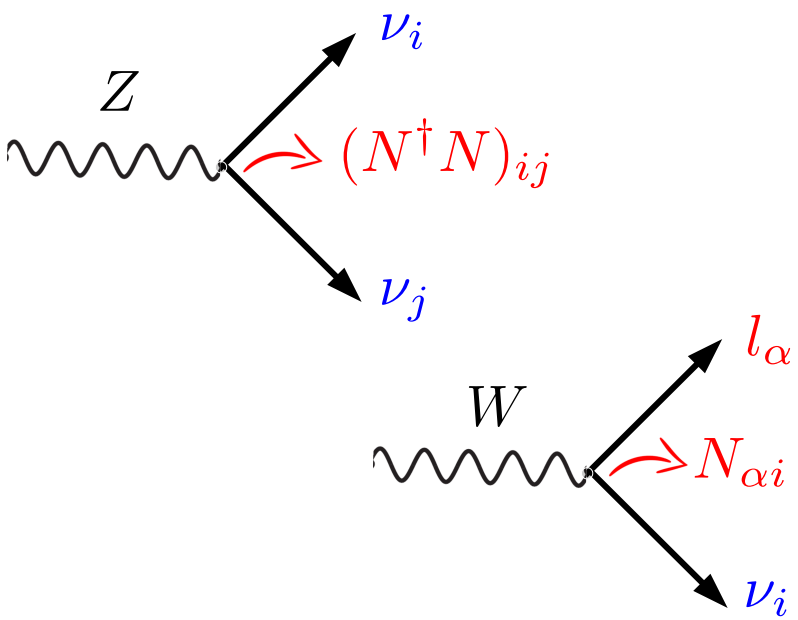
Non Unitarity

- CLFV and EW precision data

$$N = (1 - \eta)\, U_{PMNS}$$

$$\eta = \frac{1}{2}\Theta^\dagger \boxed{\Theta}$$

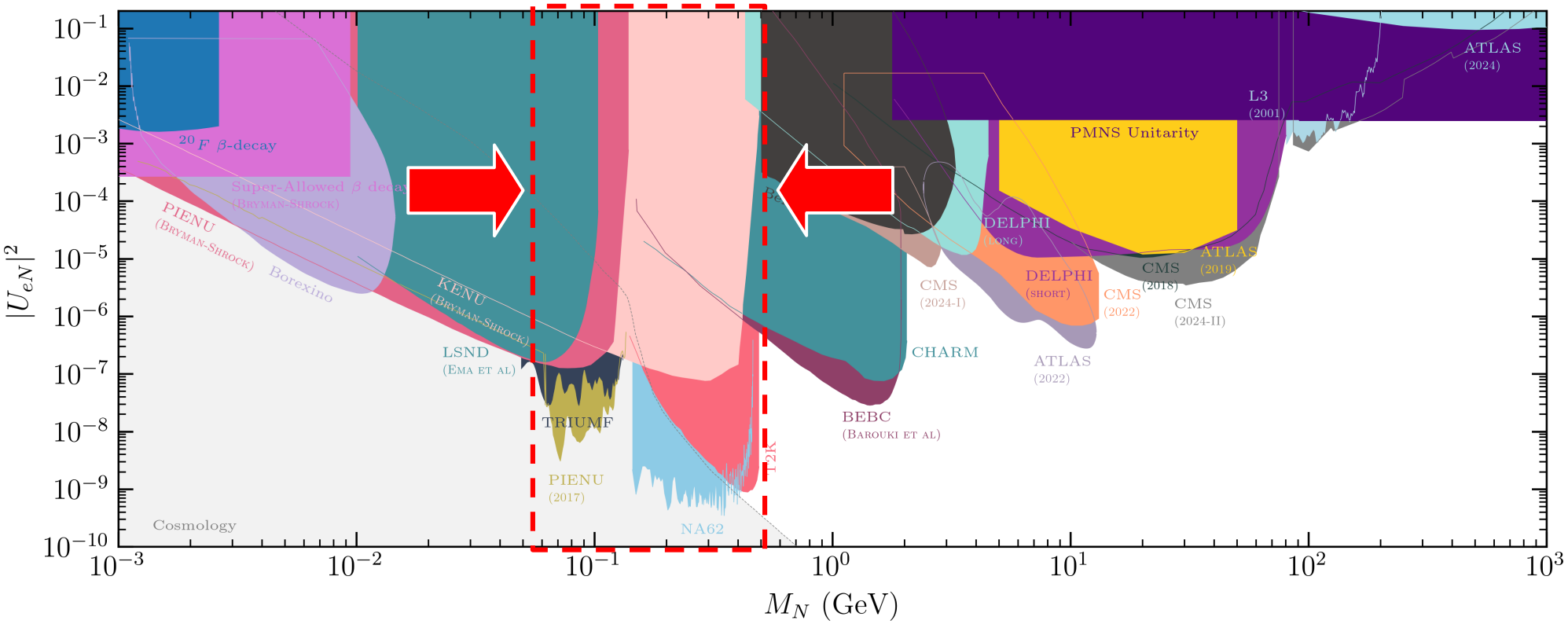
HNL mixing



- *Many EW and CLFV processes affected:* determination of G_F via muon decay, W boson mass, weak mixing angle, ratios of Z fermionic decays, invisible width of the Z, ratios of weak decays constraining EW universality, weak decays constraining CKM unitarity, CLFV decays...

Antusch, Biggio, Fernandez-Martinez, Gavela, JLP 2006
Blennow, Fernandez-Martinez, Hernandez-Garcia, Marcano, Naredo-Tuero, JLP 2306.01040

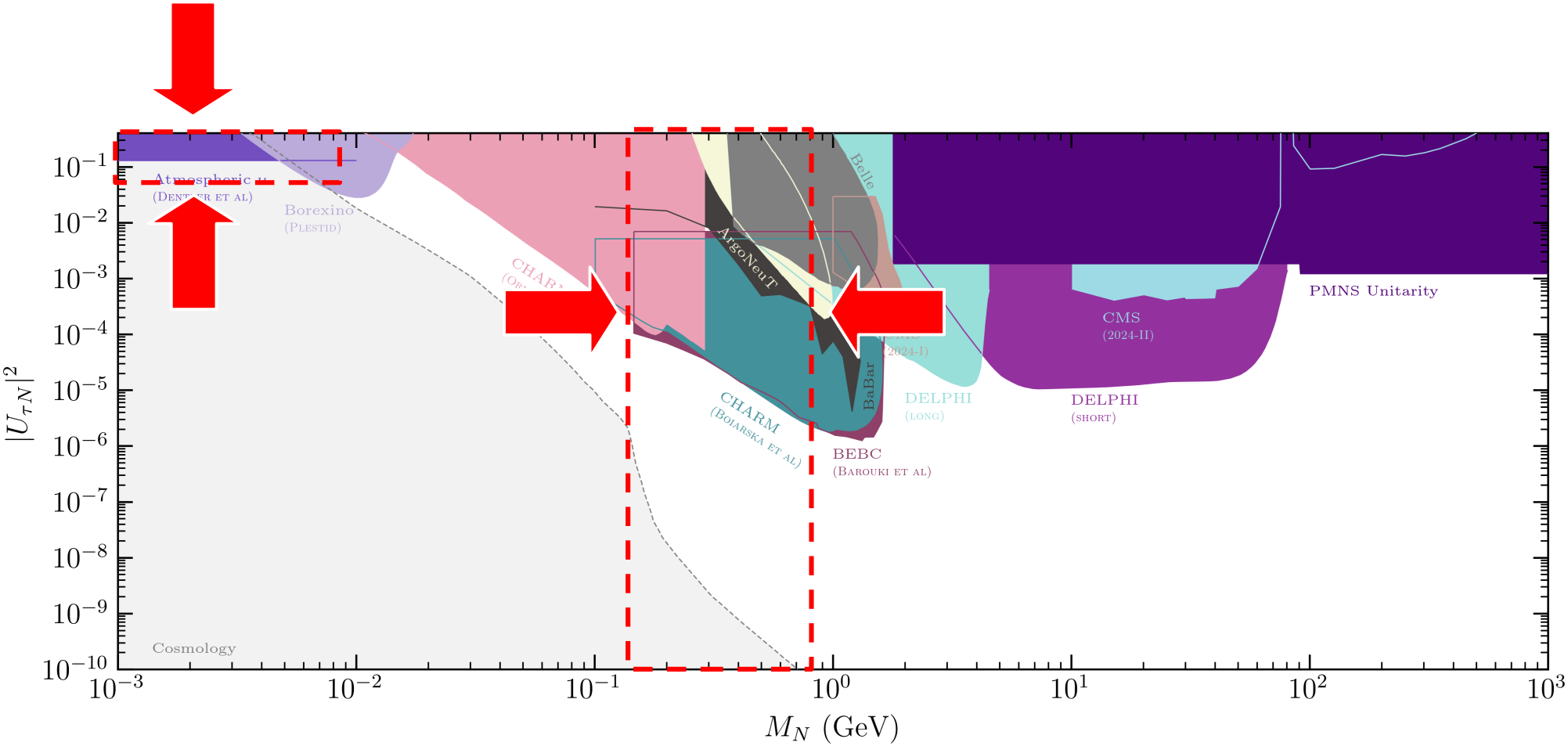
The New Physics Scale



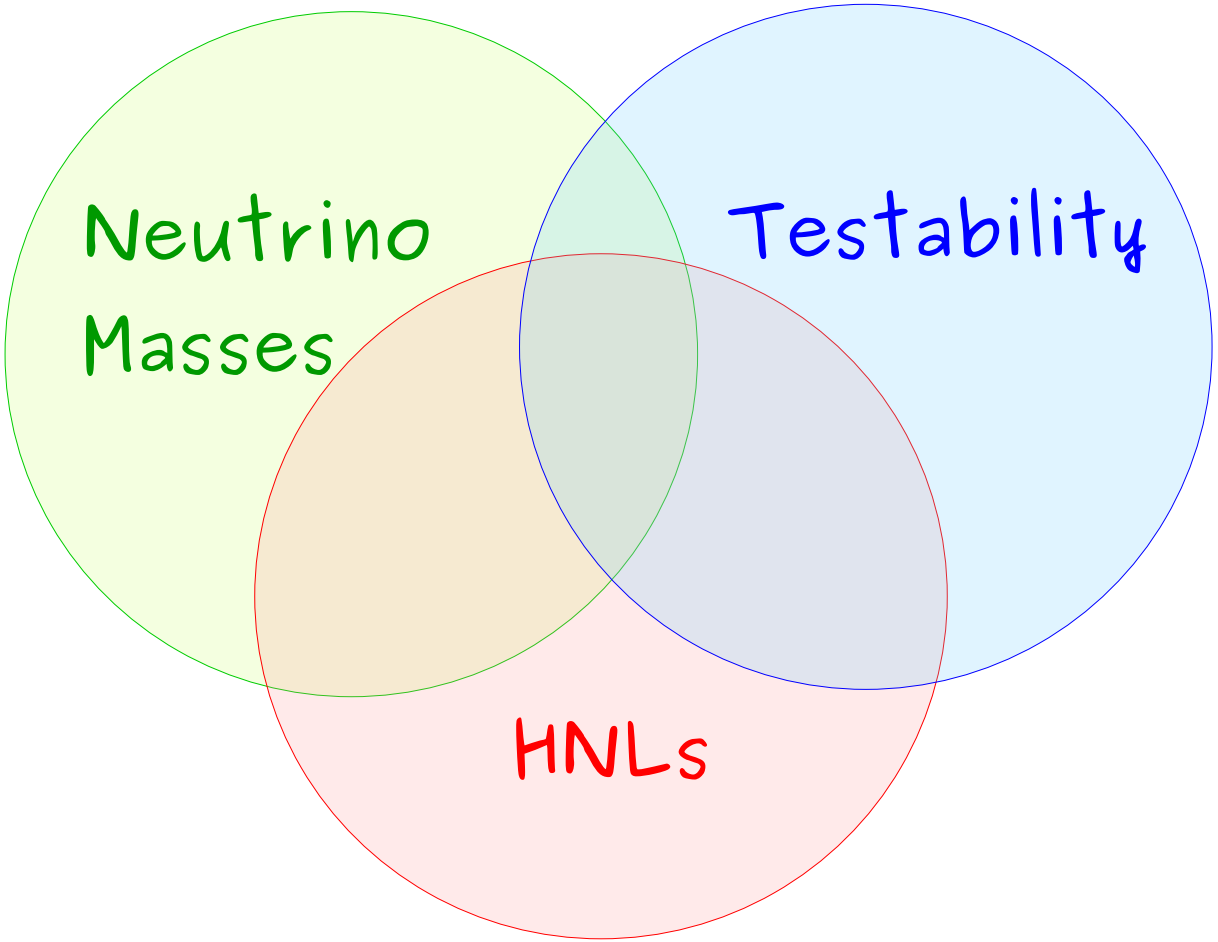
https://github.com/mhostert/Heavy-Neutrino-Limits

Fernadez-Martinez, Hernandez-Garcia, Gonzalez-Lopez, Hostert, JLP 2306.01040

The New Physics Scale

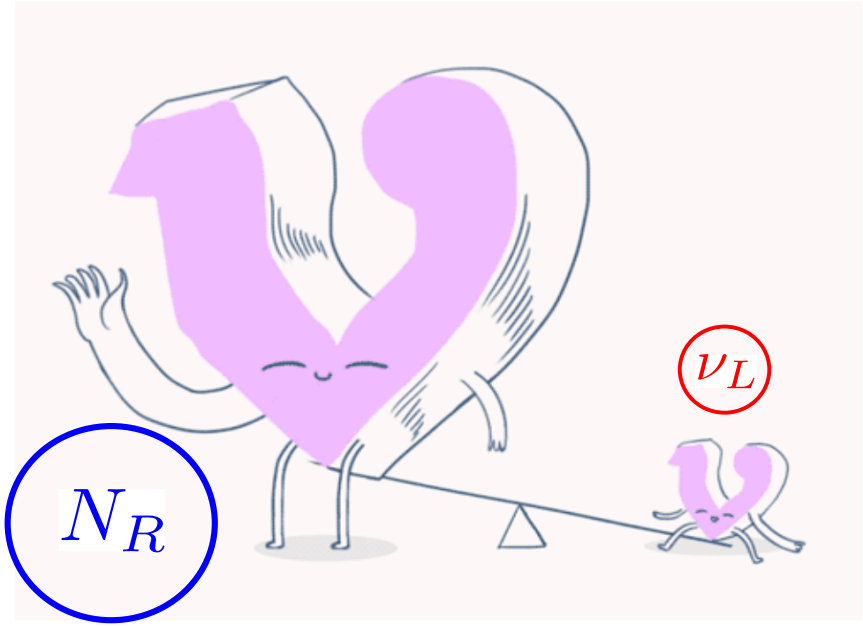


https://github.com/mhostert/Heavy-Neutrino-Limits
Fernadez-Martinez, Hernandez-Garcia, Gonzalez-Lopez, Hostert, JLP 2306.01040


Neutrino
Masses
Testability
HNLs

Constraint on HNL mixing from active sector

- Generation of light neutrino masses imposes **constraints on mixing between HNLs and active neutrinos from *light neutrino sector***

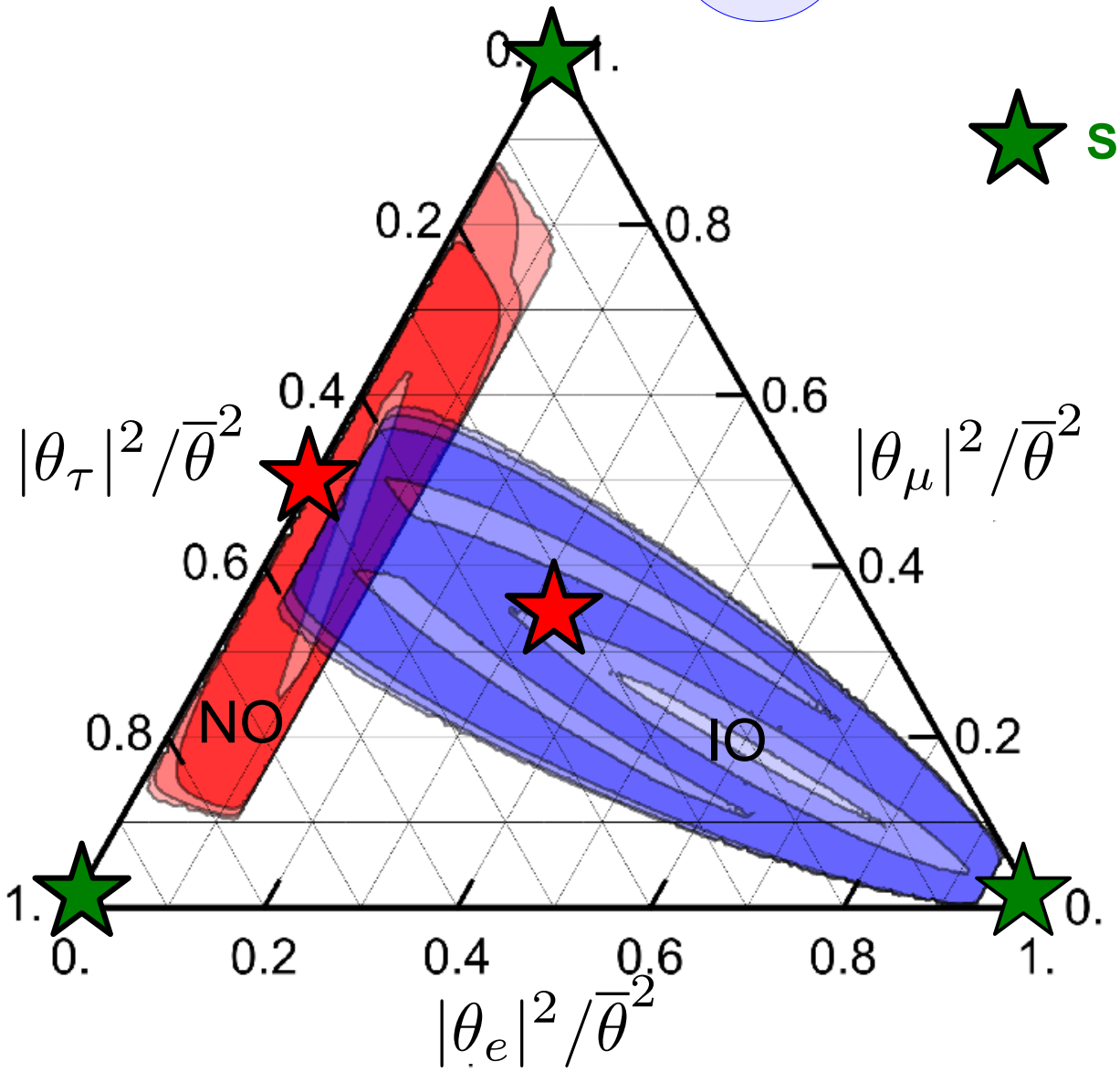


$$m_\nu = \frac{v^2}{2} Y^T M^{-1} Y = \theta\, M\, \theta^T = U\, m\, U^T$$

HNL sector

Light-active neutrino sector

Minimal model $n_R=2$: Flavor Structure

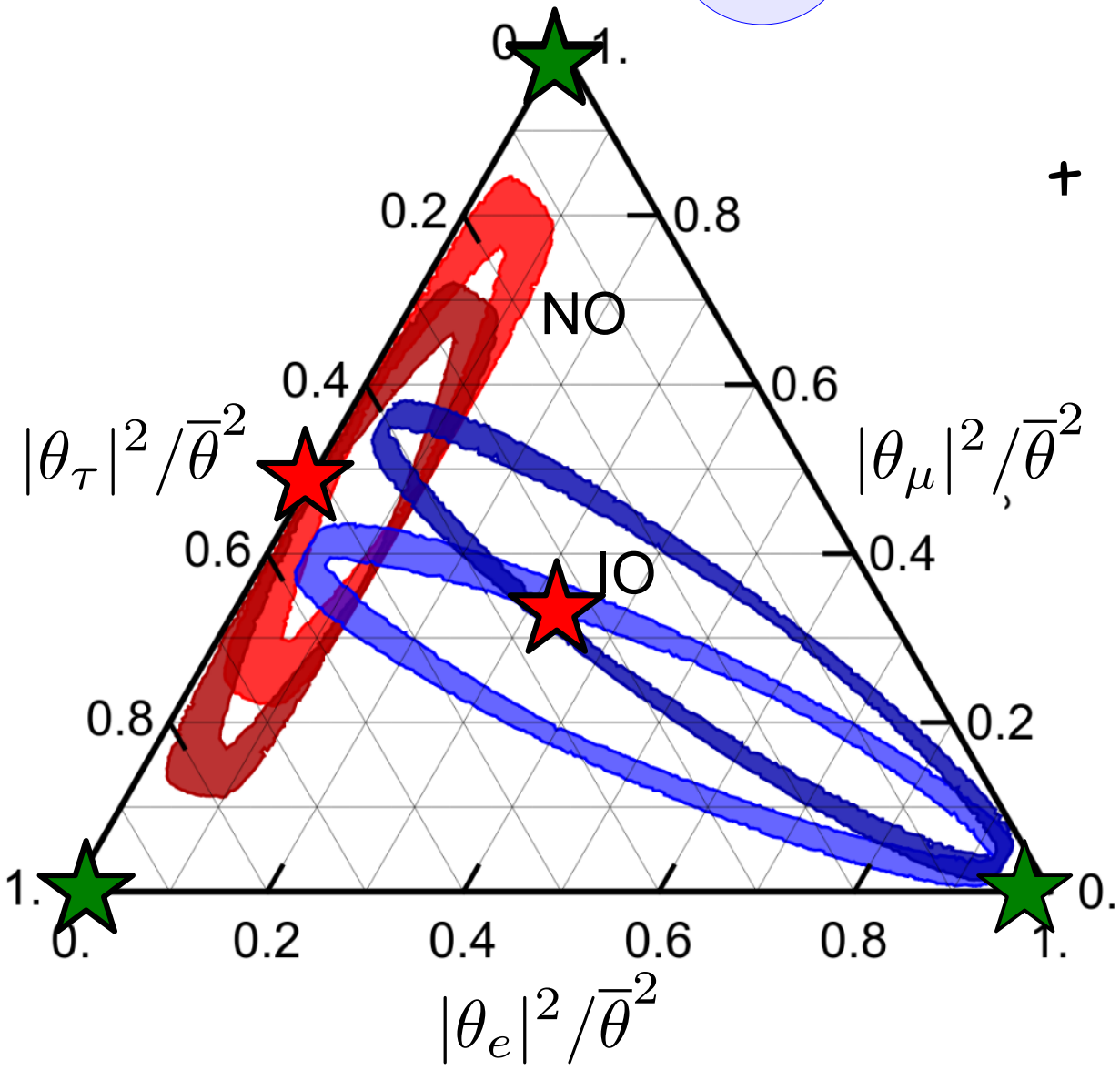


Single flavored benchmarks
(1,0,0), (0,1,0), (0,0,1)

NEW 2021
(0, 1/2, 1/2)
(1/3, 1/3, 1/3)

Abdullahi et al 2203.08039
Drewes, Klaric, JLP 2207.02742
Caputo, Hernandez, JLP, Salvado, 1704.08721

Minimal model $n_R=2$: Flavor Structure



+ DUNE/T2HK…
(future)

- NO, $s_{23}{}^2$=0.58
- NO, $s_{23}{}^2$=0.42
- IO, $s_{23}{}^2$=0.58
- IO, $s_{23}{}^2$=0.42

DUNE forecast assuming $\delta = -\pi/2$

Abdullahi et al 2203.08039

Conclusions

- Introducing HNLs allows to explain the origin of neutrino masses and baryon asymmetry of our universe

- **Low Scale Minimal Seesaw Models are testable and highly predictive**: *the mechanisms generating neutrino masses and Baryon asymmetry can be potentially tested*

- **Strong complementarity among different searches** as neutrino oscillations, *atmospheric HNLs*, cosmology, neutrinoless double beta decay, colliders, etc.

- In non minimal models HNLs may present new interactions and thus a different phenomenology (Left-Right symmetric models, dark U(1) extensions, etc).

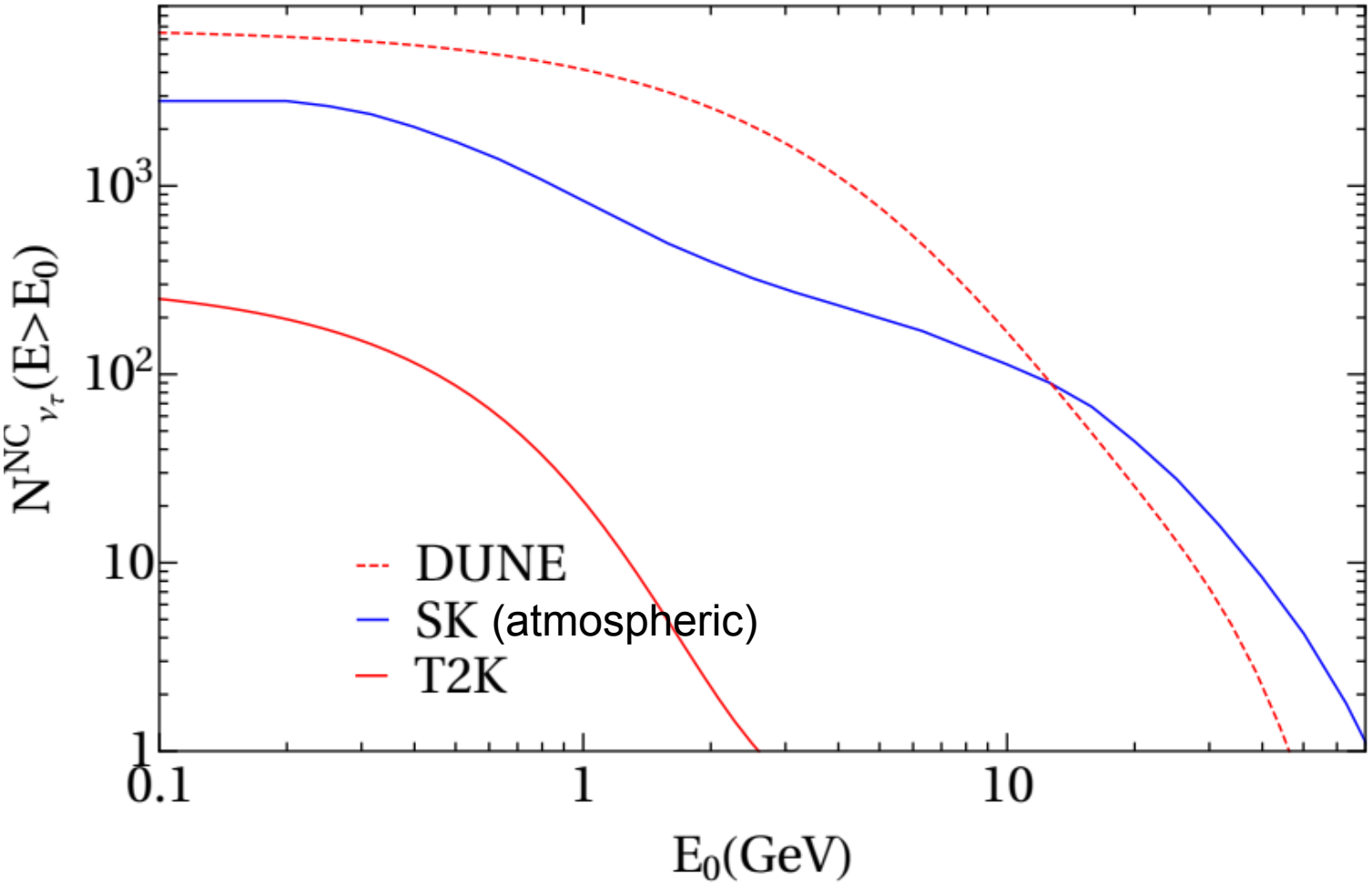
- Low energy effects of additional new physics at higher energies can be studied via an extension of the SMEFT including the HNLs as building blocks.

Fernadez-Martinez, Hernandez-Garcia, Gonzalez-Lopez, Hostert, JLP 2306.01040

Backup

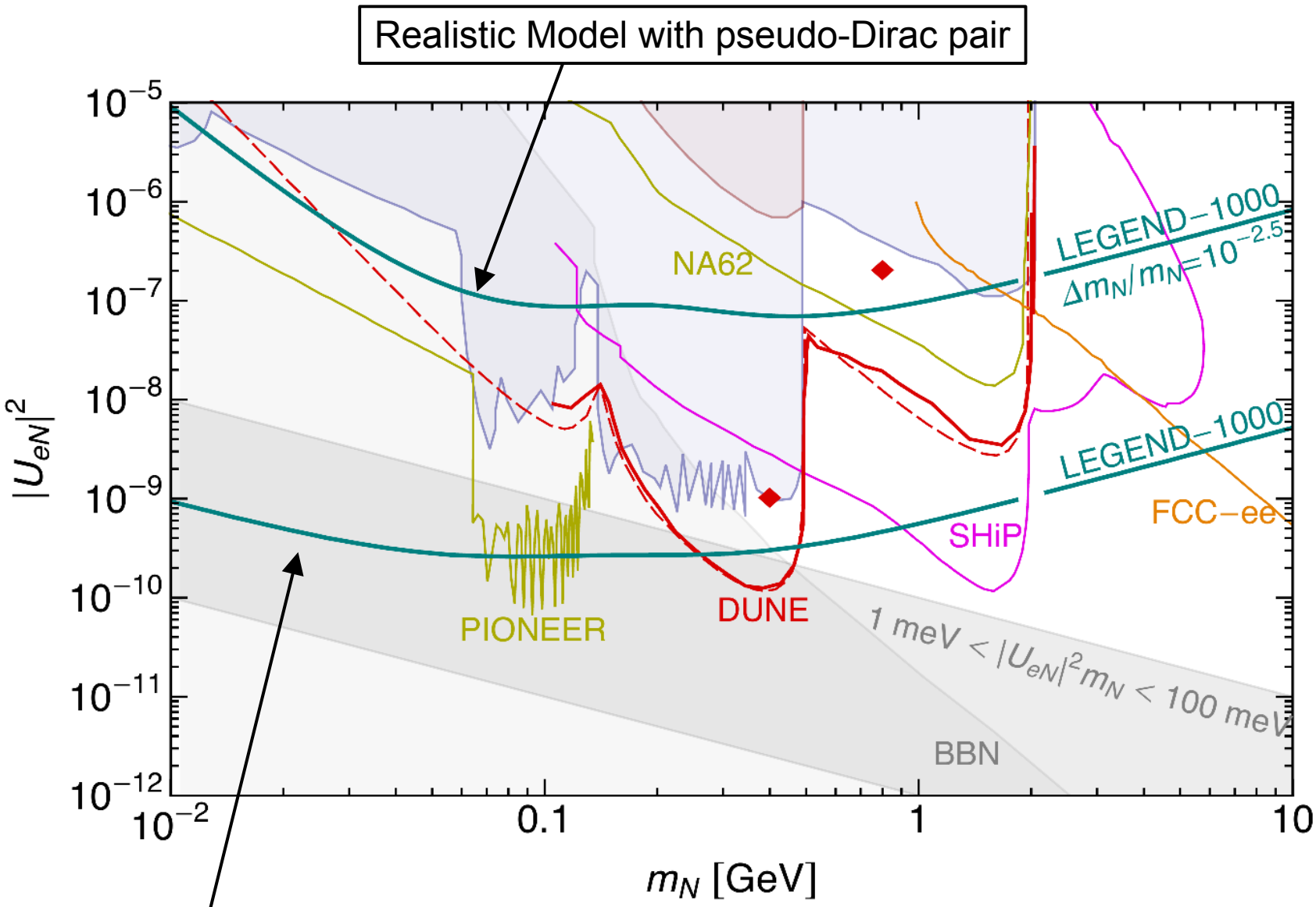
Project CNS2022-136013 funded by MICIU/AEI/10.13039/501100011033
and the European Union NextGenerationEU/PRTR

Total number standard tau nu NC events



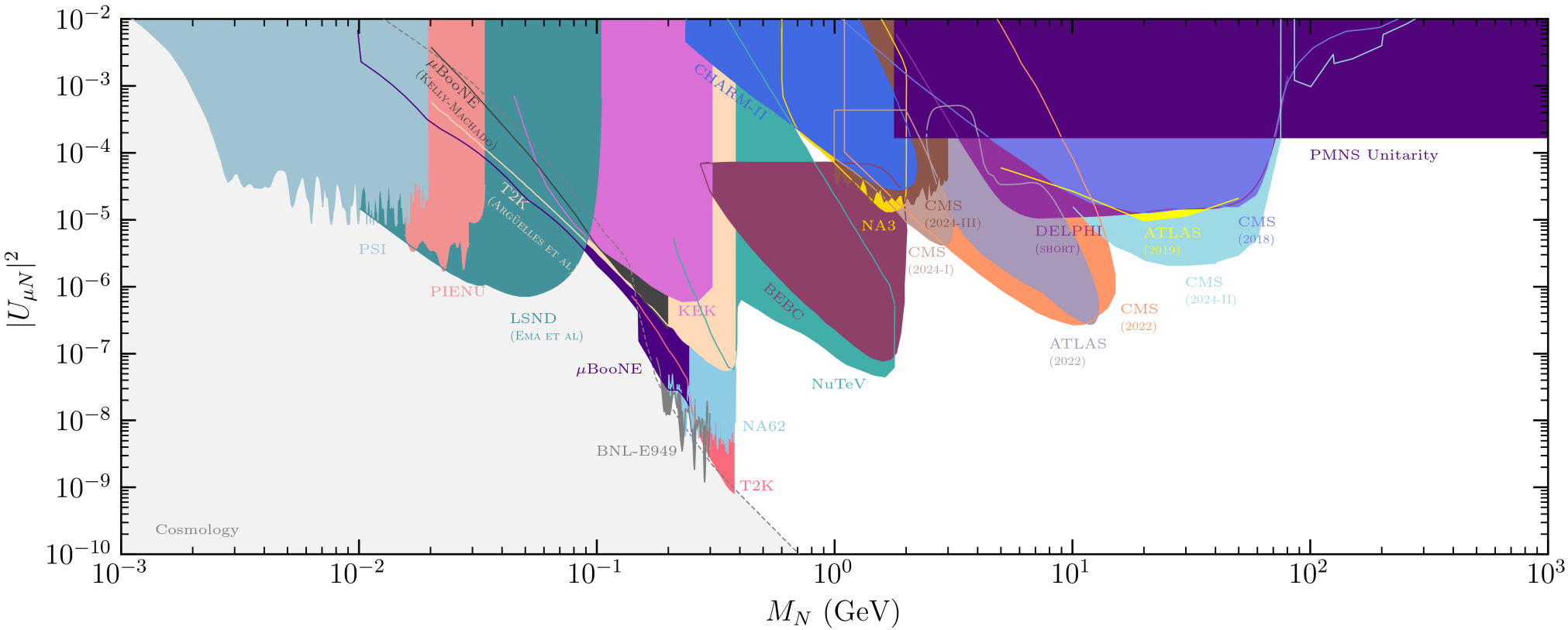
$$N^{\alpha}_{\rm DB}(c\tau) = \sum_{\beta} \mathcal{B}_{vis} \int dE_\nu dc_\theta dE_N \frac{d\phi_{\nu_\beta}}{dE_\nu} P_{\beta\alpha}(E_\nu) \frac{d^2\sigma_{\nu_\alpha N}}{dE_N dc_\theta}(E_\nu) P_d(c\tau, E_N)\, V_{\rm det}(c\tau, E_N, c_\theta)$$

Neutrinoless double beta decay



Bolton, Deppisch, Rai, Zhang 2212.14690

The New Physics Scale



$$\log_{10}(\Delta M/M_1)$$

https://github.com/mhostert/Heavy-Neutrino-Limits
Fernadez-Martinez, Hernandez-Garcia, Gonzalez-Lopez, Hostert, JLP 2306.01040

Global bounds: EW and CLFV precision data

2N-SS	Normal Ordering		Inverted Ordering	
	68%CL	95%CL	68%CL	95%CL
$\eta_{ee} = \frac{\lvert\theta_e\rvert^2}{2}$	$6.4 \cdot 10^{-6}$	$9.4 \cdot 10^{-6}$	$[0.98, 4.4] \cdot 10^{-4}$	$5.5 \cdot 10^{-4}$
$\eta_{\mu\mu} = \frac{\lvert\theta_\mu\rvert^2}{2}$	$6.9 \cdot 10^{-5}$	$1.3 \cdot 10^{-4}$	$[0.20, 1.0] \cdot 10^{-6}$	$3.2 \cdot 10^{-5}$
$\eta_{\tau\tau} = \frac{\lvert\theta_\tau\rvert^2}{2}$	$8.6 \cdot 10^{-5}$	$2.1 \cdot 10^{-4}$	$[0.94, 2.8] \cdot 10^{-5}$	$4.5 \cdot 10^{-5}$
$\mathrm{Tr}\,[\eta] = \frac{\lvert\theta\rvert^2}{2}$	$1.6 \cdot 10^{-4}$	$2.9 \cdot 10^{-4}$	$[1.1, 4.8] \cdot 10^{-4}$	$6.0 \cdot 10^{-4}$
$\lvert\eta_{e\mu}\rvert = \frac{\lvert\theta_e\theta_\mu^*\rvert}{2}$	$8.3 \cdot 10^{-6}$	$1.2 \cdot 10^{-5}$	$[0.37, 1.0] \cdot 10^{-5}$	$1.3 \cdot 10^{-5}$
$\lvert\eta_{e\tau}\rvert = \frac{\lvert\theta_e\theta_\tau^*\rvert}{2}$	$1.5 \cdot 10^{-5}$	$2.2 \cdot 10^{-5}$	$[0.25, 1.2] \cdot 10^{-4}$	$1.4 \cdot 10^{-4}$
$\lvert\eta_{\mu\tau}\rvert = \frac{\lvert\theta_\mu\theta_\tau^*\rvert}{2}$	$7.2 \cdot 10^{-5}$	$1.3 \cdot 10^{-4}$	$[0.38, 3.0] \cdot 10^{-6}$	$3.5 \cdot 10^{-5}$

Blennow, Fernandez-Martinez, Hernandez-Garcia, Marcano, Naredo-Tuero, JLP 2306.01040