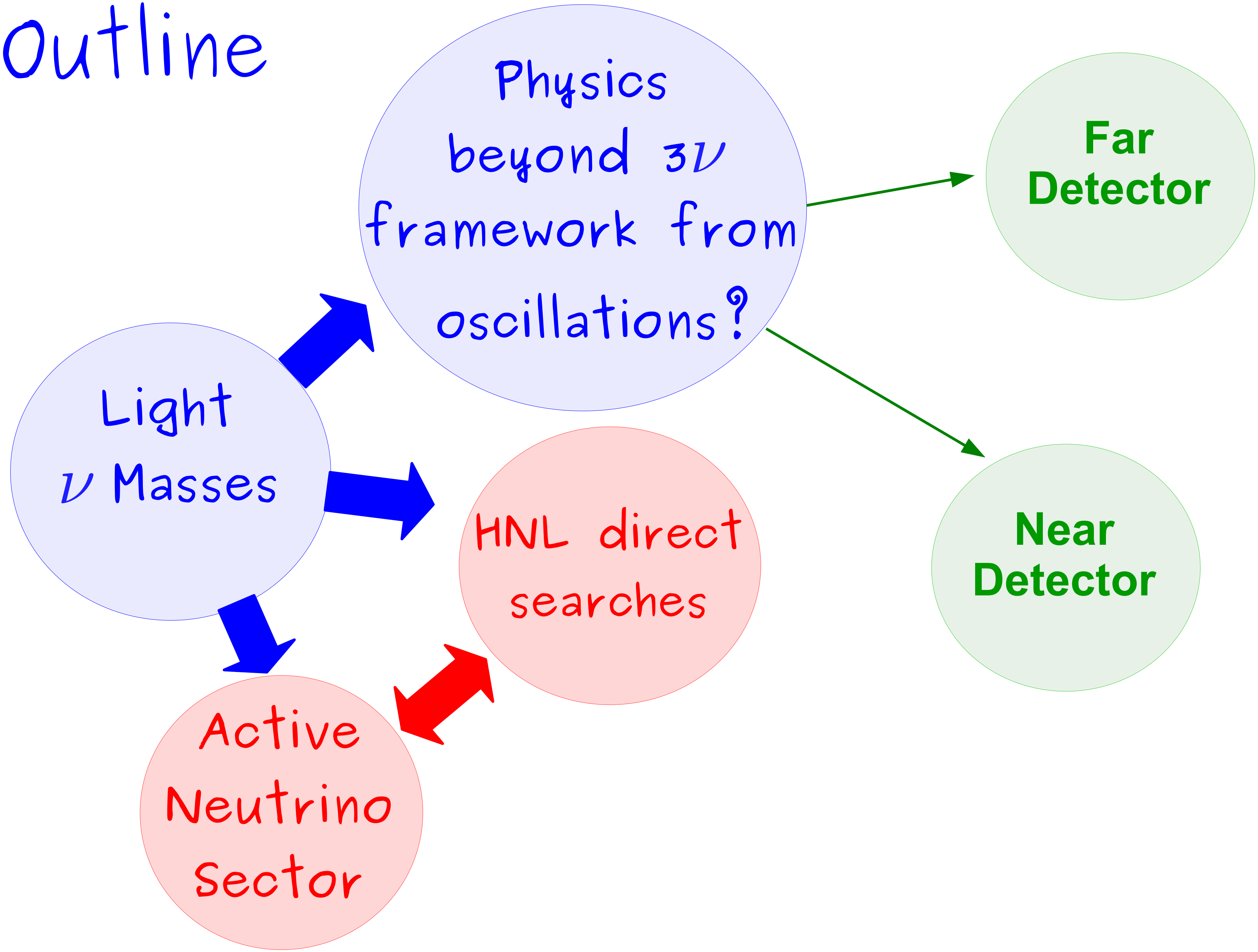
New Physics
from Neutrino Oscillations

Jacobo López-Pavón

NuTs Workshop | IFT
16 June 2022

CIDEGENT/2018/019

Outline



Physics beyond 3ν framework from oscillations?

Far Detector

Near Detector

Light ν Masses

HNL direct searches

Active Neutrino Sector

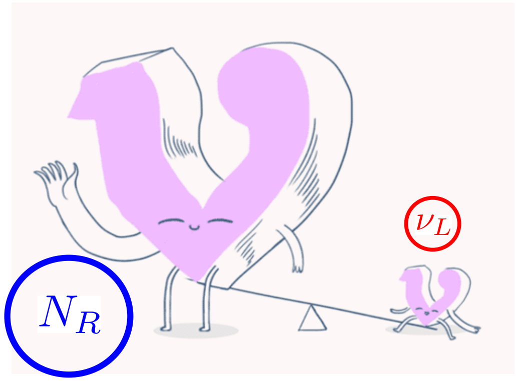
Minimal model: Seesaw Model

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

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

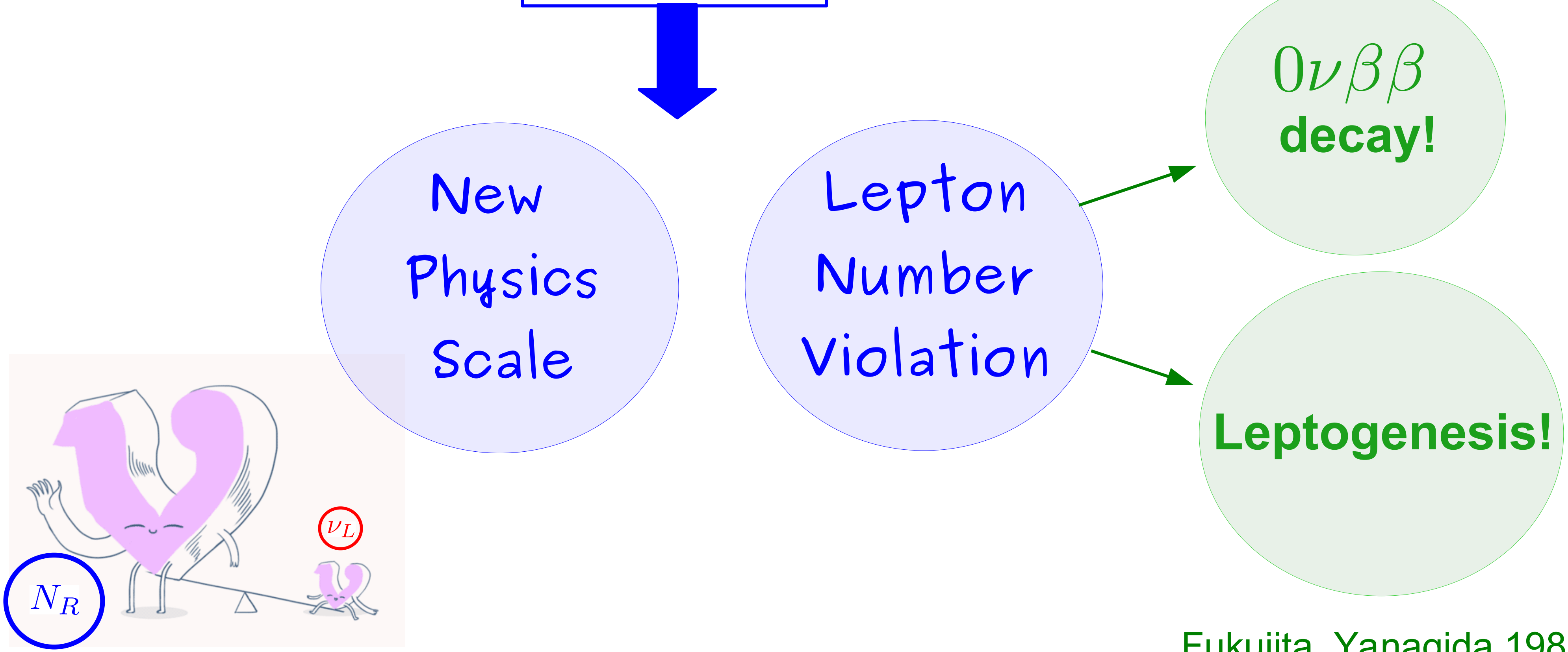


Minkowski 77; Gell-Mann, Ramond, Slansky 79
Yanagida 79; Mohapatra, Senjanovic 80

Minimal model: Seesaw Model

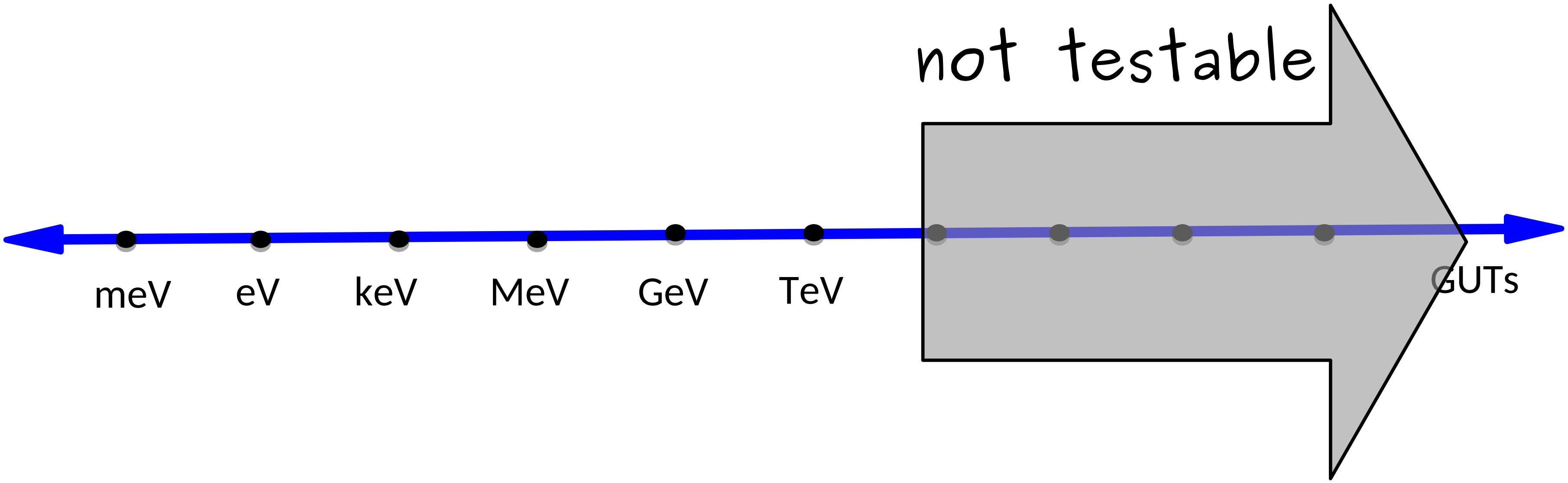
- Simplest extension of SM able to account for neutrino masses. Consists in the addition of heavy fermion singlets (N_R) to the SM field content:

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

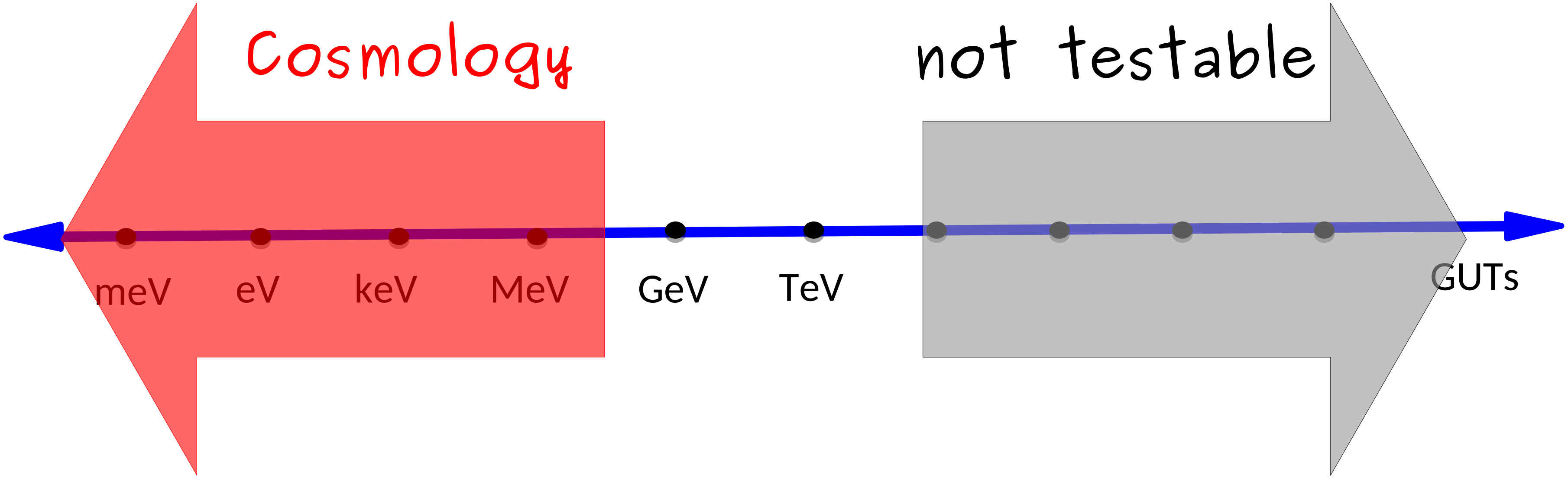


Fukujita, Yanagida 1986

The New Physics Scale



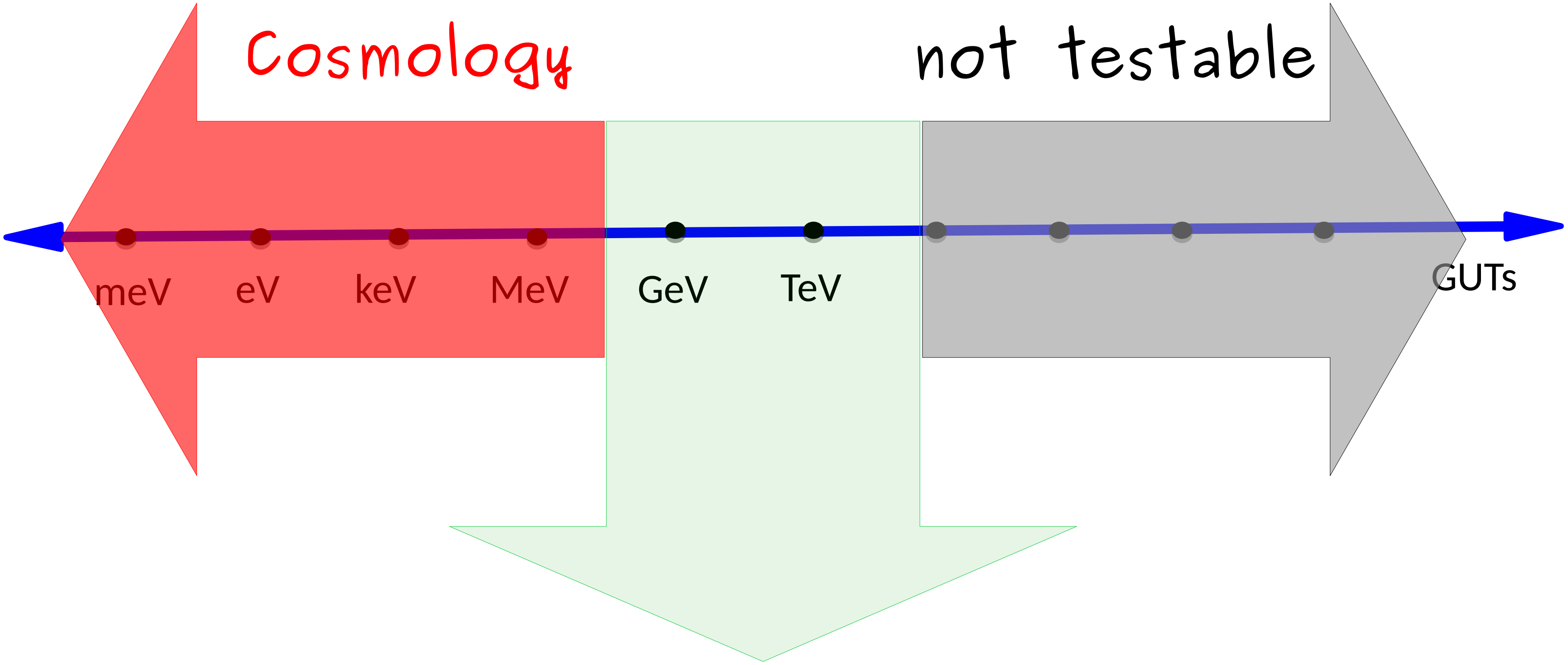
The New Physics Scale



See talk by Graciela Gelmini

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

The New Physics Scale



Cosmology

not testable

meV eV keV MeV GeV TeV GUTs

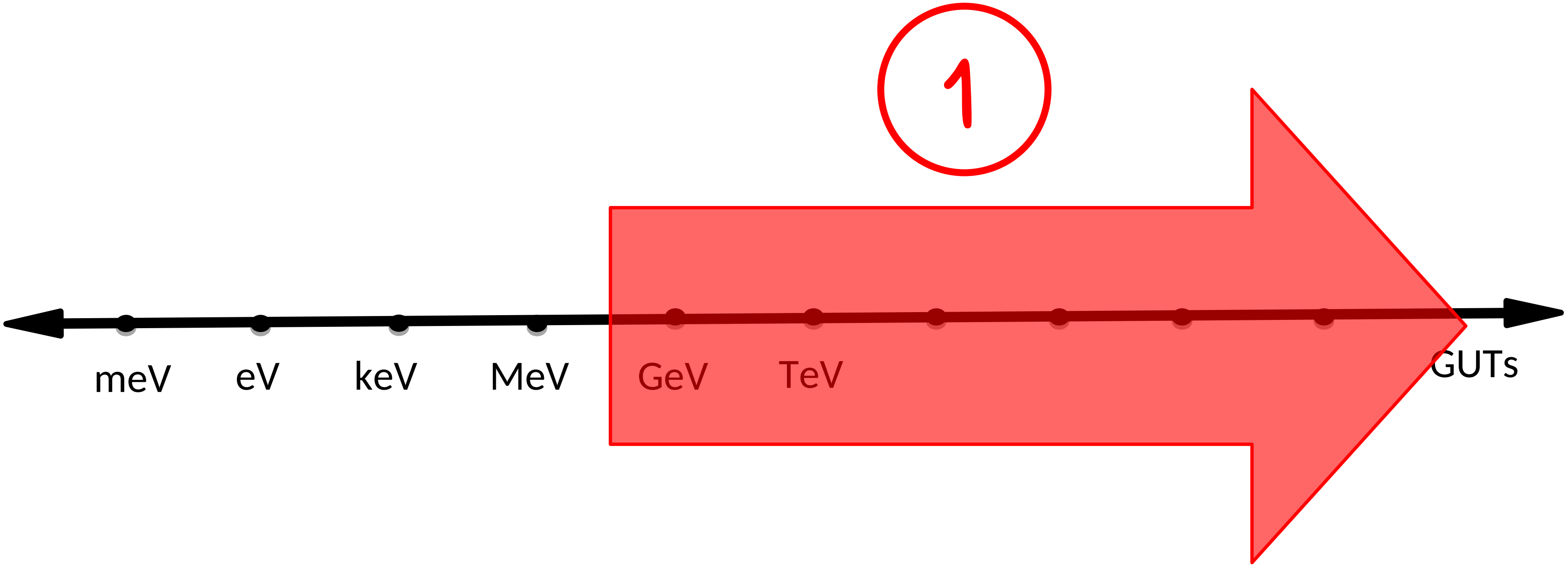
$0\nu\beta\beta$ decay, CLFV, Colliders, Beam-dump…

See also talks by Lucente, Marcano, Ruchaisky, Ruiz, and Tastet

Are Long Baseline
Neutrino Oscillation experiments
sensitive to
New Physics
beyond 3ν framework

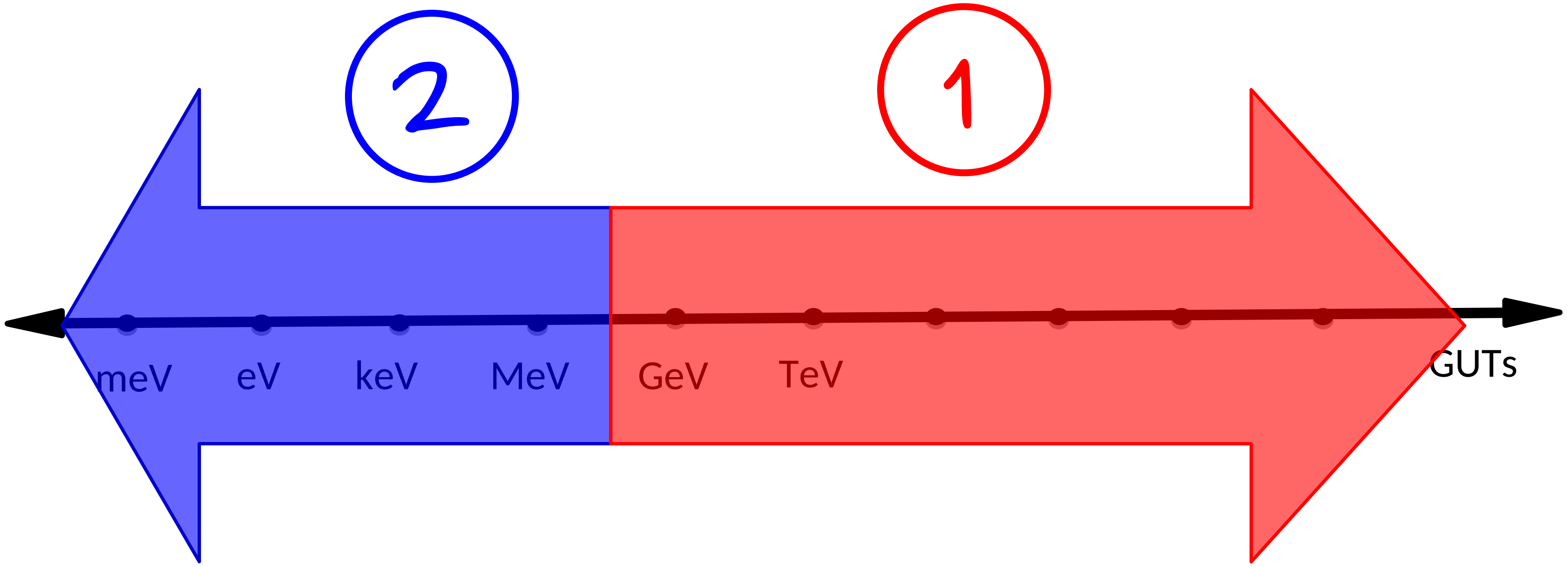
?

Neutrino Oscillations vs NP scale



Non-Unitary
mixing
(sterile states
integrated out)

Neutrino Oscillations vs NP scale



Kinematically
accessible sterile
neutrinos

Non-Unitary
mixing
(sterile states
integrated out)

Both limits can be studied
in a
unified & model independent way

Blennow, Coloma, Fernandez-Martinez, Hernandez-Garcia, JLP 1609.08637
Coloma, JLP, Rosauro-Alcaraz, **Urrea** 2105.11466.

Model Independent Approach

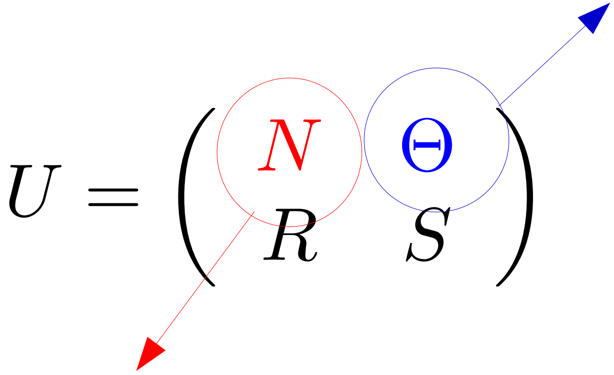
$$U = \begin{pmatrix} N & \Theta \\ R & S \end{pmatrix}$$

Model Independent Approach

$N_i - \nu_\alpha$ mixing

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

Model Independent Approach



$N_i - \nu_\alpha$ mixing

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

Deviation from unitarity of the PMNS matrix

Langacker, London 1988
Antusch, Biggio, Fernandez-Martinez, Gavela, JLP 2006

General Parameterizations

- Triangular parameterization

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

Deviation from unitarity

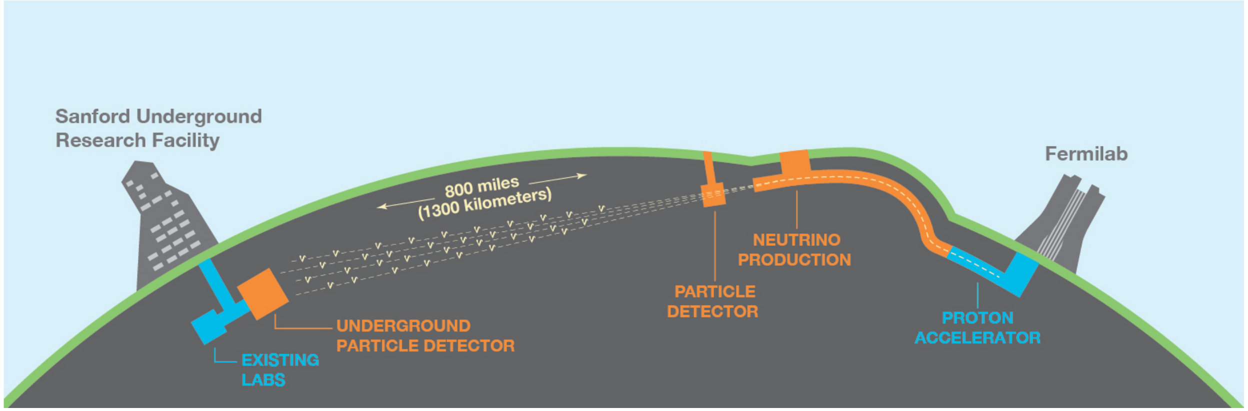
Unitary matrix

(standard unitary PMNS matrix
up to small corrections)

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

Z.-z. Xing 2008, 2012
Escrihuela, Forero, Miranda, Tortola 2015

Far Detector vs Near detector



$$N_{\nu_\alpha \to \nu_\beta} \sim \frac{\Phi_\alpha(E)}{L^2} P_{\alpha\beta}(L/E)\sigma_\beta(E)\epsilon_\beta(E)$$

- Sources of systematics

  - Cross sections
  - Neutrino flux

- ***Near detector*** *measurements* ***reduce far detector systematic uncertainties***

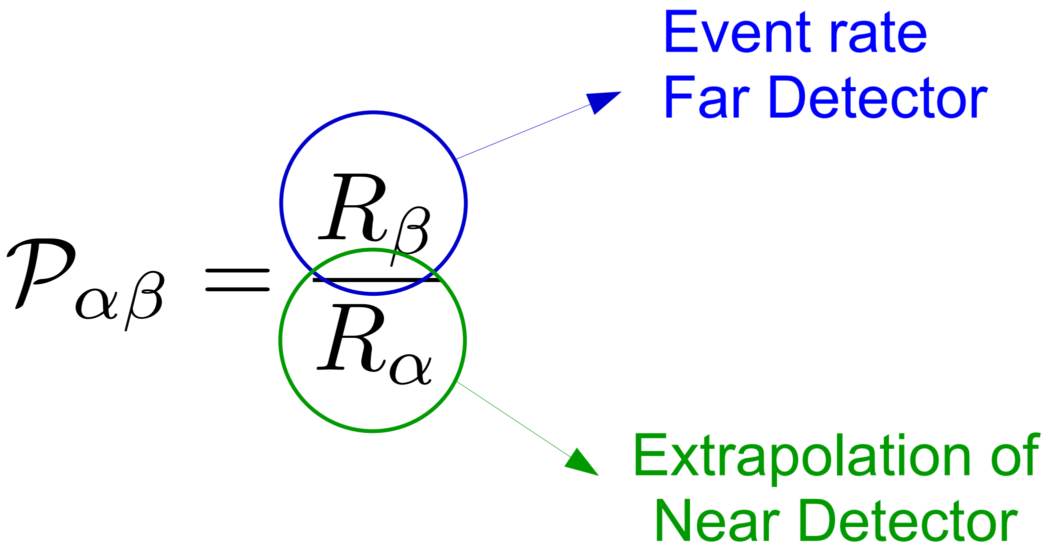
- **New Physics at near detector (strongly affected by systematic uncertainties)**

Far Detector

Blennow, Coloma, Fernandez-Martinez, Hernandez-Garcia, JLP 1609.08637

Far Detector

- What is measured in neutrino oscillation experiments

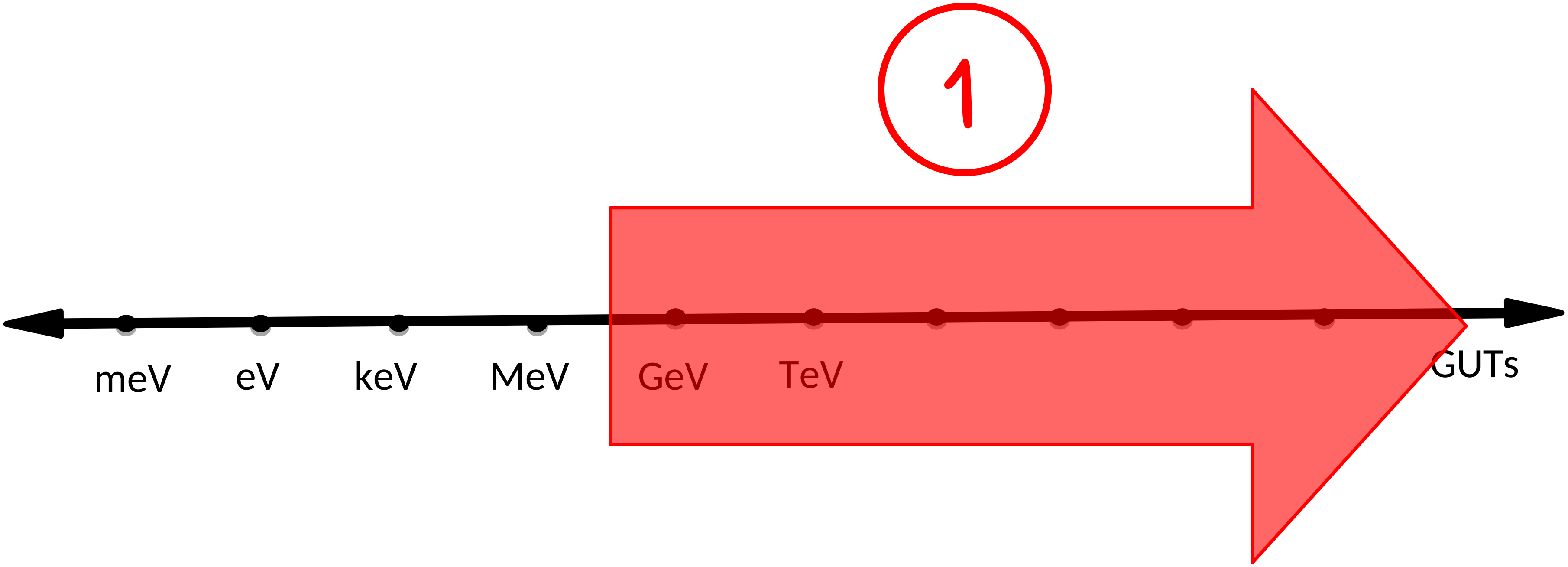


$$\mathcal{P}_{\alpha\beta} = \frac{R_\beta}{R_\alpha}$$

Event rate
Far Detector

Extrapolation of
Near Detector

① Non-Unitary Mixing



Non-Unitary mixing (sterile states integrated out)

Blennow, Coloma, Fernandez-Martinez, Hernandez-Garcia, JLP 1609.08637

① Non-Unitary Mixing

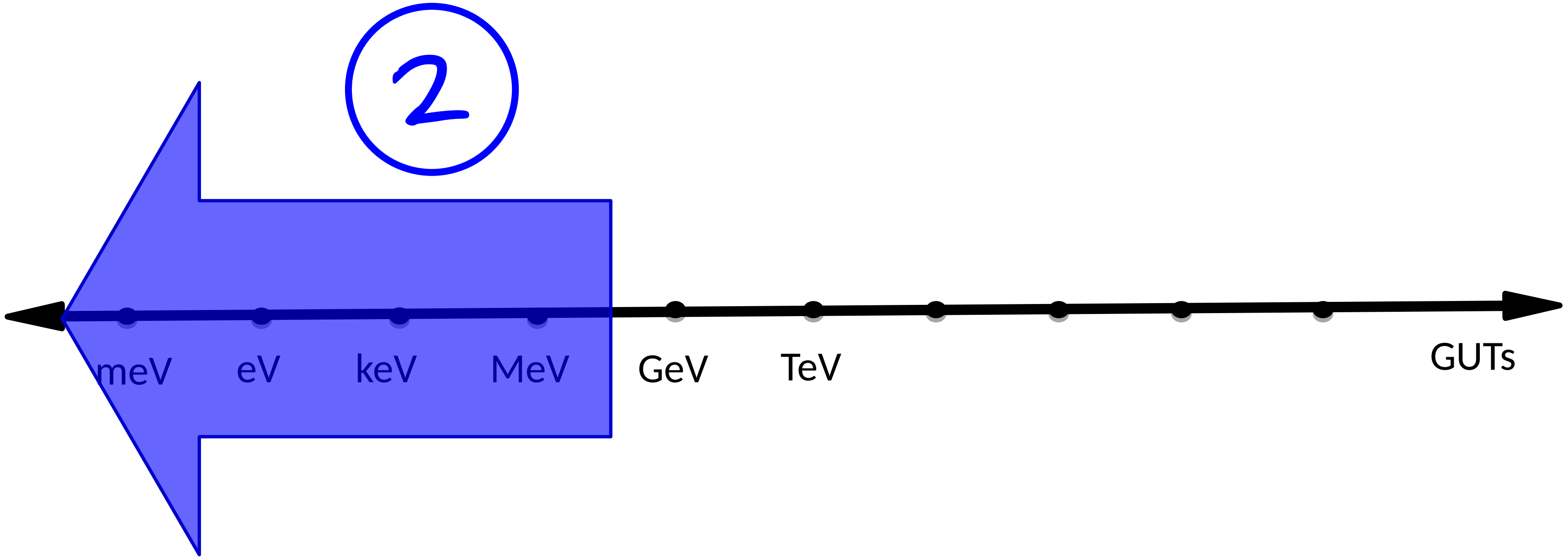
- What is measured in neutrino oscillation experiments

$$\mathcal{P}_{\alpha\beta} = \frac{\left|(N\exp(-iHL)N^\dagger)_{\beta\alpha}\right|^2}{\left[(NN^\dagger)_{\alpha\alpha}\right]^2}.$$

- When $\mathrm{NN}^\dagger = I$ $\Rightarrow$ $\mathcal{P}_{\alpha\beta} = P_{\alpha\beta}$ (SM limit recovered)

Blennow, Coloma, Fernandez-Martinez, Hernandez-Garcia, JLP 1609.08637

② Kinematically accessible Sterile ν



Kinematically accessible sterile neutrinos

Blennow, Coloma, Fernandez-Martinez, Hernandez-Garcia, JLP 1609.08637

② Kinematically accessible Sterile ν

1. The light-heavy oscillations averaged out at the near detector.

Identical to the heavy non-unitarity case

Blennow, Coloma, Fernandez-Martinez, Hernandez-Garcia, JLP 1609.08637

② Kinematically accessible Sterile ν

1. The light-heavy oscillations averaged out at the near detector.

Identical to the heavy non-unitarity case

2. The light-heavy oscillations have not yet developed at the near detector.

No normalization factor

DUNE: $0.1\,\mathrm{eV}^2 \lesssim \Delta m^2 \lesssim 1\,\mathrm{eV}^2$

Blennow, Coloma, Fernandez-Martinez, Hernandez-Garcia, JLP 1609.08637

② Kinematically accessible Sterile ν

1. The light-heavy oscillations averaged out at the near detector.

Identical to the heavy non-unitarity case

2. The light-heavy oscillations have not yet developed at the near detector.

No normalization factor

3. The oscillation frequency dictated by the light-heavy frequency matches the near detector distance.

Oscillations could be observed at the near detector

② Kinematically accessible Sterile ν

1. The light-heavy oscillations averaged out at the near detector.

Identical to the heavy non-unitarity case

2. The light-heavy oscillations have not yet developed at the near detector.

No normalization factor

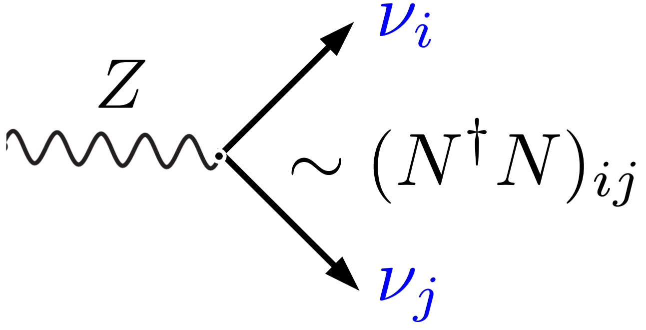
Low Scale

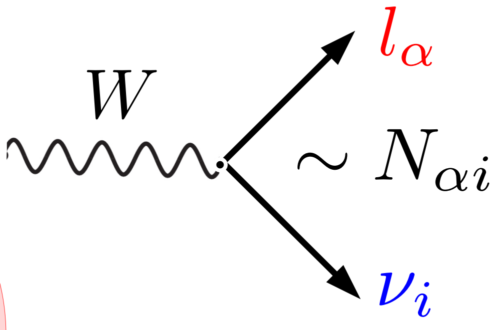
Non-Unitarity

Blennow, Coloma, Fernandez-Martinez, Hernandez-Garcia, JLP 1609.08637.

Present Bounds

	High-scale Non-Unitarity $(m > \text{EW})$
α_{ee}	$1.3 \cdot 10^{-3}$
$\alpha_{\mu\mu}$	$2.2 \cdot 10^{-4}$
$\alpha_{\tau\tau}$	$2.8 \cdot 10^{-3}$
$\lvert\alpha_{\mu e}\rvert$	$6.8 \cdot 10^{-4}\ (2.4 \cdot 10^{-5})$
$\lvert\alpha_{\tau e}\rvert$	$2.7 \cdot 10^{-3}$
$\lvert\alpha_{\tau\mu}\rvert$	$1.2 \cdot 10^{-3}$





EW & CLFV precision data

Fernandez-Martinez, Hernandez-Garcia, JLP
1605.08774
Blennow, Coloma, Fernandez-Martinez,
Hernandez-Garcia, JLP
1609.08637

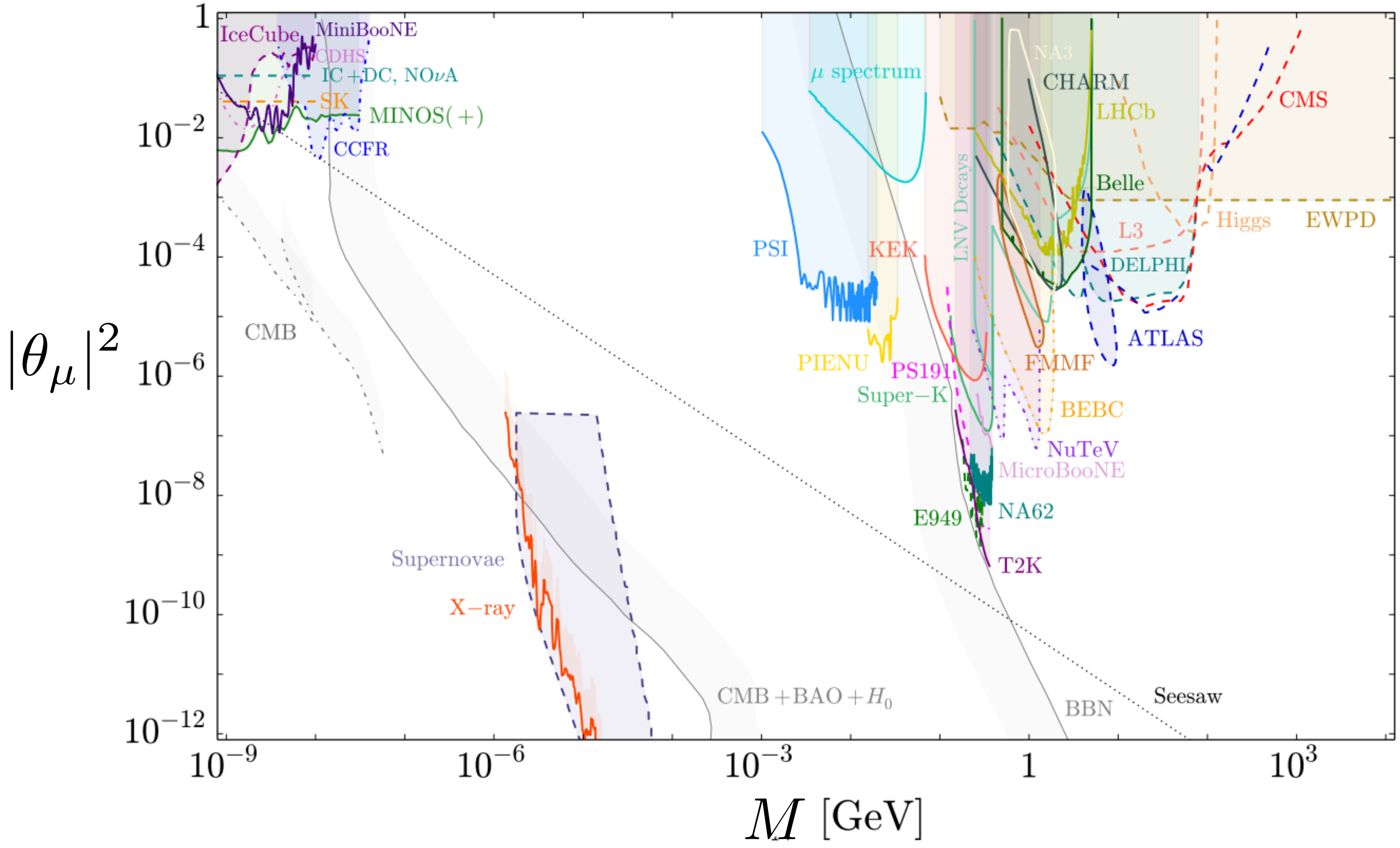
Present Bounds

	High-scale Non-Unitarity	Low-scale Non-Unitarity	
	$(m > \mathrm{EW})$	$\Delta m^2 \gtrsim 100\ \mathrm{eV}^2$	$\Delta m^2 \sim 0.1 - 1\ \mathrm{eV}^2$
α_{ee}	$1.3 \cdot 10^{-3}$	$2.4 \cdot 10^{-2}$ BUGEY	$1.0 \cdot 10^{-2}$ BUGEY
$\alpha_{\mu\mu}$	$2.2 \cdot 10^{-4}$	$2.2 \cdot 10^{-2}$ SK	$1.4 \cdot 10^{-2}$ MINOS
$\alpha_{\tau\tau}$	$2.8 \cdot 10^{-3}$	$1.0 \cdot 10^{-1}$ SK	$1.0 \cdot 10^{-1}$ SK
$\|\alpha_{\mu e}\|$	$6.8 \cdot 10^{-4}$ $(2.4 \cdot 10^{-5})$	$2.5 \cdot 10^{-2}$ NOMAD	$1.7 \cdot 10^{-2}$
$\|\alpha_{\tau e}\|$	$2.7 \cdot 10^{-3}$	$6.9 \cdot 10^{-2}$	$4.5 \cdot 10^{-2}$
$\|\alpha_{\tau\mu}\|$	$1.2 \cdot 10^{-3}$	$1.2 \cdot 10^{-2}$ NOMAD	$5.3 \cdot 10^{-2}$

Fernandez-Martinez, Hernandez-Garcia, JLP
1605.08774
Blennow, Coloma, Fernandez-Martinez, Hernandez-Garcia, JLP
1609.08637

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

Present Bounds

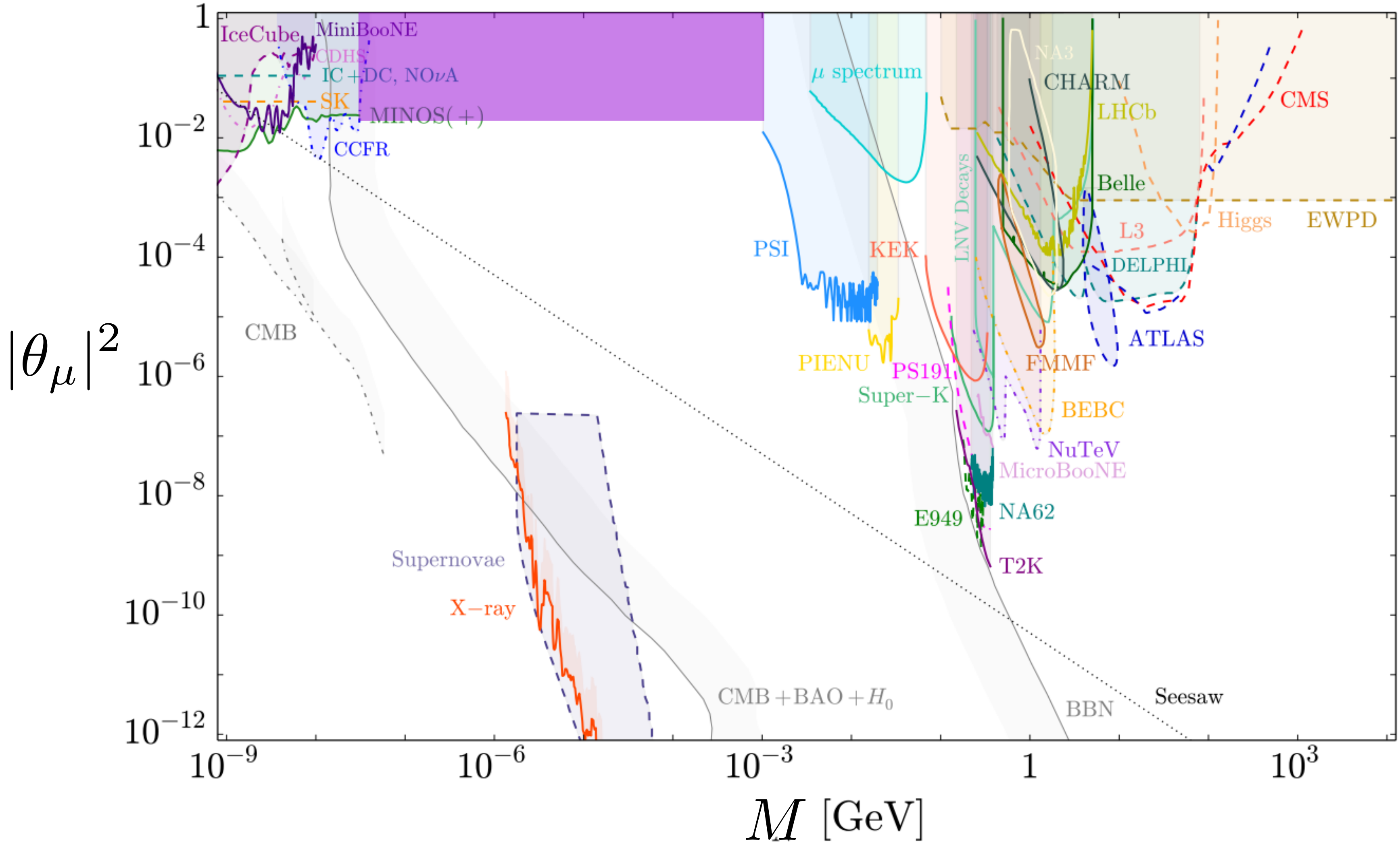


$$|\alpha_{\beta\beta}|^2 = \frac{1}{2}\sum_i |\theta_{\alpha i}|^2$$

Figure from Bolton,Deppisch, Bhupal Dev 1912.03058

Blennow, Coloma,
Fernandez-Martinez,
Hernandez-Garcia, JLP
1609.08637

Present Bounds



$$|\alpha_{\beta\beta}|^2 = \frac{1}{2}\sum_i |\theta_{\alpha i}|^2$$

Figure from Bolton,Deppisch, Bhupal Dev 1912.03058

Present Bounds (update)

Argüelles et al, 2203.10811

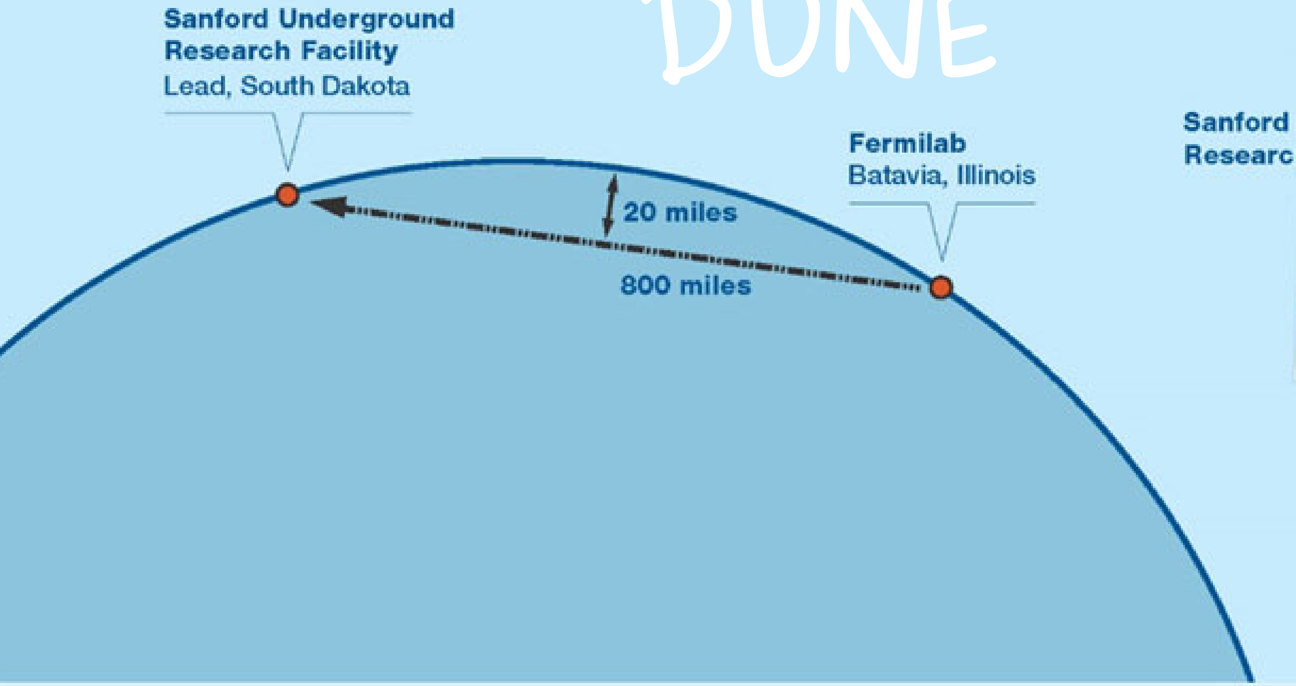
	“flavor+electroweak” $m >$ EW (2σ limit)	“Averaged-out oscillations” $\Delta m^2 \gtrsim 0.1$ eV^2 (90% CL)
α_{ee}	$1.3 \cdot 10^{-3}$	$8.4 \cdot 10^{-3}$ SOLAR
$\alpha_{\mu\mu}$	$2.2 \cdot 10^{-4}$	$5.0 \cdot 10^{-3}$ MINOS
$\alpha_{\tau\tau}$	$2.8 \cdot 10^{-3}$	$6.5 \cdot 10^{-2}$ ATM
$\lvert\alpha_{\mu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

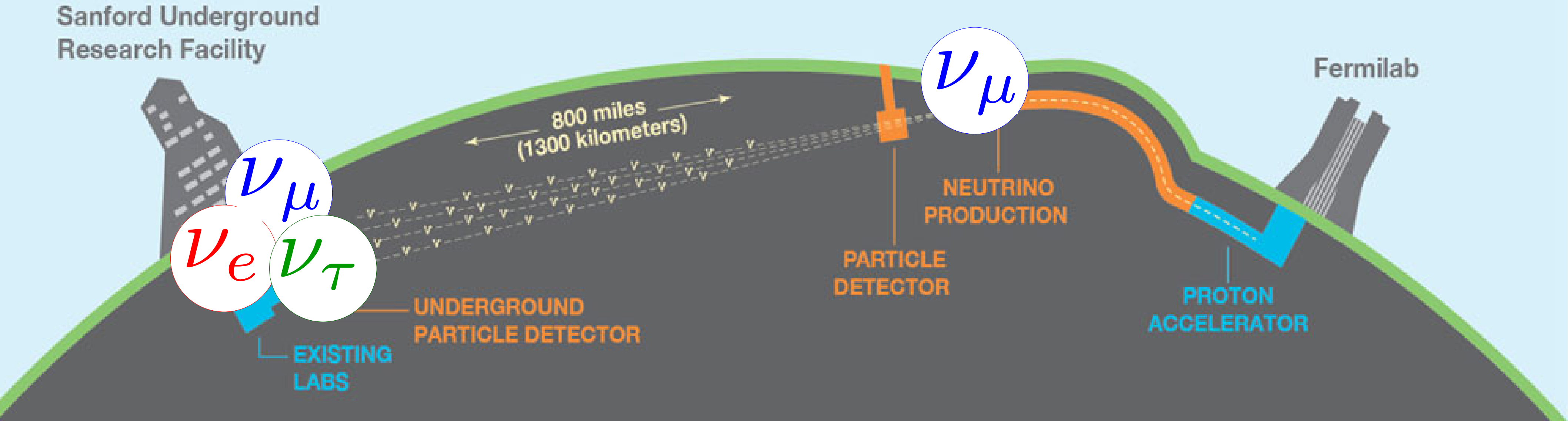
$$\alpha_{\alpha\beta} \leq 2\sqrt{\alpha_{\alpha\alpha}\alpha_{\beta\beta}}$$

Fernandez-Martinez, Hernandez-Garcia, JLP
1605.08774
Blennow, Coloma, Fernandez-Martinez,
Hernandez-Garcia, JLP
1609.08637

Deep Underground Neutrino Experiment

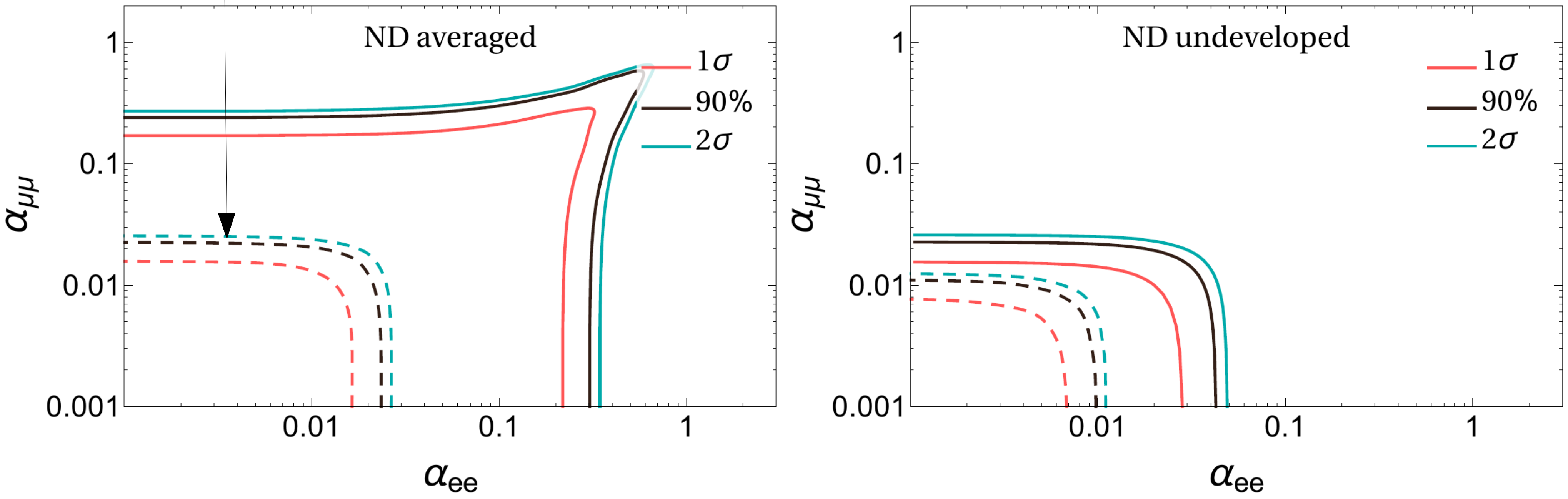
DUNE





Far Detector

Prior
(present bounds)



$$\mathcal{P}_{\alpha\beta} = \frac{\left|(N\exp(-iHL)N^\dagger)_{\beta\alpha}\right|^2}{\left[(NN^\dagger)_{\alpha\alpha}\right]^2}$$

$$\mathcal{P}_{\alpha\beta} = \left|(N\exp(-iHL)N^\dagger)_{\beta\alpha}\right|^2$$

Blennow, Coloma, Fernandez-Martinez, Hernandez-Garcia, JLP 1609.08637.
DUNE CDR configuration 1606.09550

Near Detector

Coloma, JLP, Rosauro-Alcaraz, **Urrea** 2105.11466.

See also Escrihuela, Forero, Miranda, Tortola, Valle arXiv:1503.08879 for other Near Detector configurations (without including tau detection).

High Scale Non-Unitarity

- What is measured in Near Detector

$$\mathcal{P}_{\alpha\beta} = \left|(NN^\dagger)_{\beta\alpha}\right|^2 = |\alpha_{\alpha\beta}|^2$$

zero distance effect!

$$\mathcal{P}_{\alpha\alpha} = \left|(NN^\dagger)_{\alpha\alpha}\right|^2 = 1 - 4\,\alpha_{\alpha\alpha}$$

Sterile Neutrinos: 3+1

- What is measured in Near Detector

$$\mathcal{P}_{\alpha\beta} = 4|U_{\alpha 4}|^2|U_{\beta 4}|^2 \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

$$\mathcal{P}_{\alpha\alpha} = 1 - 4|U_{\alpha 4}|^2 \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

Averaged-out regime

- What is measured in Near Detector

$\Delta m^2_{41} \gtrsim 100\,\mathrm{eV}^2$

$$\langle \mathcal{P}_{\alpha\beta} \rangle = 2|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

zero
distance
effect!

$$\langle \mathcal{P}_{\alpha\alpha} \rangle = 1 - 2|U_{\alpha 4}|^2$$

Averaged-out regime

- What is measured in Near Detector
  $\Delta m^2_{41} \gtrsim 100\,\mathrm{eV}^2$

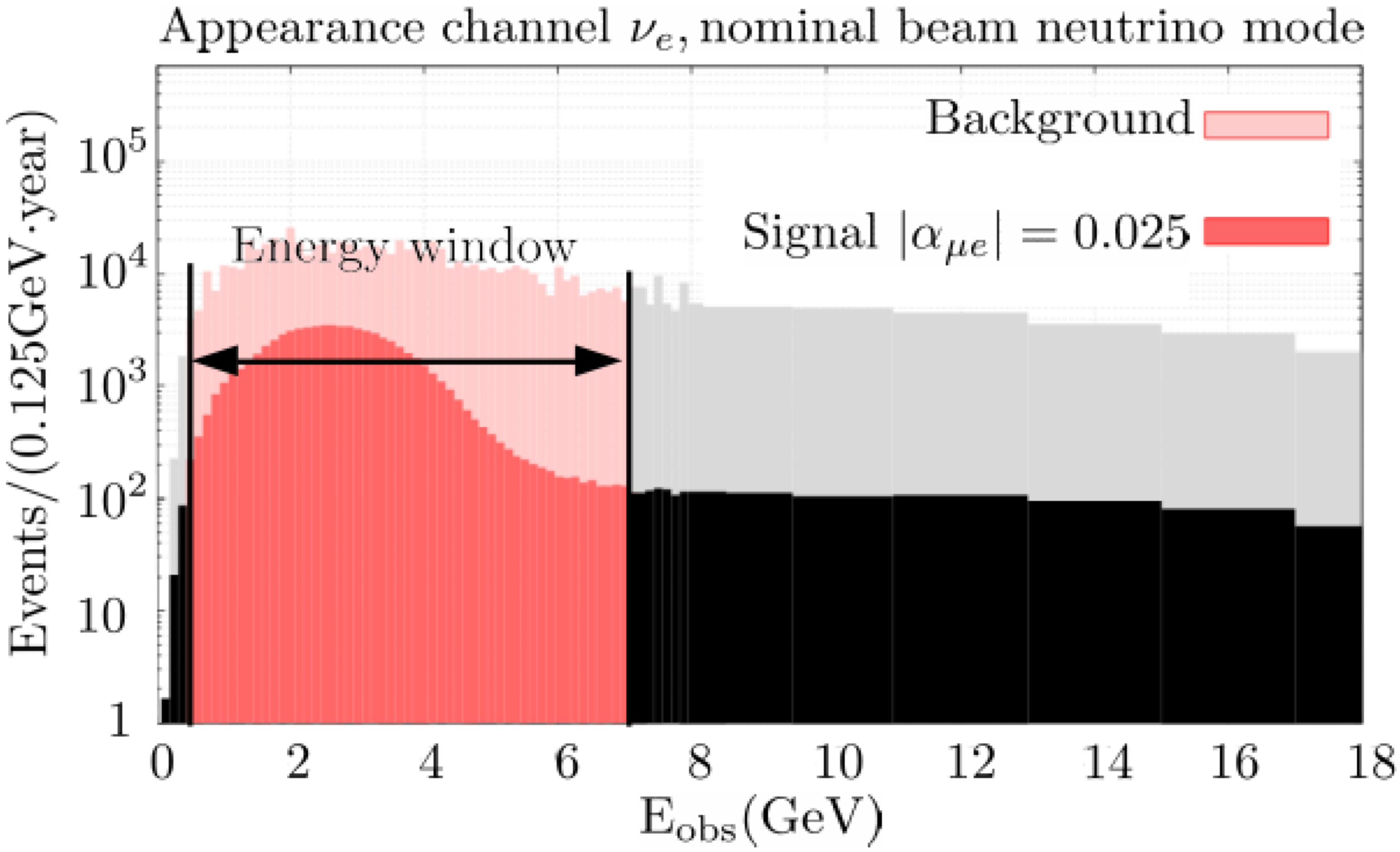
$$\langle \mathcal{P}_{\alpha\beta} \rangle = 2|\alpha_{\alpha\beta}|^2$$

zero
distance
effect!

$$\langle \mathcal{P}_{\alpha\alpha} \rangle = 1 - 4|\alpha_{\alpha\alpha}|$$

Low Scale
Non-Unitarity

Role of shape uncertainty

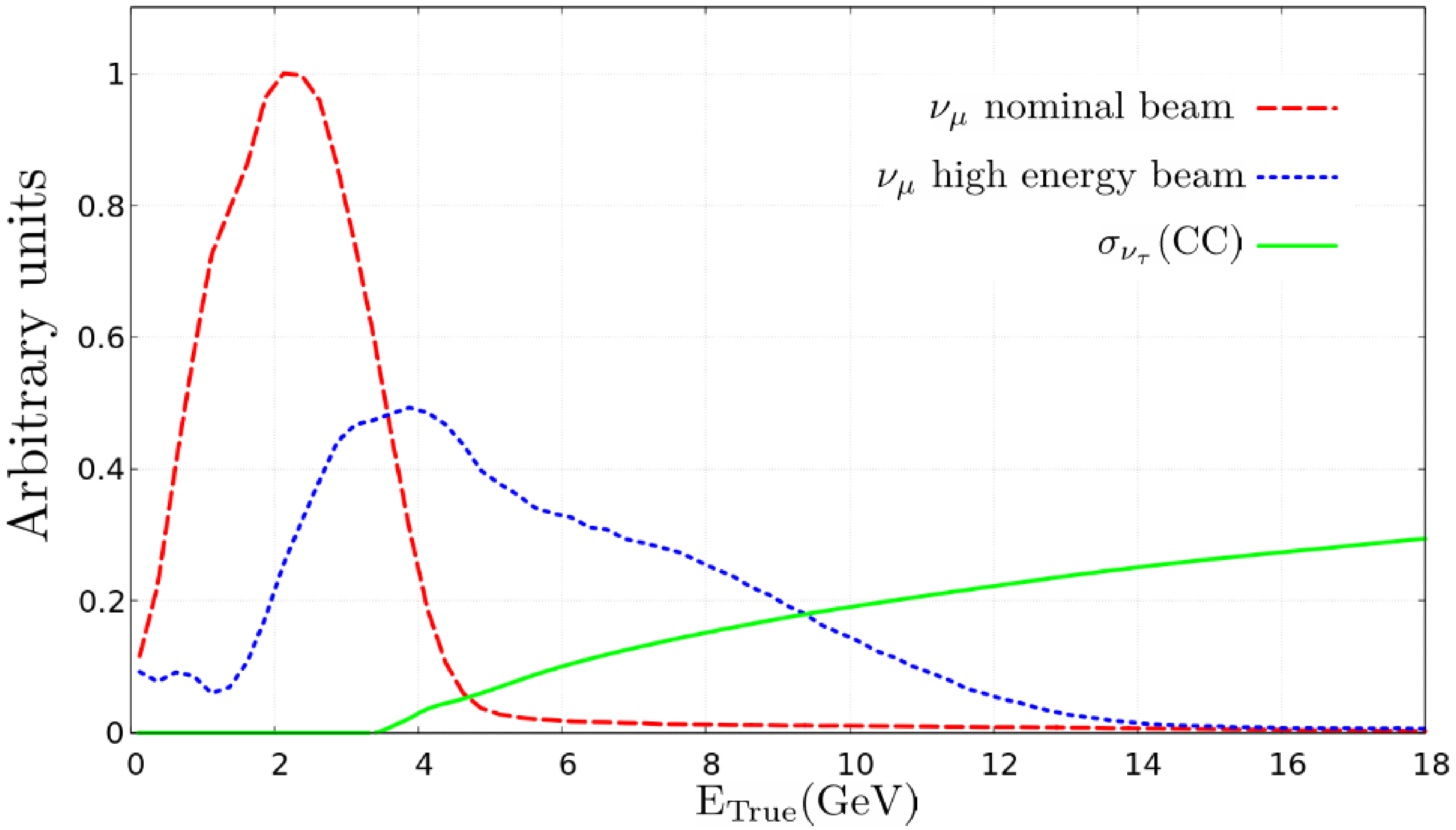


- Sensitivity driven by spectral information.
- Marginal impact of global normalization error.

Coloma, JLP, Rosauro-Alcaraz, **Urrea** 2105.11466

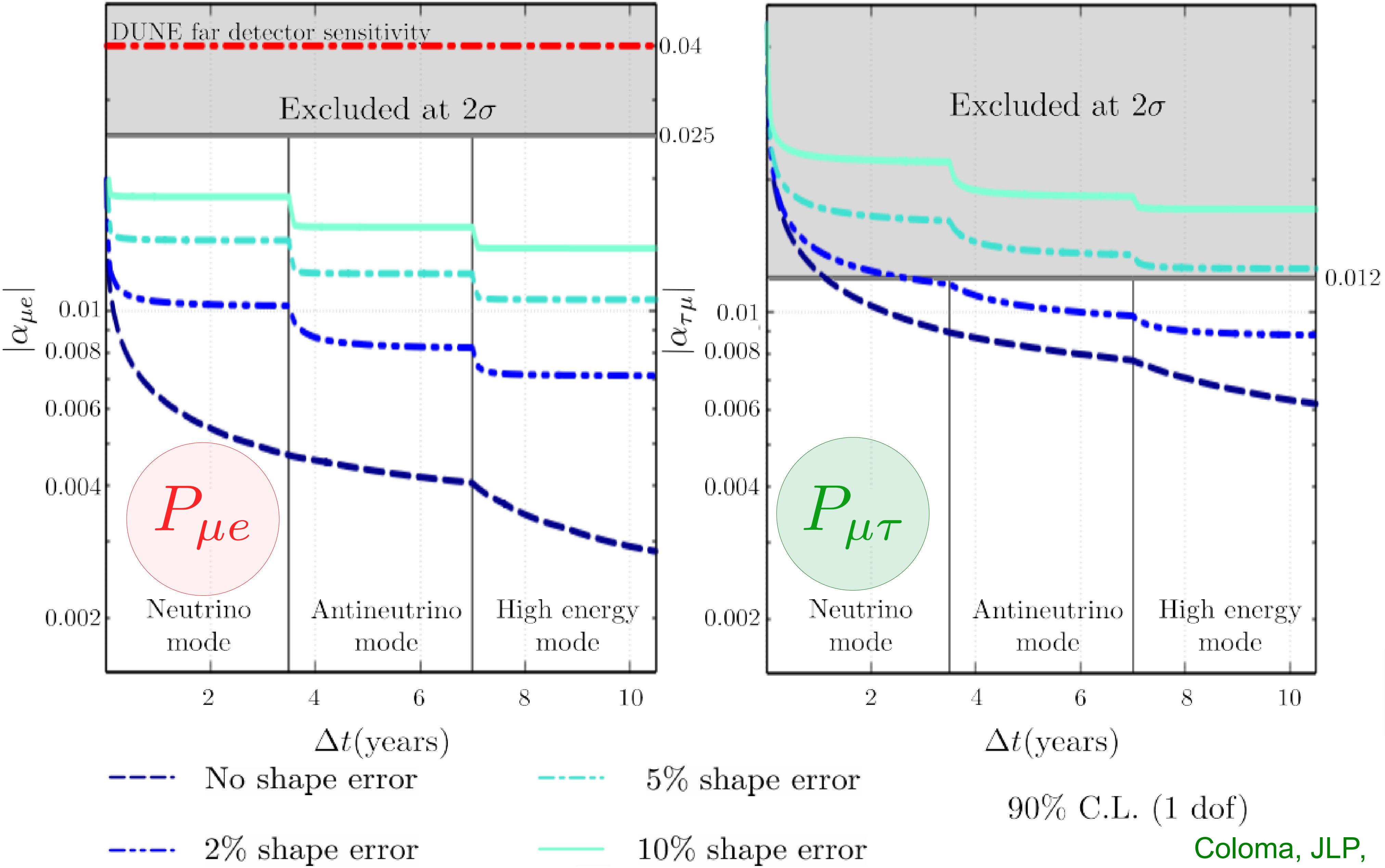
ν_τ appearance channel

- Energy threshold of τ production 3.2 GeV.



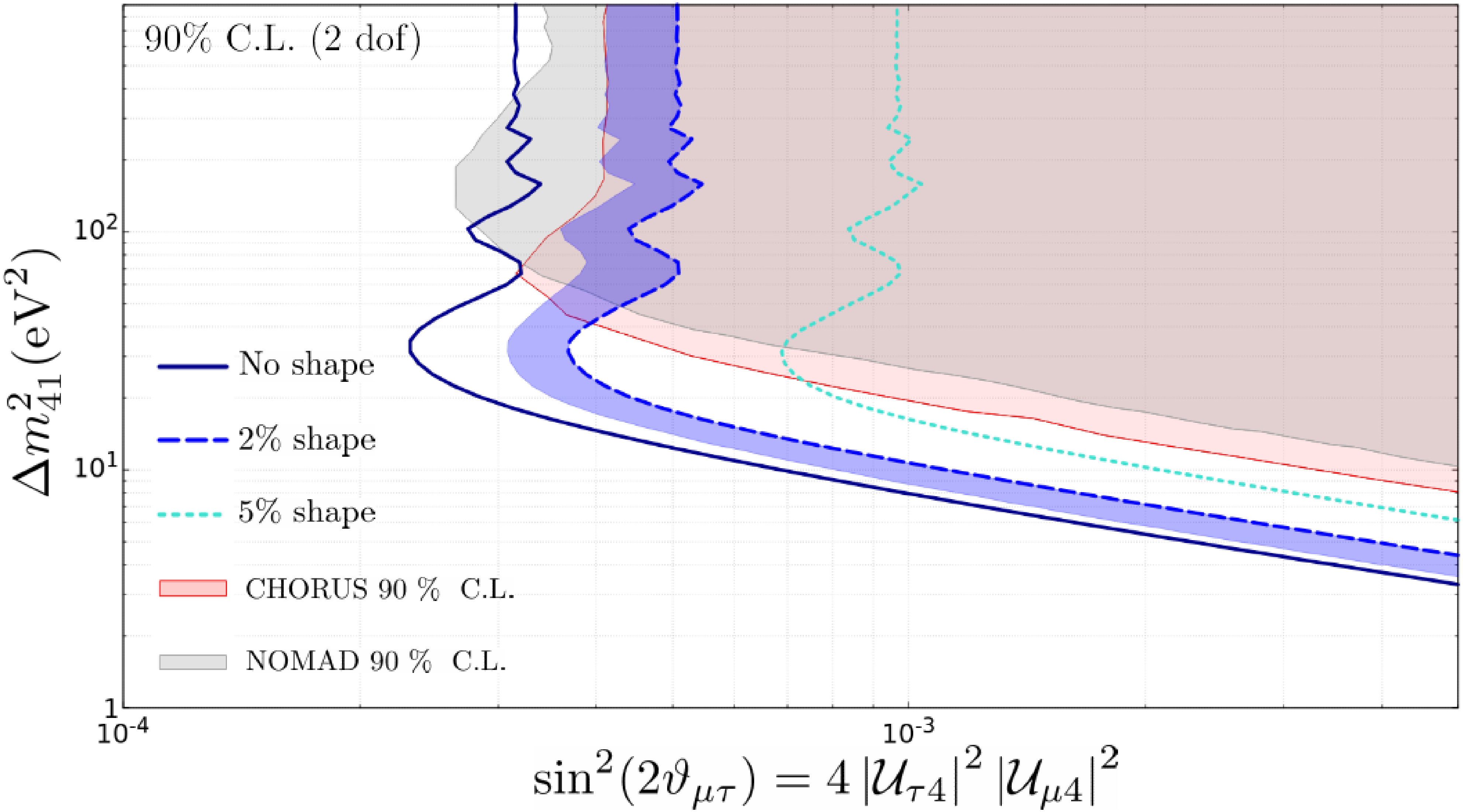
- ν_τ **detection:** we follow de Gouvêa, Kelly, Stenico, Pasquini 1904.07265

Low Scale Non-Unitarity



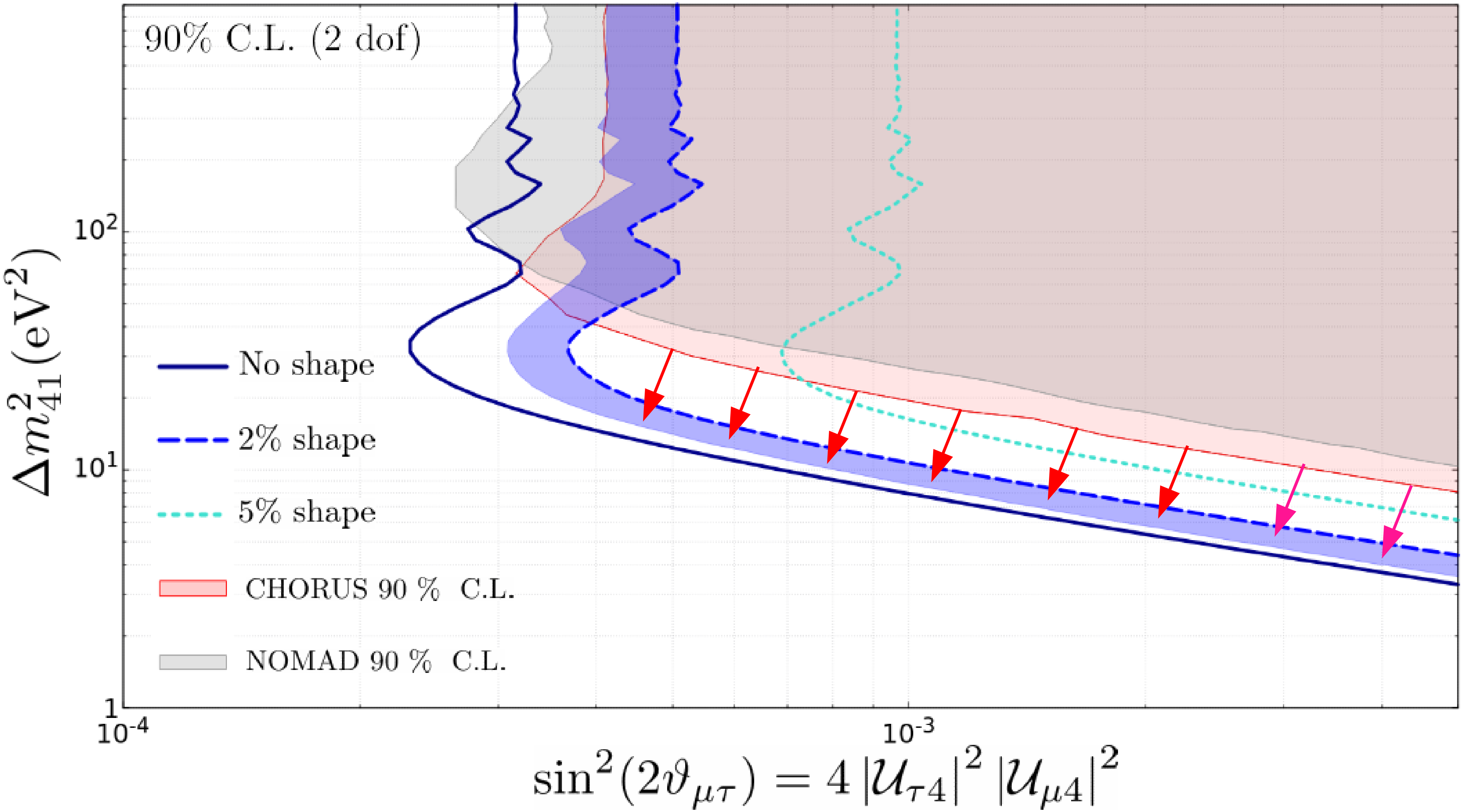
Coloma, JLP,
Rosauro-Alcaraz, **Urrea** 2105.11466

3+1 Sterile Neutrinos: $P_{\mu\tau}$



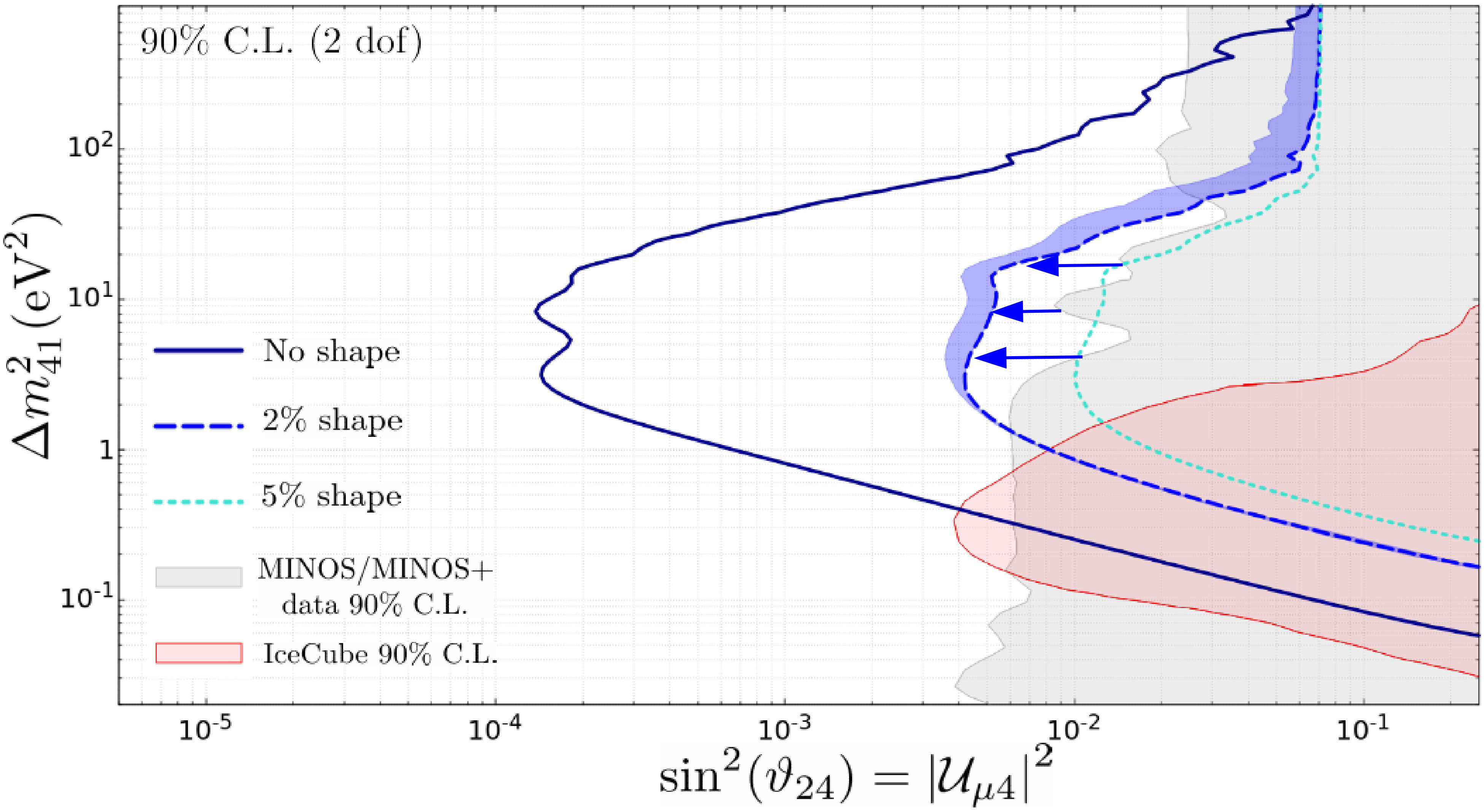
Coloma, JLP, Rosauro-Alcaraz, **Urrea** 2105.11466

3+1 Sterile Neutrinos: $P_{\mu\tau}$



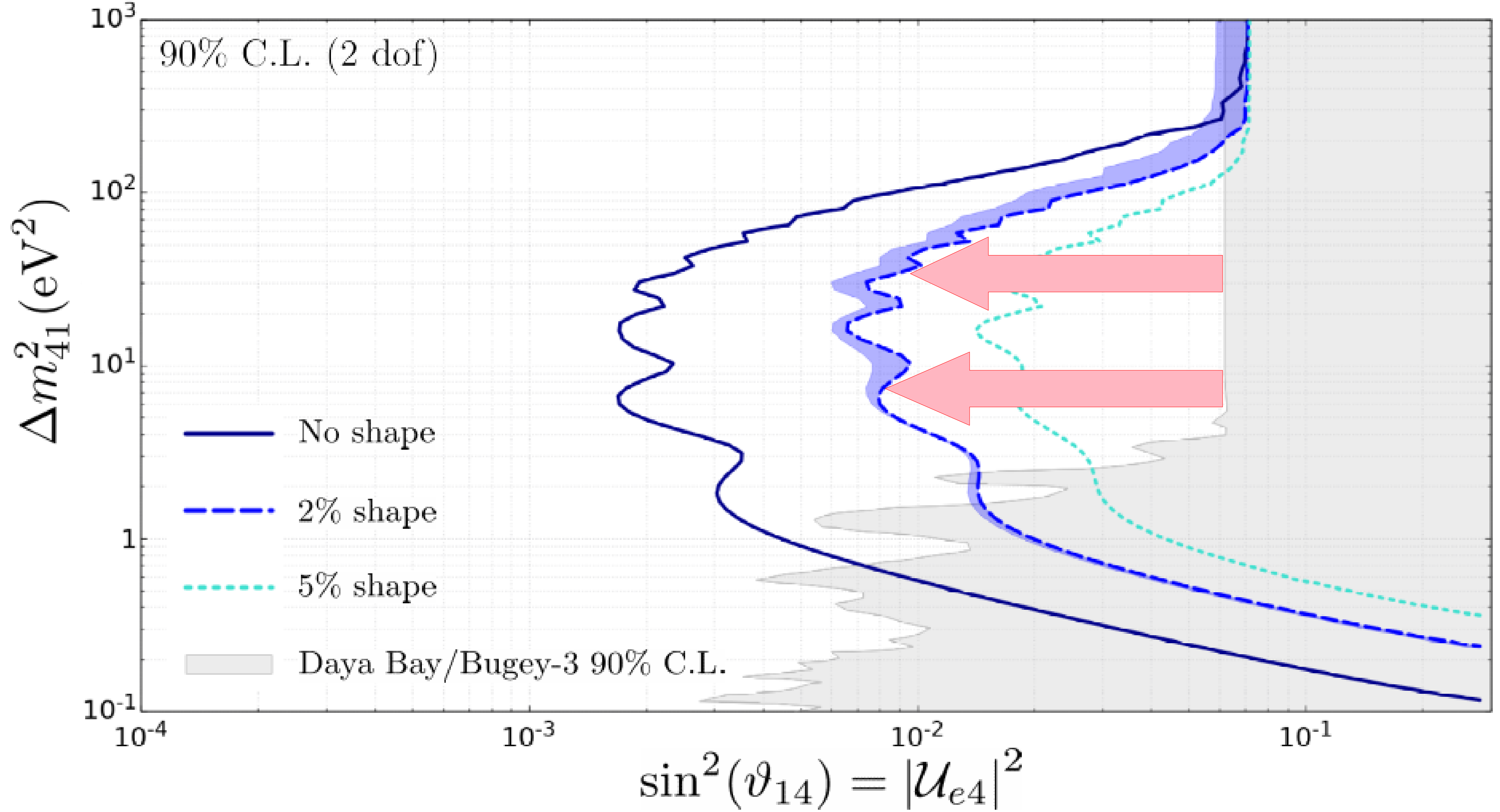
Coloma, JLP, Rosauro-Alcaraz, **Urrea** 2105.11466

3+1 Sterile Neutrinos: $P_{\mu\mu}$



Coloma, JLP, Rosauro-Alcaraz, **Urrea** 2105.11466

3+1 Sterile Neutrinos: P_{ee}



Coloma, JLP, Rosauro-Alcaraz, **Urrea** 2105.11466

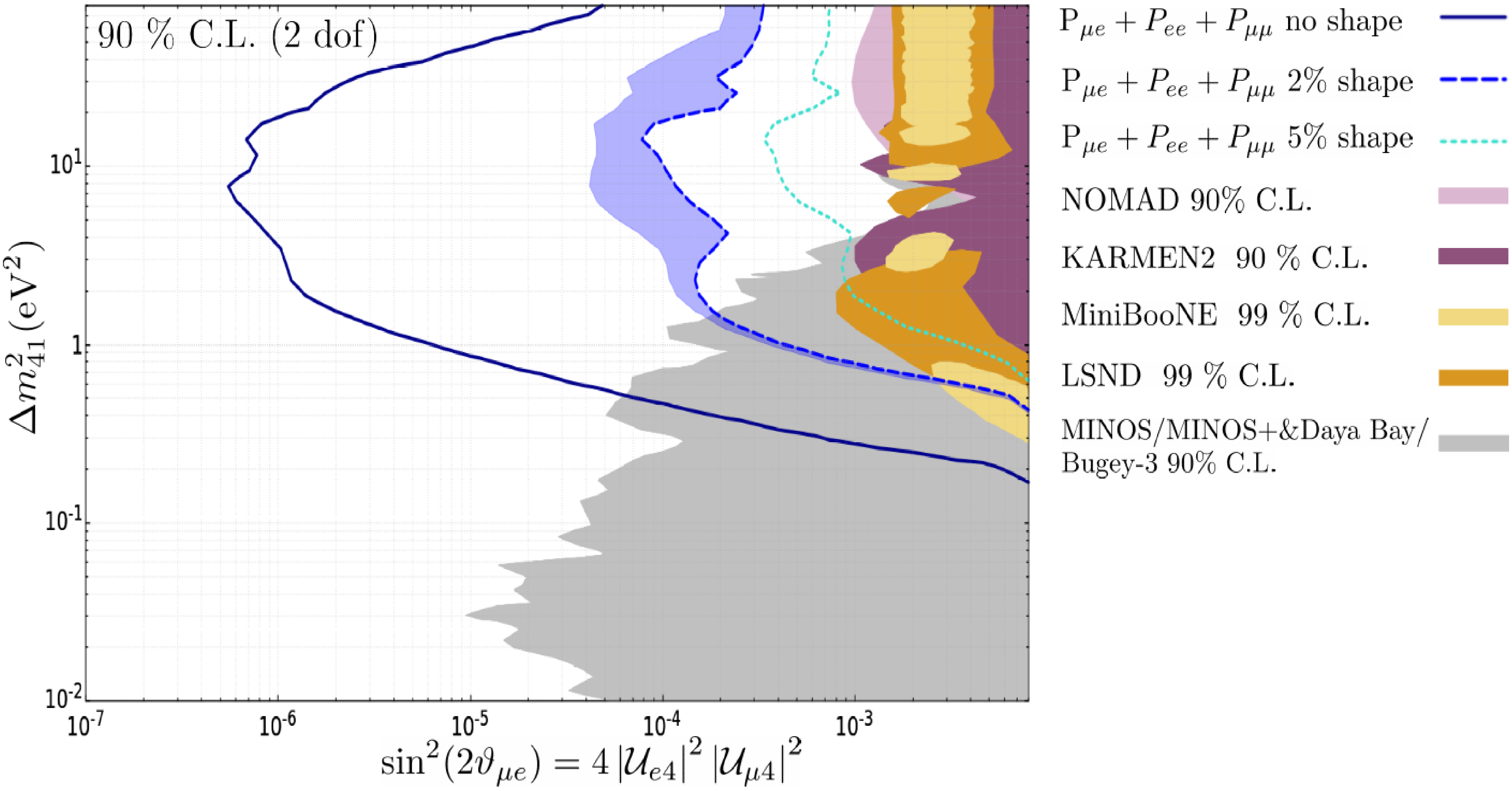
Sterile Neutrinos: 3+1

$$\mathcal{P}_{\mu e} = 4|U_{\mu 4}|^2|U_{e4}|^2 \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

$$\mathcal{P}_{\mu\mu} = 1 - 4|U_{\mu 4}|^2 \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

$$\mathcal{P}_{ee} = 1 - 4|U_{e4}|^2 \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

3+1 Sterile Neutrinos: $P_{\mu\mu} + P_{\mu e} + P_{ee}$



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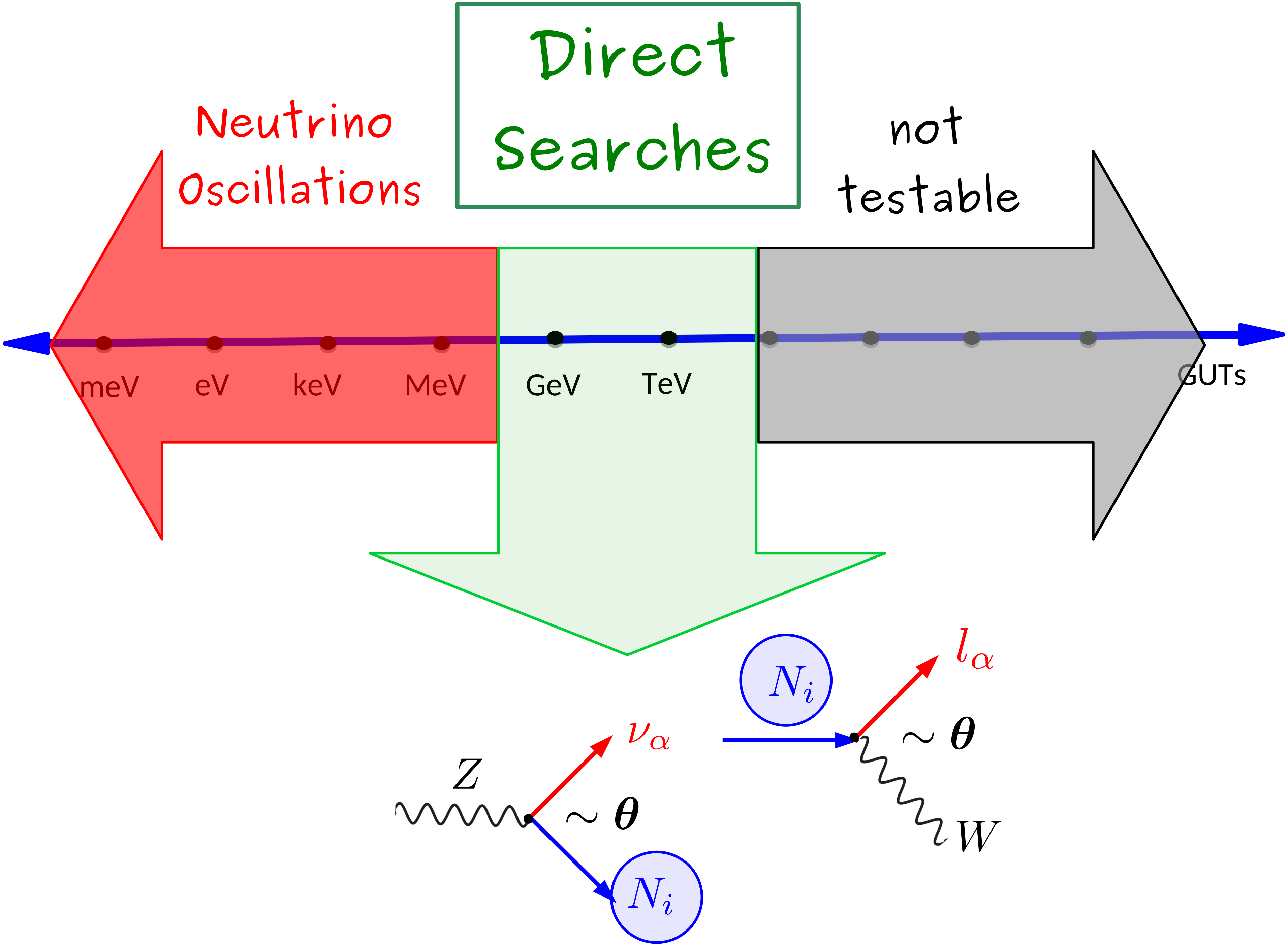
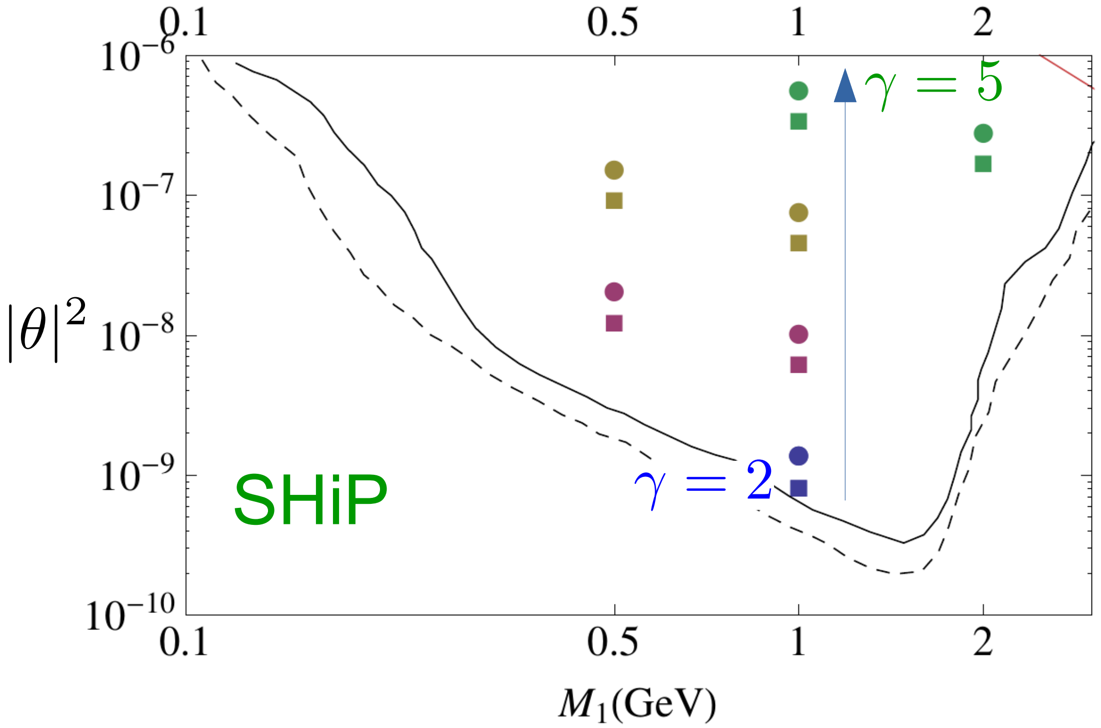


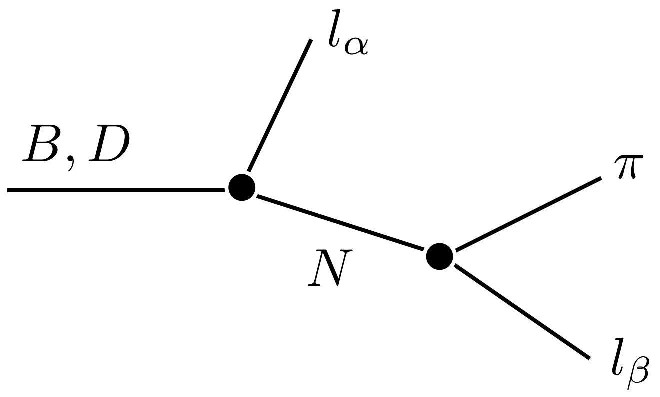
Neutrino Oscillations

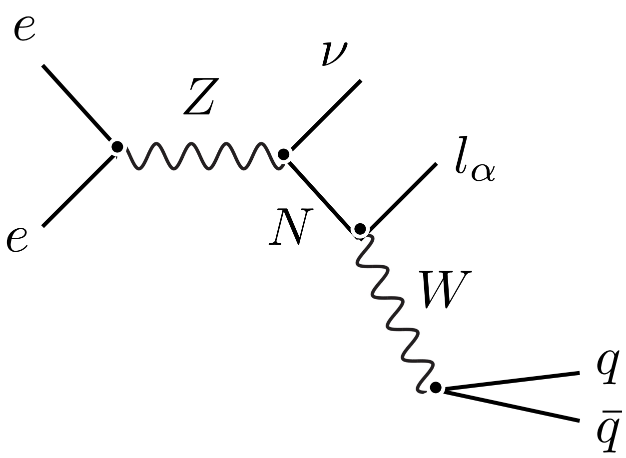
Direct Searches

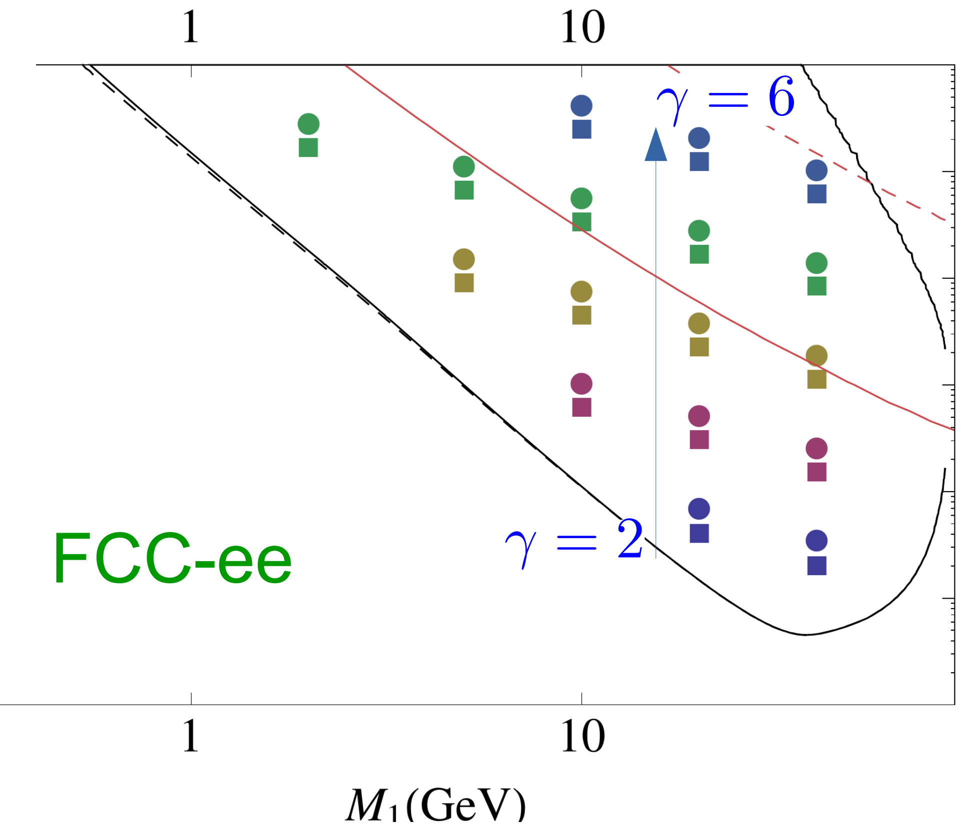
not testable

For instance…



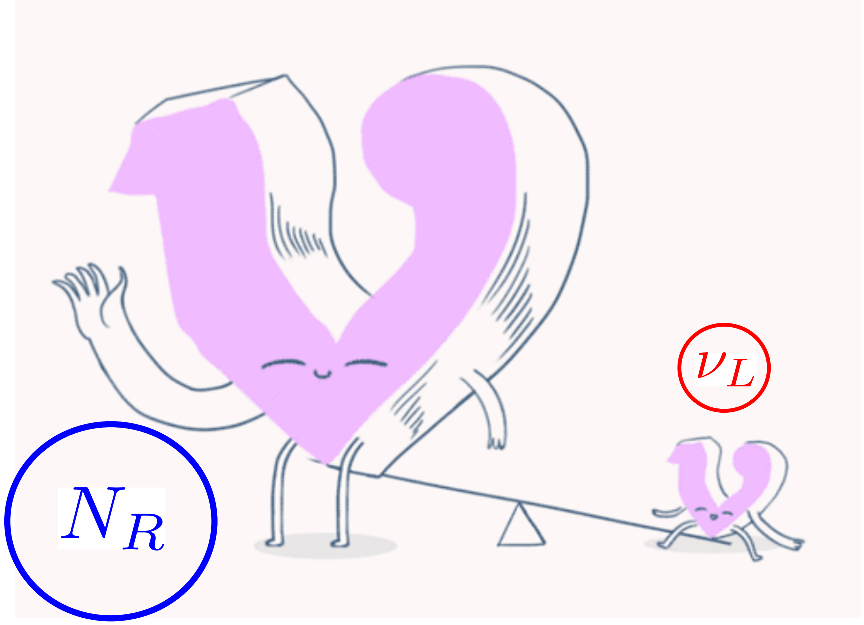






Light Neutrino mass generation

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

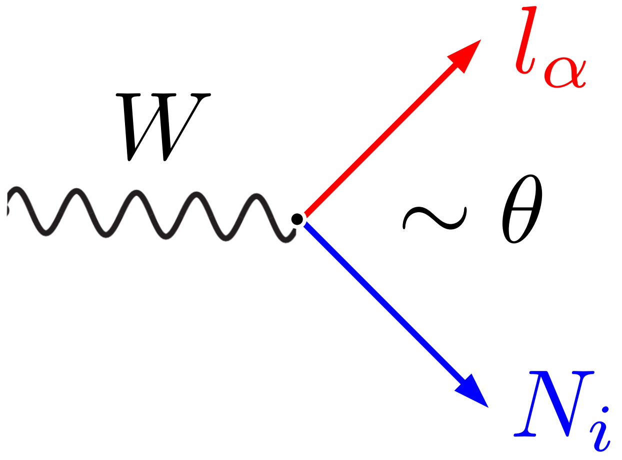


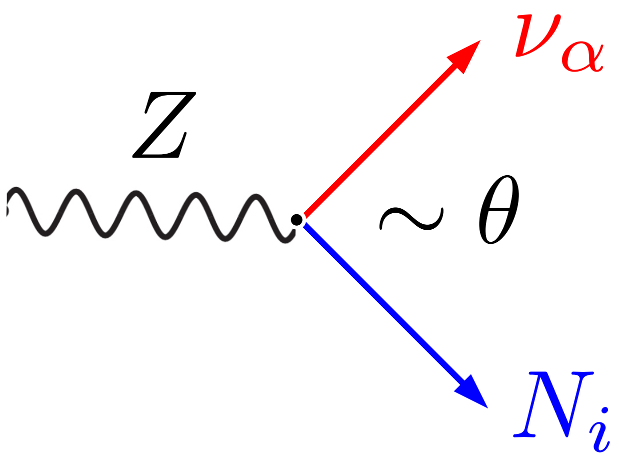
$$m_\nu = \frac{v^2}{2} Y^T M^{-1} Y = \boxed{\theta\, M\, \theta^T} = \boxed{U\, m\, U^T}$$

HNL sector

Light-active neutrino sector

Constraint on HNL mixing from active sector





Casas-Ibarra

$$\theta = \boxed{iU\,m^{1/2}}\boxed{R^\dagger M^{-1/2}}$$

Active Sector

- 3x3 PMNS mixing matrix
- light neutrino masses

HNL Sector

- Complex $3\times N_R$ orthogonal matrix
- HNL masses

Direct searches of HNLs

- Direct detection requires:

$$\theta \gg \sqrt{m/M} \quad \Longleftrightarrow \quad \boldsymbol{R_{ij}} \gg \mathbf{1}$$

- Phenomenological constraint. “Naturally” realized in inverse/linear seesaw realizations based on a symmetry protected scenario.

Mohapatra 1986; Mohapatra, Valle 1986; Bernabeu, Santamaria, Vidal, Mendez, Valle 1987; Malinsky, Romao, Valle 2005...

Approximated LNC

$$M_\nu = \begin{array}{cc} \begin{array}{ccc} \overline{\nu^c} & \overline{N}_1 & \overline{N}_2 \\ 1 & -1 & 1 \end{array} & L \\ \begin{pmatrix} 0 & Y_1^T v/\sqrt{2} & \epsilon Y_2^T v/\sqrt{2} \\ Y_1 v/\sqrt{2} & \mu' & \Lambda \\ \epsilon Y_2 v/\sqrt{2} & \Lambda & \mu \end{pmatrix} & \begin{array}{cc} 1 & \nu \\ -1 & N_1^c \\ 1 & N_2^c \end{array} \end{array}$$

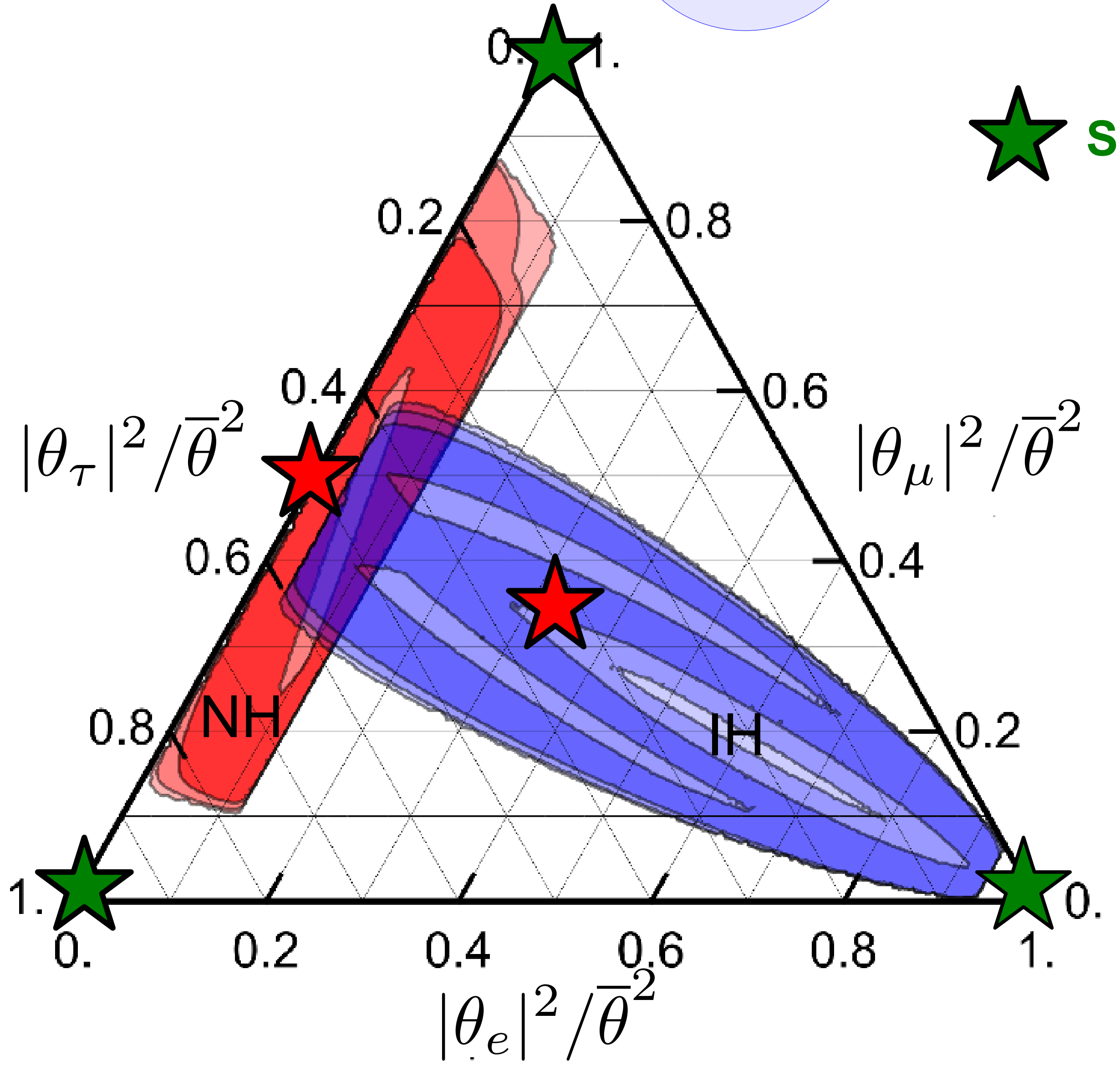
- Light nu masses suppressed with LNV parameters

$$m_\nu = \mu \frac{v^2}{2\Lambda^2} Y_1^T Y_1 + \frac{v^2}{2\Lambda} \epsilon Y_2^T Y_1 + \frac{v^2}{2\Lambda} Y_1^T \epsilon Y_2$$

- Quasi-Dirac heavy neutrinos with large mixings:

$$M_2 \approx M_1 \approx \Lambda \qquad \Delta M \approx \mu' + \mu \qquad \theta \sim Y_1 v/\Lambda$$

Minimal model $N_R=2$: Flavor Structure



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

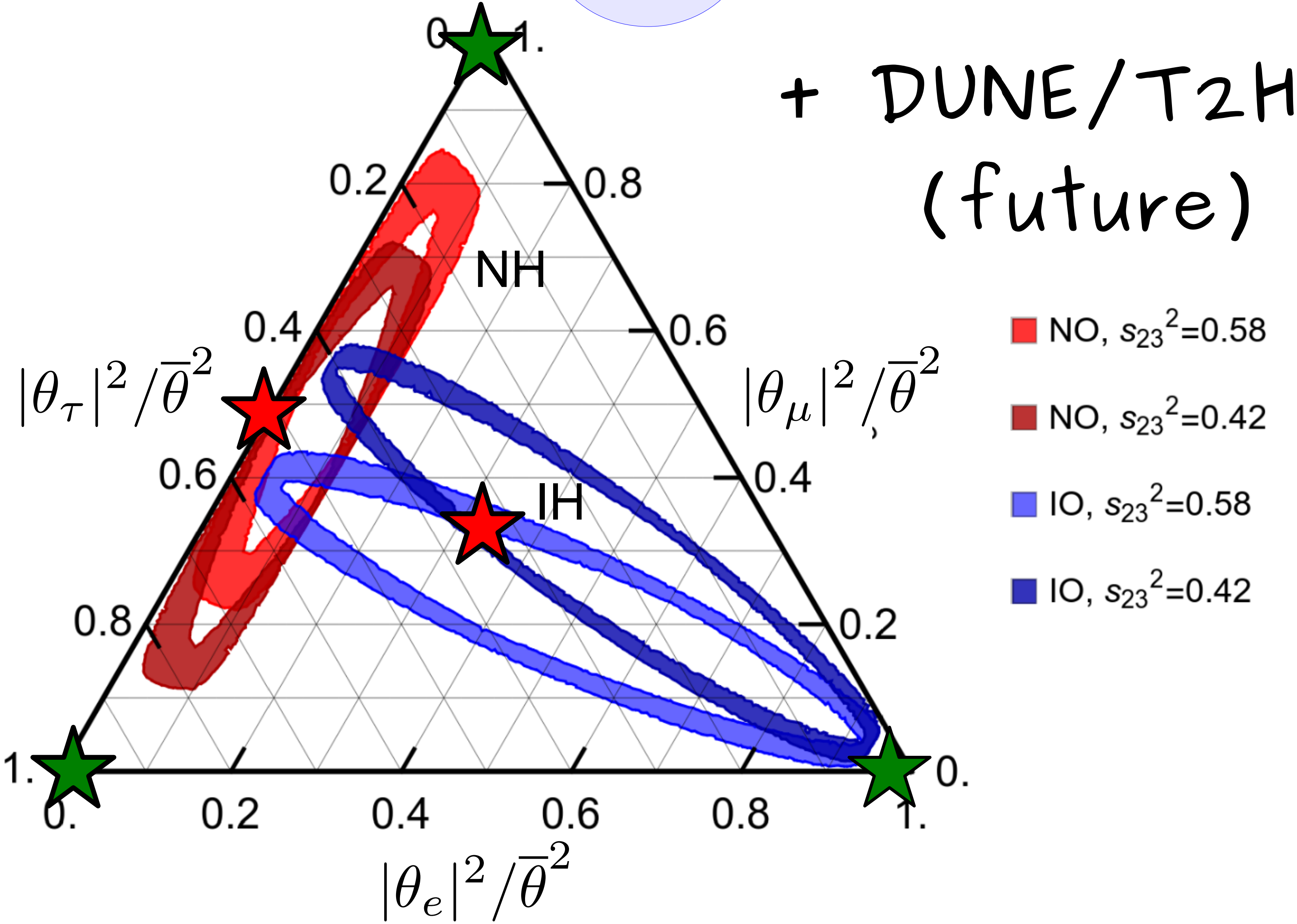
★ **NEW** 2021
(0, 1/2, 1/2)
(1/3, 1/3, 1/3)

Abdullahi et al arXiv:2203.08039

Caputo, Hernandez, JLP, Salvado arXiv:1704.08721

Minimal model $N_R=2$: Flavor Structure

+ DUNE/T2HK…
(future)



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

Abdullahi et al arXiv:2203.08039

Direct searches of HNLs

- Direct detection requires:

$$\theta_{\alpha i} \gg \sqrt{m/M} \Longleftrightarrow \boldsymbol{R_{ij} \gg 1}$$

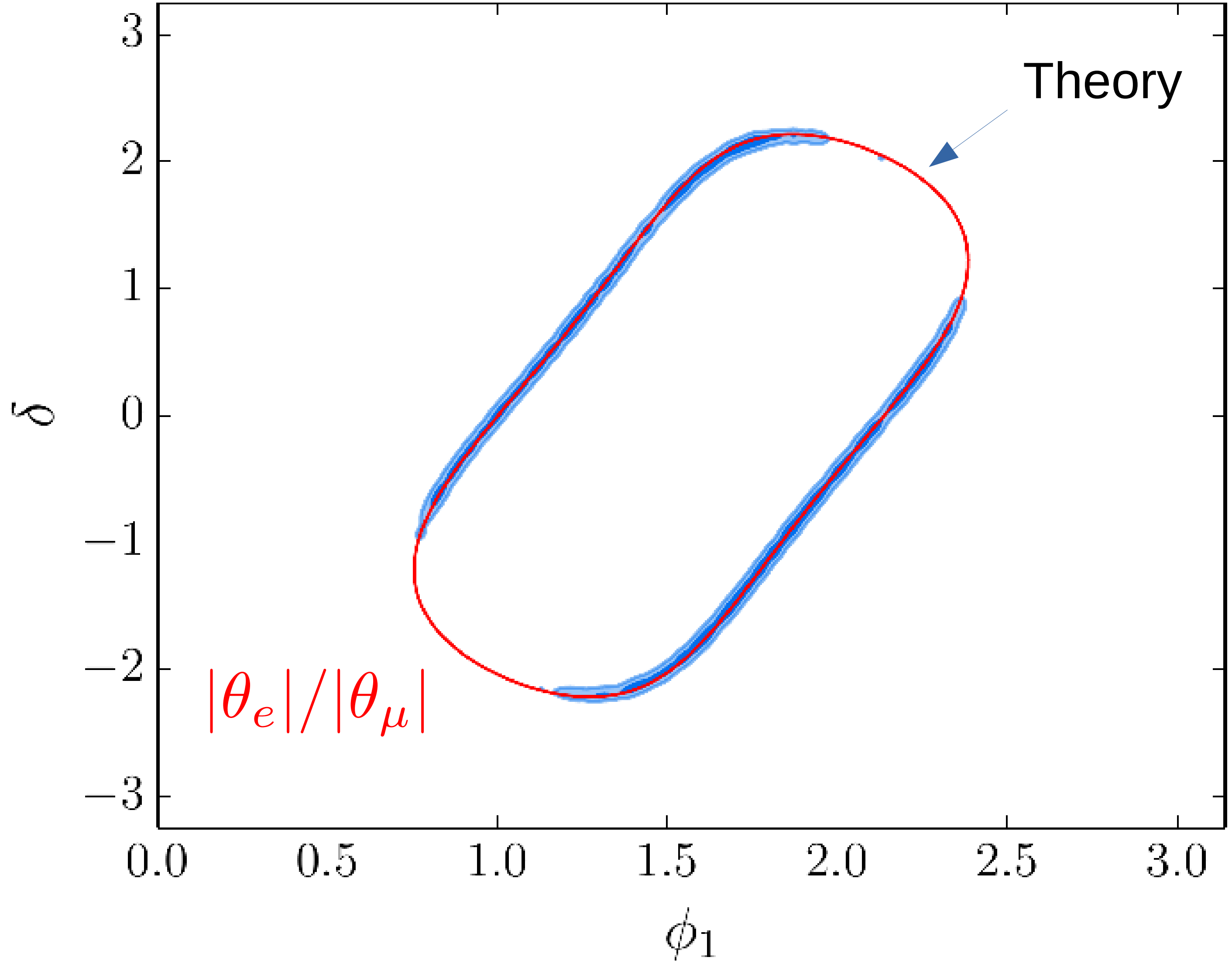
$$\Longleftrightarrow \theta^2_{\alpha i} \propto e^{-2\theta i} \boxed{e^{2\gamma} f\left(\delta, \phi_1, M_j\right)}$$

Sensitivity to PMNS CP-phases! δ, ϕ_1

- $|\theta_{e1}|^2/|\theta_{\mu 1}|^2 \simeq |\theta_{e2}|^2/|\theta_{\mu 2}|^2 \simeq$

$$\frac{(1+s_{\phi_1}\sin 2\theta_{12})(1-\theta_{13}^2)+\frac{1}{2}r^2 s_{12}(c_{12}s_{\phi_1}+s_{12})}{\left(1-\sin 2\theta_{12}s_{\phi_1}\left(1+\frac{r^2}{4}\right)+\frac{r^2c_{12}^2}{2}\right)c_{23}^2+\theta_{13}(c_{\phi_1}s_\delta-\cos 2\theta_{12}s_{\phi_1}c_\delta)\sin 2\theta_{23}+\theta_{13}^2(1+\sin 2\theta_{12})s_{23}^2 s_{\phi_1}}$$

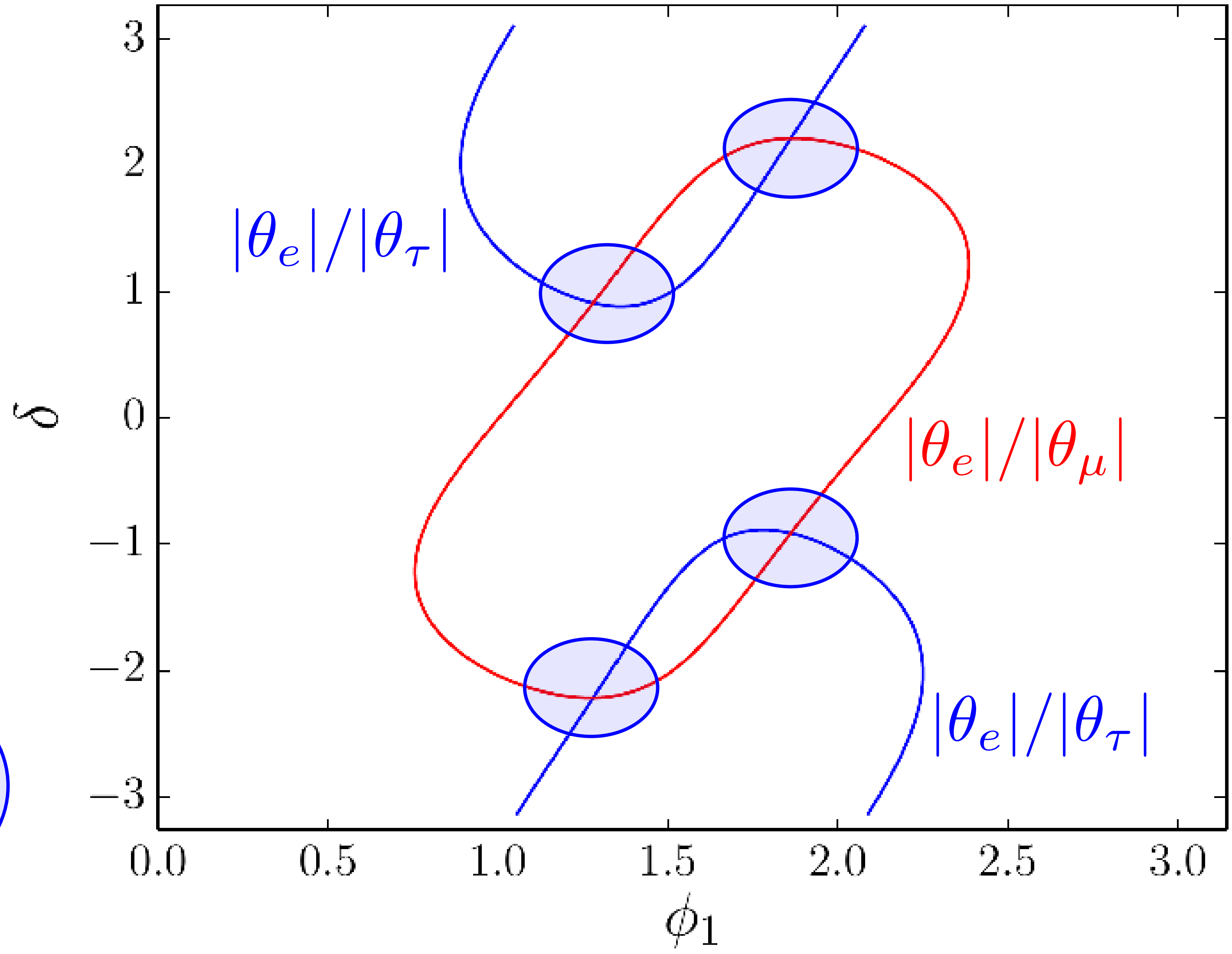
PMNS CP-phases from HNLs searches



Hernandez, Kekic, JLP, Racker, Salvado 1606.06719
Caputo, Hernandez, Kekic, JLP, Salvado 1611.05000

$N_R = 2$

PMNS CP-phases from HNLs searches

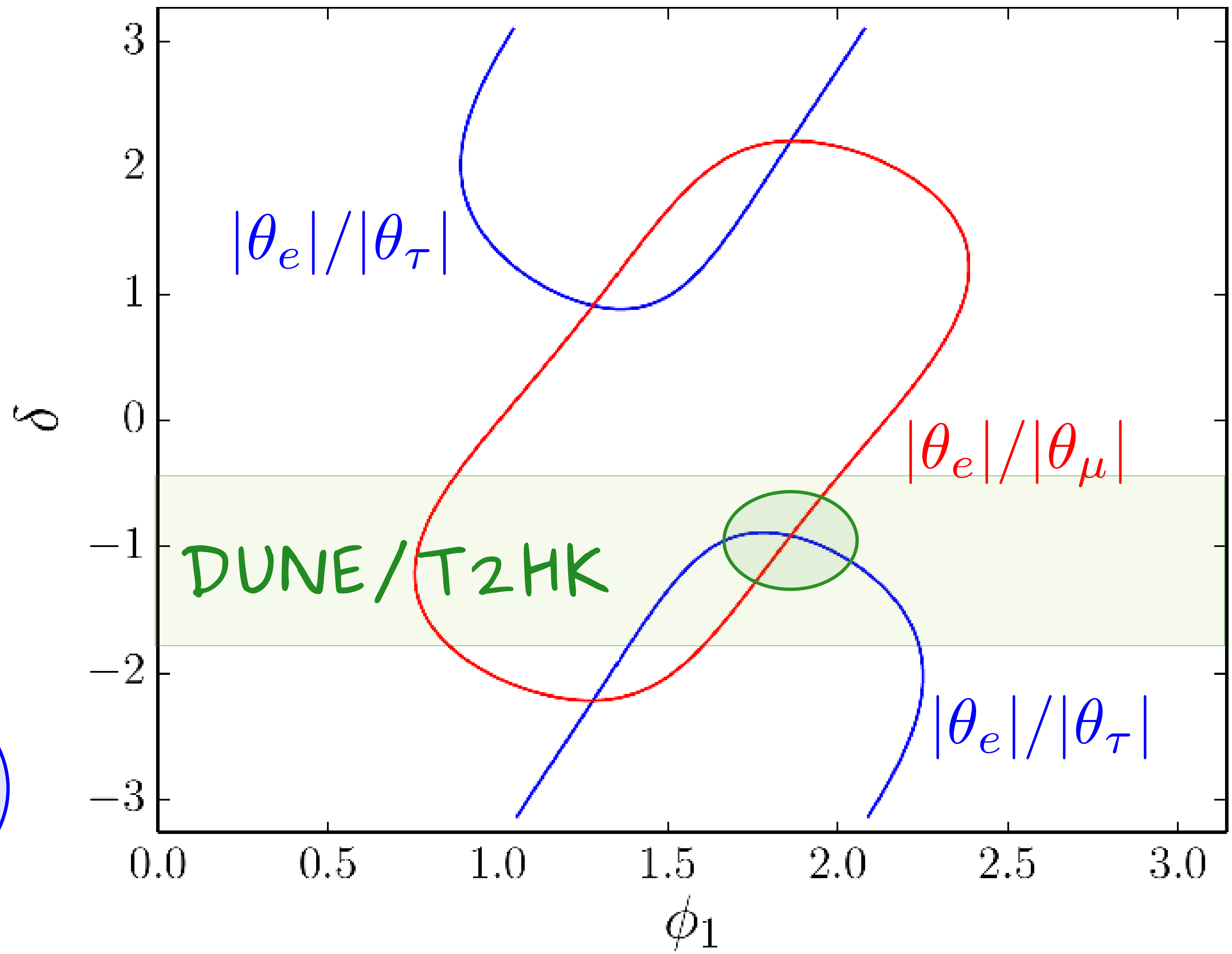


$N_R=2$

- **Measurement of mixing with tau neutrinos would allow to break degeneracies.**

Hernandez, Kekic, JLP, Racker, Salvado 1606.06719

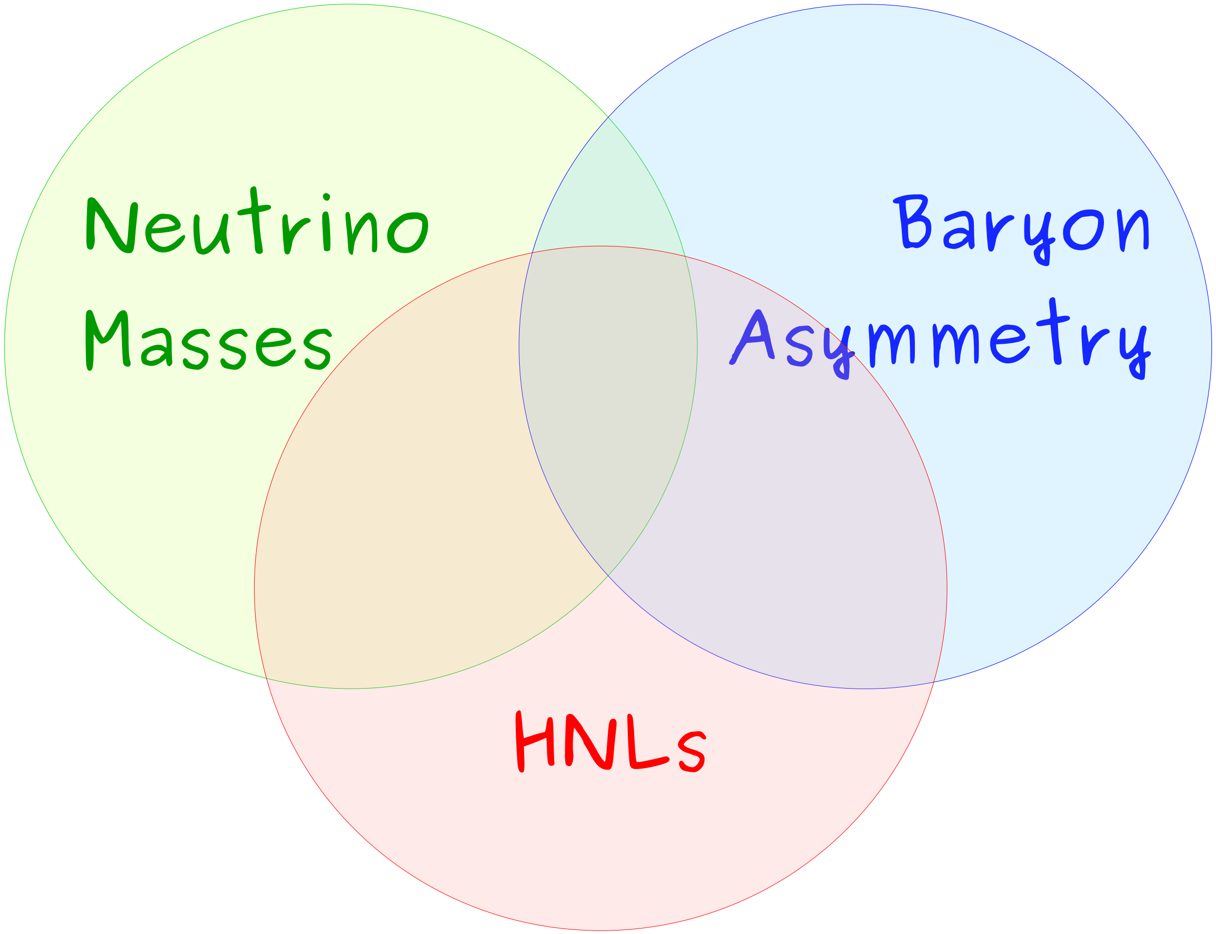
PMNS CP-phases from HNLs searches



$N_R = 2$

- **Potential determination of the PMNS Majorana phase!**

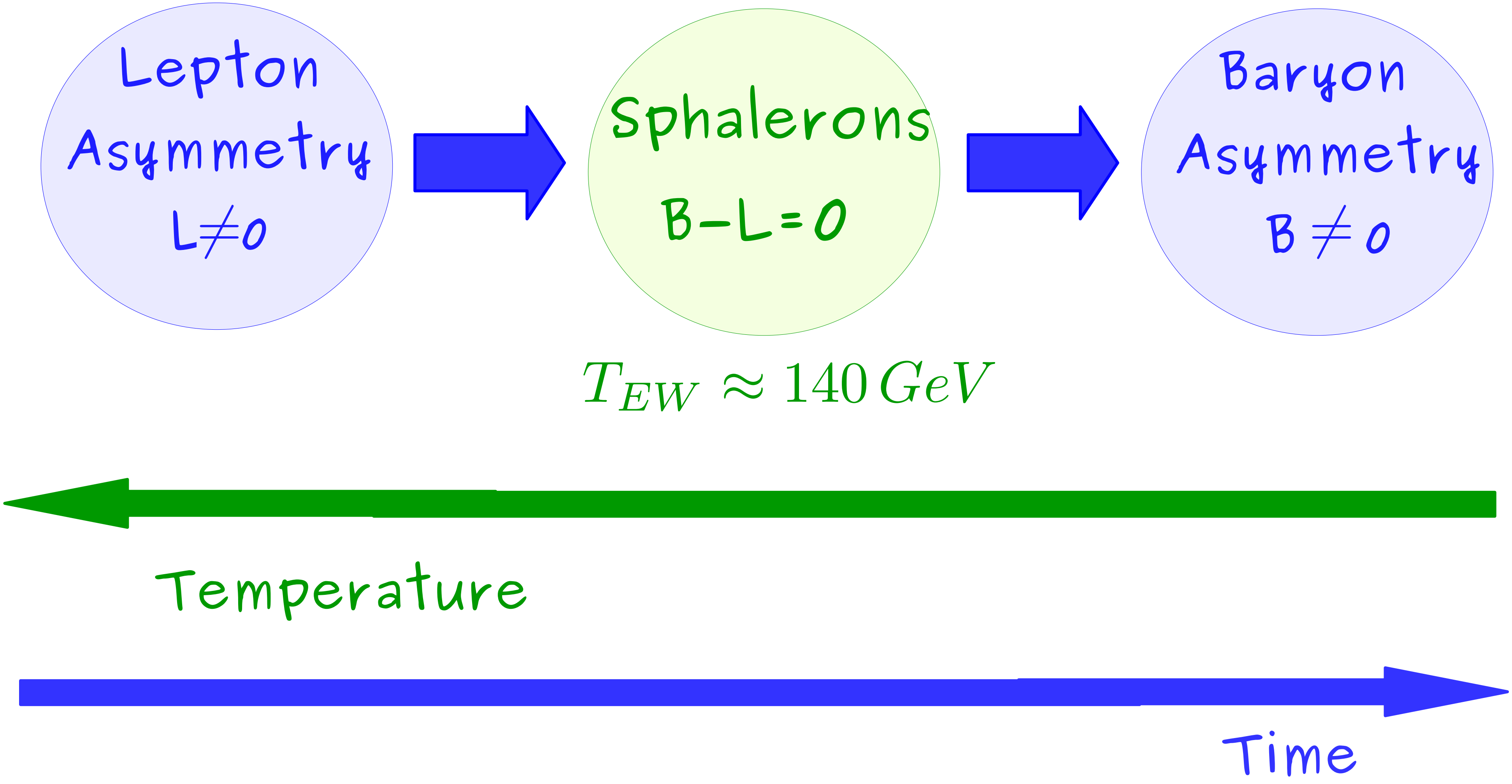
Hernandez, Kekic, JLP, Racker, Salvado 1606.06719



See talks by Michele Lucente and Nuria Rius

Standard Leptogenesis

Right-handed neutrino decays which violate CP and lepton number generate lepton asymmetry before $T_{EW} \approx 140\, GeV$



Lepton Asymmetry $L \neq 0$

Sphalerons $B-L=0$

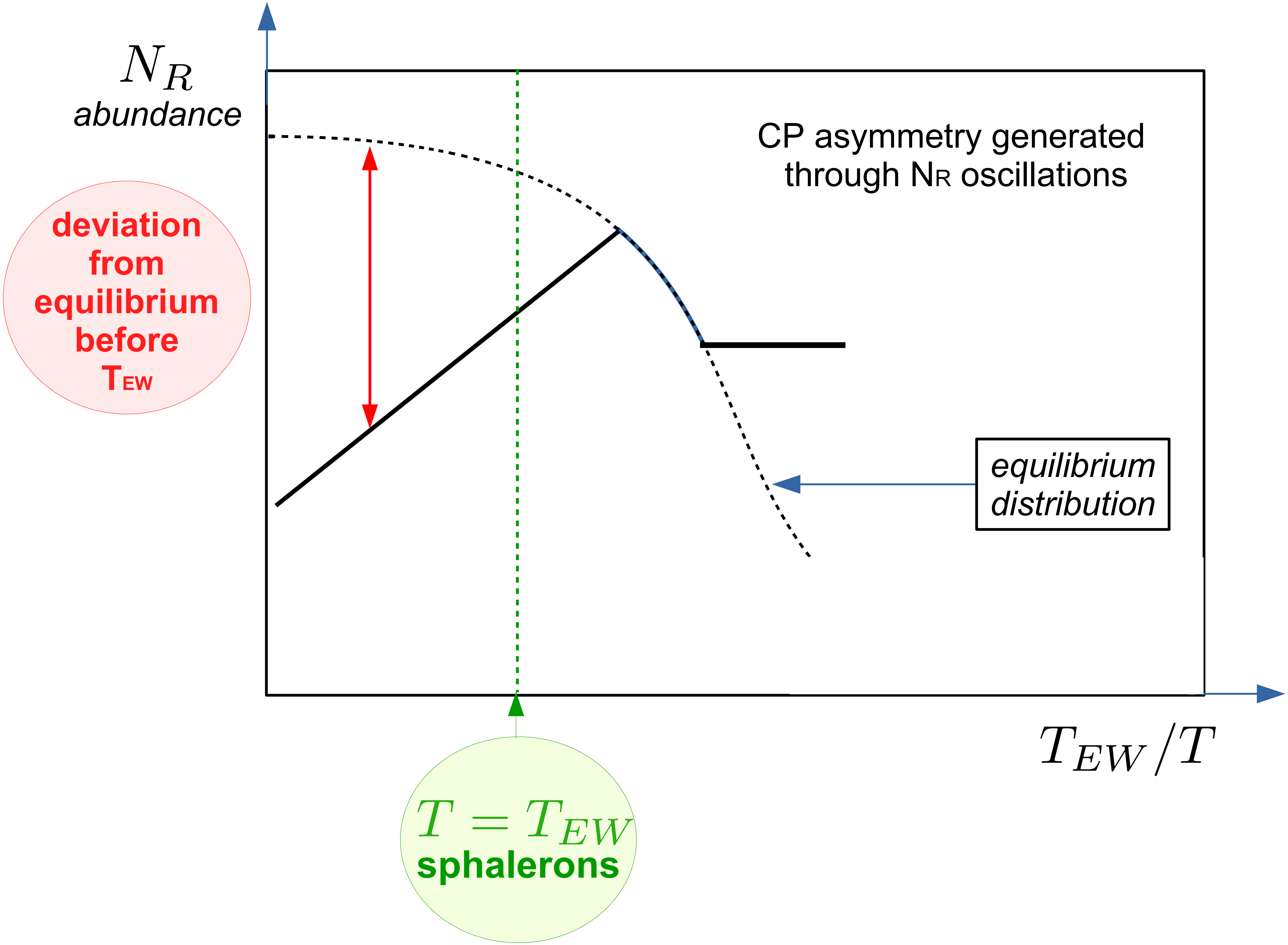
Baryon Asymmetry $B \neq 0$

$T_{EW} \approx 140\, GeV$

Temperature

Time

Low Scale Leptogenesis (ARS)



CP asymmetry generated through N_R oscillations

equilibrium distribution

deviation from equilibrium before T_{EW}

$T = T_{EW}$
sphalerons

Predicting Y_B in minimal model $N_R=2$

- **Baryon asymmetry depends on all the unknown parameters**

- **Experimental sensitivity** $\Longleftrightarrow |\theta^2_{\alpha j}| \gg m_\nu/M \Longleftrightarrow \boldsymbol{R_{ij} \gg 1} \Longleftrightarrow \boldsymbol{e^{\gamma} \gg 1}$

SHiP sensitive to $|\theta_{\alpha j}|(\delta, \phi_1, \gamma),\ M_j$

$$(\theta_{\alpha j})^2 \propto \boxed{e^{-2\theta i}}\ \boxed{e^{2\gamma} f\left(\delta, \phi_1, M_j\right)}$$

Neutrinoless double beta decay sensitive to θ through interference between light and heavy contribution

Hernandez, Kekic, JLP, Racker, Salvado 1606.06719

Predicting Y_B in minimal model $N_R=2$

- Neutrinoless double beta decay effective mass in the IH case

LIGHT NEUTRINO
contribution

$$
\begin{aligned}
|m_{\beta\beta}|_{IH} \simeq & \\
\simeq & \sqrt{\Delta m^2_{atm}} \left| \boxed{c_{13}^2 \left(c_{12}^2 + e^{2i\phi_1} s_{12}^2 \left(1 + \frac{r^2}{2} \right) \right)} \right. \\
& \boxed{- \quad f(A)\, e^{2i\theta} e^{2\gamma} (c_{12} - i e^{i\phi_1} s_{12})^2 \frac{(0.9\,\mathrm{GeV})^2}{2M_1^2} \frac{\Delta M}{M_1}} \left. \vphantom{\frac{(0.9)^2}{2M_1^2}} \right|
\end{aligned}
$$

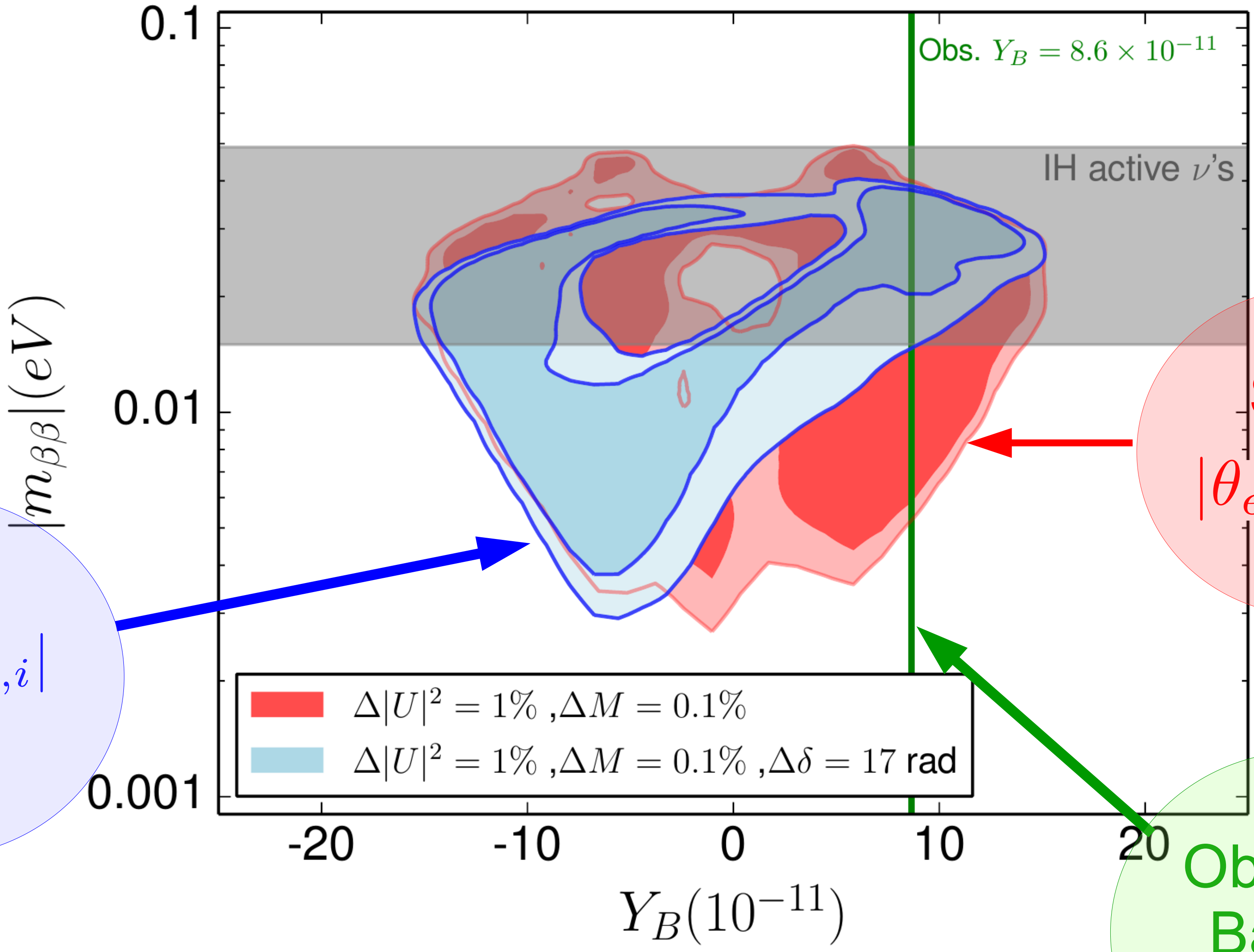
θ

HEAVY NEUTRINO
contribution

- Heavy neutrino contribution can be sizable for $M \sim O\left(GeV\right)$ ✓

Mitra, Senjanovic, Vissani 2011
JLP, Pascoli, Wong 2012

GeV Scale Leptogeneis $N_R=2$



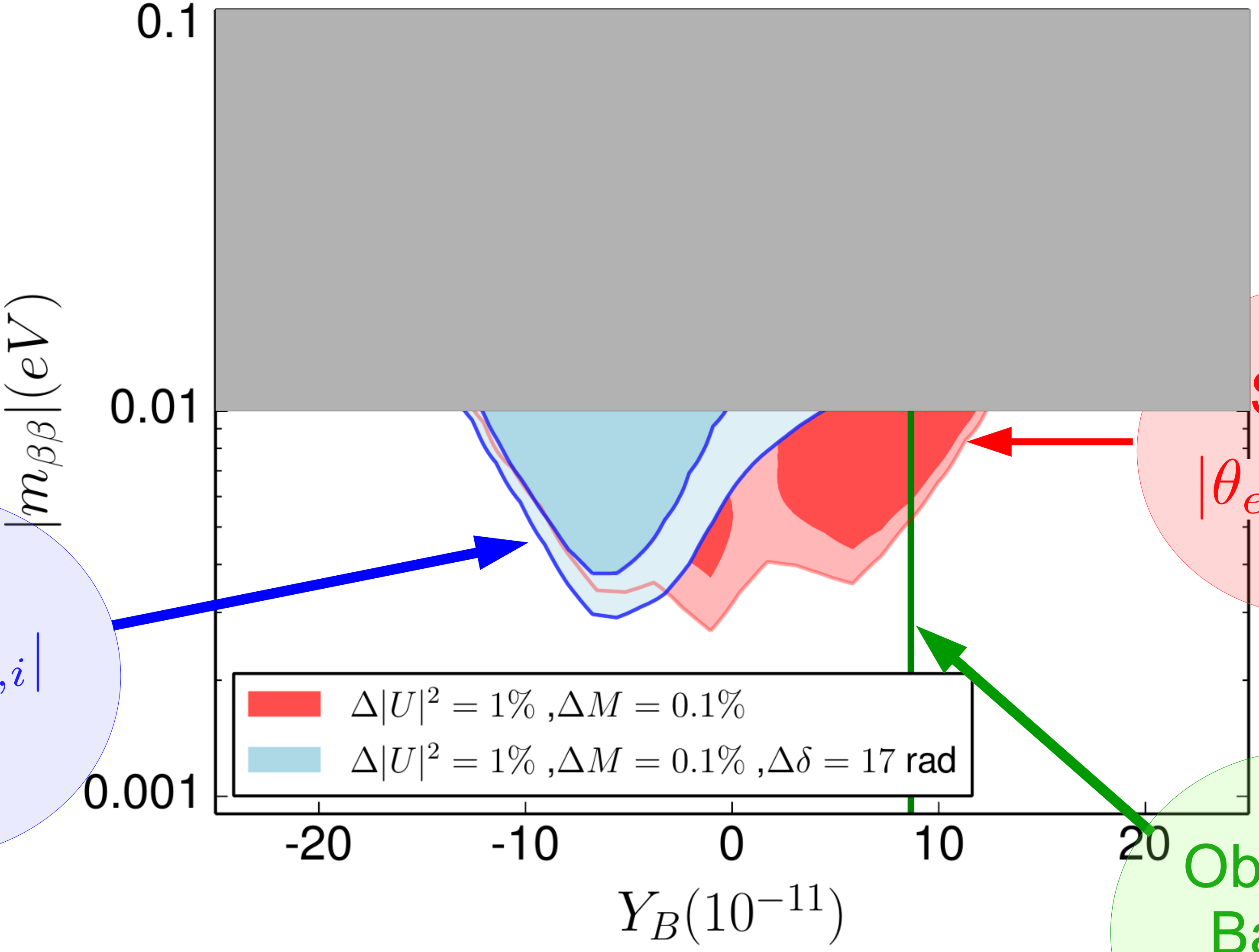
SHiP
$|\theta_{ei}|, |\theta_{\mu i}|$

SHiP
$|\theta_{ei}|, |\theta_{\mu,i}|$
+
δ

Observed Baryon asymmetry

Hernandez, Kekic, JLP, Racker, Salvado 1606.06719

GeV Scale Leptogeneis $N_R=2$



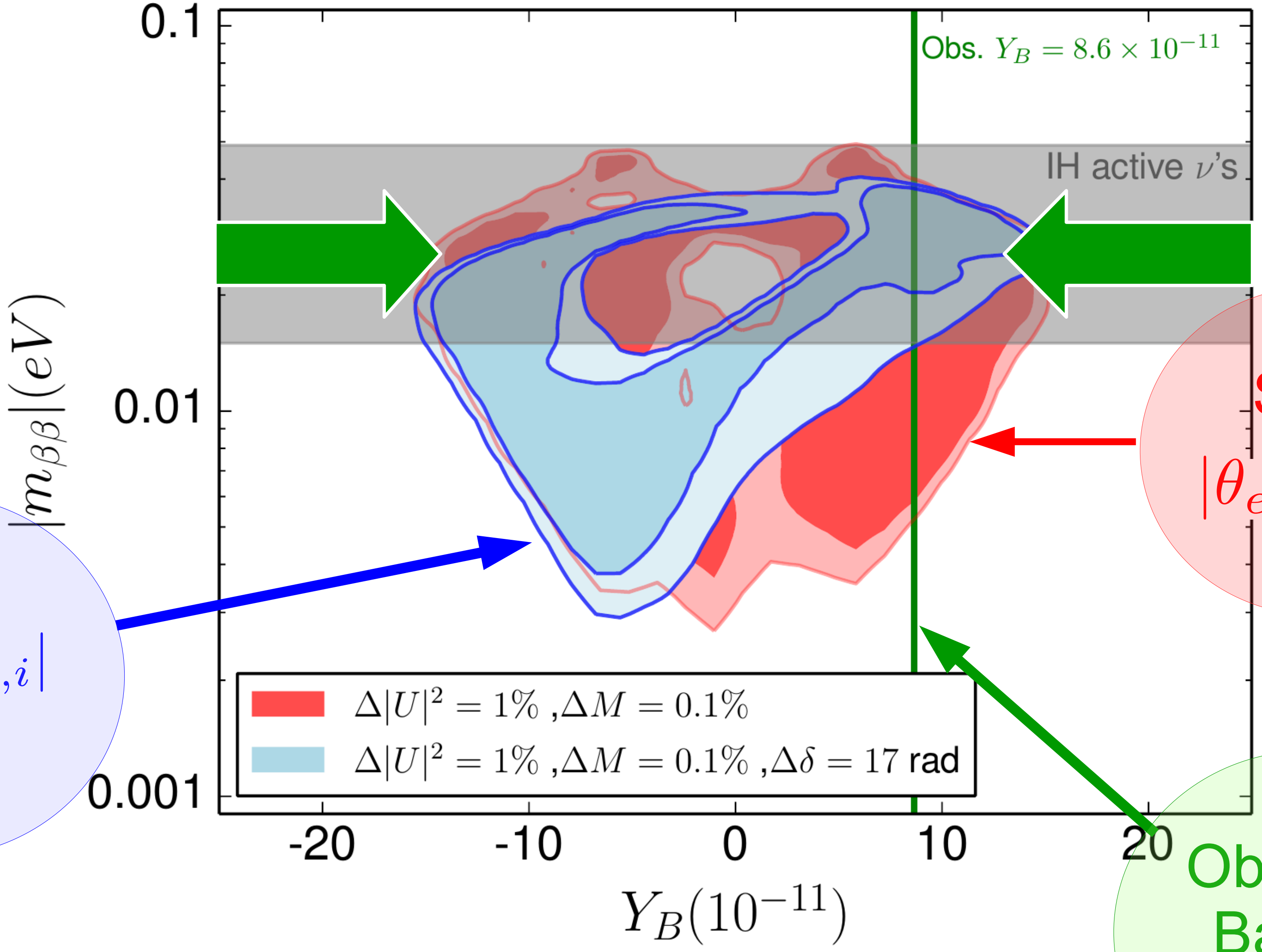
SHiP
$|\theta_{ei}|,|\theta_{\mu i}|$

SHiP
$|\theta_{ei}|,|\theta_{\mu,i}|$
+
δ

Observed Baryon asymmetry

Hernandez, Kekic, JLP, Racker, Salvado 1606.06719

GeV Scale Leptogeneis $N_R=2$



SHiP
$|\theta_{ei}|, |\theta_{\mu i}|$

SHiP
$|\theta_{ei}|, |\theta_{\mu,i}|$
+
δ

Observed
Baryon
asymmetry

Hernandez, Kekic, JLP, Racker, Salvado 1606.06719

Conclusions

- Near detectors in future neutrino oscillation experiments can play a relevant role in testing the robustness of the 3-neutrino picture

Low scale Non-Unitarity, sterile neutrino oscillations, NSI (Non-Unitarity results can be easily mapped to NSI framework, see 2105.11466)

- *Keeping under control shape uncertainties is a key issue.*

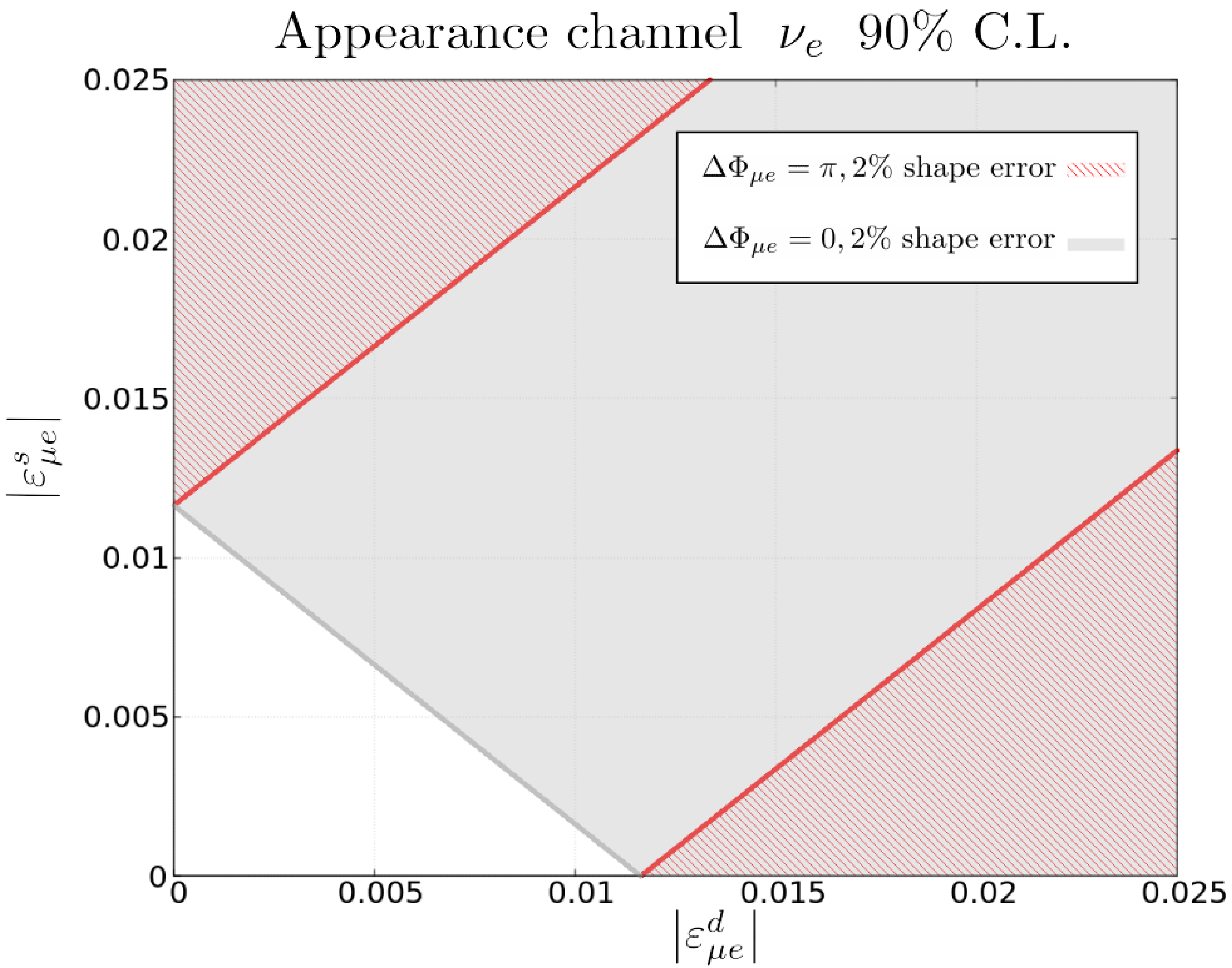
Joint experimental and theoretical effort required to reduce systematics.

- Minimal neutrino mass model

measurement of HNLs mass & mixing would allow to
test the mechanisms generating neutrino masses and Baryon asymmetry
and to indirectly measure the PMNS phases.

Thank you!

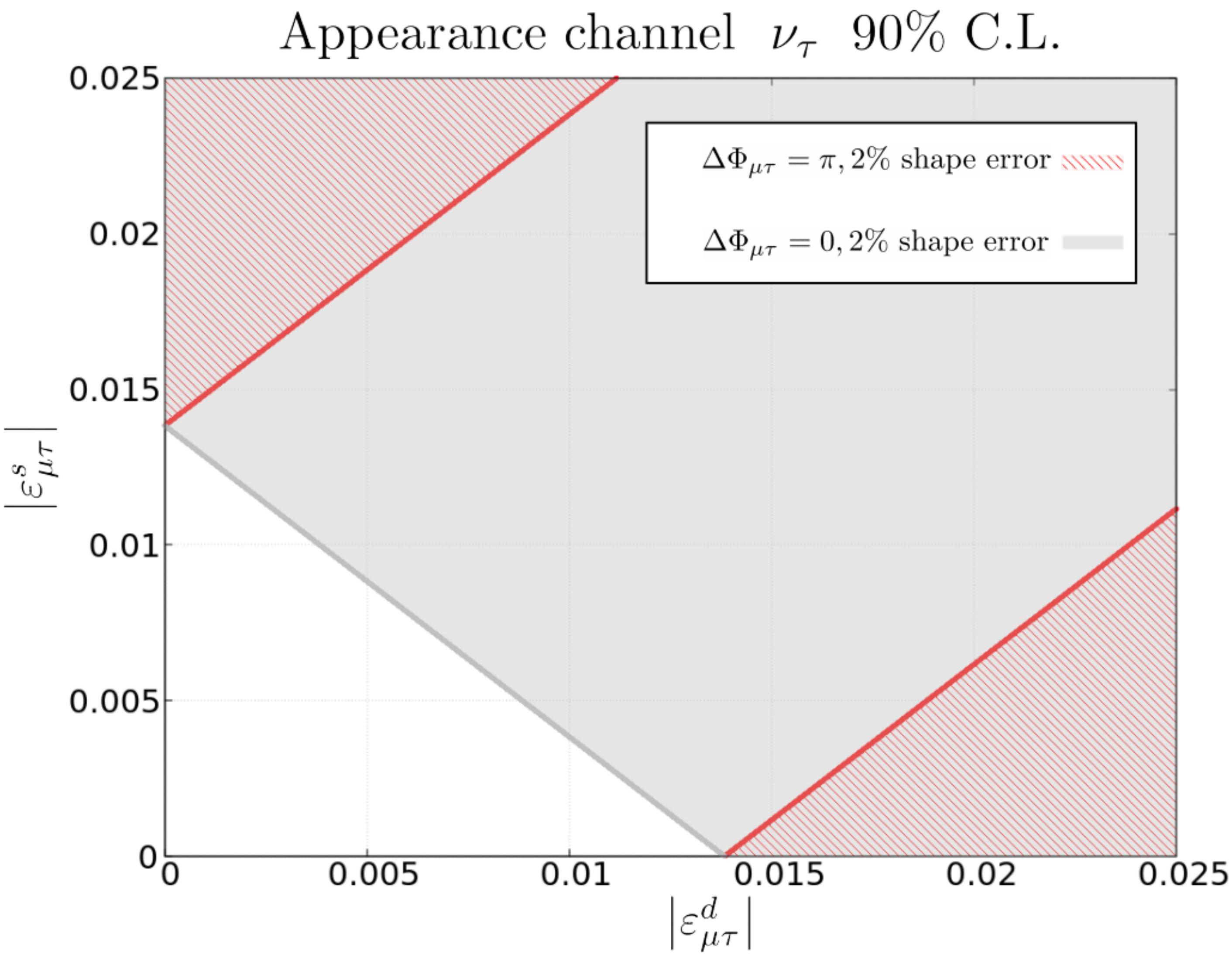
NSI in production/detection: $P_{\mu e}$



Coloma, JLP,
Rosauro-Alcaraz,
Urrea 2105.11466

- Mapping: $2|\alpha_{\beta\gamma}|^2 = |\epsilon^d_{\beta\gamma}|^2 + |\epsilon^s_{\beta\gamma}|^2 + 2|\epsilon^d_{\beta\gamma}||\epsilon^s_{\beta\gamma}|\cos(\Phi^s_{\beta\gamma} - \Phi^d_{\beta\gamma})$

NSI in production/detection

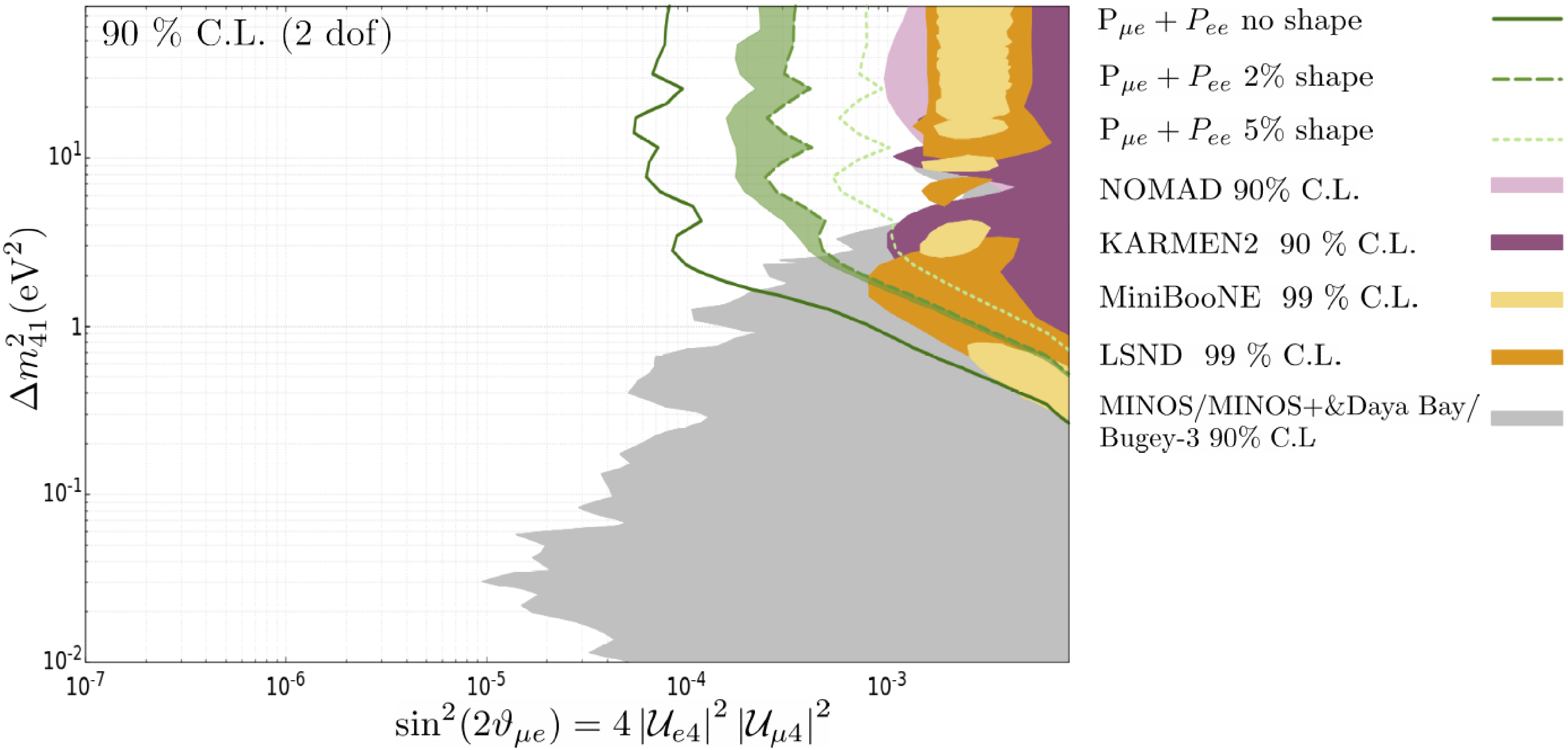


ν_τ appearance channel

Coloma, JLP,
Rosauro-Alcaraz,
Urrea 2105.11466

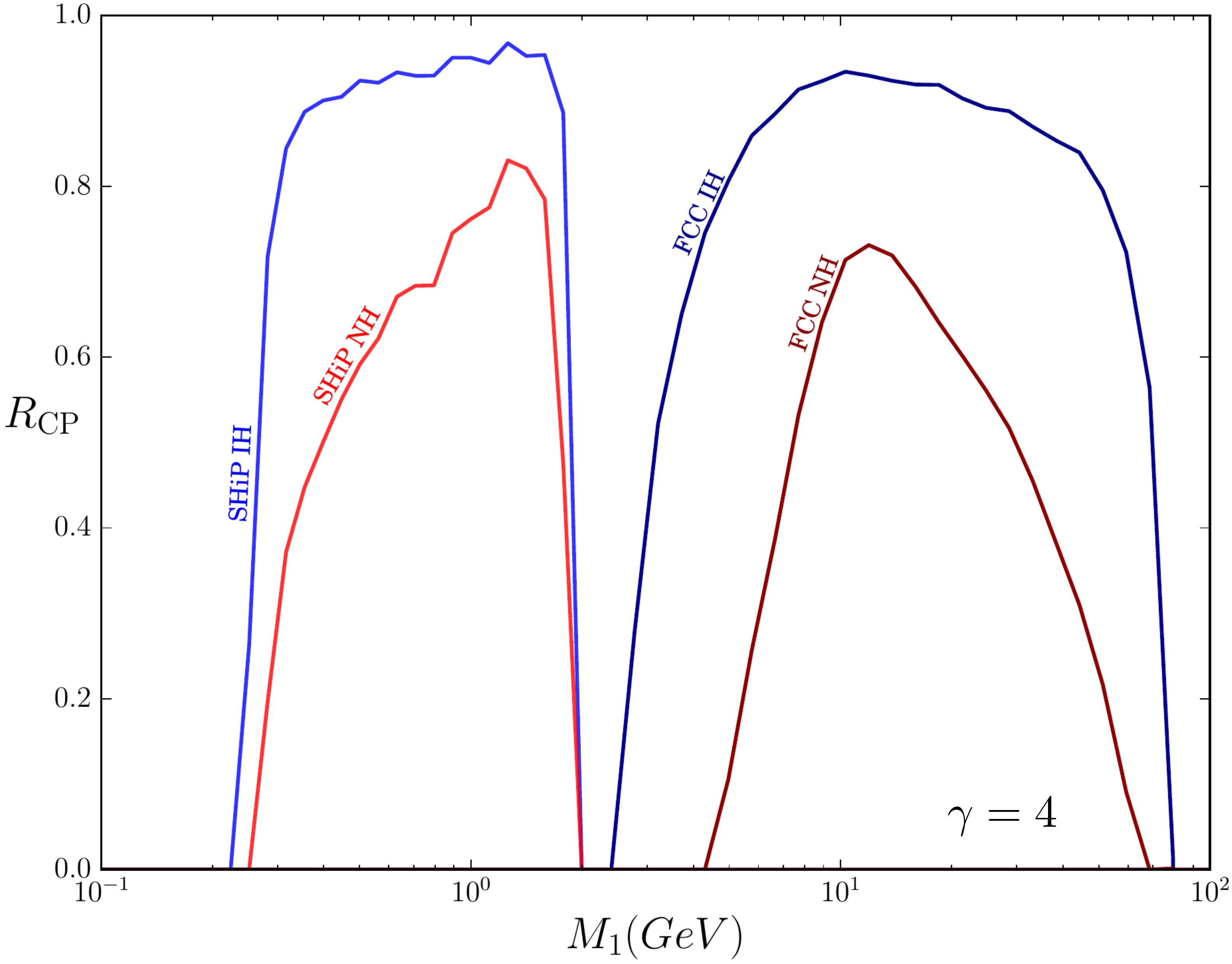
- Mapping: $2|\alpha_{\beta\gamma}|^2 = |\epsilon^d_{\beta\gamma}|^2 + |\epsilon^s_{\beta\gamma}|^2 + 2|\epsilon^d_{\beta\gamma}||\epsilon^s_{\beta\gamma}|\cos(\Phi^s_{\beta\gamma} - \Phi^d_{\beta\gamma})$

3+1 Sterile Neutrinos: $P_{\mu e} + P_{ee}$



Coloma, JLP, Rosauro-Alcaraz, Urrea 2105.11466

5σ discovery PMNS CP-violation



Caputo, Hernandez, Kekic, JLP, Salvado arXiv:1611.05000

ν_τ appearance channel

ν_τ detection:

- Energy threshold of τ production 3.2 GeV.
- Short lifetime of τ, indirect measurement via hadronic decays (~ 65% branching ratio).
- NC background. We have considered a sample in which 30% of the hadronic events are identified keeping 0.5% of NC background.

de Gouvêa, Kelly, Stenico, Pasquini 1904.07265

See talks by Pedro Machado & Adam Aurisano

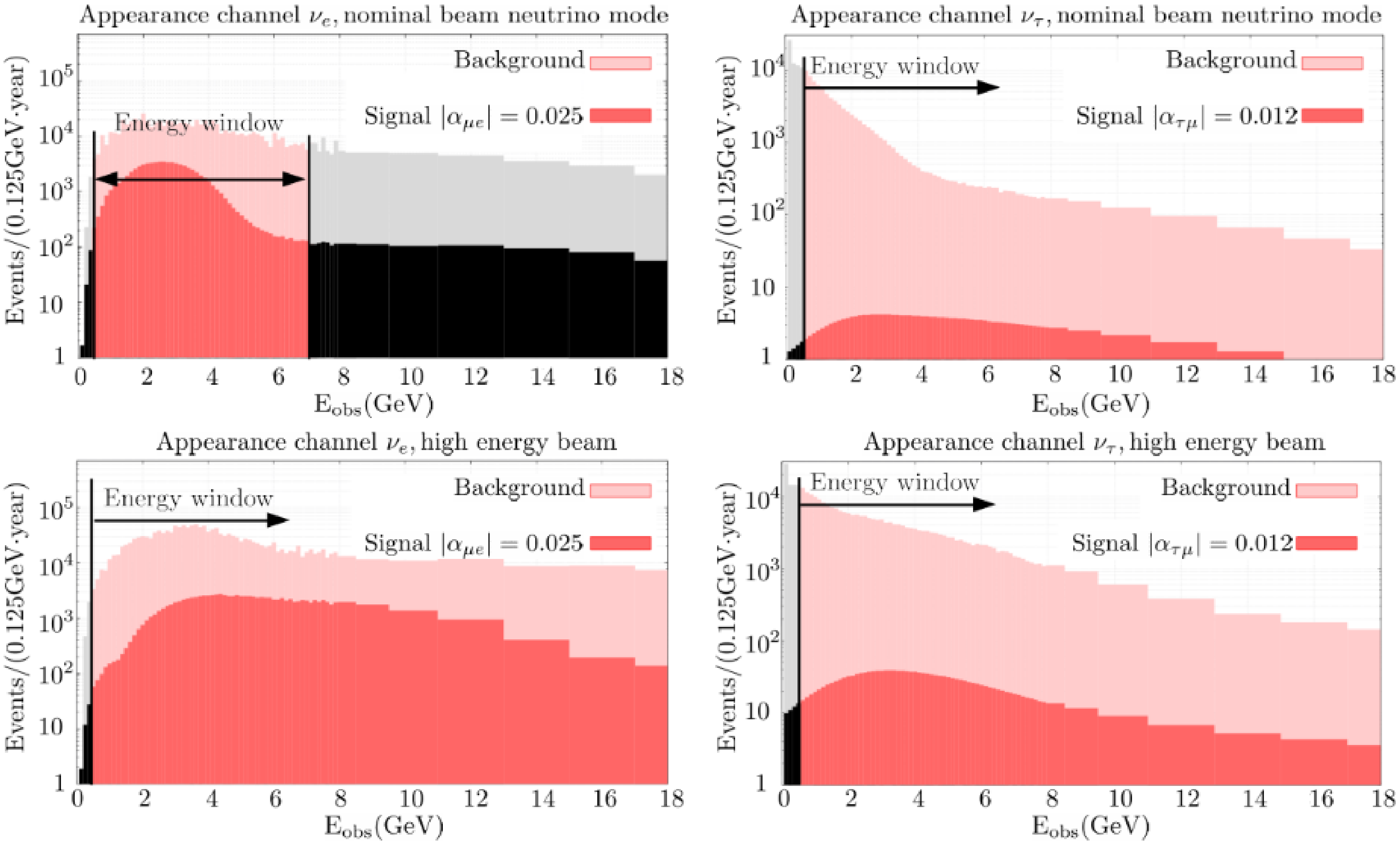
DUNE set up

Globes files

DUNE Collaboration, arXiv:2103.04797 [hep] 8 Mar 2021.

Flux configuration

Beam configuration	Power	E_p	PoT/yr	t_ν (yr)	$t_{\bar{\nu}}$ (yr)	$M_{\rm det}$
Nominal	1.2 MW	120 GeV	1.1×10^{21}	3.5	3.5	67.2 tons
High-Energy	1.2 MW	120 GeV	1.1×10^{21}	3.5	–	67.2 tons

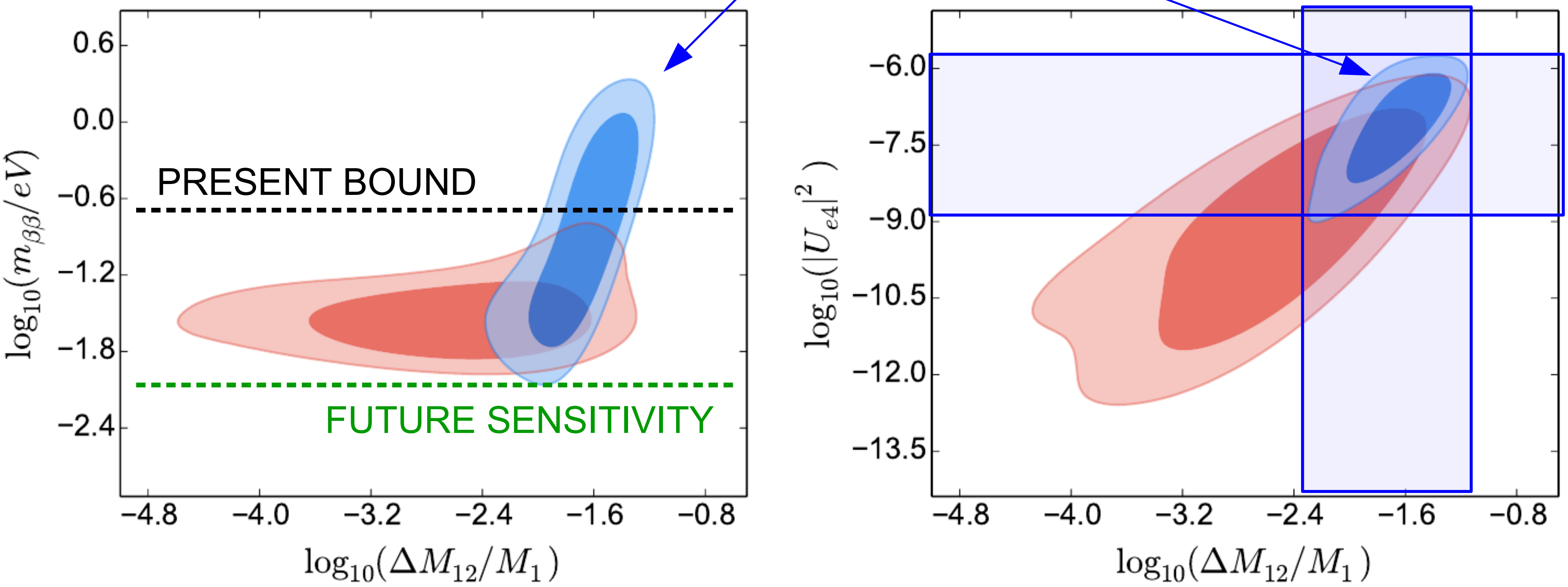

Appearance channel ν_e, nominal beam neutrino mode
Background
Signal $|\alpha_{\mu e}| = 0.025$
Energy window
Events/(0.125GeV·year)
1
10
10^2
10^3
10^4
10^5
0
2
4
6
8
10
12
14
16
18
E_{obs}(GeV)
Appearance channel ν_τ, nominal beam neutrino mode
Background
Signal $|\alpha_{\tau\mu}| = 0.012$
Energy window
Events/(0.125GeV·year)
1
10
10^2
10^3
10^4
0
2
4
6
8
10
12
14
16
18
E_{obs}(GeV)
Appearance channel ν_e, high energy beam
Background
Signal $|\alpha_{\mu e}| = 0.025$
Energy window
Events/(0.125GeV·year)
1
10
10^2
10^3
10^4
10^5
0
2
4
6
8
10
12
14
16
18
E_{obs}(GeV)
Appearance channel ν_τ, high energy beam
Background
Signal $|\alpha_{\tau\mu}| = 0.012$
Energy window
Events/(0.125GeV·year)
1
10
10^2
10^3
10^4
0
2
4
6
8
10
12
14
16
18
E_{obs}(GeV)

Running mode	Sample	Contribution	Event rates ($\times 10^5$)	$E_{\text{obs}}^{\text{max}}$ (GeV)
ν mode (nominal)	ν_e-like	Intrinsic cont.	20.18	7.125
		Flavor mis-ID	4.61	
		NC	6.77	
	ν_μ-like	$\nu_\mu, \bar{\nu}_\mu$ CC ($P_{\mu\mu} = 1$)	2,235.72	7.125
		NC	17.35	
	ν_τ-like	$\nu_\tau, \bar{\nu}_\tau$ CC ($P_{\mu\tau} = 1$)	39.33	18
		NC	3.23	
$\bar{\nu}$ mode (nominal)	$\bar{\nu}_e$-like	Intrinsic cont.	11.18	7.125
		Flavor mis-ID	1.07	
		NC	3.89	
	$\bar{\nu}_\mu$-like	$\nu_\mu, \bar{\nu}_\mu$ CC ($P_{\mu\mu} = 1$)	1,013.42	7.125
		NC	9.76	
	$\bar{\nu}_\tau$-like	$\nu_\tau, \bar{\nu}_\tau$ CC ($P_{\mu\tau} = 1$)	27.75	18
		NC	1.80	
ν mode (HE)	ν_e-like	Intrinsic cont.	38.10	18
		Flavor mis-ID	12.98	
		NC	30.51	
	ν_μ-like	$\nu_\mu, \bar{\nu}_\mu$ CC ($P_{\mu\mu} = 1$)	5,784.30	18
		NC	72.15	
	ν_τ-like	$\nu_\tau, \bar{\nu}_\tau$ CC ($P_{\mu\tau} = 1$)	259.67	18
		NC	9.42	

Event sample	Contribution	Benchmark 1		Benchmark 2		Benchmark 3	
		σ_{norm}	σ_{shape}	σ_{norm}	σ_{shape}	σ_{norm}	σ_{shape}
ν_e-like	Signal	5%	–	5%	–	5%	–
	Intrinsic cont.	10%	–	10%	2%	10%	5%
	Flavor mis-ID	5%	–	5%	2%	5%	5%
	NC	10%	–	10%	2%	10%	5%
ν_μ-like	$\nu_\mu, \bar{\nu}_\mu$ CC (signal)	10%	–	10%	2%	10%	5%
	NC	10%	–	10%	2%	10%	5%
ν_τ-like	Signal	20%	–	20%	–	20%	–
	NC	10%	–	10%	2%	10%	5%

Leptogenesis in Minimal Model $n_R=2$

Non very degenerate solutions

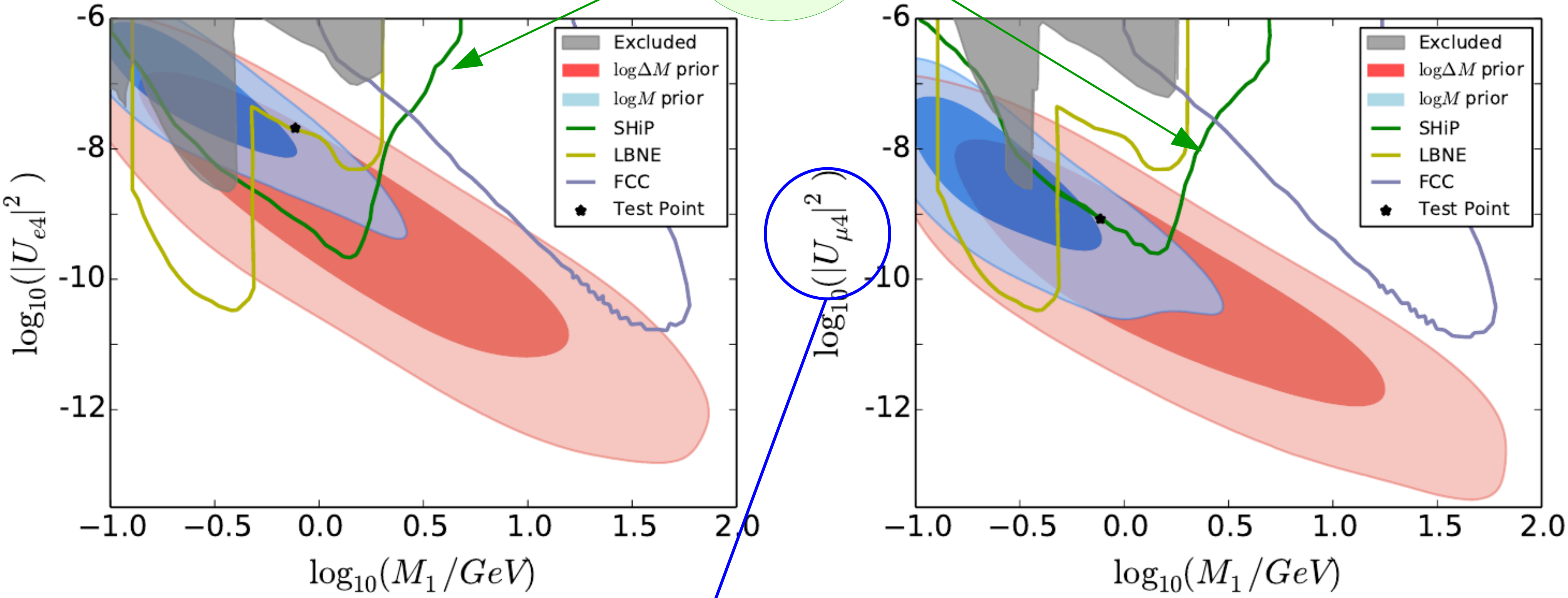


Inverted light neutrino ordering (IH)

Hernandez, Kekic, JLP, Racker, Salvado 1606.06719

Leptogenesis in Minimal Model $N_R=2$

SHiP



Yv/M

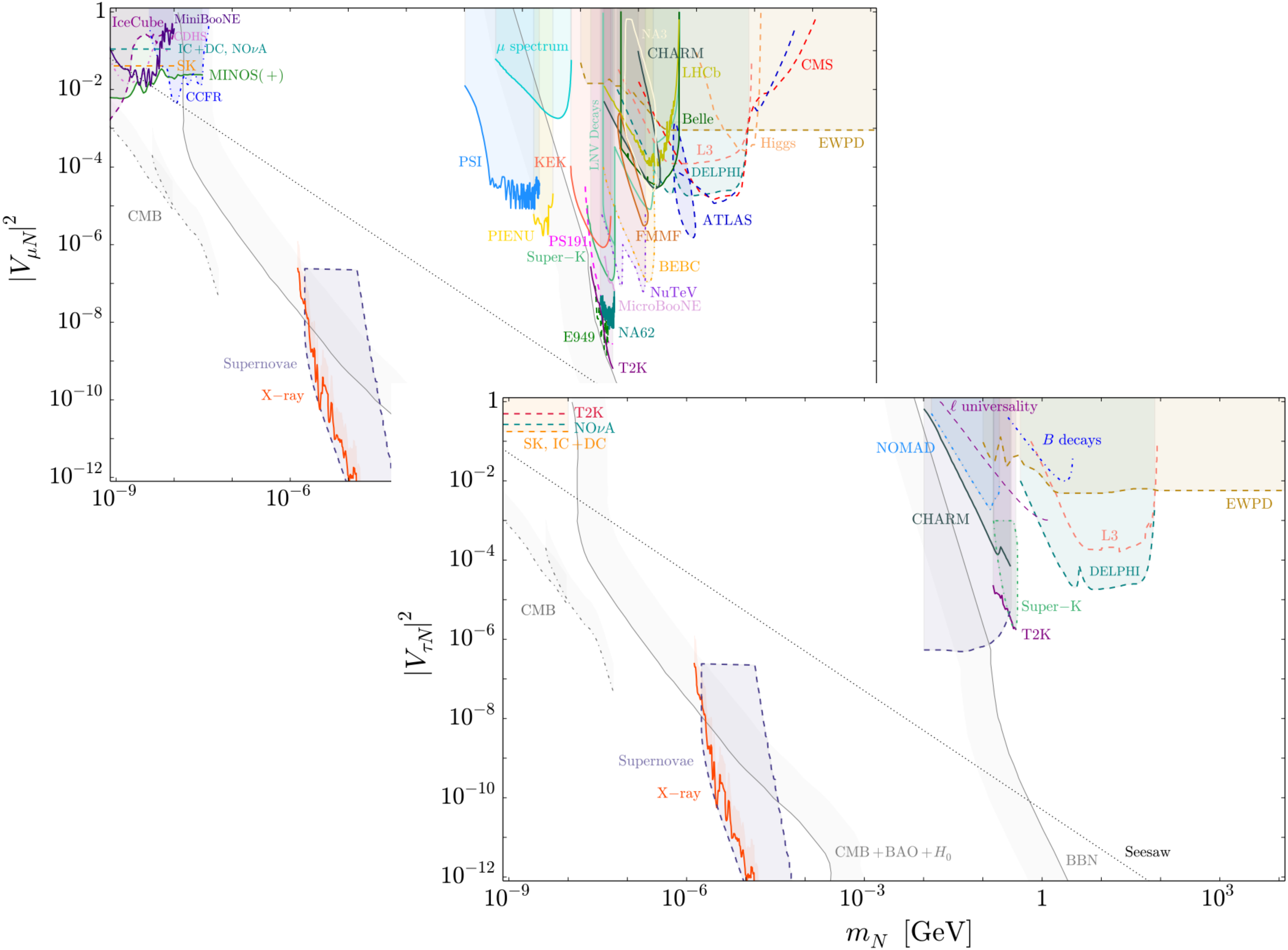
Inverted light neutrino ordering

Hernandez, Kekic, JLP, Racker, Salvado 1606.06719

$$\chi^2_{\text{min}}(\{\Theta\}) = \min_{\{\xi,\zeta\}} \left[\chi^2_{\text{stat}}(\{\Theta,\xi,\zeta\}) + \sum_s \left(\frac{\zeta_s}{\sigma_{\text{norm},s}}\right)^2 + \sum_b \left(\frac{\zeta_b}{\sigma_{\text{norm},b}}\right)^2 \right.$$
$$\left. + \sum_i \left(\frac{\xi_i^{\text{sig}}}{\sigma_{\text{shape,sig}}}\right)^2 + \sum_i \left(\frac{\xi_i^{\text{bg}}}{\sigma_{\text{shape,bg}}}\right)^2 \right] ,$$

$$\chi^2_{\text{stat}}(\{\Theta,\xi,\zeta\}) = \sum_i 2\left(N_i(\{\Theta,\xi,\zeta\}) - O_i + O_i \ln \frac{O_i}{N_i(\{\Theta,\xi,\zeta\})}\right)$$

$$N_i(\{\Theta,\xi,\zeta\}) = \sum_s (1 + \xi_i^{\text{sig}} + \zeta_s)\, s_i(\{\Theta\}) + \sum_b (1 + \xi_i^{\text{bg}} + \zeta_b)\, b_i(\{\Theta\})$$



IceCube
MiniBooNE
CDHS
IC+DC, NOνA
SK
MINOS(+)
CCFR
μ spectrum
NA3
CHARM
LHCb
CMS
Belle
L3
Higgs
EWPD
PSI
KEK
LNV Decays
DELPHI
ATLAS
PIENU
PS191
FMMF
Super−K
BEBC
NuTeV
MicroBooNE
E949
NA62
T2K
CMB
Supernovae
X−ray
$|V_{\mu N}|^2$
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-9}
10^{-6}
T2K
NOνA
SK, IC+DC
ℓ universality
NOMAD
B decays
EWPD
CHARM
L3
DELPHI
Super−K
T2K
CMB
Supernovae
X−ray
CMB+BAO+H_0
BBN
Seesaw
$|V_{\tau N}|^2$
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-9}
10^{-6}
10^{-3}
1
10^{3}
m_N [GeV]

Systematics: Disappearance

$$N_{\nu_\alpha \to \nu_\beta} \sim \frac{\Phi_\alpha(E)}{L^2} P_{\alpha\beta}(L/E)\sigma_\beta(E)\epsilon_\beta(E)$$

- Using near detectors is a very effective way of reducing systematics in disappearance experiments (K2K, MINOS, reactors...).

$$\frac{N^{\mathrm{FD}}_{\nu_\alpha}}{N^{\mathrm{ND}}_{\nu_\alpha}} \sim \frac{L^2_{\mathrm{ND}}}{L^2_{\mathrm{FD}}} \xcancel{\frac{\Phi_\alpha \sigma_\alpha \epsilon_\alpha}{\Phi_\alpha \sigma_\alpha \epsilon_\alpha}} P_{\alpha\alpha}$$

Systematics: Disappearance

$$N_{\nu_\alpha \to \nu_\beta} \sim \frac{\Phi_\alpha(E)}{L^2} P_{\alpha\beta}(L/E)\sigma_\beta(E)\epsilon_\beta(E)$$

- Using near detectors is a very effective way of reducing systematics in disappearance experiments (K2K, MINOS, reactors...).

$$\frac{N^{\mathrm{FD}}_{\nu_\alpha}}{N^{\mathrm{ND}}_{\nu_\alpha}} \sim \frac{L^2_{\mathrm{ND}}}{L^2_{\mathrm{FD}}} \cancel{\frac{\Phi_\alpha \sigma_\alpha \epsilon_\alpha}{\Phi_\alpha \sigma_\alpha \epsilon_\alpha}} P_{\alpha\alpha}$$

Systematics: Appearance (CP violation)

$$N_{\nu_\alpha \to \nu_\beta} \sim \frac{\Phi_\alpha(E)}{L^2} P_{\alpha\beta}(L/E)\sigma_\beta(E)\epsilon_\beta(E)$$

- For appearance experiments the situation is more complicated

$$\frac{N_{\nu_e}^{\mathrm{FD}}}{N_{\nu_\mu}^{\mathrm{ND}}} \sim \frac{L_{\mathrm{ND}}^2}{L_{\mathrm{FD}}^2} \frac{\sigma_e \epsilon_e}{\sigma_\mu \epsilon_\mu} P_{\mu e}$$

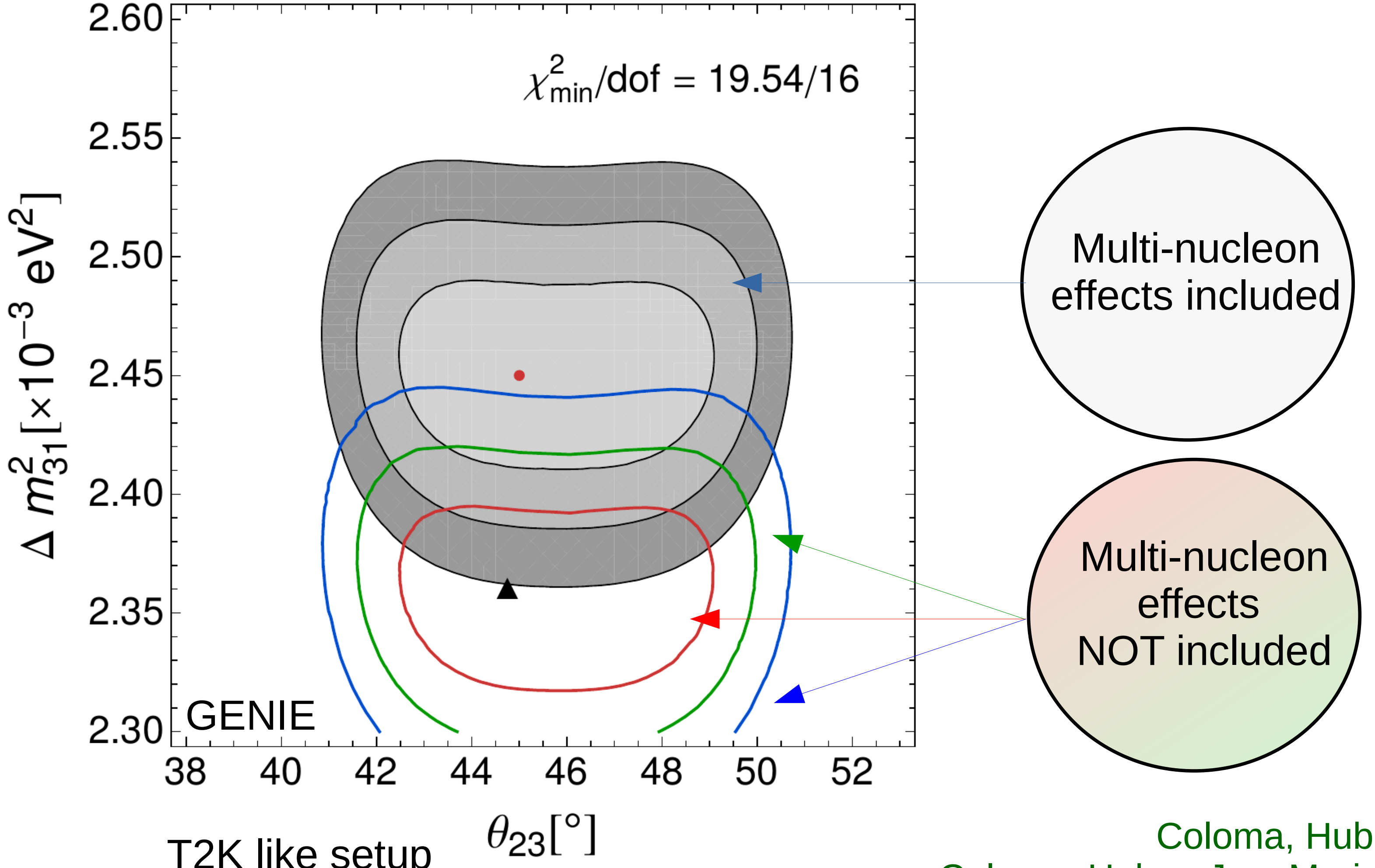
- CP violation requires comparison between neutrino and anti-netrino signals.

$$\frac{N_{\nu_e}^{\mathrm{Far}}}{N_{\bar{\nu}_e}^{\mathrm{Far}}} \sim \frac{N_{\nu_\mu}^{\mathrm{ND}}}{N_{\bar{\nu}_\mu}^{\mathrm{ND}}} \frac{\sigma_e \epsilon_e}{\sigma_\mu \epsilon_\mu} \frac{\sigma_{\bar{\mu}} \epsilon_{\bar{\mu}}}{\sigma_{\bar{e}} \epsilon_{\bar{e}}} \frac{P_{\mu e}}{P_{\bar{\mu}\bar{e}}}$$

Huber, Mezzetto, Schwetz, 0711.2950
Coloma, Huber, Kopp, Winter, 1209.5973

Nuclear Cross sections

- Neutrino-nucleus cross section missmodeling could lead to unacceptably large systematic uncertainties or biased measurements, even after the inclusion of a near detector.



Multi-nucleon effects included

Multi-nucleon effects NOT included

T2K like setup

Coloma, Huber 1307.1243
Coloma, Huber, Jen, Mariani 1311.4506
….

Present Bounds

	High-scale Non-Unitarity	Low-scale Non-Unitarity	
	$(m > \text{EW})$	$\Delta m^2 \gtrsim 100\ \text{eV}^2$	$\Delta m^2 \sim 0.1 - 1\ \text{eV}^2$
α_{ee}	$1.3 \cdot 10^{-3}$	$2.4 \cdot 10^{-2}$	$1.0 \cdot 10^{-2}$
$\alpha_{\mu\mu}$		$2.2 \cdot 10^{-2}$	$^{\cdot 2}$
$\alpha_{\tau\tau}$		$1.0 \cdot 10^{-1}$	$^{\cdot 1}$
$\|\alpha_{\mu e}\|$		$2.5 \cdot 10^{-2}$	0^{-2}
$\|\alpha_{\tau e}\|$	$2.7 \cdot 10^{-3}$	$6.9 \cdot 10^{-2}$	$4.5 \cdot 10^{-2}$
$\|\alpha_{\tau\mu}\|$	$1.2 \cdot 10^{-3}$	$1.2 \cdot 10^{-2}$	$5.3 \cdot 10^{-2}$

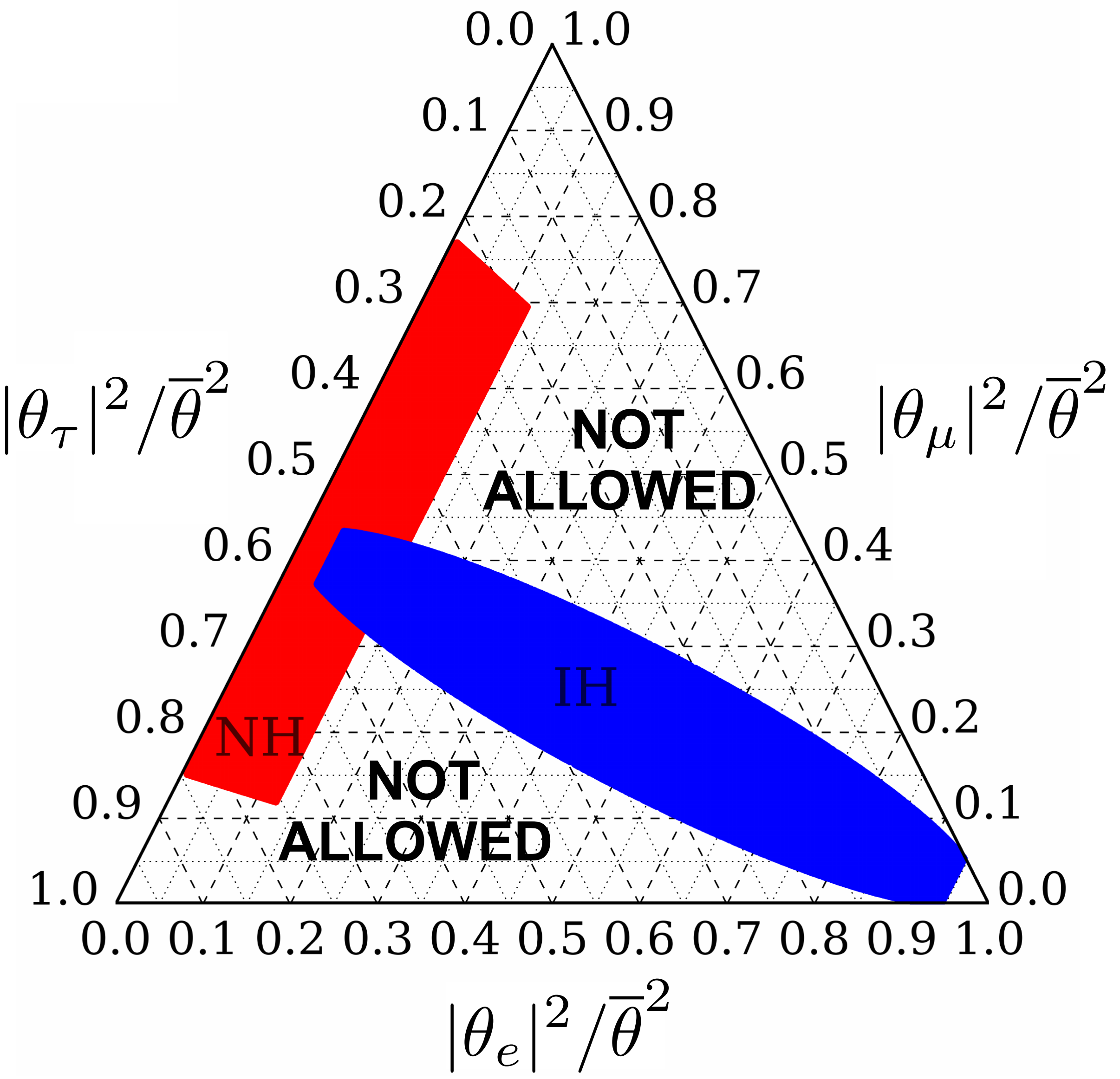
0.1-0.001% level

10-1% level

Fernandez-Martinez, Hernandez-Garcia, JLP
1605.08774
Blennow, Coloma, Fernandez-Martinez,
Hernandez-Garcia, JLP
1609.08637

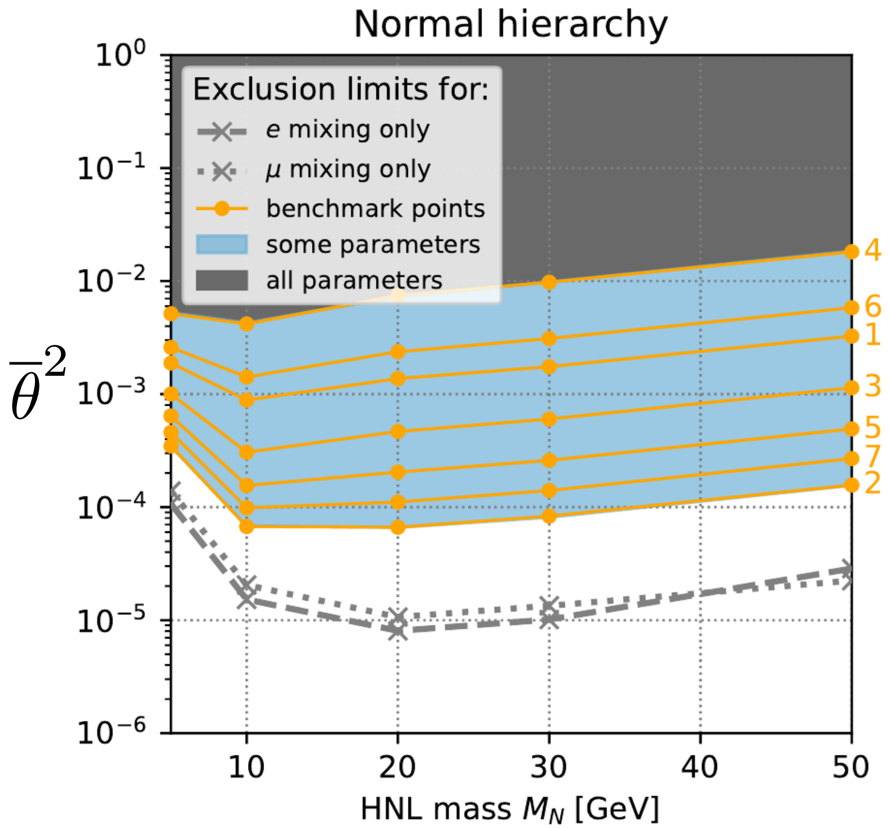
See also
Park, Ross-Lonergan 1508.05095
Ellis, Kelly, Weishi Li 2004.13719
Ellis, Kelly, Weishi Li 2008.01088

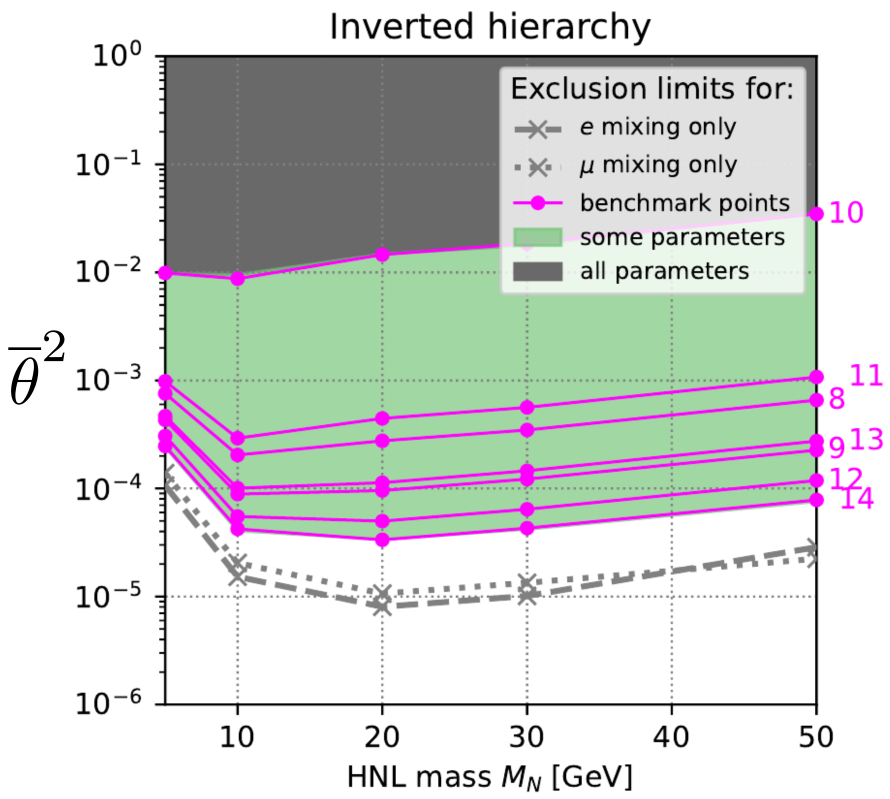
Minimal model $N_R=2$: Flavor Structure



Caputo, Hernandez, JLP, Salvado arXiv:1704.08721

Flavor pattern vs sensitivity





- Interpretation of ATLAS data depends on assumptions about “flavor mixing pattern”

Tastet, Ruchayskiya, Timiryasov 2107.12980

See talks by Tastet and Xabier Marcano

- Same conclusion applies to other experimental searches.