

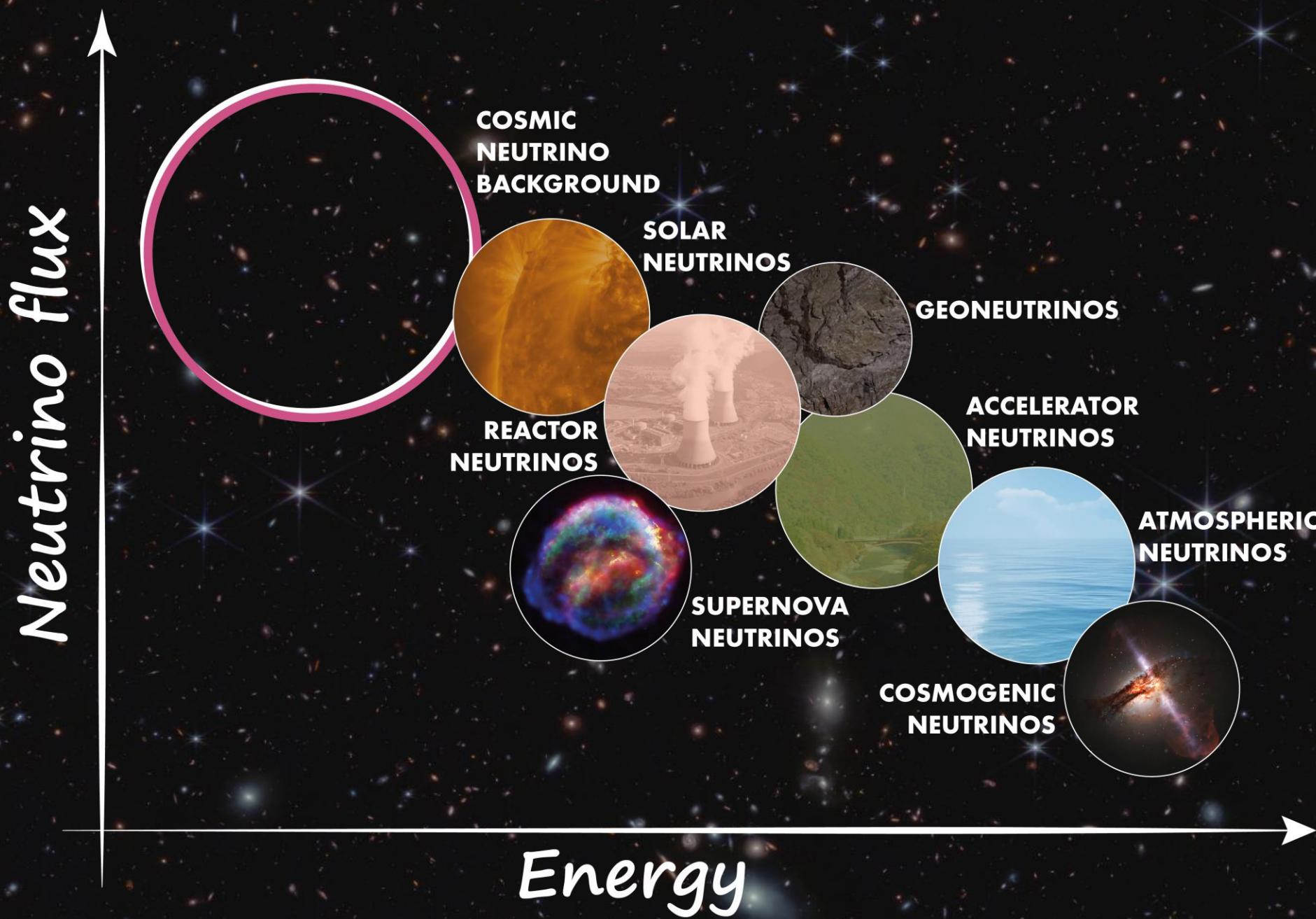
Neutrino decoupling

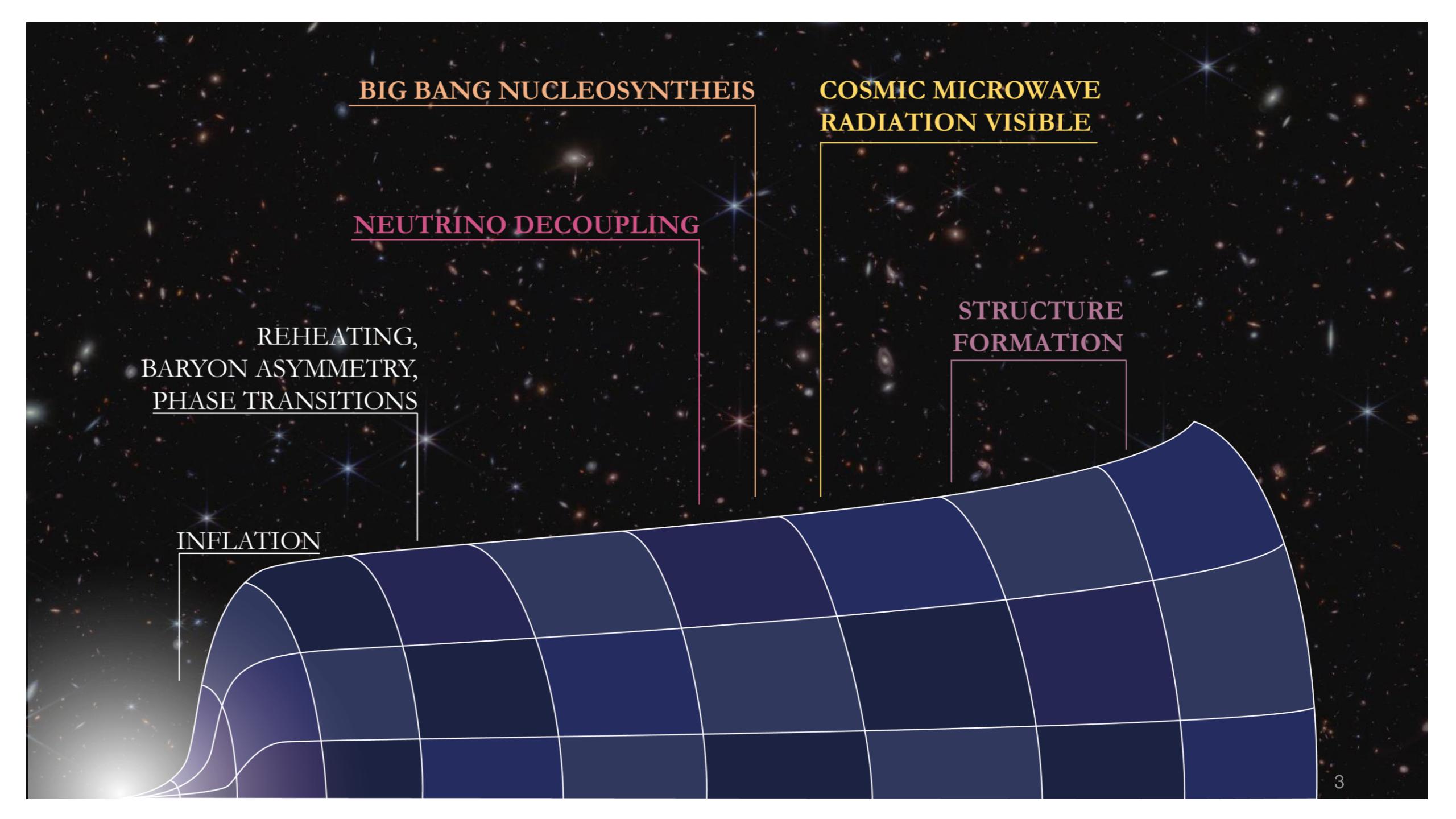
IN STANDARD AND NON-STANDARD SCENARIOS

Pablo Martínez-Miravé, IFIC (CSIC – Univ.Valencia)

TAUP 2023, Wien







REHEATING,
BARYON ASYMMETRY,
PHASE TRANSITIONS

INFLATION

BIG BANG NUCLEOSYNTHESIS

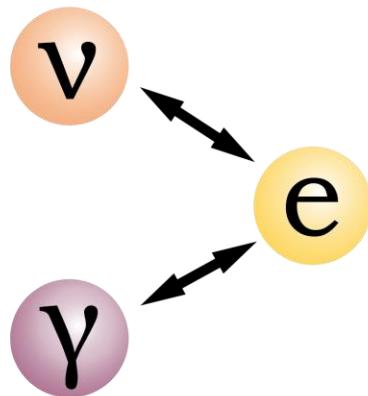
NEUTRINO DECOUPLING

COSMIC MICROWAVE
RADIATION VISIBLE

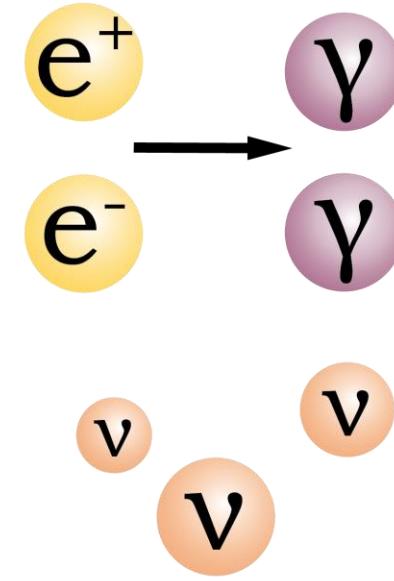
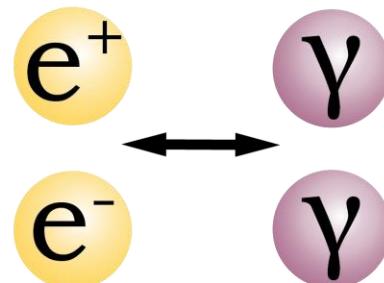
STRUCTURE
FORMATION

Neutrino decoupling *in context*

Neutrinos
coupled to the
cosmic plasma



Weak interactions stop
being effective and
neutrinos decouple



Electron-positron
annihilation only

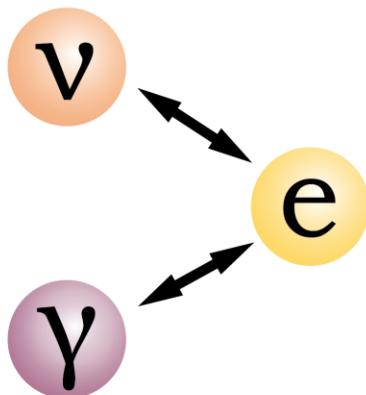
TIME

$T \sim 1 \text{ MeV}$

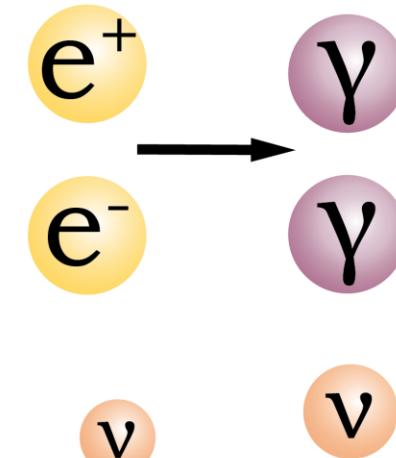
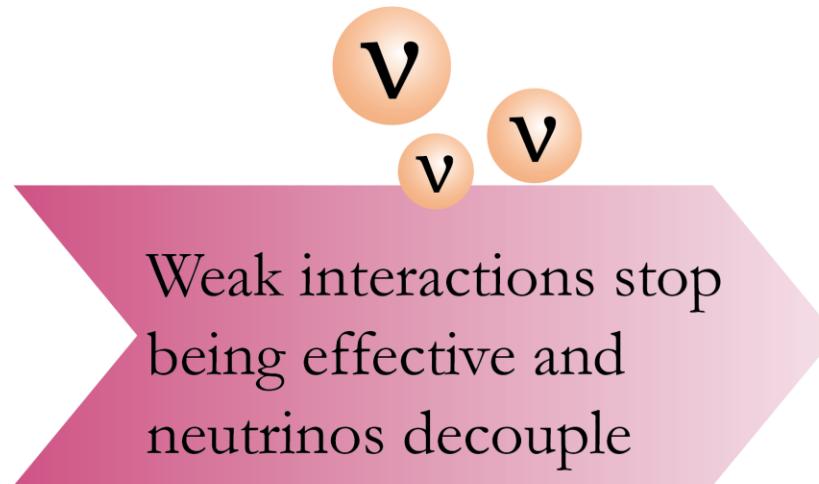
$T \sim 0.511 \text{ MeV}$

Neutrino decoupling *in context*

Neutrinos
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Weak interactions stop
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TIME

$T \sim 1 \text{ MeV}$

$T \sim 0.511 \text{ MeV}$



Effective number of neutrinos *in a nutshell*

At $T < m_e$, the **cosmological radiation density** is

$$\rho_{rad} = \rho_\gamma + \rho_\nu + \rho_x = \rho_\gamma \left(1 + \frac{7}{8} \left(\frac{4}{11} \right)^{4/3} N_{\text{eff}} \right)$$

where N_{eff} is the **effective number of relativistic species**.

In the Standard Model, **deviations from $N_{\text{eff}} = 3$** are due to:

- Non-instantaneous neutrino decoupling and e^+e^- annihilation.
- Finite temperature QED corrections.
- Neutrino oscillations.

Standard calculation of N_{eff}

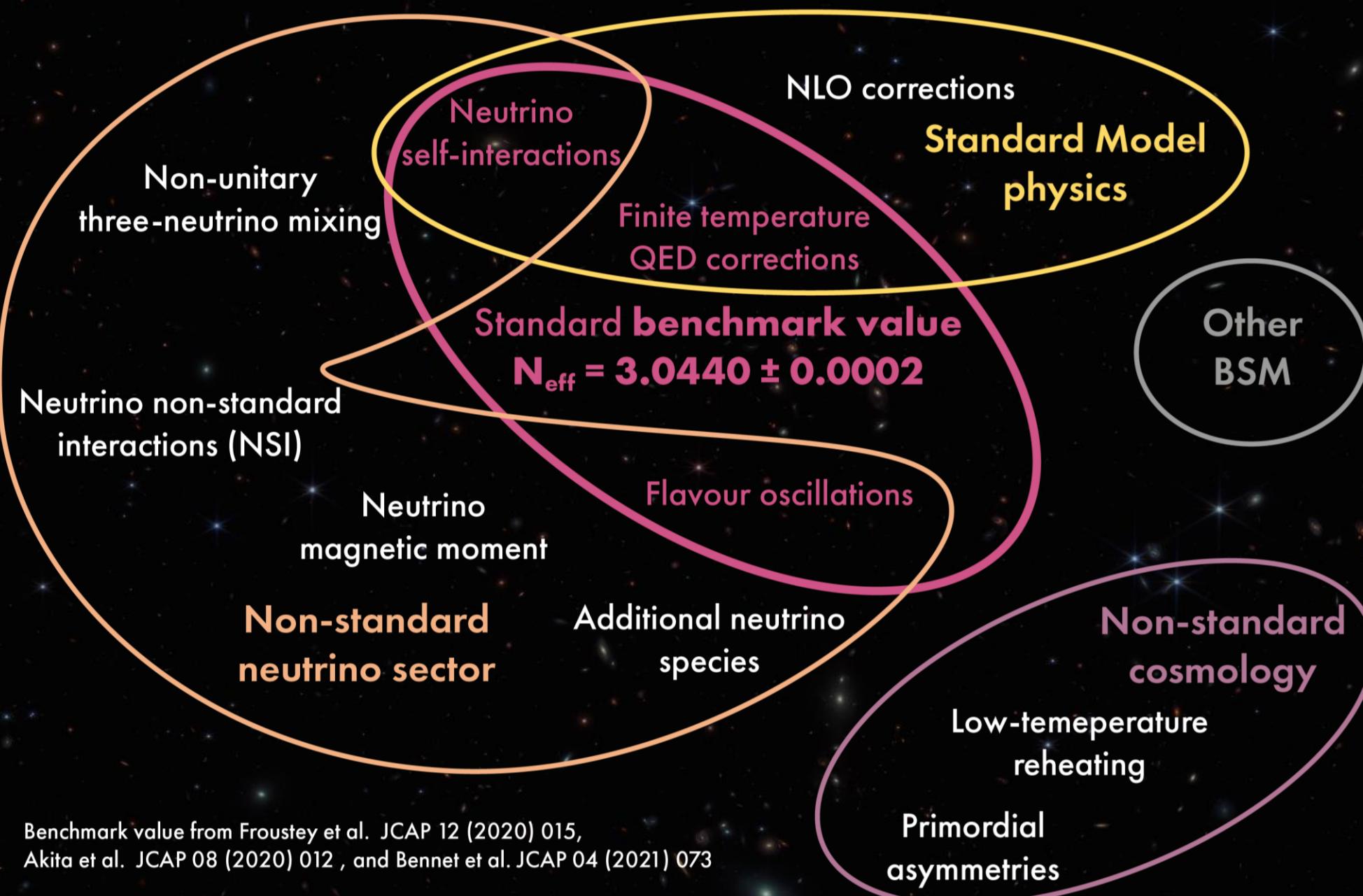


**Recent calculations yield
 $N_{\text{eff}} = 3.0440 \pm 0.0002$**

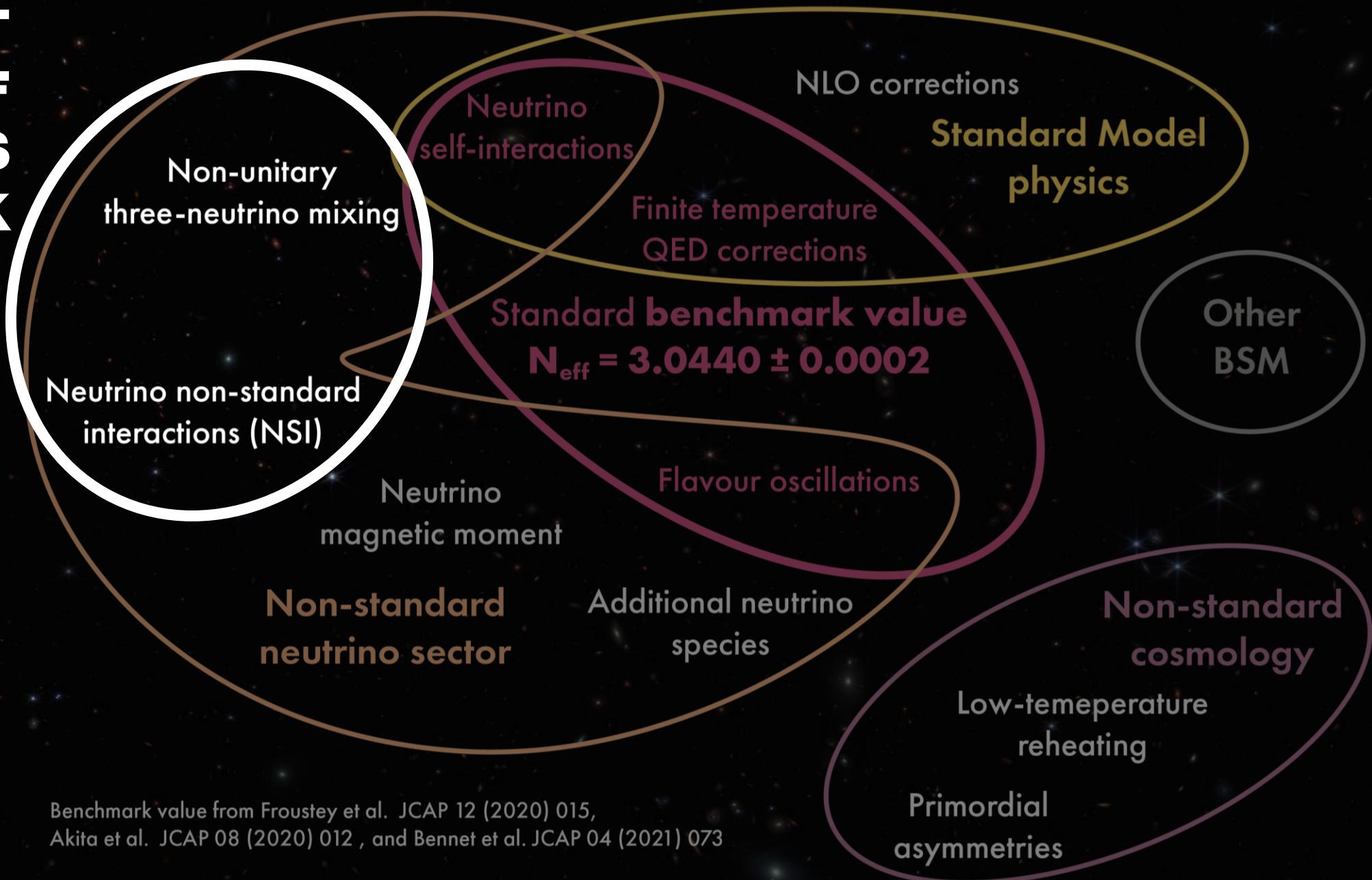
Bennett et al. JCAP 04 (2021) 073
Froustey et al. JCAP 12 (2020) 015
Akita et al. JCAP 08 (2020) 012

A precise determination of N_{eff} is expected for the forthcoming CMB observations in this decade, such as:

- **Simons Observatory**, $\sigma(N_{\text{eff}}) = 0.05-0.07$,
 - **CMB-S4 project**, $\sigma(N_{\text{eff}}) = 0.02-0.03$
- 



REST OF THIS TALK



Non-unitarity (NU) of three-neutrino mixing matrix

A **non-unitary 3x3 lepton mixing matrix (LMM)** is expected in some neutrino mass models.

Mixing between active flavour states and mass states

$$U_{n \times n} = \begin{pmatrix} N & S \\ T & V \end{pmatrix}$$

Parametrisation

$$N = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U$$

where U is the usual unitary 3x3 LMM.

Non-unitarity (NU) of three-neutrino mixing matrix

NU effectively changes the **strength and flavour structure** of weak interactions

$$\mathcal{L}_{\text{CC}} = -2\sqrt{2}G_F \sum_{i,j} (\mathbf{K}^\dagger)_{ie} \mathbf{K}_{ej} (\bar{\nu}_i \gamma^\mu P_L \nu_j) (\bar{e} \gamma_\mu P_L e)$$

$$\mathcal{L}_{\text{NC}} = -2\sqrt{2}G_F \sum_{X=L,R} g_X \sum_{i,j} \left(\mathbf{K}^\dagger \mathbf{K} \right)_{ij} (\bar{\nu}_i \gamma^\mu P_L \nu_j) (\bar{e} \gamma_\mu P_X e)$$

Non-unitarity (NU) of three-neutrino mixing matrix

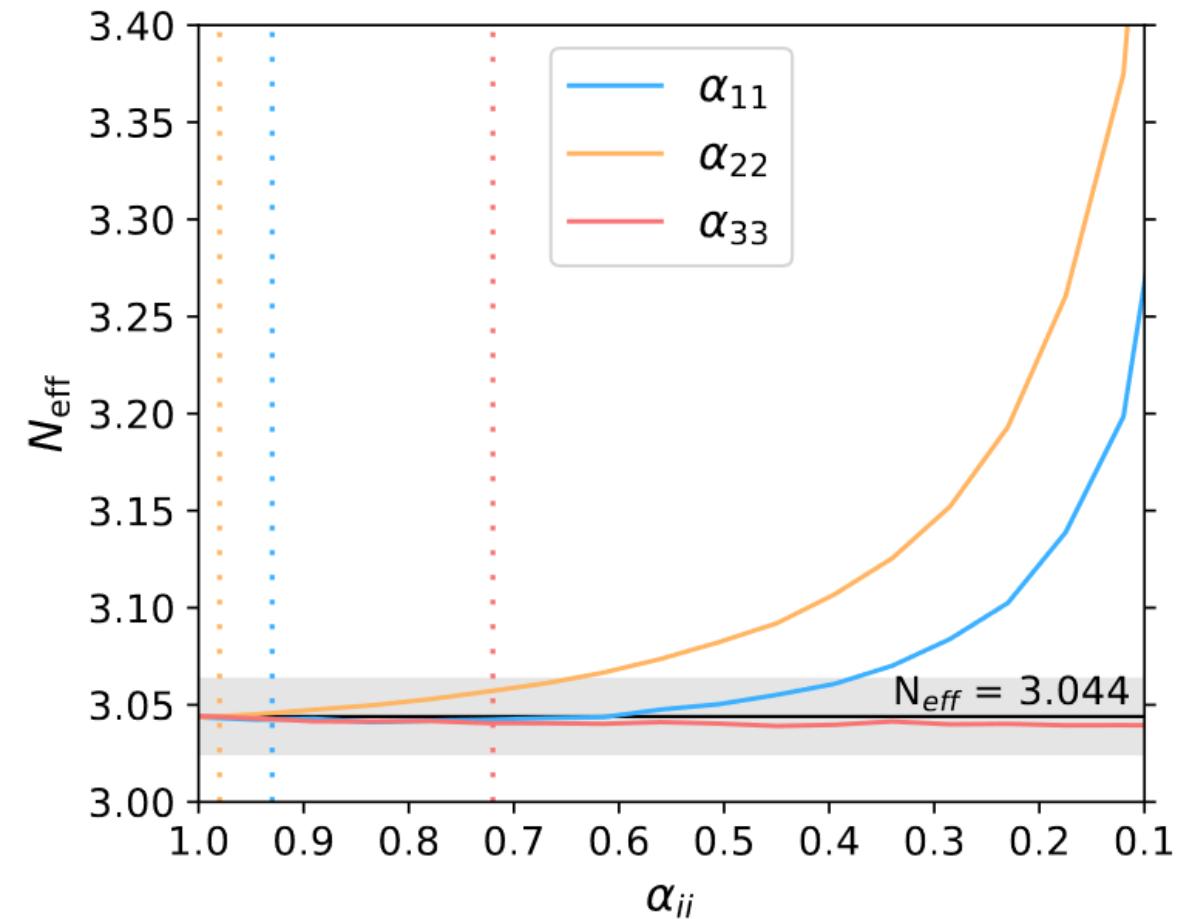
The contribution of heavy states is **Boltzmann-suppressed**.
Decoupling has to be computed in the **mass basis**.

$$\mathcal{L}_{\text{CC}} = -2\sqrt{2}G_F \sum_{i,j} (N^\dagger)_{ie} N_{ej} (\bar{\nu}_i \gamma^\mu P_L \nu_j) (\bar{e} \gamma_\mu P_L e)$$

$$\mathcal{L}_{\text{NC}} = -2\sqrt{2}G_F \sum_{X=L,R} g_X \sum_{i,j} \left(N^\dagger N \right)_{ij} (\bar{\nu}_i \gamma^\mu P_L \nu_j) (\bar{e} \gamma_\mu P_X e)$$

Non-unitarity (NU) of three-neutrino mixing matrix

Main effect comes from the **changes in the interactions** keeping neutrinos in thermal equilibrium with the rest of the plasma.



Non-unitarity (NU) of three-neutrino mixing matrix

One can derive bounds on NU parameter from the requirement that electroweak and cosmological observables (G_F and N_{eff}) are consistent.

After Planck:

$$\alpha_{11} > 0.07$$

$$\alpha_{22} > 0.15$$

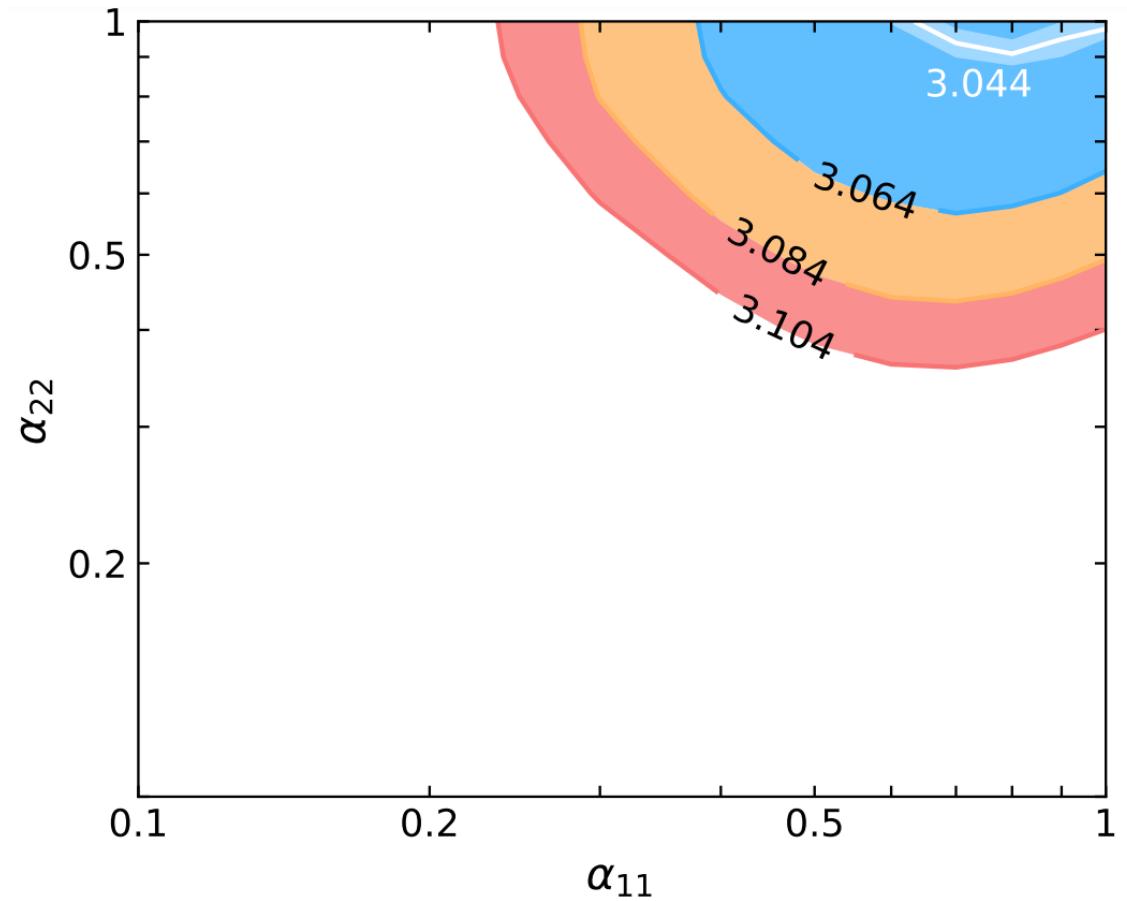
Future prospects:

$$\alpha_{11} > 0.29$$

$$\alpha_{22} > 0.50$$

Non-unitarity (NU) of three-neutrino mixing matrix

There exist degeneracies
between parameters.



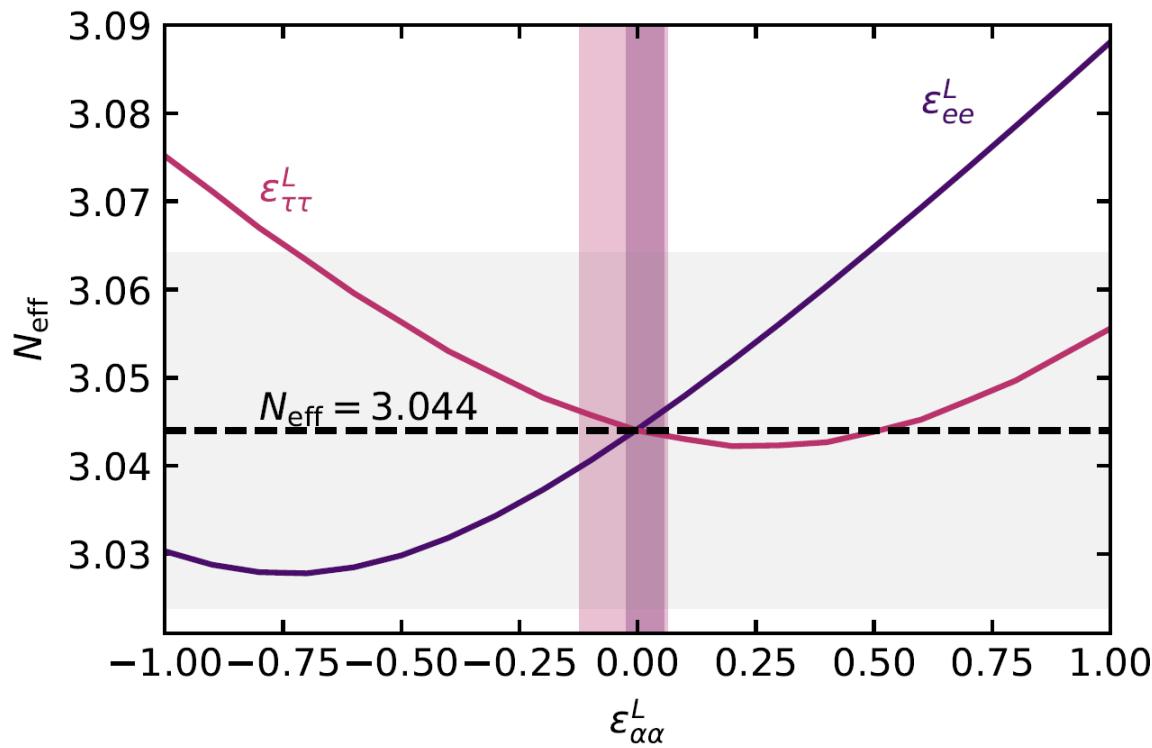
Non-standard neutrino -electron interactions (**NSI**)

Neutral-current non-standard interactions (**NSI**) between neutrinos and electrons can be parametrised as follows:

$$\mathcal{L}_{\text{NSIe}} = -2\sqrt{2}G_F \sum_{\alpha,\beta} \varepsilon_{\alpha\beta}^X (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta) (\bar{e} \gamma_\mu P_X e)$$

with $X \in \{L, R\}$
 $\alpha, \beta \in \{e, \mu, \tau\}$

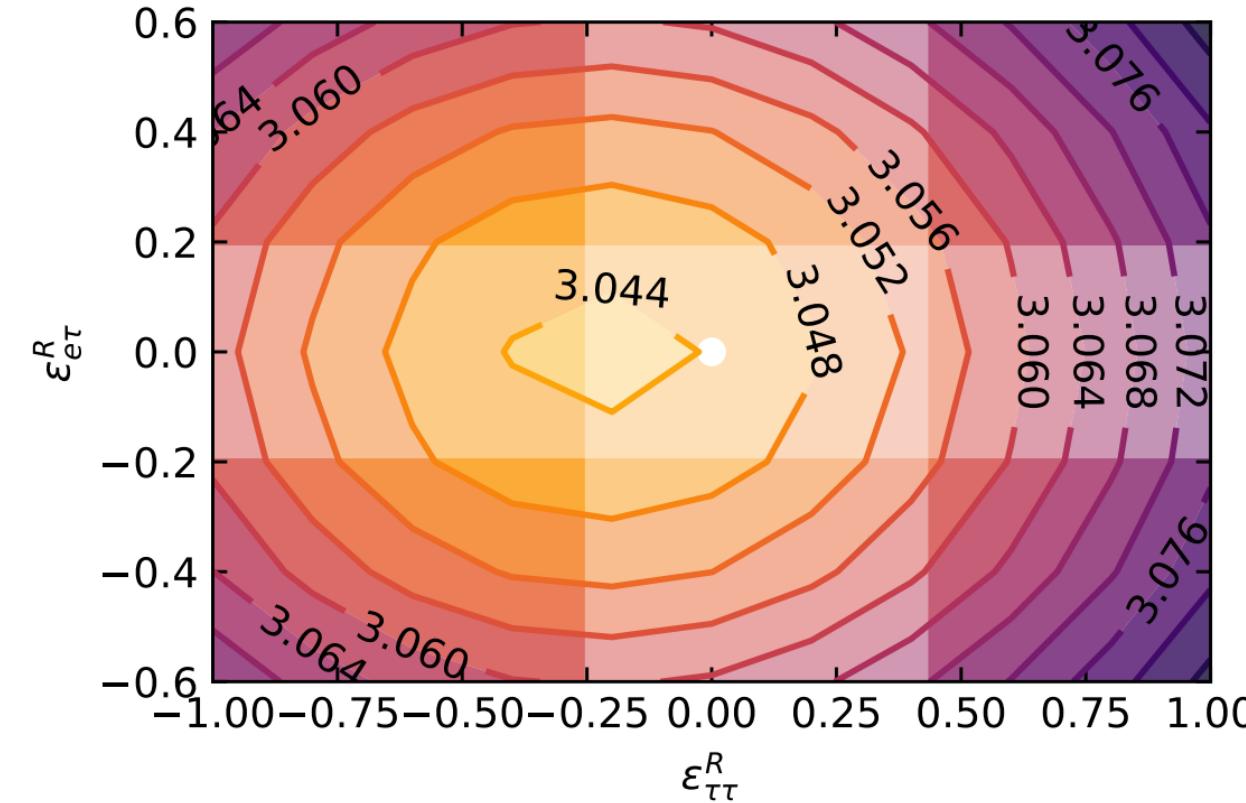
Dimensionless coefficients $\varepsilon_{\alpha\beta}^X$ quantify the strength of the interactions with respect to the SM.



Non-standard neutrino -electron interactions (NSI)

NSI can:

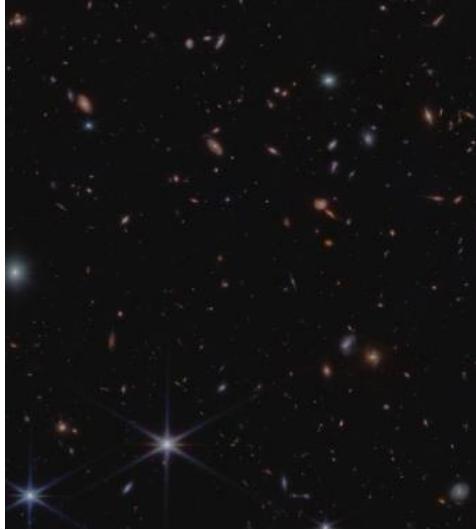
- cancel out SM interactions, leading to a **smaller N_{eff}** .
- enhance SM interactions, leading to a delayed decoupling (**larger N_{eff}**)



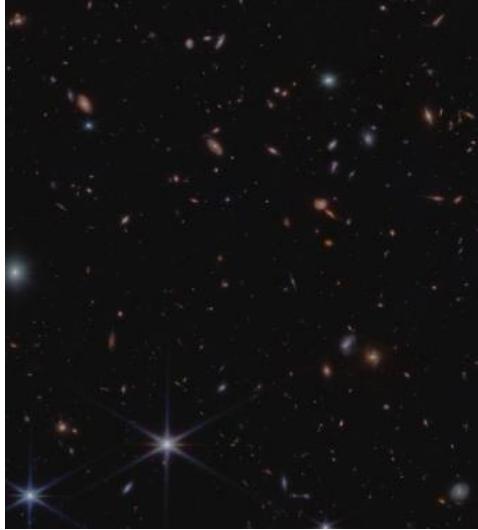
Non-standard neutrino -electron interactions (NSI)

Degeneracies between parameters can also be explored in this scenario.

TAKE-HOME
MESSAGE



Forthcoming cosmological observation will allow to study **neutrino properties** using a **complementary** approach to terrestrial experiments.



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Accurate calculation of **neutrino decoupling** is feasible in **standard and non-standard scenarios**.

Non-unitarity



JCAP 03 (2023) 046

Non-standard interactions



Phys.Lett.B 820 (2021) 136508

SPARE SLIDES

Non-standard neutrino -electron interactions (NSI)

In the presence of NSI, the picture of neutrino decoupling changes because:

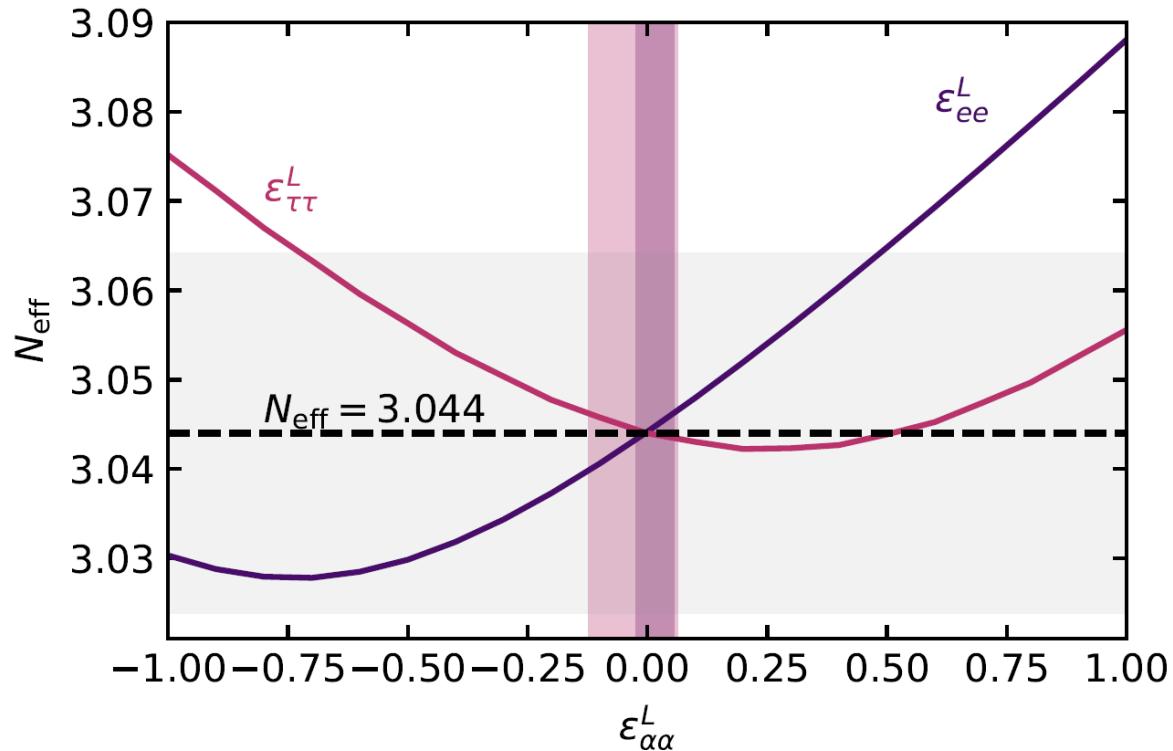
- **Oscillations** are modified (subleading effect)
- **Interactions** keeping neutrinos in thermal contact with the rest of the plasma are **enhanced or suppressed**.

$$g_L^2 \rightarrow \left(g_L + \varepsilon_{\alpha\alpha}^L \right)^2 + \sum_{\beta \neq \alpha} |\varepsilon_{\alpha\beta}^L|^2$$

$$g_R^2 \rightarrow \left(g_R + \varepsilon_{\alpha\alpha}^R \right)^2 + \sum_{\beta \neq \alpha} |\varepsilon_{\alpha\beta}^R|^2$$

$$g_L g_R \rightarrow \left(g_L + \varepsilon_{\alpha\alpha}^L \right) \left(g_R + \varepsilon_{\alpha\alpha}^R \right) + \sum_{\beta \neq \alpha} |\varepsilon_{\alpha\beta}^L| |\varepsilon_{\alpha\beta}^R|$$

SM coefficients are effectively shifted



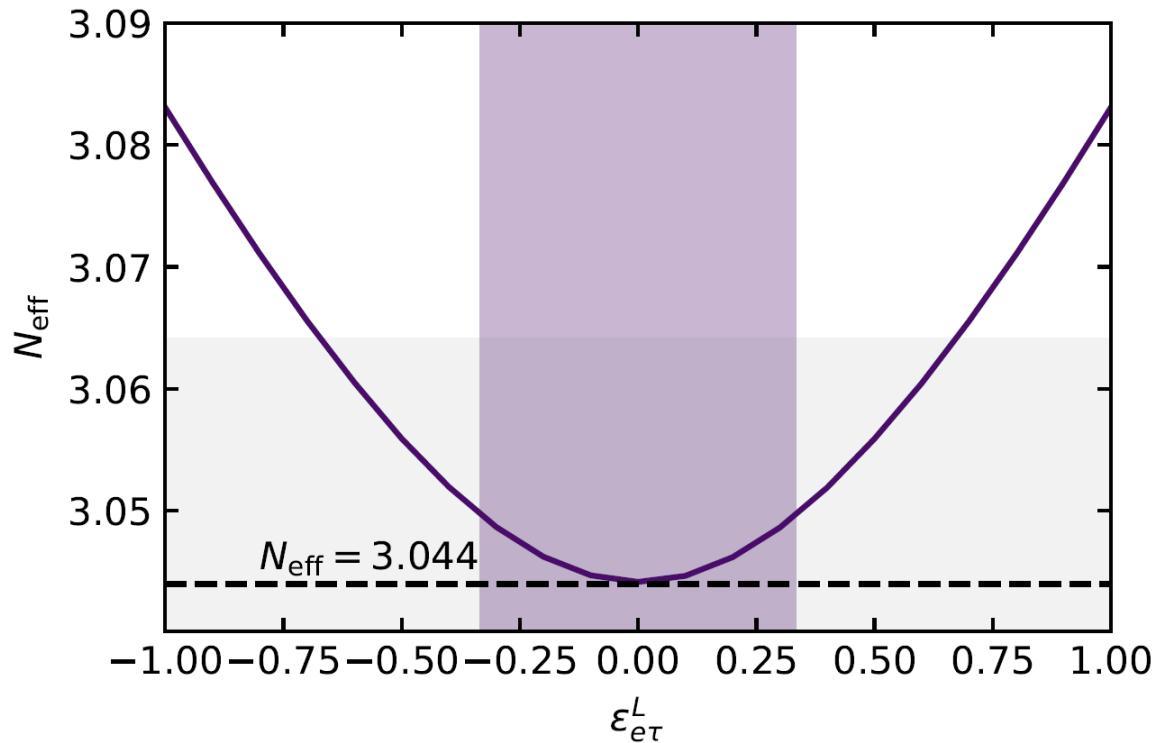
Minima correspond to

$$\begin{aligned}\varepsilon_{ee}^L &= -(1 + g_L) \\ &= -\frac{1}{2} - \sin^2 \theta_W \sim -0.72\end{aligned}$$

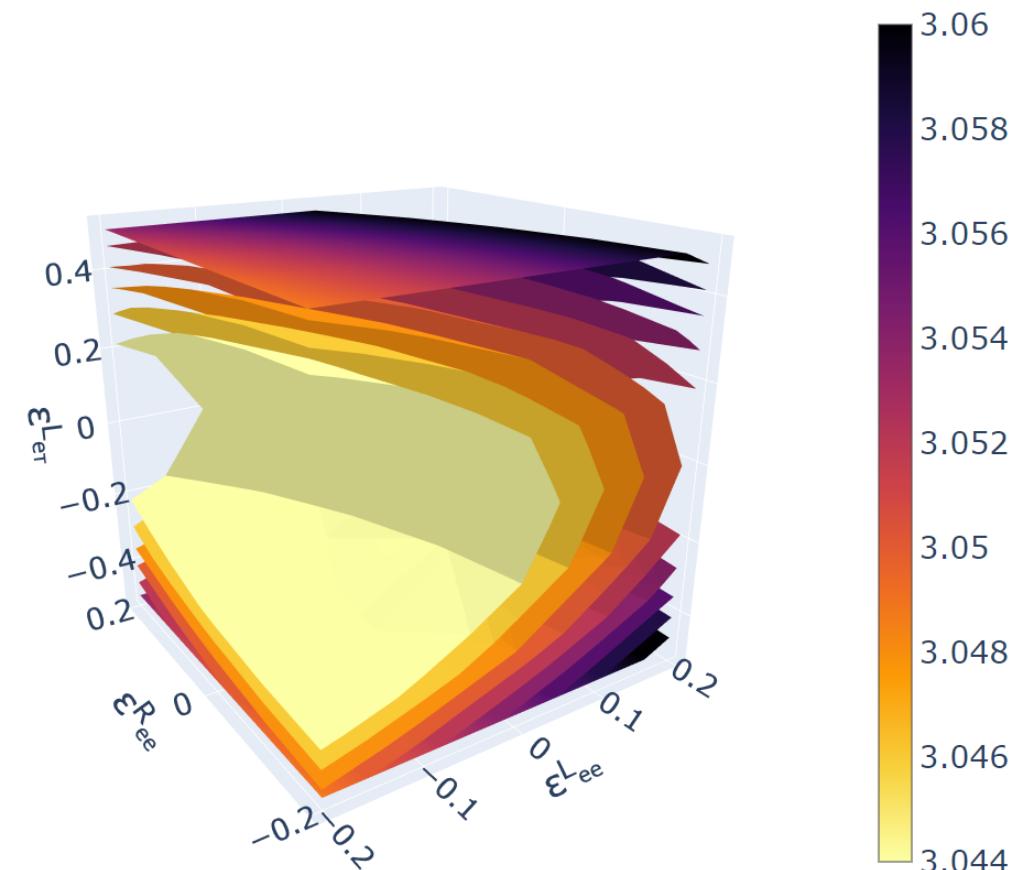
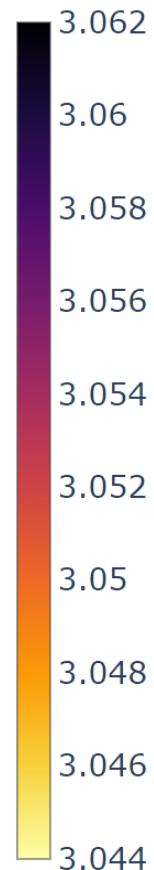
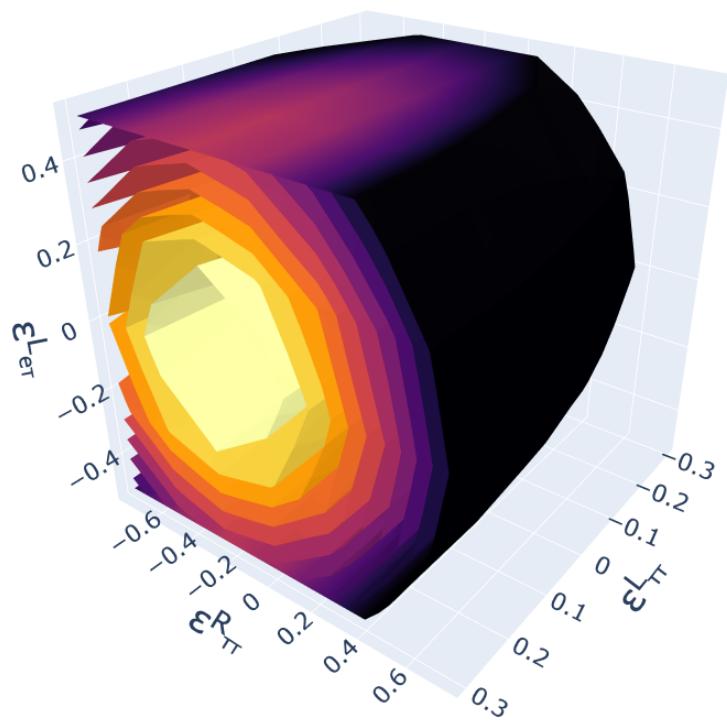
and

$$\begin{aligned}\varepsilon_{\tau\tau}^L &= -g_L \\ &= \frac{1}{2} - \sin^2 \theta_W \sim 0.28\end{aligned}$$

FLAVOUR-CHANGING NSI enhance the interactions between neutrinos and the cosmic plasma, delaying the decoupling and leading to a larger value of N_{eff} .



VARYING THREE PARAMETERS AT A TIME

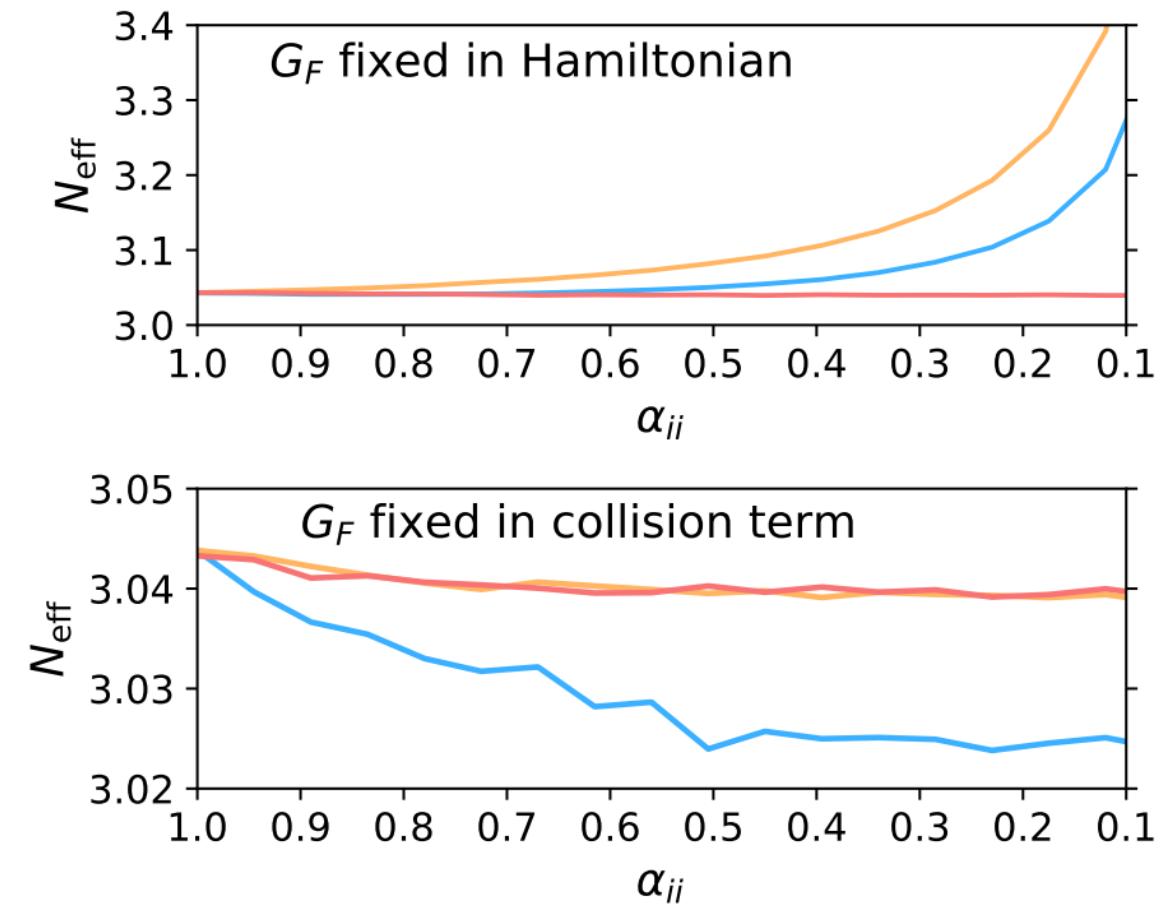
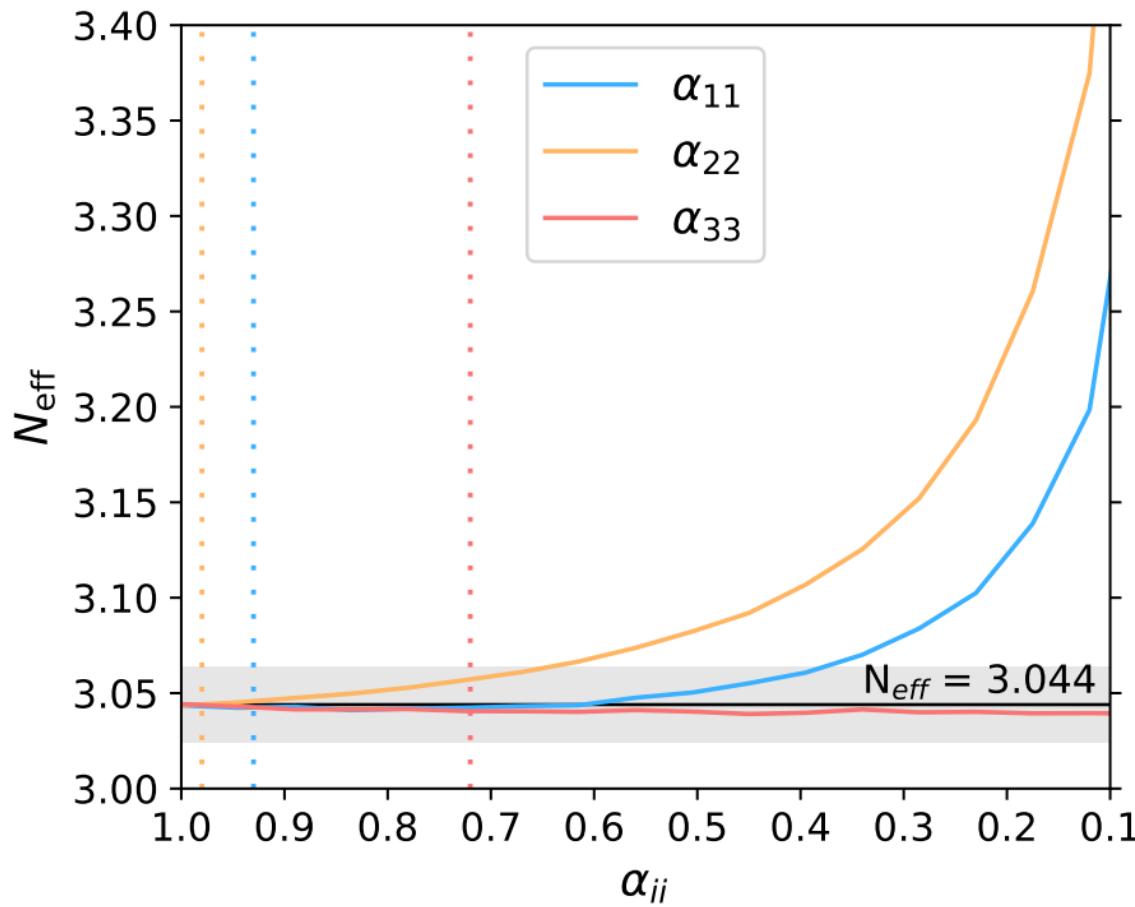


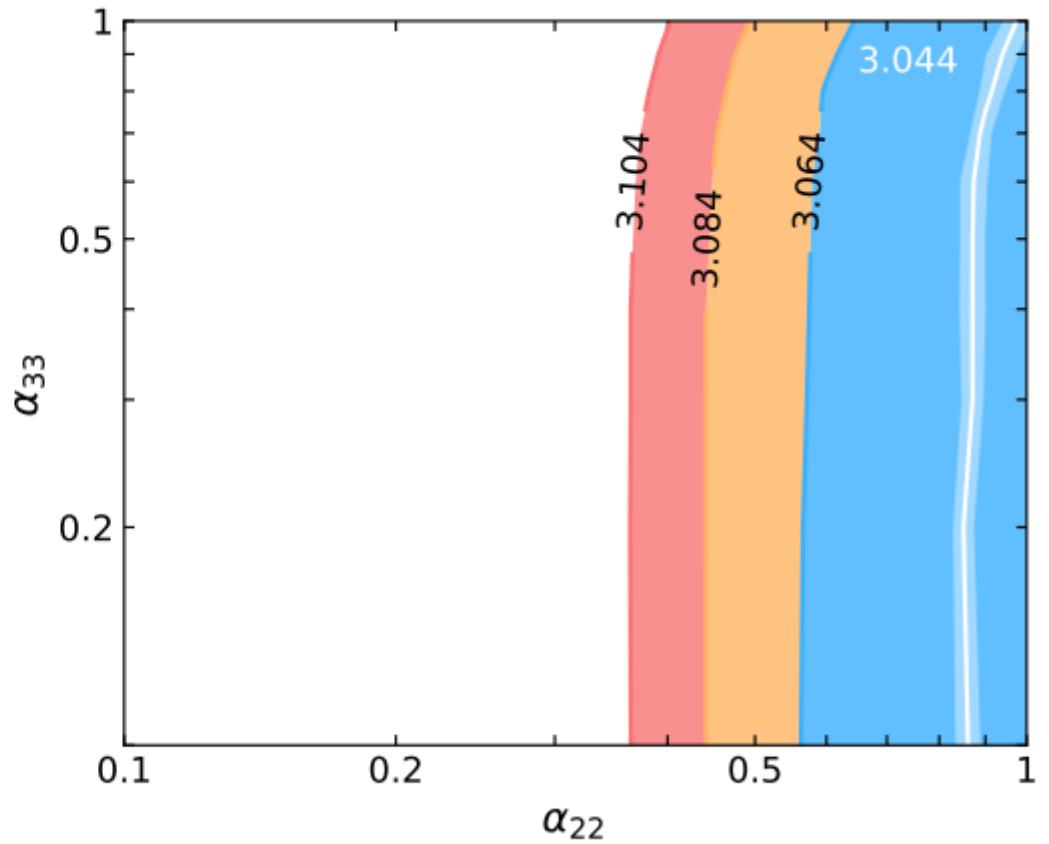
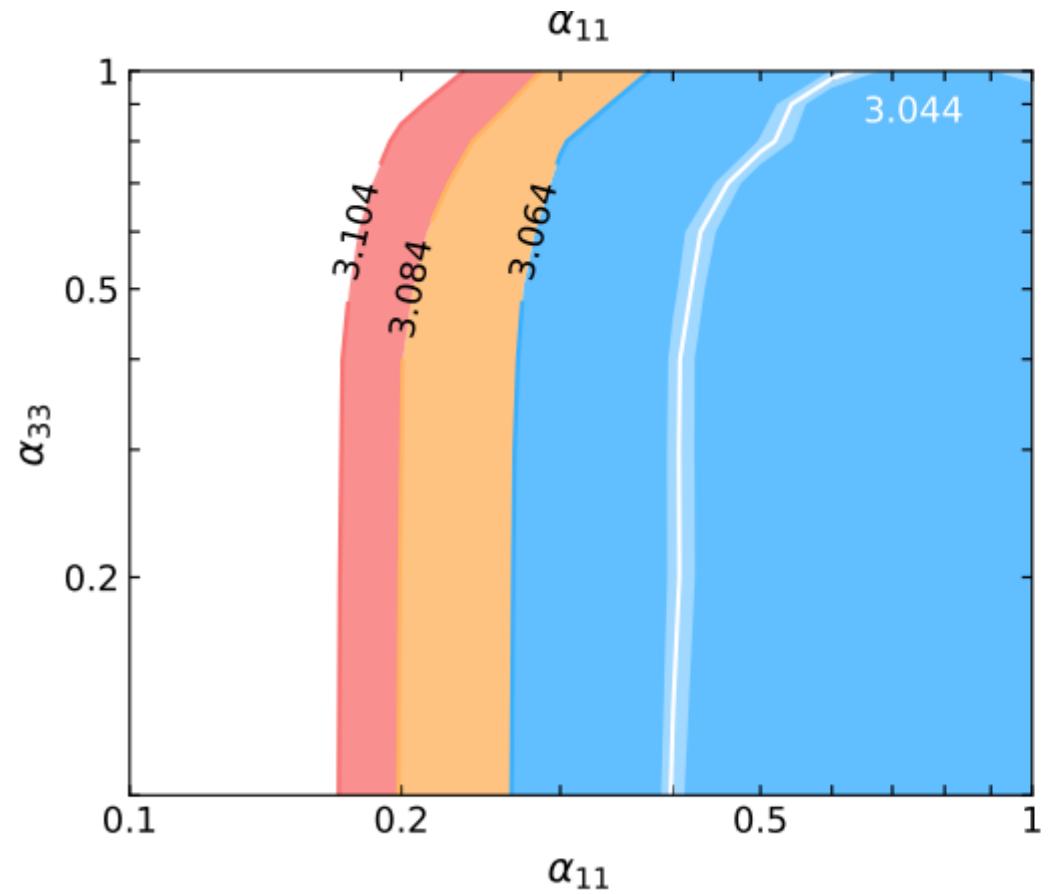
INTERACTIVE VERSIONS [HERE](#) & [HERE](#)

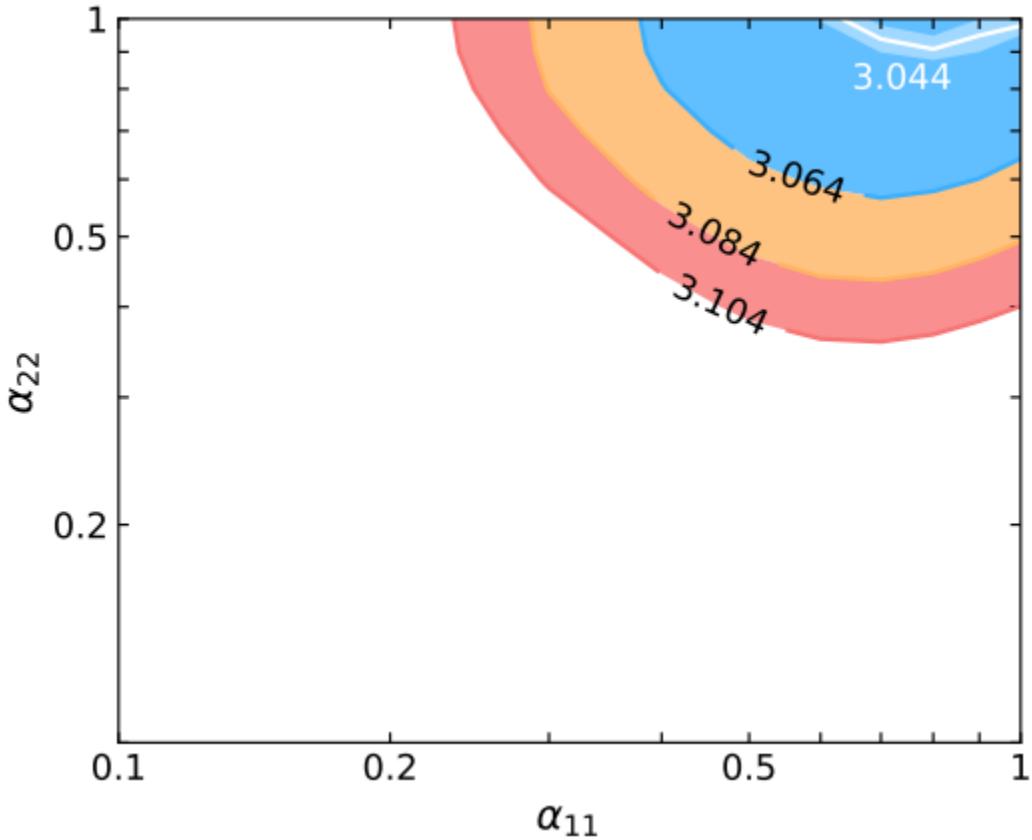
Non-unitarity (NU) of three-neutrino mixing matrix

$$G_F^\beta = G_F \sqrt{(NN^\dagger)_{ee}} = G_F \alpha_{11}$$

$$G_F^\mu = G_F \sqrt{(NN^\dagger)_{ee}(NN^\dagger)_{\mu\mu}} = G_F \sqrt{\alpha_{11}^2 (\alpha_{22}^2 + |\alpha_{21}|^2)}$$







$$\alpha_{11}^2 |\alpha_{21}|^2 \leq (1 - \alpha_{11}^2)(1 - \alpha_{22}^2 - |\alpha_{21}|^2),$$

