PRIN NAT-NET 3rd meeting

L’Aquila 18 Luglio 2023

WP2
Beyond the Standard ν Framework

Antonio & Ninetta

WP2 - Beyond the standard neutrino framework

Light sterile neutrino oscillations in the light of upcoming laboratory and cosmological data; (see also WP4)

Constraints on new neutrino interactions; (see also WP4)

Neutrinoless double beta decay beyond light Majorana neutrinos;

Long-distance and multi-messenger tests of dispersion relations;

Neutrinos as components or signals of dark matter; (see also WP3)

Neutrino model building and leptogenesis.

Outline

Non-interfering ν exchange in $0\nu2\beta$ decay and NMEs (A)

Complementarity of $0\nu2\beta$ with LHC in composite ν searches (A)

Impact of light sterile neutrinos at LBLs (A)

Radiative SM extension to explain g-2 and W-mass (N)

Violation of Equivalence Principle in Km3NET (N)

ν conversion in high density environments (N)

Scalar leptoquark at COHERENT (N) + Talk by Roberta

Primordial black holes and leptogenesis (N) + Talk by Jacob

Interplay between non-interfering neutrino exchange mechanisms and nuclear matrix elements in $0\nu\beta\beta$ decay

Eligio Lisi,[1,*] Antonio Marrone,[2,1,†] and Newton Nath[1,‡]

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[2] *Dipartimento Interateneo di Fisica "Michelangelo Merlin," Via Amendola 173, 70126 Bari, Italy*

We revisit the phenomenology of neutrinoless double beta ($0\nu\beta\beta$) decay mediated by non-interfering exchange of light and heavy Majorana neutrinos, in the context of current and prospective ton-scale experimental searches, as well as of recent calculations of nuclear matrix elements (NME) in different nuclear models. We derive joint upper bounds on the light and heavy contributions to $0\nu\beta\beta$ decay, for different sets of NME, through separate and combined data coming from the following experiments (and isotopes): KamLAND-Zen and EXO (Xe), GERDA and MAJORANA (Ge) and CUORE (Te). We further consider three proposed projects that could provide, within current bounds, possible $0\nu\beta\beta$ decay signals at $>3\sigma$ level with an exposure of 10 ton years: nEXO (Xe), LEGEND (Ge) and CUPID (Mo). Separate and combined (Xe, Ge, Mo) signals are studied for different representative cases and NME sets, and the conditions leading to (non)degenerate light and heavy neutrino mechanisms are discussed. In particular, the role of heavy-to-light NME ratios in different isotopes is highlighted through appropriate graphical representations. By using different sets of "true" and "test" NME as a proxy for nuclear uncertainties, it is shown that the relative contributions of light and heavy neutrino exchange to $0\nu\beta\beta$ signals may be significantly biased in some cases. Implications for theoretical models connecting light and heavy Majorana neutrino masses are also briefly illustrated. These results provide further motivations to improve NME calculations, so as to better exploit the physics potential of future multi-isotope $0\nu\beta\beta$ searches at the ton scale.

Submitted to PRD

Basic formulae

$$(Z,\, A) \to (Z+2,\, A) + 2e^- \;,$$

$$m_\nu = \left| \sum_{k=1}^{3} U_{ek}^2 m_k \right|$$

effective majorana mass for light ν_k

$$m_N = \frac{m_W^4}{m_{W_R}^4} \left| \sum_h V_{eh}^2 \frac{m_p\, m_e}{M_h} \right|$$

effective majorana mass for heavy N_h

$$(T_i)^{-1} = S_i = G_i\, \left(M_{\nu,i}^2\, m_\nu^2 \;+ M_{N,i}^2\, m_N^2 \right)$$

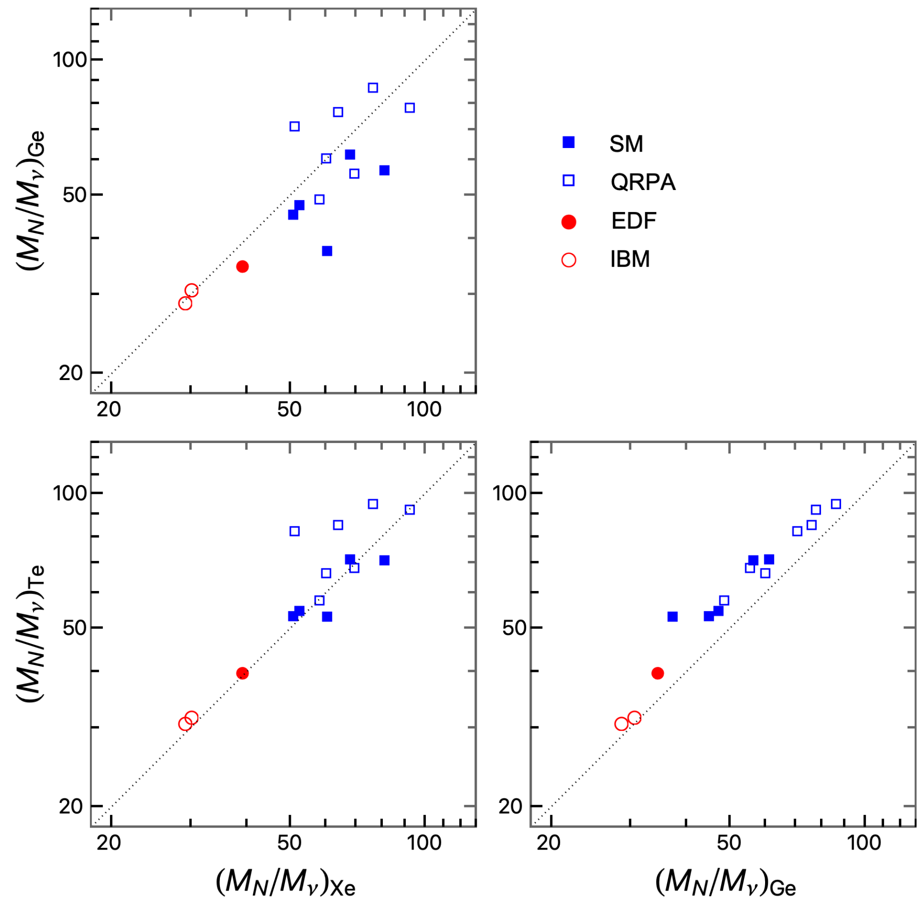
signal strength for non-interfering exchange of ν_k and N_h

$$\begin{bmatrix} S_i G_i^{-1} \\ S_j G_j^{-1} \end{bmatrix} = \begin{bmatrix} M_{\nu,i}^2 & M_{N,i}^2 \\ M_{\nu,j}^2 & M_{N,j}^2 \end{bmatrix} \begin{bmatrix} m_\nu^2 \\ m_N^2 \end{bmatrix}$$

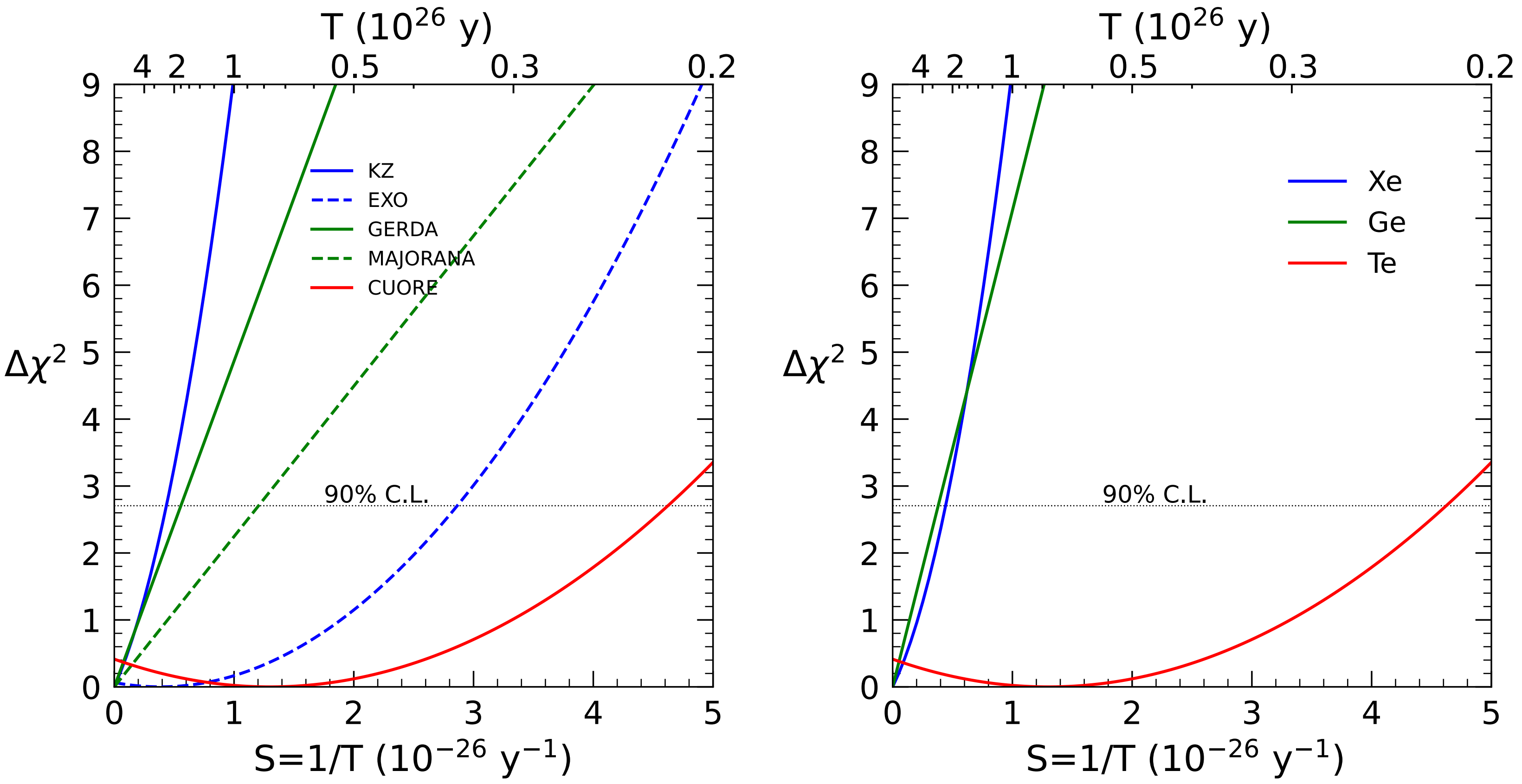
In principle the measurement of two S_i would be suffiient to determine m_ν and M_N

Provided that $$\frac{M_{N,i}}{M_{\nu_i}} \neq \frac{M_{N,j}}{M_{\nu_j}} \;.$$

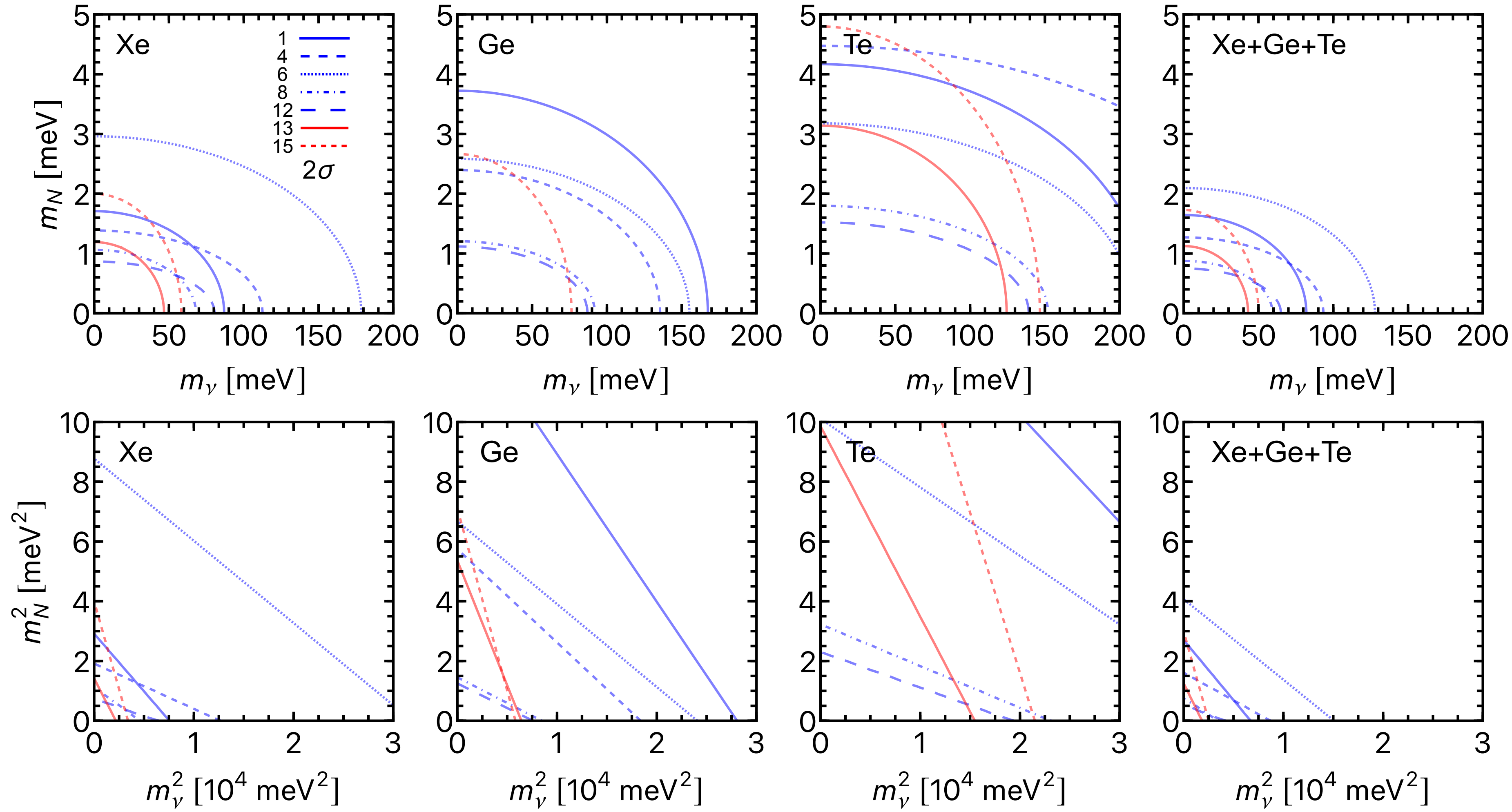
Degenaracy analysis



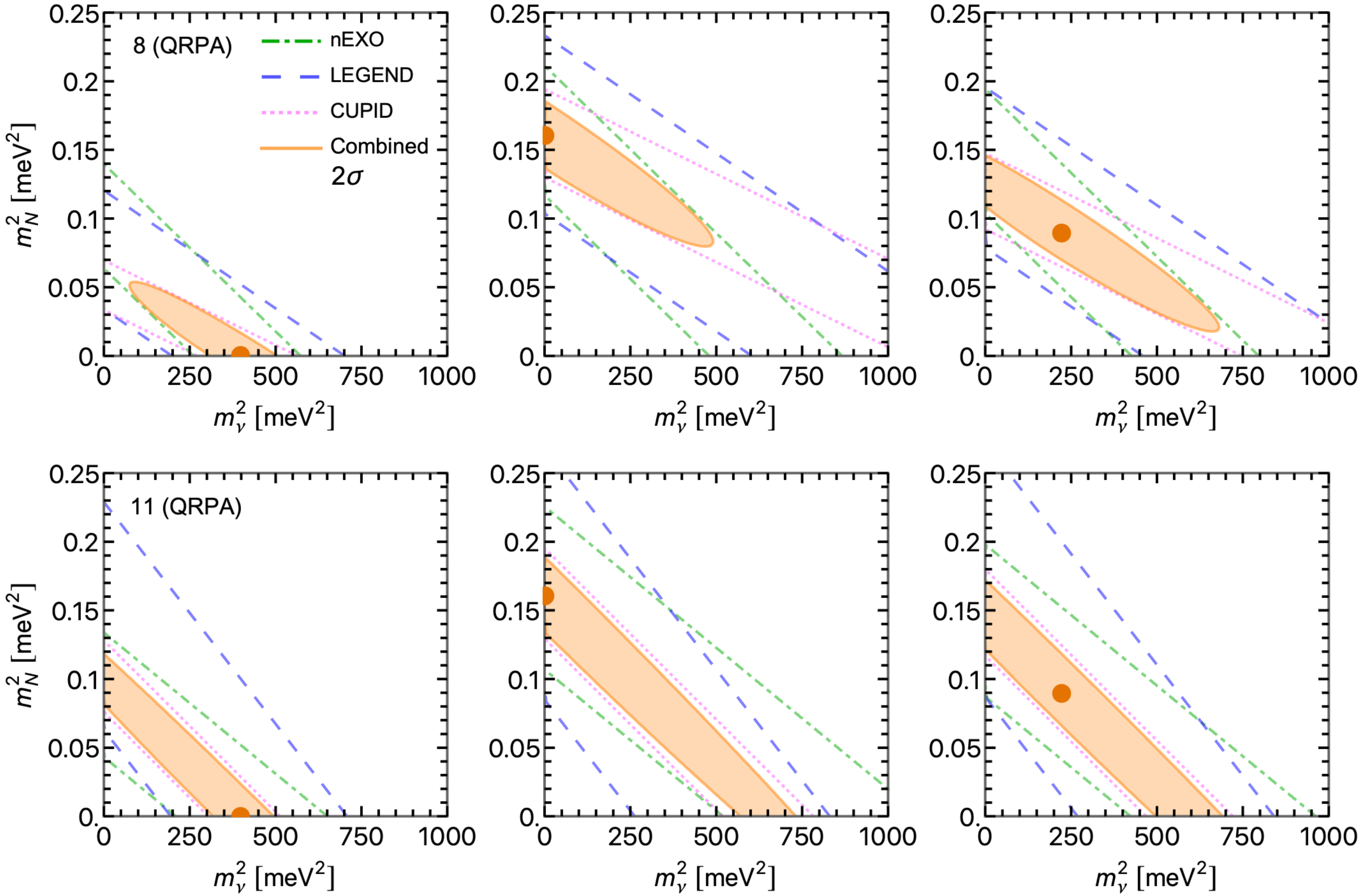
Current bounds on the signal strengths



Present joint bounds on light and heavy effective majorana masses



Fit to prospective data from ton-scale experiments



Complementarity between neutrinoless double beta decay and collider searches for heavy neutrinos in composite-fermion models

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(Dated: November 2, 2021)

Composite-fermion models predict excited quarks and leptons with mass scales which can potentially be observed at high-energy colliders like the LHC; the most recent exclusion limits from the CMS and ATLAS Collaborations corner excited-fermion masses and the compositeness scale to the multi-TeV range. At the same time, hypothetical composite Majorana neutrinos would lead to observable effects in neutrinoless double beta decay ($0\nu\beta\beta$) experiments. In this work, we show that the current composite-neutrino exclusion limit $M_N > 4.6$ TeV, as extracted from direct searches at the LHC, can indeed be further improved to $M_N > 8.8$ TeV by including the bound on the nuclear transition $^{136}\mathrm{Xe} \to {}^{136}\mathrm{Ba} + 2\,\mathrm{e}^-$. Looking ahead, the forthcoming HL-LHC will allow probing a larger portion of the parameter-space, nevertheless, it will still benefit from the complementary limit provided by $0\nu\beta\beta$ future detectors to explore composite-neutrino masses up to 12.6 TeV.

Basic formulae

Gauge term

$$\mathcal{L}_{\mathrm{GI}} = \frac{g f}{\sqrt{2}\Lambda} \bar{N} \, \sigma_{\mu\nu} \, \ell_L \, \partial^\nu \, W^\mu \; + h.\,c\,,$$

Contact term

$$\mathcal{L}_{\mathrm{CI}} = \frac{\eta_L \, g_*^2}{\Lambda^2} \left(\sum_{q,q'} \bar{q}_L \gamma^\mu q'_L \right) \bar{N}_L \gamma_\mu \ell_L + h.\,c.\,,$$

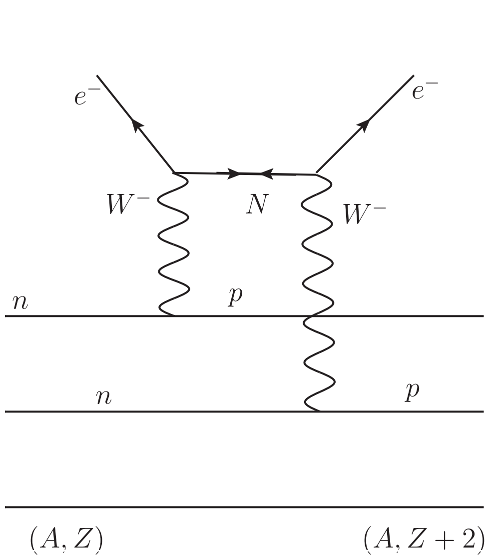
Lower bound on $T_{1/2}$

$$T_{1/2} \;(90\%\,\mathrm{C.\,L.}) > \begin{cases} 1.8 \times 10^{26}\mathrm{yr} & ({}^{76}\mathrm{Ge},\ [57]) \\ 1.07 \times 10^{26}\mathrm{yr} & ({}^{136}\mathrm{Xe},\ [60]) \end{cases}$$

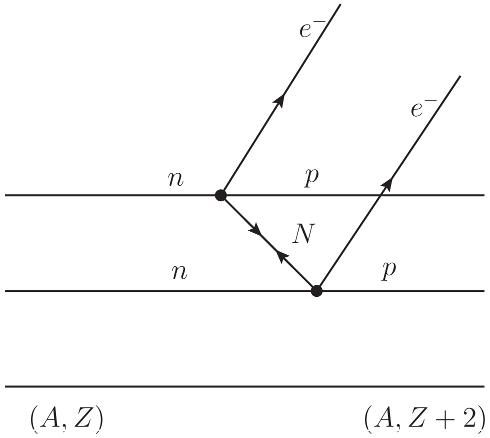
Lower bound on Λ

$$\Lambda \geq \frac{g_*}{2^{3/4}} \sqrt{\frac{\eta_L \, g_A}{G_F \cos\theta_c}} \left(\frac{m_p}{M_N} \right)^{\frac{1}{4}} \left(G_{01} \, |\mathcal{M}^{0N}|^2 \, T_{1/2}^{\mathrm{exp.}} \right)^{\frac{1}{8}}$$

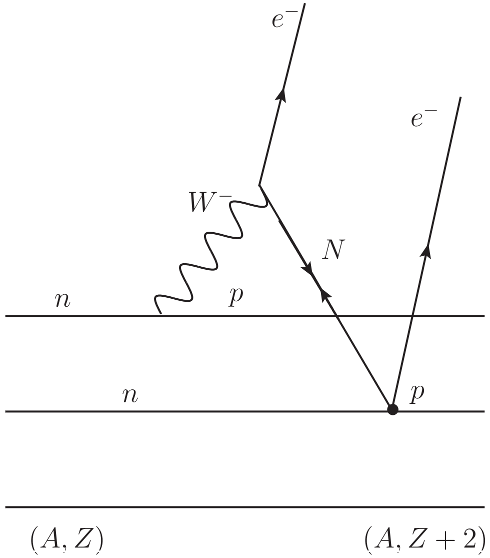
Diagrams involving a heavy composite-neutrino contributing to 0ν2β decay



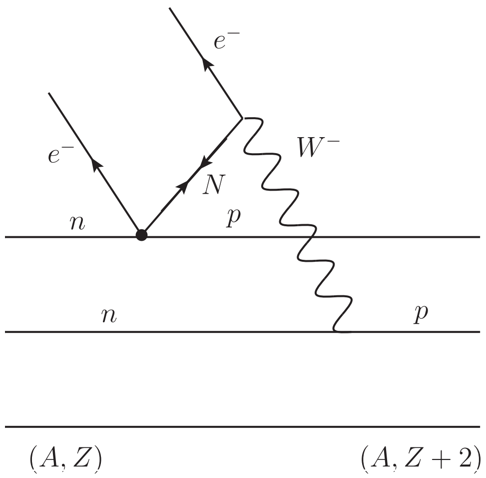
(a) Gauge interactions.



(b) Contact interactions.

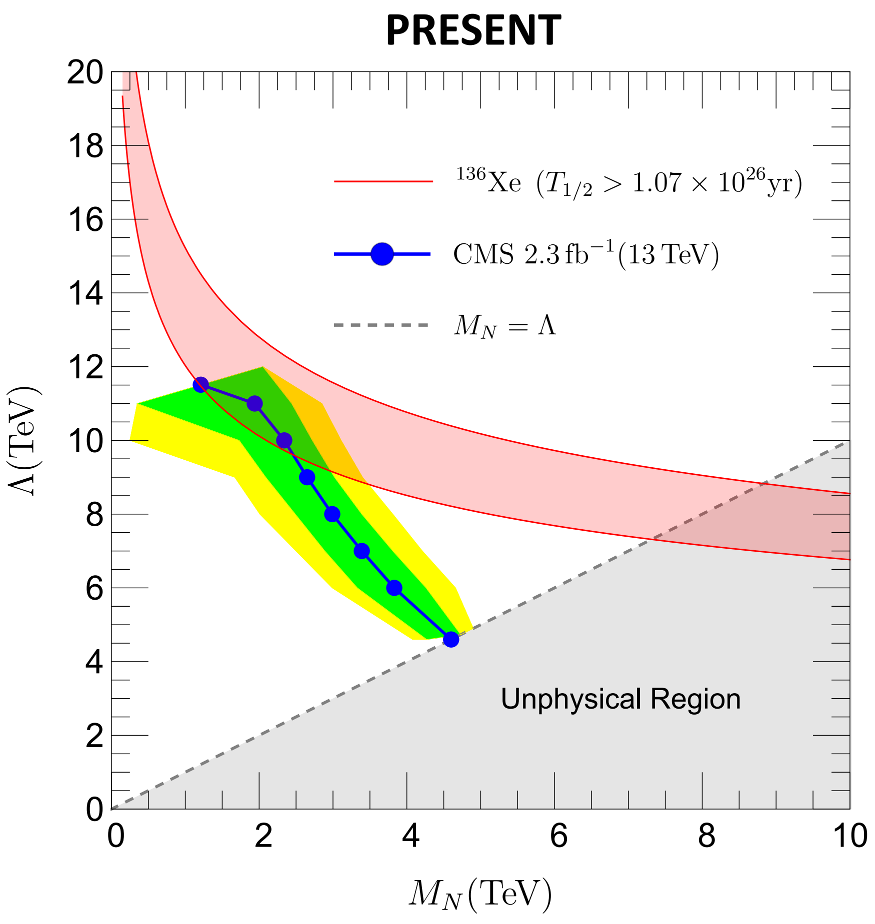


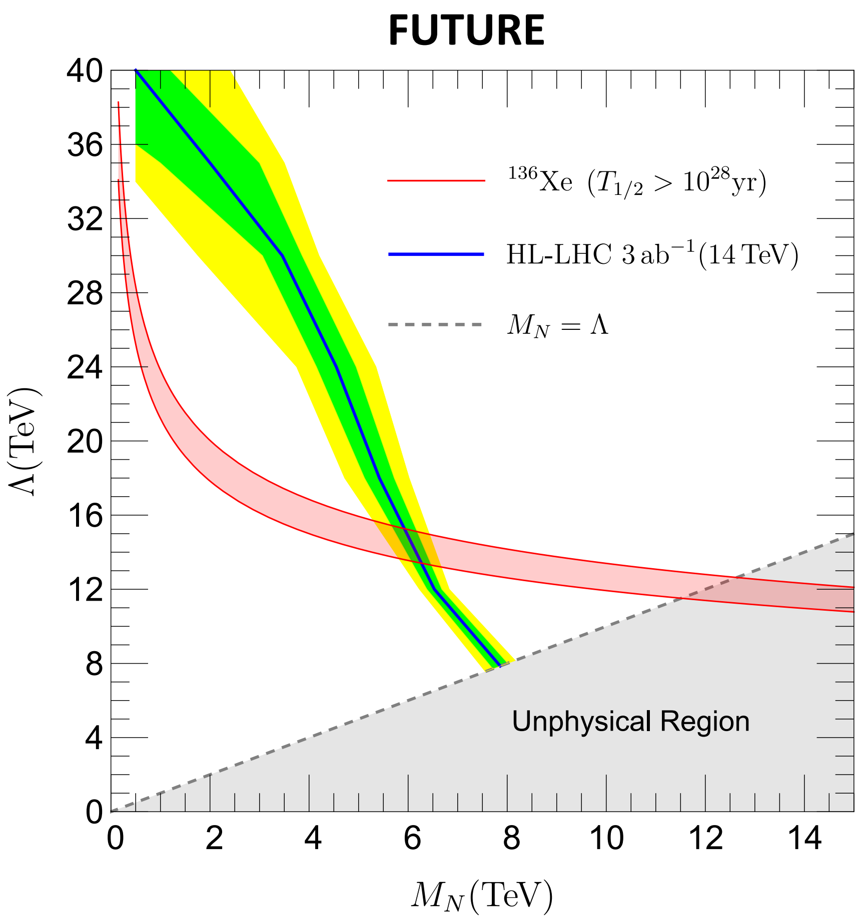
(c) Mixed term I.



(d) Mixed term II.

Lower bounds on the compositness scale Λ as a funcion of M_N





Interpretation of NOνA and T2K data in the presence of a light sterile neutrino

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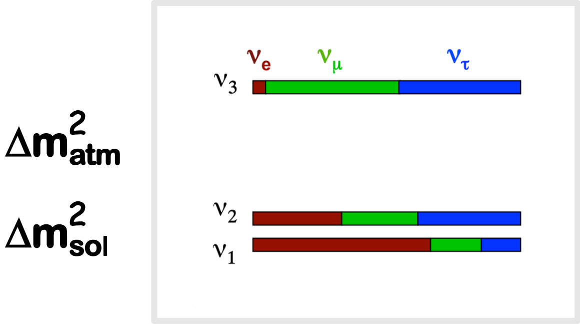
We study in detail the impact of a light sterile neutrino in the interpretation of the latest data of the long baseline experiments NOνA and T2K, assessing the robustness/fragility of the estimates of the standard 3-flavor parameters with respect to the perturbations induced in the 3+1 scheme. We find that all the basic features of the 3-flavor analysis, including the weak indication ($\sim$1.4σ) in favor of the inverted neutrino mass ordering, the preference for values of the CP-phase $\delta_{13} \sim 1.2\pi$, and the substantial degeneracy of the two octants of θ_{23}, all remain basically unaltered in the 4-flavor scheme. Our analysis also demonstrates that it is possible to attain some constraints on the new CP-phase δ_{14}. Finally, we point out that, differently from non-standard neutrino interactions, light sterile neutrinos are not capable to alleviate the tension recently emerged between NOνA and T2K in the appearance channel.

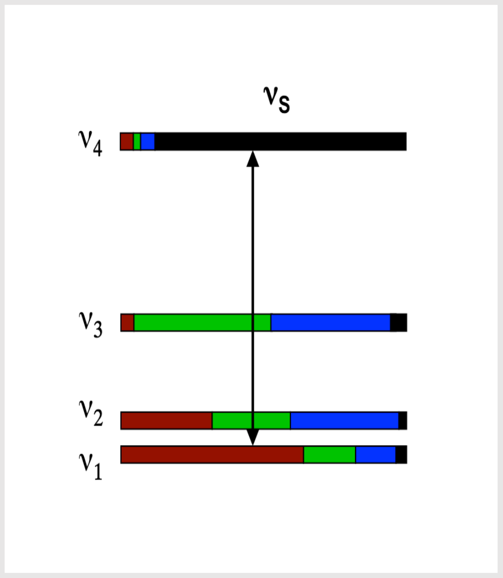
Submitted to New Journal of Physics

How to enlarge the 3-flavor scheme

3ν scheme



3+1 scheme



$|U_{s4}| \sim 1$

$\Delta m^2_{14} \sim 1\ eV^2$

At LBL the effective 2-flavor SBL description is no more valid and calculations should be done in the 3+1 (or 3+N_s) scheme

Mixing Matrix in the 3+1 scheme

$$U = \tilde{R}_{34}\, R_{24}\, \tilde{R}_{14}\, \underbrace{R_{23}\, \tilde{R}_{13}\, R_{12}}_{3\nu}$$

$$R_{ij} = \begin{bmatrix} c_{ij} & s_{ij} \\ -s_{ij} & c_{ij} \end{bmatrix}$$

$$\tilde{R}_{ij} = \begin{bmatrix} c_{ij} & \tilde{s}_{ij} \\ -\tilde{s}^*_{ij} & c_{ij} \end{bmatrix}$$

$$\begin{aligned} s_{ij} &= \sin\theta_{ij} \\ c_{ij} &= \cos\theta_{ij} \\ \tilde{s}_{ij} &= s_{ij} e^{-i\delta_{ij}} \end{aligned}$$

3ν $\left\{ \begin{array}{l} \text{3 mixing angles} \\ \text{1 Dirac phase} \\ \text{2 Majorana phases} \end{array} \right.$

3+1 $\left\{ \begin{array}{l} 6 \\ 3 \\ 3 \end{array} \right.$

3+N $\left\{ \begin{array}{l} 3+3N \\ 1+2N \\ 2+N \end{array} \right.$

In general, we have additional sources of CPV

A new interference term in the 3+1 scheme

N. Klop & A.P., PRD (2015)

- Δ_{14} >> 1 : fast oscillations are averaged out

- But interference of Δ_{14} & Δ_{13} survives and is observable

$$P_{\mu e}^{4\nu} \simeq P^{\rm ATM} + P_{\rm I}^{\rm INT} + P_{\rm II}^{\rm INT}$$

$s_{13} \sim s_{14} \sim s_{24} \sim 0.15 \sim \varepsilon$

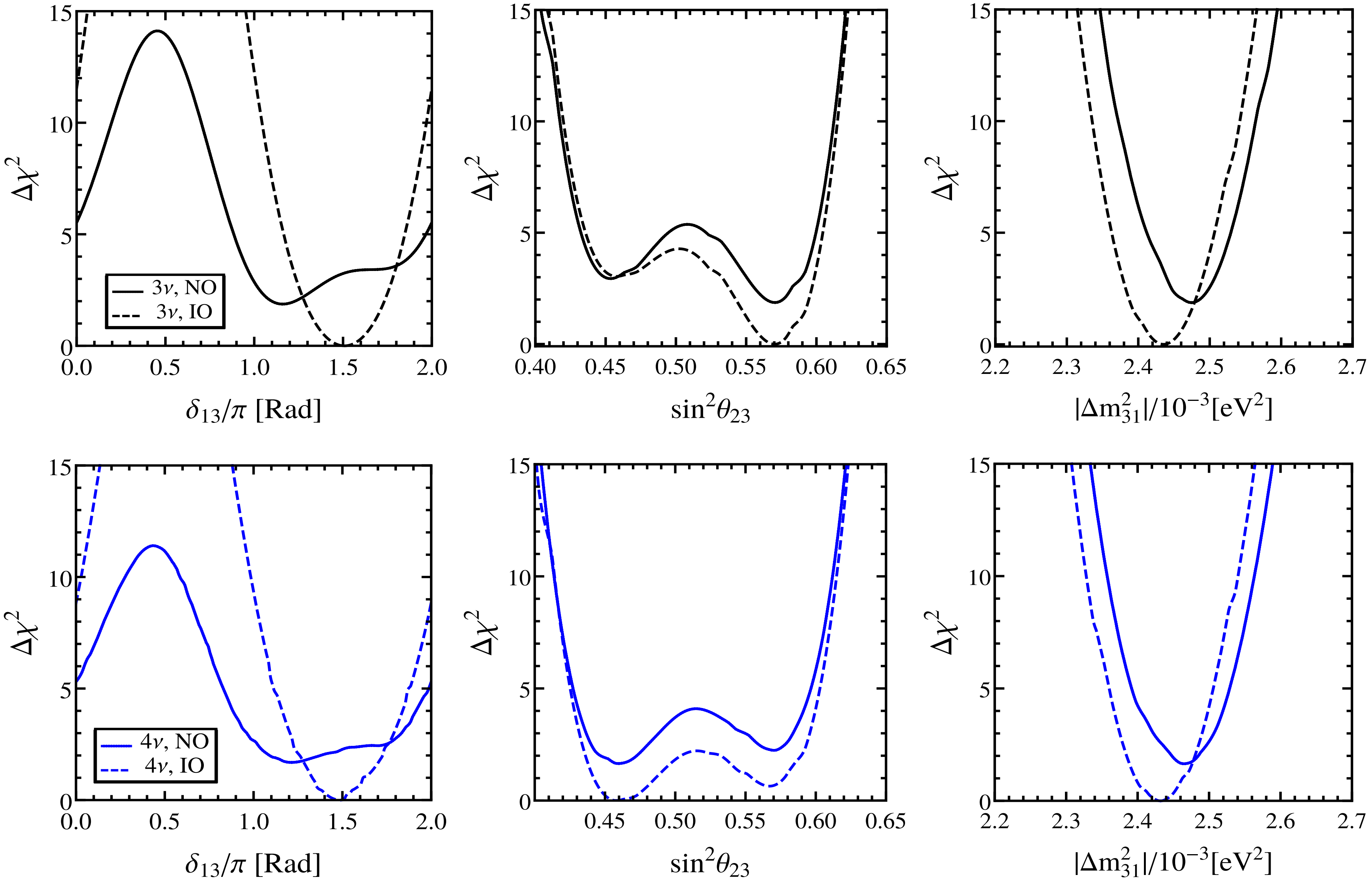
$\alpha = \delta m^2/\Delta m^2 \sim 0.03 \sim \varepsilon^2$

$$\begin{cases} P^{\rm ATM} \simeq 4 s_{23}^2 s_{13}^2 \sin^2\Delta & \sim \varepsilon^2 \\ P_{\rm I}^{\rm INT} \simeq 8 s_{13} s_{23} c_{23} s_{12} c_{12} (\alpha\Delta) \sin\Delta \cos(\Delta + \delta_{13}) & \sim \varepsilon^3 \\ P_{\rm II}^{\rm INT} \simeq 4 s_{14} s_{24} s_{13} s_{23} \sin\Delta \sin(\Delta + \delta_{13} - \delta_{14}) & \sim \varepsilon^3 \end{cases}$$

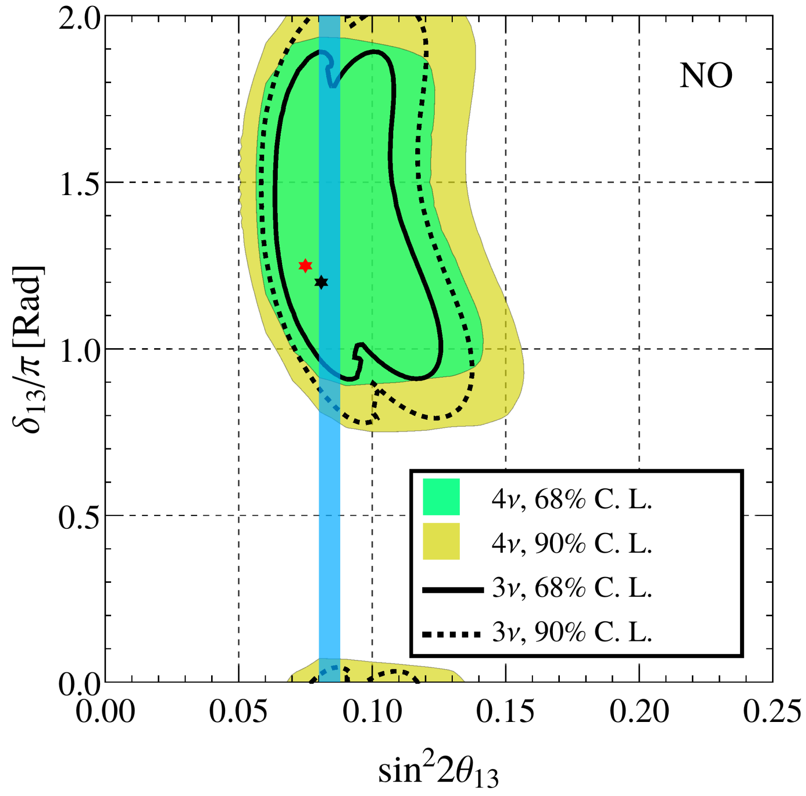
Sensitivity to the new CP-phase δ_{14}

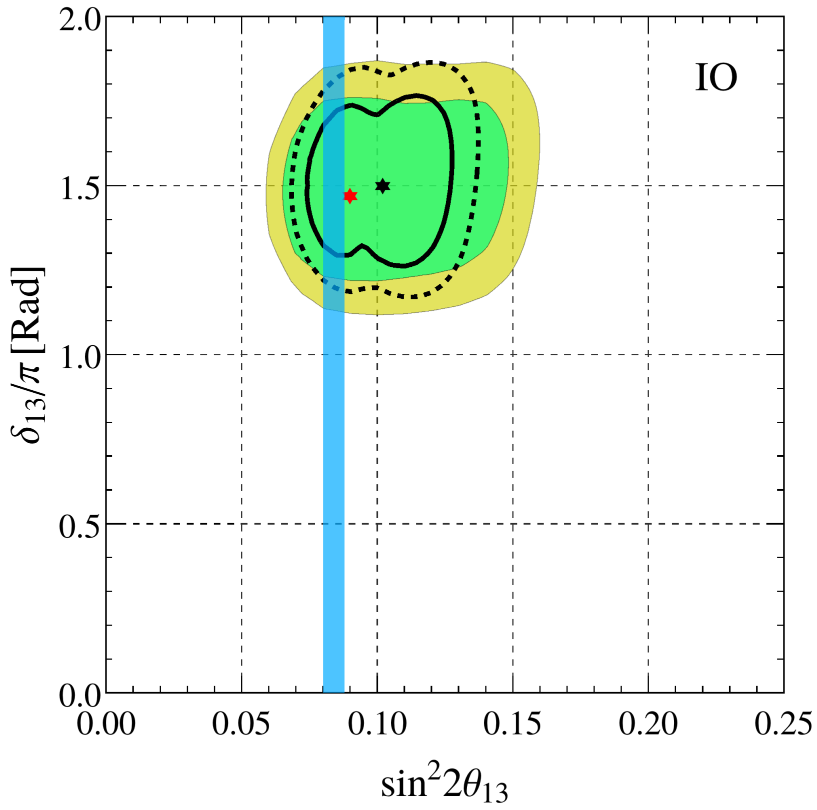
3ν

4ν

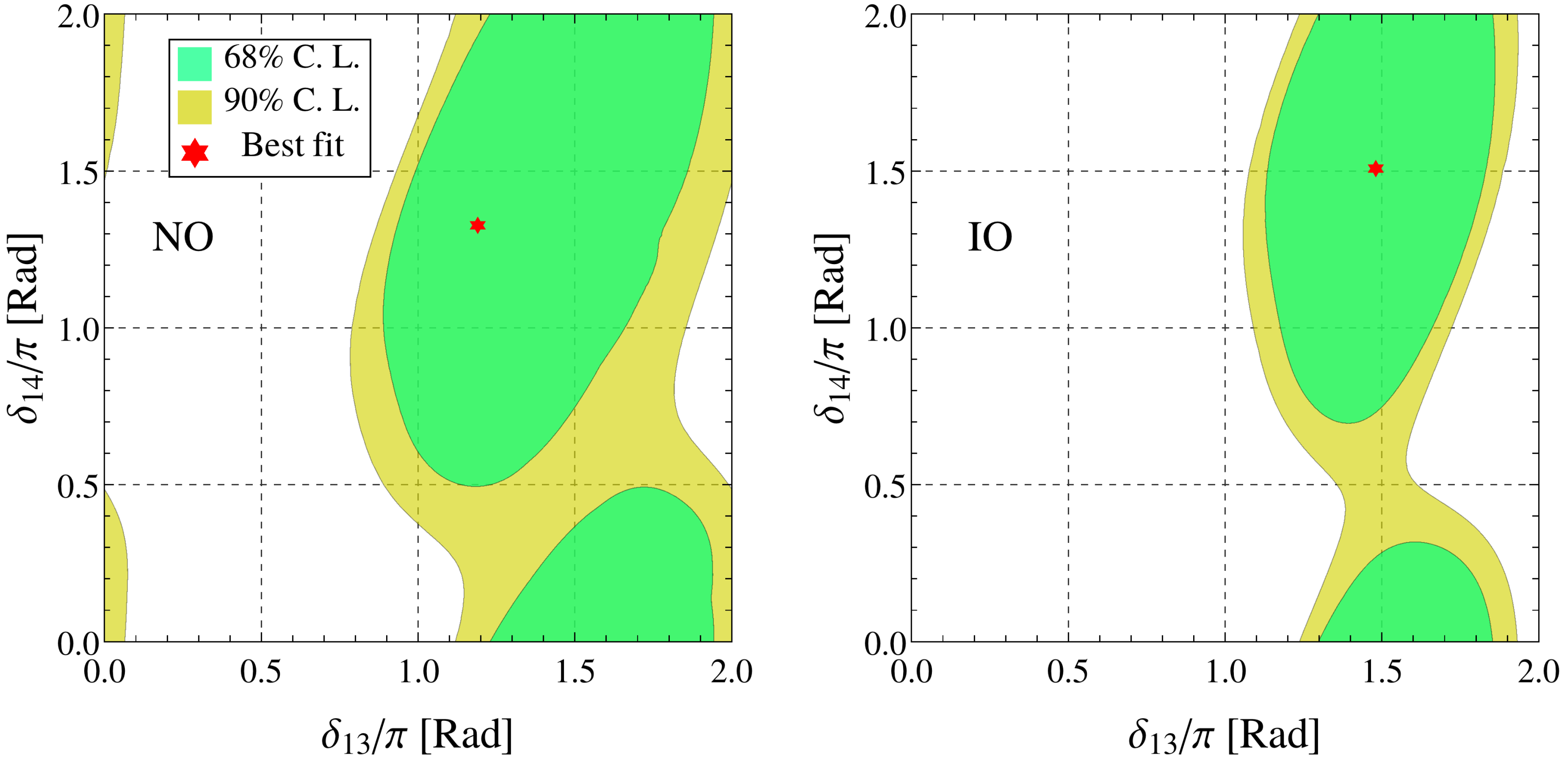

$\Delta\chi^2$
δ_{13}/π [Rad]
$\sin^2\theta_{23}$
$|\Delta m^2_{31}|/10^{-3}[\mathrm{eV}^2]$
3ν, NO
3ν, IO
4ν, NO
4ν, IO
0 5 10 15
0.0 0.5 1.0 1.5 2.0
0.40 0.45 0.50 0.55 0.60 0.65
2.2 2.3 2.4 2.5 2.6 2.7

Esitimates of θ_{13} and δ are stable





There is some sensitivity to the new CP phase δ_{14}



The Radiative Flavor Template at the LHC: g-2 and W-mass

Giacomo Cacciapaglia,[1,2,*] Antimo Cagnotta,[3,4,†] Roberta Calabrese,[3,4,‡] Francesco Carnevali,[3,4,§] Agostino De Iorio,[3,4,¶] Alberto Orso Maria Iorio,[3,4,**] Stefano Morisi,[3,4,††] and Francesco Sannino[3,4,5,6,‡‡]

Abstract

The Standard Model of particle physics and its description of nature have been recently challenged by a series of precision measurements performed via different accelerator machines. Statistically significant anomalies emerged when measuring the muon magnetic momentum, and very recently when deducing the mass of the W boson. Here we consider a radiative extension of the Standard Model devised to be sufficiently versatile to reconcile the various experimental results while further predicting the existence of new bosons and fermions with a mass spectrum in the TeV energy scale. The resulting spectrum is, therefore, within the energy reach of the proton-proton collisions at the LHC experiments at CERN.

The model investigated here allows us to interpolate between composite and elementary extensions of the Standard Model with an emphasis on a new modified Yukawa sector that is needed to accommodate the anomalies. Focusing on the radiative regime of the model, we introduce interesting search channels of immediate impact for the ATLAS and CMS experimental programs such as the associate production of Standard Model particles with either invisible or long-lived particles. We further show how to adapt earlier supersymmetry-motivated searchers of new physics to constrain the spectrum and couplings of the new scalars and fermions. Overall, the new physics template simultaneously accounts for the bulk of the observed experimental anomalies while suggesting a wide spectrum of experimental signatures relevant for the current LHC experiments.

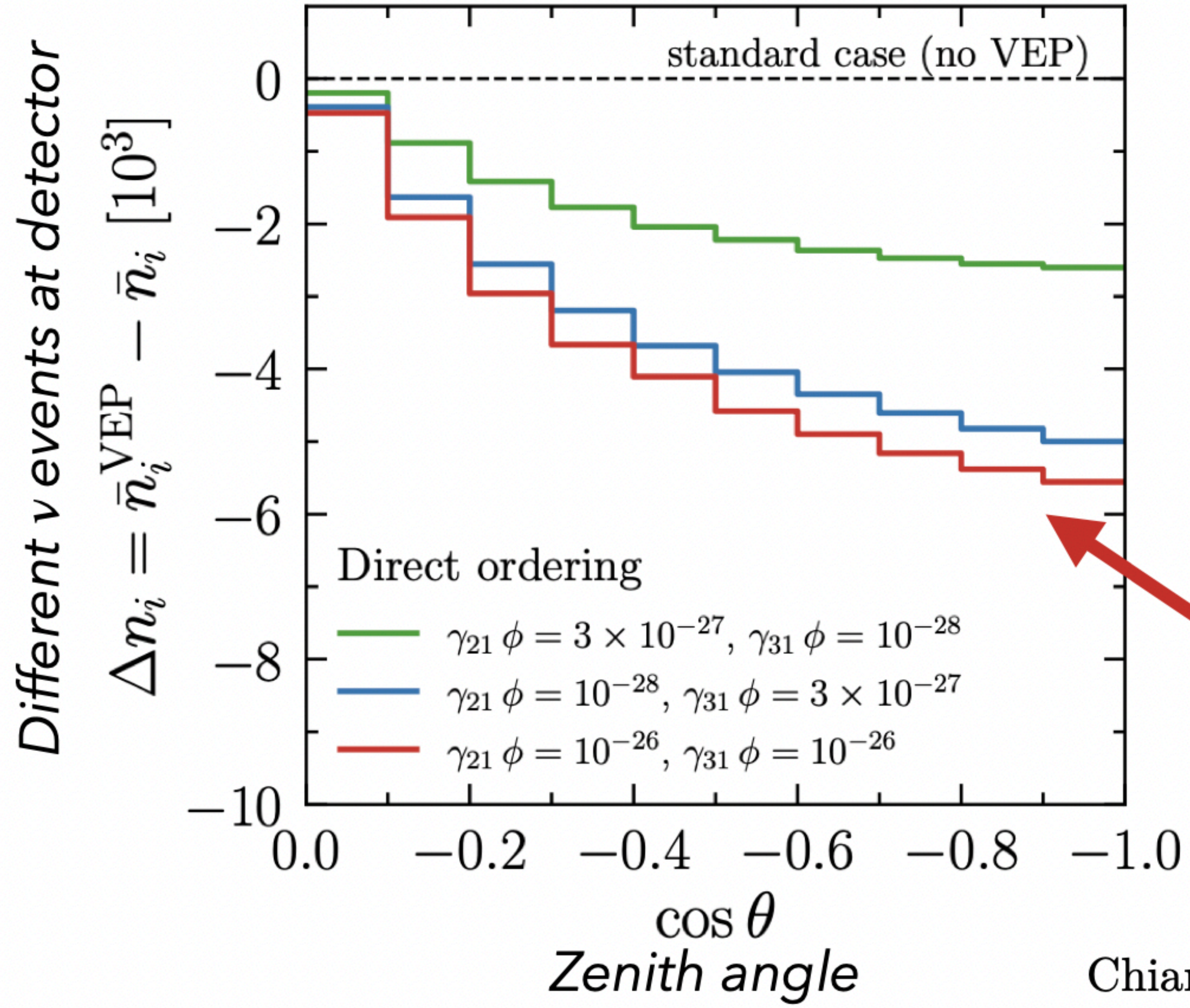
Violation of Equivalence Principle (VEP) in KM3NeT

It induces an energy shift between different combination of flavor ν eigenstates propagating in a **gravitational potential ϕ** ➜ Non-standard oscillations with a peculiar energy dependence!

propagation of muon atmospheric ν in Earth

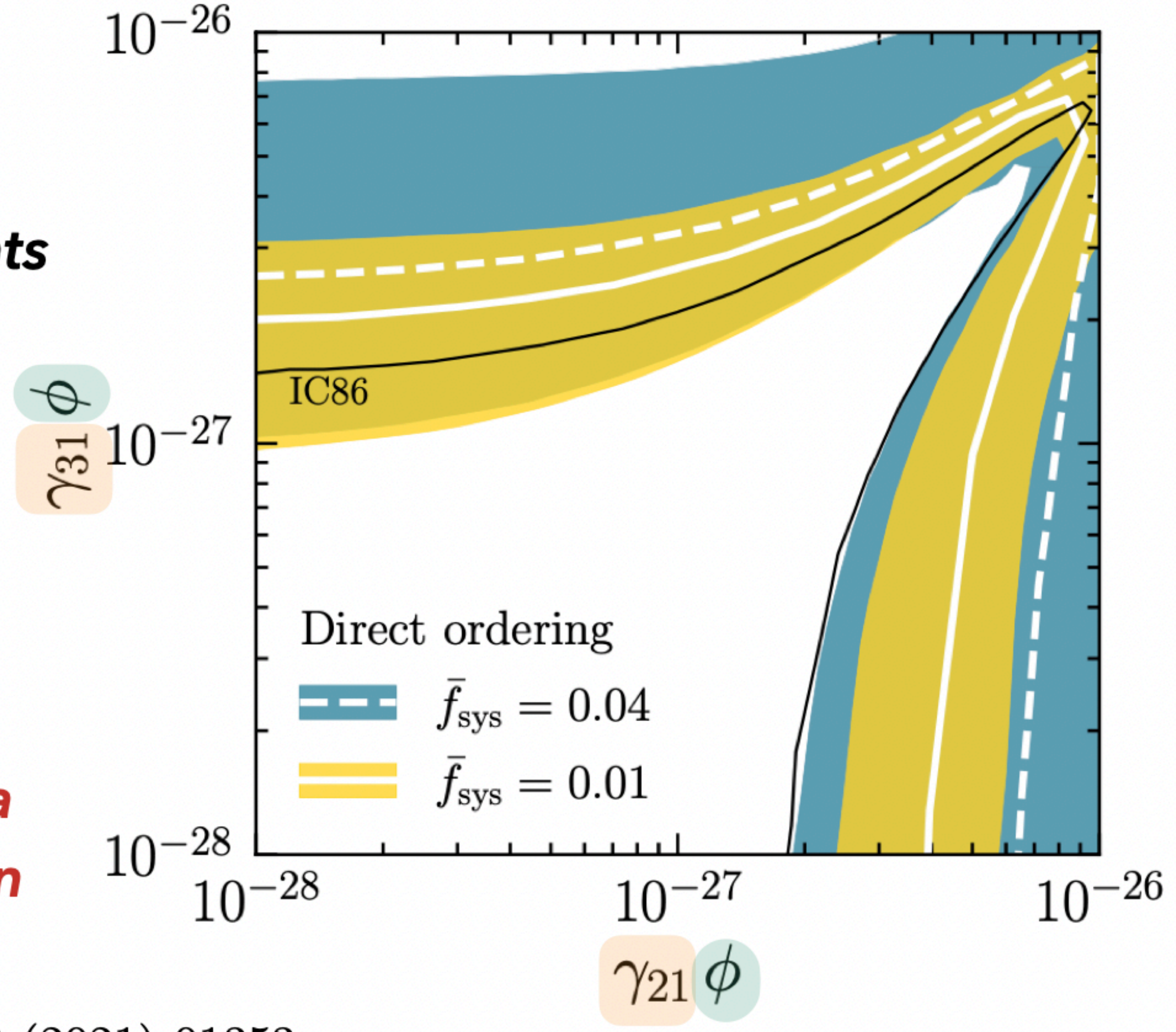
$$i\frac{\mathrm{d}\nu_\alpha}{\mathrm{d}l} = \text{standard} + 2E\phi\sum_{\alpha,\beta} U_{\beta a}U^*_{\alpha a}\gamma_\alpha\nu_\beta$$

Coupling to gravity



Depletion due to a longer propagation

Forecast constraints in KM3NeT ➜



Chianese et al., Symmetry 13 (2021) 01353

Review (2022):

Neutrino Flavor Conversions in High-Density Astrophysical and Cosmological Environments

Francesco Capozzi
Instituto de Física Corpuscular, Universidad de Valencia & CSIC,
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(Dated: February 2, 2022)

Despite being a well understood phenomenon in the context of current terrestrial experiments, neutrino flavor conversions in dense astrophysical environments probably represent one of the most challenging open problems in neutrino physics. Apart from being theoretically interesting, such a problem has several phenomenological implications in cosmology and in astrophysics, including the primordial nucleosynthesis of light elements abundance and other cosmological observables, nucleosynthesis of heavy nuclei and the explosion of massive stars. In this review, we briefly summarize the state of the art on this topic, focusing on three environments: early universe, core-collapse supernovae and compact binary mergers.

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EQUATIONS OF MOTIONS:

$$\boxed{\hat{L}[\varrho_{\mathbf{p},\mathbf{x}}] = -i[\Omega_{\mathbf{p},\mathbf{x}}, \varrho_{\mathbf{p},\mathbf{x}}] + \hat{C}[\varrho_{\mathbf{p},\mathbf{x}}]}$$

$$\hat{L}[\varrho_{\mathbf{p},\mathbf{x}}] = \partial_t \varrho_{\mathbf{p},\mathbf{x}} + \mathbf{v}_{\mathbf{p}} \cdot \nabla_{\mathbf{x}}\, \varrho_{\mathbf{p},\mathbf{x}} + \dot{\mathbf{p}} \cdot \nabla_{\mathbf{p}}\, \varrho_{\mathbf{p},\mathbf{x}},$$

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EARLY UNIVERSE: $\partial_t \to \partial_t - Hp\,\partial_{\mathbf{p}}$

Active-sterile oscillations; non zero neutrino-antineutrino asymmetry; eV, keV, MeV sterile neutrinos; Secret interactions….

CORE-COLLAPSE SUPERNOVAE

$$\Omega^{\nu\nu}_{\mathbf{p},\mathbf{x}} = \sqrt{2}G_F \int \frac{\mathrm{d}^3\mathbf{q}}{(2\pi)^3} (\varrho_{\mathbf{q},\mathbf{x}} - \bar{\varrho}_{\mathbf{q},\mathbf{x}})(1 - \mathbf{q}\cdot\mathbf{p})$$

MSW-resonance, collective effects, explosion mechanism, physics of SN…

Massive sterile neutrinos in the early universe: From thermal decoupling to cosmological constraints

Mastrototaro, Serpico, Mirizzi, Saviano (2021)

$\boxed{10 \text{ MeV} \lesssim m_s \lesssim m_\pi \sim 135 \text{ MeV}}$: thermally produced in the early universe in collisional processes involving active neutrinos, and freezing out after the QCD phase transition.

Decay Process
$\nu_s \to \nu_\alpha + \bar{\nu}_\alpha + \nu_\alpha$
$\nu_s \to \nu_\alpha + \nu_\beta + \bar{\nu}_\beta$
$\nu_s \to \nu_\alpha + e^+ + e^-$

extra neutrino radiation and entropy production

constraints on the mixing angles and/or lifetimes using the N_{eff} and Yp observables.

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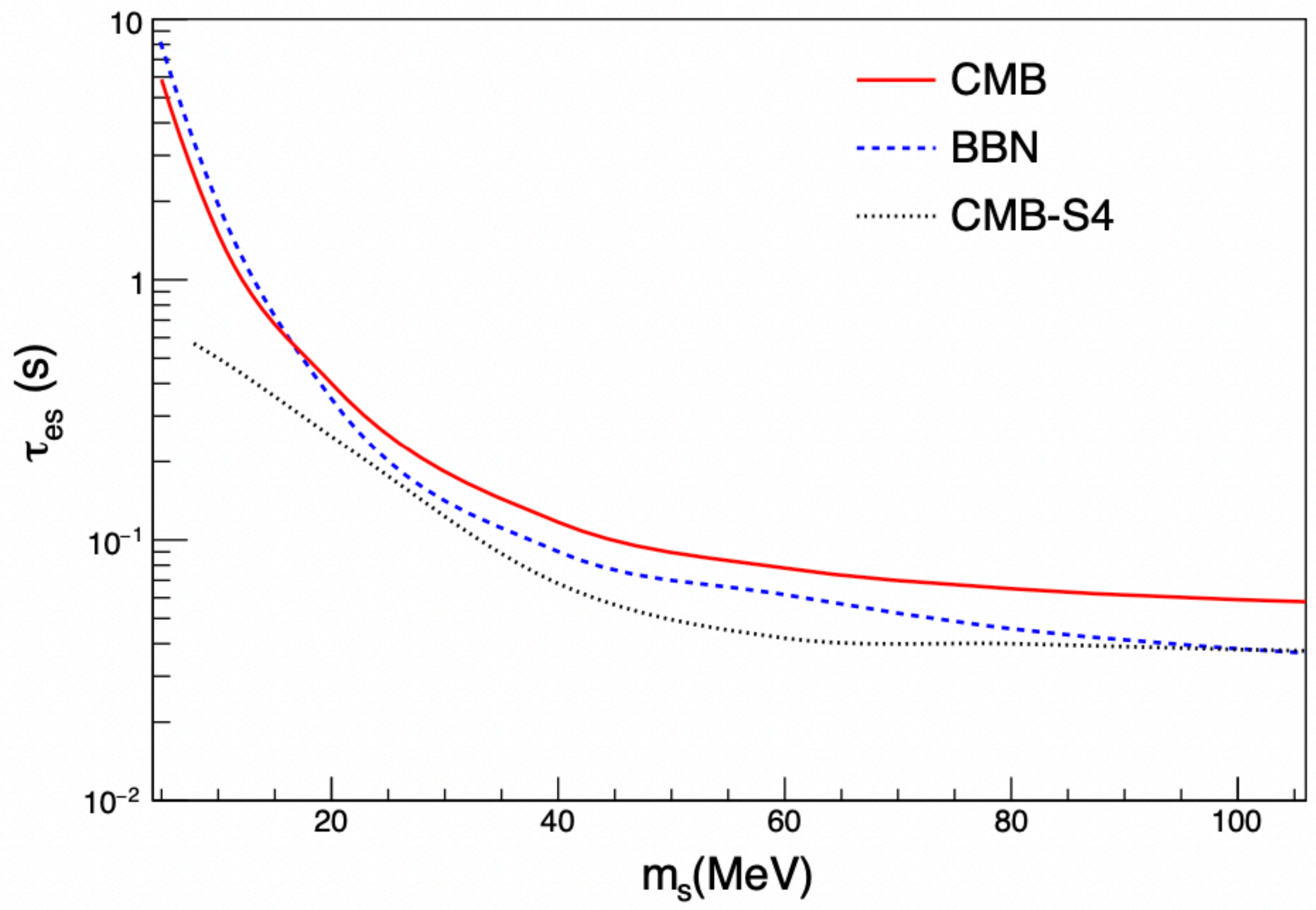
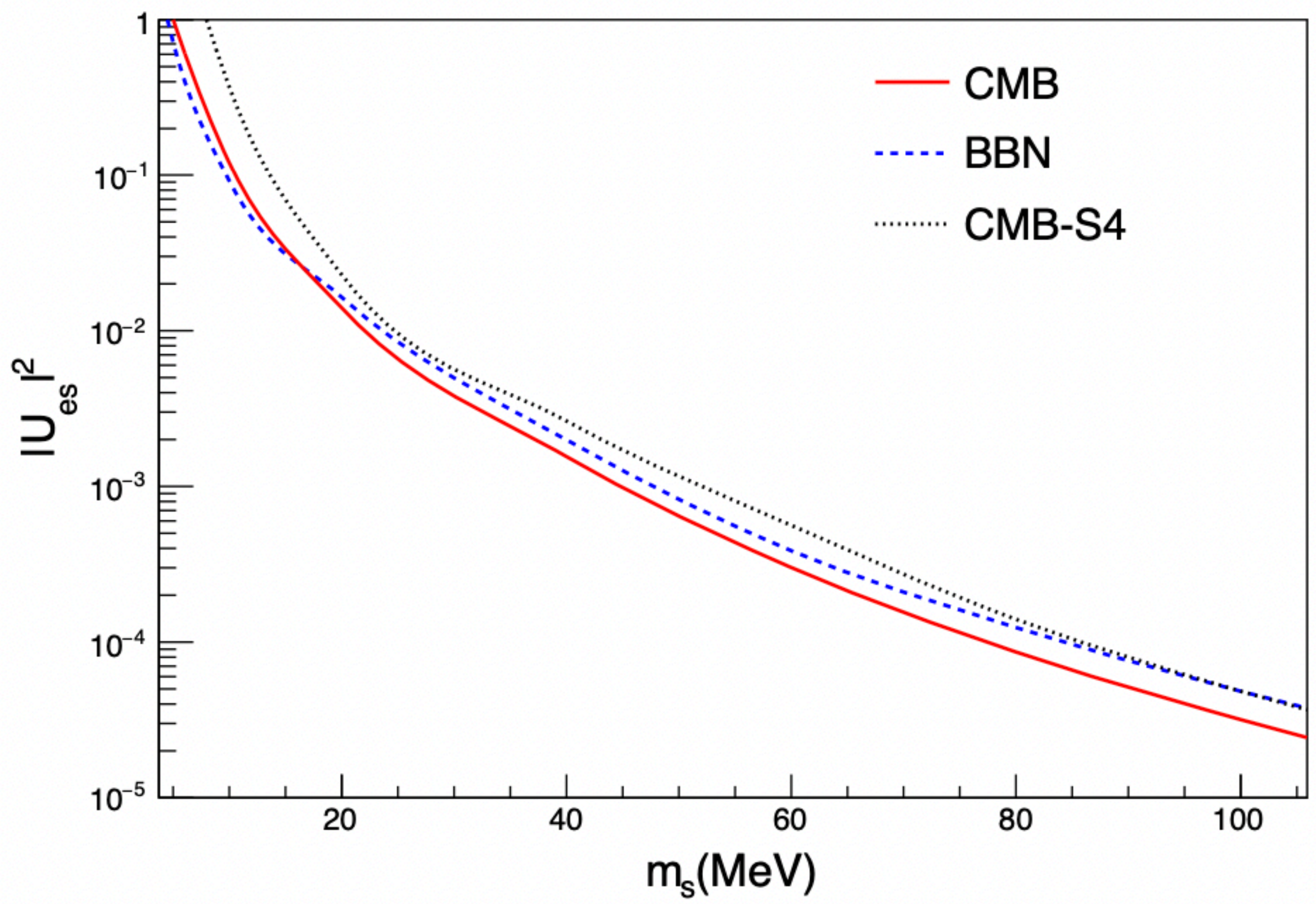


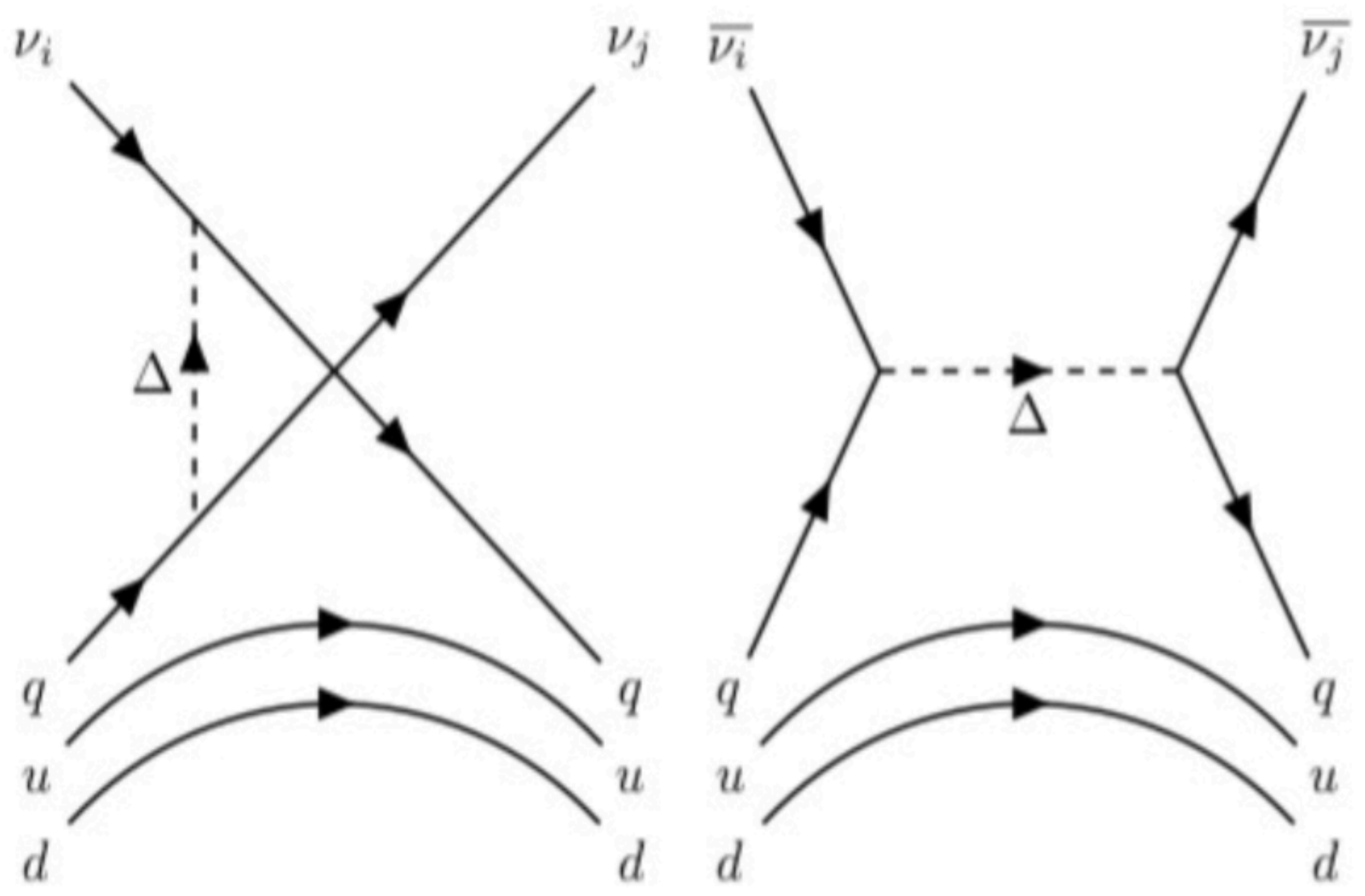


Talk by Roberta

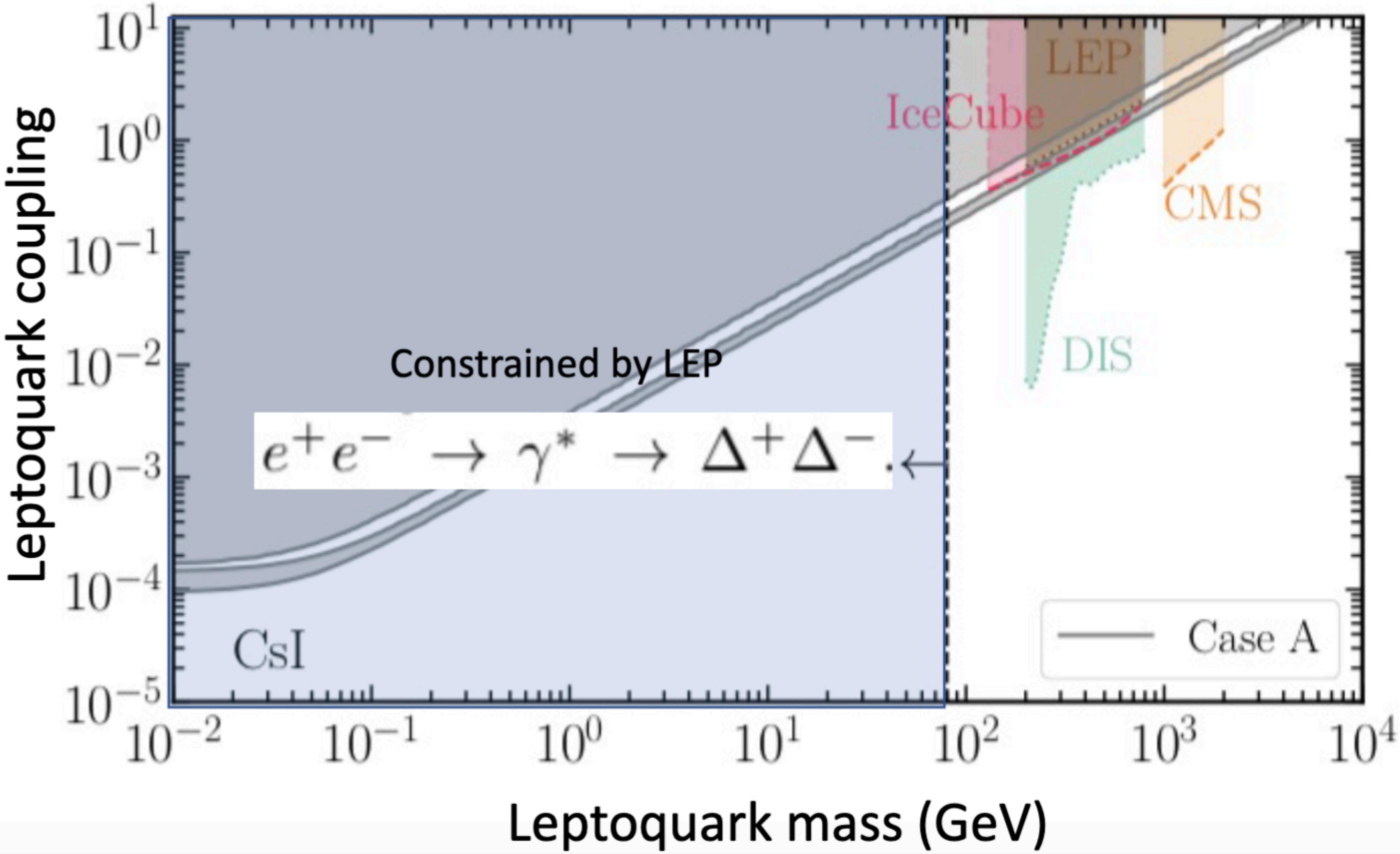
Constraining scalar leptoquarks using COHERENT data,

Calabrese, Gunn, Miele, Morisi, Roy, Santorelli, PRD 107 (2023)

Leptoquarks are expected to induce proton decay but this is not always true, like for instance for leptoquarks with hypercharge 7/6 or 1/6 (so it is possible to consider light mass range)



Leptoquark can mediate COHERENT scattering

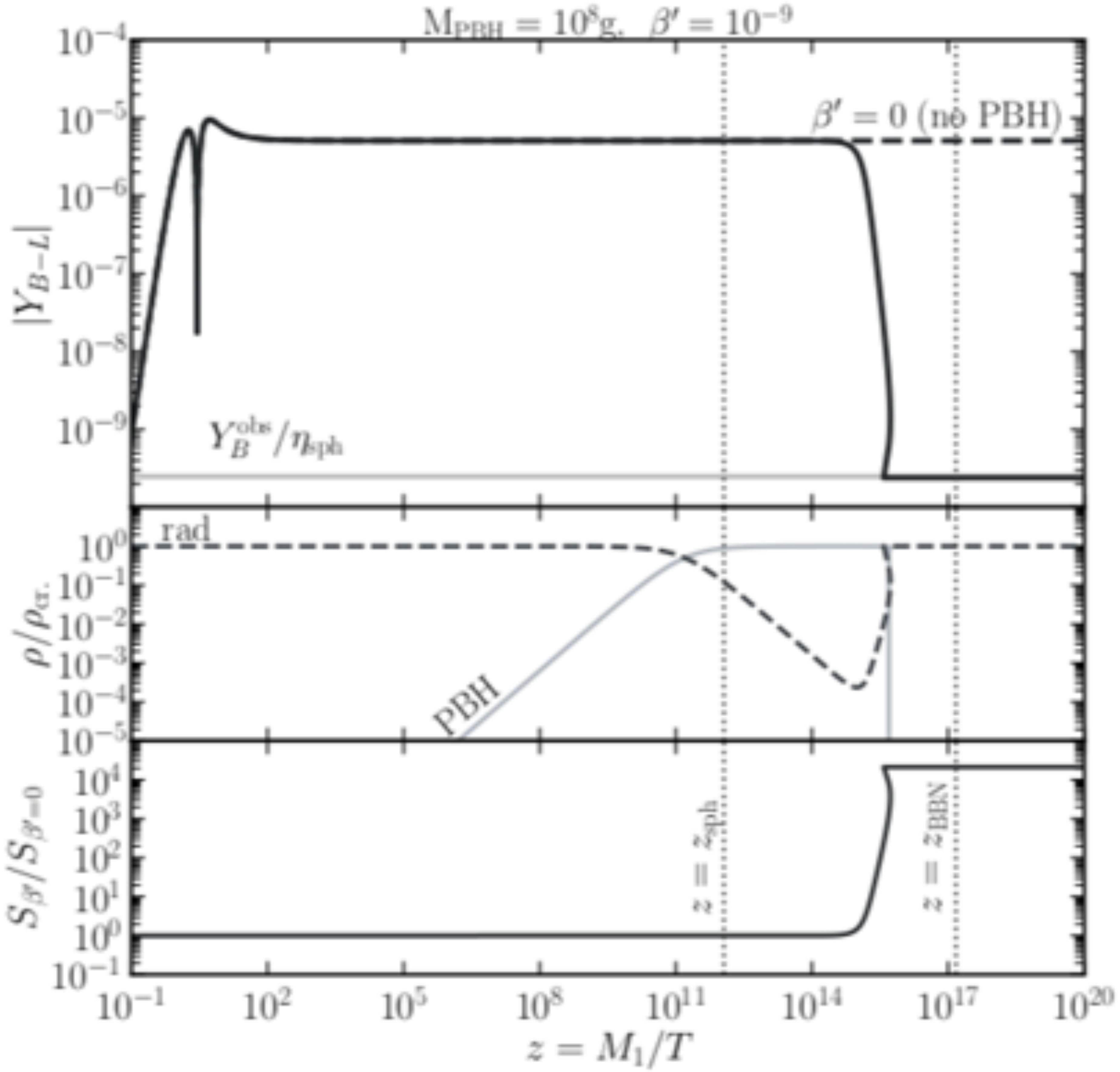


Talk by Jacob

Limits on light primordial black holes from high-scale leptogenesis,

Calabrese, Chianese, Gunn, Miele, Morisi, Saviano, 2305.13369 , PRD 107 (2023)

Evaporation of light primordial black holes [10^6 - 10^9] g can modify the production of the baryon asymmetry of the Universe through high-scale leptogenesis via entropy injection in the primordial plasma after the sphaleron freeze-out.



Mutual exclusion limits between primordial black holes and high- scale leptogenesis. Interplay between the upper bound on the initial abundance of primordial black holes and the active neutrino mass scale