Neutrino Physics - Theory

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Conselleria d'Educació, Investigació, Cultura i Esport

Lecture 1

- Historical introduction to neutrino physics

Neutrinos in the SM

- Neutrino interactions
- Neutrino mass in the SM

Neutrino oscillations

- First evidences and discovery
- Flavor oscillations in vacuum
- Flavor oscillations in matter

Lecture 2

Neutrino masses

- Current limits
- Neutrino mass models

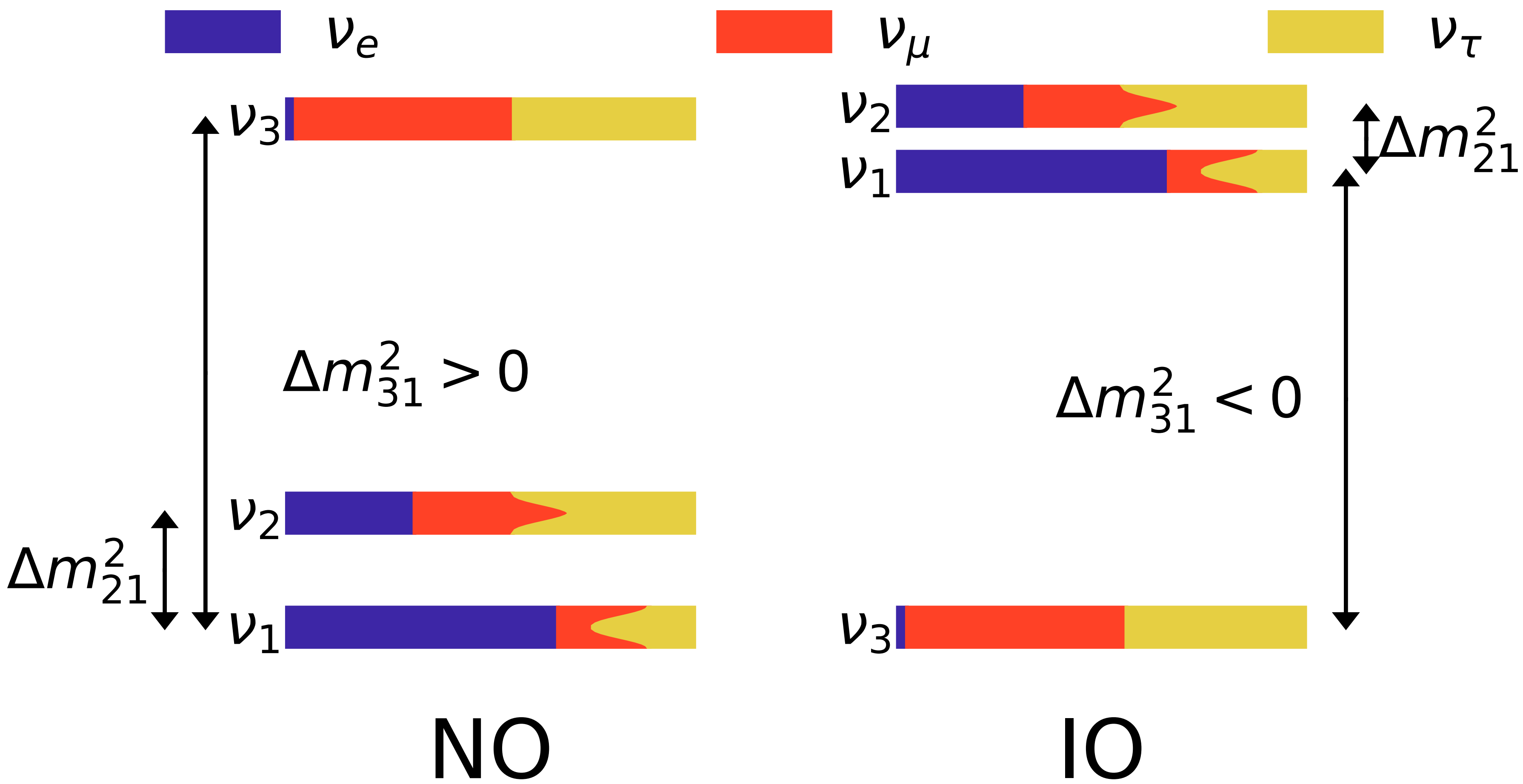
Neutrino physics BSM

- Light sterile neutrinos
- Non-unitary neutrino mixing
- Non-standard interactions
- BSM searches with CEvNS

Neutrino masses: bounds and models

Are neutrinos massive?

- In the SM neutrinos are massless
- From oscillations we know that (at least 2) neutrinos do have mass!!



- What about the absolute mass scale? Do we have information?

Sensitivity to neutrino mass

Neutrino oscillations

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

$$m_\nu \geq 0.05\,\mathrm{eV}$$

Cosmology

$$\sum m_i + \text{light d.o.f.}$$

Beta decay kinematics

$$m^2_\beta = \sum |U_{ei}|^2\, m^2_i$$

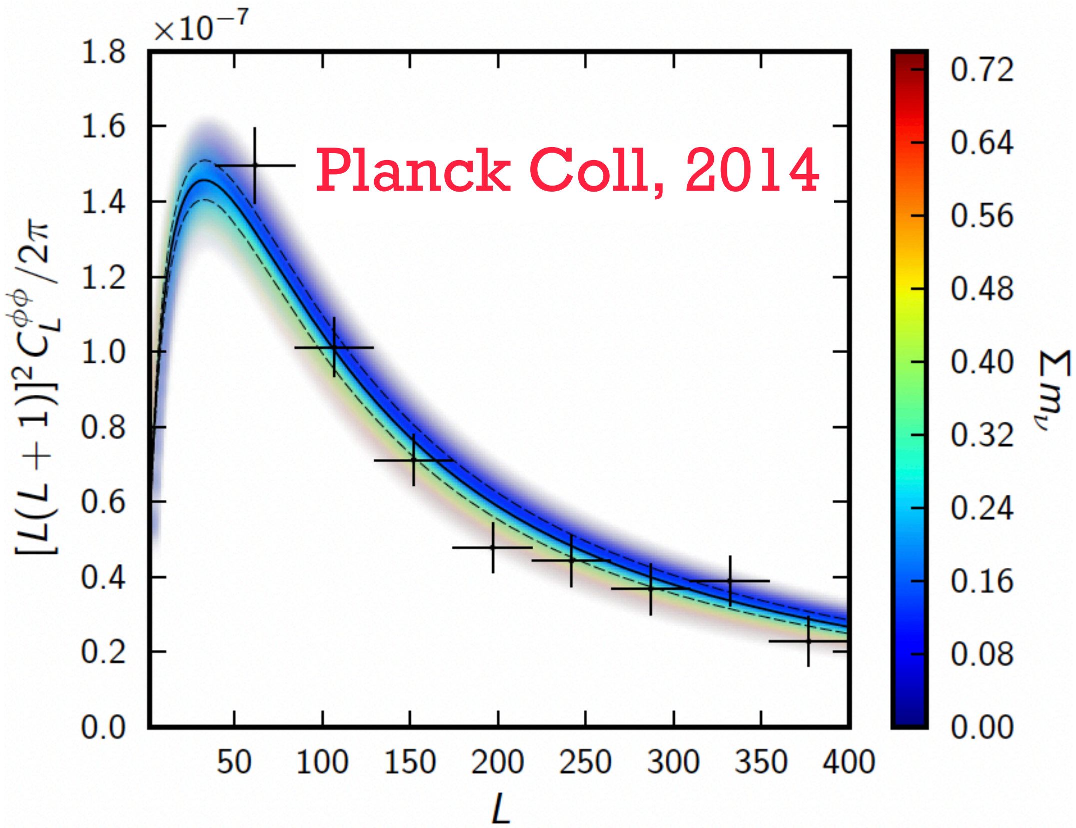
Neutrinoless 2β decay

$$m_{\beta\beta} = \left|\sum U^2_{ei} m_i\right|$$

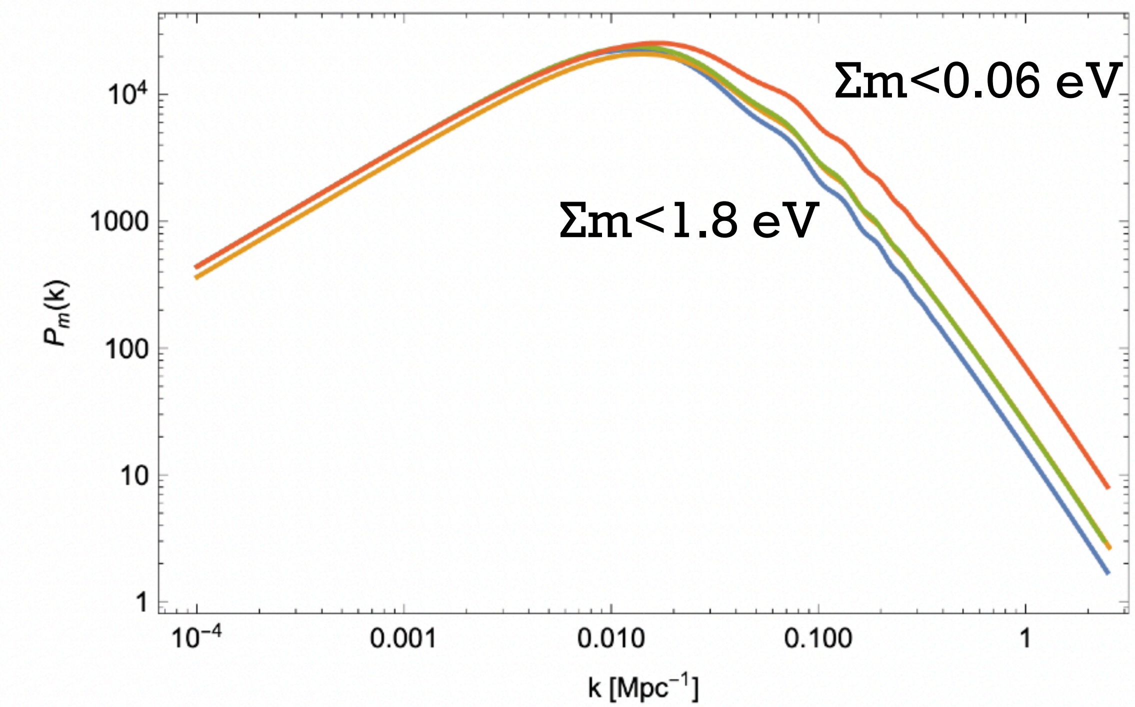
Neutrino mass in cosmology

✦ Neutrino masses may affect cosmological observables:

CMB anisotropies and lensing



Large Scale Structure formation



Lattanzi and Gerbino, Front.Phys 2018

✦ Fit ΛCDM model + experimental data (95% C.L.)

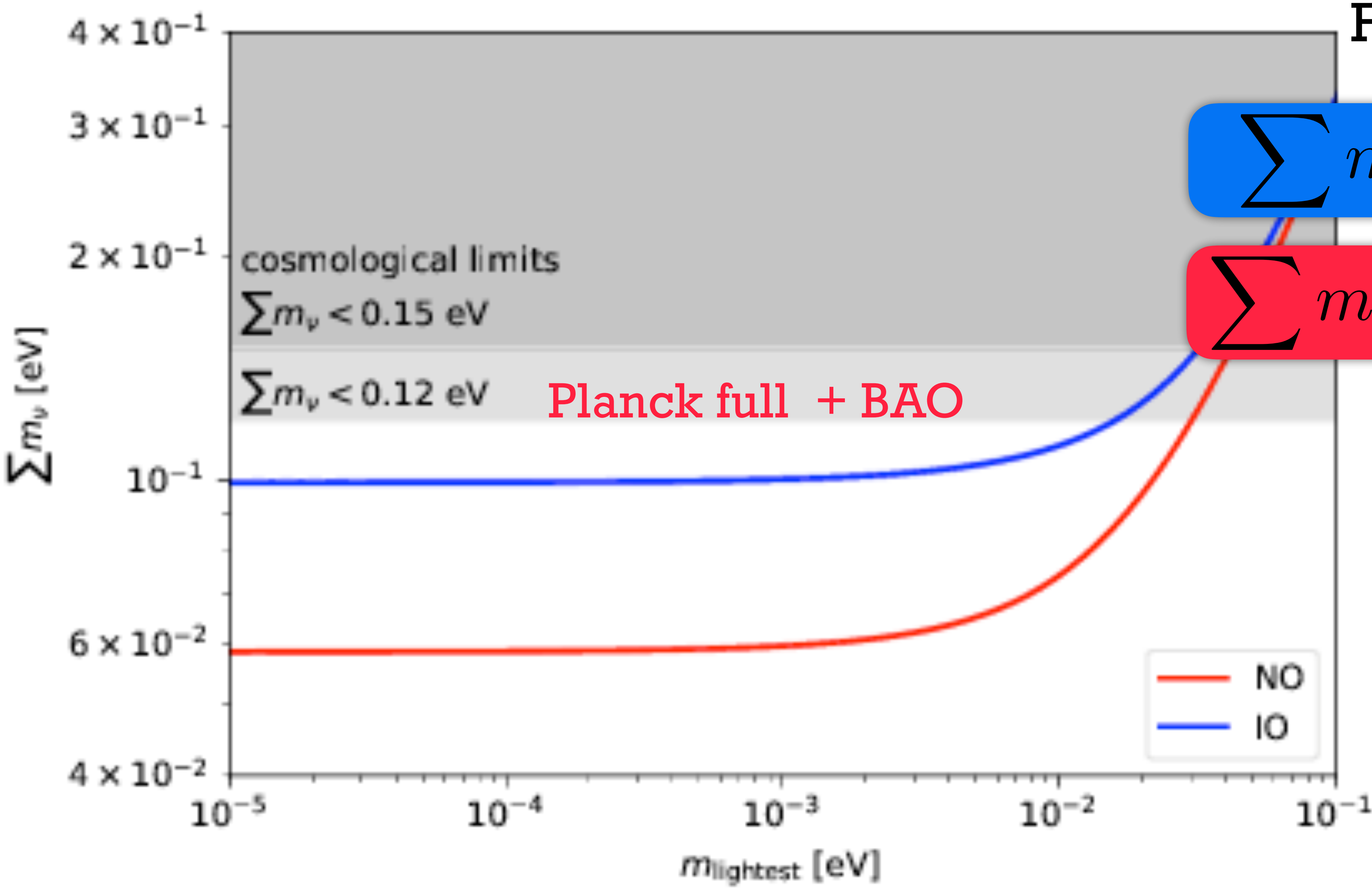
$\Sigma\, m_i < 0.12$ eV

Planck TT,TE,EE+lowE+lensing+BAO
[Planck Coll, 2018]

$\Sigma\, m_i < 0.09$ eV

Planck TT,TE,EE+lensing+ RSD+BAO +SNIa
[DiValentino et al, PRD2021]

Neutrino mass in cosmology



From oscillations:

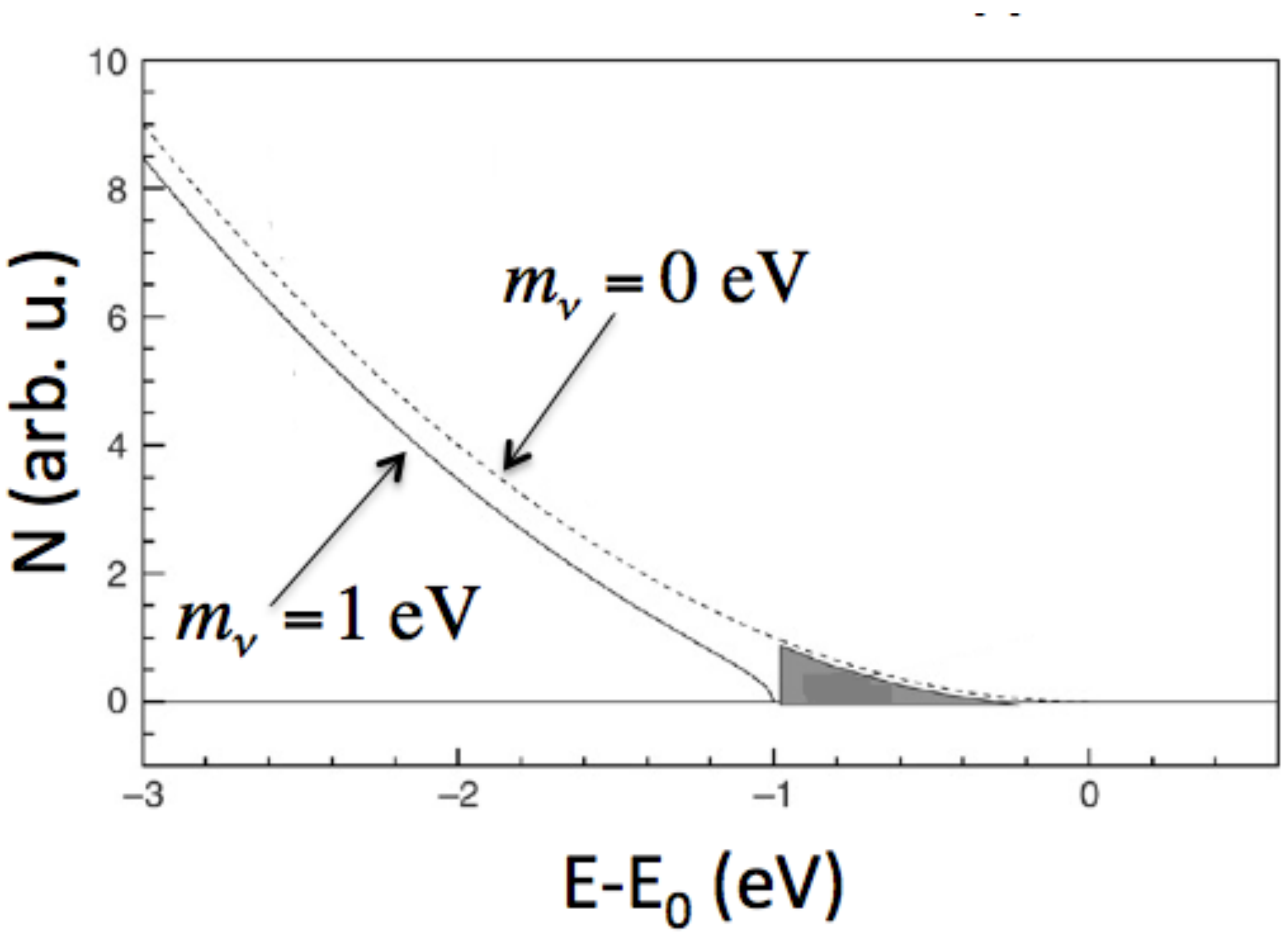
$$\sum m_\nu|_{\rm IO} \gtrsim 0.1\,{\rm eV}$$

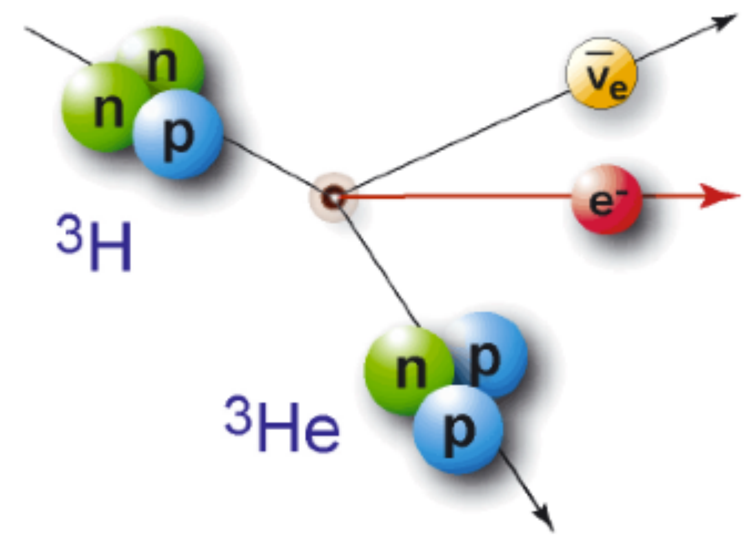
$$\sum m_\nu|_{\rm NO} \gtrsim 0.06\,{\rm eV}$$

de Salas et al, Front. Astron. Space Sci. 5 (2018) 36

Tritium β decay experiments

✦ β-decay spectrum close to the endpoint is very sensitive to the neutrino mass:





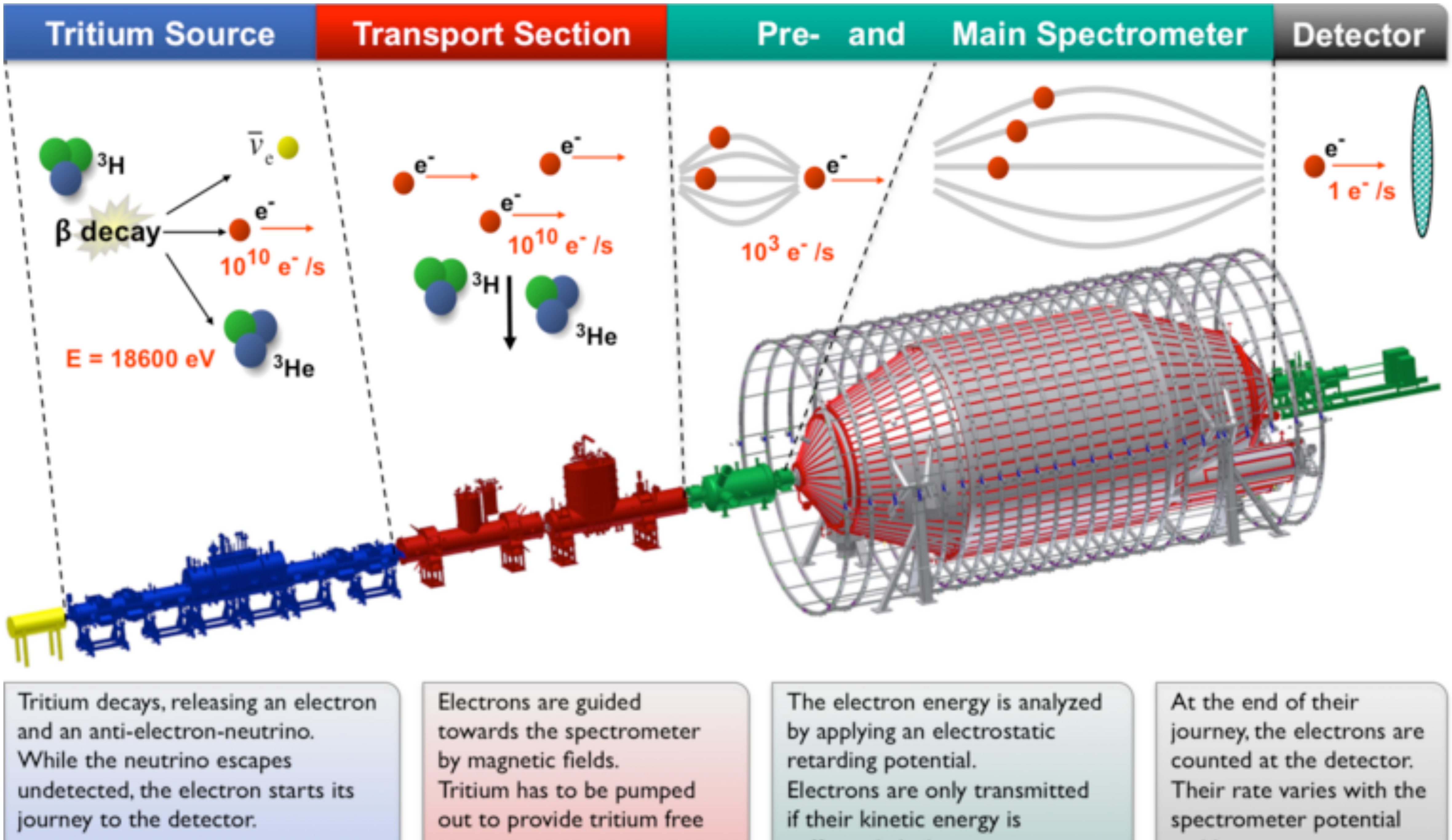
$$m_\beta^2 = \sum |U_{ei}|^2 \, m_i^2$$

Mainz and Troitsk Experiments

$$m_\beta < 2.2\,\mathrm{eV}\ (95\%\mathrm{C.L.})$$

The KATRIN experiment

Since June 2018



Current bound	Final sensitivity	Discovery potential
$m_\beta < 0.8$ eV (90% C.L.)	$m_\beta < 0.2$-0.3 eV (90%C.L.)	$m_\beta = 0.35$ eV (5σ)

The KATRIN experiment

(KArlsruhe TRItium Neutrino experiment)

Deggendorf → Karlsruhe: 400 km or 8800 km ??

(200 ton, 24 m long, 10 m diameter)

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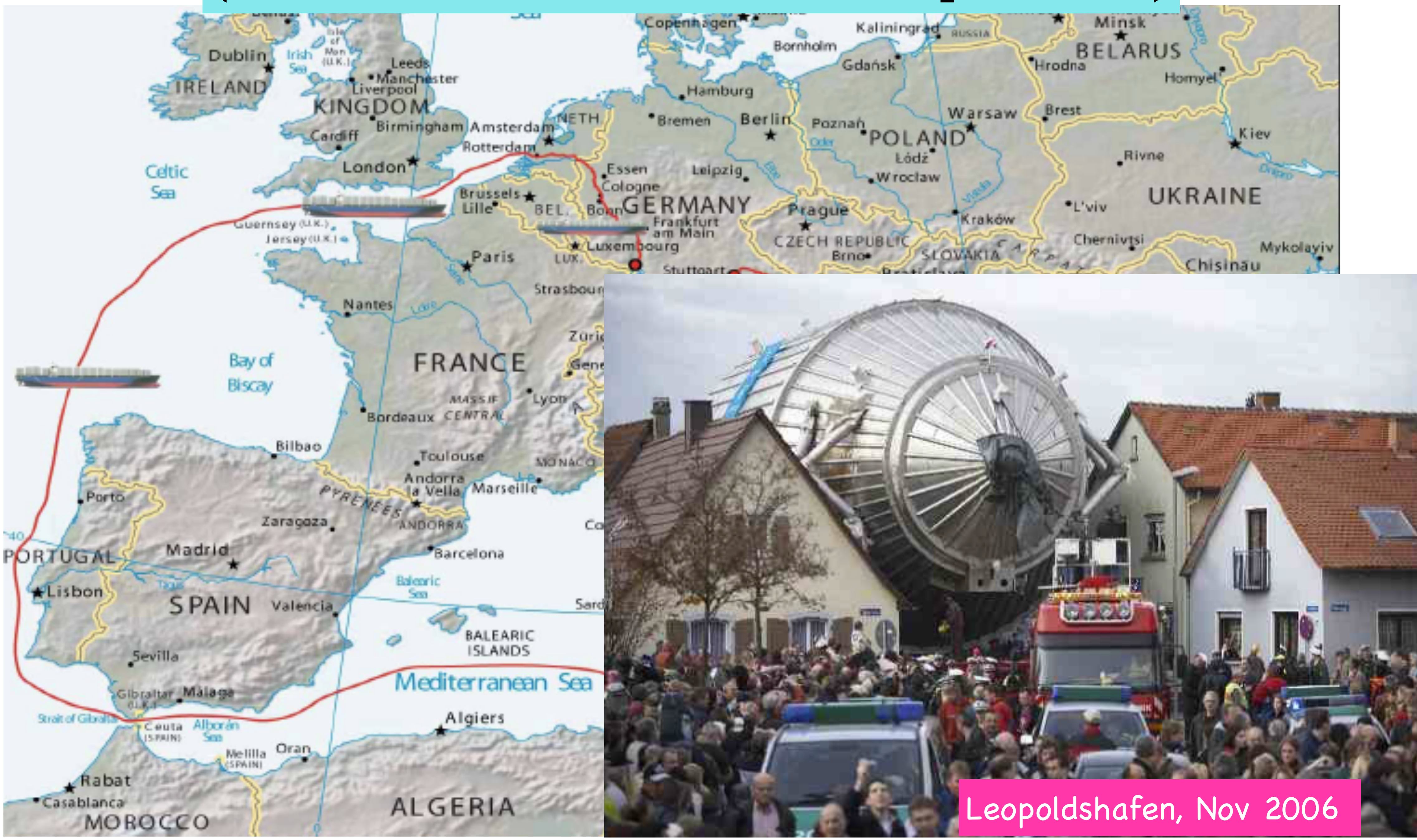


Deggendorf → Karlsruhe: 400 km or 8800 km ??

(200 ton, 24 m long, 10 m diameter)

Neutrinoless double beta decay

$2\nu\beta\beta$: rare process in the SM with $t_{1/2} \sim 10^{21}$ years

$0\nu\beta\beta$: possible for massive Majorana neutrinos.

(A,Z) →(A,Z+2) + e⁻ + e⁻ test ν nature

→ not observed yet

→ $t_{1/2} > 10^{26}$-10^{27} years

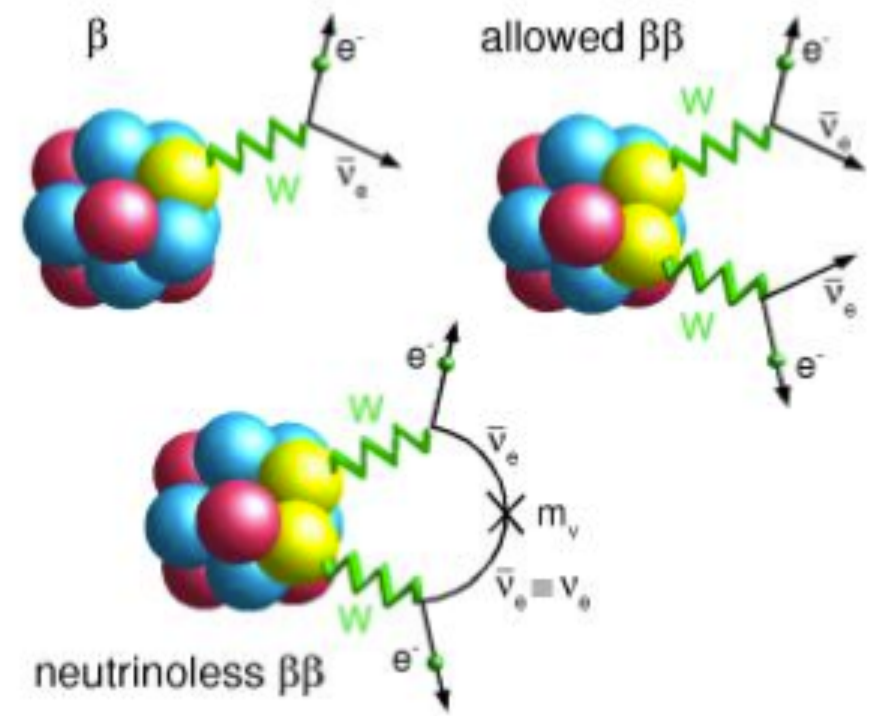
→ violates Lepton Number

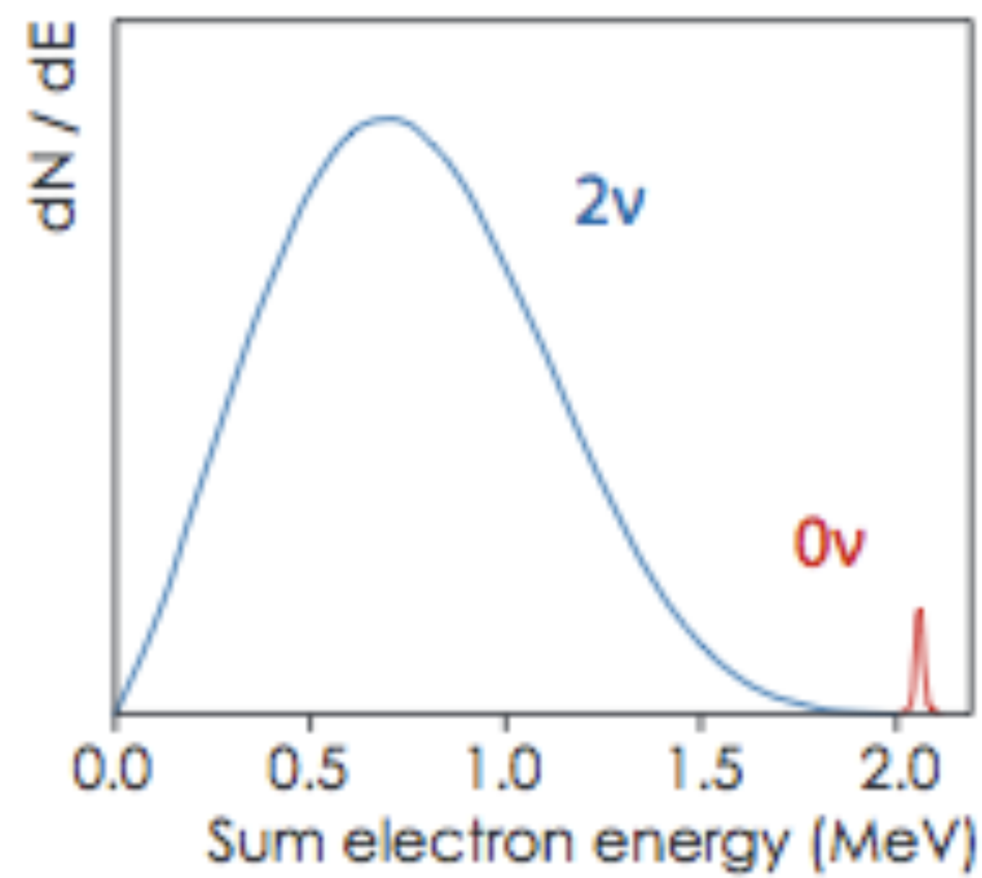
phase space — Nuclear matrix elements

$$\Gamma_{0\nu\beta\beta} = G^{0\nu}|M^{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

Effective Majorana neutrino mass

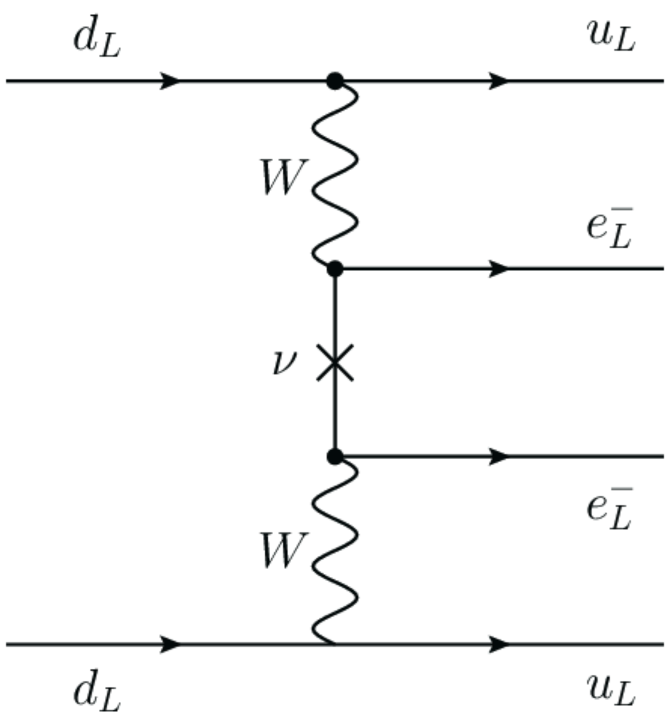
$$\langle m_{\beta\beta}\rangle = \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$$





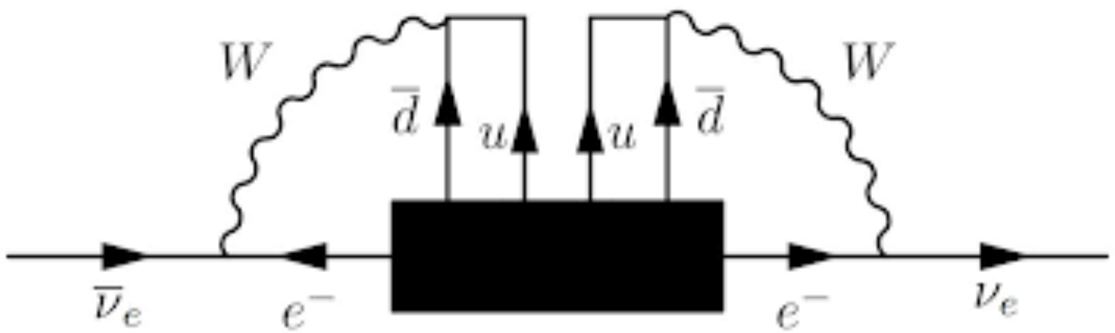
0νββ and Majorana neutrino mass

✦ Neutrinoless double beta decay can be treated as a dim-9 operator:



⟹

This leads to loop-generated Majorana mass



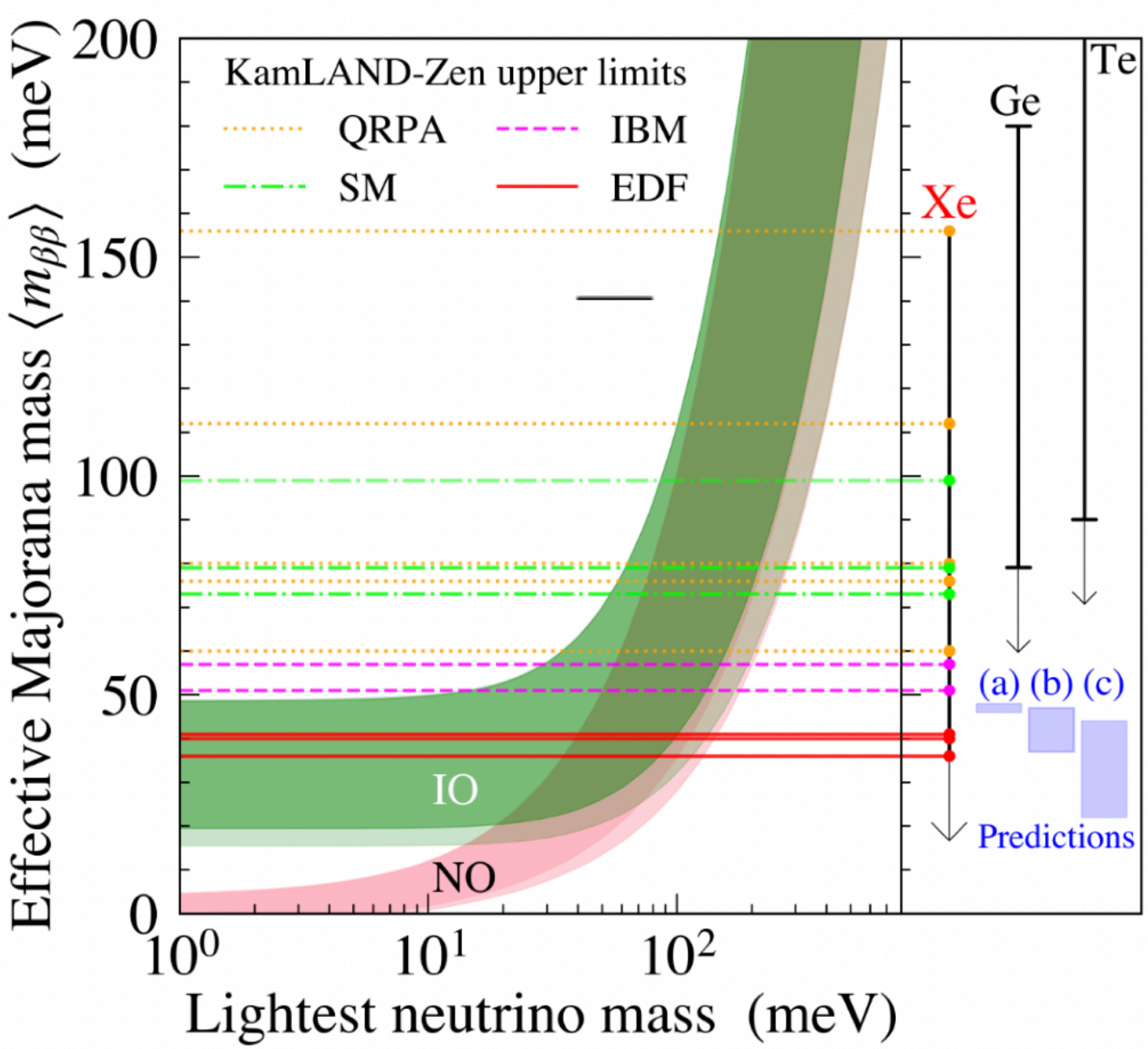
Blackbox theorem, Schechter & Valle, 1982

✦ Majorana neutrino mass is not the only mechanism leading to 0νββ: new physics models can also induce 0νββ. Bonnet, Hirsch, Ota, Winter, JHEP 2013.

✦ Only when related to Majorana neutrino masses one can use 0νββ results to constrain neutrino masses and their ordering.

$$\Gamma_{0\nu\beta\beta} = G^{0\nu}|M^{0\nu}|^2\langle m_{\beta\beta}\rangle^2 \quad \text{with} \quad \langle m_{\beta\beta}\rangle = \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$$

Bounds on neutrino mass from 0νββ



KamLAND-Zen Collab, Neutrino 2022

[Ge: Gerda, Te: Cuore]

At 90% CL:

$m_{\beta\beta}$ < 90-305 meV CUORE

$m_{\beta\beta}$ < 93-286 meV EXO-200

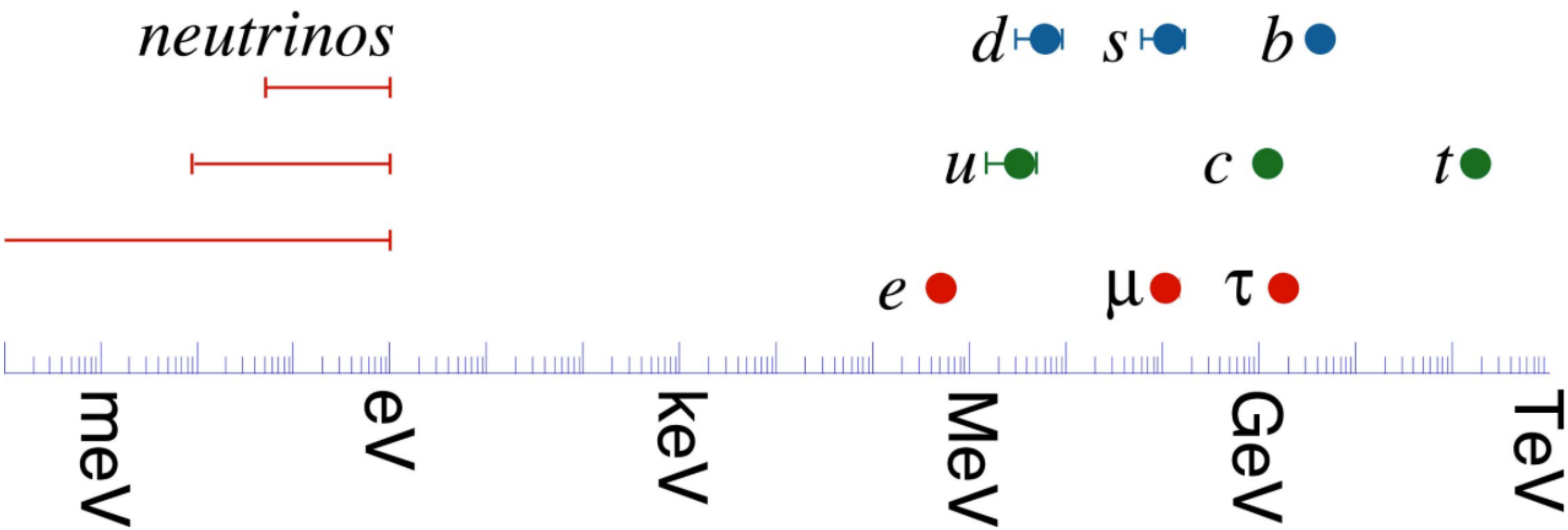
$m_{\beta\beta}$ < 79-180 meV GERDA II

$m_{\beta\beta}$ < 36-156 meV KL-Zen

F. Simkovic, Neutrino 2022

→ degenerate region explored

We need to build models to explain neutrino masses (and their size)!!



$m_\nu \sim 0 - 1$ eV

Dirac mass term

$$-\mathcal{L}_D = m_D \left(\overline{\nu_L} N_R + \overline{N_R} \nu_L \right)$$

Majorana mass term

$$-\mathcal{L}_M = \frac{1}{2} m \left(\overline{\nu_L^C} \nu_L + \overline{\nu_L} \nu_L^C \right)$$

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under U(1) transformation:

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not invariant

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→ breaks all charges in 2 units

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add N_R

add Higgs triplet

Weinberg operator

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Dirac neutrino mass term

Minimal extension SM: add N_R → "sterile" neutrino (singlet under SU(2)xU(1))

- 4 components Dirac neutrino: $\nu_L\,,\overline{\nu_L}\,,N_R\,,\overline{N_R}$

  → decomposing into its chiral states: $\psi = \nu = \nu_L + \nu_L^C$

$$-\mathcal{L}_D = m_D\overline{\nu}\nu = m_D(\overline{\nu_L}+\overline{N_R})(\nu_L+N_R) = m_D\left(\overline{\nu_L}N_R + \overline{N_R}\nu_L\right)$$

- Higgs mechanism: $$\mathcal{L}_{\text{Yukawa}} = Y_\nu\left(\overline{\nu_l}\,\overline{l}\right)\begin{pmatrix}\phi^0\\ \phi^-\end{pmatrix} N_R + \text{h.c.}$$

  → after SSB: $\langle\phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} v \\ 0\end{pmatrix}$ $\qquad m_D = Y_\nu\frac{v}{\sqrt{2}}$

- From ν oscillations: $m_\nu \geq \sqrt{\Delta m^2_{31}} = 0.05\,\text{eV}$ $\qquad \rightarrow Y_\nu \simeq 10^{-13}$

  much smaller than other Yukawas !!! $\quad Y_e \simeq 10^{-5}$

Minimal seesaw mechanism

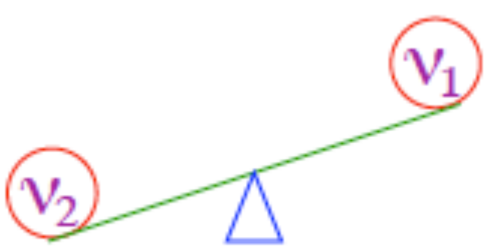
✦ Most general mass term:

$$\mathcal{L} = \mathcal{L}_D + \mathcal{L}_M = \frac{1}{2}\left(\overline{\nu_L}\,\overline{N_R^C}\right)\begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix}\begin{pmatrix} \nu_L^C \\ N_R \end{pmatrix} + \text{h.c.} \qquad (m_D \simeq v Y_\nu)$$

→ Diagonalization: $\frac{1}{2}\left(\overline{\nu} \quad \overline{N}\right)\begin{pmatrix} M_1 & 0 \\ 0 & M_2 \end{pmatrix}\begin{pmatrix} \nu \\ N \end{pmatrix}$

for $M_R \gg m_D$: $\quad M_1 \simeq \frac{m_D^2}{M_R}\,, \quad M_2 \simeq M_R$ → seesaw mechanism

✦ Provides a “natural” explanation for **smallness** of neutrino mass:



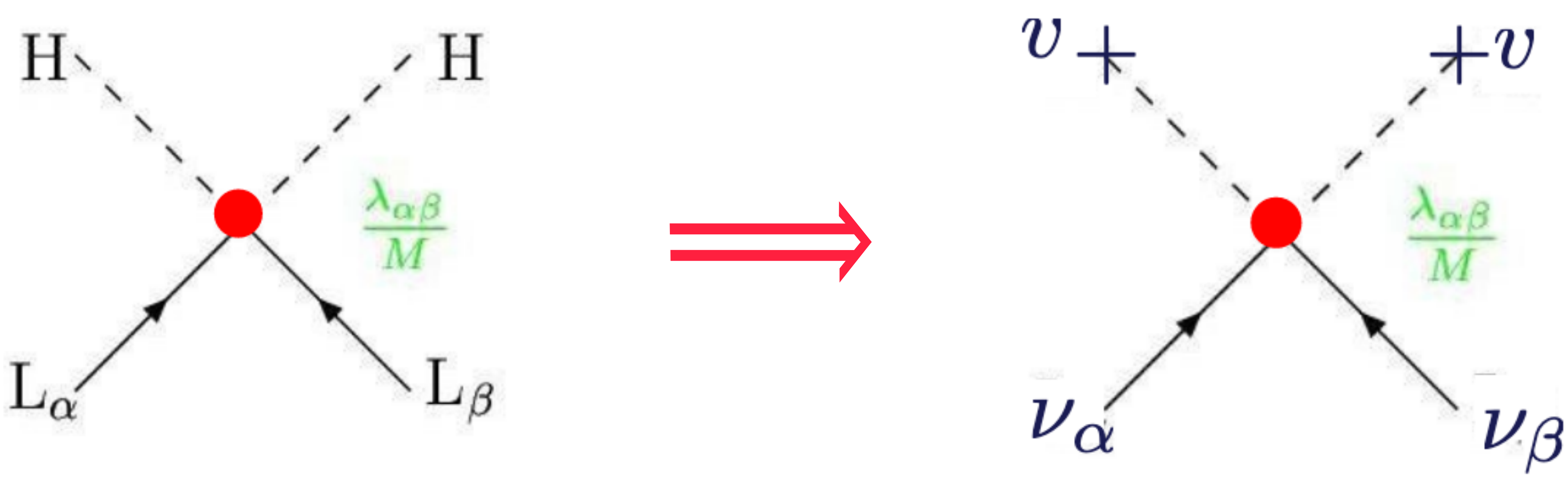
for $m_D \sim 100$ GeV and $m_\nu \sim 0.01$ - 1 eV →
$M_R \sim 10^{13}$ - 10^{15} GeV !!!

✦ Can explain baryon asymmetry of the Universe through **leptogenesis** if N decay violates CP:

$$\Gamma(N \to l + H) \neq \Gamma(N \to \bar{l} + \overline{H})$$

Weinberg operator

✦ Effective dim-5 operator for Majorana neutrino mass



$$\mathcal{L} \ni \frac{\lambda}{M}(LLHH) \quad \Longrightarrow \quad m_\nu = \frac{\lambda}{M} v^2$$

Majorana mass

$$(\Delta L = 2)$$

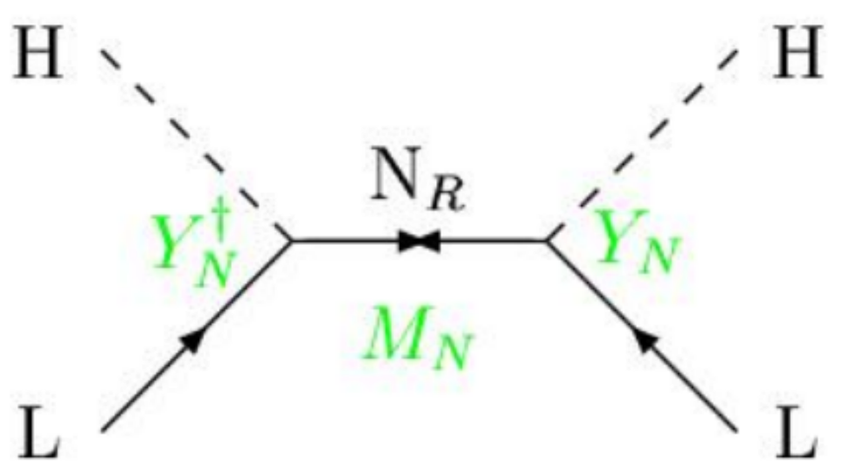
S. Weinberg PRL 43 (1979) 1566

Seesaw mass models

⇒ They led to the Weinberg operator at tree level.

⇒ ν masses are generated through mixing with heavy particles.

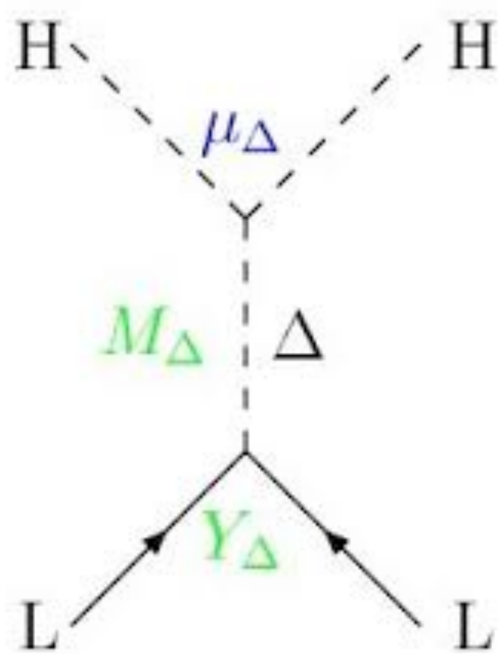
Type-I seesaw (right-handed singlet N_R)



$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$

Minkovski; Gellman, Ramond, Slansky; Yanagida; Mohapatra, Senjanovic.

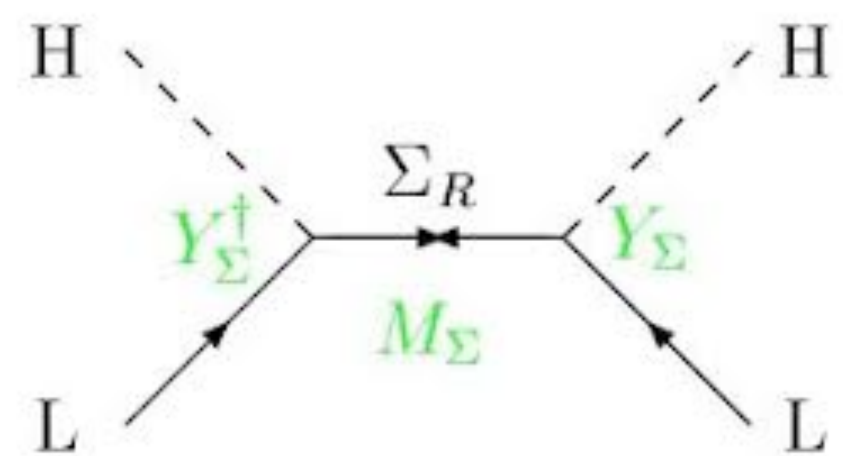
Type-II seesaw (Scalar triplet Δ)



$$m_\nu = Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

Schechter, Valle; Lazarides, Shafi, Wetterich; Cheng, Li; Mohapatra,…

Type-III seesaw (Fermion triplet Σ_R)



$$m_\nu = Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma v^2$$

Foot, Lew, He, Joshi; …

Low energy seesaw models

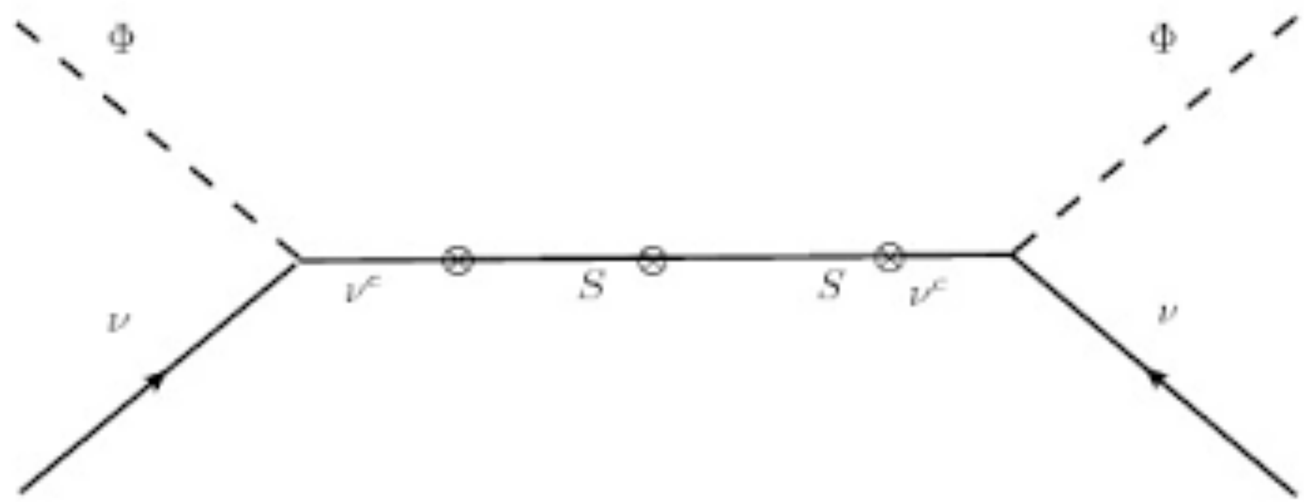
Inverse seesaw model

Mohapatra and Valle, PRD 34 (1986) 1642

Extended lepton content:

(ν, ν^c, S) L=(+1,-1,+1)

SU(2) singlets



$$M_\nu = \begin{pmatrix} 0 & M_D & 0 \\ M_D^T & 0 & M \\ 0 & M^T & \mu \end{pmatrix} \rightarrow m_\nu = M_D (M^T)^{-1} \mu M^{-1} M_D^T$$

- μ breaks L and generates neutrino mass (massless for μ=0)
- m_ν can be very light even if M is far below GUT scale:

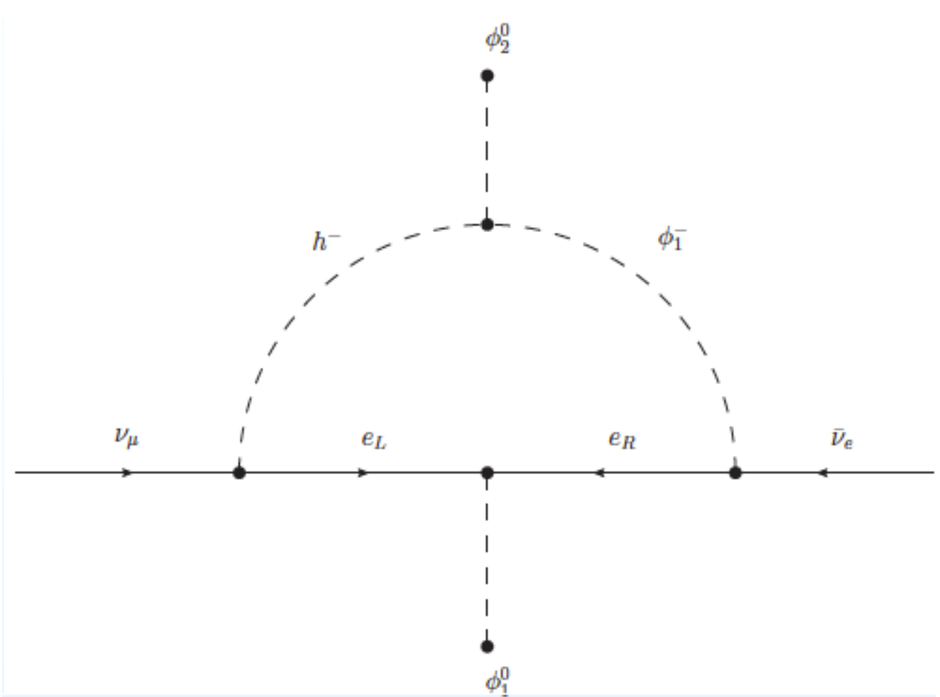
with $\mu \sim$ keV and M $\sim 10^3$ GeV $\rightarrow m_\nu \sim$ eV

Radiative models

- ✦ extension of scalar sector of the SM
- ✦ neutrino masses can be generated through loops
  - ⇒ loop suppression accounts for the smallness of m_ν

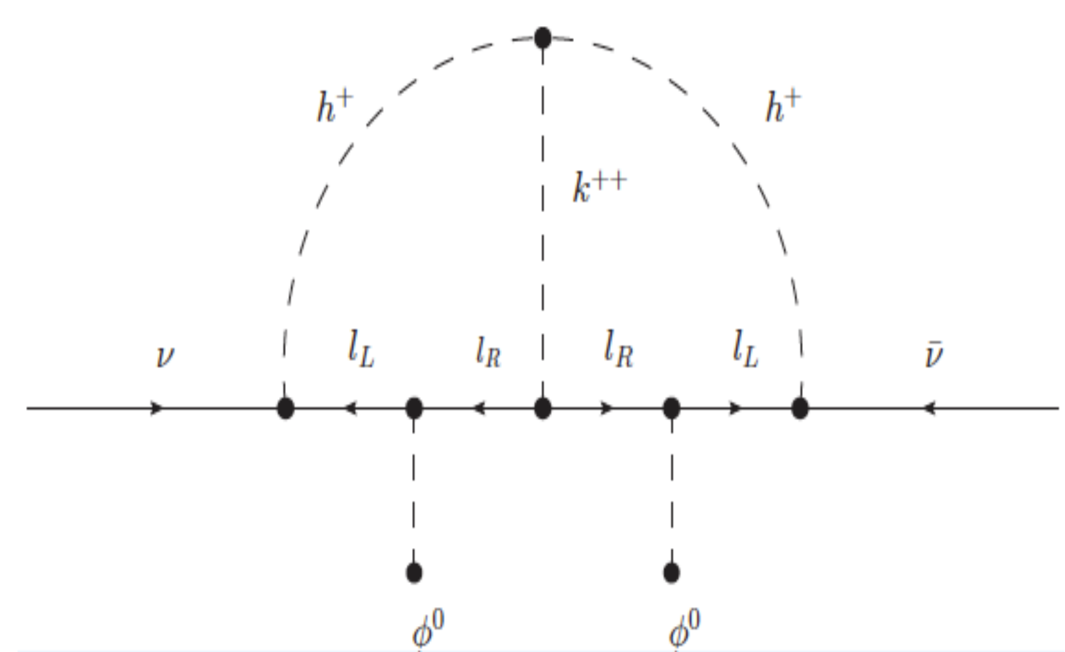
Zee model Zee, PLB 93 (1980) 389

+ singlet scalar h^+
+ extra Higgs doublet H



Zee-Babu model Zee, NPB 264 (1986) 99; Babu, PLB 203 (1988) 132

+ singlet scalar h^+
+ singlet scalar k^{++}



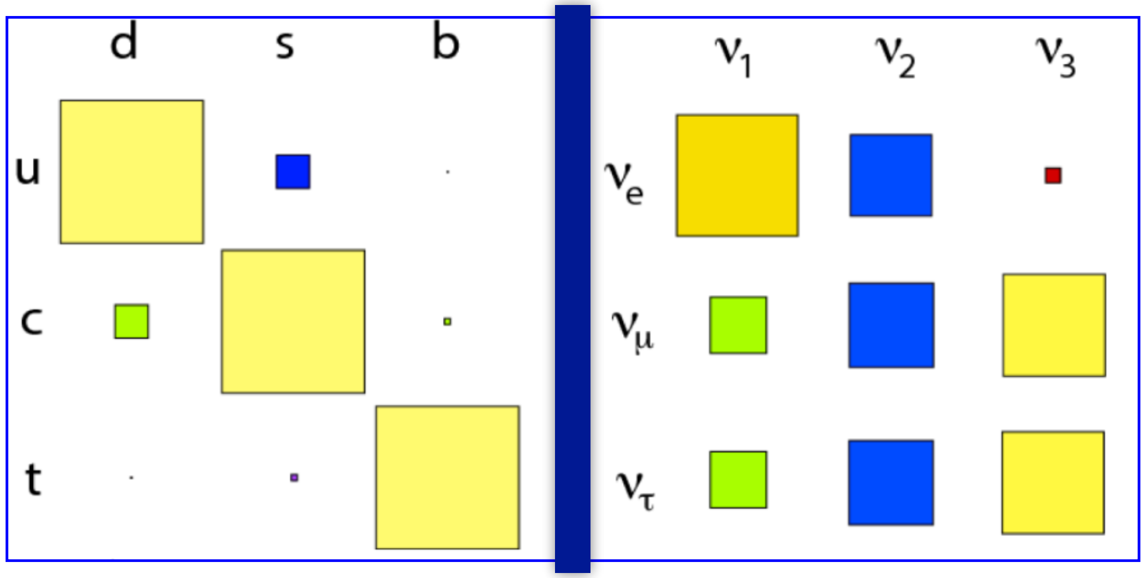
The flavour problem

✦ seesaw models explain the smallness of neutrino masses

However, they can not explain:

✦ Why quark and lepton mixings are so different?

$\theta_{12} \simeq 13°$
$\theta_{13} \simeq 0.2°$
$\theta_{23} \simeq 2.4°$



$\theta_{12} \simeq 34°$
$\theta_{13} \simeq 9°$
$\theta_{23} \simeq 49°$

✦ Why do fermion masses show these hierarchical relations?

$$m_e \ll m_\mu \ll m_\tau \qquad m_u, m_d \ll m_c, m_s \ll m_t, m_b$$

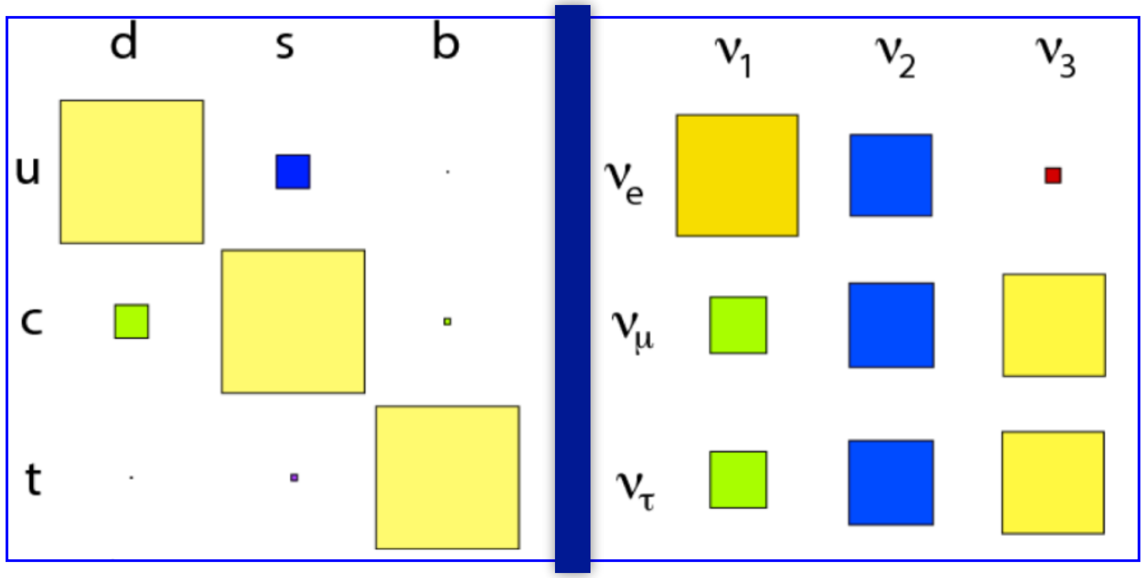
The flavour problem

✦ seesaw models explain the smallness of neutrino masses

However, they can not explain:

✦ Why quark and lepton mixings are so different?

$\theta_{12} \simeq 13°$
$\theta_{13} \simeq 0.2°$
$\theta_{23} \simeq 2.4°$



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✦ Why do fermion masses show these hierarchical relations?

$$m_e \ll m_\mu \ll m_\tau \qquad m_u, m_d \ll m_c, m_s \ll m_t, m_b$$

⇒ One can add new symmetries of leptons to the Standard Model

$$SU_c(3) \times SU_L(2) \times U_Y(1) \times G_f$$

Neutrino physics beyond the Standard Model

Beyond the 3-neutrino scenario

- Neutrino results suggest the presence of **physics BSM** to explain:
  - ✓ light neutrino masses (mass generation mechanism)
  - ✓ large neutrino mixing compared to quark sector (flavour problem)
  - ✓ short-distance anomalies (LSND, reactor and Ga anomalies)

- Many different **BSM scenarios** analyzed in the literature:
  - ✓ neutrino non-standard interactions (NSI) with matter
  - ✓ exotic neutrino electromagnetic properties
  - ✓ presence of light sterile neutrinos
  - ✓ mixing with heavy sterile neutrinos: non-unitary neutrino mixing

$\Rightarrow$ the presence of new physics may affect our current description of 3-nu oscillations as well as the future measurements

Are there light sterile neutrinos?

What is a sterile neutrino?

✦ **sterile neutrino** = singlet fermion of the Standard Model

→ it has no interactions (exceptions: Higgs, mixing and physics BSM)

Motivations: sterile neutrinos can explain...

- ✦ neutrino oscillation anomalies ($m \sim eV$)
- ✦ small neutrino masses (seesaw mechanism, $m >$ TeV-M_{Planck})
- ✦ baryon asymmetry of the universe (leptogenesis, $m \gg 1$ GeV)
- ✦ (part of) the dark matter of the universe.

How many neutrinos?

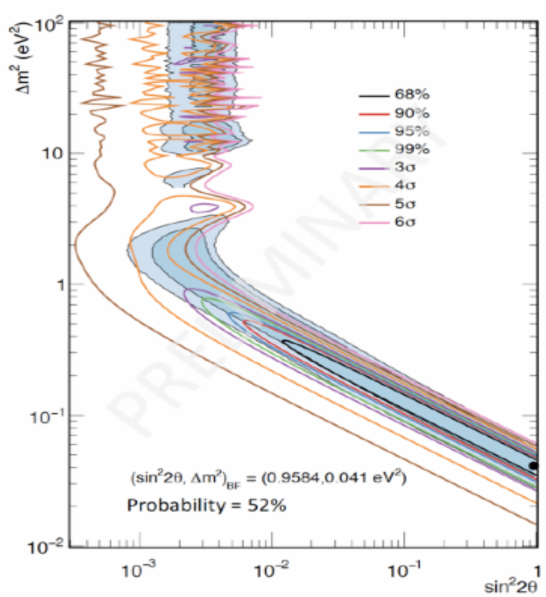
✦ According to LEP measurements of invisible Z decay width:

$\rightarrow N_\nu = 2.984 \pm 0.008$ (light, active neutrinos)

Experimental hints for a 4th sterile neutrino:

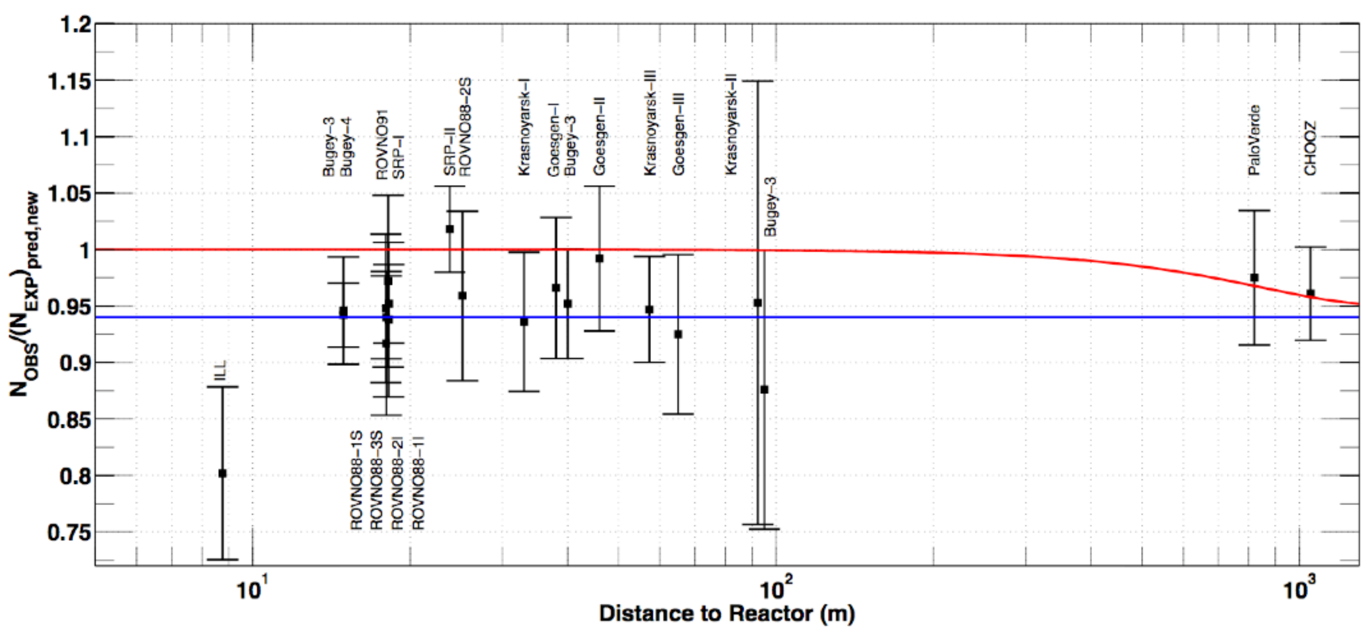
LSND & MiniBooNE

$\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$



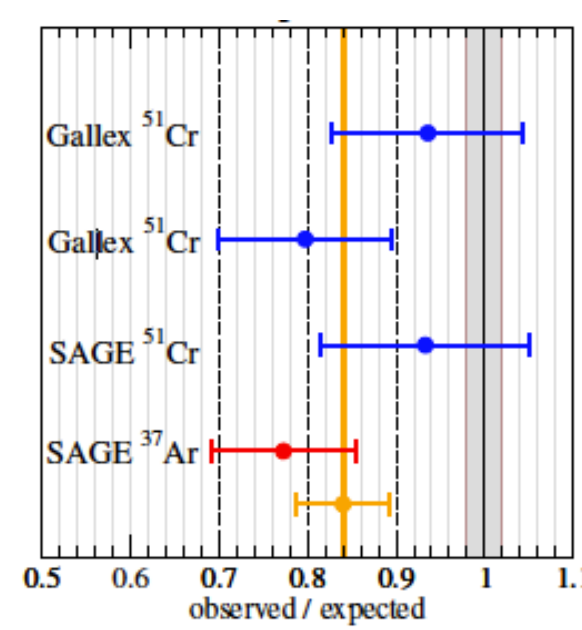
Reactor anomaly

$\overline{\nu}_e \rightarrow \overline{\nu}_e$



Gallium anomaly

$\nu_e \rightarrow \nu_e$



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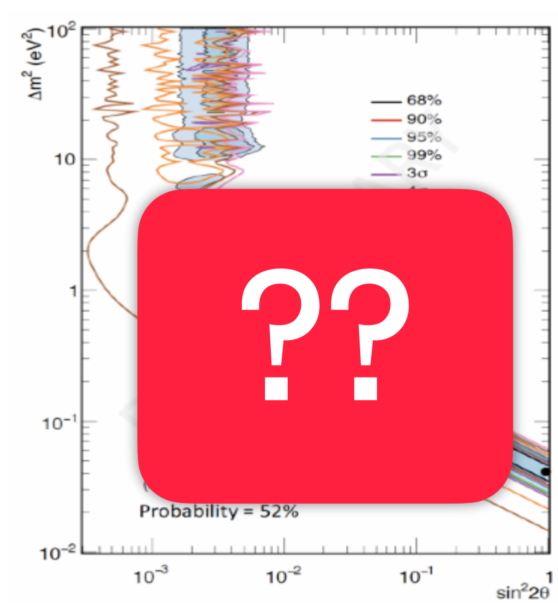

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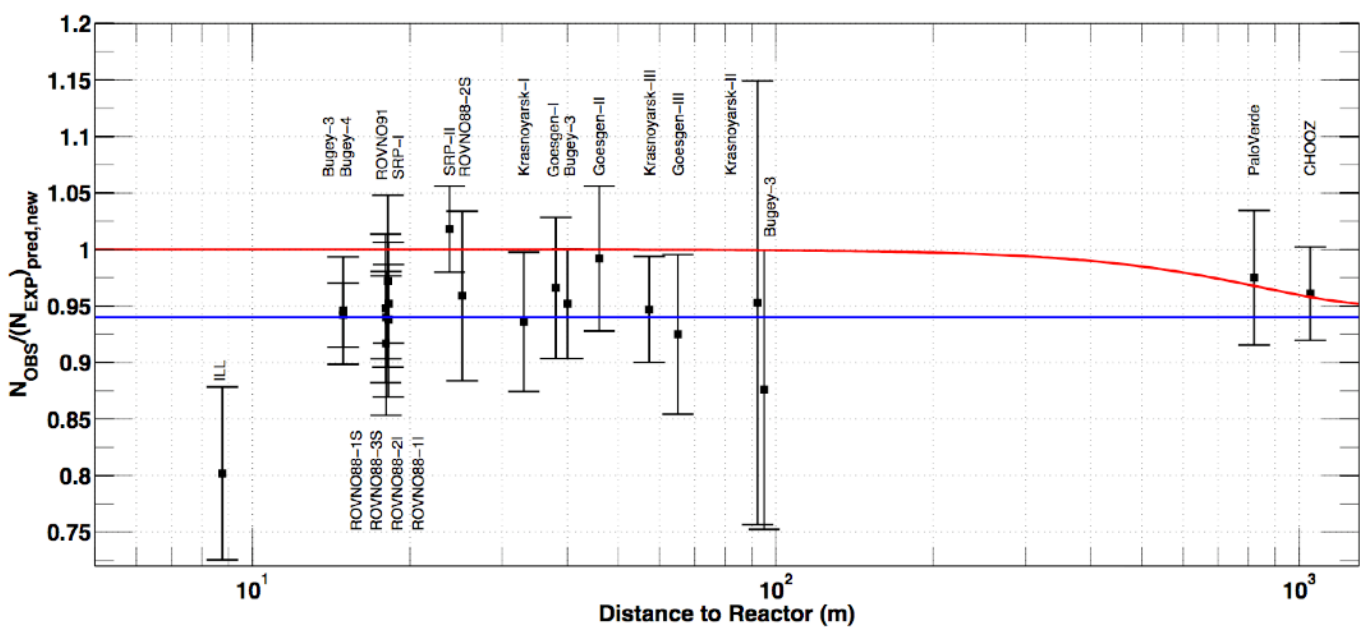

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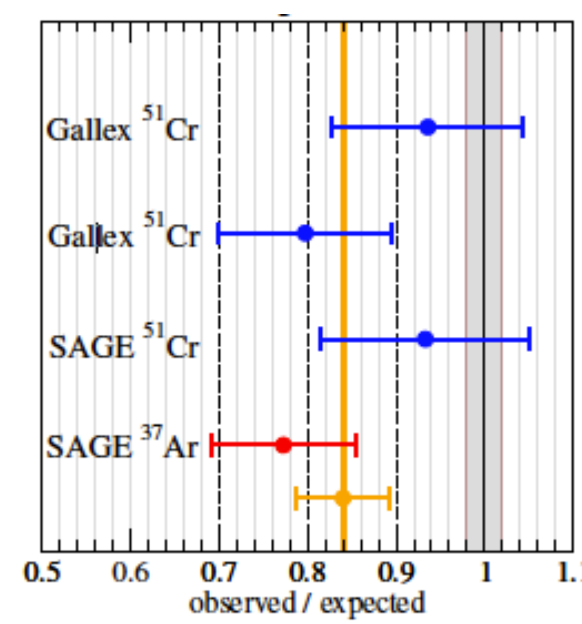
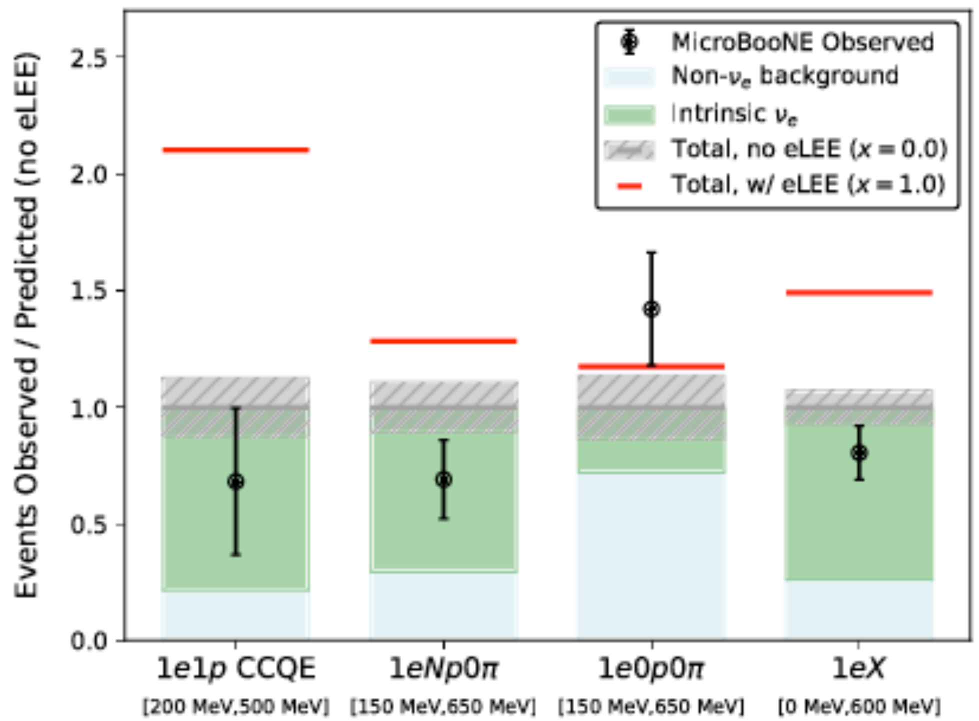
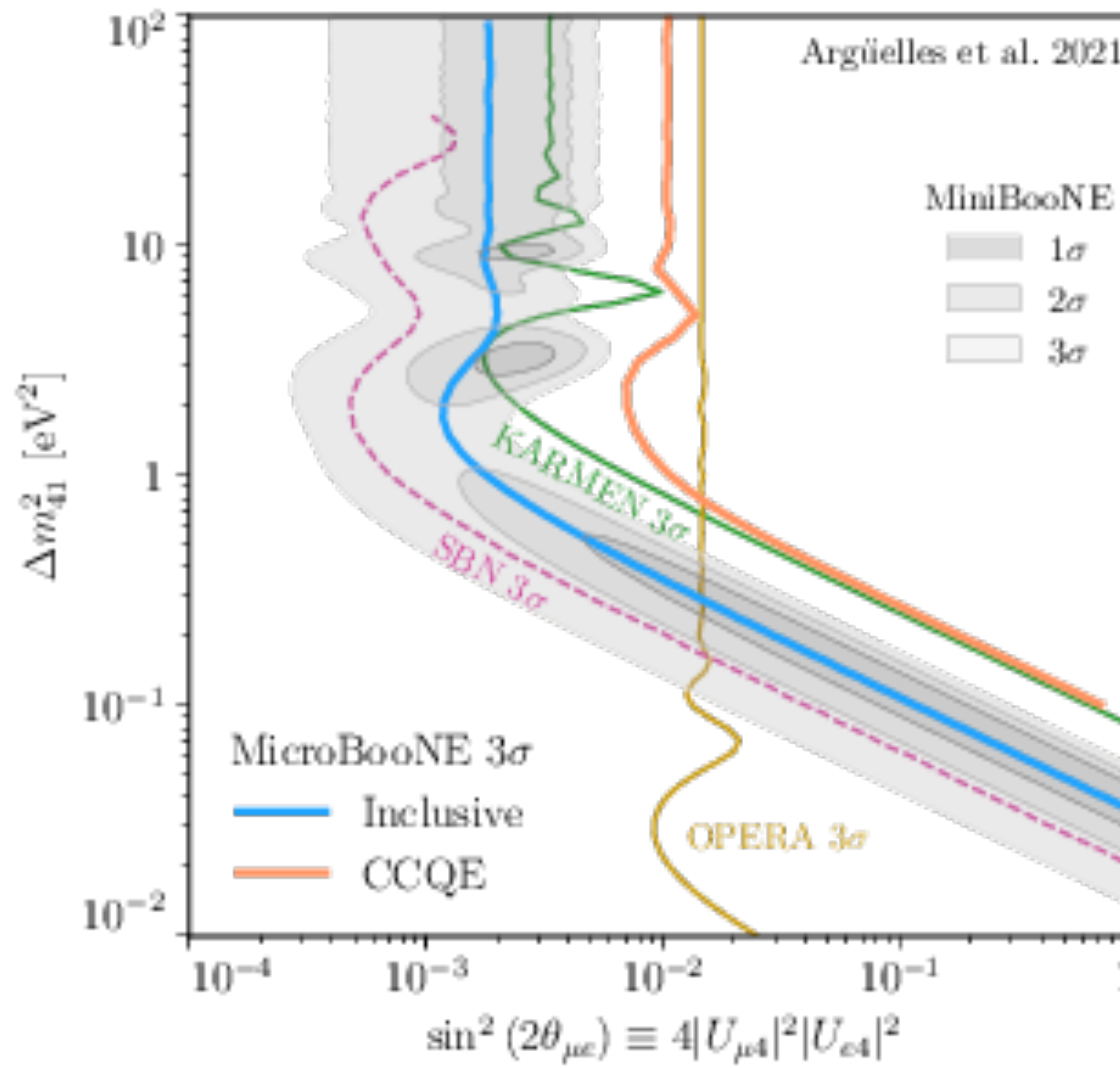


First results from MicroBooNE

MicroBooNE Collab, 2021



Argüelles et al, 2021



- MicroBooNE does not support the interpretation of the MiniBooNE low energy excess in terms of ν_e

- Overlap of 2σ MicroBooNE and MiniBooNE regions

How many neutrinos?

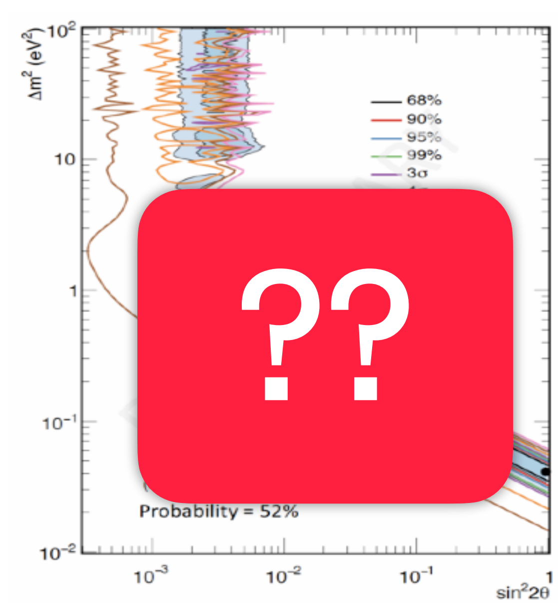
✦ According to LEP measurements of invisible Z decay width:

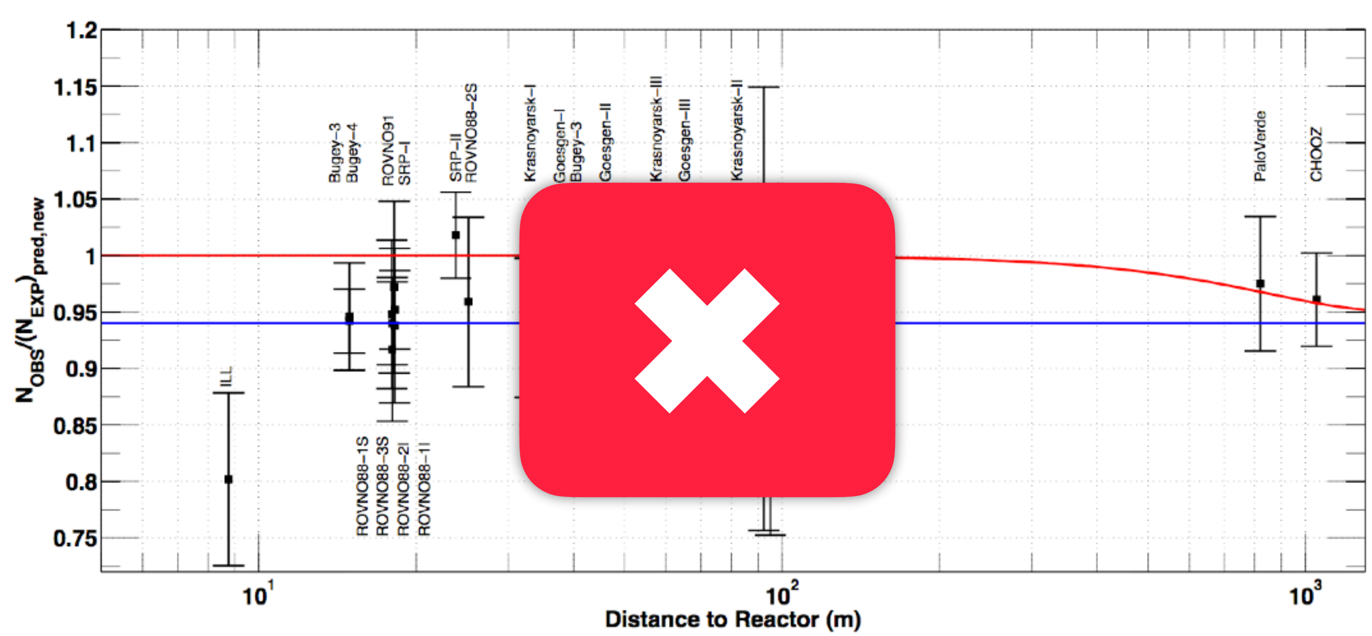
$\rightarrow N_\nu = 2.984 \pm 0.008$ (light, active neutrinos)

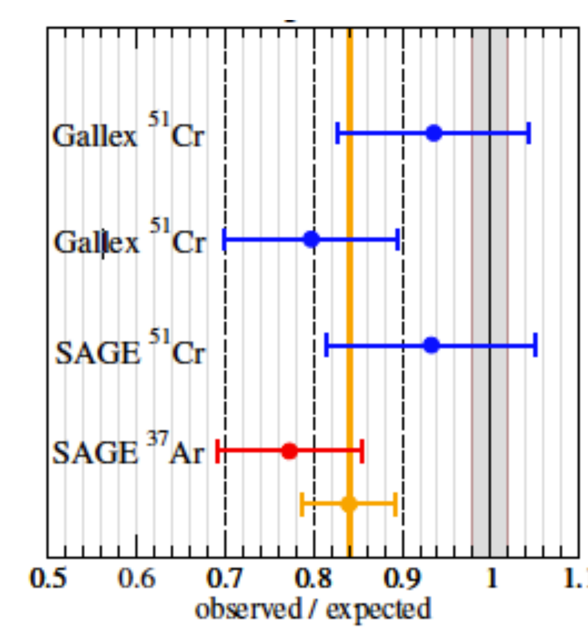
Experimental hints for a 4th sterile neutrino:

LSND & MiniBooNE | **Reactor anomaly** | **Gallium anomaly**

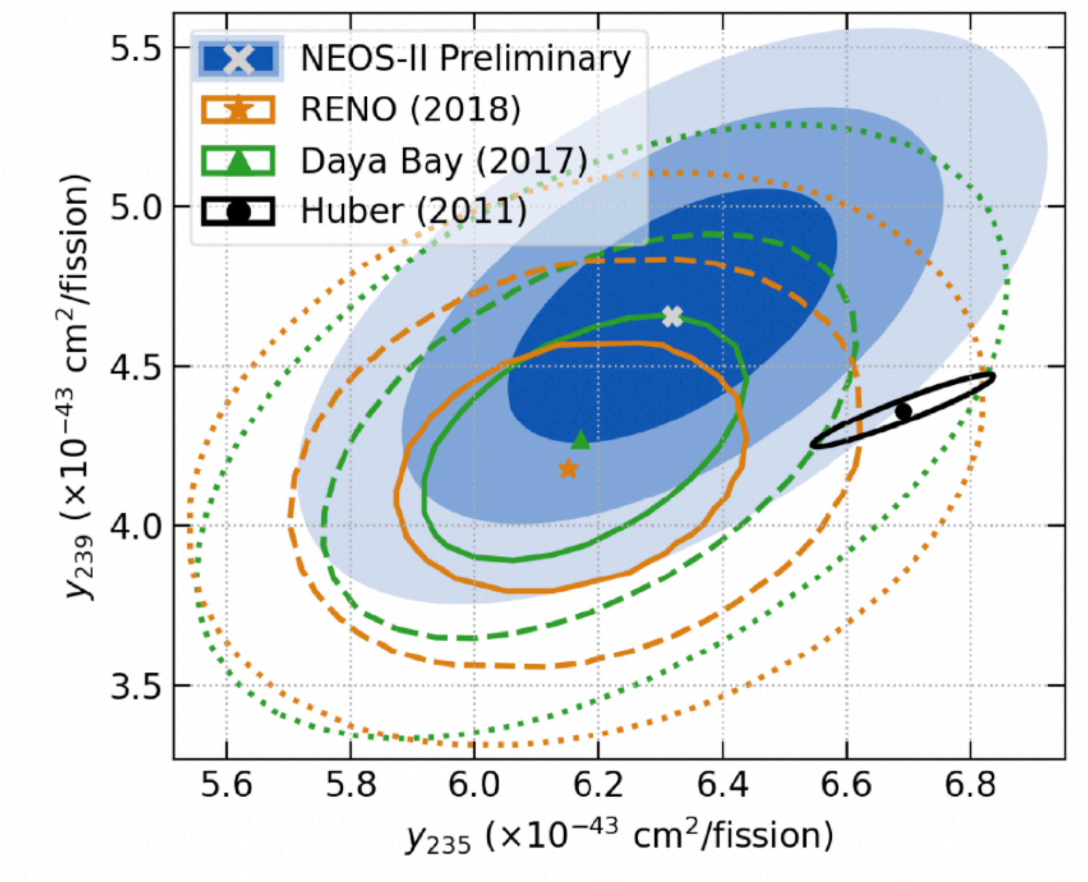
$\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$ | $\overline{\nu}_e \rightarrow \overline{\nu}_e$ | $\nu_e \rightarrow \nu_e$







Current status of the reactor anomaly

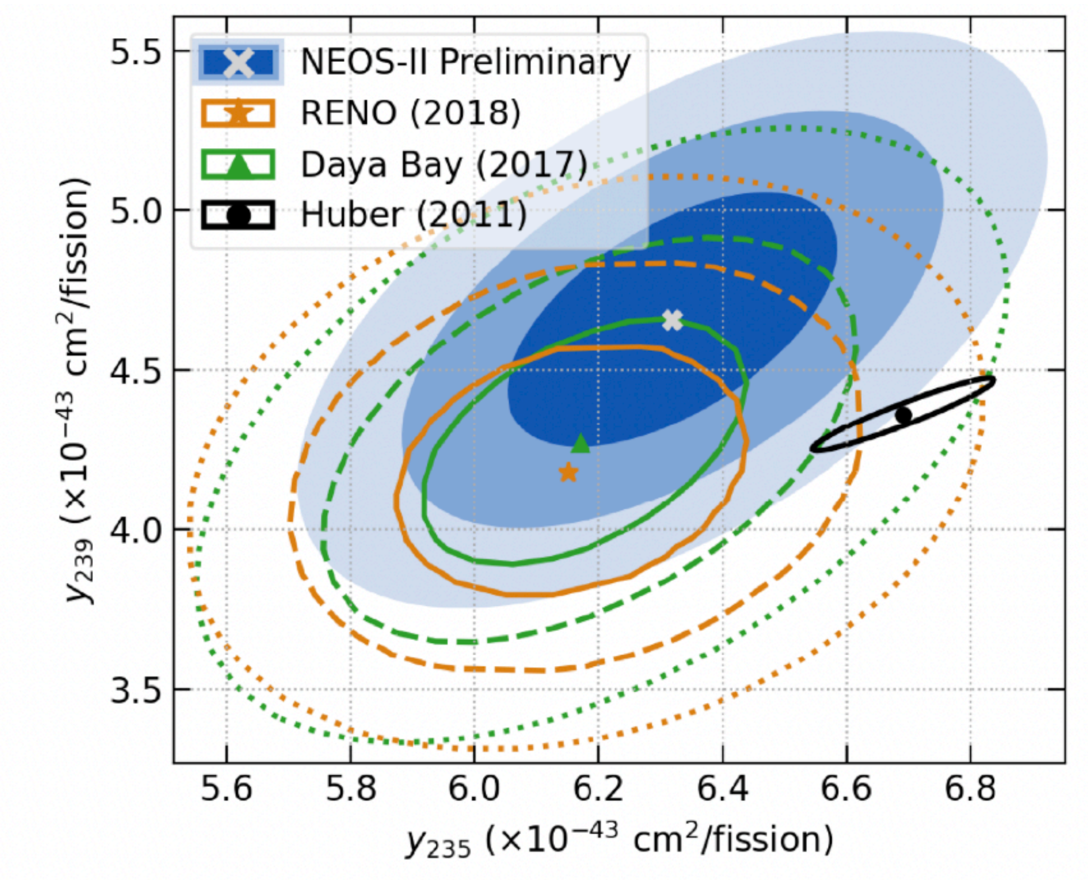


P. Vogel, Neutrino 2022

- Reactor measurements indicate that the neutrino flux for ^{235}U in the H-M model should be reduced by 5-10 %.

  → this would explain the reactor neutrino flux anomaly

Current status of the reactor anomaly



P. Vogel, Neutrino 2022

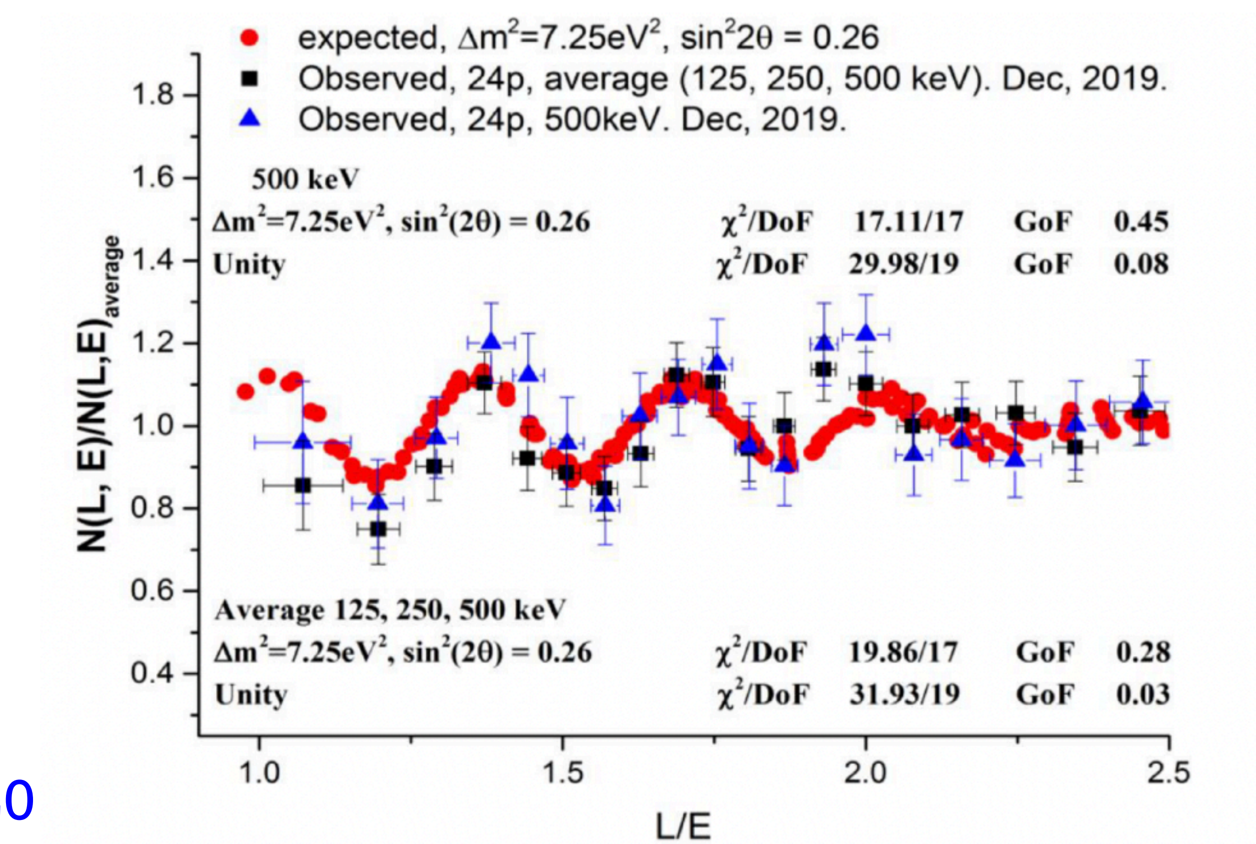
- Reactor measurements indicate that the neutrino flux for ^{235}U in the H-M model should be reduced by 5-10 %.

  → this would explain the reactor neutrino flux anomaly

- Indications of anomaly in the neutrino reactor spectra:

  → indep of flux predictions

  → low statistical significance



Neutrino-4 Collab, 2020

How many neutrinos?

✦ According to LEP measurements of invisible Z decay width:

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Experimental hints for a 4th sterile neutrino:

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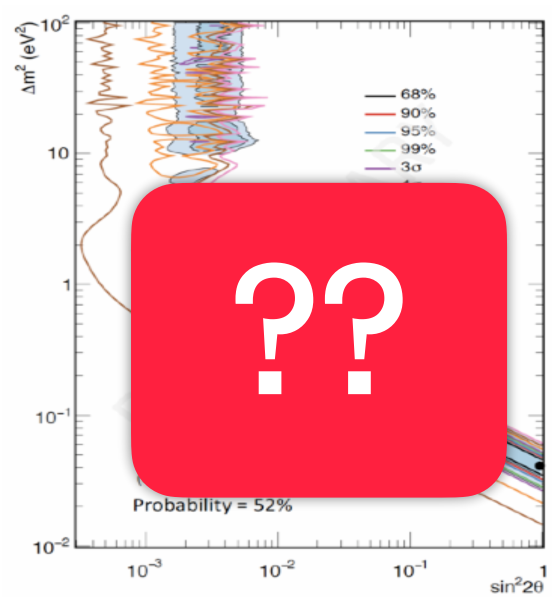
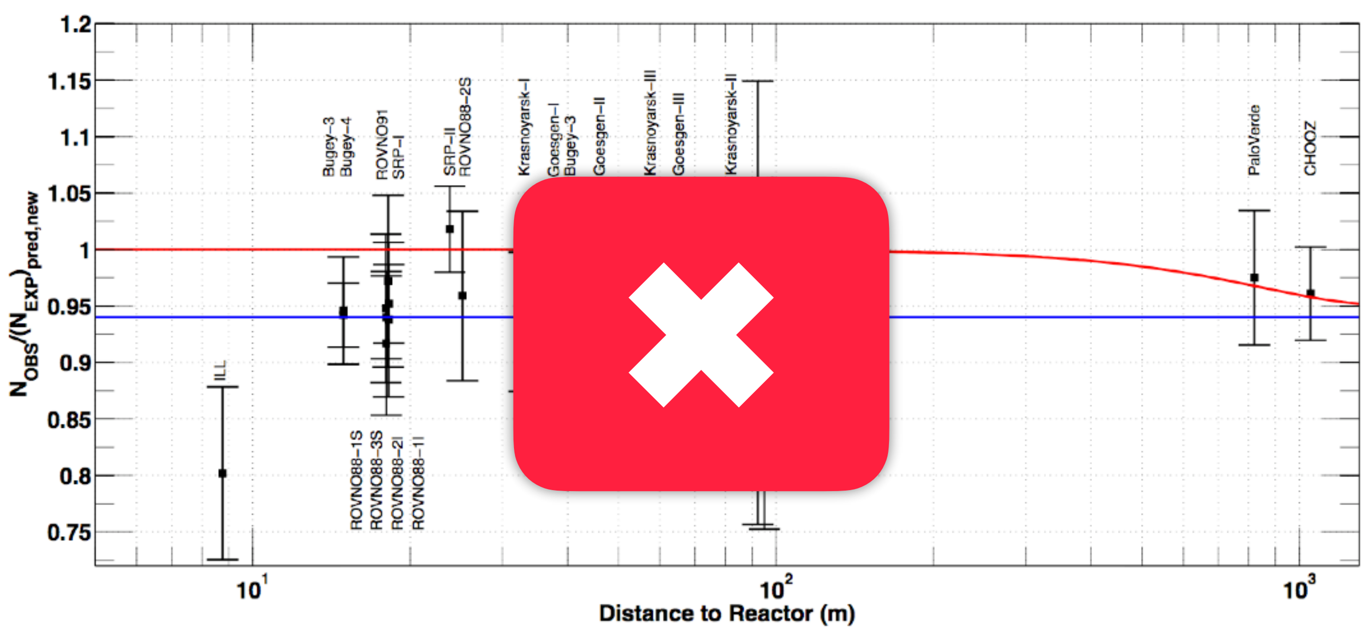


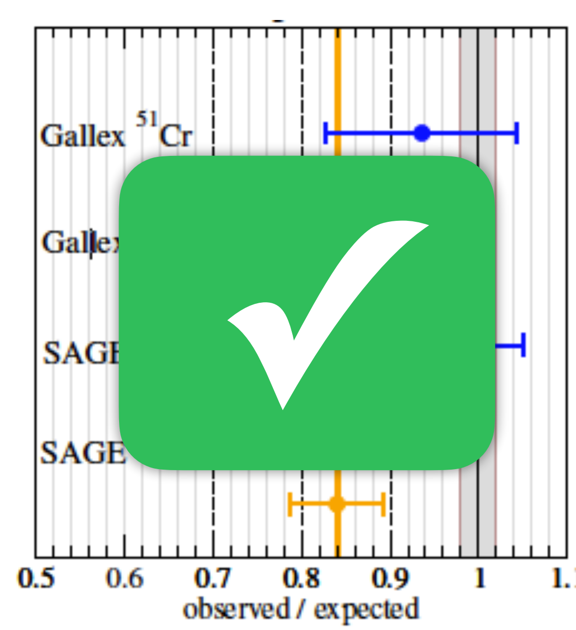
Reactor anomaly

$\overline{\nu}_e \rightarrow \overline{\nu}_e$



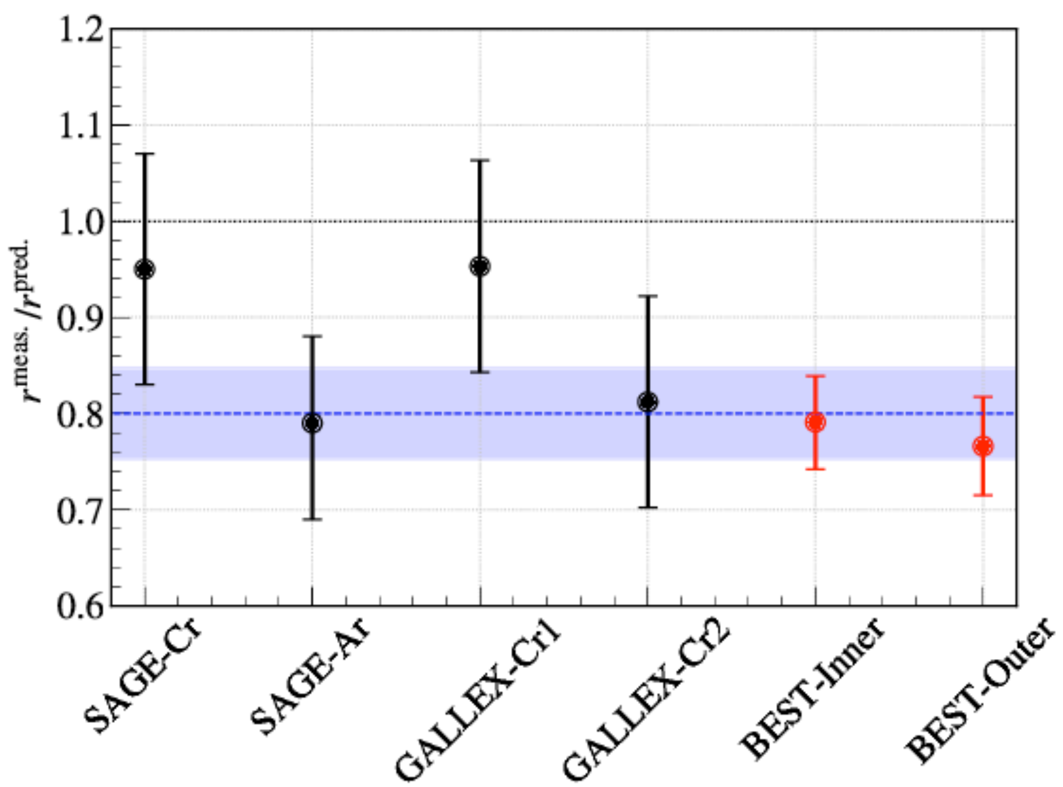
Gallium anomaly

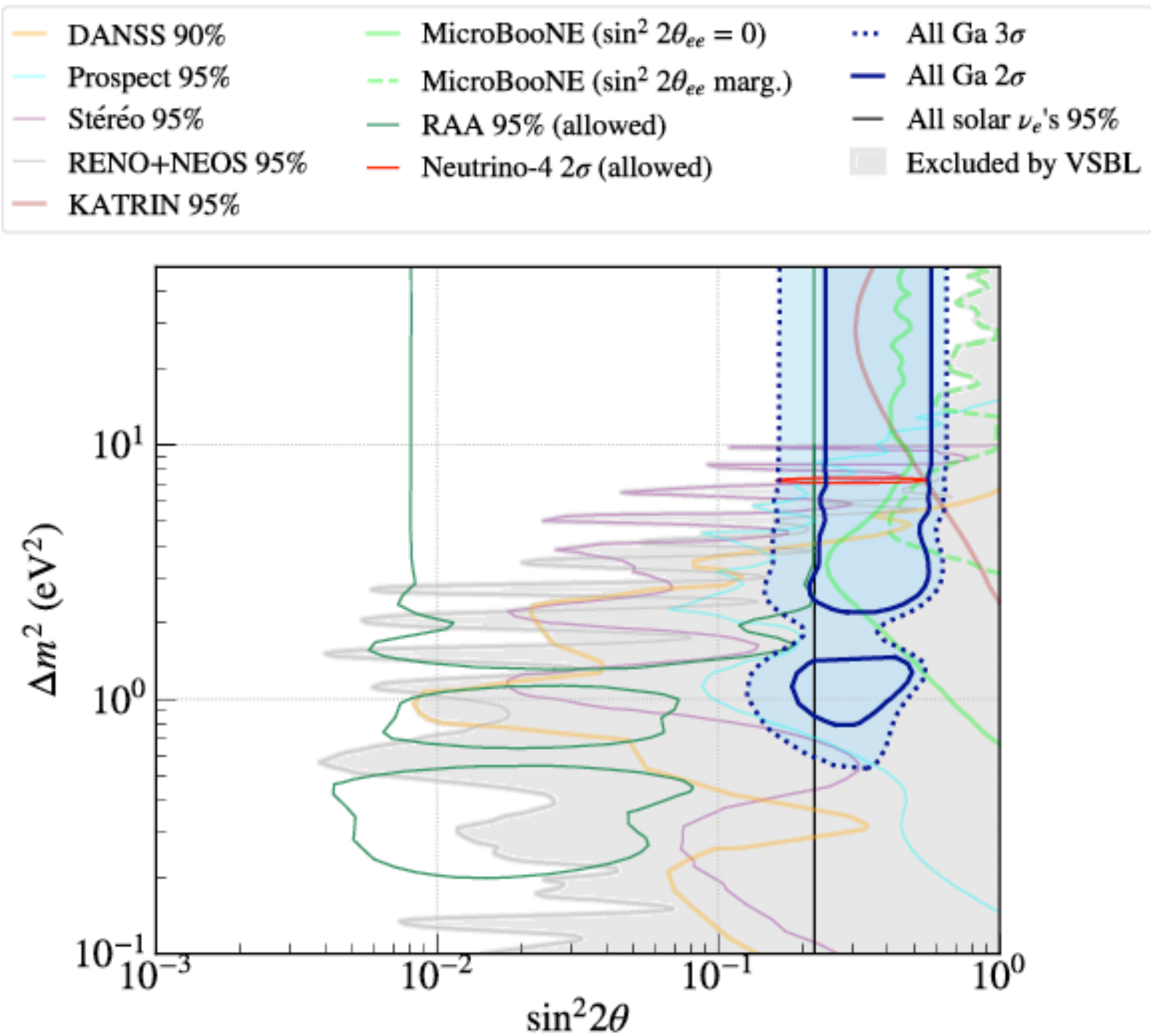
$\nu_e \rightarrow \nu_e$



Current status of the Ga anomaly

✦ Recently confirmed by BEST (Baksan Experiment on Sterile Transitions) at 4σ



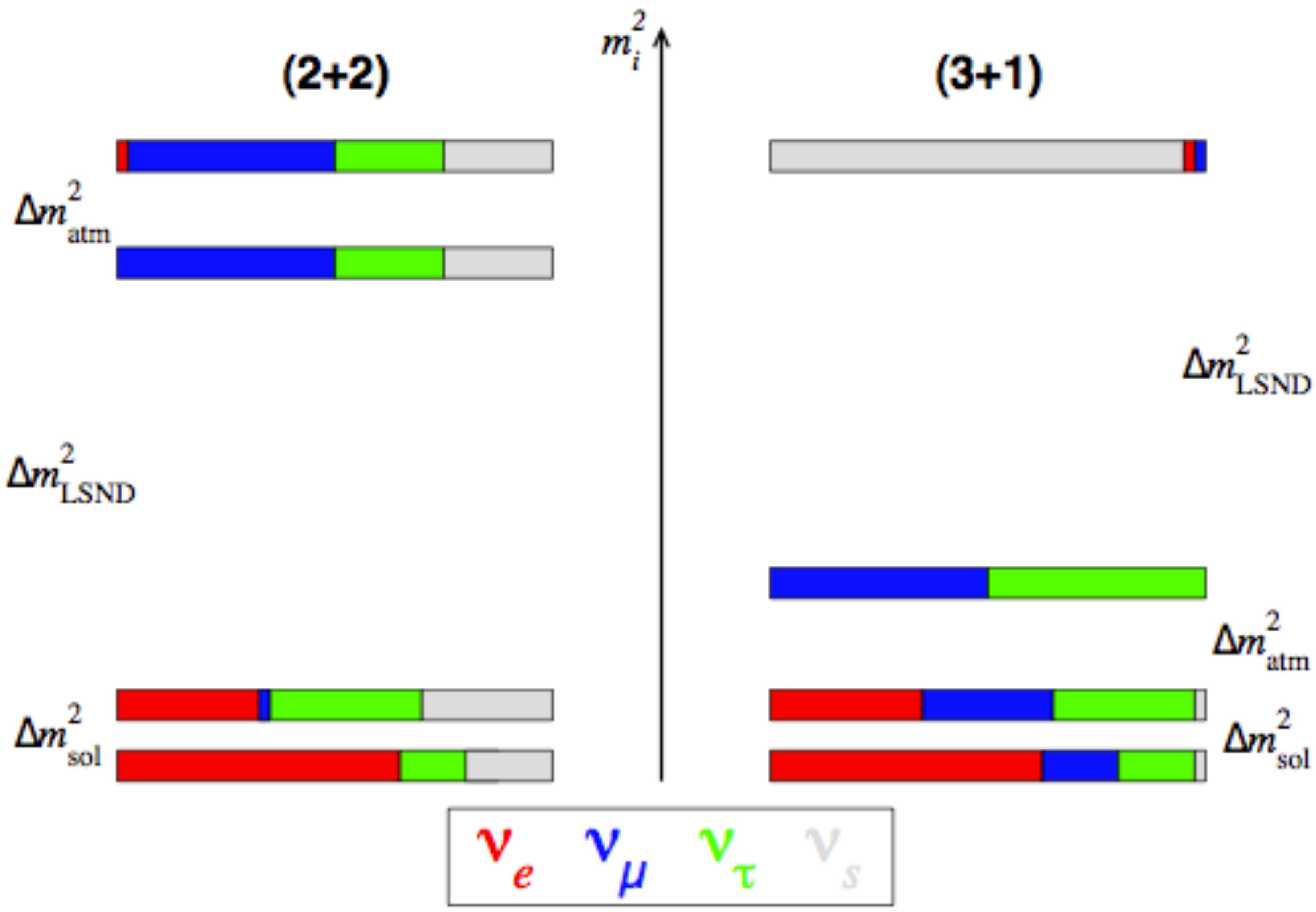


Barinov et al, PRC 2022

Interpretation of the anomalies

$\Delta m^2_{sol} \sim 8x10^{-5}\, eV^2$ $\Delta m^2_{atm} \sim 2x10^{-3}\, eV^2$ $\Delta m^2_{LSND} \sim 1\, eV^2$

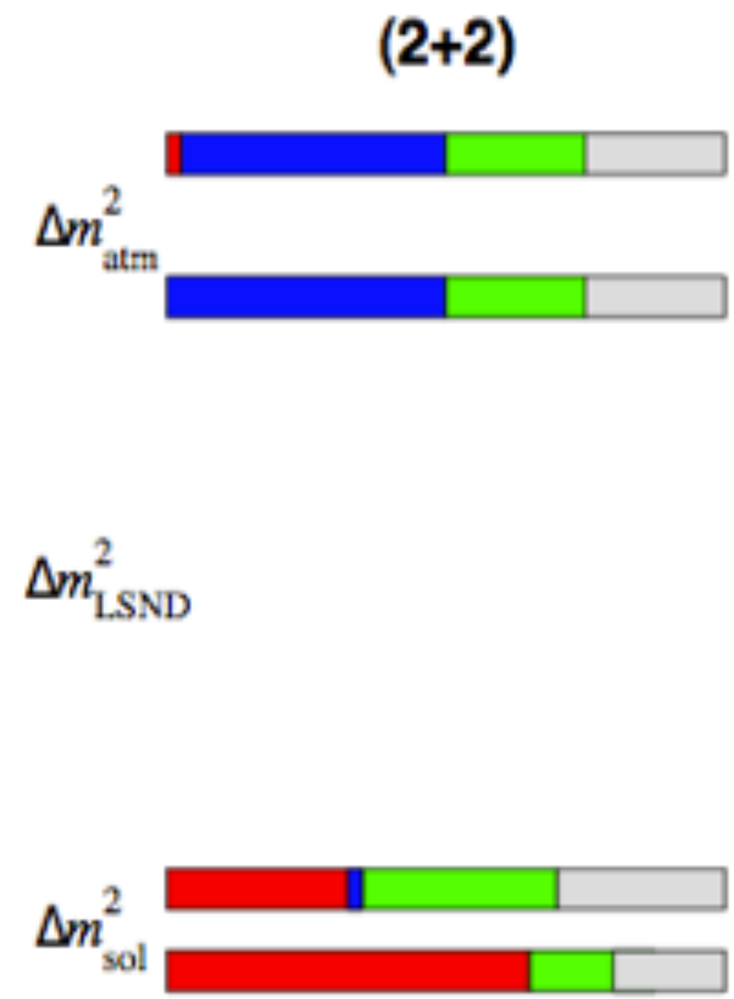
⇒ Can only be accommodated considering four neutrino states

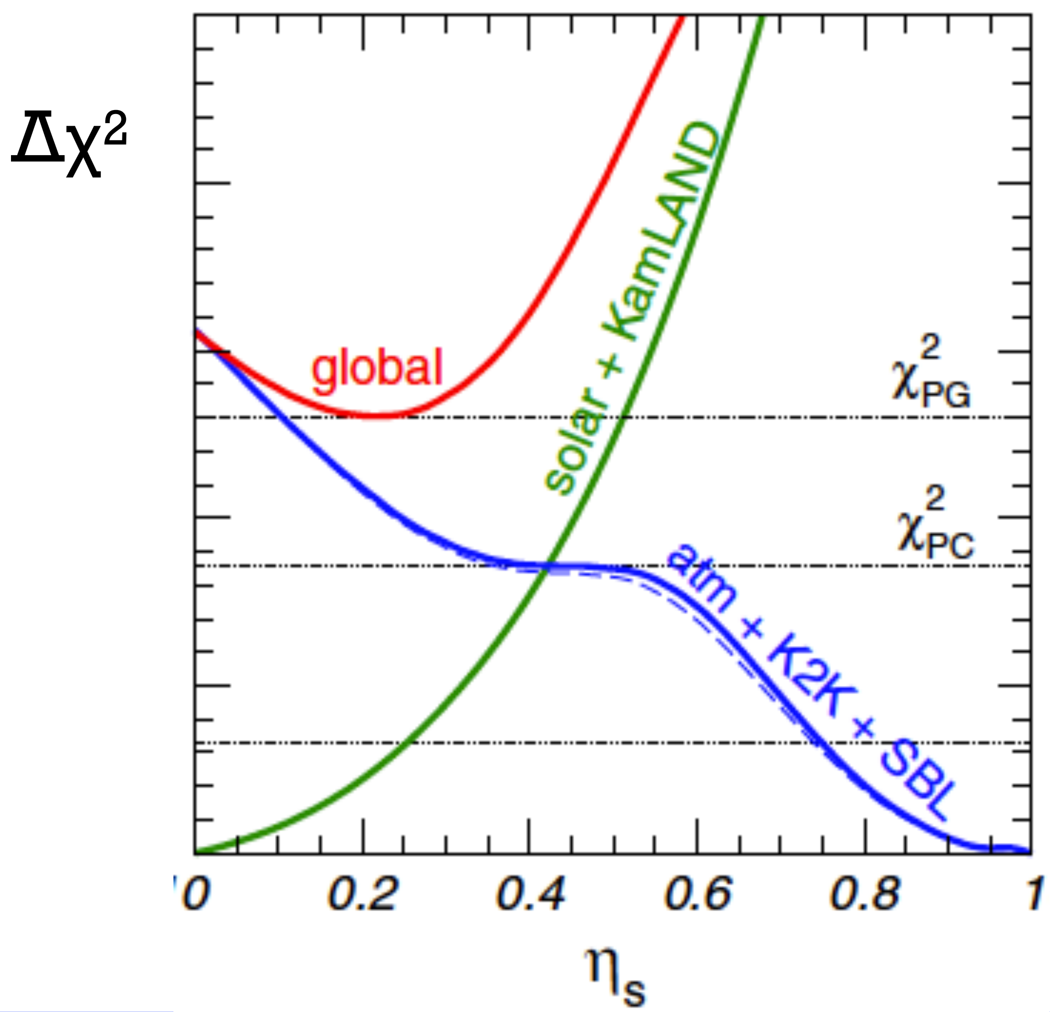


2+2 neutrino scheme

✦This scheme requires the presence of sterile neutrinos either in solar or atmospheric neutrinos

✦However, solar and atmospheric data show a strong preference for active oscillations



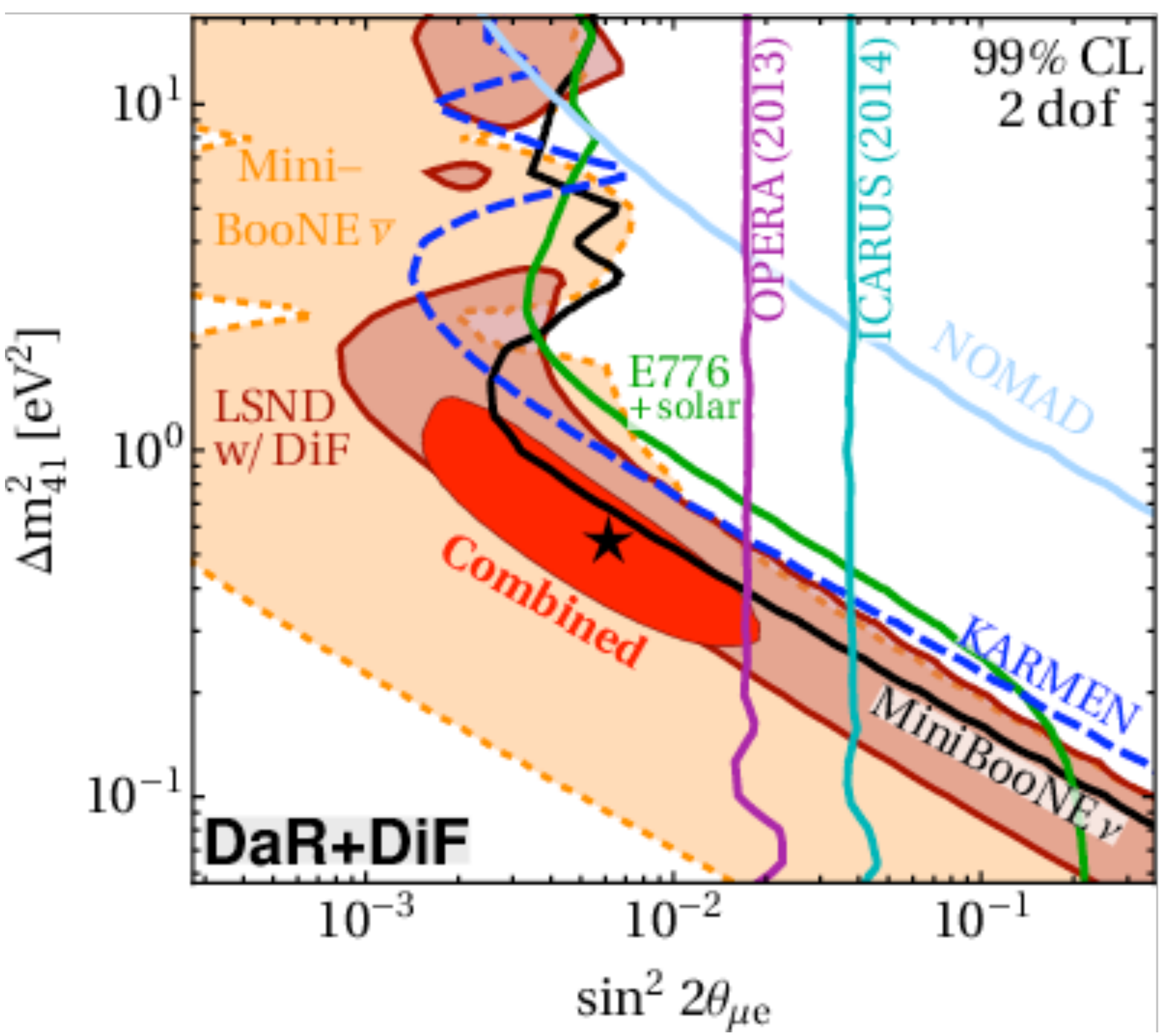


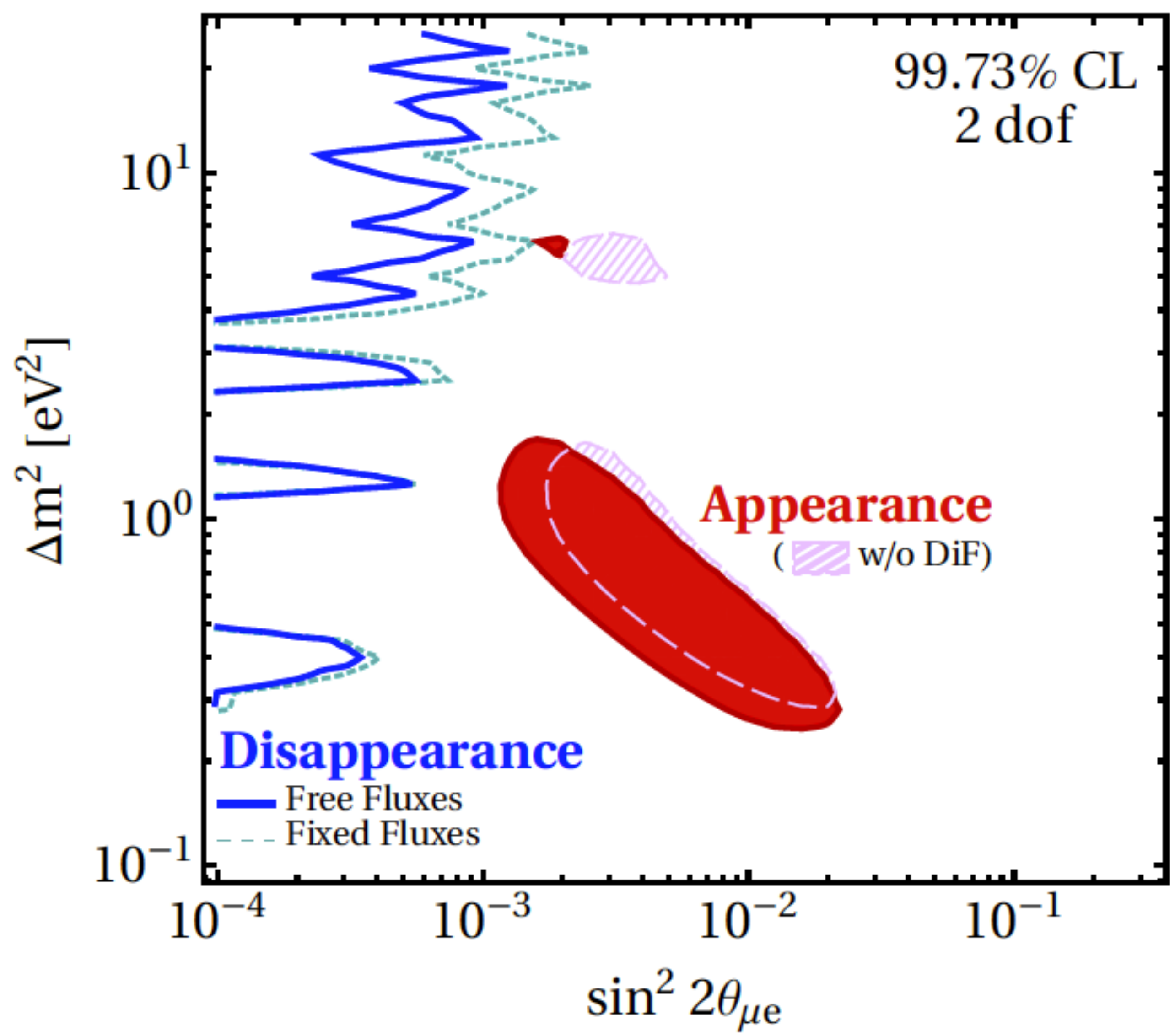
excluded by solar and atmospheric data

Maltoni et al, NPB643 (2003), NJP06 (2004)

Global fit in 3+1 neutrino scheme

Dentler et al, JHEP 2018 [See also Giunti et al]





⇒ Constraints on short-baseline $\nu_\mu \to \nu_e$ oscillations

⇒ strong tension between appearance (LSND/MiniBooNE) and disappearance experiments: SK, IceCube, MINOS/+,…

eV-sterile neutrino in Cosmology

✦ In Cosmology, sterile neutrinos with eV masses would contribute to:

Σm_ν = sum of neutrino masses

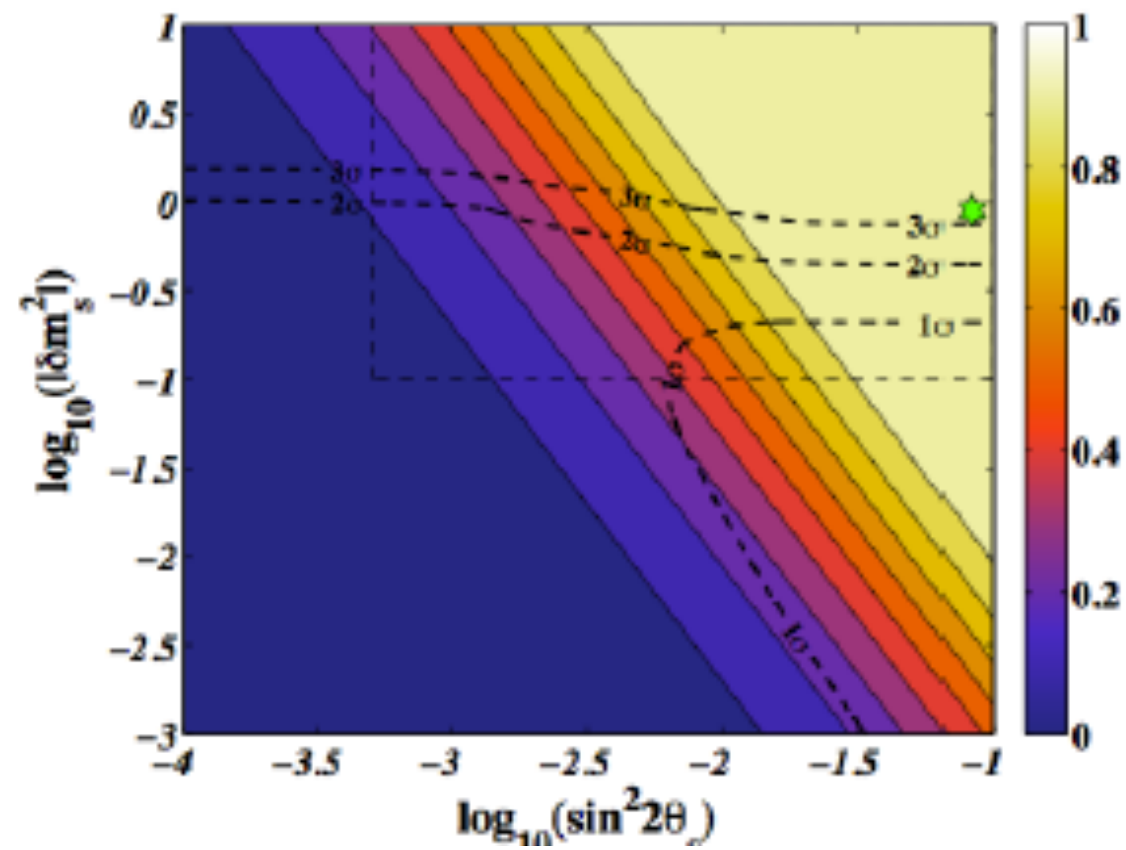
N_{eff} = relativistic degrees of freedom

✦ If the mixing active-sterile neutrino is small, one can relax limits from cosmology

✦ However, for mass & mixing parameters required to explain the anomalies, ν_s is fully thermalized in the early universe.

$$\rightarrow \sum m_\nu \gtrsim 0.05\,\mathrm{eV} + \sqrt{\Delta m^2_{41}} > 1\,\mathrm{eV}$$

$\rightarrow N_{eff} \approx 4$



Hannestad et al, 1204.5861

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$$\rightarrow \sum m_\nu \gtrsim 0.05\,\text{eV} + \sqrt{\Delta m^2_{41}} > 1\,\text{eV}$$

$\rightarrow N_{eff} \approx 4$

- Constraints from Cosmology:

$$\sum m_i < 0.12\,\text{eV}$$

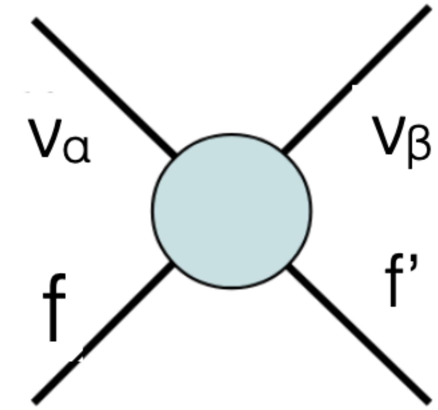
$$N_{\text{eff}} = 2.96^{+0.34}_{-0.33}$$

95%, Planck TT,TE,EE+lowE +lensing+BAO

Neutrino non-standard interactions (NSI) with matter

Neutrino NSI with matter

- New 4-fermion interactions involving neutrinos



CC-NSI: $\mathcal{L}_{\mathrm{CC-NSI}} = -2\sqrt{2}G_F\,\epsilon_{\alpha\beta}^{f f' X}\left(\bar{\nu}_\alpha \gamma^\mu P_L \ell_\beta\right)\left(\bar{f}'\gamma_\mu P_X f\right)$

$\Rightarrow$ effect on neutrino production and detection

$\epsilon^s_{\alpha\beta}$ (source) $\epsilon^d_{\alpha\beta}$ (detector)

NC-NSI: $\mathcal{L}_{\mathrm{NC-NSI}} = -2\sqrt{2}G_F\,\epsilon_{\alpha\beta}^{f X}\left(\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta\right)\left(\bar{f}\gamma_\mu P_X f\right)$

$\epsilon_{\alpha\beta} \neq 0$ $\rightarrow$ NSI violate lepton flavor (FC-NSI)

$\epsilon_{\alpha\alpha} - \epsilon_{\beta\beta} \neq 0$ $\rightarrow$ NSI violate lepton universality (NU-NSI)

$\Rightarrow$ mainly affecting neutrino propagation in matter: $\epsilon^m_{\alpha\beta}$

(but also detection, e.g., Super-K and Borexino)

- NSI may affect the 3-neutrino oscillation picture:
  - $\Rightarrow$ precision measurements at current experiments
  - $\Rightarrow$ sensitivity reach of upcoming experiments (degeneracies)

Models leading to sizeable NSI

$$\mathcal{L}_{\rm NC-NSI} = -2\sqrt{2}G_F\, \epsilon_{\alpha\beta}^{fX}\, (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)\, (\bar{f}\gamma_\mu P_X f)$$

$$\epsilon \sim \left(\frac{g_X^2}{m_X^2}\right) G_F^{-1}$$

- models with heavy mediator: $m_X >> 100$ GeV $\Rightarrow \epsilon << 1$
- models with light mediator: $m_X \sim 10$ MeV, $\epsilon \sim 1$ with $g_X \sim 10^{-4}$-10^{-5}

$\Rightarrow$ bounds on production avoided due to small coupling

$\Rightarrow$ NSI effect suppressed in scattering exp. with $q^2 >> M_X^2$ (NuTeV, CHARM, $q \sim$ GeV)

$\Rightarrow$ BBN bounds can be avoided with $m_X \gtrsim 10$ MeV

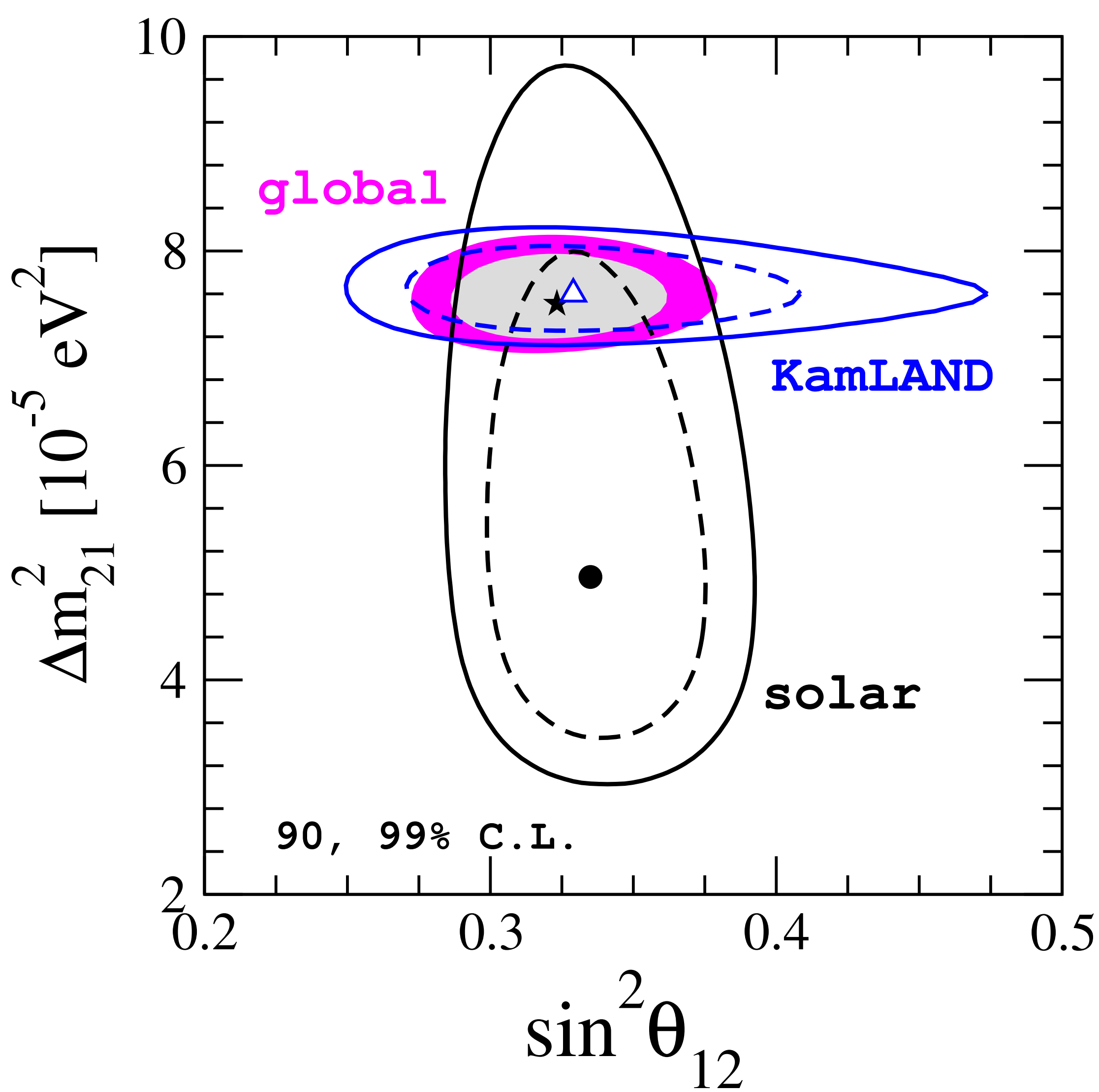
10 MeV $< m_X <$ 1 GeV

$\Rightarrow$ Strong bounds from 1st generation of leptons: avoided with $a_e = 0$

Y. Farzan, Phys. Lett. B 2015

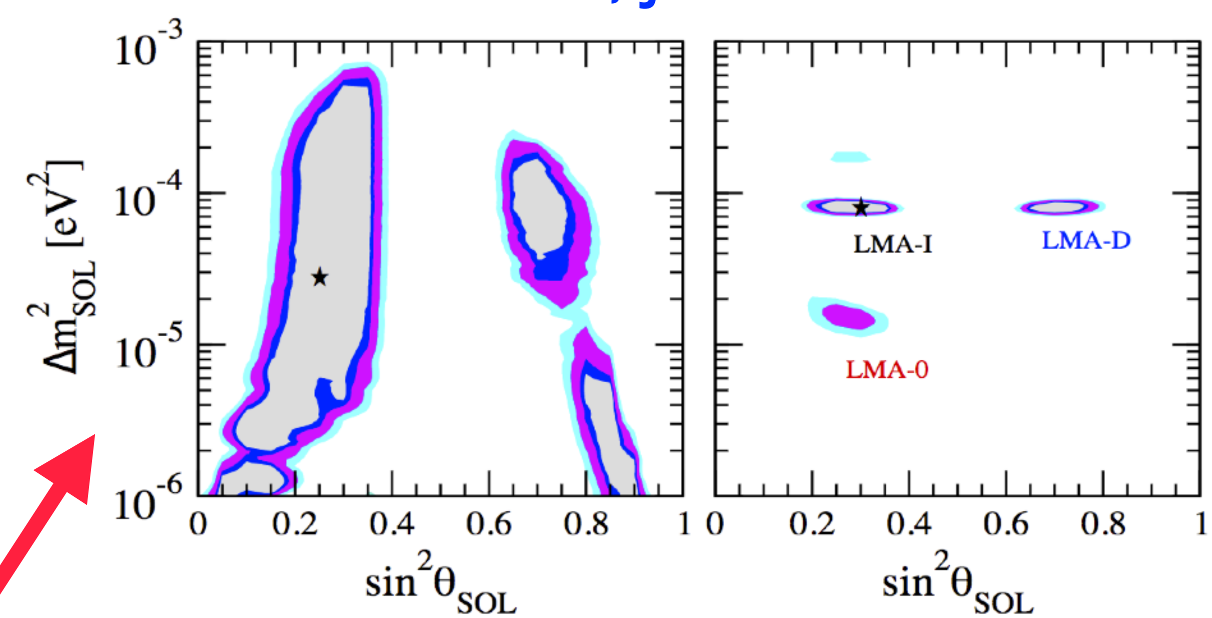
NSI in the solar neutrino sector

Standard 3ν oscillations



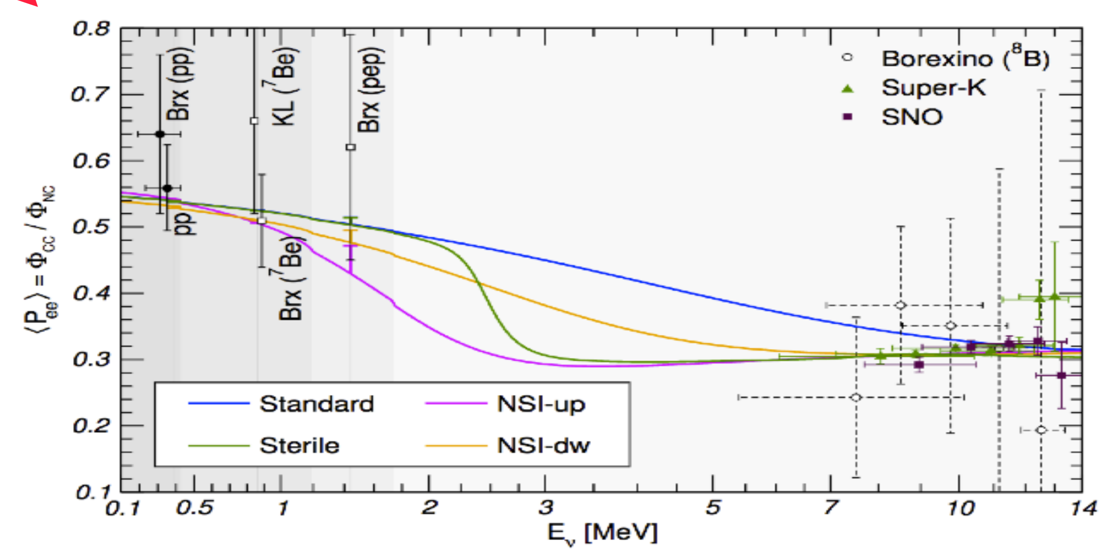
de Salas et al, PLB782 (2018) 633

Miranda et al, JHEP 2006



⇒ degenerate solar solution

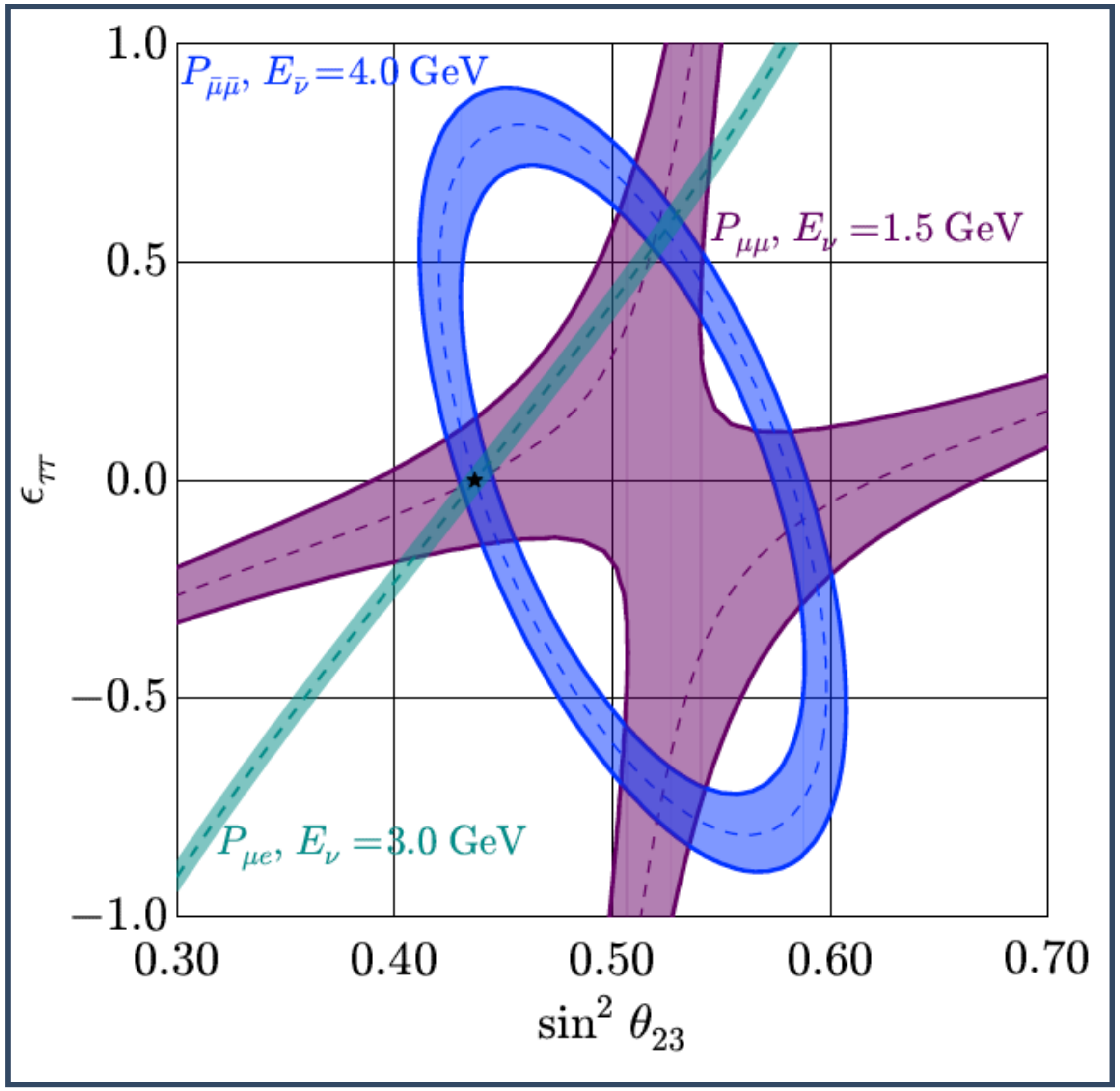
Maltoni & Smirnov, EPJ 2015



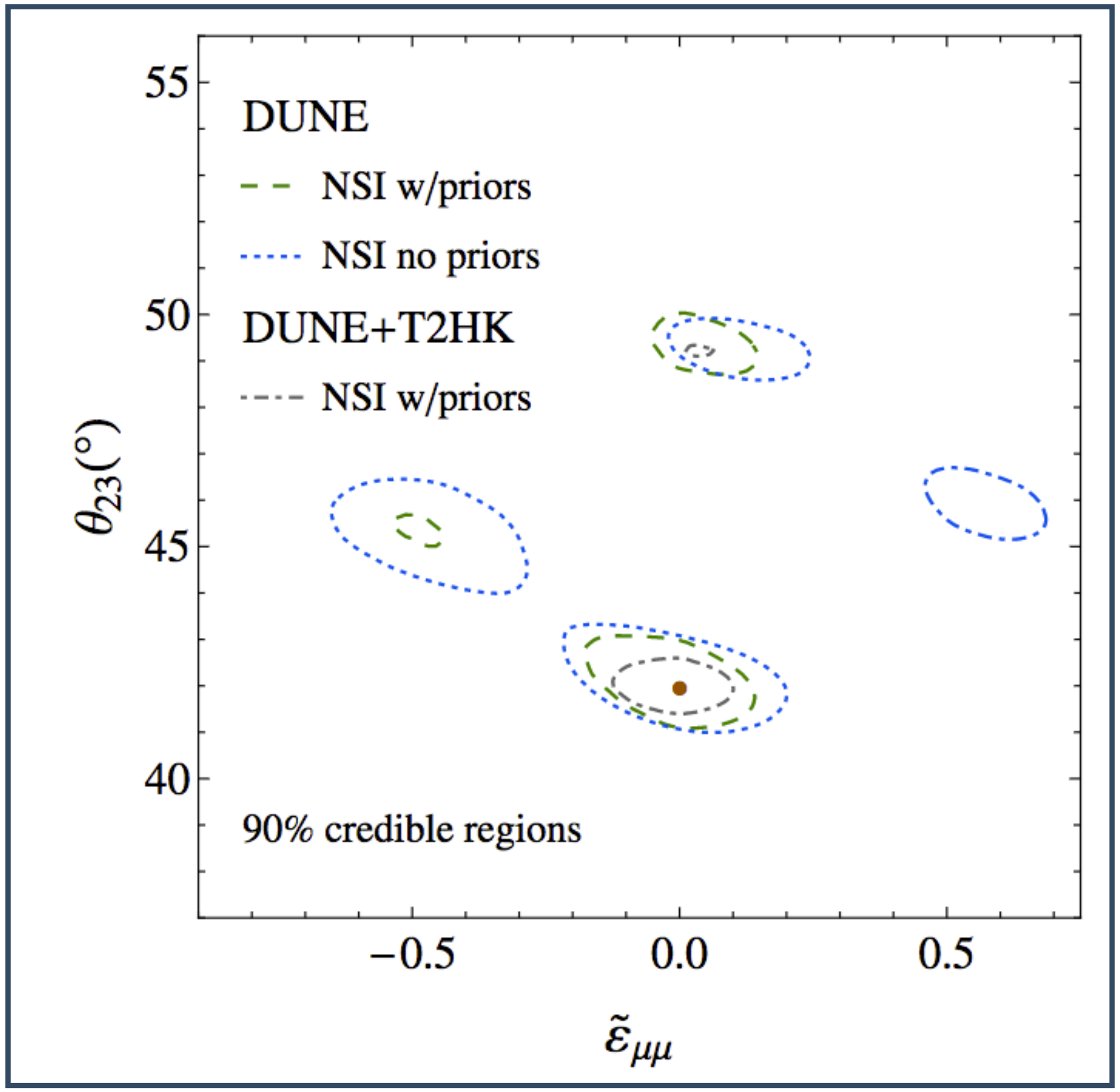
⇒ reconciles tension between Δm^2_{21}
@ KamLAND and solar data

NSI at future LBL experiments

(θ_{23}-$\epsilon_{\tau\tau}$) degeneracy in DUNE



Gouvea and Kelly, NPB 2016

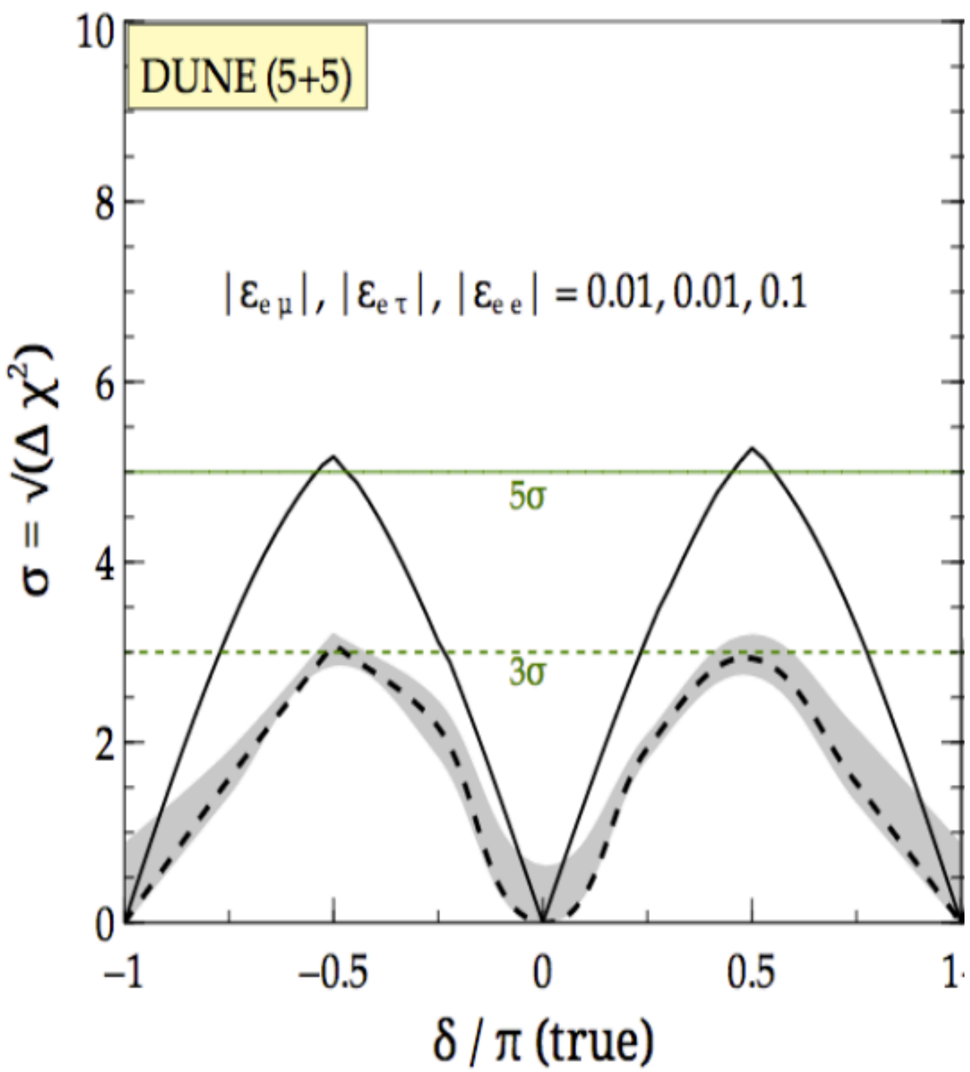


Coloma, JHEP 2016

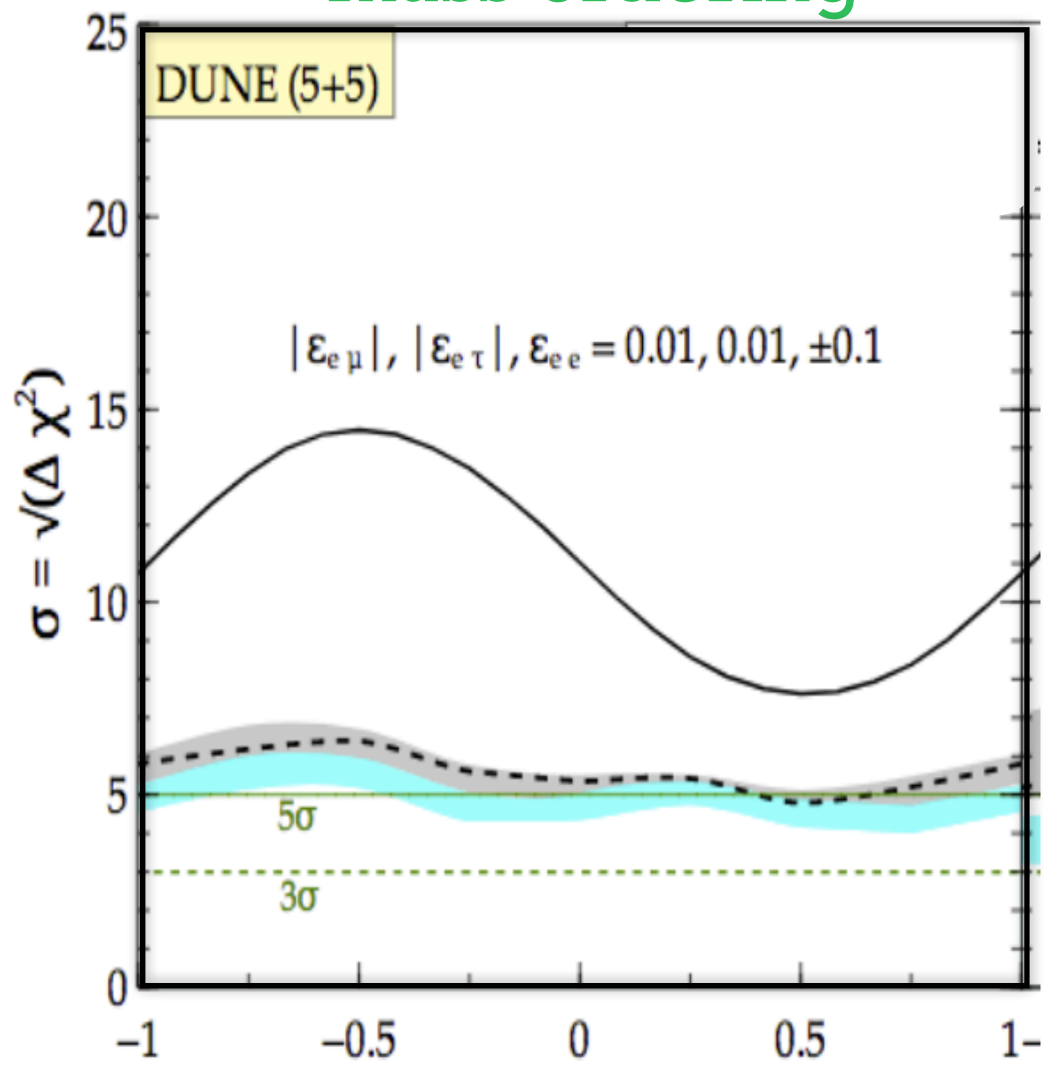
NSI at future LBL experiments

NSI can significantly spoil DUNE's sensitivity to:

CP violation



mass ordering



Masud and Mehta, PRD 2016

Non-unitary neutrino mixing

Non-unitary light neutrino mixing

✦ Most models of neutrino masses include **new extra heavy states**

Ex: type I seesaw, inverse seesaw

$$\begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix} \qquad \begin{pmatrix} 0 & M_D & 0 \\ M_D^T & 0 & M \\ 0 & M^T & \mu \end{pmatrix}$$

→ (3x3) light neutrino mixing matrix U is **non-unitary** in general

✦ NxN **non-unitary mixing matrix** described with $2N^2$-(2N-1) parameters

→ 13 parameters are needed to describe a non-unitary (3x3) matrix

→ besides the 4 standard ones (θ_{ij} and δ_{CP}), 9 more parameters are needed

✦ General parameterization for non-unitary NxN mixing matrix

$$U^{n\times n} = \begin{pmatrix} N & W \\ V & T \end{pmatrix} \quad \text{with} \quad N = N^{NP} U^{3\times 3} = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U^{3\times 3}$$

Escrihuela et al, PRD92 (2015)

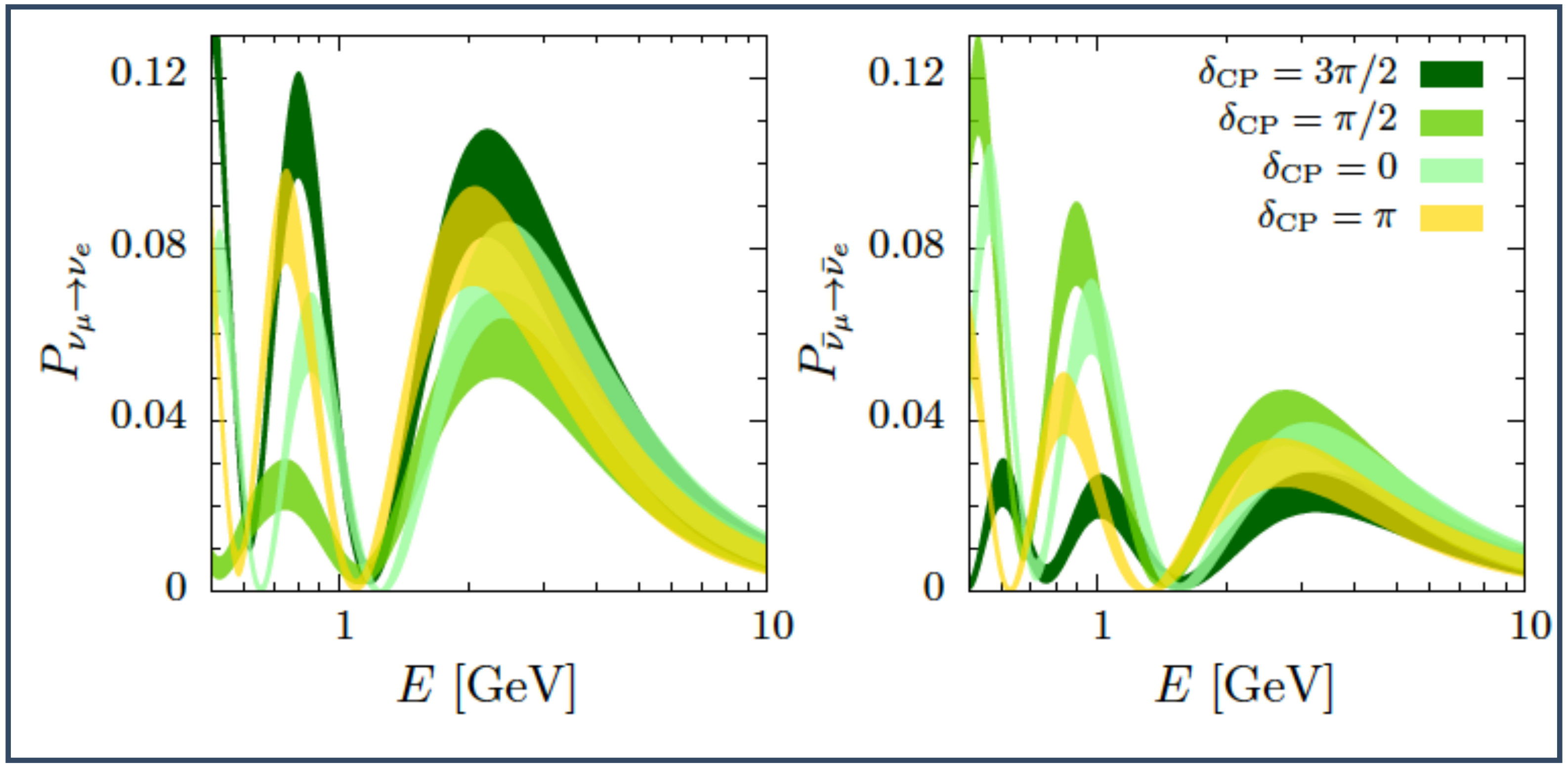
See also Xing, PRD2012 for n=6

→ α_{ii} real, α_{ij} complex: 9 new parameters

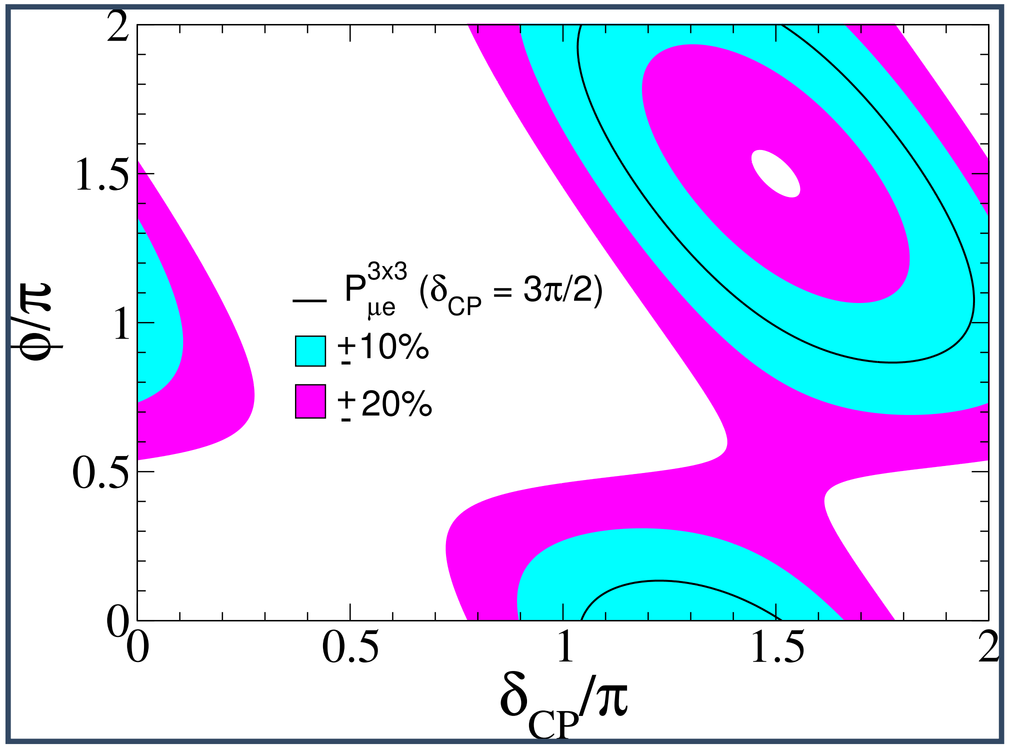
NU neutrino oscillations in DUNE

$$P_{\mu e} = (\alpha_{11}\alpha_{22})^2 P_{\mu e}^{3\times 3} + \alpha_{11}^2\alpha_{22}|\alpha_{21}|P_{\mu e}^{I} + \alpha_{11}^2|\alpha_{21}|^2$$ **with** $P_{\mu e}^{I}(\phi)$

The new phases (ϕ) will modify the standard oscillation picture in LBL experiments, such as DUNE



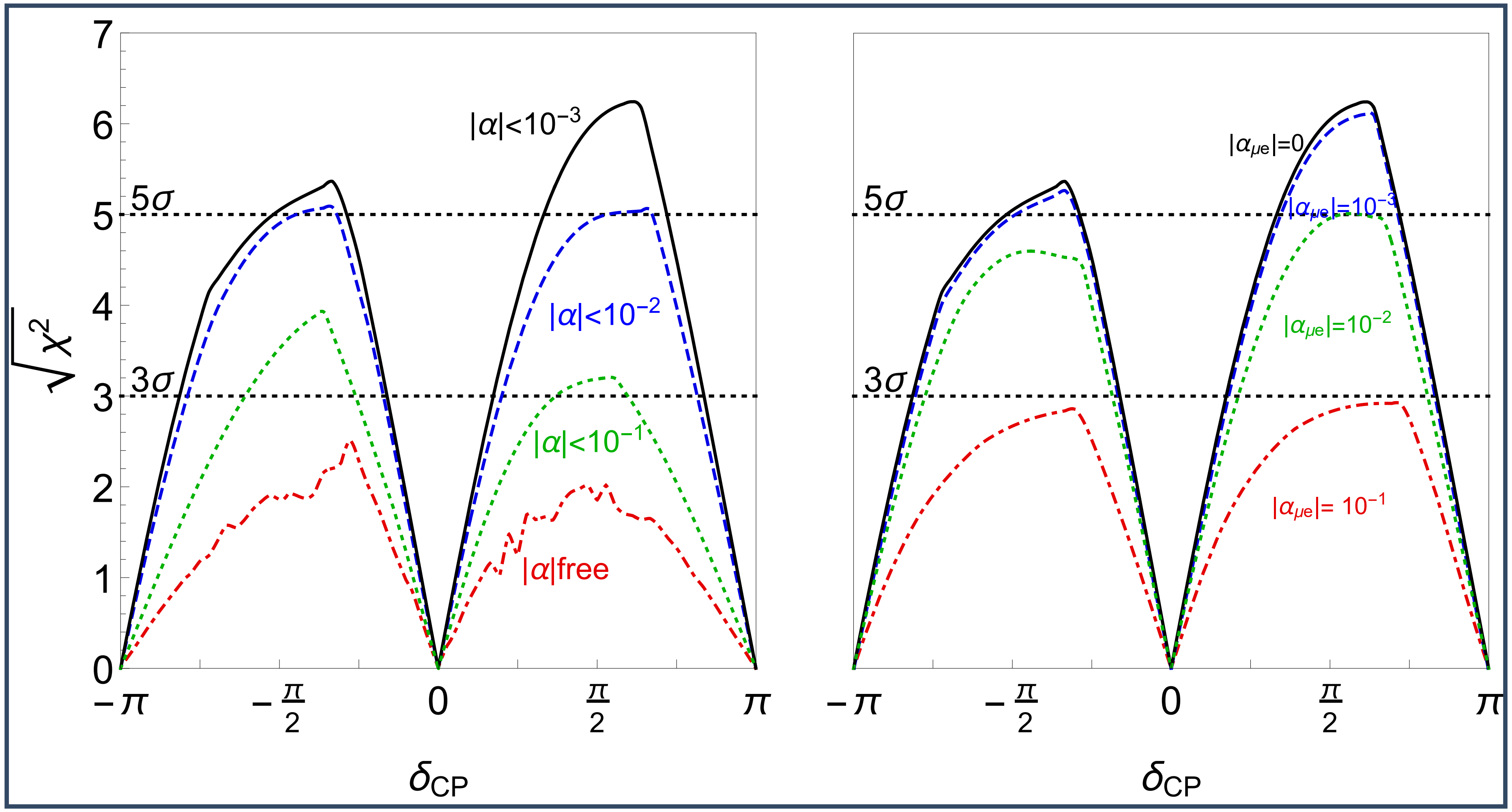
Escrihuela et al, NJP 2017



Miranda, MT, Valle, PRL 117 (2016)

→ (δ, ϕ) degeneracies in $P_{\mu e}$ for E≳ 3 GeV spoil sensitivity to δ

DUNE CP sensitivity with NU



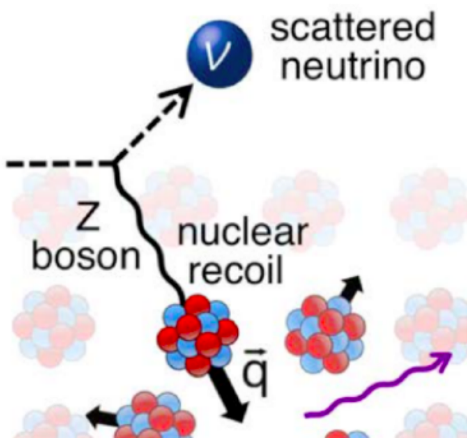
Fernández-Martínez et al (DUNE-BSM Working Group)

→ The sensitivity to CP violation might be spoiled in the absence of priors on NU

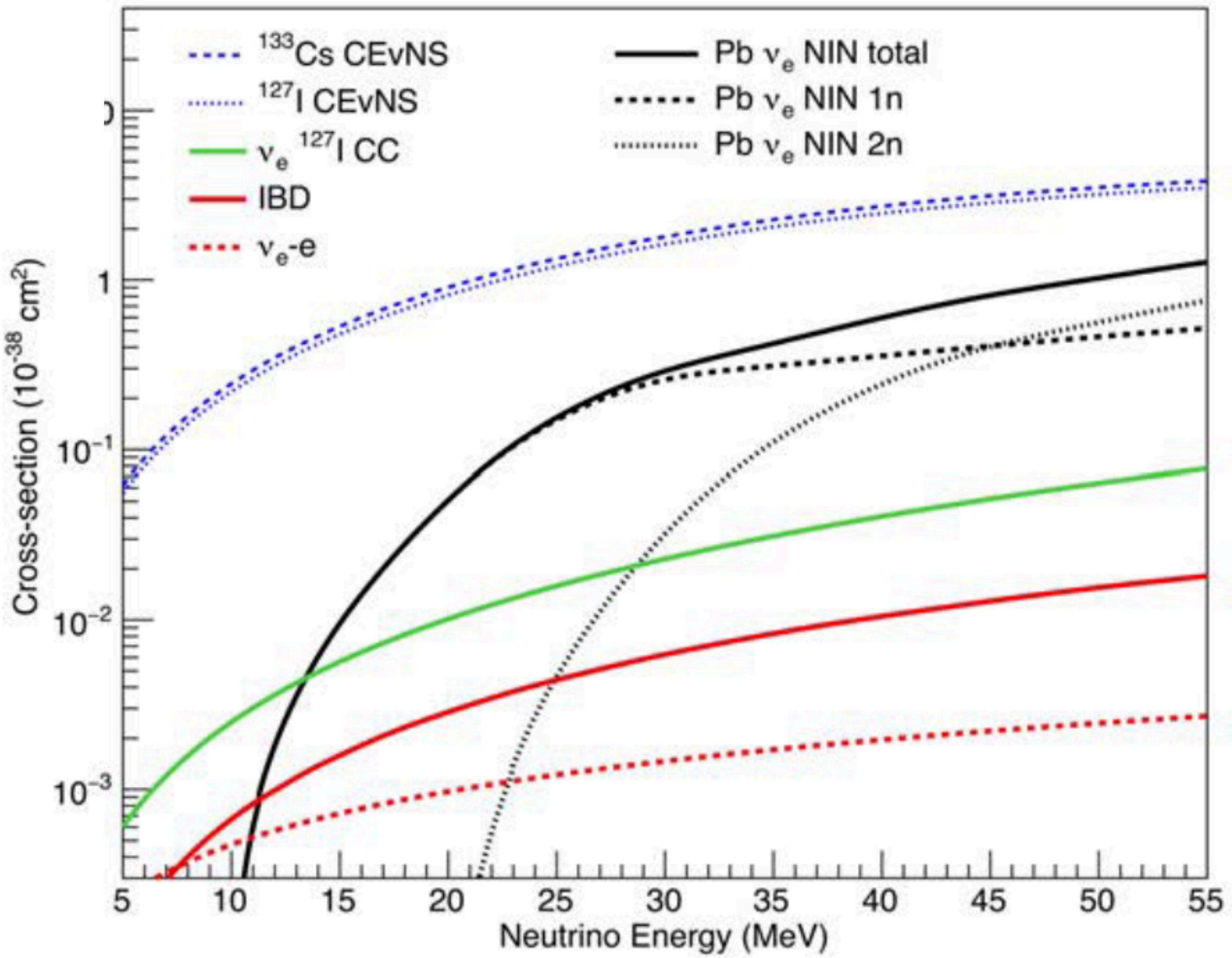
→ With priors based on current bounds (10^{-3}-10^{-2}), the effect is not less dramatic

BSM searches with CEvNS experiments

Coherent Elastic ν Nucleus Scattering (CEνNS)



D. Freedman PRD9 (1974) 1389



First observed at the Spallation Neutron Source (Oak Ridge National Laboratory) in 2017

COHERENT Coll. Science 357 (2017) 1123

What can we learn from CEνNS?

new ν interactions with quarks

ν e.m. properties

$g_V^p(\nu_e) = 0.0382$
$g_V^p(\nu_\mu) = 0.0300$
$g_V^n = -0.5117^*$

Neutrino energy — Mass of the nucleus — SM vector proton coupling — SM vector neutron coupling

$$\frac{d\sigma^{CE\nu NS}(E_\nu, T_{nr})}{dT_{nr}} \cong \frac{G_F^2\, m_N}{\pi}\left(1-\frac{m_N T_{nr}}{2E_\nu^2}\right)\left[g_V^p\left(\sin^2(\vartheta_W)\right) Z F_Z(|\vec{q}|^2) + g_V^n N F_N(|\vec{q}|^2)\right]^2 + \ldots$$

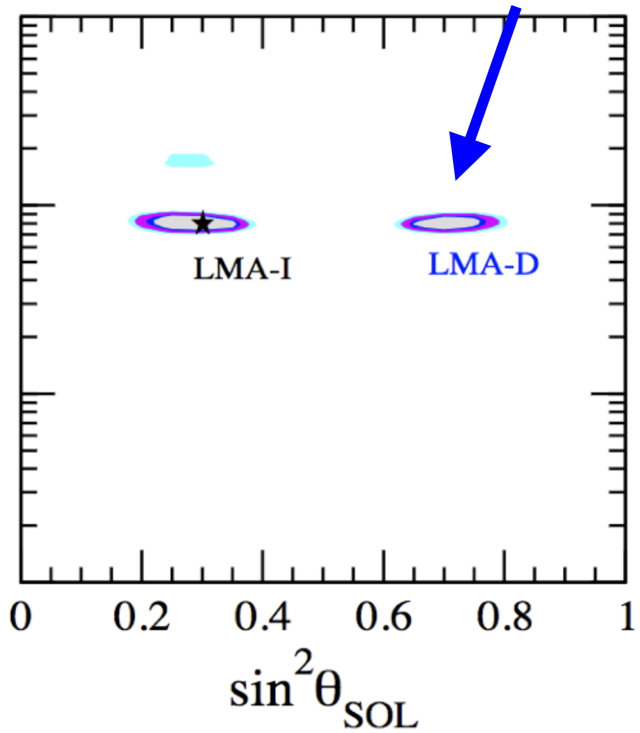
Nuclear recoil energy — Weinberg angle — Proton Form Factor — Neutron Form Factor

EW precision

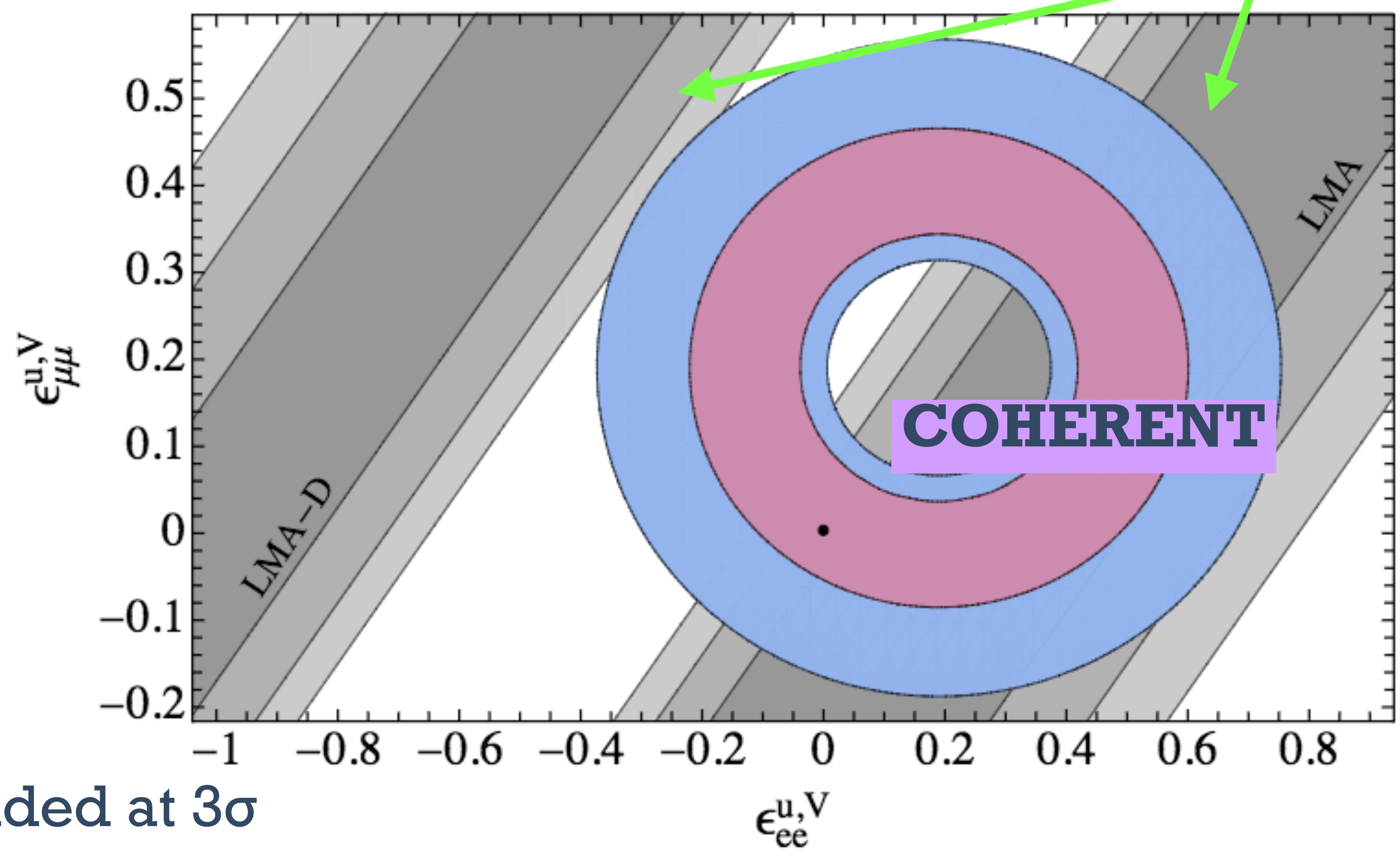
nuclear physics

Impact of CEvNS results in NSI

degenerate solution



oscillations



⇒ **LMA-Dark** excluded at 3σ

Relaxed if:

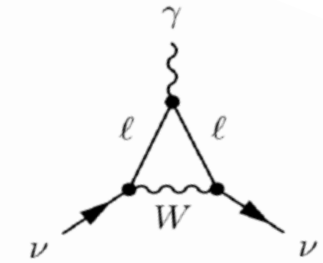
- NSI mediator lighter than 50 MeV
- degeneracies in (ε_d, ε_u)

Coloma et al, PRD 2017

Complementarity of CEvNS and oscillation data to constrain BSM physics

Constraining neutrino electromagnetic properties with CEvNS

Neutrino charge radius



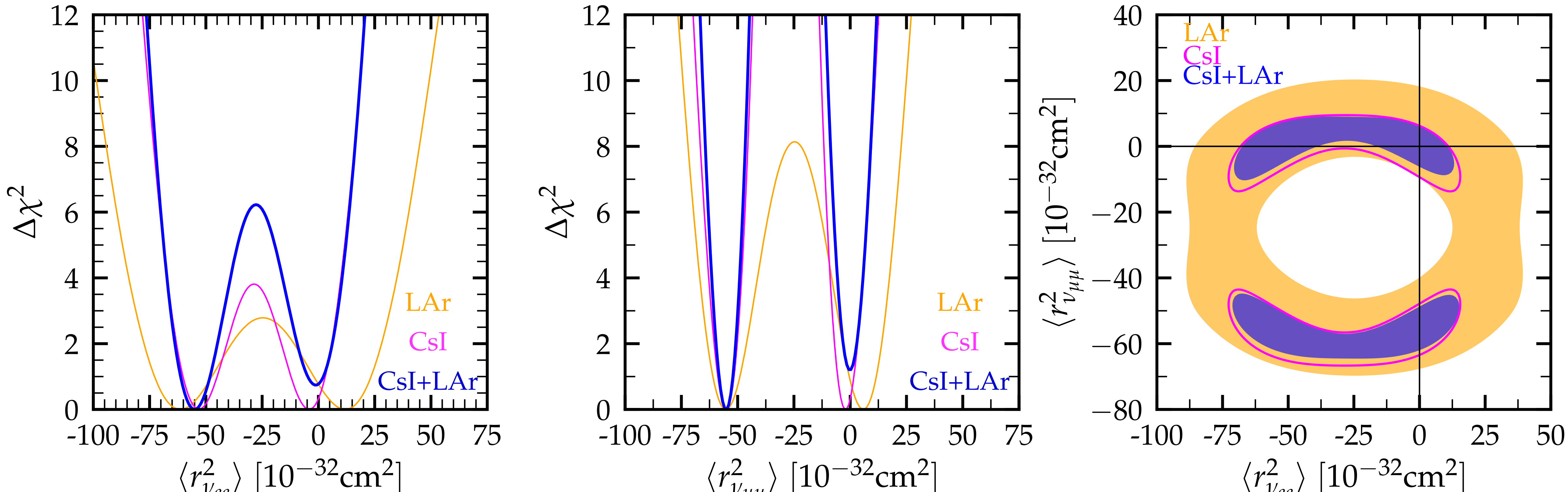
- It is the only EM neutrino parameter that is different from zero in the SM:

$$\left(\langle r^2_{\nu_{ee}}\rangle, \langle r^2_{\nu_{\mu\mu}}\rangle, \langle r^2_{\nu_{\tau\tau}}\rangle\right) = (-0.83, -0.48, -0.30) \times 10^{-32}\ \text{cm}^2$$

Bernabeu et al NPB 2004

- New contribution to the CEvNS cross section, proportional to

$$Q^{\rm CR}_{\ell\ell} = \frac{\sqrt{2}\pi\alpha_{\rm EM}}{3\,G_F}\langle r^2_{\nu_{\ell\ell}}\rangle$$



$$\langle r^2_{\nu_{ee}}\rangle \in [-61.2, -48.2] \cup [-4.7, 2.2] \times 10^{-32}\ \text{cm}^2$$

$$\langle r^2_{\nu_{\mu\mu}}\rangle \in [-58.2, -52.1] \times 10^{-32}\ \text{cm}^2$$

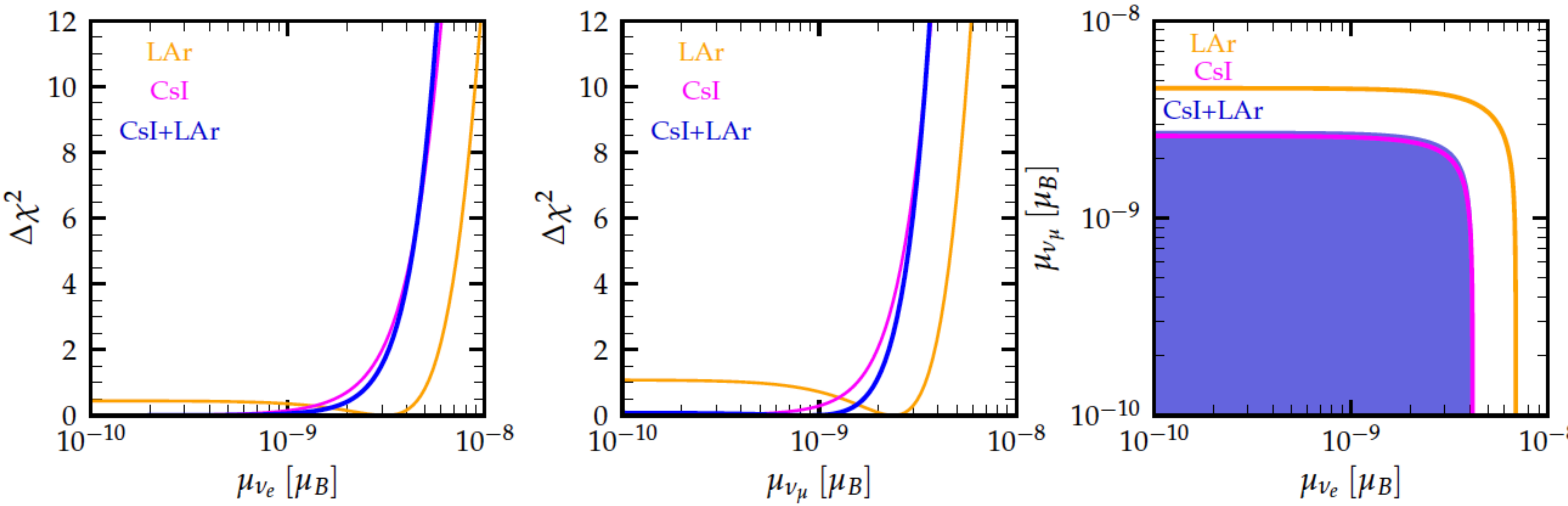
(1σ)

De Romeri et al, JHEP 2023

Neutrino magnetic moment

- Minimal SM extension (with m_ν) predicts $\mu_\nu \simeq 3 \times 10^{-19} \left(\frac{m_\nu}{\text{eV}}\right) \mu_B$ ➡ larger in BSM
- The (effective) neutrino magnetic moment gives an extra contribution to CEvNS cross section:

$$\left.\frac{d\sigma_{\nu_\ell \mathcal{N}}}{dE_{\rm nr}}\right|_{\rm CE\nu NS}^{\rm MM} = \frac{\pi \alpha_{\rm EM}^2}{m_e^2}\left(\frac{1}{E_{\rm nr}} - \frac{1}{E_\nu}\right) Z^2 F_W^2(|\vec{q}|^2) \left|\frac{\mu_{\nu_\ell}}{\mu_{\rm B}}\right|^2$$



$\mu_{\nu_e} < 3.6 \times 10^{-9} \mu_B$ $\mu_{\nu_\mu} < 2.4 \times 10^{-9} \mu_B$ (90% C.L.)

De Romeri et al, JHEP 2023

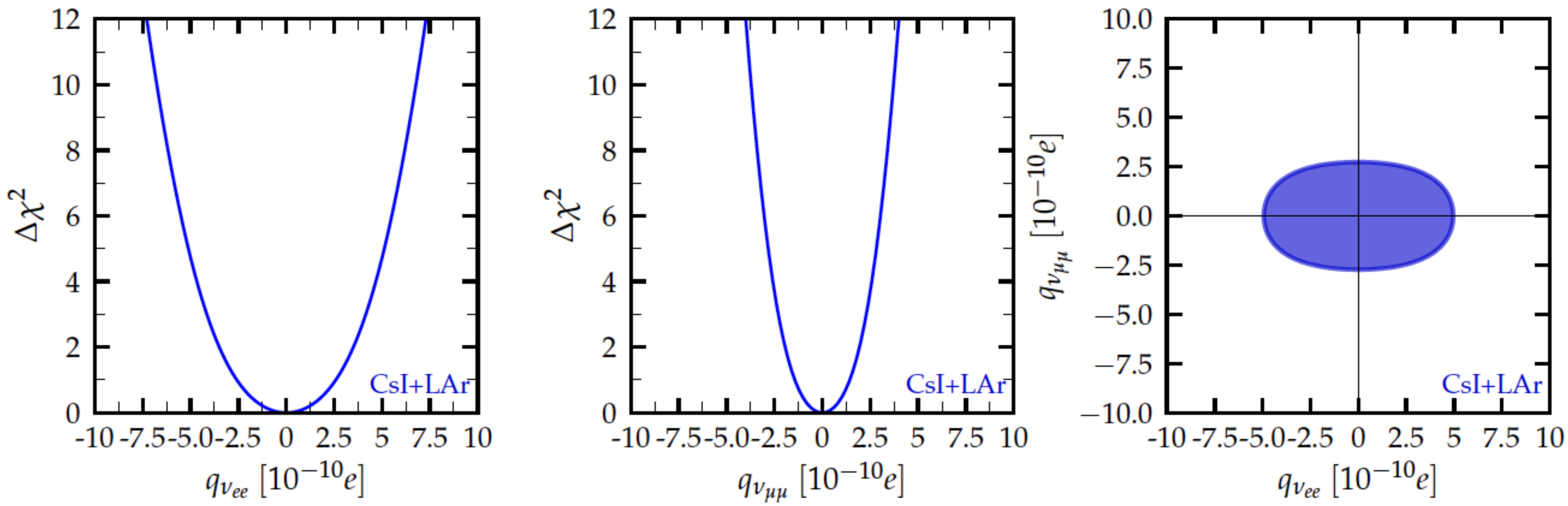
Neutrino electric (milli) charge

- In BSM models, neutrinos can acquire small electric charges: **millicharges**
- This electric charge would generate a new contribution to the CEνNS and ES cross section, proportional to

$$Q_{\ell\ell}^{\mathrm{EC}} = \frac{2\sqrt{2}\pi\alpha_{\mathrm{EM}}}{G_F q^2} q_{\nu_{\ell\ell}}$$

neutrino millicharge

momentum transfered



$$q_{\nu_{ee}} \in [-2.6, 2.6] \times 10^{-10} e \qquad q_{\nu_{\mu\mu}} \in [-1.4, 1.4] \times 10^{-10} e \qquad (1\sigma)$$

De Romeri et al, JHEP 2023

Comparison with previous results

D. Papoulias, Magnificent CEvNS workshop 2023

Flavor	$\lvert\mu_\nu\rvert$ $[10^{-11}\mu_B]$	q_ν $[10^{-12}e]$	$\langle r_\nu^2\rangle$ $[10^{-32}\text{cm}^2]$
ν_e	≤ 1.4 (LZ)	$[-0.3, 0.6]$ (LZ)	$[-121, 37.5]$ (LZ)
	≤ 0.9 (XENONnT)	$[-0.1, 0.6]$ (XENONnT)	$[-93.4, 9.5]$ (XENONnT)
	≤ 3.7 (Borexino)	≤ 1 (Reactor)	[-61.2, -48.2] ∪ [-4.7, 2.2] XONO)
	≤ 2.9 (GEMMA)	$[-9.3, 9.5]$ (Dresden-II)	$[-5.94, 8.28]$ (LSND)
	$\leq$ **360 (COHERENT)**	$\mathbf{[-260, 260]}$ **(COHERENT)**	$\mathbf{[61.2, 48.2] \cup [4.7, 2.2]}$ **(COHERENT)**
ν_μ	≤ 2.3 (LZ)	$[-0.7, 0.7]$ (LZ)	$[-109, 112.3]$ (LZ)
	≤ 1.5 (XENONnT)	$[-0.6, 0.6]$ (XENONnT)	$[-50.2, 54]$ (XENONnT)
	≤ 5 (Borexino)	≤ 11 (XMASS-I)	$[-1.2, 1.2]$ (CHARM-II)
	$\leq$ **240 (COHERENT)**	$\mathbf{[-140, 140]}$ **(COHERENT)**	$\mathbf{[-58.2, -52.1]}$ **(COHERENT)**
ν_τ	≤ 2 (LZ)	$[-0.6, 0.6]$ (LZ)	$[-93.7, 97]$ (LZ)
	≤ 1.3 (XENONnT)	$[-0.5, 0.5]$ (XENONnT)	$[-43, 46.8]$ (XENONnT)
	≤ 5.9 (Borexino)	≤ 11 (XMASS-I)	

DM exp: very low E-threshold!

In general not very competitive but they complement other searches

Summary (I)

- Neutrinos play an important role in many **physical and astrophysical scenarios**
- Important discoveries on neutrino physics along last century have provided the **first evidence for physics beyond the Standard Model**
- **Neutrino oscillations** are well stablished with observations in several experiments, with natural and artificial sources.
- Most **oscillation parameters** are measured quite accurately ($\lesssim$ 5%) by the combination of different experiments.
- The absolute scale of neutrino mass is bounded from cosmological and laboratory measurements, below 1 eV.
- Extensions of the SM can explain the **smallness of neutrino mass**, although the flavor structure is not well understood yet.

Summary (II)

- Several **scenarios of physics BSM** are motivated by the building of neutrino mass models and the observation of anomalies are being explored.

- Anomalies point towards the existence of **light (eV) sterile neutrinos.** However, some of them although some of them are in conflict with other data and the full picture is in **tension with cosmology.**

- New **physics beyond the SM** (NSI, NU mixing) may affect significantly the standard picture of neutrino oscillations but they can also help to alleviate some experimental tensions.

- Coherent elastic neutrino-nucleus scattering, CEvNS, provide a powerful tool to search for new physics BSM.