Neutrino Physics (II)

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Session 1

Neutrinos in the SM

- Main properties
- Neutrino mass in the SM

Neutrino oscillations

- Introduction & formalism
- Current status of ν oscillations
- Unknowns in the 3ν paradigm
- Future prospects

Session 2

Neutrino masses

- Current limits
- Neutrino mass models

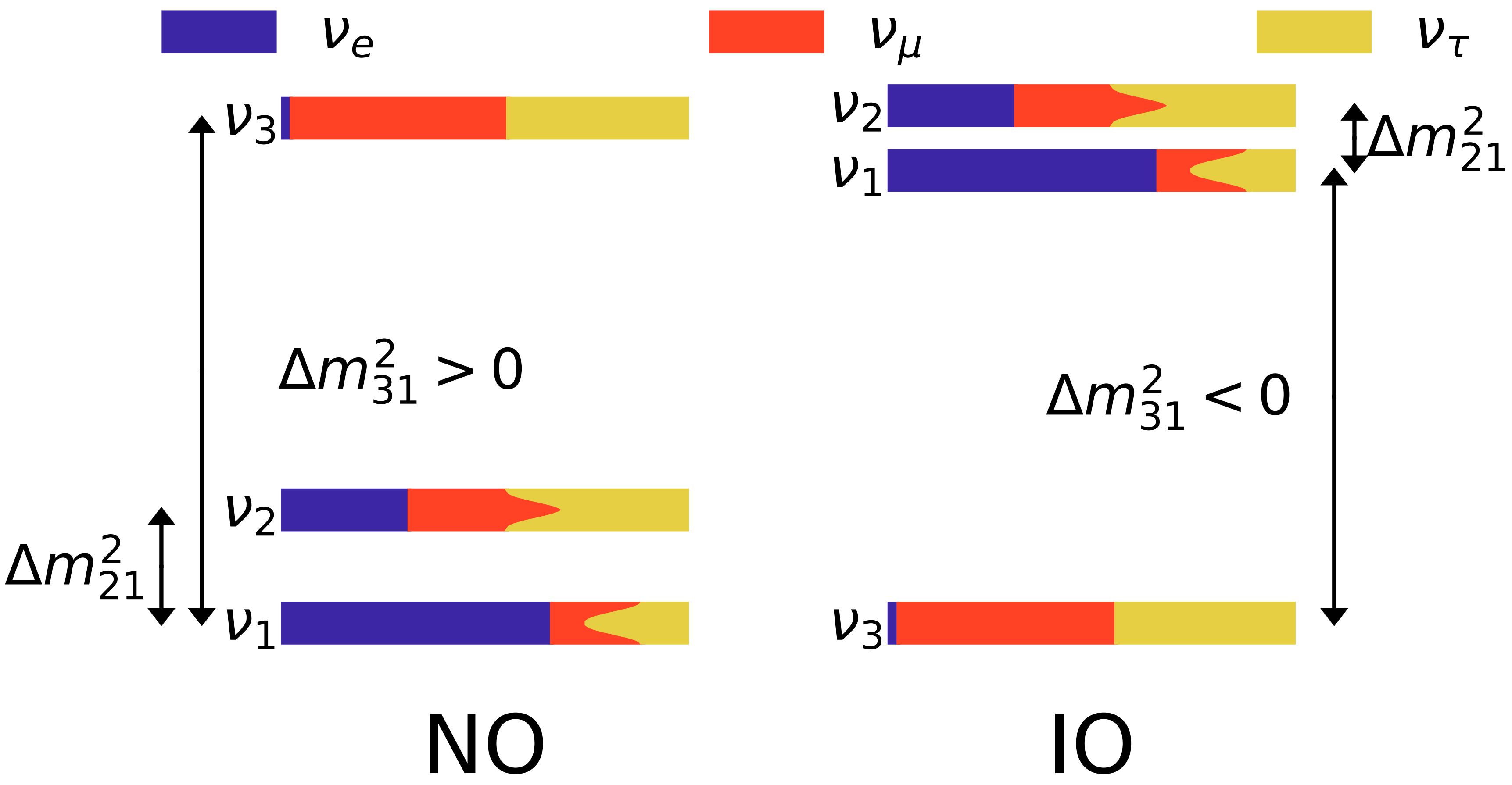
Neutrino physics BSM

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

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?

From oscillations: $\boxed{m_\nu \geq \sqrt{\Delta m^2_{31}(\mathrm{NO})} \gtrsim 0.05\,\mathrm{eV}}$

Sensitivity to neutrino mass

Neutrino oscillations

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

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

Cosmology

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

Beta decay kinematics

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

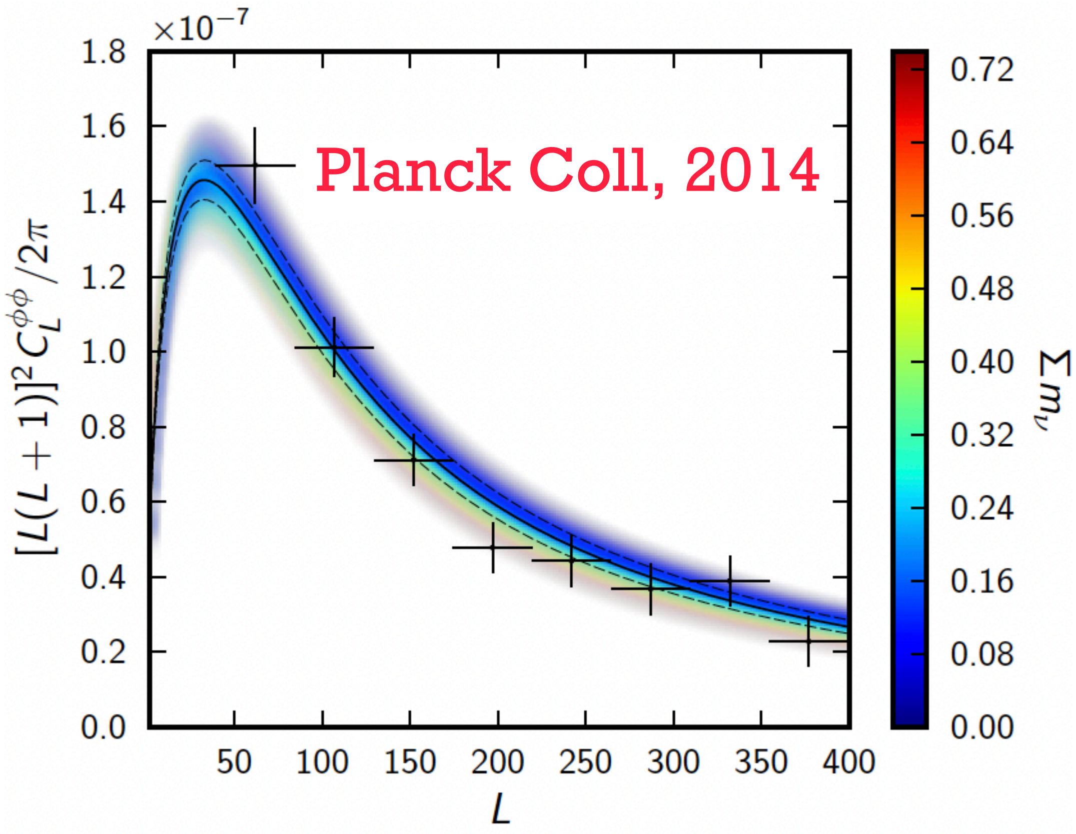
Neutrinoless 2β decay

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

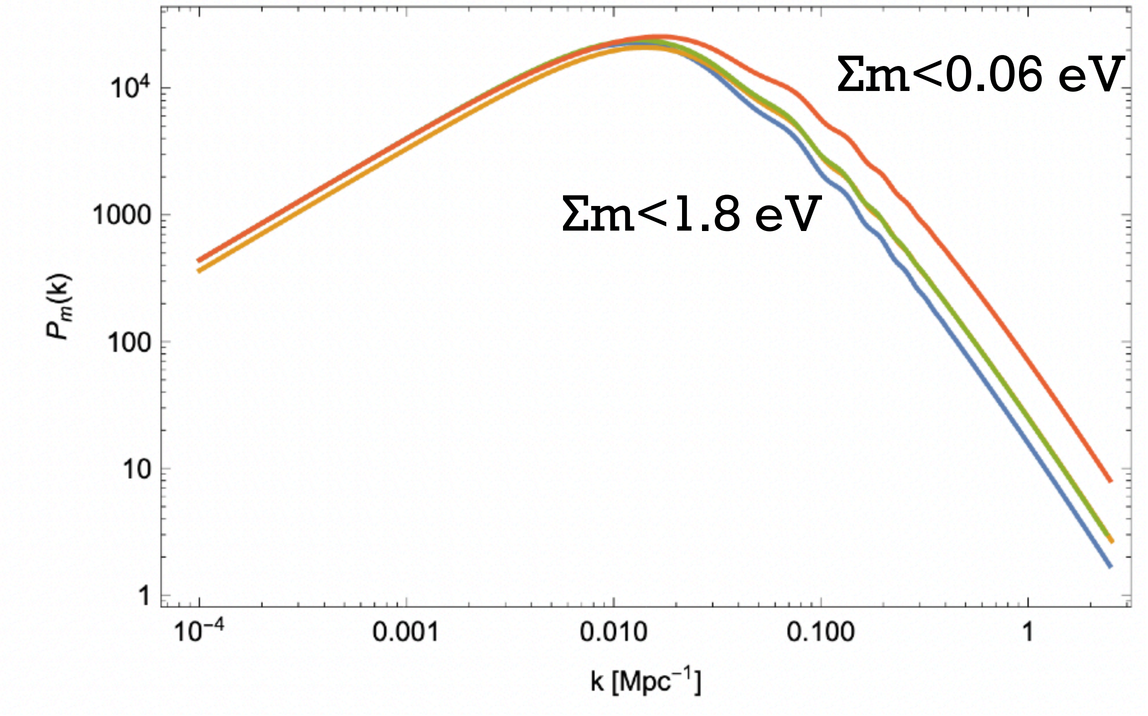
Neutrino mass in cosmology

- Neutrino masses may affect cosmological observables:

CMB anisotropies and lensing


Planck Coll, 2014

Large Scale Structure formation



Lattanzi and Gerbino, Front.Phys 2018

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

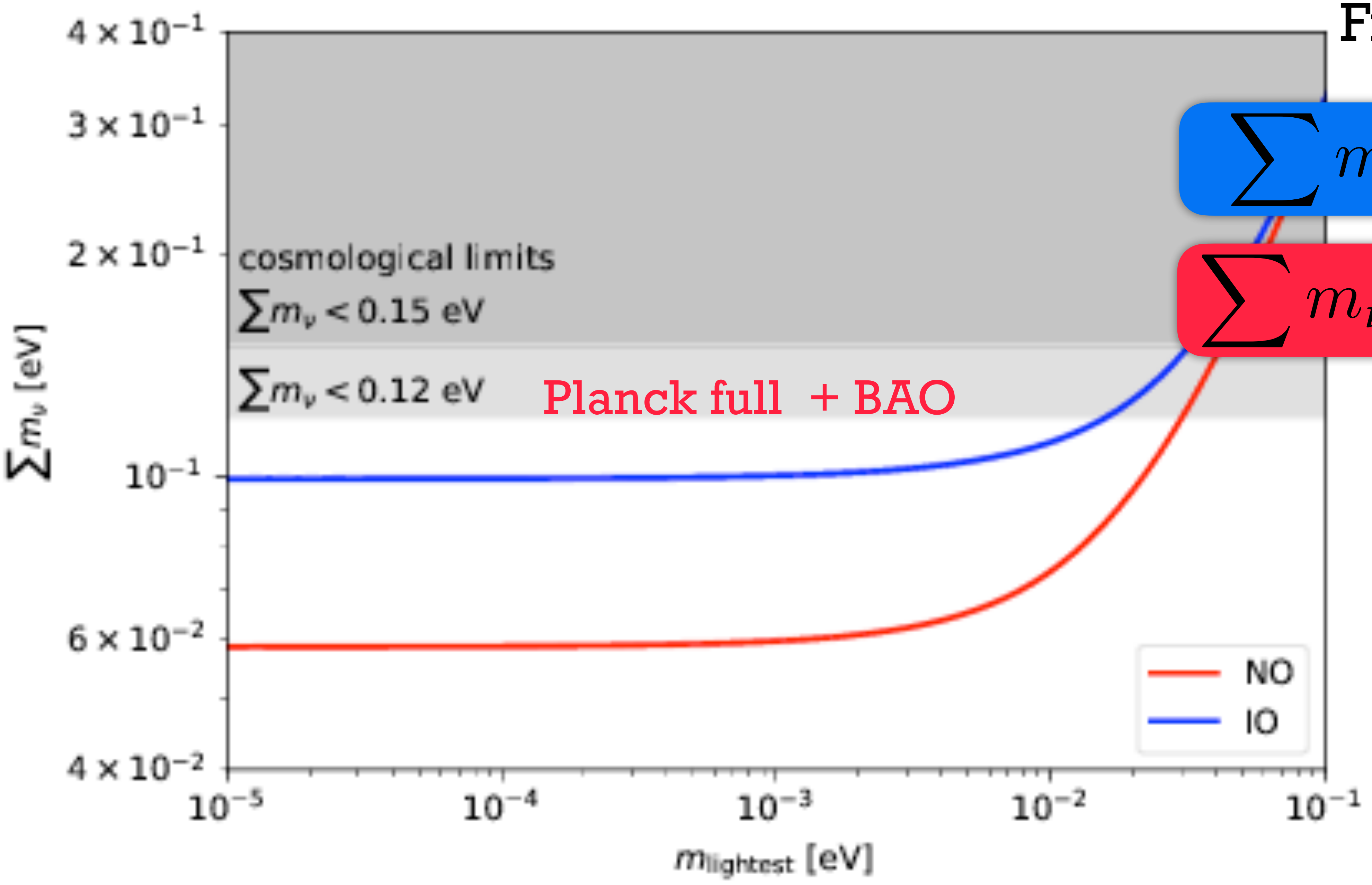
$\Sigma m_i < 0.12$ eV

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



Planck full + BAO

From oscillations:

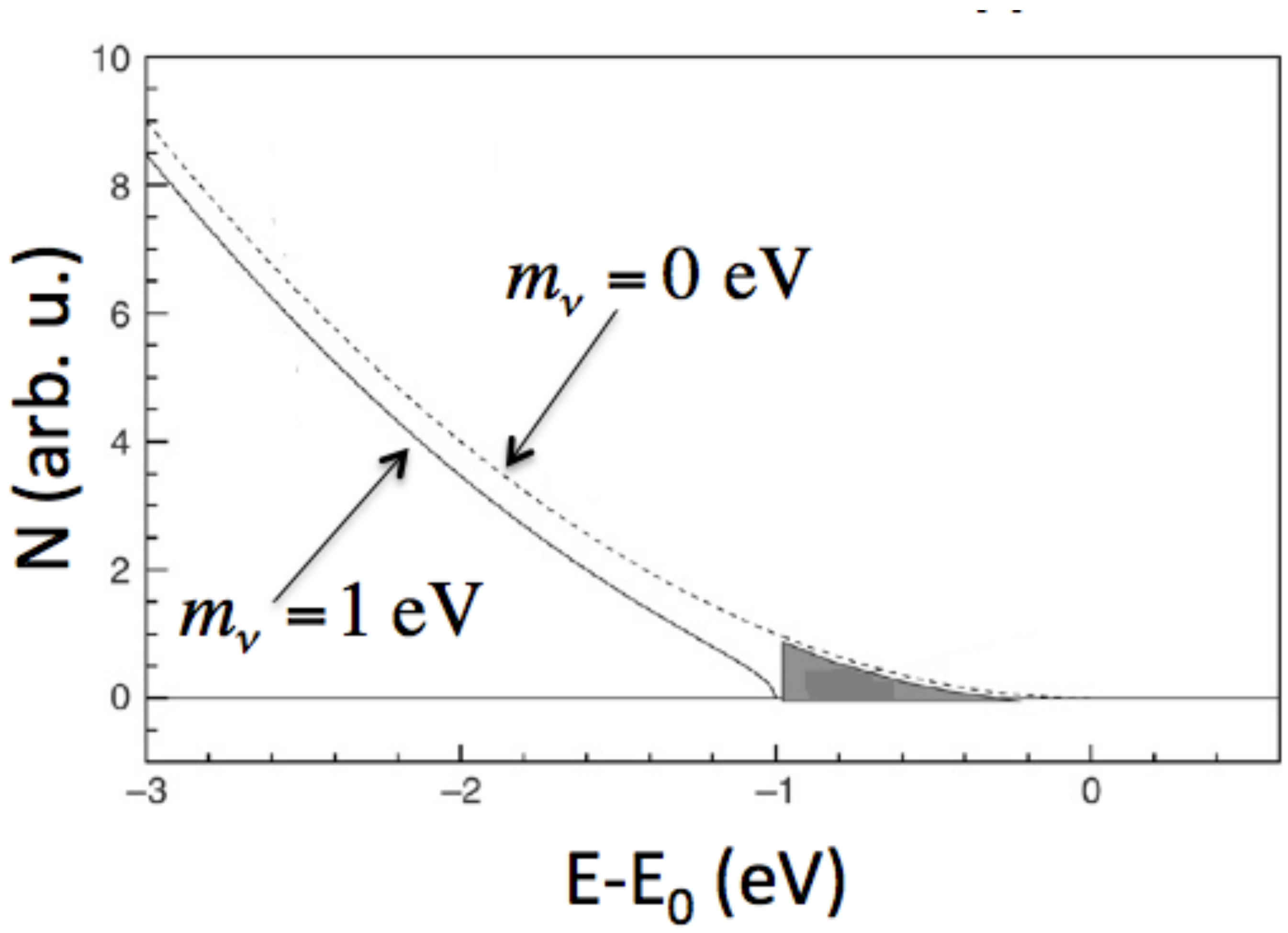
$$\sum m_\nu|_{\rm IO} \gtrsim 0.1\,{\rm eV}$$

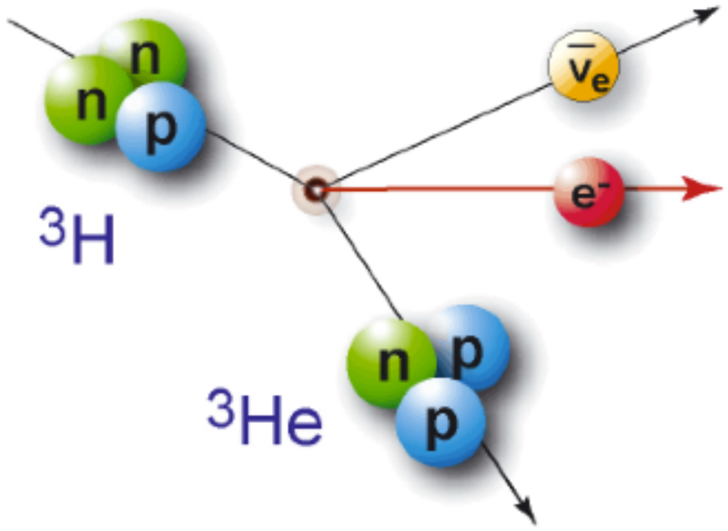
$$\sum m_\nu|_{\rm NO} \gtrsim 0.06\,{\rm eV}$$

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:



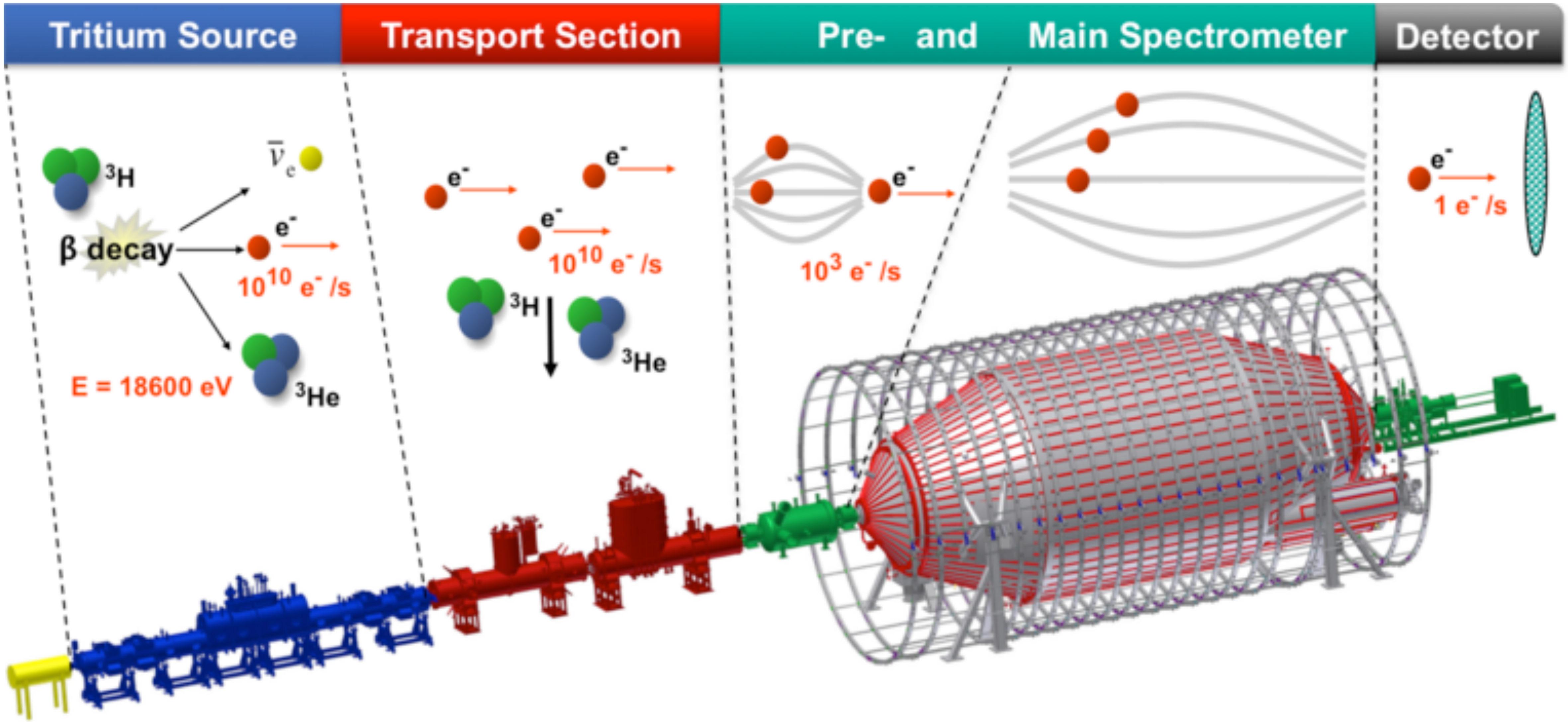


$$m_\beta^2 = \sum |U_{ei}|^2 \, m_i^2$$

Mainz and Troitsk Experiments:

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

The KATRIN experiment



Tritium decays, releasing an electron and an anti-electron-neutrino. While the neutrino escapes undetected, the electron starts its journey to the detector.

Electrons are guided towards the spectrometer by magnetic fields. Tritium has to be pumped out to provide tritium free spectrometers.

The electron energy is analyzed by applying an electrostatic retarding potential. Electrons are only transmitted if their kinetic energy is sufficiently high.

At the end of their journey, the electrons are counted at the detector. Their rate varies with the spectrometer potential and hence gives an integrated β-spectrum.

Taking data from June 2018

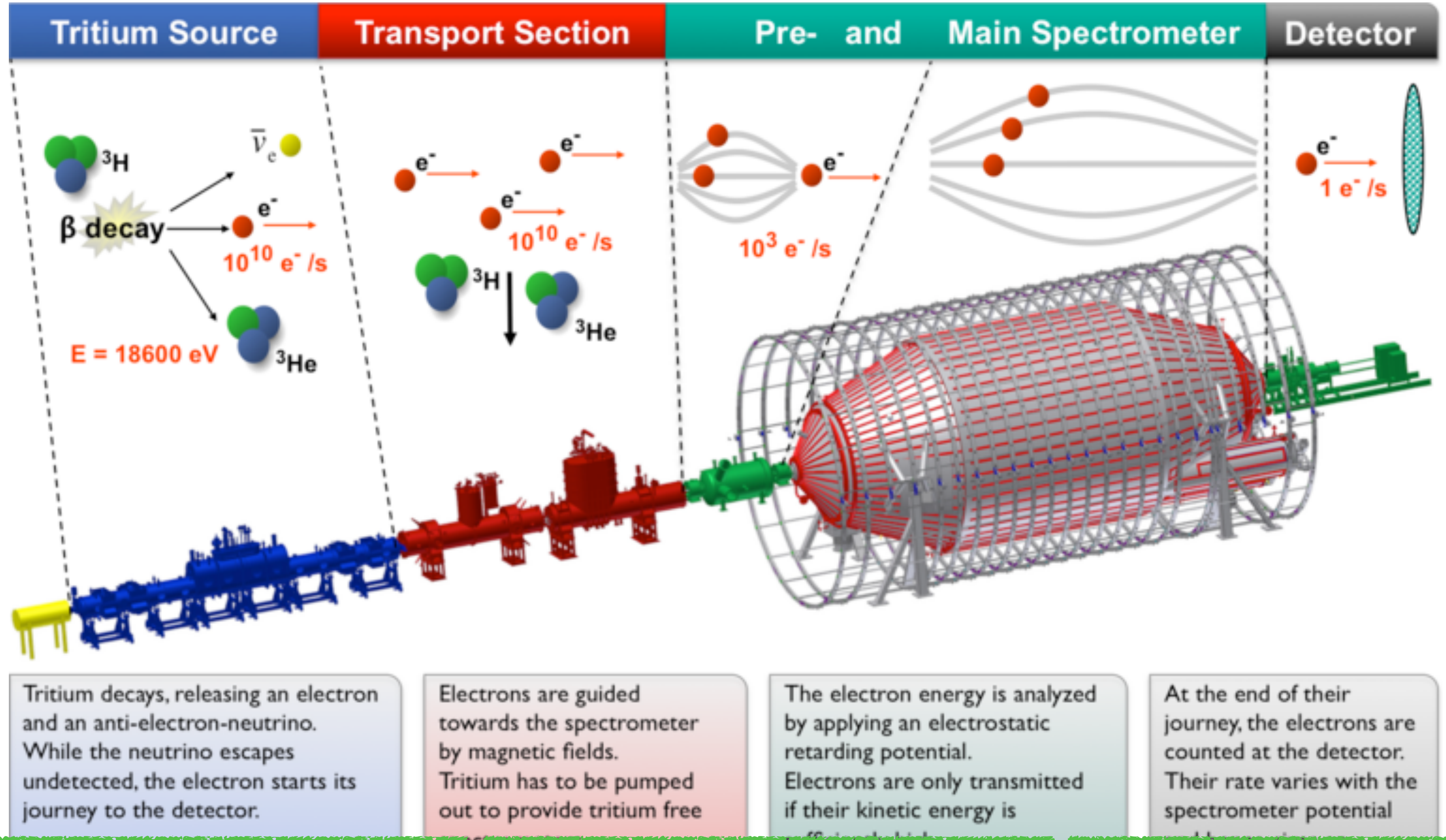
The KATRIN experiment

(KArlsruhe TRItium Neutrino experiment)

Leopoldshafen, Nov 2006

KATRIN spectrometer: 200 ton, 24 m long, 10 m diameter

The KATRIN experiment



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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)

Neutrinoless double beta decay

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

0νββ: possible for massive Majorana neutrinos.

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

test ν nature

→ not observed yet

→ $t_{1/2} > 10^{26}$-10^{27} years

→ violates Lepton Number

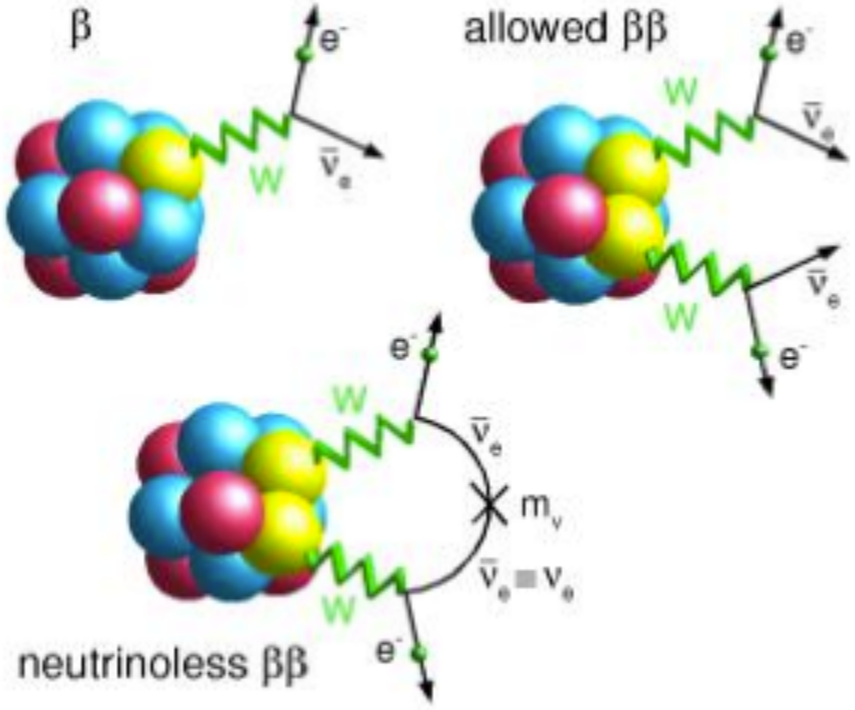
phase space

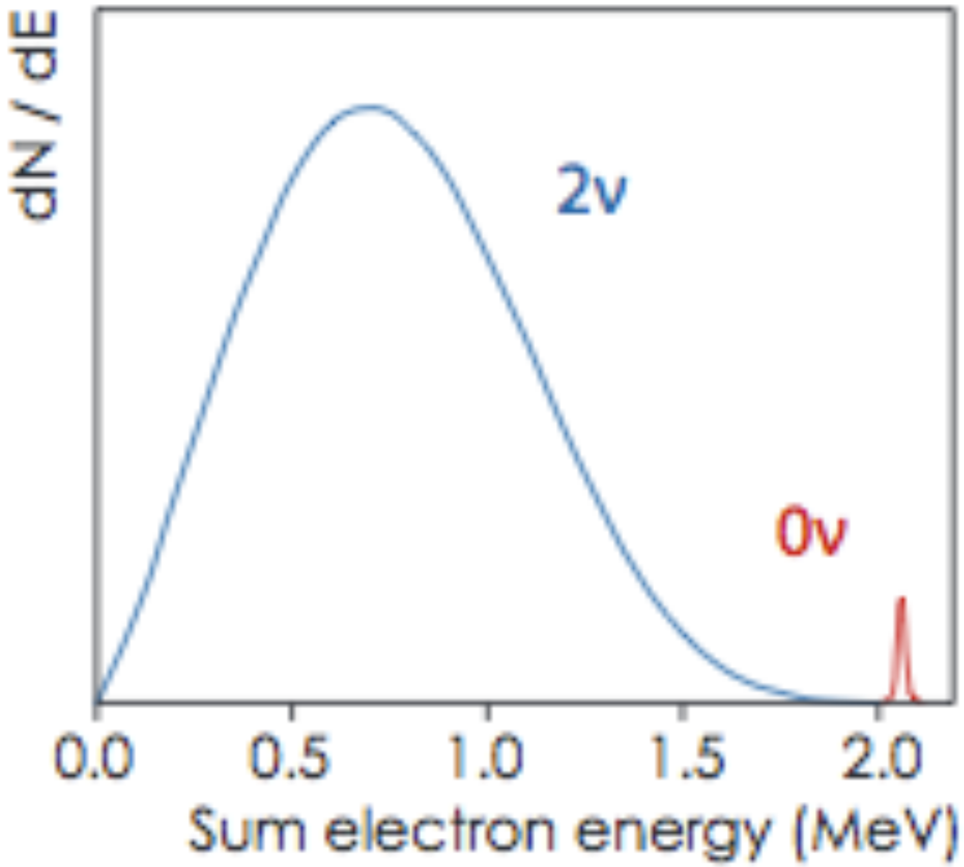
Nuclear matrix elements

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

Effective Majorana neutrino mass

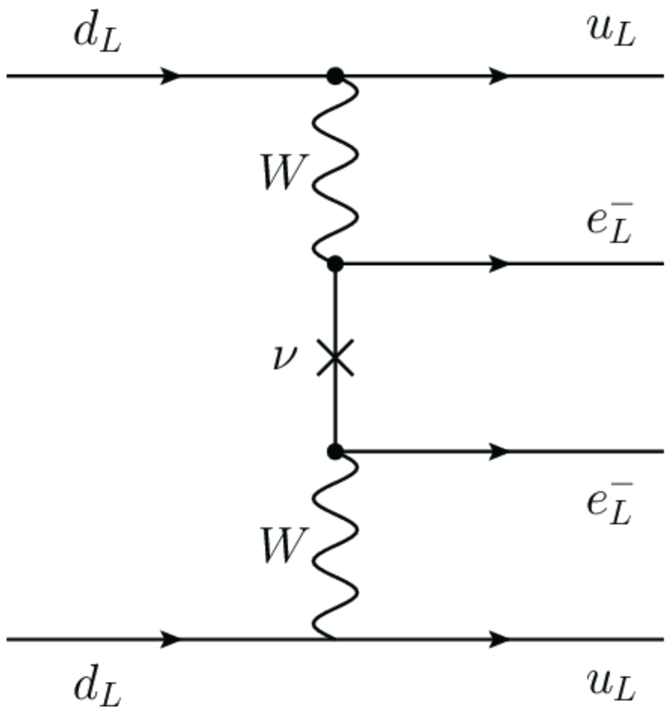
$$\langle m_{\beta\beta} \rangle = \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|$$





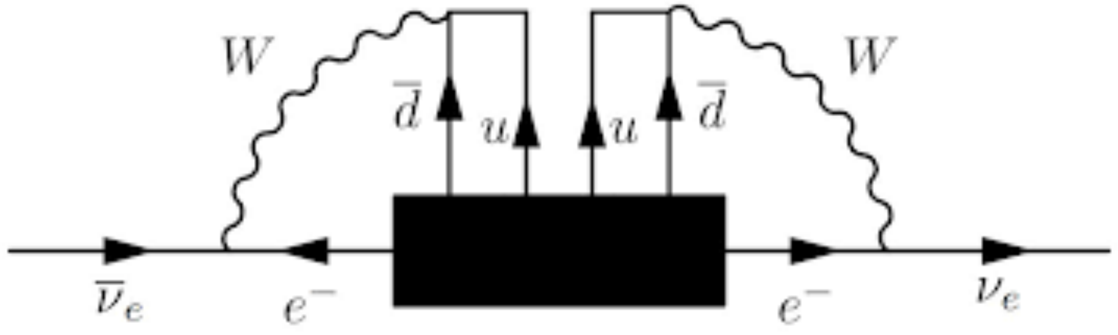
0νββ and Majorana neutrino mass

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



$\Longrightarrow$

This leads to loop-generated Majorana mass



Blackbox theorem, Schechter & Valle, 1982

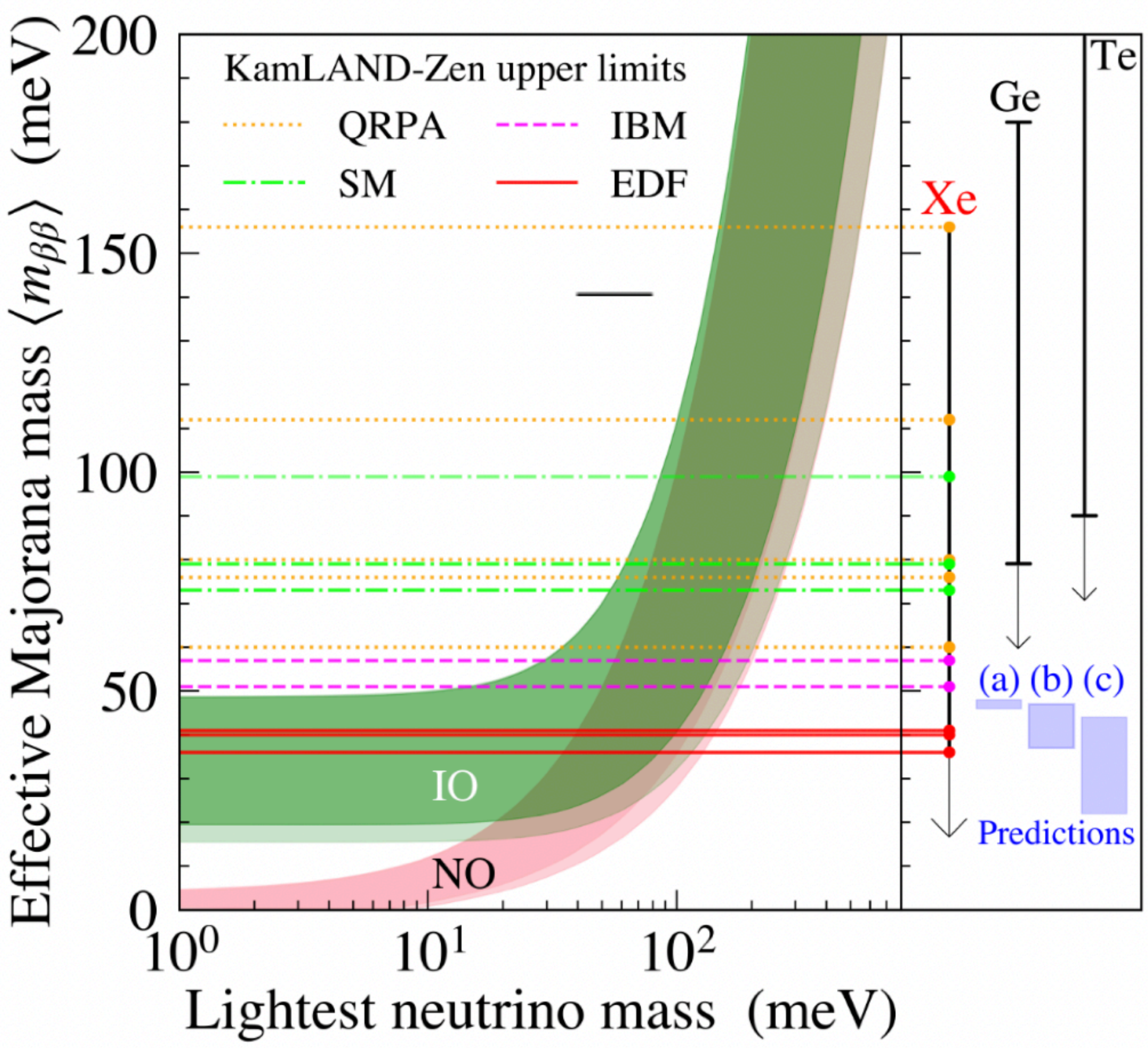
- Majorana neutrino mass is not the only mechanism leading to 0νββ: new physics models can also induce 0νββ.

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

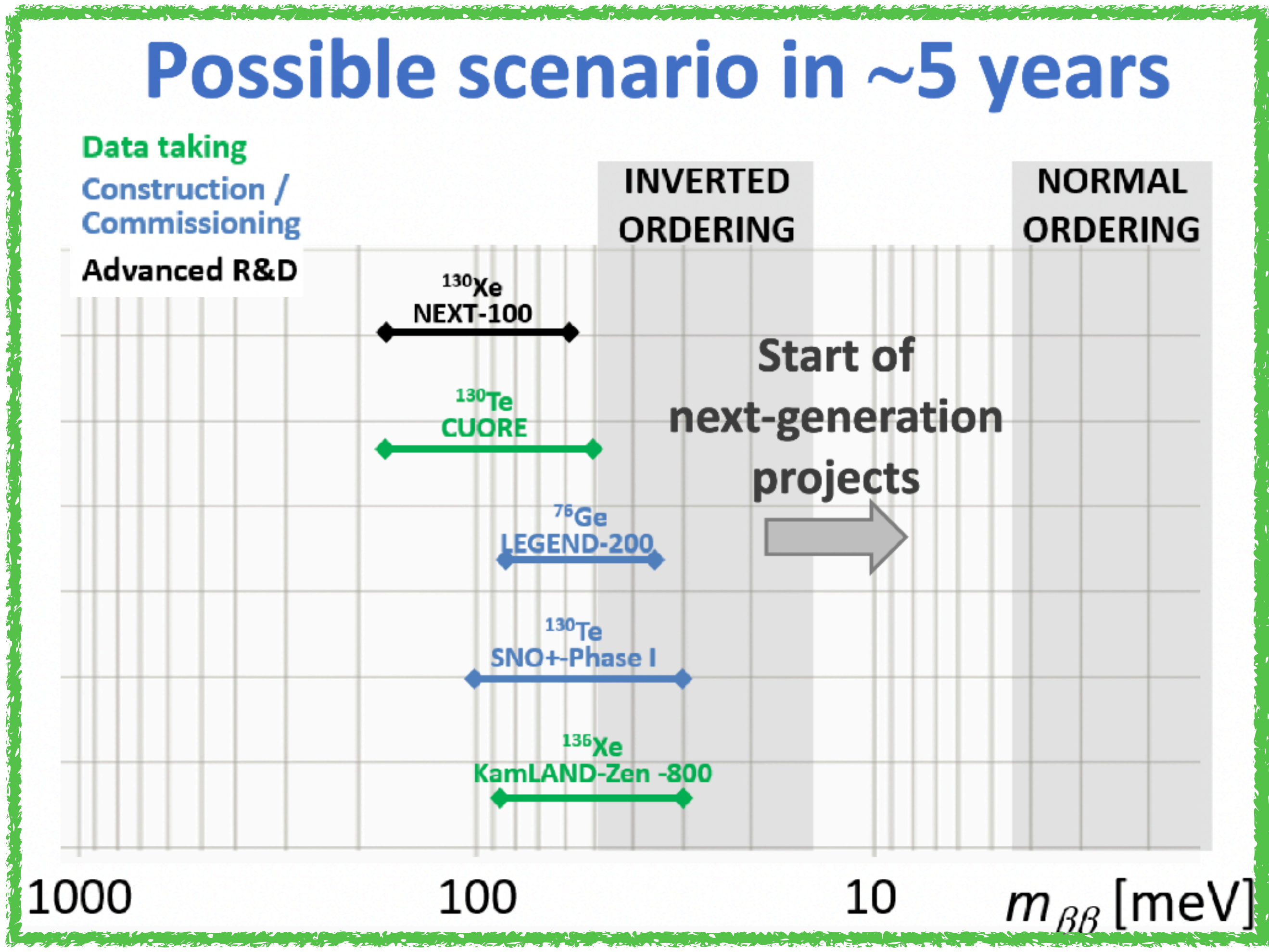
$m_{\beta\beta} <$ 36-156 meV KL-Zen

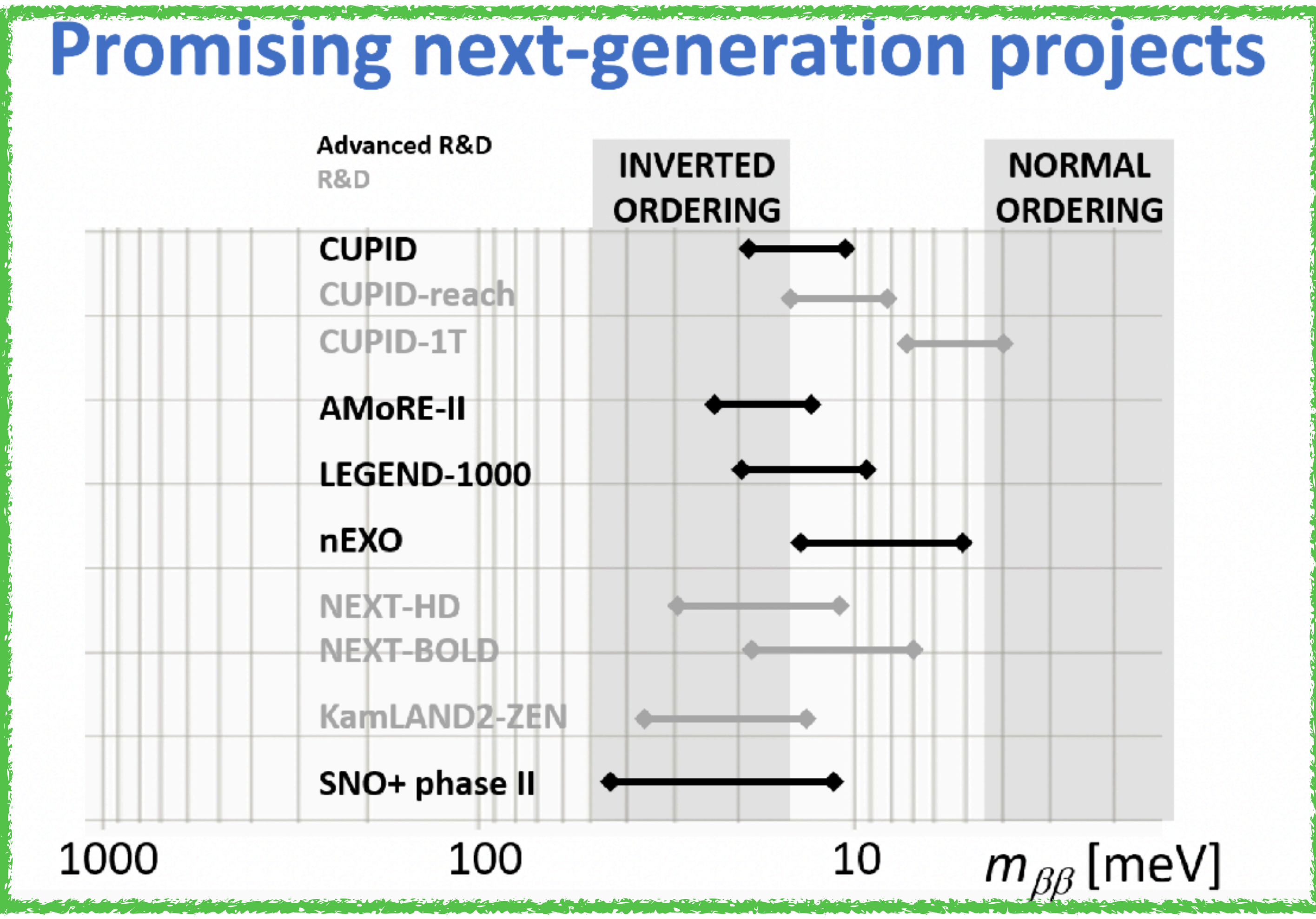
F. Simkovic, Neutrino 2022

→ degenerate region explored

Future prospects from 0νββ experiments

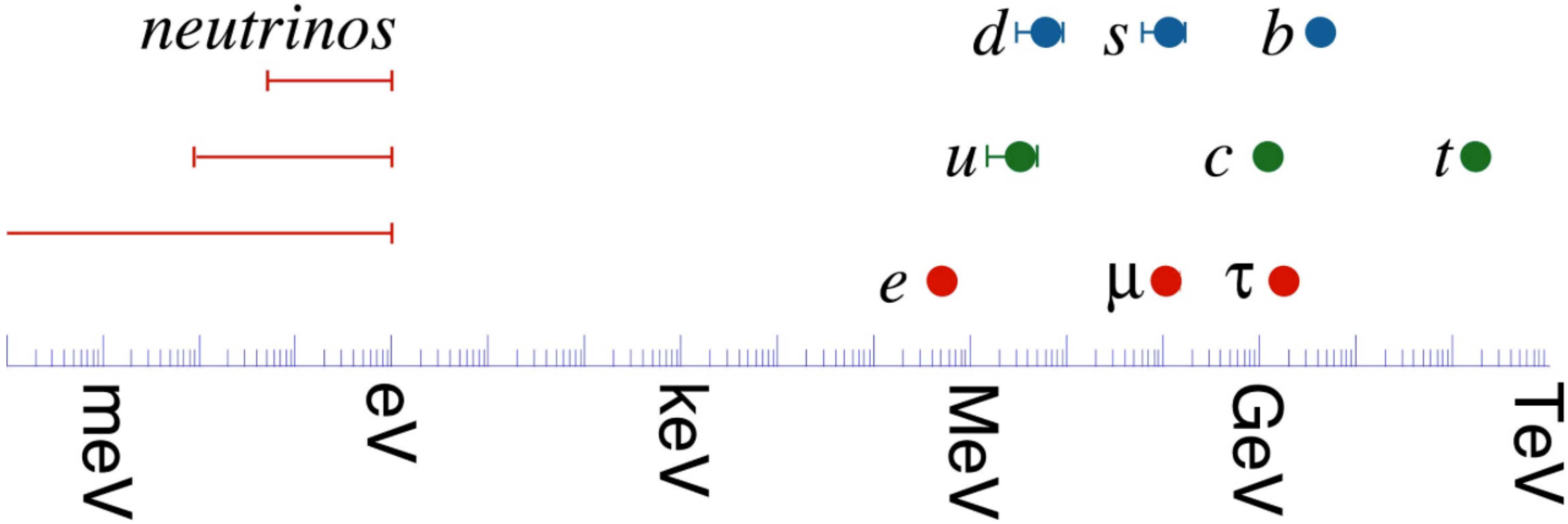
A. Giuliani, TAUP 2021





→ next generation: full exploration of the IO region (~10 years)

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



$m_\nu \sim 0 - 1$ eV

Dirac mass term

Minimal extension SM: add N$_R$

→ “sterile” neutrino (singlet under SU(2)xU(1))

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

$$\mathcal{L}_{\text{Yukawa}} = Y_\nu\,(\overline{\nu_l}\,\bar{l})\begin{pmatrix}\phi^0\\ \phi^-\end{pmatrix}N_R + \text{h.c.} \quad \longrightarrow \quad m_D = Y_\nu\frac{v}{\sqrt{2}}$$

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

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

Minimal seesaw mechanism

- Most general mass term:

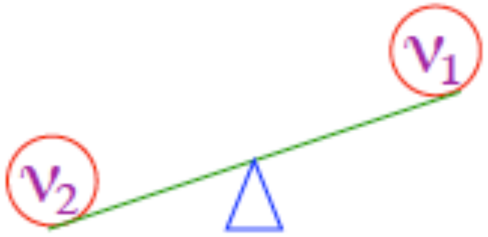
$$\mathcal{L} = \mathcal{L}_D + \mathcal{L}_M = \frac{1}{2}\left(\overline{\nu_L}\,\overline{N_R^C}\right)\begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix}\begin{pmatrix} \nu_L^C \\ N_R \end{pmatrix} + \text{h.c.} \qquad (m_D \simeq vY_\nu)$$

→ 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:



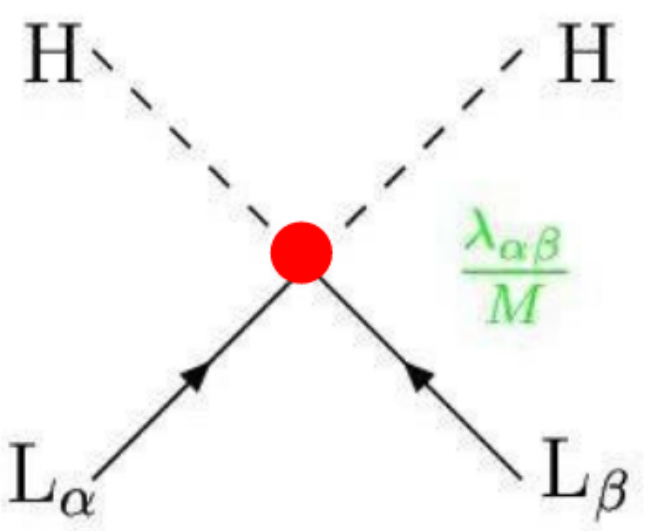
for $m_D \sim 100$ GeV and $m_\nu \sim 0.01$ - 1 eV →
$M_R \sim 10^{13}$ - 10^{15} GeV !!!

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

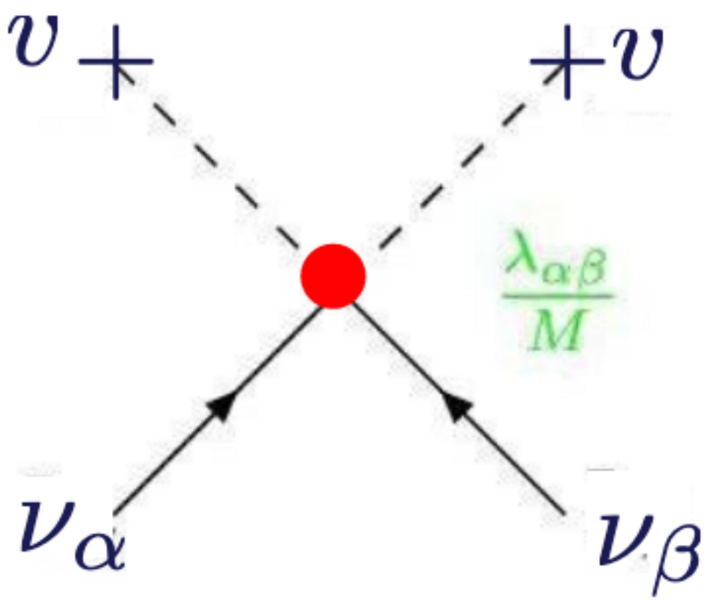
$$\Gamma(N \to l + H) \neq \Gamma(N \to \bar{l} + \overline{H})$$

Weinberg operator

- Effective dim-5 operator for Majorana neutrino mass



$\Longrightarrow$



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

Majorana mass

$$(\Delta L = 2)$$

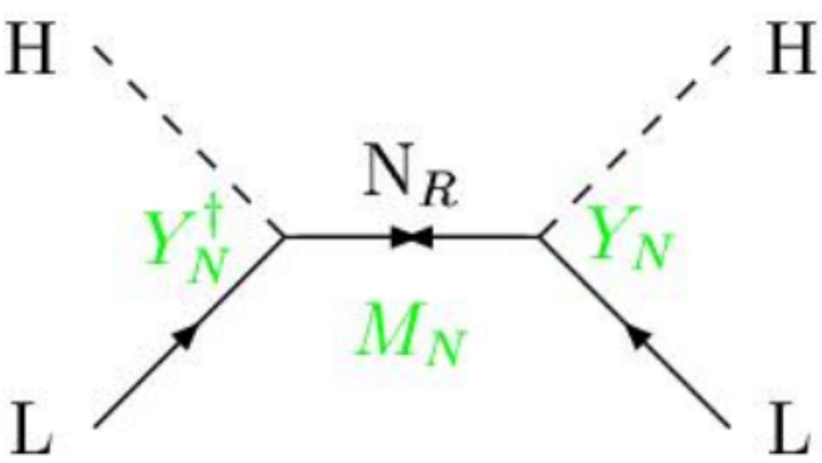
S. Weinberg PRL 43 (1979) 1566

Seesaw mass models

⇒ They led to the Weinberg operator at tree level.

⇒ ν masses are generated through mixing with heavy particles.

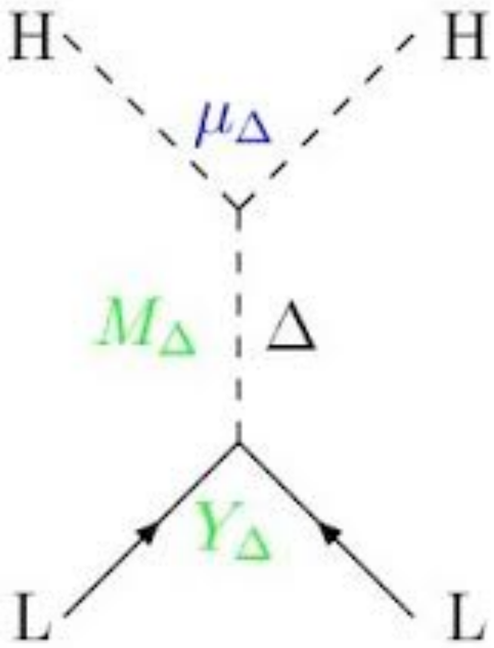
Type-I seesaw
(right-handed singlet N_R)



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

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

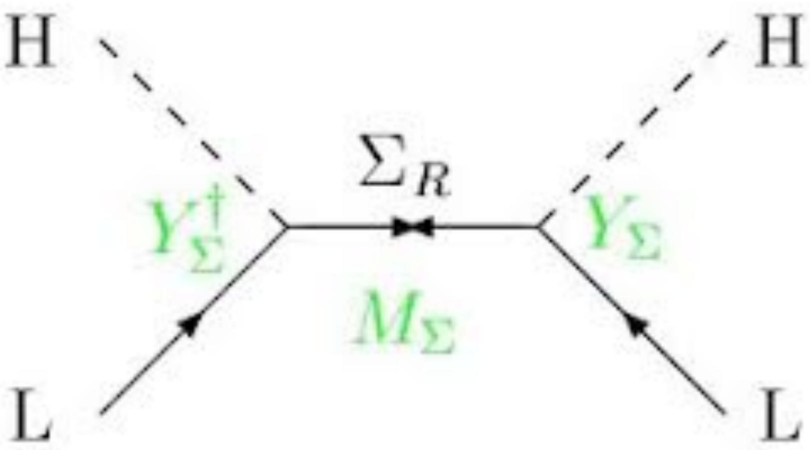
Type-II seesaw
(Scalar triplet Δ)



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

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

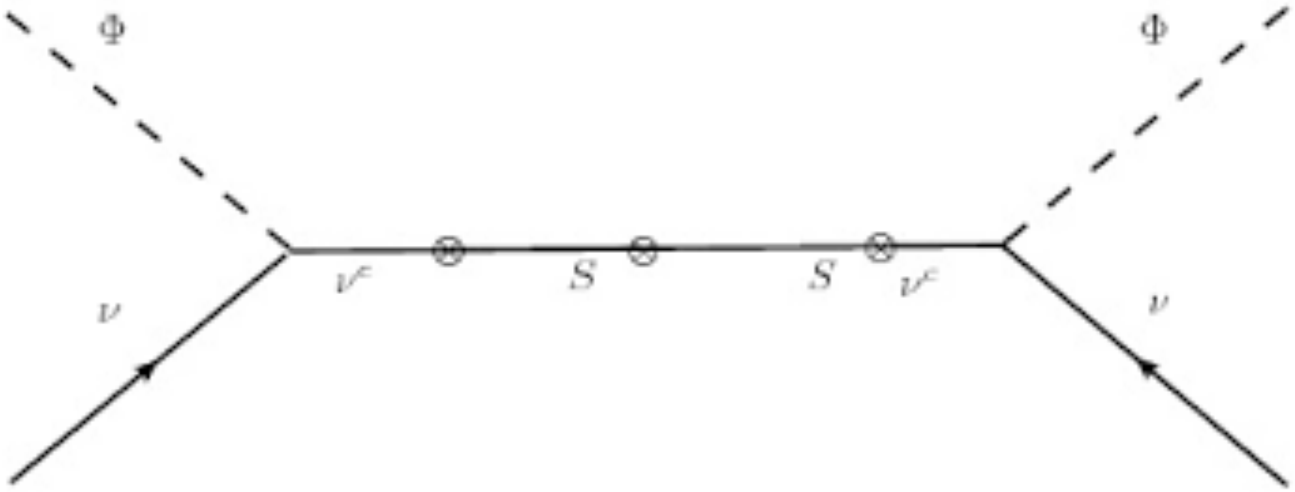
Inverse seesaw model

Mohapatra and Valle, PRD 34 (1986) 1642

Extended lepton content:

$(\nu, \underbrace{\nu^c, S})$ L=(+1,-1,+1)

SU(2) singlets



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

- 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:

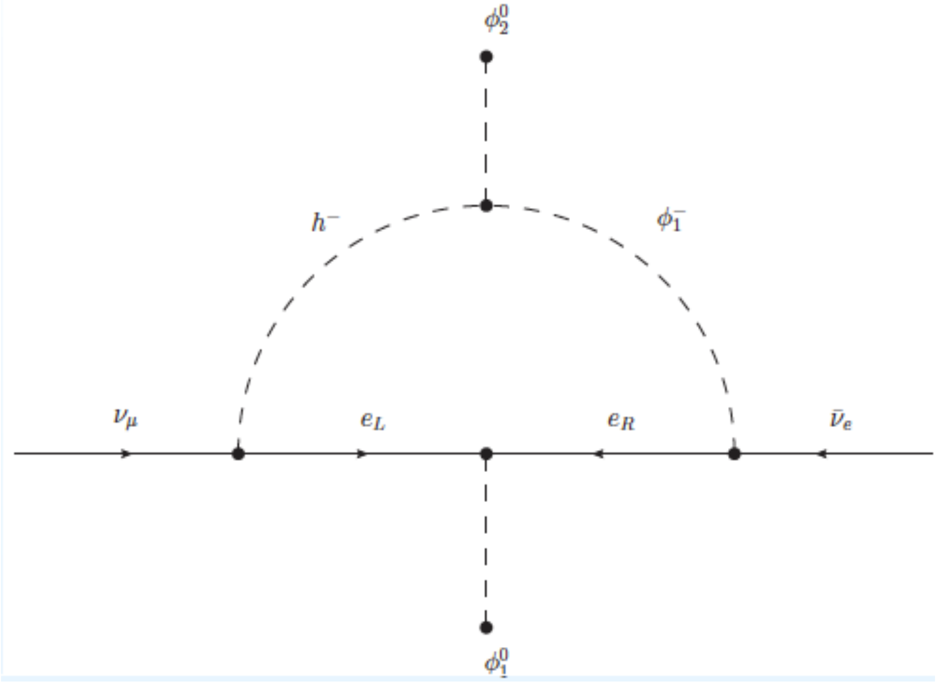
with $\mu \sim$ keV and M ~ 10^3 GeV → $m_\nu \sim$ eV

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

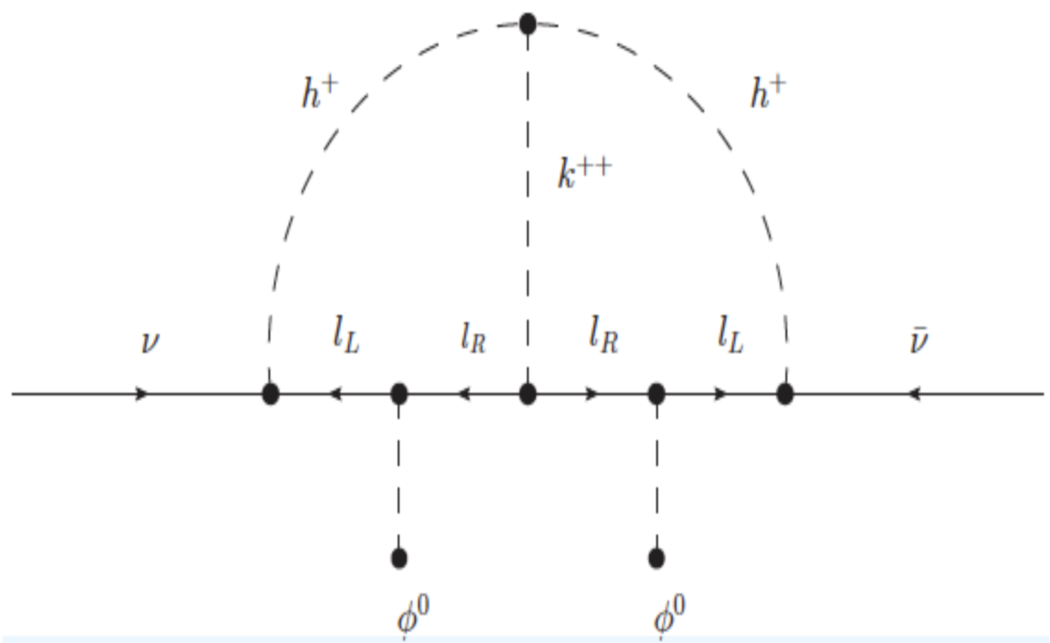
Zee model Zee, PLB 93 (1980) 389

+ 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^{++}



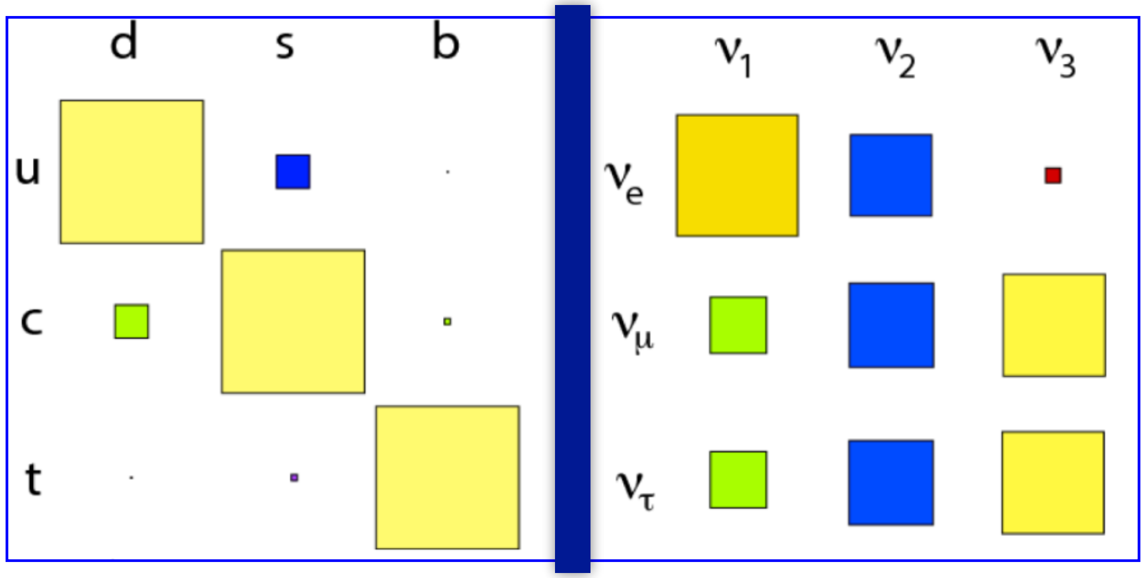
The flavour problem

- 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?

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

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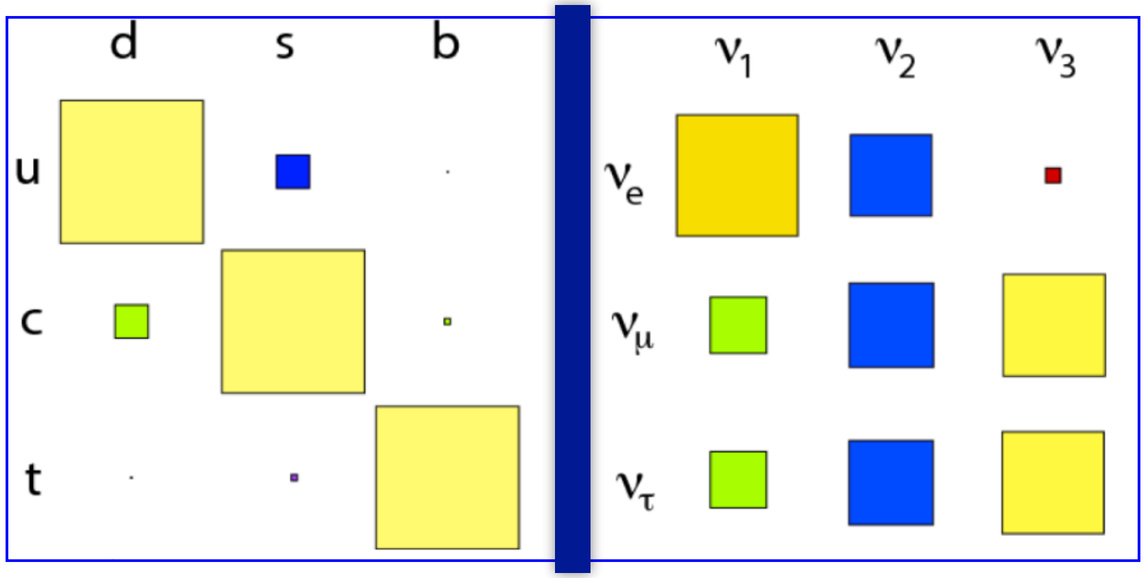

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- Why do fermion masses show these hierarchical relations?

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

$\Rightarrow$ 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

⇒ 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 ~ eV)
- small neutrino masses (seesaw mechanism, m > TeV-M_{Planck})
- baryon asymmetry of the universe (leptogenesis, m>> 1 GeV)
- (part of) the dark matter of the universe.

How many neutrinos?

- according to LEP measurements of invisible Z decay width:

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

Experimental hints for a 4th sterile neutrino:

LSND & MiniBooNE

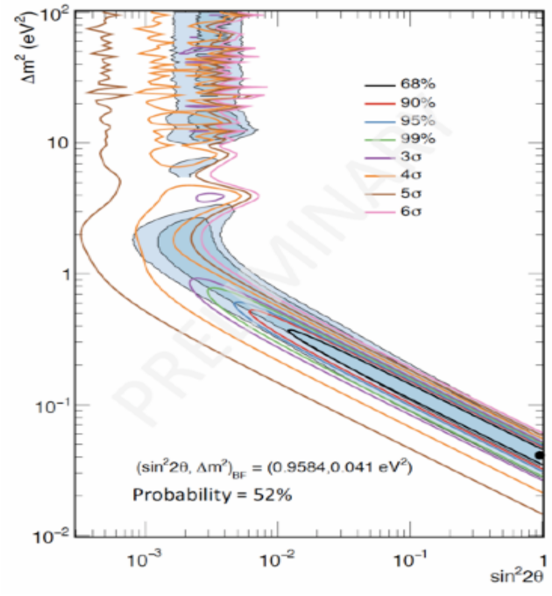
$\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$

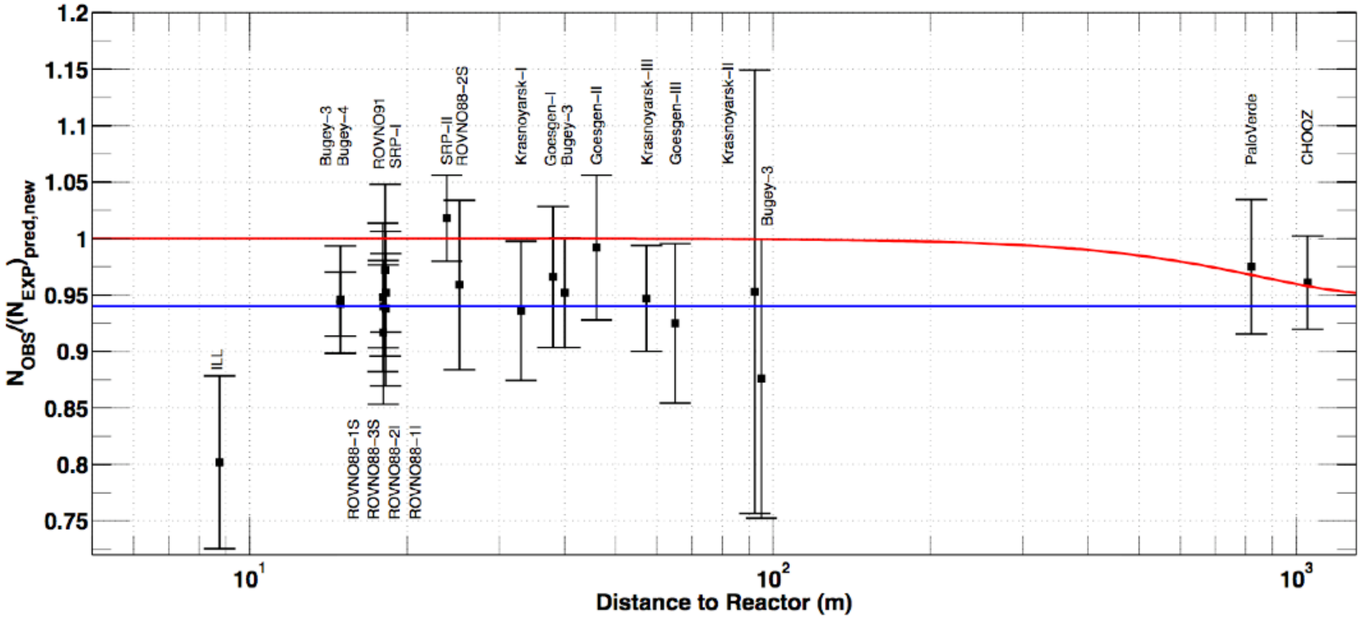
Reactor anomaly

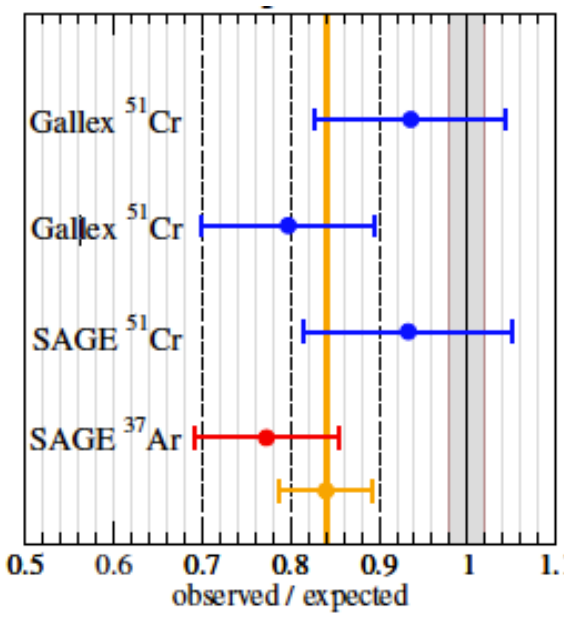
$\overline{\nu}_e \rightarrow \overline{\nu}_e$

Gallium anomaly

$\nu_e \rightarrow \nu_e$







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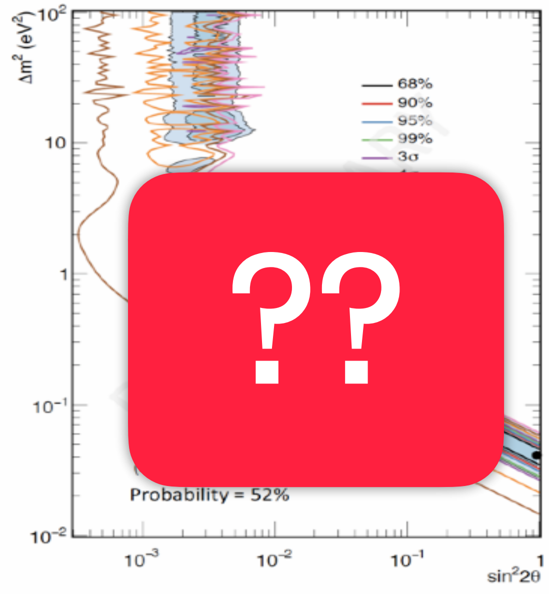
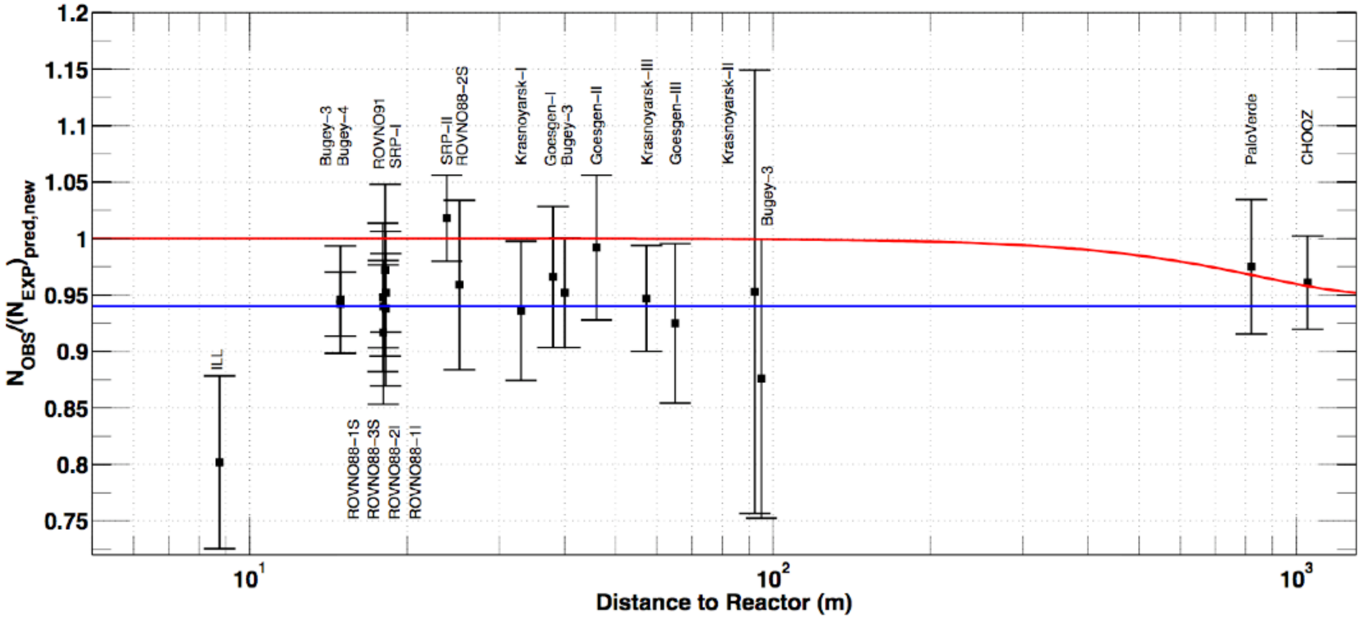


Reactor anomaly

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



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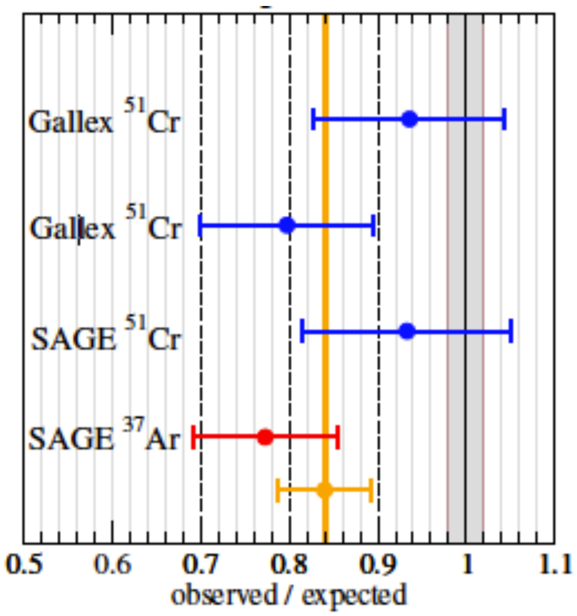
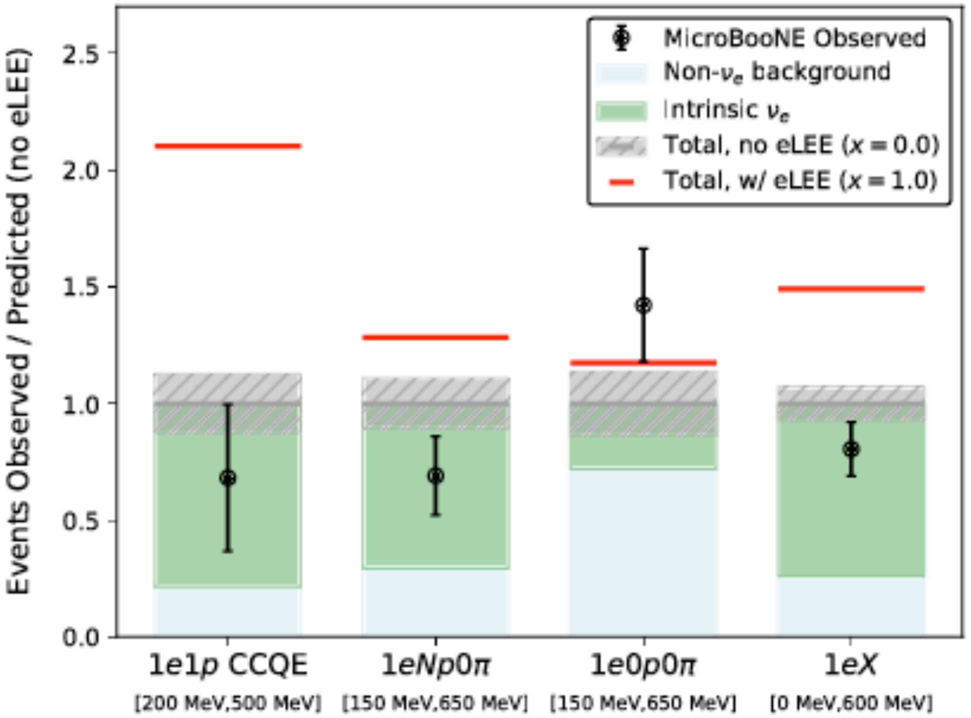
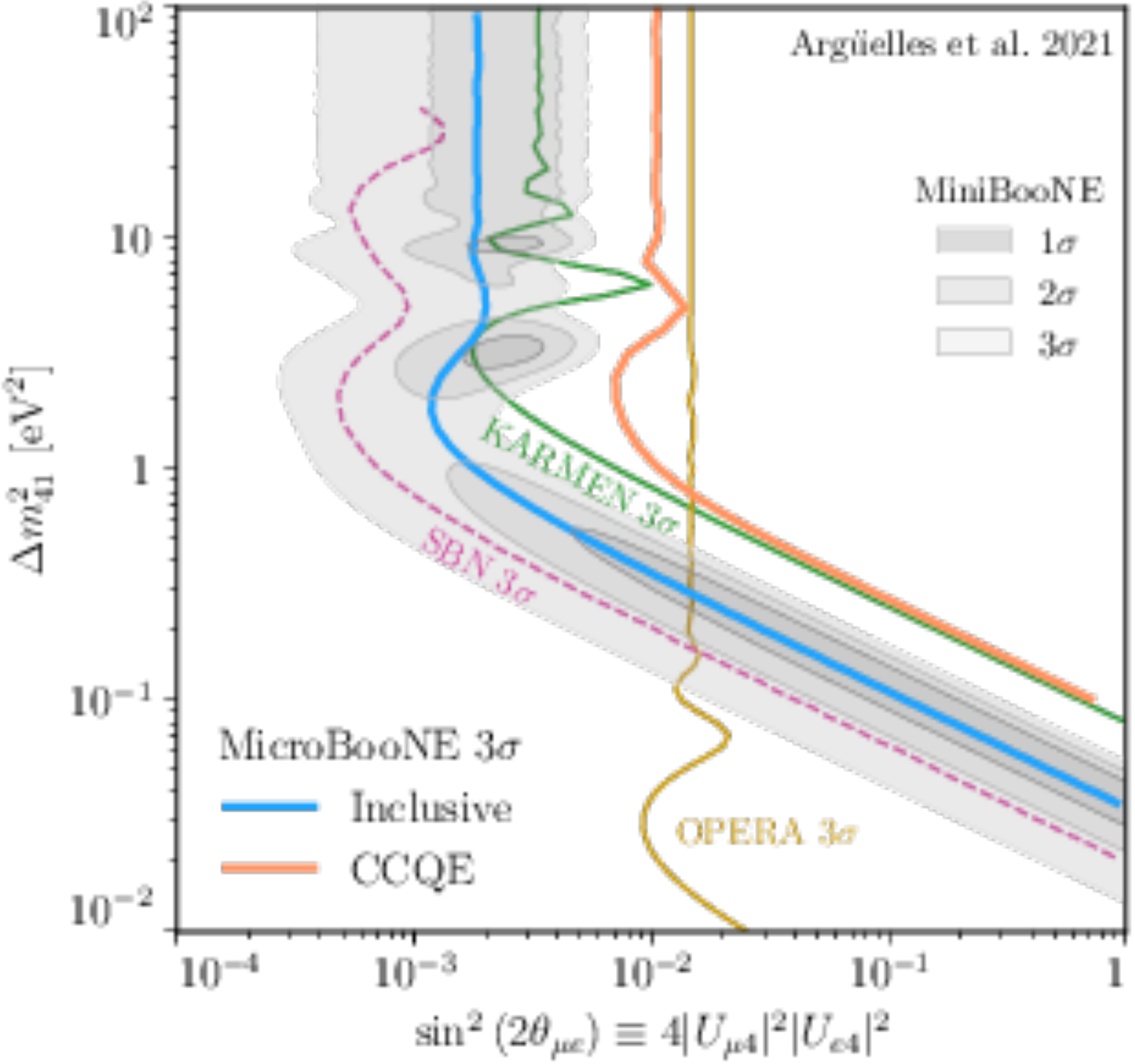


First results from MicroBooNE

Argüelles et al, 2021

MicroBooNE Collab, 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

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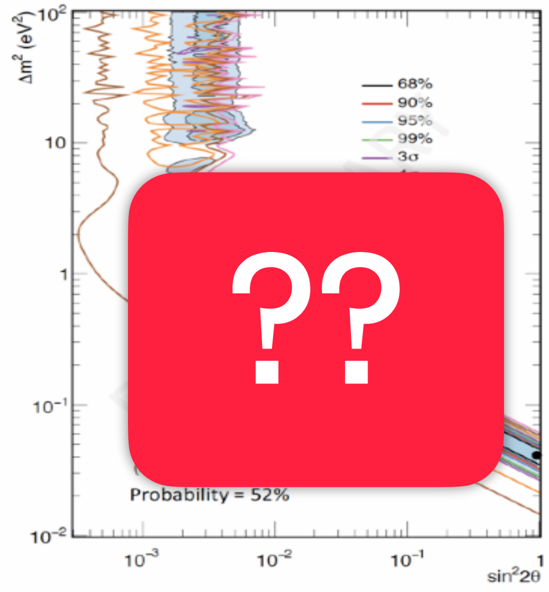
$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$



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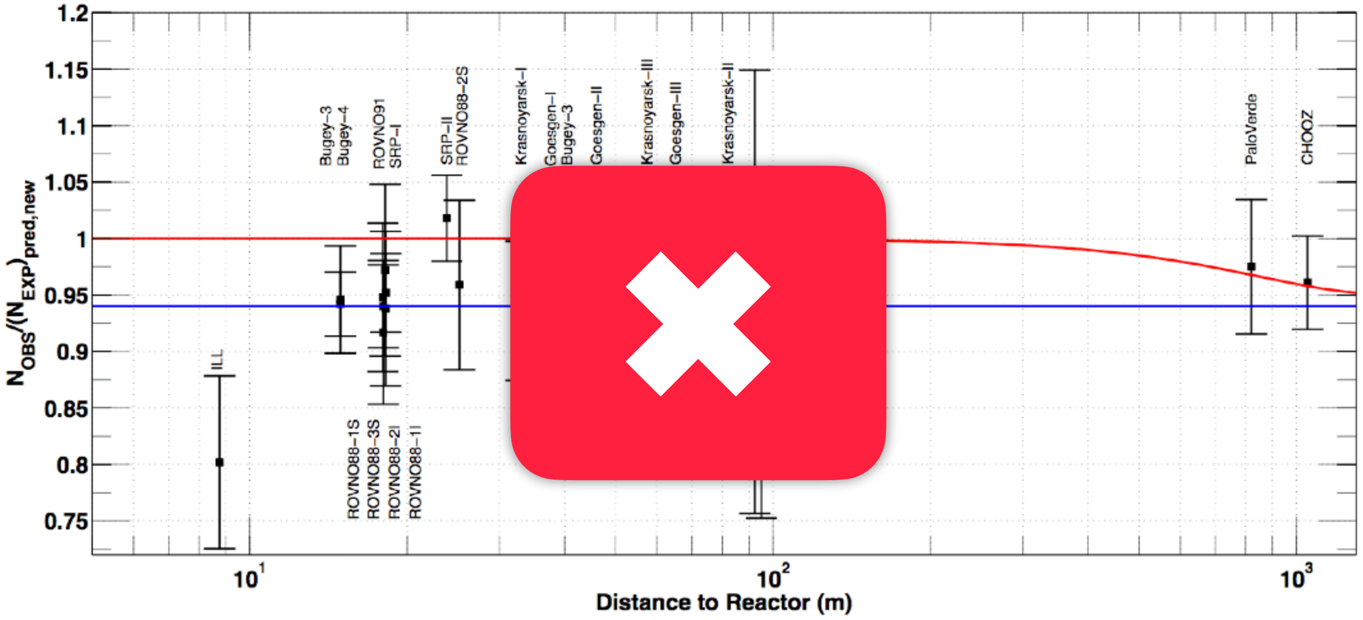
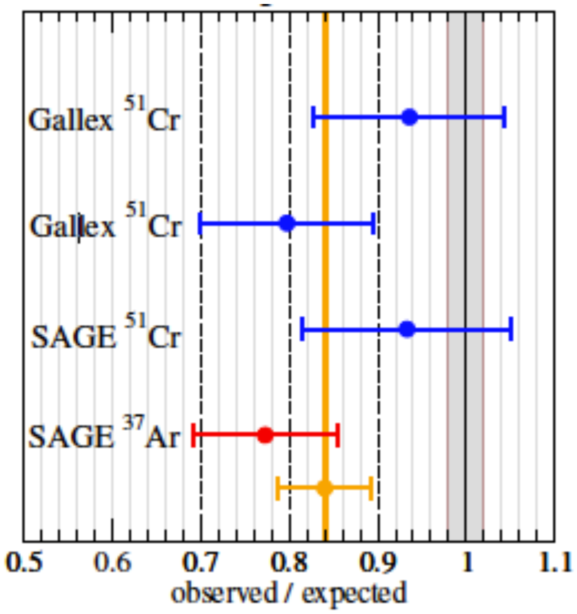
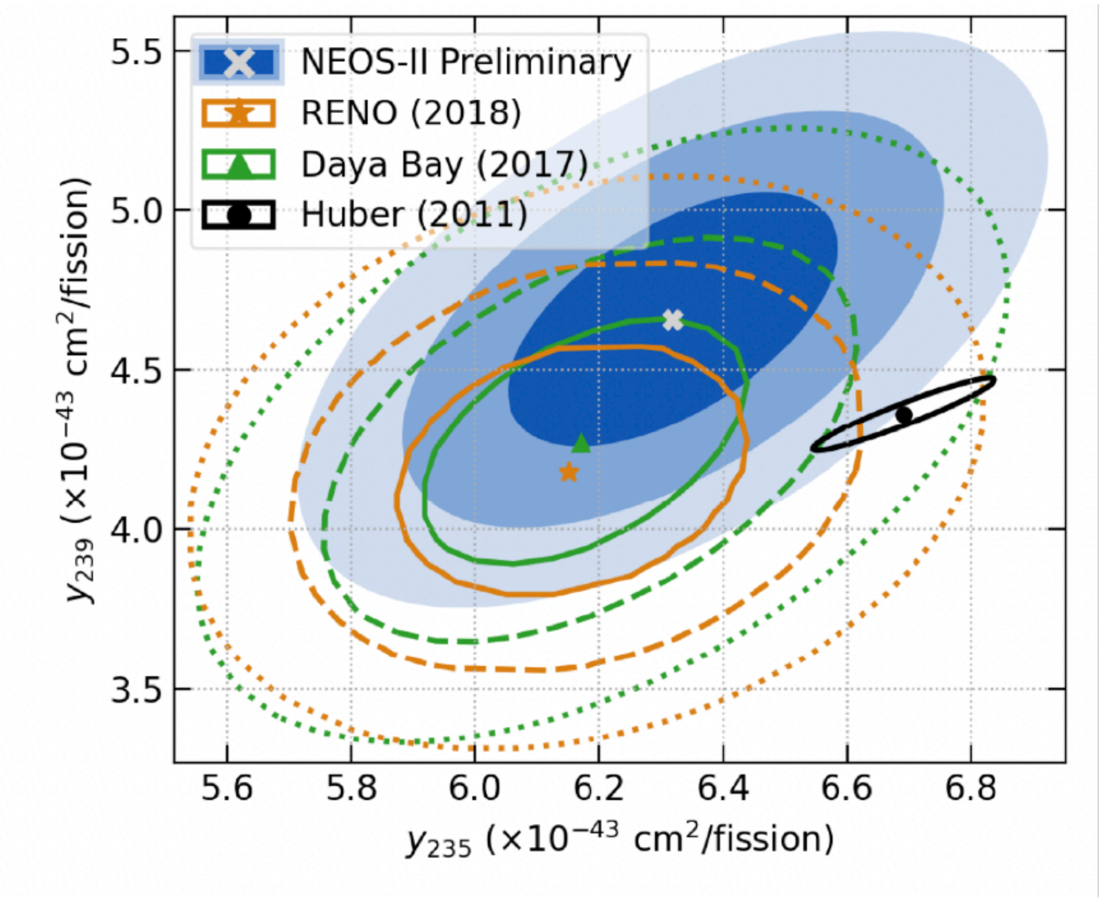


Gallium anomaly

$\nu_e \to \nu_e$



Current status of the reactor anomaly

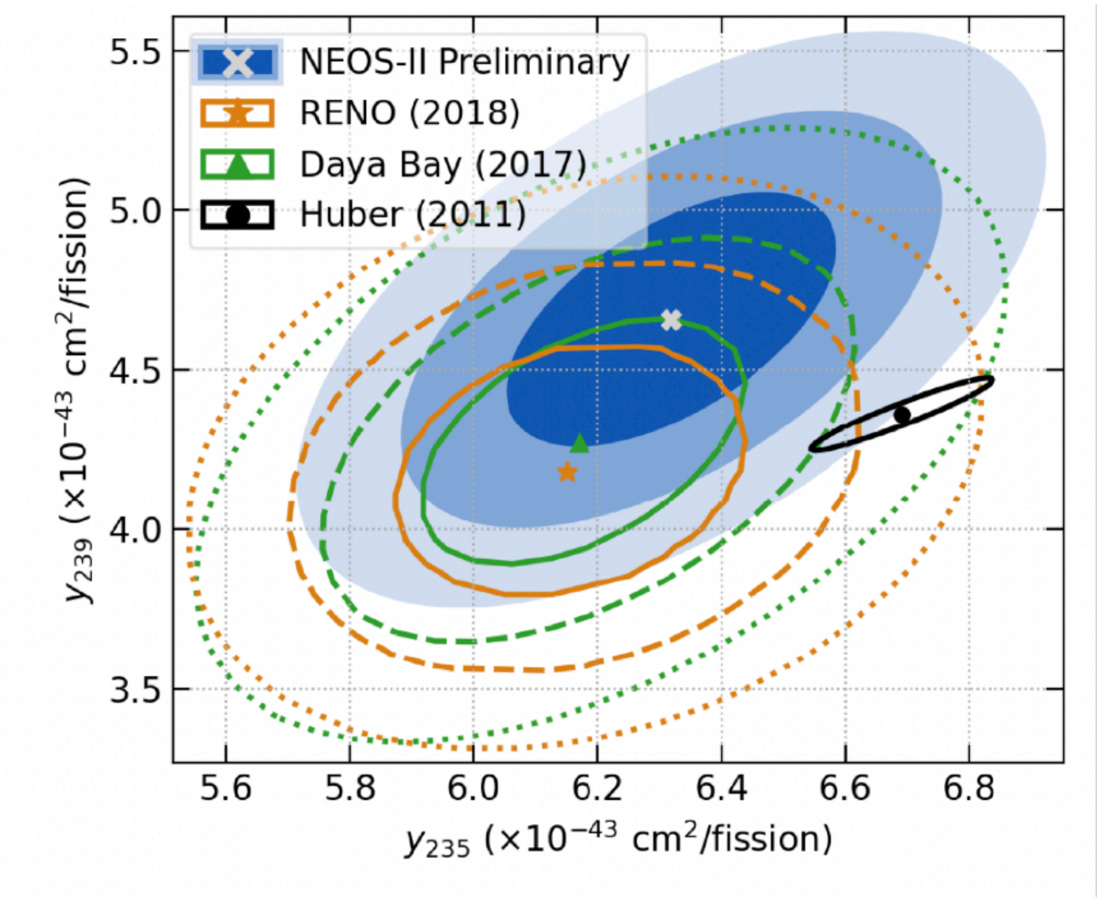


P. Vogel, Neutrino 2022

- 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

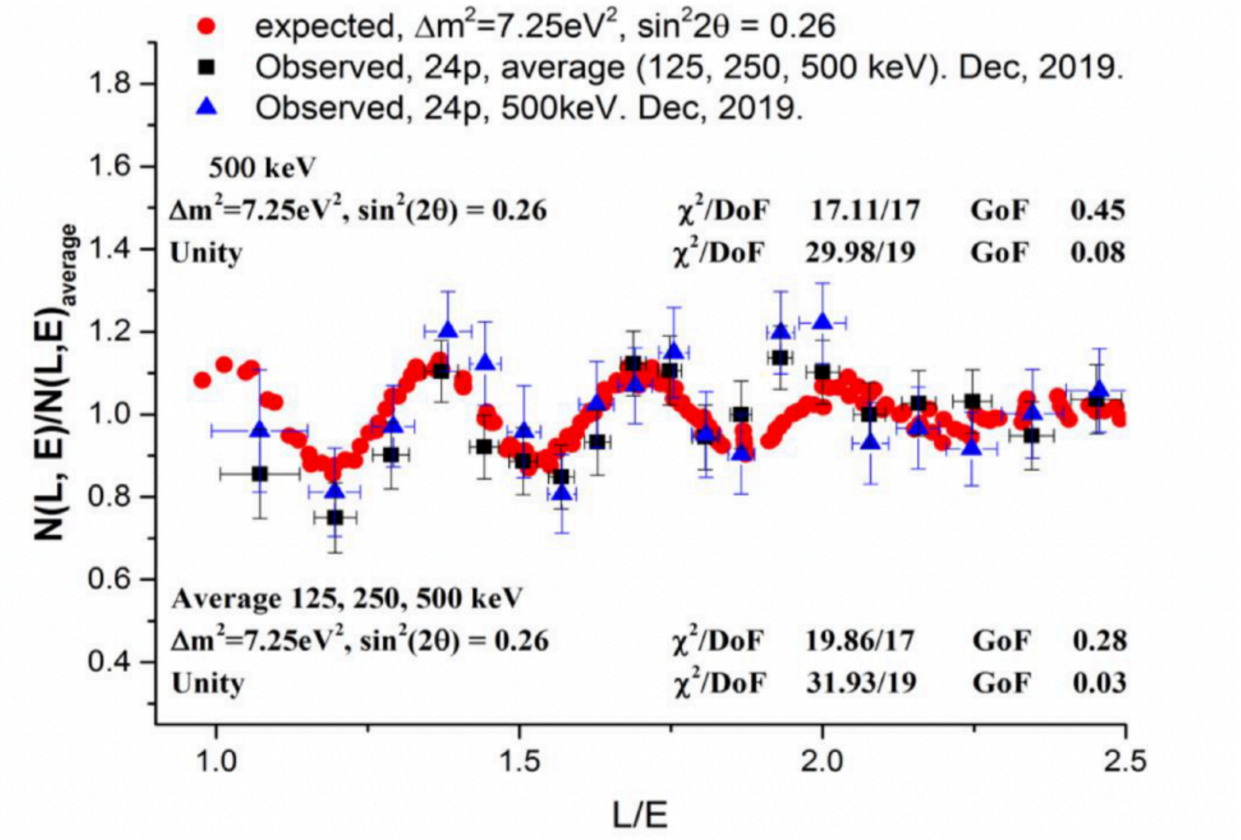
- Reactor measurements indicate that the neutrino flux for ^{235}U in the H-M model should be reduced by 5-10 %.

  → 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?

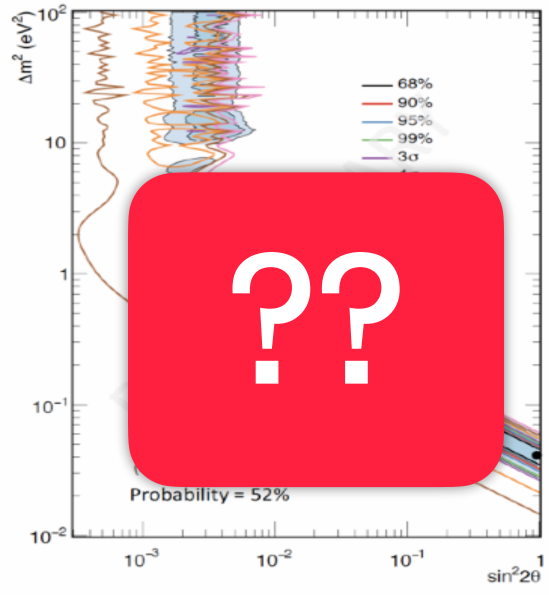
- according to LEP measurements of invisible Z decay width:

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

Experimental hints for a 4th sterile neutrino:

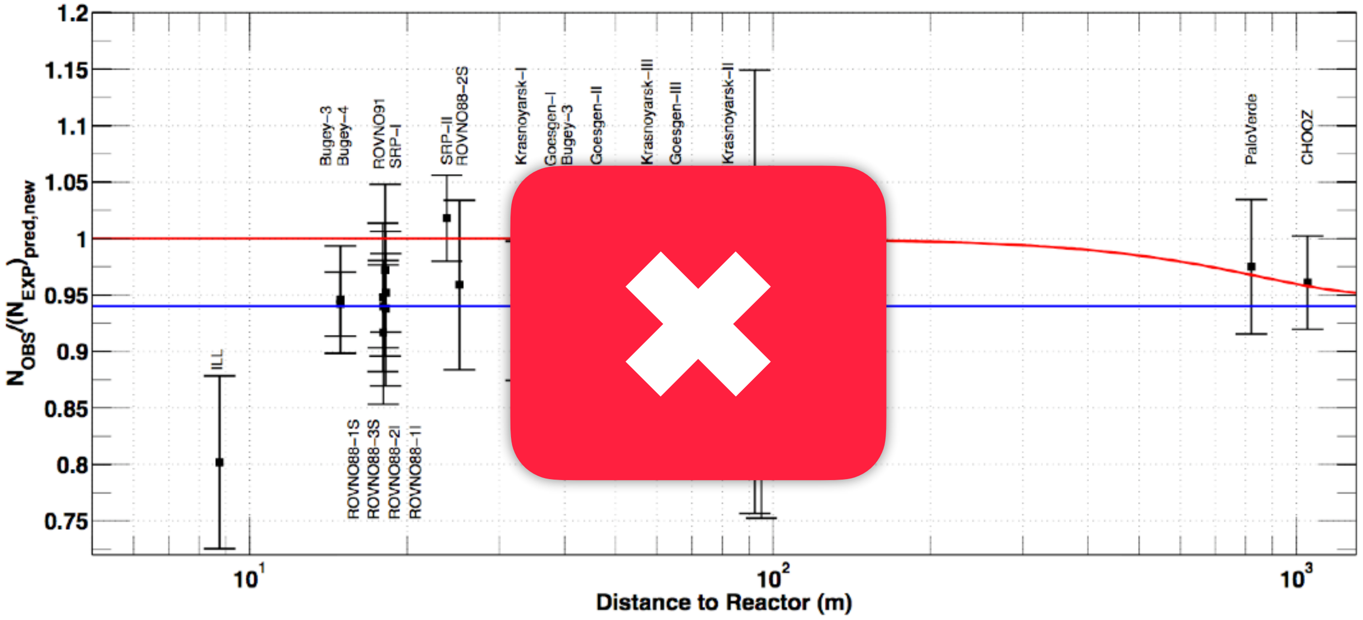
LSND & MiniBooNE

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



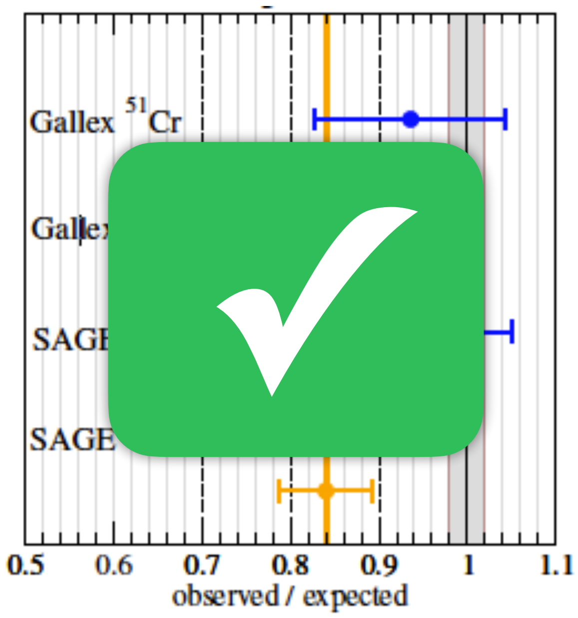
Reactor anomaly

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



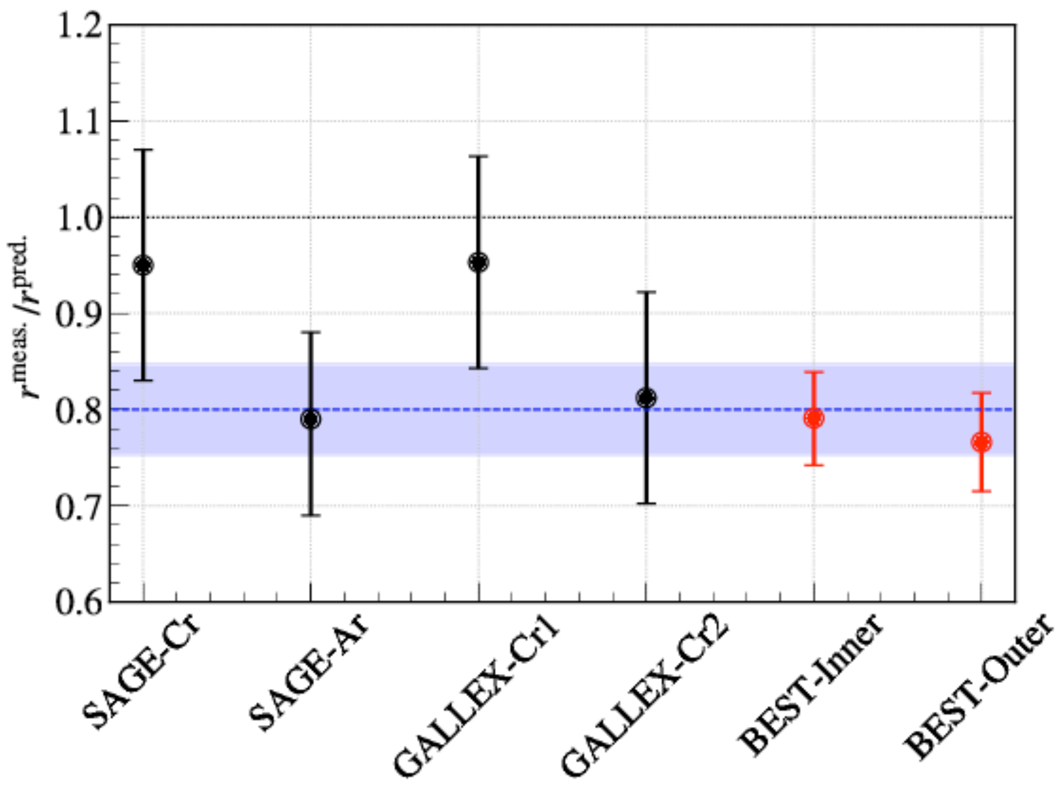
Gallium anomaly

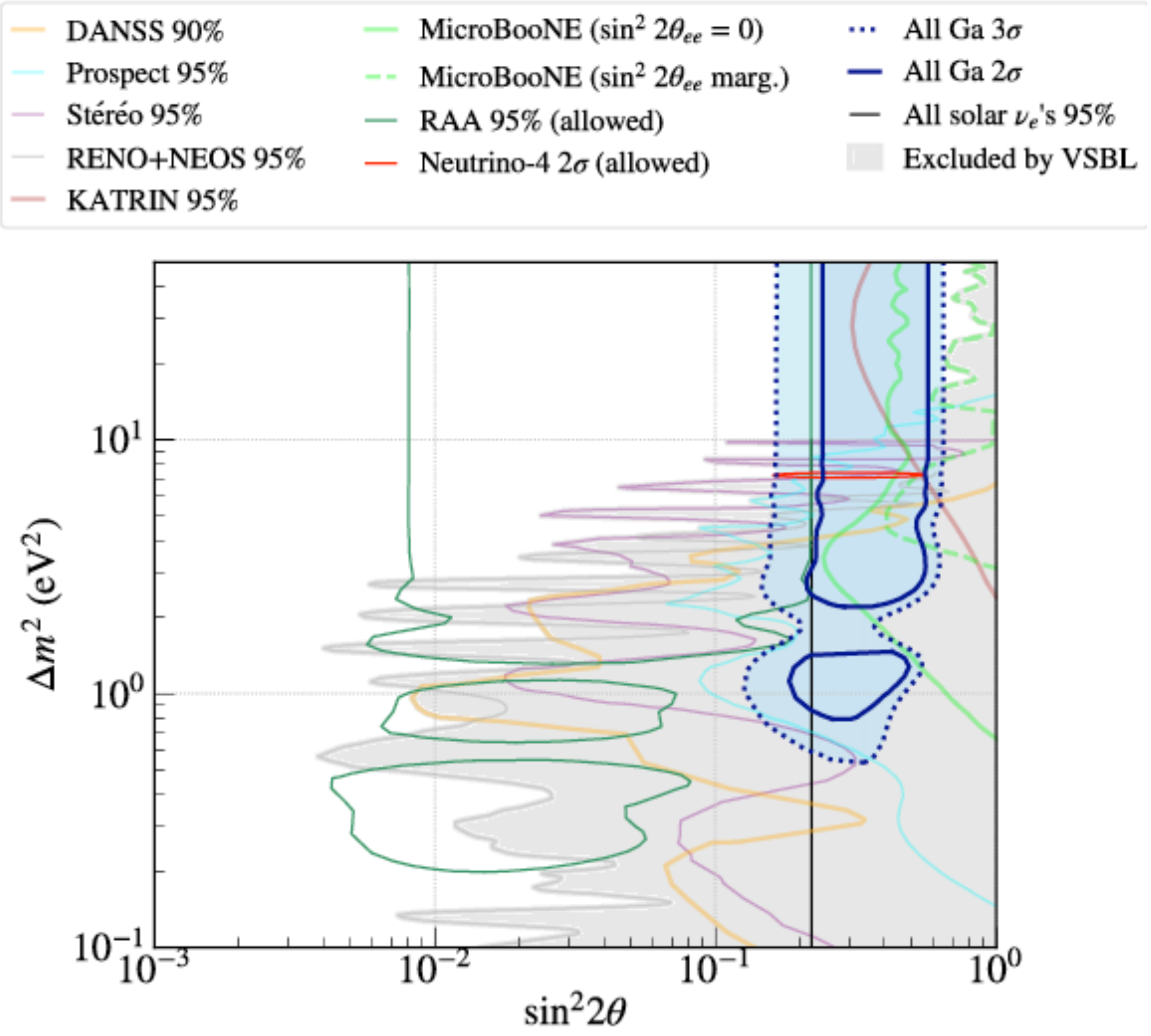
$\nu_e \rightarrow \nu_e$



Current status of the Ga anomaly

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





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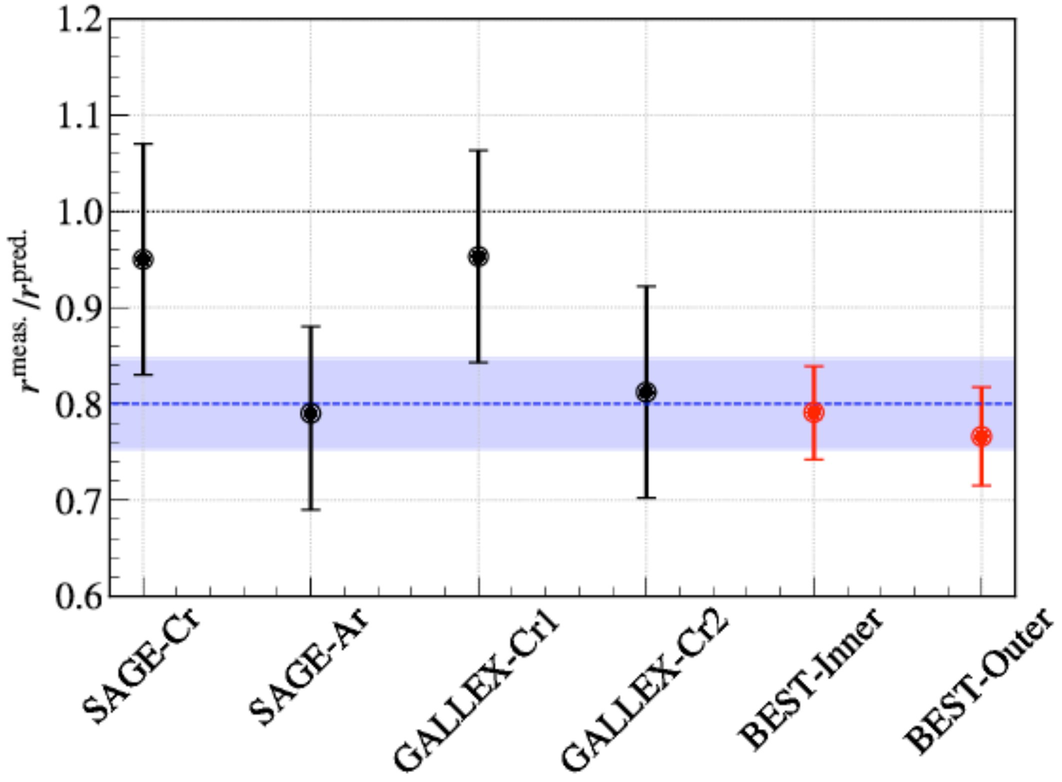
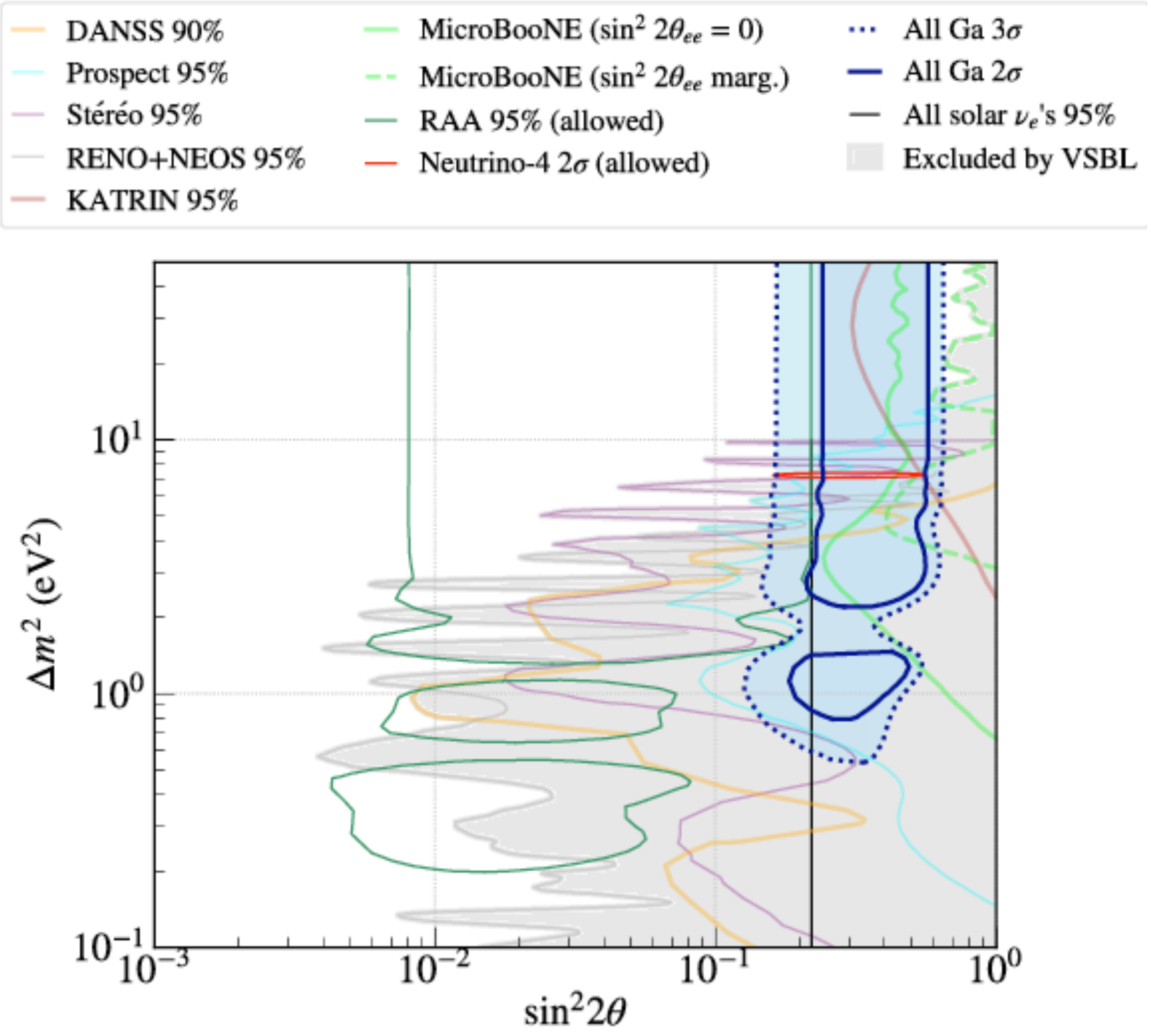


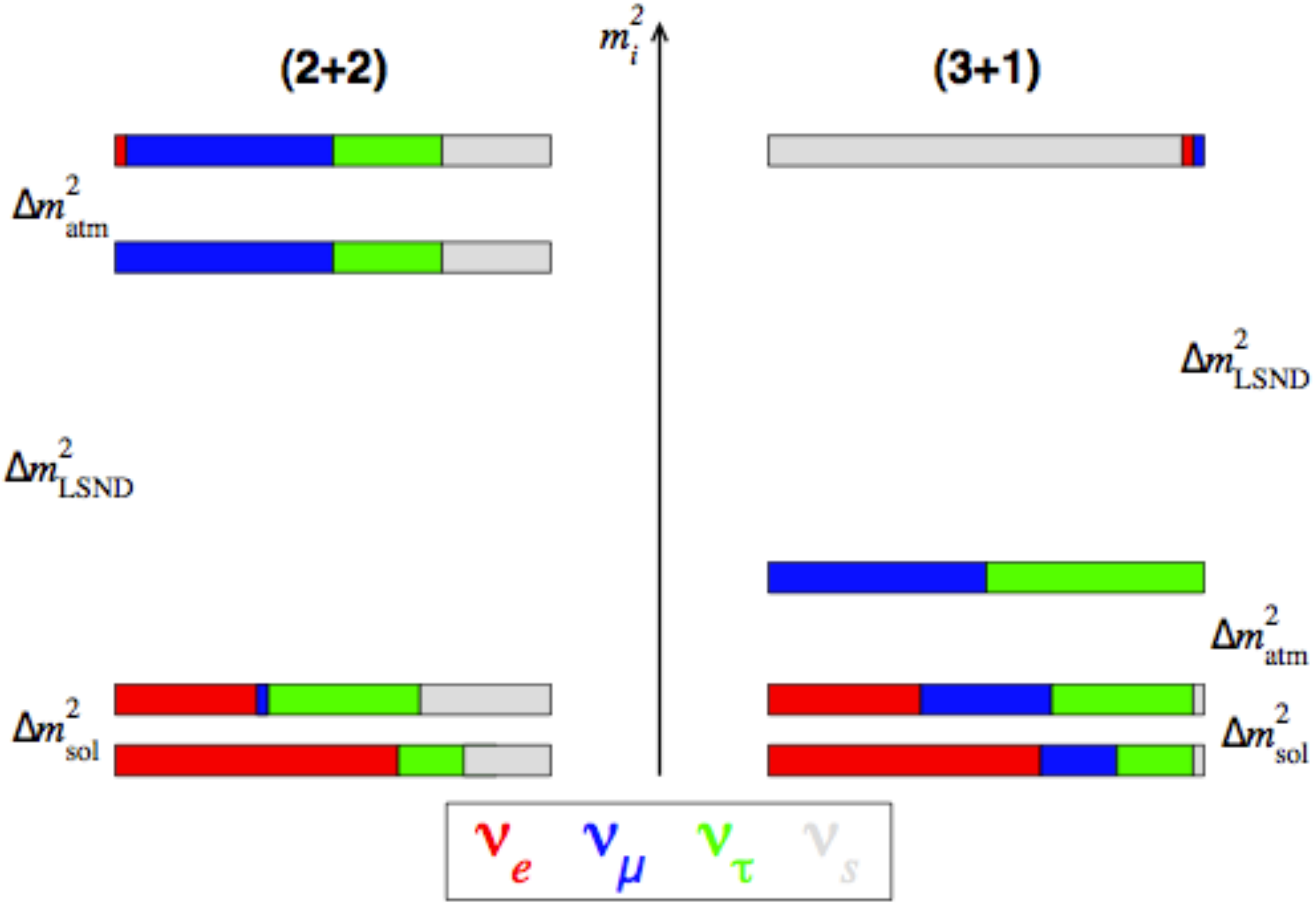


Barinov et al, PRC 2022

Interpretation of the anomalies

$\Delta m^2_{\rm sol} \sim 8\text{x}10^{-5}\,\text{eV}^2$ $\Delta m^2_{\rm atm} \sim 2\text{x}10^{-3}\,\text{eV}^2$ $\Delta m^2_{\rm LSND} \sim 1\,\text{eV}^2$

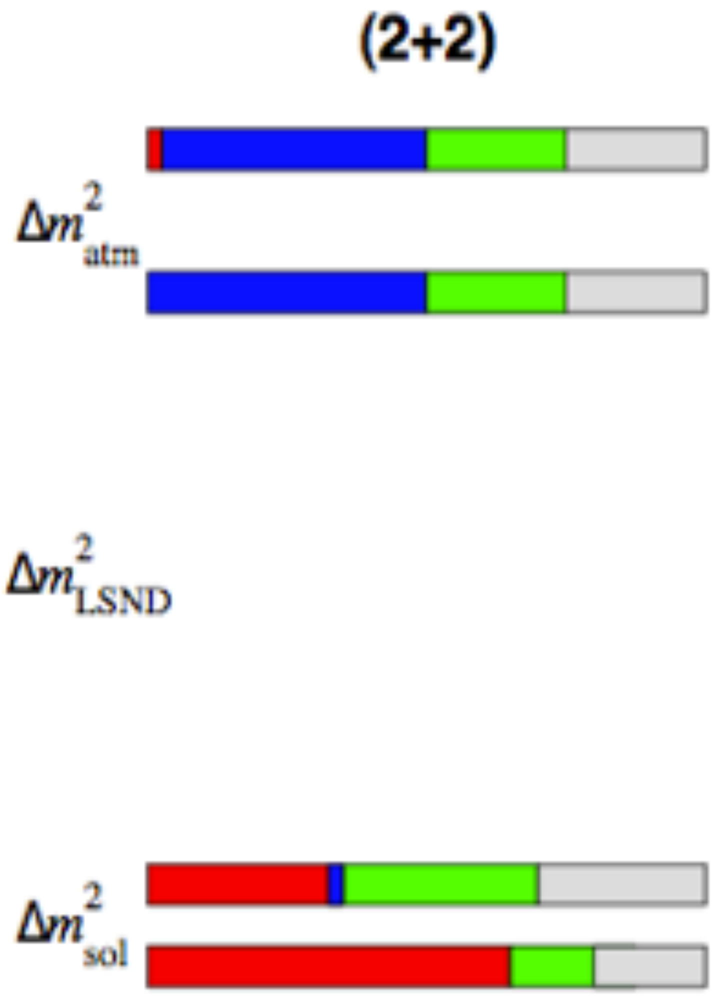
⇒ Can only be accommodated considering four neutrino states

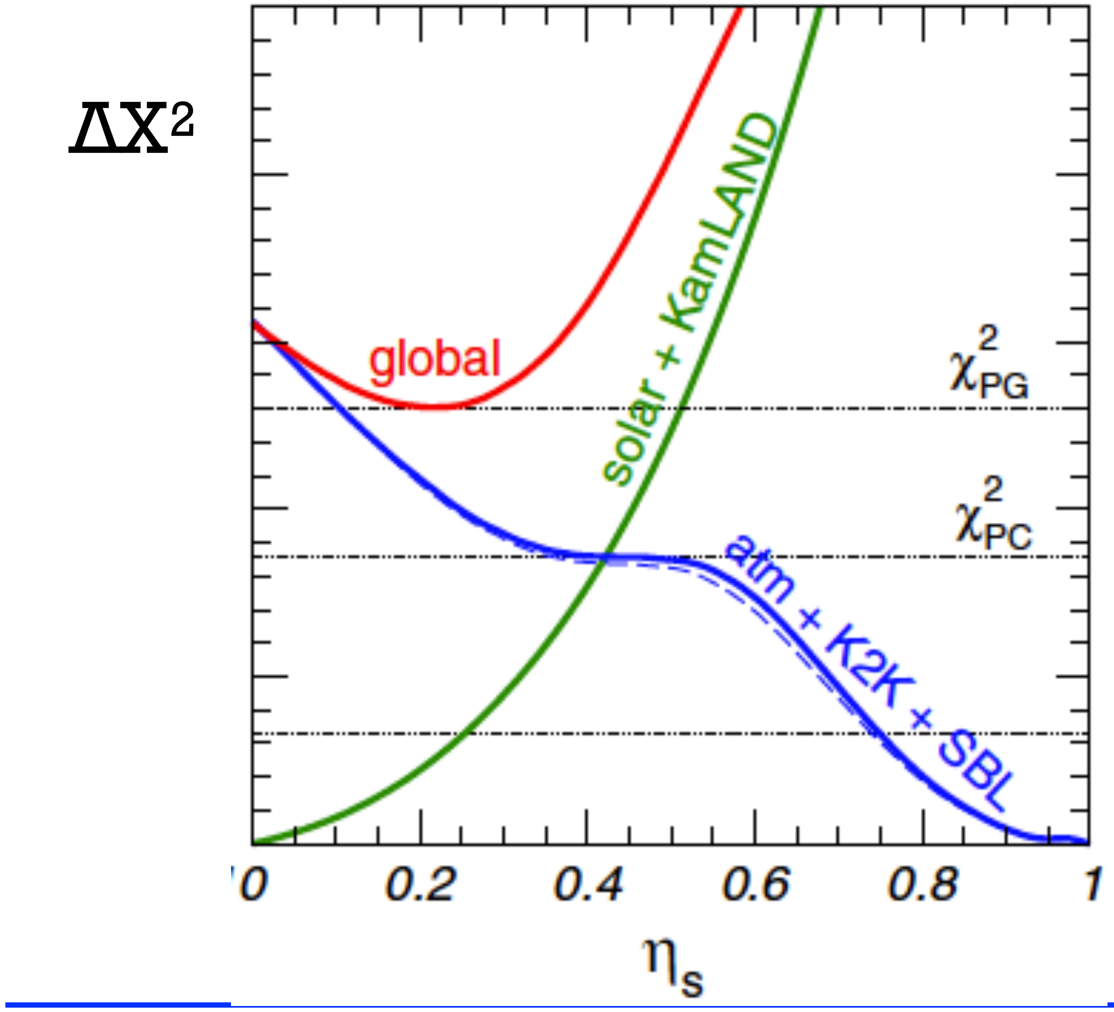


2+2 neutrino scheme

- 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



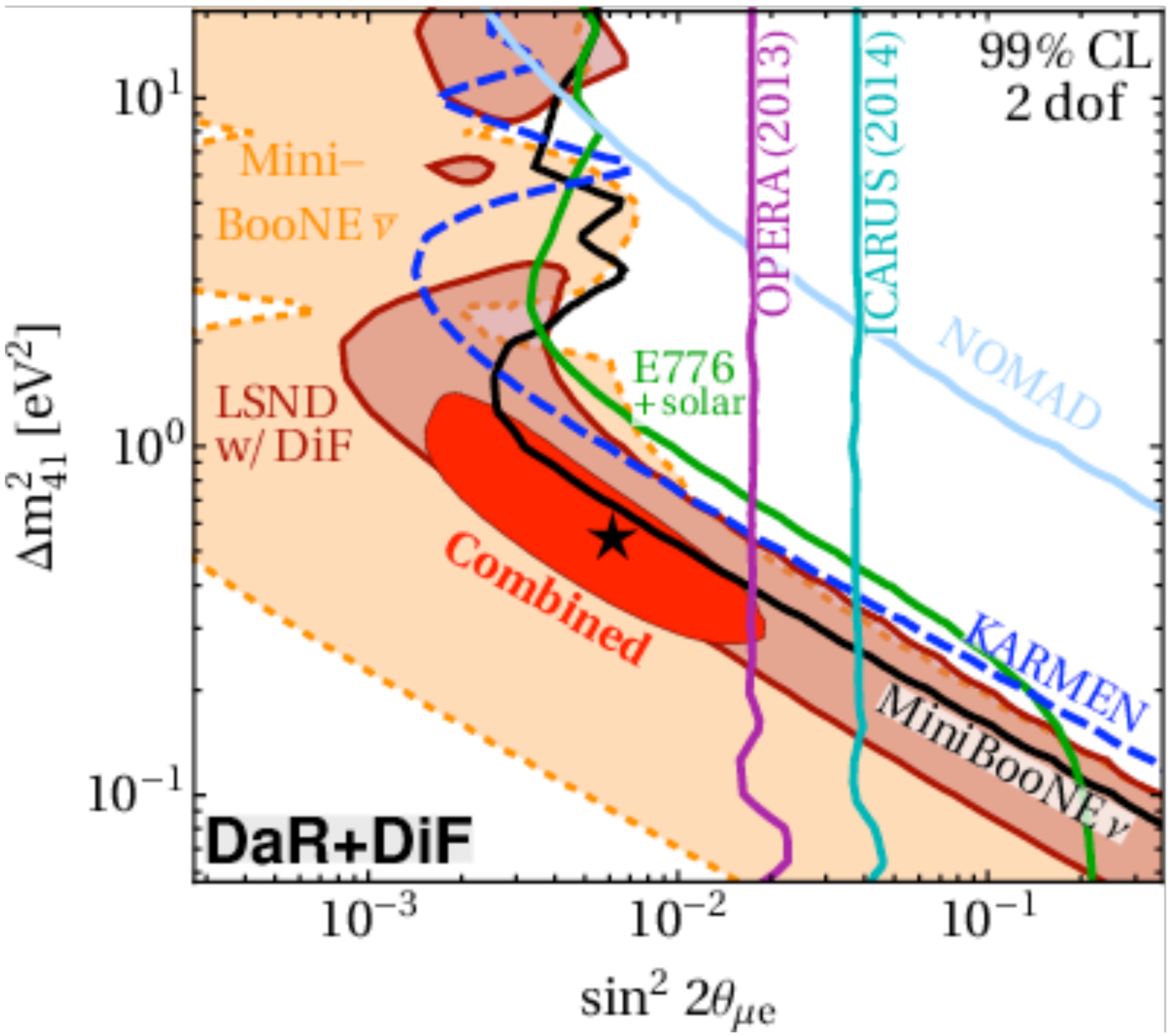


excluded by solar and atmospheric data

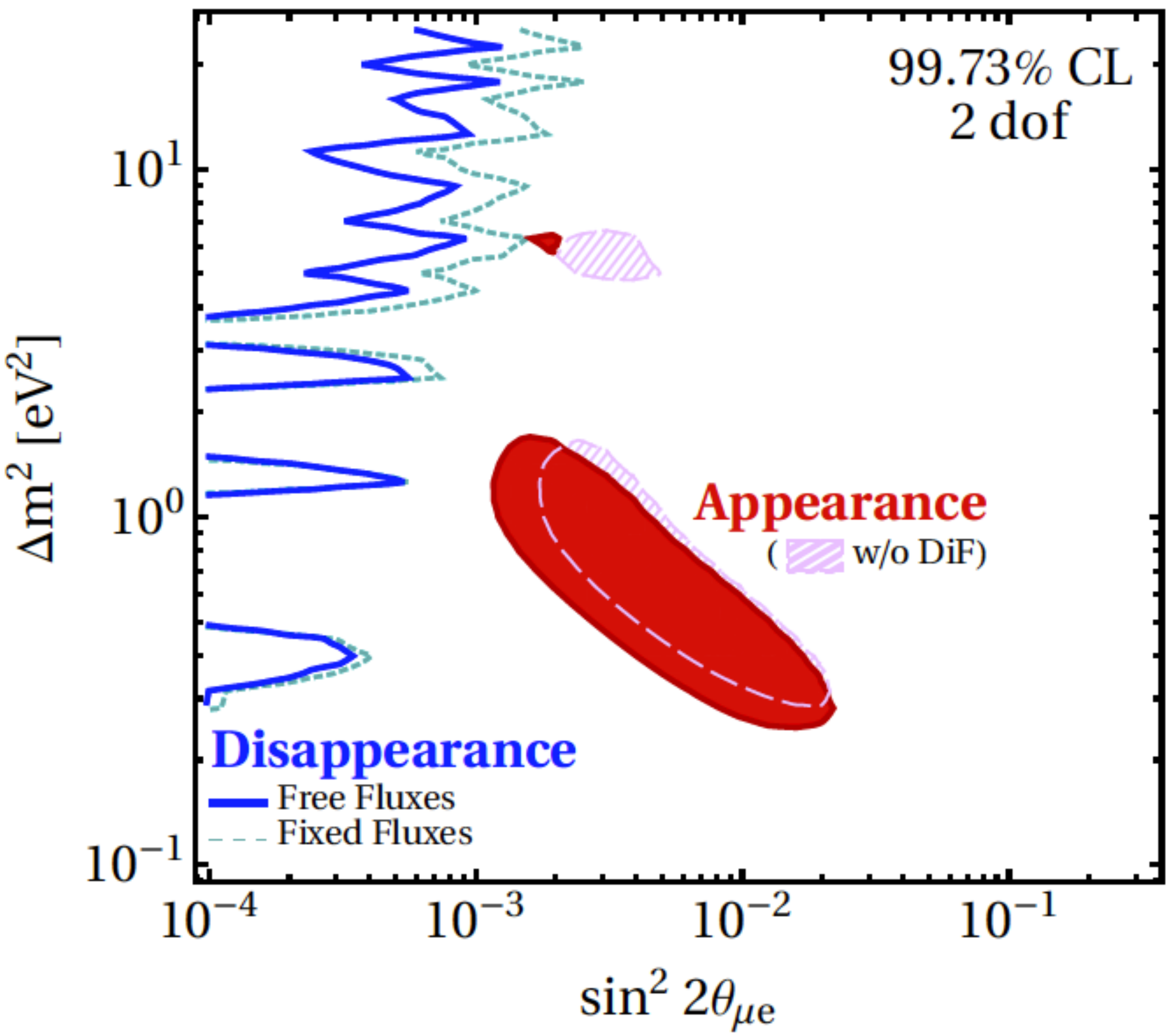
Maltoni et al, NPB643 (2003), NJP06 (2004)

Global fit in 3+1 neutrino scheme

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



⇒ Global fit to ν_e data alone is consistent



⇒ 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

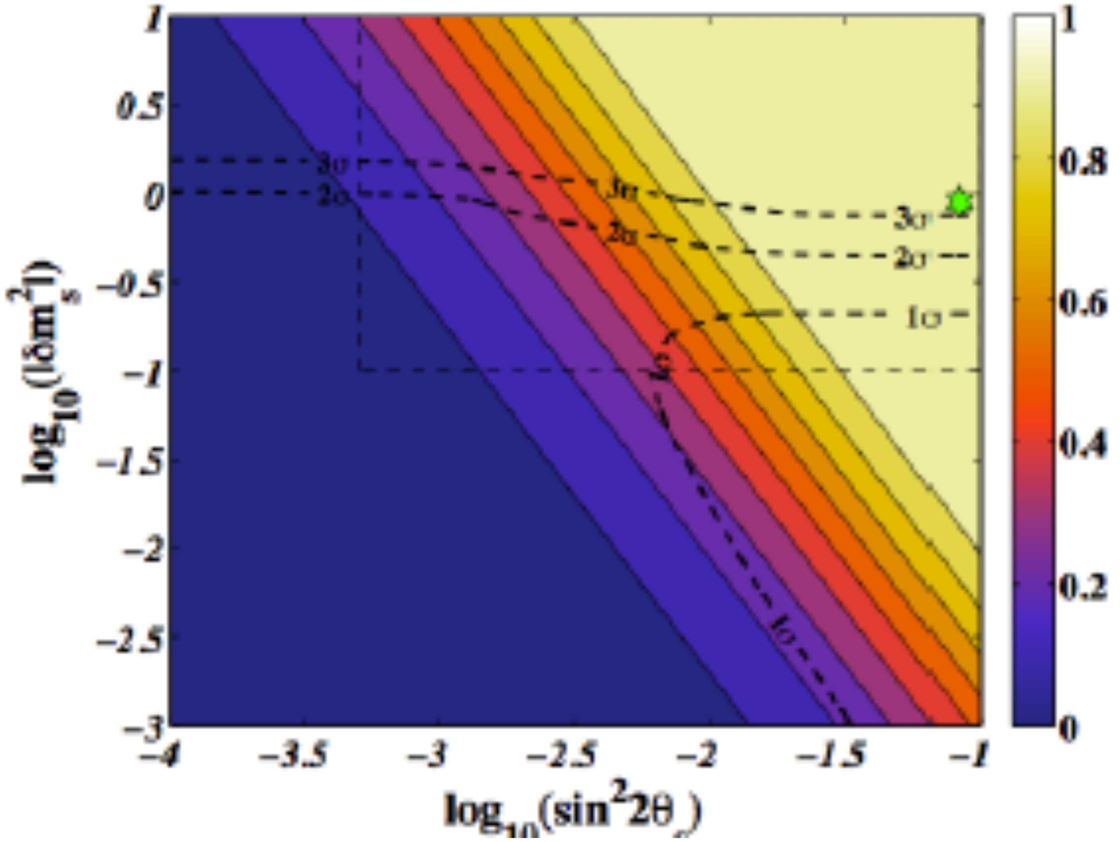
  N_{eff} = relativistic degrees of freedom.

- 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.

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

$\rightarrow N_{\text{eff}} \approx 4$



Hannestad et al, 1204.5861

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$$\rightarrow N_{\text{eff}} \approx 4$$

- Constraints from Cosmology:

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

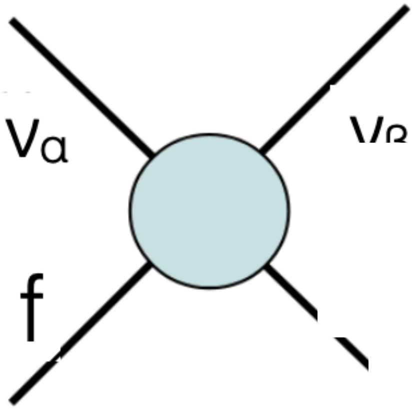
$$N_{\text{eff}} = 2.96^{+0.34}_{-0.33}$$

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

$\Rightarrow$ effect on neutrino production and detection

$\epsilon_{\alpha\beta}^{s}$ (source) $\epsilon_{\alpha\beta}^{d}$ (detector)

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

$\epsilon_{\alpha\beta} \neq 0$ $\rightarrow$ 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: $\epsilon_{\alpha\beta}^{m}$

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

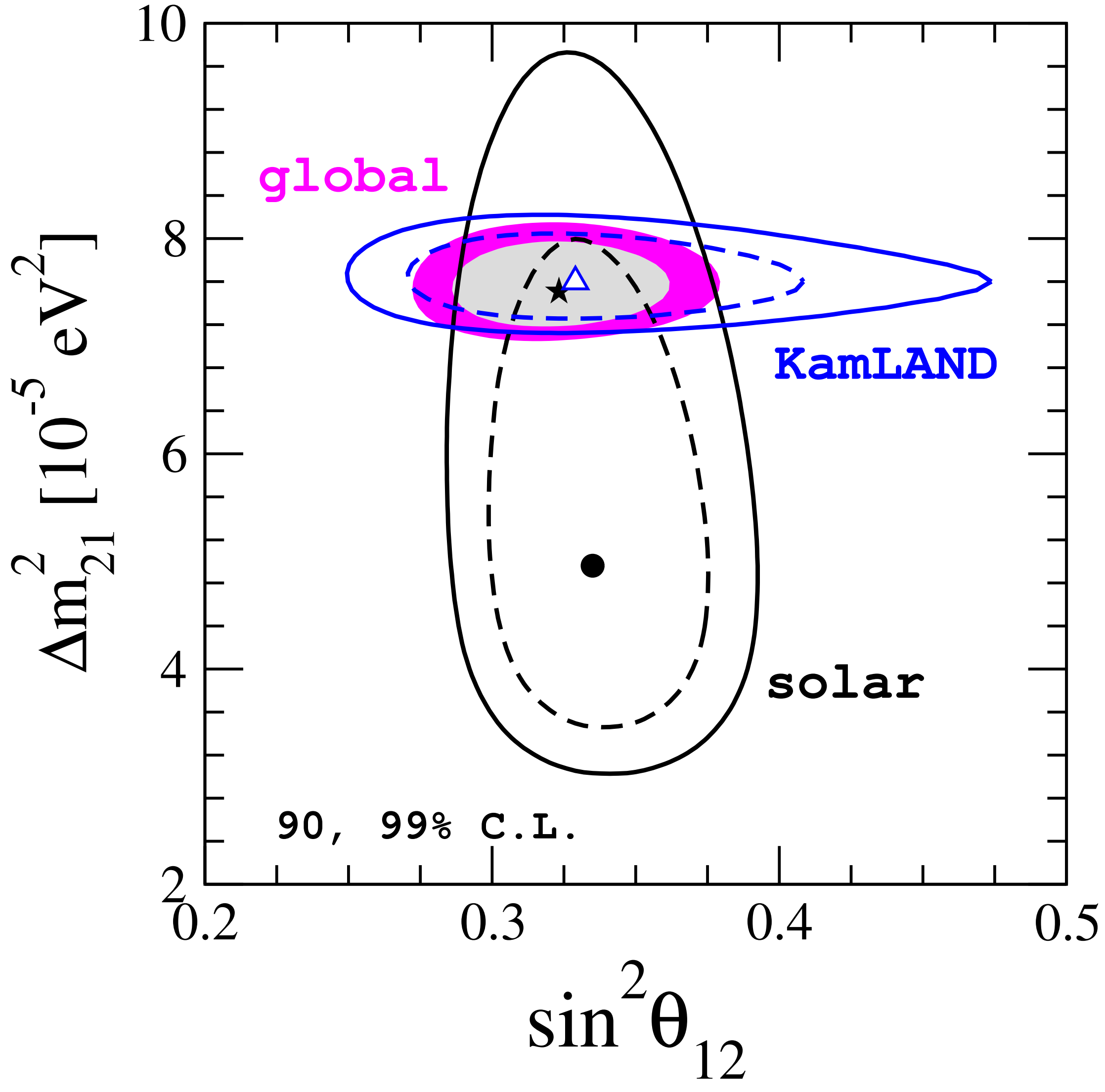
- NSI may affect the 3-neutrino oscillation picture:

$\Rightarrow$ precision measurements at current experiments

$\Rightarrow$ sensitivity reach of upcoming experiments (degeneracies)

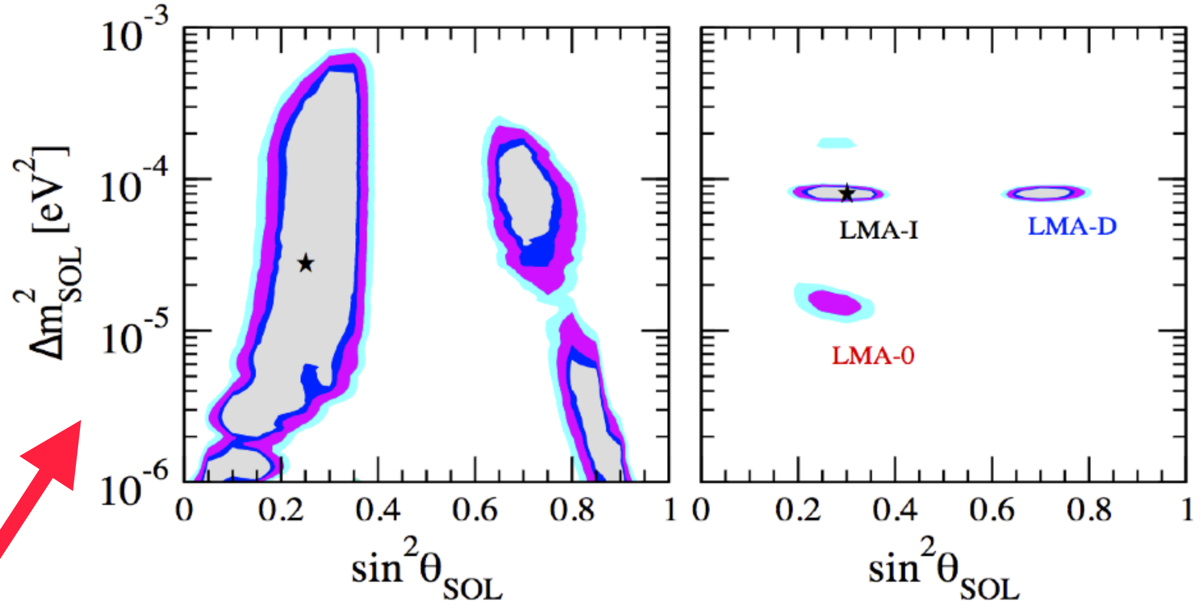
NSI in the solar neutrino sector

Standard 3ν oscillations



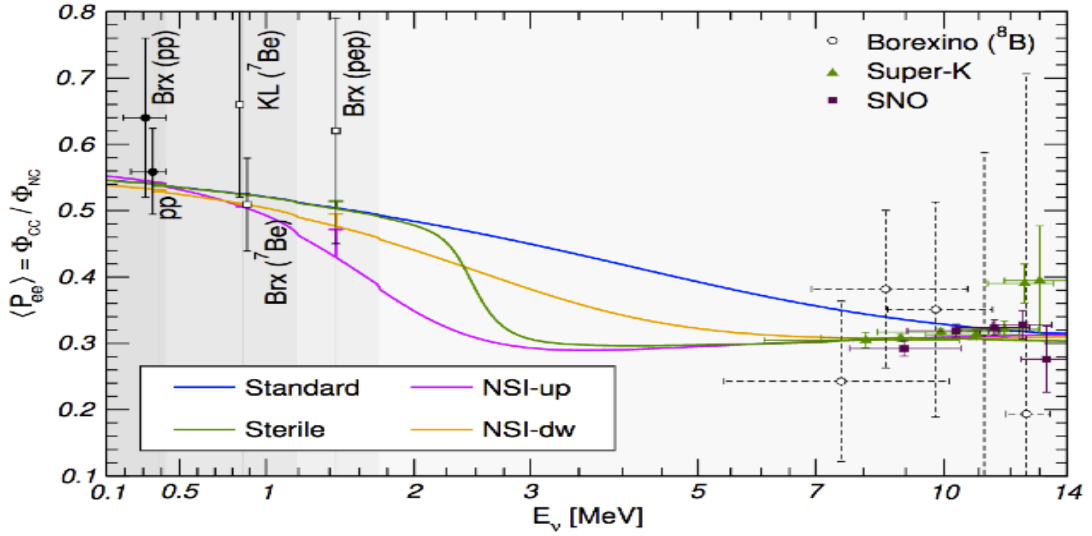
de Salas et al, PLB782 (2018) 633

Miranda et al, JHEP 2006



⇒ degenerate solar solution

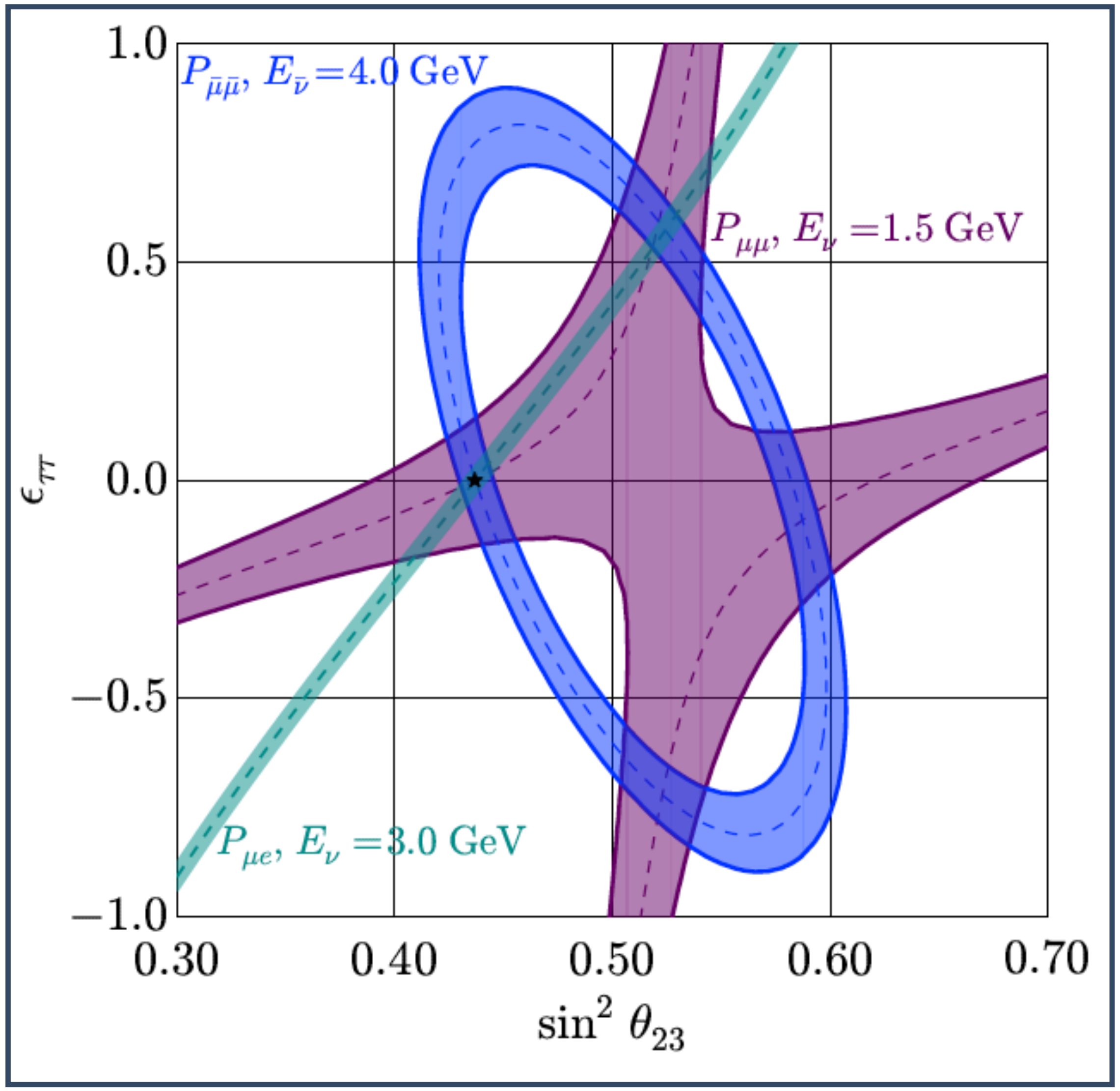
Maltoni & Smirnov, EPJ 2015



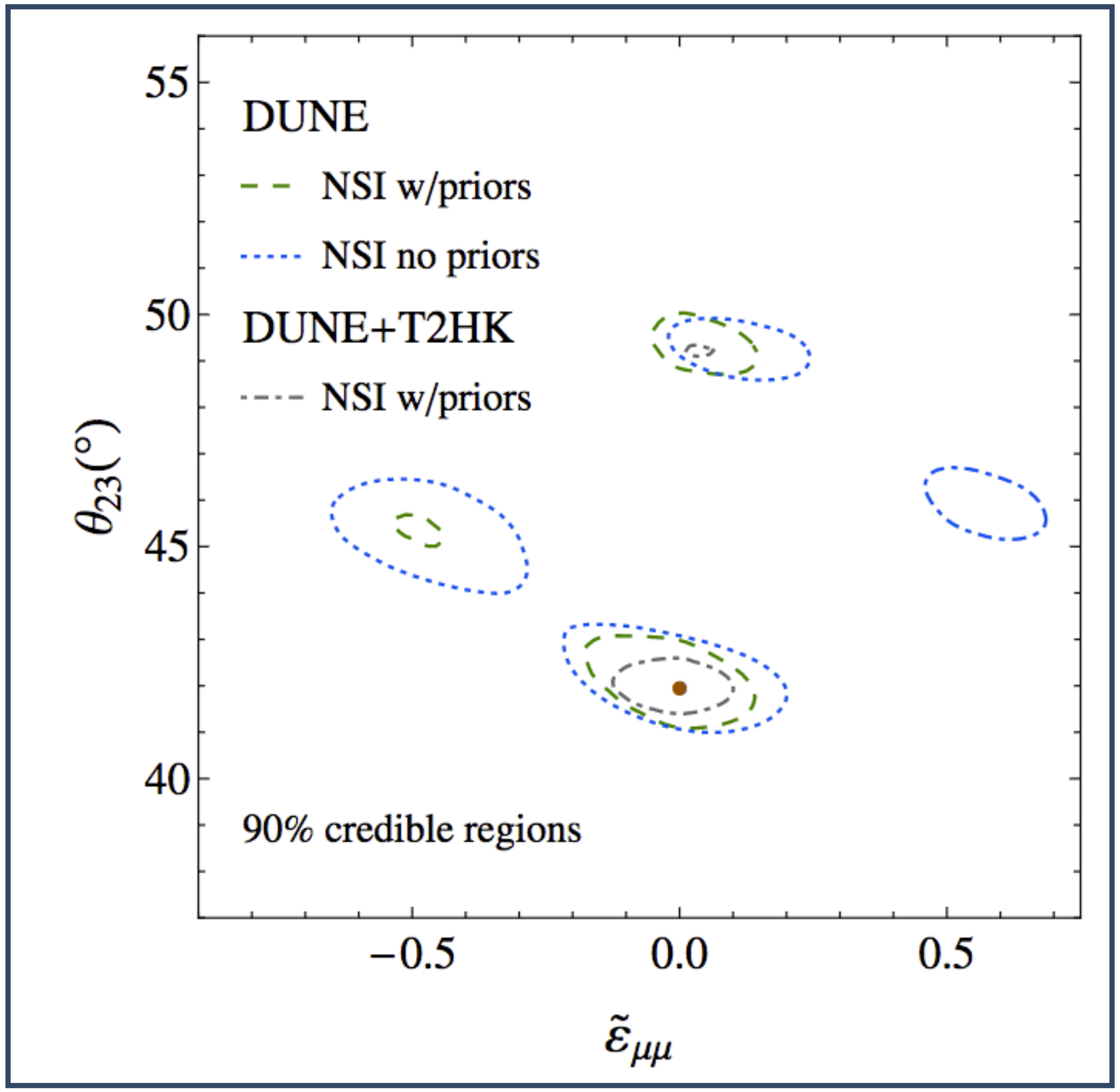
⇒ reconciles tension between Δm^2_{21} @ KamLAND and solar data

NSI at future LBL experiments

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



Gouvea and Kelly, NPB 2016

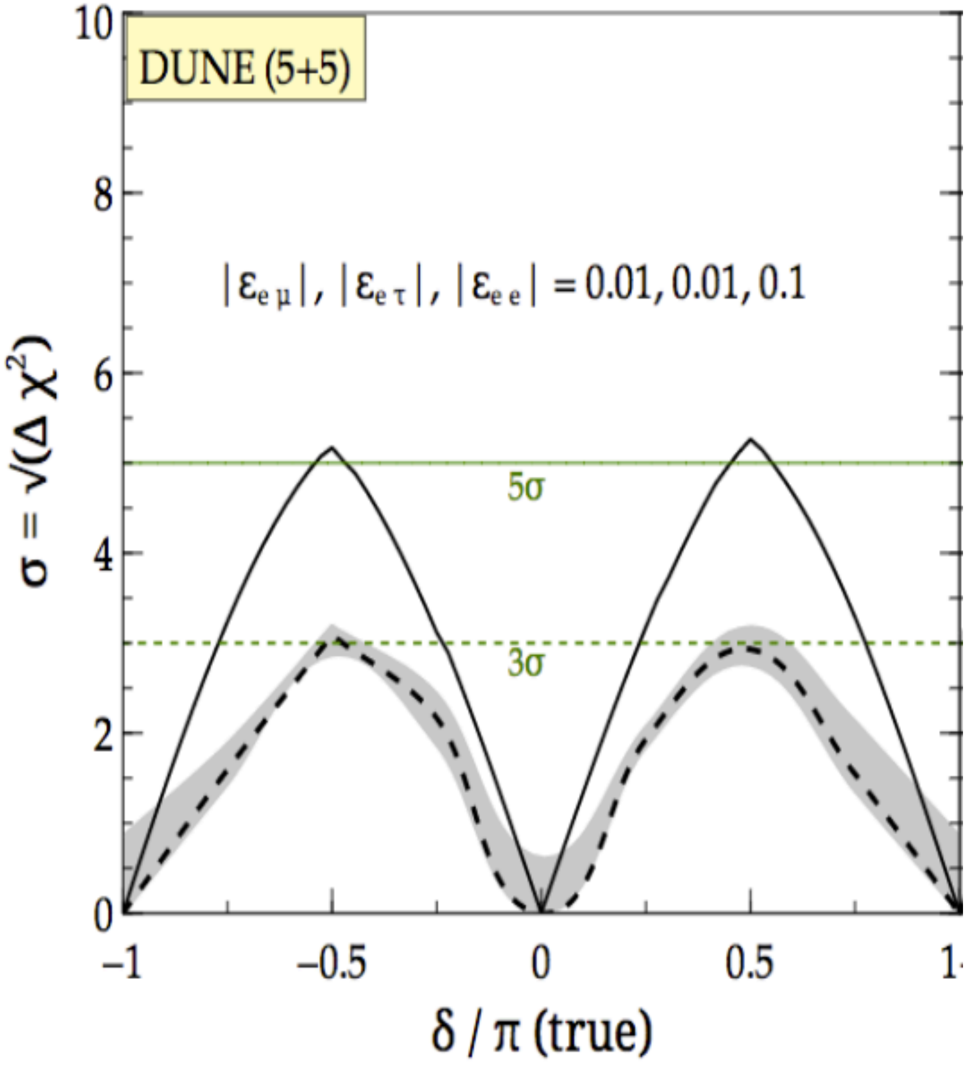


Coloma, JHEP 2016

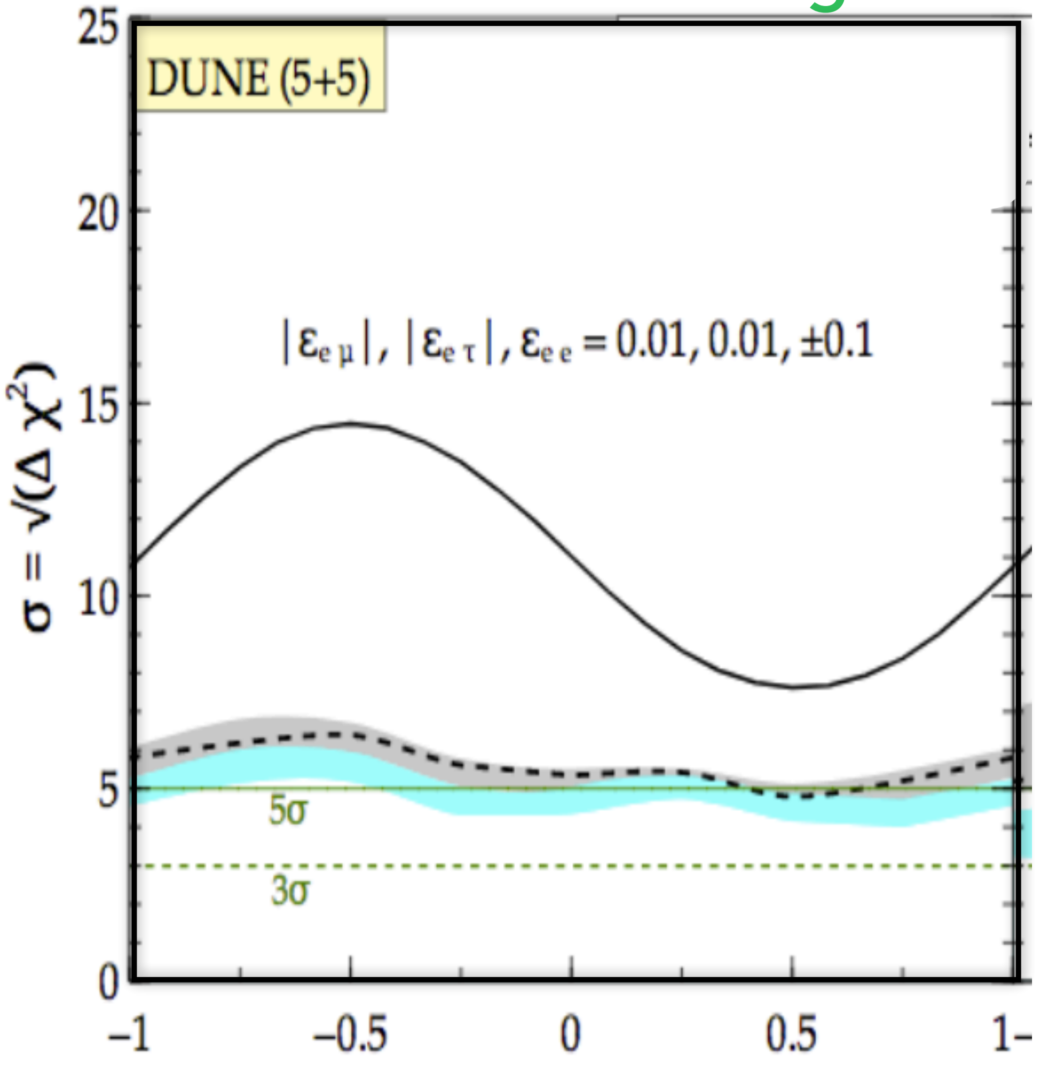
NSI at future LBL experiments

NSI can significantly spoil DUNE's sensitivity to:

CP violation



mass ordering

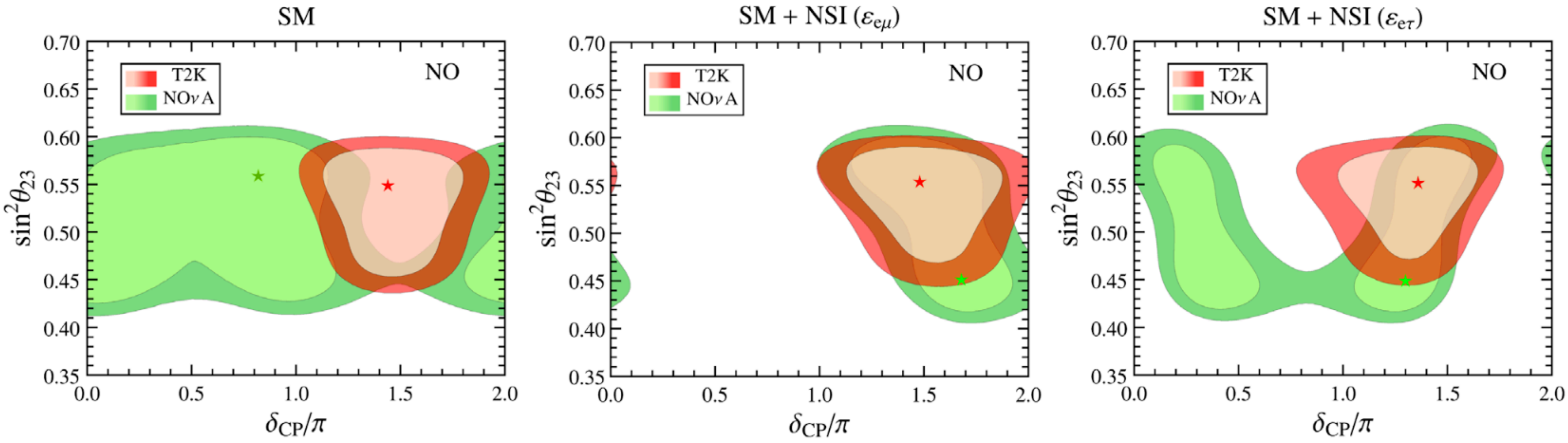


Masud and Mehta, PRD 2016

The T2K-NOvA δ_{CP} tension

- **NSI** may include new sources of CP violation besides δ_{CP}: $\varepsilon_{\alpha\beta} = |\varepsilon_{\alpha\beta}| \exp(i\phi_{\alpha\beta})$

- CP-violating NSI with a new complex phase $\phi_{e\mu}$ or $\phi_{e\tau}$ close to maximal with NSI couplings $\varepsilon_{e\mu}$ or $\varepsilon_{e\tau}$ of the order of 0.2 may reconcile T2K and NOvA results.



Chatterjee and Palazzo, PRL 2021

See also Denton et al, PRL 2021

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

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

Escrihuela et al, PRD92 (2015)

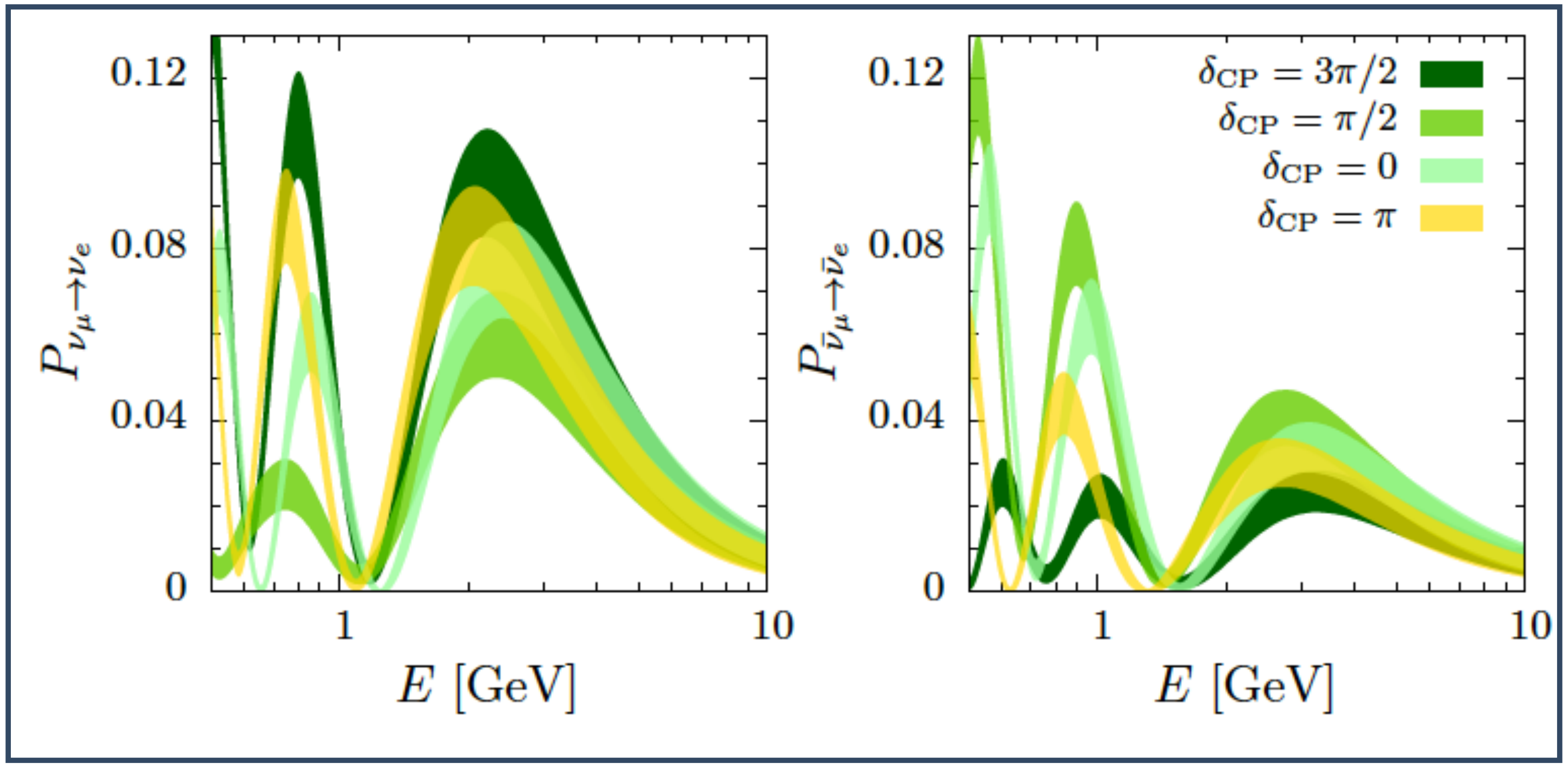
See also Xing, PRD2012 for n=6

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

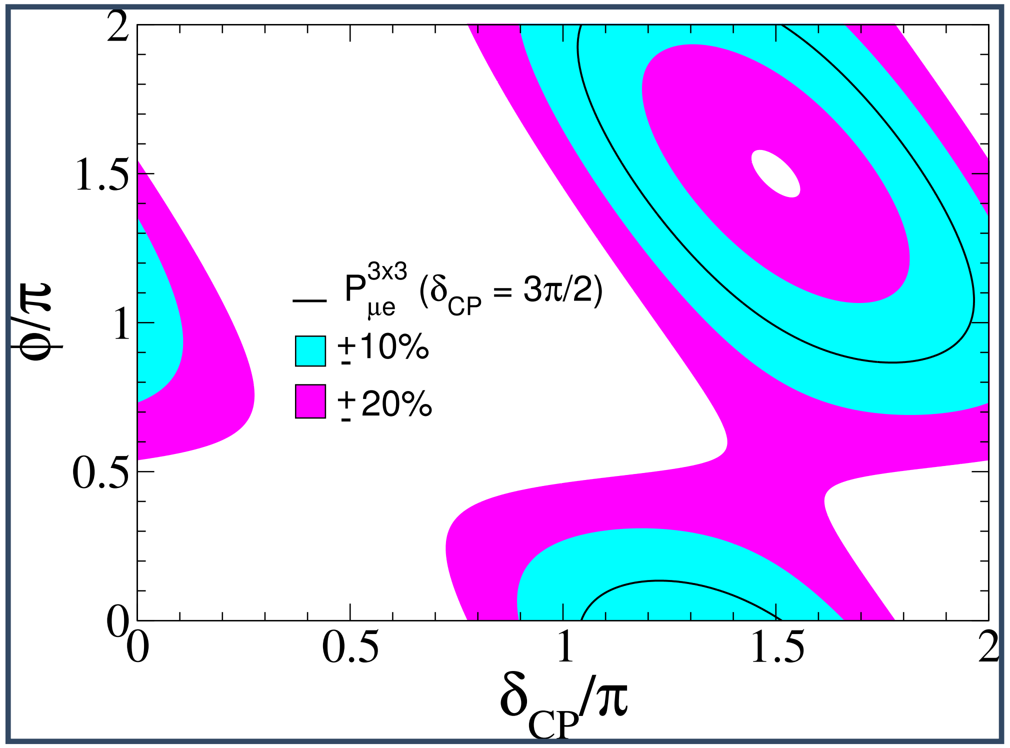
NU neutrino oscillations in DUNE

$$P_{\mu e} = (\alpha_{11}\alpha_{22})^2 P^{3\times3}_{\mu e} + \alpha_{11}^2\alpha_{22}|\alpha_{21}|P^I_{\mu e} + \alpha_{11}^2|\alpha_{21}|^2$$ **with** $P^I_{\mu e}(\phi)$

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



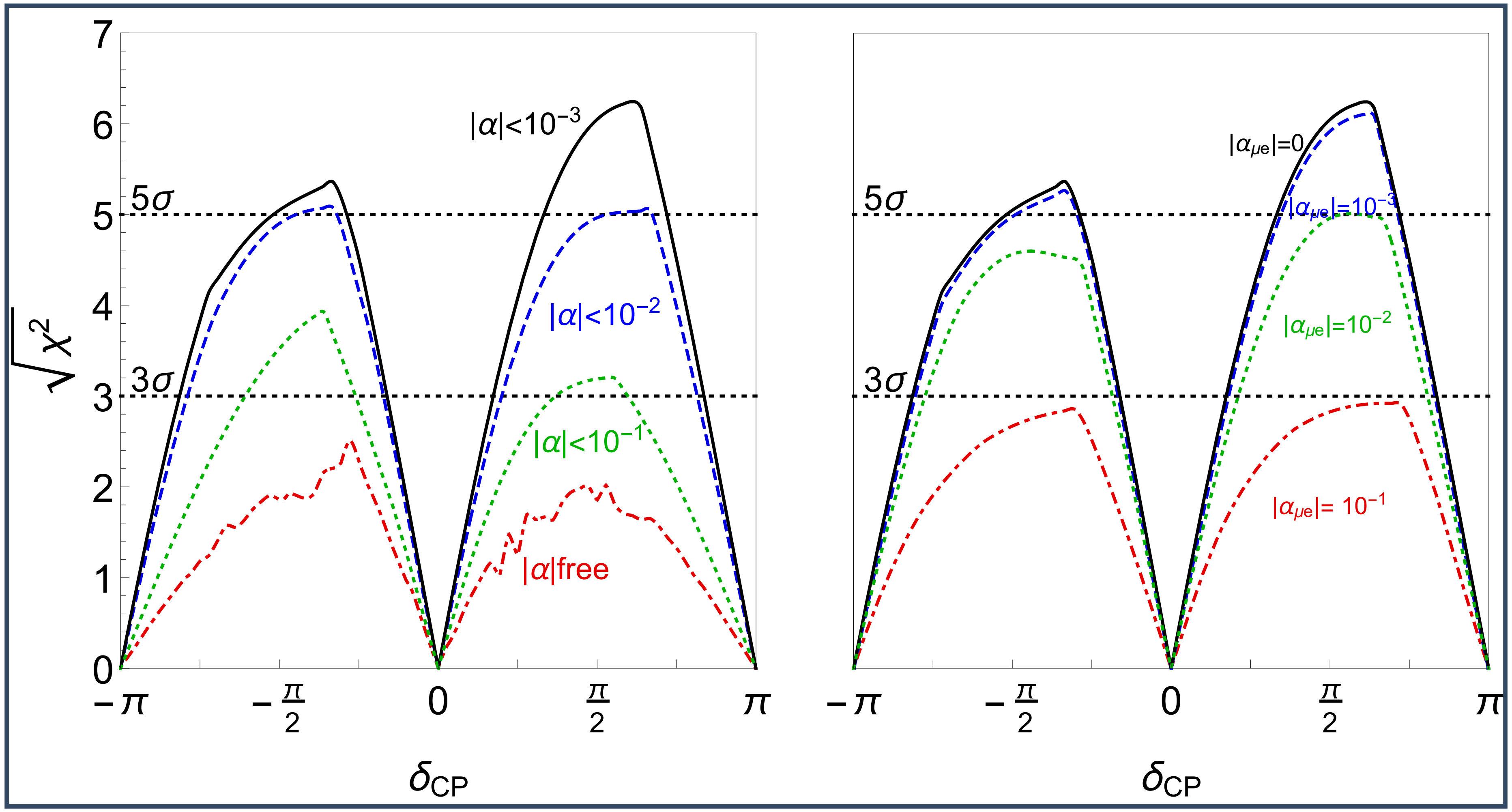
Escrihuela et al, NJP 2017



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



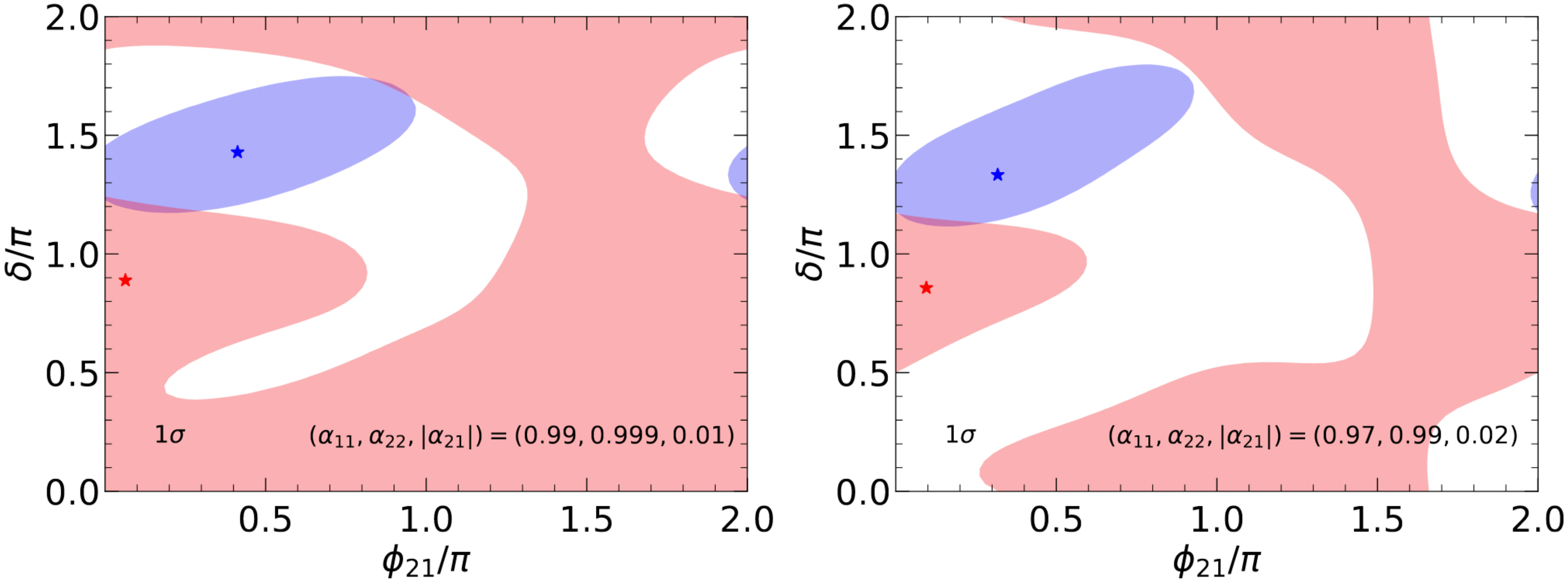
Fernández-Martínez et al (DUNE-BSM Working Group)

→ 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

The T2K-NOvA δ_{CP} tension

Non-unitary mixing analysis of T2K and NOvA (normal ordering)

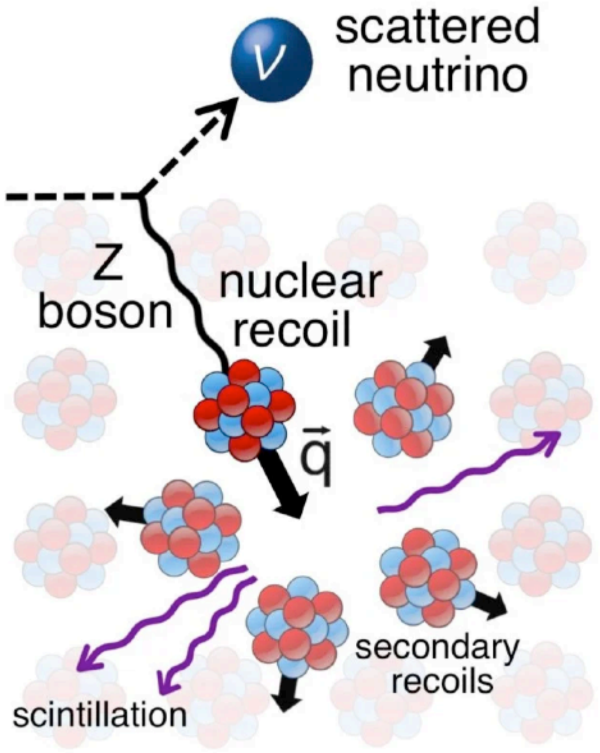


Forero et al, PRD 2022

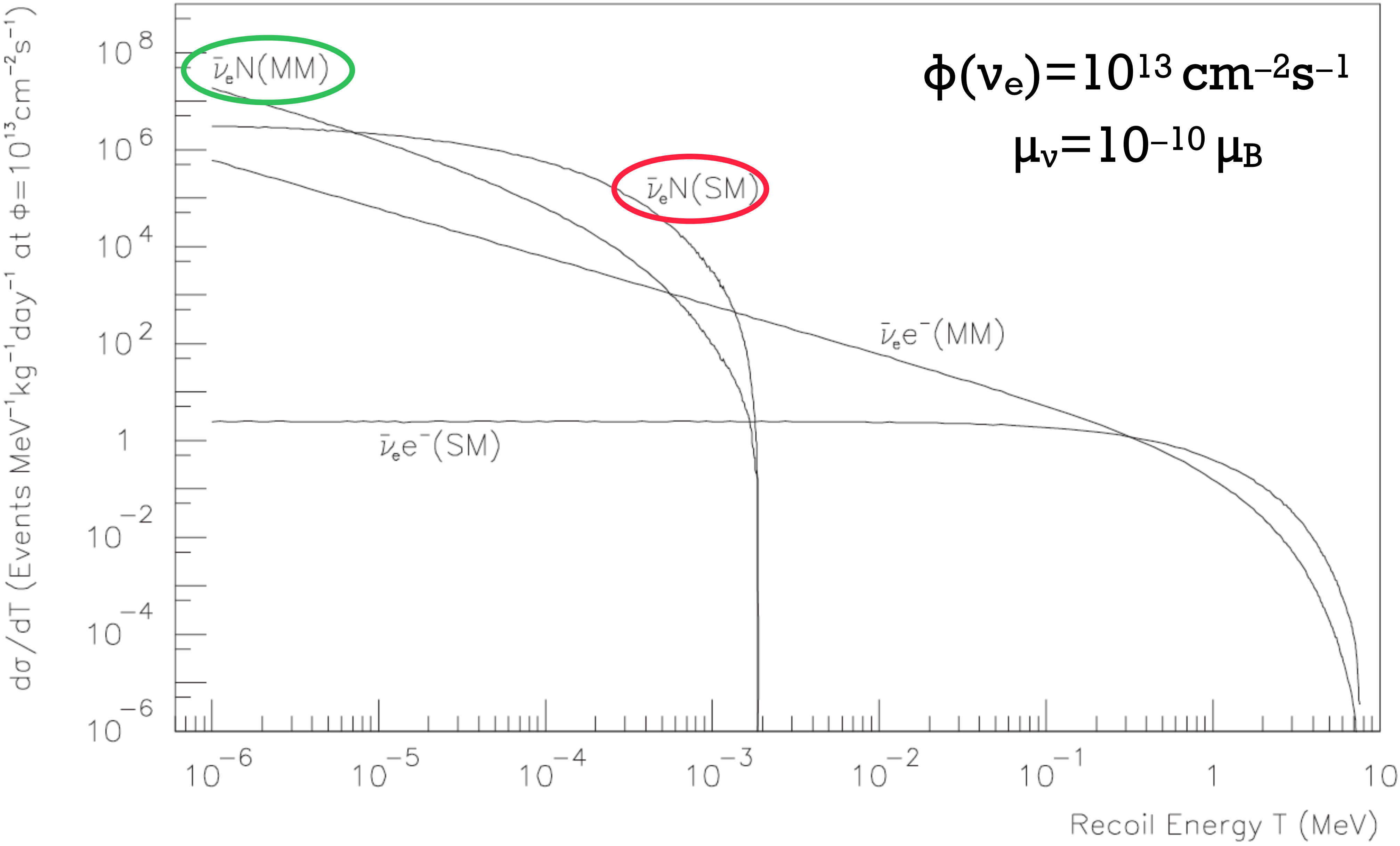
- NU includes additional sources of CP violation.
- In this case, the tension is not alleviated in the context of NU neutrino mixing, since the new phase has the same effect on T2K and NOvA

BSM searches with CEvNS experiments

Coherent Elastic ν Nucleus Scattering (CEνNS)



D. Freedman, 1974



$\phi(\nu_e)=10^{13}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

$\mu_\nu=10^{-10}\,\mu_B$

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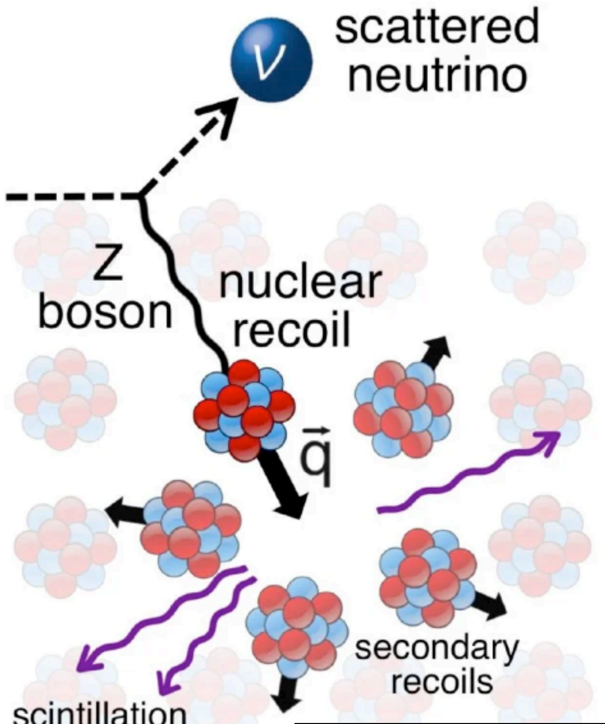
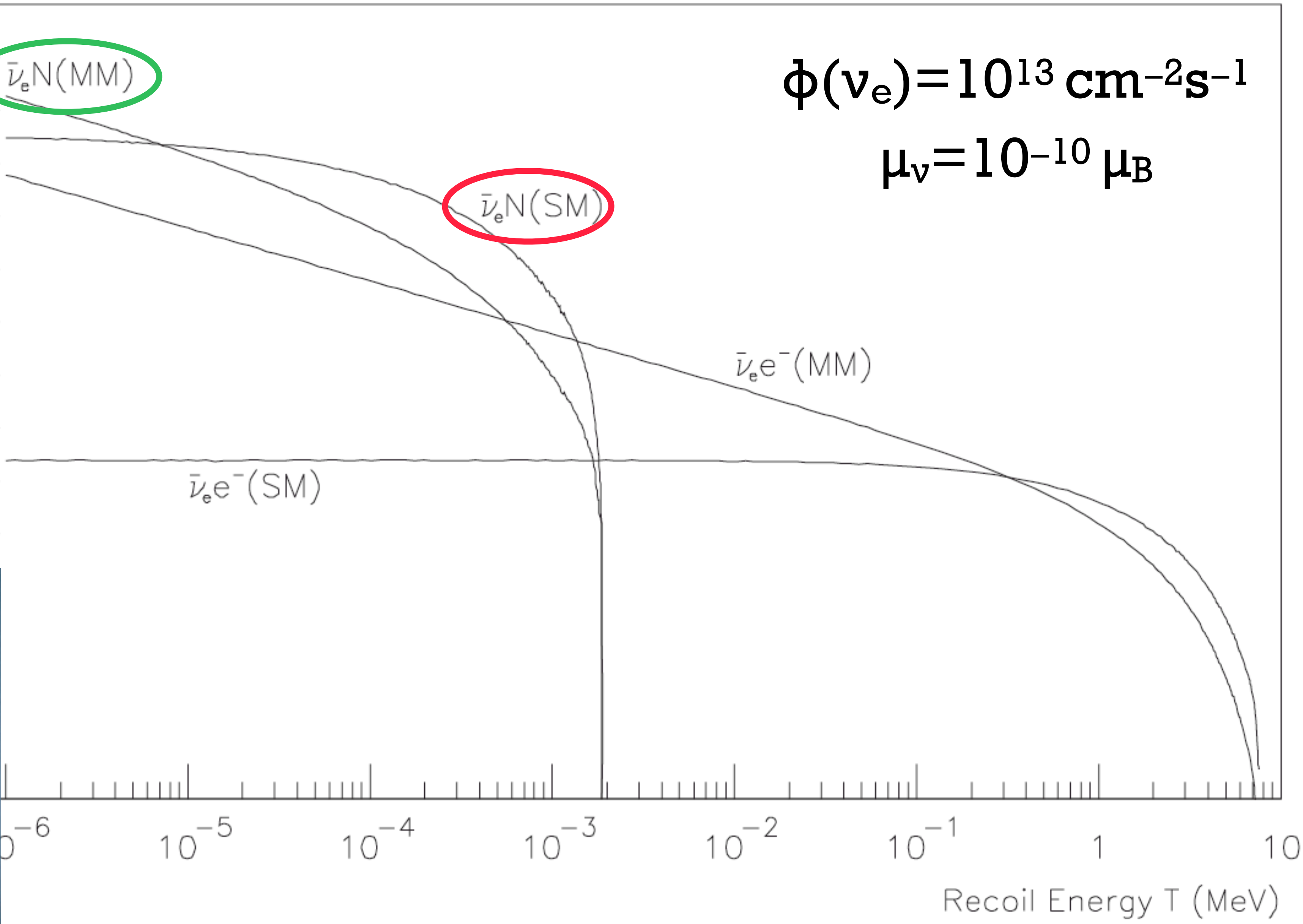


D. Freedmar



$\phi(\nu_e)=10^{13}$ cm^{-2}s^{-1}

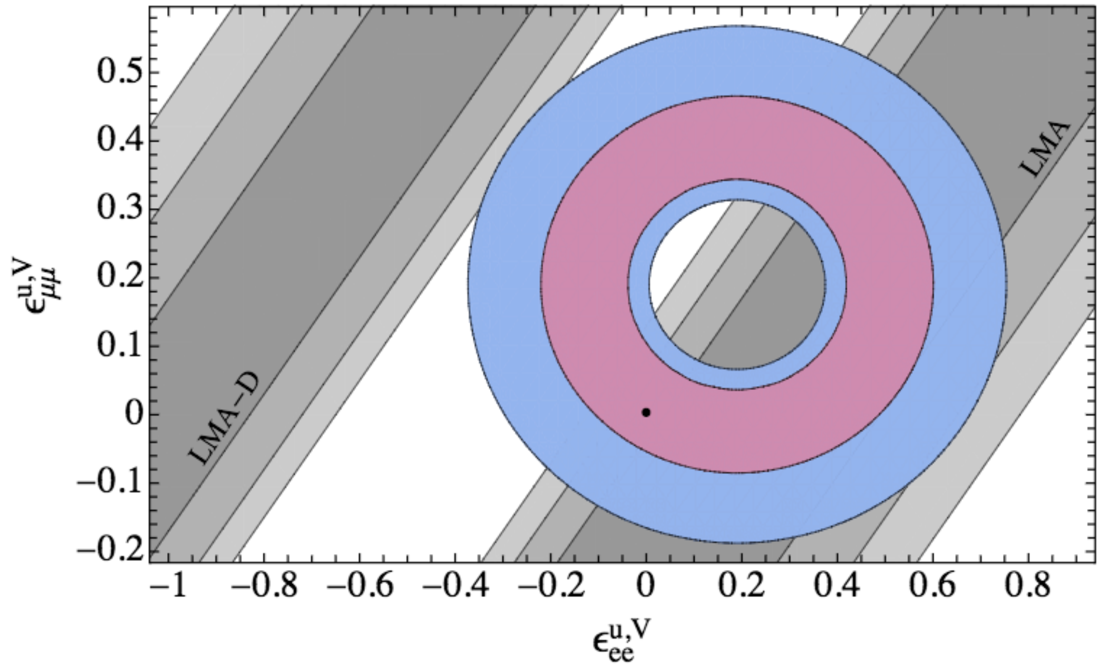
$\mu_\nu=10^{-10}\,\mu_B$

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

COHERENT Coll. Science 357 (2017) 1123

Probing BSM physics with CEvNS

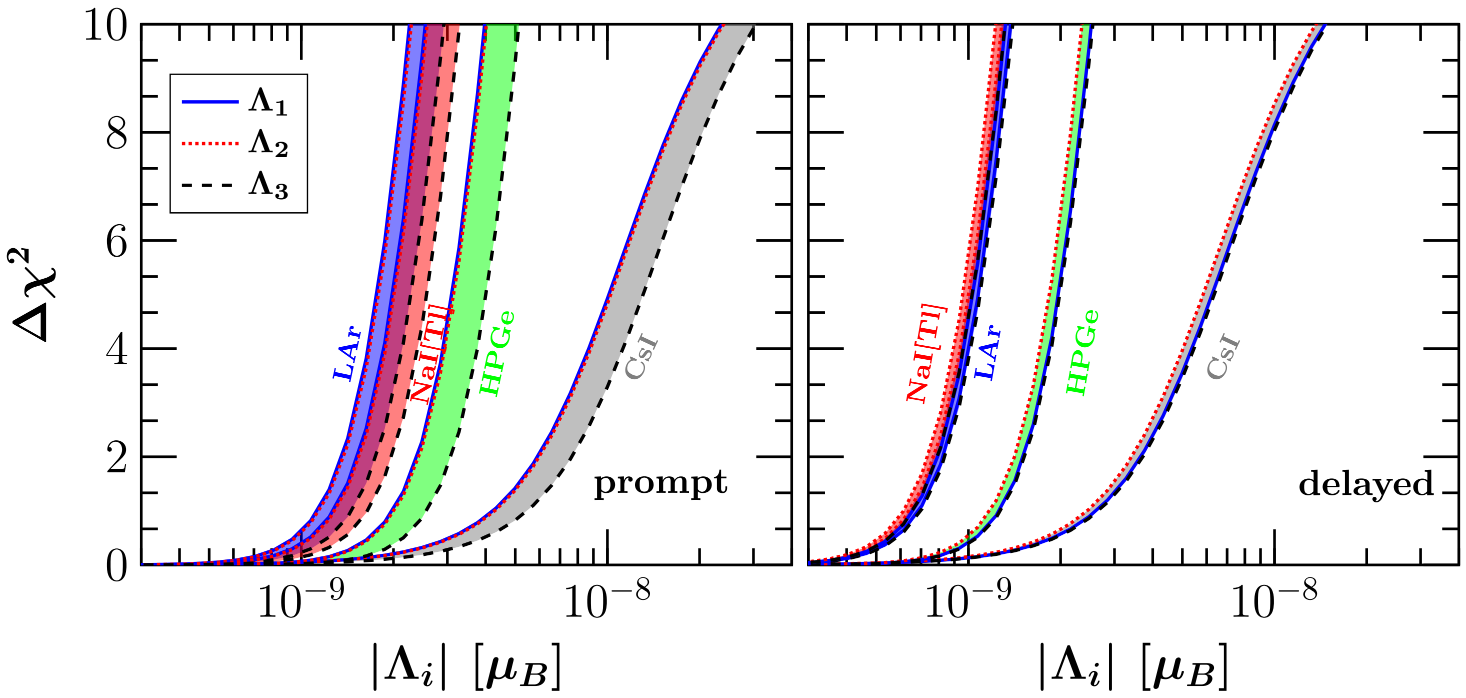
Non-standard interactions (NSI)



Coloma et al, PRD 2017

→ Very relevant to provide a complementary test of the LMA-D degenerate solution.

Neutrino electromagnetic properties



Miranda et al, JHEP 2019

→ Not competitive with other searches (Borexino), but they provide complementary information

Other searches: neutrino charge radius, models with light mediators,…

Summary (Part II)

- 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

- Several **scenarios of physics BSM** 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.