Neutrino physics overview

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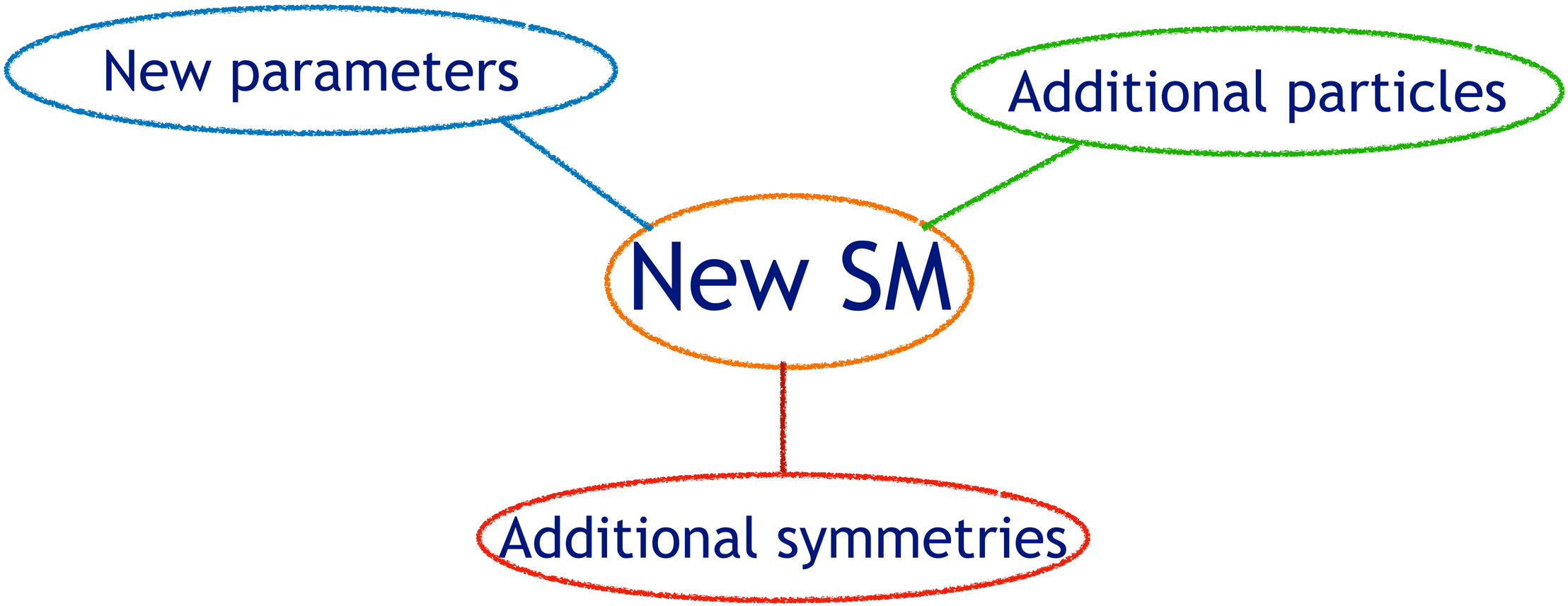
DESY Theory workshop 2025

September 26 2025

COLORADO STATE UNIVERSITY



Neutrinos can provide guidance

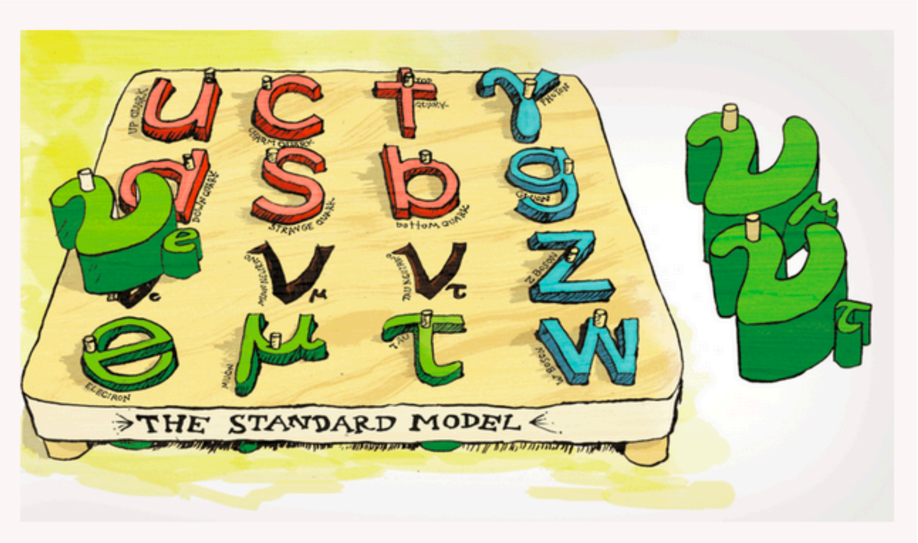
New parameters

Observation of neutrino oscillations:

→ Strong evidence of physics beyond the SM

→ introduced more parameters to the model
(3 angles, at least one phase, 3 masses)

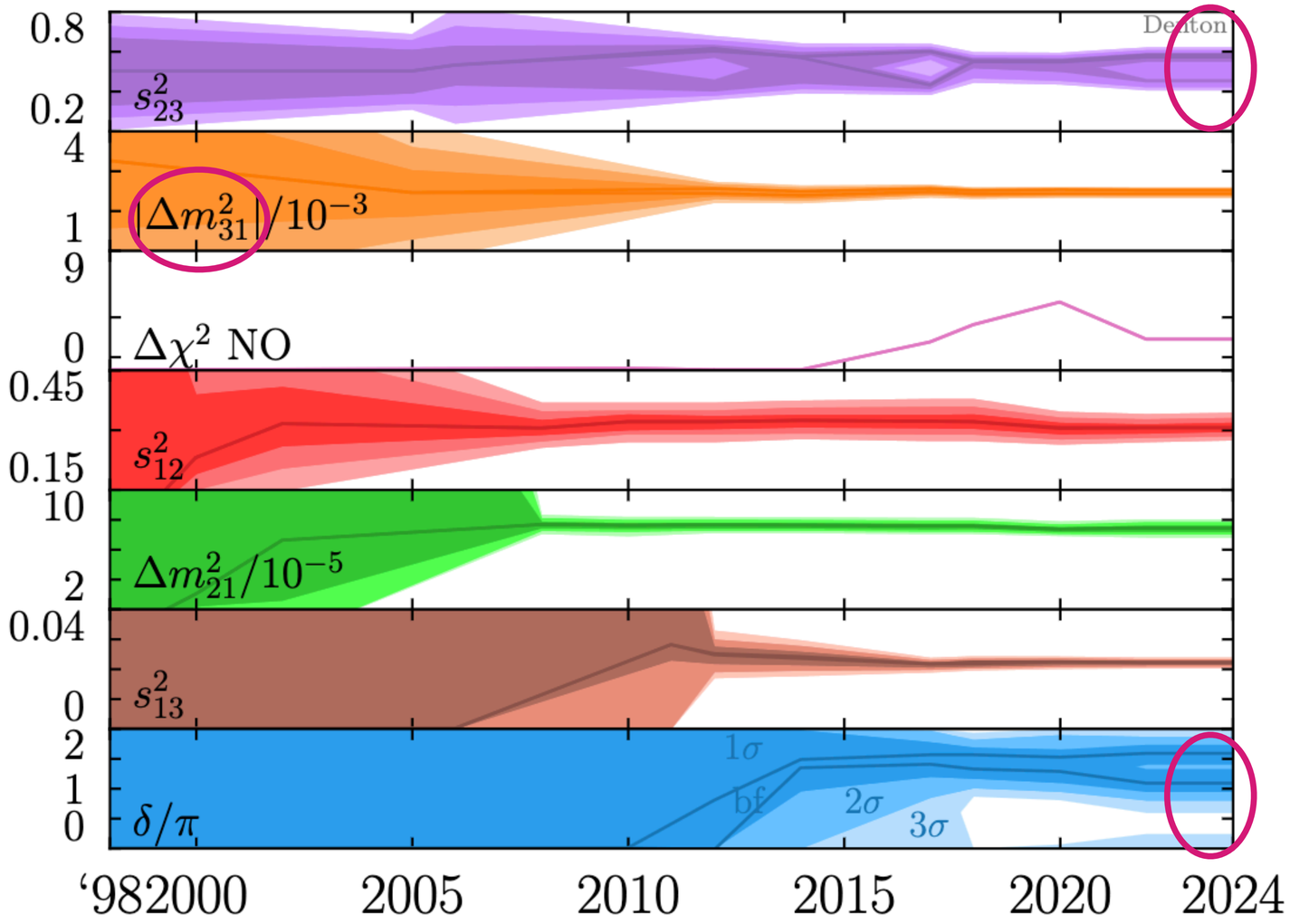
→ need to introduce neutrino mass mechanism



Neutrino parameters are an essential part of the new SM!

New parameters

Where do we stand in measuring the parameters?



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

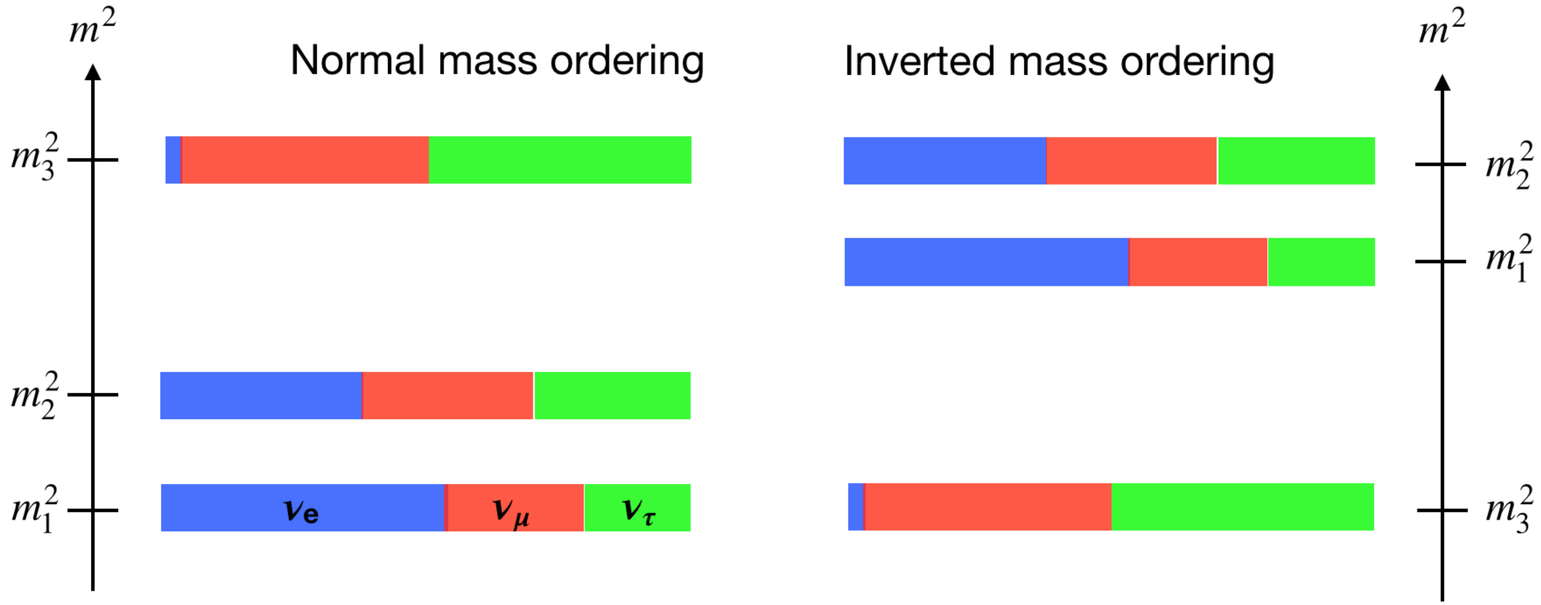
[update from Denton et al '22]

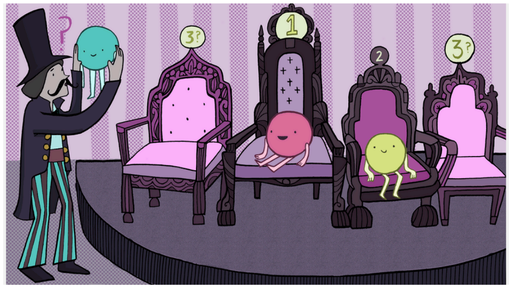
New parameters

Where do we stand in measuring the parameters?

No strong preference for mass ordering from oscillation experiments
(Depending on data sets combined)

[nufit v6.0 2410.05380]

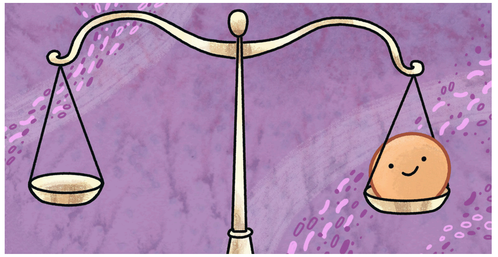




New parameters

Where do we stand in measuring the parameters?

What is the absolute neutrino mass scale?



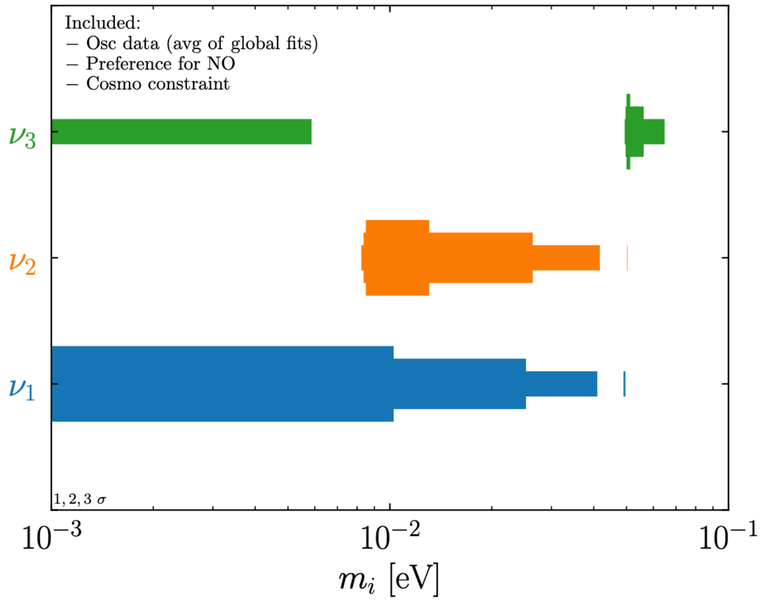
[Denton, JG '23]

Strong bound from cosmology on sum of neutrino masses:

$$\sum m_\nu \lesssim 0.072 \text{ eV}$$

[DESI, '24]

(Depends on data sets combined)



Additional particles

Neutrino sector

Neutrino mass generation

- New neutrino interactions
- Neutrino portal

Additional particles

What is the neutrino mass generation mechanism?

Dirac neutrinos

$$m_D = y_\nu \bar{\nu}_L \tilde{H} N_R$$

like other SM fermions

Majorana neutrinos

$$m_M = M_N \bar{\nu}_L \nu_L^c$$

Neutrinos are the only SM particles that could have such a mass term

Term not gauge invariant!

In any case need new particles!

→ observation of neutrino oscillations predicts new particles!

Additional particles

Neutrino mass generation mechanism

Majorana mass term arises from higher dimension operators

→ explains smallness of neutrino mass due to suppression by high scale

Majorana neutrino mass operators occur at odd dimension

[Kobach '16]

$$\mathcal{O} \propto (LLHH)(H^\dagger H)^n$$

$$\rightarrow m_\nu \propto c\frac{v^2}{\Lambda}\left(\frac{v}{\Lambda}\right)^{d-5}$$

Additional particles

Neutrino mass generation mechanism

Dimension 5 operator

$$\mathscr{L}_5 = c_5 \frac{(\bar{L}^c \tilde{H}^*)(\tilde{H}^\dagger L_L)}{\Lambda}$$

Only dim-5 operator that can be build with SM fields alone
Expect first signs of new physics from lowest SMEFT operator
→ neutrino mass

Dimension 7

$$\mathscr{L}_7 \propto c_7 \frac{(LLHH)(H^\dagger H)}{\Lambda^3}$$

Dimension 9

$$\mathscr{L}_9 \propto c_9 \frac{(LLHH)(H^\dagger H)(H^\dagger H)}{\Lambda^5}$$

...

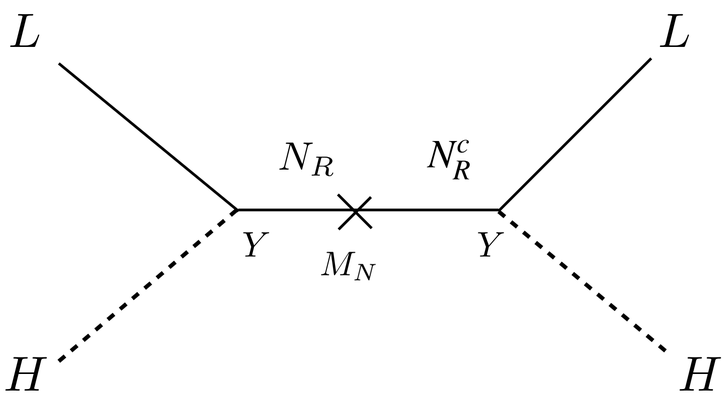
Additional particles

Neutrino mass generation mechanism

Identify UV complete models for higher dimensional operators

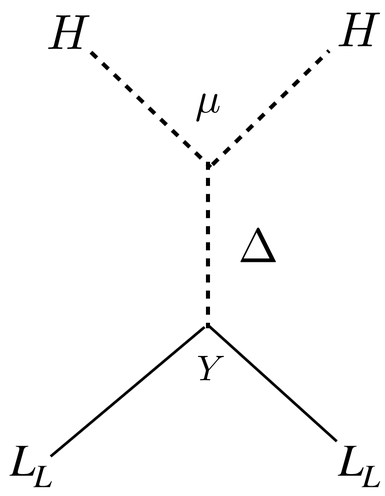
Example: realizations of dim-5 operator

Type I seesaw



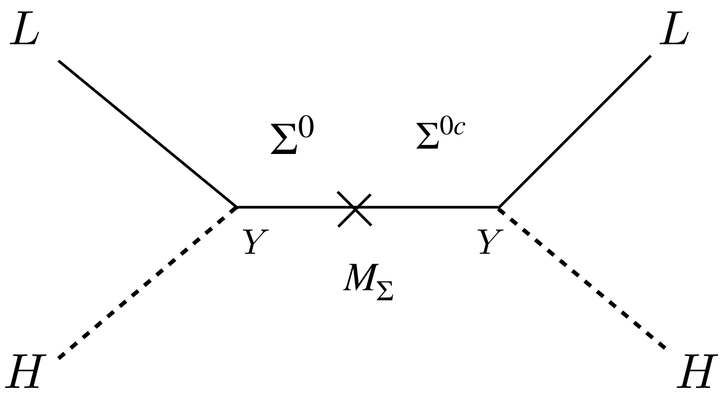
N_R : SM singlet
"Right-handed neutrino"

Type II seesaw



Δ: $SU(2)_L$ scalar triplet

Type III seesaw



Σ: $SU(2)_L$ fermion triplet

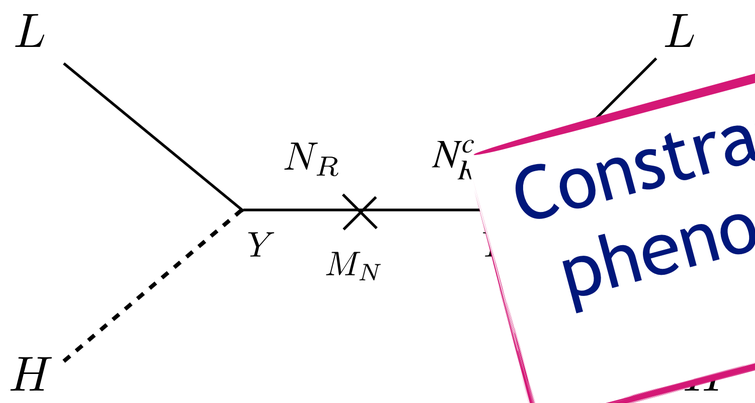
Additional particles

Neutrino mass generation mechanism

Identify UV complete models for higher dimensional operators

Example: realizations of dim-5 operator

Type I seesaw

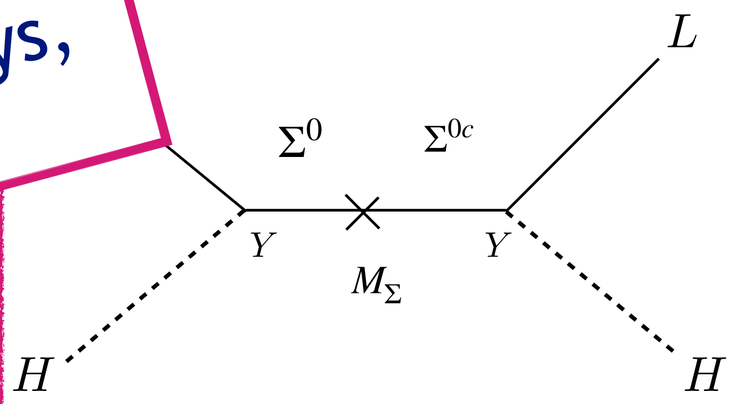


N_R : SM singlet
"Right-handed neutrino"

Type II seesaw

Δ: $SU(2)_L$ scalar triplet

Type III seesaw

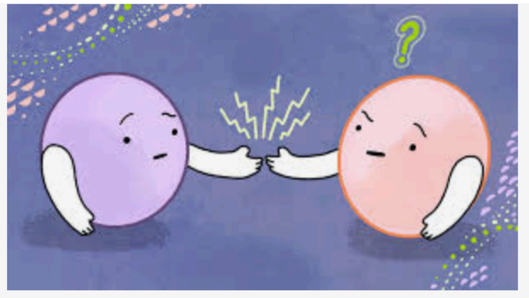


Σ: $SU(2)_L$ fermion triplet

Constraints from: EWPO, collider phenomenology, meson decays, cLFV

Additional particles

Neutrino portal



Couple right-handed neutrino to SM

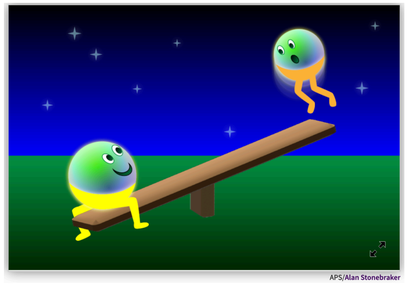
→ Neutrino portal

$$\mathscr{L} \supset y\bar{L}_L\tilde{H}N_R$$

Sterile neutrino does not need to be involved in neutrino mass generation

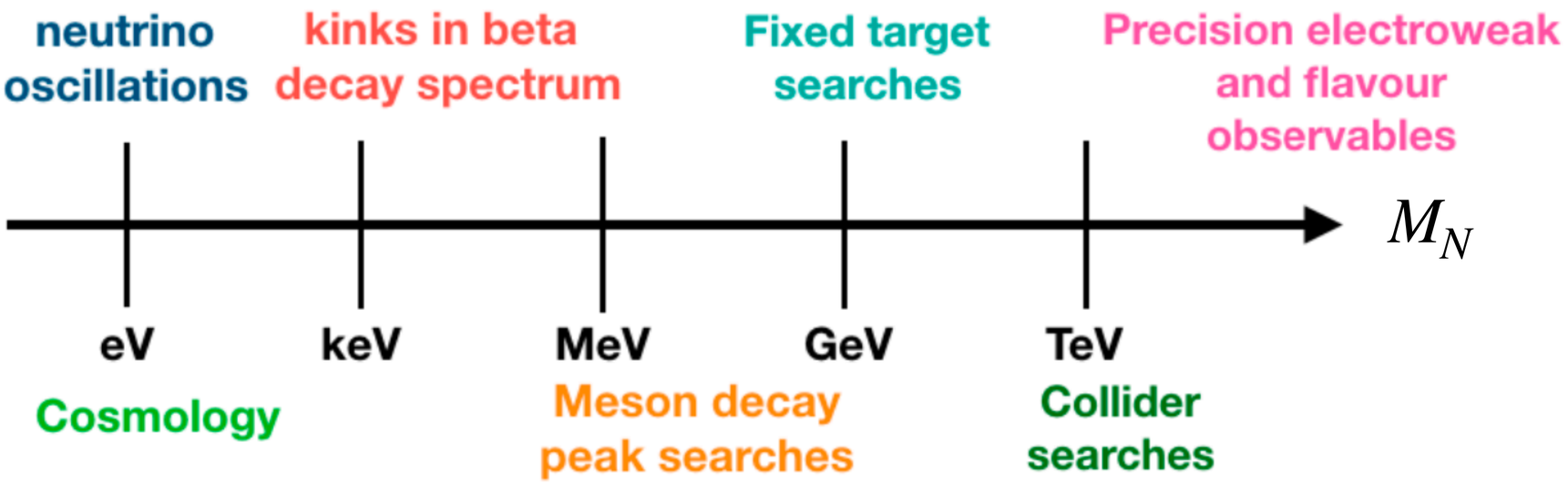
Additional particles

Neutrino portal



Interaction of sterile with SM governed by active-sterile mixing angle

$$\theta \propto \frac{yv}{M_N}, \text{ neutrino mass } m_\nu \propto \theta \times (yv)$$



Constraints are around $\theta^2 \lesssim 10^{-5}$ but depend on M_N

[Dev, Deppisch, Bolton '19]

[Fernandez-Martinez et al '23]

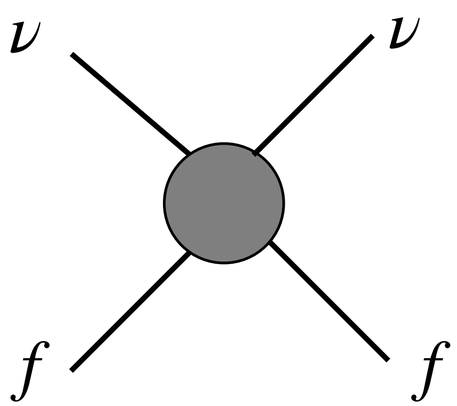
Additional particles

New neutrino interactions

4-fermion operators

→ neutrino non-standard interactions (NSI)

NC NSI: $\mathscr{L}_{NSI} = -2\sqrt{2}G_F \sum_{\alpha,\beta,f,P} \epsilon^f_{\alpha\beta}(\bar{\nu}_\alpha P \nu_\beta)(\bar{f} P f)$ [Wolfenstein '77]



$$P = S, V, A, T$$

$$P = 1,\ \mathrm{i}\gamma_5,\ \gamma^\mu,\ \gamma^\mu\gamma_5,\ \sigma^{\mu\nu},\ \sigma^{\mu\nu} = \mathrm{i}/2[\gamma^\mu, \gamma^\nu]$$

Lots of possible NSI terms!

$$\epsilon \sim \mathcal{O}(G_X/G_F)$$

Additional particles

Vector NSI effects in oscillations

In oscillations: new forward scattering with matter

→ independent of mass of new mediator!

Affect neutrino oscillations as a new matter effect

$$H = \frac{1}{2E}\left[U^\dagger M^2 U + a\begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}\right]$$

Matter potential $a \propto G_F \rho E$

→ experiments with largest E and L provide leading constraints

Additional particles

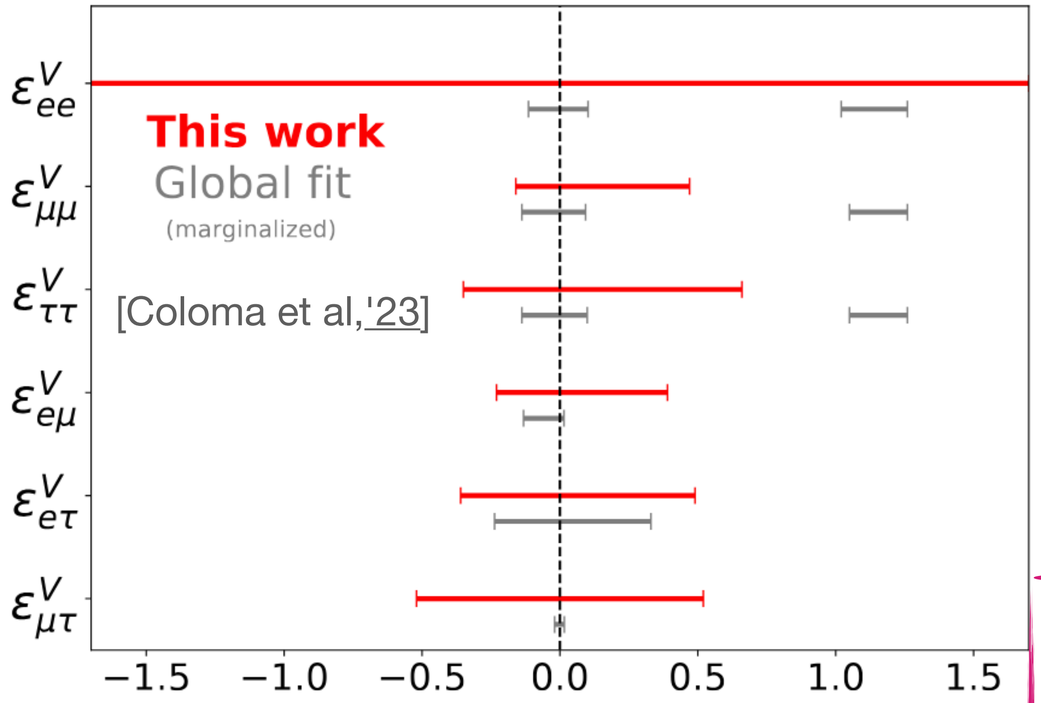
NSI effects in NC scattering

Vector NSI:
Complementarity with oscillations

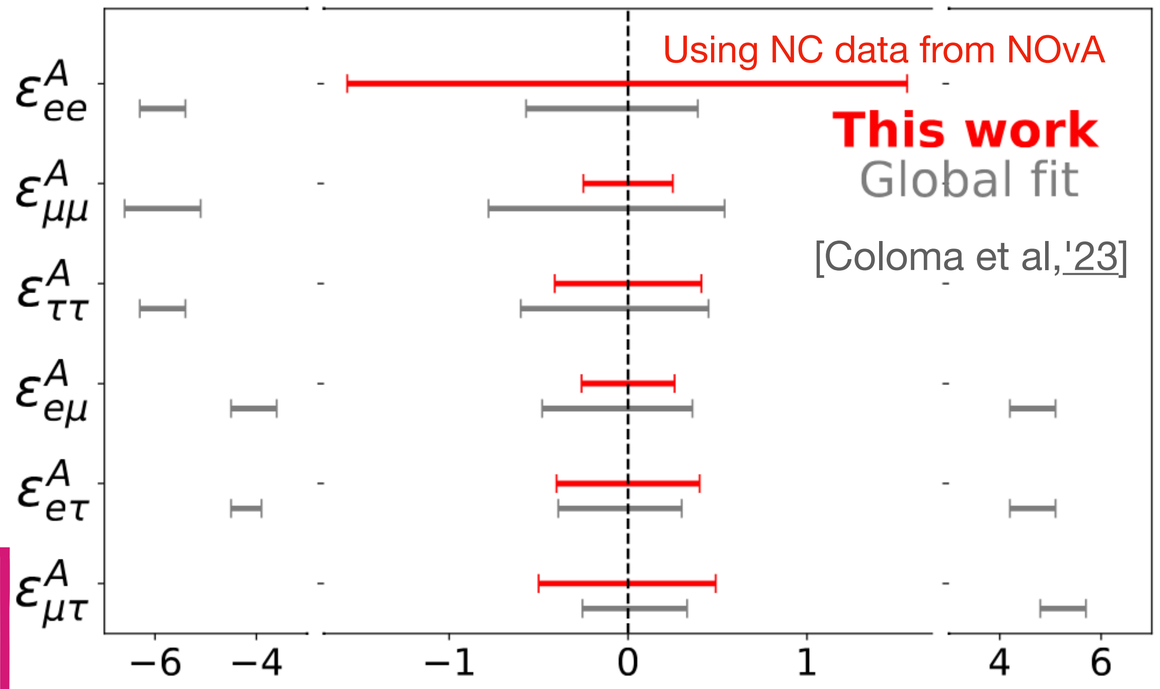
dependence on mediator mass

Axial-Vector NSI:
Data from SNO
First analysis of NOvA's NC data set

[JG, Machado, Pinheiro '24]



$\epsilon \sim \mathcal{O}(0.1)$
allowed!

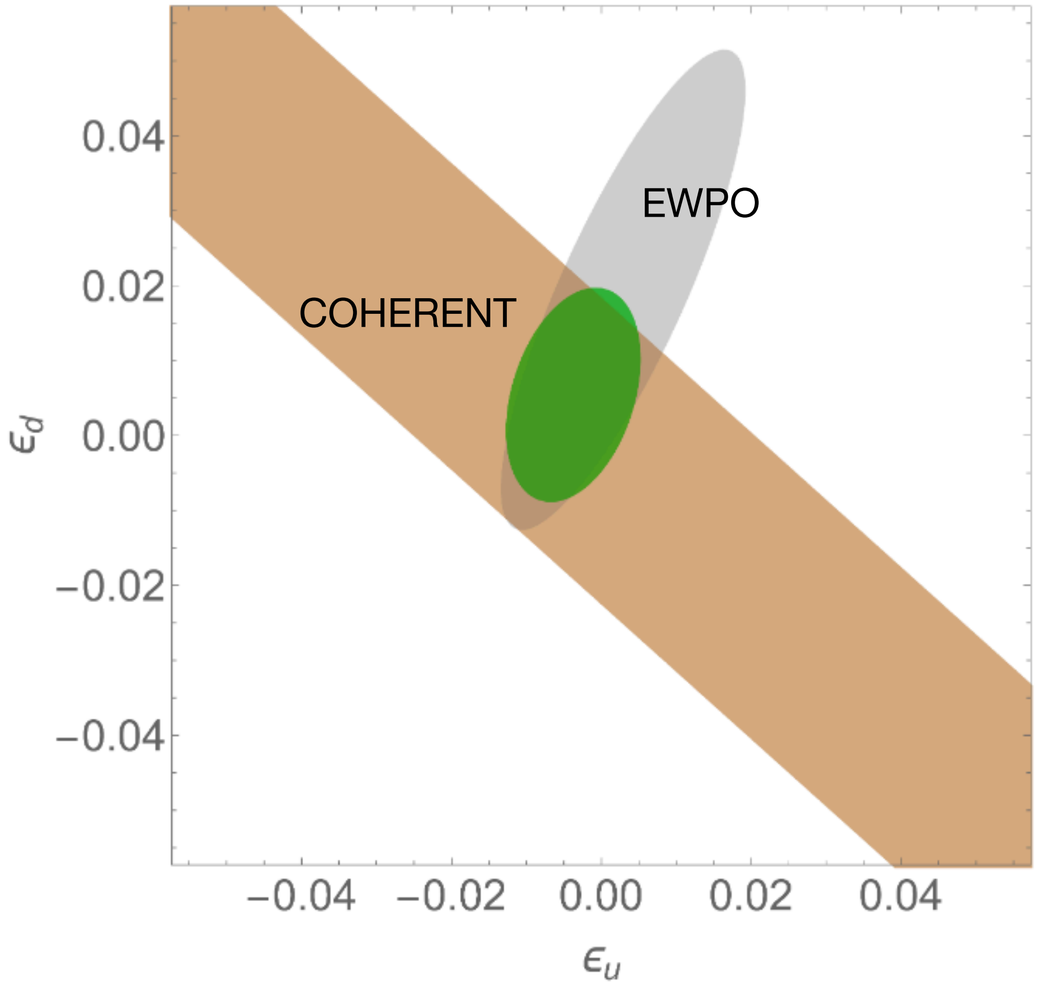


Additional particles

NSI effects in NC scattering

[Breso-Pla et al '23]

In SMEFT framework:
Complementarity with constraints from charged lepton observables



[for more on SMEFT see talk by Vryonidou]

Additional particles

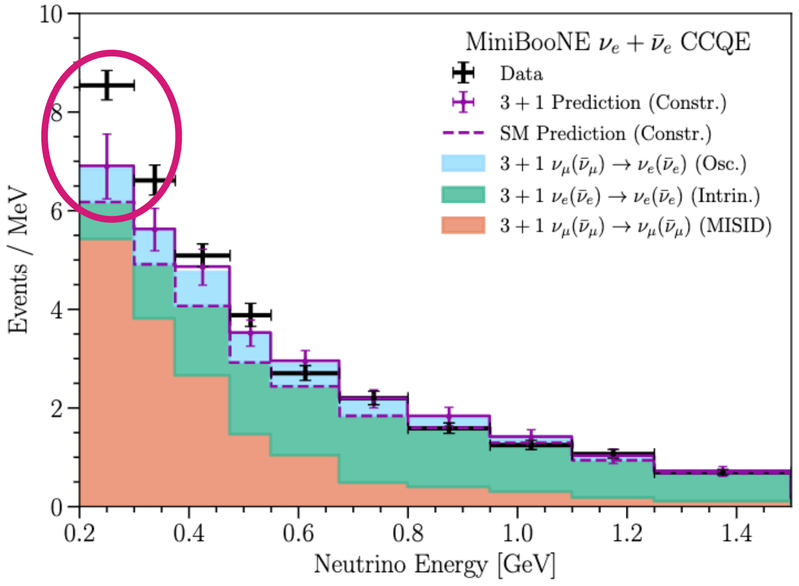
Anomalies

Some (persistent) anomalies in neutrino physics

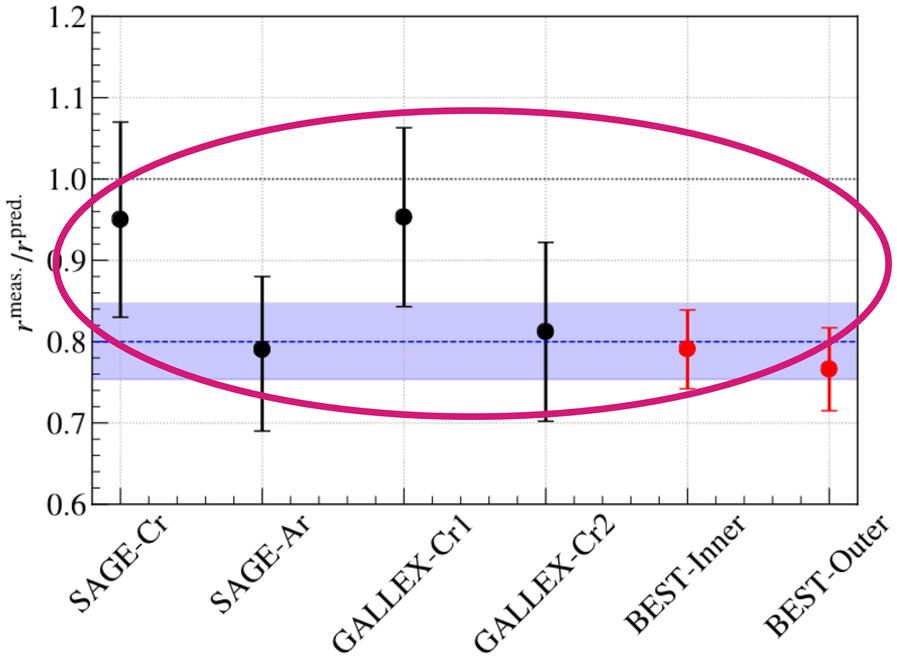
eV-scale vanilla sterile neutrino explanation not a good global fit!

So far no convincing SM explanation either

[Brdar, JG, Kopp '23]

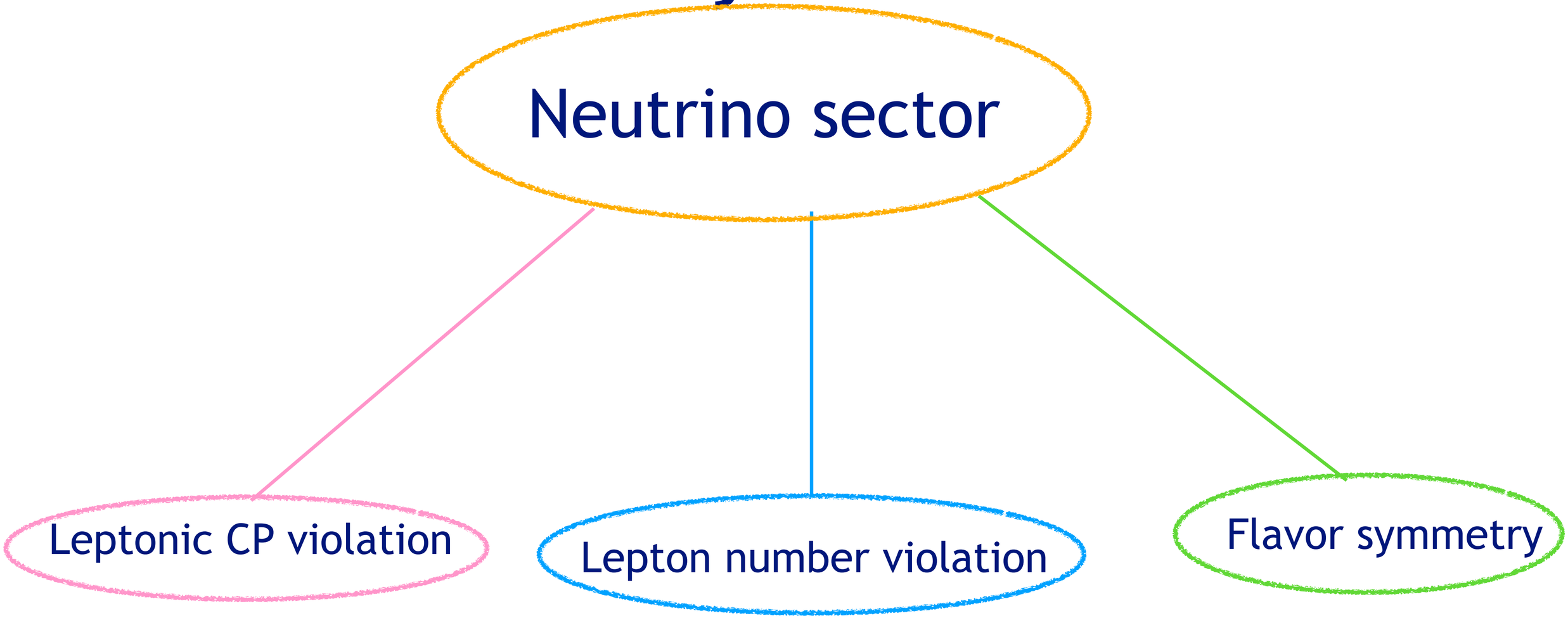


[MiniBooNE+MicroBooNE 2201.01724]



[BEST 2201.07364]

New symmetries



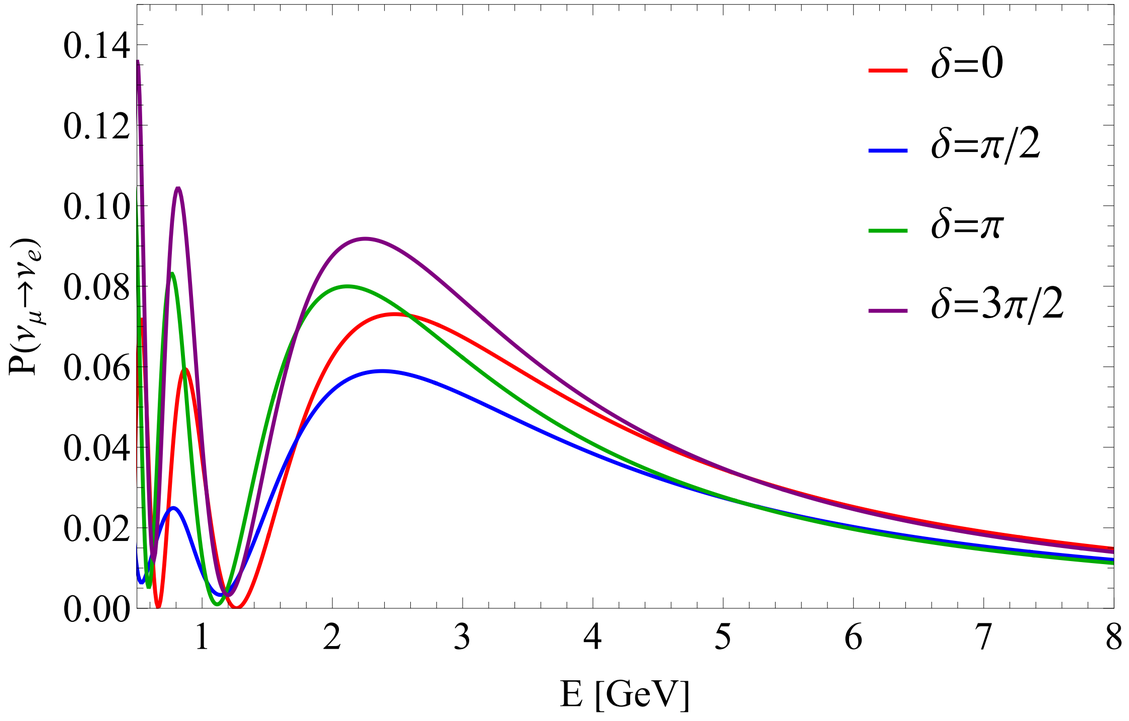
New symmetries

Leptonic CP violation

Use long-baseline experiments:

$\overset{(-)}{\nu}_e$ appearance probability in $\overset{(-)}{\nu}_\mu$ beam depends on δ

(However also dependence on mass ordering, other oscillation parameters)



To alleviate effects of systematics uncertainties:
Compare neutrino to anti-neutrino channel

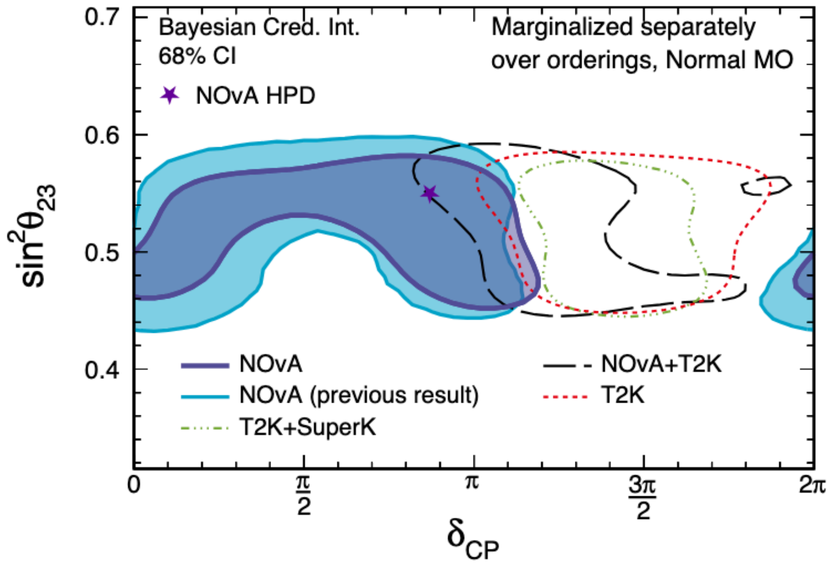
If they behave differently
$\rightarrow$ CP violation

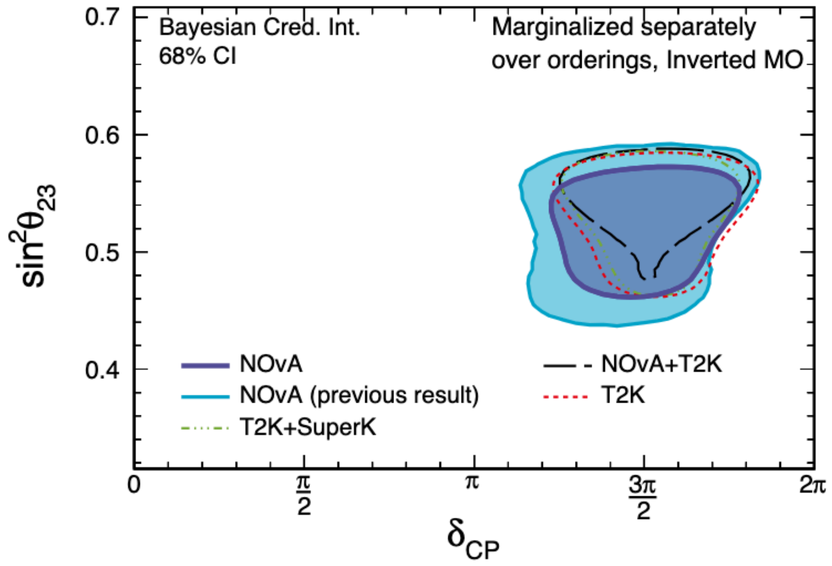
New symmetries

Leptonic CP violation

[see talk by Rusov for the status of CPV in the quark sector]

Current experiments long-baseline experiments:
NOvA (US), T2K (Japan)





[NOvA '25]

In normal ordering:
slight disagreement

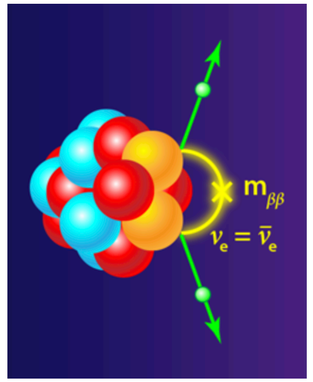
In inverted ordering:
improvement on constraints

New symmetries

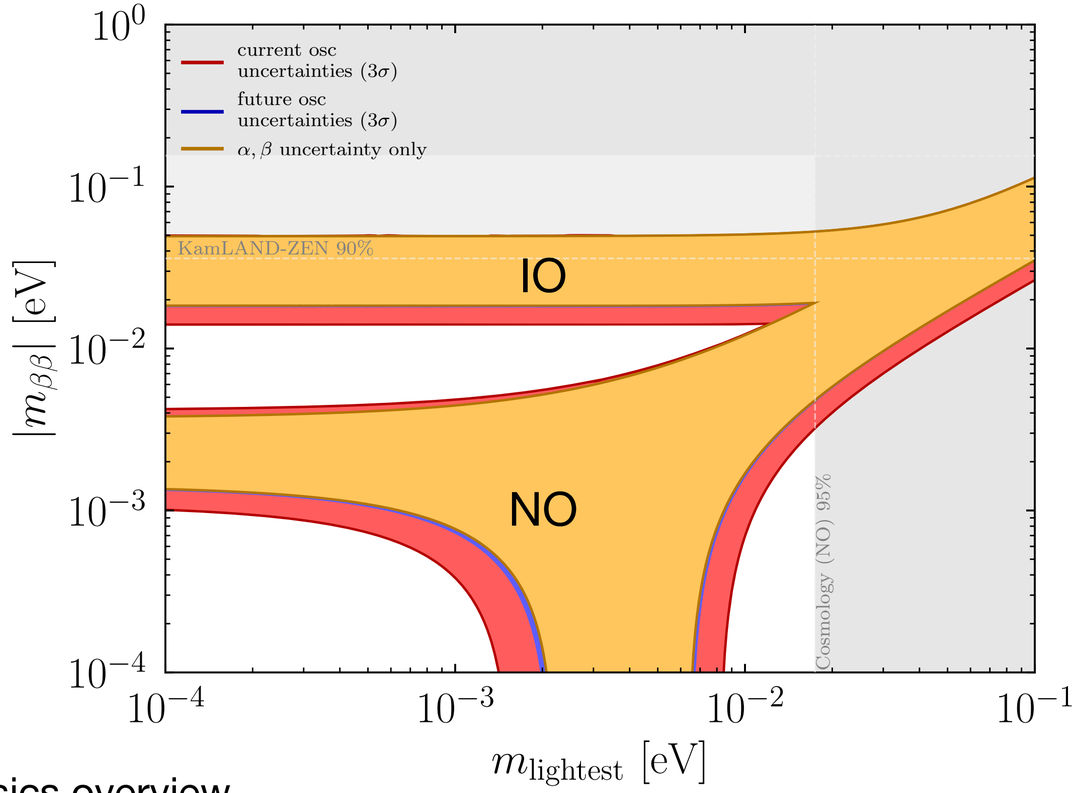
Lepton number symmetry

If neutrinos are Majorana particles ↔ lepton number is violated

Neutrinoless double beta decay most promising probe of Majorana nature of neutrinos



[Denton, JG, '23]



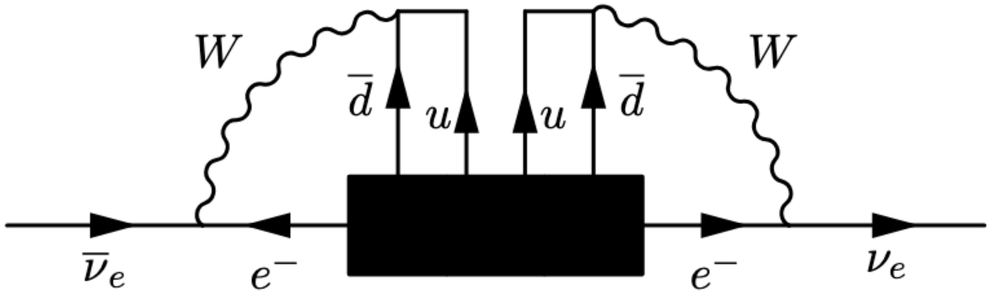
New symmetries

Lepton number symmetry

Schechter-Valle theorem

Any $\Delta L = 2$ operator contributing to $0\nu\beta\beta$ will generate Majorana neutrino mass contribution

[Schechter, Valle 1982]



Majorana mass induced by this (dim-9) operator tiny: $\lesssim \mathcal{O}(10^{-28}\ \mathrm{eV})$

Even if lepton number violation is detected: neutrino mass might be dominantly of Dirac type (=pseudo-Dirac neutrino)

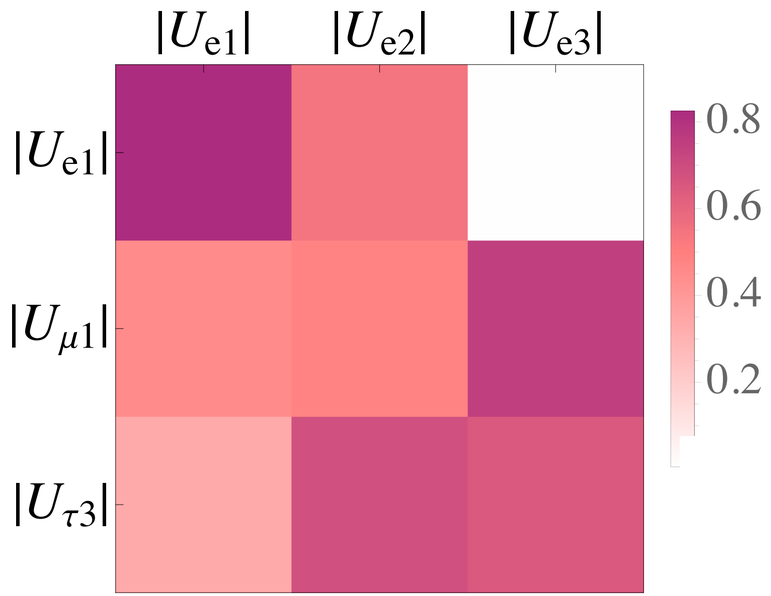
[Duerr, Lindner, Merle '11]

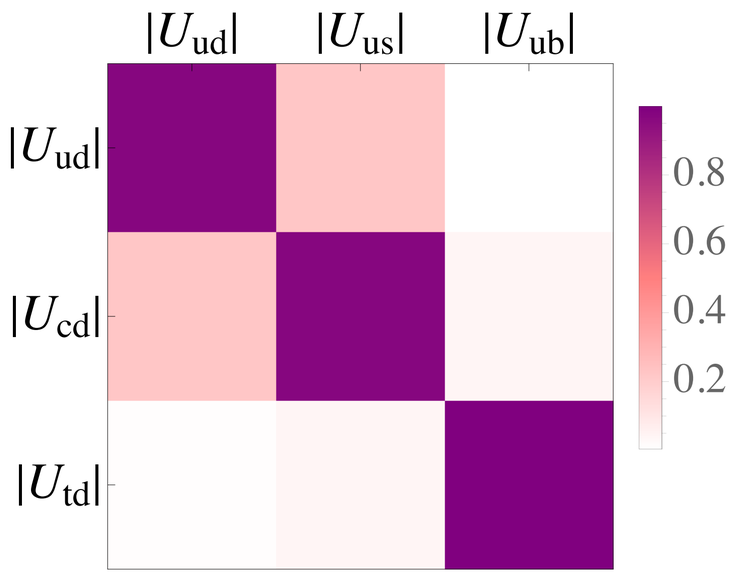
New symmetries

Flavor symmetry

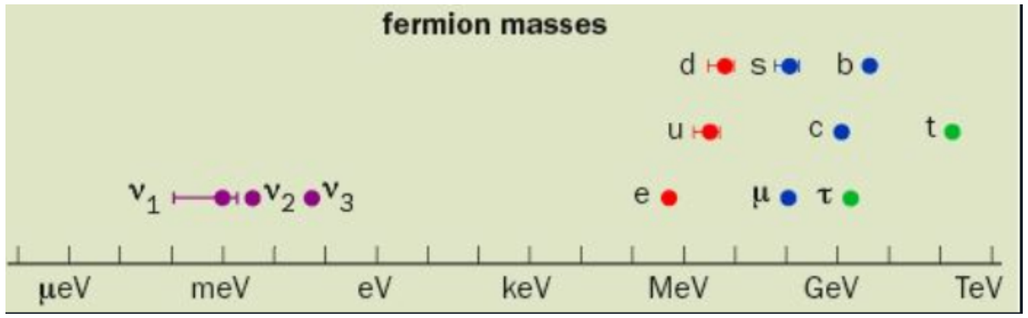
[see talk by Cornella]

Leptons





Quarks



could provide rationale between difference in mixings in quark sector and lepton sector

New symmetries

Flavor symmetry

Most successful neutrino flavor models use discrete symmetries

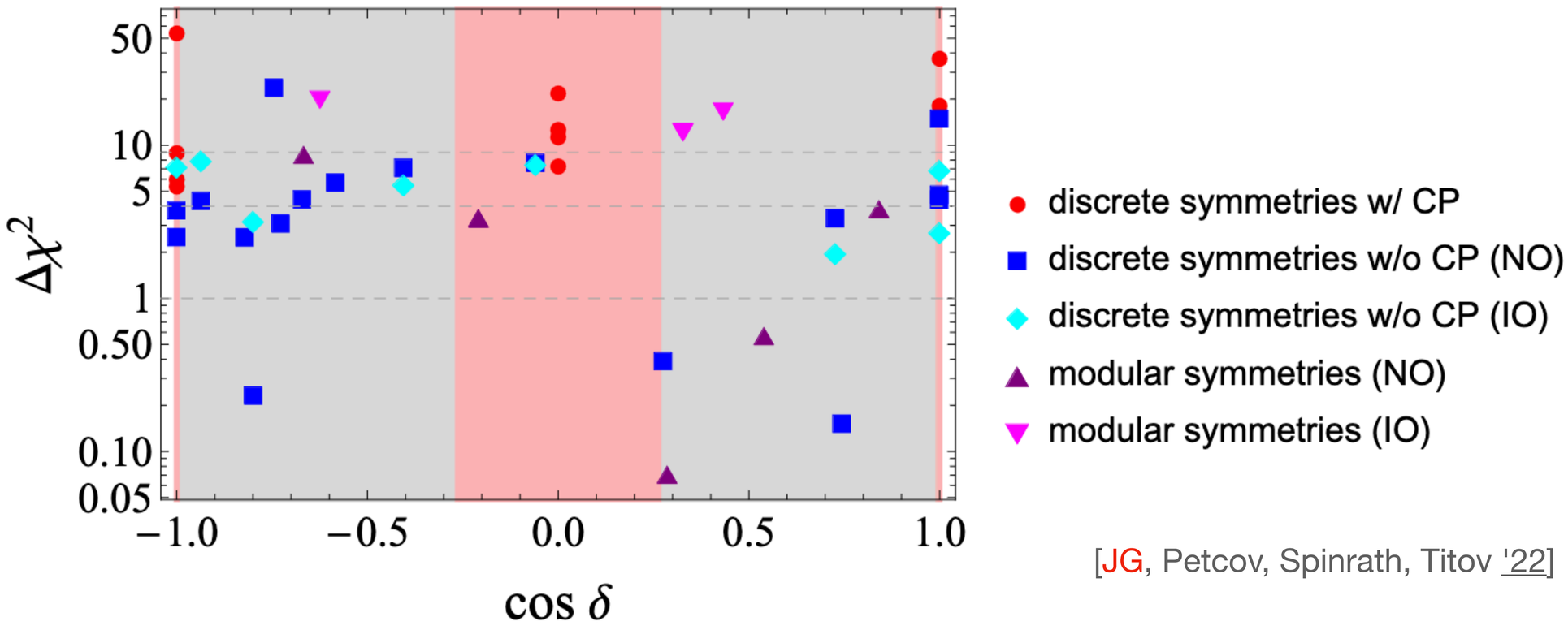
Most predictive flavor models predict relations between mixing parameter like $\theta_{12}^{\text{PMNS}} - \theta_{12}^{\nu} \approx \theta_{13}^{\text{PMNS}} \cos\delta$

Also prediction for other mixing parameters and masses

New symmetries

Flavor symmetry

Precise measurements of oscillation parameters can distinguish flavor models



[JG, Petcov, Spinrath, Titov '22]

Neutrino physics
The future

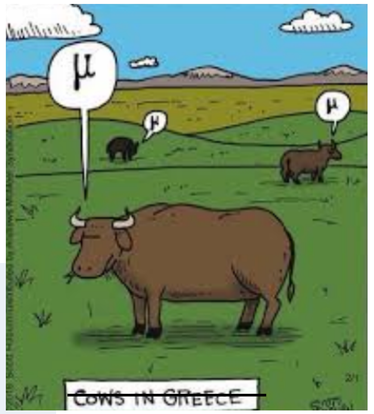
Oscillation (standard+BSM) physics

Long baseline (300 km, 1300 km) accelerator neutrino experiments:
Hyper-Kamiokande, DUNE

Atmospheric neutrino experiments:
HK, IceCube-Gen2, KM3NeT-ORCA

Medium baseline (~50 km) reactor neutrino experiment:
JUNO

Neutrino physics
The far future (maybe?)

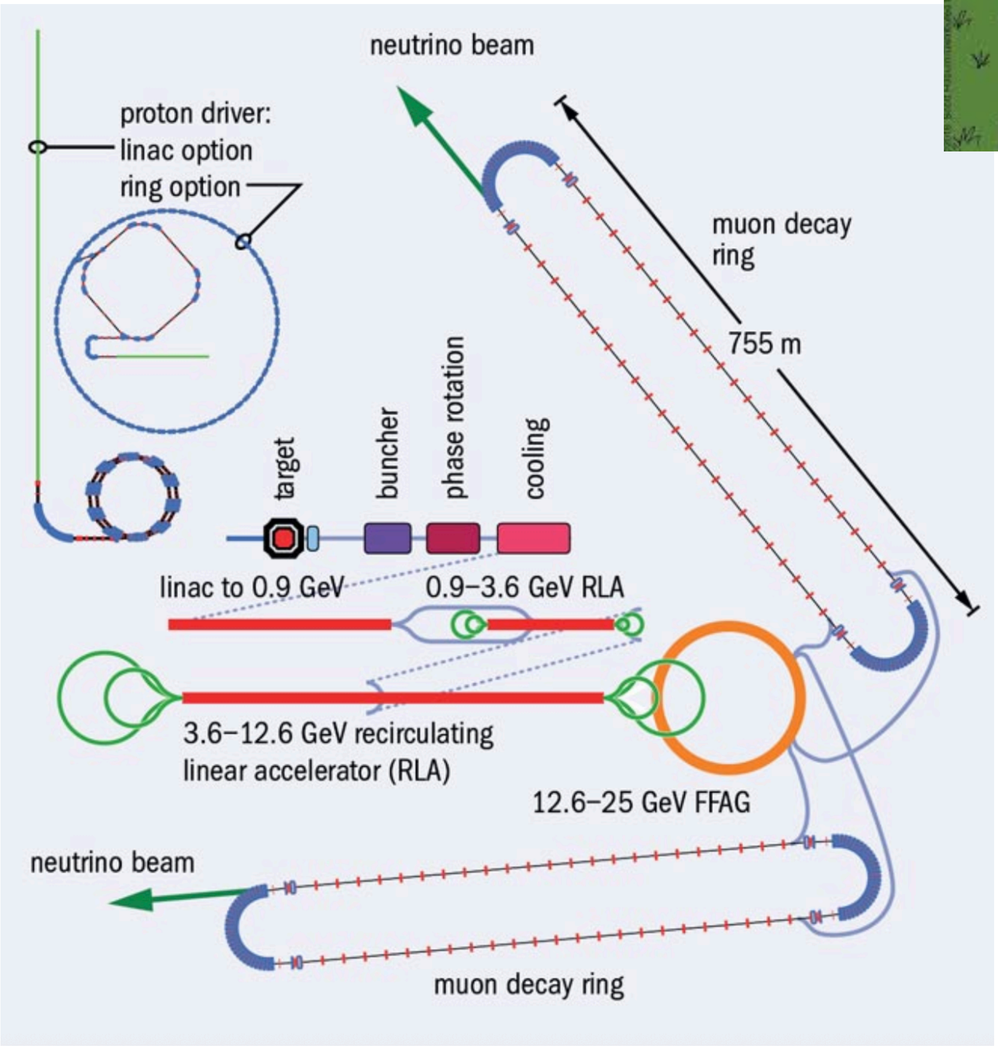


Bison at Fermilab

renewed interest of particle physics community in muon colliders

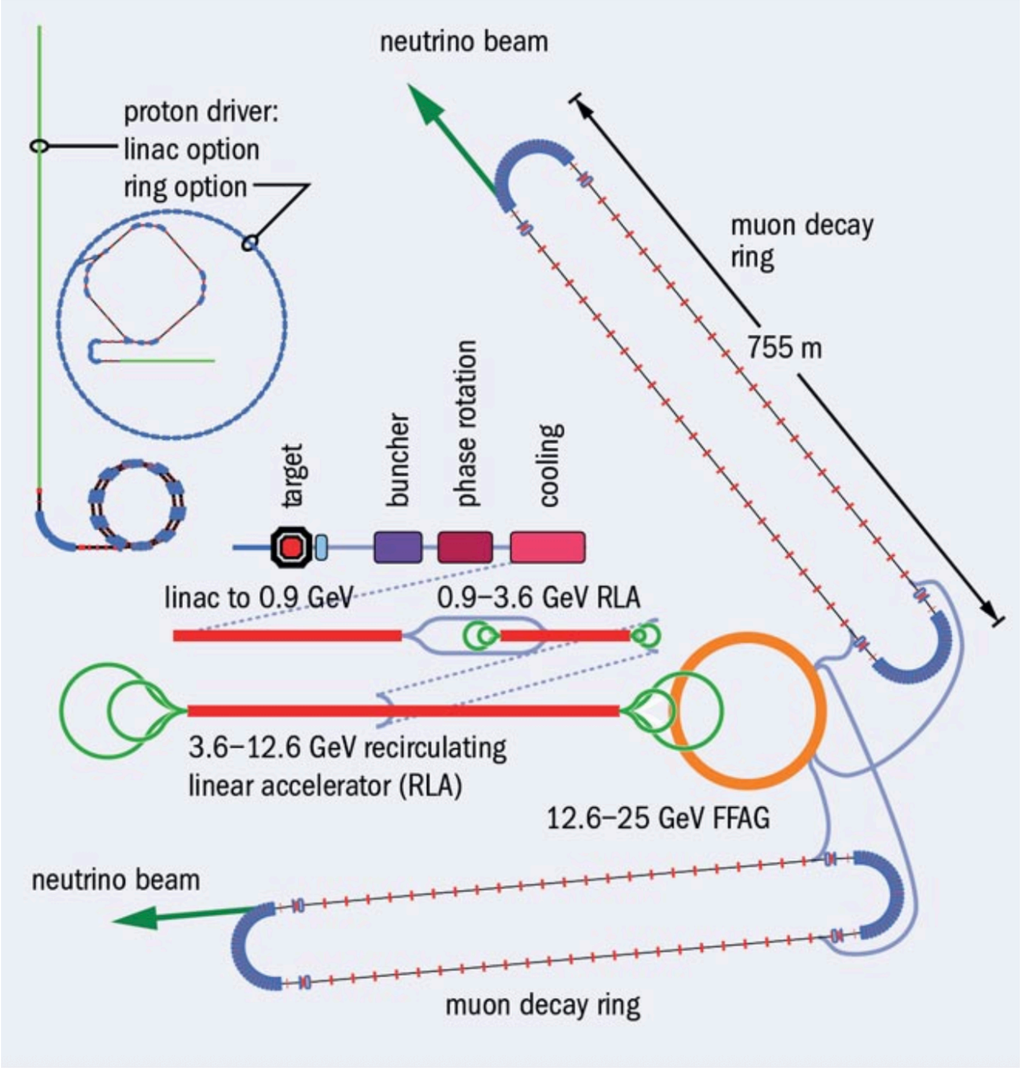
Neutrino factory could be a pre-stage of a high-energy muon collider

Synergy with future collider program



Neutrino physics

Neutrino factory

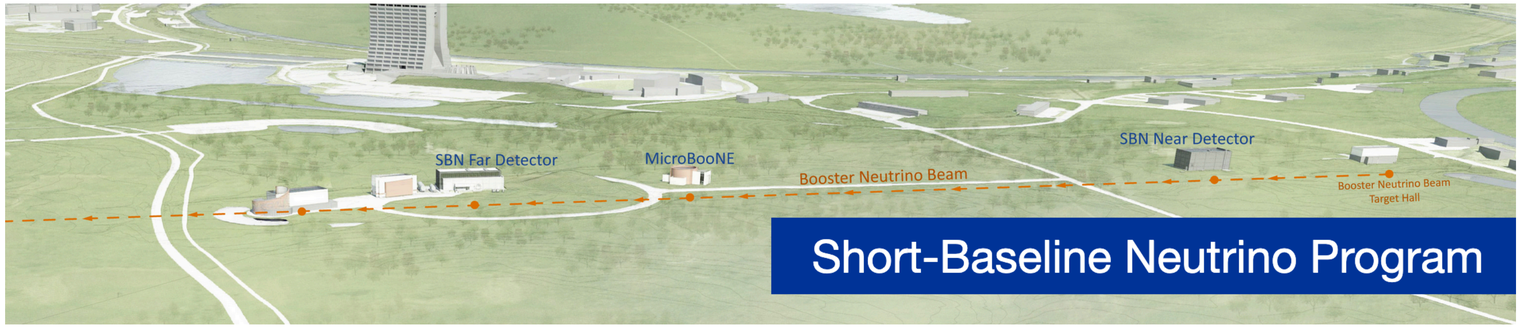


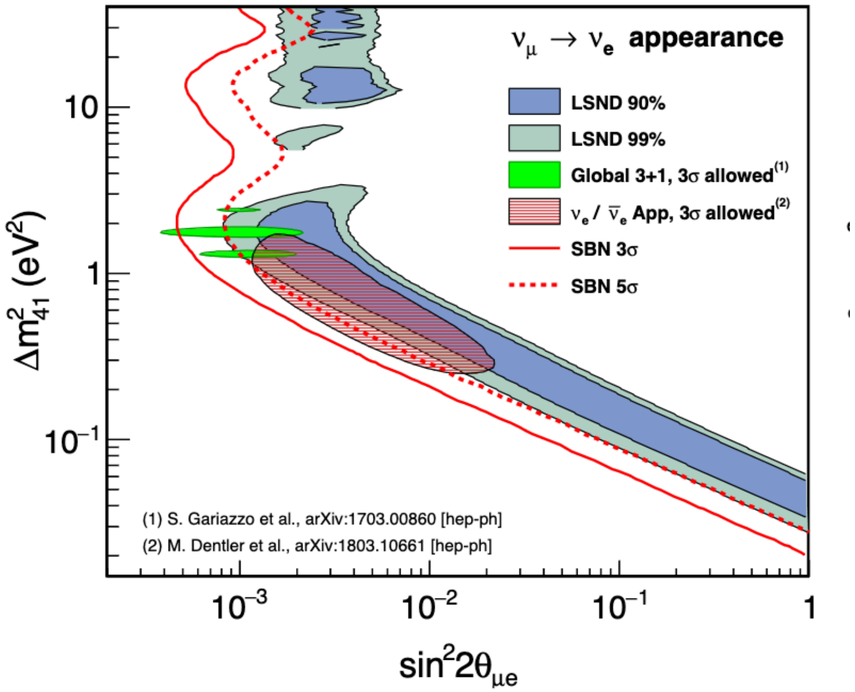
- Neutrino production from GeV (anti-)muon decays
- Muons decay along straight line of race track design → very collimated neutrino beam of known composition
- ν_e, ν_μ, ν_τ appearance & ν_e, ν_μ disappearance searches possible
- Will improve constraints on SM + BSM scenarios assuming FNAL-SURF baseline and 40 kT $- 10^{22}$ μ decays

[Denton, JG, '24] [Denton, JG, Kong, '25]

Neutrino physics
The future

Short baseline program:
Testing the MiniBooNE anomaly





3 detectors: MicroBooNE, ICARUS, SBND

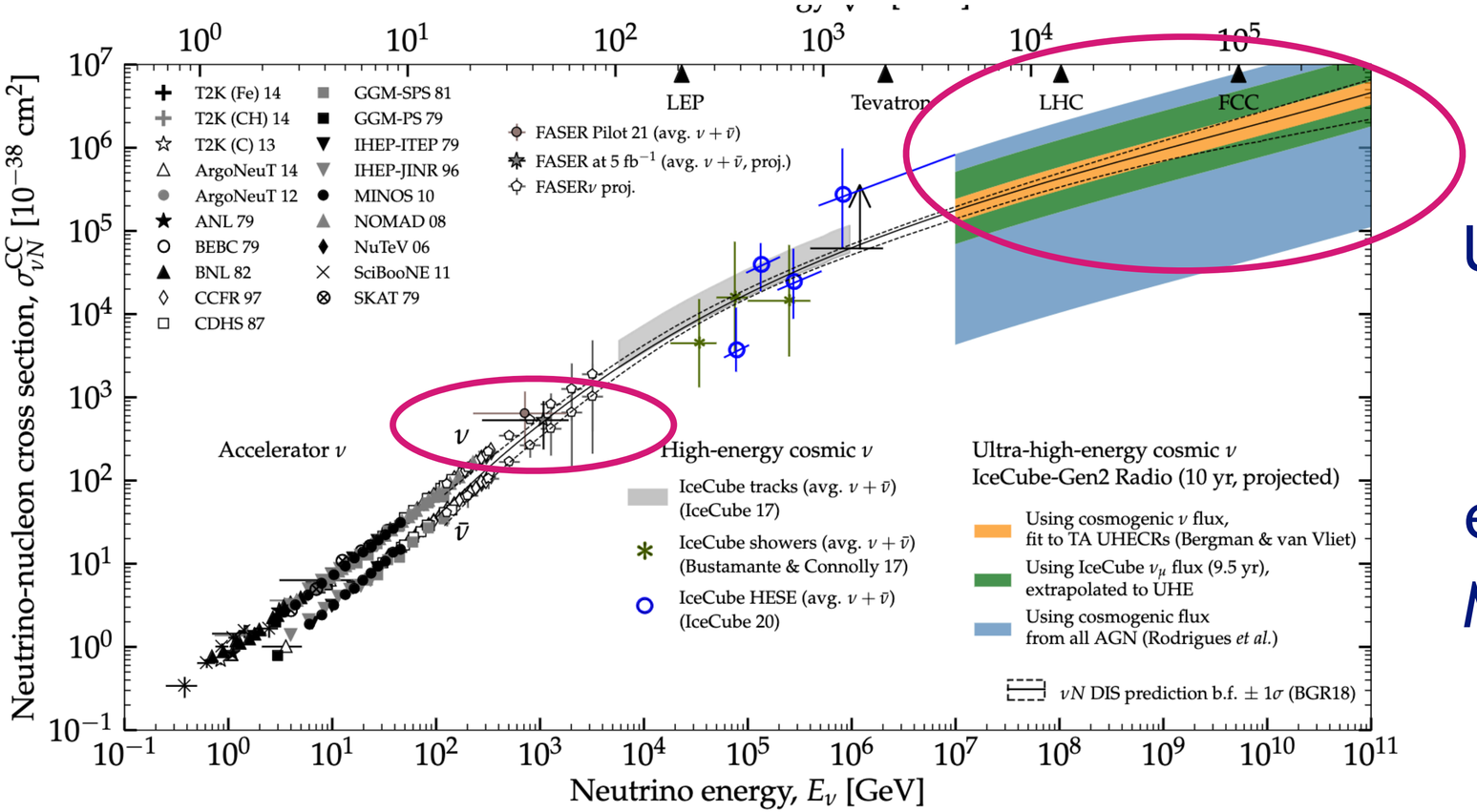
[Machado, Palamara, Schmitz 1903.04608]

Neutrino physics
The future

FASERν, SBN@LHC: xsec at TeV energies

SHIP: measurement of ν_τ xsec

Neutrino scattering



IceCube-Gen2: UHE cosmic νs

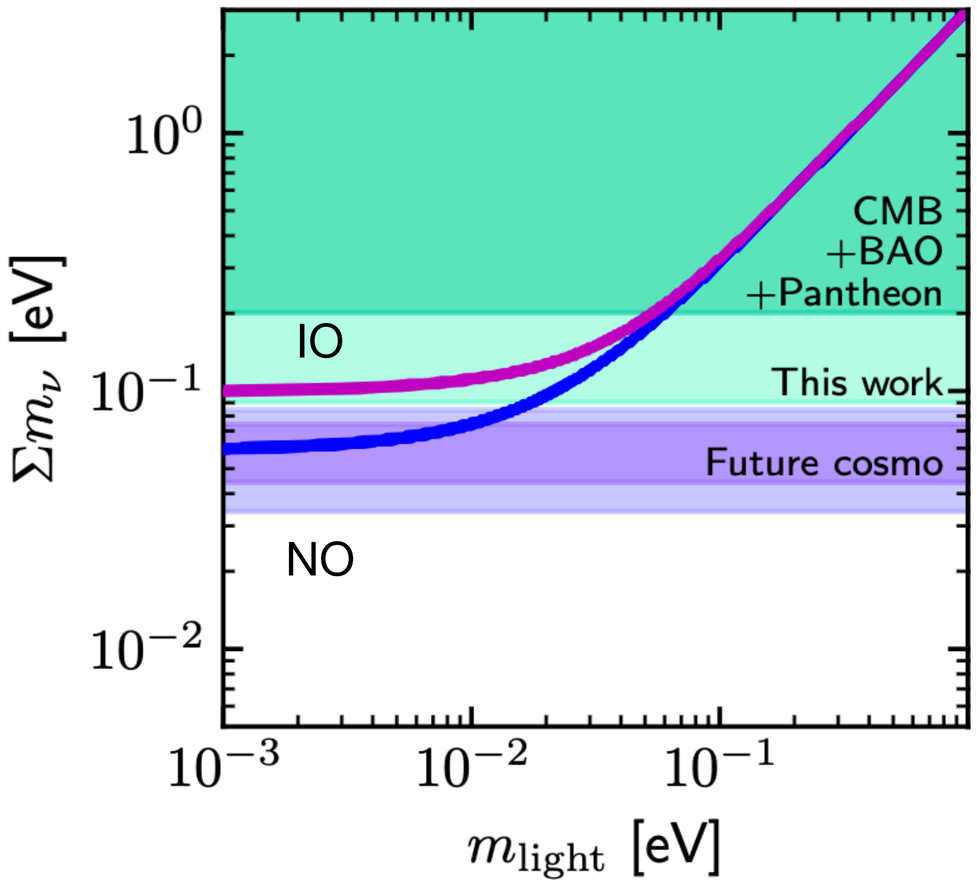
CEvNS experiments: MeV neutrino scattering

Neutrino physics
The future

[Di Valentino, Gariazzo, Mena, '21]

Absolute neutrino mass scale/ nature of neutrinos:

Future cosmological observatories will measure sum of neutrino masses (maybe very soon)
(And potentially mass ordering)



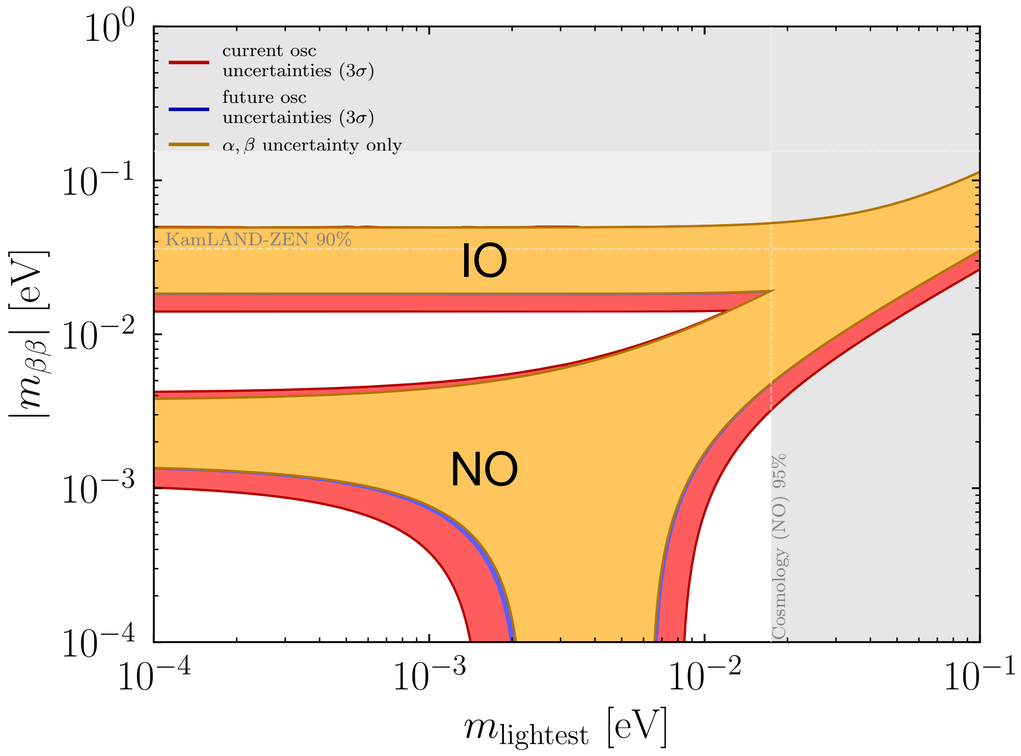
Neutrino physics
The future

[Denton, JG, '23]

Future neutrinoless double beta experiments aim to fully probe IO region

Progress on nuclear matrix element calculation (new results: matrix elements are smaller → bound on $|m_{\beta\beta}|$ weaker)

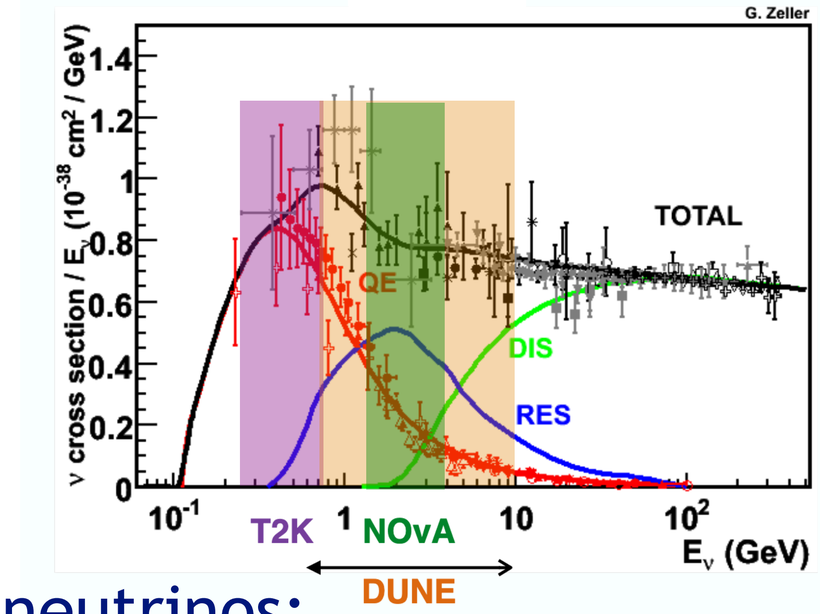
[Belley at al, '23]



Neutrino physics
Challenges

- For neutrinoless double beta decay (MeV):
  nuclear matrix element calculation

- For accelerator based neutrino experiments (GeV):
  cross section & flux prediction



- For high energy atmospheric and astrophysical neutrinos:
  hadronic interactions for flux prediction
  → forward physics program at the LHC

Neutrino physics
Conclusions

- Neutrinos play an essential role in our search for the new SM
- Future experiments will measure all neutrino parameters and potentially uncover new symmetries and particles in nature
- Possibilities that the neutrino sector will continue to amaze us in the future

Thanks for your attention!