New tau neutrino oscillation and scattering constraints on unitarity violation

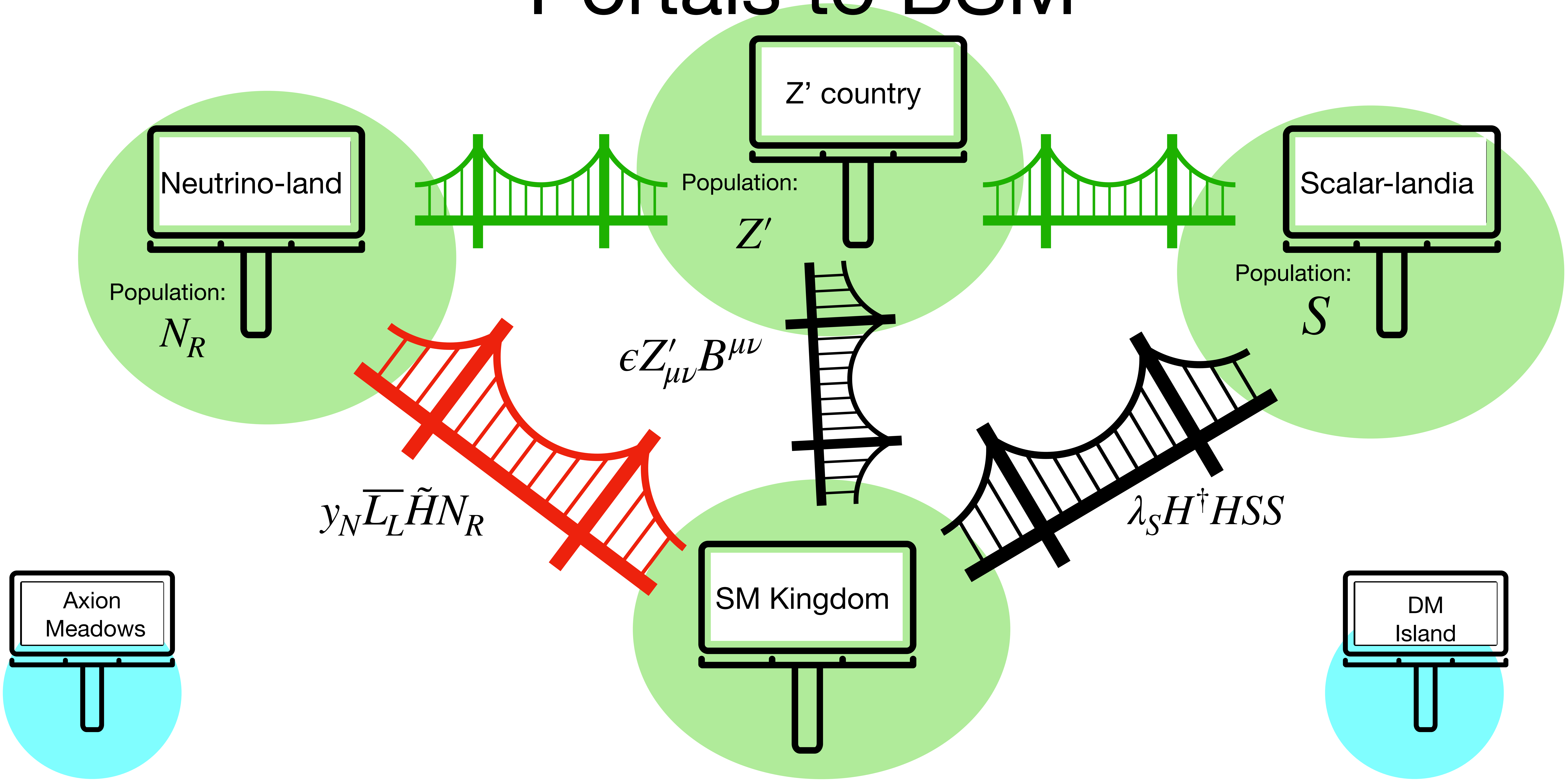
Julia Gehrlein

Brookhaven National Laboratory

BNL HET lunch seminar, October 2021

Brookhaven NDI Neutrino Discovery Initiative

Portals to BSM

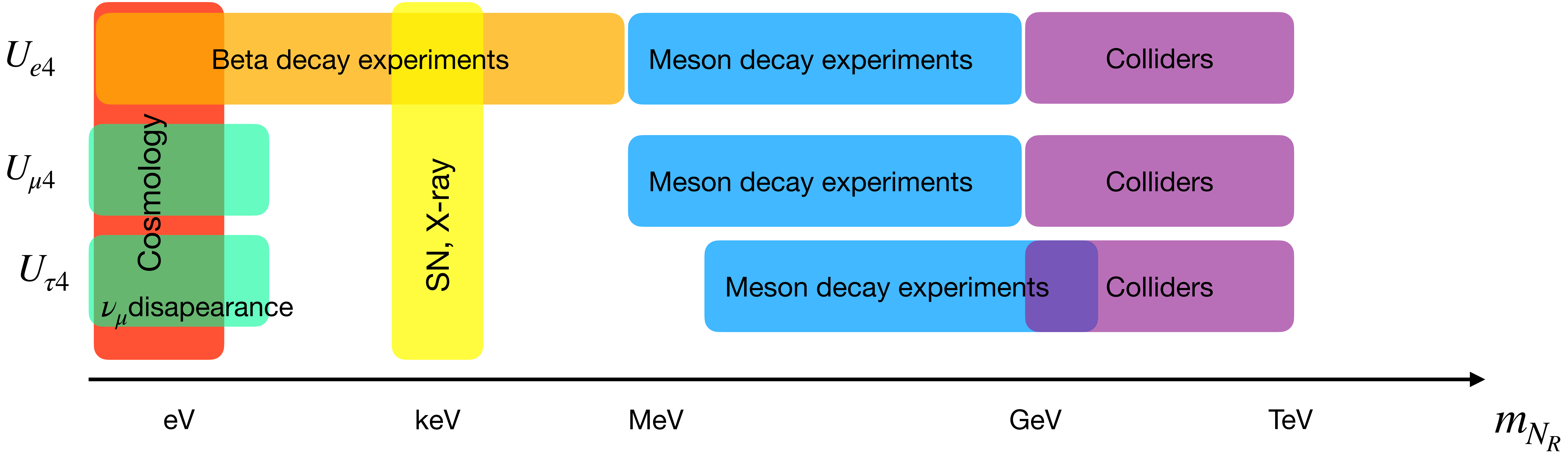


Testing the neutrino portal

Phenomenology at direct search experiments

(depends on U_{f4} and sterile mass scale):

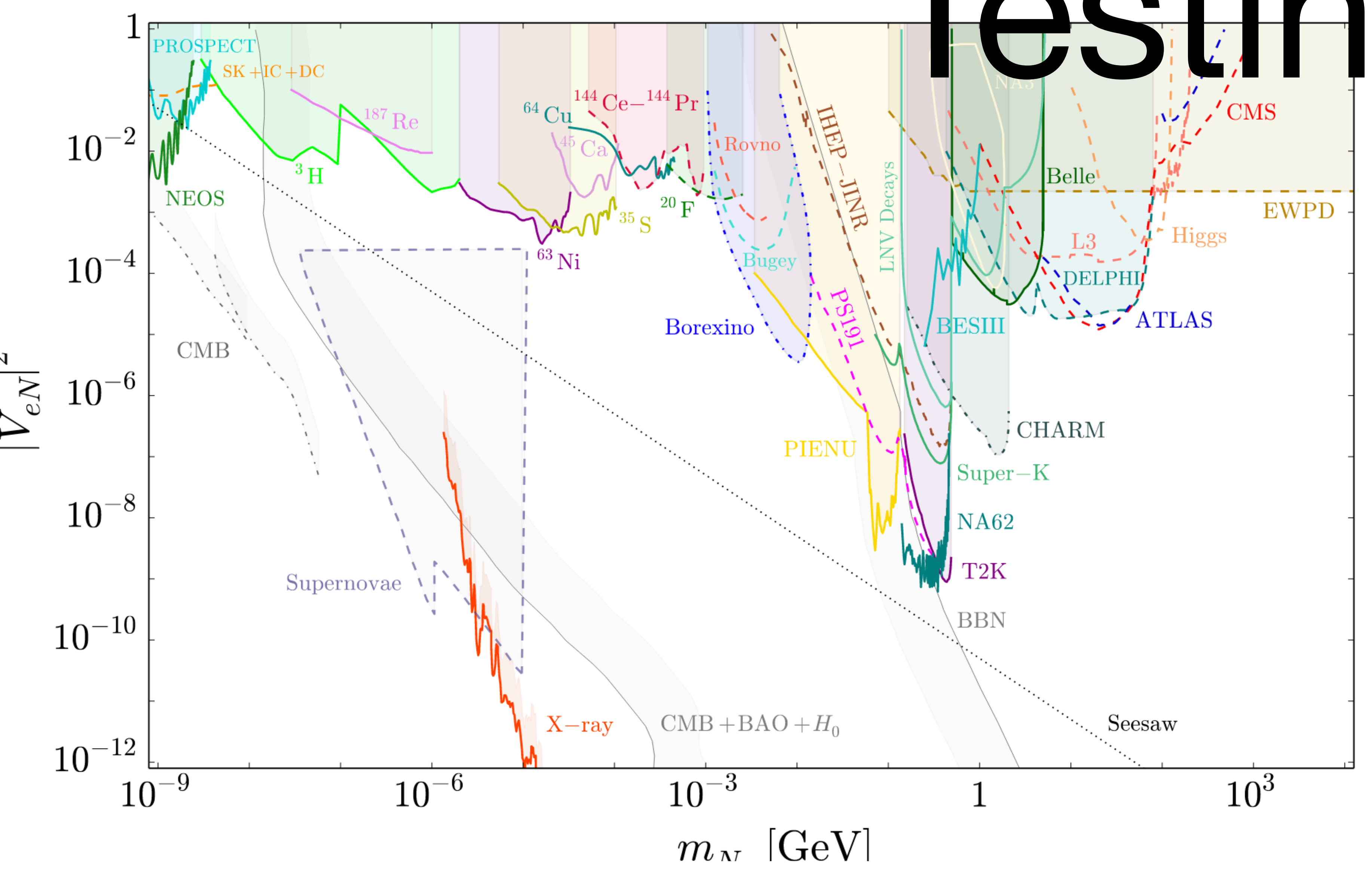
- Need to be kinematically producable
- detected via decay productions in detector

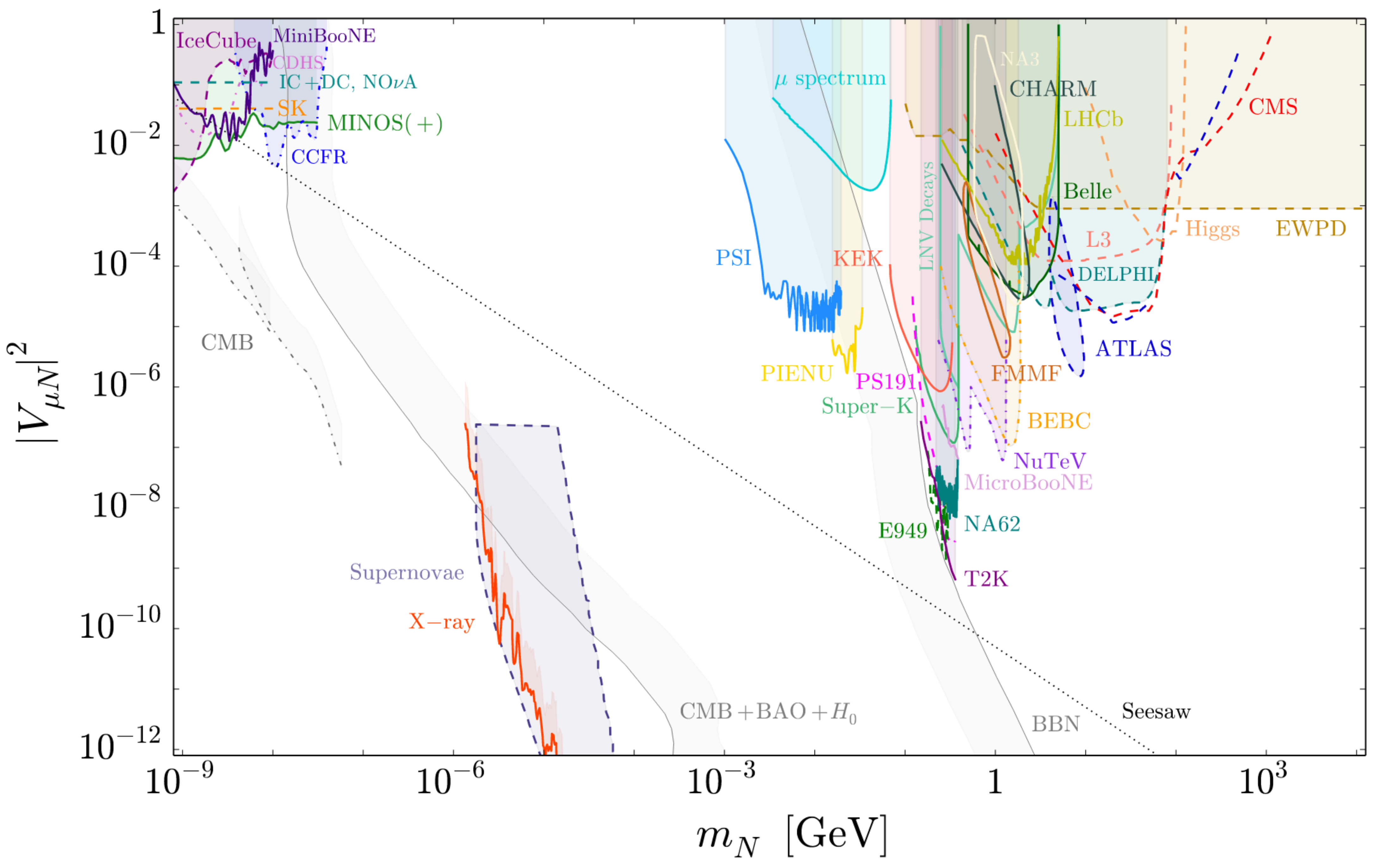


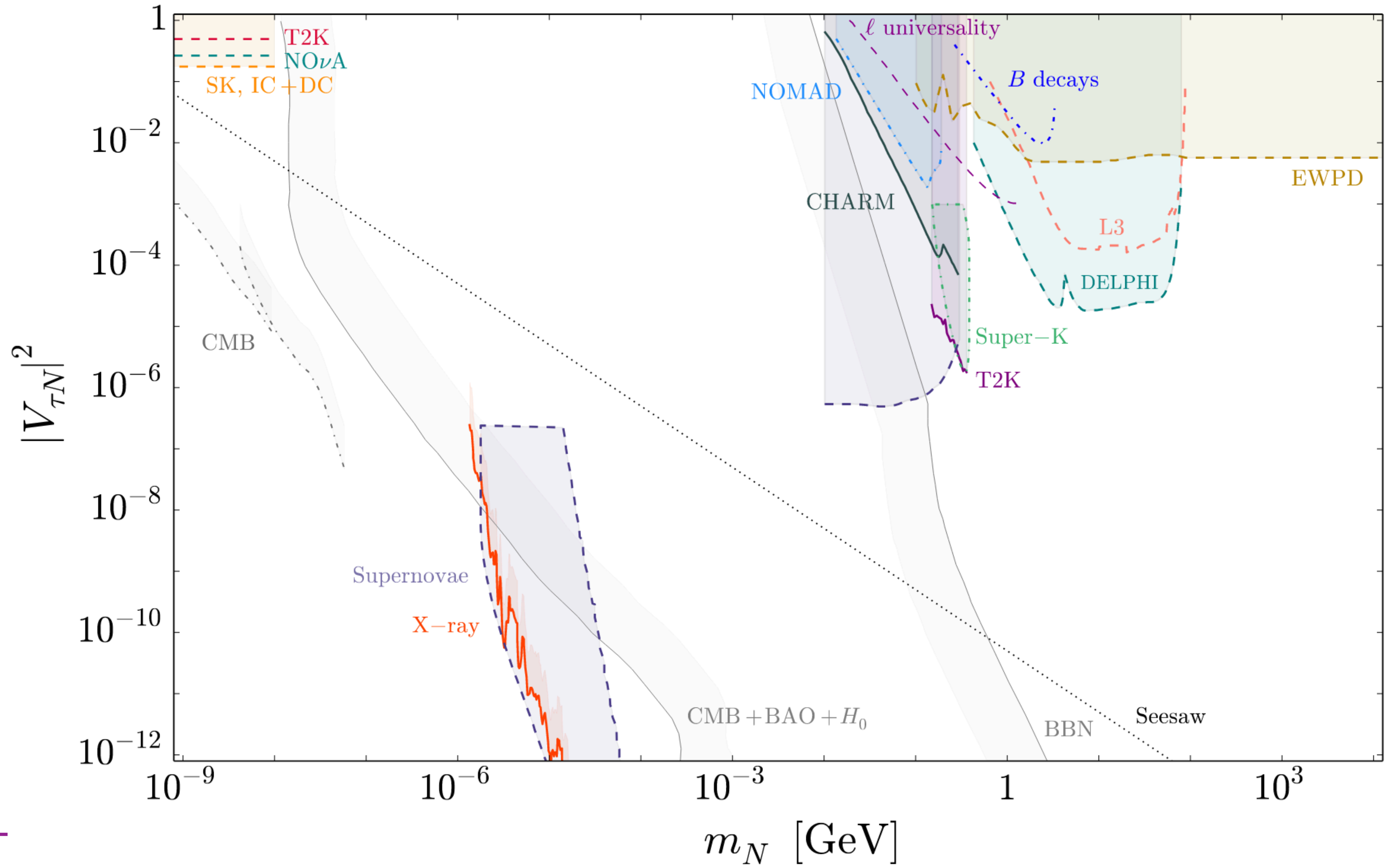
Testing the neutrino portal

Constraints from direct searches

Bolton, Deppisch, Dev '19







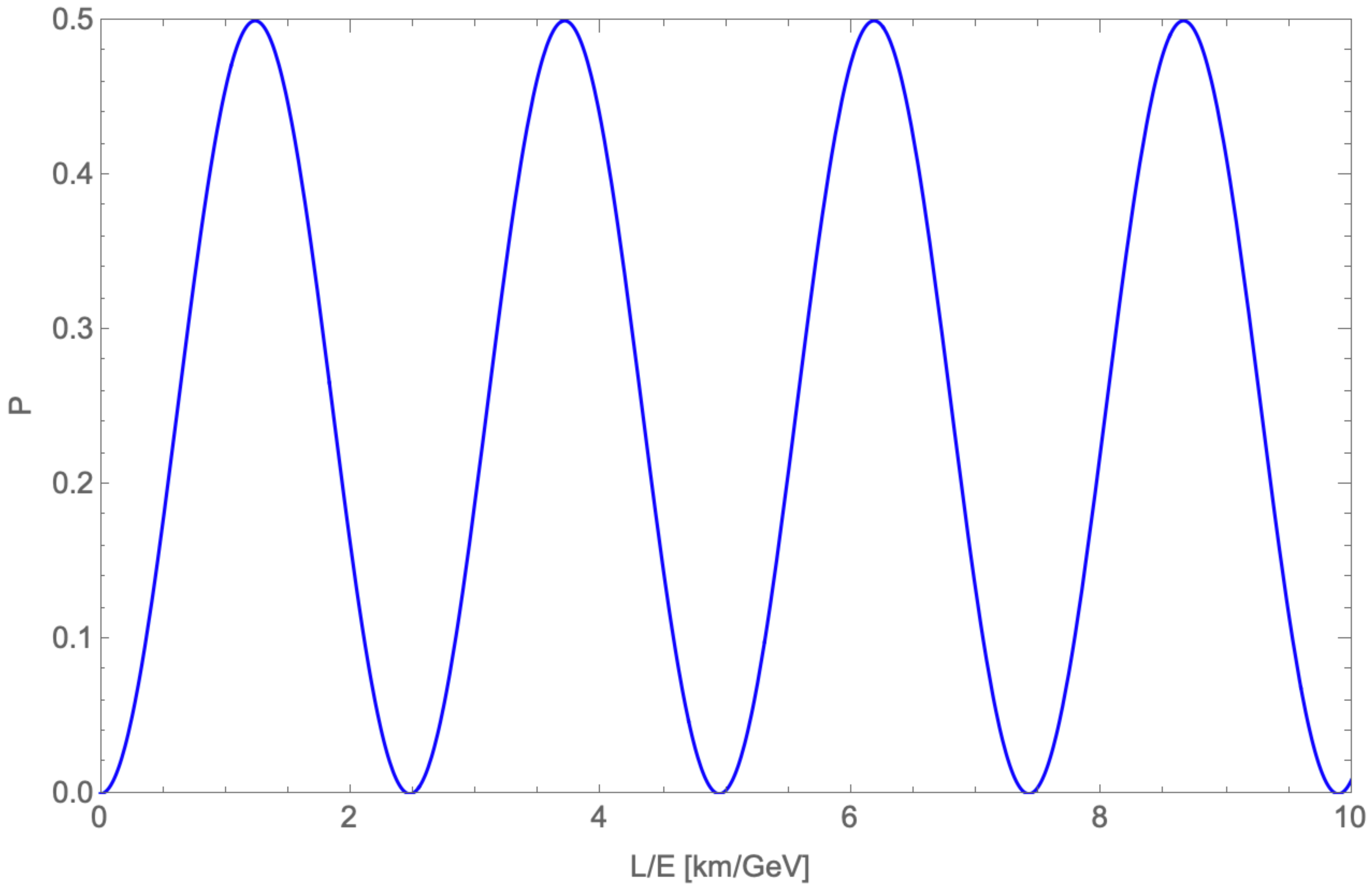
→ Several unexplored regions!

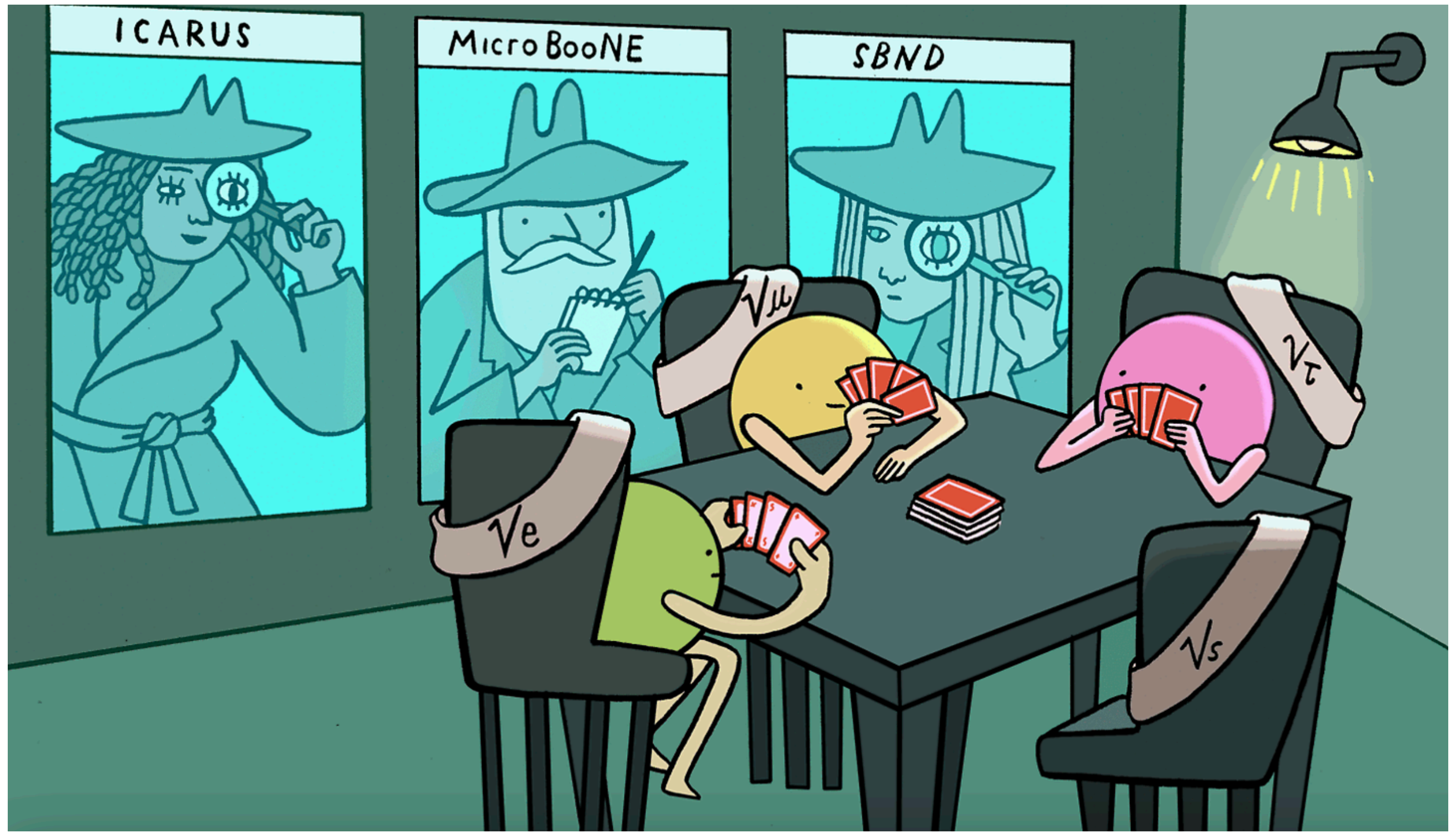
Testing the neutrino portal

Oscillation phenomenology of N_R depends on its mass scale:

- N_R light ($m_{N_R} \sim \mathcal{O}$(1 eV)) → direct sensitivity at oscillation experiments

$$P = \sin^2(2\theta)\sin^2(\Delta m^2_{41} L/(4E))$$





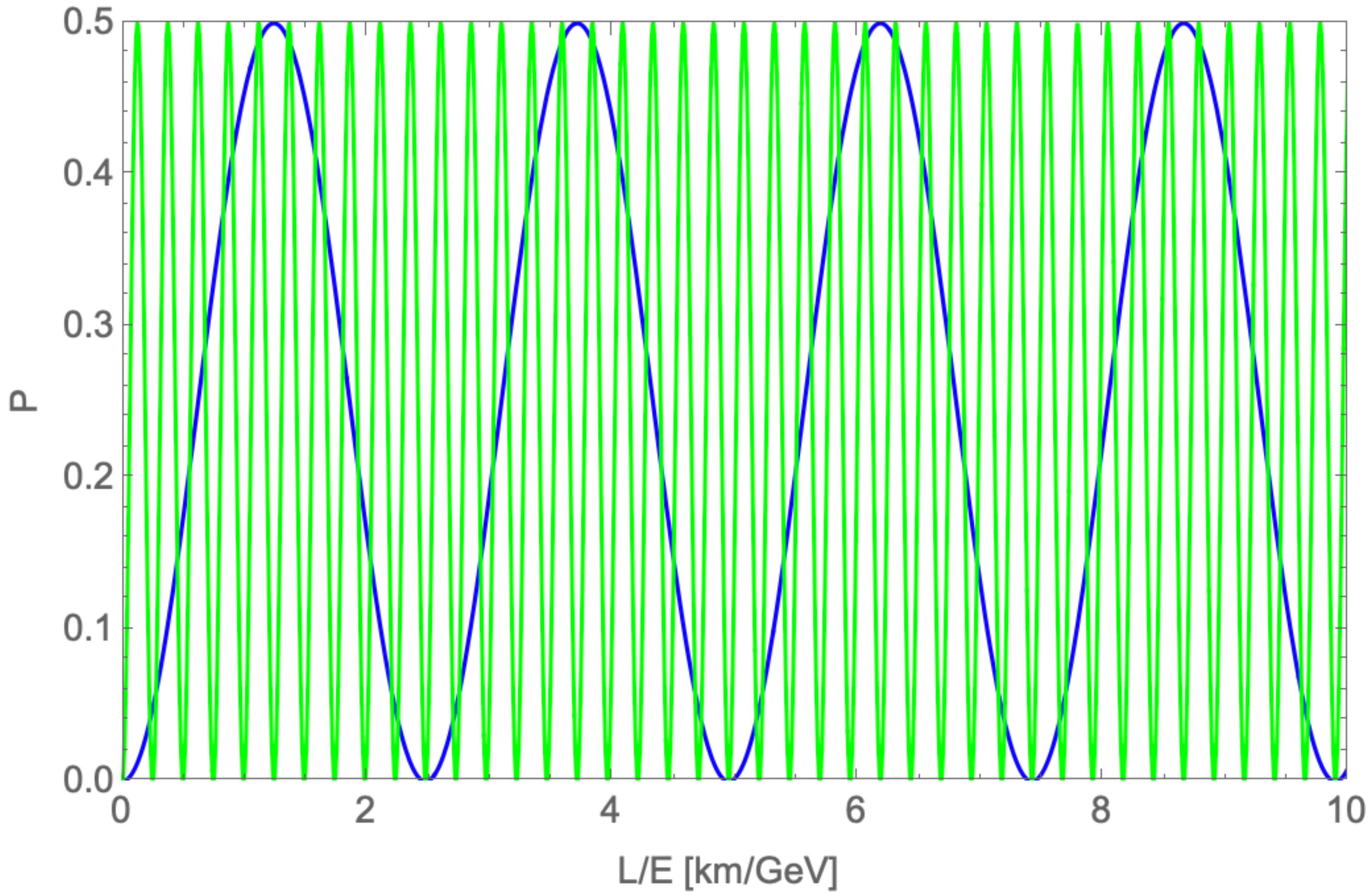
→ LSND, MiniBooNE anomalies

Constraints depend on mass scale

Testing the neutrino portal

Oscillation phenomenology of N_R depends on its mass scale:

- N_R light ($m_{N_R} \sim \mathcal{O}$(1 eV)) → direct sensitivity at oscillation experiments
- N_R heavier ($m_{N_R} \in$[10 eV, 15 MeV]) → sensitivity at oscillation experiments in averaged out regime



$$\Delta m^2_{41} L/(4E)) \gg 1$$

Constraints are insensitive to mass scale

→ Gallium, reactor flux anomalies

$\Delta m^2_{41} = 1$ eV^2

$\Delta m^2_{41} = 10$eV^2

Depends on E, L/E of experiment!

Testing the neutrino portal

Oscillation phenomenology of N_R depends on its mass scale:

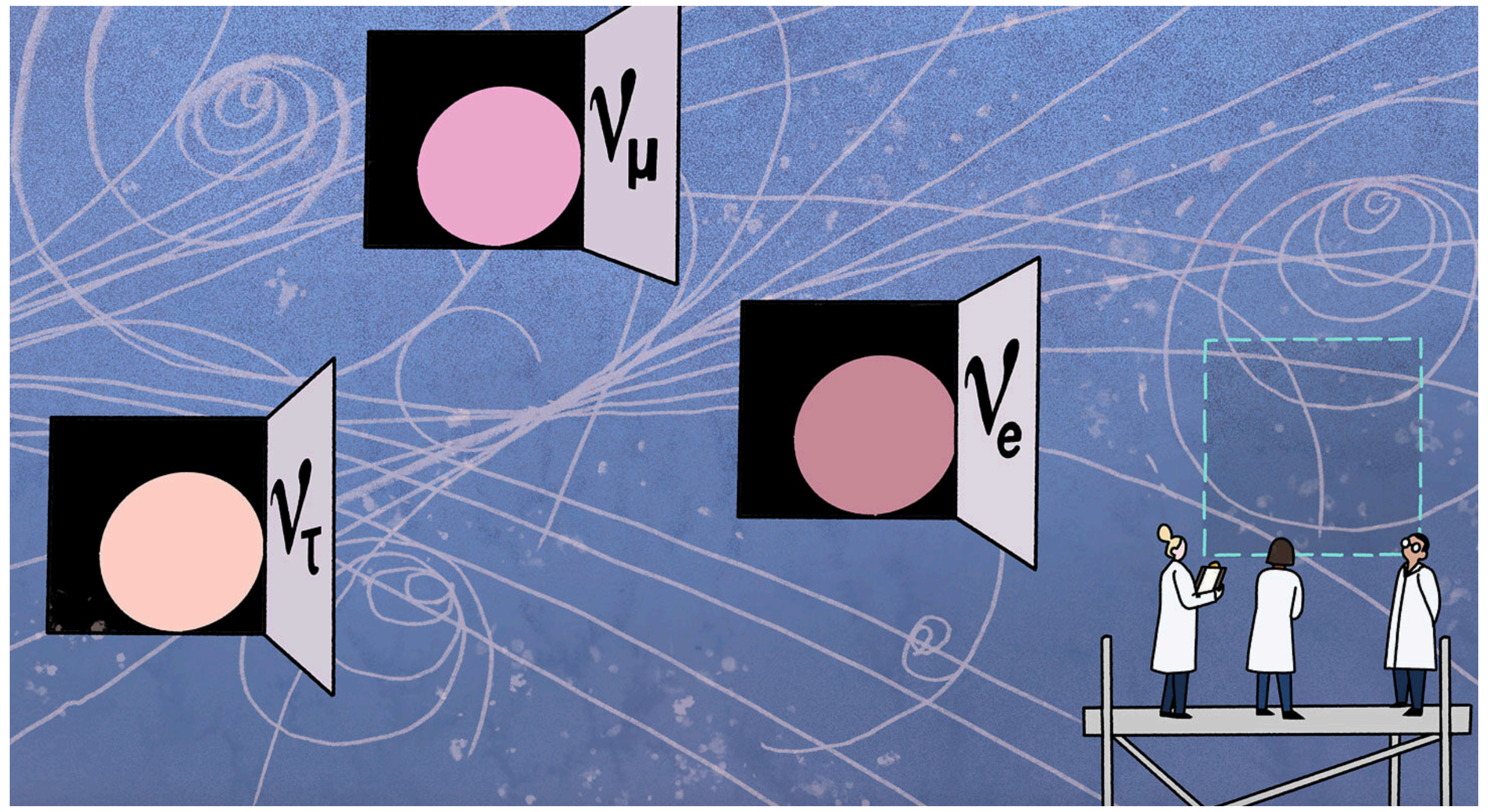
- N_R light ($m_{N_R} \sim \mathcal{O}$(1 eV)) → direct sensitivity at oscillation experiments
- N_R heavier ($m_{N_R} \in$ [10 eV, 15 MeV]) → sensitivity at oscillation experiments in averaged out regime
- N_R heavy ($m_{N_R} \gtrsim$ 40 MeV)) → too heavy to be produced in oscillation experiments

Depends on E of experiment!

Constraints are insensitive to mass scale

Impact on unitarity of PMNS matrix:
Measureable, active-light 3x3 mixing matrix is not unitary but full mixing matrix including sterile states is unitary

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \\ \vdots \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \cdots \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & \cdots \\ \cdots & \cdots & \cdots & \cdots & \ddots \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \vdots \end{pmatrix}$$



Non-unitarity

Antusch, Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon '06

Effects of non-unitarity of mixing matrix:

Production and detection of neutrinos are weak processes

$$\mathscr{L} \supset -\frac{g}{2\sqrt{2}}(W_\mu^+ \overline{l}_\alpha \gamma_\mu (1-\gamma_5) U_{\alpha i} \nu_i + h.c.) - \frac{g}{2\cos\theta_W}(Z_\mu \overline{\nu}_i \gamma^\mu (1-\gamma_5)(U^\dagger U)_{ij} \nu_j + h.c.)$$

different from unitary matrix

=1 if U is unitary

Measured number of neutrinos: $n_\beta^{meas} \sim \int dE \frac{d\phi_\alpha(E)}{dE} P_{\alpha\beta}(E,L) \sigma_\beta(E) \epsilon(E)\,,$

Inital neutrino flux

Oscillation probability

Final neutrino cross section

All terms affected by non-unitarity

Non-unitarity

Antusch, Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon '06

Effects of non-unitarity of mixing matrix:

Production and detection of neutrinos are weak processes

$$\mathscr{L} \supset -\frac{g}{2\sqrt{2}}(W_\mu^+ \overline{l}_\alpha \gamma_\mu (1-\gamma_5) U_{\alpha i} \nu_i + h.c.) - \frac{g}{2\cos\theta_W}(Z_\mu \overline{\nu}_i \gamma^\mu (1-\gamma_5)(U^\dagger U)_{ij} \nu_j + h.c.)$$

different from unitary matrix

=1 if U is unitary

Oscillation probability

$$P_{\alpha\beta}(E,L) = \frac{|\sum_{i=1}^{acc} U_{\alpha i}^* e^{iP_i L} U_{\beta i}|^2}{(UU^\dagger)_{\alpha\alpha}(UU^\dagger)_{\beta\beta}}$$

Initial neutrino flux

$$\frac{d\phi_\alpha^{CC}}{dE} = \frac{d\phi_\alpha^{CC,SM}}{dE}(UU^\dagger)_{\alpha\alpha}$$

CC neutrino cross section

$$\sigma_\alpha^{CC} = \sigma_\alpha^{CC,SM}(UU^\dagger)_{\alpha\alpha}$$

⟶ $$n_\beta^{CC} \sim \int dE \frac{d\phi_\alpha^{CC,SM}(E)}{dE} \tilde{P}_{\alpha\beta}(E,L) \sigma_\beta^{CC,SM}(E) \epsilon(E)$$ With $$\tilde{P}_{\alpha\beta} = |\sum_{i=1}^{acc} U_{\alpha i}^* e^{iP_i L} U_{\beta i}|^2$$

⟶ Cancellations happen if cross section and flux come from theory predictions

Only partial cancellations if flux comes from near detector and/or cross section comes from experiment

Non-unitarity

Antusch, Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon '06

Effects of non-unitarity of mixing matrix:
Production and detection of neutrinos are weak processes

$$\mathscr{L} \supset -\frac{g}{2\sqrt{2}}(W_\mu^+ \overline{l}_\alpha \gamma_\mu (1-\gamma_5) U_{\alpha i} \nu_i + h.c.) - \frac{g}{2\cos\theta_W}(Z_\mu \overline{\nu}_i \gamma^\mu (1-\gamma_5)(U^\dagger U)_{ij} \nu_j + h.c.)$$

different from unitary matrix

=1 if U is unitary

Oscillation probability

$$P_{\alpha\beta}(E,L) = \frac{|\sum_{i=1}^{acc} U_{\alpha i}^* e^{iP_i L} U_{\beta i}|^2}{(UU^\dagger)_{\alpha\alpha}(UU^\dagger)_{\beta\beta}}$$

Initial neutrino flux

$$\frac{d\phi_\alpha^{CC}}{dE} = \frac{d\phi_\alpha^{CC,SM}}{dE}(UU^\dagger)_{\alpha\alpha}$$

NC neutrino cross section

$$\sigma_\beta^{NC} = \sigma^{NC,SM} |(UU^\dagger)_{\beta\beta}|^2$$

$$\sigma_i^{NC} = \sigma^{NC,SM} \sum_{j=1}^{acc} |(U^\dagger U)_{ij}|^2$$

$$\longrightarrow \quad n^{NC} \sim \int dE \sigma^{NC,SM} \sum_{\alpha=e}^{\tau} \frac{d\phi_\alpha^{CC,SM}(E)}{dE} \sum_{\beta=e}^{\tau} \tilde{P}_{\alpha\beta}(UU^\dagger)_{\beta\beta} \epsilon(E)$$

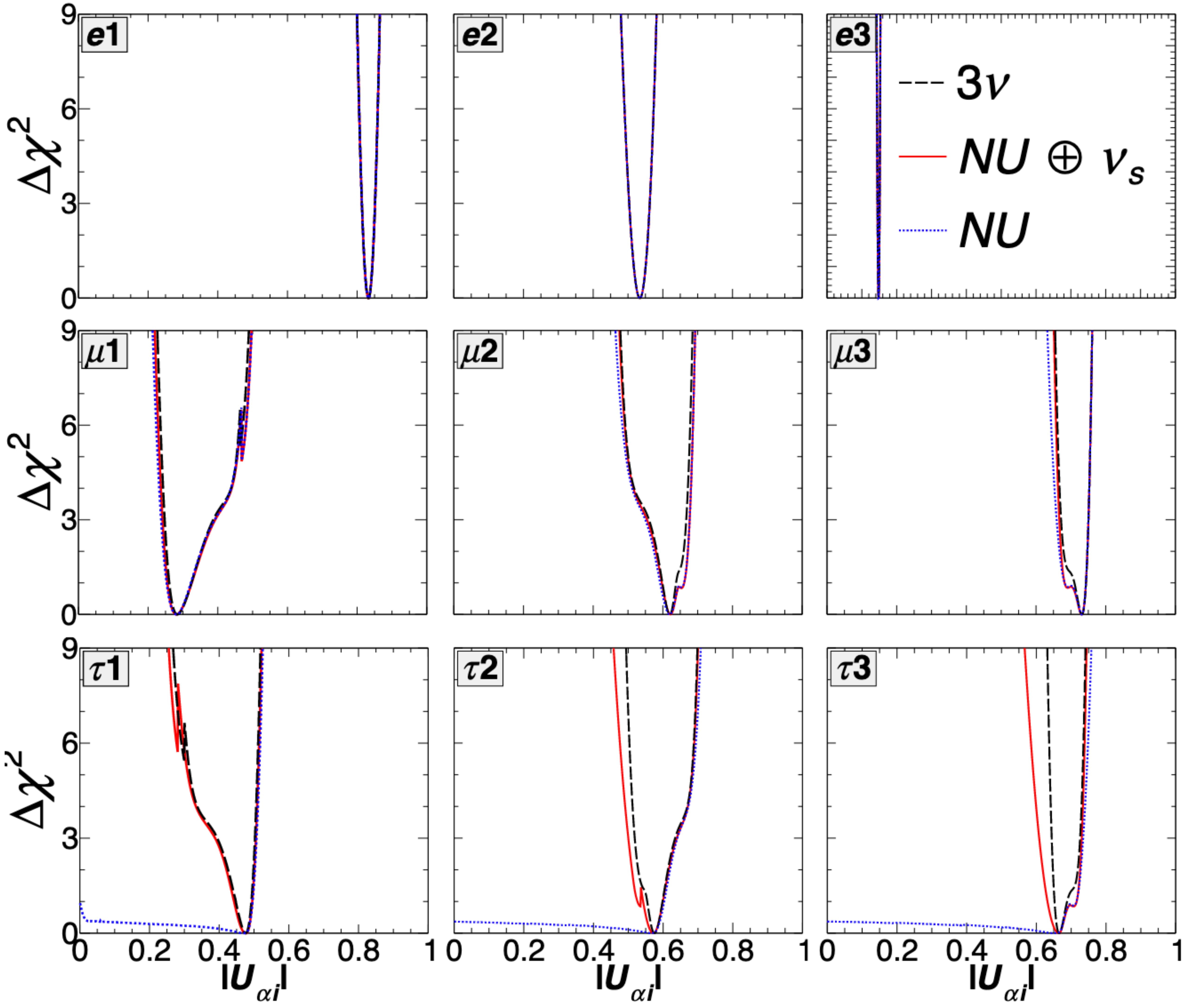
$$n_{solar}^{NC} \sim \int dE \sigma^{NC,SM} \sum_{\alpha=e}^{\tau} \frac{d\phi_\alpha^{CC,SM}(E)}{dE} \sum_{i=1}^{acc} \tilde{P}_{\alpha i}(E,L) \sum_{j=1}^{acc} |(U^\dagger U)_{ij}|^2 \epsilon(E)$$

$\longrightarrow$ Only partical cancellations happen

Even if not all flavours involved in process there is a dependence on all matrix elements

Non-unitarity

Results in literature for kinematically accessible sterile



From Hu, Ling, Tang, Wang '20

See also Parke, Ross-Lonergan '15

Ellis, Kelly, Li '20

Electron row precisely determined:

Driven by reactor experiments → lots of statistics

Improvements in future by JUNO

Qian, Zhang, Diwan, Vogel '13

Muon row less precise:

Ongoing and future LBL experiments will lead to more muon neutrino data

Tau row not precise:

Small tau neutrino data set

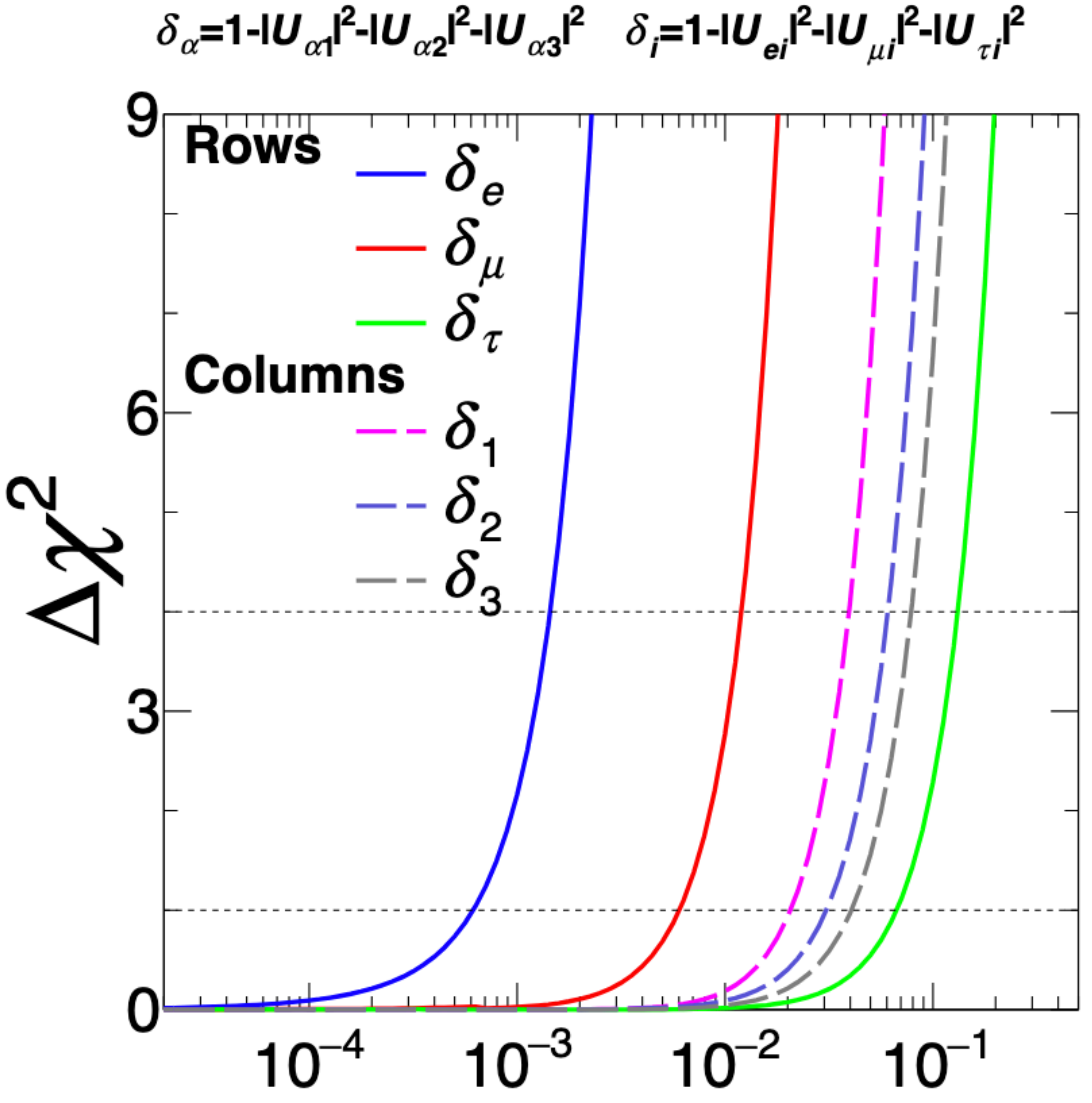
Non-unitarity

Results in literature for kinematically accessible sterile

See also [Parke, Ross-Lonergan ‘15]

[Ellis, Kelly, Li ‘20]

From [Hu, Ling,Tang, Wang ’20]



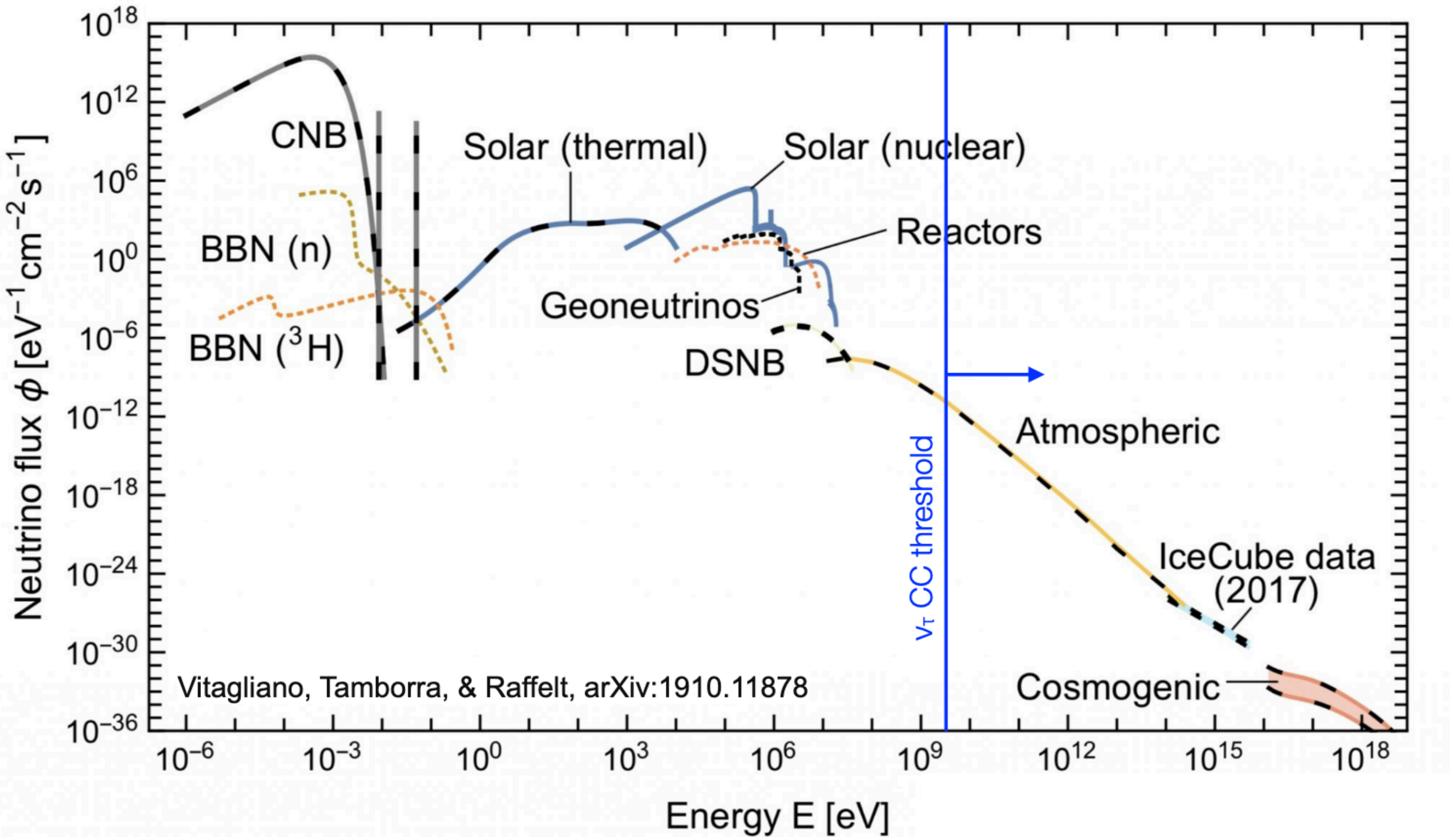
Tau row worst determined:
new physics could be hiding there

Necessary to understand tau row better

Unitarity of tau row

Why is the tau row so bad?

Identify neutrino flavour by identifying associated charged lepton: taus are difficult, and heavy



Need high energy neutrino beam

Need good understanding of tau identification, tau systematics, …

Unitarity of tau row

Denton, JG ‘21

Data sets considered in literature:

- muon neutrino disappearance experiments (IceCube, DeepCore, SuperKamiokaNDE)
- LBL tau appearance experiments (OPERA) (8 events)

New unitarity constraints on tau row

Denton, JG '21

Data sets considered in literature:

- muon neutrino disappearance experiments (IceCube, DeepCore, SuperKamiokaNDE)
- LBL tau appearance experiments (OPERA) (8 events)

More tau neutrino data sets available!

Rich data previously not considered!

Experiment	Source	~Events detected
DONuT	Production	7.5
OPERA	Long-baseline	8
SK	Atmospheric	291
IceCube	Atmospheric	1804
IceCube	Astrophysical	2

Denton '21

New unitarity constraints on tau row

Denton, JG '21

Data sets considered in literature:

- muon neutrino disappearance experiments (IceCube, DeepCore, SuperKamiokaNDE)
- LBL tau appearance experiments (OPERA) (8 events)

More tau neutrino data sets available!

Rich data previously not considered!

Experiment	Source	~Events detected
DONuT	Production	7.5
OPERA	Long-baseline	8
SK	Atmospheric	291
IceCube	Atmospheric	1804
IceCube	Astrophysical	2

Denton '21

Peter B. Denton and Julia Gehrlein,
"New tau neutrino oscillation and scattering constraints on unitarity violation"
arXiv:2109.14575 [hep-ph]

Pioneer the use of these data sets to derive novel constraints on tau row matrix elements and tau row normalization

New unitarity constraints on tau row

Denton, JG '21

Overloaded data sets:

- Atmospheric ν_μ disappearance (DeepCore, SuperK, IceCube ➜ IceCube, HyperK, KM3NeT)
- Long baseline ν_τ appearance data (OPERA ➜ DUNE)
- **new:** ν_τ CC scattering data from DOnuT ➜FASERnu
- **new:** Atmospheric ν_τ appearance (IceCube, SuperK ➜IceCube, HyperK, KM3NeT)
- **new:** Astrophysical ν_τ appearance (IceCube ➜IceCube-Gen2)
- **new:** NC data from SNO
- **new:** NC data from CEvNS ➜ more CEvNS data

Focus on effect of these data sets on tau row
Use priors on electron and muon row from literature

New unitarity constraints on tau row

Denton, JG '21

Overlooked data sets:

- Atmospheric ν_μ disappearance (DeepCore, SuperK, IceCube ➜ IceCube, HyperK, KM3NeT)
- Long baseline ν_τ appearance data (OPERA ➜ DUNE)
- **new:** ν_τ CC scattering data from DOnuT ➜FASERnu
- **new:** Atmospheric ν_τ appearance (IceCube, SuperK ➜IceCube, HyperK, KM3NeT)
- **new:** Astrophysical ν_τ appearance (IceCube ➜IceCube-Gen2)
- **new:** NC data from SNO
- **new:** NC data from CEvNS ➜ more CEvNS data

Focus on effect of these data sets on tau row
Use priors on electron and muon row from literature

Considered scenarios

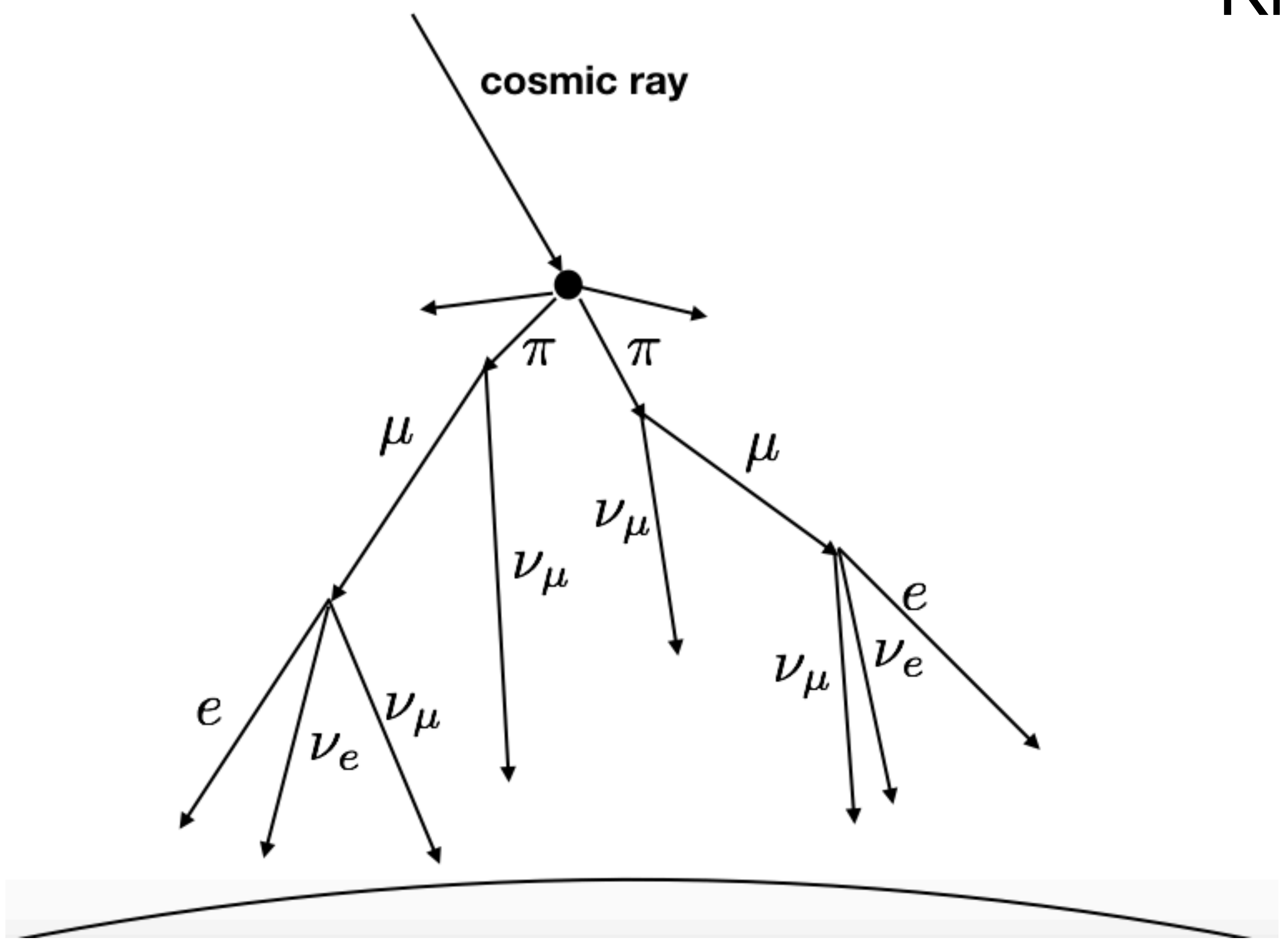
- 1 additional accessible sterile neutrino →4x4 matrix
- 2 additional, kinematically inaccesible sterile neutrinos →enough dofs to parametrize 3x3 submatrix

New unitarity constraints on tau row

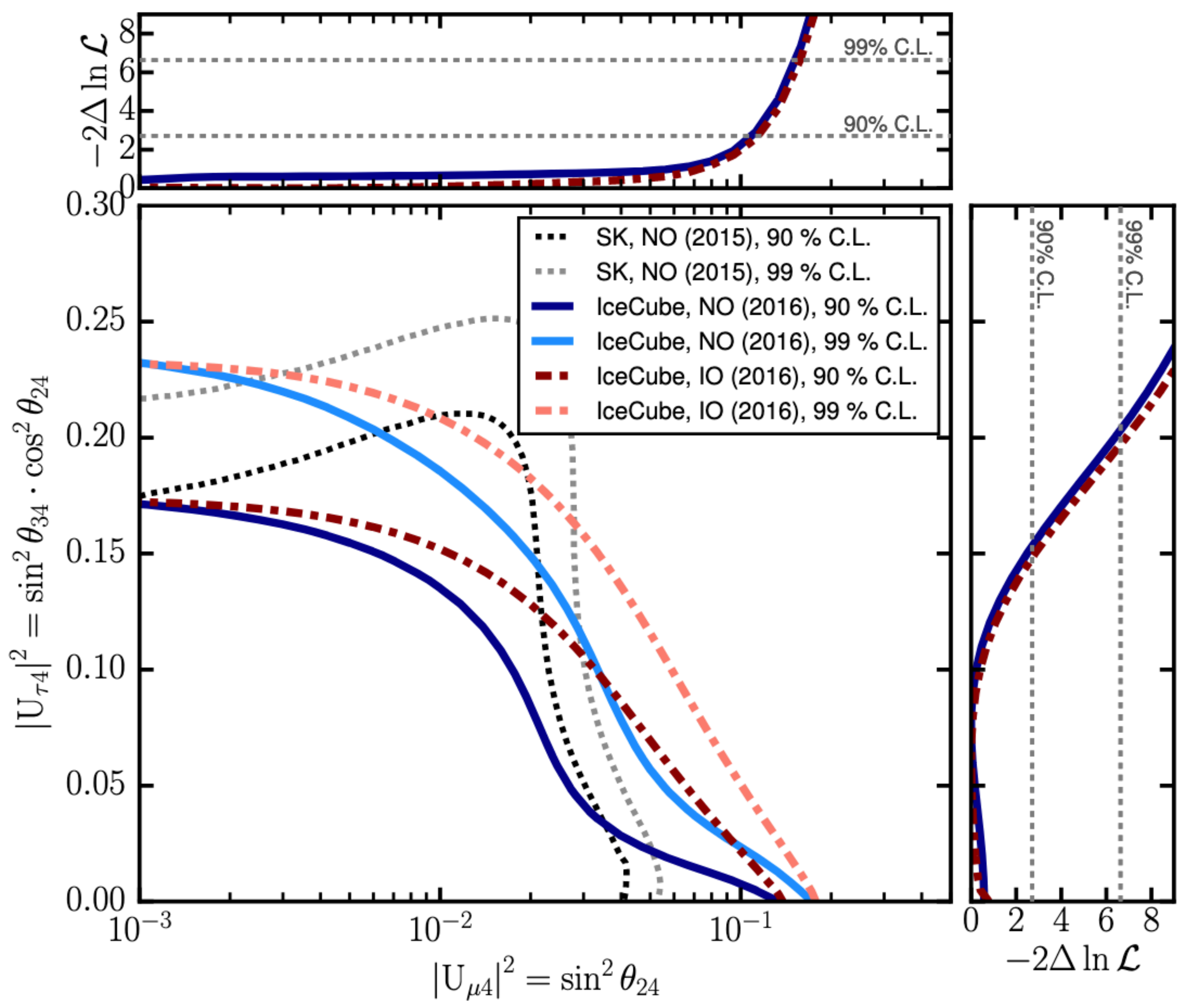
Denton, JG '21

Atmospheric ν_μ disappearance

Cosmic rays hit the atmosphere → produce mesons → decay into muons→ muon neutrinos are produced
Muon neutrinos travel through Earth and experience matter effects



Kinematically accessible sterile does not experience matter effects
→ sensitivity to presence of sterile state



DeepCore '19

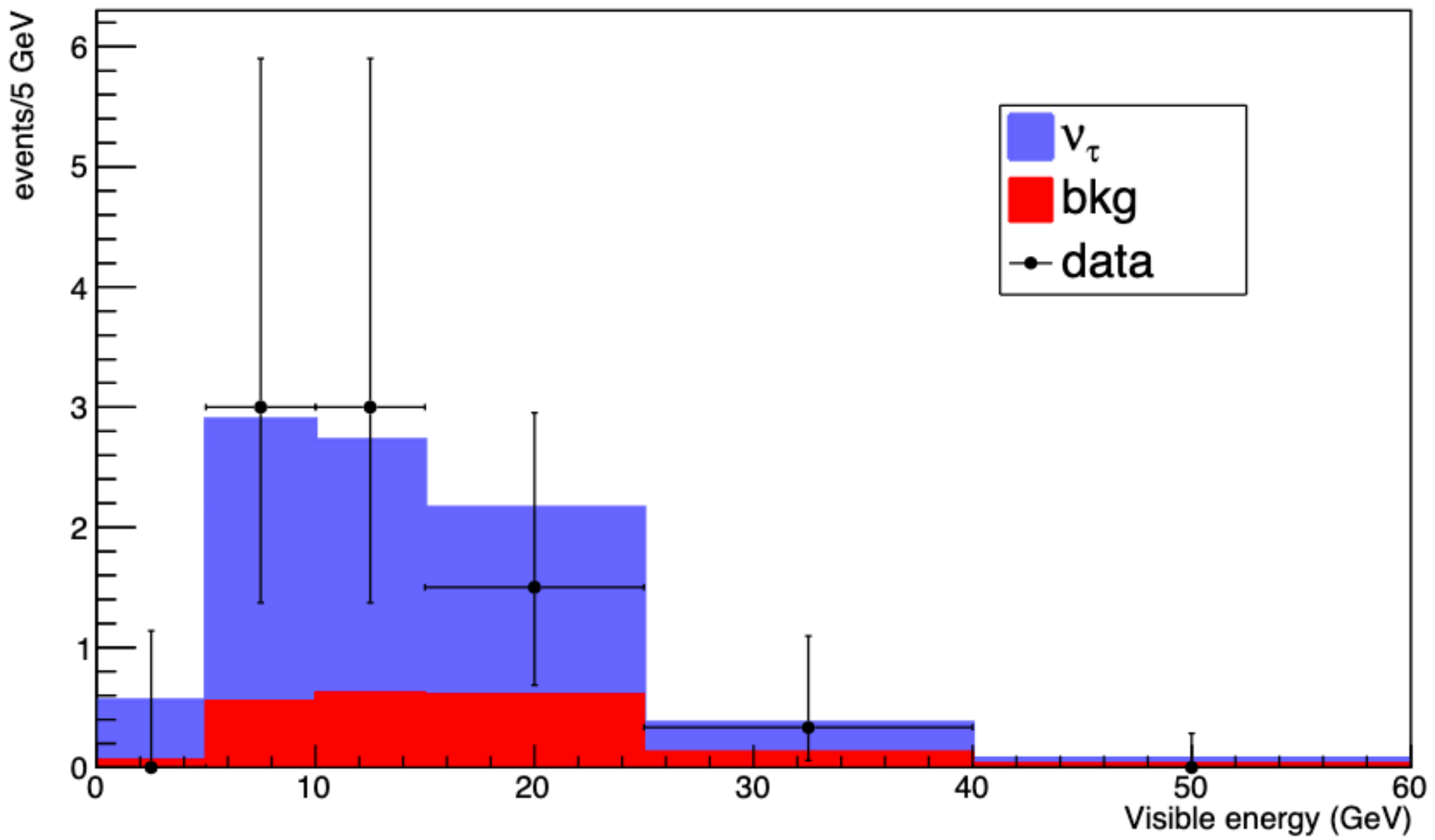
Only valid for (4,4) scenario!

New unitarity constraints on tau row

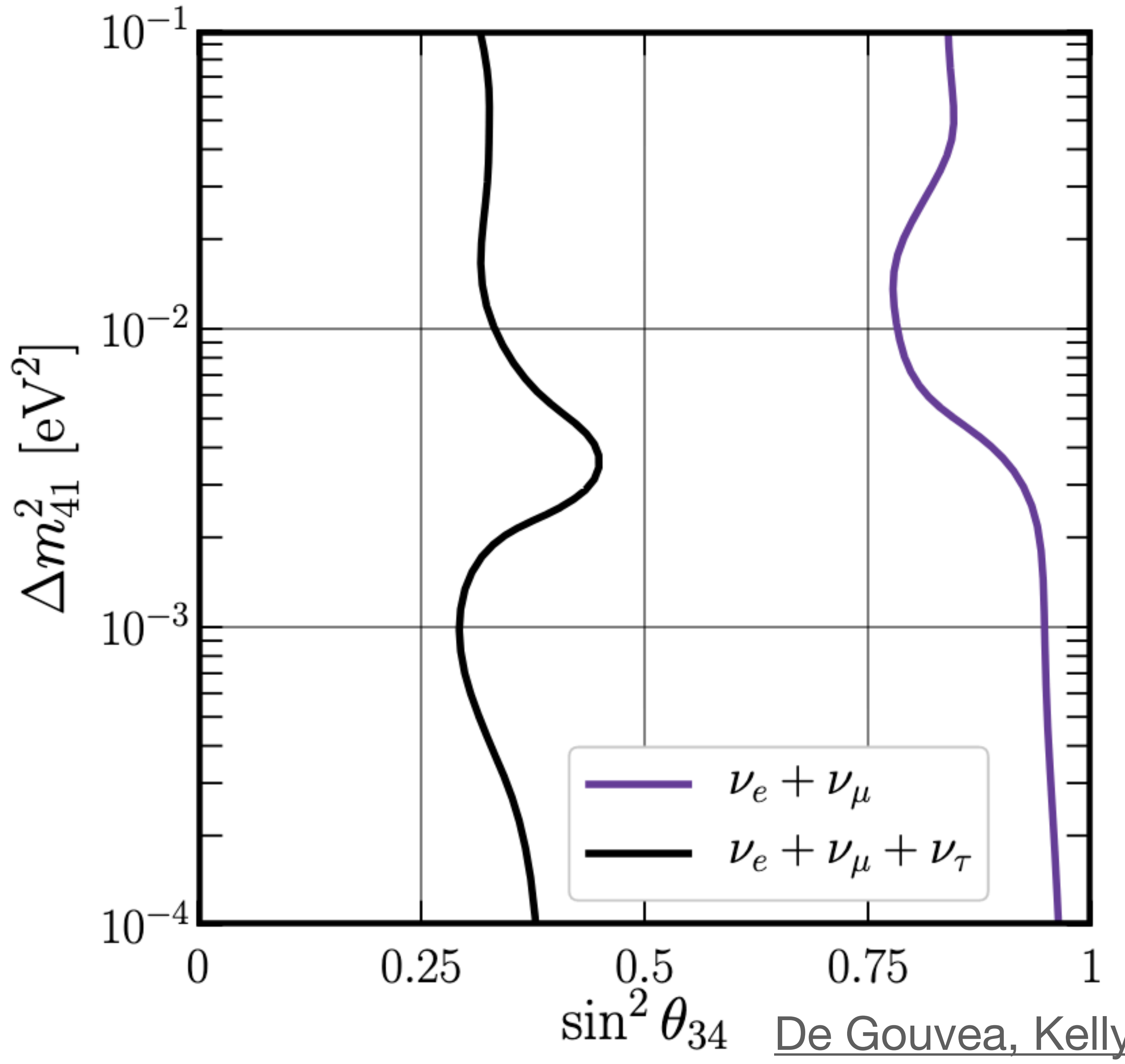
Denton, JG ‘21

Long baseline searches

Consider $P(\nu_\mu \to \nu_\tau)$
in the beam at OPERA and DUNE



OPERA ‘18



De Gouvea, Kelly, Stenico, Pasquini ‘19

New unitarity constraints on tau row

Denton, JG '21

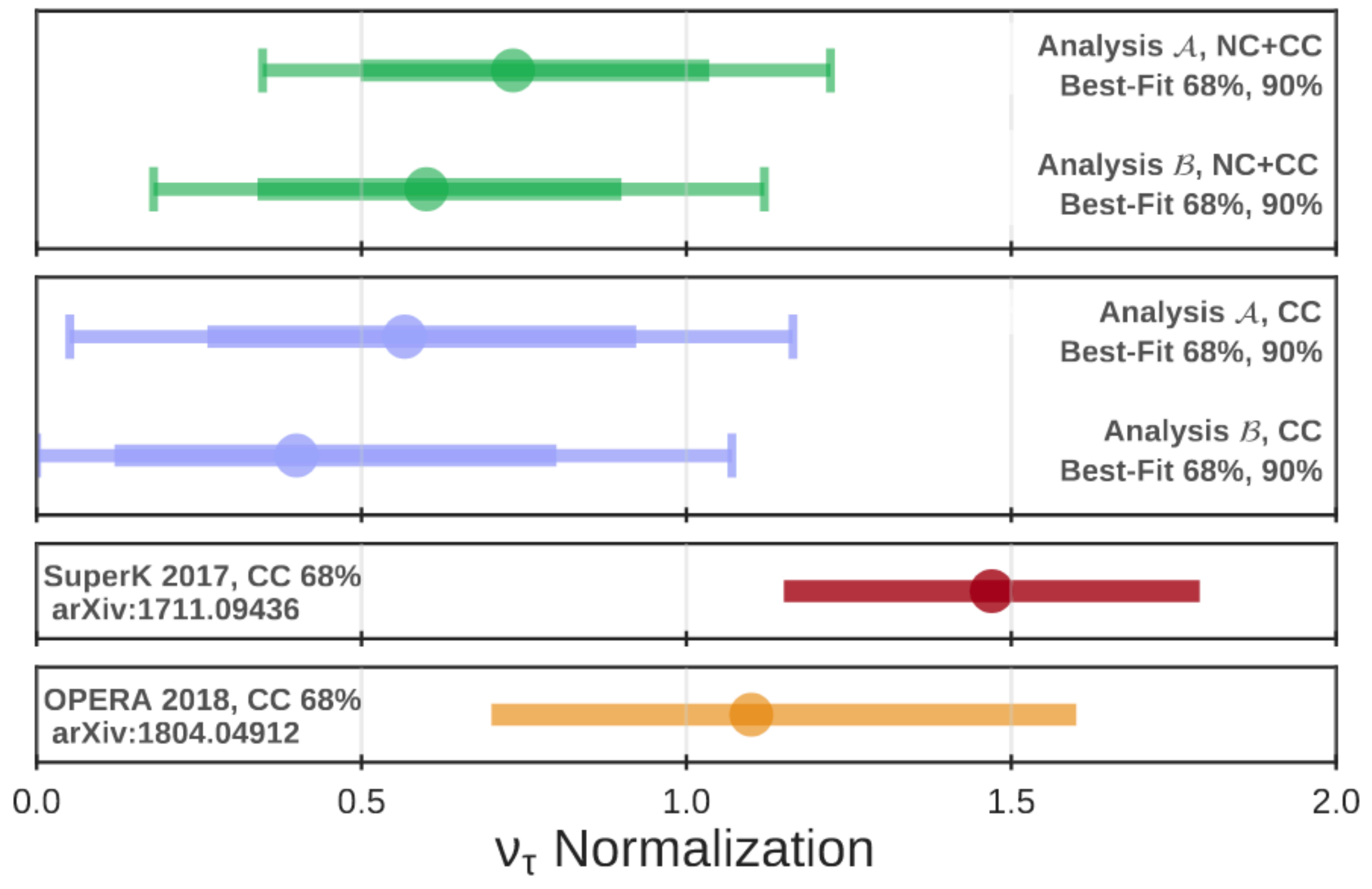
Atmospheric ν_τ appearance

$$P(\nu_\mu \to \nu_\tau)$$

Sensitivity comes primarily from a combination of the matter effect, the lower tau neutrino reconstructed energy, and the rising cross section due to the tau lepton's threshold

Denton '21

Constraint parametrized as $N_\tau = \frac{\phi^{meas}_{\nu_\tau}}{\phi^{theo}_{\nu_\tau}} = \frac{\tilde{P}^{UV}_{\mu\tau}}{\tilde{P}^{3U}_{\mu\tau}}$



New unitarity constraints on tau row

Denton, JG ‘21

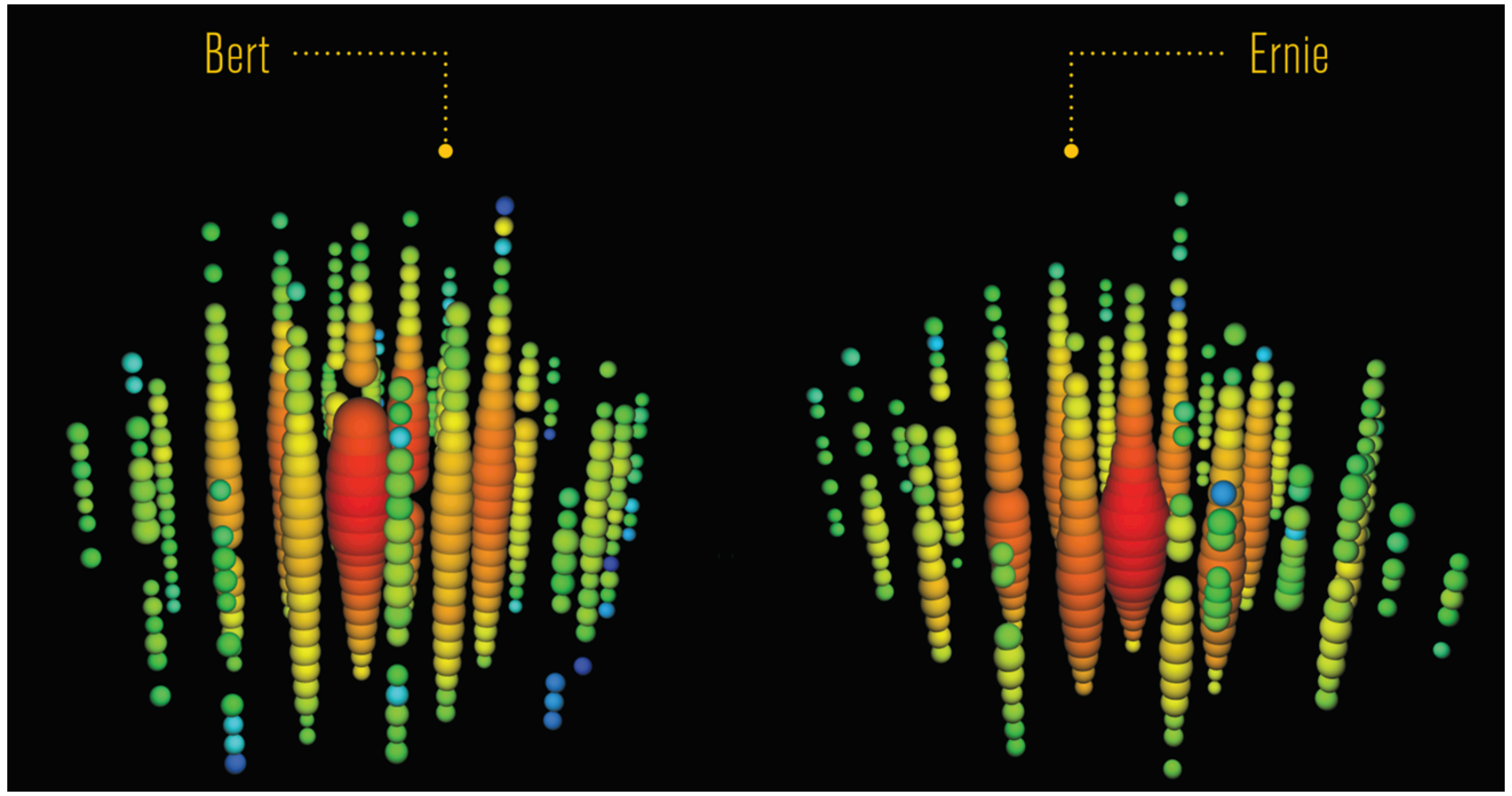
Astrophysical ν_τ appearance

- Don’t expect astrophysical sources to produce ν_τ → any detected ν_τ indicate flavour change
- Neutrinos have travelled very long distances → decoherent oscillations
- Source of astrophysical neutrinos not clear → No theoretical prediction for number of expected events

IceCube has seen 2 astrophysical tau neutrinos
IceCube has also constrained astrophysical muon neutrino flux
$\Longrightarrow$ use ratio of fluxes (should be 1 for unitary matrix)

$$n_{\nu_\alpha}^{theo} = \sigma_\alpha^{CC,SM}(UU^\dagger)_{\alpha\alpha} \times \phi_p(\xi(UU^\dagger)_{ee}P_{e\alpha} + (1-\xi)(UU^\dagger)_{\mu\mu}P_{\mu\alpha})$$

$$\left(\frac{\phi_{\nu_\tau}}{\phi_{track}}\right)^{meas} = \frac{\xi\sum_{i=1}^{acc}|U_{ei}|^2|U_{\tau i}|^2 + (1-\xi)\sum_{i=1}^{acc}|U_{\mu i}|^2|U_{\tau i}|^2}{(1-\xi)\sum_{i=1}^{acc}|U_{\mu i}|^4 + \xi\sum_{i=1}^{acc}|U_{ei}|^2|U_{\mu i}|^2}$$



New unitarity constraints on tau row

Denton, JG ‘21

CC scattering

First observation of tau neutrinos by DONuT (in 2000)!

DONuT/FASERnu:

- High energy tau neutrino source (decay of Ds meson)
- Short baseline, high energy → no oscillations have developped
- Compare predicted to observed events

$$\tilde{P}(\nu_\tau \to \nu_\tau) = \left| \sum_{i=1}^{acc} U_{\tau i}^* U_{\tau i} \right|^2 - 2\Re \left(\sum_{j=heavy}^{acc} U_{\tau j}^* U_{\tau j} \sum_{i=1}^{3} U_{\tau i} U_{\tau i}^* \right),$$

Constrains (5,3) scenario

Constrains (4,4) scenario

New unitarity constraints on tau row

Denton, JG '21

CC scattering

First observation of tau neutrinos by DONuT (in 2000)!

DONuT/FASERnu:

- High energy tau neutrino source (decay of Ds meson)
- Short baseline, high energy → no oscillations have developped
- Compare predicted to observed events

$$\tilde{P}(\nu_\tau \to \nu_\tau) = \left| \sum_{i=1}^{acc} U^*_{\tau i} U_{\tau i} \right|^2 - 2\Re \left(\sum_{j=heavy}^{acc} U^*_{\tau j} U_{\tau j} \sum_{i=1}^{3} U_{\tau i} U^*_{\tau i} \right),$$

NOMAD:

- Short baseline, high energy → no oscillations have developped
- Upper limit on $\tilde{P}(\nu_\mu \to \nu_\tau)$, $\tilde{P}(\nu_e \to \nu_\tau)$

$$\tilde{P}(\nu_\mu \to \nu_\tau) = \left| \sum_{i=1}^{acc} U^*_{\mu i} U_{\tau i} \right|^2 - 2\Re \left(\sum_{j=heavy}^{acc} U^*_{\mu j} U_{\tau j} \sum_{i=1}^{3} U_{\mu i} U^*_{\tau i} \right)$$

(4,4): $U_{\mu 4}$ compatible with zero

→ no constraint on $U_{\tau 4}$

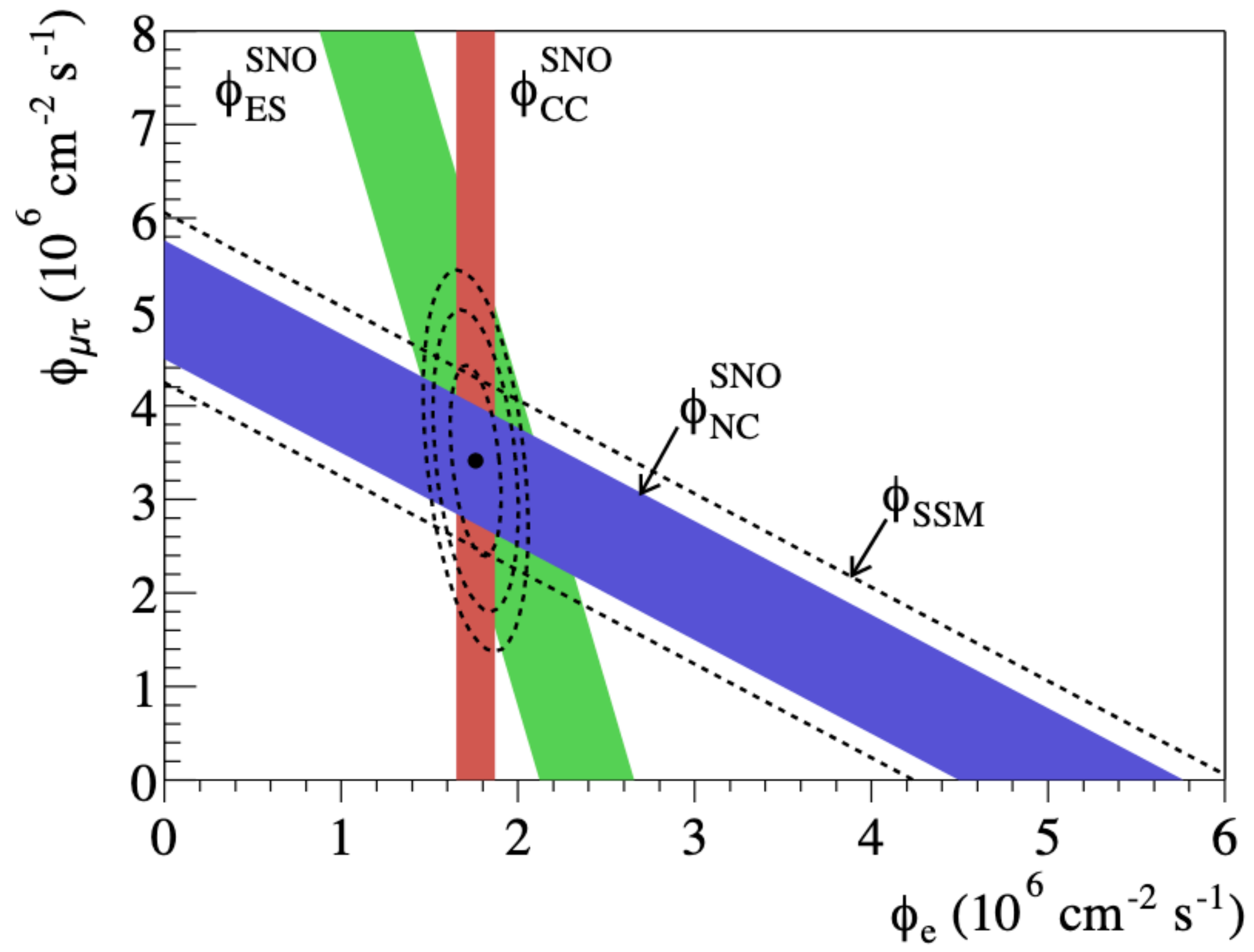
New unitarity constraints on tau row

Denton, JG '21

NC scattering

SNO

- NC measurement fundamental to establish neutrino oscillations
- Compare NC theoretical prediction to NC measurement
- Uncertainty of prediction > experimental uncertainty → only weak constaints from SNO



New unitarity constraints on tau row

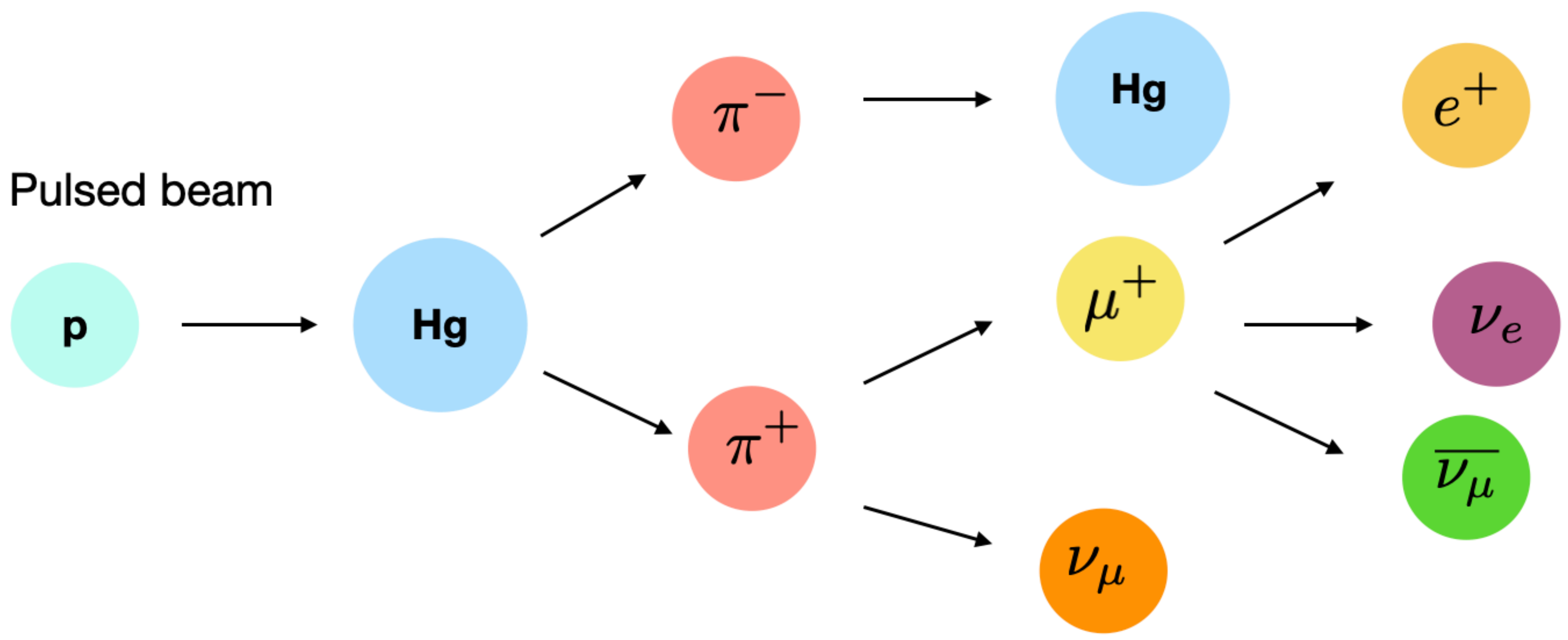
Denton, JG '21

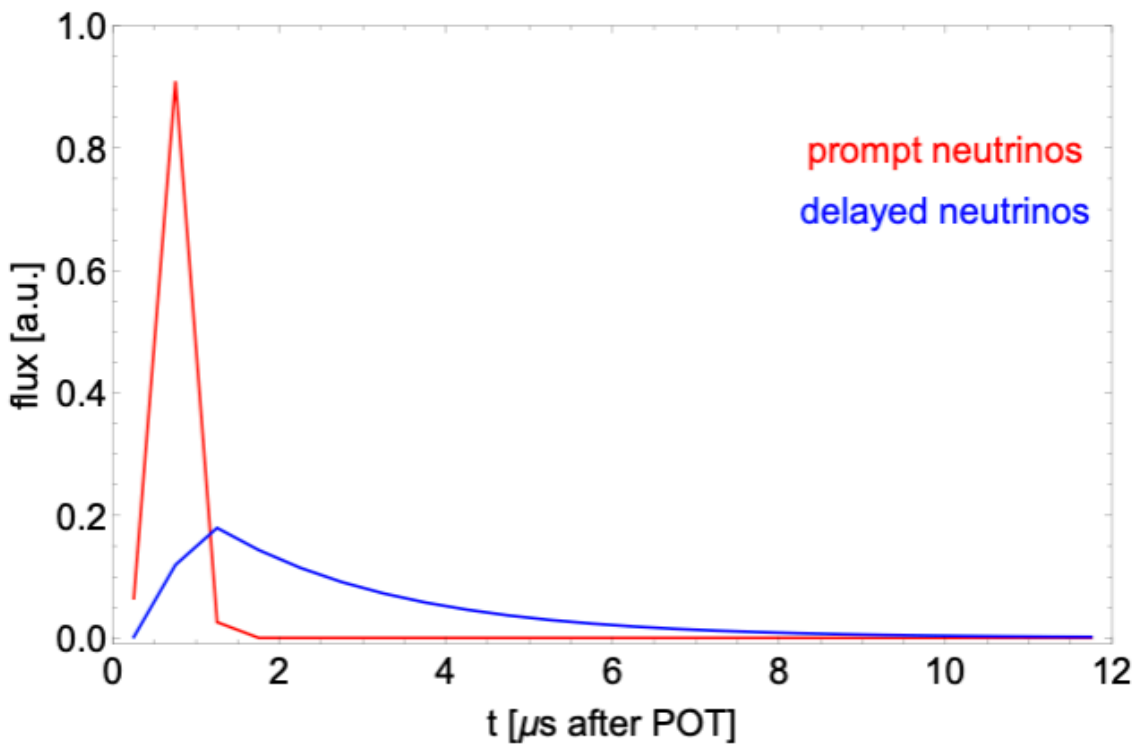
NC scattering

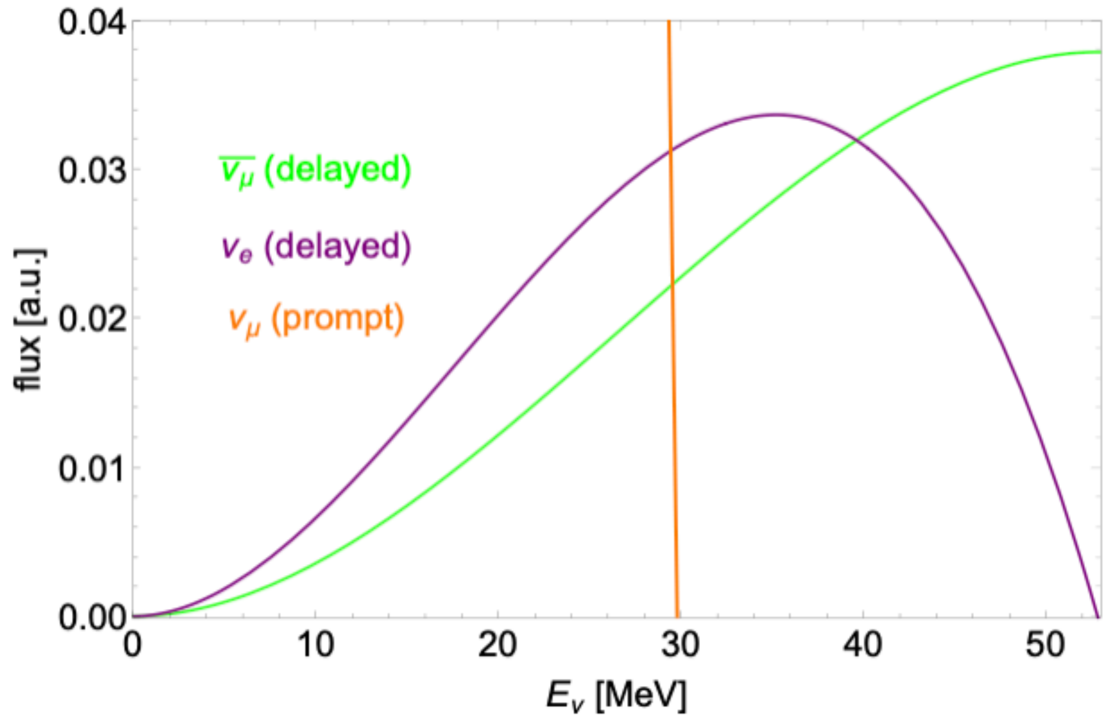
CEvNS

- NC process
- Electron and muon neutrinos from stopped pion source → no tau neutrino involved!

$\Longrightarrow$ sensitivity to tau matrix elements from NC process







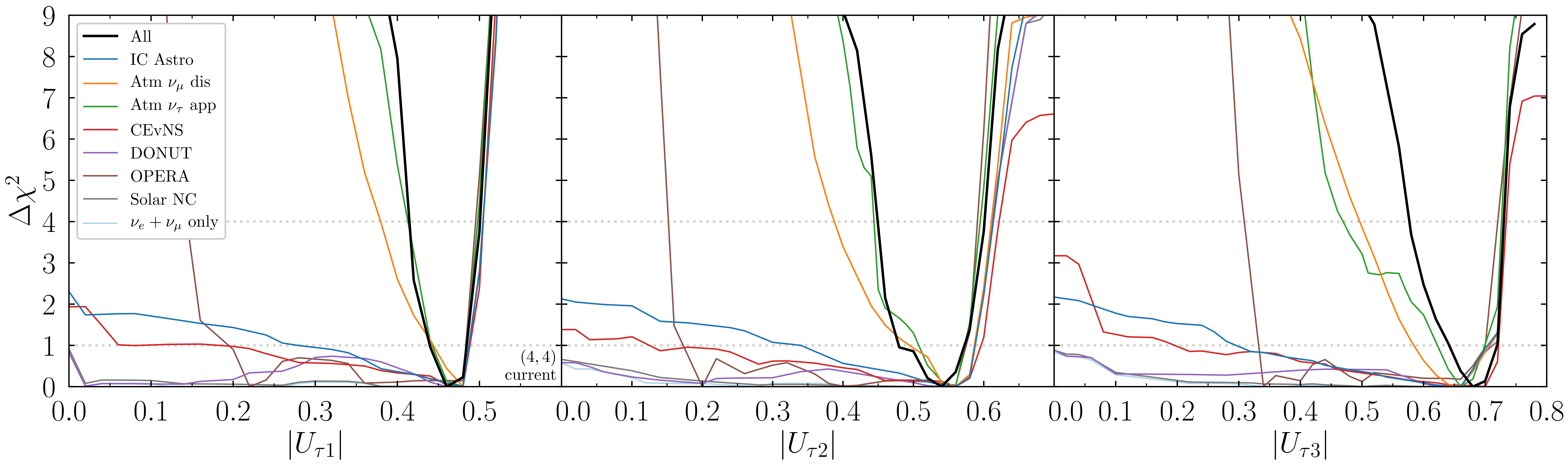
$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\mu^+ \to e^+ + \overline{\nu_\mu} + \nu_e$$

Don't need to identify tau neutrino to constrain tau matrix elements!

New unitarity constraints on tau row

Denton, JG '21

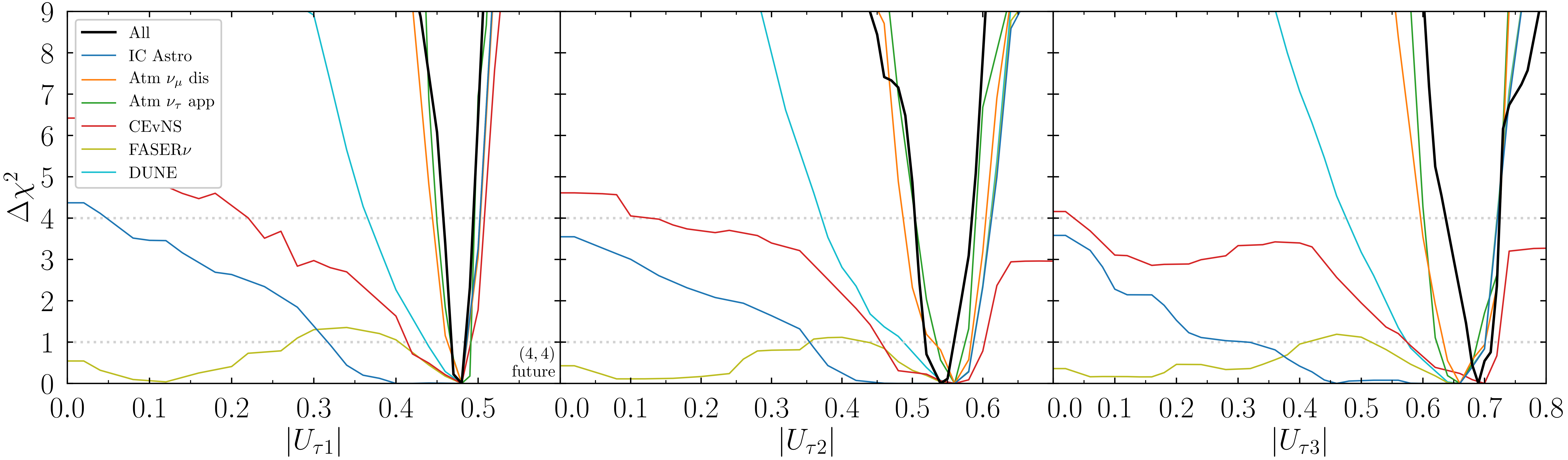
Results for kinematically accessible sterile



New unitarity constraints on tau row

Denton, JG ‘21

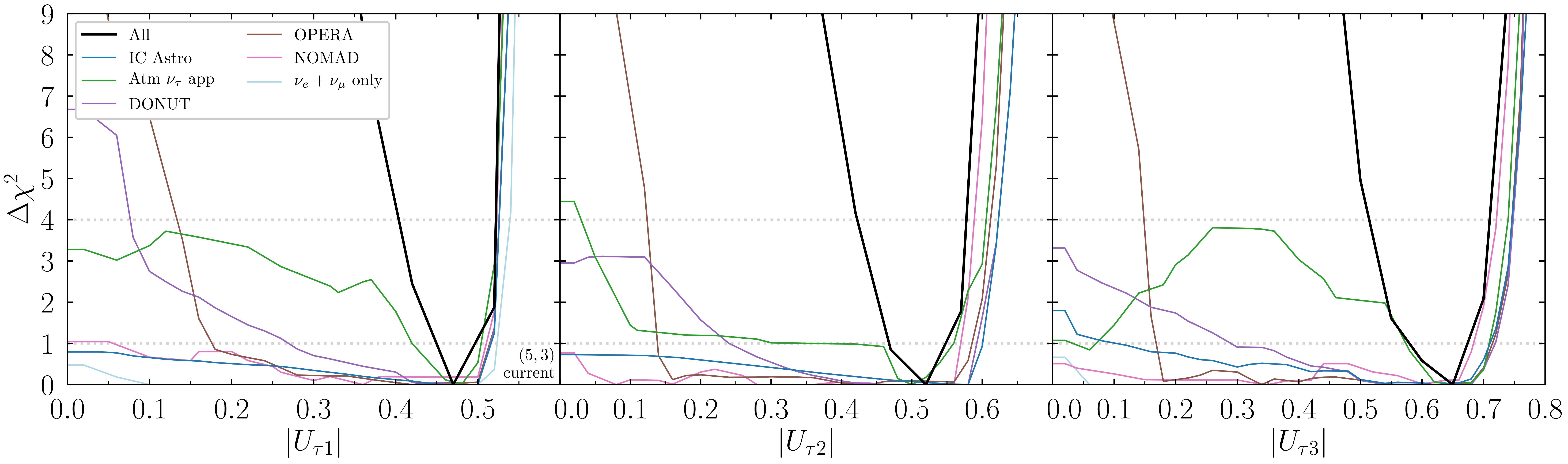
Results for kinematically accessible sterile



New unitarity constraints on tau row

Denton, JG '21

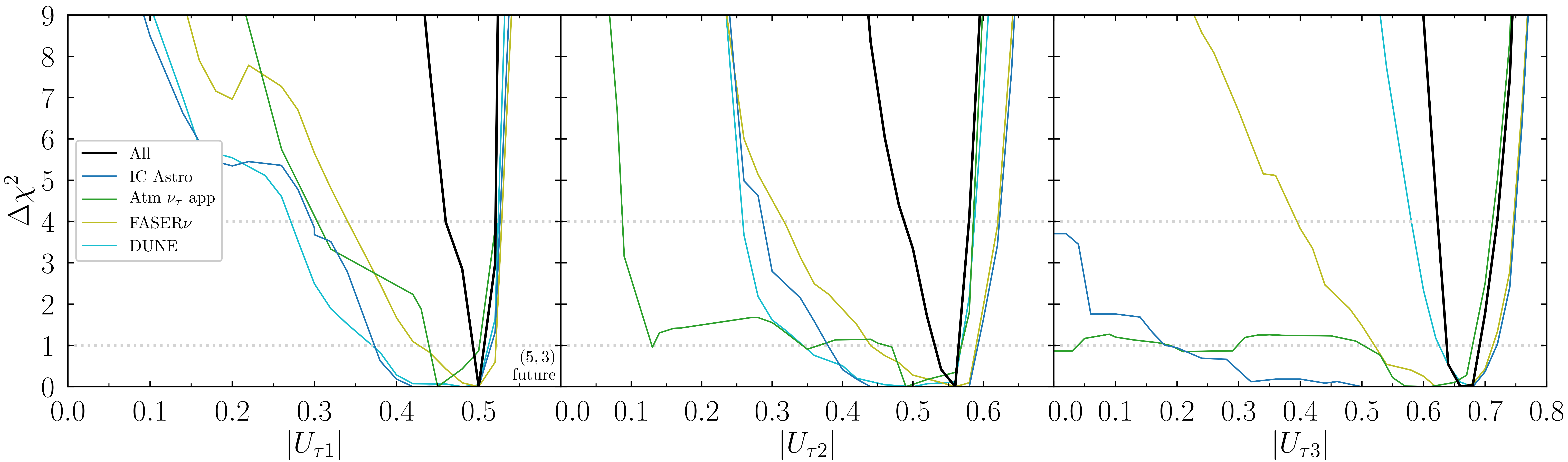
Results for inaccessible steriles



New unitarity constraints on tau row

Denton, JG '21

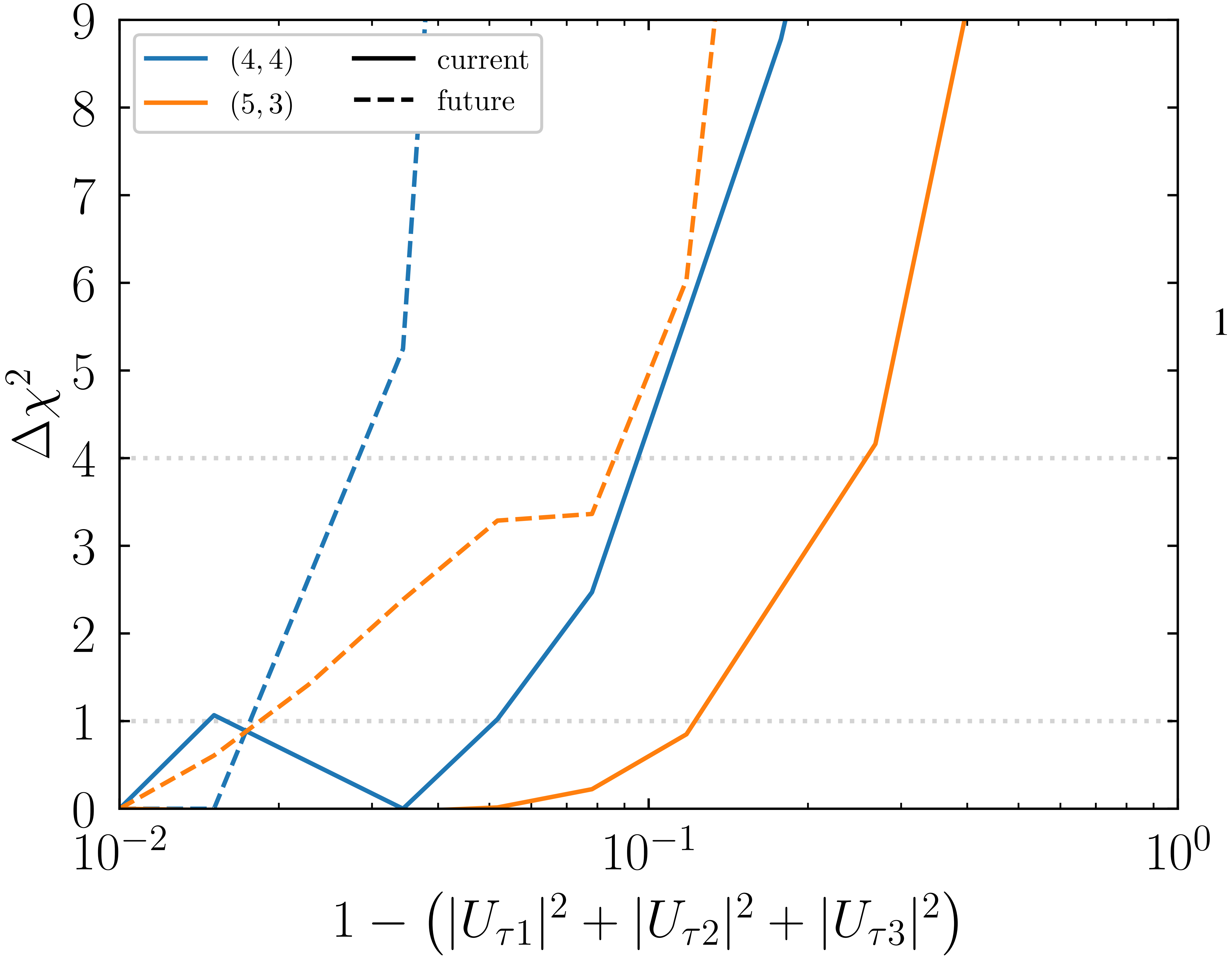
Results for inaccessible steriles



New unitarity constraints on tau row

Denton, JG '21

Constraints on tau row normalization



No hints for non-unitarity in either scenario

(4,4):

$1 - (|U_{\tau 1}|^2 + |U_{\tau 2}|^2 + |U_{\tau 3}|^2) < 0.097(0.029)$ for current (future) data

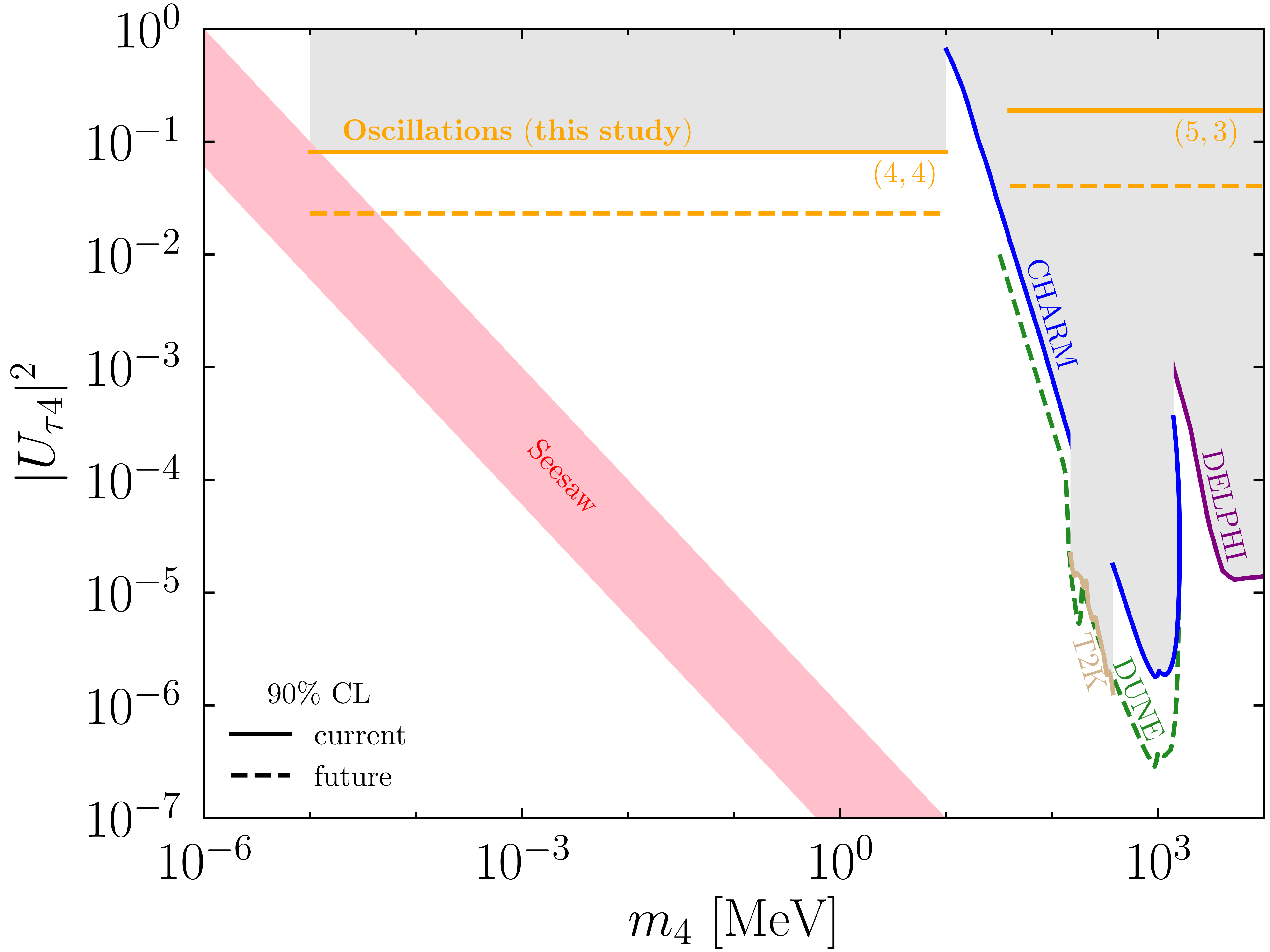
(5,3):

$1 - (|U_{\tau 1}|^2 + |U_{\tau 2}|^2 + |U_{\tau 3}|^2) < 0.259(0.088)$ for current (future) data

New unitarity constraints on tau row

Denton, JG '21

Comparison to direct searches



- Cover an unexplored parameter space for small sterile masses
- Probe region predicted by seesaw mechanism
- Complementary and new constraints for large masses
- Most direct searches (apart from T2K) rely on one dominant sterile mixing paramter ↔ oscillation constraints allow all sterile mixing to be non-zero

New unitarity constraints on tau row

Denton, JG '21

Summary & Conclusions

- introduced new, previously overlooked tau neutrino data sets
- derived constraints on tau row matrix elements and tau row normalization with current data as well as forecasted prospects
- No hints of unitarity violation
- Tau matrix elements non-zero at high confidence level
- complementary constraints to direct searches
- tau row in better shape than previously assumed in the literature
  $\Rightarrow$ in the future the tau row can be measured potentially as well as the muon row!

Tau neutrino physics

- New unitarity constraints is just one application of tau neutrino data
- Future of tau neutrinos is bright: Many new experiments sensitive to tau neutrinos are coming up at different energy scales
- Improvements in understanding of tau neutrino phyiscs
- → better constraints on tau sector
- Brought community together in Tau neutrino workshop and whitepaper
-

Thanks!