

# Beyond the 3-flavour paradigm

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21st Conference on Flavor Physics  
and CP Violation 2023

31. May 2023



# Neutrinos

Observation of neutrino oscillations

⇒ neutrino masses ⇒ need for physics **beyond the SM**

**New** phenomenology (at least 7 new parameters to measure):  
**Fully explore** 3 flavor paradigm with next generation experiments!

See talks in previous session



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# Neutrinos

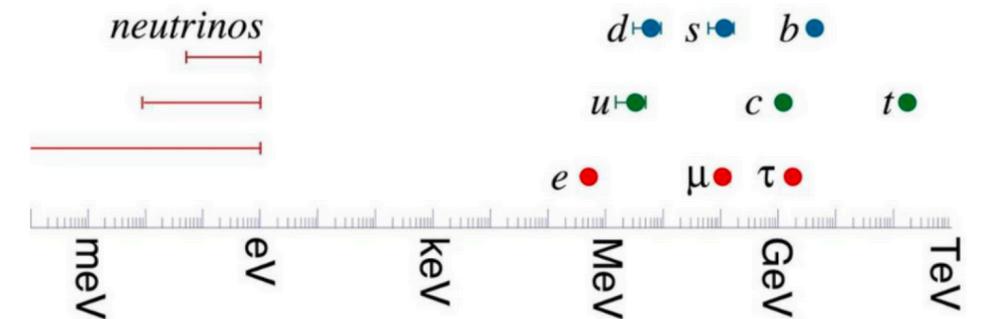
Observation of neutrino oscillations

⇒ neutrino masses ⇒ need for physics beyond the SM

Easy way to generate neutrino masses & explain their lightness

With dimension 5 operator

$$\mathcal{O}_W = \frac{(\bar{L}_L H)(\tilde{H} L)}{\Lambda}$$



Consider SM as EFT → expect **first new physics signals** to come from lowest dimension operators

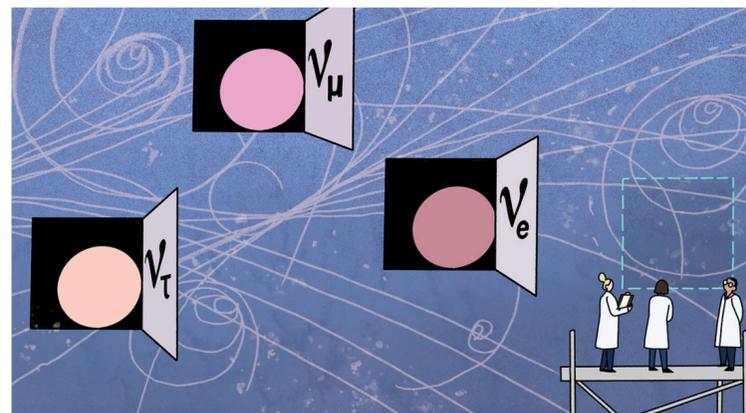
( $\mathcal{O}_W$  only dim-5 operator possible with SM fields only!)

# Neutrinos

Neutrinos as **first messengers** of new physics?

Use neutrinos as **portal** to BSM!

- What are the new physics scenarios we can explore with neutrinos?
- What do we already know about new physics in the neutrino sector?
- Any hints for new physics?



# Neutrino portal

Add fermionic singlet  $N_R$  to SM

Only possible coupling to SM

$$\mathcal{L}_N = y_N \bar{L}_L \tilde{H} N_R$$

After EWSB: active-sterile mixing  $\theta = y v_H / m_{N_R}$

Neutrino sector **ideal** way to test presence of extra fermion singlet!

$N_R$ : Sterile neutrino/right-handed neutrino/heavy neutral lepton

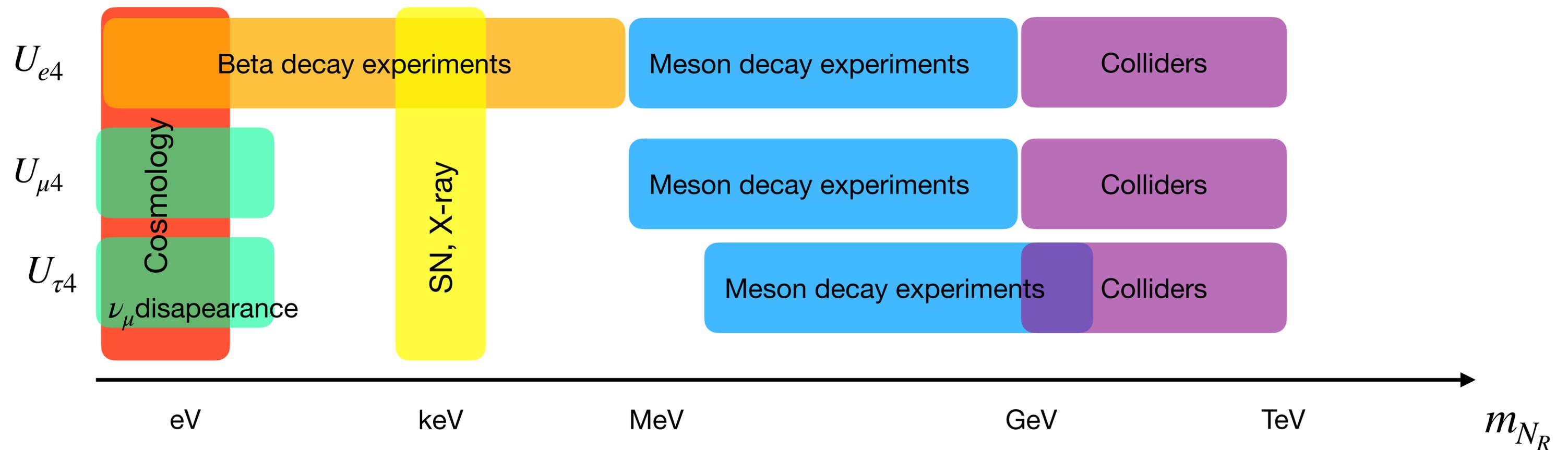
Phenomenology depends on sterile neutrino mass scale

# Testing the neutrino portal

## Phenomenology at direct search experiments

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

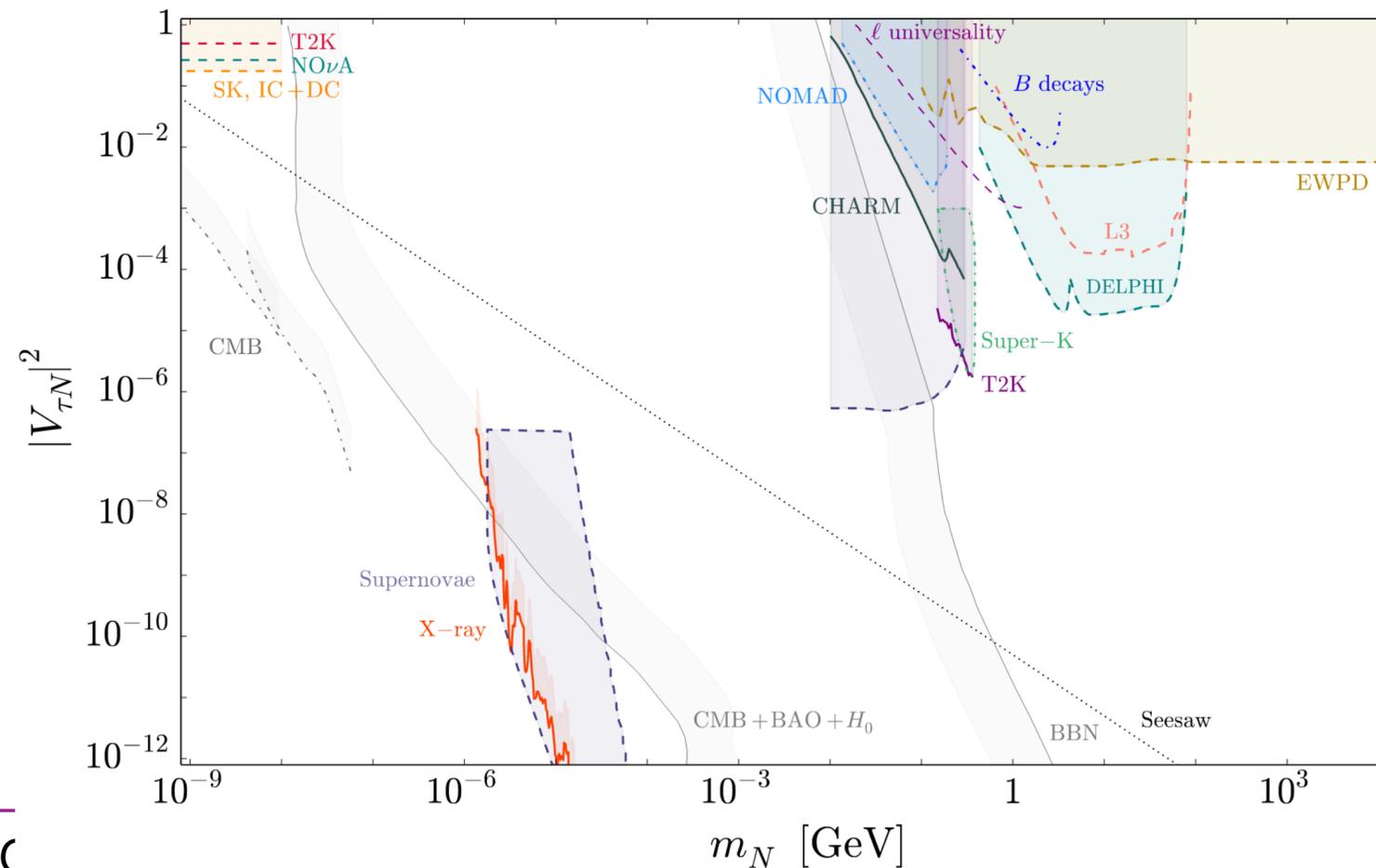
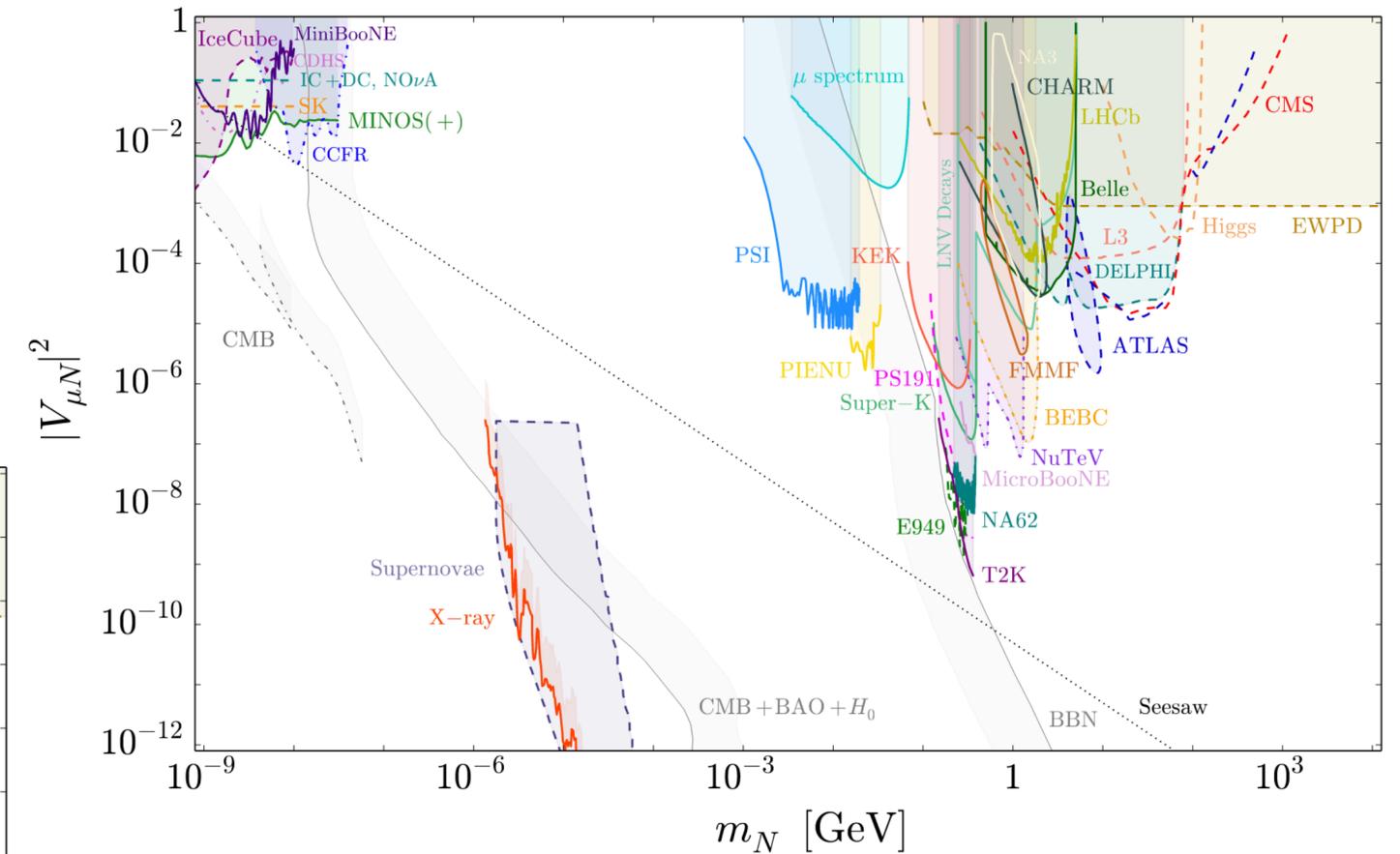
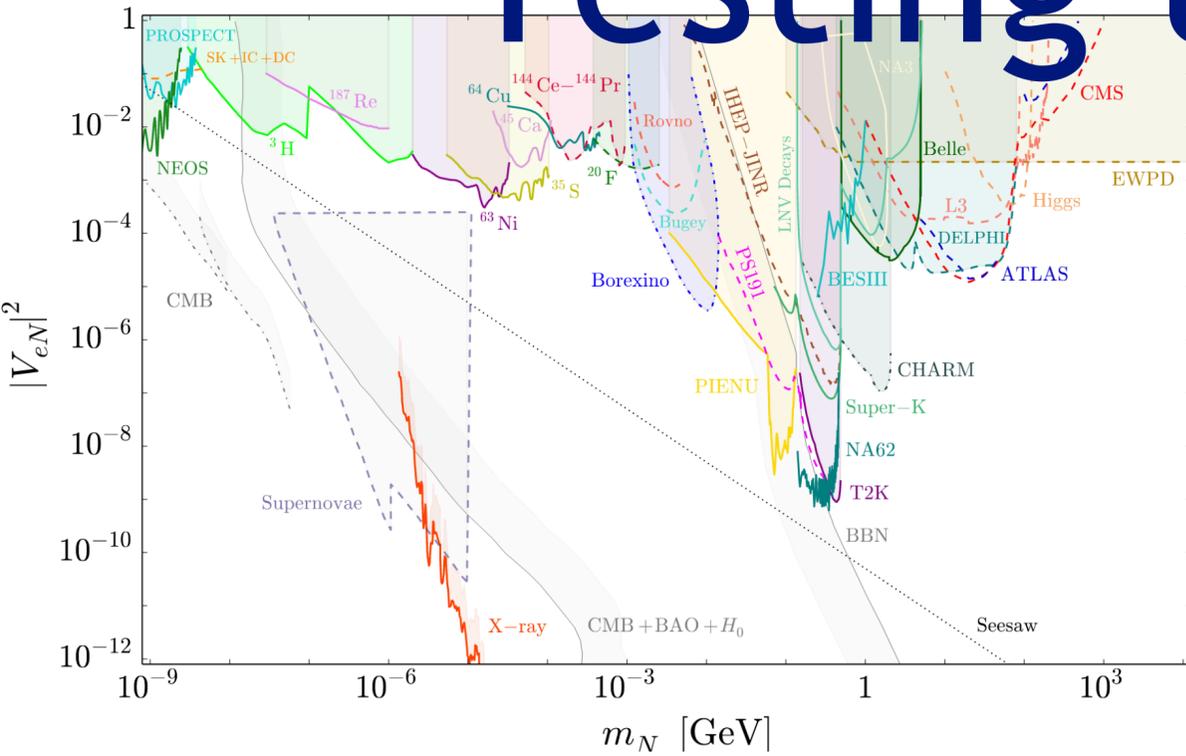
- Need to be kinematically producible
- detected via decay productions in detector



# Testing the neutrino portal

## Constraints from direct searches

Bolton, Deppisch, Dev '19

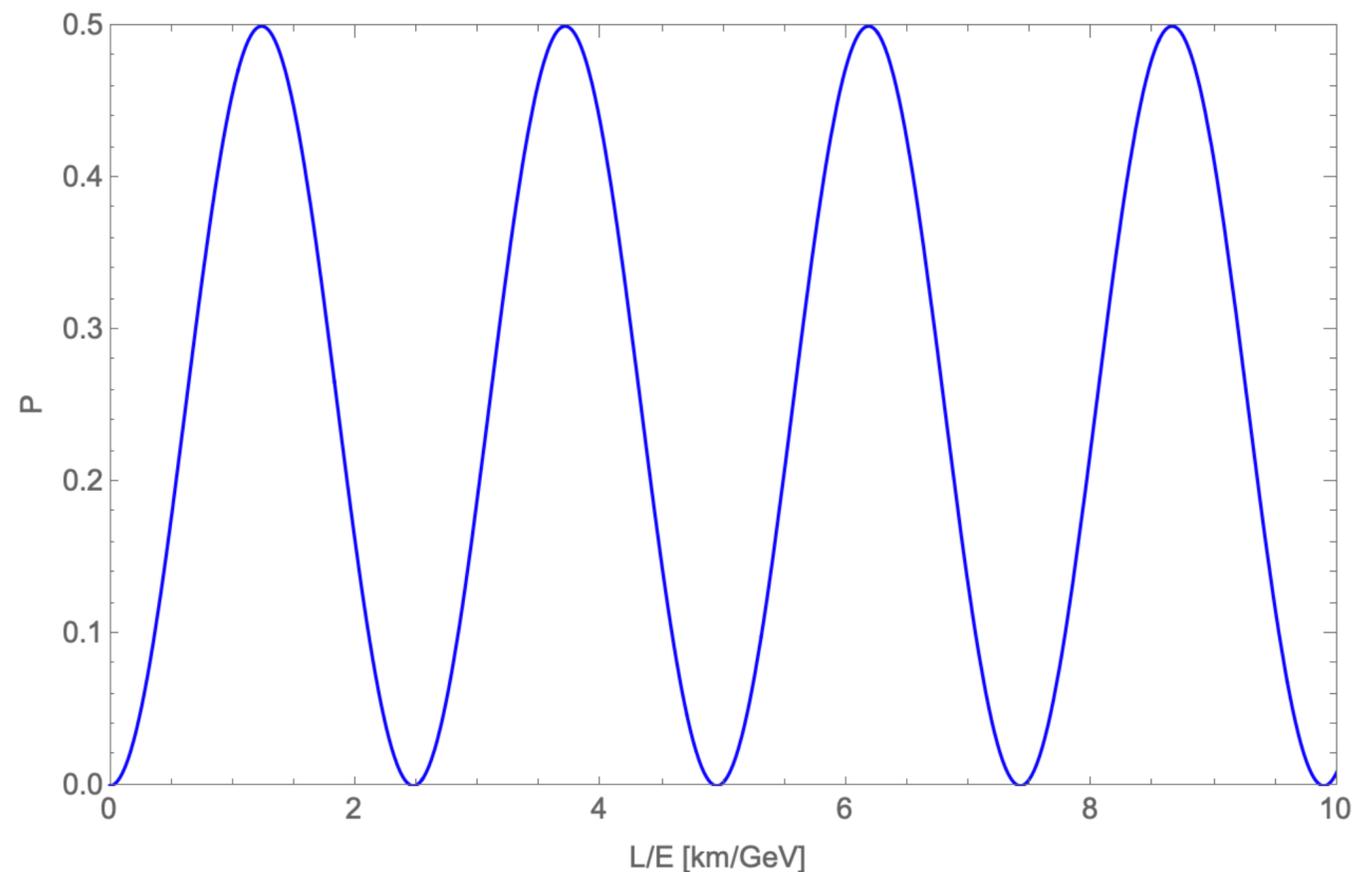


# Testing the neutrino portal

Oscillation phenomenology of  $N_R$  depends on its mass scale:

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

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

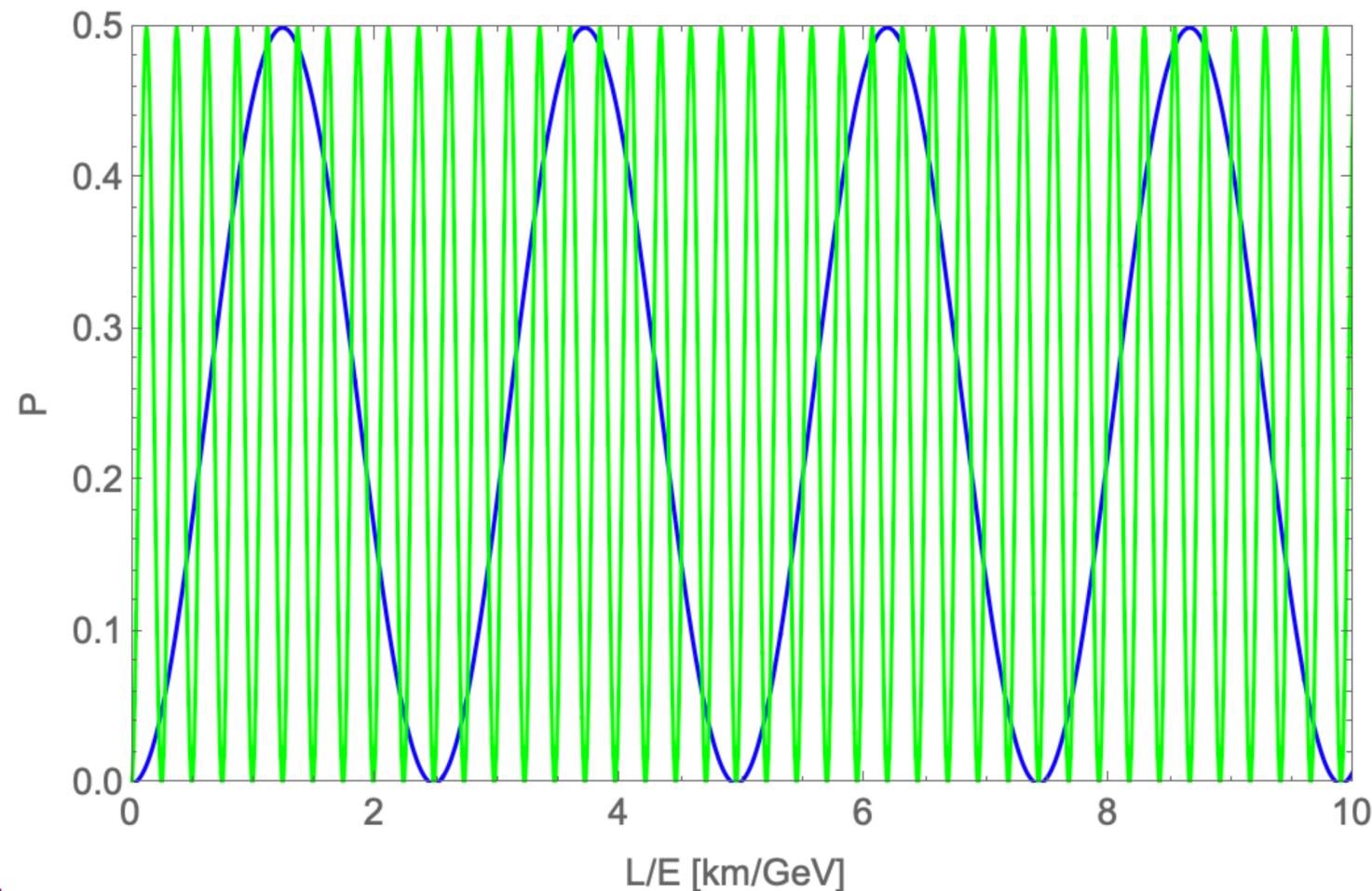


Constraints depend  
on mass scale

# Testing the neutrino portal

Oscillation phenomenology of  $N_R$  depends on its mass scale:

- $N_R$  light ( $m_{N_R} \sim \mathcal{O}(1 \text{ eV})$ )  $\rightarrow$  direct sensitivity at oscillation experiments
- $N_R$  heavier ( $m_{N_R} \in [10 \text{ eV}, 15 \text{ MeV}]$ )  $\rightarrow$  sensitivity at oscillation experiments in averaged out regime  $\Delta m_{41}^2 L / (4E) \gg 1$

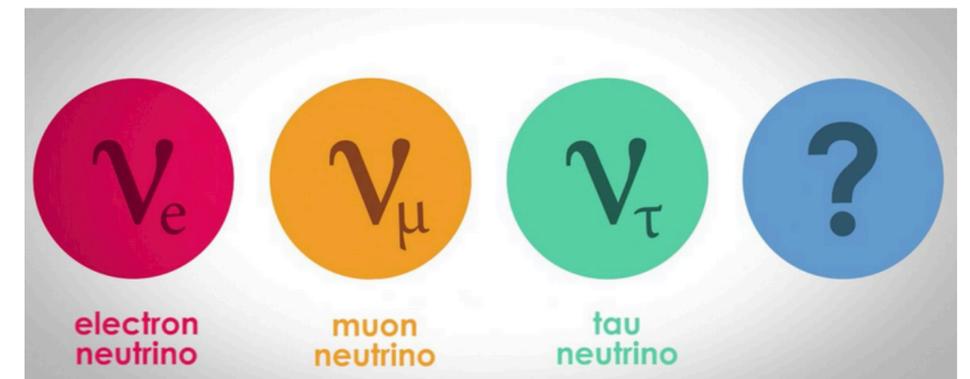


$$\Delta m_{41}^2 = 1 \text{ eV}^2$$

$$\Delta m_{41}^2 = 10 \text{ eV}^2$$

Constraints are insensitive to mass scale

Depends on E, L/E of experiment!

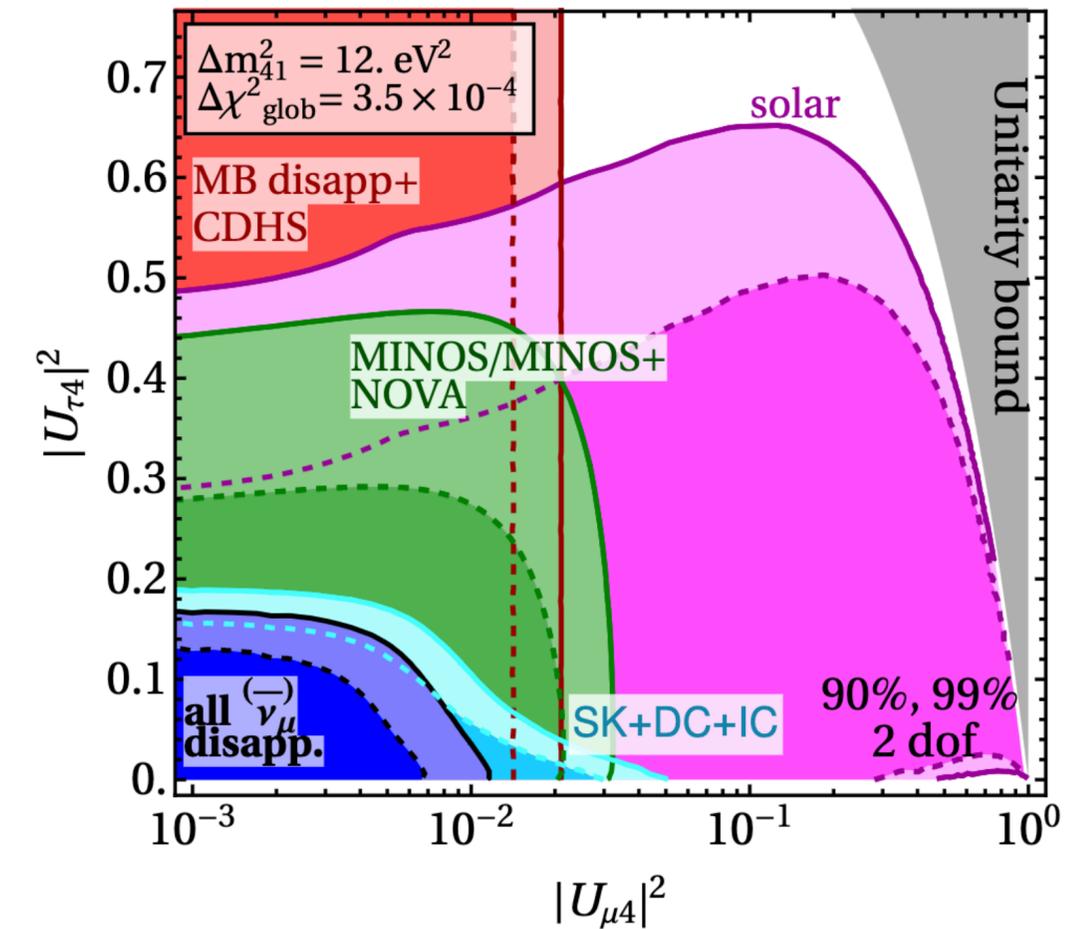
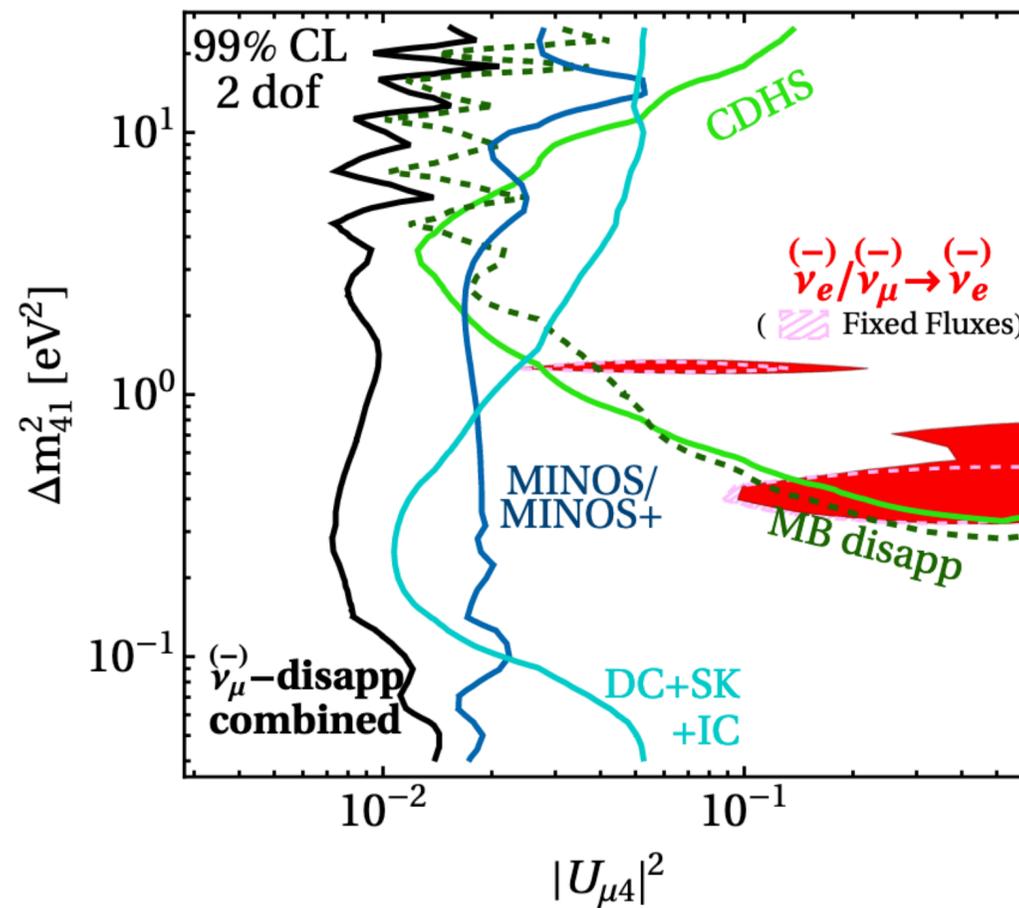
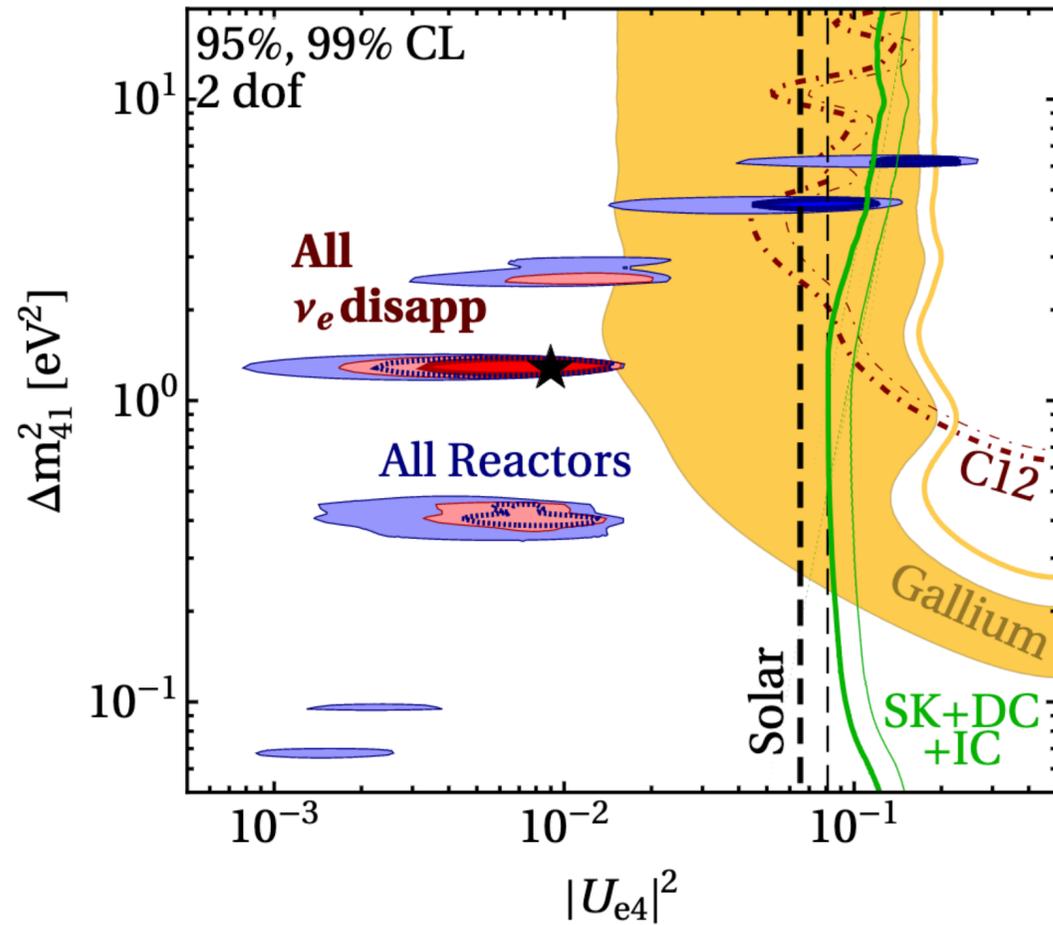


# Testing the neutrino portal

## Constraints from oscillation searches

[Dentler et al, [1803.10661](#)]

Light steriles ( $m < 10$  eV)



# Testing the neutrino portal

Oscillation phenomenology of  $N_R$  depends on its mass scale:

- $N_R$  light ( $m_{N_R} \sim \mathcal{O}(1 \text{ eV})$ )  $\rightarrow$  direct sensitivity at oscillation experiments
- $N_R$  heavier ( $m_{N_R} \in [10 \text{ eV}, 15 \text{ MeV}]$ )  $\rightarrow$  sensitivity at oscillation experiments in averaged out regime  $\Delta m_{41}^2 L / (4E) \gg 1$
- $N_R$  heavy ( $m_{N_R} \gtrsim 40 \text{ MeV}$ )  $\rightarrow$  too heavy to be produced in oscillation experiments

Impact on **unitarity** of PMNS matrix:

Measurable, active-light 3x3 mixing matrix is **not unitary**  
but full mixing matrix including sterile states is unitary

**Depends on E of experiment!**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \\ \vdots \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} & \cdots \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} & \cdots \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & \cdots \\ \cdots & \cdots & \cdots & \cdots & \ddots \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \vdots \end{pmatrix}$$

**Constraints are insensitive to mass scale**

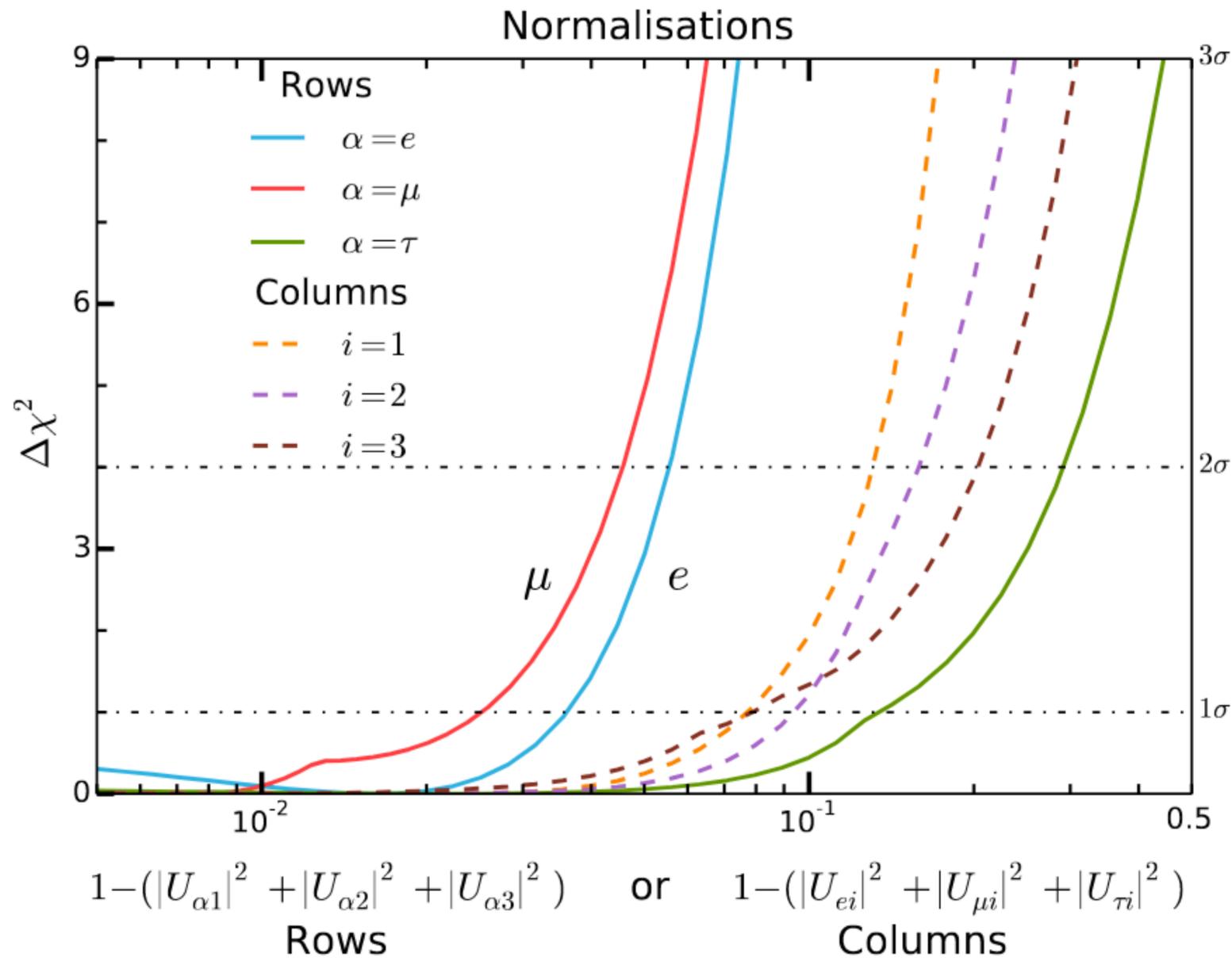
# Testing the neutrino portal

## Results for non-unitarity of mixing matrix

See also [Hu, Ling, Tang, Wang '20](#)

From [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

More data present,  
needs to be included in global studies!

[Denton, [JG](#), [2109.14575](#)]

# New neutrino interactions

New neutrino interactions:  
neutrino non-standard interactions (NSI)

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda} \delta \mathcal{L}^{d=5} + \boxed{\frac{1}{\Lambda^2} \delta \mathcal{L}^{d=6}} + \dots$$

**CC NSI:** 
$$\mathcal{L}_{NSI}^{CC} = -2\sqrt{2}G_F \sum_{\alpha,\beta,f,f',P} \epsilon_{\alpha\beta}^{f,f'} (\bar{\nu}_\alpha P l_\beta) (\bar{f} P f')$$

**NC NSI:** 
$$\mathcal{L}_{NSI}^{NC} = -2\sqrt{2}G_F \sum_{\alpha,\beta,f,P} \epsilon_{\alpha\beta}^f (\bar{\nu}_\alpha P \nu_\beta) (\bar{f} P f)$$

Operators are only  
valid below weak scale!

# New neutrino interactions

**CC** NSI: 
$$\mathcal{L}_{NSI}^{CC} = -2\sqrt{2}G_F \sum_{\alpha,\beta,f,f',P} \epsilon_{\alpha\beta}^{f,f'} (\bar{\nu}_\alpha P l_\beta) (\bar{f} P f')$$
$$P : S, P, V, A, T$$

**NC** NSI: 
$$\mathcal{L}_{NSI}^{NC} = -2\sqrt{2}G_F \sum_{\alpha,\beta,f,P} \epsilon_{\alpha\beta}^f (\bar{\nu}_\alpha P \nu_\beta) (\bar{f} P f)$$

NSI parameter  $\epsilon$ : strength of new interaction  
relative to weak interaction  $\epsilon \sim \mathcal{O}(G_X/G_F)$

NSI can be flavor diagonal or off-diagonal  
Lots of new physics to explore!

# New neutrino interactions

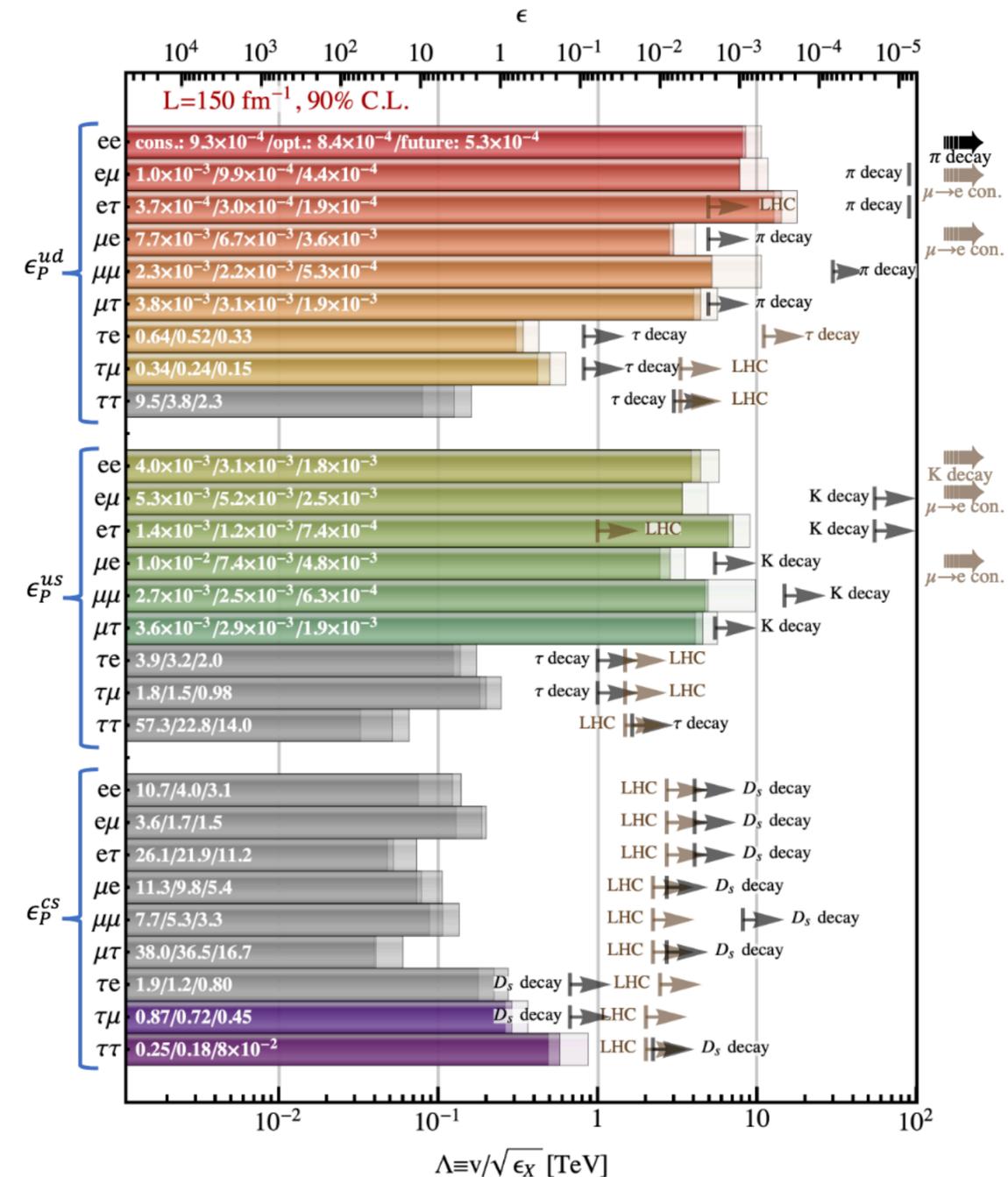
## Results CC NSI

[Falkowski, Gonzalez-Alonso, Kopp, Soreq, Tabrizi 2105.12136]

$$\mathcal{L}_{NSI}^{CC} = -2\sqrt{2}G_F \sum_{\alpha,\beta,f,f',P} \epsilon_{\alpha\beta}^{f,f',P} (\bar{\nu}_\alpha P l_\beta)(\bar{f} P f')$$

Strong constraints on **CC NSI**!

e.g.: constraints on pseudoscalar couplings



# New neutrino interactions

Example: vector NC NSI

[Wolfenstein '78]

New forward scattering with matter

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

Affect neutrino oscillations as a new matter effect

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

Matter potential  $a \propto G_F \rho E$

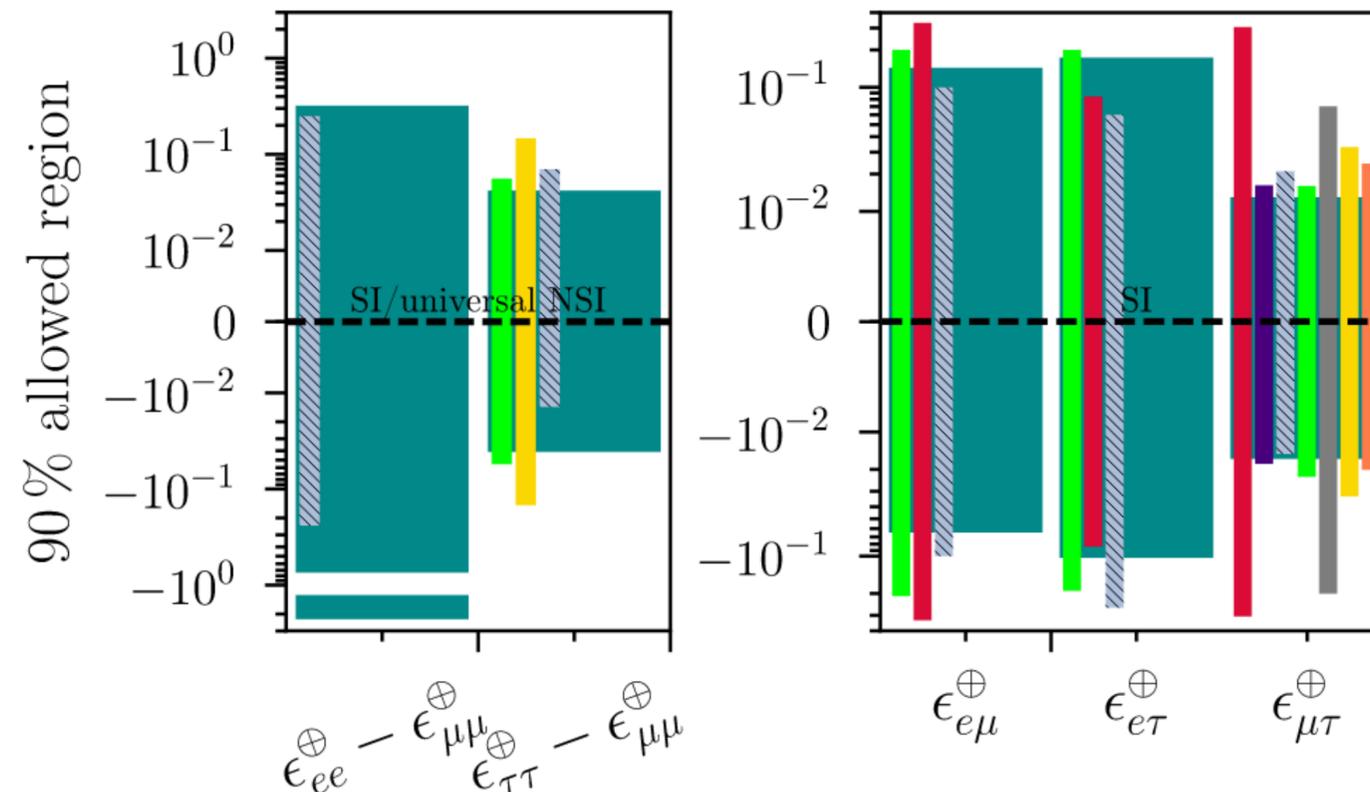
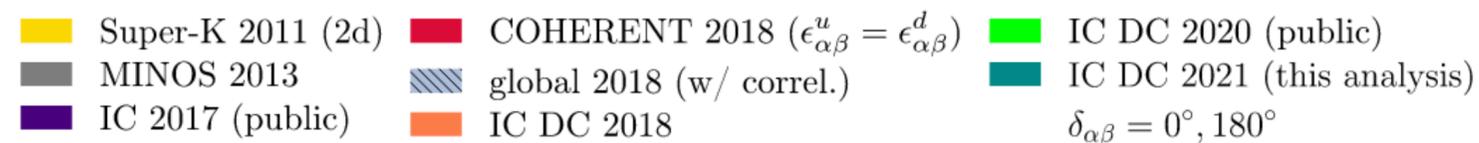
# New neutrino interactions

Effect of NSI in neutrino oscillations:

effect of NSI scales with **energy**, **baseline**, and **matter density**

⇒ use high-energy neutrino sources with long baselines

→ atmospheric neutrinos at IceCube



New couplings with size up to  $\mathcal{O}(10\%)G_F$  allowed!

Similar constraints from neutrino scattering experiments

[IceCube [2106.07755](#)]

# Any signs for new physics in neutrinos?

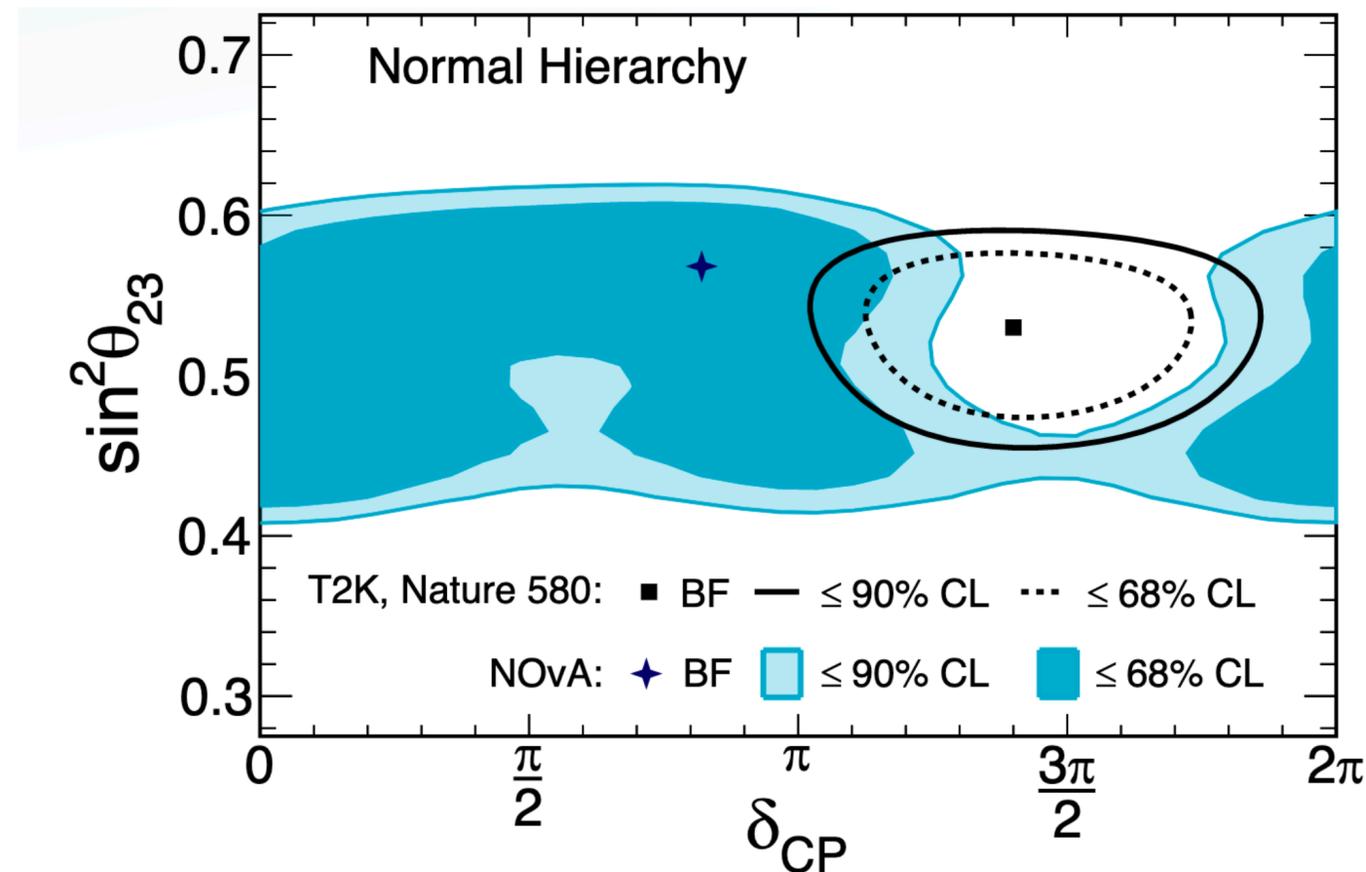
Many constraints on new physics scenarios!

However also **several** exciting anomalies

# Neutrino anomaly at long-baselines

## Current status of CPV in lepton sector

[Himmel '20]



NOvA, T2K experiments prefer NO

no strong preference for NOvA, generally around  $\delta \approx \pi$ ,

T2K prefers  $\delta \approx 3\pi/2$

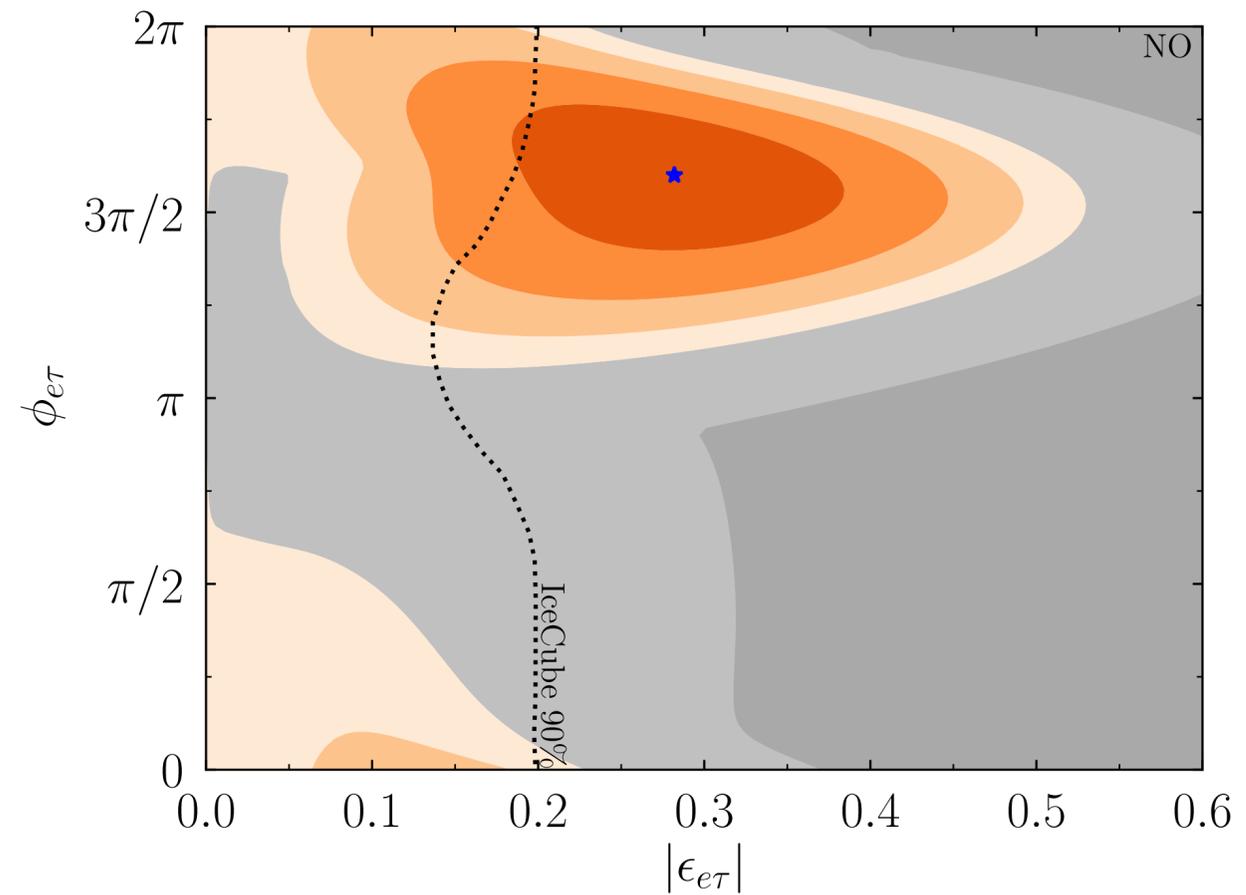
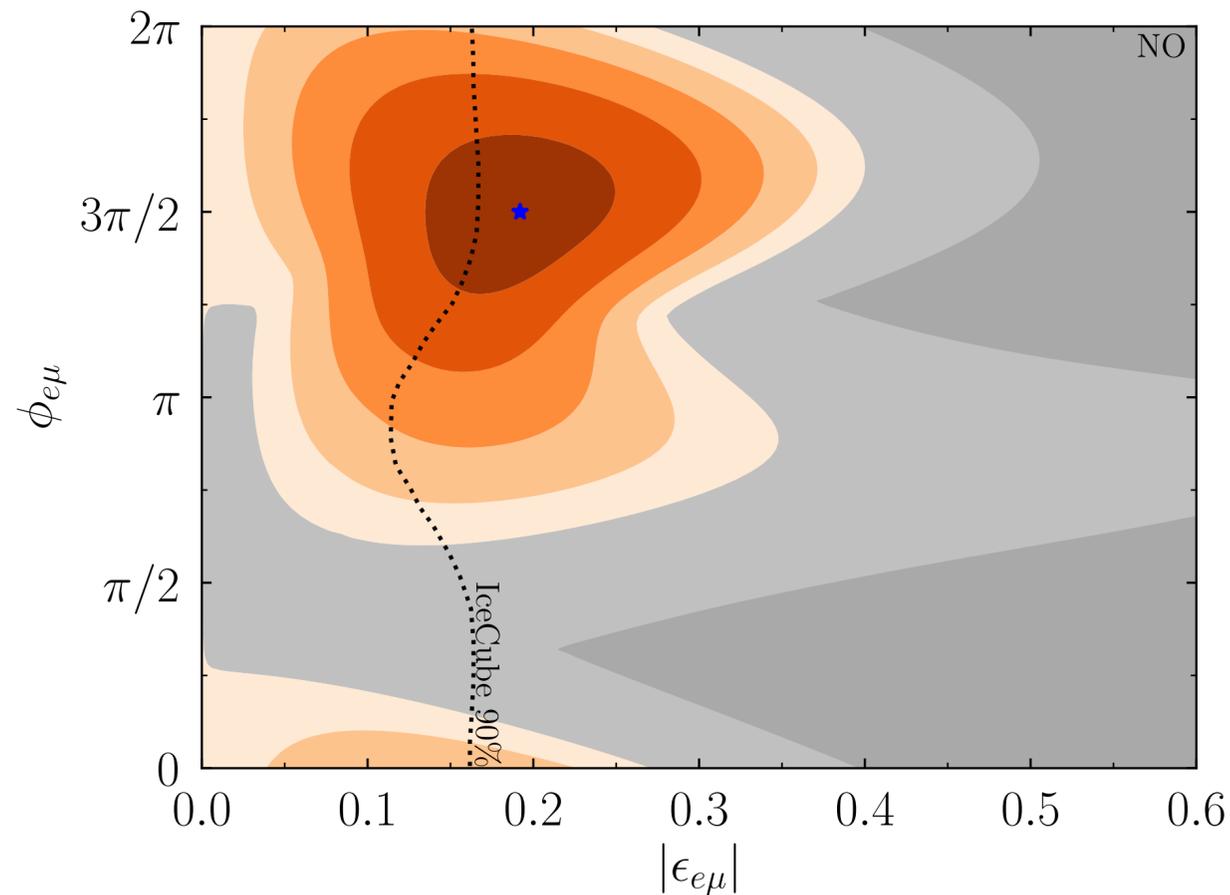
⇒ slight **disagreement!**

Neutrino 2022 update:  
similar results of T2K and NOvA using  
different statistical framework

# Neutrino anomaly at long-baselines

[Denton, JG, Pestes, 2008.01110,  
See also Chatterjee, Palazzo, 2008.04161]

Complex NSI with  $|\epsilon| \approx 0.2$ ,  $\phi \approx 3\pi/2$ ,  $\delta \approx 3\pi/2$ , NO can **fully resolve the tension**



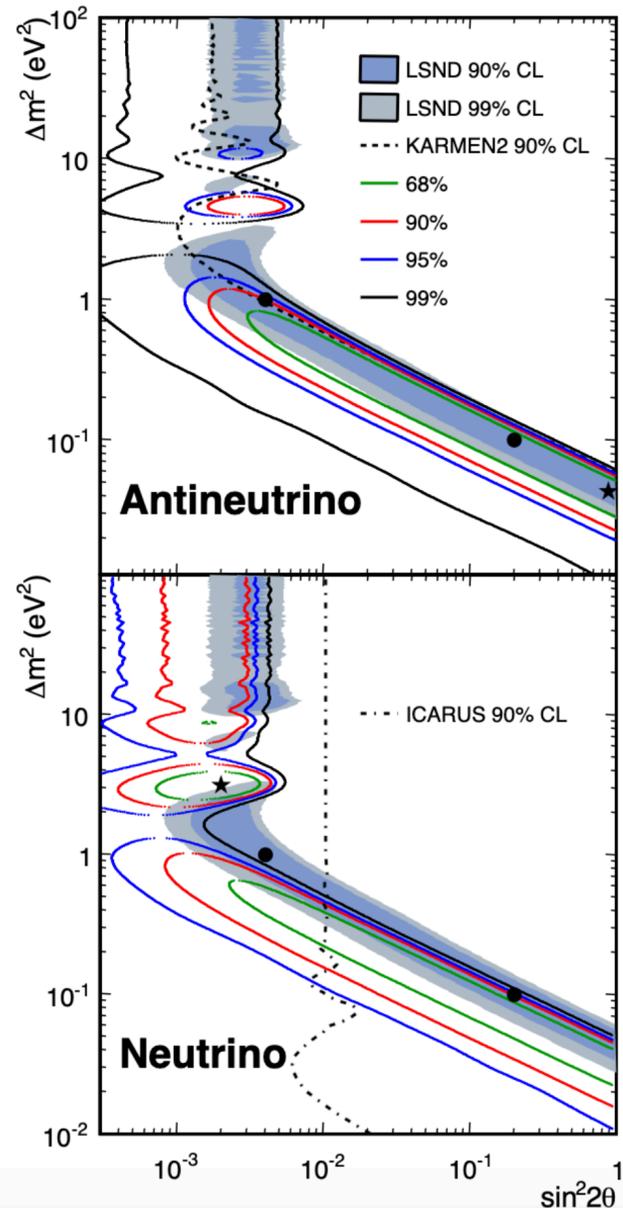
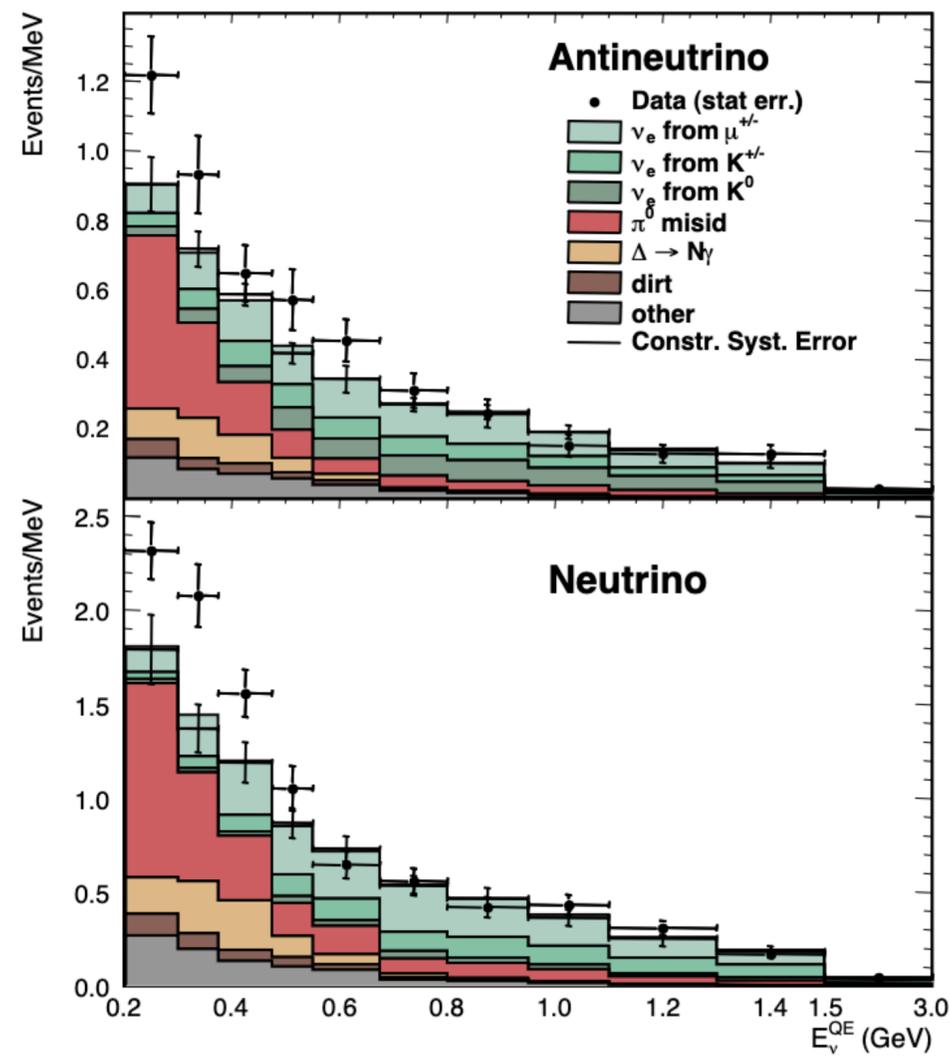
orange preferred over SM at integer values of  $\Delta\chi^2$ , dark gray disfavored at  $\Delta\chi^2 = 4.61$

Allowed region evades constraints from atmospheric neutrinos at IceCube and neutrino scattering experiments

# Neutrino anomaly at short baselines

MiniBooNE and LSND anomalies:  
Anomalous appearance of electron neutrinos from muon beam

[MiniBooNE, [1303.2588](#)]



Possible solution  
provided  
by **sterile neutrino**

But solution in **tension**  
with disappearance searches  
and cosmology!

# Neutrino anomaly at short baselines

MiniBooNE and LSND anomalies:  
Anomalous appearance of electron neutrinos from muon beam

[MiniBooNE, [1303.2588](#)]

Possible solution provided  
by **sterile neutrino** but tension  
with disappearance searches and  
cosmology!

But sign of anomalous electron  
neutrino appearance

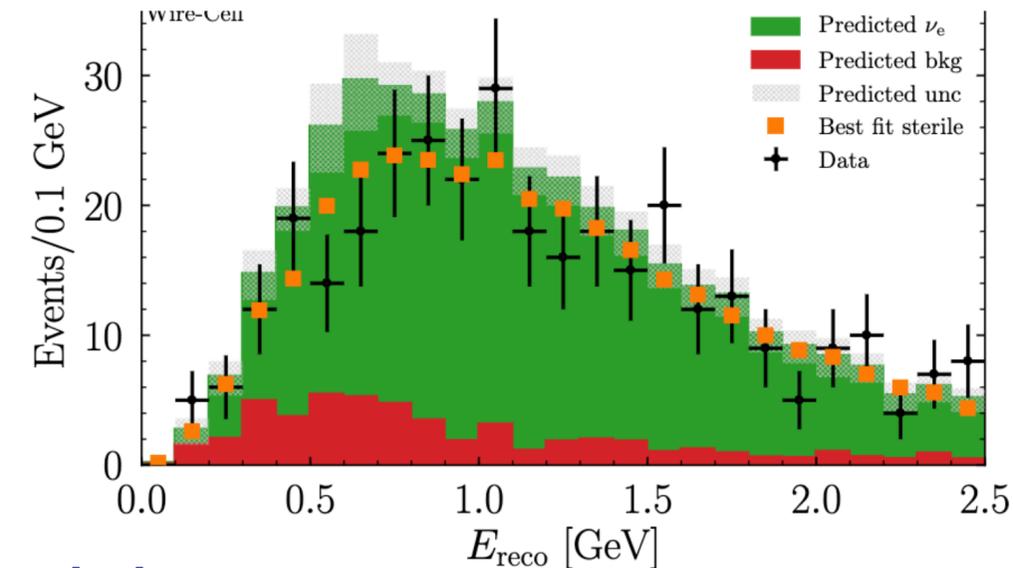
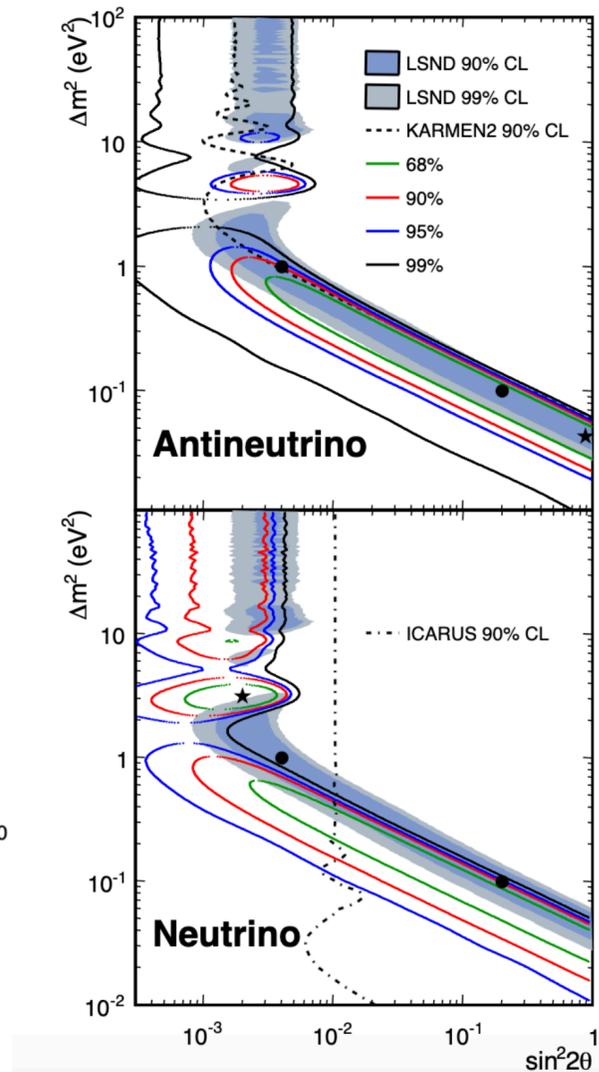
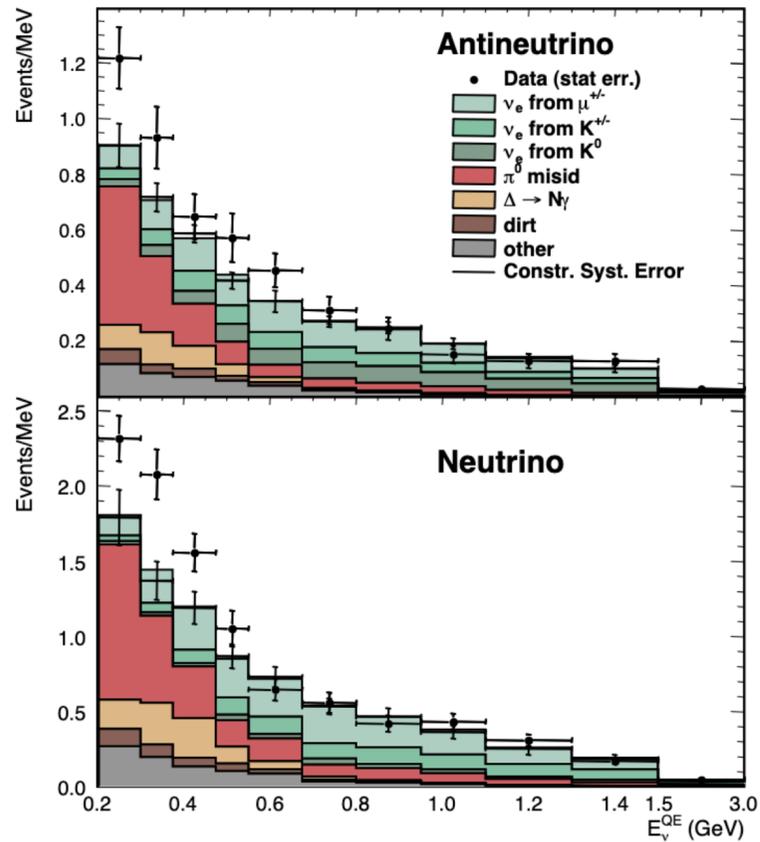
[Denton, [2111.05793](#)]

Anomalous appearance  
**not confirmed**  
by MicroBooNE!

[MicroBooNE, [2110.14054](#)]

See talk by M. Ross-Lonergan

Resolution of anomaly:  
Short baseline program at Fermilab

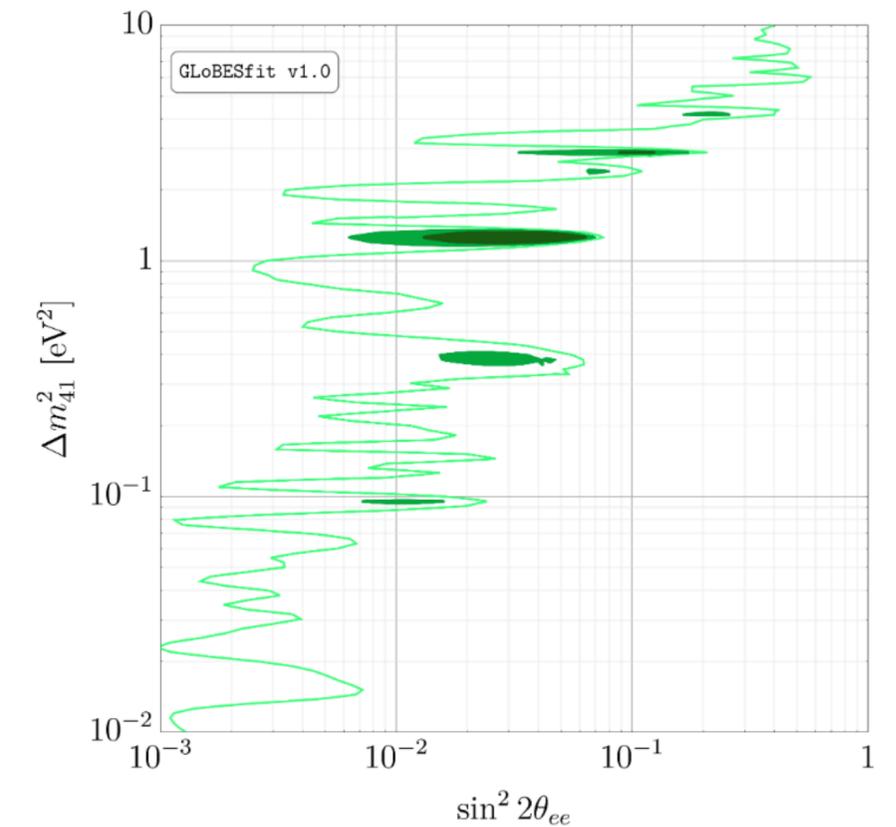
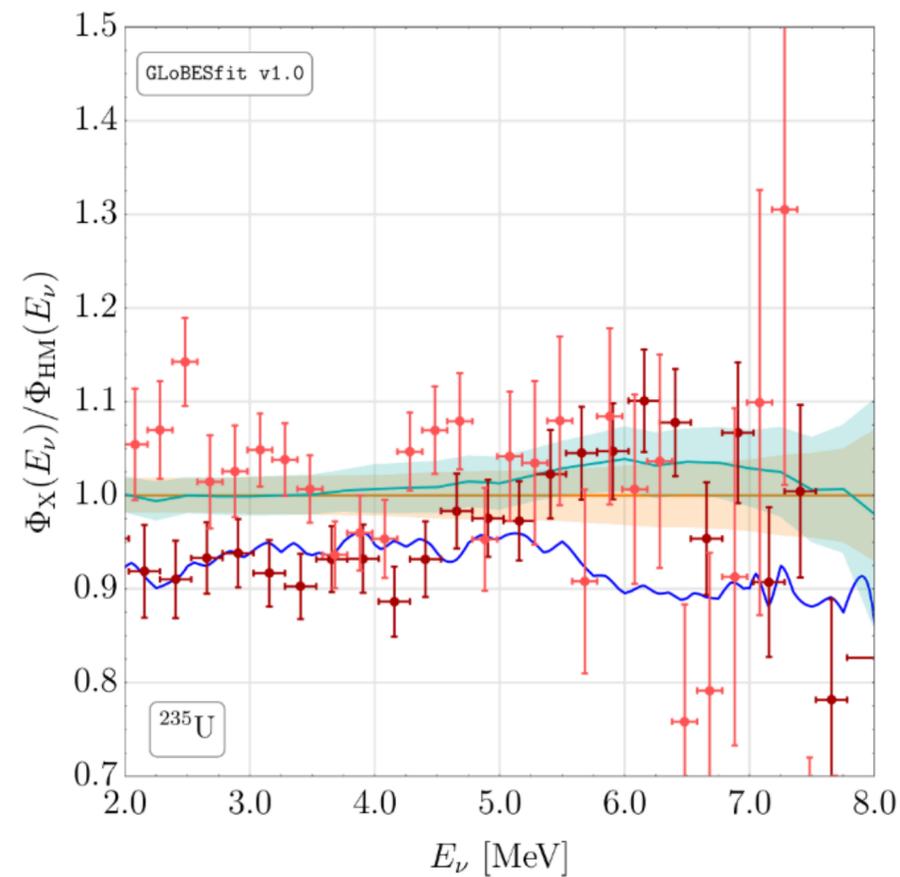
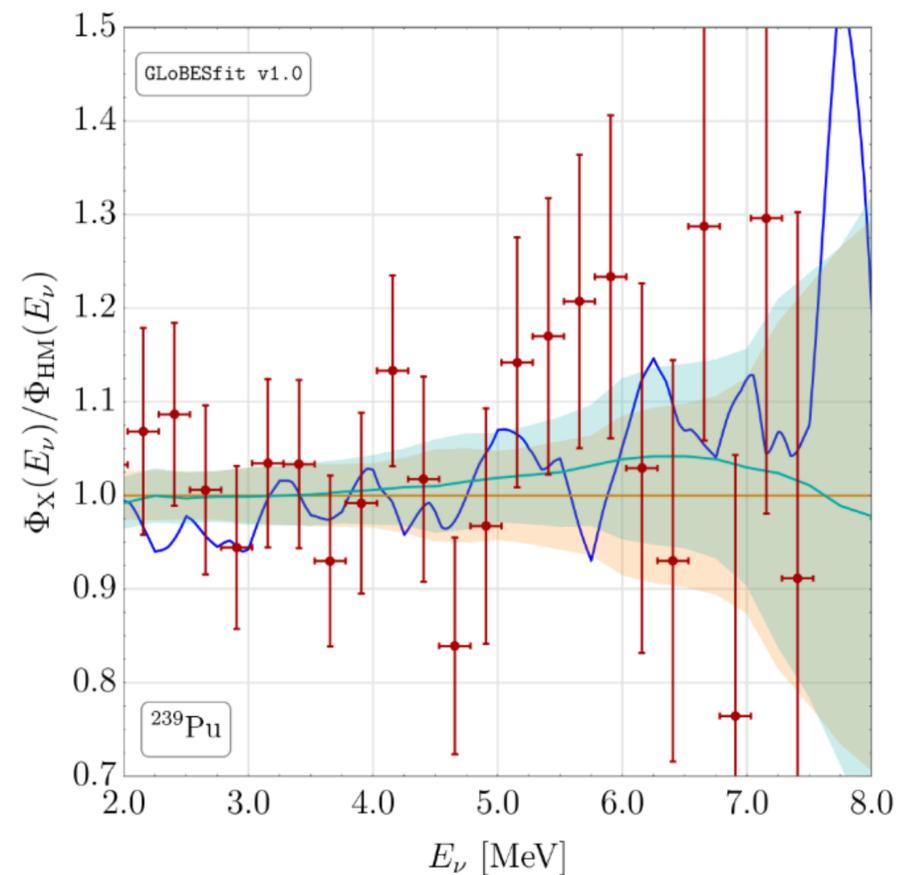


# Neutrino anomaly at short baselines

Measured reactor spectrum deviates from theoretical prediction

$\sim 3\sigma$  preference for **sterile neutrino**

[Berryman, Huber [2005.01756](#)]



**Anomaly**  
in total rate is  $< 2\sigma$   
[Giunti, Li, Ternes, Xin [2110.06820](#)]

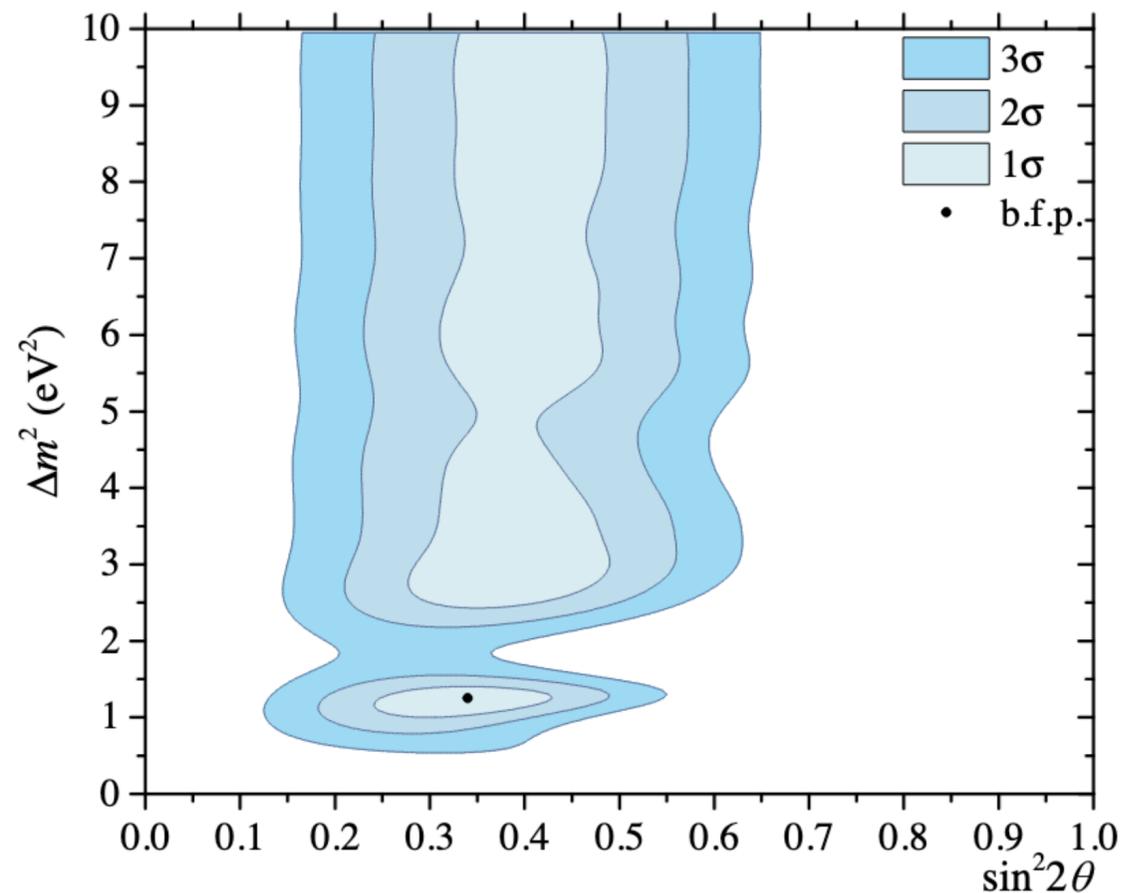
# Neutrino anomaly at short baselines

Use neutrinos from beta decays: Gallium experiments (GALLEX, SAGE, BEST)

Electron neutrinos from decay of radioactive source, captured after propagating  $\sim 1$  m

$\sim 20\%$  deficit with theoretical prediction of flux ( $> 5\sigma$ )

[BEST, [2201.0736](#)]



Possible solution provided by **sterile neutrino**

But region of parameter space **disfavoured** by solar data, cosmology

Nuclear physics resolution possible but unlikely, exotic new physics required

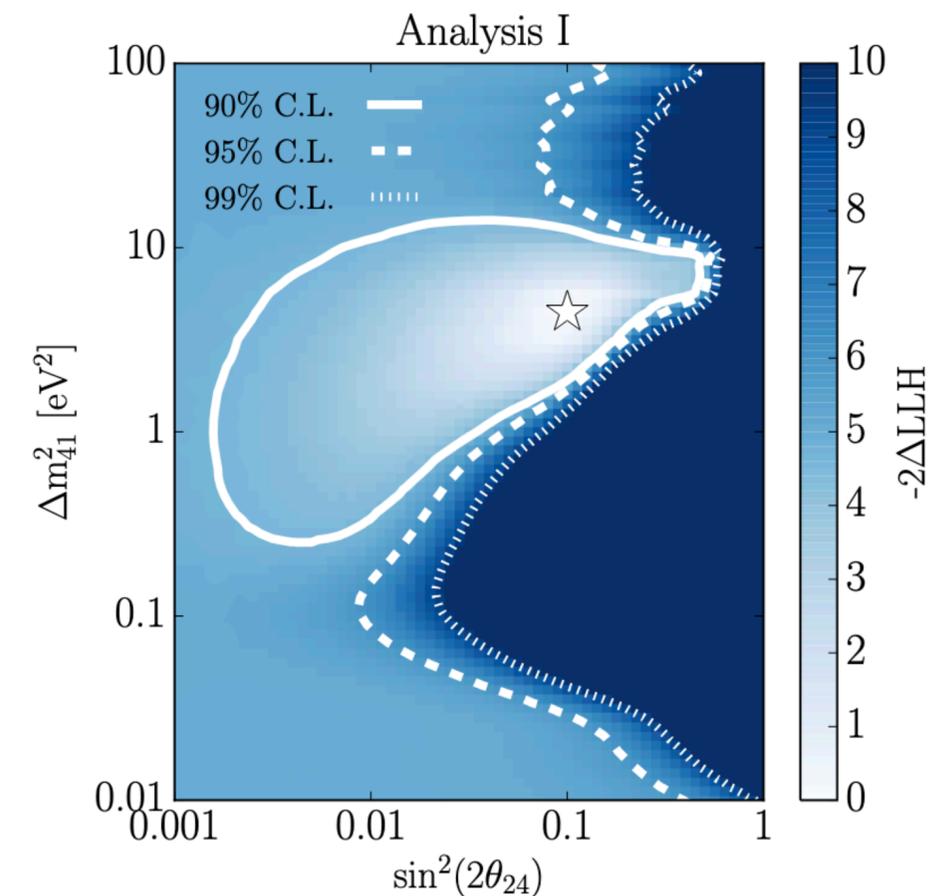
[Brdar, Kopp, [JG](#), [2303.05528](#)]

# Neutrino anomaly from upgoing atmospheric neutrinos

[IceCube, [2005.12943](#)]

Deficit of upgoing atmospheric muon neutrinos at IceCube

Hint for **sterile neutrino** at 90%CL!



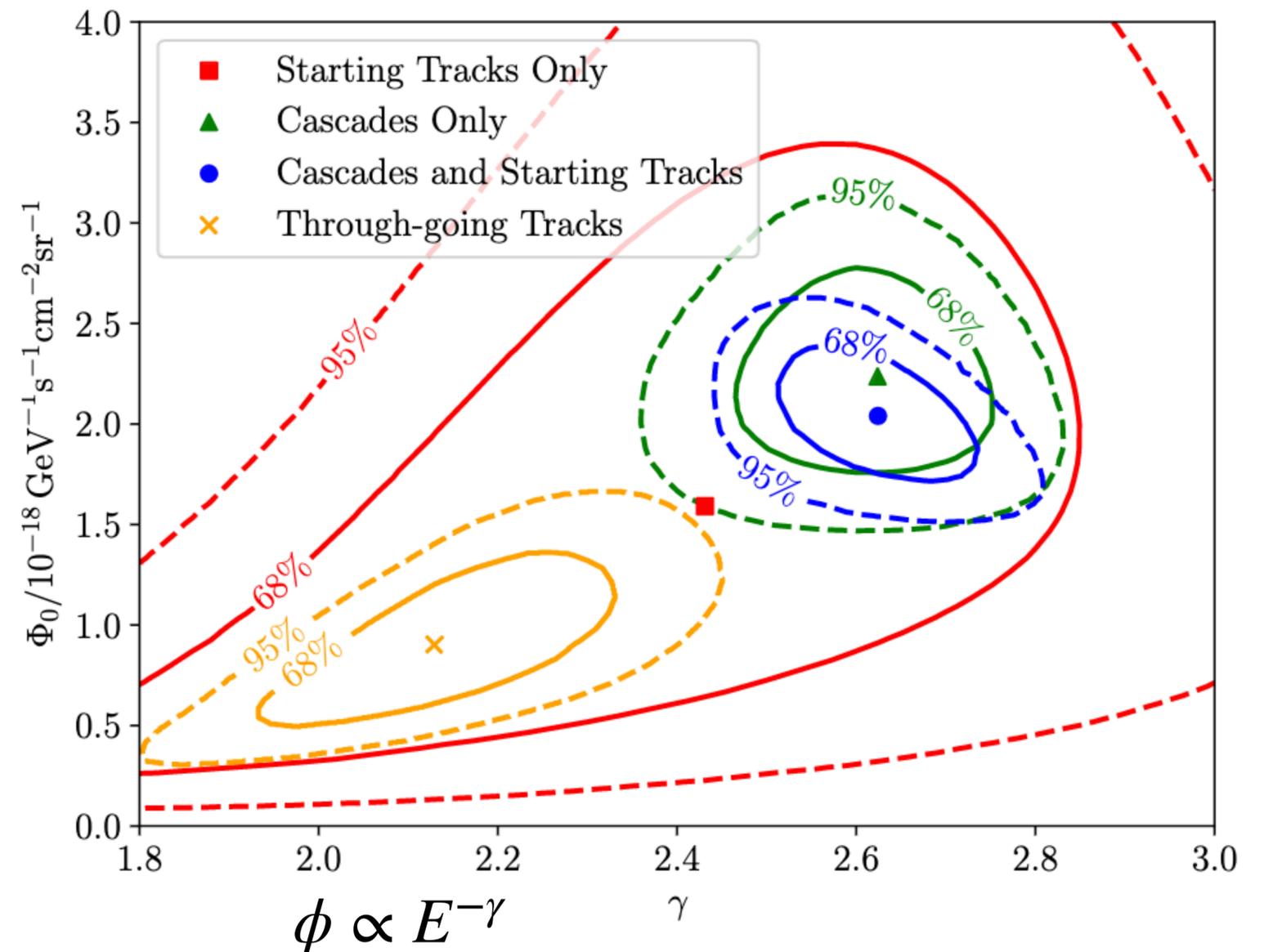
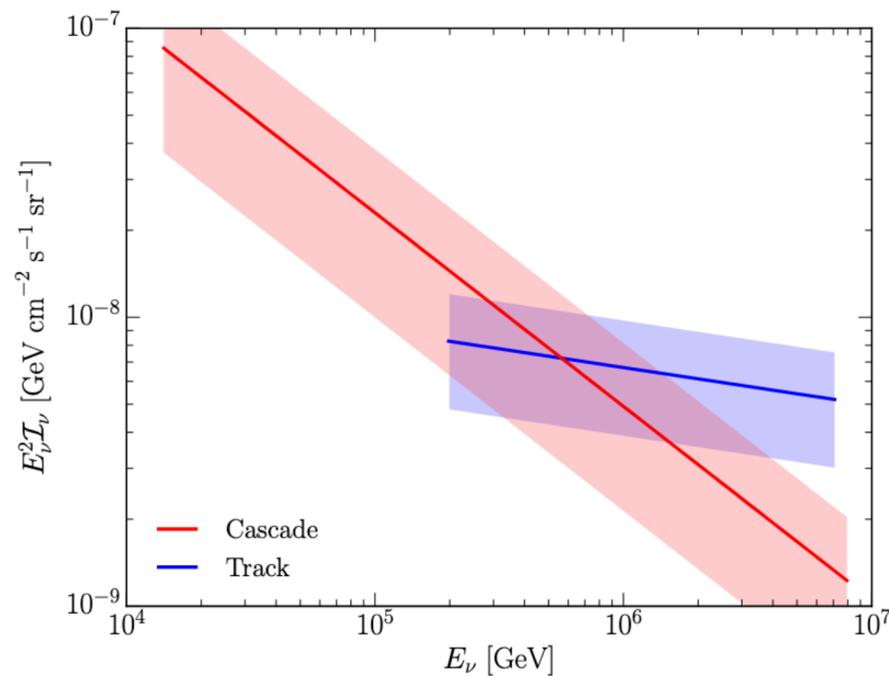
# Astrophysical neutrino anomaly

expect flavor ratio of 1:1:1 at Earth and single power law

[IceCube [1808.07629](#)]

Data shows  $> 3\sigma$  tension!

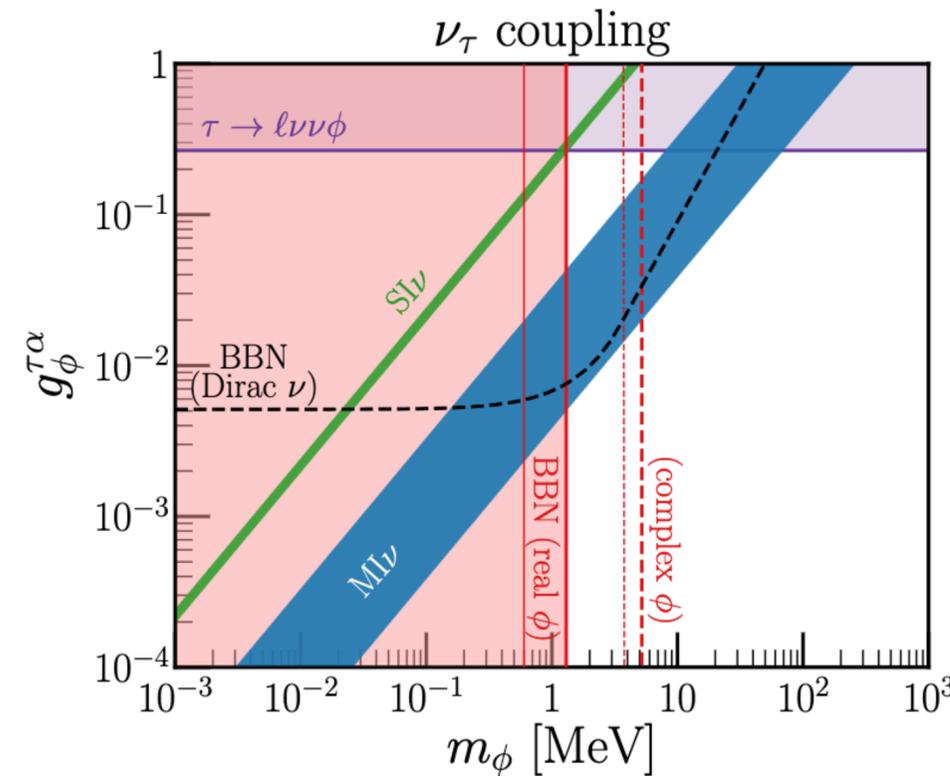
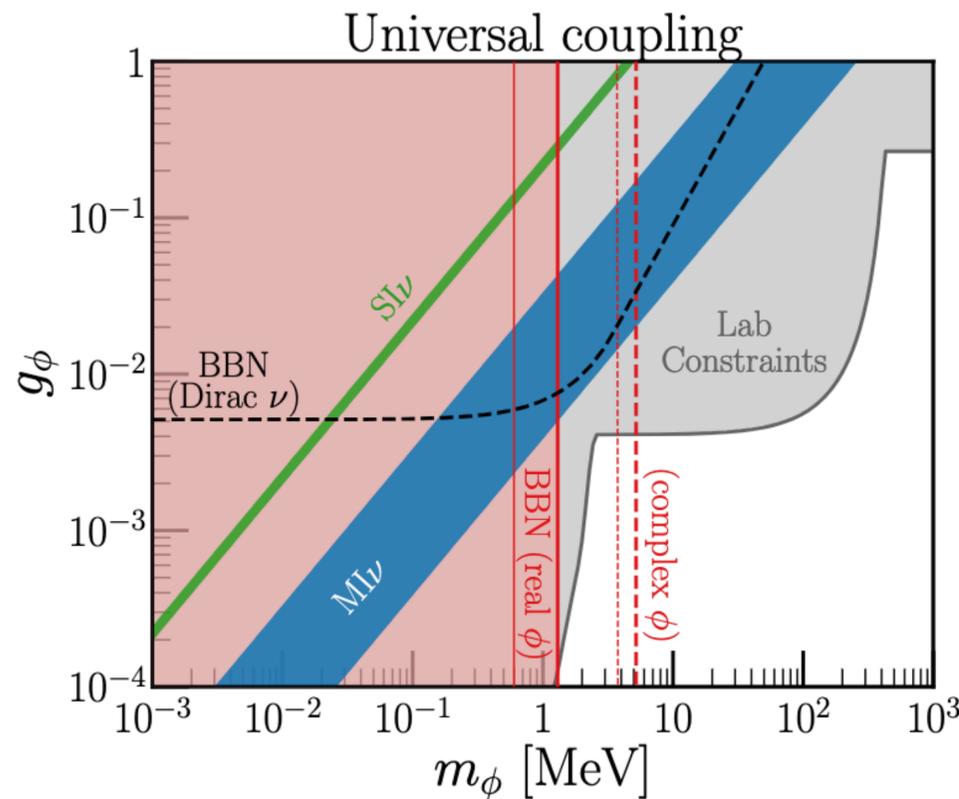
[Denton, Tamborra [1805.05950](#)]



# Neutrino anomaly in the early Universe

Hubble tension can be alleviated by new neutrino interactions to delay onset of neutrino free streaming

Example: neutrino self-interactions



[Blinov et al [1905.02727](#)]

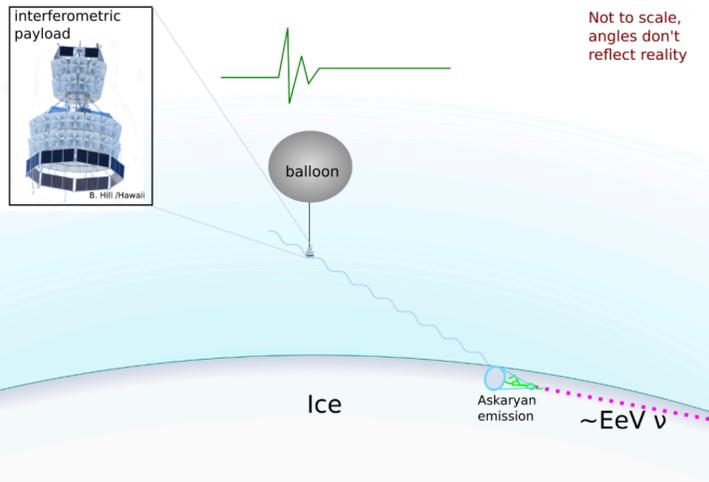
Meson decays exclude solution with universal or  $\nu_e, \nu_\mu$  coupling of new mediator

Hubble tension can be **alleviated** with MeV mediator coupling to  $\nu_\tau$  only

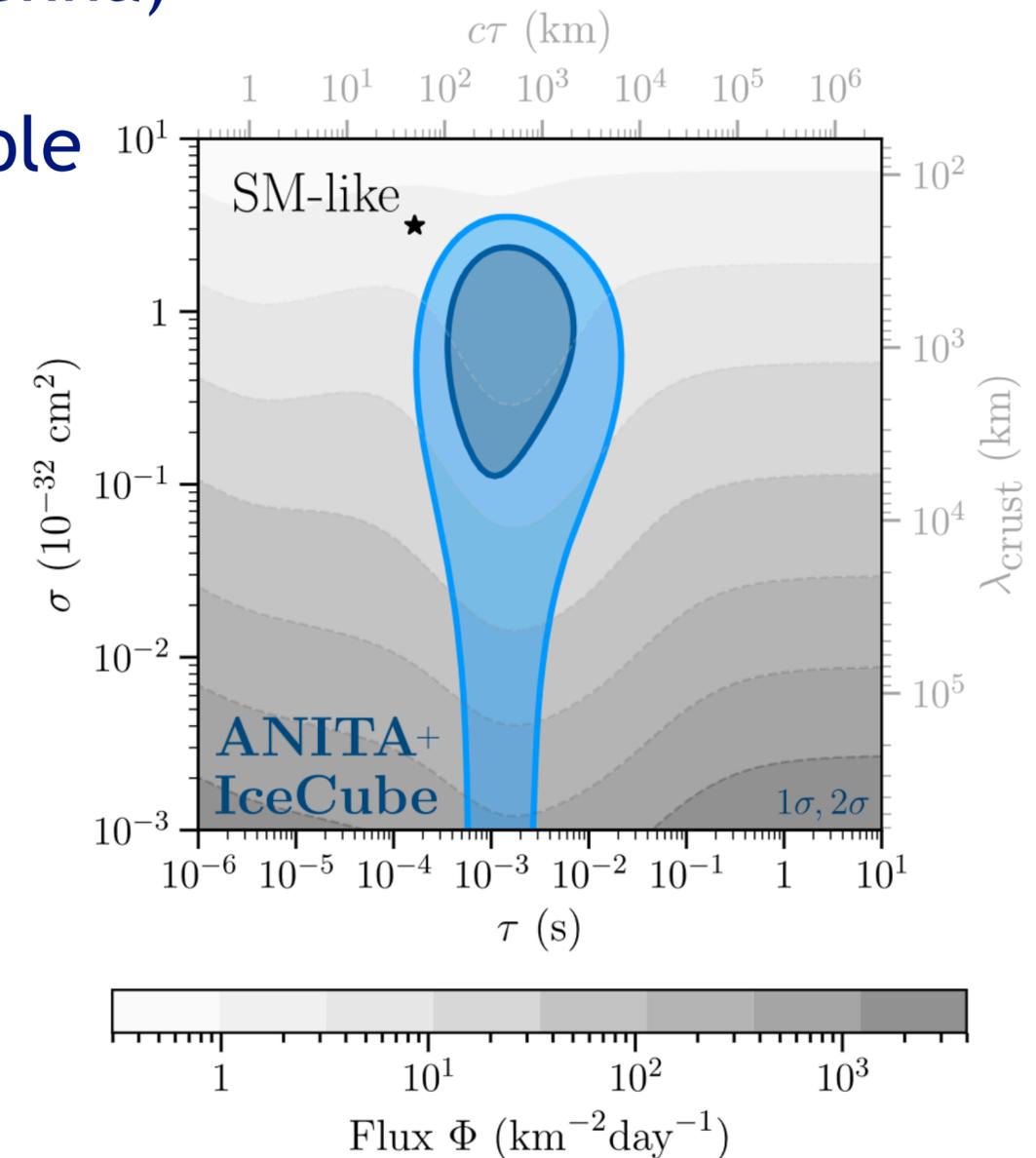
# UHE neutrino anomaly

Ultra high energy (EeV) neutrinos detection by ANITA  
(Antarctic Impulse Transient Antenna)

Ballon experiments @36km above South Pole  
4 flights (each ~30 days)



- Idea: detect UHE ( $E \sim 10^{18}$  eV) neutrinos via radio pulses from interactions in ice (Askaryan radiation) not observed  $\rightarrow$  limit on diffuse UHE  $\nu$  flux
- CR induced air showers reflecting off the ice observed
- ANITA saw 6 **anomalous events** (significance  $> 3\sigma$ ) cannot be explained by SM!



[Bertolez-Martinez, Arguelles, Esteban, Lopez-Pavon, Martinez-Solver, Salvado

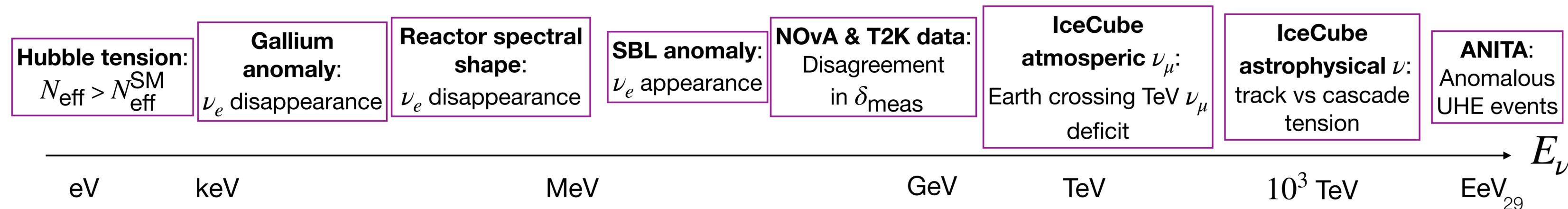
# Conclusions

Enter **precision era** for neutrino physics:  
fully test 3-flavour oscillations & test BSM  
in neutrino sector

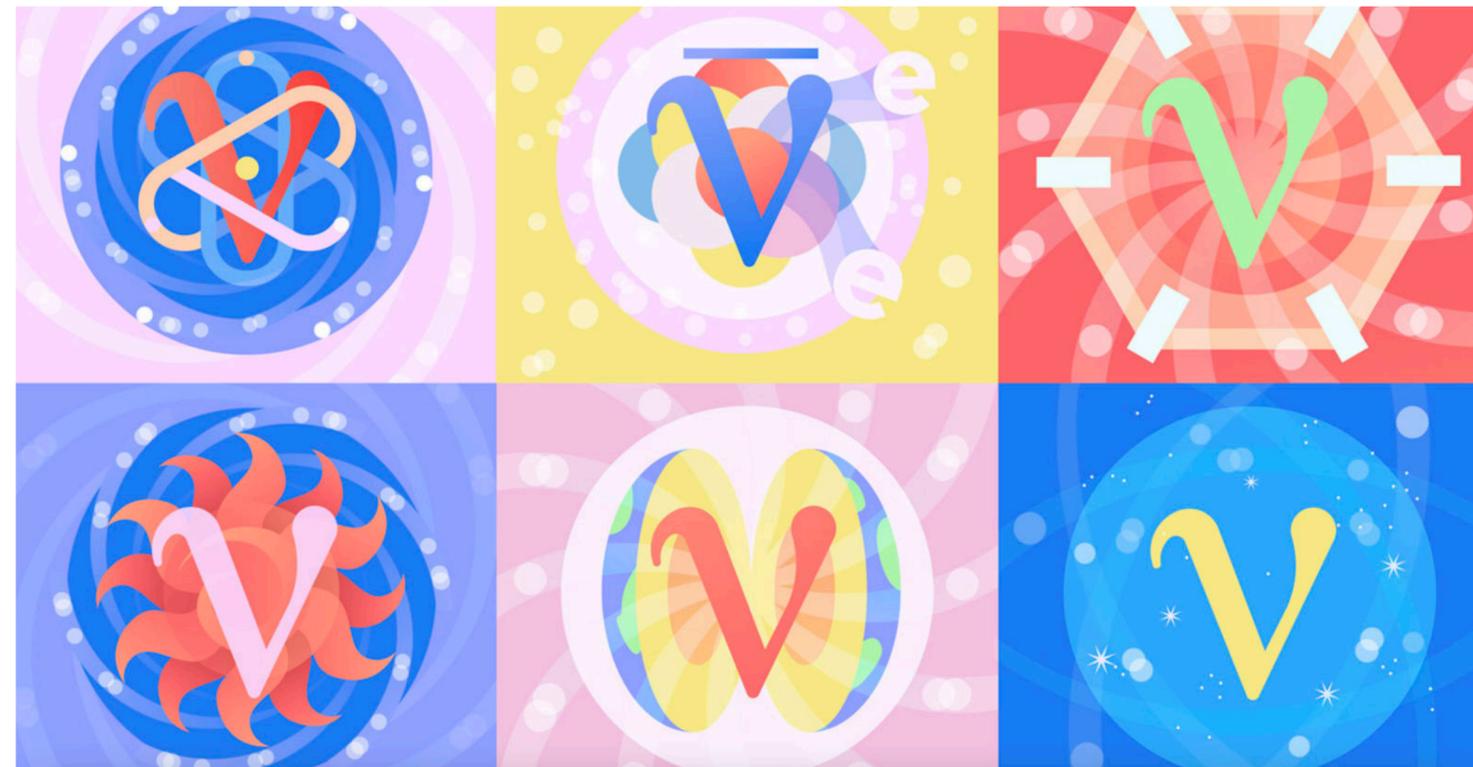
- Neutrinos provide **unique probe** of presence of additional fermion
- More theoretical work and model building needed **correctly** study and interpret NSI

Several neutrino anomalies → new physics could be **hiding** in neutrino sector

⇒ uncovered already **surprises** in neutrino sector, maybe more to come..



# Thanks for your attention!



# Backup: Non-unitarity

[Denton, [JG](#), [2109.14575](#)]

## Overlooked data sets:

- Atmospheric  $\nu_\mu$  disappearance (DeepCore, SuperK, IceCube → IceCube, HyperK, KM3NeT)
- Long baseline  $\nu_\tau$  appearance data (OPERA → DUNE)
- **new:**  $\nu_\tau$  CC scattering data from DOnuT → FASERnu
- **new:** Atmospheric  $\nu_\tau$  appearance (IceCube, SuperK → IceCube, HyperK, KM3NeT)
- **new:** Astrophysical  $\nu_\tau$  appearance (IceCube → IceCube-Gen2)
- **new:** NC data from SNO
- **new:** NC data from CEvNS → more CEvNS data

# Appendix: NSI models

## NSI models

general idea to allow for sizable NSI: constraining the direct coupling of the NSI mediator to the heavier generations or to sterile neutrinos that mix with the active ones

- D. V. Forero and W.-C. Huang, JHEP 03, 018 (2017), arXiv:1608.04719 [hep-ph].
- P. B. Denton, Y. Farzan, and I. M. Shoemaker, Phys. Rev. D 99, 035003 (2019), arXiv:1811.01310 [hep-ph].
- U. K. Dey, N. Nath, and S. Sadhukhan, Phys. Rev. D 98, 055004 (2018), arXiv:1804.05808 [hep-ph].
- K. Babu, A. Friedland, P. Machado, and I. Mocioiu, JHEP 12, 096 (2017), arXiv:1705.01822 [hep-ph].
- Y. Farzan and J. Heeck, Phys. Rev. D 94, 053010 (2016), arXiv:1607.07616 [hep-ph].
- Y. Farzan and I. M. Shoemaker, JHEP 07, 033 (2016), arXiv:1512.09147 [hep-ph].
- Y. Farzan, Phys. Lett. B 748, 311 (2015), arXiv:1505.06906 [hep-ph].
- K. Babu, P. B. Dev, S. Jana, and A. Thapa, JHEP 03, 006 (2020), arXiv:1907.09498 [hep-ph].

# Backup: LMA-D degeneracy

- **LMA-D degeneracy**: Neutrino oscillations exhibit a degeneracy in the presence of NSI which makes it impossible to determine the neutrino mass ordering  
If  $\epsilon_{ee} = -2$ , all other NSI parameters zero

$$P_{\alpha\beta}(\text{NO}, L, E, \rho, \epsilon = 0) = P_{\alpha\beta}(\text{IO}, L, E, \rho, \epsilon = -2)$$

$$P_{\alpha\beta}(\text{IO}, L, E, \rho, \epsilon = 0) = P_{\alpha\beta}(\text{NO}, L, E, \rho, \epsilon = -2)$$

In **all oscillation** channels

⇒ use **neutrino scattering** data to probe parameter space

Ruled out LMAD solution in electron sector

[Denton, **JG** [2204.09060](#)]

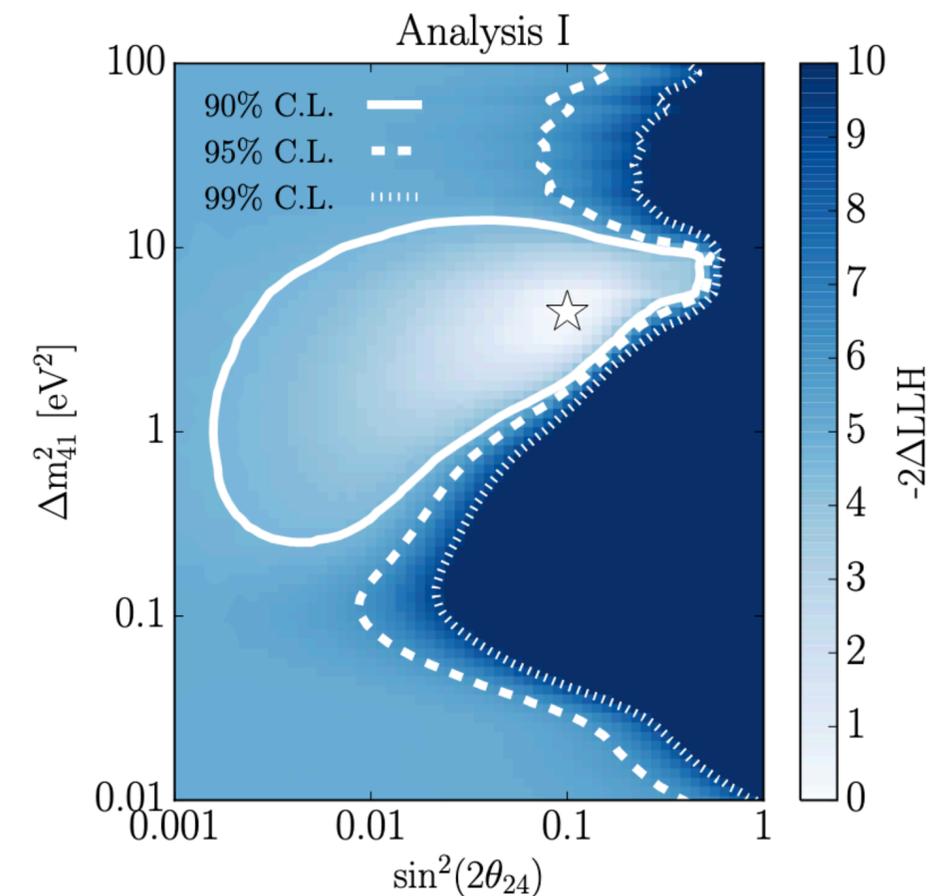
# Backup: Neutrino anomaly from upgoing atmospheric neutrinos

System of active neutrinos and sterile exhibits a resonance where the mixing angle is maximal in matter at resonance energy [IceCube, [2005.12943](#)]

For matter densities of Earth,  $\Delta m_{41}^2 \approx 1 \text{ eV}^2$   
 $E_{\text{res}} \sim 1 \text{ TeV} \rightarrow$  energy of atmospheric neutrinos

$\Rightarrow$  search for eV-scale steriles with upgoing atmospheric neutrinos at IceCube

Hint for **sterile neutrino** at 90%CL!



# Backup: Neutrino anomaly in the early Universe

Measurements of Hubble constant  $H_0$   
Expansion rate

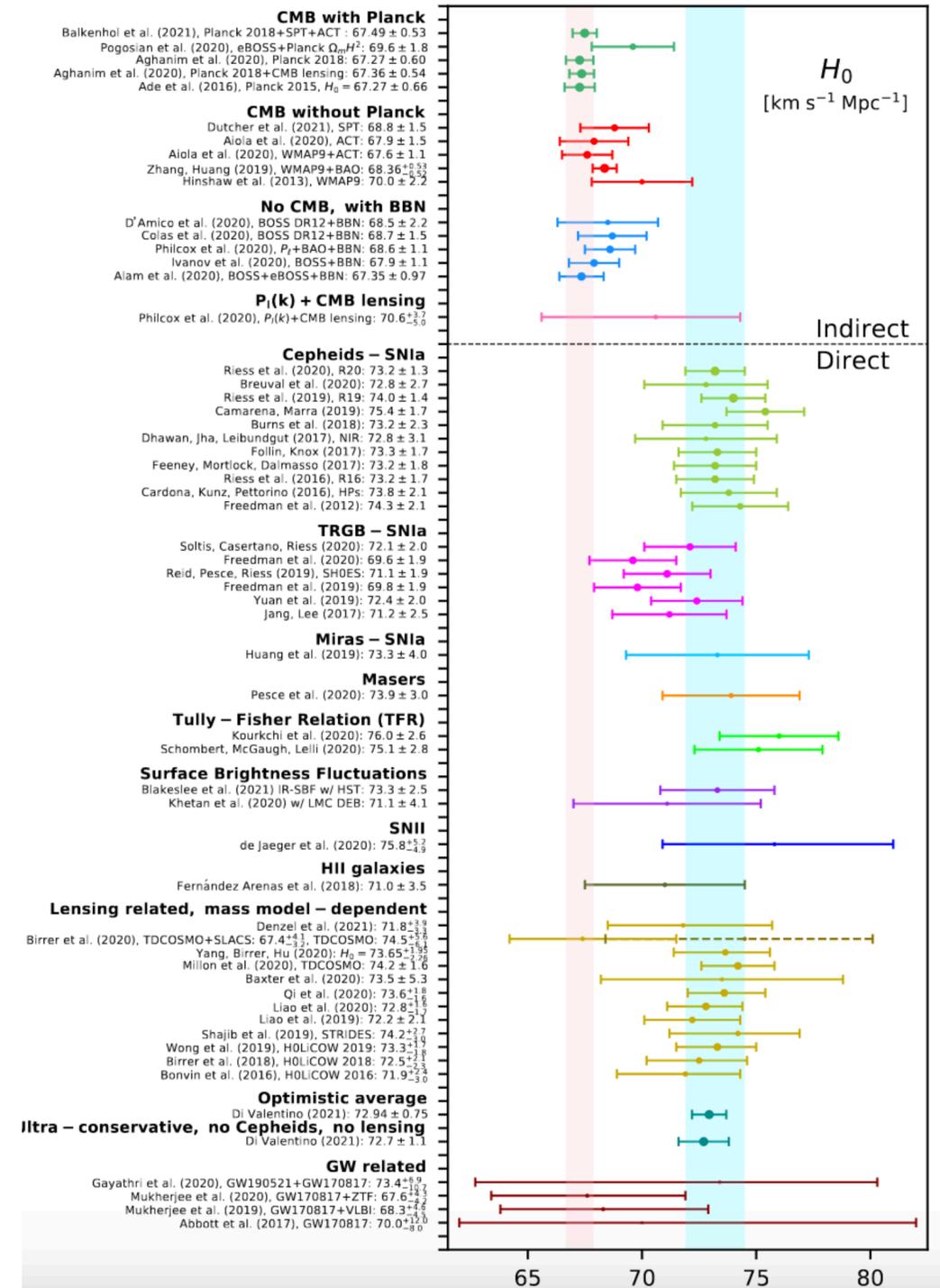
$$H^2(a(t)) = H_0^2(\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_\Lambda + \Omega_k a^{-2} + \dots)$$

**Disagreement** between early time data  
and late time data  $> 4\sigma$

Different proposals to solve the tension:

- Systematics in measurements,
- physics beyond  $\Lambda$ CDM  
(including scenarios involving neutrinos)

[Di Valentino et al, [2103.01183](#)]



# Backup: Neutrino anomaly in the early Universe

Hubble tension:

Relativistic species in early Universe drive expansion of the Universe, so does  $H_0$ !

$$H^2(a(t)) = H_0^2(\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_\Lambda + \Omega_k a^{-2} + \dots)$$

Relation between  $N_{\text{eff}}$  and  $H_0$

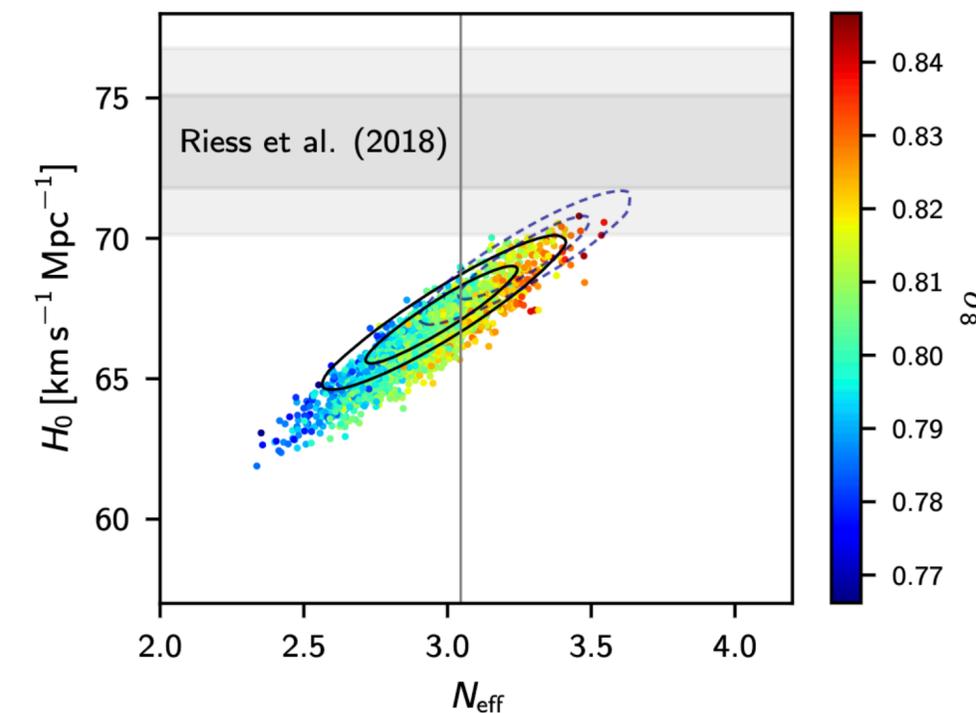
$$H_0 \simeq [67.5 + 6.2\Delta N_{\text{eff}}] \text{ km/s/Mpc}$$

$\Delta N_{\text{eff}} \sim 1$  required to solve tension



Planck constraints  $\Delta N_{\text{eff}} < 0.33$

[PLANCK18 1807.06209]



# Backup: Neutrino anomaly in the early Universe

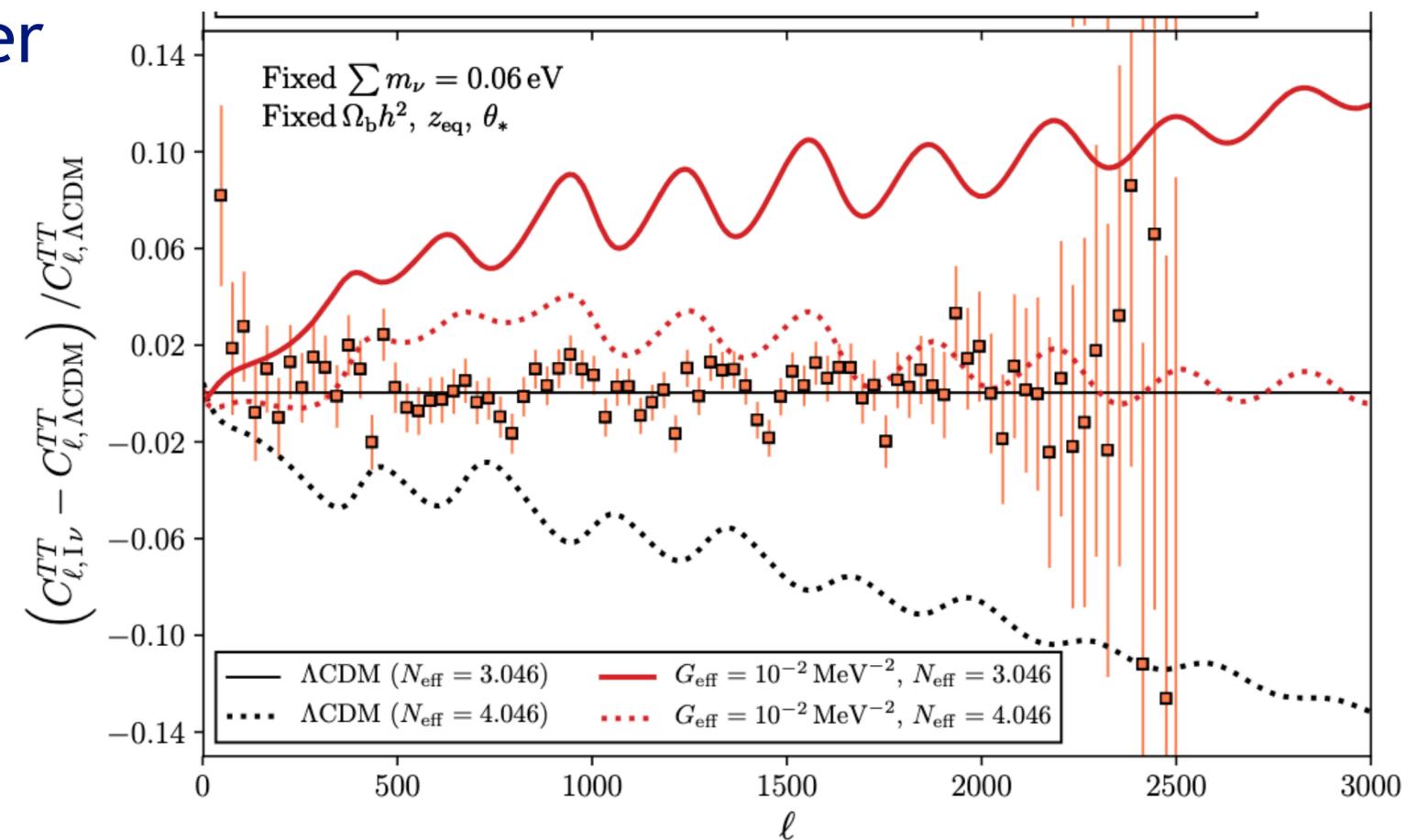
**Counteract** effects of larger  $N_{\text{eff}}$  in CMB and matter power spectrum!

[Kreisch, Cyr-Racine, Dore [1902.00534](#)]

Effects on CMB: decreases the amplitude of acoustic peaks, shift them to larger scales/smaller multipoles

Introduce **new neutrino interactions** to delay onset of neutrino free streaming

Example: neutrino self-interactions



# Backup: Astrophysical neutrino anomaly

expect flavor ratio of 1:1:1 at Earth and single power law

Data shows  $> 3\sigma$  tension!

Invisible  
neutrino decay scenario:

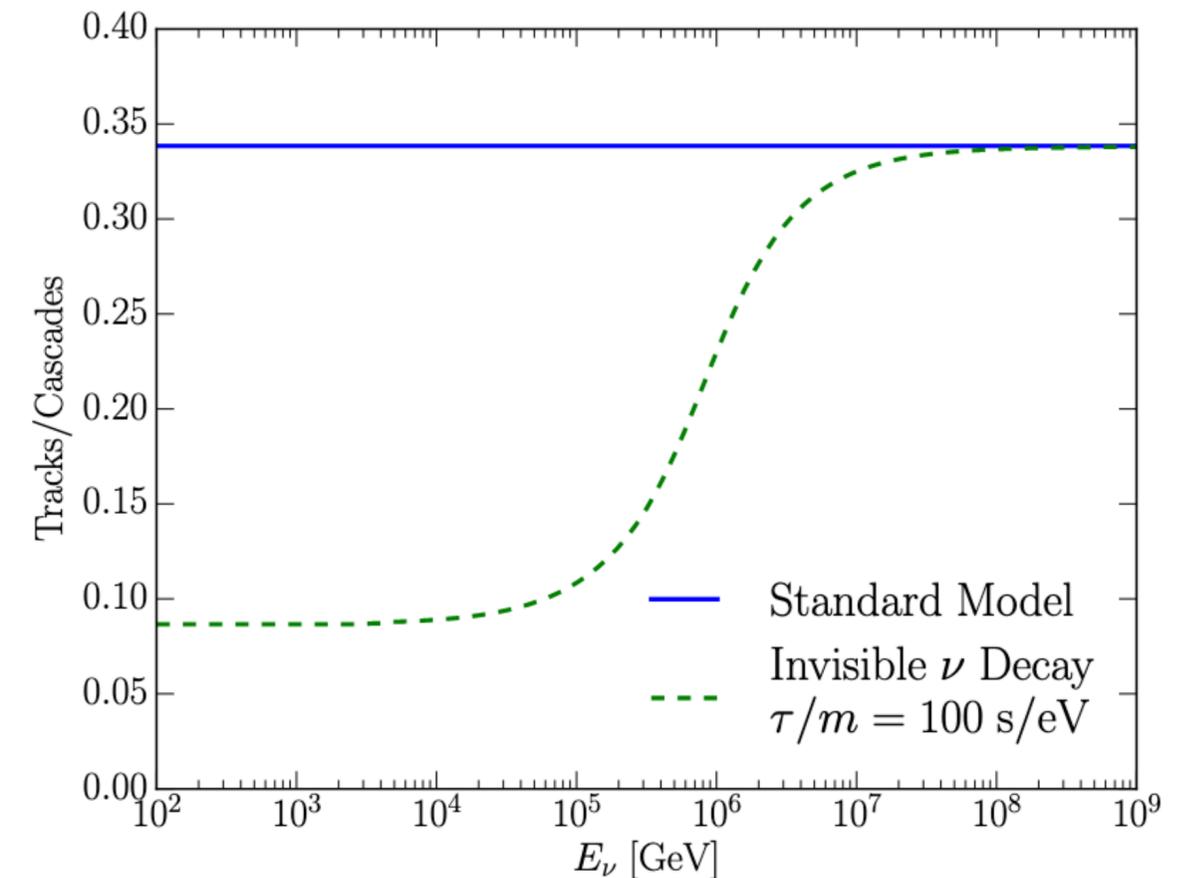
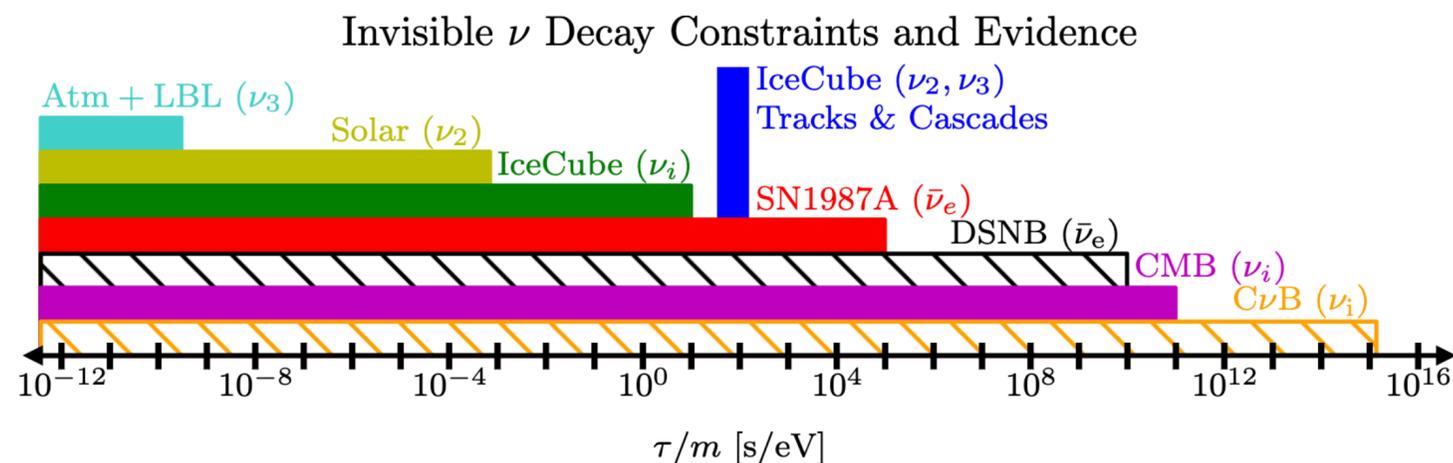
$$\nu_{(2,3)L} \rightarrow \nu_{1R} + J$$

Stable, least amount of  $\nu_{\mu}$

→ suppresses  $\nu_{\mu}$  at low energies

[Denton, Tamborra [1805.05950](#)]

[Arguelles et al [2203.10811](#)]

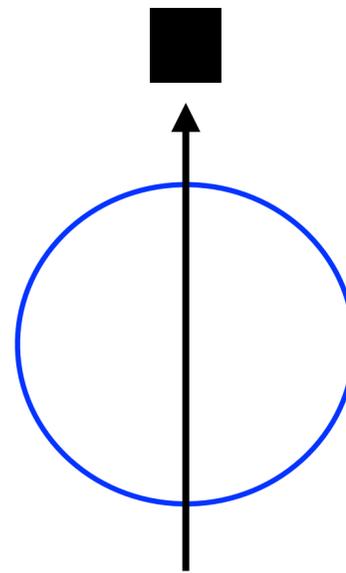


# Backup: UHE neutrino anomaly

ANITA saw anomalous events!

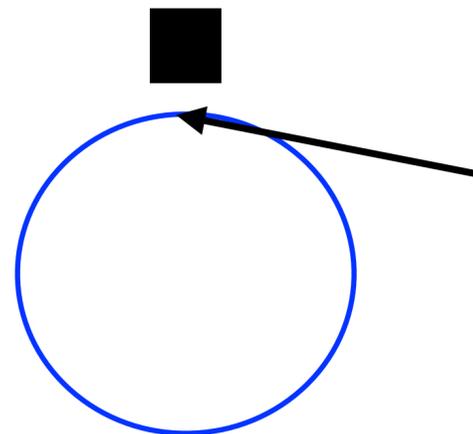
2 steeply upward going events in ANITA-I and ANITA-II

[ANITA [1603.05218](#), [1803.05088](#)]



4 anomalous events near horizon in ANITA-IV

[ANITA [1603.05218](#)]



# Backup: UHE neutrino anomaly

ANITA saw anomalous events!

[ANITA [1603.05218](#), [1803.05088](#)]

2 steeply upward going events in ANITA-I and ANITA-II

Events could come from  $\tau$  decay above surface from parent  $\nu_\tau$

- however EeV-energy  $\nu_\tau$  has interaction length  $<$  diameter of Earth  
→  $\nu_\tau$  origin unlikely

# Backup: UHE neutrino anomaly

ANITA saw anomalous events!

4 anomalous events very near horizon in ANITA-IV  
 Better sensitivity but no anomalous upgoing events

[ANITA 1603.05218]

“not observationally inconsistent with  $\tau$  -induced extended air showers from Earth skimming

$\nu_\tau$ ”

[Bertolez-Martinez, Arguelles, Esteban, Lopez-Pavon, Martinez-Solver, Salvado

[ANITA 2112.07069]

2305.03746]

- however required diffuse UHE  $\nu_\tau$  flux in tension with IceCube/Auger bounds
- $\nu_\tau$  flux from transient source in tension with Auger and ANITA Askaryan channel

