Using the IceCube data to constraint the (3+2) neutrino scenario

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ABSTRACT

In this letter we are using the IceCube experiment to test, phenomenologically, the (3+2) sterile neutrino scenario. As far is known, the presence of sterile states with mass splitting $\Delta m^2 \sim 1 eV^2$ distorts the angular and energy distributions of reconstructed muon events, observed by IceCube, through parametric and MSW resonances.

Since the distortions introduced by the sterile neutrino (3+2) scenario appear arround of few TeV, where the Ice-Cube detection is highly optimized, here we have a great opportunity to prove scenarios with sterile states. Supporting by previous works, some considerations have be done in order to guarantee a conservative and robust bounds.

Then, by using one year data colleted by IceCube between 2011-2012 we constrain the (3+2) parameter space scenario

Standard Neutrino Oscillation Scenario

Over years, many experiments had proved that neutrinos oscillate

$$P_{\nu_\alpha \to \nu_\beta}(L,E) = \left|\langle \nu_\beta | \nu_\alpha(t) \rangle\right|^2 = \sum_{k,j} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} \exp\left(-i \frac{\Delta m^2_{kj} L}{2E}\right)$$

were $|\nu_\alpha\rangle = \sum_k U^*_{\alpha k} |\nu_k\rangle$ where a flavor neutrino state is a linear combination with mass eigenstates

In this standard framework there are 3 actives neutrinos with

3 masses $\Delta m^2_{21}, \quad \Delta m^2_{31} \quad \Delta m^2_{32}$

3 mixing angles $\theta_{12}, \quad \theta_{13}, \quad \theta_{23}$

1 CP violating phase δ_{CP}

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with $|\nu_\alpha(t)\rangle = \sum U^*_{\alpha k}$ … is a linear … nstates

With the U's been PMNS matrix

$$\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

In this standard framework there …

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$$\begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{\rm CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{\rm CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{\rm CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{\rm CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{\rm CP}} & c_{23}c_{13} \end{bmatrix}$$

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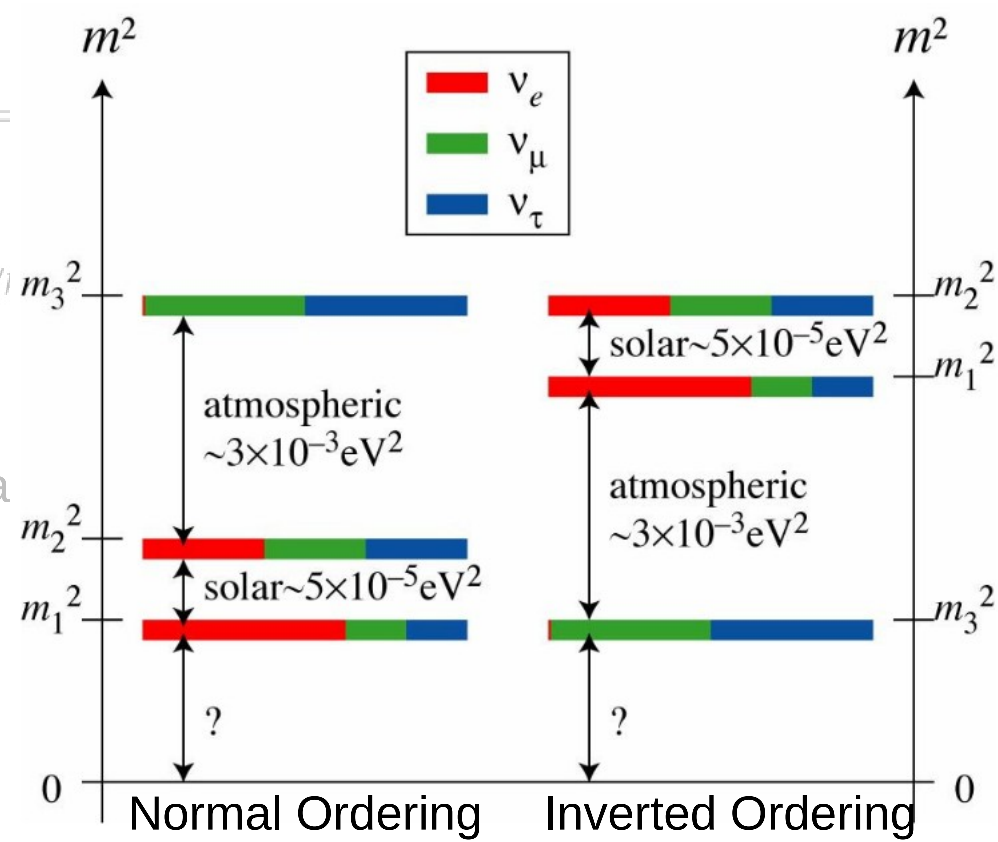

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Sterile Neutrino Scenario

The three active neutrino framework can (almost?) fit, by global analisys, the oscillation parameters, but STILL, there are some anomalies that have been deteted in:

The LSND anomaly

The Reactor neutrino anomaly

The Galluim anomaly

Sterile Neutrino Scenario

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The Galluim anomaly Phys. Rev. C 80 (2009) 015807 SAGE Collaboration and Phys. Lett. B 685 (2010) 47 Kaether et al

Originating from the observed deficit in calibration tests of solar neutrino detectors, SAGE and GALLEX/GNO, by electron-capture source

Sterile Neutrino Scenario

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Experiment	Type	Channel	Significance
LSND	DAR	$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	$3.8\,\sigma$
MiniBooNE	SBL accelerator	$\nu_\mu \to \nu_e$ CC	$3.4\,\sigma$
MiniBooNE	SBL accelerator	$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	$2.8\,\sigma$
Gallex/SAGE	Radioactive	ν_e dissap	$2.8\,\sigma$
Reactors	Beta-decay	$\bar{\nu}_e$ dissap	$3.0\,\sigma$

K. N. Abazajian et al. "Light Sterile Neutrinos: A Whitepaper" arxiv:1204.5379

Each of them, individually, are not significant enough to confirm something, but They could show a directions to something eles….

...this could be, as the most commum interpretation as a glimpse of "sterile" neutrinos

Sterile Neutrino Scenario–IceCube Experiment

If sterile neutrino exist, with mass-square diferences $\sim \mathcal{O}(\mathrm{eV}^2)$ then Earth matter induces a very interesting features

Parametric Resonance

Phys. Lett. B 440 (1998) 319 and
Nucl. Phys. B 524 (1998) 505
Liu, Smirnov, Mikheyev

Change the energy and zenith distributions of Atmospheric netrutrinos $\gtrsim$100 GeV

MSW Resonance

Phys. Lett. B 562 (2003) 279 and
Hep-ph/0102166
Nunokawa, Peres, Funchal, Yasuda

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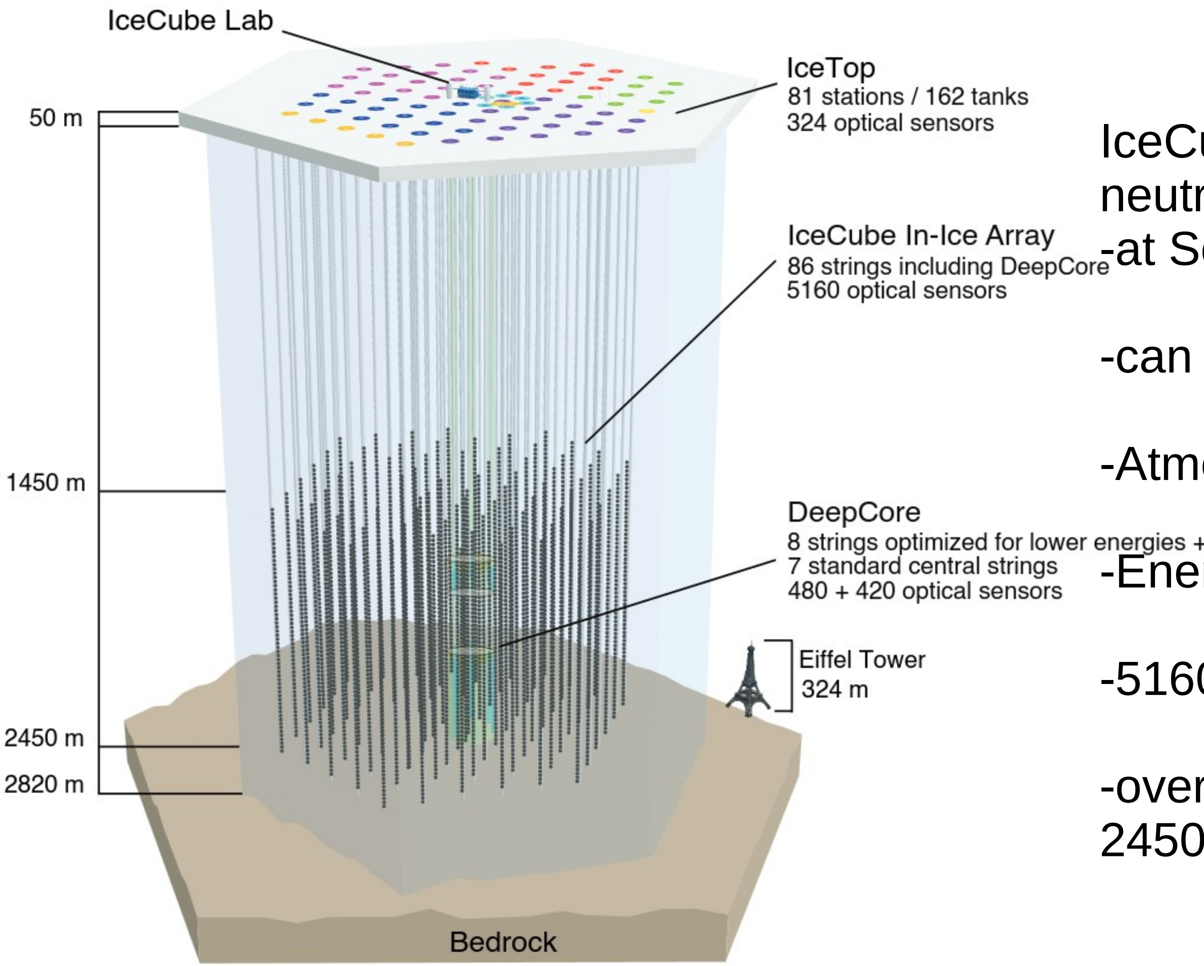
IceCube is sensitive to these scanarios

IceCube Experiment



IceCube is gigaTon ice-Cherenkov neutrino detector:
-at South Pole

-can observe TeV neutrinos

-Atmospheric and astrophysical

-Energies above 100Gev and ~PeV

-5160 DOM in 86 strings

-over a cubic kilometer 1450m to 2450m

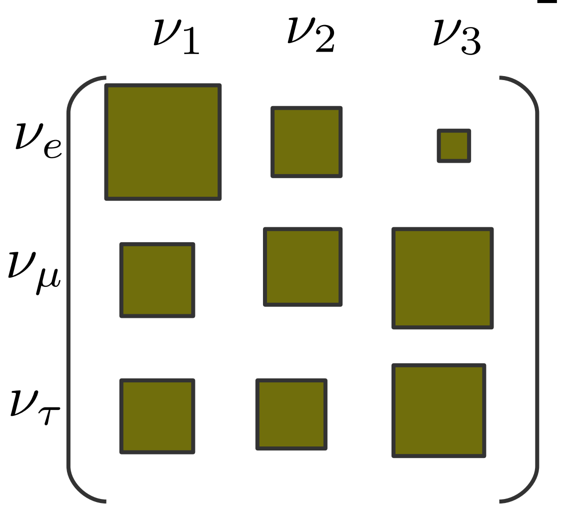
M. Aartsen et al., "The IceCube Neutrino Observatory: Instrumentation and Online Systems," JINST, vol. 12, no. 03, p. P03012, 2017.

Sterile Neutrino phenomenology in IceCube

The evolution sterile neutrino equation is given by:

$$i\frac{d}{dr}\nu_f = \left[U\frac{M^2}{2E_\nu}U^\dagger + A\right]\nu_f$$

Where U is:



For the three active neutrinos scenario

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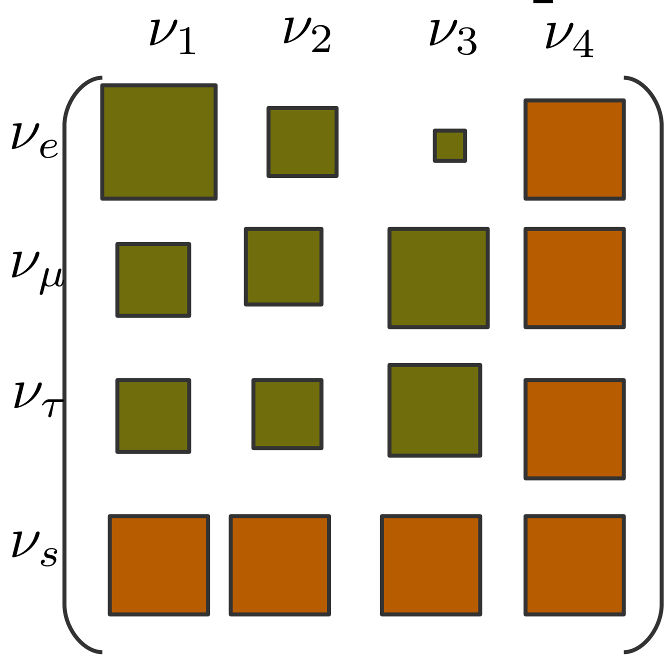

For the 3+1 sterile neutrino scenario

Sterile Neutrino phenomenology in IceCube

The evolution sterile neutrino equation is given by:

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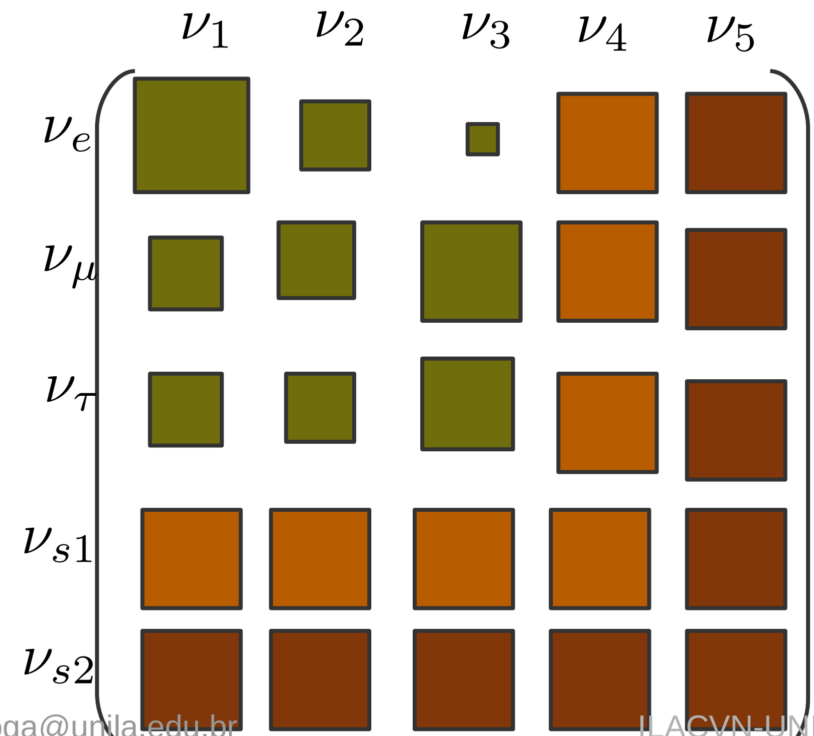
Where U is:

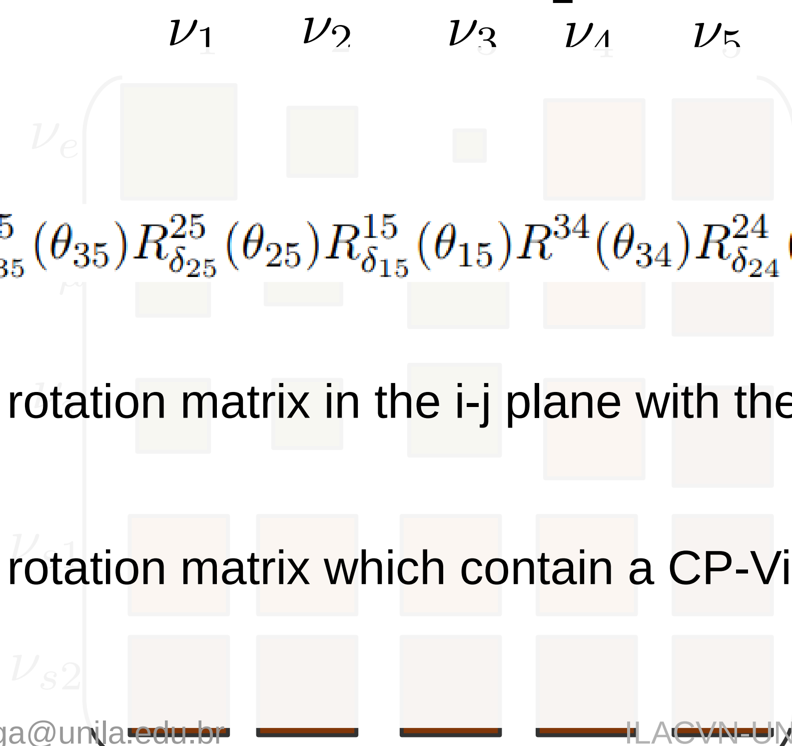


For the 3+2 sterile neutrino scenario

Sterile Neutrino phenomenology in IceCube

The evolution sterile neutrino equation is given by:

$$i\frac{d}{dr}\nu_f = \left[U\frac{M^2}{2E_\nu}U^\dagger + A\right]\nu_f$$



Where U is:

$$= R^{45}(\theta_{45})R^{35}_{\delta_{35}}(\theta_{35})R^{25}_{\delta_{25}}(\theta_{25})R^{15}_{\delta_{15}}(\theta_{15})R^{34}(\theta_{34})R^{24}_{\delta_{24}}(\theta_{24})R^{14}_{\delta_{14}}(\theta_{14})R^{23}(\theta_{23})R^{13}_{\delta_{13}}(\theta_{13})R^{12}(\theta_{12})$$

R^{ij} Is the rotation matrix in the i-j plane with the angle θ_{ij}

$R^{ij}_{\delta_{ij}}$ Is the rotation matrix which contain a CP-Violating angle δ_{ij}

For this 3+2 sterile neutrino scenario them:

$$M^2 = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 & 0 & 0 \\ 0 & 0 & \Delta m_{31}^2 & 0 & 0 \\ 0 & 0 & 0 & \Delta m_{41}^2 & 0 \\ 0 & 0 & 0 & 0 & \Delta m_{51}^2 \end{pmatrix} \qquad A = \begin{pmatrix} A_{\mathrm{CC}} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & A_{\mathrm{NC}} & 0 \\ 0 & 0 & 0 & 0 & A_{\mathrm{NC}} \end{pmatrix}$$

with $\Delta m_{ij}^2 = m_j^2 - m_i^2$

$$A_{\mathrm{CC}} = 2\sqrt{2}\mathrm{G}_F E_\nu \mathrm{N}_e(\mathrm{r})$$

$$A_{\mathrm{NC}} = \sqrt{2}\mathrm{G}_F E_\nu \mathrm{N}_n(\mathrm{r})$$

Sterile Neutrino phenomenology in IceCube

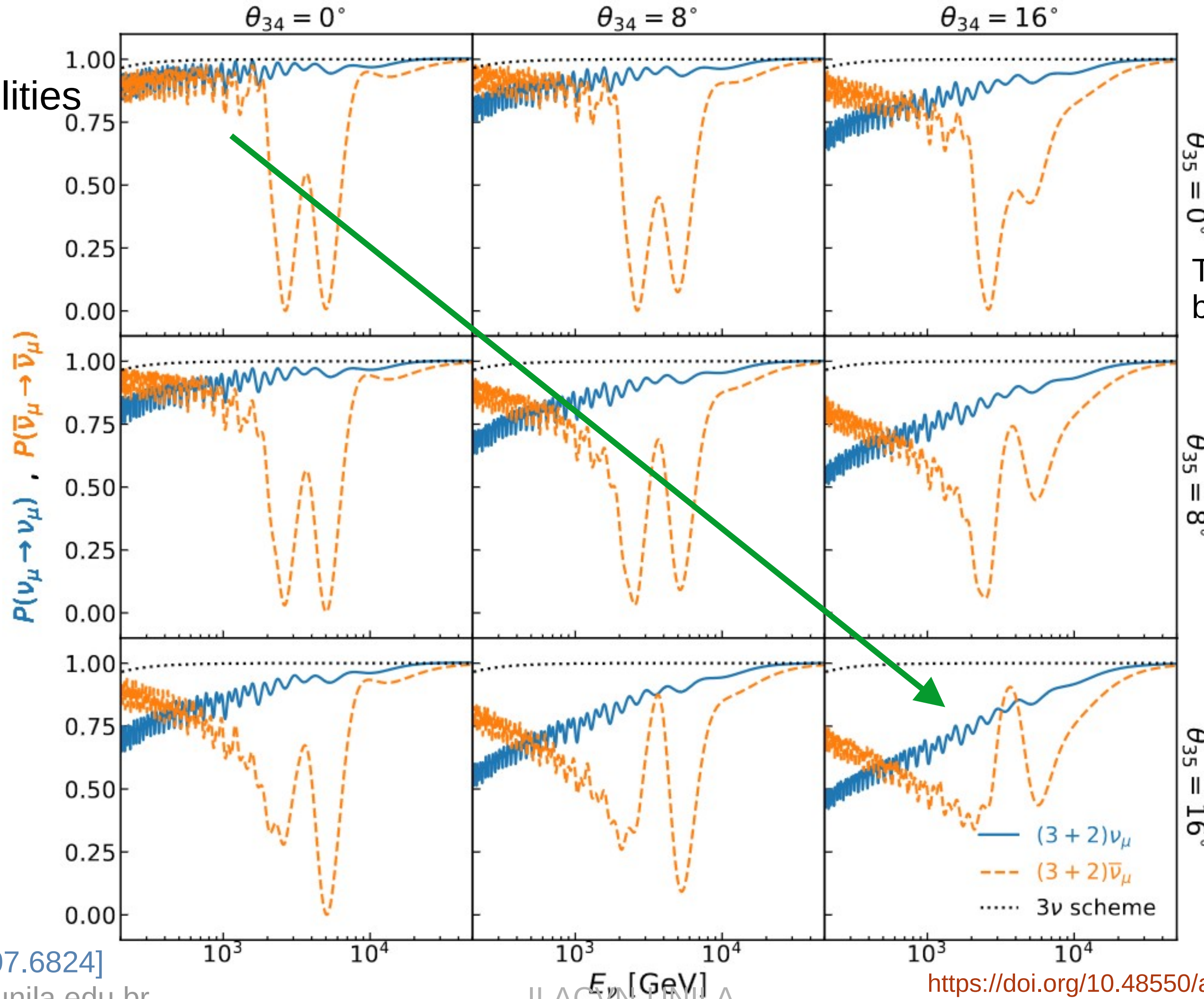
In this scenario there are **20** parameters, 10 mixing angles, 6 CP-Violating phases and 4 mass-square differences….but we dont need to use all them..

Parameter	Reason for elimination
Standard oscillations	For $E_\nu \geq 100\mathrm{GeV}$ ν_e mixing strongly suppressed and L_{osc} for ν_μ and ν_τ is bigger than earth
θ_{45}	Can be rotated away be redefinition of the sterile state
$\theta_{14}\ \theta_{15}\ \delta_{14}\ \delta_{15}$	Do not impact survival probabilities ν_μ and $\bar{\nu}_\mu$
$\theta_{34}\ \theta_{35}\ \delta_{24}\ \delta_{25}\ \delta_{35}$	If fixed to zero allow conservatives constraints

Sterile Neutrino phenomenology in IceCube

Survival probabilities

$$\cos\theta_z = -1$$
$$\theta_{24} = \theta_{25} = 8^o$$
$$\Delta m^2_{41} = 1\,\mathrm{eV}$$
$$\Delta m^2_{51} = 2\,\mathrm{eV}$$



The orange curves become shallower

Is strengthening the limits on the (3+2) scenario

JHEP 12 (2013) 014 [1307.6824]

https://doi.org/10.48550/arXiv.2405.10419

Sterile Neutrino phenomenology in IceCube

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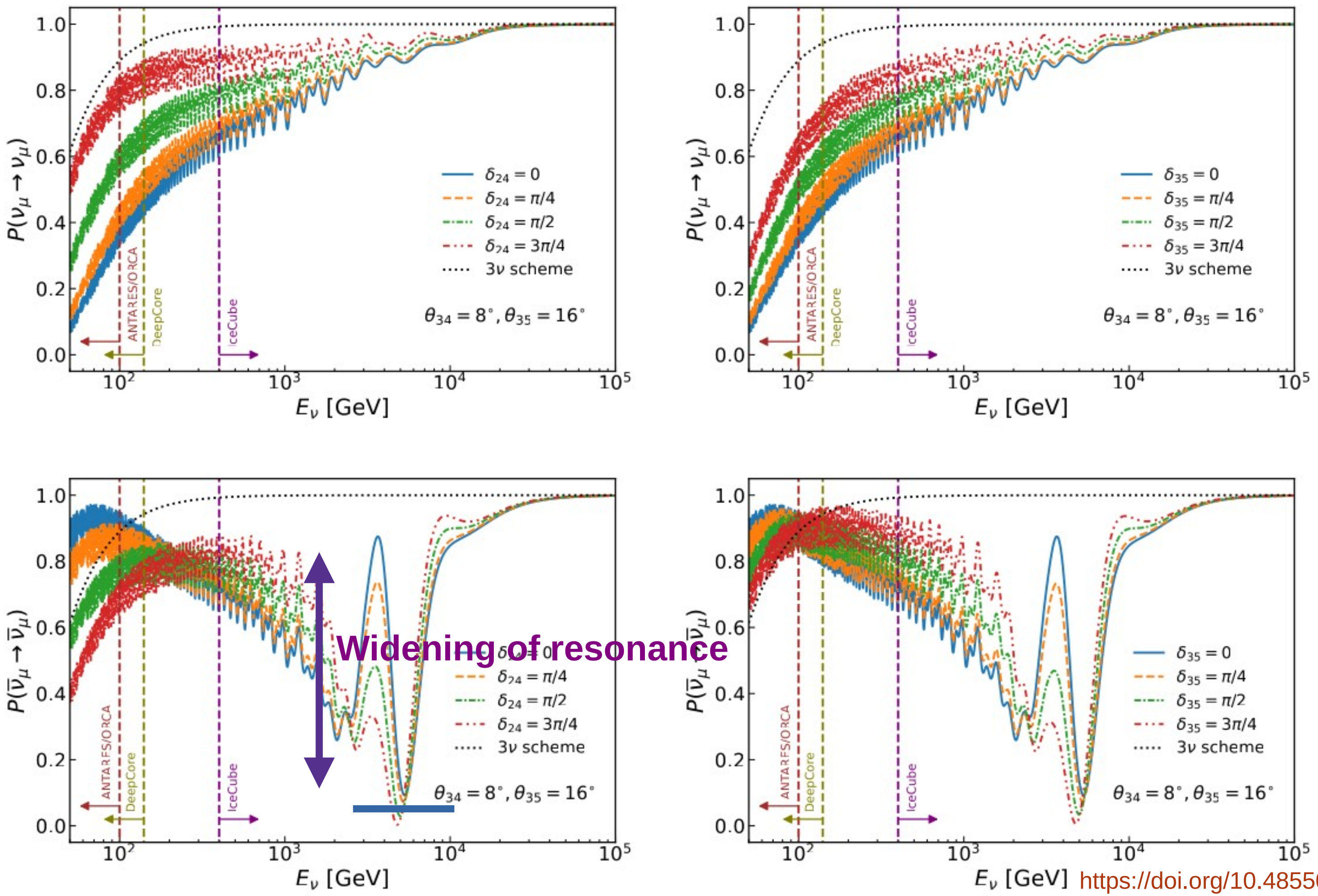
Survival probabilities



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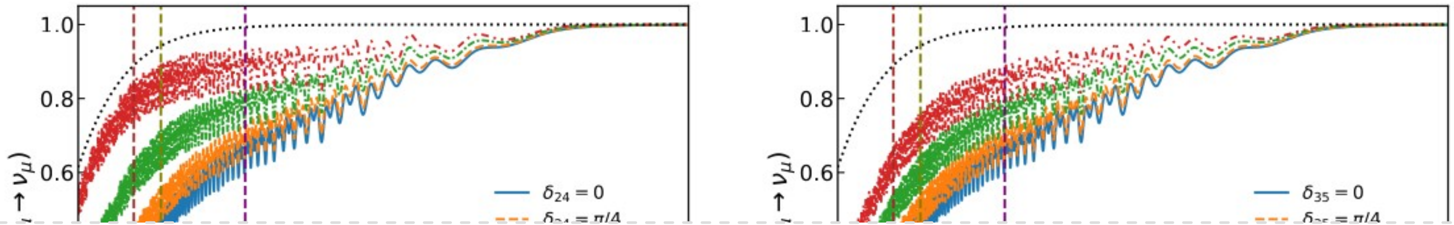
Sterile Neutrino phenomenology in IceCube

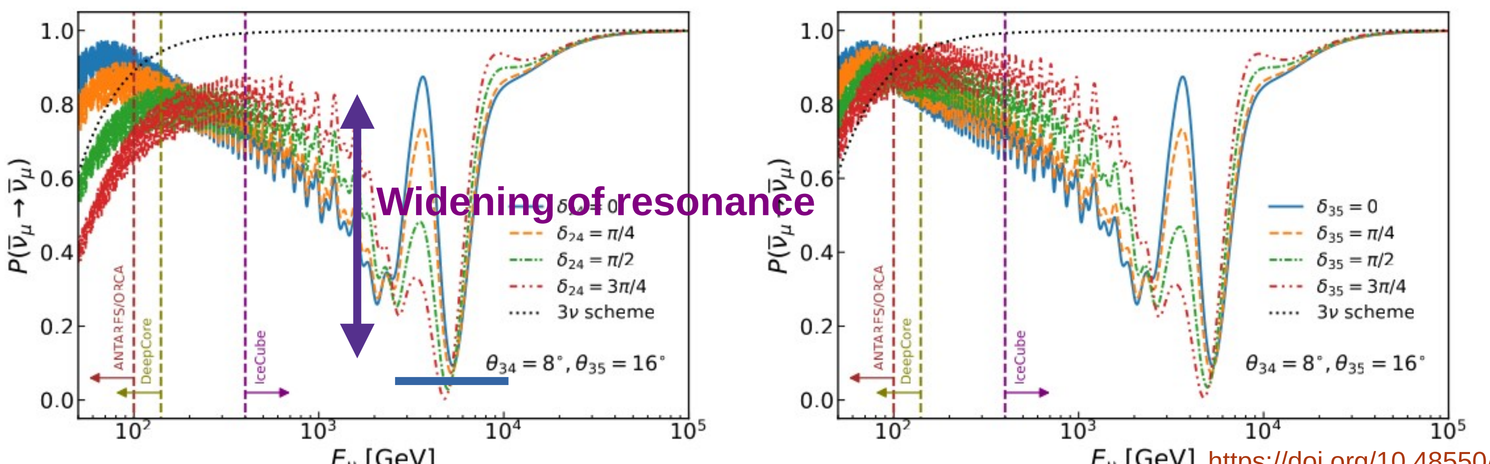
Survival probabilities



We can conclude that in order to probe the 3+2 neutrino scenario using the atmospheric neutrino data from IceCube is just necessarilly to manage:

$$\theta_{24},\, \theta_{25},\, \Delta m^2_{41},\, \Delta m^2_{51}$$

………the rest go to zero...



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Analisys

We compute the survival probabilities of atmospheric ν_μ and $\bar{\nu}_\mu$ numerically, as function of E_ν and cos θ_z and scanning over the parameter space of (θ_{24} , θ_{25} , Δm^2_{41} , Δm^2_{51}).

$$\chi^2(\vec{\theta}) = -2\ln\mathcal{L}(\vec{\theta}) =$$

$$\min_{\vec{\xi},\{d\}}\left(2\sum_{j,k}\left[N^{\text{exp}}_{jk}(\vec{\theta},\vec{\xi},d) - N^{\text{obs}}_{jk} + N^{\text{obs}}_{jk}\ln\frac{N^{\text{obs}}_{jk}}{N^{\text{exp}}_{jk}(\vec{\theta},\vec{\xi},d)}\right] + \sum_{\eta}\frac{(\xi_\eta - \Xi_\eta)^2}{\sigma^2_\eta}\right)$$

we use a public data of IceCube collected over a period of 343.7 days between 2011-2012.

Analisys

$$\chi^2(\vec{\theta}) = -2\ln\mathcal{L}(\vec{\theta}) =$$

$$\min_{\vec{\xi},\{d\}}\left(2\sum_{j,k}\left[N_{jk}^{\exp}(\vec{\theta},\vec{\xi},d) - N_{jk}^{\text{obs}} + N_{jk}^{\text{obs}}\ln\frac{N_{jk}^{\text{obs}}}{N_{jk}^{\exp}(\vec{\theta},\vec{\xi},d)}\right] + \sum_{\eta}\frac{(\xi_\eta - \Xi_\eta)^2}{\sigma_\eta^2}\right)$$

$$N_{jk}^{\exp} = \sum_i \left[\eta_{ijk}\phi_{ik}^{\nu,\text{atm}}\langle P(\nu_\mu\to\nu_\mu)\rangle_{ik} + \bar{\eta}_{ijk}\phi_{ik}^{\bar{\nu},\text{atm}}\langle P(\bar{\nu}_\mu\to\bar{\nu}_\mu)\rangle_{ik}\right]$$

Response array tensor

$$ijk = E_\nu, E_\mu, \cos\theta_z$$

- -incoming neutrino energy
- -muon energy
- -direction E_ν, E_μ
- -optical efficiency

averaged survival probability

Analisys

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the average atmospheric ν_μ flux in the (i, k)th bin originating from the decay of pions and kaons

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the average atmospheric ν_μ flux in the (i, k)th bin originating from the decay of pions and kaons

$$\phi_{ik}^{\nu,\rm atm} = N_0\left[\phi_{ik}^{\nu,\pi} + (1.1 - R_{\pi/K})\,\phi_{ik}^{\nu,K}\right]\left(\frac{E_{\nu,i}}{E_0}\right)^{-\gamma} \qquad \phi_{ik}^{\bar{\nu},\rm atm} = N'N_0\left[\phi_{ik}^{\bar{\nu},\pi} + (1.1 - R_{\pi/K})\,\phi_{ik}^{\bar{\nu},K}\right]\left(\frac{E_{\nu,i}}{E_0}\right)^{-\gamma}$$

Provided by IceCube

Results

After performing the analysis with the x(theta) was found the allowed region of the 3+2 parameters space by IceCube.

The best fit point is $\Delta m^2_{41} = \Delta m^2_{51} = 16\,\mathrm{eV}^2$

$$\sin^2 2\theta_{24} = 0.3 \quad \sin^2 2\theta_{25} = 0.23$$

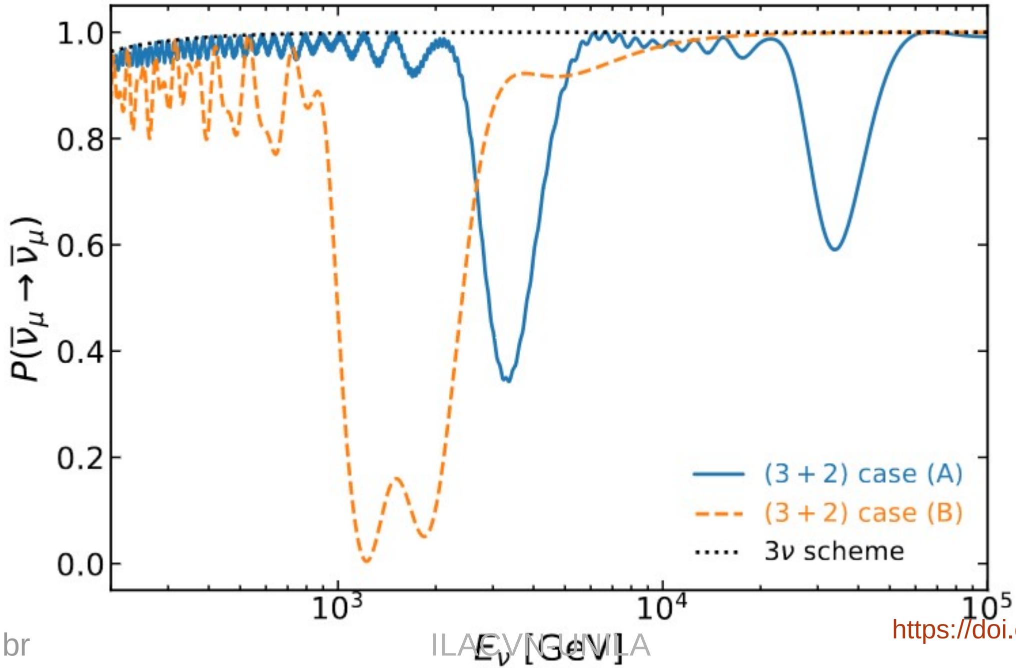
Which means that the IceCube data do not show preference to (3+2) scenario over the standard one

https://doi.org/10.48550/arXiv.2405.10419

Results

	$\sin^2 2\theta_{24}$	$\sin^2 2\theta_{25}$	Δm^2_{41} [eV^2]	Δm^2_{51} [eV^2]	$\Delta\chi^2$
Case (**A**) from Ref. [35]	2.8×10^{-2}	1.5×10^{-2}	1.32	13.9	4.32
Case (**B**) from Ref. [36]	9.1×10^{-2}	6.8×10^{-2}	0.46	0.77	36.43

[35] A. Diaz, C.A. Argüelles, G.H. Collin, J.M. Conrad and M.H. Shaevitz - Phys. Rept. 884 (2020) 1
[36] D. Cianci, A. Furmanski, G. Karagiorgi and M. Ross-Lonergan - Phys. Rev. D 96 (2017) 055001



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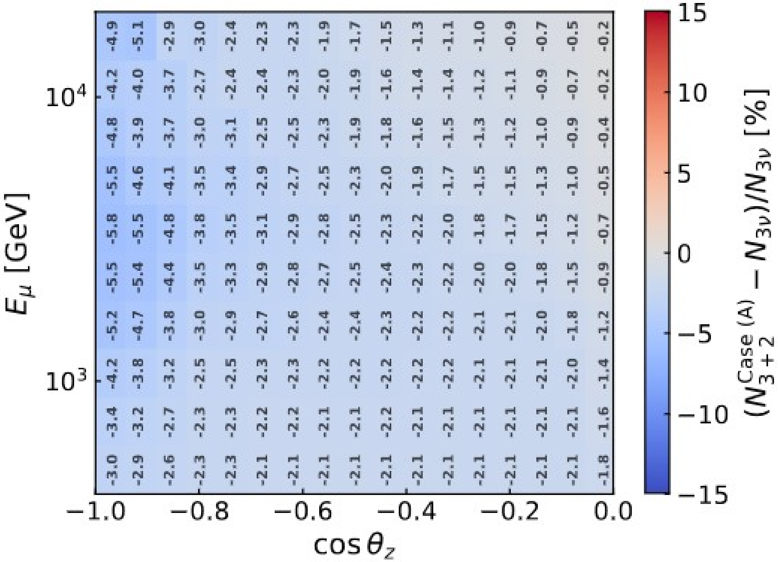
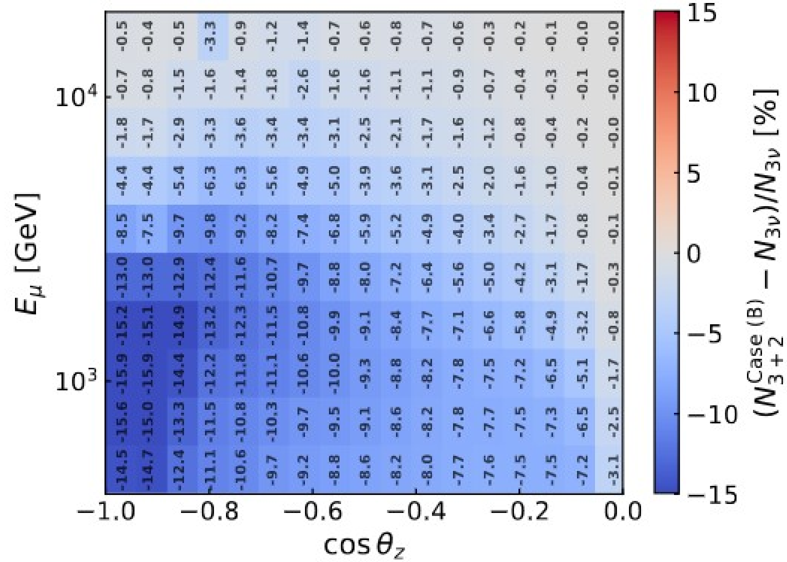


(a)



(b)

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E_ν [GeV]

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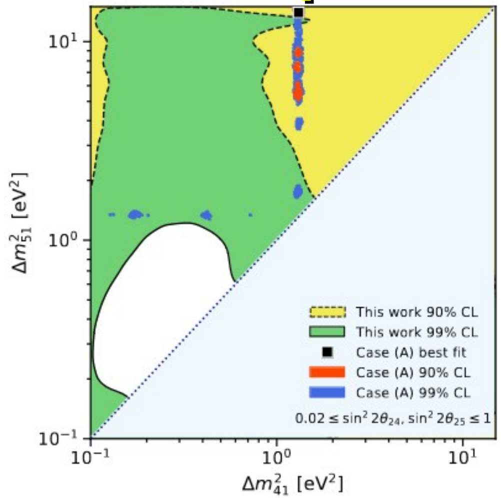
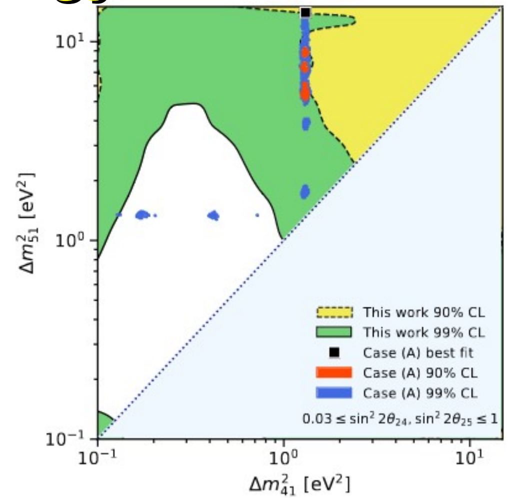
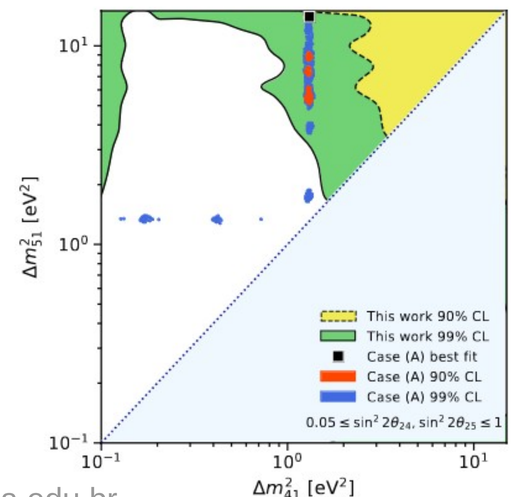
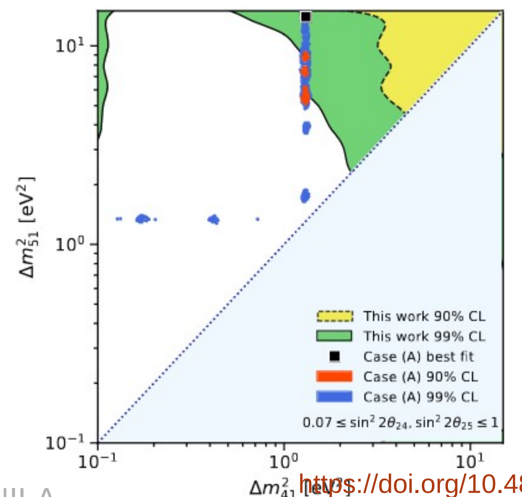
Results









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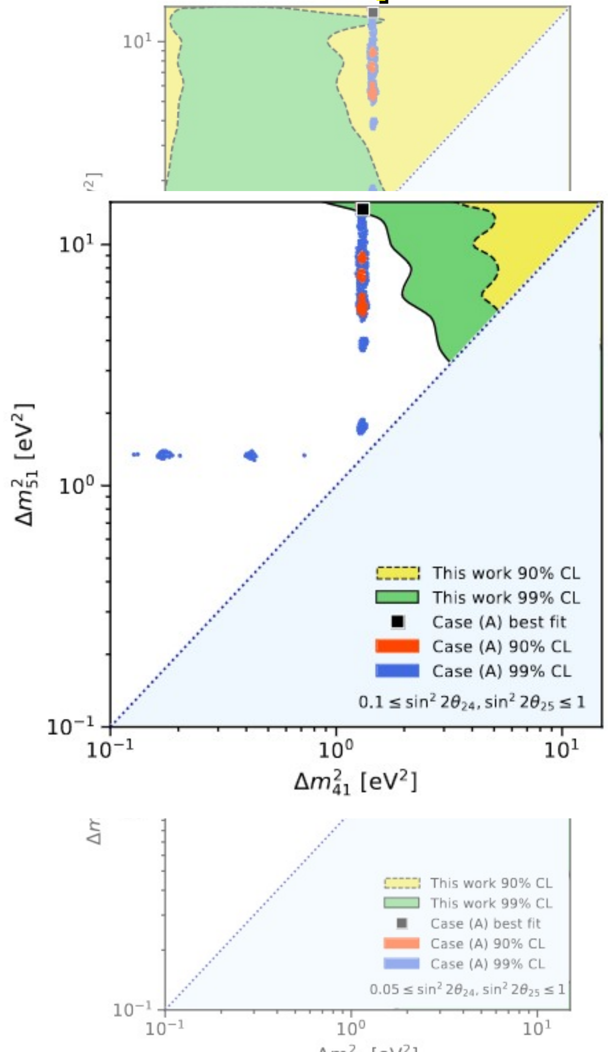

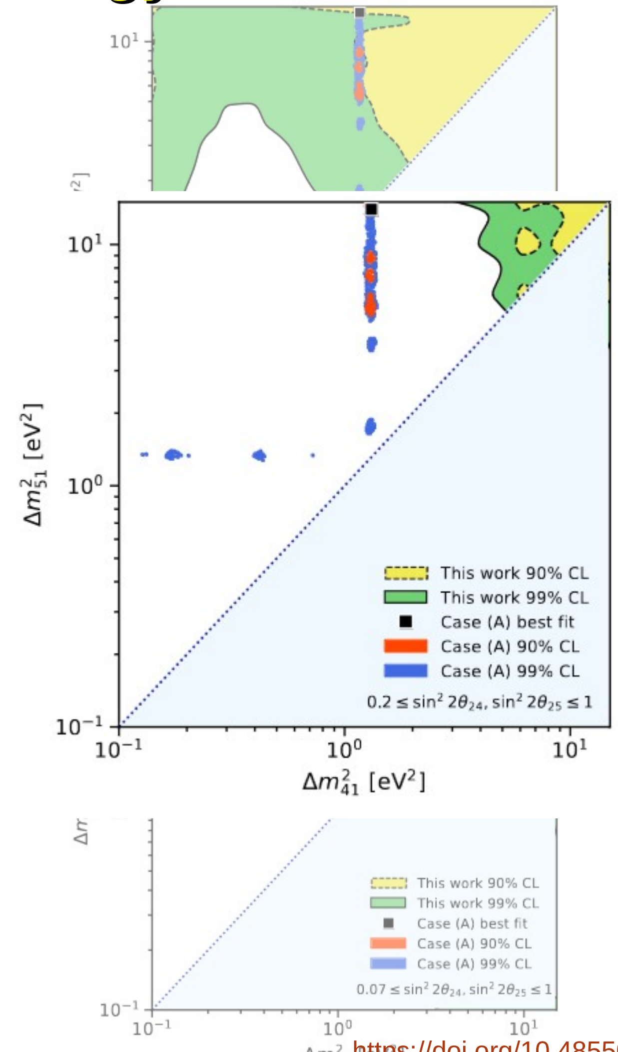

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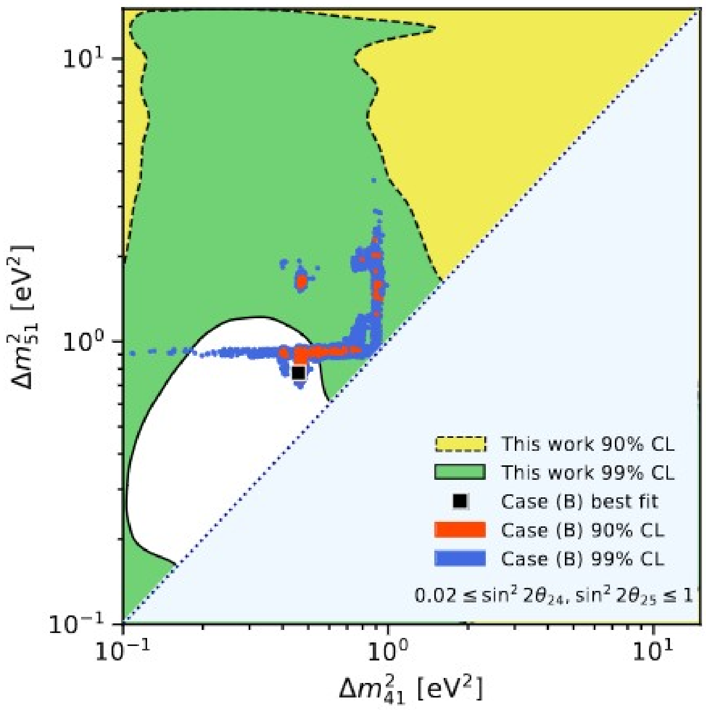
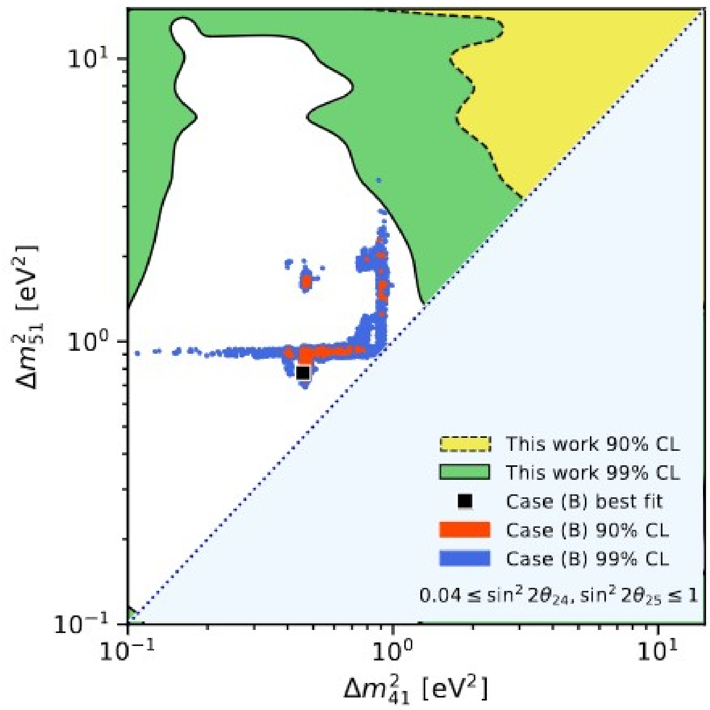
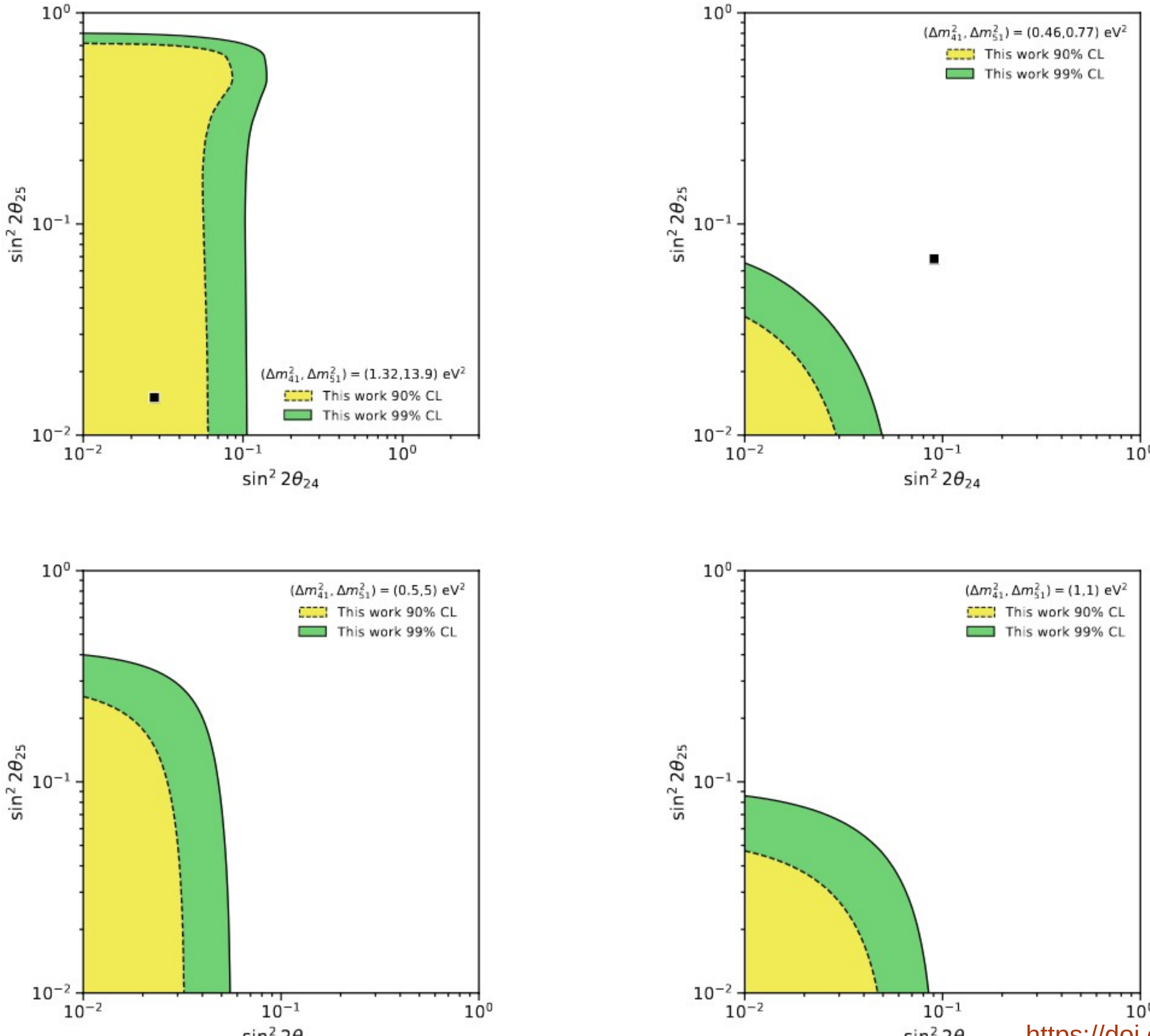




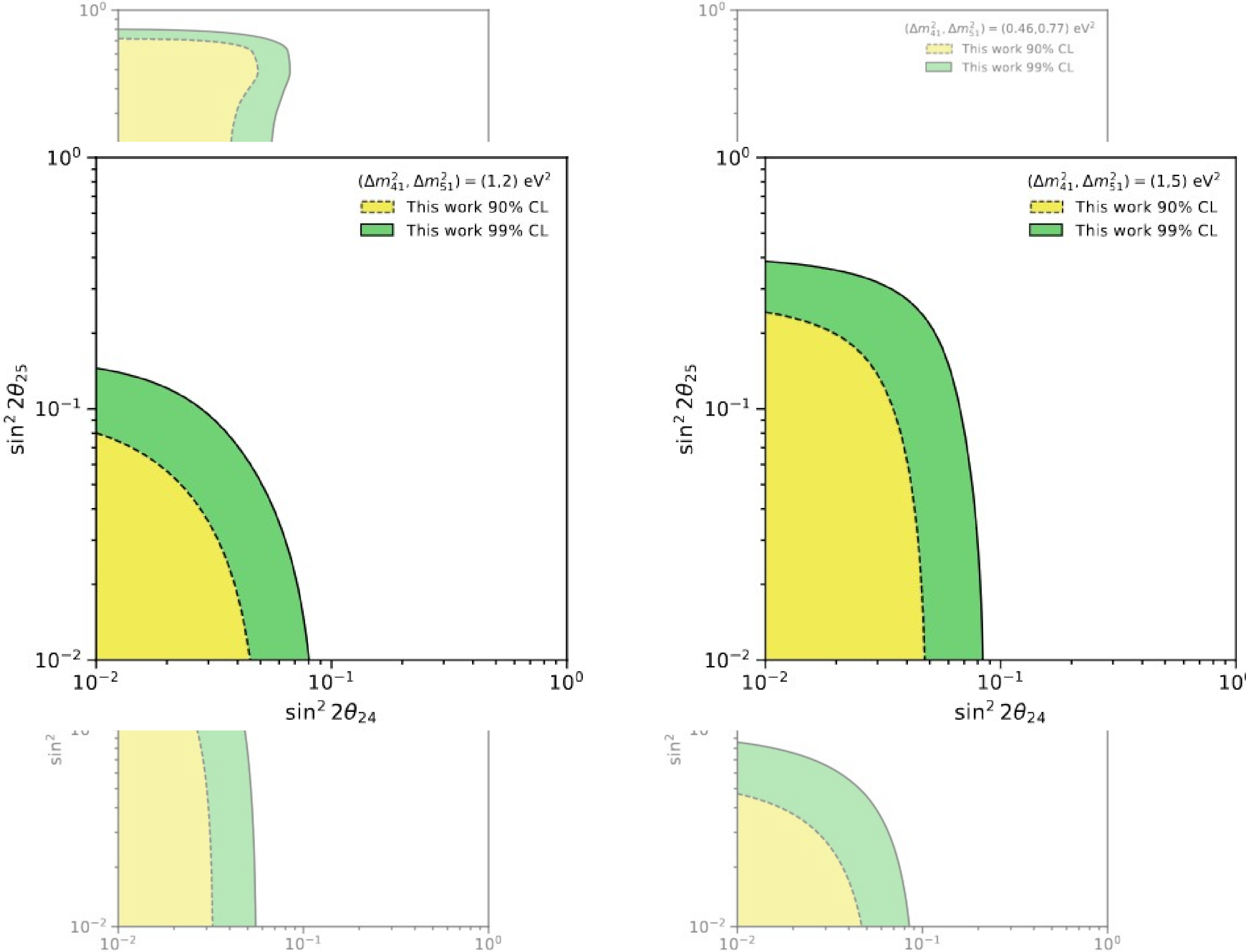
https://doi.org/10.48550/arXiv.2405.10419

Results



https://doi.org/10.48550/arXiv.2405.10419

Results



https://doi.org/10.48550/arXiv.2405.10419

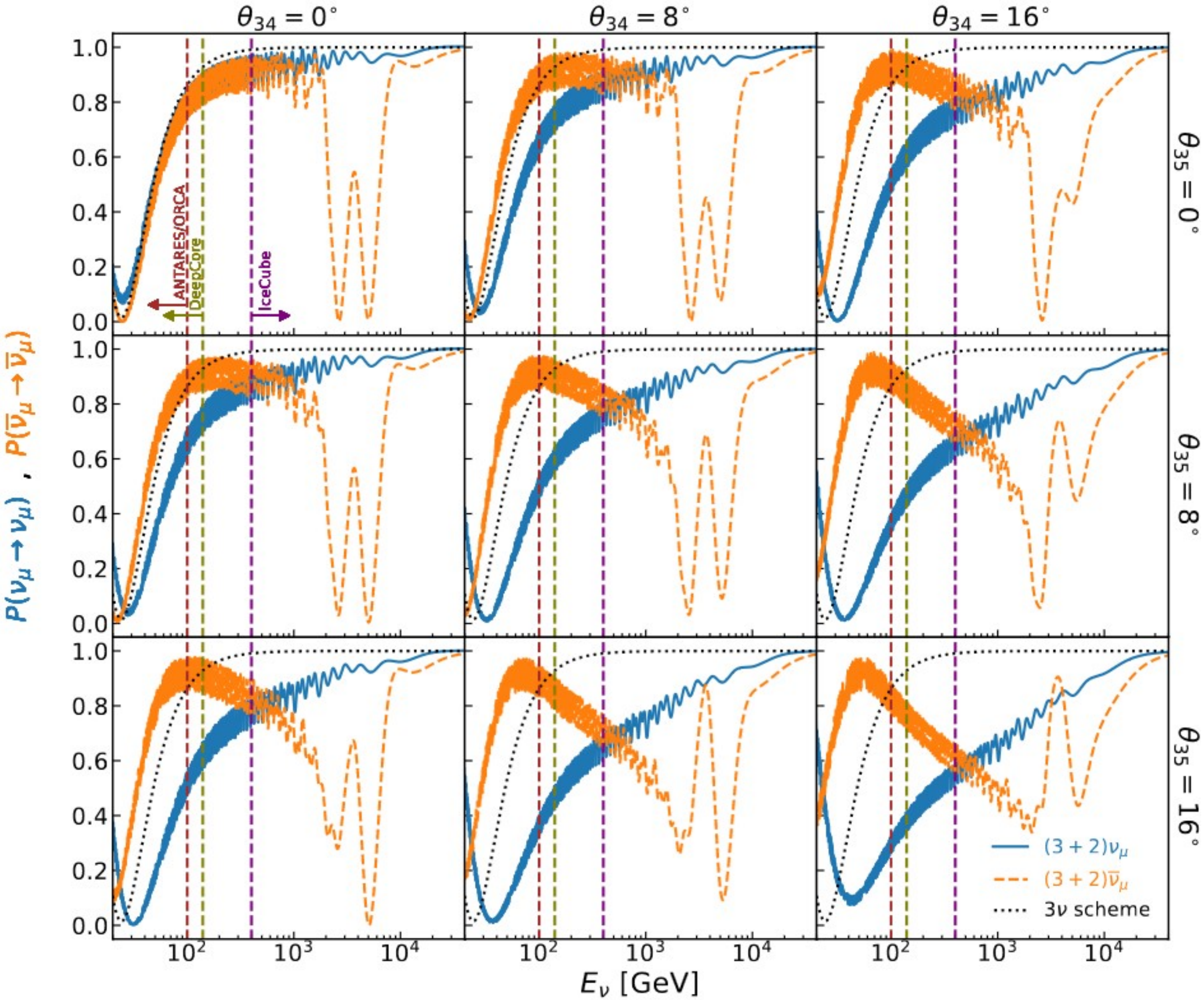
Conclusions

- Anomalies in the SBL, reactor and Solar experiments could indicate the presence of sterile(s) neutrinos,
- In principle the number of sterile neutrinos is free,
- To IceCube, more sterile states means more resonances that also means stronger contraints,
- Only 4 parameter are needed to get a conservative constraint,
- We performed a binned Poisson likelihood analysis with varius systematics and statistical uncertanties,
- Best fit $\Delta m^2_{41} = \Delta m^2_{51} = 16eV^2, \sin^2(2\theta_{24}) = 0.3, \sin^2(2\theta_{25}) = 0.23$
- The bounds were compared with the allowed regions of the SBL (A) and (B),
- Case (A) in compatible with IceCube data; Case (B) seems in tension,

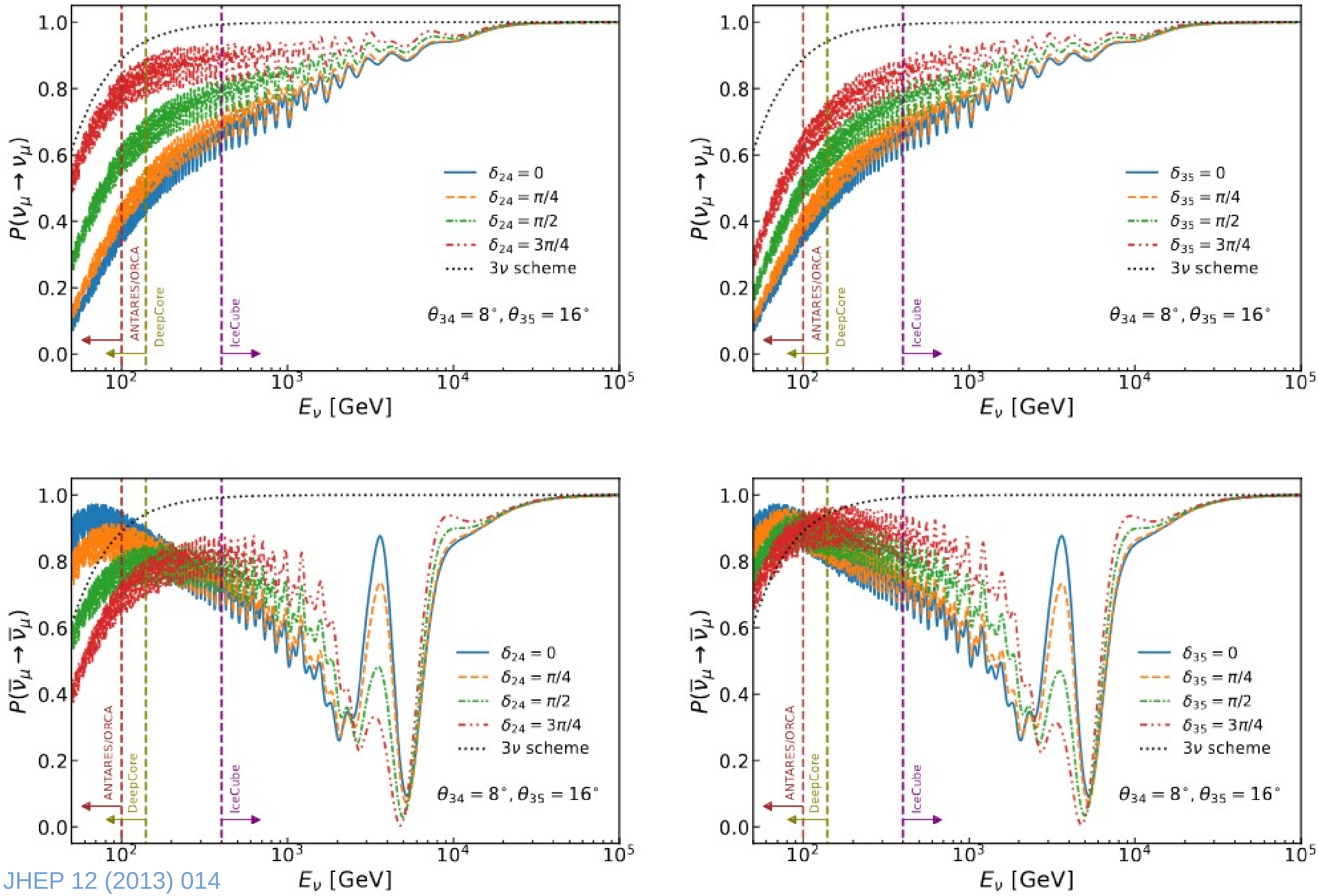
https://doi.org/10.48550/arXiv.2405.10419

Thanks
Gracias
Obrigado
Mercy
Grazie
Danke
Arigato
Xièxiè

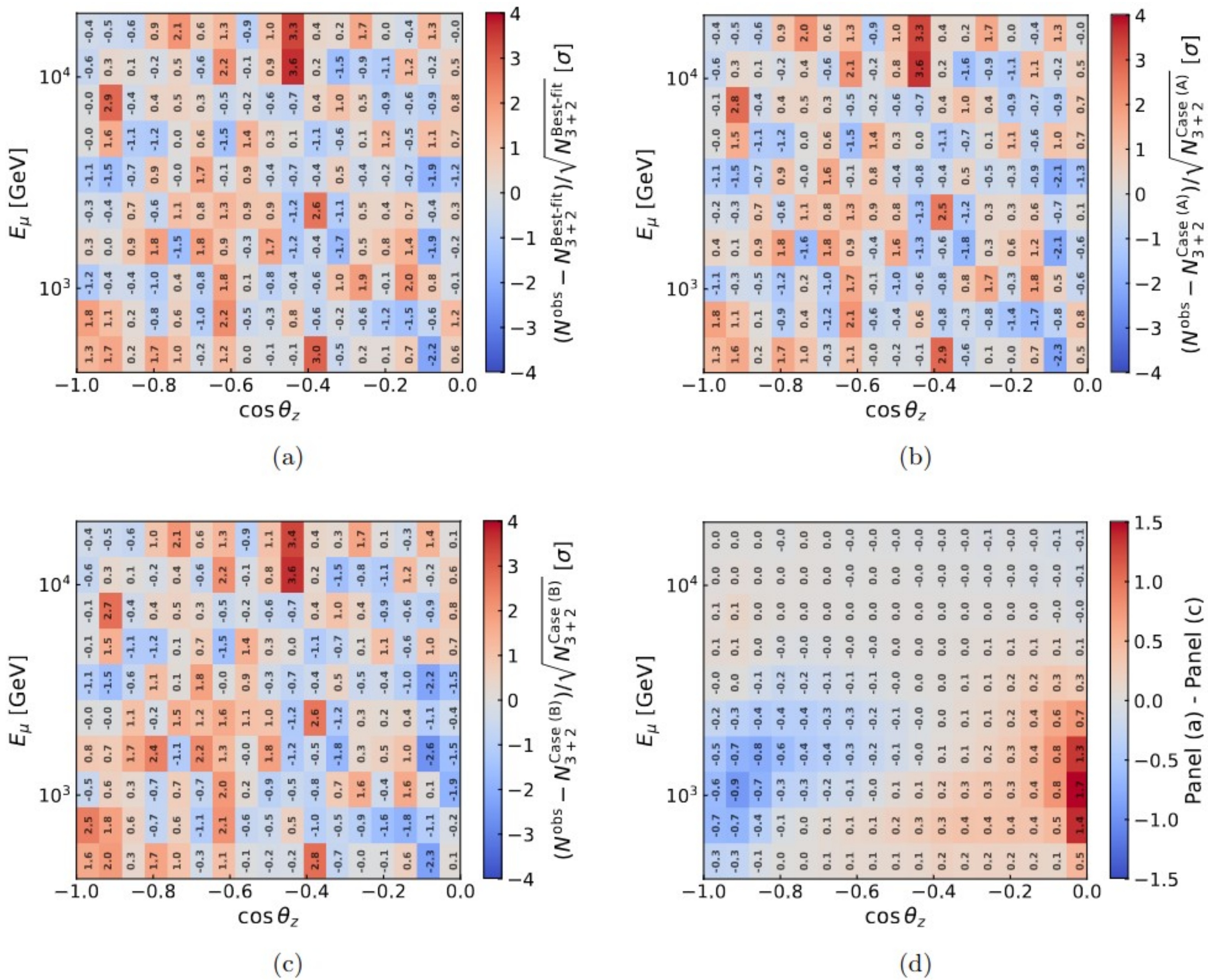
Backup

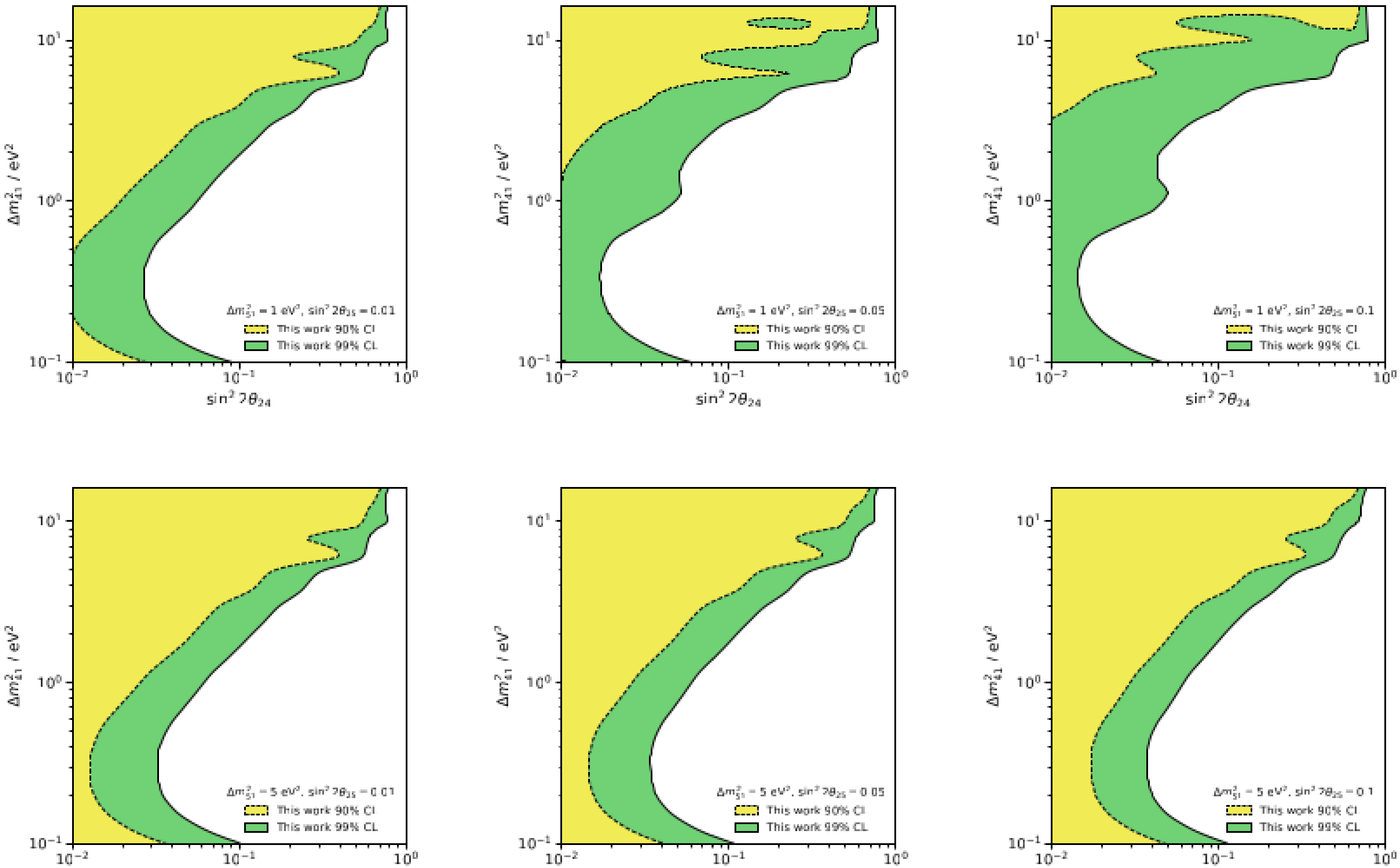


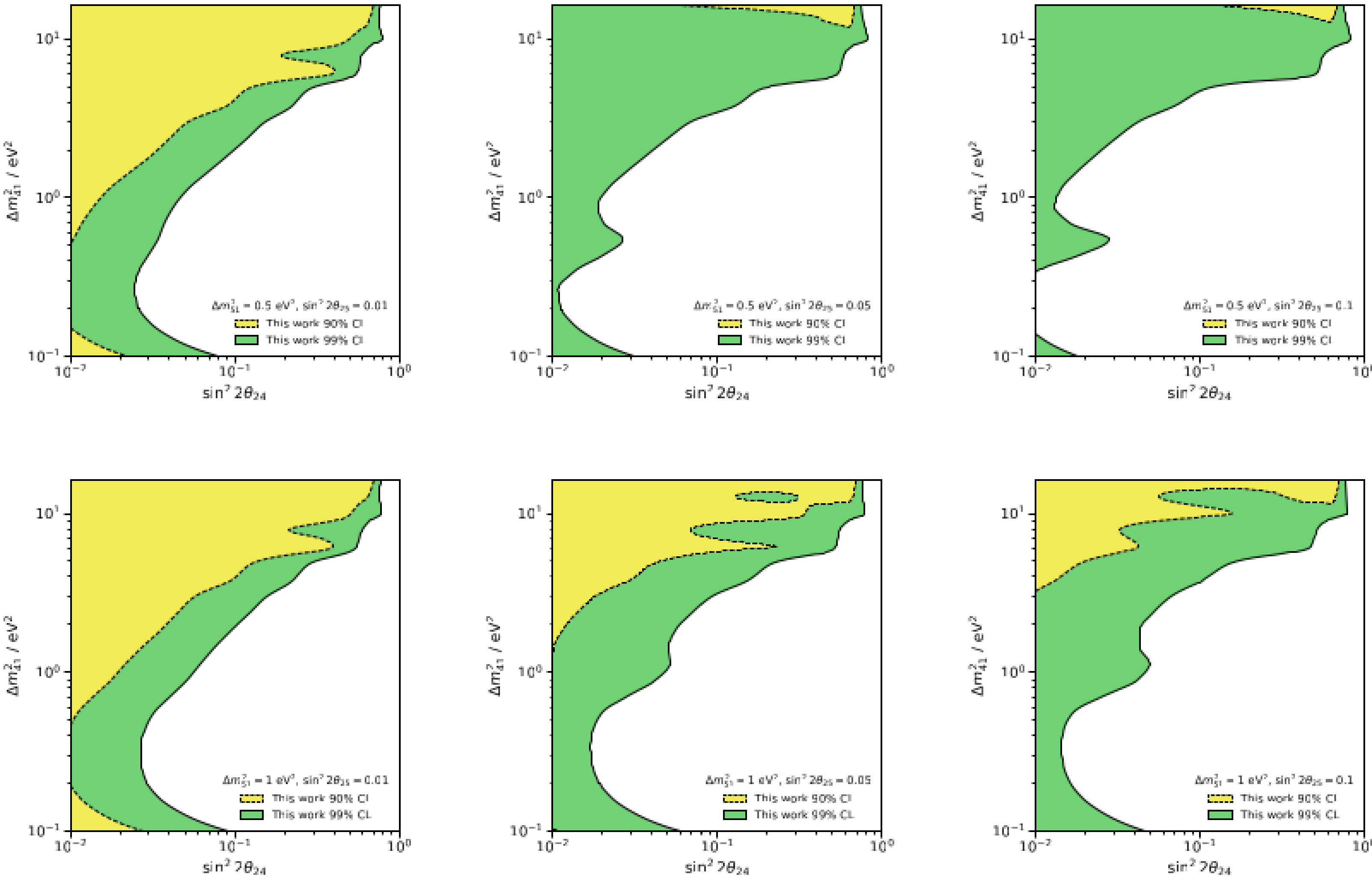
$\theta_{34} = 0^\circ$
$\theta_{34} = 8^\circ$
$\theta_{34} = 16^\circ$
$\theta_{35} = 0^\circ$
$\theta_{35} = 8^\circ$
$\theta_{35} = 16^\circ$
ANTARES/ORCA
DeepCore
IceCube
$P(\nu_\mu \to \nu_\mu)$, $P(\overline{\nu}_\mu \to \overline{\nu}_\mu)$
E_ν [GeV]
$(3+2)\nu_\mu$
$(3+2)\overline{\nu}_\mu$
3ν scheme



Esmaili and Smirnov JHEP 12 (2013) 014
A discusion about the CP violating phases


E_μ [GeV]
$\cos\theta_z$
$(N^{obs} - N^{Best-fit}_{3+2})/\sqrt{N^{Best-fit}_{3+2}}$ [σ]
(a)
$(N^{obs} - N^{Case\,(A)}_{3+2})/\sqrt{N^{Case\,(A)}_{3+2}}$ [σ]
(b)
$(N^{obs} - N^{Case\,(B)}_{3+2})/\sqrt{N^{Case\,(B)}_{3+2}}$ [σ]
(c)
Panel (a) - Panel (c)
(d)


Δm^2_{41} / eV^2
$\sin^2 2\theta_{24}$
Δm^2_{51} = 1 eV^2, $\sin^2 2\theta_{25}$ = 0.01
Δm^2_{51} = 1 eV^2, $\sin^2 2\theta_{25}$ = 0.05
Δm^2_{51} = 1 eV^2, $\sin^2 2\theta_{25}$ = 0.1
Δm^2_{51} = 5 eV^2, $\sin^2 2\theta_{25}$ = 0.01
Δm^2_{51} = 5 eV^2, $\sin^2 2\theta_{25}$ = 0.05
Δm^2_{51} = 5 eV^2, $\sin^2 2\theta_{25}$ = 0.1
This work 90% CL
This work 99% CL


Δm^2_{41} / eV^2
$\sin^2 2\theta_{24}$
$\Delta m^2_{51} = 0.5$ eV^2, $\sin^2 2\theta_{25} = 0.01$
$\Delta m^2_{51} = 0.5$ eV^2, $\sin^2 2\theta_{25} = 0.05$
$\Delta m^2_{51} = 0.5$ eV^2, $\sin^2 2\theta_{25} = 0.1$
$\Delta m^2_{51} = 1$ eV^2, $\sin^2 2\theta_{25} = 0.01$
$\Delta m^2_{51} = 1$ eV^2, $\sin^2 2\theta_{25} = 0.05$
$\Delta m^2_{51} = 1$ eV^2, $\sin^2 2\theta_{25} = 0.1$
This work 90% CI
This work 99% CI