NSI with IceCube

Jordi Salvado

NTN Workshop on Neutrino Non-Standard Interactions

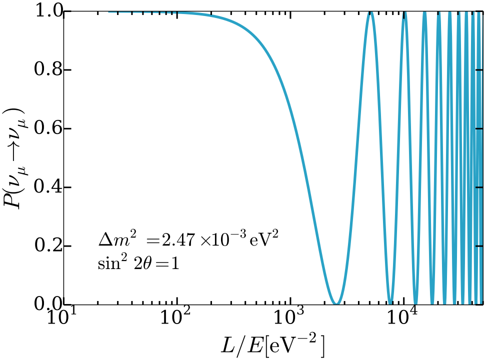
Neutrino Oscillations

$$H = \frac{1}{2E} U M^2 U^\dagger + V_m$$

M, V and U are 3×3 matrices. In two generations the oscillation probability at a given distance L and energy E in vacuum

$$P_{\nu_\alpha \to \nu_\alpha}\left(\frac{L}{E}\right) = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

- $\sin^2 2\theta$: oscillation amplitude
- Δm^2: oscillation frequency
  - $L/E \ll 1/\Delta m^2 \to$ no oscillations
  - $L/E \sim 1/\Delta m^2 \to$ oscillations
  - $L/E \gg 1/\Delta m^2 \to$ fast oscillations ("averaged")



Neutrino Oscillations Quantum Evolution

- Neutrinos propagate in a non trivial way.
- Well described by 3D quantum mechanics coherent evolution.

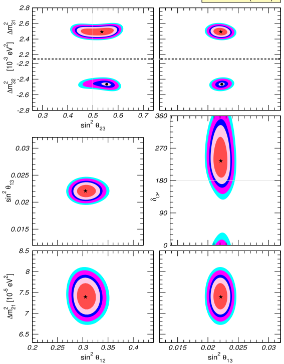
$$H = U \begin{pmatrix} \varepsilon_1 & 0 & 0 \\ 0 & \varepsilon_2 & 0 \\ 0 & 0 & \varepsilon_3 \end{pmatrix} U^\dagger + \begin{pmatrix} V_{NC}+V_{CC} & 0 & 0 \\ 0 & V_{NC} & 0 \\ 0 & 0 & V_{NC} \end{pmatrix}$$

Using the dispersion relation $\varepsilon_i^2 = p^2 + m_i^2$

$$H = \frac{1}{2E} U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} U^\dagger + \begin{pmatrix} V_{NC}+V_{CC} & 0 & 0 \\ 0 & V_{NC} & 0 \\ 0 & 0 & V_{NC} \end{pmatrix}$$

- Quantum interference is very sensible to small parameters $\Delta m_{21}^2 = 7.4 \times 10^{-5}\mathrm{eV}^2$ and $\Delta m_{31}^2 = 2.49 \times 10^{-3}\mathrm{eV}^2$
- Can we use that?

Current knowledge



NuFIT 3.2 (2018)

$$|U|_{3\sigma} = \begin{pmatrix} 0.799 \to 0.844 & 0.516 \to 0.582 & 0.141 \to 0.156 \\ 0.242 \to 0.494 & 0.467 \to 0.678 & 0.639 \to 0.774 \\ 0.284 \to 0.521 & 0.490 \to 0.695 & 0.615 \to 0.754 \end{pmatrix}$$

JHEP 01 (2017) 087 Ivan Esteban et al.
Prog.Part.Nucl.Phys. 102 (2018) 48-72 F. Capozzi et al.
Phys.Lett. B782 (2018) 633-640 P.F. de Salas et al.

www.nu-fit.org

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Non-standard interactions with matter

NSI

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- Can we use that?

Non-Standard Interactions

- We can test non-standard interactions with ordinary matter.

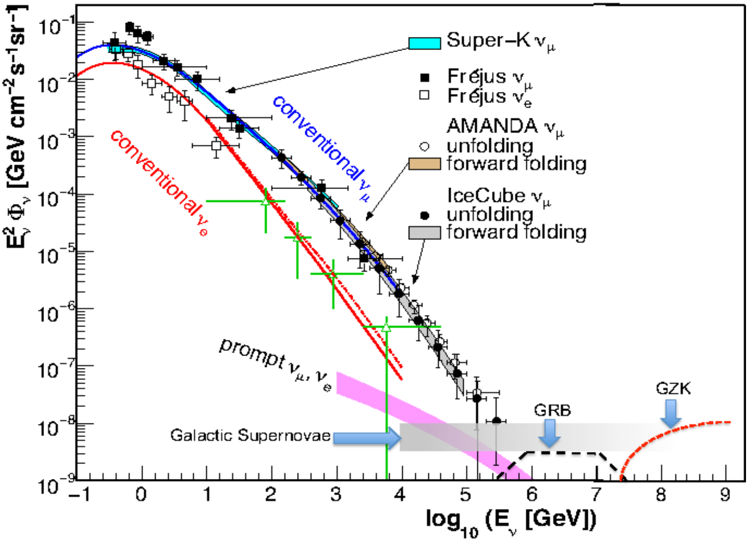
$$\mathcal{L}_{\text{NSI}} = -2\sqrt{2}G_F\left[\sum_{\alpha,\beta}\varepsilon^{\eta}_{\alpha\beta}(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)\right]\left[\sum_{f,P}\xi^{f,P}(\bar{f}\gamma_\mu P f)\right]$$

- This induces a modification in the matter potential.

$$H = \frac{1}{2E}U\begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^\dagger + \sqrt{2}G_F N_e(x)\begin{pmatrix} 1+\varepsilon_{ee}(x) & \varepsilon_{e\mu}(x) & \varepsilon_{e\tau}(x) \\ \varepsilon^*_{e\mu}(x) & \varepsilon_{\mu\mu}(x) & \varepsilon_{\mu\tau}(x) \\ \varepsilon^*_{e\tau}(x) & \varepsilon^*_{\mu\tau}(x) & \varepsilon_{\tau\tau}(x)\end{pmatrix}$$

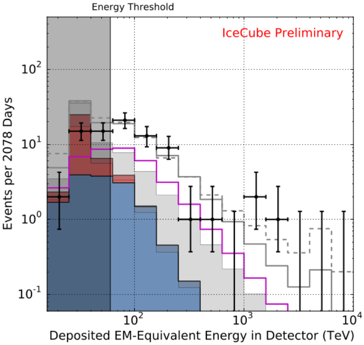
$$\varepsilon_{\alpha\beta}(x) = \varepsilon^{\eta}_{\alpha\beta}\left[\xi^p + Y_n(x)\xi^n\right] \quad \text{with} \quad \xi^p = \sqrt{5}\cos\eta \quad \xi^n = \sqrt{5}\sin\eta$$

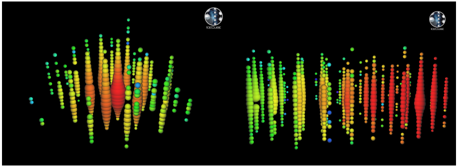
Icecube Energy Range

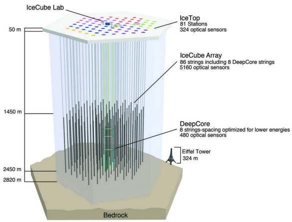


IceCube Discovery

- More that 5σ evidence.
- Consistent with the other limits.
- We have 82 neutrinos from few 100GeV to few PeV
- Still a lot of questions

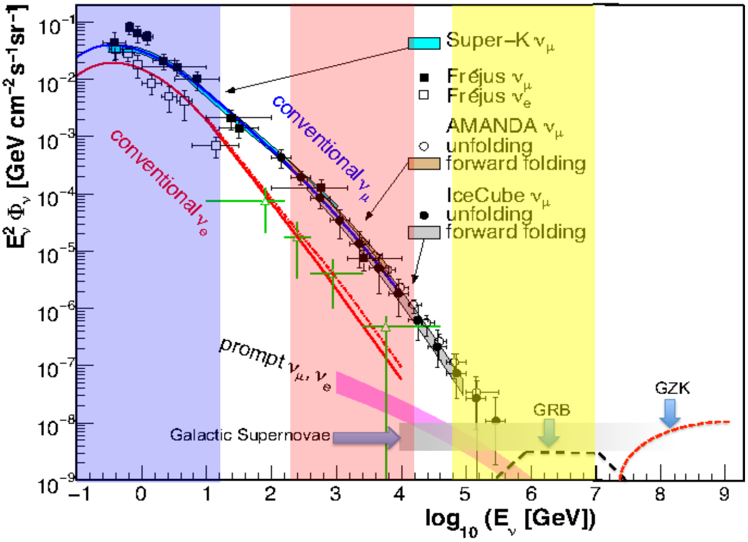




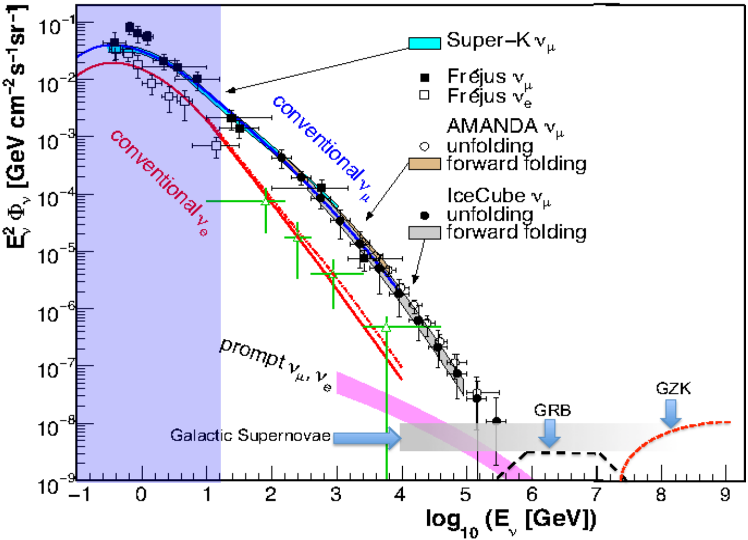


First Publication: Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

Icecube Energy Range (Different possibilitie)

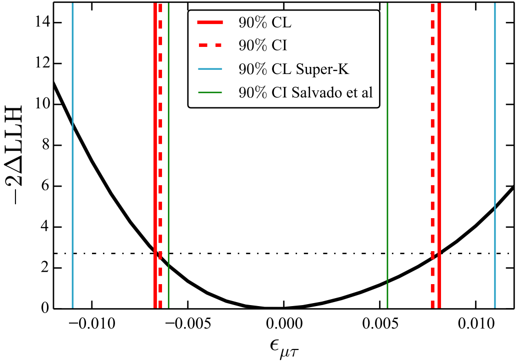


Icecube Energy Range Low Energy with DeepCore



Low energy

Physical Review D97,072009 (2018) IceCube Col.

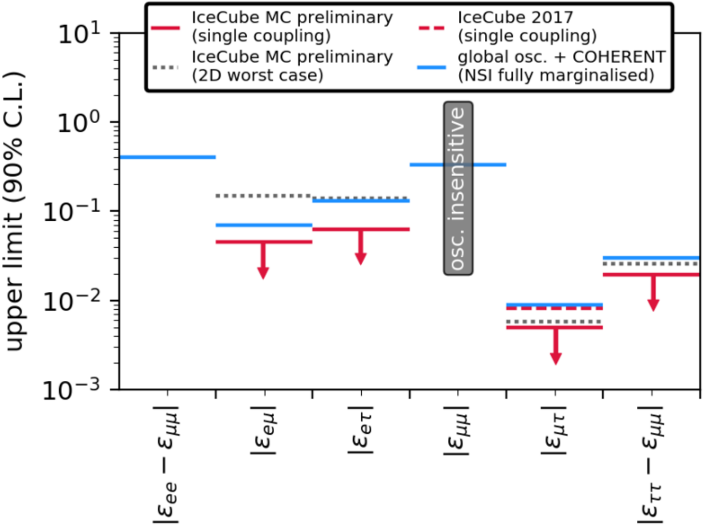


Some uncertanties

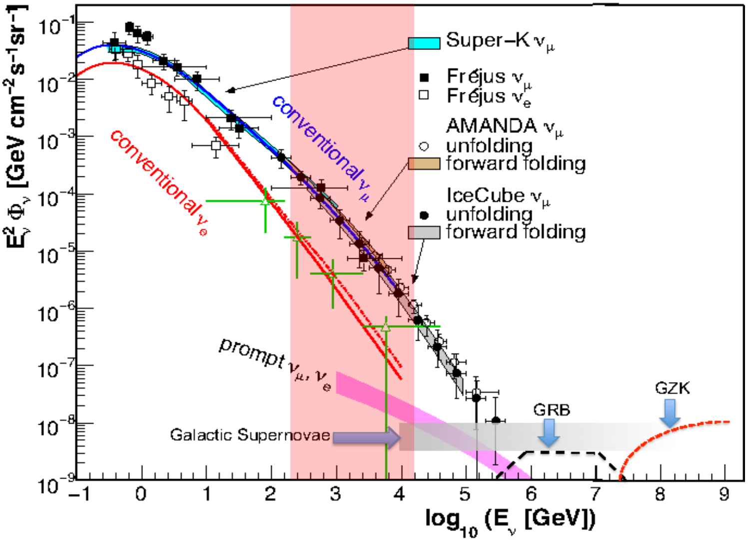
- π/K ratio
- Normalization
- Spectral Tilt
- DOM eff
- Ice Properties

Icecube Energy Range Low Energy with DeepCore

Soon more results for the low energy



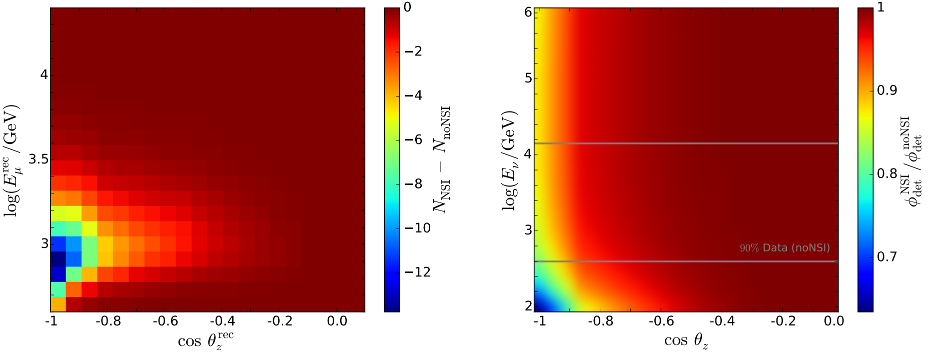
Icecube Energy Range Medium Energy, Used for Steriles



Icecube Energy Range Medium Energy, Used for Steriles

JHEP 1701 (2017) 141 JS, O. Mena, S. Palomares-Ruiz, N. Rius

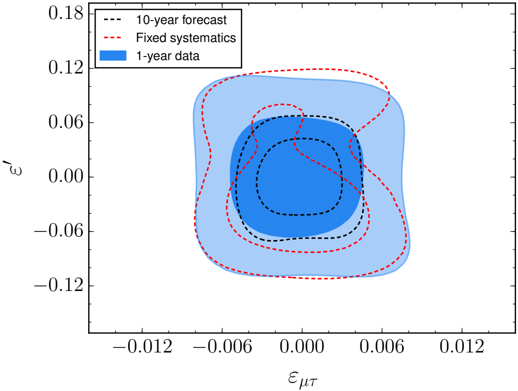
With 1 year of IceCube muon data



Zenith seams the place to look at this energies due to non oscillations.

Icecube Energy Range Medium Energy, Used for Steriles

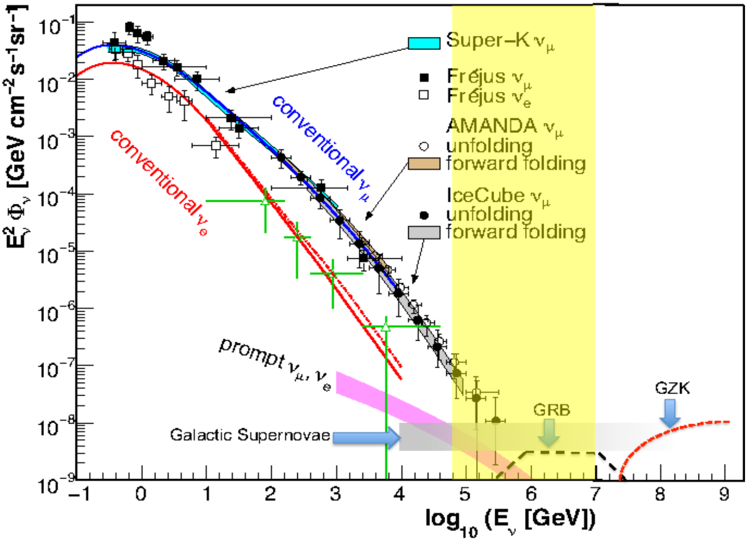
JHEP 1701 (2017) 141 JS, O. Mena, S. Palomares-Ruiz, N. Rius



Some uncertanties

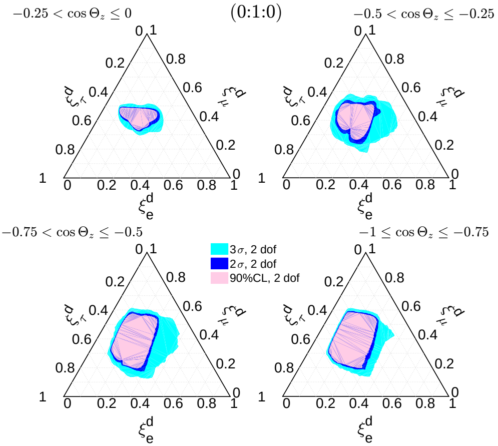
- π/K ratio
- Normalization
- Spectral Tilt
- Primordial CR and Hadronic Models
- DOM eff
- Ice Properties

Icecube Energy Range: The highest energy



IceCube Energy Range: The highest energy

Astropart.Phys. 84 (2016) 15-22 M.C. Gonzalez-Garcia, M. Maltoni, I. Martinez-Soler, N. Song

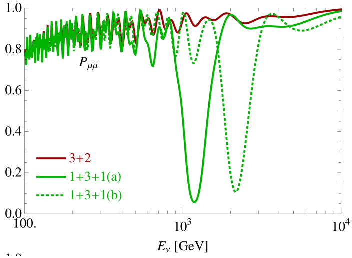


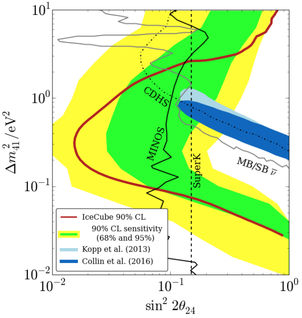
Regions in the flavor triangle with NSI

- The flavor content may change for different zenith angles.
- Very hard to measure, we need a lot more statistics.
- Generically better to test Lorentz violation.

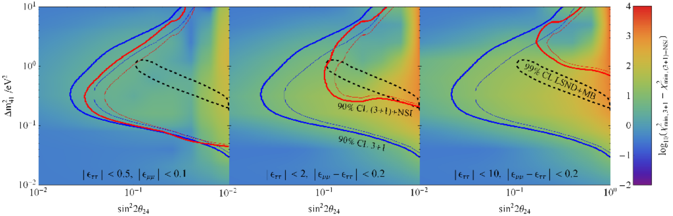
NSI questioning sterile neutrinos

Phys.Rev.Lett. 117 (2016) no.7, 071801



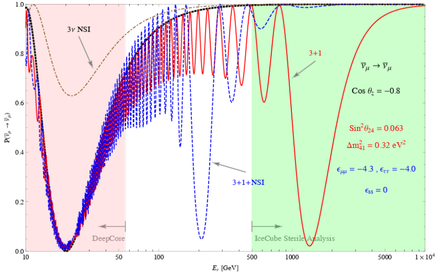


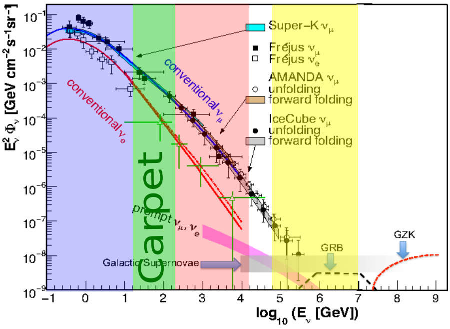
- NSI may move the resonance and remove the sensitivity.



J. Liao, D. Marfatia Phys. Rev. Lett. 117, 071802 (2016)

NSI questioning sterile neutrinos

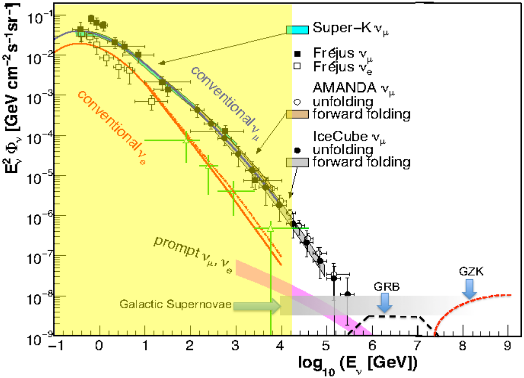




- Liao and Marfatia just hide the resonance under the carpet!
- Carpet ≡ never looked atmospheric neutrino spectrum between the midium and low energy.

A. Esmaili, H. Nunokawa, Eur.Phys.J. C79 (2019) no.1, 70

Why not the full Energy Range



- Technically not as easy as it looks.
- IceCube at High energy can have a good reconstruction, not so good in the non analyzed.
- In the low energy IceCube is more a veto for the Deepcore region.
- Systematic error are less correlated than what may seam. Pion vs Kaon, ...

NSI or not NSI

10.1007/JHEP04(2017)153 M. Blennow, P. Coloma, E. Fernandez-Martinez, J. Hernandez-Garcia, J. Lopez-Pavon

Eur.Phys.J. C78 (2018) no.10, 807 M. Blennow, E. Fernandez-Martinez, J. Gehrlein, J. Hernandez-Garcia, JS

Heavy but still kinematically allowed sterile neutrinos look like NSI
The mixing matrix with sterile neutrinos can be written as:

$$\mathcal{U} = \begin{pmatrix} N & \Theta \\ R & S \end{pmatrix}, \quad (1)$$

$$S_{\alpha\beta} = \sum_{i \in \text{light}} N_{\alpha i} S^0_{ij} N^*_{\beta j} + \sum_{J \in \text{heavy}} \Theta_{\alpha J} \Theta^*_{\beta J} \Phi_J, \quad (2)$$

FAST, Averaged out

NSI or not NSI

10.1007/JHEP04(2017)153 M. Blennow, P. Coloma, E. Fernandez-Martinez, J. Hernandez-Garcia, J. Lopez-Pavon

Eur.Phys.J. C78 (2018) no.10, 807 M. Blennow, E. Fernandez-Martinez, J. Gehrlein, J. Hernandez-Garcia, JS

Heavy but still kinematically allowed sterile neutrinos look like NSI
In the averaged regime the full mixing matrix can be parameterized as:

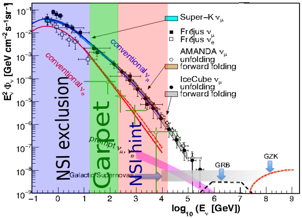
$$\begin{aligned} H &= \frac{1}{2E}\begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}{}^2 & 0 \\ 0 & 0 & \Delta m_{31}{}^2 \end{pmatrix} + \\ &+ \left((1-\alpha)N\right)^\dagger \begin{pmatrix} V_{\rm CC}+V_{\rm NC} & 0 & 0 \\ 0 & V_{\rm NC} & 0 \\ 0 & 0 & V_{\rm NC} \end{pmatrix} (1-\alpha)N \end{aligned}$$

$$\alpha \simeq \begin{pmatrix} \frac{1}{2}\left(s_{14}^2+s_{15}^2+s_{16}^2\right) & 0 & 0 \\ \hat{s}_{14}\hat{s}_{24}^* + \hat{s}_{15}\hat{s}_{25}^* + \hat{s}_{16}\hat{s}_{26}^* & \frac{1}{2}\left(s_{24}^2+s_{25}^2+s_{26}^2\right) & 0 \\ \hat{s}_{14}\hat{s}_{34}^* + \hat{s}_{15}\hat{s}_{35}^* + \hat{s}_{16}\hat{s}_{36}^* & \hat{s}_{24}\hat{s}_{34}^* + \hat{s}_{25}\hat{s}_{35}^* + \hat{s}_{26}\hat{s}_{36}^* & \frac{1}{2}\left(s_{34}^2+s_{35}^2+s_{36}^2\right) \end{pmatrix}$$

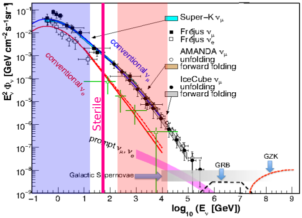
NSI or not NSI

Heavy but still **kinematically allowed** sterile neutrinos look like NSI

- Careful with blindly doing the full energy range study!



$\Longrightarrow$



- May be we should look there!

NSI or not NSI

- IceCube measures the atmospheric neutrino flux in the high energy region.
- Good for NSI spatially in the $\mu\tau$ sector.
- IceCube has a lot more data collected, 8 times more for the sterile!
- A careful full energy range would be great!