Effect of neutrino decay on sterile neutrino searches in IceCube

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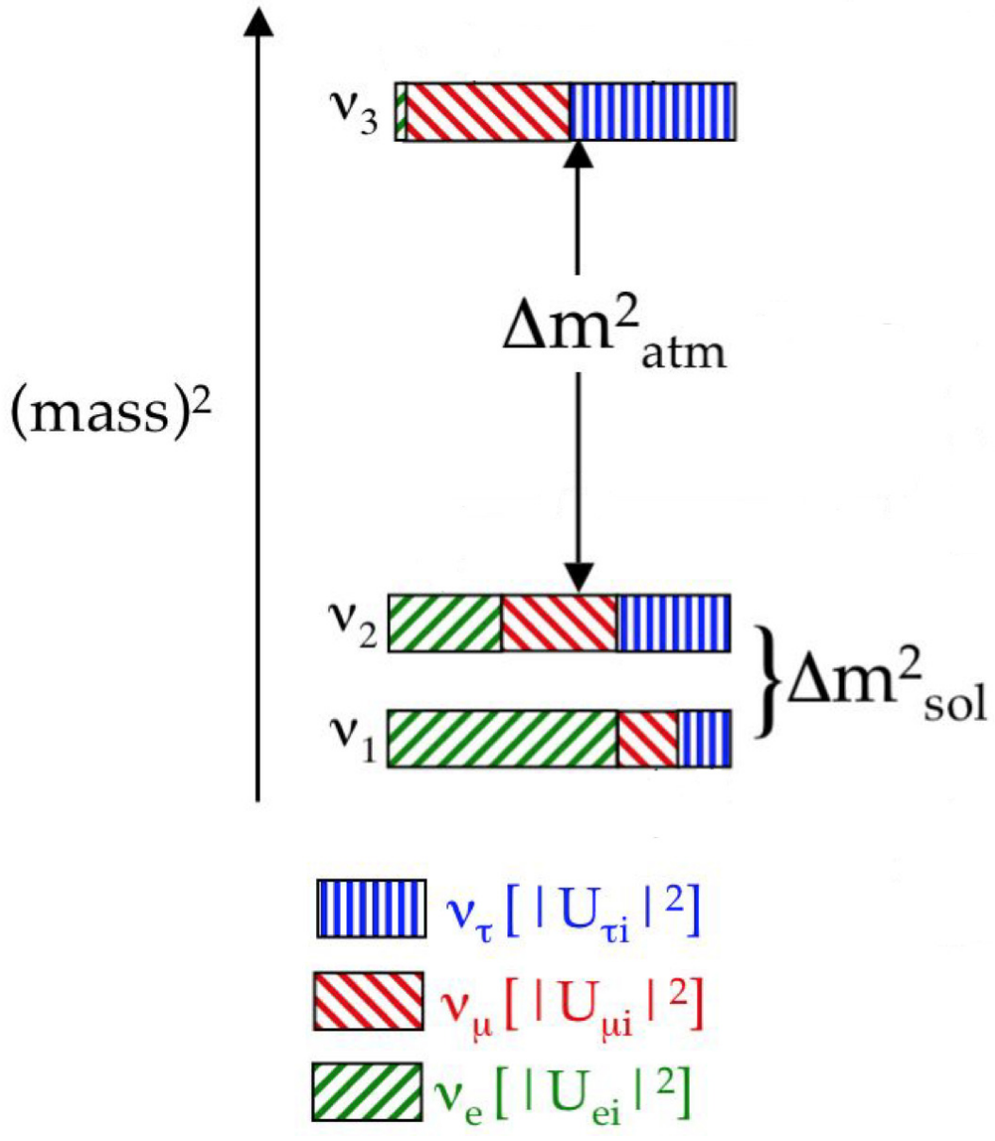
in collaboration with Z. Moss, M. Moulai, and J. Conrad

IPA,MADISON, MAY, 2017

Our current picture

Neutrino oscillations : mass eigenstates (ν_i; $i = 1, 2, 3$) and flavor eigenstates (ν_α; $\alpha = e, \mu, \tau$) are not the same.



$$\Delta m^2_{\rm sol} = 7.5 \times 10^{-5} {\rm eV}^2$$
$$|\Delta m^2_{\rm atm}| = 2.4 \times 10^{-3} {\rm eV}^2$$

$$\nu_i = \sum_\beta U_{\beta i} \nu_\beta$$

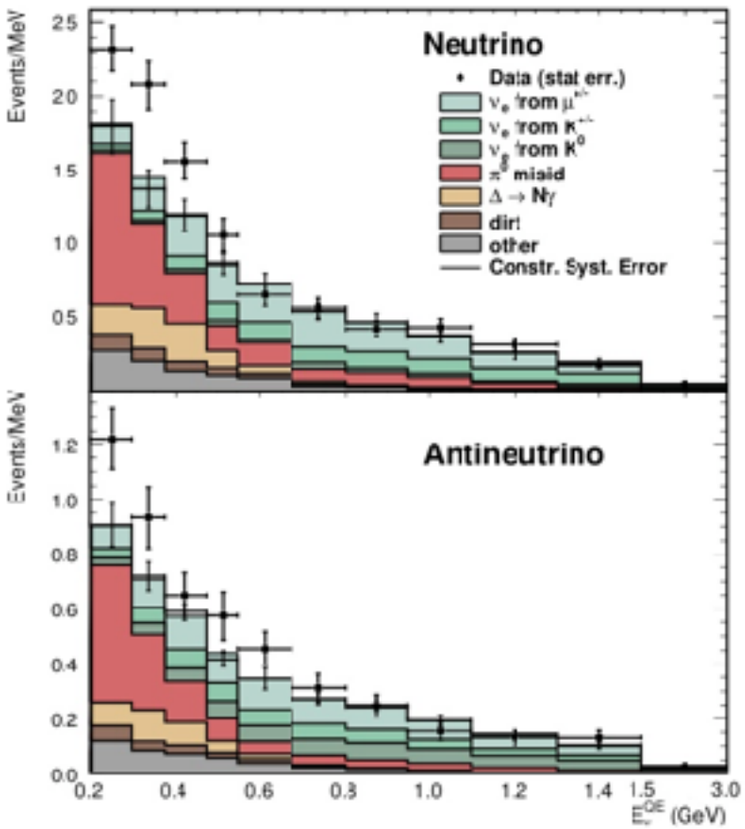
$$U = {\rm U}(\theta_{12}, \theta_{23}, \theta_{13}, \delta^{CP})$$

$$|{\rm U}| \simeq \begin{pmatrix} 0.8 & 0.5 & 0.1 \\ 0.3 & 0.7 & 0.6 \\ 0.4 & 0.5 & 0.8 \end{pmatrix}$$

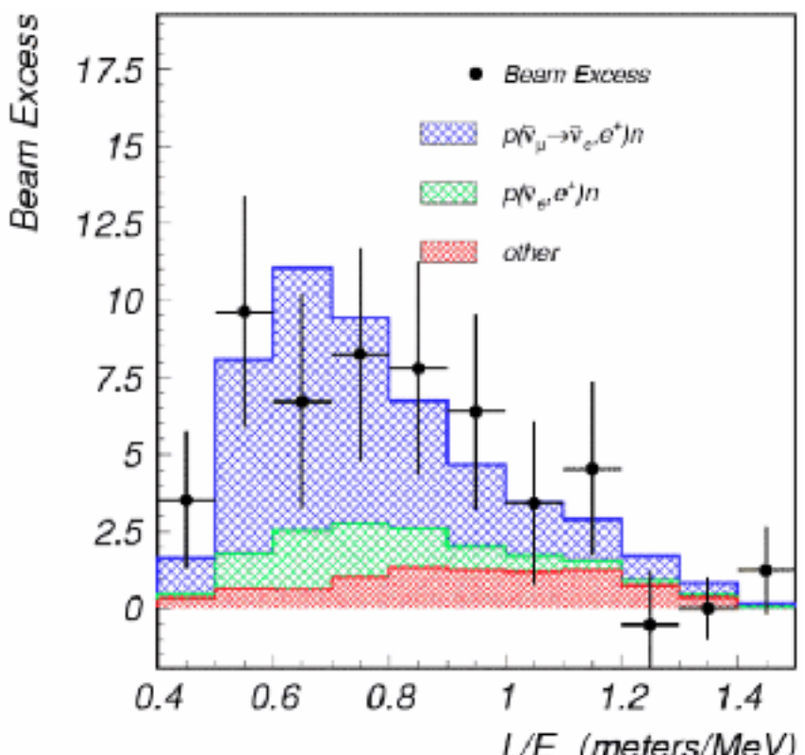
[B. Kayser, hep-ph/0506165 (2004)]

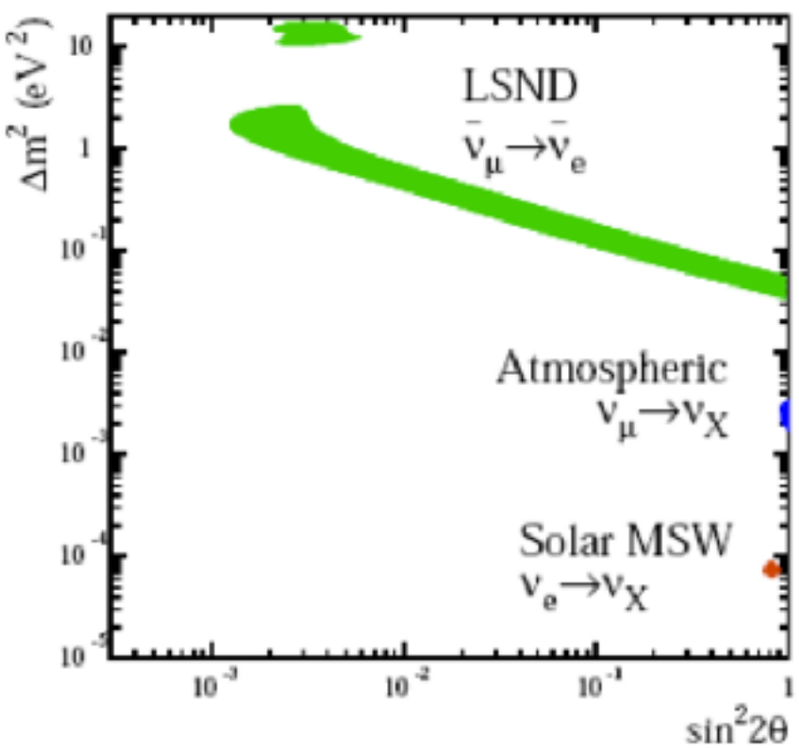
[C. Gonzalez-Garcia et al., JHEP 12 (2012)]

The pieces that do not fit …



Oscillation Channel	Class	Experiments	Oscillation amplitude
Electron Disappearance $P(\nu_e \rightarrow \nu_e)$	Reactor Experiments	GALLEX ($\underline{\nu}$) SAGE ($\underline{\nu}$) {Global Reactors}	$4\|U_{e4}\|^2 (1-\|U_{e4}\|^2)$
Muon Disappearance $P(\nu_\mu \rightarrow \nu_\mu)$	Long Baseline Experiments	Anomolous-less	$4\|U_{\mu 4}\|^2 (1-\|U_{\mu 4}\|^2)$
Electron Appearance $P(\nu_\mu \rightarrow \nu_e)$	Short Baseline Experiments	LSND ($\underline{\nu}$) MiniBooNe ($\underline{\nu}$, ν)	$4\|U_{\mu 4}\, U_{e4}\|^2$



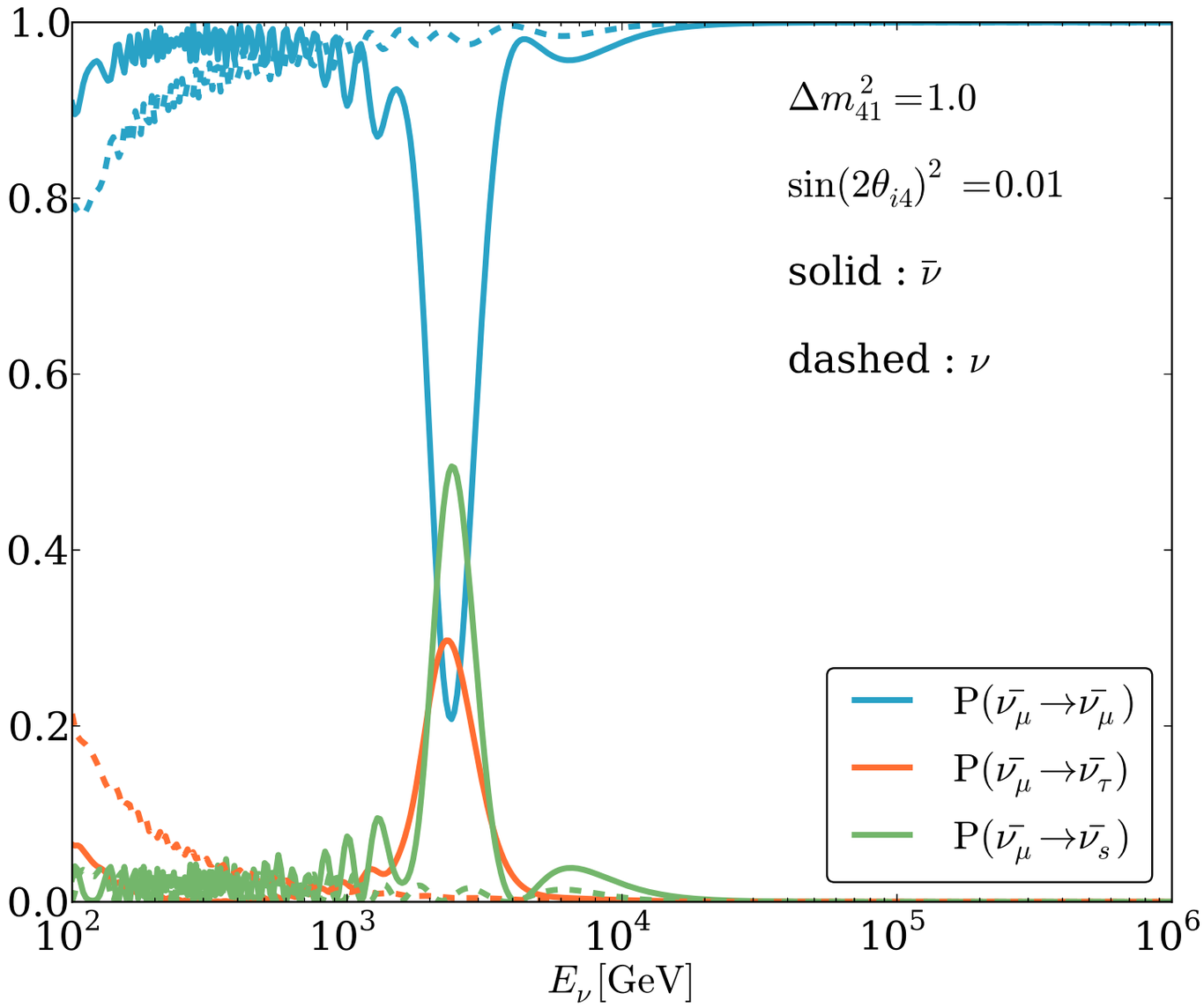


$$\Delta m^2 \sim 1\mathrm{eV}^2$$

Stroke of luck...

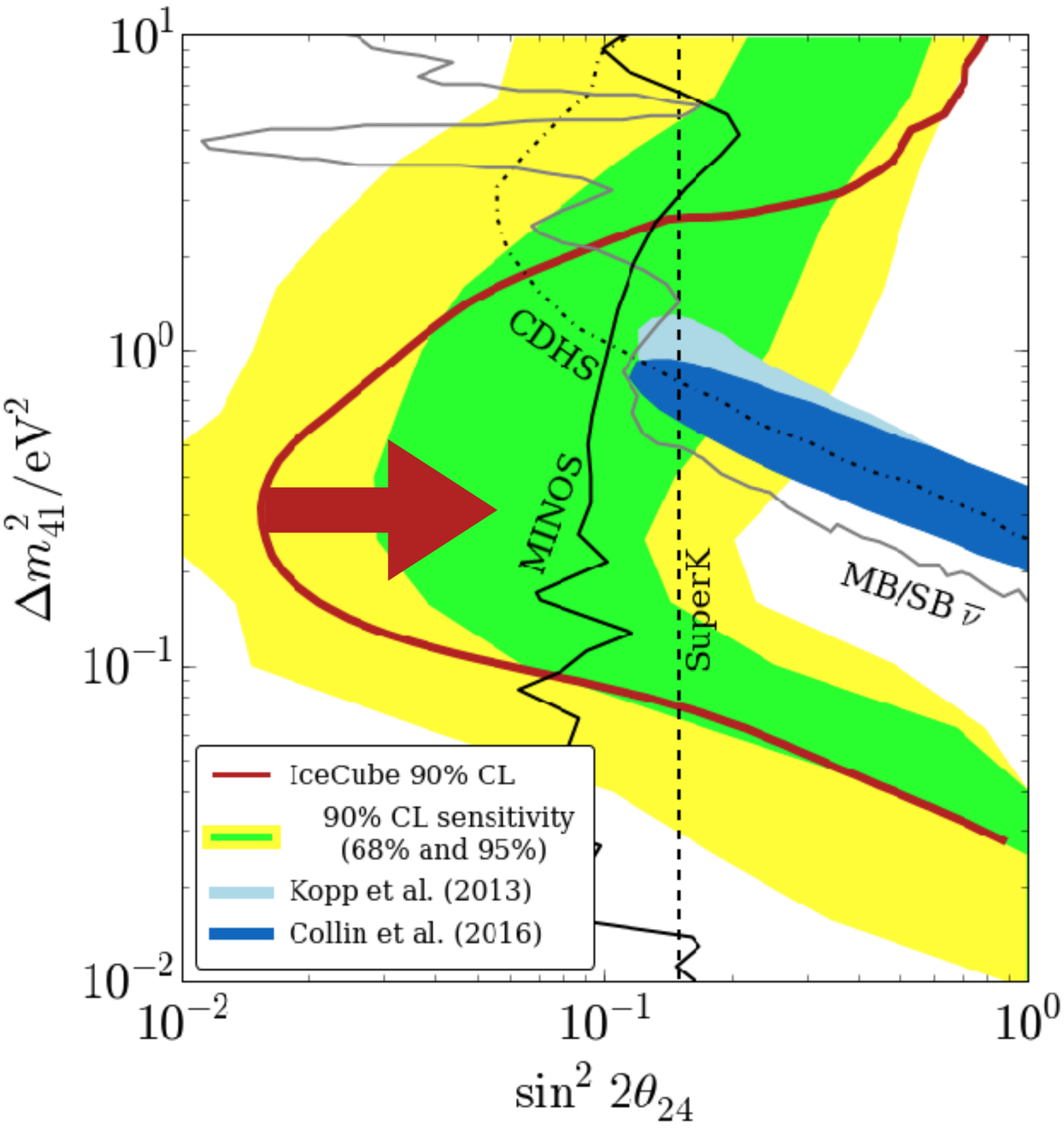
In the **Earth**, for sterile neutrino of $\Delta m^2 = O(1eV^2)$ there is a matter resonant effect when

$$E_\nu^{res} = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2} G_F N} \sim O(TeV)$$



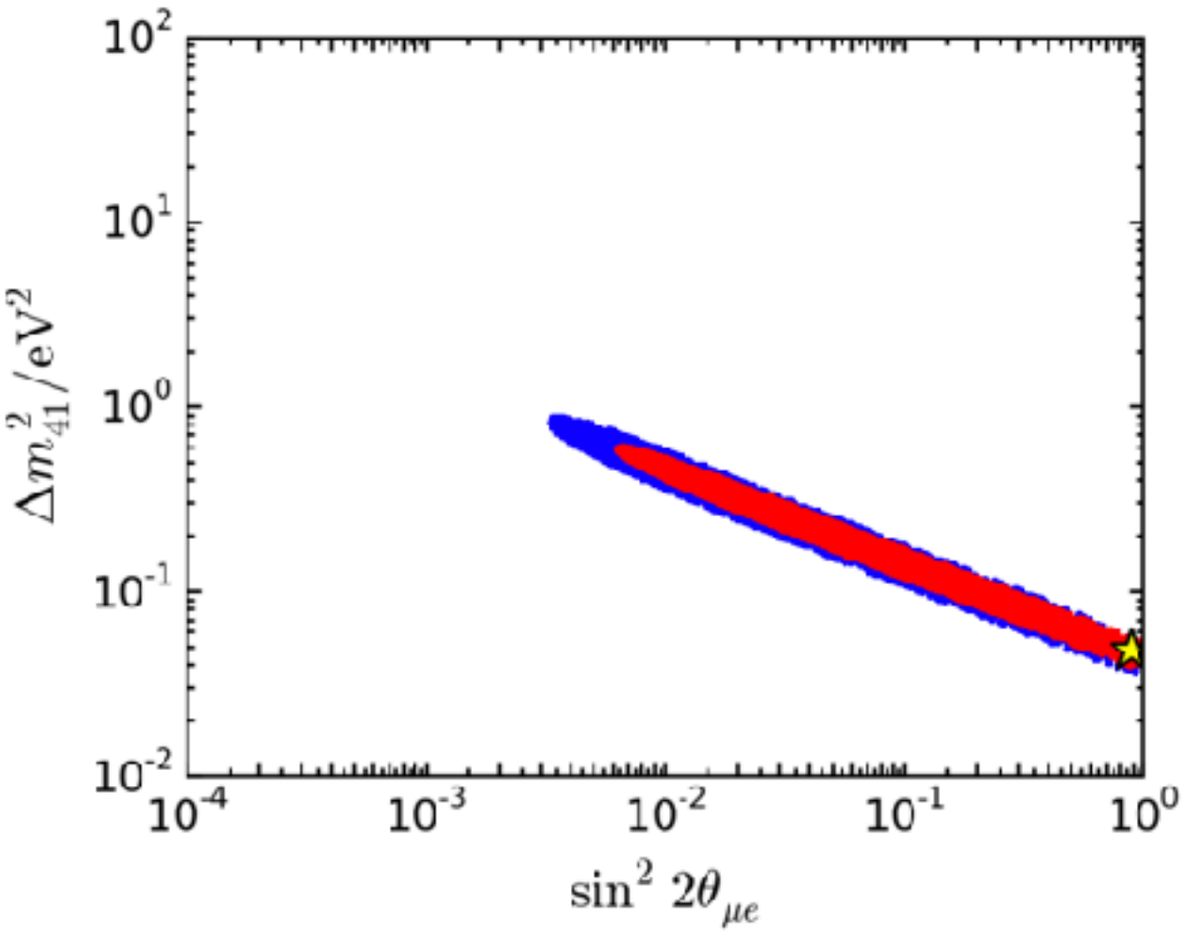
Nunokawa et al. PLB, B562, 279 (2003). arXiv:hep-ph/0302039

IceCube high-energy sterile neutrino result

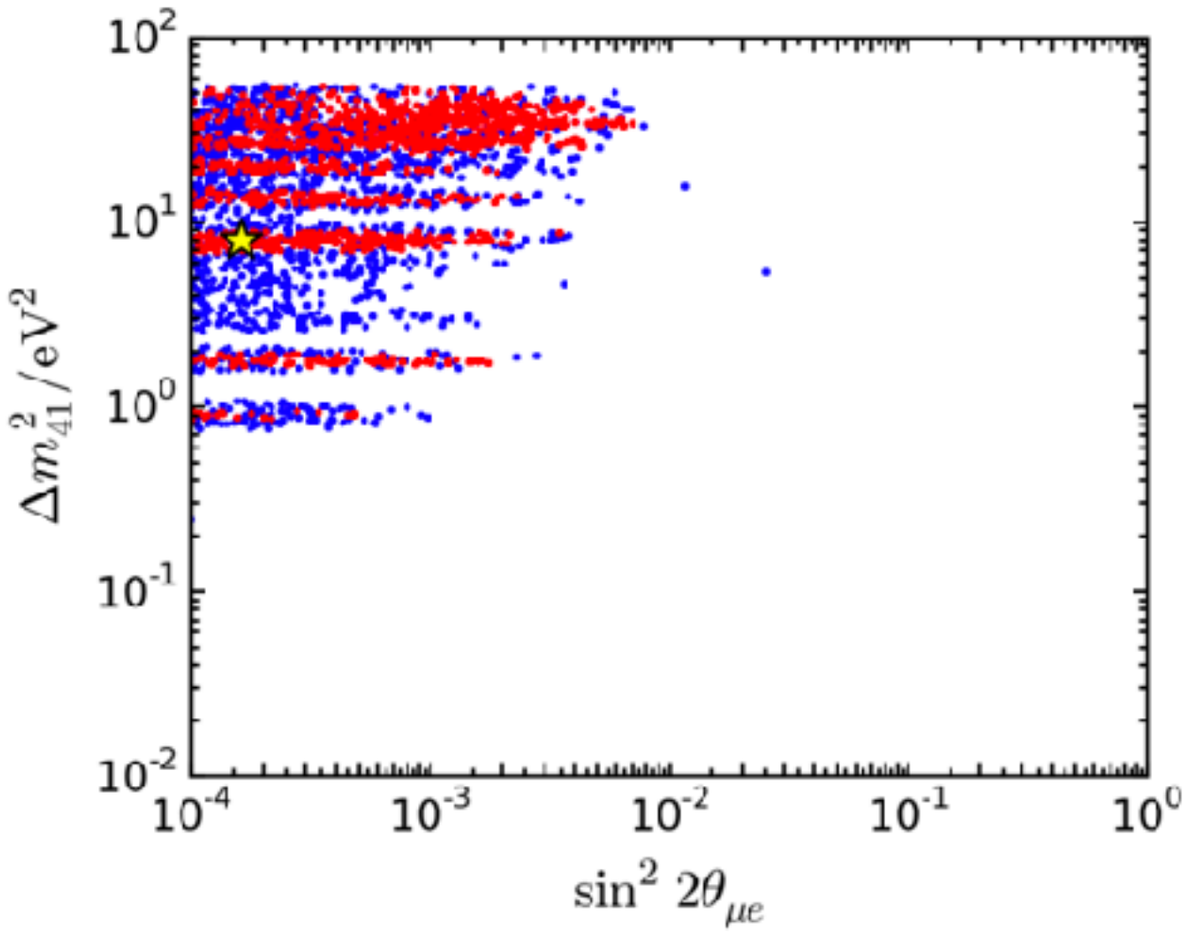


MORE TENSION!

What if it's not so *simple*?



(appearance)



(disappearance)

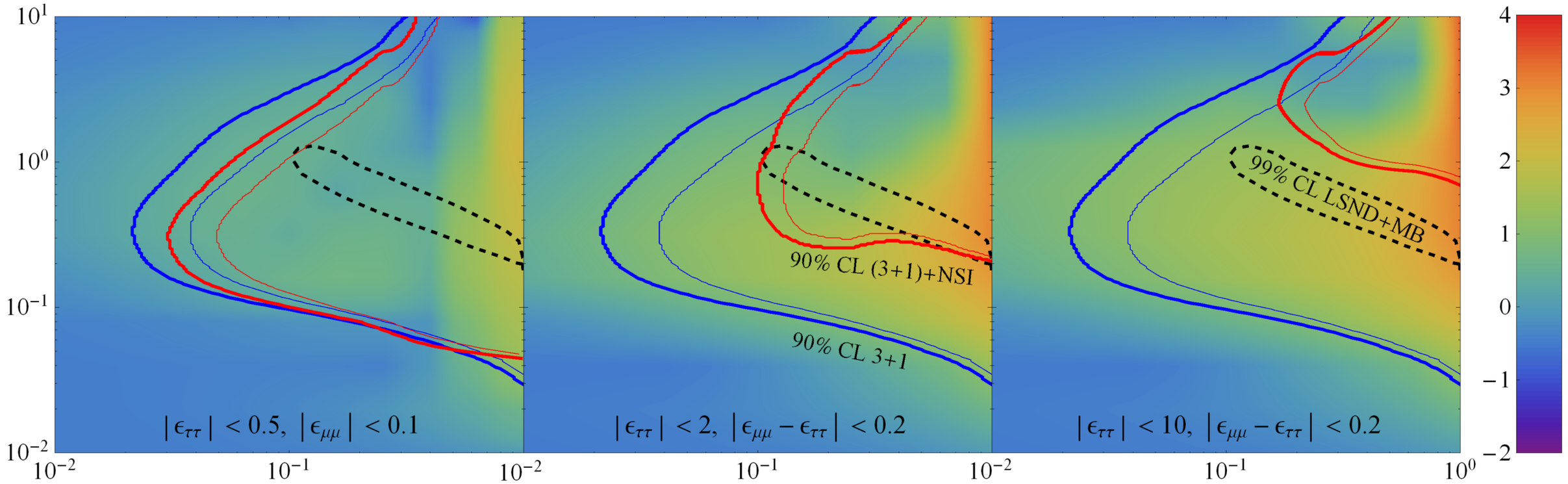
G.Collin, C.A., J. Conrad, M. Shaevitz (Nucl.Phys. B908 (2016), Phys.Rev.Lett. 117 (2016) no.22)

sterile neutrino + new element ?= all is good

For a extended discussion see **J. Conrad** talk in **this session**!

Sterile Neutrino + NSI

Increasing NSI strength



$$H = \frac{\Delta m^2_{41}}{2E_\nu}\left[\begin{pmatrix} 0 & s_{24}s_{34} & s_{24}c_{34} \\ s_{24}s_{34} & s^2_{34} & s_{34}c_{34} \\ s_{24}c_{34} & s_{34}c_{34} & c^2_{34} \end{pmatrix} + \hat{A}\begin{pmatrix} \epsilon_{\mu\mu} & \epsilon_{\mu\tau} & 0 \\ \epsilon_{\mu\tau} & \epsilon_{\tau\tau} & 0 \\ 0 & 0 & \kappa \end{pmatrix}\right]$$

Liao & Marfatia, Phys.Rev.Lett. 117 (2016) no.7, 071802

See also Pospelov (1103.3261), J. Kopp et al. (1408.0289), Cherry et al. (1411.1071), Y. Farzan (1505.06906), and X. Chu et al. (1505.02795)

Sterile Neutrino + Decay?

✤In the Standard Model (SM) stable particles are the ones *protected* by a symmetry.

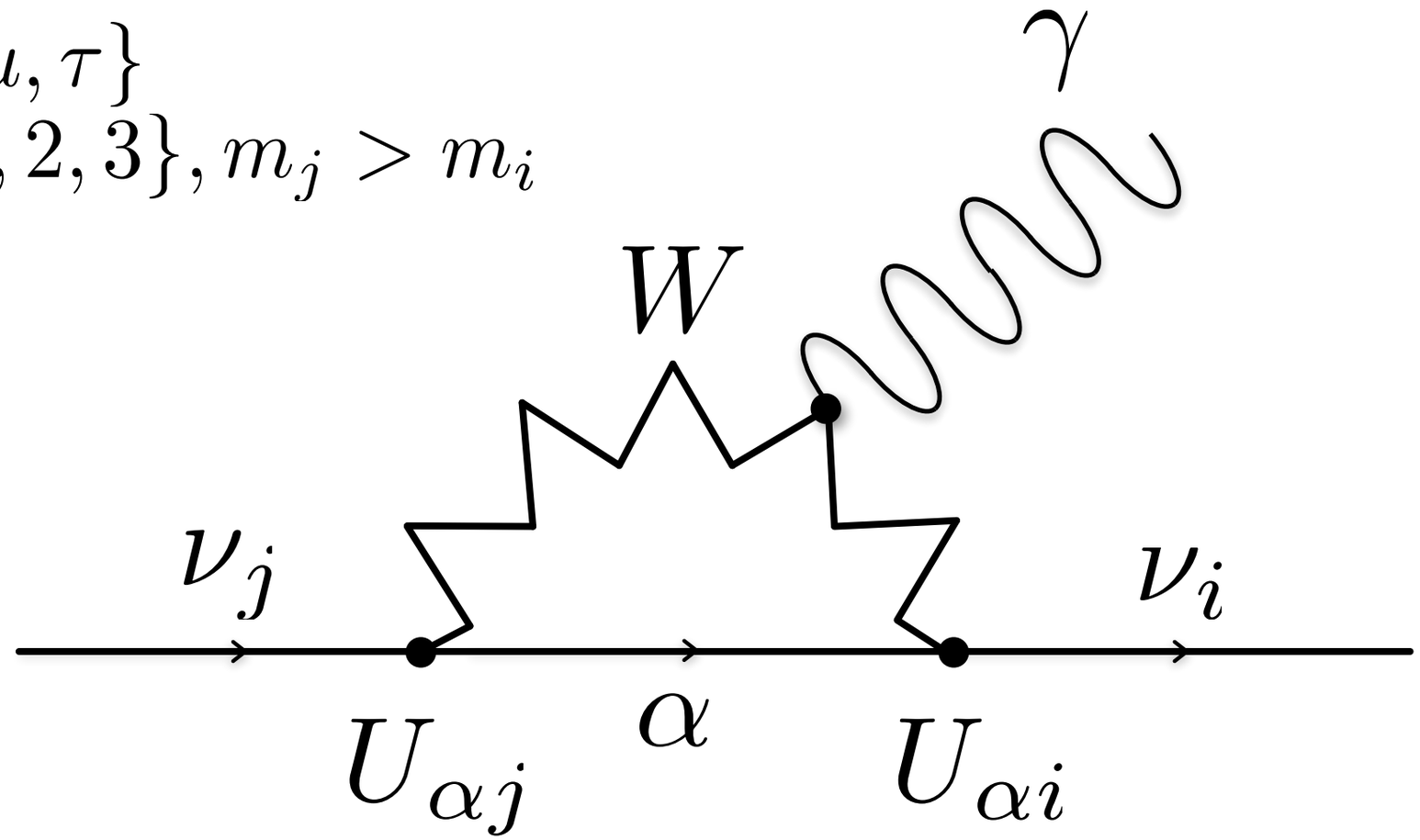
✤Heavy (keV-MeV) sterile neutrino decay has been considered before as an explanation of the LSND/MB anomaly, *e.g.*

- Palomares-Ruiz et al. (hep-ph/0505216),
- Gninenko (1009.5536),
- Dip et al. (1105.4664),
- Bai et al. (1512.05357),
- …

Our model: eV-sterile neutrino + decay!

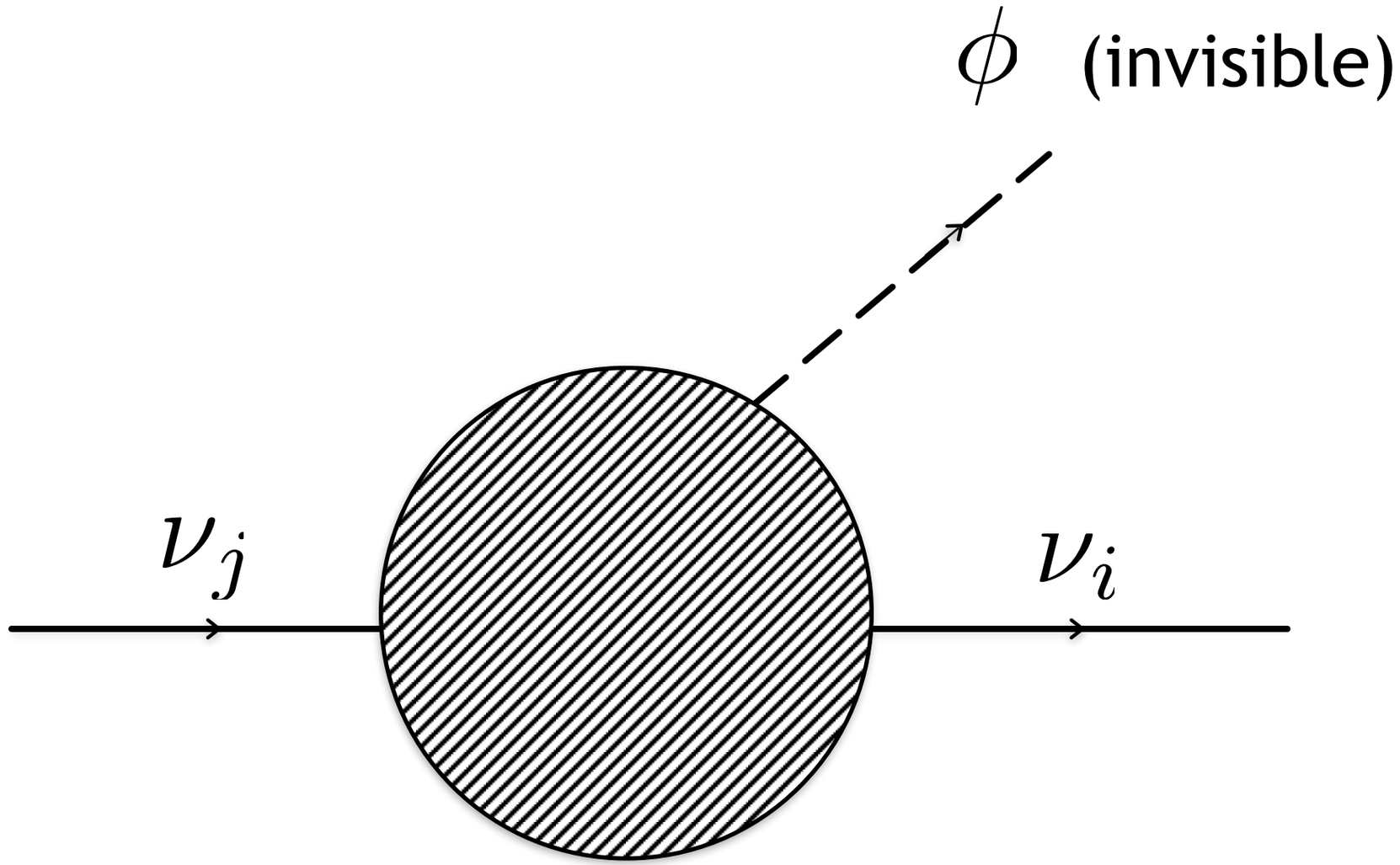
Standard model neutrino decay

$\alpha \in \{e, \mu, \tau\}$
$i, j \in \{1, 2, 3\}, m_j > m_i$



$$\nu_i \to \nu_j + \gamma : \quad \tau \simeq 10^{36}(m_i/eV)^{-5} yr$$
$$\nu_i \to \nu_j + \gamma + \gamma : \quad \tau \simeq 10^{57}(m_i/eV)^{-9} yr$$
$$\nu_i \to \nu_j + \nu_l + \bar{\nu}_k : \quad \tau \simeq 10^{55}(m_i/eV)^{-5} yr$$

BSM neutrino decay



"Active" neutrino decay is very constrained.

"Sterile" neutrino decay is mostly unconstrained.

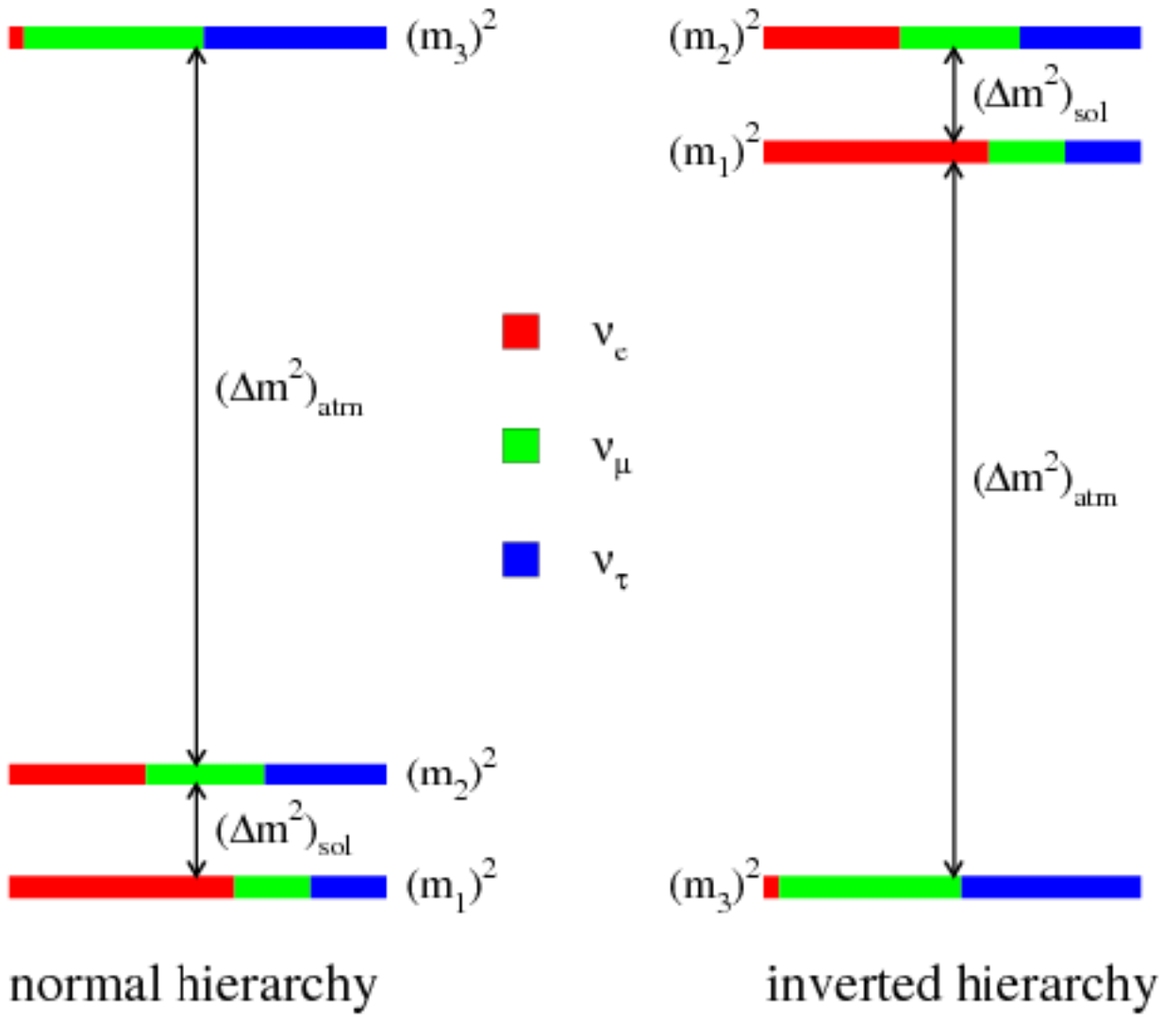
$$m_j > m_i$$

Choosing the decay channel

$$\boxed{\nu_4 \rightarrow \nu_3}$$

$$\nu_4 \nrightarrow \nu_2$$

$$\nu_4 \nrightarrow \nu_1$$



In a complete model we can allow decay to all lighter neutrinos, for the moment we assume a single decay channel.

Neutrino Oscillations + Decay

✤We use the nuSQuIDS package to calculate neutrino oscillations + decay.

oscillations regeneration

$$\frac{\partial \rho}{\partial x} = -i[\tilde{H}_0, \rho] - \frac{1}{2}\{\Gamma, \rho\} + \mathcal{R}(E)$$

decay

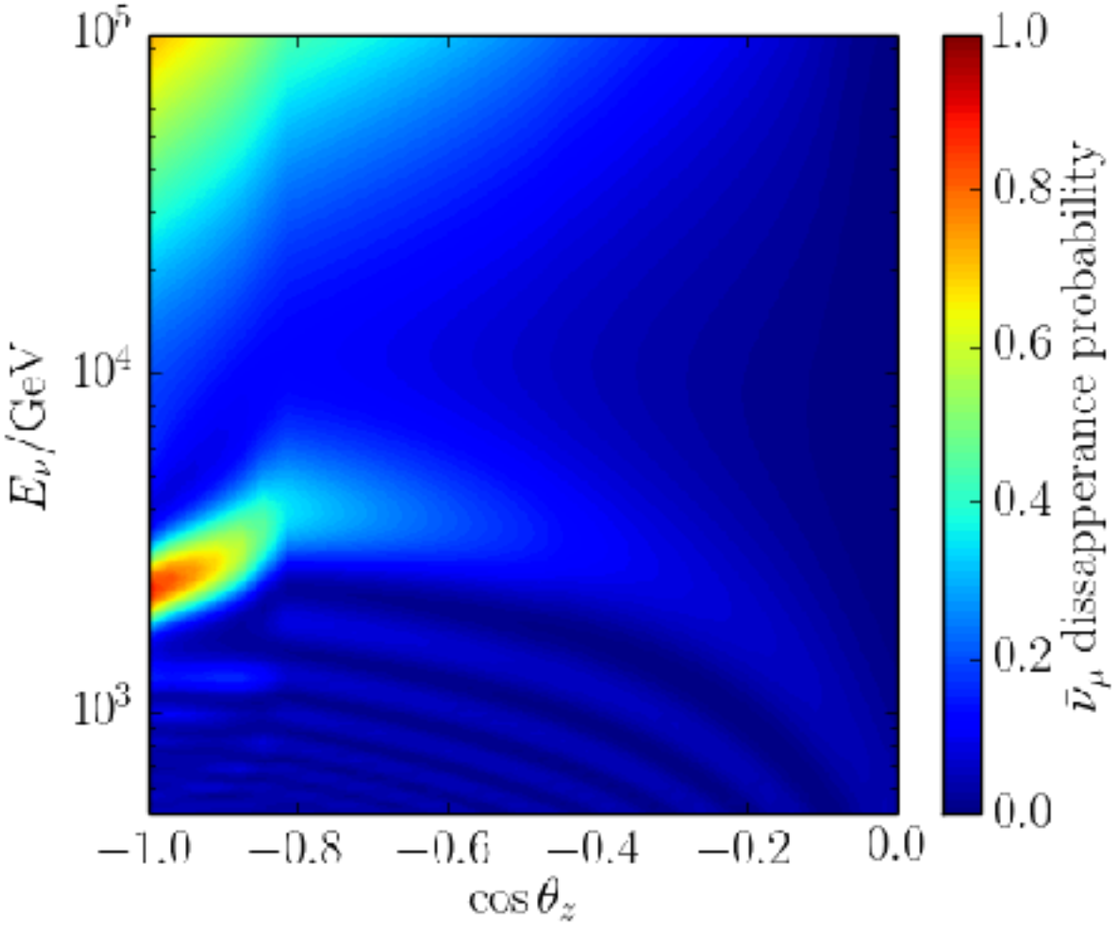
$$\mathcal{R}(E) = \sum_{i,j} \mathrm{Tr}\left(\rho(\gamma(E)m_1)\Pi_i(\gamma(E)m_1)\right) \frac{1}{\tau_{i,j}\gamma(E)}\Pi_j(E).$$

$\gamma(E)$: boost factor

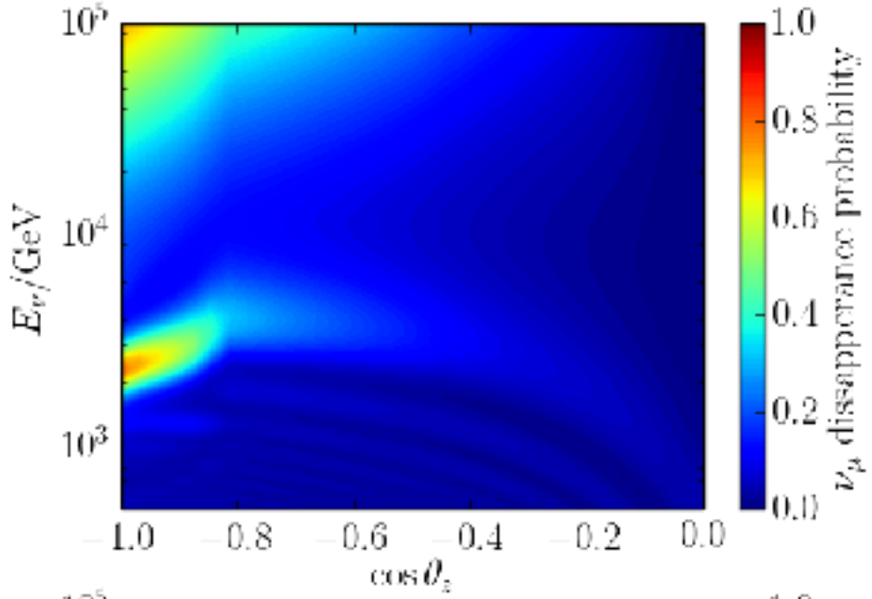
$\tau_{ij}^{-1} = \Gamma_{ij}$: partial decay rates

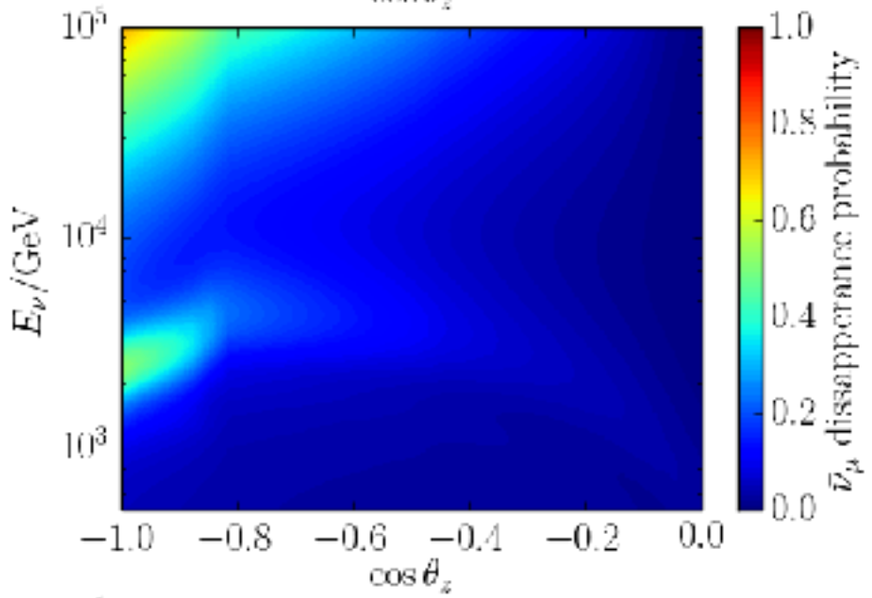
Oscillograms

Sterile (anti)neutrino no decay

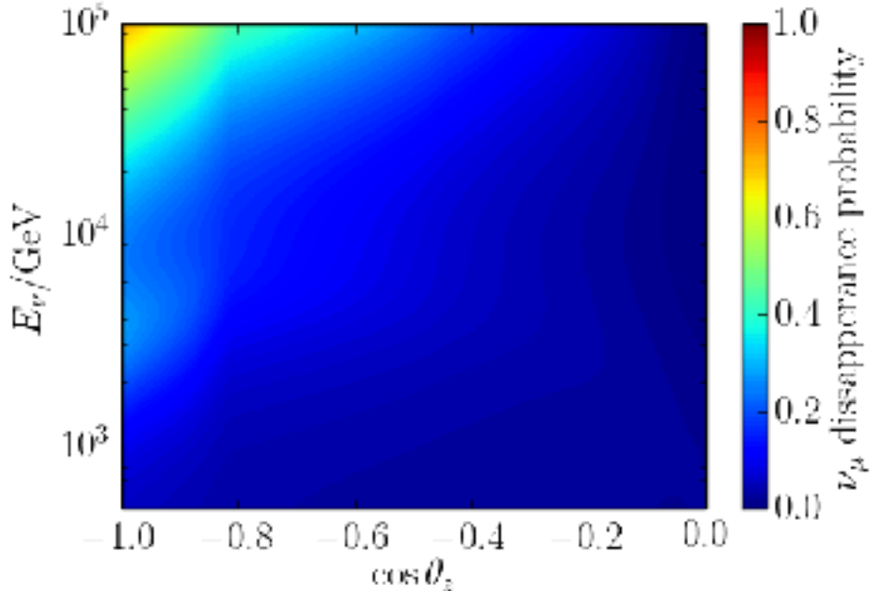


$\tau_{43} = 20/eV$





$\tau_{43} = 1/eV$



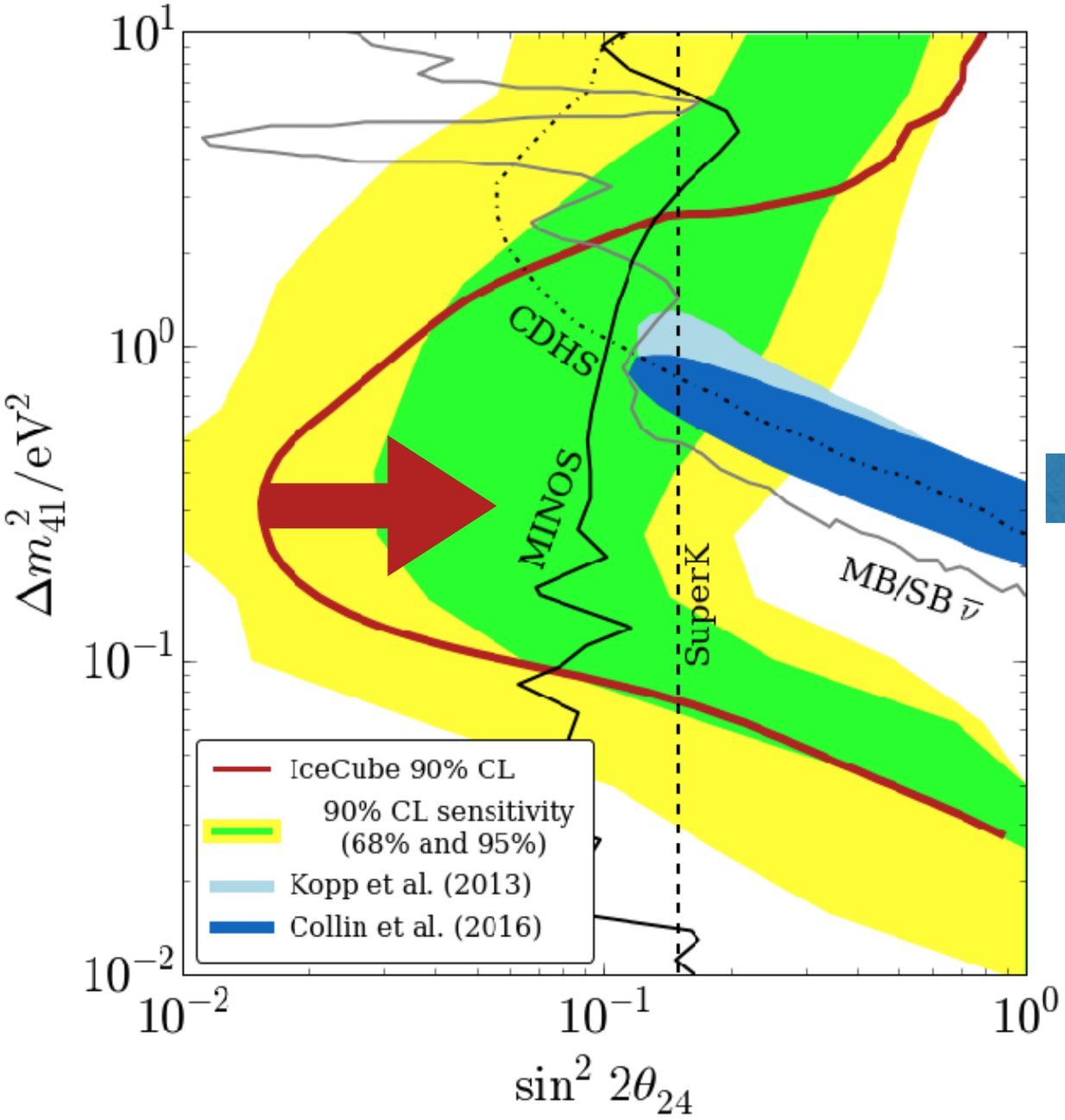
more decay

https://github.com/jsalvado/SQuIDS

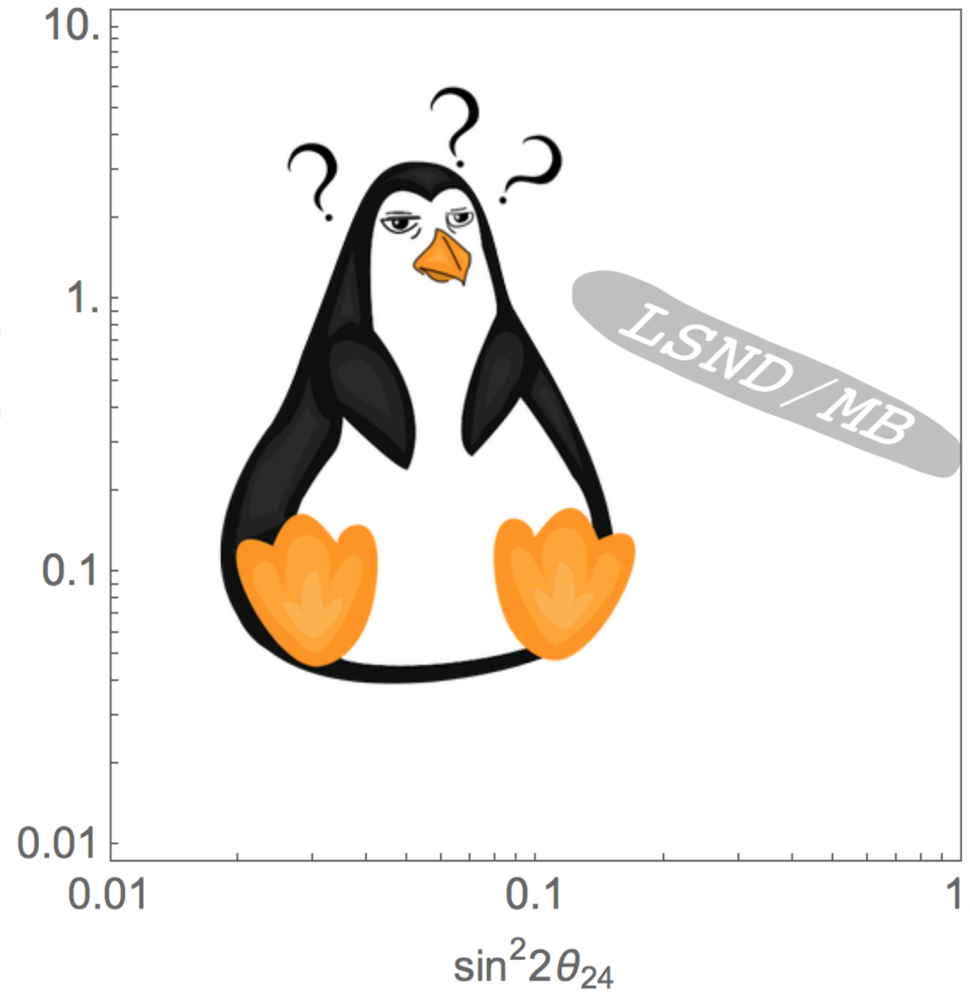
https://github.com/arguelles/nuSQuIDS

Soon…

Sterile neutrino only



Sterile neutrino + decay



Take home message

- We consider a new scenario: eV-sterile neutrinos + decay
- Interesting effects on the IceCube disappearance analysis, but effects across all experiments of interest — See Janet's talk later in this session!
- **Stay tuned for our upcoming paper with a complete analysis!**

THANKS!

*things in this talk were calculated with nuSQuIDS! Ask me about it!
https://github.com/arguelles/nuSQuIDS/

BONUS SLIDES!

SQuIDS/nu-SQuIDS

C.A., J. Salvado, and C. Weaver. [arXiv:**1412.3832, CPC 2015.06.022.**]
C.A., J. Salvado, and C. Weaver. . [*In preparation*]

What is it?

Is a software framework written in C++ that **evolves quantum mechanical ensembles**.
nu-SQuIDS **calculates neutrino propagation** (oscillation+interactions).

What can it do?

- ❑ Calculate neutrino oscillation probabilities in 3 generations (can configure mixing angles, CP phases, and mass splittings).
- ❑ Ready to use in: short baseline, long baseline, atmospheric, and solar neutrino oscillation experiments.
- ❑ Incorporates neutrinos' non-coherent interactions (includeing tau regeneration).
- ❑ Can handle collective neutrino interactions (e.g. supernova), as well as neutrino-antineutrino interactions.
- ❑ Easily extendable to BSM physics scenarios. **Sterile neutrinos,** NSI, and LV already implemented!

Get it here:

https://github.com/jsalvado/SQuIDS

https://github.com/arguelles/nuSQuIDS