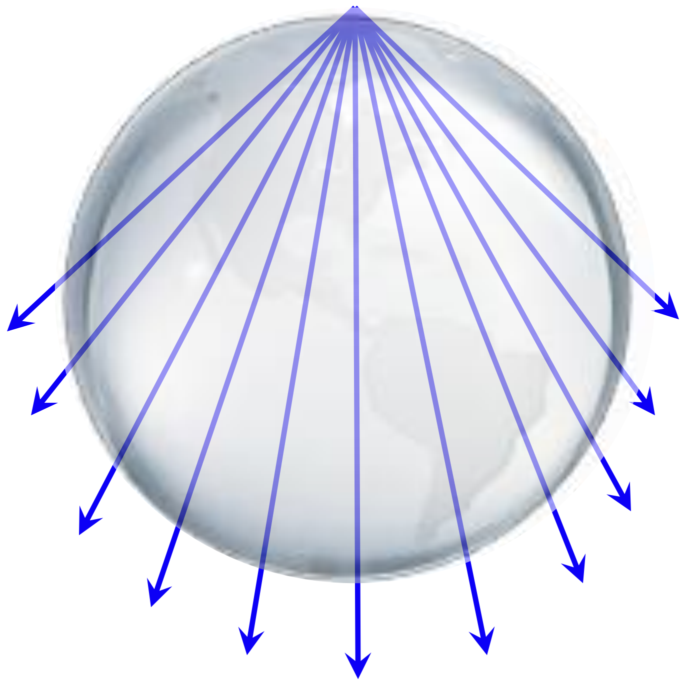
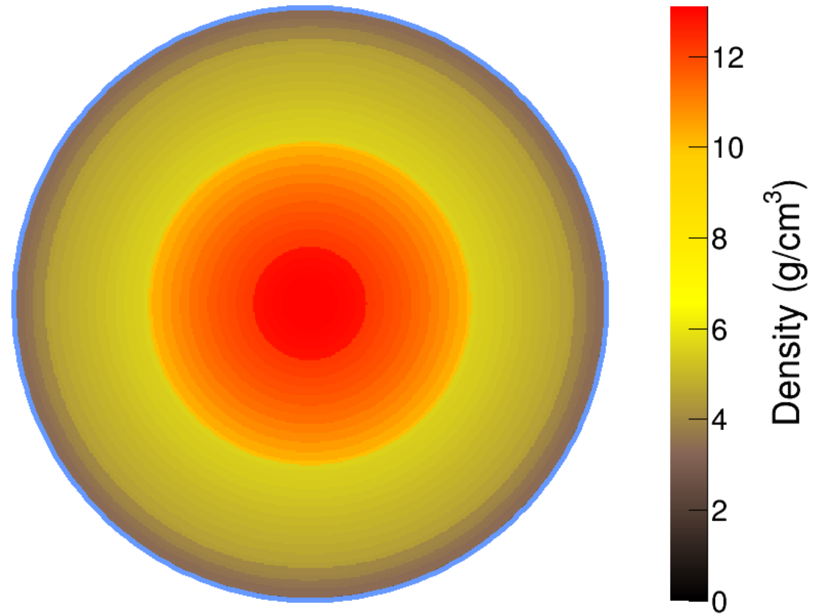
New Physics with ORCA/PINGU

João Coelho

1st October 2016

Matter Effects

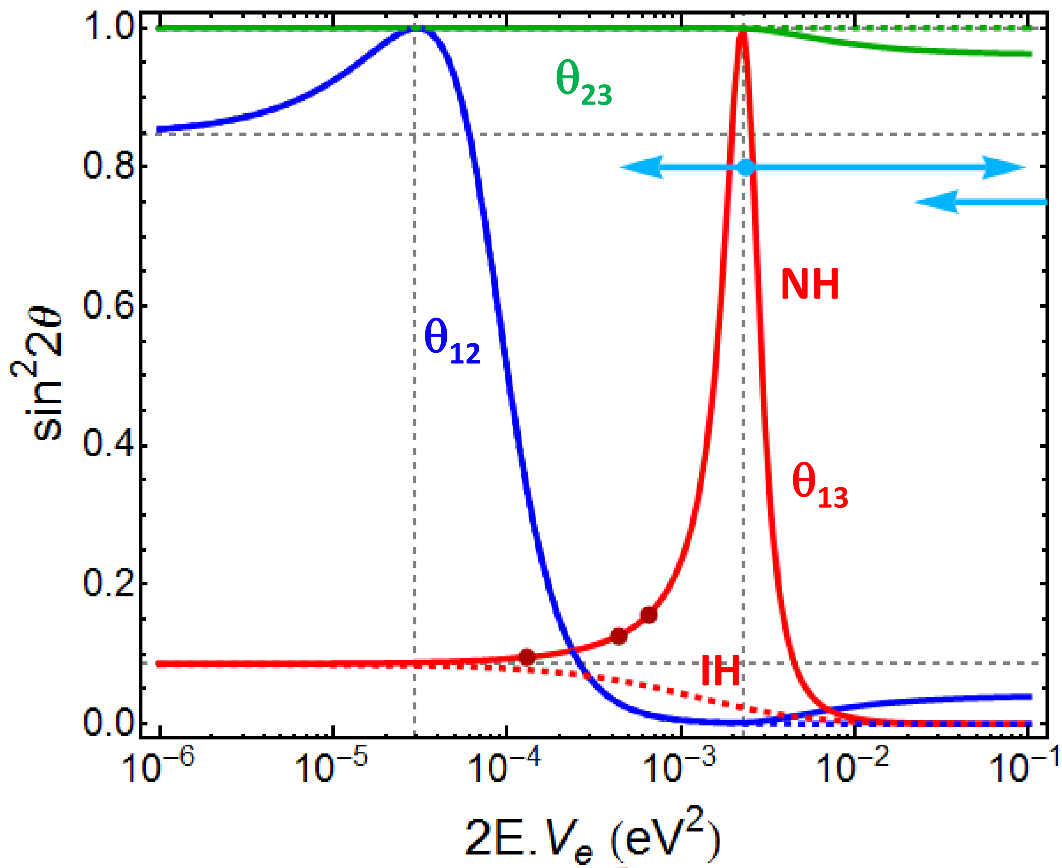




Interplay between these two terms

$$H_{eff} = U \begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{bmatrix} U^\dagger + V_e \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

Resonances



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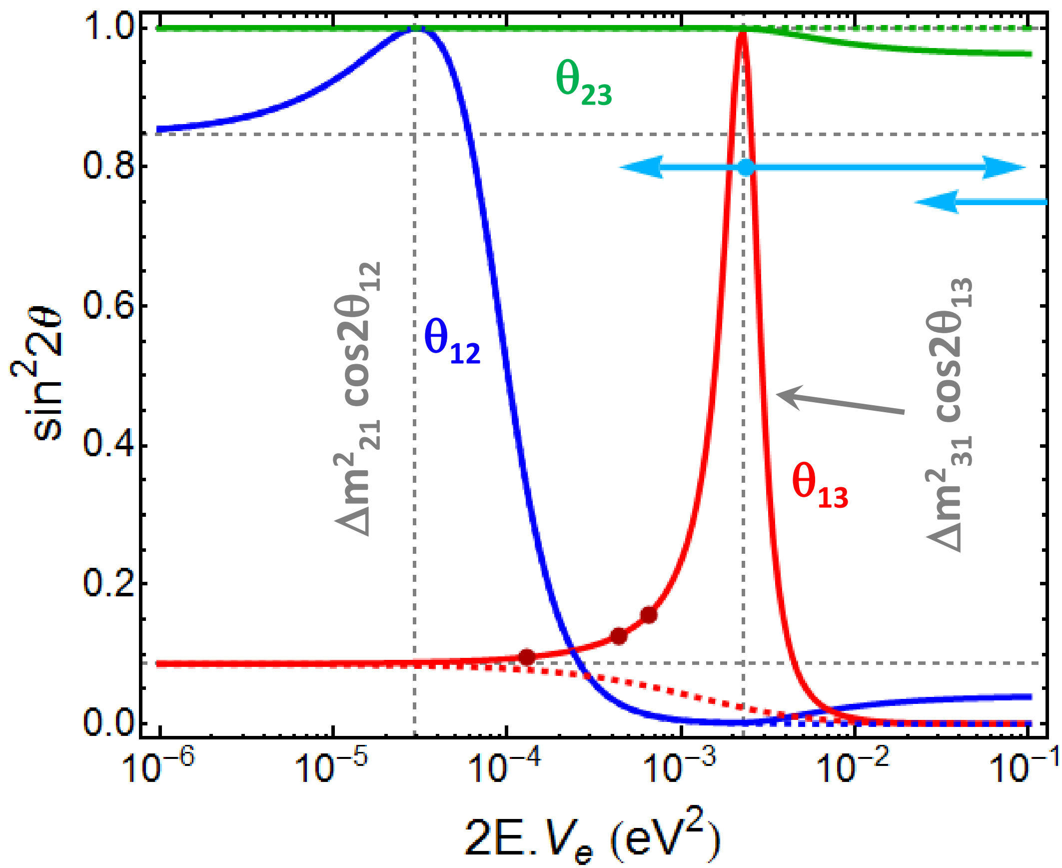
Resonances



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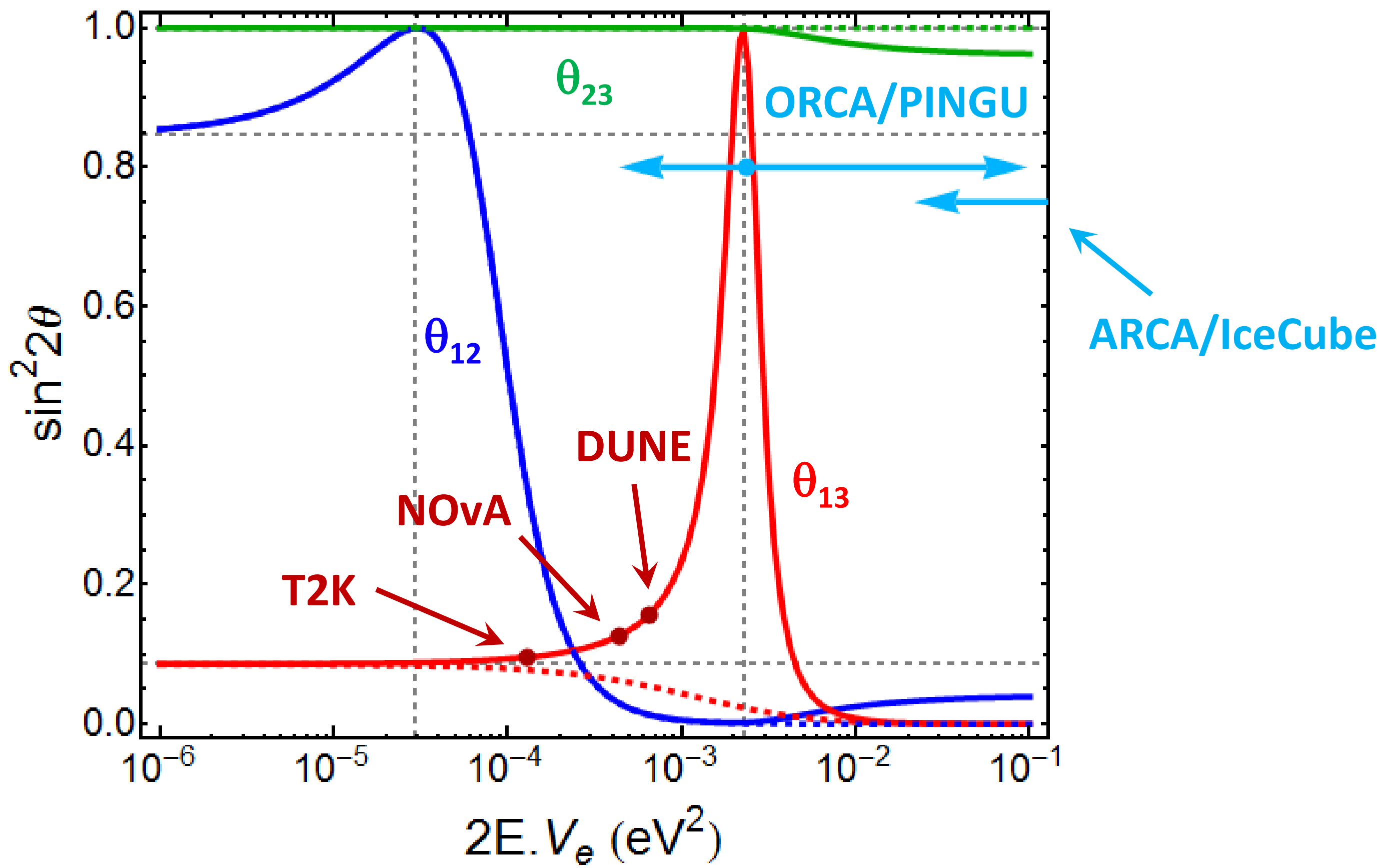
Resonances



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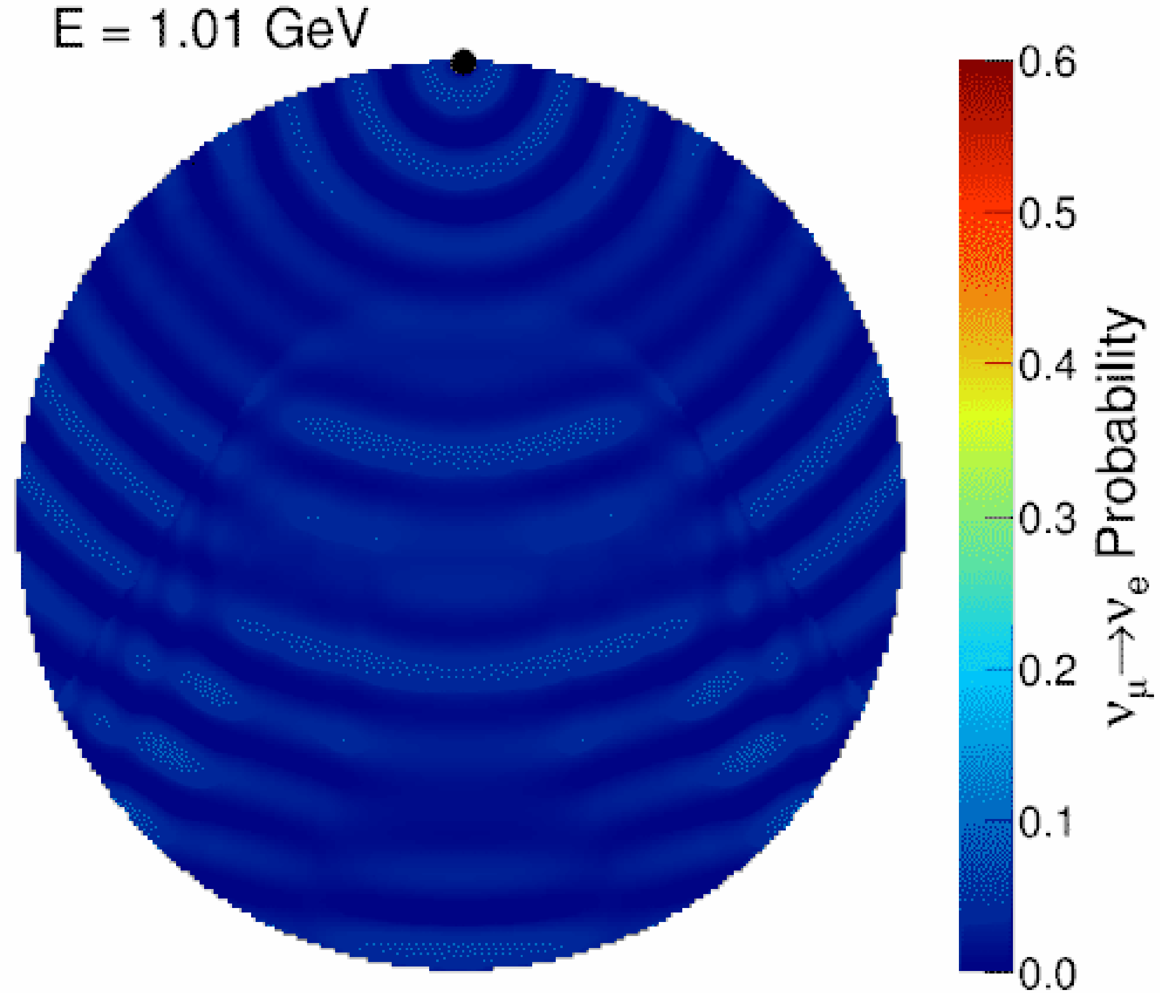
Effect on Oscillation



Extended Models

Arbitrary Perturbation

Non-Standard Interactions (NSI)

$$H_{eff} = U \begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{bmatrix} U^\dagger + V_e \begin{bmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{bmatrix}$$

Sterile Neutrinos (3+N Flavours)

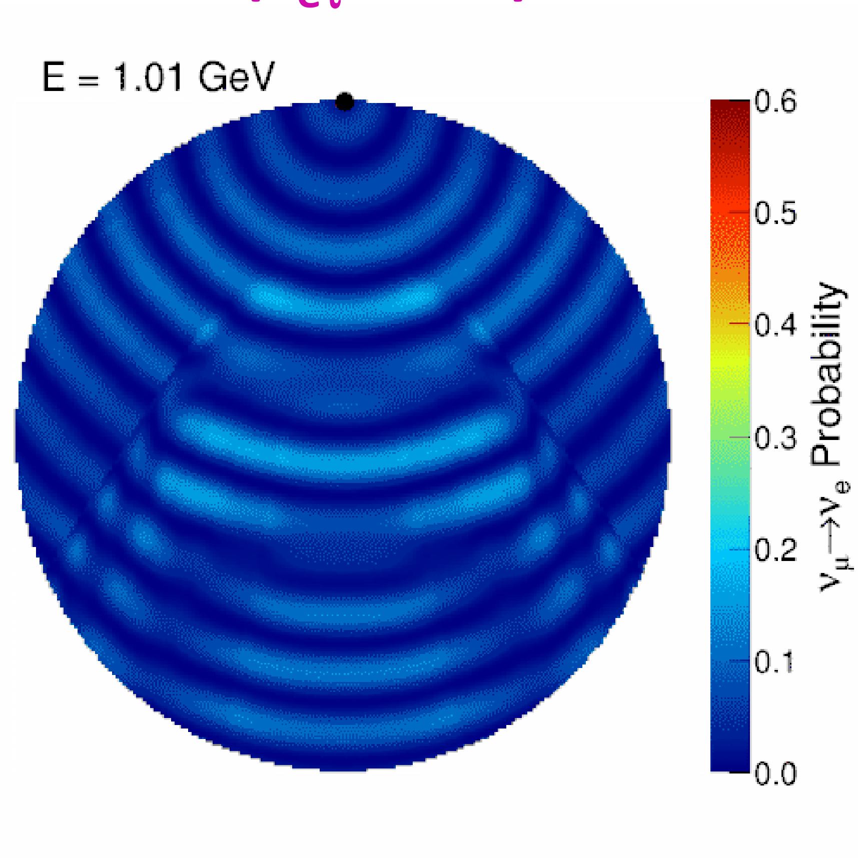
$$H_{eff} = U_S \begin{bmatrix} 0 & 0 & 0 & 0 & \cdots \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 & 0 & \cdots \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} & 0 & \cdots \\ 0 & 0 & 0 & \frac{\Delta m^2_{41}}{2E} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{bmatrix} U_S^\dagger + \begin{bmatrix} V_e & 0 & 0 & 0 & \cdots \\ 0 & 0 & 0 & 0 & \cdots \\ 0 & 0 & 0 & 0 & \cdots \\ 0 & 0 & 0 & V_n/2 & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{bmatrix}$$

NC Contribution

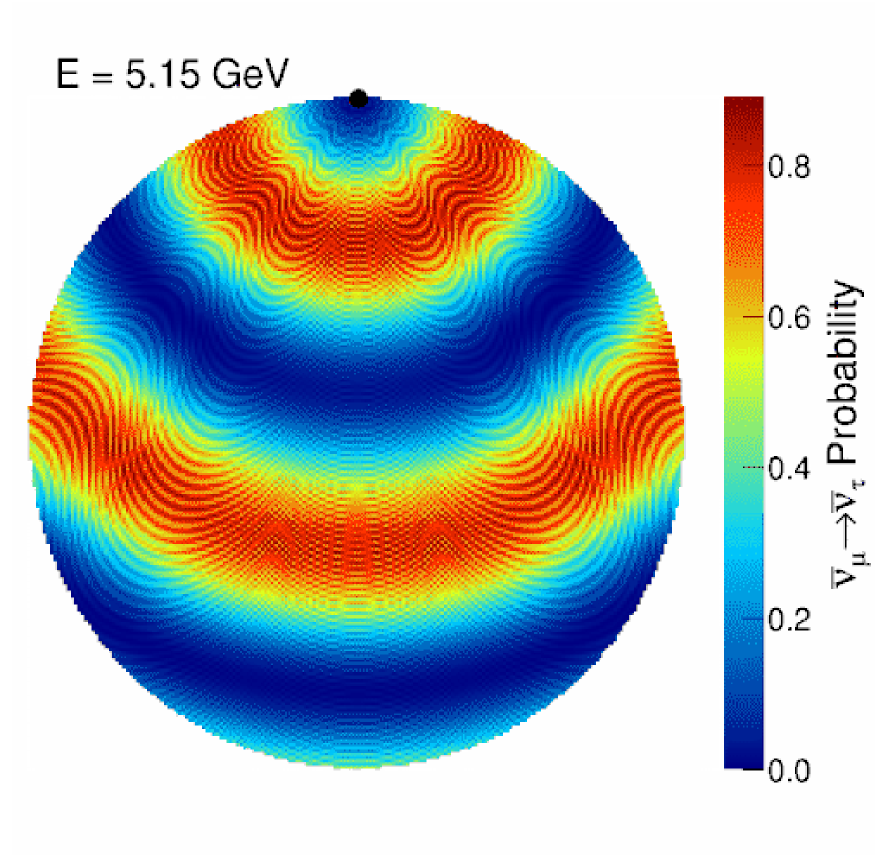
$$U_S = U_{N-1,N} \cdots U_{34} U^{(c)}_{24} U^{(c)}_{14} U_{23} U^{(c)}_{13} U_{12}$$

Enhanced Matter Effects

NSI ($\varepsilon_{e\tau}$ = 0.2)



Steriles ("Curr." Limits)



Visit https://goo.gl/CJyFoK for more

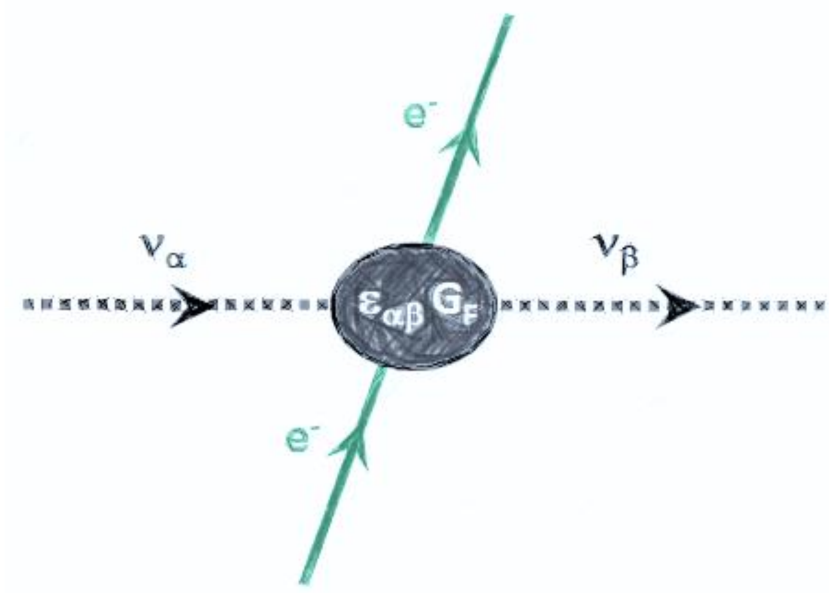
Non-Standard Interactions

NSI Motivation

Arbitrary Perturbation

Non-Standard Interactions (NSI)

$$H_{eff} = U \begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m_{21}^2}{2E} & 0 \\ 0 & 0 & \frac{\Delta m_{31}^2}{2E} \end{bmatrix} U^\dagger + V_e \begin{bmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{bmatrix}$$



Dimension-6
+ Naturalness

$$\boxed{\varepsilon \propto \frac{m_W^2}{m_X^2}}$$

TeV Scale
~ 10^{-2}

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2} G_F \varepsilon_{\alpha\beta}^{ff'C} \left(\overline{\nu_\alpha}\gamma^\mu P_L \nu_\beta\right)\left(\overline{f}\gamma_\mu P_C f'\right)$$

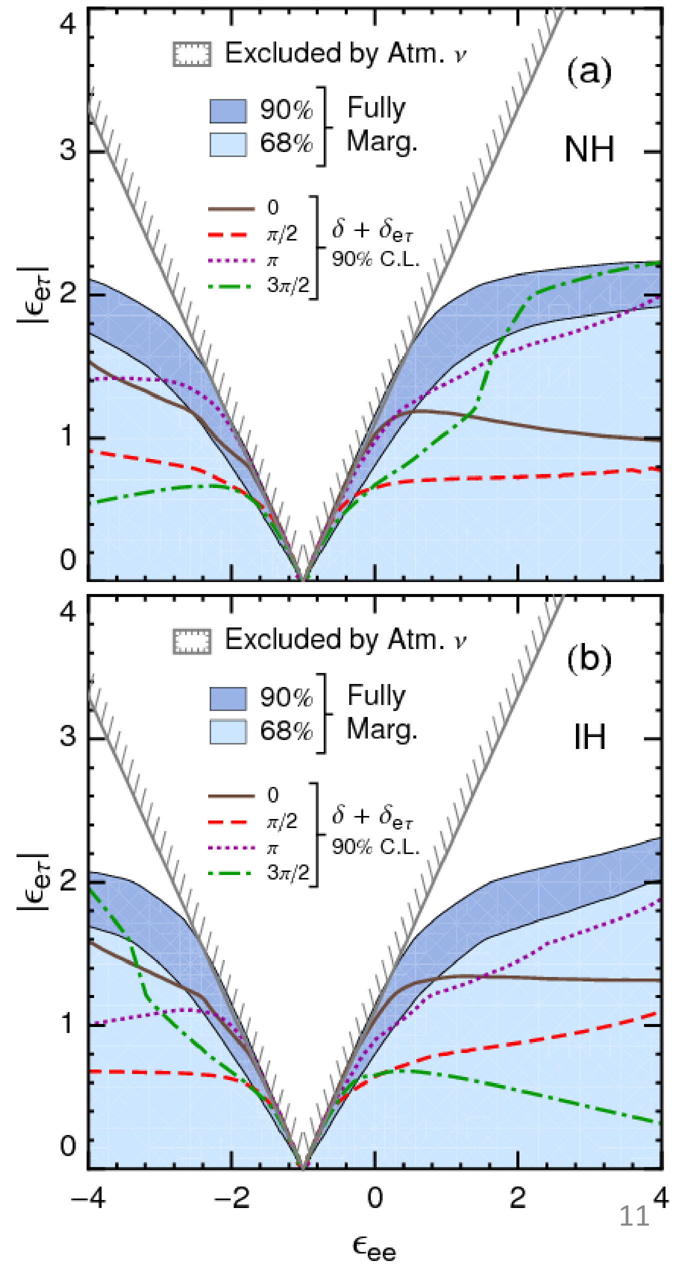
Non-Standard Interactions

- Direct limits are very weak on 3 of the 6 possible new couplings
- Rich phenomenology, i.e. complicated analysis with many free parameters
- Still need to study the ideal approach for ORCA
- Often correlated: $\epsilon_{\tau\tau} \simeq |\epsilon_{e\tau}|^2/(1+\epsilon_{ee}).$

$$\begin{pmatrix} |\epsilon_{ee}| < 4.2 & |\epsilon_{e\mu}| < 0.33 & |\epsilon_{e\tau}| < 3.0 \\ & |\epsilon_{\mu\mu}| < 0.07 & |\epsilon_{\mu\tau}| < 0.33 \\ & & |\epsilon_{\tau\tau}| < 21 \end{pmatrix}$$

Direct Bounds

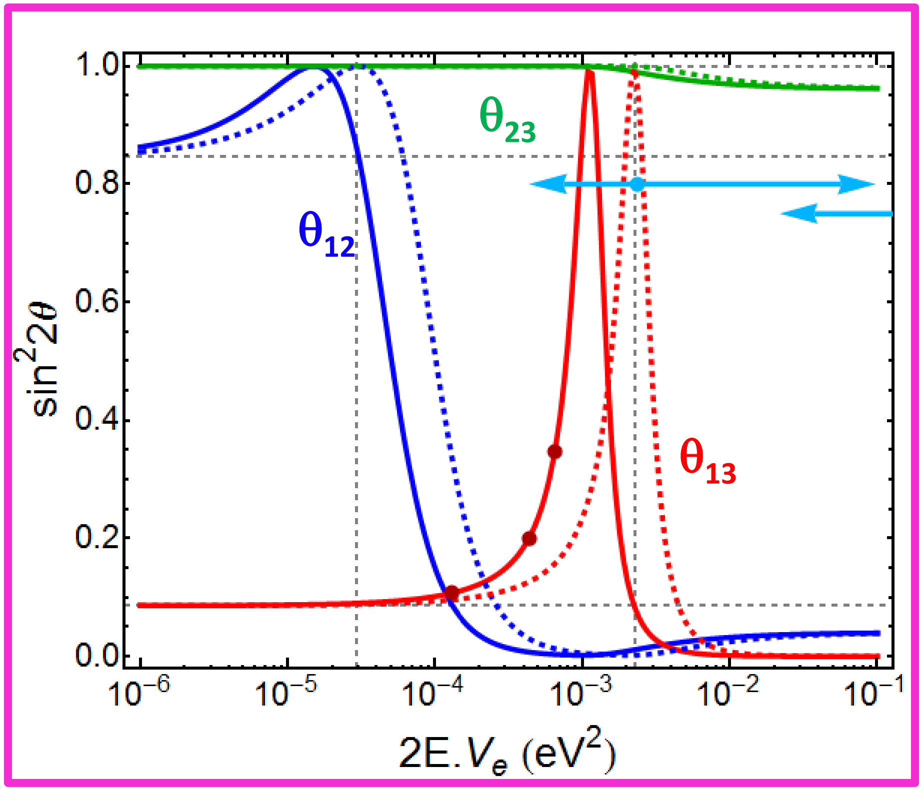
See T. Ohlsson, Rep. Prog. Phys. 76, 044201 (2013) for a review



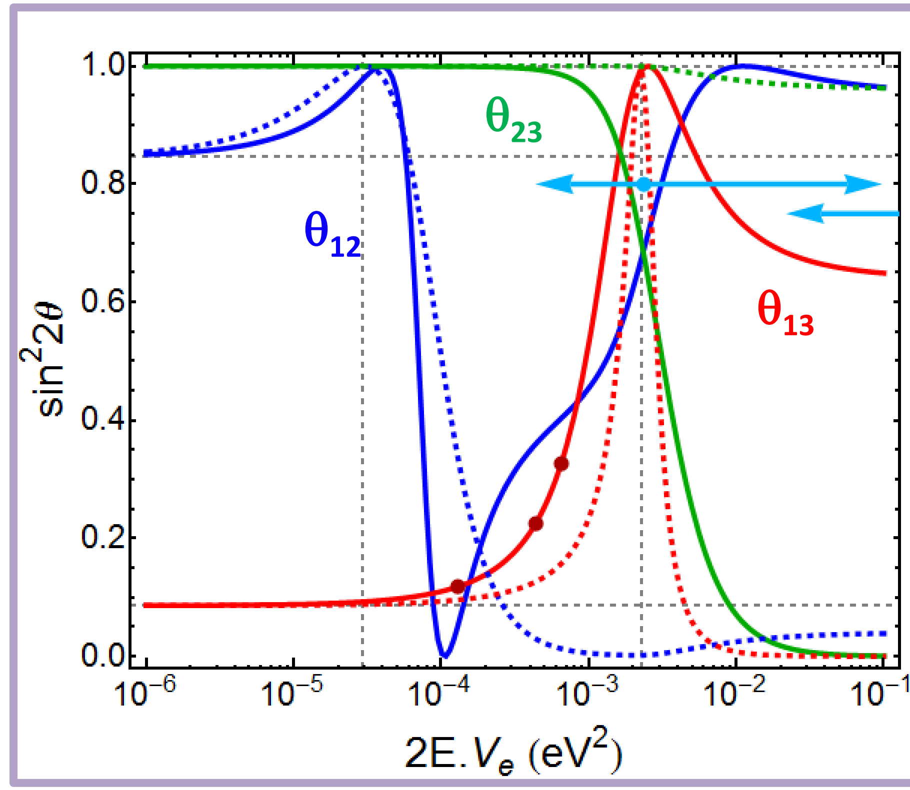
J. Coelho et al., Phys. Rev. D86, 113015 (2012)

Resonances w/ NSI

$\varepsilon_{ee} = 1$



$\varepsilon_{e\tau} = 0.5$, $\varepsilon_{\tau\tau} = 0.25$



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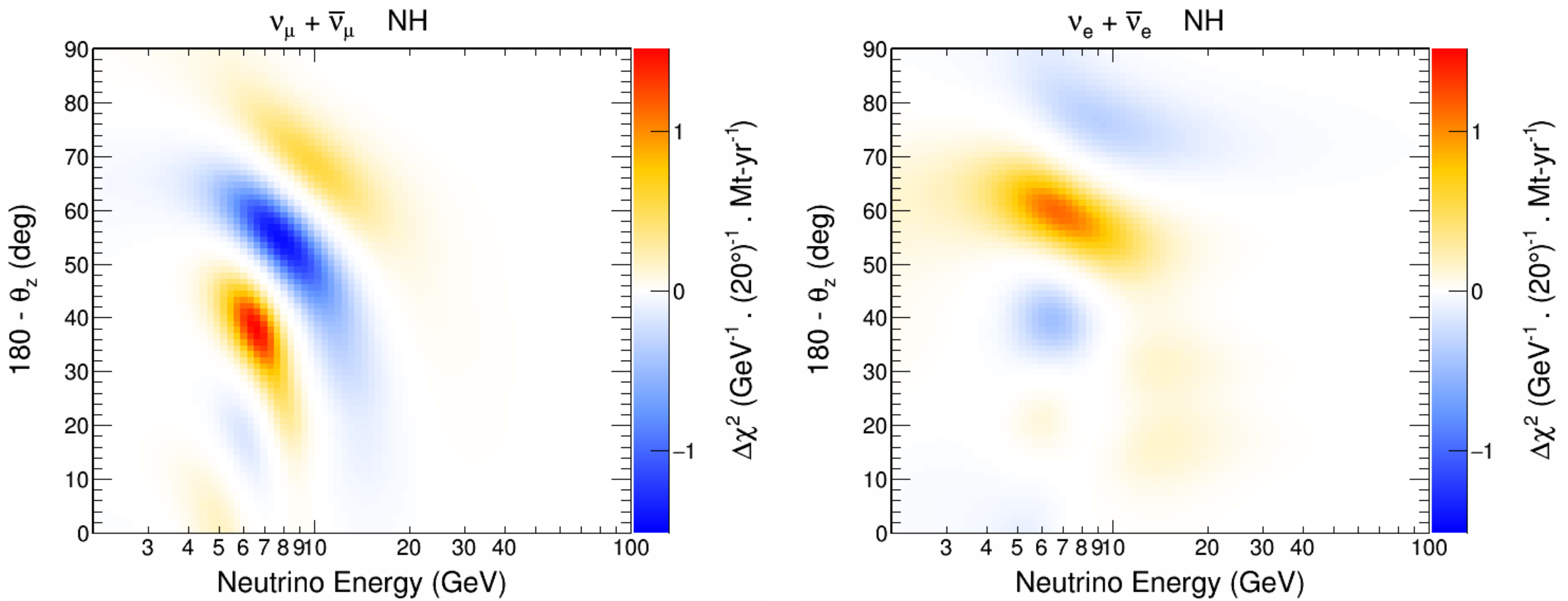
NSI Phase Space

- Very different from MH for nue
- Sensitivity in both channels, but numu is correlated with MH
- Still under unrealistic assumptions:
  - Perfect flavour selection
  - No systematics or nuisance pars.

$\varepsilon_{e\tau} = 0.2$, $\varepsilon_{\tau\tau} = 0.04$



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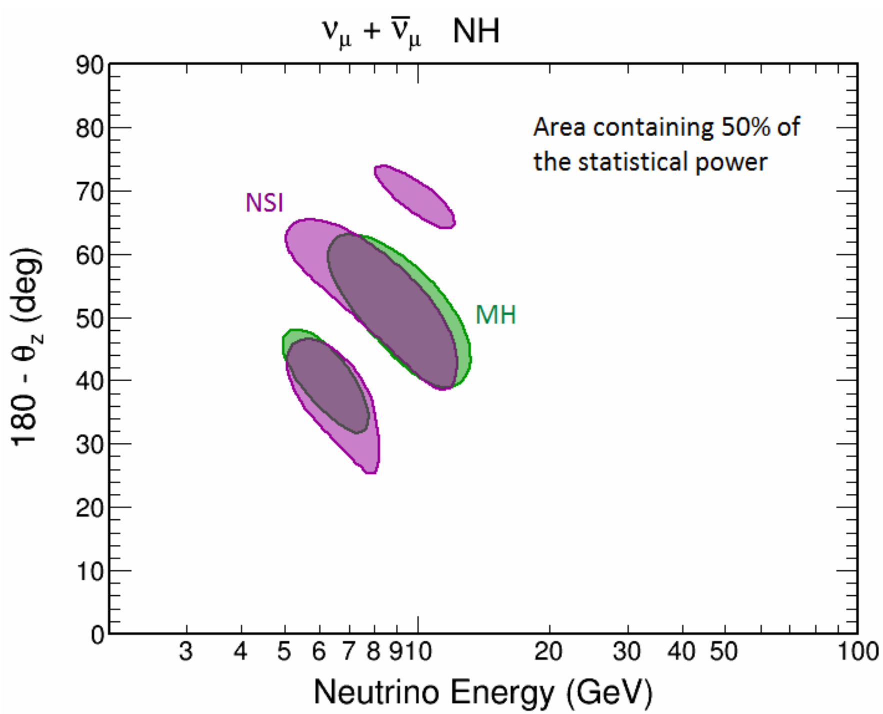
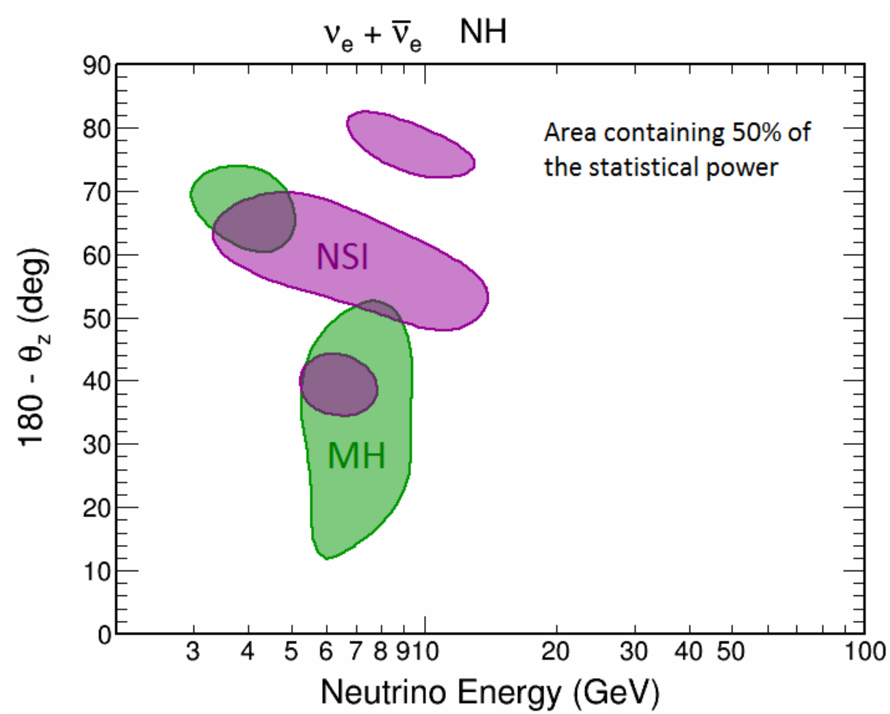
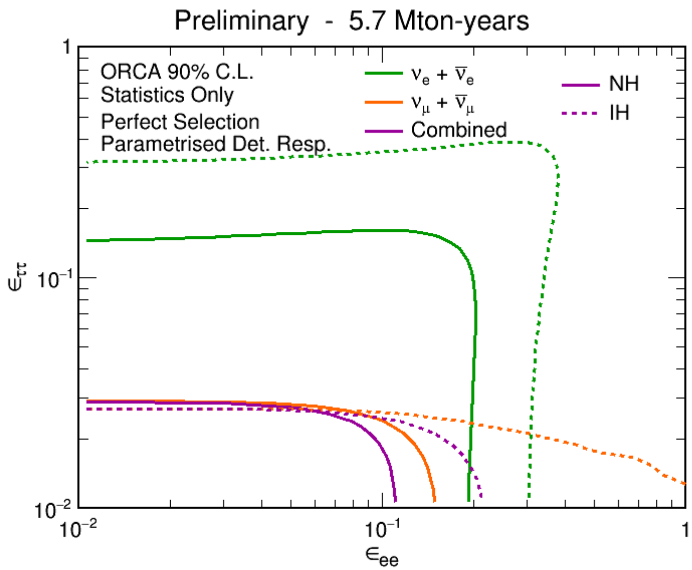
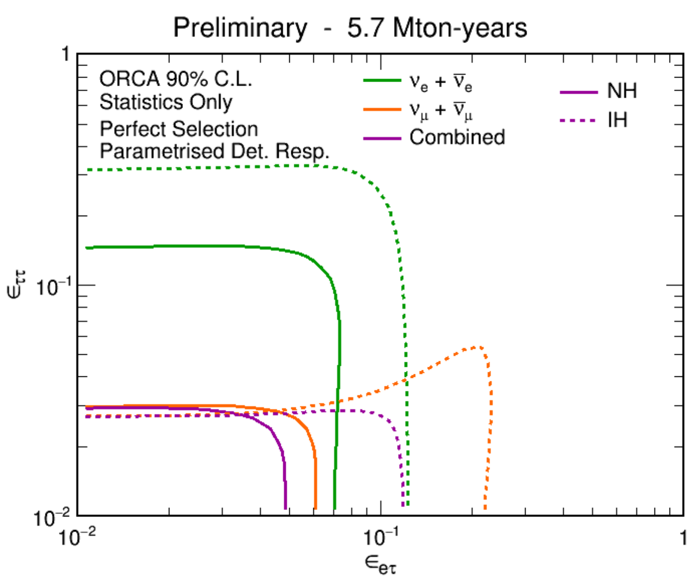
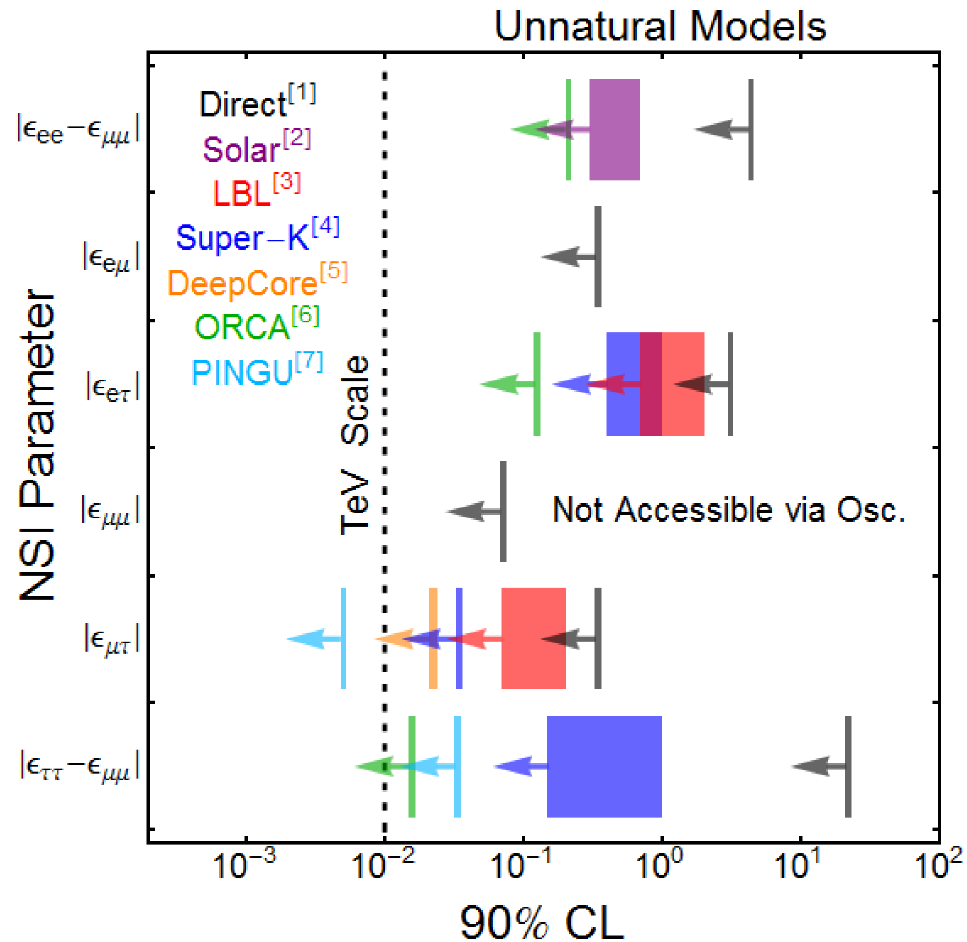




ORCA et al.



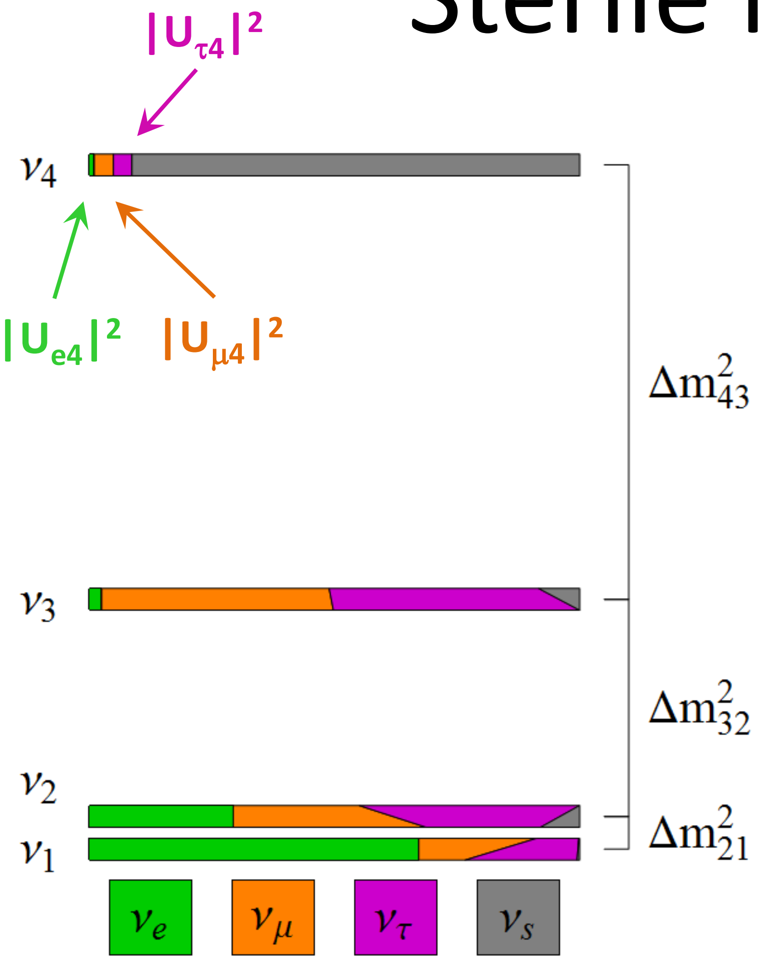


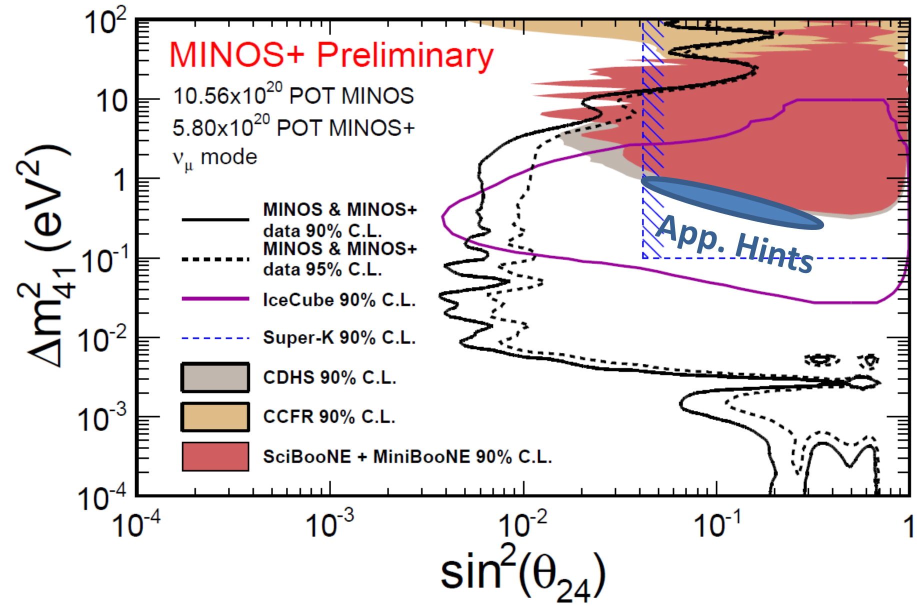


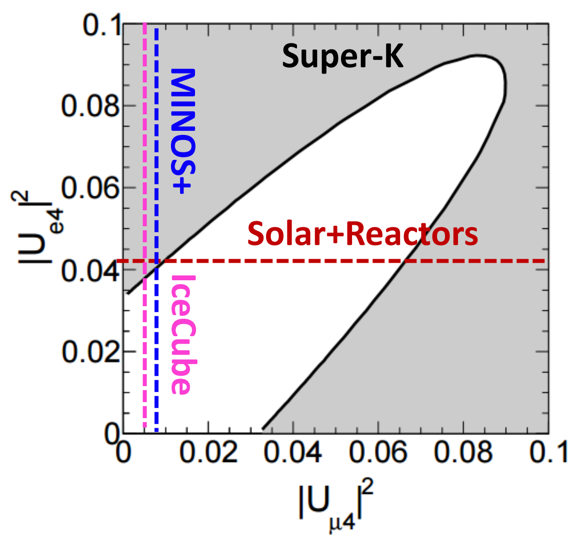
[1] JHEP 0908:090 (2009)
[2] Phys. Lett. B594:347 (2004)
[3] PRD 86, 113015 (2012); PRD 88, 072011 (2013)
[4] Phys. Rev. D 84, 113008 (2011)
[5] M. Day and A. Karle, P3.093 Neutrino 2016
[6] Joao Coelho, P2.026 Neutrino 2016
[7] Phys. Lett. B739:357 (2014)

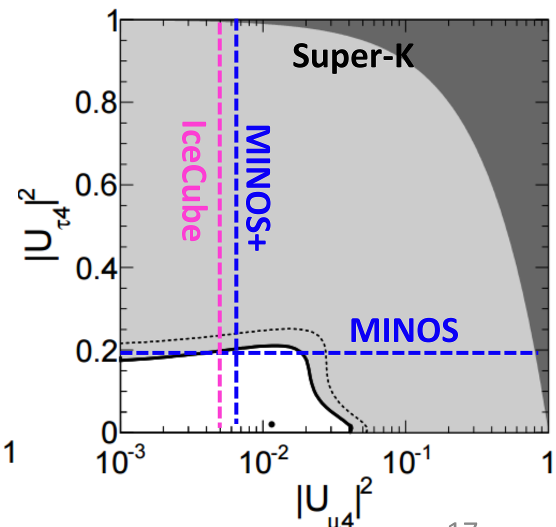
Sterile Neutrinos

Sterile Neutrinos (3+1)





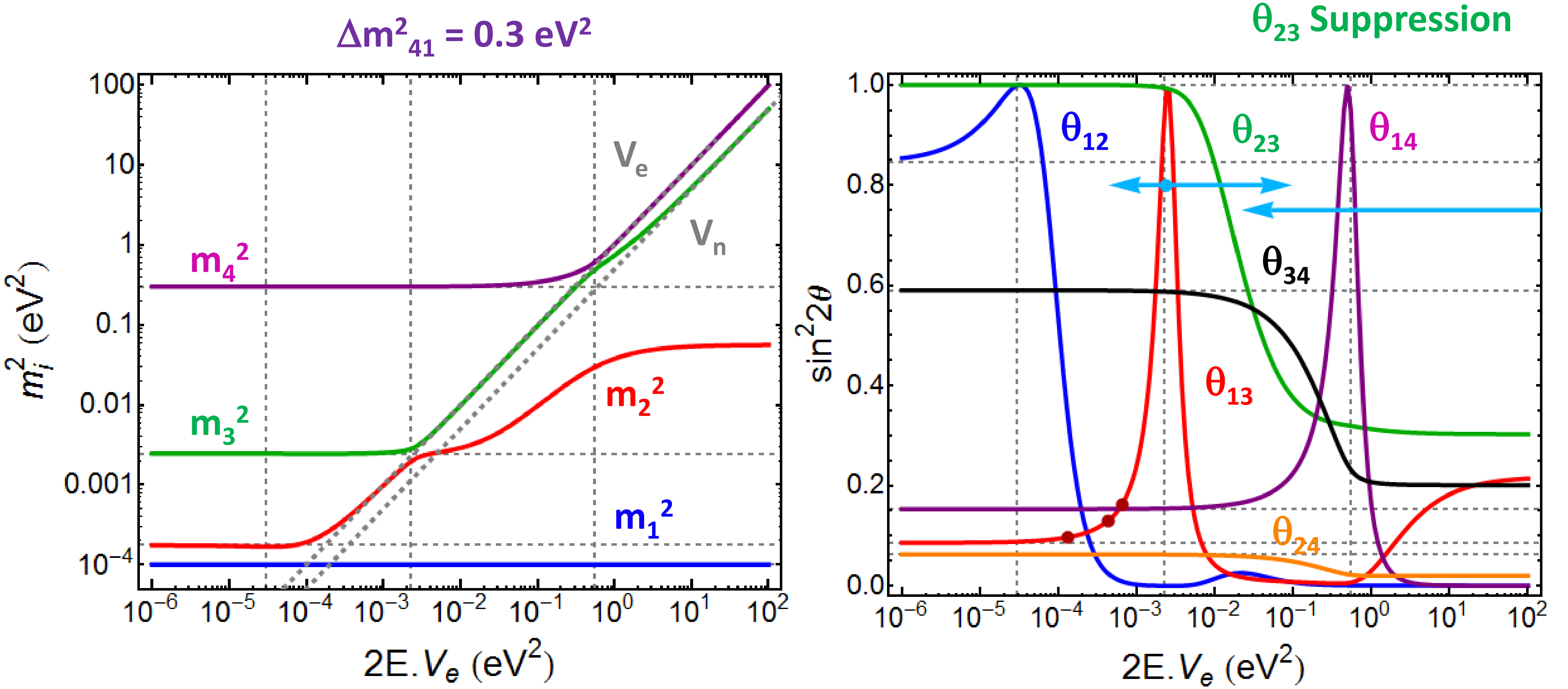




Super-Kamiokande: Phys. Rev. D 91, 052019 (2015)
IceCube: Phys. Rev. Lett. 117, 071801 (2016)
MINOS+: Justin Evans, Neutrino 2016
Solar+Reactors: Mod. Phys. Lett. A 28, 1330004 (2013)

Resonances w/ Steriles

- New resonant peak due to Δm^2_{41}
- Some intermediate behaviour between θ_{13} and θ_{14} resonances
- θ_{23} suppression seems to be fairly independent of Δm^2_{41}



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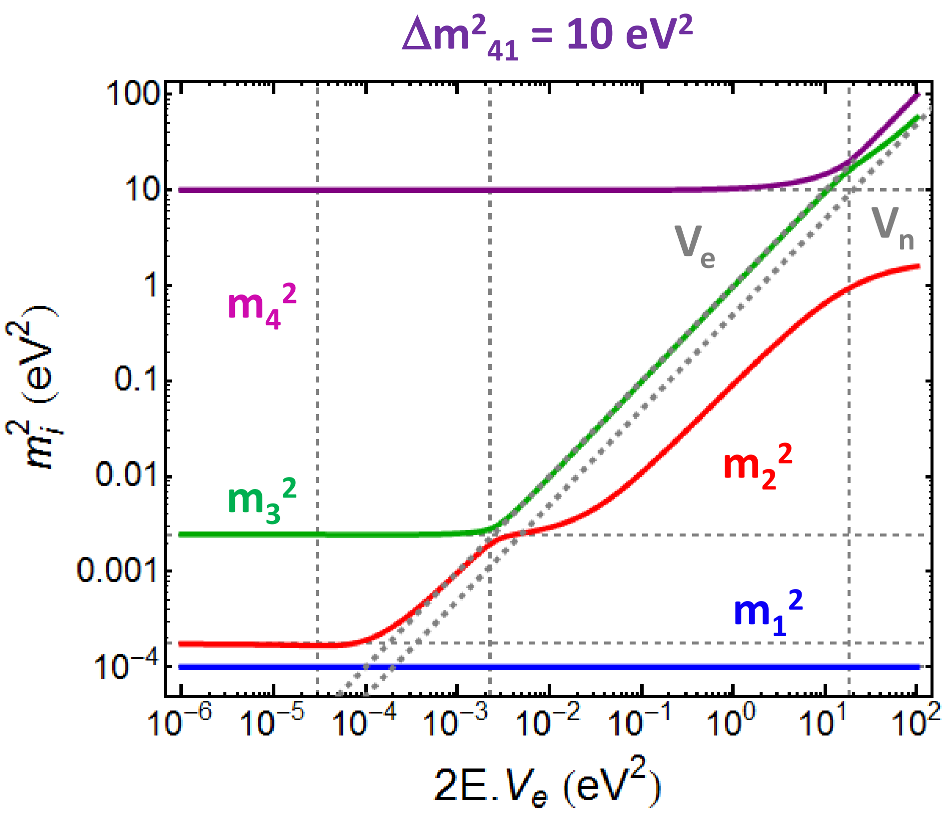
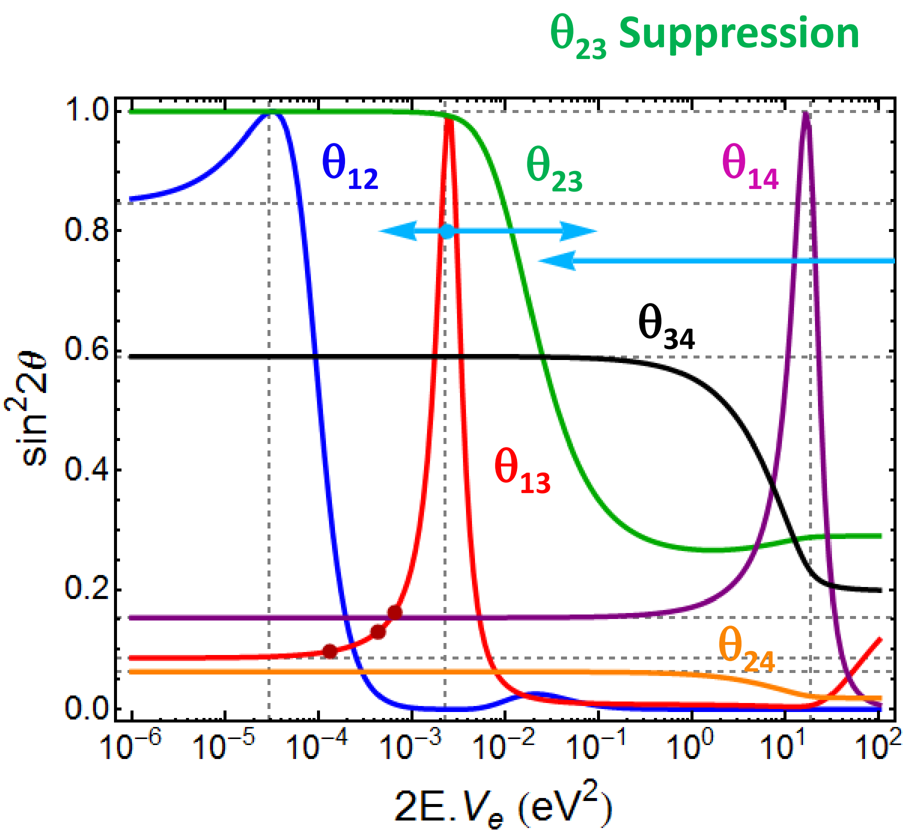
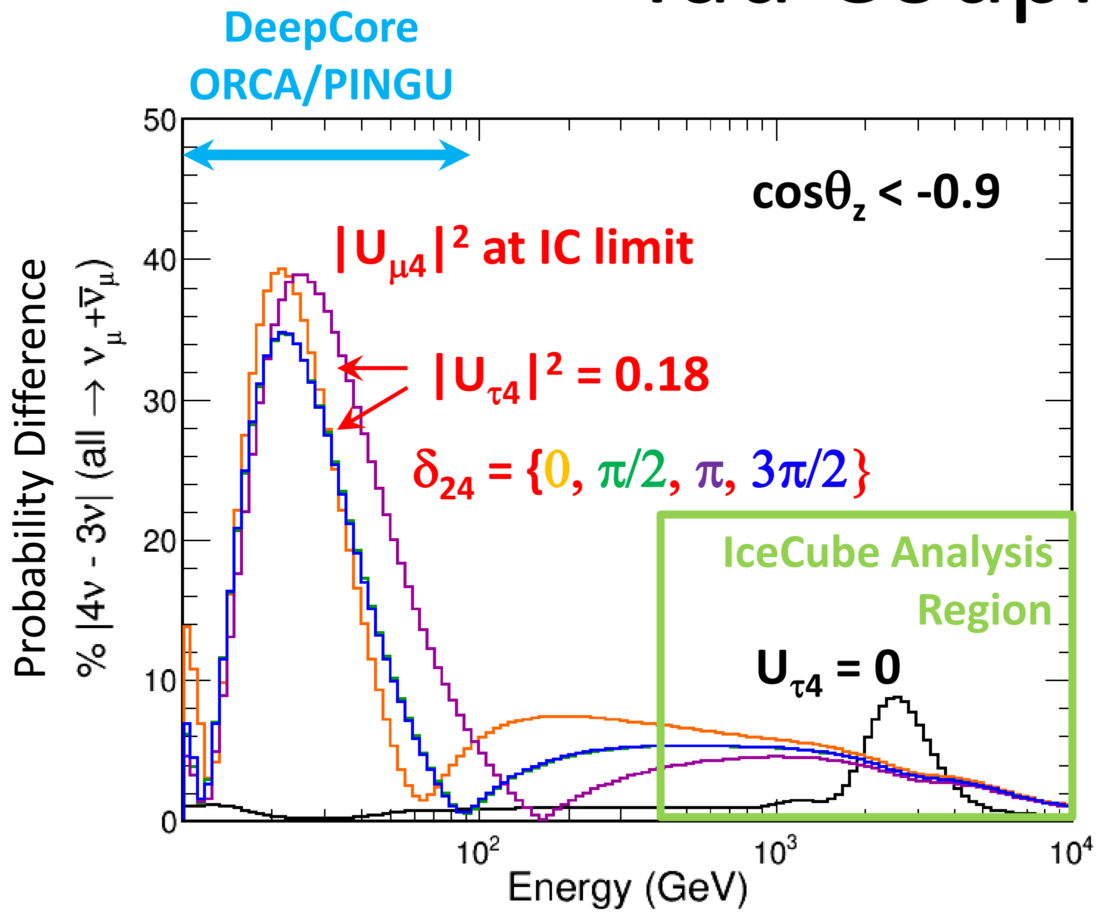
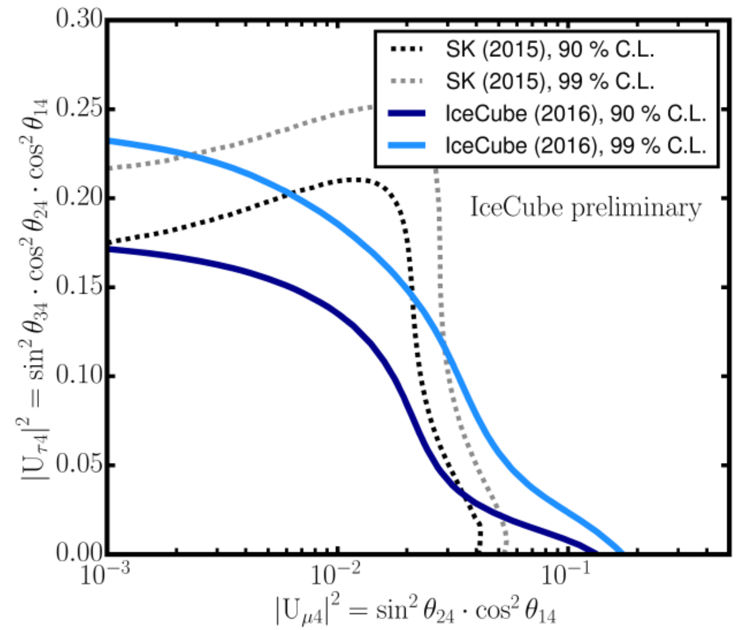




Tau Coupling



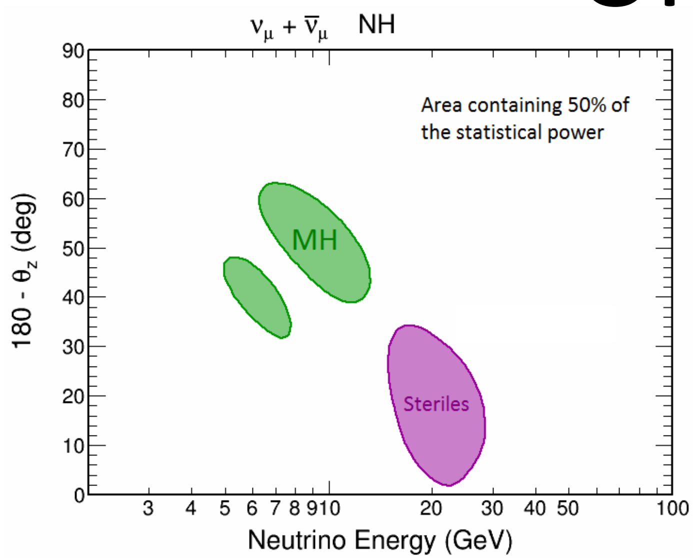
Super-K and DeepCore probed low-E with similar sensitivity



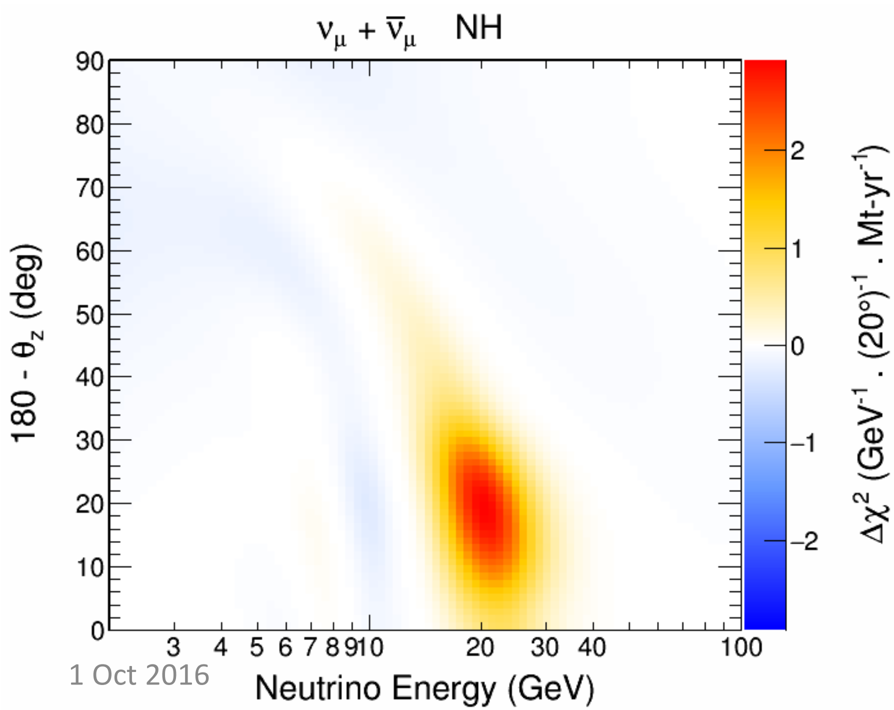
A. Terliuk, P2.024 Neutrino 2016

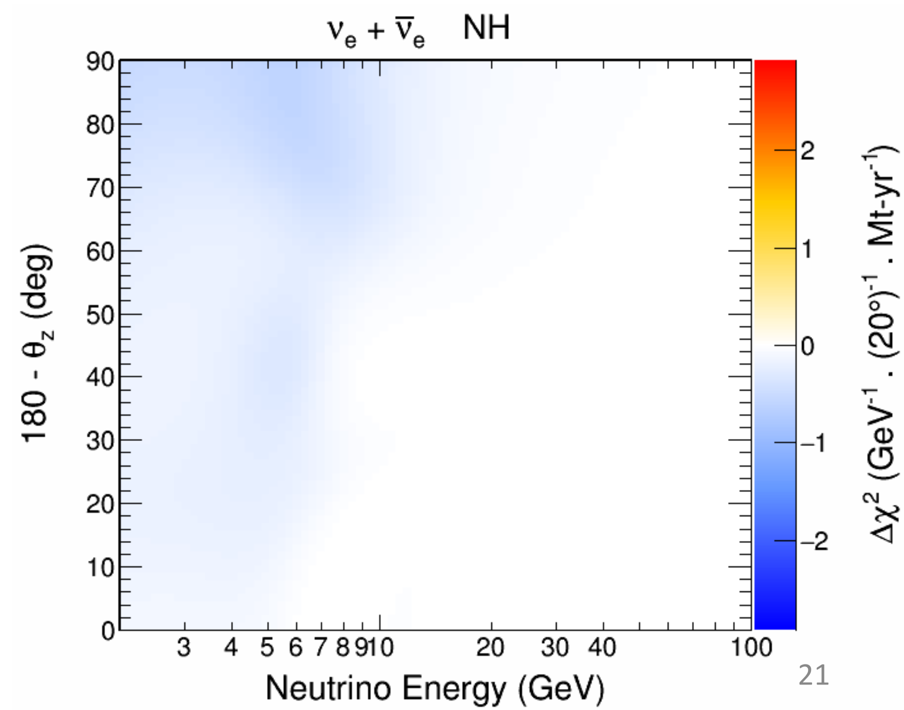
- ORCA/PINGU can probe the $U_{\tau4}$ coupling at low energies
- At high energies, effect is related to $U_{\mu4}$
- New constraints on $U_{\mu4}$ impact sensitivity at low energy too

ORCA Studies



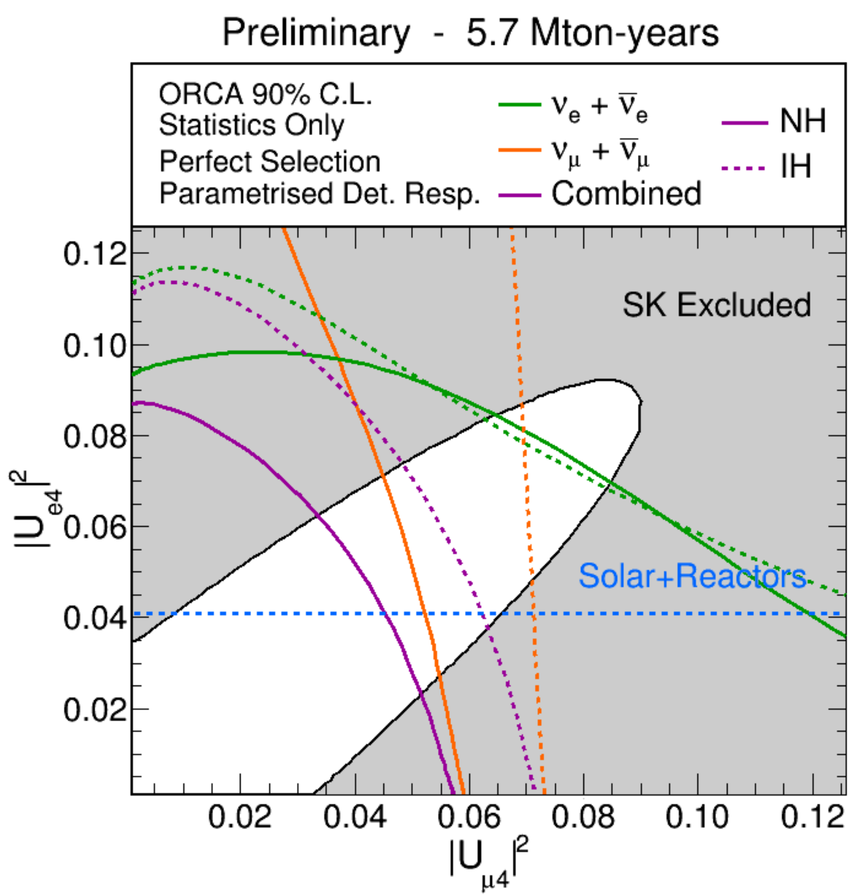
- Strong sensitivity with ν_μ channel
- Very different from 3ν resonance
- Still under unrealistic assumptions:
  - Perfect flavour selection
  - No systematics or nuisance pars.

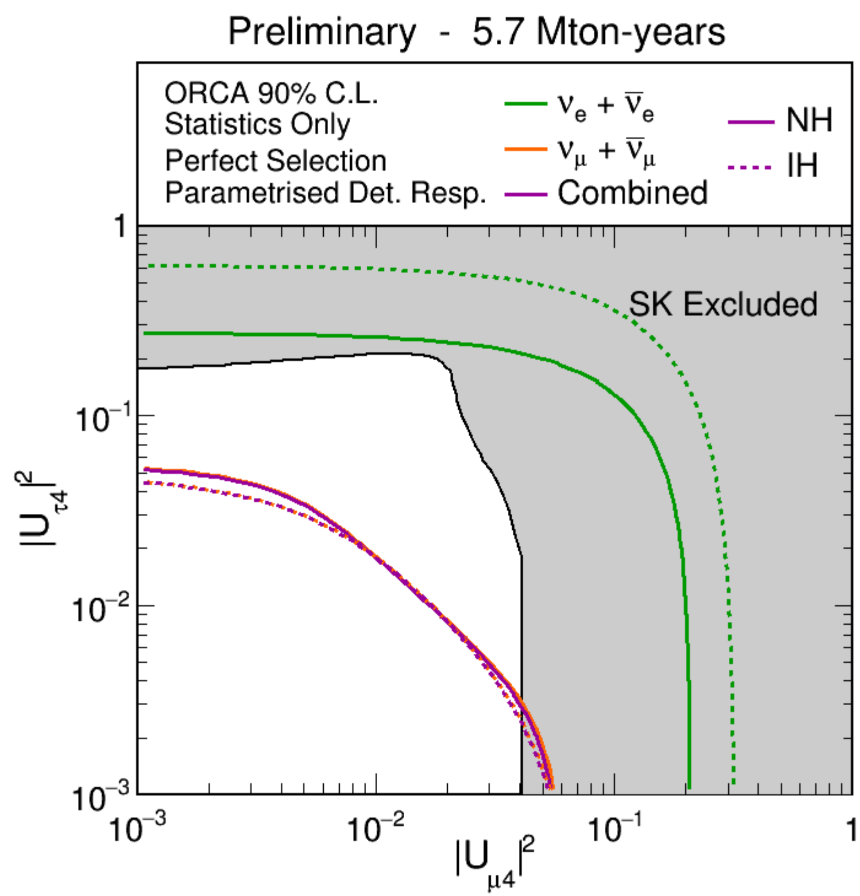




Preliminary Sensitivities

- Promising sensitivity in $U_{\tau 4}$ mixing
- Consider only 1-year of data (statistics dominated)





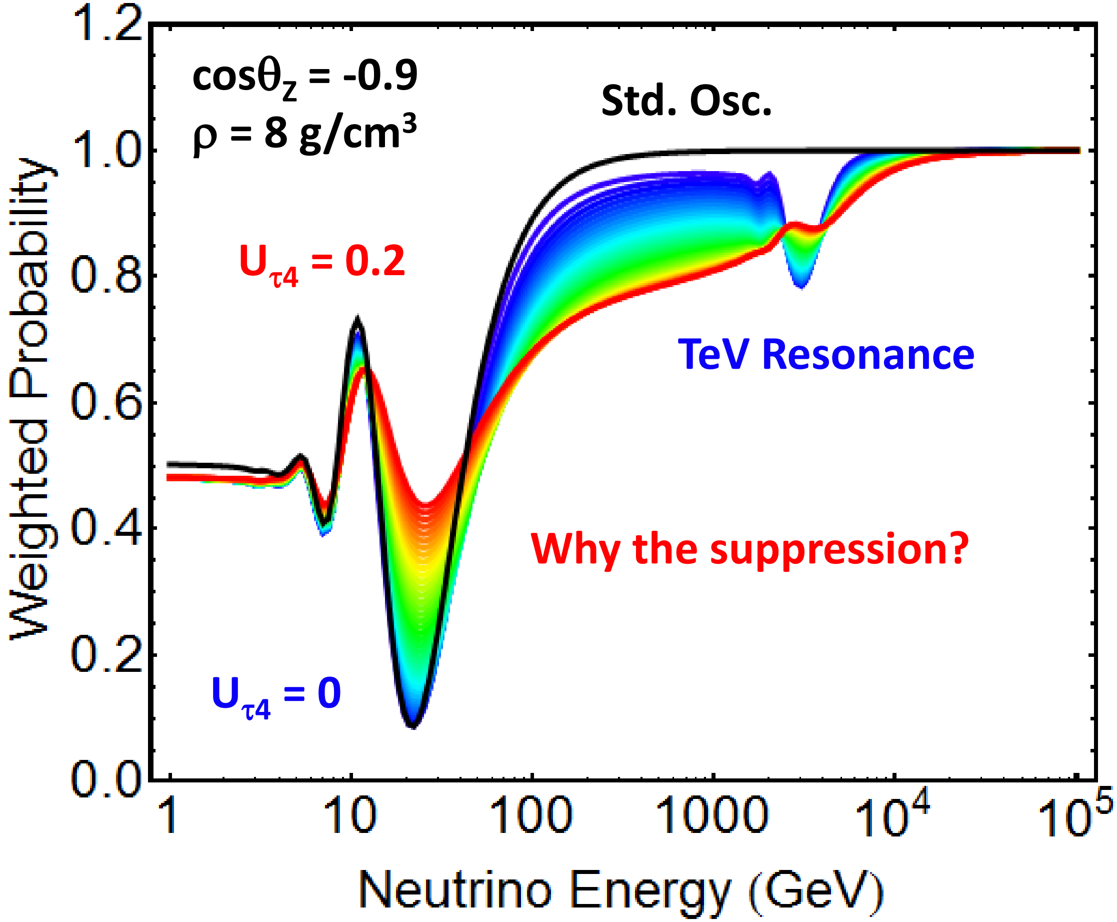
Summary

- **ORCA and PINGU** were designed to look for **matter effects**
- The full structure of the MSW potential is poorly known
- We should take advantage of that to look for **new physics**
- **Sterile neutrinos** and **NSI** are good examples in that direction
- **Promising results** so far from preliminary studies

Backup Slides

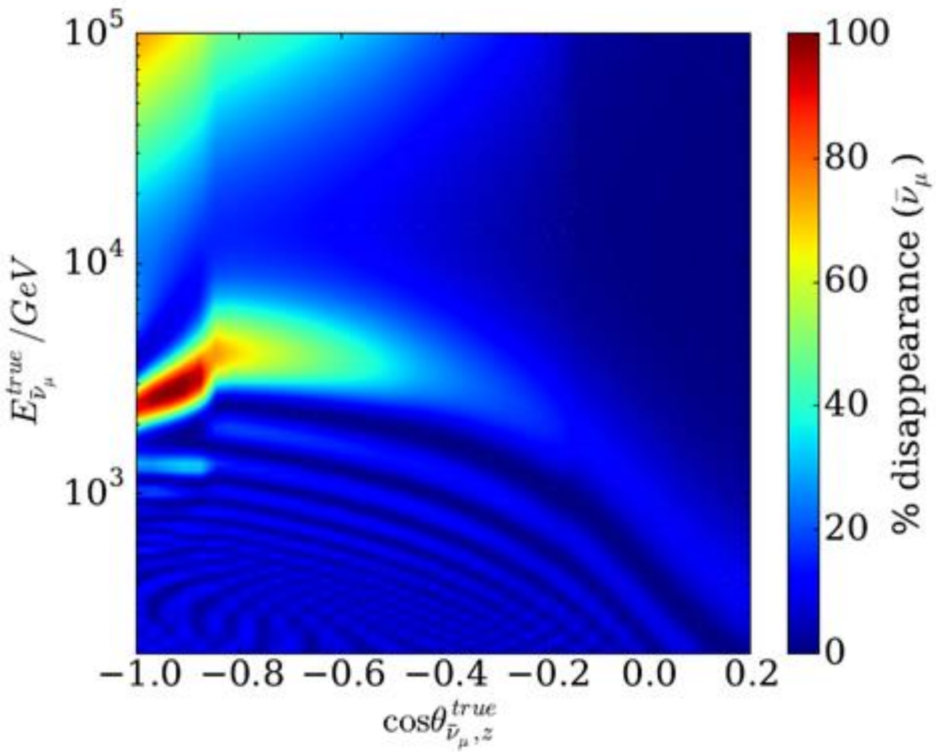
"ν_μ" "Probability"

- 20% energy resolution
- Weighted according to neutrino flux
- ν_μ at the detector

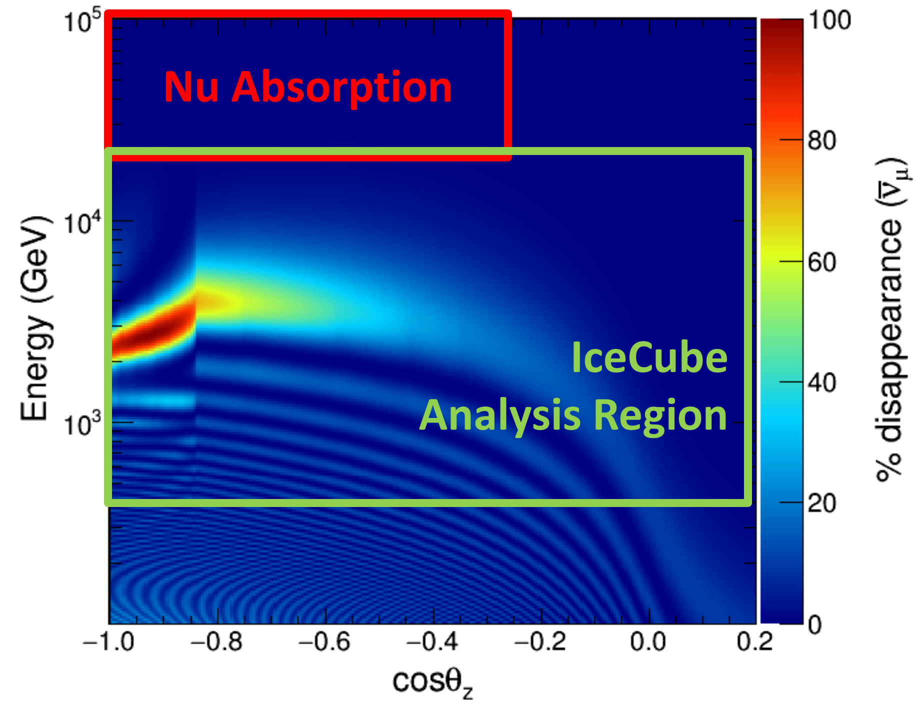


New IceCube Paper

IceCube arXiv:1605.01990 (2016)

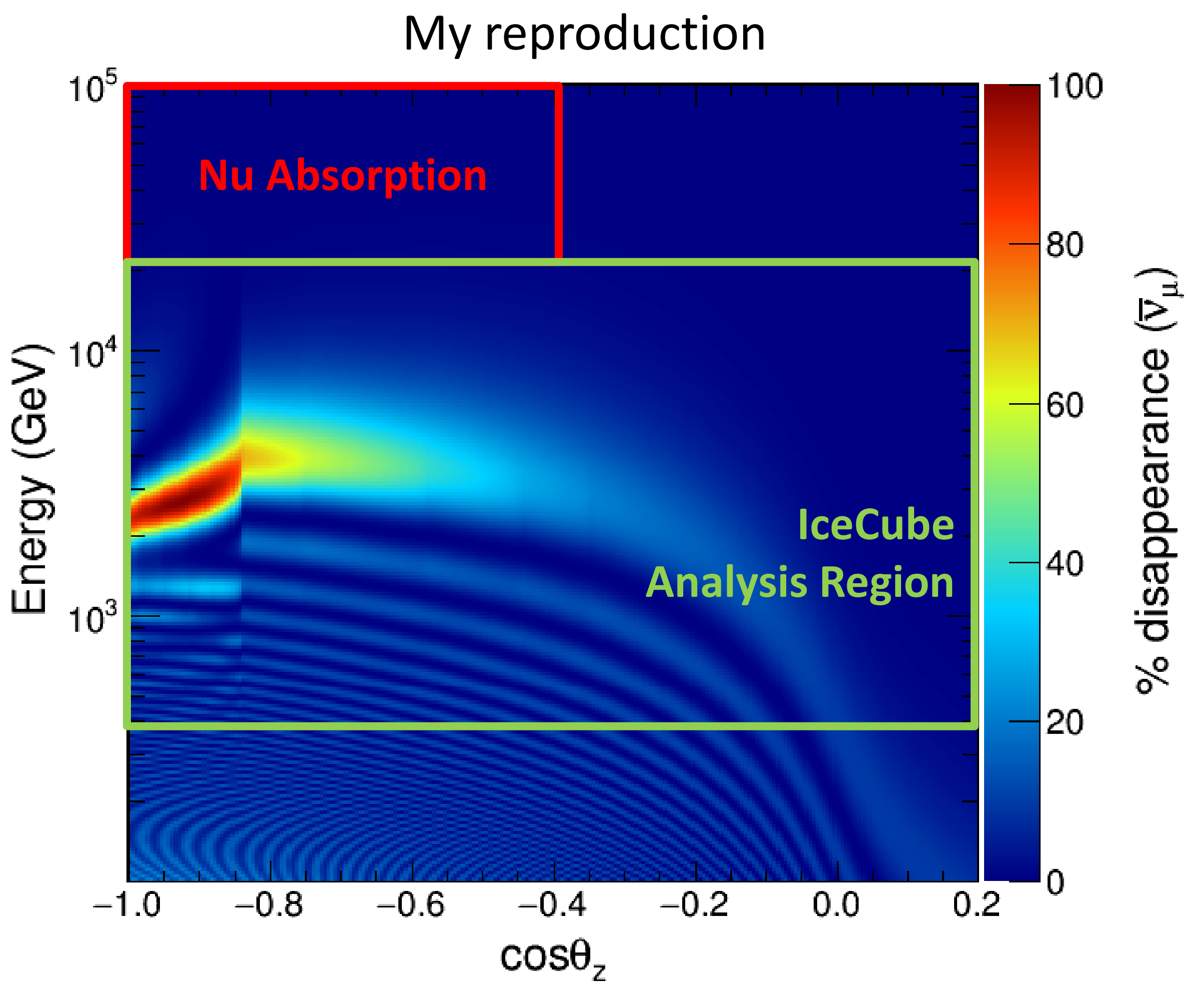


My reproduction



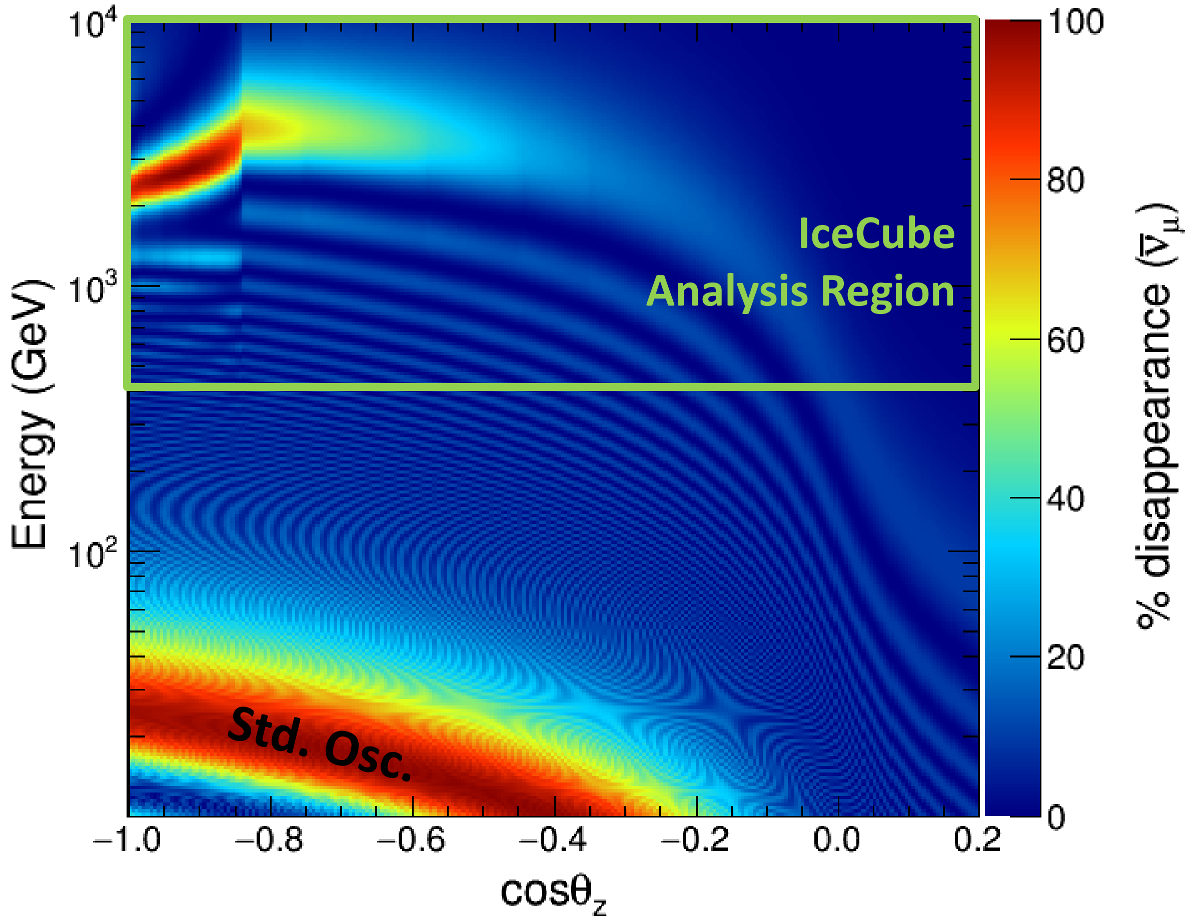
- Simplified model with $U_{e4} = U_{\tau4} = 0$
- Most sensitive to few TeV resonance

Reality Check



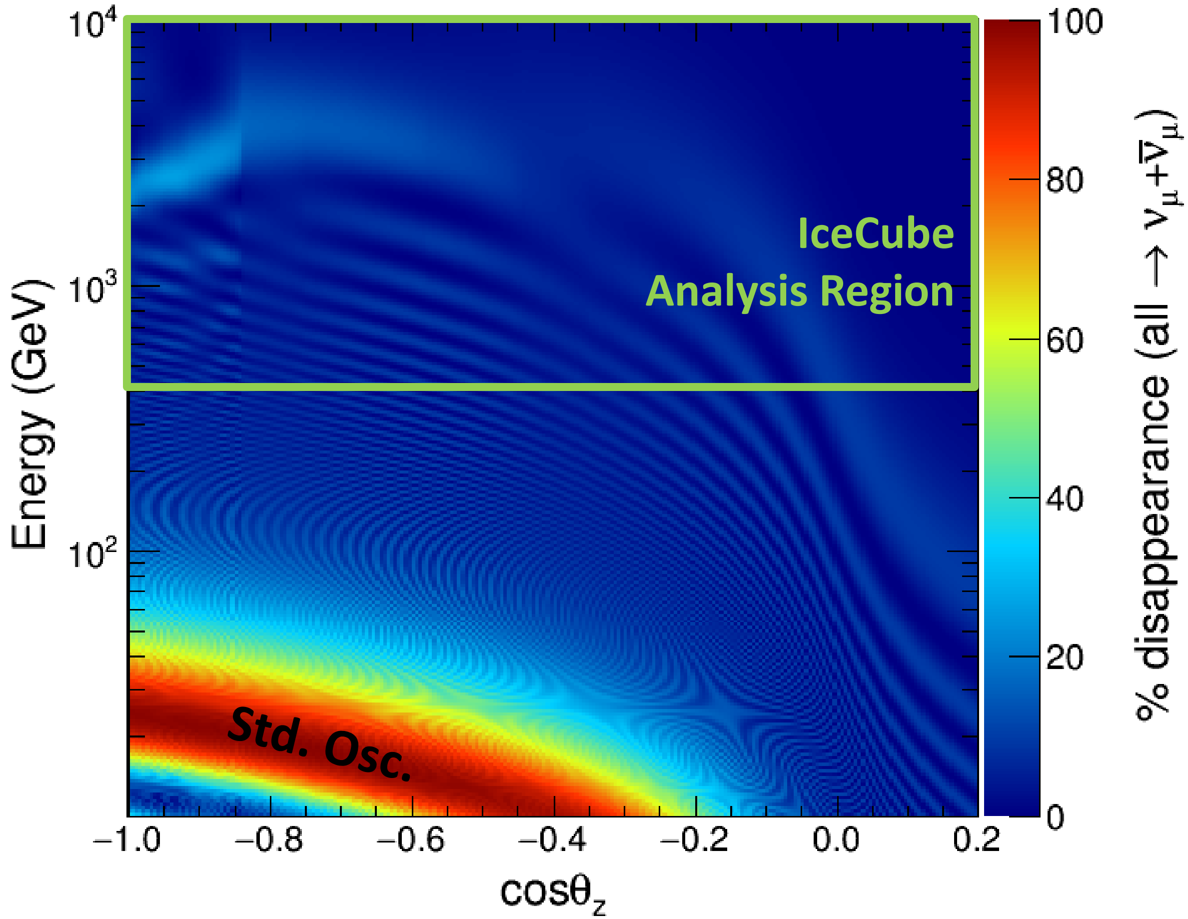
- Starting point: Reproduce plot

Reality Check



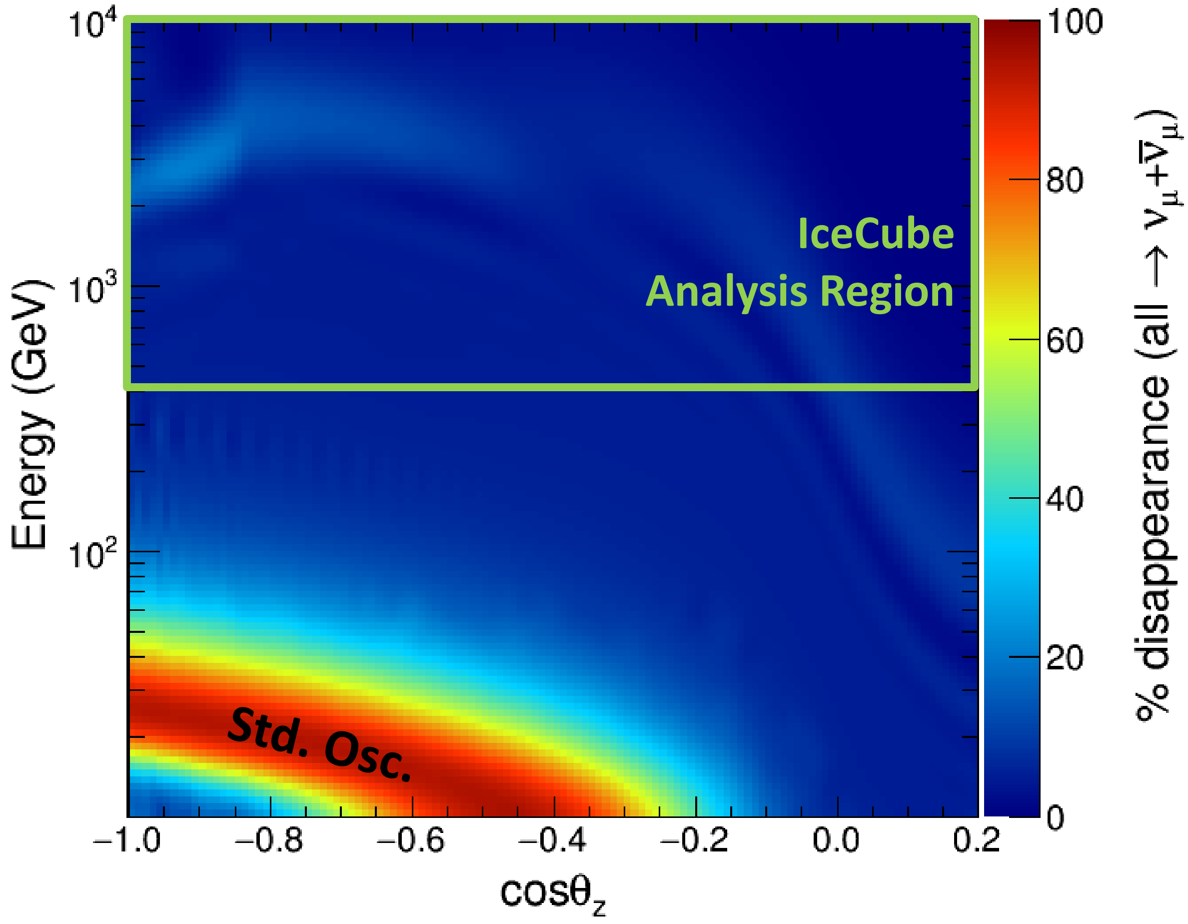
- Step 1: Look at lower energies

Reality Check



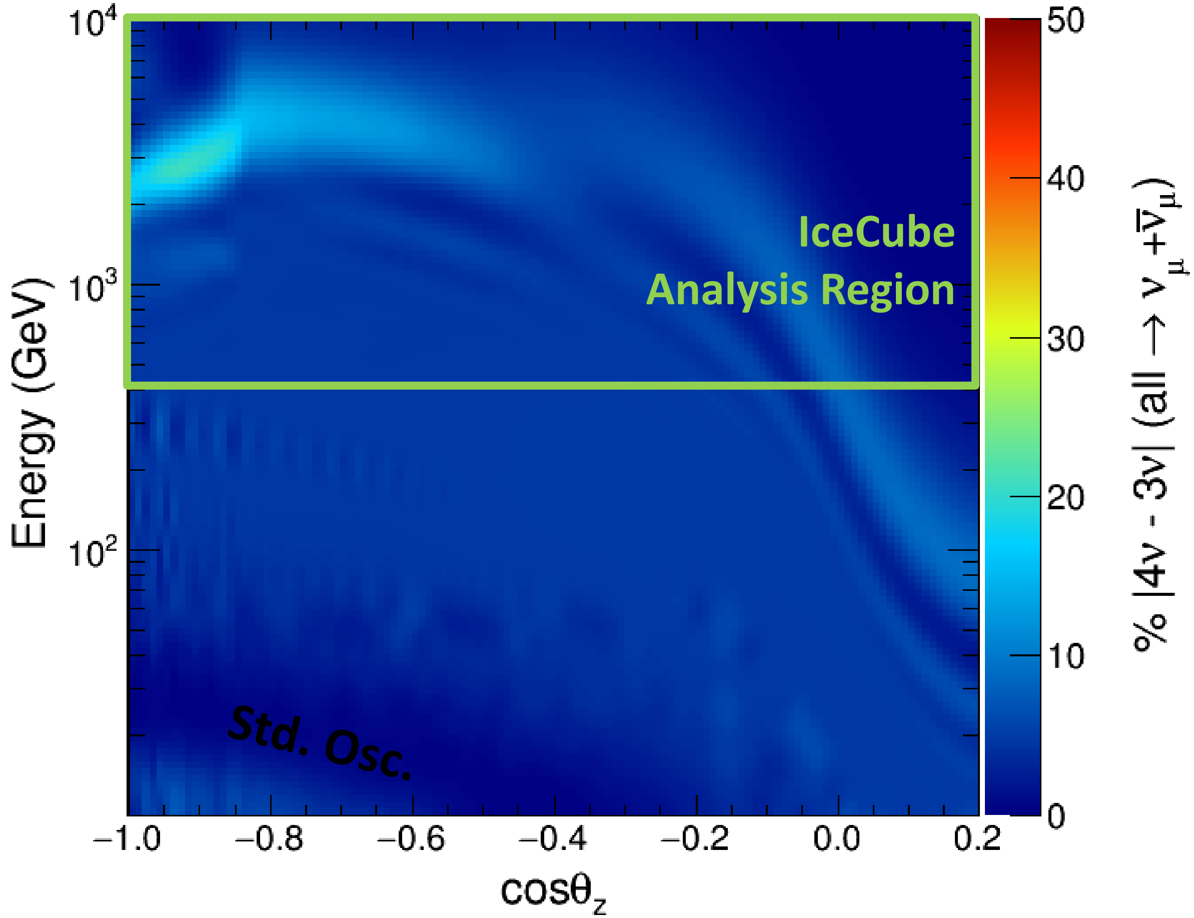
- Step 2: Account for mixed flavour content from flux

Reality Check



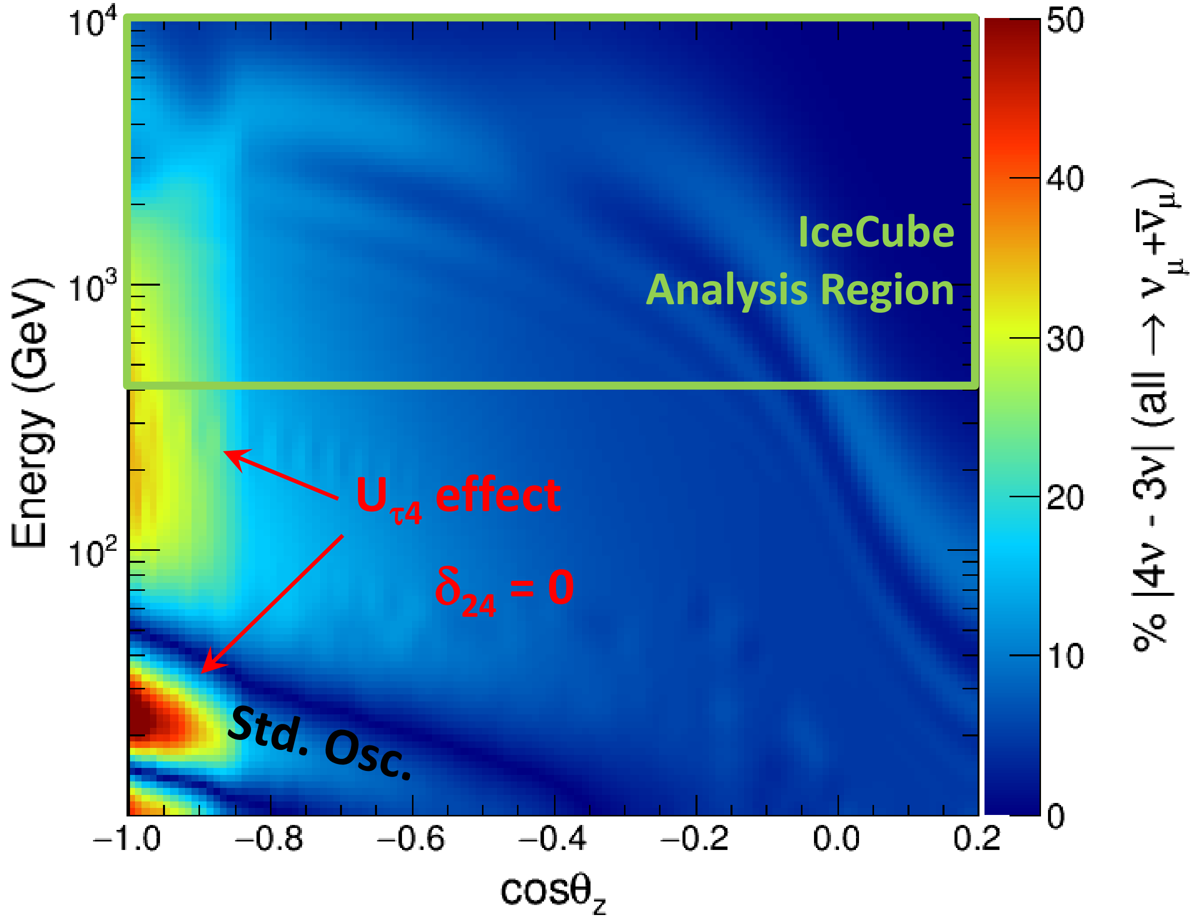
- Step 3: Add some finite resolution (20% in Energy)

Residuals



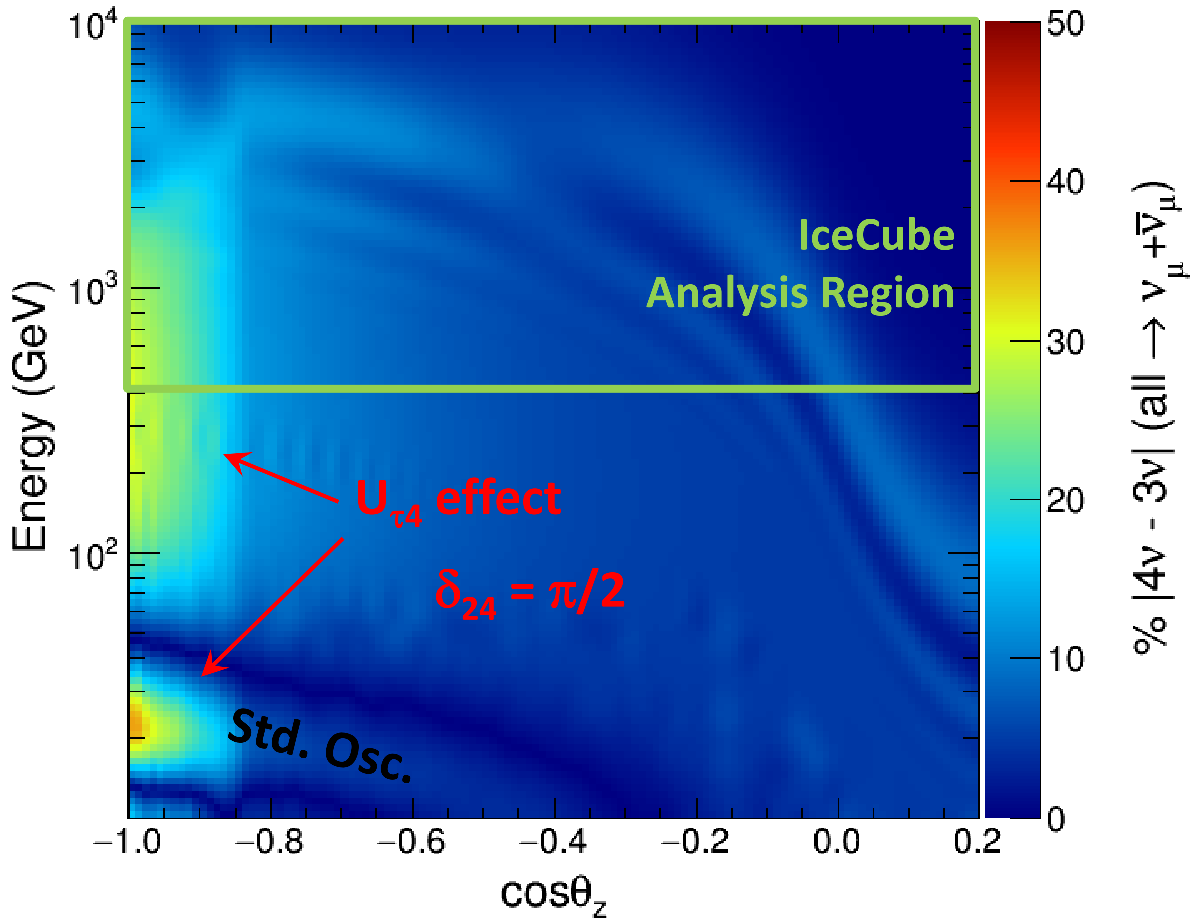
- We can look at deviations from the Std. Osc.
- Roughly a 20% effect with $\sin^2 2\theta_{24} = 0.1$

Residuals



- Much larger effect at current $U_{\tau4}$ limit ($|U_{\tau4}|^2 = 0.18$)
- Extra sensitivity from few 100 GeV region
- Large effect in the Std. Osc. Region (Super-K)

Residuals



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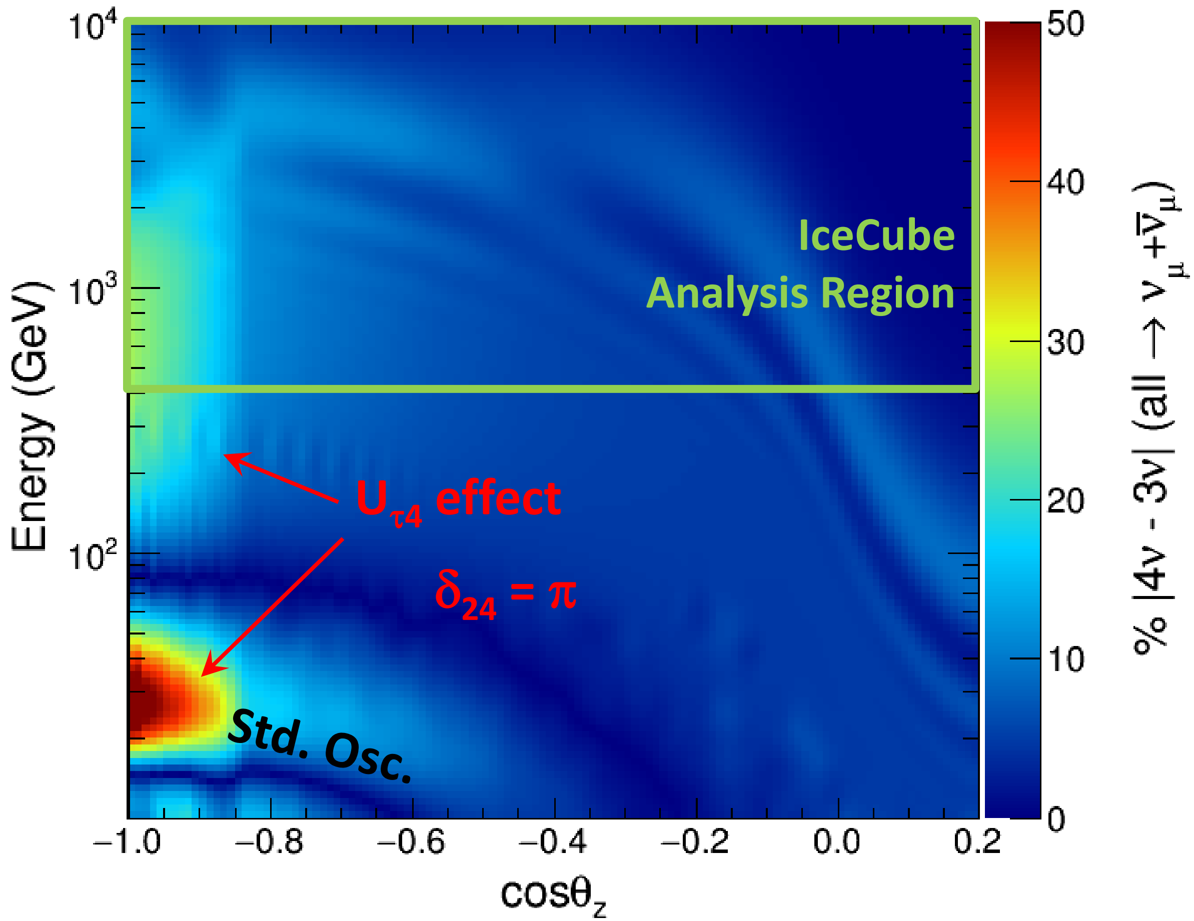
- Extra sensitivity from few 100 GeV region
- Very dependent on new CP phase at low energy

Residuals



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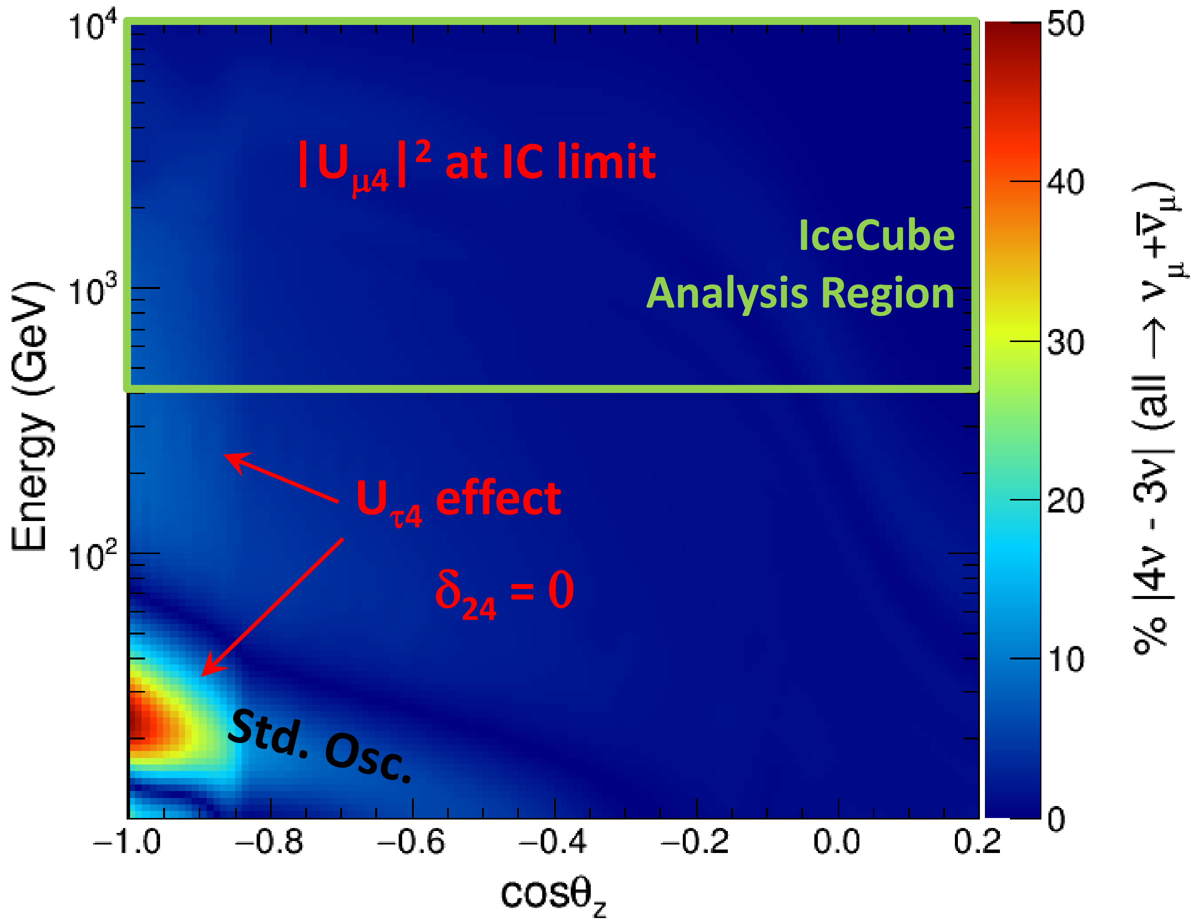
Reality Check 2



- At high energies, effect is very linked to $U_{\mu4}$
- Constraints from IceCube are very strong already