Taster of “low-energy” analyses@IceCube

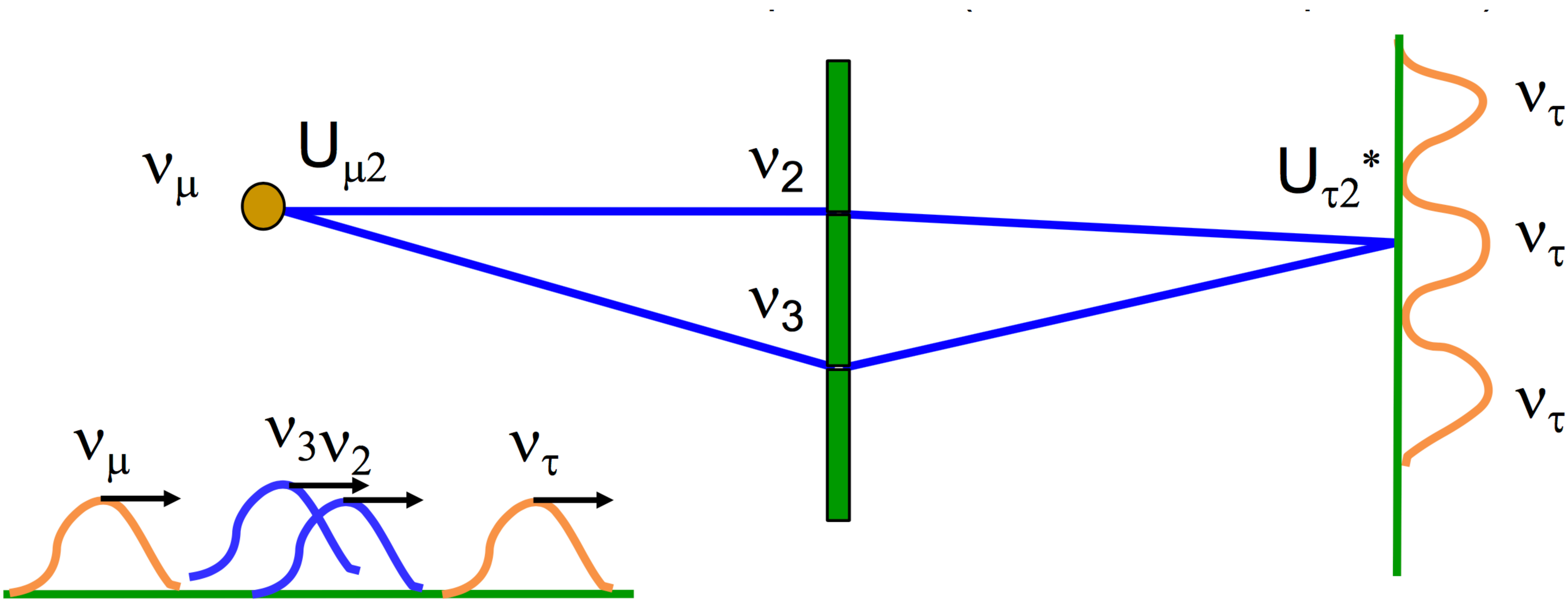
Carlos Argüelles

IceCube Bootcamp
Madison, WI, USA 2018

Our “low-energy” is everybody* else “high-energy”

*everybody in neutrino oscillation physics, not ANITA and so on.

Neutrino oscillation cartoon idea

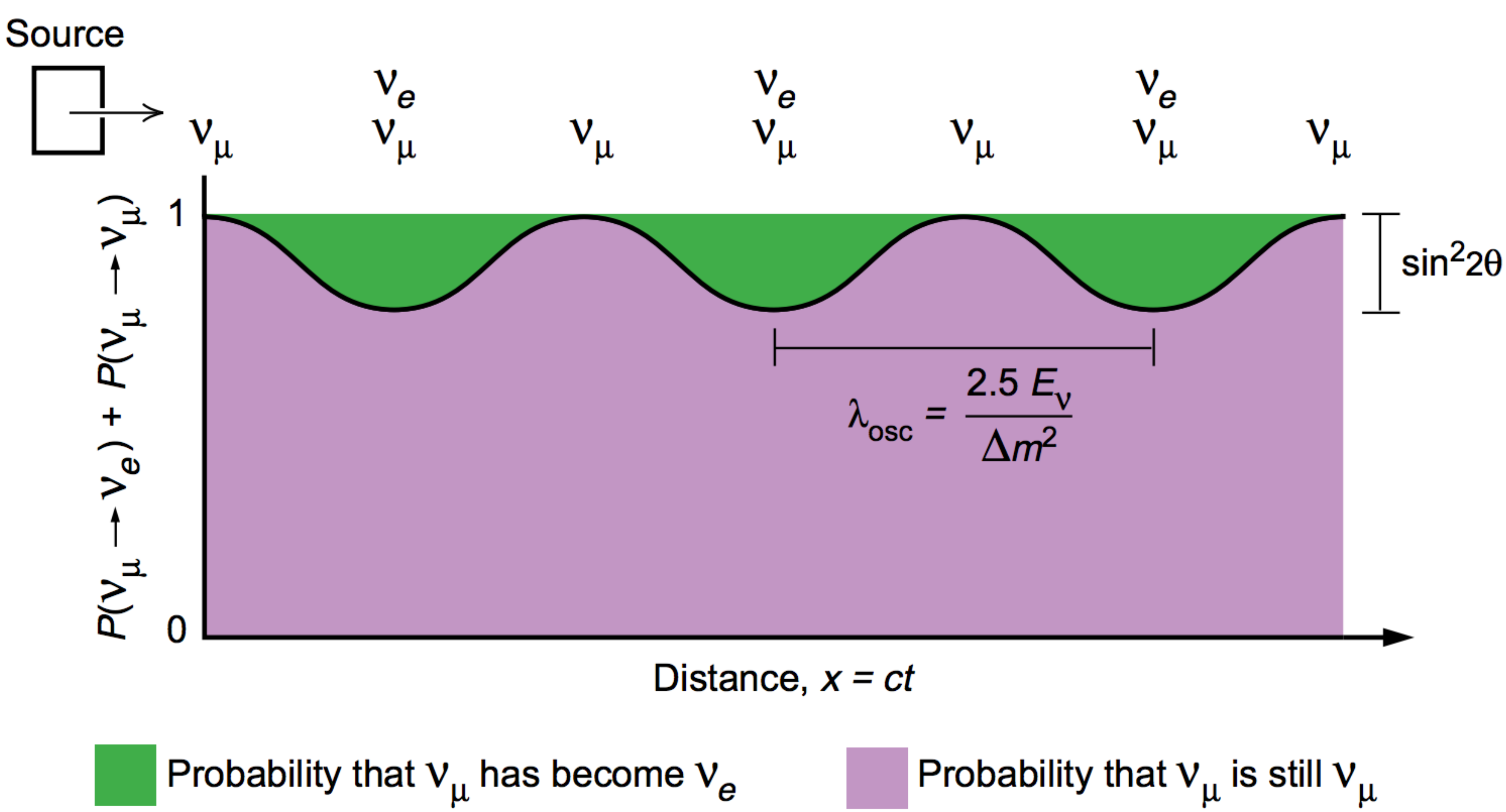


If two neutrino eigenstates have different rotation they cause quantum interference: neutrino oscillations.

Neutrino Oscillations primer

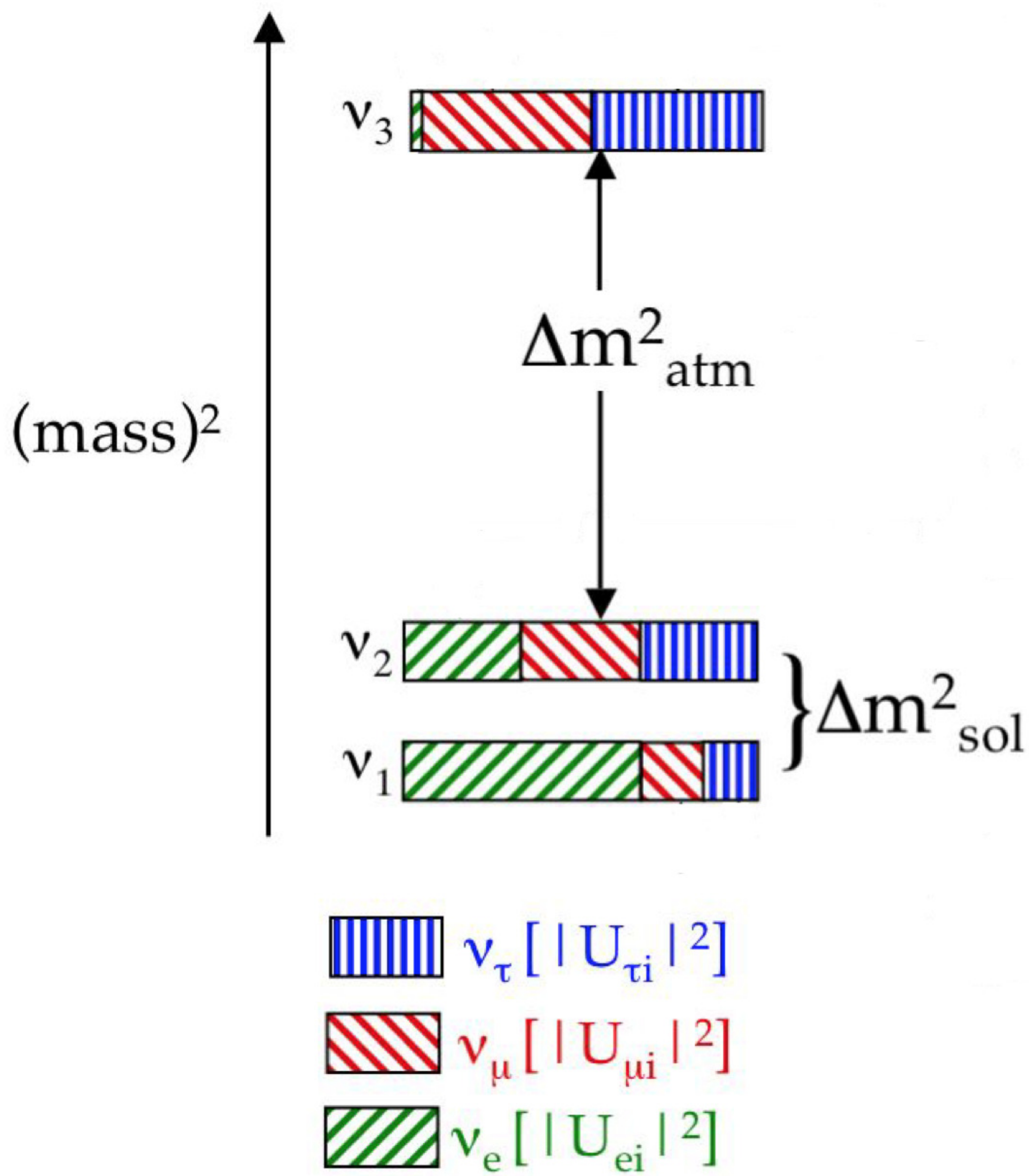
In two generations the oscillation probability at a given distance L and energy E in vacuum

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



Our current picture

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



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

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

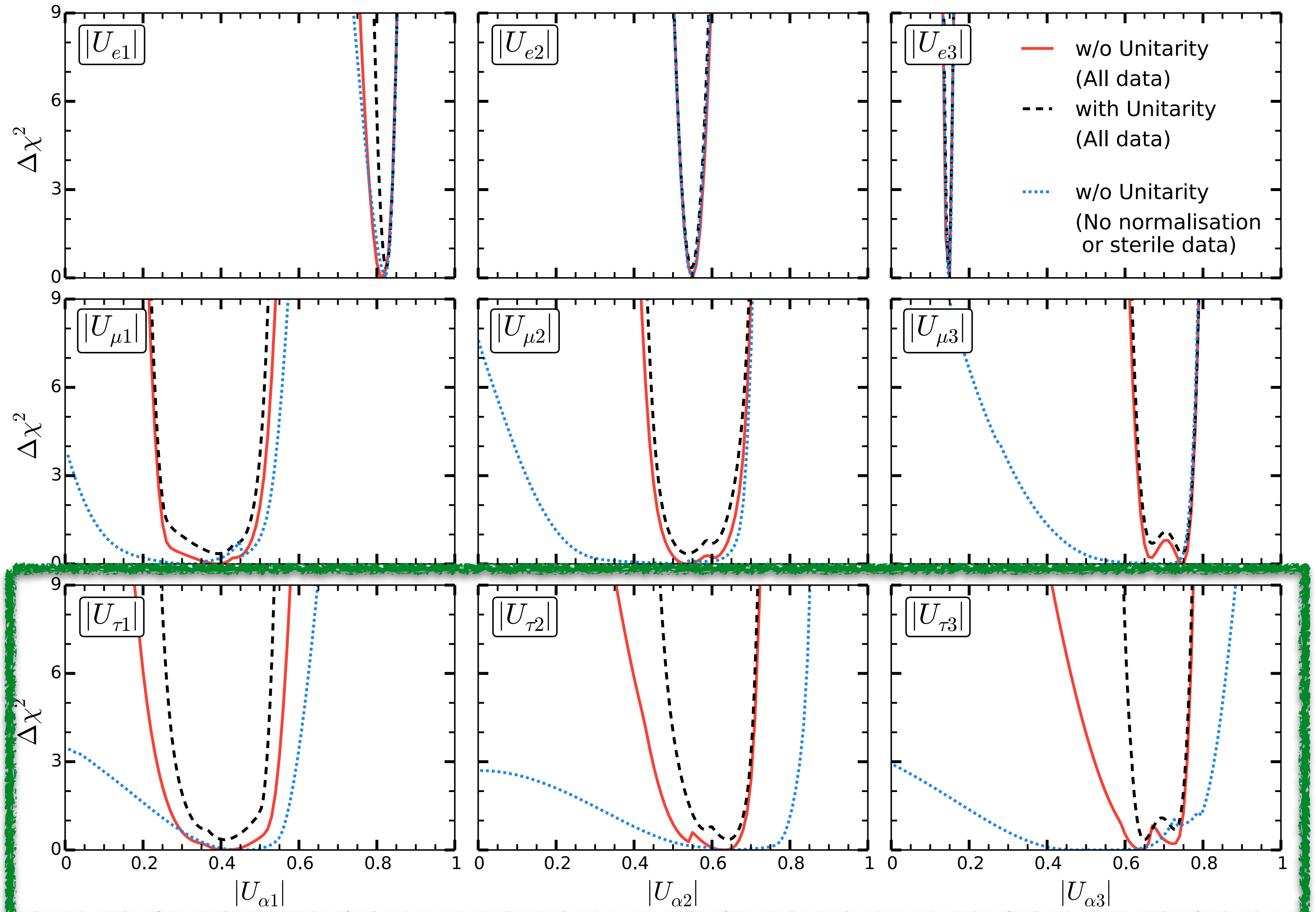
$$U = \mathrm{U}(\theta_{12}, \theta_{23}, \theta_{13}, \delta^{CP})$$
$$|\mathrm{U}| \simeq \begin{pmatrix} 0.8 & 0.5 & 0.1 \\ 0.3 & 0.7 & 0.6 \\ 0.4 & 0.5 & 0.8 \end{pmatrix}$$

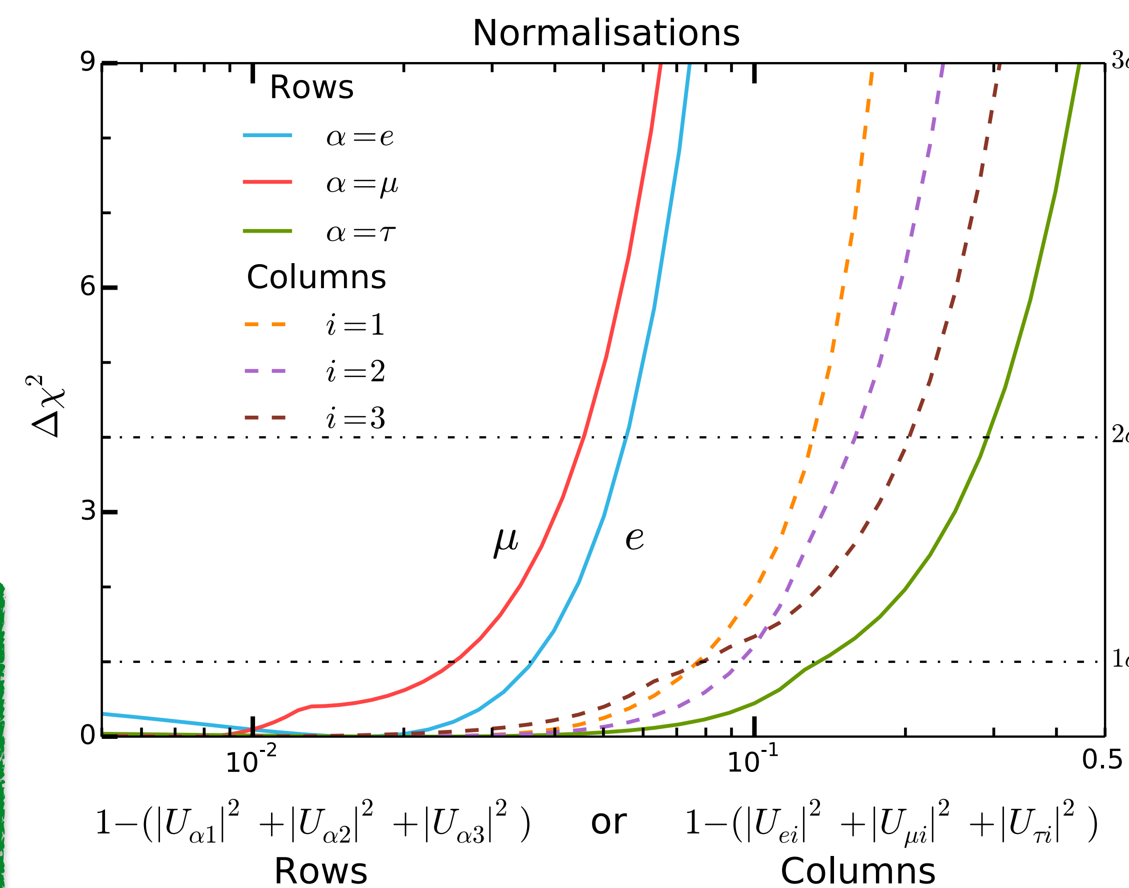
[B. Kayser, hep-ph/0506165 (2004)]

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

Next generation experiments are to test this framework!

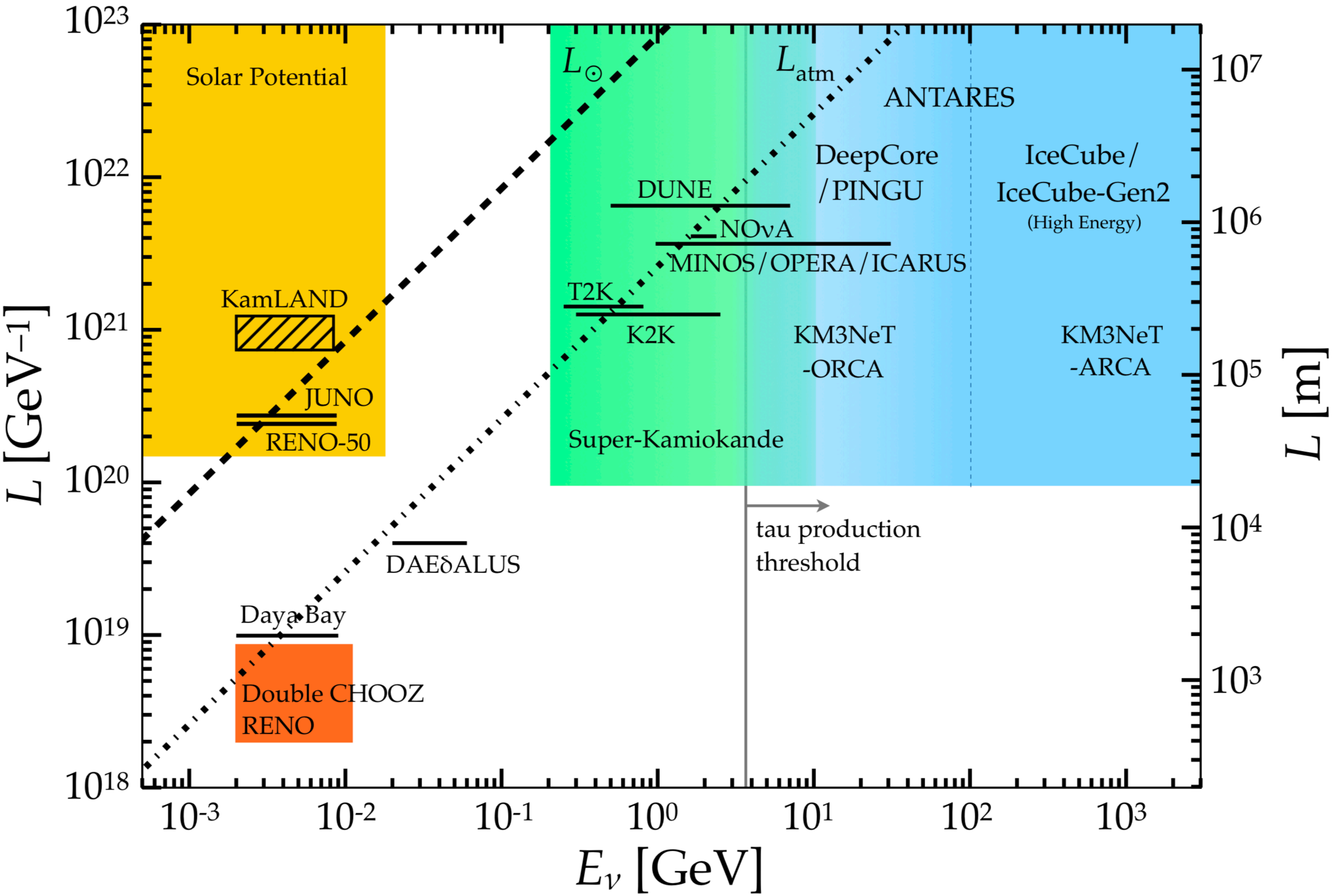
Testing PMNS matrix unitarity





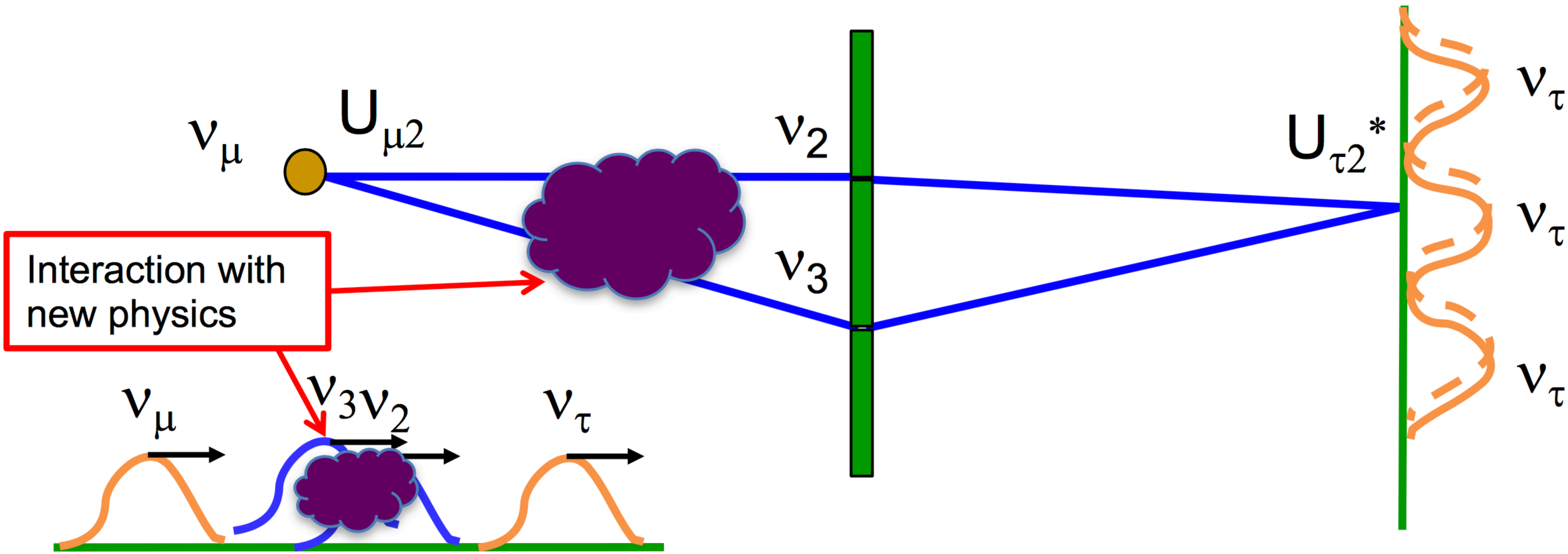
(Parke et al. arXiv:1508.05095)

Global picture



IceCube measurements *are* at different energies and baselines! We are testing the three massive neutrino picture, (L/E scaling).

How to look for new physics with neutrino oscillation?



If new physics potential affects differently neutrinos propagation states: new oscillation phenomena.

Because we are trying to test (put stress) on the current picture, we use blind analysis to avoid bias.

What is a blind analysis? It's a technique that purposely hides information from the analyzers in order to avoid tweaking the cuts and/or systematics to change the result significance and/or interpretation.

Is my analysis "wrong" if its not blind? No, one just need to be more careful to not accidentally bias yourself. Corollary: things move much slower after unblinding than prior to it.

Typical **unblinding procedure looks something like this:**

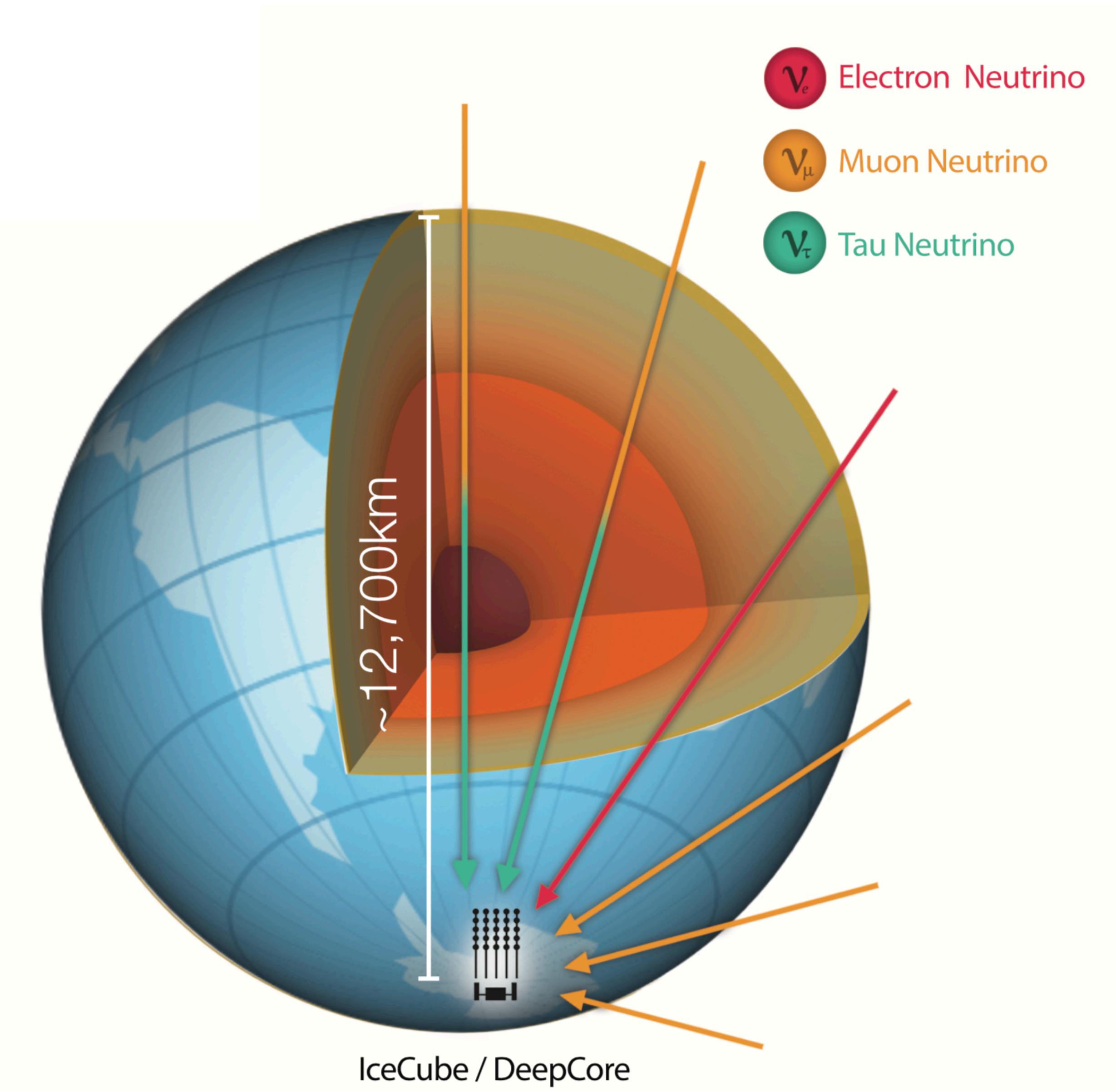
1. **Basic checks:** check goodness-of-fit, check sideband distributions (e.g. azimuth).
2. **Check non-physics parameters:** look at the nuisance parameters pulls.
3. **Check physics distributions stability:** are your physics distributions compatible when sliced in time or in detector splittings?
4. **Check pulls at best-fit point:** look at the pull distribution on your physics variables (e.g. energy, zenith)
5. **Reveal physics parameters.**

There is no universal unblinding procedure, they change analysis to analysis.

Analysis strategy

- ✤Use atmospheric neutrinos from few GeV to 100 GeV.
- ✤In this energy range the neutrinos are coming predominantly from pion and muon decay.
- ✤Cross section is dominated by DIS.
- ✤Oscillation probability baseline proportional to zenith angle.

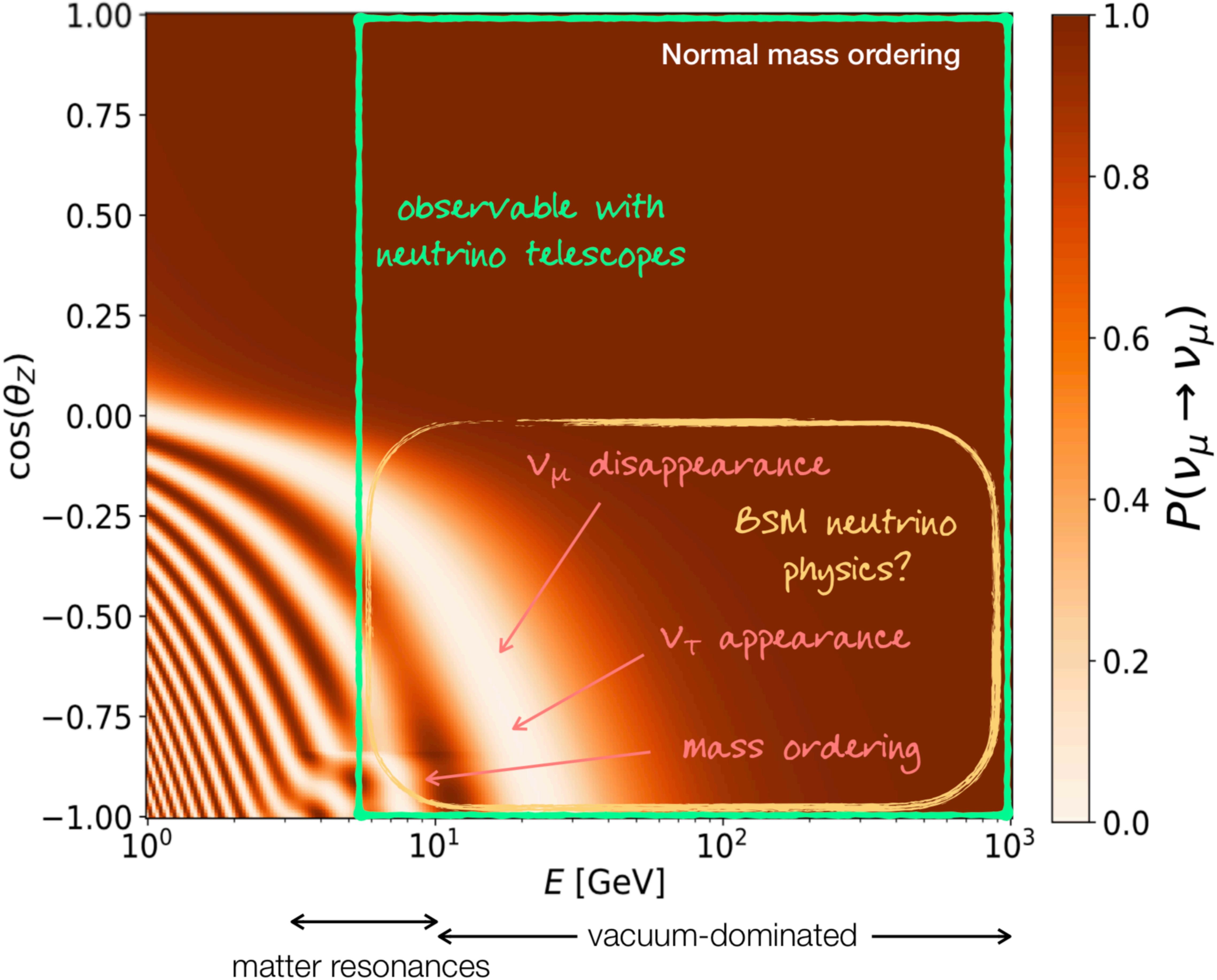
- ✤Make 3D histograms in: \cos\theta, energy, PID for each component.
- ✤Systematics are implemented as nuisance parameters and fitted simultaneously. Broad L/E range and large statistics allows to control the systematics.



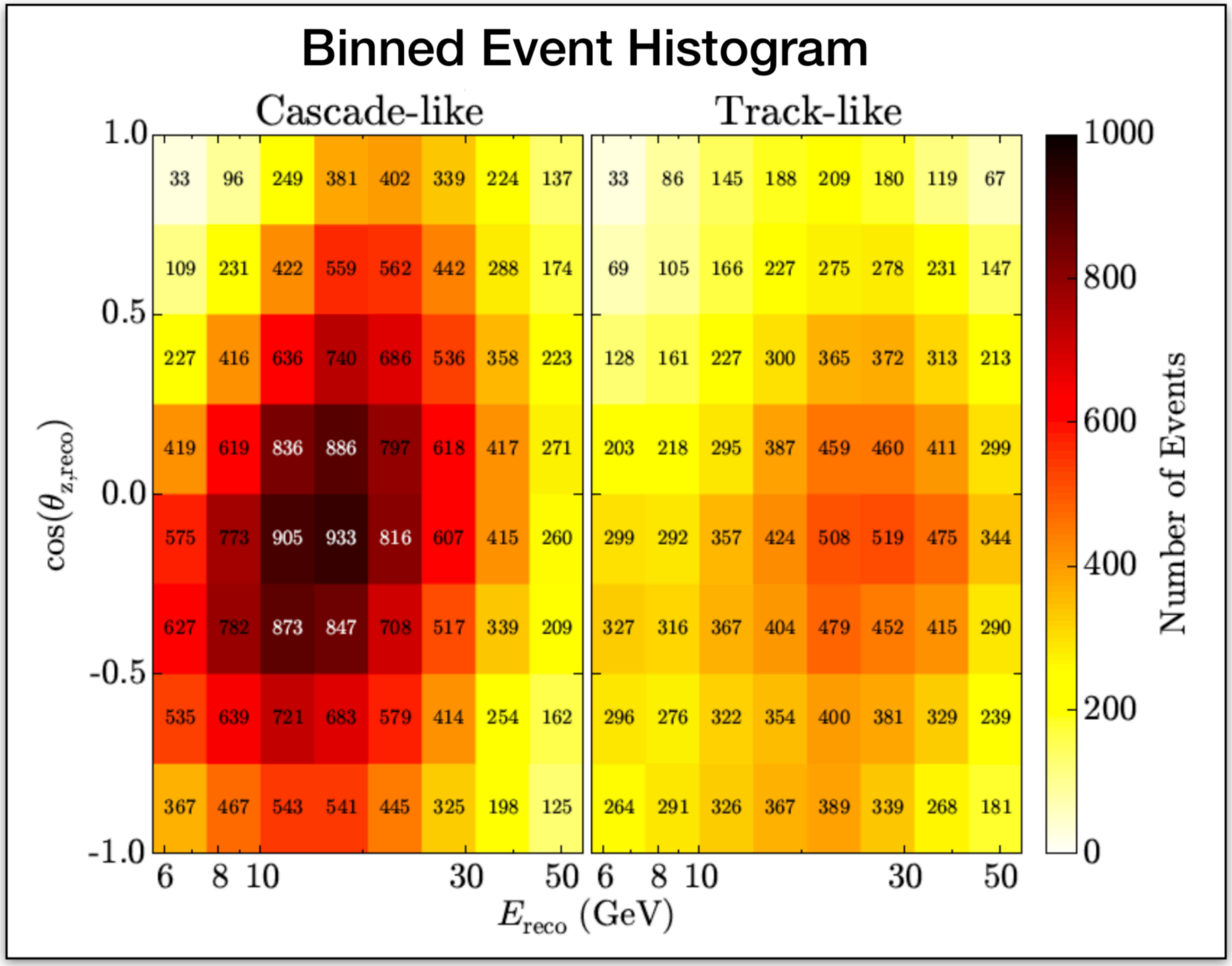
$$\cos\theta \sim L$$

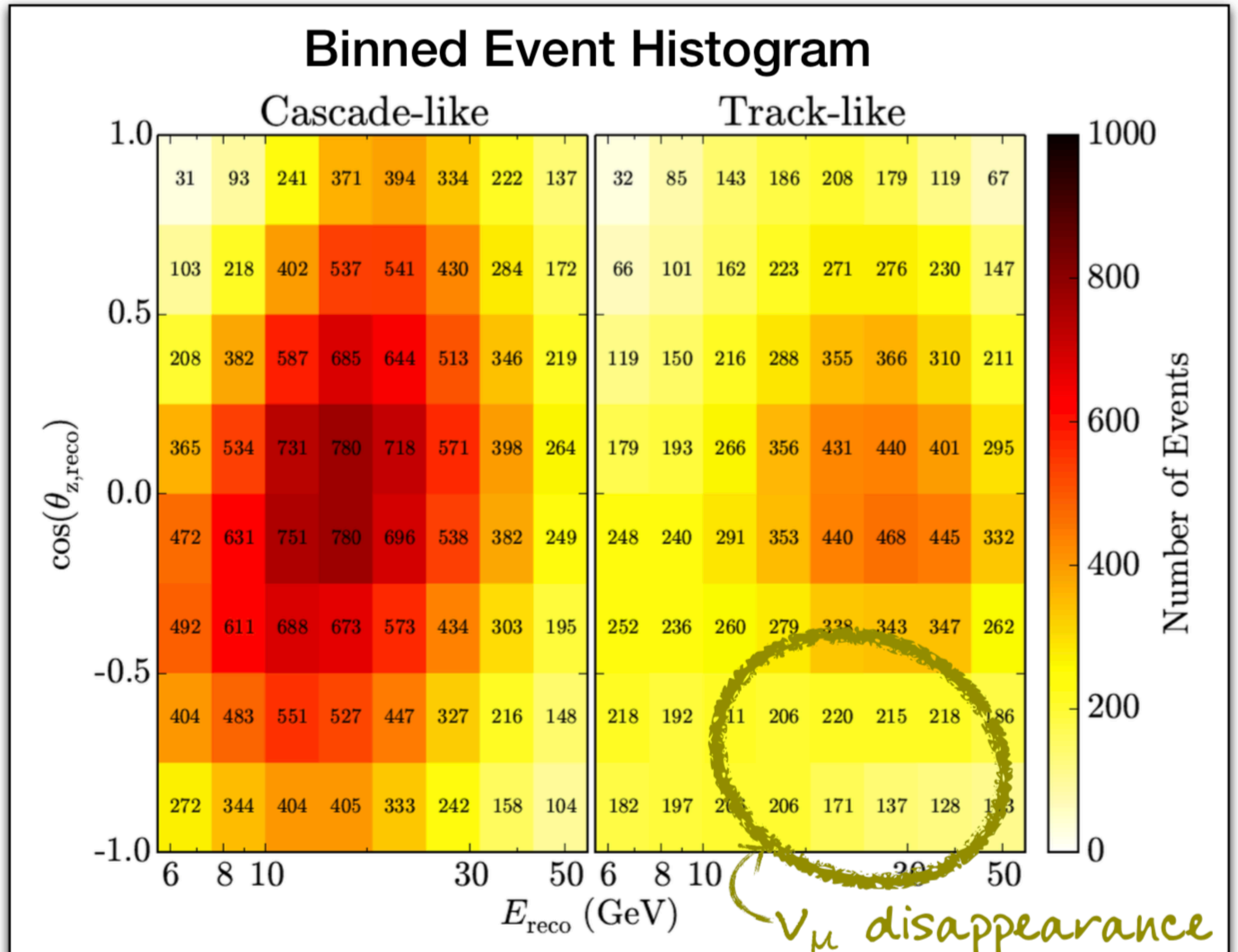
Oscillograms

T. DeYoung, Neutrino2018

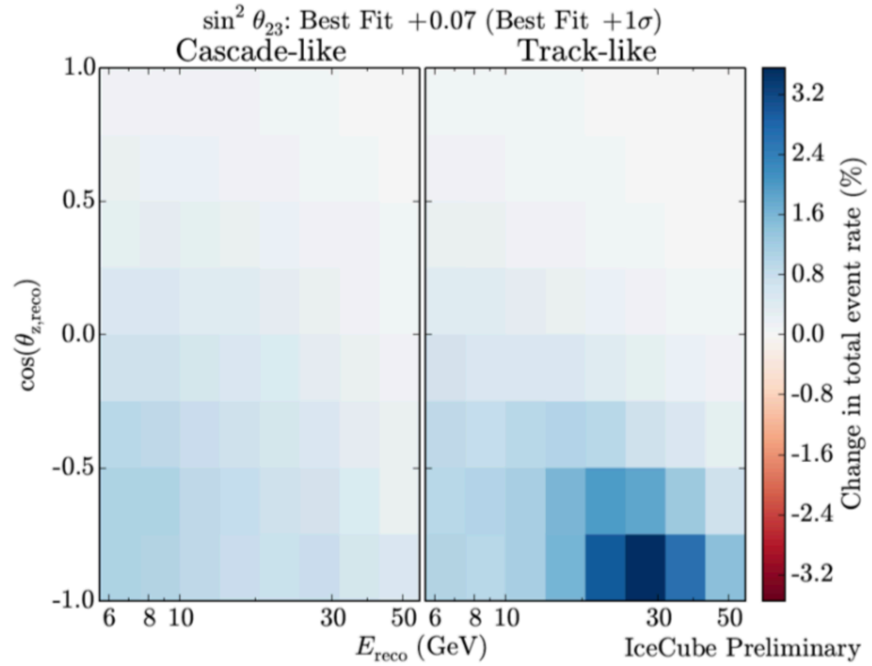


T. DeYoung, Neutrino2018

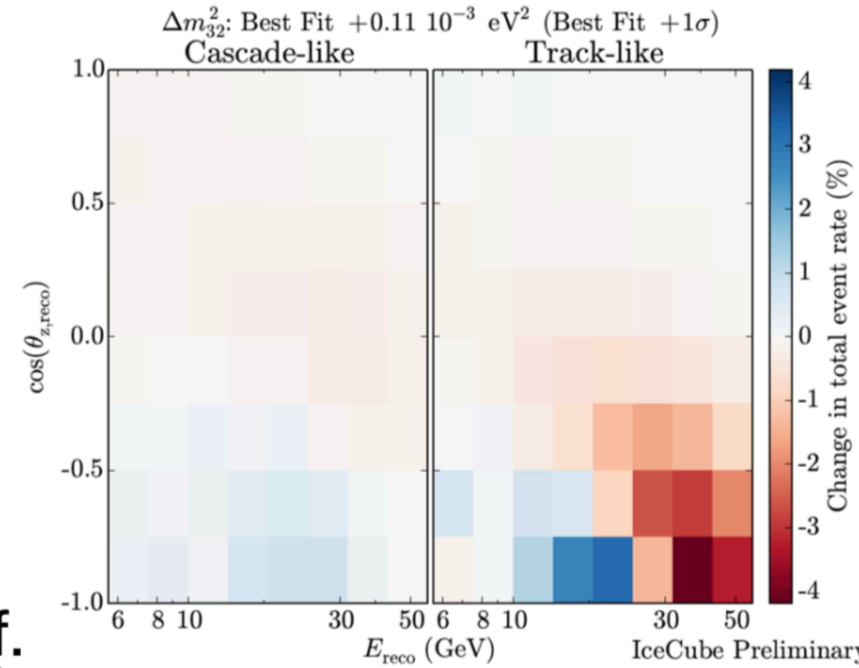




sin^2 θ_{23}

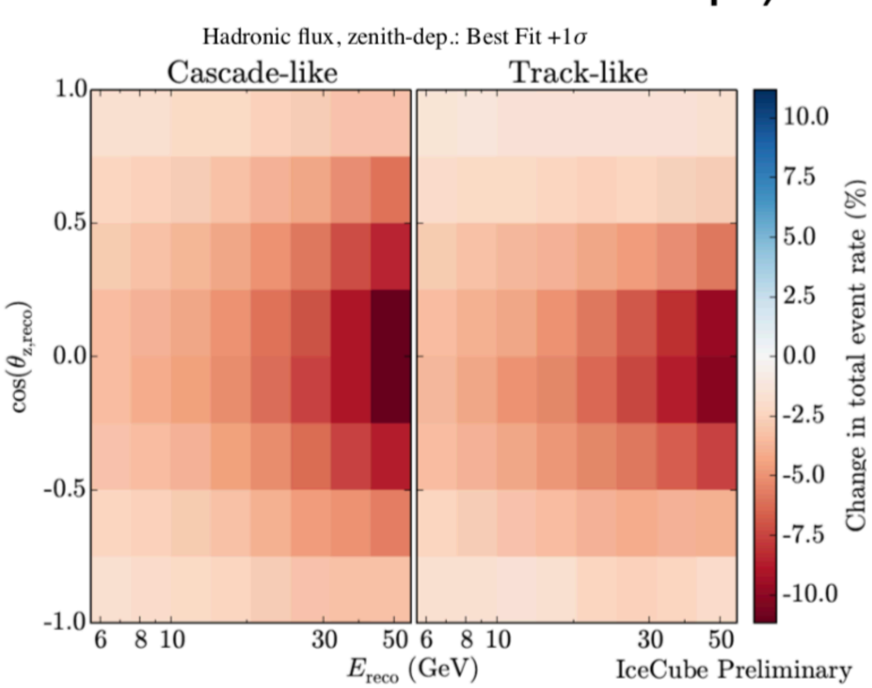


Δm^2_{32}

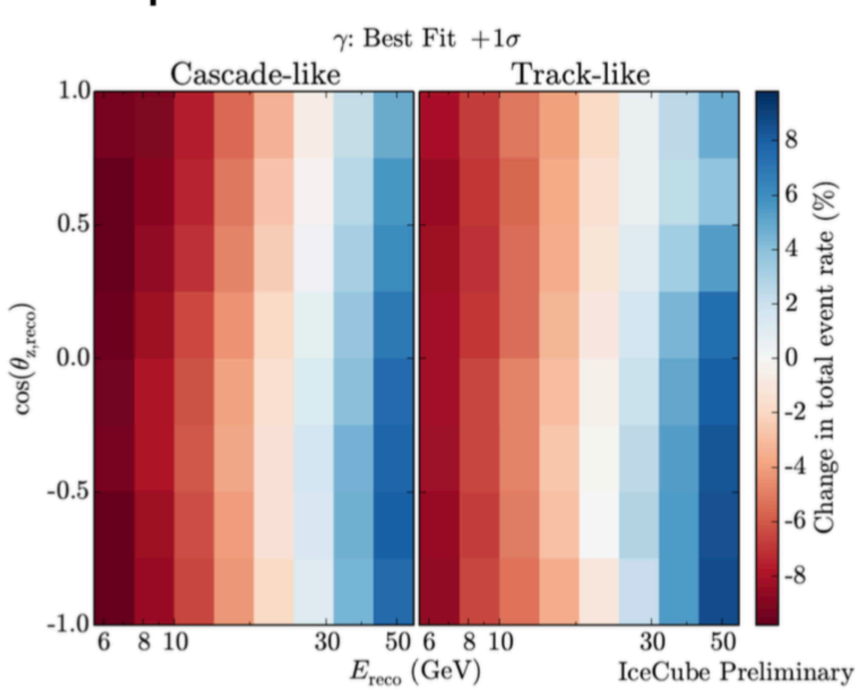


T. DeYoung, Neutrino2018

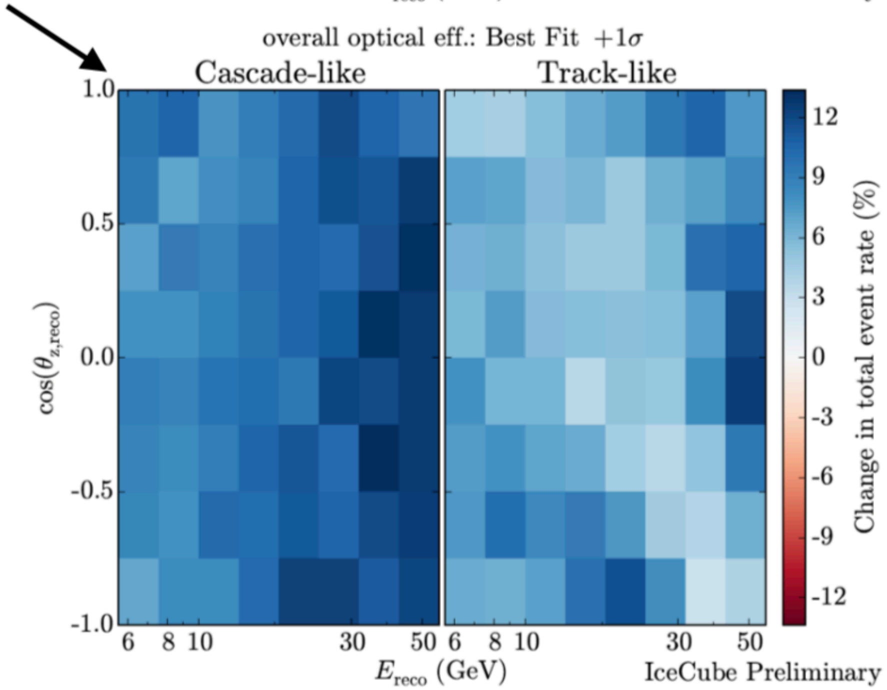
flux hadr. effects (θ-dep.)



spectral index



DOM eff.



Typical systematics

Flux and cross section uncertainties (highly degenerate)	Typical prior/method
Overall rate	unconstrained
Linear energy-dependent effects (flux spectral index, DIS effects)	±0.10 in index
$(\nu_e + \bar{\nu}_e) / (\nu_\mu + \bar{\nu}_\mu)$ ratio	±5%
NC / CC ratio	±20%
hadronic flux effects (degenerate with $\bar{\nu}/\nu$ ratio) – energy dependence	from Barr et al. 2006
hadronic flux effects (degenerate with $\bar{\nu}/\nu$ ratio) – angular dependence	from Barr et al. 2006
Axial vector mass M_A (some effect for resonances, negligible for CCQE)	from GENIE
Detector/background uncertainties: IceCube	
DOM overall sensitivity	±10%
DOM angular-dependent response: two parameters	from LED data
Photon scattering and absorption in glacial ice: two parameters	±10%
Atmospheric muon background shape (rate unconstrained)	from MC or tagged veto data

Mix top-bottom and bottom-top approaches

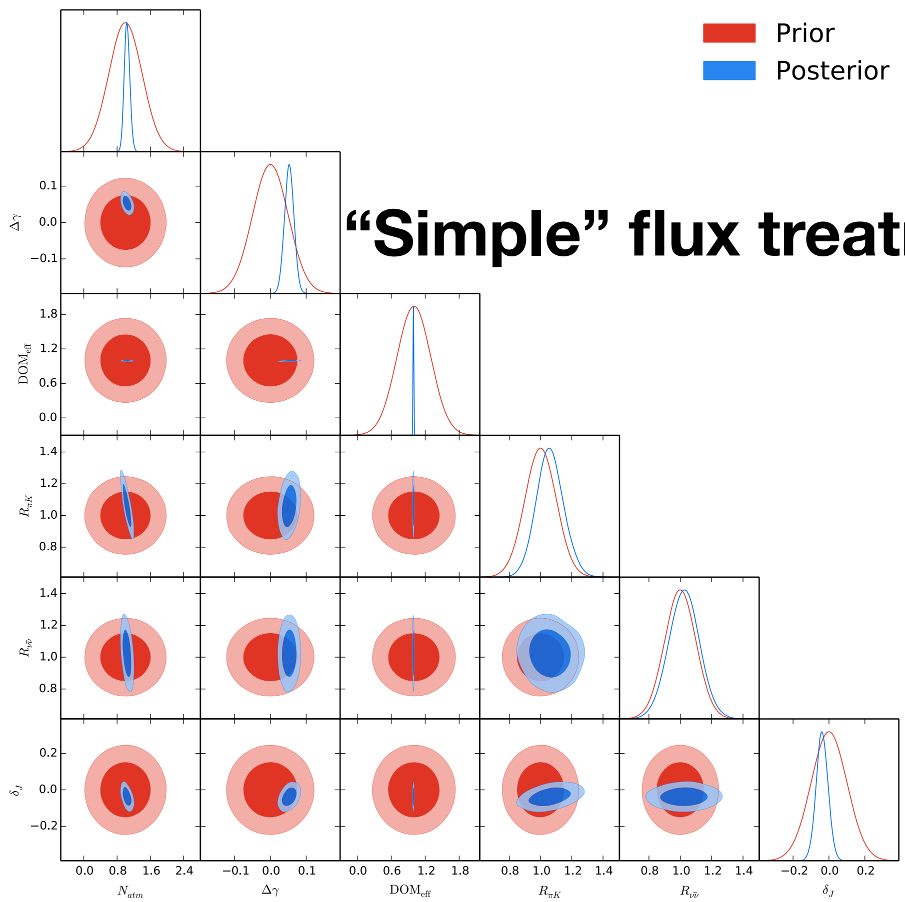
Bottom-top: construct a detail model of the systematic effect.

Top-bottom: construct an ad hoc parameterization that mimics the effect of the systematic.

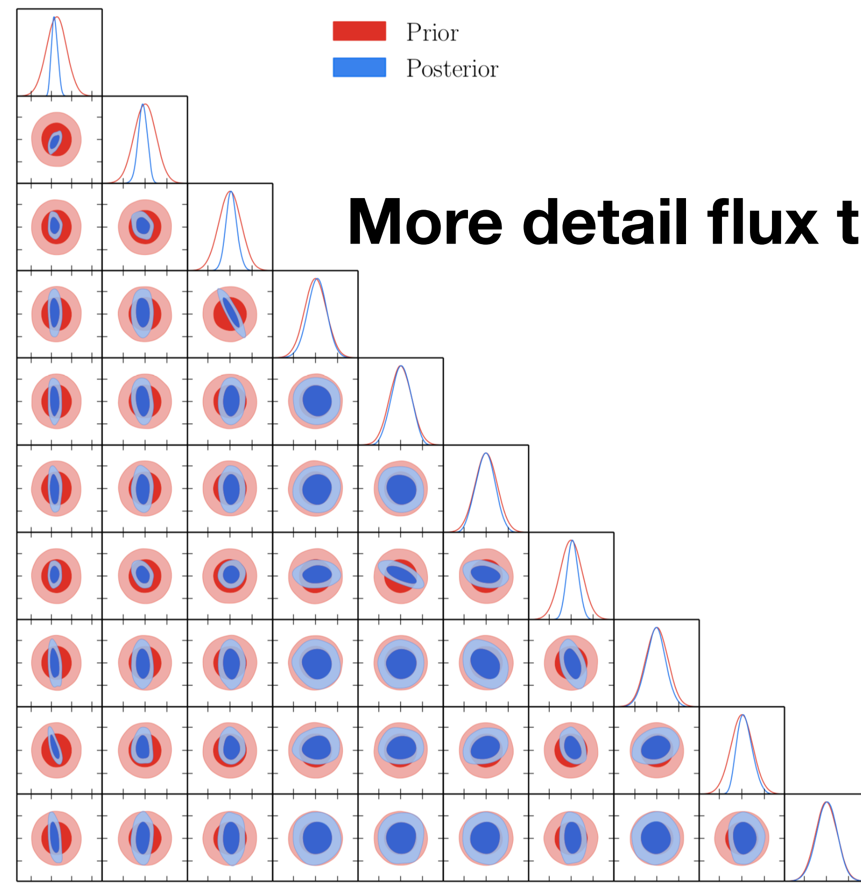
More comments on systematics

1 year analysis systematic treatment

7 year analysis systematic treatment



"Simple" flux treatment



More detail flux treatment

+

Atmospheric flux		
ν flux template	discrete (7)	
ν / $\bar{\nu}$ ratio	continuous	0.025
π / K ratio	continuous	0.1
Normalization	continuous	none[1]
Cosmic ray spectral index	continuous	0.05
Atmospheric temperature	continuous	model tuned
Detector and ice model		
DOM efficiency	continuous	
Ice properties	discrete (4)	
Hole ice effect on angular response	discrete (2)	
Neutrino propagation and interaction		
DIS cross section	discrete (6)	
Earth density	discrete (9)	

"Simple" detector treatment

+

New continuous and more precise detector systematic treatment!

Systematic treatment is not universal it depends on the sample at hand and the objective measurement. What is appropriate or not depends on statistical power of the sample.

People working in flux and detector systematics are the superheroes of our times!

"With great statistical power comes great systematic responsibility"

Analysis software

Currently two fitting frameworks (packages) use for oscillation analysis:

PISA

https://icecube.wisc.edu/~peller/pisa_docs/index.html

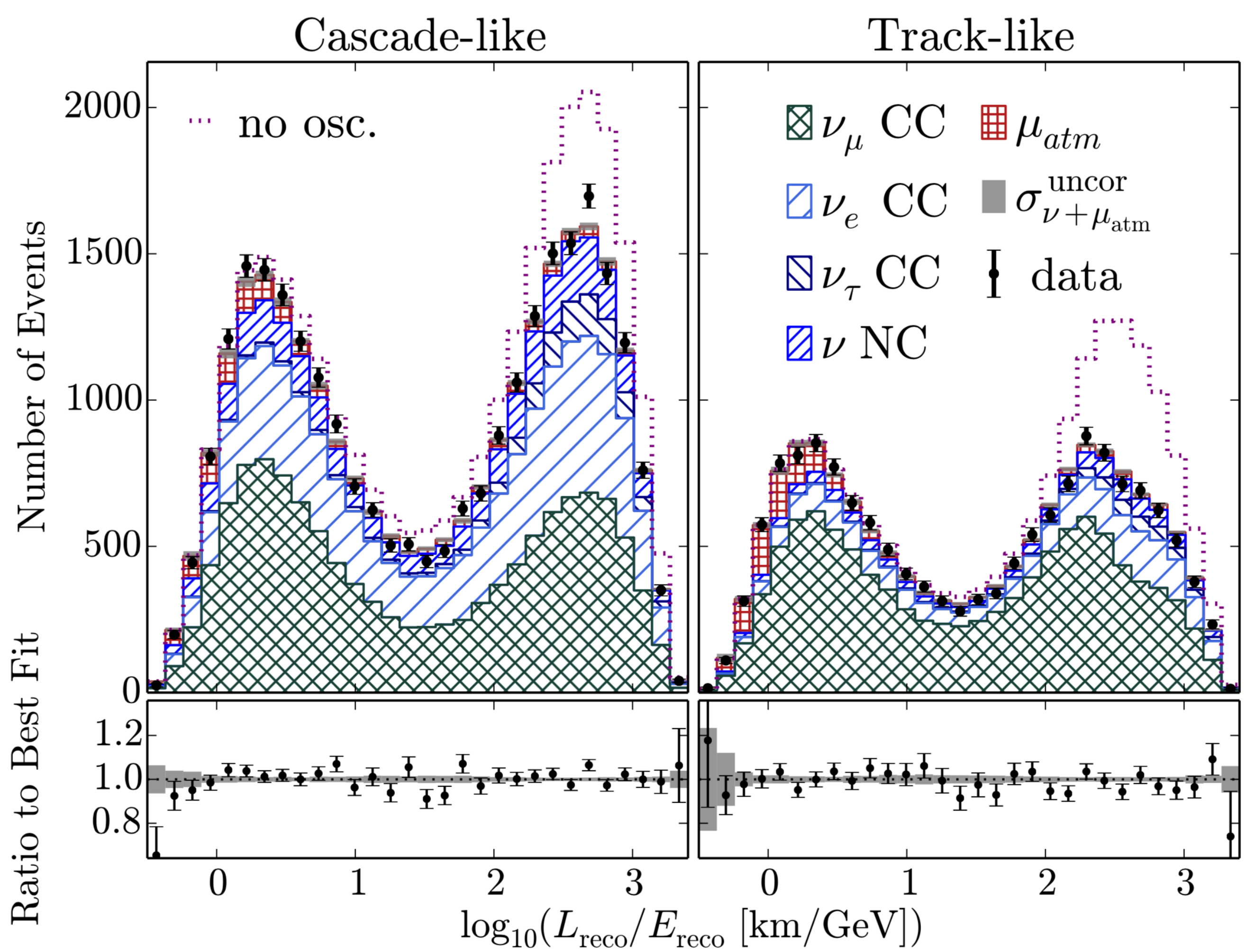
GOLEM Fit

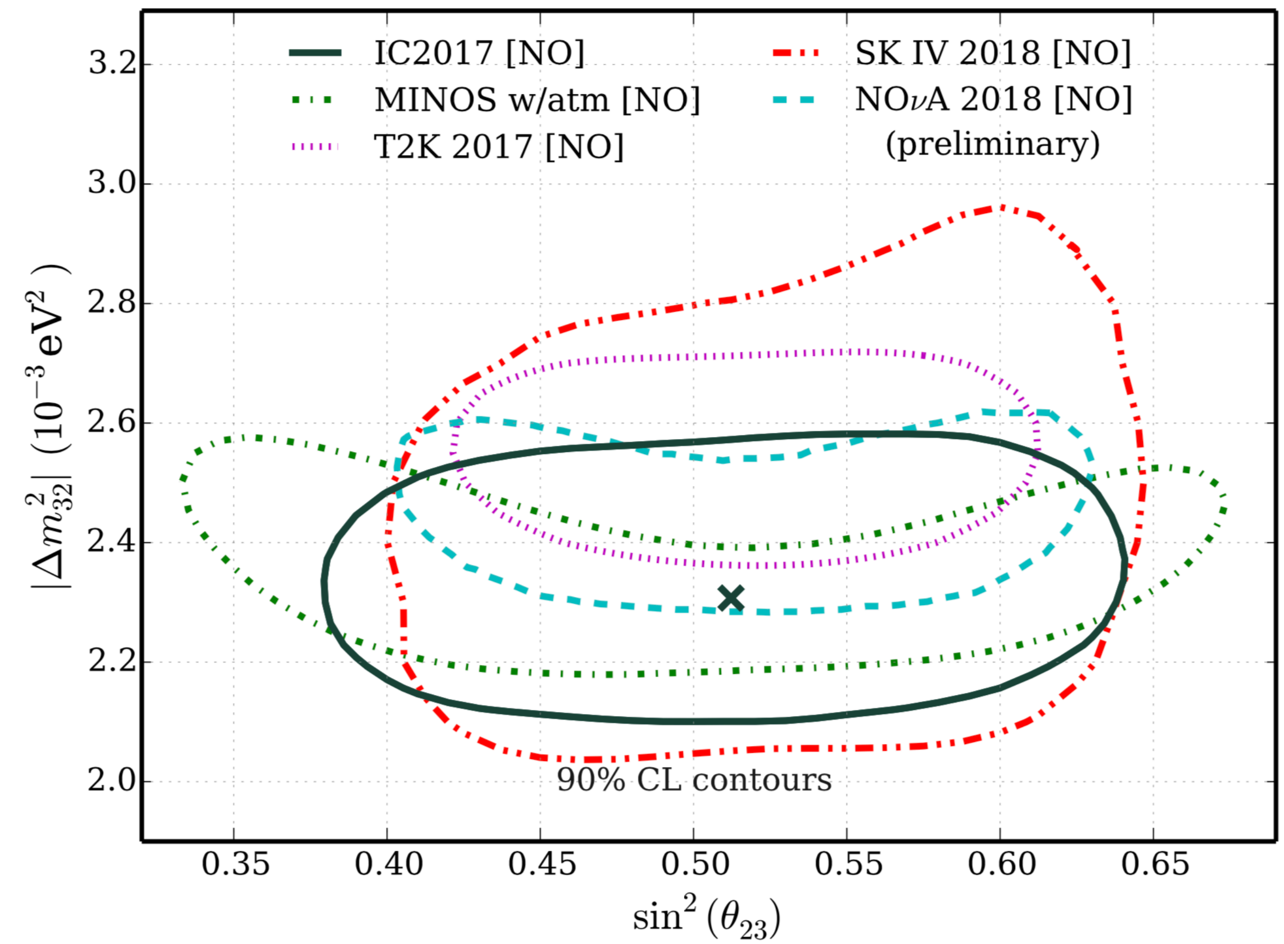
https://github.com/hogenshpogen/Golem

- ✤PISA is written in python, GolemFit in c++ with python bindings.
- ✤Core concepts very similar: event by event reweighing for syst. treatment.
- ✤PISA is more specialized for oscillation analysis at low energies. GolemFit has been used in other analysis such as high energy analysis and is a more recent development, but it follows from a series of previous fitting tools.

Some current on-going analyses and results

Latest nu-mu disappearance





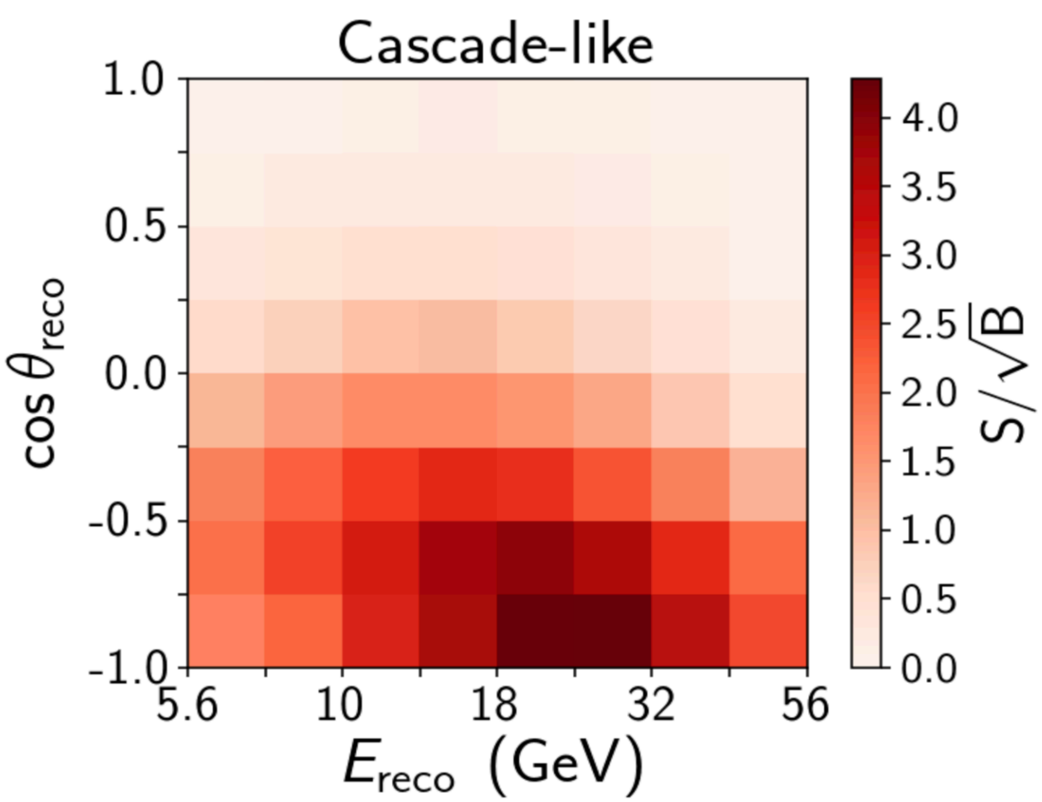
✤Starting to be competitive with dedicated accelerator experiments.

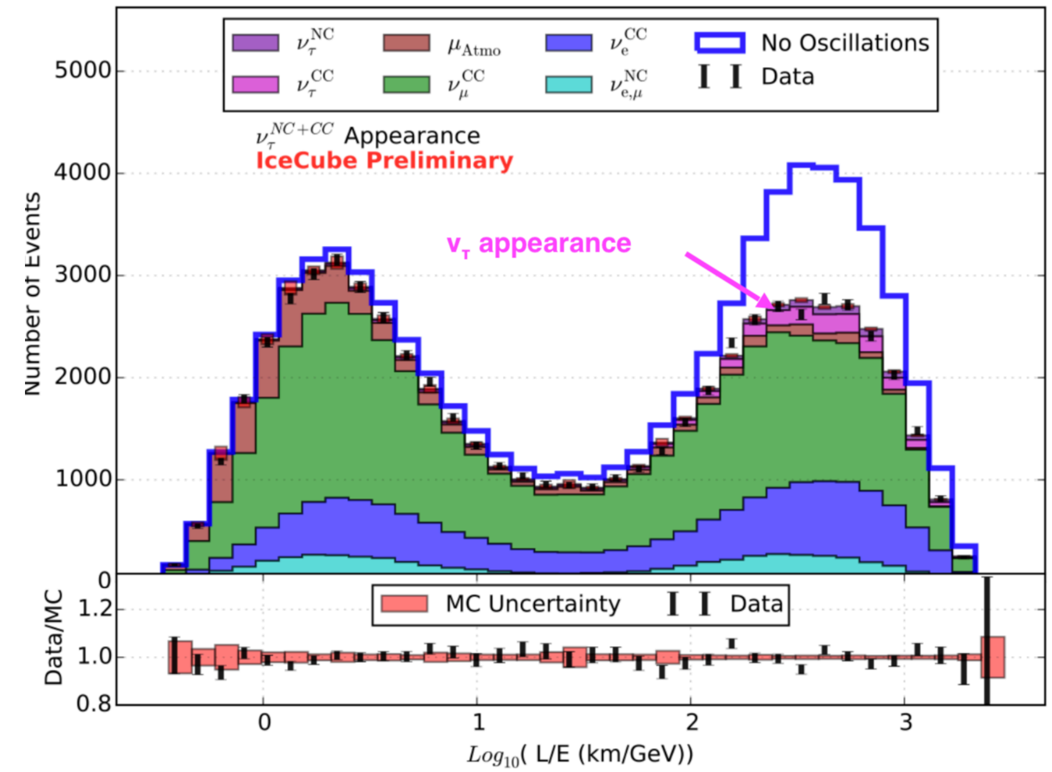
✤Best measurement with natural sources.

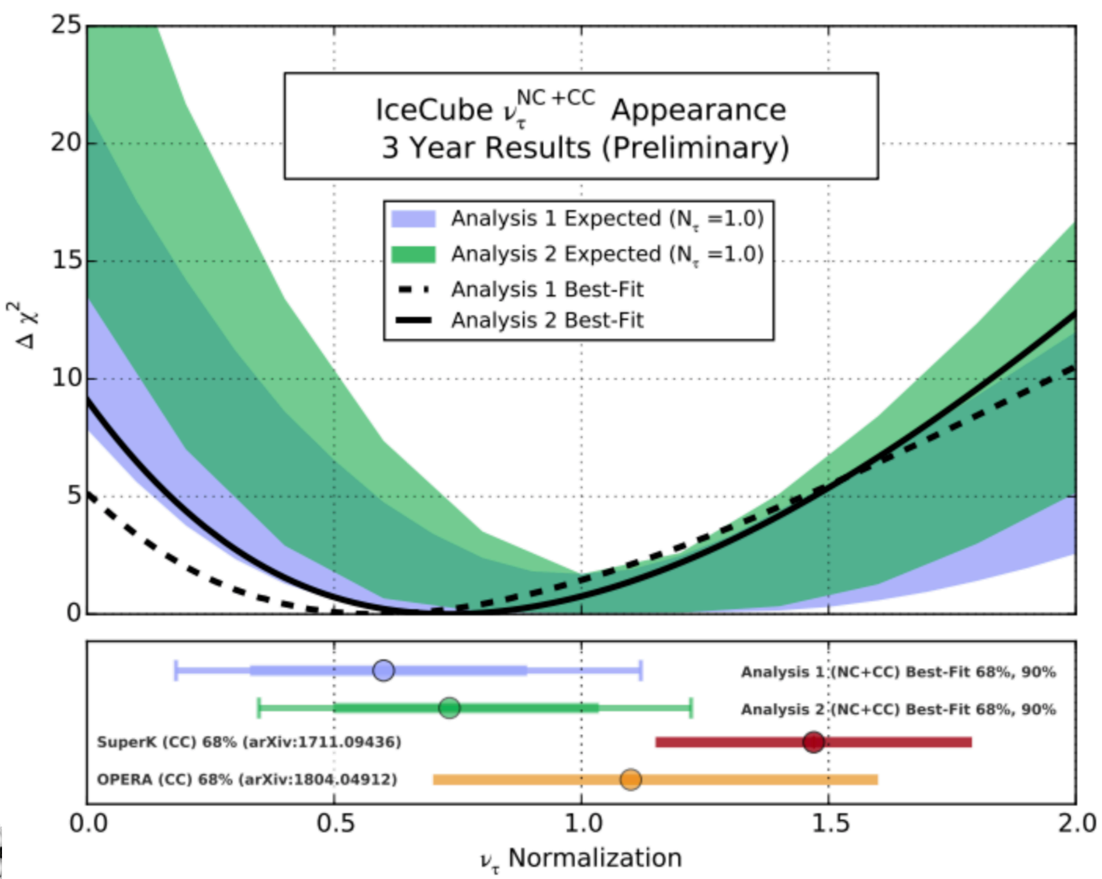
✤Remember that we are measuring it at different energies, but same L/E. This is a test of the current framework.

M. Aartsen et al. (IceCube), *Phys. Rev. Lett.* 120, 071801 (2018)

First nu-tau appearance

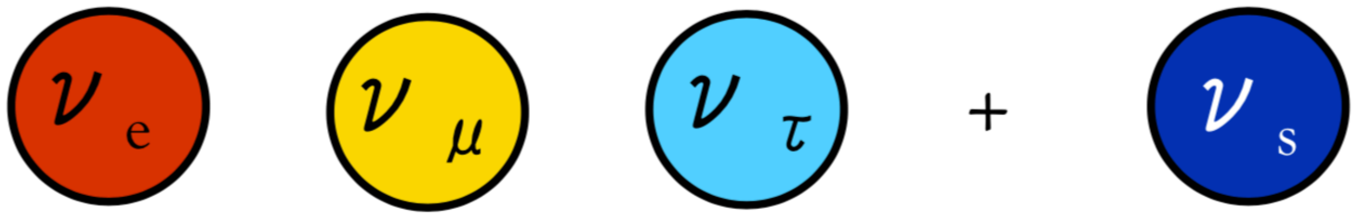


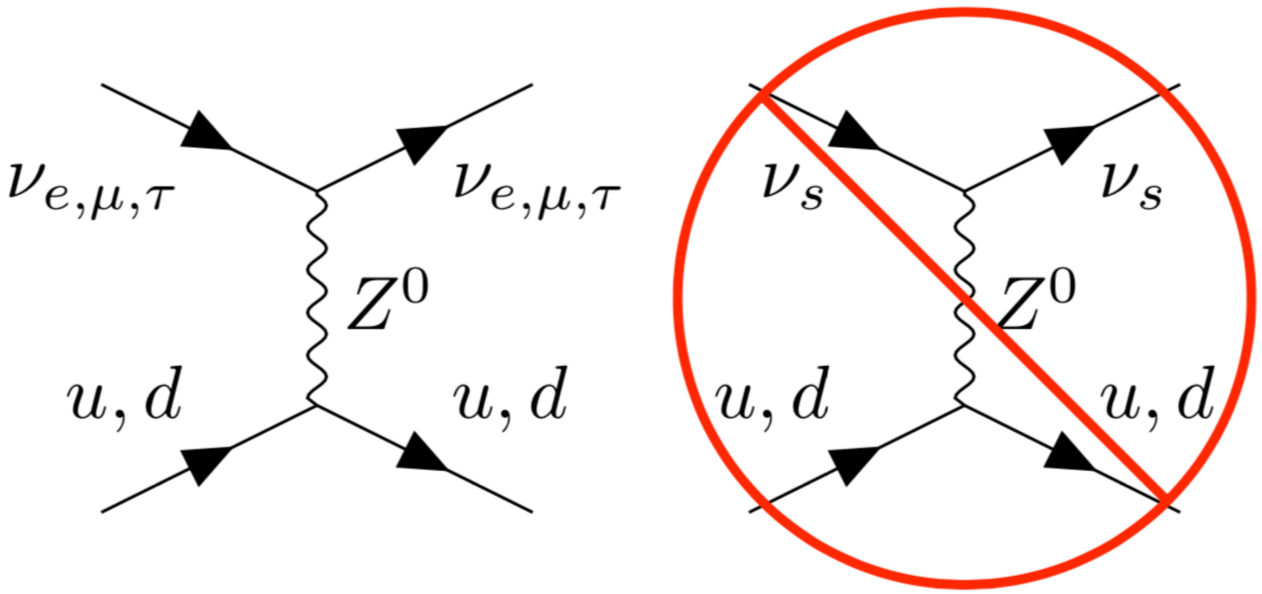




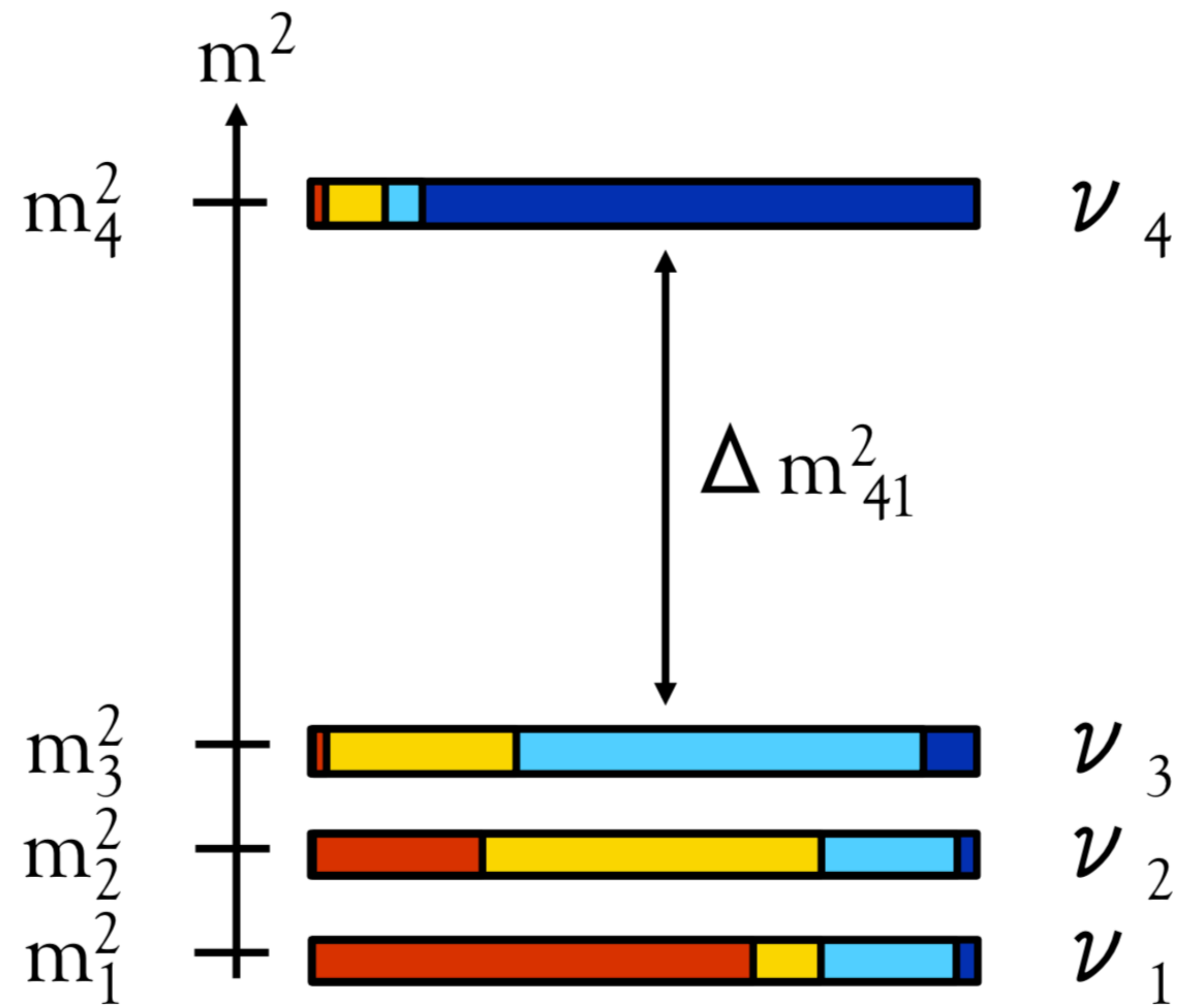
- Nu-tau appearance constraints comparable to OPERA and SK.

Sterile neutrinos

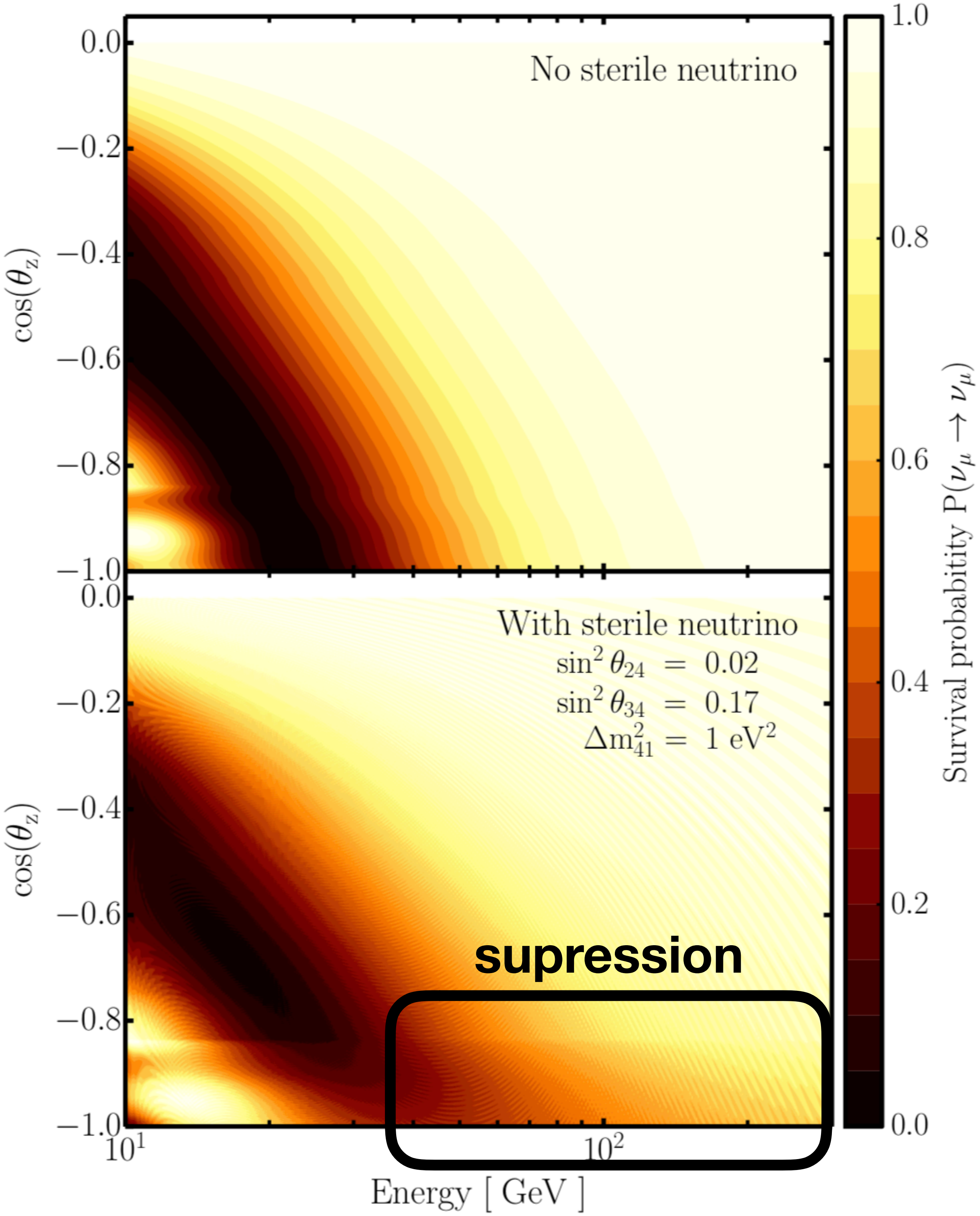


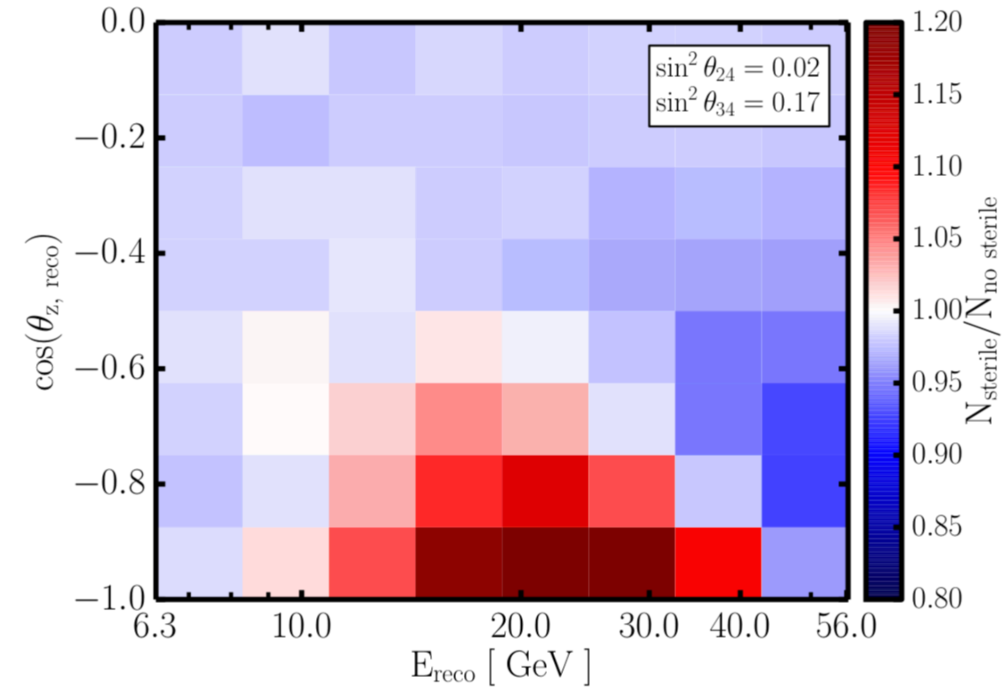


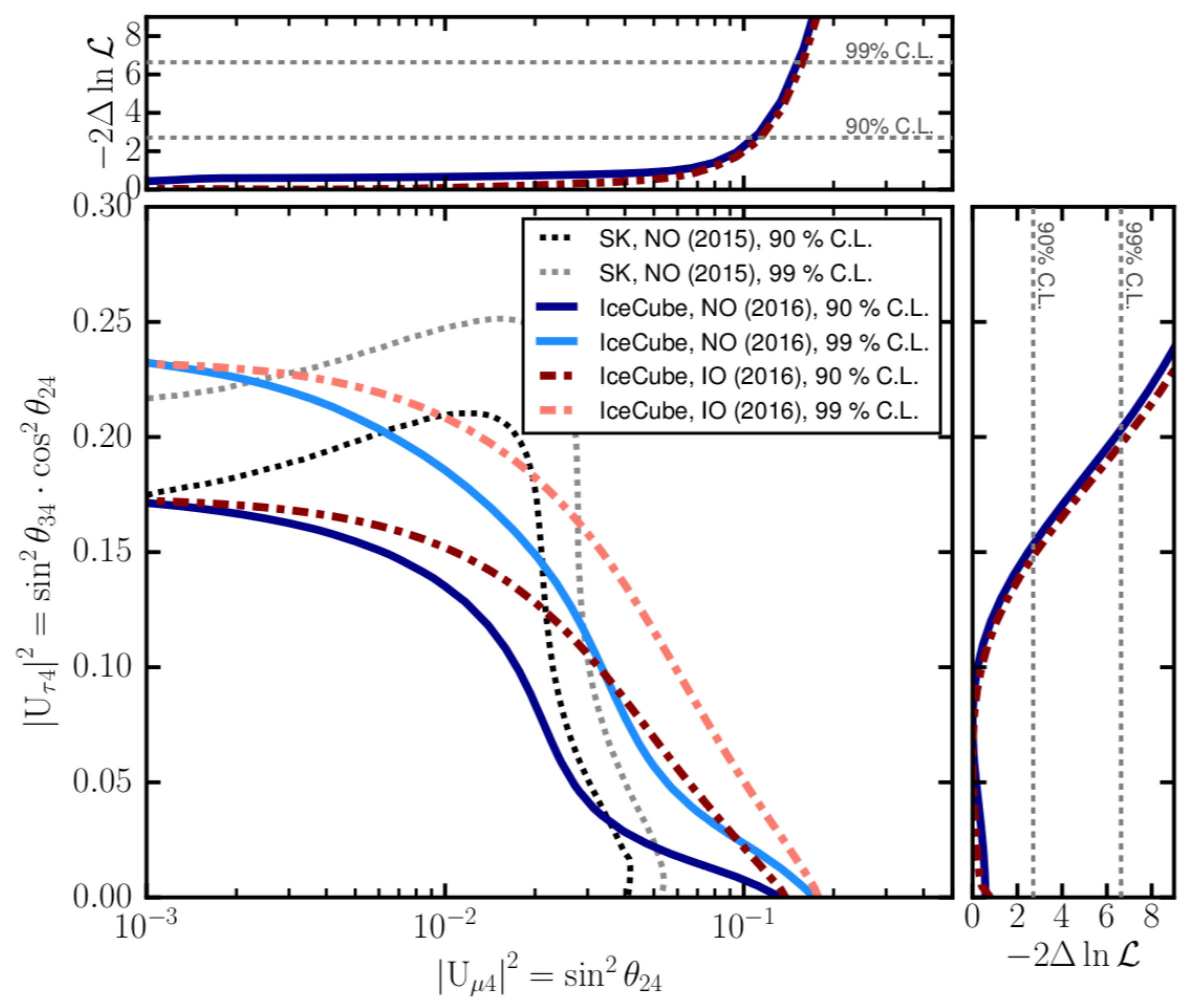
$$U_{3+1} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ \vdots & & \vdots & U_{\mu 4} \\ \vdots & & \vdots & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix},$$



Sterile neutrino: low-energy signature



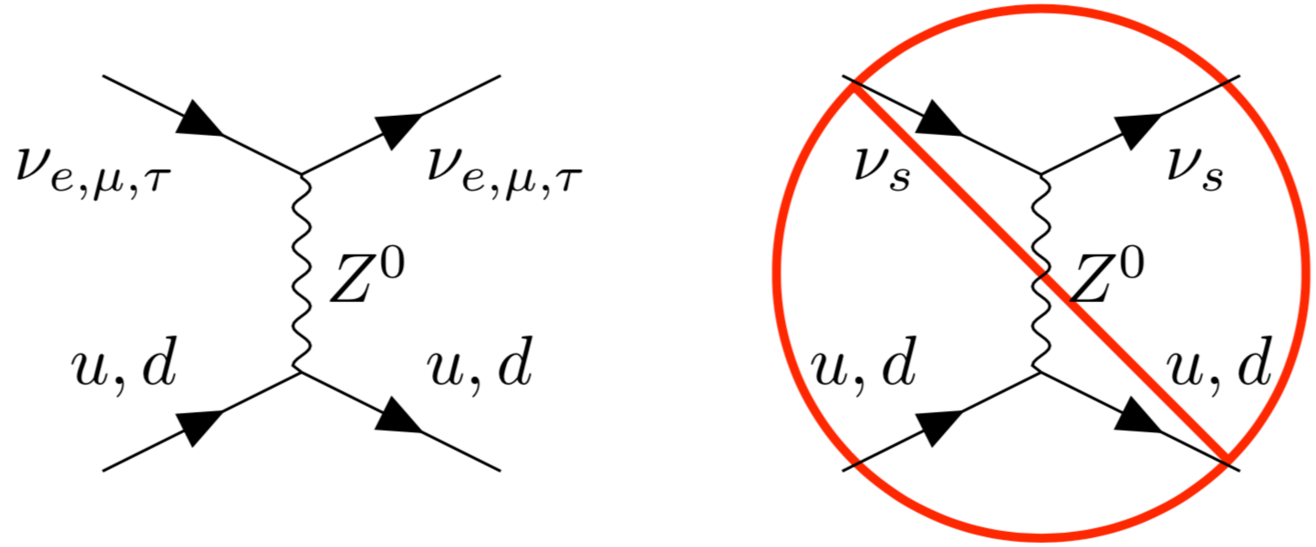


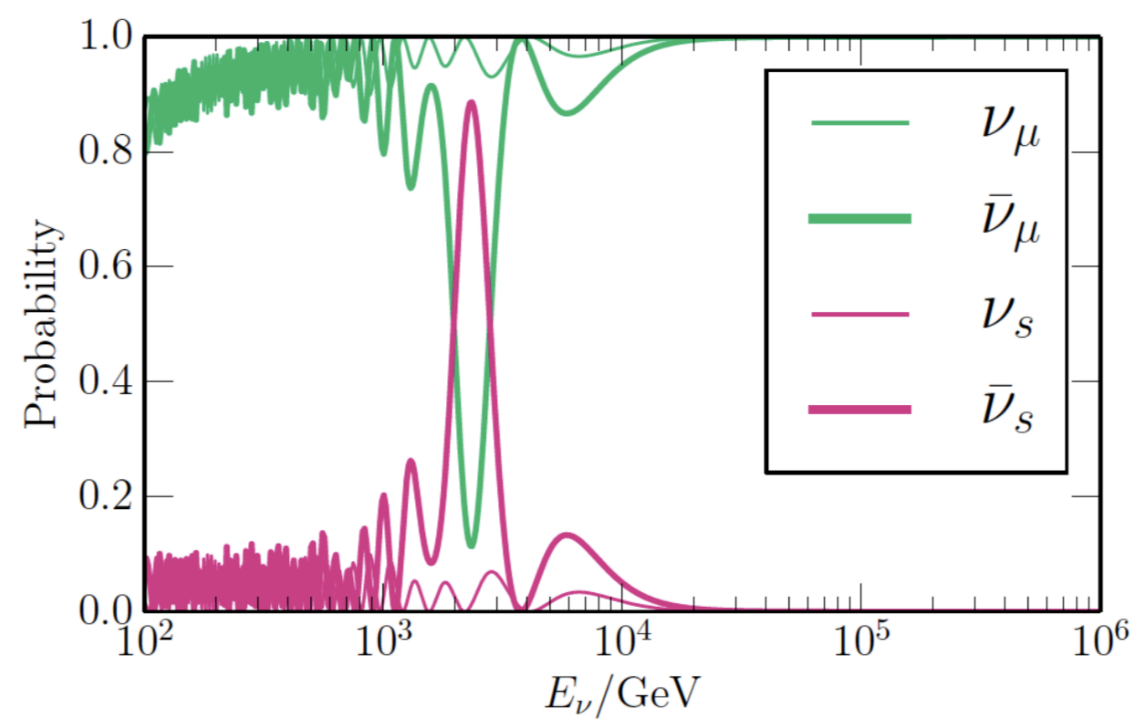


Sterile neutrino: high-energy signature

*

Matter effects in the Earth introduce a resonance flavor transition at TeV energies.





$\Delta m^2_{41} = 1\ \mathrm{eV}^2,\ \sin^2 2\theta_{24} = 0.1$

*Matter Enhanced Oscillations With Sterile neutrinos

Sterile neutrino: high-energy signature

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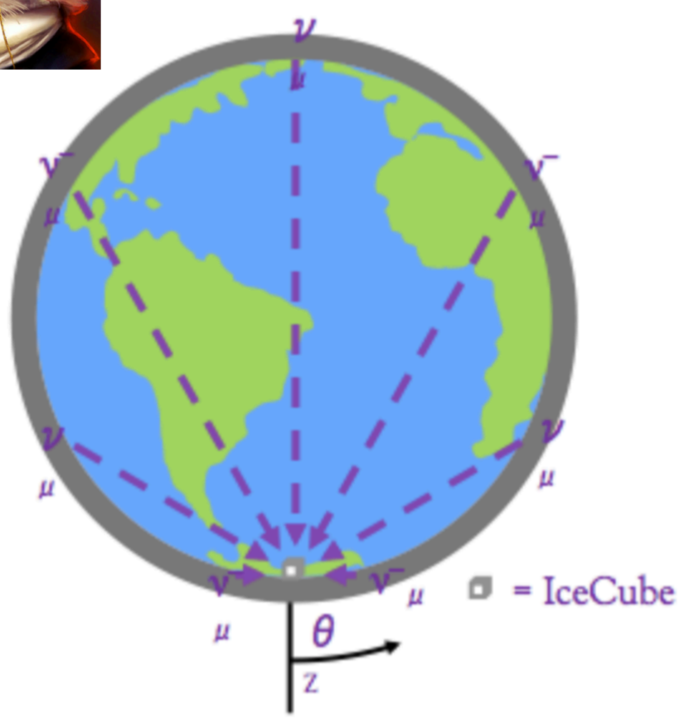
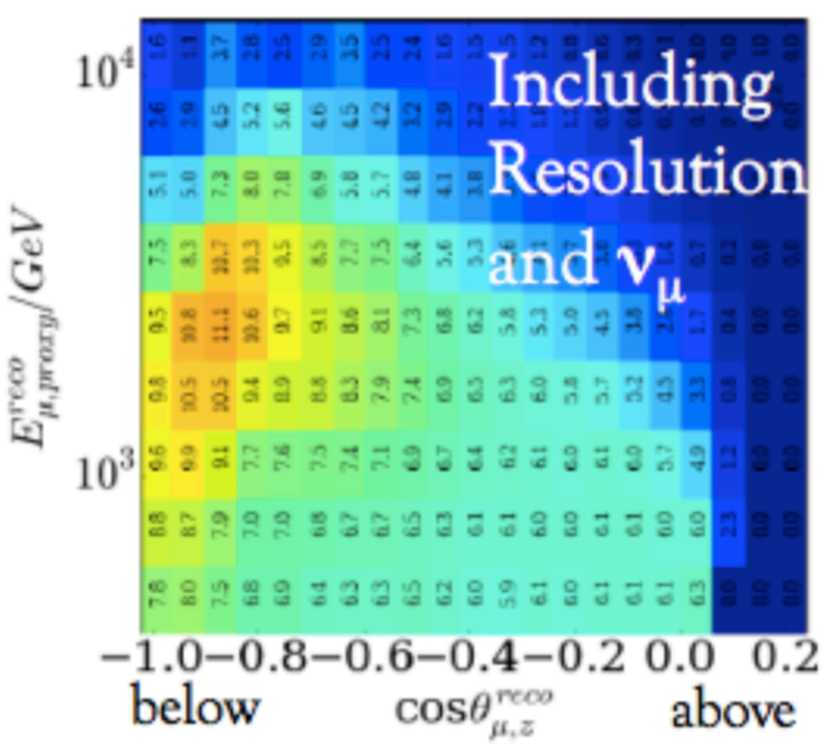
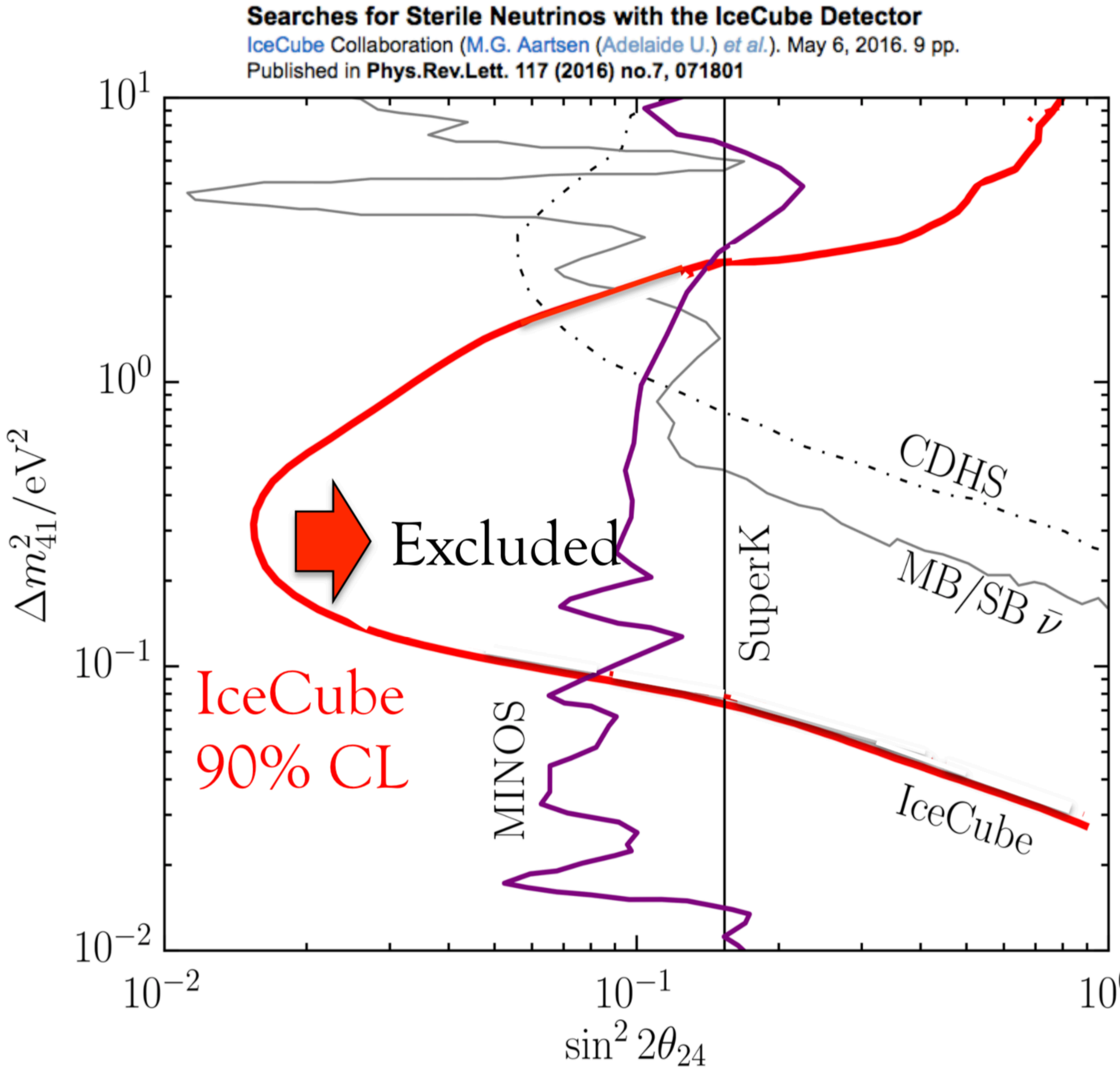
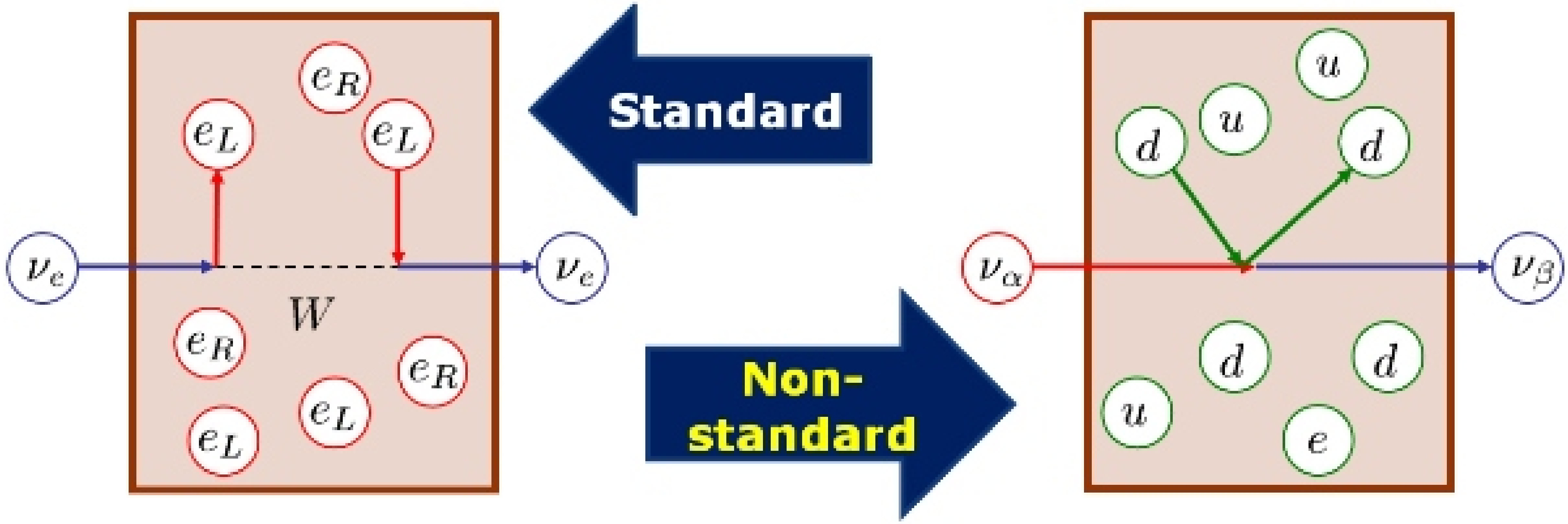






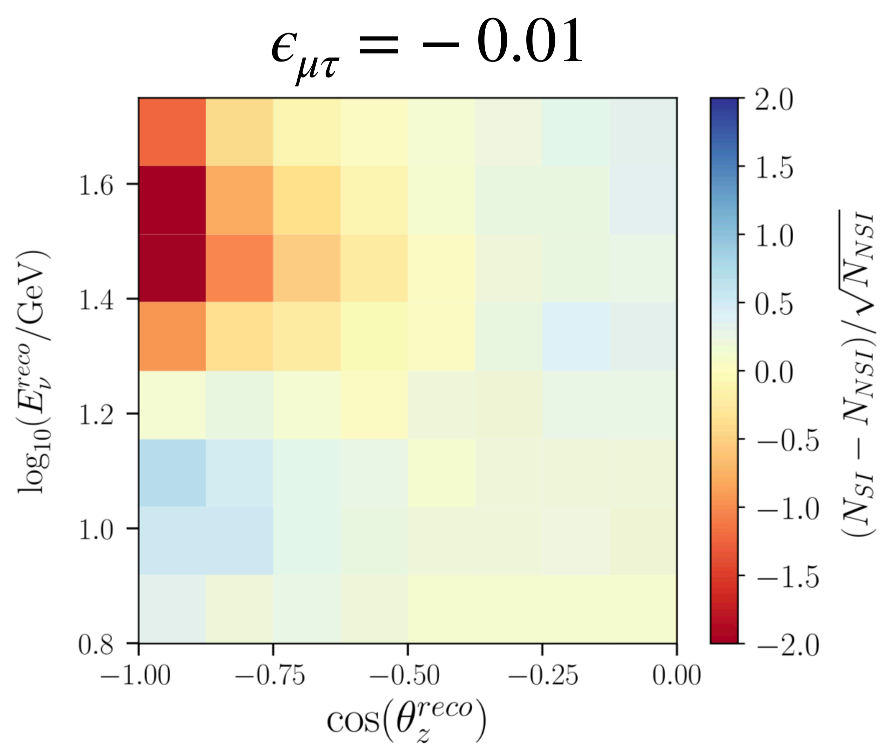
Nonstandard neutrino interactions

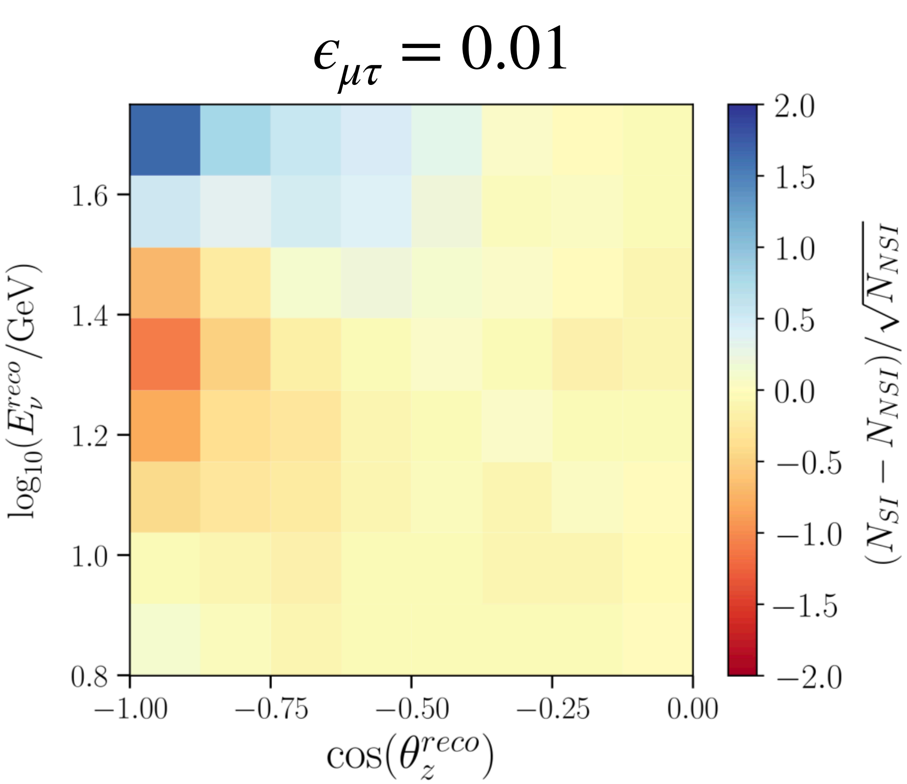
(from T. Ohlsson arXiv:1209.2710)



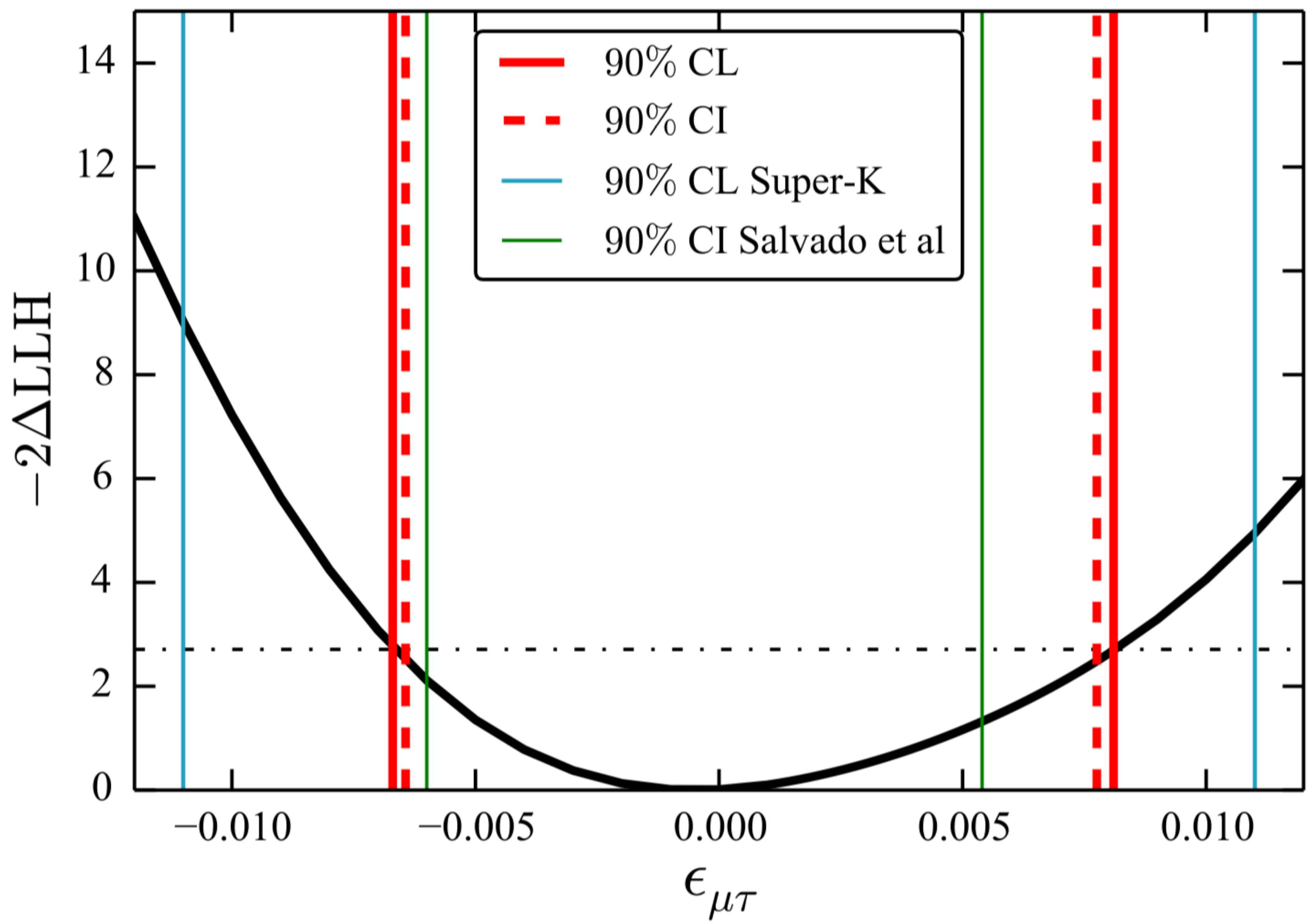
$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \frac{1}{2E}\left[U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^\dagger + A\begin{pmatrix}1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau}\\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau}\\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

Nonstandard neutrino interactions





$$\epsilon = \begin{pmatrix} \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$$



Phys. Rev. D 97, 072009 (2018)

*Salvado et al. uses public high-energy IceCube data

Violation of Lorentz invariance

If one **extends the standard model to include LV/CPT violating terms** using the SME:

$$H = H_{std} + \frac{p_\lambda}{E}\begin{pmatrix} a^\lambda_{ee} & a^\lambda_{e\mu} & a^\lambda_{e\tau} \\ a^{\lambda*}_{e\mu} & a^\lambda_{\mu\mu} & a^\lambda_{\mu\tau} \\ a^{\lambda*}_{e\tau} & a^{\lambda*}_{\mu\tau} & a^\lambda_{\tau\tau} \end{pmatrix} + \frac{p_\lambda p_\sigma}{E}\begin{pmatrix} c^{\lambda\sigma}_{ee} & c^{\lambda\sigma}_{e\mu} & c^{\lambda\sigma}_{e\tau} \\ c^{\lambda\sigma*}_{e\mu} & c^{\lambda\sigma}_{\mu\mu} & c^{\lambda\sigma}_{\mu\tau} \\ c^{\lambda\sigma*}_{e\tau} & c^{\lambda\sigma*}_{\mu\tau} & c^{\lambda\sigma}_{\tau\tau} \end{pmatrix}$$

here $p_\lambda = (E, \vec{p})$

Simplifying assumption: lets assume that “a” and “c” only have a time component.

$$H = H_{std} + \tilde{a}^{\mathrm{T}} + E\tilde{c}^{\mathrm{TT}}$$

Kostelecky Phys.Rev. D69 (2004) 016005

Hamiltonian dominance

$$H = H_{vac} + H_{matter} + \tilde{a}^{\mathrm{T}} + E\tilde{c}^{\mathrm{TT}}$$

$\sim 10^{-24}\mathrm{GeV}\left(\frac{TeV}{E}\right)$ $(\sim 10^{-23}\mathrm{GeV})$? E*?

note that the matter potential only affects the *ee* component

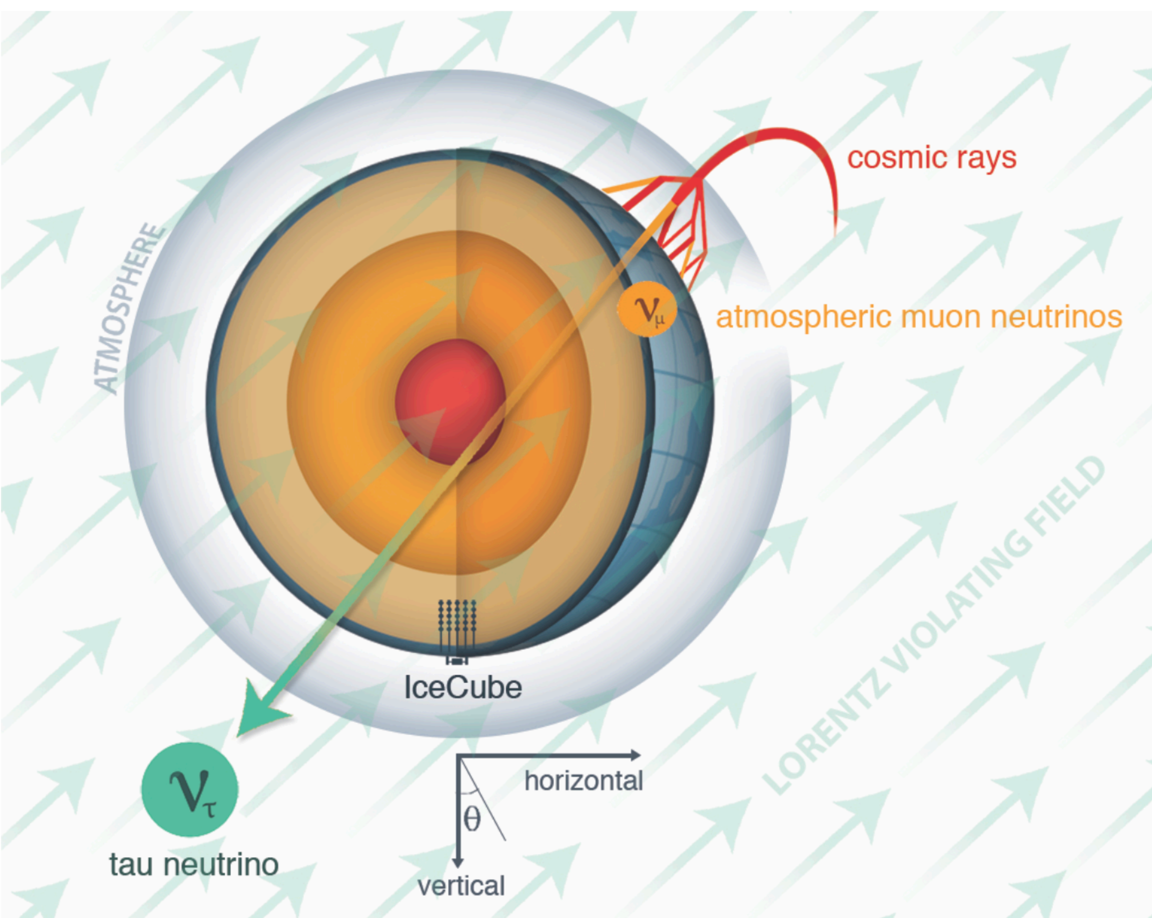
back of the envelope sensitivity

$$\tilde{a}^{\mathrm{T}} \sim 10^{-24}\mathrm{GeV} \rightarrow 10^{-27}\mathrm{GeV}$$

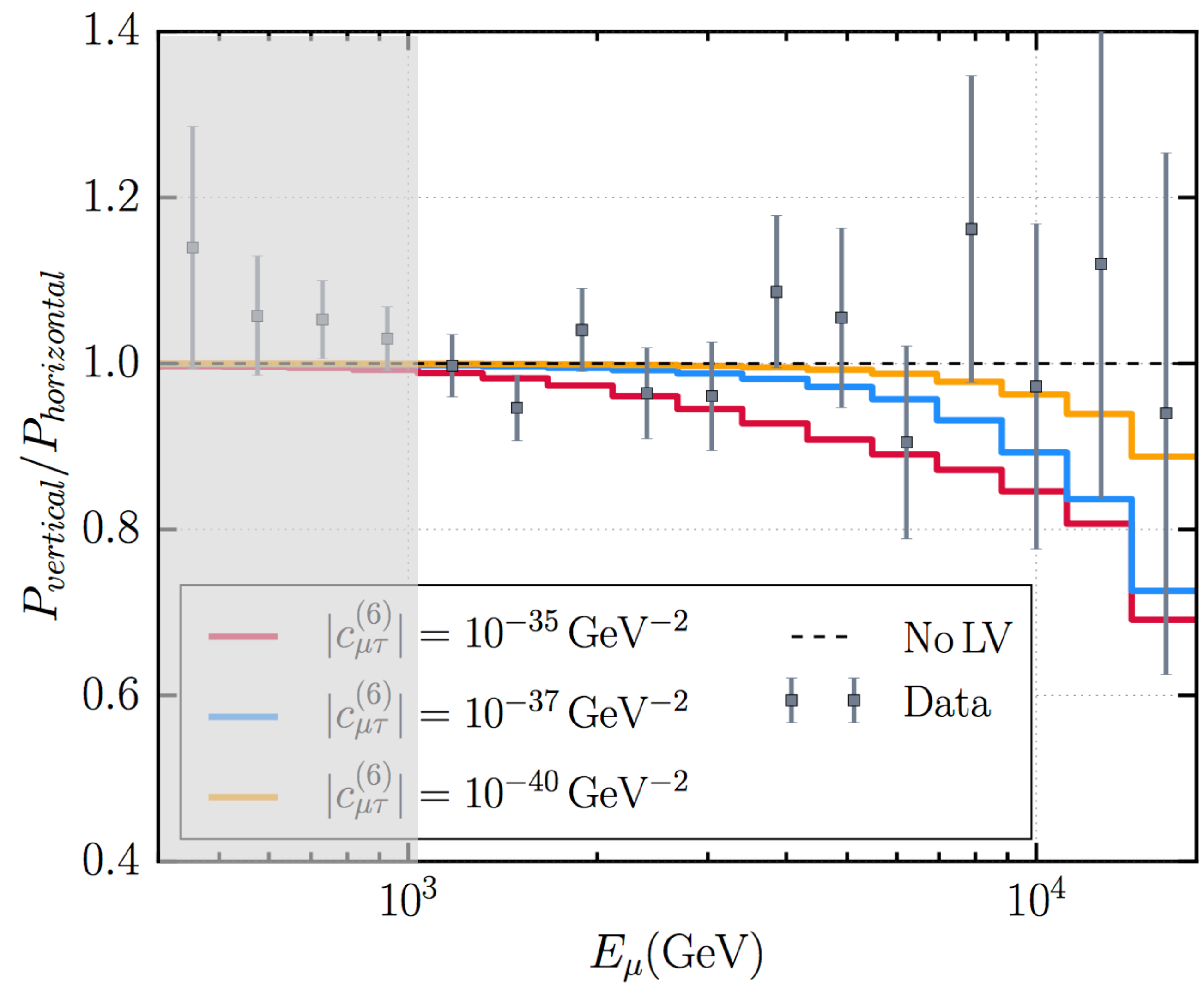
$$\tilde{c}^{\mathrm{TT}} \sim 10^{-27} \rightarrow 10^{-32}$$

Signal kicks in at high energies

- ✤The analysis sensitivity, specially for high-dimension operators, is dominated by the highest energy events.
- ✤We are **very much** statistically limited.



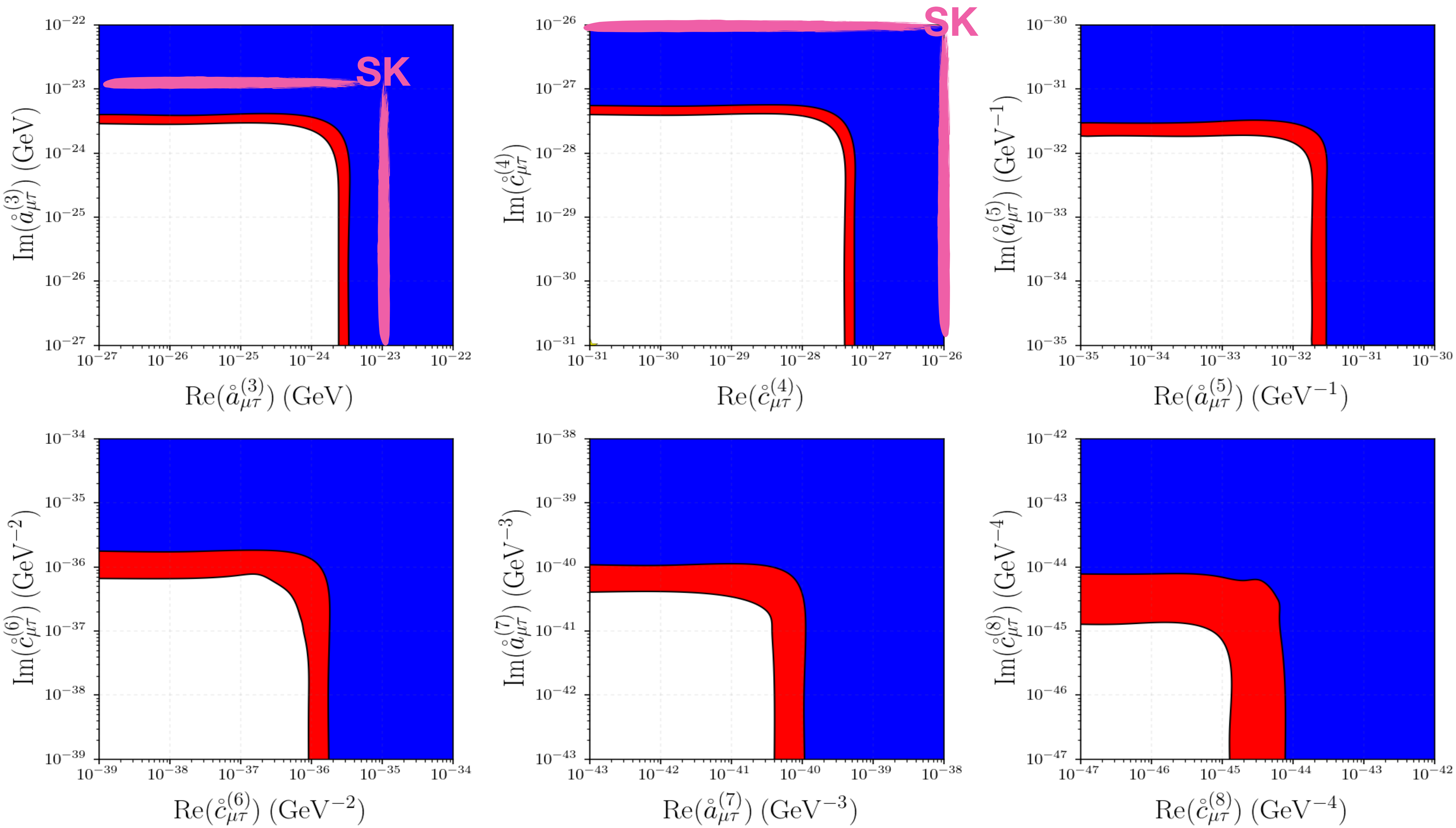
$$P_{osc}(c^{(6)}_{\mu\tau} E_\nu L)$$



Gray region is irrelevant for the analysis. Removing it changes it marginally.

Our results in the maximum-flavor violating assumption

Maximum flavor violation = set diagonal terms to zero.
(same assumption as SK)



IceCube Collaboration, arXiv:1709.03434

White: allowed, red: 90% CL, blue: 99% CL.

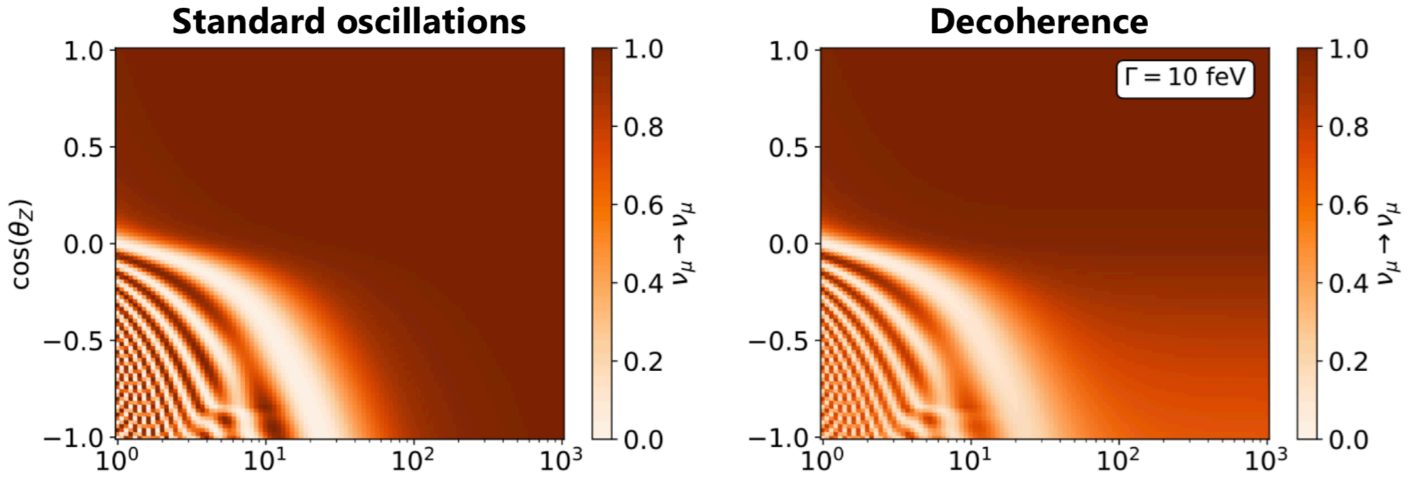
Comparison with other sectors

dim.	method	type	sector	limits		ref.
3	CMB polarization	astrophysical	photon		$\sim 10^{-43}$ GeV	[6]
	He-Xe comagnetometer	tabletop	neutron		$\sim 10^{-34}$ GeV	[10]
	torsion pendulum	tabletop	electron		$\sim 10^{-31}$ GeV	[12]
	muon g-2	accelerator	muon		$\sim 10^{-24}$ GeV	[13]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(3)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}^{(3)}_{\mu\tau})\rvert$	$< 2.9 \times 10^{-24}$ GeV (99% C.L.) $< 2.0 \times 10^{-24}$ GeV (90% C.L.)	this work
4	GRB vacuum birefringence	astrophysical	photon		$\sim 10^{-38}$	[7]
	Laser interferometer	LIGO	photon		$\sim 10^{-22}$	[8]
	Sapphire cavity oscillator	tabletop	photon		$\sim 10^{-18}$	[5]
	Ne-Rb-K comagnetometer	tabletop	neutron		$\sim 10^{-29}$	[11]
	trapped Ca^{+} ion	tabletop	electron		$\sim 10^{-19}$	[14]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{c}^{(4)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{c}^{(4)}_{\mu\tau})\rvert$	$< 3.9 \times 10^{-28}$ (99% C.L.) $< 2.7 \times 10^{-28}$ (90% C.L.)	this work
5	GRB vacuum birefringence	astrophysical	photon		$\sim 10^{-34}$ GeV^{-1}	[7]
	ultra-high-energy cosmic ray	astrophysical	proton		$\sim 10^{-22}$ to 10^{-18} GeV^{-1}	[9]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(5)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}^{(5)}_{\mu\tau})\rvert$	$< 2.3 \times 10^{-32}$ GeV^{-1} (99% C.L.) $< 1.5 \times 10^{-32}$ GeV^{-1} (90% C.L.)	this work
6	GRB vacuum birefringene	astrophysical	photon		$\sim 10^{-31}$ GeV^{-2}	[7]
	ultra-high-energy cosmic ray	astrophysical	proton		$\sim 10^{-42}$ to 10^{-35} GeV^{-2}	[9]
	gravitational Cherenkov radiation	astrophysical	gravity		$\sim 10^{-31}$ GeV^{-2}	[15]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{c}^{(6)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{c}^{(6)}_{\mu\tau})\rvert$	$< 1.5 \times 10^{-36}$ GeV^{-2} (99% C.L.) $< 9.1 \times 10^{-37}$ GeV^{-2} (90% C.L.)	this work
7	GRB vacuum birefringence	astrophysical	photon		$\sim 10^{-28}$ GeV^{-3}	[7]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{a}^{(7)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{a}^{(7)}_{\mu\tau})\rvert$	$< 8.3 \times 10^{-41}$ GeV^{-3} (99% C.L.) $< 3.6 \times 10^{-41}$ GeV^{-3} (90% C.L.)	this work
8	gravitational Cherenkov radiation	astrophysical	gravity		$\sim 10^{-46}$ GeV^{-4}	[15]
	neutrino oscillation	atmospheric	neutrino	$\lvert\mathrm{Re}\,(\mathring{c}^{(8)}_{\mu\tau})\rvert, \lvert\mathrm{Im}\,(\mathring{c}^{(8)}_{\mu\tau})\rvert$	$< 5.2 \times 10^{-45}$ GeV^{-4} (99% C.L.) $< 1.4 \times 10^{-45}$ GeV^{-4} (90% C.L.)	this work

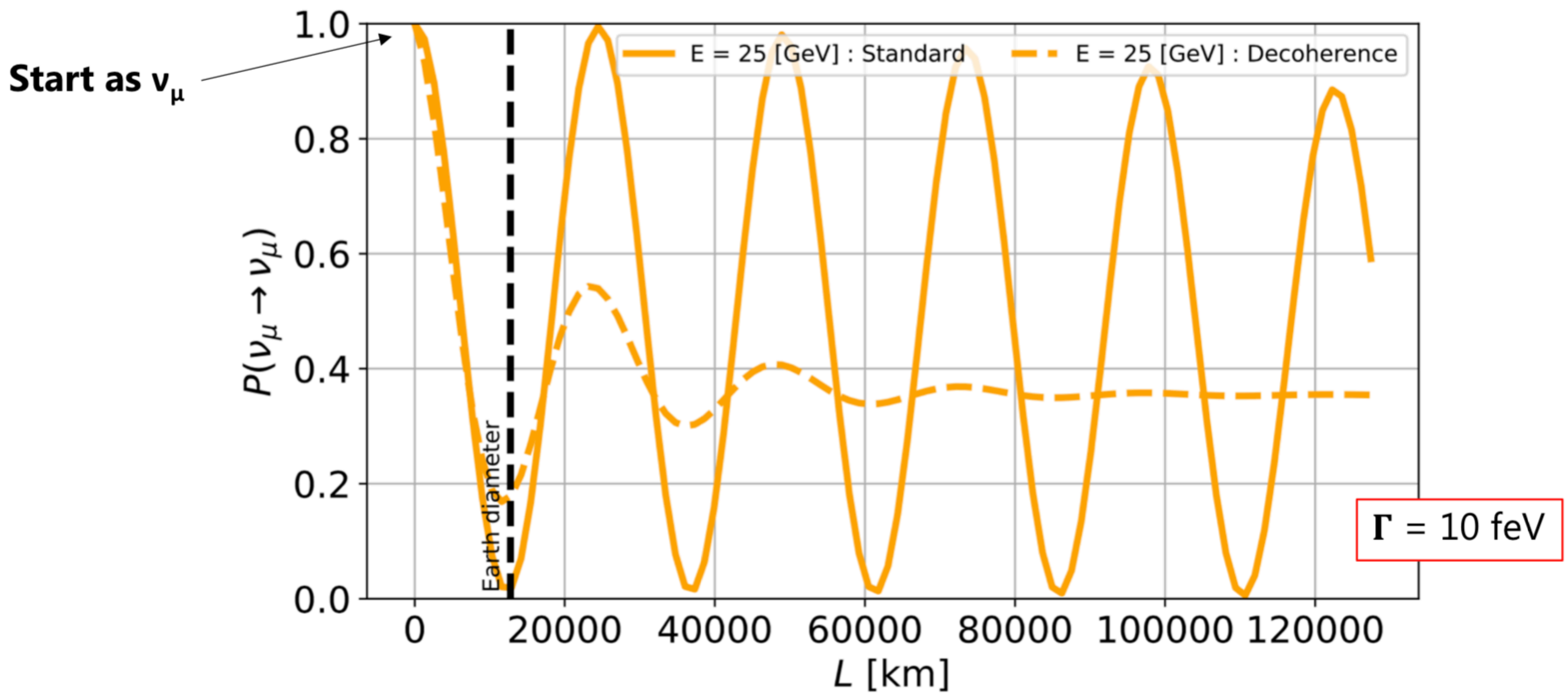
Very strong limits on Lorentz Violation induced by dimension-6 operators!

Decoherence

$$\dot{\rho} = -i[H,\rho] - \begin{pmatrix} 0 & \rho_{12}\Gamma_{21} & \rho_{13}\Gamma_{31} \\ \rho_{21}\Gamma_{21} & 0 & \rho_{23}\Gamma_{32} \\ \rho_{31}\Gamma_{31} & \rho_{32}\Gamma_{32} & 0 \end{pmatrix}$$



$$\mathcal{P}^{(2\nu)}_{\mu\mu} = 1 - \frac{1}{2}\sin^2 2\theta_{23} \cdot \left[1 - e^{-\Gamma_{32}L} \cdot \cos\left(\frac{\Delta m^2_{32}}{2E_\nu}L\right)\right]$$



Join the oscillation or BSM wg to do this kind of physics!

THANKS

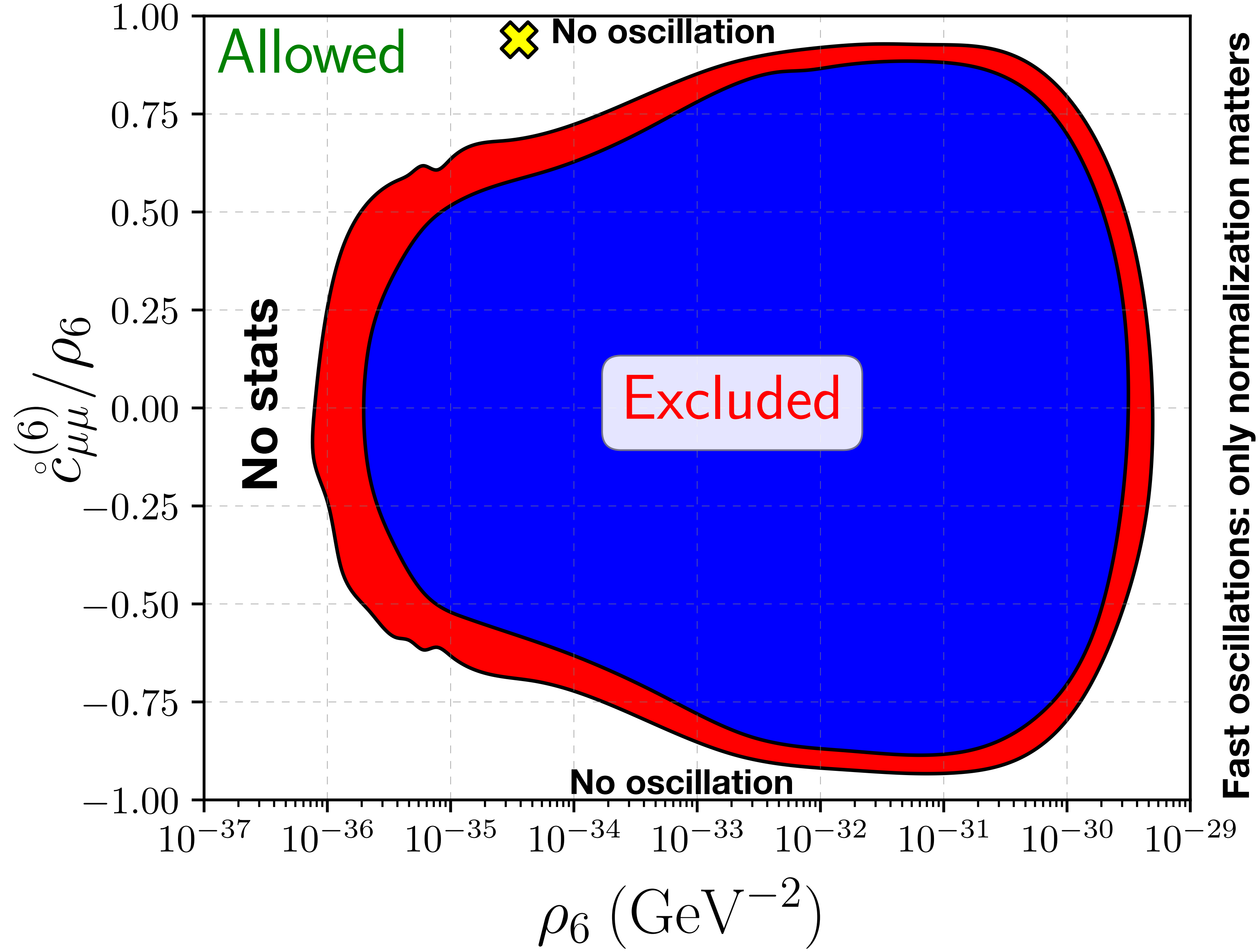
BONUS SLIDES!

Anatomy of the dim-6 operator constraint

- X marks the best-fit point: no significance evidence for LV.
- We use Wilk's theorem with 3 dof.

$$\mathring{c}^{(6)} = \begin{pmatrix} \mathring{c}^{(6)}_{\mu\mu} & \mathring{c}^{(6)}_{\mu\tau} \\ \mathring{c}^{(6)*}_{\mu\tau} & -\mathring{c}^{(6)}_{\mu\mu} \end{pmatrix}$$

$$P(\nu_\mu \to \nu_\tau) \sim \left(\frac{\mathring{a}^{(d)}_{\mu\tau} - \mathring{c}^{(d)}_{\mu\tau}}{\rho_d} \right)^2 \sin^2(L\rho_d \cdot E^{d-}$$

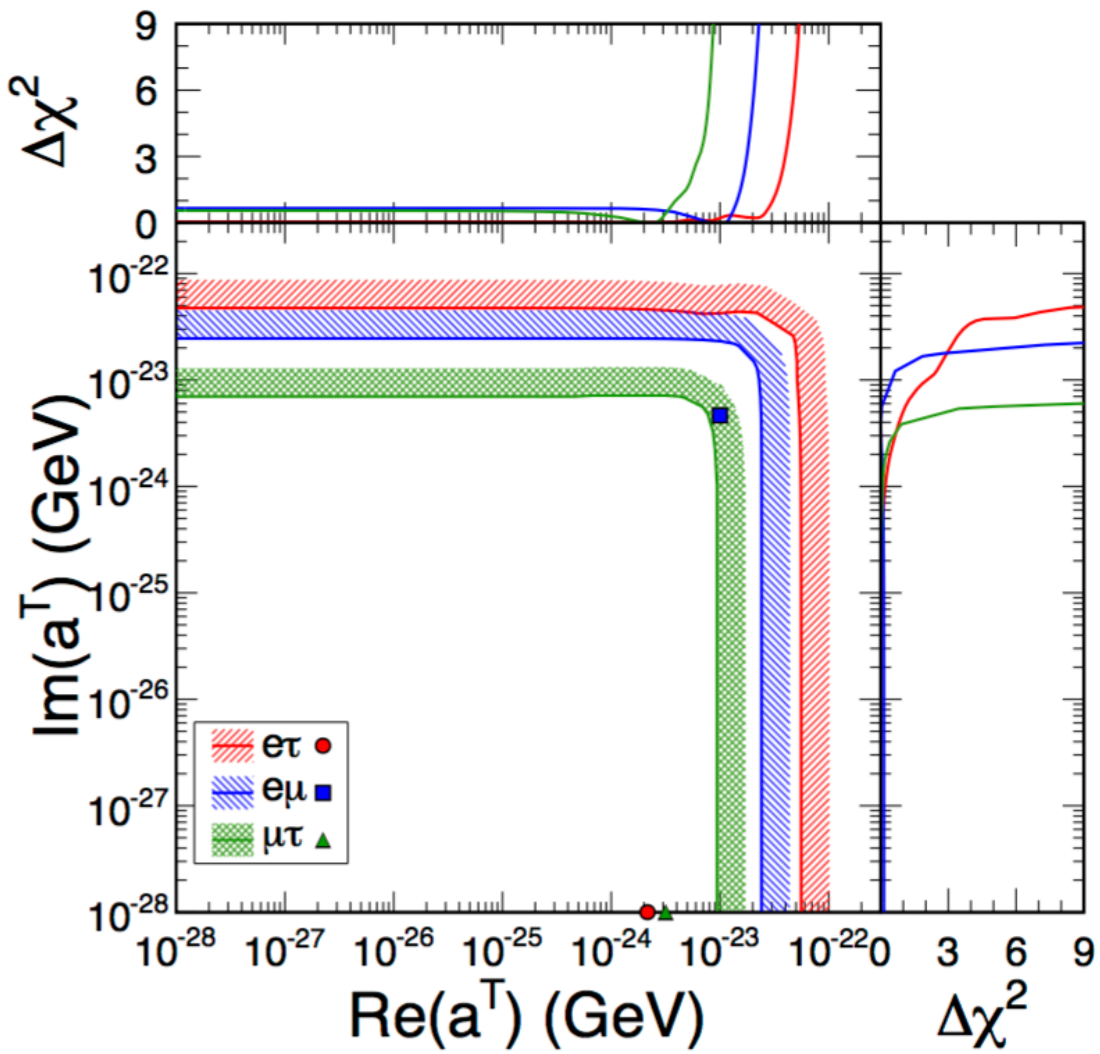


$$\rho_d \equiv \sqrt{(\mathring{c}^{(d)}_{\mu\mu})^2 + \mathrm{Re}\,(\mathring{c}^{(d)}_{\mu\tau})^2 + \mathrm{Im}\,(\mathring{c}^{(d)}_{\mu\tau})^2}$$

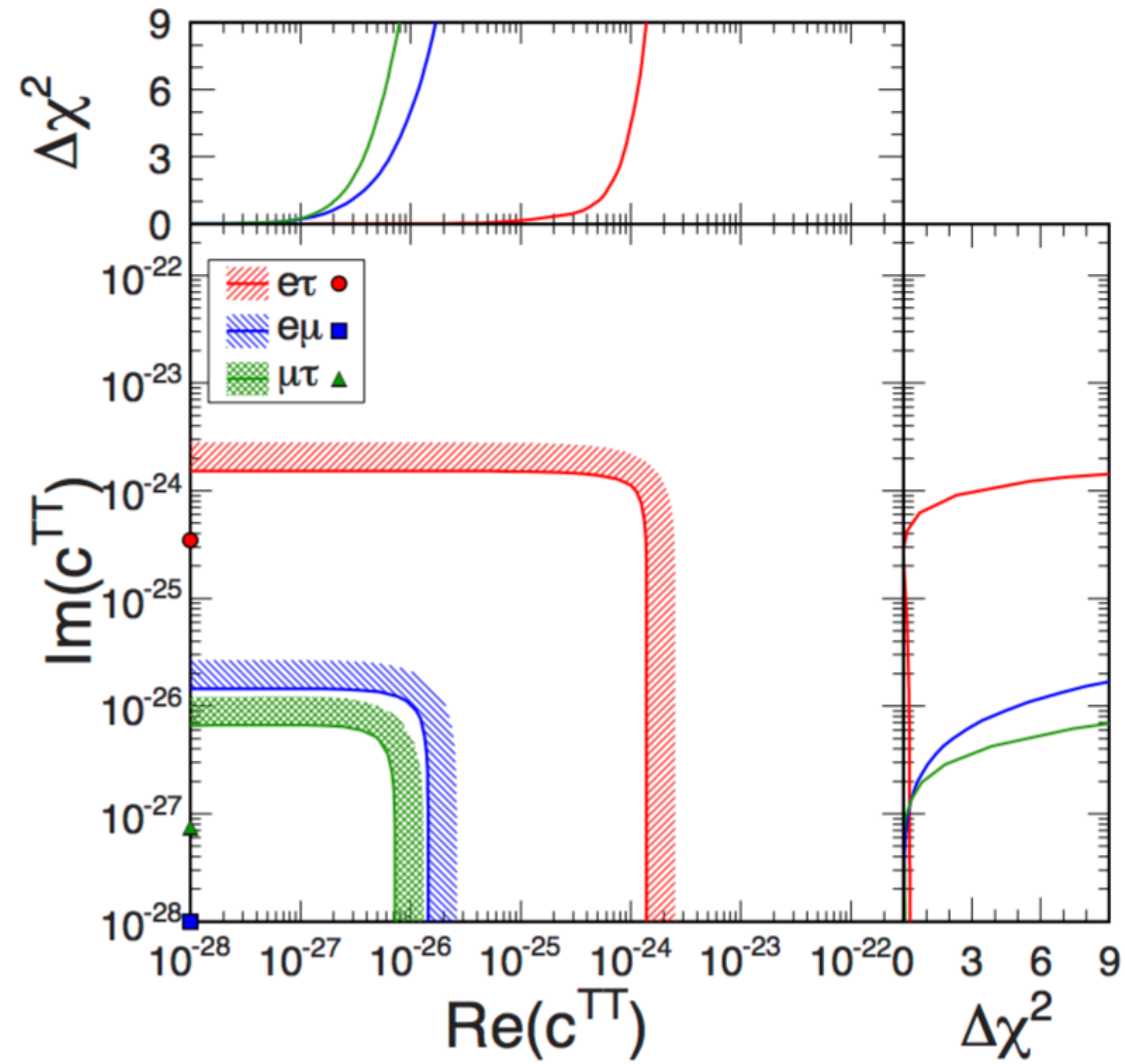
IceCube Collaboration, arXiv:1709.03434

arXiv:1410.4267

Current bounds from SK

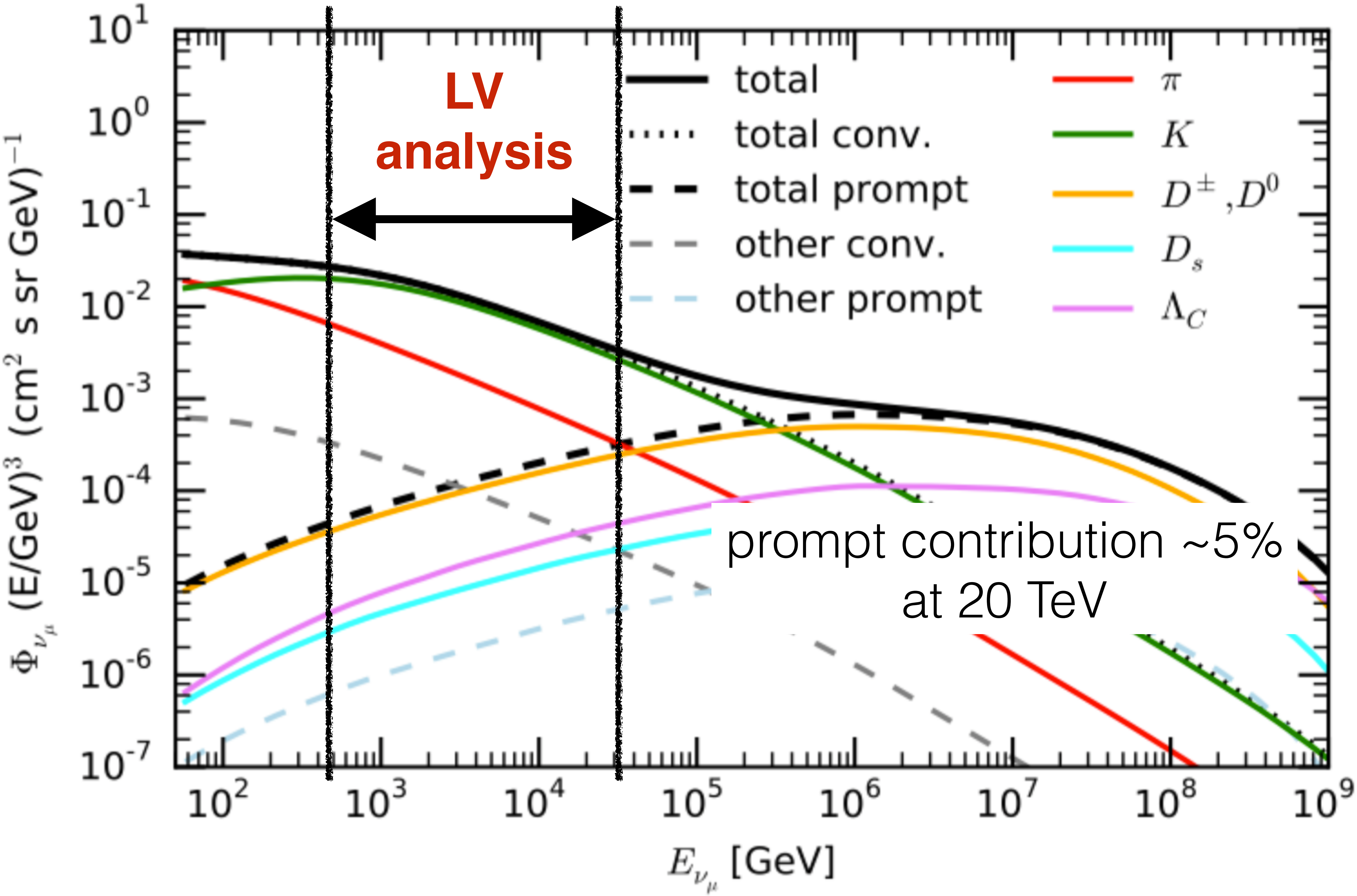


$$\begin{pmatrix} 0 & a^T_{e\mu} & a^T_{e\tau} \\ (a^T_{e\mu})^* & 0 & a^T_{\mu\tau} \\ (a^T_{e\tau})^* & (a^T_{\mu\tau})^* & 0 \end{pmatrix} \qquad \begin{pmatrix} 0 & c^{TT}_{e\mu} & c^{TT}_{e\tau} \\ (c^{TT}_{e\mu})^* & 0 & c^{TT}_{\mu\tau} \\ (c^{TT}_{e\tau})^* & (c^{TT}_{\mu\tau})^* & 0 \end{pmatrix}$$



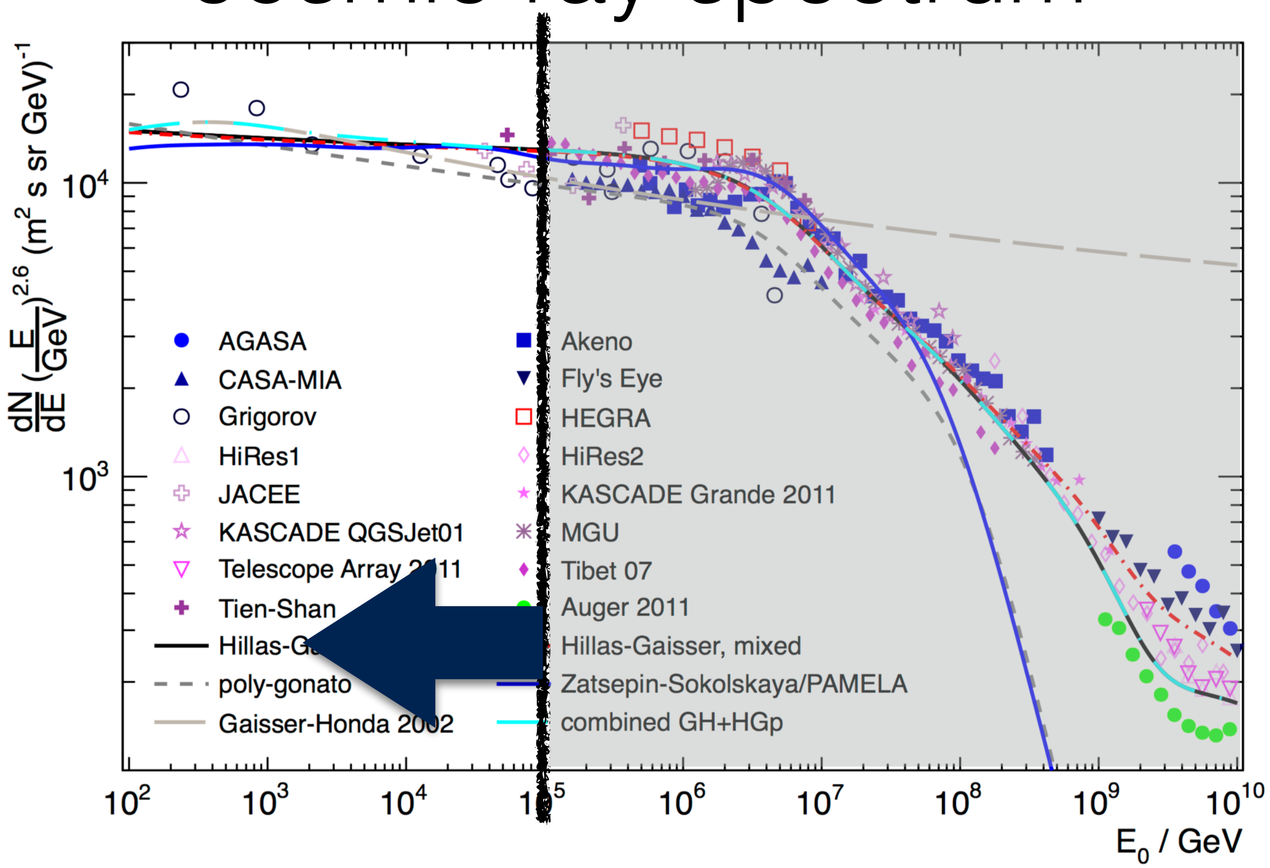
LV Parameter		Limit at 95% C.L.	Best Fit	No LV $\Delta\chi^2$	Previous Limit	
$e\mu$	Re (a^T)	1.8×10^{-23} GeV	1.0×10^{-23} GeV	1.4	4.2×10^{-20} GeV	[58]
	Im (a^T)	1.8×10^{-23} GeV	4.6×10^{-24} GeV			
	Re (c^{TT})	8.0×10^{-27}	1.0×10^{-28}	0.0	9.6×10^{-20}	[58]
	Im (c^{TT})	8.0×10^{-27}	1.0×10^{-28}			
$e\tau$	Re (a^T)	4.1×10^{-23} GeV	2.2×10^{-24} GeV	0.0	7.8×10^{-20} GeV	[59]
	Im (a^T)	2.8×10^{-23} GeV	1.0×10^{-28} GeV			
	Re (c^{TT})	9.3×10^{-25}	1.0×10^{-28}	0.3	1.3×10^{-17}	[59]
	Im (c^{TT})	1.0×10^{-24}	3.5×10^{-25}			
$\mu\tau$	Re (a^T)	6.5×10^{-24} GeV	3.2×10^{-24} GeV	0.9	–	
	Im (a^T)	5.1×10^{-24} GeV	1.0×10^{-28} GeV			
	Re (c^{TT})	4.4×10^{-27}	1.0×10^{-28}	0.1	–	
	Im (c^{TT})	4.2×10^{-27}	7.5×10^{-28}			

Atmospheric flux decomposed



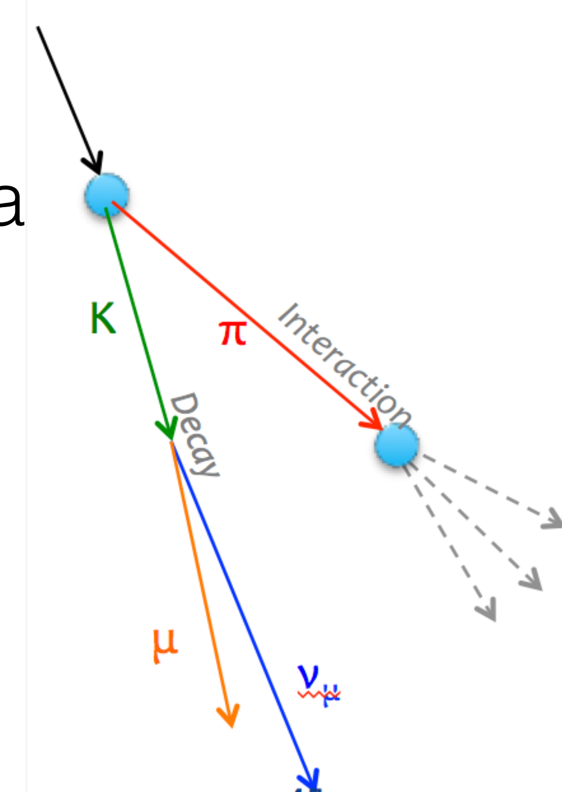
Atmospheric neutrino flux uncertainties

cosmic ray spectrum



Cosmic ray models:

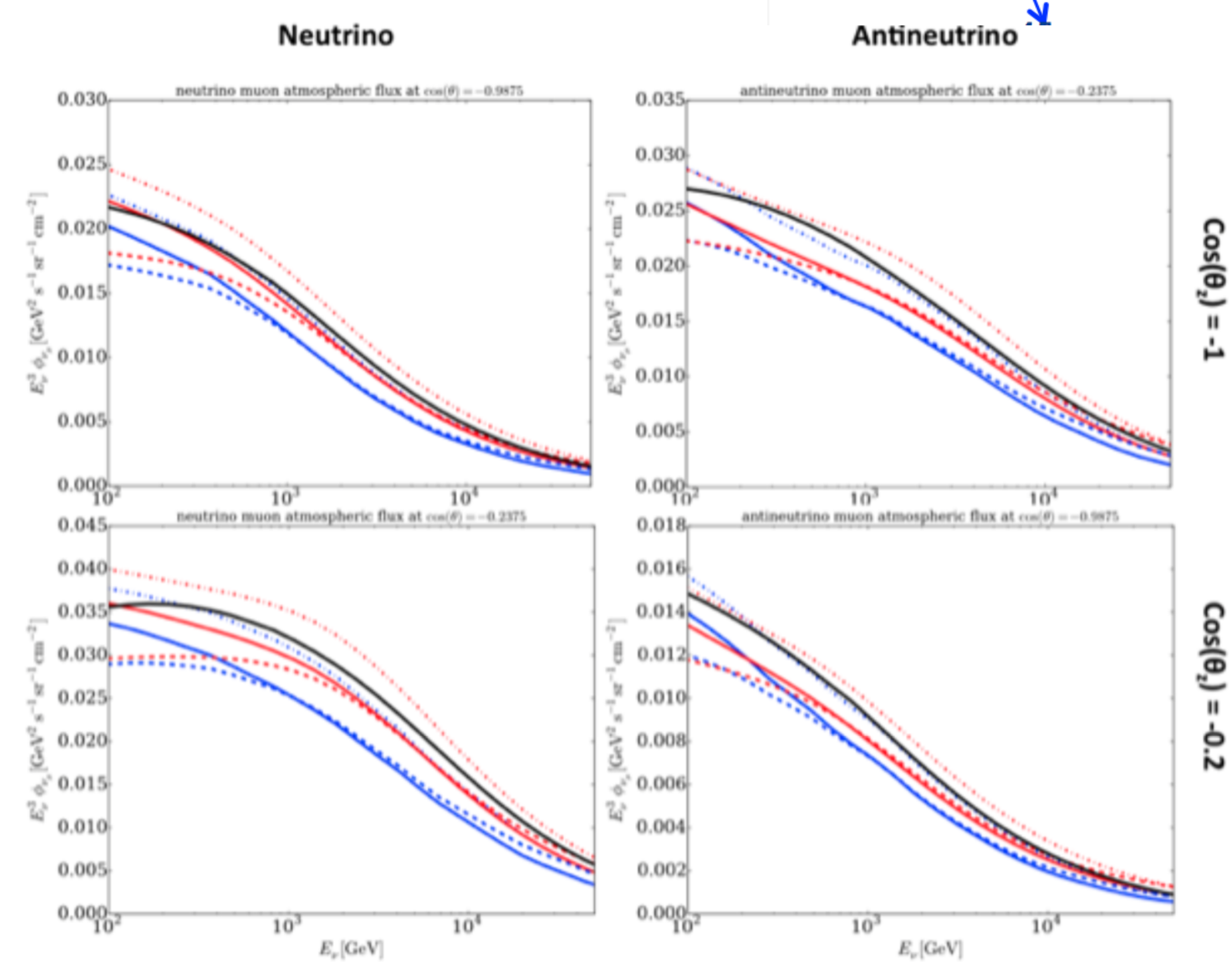
- Zatsepin-Sokolskaya
- Polygonato
- Gaisser+Honda



Hadronic models:

- Sibyll 2.3
- QGSJET II

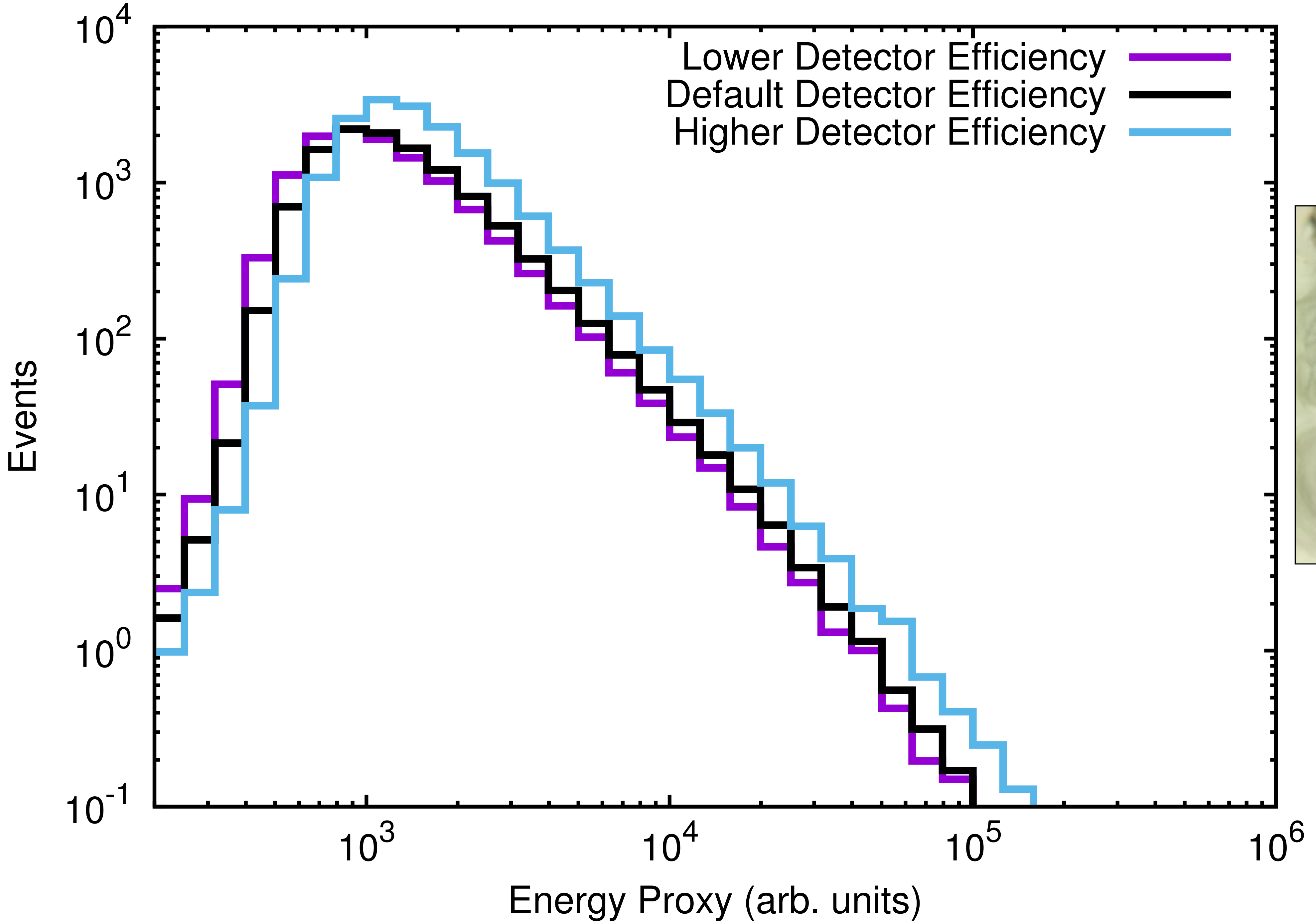
$$\phi_{atm} = N_0 \left(\phi_K + R_{\pi/K} \phi_\pi \right) \times E_\nu^{-\Delta\gamma}$$

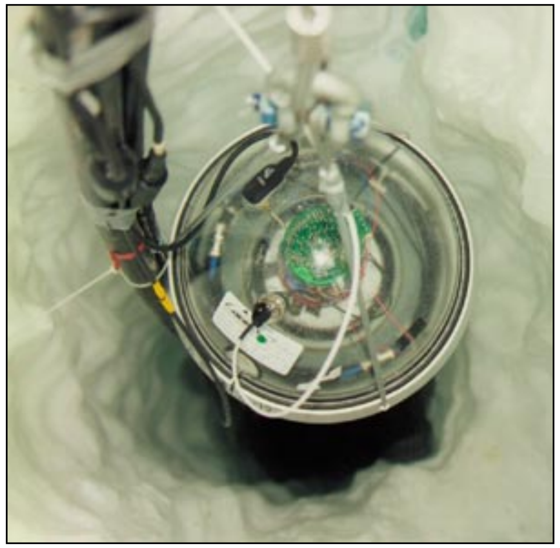


[Fedynitch et al. arXiv:1504.06639]
[Collins et al. URL: http://dspace.mit.edu/handle/1721.1/98078]

Detector Systematics: DOM efficiency!

Effect of changing the DOM efficiency in the parameter space:

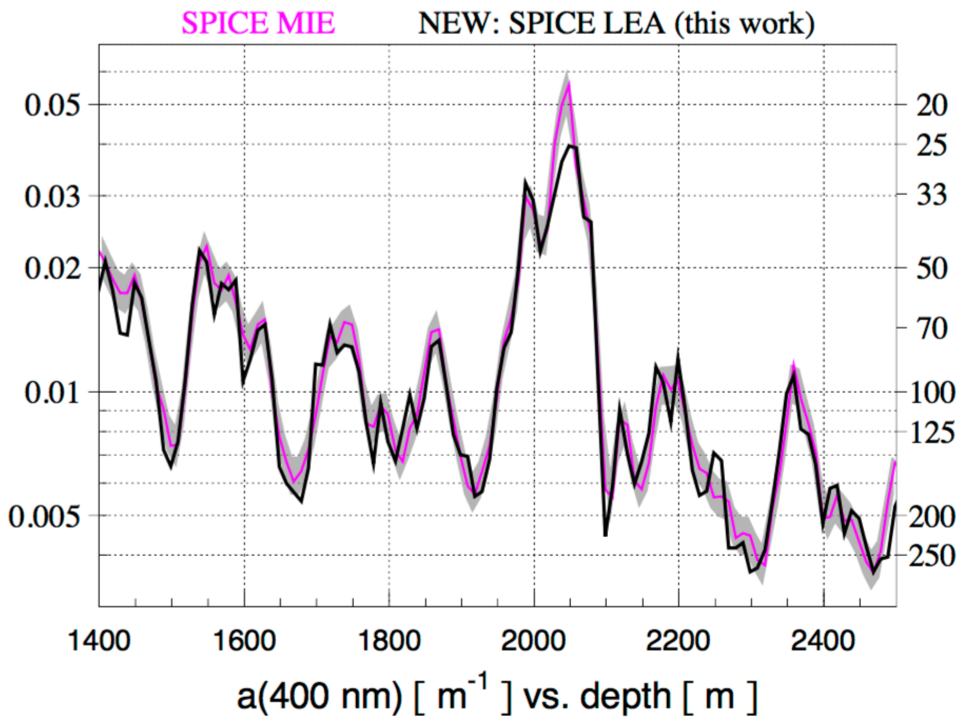


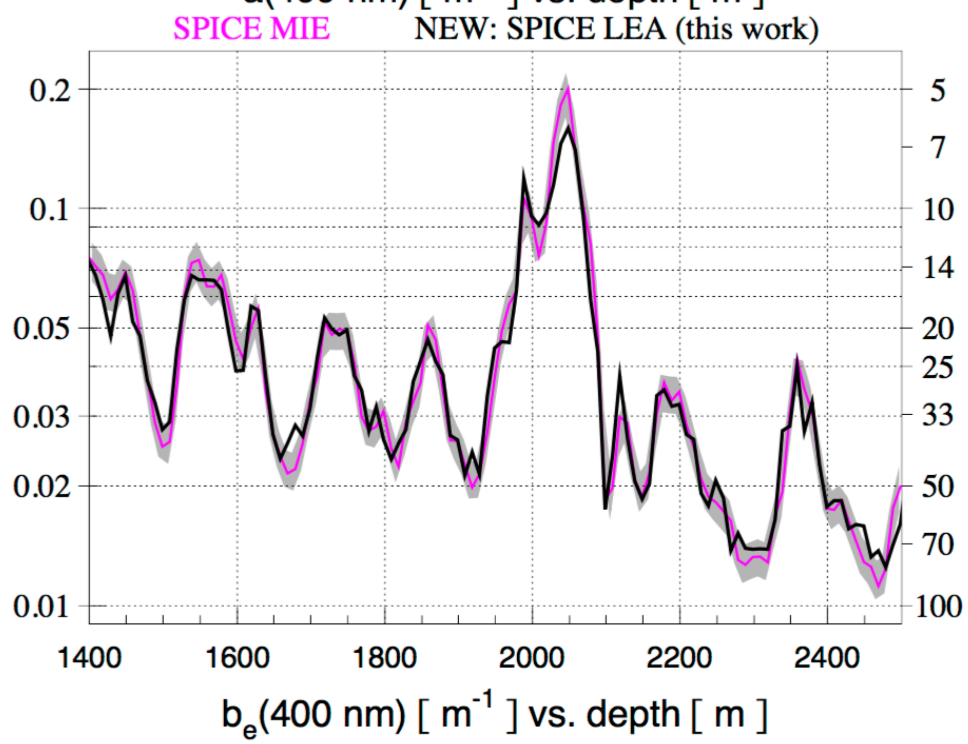


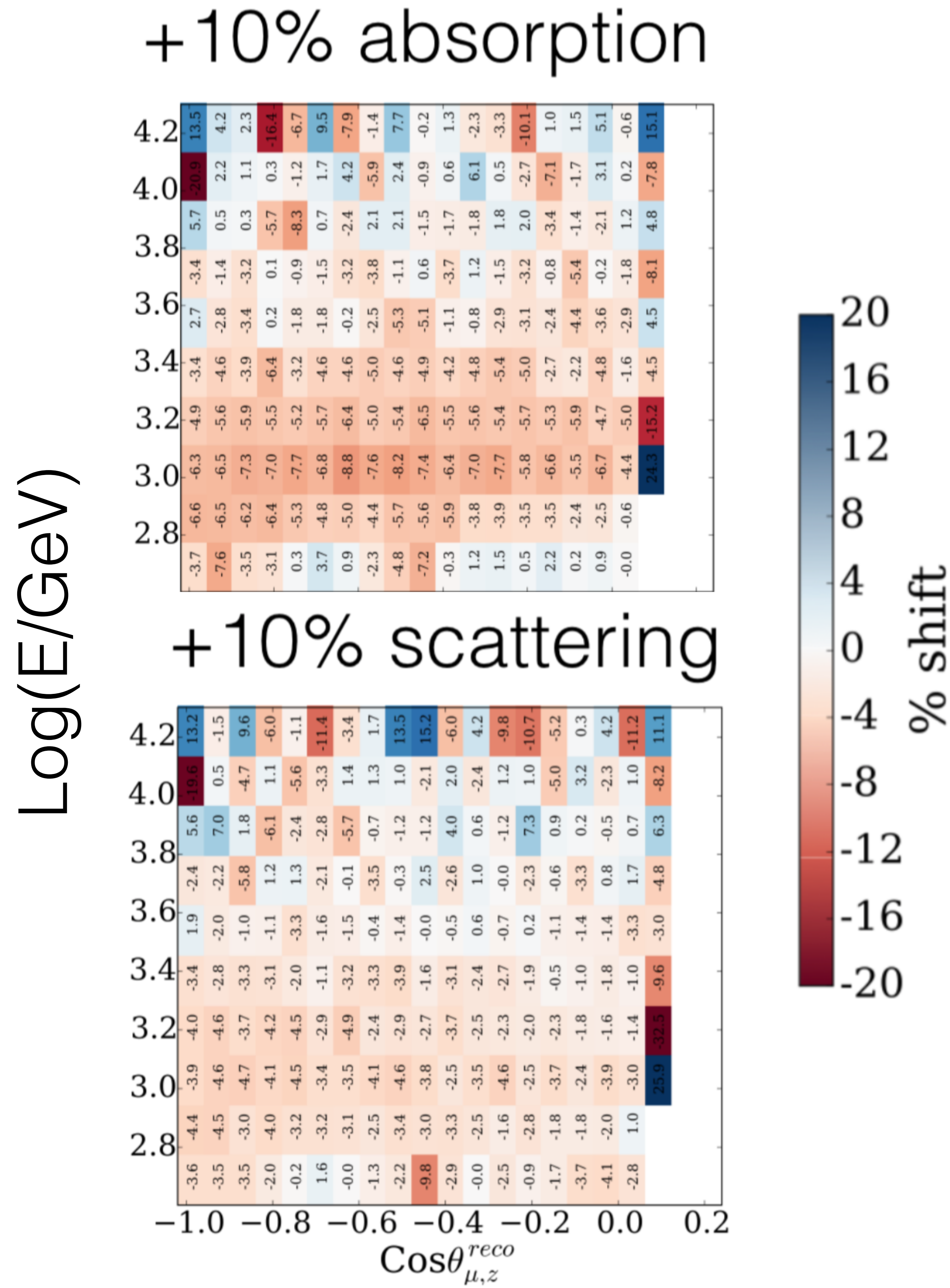
Efficiency of the DOM is imprecisely know. We apply corrections due to ice and cable shadow.

Ice uncertainties

Fit for ice properties as a function of depth.

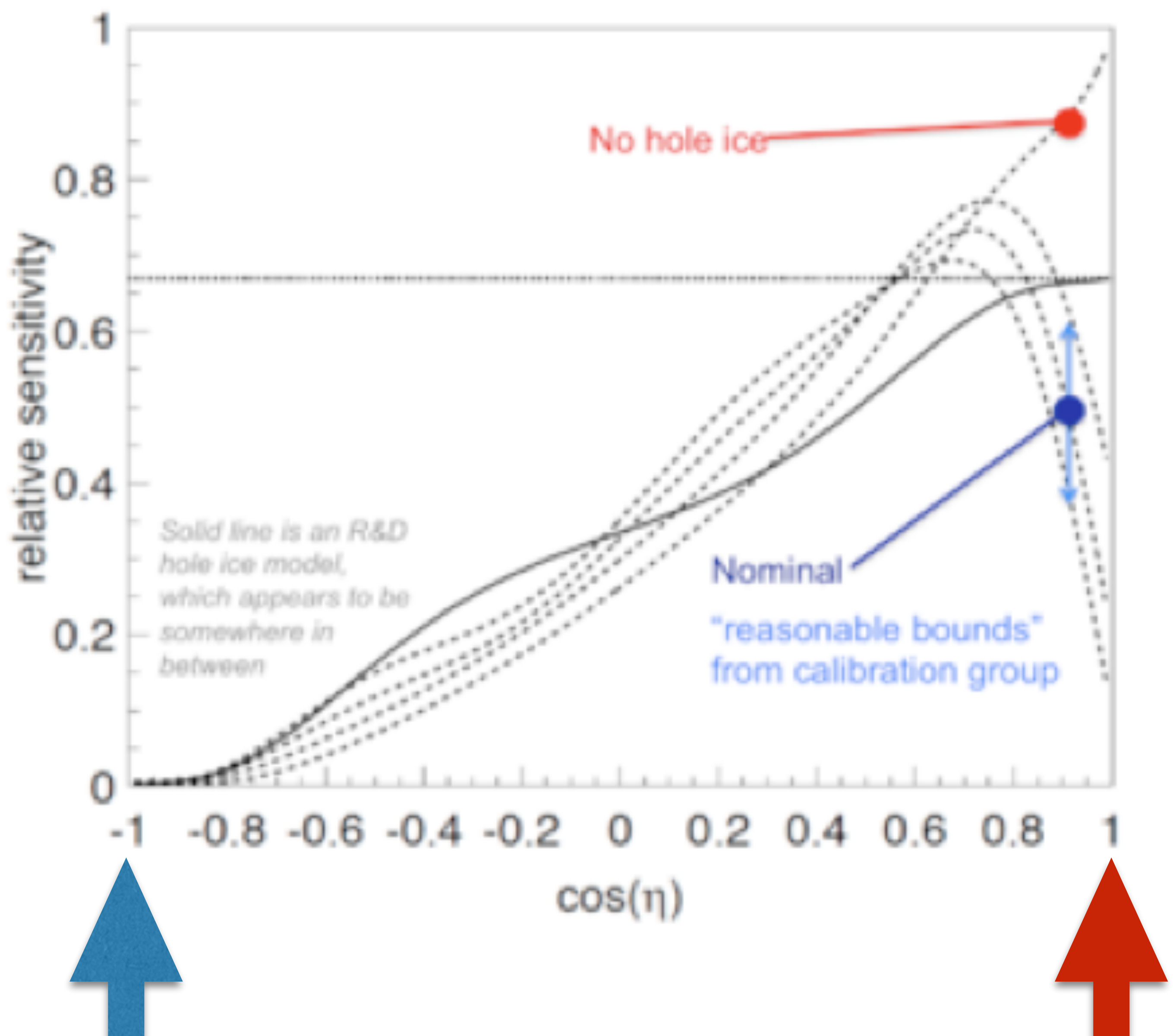


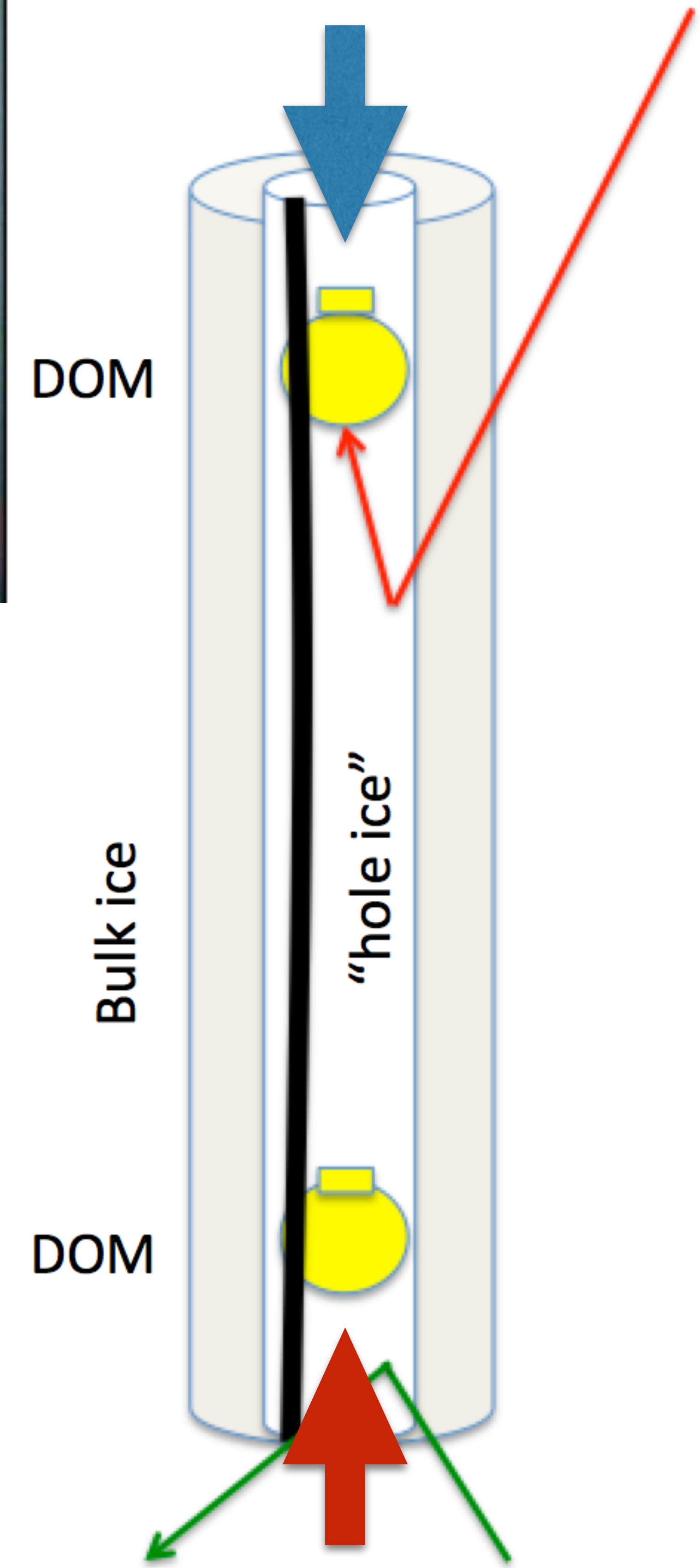




Hole Ice

Refrozen ice in the hole have **air bubbles** that produce **extra scattering**.





arXiv:1410.4267

Current bounds from SK

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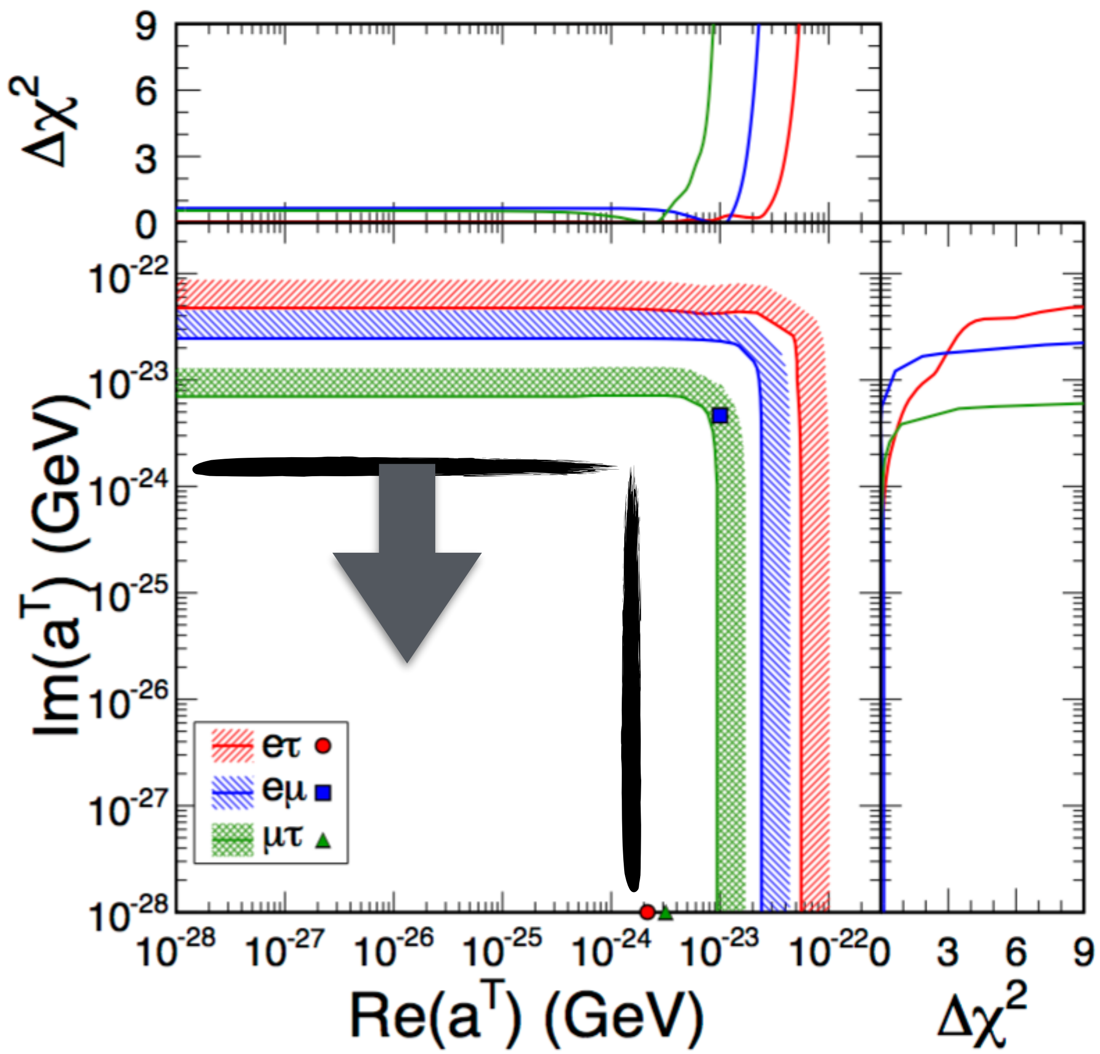

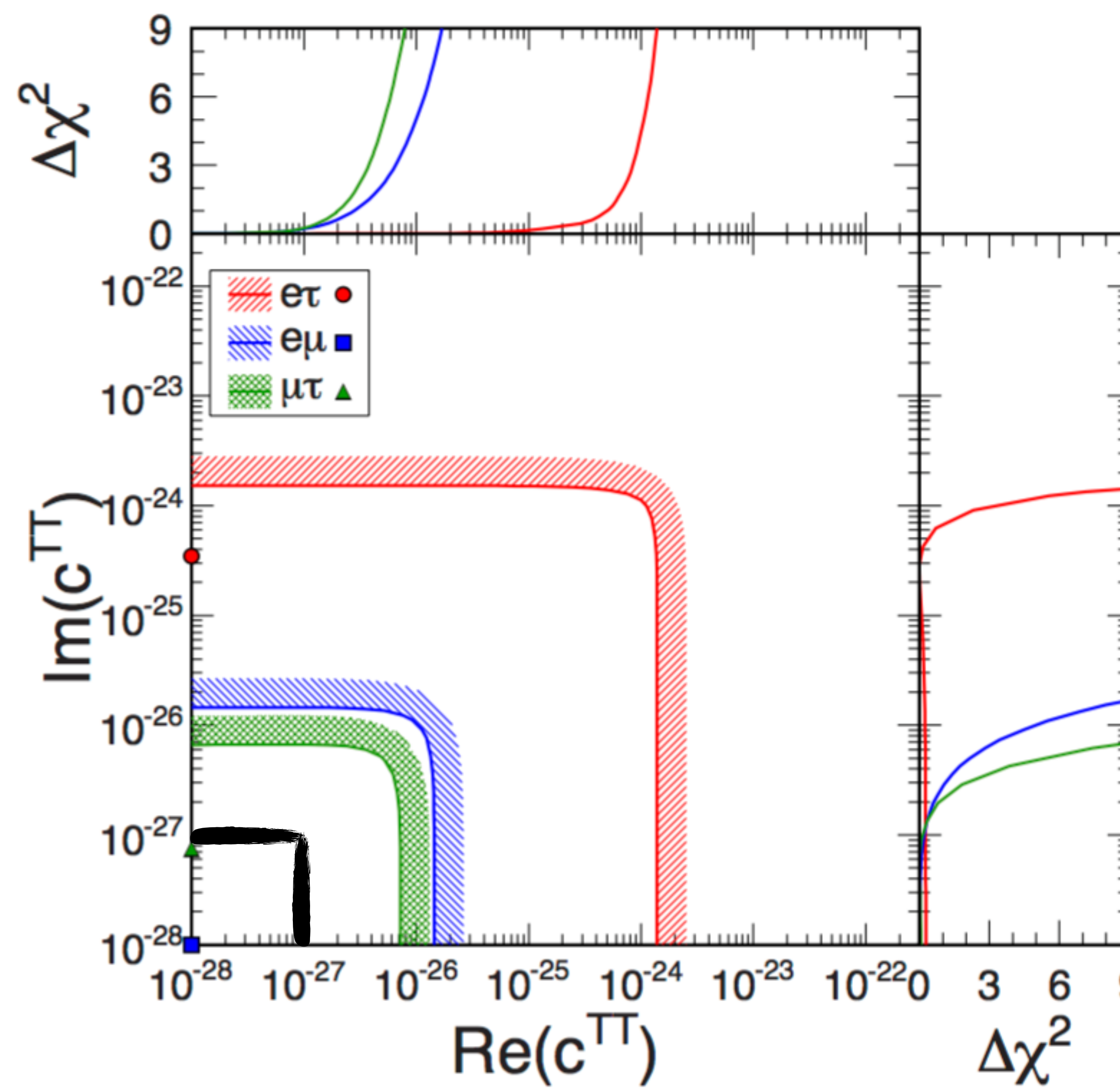

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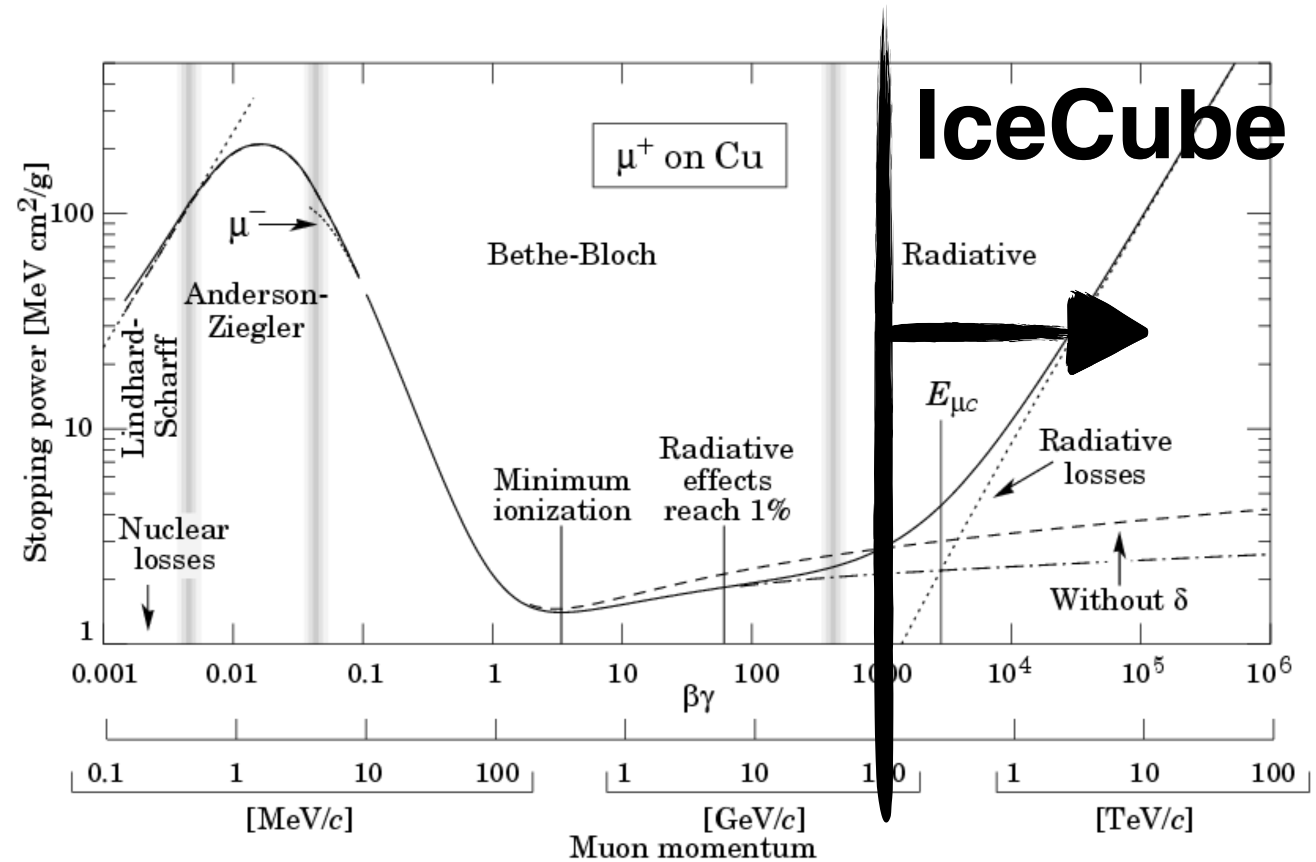
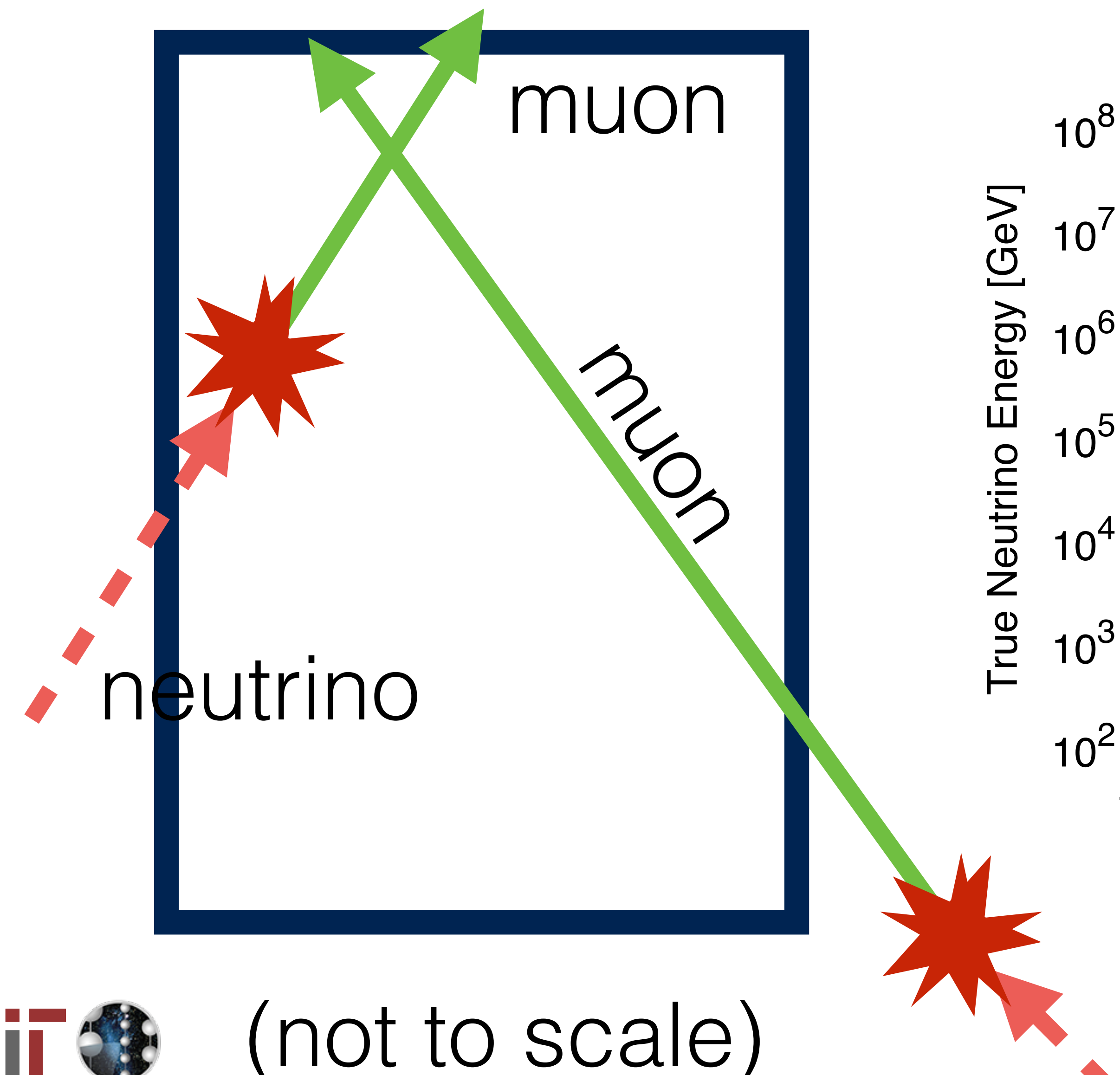
IC wins a lot in c due to the E factor

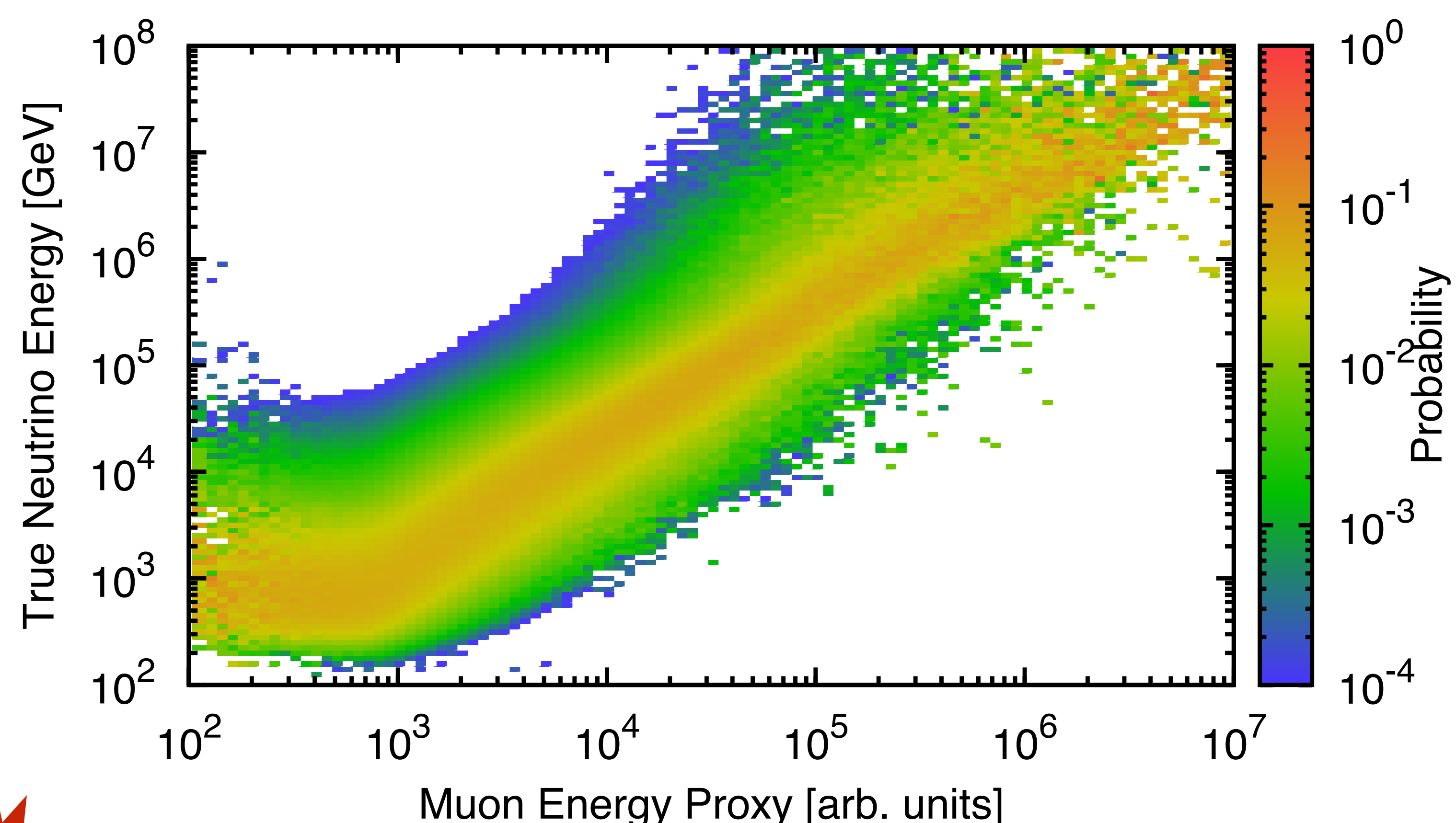
Through-going muons in IceCube



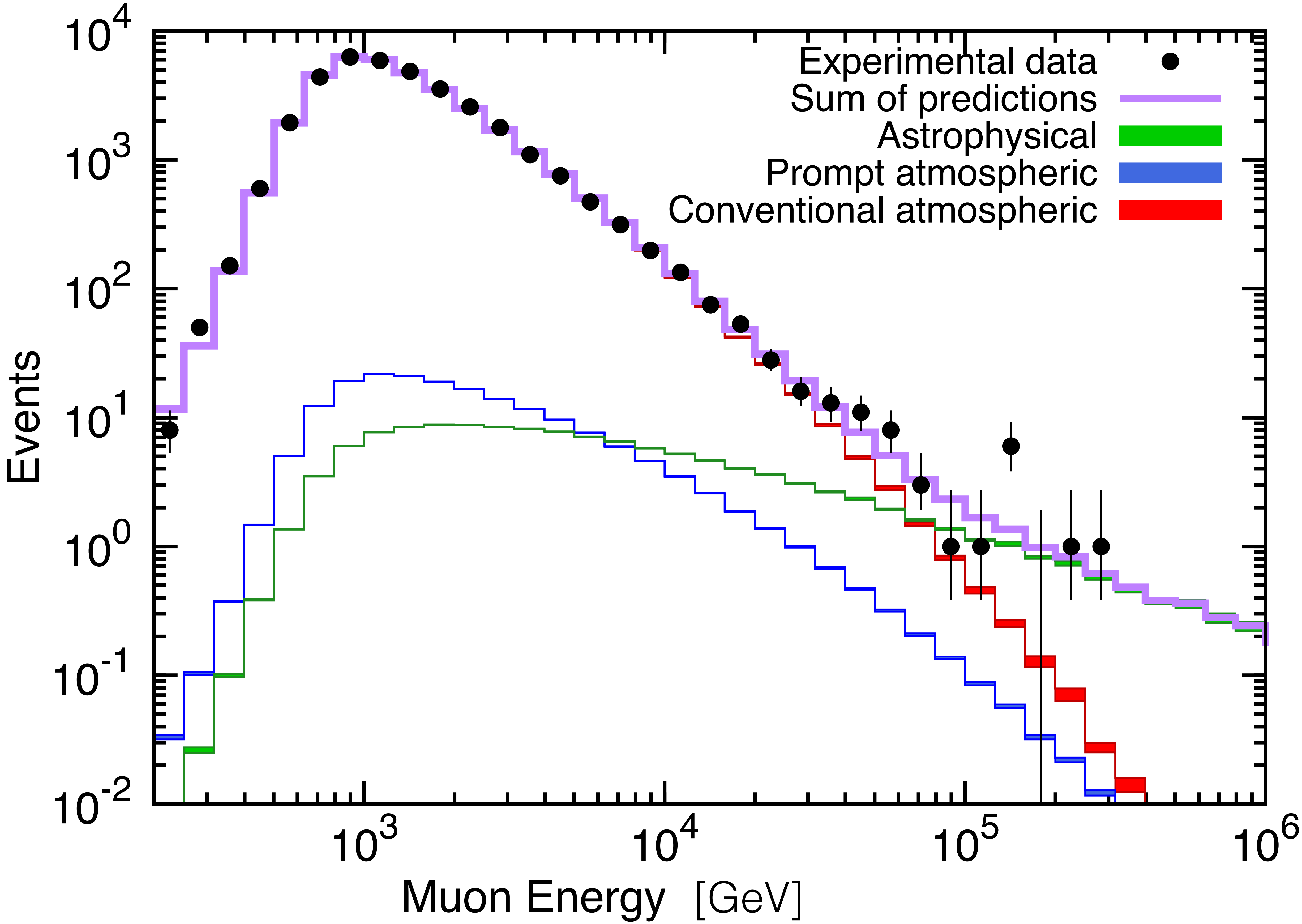
$$\Delta\theta \sim 1^o$$



(not to scale)

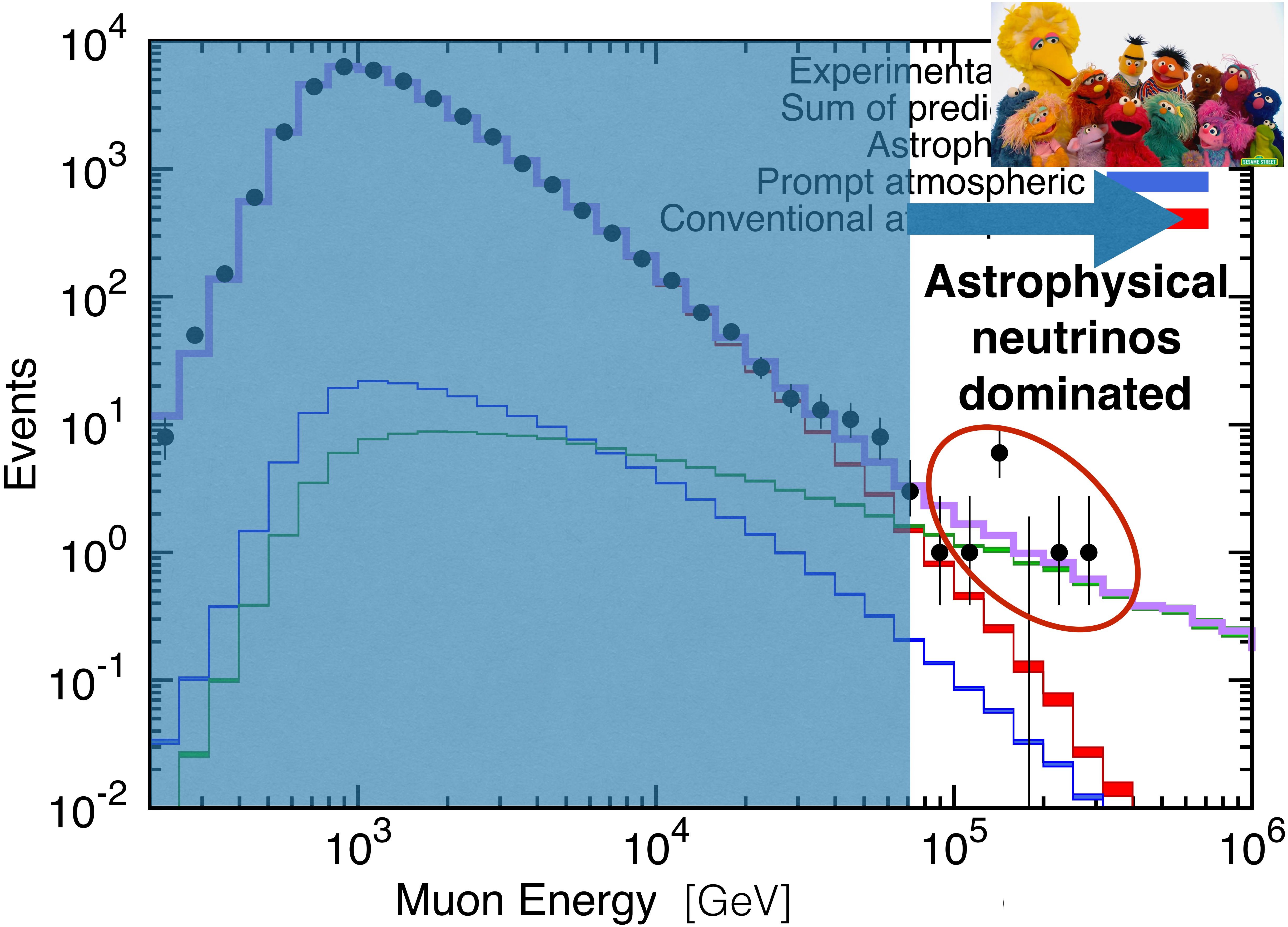


Through-going nu-mu energy distribution



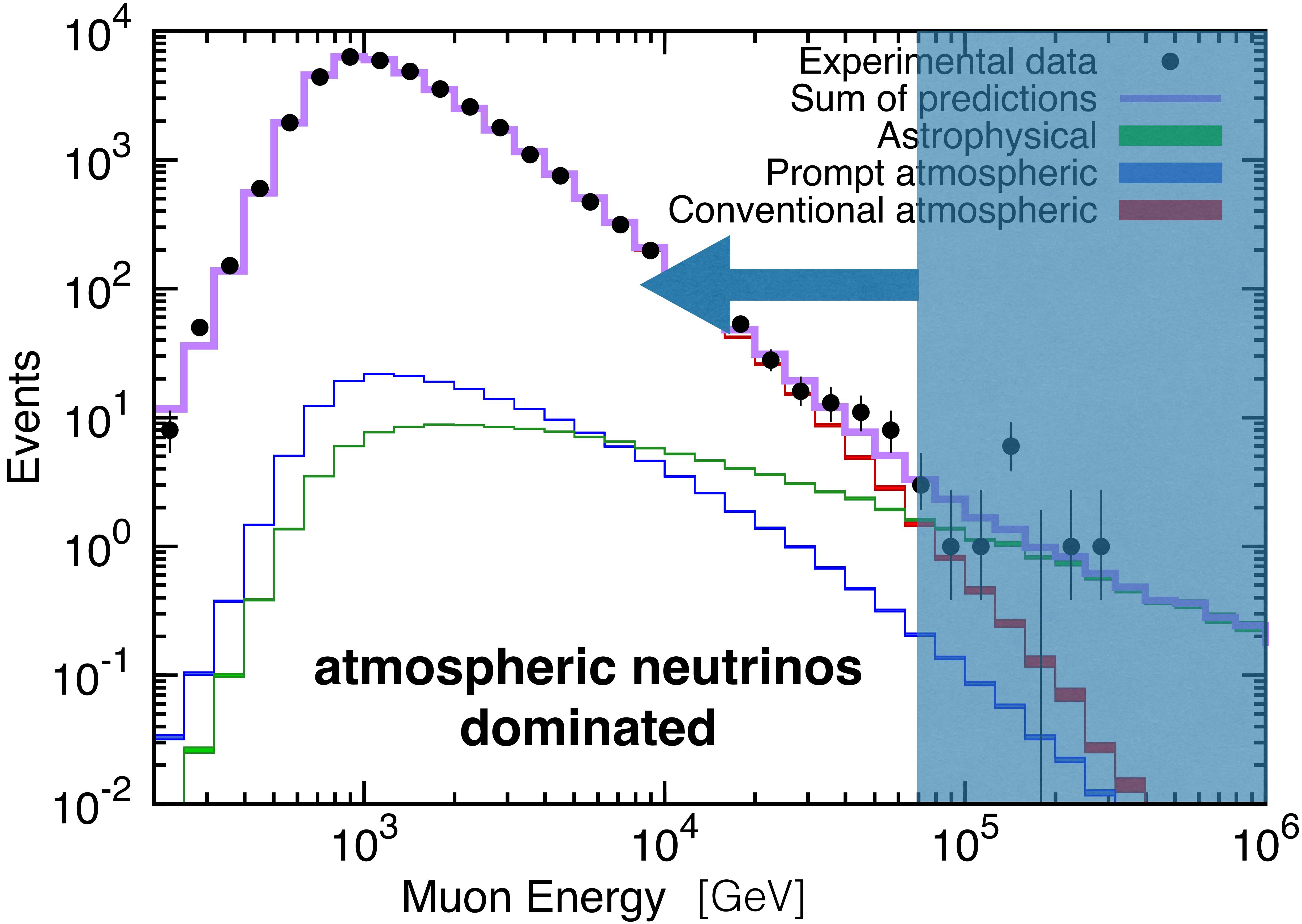
Phys. Rev. Lett. 115, 081102 (2015)

Astrophysical neutrino dominate at highest energies!



Phys. Rev. Lett. 115, 081102 (2015)

IceCube observes a lot of atmospheric neutrinos!



Phys. Rev. Lett. 115, 081102 (2015)