Measurement of Atmospheric Neutrino Oscillations with IceCube and DeepCore

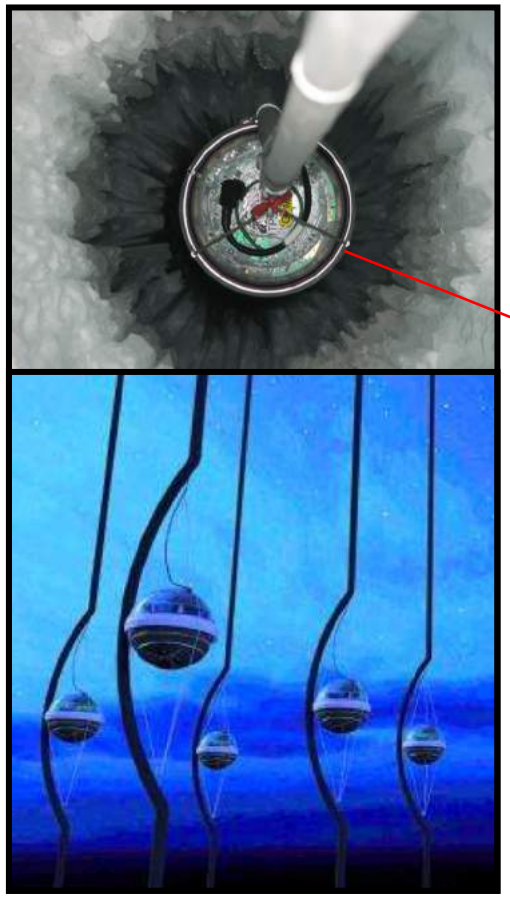
Tom Stuttard for the IceCube collaboration
Niels Bohr Institute

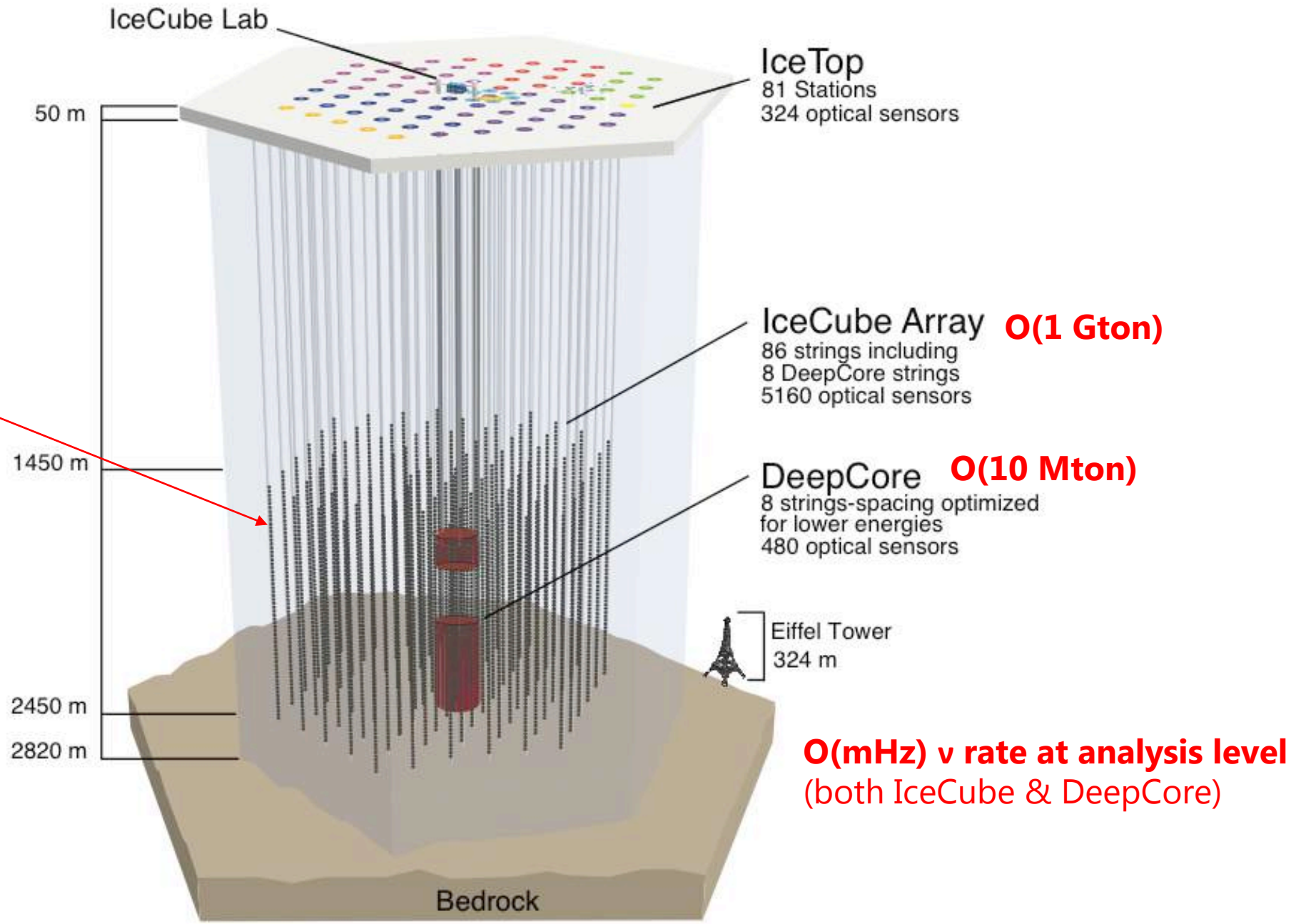
PANE 2018

IceCube
SOUTH POLE NEUTRINO OBSERVATORY

Oscillations in IceCube/DeepCore

- IceCube/DeepCore is an extremely **versatile** oscillations detector
- Huge range of neutrino **energies** and **baselines** observed
  GeV – PeV km to astrophysical
- **Matter effects** for Earth-crossing ν
- Enormous detector → **high statistics**
  - ~100% uptime, multiple ν per hour
- Can test standard oscillations picture
  - **ν_μ disappearance, ν_τ appearance, mass ordering**
- Broad spectrum of **BSM** oscillation physics probed

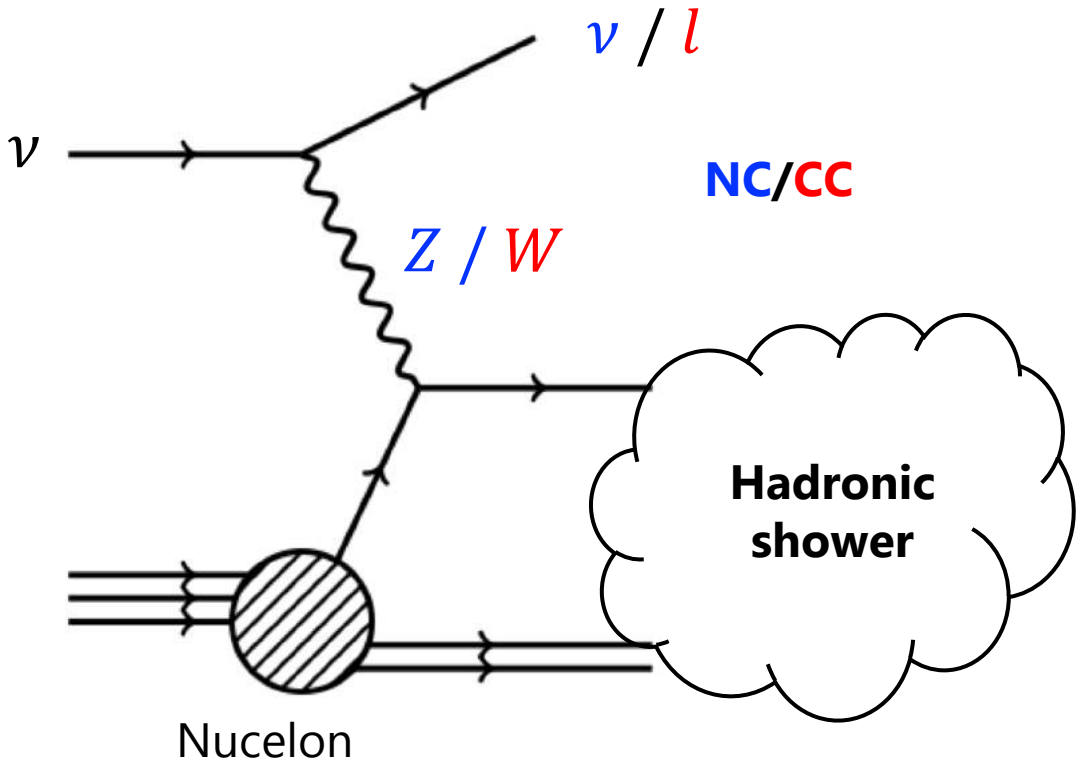


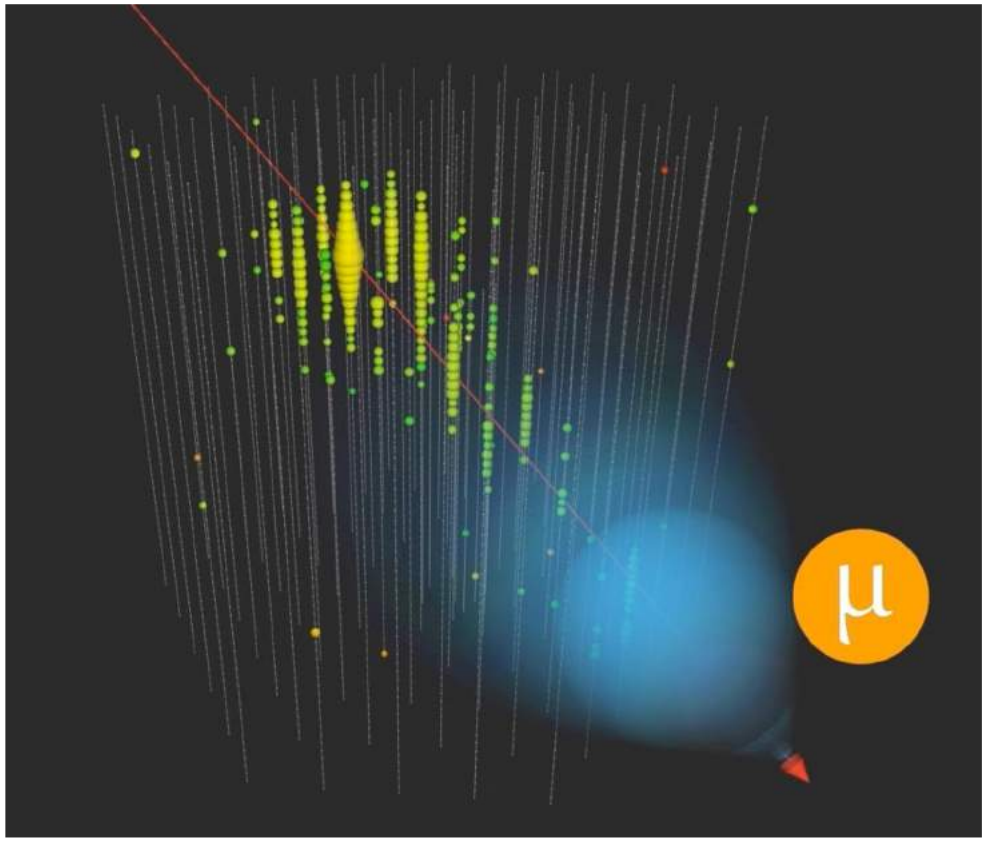


O(mHz) ν rate at analysis level
(both IceCube & DeepCore)

Neutrino interactions in the ice

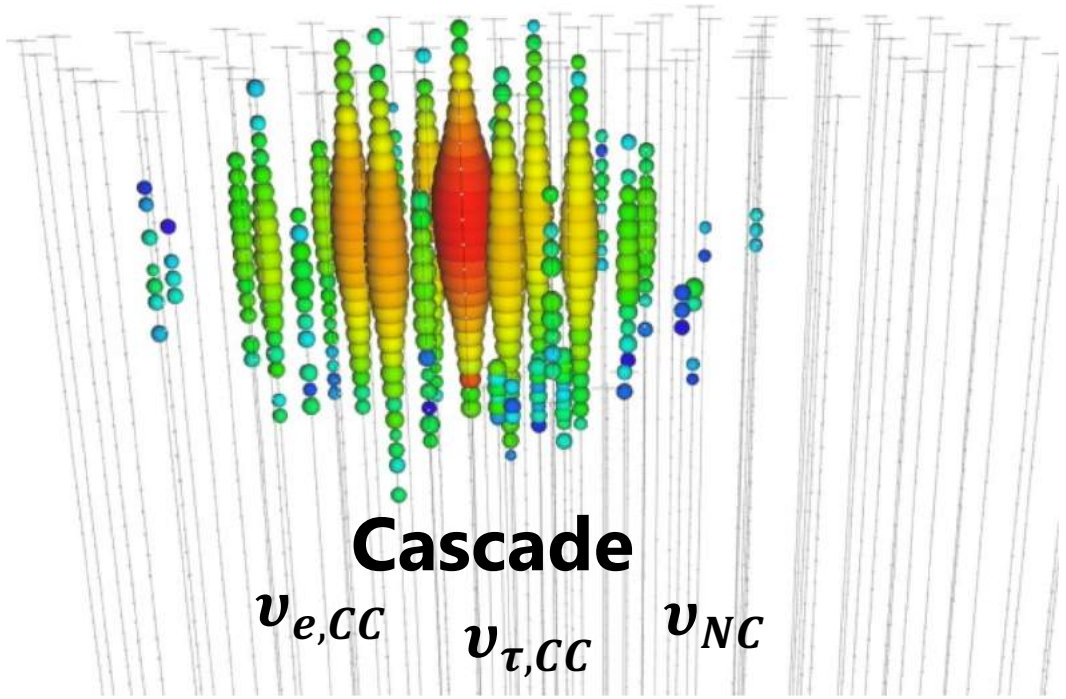
- Charged Current (**CC**) and Neutral Current (**NC**) ν-ice interactions
  - **DIS** dominates above a few GeV
- Charged particles produce **Cherenkov** photons → detected by PMTs



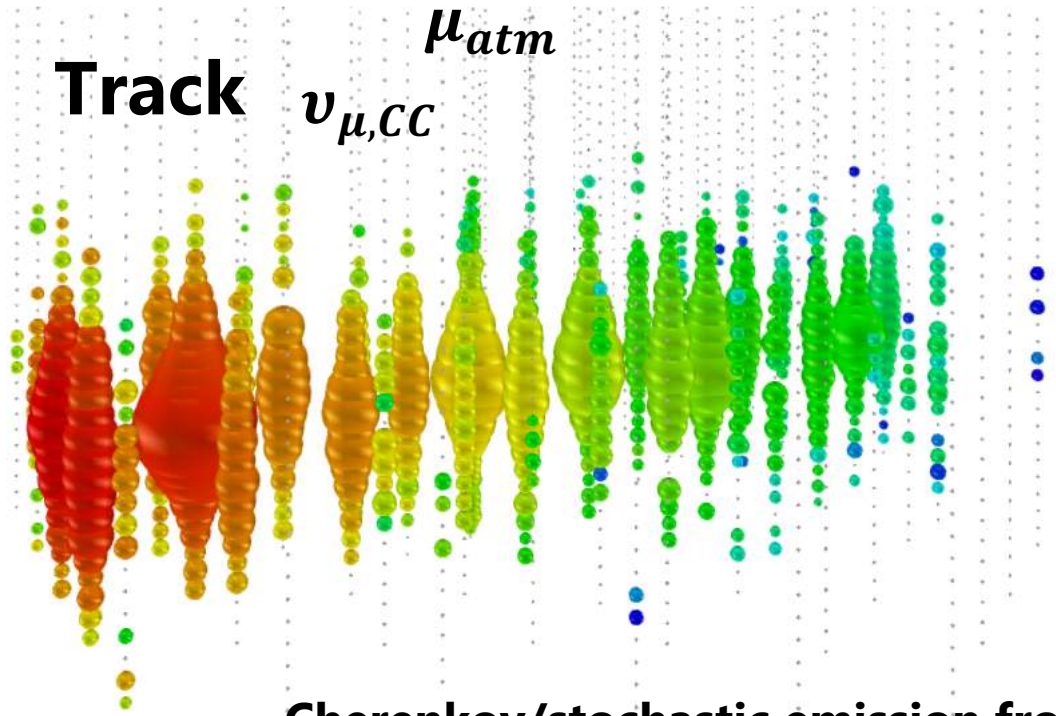


Event types

- Events categorised by two distinct types
  - Also more exotic cases at high energies



Hadronic/EM showers

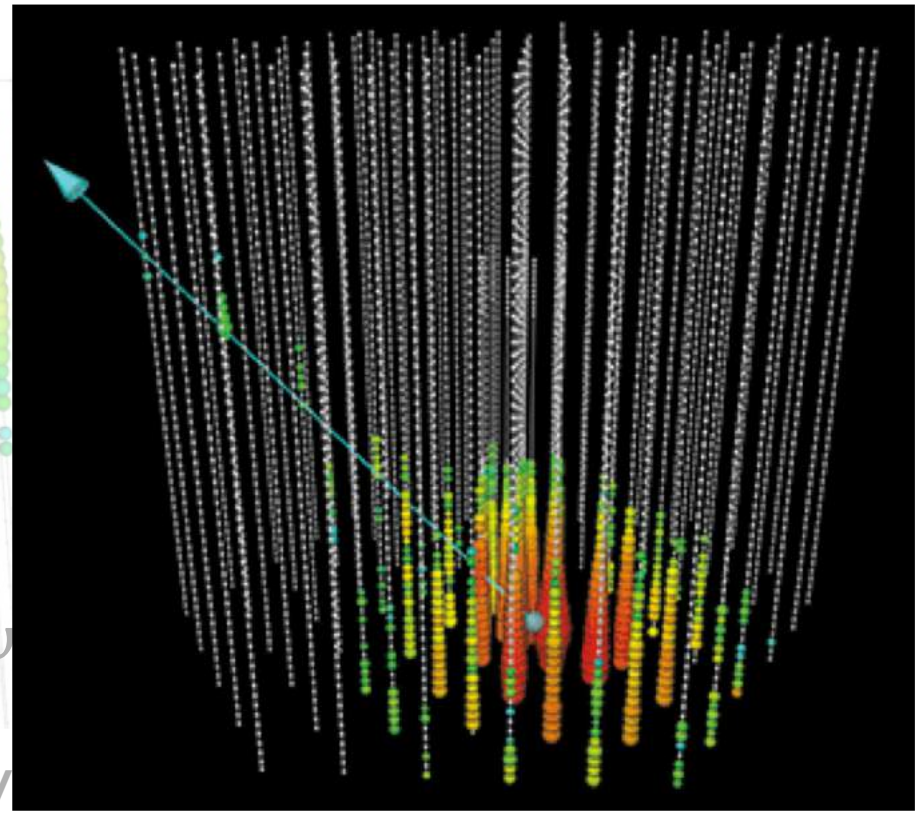


Cherenkov/stochastic emission from μ

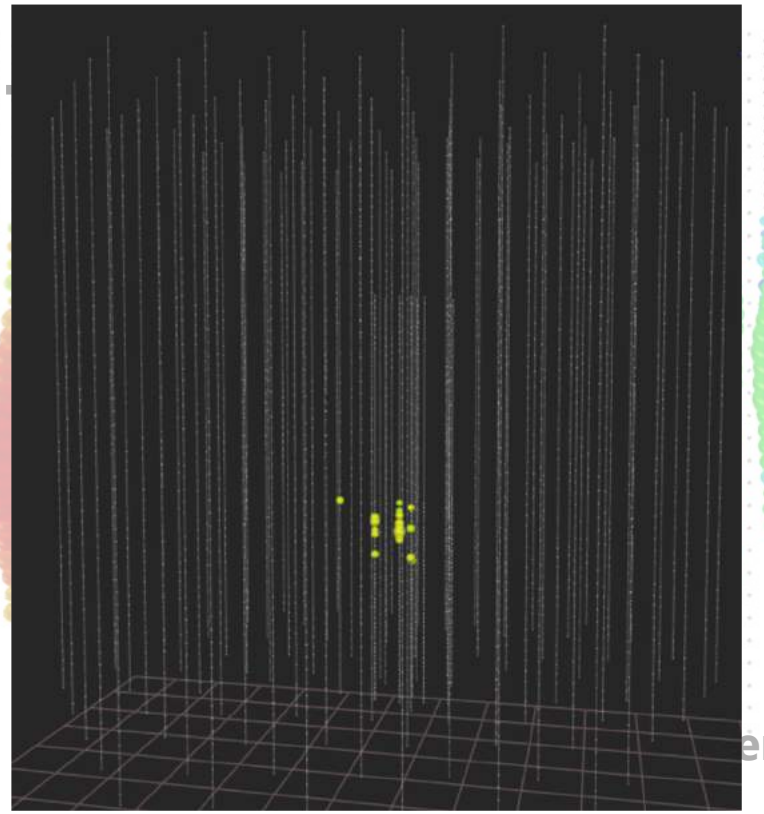
Event types

- Events categorised by two distinct types
  - Also more exotic cases at high energies

250 TeV



32 GeV



Hadronic/ emission from μ

Picture is less clear at low energy!

Oscillations in DeepCore

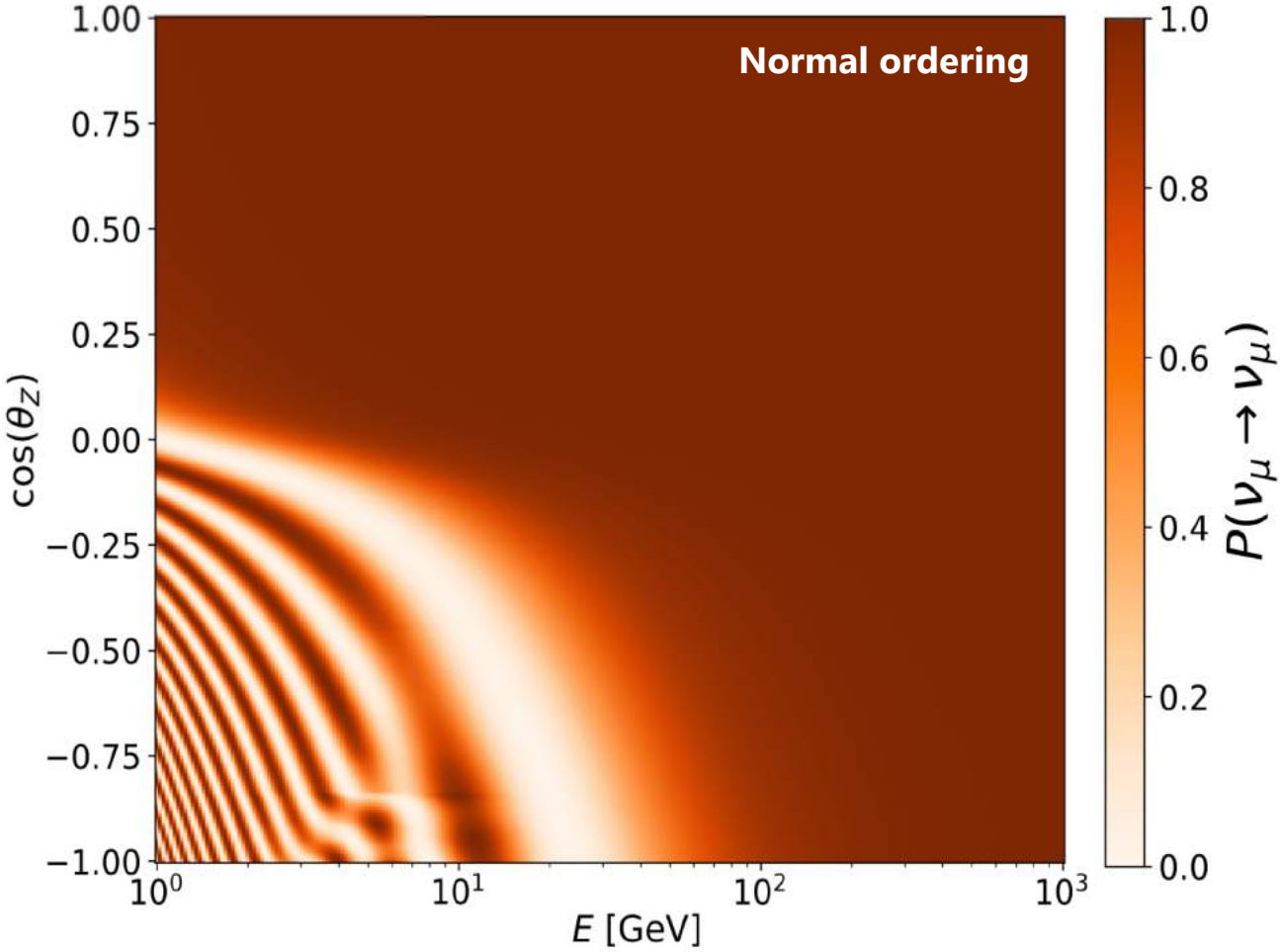
Particle ID

- Search for 3D distortions in event rates: $[E, cos(\theta_{zenith}), PID]$
- Atmospheric ν_μ **disappearance** is dominant oscillation channel

Down-going

Horizon

Up-going



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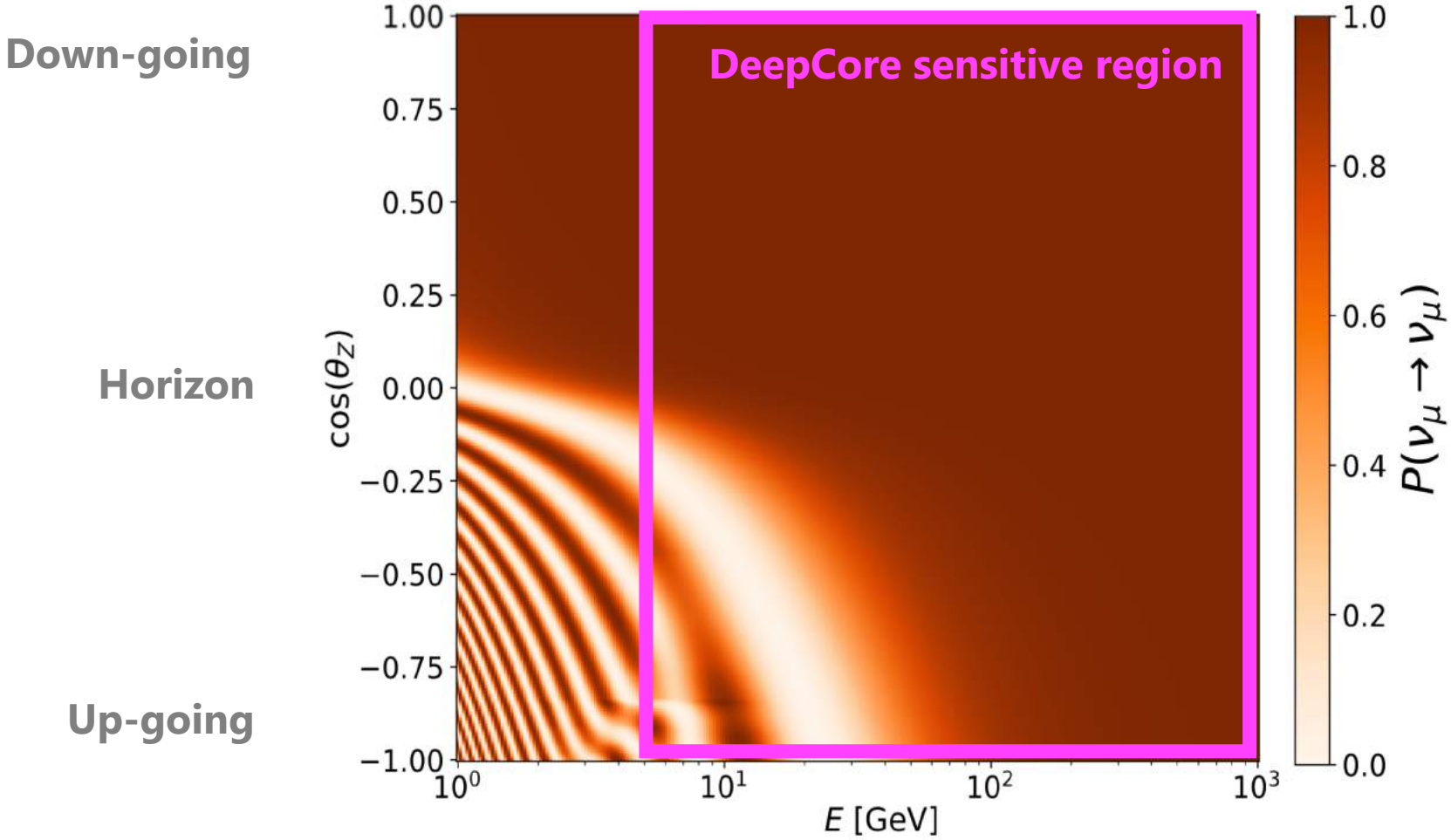

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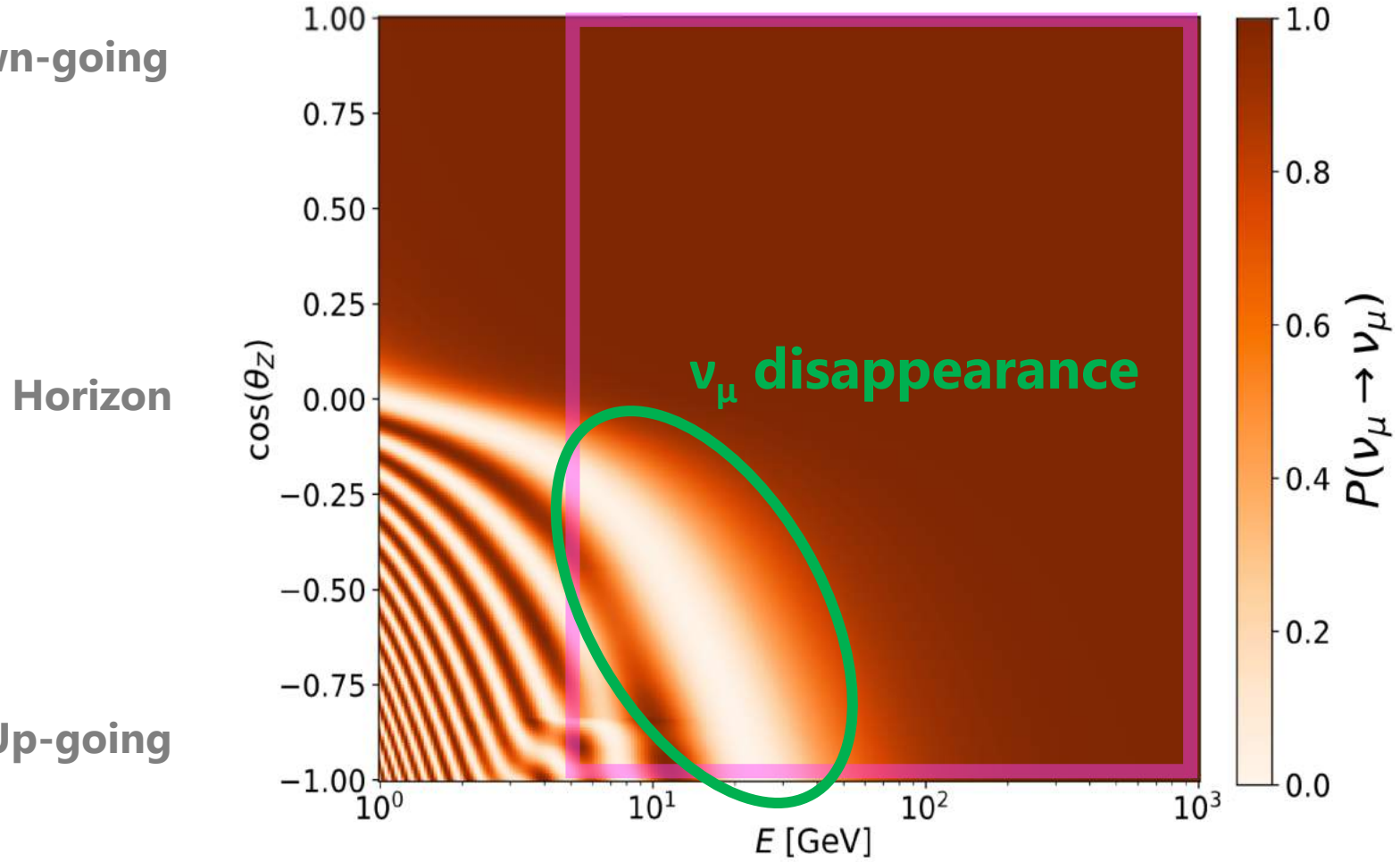

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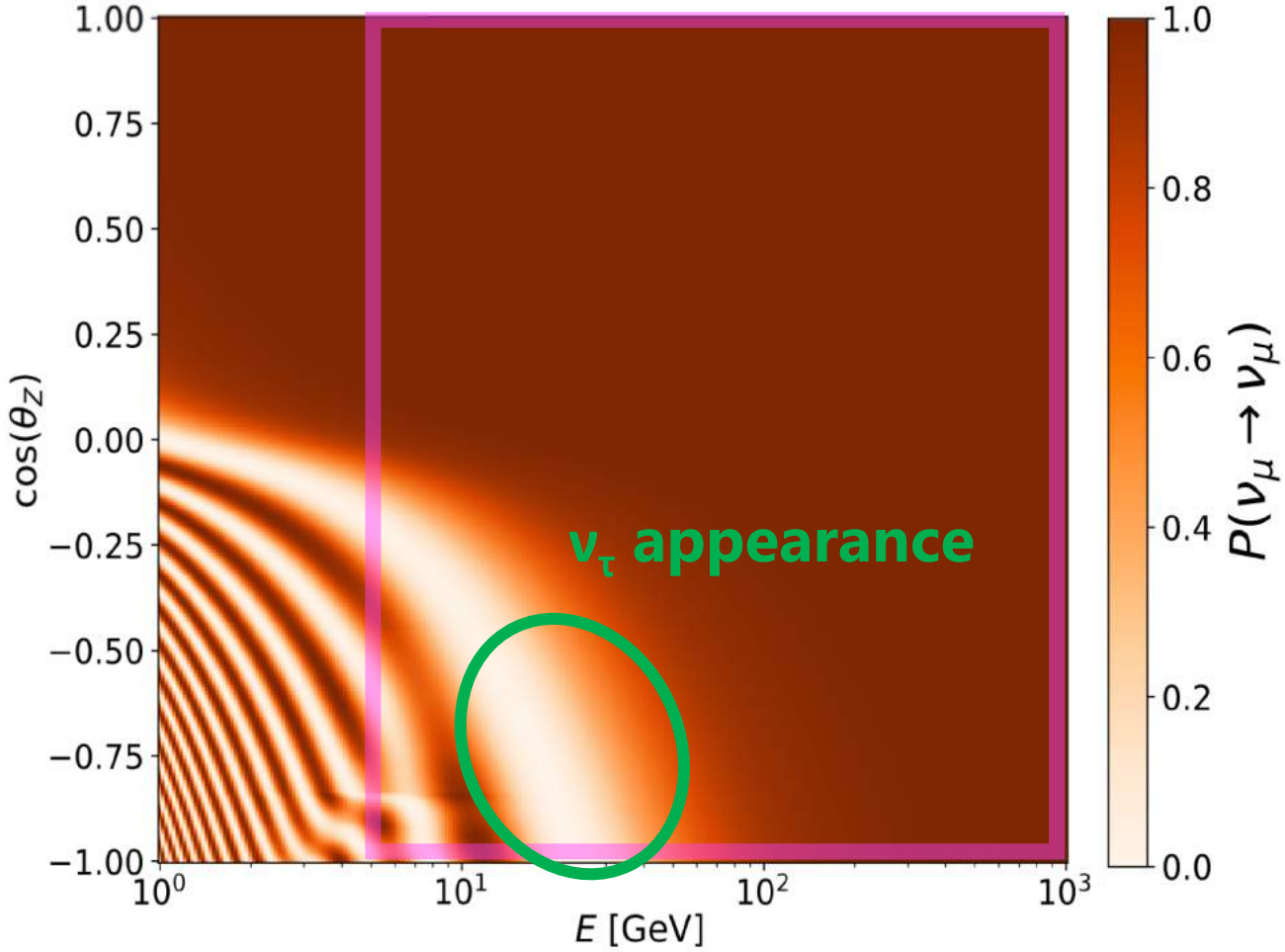

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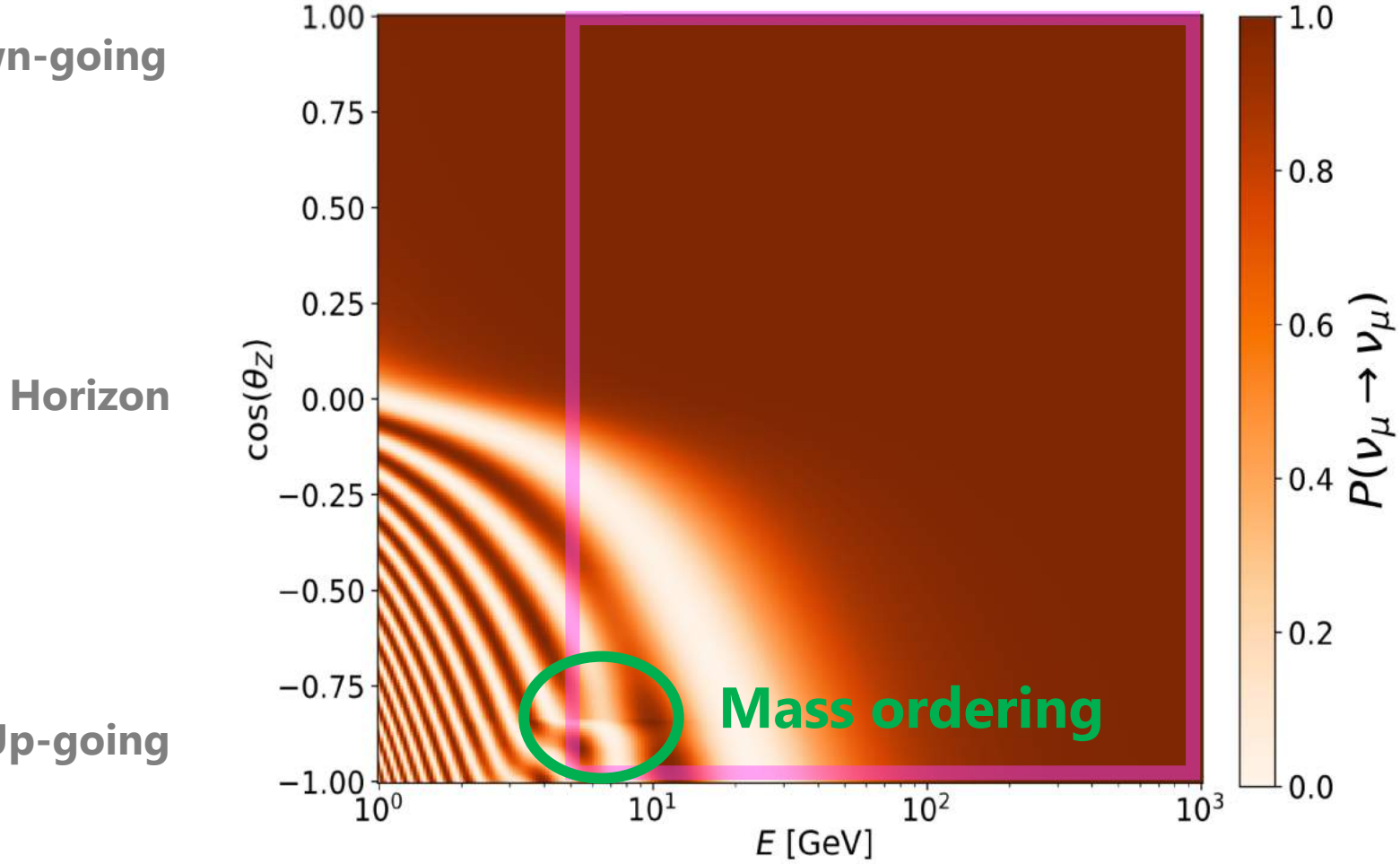

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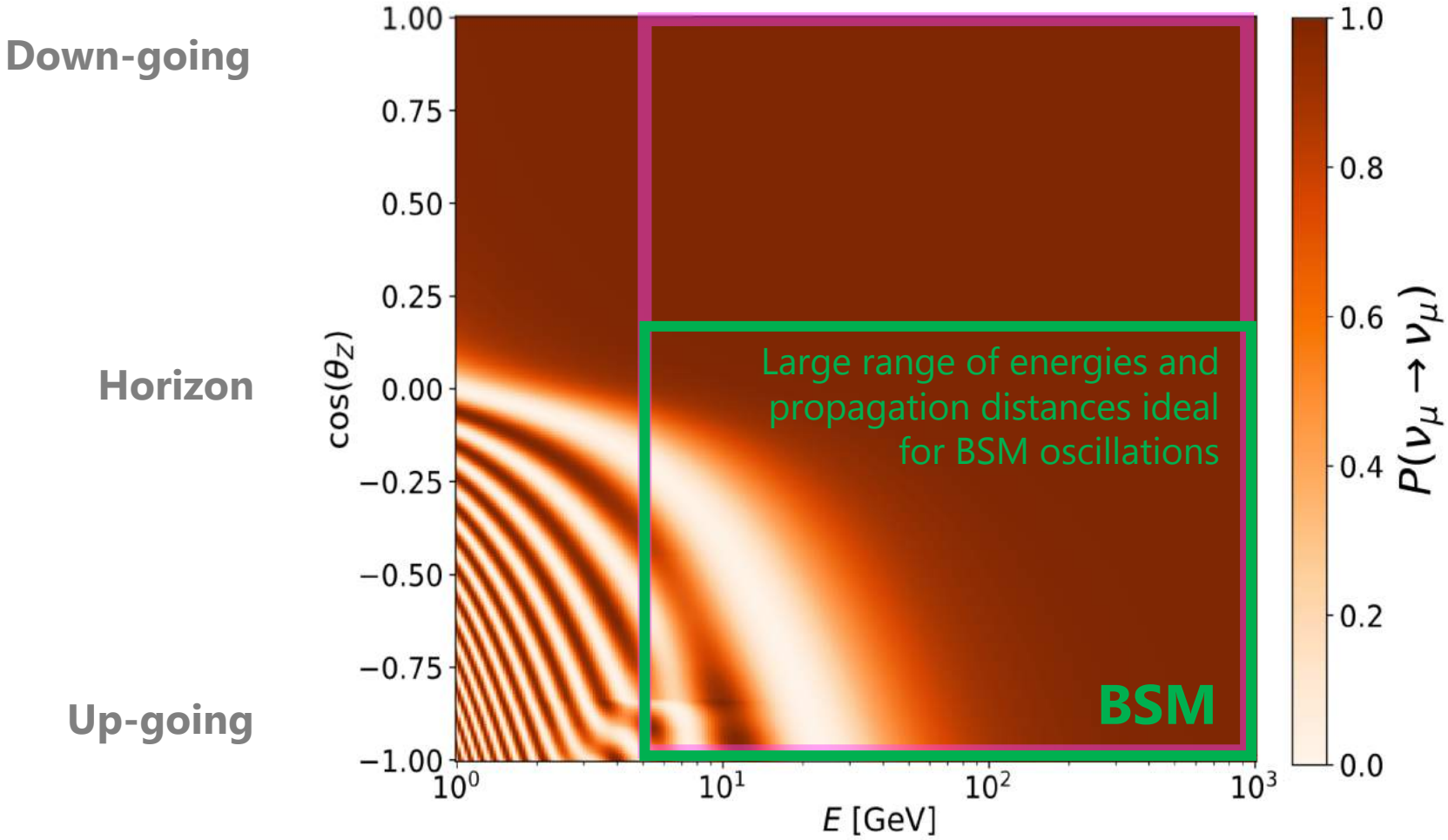
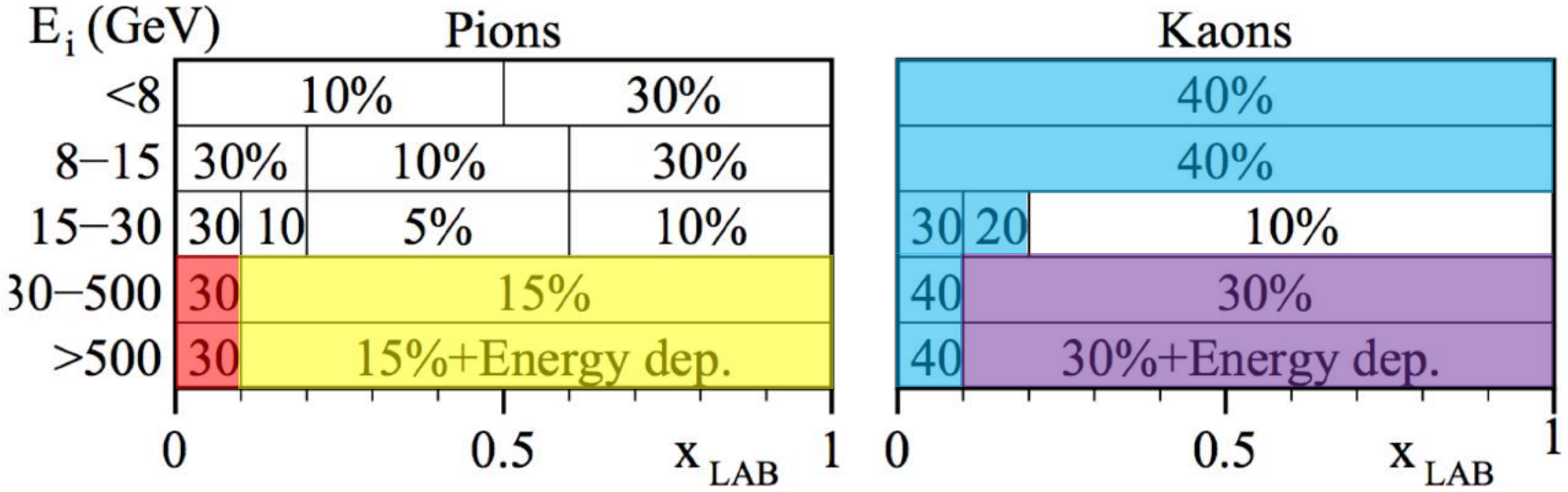


arXiv:astro-ph/0611266
arXiv:1503.00544

Flux systematics with MCEq

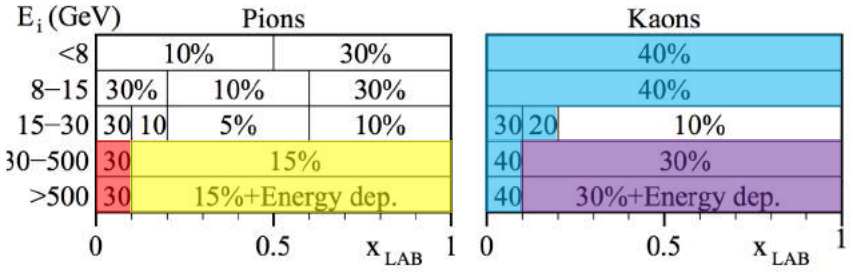
- Barr et al (2006) estimated uncertainty in inputs to atmospheric neutrino flux calculations
- MCEq can be used for fast flux calculations
  - Can use Barr –like inputs
- Combine to treat systematic uncertainty in analyses

π and K production uncertainty regions (Barr blocks)

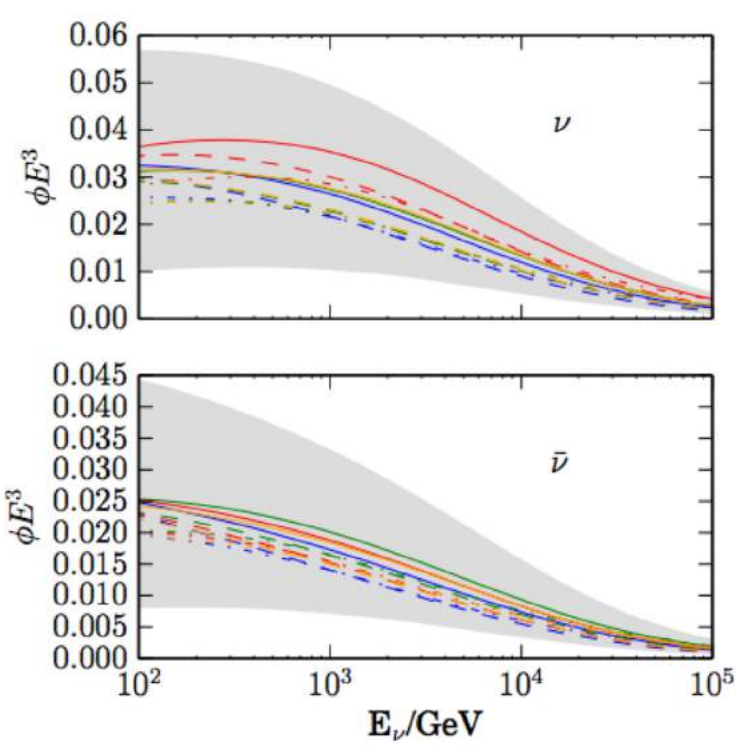


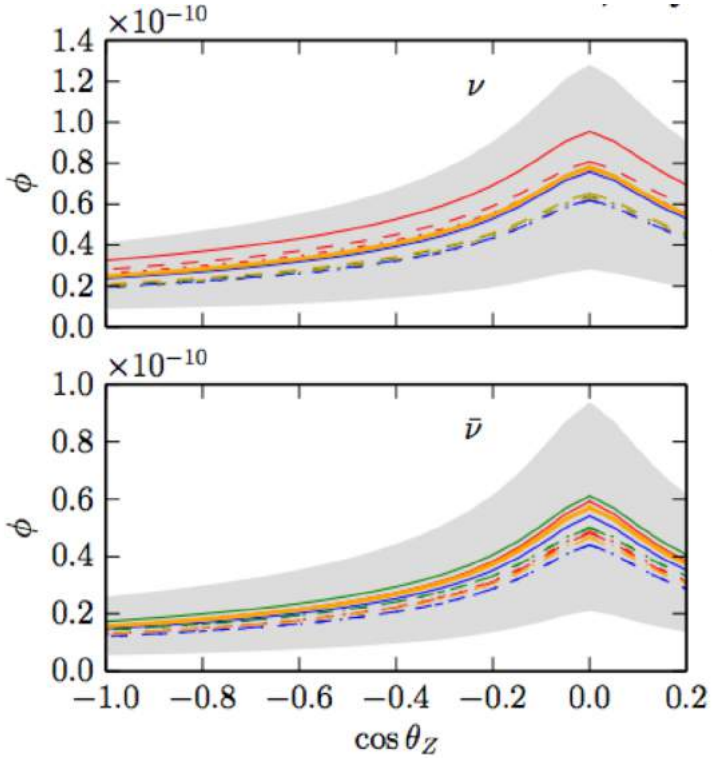
Coloured regions relevant for DeepCore and IceCube

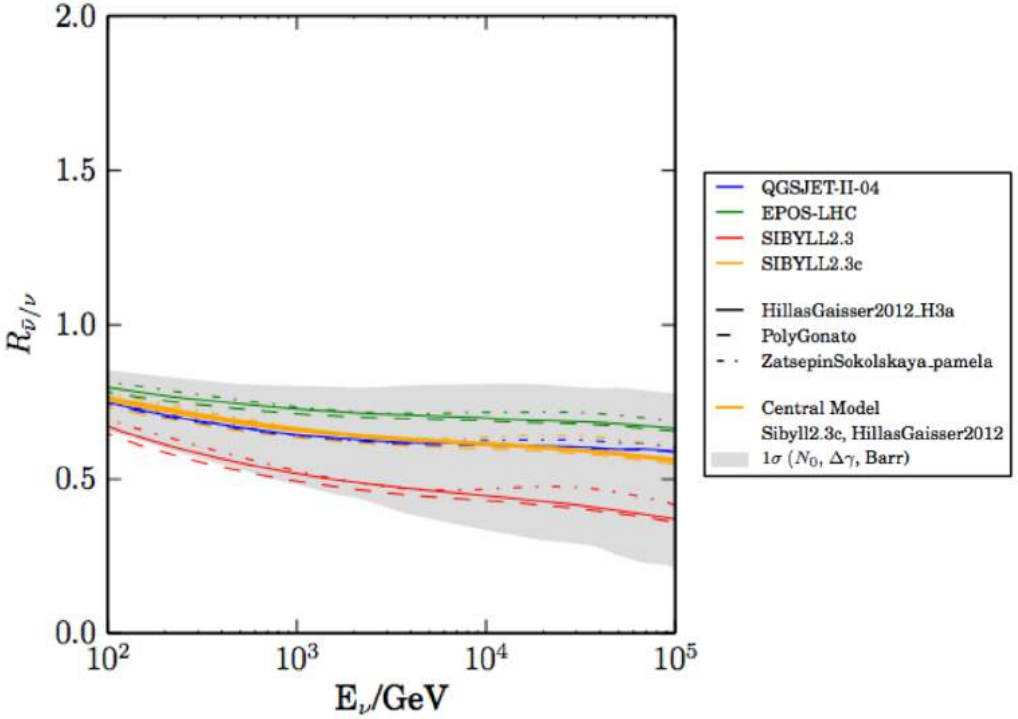
Flux systematics with MCEq



- Implementation in analyses:
  - Treat **"Barr blocks"** as nuisance parameters (Gaussian priors)
    - Also **normalisation** and **spectral index**
  - Re-calculate flux using MCEq for each case and re-weight simulation accordingly
  - Fit to find best fit physics and nuisance parameters to data

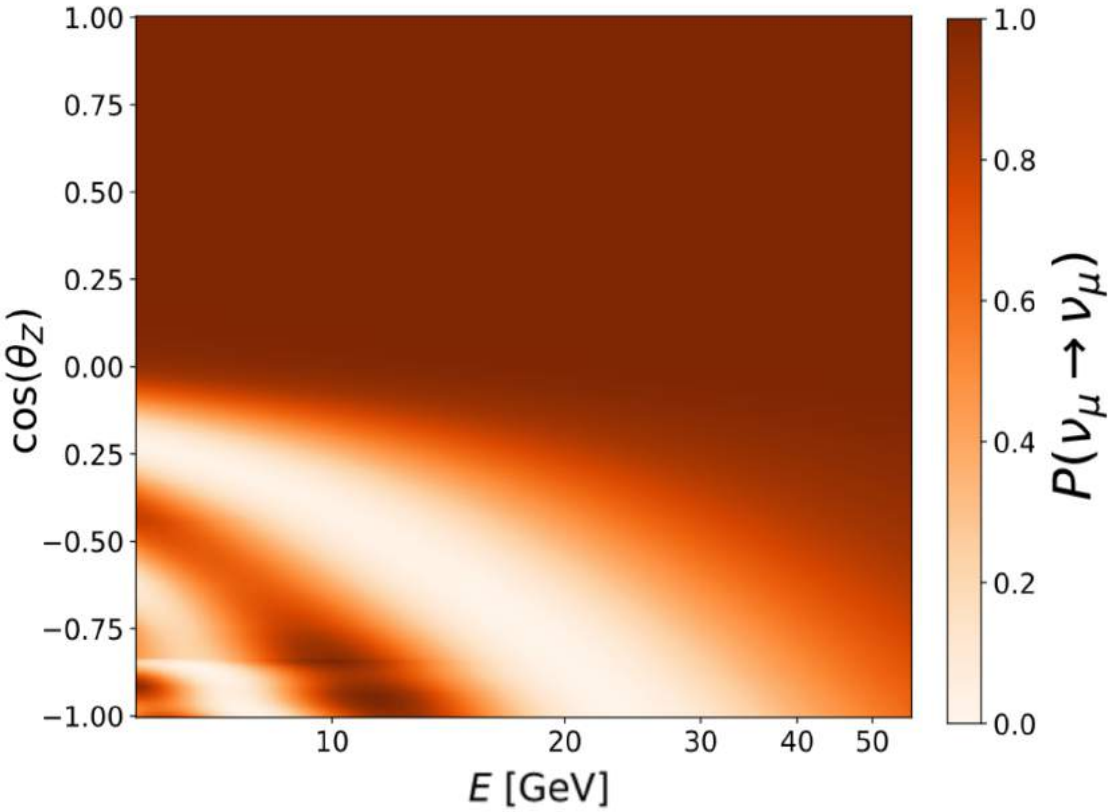


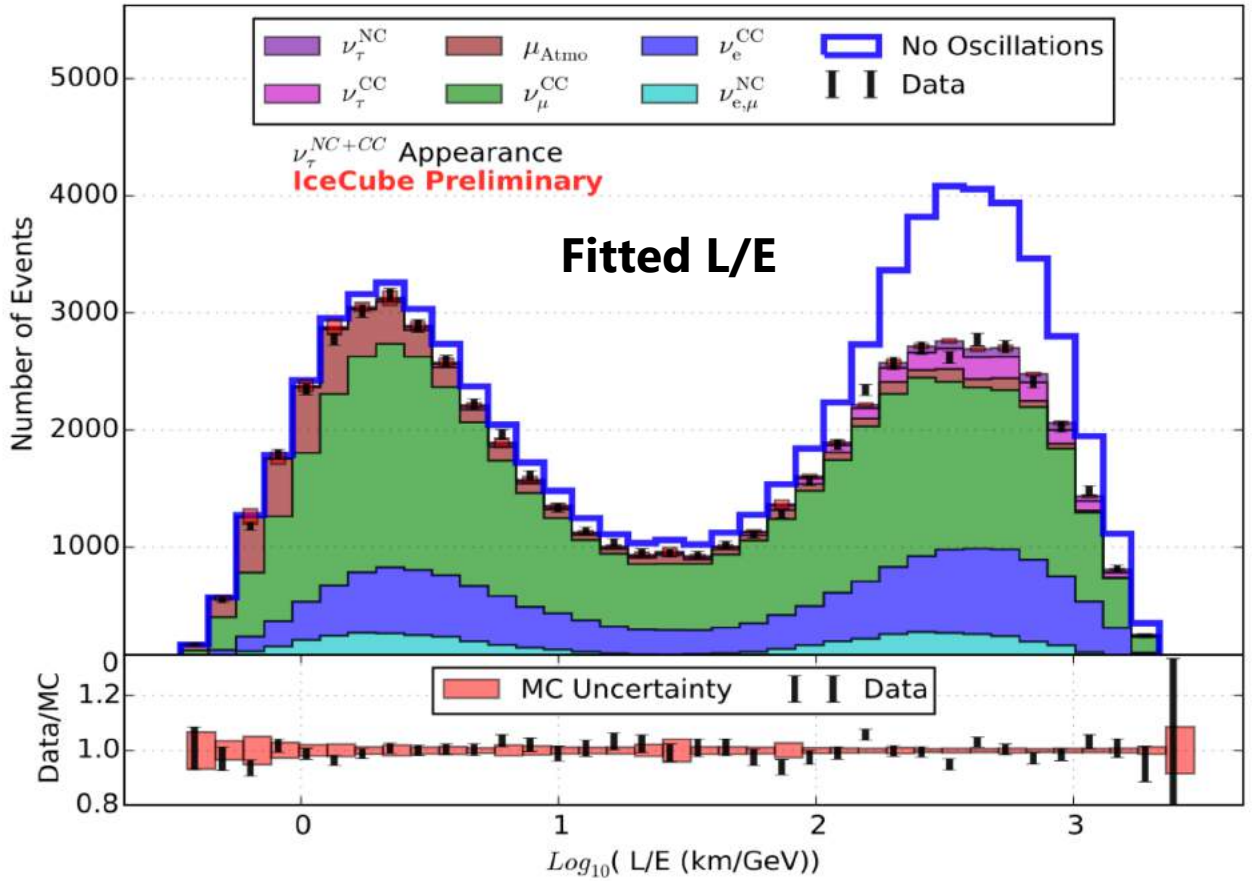




ν_μ disappearance

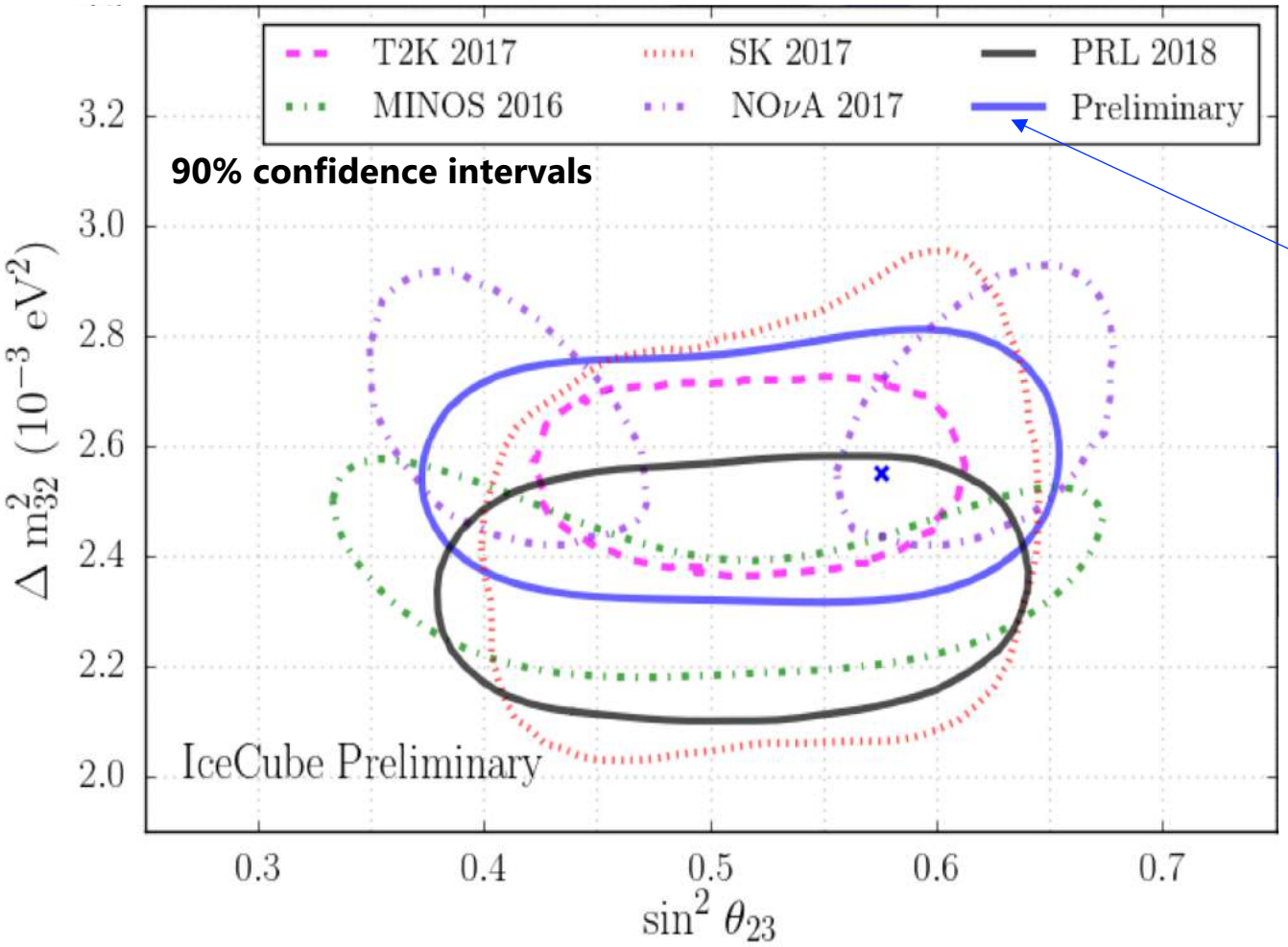
- ν_μ disappearance measured in E_{reco} = [5.6,56] GeV energy range
  - θ_{23} and Δm^2_{32} measured
  - PMNS unitarity assumed, insensitive to other mixing parameters





ν_μ disappearance results

- 2018 PRL published (3 years), arXiv:1707.07081
- New: 2018 high statistics sample (3 years) *Paper in preparation (combined with ν_τ appearance)*



2018 high stats sample
(samples largely non-overlapping)

Results consistent with T2K
(higher E_ν → complimentary)

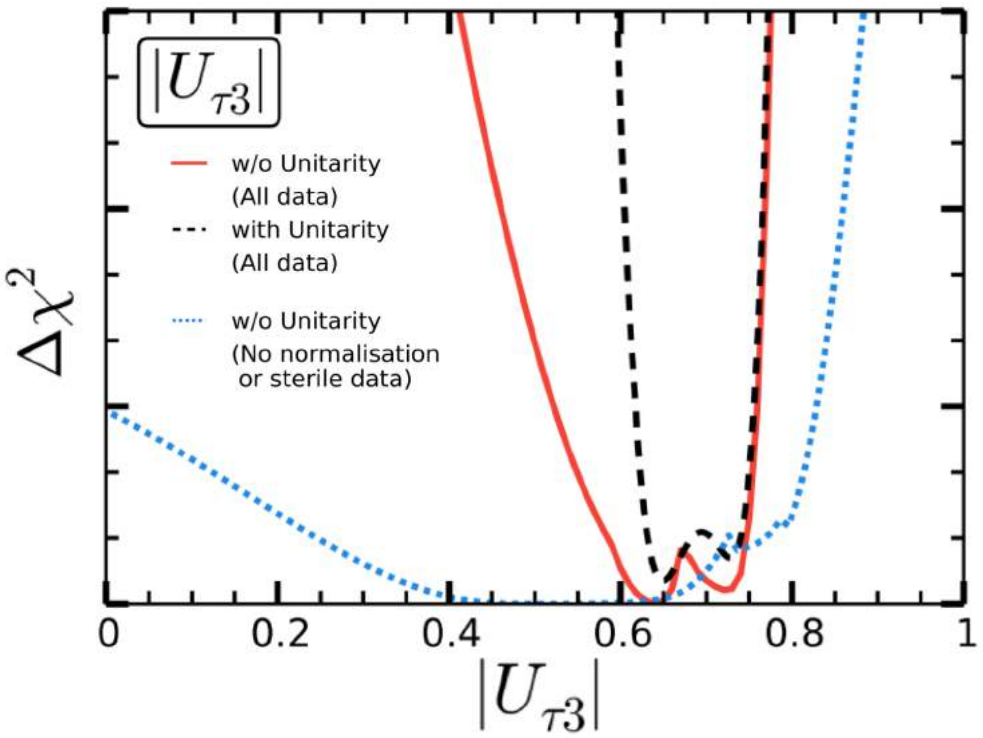
ν_τ appearance (1 of 2)

- Decades of atmospheric and long baseline accelerator experiments have observed ν_μ disappearance

- Standard 3 flavour picture: dominated by $\nu_\mu \rightarrow \nu_\tau$
- Want to detect these ν_τ to confirm
  - Tests unitarity of PMNS mixing matrix
  - Directly measure $U_{\tau i}$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \vdots \end{pmatrix} = \overbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & \\ \vdots & & & \ddots \end{pmatrix}}^{\mathrm{U_{PMNS}}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \vdots \end{pmatrix}$$

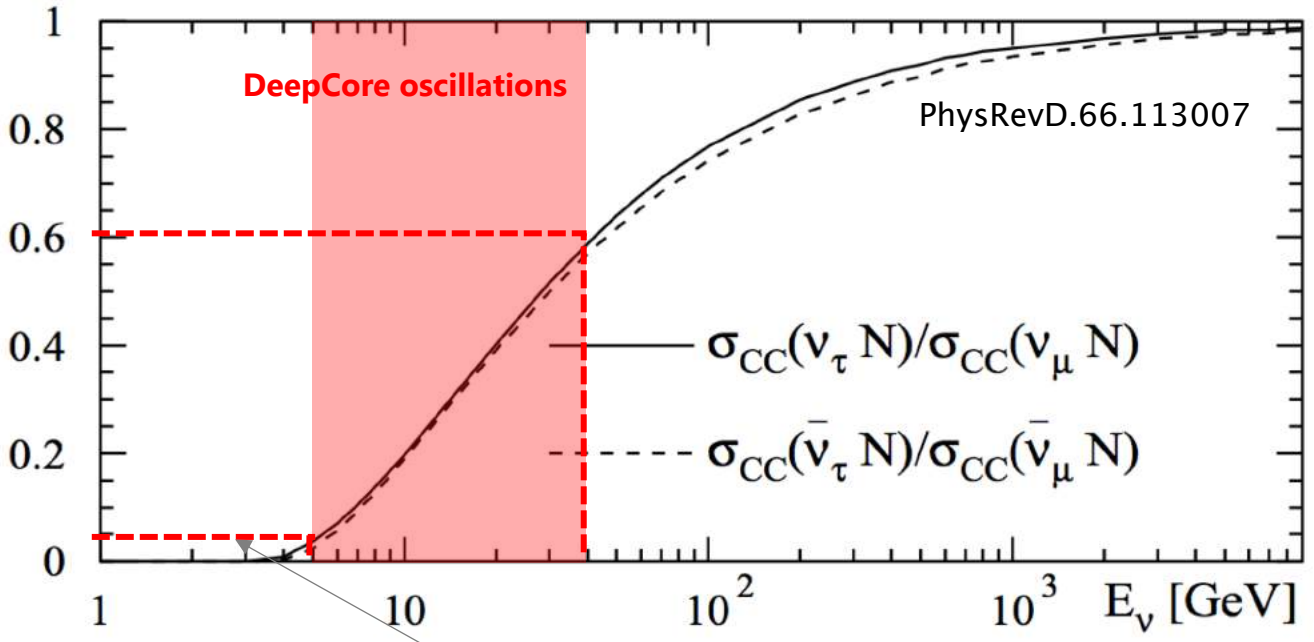
Parke, Ross-Lonergan, arXiv:1508.05095



ν_τ appearance (2 of 2)

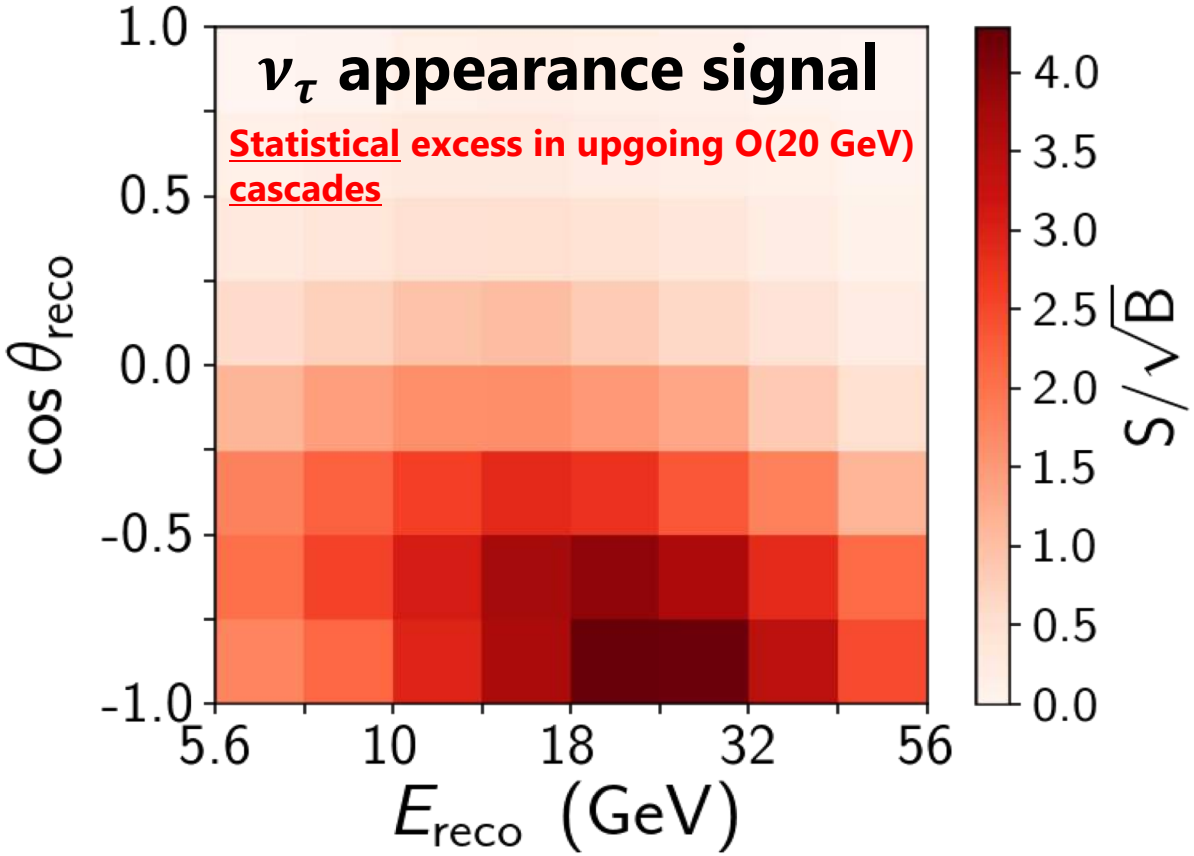
- However, difficult to detect:
  - Large τ mass → **suppressed CC cross section** for E_ν < 1 TeV
  - DeepCore: ν_τ are **cascade** events, cannot be distinguished from ν_e, ν_{NC}

ν_τ cross-section, σ



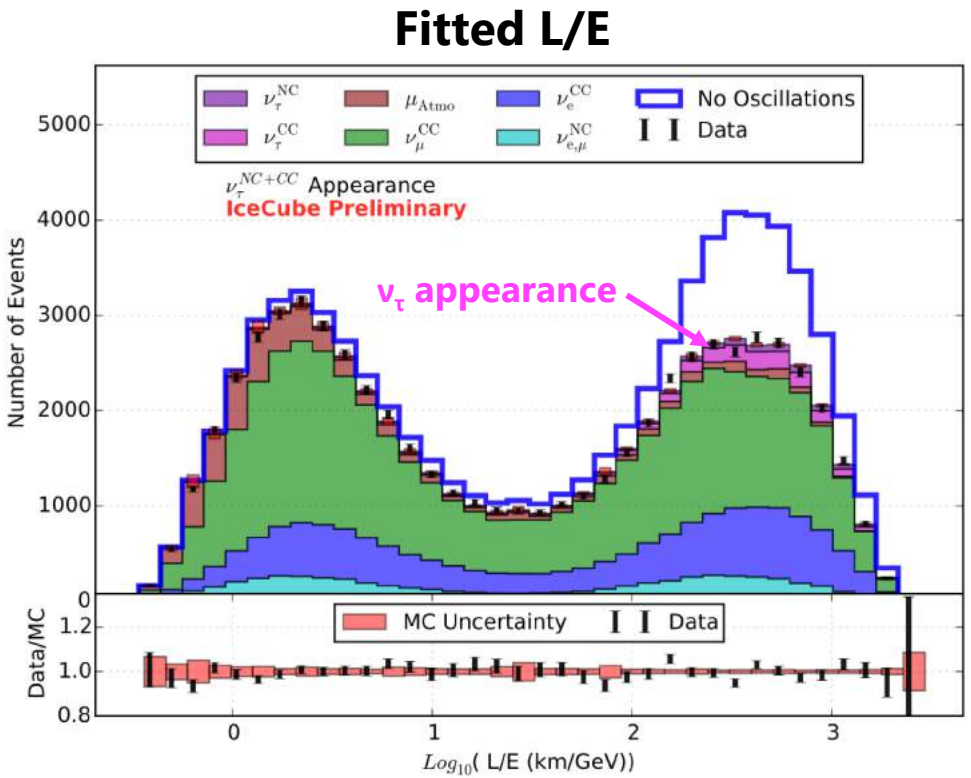
$\sigma_{\tau,CC}$ ~ 0 for most accelerator ν_μ energies (except OPERA)

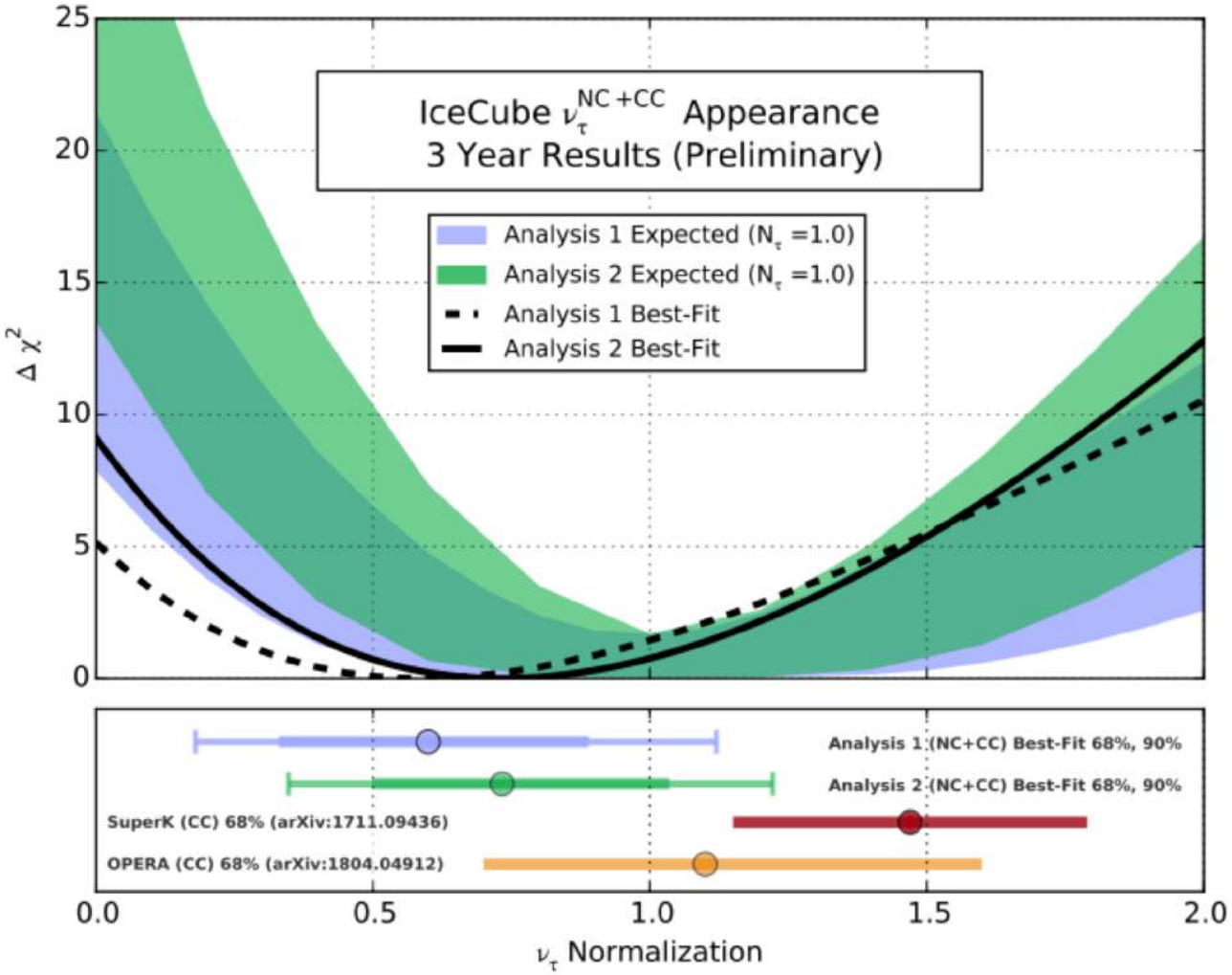
ν_τ appearance signal



ν_τ appearance results

- First DeepCore results in last year (3 years of data)
  - Two analyses, comparable sensitivity and results *Joint paper in preparation*
- 6 year analysis underway





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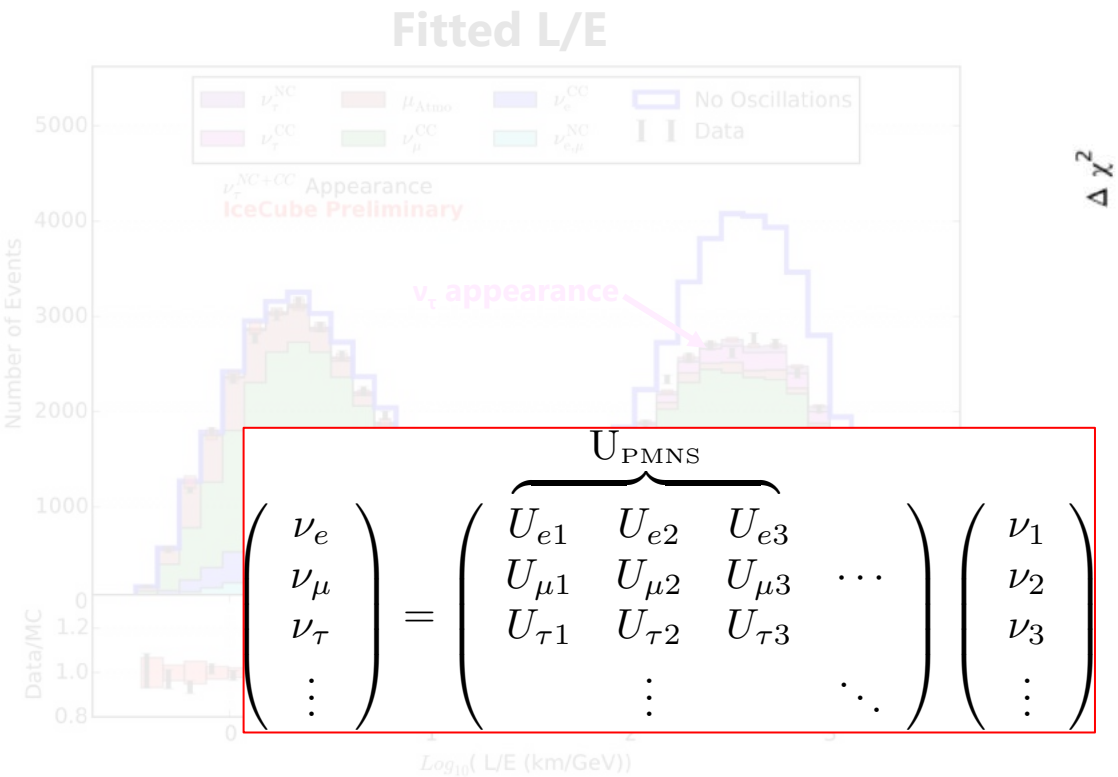

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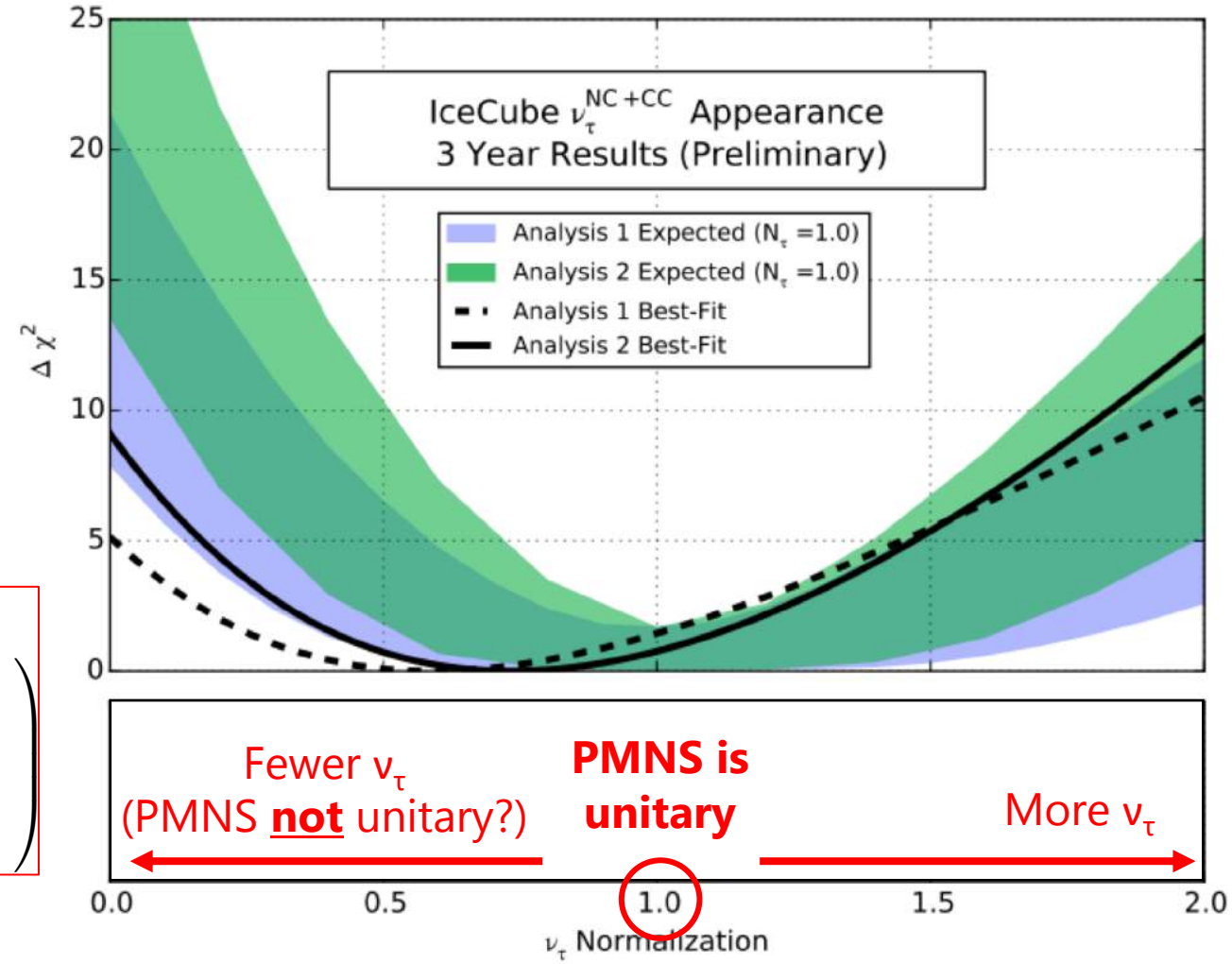

ν_τ appearance results

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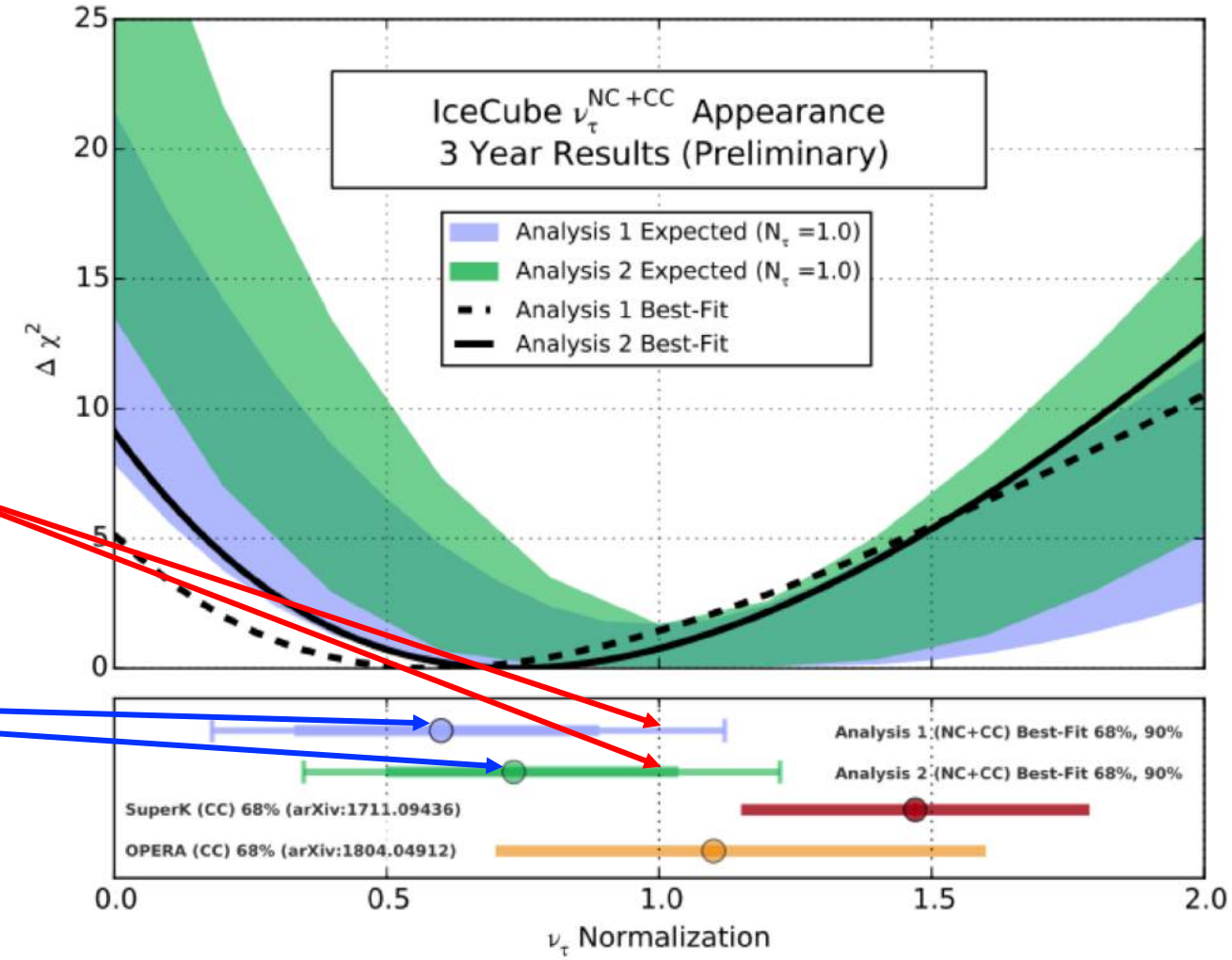
DeepCore results consistent with unitarity within 90% confidence interval

Best fit lower than OPERA, SuperK

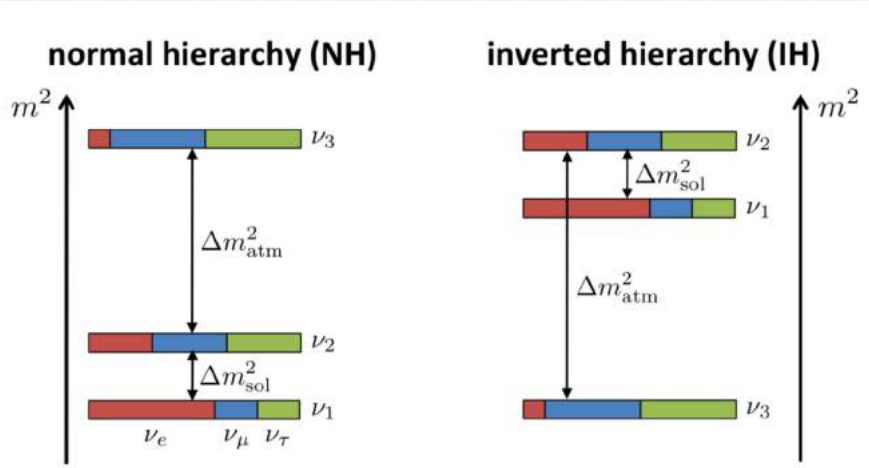


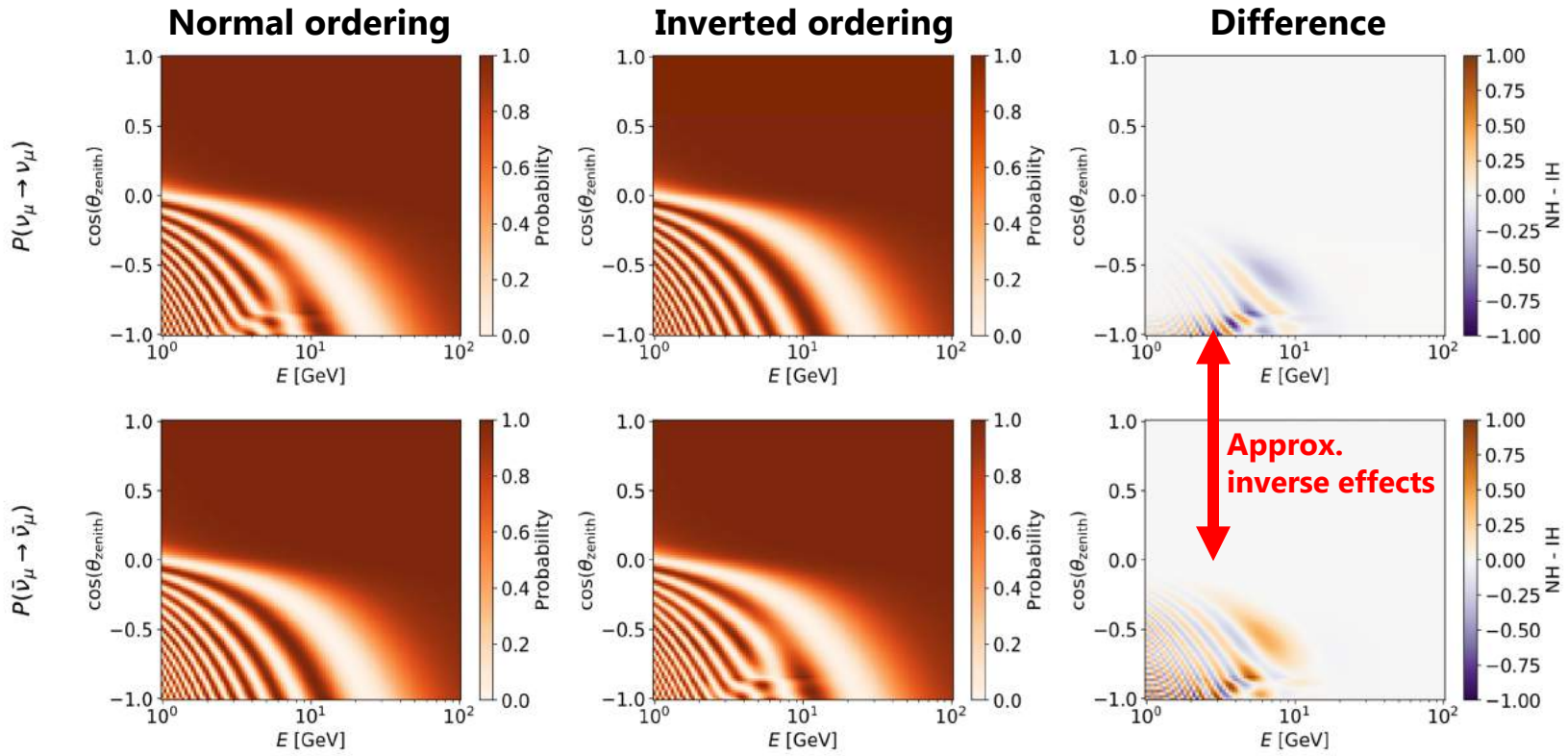
Mass ordering

- Sign of Δm^2_{atm} (mass ordering) unknown

- Atmospheric ν experiments sensitive to mass ordering via matter effects
  - Resonance < 15 GeV
  - NO: $\nu_\mu \leftrightarrow \nu_e$ enhanced
  - IO: $\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$ enhanced

- Cannot discriminate $\nu/\bar{\nu}$ in DeepCore
- Net effect due to higher ν rate

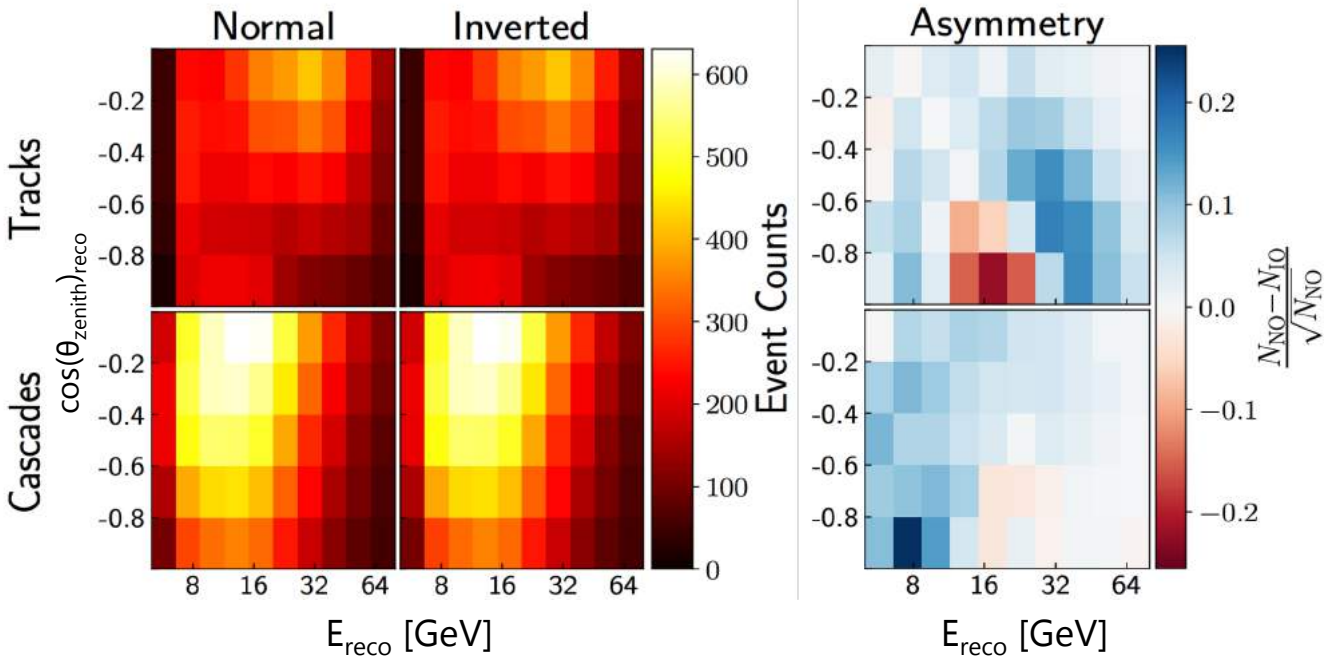




Mass ordering results

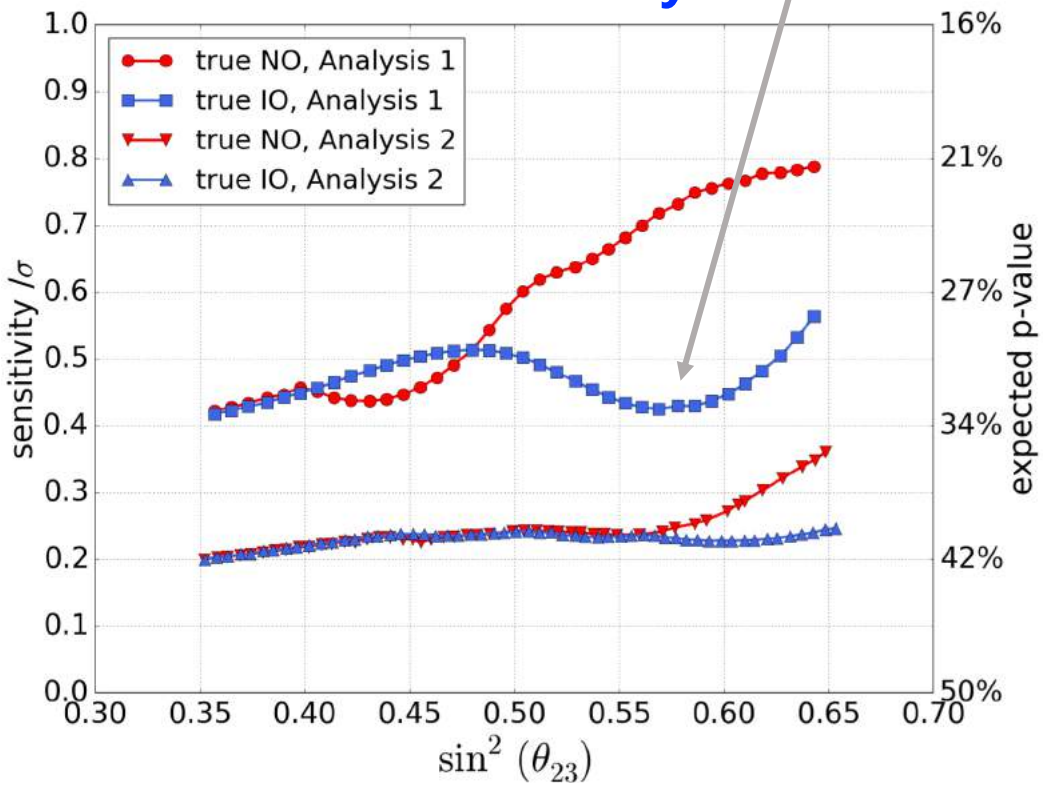
- Two DeepCore analyses (2017) *Joint paper in preparation*
- Signal at/below detector threshold → weak signal → low sensitivity
  - Will improve with IceCube upgrade and PINGU

Signal



Degeneracy with octant

Sensitivity



High energy steriles

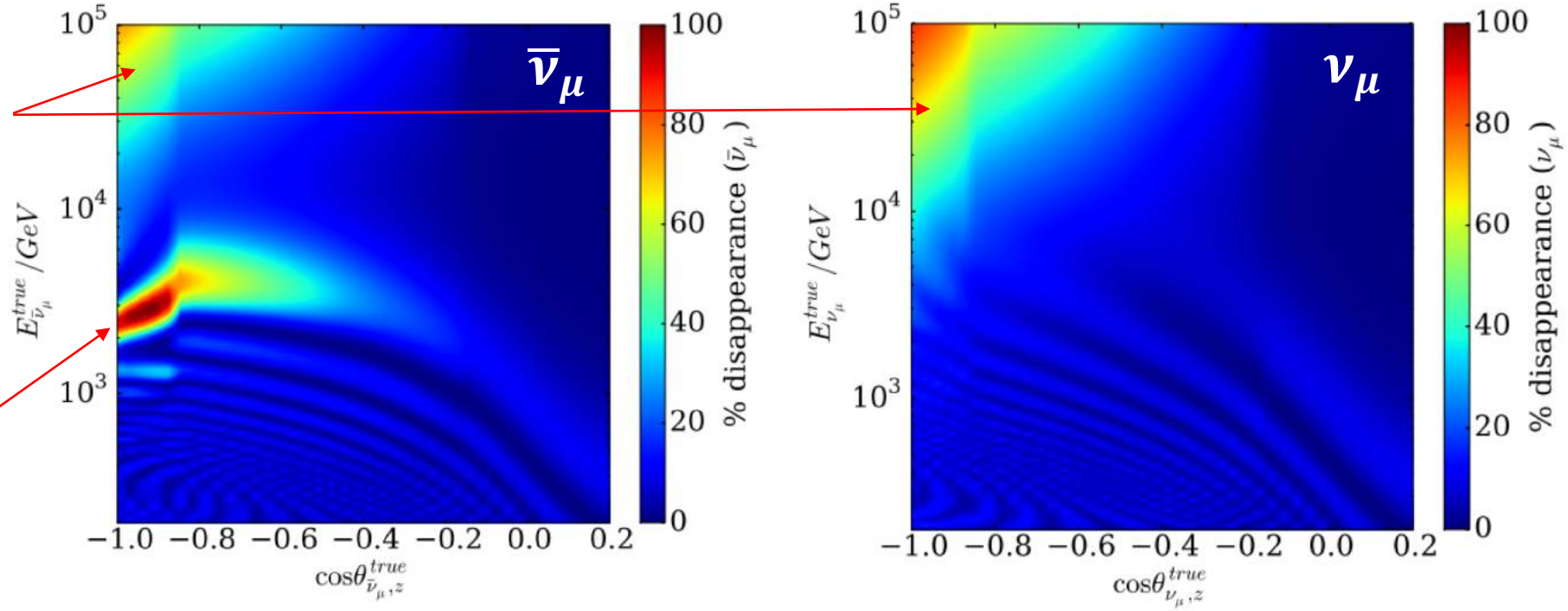
$$\mathbf{U} \equiv \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

- Search for sterile ν signatures via mixing with active states
- Expect matter-induced resonance in ν_μ disappearance in 3+1 scenario
  - $|\Delta m^2_{41}| = O(1eV^2)$ → O(1 TeV), up-going ν_μ
  - ν_μ for $\Delta m^2_{41} < 0$ (lighter), $\bar{\nu}_\mu$ for $\Delta m^2_{41} > 0$ (heavier)

Disappearance, $\Delta m^2_{41} > 0$

Earth absorption

Signal



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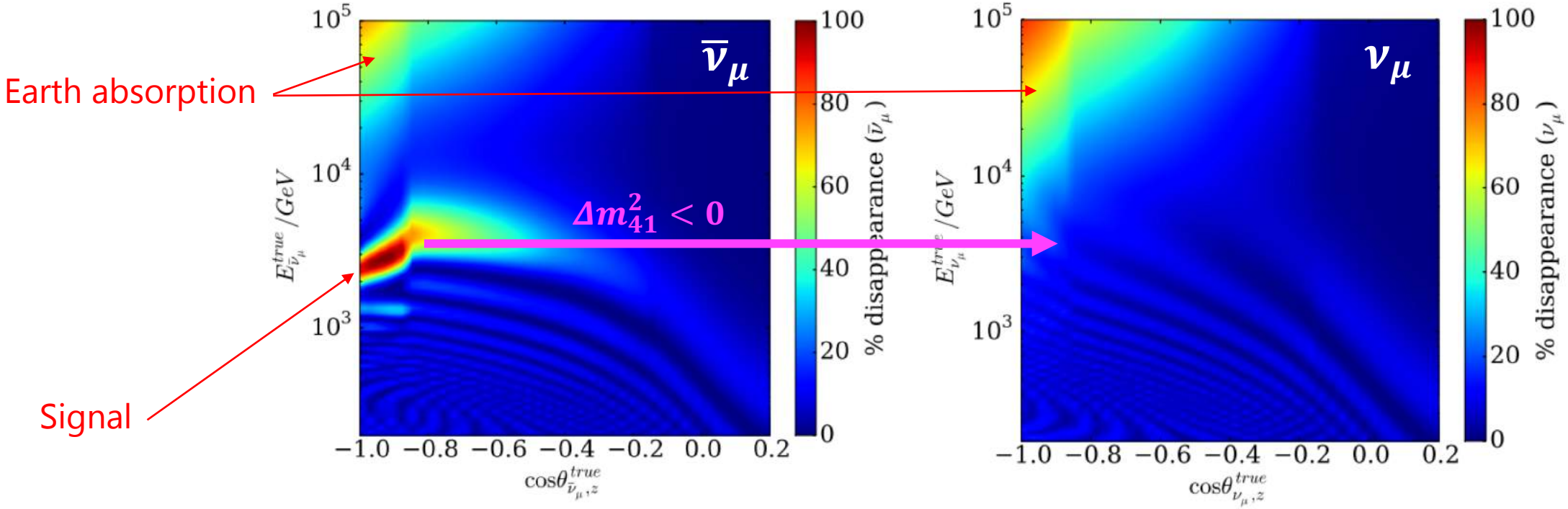
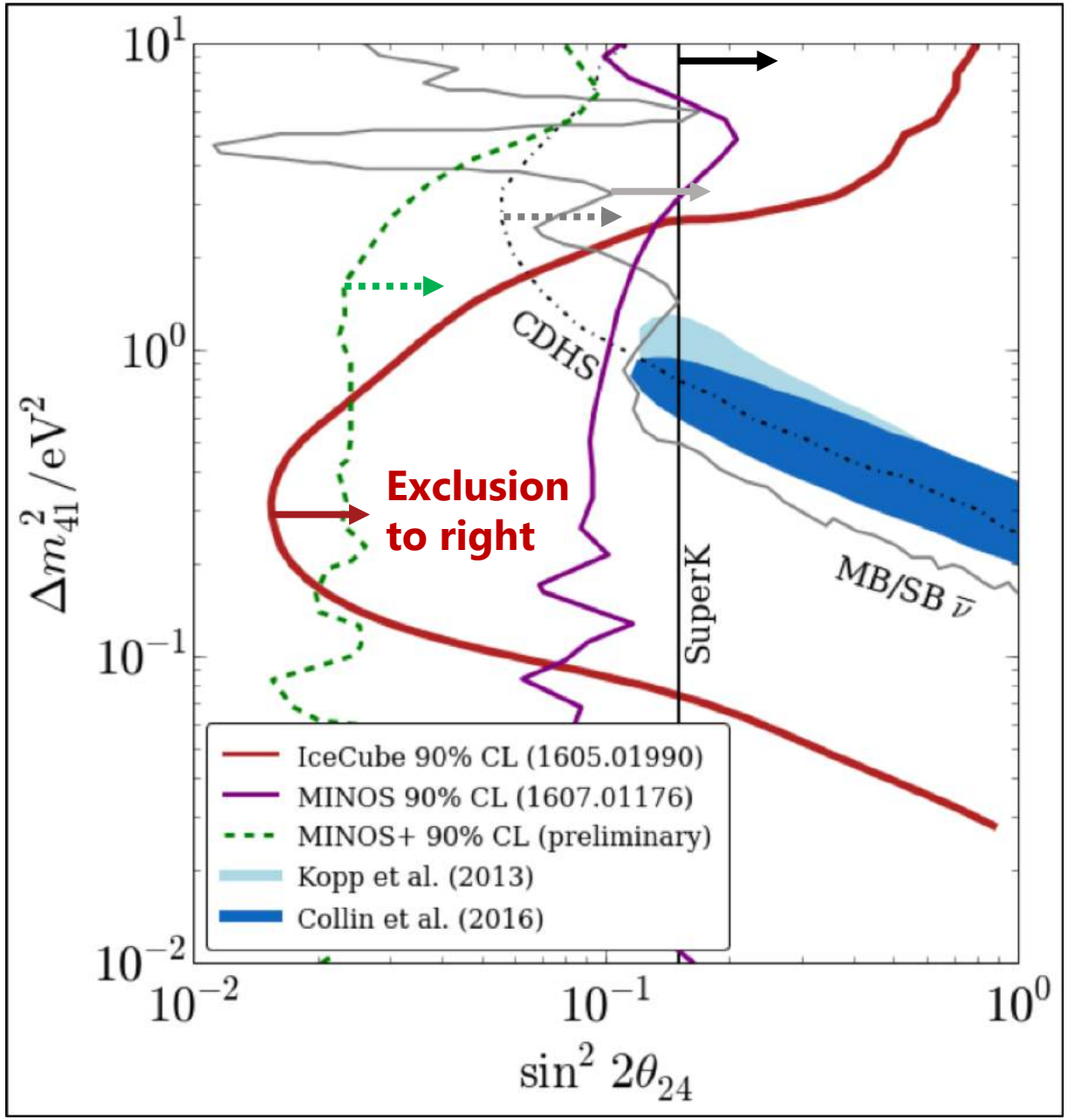


High energy sterile results

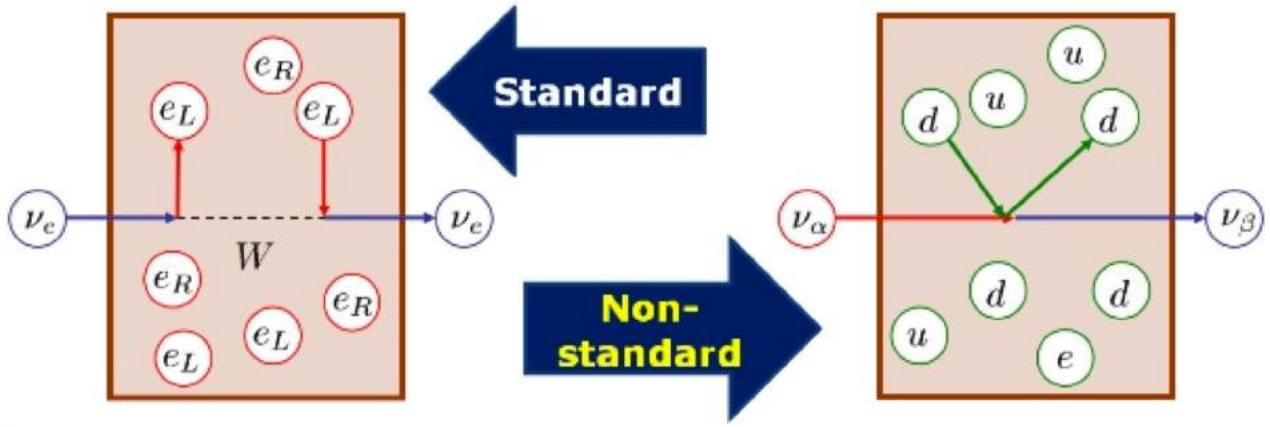
- PRL 2016 (1 year)
  - arXiv:1605.01990
  - $\Delta m^2_{41} > 0$ (conservative)
  - Null result
  - Tension with LSND/MiniBooNE
- Also DeepCore sterile result (2017)
  - arXiv:1702.05160
- New results soon:
  - 7 year
  - $\Delta m^2_{41} < 0$



Other sterile mixing parameters = 0 (conservative)

Non Standard Interactions (NSI)

- Search for coherent forward scattering of neutrinos in matter due to new mediator (e.g. Z')
- Additional effective matter potential (coupling to u/d quarks)



$$\hat{H} = U\,\mathrm{diag}\left(\frac{m_1^2}{2E}, \frac{m_2^2}{2E}, \frac{m_3^2}{2E}\right) U^\dagger + V_e(r)\left(\mathrm{diag}(1,0,0) + \sum_f \frac{N_f}{N_e}\begin{pmatrix} \epsilon_{ee}^f & \epsilon_{e\mu}^f & \epsilon_{e\tau}^f \\ \epsilon_{e\mu}^{f*} & \epsilon_{\mu\mu}^f & \epsilon_{\mu\tau}^f \\ \epsilon_{e\tau}^{f*} & \epsilon_{\mu\tau}^{f*} & \epsilon_{\tau\tau}^f \end{pmatrix}\right)$$

Flavor conserving

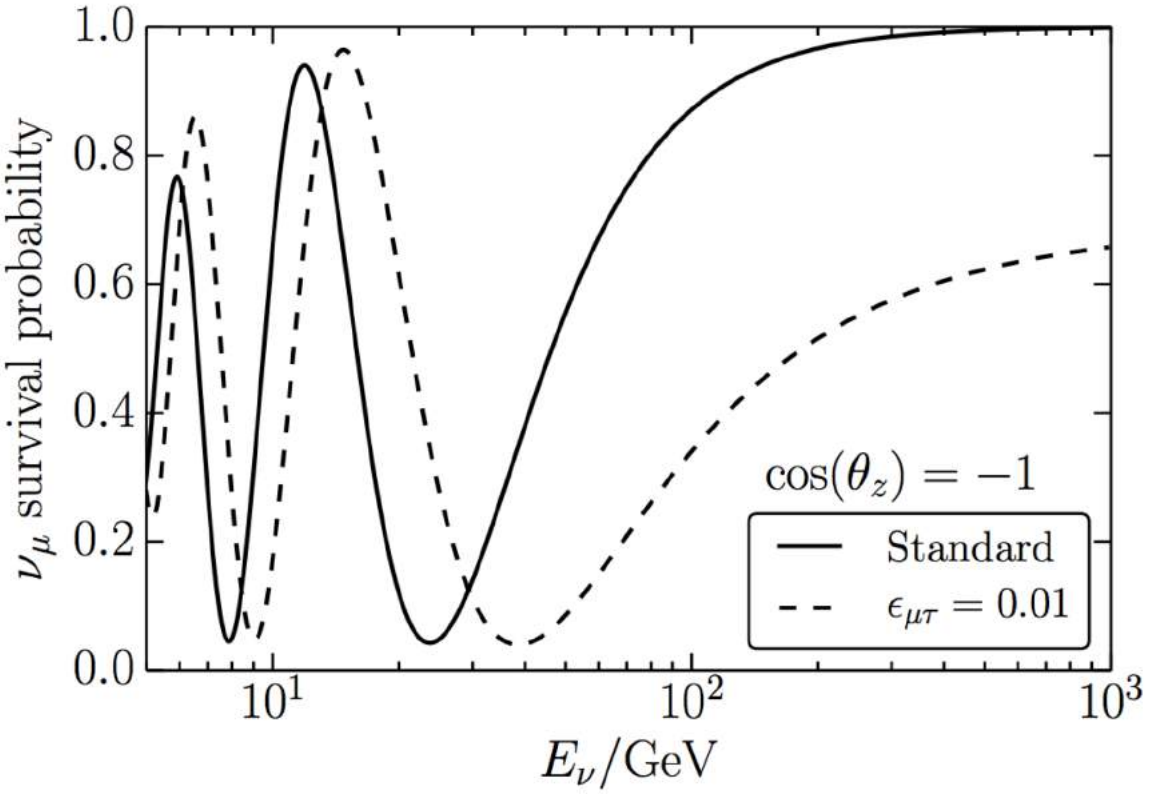
Flavor changing

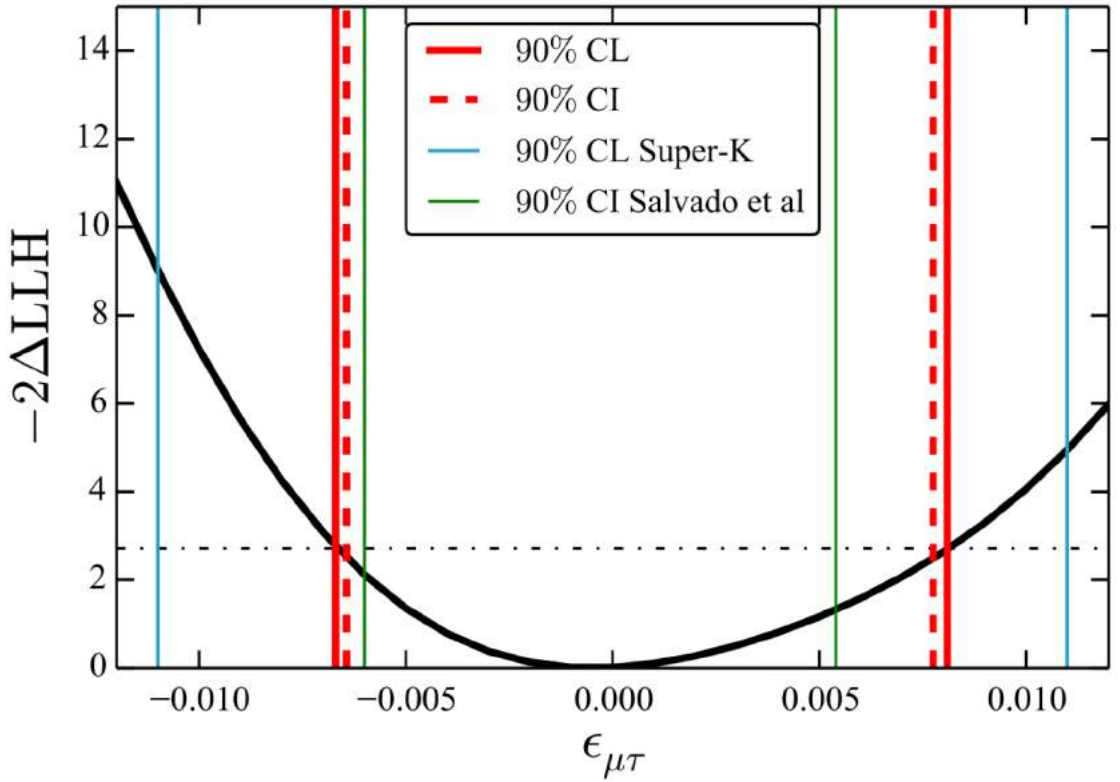
Generalised NSI potential

NSI results

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

- PRL 2017, arXiv:1709.07079 (DeepCore, 3 years)
  - $\epsilon_{\mu\tau}$ measured (modifies ν_μ disappearance), null result





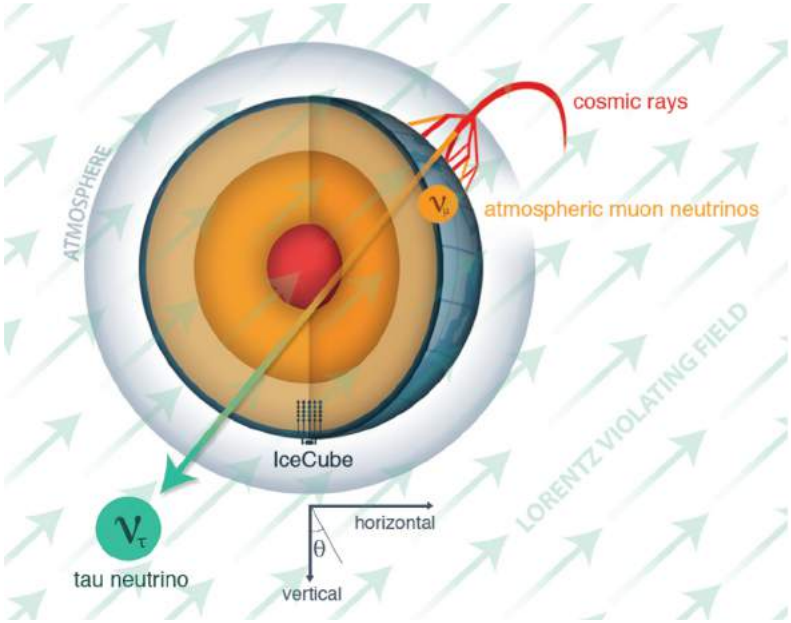
- New DeepCore analysis underway
  - Higher stats, more $\epsilon_{\alpha\beta}$, 1D and 2D

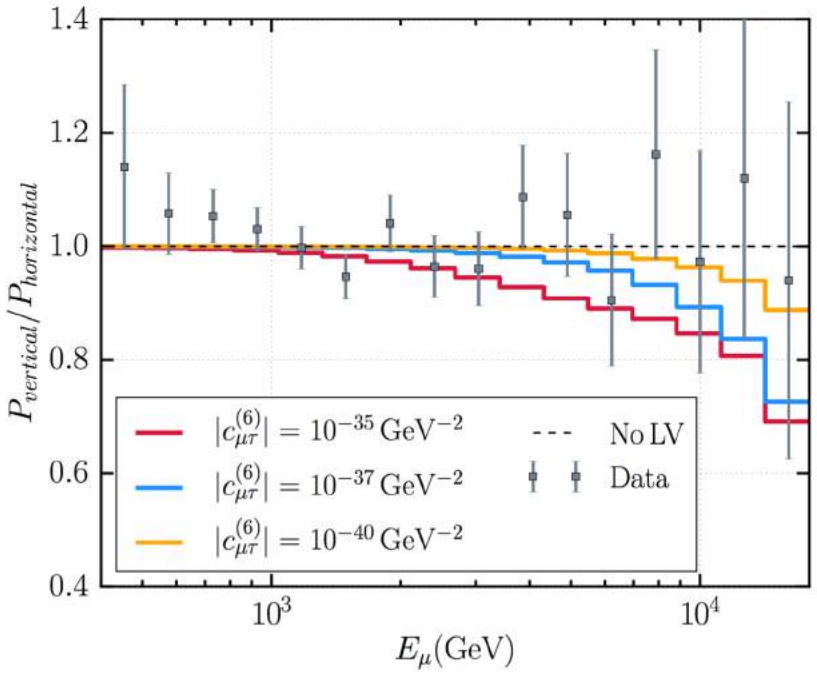
See poster by T. Ehrhardt

Lorentz Violation (LV)

See talk on Friday by C. Argüelles

- Lorentz symmetry underpins the SM
- SM Extension (SME) includes LV terms → modified neutrino oscillations
- 2017 IceCube search for modified in ν_μ disappearance due to isotropic LV field
  - Null result, strong constraints on SME operators



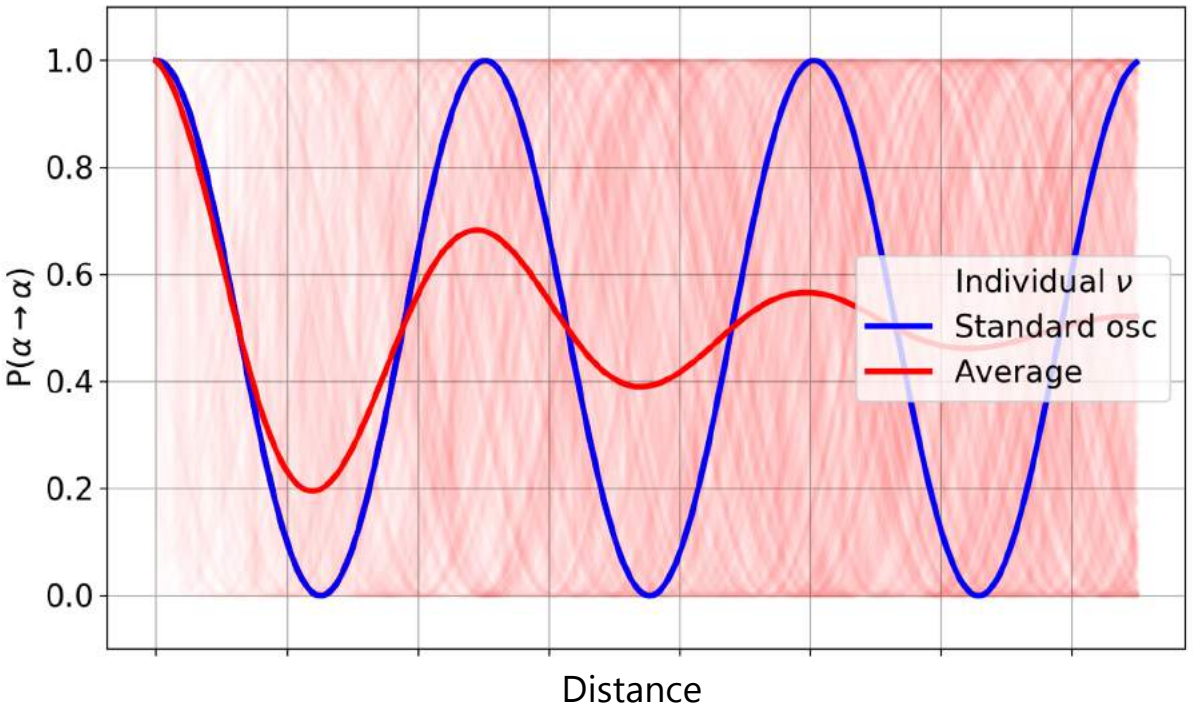


Poster

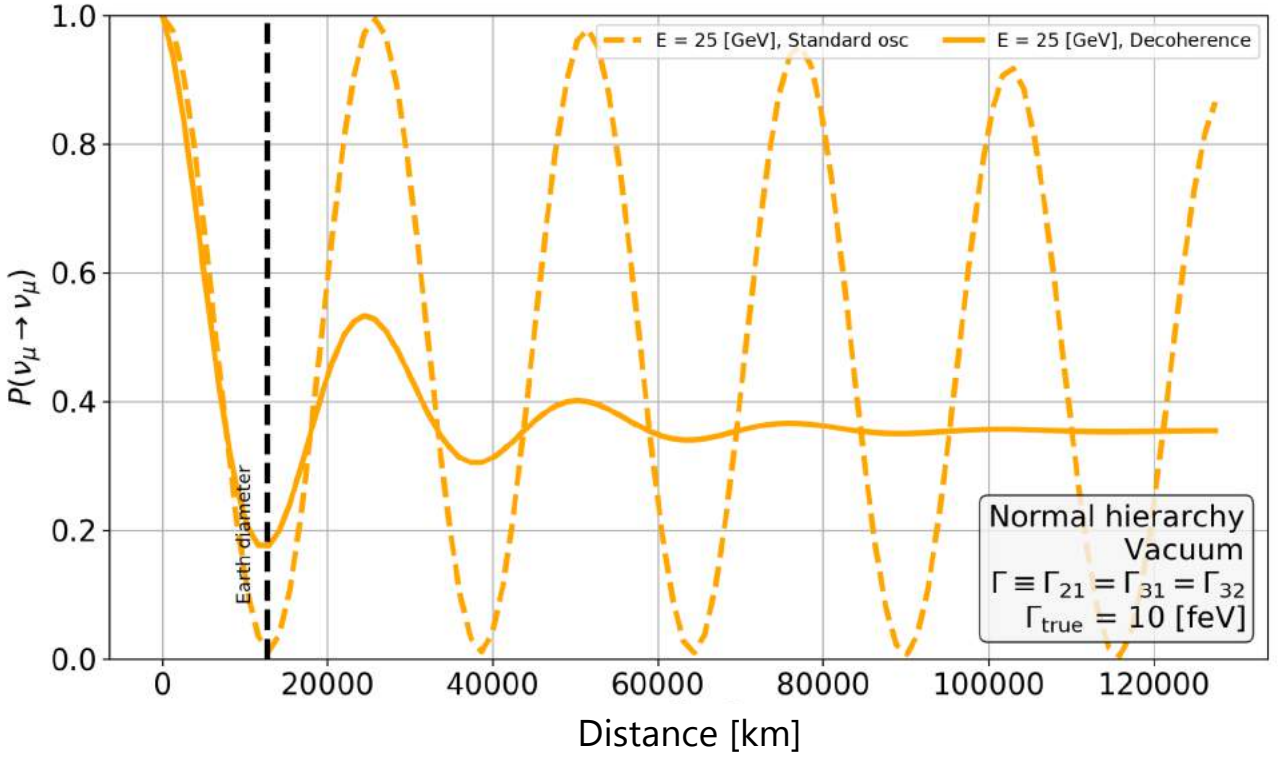
Neutrino decoherence

- Weak coupling between neutrino and environment → decoherence
  - Prediction of e.g. "foamy" quantum gravity
- Damping of oscillation probability over distance/time

Toy model, 2 flavor



Atmospheric ν



Decoherence phenomenology

Lisi et al, arXiv:hep-ph/0002053
Farzan et al, arXiv:0805.2098

- Open quantum system
- Decoherence → mixed quantum states: use density matrices: $\rho = \sum_i p_i \left|\psi_i\right\rangle \left\langle\psi_i\right|$
- Introduce general decoherence operator (Lindblad form): $\mathcal{D}[\rho]$

$$\dot{\rho} = \underbrace{-i[H,\rho]}_{\text{Standard oscillations}} \underbrace{- \mathcal{D}[\rho]}_{\text{Decoherence}}$$

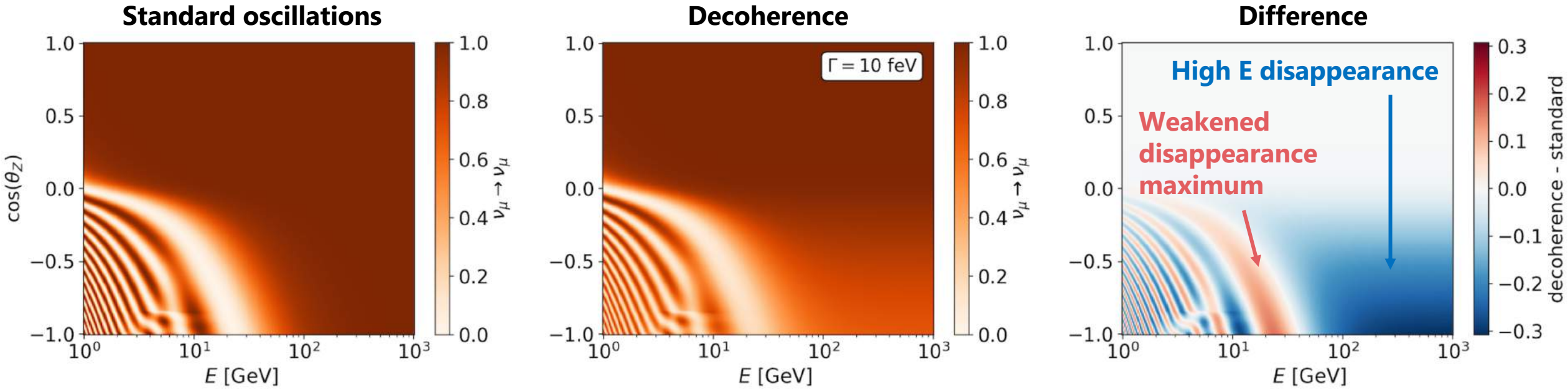
- Microphysics-independent, minimal assumptions (physicality)
- 3 effective damping parameters, Γ_{ij}
  - Could be energy-dependent

$$\mathcal{D}[\rho] = \begin{pmatrix} 0 & \rho_{12}\Gamma_{21} & \rho_{13}\Gamma_{31} \\ \rho_{21}\Gamma_{21} & 0 & \rho_{23}\Gamma_{32} \\ \rho_{31}\Gamma_{31} & \rho_{32}\Gamma_{32} & 0 \end{pmatrix}$$

Decoherence signal in IceCube

- Dominant signal is modified ν_μ disappearance
- Varies with zenith angle (and energy)

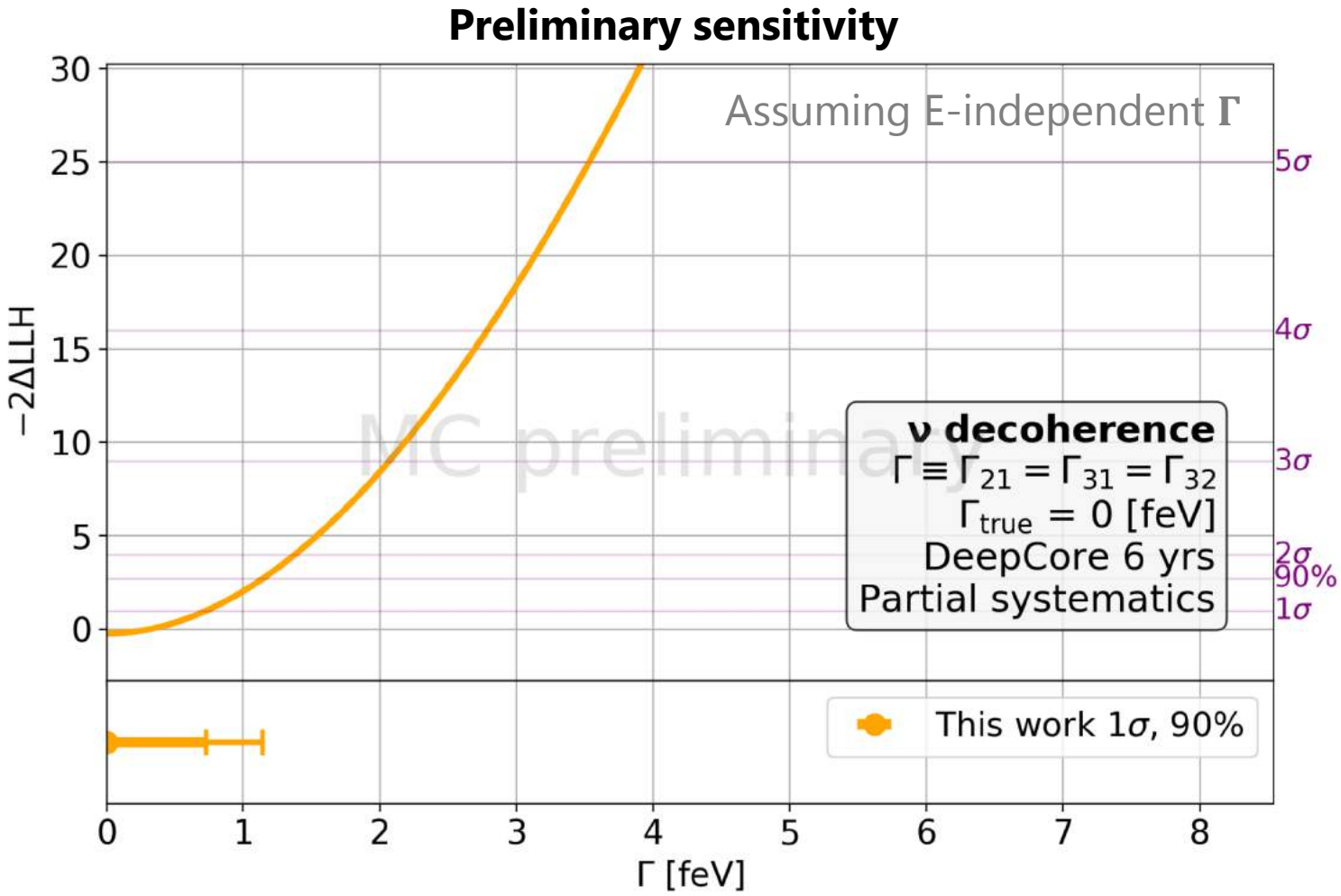
ν_μ disappearance



Neutrino decoherence in IceCube

- DeepCore/IceCube analyses underway (6 years)

$$\mathcal{D}[\rho] = \begin{pmatrix} 0 & \rho_{12}\Gamma & \rho_{13}\Gamma \\ \rho_{21}\Gamma & 0 & \rho_{23}\Gamma \\ \rho_{31}\Gamma & \rho_{32}\Gamma & 0 \end{pmatrix}$$



Poster

The future

- Next-generation oscillation analyses underway now
  - **Double** or more **statistics** (6/7 years)
  - More sophisticated event selections, reconstructions, systematics treatment
  - Expanding BSM scope

- In the pipeline:
  - 3 year NSI (expanded parameter space, high stats sample)
  - 7 year high energy sterile search
  - 6 year ν_μ disappearance
  - 6 year ν_τ appearance
  - 6 year decoherence, + more…

See talk by J. Hignight

- Oscillations measurements will hugely benefit from the **IceCube upgrade**
  - Lower energy threshold, improved stats, reconstruction, calibration, …

Summary

- IceCube/DeepCore has established itself as potent detector for oscillation measurements

- Standard oscillation picture tested at O(10 GeV), consistent with SM
  - World-leading ν_τ appearance measurement

- Rich potential for BSM oscillation searches
  - Only just starting to be realised

- Other atmospheric physics measurements not covered here
  - Cross section, inelasticity, flux

- Expect much more in the next few years…