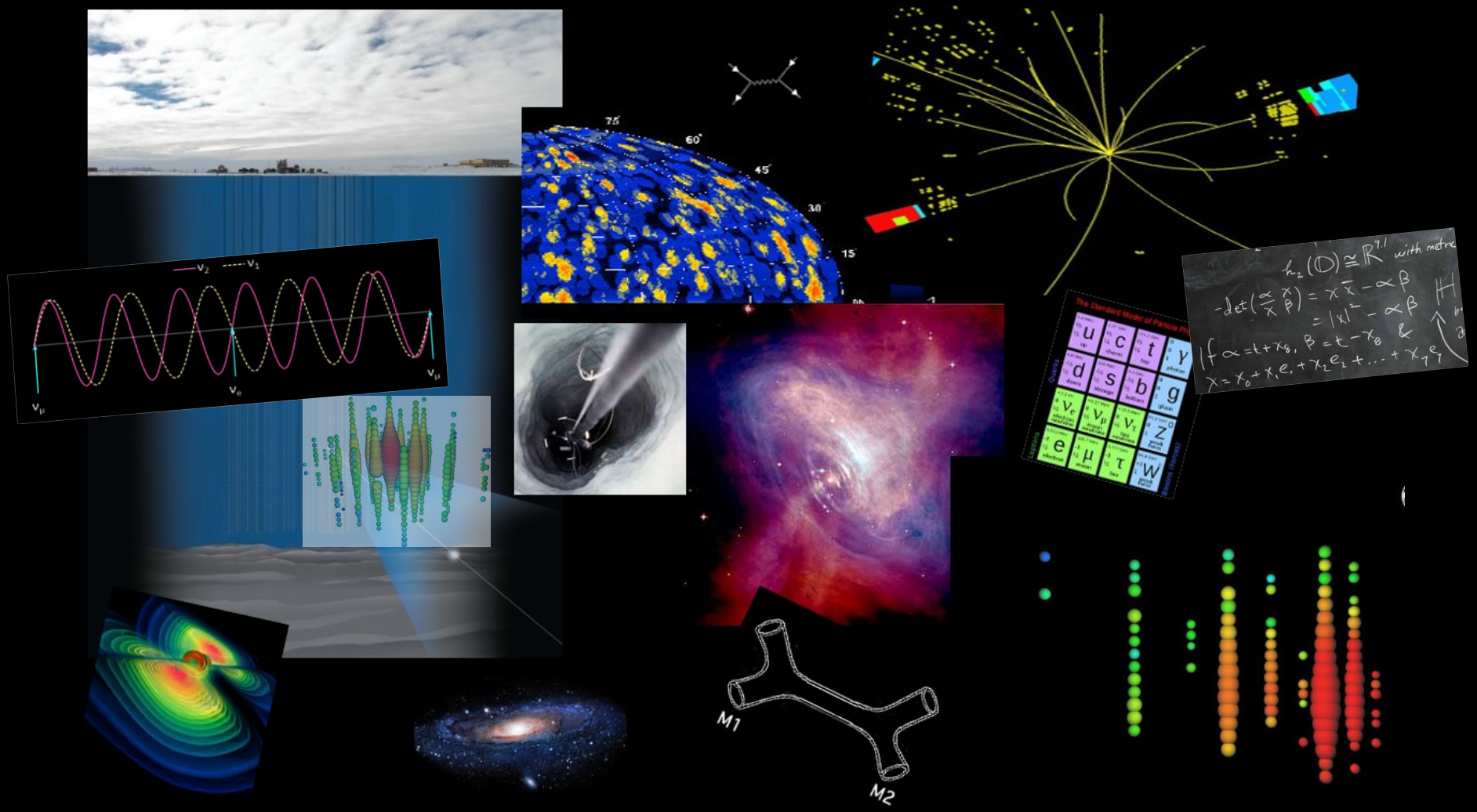
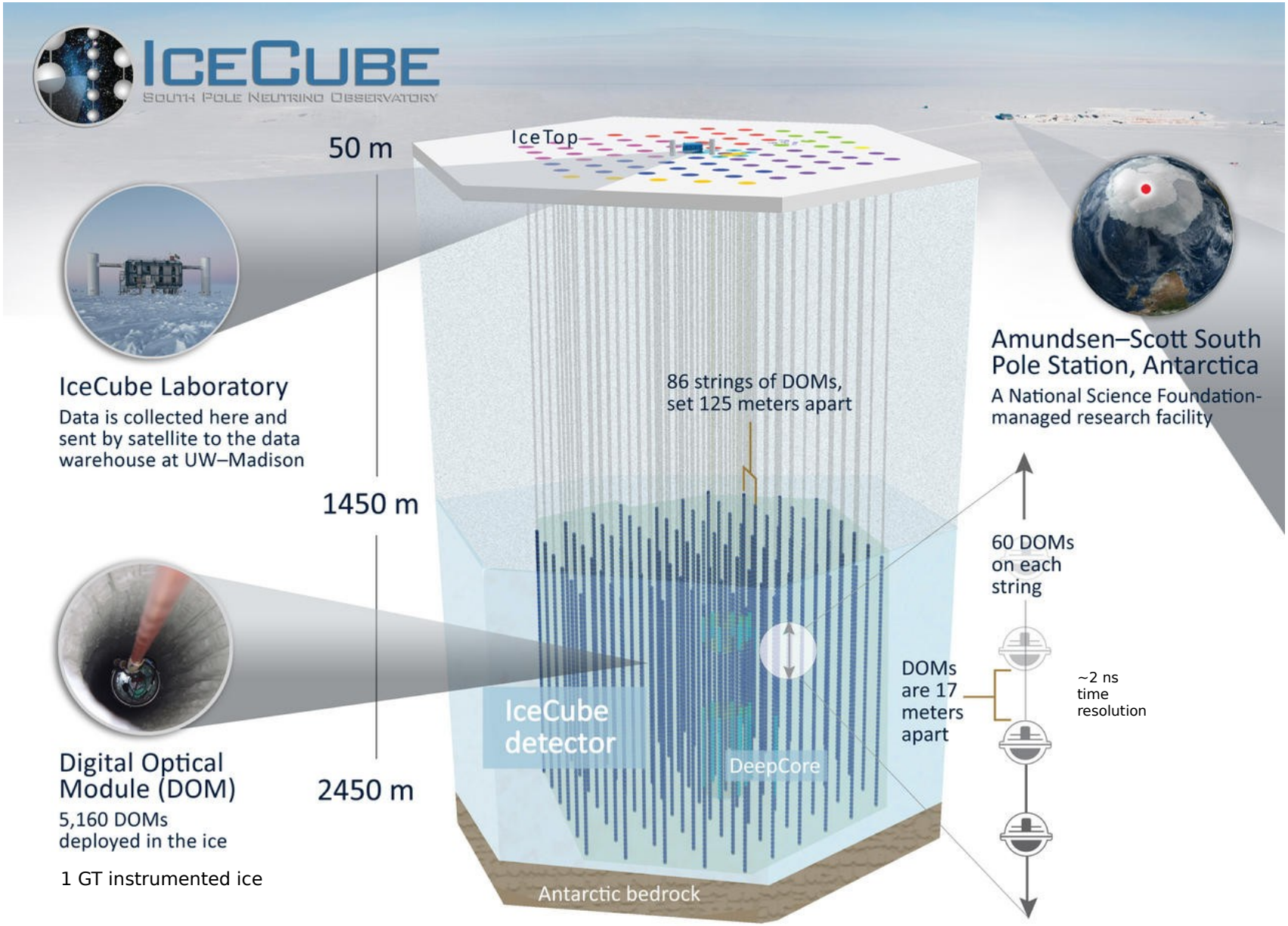
selected topics of BSM physics with IceCube



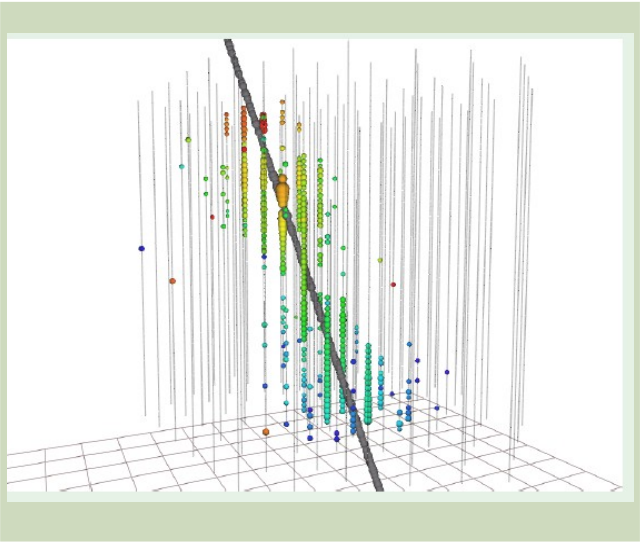
Carlos de los Heros, Uppsala University

NEUTEL 2023, Venice

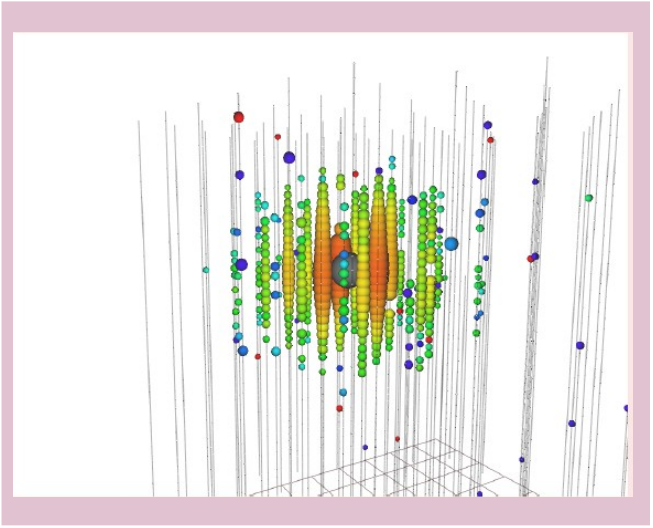

IceCube
South Pole Neutrino Observatory
50 m
IceTop
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
86 strings of DOMs, set 125 meters apart
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
1450 m
60 DOMs on each string
DOMs are 17 meters apart
~2 ns time resolution
IceCube detector
DeepCore
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
2450 m
Antarctic bedrock
1 GT instrumented ice

event signatures

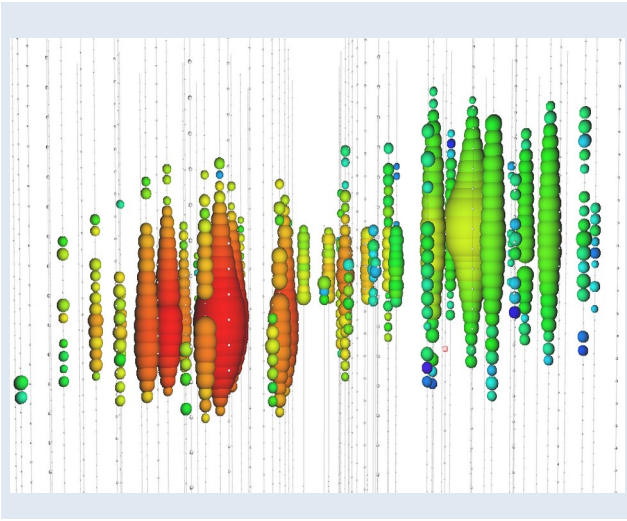
track



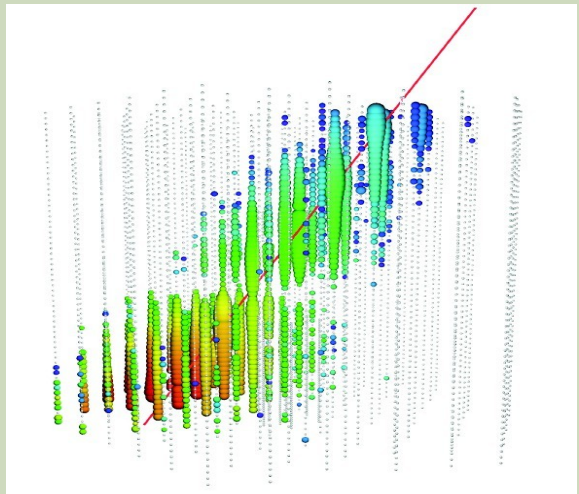
cascade



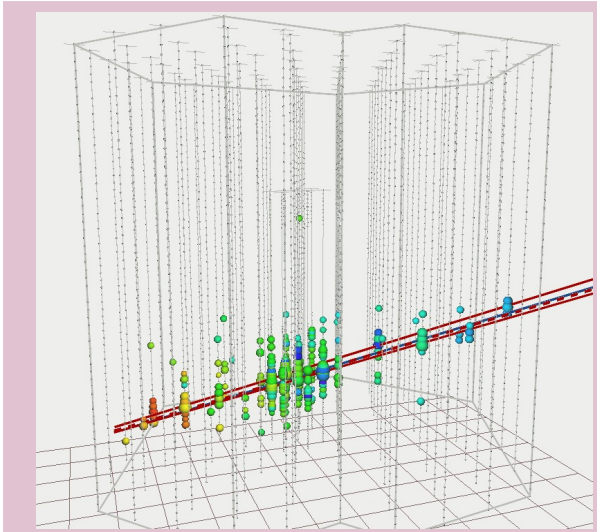
double-bang



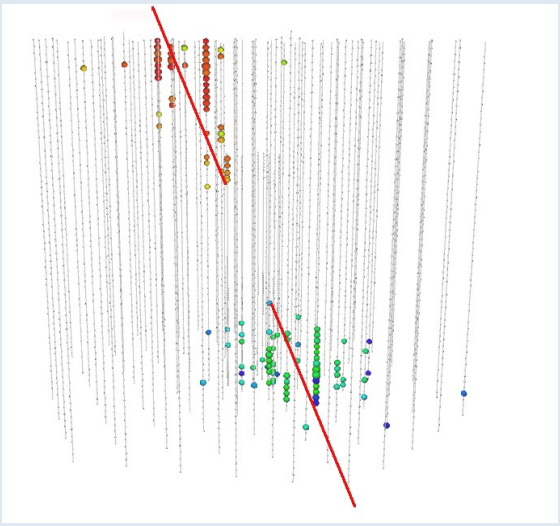
monopole



double track



neutral lepton



Our *"beams"* are

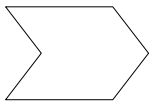
- atmospheric muons (~10^{11}/y)

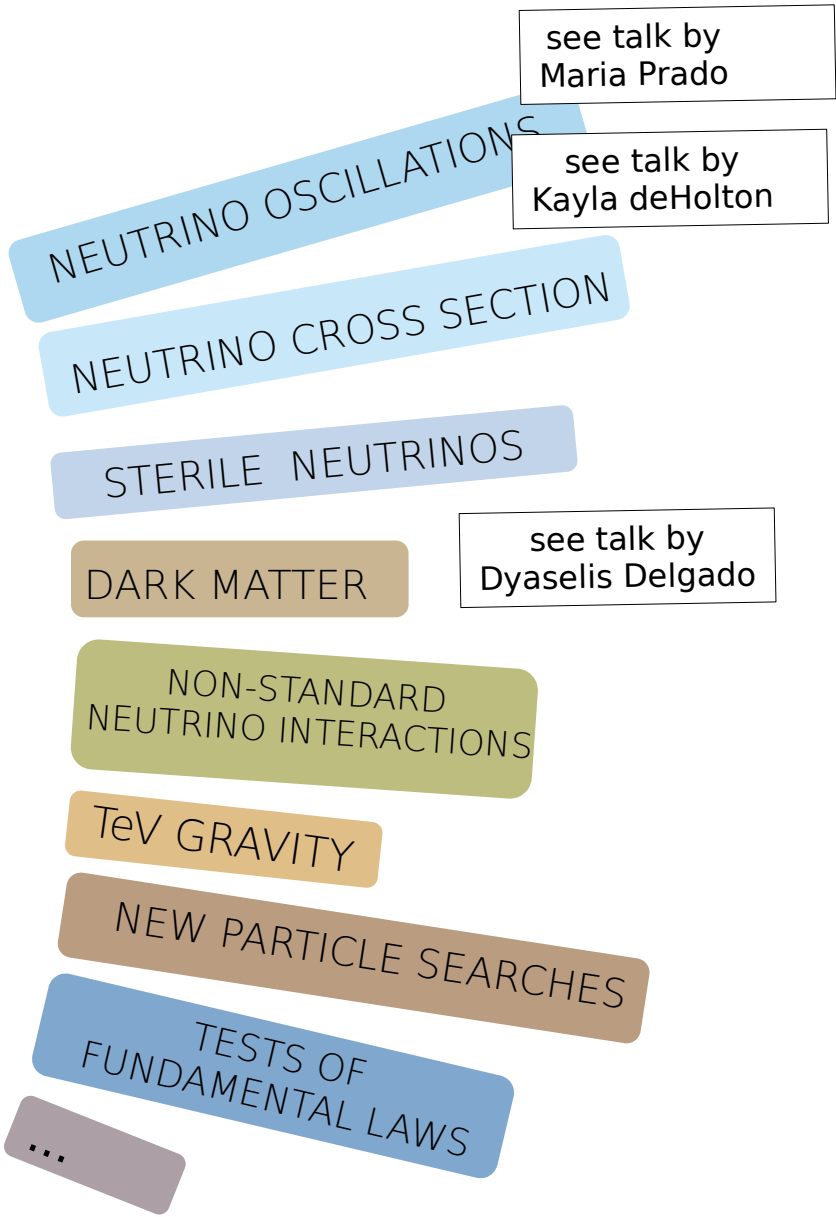
- atmospheric neutrinos (~10^{5} /y)

- astrophysical neutrinos (~10^{2}/y)

- exotica (of cosmic origin or from CR interactions in the atmosphere)

and we have > 10yr of data





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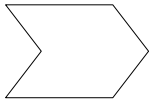
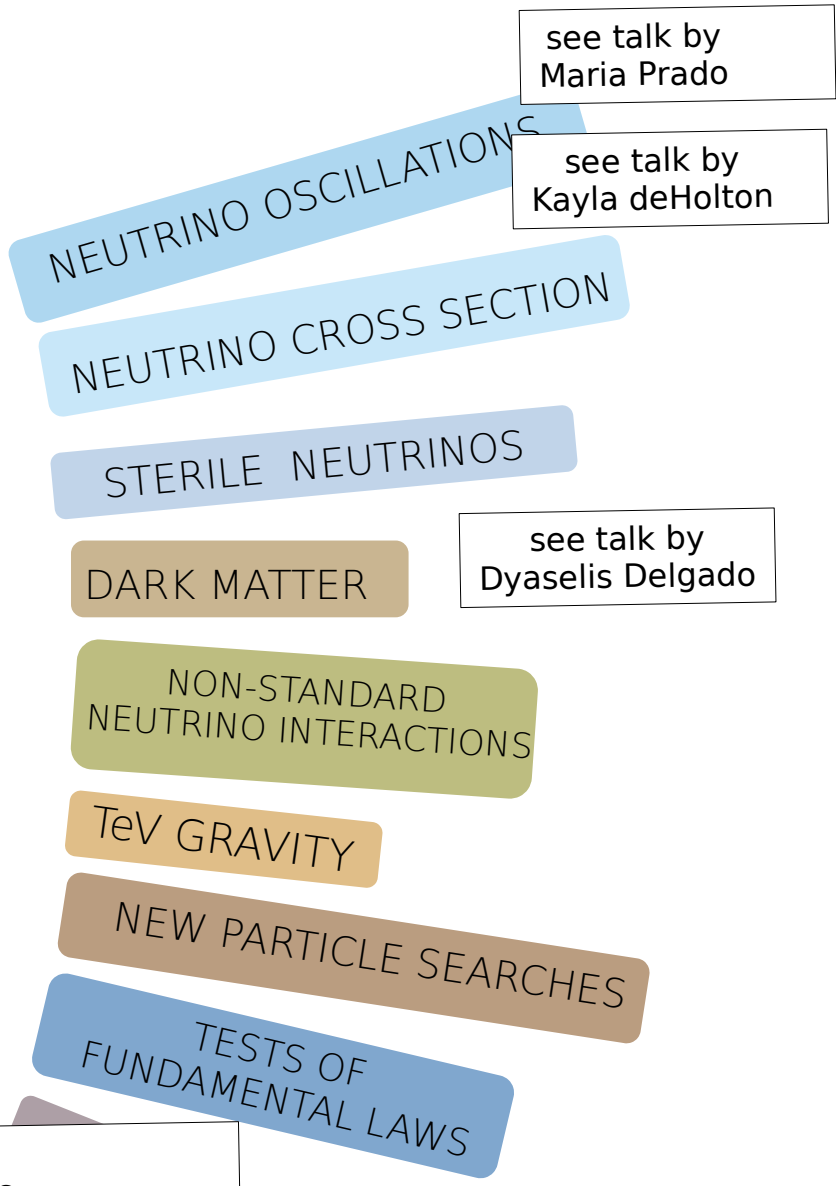




and we hav

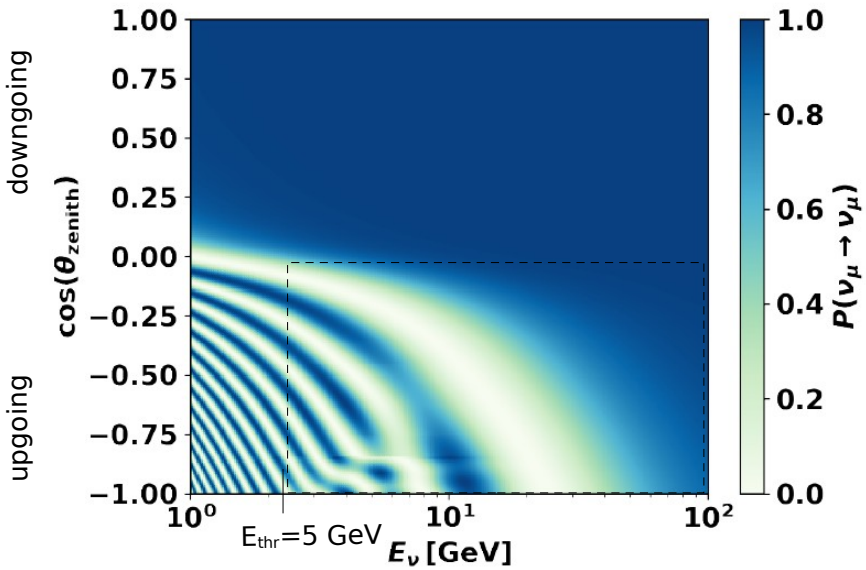
see talk by Mauricio Bustamante for
BSM searches with neutrino telescopes

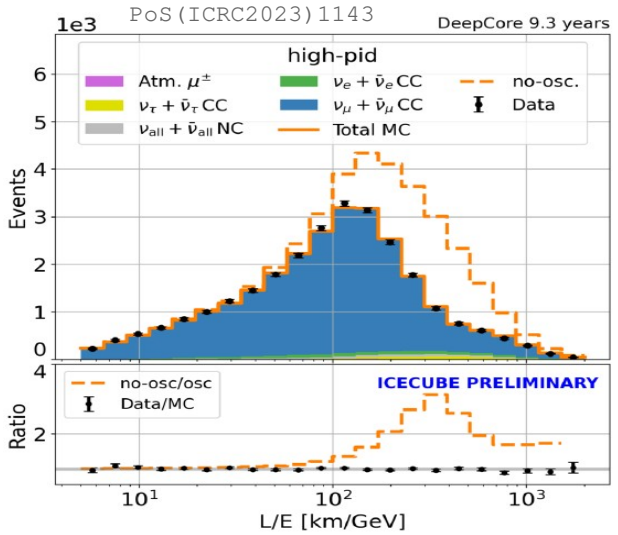
150.000 sub-100 GeV atmospheric neutrinos in 9 years of DeepCore data

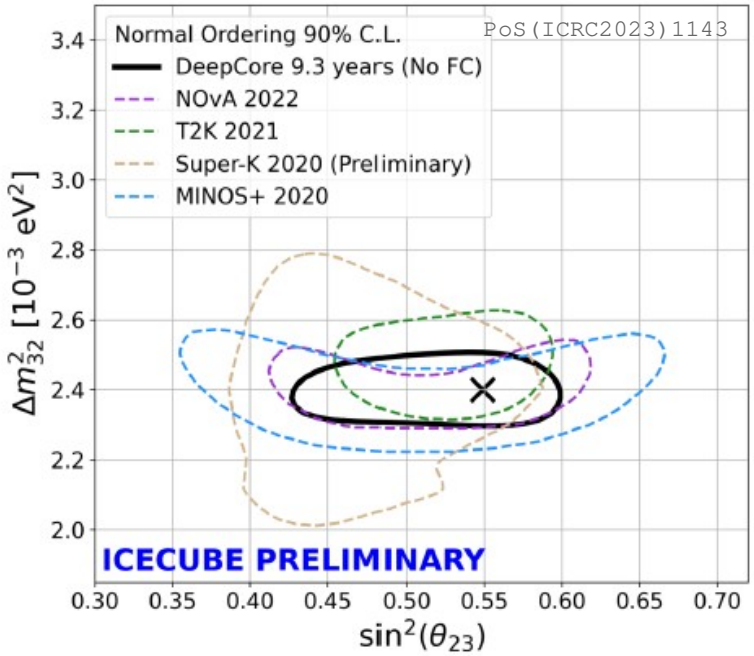
CNNs for energy, direction and particle ID classification

Focus on ν_μ disapearance

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2 \frac{1.27 \Delta m^2_{32} L}{E}$$







$\Delta m^2_{32} = 2.40\ ^{+0.03}_{-0.06} \times 10^{-3}\ eV^2$, $\sin^2\theta_{23} = 0.544^{+0.030}_{-0.096}$

search for non-standard neutrino interactions

Phys. Rev. Lett 129 011804 (2022). See also Phys. Rev. D 104, 072006 (2021)

- Distorted oscillation pattern due to NSI mediated by non-SM bosons

$$H_{\alpha\beta} = \frac{1}{2E} U_{\alpha j} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} (U^T)_{k\beta} + V_{MSW} + \sqrt{2} G_F N_f \begin{pmatrix} \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$$

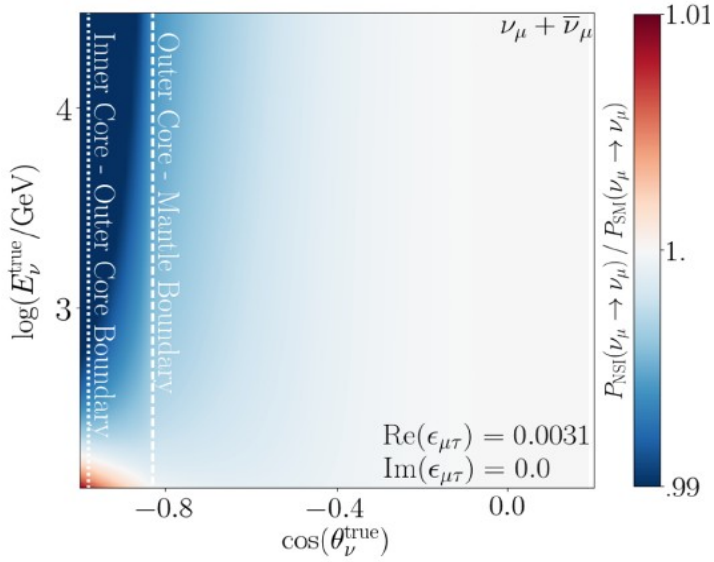
standard MSW NSI

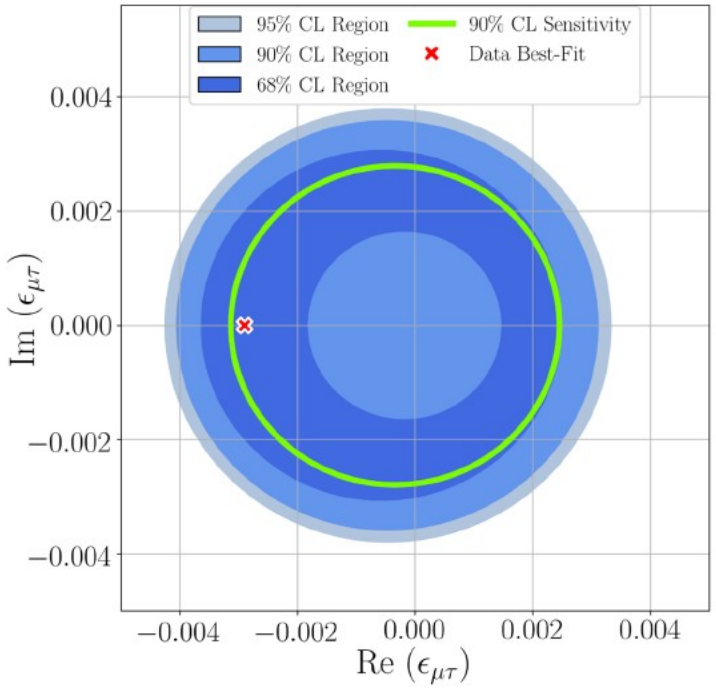
→ 6 additional “interaction terms” (if hermicity and unitarity are imposed)

- Effect proportional to LxE ← advantage of NTs
- shows in complementary range of parameter space with respect to standard oscillations

$$P(\nu_\mu \to \nu_\tau) = \left| \sin(2\theta_{23}) \frac{\Delta m^2_{31}}{2E_\nu} + 2V_d \epsilon_{\mu\tau} \right|^2 \left(\frac{L}{2}\right)^2$$

- **IceCube analysis on $\epsilon_{\mu\tau}$** (see Phys. Rev. D 104 072006 (2021) for other parameters)
  - 305.000 upgoing CC events in 8 years of data
  - 500 GeV < E < 1 TeV





search for Lorenz invariance violation

- Distorted oscillation pattern due to NSI mediated by non-SM bosons

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standard MSW

$$\frac{p_\lambda}{E} \begin{pmatrix} a^\lambda_{ee} & a^\lambda_{e\mu} & a^\lambda_{e\tau} \\ a^{\lambda *}_{e\mu} & a^\lambda_{\mu\mu} & a^\lambda_{\mu\tau} \\ a^{\lambda *}_{\mu\tau} & a^{\lambda *}_{e\tau} & a^\lambda_{\tau\tau} \end{pmatrix} - \frac{p_\lambda p_\sigma}{E} \begin{pmatrix} c^{\lambda\sigma}_{ee} & c^{\lambda\sigma}_{e\mu} & c^{\lambda\sigma}_{e\tau} \\ c^{\lambda\sigma *}_{e\mu} & c^{\lambda\sigma}_{\mu\mu} & c^{\lambda\sigma}_{\mu\tau} \\ c^{\lambda\sigma *}_{\mu\tau} & c^{\lambda\sigma *}_{e\tau} & c^{\lambda\sigma}_{\tau\tau} \end{pmatrix}$$

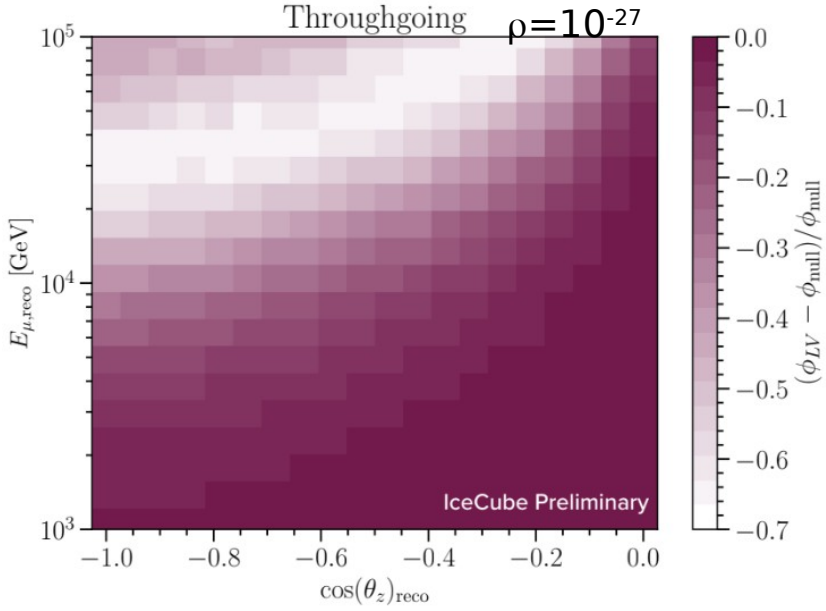
LIV

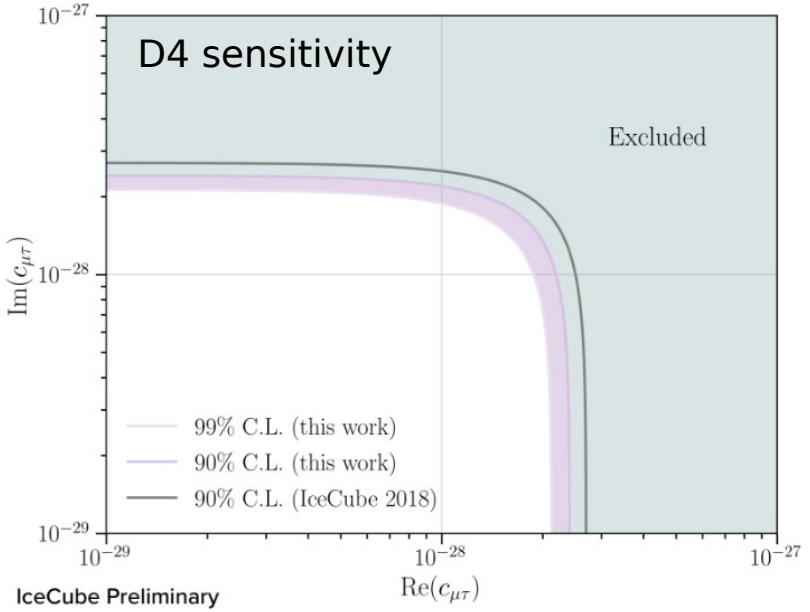
→ Interesting for neutrino telescopes: anomalous neutrino oscillation to tau neutrinos → signal of LV is the anomalous disappearance of ν_μ

- Distorsion of the vertical versus horizontal neutrino flux
- Shows in complementary range of parameter space with respect to standard oscillations

- **IceCube ongoing analysis**

(See also Nature Physics, vol 14, September 2018 and Phys. Rev. D104 072006 (2021))





• Minimal extension to SM: new mass state ν_4

$$\nu_{\alpha L} = \sum_{k=1}^{3} U_{\alpha k} \nu_{k L} \quad (\alpha = e, \mu, \tau) \longrightarrow \nu_{\alpha L} = \sum_{k=1}^{4} U_{\alpha k} \nu_{k L} \quad (\alpha = e, \mu, \tau, s)$$

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

Minimal 3+1 scenario adds 6 parameters:

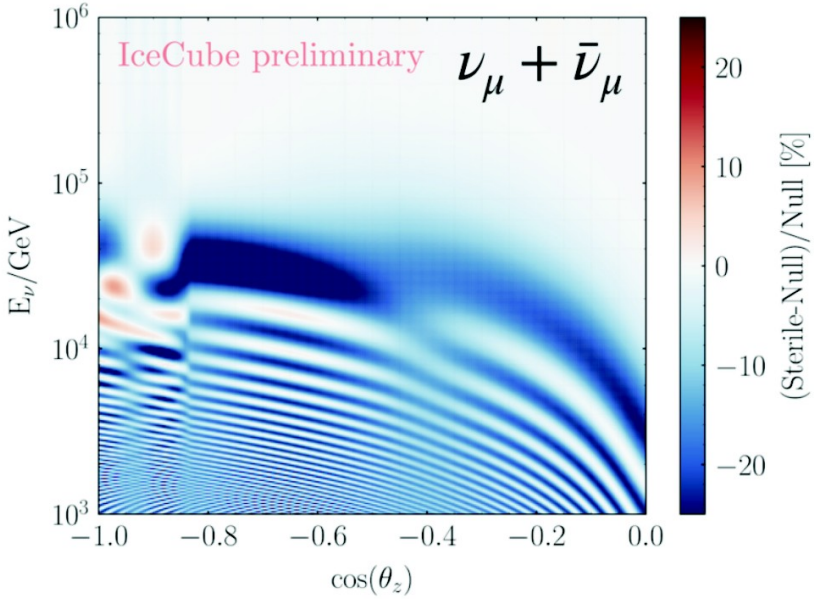
Δm^2_{41}, θ_{14}, θ_{24}, θ_{34}, δ_{14} and δ_{34}

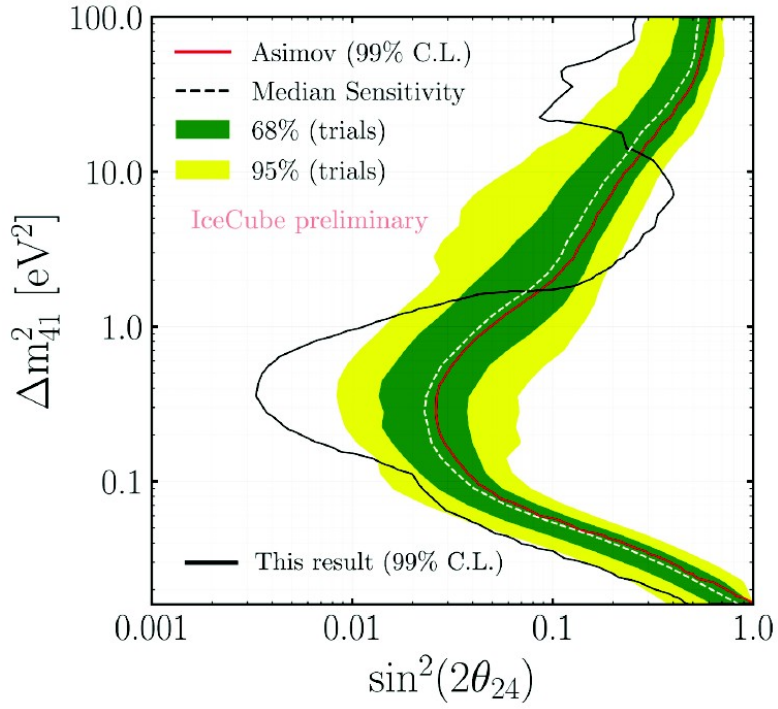
Search for ν_μ dissapearance in 10.7 y of data

(conservatively assume $\theta_{14} = \theta_{34} = 0$)

Using new energy reconstruction, ice model and background flux

Best fit: $\Delta m^2_{41} = 7.1$ eV^2, $\theta_{24} = 15°$





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(α = e, μ, τ) (α = e, μ, τ, s)

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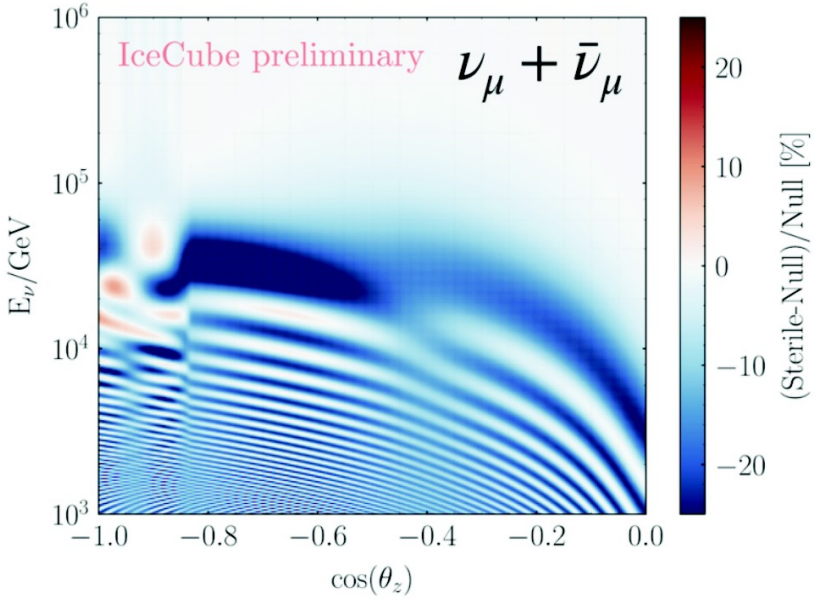
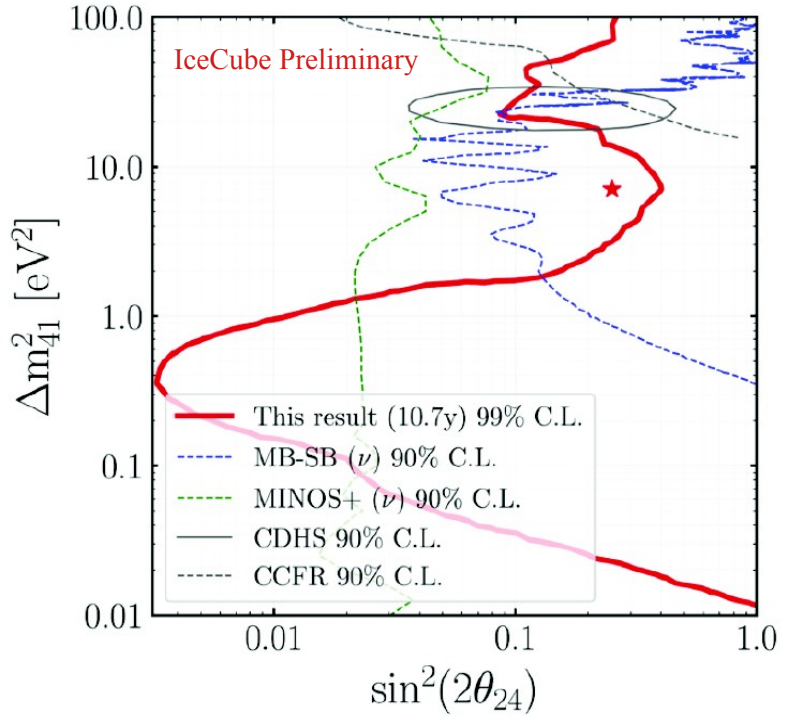
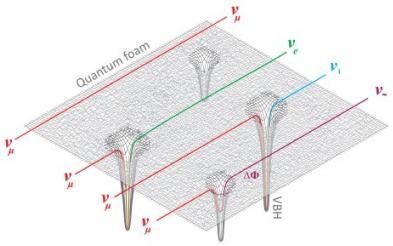




neutrino decoherence from Quantum Gravity

arXiv:2308.00105

• Distorted oscillation pattern due to propagation in spacetime foam



→ evolution of neutrino “beam” includes a decoherence operator D,

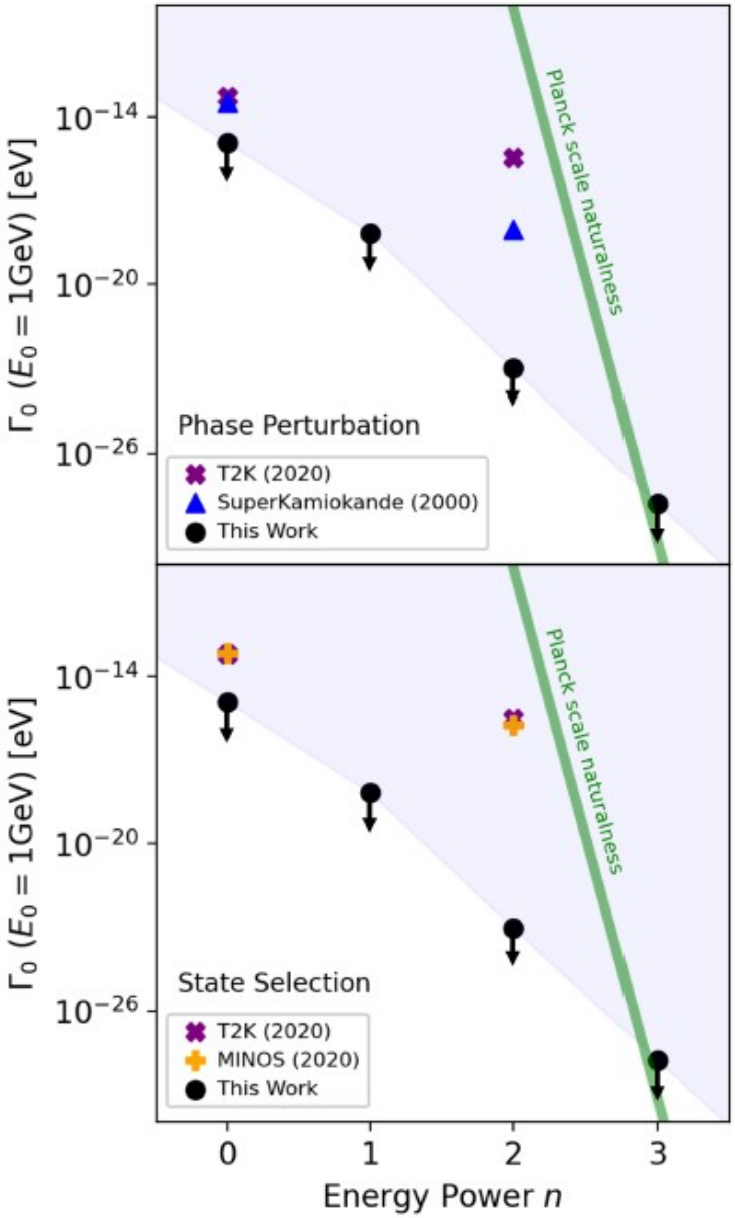
$$\dot{\rho} = -i[H,\rho] - D[\rho] = -i[H,\rho] - \begin{pmatrix} 0 & \rho_{12}\Gamma_{21} & \rho_{13}\Gamma_{31} \\ \rho_{21}\Gamma_{21} & 0 & \rho_{23}\Gamma_{32} \\ \rho_{31}\Gamma_{31} & \rho_{32}\Gamma_{32} & 0 \end{pmatrix}$$

standard oscillations — decoherence term

$$\Gamma_{ij} = \Gamma_{ij}(E_0)\left(\frac{E}{E_0}\right)^n = \Gamma_0(E_0)\left(\frac{E}{E_0}\right)^n$$

Γ_0 and n free parameters

look for deviations from standard oscillations in atmospheric neutrinos of 500 GeV <E< 10 TeV



search for Quantum Gravity with astrophysical neutrinos

Nature Physics volume 18, pages 1287–1292 (2022)

$$H = U\frac{m^2}{2E}U^\dagger + \begin{pmatrix} \mathring{a}^{(3)}_{ee} & \mathring{a}^{(3)}_{e\mu} & \mathring{a}^{(3)}_{\tau e} \\ \mathring{a}^{(3)*}_{e\mu} & \mathring{a}^{(3)}_{\mu\mu} & \mathring{a}^{(3)}_{\mu\tau} \\ \mathring{a}^{(3)*}_{\tau e} & \mathring{a}^{(3)*}_{\mu\tau} & \mathring{a}^{(3)}_{\tau\tau} \end{pmatrix} - E \cdot \begin{pmatrix} \mathring{c}^{(4)}_{ee} & \mathring{c}^{(4)}_{e\mu} & \mathring{c}^{(4)}_{\tau e} \\ \mathring{c}^{(4)*}_{e\mu} & \mathring{c}^{(4)}_{\mu\mu} & \mathring{c}^{(4)}_{\mu\tau} \\ \mathring{c}^{(4)*}_{\tau e} & \mathring{c}^{(4)*}_{\mu\tau} & \mathring{c}^{(4)}_{\tau\tau} \end{pmatrix} + \cdots$$

CPT-odd CPT-even

(°=spacial isotropy)

$$\phi_\beta^{Earth} \propto \int \sum_\alpha P_{\nu_\alpha \to \nu_\beta}(E)\ \phi(E)_\alpha^{source}\ dE$$

measure constrain (depends on new physics) assume

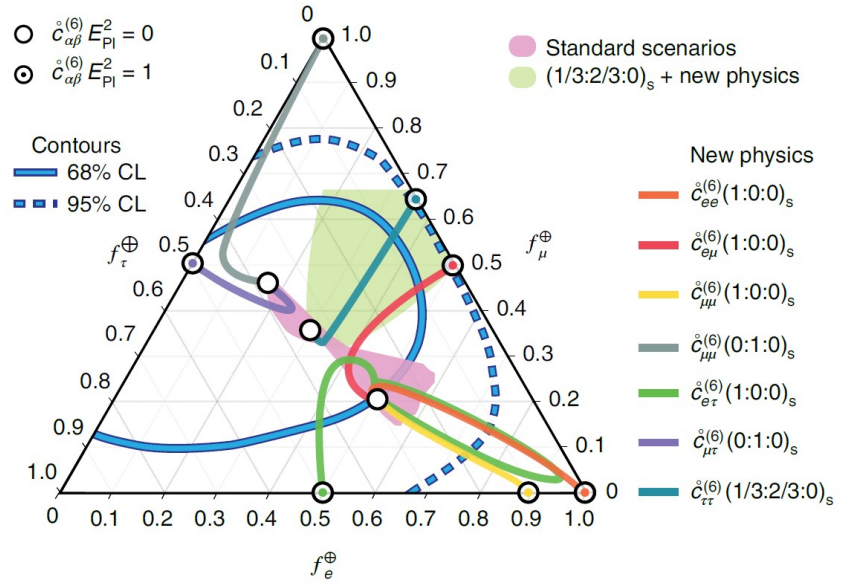
Astrophysical neutrinos = higher energies and longer propagation distances

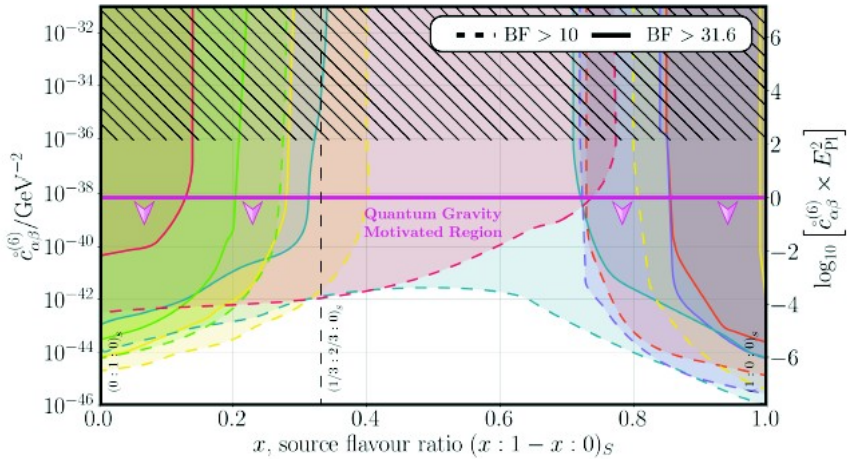
→ enhanced sensitivity to QG effects

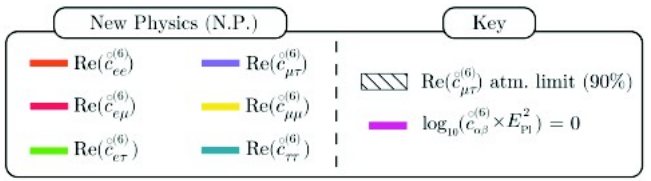
Analysis: flavour composition in 7.5 y of HESE sample

For some scenarios we reach limits on the Planck scale

Still compatible with standard oscillations







outlook

IceCube has access to a high-statistics, high-energy neutrino beam (atm. neutrinos), and to a ultra high-energy beam from cosmological distances (the astrophysical flux)

→ Extremely rich particle physics program

~10 years of operation: statistics starts to be sufficient to test BSM effects:
many analyses are systematics limited

Results on neutrino oscillations (and ν cross section) complementary to accelerator physics:
different energy regimes. Consistent picture so far.

Reach Planck scale on QG searches

IceCube is sensitive to any light-emitting particle besides muons
→ possibility to search for new particles: monopoles, DM, SUSY...

FINE