Search for Quantum-Gravity-Motivated Effects in IceCube

outline

1. Introduction
2. IceCube experiment
3. Astrophysical neutrino diffuse samples
4. Astrophysical neutrino sources
5. Search for Quantum-Gravity-Motivated Effects
6. Conclusions

Teppei Katori for the IceCube collaboration
King's College London
"Quantum gravity phenomenology in the multi-messenger approach"
COST CA18108 Fourth Annual Conference
University of Rijeka, Croatia, July 11, 2023
teppei.katori@kcl.ac.uk

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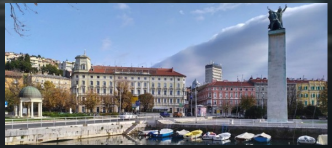

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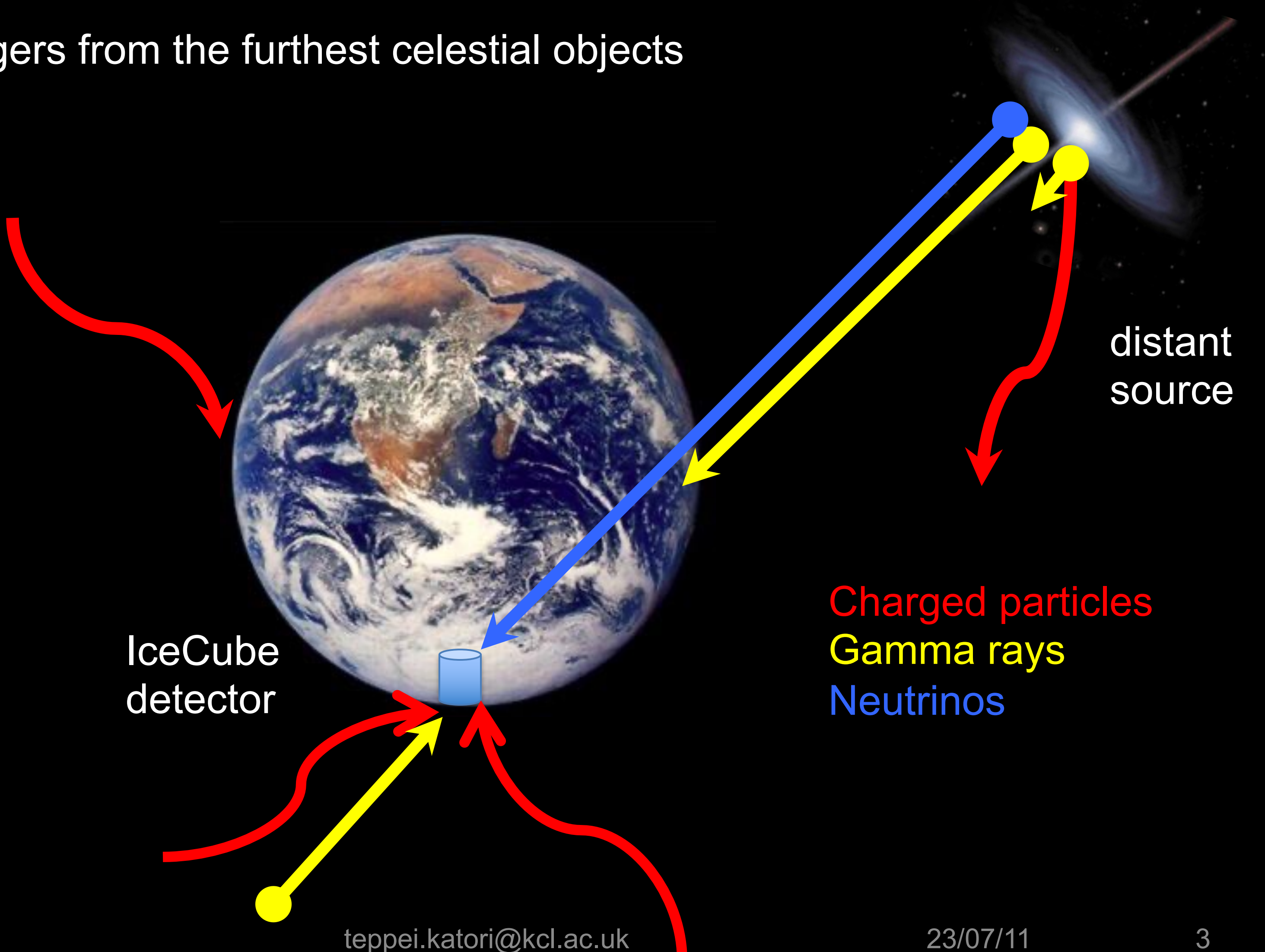
1. High-energy astrophysical neutrinos

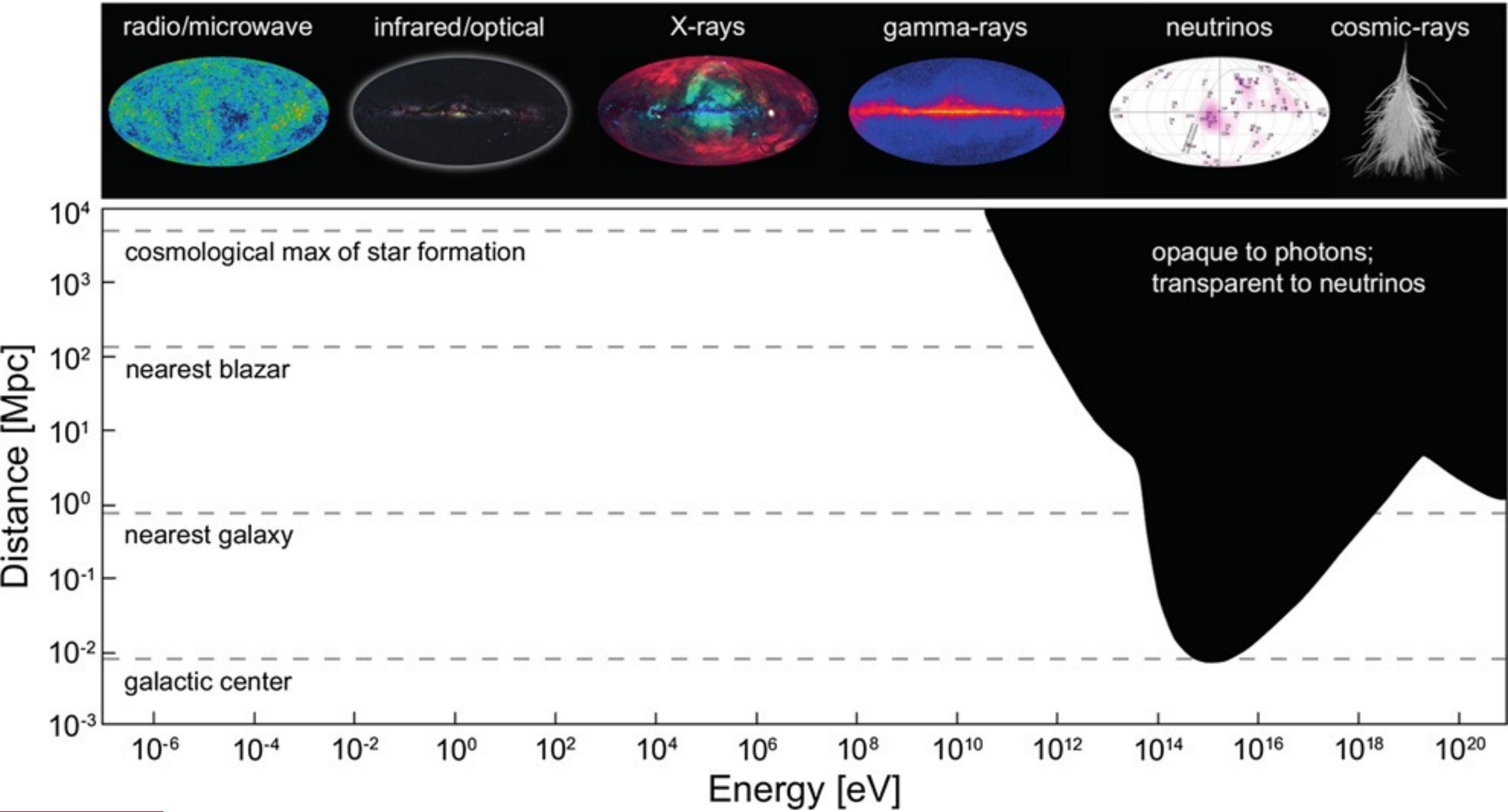
Direct messengers from the furthest celestial objects



IceCube-Gen2, J.Phys.G.48(2021) 060501

1. High-energy astrophysical neutrinos

Above ~10-100 TeV neutrinos are only direct extra-galactic messengers

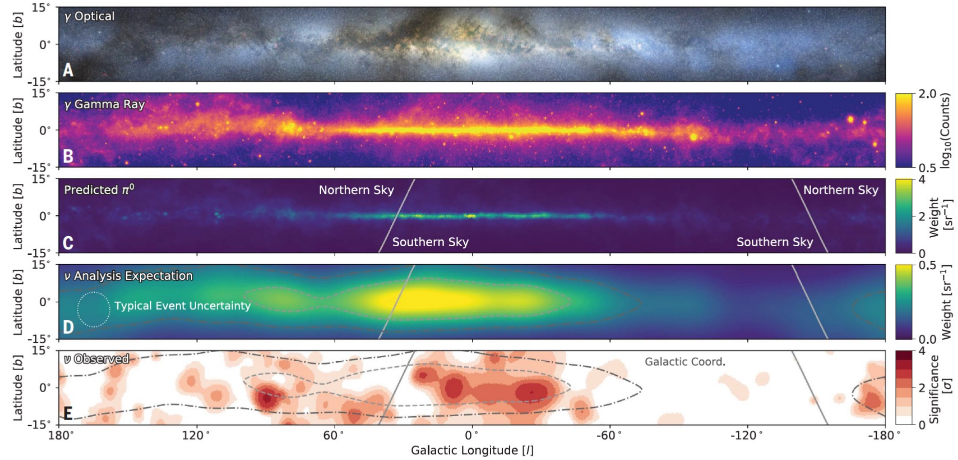


IceCube, Science 380(2023)1338
IceCube et al, Science 361(2018)146

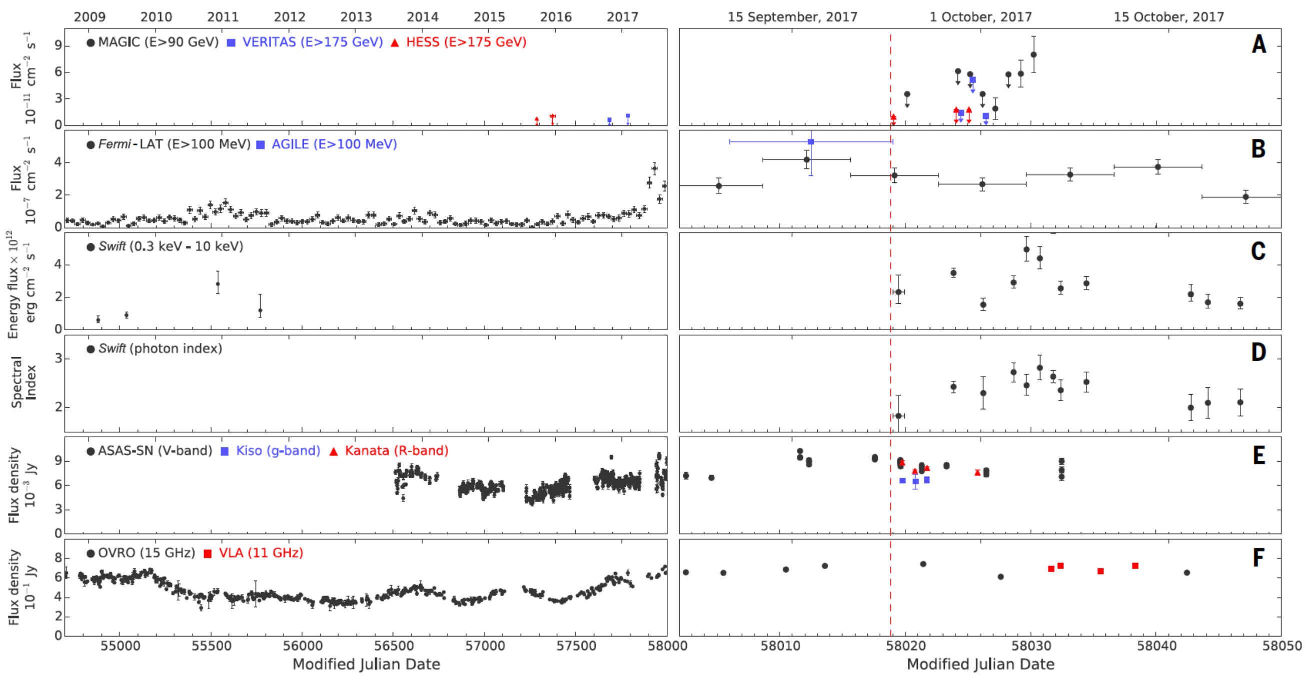
1. Multi-messenger astronomy

Astrophysical point sources may emit photons, neutrinos (and gravitational waves)

Galactic plane in photons and neutrinos



TXS0506+056 blazar photons and neutrinos



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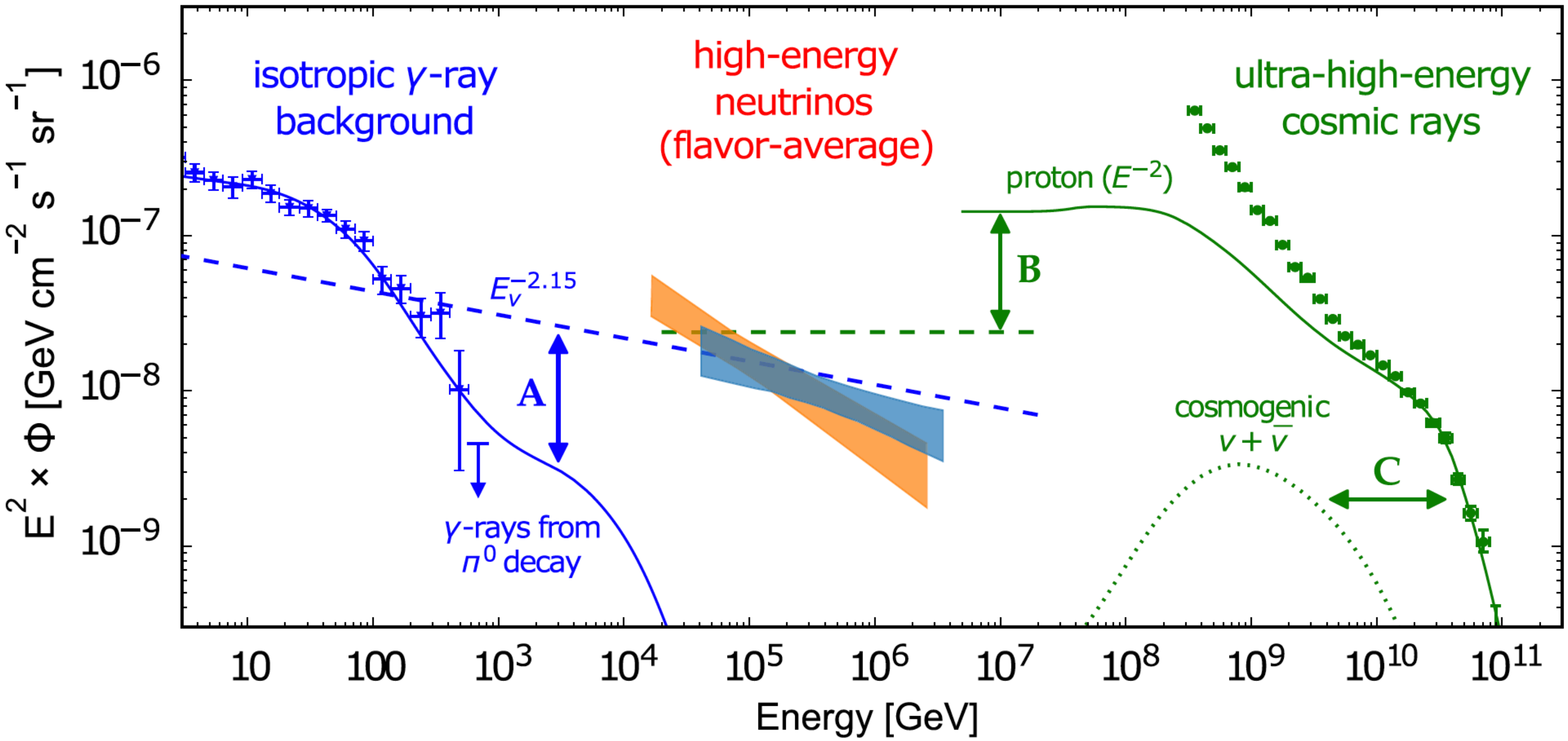
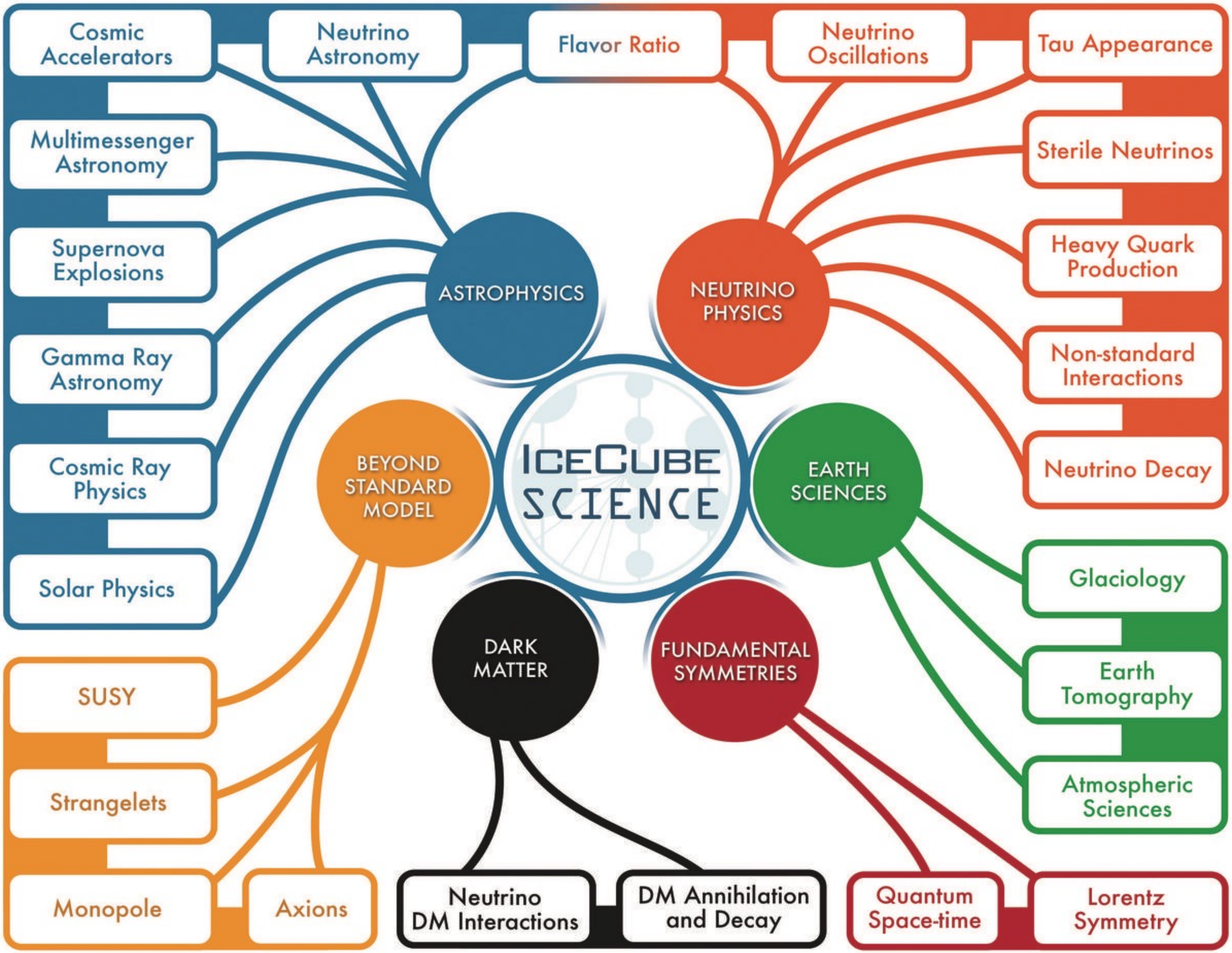
1. Multi-messenger astronomy

High-energy protons, gamma rays, and neutrinos are all related

$$\begin{matrix} p+p \\ p+\gamma \end{matrix} \rightarrow X+\pi \begin{cases} \pi^0 \rightarrow \gamma\gamma \\ \pi^+ \rightarrow \mu^+ + \nu_\mu \\ \mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e \\ n \rightarrow p + e^- + \bar{\nu}_e \end{cases}$$





ICECUBE SCIENCE
ASTROPHYSICS
Cosmic Accelerators
Neutrino Astronomy
Multimessenger Astronomy
Supernova Explosions
Gamma Ray Astronomy
Cosmic Ray Physics
Solar Physics
Flavor Ratio
NEUTRINO PHYSICS
Neutrino Oscillations
Tau Appearance
Sterile Neutrinos
Heavy Quark Production
Non-standard Interactions
Neutrino Decay
EARTH SCIENCES
Glaciology
Earth Tomography
Atmospheric Sciences
FUNDAMENTAL SYMMETRIES
Quantum Space-time
Lorentz Symmetry
DARK MATTER
Neutrino DM Interactions
DM Annihilation and Decay
BEYOND STANDARD MODEL
SUSY
Strangelets
Monopole
Axions

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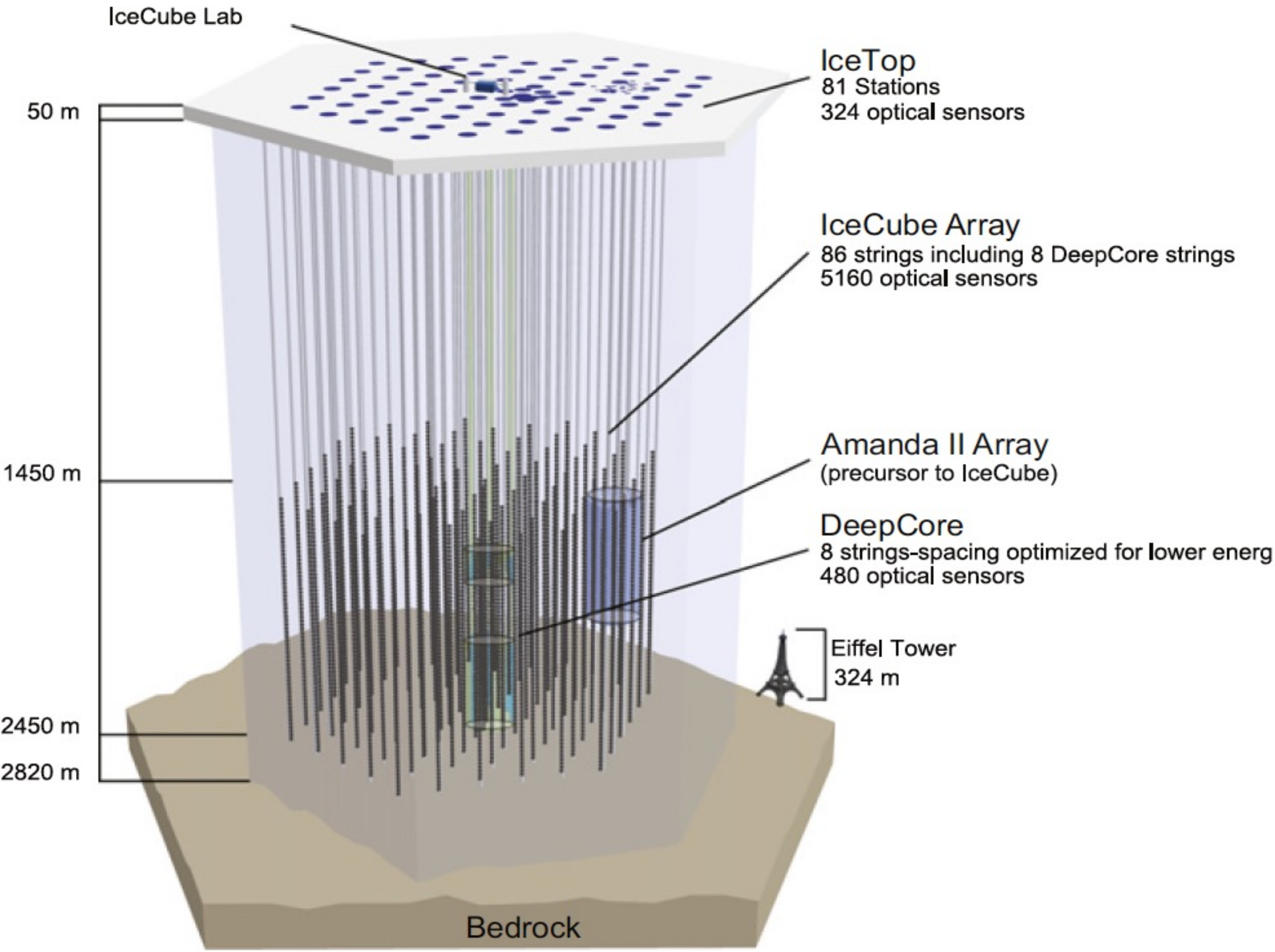
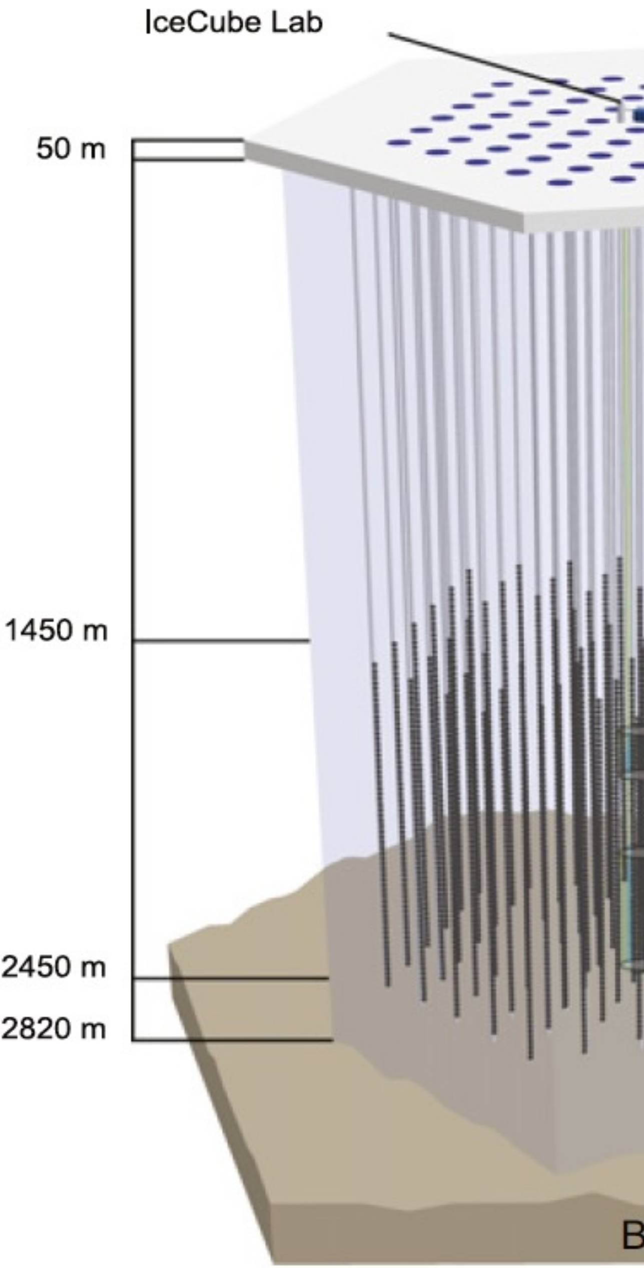
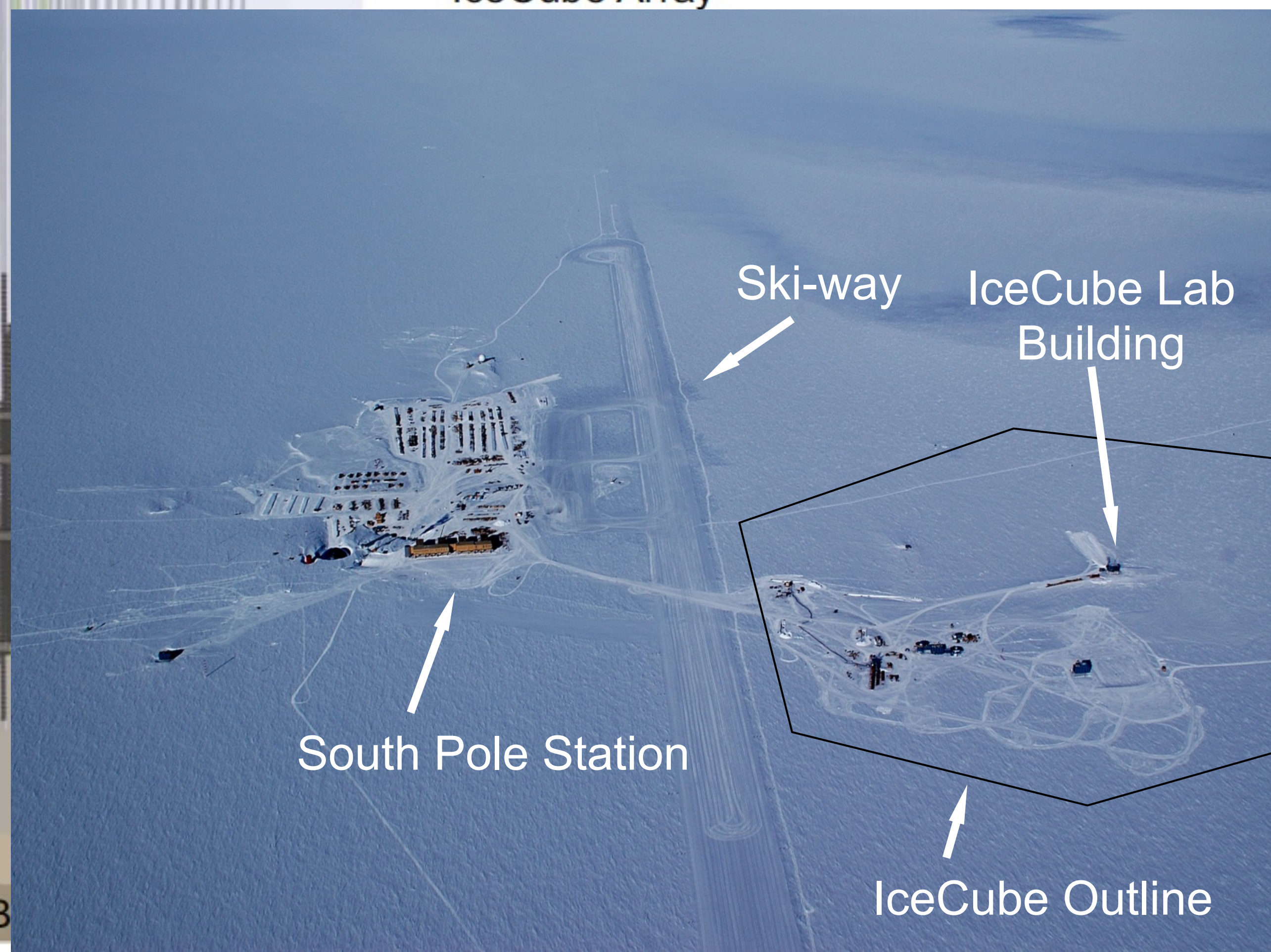
2. IceCube detector



IceCube, JINST12(2017)P03012

2. IceCube detector





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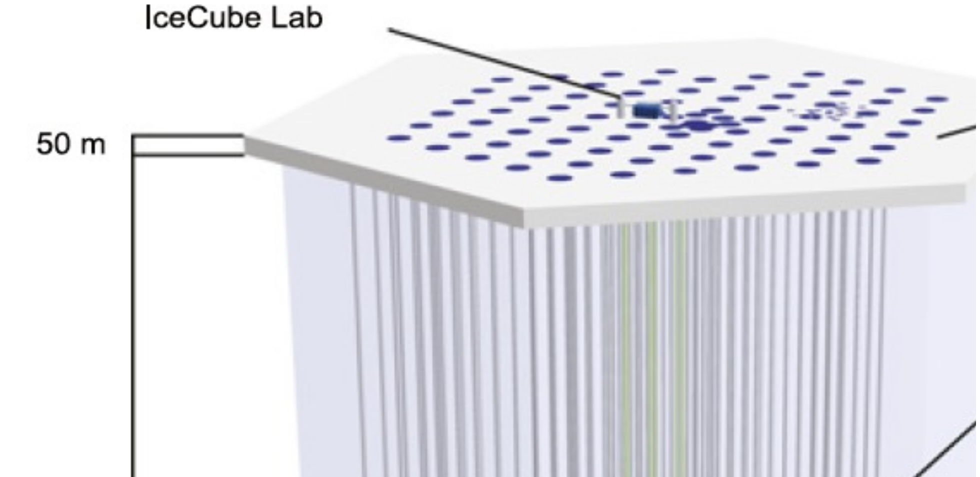

digital optical module (DOM)

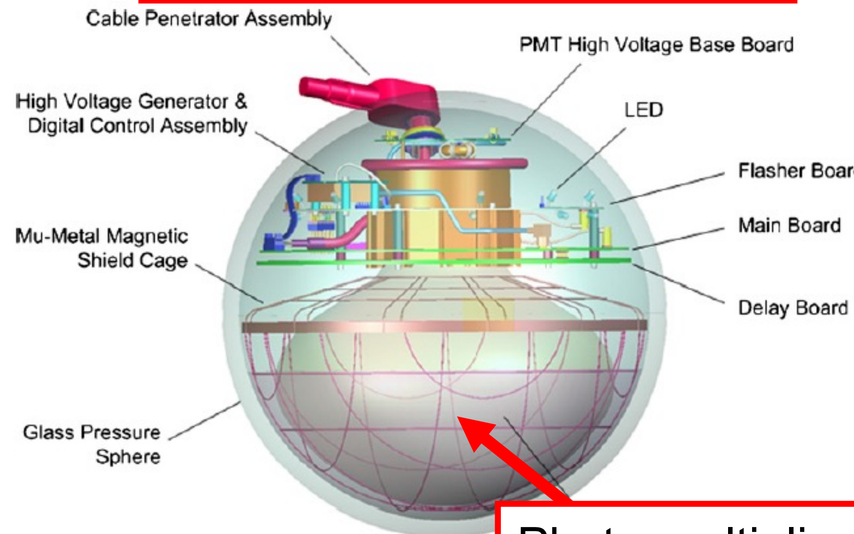

Photo-multiplier tube (PMT)

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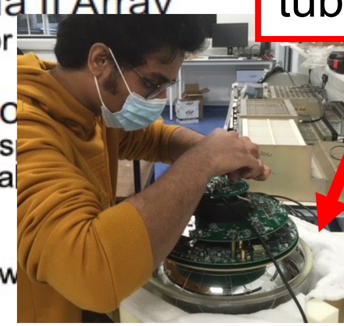
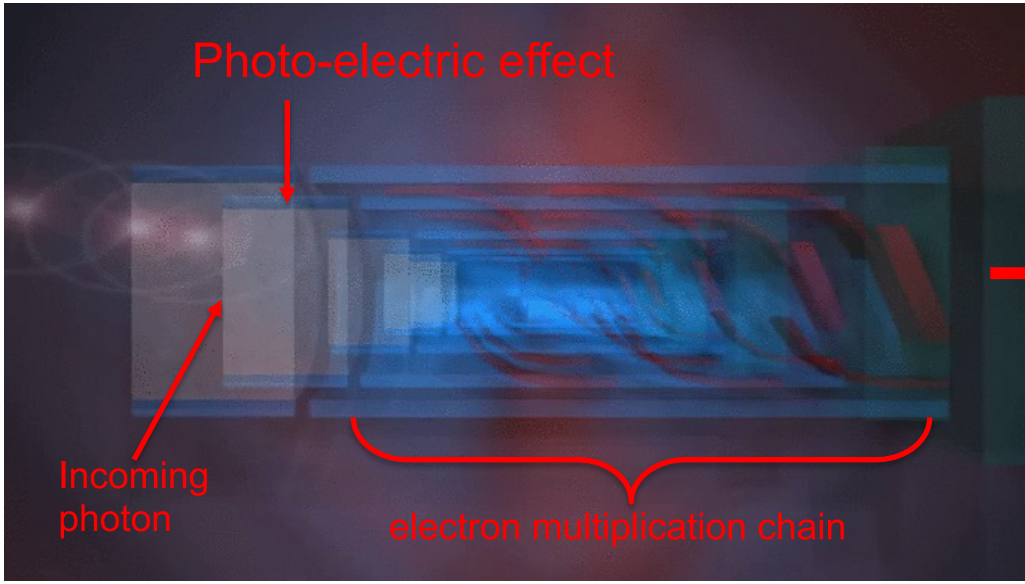
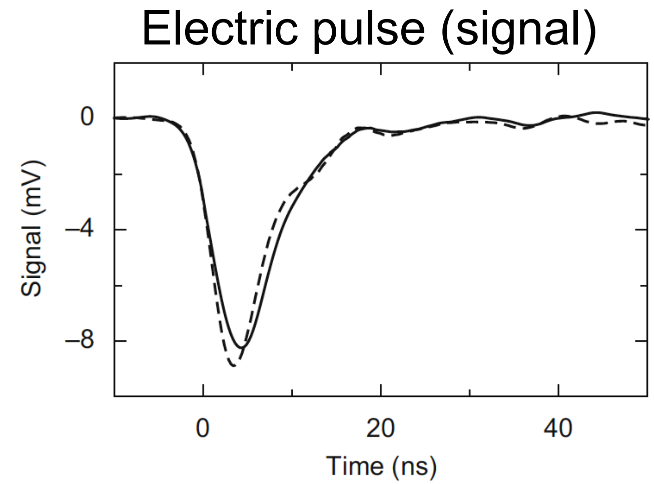
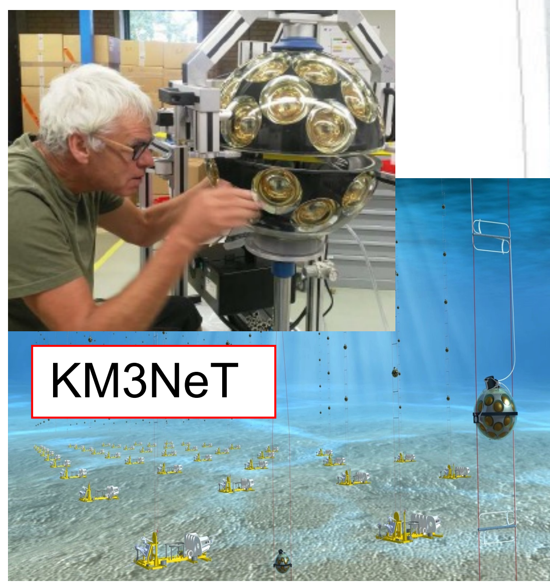


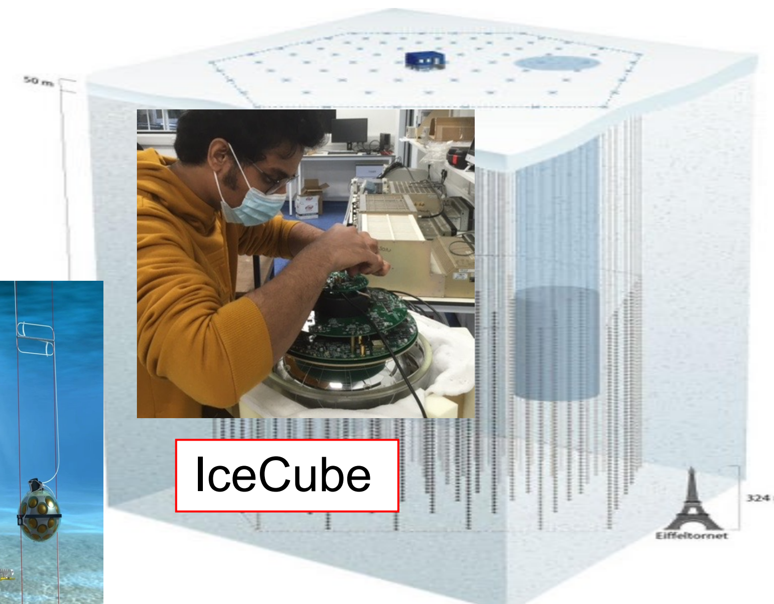
IceCube, NIMA618(2010)139

2. Photo-multiplier tube (PMT)

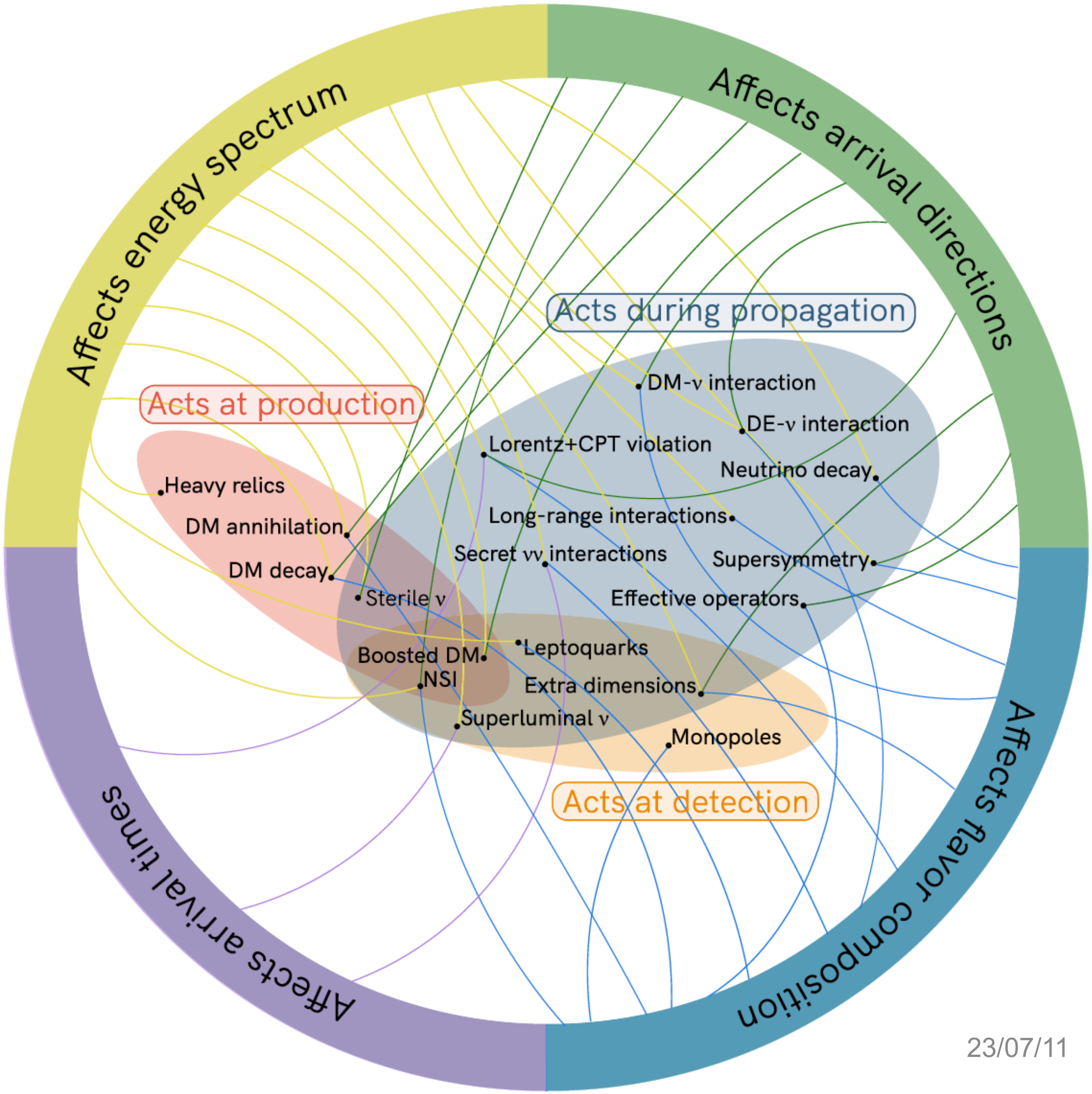








Snowmass21 white paper, "Beyond the Standard Model effect with Neutrino Flavour", EPJC83(2023)15
Ackermann, Bustamante, Lu et al.JHEA.36(2022)55

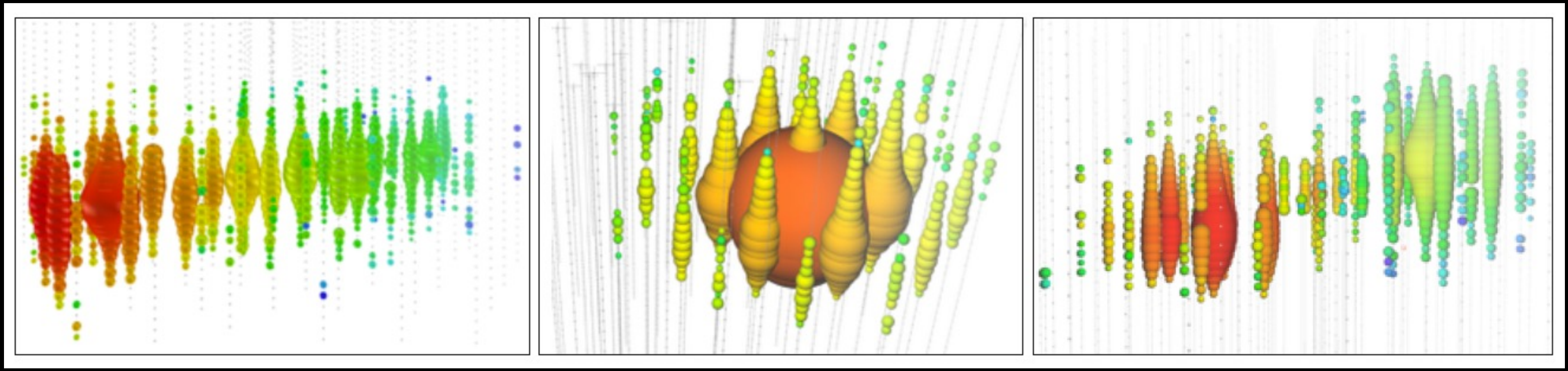


2. IceCube event morphology

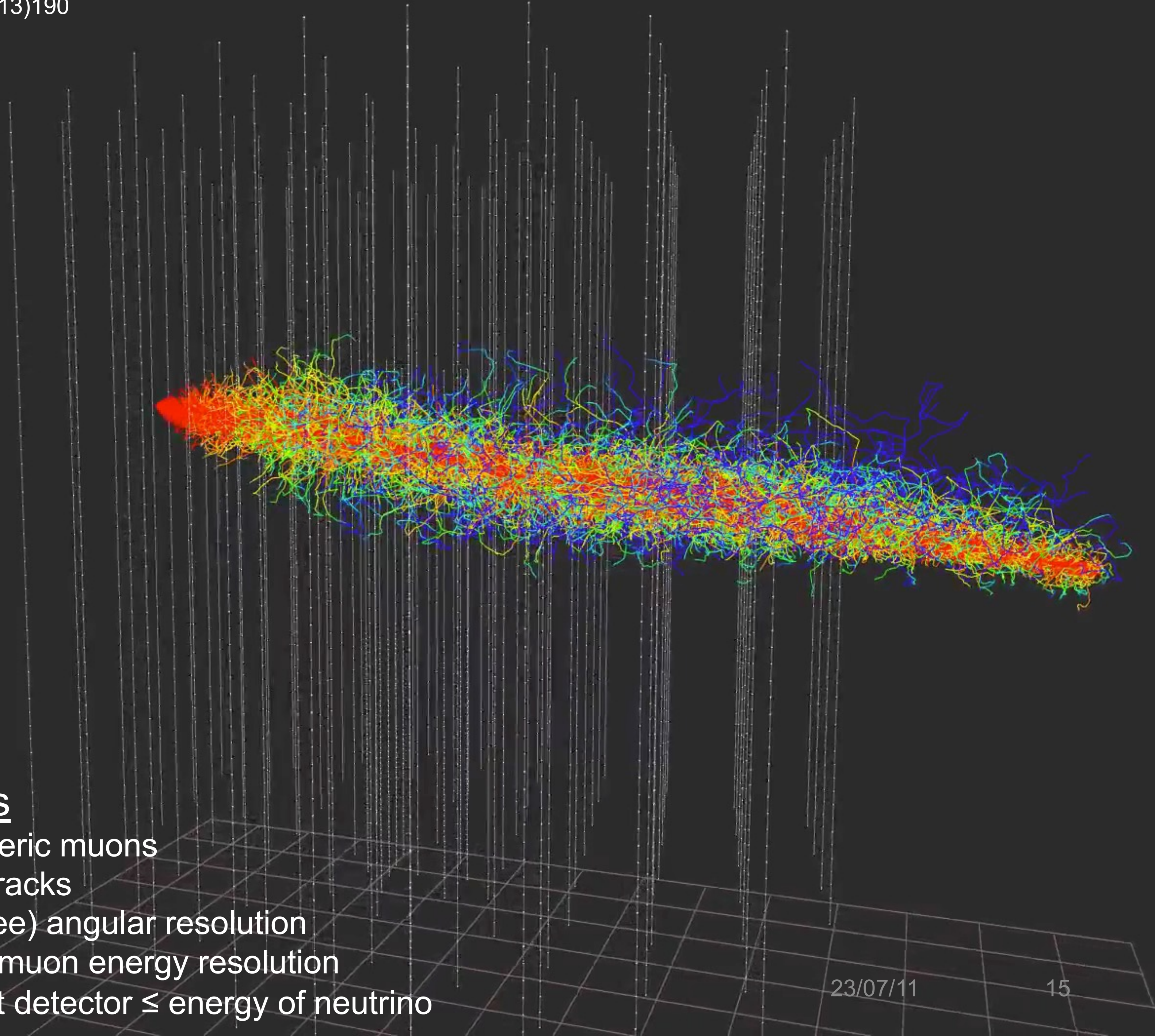
Track
ν_μCC
$$\nu_\mu + N \rightarrow \mu + X$$

Cascade
ν_eCC, ν_τCC, NC
$$\nu_e + N \rightarrow e + X$$
$$\nu_\tau + N \rightarrow \tau + X$$
$$\nu_x + N \rightarrow \nu_x + X$$

Double cascade
ν_τCC (L~50m•E/PeV)
$$\nu_\tau + N \rightarrow \tau + X$$
$$\tau \rightarrow X'$$



IceCube, NIMA703(2013)190



Track events

ν_μCC, atmospheric muons

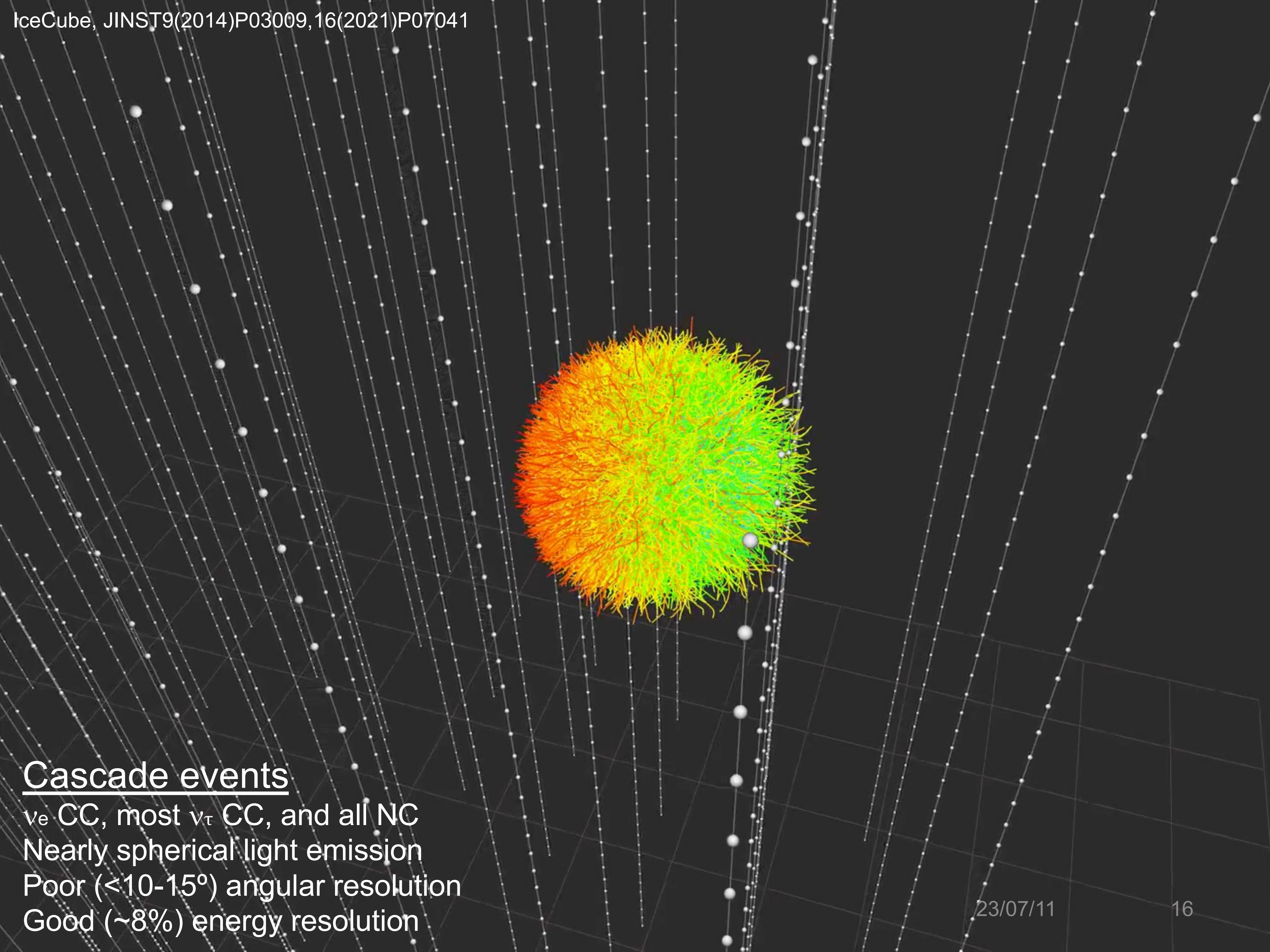
Long, straight tracks

Good (<1 degree) angular resolution

Poor (11-22%) muon energy resolution

Muon energy at detector ≤ energy of neutrino

IceCube, JINST9(2014)P03009,16(2021)P07041



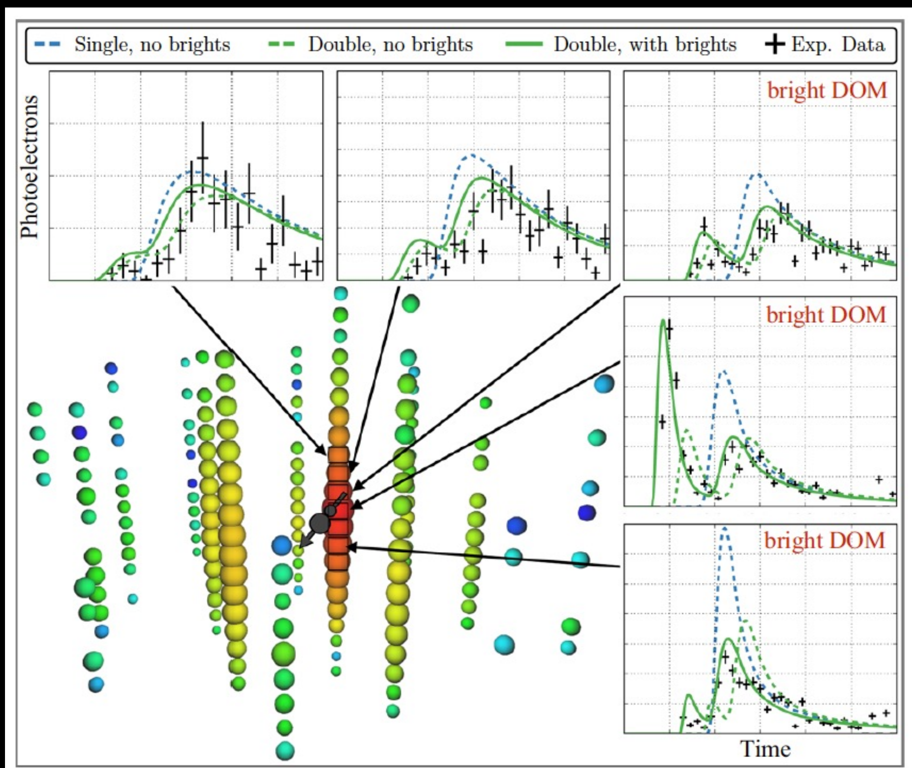
Cascade events

ν_e CC, most ν_τ CC, and all NC
Nearly spherical light emission
Poor (<10-15°) angular resolution
Good (~8%) energy resolution

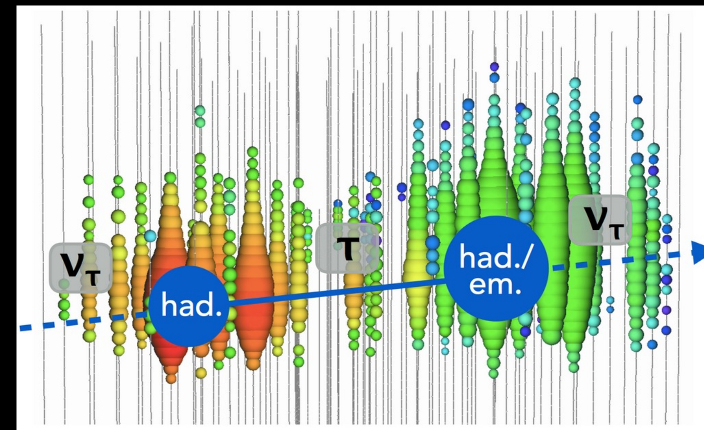
2. Double cascade events

Double bang → double pulse

- Tau propagation, ~50m(E/PeV)
- Astrophysical tau neutrino candidates (x7)



Astrophysical tau neutrino candidate
“Double Double”



Double pulse can be found using timing information.

Improved tau PID algorithm is used for the flavour analysis

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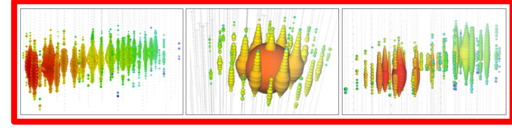
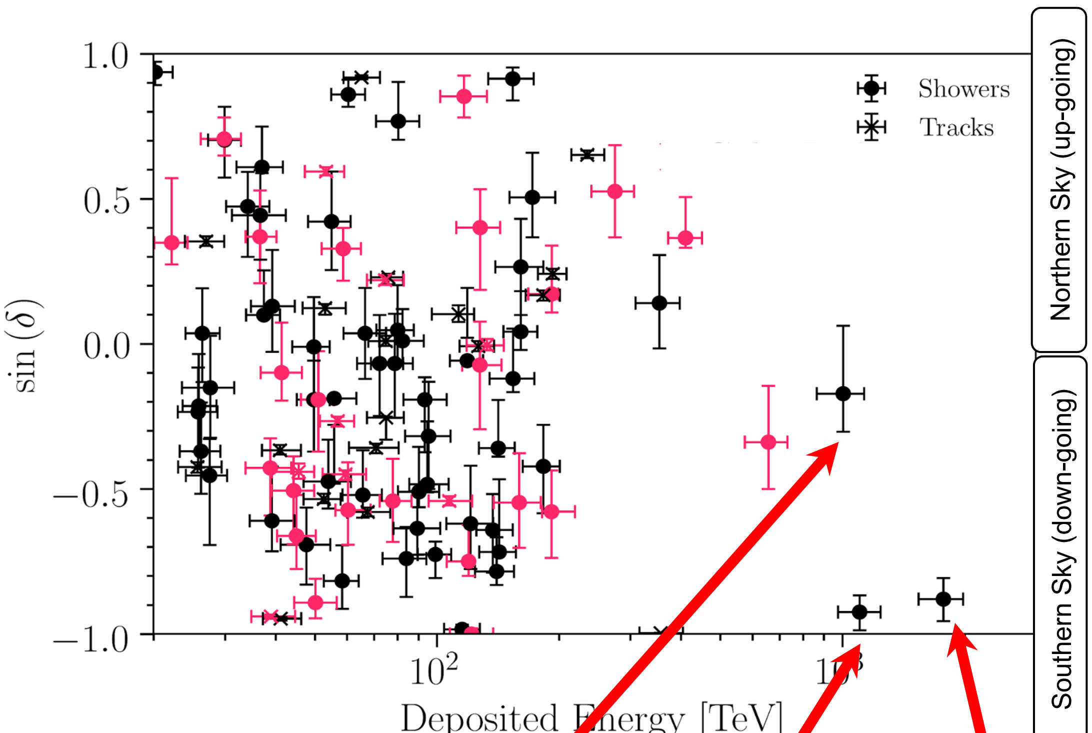
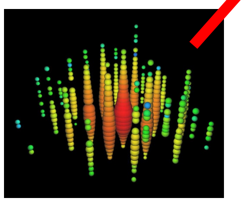


3. High-energy starting event (HESE) sample

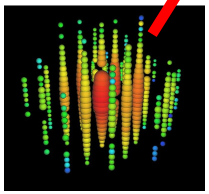
60 events in 60-2000 TeV (7.5-yr data)

- Mostly down-going events (Southern sky)

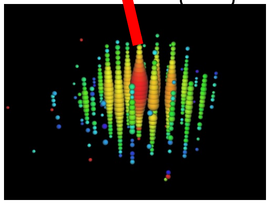




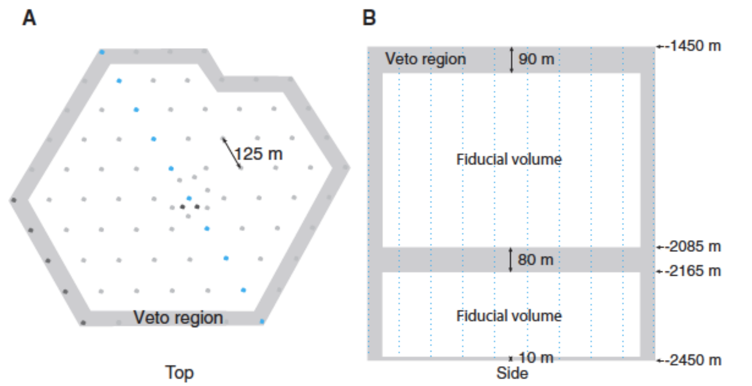
"Bert"
1.1 PeV

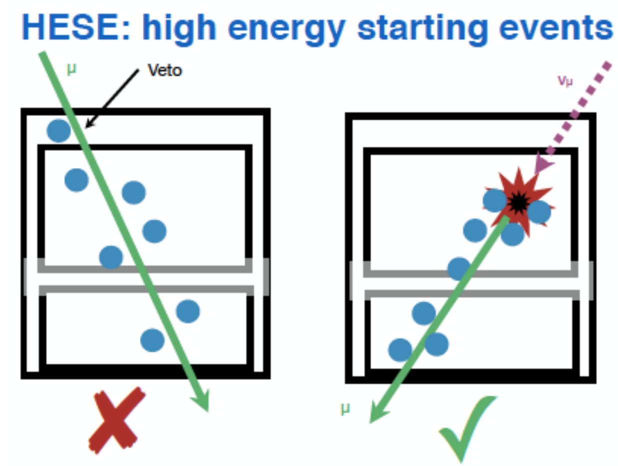


"Ernie"
1.0 PeV



"Big Bird"
2.0 PeV





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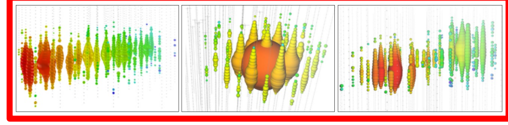
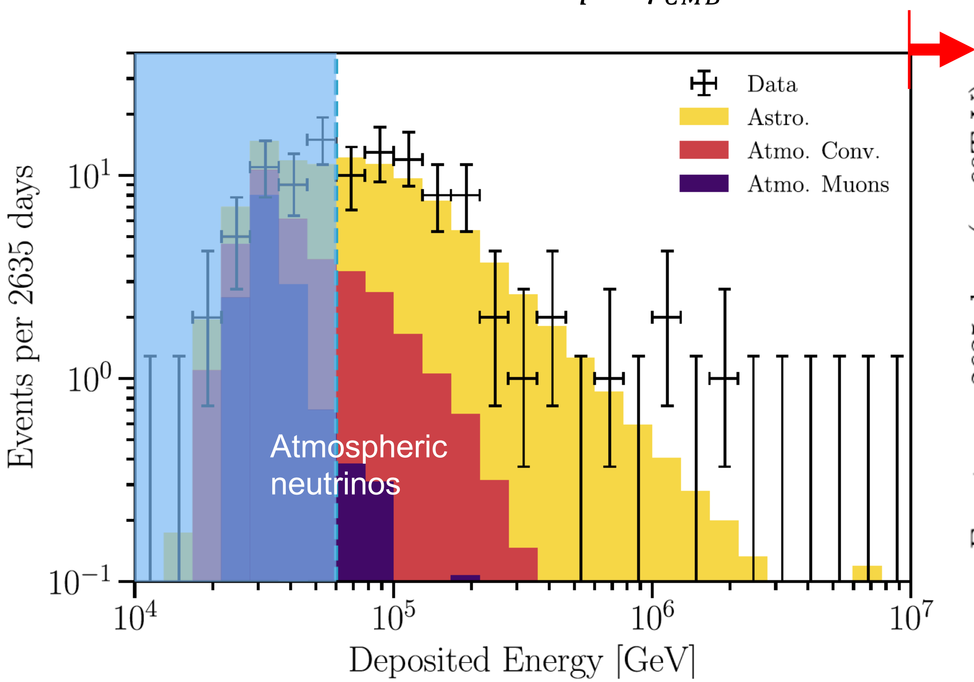


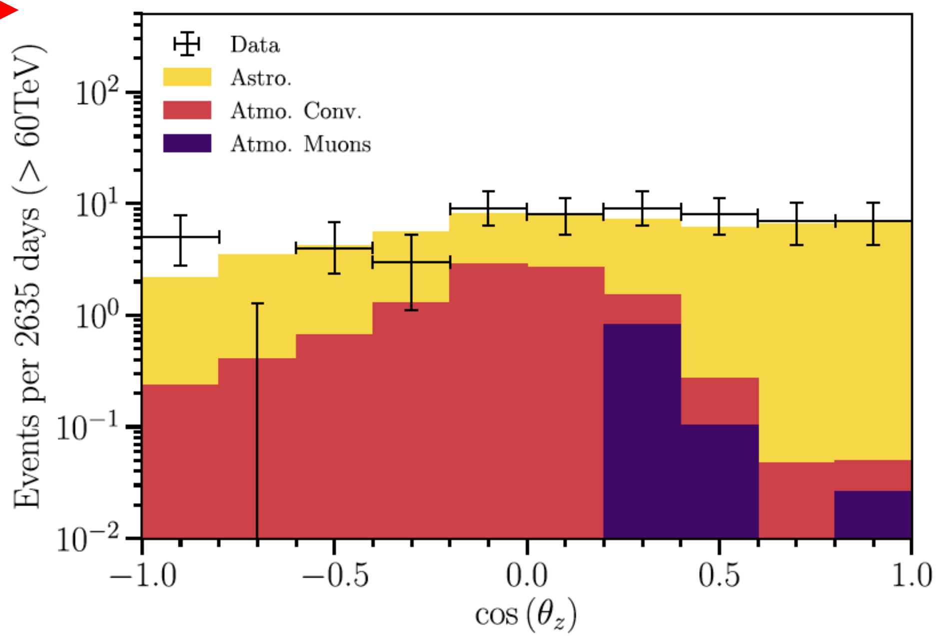
60 events in 60-2000 TeV (7.5-yr data)
- Mostly down-going events (Southern sky)
- Not atmospheric and cosmogenic neutrinos

Cosmogenic “UHE” neutrinos

$$p + \gamma_{CMB} \rightarrow \Delta \rightarrow \pi \rightarrow \nu$$

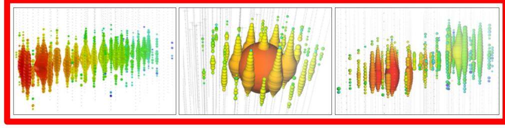


HESE energy spectrum



HESE angular distribution

3. High-energy starting event (HESE) sample



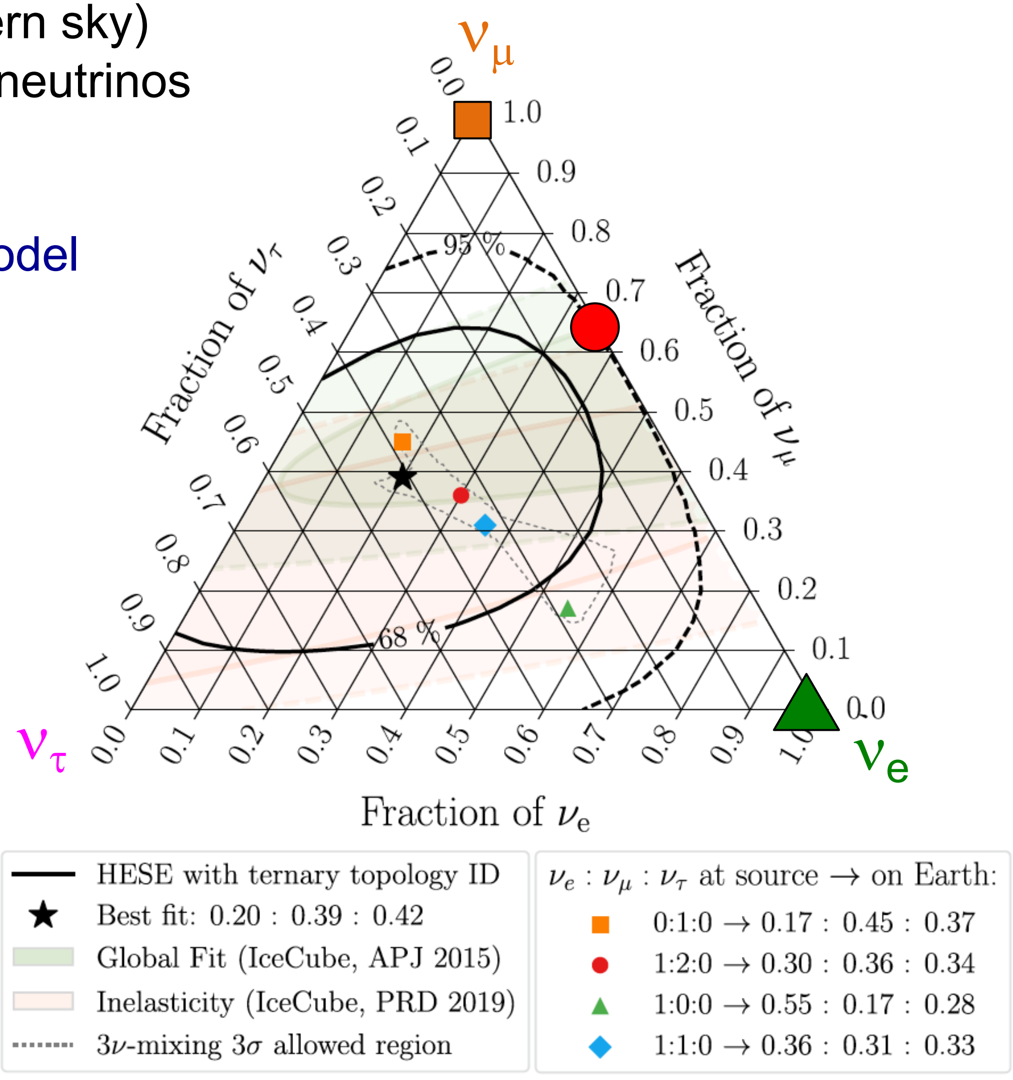
60 events in 60-2000 TeV (7.5-yr data)

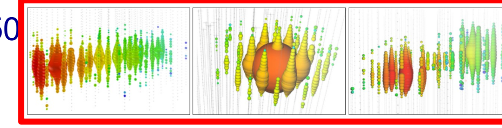
- Mostly down-going events (Southern sky)
- Not atmospheric and cosmogenic neutrinos
- Flavour structure not understood

Astrophysical neutrino production model

- $\nu_e:\nu_\mu:\nu_\tau \sim 1:2:0$
- After mixing, $\nu_e:\nu_\mu:\nu_\tau \sim 1:1:1$

Flavour ratio is obtained from the likelihood function including double cascade hypothesis

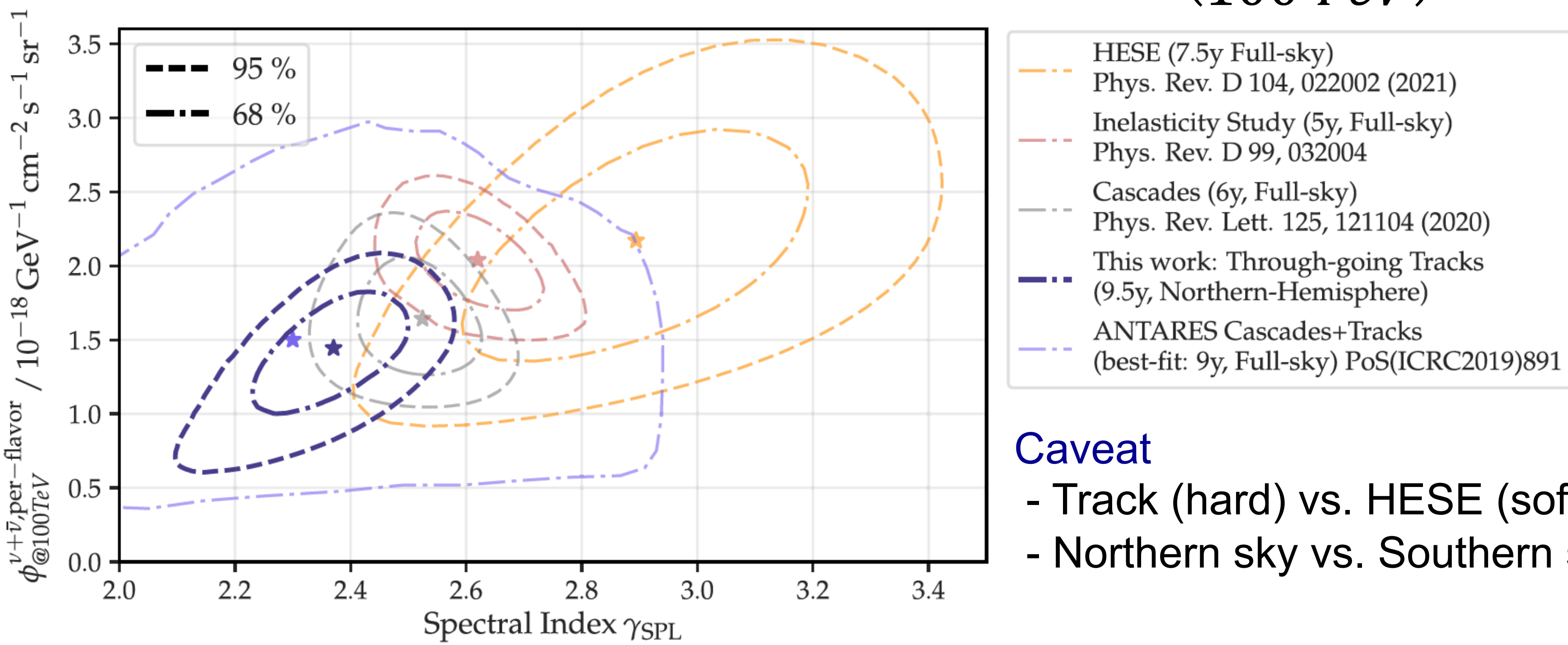




3. High-energy starting event (HESE) sample

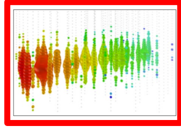
60 events in 60-2000 TeV (7.5-yr data)
- Mostly down-going events (Southern sky)
- Not atmospheric and cosmogenic neutrinos
- Flavour structure not understood
- Spectrum not understood

$$\Phi_\nu \sim \phi_{SPL} \cdot \left(\frac{E_\nu}{100\ TeV}\right)^{-\gamma_{SPL}}$$



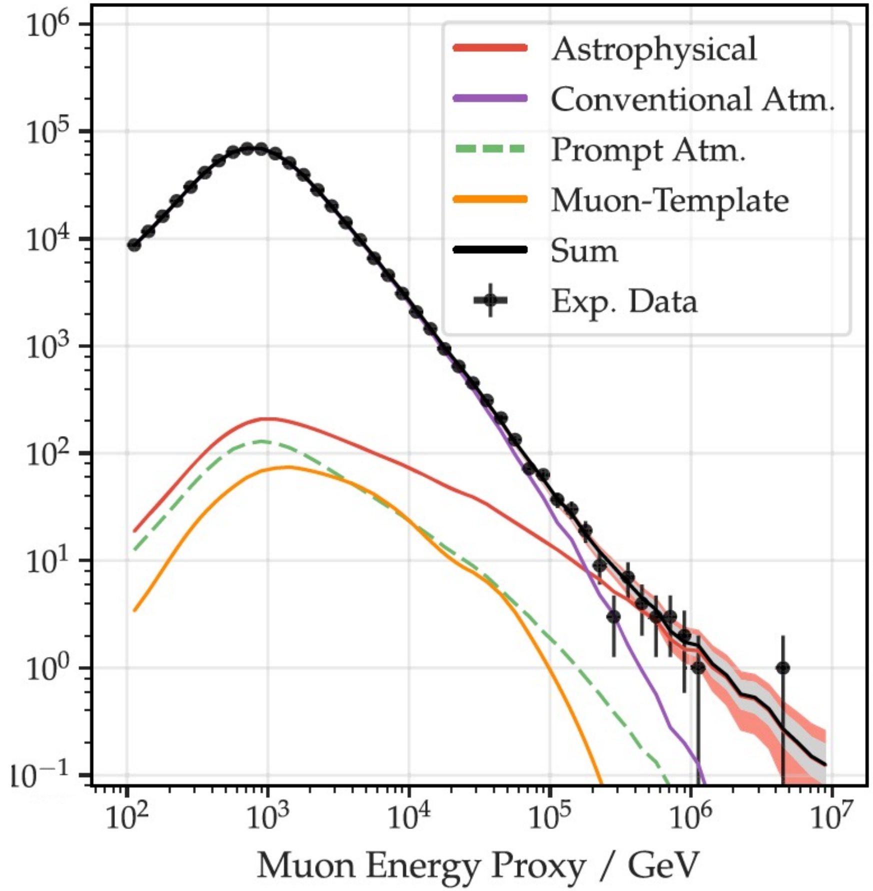
Caveat
- Track (hard) vs. HESE (soft)
- Northern sky vs. Southern sky

3. Track event sample

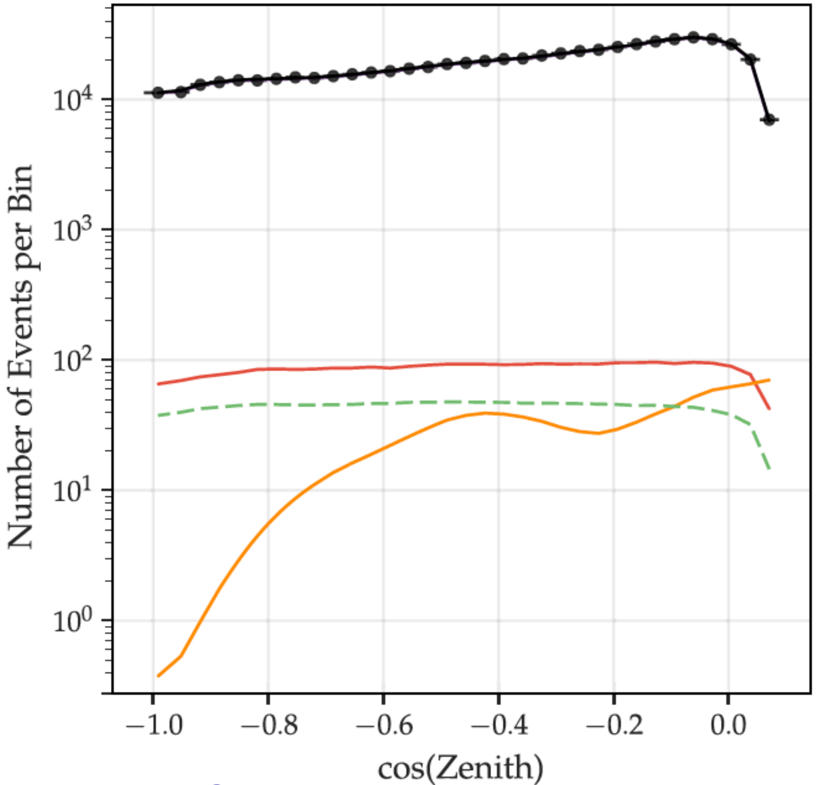


35 events >200 TeV (9.5yr data)

- Mostly through-going events
- Mostly up-going events (Northern sky)



Track events

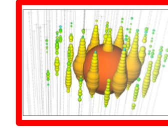


Caveat

- Track (hard) vs. HESE (soft)
- Northern sky vs. Southern sky

IceCube,PRD98(2018)062003
IceCube-Gen2,J.Phys.G48(2021)060501

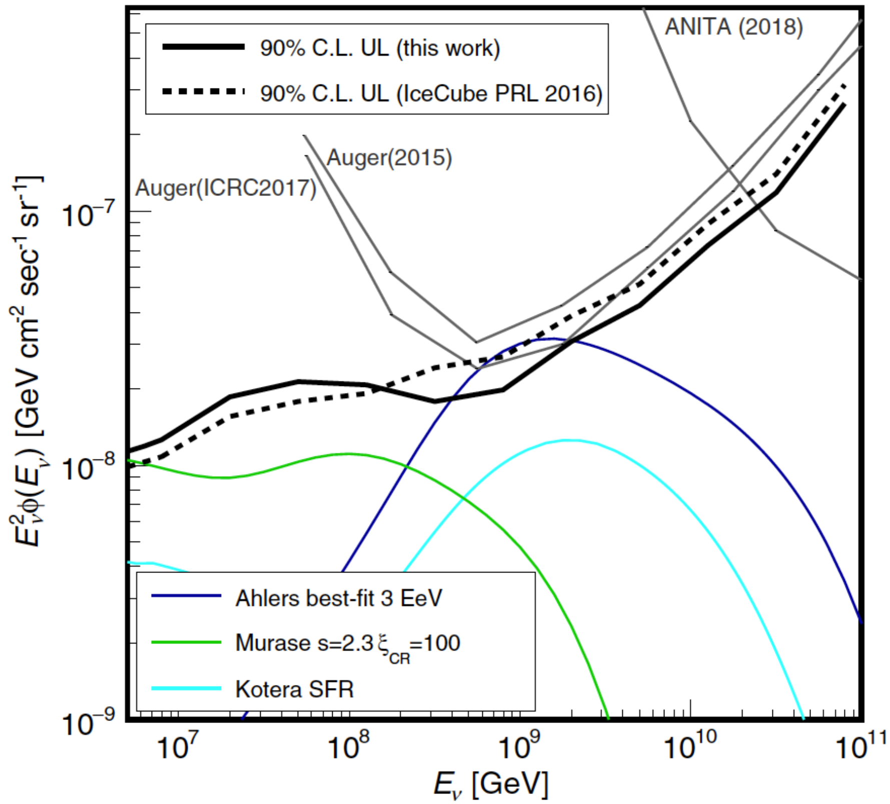
3. Extremely high-energy (EHE) neutrino flux

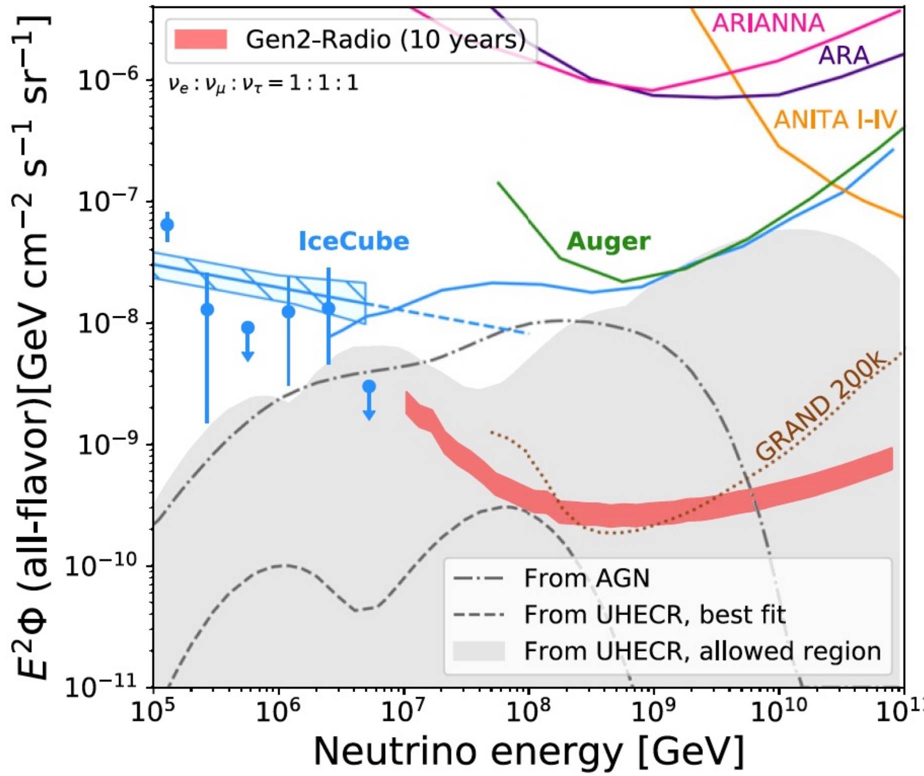


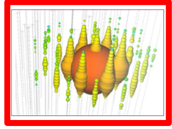
cascade

Flux limits

- Flux limit for > 5 PeV neutrinos in IceCube
- Need air shower Cherenkov/radio for > 10 PeV

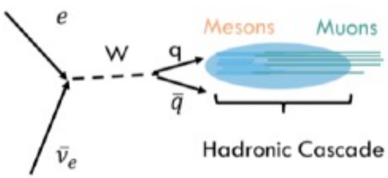






cascade

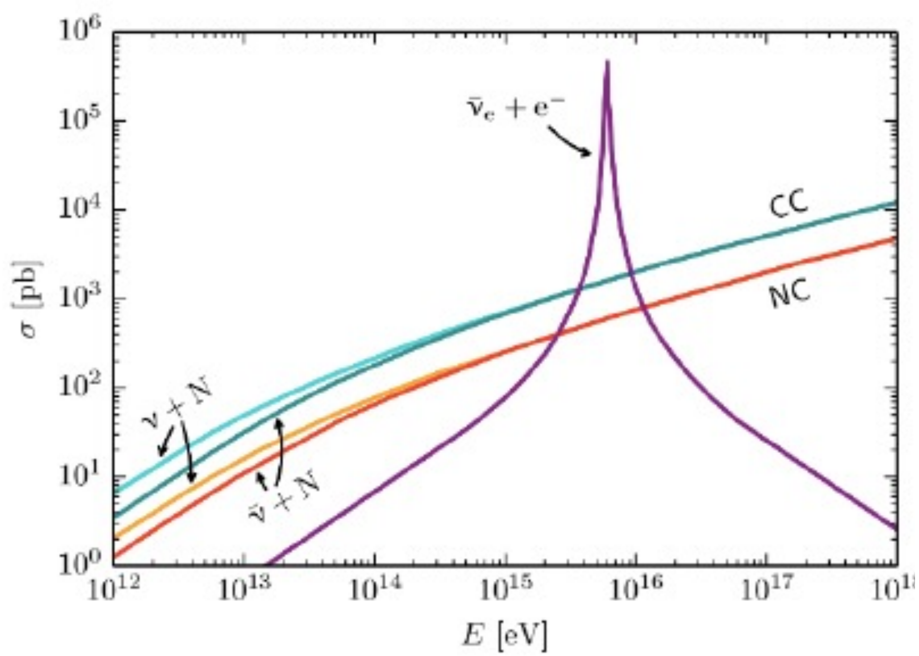
3. PeV energy partially contained events (PEPE)

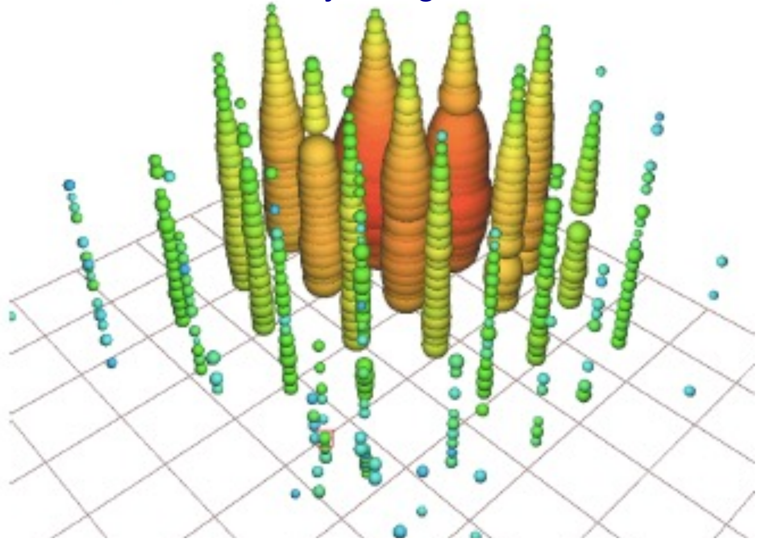


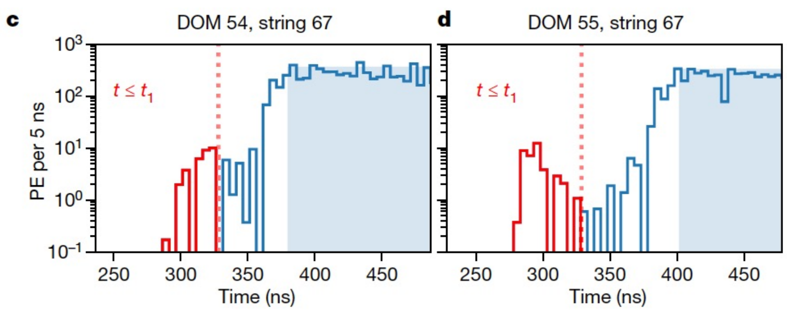
Glashow resonance

- With muon front event
- 5.9±0.2 PeV
- Access to neutrino vs. antineutrino

Glashow resonance candidate
"Hydrangea"







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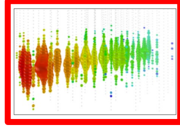
IceCube, Science361(2018)147, IceCube et al,(2018)eaat1378

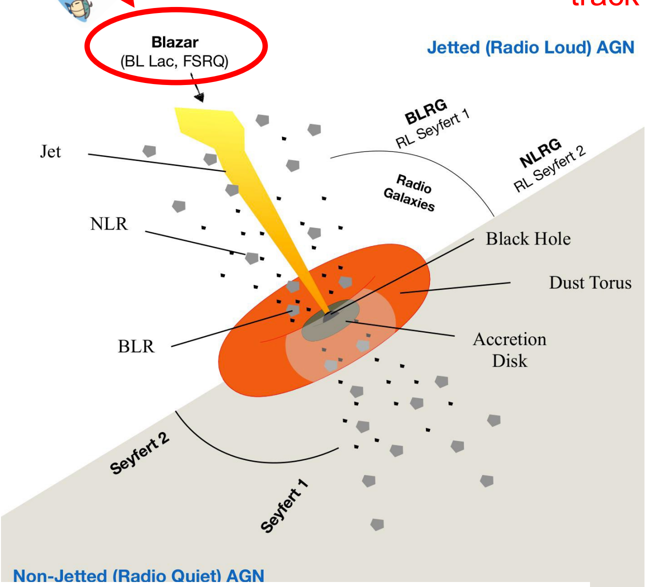
IceCube-san
Higgstan.com

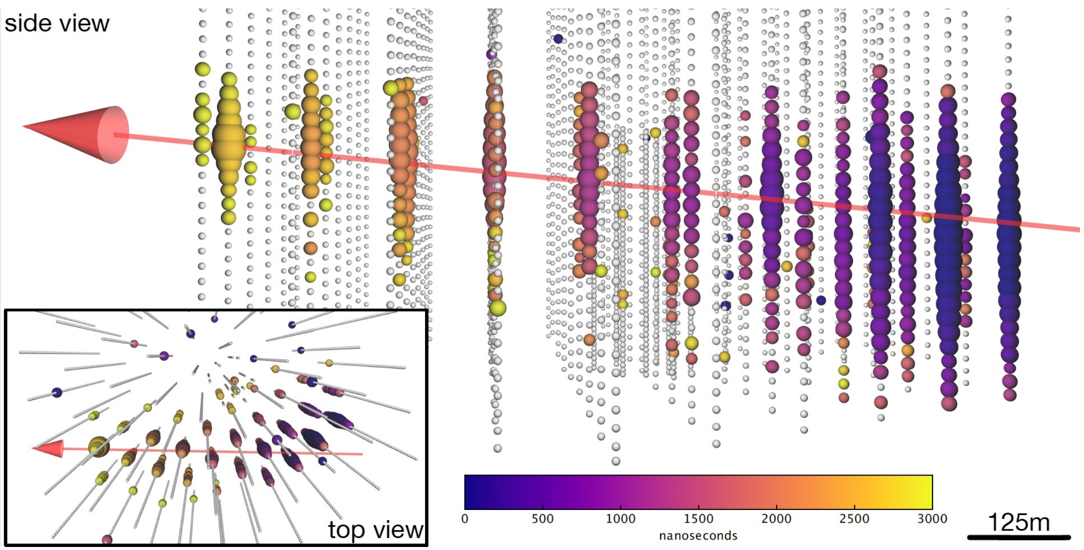


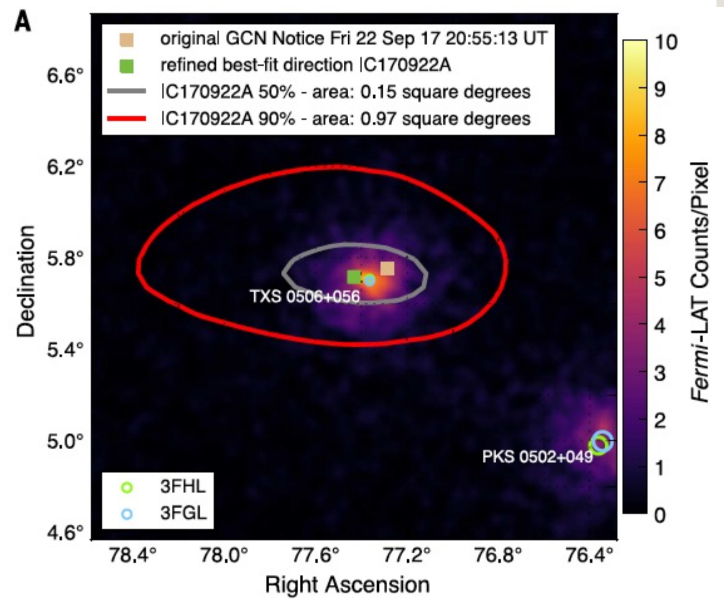
4. AGN neutrinos

TXS056+0506 (blazar)
- 3rd astrophysical neutrino source
- 1.8 Gpc (z=0.34)
- One of the brightest blazar

IC170922
- 290 TeV
- Horizontal long track event

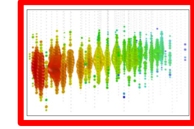






IceCube, PRL124(2020)051103, Science378(2022)538

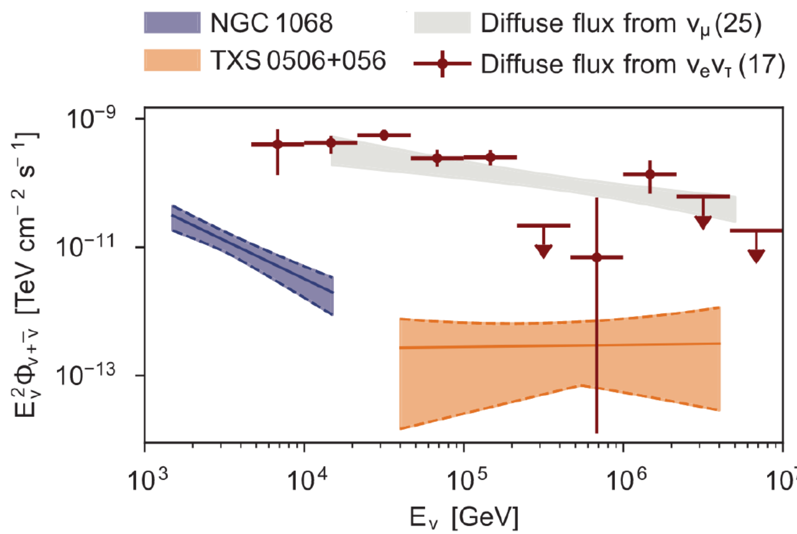
4. AGN neutrinos

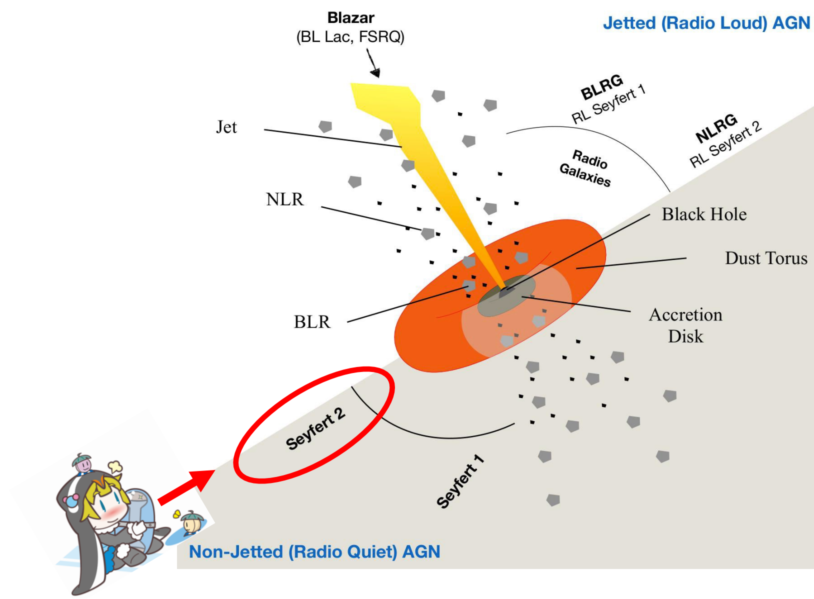


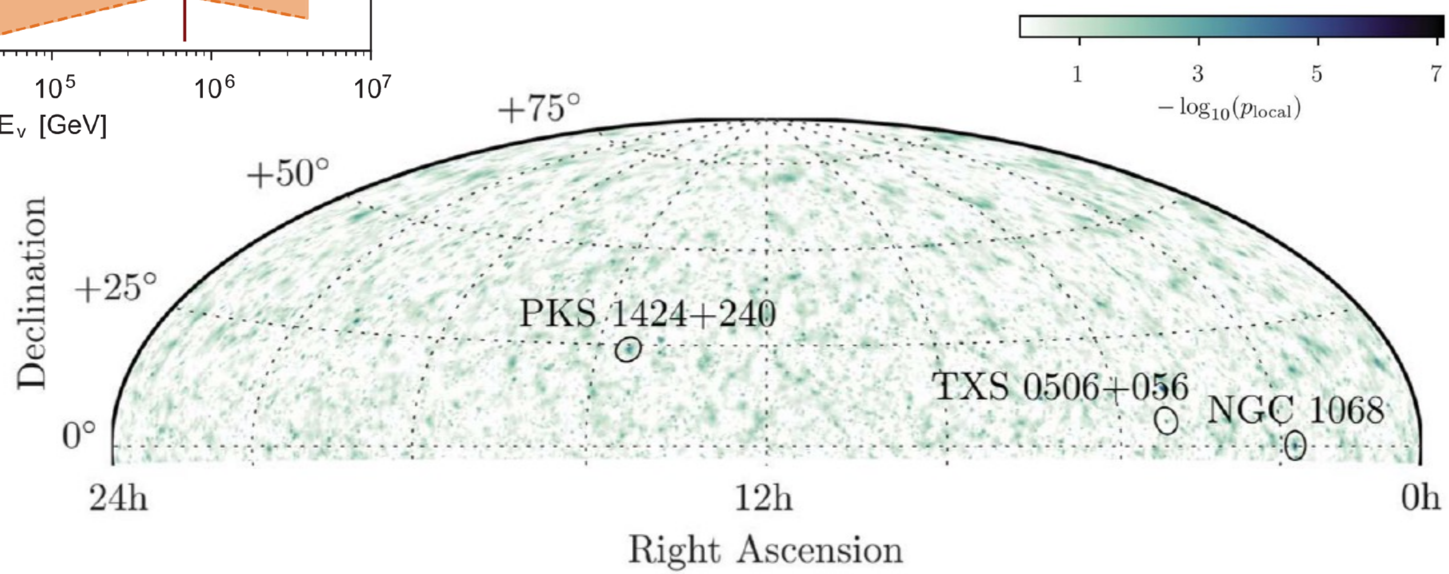
track

NGC1068 (radio galaxy)

- 4^{th} astrophysical neutrino source
- Nearby AGN (14.4Mpc)
- 1.5 – 15 TeV with γ~3.2±0.2







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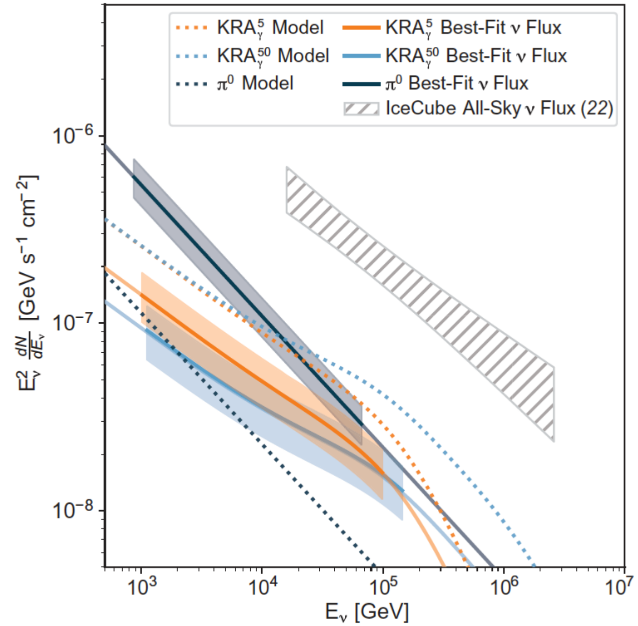
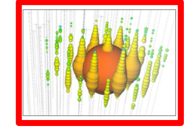
IceCube, Science 380(2023)1338

4. Galactic neutrinos

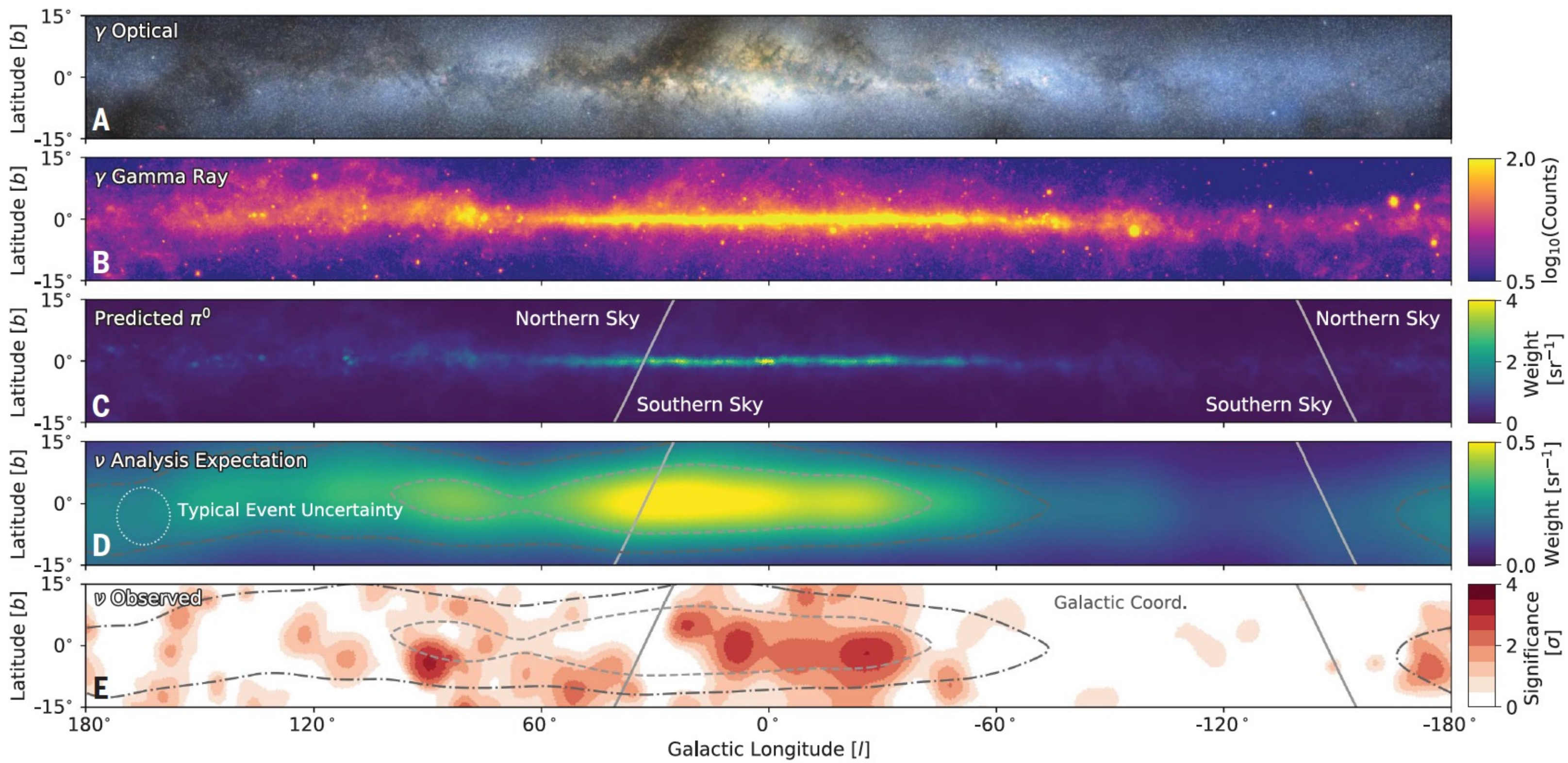
Cascade sample (southern sky)

- 5th astrophysical neutrino source
- Cascade sample + ML reconstruction
- γ~2.5 assumed (π^o model)
- Can be improved to identify point sources





cascade



1. Introduction

2. IceCube experiment

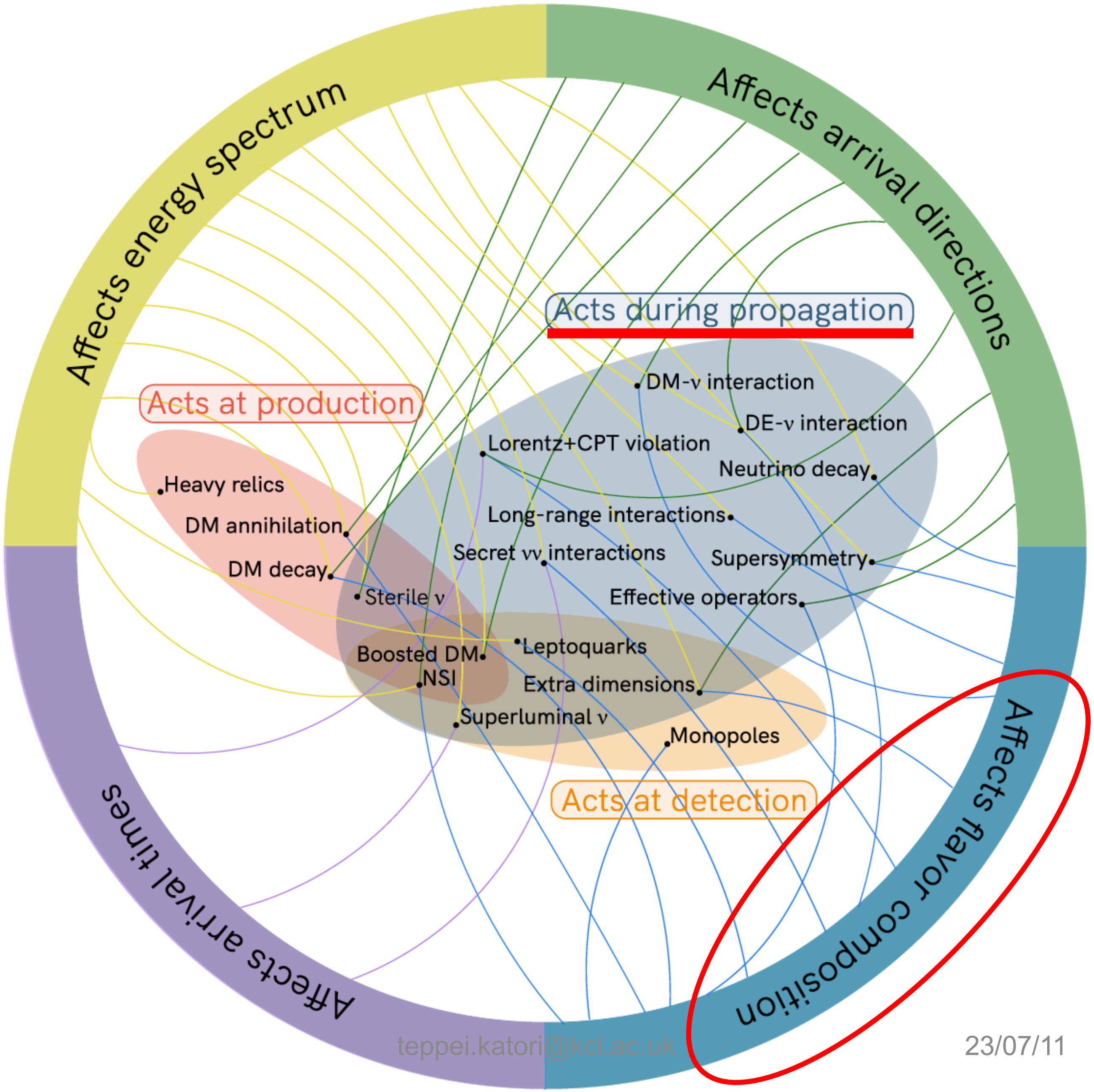
3. Astrophysical neutrino diffuse samples

4. Astrophysical neutrino sources

5. Search for Quantum-Gravity-Motivated Effects

6. Conclusions

Snowmass21 white paper, "Beyond the Standard Model effect with Neutrino Flavour", EPJC83(2023)15
Ackermann, Bustamante, Lu et al.JHEA.36(2022)55



5. Violation of fundamental physics

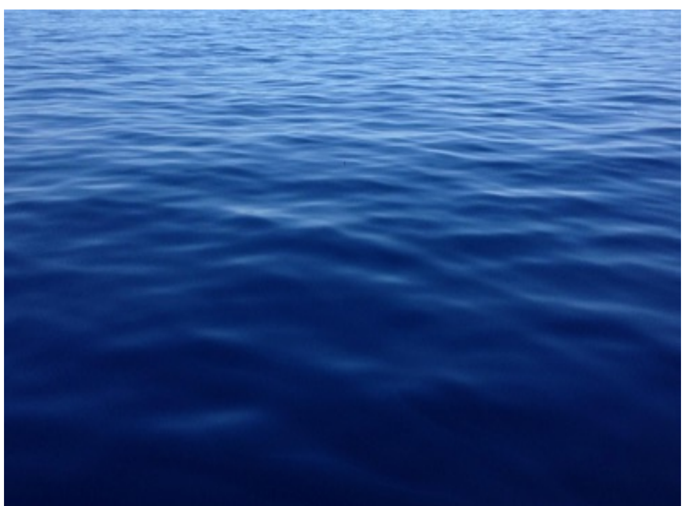
Neutrino propagation may be affected by quantum-gravity-motivated effects in vacuum, and neutrino properties might be modified

- Energy (spectrum distortion)
- Arrival time (neutrino delay)
- Neutrino flavour (anomalous mixings)

Expected effect is small. We need high-precision measurements to find such new physics

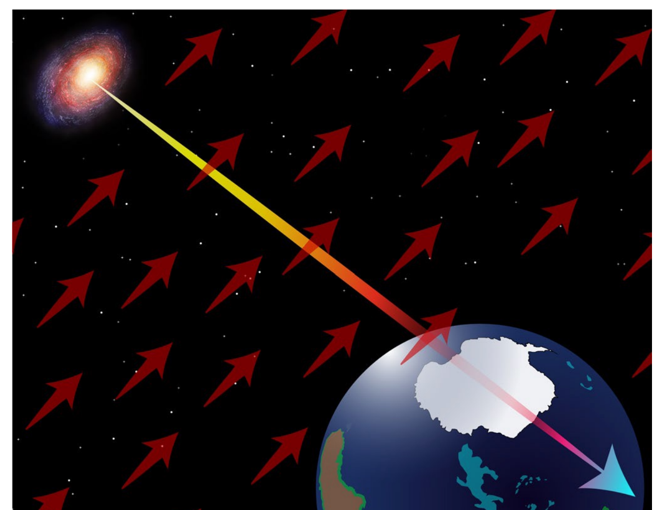
quantum foam

- quantum fluctuation of space-time



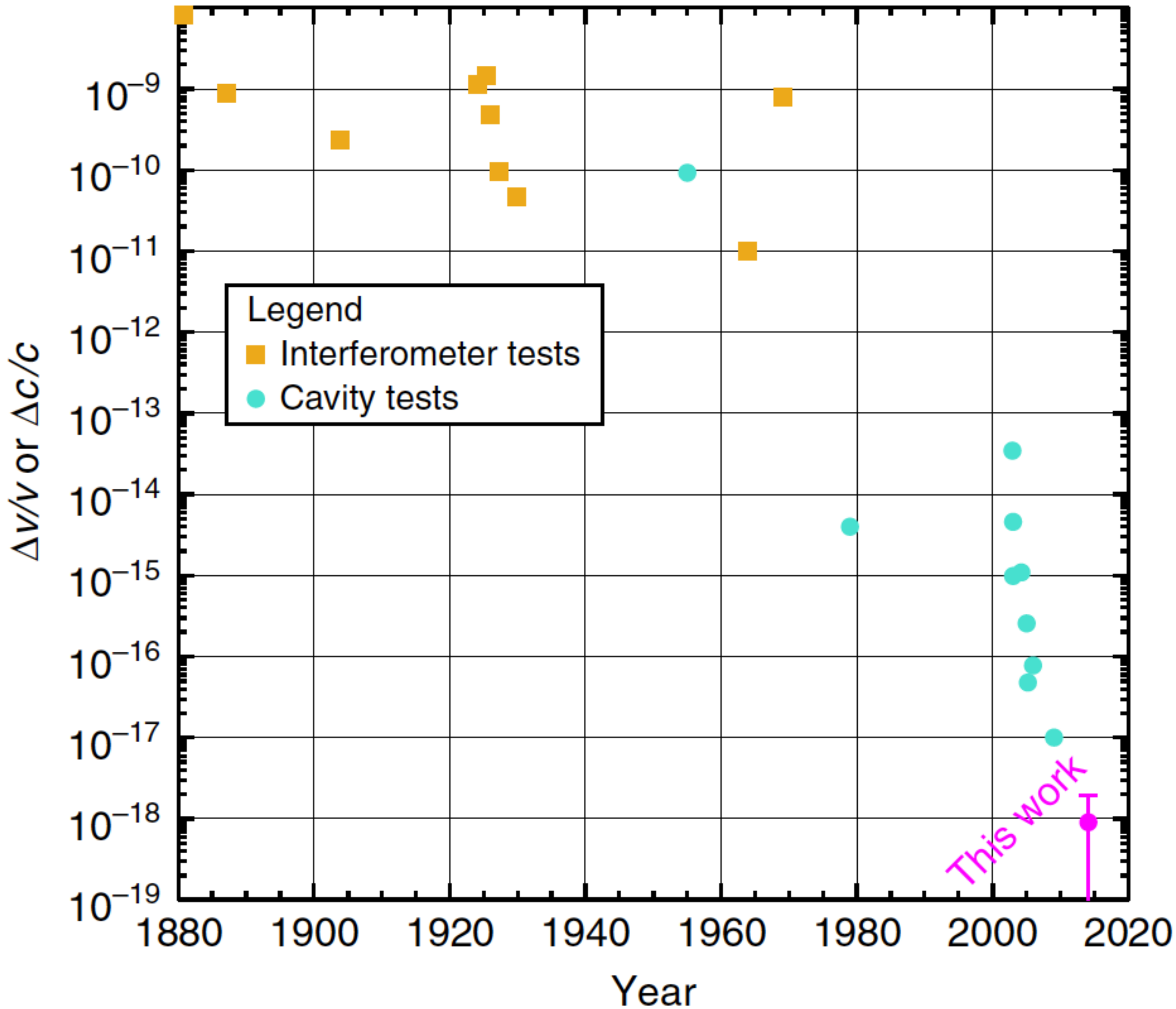
Lorentz violating field

- new field saturating the universe (æther)



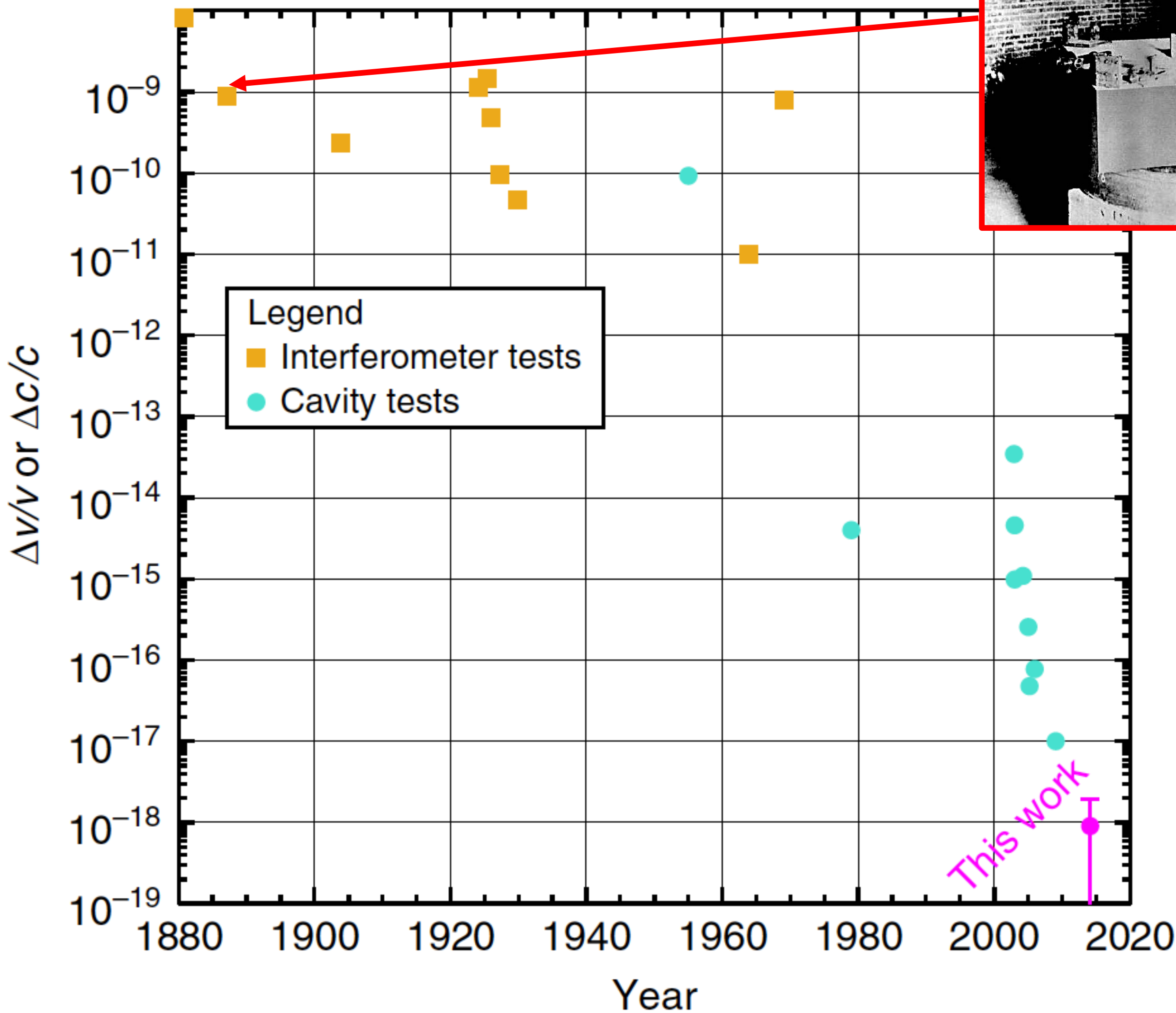
Nagel et al, Nature Comm., 6(2015)8174

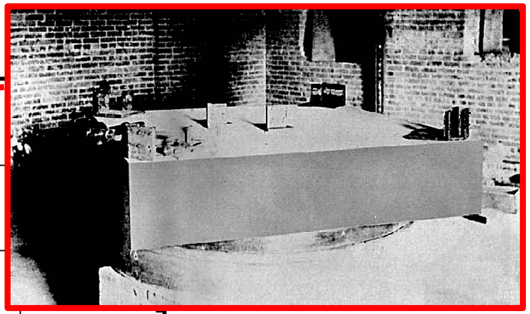
5. History of Michelson-Morley experiment



Nagel et al, Nature Comm., 6(2015)8174

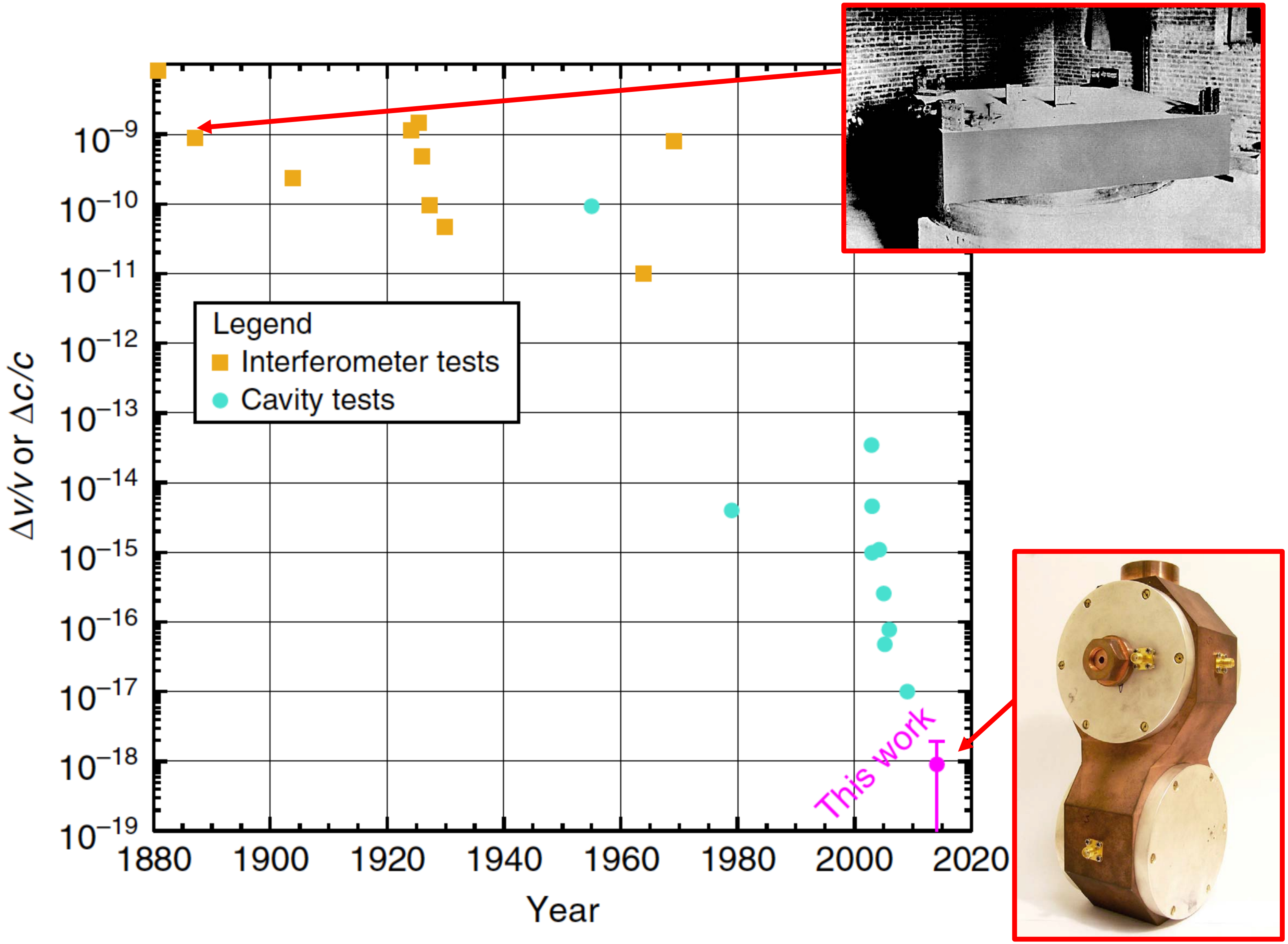
5. History of Michelson-Morley experiment (1887)





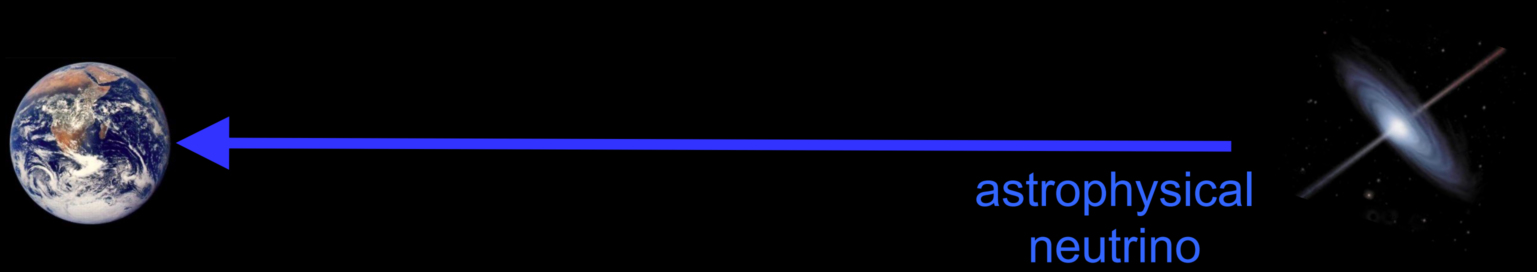
Nagel et al, Nature Comm., 6(2015)8174

5. History of Michelson-Morley experiment (2015)



5. High-energy astrophysical neutrinos

High-energy particles (>60 TeV) propagating a long distance (>100 Mpc) in vacuum
- Astrophysical neutrino flavour is sensitive to tiny space-time effect



Snowmass21 white paper, “Beyond the Standard Model effect with Neutrino Flavour”, EPJC83(2023)15

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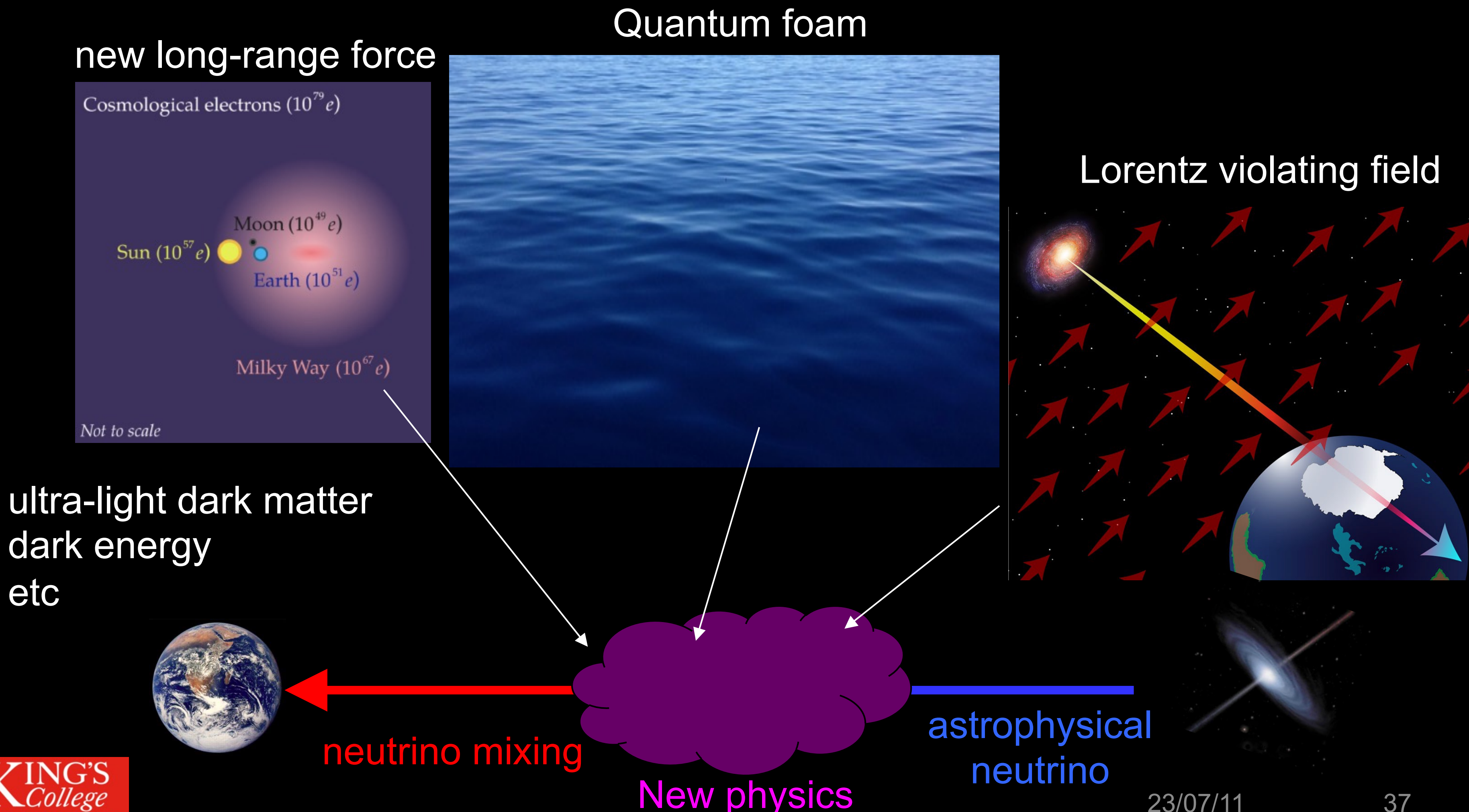
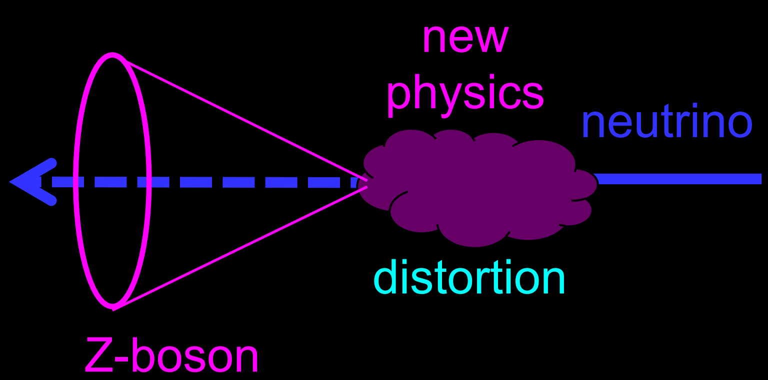
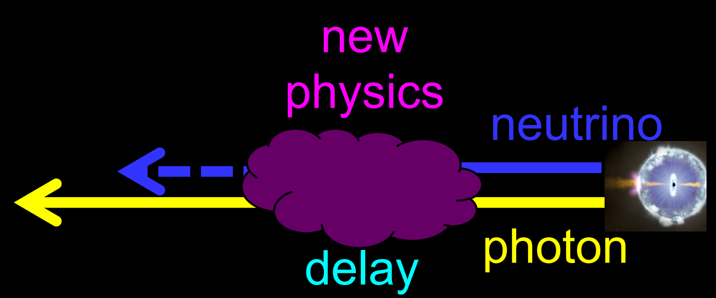


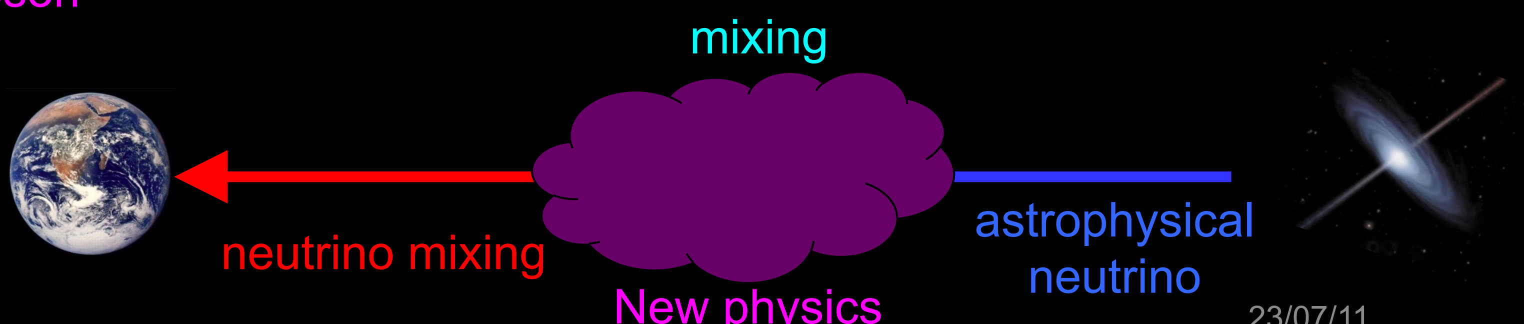
5. Search for QG-motivated effects with astrophysical neutrinos

High-energy particles (>60 TeV) propagating a long distance (>100 Mpc)
- Neutrinos can probe new physics in the universe

New physics search
- Spectrum distortion (energy)
- Time of Flight (time)
- Anomalous mixing (flavour)







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Diaz et al, PRD89(2014)043005, Borriello et al, PRD87(2013)116009, Stecker et al, PRD91(2015)045009

5. Search for QG-motivated effects with astrophysical neutrinos

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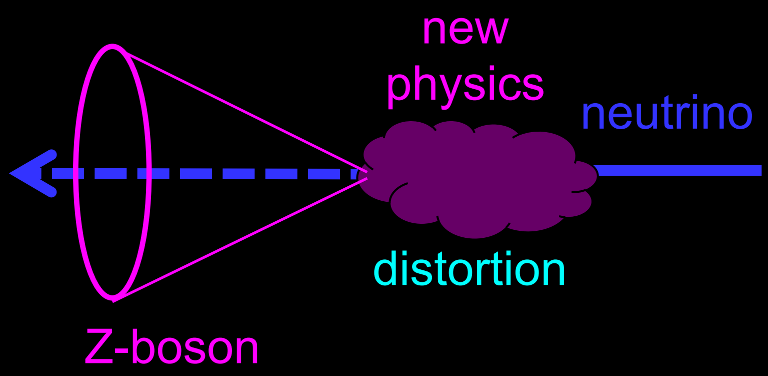
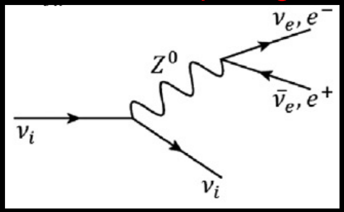
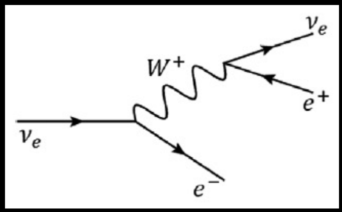


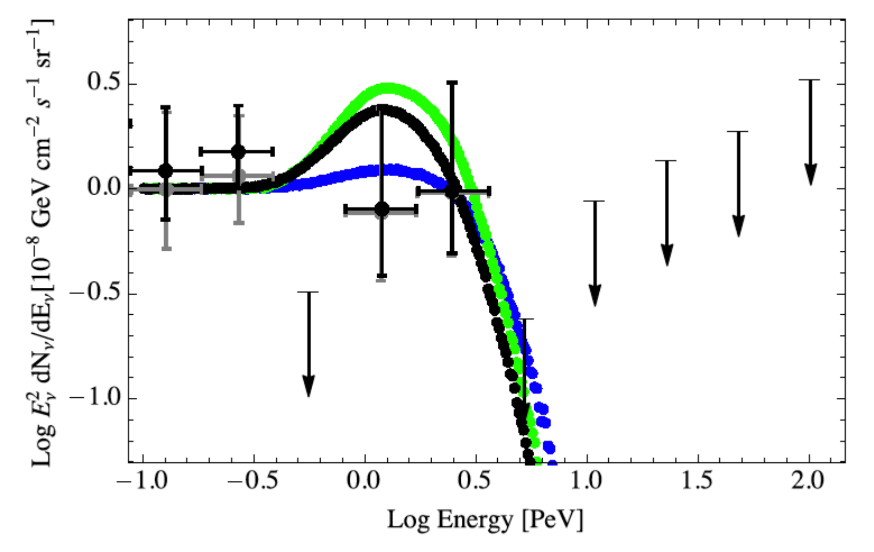
Lorentz violating field cause
Cherenkov radiation in vacuum

neutrino splitting



vacuum pair emission





Neutrino spectrum with new physics

Ellis et al, PLB789(2019)352, Laha PRD100(2019)103002, Wei et al, JHEA22(2019)1,
Amelino-Camelia et al., Nat.Astro (2023)

5. Search for QG-motivated effects with astrophysical neutrinos

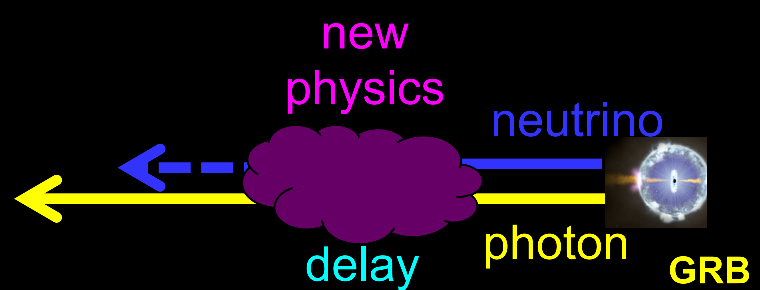
High-energy particles (>60 TeV) propagating a long distance (>100 Mpc)
- Neutrinos can probe new physics in the universe

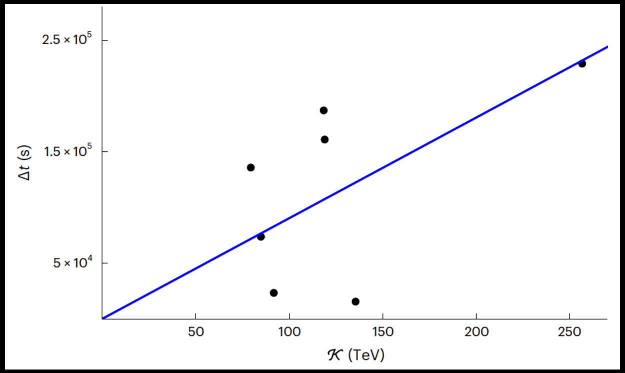
New physics search
- Spectrum distortion (energy)
- Time of Flight (time)
- Anomalous mixing (flavour)

Modified dispersion due to quantum foam cause unexpected delay/advance for neutrinos

$$E^2 = p^2 + m^2 \pm p^2 \left(\frac{p}{\xi_n E_P}\right)^n$$

$$\Delta t = \eta D(1) \frac{K(E,Z)}{M_P}$$





Argüelles, TK, Salvado, PRL115(2015)161303
Bustamante, Beacom, Winter, PRL115(2015)161302

5. Search for QG-motivated effects with astrophysical neutrinos

High-energy particles (>60 TeV) propagating a long distance (>100 Mpc)

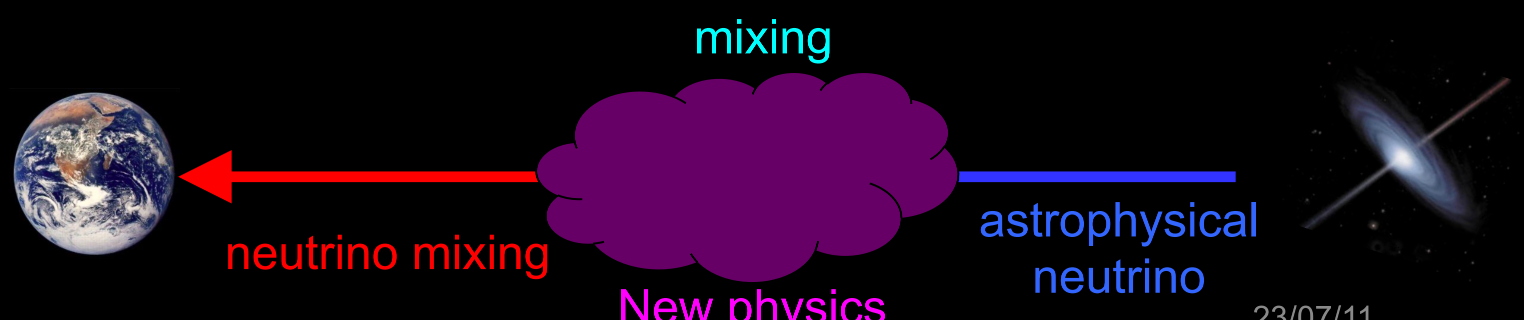
- Neutrinos can probe new physics in the universe

New physics search

- Spectrum distortion (energy)
- Time of Flight (time)
- Anomalous mixing (flavour)

Flavour effect

- Macroscopic quantum effect and sensitive to small effects



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5. Search for QG-motivated effects with astrophysical neutrinos

Standard Model Extension (SME) is an effective field theory to look for Lorentz violation

Standard Model | New physics

$$L = i\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\bar{\psi}\psi + \bar{\psi}\gamma^{\mu}a_{\mu}\,\psi + \bar{\psi}\gamma^{\mu}c_{\mu\nu}\partial^{\nu}\psi \cdots$$

Effective Hamiltonian can be written from here

Standard Model | New physics (renormalizable) | higher dimension operator (non-renormalizable)

$$h_{eff} \sim \frac{1}{2E}U^{\dagger}M^{2}U + a_{\alpha\beta}^{(3)} - Ec_{\alpha\beta}^{(4)} + E^{2}a_{\alpha\beta}^{(5)} - E^{3}c_{\alpha\beta}^{(6)} \cdots$$

IceCube is sensitive to higher dimension operators

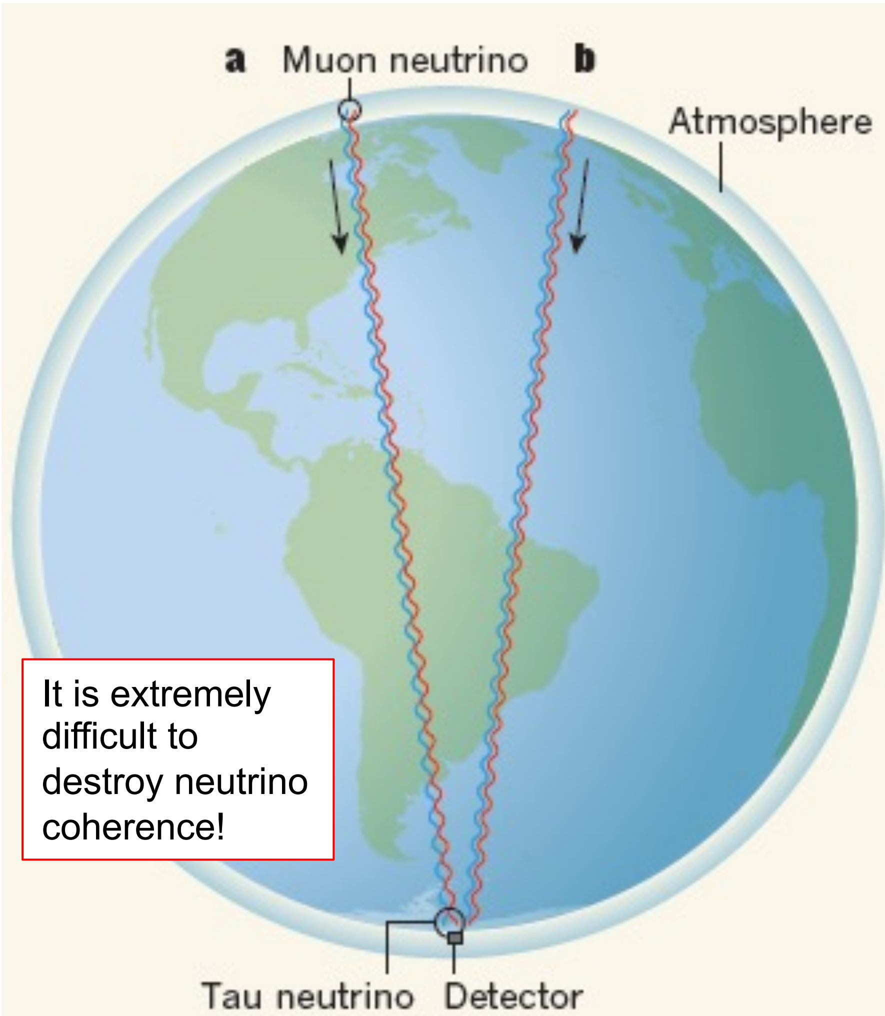
$$E^3 c_{\alpha\beta}^{(6)} = E^3 \begin{pmatrix} c_{ee}^{(6)} & c_{e\mu}^{(6)} & c_{\tau e}^{(6)} \\ c_{e\mu}^{(6)*} & c_{\mu\mu}^{(6)} & c_{\mu\tau}^{(6)} \\ c_{\tau e}^{(6)*} & c_{\mu\tau}^{(6)*} & c_{\tau\tau}^{(6)} \end{pmatrix}$$

dimension-6 operator natural scale: $c^{(6)} \sim \frac{1}{E_{Planck}^{2}} \sim 10^{-38}GeV^{-2}$

In modified dispersion, $E^2 \sim p^2 + m^2 \pm E^2\left(\frac{E}{\xi_n E_{Panck}}\right)^n \rightarrow c^{(6)} \sim \frac{1}{\left(\xi_2 E_{Planck}\right)^2}$

IceCube, Nature Physics 14 (2018) 961
Mewes, Nature 560 (2018) 316

5. Neutrino interferometry – Atmospheric neutrinos

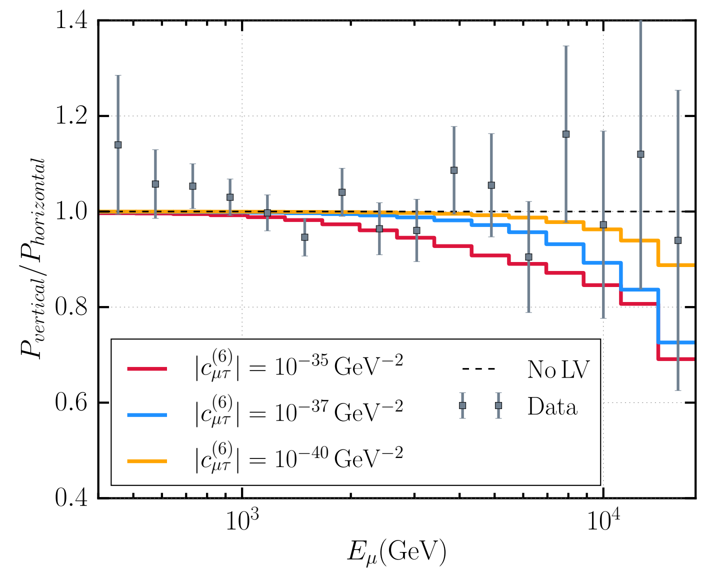


It is extremely difficult to destroy neutrino coherence!

Neutrino oscillation is a nature interferometer. Any extra interactions in the Lagrangian contribute the phase shift

The highest energy - 20 TeV
The longest baseline - 12700km

If anomalous coupling with neutrinos in vacuum cause a phase shift in similar order, we can see it from spectrum distortion of atmospheric neutrinos



IceCube, Nature Physics 14 (2018) 961
Mewes, Nature 560 (2018) 316

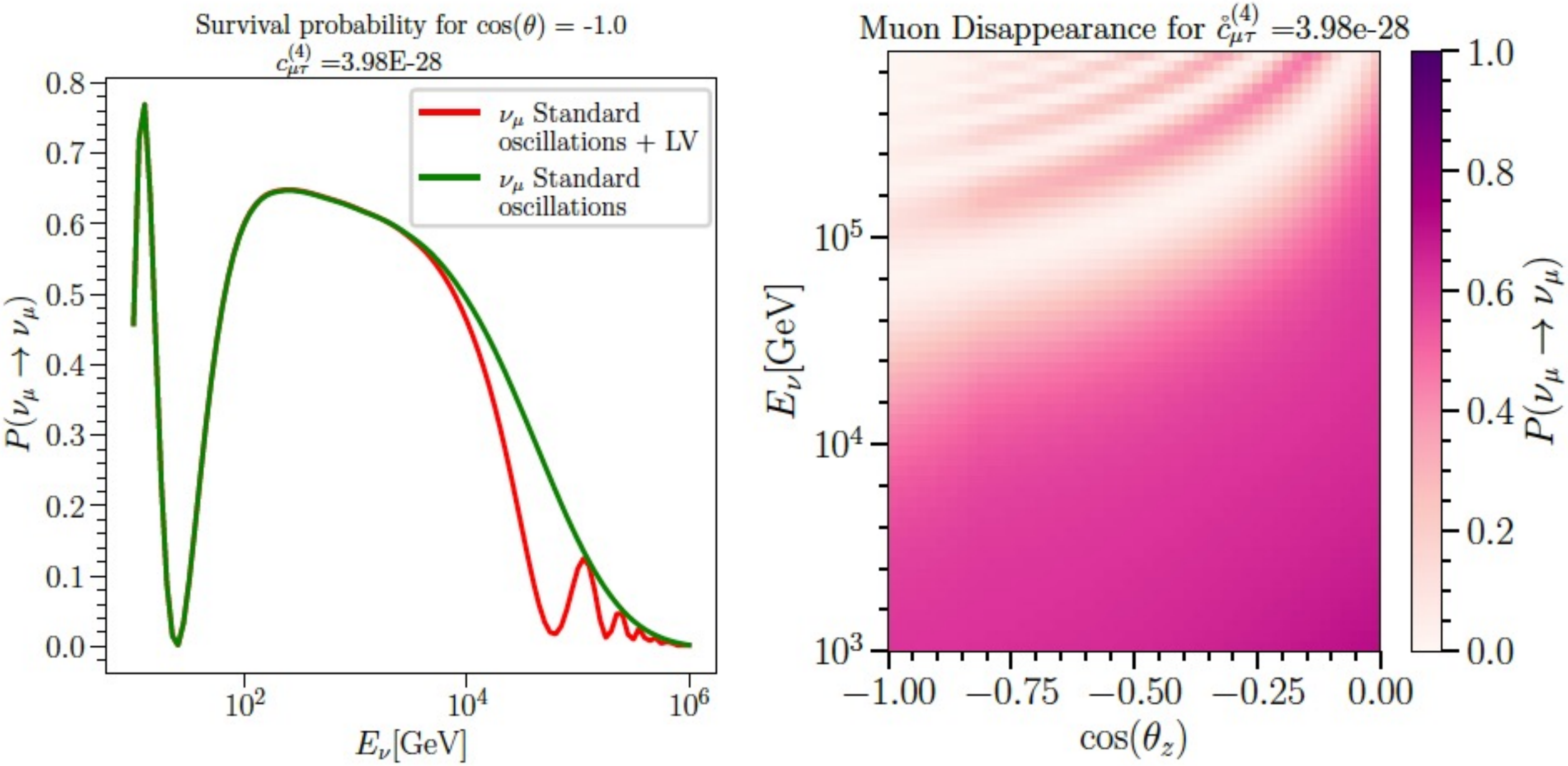
5. Neutrino interferometry – Atmospheric neutrinos

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	$\|\mathrm{Re}\,(\mathring{a}^{(3)}_{\mu\tau})\|, \|\mathrm{Im}\,(\mathring{a}^{(3)}_{\mu\tau})\|$ $< 2.9 \times 10^{-24}$ 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	$\|\mathrm{Re}\,(\mathring{c}^{(4)}_{\mu\tau})\|, \|\mathrm{Im}\,(\mathring{c}^{(4)}_{\mu\tau})\|$ $< 3.9 \times 10^{-28}$ (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	$\|\mathrm{Re}\,(\mathring{a}^{(5)}_{\mu\tau})\|, \|\mathrm{Im}\,(\mathring{a}^{(5)}_{\mu\tau})\|$ $< 2.3 \times 10^{-32}$ 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	$\|\mathrm{Re}\,(\mathring{c}^{(6)}_{\mu\tau})\|, \|\mathrm{Im}\,(\mathring{c}^{(6)}_{\mu\tau})\|$ $< 1.5 \times 10^{-36}$ 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	$\|\mathrm{Re}\,(\mathring{a}^{(7)}_{\mu\tau})\|, \|\mathrm{Im}\,(\mathring{a}^{(7)}_{\mu\tau})\|$ $< 8.3 \times 10^{-41}$ 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	$\|\mathrm{Re}\,(\mathring{c}^{(8)}_{\mu\tau})\|, \|\mathrm{Im}\,(\mathring{c}^{(8)}_{\mu\tau})\|$ $< 5.2 \times 10^{-45}$ GeV^{-4} (99% C.L.) $< 1.4 \times 10^{-45}$ GeV^{-4} (90% C.L.)	this work

TABLE I: Comparison of attainable best limits of SME coefficients in various fields.

5. Neutrino interferometry – Atmospheric neutrinos

New analysis will improve the results
- Better reconstruction, systematics
- Higher energy track sample (up to 100 TeV)
- Full 3 flavour oscillation analysis to look for all possible exotic oscillations

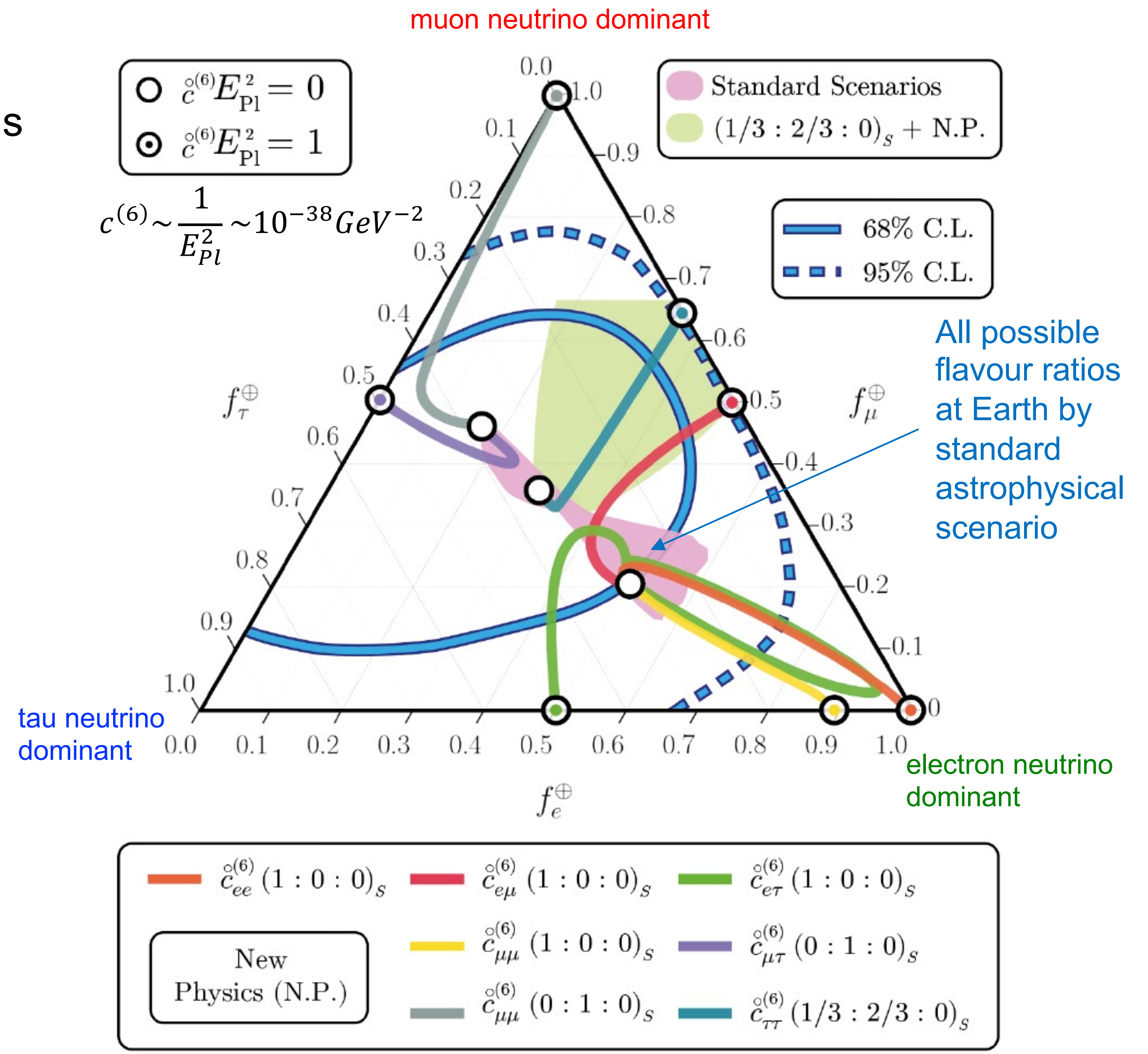


IceCube, Nature Physics 18(2022)1287

5. Flavor ratio – Astrophysical neutrinos

Nonzero new physics moves standard predictions ○ to different locations ⊙ depending on the types of new physics operators.

If the new physics models bring the standard predictions outside of the data contour, such model can be rejected by current data



$$c^{(6)} \sim \frac{1}{E_{Pl}^2} \sim 10^{-38} GeV^{-2}$$

5. Flavor ratio – Astrophysical neutrinos

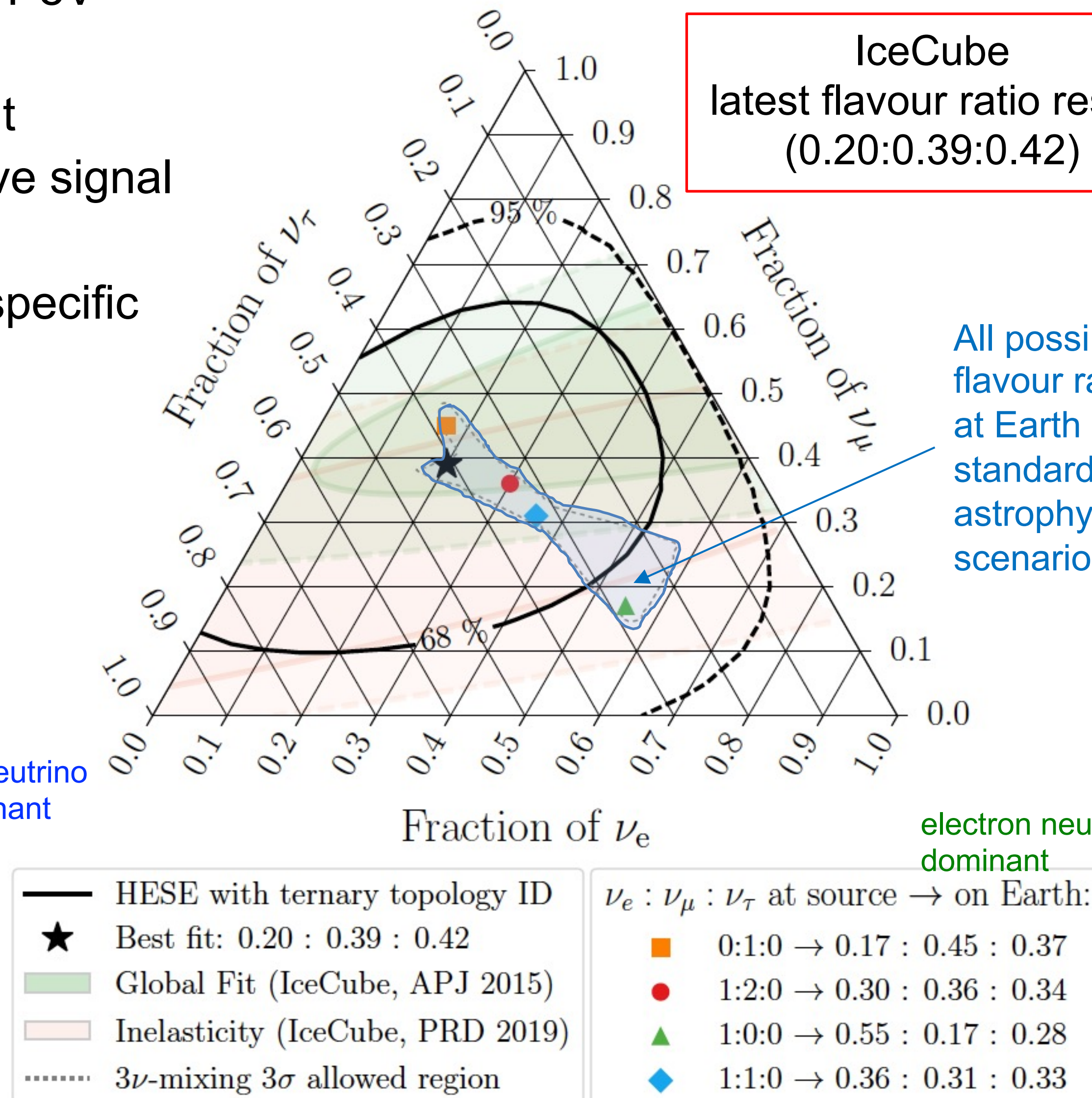
60 HESE events in 60 TeV – 2 PeV

New flavour ratio measurement
 - contour is very big, no positive signal of new physics
 - Data are used to test some specific new physics models

We focus on setting limits on certain SME coefficients

muon neutrino dominant

IceCube
latest flavour ratio result
(0.20:0.39:0.42)



All possible flavour ratios at Earth by standard astrophysical scenario

tau neutrino dominant

electron neutrino dominant

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5. HESE 7.5-yr flavor Lorentz violation search

60 HESE events in 60 TeV – 2 PeV

IceCube data start to explore quantum gravity-motivated signal region for some parameters

$$c^{(6)} \leq \frac{1}{M_{Planck}^2} \sim 10^{-38} GeV^{-2}$$

10^{-26} GeV ~ dim-3 LV limit

10^{-31} ~ dim-4 LV limit

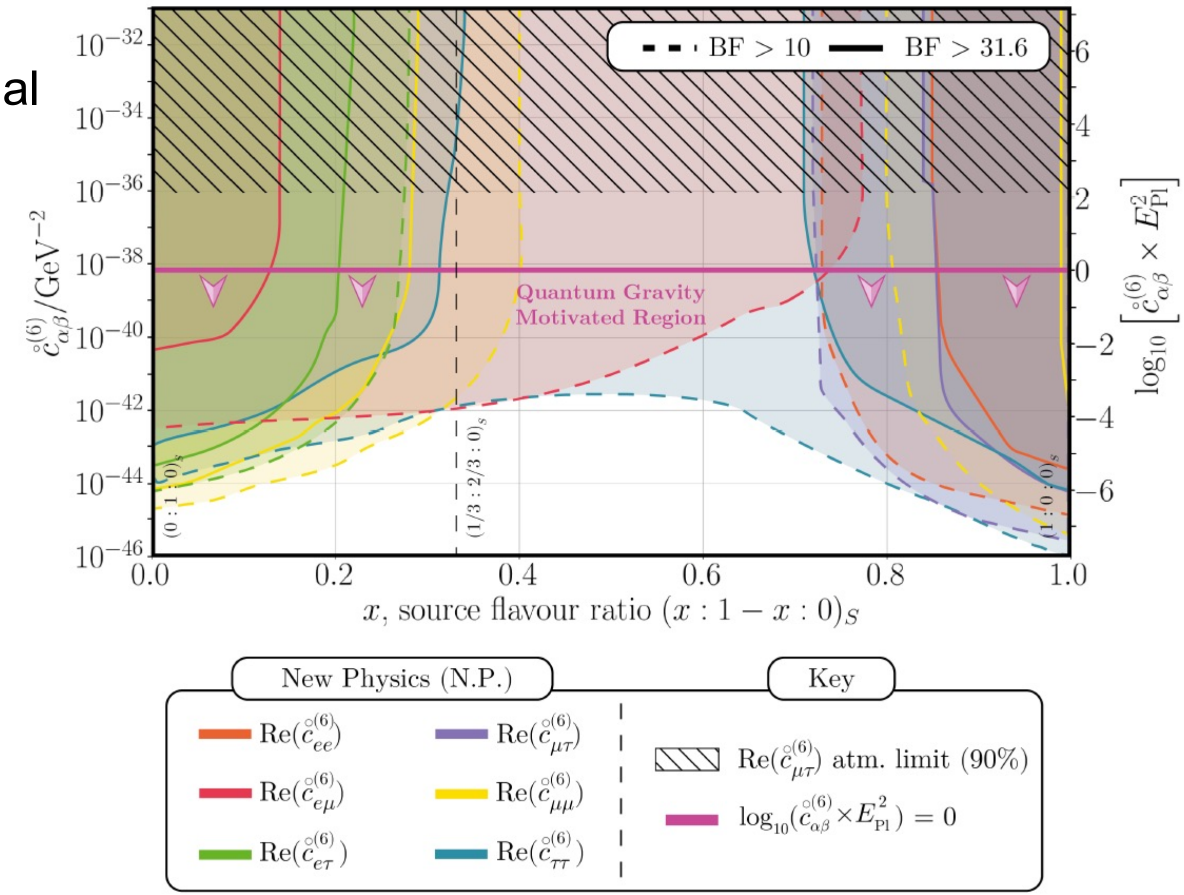
10^{-37} GeV^{-1} ~ dim-5 LV limit

10^{-42} GeV^{-2} ~ dim-6 LV limit

10^{-47} GeV^{-3} ~ dim-7 LV limit

10^{-52} GeV^{-4} ~ dim-8 LV limit

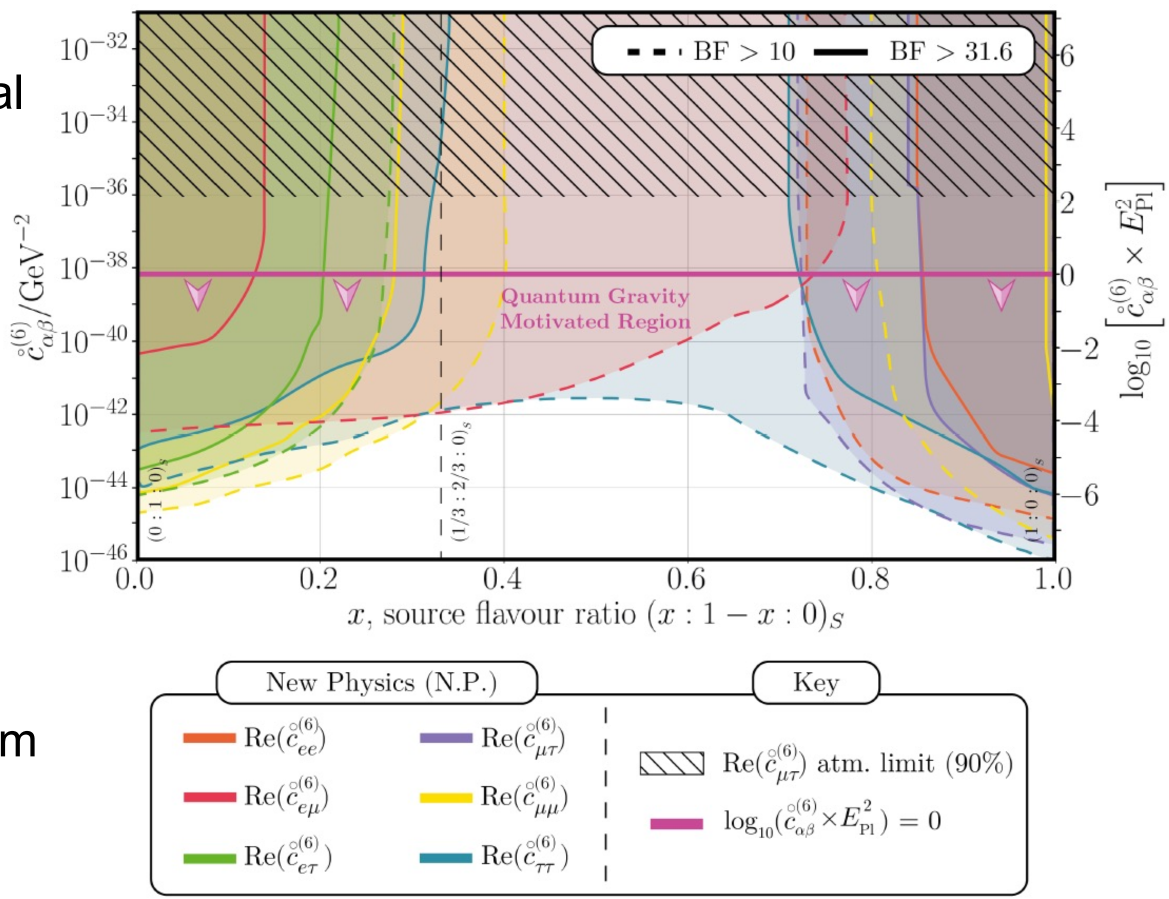
dim-6 new physics operator limit



5. HESE 7.5-yr flavor Lorentz violation search

60 HESE events in 60 TeV – 2 PeV

dim-6 new physics operator limit



IceCube data start to explore quantum gravity-motivated signal region for some parameters

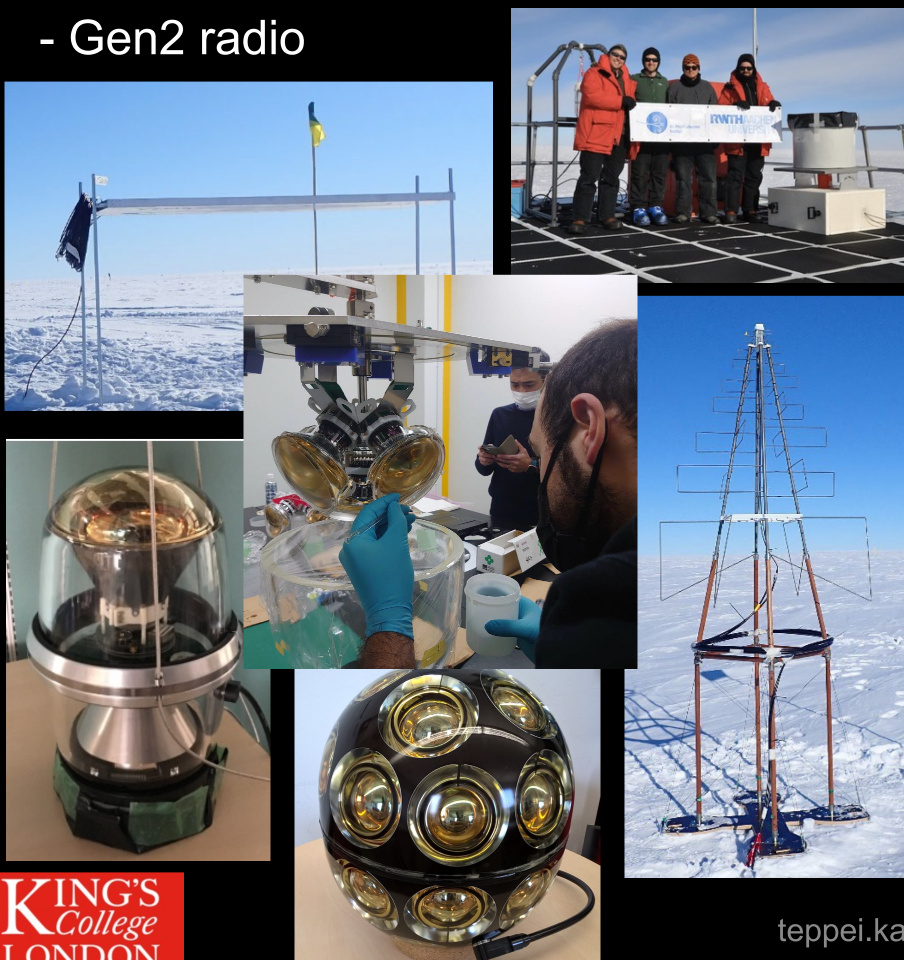
$$c^{(6)} \leq \frac{1}{M_{Planck}^2} \sim 10^{-38} GeV^{-2}$$

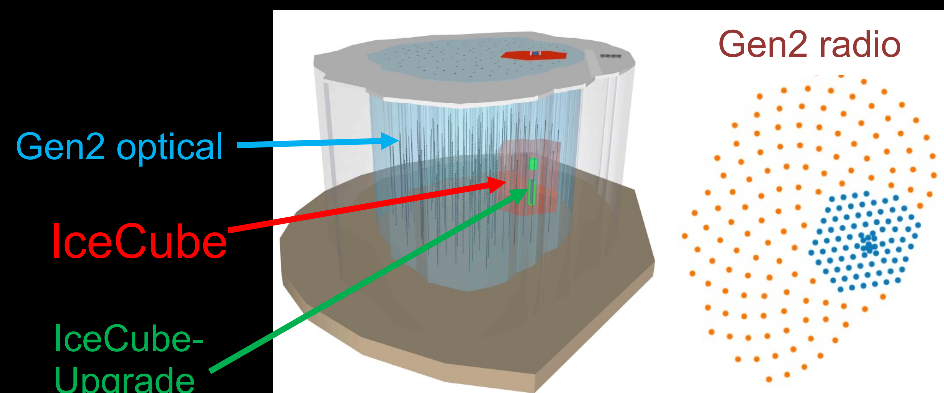
So far, IceCube neutrinos don't show the evidence of quantum gravity

1. quantum gravity is wrong
2. Multi-messenger astronomy
3. Flavour identification algorithm
4. More data

3. IceCube-Gen2

larger separation (125m → ~200-300m) to cover larger volume (x8)
R&D is underway
- Gen2 optical
- Gen2 surface
- Gen2 radio





The first stage of Gen2 (IceCube upgrade) is ongoing

Conclusion

Quantum gravity may create a new effect on neutrinos in vacuum.

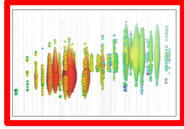
High-energy astrophysical neutrino observed at IceCube are powerful tools to look for quantum-gravity-motivated new physics.

Astrophysical neutrino flavour structure is used to look for quantum-gravity-motivated effect in IceCube. The results can be improved in near future.

IceCube-Gen2 collaboration

Thank you for your attention!

Backup

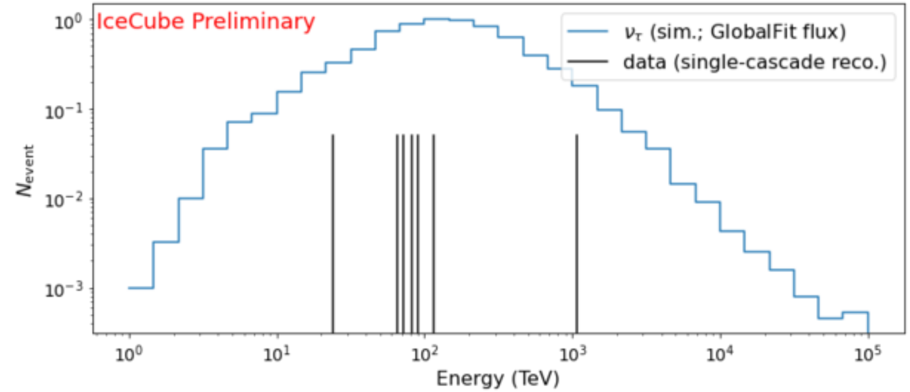


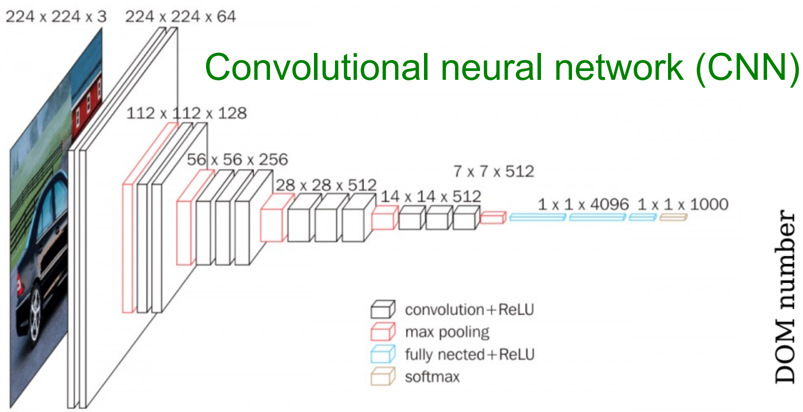
double cascade

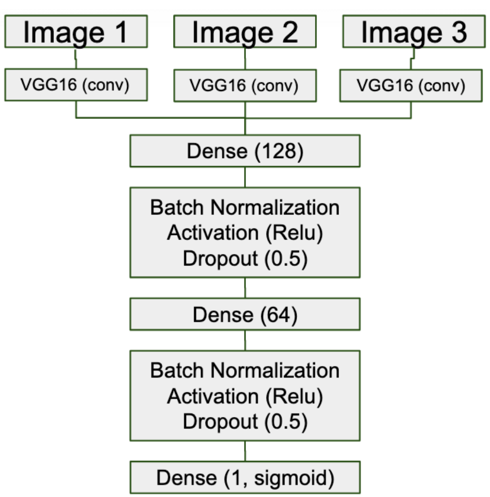
4 . New astrophysical tau neutrino sample

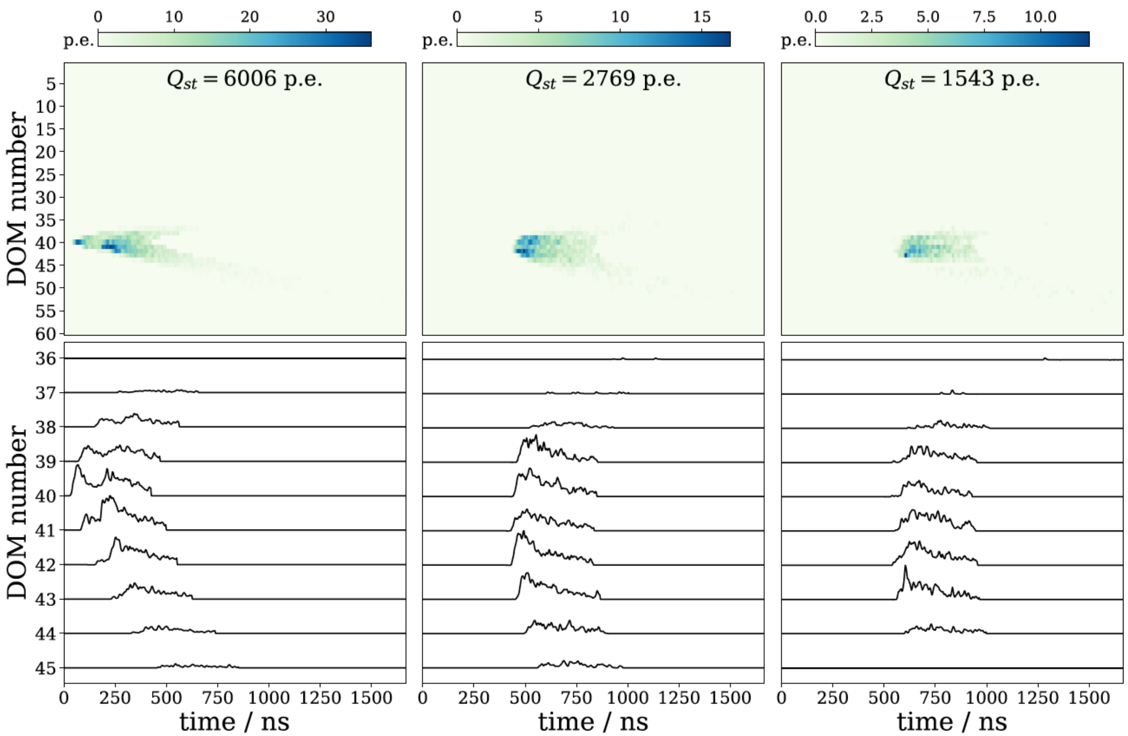
7 astrophysical tau neutrinos

- ML-based dedicated selection
- Data consistent with prediction



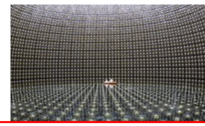






5. Test of Lorentz violation with neutrinos

Spectral distortion

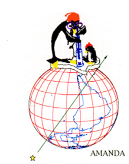


Super-Kamiokande

PRD91(2015)052003

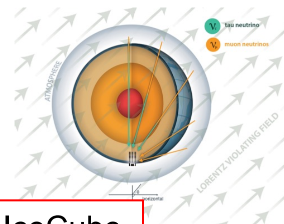
Daya Bay

PRD98(2018)092013



AMANDA

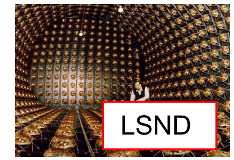
PRD79(2009)102005



IceCube

Nature Physics 14(2018)961

Sidereal variation



LSND

PRD72(2005)076004

MiniBooNE

PLB718(2013)1303

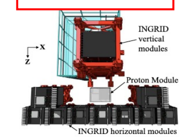
MINOS ND

PRL101(2008)151601

MINOS FD

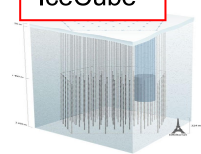
PRL105(2010)151601

T2K ND



PRD95(2017)111101

IceCube

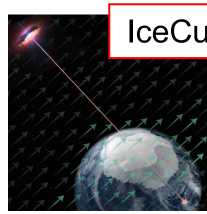


PRD82(2010)112003

Double Chooz

PRD86(2013)112009

Flavor ratio

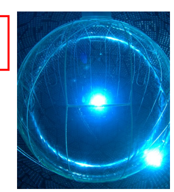


IceCube

Nature Physics, 18(2022)1287

Seasonal variation

SNO



PRD98(2018)112013

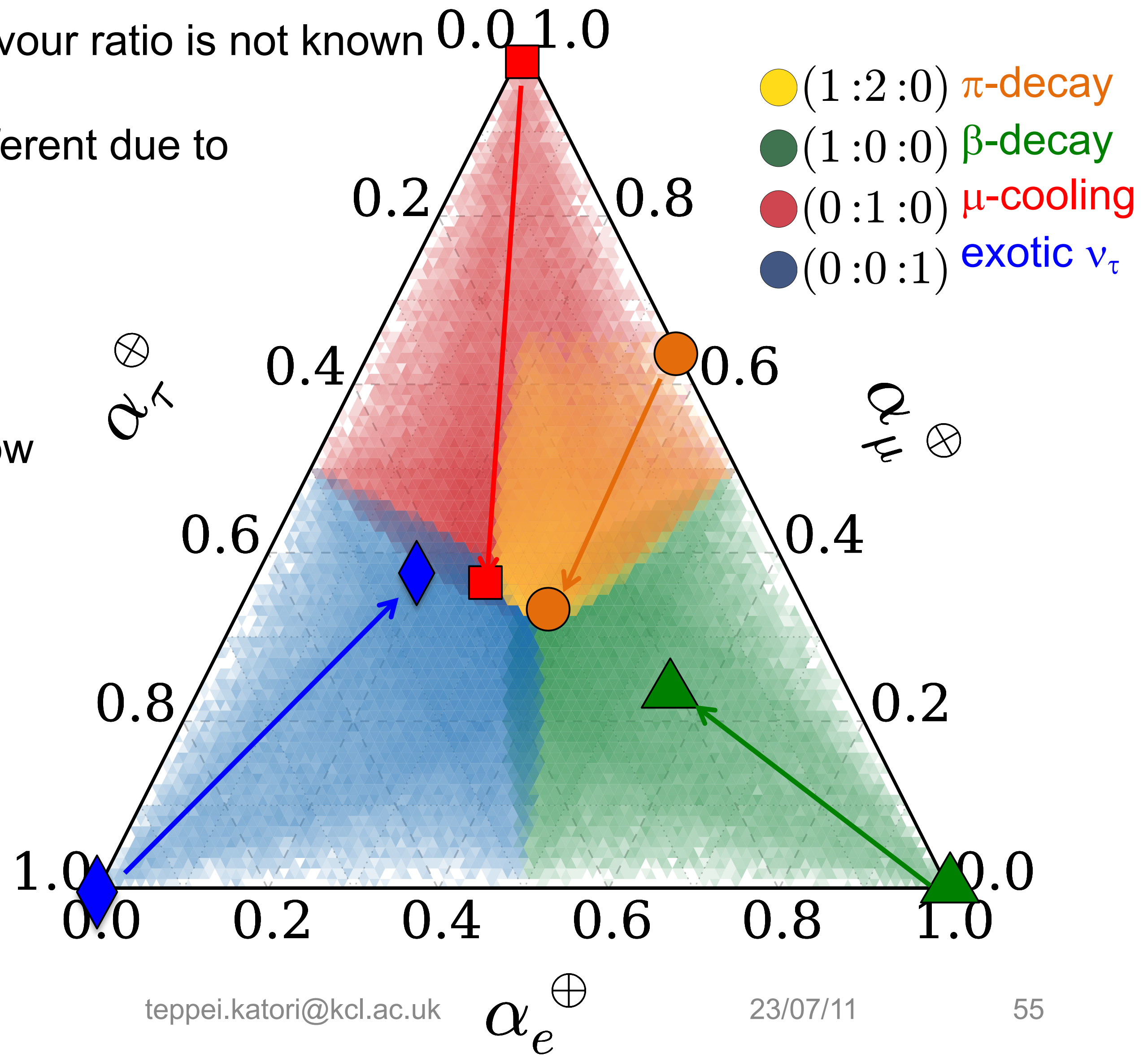
5. Neutrino flavor ratio ($\nu_e : \nu_\mu : \nu_\tau$)

Astrophysical neutrino production mechanism is not known → production flavour ratio is not known

Flavour ratio on Earth is different due to mixing by neutrino masses

All possible flavour ratio is confined in a small space

e.g.) New physics just below the limit can produce any flavour ratio



5. HESE 7.5-yr flavor Lorentz violation search

Data, 2635 days HESE sample IceCube, PRD104(2021)022002

- 17 track events, 20 log(E) bins [60 TeV, 10 PeV], 10 cosθ bins [-1.0, +1.0]
- 41 cascade events, 20 log(E) bins [60 TeV, 10 PeV], 10 cosθ bins [-1.0, +1.0]
- 2 double cascades, 20 log(E) bins [60 TeV, 10 PeV], 10 log(L) bins [10m, 100m]

Simulation

Bhattacharya et al.,JHEP06(2015)110

- Foregrounds, conventional (Honda flux), prompt (BERSS model), muon (CORSIKA)
- Astrophysical neutrinos, simple power law
- Interaction, NLO PDF DIS (CSMS model) Cooper-Sarkar et al., JHEP08(2011)042

Systematics (15 nuisance parameters)

- oscillation parameters (6)
- normalization of flux : conventional (40%), prompt (free), muon (50%), astrophysical (free)
- spectrum index : primary cosmic ray (5%) astrophysical neutrinos (free)
- Ice model : (20%)
- DOM efficiency : overall (10%), angular dependence (50%)

Limits

Feroz et al., Mon. Not. Roy. Astron. Soc. 398,1601(2009)1601

- Bayesian: MCMC with Multinest, Bayes factor with Jefferey’ scale “strong” limit
- Frequentist: Wilks’ theorem

Kostelecký and Mewes, PRD85(2012)096005
Argüelles, TK, Salvado, PRL115(2015)161303

5. HESE 7.5-yr flavor Lorentz violation search

We start from isotropic model of nonminimal SME

$$h_{eff} \sim \frac{1}{2E} U^{\dagger} M^2 U + a^{(3)}_{\alpha\beta} - E c^{(4)}_{\alpha\beta} + E^2 a^{(5)}_{\alpha\beta} - E^3 c^{(6)}_{\alpha\beta} + E^4 a^{(7)}_{\alpha\beta} - E^5 c^{(8)}_{\alpha\beta} \cdots$$

Neutrino oscillation formula is written with mixing matrix elements and eigenvalues

$$P_{\alpha\to\beta}(E,L) = 1 - 4\sum_{i>j} Re\left(V^*_{\alpha i} V^*_{\beta i} V_{\alpha j} V_{\beta j}\right) sin^2\left(\frac{\lambda_i - \lambda_j}{2} L\right) + 2\sum_{i>j} Im\left(V^*_{\alpha i} V^*_{\beta i} V_{\alpha j} V_{\beta j}\right) sin\left(\left(\lambda_i - \lambda_j\right) L\right)$$

However, astrophysical neutrinos propagate O(100Mpc) → lost coherence

$$P_{\alpha\to\beta}(E,\infty) \sim 1 - 2\sum_{i>j} Re\left(V^*_{\alpha i} V^*_{\beta i} V_{\alpha j} V_{\beta j}\right) = \sum_i |V_{\alpha i}|^2 |V_{\beta i}|^2$$

Finally, fraction of neutrino flavour β on the earth is

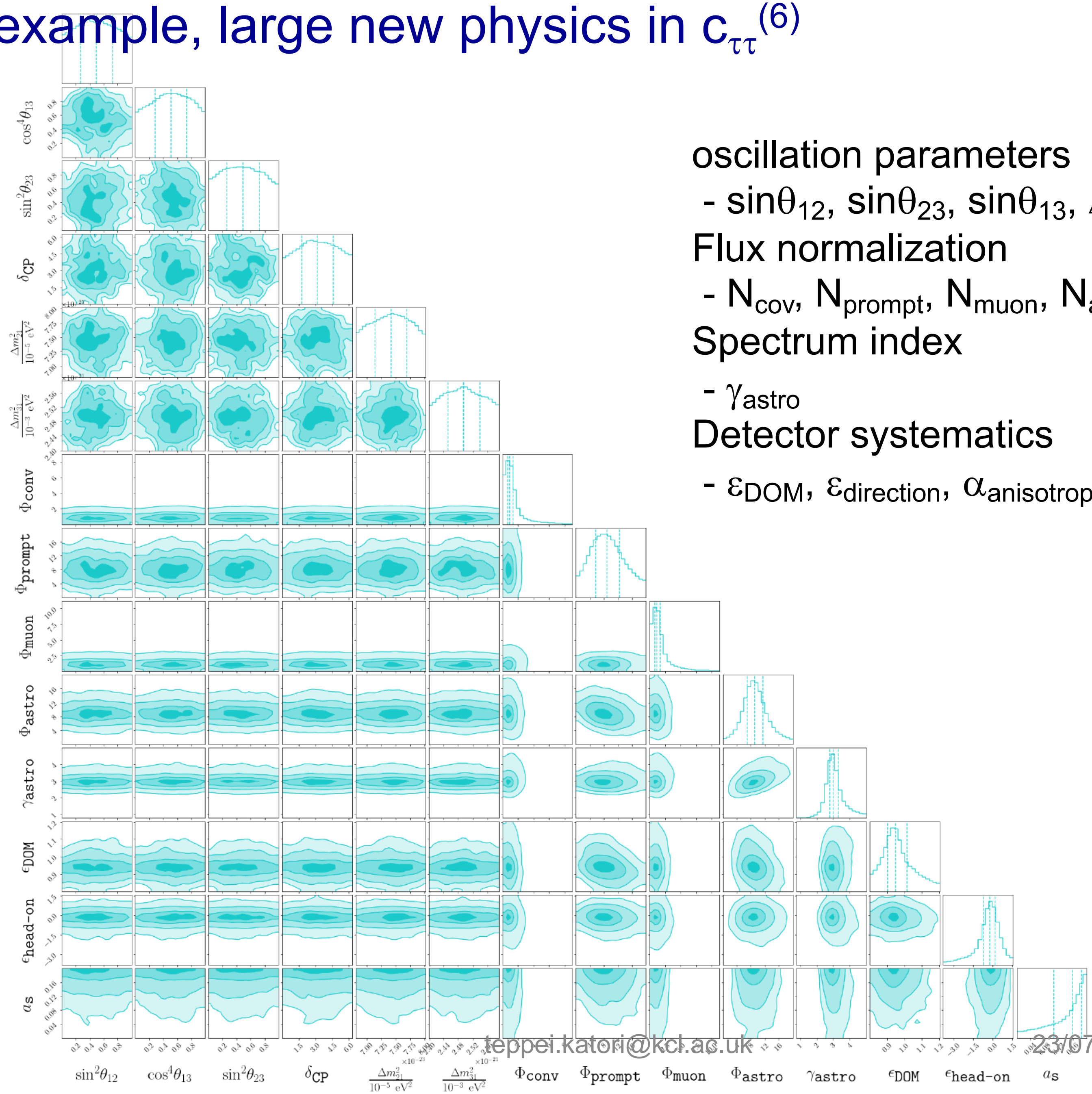
$$\alpha^{\oplus}_{\beta} \sim \int_{Emin}^{Emax} \sum_{\alpha} P_{\alpha\to\beta}(L\to\infty, E)\phi_\alpha(E) dE$$

→ Information of small Lorentz violation is encoded on neutrino mixing probability, so by measuring (tasting) astrophysical neutrino flavours, you can explore Lorentz violation

5. Systematic errors

Parameter	Prior (constraint)	Range	Description
Astrophysical neutrino flux:			
$\Phi_{\mathtt{astro}}$	-	$[0, \infty)$	Normalization scale
$\gamma_{\mathtt{astro}}$	-	$(-\infty, \infty)$	Spectral index
Atmospheric neutrino flux:			
$\Phi_{\mathtt{conv}}$	1.0 ± 0.4	$[0, \infty)$	Conventional normalization scale
$\Phi_{\mathtt{prompt}}$	-	$[0, \infty)$	Prompt normalization scale
$R_{K/\pi}$	1.0 ± 0.1	$[0, \infty)$	Kaon-Pion ratio correction
$2\nu/\left(\nu+\bar{\nu}\right)_{\mathtt{atmo}}$	1.0 ± 0.1	$[0, 2]$	Neutrino-anti-neutrino ratio correction
Cosmic-ray flux:			
$\Delta\gamma_{\mathtt{CR}}$	0.0 ± 0.05	$(-\infty, \infty)$	Cosmic-ray spectral index modification
Φ_{μ}	1.0 ± 0.5	$[0, \infty)$	Muon normalization scale
Detector:			
$\epsilon_{\mathtt{DOM}}$	0.99 ± 0.1	$[0.80, 1.25]$	Absolute energy scale
$\epsilon_{\mathtt{head\text{-}on}}$	0.0 ± 0.5	$[-3.82, 2.18]$	DOM angular response
$a_{\mathtt{s}}$	1.0 ± 0.2	$[0.0, 2.0]$	Ice anisotropy scale

5. Fit example, large new physics in $c_{\tau\tau}^{(6)}$



oscillation parameters

- $\sin\theta_{12}$, $\sin\theta_{23}$, $\sin\theta_{13}$, Δm_{12}, Δm_{23}, δ

Flux normalization

- N_{cov}, N_{prompt}, N_{muon}, N_{astro}

Spectrum index

- γ_{astro}

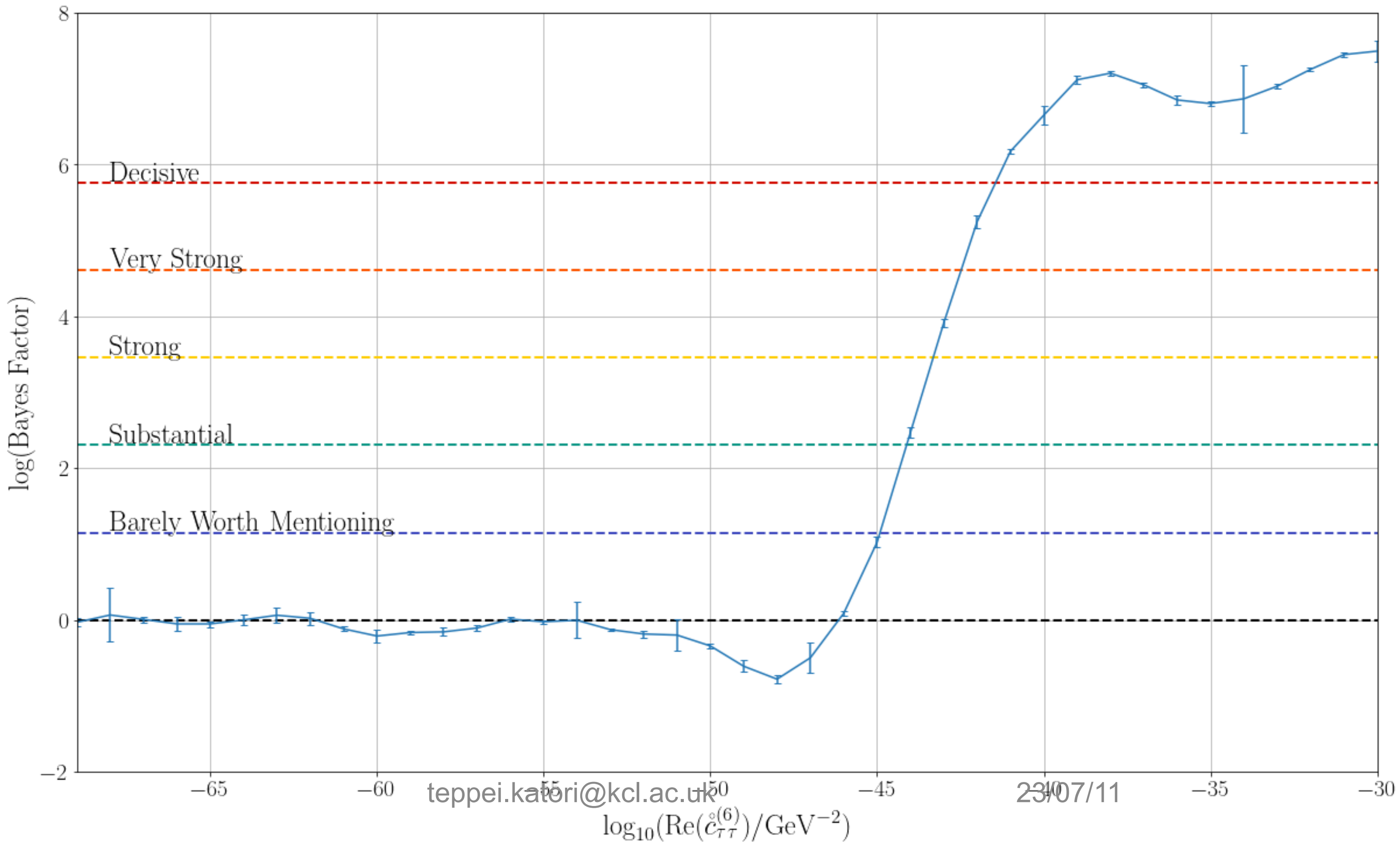
Detector systematics

- ε_{DOM}, $\varepsilon_{direction}$, $\alpha_{anisotropy}$

5. Fit example, large new physics in $c_{\tau\tau}^{(6)}$

Bayesian analysis

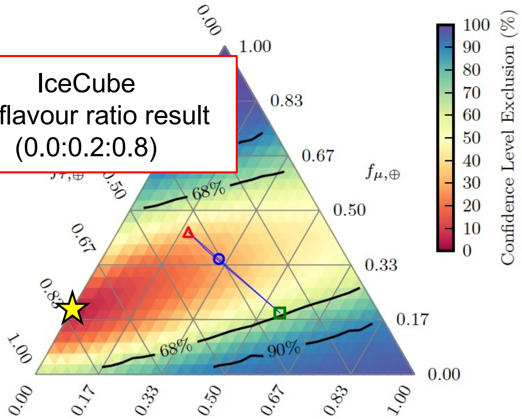
- Bayes factor is computed with new physics parameter
- Repeat this to find the threshold to set the limit



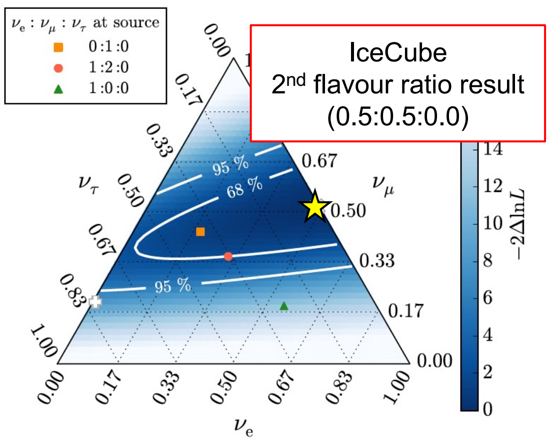
IceCube, PRL114(2015)171102, Astro.J.809:98(2015), PRD99(2019)032004, ArXiv:2011:03560

5. HESE 7.5-yr data (2018)

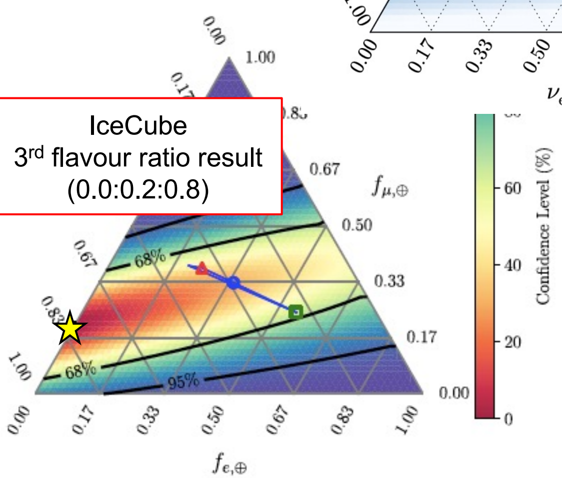
IceCube
1st flavour ratio result
(0.0:0.2:0.8)

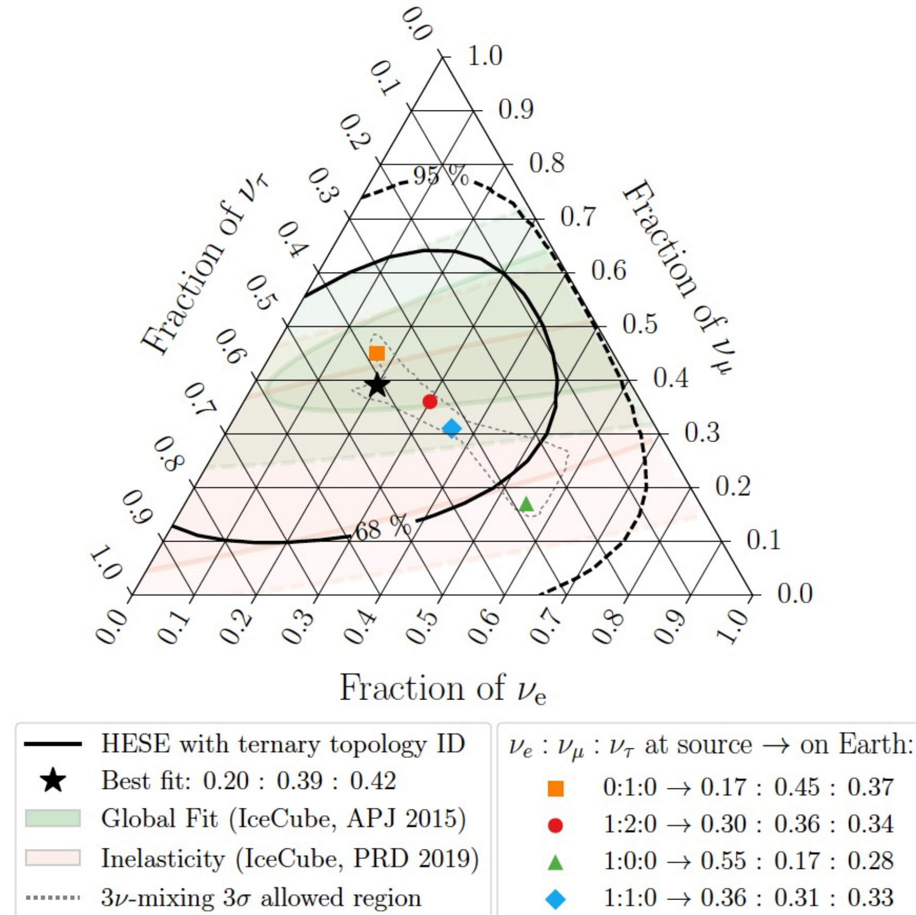


IceCube
2nd flavour ratio result
(0.5:0.5:0.0)



IceCube
3rd flavour ratio result
(0.0:0.2:0.8)

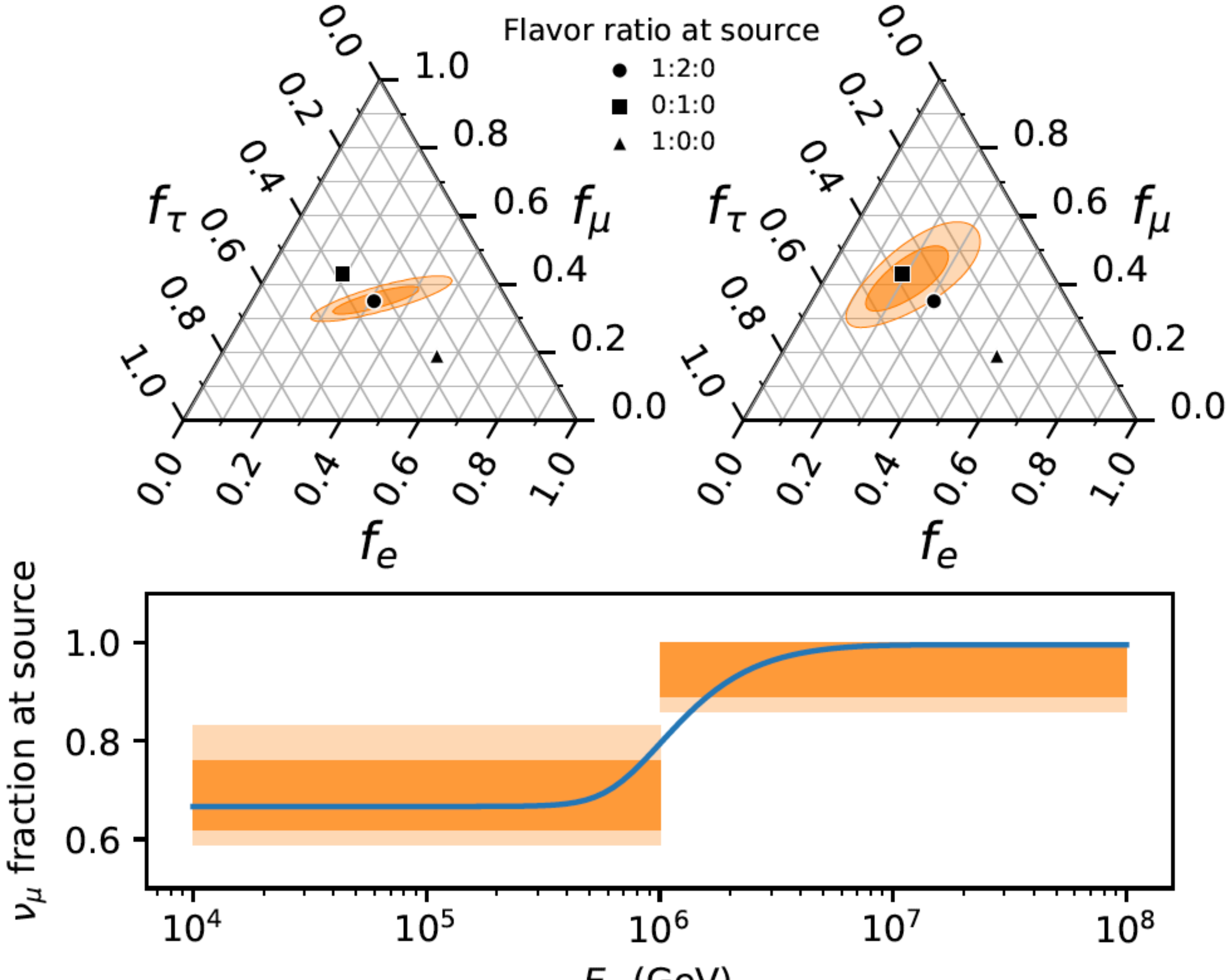




New flavour ratio measurement

- Likelihood is very shallow and fit often confuses between ν_e and ν_τ
- New flavour ratio result has some power to distinguish ν_e and ν_τ

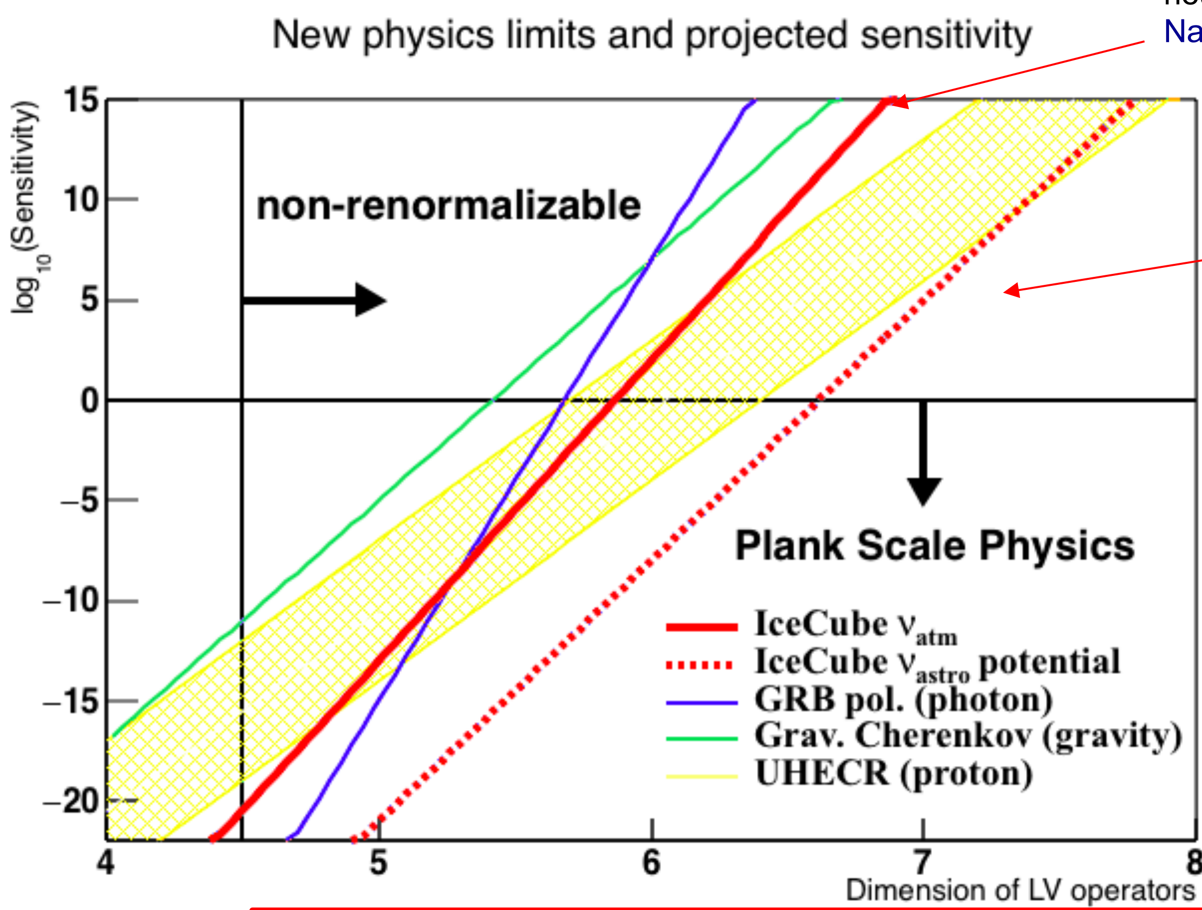
5. Energy dependence of flavor ratio



5. Neutrino interferometry – Astrophysical neutrinos

Higher-dimension operators may be related to new physics
- Dimension-5 operator (unit: GeV^{-1}), example: Majorana mass
- Dimension-6 operator (unit: GeV^{-2}), example: Fermi constant (G_F)

IceCube atmospheric neutrino LV sensitivity
Nature Physics 14(2018)961

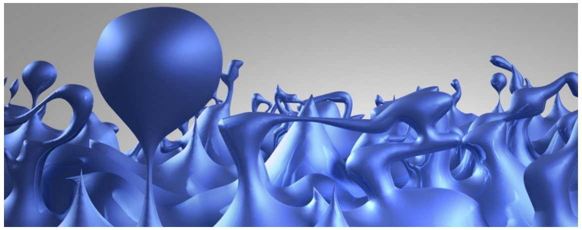


IceCube astrophysical neutrino LV sensitivity

Astrophysical neutrino dim-6 LV operator search can reach quantum gravity motivated region ($\sim 1/M_{Planck}^2 \sim 10^{-38}$ GeV^{-2})

Ellis, Mavromatos, Nanopoulos, MPLA12(1997)1759:1773
Farzan, Schwetz, Smirnov, JHEP07(2008)067

5. Neutrino decoherence



Space-time foam

Quantum gravity motivated quantum fluctuation of space-time.
- Planck scale black hole background
- D-brane fluctuation

Propagating particles lose coherence with interactions with these background

Open quantum system

$$P_{\alpha\beta}^{OQS} = Tr\left|\rho_\alpha(t)\rho_\beta(0)\right|^2$$

- Model independent search of decoherence
- Density matrix formalism and decoherence term

$$\frac{d\rho}{dt} = -i\left[h_{eff},\rho\right] - D[\rho], \quad D[\rho] = \begin{pmatrix} 0 & \rho_{12}\gamma_{12} & \rho_{31}\gamma_{31} \\ \rho_{12}\gamma_{12} & 0 & \rho_{23}\gamma_{23} \\ \rho_{31}\gamma_{31} & \rho_{23}\gamma_{23} & 0 \end{pmatrix}$$

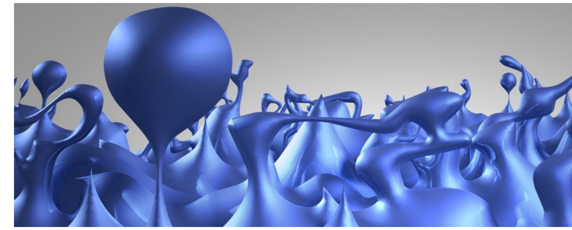
Damping term

$$P_{\alpha\beta} = A\cdot\left[1 - e^{-\gamma_{ij}}cos\left(\frac{\Delta m_{ij}^2}{2E}L\right)\right], \quad \gamma_{ij} = \gamma_{ij}^0\cdot\left(\frac{E}{GeV}\right)^n$$

- Analysis can be designed to find nonzero γ_{ij}^0.
- Experimental sensitivity is many order far away than expected Planck scale physics region?
(naturalness: decoherence length of neutrino with E~M_{Planck} is Planck length)

Coloma et al, EPJC(2018)78:614
Stuttard and Jensen, PRD102(2020)115003,PRD104(2021)056007

5. Neutrino decoherence



Stronger sensitivity on γ_0 (damping term scale) can be obtained by assuming larger n

New analysis (Tom Stuttard, NBI)

- DeepCore data
- Weak dependence on mass ordering
- Exotic ν_μ disappearance (different pattern, new structure)