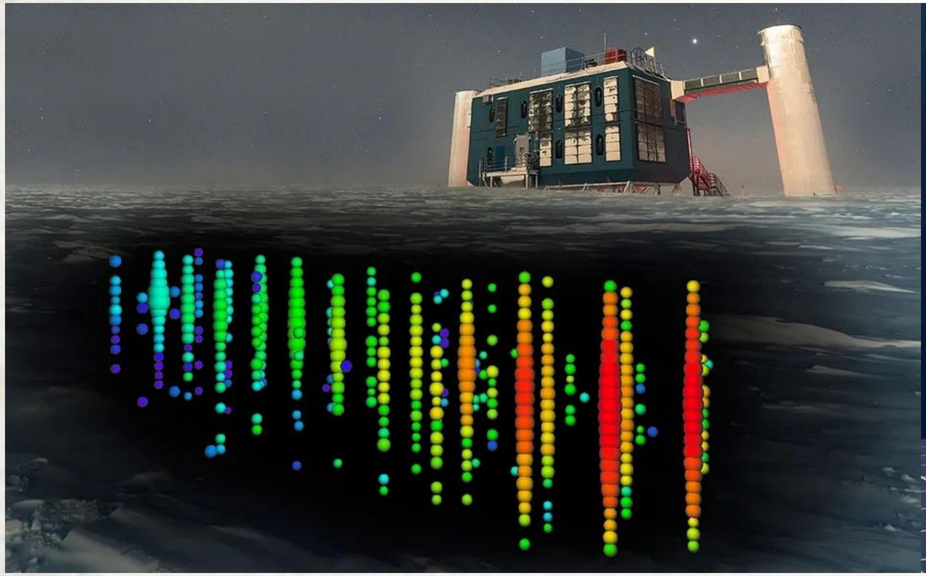
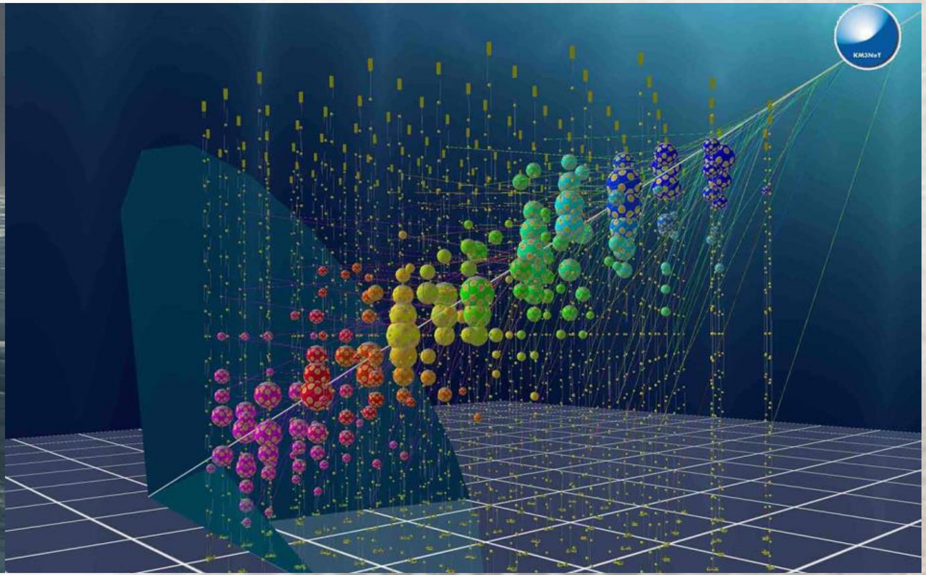
Clash of the Titans: ultra-high energy KM3NeT event versus IceCube data





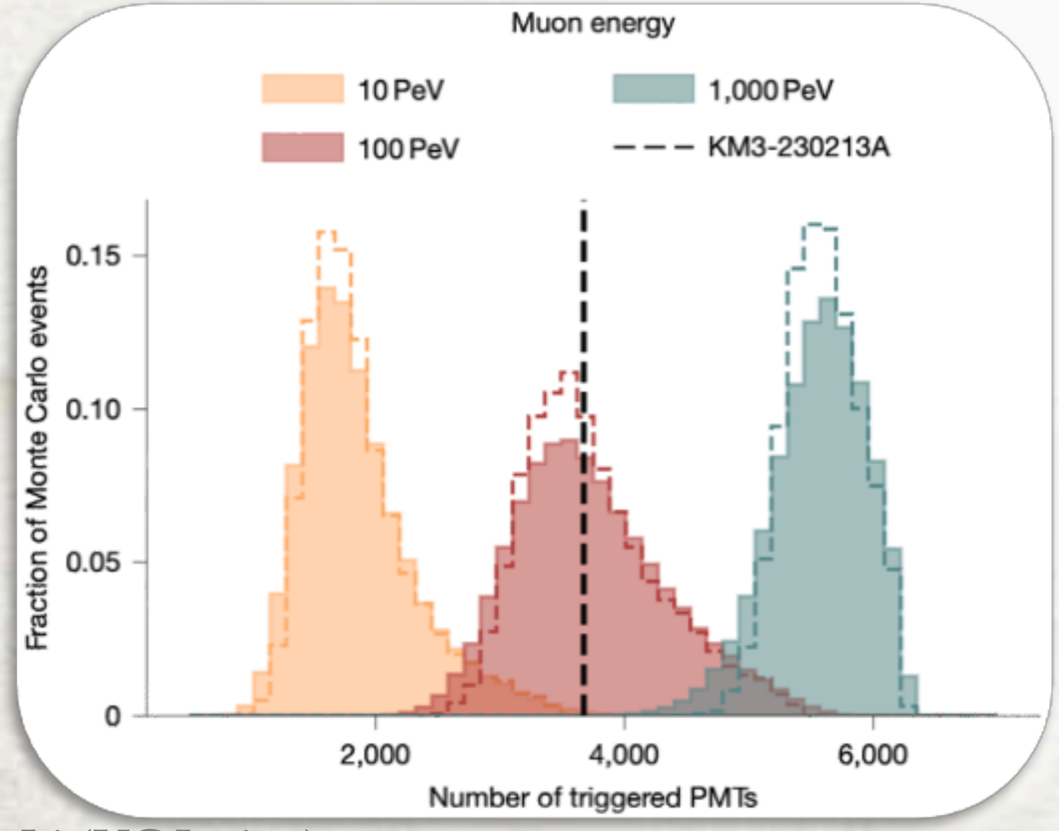
Shirley Li (UC Irvine)

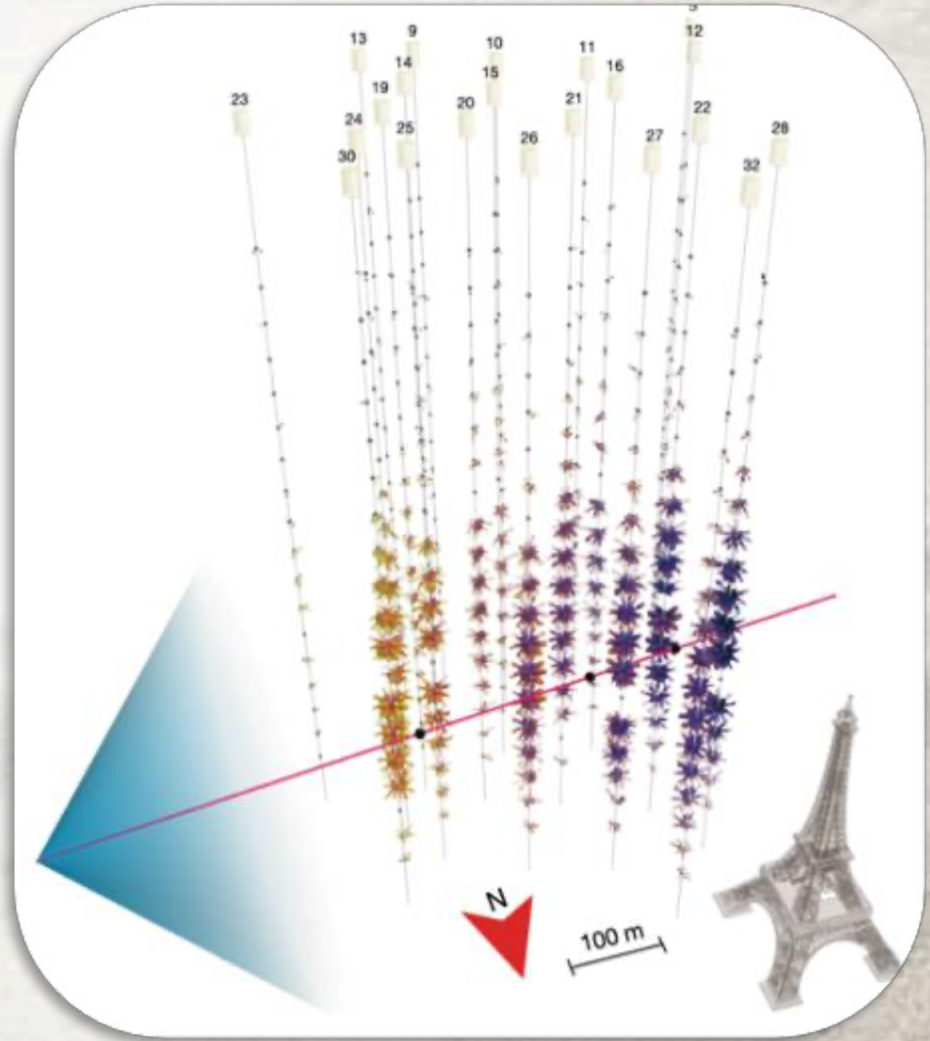
Based on 2502.04508 with Pedro Machado, Daniel Naredo-Tuero, and Tom Schwemberger

Article

Observation of an ultra-high-energy cosmic neutrino with KM3NeT

$$E_\mu = 120^{+110}_{-60}\ \text{PeV}$$



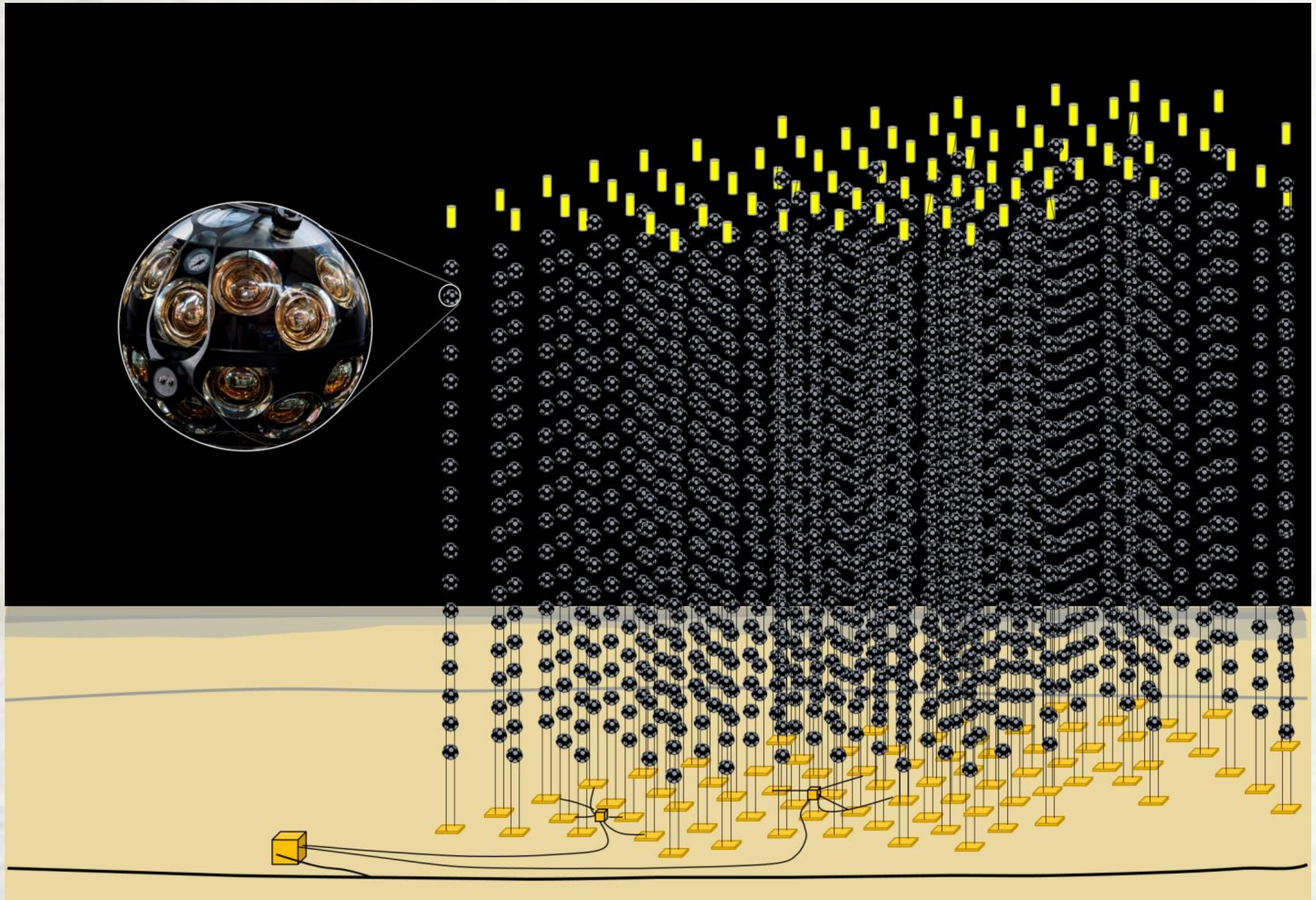


Outline

1. KM3-230213A
2. Neutrino sources
3. Where does KM3-230213A come from?

1 KM3-230213A

KM3NeT detector



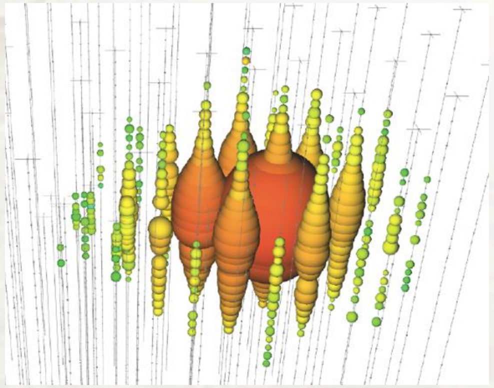
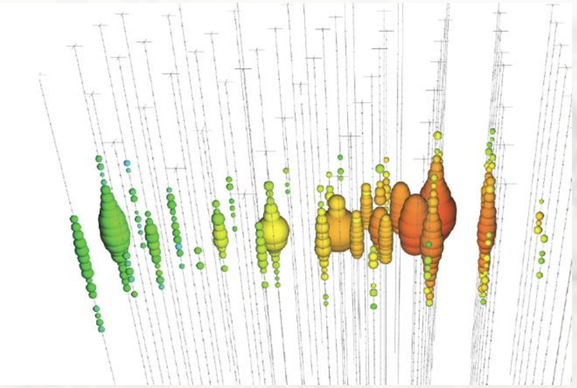
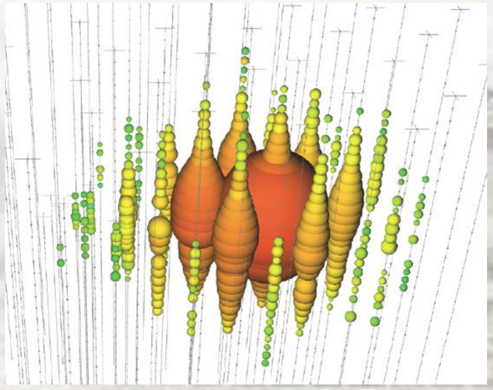
km3net.org

- Mediterranean Sea
- Under construction
- Full volume 1 Gton
- ~ About 1/10 installed

Event topology

Neutrinos produce different charged particles

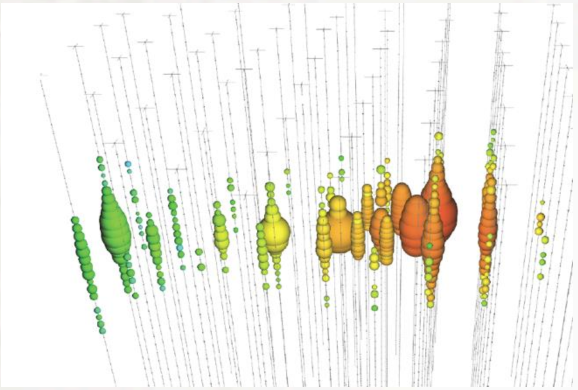
Note: ν and $\bar{\nu}$ are indistinguishable

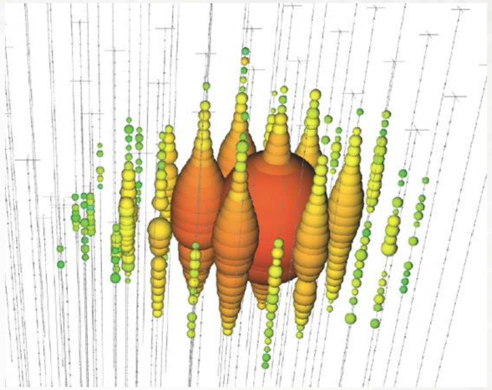
ν_e	ν_μ	ν_τ
$\nu_e + N \to e^- +$ hadrons	$\nu_\mu + N \to \mu^- +$ hadrons	$\nu_\tau + N \to \tau^- +$ hadrons $\tau \to$ hadrons (65%)
Shower 	Track 	Shower 

icecube.wisc.edu

Pros and cons of different event topologies

Roughly, ν_e, ν_μ, and ν_τ have comparable fluxes



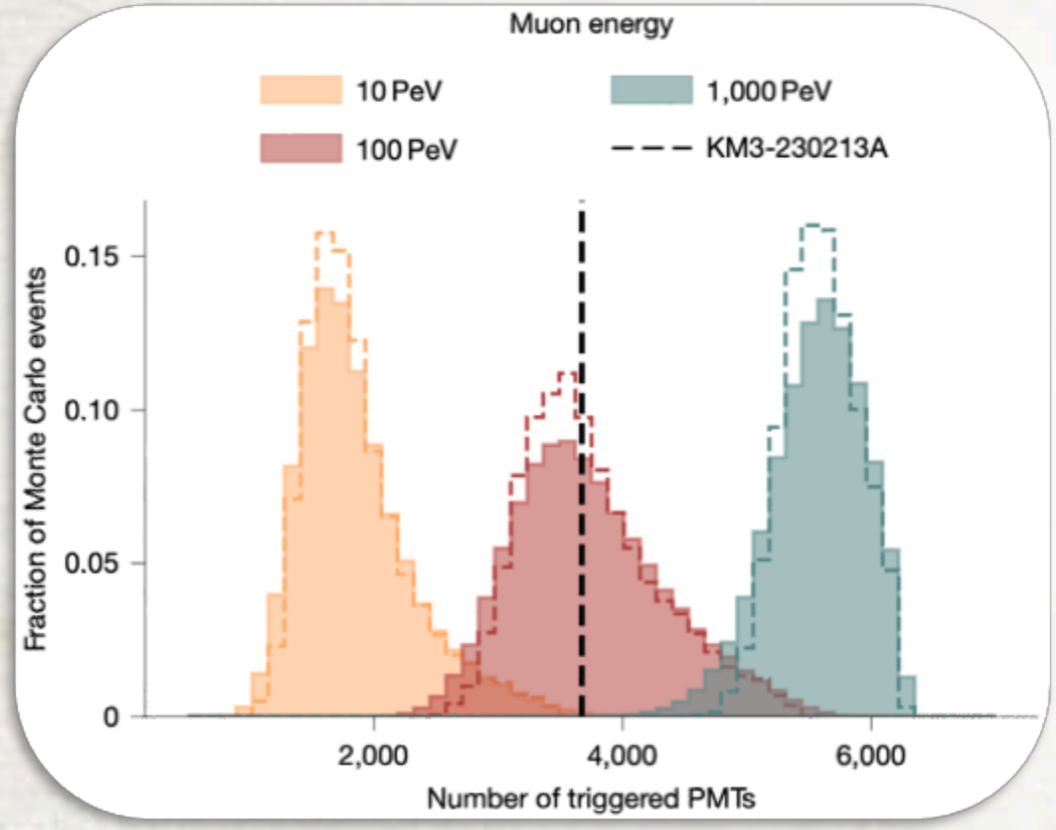


- Good angular resolution
- Bad energy resolution
- Can interact outside the detector ⇒ larger event rate

- Bad angular resolution
- Good energy resolution
- Cannot interact outside the detector

About KM3-230213A

$E_\mu = 120^{+110}_{-60}$ PeV

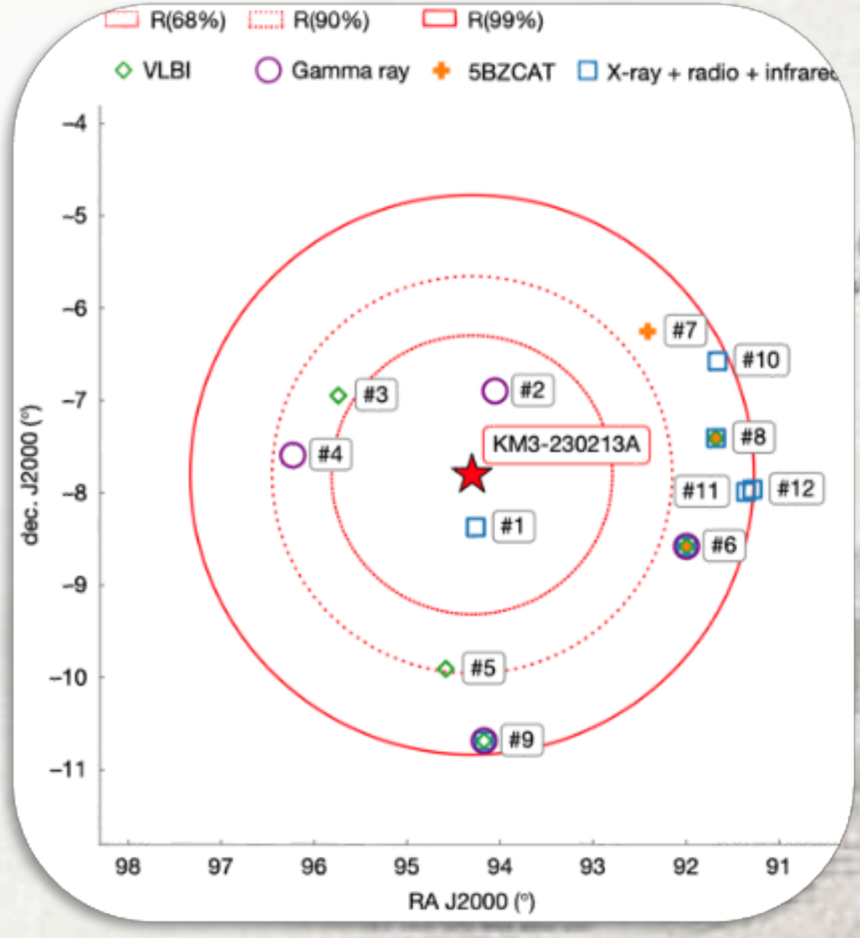


E_ν = 220 PeV most likely

72-2600 PeV at 90%

Good pointing

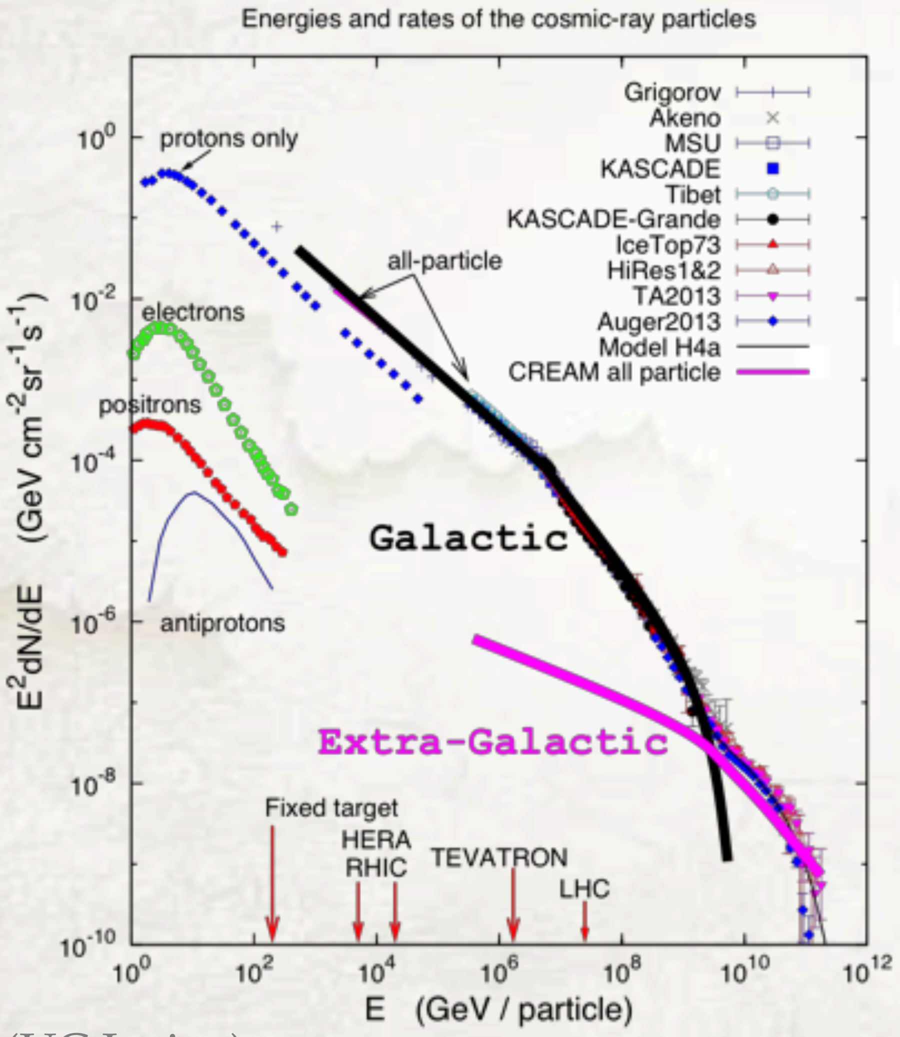
0.6° above horizon



2 Neutrino sources

We do not understand astrophysical sources

Where and how are cosmic rays produced?

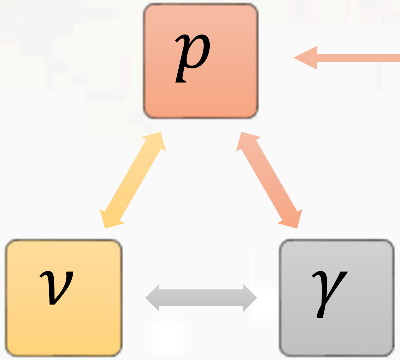


Blasi 2013

We have been detecting cosmic rays for over 100 years. We still do not have a good understanding of where they are produced, especially at the highest energies

The appeal of neutrinos and photons

They should also be produced at sources



Accelerated at the source

$$p + \gamma \to \Delta^+ \to \begin{cases} n\pi^+ \\ p\pi^0 \end{cases}$$

$$\pi^+ \to \mu^+\nu_\mu \to \bar{\nu}_\mu e^+ \nu_e \nu_\mu$$

$$\pi^0 \to \gamma\gamma$$

Can happen either

1. at the source – neutrinos from the source
2. on route – cosmogenic neutrinos

Neutrino astronomy

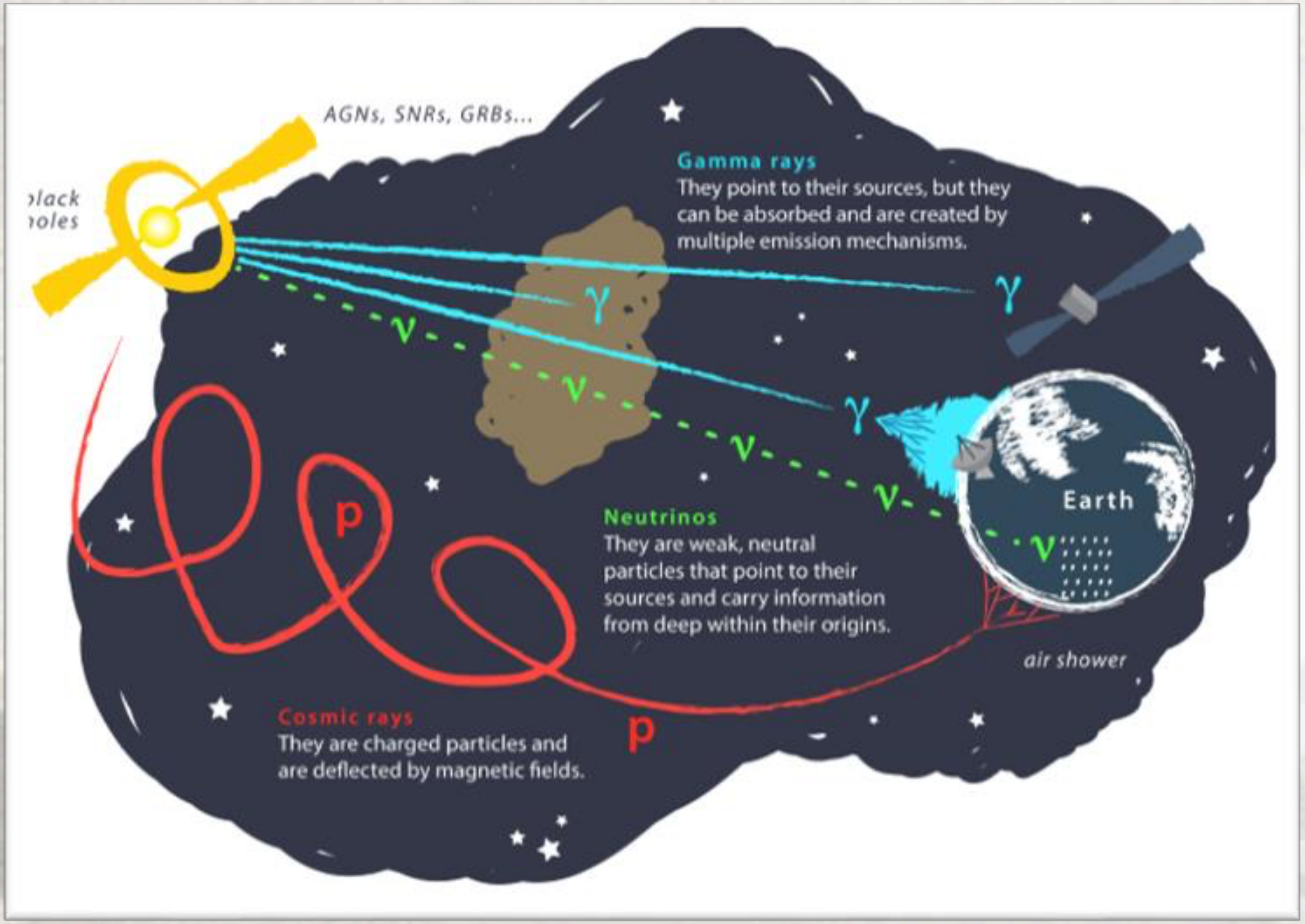
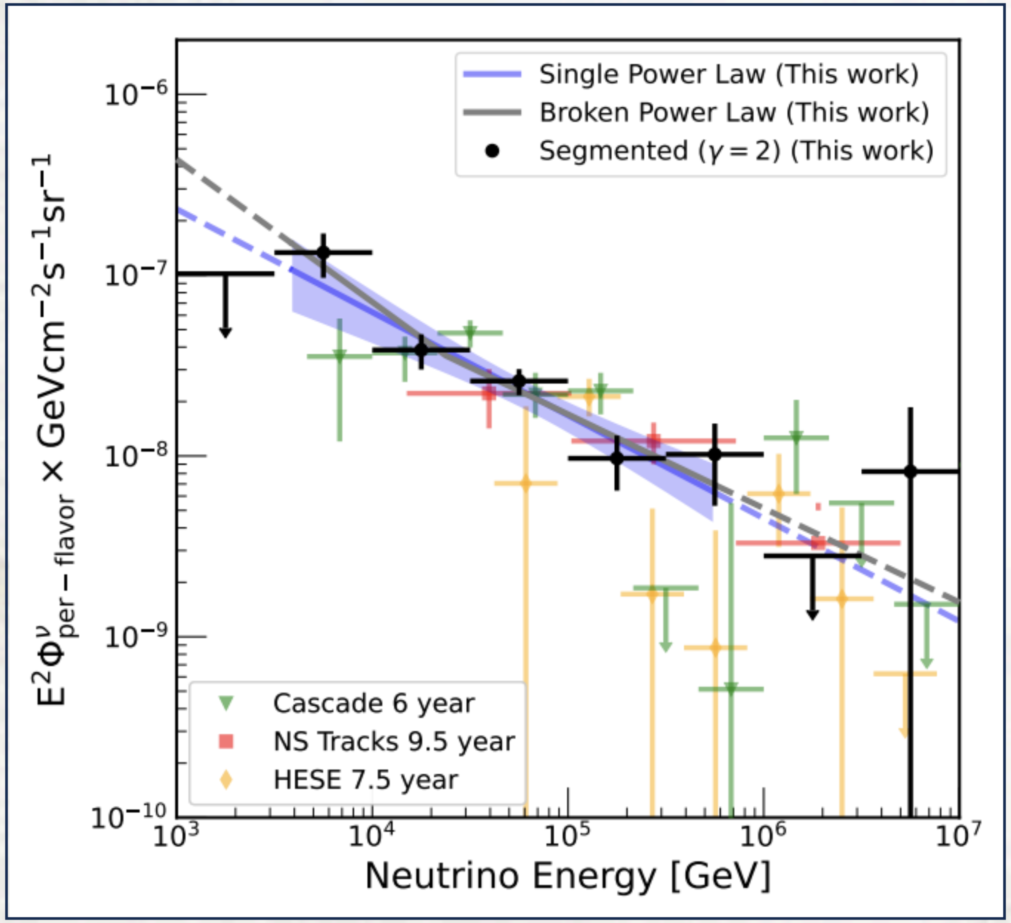


Figure credit: J. Aguilar and J. Yang

- p: no pointing 😥
- γ:
  short distance 😥
- ν:
  pointing 😀
  long distance 😀

What have we figured out about sources?

IceCube diffuse flux



IceCube 2024

Measured flux

Steady, isotropic – diffuse

Source still unclear

What have we figured out about sources?

IceCube identified sources

Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert

ICECUBE COLLABORATION , MARK AARTSEN, MARKUS ACKERMANN, JENNI ADAMS, JUAN ANTONIO AGUILAR, MARKUS AHLERS, MARYON AHRENS, IMEN AL SAMARAI, DAVID ALTMANN, [...], AND TIANLU YUAN +321 authors Authors Info & Affiliations

SCIENCE • 13 Jul 2018 • Vol 361, Issue 6398 • pp. 147-151 • DOI: 10.1126/science.aat2890

5,125 651 CHECK ACCESS

Neutrino emission from a flaring blazar

Neutrinos interact only very weakly with matter, but giant detectors have succeeded in detecting small numbers of astrophysical neutrinos. Aside from a diffuse background, only two individual sources have been identified: the Sun and a nearby supernova in 1987. A multiteam collaboration detected a high-energy neutrino

Evidence for neutrino emission from the nearby active galaxy NGC 1068

ICECUBE COLLABORATION, R. ABBASI, M. ACKERMANN, J. ADAMS, J. A. AGUILAR, M. AHLERS, M. AHRENS, J. M. ALAMEDDINE, C. ALISPACH, [...], AND P. ZHELNIN +376 authors Authors Info & Affiliations

SCIENCE • 3 Nov 2022 • Vol 378, Issue 6619 • pp. 538-543 • DOI: 10.1126/science.abg3395

13,735 196 CHECK ACCESS

Nearby active galaxy emits neutrinos

Observations have shown a diffuse background of high-energy neutrinos, which is known to be of extragalactic origin. However, it has been difficult to identify individual sources that contribute to this background. The IceCube Collaboration reanalyzed the arrival directions of astrophysical neutrinos and then searched for

Blazers seem extremely promising

3 Where does KM3-230213A come from?

1. IceCube diffuse flux
2. Cosmogenic neutrino fluxes
3. Point sources

2502.04508

The crust of the problem – KM3NeT vs. IceCube

How come that IceCube,
running for 10 times longer and with 10 times larger size,
did not see neutrinos above 10 PeV?

Before test of origin…

$E_\nu = 72\text{-}2600$ PeV at 90%

Need neutrino energy information first

Our reconstruction of neutrino energy

$$P(E_\nu|N_{\rm hit}) = \frac{1}{P(N_{\rm hit})}\int dE_\mu P(N_{\rm hit}|E_\mu)P(E_\mu|E_\nu)P(E_\nu)$$

1. Prior on neutrino flux – we tested a few

Before test of origin…

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2. Probability that E_ν gives E_μ, cross section, detector size, cuts all included in $A_{\rm eff}$

   ν interaction using MadGraph, analytic method μ dE/dx

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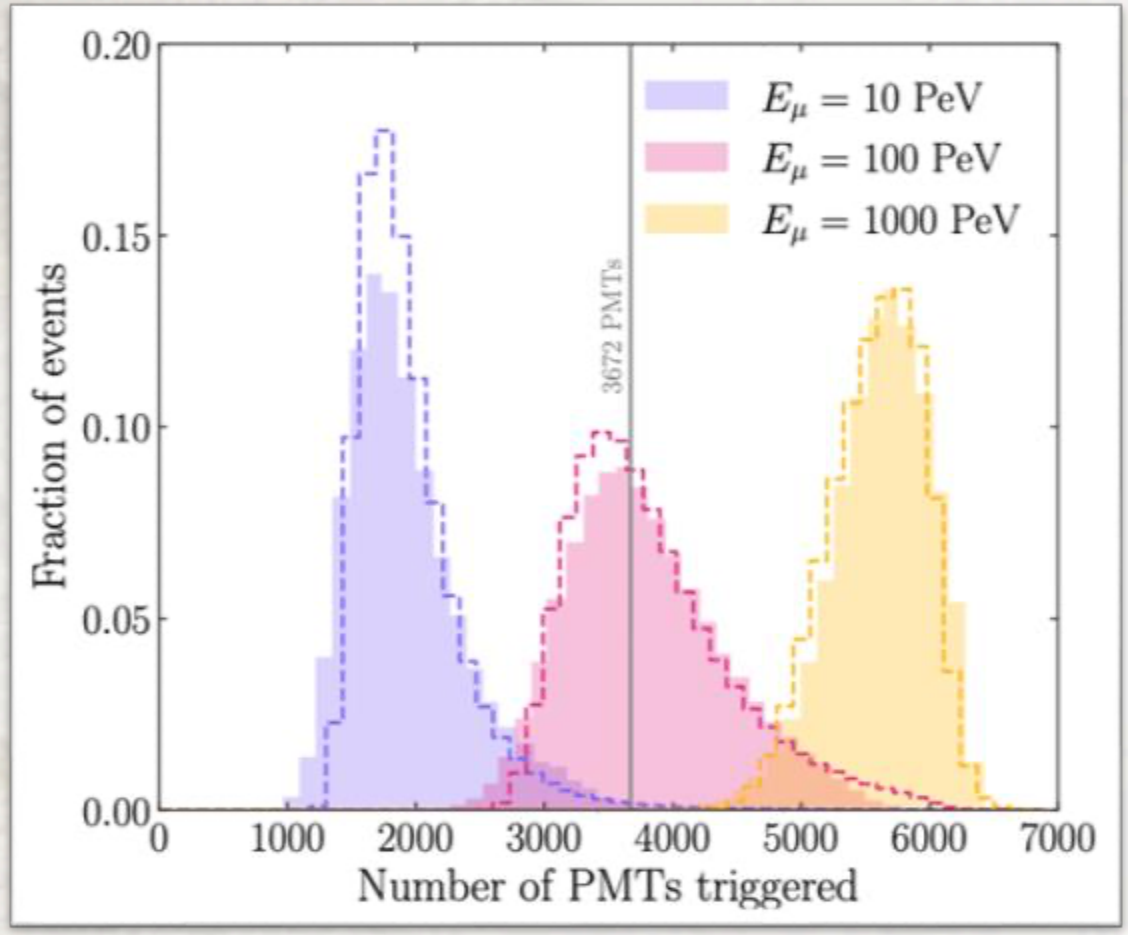
1. Prior on neutrino flux – we tested a few
2. Probability that E_ν gives E_μ, cross section, detector size, cuts all included in $A_{\rm eff}$

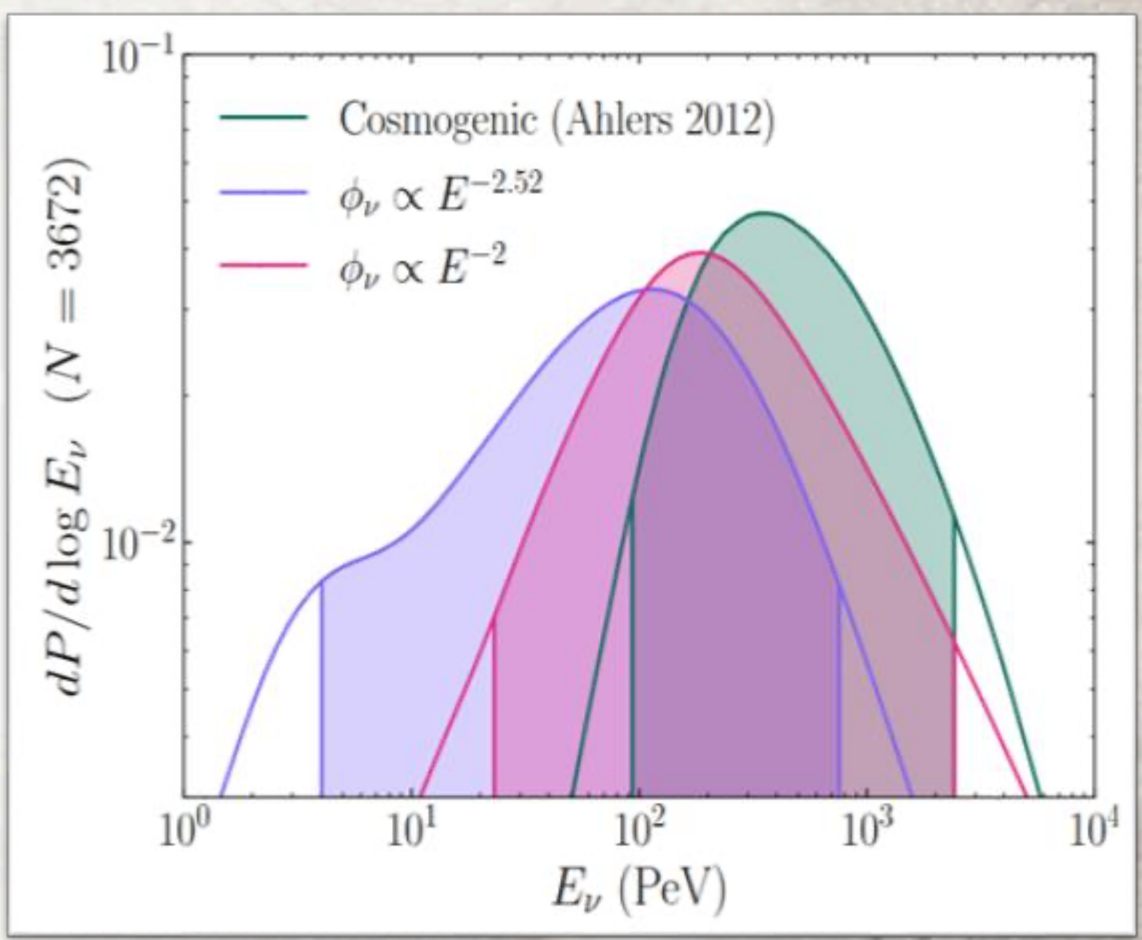
   ν interaction using MadGraph, analytic method μ dE/dx
3. Probability that E_μ trigger Nhit

   μ dE/dx using PROPOSAL, mock photon propagation/absorption in water

2502.04508, SL with Pedro Machado, Daniel Naredo-Tuero, and Tom Schwemberger

Our reconstructed neutrino energy PDF





We get E_ν in 23-2400 PeV, for E^{-2} power-law, in very good agreement with KM3NeT

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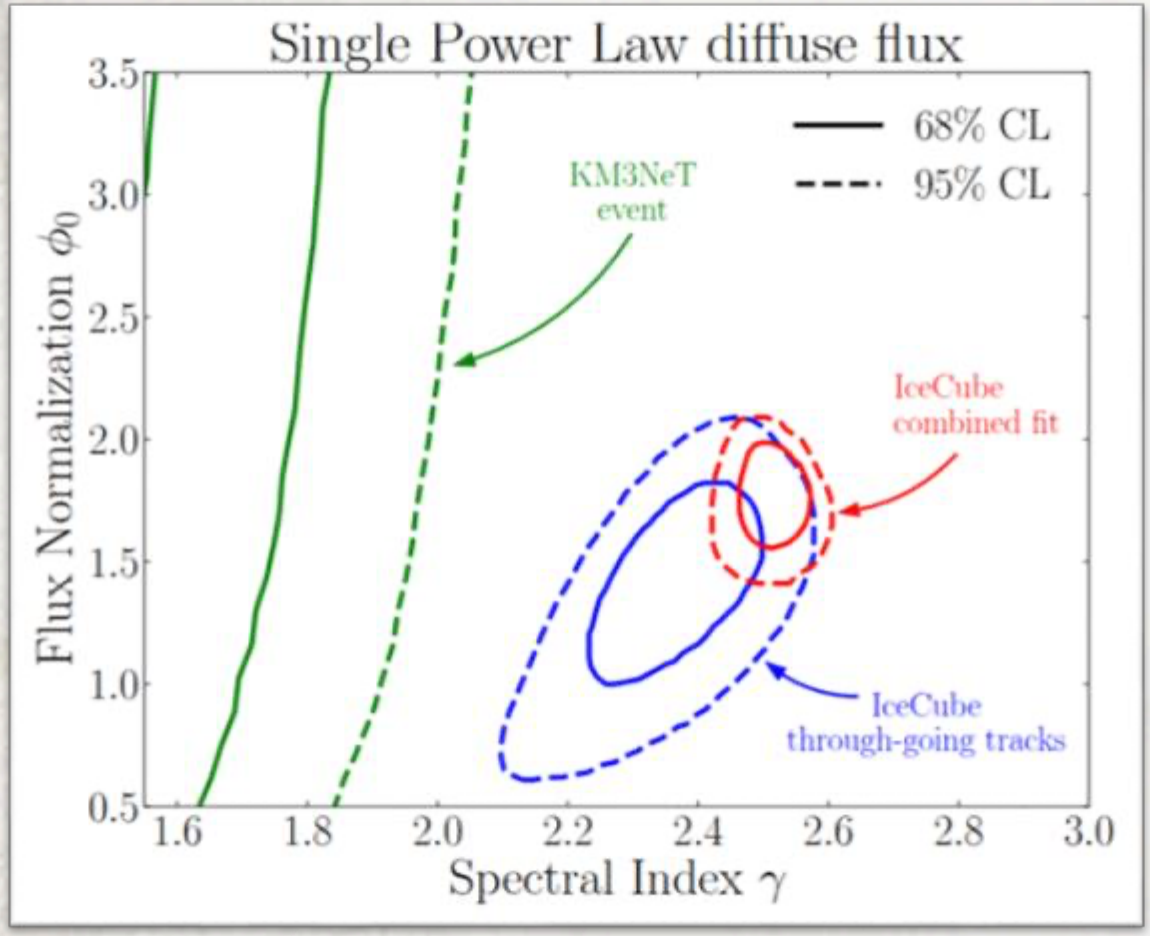
Test origin 1. IceCube diffuse flux



$$\mathcal{L}(\phi_0, \gamma) = \mathcal{L}_{\text{flux}}(\phi_0, \gamma) \cdot \mathcal{L}_{\text{evt}}(N_{\text{evt}}(\phi_0, \gamma))$$

$$\mathcal{L}_{\text{evt}} = N_{\text{evt}} e^{-N_{\text{ev}}}$$

Tension:

3.5σ for combined

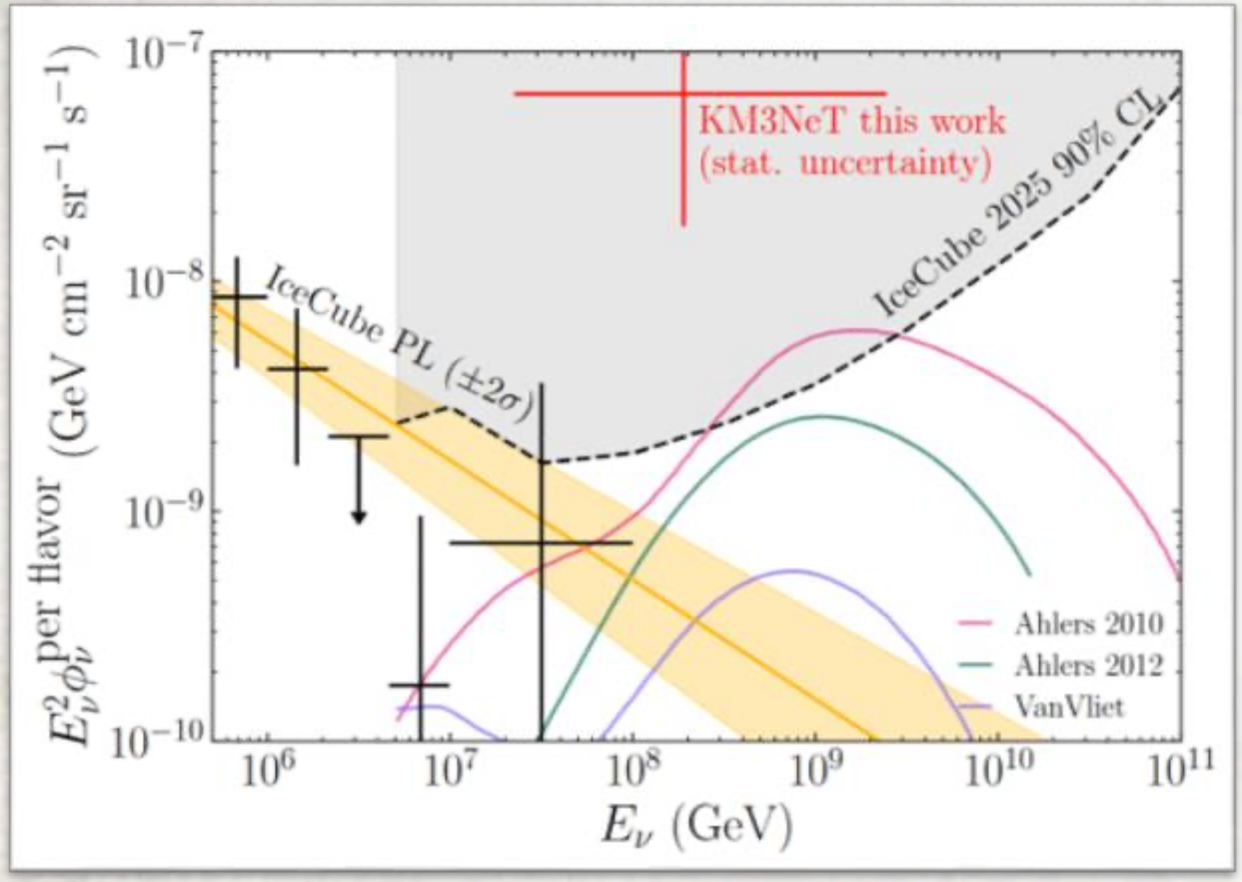
3.2σ for throughgoing

For $E^{-2.52}$

KM3NeT ⇒ 75 evts at IceCube

IceCube ⇒ 0.005 evts at KM3NeT

Test origin 2. cosmogenic flux



Tension:

Ahlers 2010: 3.6σ

Ahlers 2012: 3.1σ

Van Vliet 2019: 3.1σ

No good flux:

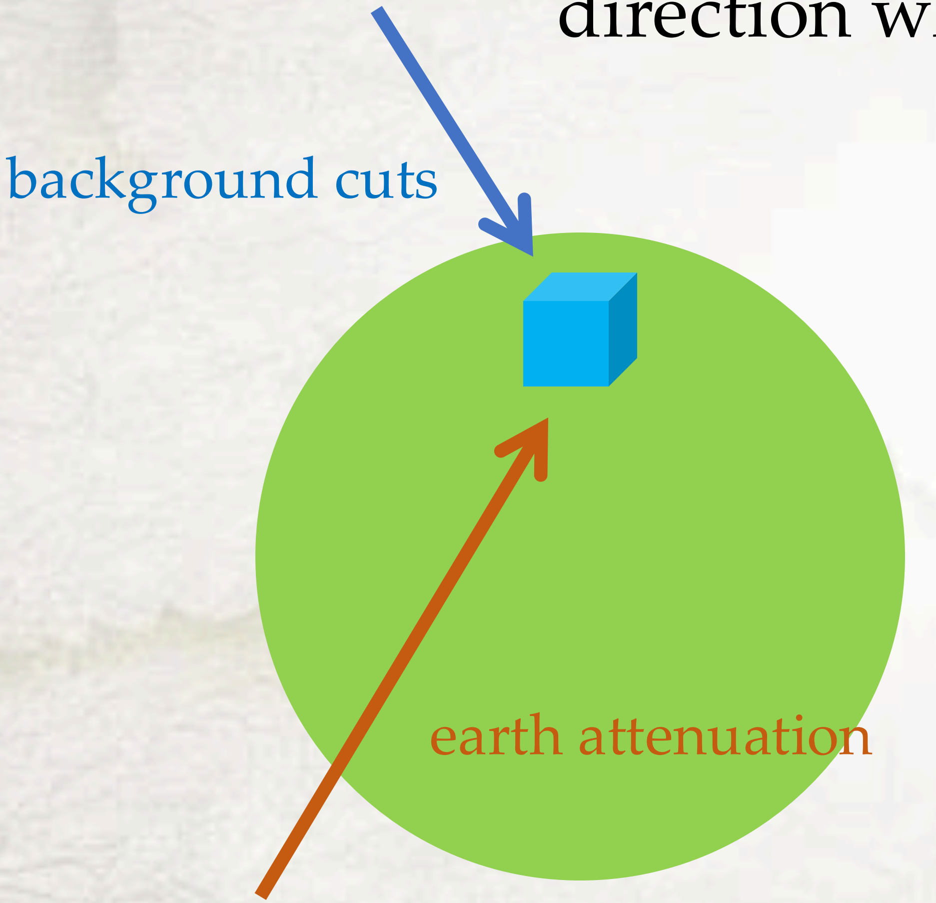
A10 ⇒ 0.006 evts@KM, p_{IC}=0.3%

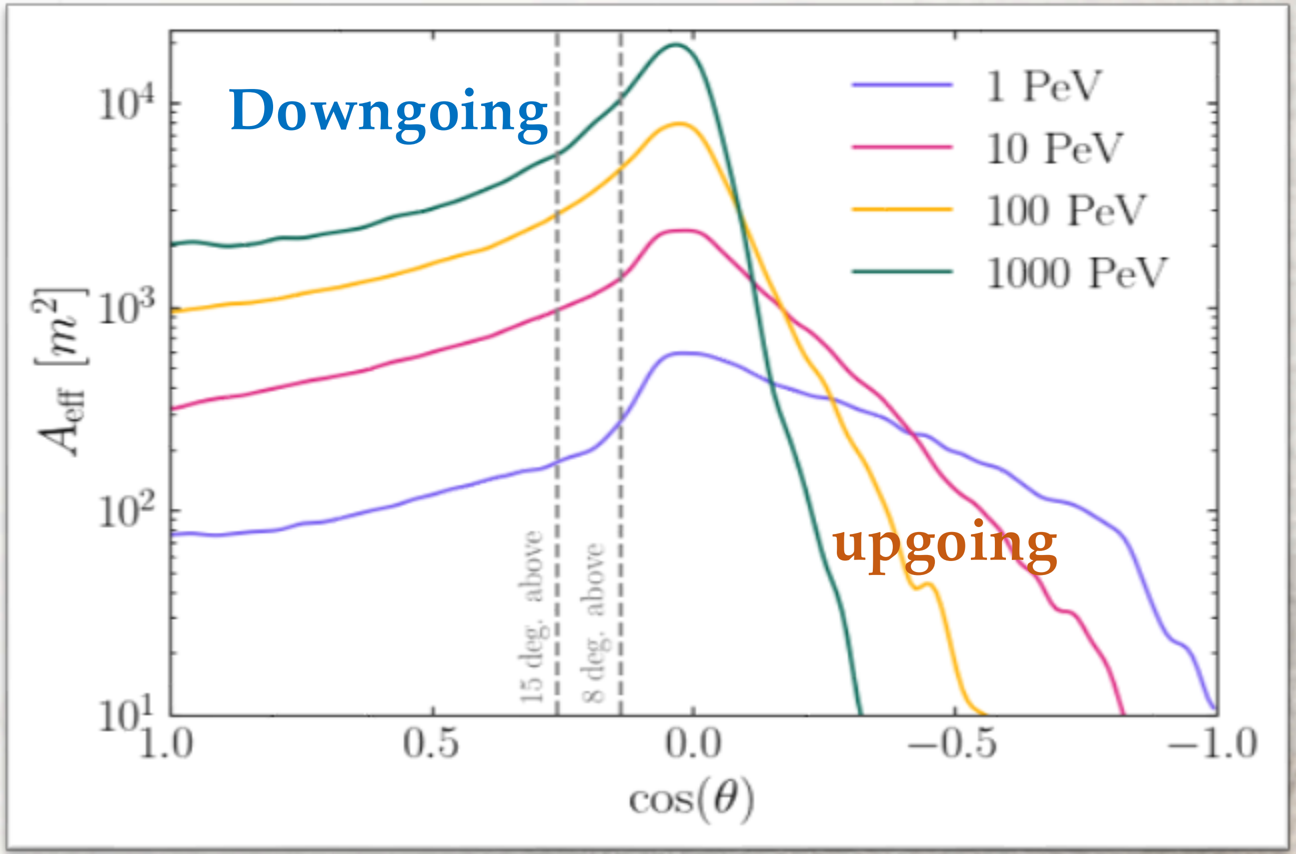
A12 ⇒ 0.003 evts@KM, p_{IC}=4.3%

VV19 ⇒ 6.10^{-4} evts@KM, p_{IC}=27%

Test origin 3. point sources

Most natural guess for the tension: It is not in a direction where IceCube could have seen it



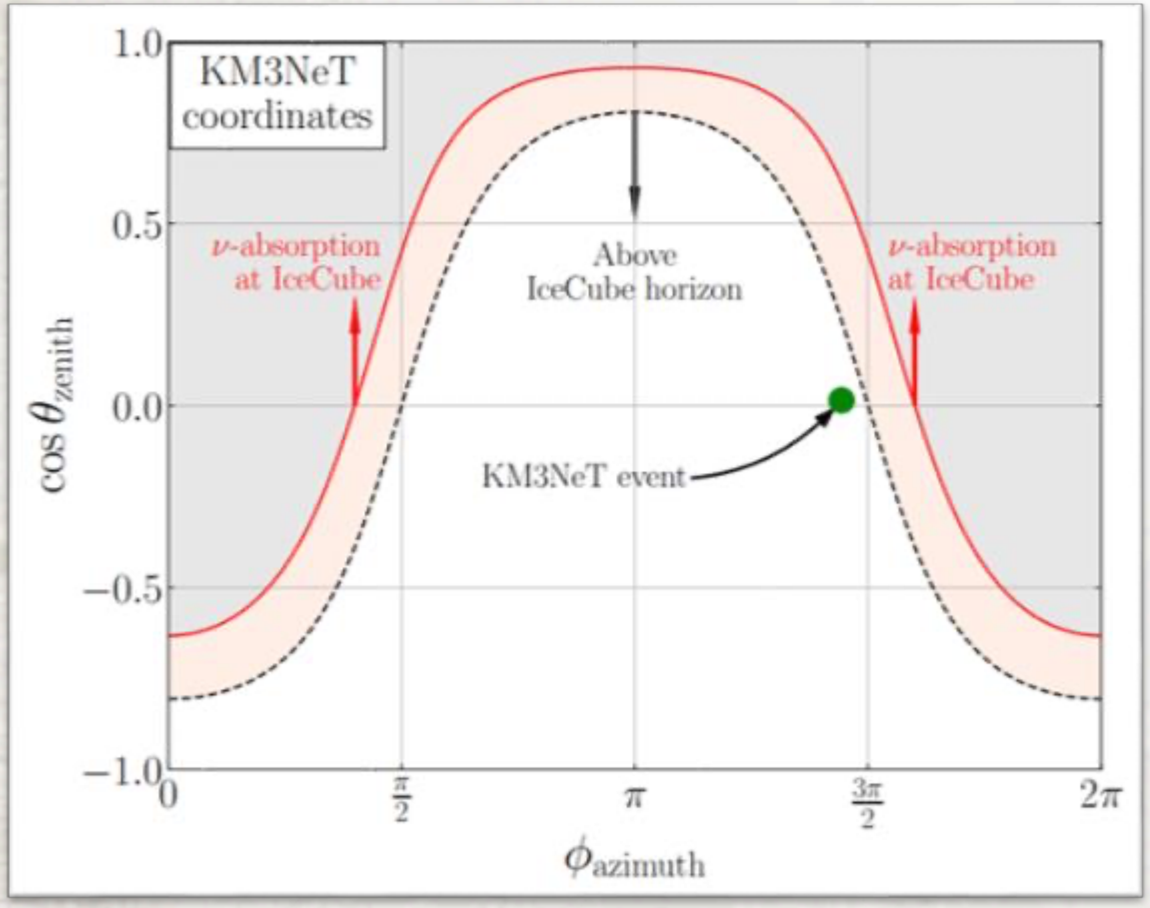


https://icecube.wisc.edu/data-releases/2018/10/all-sky-point-source-icecube-data-years-2010-2012/

Test origin 3. point sources

Not the case!

It should be quite visible in IceCube



No specific flux: $$\frac{N_{IC}}{N_K} = \frac{(A_{eff}T)_{IC}}{(A_{eff}T)_K}$$

Take the Bayes factor of getting (1,0) evts in two exp vs. getting (0,0) evts

Tension:

Steady: 2.9σ

Transient: 2σ

Compare to KM3NeT official numbers

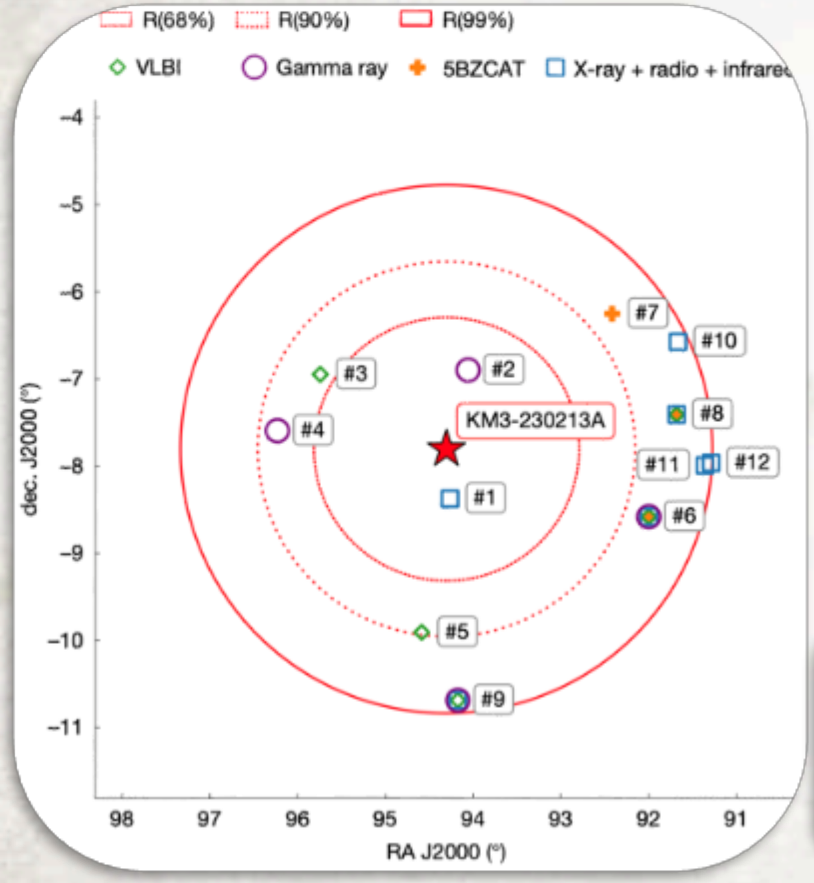
The ultra-high-energy event KM3-230213A within the global neutrino landscape
(The KM3NeT Collaboration)

Pierre Auger. In all cases, the observed tension between KM3NeT and other datasets is of the order of $2.5\sigma - 3\sigma$, and increased statistics are required to resolve this apparent tension and better characterise the neutrino landscape at ultra-high energies.

1. We used the PDF of neutrino energy; KM3NeT only used the energy window 72-2600 PeV
2. For the cosmogenic test, KM3NeT used an older IceCube search from 2018; we used IceCube 2025 results

Comment on the point source possibility

KM3NeT conducted a thorough search of various source catalogs!



Extragalactic neutrino sources should be dominated by active galactic nuclei, and blazars are of particular interest considering the very-high energy of KM3-230213A. To compile a census of potential blazar counterparts within the 99% confidence region of KM3-230213A, archival multiwavelength data were also explored. The following catalogues were cross-matched to investigate a possible blazar counterpart: the 4FGL-DR4 Fermi-LAT gamma-ray catalogue[17], the first eROSITA X-ray catalogue[22], the Wide-field Infrared Survey Explorer (WISE) optical catalogue[23], the RFC 2024b (https://astrogeo.org/rfc/) and NRAO VLA Sky Survey (NVSS)[24] radio catalogues and Roma-BZCAT[25]. Four

Characterizing Candidate Blazar Counterparts of the Ultra-High-Energy Event KM3-230213A

O. Adriani,[1,2] S. Aiello,[3] A. Albert,[4,5] A. R. Alhebsi,[6] M. Alshamsi,[7] S. Alves Garre,[8] A. Ambrosone,[9,10] F. Ameli,[11] M. Andre,[12] L. Aphecetche,[13] M. Ardid,[14] S. Ardid,[14] J. Aublin,[15] F. Badaracco,[16,17] L. Bailly-Salins,[18] Z. Bardačová,[19,20] B. Baret,[15] A. Bariego-Quintana,[8] Y. Becherini,[15] M. Bendahman,[10] F. Benfenati Gualandi,[21,22] M. Benhassi,[23,10] M. Bennani,[18] D. M. Benoit,[24] E. Berbee,[25] E. Berti,[1] V. Bertin,[7] P. Betti,[1] S. Biagi,[26] M. Boettcher,[27] D. Bonanno,[26] S. Bottai,[1] A. B. Bouasla,[28] J. Boumaaza,[29]

No source was confirmed

Other work examining KM3-230213A

Examining a particular source or flux

Emergence of a neutrino flux above 5 PeV and implications for ultrahigh-energy cosmic rays

Marco S. Muzio[1*], Tianlu Yuan[1] and Lu Lu[1]

KM3-230213A: An Ultra-High Energy Neutrino from a Year-Long Astrophysical Transien

Andrii Neronov[1,2], Foteini Oikonomou[3], Dmitri Semikoz[1]
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The blazar PKS 0605-085 as the origin of th ultra high energy neutrino event

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Evoking new physics

Possible origin of the KM3-230213A neutrino event from dark matter decay

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Neutron portal to ultra-high-energy neutrinos

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Does the 220 PeV Event at KM3NeT Point to New Physics?

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2502.04508, SL with Pedro Machado, Daniel Naredo-Tuero, and Tom Schwemberger

Conclusions

We do not know the origin of KM3-230213A

All steady sources lead to a 2.9-3.6σ tension between KM3-230213A and IceCube

A low tension is only achieved if it comes from a transient source

This is very likely the first observation of a new ultrahigh energy neutrino source

We need more observations!