Neutrino astrophysics – What have we learnt?

DSU Sydney 2022

Second Gordon Godfrey Workshop

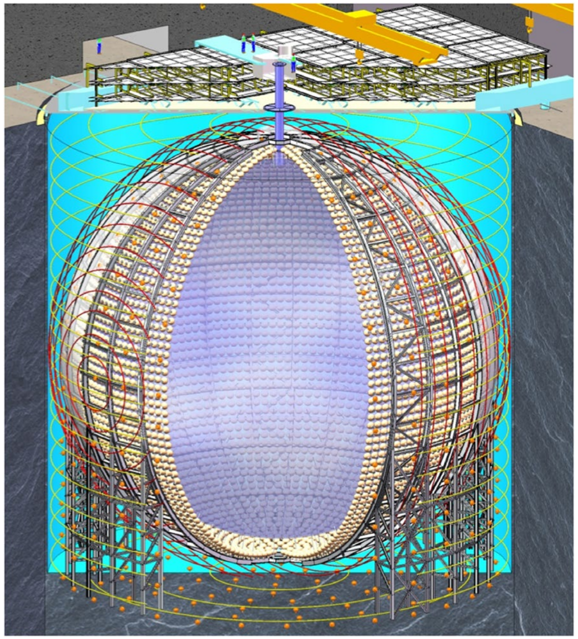
Jenni Adams

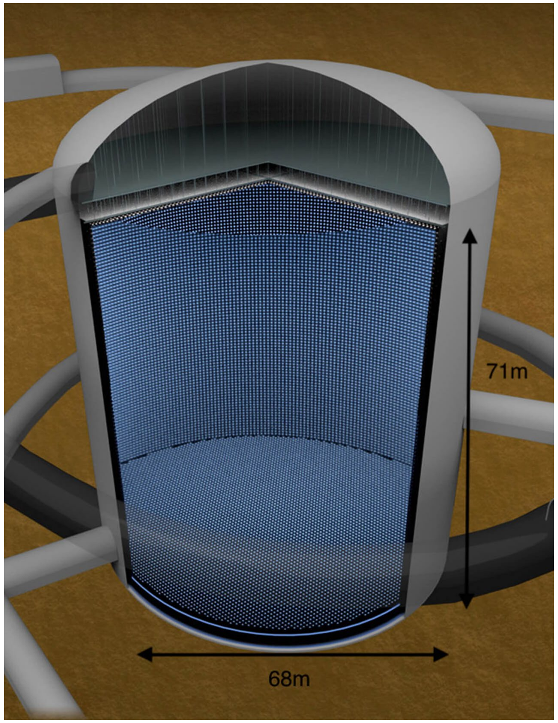
University of Canterbury, New Zealand

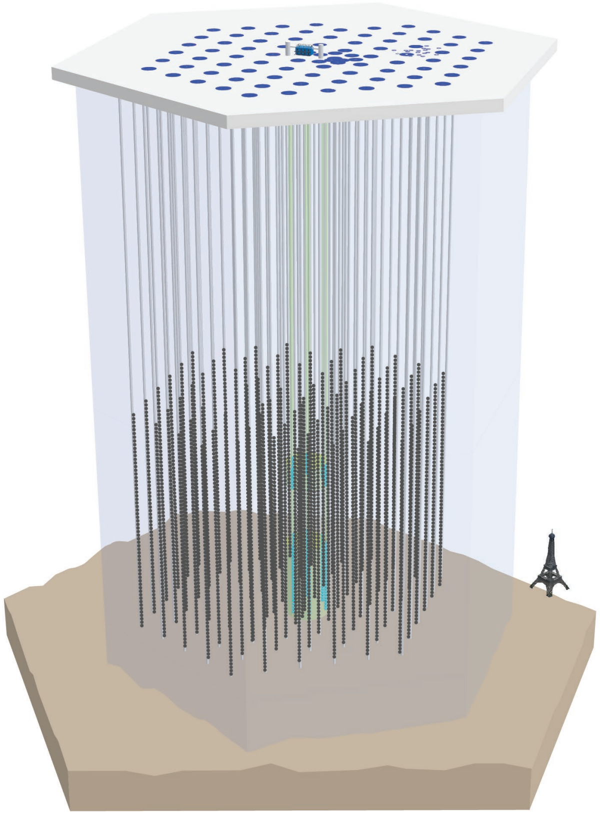
Photo credit: Ian Rees

Neutrino telescopes

Big cousins of neutrino detectors







JUNO

Hyper-Kamiokande

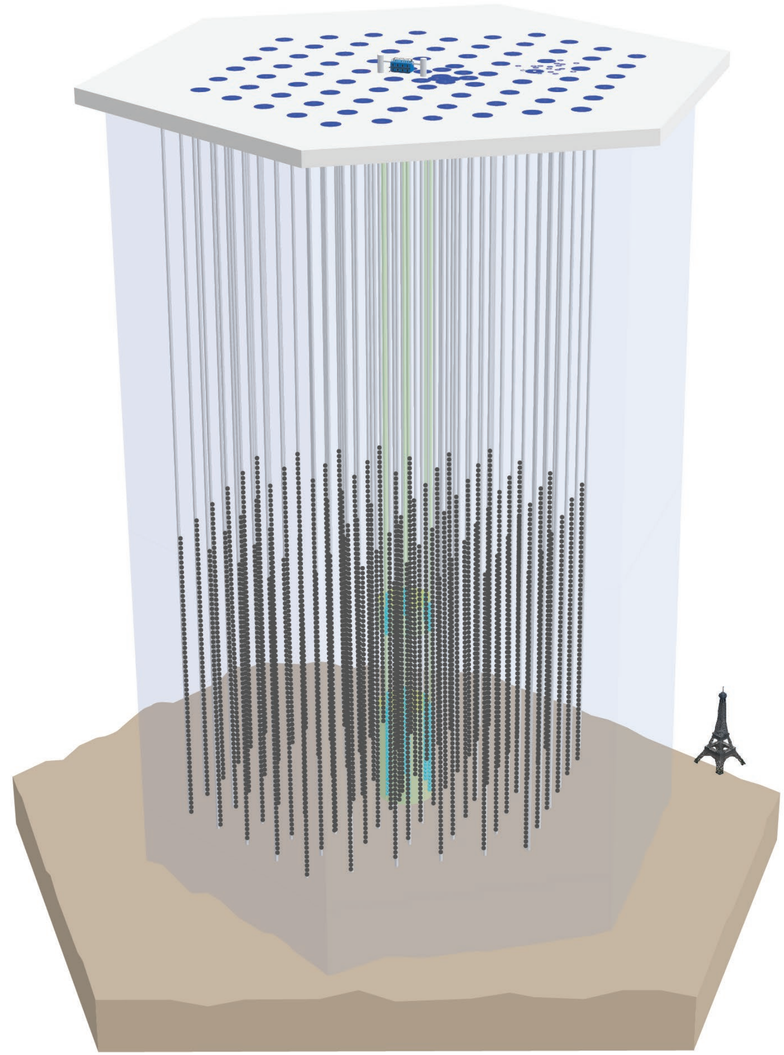
IceCube

Neutrino telescopes

Big cousins of neutrino detectors

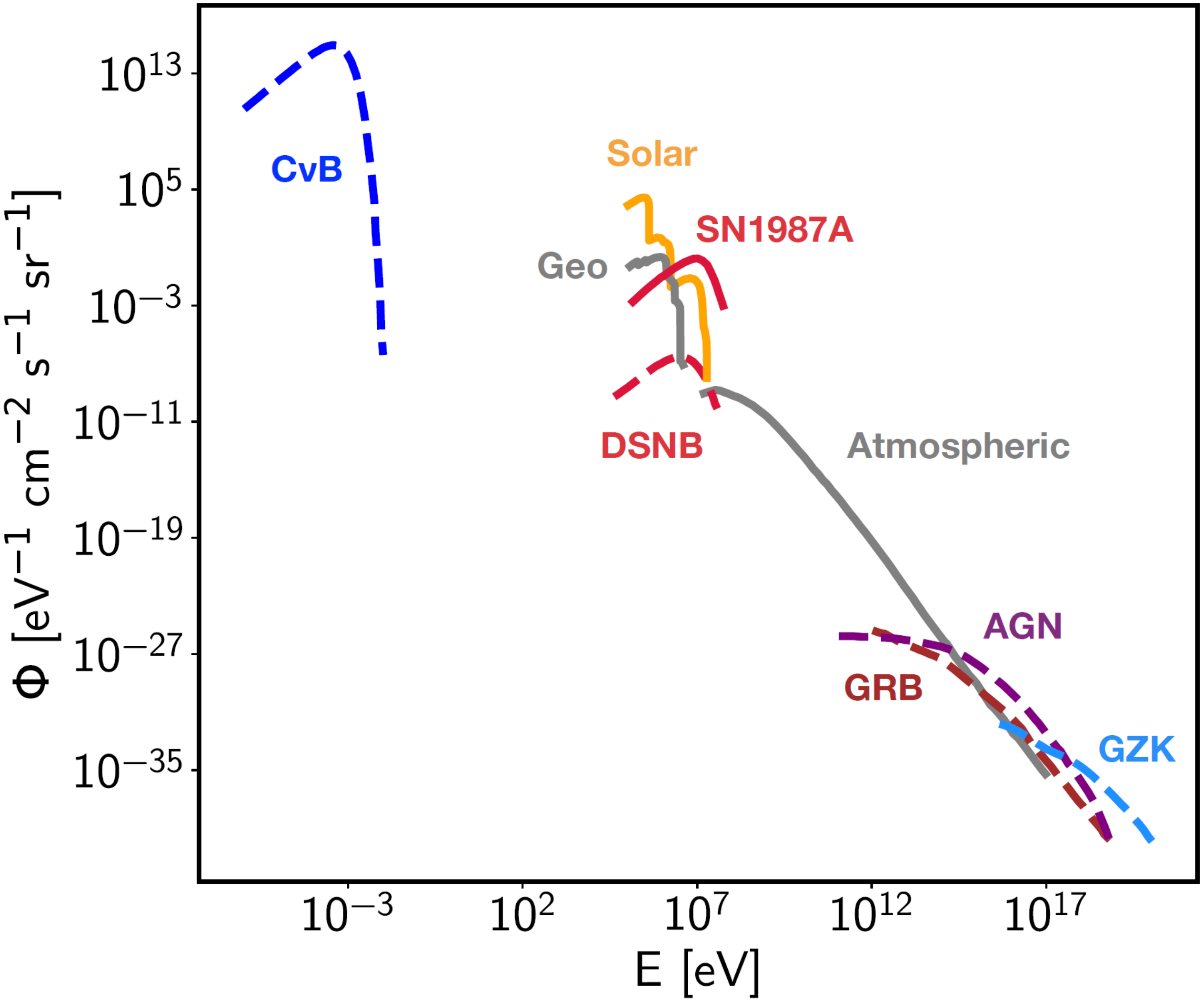
JUNO

Hyper-Kamiokande

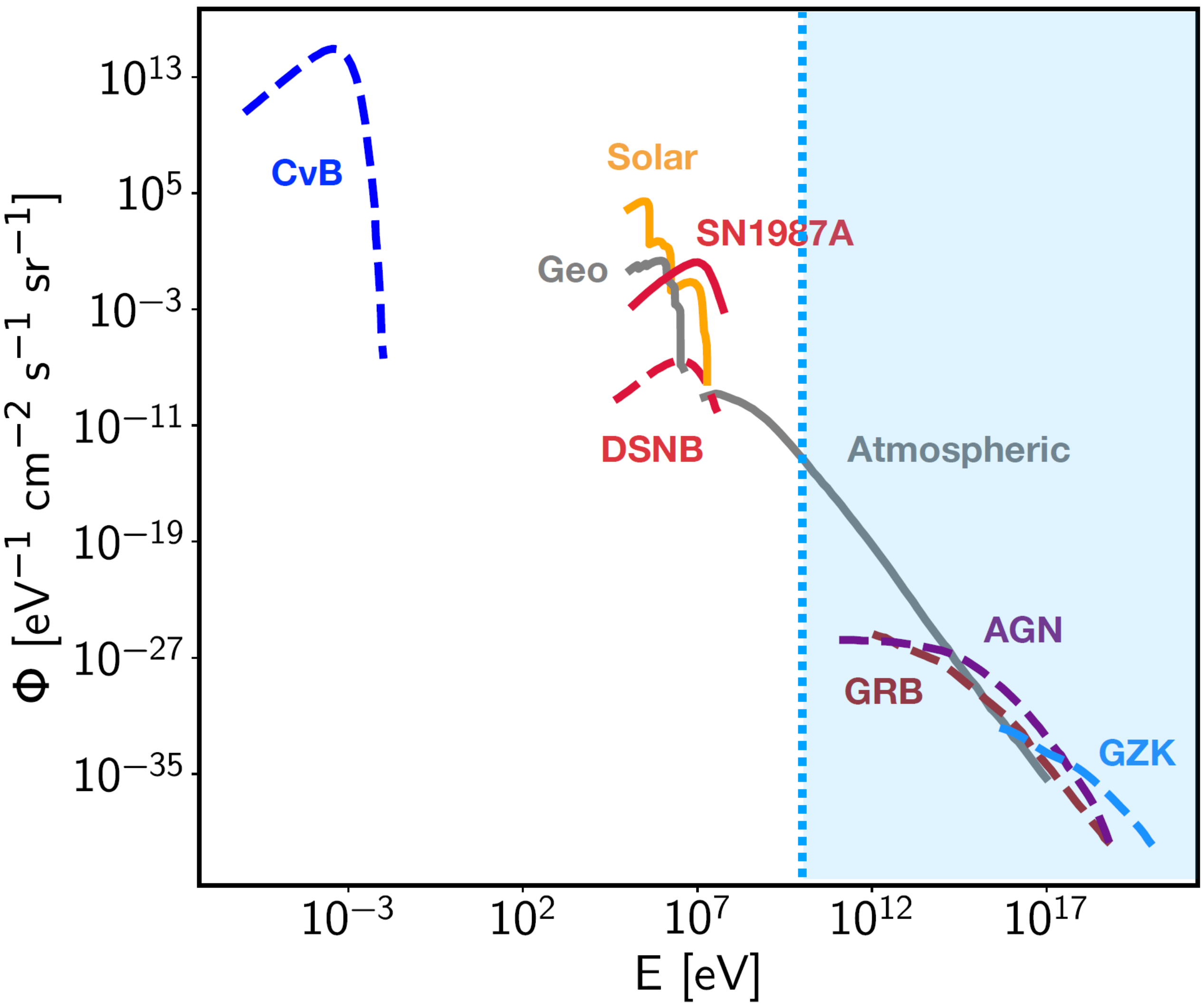


IceCube

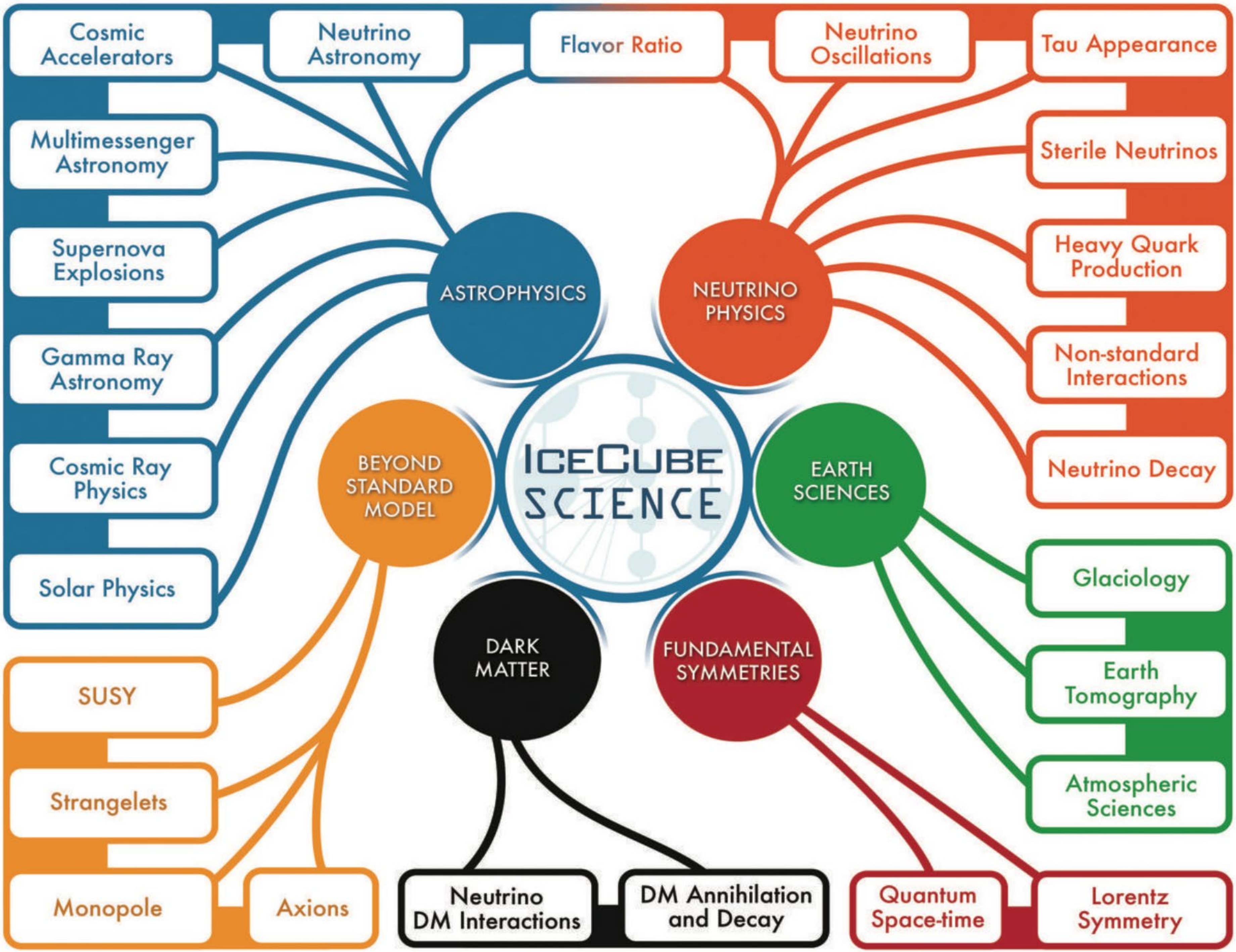
Astrophysical neutrino spectra



Astrophysical neutrino spectra



Astrophysical neutrinos- challenge of small cross-section AND low fluxes



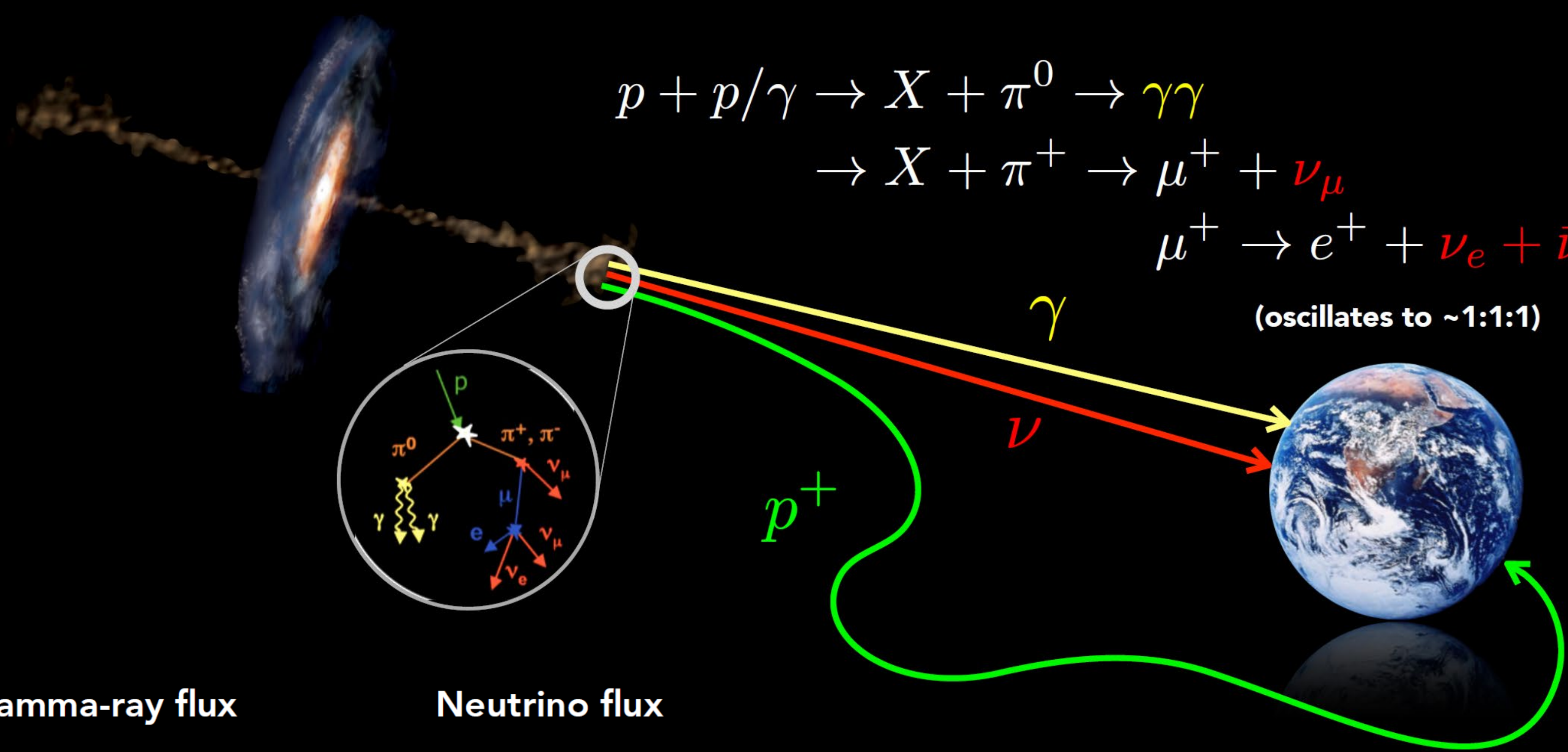
ICECUBE SCIENCE
ASTROPHYSICS
Cosmic Accelerators
Neutrino Astronomy
Flavor Ratio
Multimessenger Astronomy
Supernova Explosions
Gamma Ray Astronomy
Cosmic Ray Physics
Solar Physics
NEUTRINO PHYSICS
Neutrino Oscillations
Tau Appearance
Sterile Neutrinos
Heavy Quark Production
Non-standard Interactions
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

Neutrino mass ordering

KM3Net and JUNO Collaborations arXiv/2108.06293

Neutrinos – messengers from cosmic-ray acceleration sites

$$p + p/\gamma \rightarrow X + \pi^0 \rightarrow \gamma\gamma$$
$$\rightarrow X + \pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$



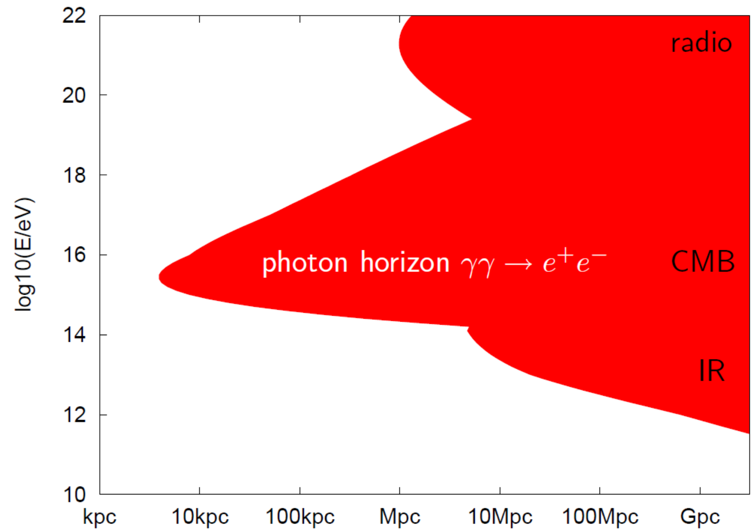
Gamma-ray flux **Neutrino flux**

$$\frac{K_\pi}{4} E_\gamma^2 F_\gamma(E_\gamma) \approx \frac{1}{3} \sum E_\nu^2 F_\nu(E_\nu)$$

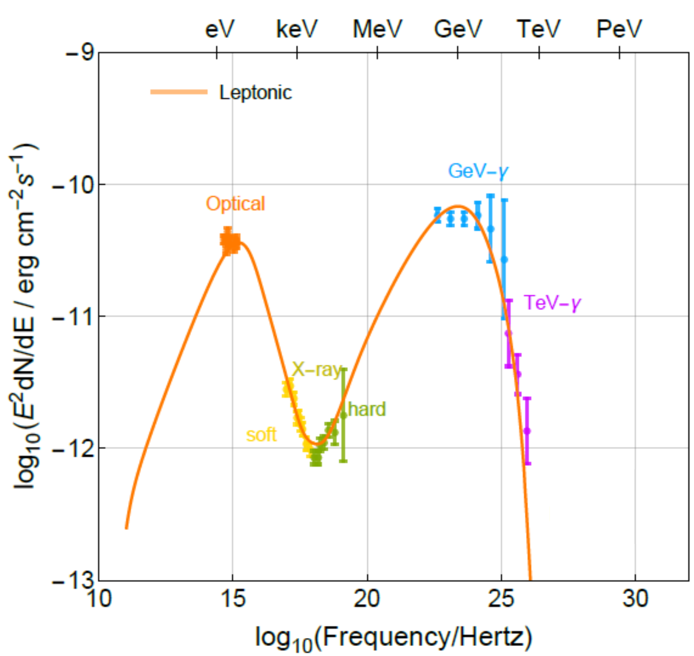
$E_\gamma = 2E_\nu$

Neutrinos complement gamma rays

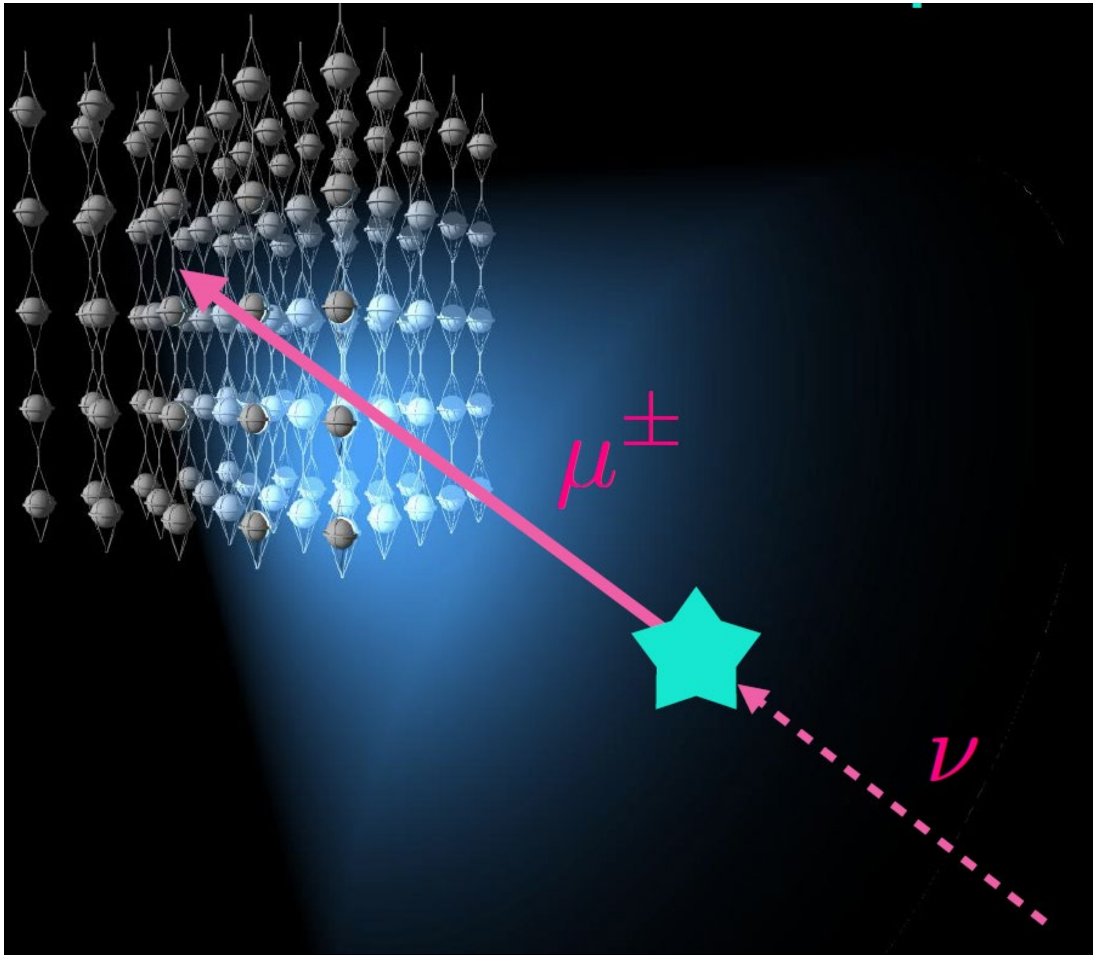
- Astronomy with VHE photons is restricted to a few Mpc



- Neutrinos are a definitive signature of hadronic acceleration

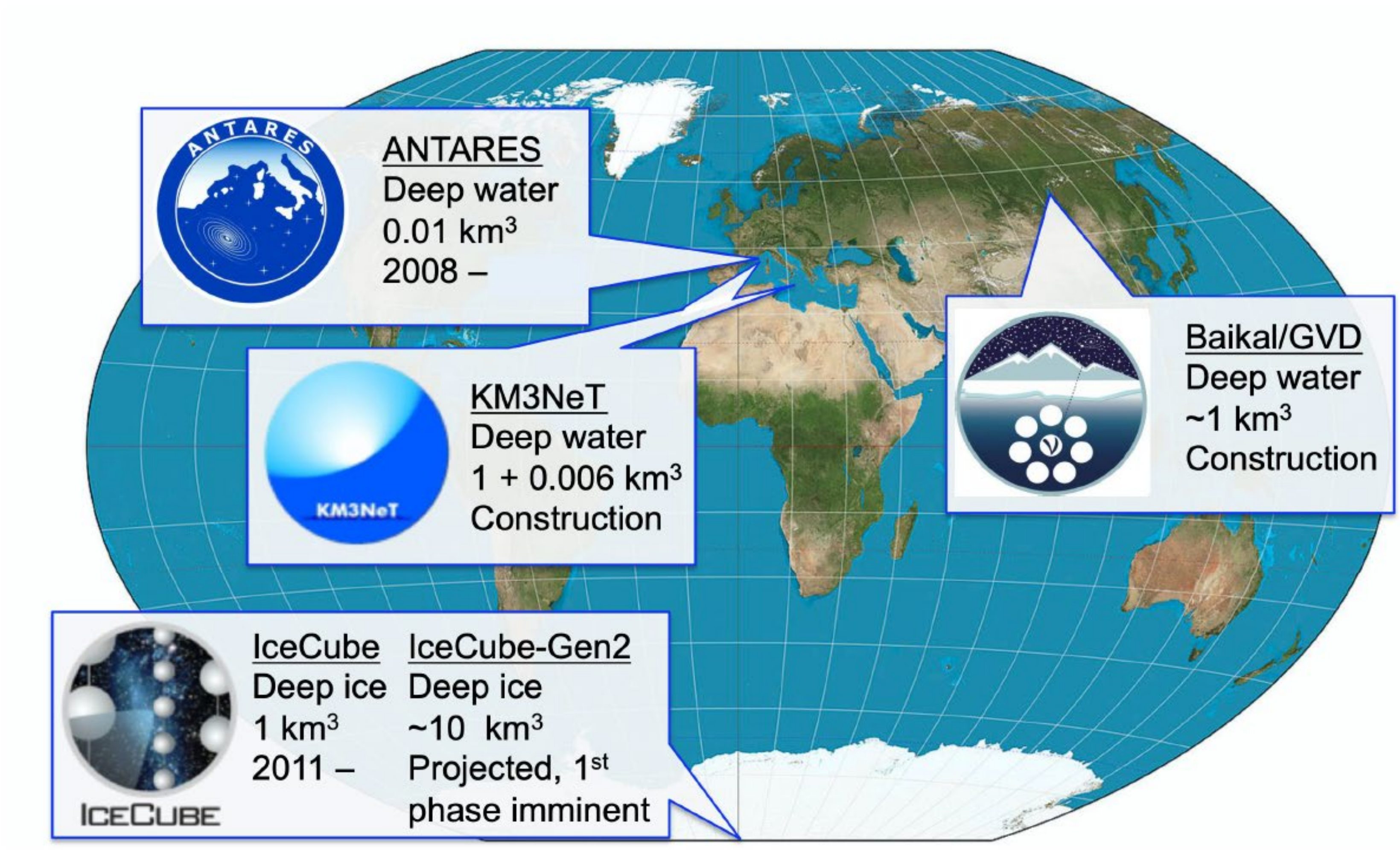


Cherenkov neutrino telescopes

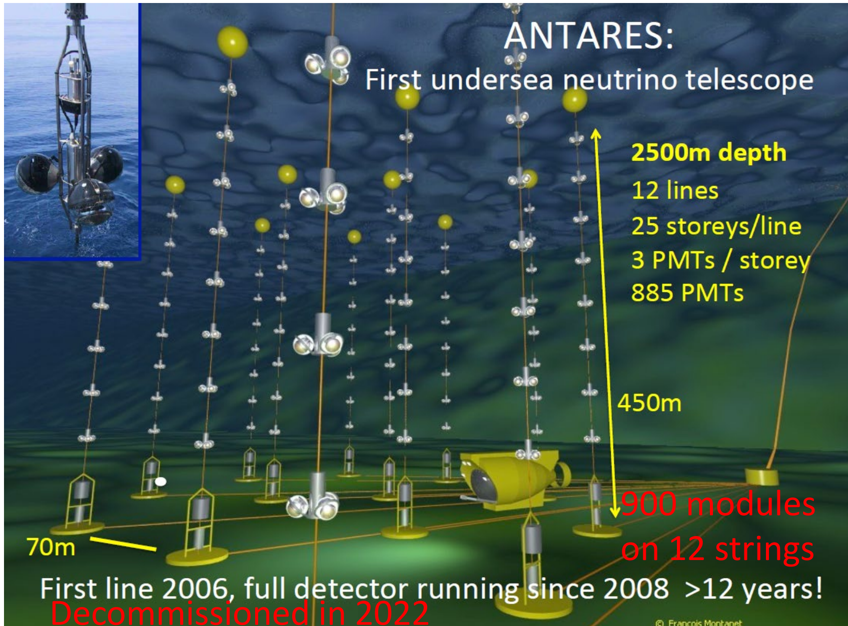


Detect the Cherenkov light from the charged products of neutrino interactions

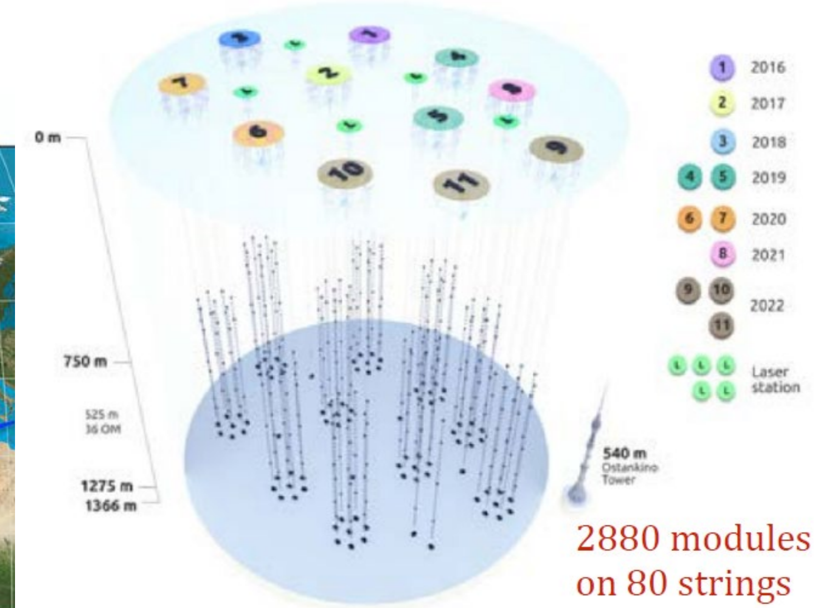
Neutrino telescope network

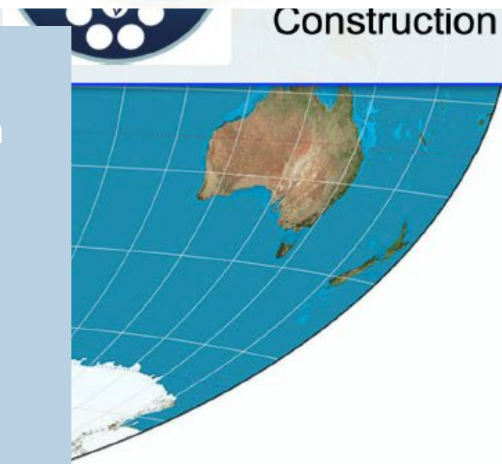


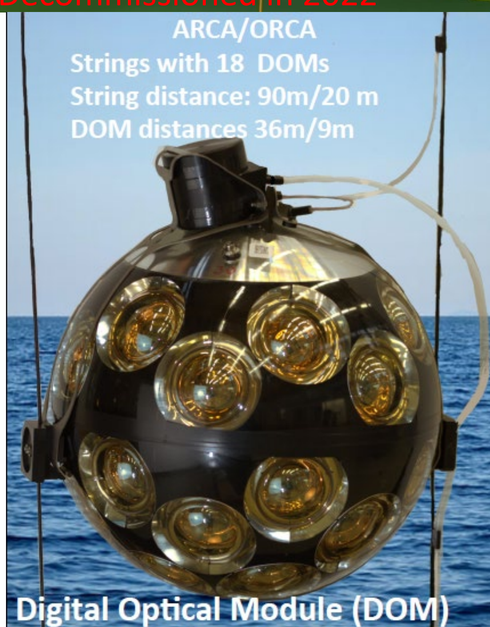
Neutrino telescope network



Baikal-GVD







KM3NeT ARCA/ORCA

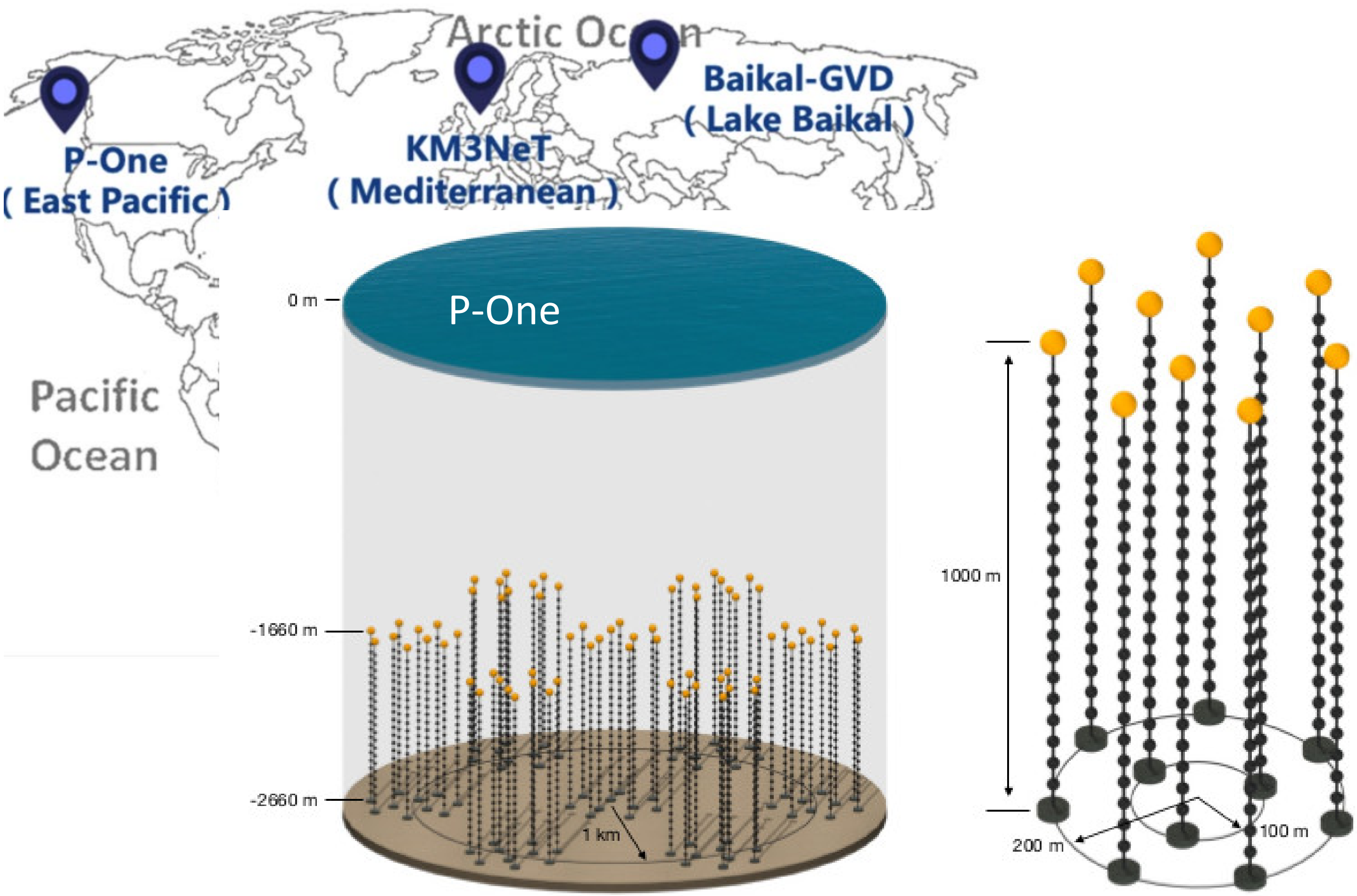
Astrophysics/Oscillation Research with Cosmics in the Abyss

ARCA 3.5km depth, Sicily
Large sparse grid, 1-2 strings operational
Goal: 2 X 115 strings 2026

ORCA 2.5km depth, Toulon
Small dense grid,6 strings operational
Goal: 115 strings 2024

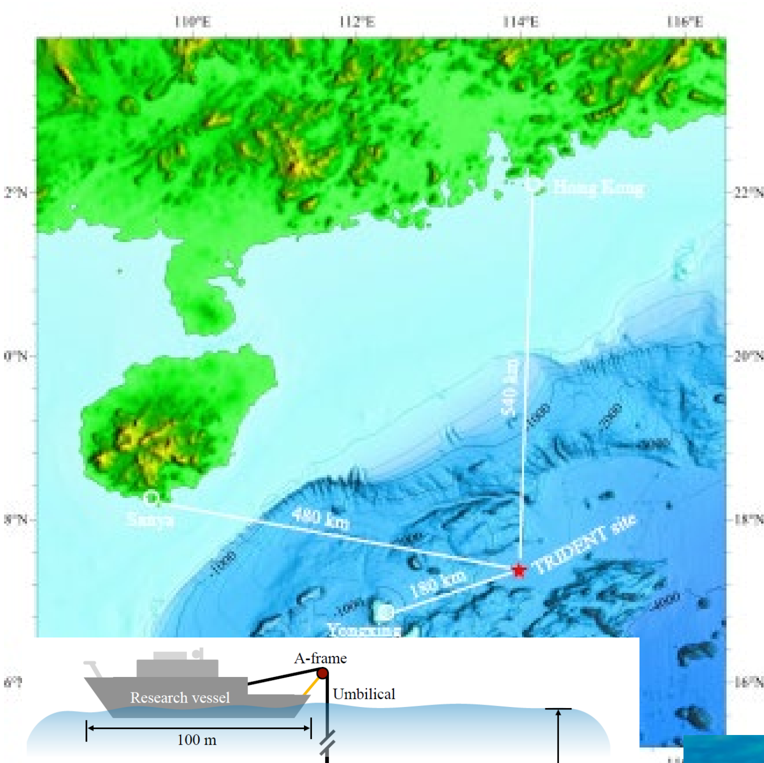
Neutrino telescope network - future

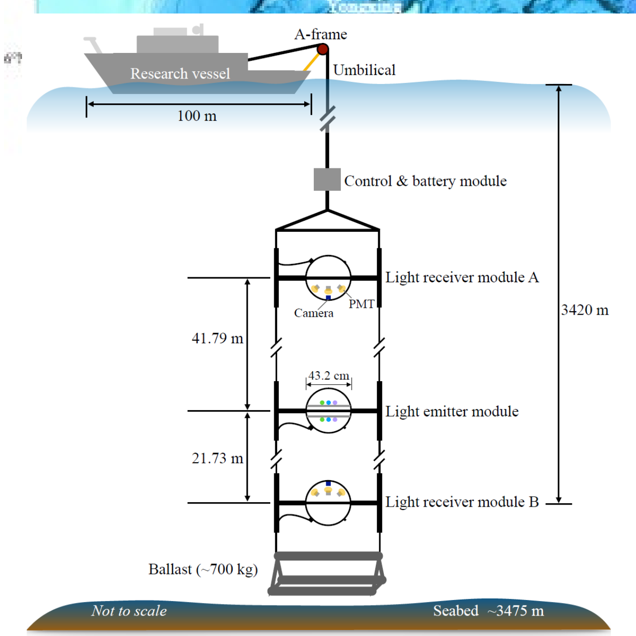
Neutrino telescope network - future

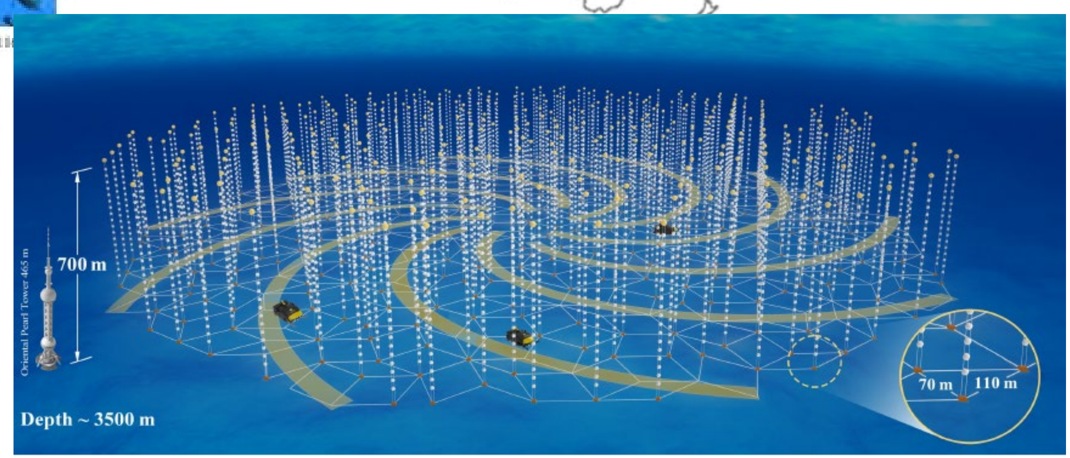


70 strings ~3 km^3

Neutrino telescope network - future

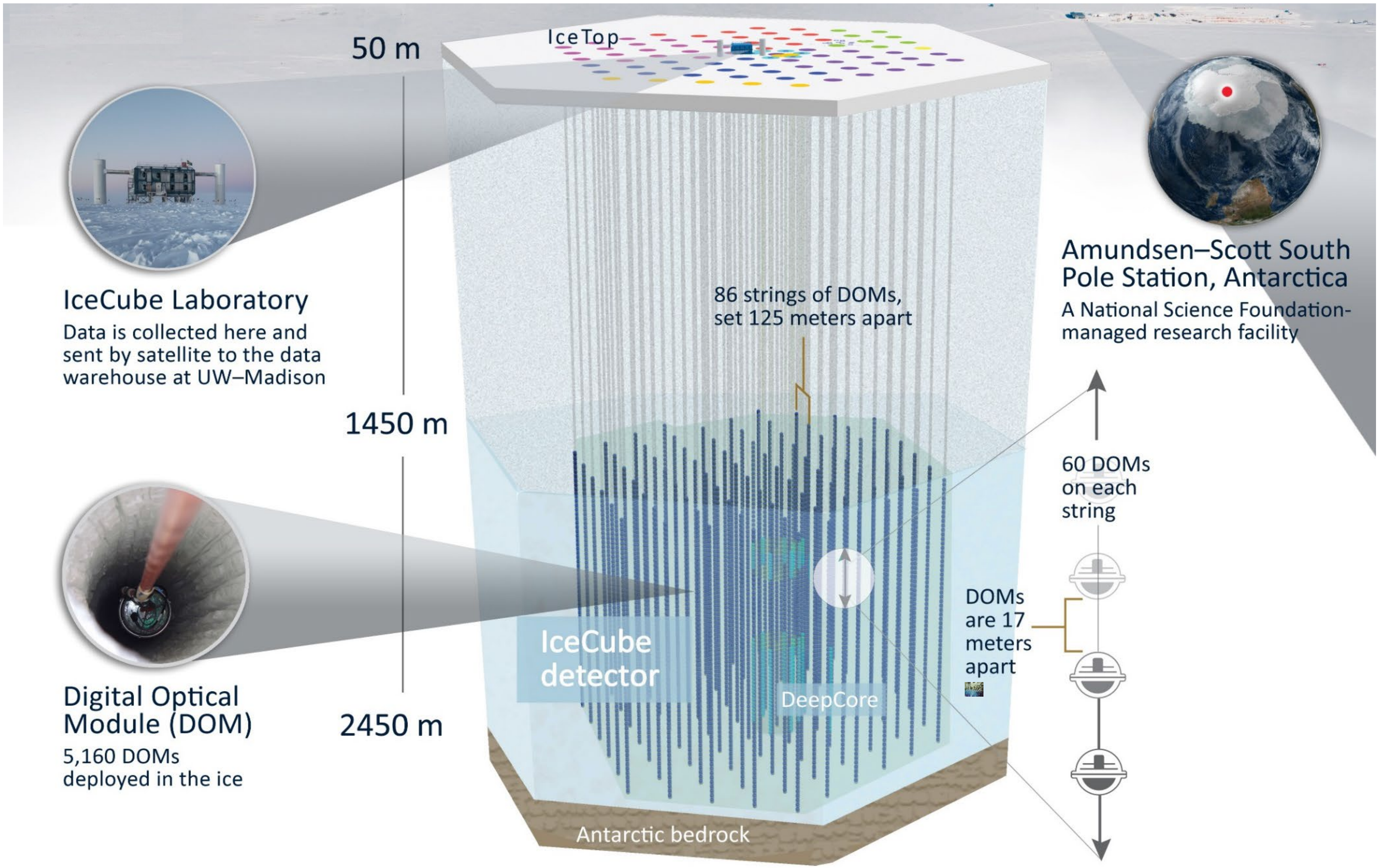






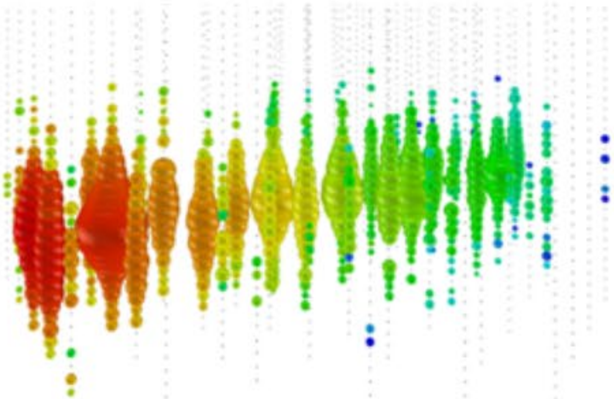
1200 string 7.5 km^3

IceCube Neutrino Observatory



Neutrino signatures

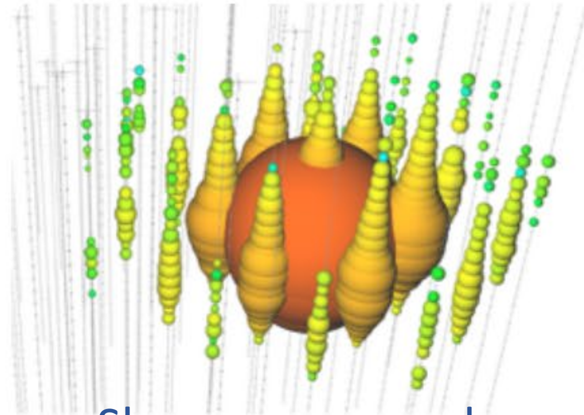
$L_\tau \simeq 50\text{m} \cdot E_\tau \ /\text{PeV}$



Track
(Data)

CC Muon neutrinos

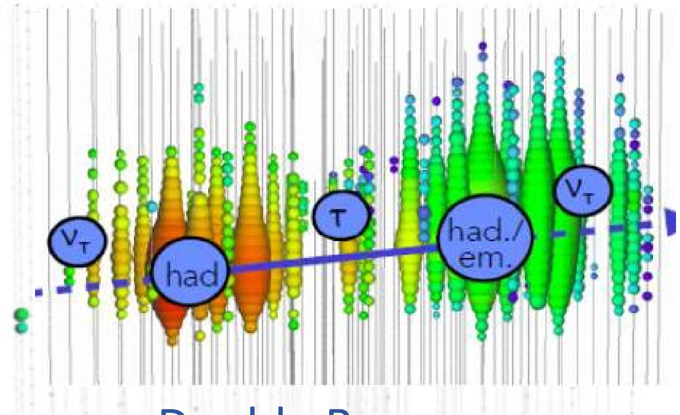
factor of ≈ 2
energy resolution
(in E_μ rather than E_ν)
< 1° angular resolution



Shower or cascade
(Data)

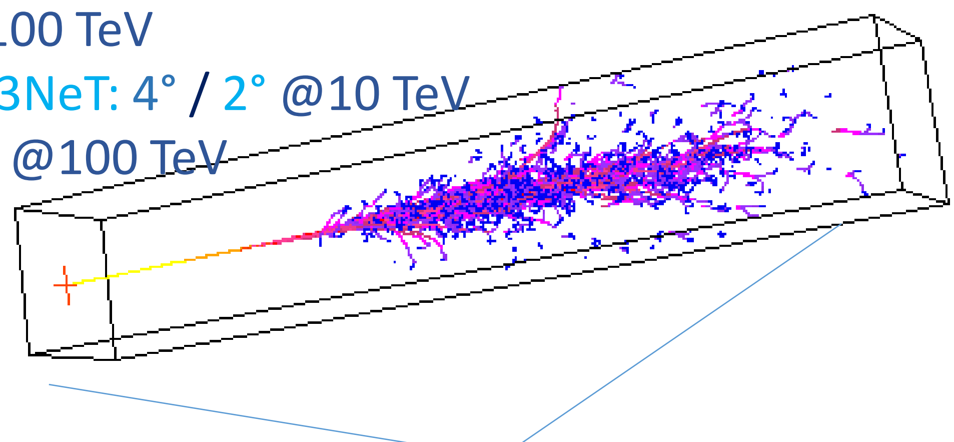
NC all neutrino flavours
CC Electron and Tau neutrinos

15% deposited energy resolution
angular resolution
ice: 10° for >100 TeV
Antares / KM3NeT: 4° / 2° @10 TeV
Baikal 3°-3.5° @100 TeV

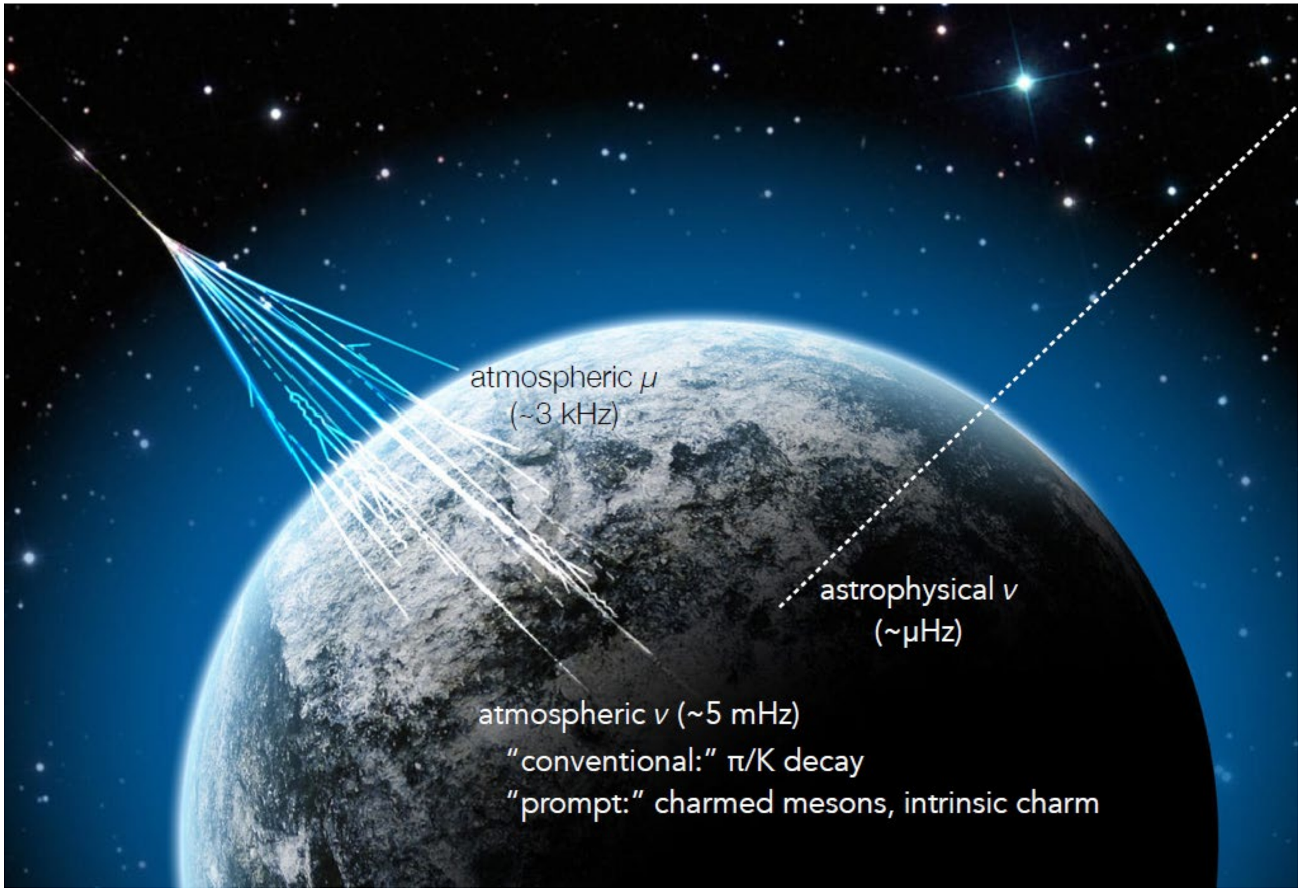


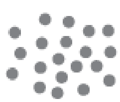
Double Bang
(Simulation)

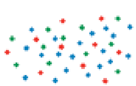
~PeV Tau neutrinos

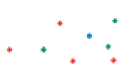


Backgrounds



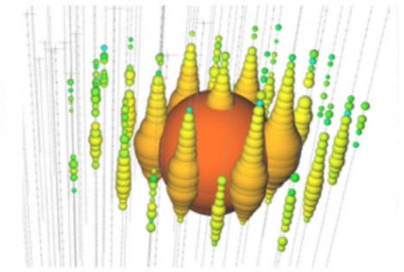

275 million atmospheric muons are detected daily, created by interactions of cosmic rays with the earth's atmosphere


8,250 atmospheric neutrinos are detected monthly


only 10s of cosmic neutrinos are detected per year

Background removal strategies

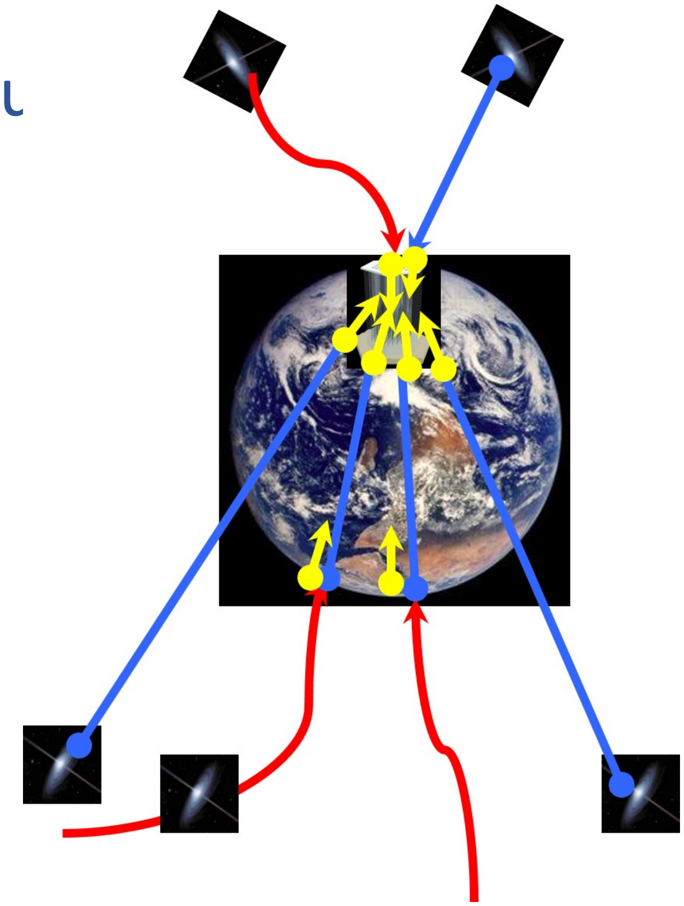
- Select cascade events to reject muon events



Background removal strategies

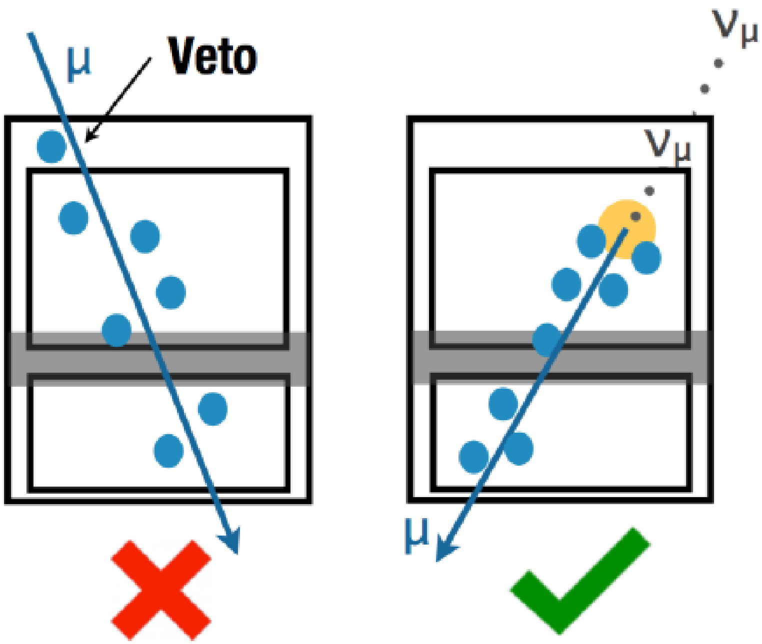
- Select cascade events to reject mu

- Select upward going events
to reject muon events



Background removal strategies

- Select cascade events to reject
- Select upward going events to events
- Use the outer part of the detector to reject muon events and select “starting events”



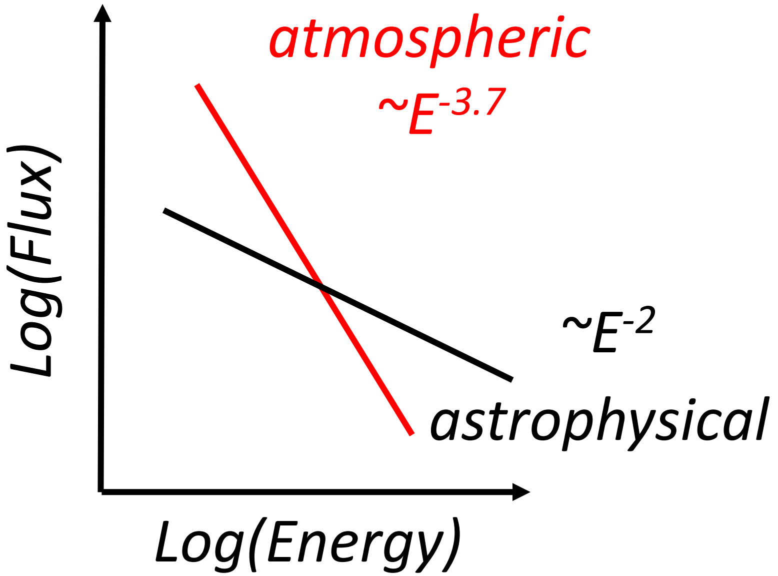
Background removal strategies

- Select cascade events to reject muon events

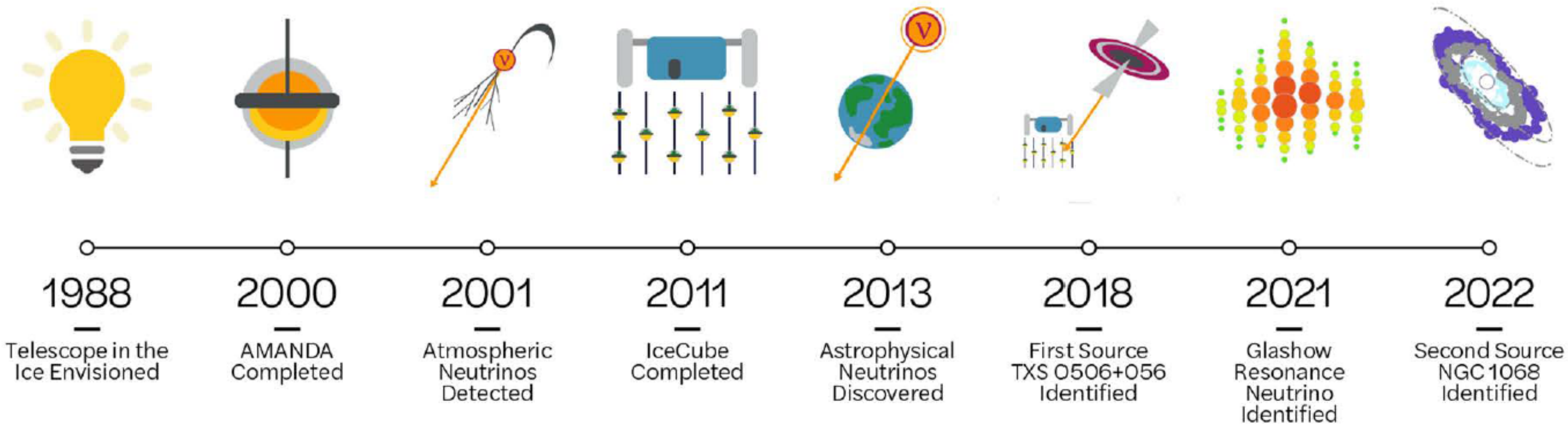
- Select upward going events to reject muon events

- Use the outer part of the detector to reject muon events and select “starting events”

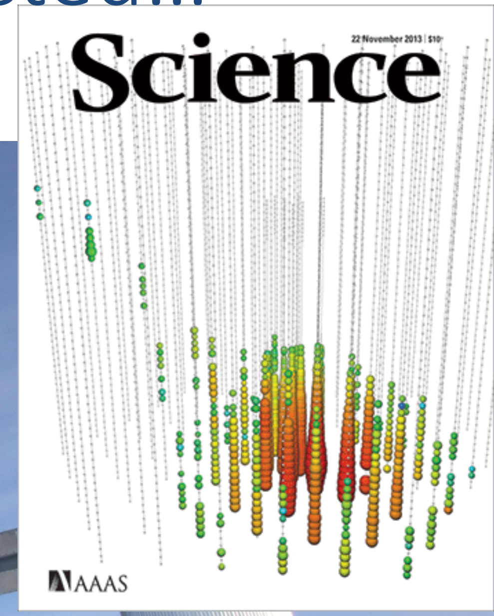
- Use the different spectral slopes to discriminate atmospheric and astrophysical neutrinos



IceCube milestones

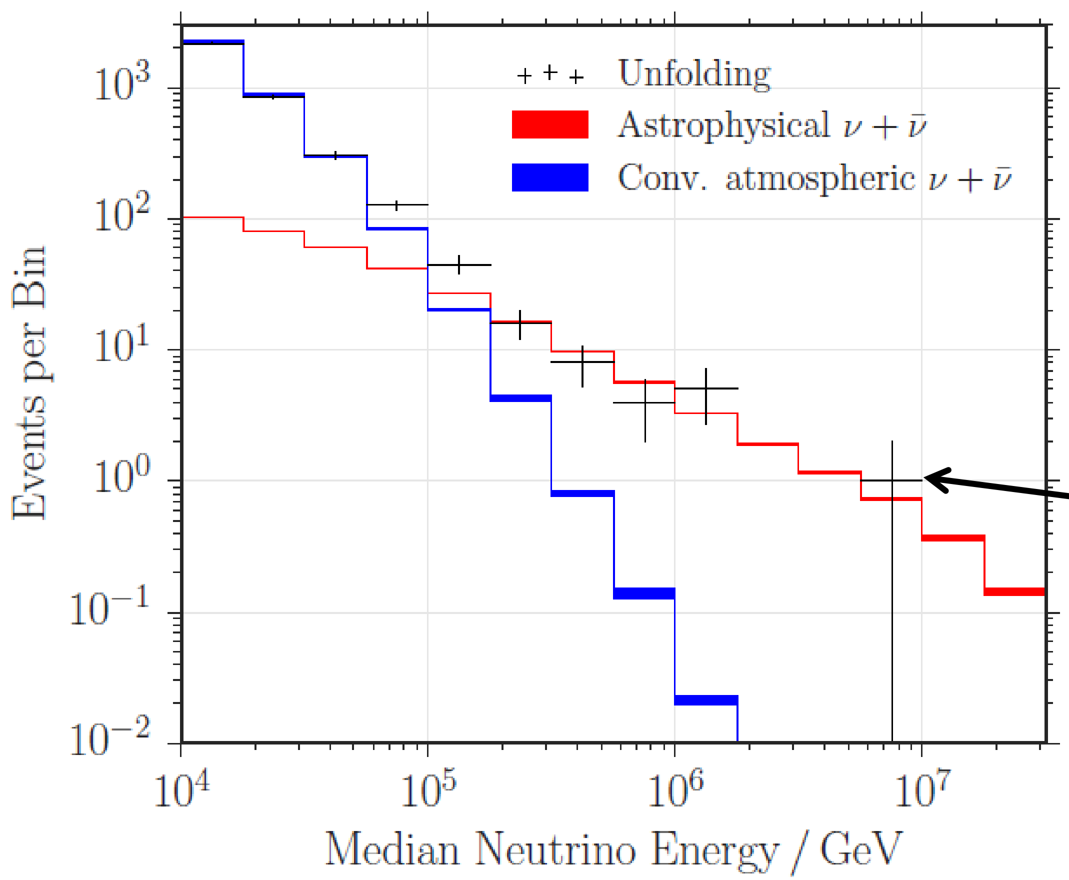


First astrophysical neutrinos detected…

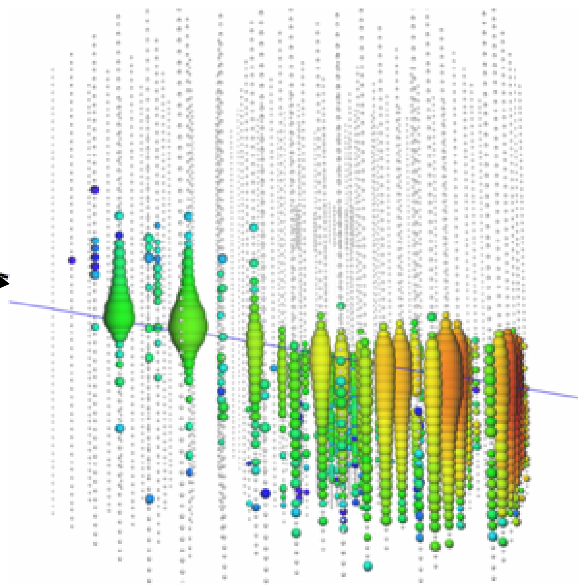


Upward-going muon search

unfolded data assuming unbroken best-fit power law

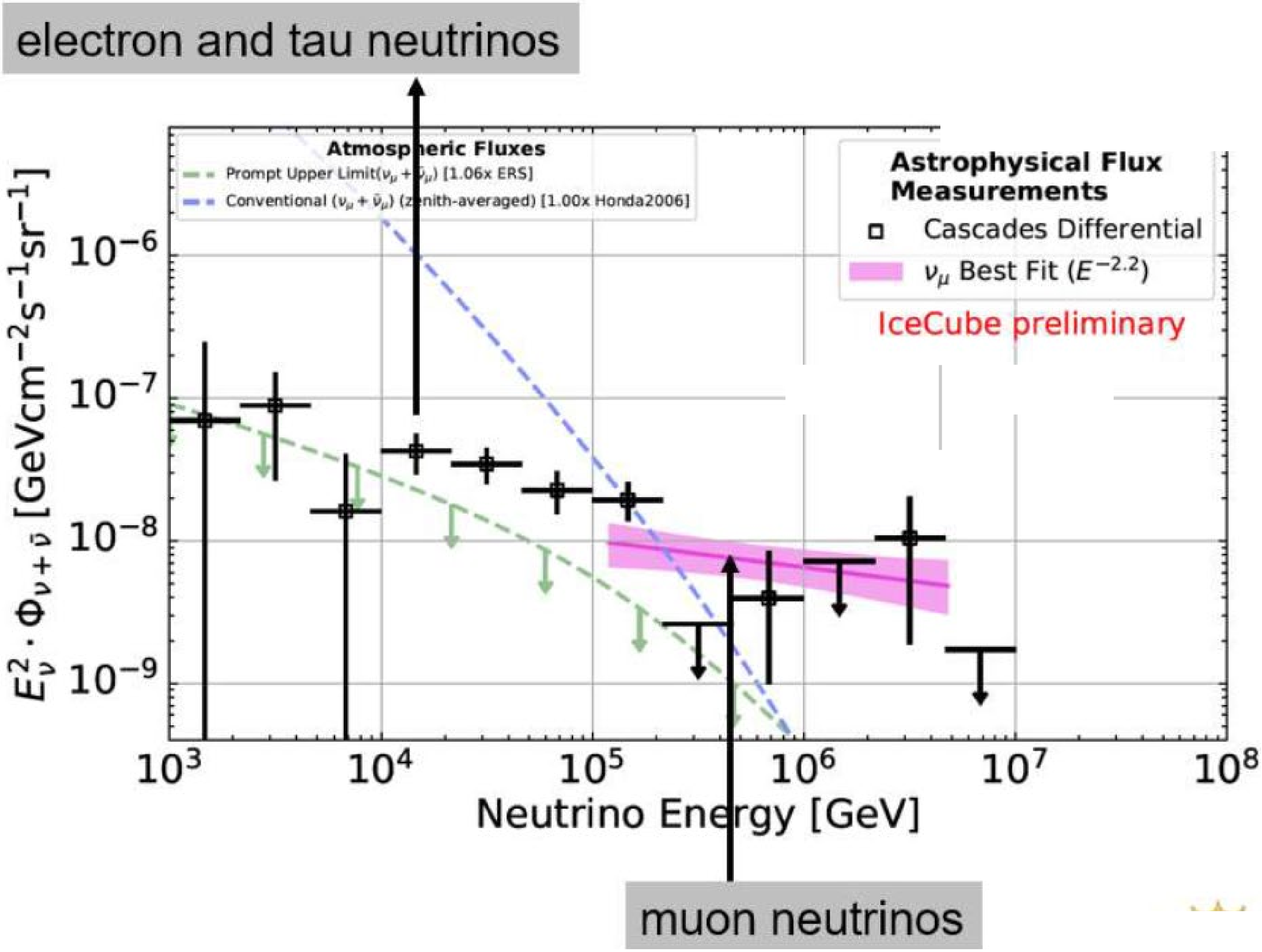


Now 10 years of observations
8 year → 6.7 σ
~500 astrophys neutrinos



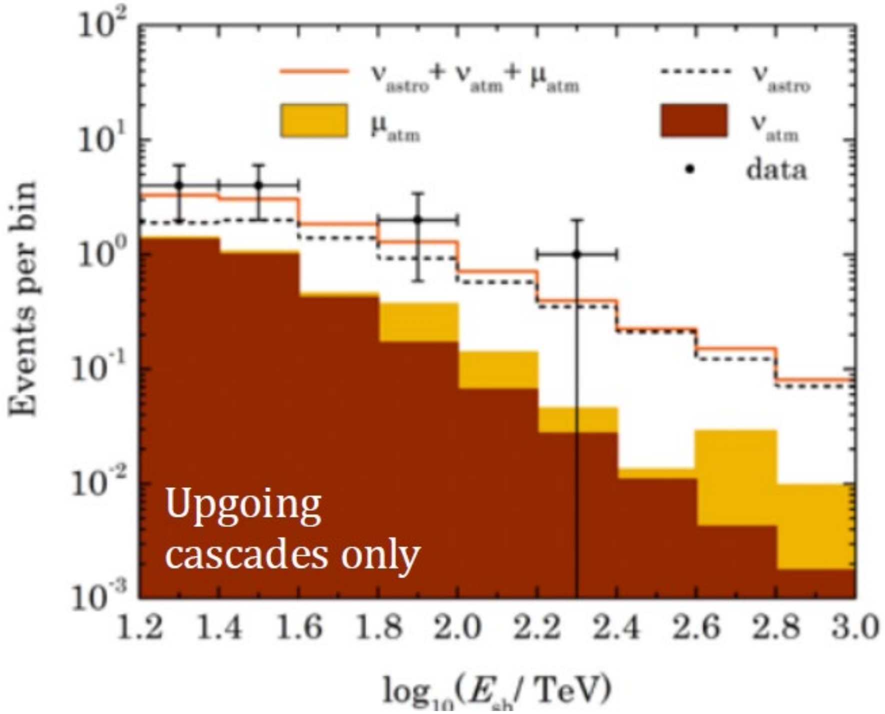
Deposited energy:
2.6±0.3 PeV

Diffuse astrophysical neutrino spectrum



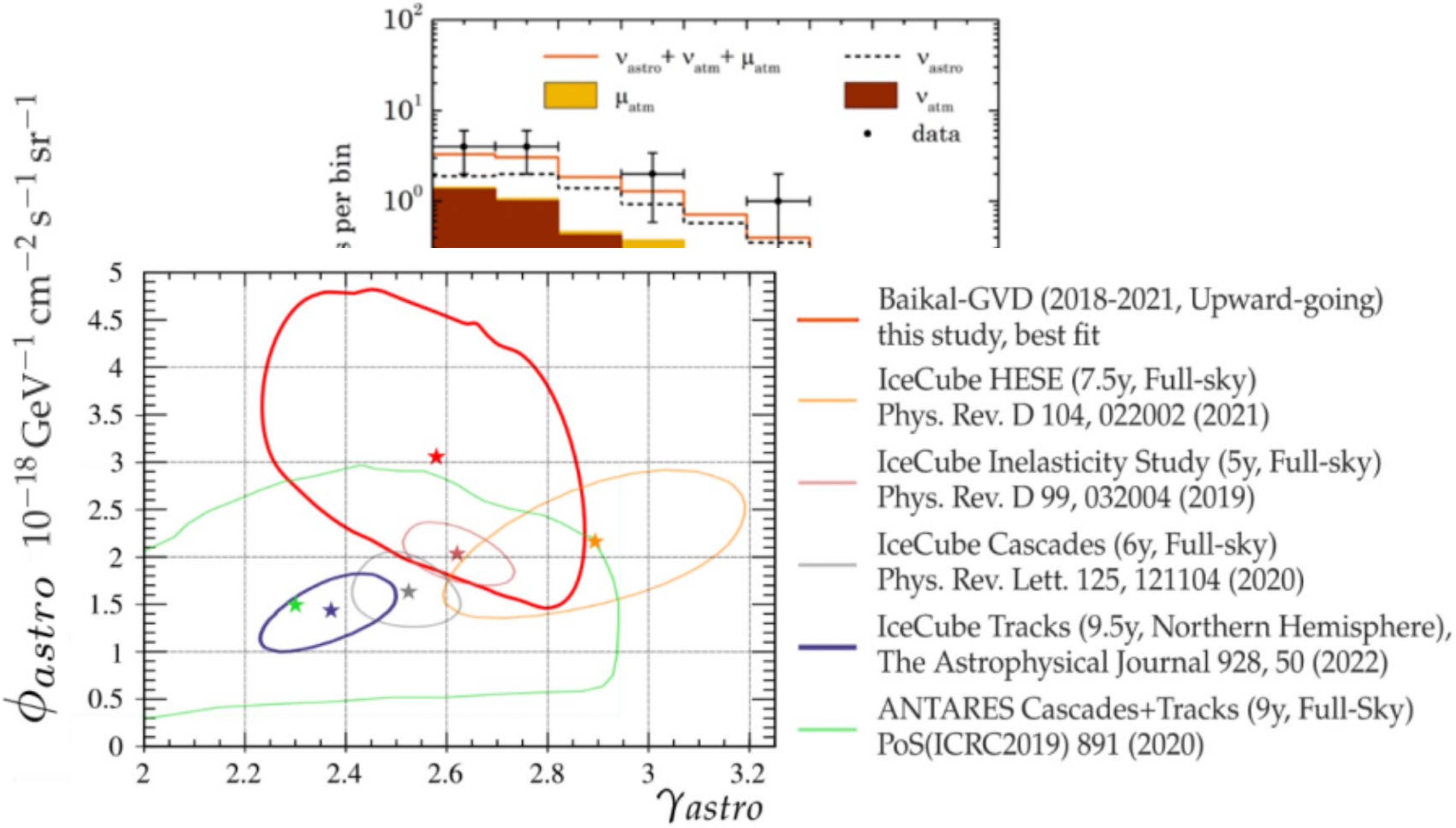
Inconsistent with pure υ^{atm} > 5 σ (> 3 σ, > 1.8 σ)
by IceCube (GVD, ANTARES)

ANTARES and GVD results consistent with IceCube



GVD collaboration arXiv 2211.09447.pdf

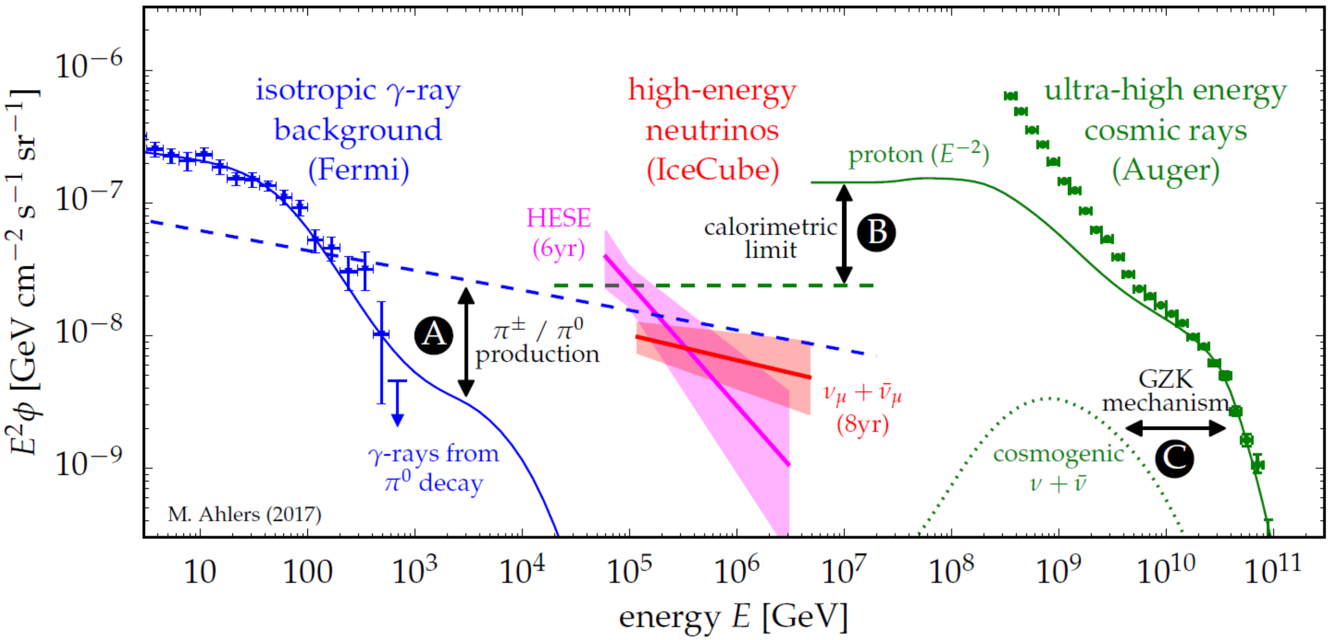
ANTARES and GVD results consistent with IceCube



GVD collaboration arXiv 2211.09447.pdf

Energy in gamma rays, cosmic rays and neutrinos

Ahlers & Halzen arXiv1805.11112
Progress in Particle and Nuclear Physics
Vol. 102, 17.05.2018

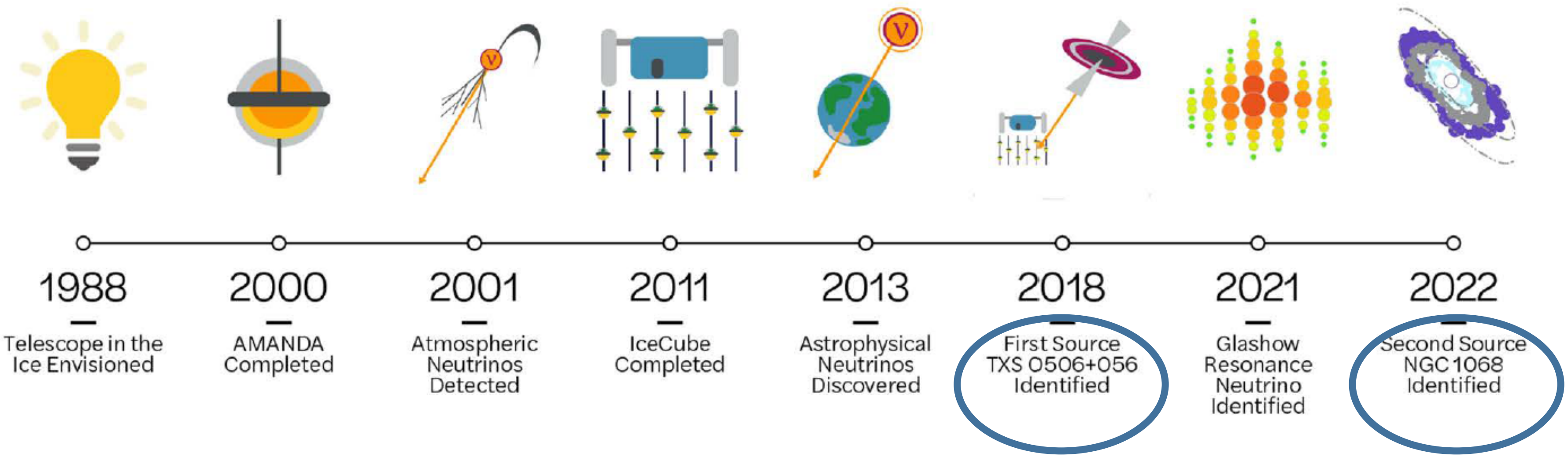


A: Calculated neutrino flux (- - -) from fit to Fermi data (——) assuming both from cosmic ray interactions

B: Calculated neutrino limit (- - -) from fit to Auger data (——) assuming all cosmic rays convert to neutrinos

C: Calculated cosmogenic flux (······) from fit to Auger data (——) assuming protons to highest energy

IceCube milestones



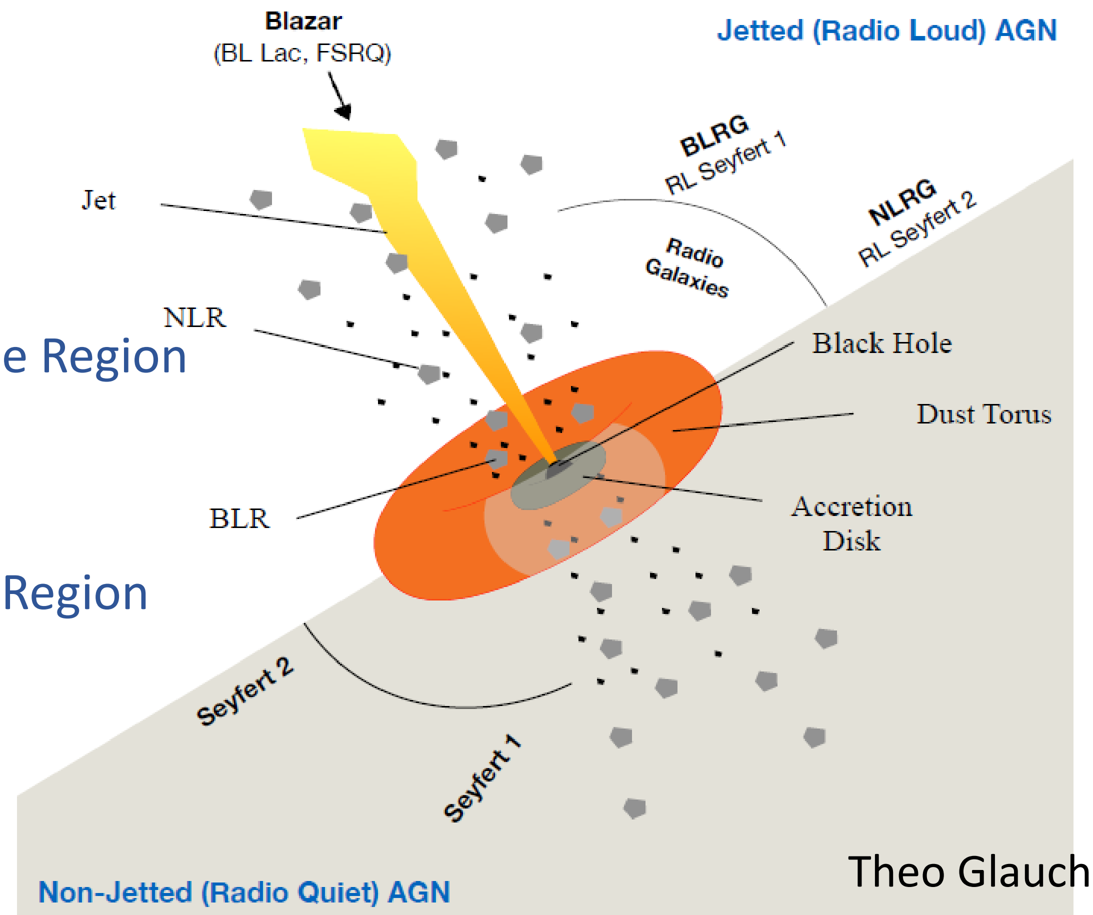
AGN Taxonomy

Different classes related to:

- Jetted or non-jetted
- Line of sight orientation

NLR Narrow Line Region

BLR Broad Line Region



Theo Glauch PhD thesis

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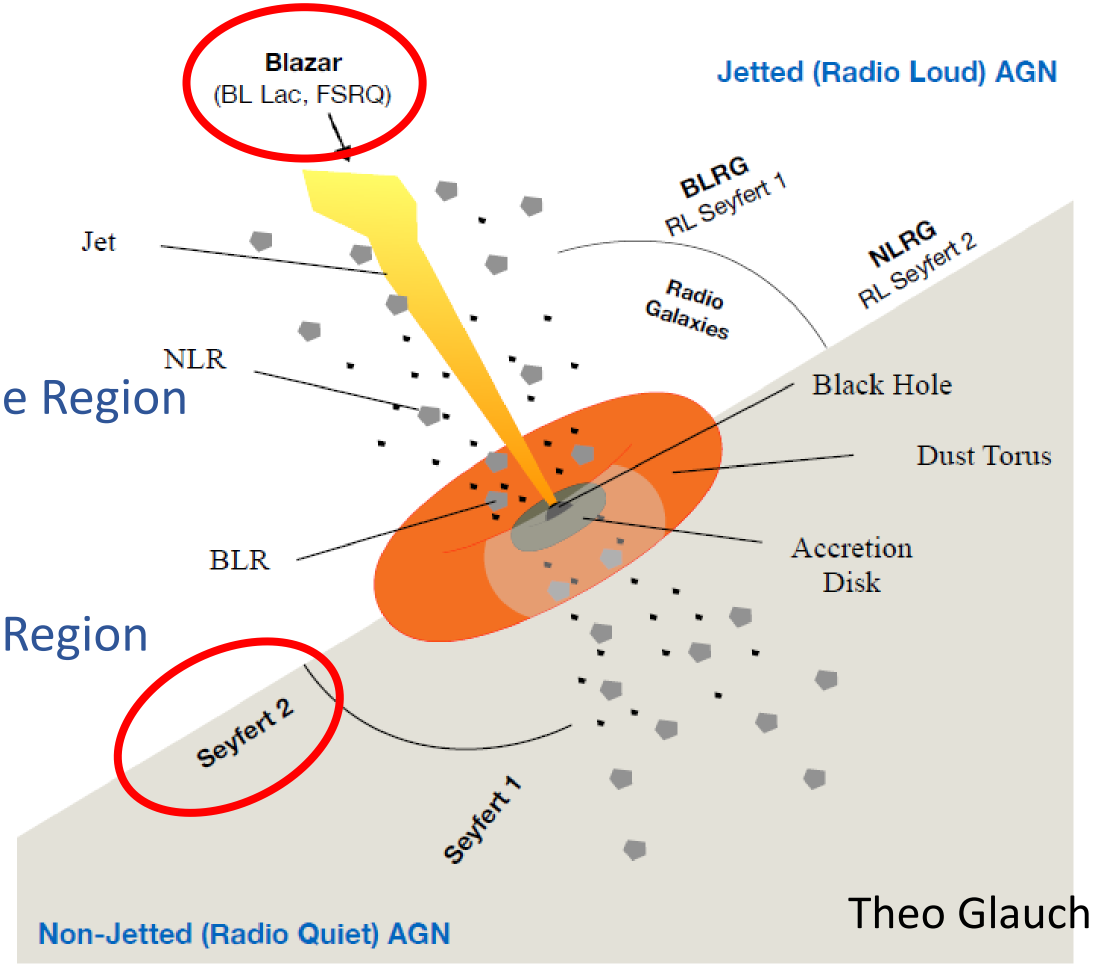
BLR Broad Line Region



Theo Glauch PhD thesis

IceCube neutrino source detections

Blazar – AGN with relativistic jets orientated towards line of sight

Transient emission

z = 0.3365   5.7 billion light years

Non-jetted AGN with obscured black hole

Steady state emission

z = 0.00381   47 million light years

TXS0506+056

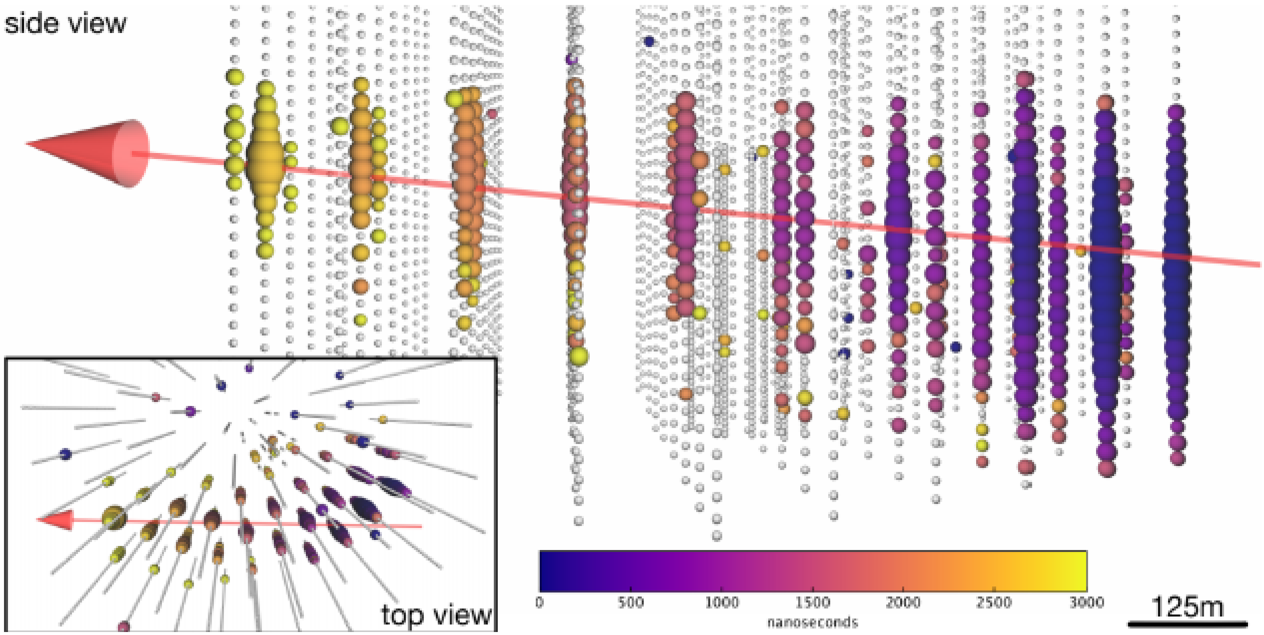
Two papers in Science (2018)

Vol. 361, Issue 6398

Describing neutrinos detected from the direction of the blazar TXS0506+056

IceCube-170922A and TXS 0506+056

- IceCube issued an alert on September 22nd, 2017



IceCube-170922A and TXS 0506+056

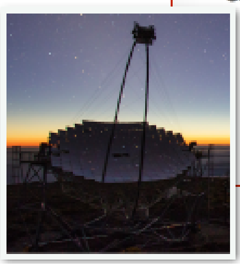
- IceCube issued an alert on September 22nd, 2017
- Follow up observations by ANTARES, HESS, Fermi-LAT, Swift, AGULE, MAGIC, HAWC, VERITAS…

Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; *Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration*
on 28 Sep 2
Credential Certification: David J. Th

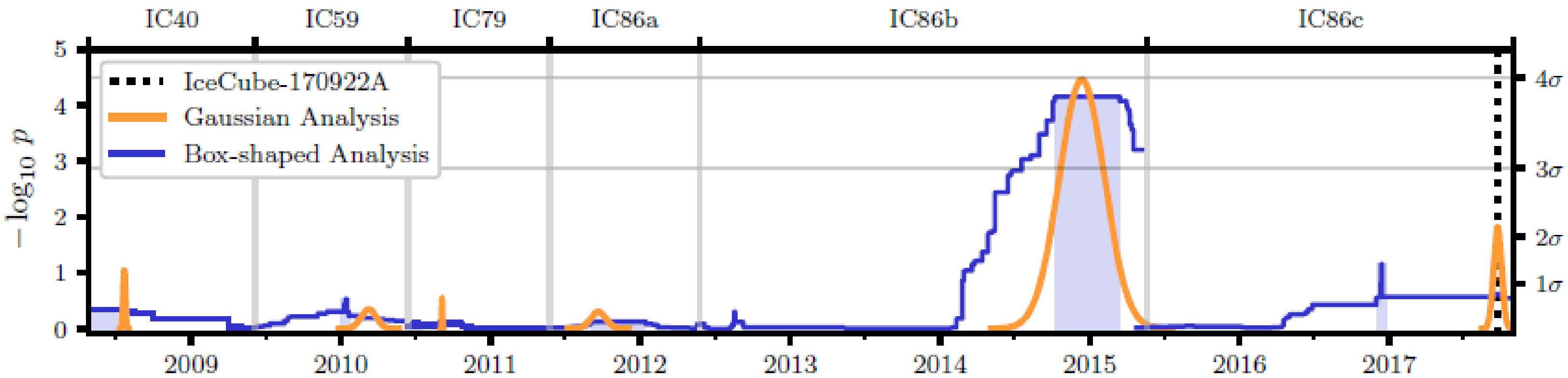
First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

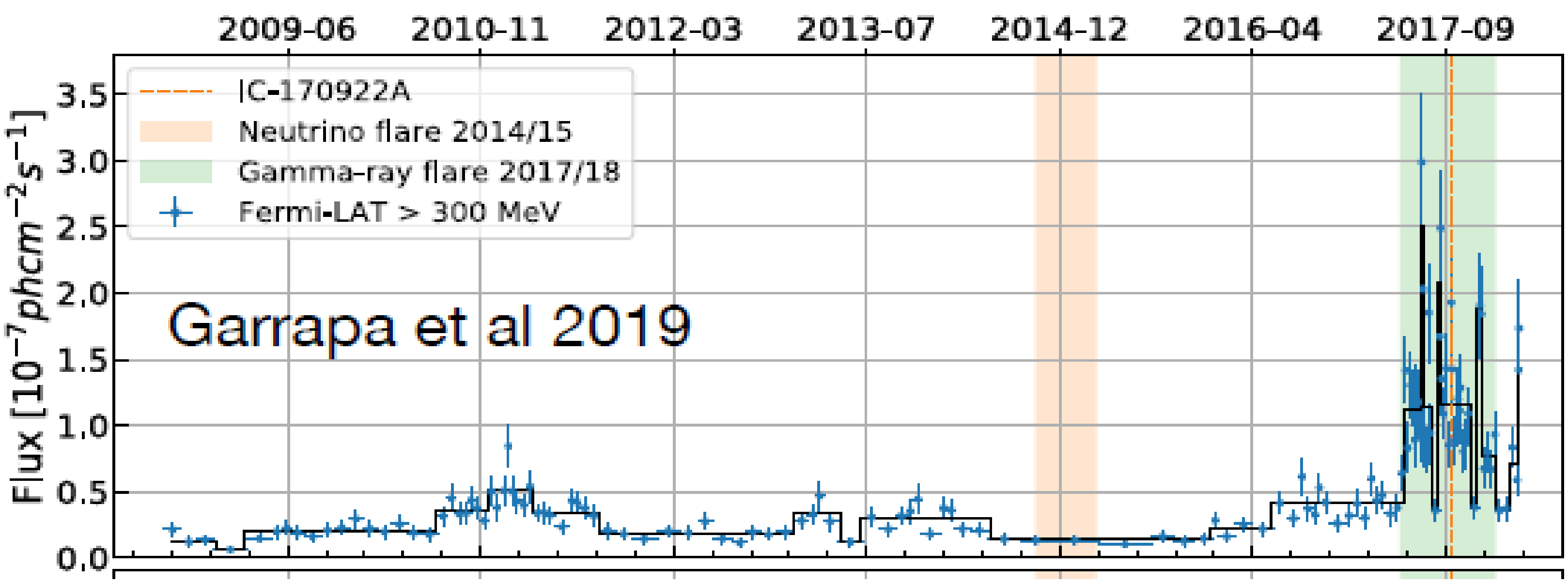
ATel #10817; *Razmik Mirzoyan for the MAGIC Collaboration*
on 4 Oct 2017; 17:17 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)



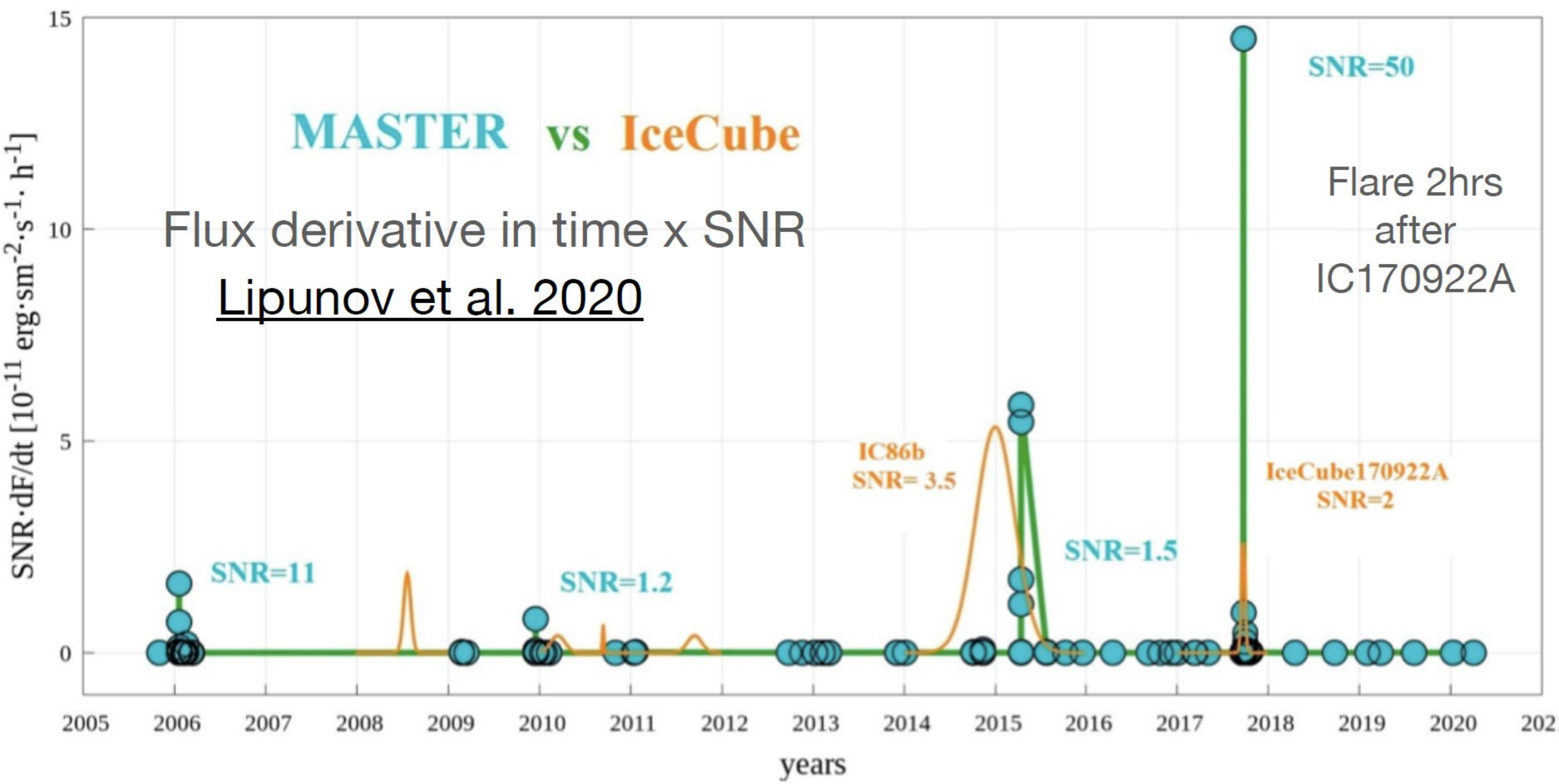
- TXS 0506+056 flaring at the time of neutrino observation
- Archival search of IceCube neutrino data found neutrino burst in 2014

Neutrinos compared with Fermi gamma rays





Neutrinos compared with MASTER optical



The robotic optical telescope MASTER network has been monitoring the source since 2005 and found the strongest time variation of the source over a period of two hours after the emission of IC170922, with a second variation following the 2014-15 burst

TXS0506+056 neutrino source

Halzen and Kheiransdish arXiv:2202.00694

- Flaring source; the fact that the source state is special is argued by noting that there are many closer blazars without observed neutrino emission
- A subset of blazars, around 1 -10% of all blazars, bursting once in 10 years at the levels of TXS 0506+056, can accommodate the diffuse cosmic neutrino flux.
- A source which is transparent to gamma rays is unlikely to host the material necessary to produce neutrinos –some evidence for neutrino emission during gamma-ray suppressed state (arXiv2009.09792)

NGC1068

Science — Nov. 4, 2022

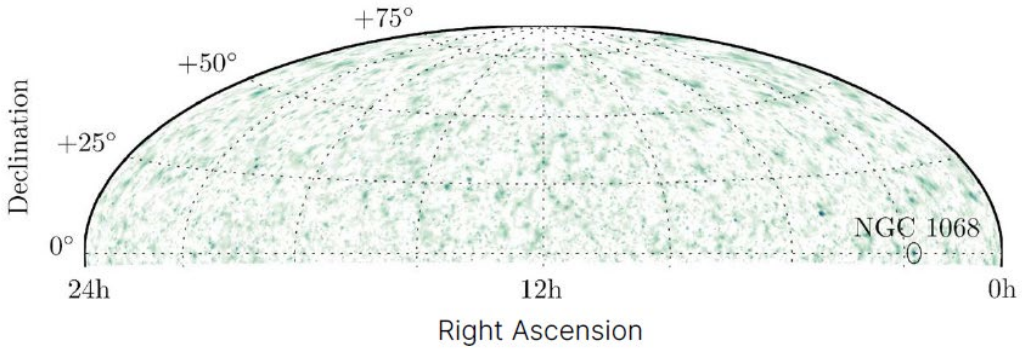
RESEARCH

RESEARCH ARTICLE

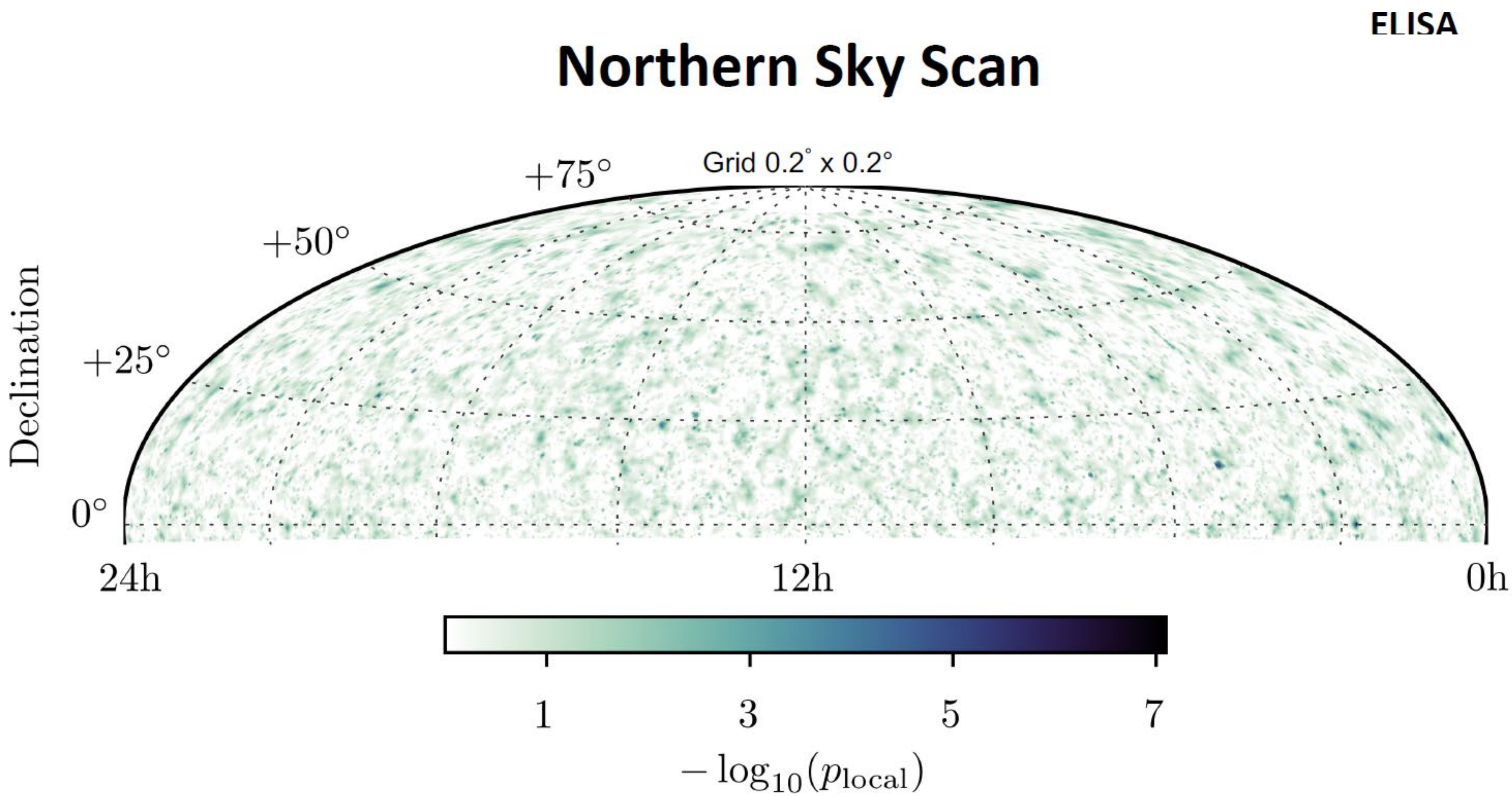
NEUTRINO ASTROPHYSICS

Evidence for neutrino emission from the nearby active galaxy NGC 1068

IceCube Collaboration*†

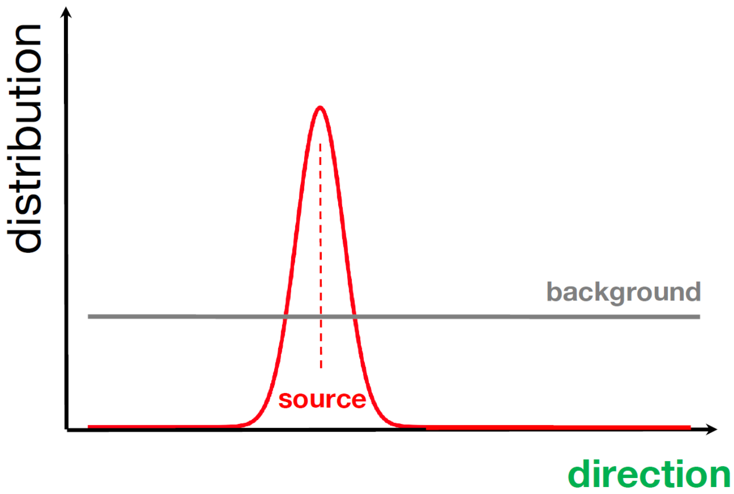


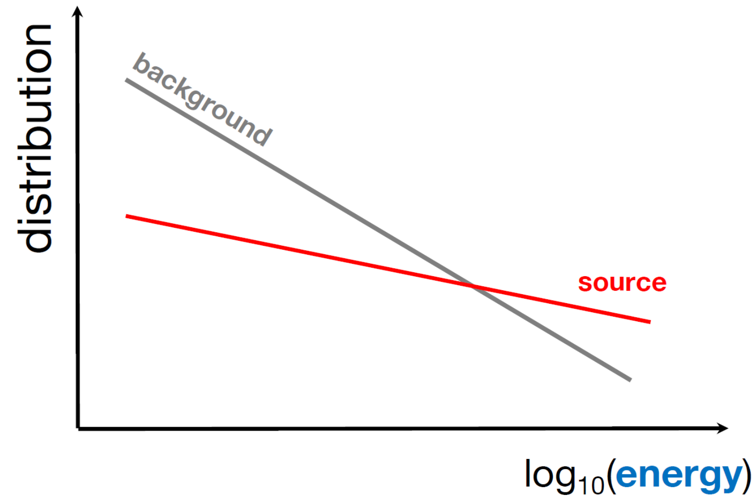
Search for excess over background



- 670 000 neutrino events
- Pixels in the sky evaluated for source significance

Search for excess over background





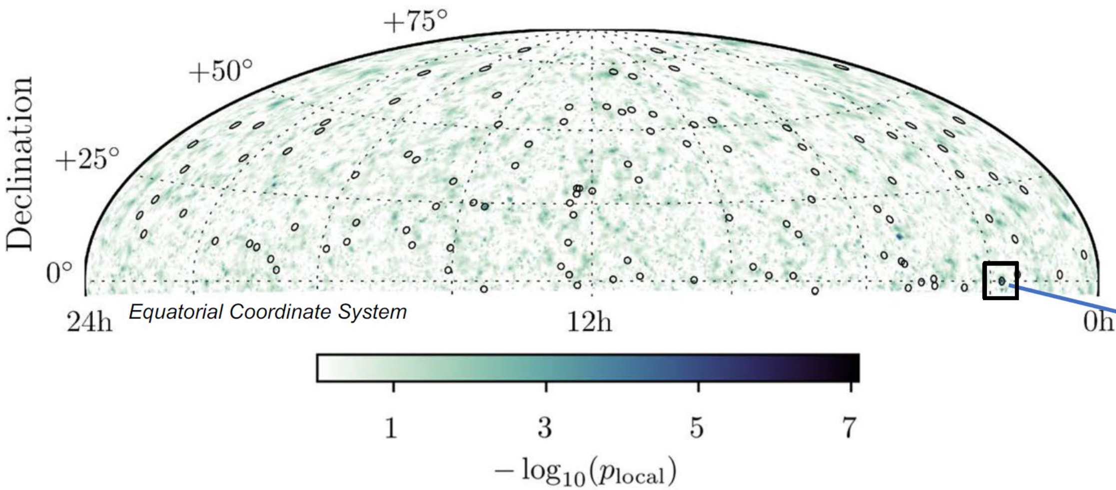
- Need good reconstruction of directions and energies
- Need good models for how directions and energies differ between signal and background

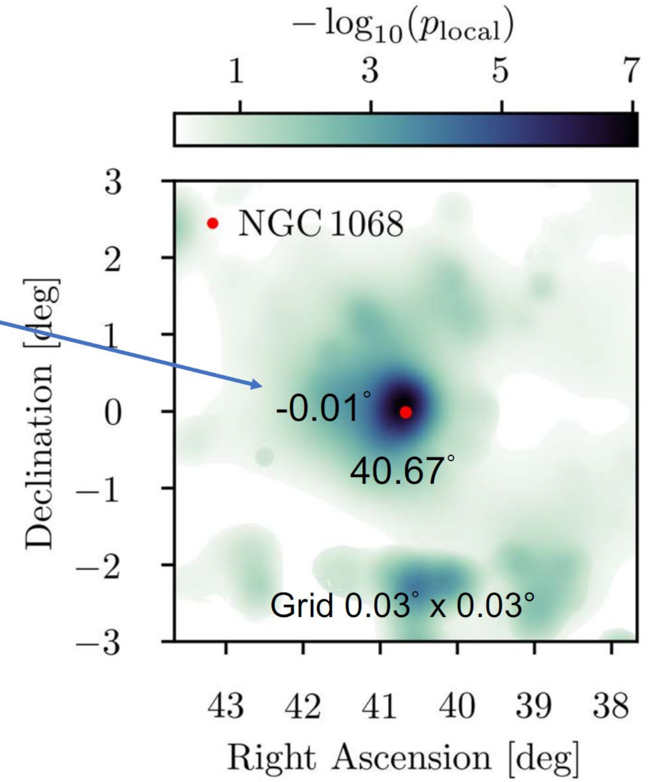
Sky scan and source search

Source Name	Source Type	α [°]	δ [°]	$\hat{n}_s$	$\hat{\gamma}$	$-\log_{10} p_{\rm local}$	$\Phi_{90\%}$
NGC 1068	SBG/AGN	40.67	-0.01	79	3.2	7.0 (5.2 σ)	9.6
PKS 1424+240	BLL	216.76	23.80	77	3.5	4.0 (3.7 σ)	11.4
TXS 0506+056	BLL/FSRQ	77.36	5.70	5	2.0	3.6 (3.5 σ)	7.5
PKS 0019+058	BLL	5.64	6.13	1	2.4	0.4 (0.2 σ)	2.6
1ES 0033+595 (*)	BLL	8.98	59.83	0	4.3	0.0 (0.0 σ)	5.0
M 31	GAL	10.82	41.24	13	3.3	0.8 (1.0 σ)	6.2
4C +01.02	FSRQ	17.17	1.58	0	4.3	0.0 (0.0 σ)	2.1
S2 0109+22	BLL	18.03	22.75	10	2.8	0.7 (0.8 σ)	4.8
B3 0133+388	BLL	24.14	39.10	0	4.3	0.0 (0.0 σ)	3.8
TXS 0141+268	BLL	26.15	27.09	0	4.3	0.0 (0.0 σ)	3.2
MITG J021114+1051	BLL	32.81	10.86	0	4.3	0.0 (0.0 σ)	2.6
PKS 0215+015	FSRQ	34.46	1.73	2	3.9	0.2 (0.0 σ)	1.9
B2 0218+357	FSRQ	35.28	35.94	8	4.3	0.4 (0.2 σ)	4.1
3C 66A	BLL	35.67	43.04	0	4.3	0.0 (0.0 σ)	3.9
4C +28.07	FSRQ	39.47	28.80	3	2.9	0.3 (0.0 σ)	3.4
PKS 0235+164	BLL	39.67	16.62	5	3.9	0.3 (0.0 σ)	2.8
NGC 1275	RDG	49.96	41.51	8	3.0	0.5 (0.5 σ)	5.1
PKS 0336-01	FSRQ	54.88	-1.78	4	4.3	0.3 (0.1 σ)	2.1
PKS 0420-01	FSRQ	65.83	-1.33	0	4.3	0.0 (0.0 σ)	2.0
4C +41.11 (*)	BLL	65.98	41.83	0	4.3	0.0 (0.0 σ)	3.9
PKS 0422+00	BLL	66.19	0.60	0	4.3	0.0 (0.0 σ)	2.1
MG2 J043337+2905	BLL	68.41	29.10	0	4.3	0.0 (0.0 σ)	3.4
PKS 0440-00	FSRQ	70.66	-0.30	1	2.7	0.3 (0.0 σ)	2.0
S3 0458-02	FSRQ	75.30	-1.97	9	4.3	0.5 (0.4 σ)	2.4
PKS 0502+049	FSRQ	76.34	5.00	0	4.3	0.0 (0.0 σ)	2.3

...

Evidence for neutrino emission from NGC1068

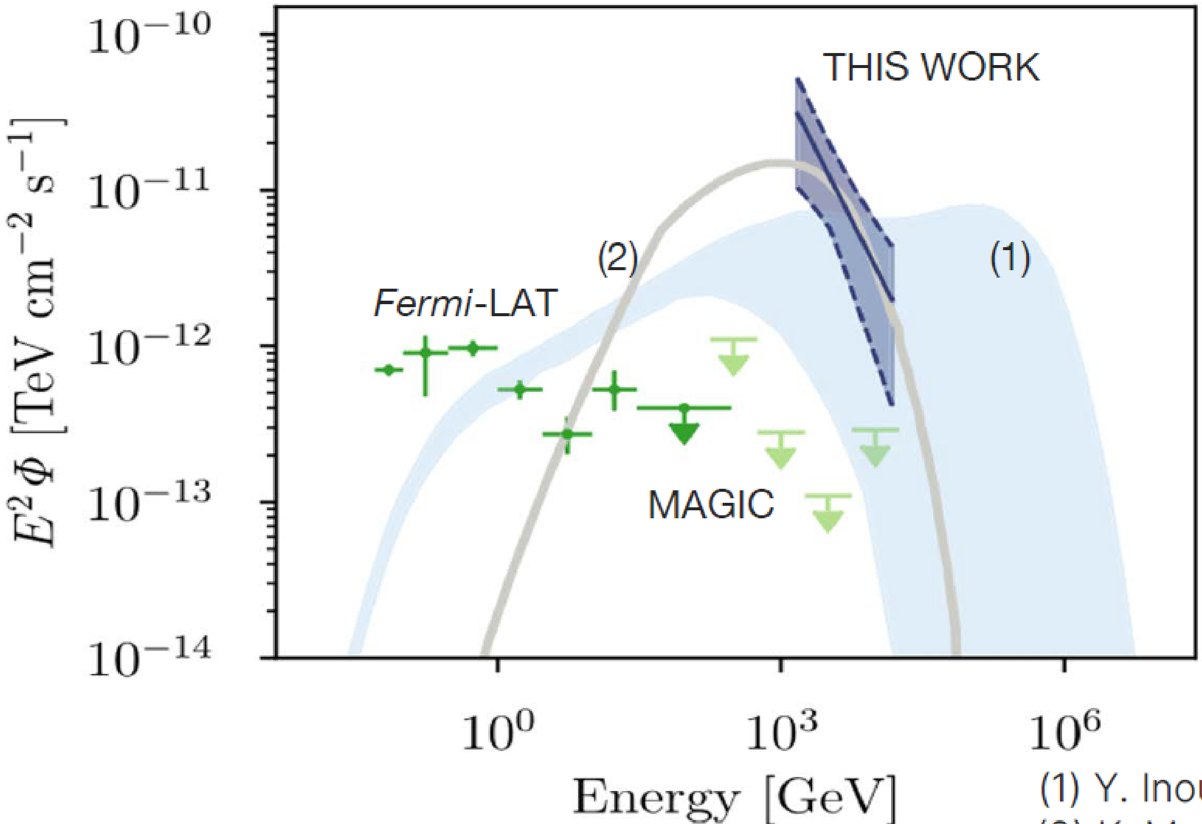




At the NGC 1068 location:
Astrophysical neutrino events = 79^{+22}_{-20}
Spectral index = 3.2 ± 0.2

Global significance 4.2 σ

NGC1068 Neutrino spectrum

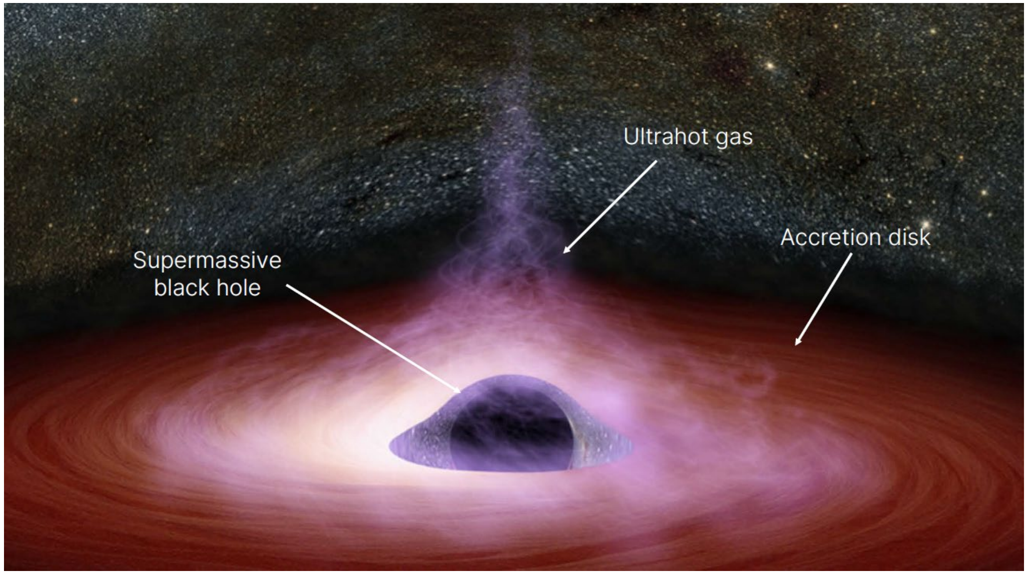


(1) Y. Inoue et al., ApJL'20
(2) K. Murase et al., PRL'20

$$\Phi^{1\mathrm{TeV}}_{\nu_\mu+\bar{\nu}_\mu} = (5.0 \pm 1.5_{\mathrm{stat}} \pm 0.6_{\mathrm{sys}}) \times 10^{-11} \mathrm{TeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

Main contribution to the excess from 1.5 TeV to 15TeV

Models for neutrino emission from NGC1068



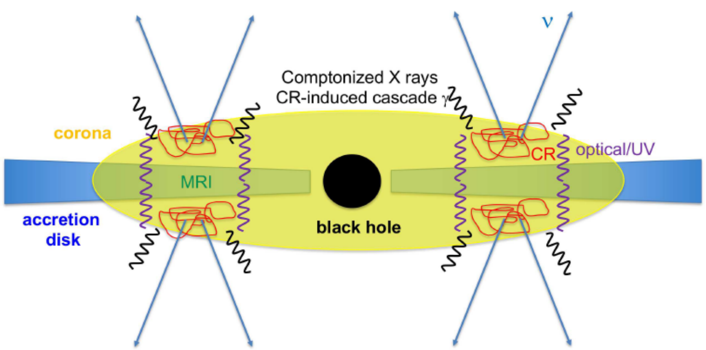


FIG. 1: Schematic picture of the AGN disk-corona scenario. Protons are accelerated by plasma turbulence generated in the coronae, and produce high-energy neutrinos and cascaded gamma rays via interactions with matter and radiation.

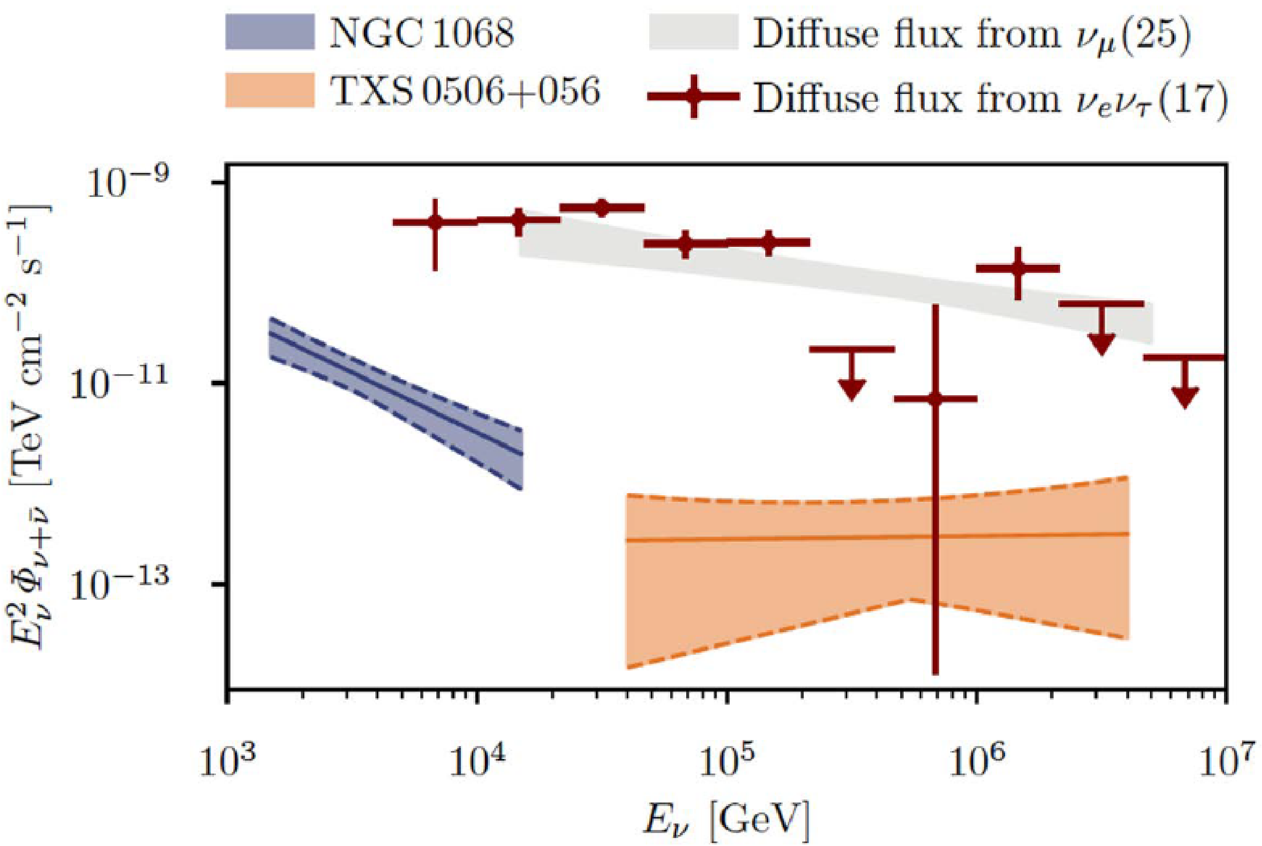
K. Murase et al PRL 20, arXiv:1904.04226v2

Starburst activity, outflows and Compton-thick nucleus

Neutrino emission factor higher than gamma-ray suggests from optically-thick environment

X-ray photons generated through photon Comptonization from the accretion disk in the corona, the hot plasma above the disk, providing the conditions for the production of neutrinos and absorption of gamma rays.

Sources and the diffuse flux

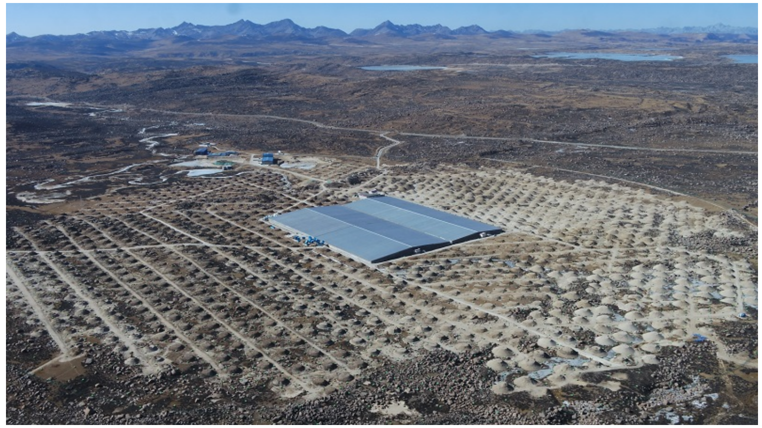


[25] IceCube. ApJ 928, 50 (2020)
[17] IceCube. PRL. 125, 121104 (2020)

IceCube neutrino limits on LHAASO sources

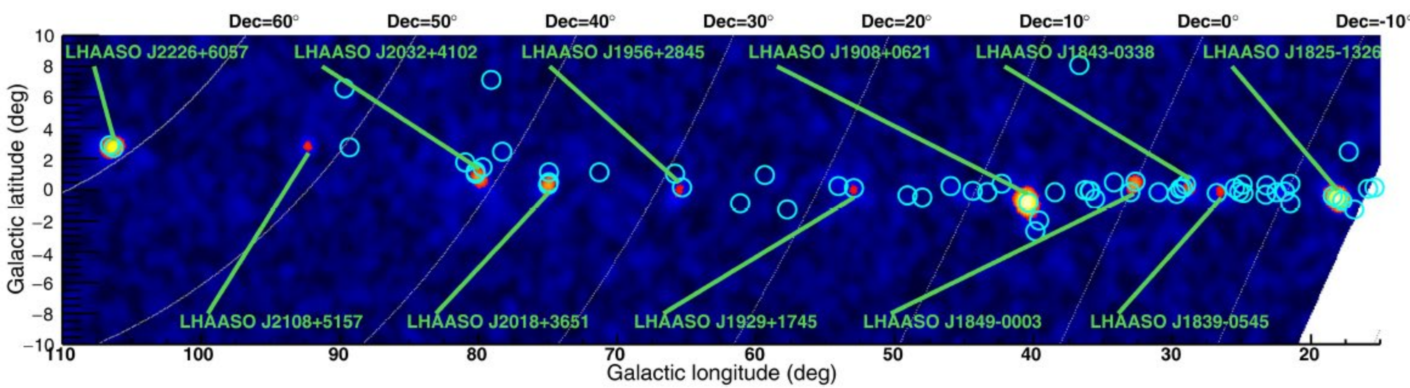
“Searches for Neutrinos from LHAASO ultra-high-energy γ-ray sources using the IceCube Neutrino Observatory,” The IceCube Collaboration: R. Abbasi et al. Submitted to *The Astrophysical Journal Letters.* arxiv.org/abs/2211.14184

LHAASO Galactic Sources



Article *Nature* **594**, 30-31 (2021)

Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ-ray Galactic sources



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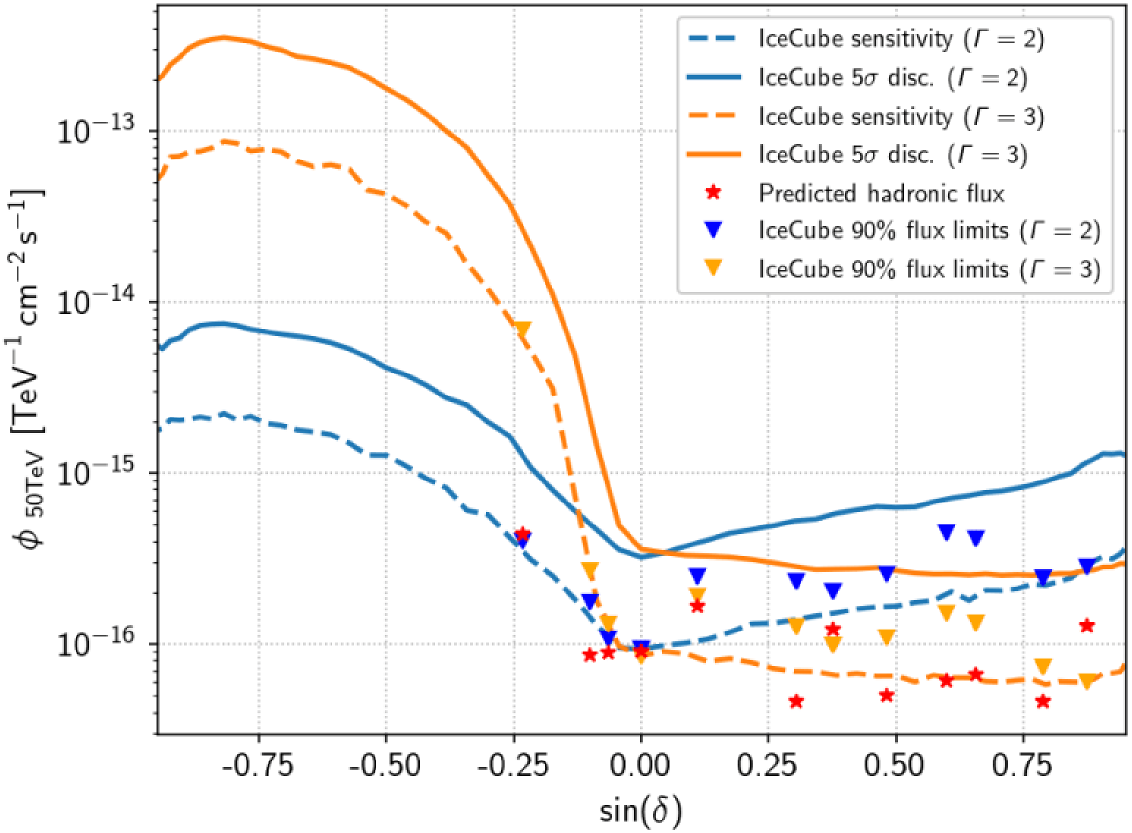
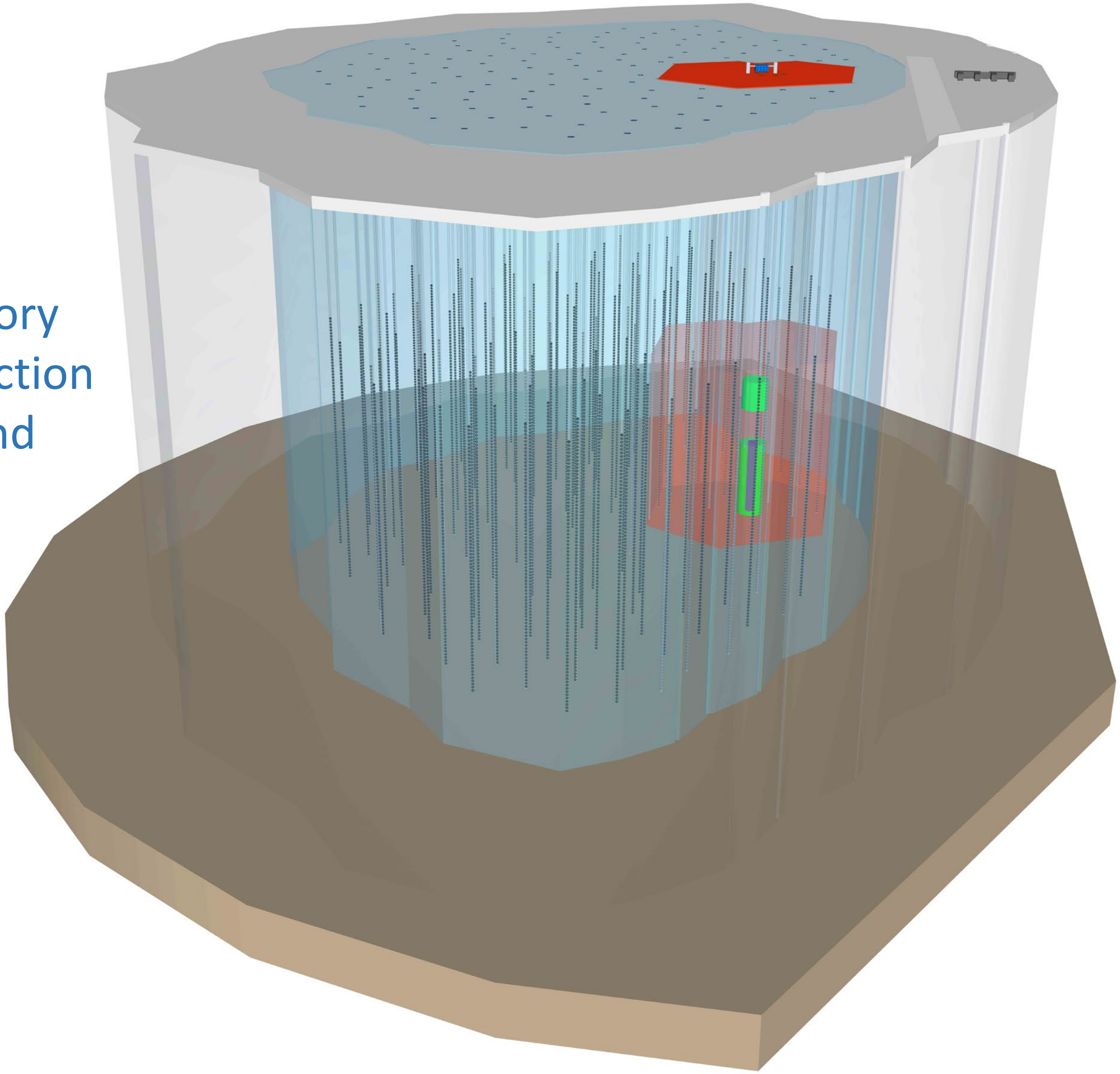


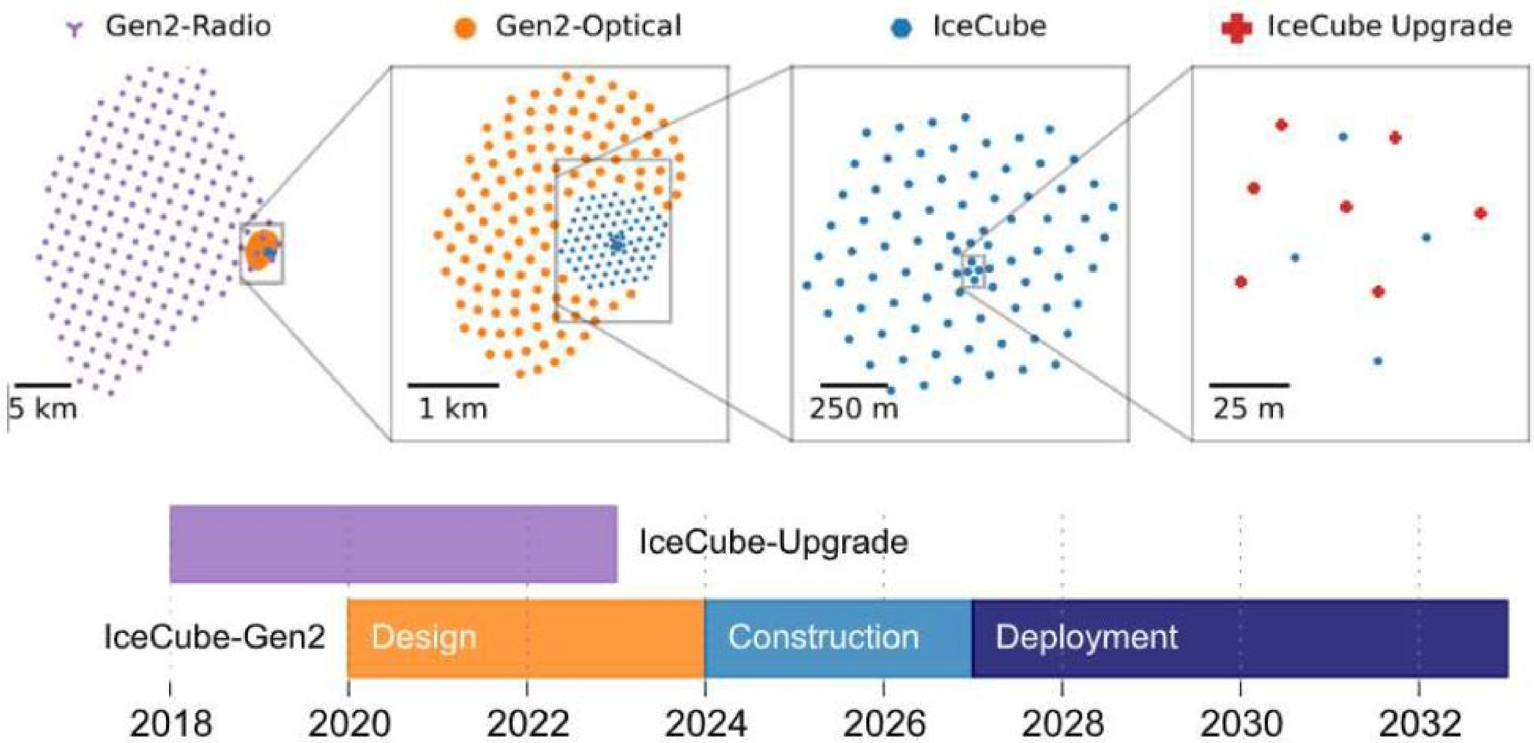
Next generation IceCube facilities

From discovery to astronomy

The next Generation IceCube:
A wide band neutrino observatory (MeV – EeV) using several detection technologies – optical, radio, and surface veto.



Next generation IceCube facilities



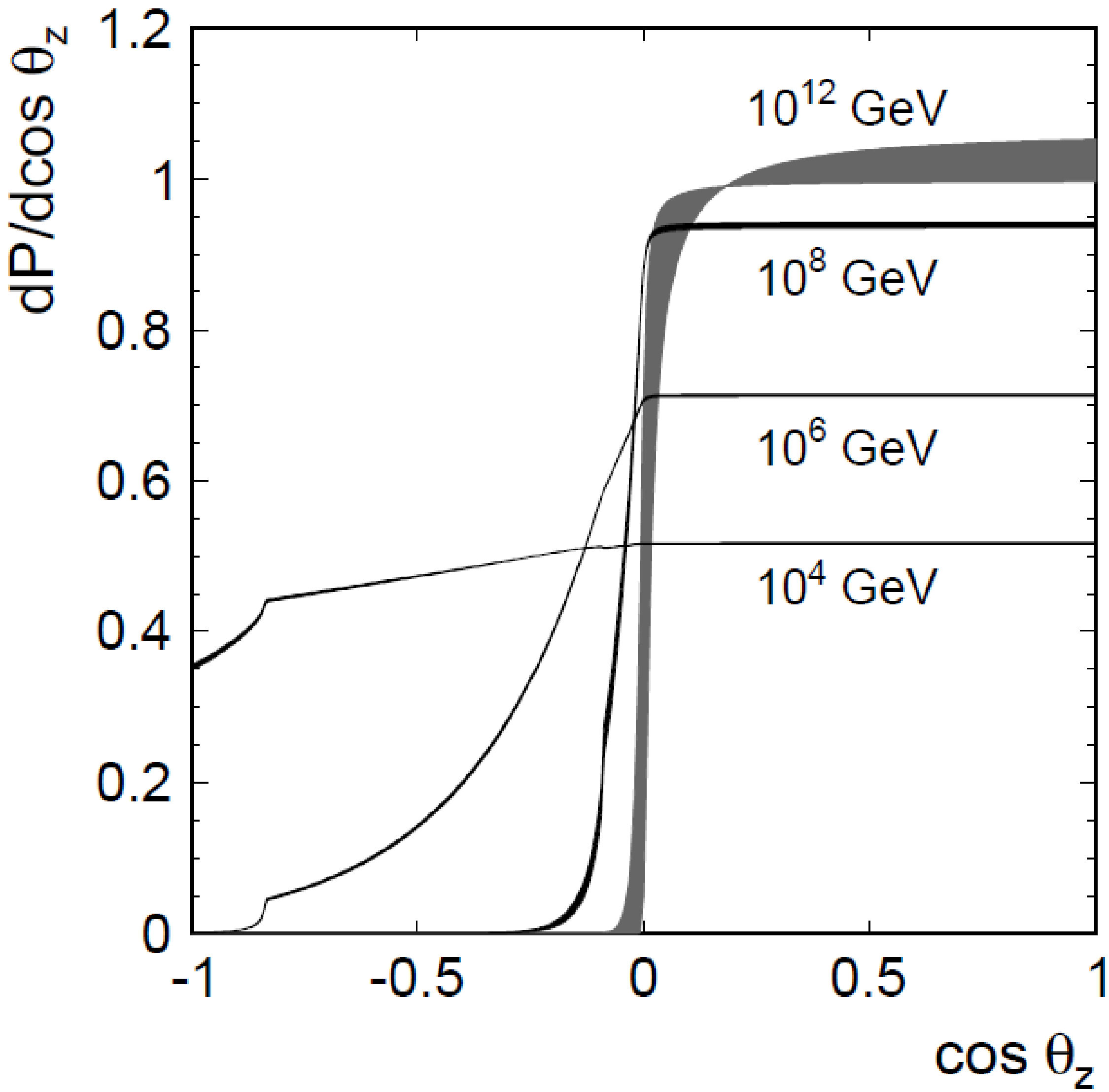
Timeline for the IceCube Upgrade and projected timeline for IceCube-Gen2.

Timeline shifted ~3 years due to Covid
Current plan: Upgrade complete by Feb 2026
Gen 2 still under review, drilling starting in 2028-29…?

Summary

- Neutrino astronomy has come of age allowing a unique view into the high-energy Universe

Earth absorption

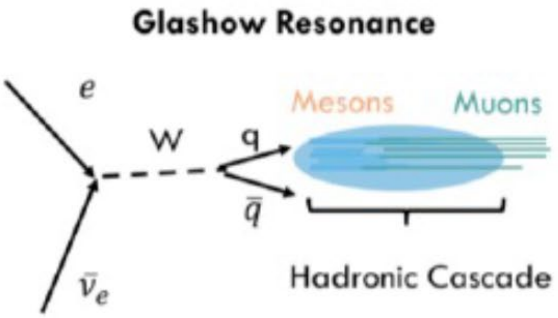


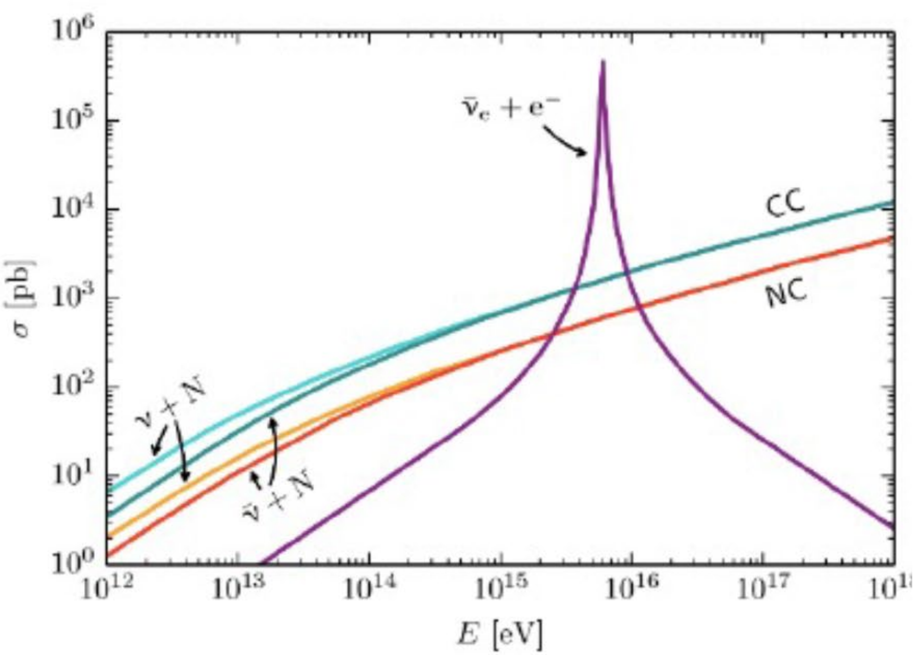
Glashow Resonance

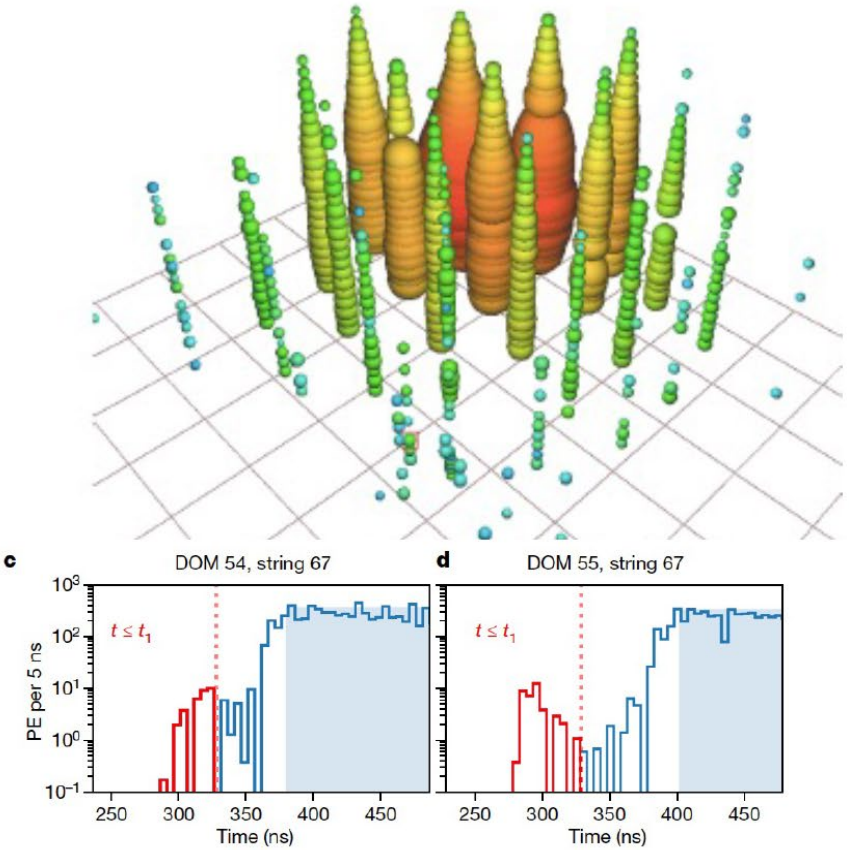
IceCube, Nature591(2021)220

Hydrangea

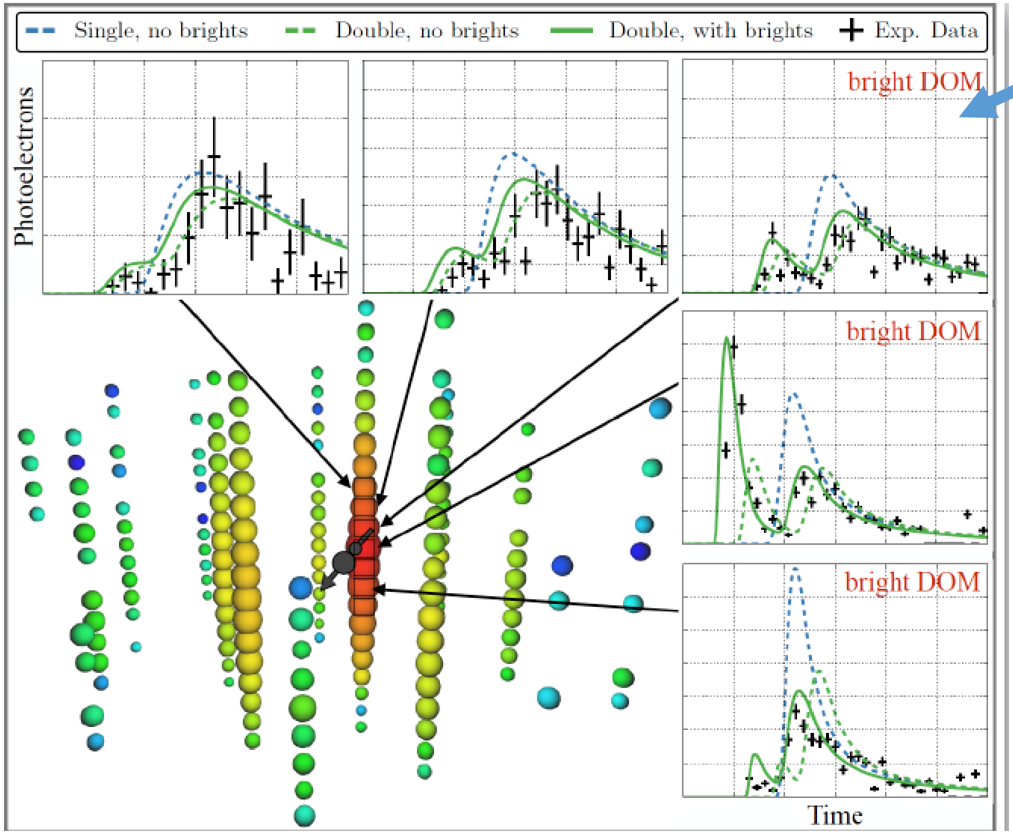
- Partially contained
- Detected muon from faster than Cherenkov cone
- 5.9±0.2 PeV







Use waveform double pulse pattern for ν_τ^{astr}



Previous analysis

New analysis soon to be published using waveform information and neural networks:

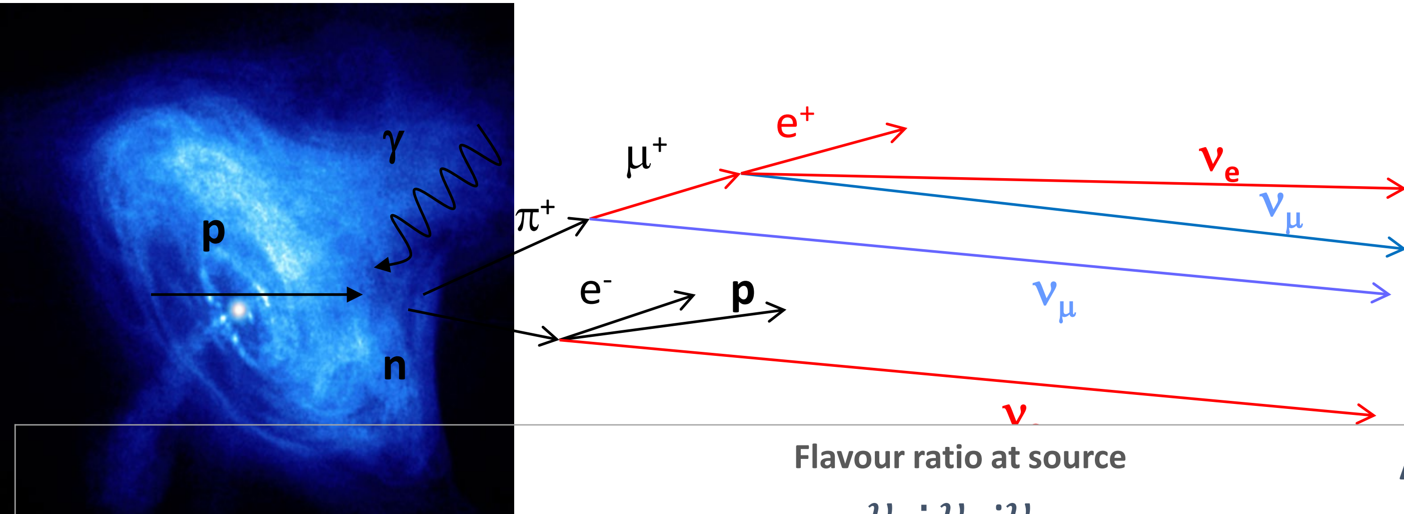
- C_1: DP vs. SP (ν_τ^{CC} vs. ν_e^{CC}, ν_x^{NC})
- C_2: DP vs track (ν_τ^{CC} vs. $\mu_\downarrow$)
- C_3: DP vs Track (ν_τ^{CC} vs. ν_μ^{CC})

- $C_1 \geq 0.99,\ C_2 \geq 0.98,\ C_3 \geq 0.85$
  - Gives S/N ~ 14.

Sees 7 candidate ν_τ^{astr} events

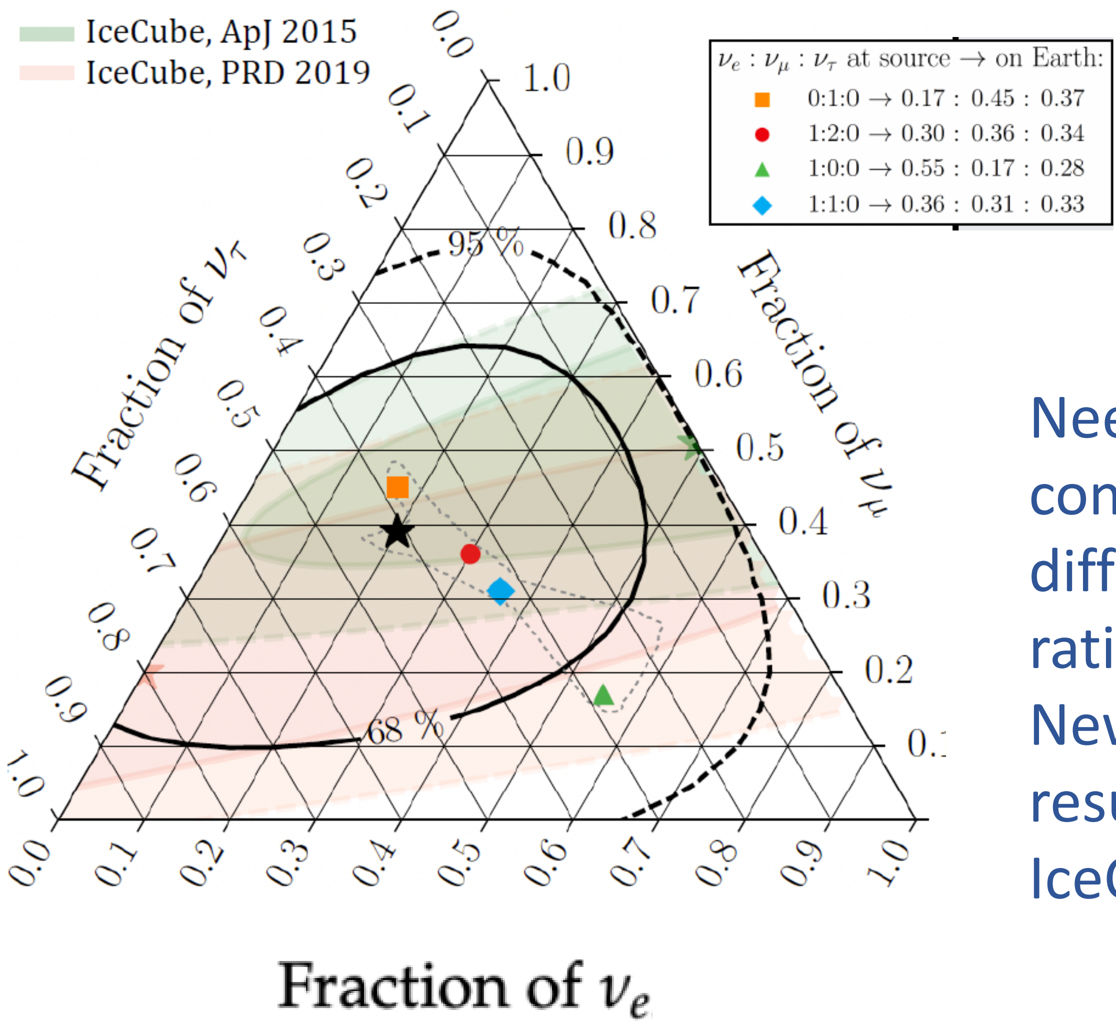
Flavour ratio astrophysical neutrinos

Neutrinos from cosmic ray interactions at **acceleration site**



	Flavour ratio at source $\upsilon_e : \upsilon_\mu : \upsilon_\tau$	After oscillations $\upsilon_e : \upsilon_\mu : \upsilon_\tau$ at Earth
Protons **(complete pion decay)**	1:2:0	0.30 : 0.36 : 0.34
Neutrons	1:0:0	0.55 : 0.17 : 0.28
Protons **(Muon-damped pion decay)**	0:1:0	0.17 : 0.45 : 0.37
Protons **(Muon decay)**	1:1:0	0.36 : 0.31 : 0.33

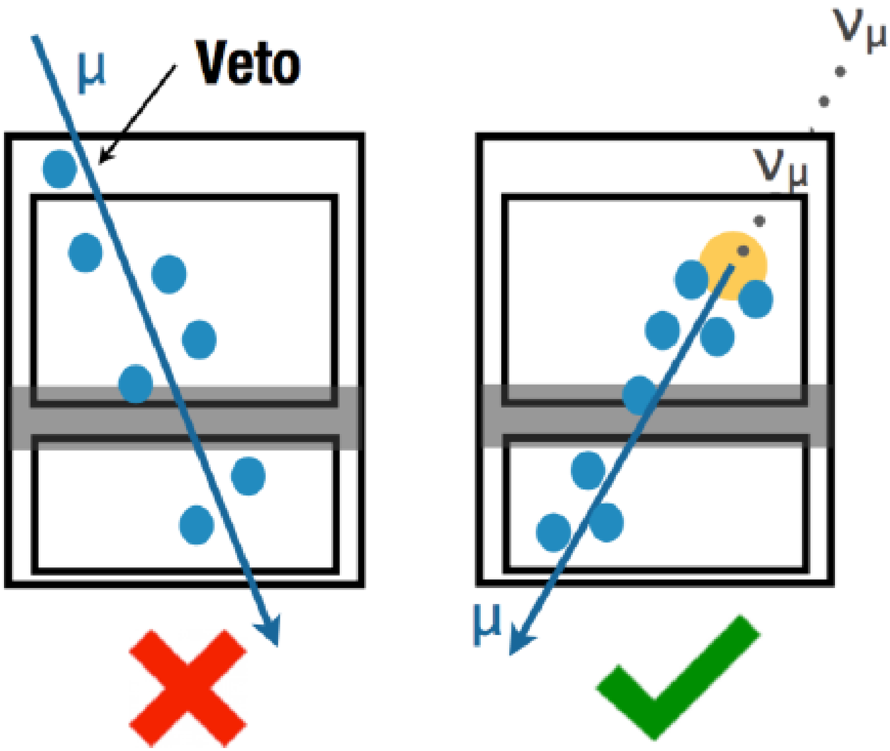
Current flavour results

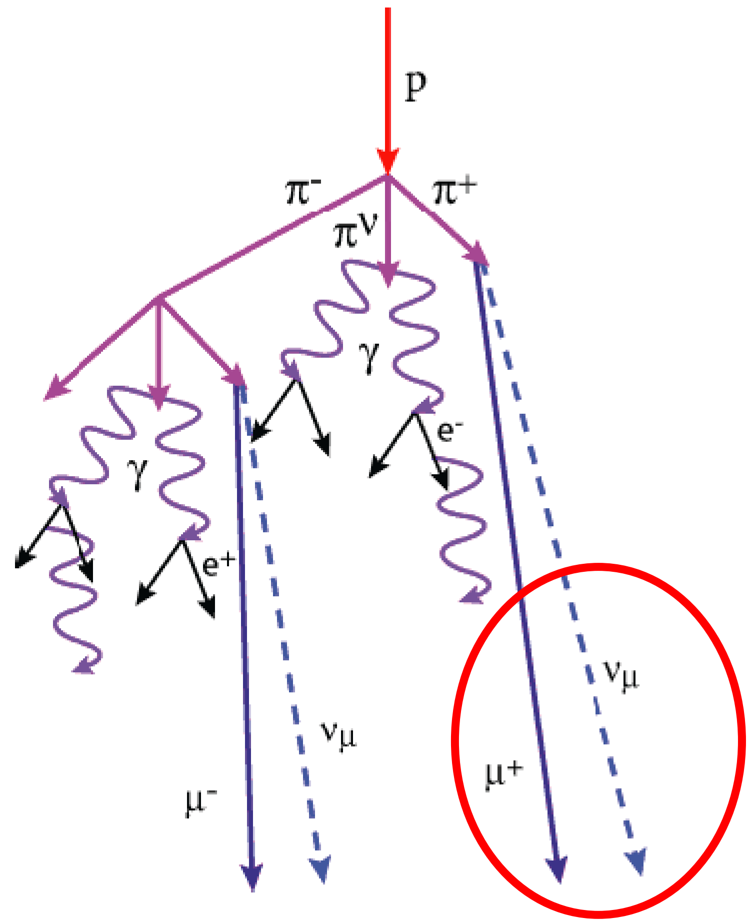


Need to shrink the contours to probe different source ratios and
New Physics, new result soon from IceCube

High Energy Starting Event search strategy

- Use outer parts of the detector as a veto-region
- Reduces both muon and southern hemisphere atmospheric neutrino backgrounds





Muon accompanying the neutrino trips the veto

Schönert et al, 2009, Gaisser et al. 2014, Argüelles et al 1805.11003

Neutrino emission during blazar γ-suppressed state

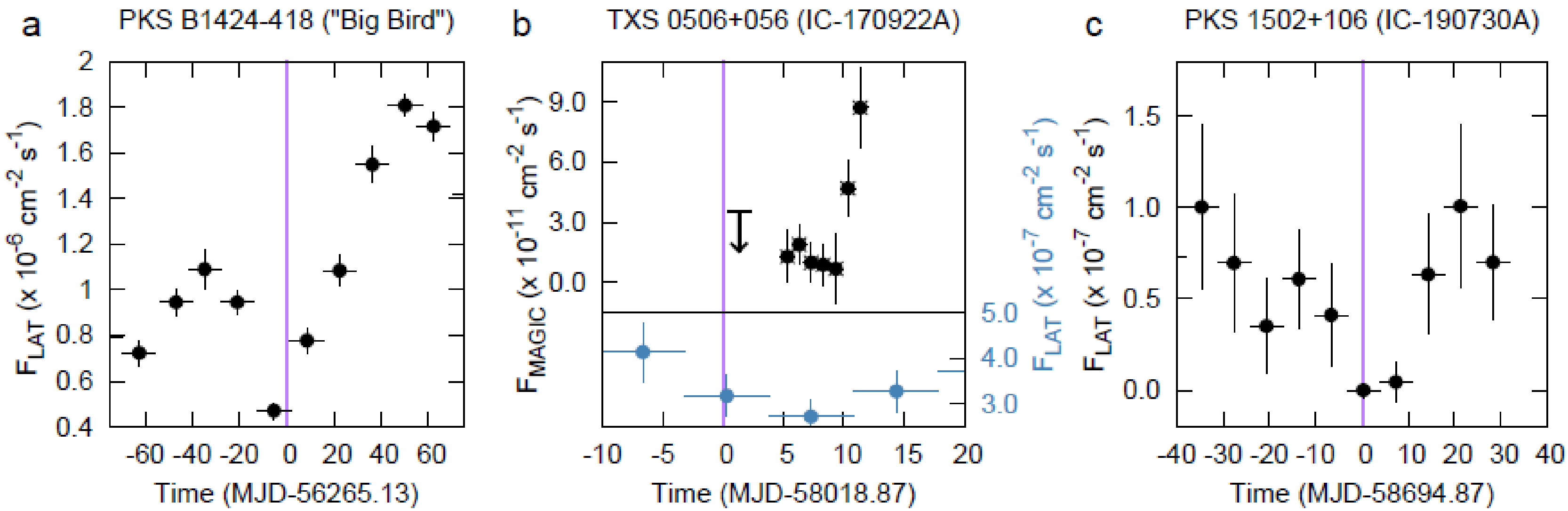


FIG. 4: γ-ray light curves for three blazars with coincident high-energy neutrinos. a: PKS B1424-418 as measured

Association with radio blazars?

arXiv2009.08914

Directional association of TeV to PeV astrophysical neutrinos with radio blazars

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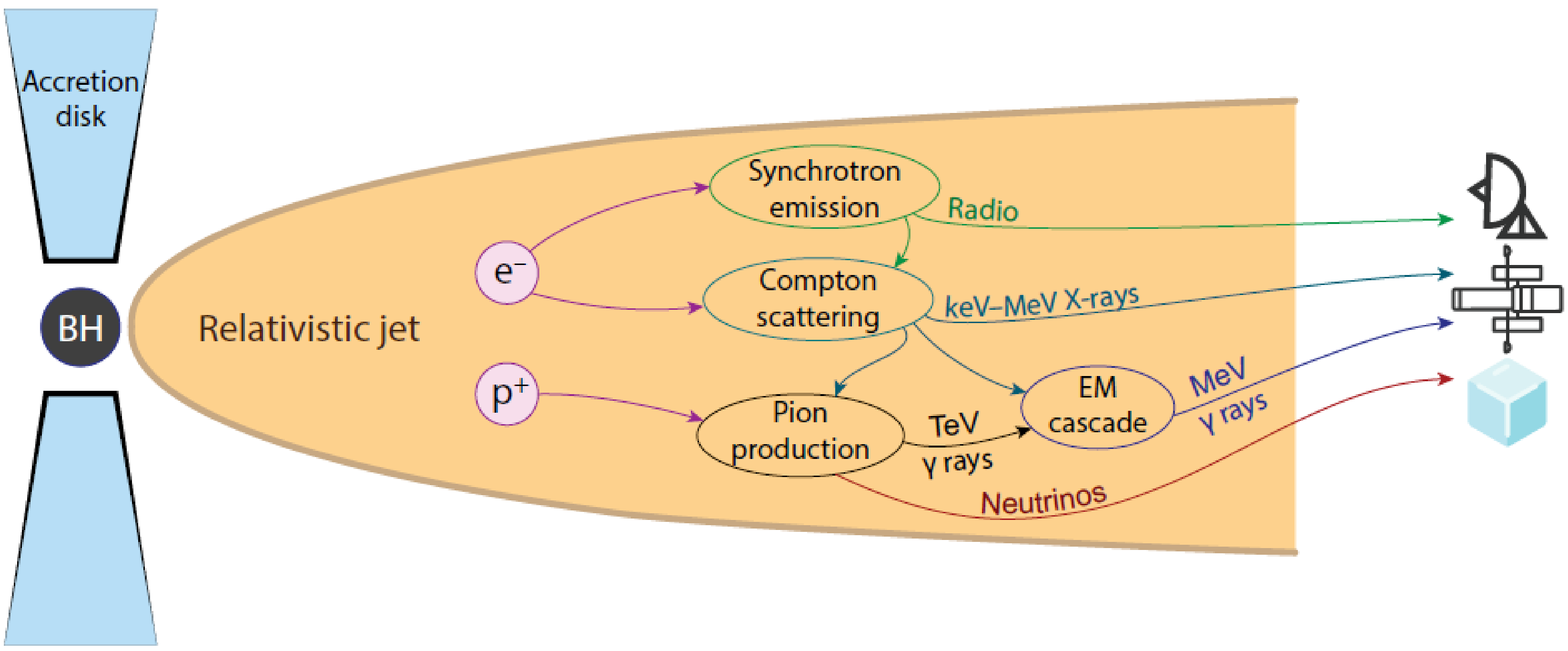
(Received 2020 September 18; Revised 2020 October 25)

Submitted to ApJ

ABSTRACT

Recently we have shown that high-energy neutrinos above 200 TeV detected by IceCube are produced within several parsecs in the central regions of radio-bright blazars, that is active galactic nuclei with jets pointing towards us. To independently test this result and extend the analysis to a wider energy range, we use public data for all neutrino energies from seven years of IceCube observations. The IceCube point-source likelihood map is analyzed against the positions of blazars from a statistically complete sample selected by their compact radio flux density. The latter analysis delivers a 3.0σ significance with the combined post-trial significance of both studies being 4.1σ. The correlation is driven by a large number of blazars. Together with fainter but physically similar sources not included in the sample, they may explain the entire IceCube astrophysical neutrino flux as derived from muon-track analyses. The neutrinos can be produced in interactions of relativistic protons with X-ray self-Compton photons in parsec-scale blazar jets.

Association with radio blazars?



Neutrino emission during blazar γ-suppressed state

arXiv2009.09792

Neutrino emission during the γ-suppressed state of blazars

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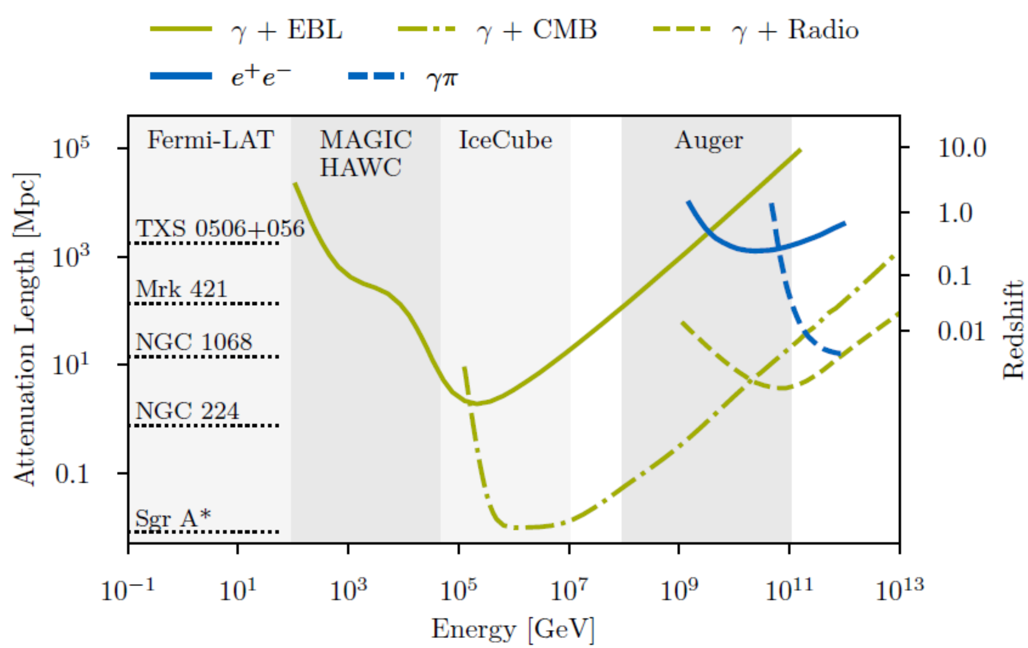
(Dated: September 22, 2020)

Despite the uncovered association of a high-energy neutrino with the apparent flaring state of blazar TXS 0506+056 in 2017, the mechanisms leading to astrophysical particle acceleration and neutrino production are still uncertain. Recent studies found that blazars in a γ-flaring state are too sparse for neutrino production, making the multi-messenger observation of TXS 0506+056 difficult to explain. Here we show that the Fermi-LAT γ flux of another blazar, PKS 1502+106 was at a local minimum when IceCube recorded a coincident high-energy neutrino IC-190730A. This suggests the presence of a large target photon and proton density that helps produce neutrinos while temporarily suppressing observable γ emission. Using data from the OVRO 40-meter Telescope, we find that radio emission from PKS 1502+106 at the time of the coincident neutrino IC-190730A was in a high state, in contrast to other time periods when radio and γ fluxes are correlated. This points to an active outflow that is γ-suppressed at the time of neutrino production. We find similar local γ suppression in other blazars, including the MAGIC flux of TXS 0506+056 and the Fermi-LAT flux of PKS B1424-418 at the time of coincident IceCube neutrino detections, further supporting the above model. Using temporary γ-suppression, neutrino-blazar coincidence searches could be substantially more sensitive than previously assumed, enabling the identification of the origin of IceCube's diffuse neutrino flux possibly with already existing data.

Gamma-ray and cosmic-ray horizon

Figure 2.3: Attenuation length of cosmic rays (green) and gamma rays (blue as a function of their energy. Different line styles indicate different interaction processes as given in the legend. For comparison, the energy ranges of relevant observatories and the distance of well-known sources are shown. Model predictions from Harari, Mollerach, and Roulet, "On the ultrahigh energy cosmic ray horizon" and De Angelis, Galanti, and Roncadelli, "Transparency of the Universe to gamma rays".



Theo Glauch PhD thesis