THE DAWN OF HIGH ENERGY NEUTRINO ASTRONOMY

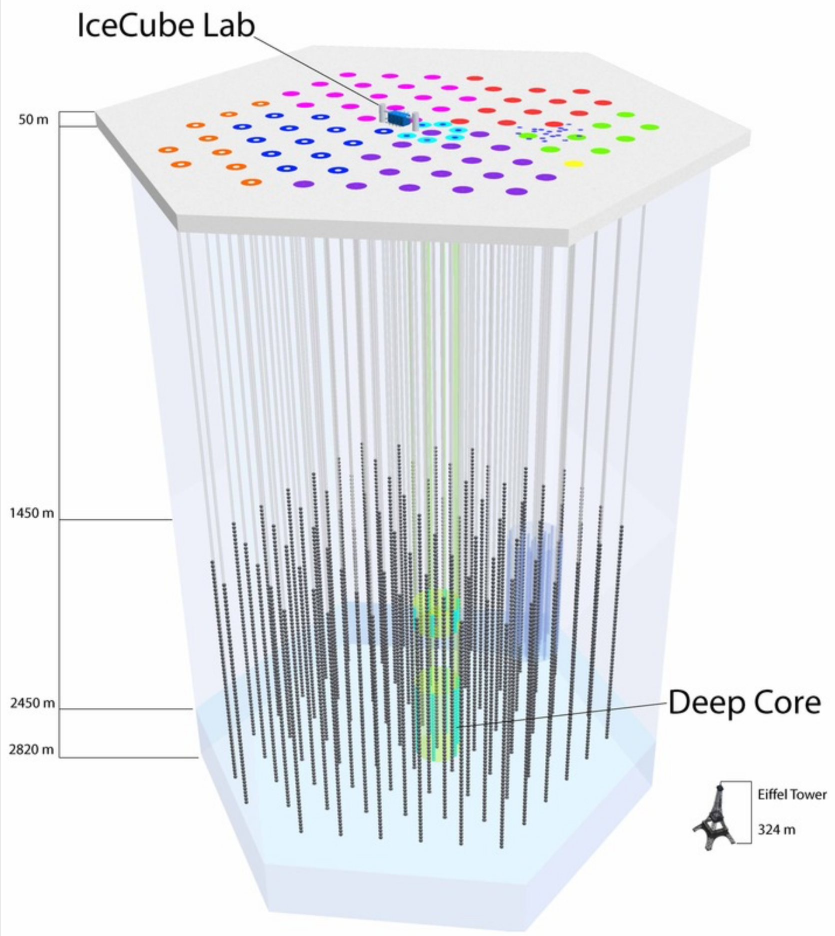
E. Resconi I RICAP-2022

Bundesministerium für Bildung und Forschung
DFG
SFB 1258 Neutrinos Dark Matter Messengers
TUM LMU ORIGINS Excellence Cluster
MAX-PLANCK-GESELLSCHAFT
erc European Research Council

NSF/Wenceslas Marie-Sainte

ICECUBE NEUTRINO OBSERVATORY

- Neutrino telescope sensitive to TeV-PeV cosmic neutrinos;
- Data taken (full configuration) since 2010;
- Up-time 99.9%.



https://icecube.wisc.edu

ICECUBE NEUTRINO OBSERVATORY

- Neutrino telescope sensitive to TeV-PeV cosmic neutrinos;
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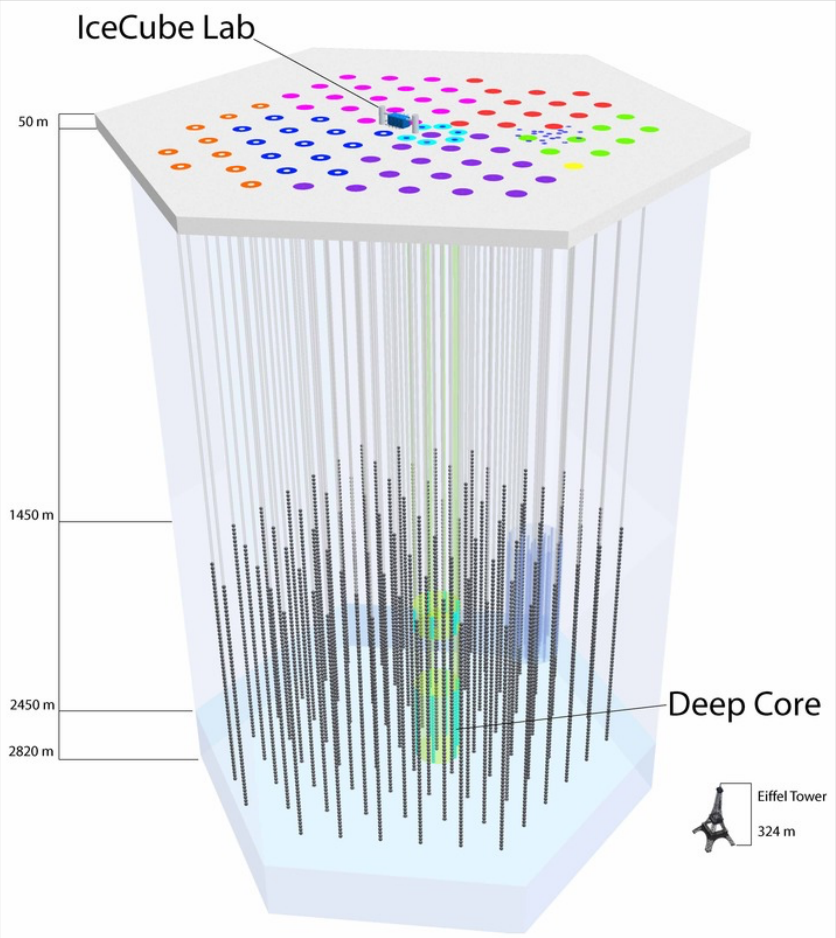
In this talk:

- Discovery of high energy cosmic neutrinos;
- Evidences for cosmic neutrino sources;
- The urgent need for more neutrinos.



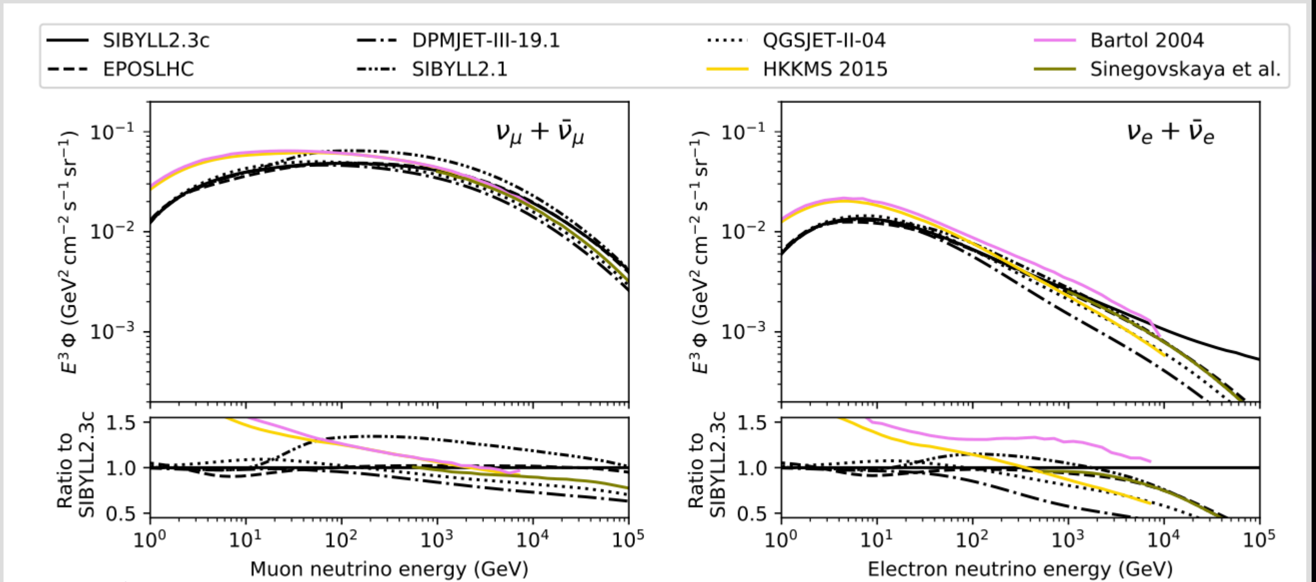
https://icecube.wisc.edu

01

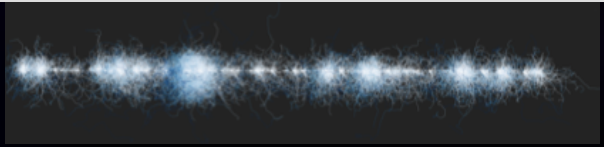
The discovery of Cosmic Neutrinos

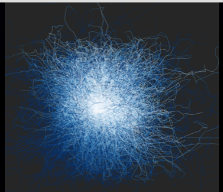
THE BACKGROUND - ATMOSPHERIC MUONS AND NEUTRINOS

Atmospheric neutrino fluxes averaged over the zenith angle.



A. Fedynitch et al., PRD '19





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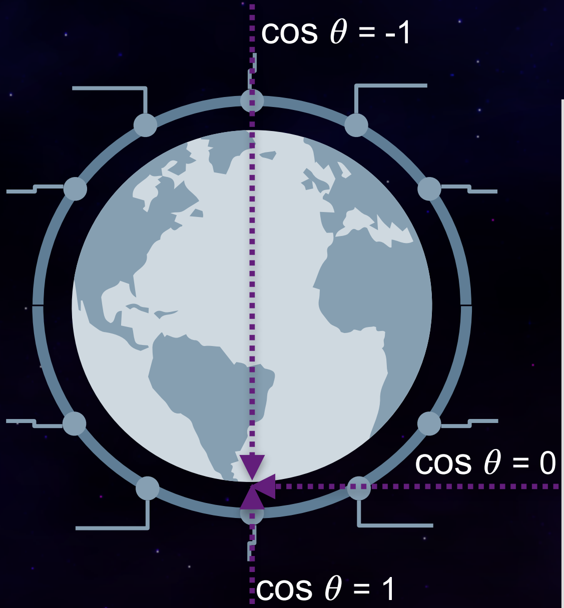
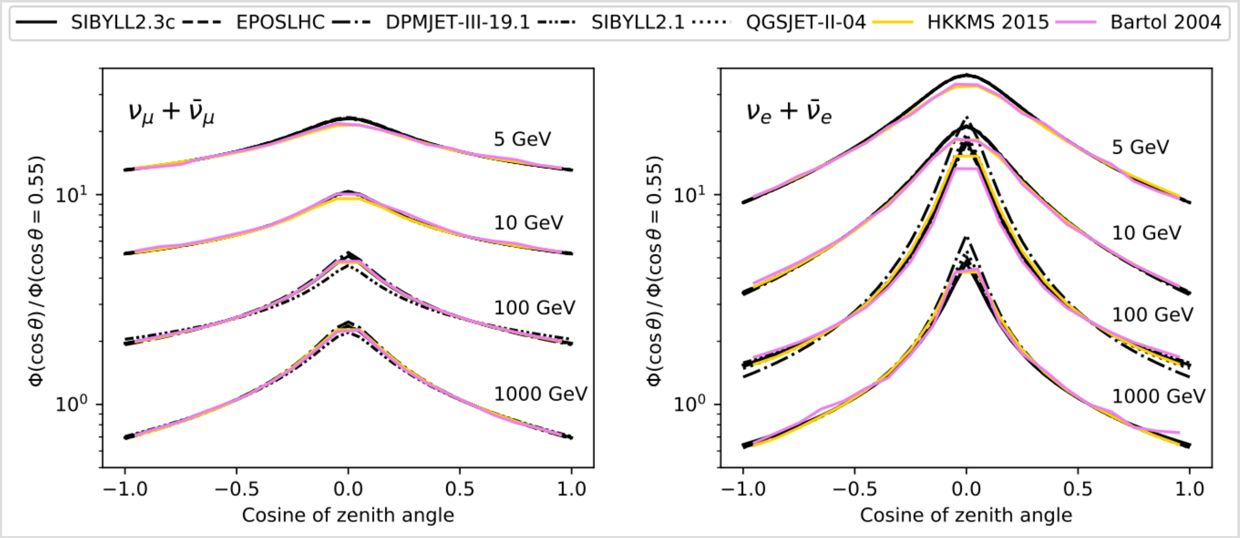


Azimuth-averaged zenith distributions at fixed neutrino energies

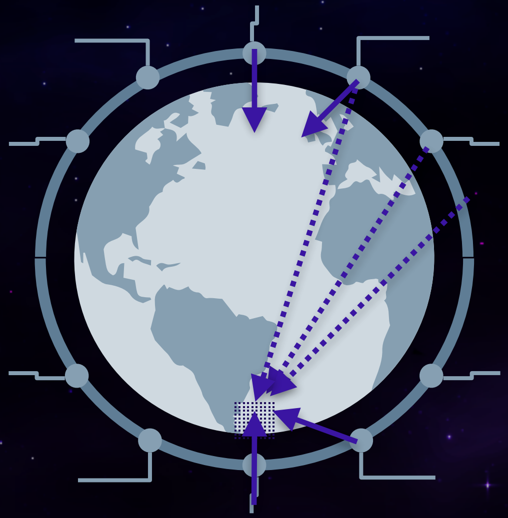
A. Fedynitch et al., PRD '19



The Background - Suppression Methods

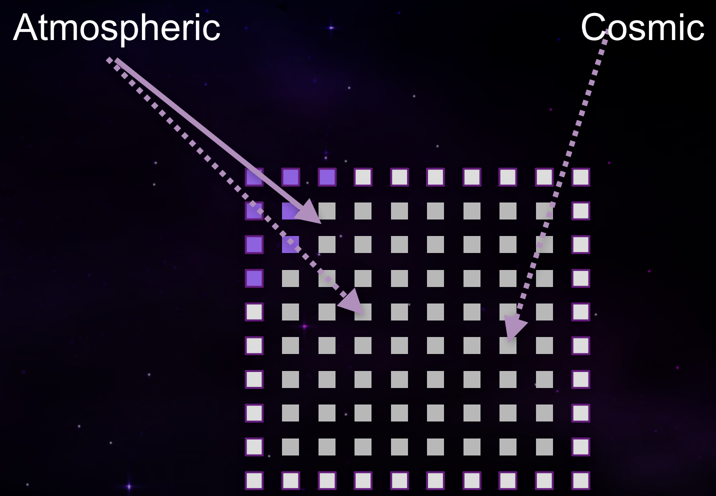
Atmospheric muons: shield via Earth absorption

C. Spiering, EPJ H '12



Atmospheric muons & neutrinos: containment

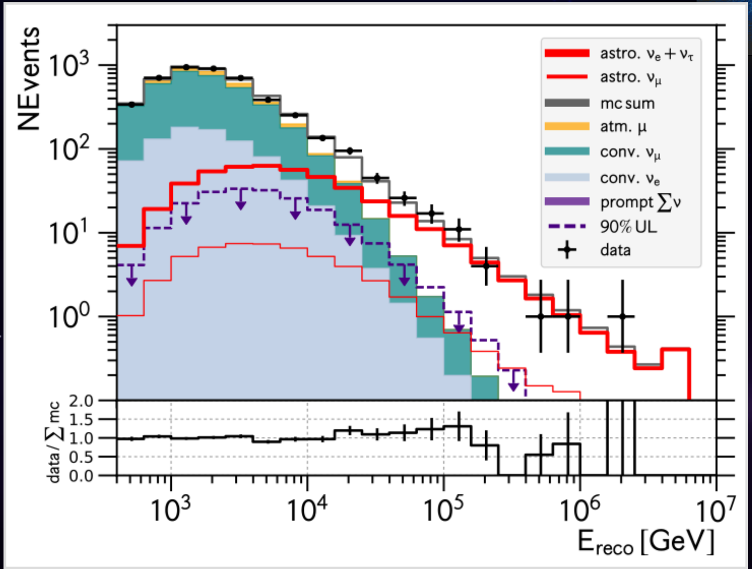
S. Schönert, T.K.Gaisser, E.R., O. Shulz, PRD'09
T.K.Gaisser, K.Jero, A.Karle, J.van Santen, PRD'14

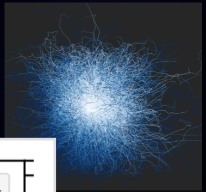


THE SIGNAL - COSMIC NEUTRINOS

9.9σ

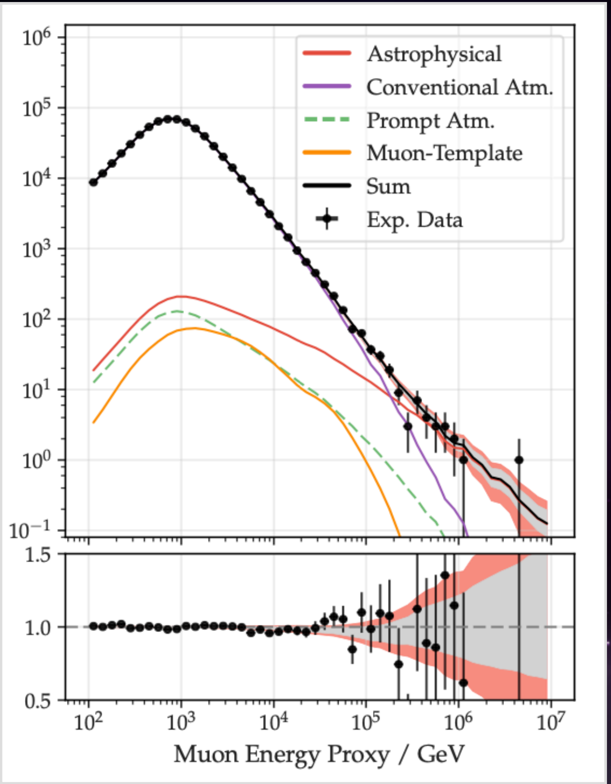
The IceCube Coll., PRL'20

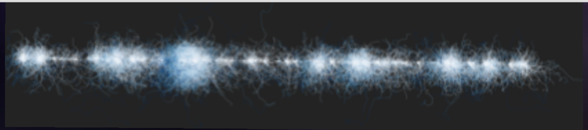




5.6σ

The IceCube Coll., ApJ'22





The signal - cosmic neutrinos

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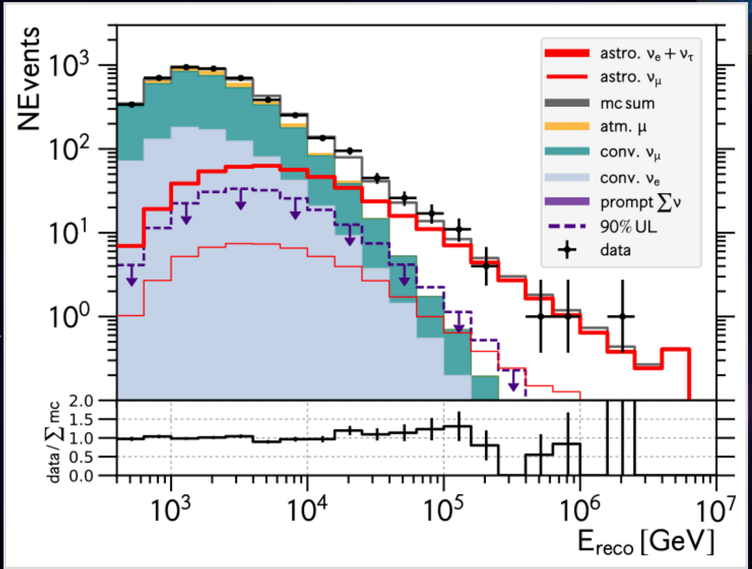
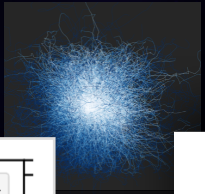
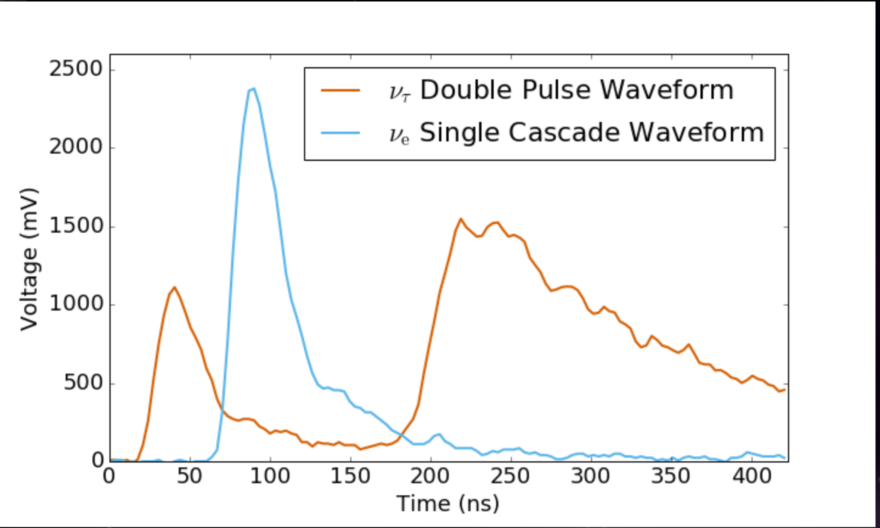
The IceCube Coll., PRL’20





Few nu_tau candidates identified

The IceCube Coll., ICRC’19



02.1 Resolving the Cosmic Neutrino Flux

The jetted (blazar) AGN case

The principle

K. Mannheim, P. Biermann, A&A (1989)

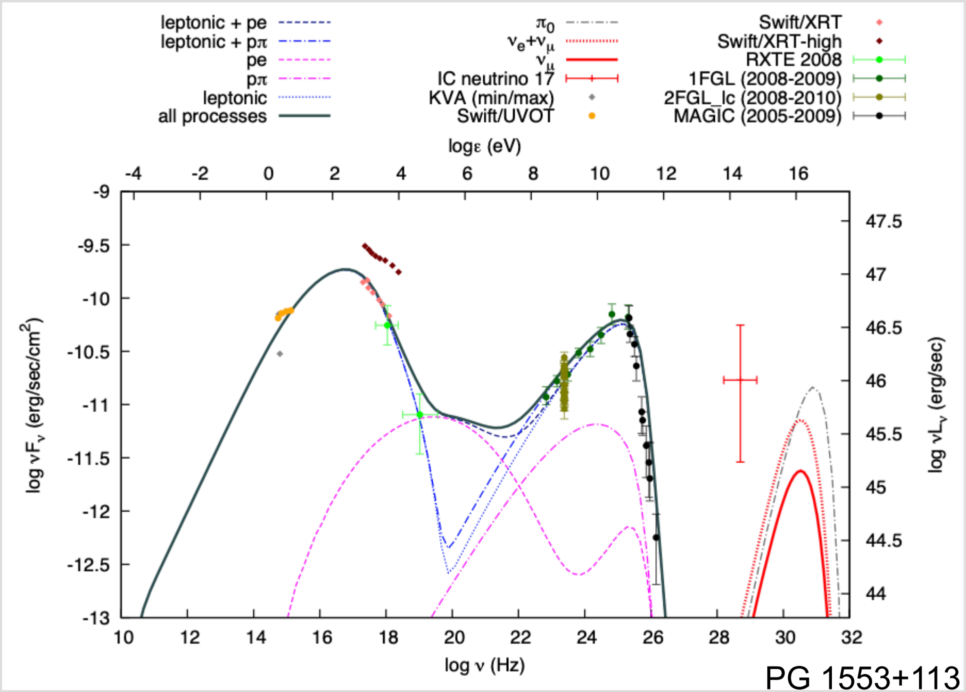
Summary. A key step in understanding the high energy particle populations and their emissions in active galactic nuclei and their plasma jets is a thorough consideration of photomeson production. Utilizing elementary particle physics phenomenology we calculate here the energy distribution of secondary pions arising from photon-proton collisions. The highly relativistic protons necessary for pion production in a radiation field are expected to be generated in shockwaves by the first-order Fermi process up to $\approx 10^{12}$ GeV in the hot spots of radio galaxies and up to $\approx 10^{9}$ GeV in the compact cores (Biermann and Strittmatter 1987). Due to the pion decay the resulting primary

02.1 Resolving the Cosmic Neutrino Flux

The jetted (blazar) AGN case

The jetted (blazar) AGN case

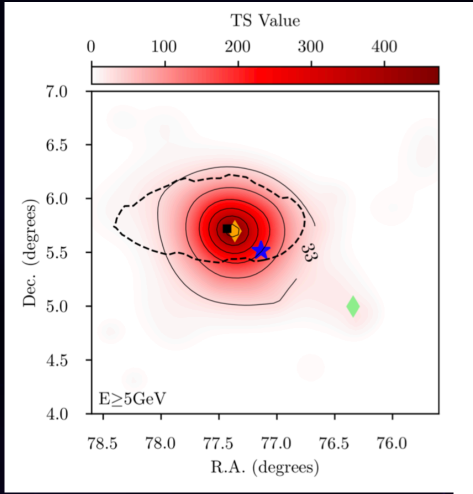
P.Padovani, E.R., MNRAS'14
M.Petropoulou, S.Dimitrakoudis, P. Padovani, A. Mastichiadis, E.R., MNRAS'15



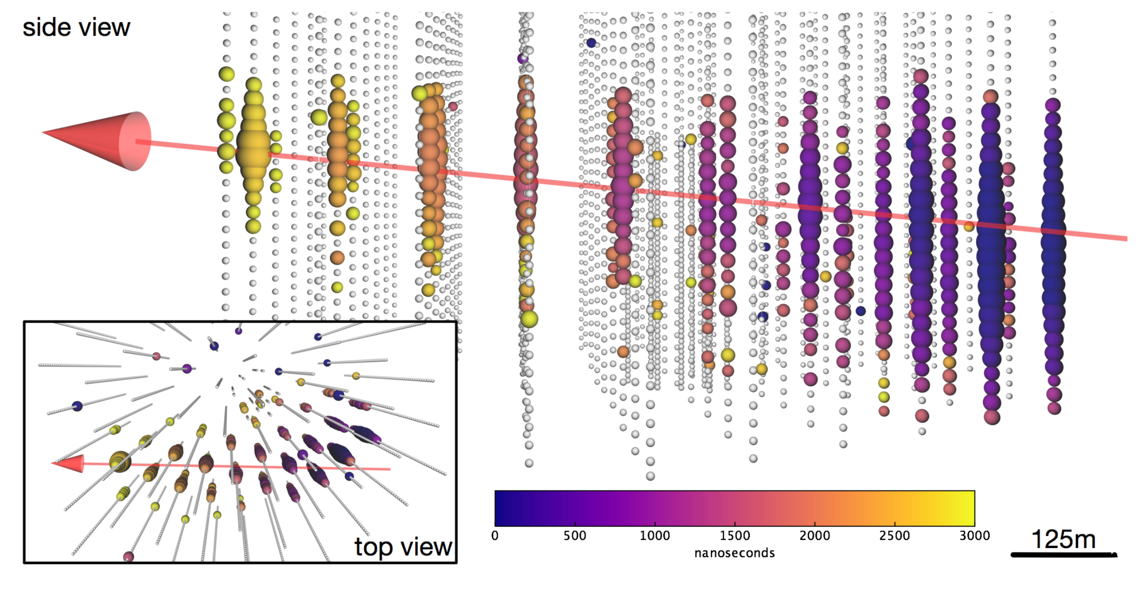
The order of magnitude - plausible candidates

IceCube-170922 (~290 TeV, Dec ~5.72 deg) pointing to TXS0506+056

"Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A", The IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool telescope, Subaru, Swift/NuSTAR, VERITAS, and VLA/17B-403 teams. ***Science* 361, 2018**



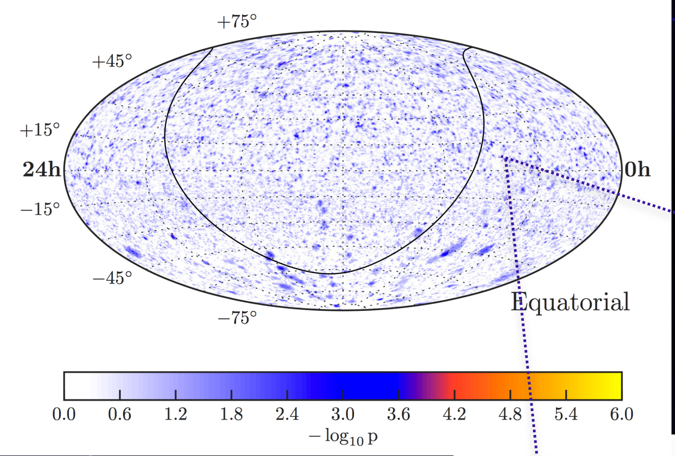
P.Padovani,P. Giommi, E.R., T. Glauch, B. Arsioli, MNRAS (2018)

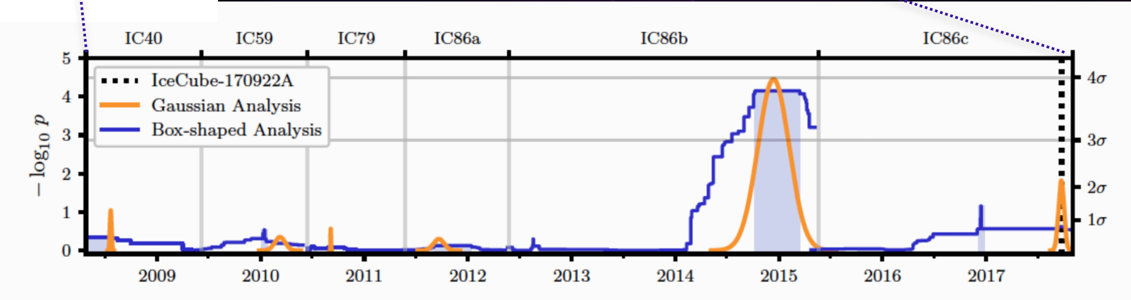


Random coincidence excluded ~ 99.7%CL (a-posteriori)

More neutrinos (~10) emission from the direction of the blazar TXS 0506+056

"Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert", IceCube Collaboration: M.G. Aartsen et al. ***Science*** **361, 147-151 (2018).**



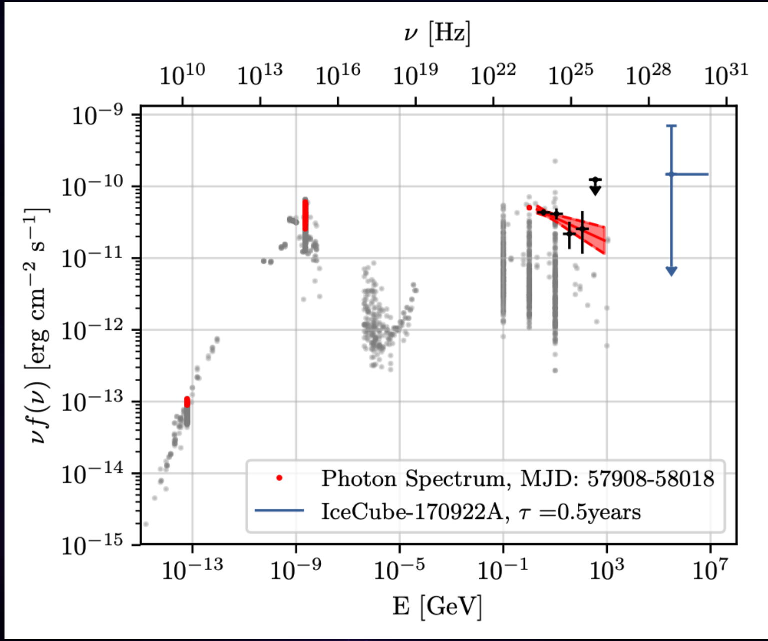


3.5σ evidence (a-priori following predefined tests procedures)

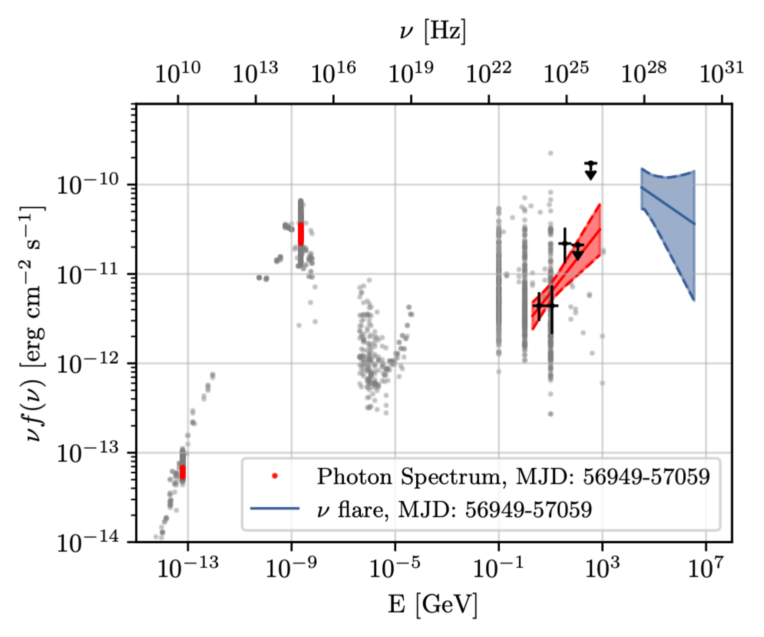
The photon - neutrino Spectral Energy Distribution of TXS 0506+056

P.Padovani, P. Giommi, E.R., T. Glauch, B. Arsioli, MNRAS (2018)

Neutrino alert 179022A



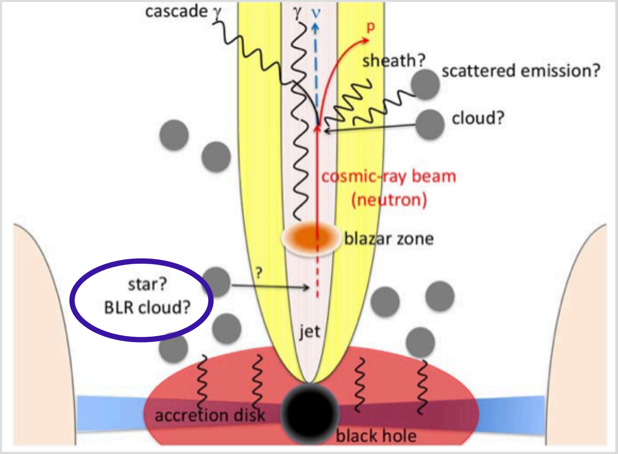
Neutrino 'flare, 2014-2015



... limited by too few photons and too few neutrinos

Is TXS 0506+056 special? YES

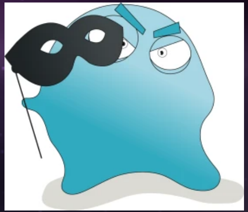
S. Paiano et al., ApJ 2018
K. Murase, F. Oikonomou, M. Petropoulou, ApJ 2018
P. Padovani, F. Oikonomou, M. Petropoulou, et al., MNRAS 2019



- Originally classified as BL Lac
- Emission line ratios Seyfert-like
- It is a high-excitation galaxy!
- z = 0.3365

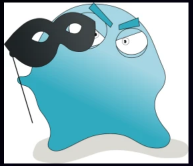
TXS0506+056 is a **high synchrotron peak FSRQ** (Masquerading BL Lac)

Meaning: radiation fields external to the jet (i.e. the accretion disc, photons reprocessed in the broad-line region or from the dusty torus) providing more targets for the protons might enhance neutrino production



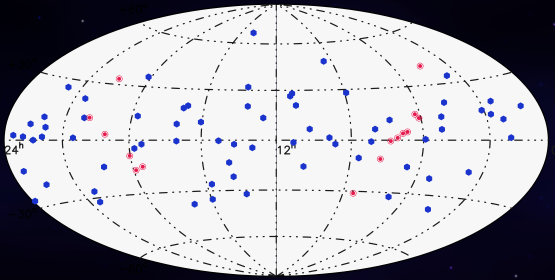
Springer Nature Limited

Where are the others



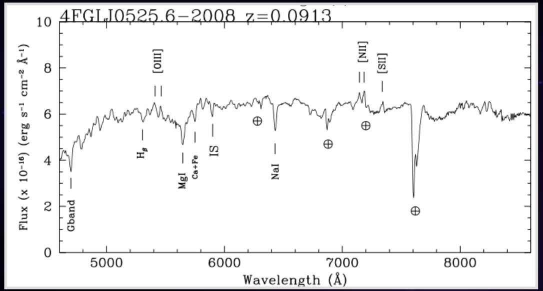
Springer Nature Limited

47 blazars / 16 good candidates



Giommi, Glauch, Padovani et al., MNRAS'20
see also M. Karl poster this conference

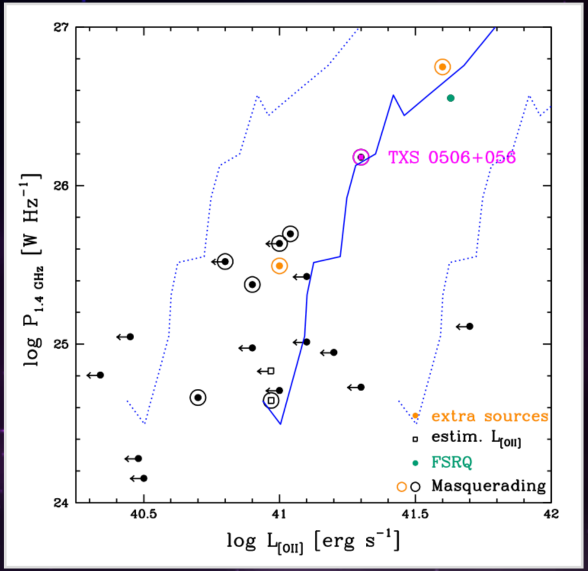
Optical spectroscopy of 17 extragalactic sources,
For 9 of them redshift (0.09 < z < 1.6)



Paiano, Falomo, Treves et al., MNRAS'21
Paiano et al., in preparation

- Dissect IceCube alerts ✓
- Identify counterparts ✓
- Get optical spectra ✓
- Classify & Model ✓
- Test on neutrinos
- Test on more neutrinos

The radio power – emission line diagram



Padovani, Giommi, Falomo et al., MNRAS'21

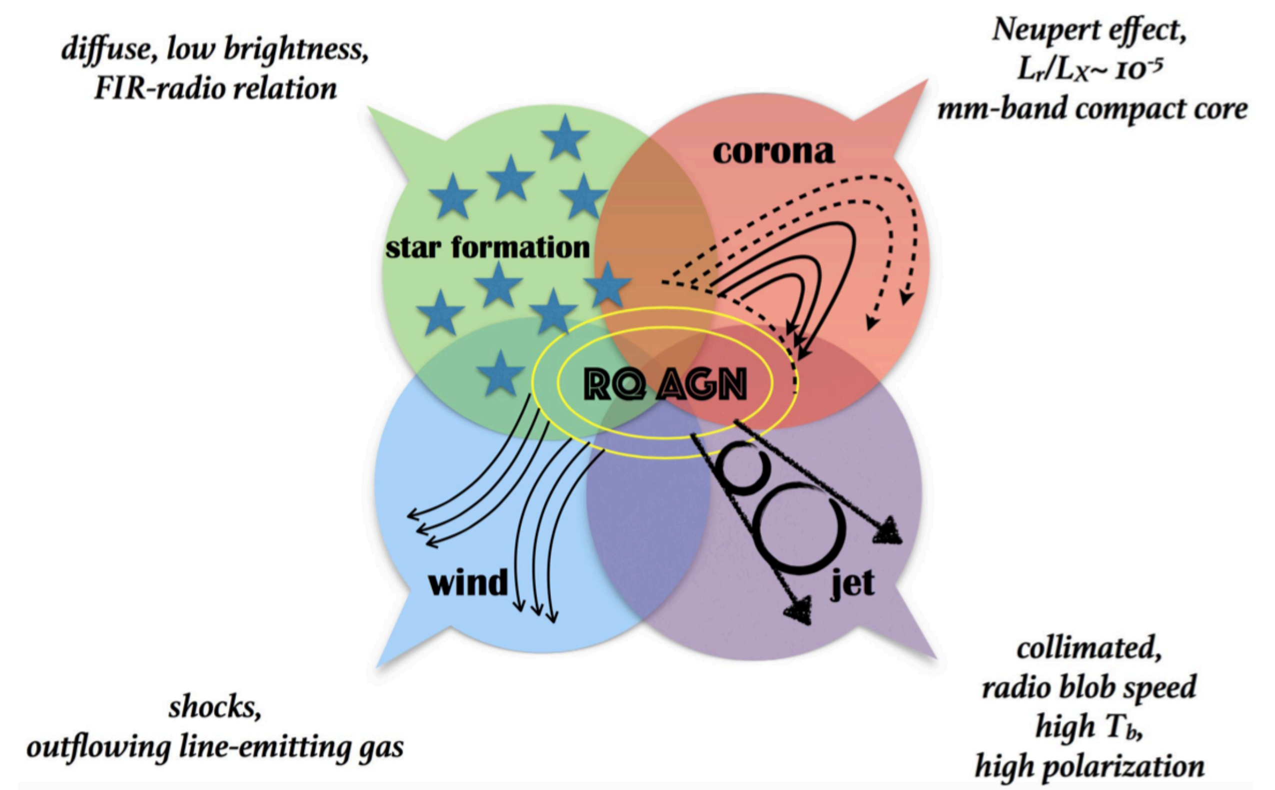
Very rare objects in the universe

02.2 Resolving the Cosmic Neutrino Flux

The non-jetted AGN case

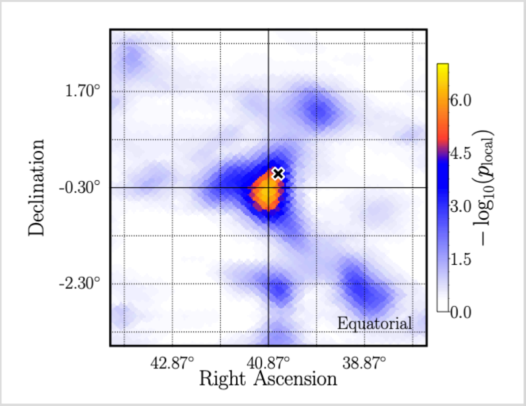
Panessa, Baldi, Laor et al., Nature Astronomy '19

02.2



Emergence of NGC1068? z=0.004

2.9 σ excess



The IceCube Coll., PRL'20

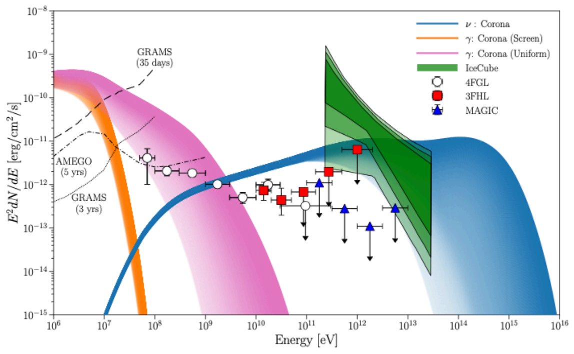


Figure 2. The gamma-ray and neutrino spectrum of NGC 1068. The circle, square, and triangle data points are from The Fermi-LAT collaboration (2019), Ajello et al. (2017), and MAGIC Collaboration et al. (2019), respectively. The green shaded regions represent the 1, 2, and 3σ regions on the spectrum measured by IceCube (IceCube Collaboration et al. 2019). The expected gamma-ray and neutrino spectrum from the corona are shown for $30 \leq \eta_g \leq 3 \times 10^4$. The darker region corresponds to lower η_g. The blue region shows the expected neutrino spectrum. The orange and magenta shaded region shows the gamma-ray spectrum for the uniform case and the screened case, respectively. We also overplot the sensitivity curves of *GRAMS* (Aramaki et al. 2019) and *AMEGO* (McEnery et al. 2019) for for comparison.

The Astrophysical Journal Letters, 891:L33 (5pp), 2020 March 10 https://doi.org/10.3847/2041-8213/ab7661

On the Origin of High-energy Neutrinos from NGC 1068: The Role of Nonthermal Coronal Activity

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[5] Department of Space and Astronautical Science, The Graduate University for Advanced Studies (SOKENDAI), 3-1-1 Yoshinodai, Chuou-ku, Sagamihara, Kanagawa 252-5210, Japan
Received 2020 January 21; revised 2020 February 13; accepted 2020 February 13; published 2020 March 9

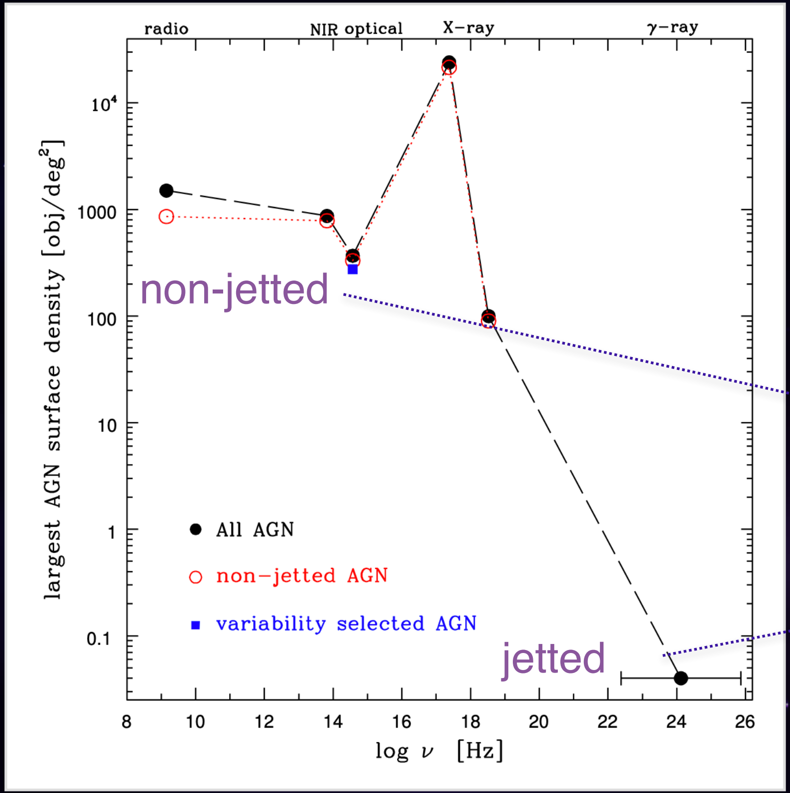
Abstract

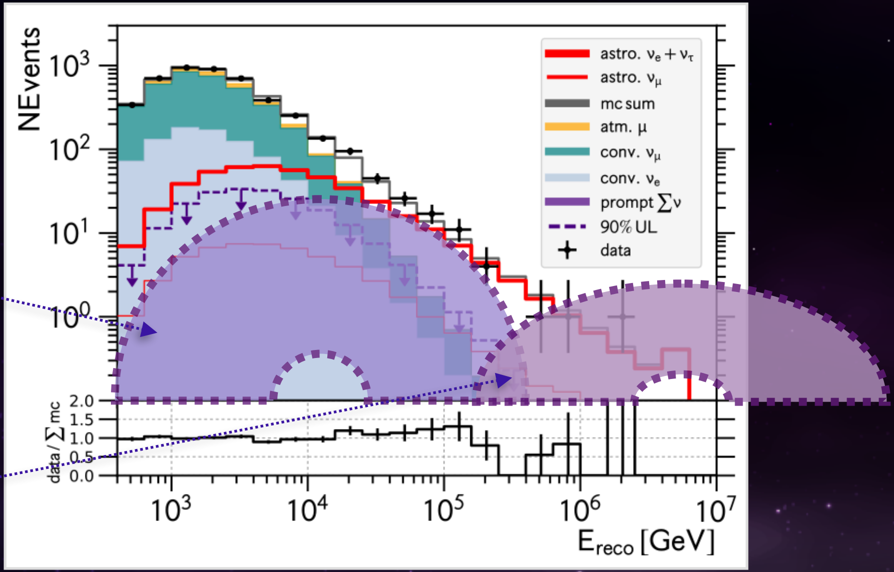
NGC 1068, a nearby type-2 Seyfert galaxy, is reported as the hottest neutrino spot in the 10 yr survey data of IceCube. Although there are several different possibilities for the generation of high-energy neutrinos in astrophysical sources, feasible scenarios allowing such emission in NGC 1068 have not yet been firmly defined. We show that the flux level of GeV and neutrino emission observed from NGC 1068 implies that the neutrino emission can be produced only in the vicinity of the supermassive black hole in the center of the galaxy. The coronal parameters, such as magnetic field strength and corona size, that make this emission possible, are consistent with the spectral excess registered in the millimeter range. The suggested model and relevant physical parameters are similar to those revealed for several nearby Seyferts. Due to the internal gamma-ray attenuation, the suggested scenario cannot be verified by observations of NGC 1068 in the GeV and TeV gamma-ray energy bands. However, the optical depth is expected to become negligible for MeV gamma-rays, thus future observations in this band will be able to validate our model.

Unified Astronomy Thesaurus concepts: Astrophysical black holes (98); Black hole physics (159); Black holes (162); Supermassive black holes (1663); Neutrino astronomy (1100); Active galactic nuclei (16); Seyfert galaxies (1447); Particle astrophysics (96); High energy astrophysics (739); Accretion (14)

Emergence of a scenario?

P.Padovani, A&A Rev '17



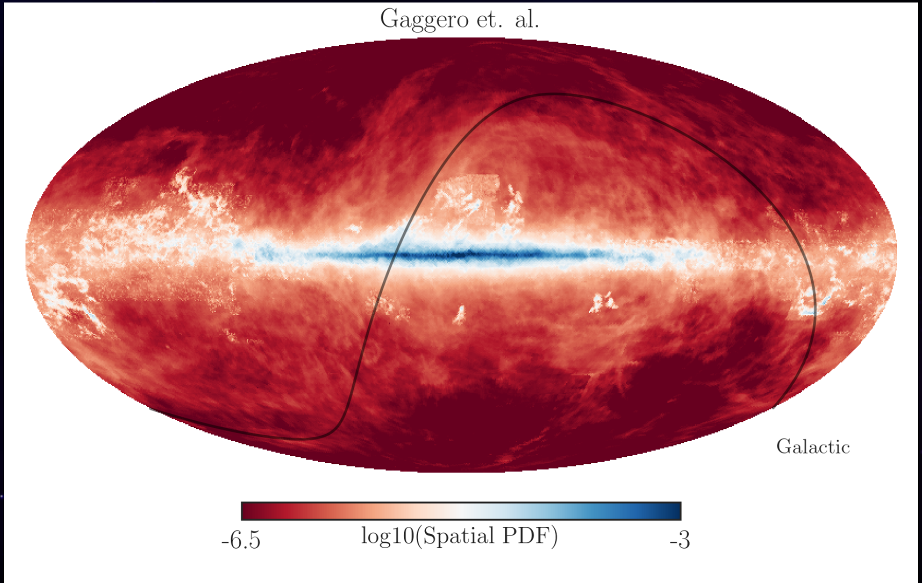


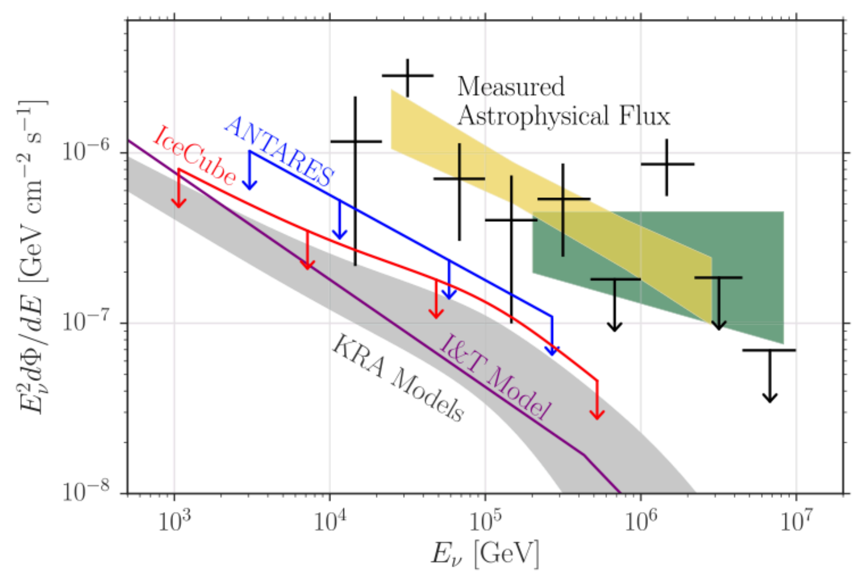
02.3 Resolving the Cosmic Neutrino Flux

The Galactic ‘guaranteed’ case

see Giovanna Ferrara this conference

The ‘guaranteed’ signal





The IceCube Coll., ApJ 2017

03

The next generation observatories - a network

Boost Exposure

Boost Exposure to Neutrinos

P-ONE

KM3NeT
see Simone Biagi this conference

Baikal-GVD

TRIDENT
https://arxiv.org/pdf/2207.04519.pdf

IceCube & Gen2

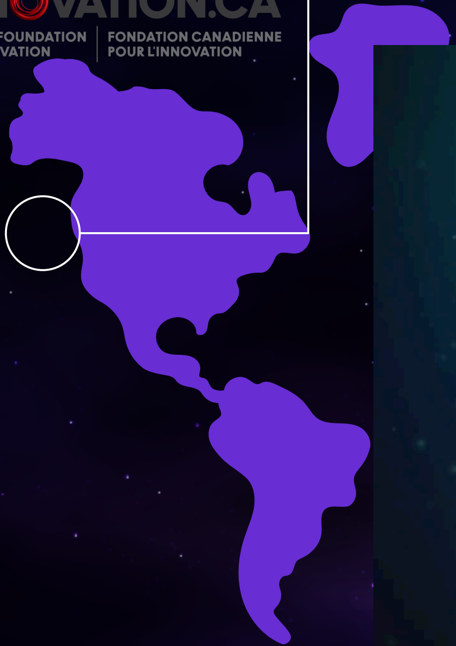
see https://arxiv.org/abs/2203.08096
High-Energy and Ultra-High-Energy Neutrinos
A Snowmass White Paper

P-ONE (Pacific Ocean Neutrino Experiment)

@Existing oceanographic infrastructure Ocean Networks Canada

INNOVATION.CA
CANADA FOUNDATION FOR INNOVATION | FONDATION CANADIENNE POUR L'INNOVATION

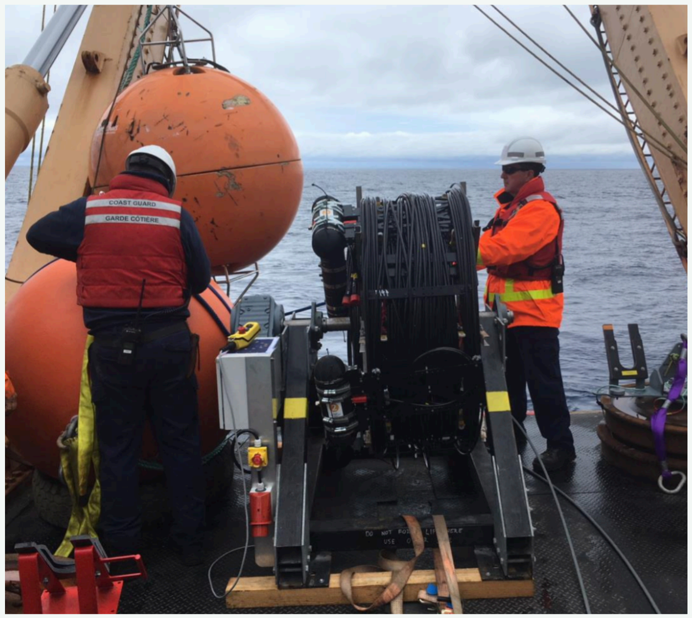
P-ONE



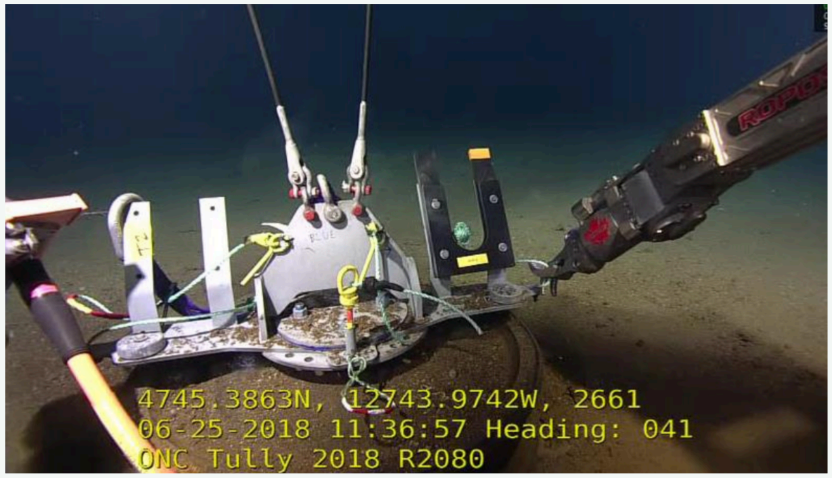
P-ONE: > 4 years pathfinder missions

J. Bedard, E.R. et al., JINST (2019) - STRAW hardware
N. Bailly, E.R. et al., Eur. Phys. J. C (2021) - STRAW results

P-ONE

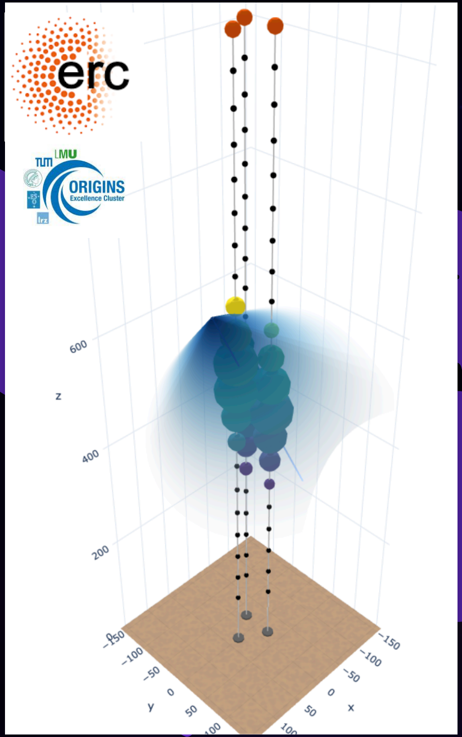


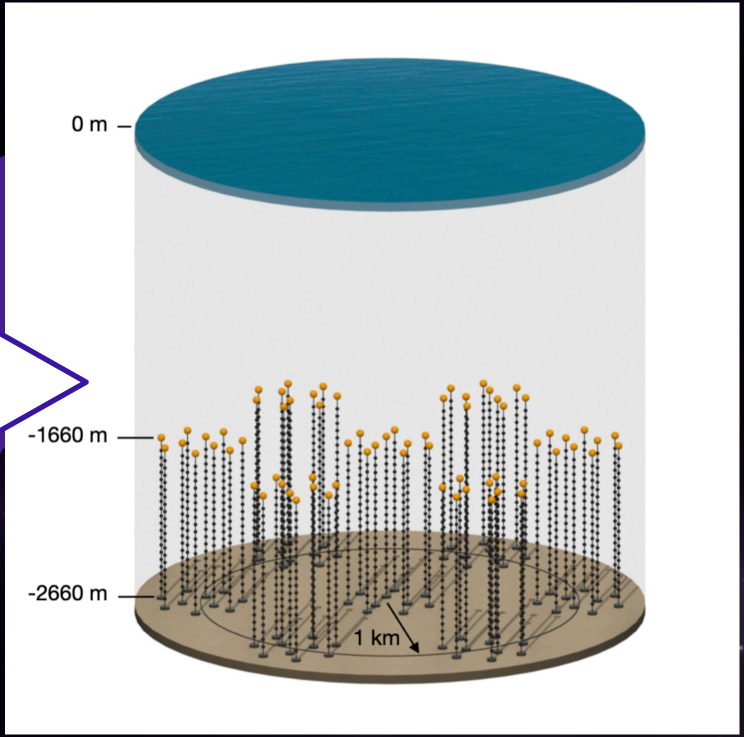
Credit: ONC



Attenuation Length (450nm) ~ 30 meters
~98% up time 4 years
~10% connector failure rate

P-ONE: demonstrator phase started





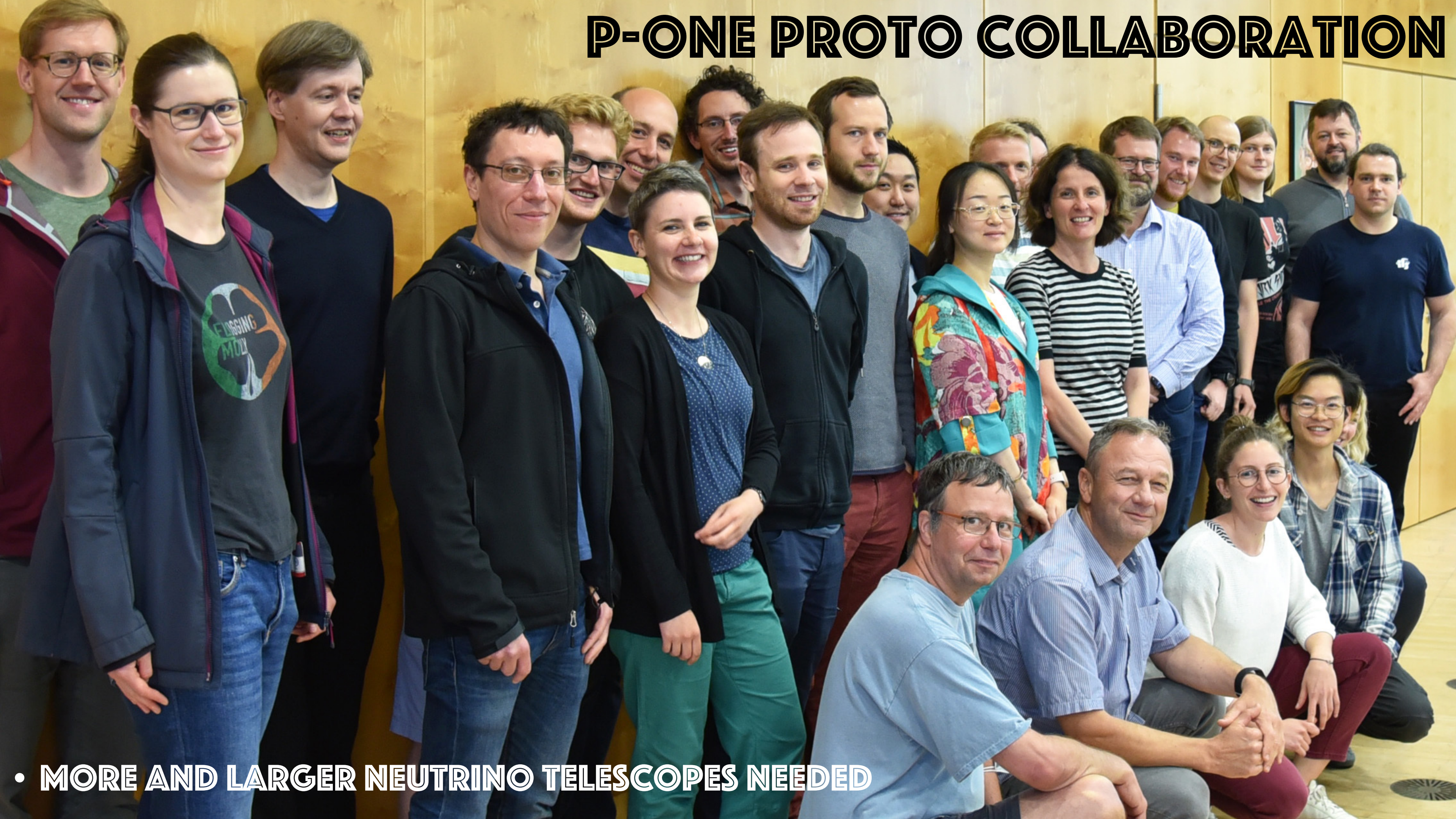
SUMMARY

HE Neutrino Astronomy is here

- Diffuse flux of high energy cosmic neutrinos
- Potential associations:
  - Jetted AGN: TXS0506+056 as template source, other tentative associations published;
  - Non-Jetted AGN: a new (old) scenario emerging;
  - Promising: Galactic component as guaranteed flux.

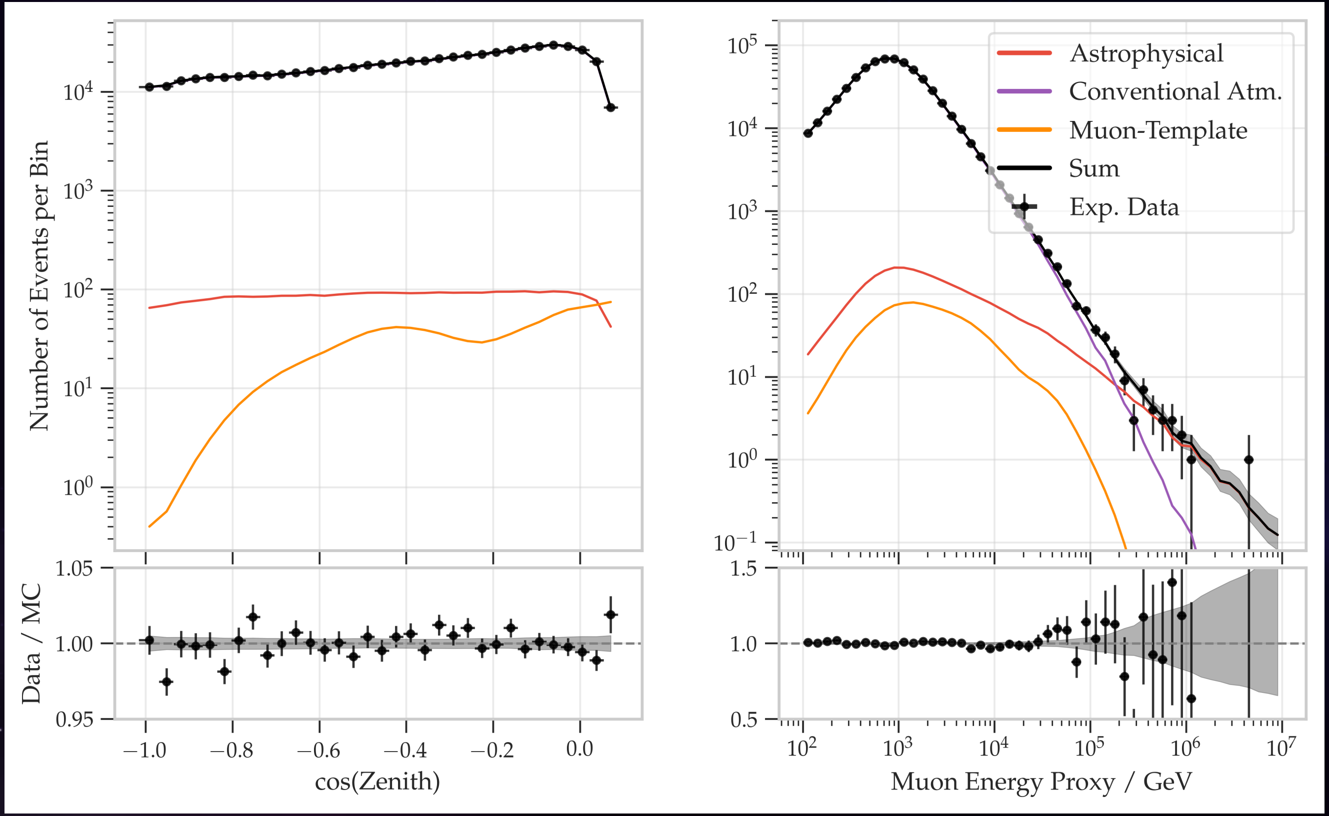
- **MORE AND LARGER NEUTRINO TELESCOPES NEEDED**

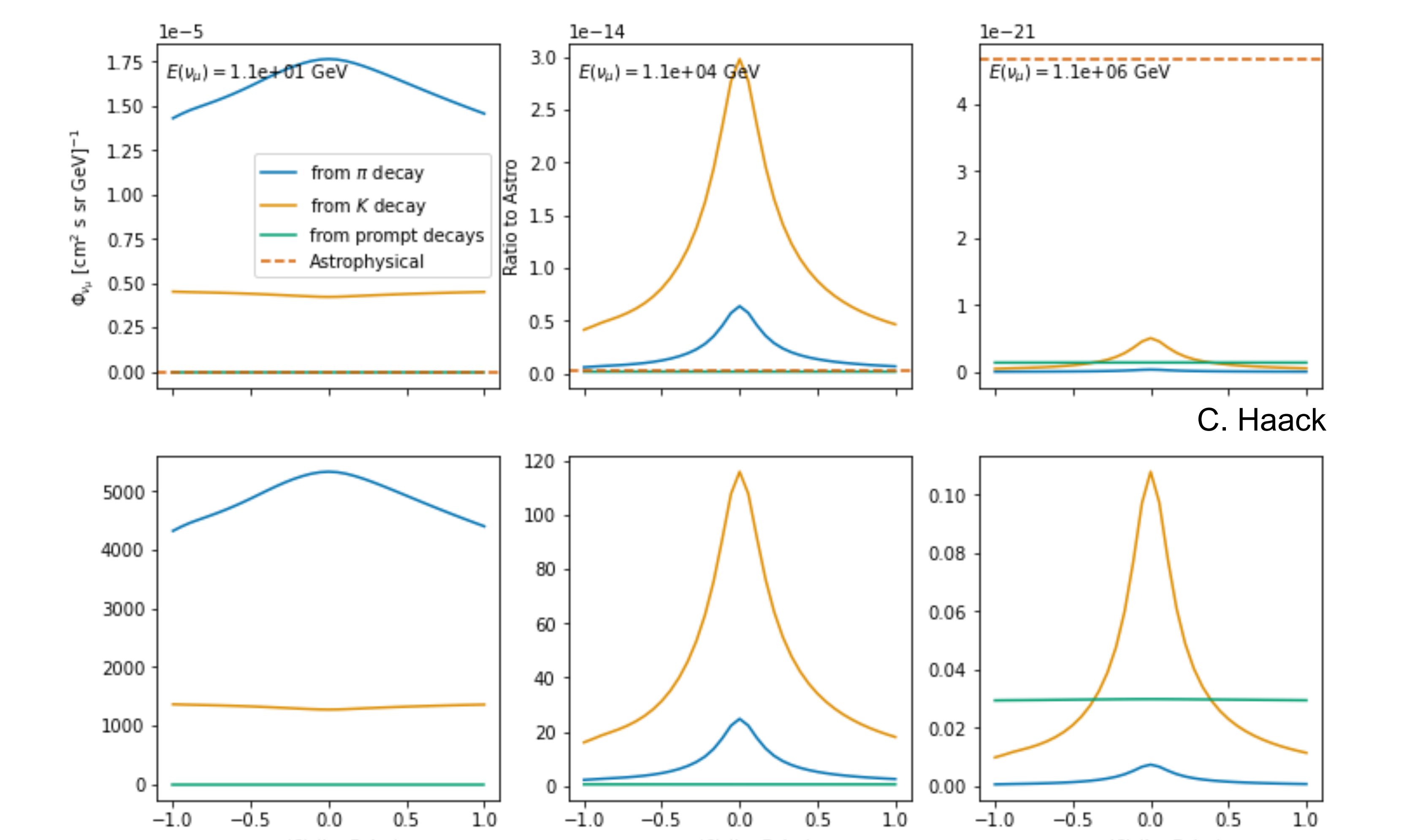
P-ONE PROTO COLLABORATION



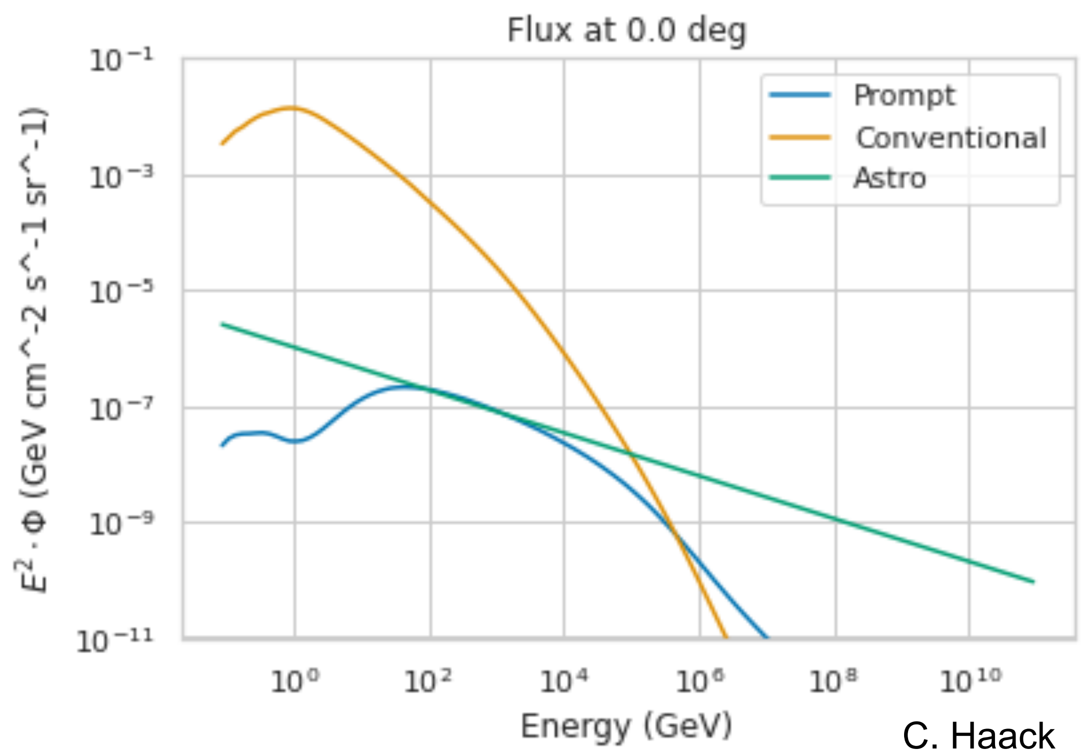
- MORE AND LARGER NEUTRINO TELESCOPES NEEDED

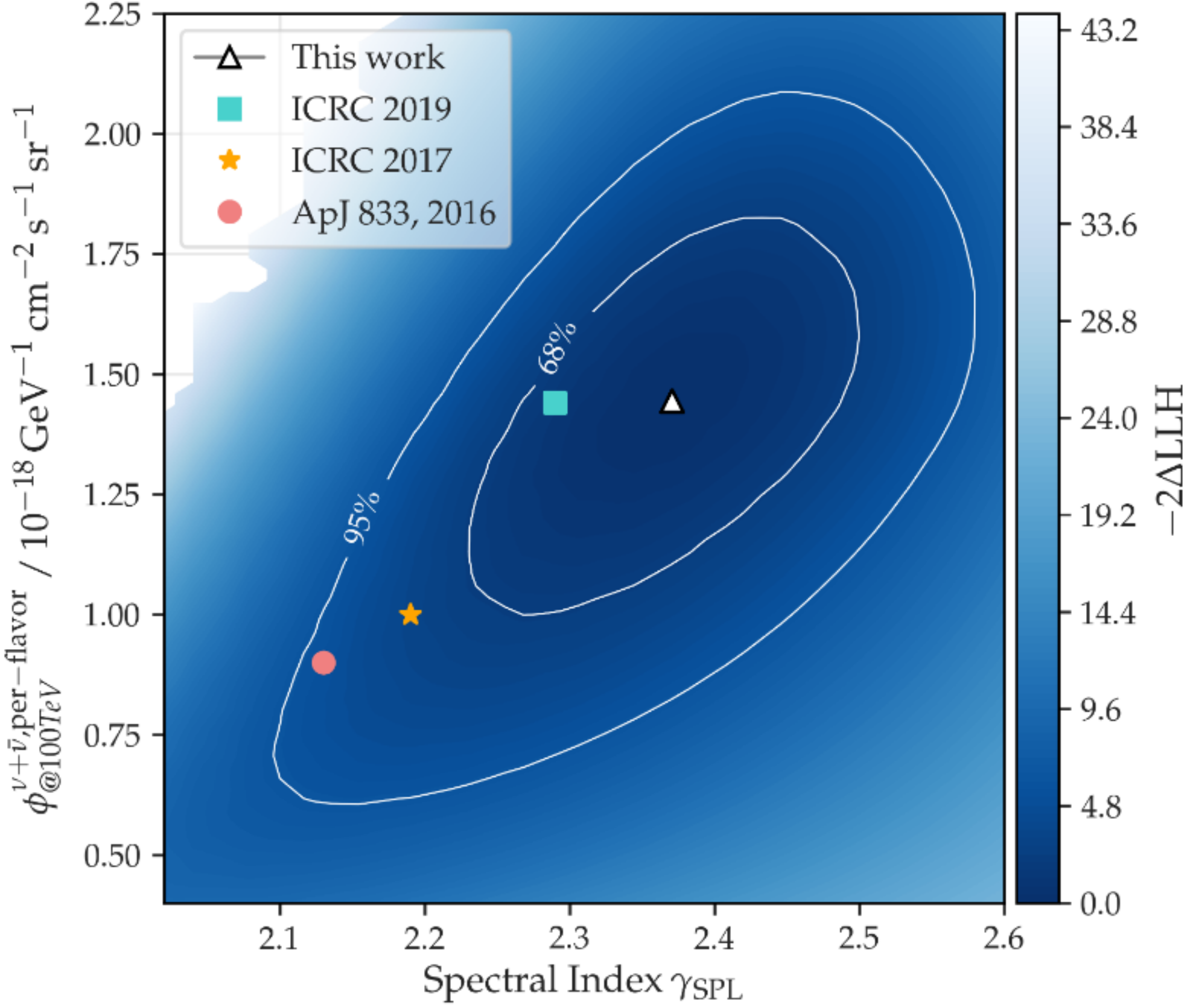
P-ONE proto collaboration


Astrophysical
Conventional Atm.
Muon-Template
Sum
Exp. Data
Number of Events per Bin
Data / MC
cos(Zenith)
Muon Energy Proxy / GeV
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{5}
10^{-1}
1.05
1.00
0.95
1.5
1.0
0.5
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}



1e−5
1e−14
1e−21
$E(\nu_\mu) = 1.1e+01$ GeV
$E(\nu_\mu) = 1.1e+04$ GeV
$E(\nu_\mu) = 1.1e+06$ GeV
Φ_{ν_μ} [cm² s sr GeV]$^{-1}$
Ratio to Astro
from π decay
from K decay
from prompt decays
Astrophysical
C. Haack


Flux at 0.0 deg
$E^2 \cdot \Phi$ (GeV cm^-2 s^-1 sr^-1)
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{0}
10^{2}
10^{4}
10^{6}
10^{8}
10^{10}
Energy (GeV)
Prompt
Conventional
Astro
C. Haack



This work
ICRC 2019
ICRC 2017
ApJ 833, 2016
68%
95%
2.25
2.00
1.75
1.50
1.25
1.00
0.75
0.50
2.1
2.2
2.3
2.4
2.5
2.6
Spectral Index γ_{SPL}
$\phi^{\nu+\bar{\nu},\text{per-flavor}}_{@100TeV}$ / $10^{-18}\,\text{GeV}^{-1}\,\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$
43.2
38.4
33.6
28.8
24.0
19.2
14.4
9.6
4.8
0.0
$-2\Delta\text{LLH}$

P-ONE optical module design and deployment strategy