IceCube: opening a new window on the universe from the South Pole

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for The IceCube Collaboration

UNIVERSITÉ DE GENÈVE

ICECUBE

NSF

La Thuile 2019 - Les Rencontres de Physique de la Vallée d'Aoste   11 March 2019

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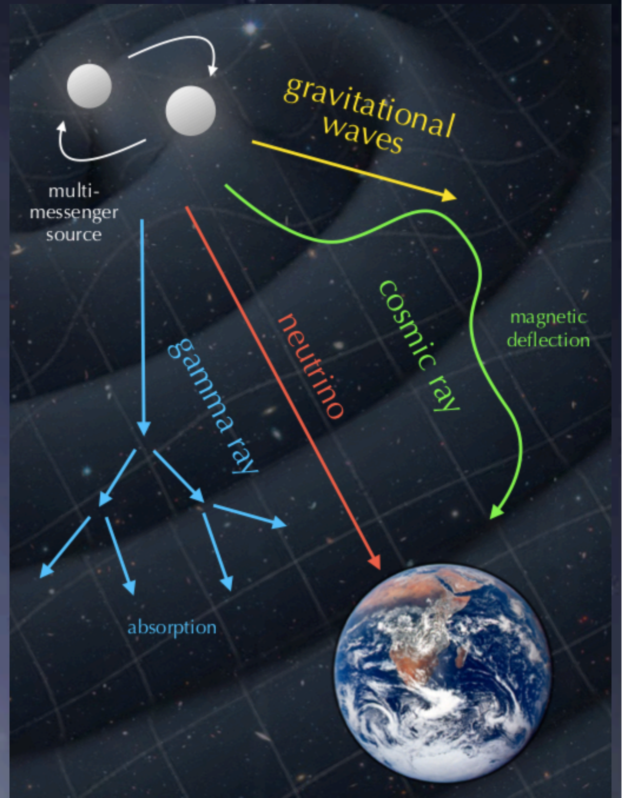
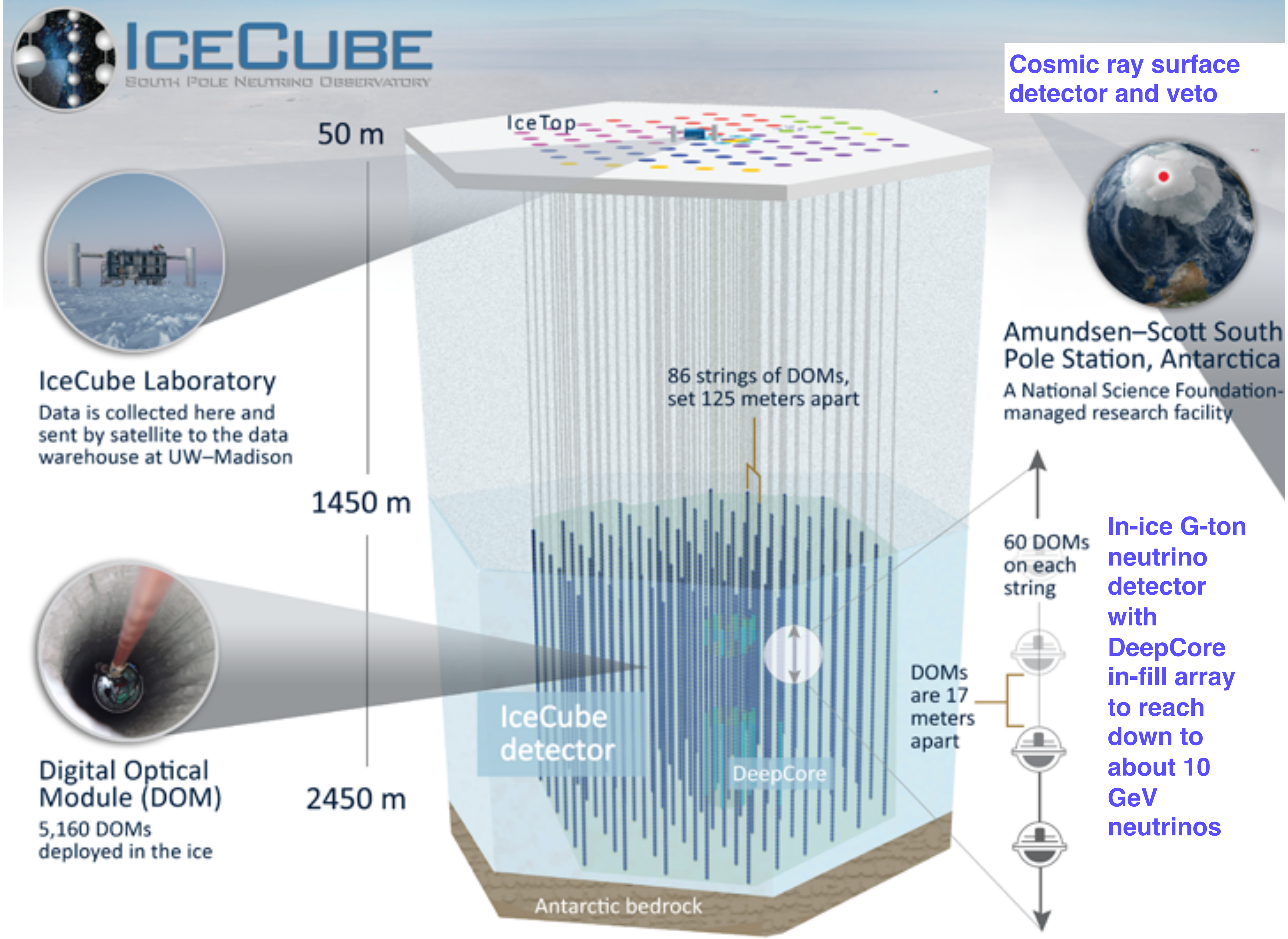


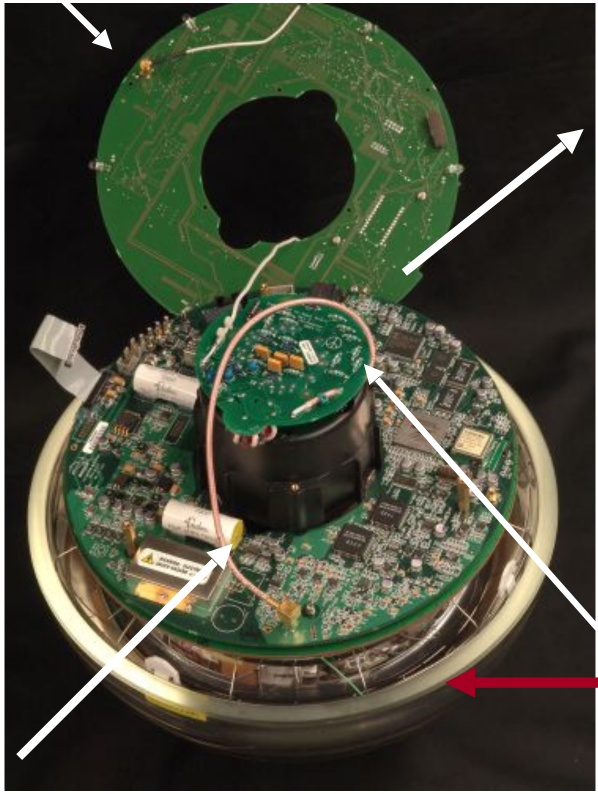
- IceCube
- Diffuse flux and point source measurements
- The multi-messenger strategy and the TXS 0506+056 obervations
- Results on neutrino properties
- Future experiments



ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
Cosmic ray surface detector and veto
IceTop
50 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
86 strings of DOMs, set 125 meters apart
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
1450 m
60 DOMs on each string
In-ice G-ton neutrino detector with DeepCore in-fill array to reach down to about 10 GeV neutrinos
DOMs are 17 meters apart
IceCube detector
DeepCore
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
2450 m
Antarctic bedrock

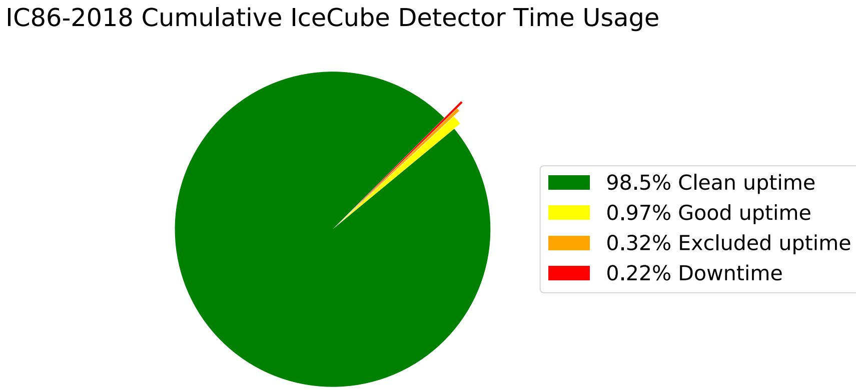
The IceCube Digital Optical Module

LED flasher board

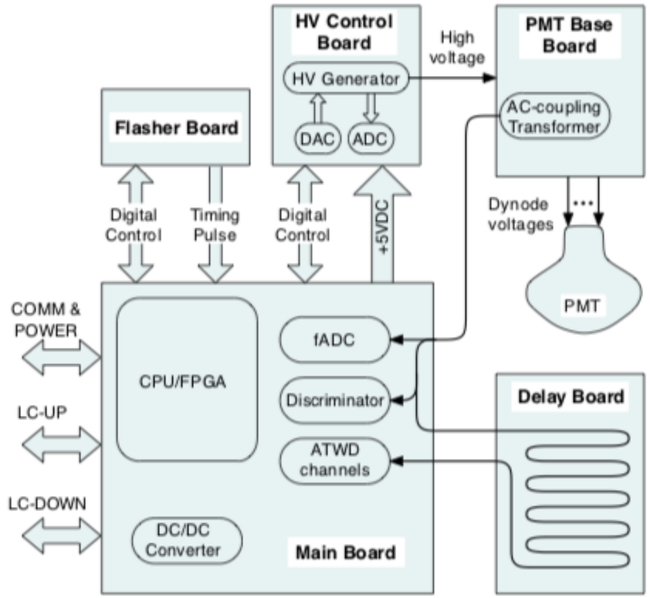


motherboard

R7081-02 10 inch
QE = 25%
R7081-MOD
QE = 34% DpCore

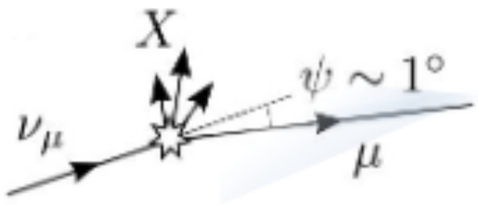


DAQ raw data output for normal operation ~1 TB per day.
Filtered data archive, after data compression ~90 GB/day.

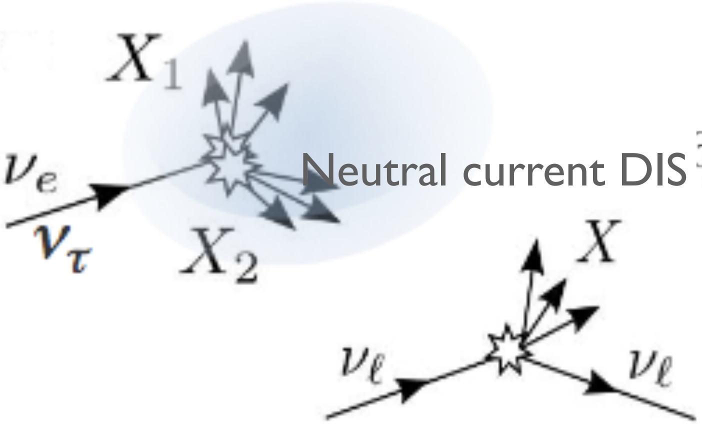


IceCube, J. Inst. 12 (2017) P03012
IceCube, NIM A 618 (2010) 139-152

Neutrino events

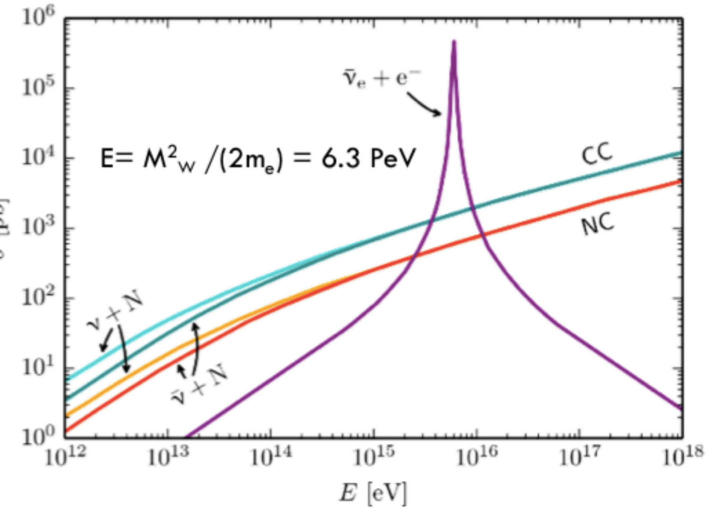


Charged current DIS



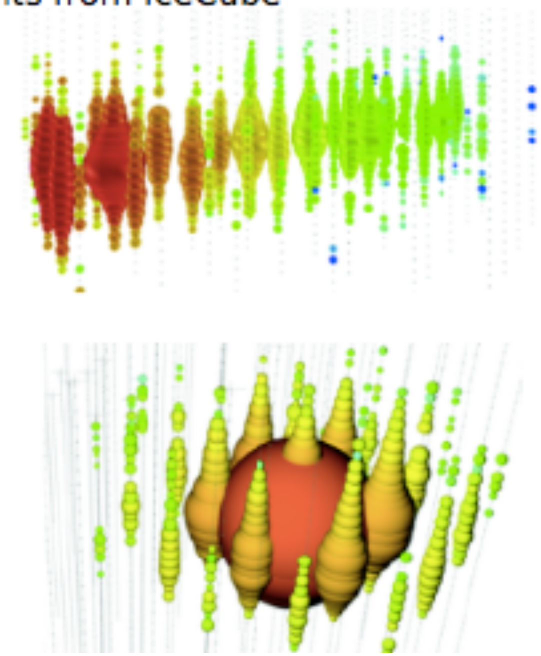
Neutral current DIS

Tracks
Standard reconstruction;
about x2 energy resolution
Angular resolution < 1°



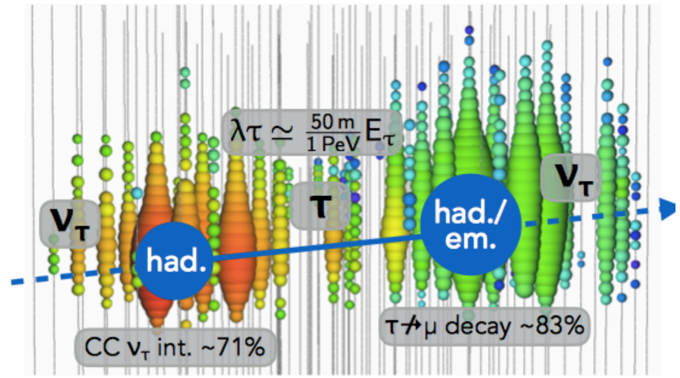
Detected charge ∝ size

events from IceCube



double bang channel

Learned and Pakvasa, Astropart. Phys. 3, 1995

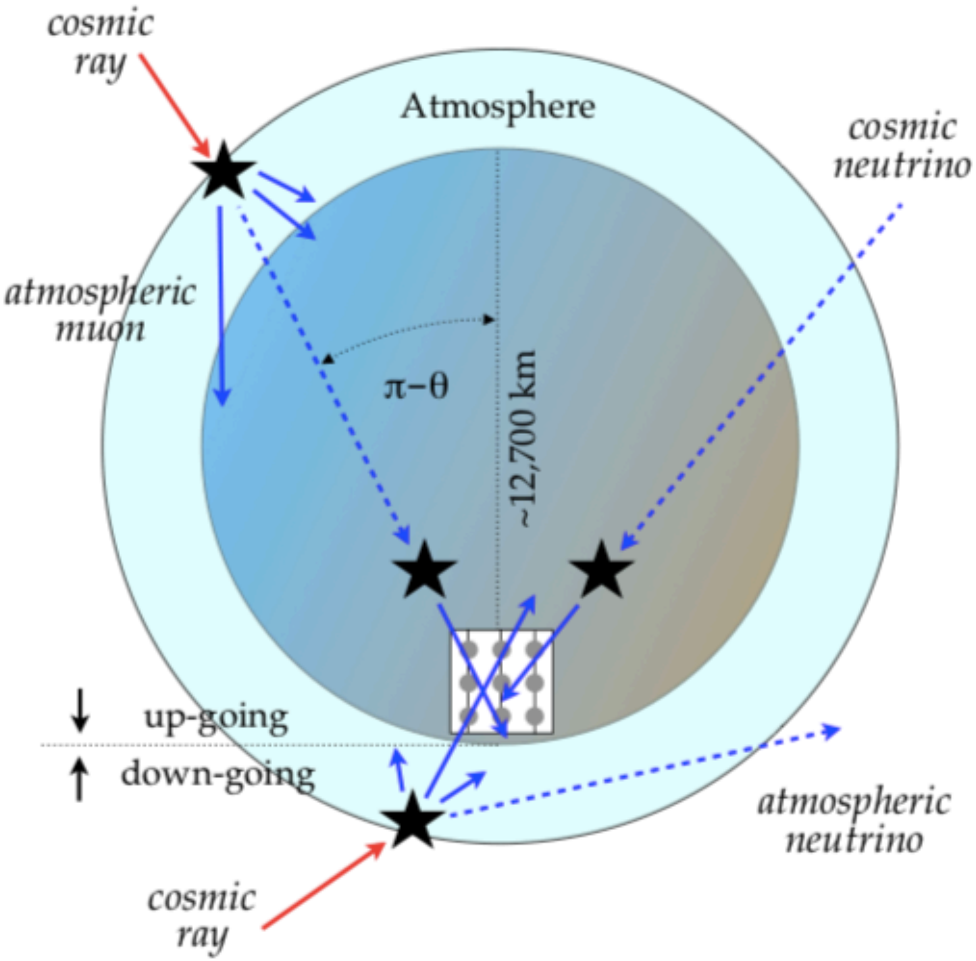


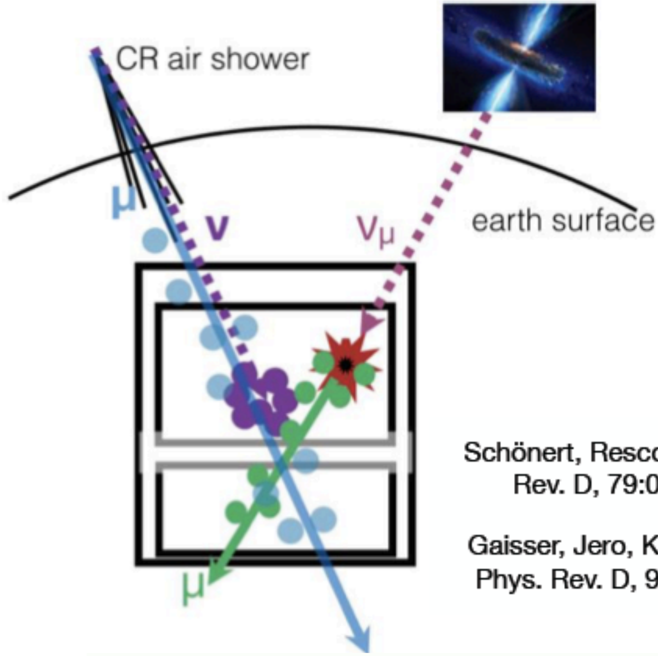
simulated double bang event with ~10 PeV neutrino energy

Charged current DIS

Cascades
15% energy resolution
Angular resolution O(10°)

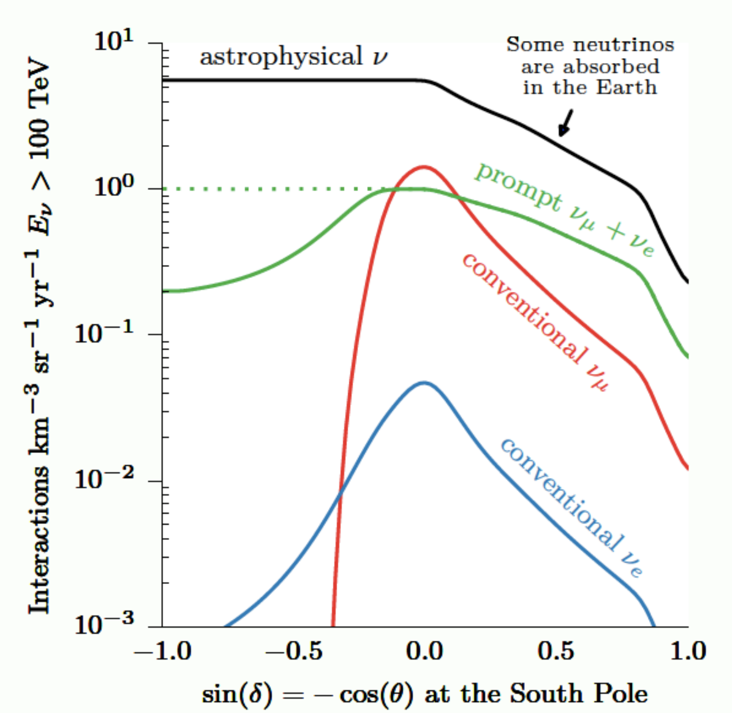
Detection principle





Schönert, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)

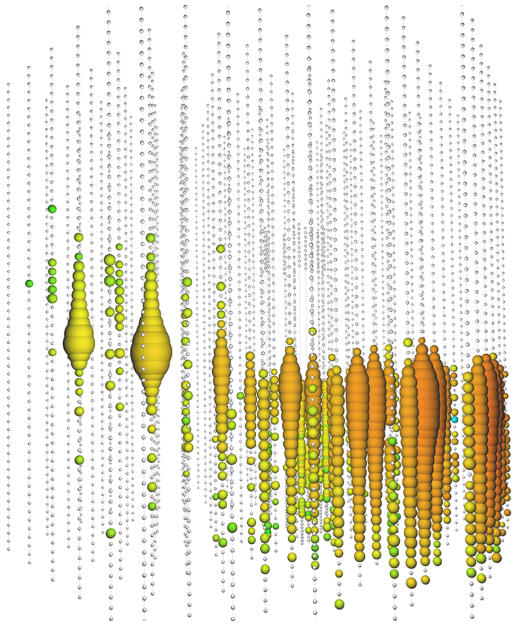
Gaisser, Jero, Karle, van Santen, Phys. Rev. D, 90:023009 (2014)



- **10,000,000,000** atmospheric muons
- **100,000** atmospheric neutrinos
- **10** cosmic neutrinos (per year and km³)

The biggest events

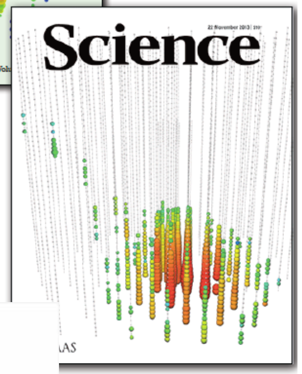
Upgoing tracks

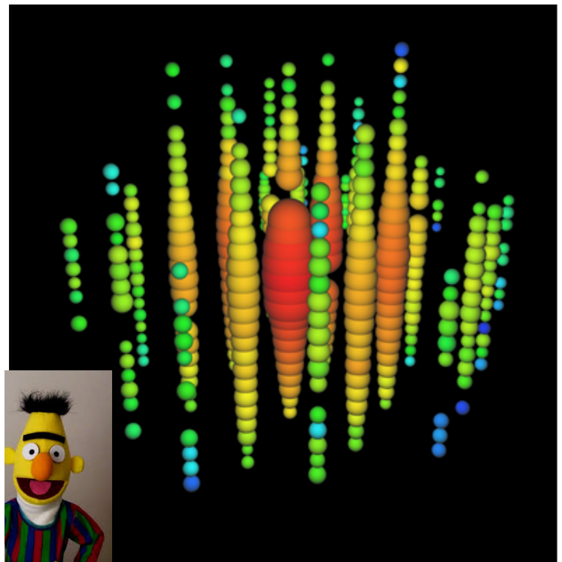


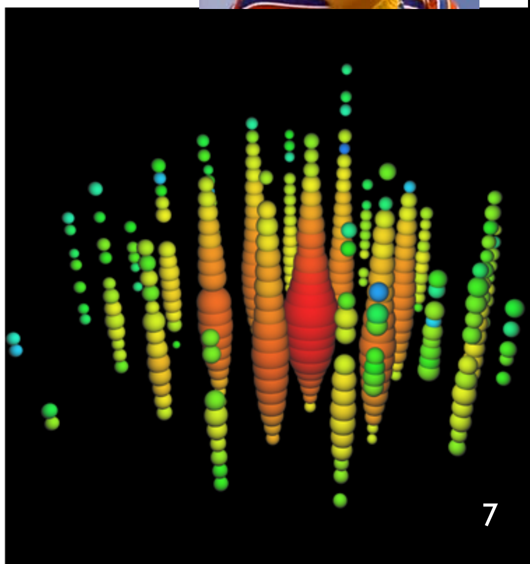
Deposited 2.6 ± 0.3 PeV (June 11, 2014)
< 0.01% prob. of being an atmospheric ν_μ

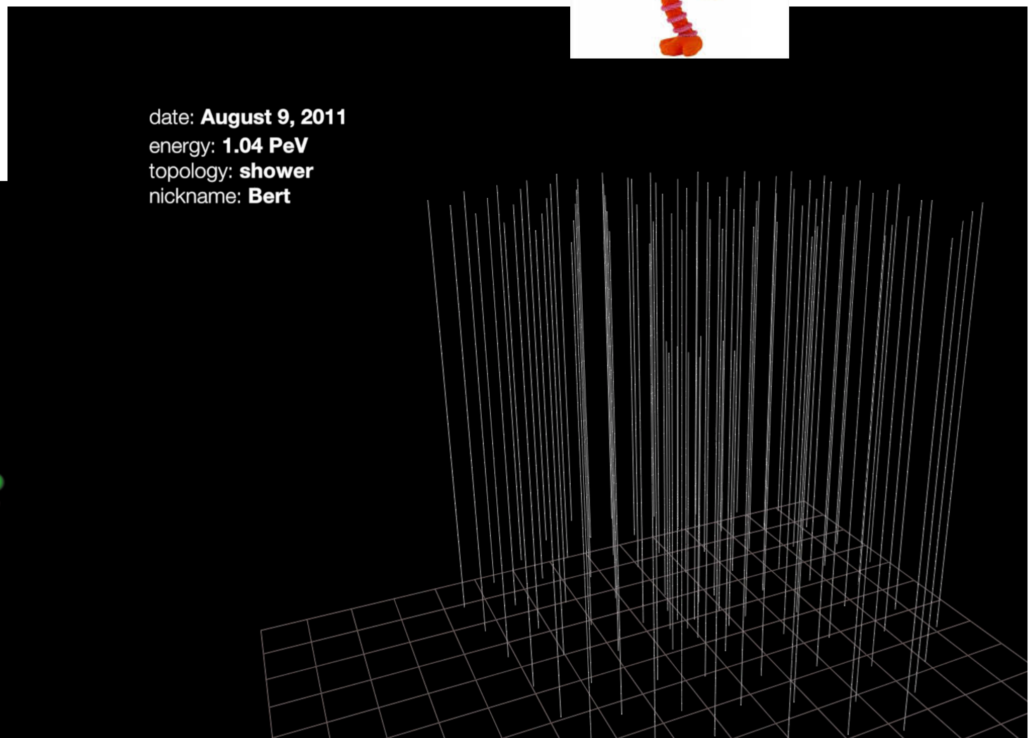
High energy starting events

IceCube, PRL 111 (2013)
Science 342 (2013):
28 neutrino events/662 d : flux > 30 TeV
incompatible with atm. neutrinos at 4.1σ and best fit $E^{-2.3}$
PRL 113 (2014): 37 neutrinos/998 d and third PeV event, 5.7σ and $E^{-2.39}$
82 events/6 yrs $E^{-2.9}$





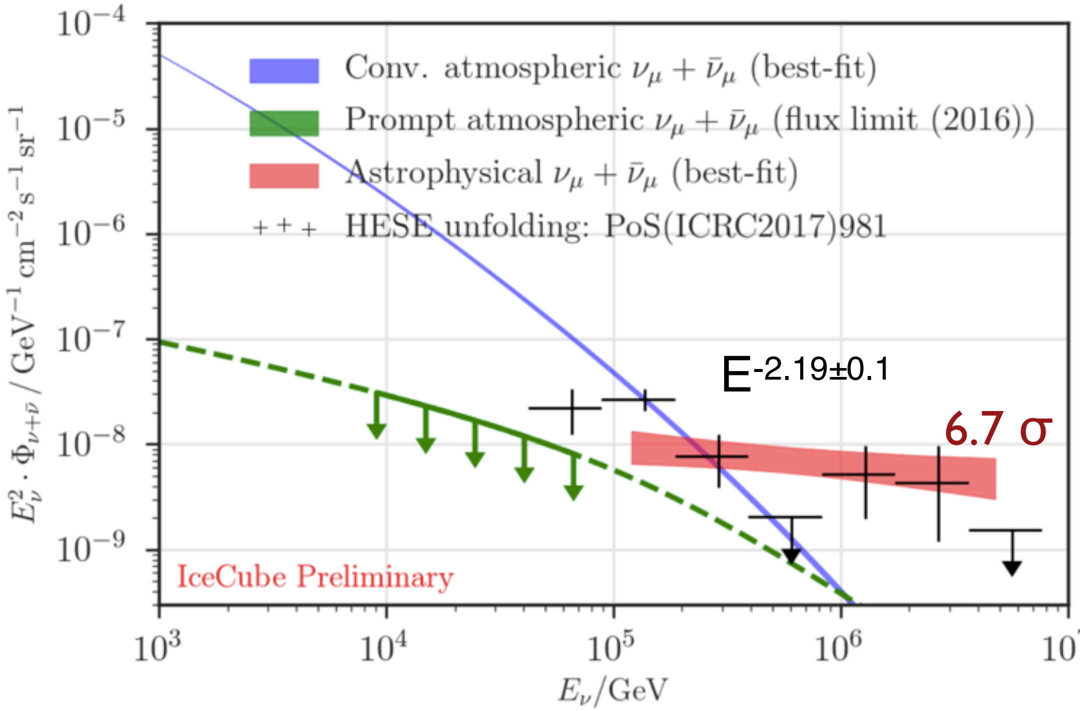




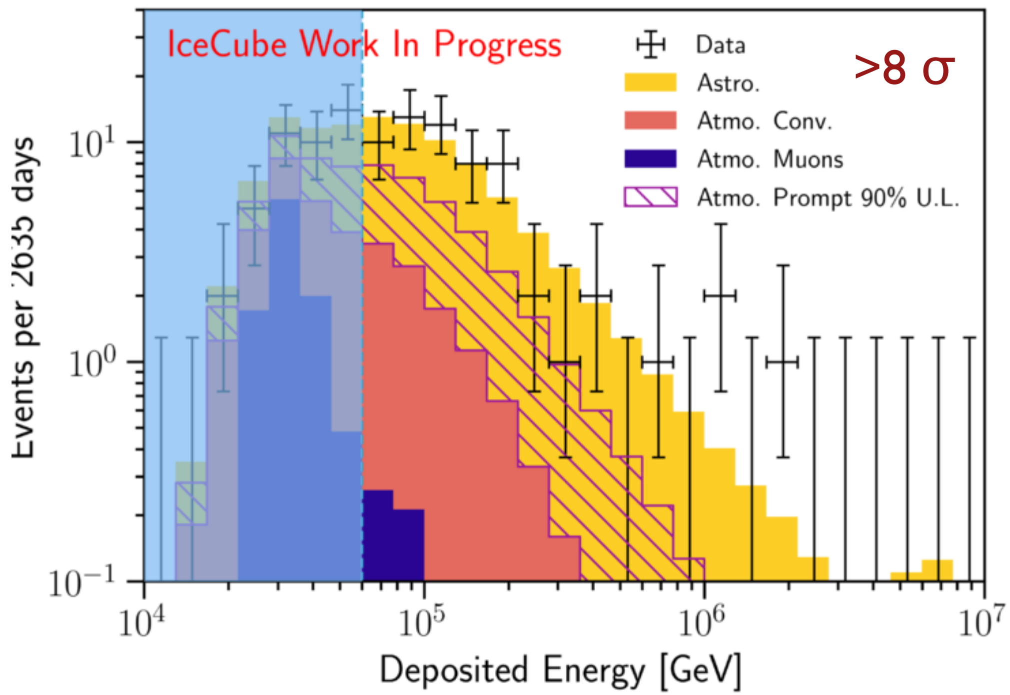
Diffuse cosmic neutrino fluxes in IceCube

8 years of muon tracks (2009-2017)

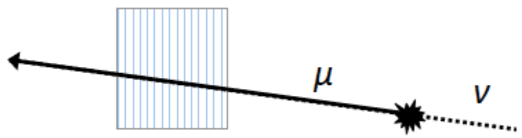
$E_\nu \sim$ 120 TeV - 5 PeV



$E^{-2.87\pm0.3}$



Neutrino energy inferred from visible muon energy



M. G. Aartsen *et al.* (IceCube Collaboration), Phys. Rev. Lett. **115**, 081102 (2015), arXiv:1507.04005 .

M. G. Aartsen *et al.* (IceCube Collaboration), Astrophys. J. **833**, 3 (2016), arXiv:1607.08006 .

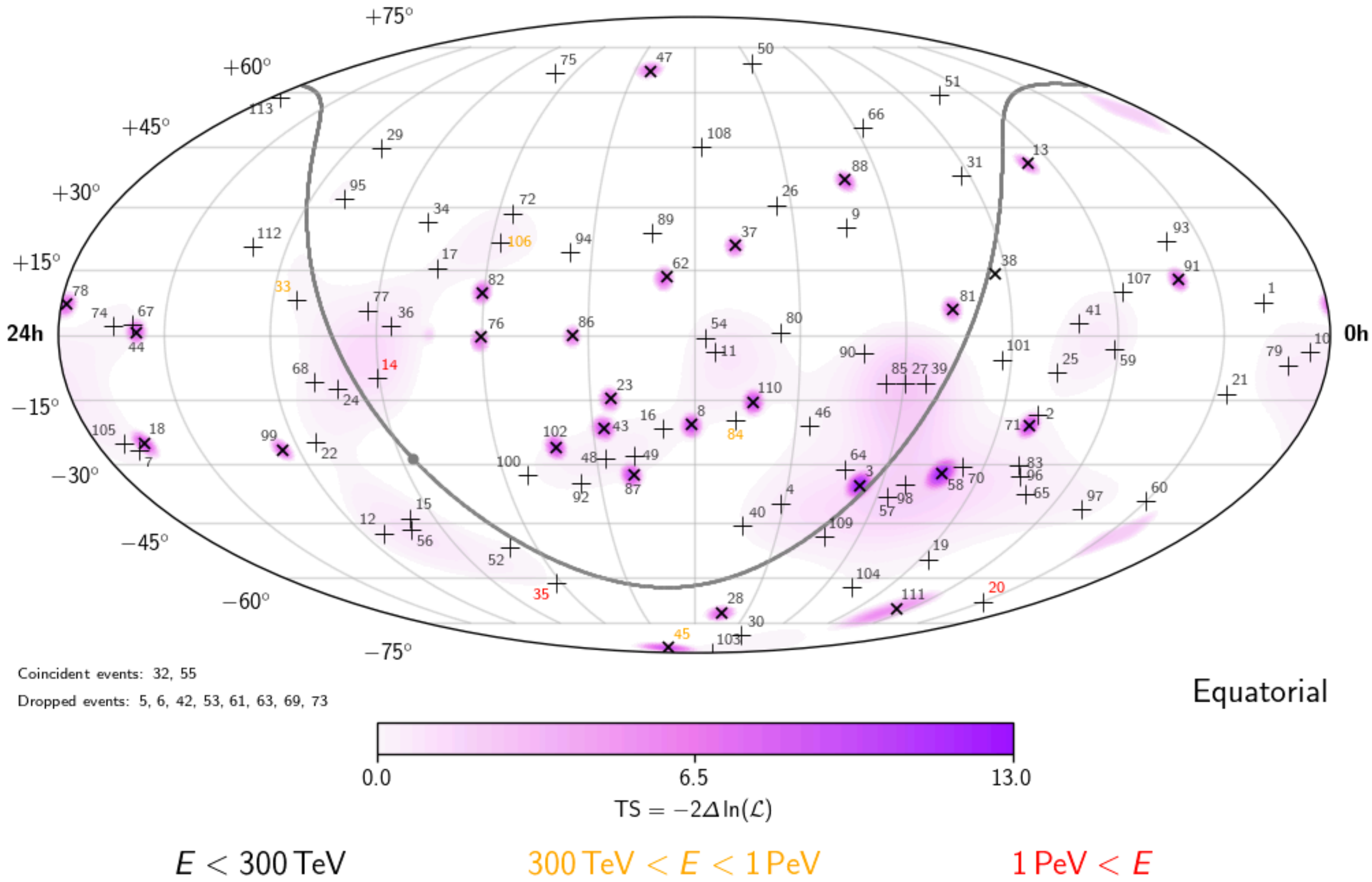
C. Haack (IceCube Collaboration), PoS **ICRC2017**, 1005 (2017), arXiv:1710.01191 .

Preliminary: 103 High-Energy Starting Events in 7.5 yr , 60 with E_{vis}>60 TeV

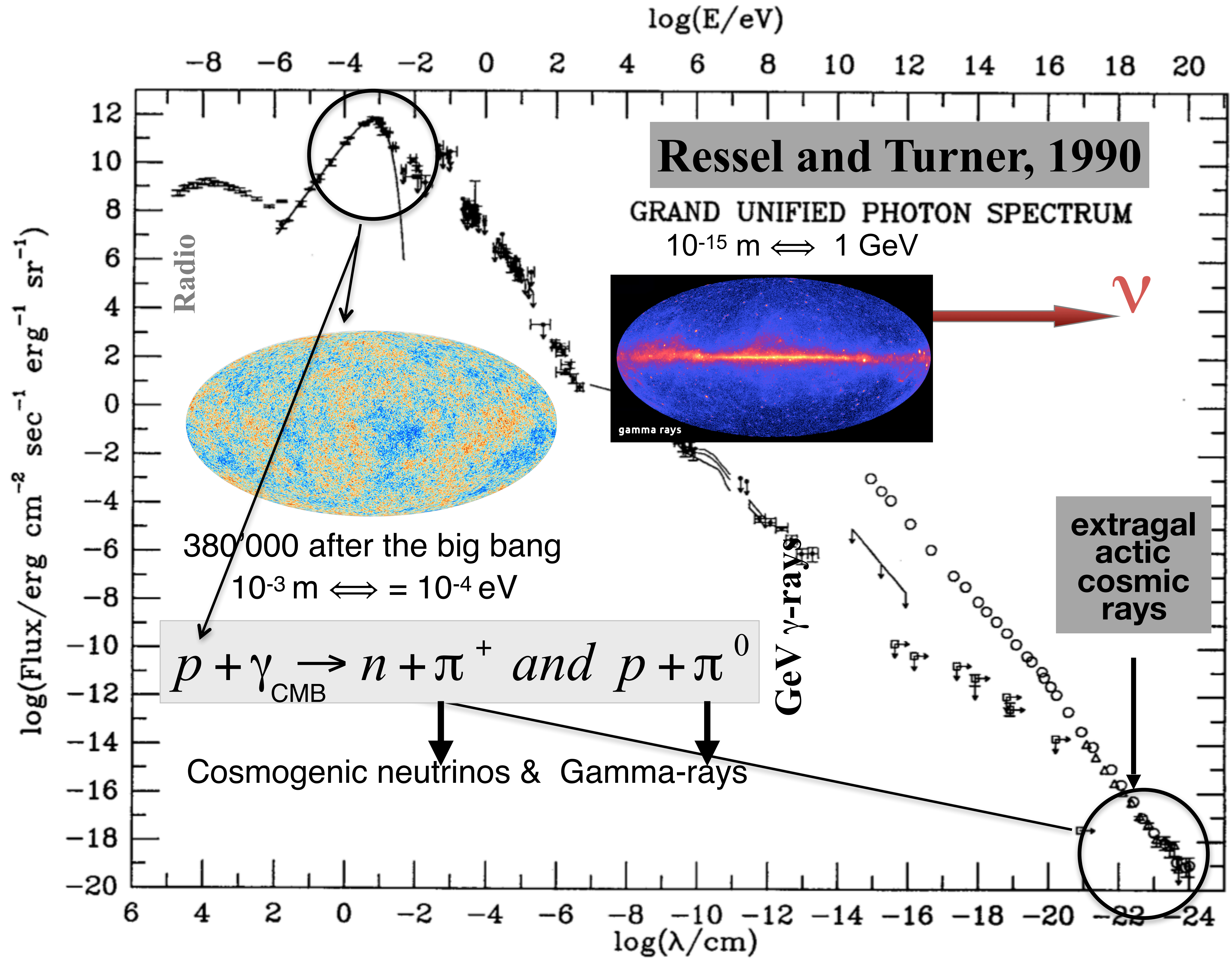
Background: 0.65±0.2 (atm.μ) , $14.5^{+10.1}_{-8.1}$ (atm.ν, incl. prompt)

Schneider,TeVPA2018

Searching for the origin of the IceCube diffuse cosmic neutrino flux

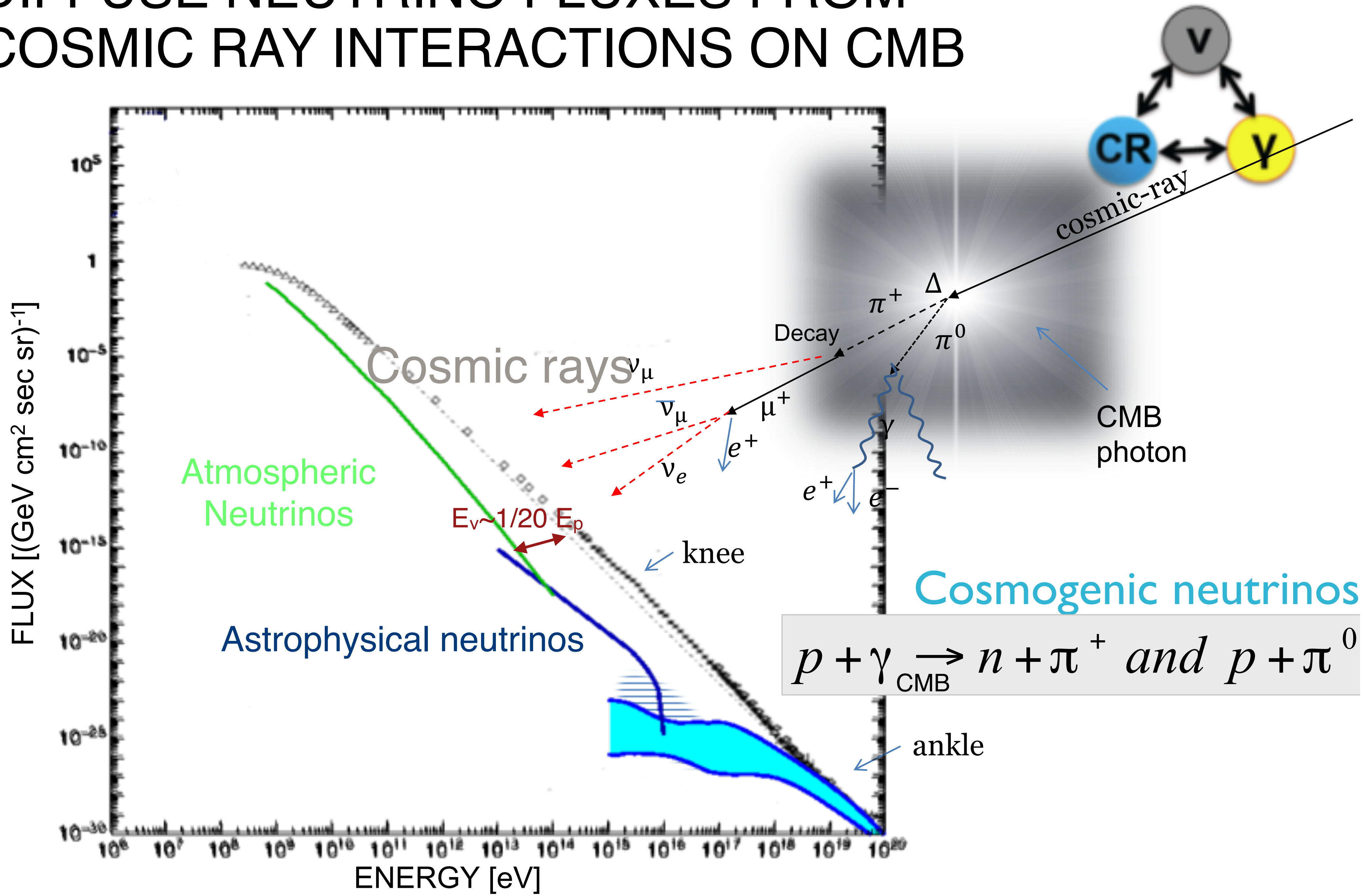


No significant cluster or correlation with the galactic plane



Ressel and Turner, 1990
GRAND UNIFIED PHOTON SPECTRUM
10-15 m ⟺ 1 GeV
gamma rays
ν
Radio
380'000 after the big bang
10-3 m ⟺ = 10-4 eV
p + γCMB → n + π+ and p + π0
GeV γ-rays
extragalactic cosmic rays
Cosmogenic neutrinos & Gamma-rays
log(E/eV)
log(Flux/erg cm-2 sec-1 erg-1 sr-1)
log(λ/cm)

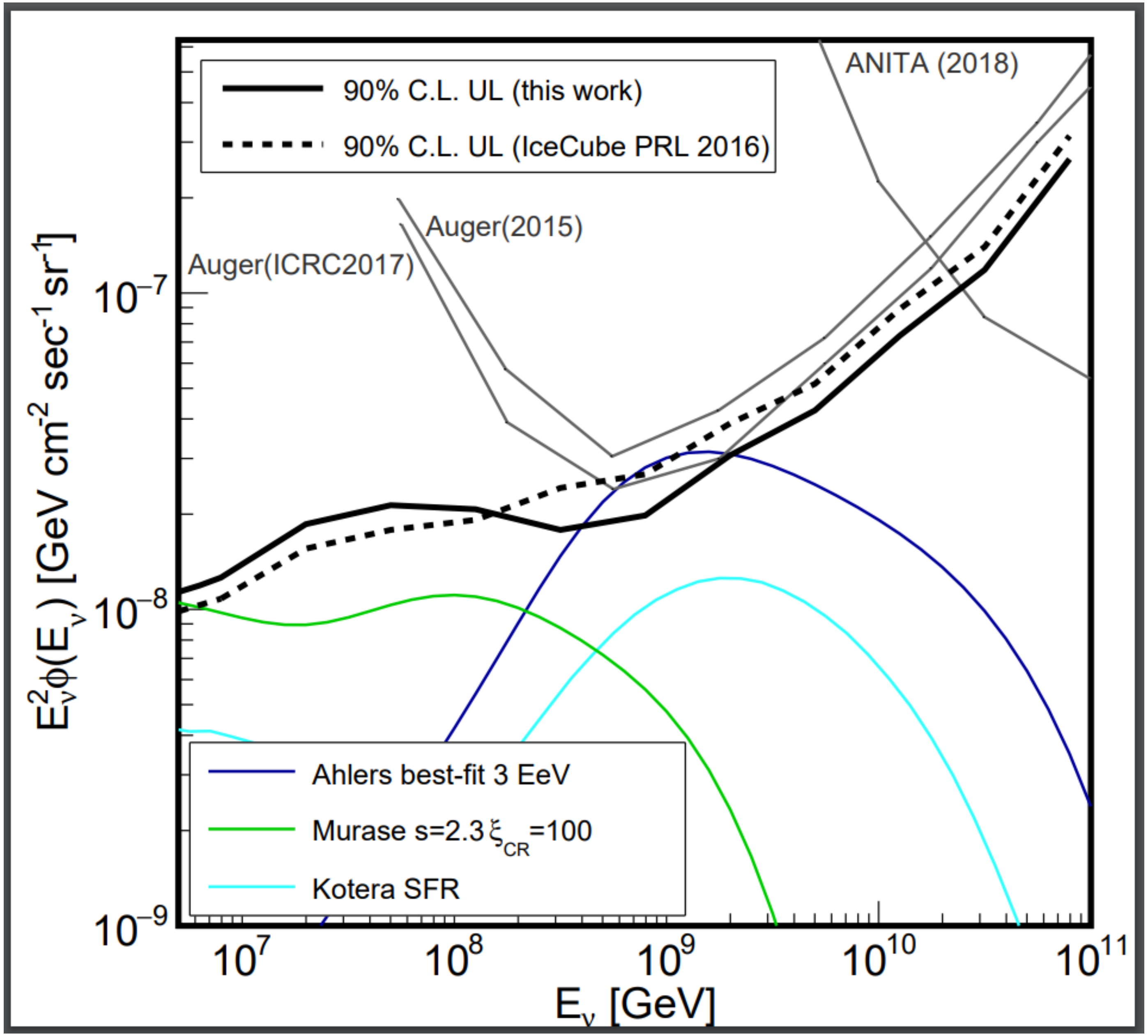
DIFFUSE NEUTRINO FLUXES FROM COSMIC RAY INTERACTIONS ON CMB



$$p + \gamma_{CMB} \rightarrow n + \pi^{+} \ and \ p + \pi^{0}$$

Cosmogenic neutrinos

9 yr limit for neutrino energy between 5×10^6 - 2×10^{10} GeV

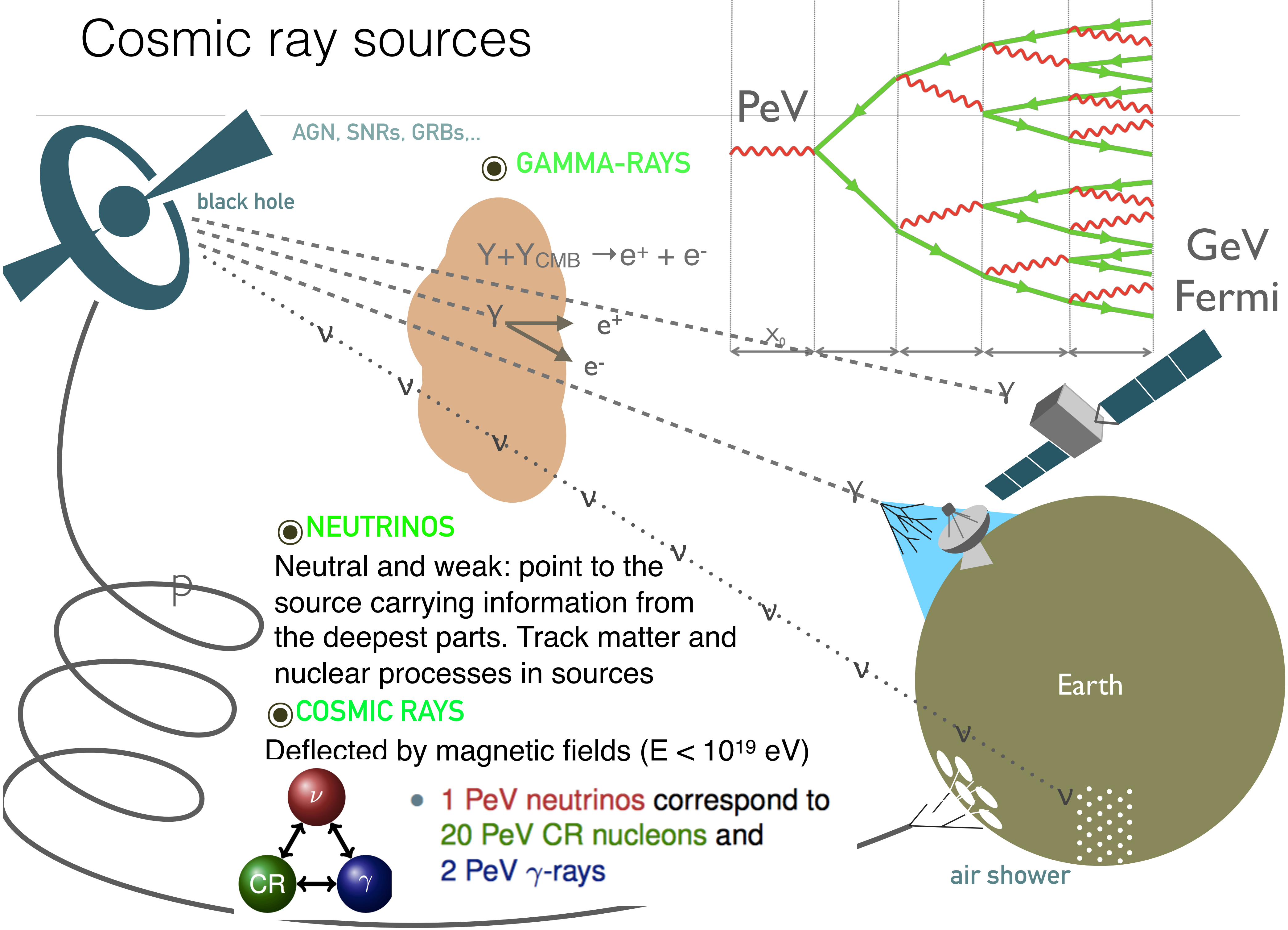


https://doi.org/10.1103/PhysRevD.98.062003

Evolution function of UHECR sources parameterized as $\psi(z)=(1+z)^m$ for $z \le z_{max}$

2 observed events
4.8-6.3 expected for star formation models $m=3.5$ and $z_{max} > 2$ disfavored => proton dominated UHECR sources evolve more slowly than star formation rate.
2 events are not of atmospheric origin at 0.024% (3.5σ) and not of cosmogenic origin with 2.5% probability.

Cosmic ray sources



NEUTRINOS

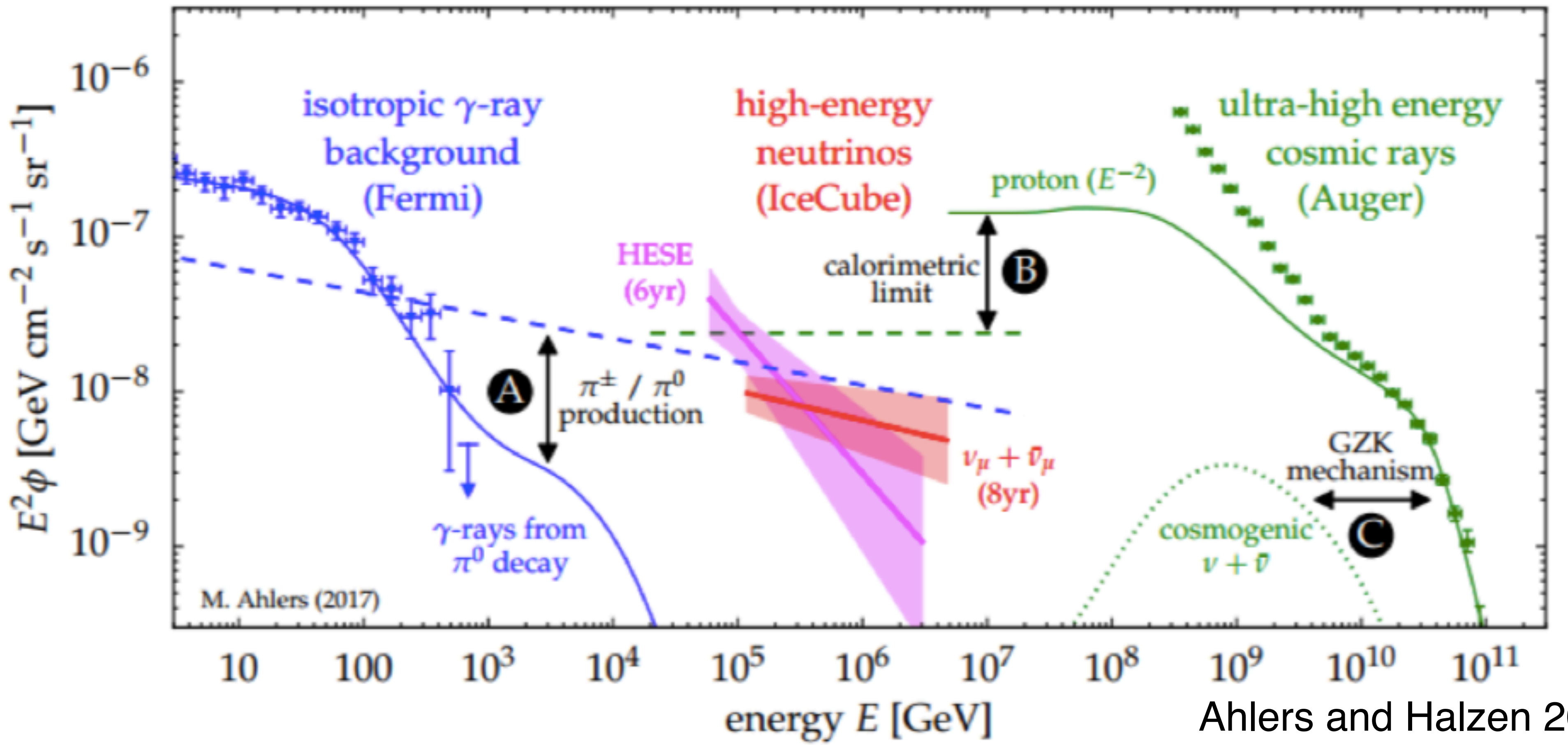
Neutral and weak: point to the source carrying information from the deepest parts. Track matter and nuclear processes in sources

COSMIC RAYS

Deflected by magnetic fields ($E < 10^{19}$ eV)

- 1 PeV neutrinos correspond to 20 PeV CR nucleons and 2 PeV γ-rays

Multi-messenger diffuse fluxes



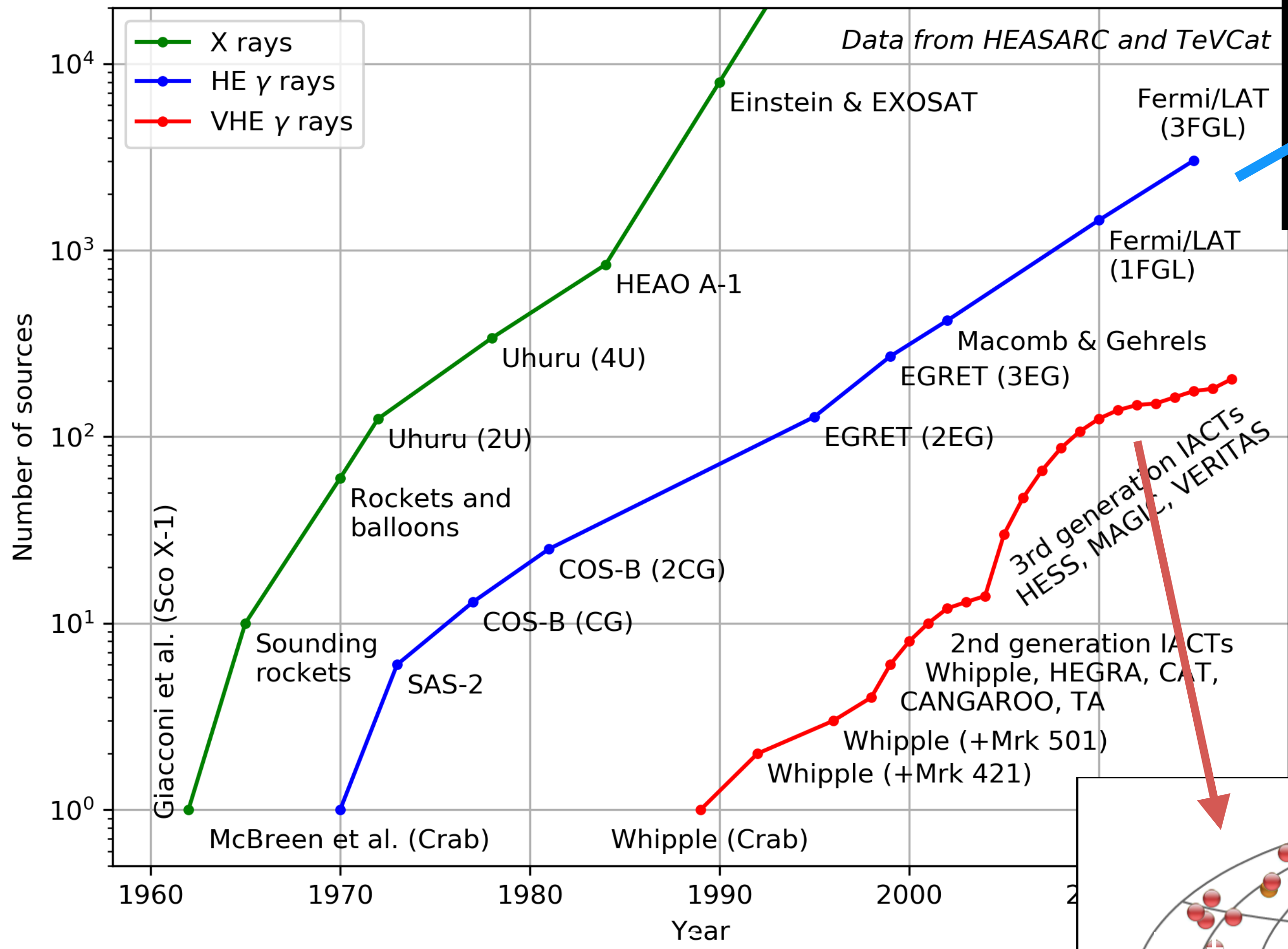
Ahlers and Halzen 2017

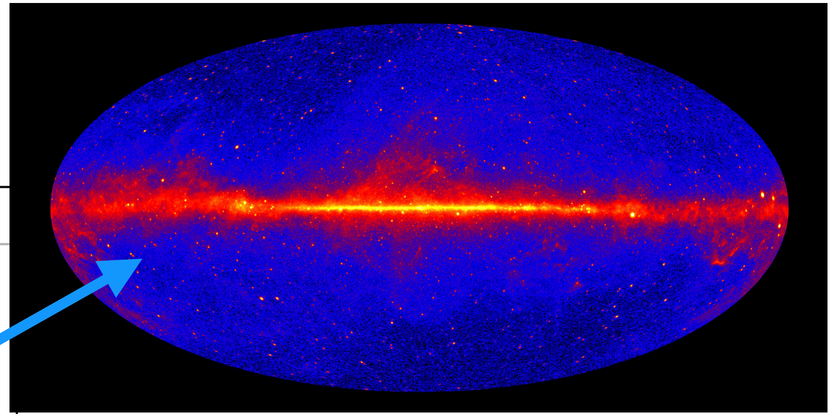
A. Diffuse flux
B. Modern version of Waxman & Bahcall, 1998 upper bound
C. GZK mechanism

IceCube upgoing diffuse muons: Astrophys.J. 833 (2016); update ICRC 2017
HESE 7.5 yrs (Neutrino 2018)

The non-thermal universe

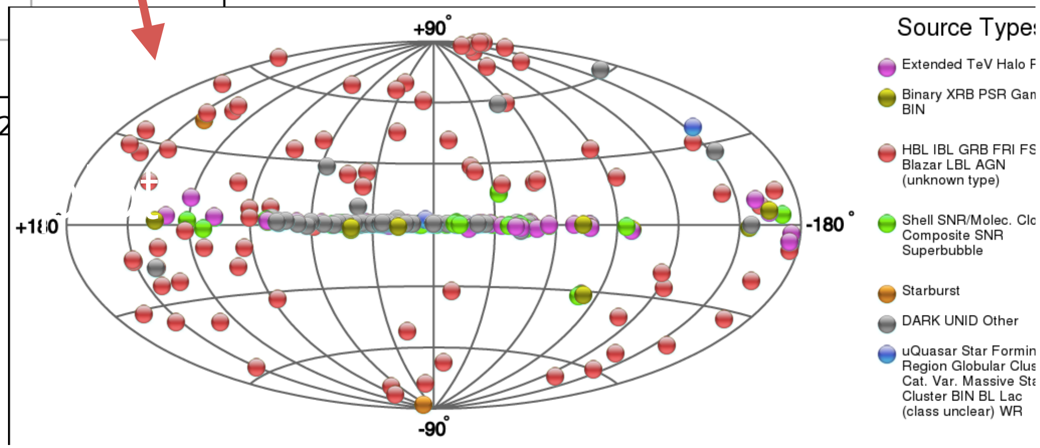
Kifune's plot https://github.com/sfegan/kifune-plot





LAT 8 yr catalogue (4FGL)
5098 sources (50 MeV-1 TeV)
58% AGN, 5% pulsars, 30% UNID
+ Fermi bubbles

https://fermi.gsfc.nasa.gov/ssc/data/access/lat/8yr_catalog/



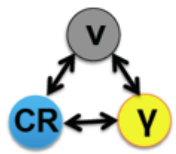
tevcat.uchicago.edu
223 sources from ground (> 300 GeV)
up to z ~1

Cosmic ray sources

- accelerators (steady or variable) of protons, nuclei, electrons and positrons to extreme energies
- The presence of neutrino is the smoking gun to trace matter in sources
- Distance sensitivity is limited not by messenger but by sensitivity of detectors (like for GWs)
- Neutrinos are connected to gamma-rays but the opacity of sources degrades the gamma-ray energy and intensity.

Hadronuclear (e.g. star burst galaxies and galaxy clusters)

$$pp \rightarrow \begin{cases} \pi^0 \rightarrow \gamma\,\gamma \\ \pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \nu_\mu \bar{\nu}_\mu \\ \pi^- \rightarrow \mu^- \bar{\nu}_\mu \rightarrow e^- \bar{\nu}_e \bar{\nu}_\mu \nu_\mu \end{cases}$$

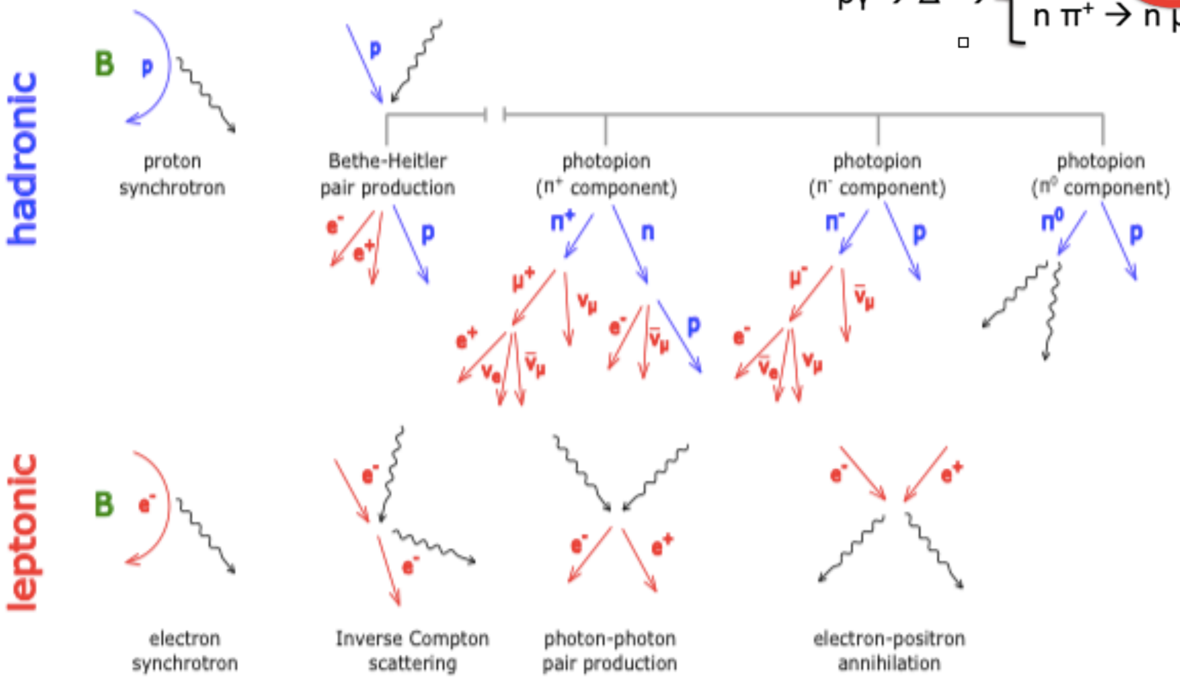


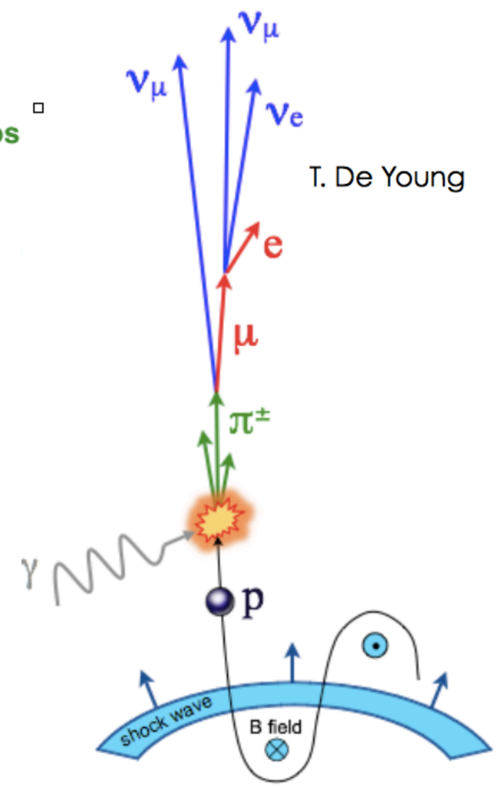
Photohadronic (e.g. gamma-ray bursts, active galactic nuclei)

$$p\gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p\,\pi^0 \rightarrow p\,\gamma\,\gamma \\ n\,\pi^+ \rightarrow n\,\mu^+ \nu_\mu \rightarrow n\,e^+ \nu_e \bar{\nu}_\mu \nu_\mu \end{cases}$$

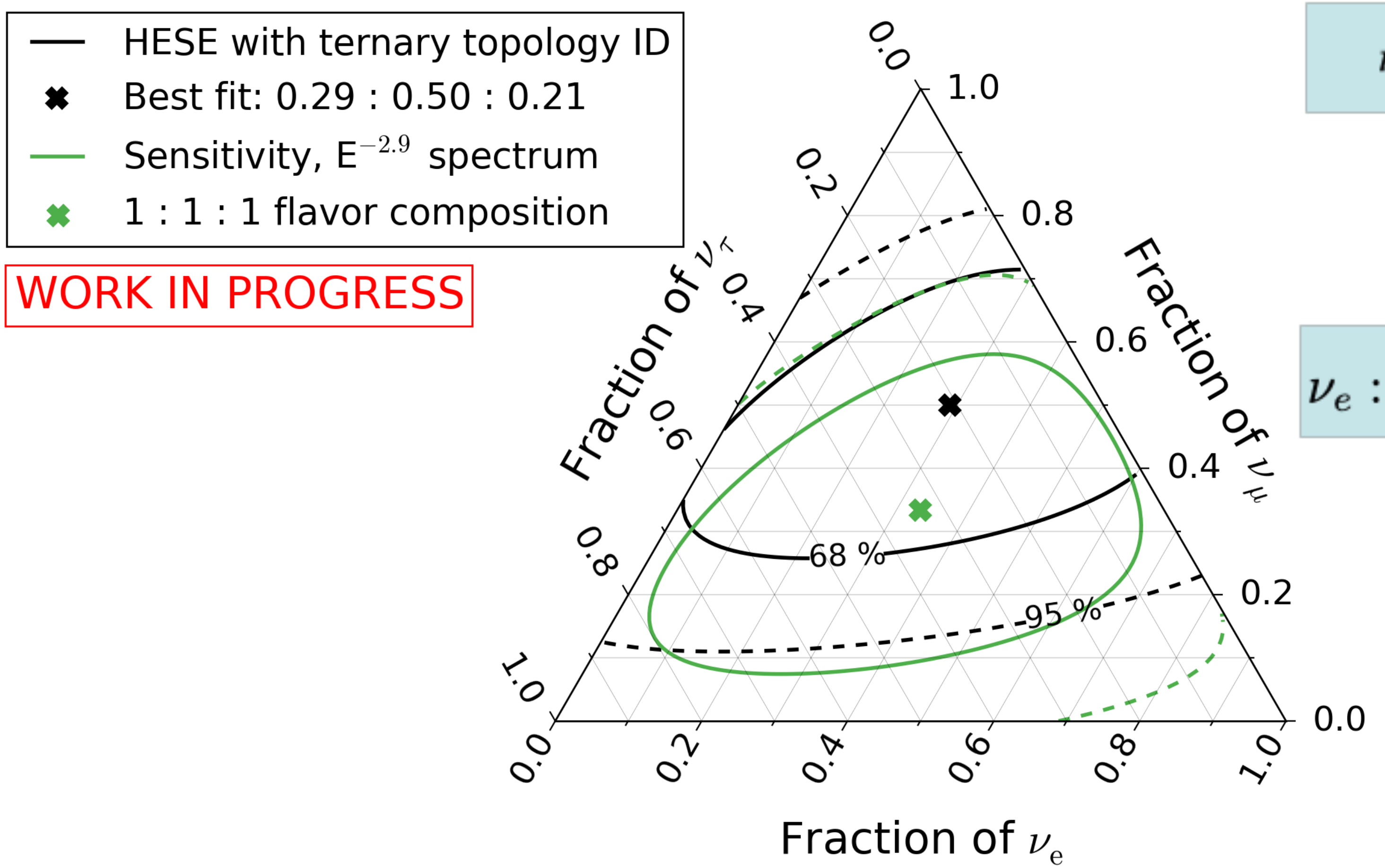
cosmic ray + gamma

cosmic ray + neutrinos





HESE all flavor



WORK IN PROGRESS

Neutrino flavour ratio at source:

pion-muon decay

$\nu_e : \nu_\mu : \nu_\tau \sim 1:2:0$

Oscillations average out over cosmic baselines

$\nu_e : \nu_\mu : \nu_\tau \sim 1:1:1$

Previous result in ApJ 809 (2015)

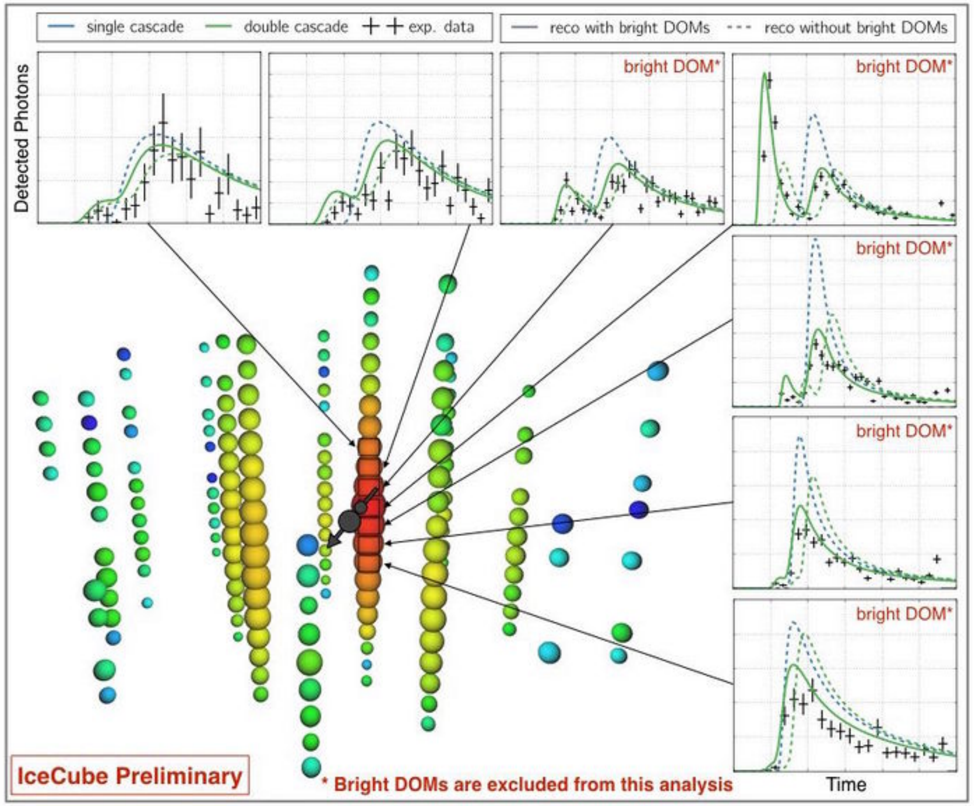
$$P(\nu_l \rightarrow \nu_{l'}) = \sum_{i,k} U_{l'i} U^*_{l'k} U^*_{li} U_{lk} e^{-i\frac{\Delta m^2_{ji}}{2E}L}$$

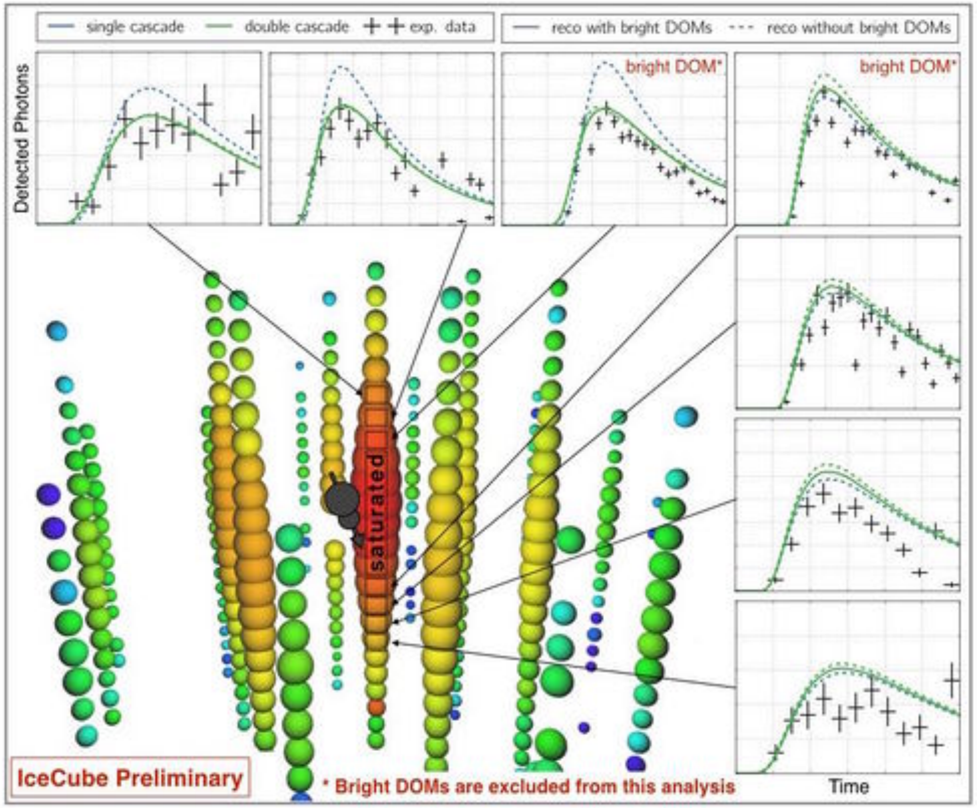
$$= \sum_i |U_{l'i}|^2 |U_{li}|^2 + 2\mathrm{Re} \sum_{i>k} (U_{l'i} U^*_{l'k} U^*_{li} U_{lk} e^{-i\frac{\Delta m^2_{ji}}{2E}L})$$

Oscillations average out

$$\varphi \sim 3 \cdot 10^8 \left(\frac{\Delta m^2}{8 \cdot 10^{-5}\ \mathrm{eV}^2}\right)\left(\frac{D}{1\ \mathrm{kpc}}\right)\left(\frac{10\ \mathrm{TeV}}{E_\nu}\right)$$

Probable cosmic tau neutrinos

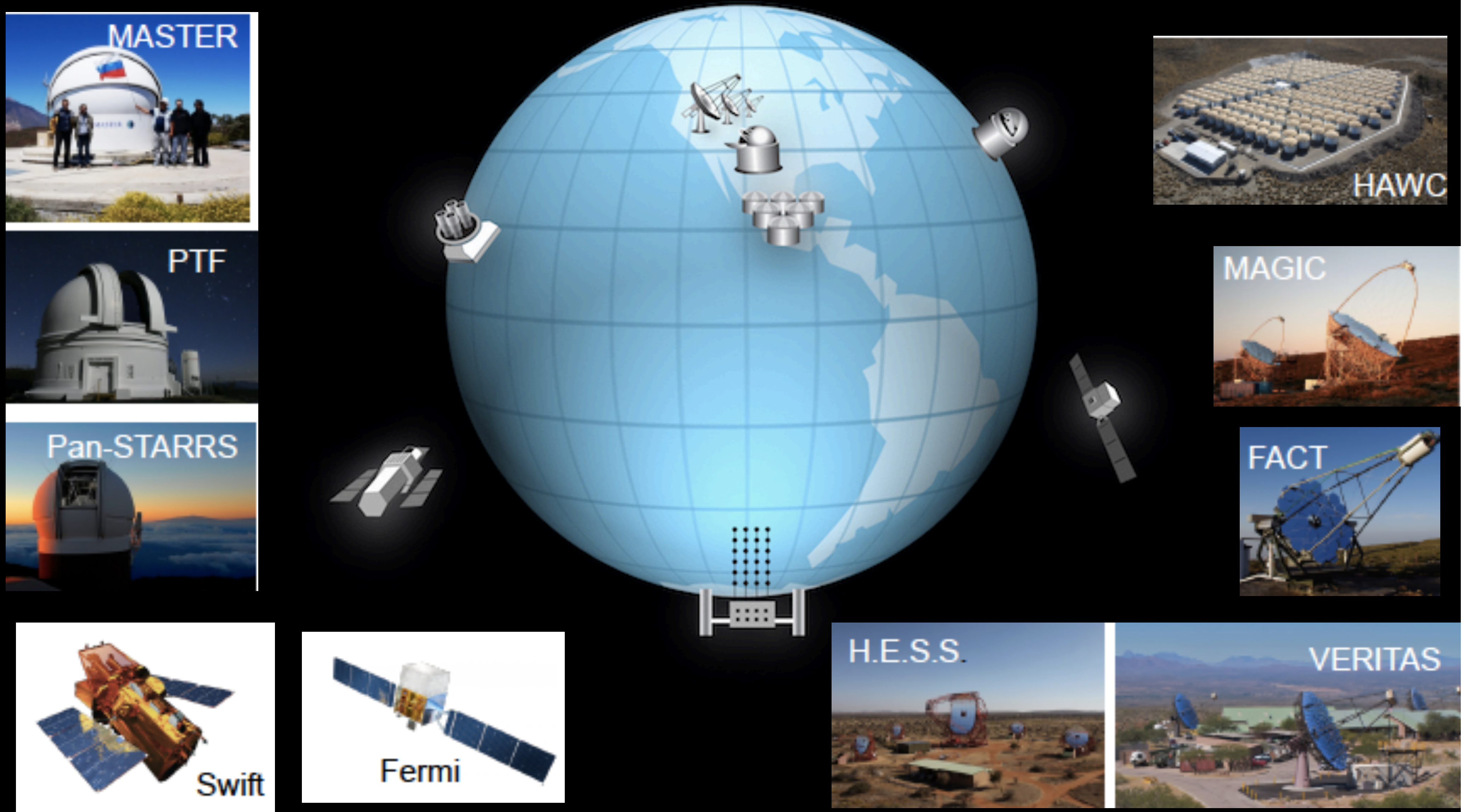




The multi-messenger network

IceCube Alert system 6-8 / yr (>50% signalness, median latency 30 s) Astrop. Phys 92 (2017) 30
Follow ups: A&A 607 (2017) A115
Real time GW searches
ApJ 850 (2017) L35, Astrophys.J. 870 (2019) no.2, 134

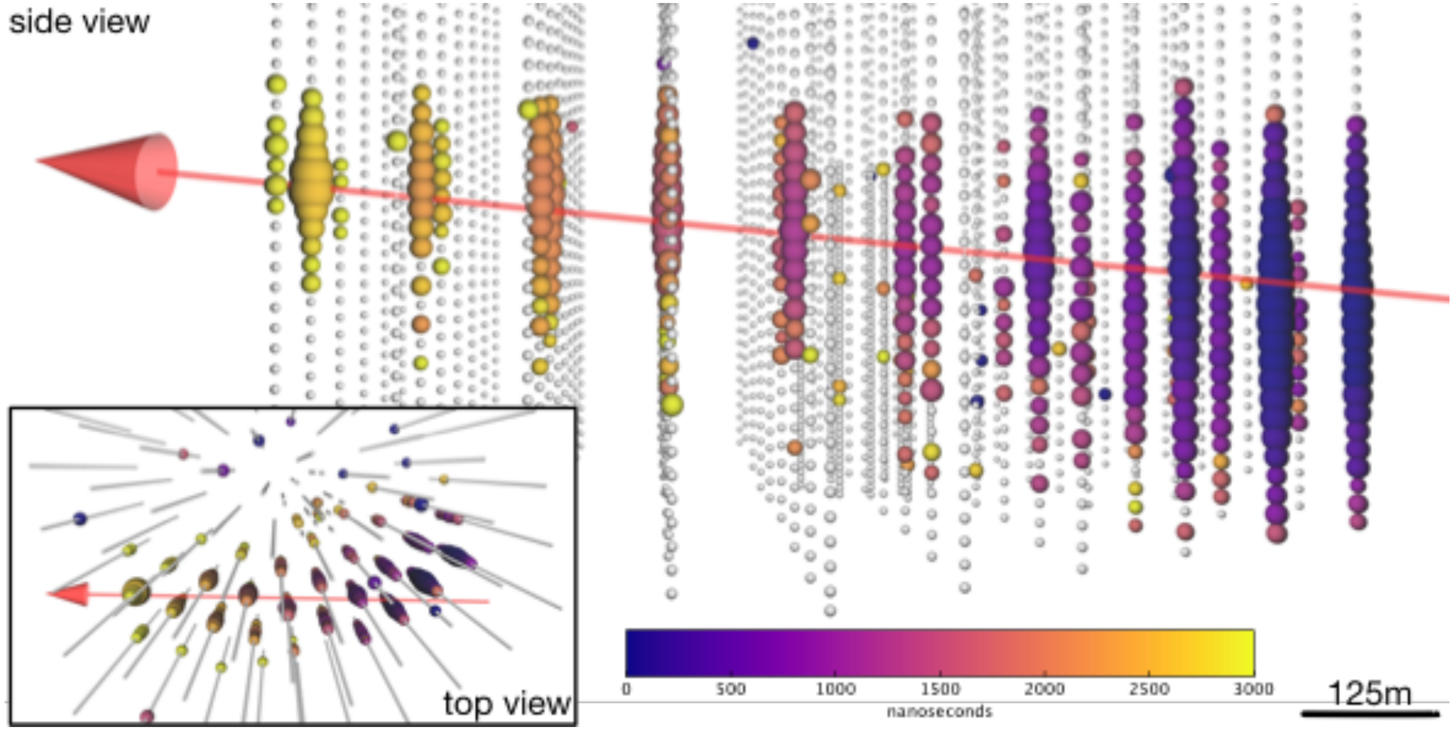
ANTARES Alert system: median latncy 5 s
~0.04 ν doublets, ~4 events/yr > 30 TeV
JCAP 02 (2016) 062
(FRBs) MNRAS 475, 1427 (2018)
(GRBs) MNRAS 469, 906 (2017)



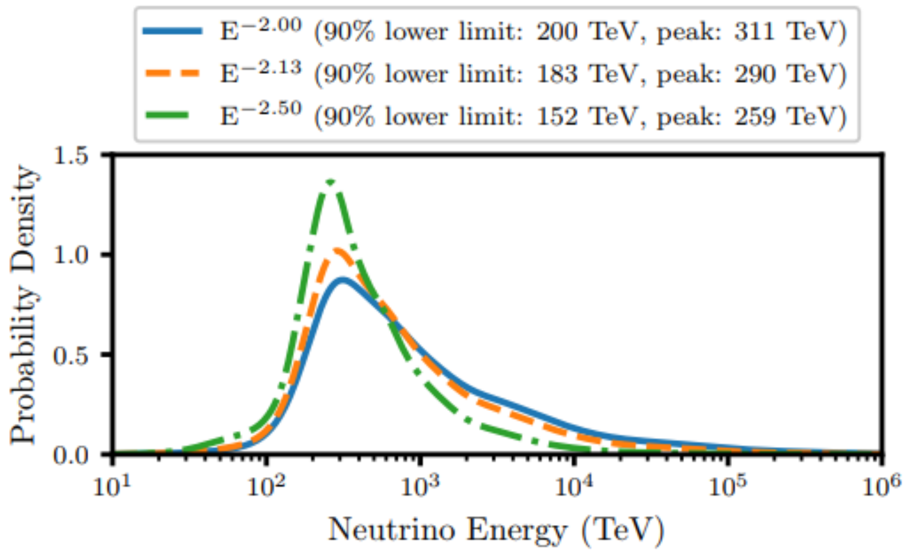
IceCube alert IC170922A

Signalness: 56.5%

23.7±2.8 TeV muon energy loss in the detector, 15 arcmin error (50% containment)
Alert sent after 43 s



Most probable neutrino energy ~290 TeV. Upper limit at 90% CL is 4.5 PeV (7.5) PeV) for a spectral index of -2.13 (-2).

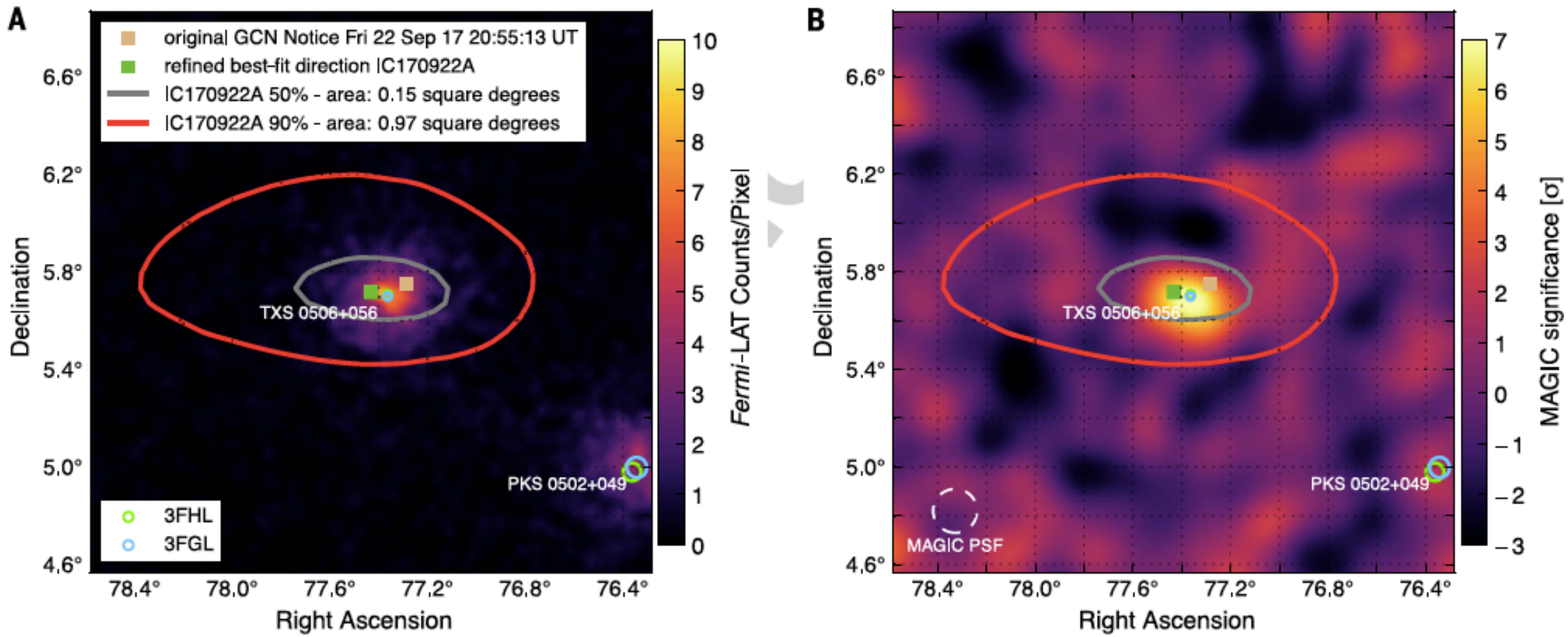


IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018

https://gcn.gsfc.nasa.gov/notices_amon/50579430_130033.amon

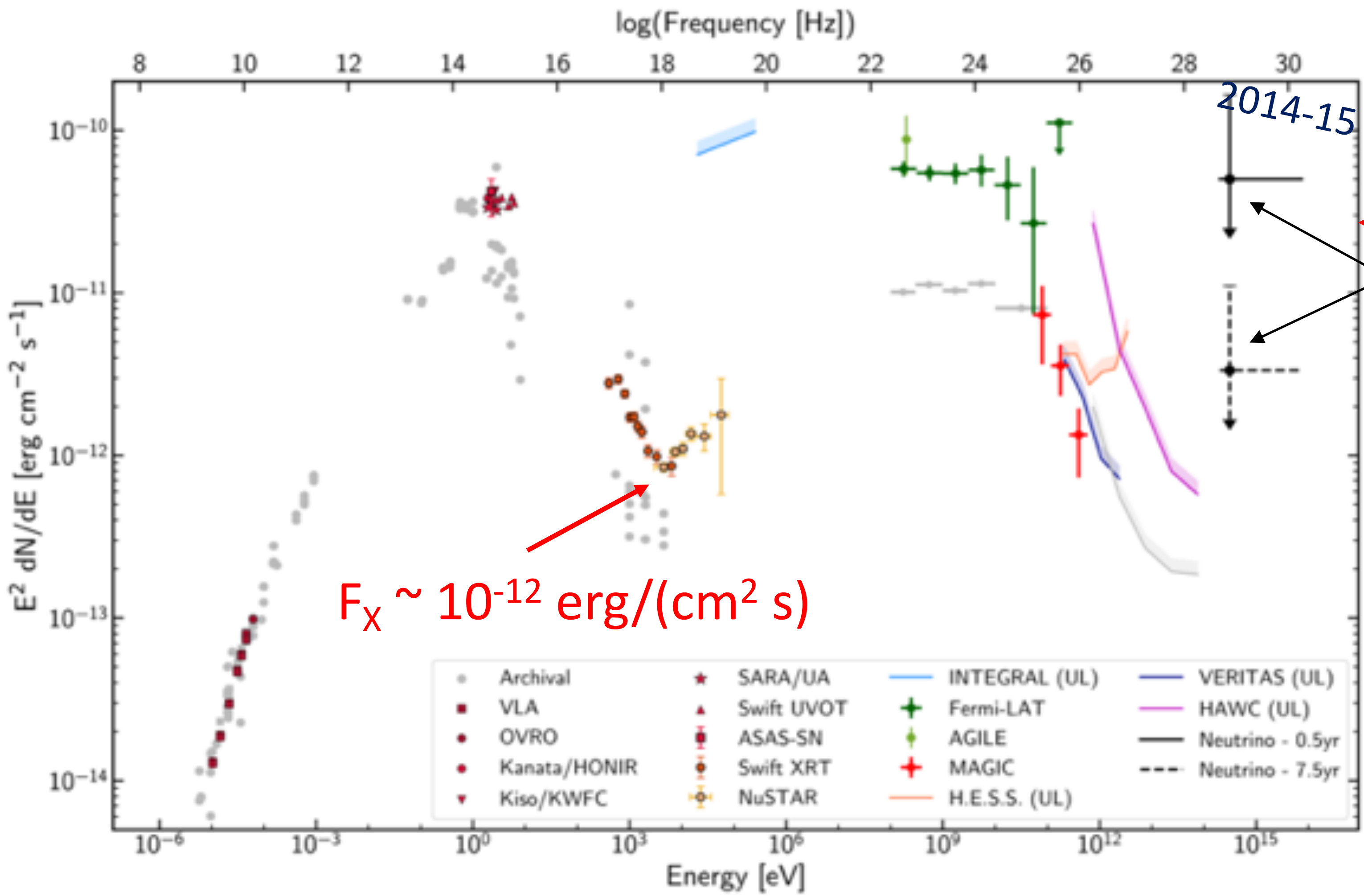
The gamma-ray partner observations

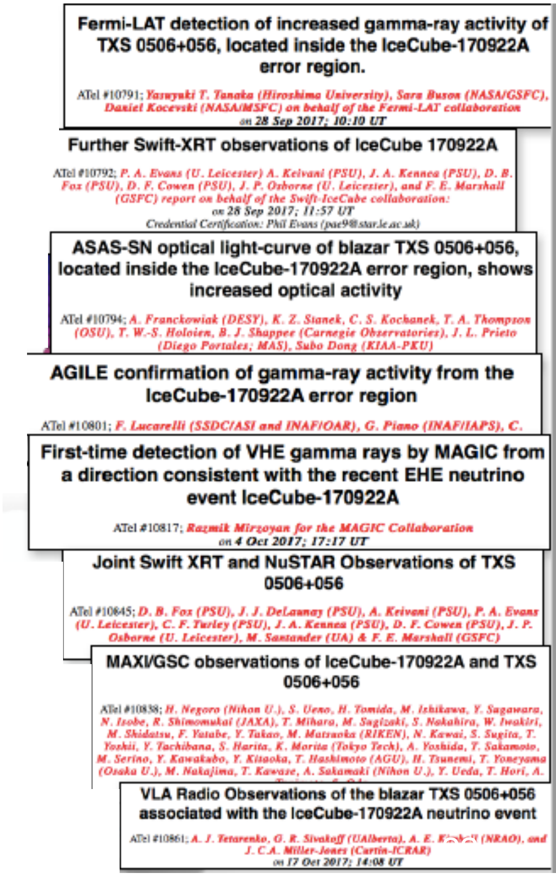
Science 361, 147-151 (2018) [DOI:10.1126/science.aat2890](https://doi.org/10.1126/science.aat2890)



Shortly after, Fermi-LAT (20 MeV-300 GeV) detected the TXS 0506+056 blazar in a high state at 0.06° from IceCube event (ATel#10791). MAGIC followed up and the blazar was observed at > 100 GeV energies with >6.2σ (ATel#10817, Ahnen, M. L., et al., ApJL 2018), later confirmed by VERITAS (Abeysekara et al, ApJL, 2018). **The probability that this coincidence happens by chance is excluded at 3σ level.**

Spectral energy distribution of TXS 0506+056





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 2017; 10:10 UT

Further Swift-XRT observations of IceCube 170922A

ATel #10792; *P. A. Evans (U. Leicester) A. Keivani (PSU), J. A. Kennea (PSU), D. B. Fox (PSU), D. F. Cowen (PSU), J. P. Osborne (U. Leicester), and F. E. Marshall (GSFC) report on behalf of the Swift-IceCube collaboration:*
on 28 Sep 2017; 11:57 UT
Credential Certification: Phil Evans (pae9@star.le.ac.uk)

ASAS-SN optical light-curve of blazar TXS 0506+056, located inside the IceCube-170922A error region, shows increased optical activity

ATel #10794; *A. Franckowiak (DESY), K. Z. Stanek, C. S. Kochanek, T. A. Thompson (OSU), T. W.-S. Holoien, B. J. Shappee (Carnegie Observatories), J. L. Prieto (Diego Portales; MAS), Subo Dong (KIAA-PKU)*

AGILE confirmation of gamma-ray activity from the IceCube-170922A error region

ATel #10801; *F. Lucarelli (SSDC/ASI and INAF/OAR), G. Piano (INAF/IAPS), C.*

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

Joint Swift XRT and NuSTAR Observations of TXS 0506+056

ATel #10845; *D. B. Fox (PSU), J. J. DeLaunay (PSU), A. Keivani (PSU), P. A. Evans (U. Leicester), C. F. Turley (PSU), J. A. Kennea (PSU), D. F. Cowen (PSU), J. P. Osborne (U. Leicester), M. Santander (UA) & F. E. Marshall (GSFC)*

MAXI/GSC observations of IceCube-170922A and TXS 0506+056

ATel #10838; *H. Negoro (Nihon U.), S. Ueno, H. Tomida, M. Ishikawa, Y. Sugawara, N. Isobe, R. Shimomukai (JAXA), T. Mihara, M. Sugizaki, S. Nakahira, W. Iwakiri, M. Shidatsu, F. Yatabe, Y. Takao, M. Matsuoka (RIKEN), N. Kawai, S. Sugita, T. Yoshii, Y. Tachibana, S. Harita, K. Morita (Tokyo Tech), A. Yoshida, T. Sakamoto, M. Serino, Y. Kawakubo, Y. Kitaoka, T. Hashimoto (AGU), H. Tsunemi, T. Yoneyama (Osaka U.), M. Nakajima, T. Kawase, A. Sakamaki (Nihon U.), Y. Ueda, T. Hori, A.*

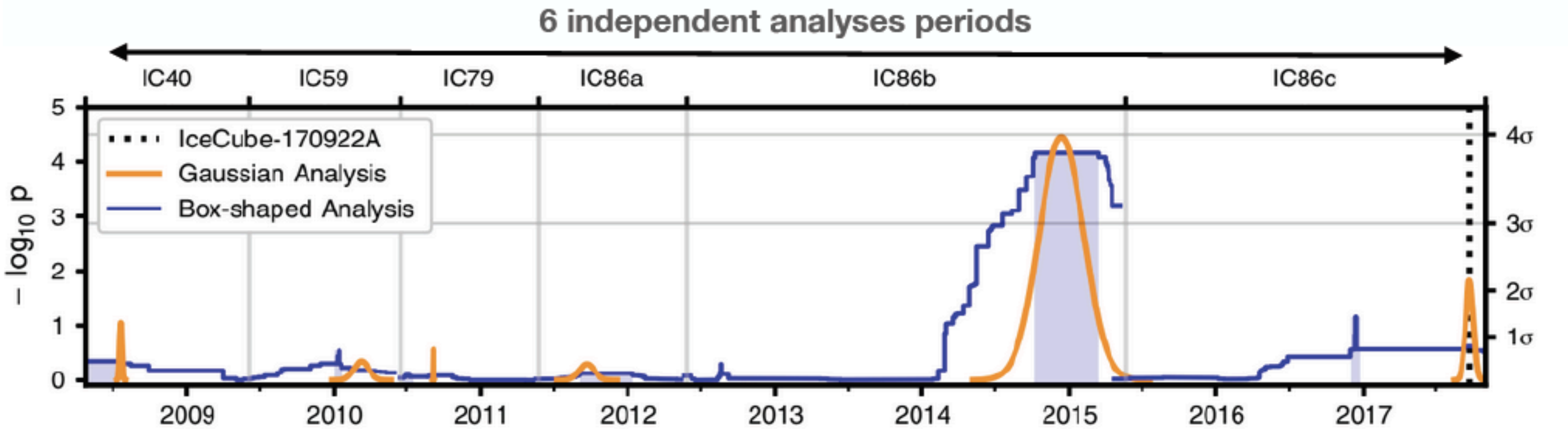
VLA Radio Observations of the blazar TXS 0506+056 associated with the IceCube-170922A neutrino event

ATel #10861; *A. J. Tetarenko, G. R. Sivakoff (UAlberta), A. E. K. (NRAO), and J. C. A. Miller-Jones (Curtin-ICRAR)*
on 17 Oct 2017; 14:08 UT

Use observed neutrino luminosity and limits on observed UV/X-ray flux of $F_X \sim 10^{-12}$ erg cm^{-2} s^{-1} for TXS 0506+056 to constrain the target photon luminosity

IceCube archival data results

Analysis of 9.5 yr in 6 independent periods. An excess of 13 muon neutrino events in a period of ~5 months (2014-2015) in sample of 3yr is inconsistent with atmospheric neutrino origin at 3.5σ CL correcting for lifetime of IC86b: 9.5/3.



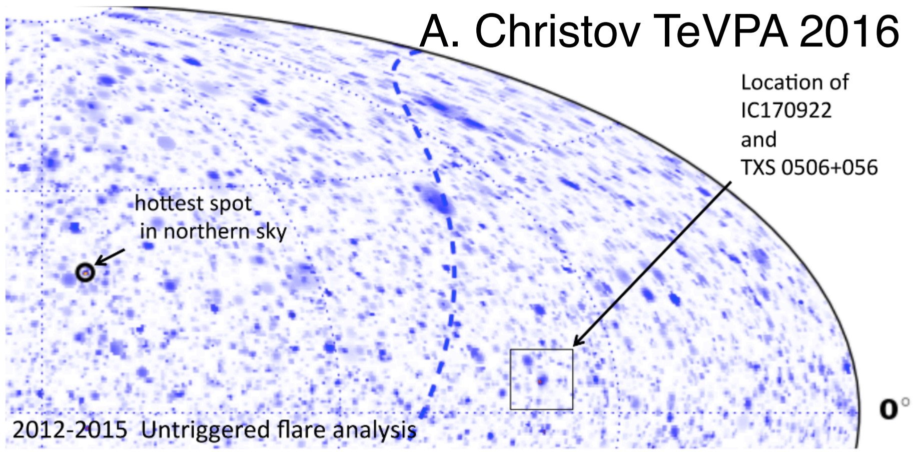
Best fit parameters of two flares:

2012-2015 period	Gaussian PDF	Box PDF
ns	13	14
γ	2.1	2.2
Width	110 days	158 days
Time	2014-12-26 2015-03-05	2014-12-13
Significance	3×10^{-5}	7×10^{-5}

Science 361, eaat1378 (2018). DOI:10.1126/science.aat1378

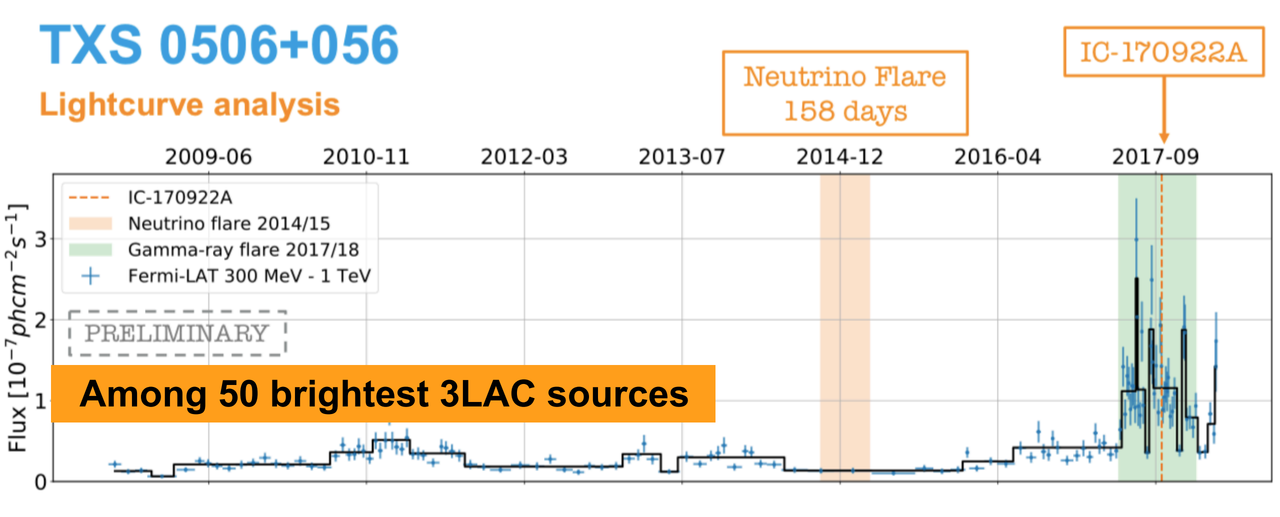
ns	1.4 +2.5/- 1.0
γ	1.7 +/- 0.6
Width	19 days
Time	2017-09-22

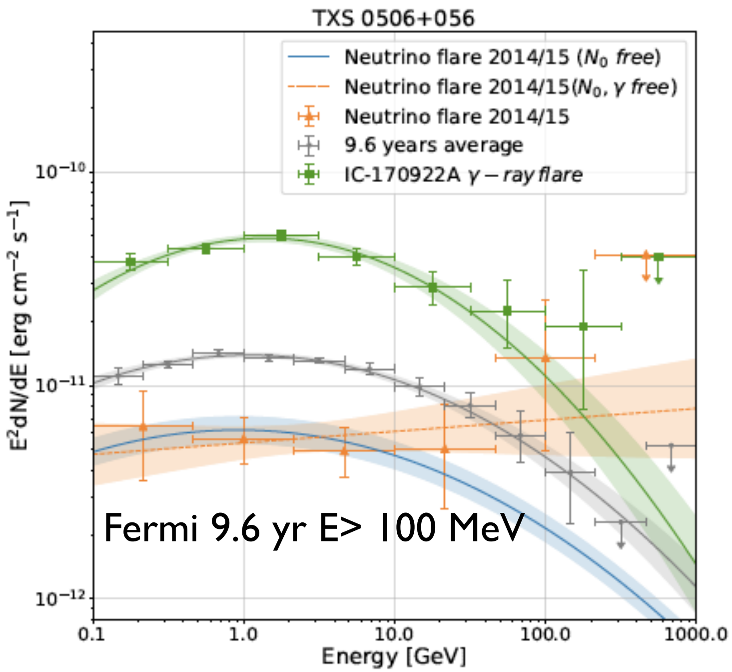
A. Christov TeVPA 2016



Neutrino - gamma correlation

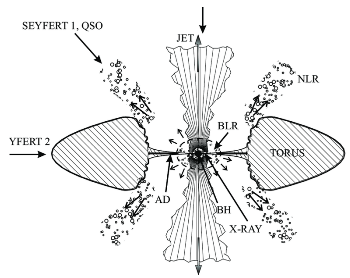
Fermi 300 MeV - 1 TeV



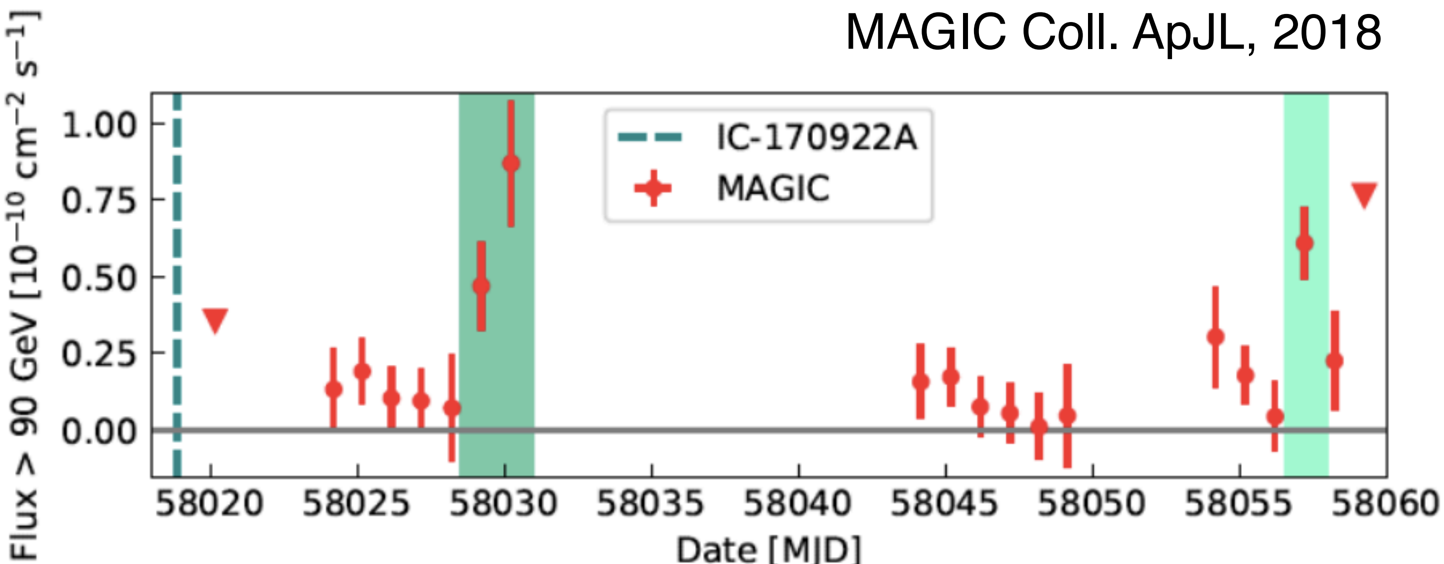


During 2014/15 neutrino flare no significant gamma-ray flaring activity or spectral change have been observed. A gamma-ray flare is not expected when the source is a highly efficient neutrino emitter. The absorption and interactions intrinsic to the source, followed by the interaction with the EBL, may result in a gamma-ray flux consistent with the Fermi observations.

Garrappa et al, TeVPA18
IceCube arXiv:1901.10806



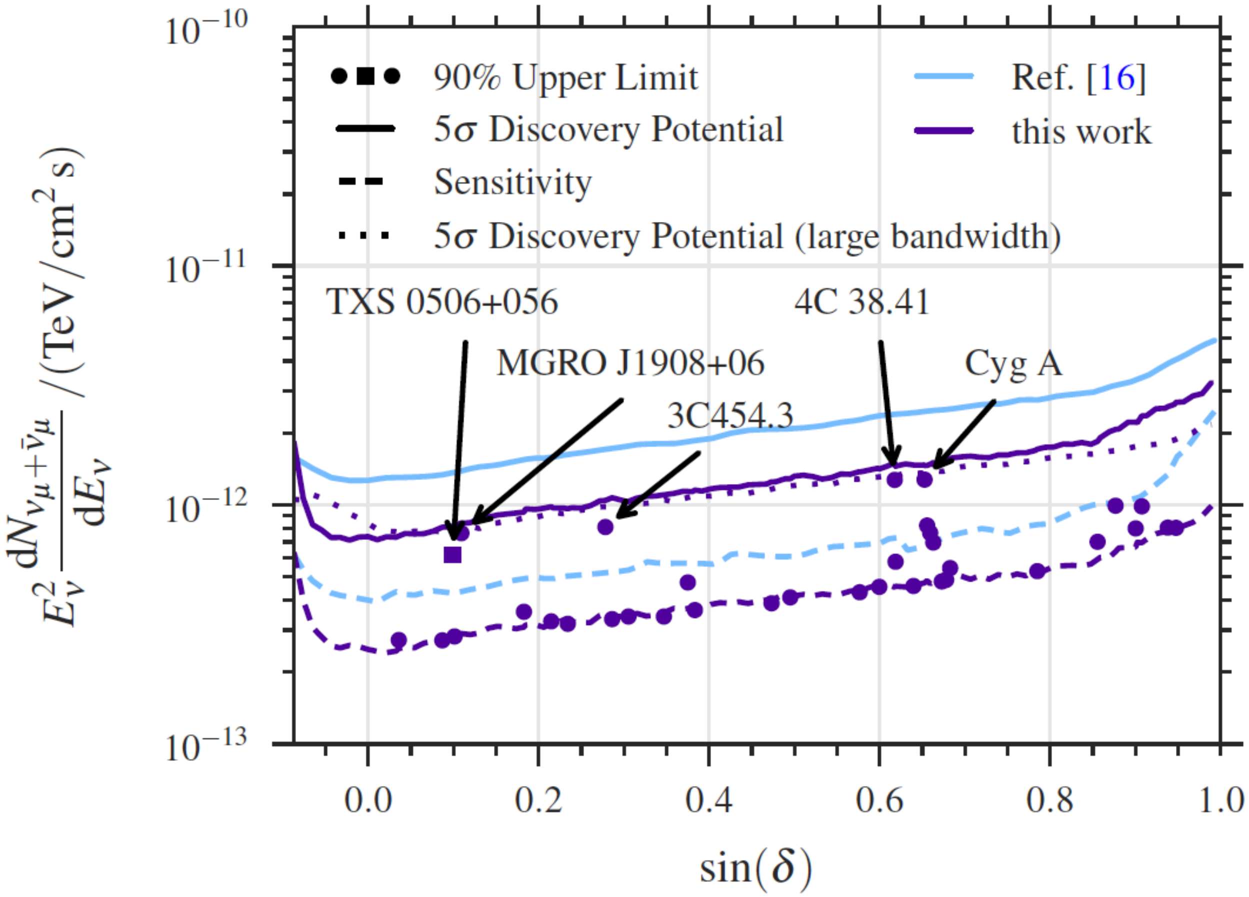
MAGIC Coll. ApJL, 2018



41 hrs 24/9-2/11
Energy spectrum up to 400 GeV with spectral index between -3.5 ÷ -4. Two flares on Oct 3-4 & Oct 31, 2017.

Time integrated point source searches

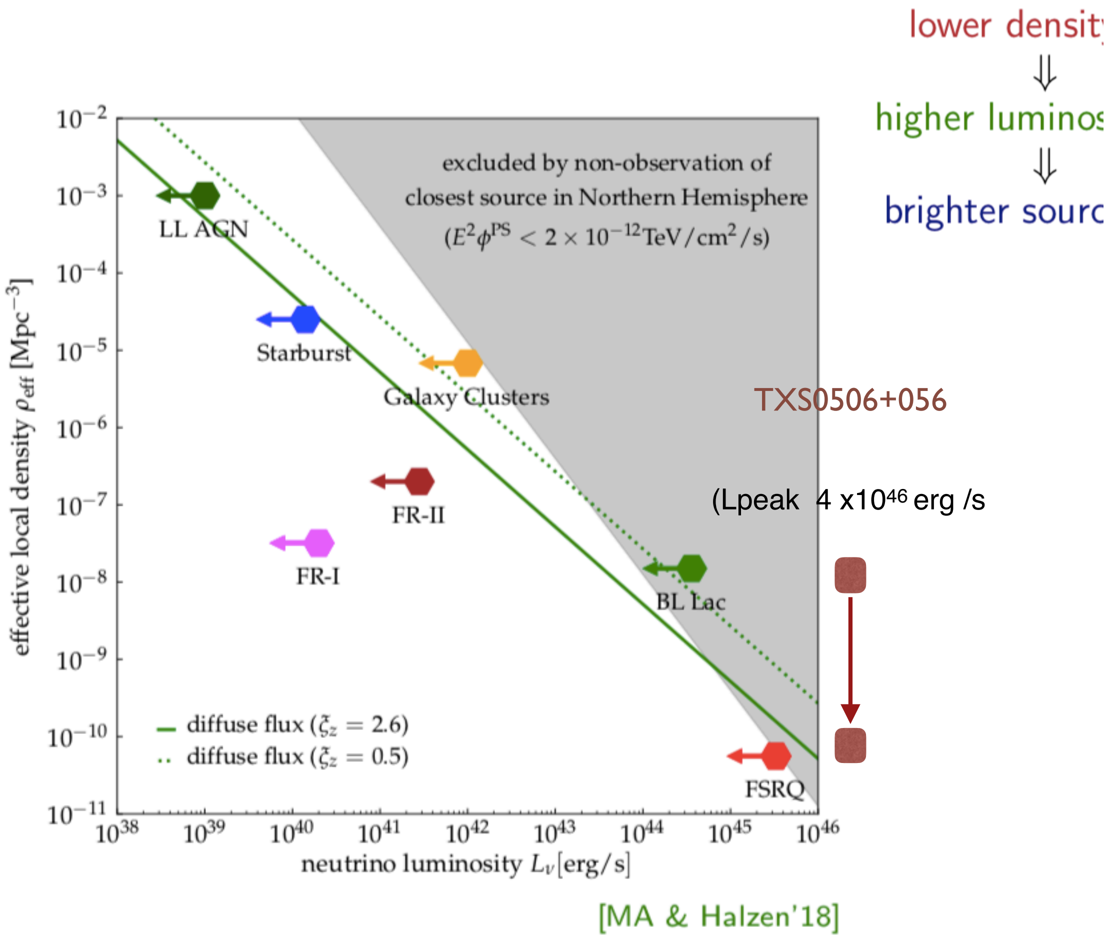
8 yr data, 497'072 upgoing muon tracks from diffuse flux analysis (95% of events have energies > 1 TeV).
Hottest spot post-trial p-value in all sky scan 30% (compatible with atmospheric background)



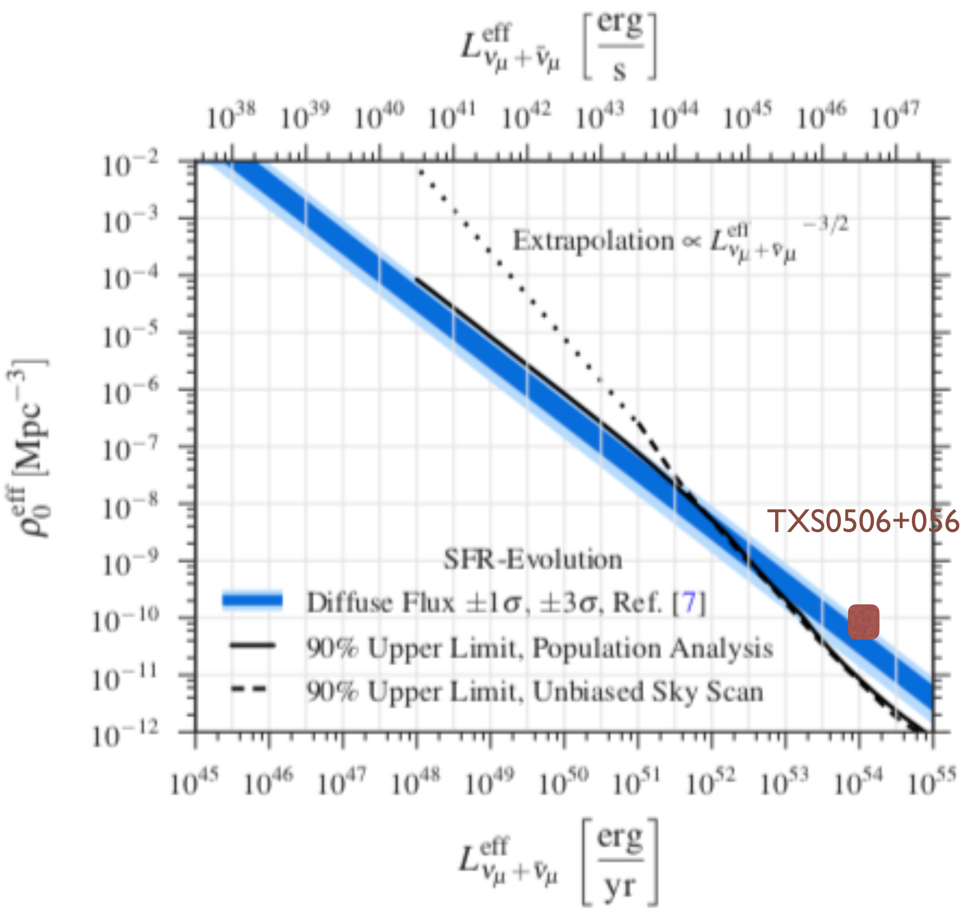
4C 38.41, MGRO J1908+06 and Cyg A, have a local p-value below or close to 1%
TXS 0506+056 has local p-value of 2.93% consistent with Science results

Implications of Point-Source limits

Diffuse flux observed by IceCube is composed of many individual sources. Their non-observation constrains source populations



K. Murase && E. Waxman, PRD 94 (2016) 103006



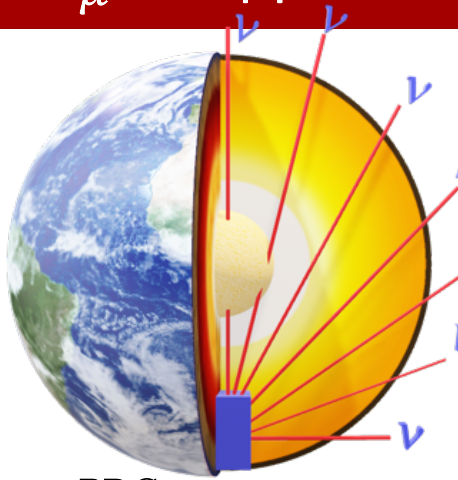
Assuming one effective luminosity for a source population and energy range of flux 10^4-10^7 GeV

IceCube, arXiv:1811.07979, subm. toEPJC

TXS 0506+056 is an outlier in the blazar sequence =>intrinsically an FSRQ. Gamma-rays > 100 GeV are not attenuated by EBL since the opacity would be smaller at z = 0.33 but by BLR
Padovani et al,arXiv:1901.06998

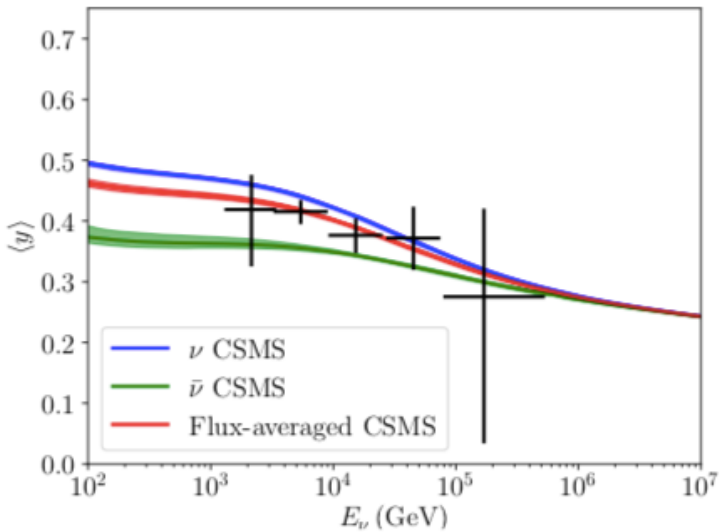
NEUTRINO CROSS SECTION

$\nu_\mu \rightarrow \nu_\mu$ disappearance probes high energy (TeV scale) neutrino cross-section

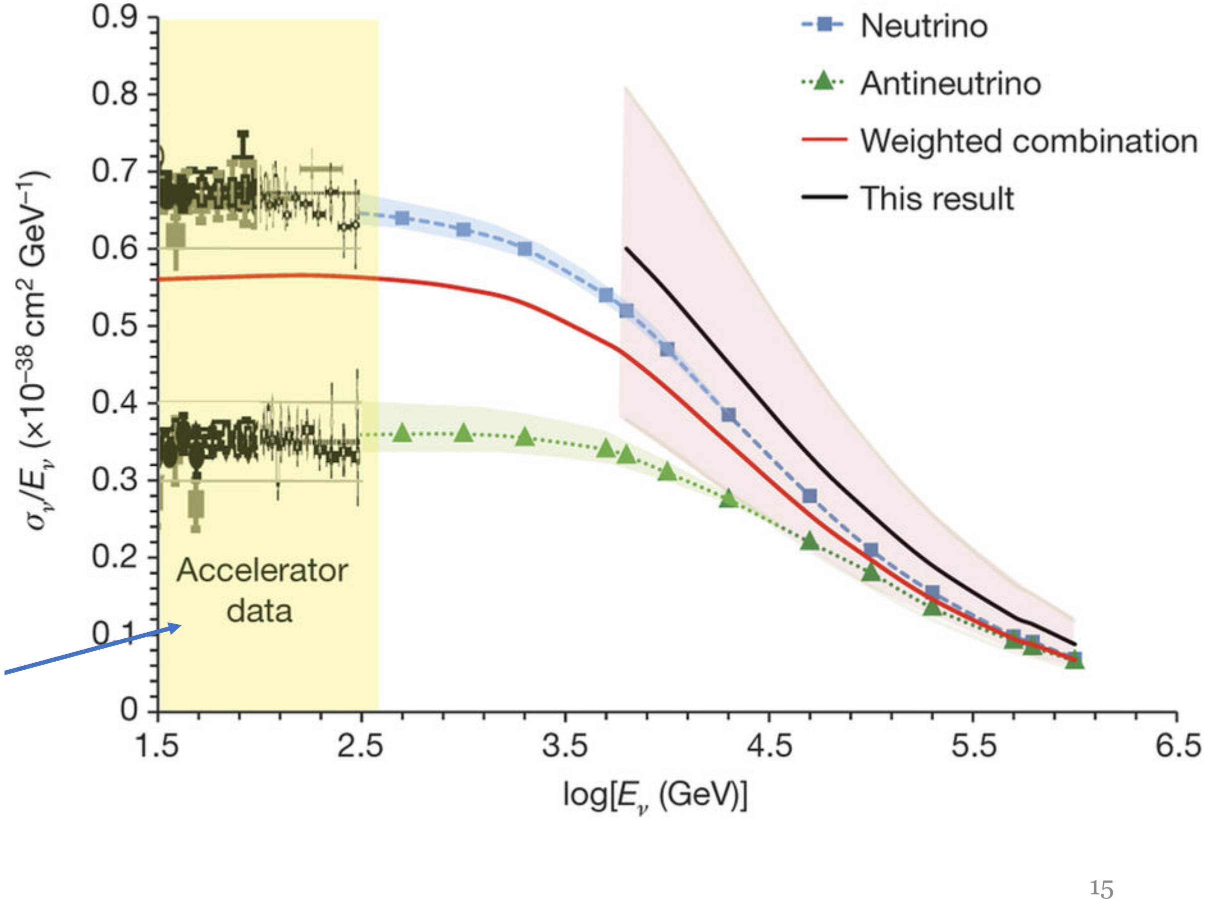


PDG

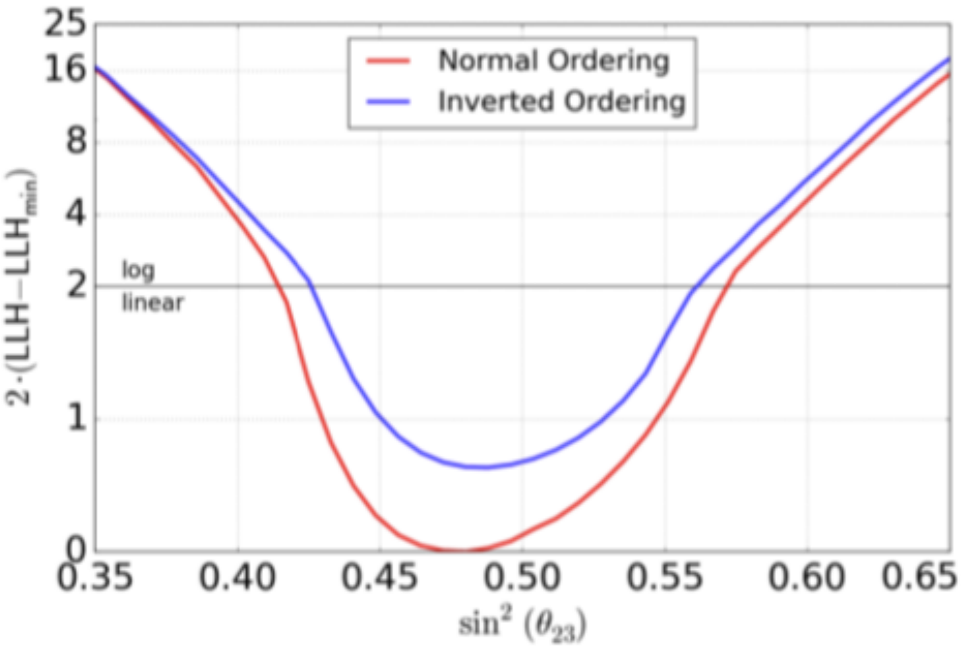
Inelasticity measurement

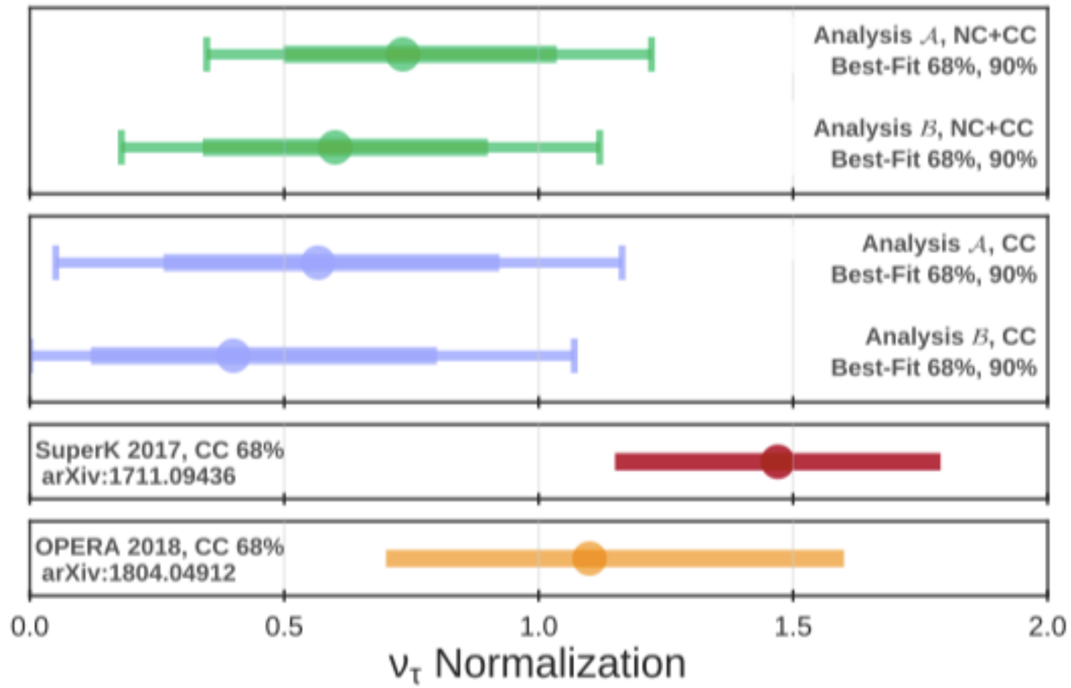


Nature ***551*** *596 (2017)*



Hierarchy and nutau appearance





Preference for NO at (CLs = 53.3%).This result is in line with recently reported preferences for the NO by Super-Kamiokande, T2K, NOvA, MINOS, and recent global best fits. arXiv:1902.07771

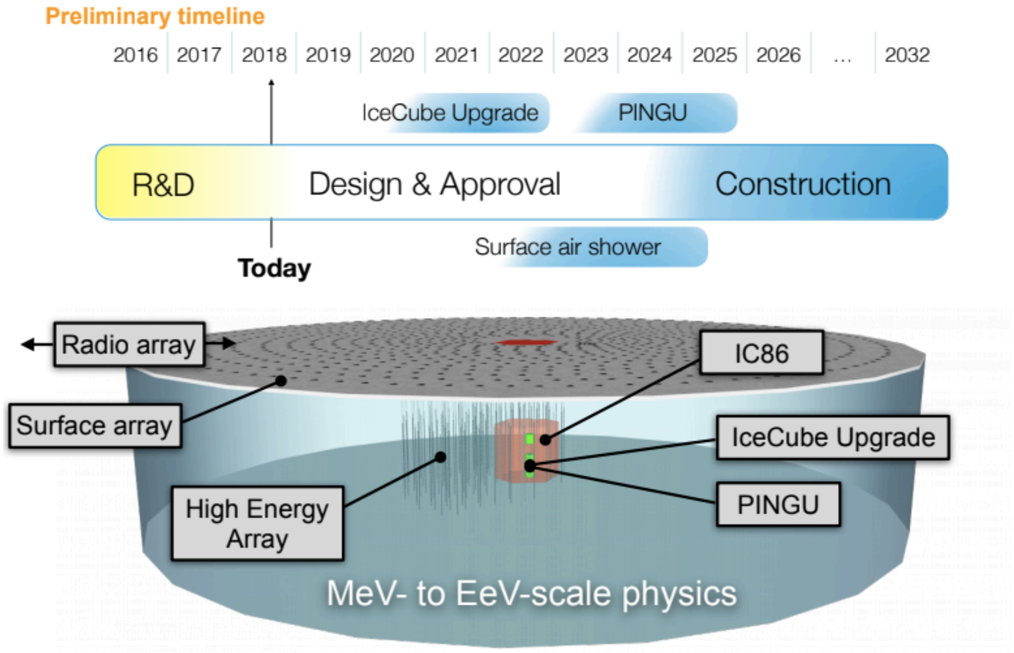
Exclude the absence of tau neutrino oscillations at a significance of > 2.0σ

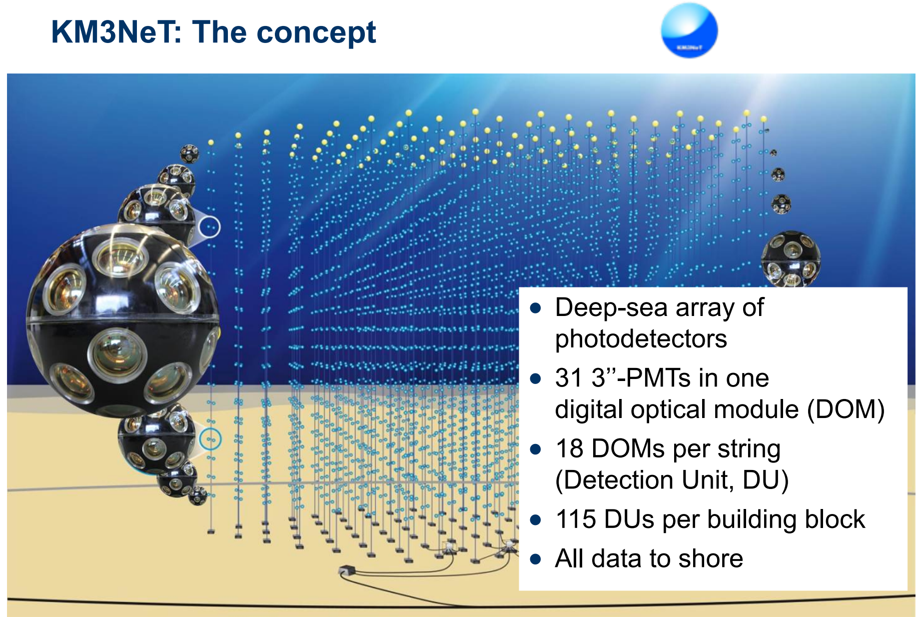
PRD99, 2019 https://arxiv.org/abs/1901.05366
https://arxiv.org/abs/1707.07081, PRL120, 071801 (2018)

The Future

PINGU LoI: https://arxiv.org/pdf/1401.2046.pdf

update: arXiv:1607.02671



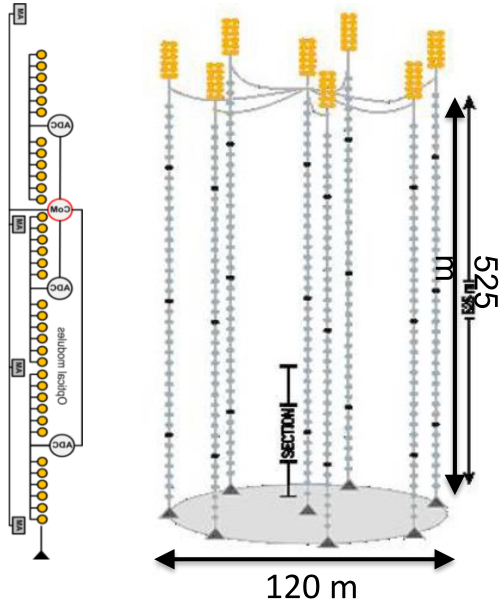


The Baikal GVD:

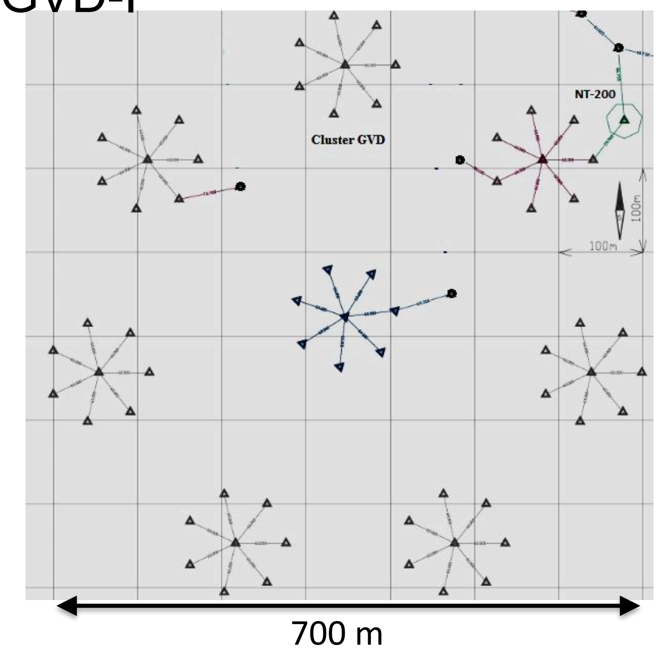
3 clusters 864 OMs currently in operation

Completion of GVD-I (9 clusters of 2592 OMs) in 2021

Final goal: 27 clusters of 8 strings, 1.5 km^3



GVD-I



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