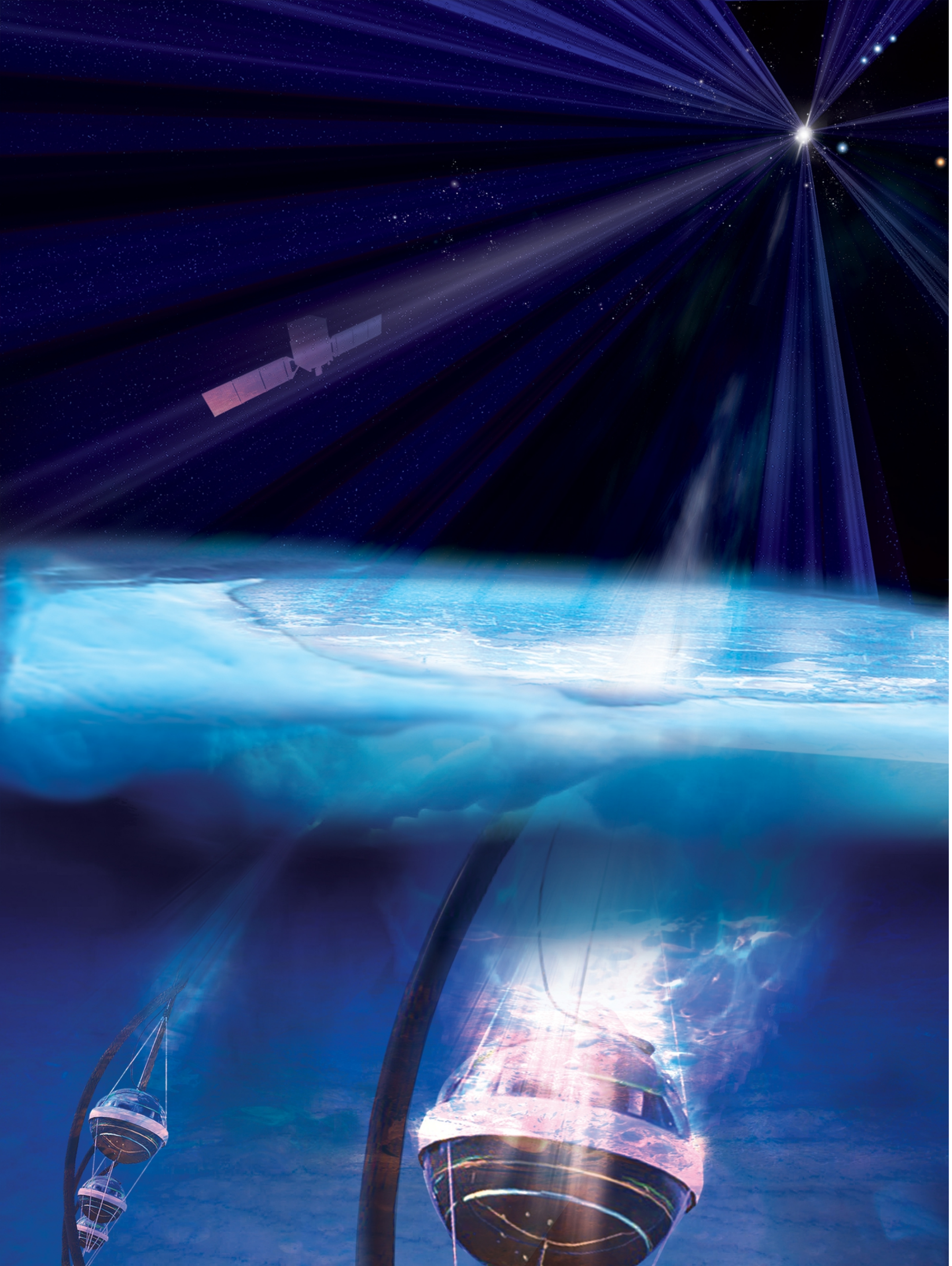


Multi-messenger Astrophysics with IceCube

- Fermi's guiding light in neutrino astrophysics -

Naoko Kurahashi Neilson
(Drexel University)

On Behalf of the IceCube Collaboration

Fermi Symposium 2018
Oct 16, 2018

First Indication of a Neutrino Source – A true multi-messenger feat!

RESEARCH

RESEARCH ARTICLES

NEUTRINO ASTROPHYSICS

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

tion of TXS 0506+056 and coincident with a state of enhanced gamma-ray activity observed since April 2017 (*23*) by the Large Area Telescope (LAT) on the Fermi Gamma-ray Space Telescope (*24*). Follow-up observations of the blazar led to the detection of gamma rays with energies up to 400 GeV by the Major Atmospheric Gamma Imaging Cherenkov (MAGIC) Telescopes (*25*, *26*). IceCube-170922A and the electromagnetic observations are described in detail in (*20*). The significance of the spatial and temporal coincidence of the high-energy neutrino and the blazar flare is estimated to be at the 3σ level (*20*). On the basis of this result, we consider the hypothesis

RESEARCH

RESEARCH ARTICLE

NEUTRINO ASTROPHYSICS

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*†

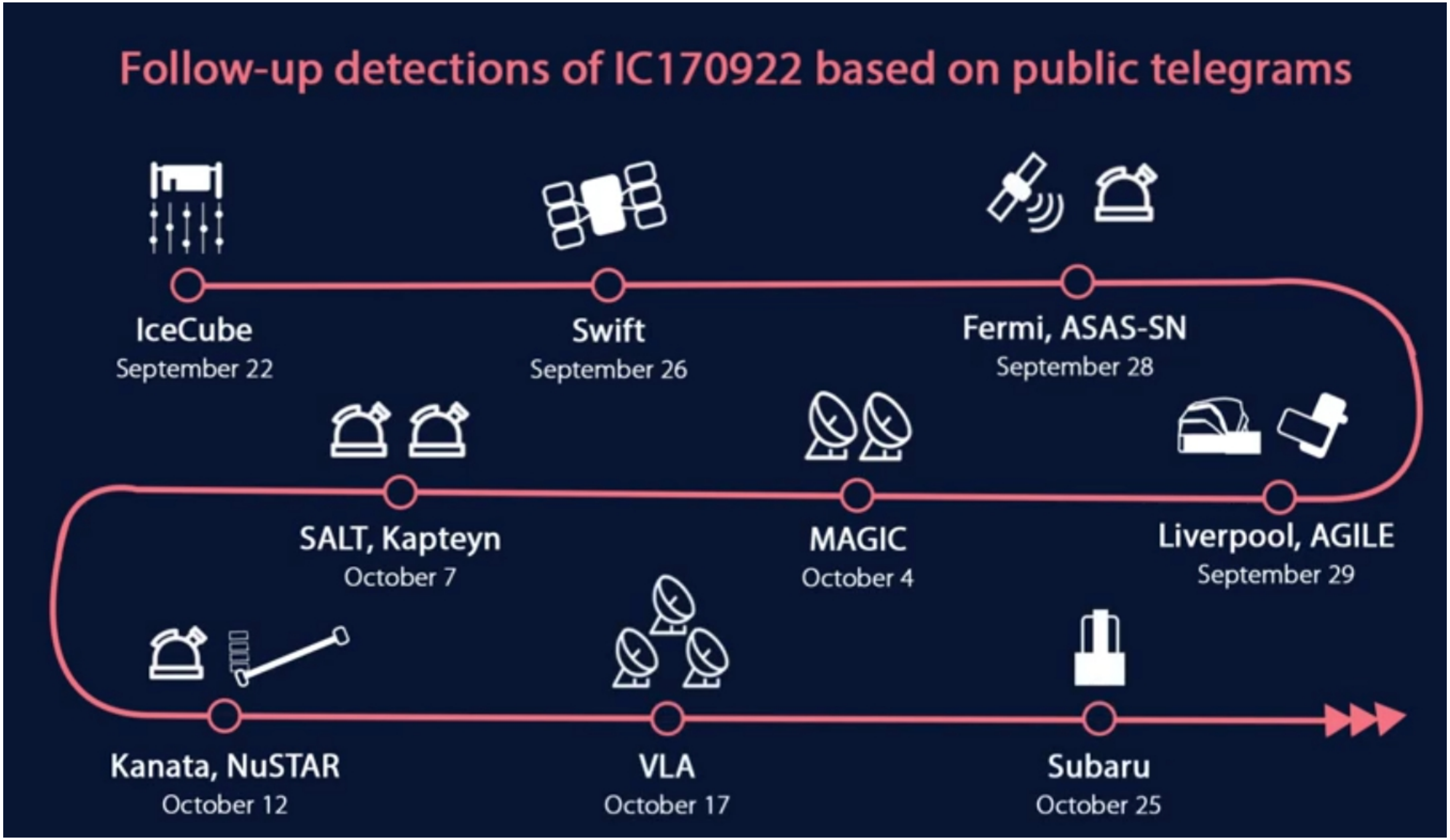
Previous detections of individual astrophysical sources of neutrinos are limited to the Sun and the supernova 1987A, whereas the origins of the diffuse flux of high-energy cosmic neutrinos remain unidentified. On 22 September 2017, we detected a high-energy neutrino, IceCube-170922A, with an energy of ~290 tera–electronvolts. Its arrival direction was consistent with the location of a known γ-ray blazar, TXS 0506+056, observed to be in a flaring state. An extensive multiwavelength campaign followed, ranging from radio frequencies to γ-rays. These observations characterize the variability and energetics of the blazar and include the detection of TXS 0506+056

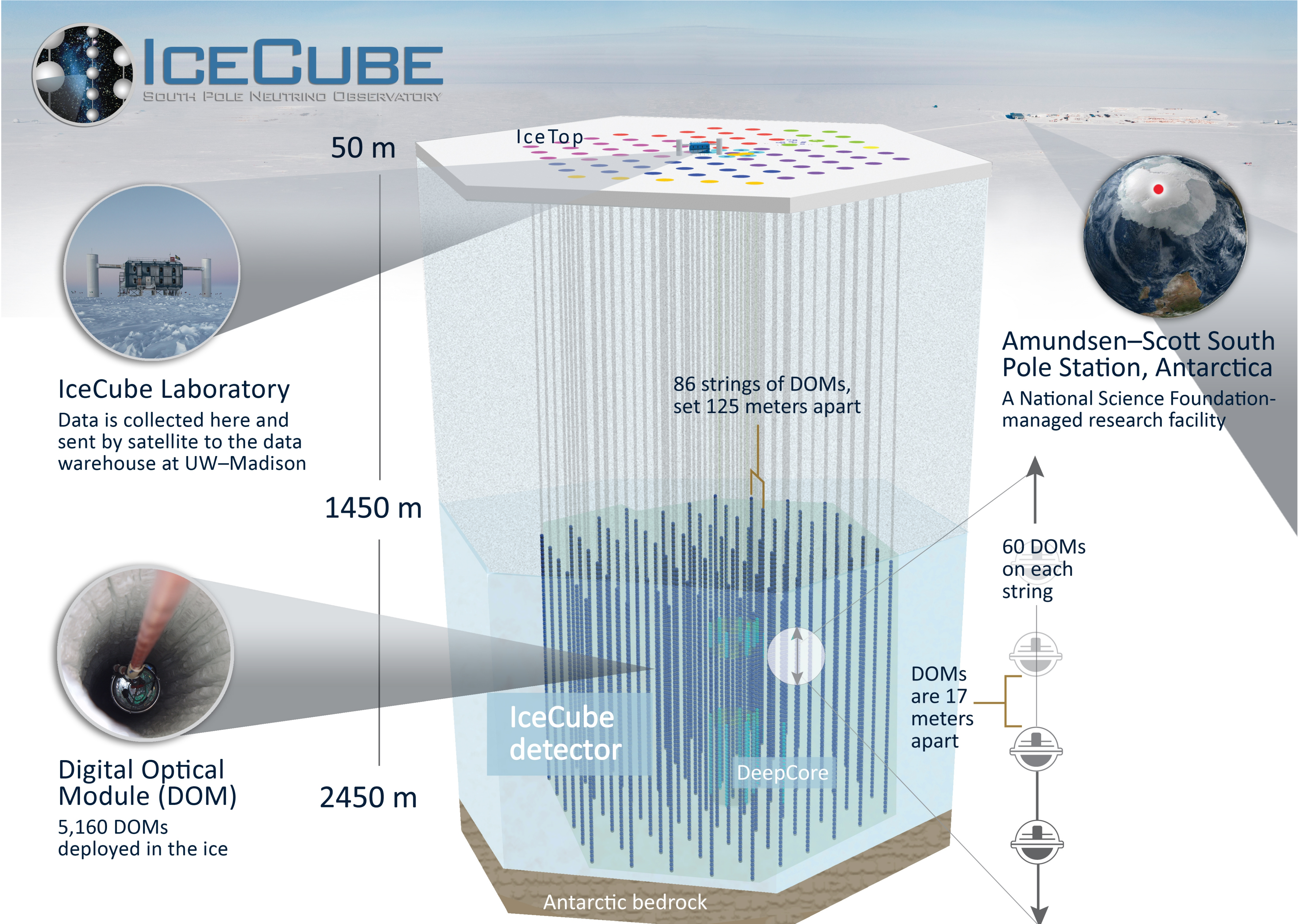
evaluated below, associating neutrino and γ-ray production.

The neutrino alert

IceCube is a neutrino observatory with more than 5000 optical sensors embedded in 1 km^3 o the Antarctic ice-sheet close to the Amundsen Scott South Pole Station. The detector consists o 86 vertical strings frozen into the ice 125 m apart each equipped with 60 digital optical module (DOMs) at depths between 1450 and 2450 m When a high-energy muon-neutrino interact with an atomic nucleus in or close to the detector array, a muon is produced moving through the ice at superluminal speed and creating Cherenkov radiation detected by the DOMs. On 22 September 2017 at 20:54:30.43 Coordinated Universal Time (UTC), a high-energy neutrino induced muon track event was detected in an automated analysis that is part of IceCube's real time alert system. An automated alert was dis tributed (*17*) to observers 43 s later, providing an initial estimate of the direction and energy of the event. A sequence of refined reconstruction algo rithms was automatically started at the same time, using the full event information. A repre

First Indication of a Neutrino Source – A true multi-messenger feat!





Almost 8 years of full-detector data on our hands

IceCube's Realtime Efforts

Individual MOU observatories:

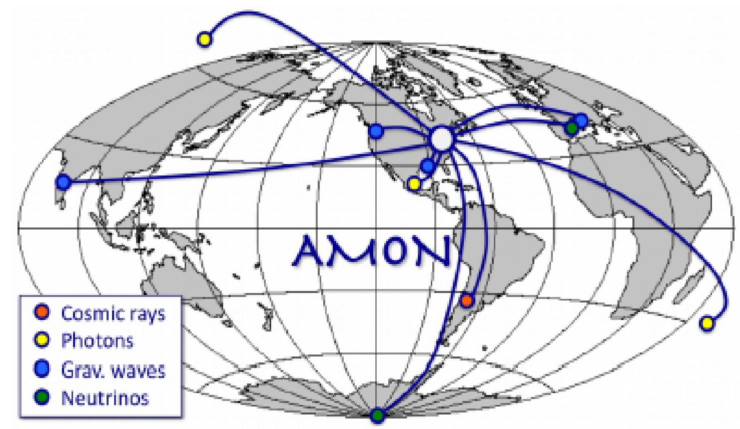
- Swift XRT
- ZTF
- Magic Gamma Ray Telescope
- VERITAS
- HAWC
- HESS
- LIGO/VIRGO
- Murchison Widefield Array

HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

VERITAS

H.E.S.S.

Networks & public alerts:



The Astrophysical Multimessenger Oberservatory Network:
FACT, VERITAS, MASTER,
LMT, ASAS-SN, LCOGT

„The Astronomer's Telegram“

SNEWS

The **G**amma-ray **C**oordinates **N**etwork

Alerts Currently “Online”

* All alerts have latency < 3 min!

Optical/X-ray Followups

Multiple neutrino candidate events from the same location around the same time
→ Alert PTF / Swift XRT

Gamma-ray Monitoring

Monitor for multiple neutrino candidate events from AGNs known to flare in gamma-rays
→ Alert MAGIC / VERITAS

GCN Issuing

GCNs are issued publicly when a high-energy event most likely to be a neutrino is observed, and the event has good pointing

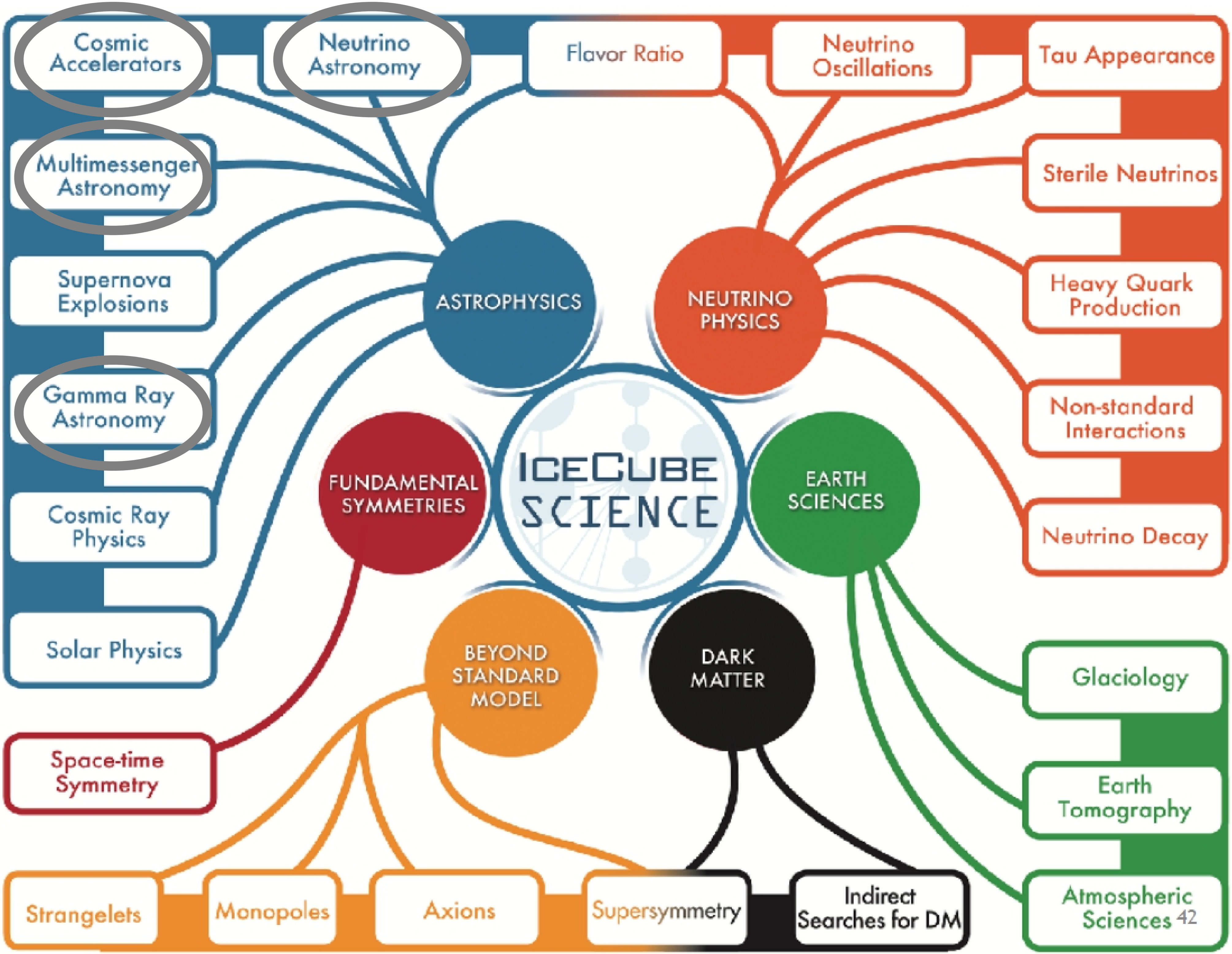
IceCube Realtime v2.0 imminent!

Updated event selection → double the alerts at the same signal-ness!

IceCube doesn't just wait for interesting single events and issue alerts!

My personal lesson from TXS 0506+056

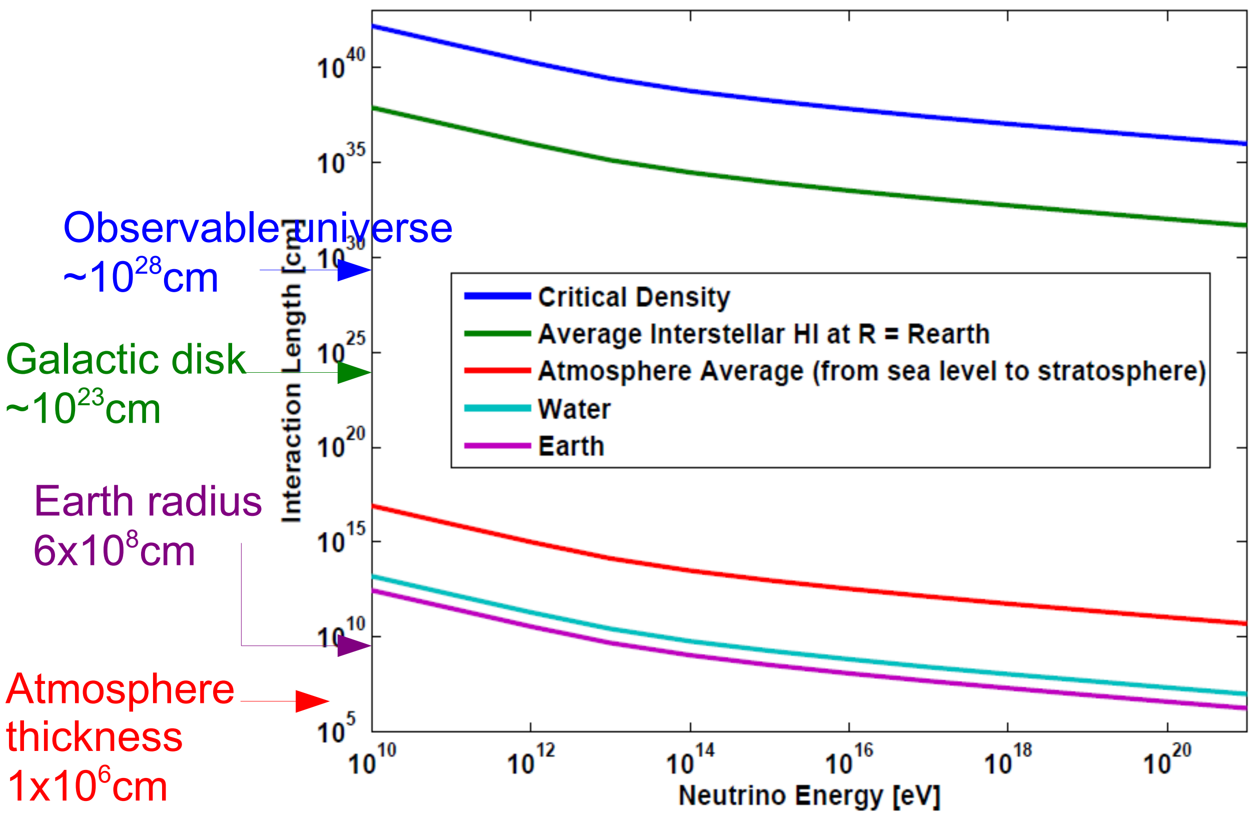
- Realtime alerts is absolutely crucial, but one neutrino event is still one event
- Neutrinos also need to be able to make a statement about a source to contribute to multi-messenger astronomy in a meaningful way!


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

Naoko Kurahashi Neilson, Drexel University

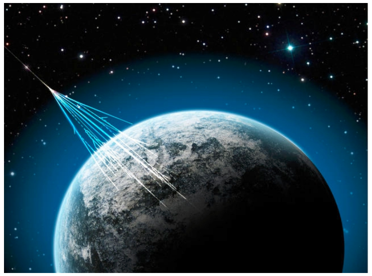
Neutrino Astronomy – The Issues

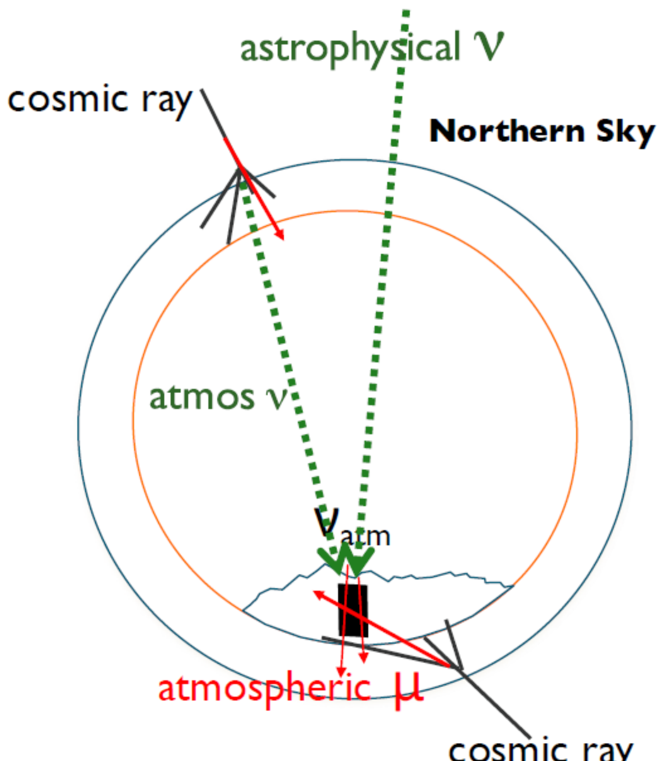
Issue 1: cross section



Cross section from **Gandhi et al., Phys. Rev. D 58 (1998) 093009**

Issue 2: backgrounds





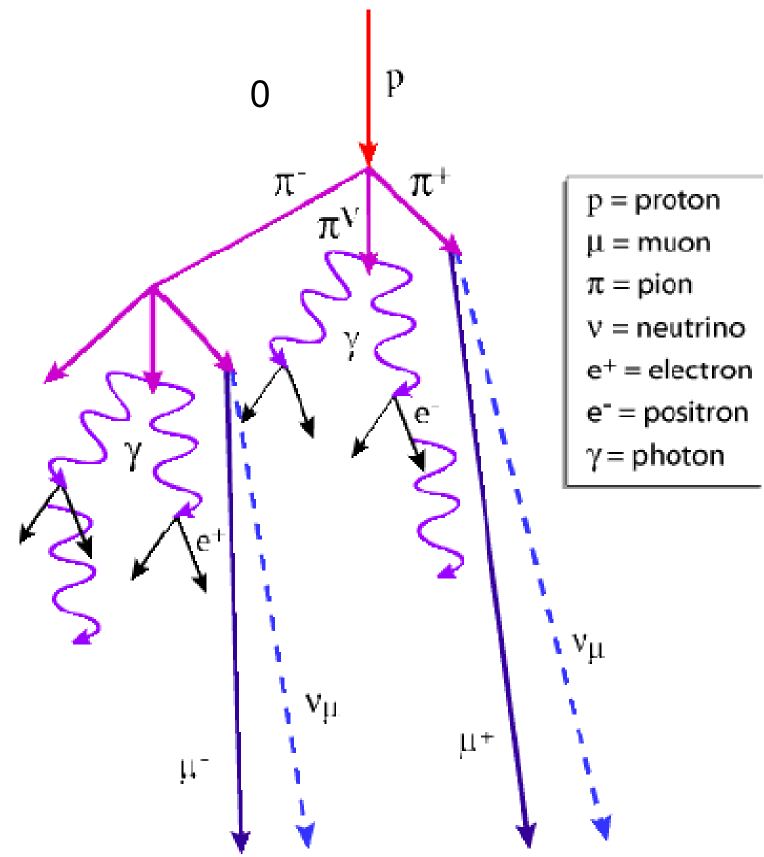
Fighting Backgrounds = atmospheric shower components

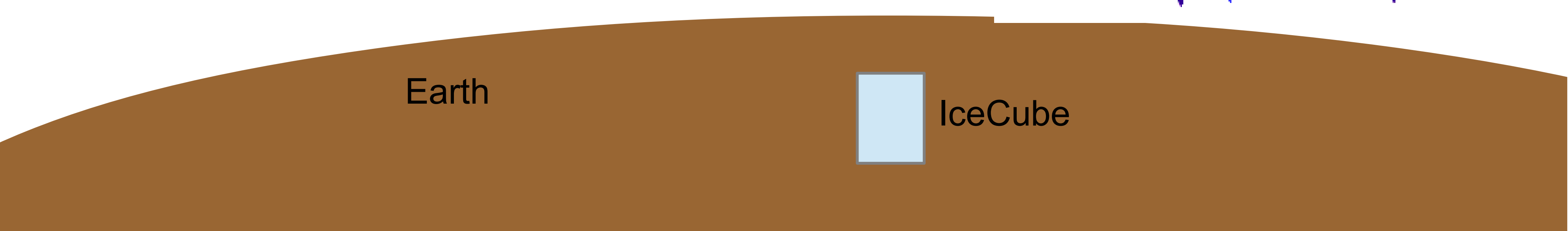
- Most charged π/K decay to μ rather than e
- ν produced in the same interaction, but lower cross section
  - Most common bkg: $\mu > \nu_\mu > \nu_e$ (Southern Hemisphere)
  - $\nu_\mu > \nu_e$ (Northern Hemisphere)

- <u>Atmospheric backgrounds are many orders of magnitude higher than signal astrophysical neutrinos</u>

- 3 ways to combat background domination

  → events from sources cluster, background is isotropic
  → events from sources have harder spectra
  → knowledge of position/time of source events *a priori*





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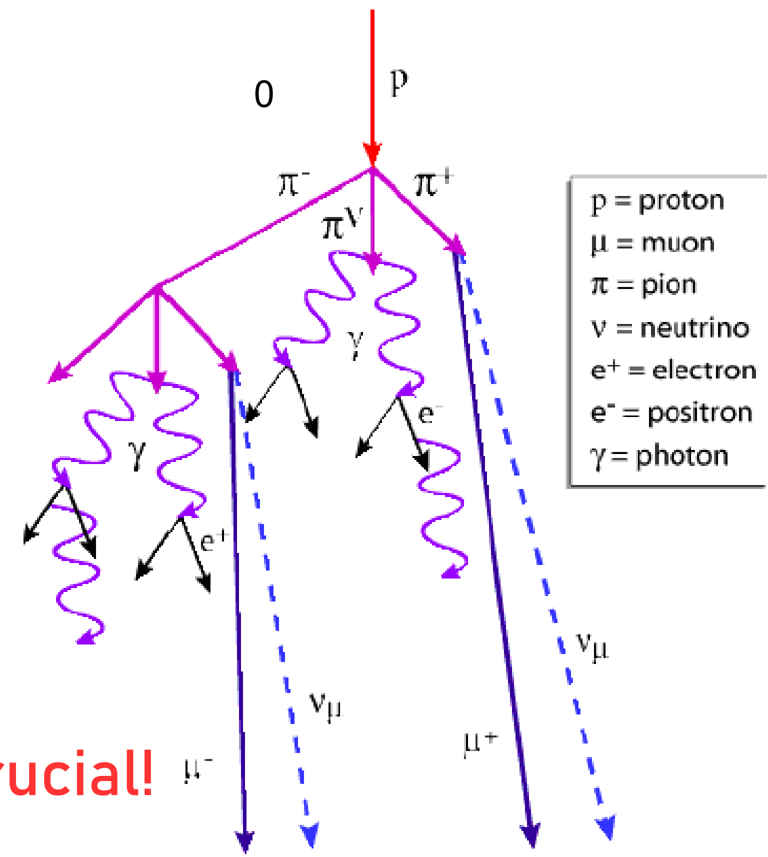
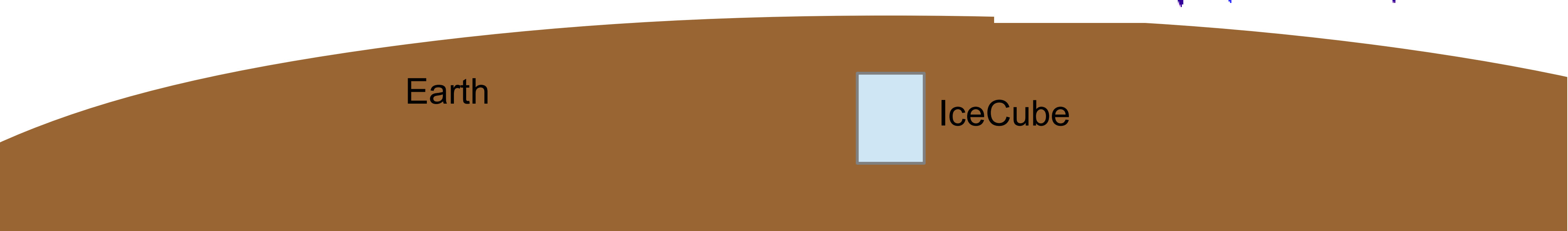
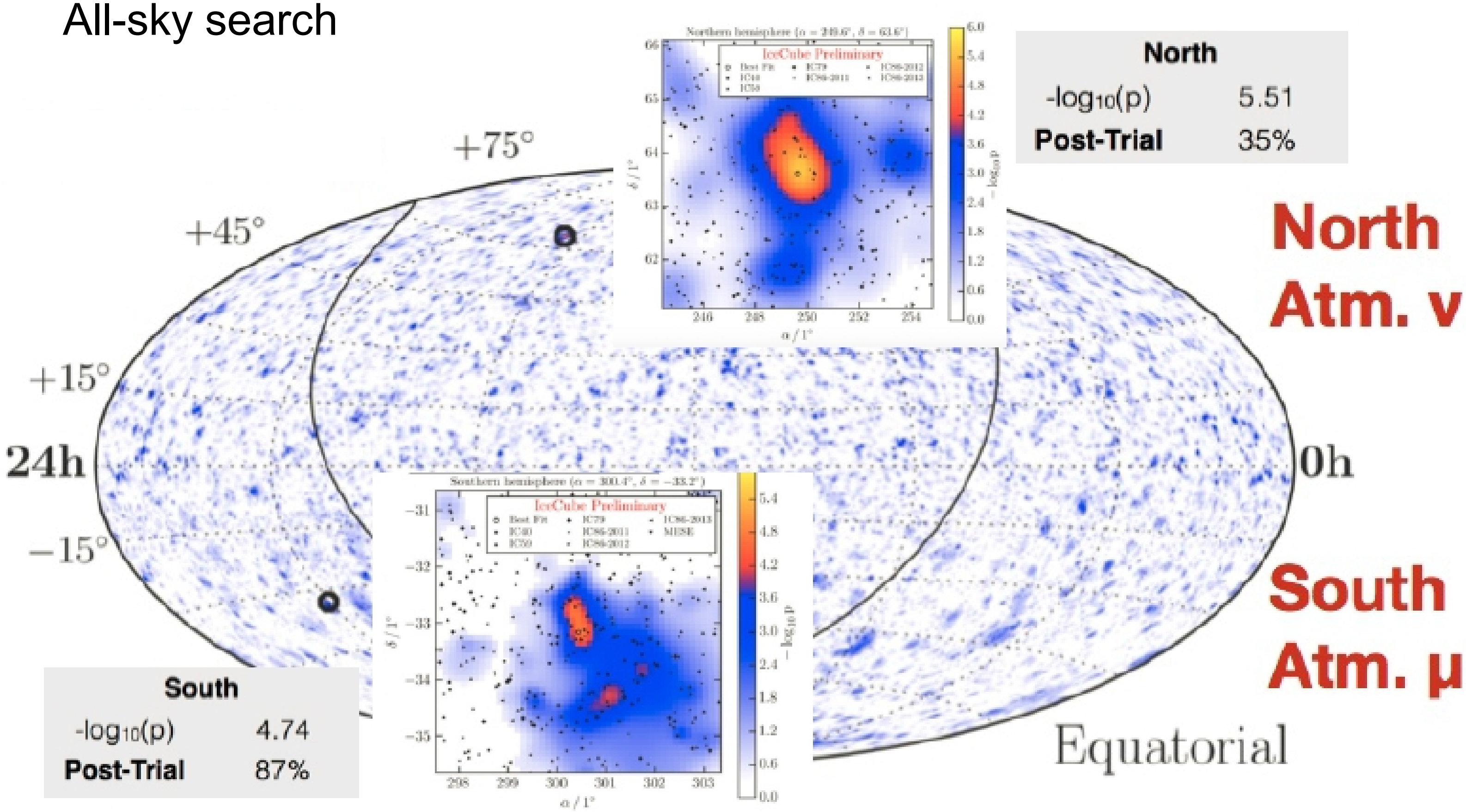


Fermi input is crucial!



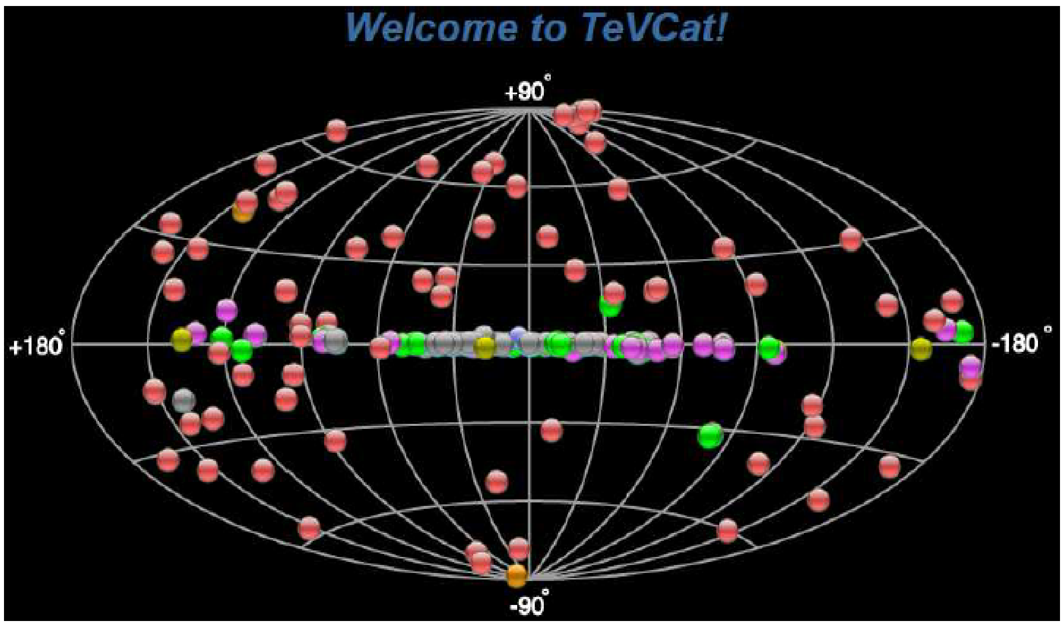
Point Source Analysis 1
Search for cluster: all-sky and around known sources

All-sky search



Time-integrated unbinned search of hot spots in 7 years of data
(Astrophys.J. 835 (2017) no2, 151)

Search for clustering around known sources



http://tevcat.uchicago.edu/

Study our data at positions of
- known high-energy gamma ray emitters
- gamma ray sources with hard spectra
- gamma ray sources thought to be hadronic emission

BL Lac
- PKS 0537-441
- PKS 2155-304
- PKS 0235+164
- 1ES 0229+200
- W Comae
- Mrk 421
- Mrk 501
- H 1426+428
- 3C66A
- 1ES 2344+514
- 1ES 1959+650
- S5 0716+71
- PKS 2005-489
- PKS 0426-380
- PKS 0548-322
- H 2356-309
- 1ES 1101-232
- 1ES 0347-121

FSRQ
- PKS 1454-354
- PKS 1622-297
- QSO 1730-130
- PKS 1406-076
- QSO 2022-077
- 3C279
- 3C 273
- PKS 1502+106
- PKS 0528+134
- 3C 454.3
- 4C 38.41
- PKS 0454-234
- PKS 0727-11

GC
- Sgr A*

NI
- MGRO J1908+06
- HESS J1507-622
- HESS J1503-582
- HESS J1741-302
- HESS J1834-087

PWN
- Geminga
- Crab Nebula
- MGRO J2019+37
- HESS J1356-645
- PSR B1259-63
- HESS J1303-631
- MSH 15-52
- HESS J1023-575
- HESS J1616-508
- HESS J1632-478
- Vela X
- HESS J1837-0

SFR
- Cyg OB2

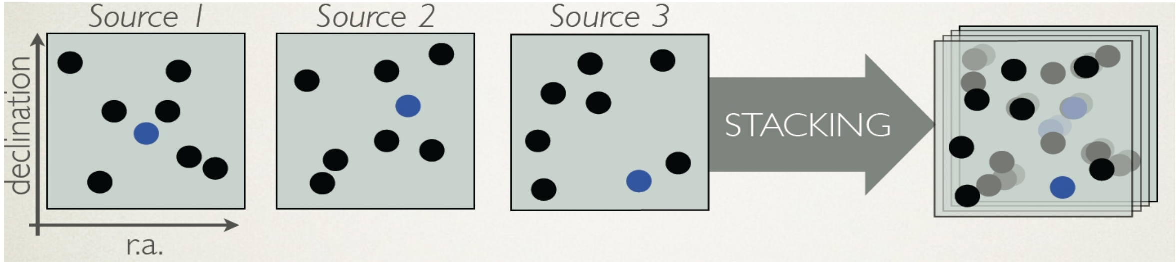
SNR
- IC443
- Cas A
- TYCHO
- Cen A
- M87
- 3C 123.0
- Cyg A
- NGC 1275
- M82
- RCW 86
- RX J0852.0-4622
- RX J1713.7-3946
- W28

Seyfert
- ESO 139-G12

XB/mqso
- SS433
- HESS J0632+057
- Cyg X-1
- Cyg X-3
- LSI 30
- Cir X-1
- GX 339-4
- S 5039

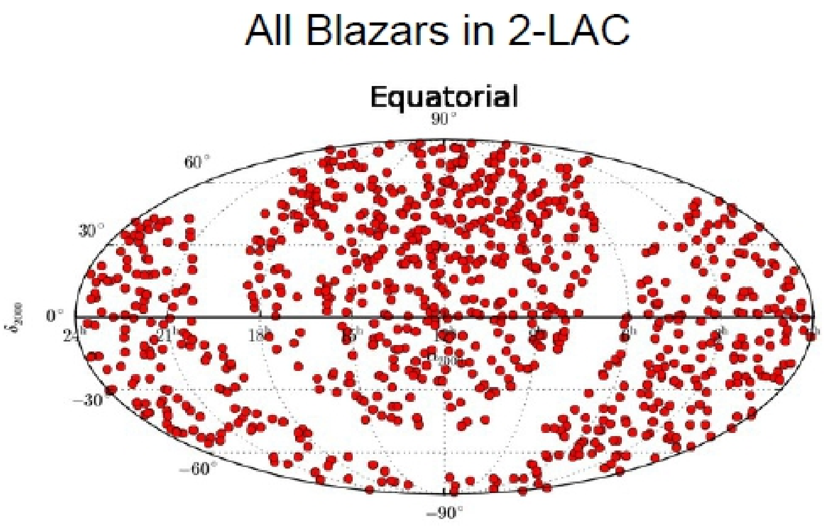
cluster
- HESS J1614-51

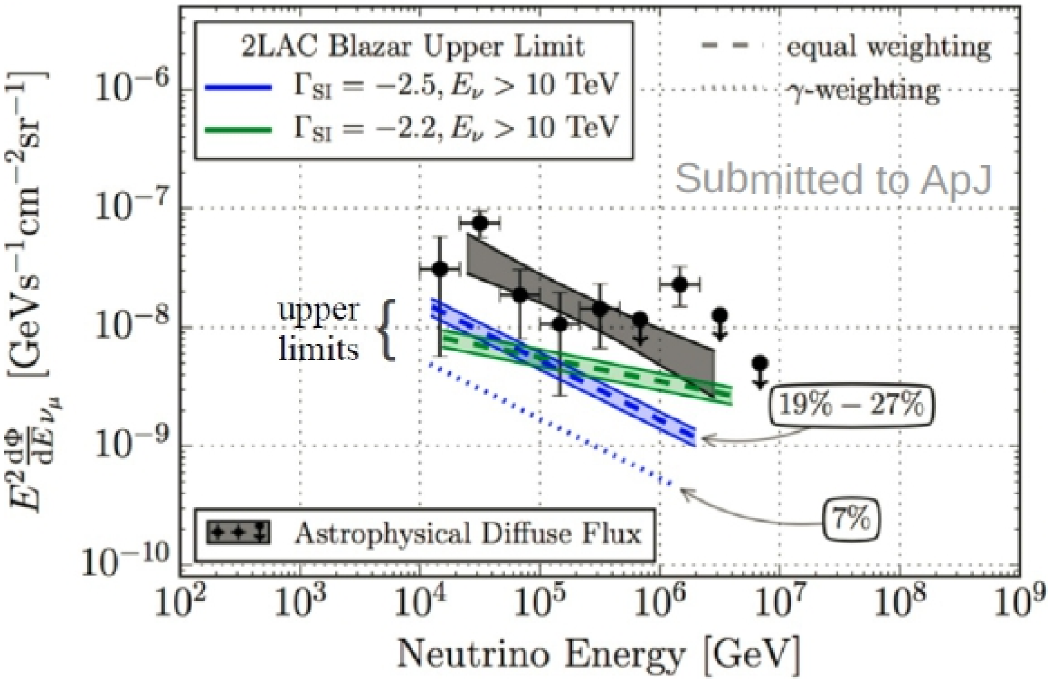
Point Source Analysis 2
Stack the sources



Stacking of 862 Fermi 2LAC Blazars

Quasi-diffuse search (~10% of the sky at our angular resolution)





Limits in terms of % of diffuse flux

Astrophys.J. 796:10 (,2014), ApJ, 805, L5 (2015)

		Upper limit in diffuse flux	notes
Blazars		~ 17%	862 from Fermi 2nd AGN cat. Spectral index = -2.5
Nearby Starburst Galaxies		~ 8%	127 nearby Spectral index = -2
Galactic Sources	Young SNR	~ 5%	30 with no PWN or MC Spectral index = -2
	Young PWN	~ 3%	10 with no MC Spectral index = -2
Galactic Plane		~14%	Fermi Diffuse γ Spatial template Spectral index = -2.5 to -2.7
GRBs		~1%	506 bursts observed Spectral index = -2 to -2.7

Updated analysis
Poster by Qinrui Liu!

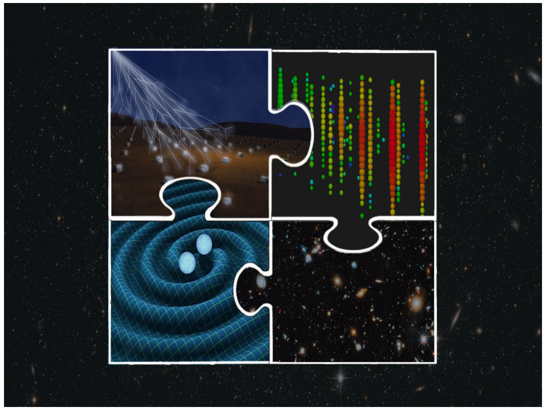
Some specific sources may be special enough for IceCube to see, but not as a source class under these assumptions
→ what makes a source special?

We need to build a "neutrino catalog" of astronomical objects

- Realtime alerts important for multi-messenger astronomy
- Neutrinos need to make a statement by themselves too
- Only some sources are special – which ones? why?

How do neutrinos fit in with multimessenger astronomy to reveal sources and processes of the high energy universe?

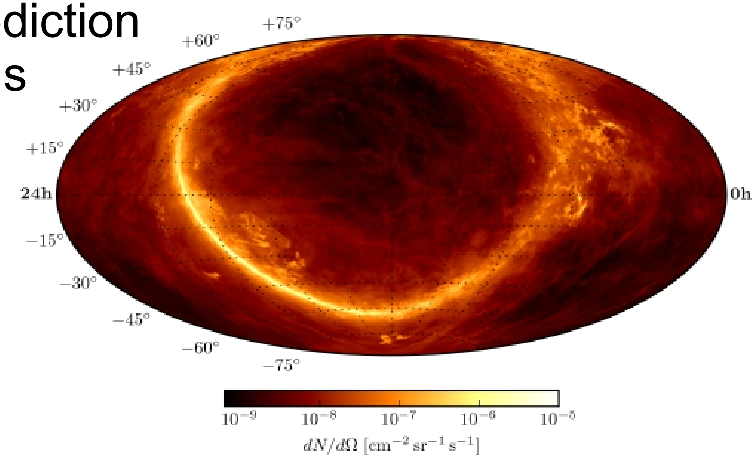
We need Fermi data to compare to!



Diffuse Galactic Plane Emission

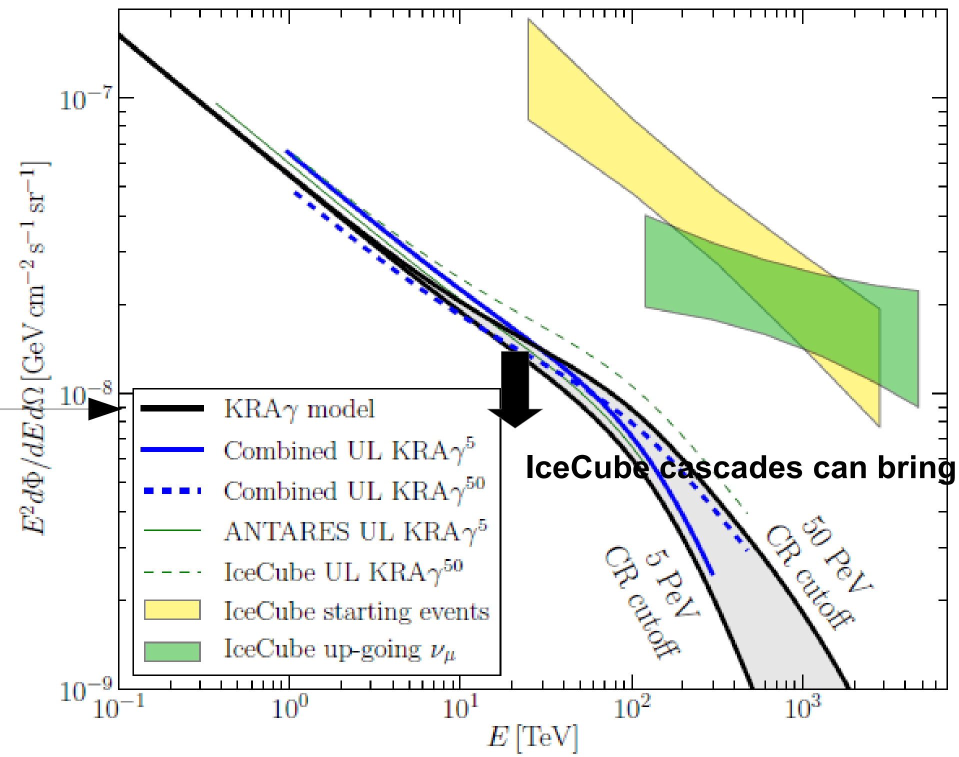
IceCube (2018) arXiv:1808.03531

Diffuse galactic neutrino prediction based on Fermi observations



Gaggero, D., Grasso, D., Marinelli, A., Urbano, A., & Valli, M. 2015, ApJ, 815, L2

Gaggero, D., Grasso, D., Marinelli, A., Taoso, M., & Urbano, A. 2017, PhRvL, 119, 031101



IceCube cascades can bring it down by a further x2

We recently had a collaboration meeting
This was our agenda in the Neutrino Sources working group

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- UHECR correlation analysis - Lisa Schumacher
- Blazar flare stacking results - Christoph Raab
- Fast-Response Analysis Update - Alex Pizzuto, Kevin Meagher
- LIGO coincidence next observing period plans - Imre Bartos
- Searching for common sources of gravitational waves and neutrinos - Raamis Hussain
- realtime HESE alert update - Chris Tung
- Proposed ATel/GCN policy for ROC - Erik Blaufuss
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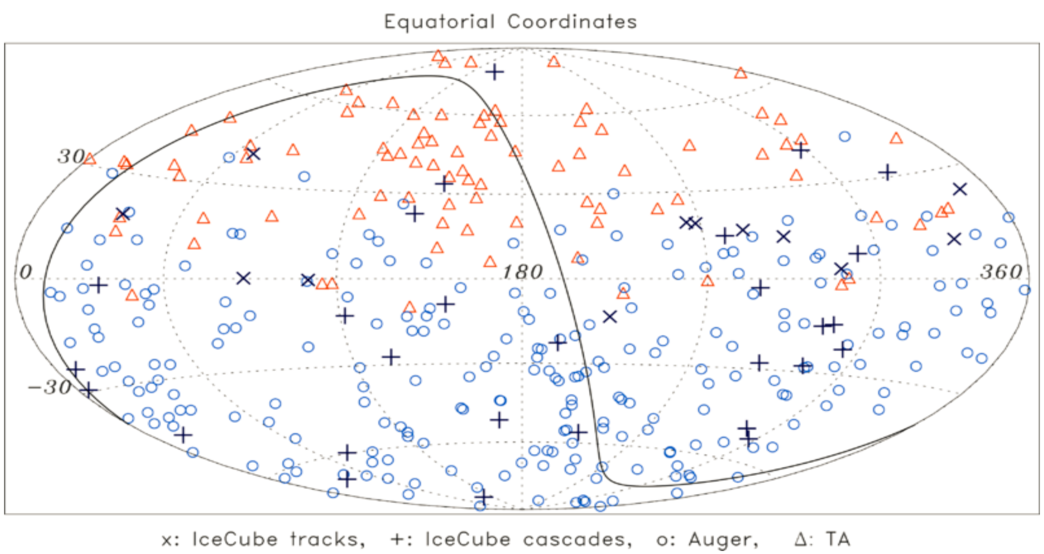
We need Fermi!

Multi-Messenger Astronomy with Non-EM partners

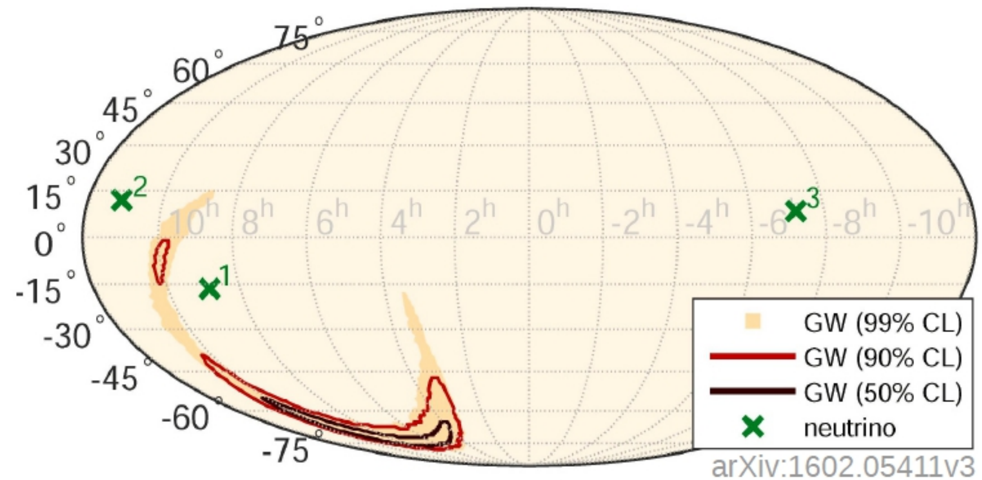
Ultra-high Energy Cosmic Rays



JCAP 1601 (2016) 01, 037

Correlation study with highest energy events from Auger and TA
No correlation beyond 3.3σ

Gravity Waves



LIGO gravity signal and neutrino events within +/-500s

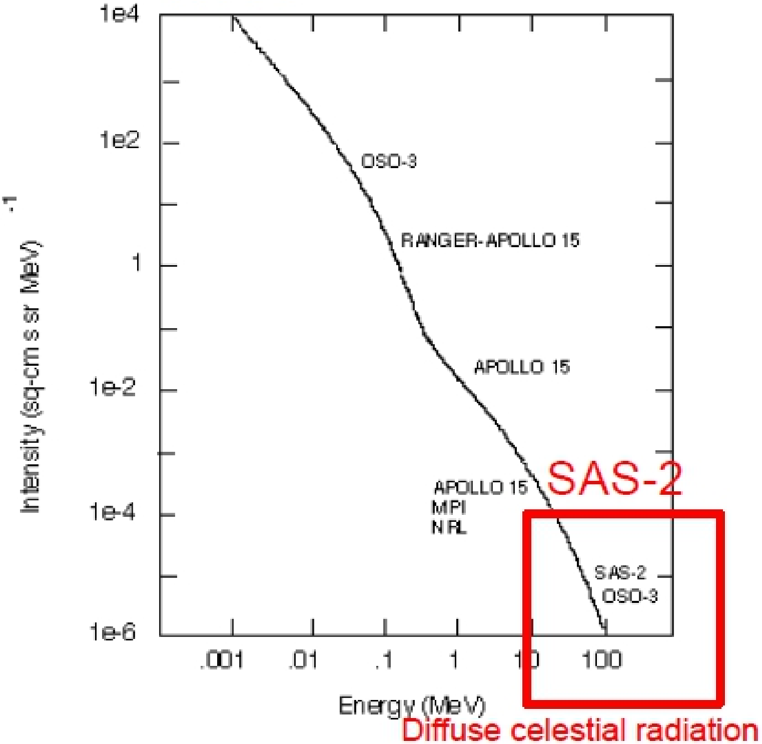
Alerts - what about the other way around?

- When other messengers see interesting flares, we'd like to say if IceCube saw anything
- This has been a weak spot historically
  - IceCube is an all-sky observatory taking data 99.9% of the time. No urgency.
  - IceCube-issued alerts have algorithms running at the South Pole, they get “pushed” out. This requires us to “pull” data.
- We now have a mechanism for “fast flare analysis”
  - Data available ~ 1min, human decisions take longer
  - Discussions on how to disseminate results ongoing

Historical Perspective: Gamma-ray Astronomy

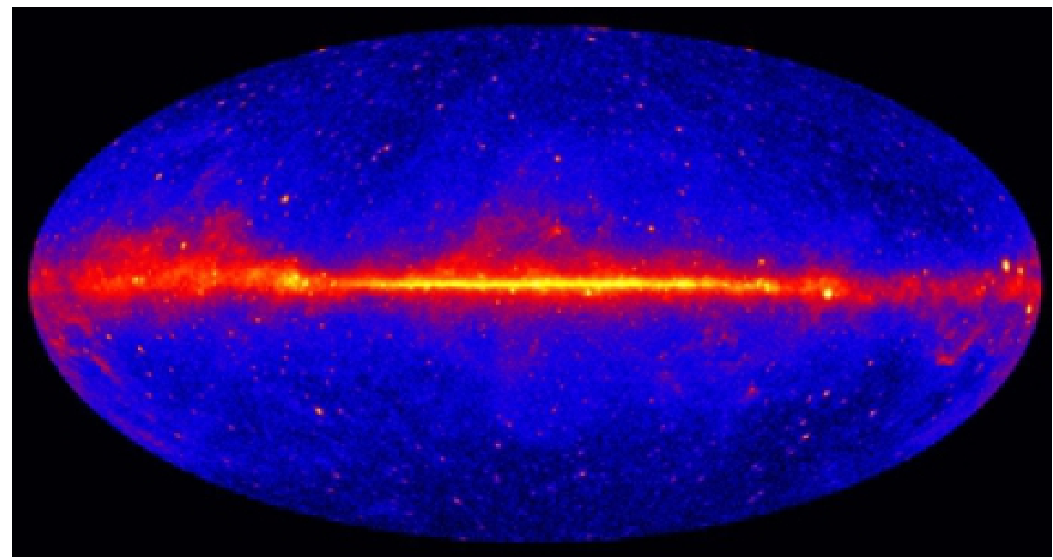
Diffuse signal → first source → catalog!

1970's



NOW

Fermi!

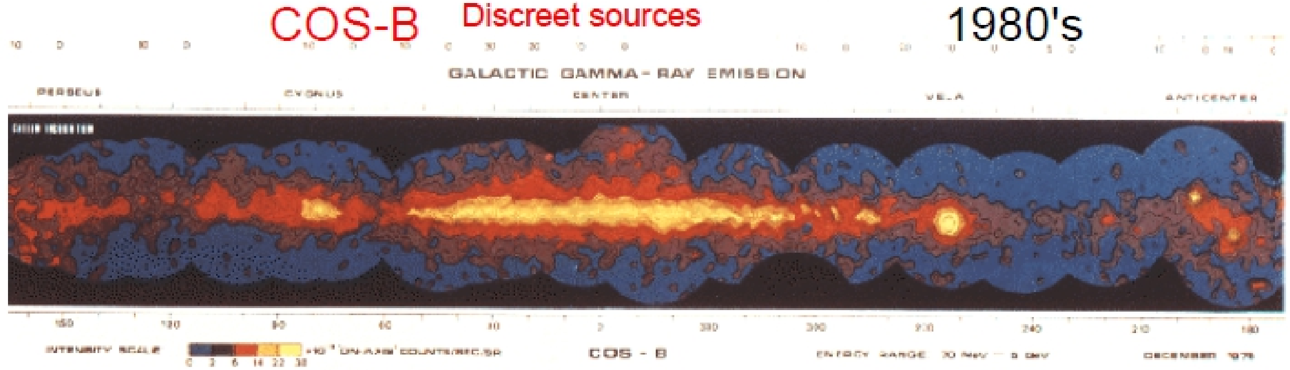


GSFC nasa.gov

COS-B

Discreet sources

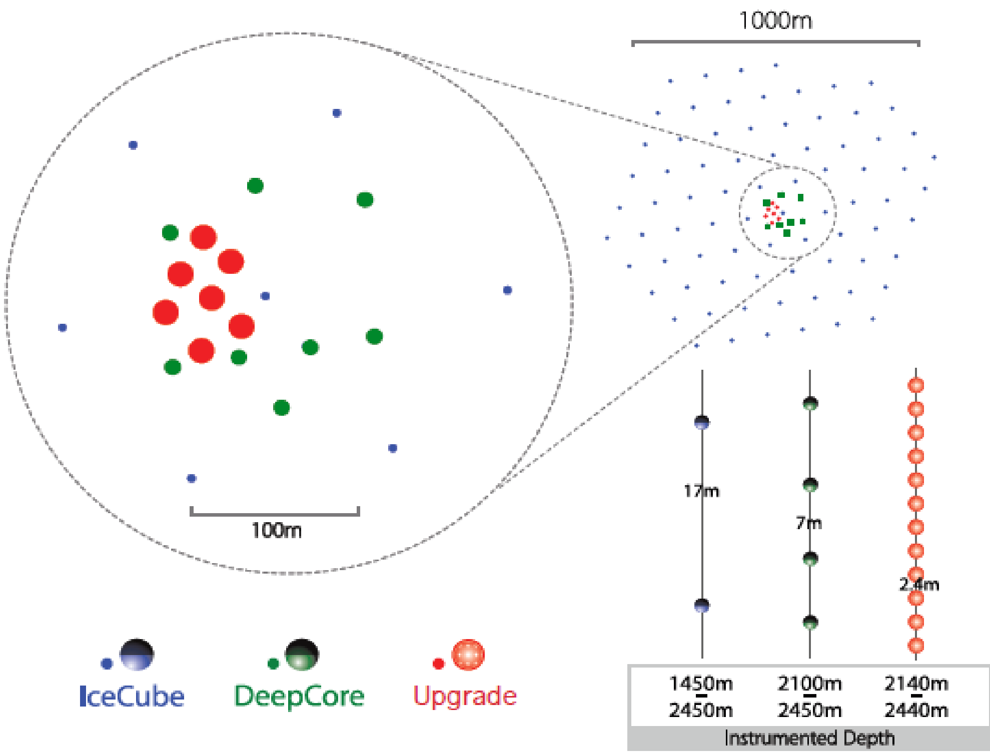
1980's



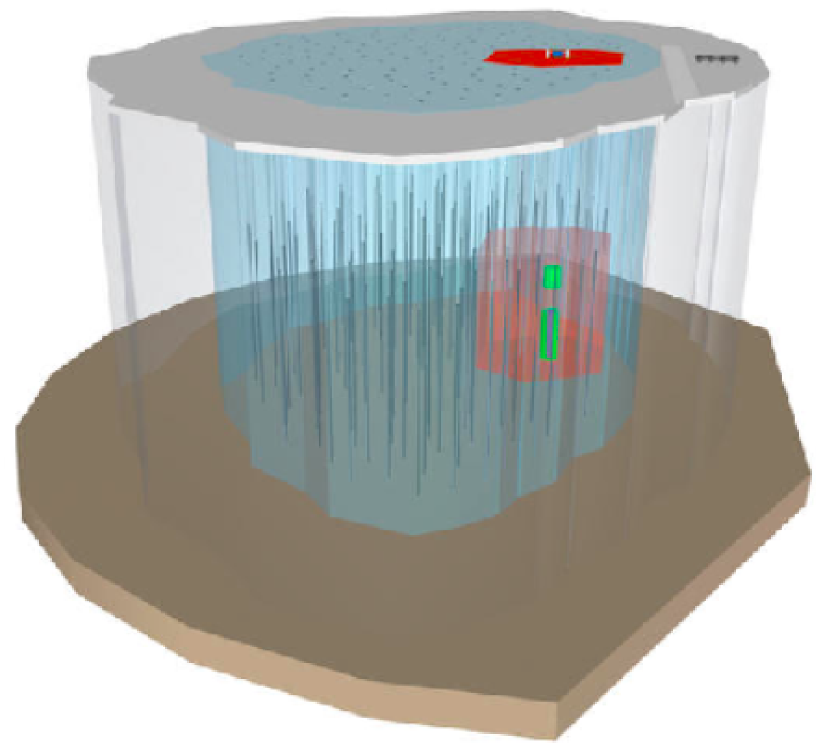
GSFC nasa.gov

Future prospects

The IceCube Upgrade



IceCube Gen2



Near Term

- Add 6-7 strings with > 800 advanced DOMs
- Advanced calibration devices
- Improved measurement of neutrino oscillations
- Improved angular resolution for neutrino astronomy

Funding just approved!

Long Term

- ~8-10 larger volume than IceCube
- Larger samples of astrophysical neutrinos
- Radio neutrino detection and air shower detection/veto all under consideration

A pitch for continued “special relationship” between Fermi and IceCube

- Our alerts give ~0.5 degree error circle → not great for deep follow-up observations
- Many (most) of the EM observatories need Fermi input for follow-up
- Many (most) of our non-realtme analyses need Fermi input
- We don't have a self-triggered 5σ source.... yet
- But lets not forget, the upshot is huge here! As we have shown, together we can build the first catalog of neutrino sources, which is crucial in understanding the HE universe!