Neutrino Astronomy at the South Pole with IceCube

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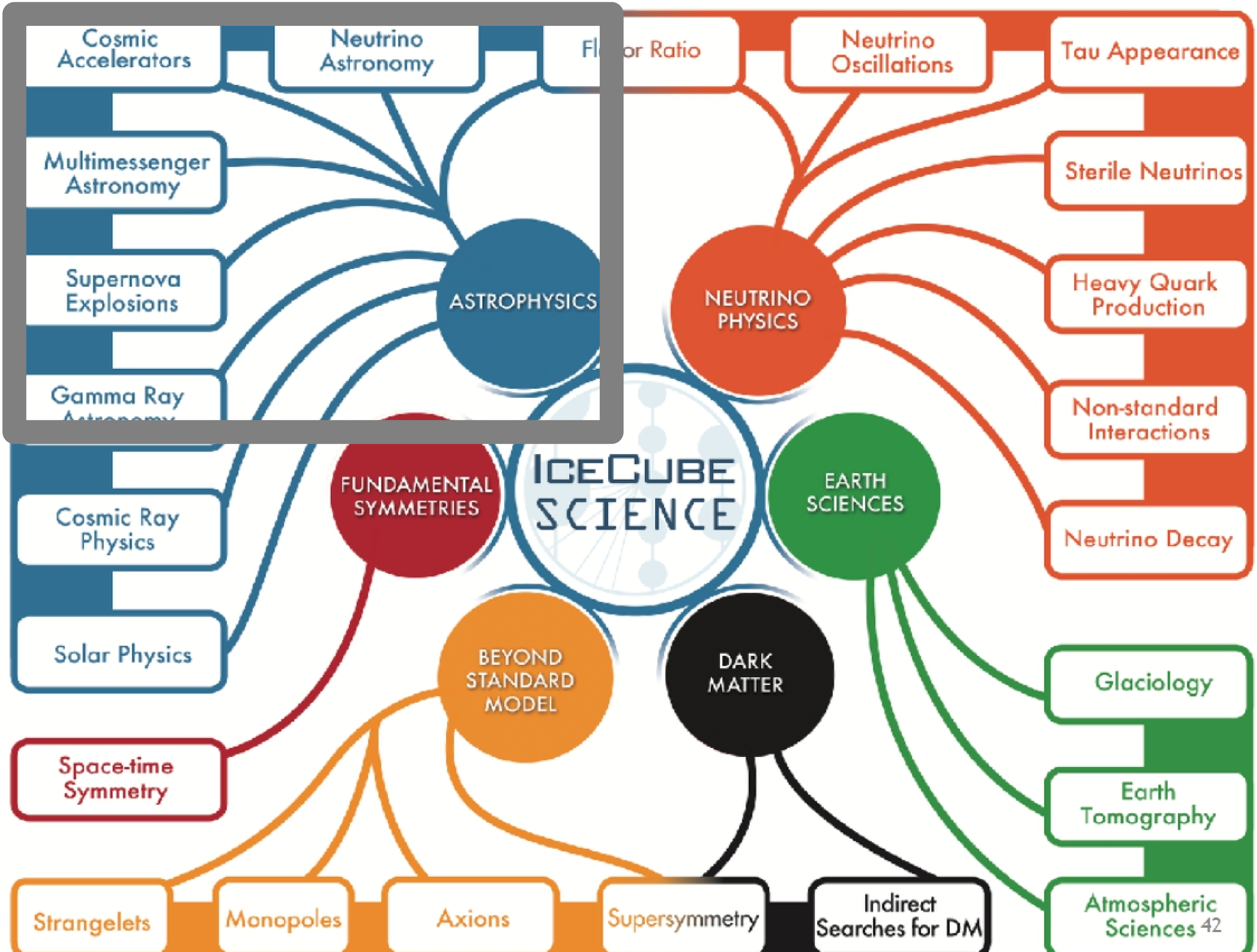
IPMU Seminar
October 11th, 2022

Naoko Kurahashi Neilson, Drexel University



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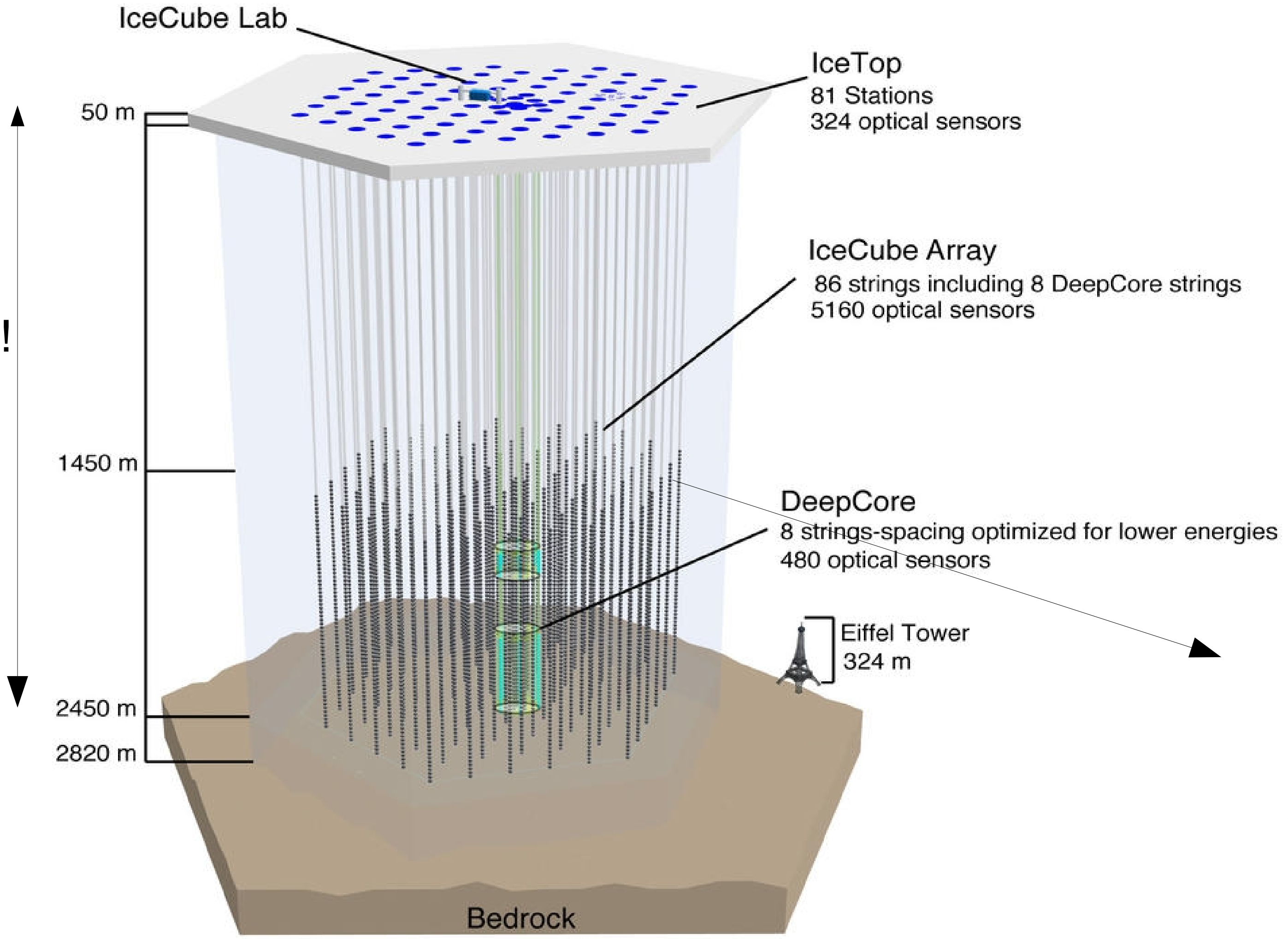
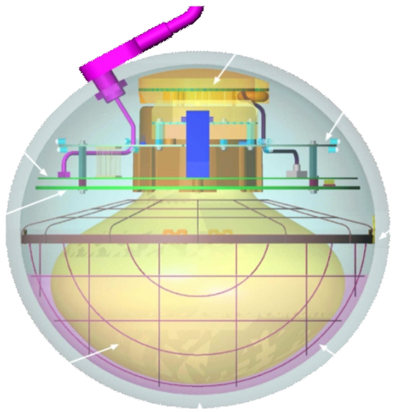
Atmospheric Sciences
BEYOND STANDARD MODEL
Strangelets
Monopoles
Axions
Supersymmetry
DARK MATTER
Indirect Searches for DM

Glacier at the South Pole

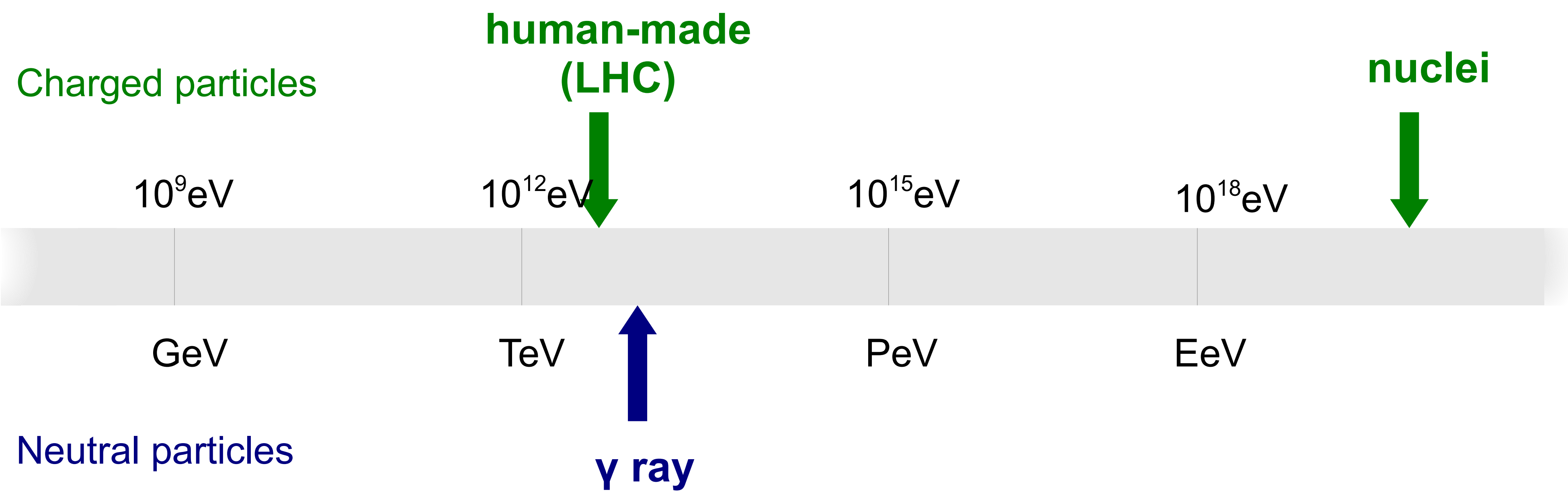
2.8km deep!



Light Sensor



Highest energy particles observed



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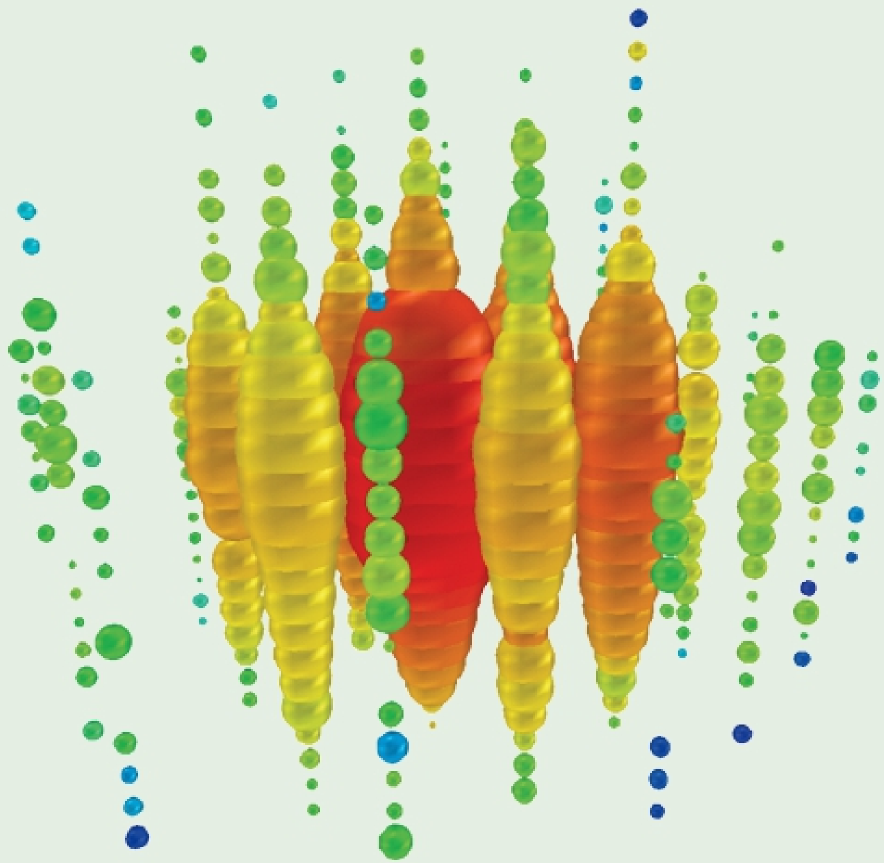

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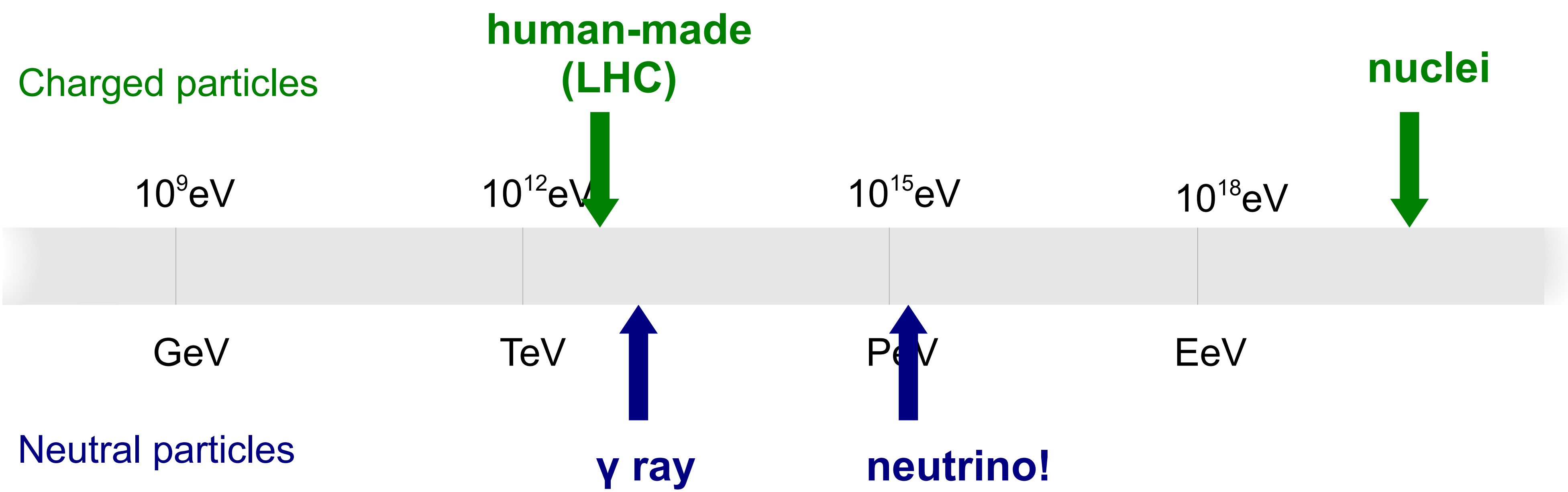
APS physics

Volume 111, Number 2

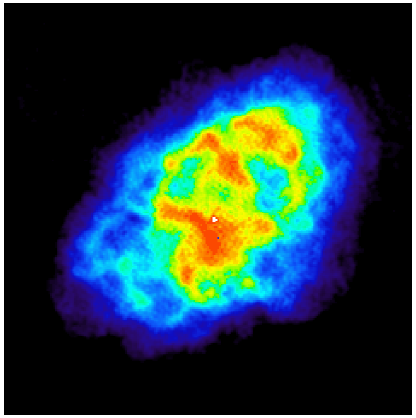
Highest energy particles observed



- How are neutral particles created at such high energies?
- Can neutrinos be created the same way γ-rays are?
- What are the most likely sources of these observed neutrinos?

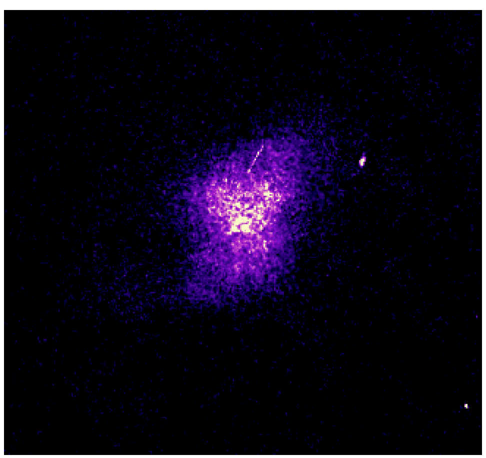
The Crab Nebula

Star with gas cloud around it

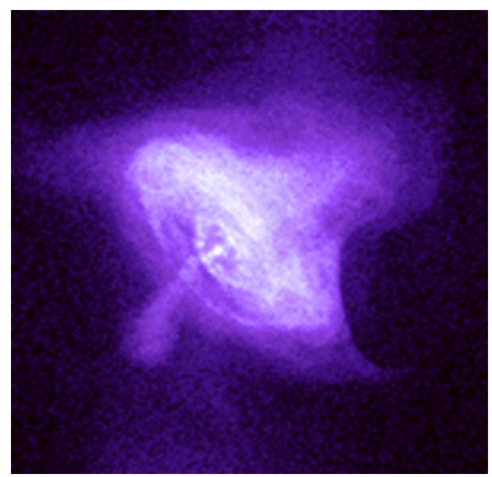


Radio image

Ultraviolet image



Optical image

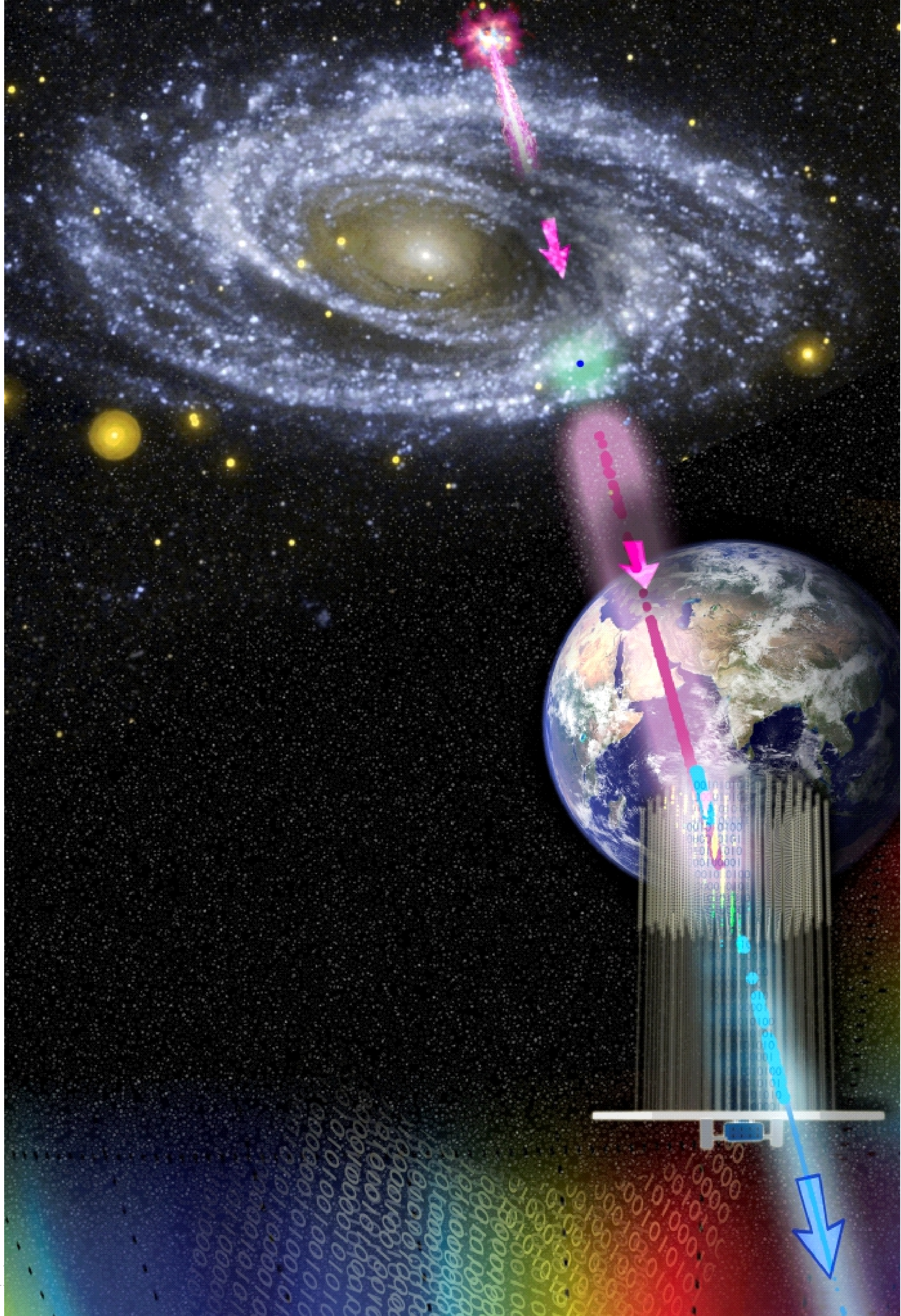


X-ray image

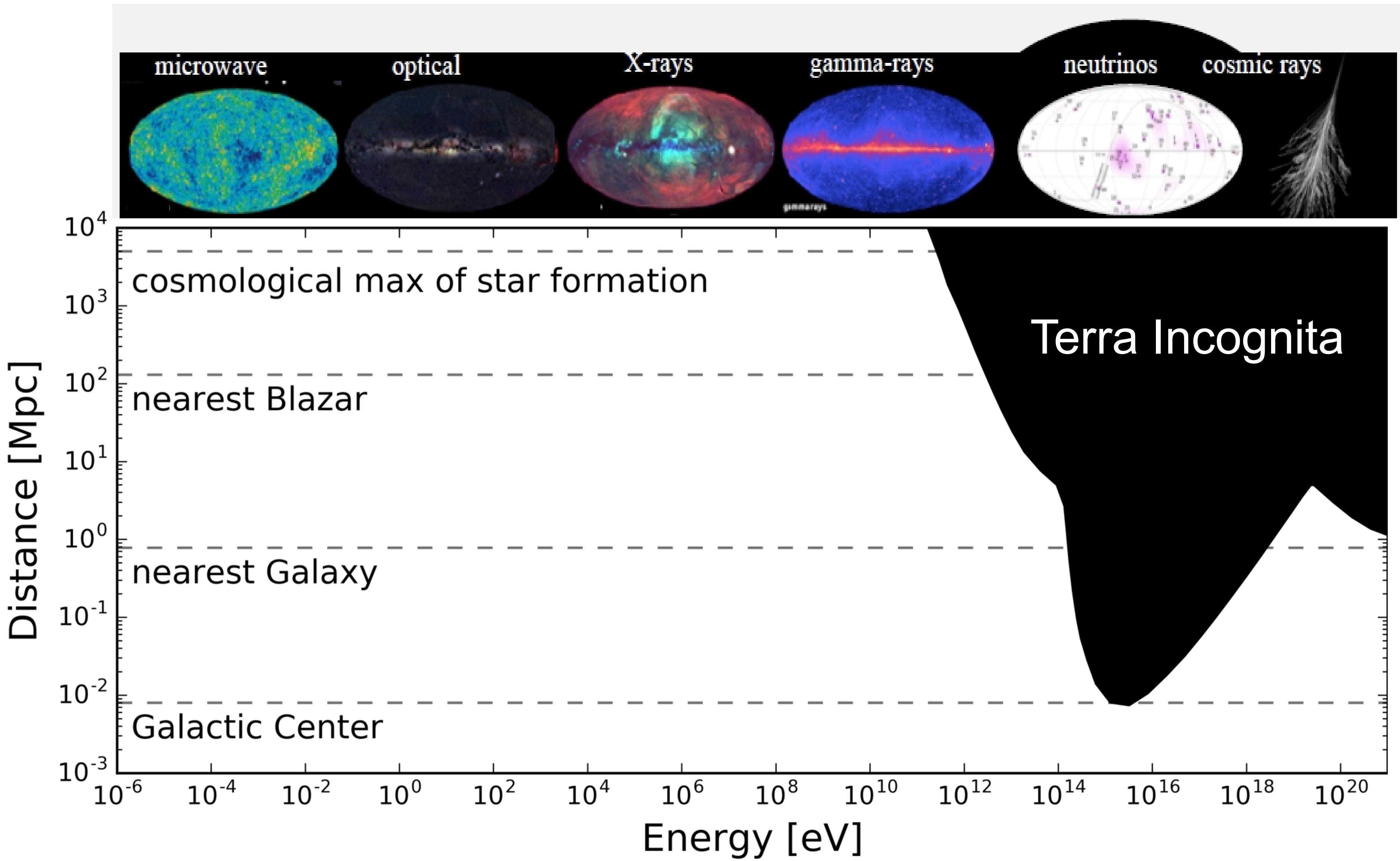
Multi-wavelength Astronomy

Seeing the universe in Neutrinos!

Multi-messenger Astronomy!



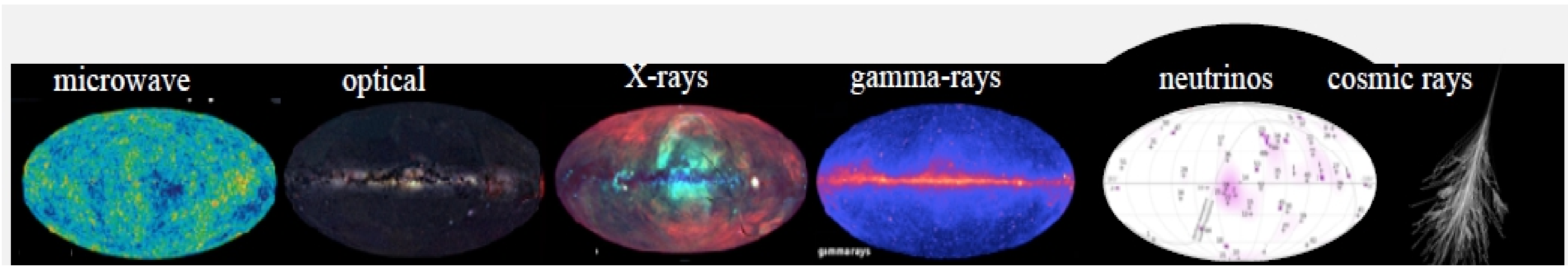
Why Neutrinos for MultiMessenger Astronomy?



Neutrinos – Bridge the Gap between γ rays and cosmic rays

→ in energy

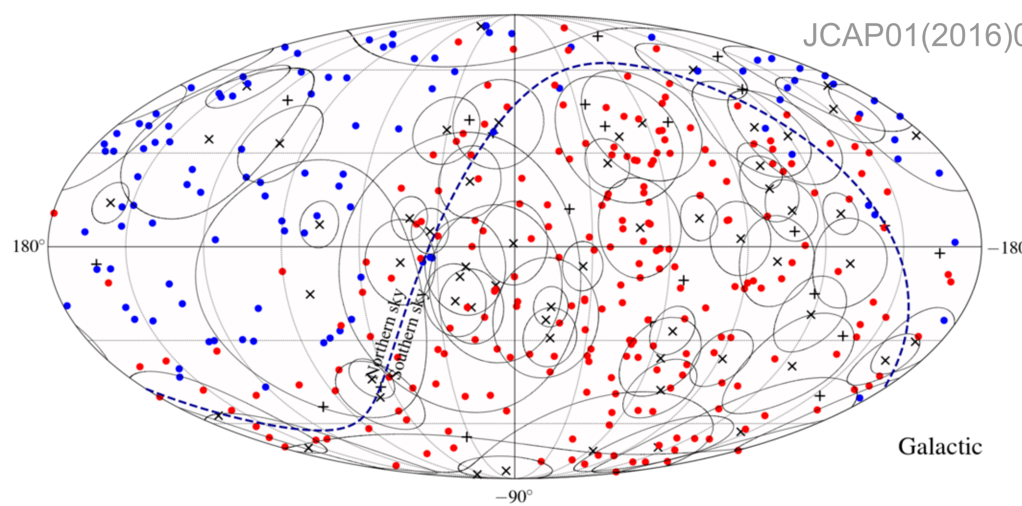
→ in resolved vs unresolved



Able to resolve sources

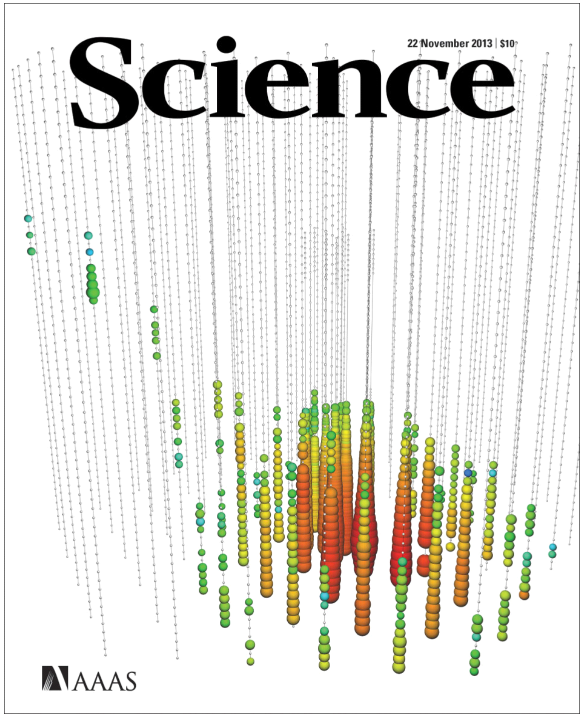
JCAP01(2016)037

Deflected by magnetic fields
(charged nuclei)

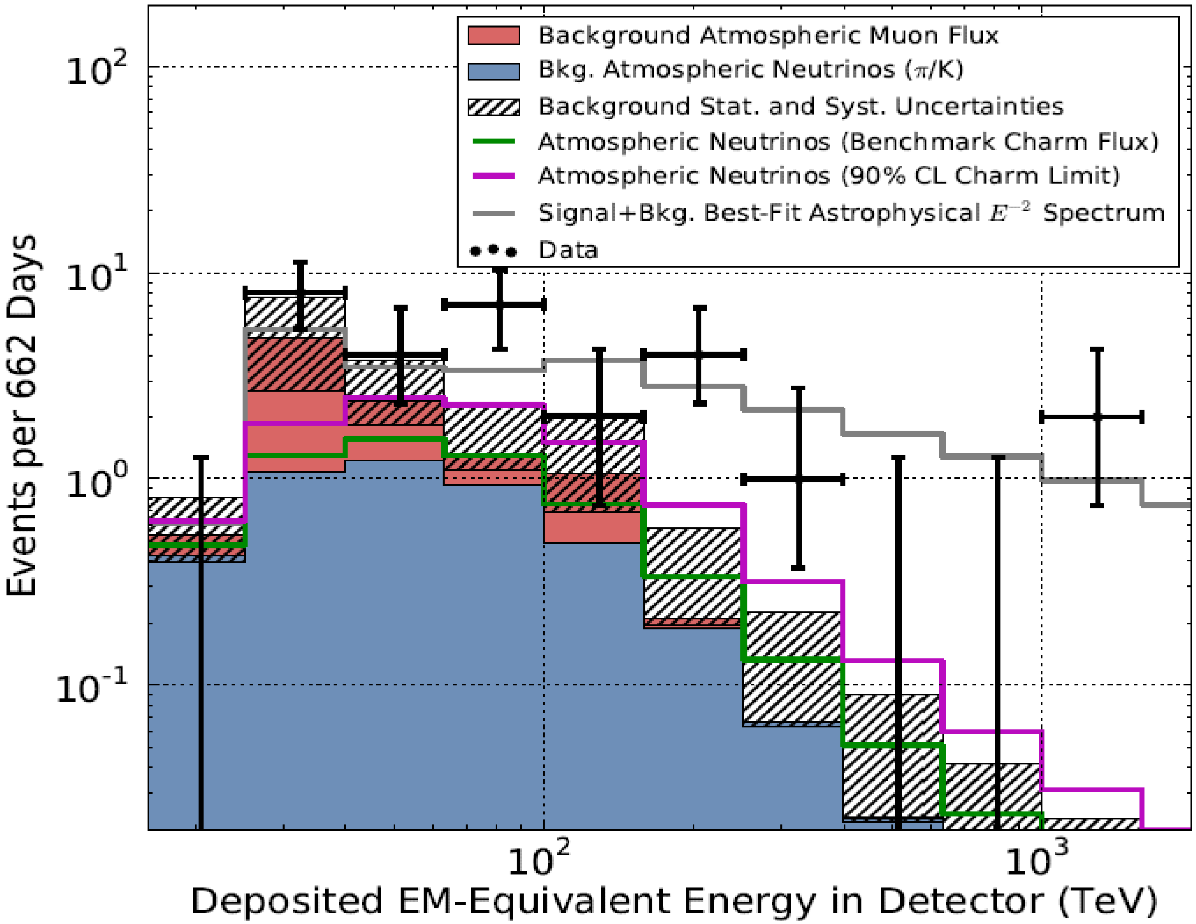


History of IceCube's Results

2013: Diffuse Neutrino Emission



IceCube Collaboration
Science 342, 1242856 (2013)



Press!

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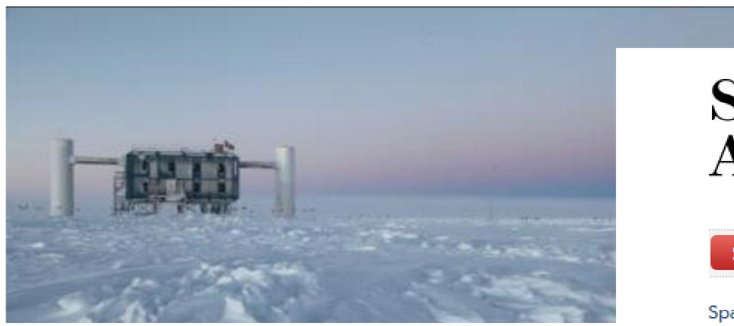
SCIENCE

Subatomic particles found in mile-deep ice are of interstellar origins

Physicists working with the particle detector IceCube, buried near the South Pole, have detected neutrinos of high enough energies to suggest origins in the cataclysms at the Milky Way's fringes, or perhaps even past its doorstep.

By Elizabeth Barber, Staff Writer NOVEMBER 21, 2013



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SCIENCE / SPACE

Alien neutrinos reveal new frontier in astronomy at Antarctica's IceCube

BY ALAN BOYLE, SCIENCE EDITOR

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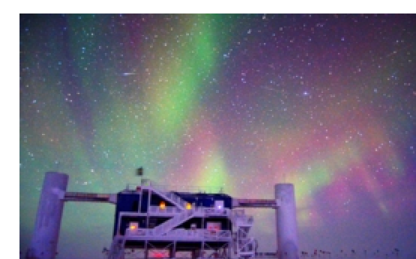
Exotic Space Particles Slam into Buried South Pole Detector

The IceCube experiment has taken hits from three neutrinos carrying energies above the outlandishly high peta–electron volt range that suggest they may radiate from titanic explosions in the depths of space

April 9, 2014 | By Clara Moskowitz

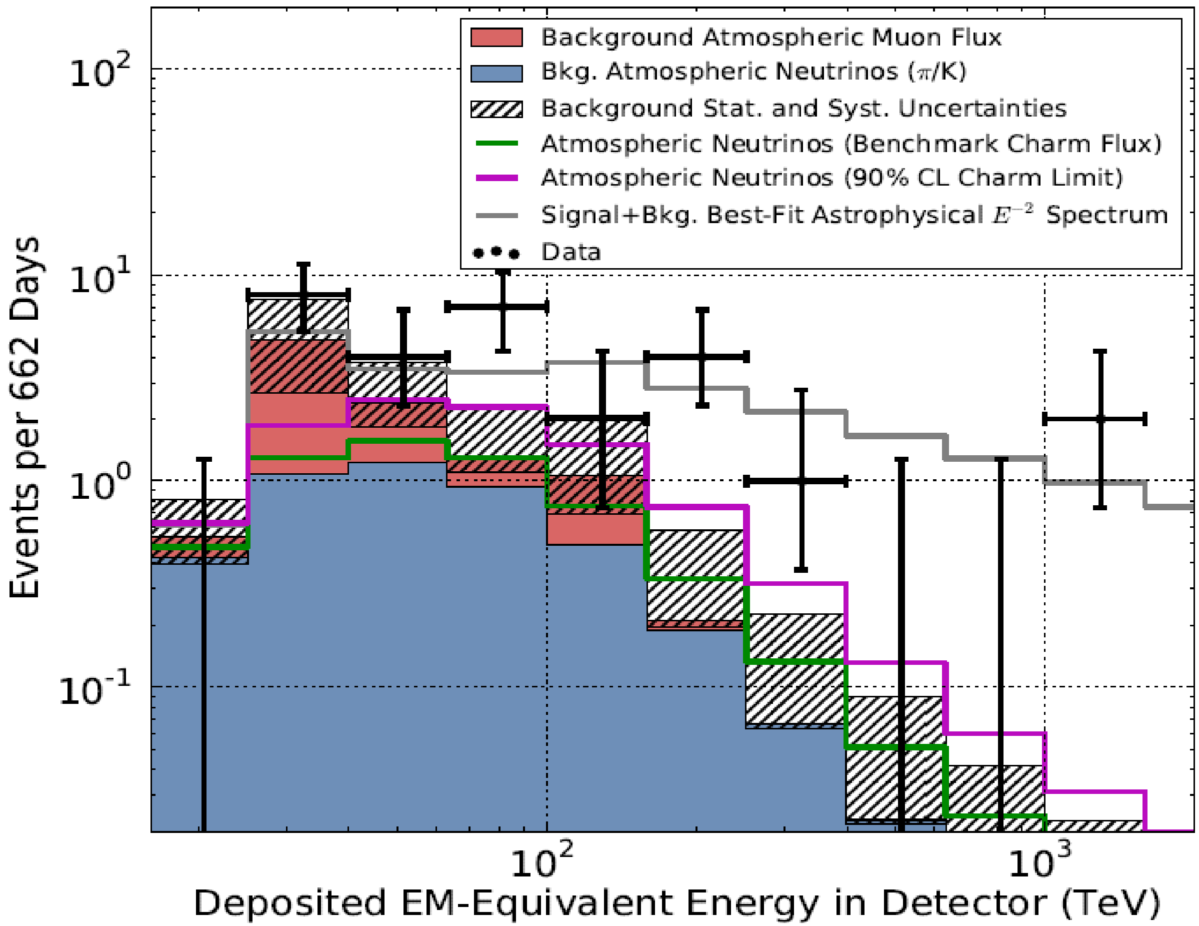
SAVANNAH, Ga.—A belowground experiment at the South Pole has now discovered three of the highest-energy neutrinos ever found, particles that may be created in the most violent explosions of the universe. These neutrinos all have energies at the absurdly high scale of peta–electron volts—roughly the energy equivalent of one million times a proton's mass. (As Albert Einstein showed in his famous $E = mc^2$ equation, energy and mass are equivalent,

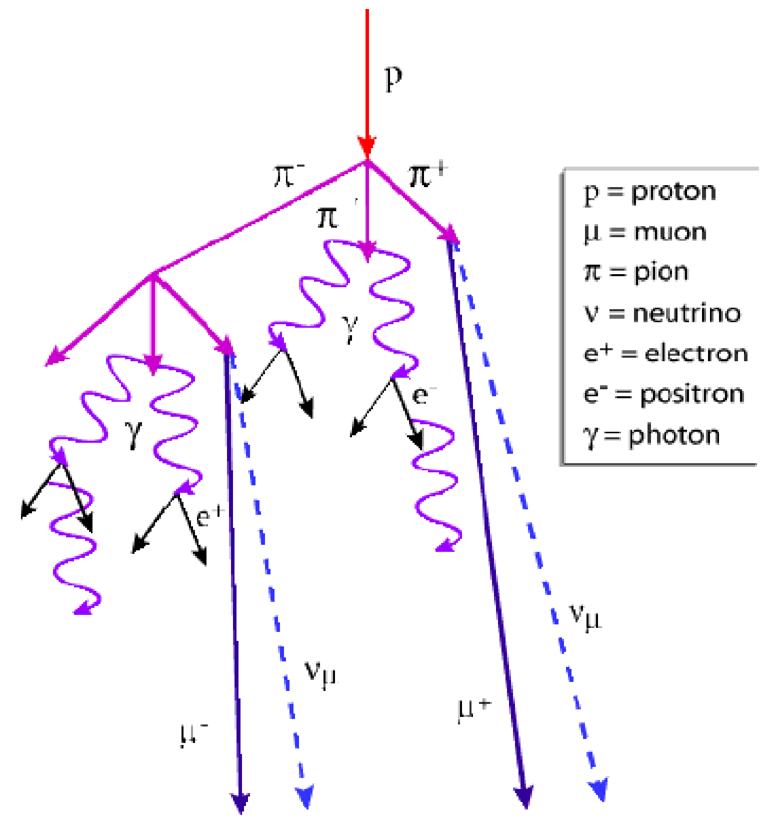


The IceCube lab at the South Pole has found neutrinos that may arise in the universe's most violent events.

Neutrinos in a Haystack

IceCube Collaboration
Science 342, 1242856 (2013)

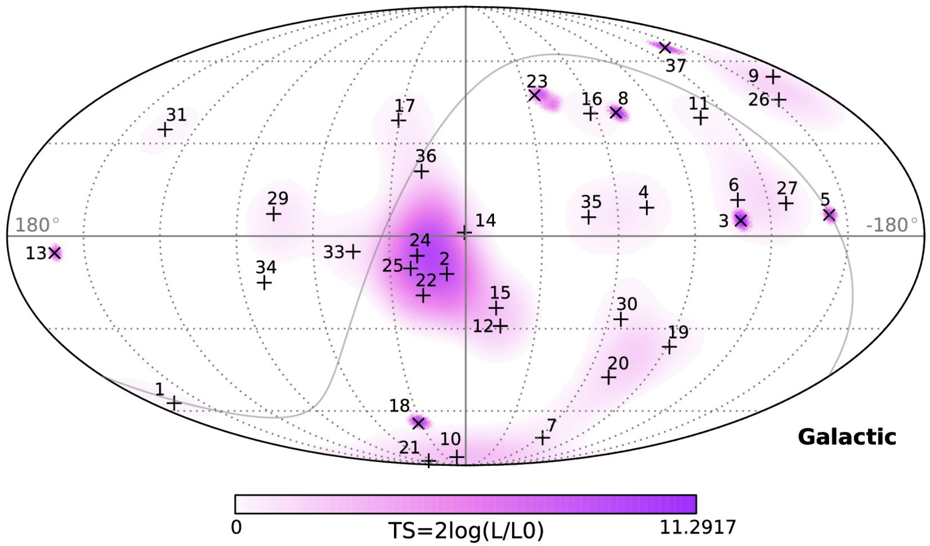


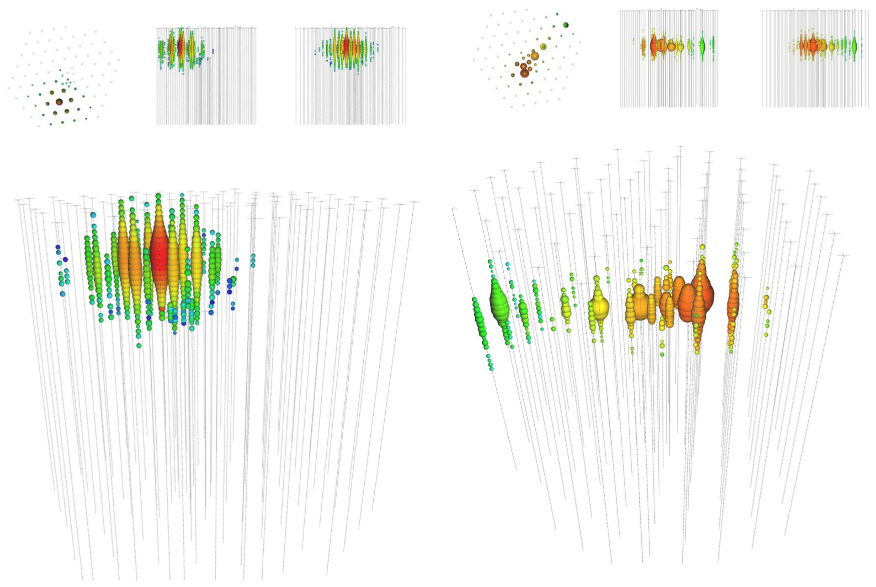


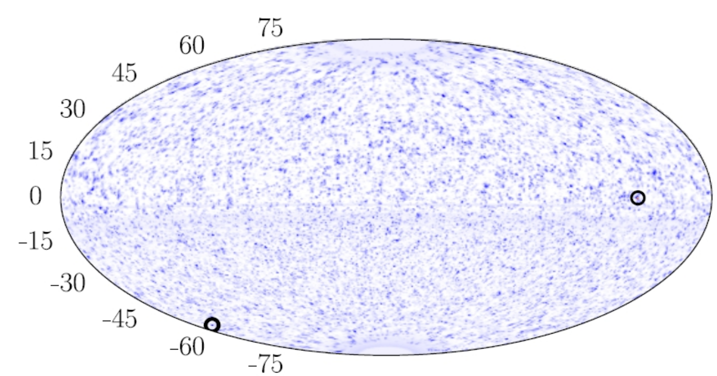
Background Rates:

Atmospheric Muons x~10^9
Atmospheric Neutrinos x~10^3

Where do they come from?
(my lesson 1)







2018: First high-energy neutrino source

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

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 of the Antarctic ice-sheet close to the Amundsen-Scott South Pole Station. The detector consists of 86 vertical strings frozen into the ice 125 m apart, each equipped with 60 digital optical modules (DOMs) at depths between 1450 and 2450 m. When a high-energy muon-neutrino interacts with an atomic nucleus in or close to the detec-

RESEARCH

RESEARCH ARTICLES

NEUTRINO ASTROPHYSICS

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

IceCube Collaboration*†

A high-energy neutrino event detected by IceCube on 22 September 2017 was coincident in direction and time with a gamma-ray flare from the blazar TXS 0506+056. Prompted by this association, we investigated 9.5 years of IceCube neutrino observations to search for excess emission at the position of the blazar. We found an excess of high-energy neutrino events, with respect to atmospheric backgrounds, at that position between September 2014 and March 2015. Allowing for time-variable flux, this constitutes 3.5σ evidence for neutrino emission from the direction of TXS 0506+056, independent of and prior to the 2017 flaring episode. This suggests that blazars are identifiable sources of the high-energy astrophysical neutrino flux.

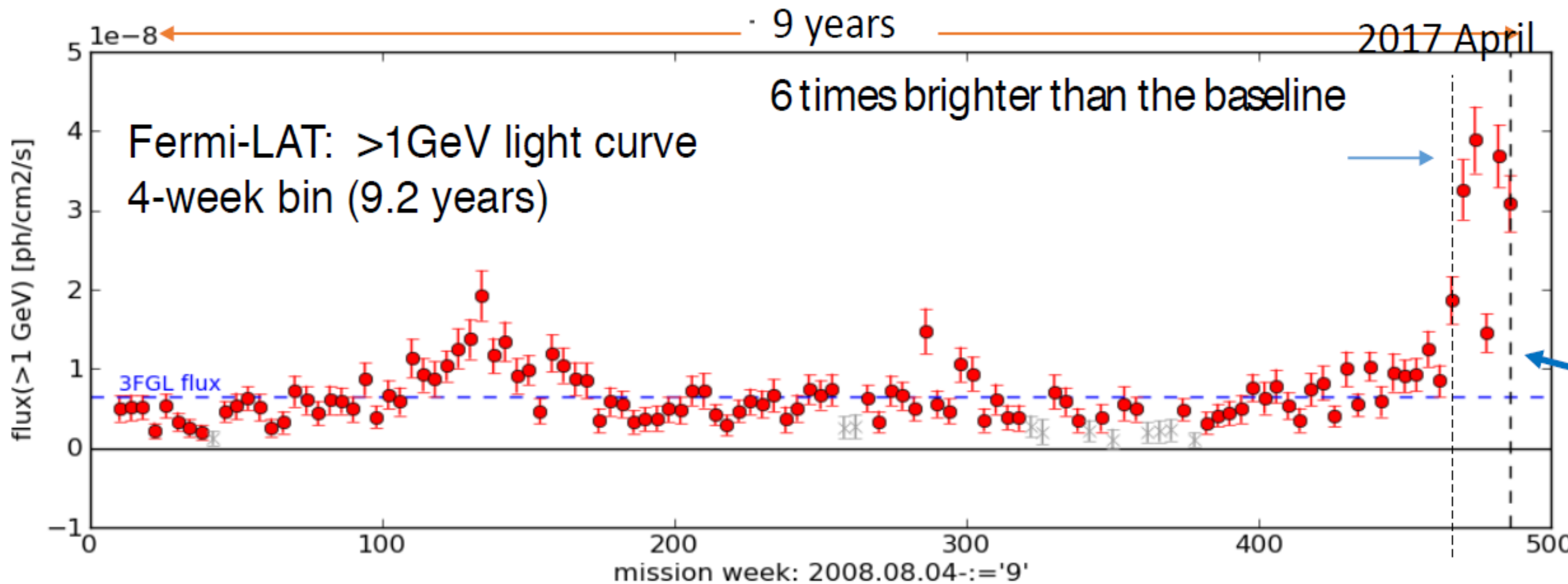
tion of TXS 0506+056 and coincident with a state of enhanced gamma-ray activity observed since April 2017 (*23*) by the Large Area Telescope (LAT) on the Fermi Gamma-ray Space Telescope (*24*). Follow-up observations of the blazar led to the detection of gamma rays with energies up to 400 GeV by the 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 that the blazar TXS 0506+056 has been a source of high-energy neutrinos beyond that single event.

Searching for neutrino emission

IceCube monitors the whole sky and has maintained essentially continuous observations since 5 April 2008. Searches for neutrino point sources using two model-independent methods, a time-integrated and a time-dependent unbinned maximum likelihood analysis, have previously been published for the data collected between 2008

Blazar TXS 0506+056

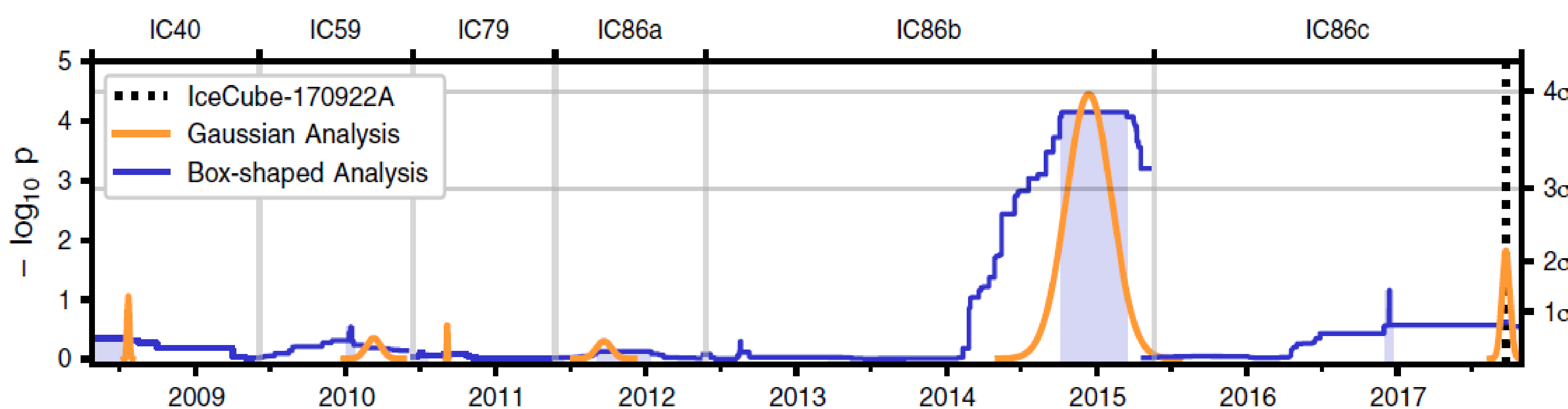
a) Multi-messenger Coincidence (Science 361 (2018) eaat1378)



p-value = 3σ

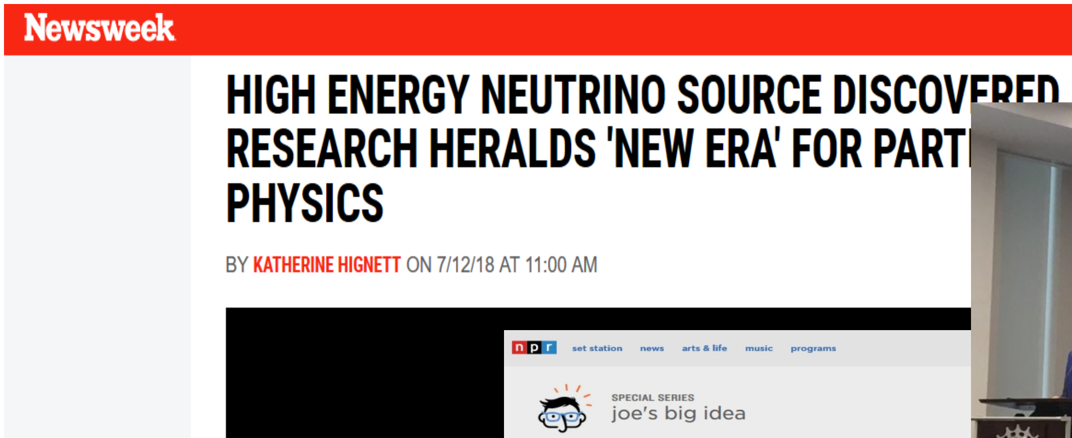
IceCube 170922A

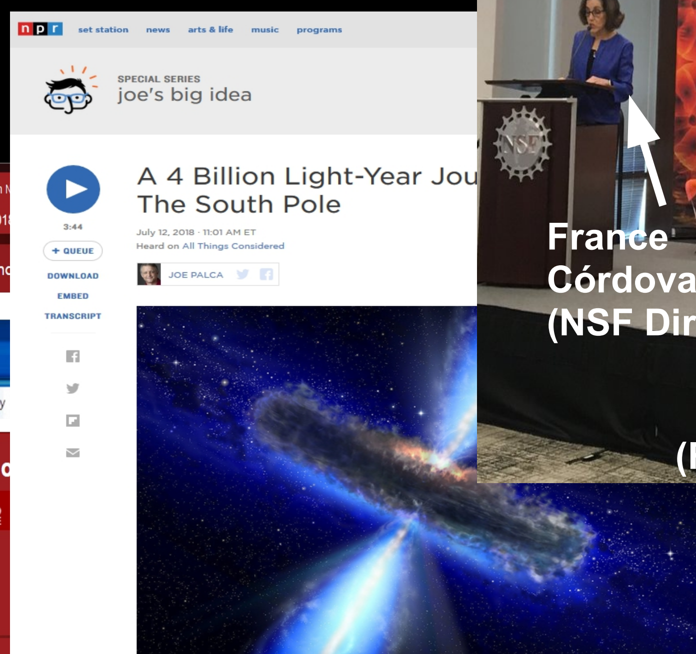
b) Archival neutrino search (Science 361 (2018) 147-151)

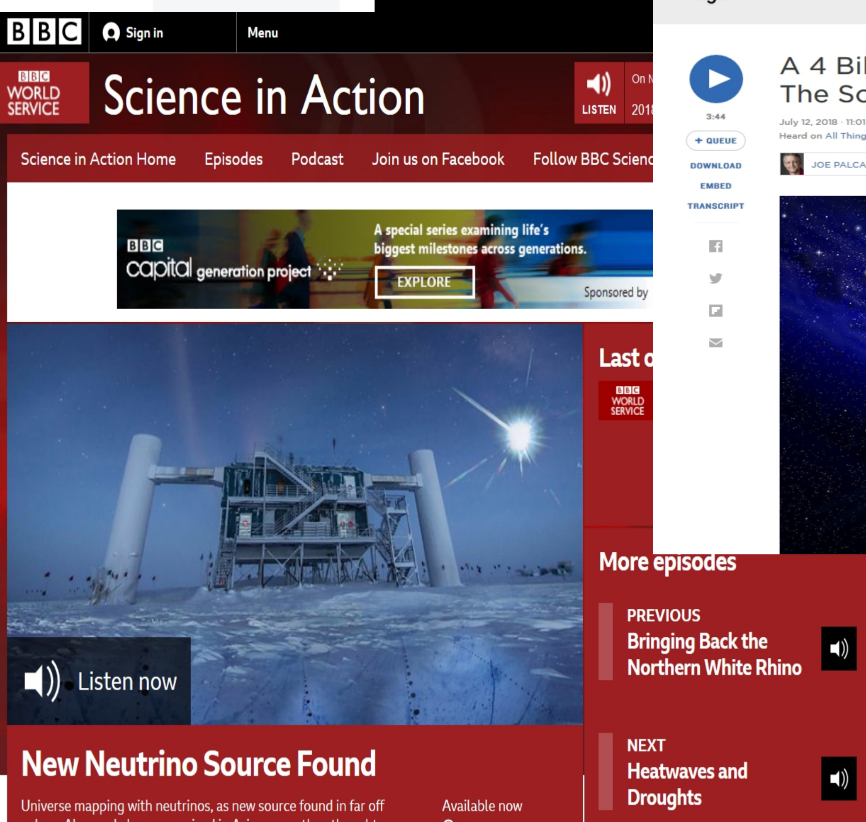


p-value = 3.5σ

More Press and A Press Conference!



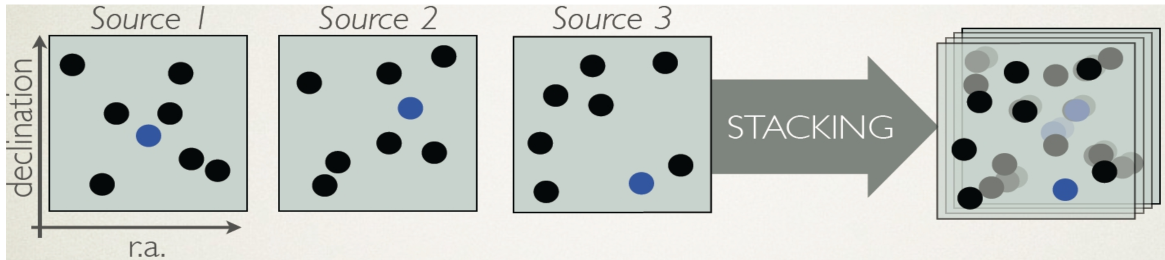




Only the two results together make this an interesting source (my lesson 2)

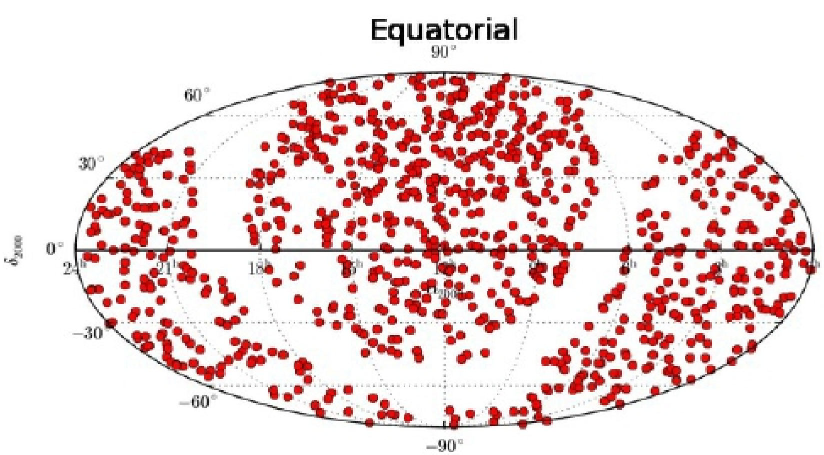
Neutrinos need to make statements alone to be a vital partner of multi-messenger astronomy

Try looking at where the gamma-ray sources are

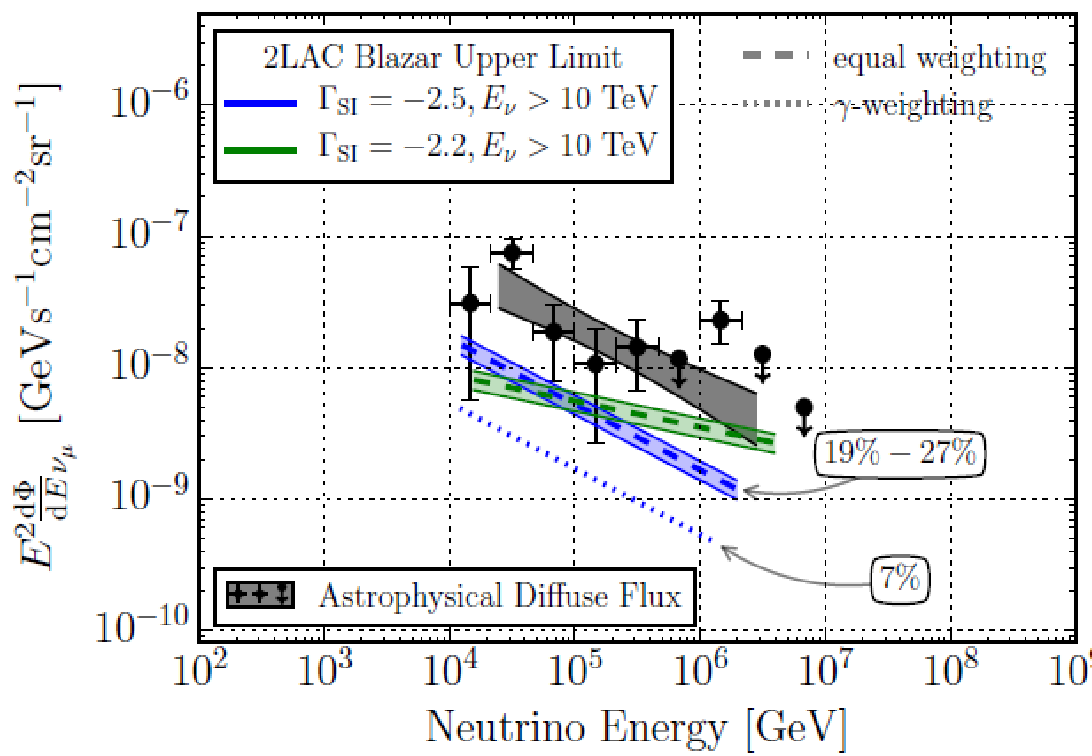


Stacking of 862 Fermi 2LAC Blazars ApJ vol. 835, no. 1, p. 45 (2017)

All Blazars in 2-LAC



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



We don't know what source population makes the neutrinos flux

		Upper limit in diffuse flux	notes
2LAC Blazars	All blazars	~ 7%	862 sources, E-2.5
	FSRQs	~5%	310 sources, E-2.5
	LSPs BL Lacs	~5%	68 sources, E-2.5
	ISP/HSP	~6%	301 sources, E-2.5
3FHL Blazars	All blazars	~17%	745 northern sources, E-2
	HSP BL Lacs	~15%	356 northern sources, E-2
	LSP/ISP BL Lacs	~12%	212 north sky sources, E-2
	FSRQs	~17 %	101 north sky sources, E-2
Nearby Starburst Galaxies		~ 8%	127 sources, E-2
Galactic Sources	Young SNR	~ 5%	30 sources no PWN or MC, E-2
	Young PWN	~ 3%	10 sources with no MC, E-2
GRBs		~1%	506 bursts, E-2 to -2.7

ApJ vol. 835 (2017), Astrophys.J. 796:10 (2014), ApJ, 805, L5 (2015), PoS-ICRC2019-916

1. Maybe GeV gamma not the right/only energy band for neutrino counterparts?

2. But there are some correlations (sometimes), so what are the conditions?

IceCube publications from point source working group, 2018-2020

IceCube Search for Neutrinos Coincident with Compact Binary Mergers from LIGO-Virgo's First Gravitational-wave Transient Catalog
Astrophys.J.Lett. 898 (2020) 1, L10, Astrophys.J. 898 (2020) 1, L10

IceCube Search for High-Energy Neutrino Emission from TeV Pulsar Wind Nebulae.
Astrophys.J. 898 (2020) 2, 117

ANTARES and IceCube Combined Search for Neutrino Point-like and Extended Sources in the Southern Sky
Astrophys.J. 892 (2020), 92

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Astrophys. J., 892 (2020), 1

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JCAP 07 (2020), 042

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Phys.Rev.Lett. 124 (2020) 5, 051103

A Search for Neutrino Point-source Populations in 7 yr of IceCube Data with Neutrino-count Statistics
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Eur.Phys.J.C 79 (2019) 3, 234

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Astrophys.J.Lett. 868 (2018) 2, L20, Astrophys.J. 868 (2018) 2, L20

Constraints on minute-scale transient astrophysical neutrino sources
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A Search for Neutrino Emission from Fast Radio Bursts with Six Years of IceCube Data
Astrophys.J. 857 (2018) no.2, 117..

IceCube publications from point source working group, 2018-2020 that uses Fermi-LAT data

IceCube Search for Neutrinos Coincident with Compact Binary Mergers from LIGO-Virgo's First Gravitational-wave Transient Catalog
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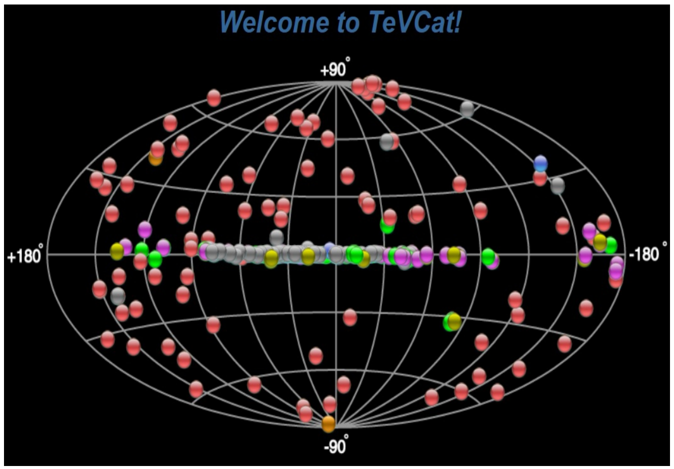
TeVCAT, x-rays, optical, IR, radio



"IceCube Search for High-Energy Neutrino Emission from TeV Pulsar Wind Nebulae"
IAstrophys.J. 898 (2020) 2, 117

The Detection of a SN IIn in Optical Follow-up Observations of IceCube Neutrino Events
Astrophys.J. 811 (2015) no.1, 52

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Science 361 (2018) no.6398, eaat1378

Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert
Science 361 (2018) no.6398, 147-151.

A Search for Neutrino Emission from Fast Radio Bursts with Six Years of IceCube Data
Astrophys.J. 857 (2018) no.2, 117..

IceCube publications from point source working group, 2018-2020 that uses track events

IceCube Search for Neutrinos Coincident with Compact Binary Mergers from LIGO-Virgo's First Gravitational-wave Transient Catalog
Astrophys.J.Lett. 898 (2020) 1, L10, Astrophys.J. 898 (2020) 1, L10

IceCube Search for High-Energy Neutrino Emission from TeV Pulsar Wind Nebulae.
Astrophys.J. 898 (2020) 2, 117

ANTARES and IceCube Combined Search for Neutrino Point-like and Extended Sources in the Southern Sky
Astrophys.J. 892 (2020), 92

A search for IceCube events in the direction of ANITA neutrino candidates
Astrophys. J., 892 (2020), 1

Constraints on neutrino emission from nearby galaxies using the 2MASS redshift survey and IceCube
JCAP 07 (2020), 042

Time-Integrated Neutrino Source Searches with 10 Years of IceCube Data
Phys.Rev.Lett. 124 (2020) 5, 051103

A Search for Neutrino Point-source Populations in 7 yr of IceCube Data with Neutrino-count Statistics
Astrophys.J. 893 (2020) 2, 102

A Search for MeV to TeV Neutrinos from Fast Radio Bursts with IceCube
Astrophys.J. 890 (2020) 2, 111

Search for Sources of Astrophysical Neutrinos Using Seven Years of IceCube Cascade Events
Astrophys.J. 886 (2019), 12

Neutrinos below 100 TeV from the southern sky employing refined veto techniques to IceCube data
Astropart.Phys. 116 (2020), 102392

Investigation of two Fermi-LAT gamma-ray blazars coincident with high-energy neutrinos detected by IceCube
Astrophys.J. 880 (2019) 2, 880:103

Search for transient optical counterparts to high-energy IceCube neutrinos with Pan-STARRS1
Astron.Astrophys. 626 (2019), A117

Search for steady point-like sources in the astrophysical muon neutrino flux with 8 years of IceCube data
Eur.Phys.J.C 79 (2019) 3, 234

Search for Multimessenger Sources of Gravitational Waves and High-energy Neutrinos with Advanced LIGO during Its First Observing Run, ANTARES, and IceCube
Astrophys.J. 870 (2019) 2, 134

Joint Constraints on Galactic Diffuse Neutrino Emission from the ANTARES and IceCube Neutrino Telescopes
Astrophys.J.Lett. 868 (2018) 2, L20, Astrophys.J. 868 (2018) 2, L20

Constraints on minute-scale transient astrophysical neutrino sources
Phys.Rev.Lett. 122 (2019) 5, 051102

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A
Science 361 (2018) no.6398, eaat1378

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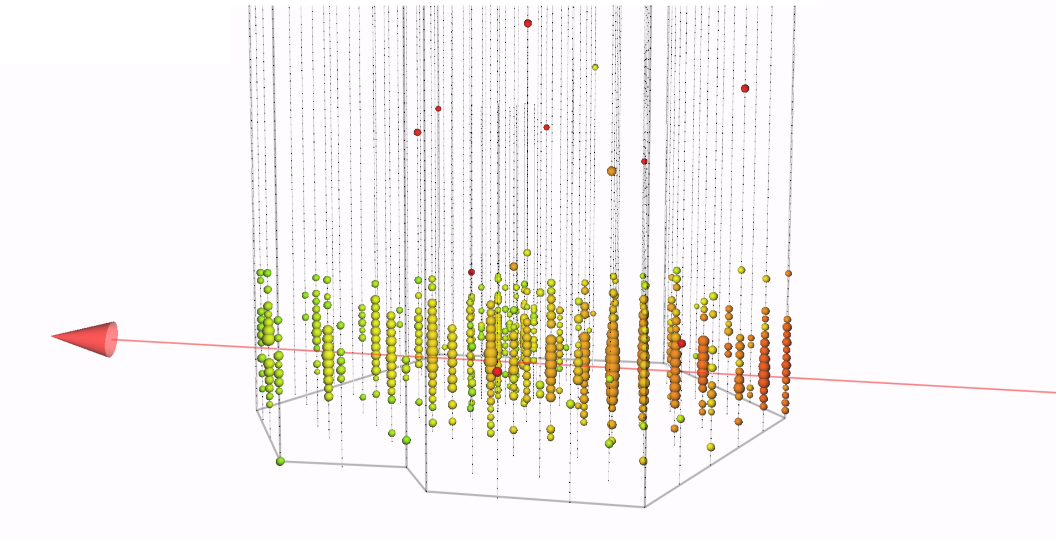
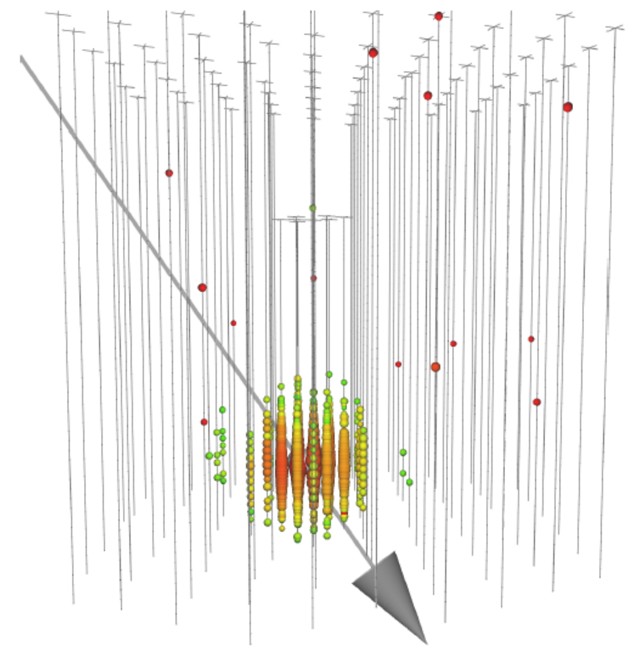
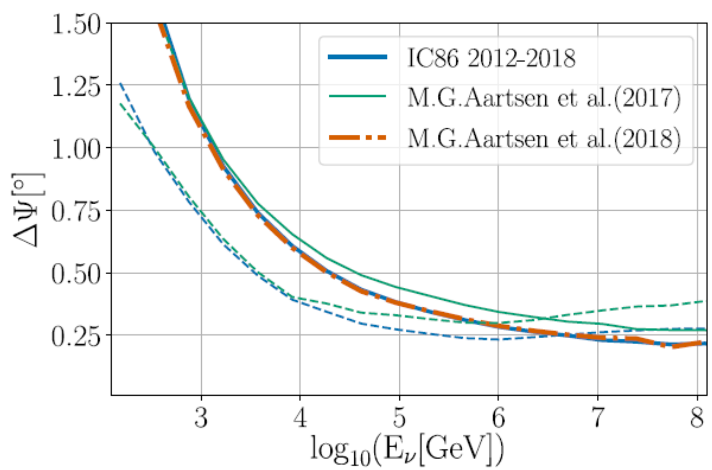
A Search for Neutrino Emission from Fast Radio Bursts with Six Years of IceCube Data
Astrophys.J. 857 (2018) no.2, 117..

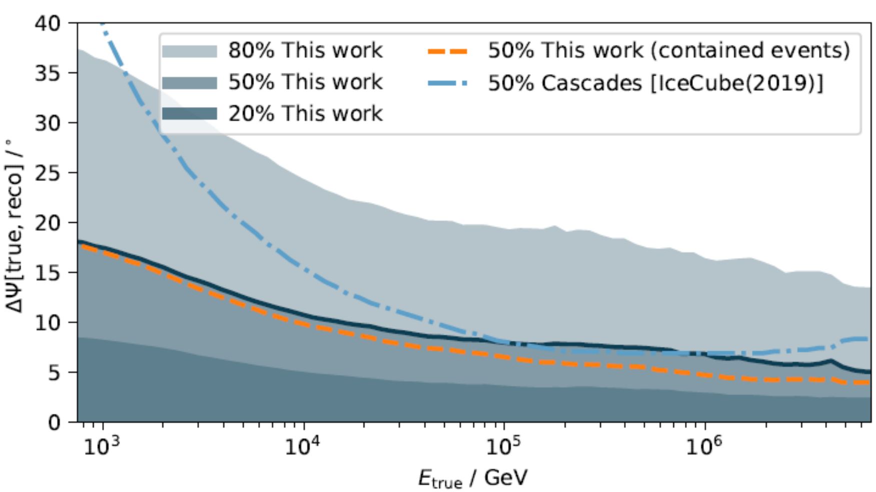
Track Events vs Cascade Events







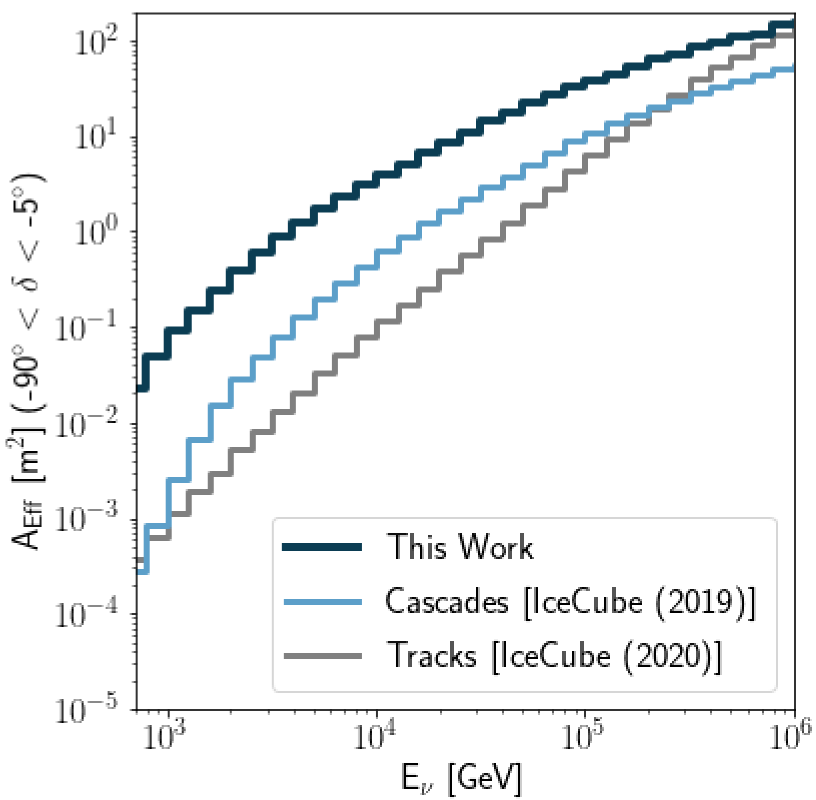
Phys. Rev. Lett. 124, 051103 (2020)



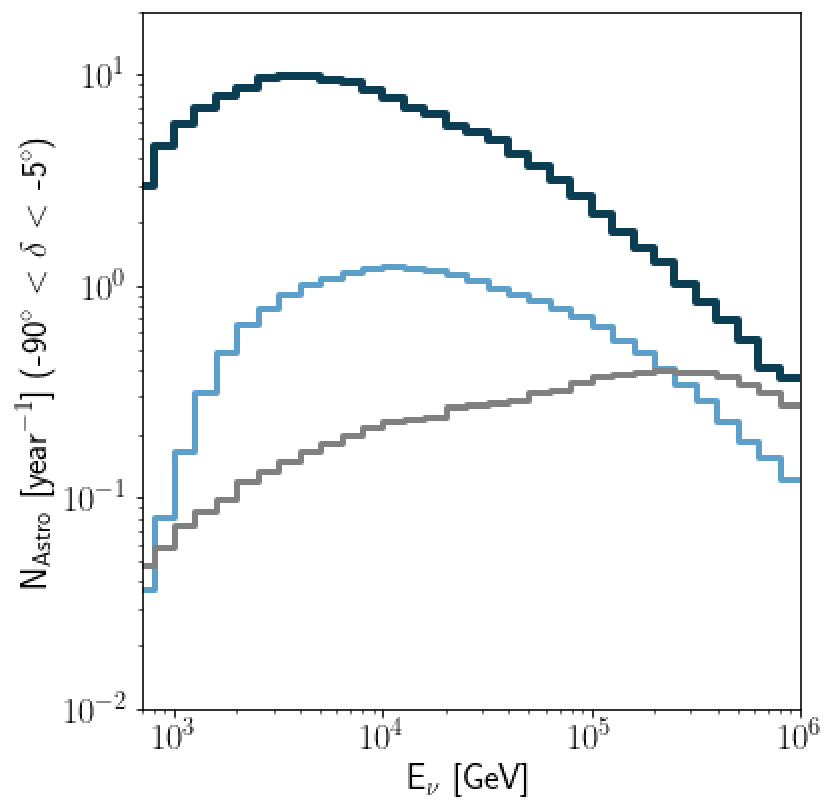
Naoko Kurahashi Neilson,

Southern Sky

Effective Area

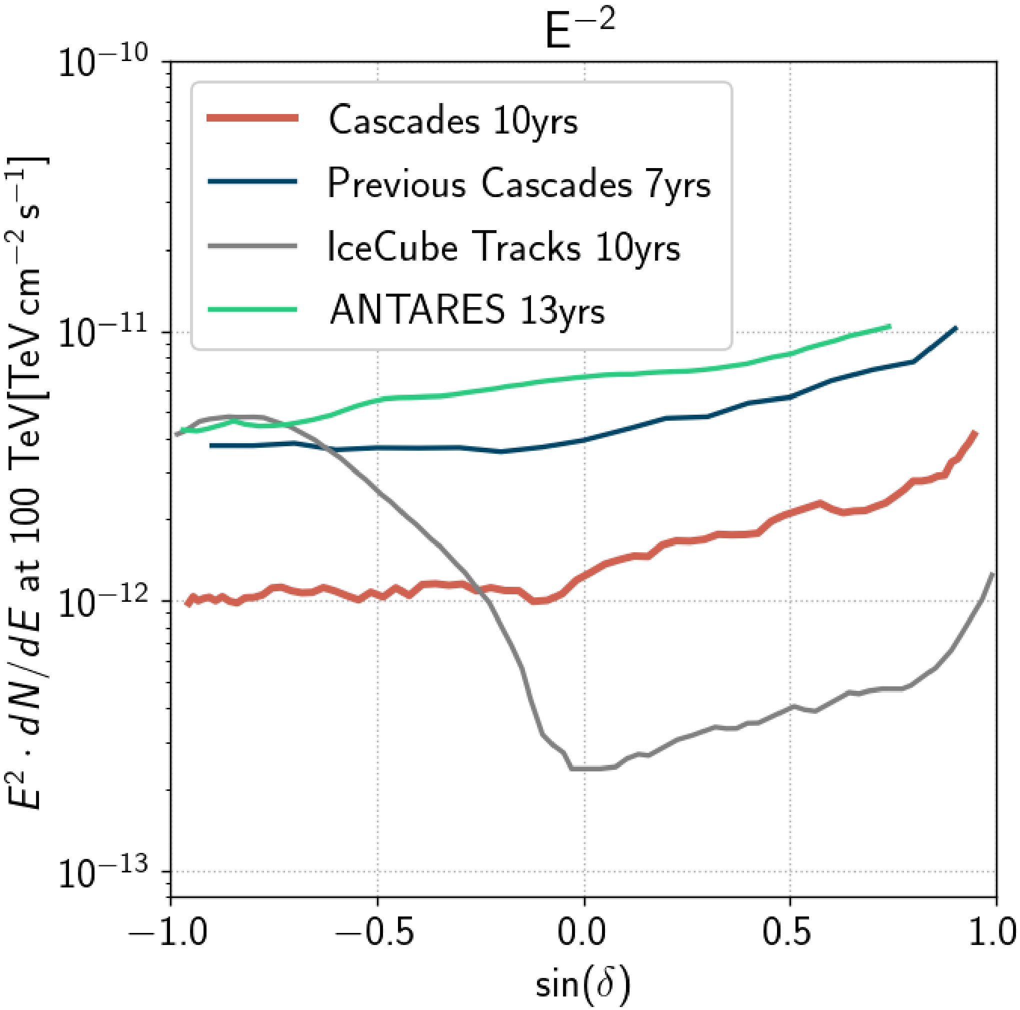


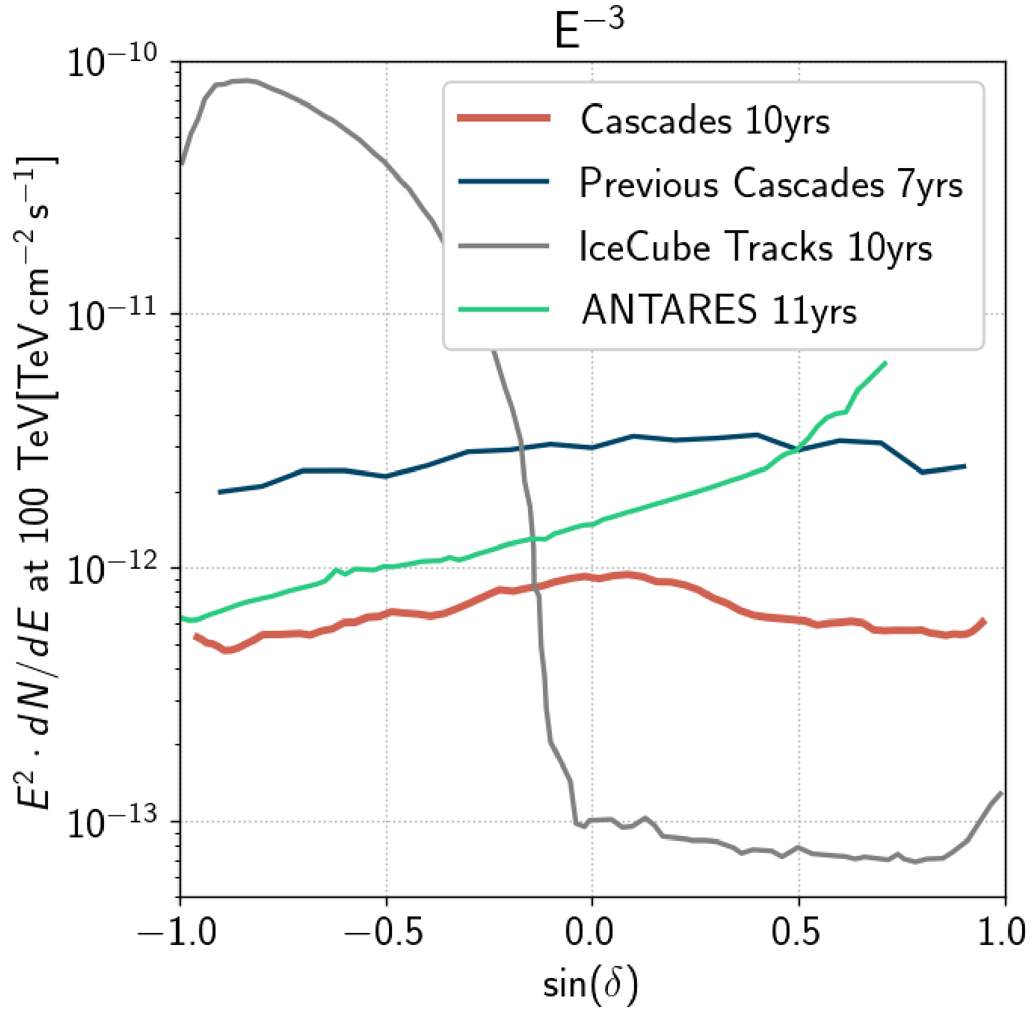
Event Counts



Tracks ~300 events/day
Cascades (New) ~17 events/day

Sensitivity to a Point Source





- Worse pointing

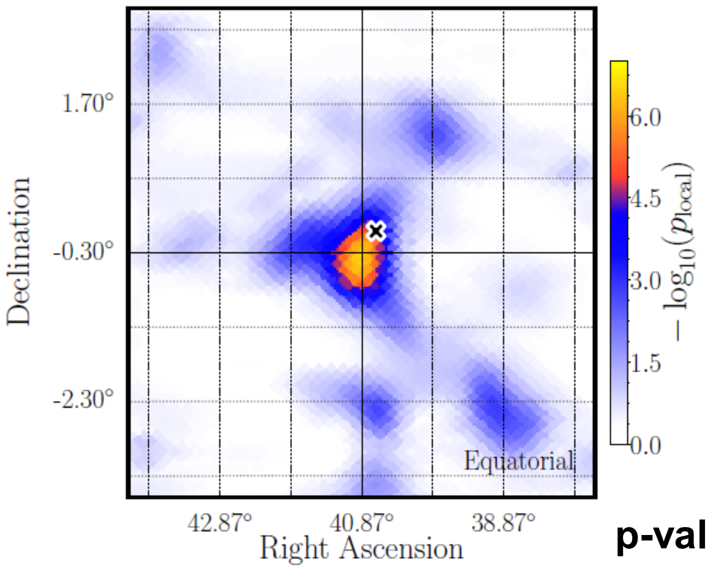
  but

- Better in Southern Sky
- Better in Soft spectrum
- Better Signal to Background

Sources that are soft spectrum and southern (ie Galactic!) does MUCH better with cascades. Even more so if it's extended sources

More interesting spots emerging!

IceCube: Phys. Rev. Lett. 124 (2020) 051103



NGC1068

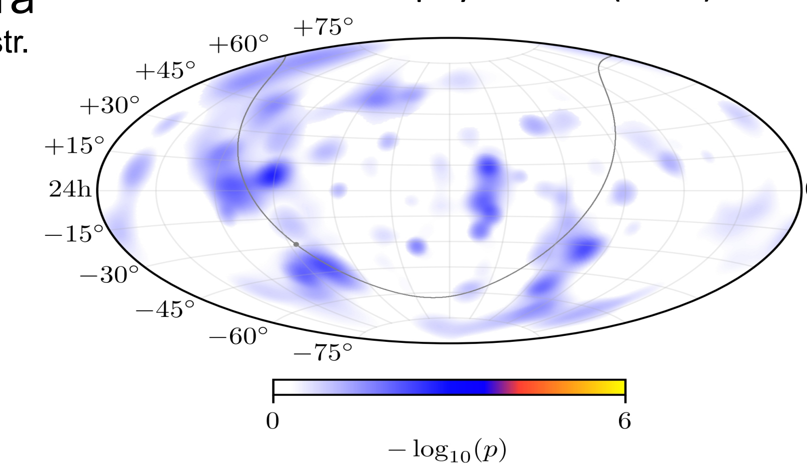
- Starburst Galaxy
- Seyfert II
- 14 Mpc
- AGN-driven particle accelera

(A. Lamastra, et al, Astr. Astrop. 596 (2016))

p-value = 0.2% (~2.9 σ)

Galactic Plane

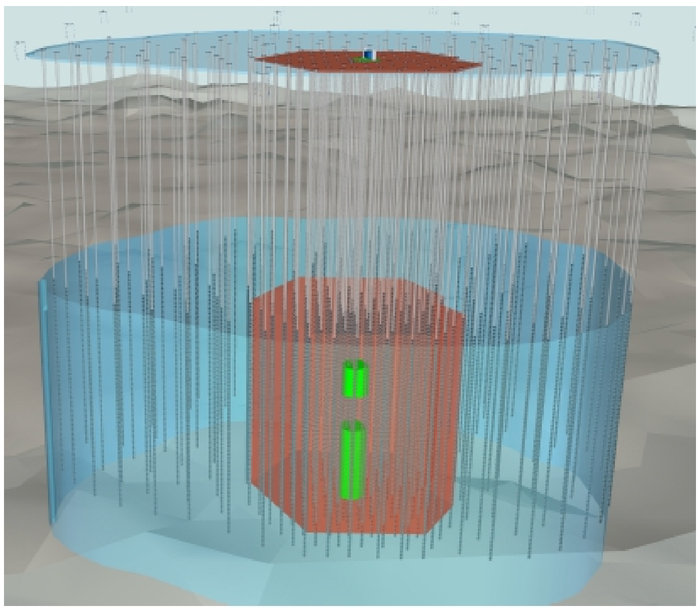
Astrophys. J. 886 (2019) 12

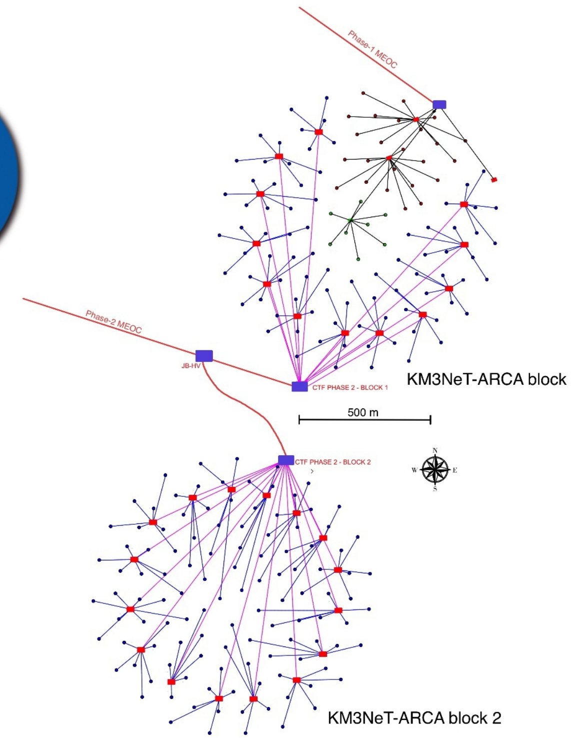


P-value = 2.1%

Template	7yr Cascades				Previous Work			
	p-value	Sensitivity	Fitted Flux	UL	p-value	Sensitivity	Fitted Flux	UL
KRA_{γ}^{5}	0.021	0.58	0.85	1.7	0.29	0.81	0.47	1.19
KRA_{γ}^{50}	0.022	0.35	0.65	0.97	0.26	0.57	0.37	0.90
Fermi-LAT π^0	0.030	2.5	3.3	6.6	0.37	2.97	1.28	3.83

The Future of Neutrino Astronomy is Already Being Built





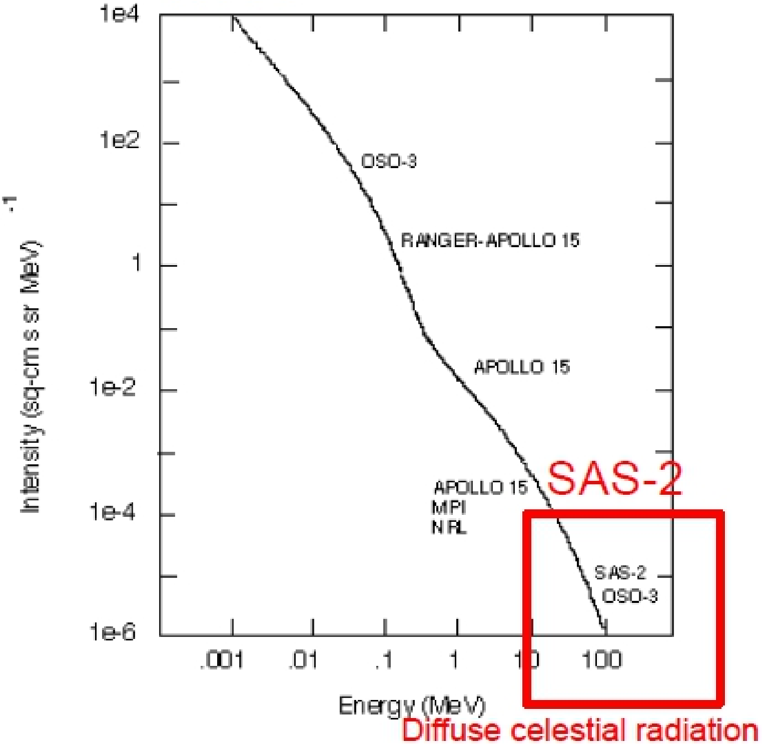
IceCube Gen2
Upgrade currently being built
Full Gen2 ~2026-2033 deployment?

KM3NeT
Strings being deployed since 2015
~2026 completion?

Historical Perspective: Gamma-ray Astronomy

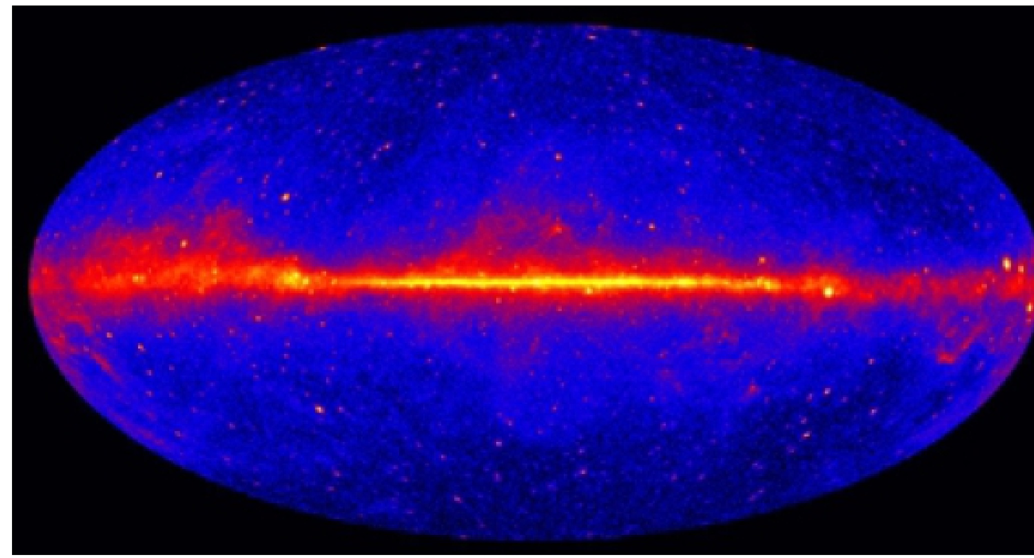
Diffuse signal → first source → catalog!

1970's



NOW

Fermi!

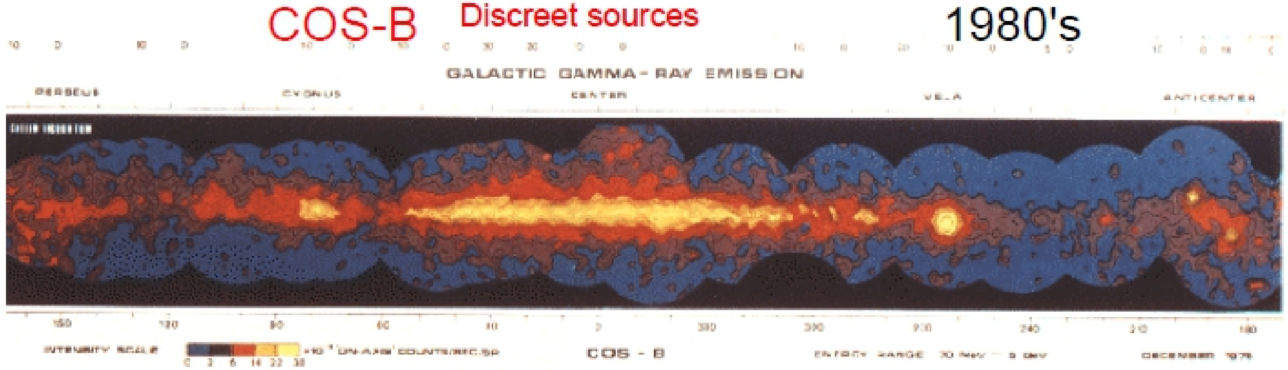


GSFC nasa.gov

COS-B

Discreet sources

1980's



GSFC nasa.gov

Historical Perspective: X-ray Astronomy

Diffuse signal → first source → catalog

Diffuse emission and Scorpius X-1 1960's

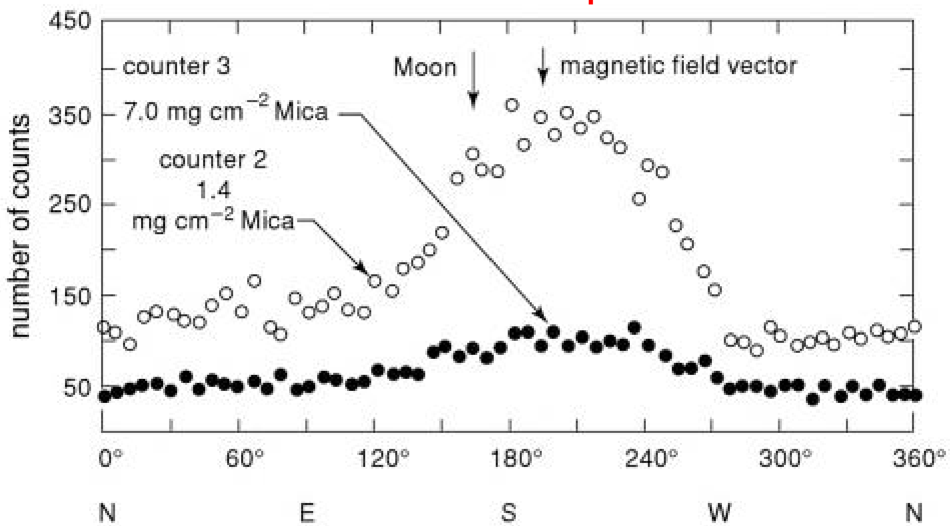
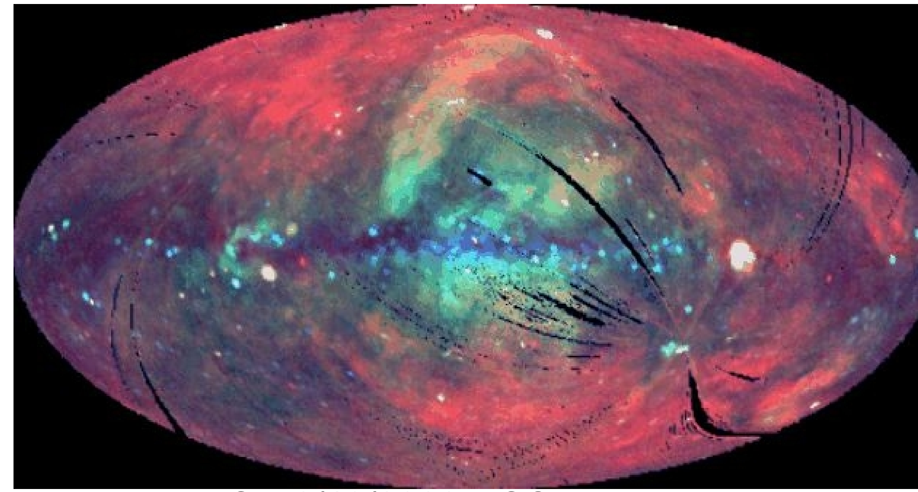
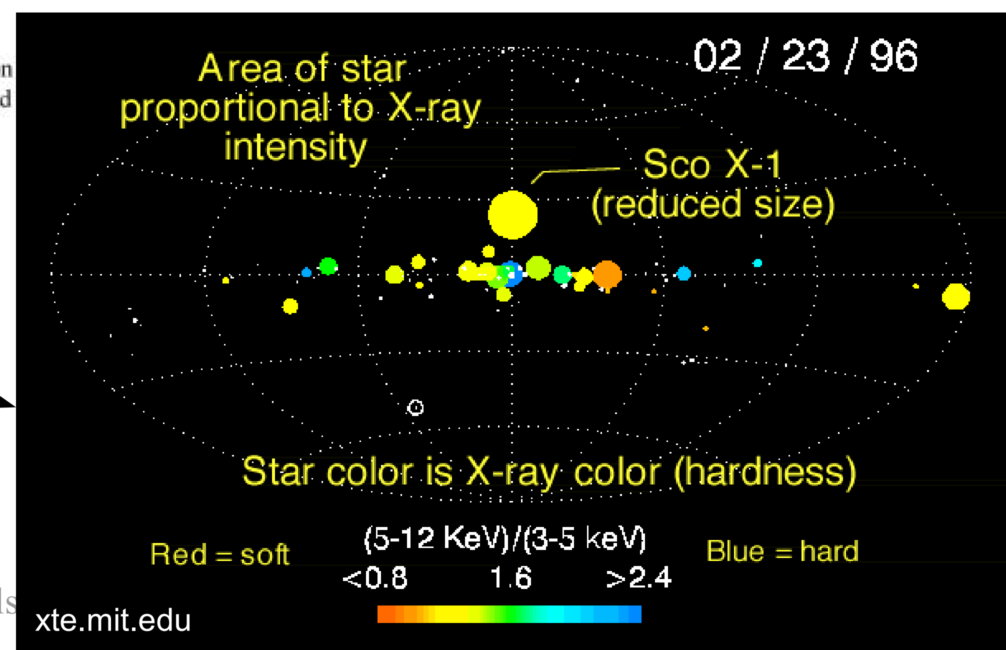


Figure 7.7: The discovery record of the X-ray source Sco X-1 and the X-ray background emission Giacconi and his colleagues in a rocket flight of June 1962. The prominent source was observed both detectors, as was the diffuse background emission (Giacconi *et al.*, 1962).

"The Cosmic Century" M. S. Longair



APOD 8/19/2000 ROSAT



Conclusions

We are on the cusp of a “neutrino source catalog”

We are finally at a point where neutrino data can ask the questions.

Next generation detectors will help, but until then, can we get more out of the current data by

- Figuring out the relationship between GeV gamma rays and TeV neutrinos?
- What other wavelength/messenger can work?