Neutrino Astronomy: Historical Milestones and Future Directions

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Drexel University

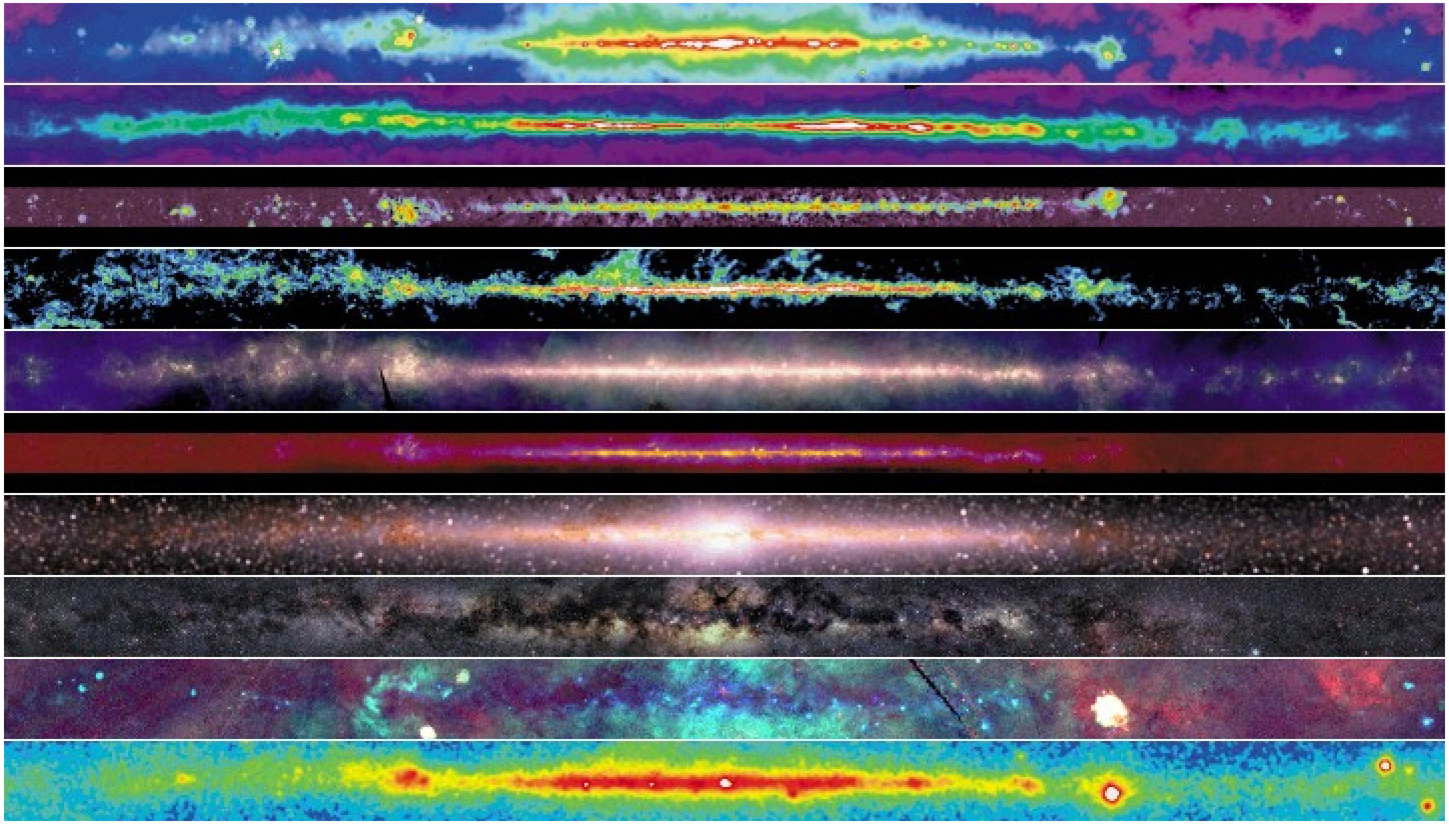
The third annual conference of Transformative Research Areas (A), "Multimessenger Astrophysics"
Naruko Onsen, Nov 17th, 2025

The Prelude:
Intro to HE Neutrino Astronomy


img credit: Yuya Makino/NSF

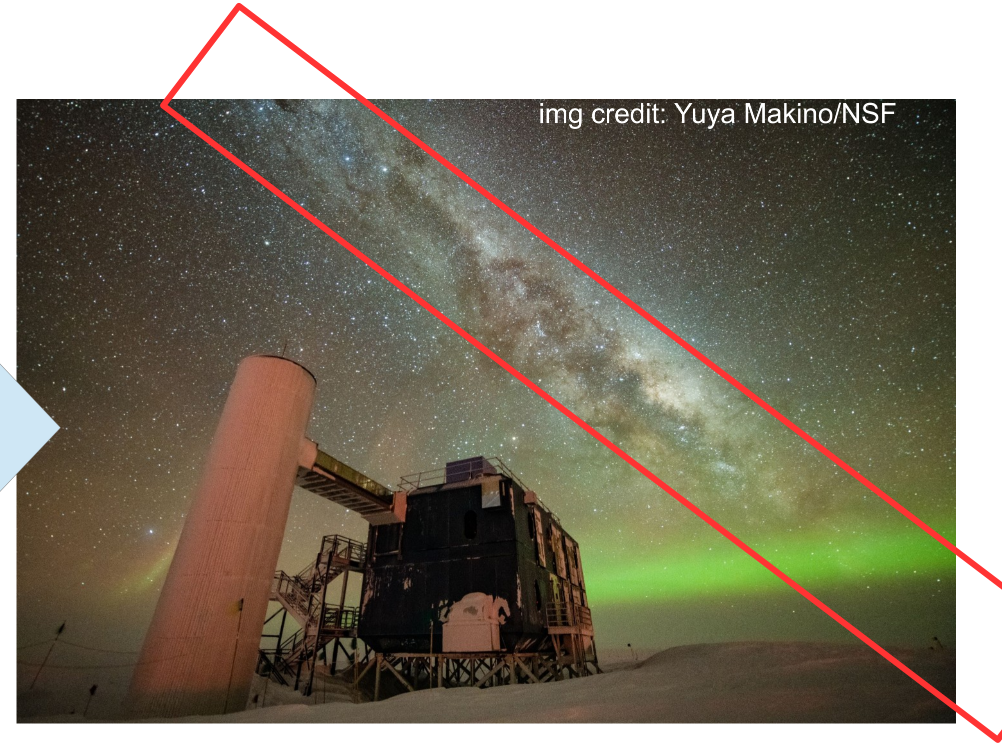
The Milky Way

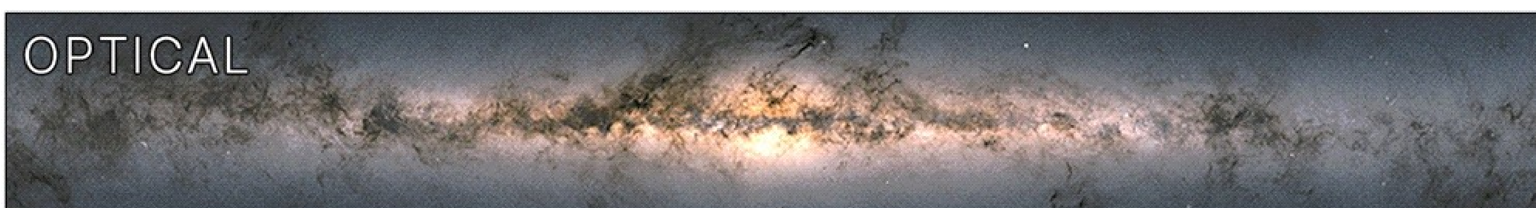
Iconic image of the multiwavelength Milky Way
(+/- 10° in latitude, from radio to gamma ray)



https://asd.gsfc.nasa.gov/archive/mwmw/mmw_images.html

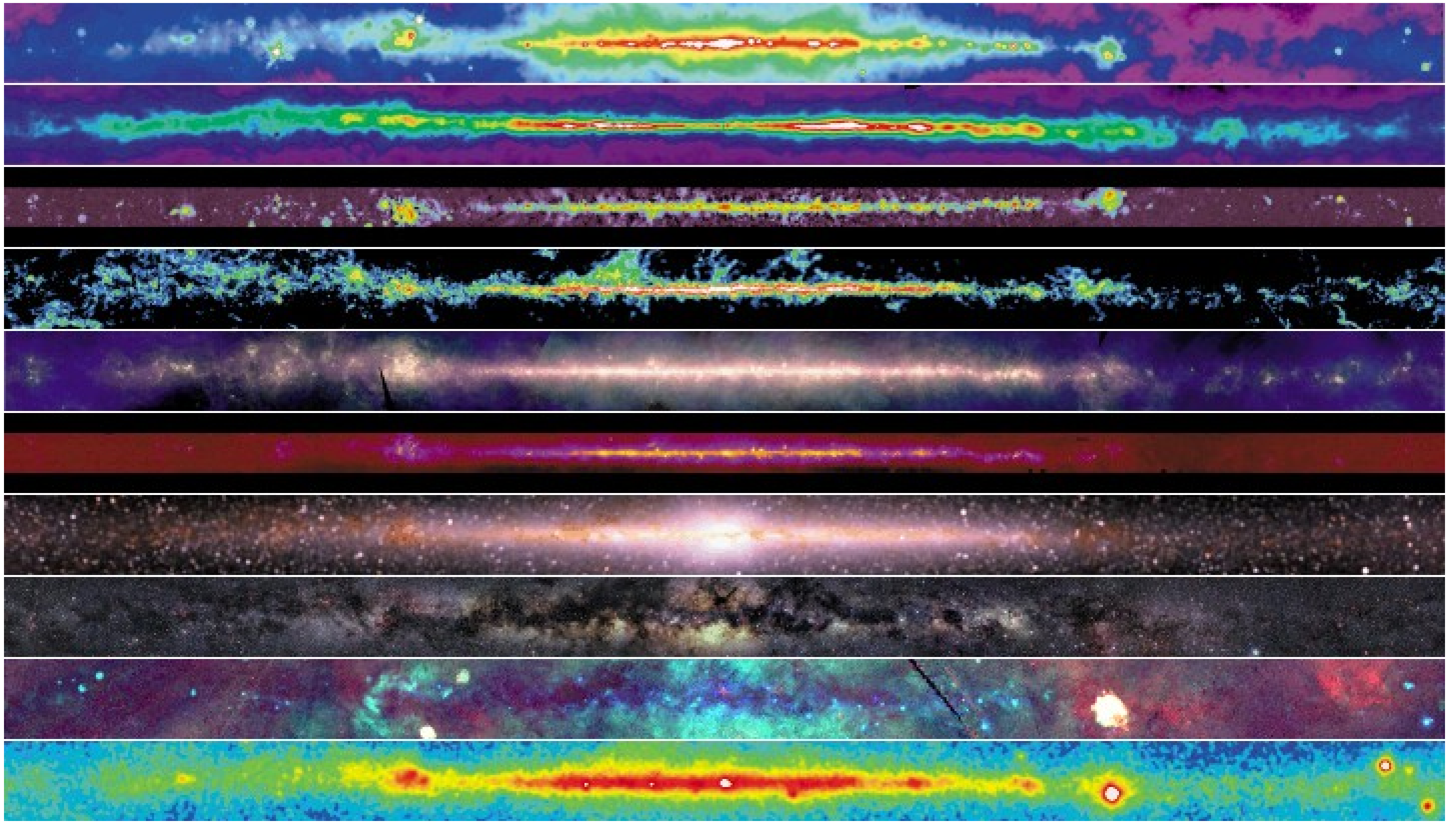

Look this way
WE ARE HERE


img credit: Yuya Makino/NSF


OPTICAL

The Milky Way

Iconic image of the multiwavelength Milky Way
(+/- 10^{o} in latitude, from radio to gamma ray)

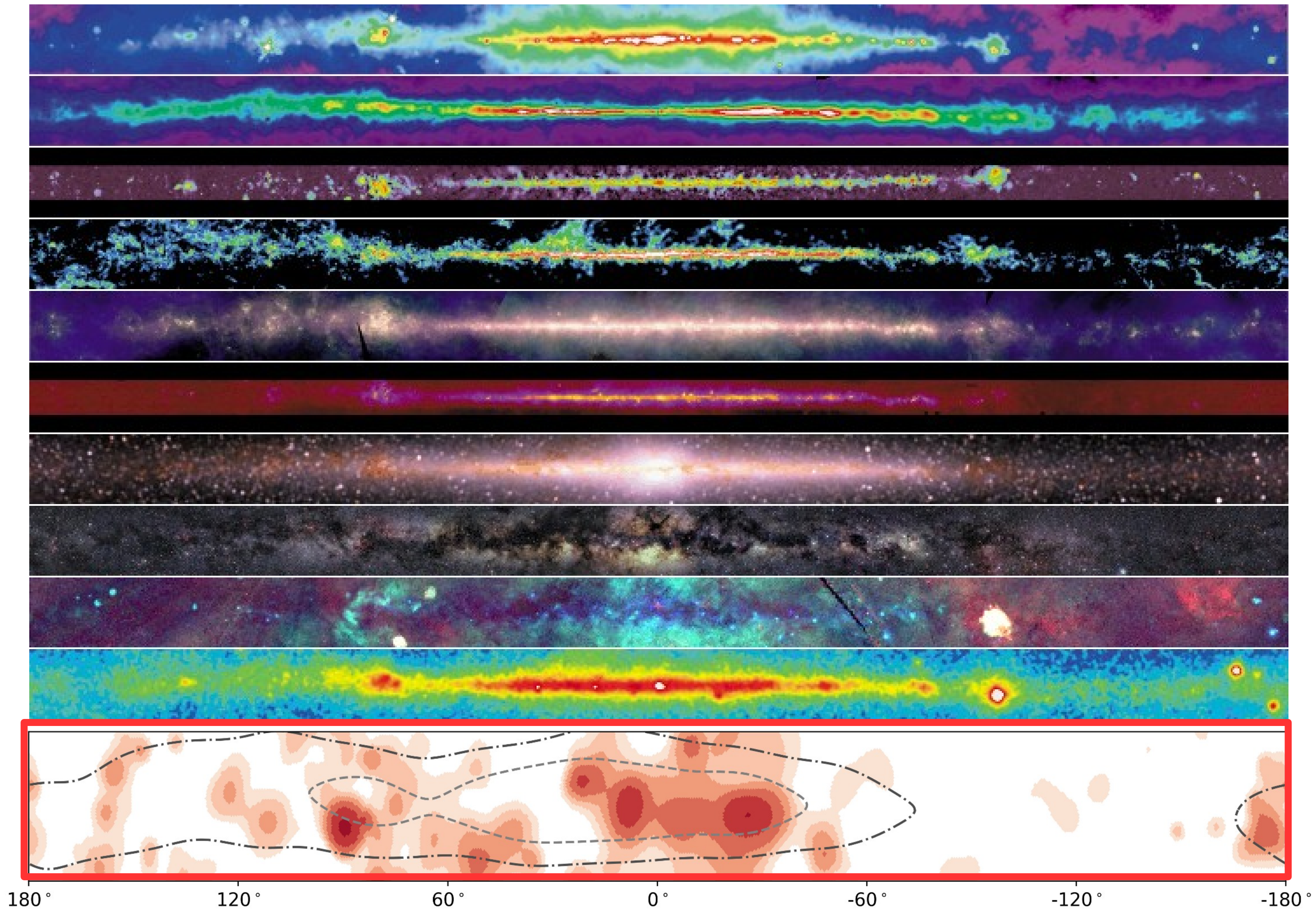


https://asd.gsfc.nasa.gov/archive/mwmw/mmw_images.html


Galactic Longitude
atomic hydrogen
molecular hydrogen
infrared
near infrared
optical
x-ray
gamma ray
Galactic Latitude
CYGNUS LOOP
KEPLER'S SNR
GALACTIC BULGE
CARINA NEBULA
VELA
PUPPIS A
CRAB
GEMINGA
Multiwavelength Milky Way
NASA
Periodic Table of Elements

The Milky Way

In Neutrinos!!!



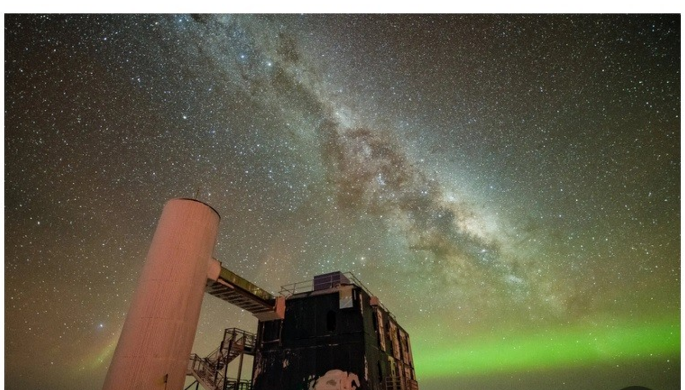
First time, a non-EM view of our Galaxy!

The New York Times

Neutrinos Build a Ghostly Map of the Milky Way

Astronomers for the first time detected neutrinos that originated within our local galaxy using a new technique.

Share full article



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RESEARCH

RESEARCH ARTICLES

NEUTRINO ASTROPHYSICS

Observation of high-energy neutrinos from the Galactic plane

IceCube Collaboration*†

The origin of high-energy cosmic rays, atomic nuclei that continuously impact Earth's atmosphere, is unknown. Because of deflection by interstellar magnetic fields, cosmic rays produced within the Milky Way arrive at Earth from random directions. However, cosmic rays interact with matter near their sources and during propagation, which produces high-energy neutrinos. We searched for neutrino emission using machine learning techniques applied to 10 years of data from the IceCube Neutrino Observatory. By comparing diffuse emission models to a background-only hypothesis, we identified neutrino emission from the Galactic plane at the 4.5σ level of significance. The signal is consistent with diffuse emission of neutrinos from the Milky Way but could also arise from a population of unresolved point sources.

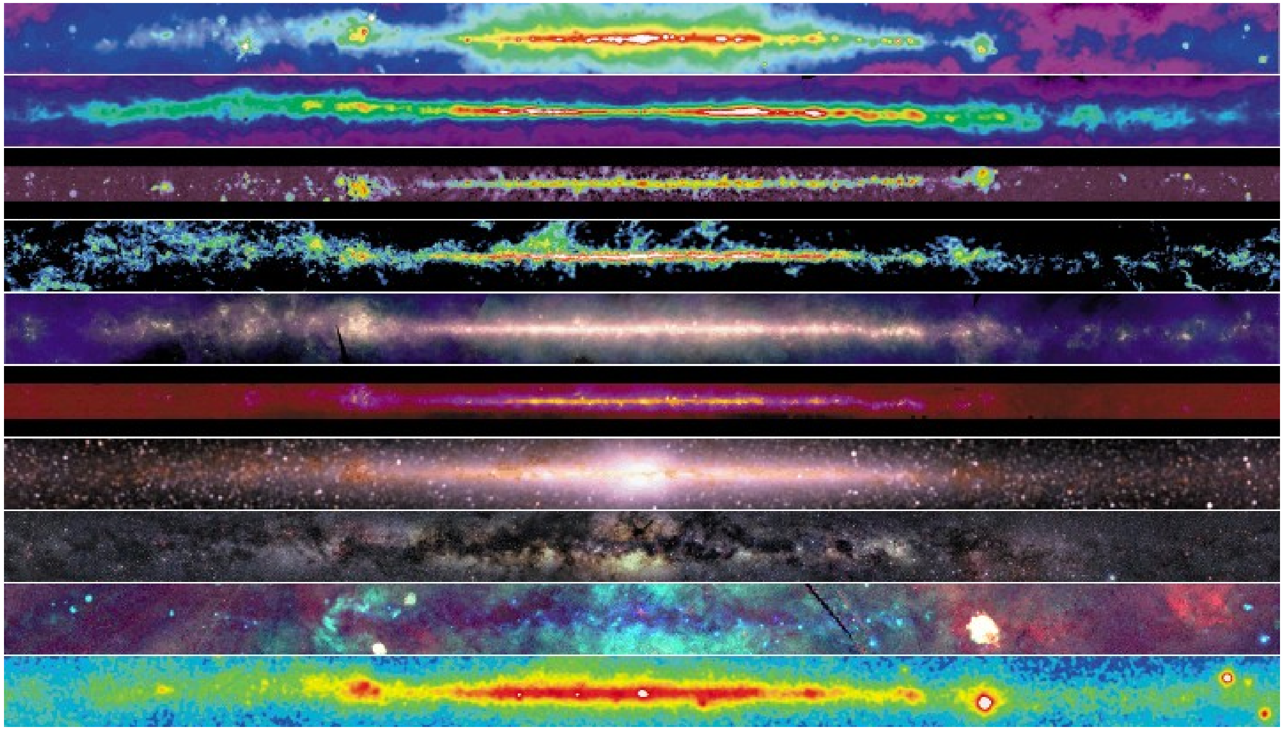
The Milky Way emits radiation across the electromagnetic spectrum, from radio waves to gamma rays. Observations at different wavelengths provide insight into the structure of the Galaxy and have iden- energy gamma-ray point sources (also visible in Fig. 1B), several classes of which are potential cosmic-ray accelerators and therefore possible neutrino sources (*6–10*). This makes the Galactic plane an expected location of

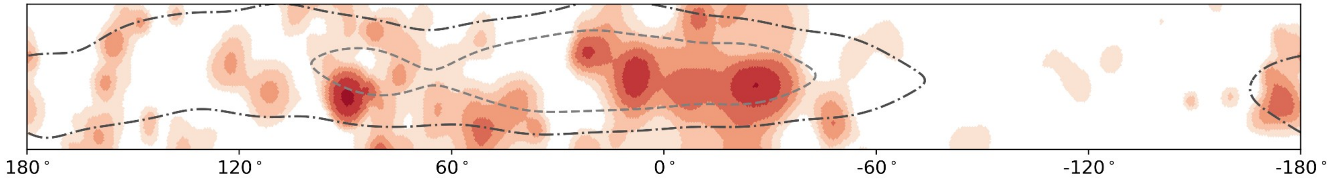
neutrino (v_τ) with nuclei, as well as scattering interactions of all three neutrino flavors [v_e, muon neutrino (v_μ), and v_τ] on nuclei. Because the charged particles in cascade events travel only a few meters, these energy depositions appear almost point-like to IceCube's 125-m (horizontal) and 7- to 17-m (vertical) instrument spacing. This results in larger directional uncertainties than tracks. Tracks are elongated energy depositions (often several kilometers long), which arise predominantly from muons generated in cosmic-ray particle interactions in the atmosphere or muons produced by interactions of v_μ with nuclei. The energy deposited by cascades is often contained within the instrumented volume (unlike tracks), which provides a more complete measure of the neutrino energy (*19*).

Searches for astrophysical neutrino sources are affected by an overwhelming background of muons and neutrinos produced by cosmic-ray interactions with Earth's atmosphere. Atmospheric muons dominate this background; IceCube records about 100 million muons for every observed astrophysical neutrino. Whereas muons from the Southern Hemisphere (above IceCube) can penetrate several kilometers deep

Now that we see it, the questions...

https://asd.gsfc.nasa.gov/archive/mwmw/mmw_images.html

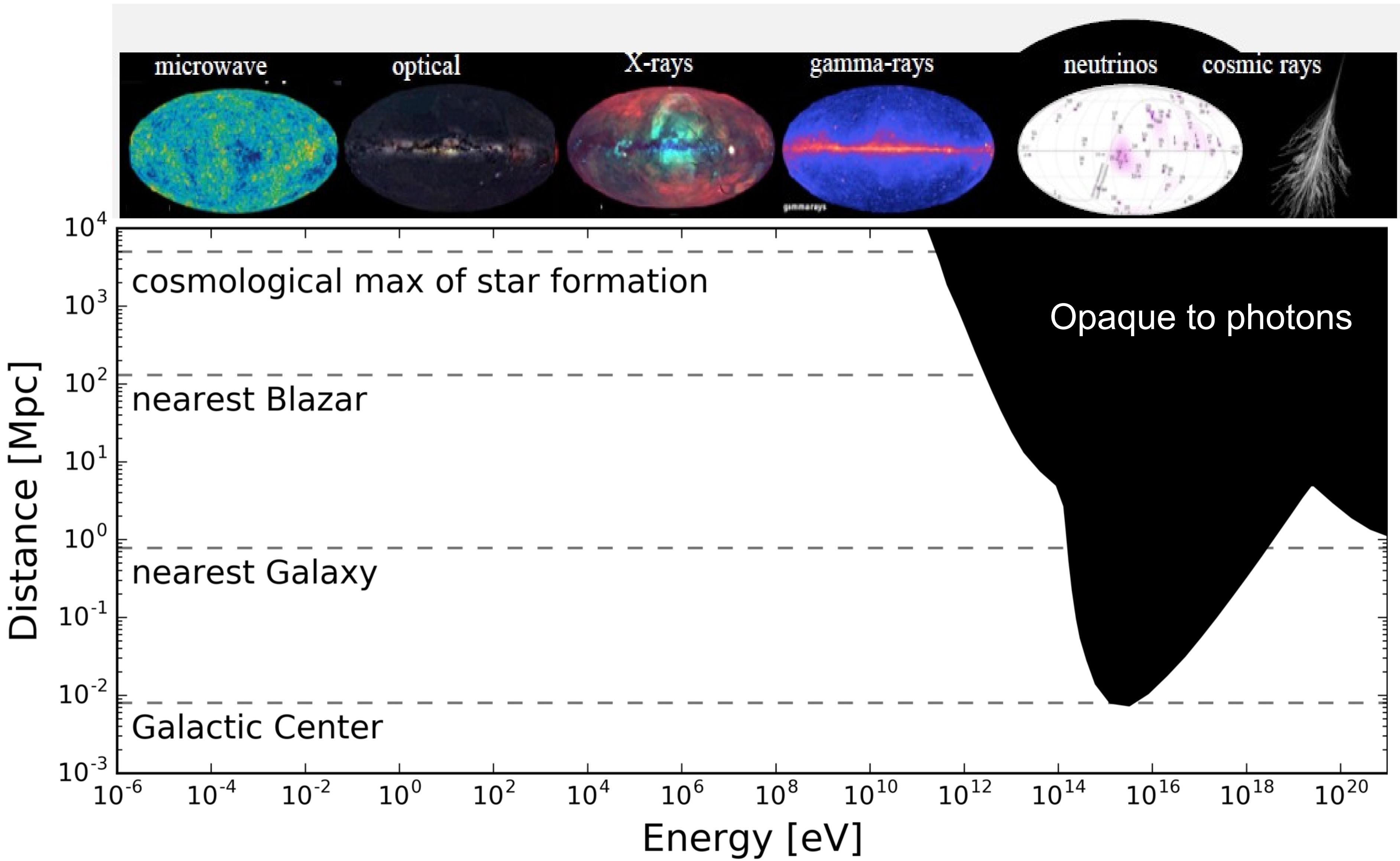




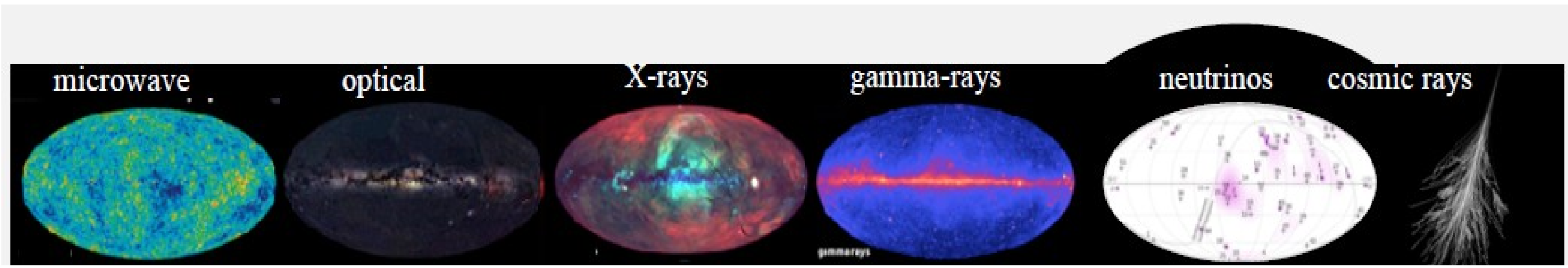
- Are there point sources mixed in with diffuse emission?
- Which ones? How much?
- Energy spectrum?
- Spatial feature?

- How does it compare to multi-wavelength emissions?

High-Energy Astronomy – Cosmic Rays, γ rays, and neutrinos



Naoko Kurahashi Neilson, Drexel University



Neutrinos: Bridge the Gap between γ rays and UHE cosmic rays

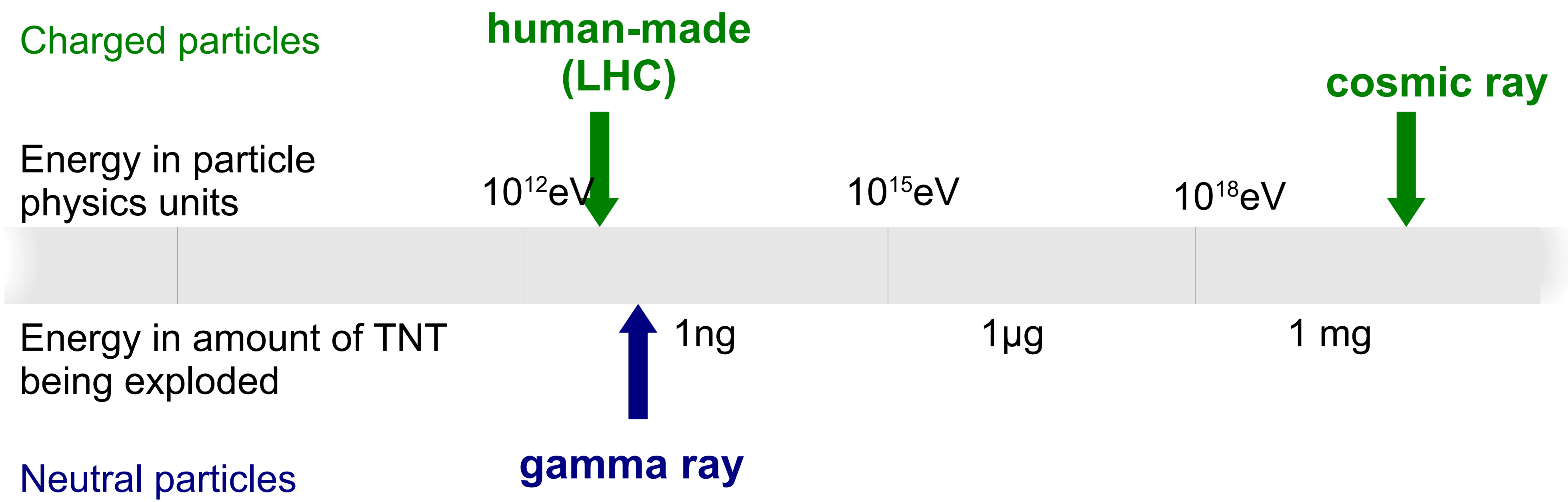
→ in energy

→ in resolved vs unresolved

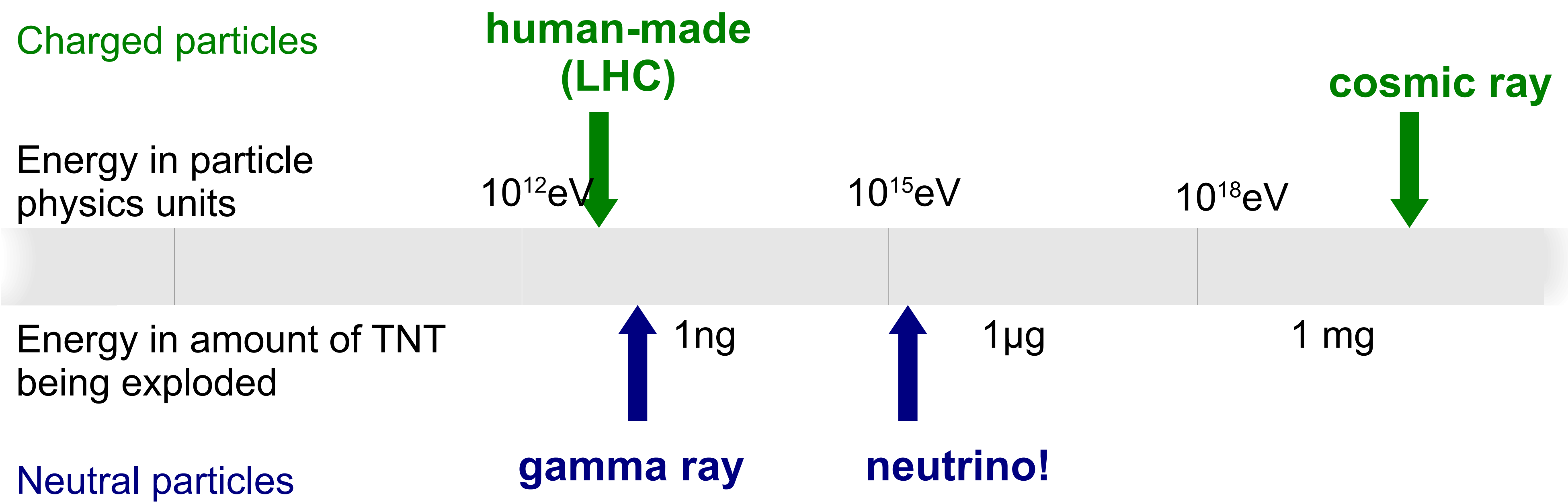
The Past and Present:
The Birth of HE Neutrino Astronomy
A Decade of First Observations


Neutrino Astronomy was a dream
until 2013*....

Highest energy particles observed (in 2013)

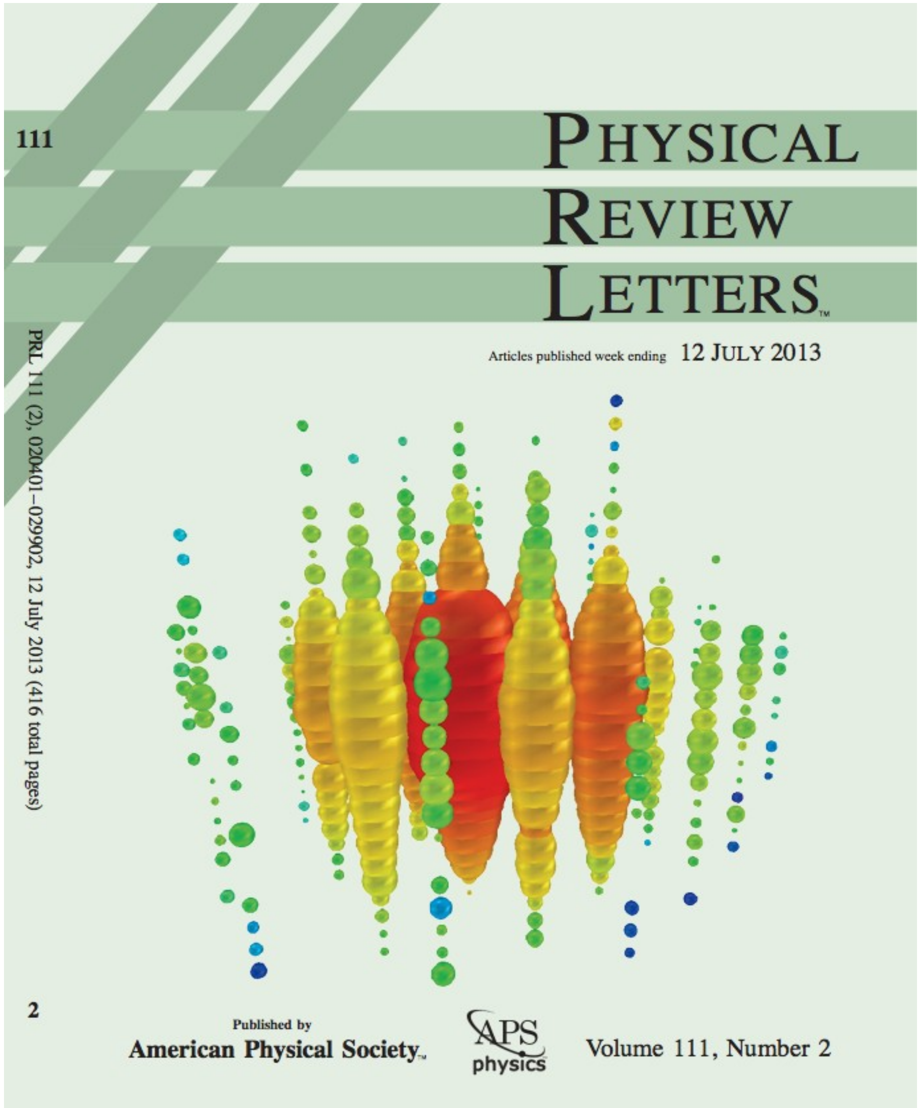


Highest energy particles observed (in 2013)



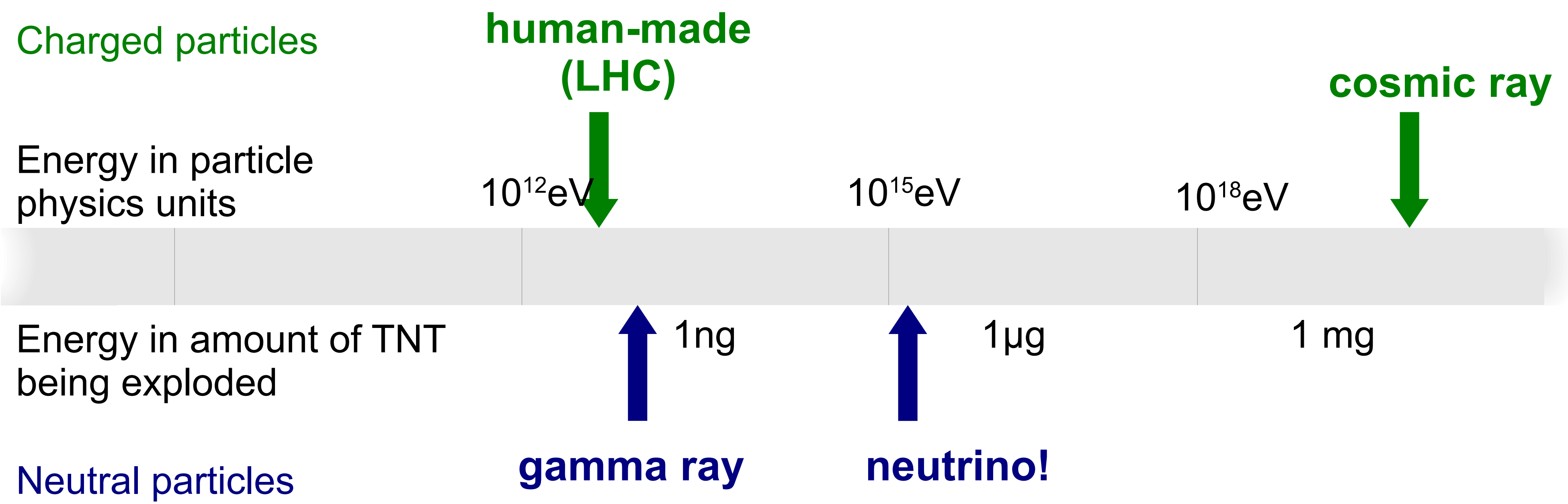
In 2013, IceCube discovered the then highest energy neutral particle.

Here it is!



111
PHYSICAL
REVIEW
LETTERS
Articles published week ending 12 JULY 2013
PRL 111 (2), 020401–029902, 12 July 2013 (416 total pages)
2
Published by
American Physical Society
APS physics
Volume 111, Number 2

Highest energy particles observed (in 2013)



High Energy is interesting because it's astrophysical!
- how is it so high energy?
- how was it created?
- what created it?

Neutrino Sources In The Sky

*salute to the “low-energy” neutrino astronomers with their sources: the sun and SN1987A

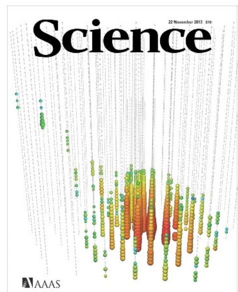
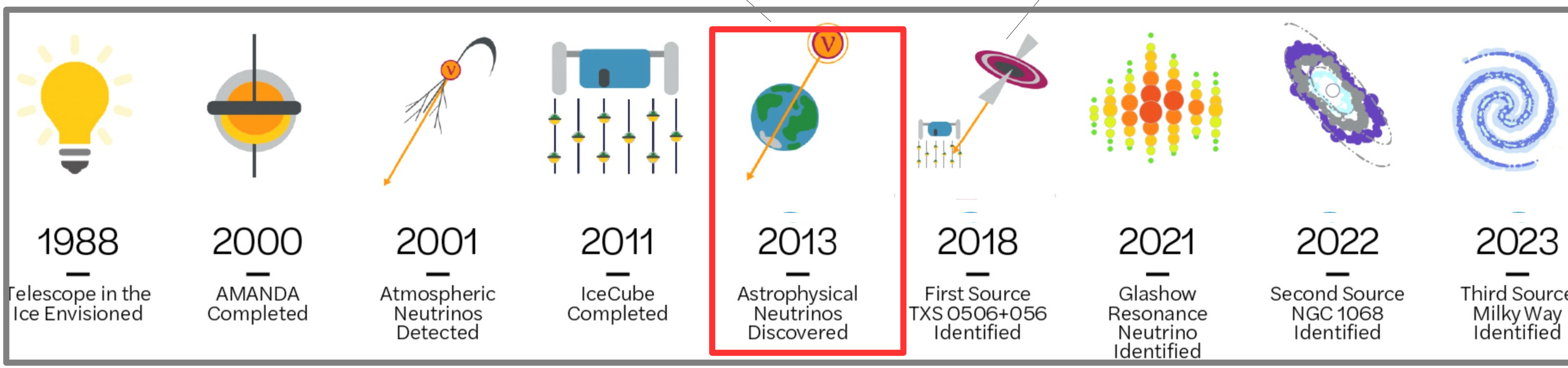
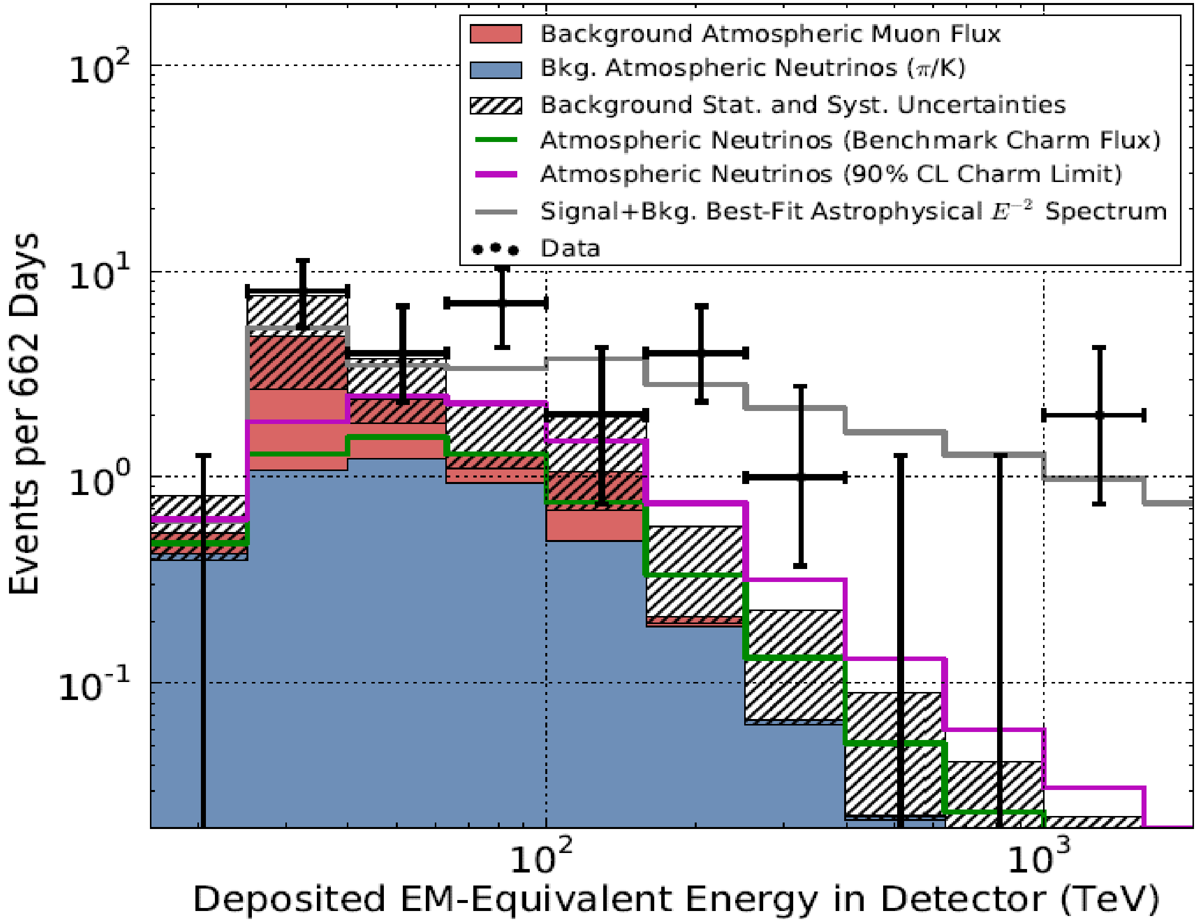


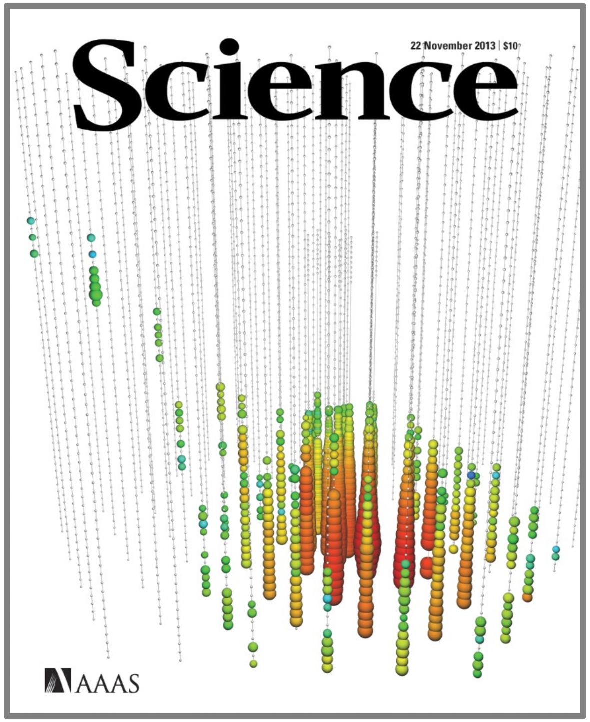
Image Credit: IceCube Collaboration



The Discovery of Diffuse Neutrino Emission

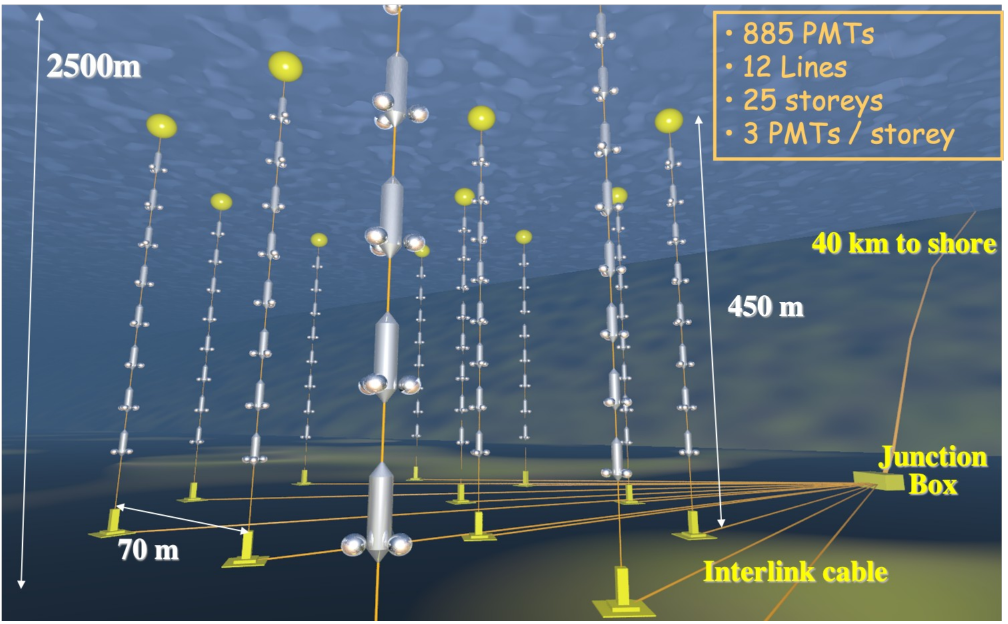
IceCube Collaboration
Science 342, 1242856 (2013)



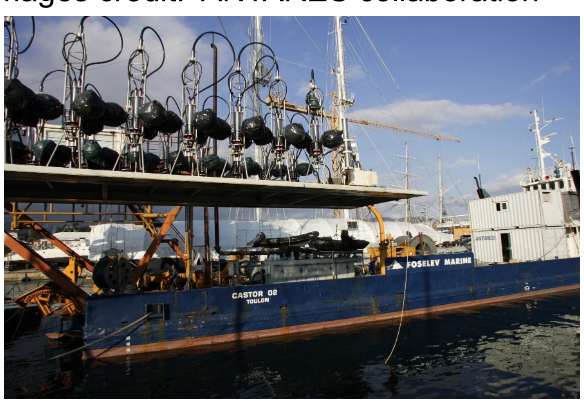


Why did it take so long?
The Size

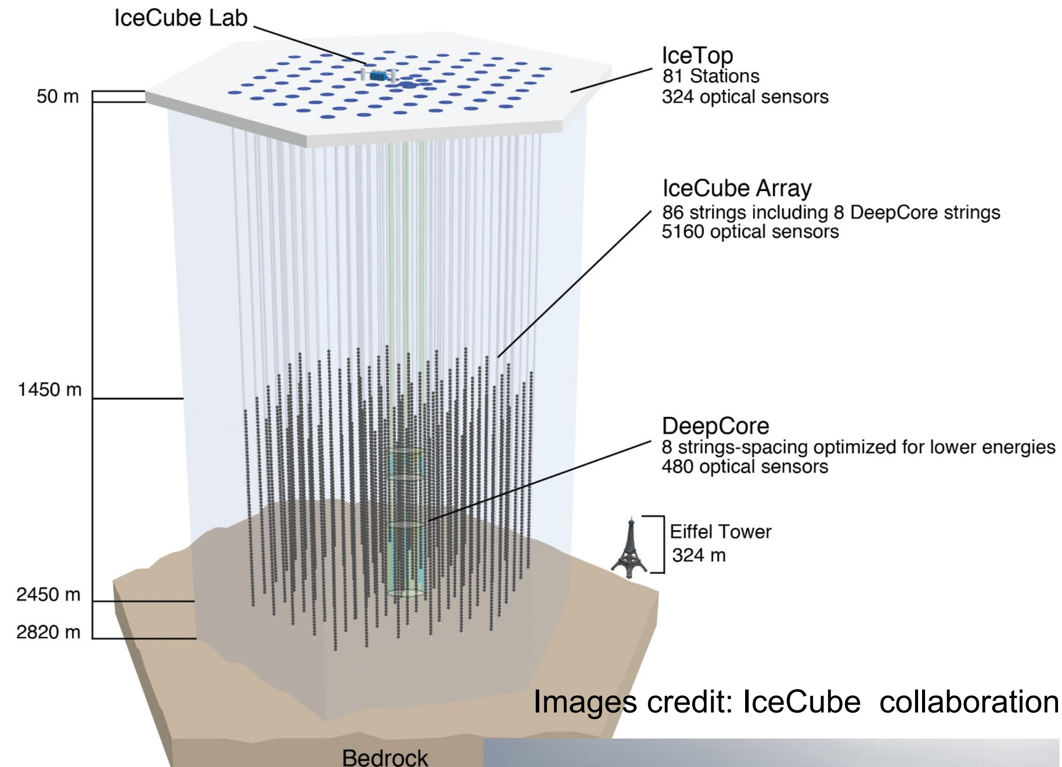
ANTARES (2007-2022)



Images credit: ANTARES collaboration



IceCube (2011-)



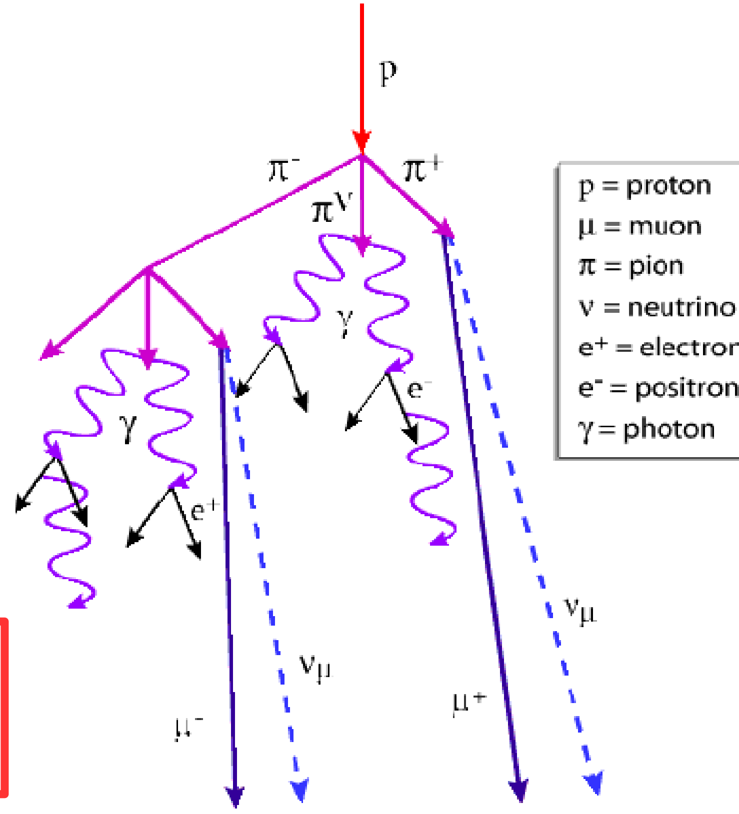
Images credit: IceCube collaboration

Why did it take so long? Backgrounds

Neutrino Telescopes must combat enormous background rates

- Atmospheric muons and neutrinos many orders higher rate
- no beam, source(s) unknown in location/time
- Overburden is what it is (~2.5km)

We had to wait for statistics and/or develop smarter ways to process the data!

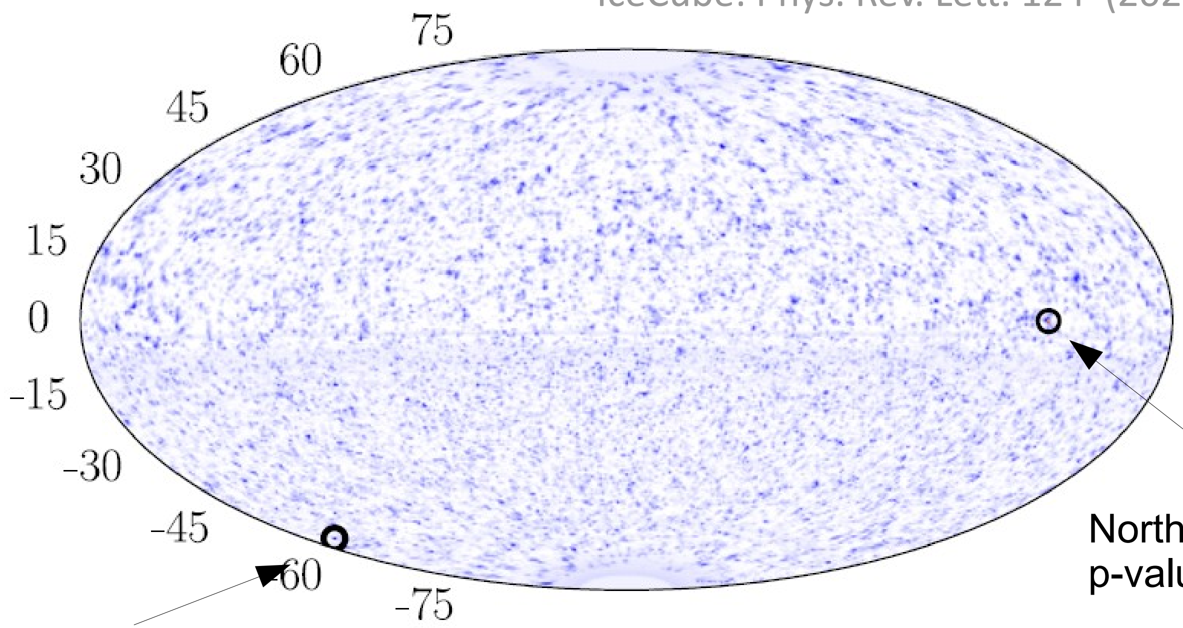


Background Rates at IceCube Trigger:
Atmospheric Muons > 10^9 x signal rate
Atmospheric Neutrinos > 10^3 x signal rate

But where do these high-energy neutrinos come from?

IceCube Neutrino Sky

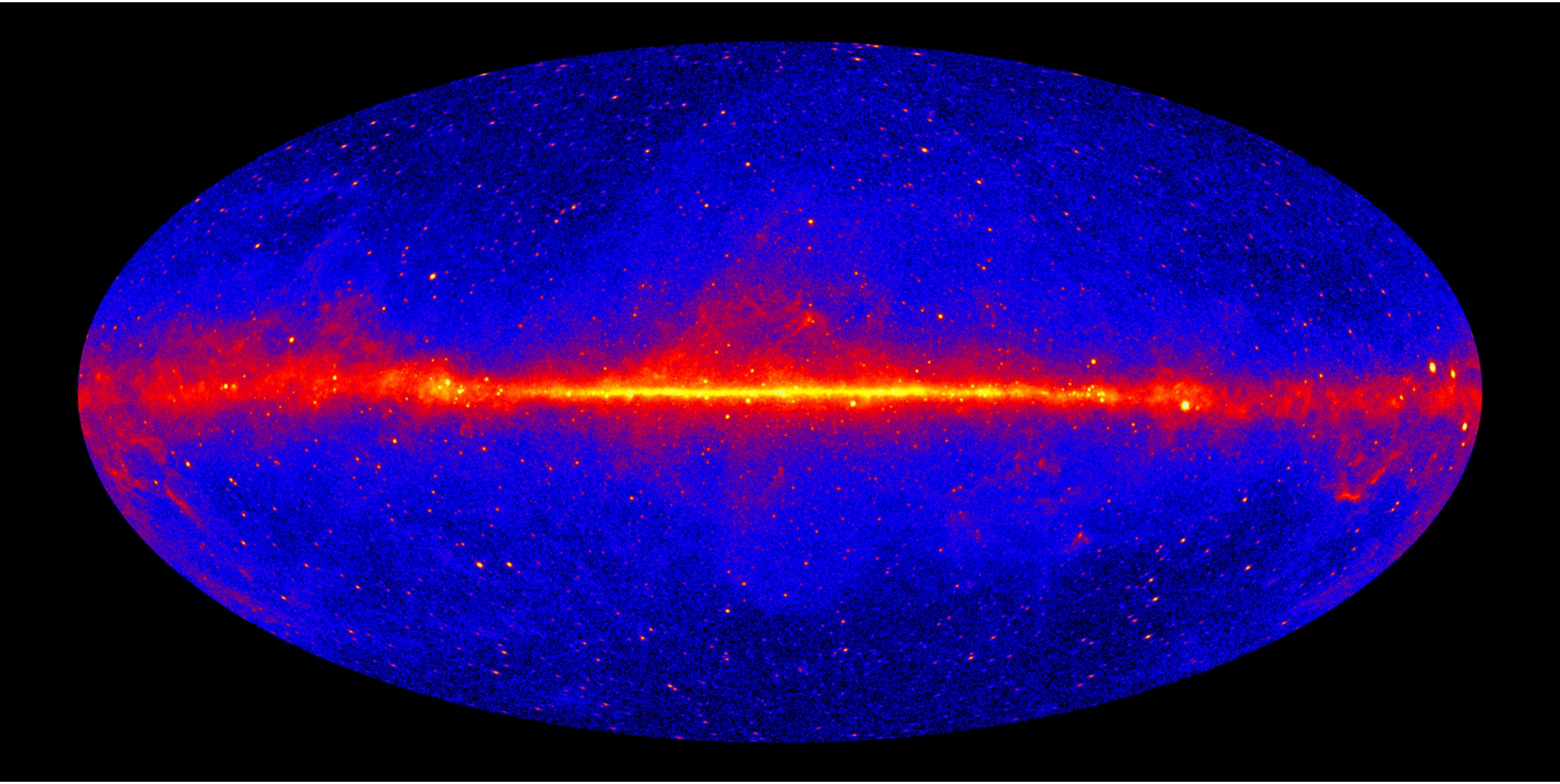
IceCube: Phys. Rev. Lett. 124 (2020) 051103



Northern Sky Hottest Spot
p-value = ~10% (1.3σ)

Southern Sky Hottest Spot
p = ~75%

P-value: The % chance that a fluctuation in the background could have produced something source-like at the level it was detected



Fermi's 12 year view of the Gamma-ray sky

The Present:
The Birth of HE Neutrino Astronomy
A Decade of First Observations

Neutrino Sources In The Sky

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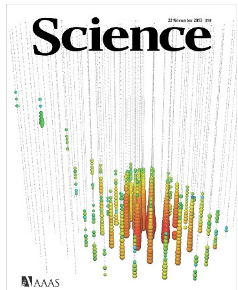
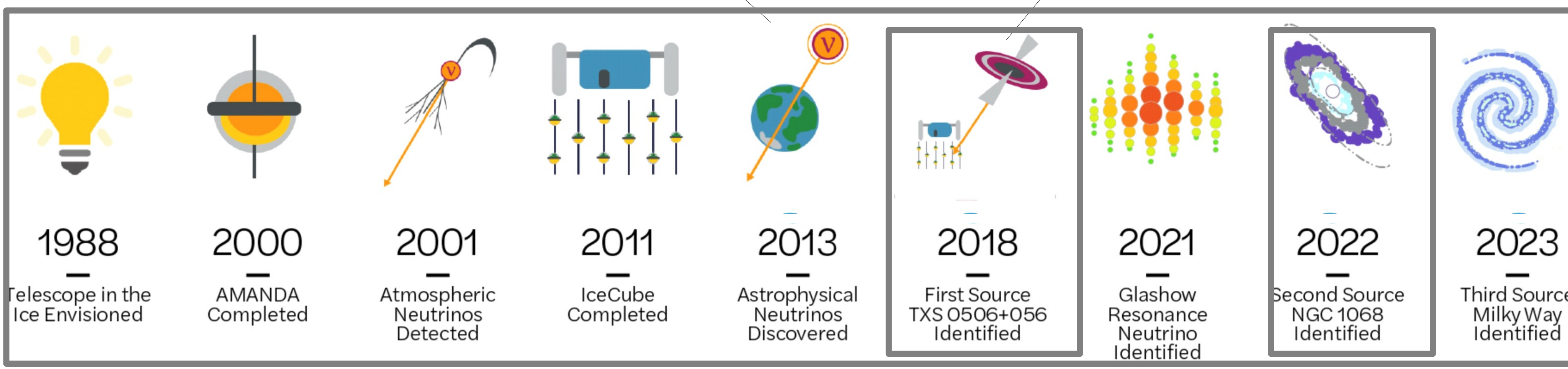


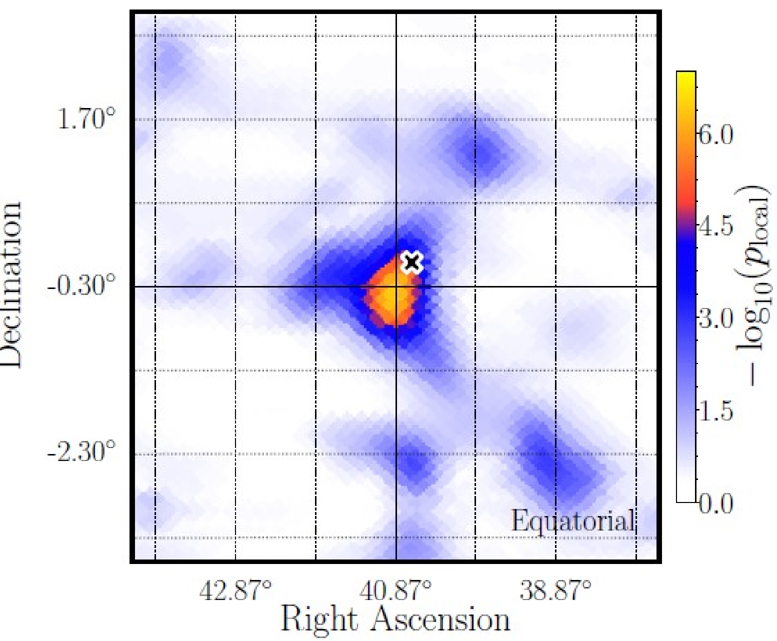
Image Credit: IceCube Collaboration



NGC 1068

- Starburst Galaxy
- Seyfert II
- 14 Mpc

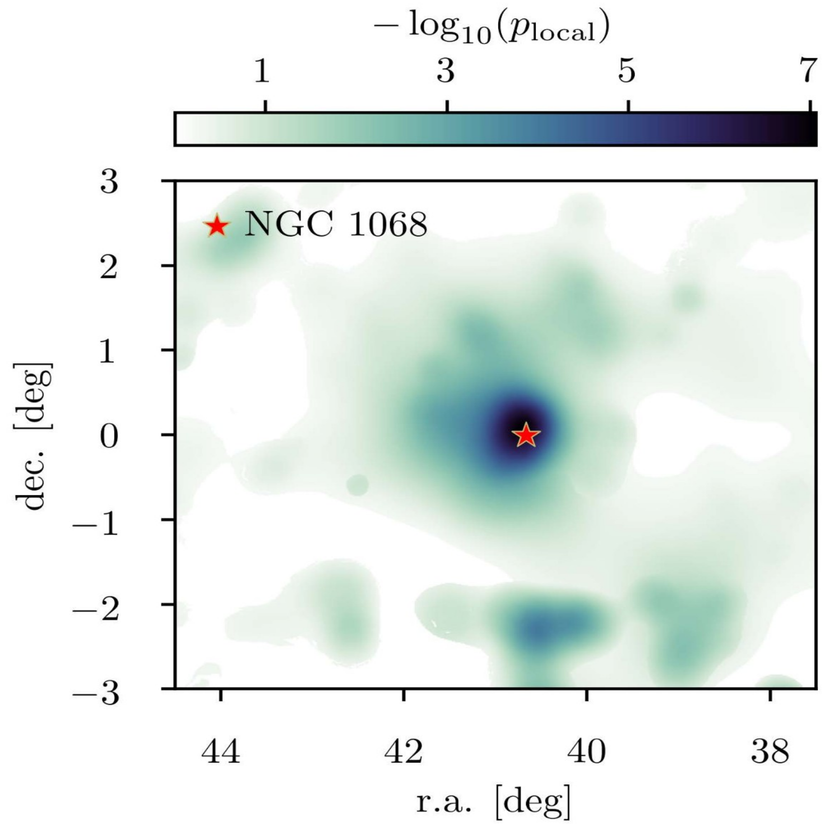
p-value = 0.2% (2.9 σ)



PRL 124, 051103 (2020)

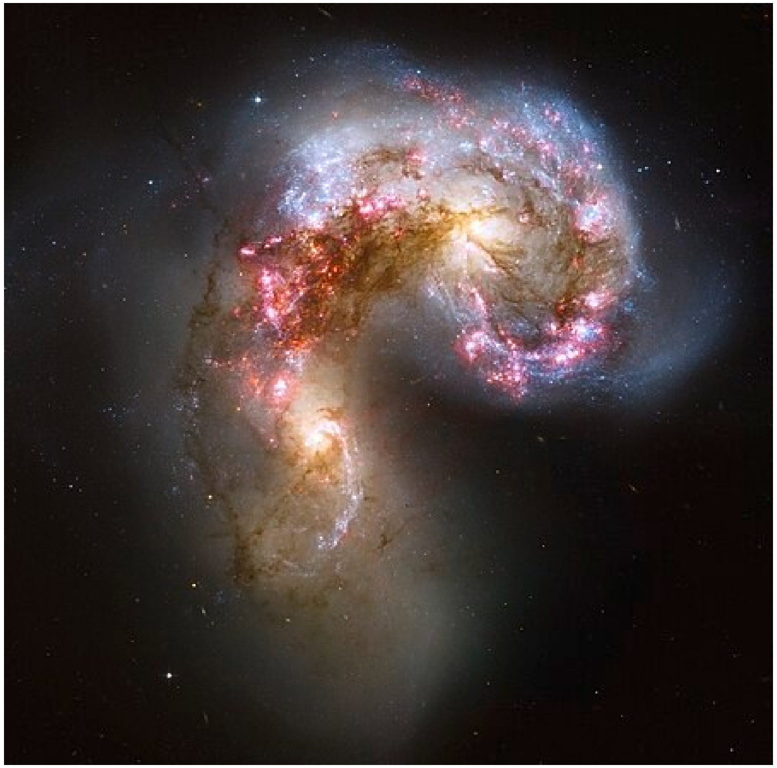
Low Level Data quality improvements (pass 2)
+
Improved reconstructions
+
Additional 2 years of data

P-value = 0.001% (4.2 σ)



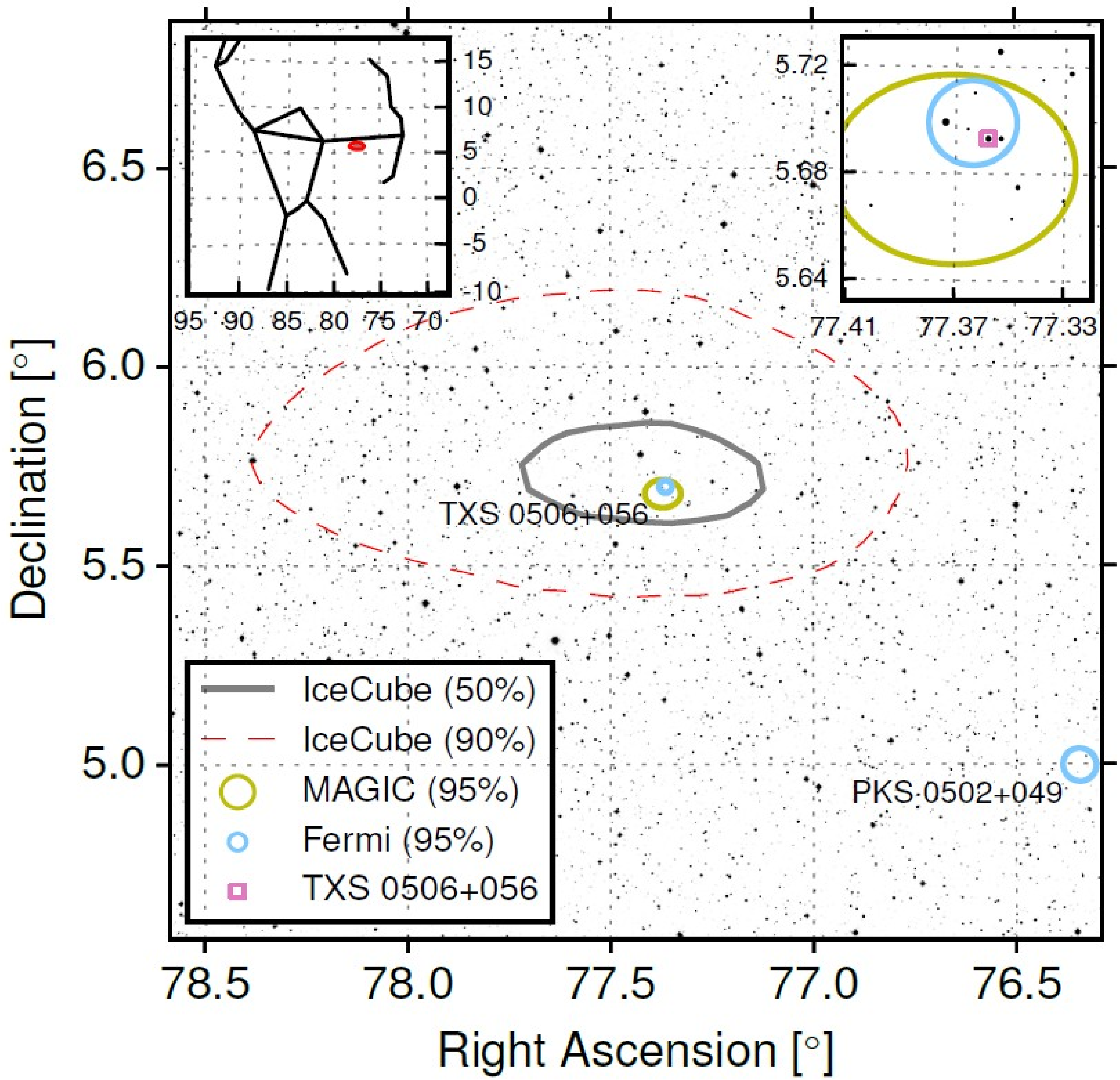
Science 378, 6619 (2022)

Starburst Galaxy



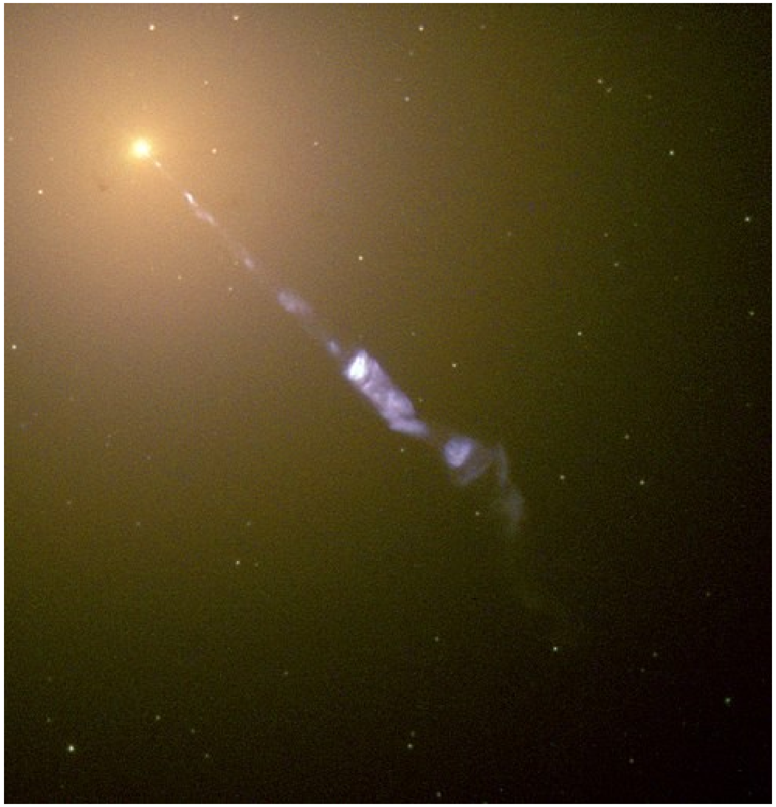
NGC 4038/NGC 4039 @NASA/ESA

- Galaxy with high star formation rate
- Lots of gas, collisions
- Young active stars



Naoko Kurahashi Neilson, Drexel University

Blazar


M87 by Hubble

- Active Galaxy
- Supermassive Black Hole
- Jet Pointed at Earth

Neutrino Sources In The Sky

*salute to the “low-energy” neutrino astronomers with their sources: the sun and SN1987A

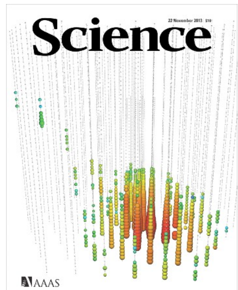
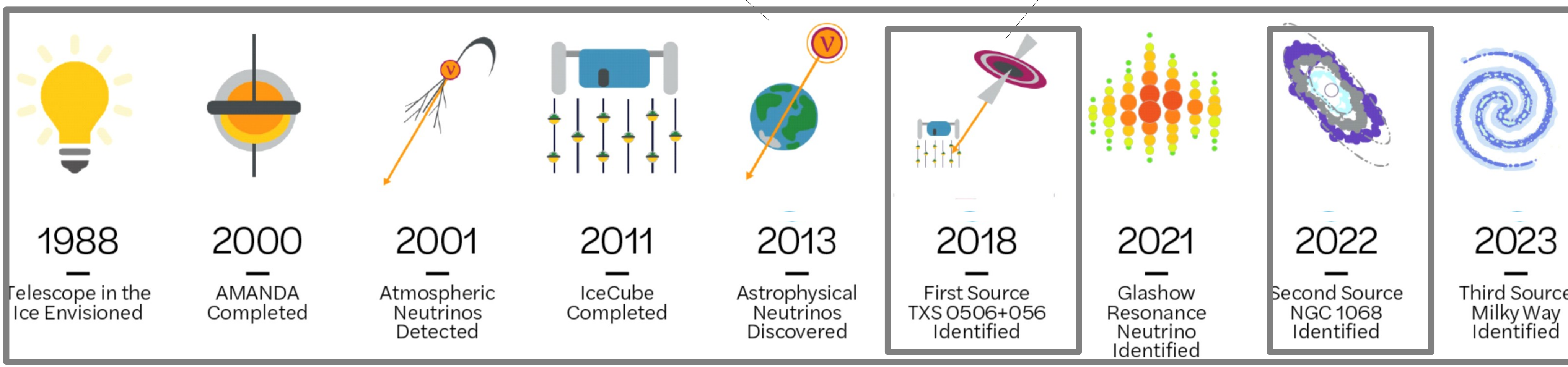


Image Credit: IceCube Collaboration



Birth of Neutrino Astronomy

- Why do these galaxies emit HE neutrinos?
- Why aren't they the same type?
- What other types emit HE neutrinos?
- Why not gamma-ray bursts?

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

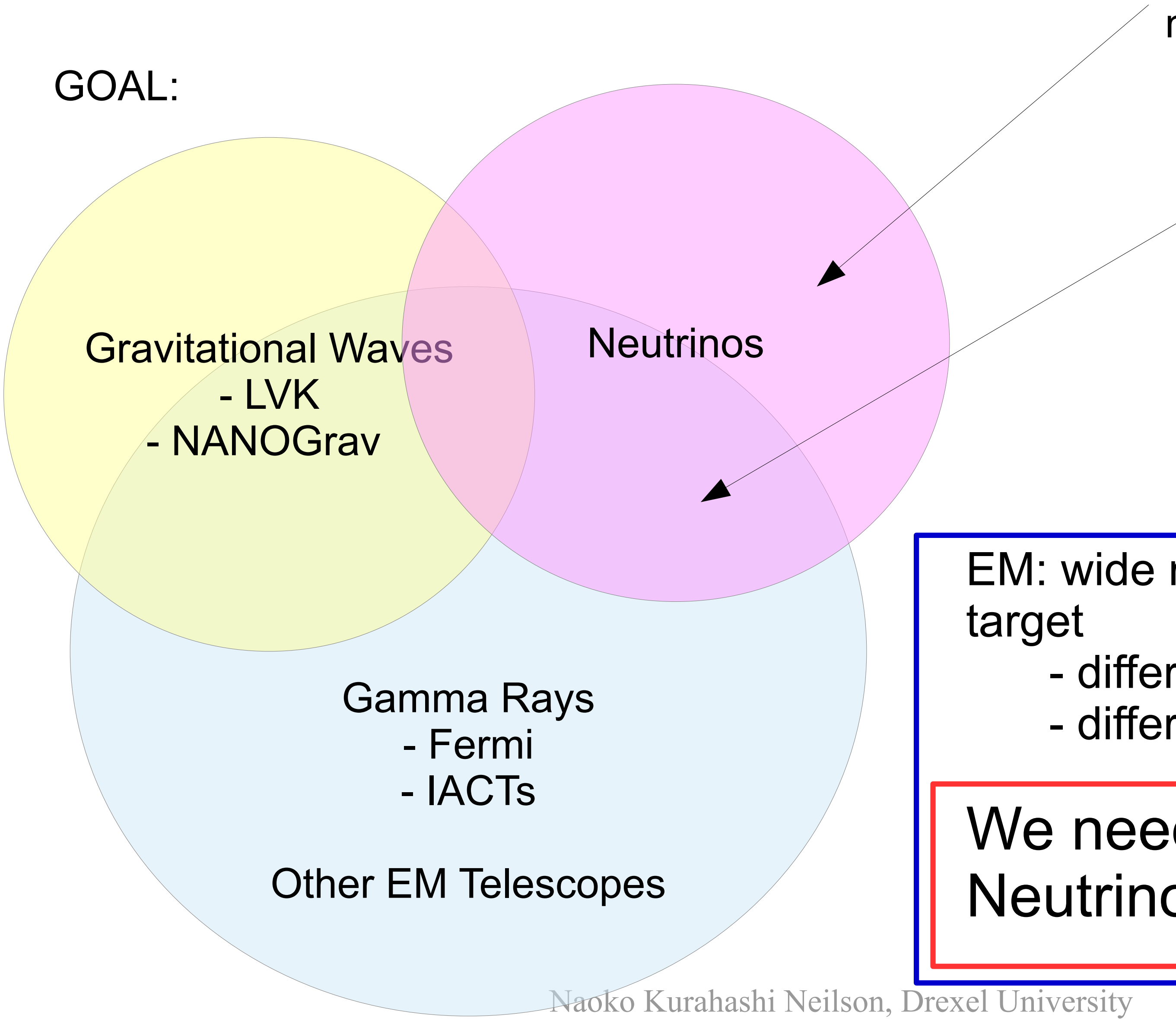
The Future: Towards Answers

A Decade To Establish the Field Firmly

A more equal partnership between multi-messenger astronomy

Sources detected only in neutrinos

Sources detected in neutrino-EM coincidence



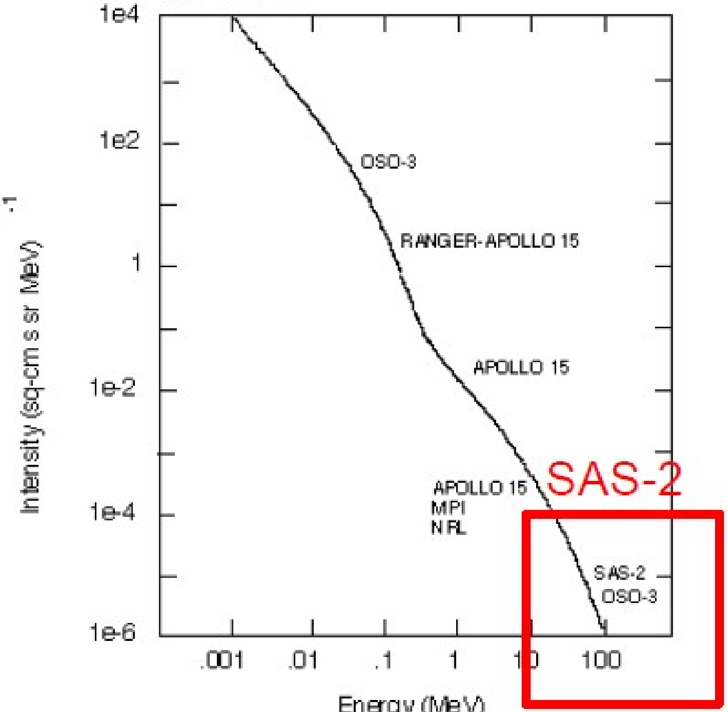
EM: wide range of telescopes that target
- different wavelengths
- different FOV

We need wide ranges of Neutrino Telescopes too!

Historical Perspective: Gamma-ray Astronomy

Diffuse signal → first source → catalog!

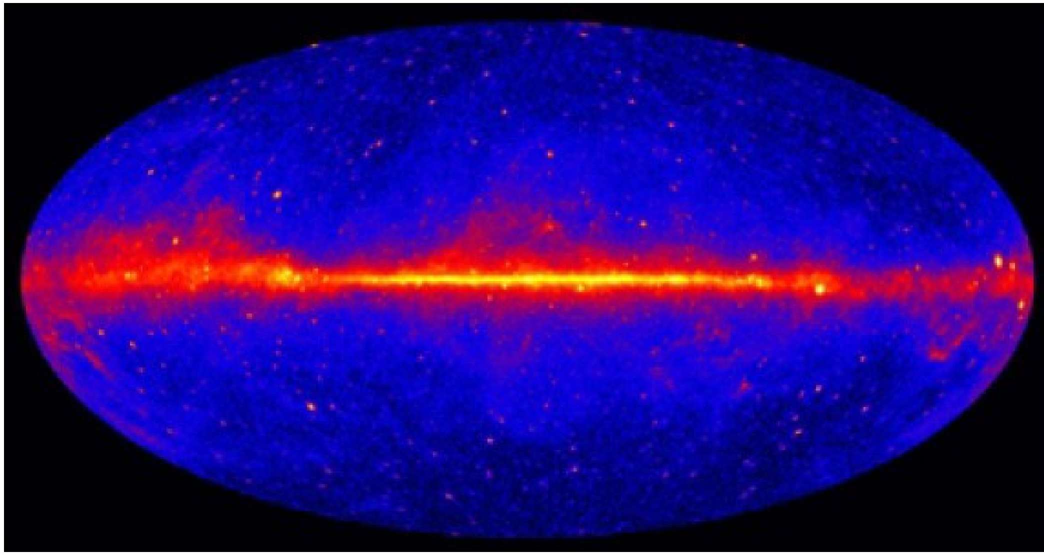
1970's



Diffuse celestial radiation

NOW

Fermi!

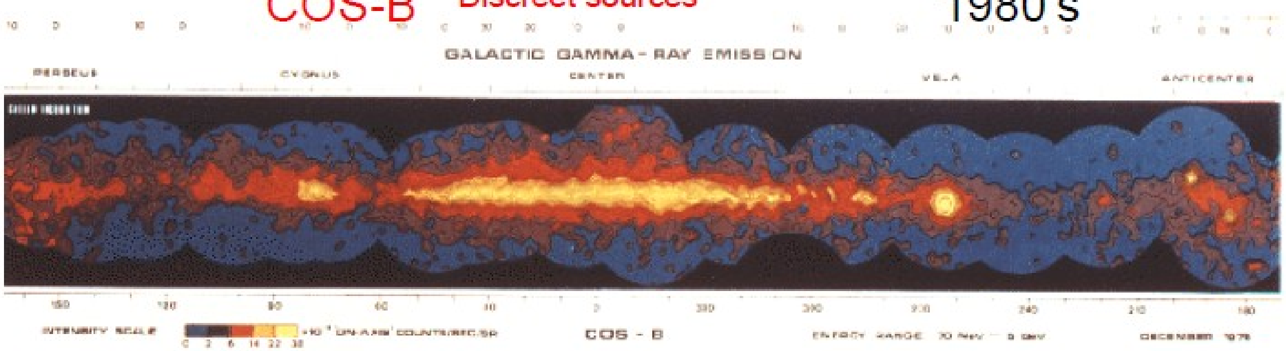


GSFC nasa.gov

COS-B

Discreet sources

1980's



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Historical Perspective: X-ray Astronomy

Diffuse signal → first source → catalog

Diffuse emission and Scorpius X-1 1960's

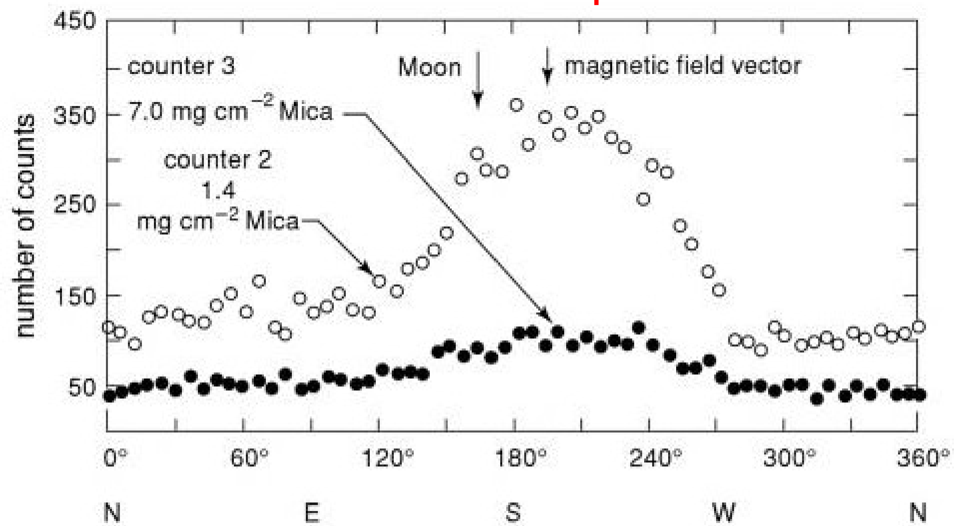
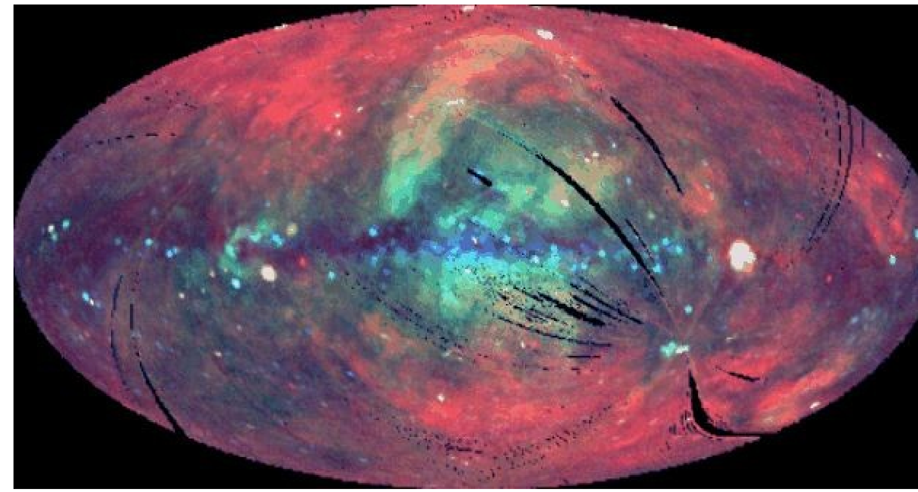
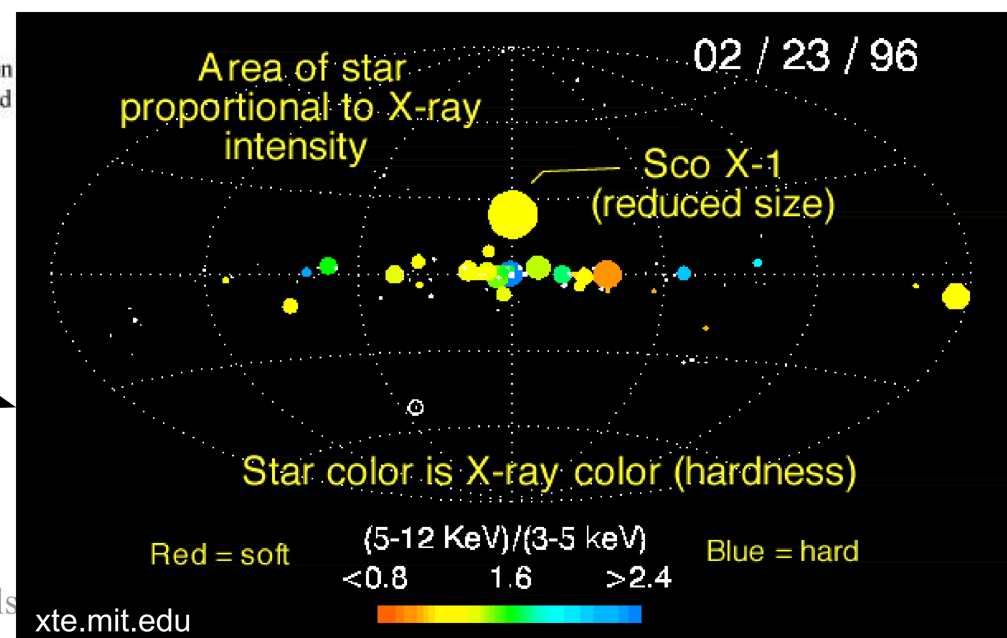


Figure 7.7: The discovery record of the X-ray source Sco X-1 and the X-ray background emission Giacconi and his colleagues in a rocket flight of June 1962. The prominent source was observed both detectors, as was the diffuse background emission (Giacconi *et al.*, 1962).

"The Cosmic Century" M. S. Longair



APOD 8/19/2000 ROSAT

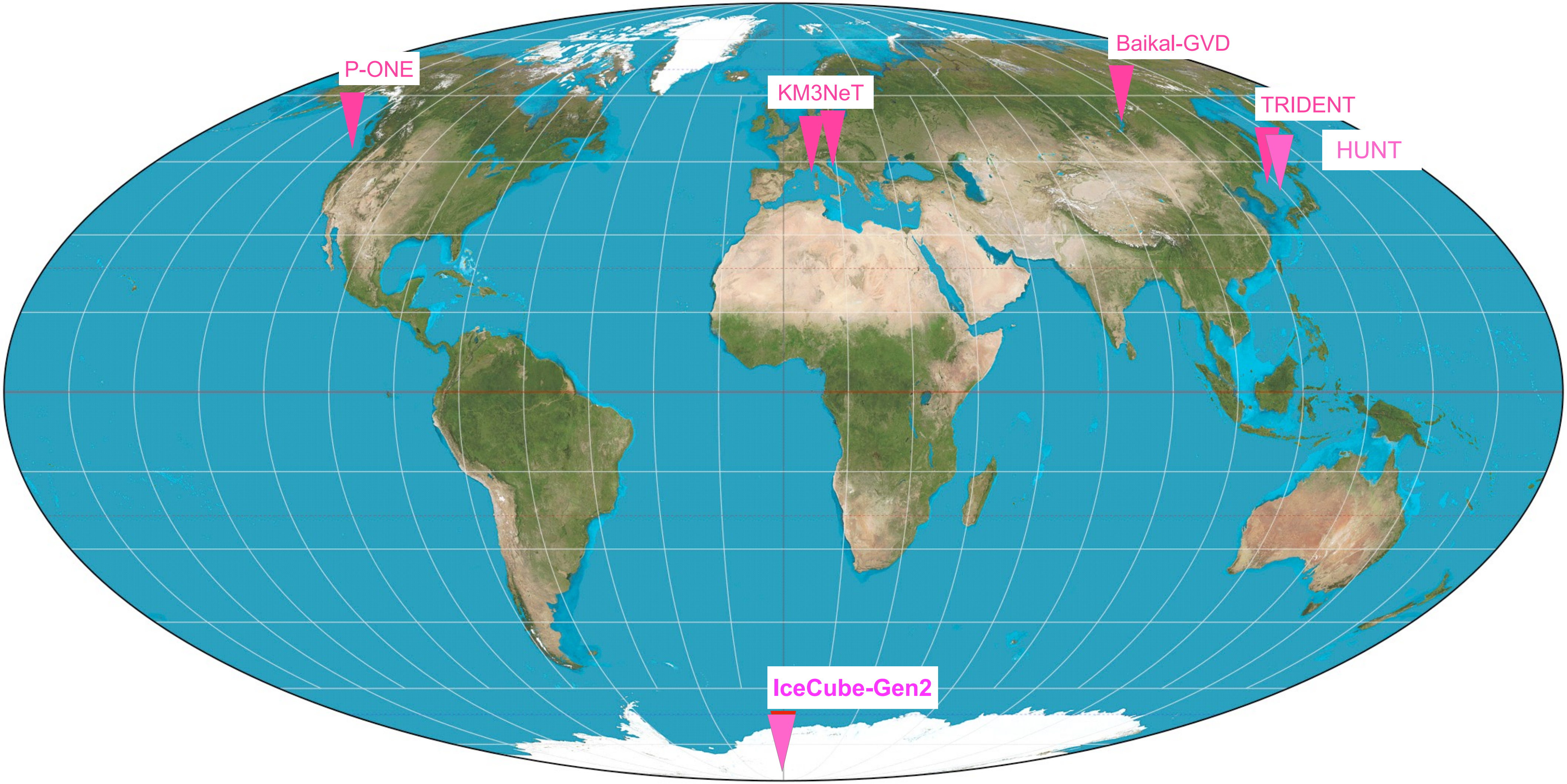


3 Priorities to Achieve this Goal

- More Neutrino Telescopes
- Complementary Location
- Complementary Technology

Priority: Complementary Locations

Global Neutrino Telescopes

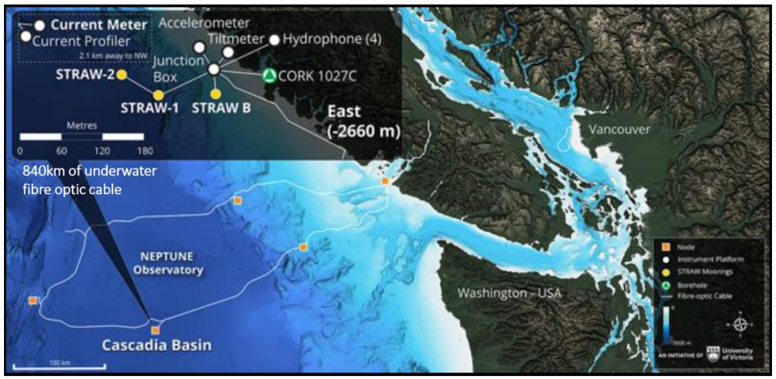


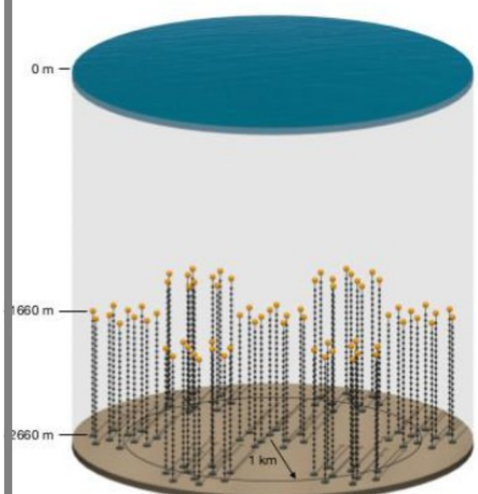
New Hemisphere New Comers

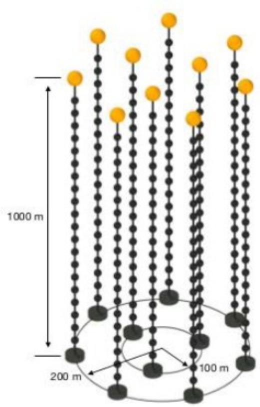
P-ONE

Pacific Ocean Neutrino Explorer

Leverage existing facilities







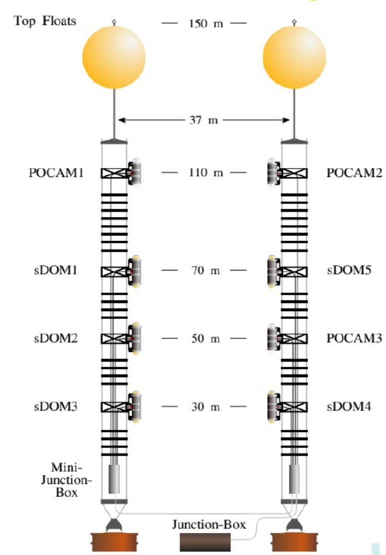
Huge telescopes in the South China Sea

TRIDENT 海铃计划

HUNT

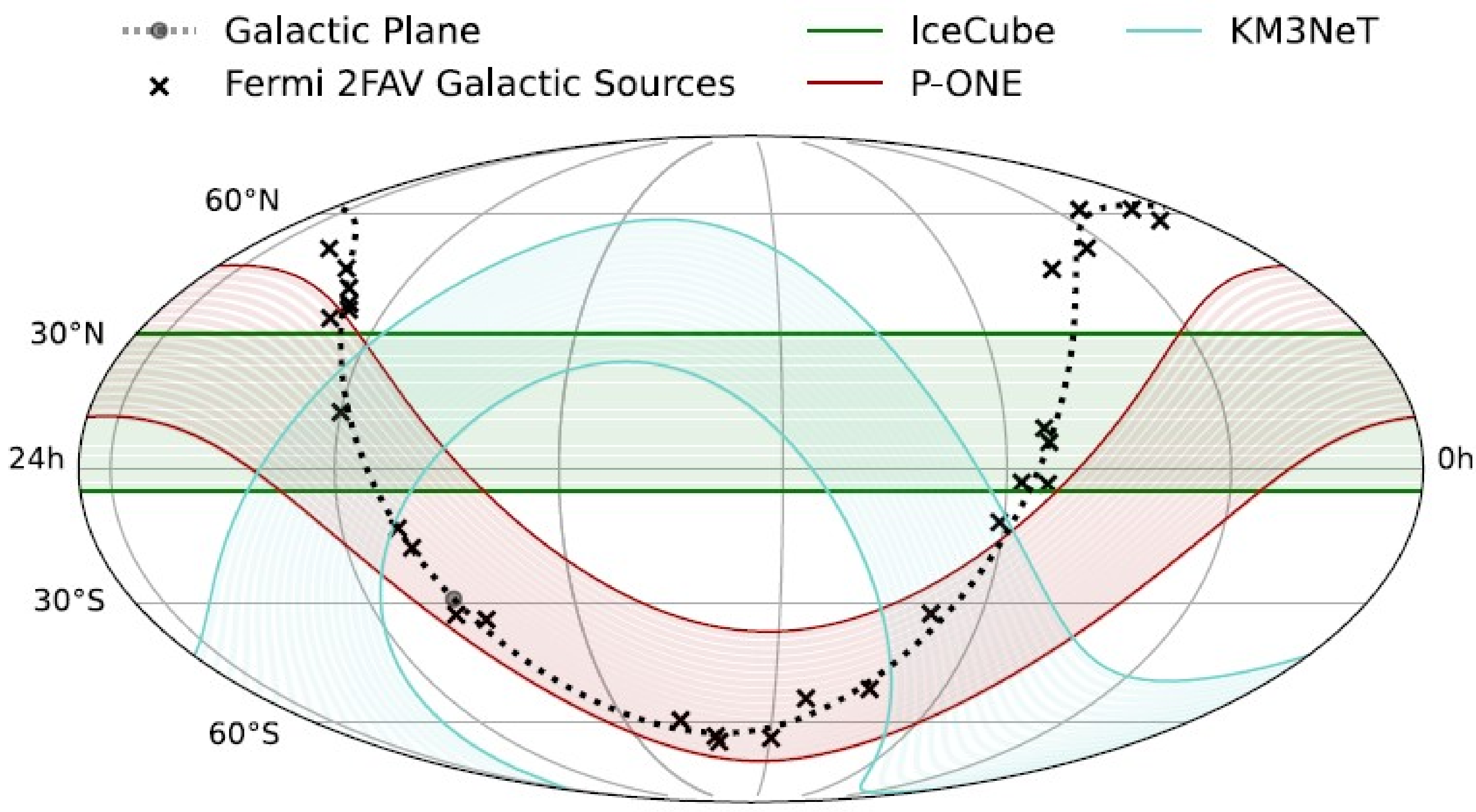
Pathfinder strings deployed and recovered

2019 JINST 14 P02013



Images: courtesy P-ONE collaboration

Complementary Peak Sensitivity → Important for Transients



Courtesy: P-ONE, L. Schumacher (Erlangen), S. Sclafani (Univ of Maryland)

Priority: Complementary Technology

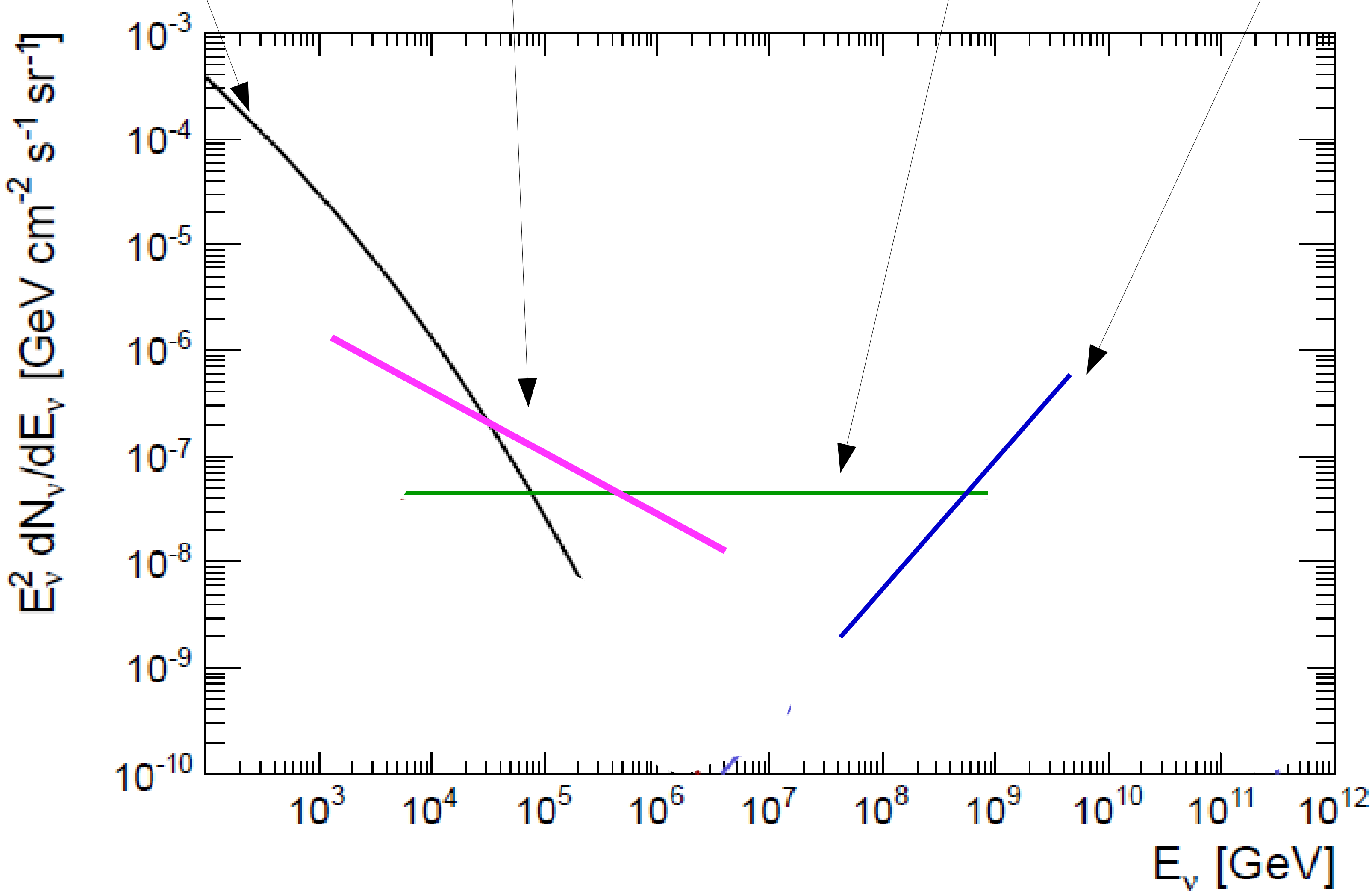
Diverse Neutrino Astronomy Targets

Atmospheric

Galactic
- good pointing (energy not as helpful)
- Northern hemisphere
- smaller okay

Extragalactic
- okay pointing
- large detector

EHE/GZK
- large detector
- signal that travels
- sparse okay



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Galactic
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Extragalactic
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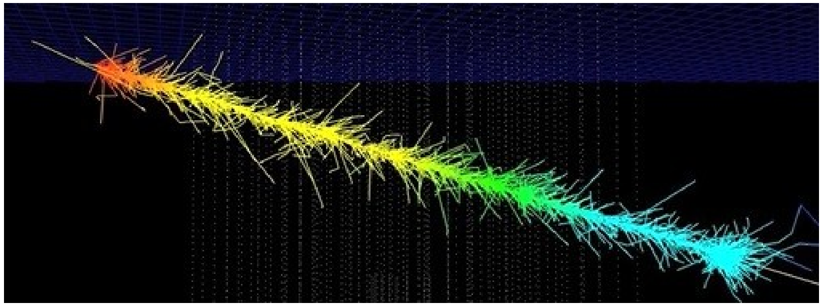
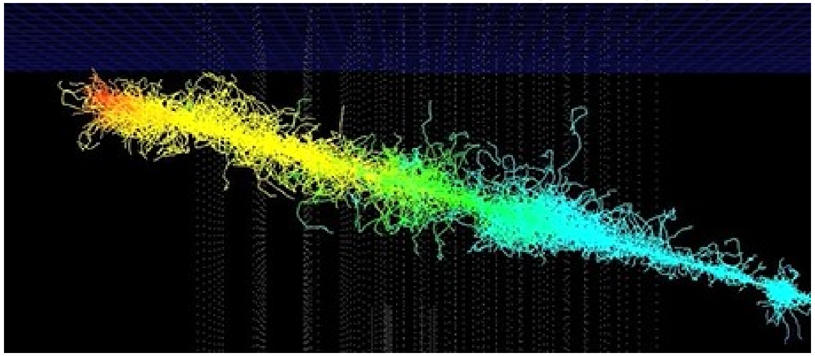
- large detector

EHE/GZK
- large detector
- signal that travels
- sparse okay

Water Cherenkov
- Scattering ✓→ Good Pointing
- Absorption ✗→ Harder to make large detector



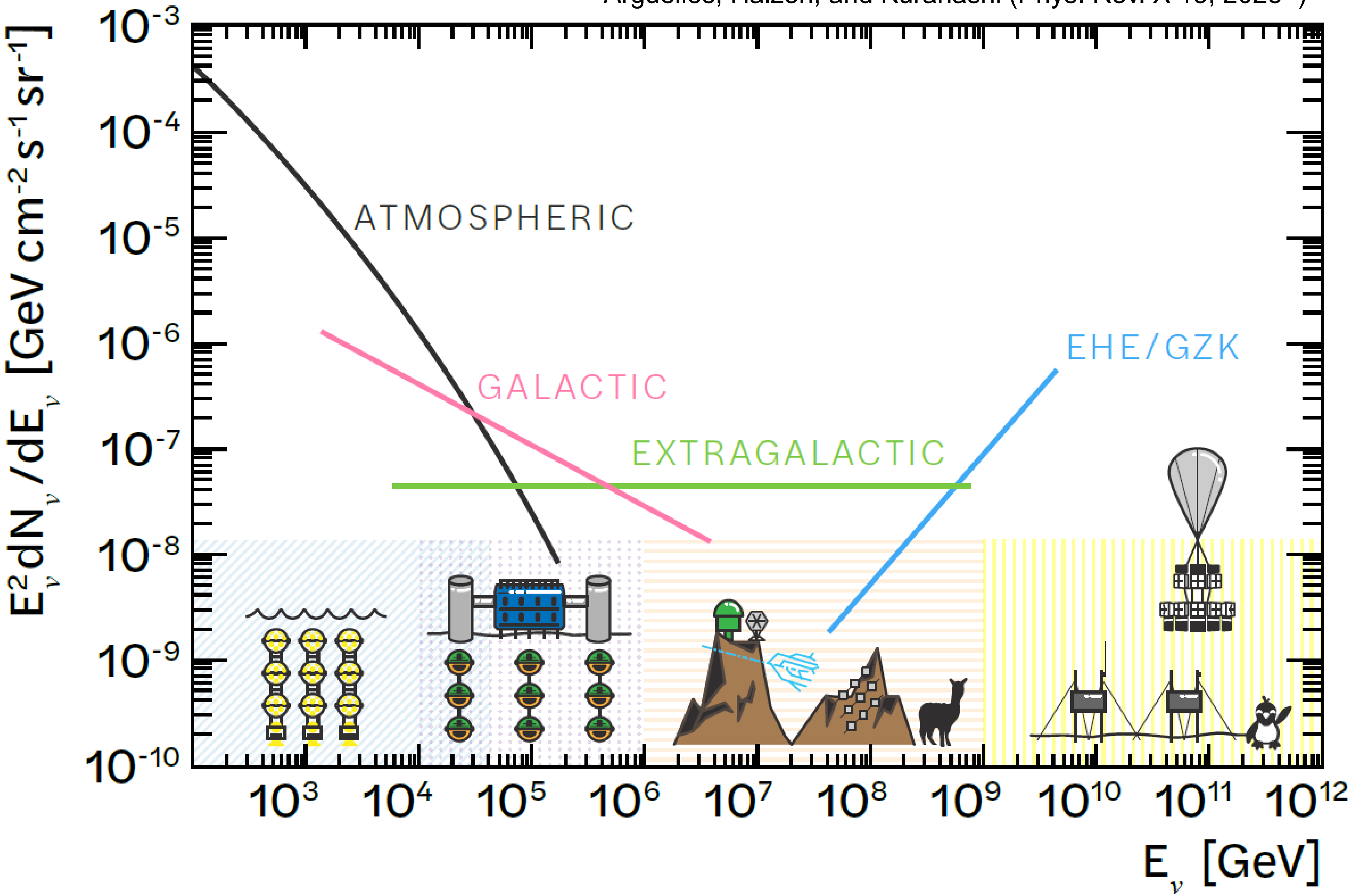
Courtesy: Claudio Kopper (Erlangen)



Ice Cherekov
- Scattering ✗→ Harder to point
- Absorption ✓→ Easier to make large detector

Radio
- Absorption ✓✓ → Can make detector very large
- Energy threshold very high

Argüelles, Halzen, and Kurahashi (Phys. Rev. X 15, 2025)

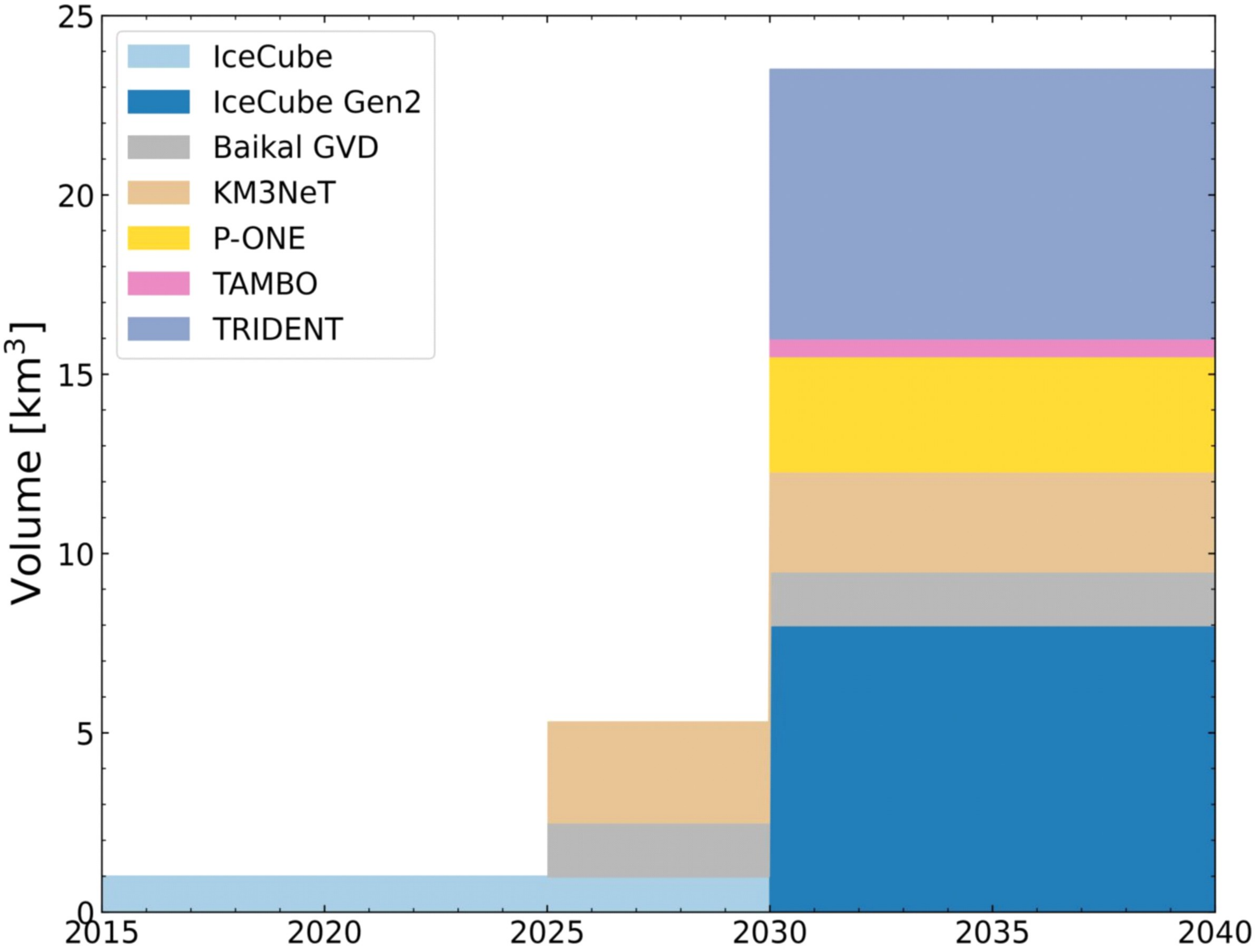


Diverging Optimizations
→ Good Sign of a Maturing Field

Priority: Instrumented Volume

- Fundamental challenge for all neutrino telescopes is the high background rate
- We need statistics! More neutrinos above background!
- More PMTs, more photo-cathode coverage around the world → more data → more signal collected

Expanding Volume of Neutrino Telescopes



Courtesy: Q. Liu (Queens) ICRC2023

Conclusions

Women Observing Stars （1936） Ota Chou
National Museum of Modern Art, Tokyo

Naoko Observing Stars and Galaxies (2012) South Pole

IceCube

- Started a new era of Neutrino Astronomy!
- We see our Galaxy for the first time in neutrinos!

Neutrino astronomy

- Needs to become a strong partner in multi-messenger astronomy
- Need for more neutrino telescopes to identify more sources

Backup Slides

2013 Discovery of Celestial HE Neutrinos

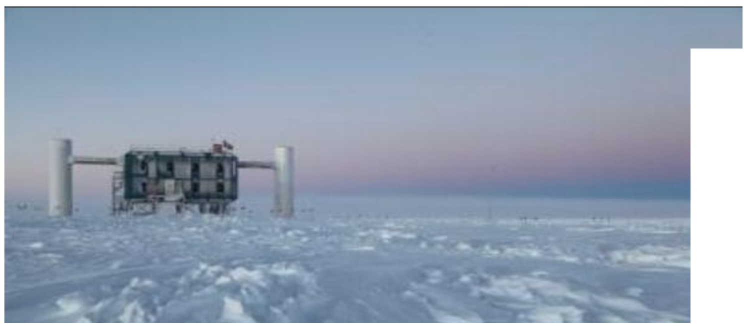
The Christian Science MONITOR

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



NBC NEWS

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

BY ALAN BOYLE, SCIENCE EDITOR

SCIENTIFIC AMERICAN™

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

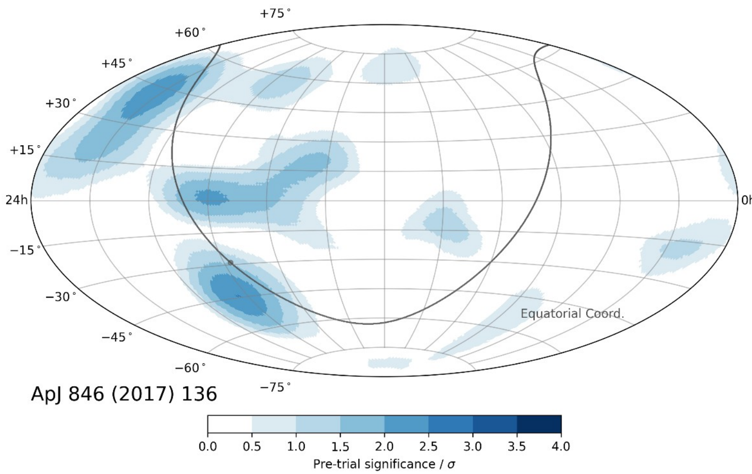
April 9, 2014 | By Clara Moskowitz

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.

Improving Astronomy with Cascade Events

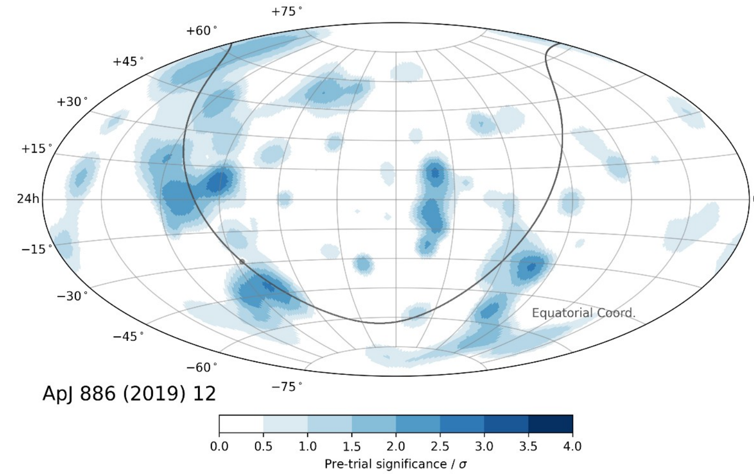
Skymap from 2017 paper



ApJ 846 (2017) 136

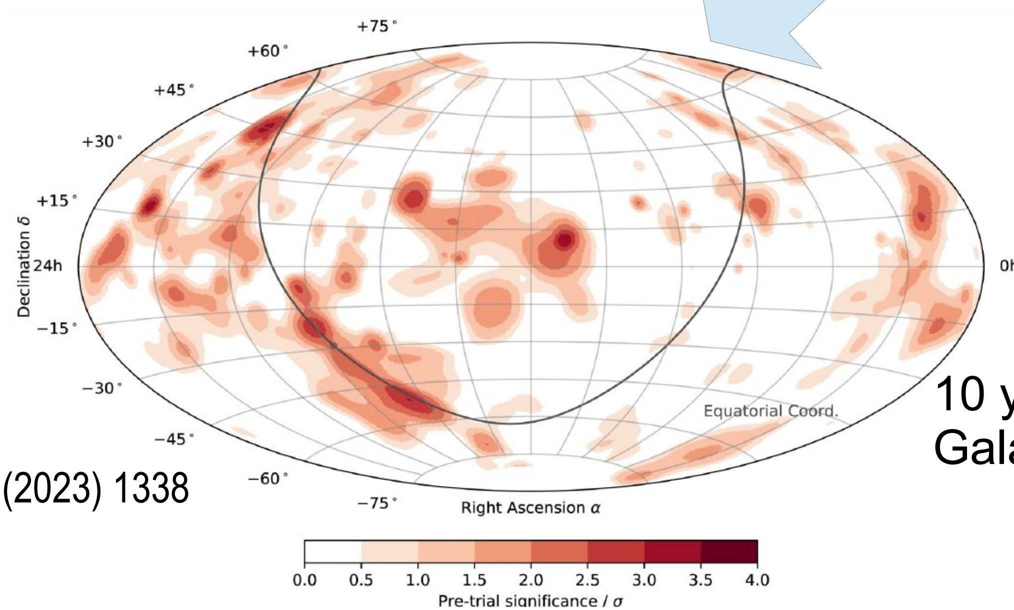
2 years of data
Galactic Plane p-value: 65%

Skymap from 2019 paper



ApJ 886 (2019) 12

7 years of data
Galactic Plane p-value: 2.1% (2σ)

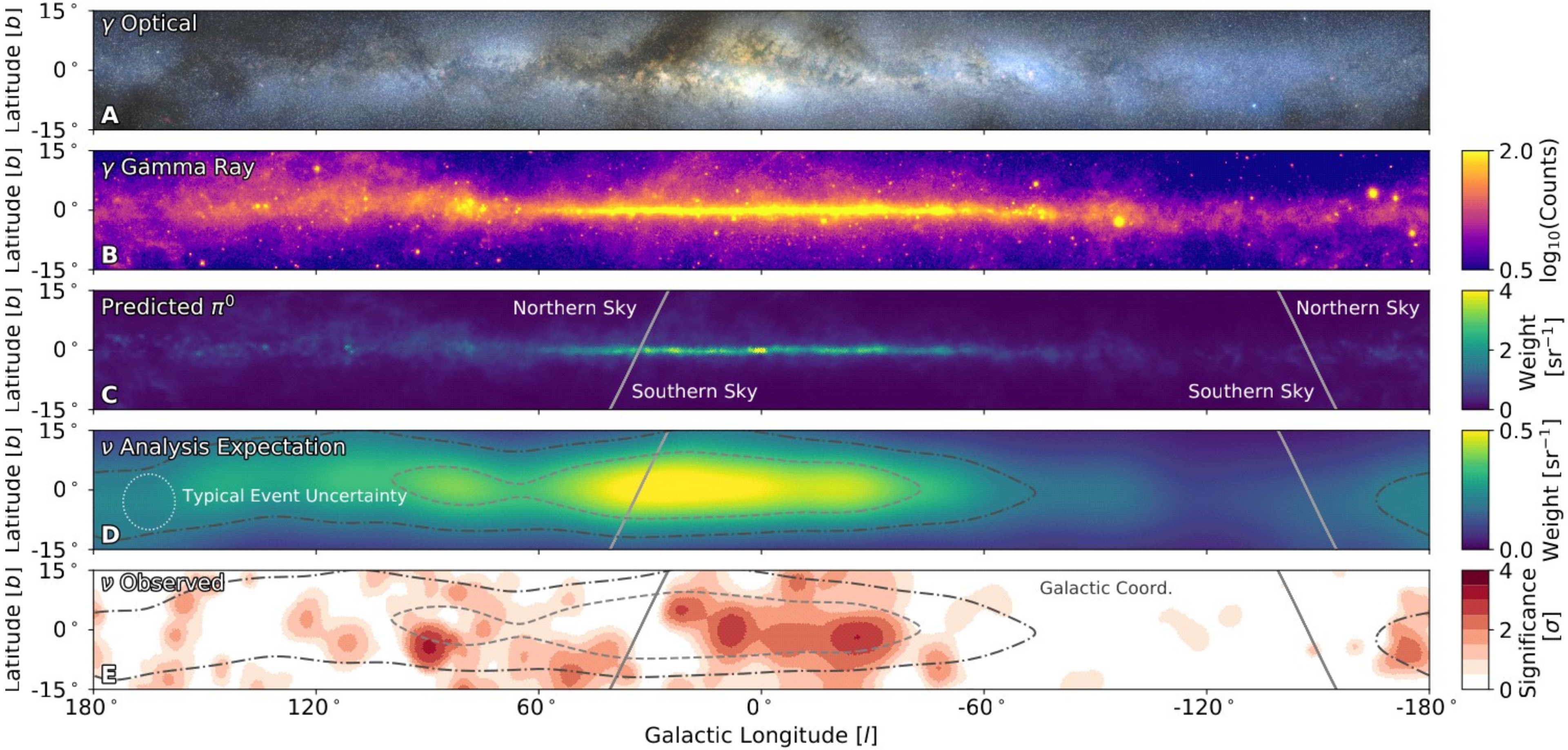


Science 380 (2023) 1338

10 years of data
Galactic Plane p-value: 0.0004% (4.5σ)

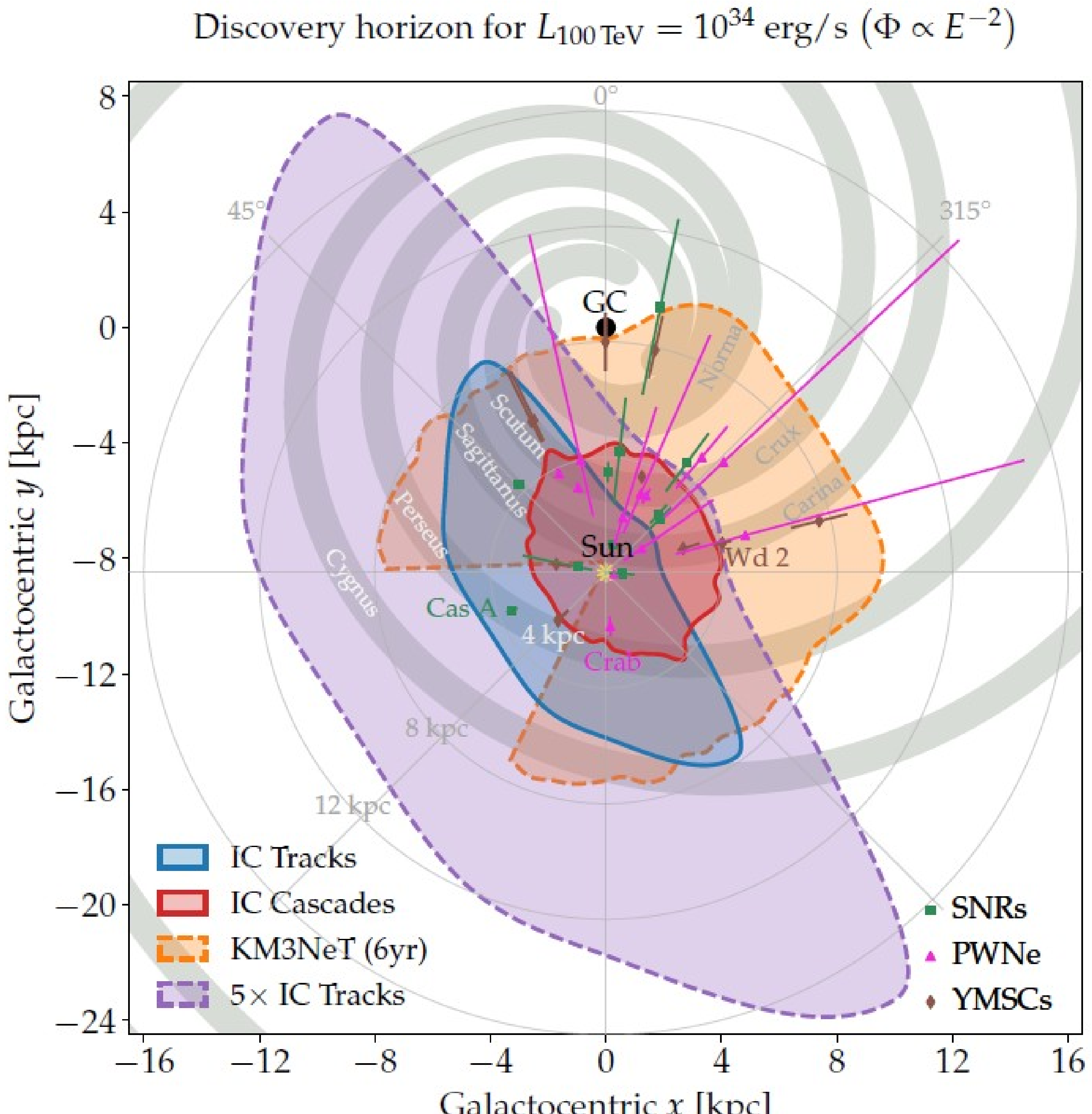
2023 Result!

4.5σ
(0.00038%)



Science 380 (2023) 1338

Galactic Neutrino Astronomy Needs

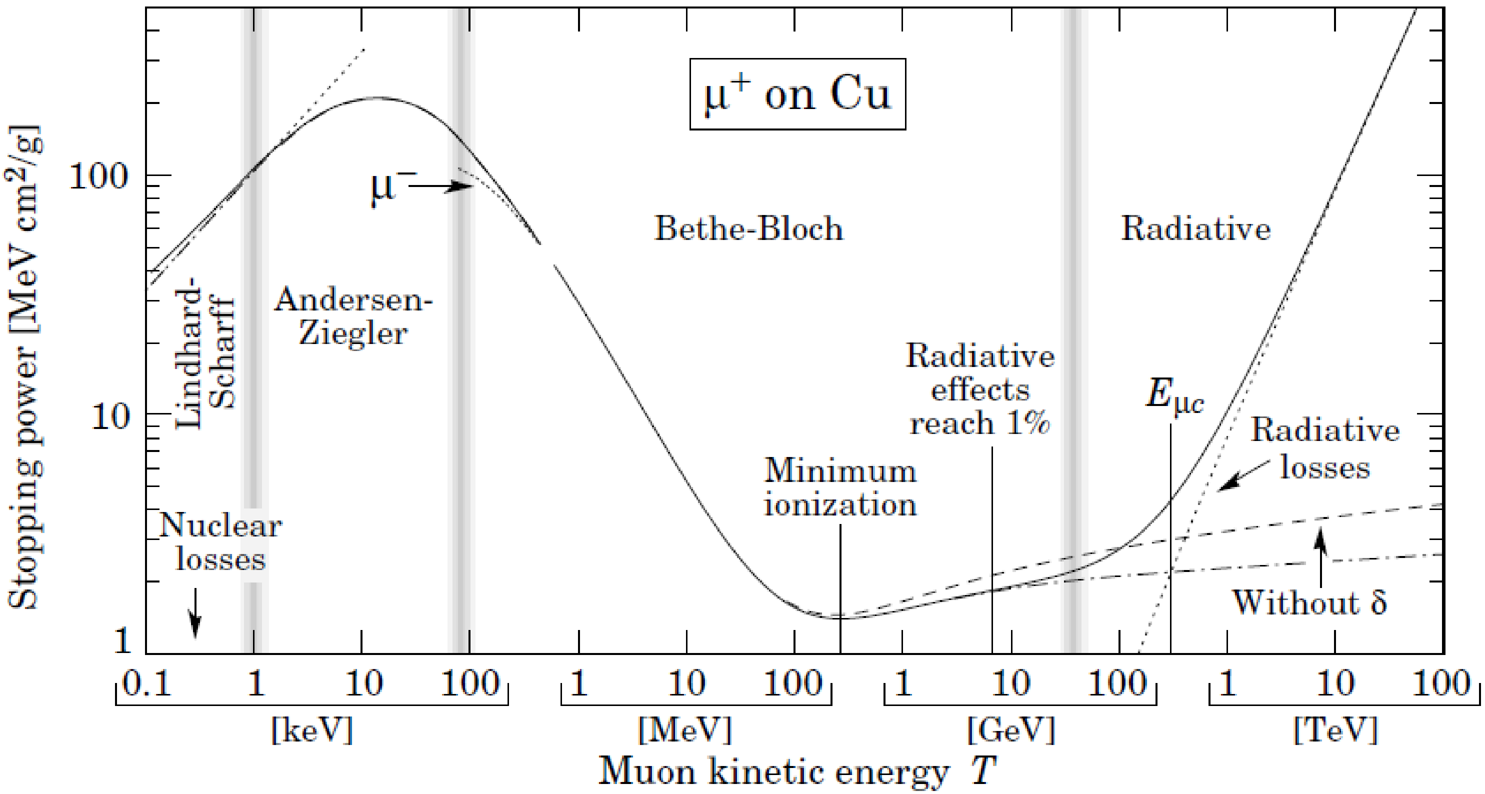


Phys. Rev. D 109, 043007 (2024)

A. Ambrosone, K. M. Groth, E. Peretti, and M. Ahlers

Bethe-Bloch Reminder

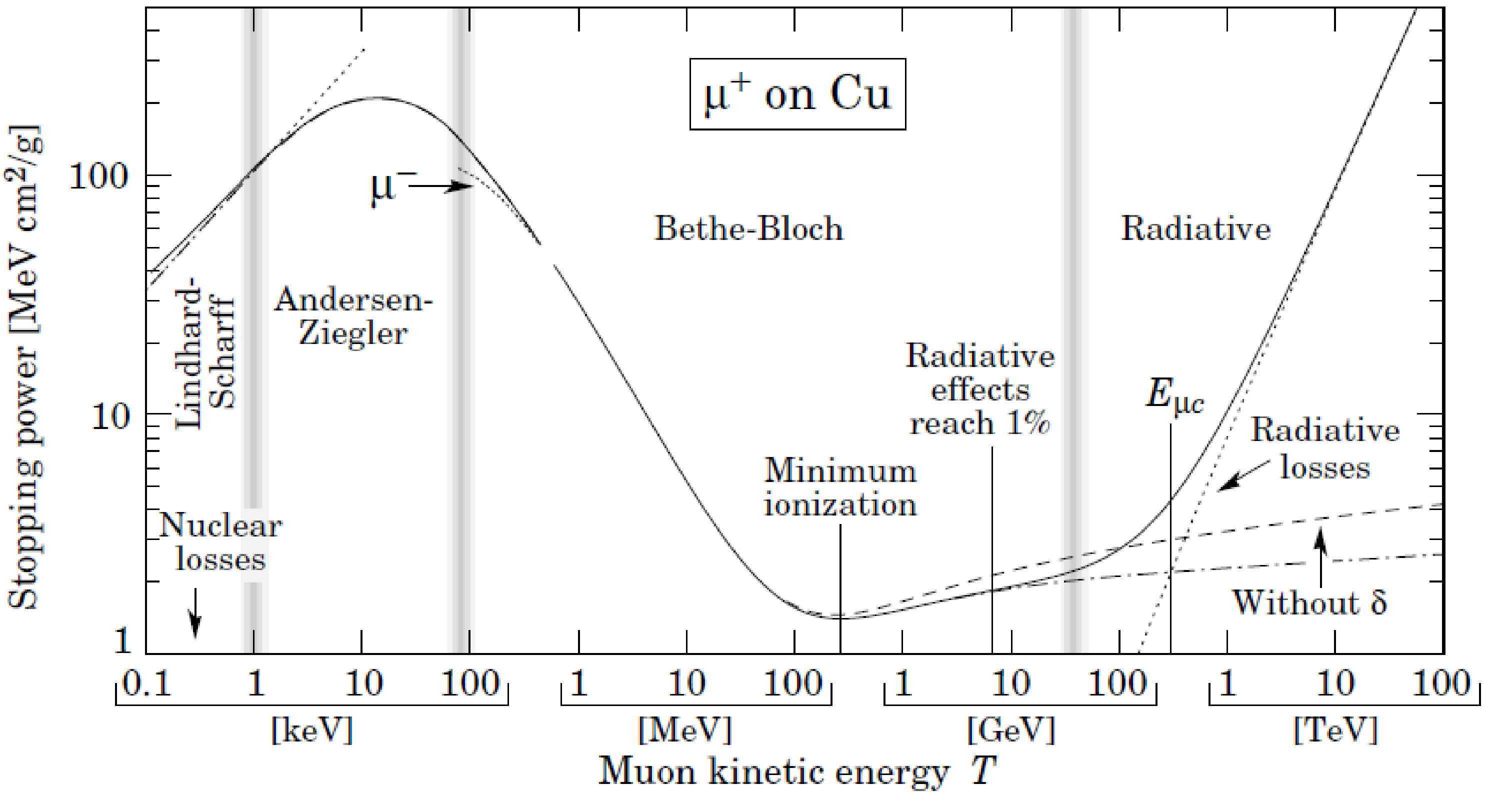
Muon Stopping Power and Range (PDG)



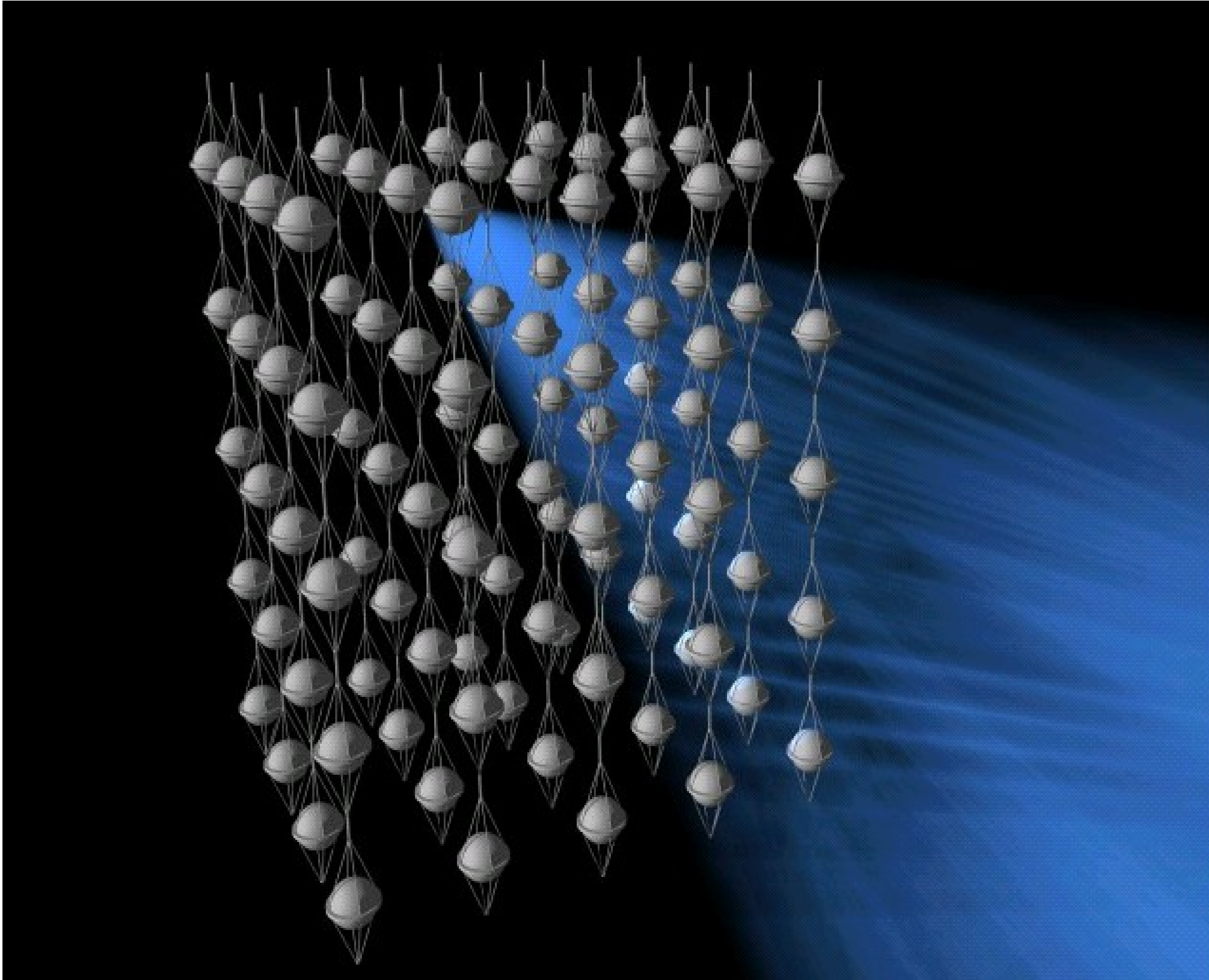
Radiative loss regime – stochastic energy loss

Bethe-Bloch Reminder

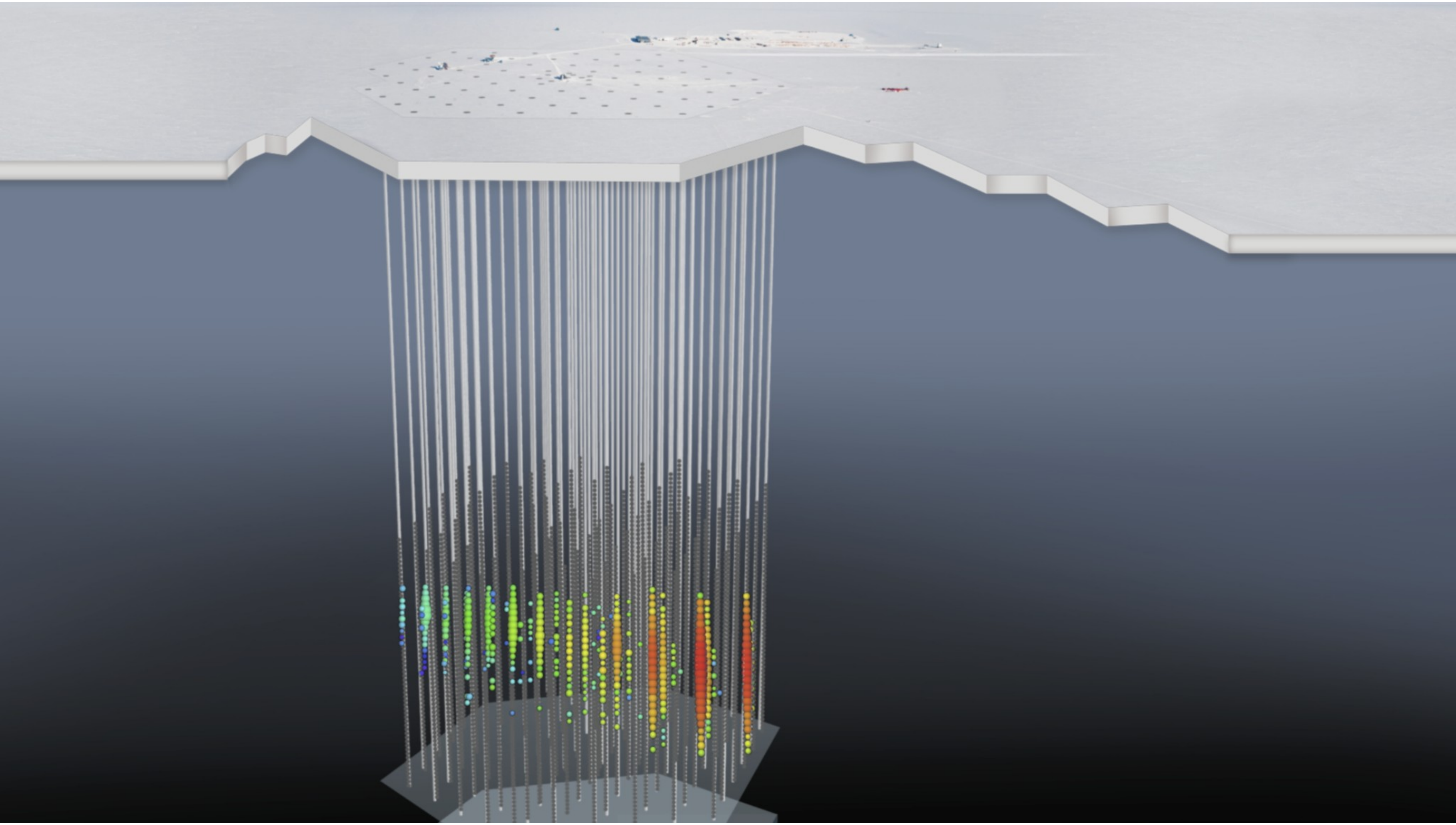
Muon Stopping Power and Range (PDG)



Radiative loss regime – stochastic energy loss



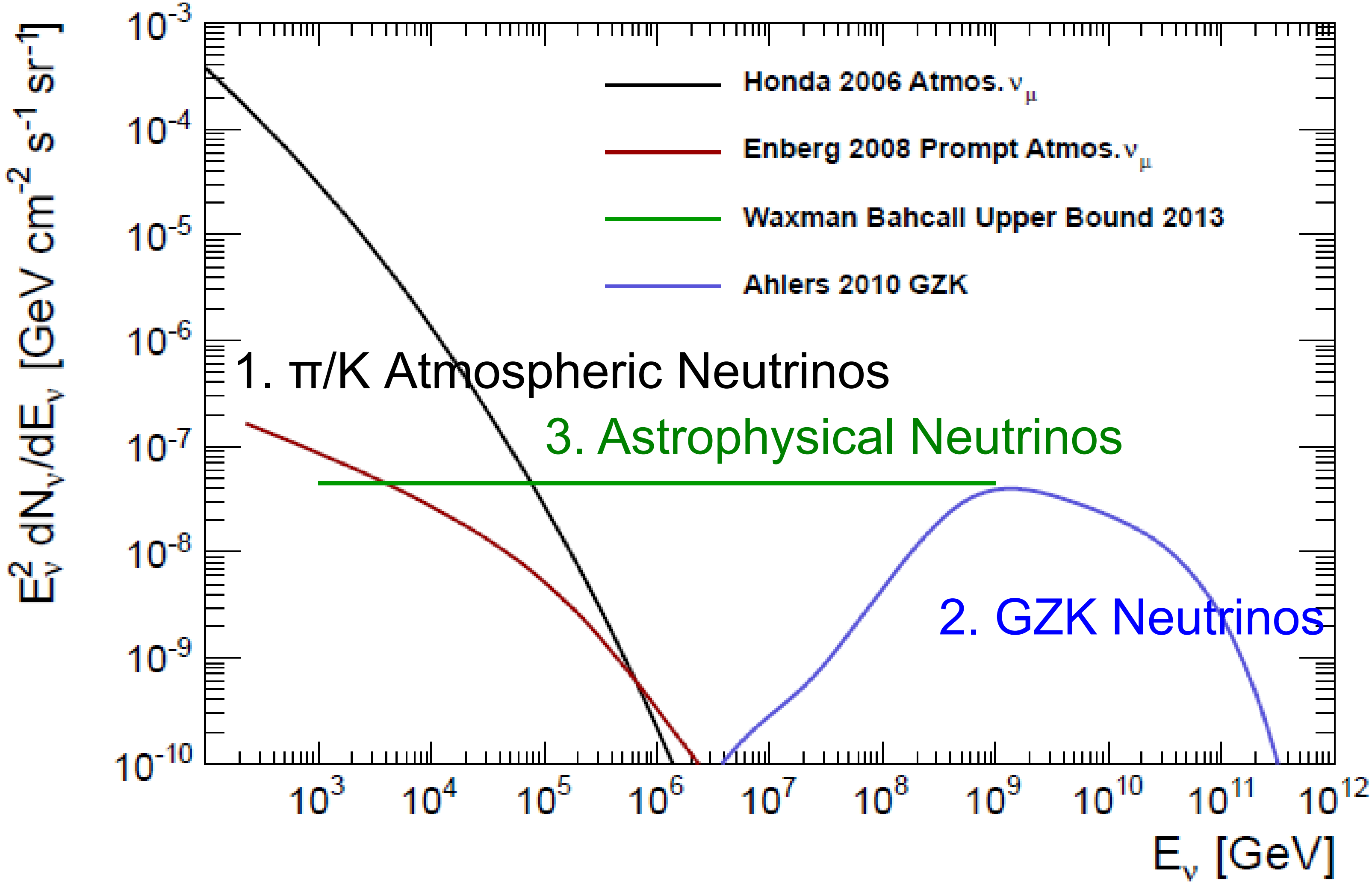
Observe light from Cherenkov Radiation of High-Energy Particles



Naoko Kurahashi Neilson, Drexel University

AGN Unification

The Predicted Neutrino Spectrum



Likelihood Search for a Source
- Test Statistic (TS) Calculation -

Maximize the likelihood L assuming a source at point x with energy spectrum $E^{-\gamma}$

$$L(x) = \prod_{i}^{n_{tot}} \left[\frac{n_s}{n_{tot}} \times S_i(x) + \frac{n_{tot} - n_s}{n_{tot}} \times B_i(x) \right]$$

Total # of events

# of events from source
Varied to maximize L

Probability density
that event i comes from
a source at position x

×

Probability density that
event i comes from a
source with spectrum γ

Probability density that
event i is from backgrounds
expected at position x

×

Probability density that
event i comes form a known
background energy spectrum

TS is calculated for every point in the sky x

$$TS(x) = 2 \times \log\left(L(x) / L_0(x) \right)$$

where $L_0 = L(x, n_s = 0)$