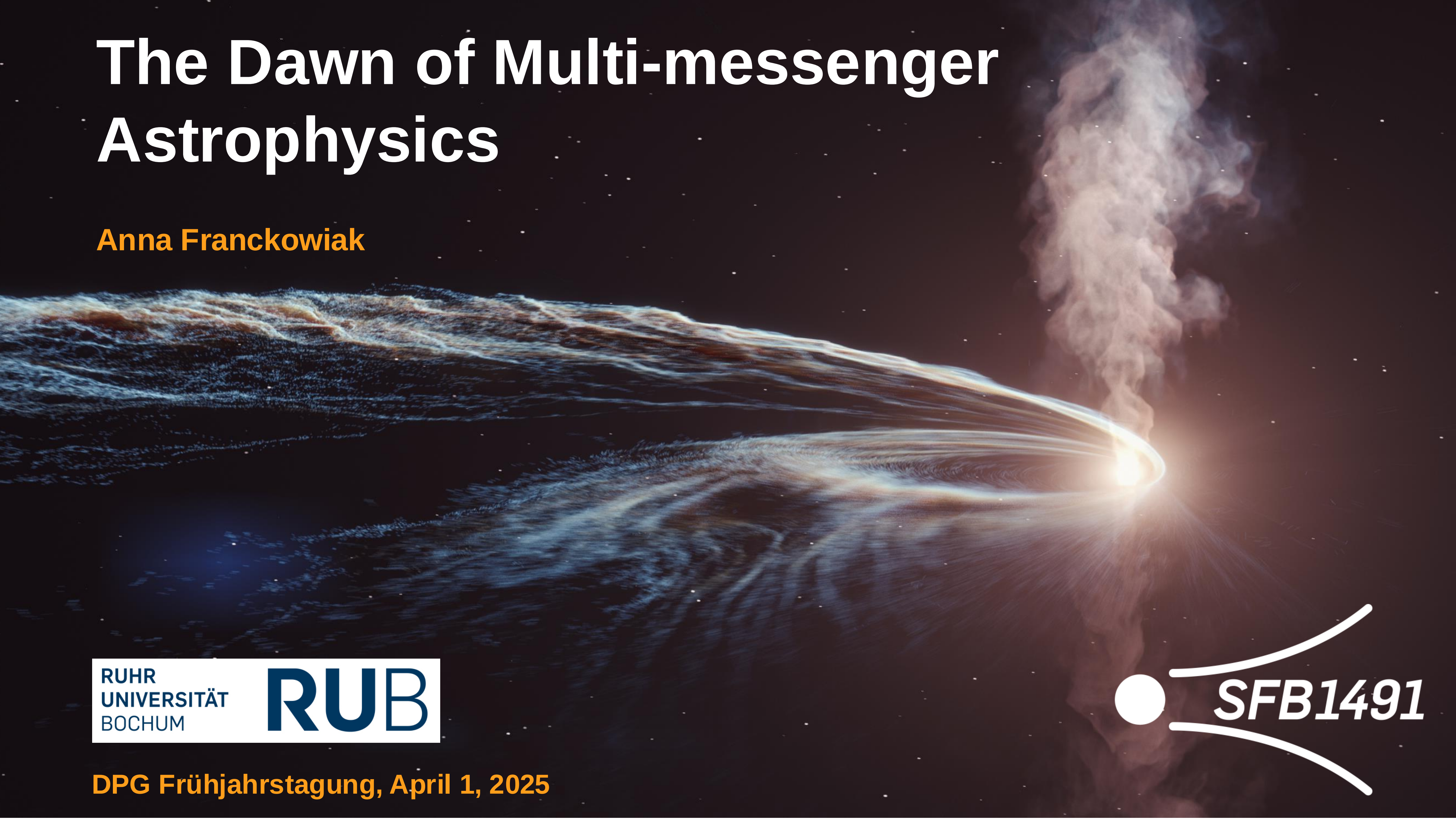
The Dawn of Multi-messenger Astrophysics

Anna Franckowiak



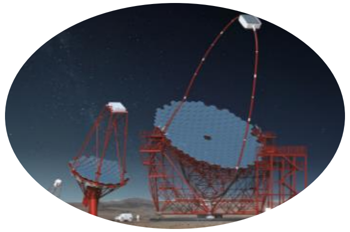
RUHR UNIVERSITÄT BOCHUM RUB

SFB1491

DPG Frühjahrstagung, April 1, 2025

The Multi-Messenger Picture

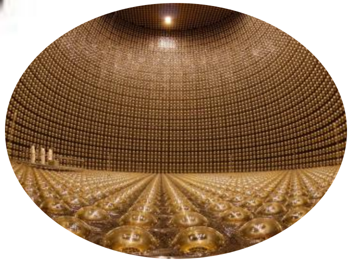
Photons



TeV-PeV Neutrinos

Cosmic Rays

MeV Neutrinos



Gravitational Waves

The Multi-Messenger Picture

Photons

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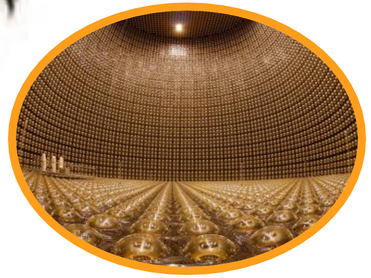
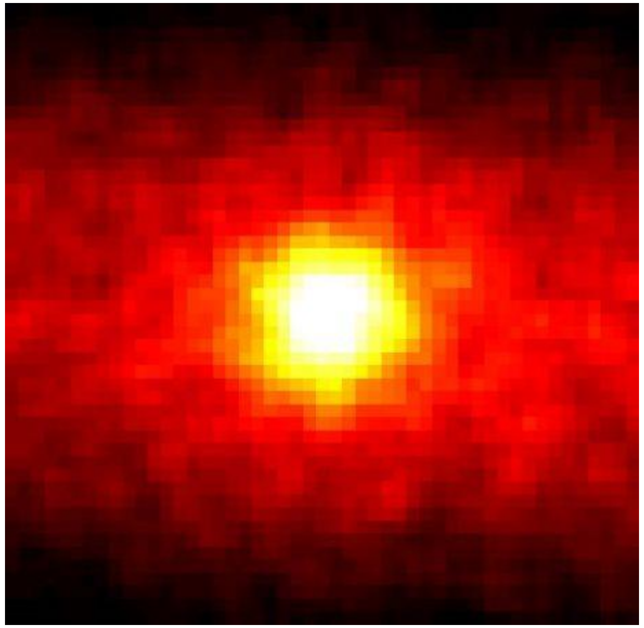


Gravitational Waves

Birth of Multi-messenger Astronomy with Neutrinos

Astronomy Picture of the Day
June 5, 1998



The Sun in Neutrinos seen by Super-Kamiokande

Combining neutrinos and electromagnetic information led to:

Birth of Multi-messenger Astronomy with Neutrinos

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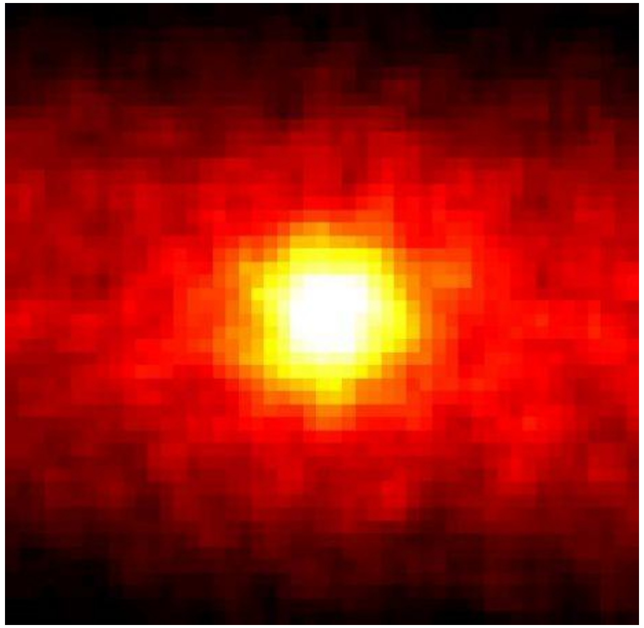

The Sun in Neutrinos seen by Super-Kamiokande

Combining neutrinos and electromagnetic information led to:

- **The solar neutrino problem**

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Birth of Multi-messenger Astronomy with Neutrinos

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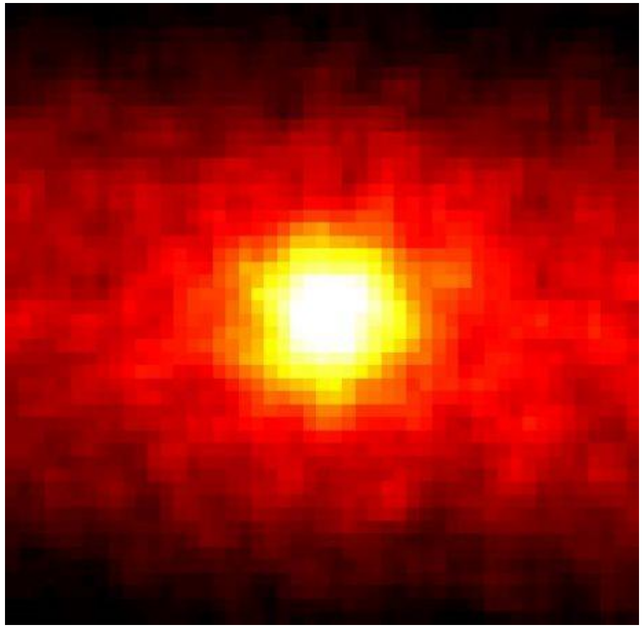
June 5, 1998



The Sun in Neutrinos seen by Super-Kamiokande

Combining neutrinos and electromagnetic information led to:

- Confirmation of model of fusion
- New understanding of the standard model of particle physics

First (and only) detection of a Supernova

Optical detection of SN1987A in LMC

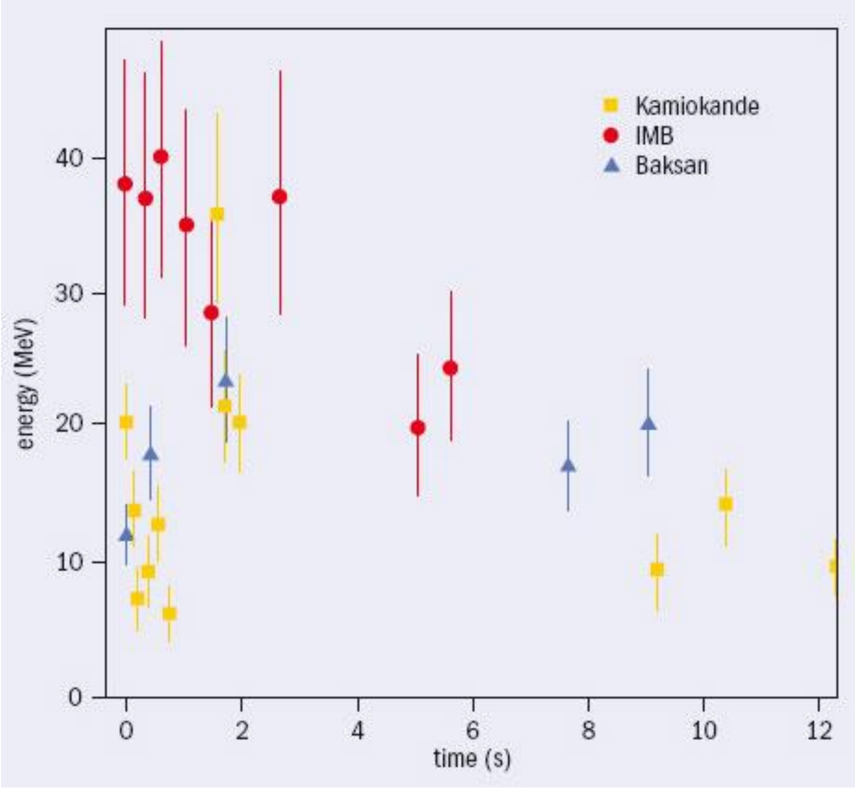
during supernova before supernova

First (and only) detection of a Supernova

Optical detection of SN1987A in LMC

during supernova before supernova

MeV neutrino burst



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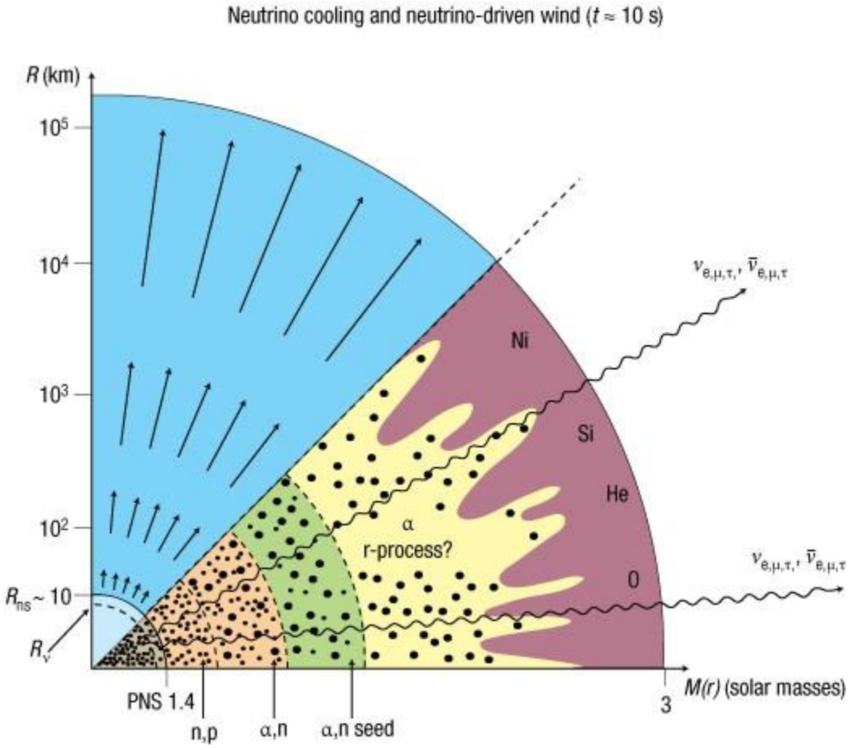
First (and only) detection of a Supernova

First direct confirmation of our basic picture of a stellar collapse



Woosely & Janka, Nature Physics 2005

First (and only) detection of a Supernova

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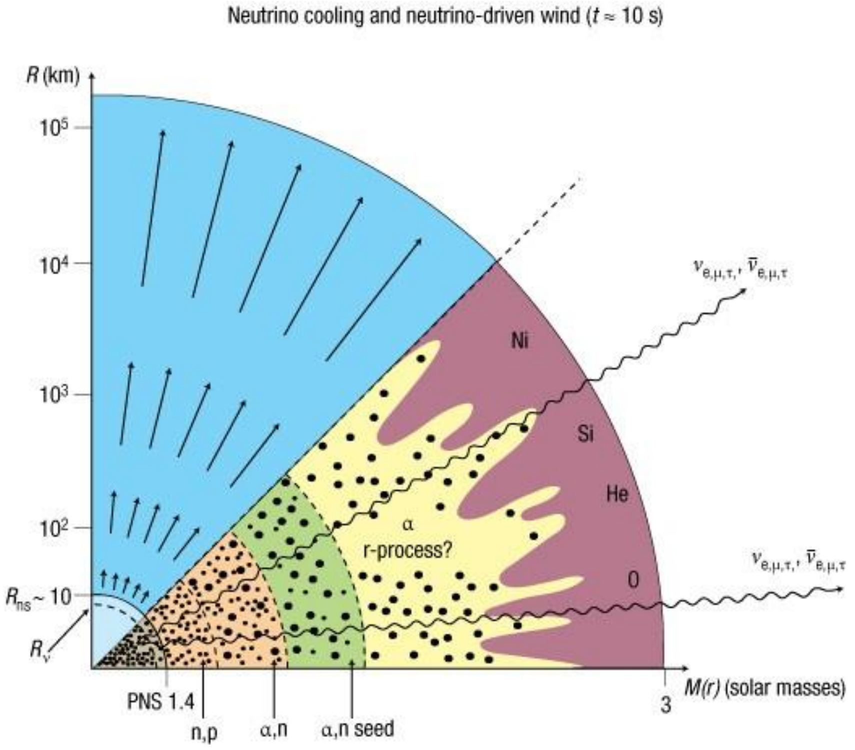
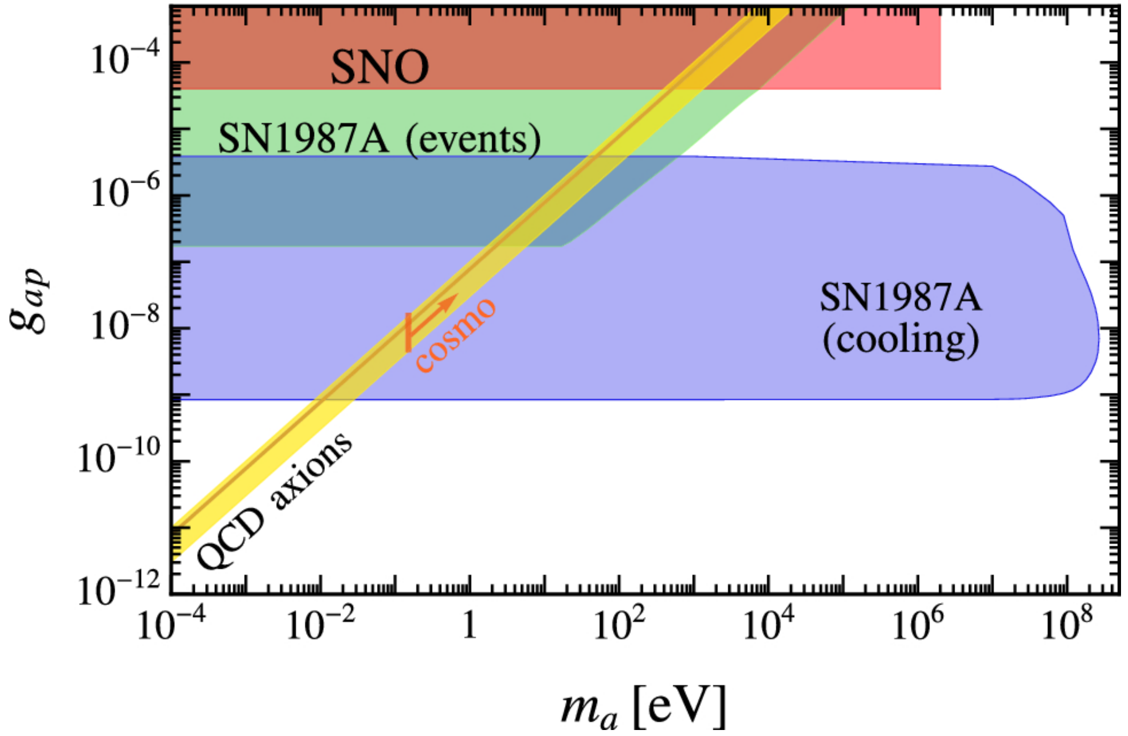


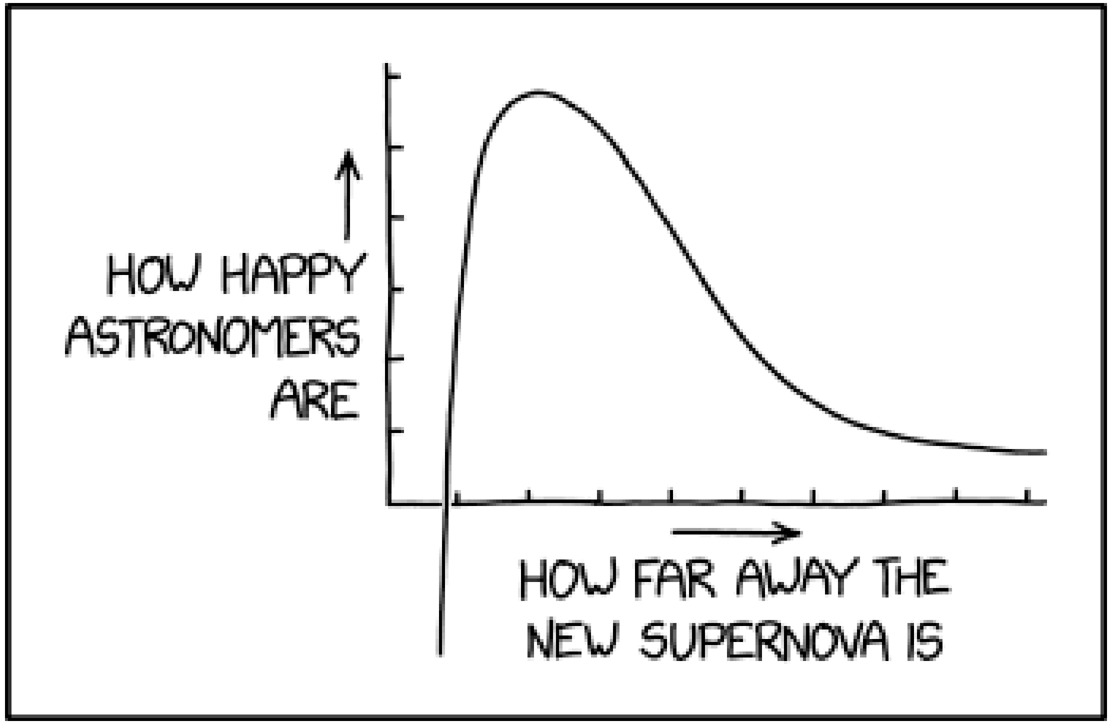
Woosely & Janka, Nature Physics 2005

Constraints on exotic physics (e.g. axions)



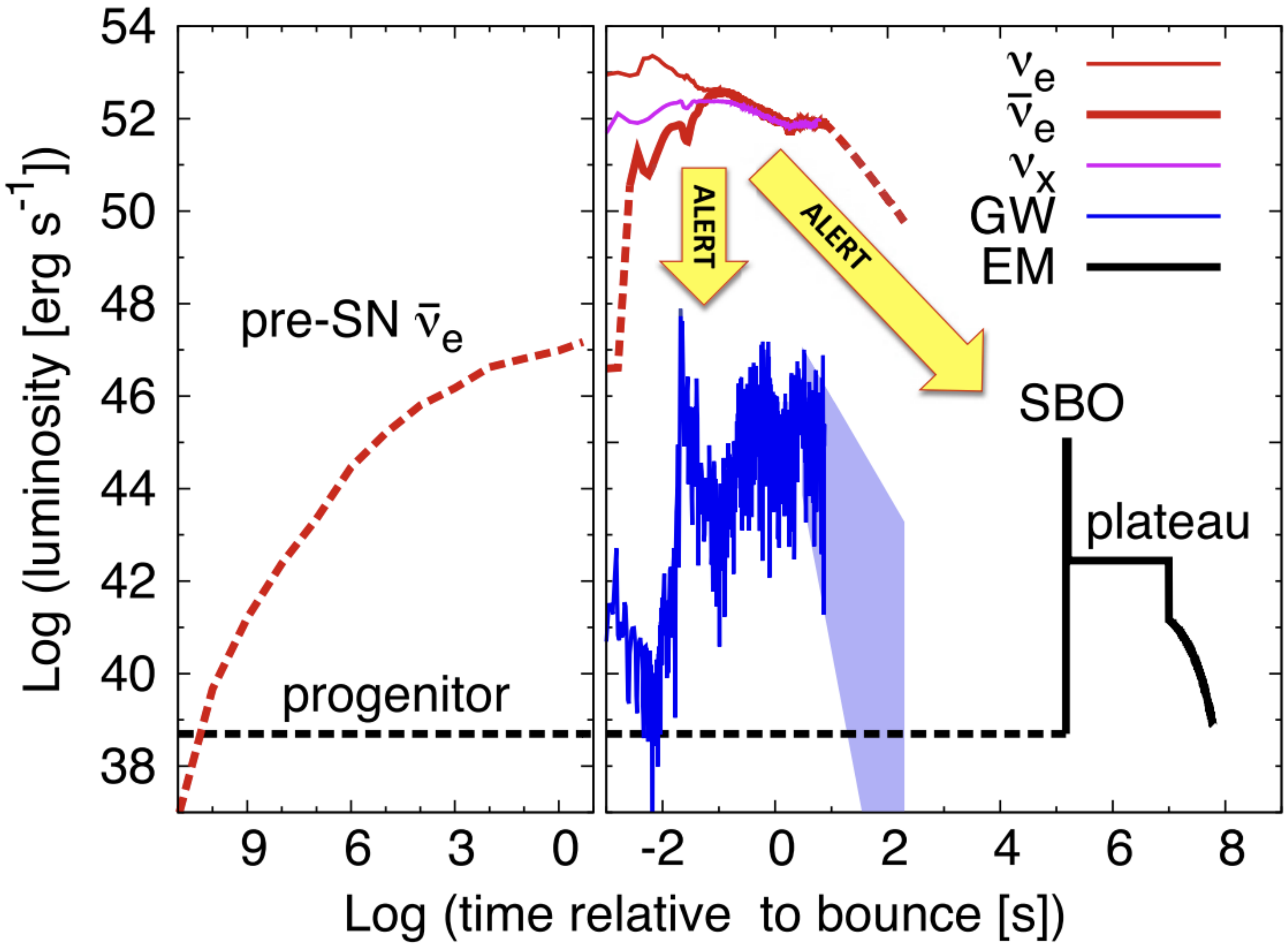
Lella et al. PRD 109 (2024)

Are we ready for the next neutrino-detected supernova?



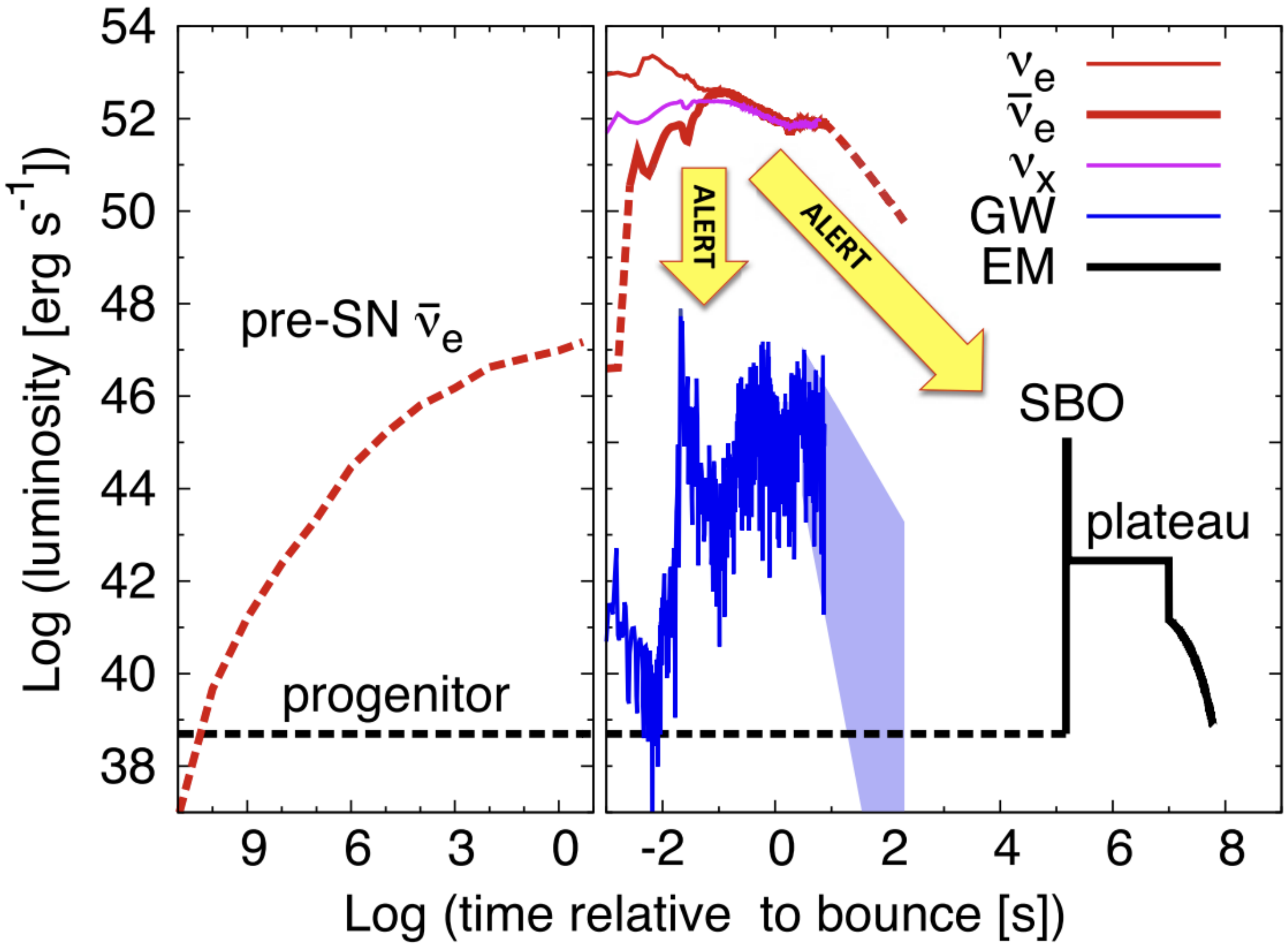
https://xkcd.com/2878/

Multi-messenger Signature of a Supernova



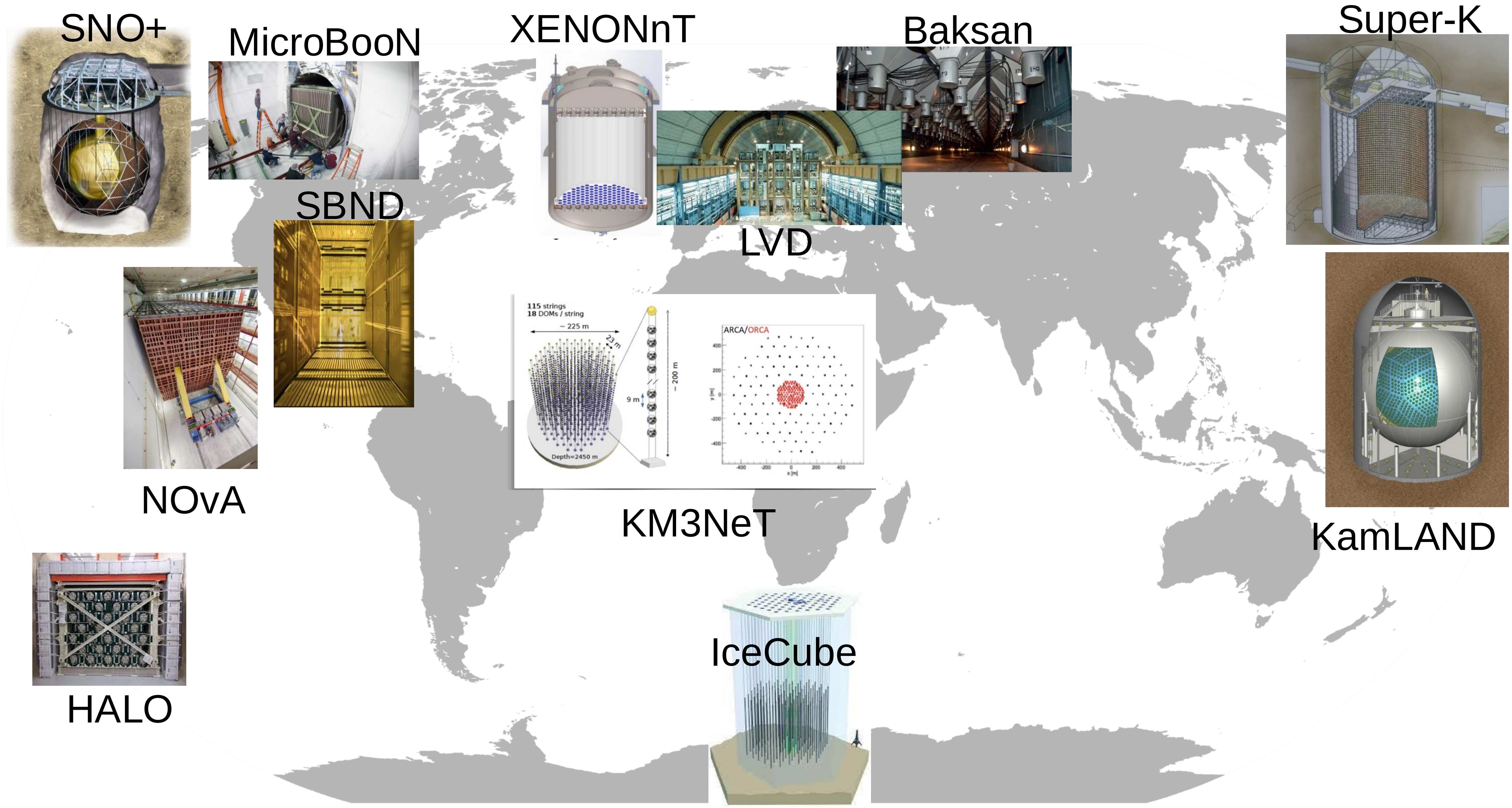
Al Kharusi et al New J. Phys. **23** 2021

Supernova early warning system



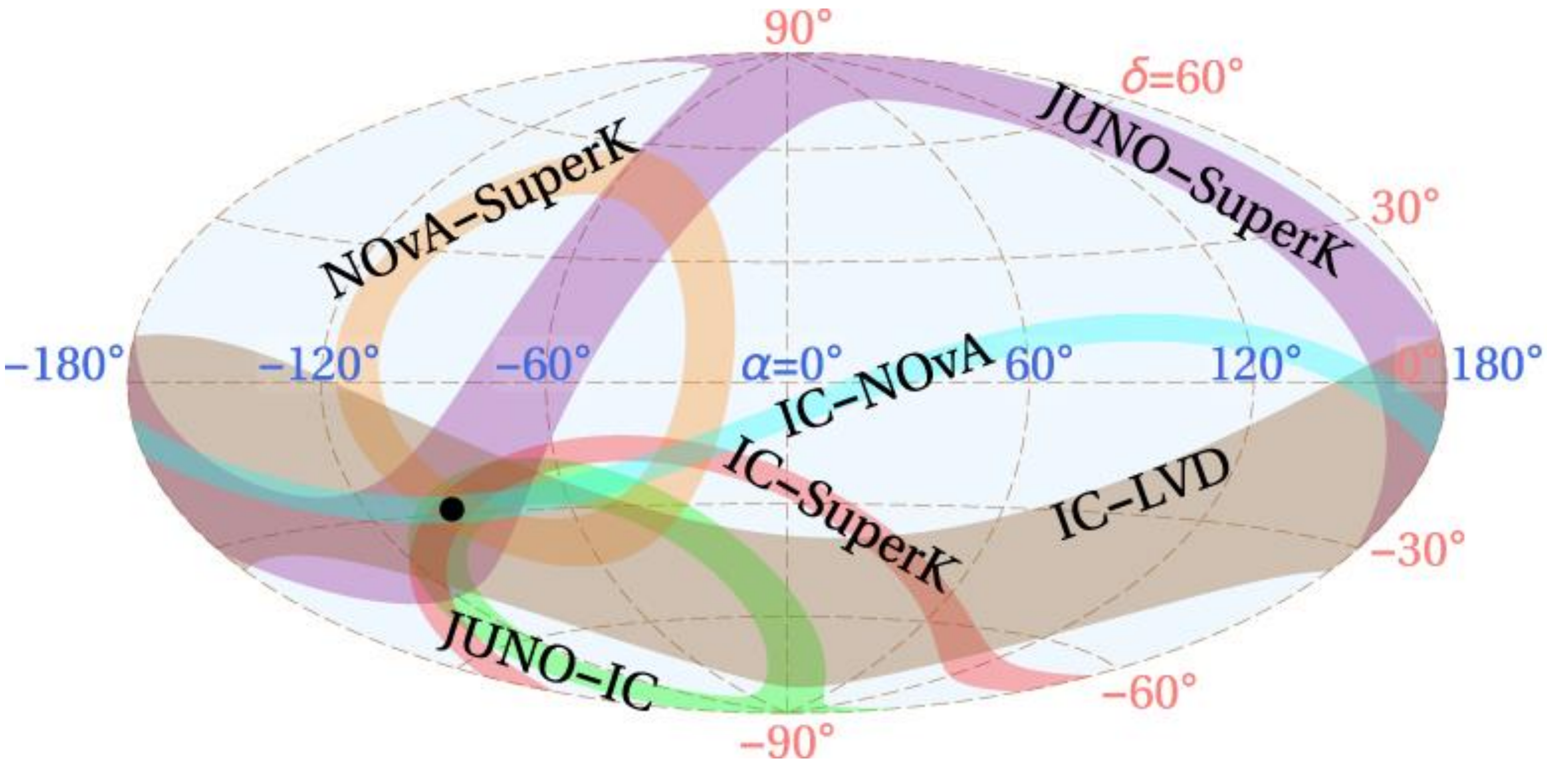
MeV neutrino burst as trigger for electromagnetic supernovae observations

Al Kharusi et al New J. Phys. **23** 2021



https://snews2.org/

Supernova localization



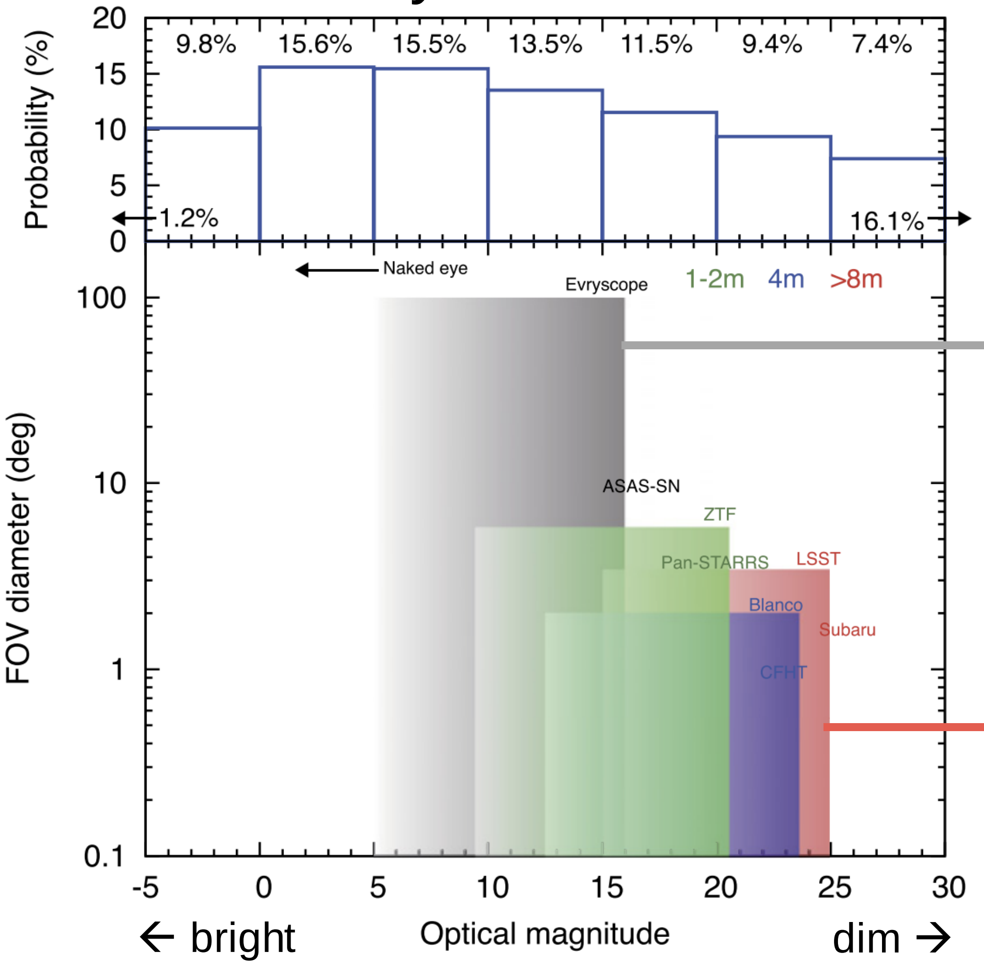
Coordinated follow-up observations with wide-field-of-view instruments are necessary

Delay between neutrino burst and optical signal: **2 min to 2 days**

Al Kharusi et al New J. Phys. **23** 2021

Catching the next Galactic Neutrino Supernova

Detectability of shock breakout



Optical counterpart can appear within minutes of neutrino alert → take full advantage of once-in-a-lifetime event

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Al Kharusi et al New J. Phys. **23** 2021

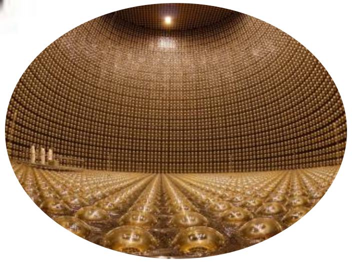
The Multi-Messenger Picture

Photons

TeV-PeV Neutrinos

Cosmic Rays

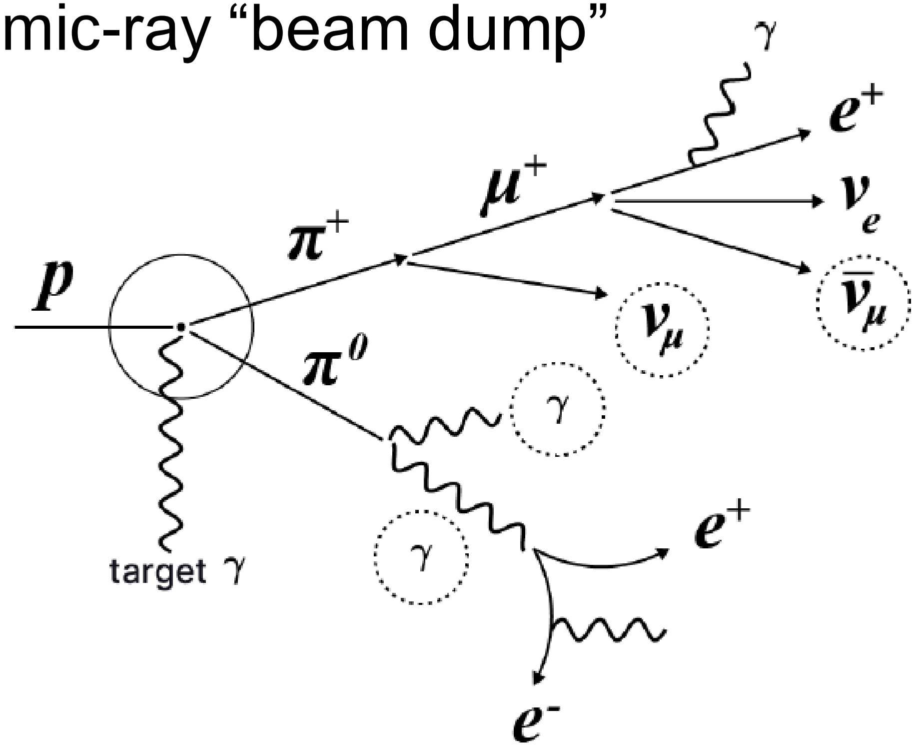
MeV Neutrinos



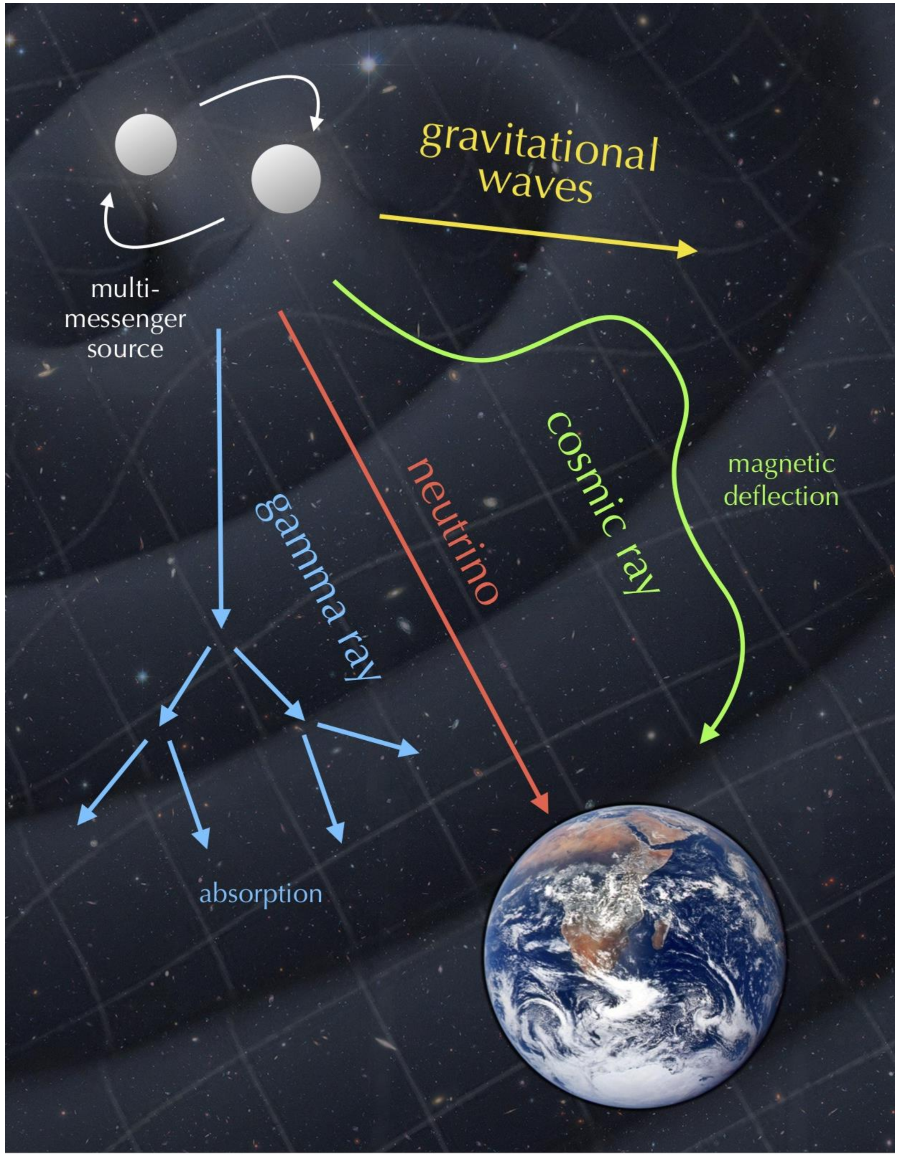
Gravitational Waves

Revealing the cosmic-ray sources

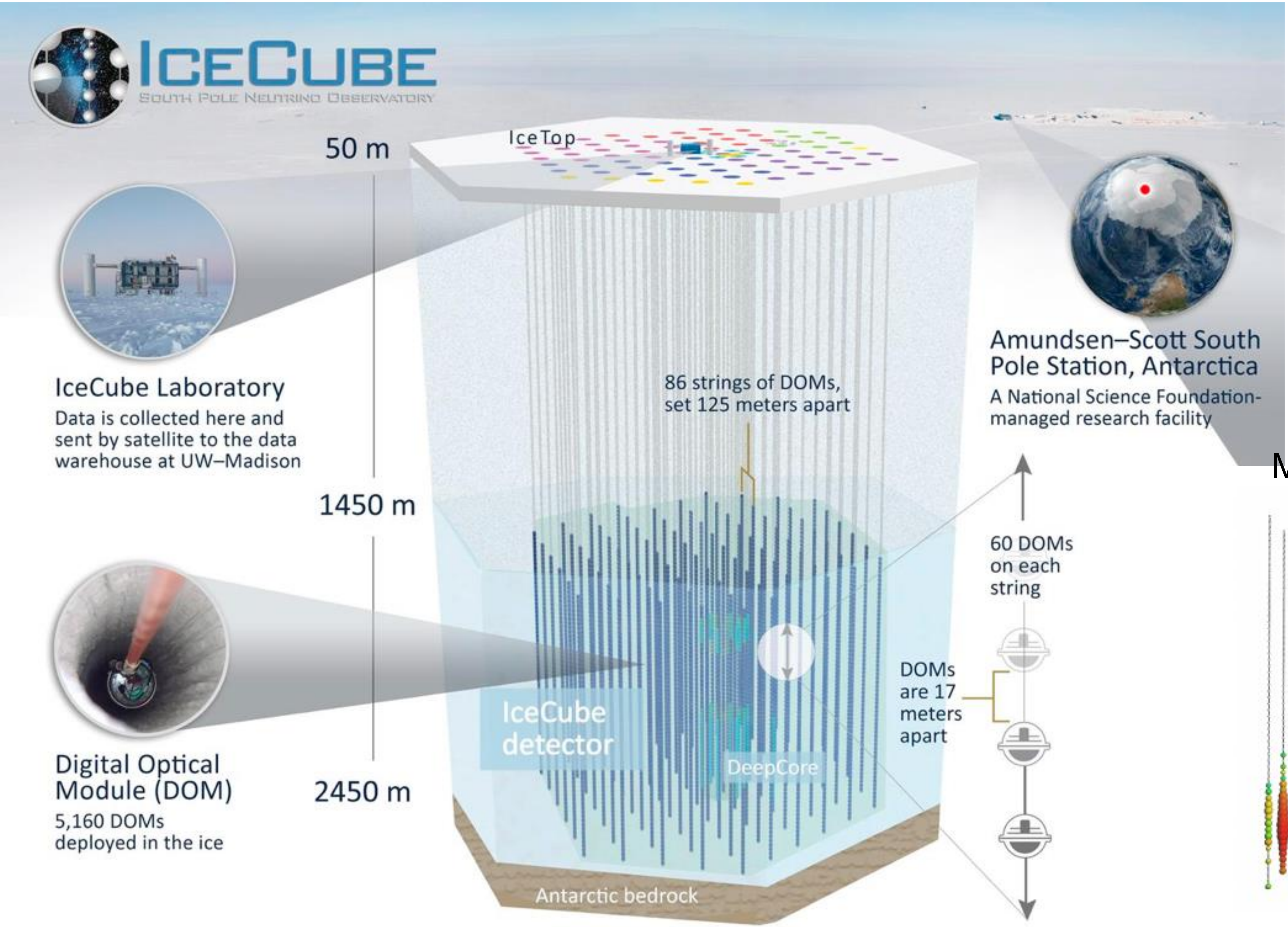
Cosmic-ray "beam dump"



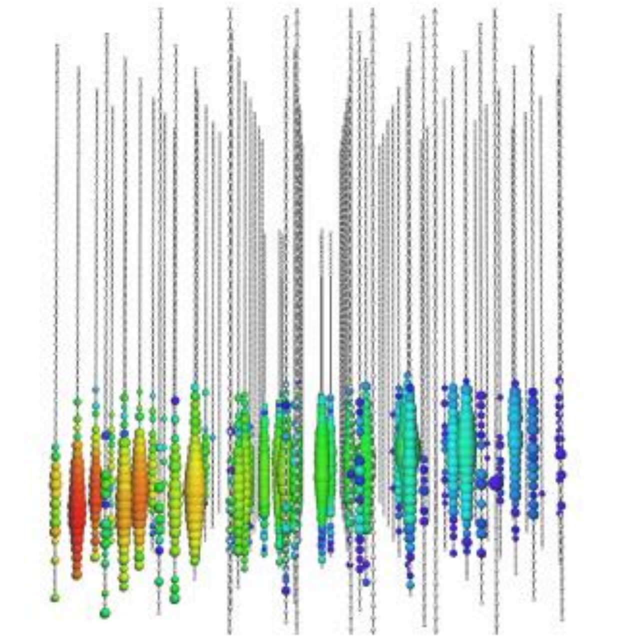
Neutrinos can unambiguously reveal the sources of cosmic rays

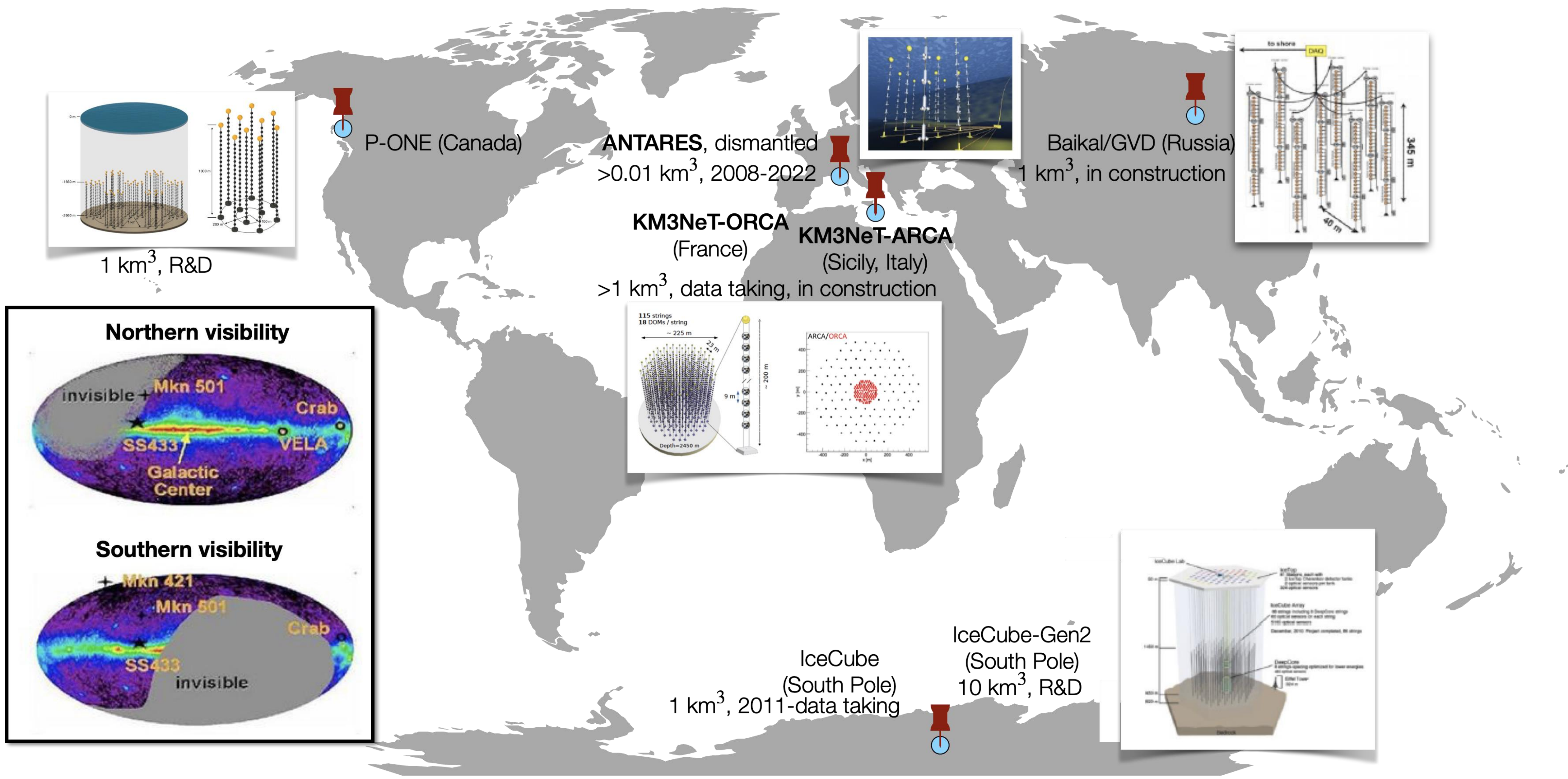


Argüelles, Halzen, Kurahashi, arXiv:2405.17623 (2024)



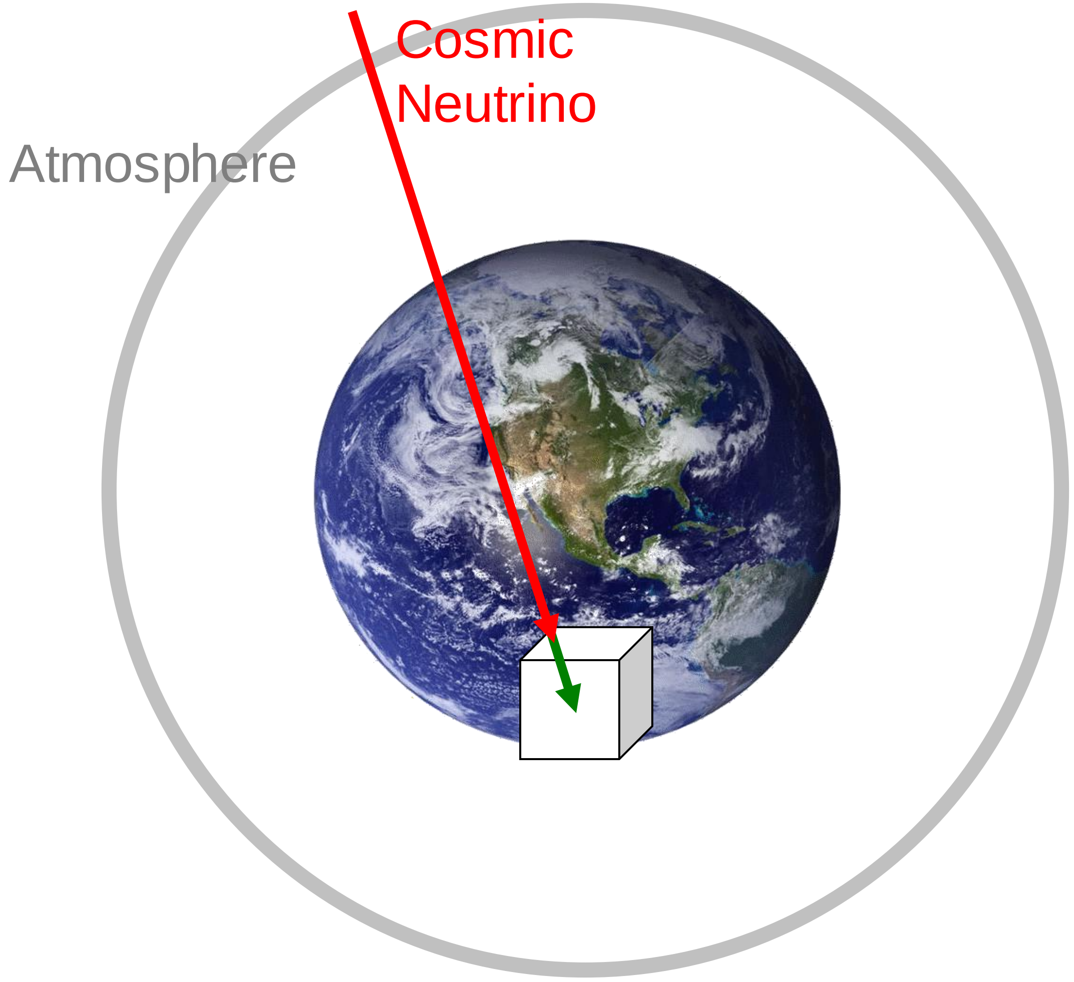
Muon track signature





1 km^3, R&D
P-ONE (Canada)
ANTARES, dismantled
>0.01 km^3, 2008-2022
Baikal/GVD (Russia)
1 km^3, in construction
to shore
DAQ
345 m
40 m
KM3NeT-ORCA
(France)
KM3NeT-ARCA
(Sicily, Italy)
>1 km^3, data taking, in construction
115 strings
18 DOMs / string
~ 225 m
9 m
~ 200 m
Depth=2450 m
ARCA/ORCA
Northern visibility
invisible
Mkn 501
Crab
SS433
VELA
Galactic
Center
Southern visibility
Mkn 421
Mkn 501
Crab
SS433
invisible
IceCube
(South Pole)
1 km^3, 2011-data taking
IceCube-Gen2
(South Pole)
10 km^3, R&D

Background in Search for Cosmic Neutrinos



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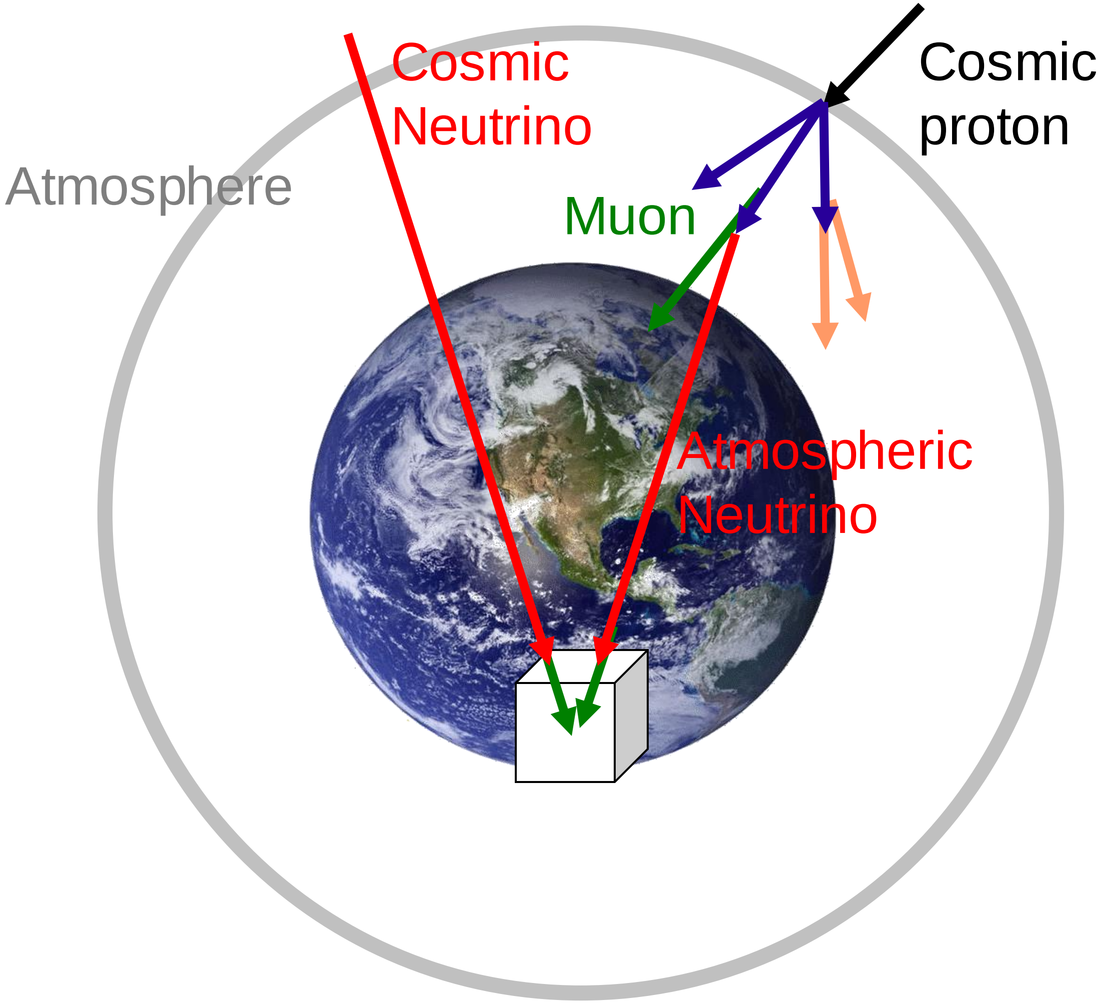

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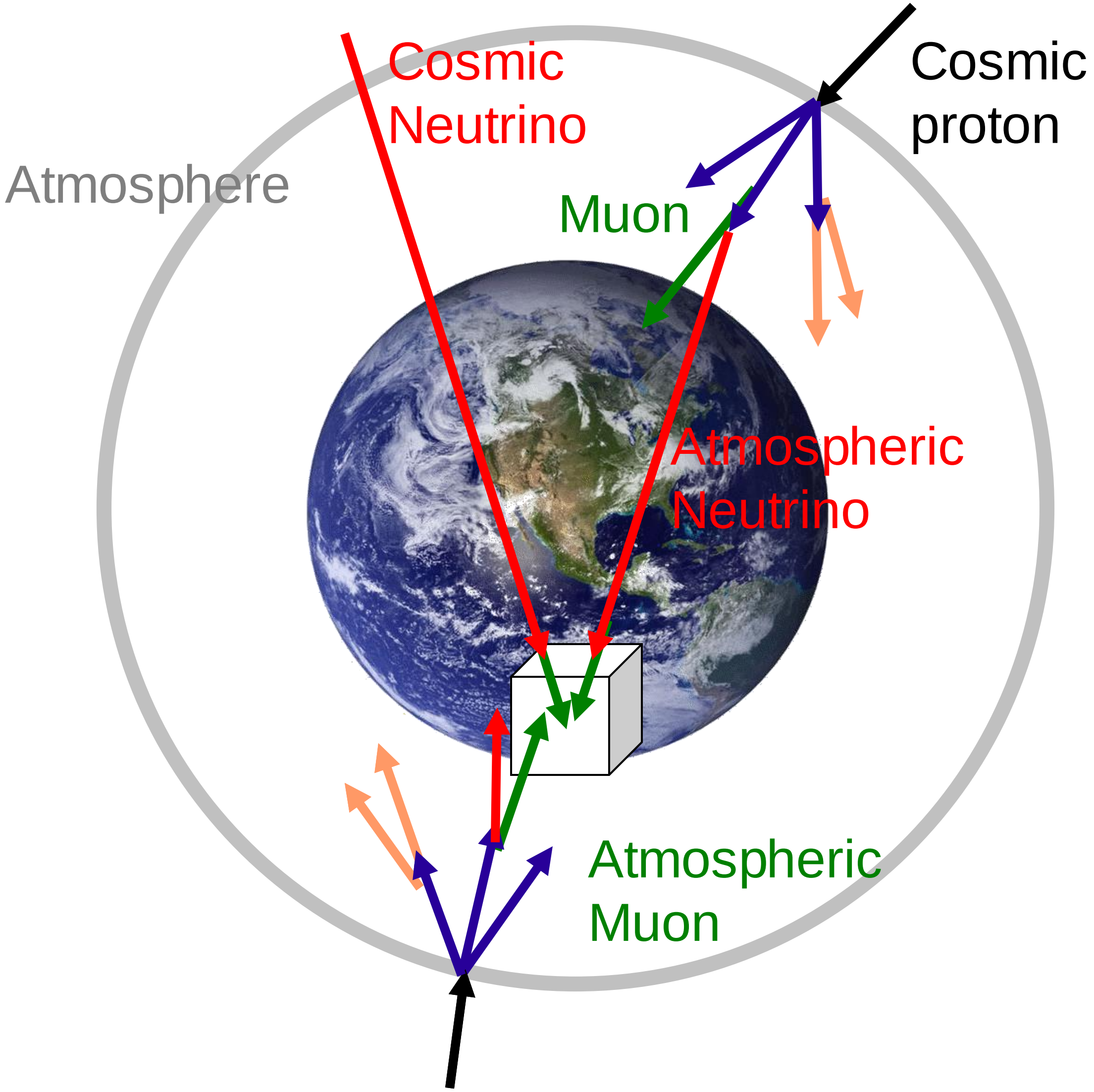

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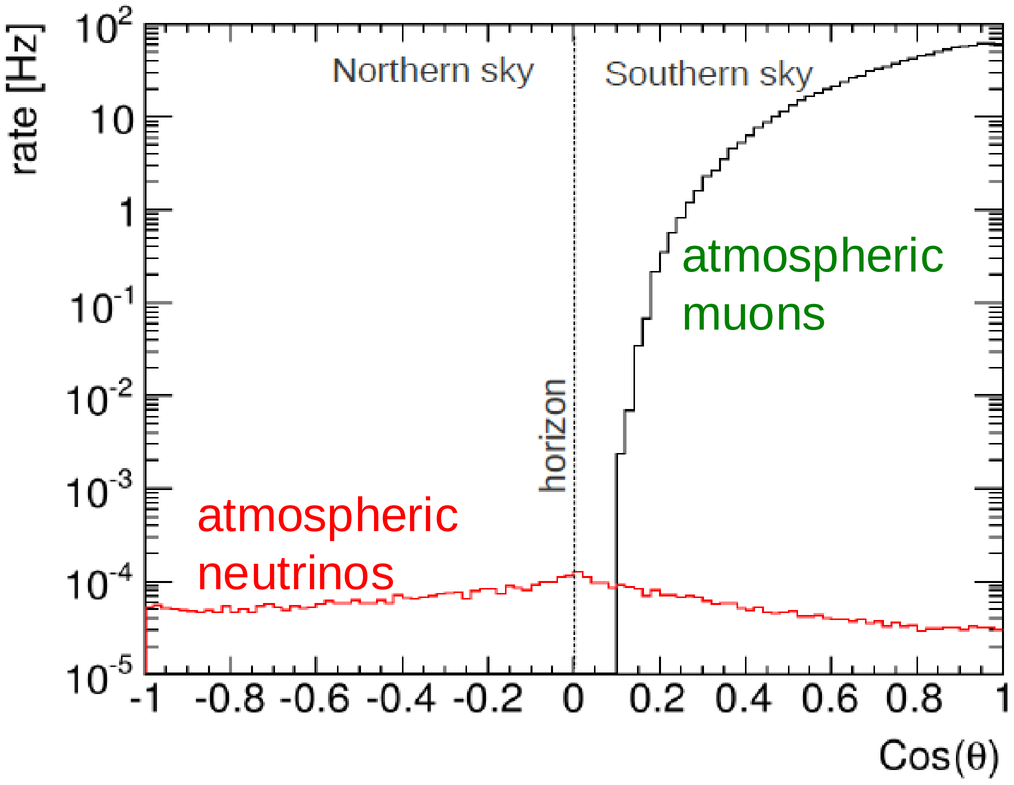
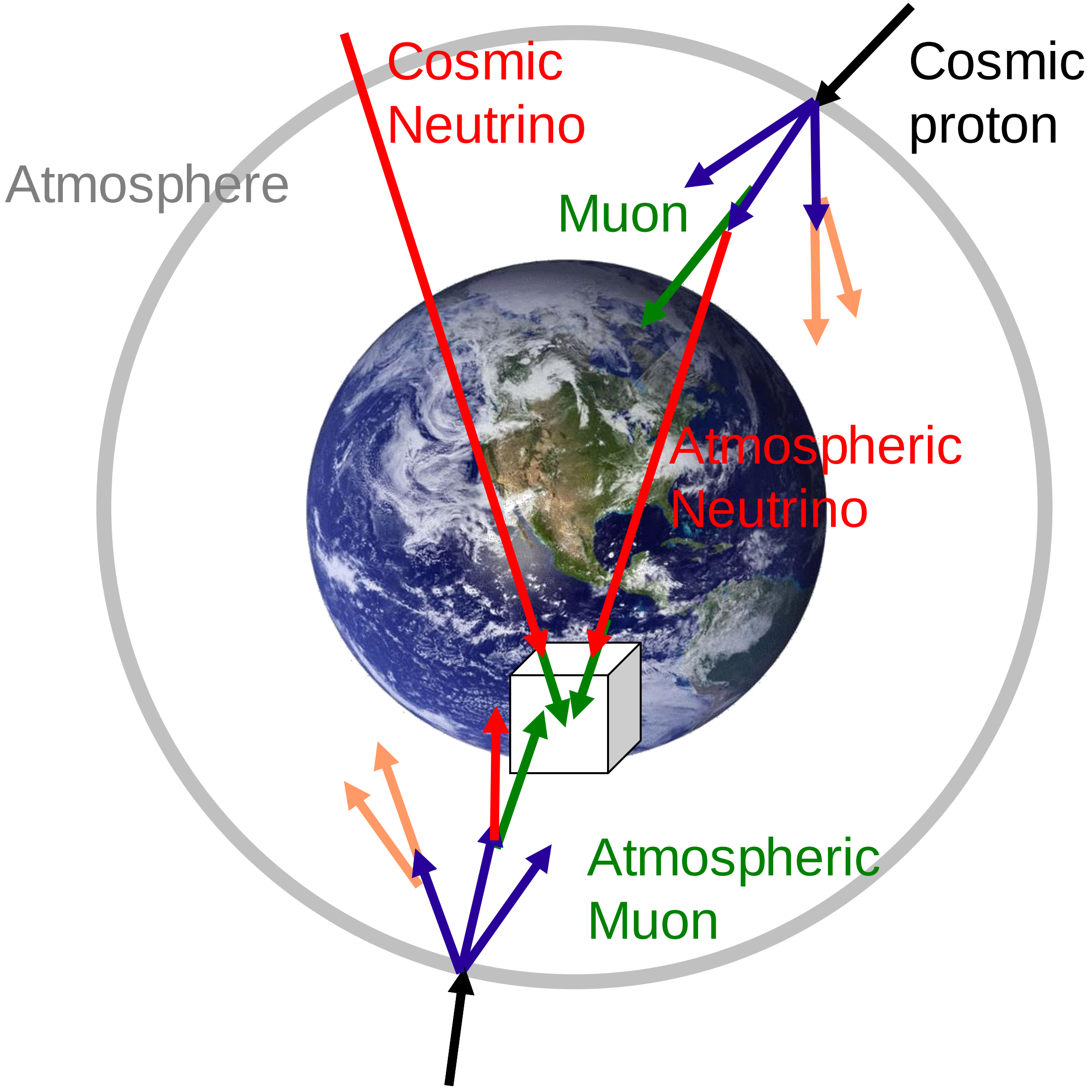
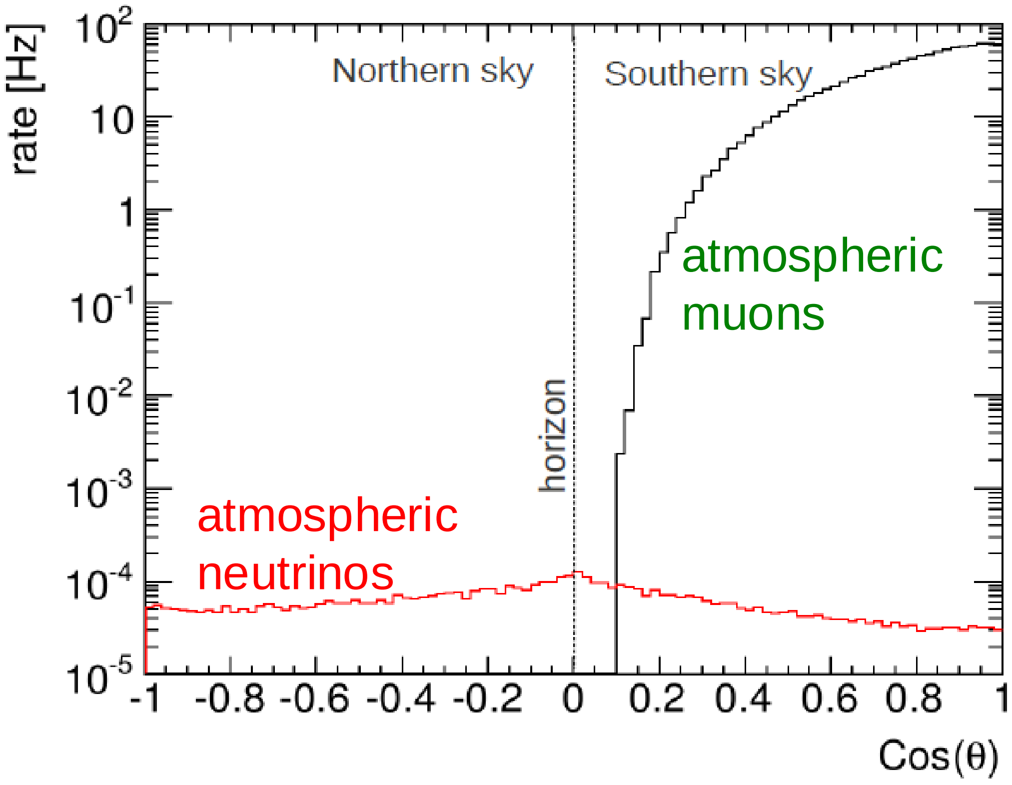


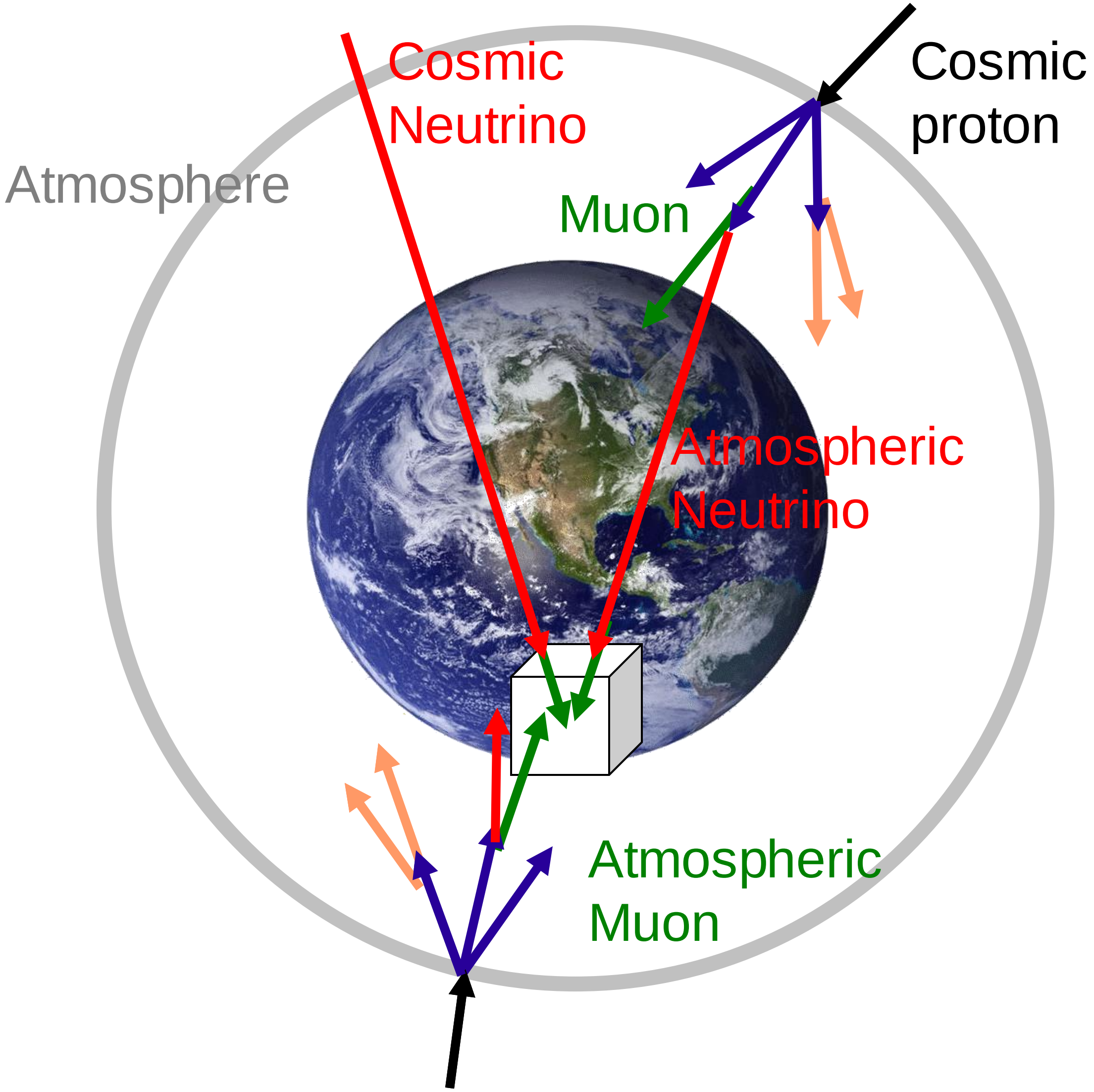


Background in Search for Cosmic Neutrinos

muons detected per year:

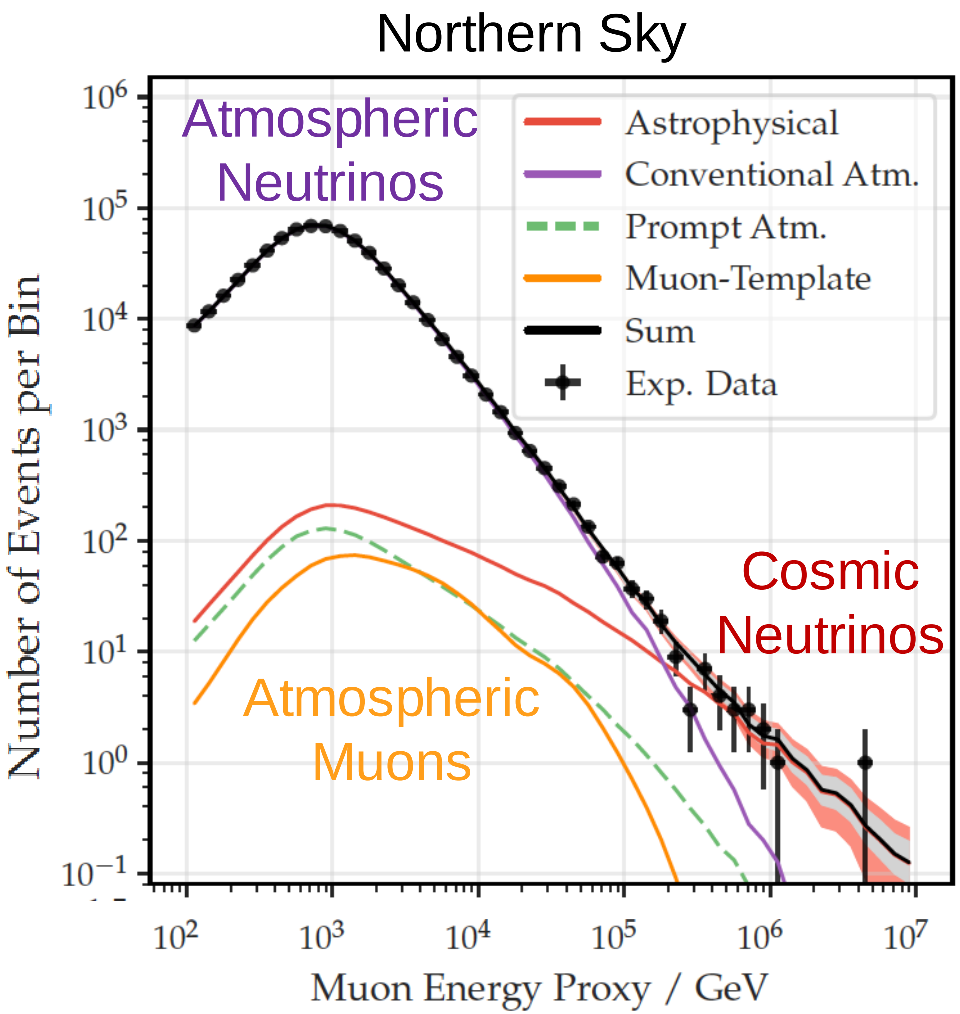
- atmospheric μ ~ 10^{11} (3000/sec)
- atmospheric $\nu \rightarrow \mu$ > 10^5 (1/5min)
- cosmic $\nu \rightarrow \mu$ > 120 / year

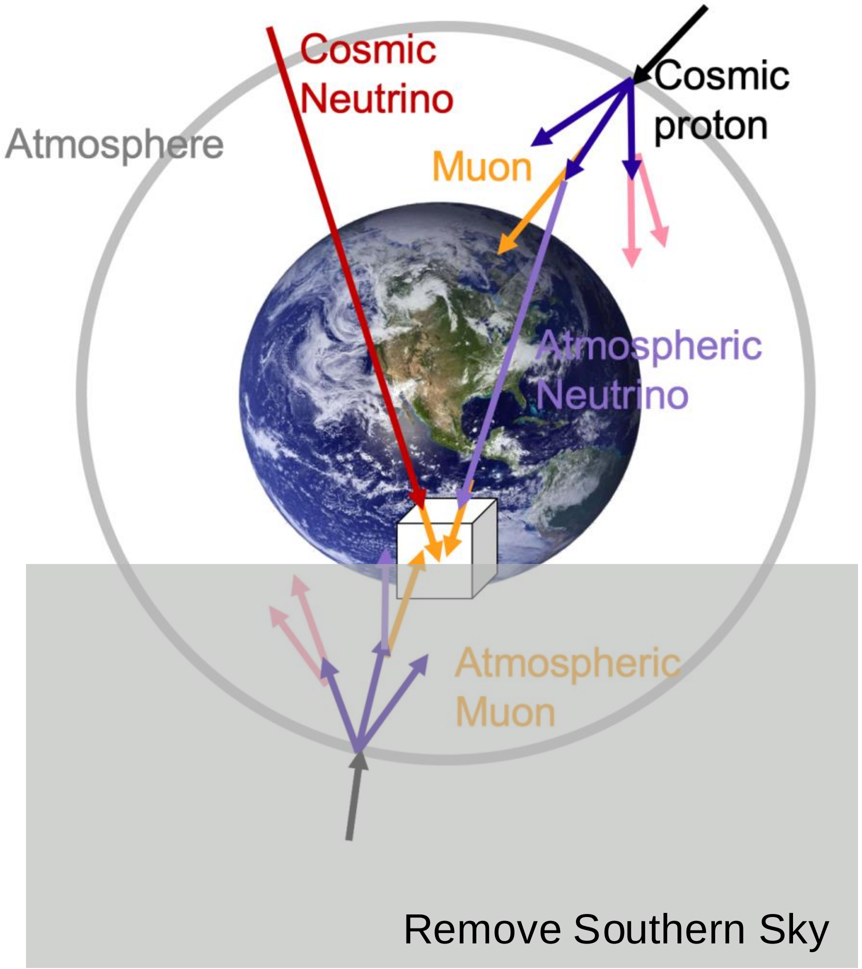




Have we seen cosmic neutrinos?

Milestone: Detection of Diffuse Neutrino Flux





IceCube Coll. ApJ 928 (2022) 50

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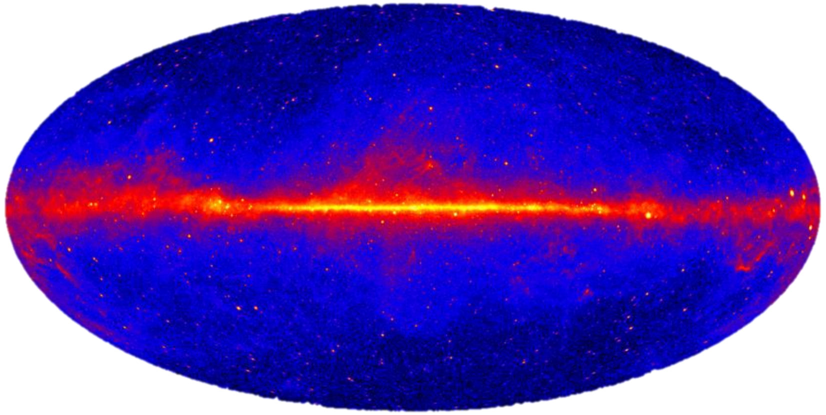
Diffuse flux discovered

What are the source?

Galactic Contribution

GeV gamma-ray sky by Fermi-LAT

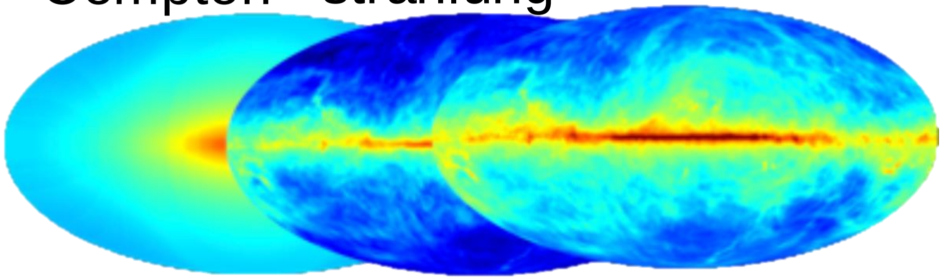


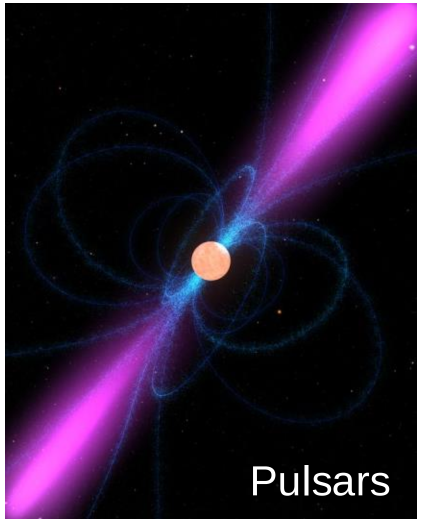
Cosmic rays propagate through the Galaxy and interact with photons and gas

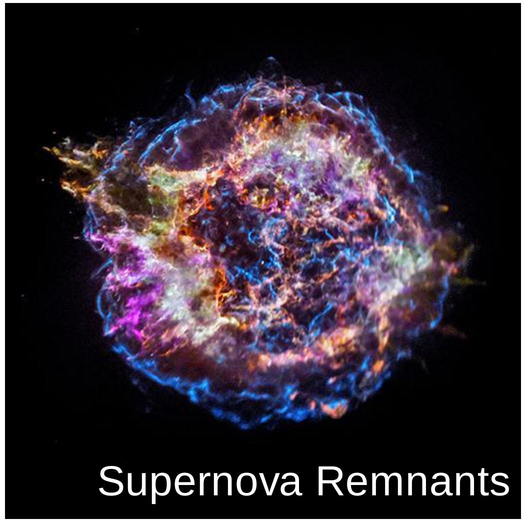
Inverse Compton

Brems-strahlung

π^0 decay

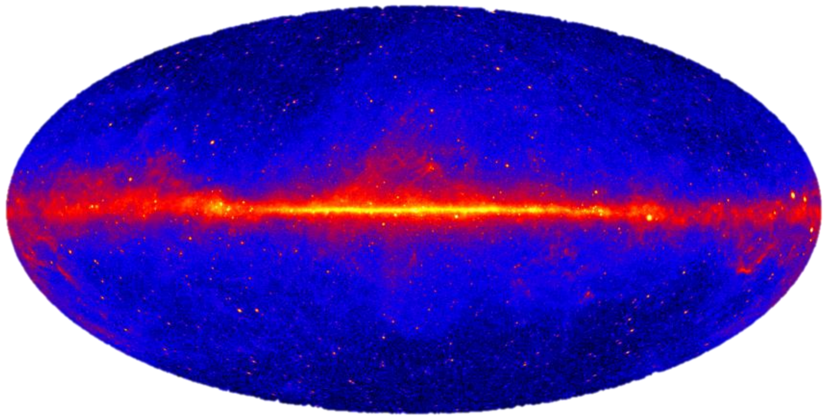






Galactic Contribution

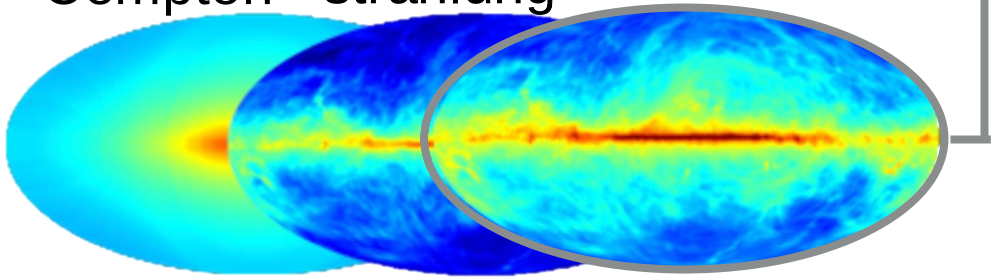
GeV gamma-ray sky by Fermi-LAT

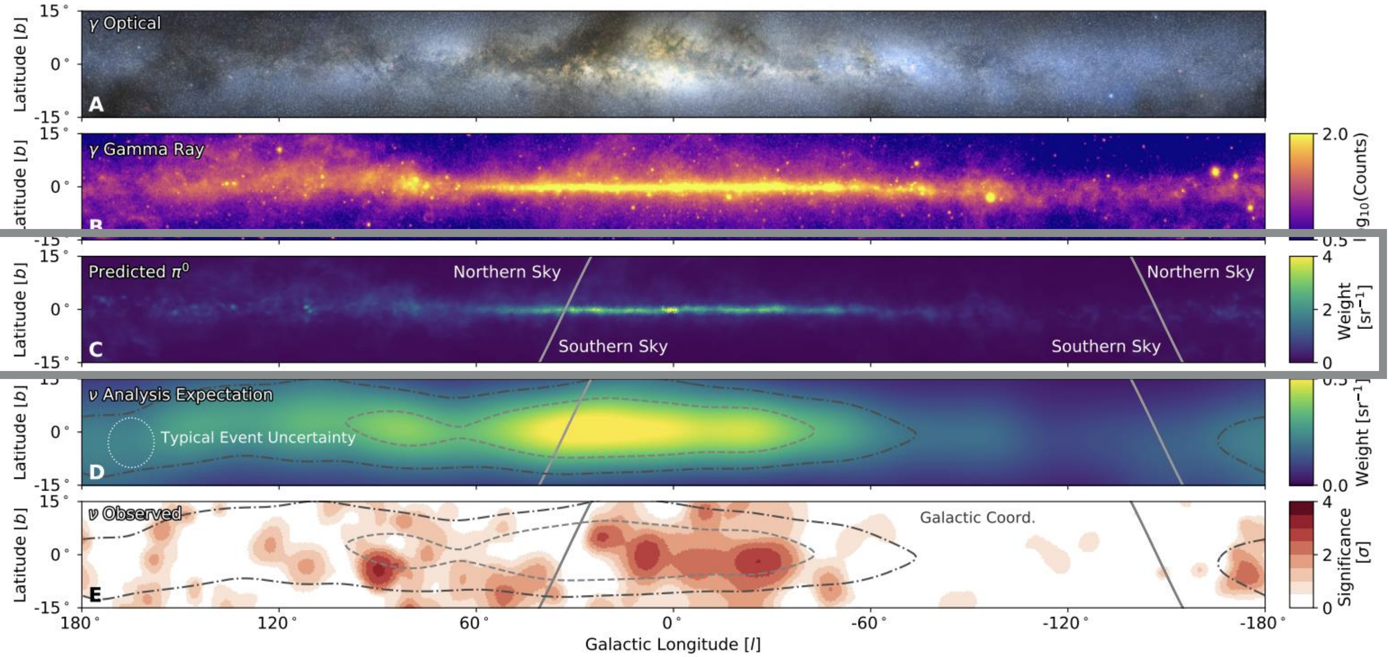


Inverse Compton

Brems-strahlung

π^0 **decay**



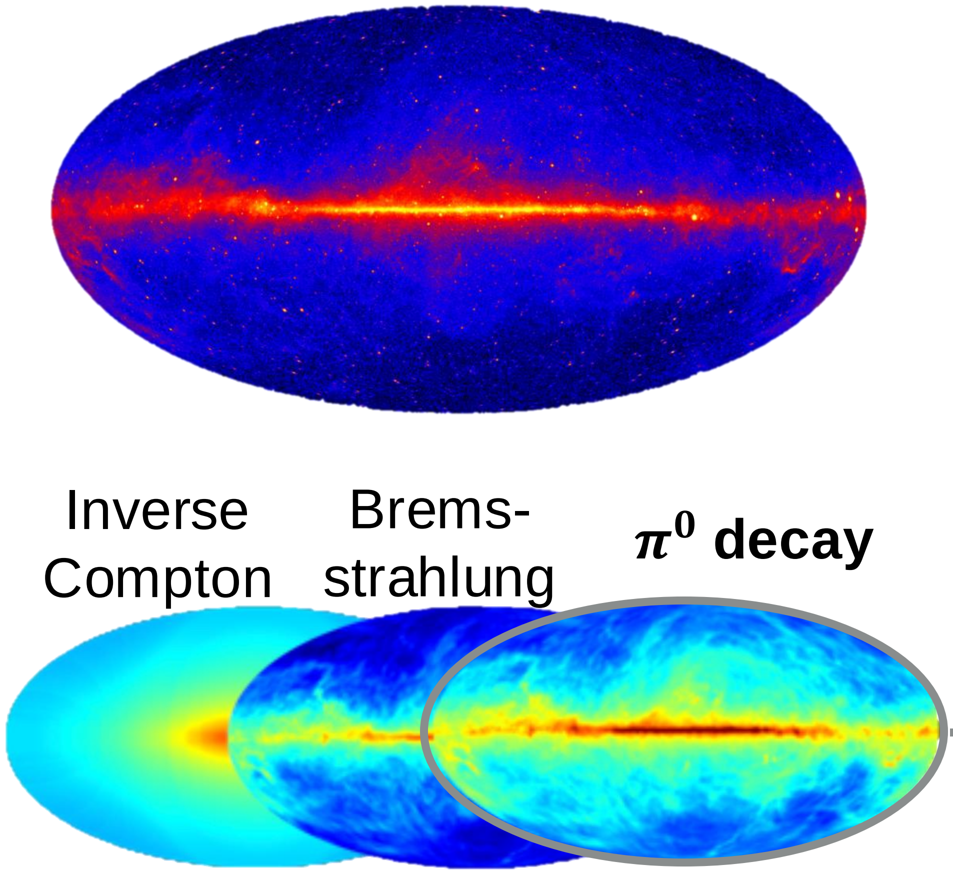


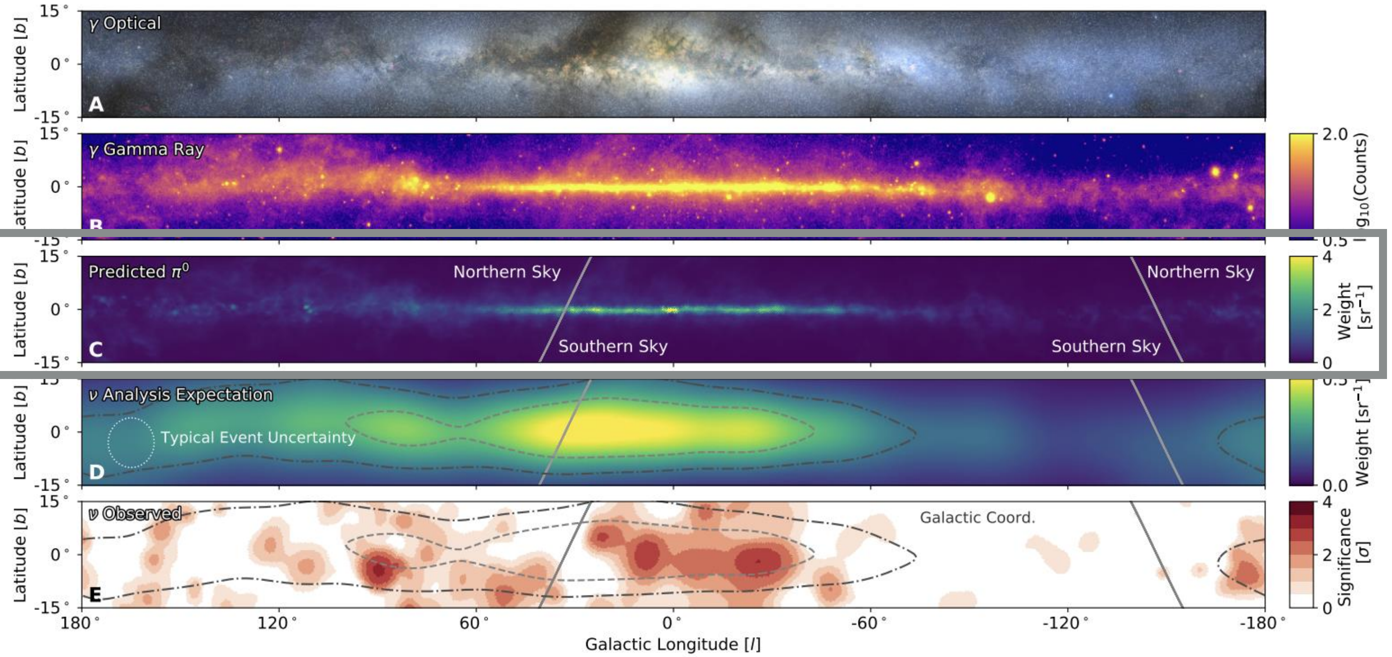
First detection of galactic plane neutrino flux thanks to gamma-ray template fit, ~10% of diffuse flux

IceCube Science 380 (2023)

Galactic Contribution

GeV gamma-ray sky by Fermi-LAT

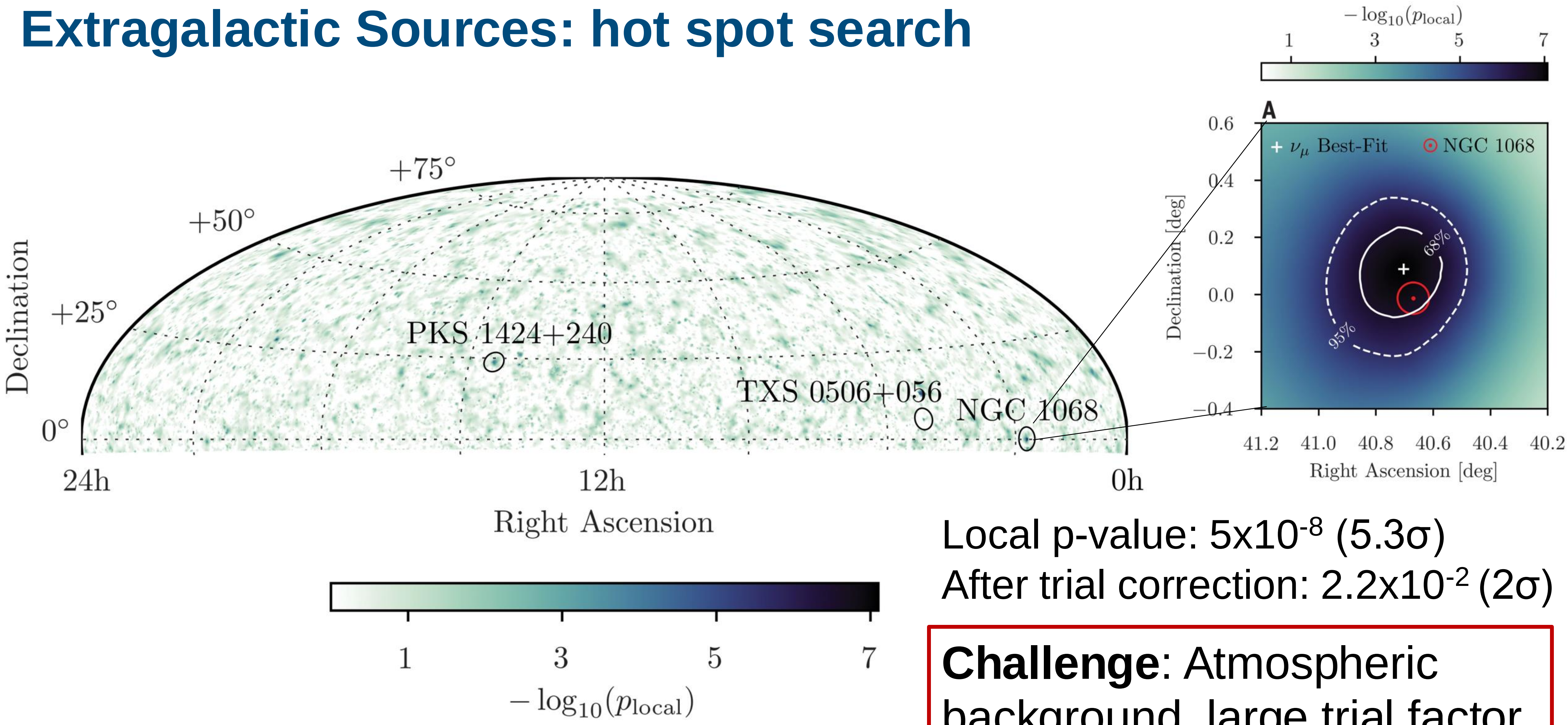




New handle to understand cosmic-ray production and propagation in our Galaxy

IceCube Science 380 (2023)

Extragalactic Sources: hot spot search



Local p-value: $5\text{x}10^{-8}$ (5.3σ)

After trial correction: $2.2\text{x}10^{-2}$ (2σ)

Challenge: Atmospheric background, large trial factor

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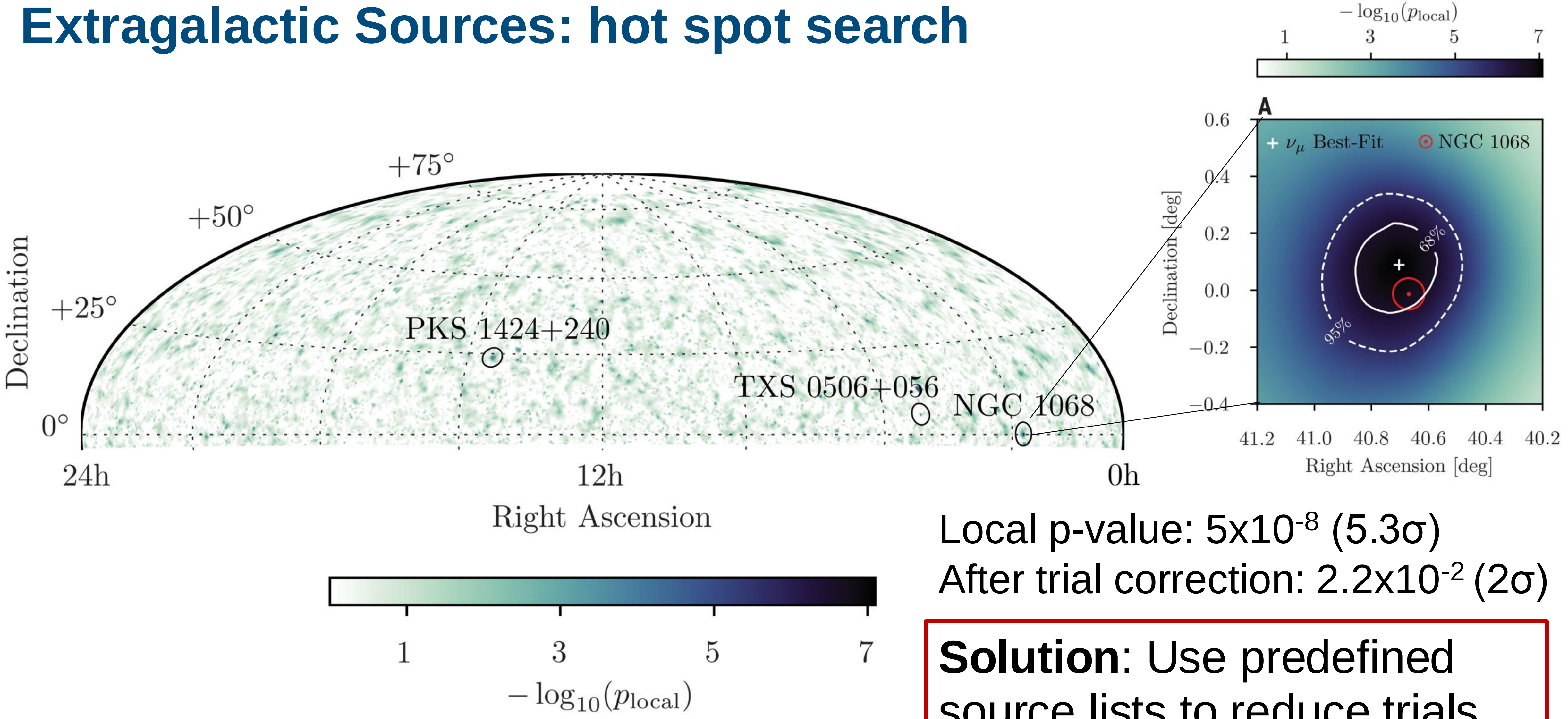
IceCube Science 378 (2022)

Extragalactic Sources: hot spot search



Local p-value: 5×10^{-8} (5.3σ)
After trial correction: 2.2×10^{-2} (2σ)

Solution: Use predefined source lists to reduce trials

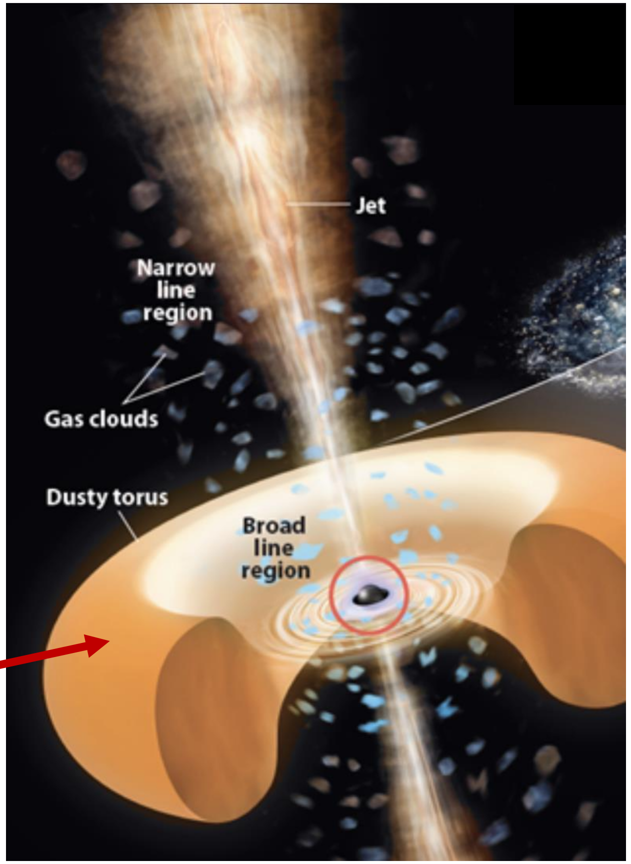
Extragalactic Sources

110 sources based on gamma-ray properties and weighted with neutrino search sensitivity

Most significant candidate:

NGC 1068 (M77), ~80 neutrinos (1-10TeV), 4.2σ

- Nearby (M=14Mpc) Seyfert 2 galaxy
- AGN and star-forming activity

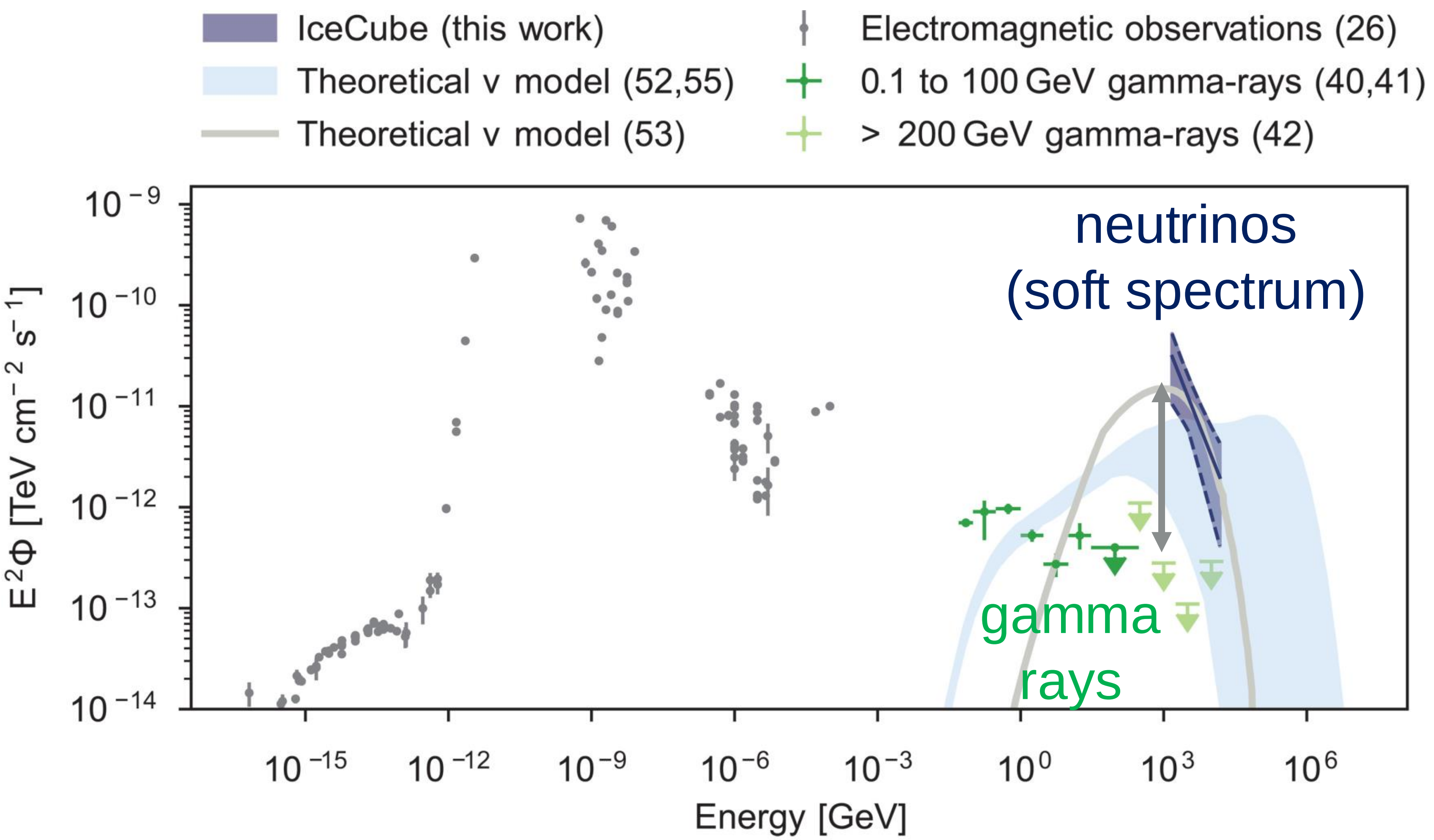


Seyfert 2

Combining gamma-ray source list with neutrino data allowed neutrino source detection

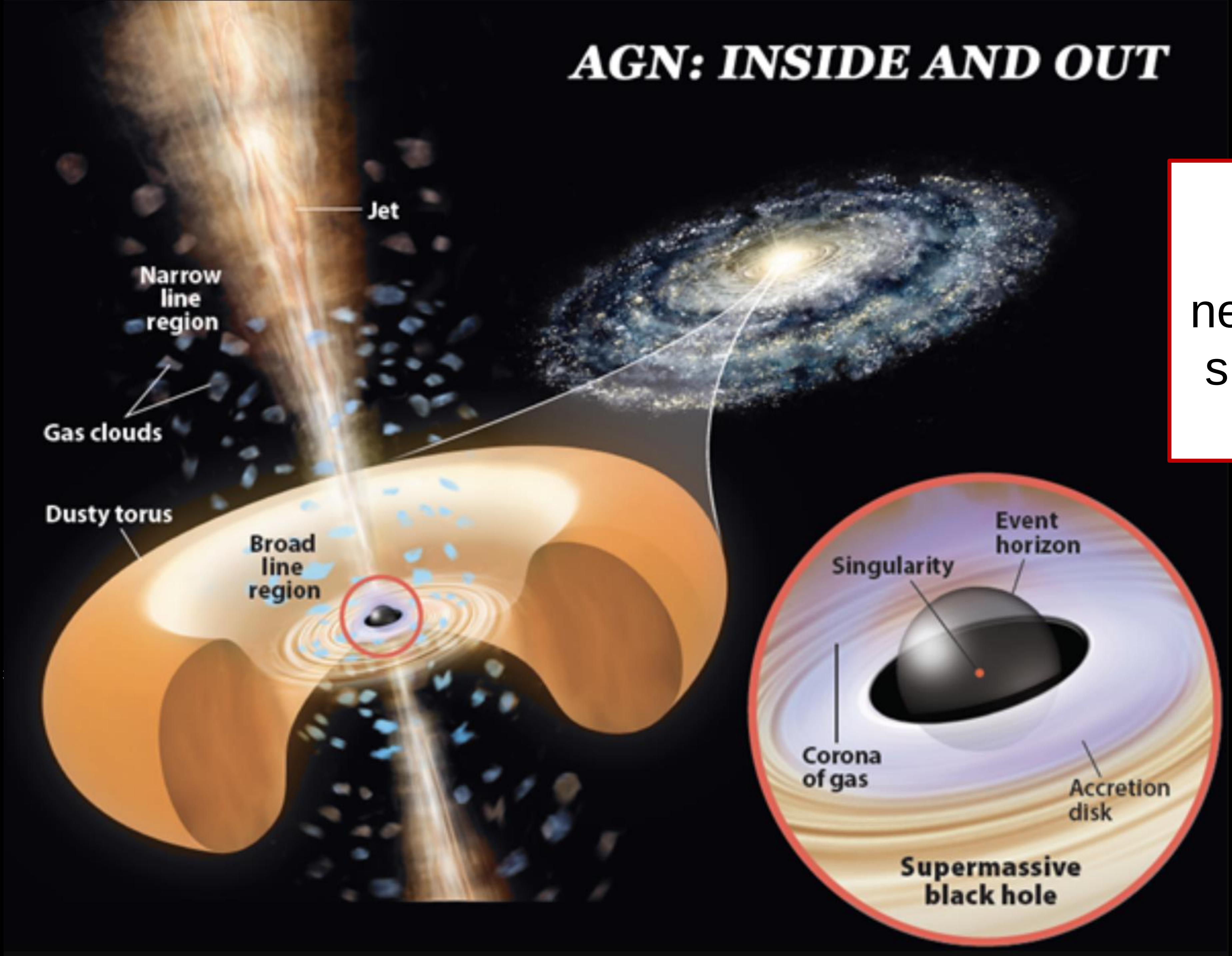
Source accelerates cosmic-rays to 40-400 TeV

Complete Multi-wavelength data of NGC 1068



Gamma rays need to be absorbed

IceCube Science 378 (2022)



Lack of gamma rays places neutrino production site in the heart of the galaxy

See e.g. Eichmann 2022, Murase 2020, Inoue 2020, Padovani 2024

Neutrinos as Triggers

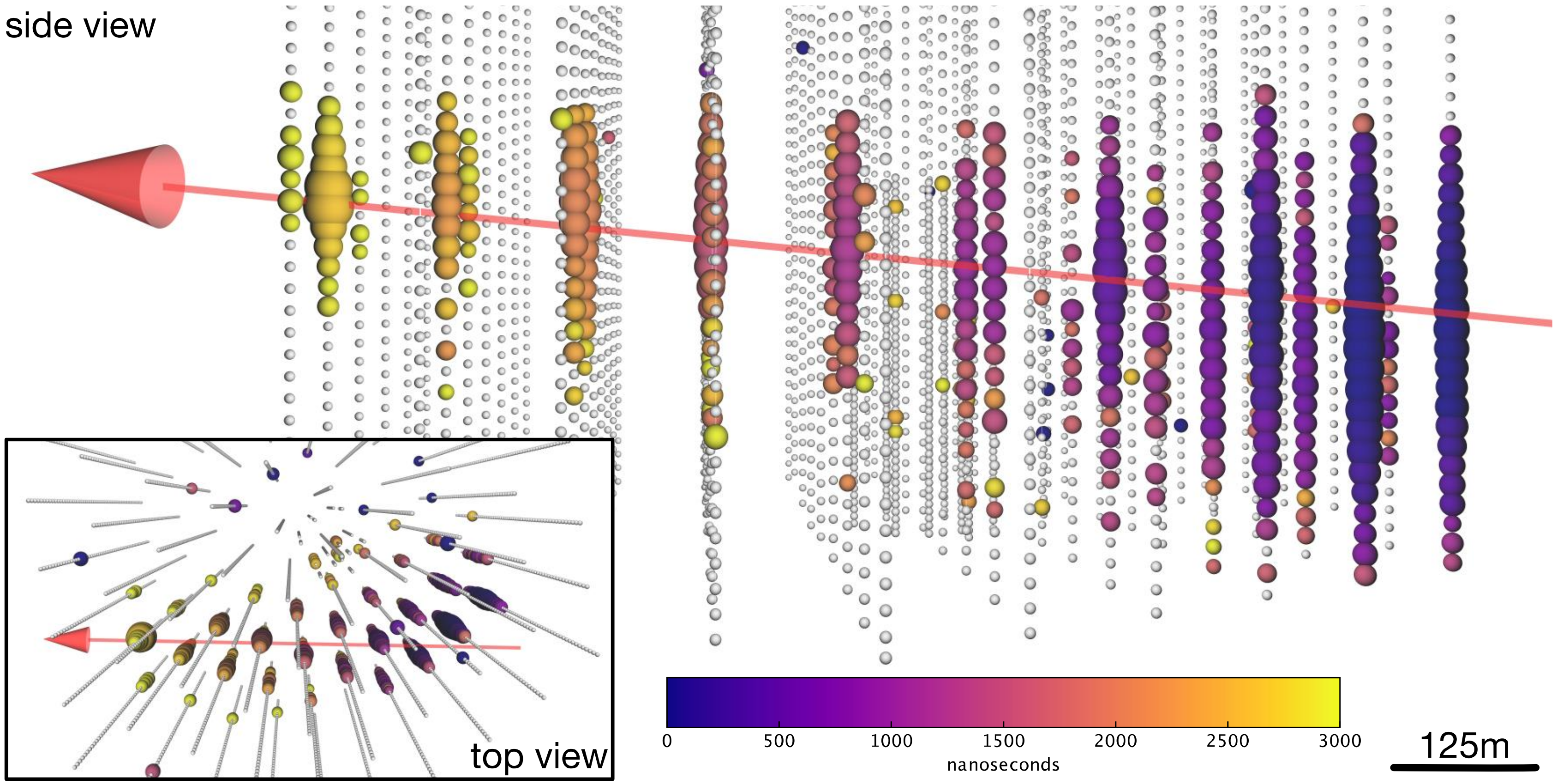
Public alerts since April 2016

- Single high-energy muon track events (> ~100TeV)
- “Gold” alert stream 10 / yr, ~5 / yr of cosmic origin
- Median latency: 30 sec

Goal: Find electromagnetic counterpart

Astropart. Phys., 92, 30 (2017)

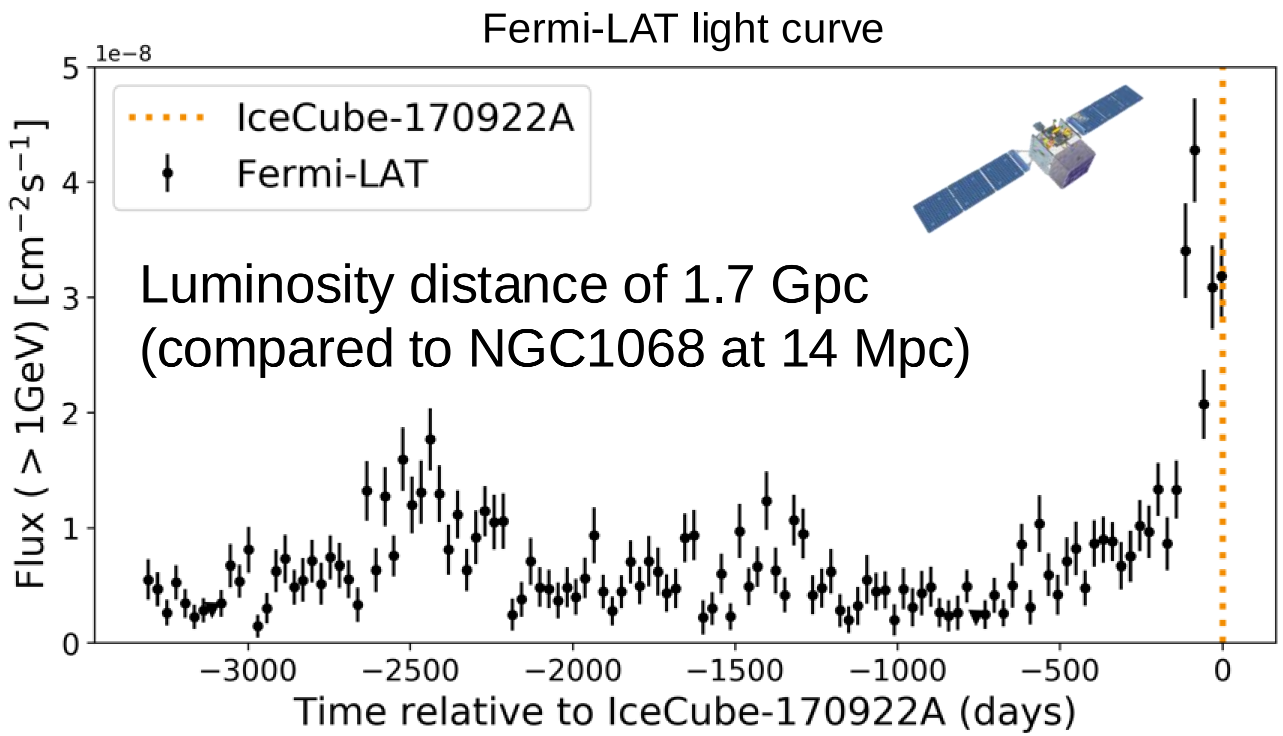
IC-170922A – a 290 TeV Neutrino



Signalness: 56.5%

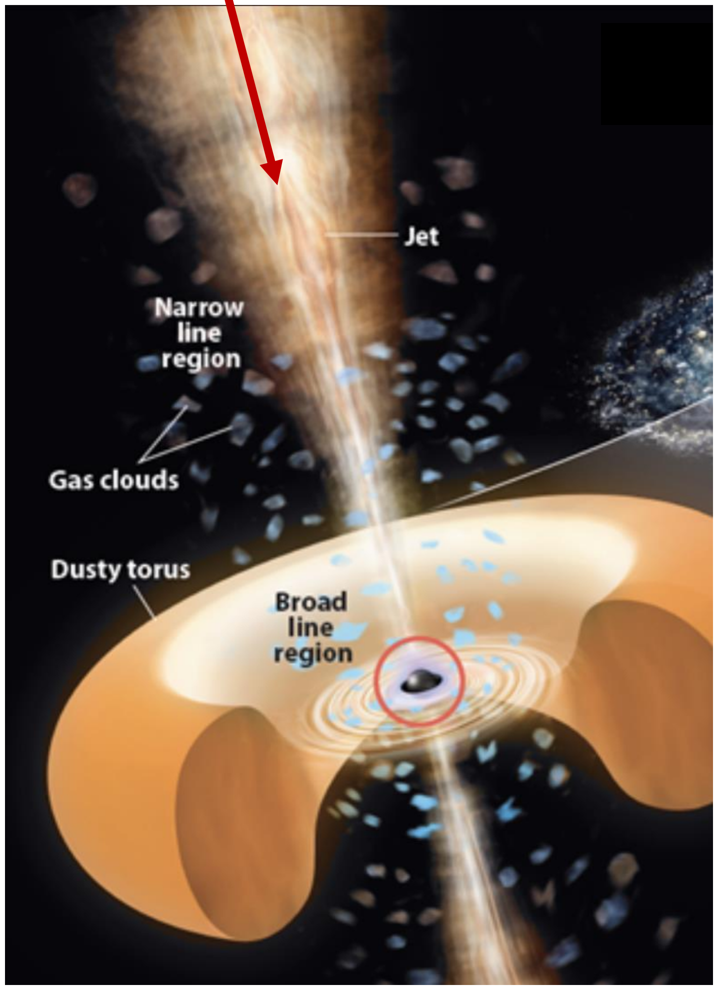
IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018

Gamma-ray Counterpart: TXS 0506+056



Luminosity distance of 1.7 Gpc
(compared to NGC1068 at 14 Mpc)

Blazar



Coincidence with source location and gamma-ray flare increases significance to 3σ

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

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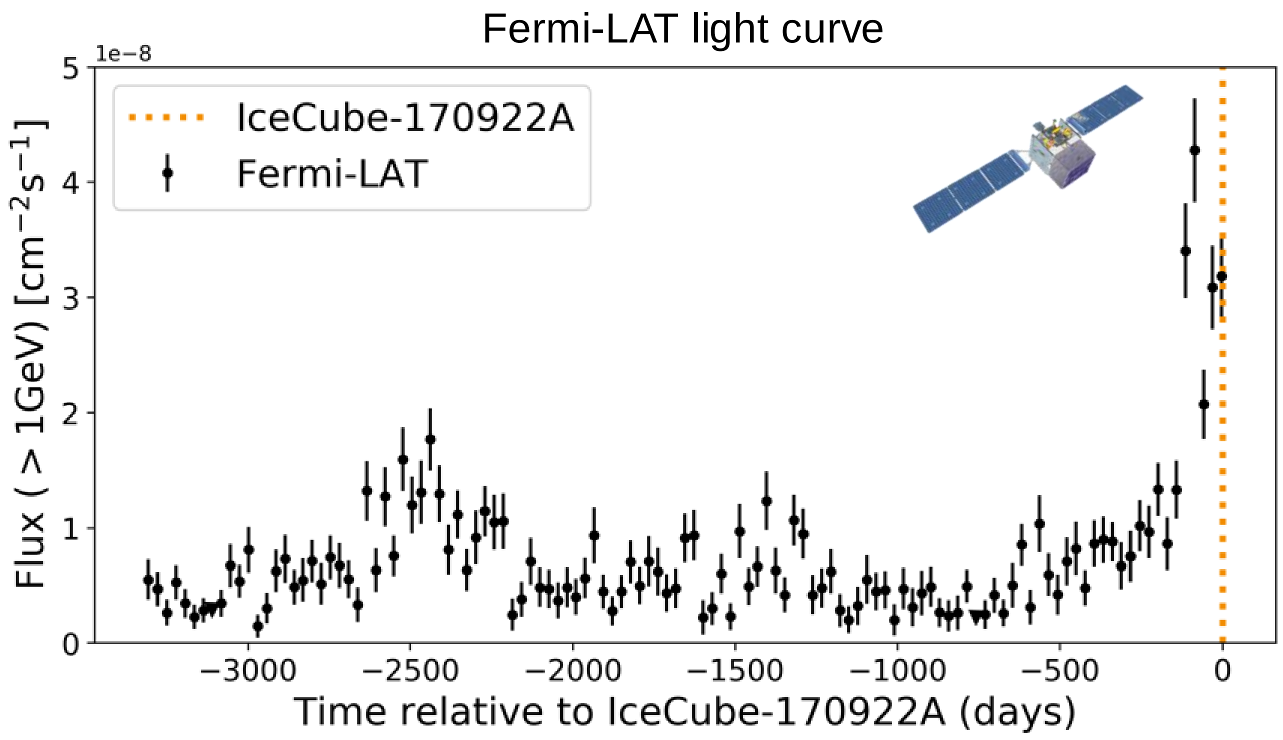

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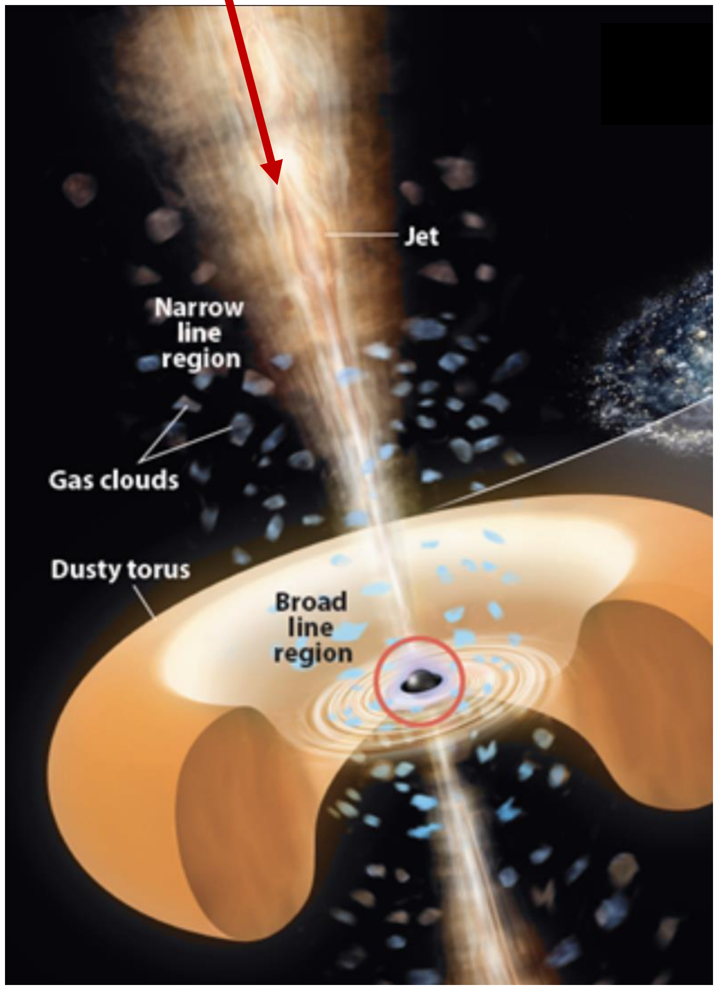
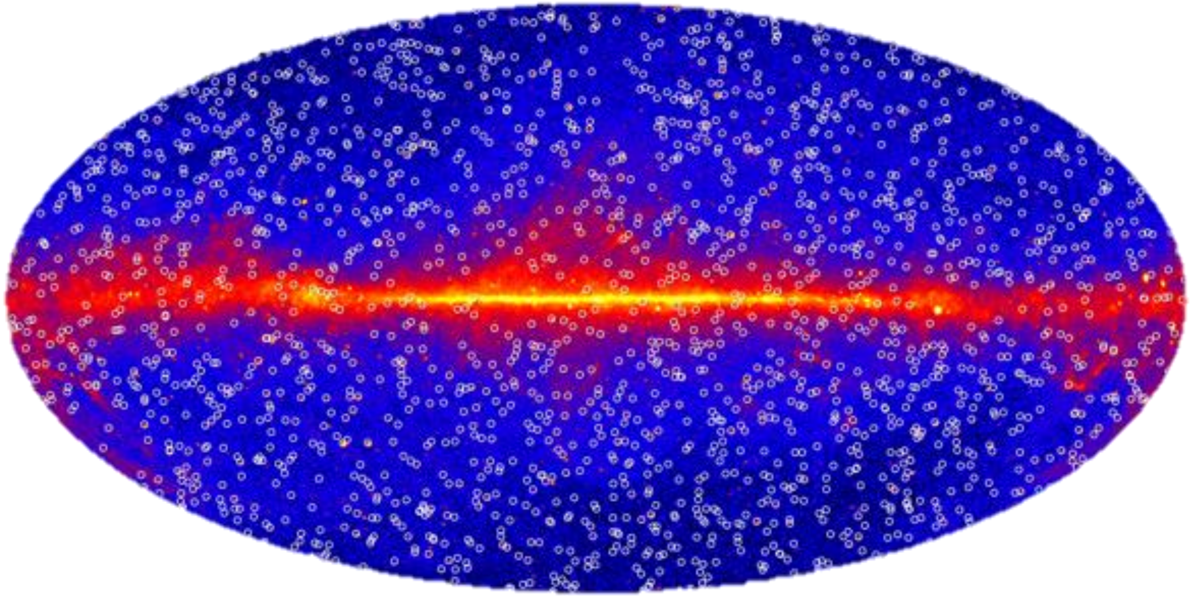


Source is a cosmic-ray source reaching energies of at least several PeV

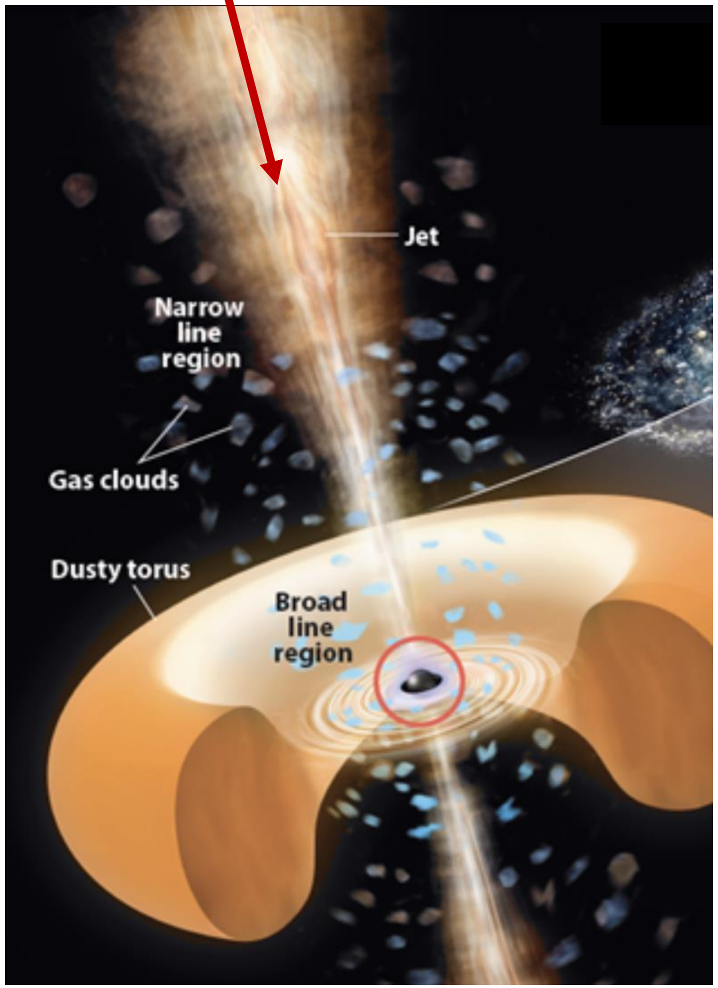
IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018

Population of gamma-ray blazars

GeV gamma-ray sky



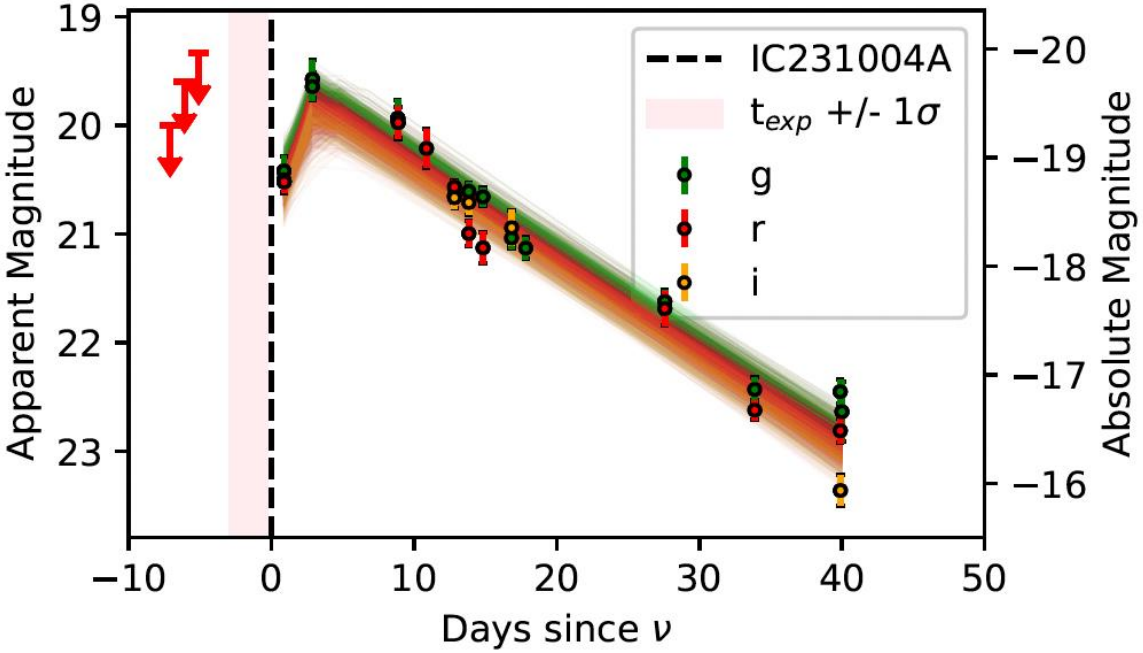
Blazar



No signal from population of gamma-ray blazars.

Optical Counterpart to a high-energy neutrino: SN2023uqf

IC-231004A
440 TeV Neutrino
84% signalness
3σ association
Distance: 700 Mpc



Stein et al. submitted

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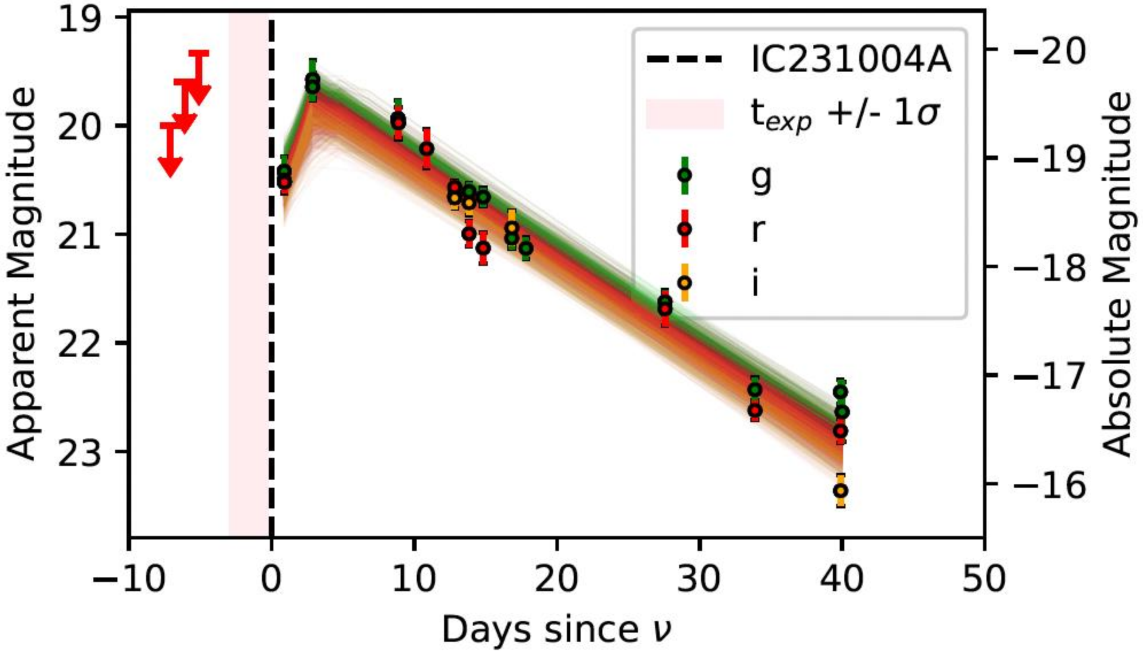

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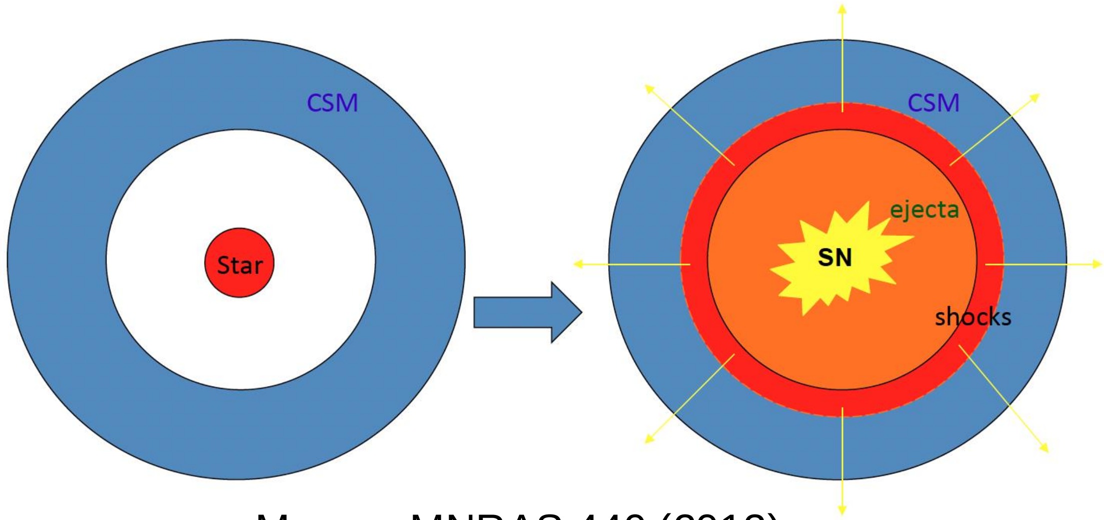
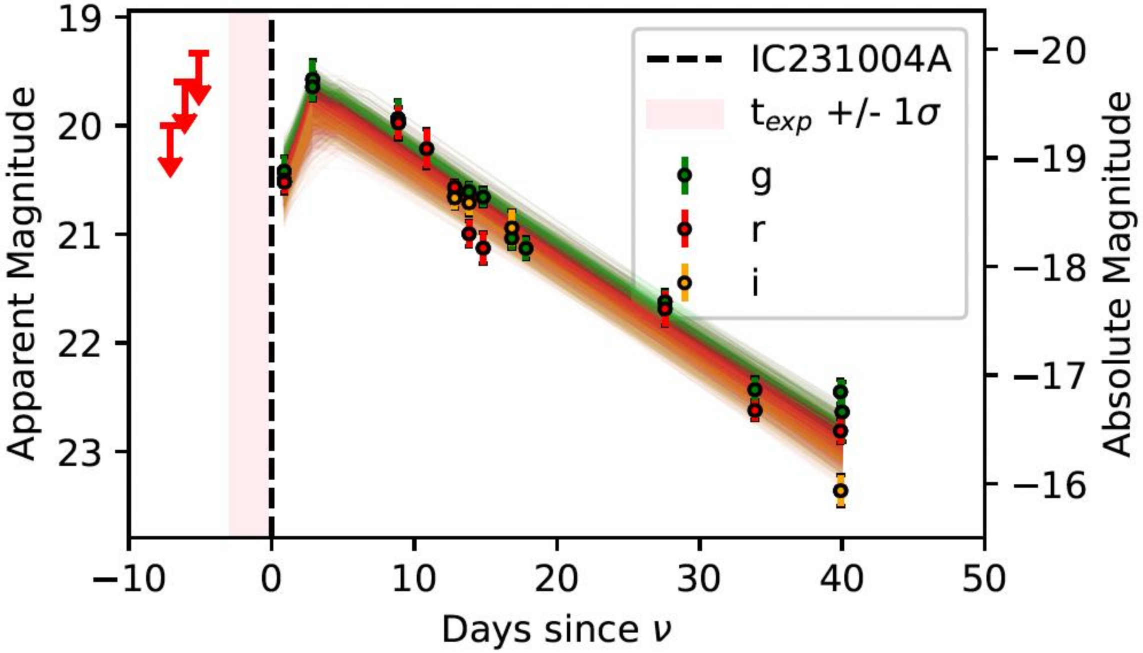


Murase MNRAS 440 (2013)

Evidence for hadronic acceleration in core-collapse supernova explosions

Optical Counterpart to a high-energy neutrino: SN2023uqf

IC-231004A
440 TeV Neutrino
84% signalness
3σ association
Distance: 700 Mpc



Stein et al. submitted

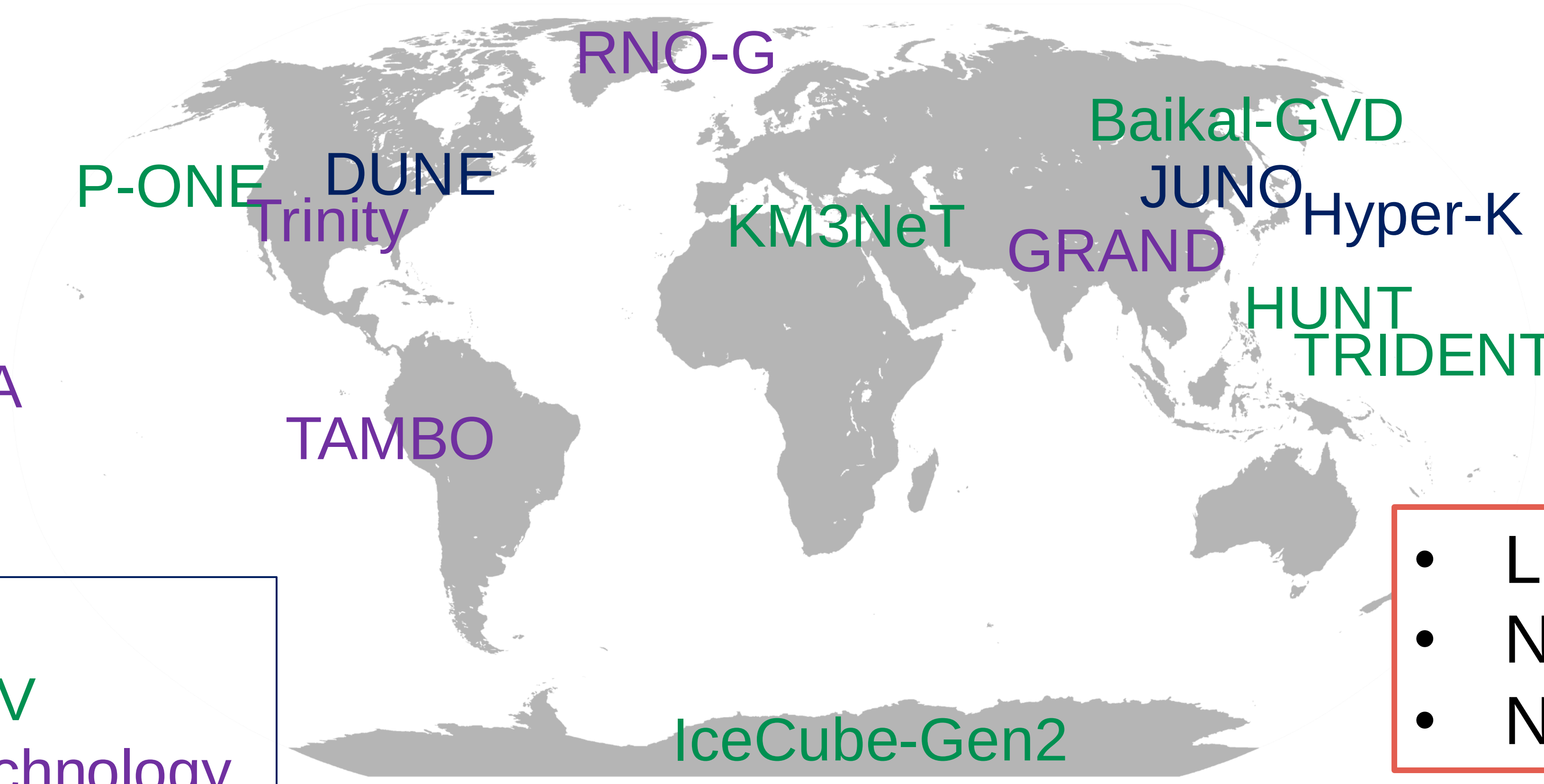
Robert Stein won DPG thesis award in 2023

Status of high-energy Neutrino Astronomy today

Diffuse flux discovered	✓	
Milky Way discovered	✓	~10% of diffuse flux
Source candidates	✓	Each ~1% of diffuse flux
Source population	?	~87% unknown

New Neutrino Detectors

NuMoon

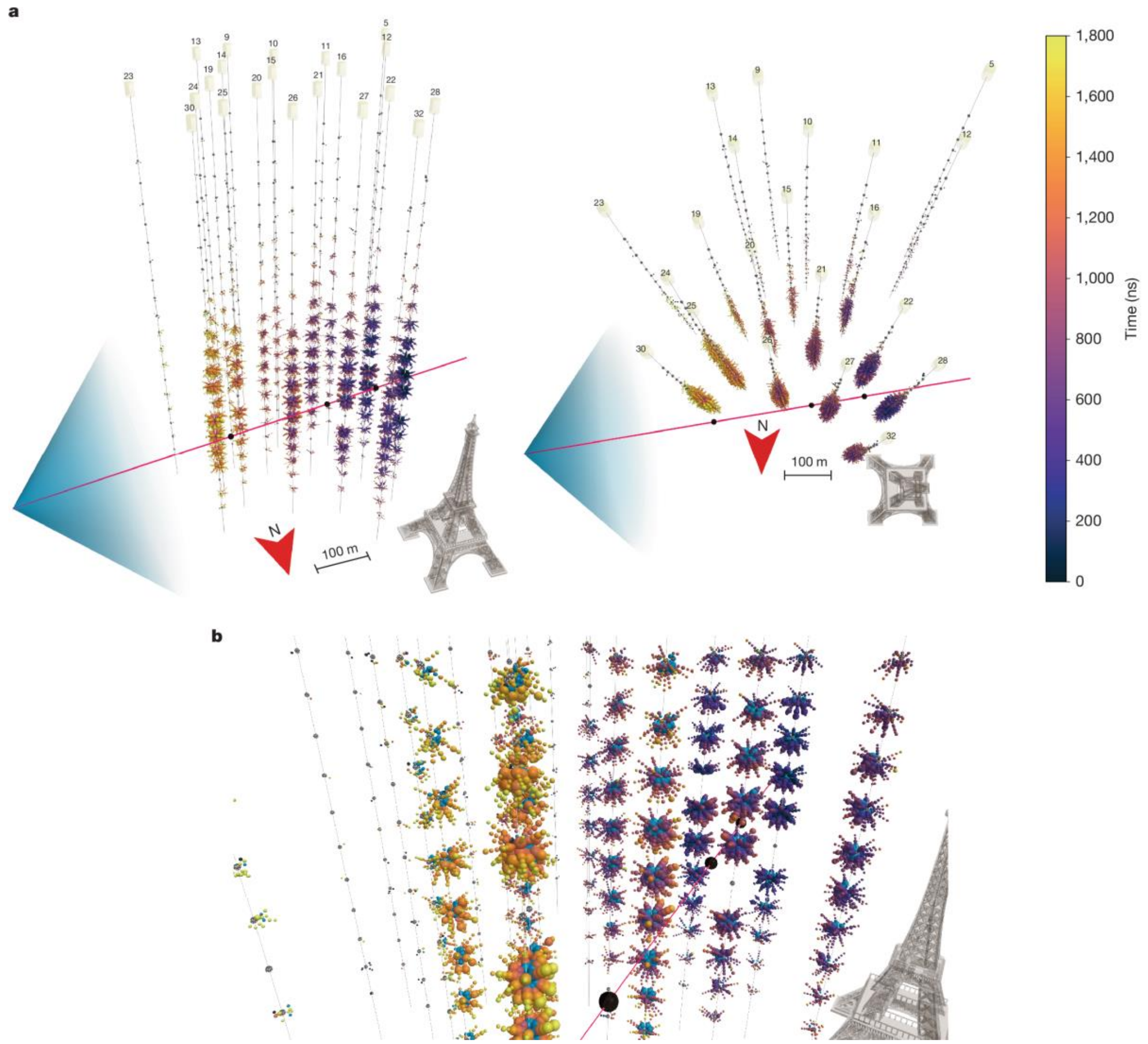


POEMMA
PUEO

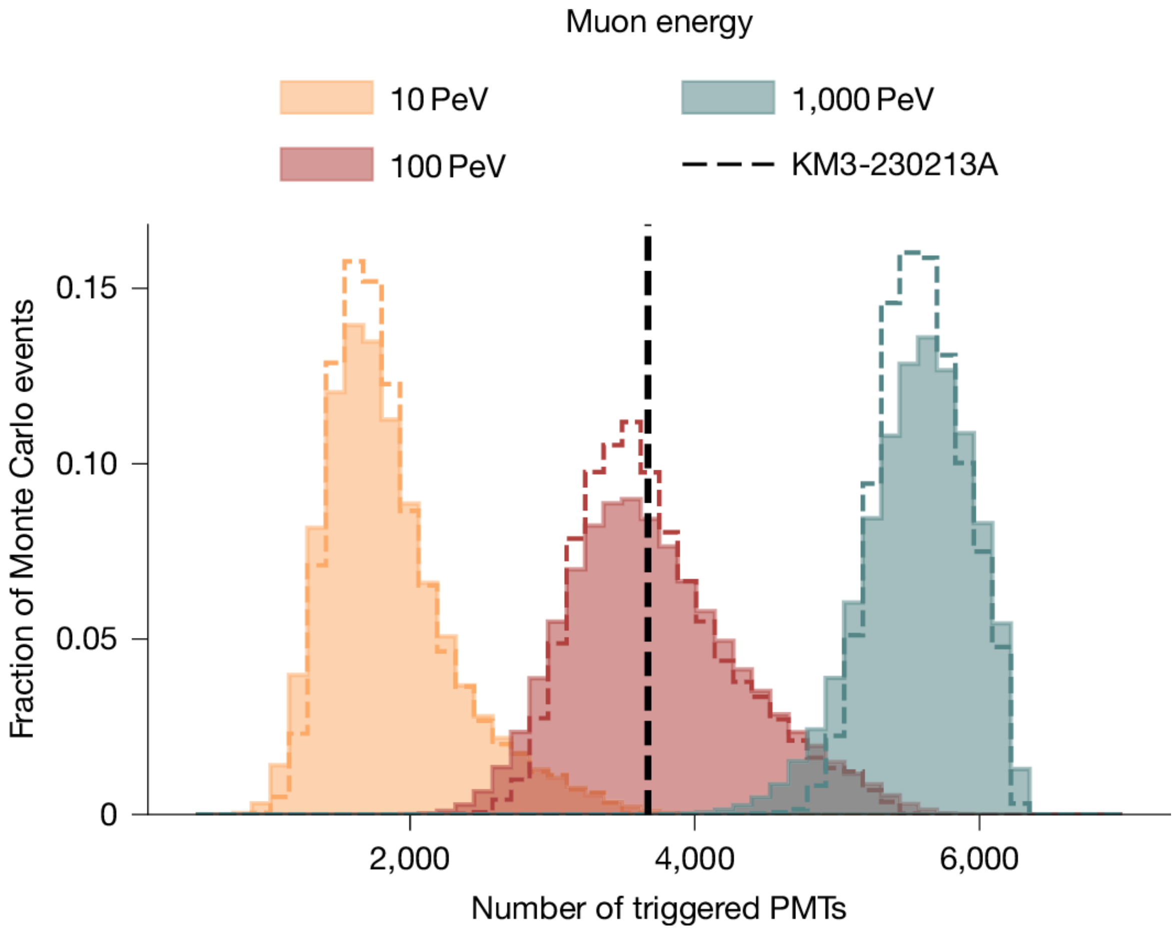
MeV
TeV-PeV
New technology

- Larger detectors
- New sites
- New technologies

KM3NeT finds 220 PeV Neutrino with partial Detector



Highest energy neutrino ever detected

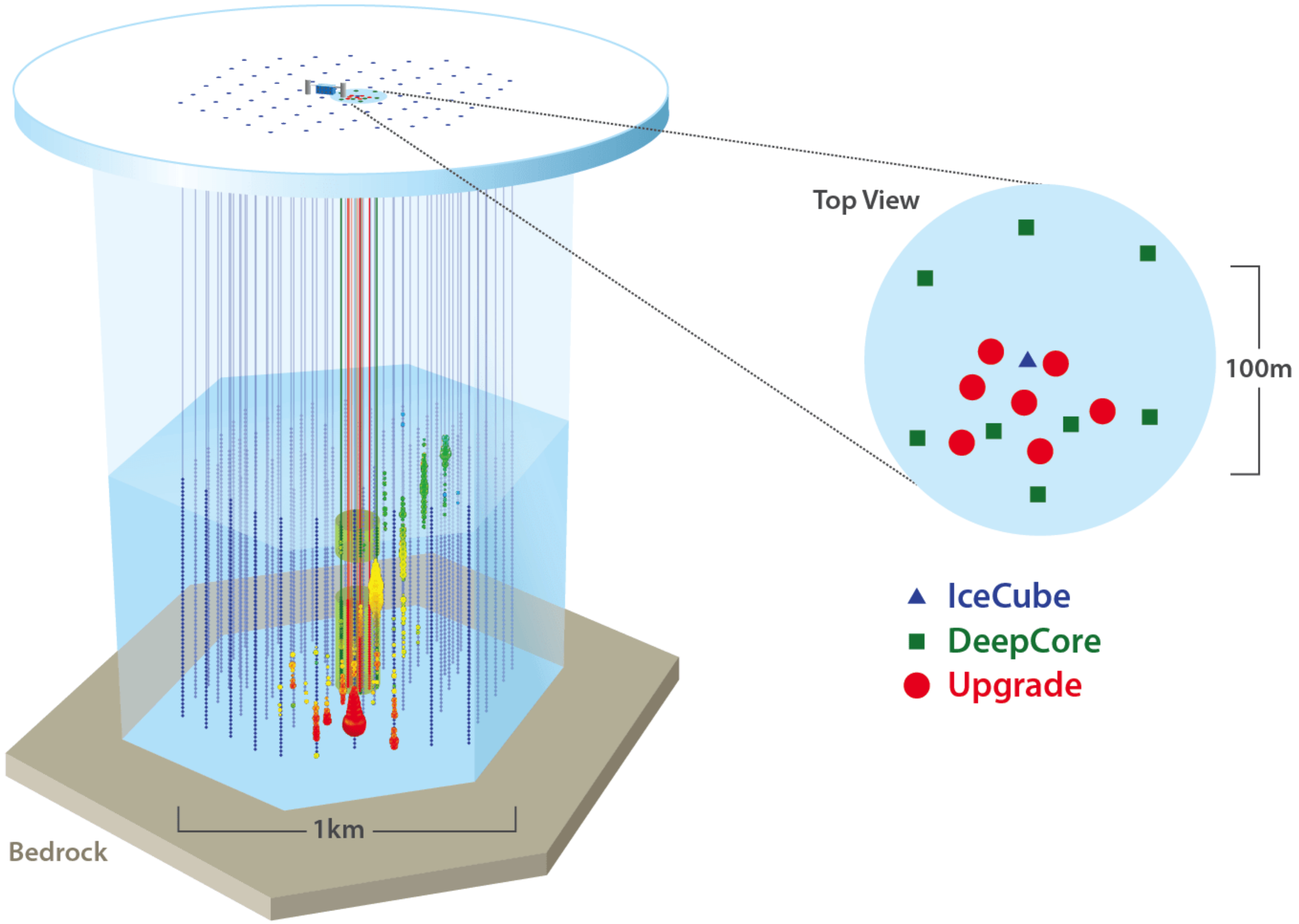


RUB

KM3NeT Nature 638 (2025)

IceCube-Upgrade: Low-energy Extension and Calibration

- First step towards IceCube-Gen2 (8 km^3)
- 7 new strings in the center of IceCube
- **New calibration devices**
- Science focus: Neutrino properties

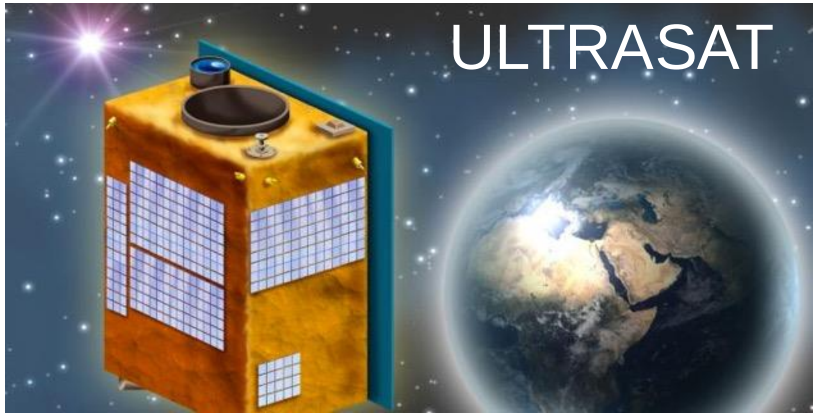


https://icecube-gen2.wisc.edu/science/publications/tdr/

New Telescopes

Multiwavelength Instruments

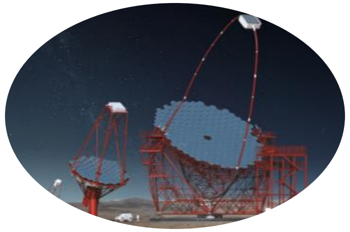
- Increased sensitivity
- Increased wavelength coverage
- Increased cadence



Large Array Survey Telescope (LAST)

The Multi-Messenger Picture

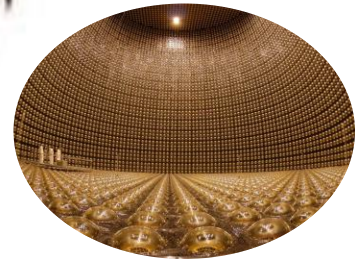
Photons



TeV-PeV Neutrinos

Cosmic Rays

MeV Neutrinos



Gravitational Waves

Stay Tuned!