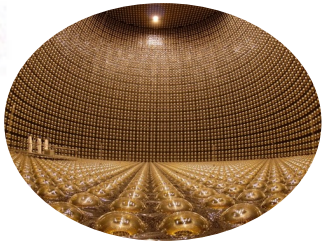
RUHR-UNIVERSITÄT BOCHUM

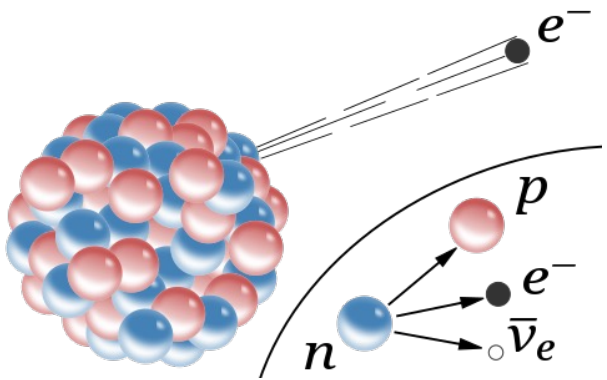
NEUTRINOS IN THE ERA OF MULTIMESSENGER ASTRONOMY

Multi-messenger Astronomy

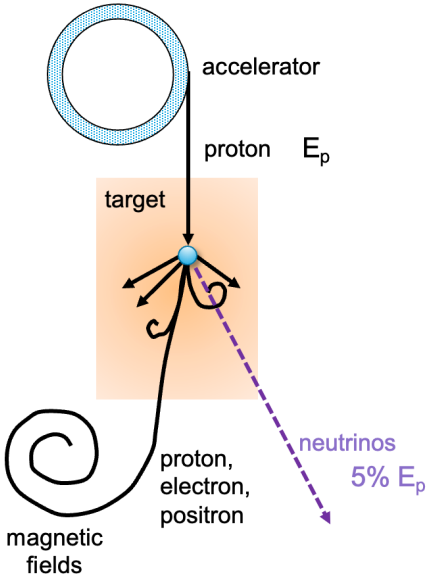


Low vs. High-energies

MeV neutrinos from nuclear processes, (inverse) beta decay



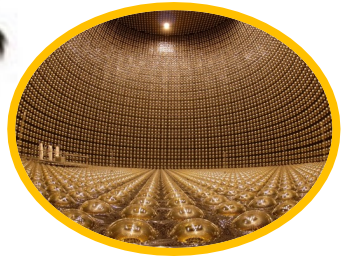
TeV-PeV neutrinos from cosmic-ray “beam dumps”



Multi-messenger Astronomy

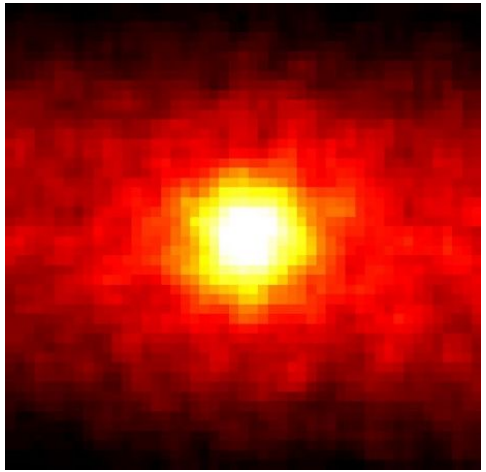
Photons

MeV neutrinos



Birth of Multi-messenger Astronomy with Neutrinos

Astronomy Picture of the Day
June 5, 1998



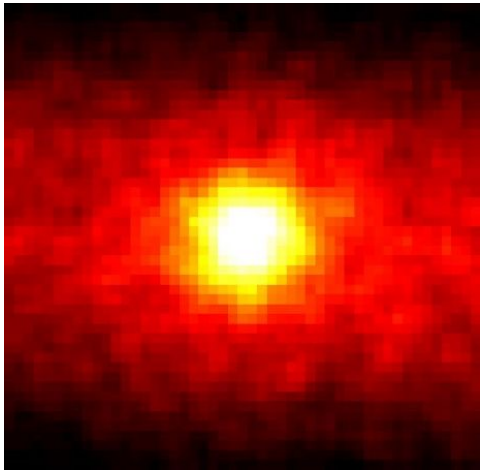
The Sun in Neutrinos seen by Super-Kamiokande

Combining neutrinos and electromagnetic information led to:

Talk 664 by J. Maneira

Birth of Multi-messenger Astronomy with Neutrinos

Astronomy Picture of the Day
June 5, 1998



The Sun in Neutrinos seen by Super-Kamiokande

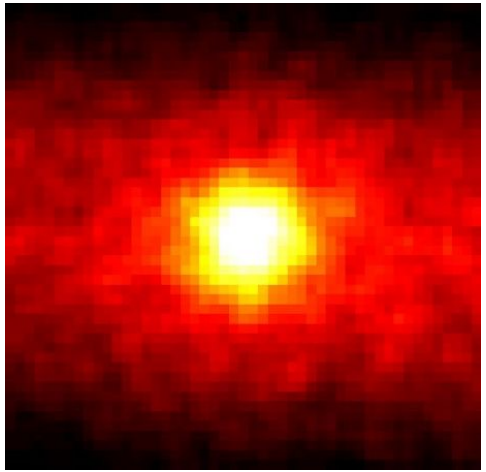
Combining neutrinos and electromagnetic information led to:

- **The solar neutrino problem**

Talk 664 by J. Maneira

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:

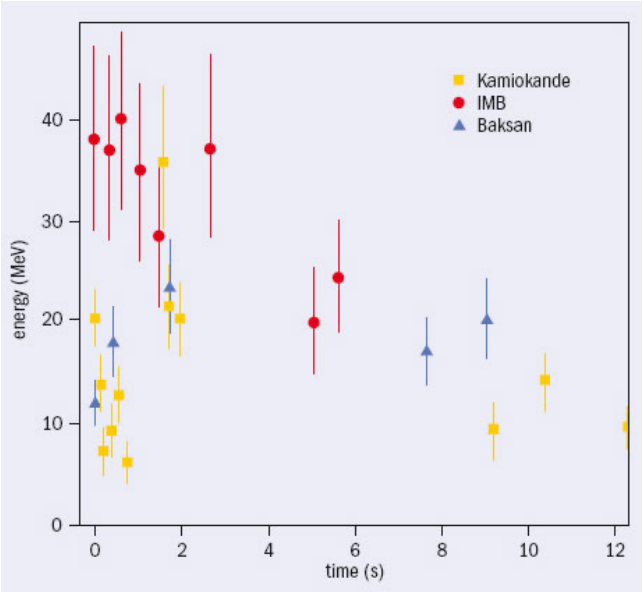
- Confirmation of model of fusion
- Breaking the standard model of particle physics

Talk 664 by J. Maneira

First (and only) detection of a Supernova

Optical detection of SN1987A in LMC

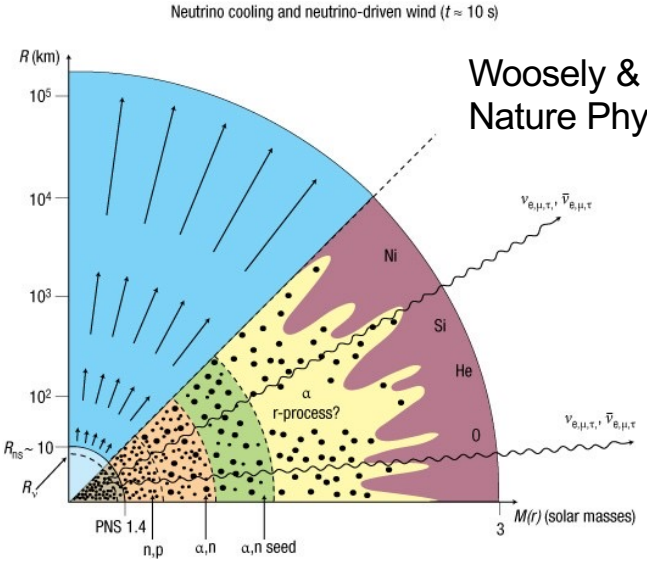
MeV neutrino burst



Talk 662 by C. Lunardini

First (and only) detection of a Supernova

First direct confirmation of our basic picture of a stellar collapse

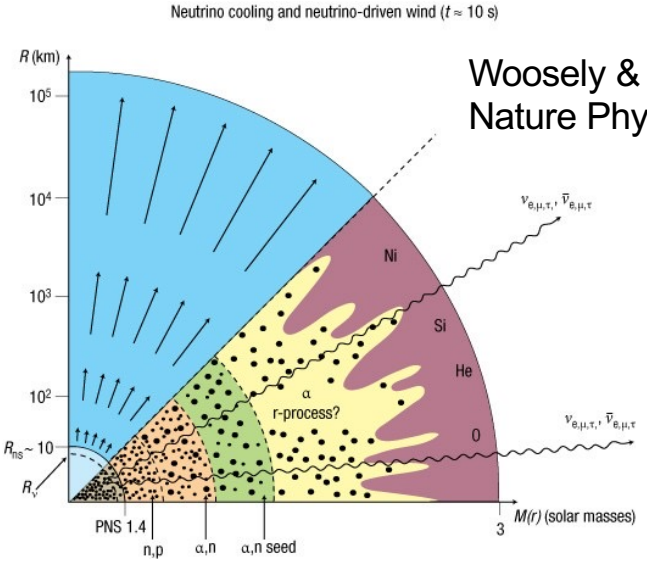


Woosely & Janka, Nature Physics 2005

Talk 662 by C. Lunardini

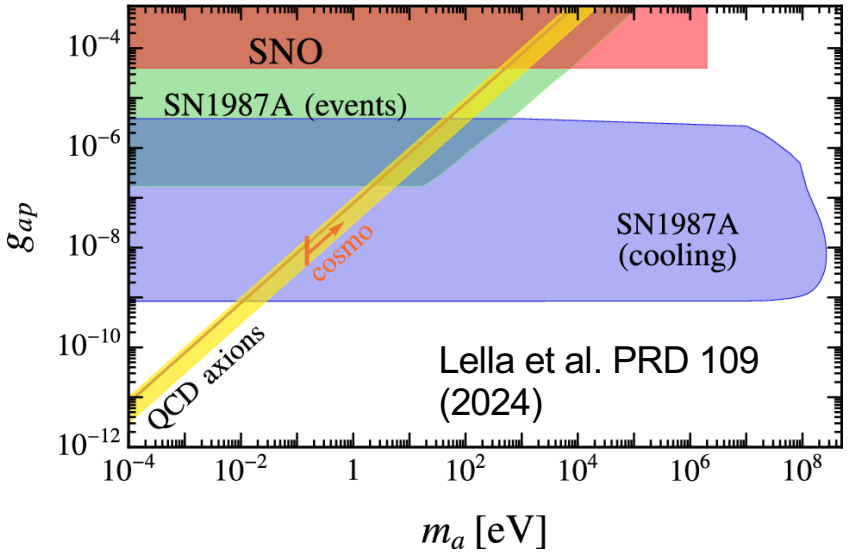
First (and only) detection of a Supernova

First direct confirmation of our basic picture of a stellar collapse



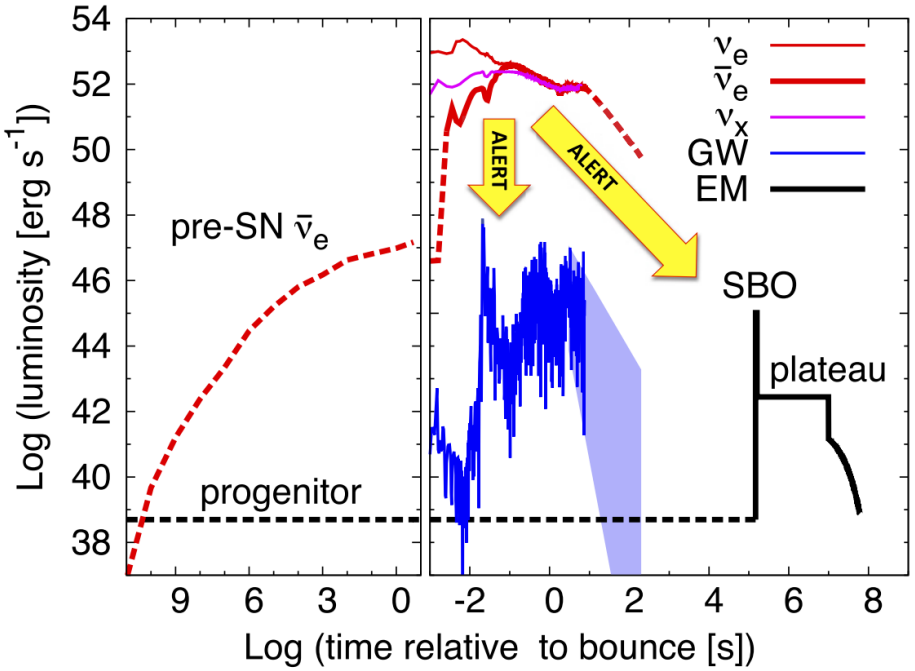
Woosely & Janka, Nature Physics 2005

Constraints on exotic physics (e.g. axions)



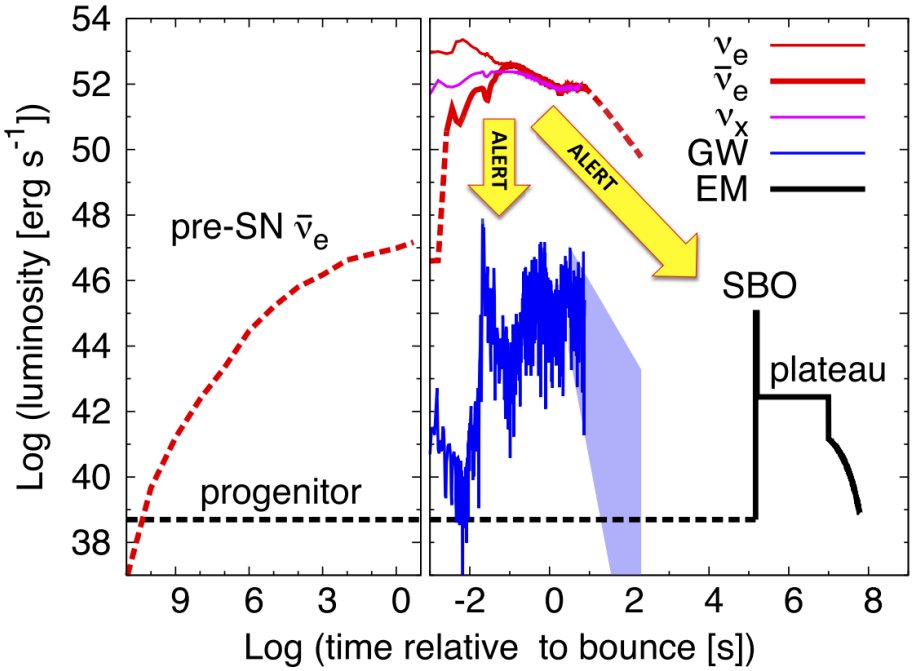
Talk 662 by C. Lunardini

Supernova early warning system



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

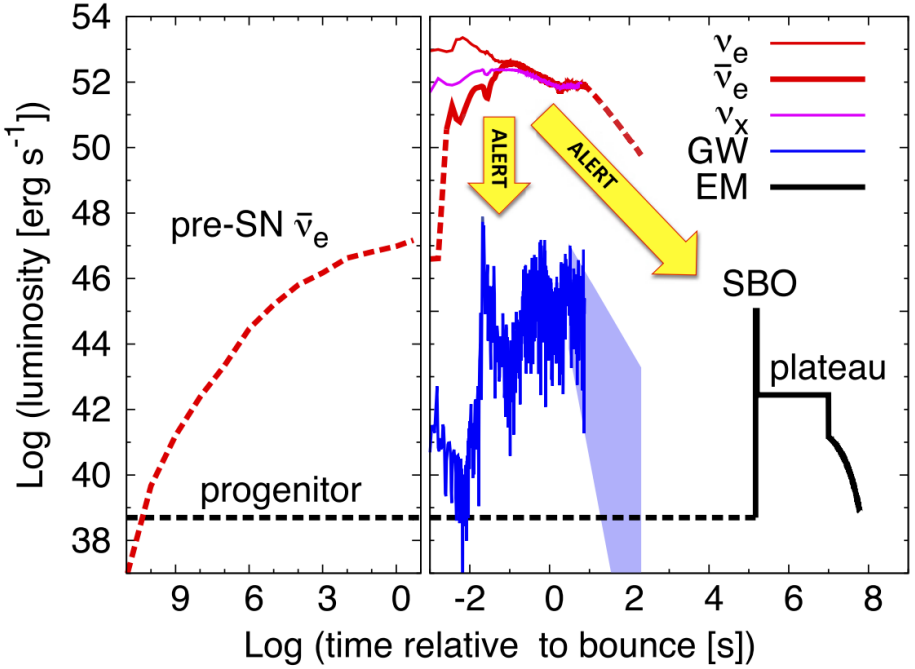
Supernova early warning system



MeV neutrino burst as trigger for electromagnetic supernovae observations

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

Supernova early warning system



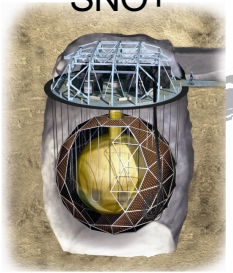
MeV neutrino burst as trigger for electromagnetic supernovae observations

SNEWS 2.0: Poster 134 by A. Habig

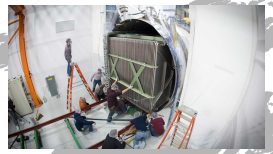
- new infrastructure
- public sub-threshold alerts
- pointing using inter-experiment triangulation
- searches for pre-supernova neutrinos

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

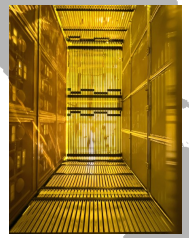
SNO+



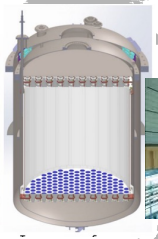
MicroBooNe



SBND



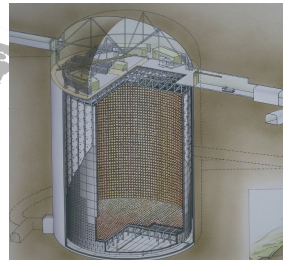
XENONnT



Baksan

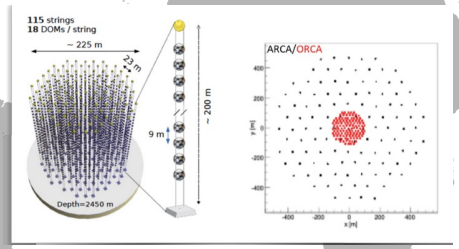
LVD

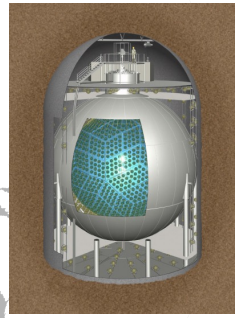
Super-K



NOvA

KM3NeT

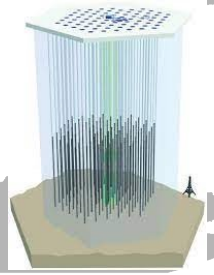




KamLAND

HALO

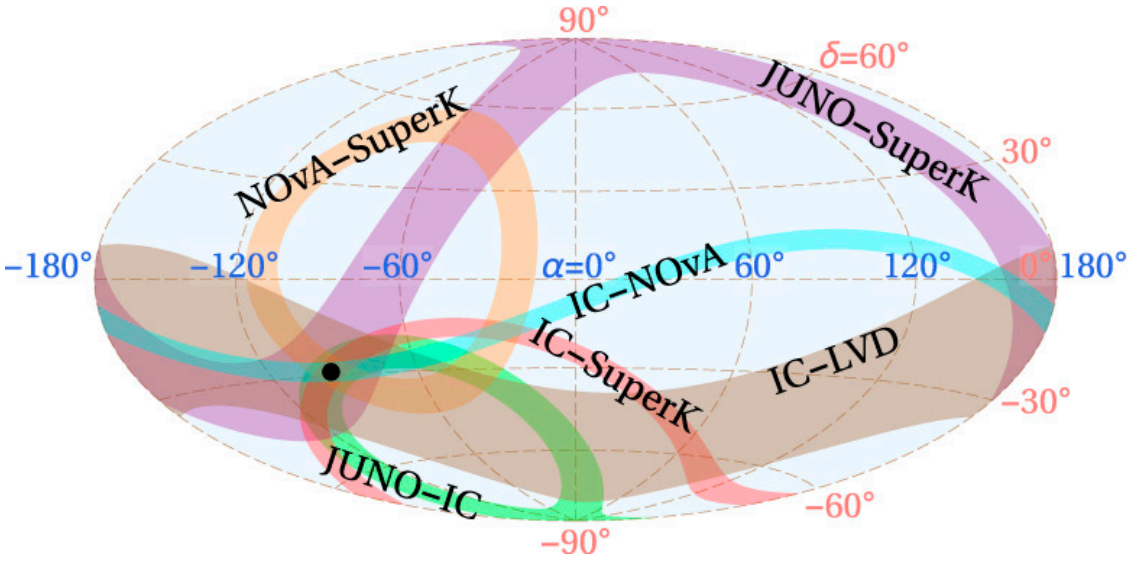
IceCube



https://snews2.org/

Supernova localization

supernova core-collapse into a neutron star



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

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

Catching the next Galactic Neutrino Supernova

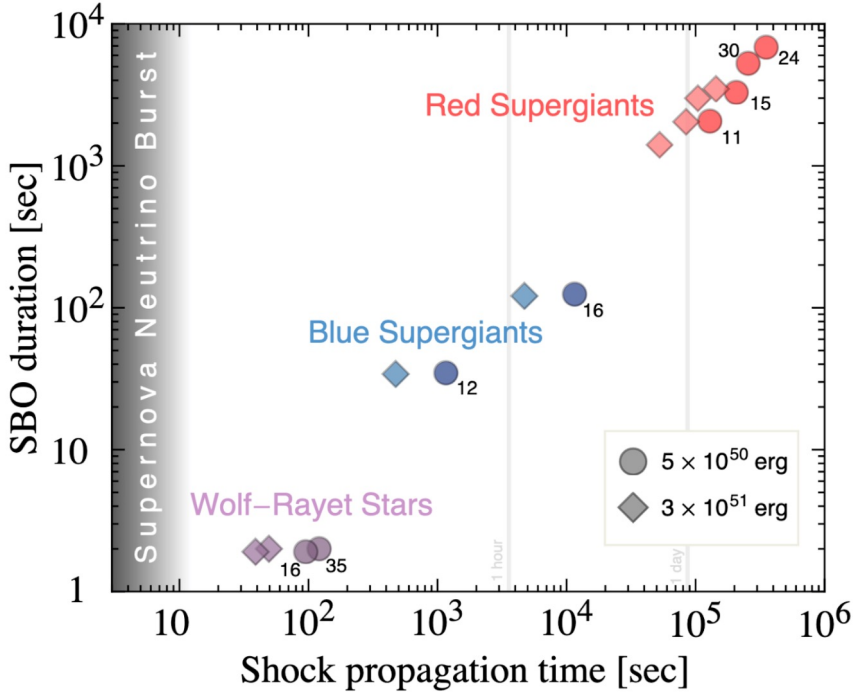
- Unprecedented insights into the explosion mechanism
- Information about surrounding material
- Spatially resolved imaging of early phases of explosion

Kistler et al., ApJ 778 (2013)

Catching the next Galactic Neutrino Supernova

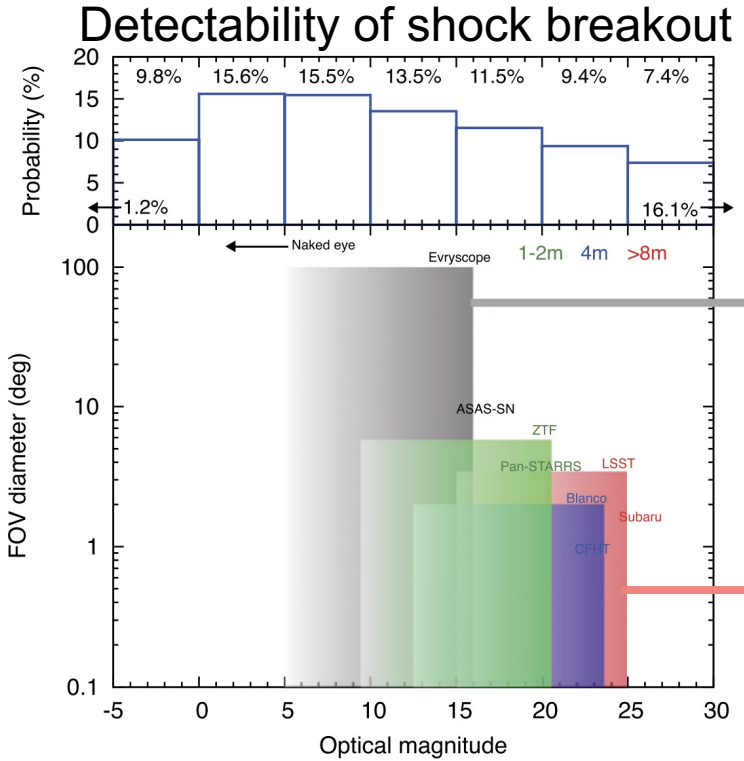
- Unprecedented insights into the explosion mechanism
- Information about surrounding material
- Spatially resolved imaging of early phases of explosion

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

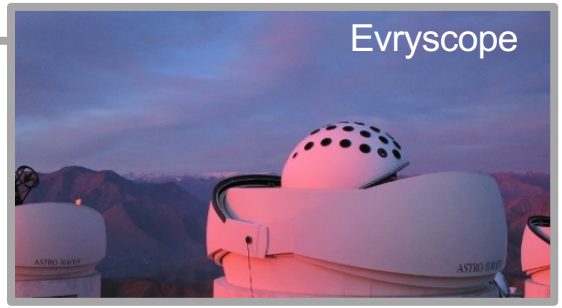


Kistler et al., ApJ 778 (2013)

Catching the next Galactic Neutrino Supernova



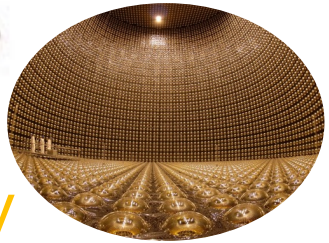
Optical counterpart can appear within minutes of neutrino alert → take full advantage of once-in-a-lifetime event



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

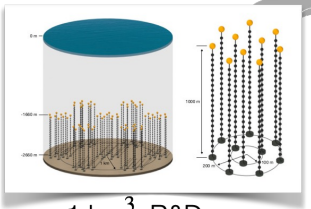
Multi-messenger Astronomy

Photons



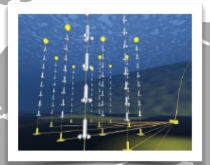
TeV-PeV neutrinos

RUHR UNIVERSITÄT BOCHUM RUB

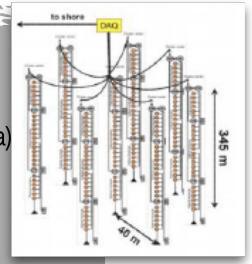


1 km^3, R&D

P-ONE (Canada)



ANTARES, dismantled
>0.01 km^3, 2008-2022

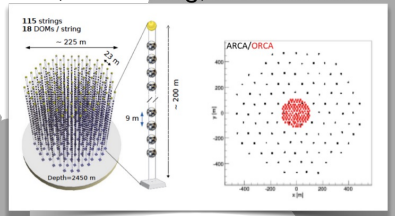


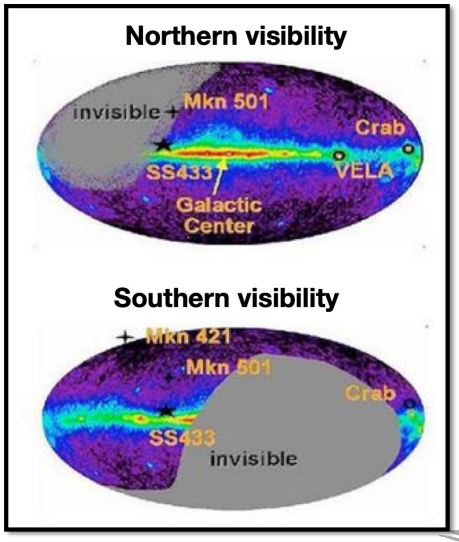
Baikal/GVD (Russia)
1 km^3, in construction

KM3NeT-ORCA
(France)

KM3NeT-ARCA
(Sicily, Italy)

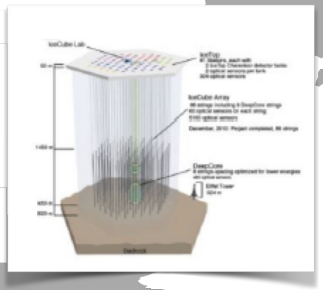
>1 km^3, data taking, in construction





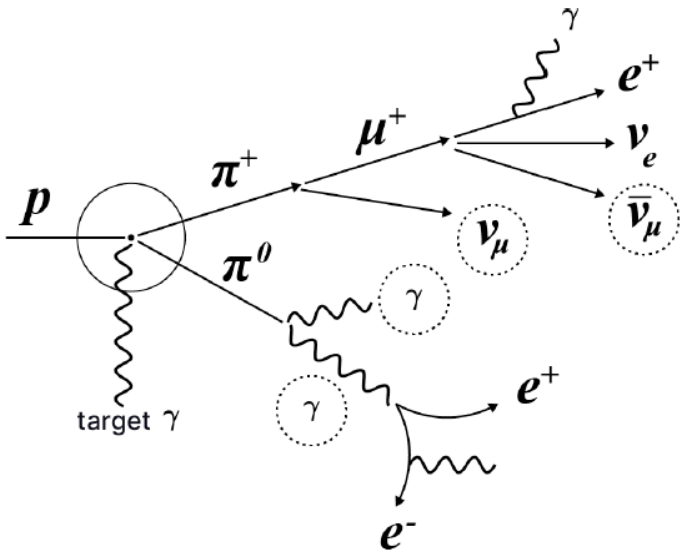
IceCube
(South Pole)
1 km^3, 2011-data taking

IceCube-Gen2
(South Pole)
10 km^3, R&D

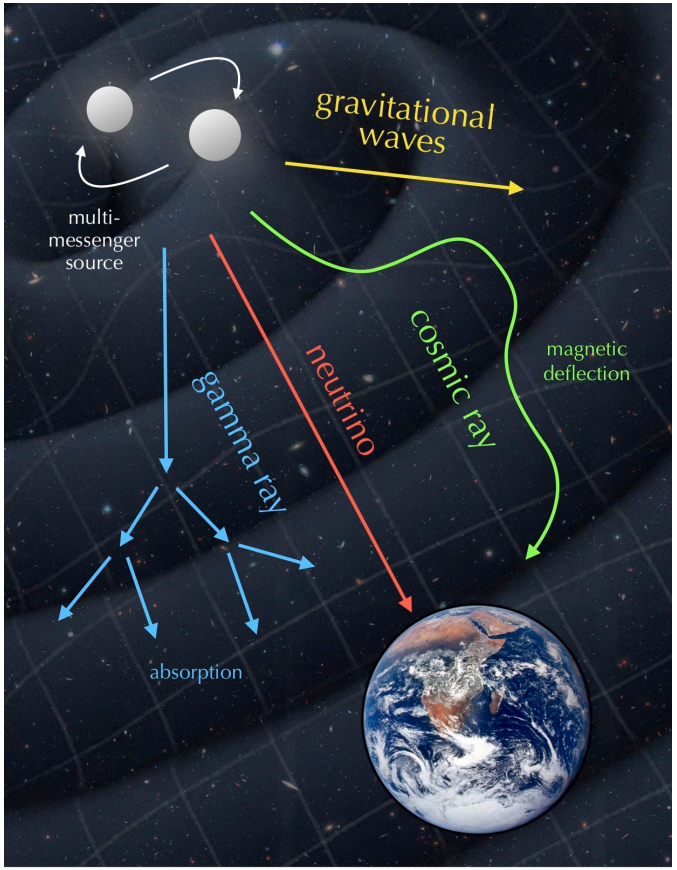


Talks 657, 658, 700, 701, 702

Revealing the cosmic-ray sources

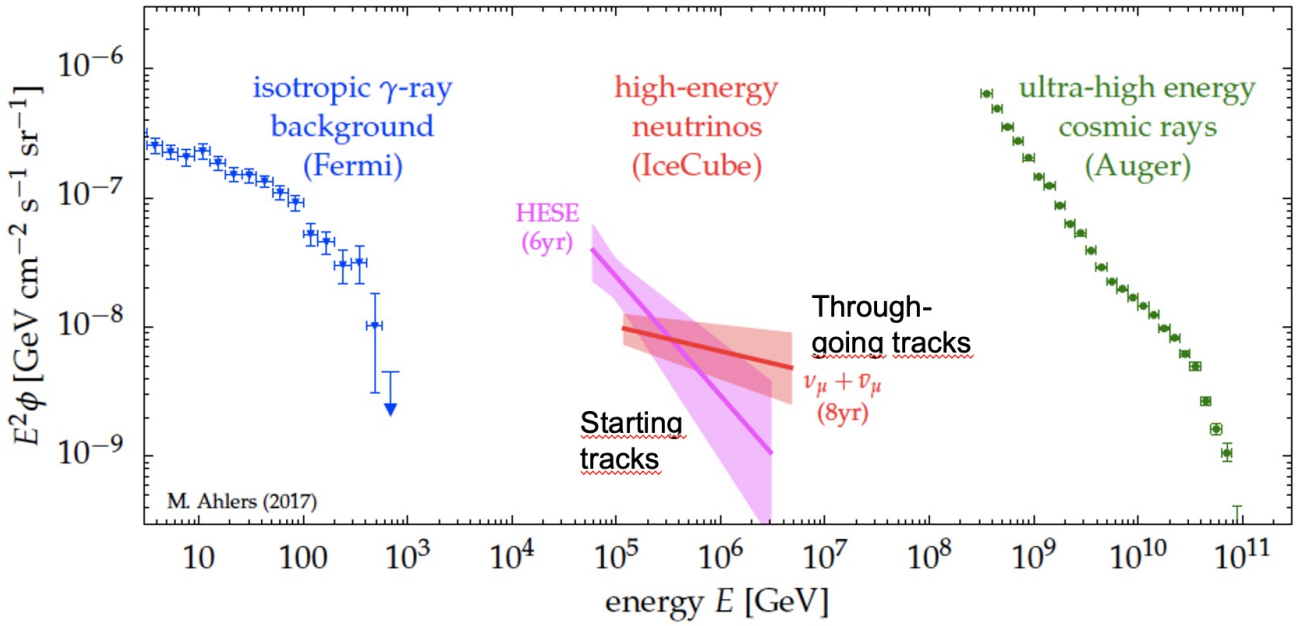


Neutrinos can unambiguously reveal the sources of cosmic rays



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

Multi-messenger Diffuse Flux

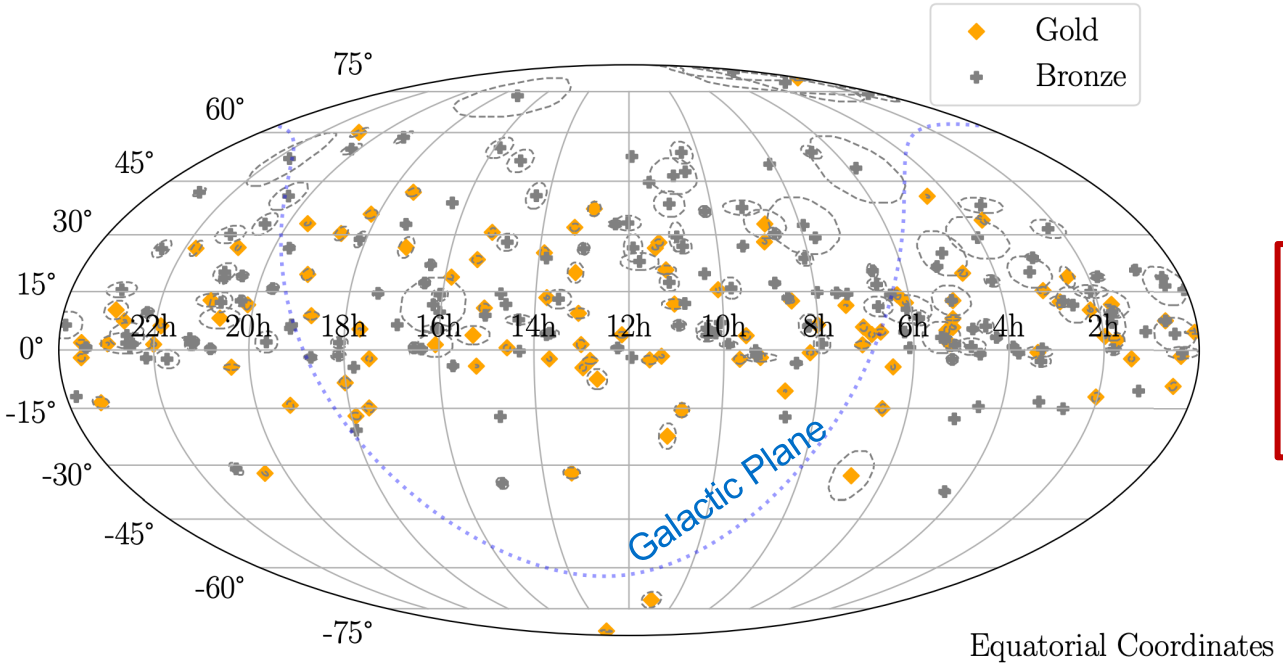


Similar energies in gamma rays, neutrinos & cosmic rays injected into our Universe

What are the sources?!

Neutrino Sky Map

IceCube neutrinos with high (>30%) probability to be of cosmic origin

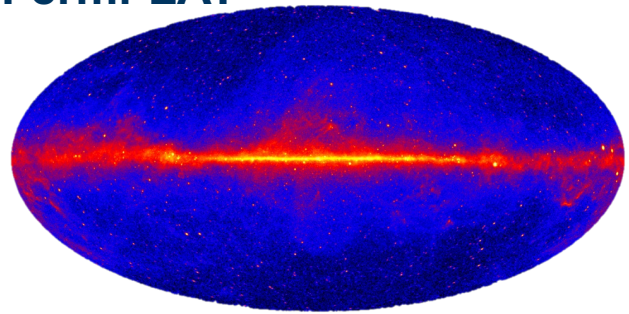


Neutrinos alone do not reveal the sources (yet)

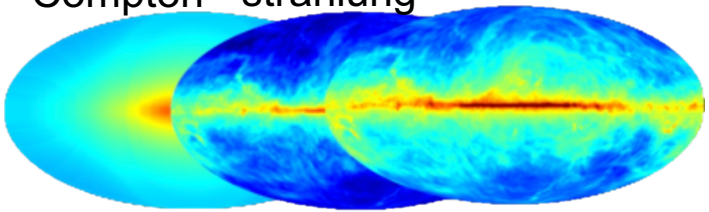
IceCube ApJS 269 (2023)

Galactic Contribution

GeV gamma-ray sky by Fermi-LAT



Inverse Compton | Brems-strahlung | π^0 decay

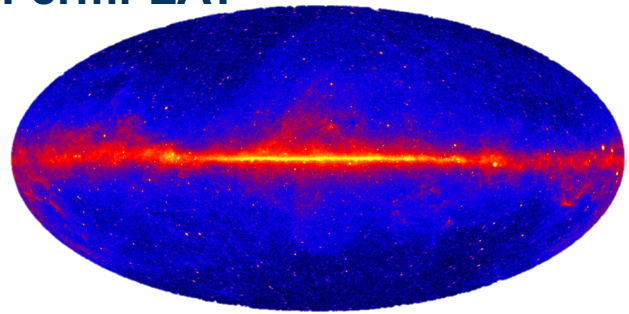


Cosmic rays propagate through the Galaxy and interact with photons and gas

Talk 657 Aguilar Sanchez

Galactic Contribution

GeV gamma-ray sky by Fermi-LAT



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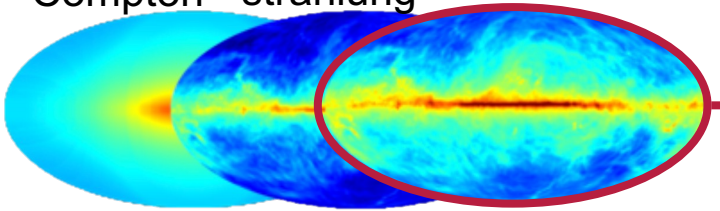
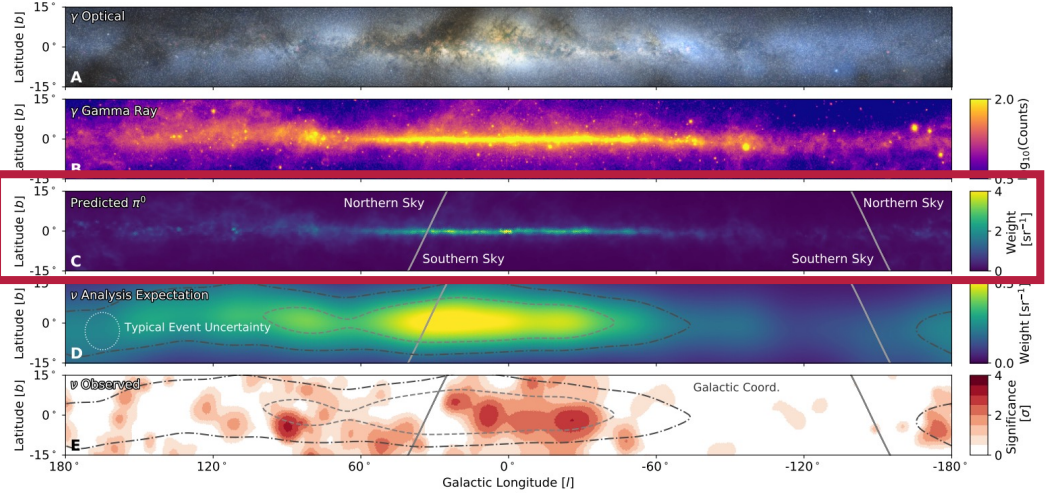


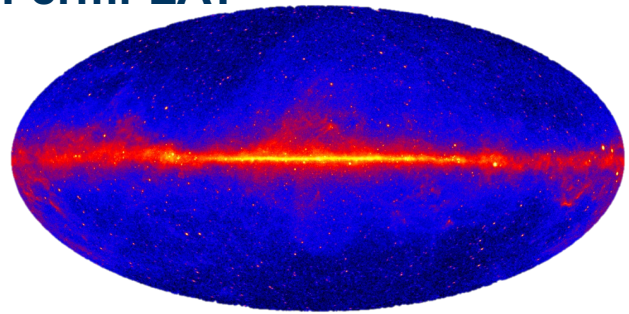


First detection of galactic plane neutrino flux thanks to gamma-ray template fit, ~10% of diffuse flux

Talk 657 Aguilar Sanchez

Galactic Contribution

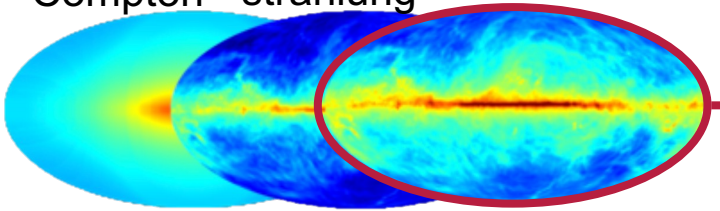
GeV gamma-ray sky by Fermi-LAT

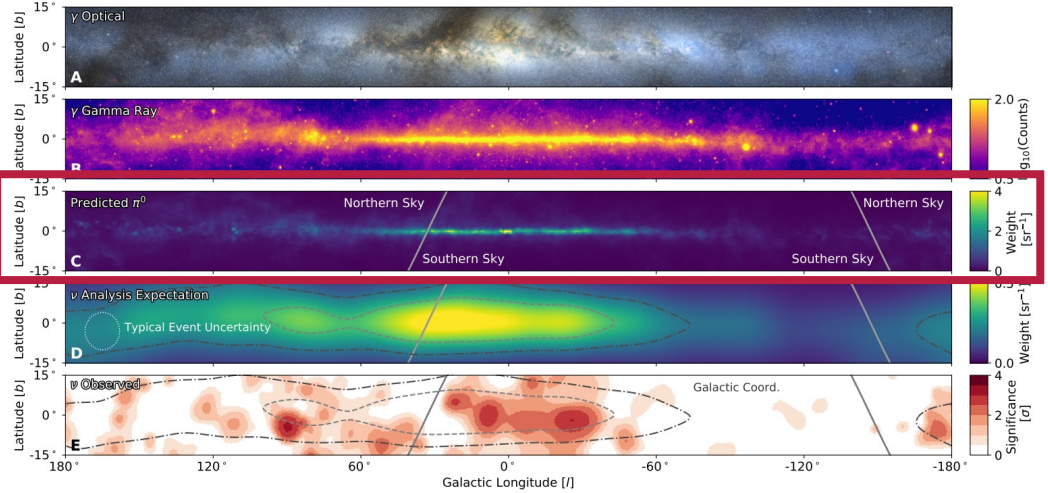


Inverse Compton

Brems-strahlung

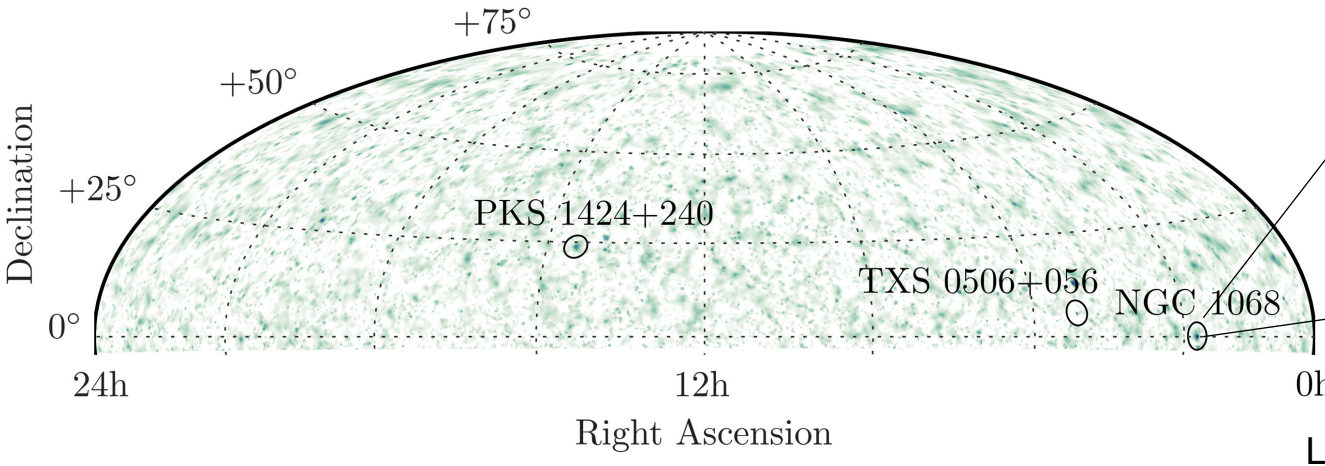
π^0 decay

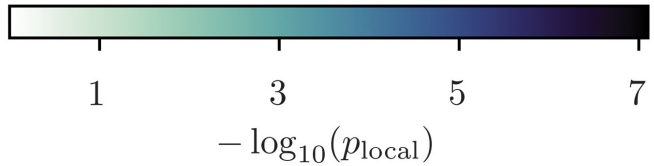


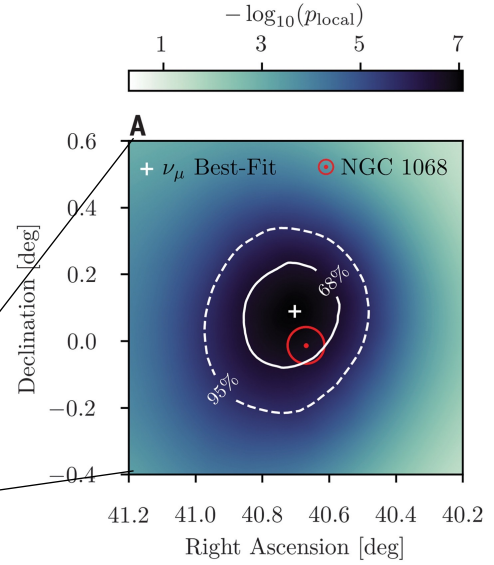


New handle to understand cosmic-ray production and propagation in our Galaxy

Extragalactic Sources: hot spot search







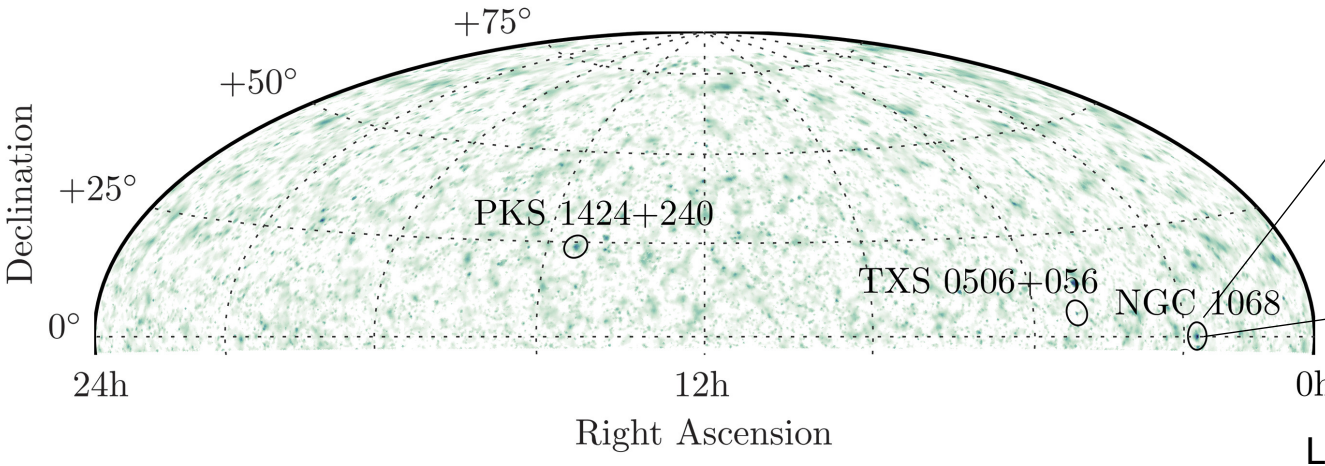
Local p-value: 5×10^{-8} (5.3σ)
After trial correction: 2.2×10^{-2} (2σ)

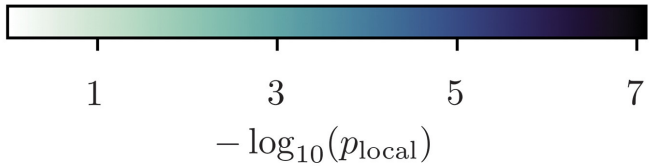
Challenge: Atmospheric background, large trial factor

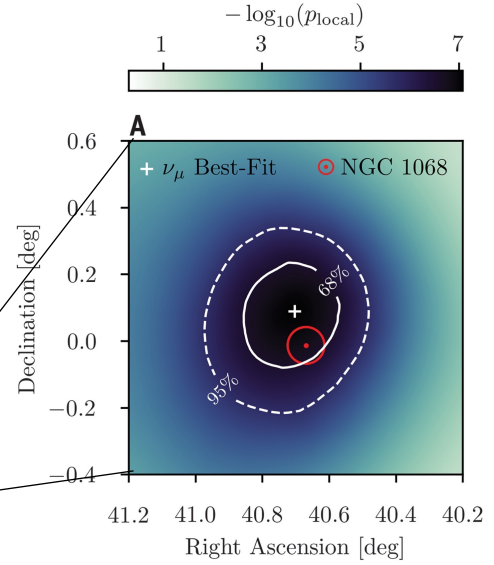
Poster 216 E. Manao

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

Poster 216 E. Manao

Extragalactic Sources

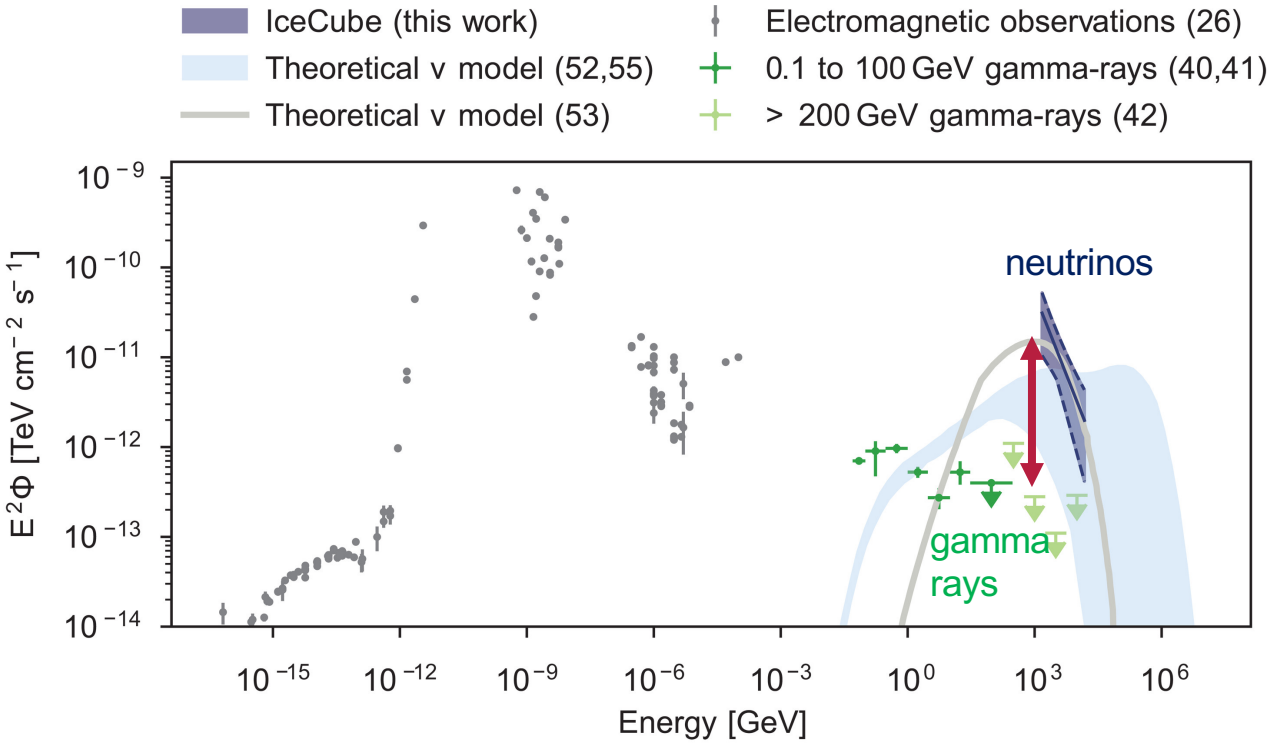
110 sources based on gamma-ray properties and weighted with neutrino search sensitivity

Most significant candidate:
NGC 1068 (M77), 4.2σ

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

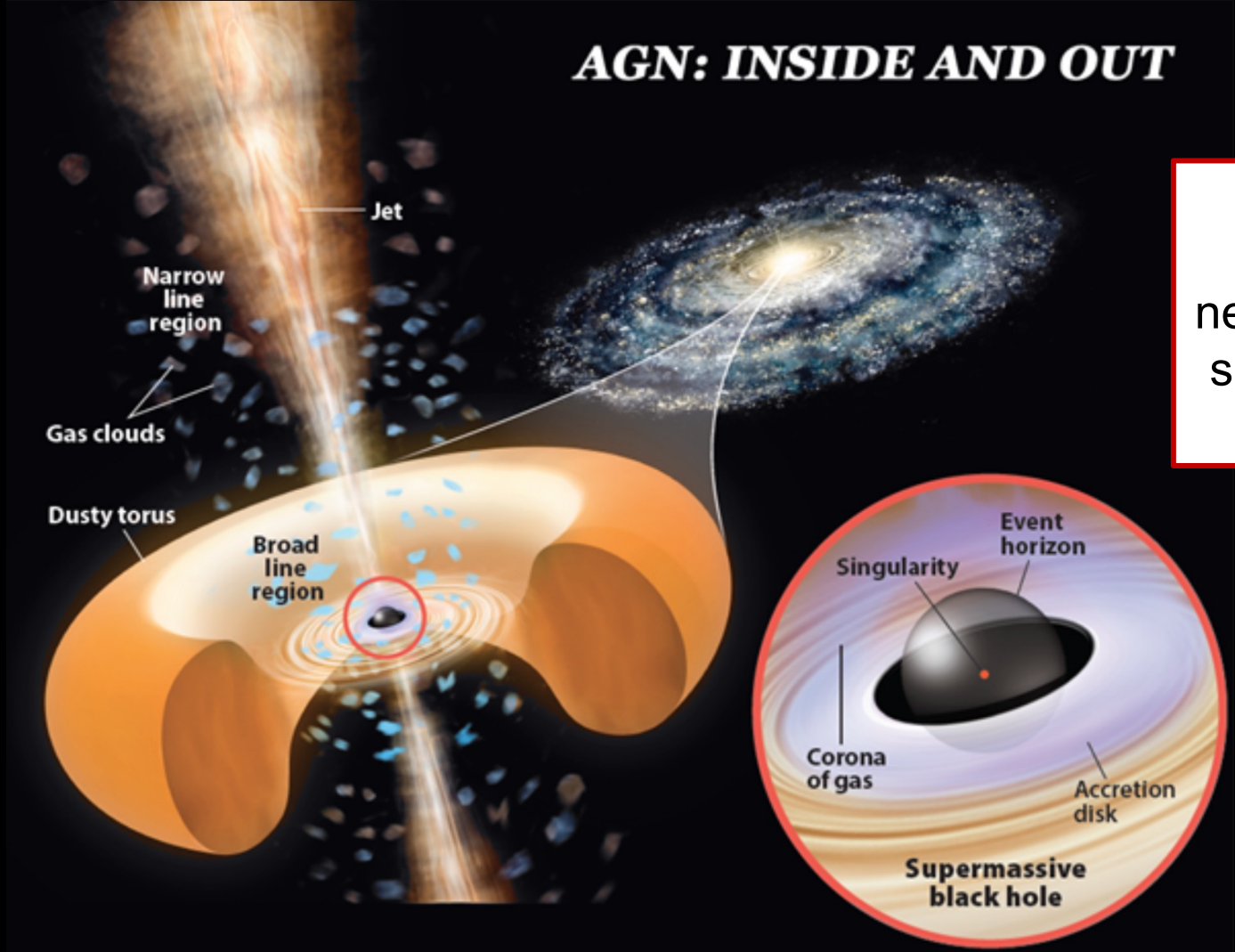
Combining gamma-ray source list with neutrino data allowed neutrino source detection

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

Neutrinos as Triggers

Public alerts since April 2016

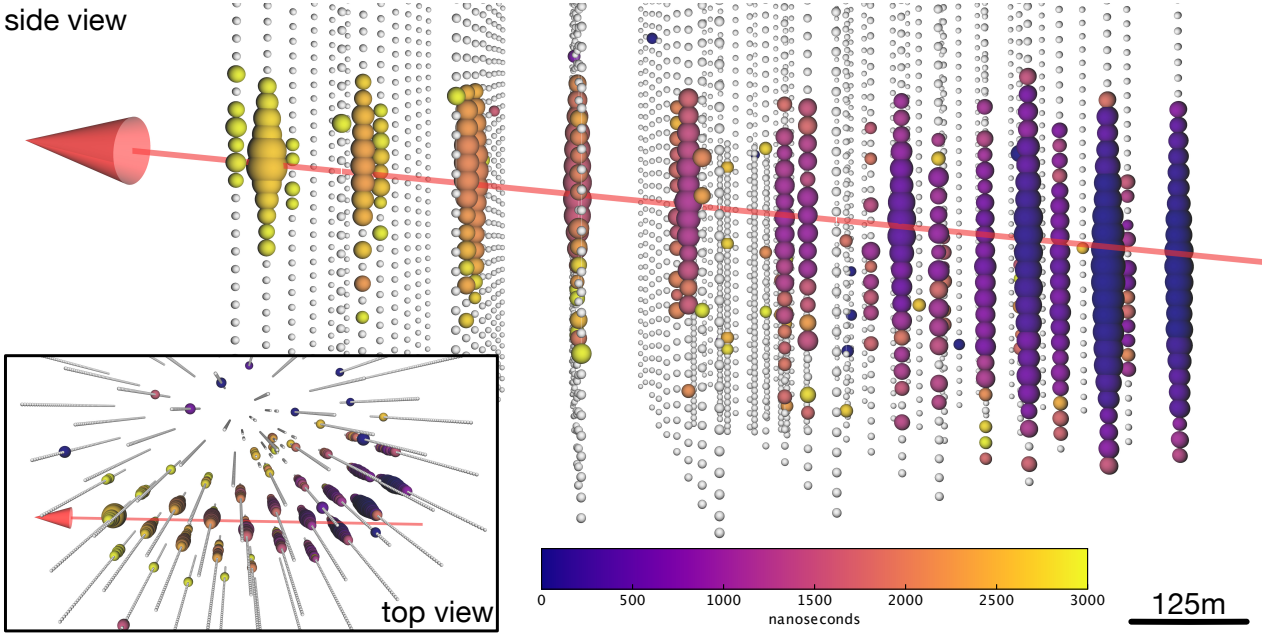
- Single high-energy muon track events (> ~100TeV)
- “Gold” alert stream:
  10 / yr, ~5 / yr of cosmic origin
- Median latency: 30 sec

Goal: Find electromagnetic counterpart

Posters 511 + 513

Astropart. Phys., 92, 30 (2017)

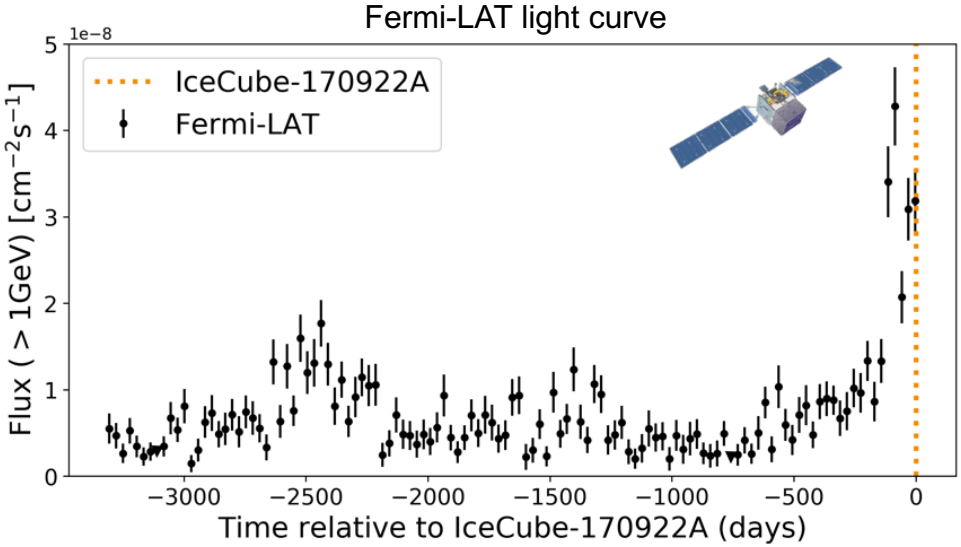
First example: IC-170922A – a 290 TeV Neutrino

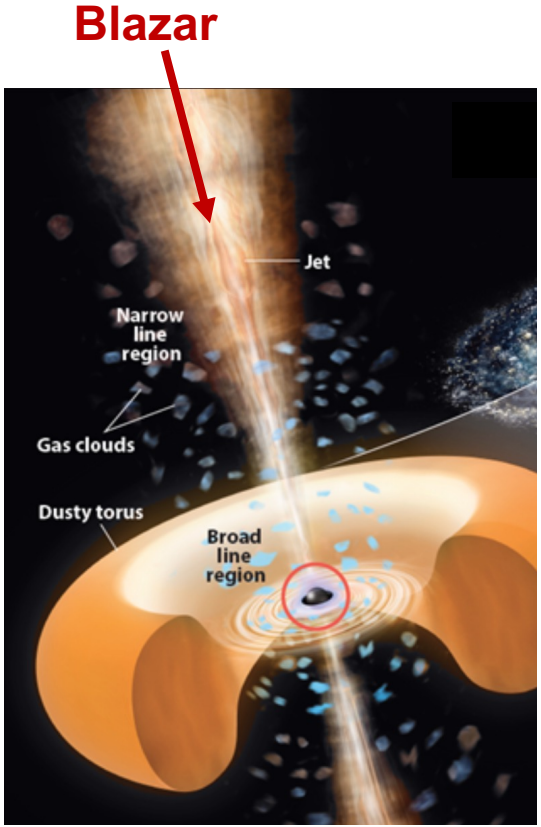


Signalness: 56.5%

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

Source Candidates: TXS 0506+056

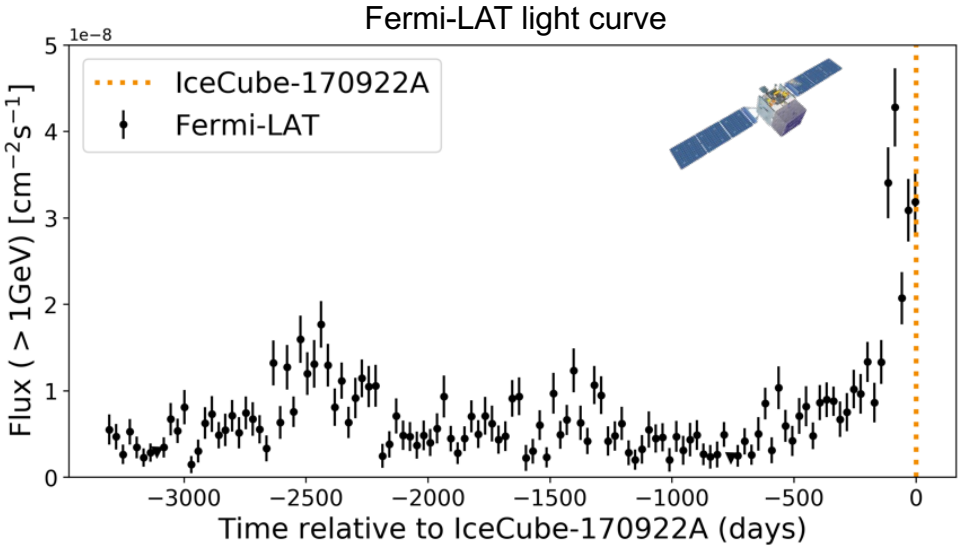


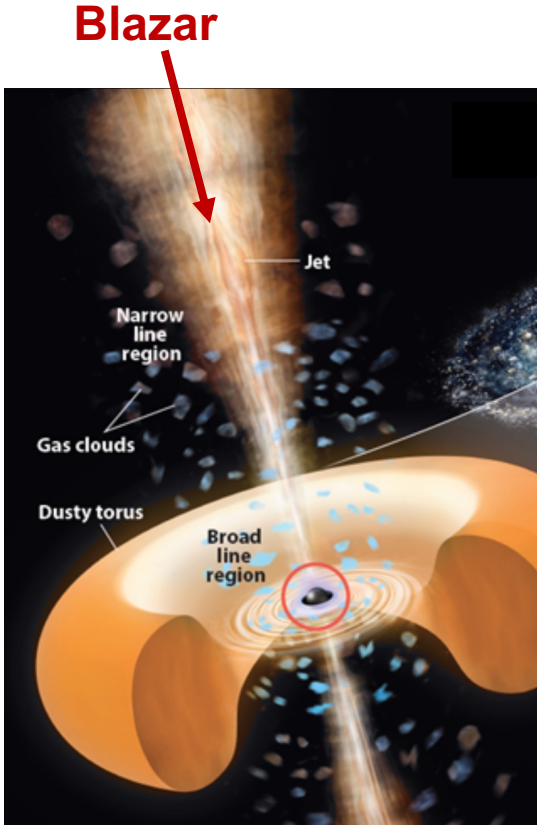


Coincidence with source location and gamma-ray flare increases significance to 3σ

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

Source Candidates: TXS 0506+056

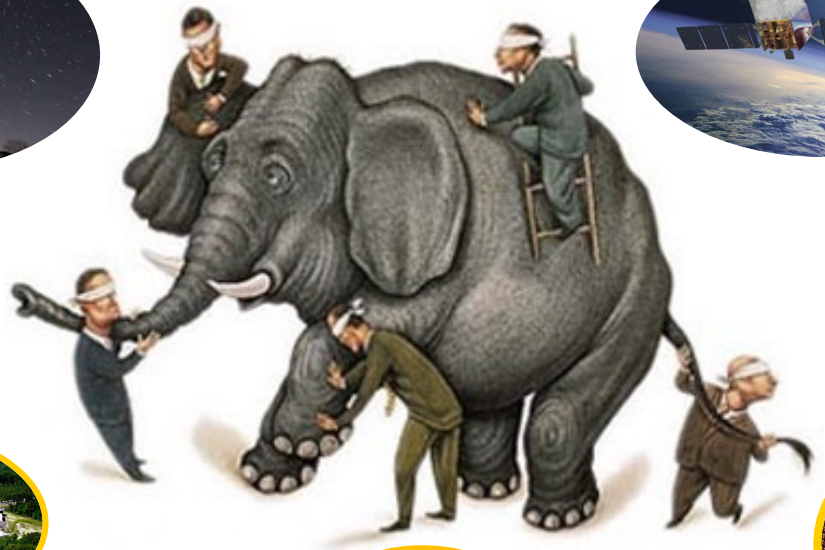




Source is a cosmic-ray source reaching energies of at least several PeV, constrain LIV

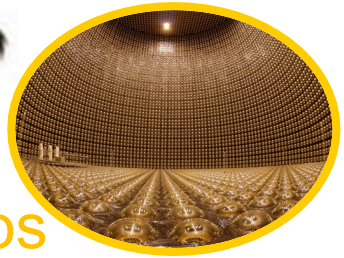
IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018

Multi-messenger Astronomy

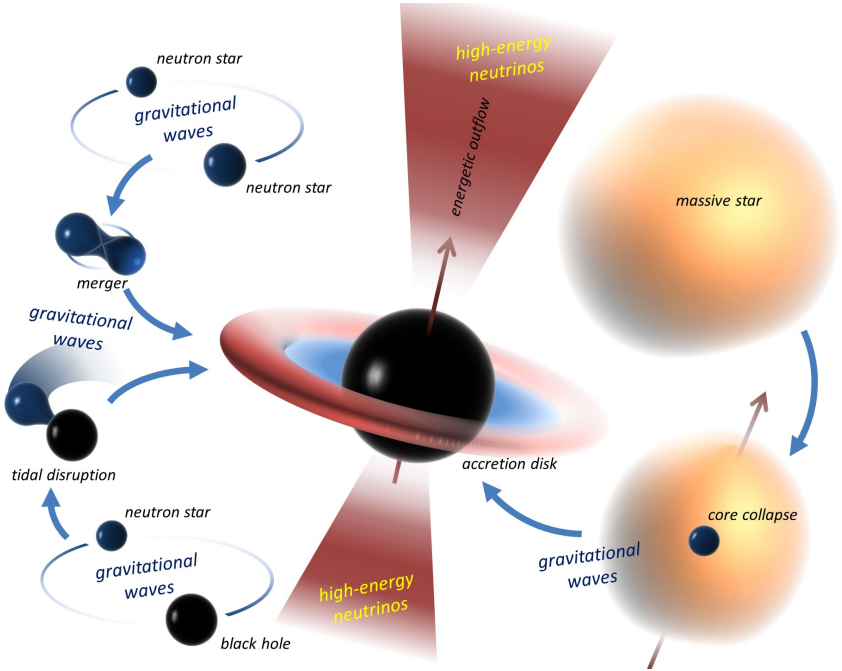


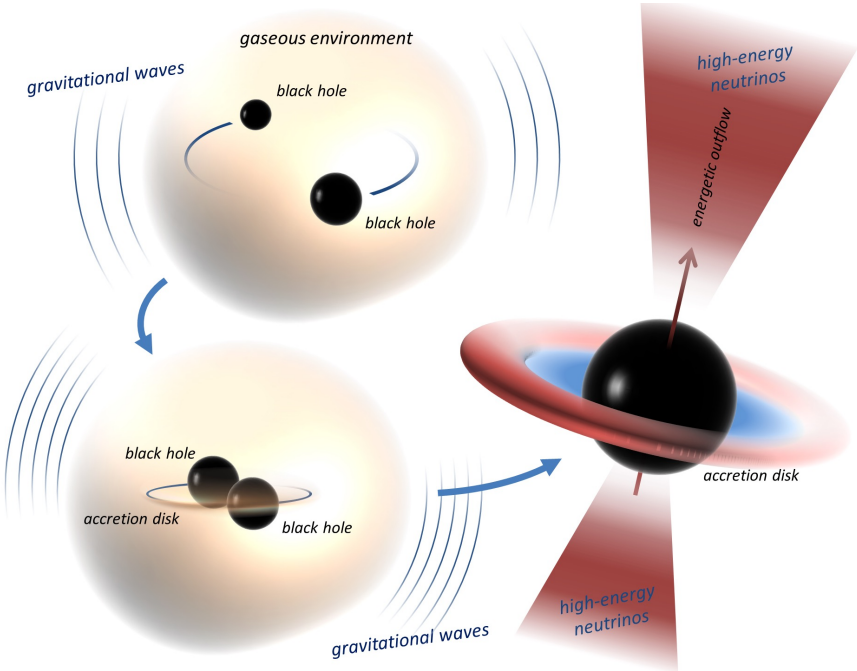
Gravitational Waves

neutrinos



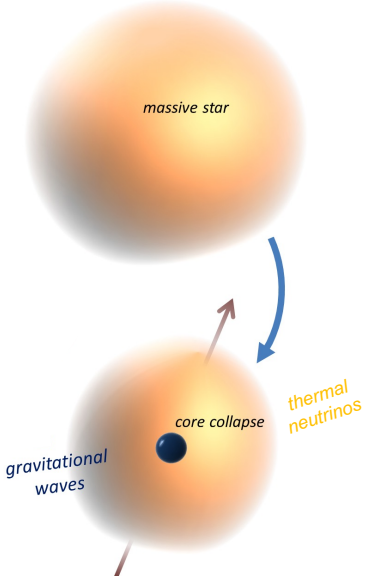
Neutrinos and Gravitational Waves





Credit: I. Bartos

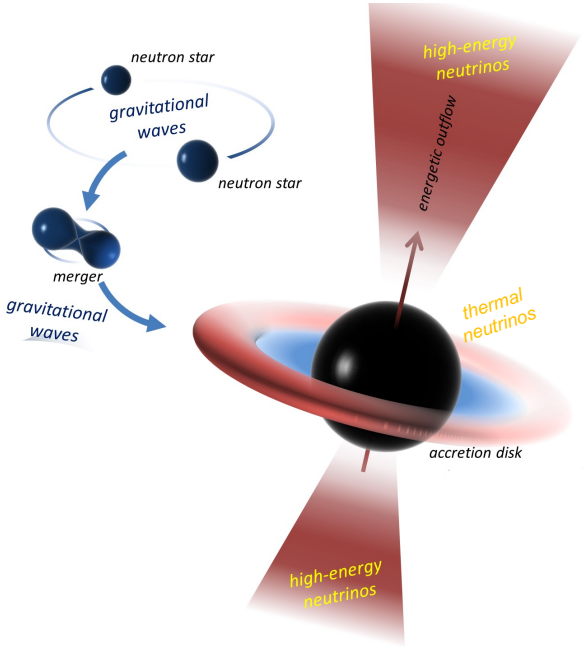
MeV Neutrinos and Gravitational Waves: CCSN



Increase detection probability of GW signal from a CCSN by combining GW and neutrino signals

O. Halim et al JCAP11(2021)021

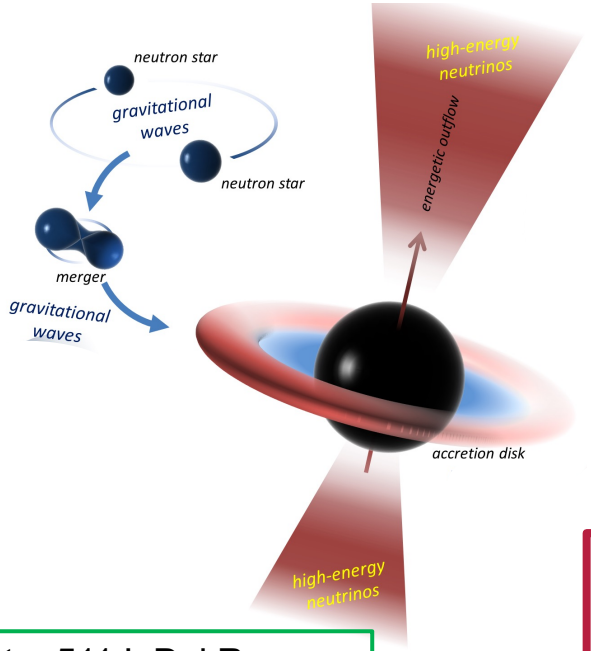
MeV Neutrinos and Gravitational Waves: BNS merger



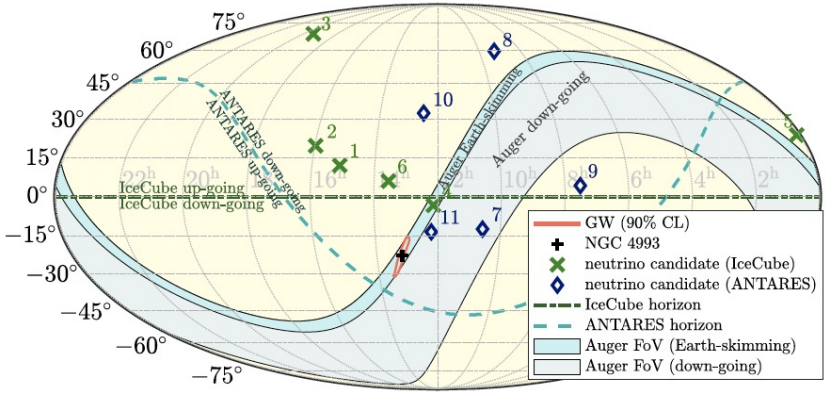
Even single MeV neutrino
→ pin down energy scale of thermal neutrino emission from BNS mergers
→ support or disfavor formation of remnant massive neutron stars

Kyutoku & Kashiyama PRD 97, 103001 (2018)

TeV Neutrinos and Gravitational Waves: BNS merger



GW170817: Search for neutrinos in ANTARES, Auger and IceCube data in +/-500 sec



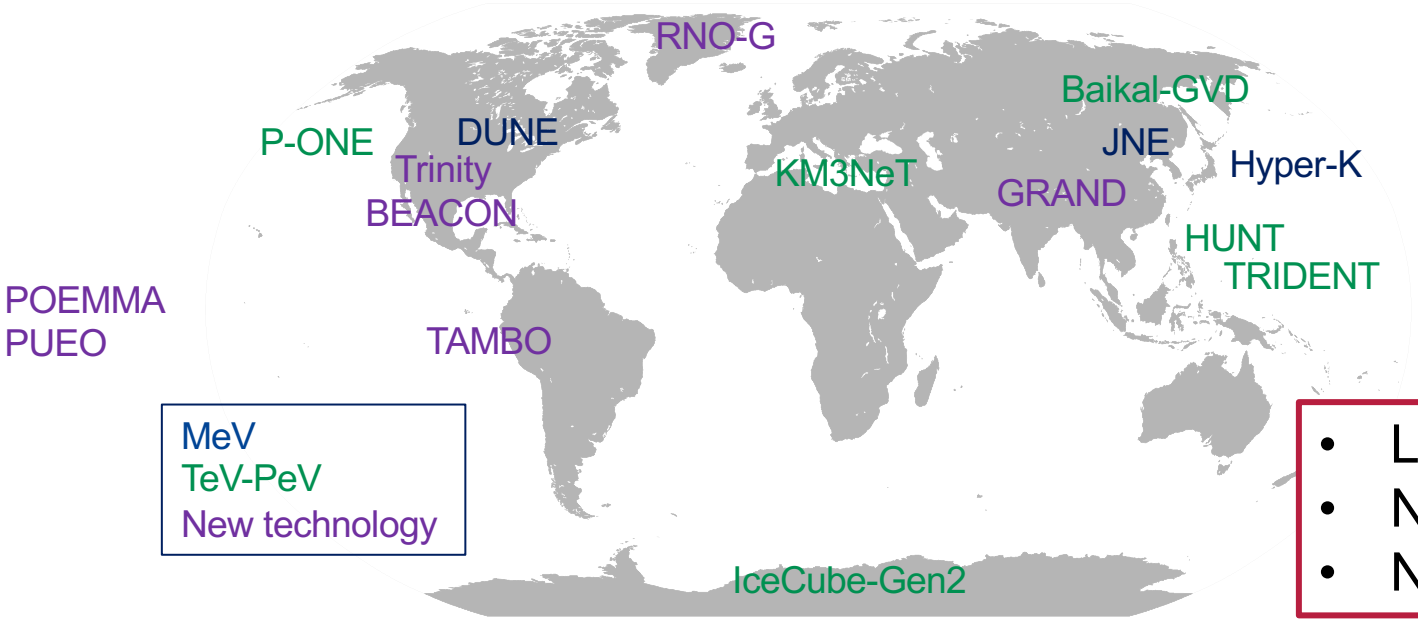
Neutrino could help to constrain direction and teach us about the GW source environment

Poster 511 I. Del Rosso

LIGO, Virgo, Auger, ANTARES, IceCube,ApJ 850 (2017)

New Neutrino Detectors

NuMoon



MeV
TeV-PeV
New technology

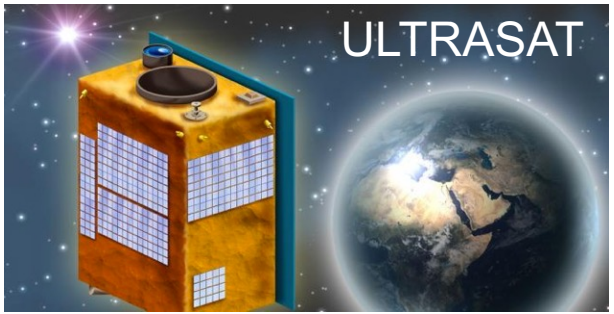
- Larger detectors
- New sites
- New technologies

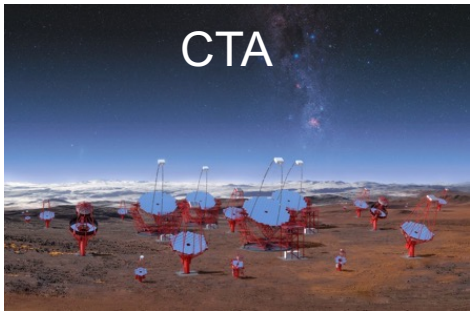
RUHR UNIVERSITÄT BOCHUM RUB

New Detectors

Multiwavelength Instruments

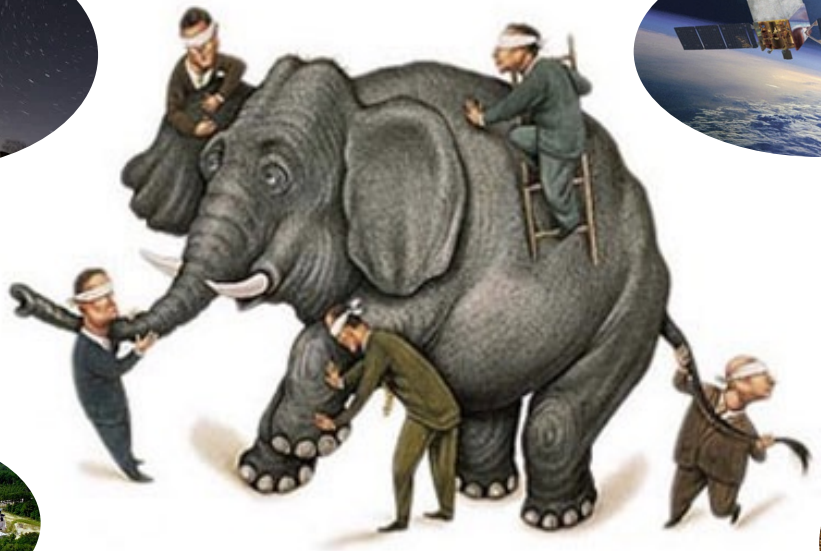
- Increased sensitivity
- Increased wavelength coverage
- Increased cadence

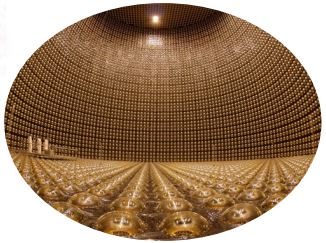




Large Array Survey Telesope (LAST)

Summary





Stay Tuned!

Backup