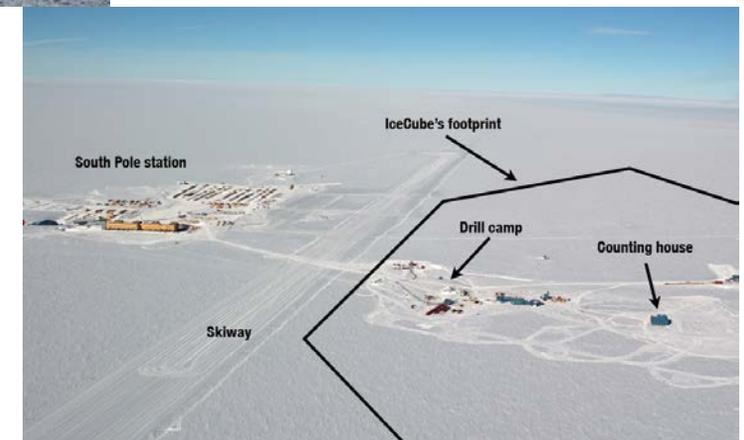
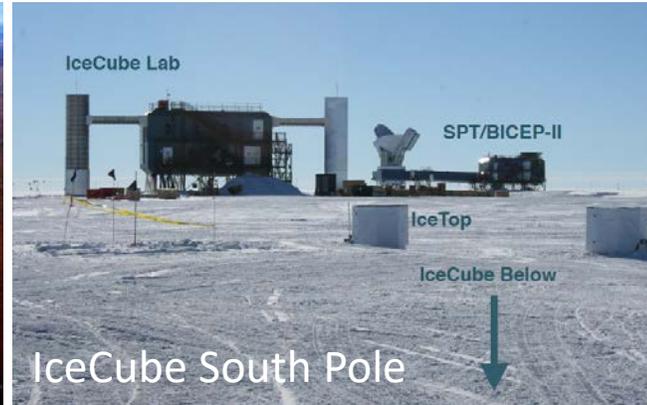


The Era of Multi-Messenger Astrophysics



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Physics Division - MPS

What is Multi-Messenger Astrophysics?

Any observation that involves two or more of these messengers

EM signals

(Radio, IR, Optical, UV, X-rays, Gamma-rays)



Particles

(neutrinos, cosmic rays)



Gravitational Waves



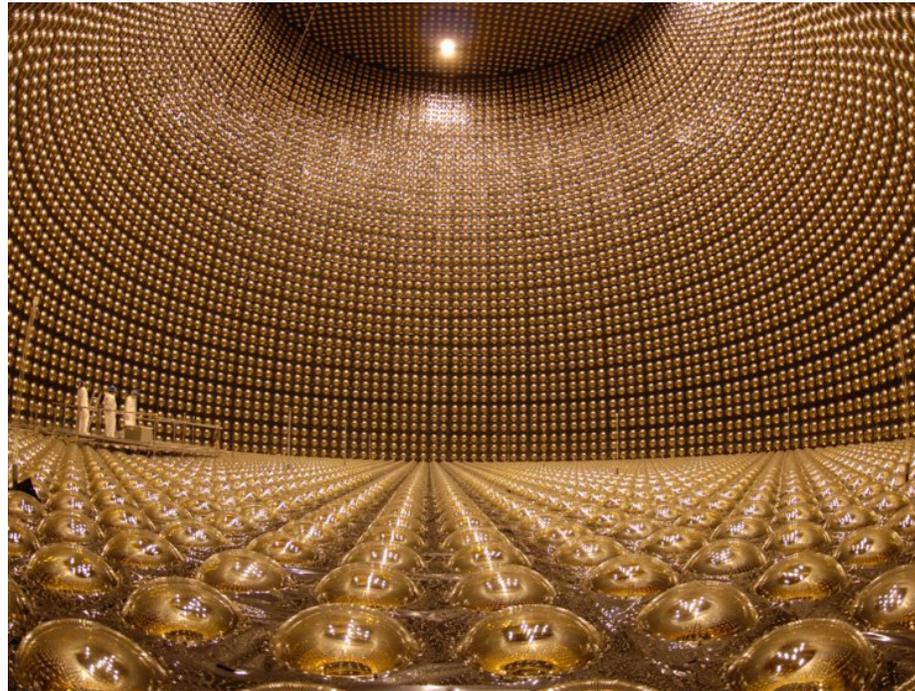
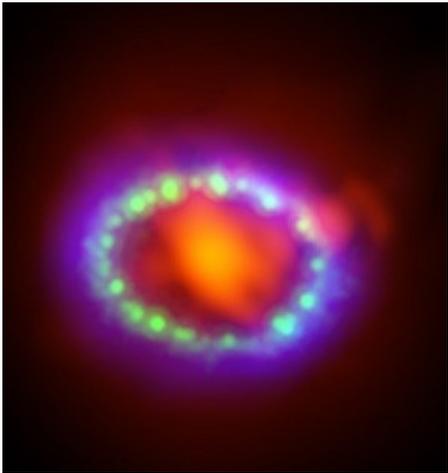
Images: LSST, Fermi Gamma-ray satellite, VLBA, IceCube (M. Lucibella), HAWC (J. Goodman), Virgo, Kagra

A bit of history

SN 1987a

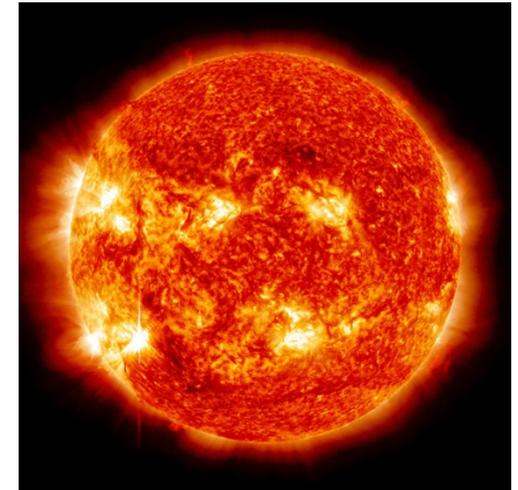
Supernova in Large Magellanic Cloud (~50 Kpc).

25 antineutrinos detected by Kamiokande, IMB and Baksan observatories.



Solar Neutrinos

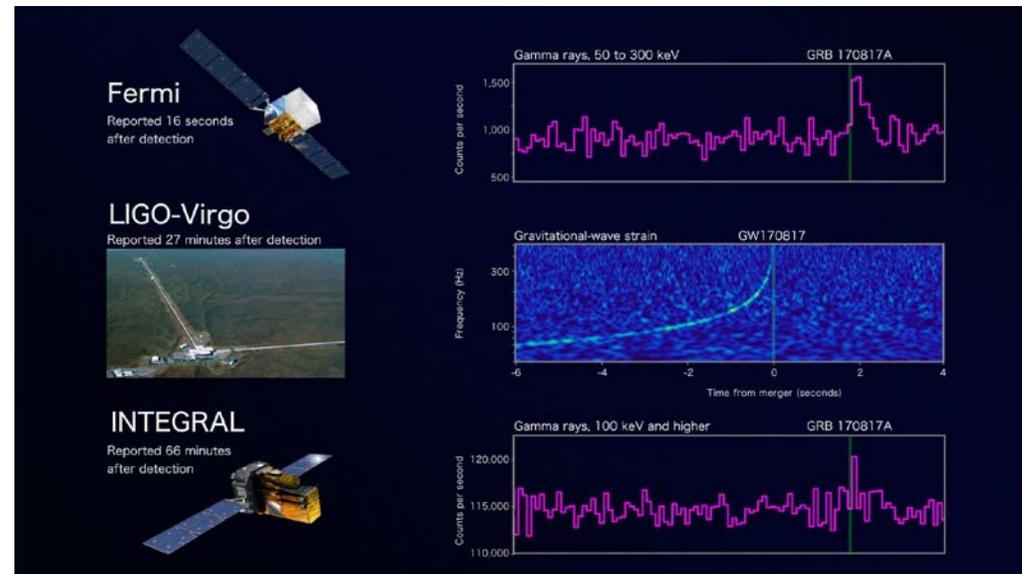
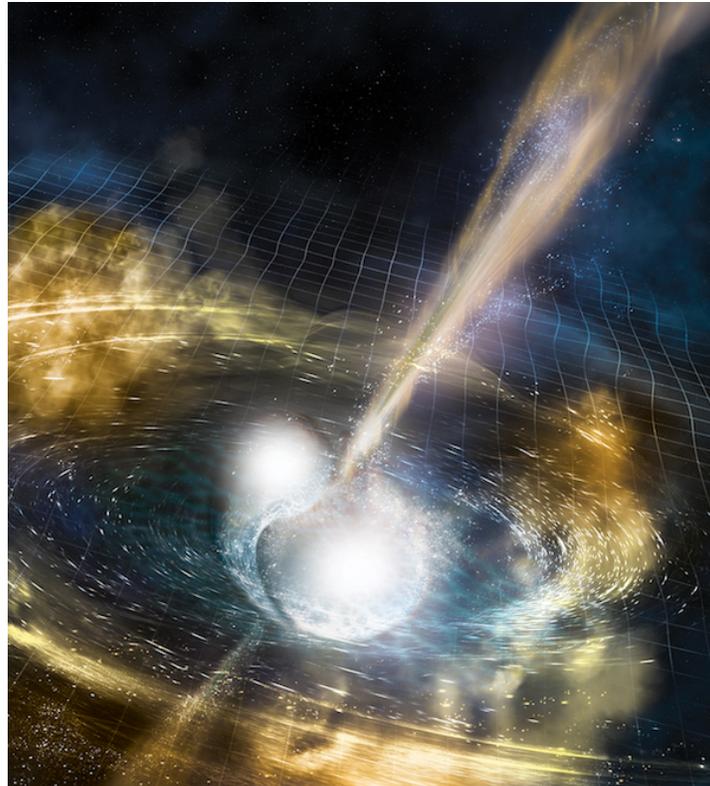
First detected in the late '80s by Kamiokande obs.



Images: SN1987a (ALMA, Chandra obs.), Kamioka obs., NASA Solar Dynamics obs.

Binary Neutron Star Merger (August 17, 2017)

First MMA observation involving gravitational waves



FIRST COSMIC EVENT OBSERVED IN GRAVITATIONAL WAVES AND LIGHT

Colliding Neutron Stars Mark New Beginning of Discoveries

Collision creates light across the entire electromagnetic spectrum. Joint observations independently confirm Einstein's General Theory of Relativity, help measure the age of the Universe, and provide clues to the origins of heavy elements like gold and platinum

Gravitational wave lasted over 100 seconds

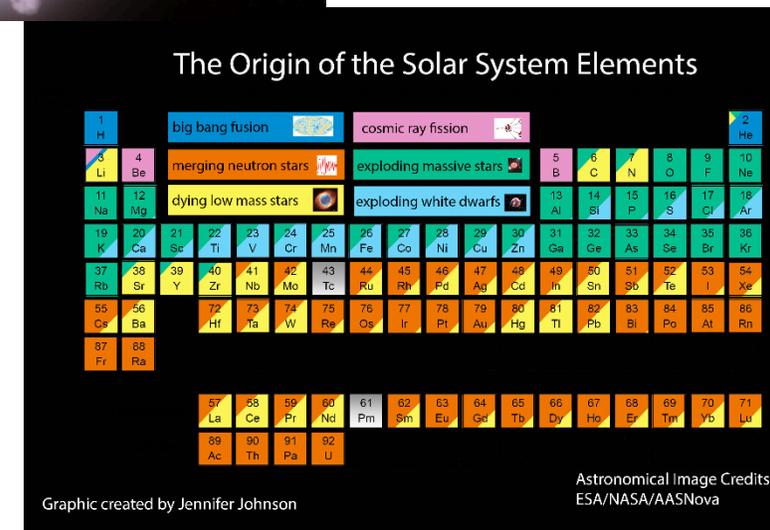
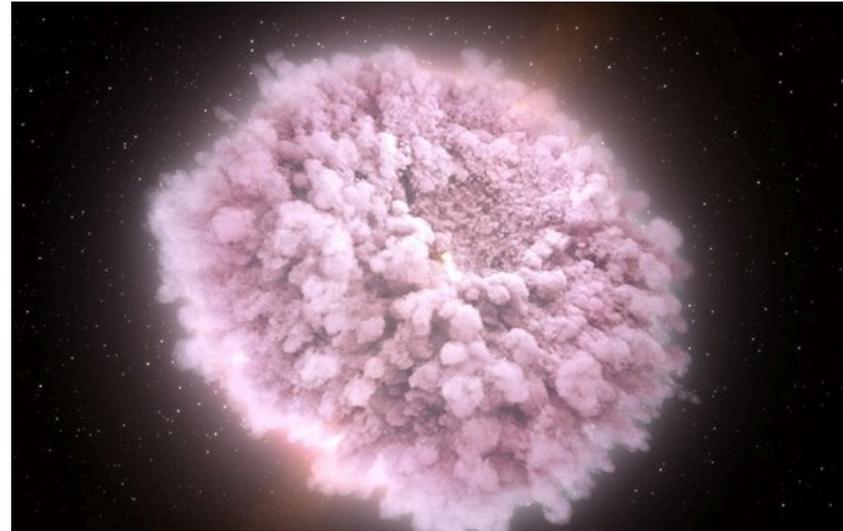
On August 17, 2017, 12:41 UTC, LIGO (US) and Virgo (Europe) detect gravitational waves from the merger of two neutron stars, each around 1.5 times the mass of our Sun. This is the first detection of spacetime ripples from neutron stars.

Within two seconds, NASA's Fermi Gamma-ray Space Telescope detects a short gamma-ray burst from a region of the sky overlapping the LIGO/Virgo position. Optical telescope observations pinpoint the origin of this signal to NGC 4993, a galaxy located 130 million light years distant.



BNS GW170817: What did we learn?

- BNS mergers are sources short gamma-ray bursts
- GW and light propagate at the same speed (within 1 part in 10^{15})
- Confirms General Relativity: Many alternative theories that exhibit Lorentz Invariance violations have been constrained to the point of irrelevance!
- Strong constraints on nuclear matter equation of state
- Independent measurement of the Hubble constant: 70 (km/s)/Mpc, roughly consistent with current estimates
- BNS mergers create a significant fraction of heavy elements



Images: NASA/ESA/AASNova (J. Johnson)

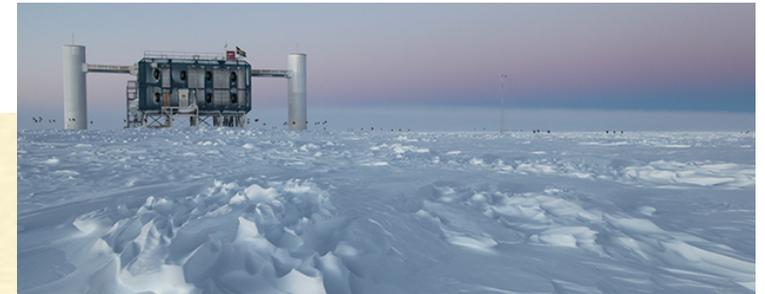


IceCube UHE Neutrino on Sept. 22, 2017

Last year, we had another “first” in multi-messenger discoveries, when several observatories measured VHE gamma rays coming from a direction consistent with a UHE neutrino event detected by the IceCube Neutrino Observatory in Antarctica.

Telegram:

ICECUBE-170922A



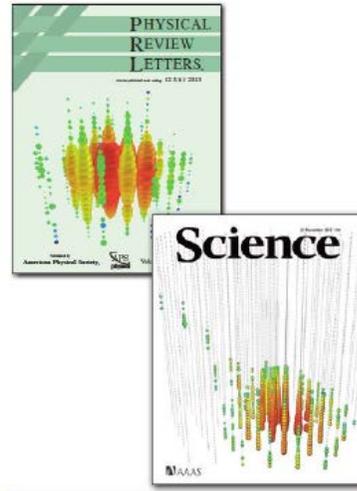
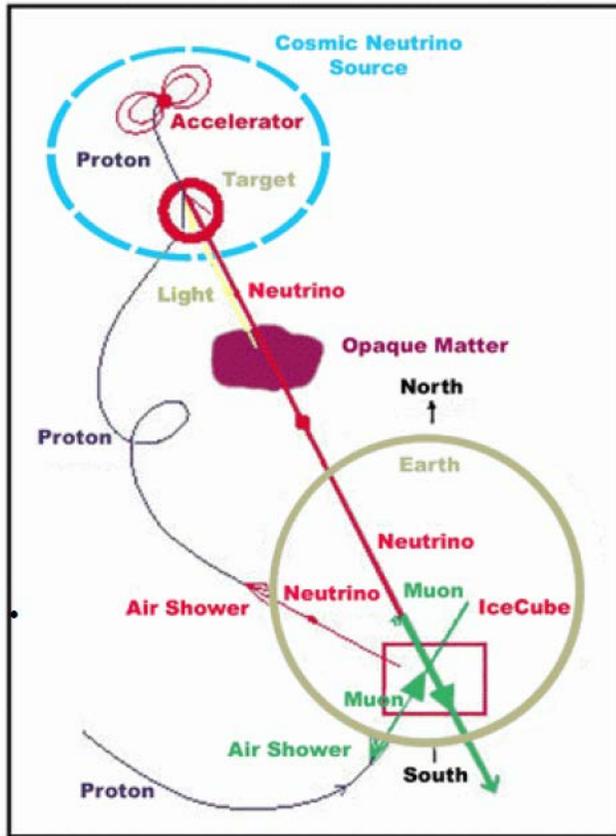
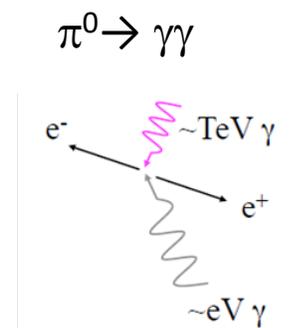
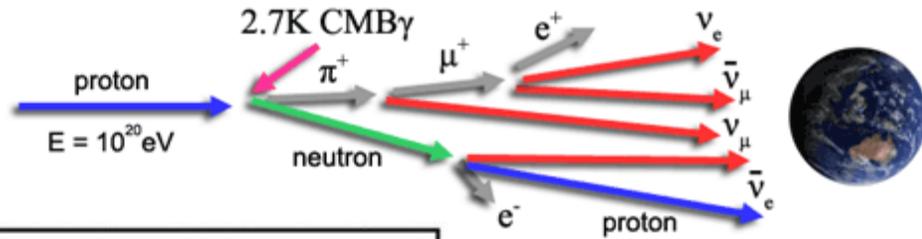
GCN AMON notice:https://gcn.gsfc.nasa.gov/notices_amon/50579430_130033.amon

1. Fermi-LAT detected gamma-rays -- 20 MeV to 300 GeV
2. AGILE detected gamma-rays -- above 0.1 GeV
3. MAGIC detected gamma-rays -- up to 400 GeV
4. VLA detected Radio Observations -- 2-4, 4-8, and 8-12 GHz
5. SWIFT detected X-rays and H.E.S.S. detected gamma-rays

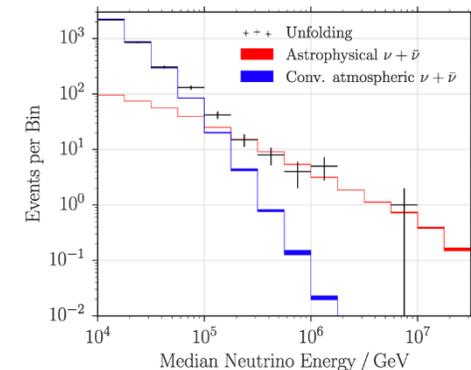
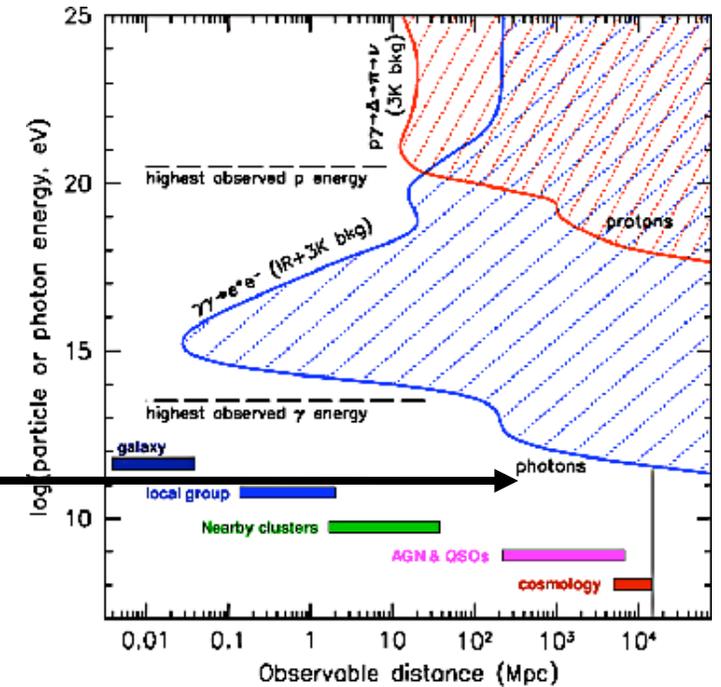
Wide range of EM activity in Response to IceCube's neutrino



High Energy Cosmic and Gamma Rays



The IceCube Neutrino Observatory observed (in July 2013) a diffuse flux of TeV-PeV astrophysical neutrinos at 5.7σ significance from an all-flavor search. (Between 100 TeV and 10 PeV.)

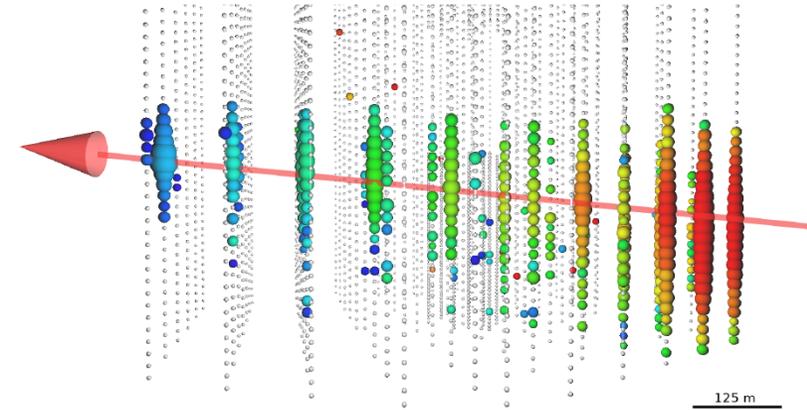


Paper Multiwavelength observations of a flaring blazar coincident with an IceCube high-energy neutrino

#1

IceCube, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S, *INTEGRAL*, Kapteyn, Kanata, Kiso, Liverpool, Subaru, *Swift*, VERITAS, VLA/17B-403 team

On September 22, 2017, a high-energy neutrino, IceCube-170922A, with $E_\nu \sim 290$ TeV was detected arriving from a direction consistent with the location of the γ -ray blazar TXS 0506+056, observed to be in a flaring state. These observations characterize the variability and energetics of the blazar and include the first detection of TXS 0506+056 in very-high-energy γ -rays.



This observation of a neutrino in spatial coincidence with a γ -ray emitting blazar during an active phase is suggestive of blazars as a source of high-energy neutrinos.

Paper Evidence for neutrino emission from the direction of the blazar TXS 0506+056

#2

IceCube Collaboration

“We investigated 9.5 years of IceCube data at the position of the blazar and find 3.5σ evidence for neutrino emission from this direction, independent of and prior to the 2017 flaring episode. The evidence comes from an excess of (13 ± 5) high-energy neutrino events with respect to atmospheric backgrounds between September 2014 and March 2015.

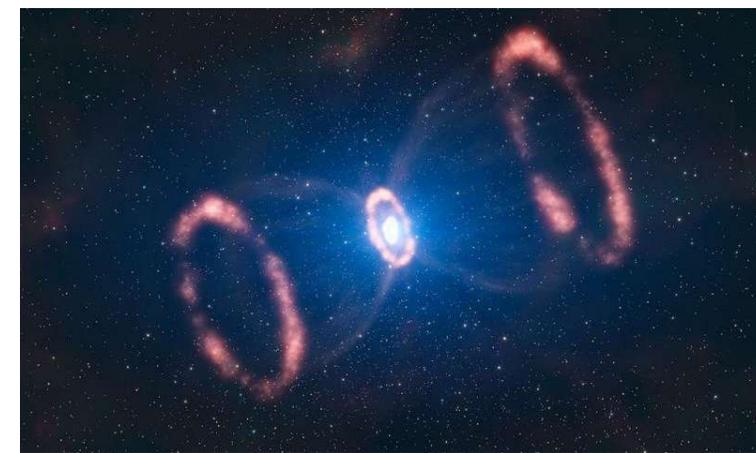
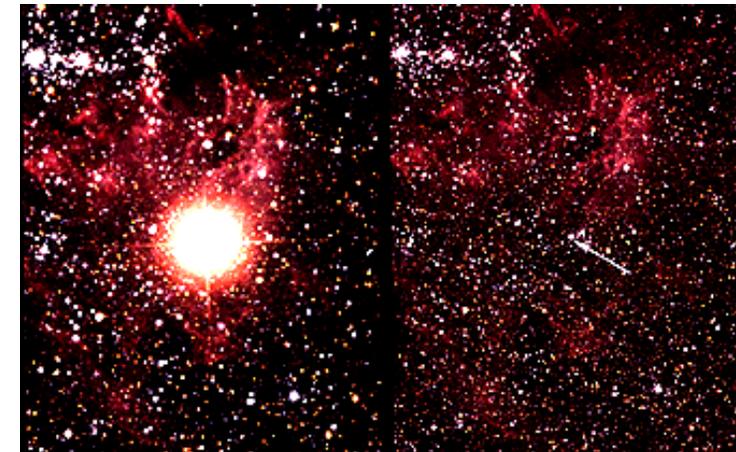
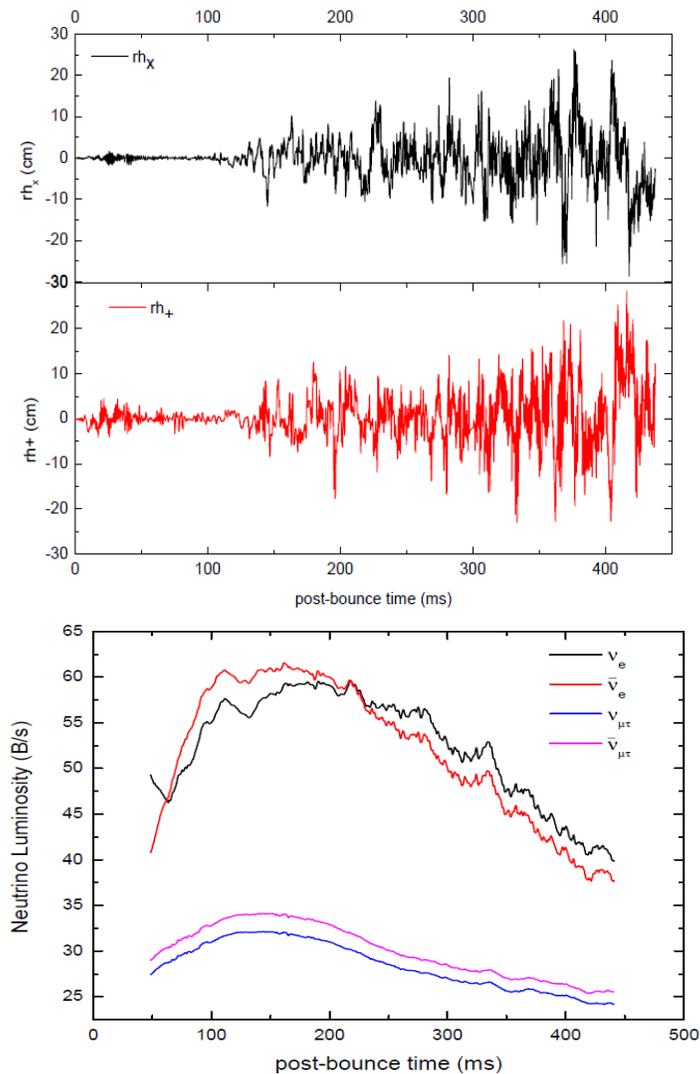
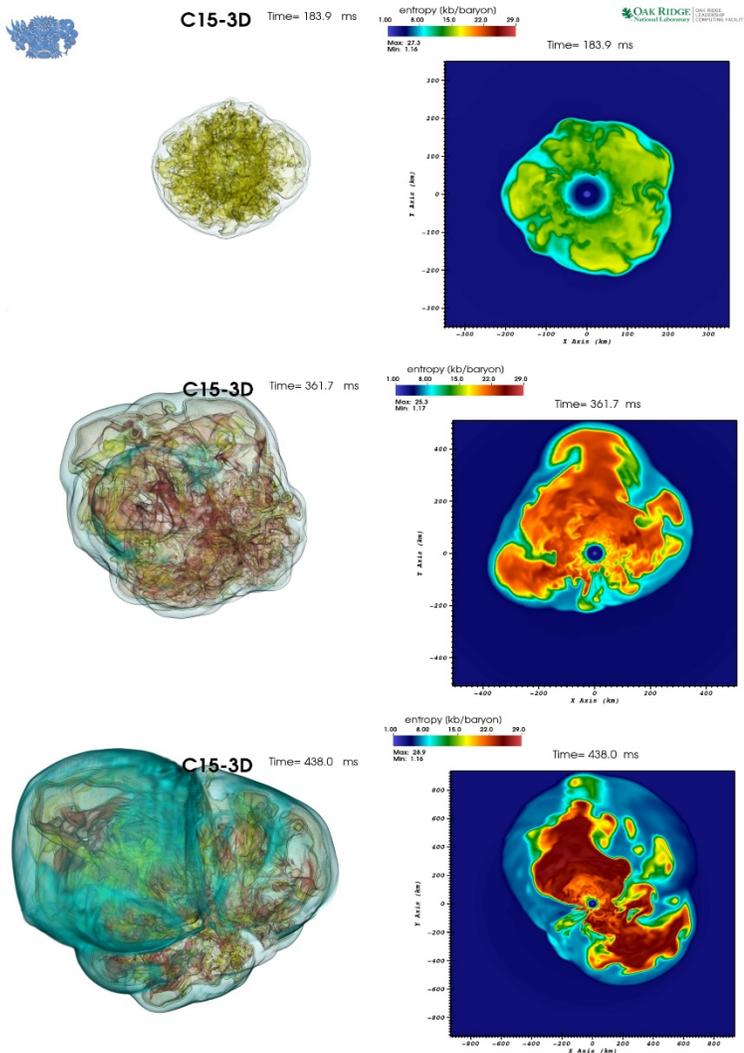
This suggests that blazars are the first identifiable sources of the high-energy astrophysical neutrino flux.

Take-away message:

- * This is the first observation of high-energy neutrinos and photons together from a distant active galaxy.
- * The results, initiated by a recent event in the IceCube Neutrino Observatory, are an important milestone in solving the more than 100-year mystery of the origin of cosmic rays.
- * This suite of observations, including those by the Fermi-LAT and MAGIC and other gamma-ray telescopes, were made possible through the coordinated efforts in the modern **Era of Multi-Messenger Astrophysics.**

“The coincidence of an IceCube alert with a flaring blazar, combined with a neutrino flare from the same object in archival IceCube data, pinpoints for the first time a likely source of high-energy cosmic rays.”

MMA Trifecta: Galactic Supernovae



Images: Chimera Coll. (ORNL/UT-Knoxville/FAU/NCSU), NASA, ESO (L. Calçada)

What could we learn from a galactic Supernova?

- Detailed description of the explosion deep inside the star: Core implosion, shock generation, envelope explosion, elements evolution.
- Birth of a neutron star!
- Supra nuclear matter dynamics: Constraints of matter at the highest possible densities.
- Stronger tests of standard model extensions and General Relativity.

However, we may have to be patient.

The rate of galactic SNe is largely unknown but in the range of one every 20 to 100 years.