# Astrophysical Neutrinos: IceCube

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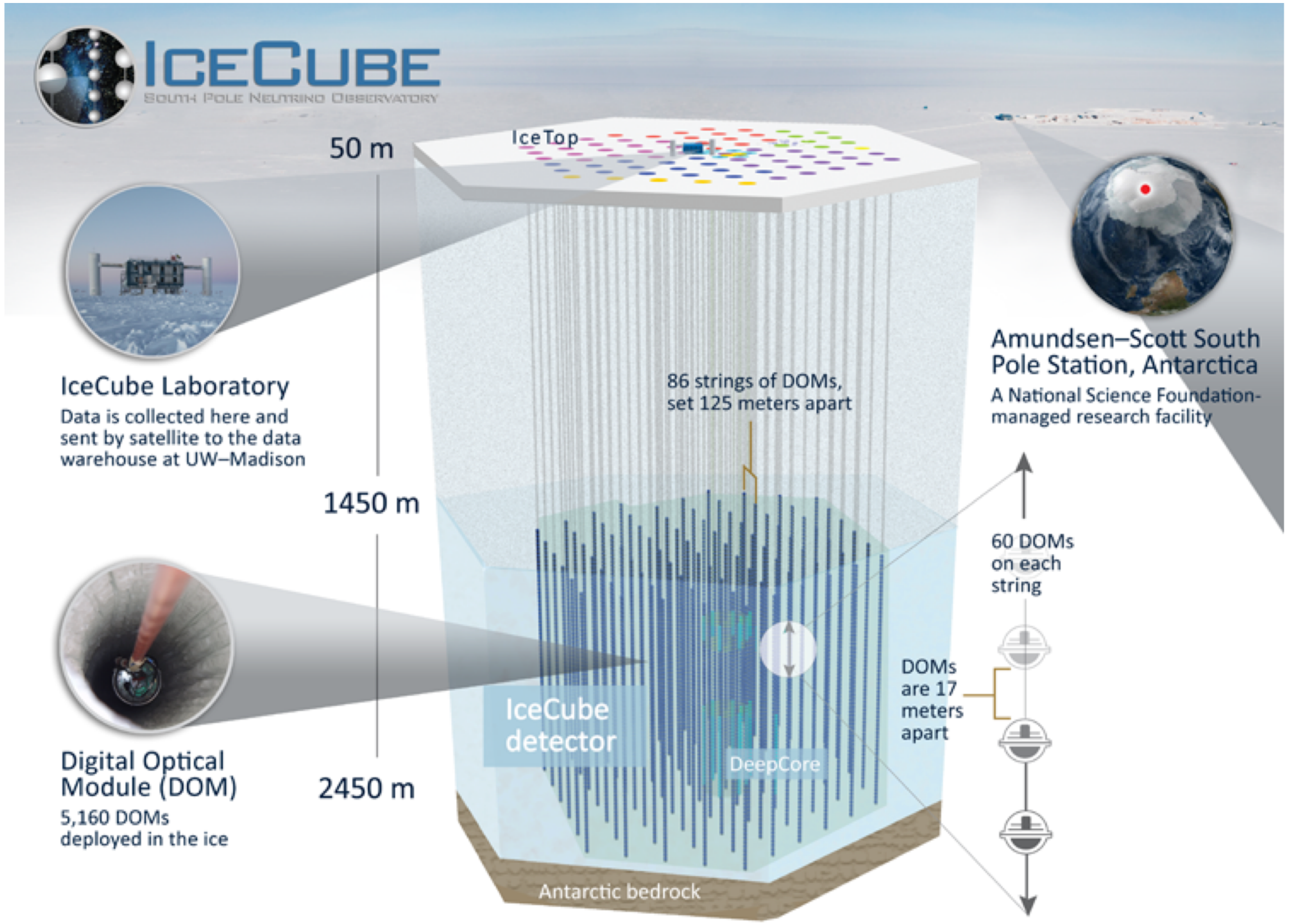
# 100-years-old riddle

- Where do ultra-high cosmic rays come from?
- By the time they reach Earth, their paths have been bent by interstellar magnetic fields
- Solution: use neutrinos! To find the source of these cosmic rays, we can study neutrinos that were produced in or near the astrophysical particle accelerator

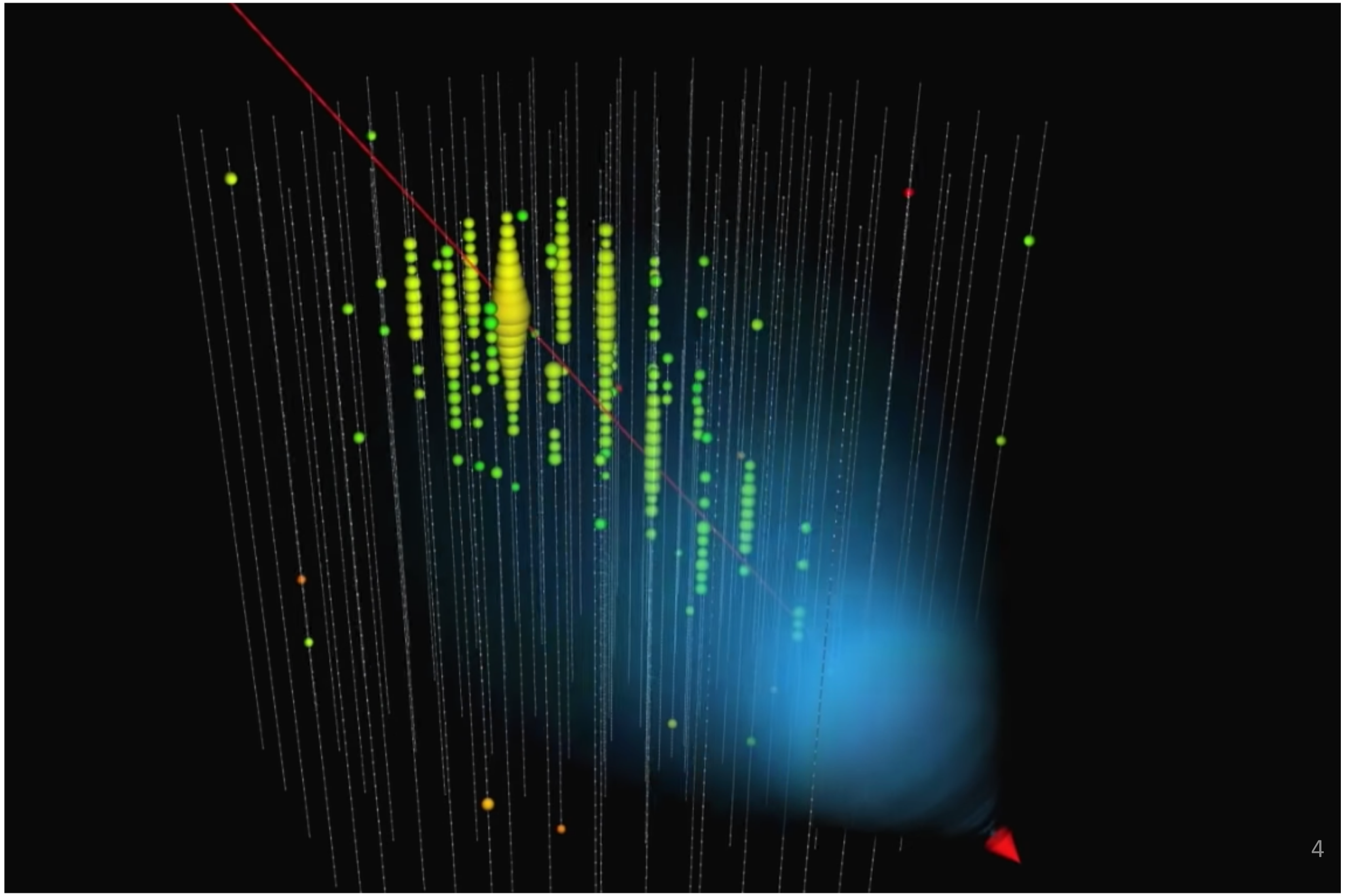
# IceCube neutrino detector

- A 1 km$^3$ detector made of Antarctic ice buried beneath the surface to a depth of about 2,500
- Contains:
    - 5,160 digital optical modules (DOMs), each with a respective PMT
    - Strings that are 1,450 to 2,450 meters in depth holding 60 DOMs each
    - DeepCore: Eight strings at the center of the array that are deployed more compactly
    - IceTop: measures the cosmic-ray arrival directions in the Southern Hemisphere as well as the flux and composition of cosmic rays



# IceCube neutrino detector

**5,160 optical sensors detect Cherenkov light from charged particles produced when neutrinos interact in the ice**



# Vetoing background

- To avoid downward-going cosmic-ray muons produced in cosmic-ray air showers:
  - Select upward-going tracks, since Earth acts as a muon shield
  - Choose only interactions that originate within the detector
- To isolate atmospheric neutrinos, IceCube uses calculations of particle production in the atmosphere to model neutrino production. These look for:
  - A softening in the energy spectrum
  - A concentration around the horizon
  - Cosmic-ray muons, which are likely produced by the same cosmic-air showers that produce atmospheric neutrinos

# Finding astrophysical neutrinos

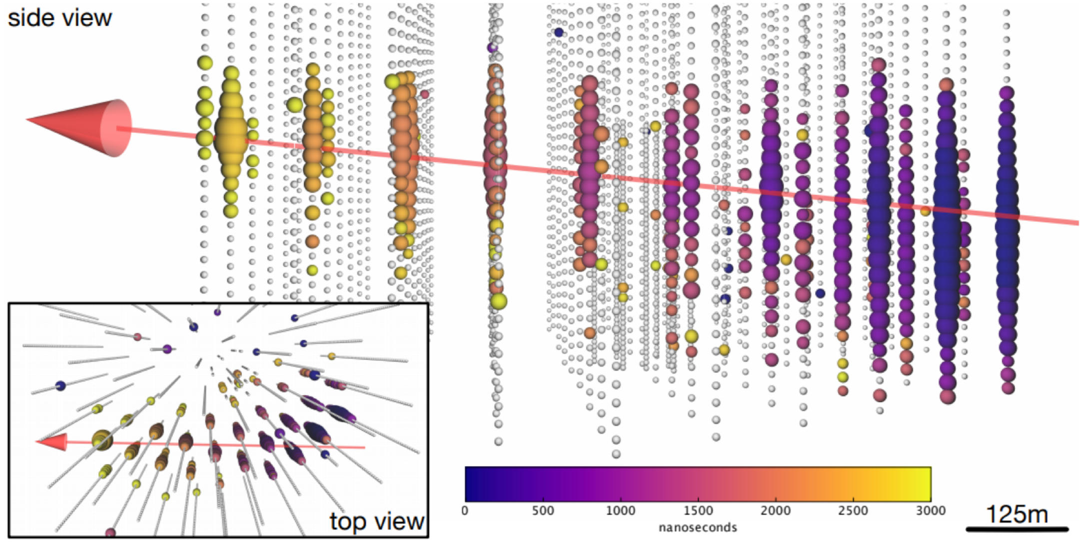
- Search for point sources that have a local concentration
- Isolate particularly energetic neutrinos
- Select downward-going neutrinos that are unaccompanied by cosmic-ray air shower and atmospheric muons
- Search for $\nu_\tau$, which are very rare in air showers but common in astrophysical flux

# Point source searches

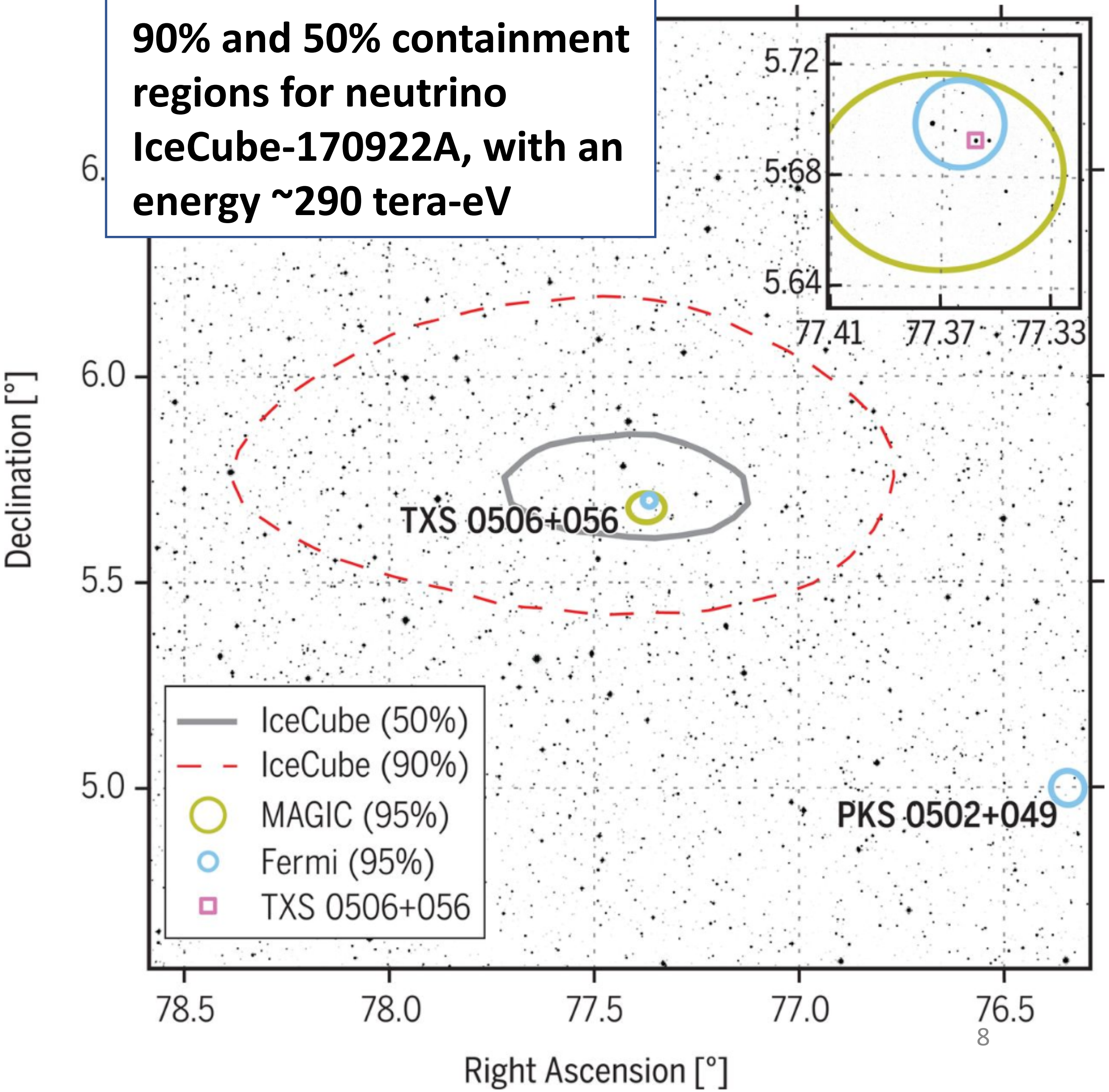
- On Sept. 22, 2017, IceCube observed a neutrino which was energetic enough to be of likely astrophysical origin
- The Fermi telescope showed that the position of IceCube's measurement was consistent with blazar TXS0506 +56, which was emitting gamma-rays with an energy above 1 GeV
- DATA from the MAGIC telescope showed that the source was also emitting photons with energies above 100 GeV
- Fulfills the mission of multimessenger astronomy, which aims for globally coordinated observations of cosmic rays, neutrinos, gravitational waves, and electromagnetic radiation

# Point source searches

**Neutrino event display. Time at which a DOM observed a signal is reflected in the color of the hit, with dark blues for earliest hits and yellow for latest**

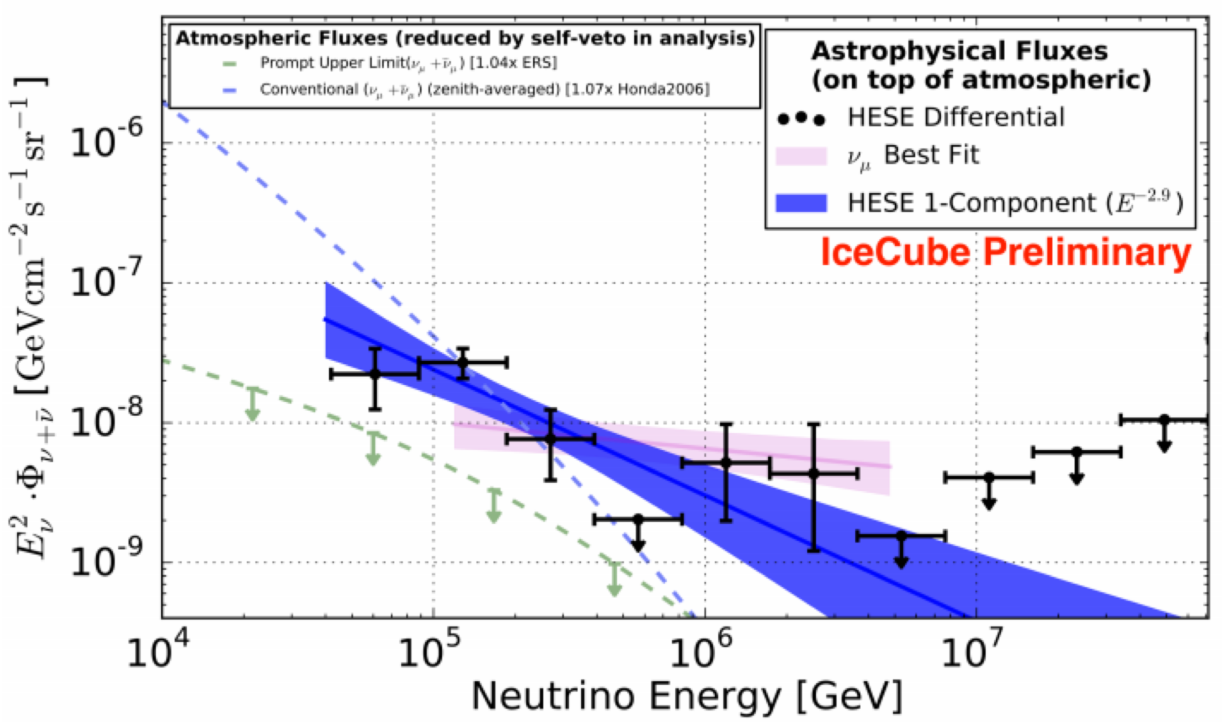



**90% and 50% containment regions for neutrino IceCube-170922A, with an energy ~290 tera-eV**



# Findings

- First find were two neutrinos, named Bert and Ernie
- “High-Energy Starting Event” (HESE) selected events that deposited more than 6,000 observed photons (photoelectrons) in the detector where the first significant deposition was in the signal region
- HESE’s three-year search crossed the 5σ discovery threshold
- Newer search which found 82 events in 2078 live days of data, with expected background from downward-going muons was 25±7 events, and atmospheric neutrinos ~16 events



# Other possibilities

- Gamma rays coincident with neutrinos
- Indirect dark matter searches
- Galactic supernovae

# Thank you!

# Refrences

M. G. Aartsen et al. [IceCube and Fermi-LAT and MAGIC and AGILE and ASAS-SN and HAWC and H.E.S.S. and INTEGRAL and Kanata and Kiso and Kapteyn and Liverpool Telescope and Subaru and Swift NuSTAR and VERITAS and VLA/17B-403 Collaborations], Science 361, no. 6398, eaat1378

M. G. Aartsen et al. [IceCube Collaboration], arXiv:1710.01191.

# Fun Slides

# Neutrinos as a the drivers of supernovae

- Massive stars end their lives in a gigantic explosions—this is supernovae!
- There is a running theory that neutrinos play into the physical processes that trigger and drive the explosion
- Leaking out from a hot interior of the neutron star, a small fraction of neutrinos are absorbed in surrounding gas
- The heating causes violent motions of the gas, which when sufficiently powerful, sets of a supernova
- Outer layers of the dying star are expelled into circumstellar space along with chemical elements the star has assembled during its life
- New radioactive species are created in the hot ejecta of the explosion
    - 44Ti (decays into calcium)
    - 56Ni (decays into iron)

# Neutrinos as a the drivers of supernovae

- The violent boiling of the neutrino-heated gas causes non-spherical blast waves
- This sets off a large-scale asymmetry on the ejected stellar matter and the supernova with two immediate consequences:
  - Neutron star receive a recoil momentum opposite the direction of the strong explosion
  - Production of heavy elements is more efficient in directions where the explosion is stronger and matter more heated
- Both these effects were predicted years ago by 3D simulations of neutrino-driven supernova explosions at the RIKEN Astrophysical Big Bang Laboratory

# Neutrinos as a the drivers of supernovaes

- New observations of Cassiopeia A (Cas A), aligned with theoretical prediction
- Cas A is:
  - the remnant of a supernova whose light reached the Earth around the year 1680, could confirm this theoretical prediction
  - 11,000 light years away
- Both from observation and simulation, the biggest and brightest clumps with most of 44Ti are found in the upper half of the gas remnant