CHIBA UNIVERSITY

IceCube
South Pole Neutrino Observatory

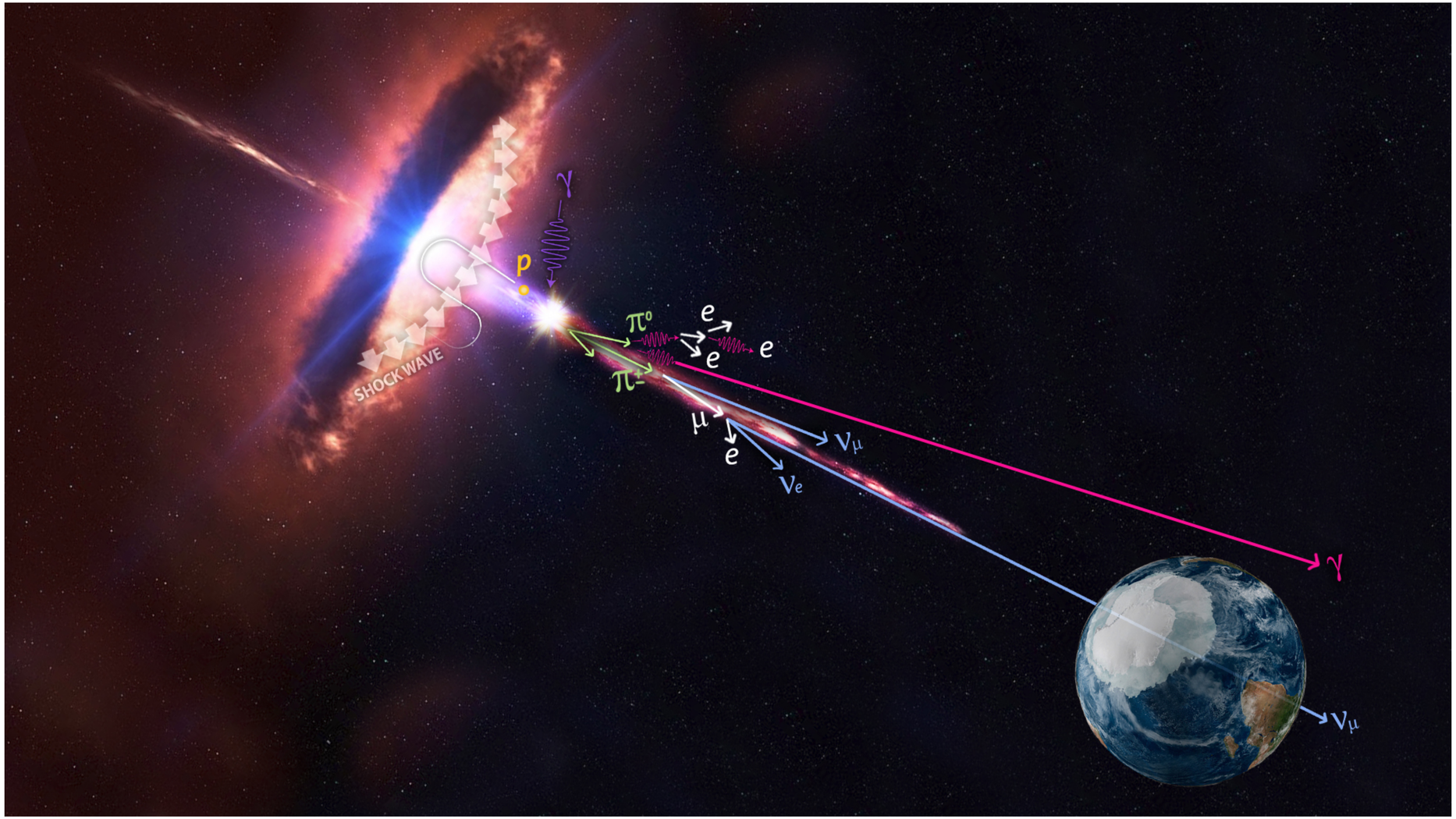
ICEHAP

Neutrino astronomy in the Multimessenger Era with IceCube

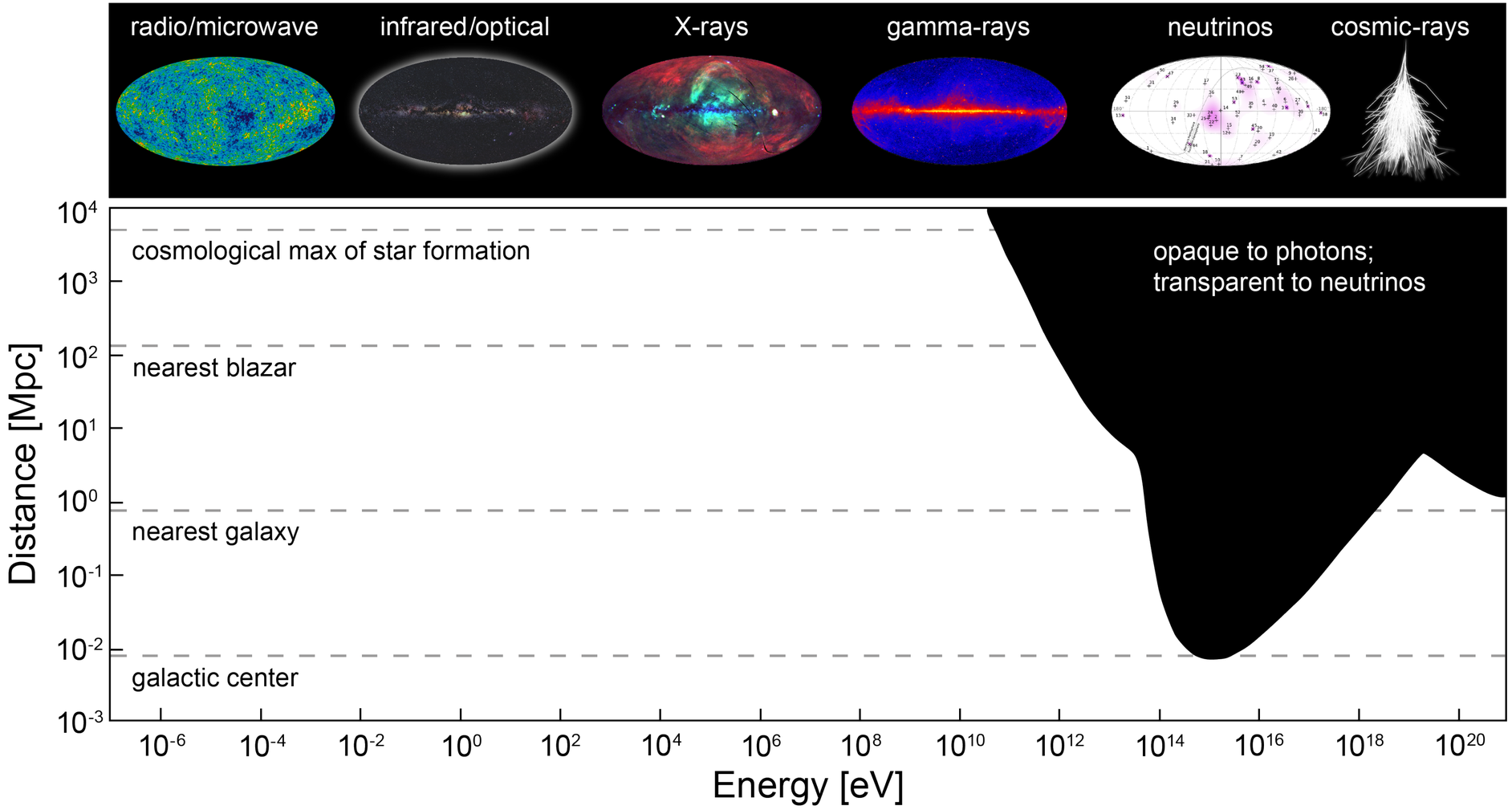
Max Meier

2020.12.03

Cosmic messengers



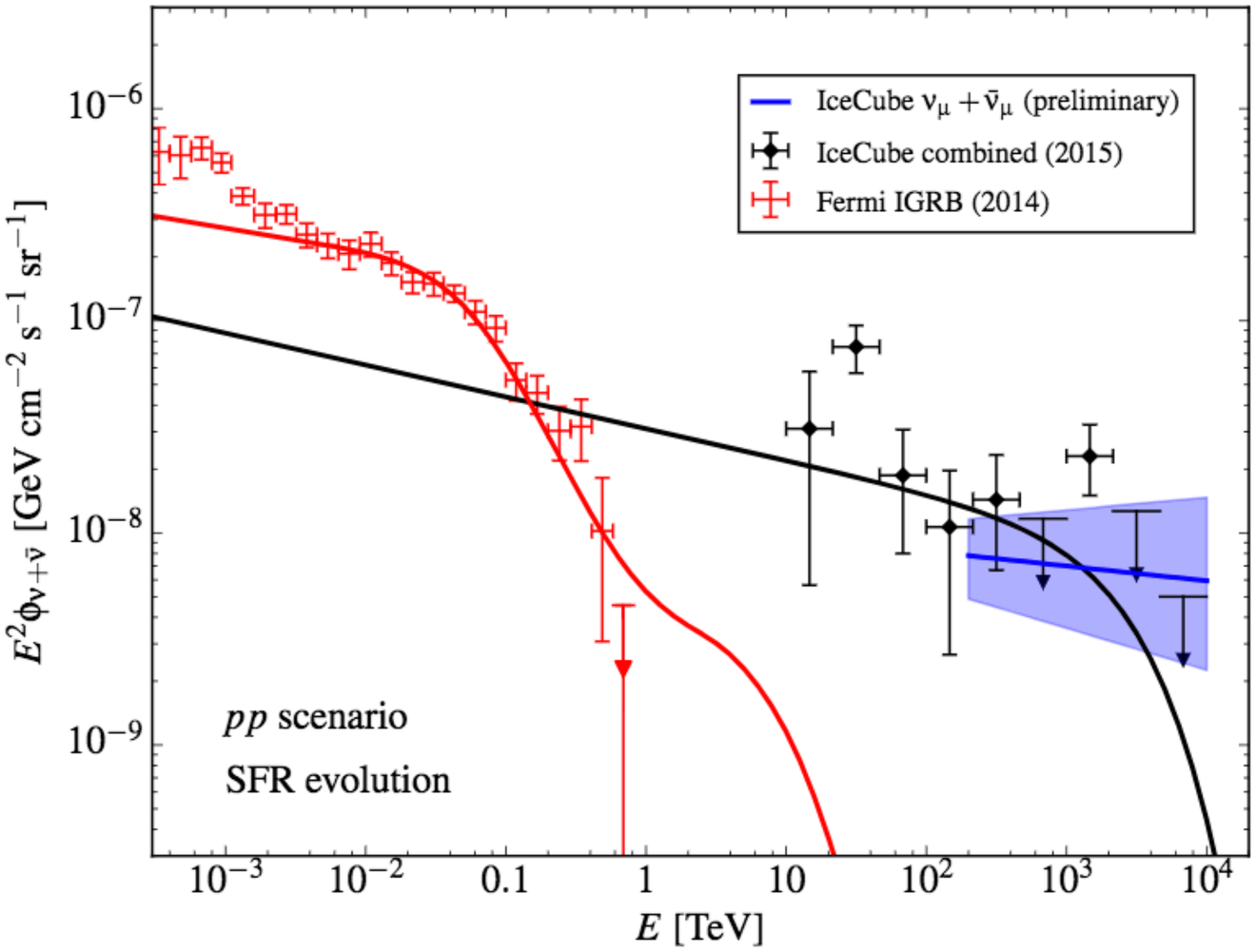
Cosmic messengers



Gamma ray / Neutrino energy spectra

- Estimation of the isotropic gamma ray background based on emission from a pp interaction scenario
- Similar energy density of neutrinos and gamma rays from non-thermal processes in the universe
- When using a more minimal assumption for the IceCube flux the contribution to the IGRB between 100 GeV and 1 TeV is still ~10%

Ahlers et al, 2015



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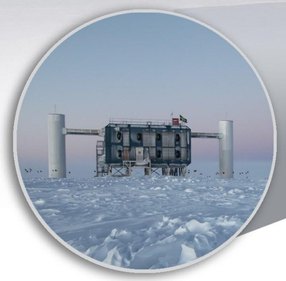
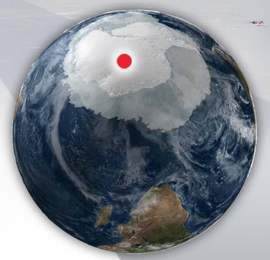
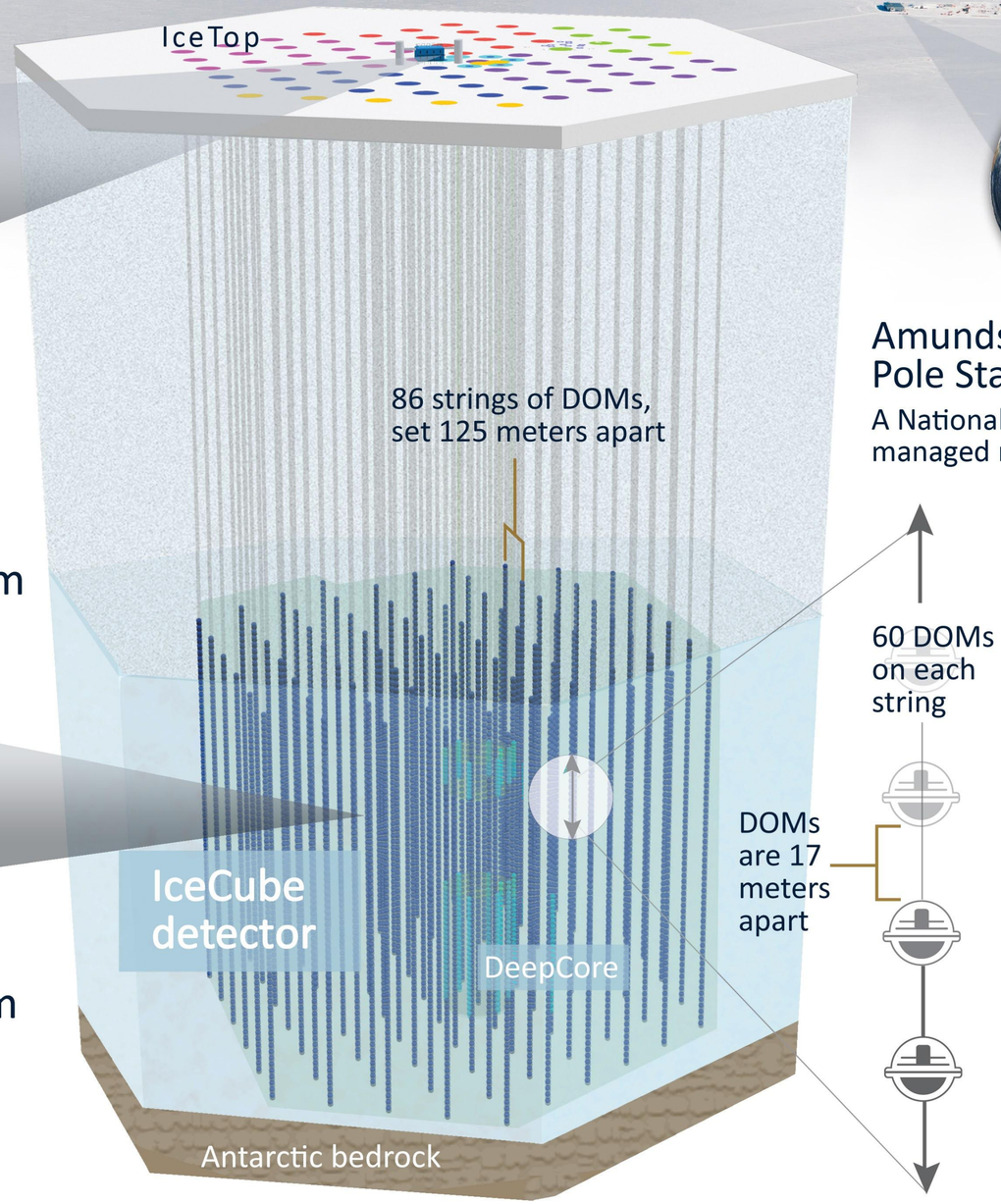


IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison

Digital Optical Module (DOM)
5,160 DOMs deployed in the ice



Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility

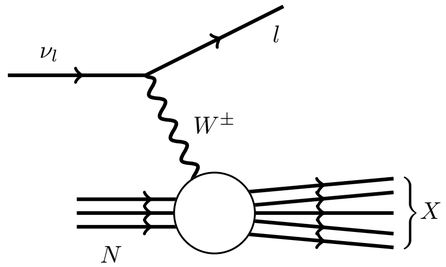


Detector Design

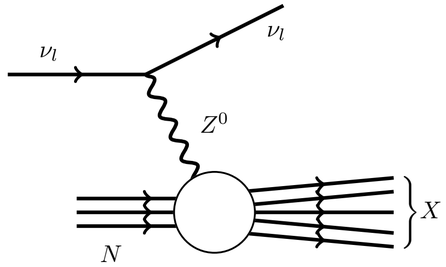
- 1 gigaton of instrumented ice
- 5,160 light sensors, or digital optical modules (DOMs), digitize and time-stamp signals
- 1 square kilometer surface array, IceTop, with 324 DOMs
- 2 nanosecond time resolution
- IceCube Lab (ICL) houses data processing and storage and sends 100 GB of data north by satellite daily

Events in IceCube

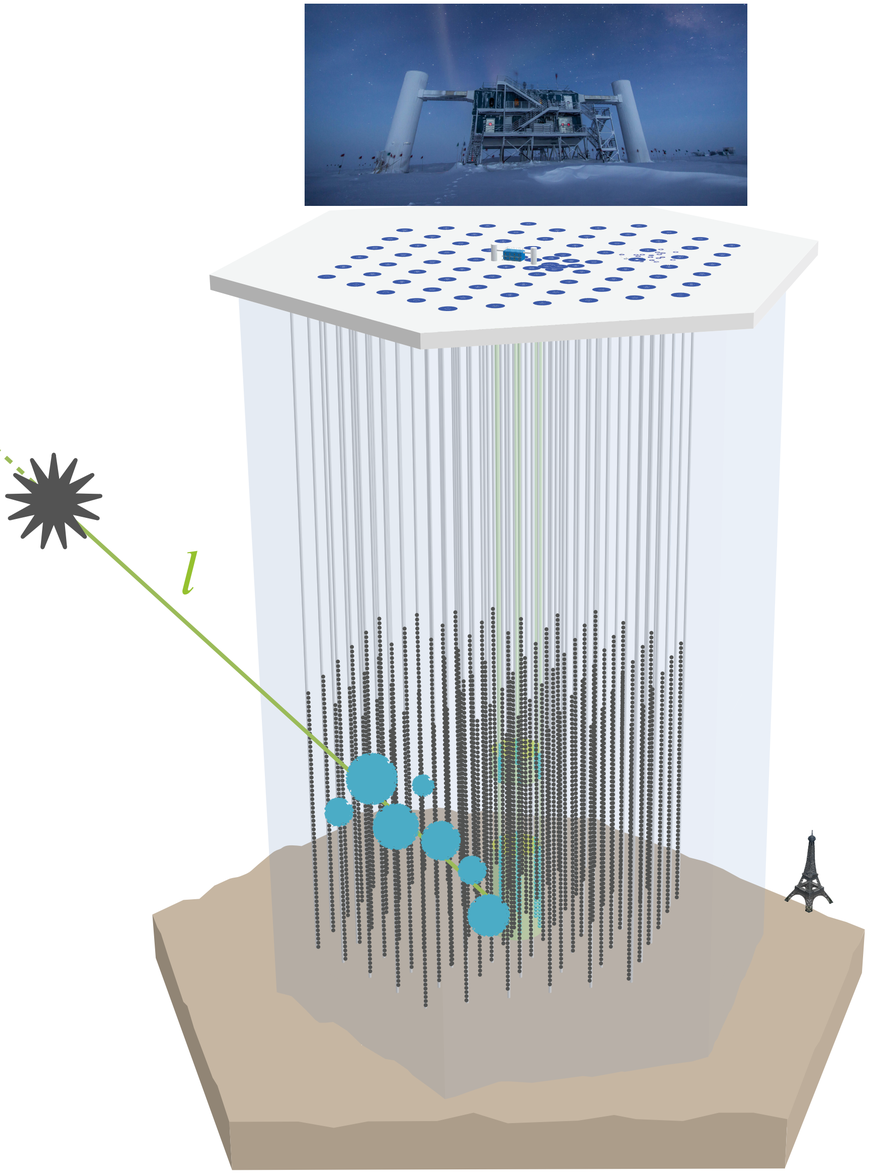
- Neutrinos interact via deep inelastic scattering
- Charged current (CC)



- Neutral current (NC)



- Charged leptons and hadrons produce Cherenkov radiation

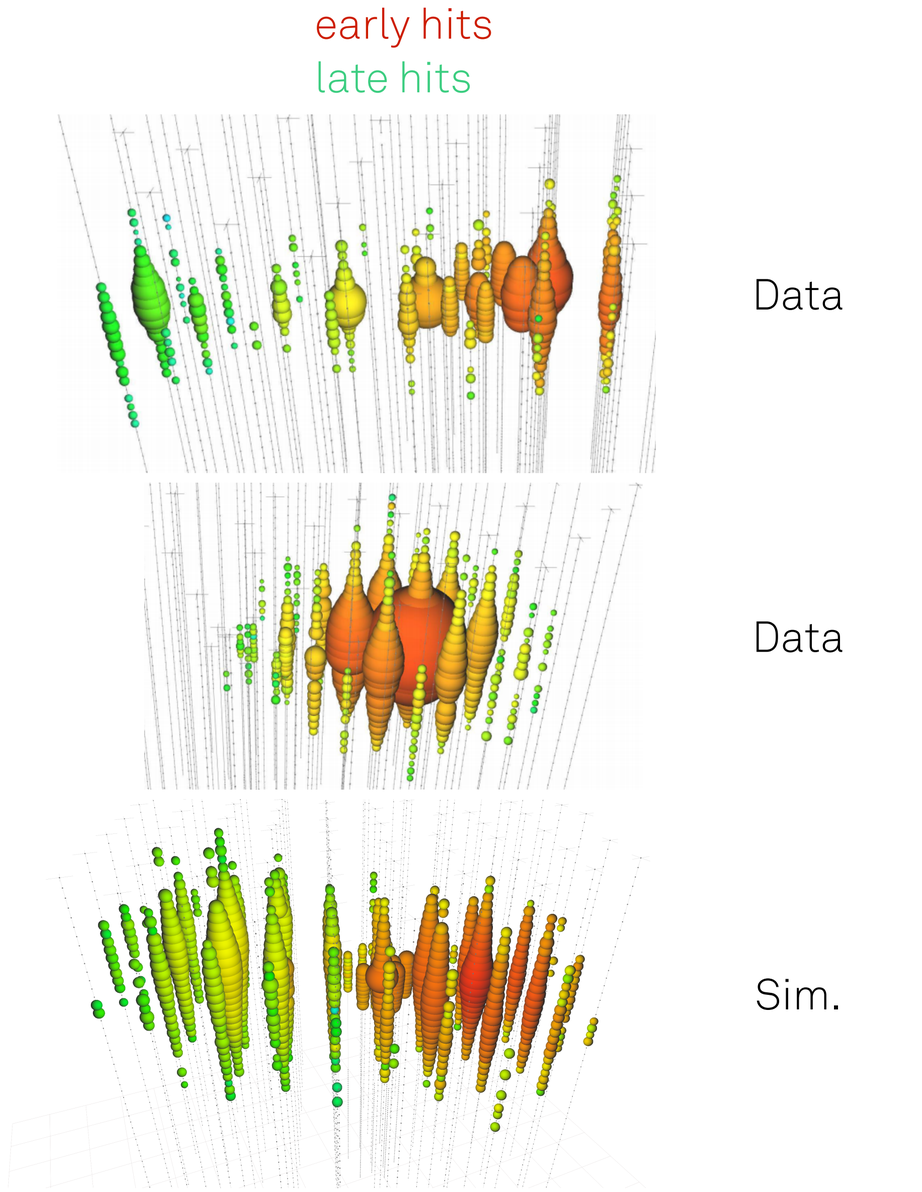


Event topologies

- Tracks:
  - Energy resolution: ~factor of 2
  - Angular resolution: 0.2° - 1°

- Cascades:
  - Energy resolution: ~15% (if contained)
  - Angular resolution: 10° - 15°

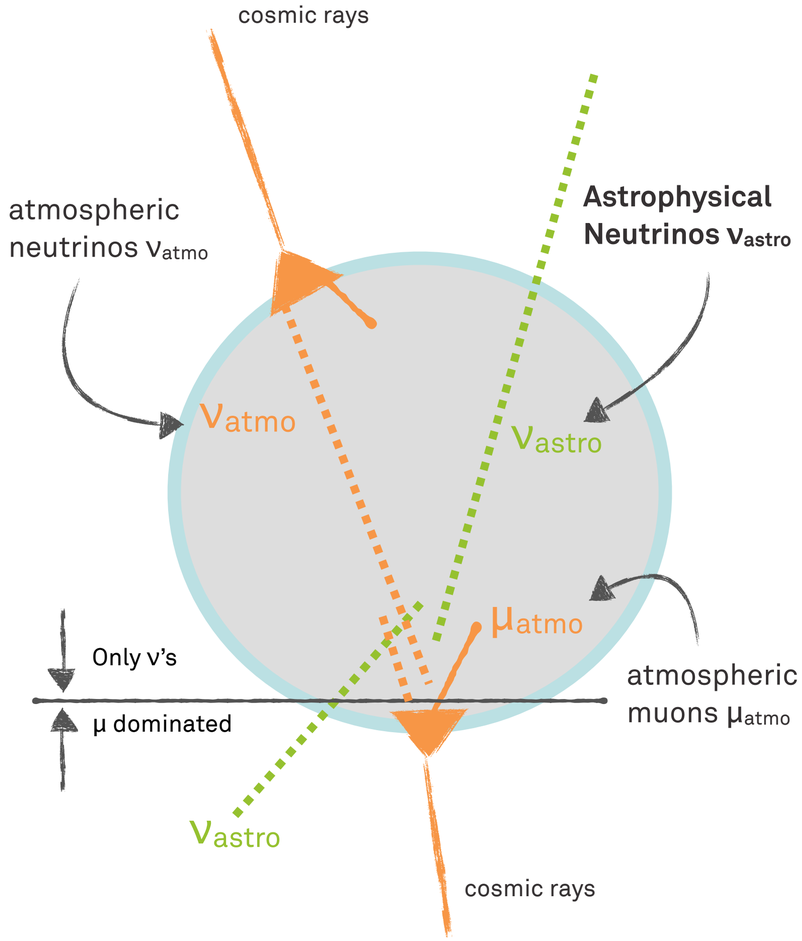
- Double Bang/Double Cascade:
  - Resolution in-between values for tracks and cascades depending on tau length
  - Inherently higher probability to be of astrophysical origin



Signal and Backgrounds

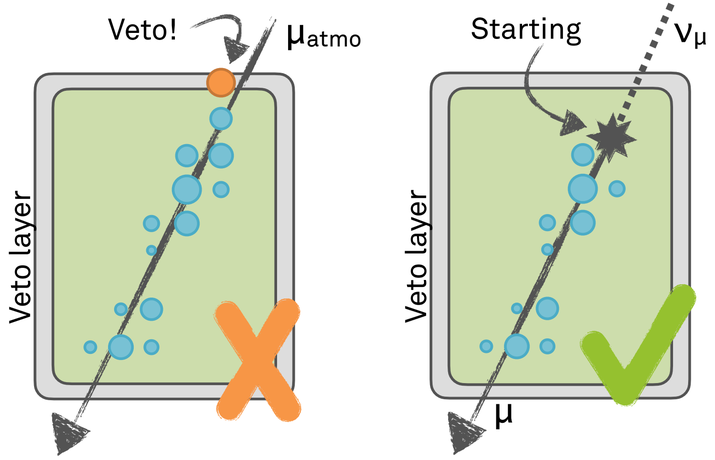
- Background from Earth's atmosphere:
  - Downgoing muons from cosmic ray air showers (~3000 / s)
  - Atmospheric neutrinos, also produced in CR air showers (~10 / hour)
    - Conventional atmos. neutrinos ($E^{-3.7}$) from π/K
    - Prompt atmos. neutrinos ($E^{-2.7}$) from charmed mesons

- Signal:
  - Astrophysical neutrinos produced in astrophysical objects (~ 10-100 / year)
  - Harder energy spectrum + different angular distribution



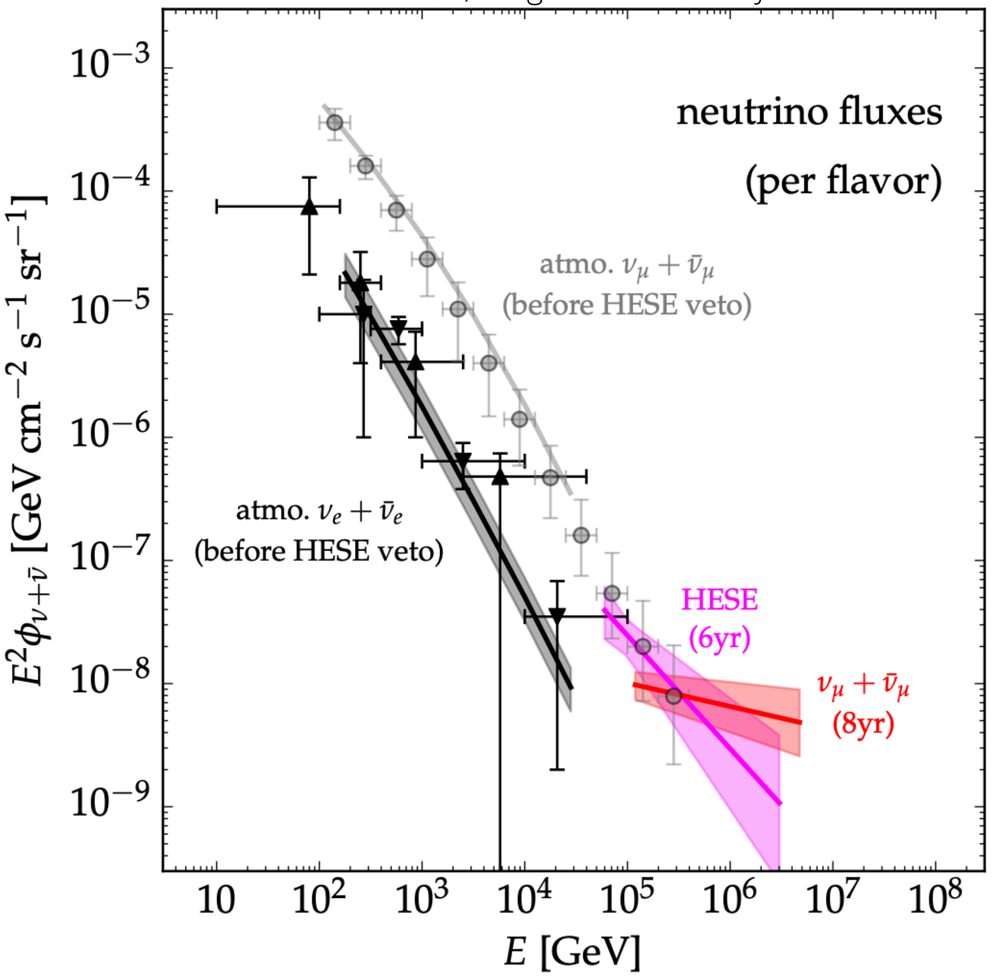
Astrophysical neutrinos

- Astrophysical neutrinos can be identified via very different event selection strategies
  - Up-going, through-going tracks using the Earth as a shield from atmospheric muons (red)
  - Selecting starting tracks and cascades to reject atmospheric muons (pink)

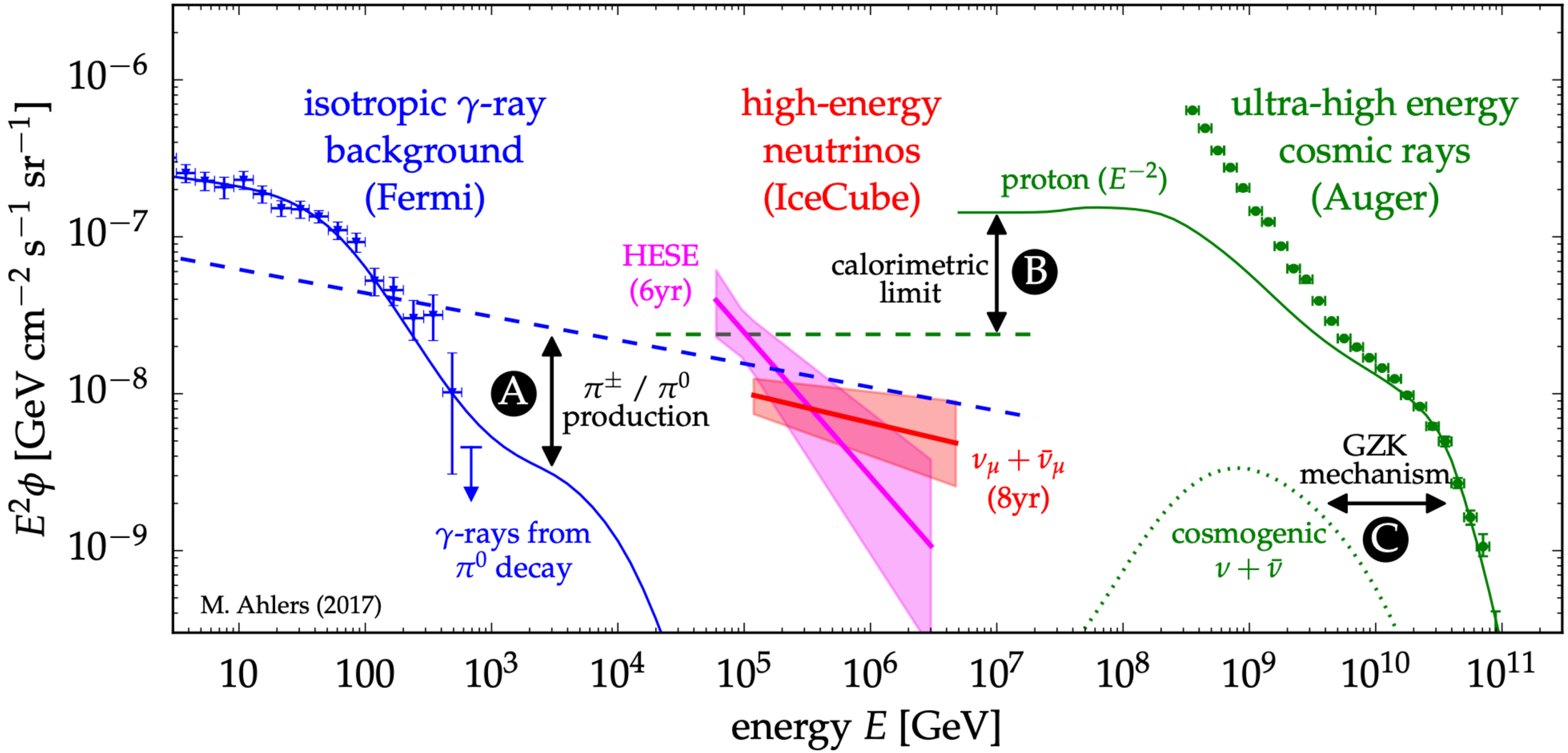


- Clear observation of a diffuse neutrino flux

Ahlers et al., Prog. Part. Nucl. Phys. 2018



Ahlers et al., Prog. Part. Nucl. Phys. 2018



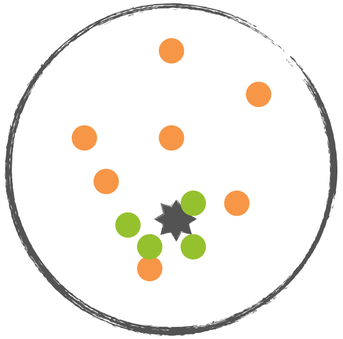
Point source analyses in IceCube

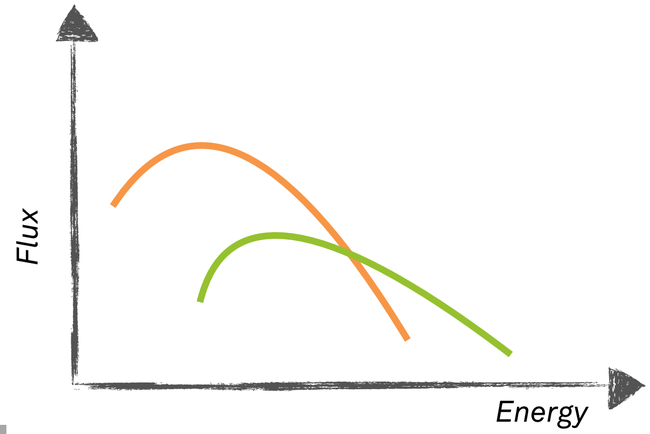
- Study the clustering of neutrinos over the atmospheric expectation

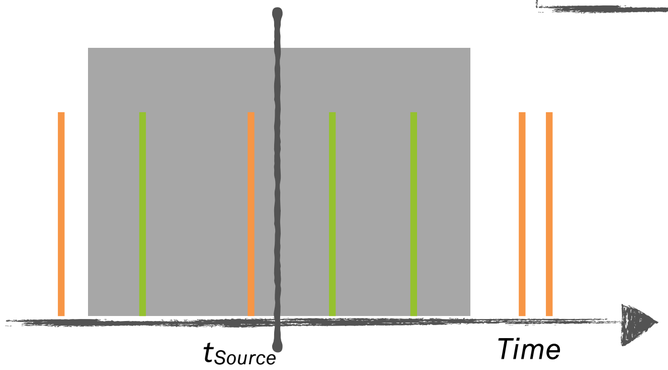
- Spatial clustering
  - Bivariate Gaussian

- Energy spectra
  - Signal has a hard spectrum

- Clustering in time
  - Box or gaussian profiles used frequently





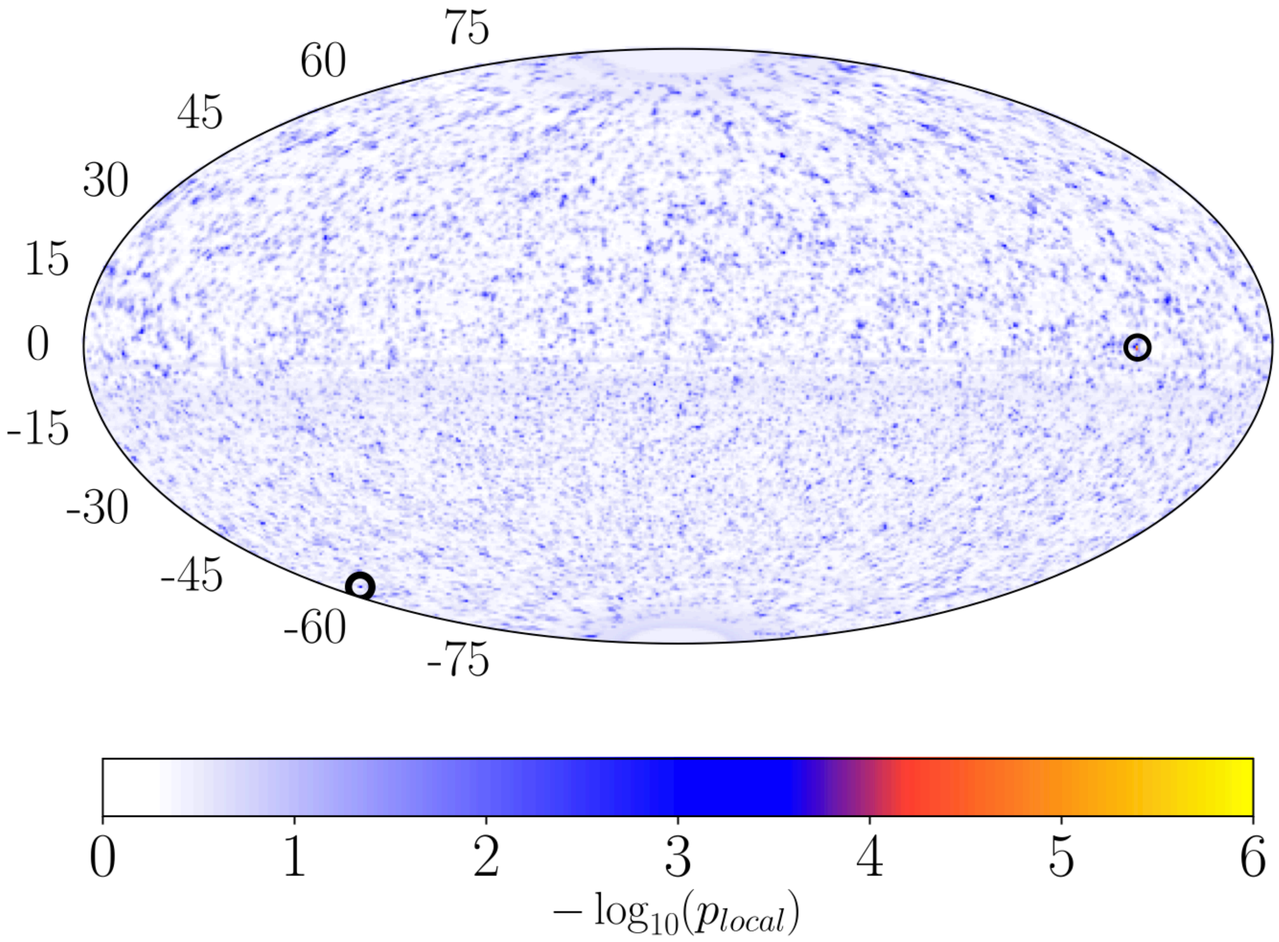


Neutrino Skymap

- Analysis of muon tracks from the northern and southern hemisphere in 10 years of IceCube data

- Most significant points on both hemispheres are marked with a circle

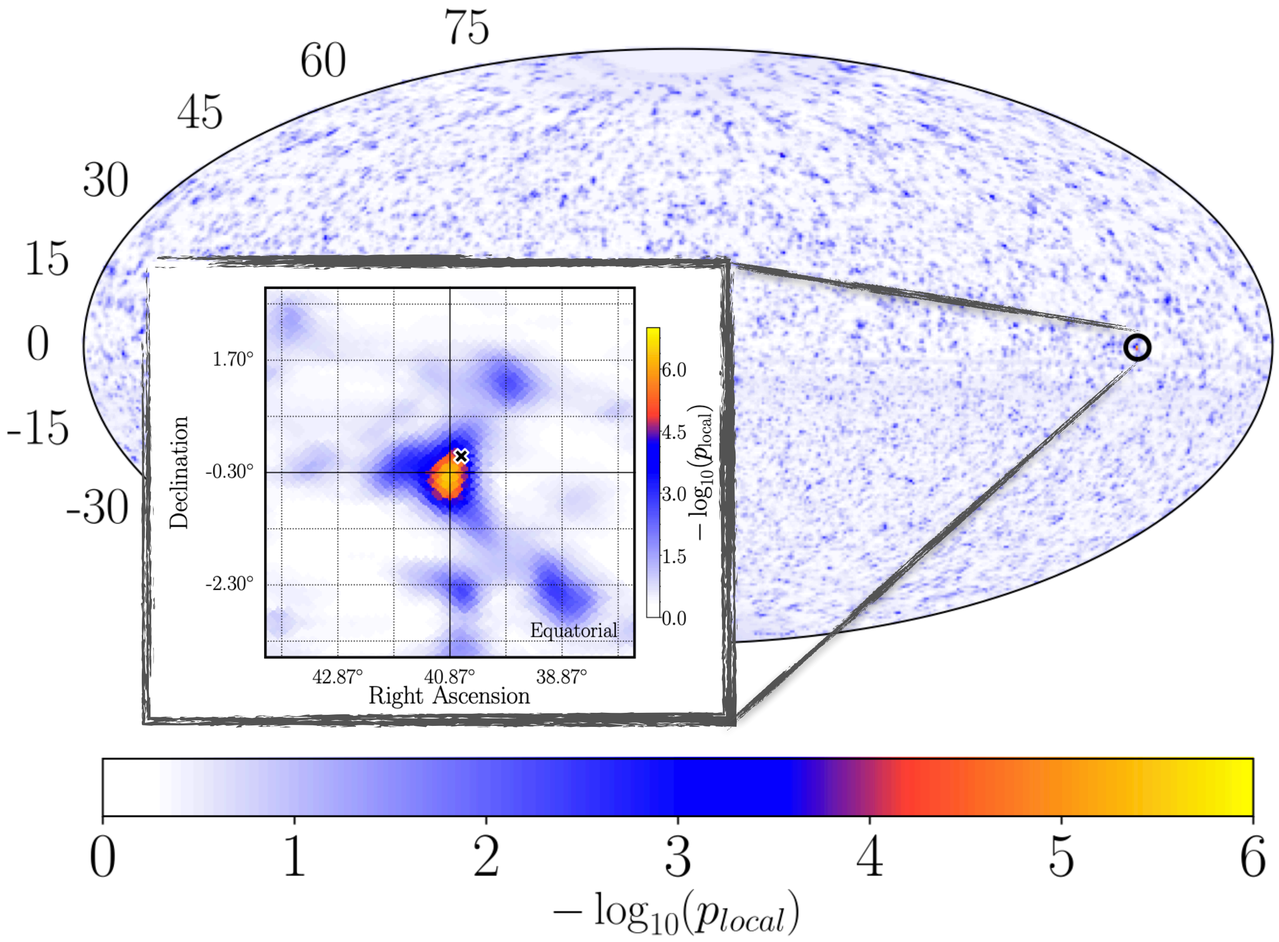
Aartsen et al., PRL124, 051103



Neutrino Skymap

- Analysis of muon tracks from the northern and southern hemisphere in 10 years of IceCube data
- Most significant points on both hemispheres are marked with a circle
- Most significant point in northern hemisphere is 0.35° away from NGC 1068
- Post trial p-value: 0.75

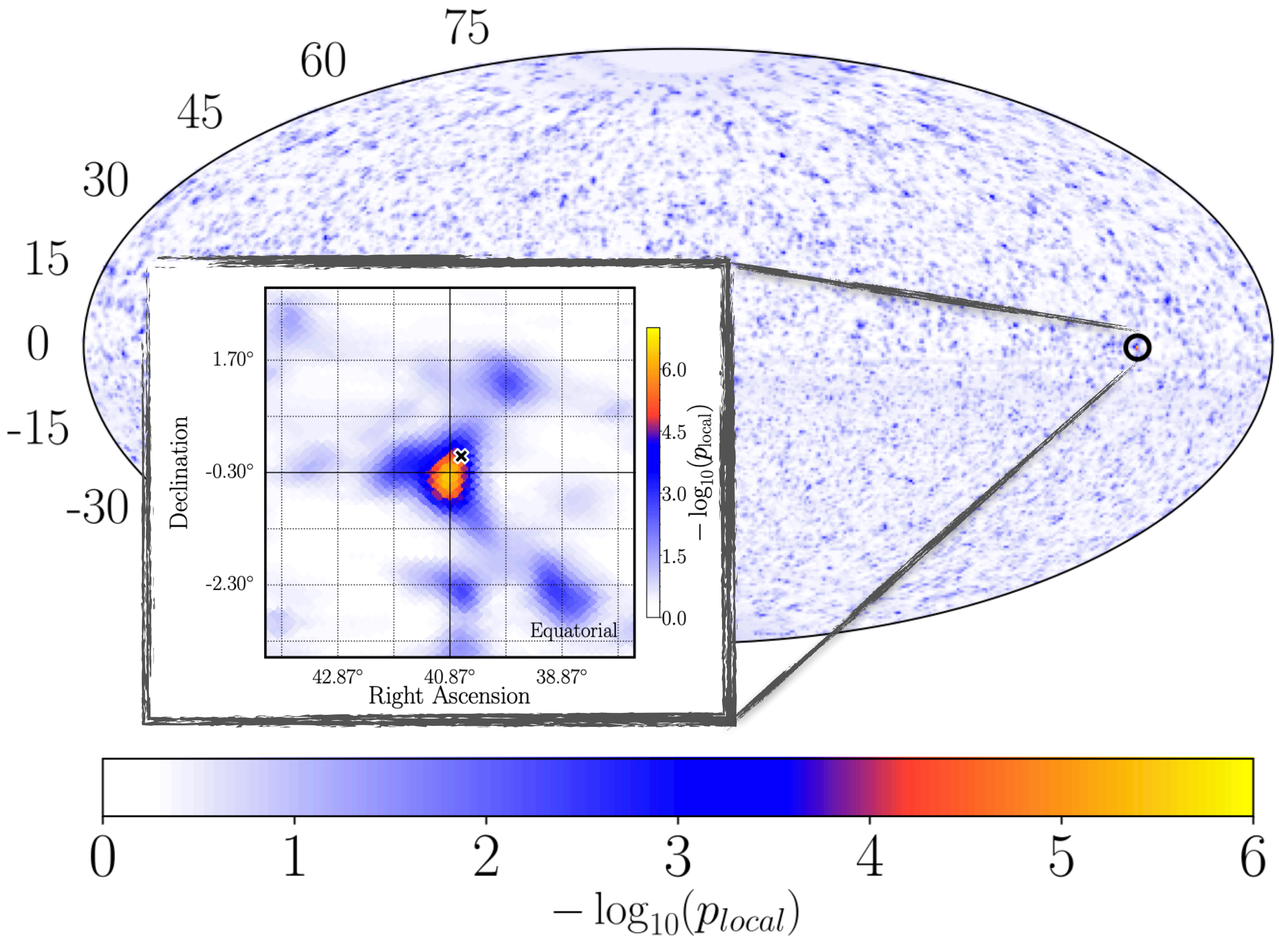
Aartsen et al., PRL124, 051103



Neutrino Skymap — Source catalog searches

- Goal: Improve sensitivity to possible neutrino source already observed in γ-rays
- Small collection of sources from 4FGL, TeVCat, and gammaCat chosen (110 γ-ray sources selected)
- Highest significance obtained for NGC1068 (post-trial): 2.9σ
  Seyfert-II-galaxy
- Notable high p-values from BL Lac objects: TXS0506+056, PKS1424+240, GB6J1542+6129

Aartsen et al., PRL124, 051103



IceCube Realtime Alerts v2

- Two types of alerts: Gold (50% signal purity) and Bronze (30% signal purity)

- Combination of multiple event selections:
  - GFU (Gamma-ray Follow Up) (~24 / year)
  - EHE (~5 / year)
  - HESE (~2 / year)
  - HESE Cascades (new addition) (~8 / year)

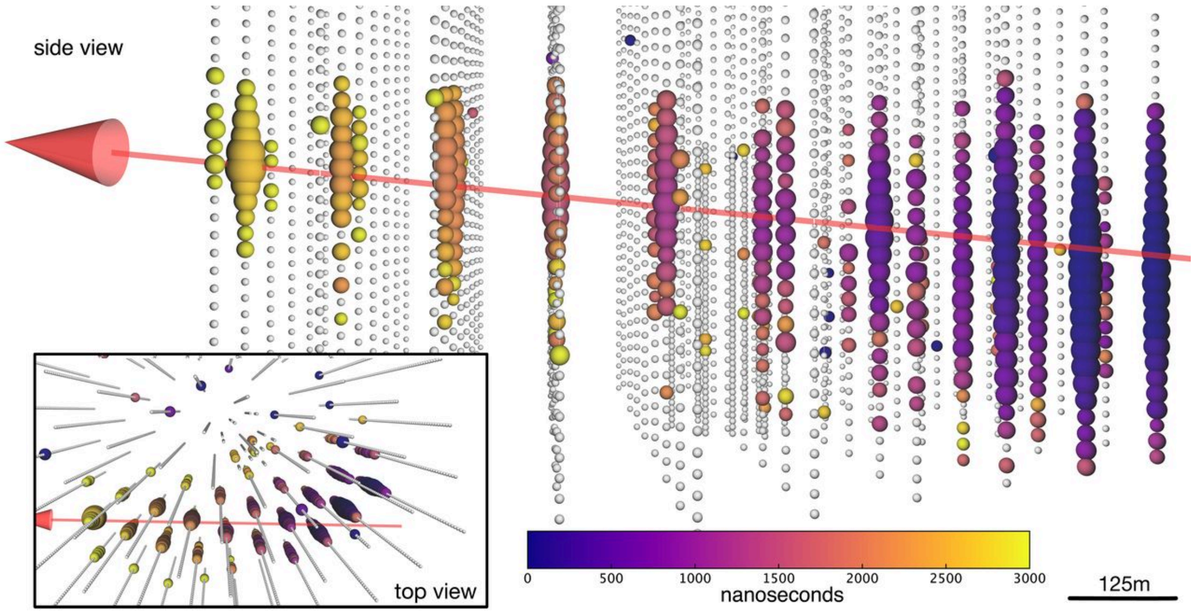
- Distributed as GCN/AMON notices

- Time delay between event and alert < 3min

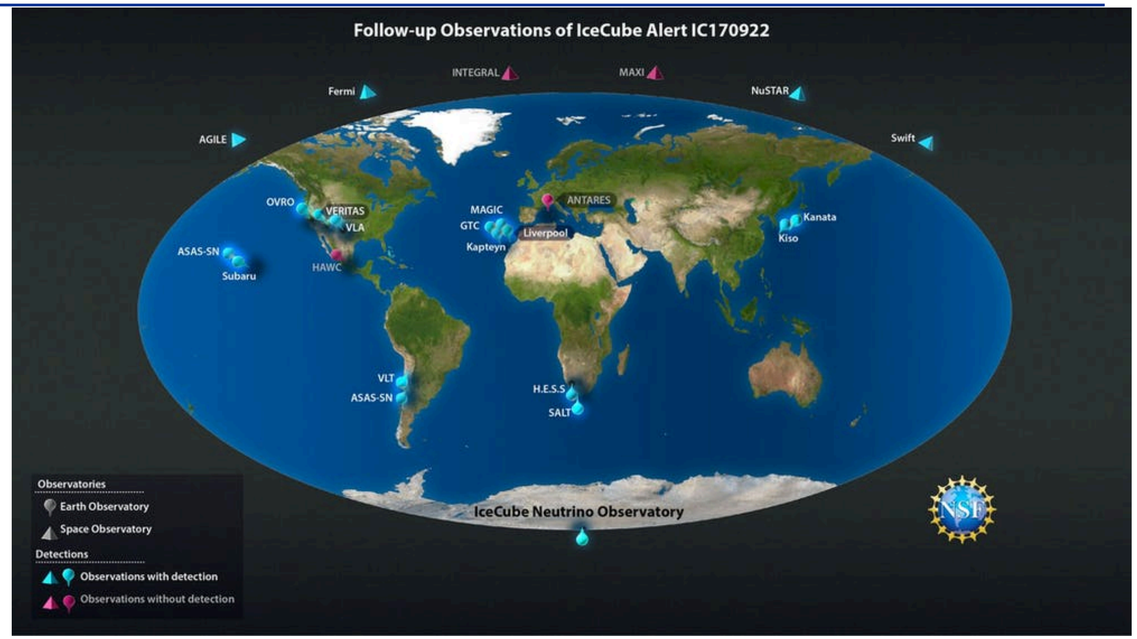
Example alert from 2 weeks ago

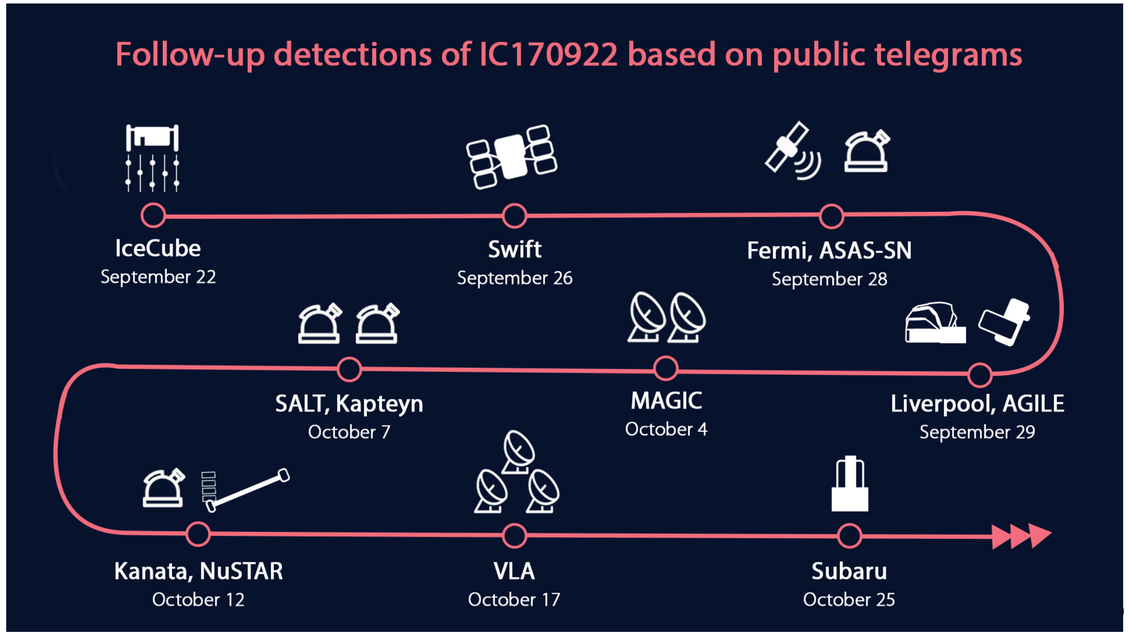
```
TITLE:           GCN/AMON NOTICE
NOTICE_DATE:     Fri 20 Nov 20 14:12:28 UT
NOTICE_TYPE:     ICECUBE Astrotrack Bronze
STREAM:          25
RUN_NUM:         134715
EVENT_NUM:       65785778
SRC_RA:          307.5299d {+20h 30m 07s} (J2000),
                 307.7180d {+20h 30m 52s} (current),
                 307.0798d {+20h 28m 19s} (1950)
SRC_DEC:         +40.7700d {+40d 46' 12"} (J2000),
                 +40.8410d {+40d 50' 28"} (current),
                 +40.6013d {+40d 36' 05"} (1950)
SRC_ERROR:       280.79 [arcmin radius, stat-only, 90% containment]
SRC_ERROR50:     158.40 [arcmin radius, stat-only, 50% containment]
DISCOVERY_DATE:   19173 TJD;   325 DOY;   20/11/20 (yy/mm/dd)
DISCOVERY_TIME:   35080 SOD {09:44:40.55} UT
REVISION:        1
ENERGY:          1.5396e+02 [TeV]
SIGNALNESS:      5.0338e-01 [dn]
FAR:             0.2947 [yr^-1]
SUN_POSTN:       236.49d {+15h 45m 58s}  -19.87d {-19d 52' 19"}
SUN_DIST:        89.62 [deg]   Sun_angle= -4.7 [hr] (East of Sun)
MOON_POSTN:      313.45d {+20h 53m 47s}  -21.60d {-21d 36' 09"}
MOON_DIST:       62.67 [deg]
GAL_COORDS:       79.44,  0.94 [deg] galactic lon,lat of the event
ECL_COORDS:      327.73, 56.93 [deg] ecliptic lon,lat of the event
COMMENTS:        IceCube Bronze event.
COMMENTS:        The position error is statistical only, there is no systematic added.
```

IC170922A — TXS0506+056



- Deposited energy: 23.7 ± 2.8 TeV
- Estimated neutrino energy: 290 TeV (> 183 TeV @ 90% CL)
- Signalness: 56.5%
- Reconstructed direction: RA $77.36^{\circ}{}^{+0.95^{\circ}}_{-0.65^{\circ}}$
  DEC $+5.72^{\circ}{}^{+0.50^{\circ}}_{-0.30^{\circ}}$

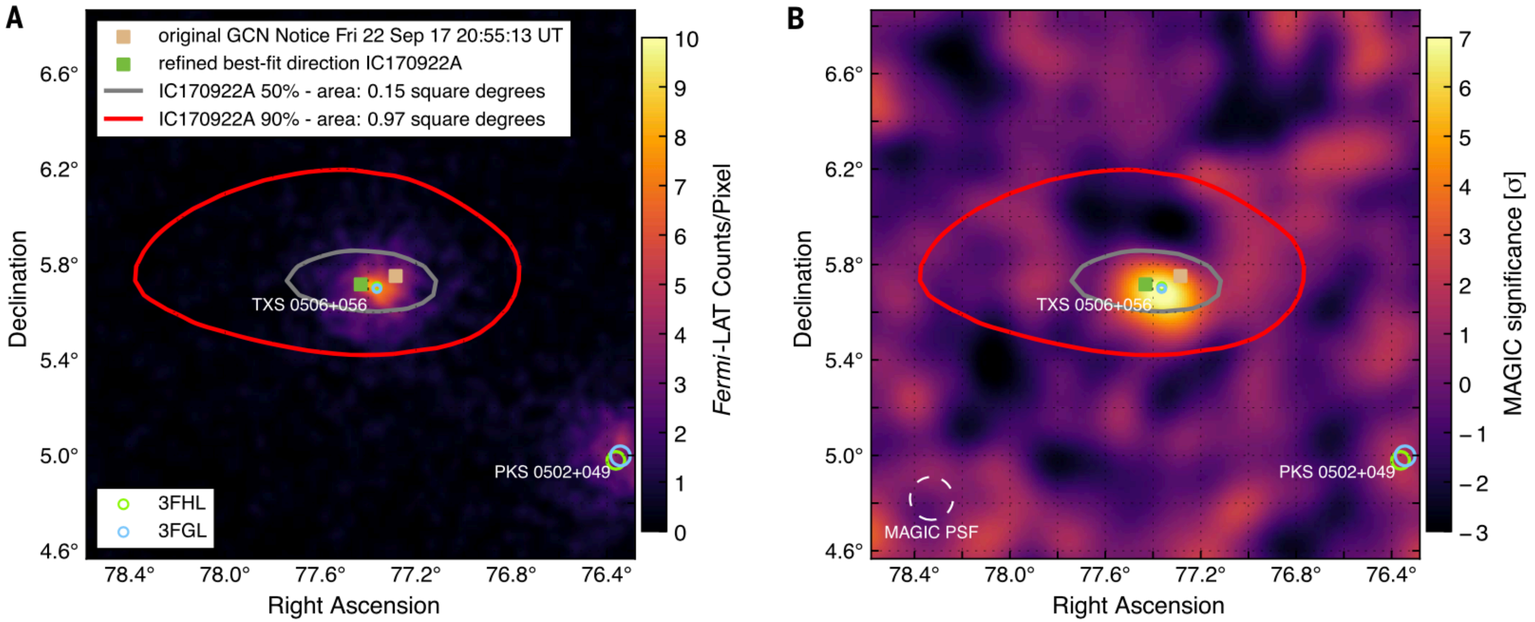




IC170922A — TXS0506+056

- Reported location consistent with known γ-ray source TXS0506+056 in a state of enhanced emission
- Observed by Fermi LAT from 20 MeV to 300 GeV
- One week later also detected by MAGIC telescopes with observed photon energies between 80 GeV and 400 GeV

- Chance coincidence (spatial and temporal) disfavored at the 3σ level

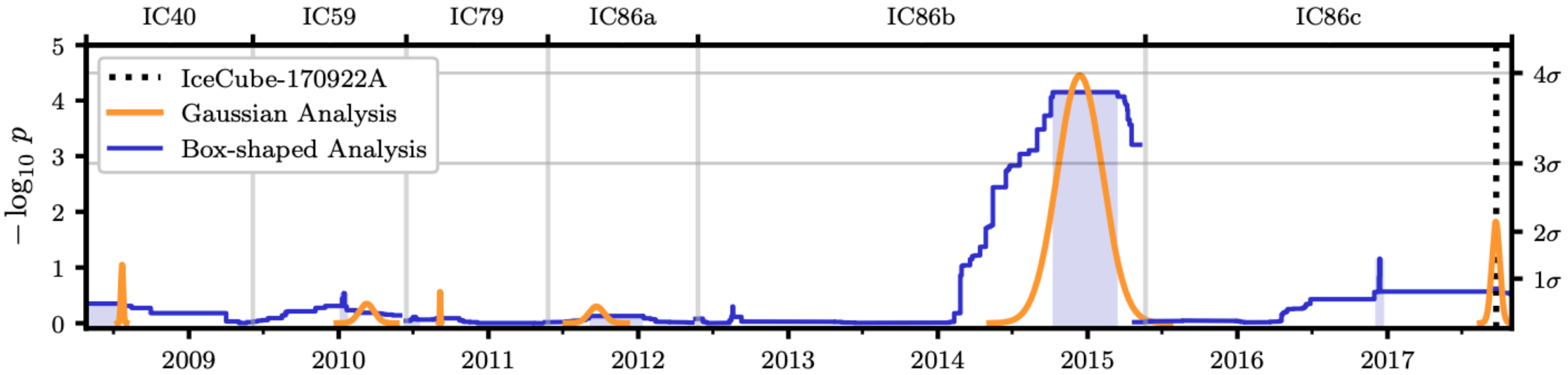


The IceCube collaboration et al., Science 2018

Archival analysis of neutrino emission from TXS0506+056

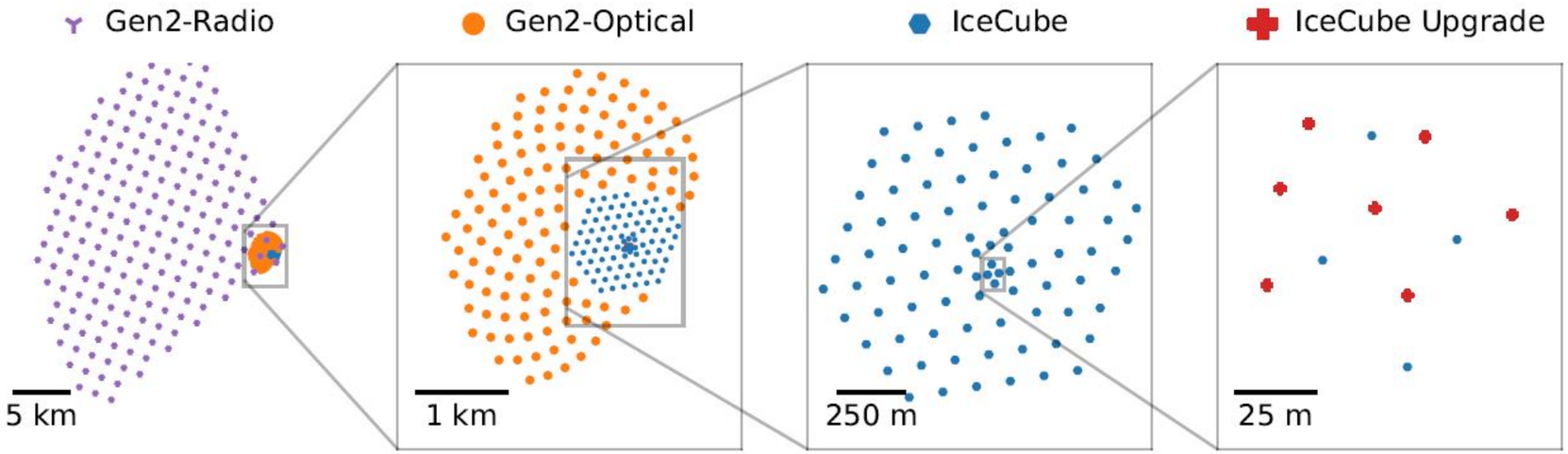
- Analysis of 9.5 years of archival data with two generic time window shapes
- Comparable results from Gaussian and box time profile
- Post-trial significance of 3.5σ

	Gaussian	Box
n_S	13	14
γ	2.1	2.2
Duration	110 d	158 d
Time window	T_0 @ 2014/12/13	2014/12/26 - 2015/03/05
P-value	$3 * 10^{-5}$ (3.7σ)	$7 * 10^{-5}$ (3.5σ)



Aartsen et al., Science 2018

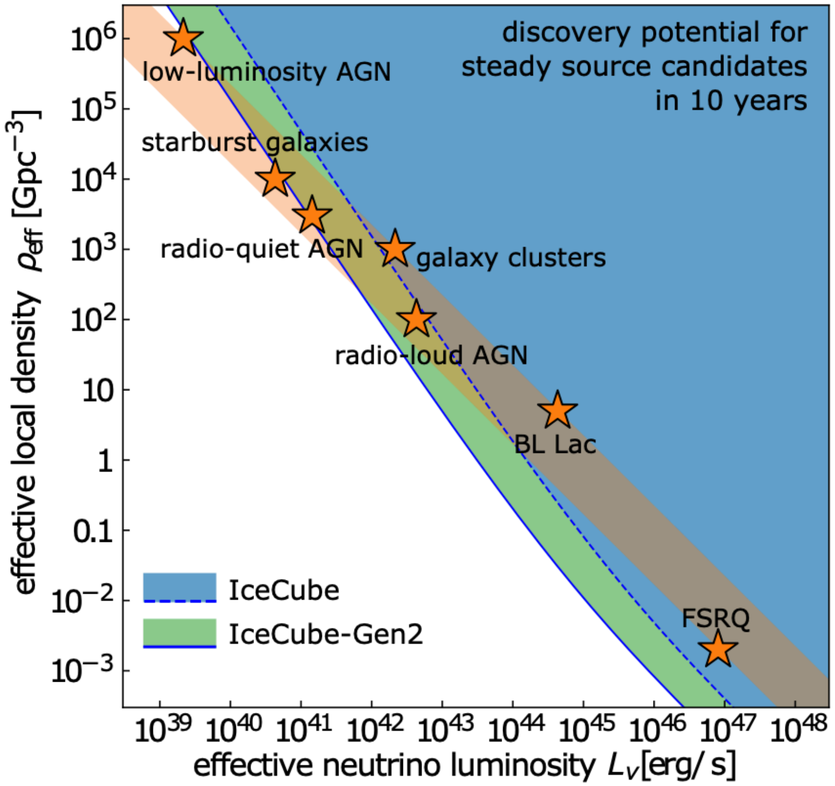
IceCube Gen2 Facilities

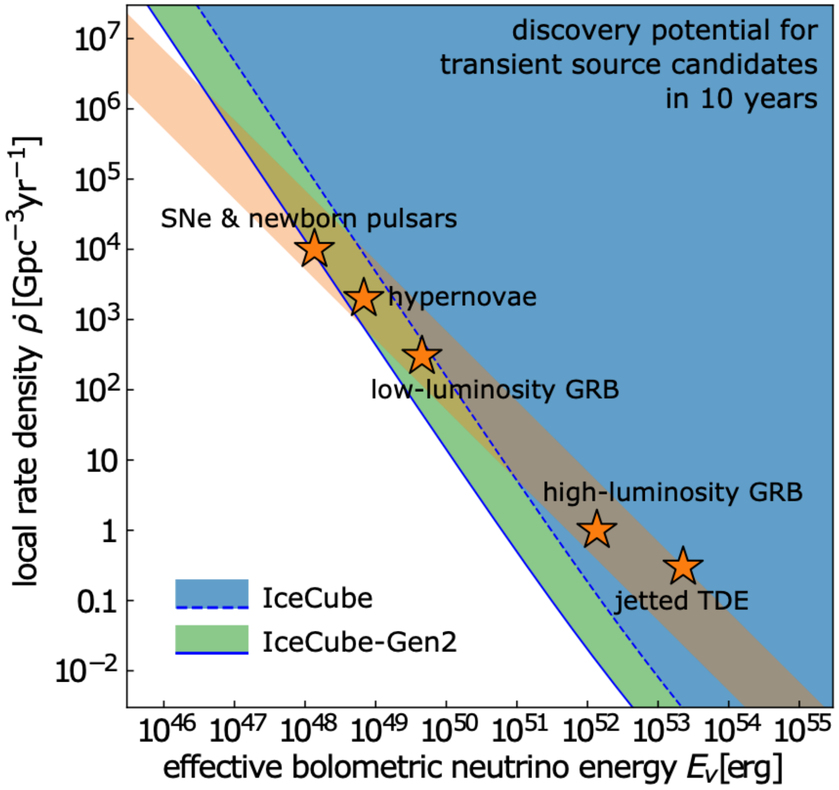


- IceCube Gen2 (design phase):
  - Optical array ~8 times larger than Gen1
  - Increase statistics around the PeV region
  - Reveal neutrino sources
  - Extend IceCubes multi messenger campaign to even higher energies
- IceCube Upgrade:
  - Sensors are already partly in production
  - Testbed for new sensor types (D-Egg, mDOM)
  - Improved detector calibration/ice model characterization

IceCube Gen2 — 10 year discovery potential

- Orange band is the region compatible with the total diffuse astrophysical neutrino flux
- Shaded regions highlight where IC / IC-Gen2 are able to discover one or more sources of the population (in the northern hemisphere, optical only)



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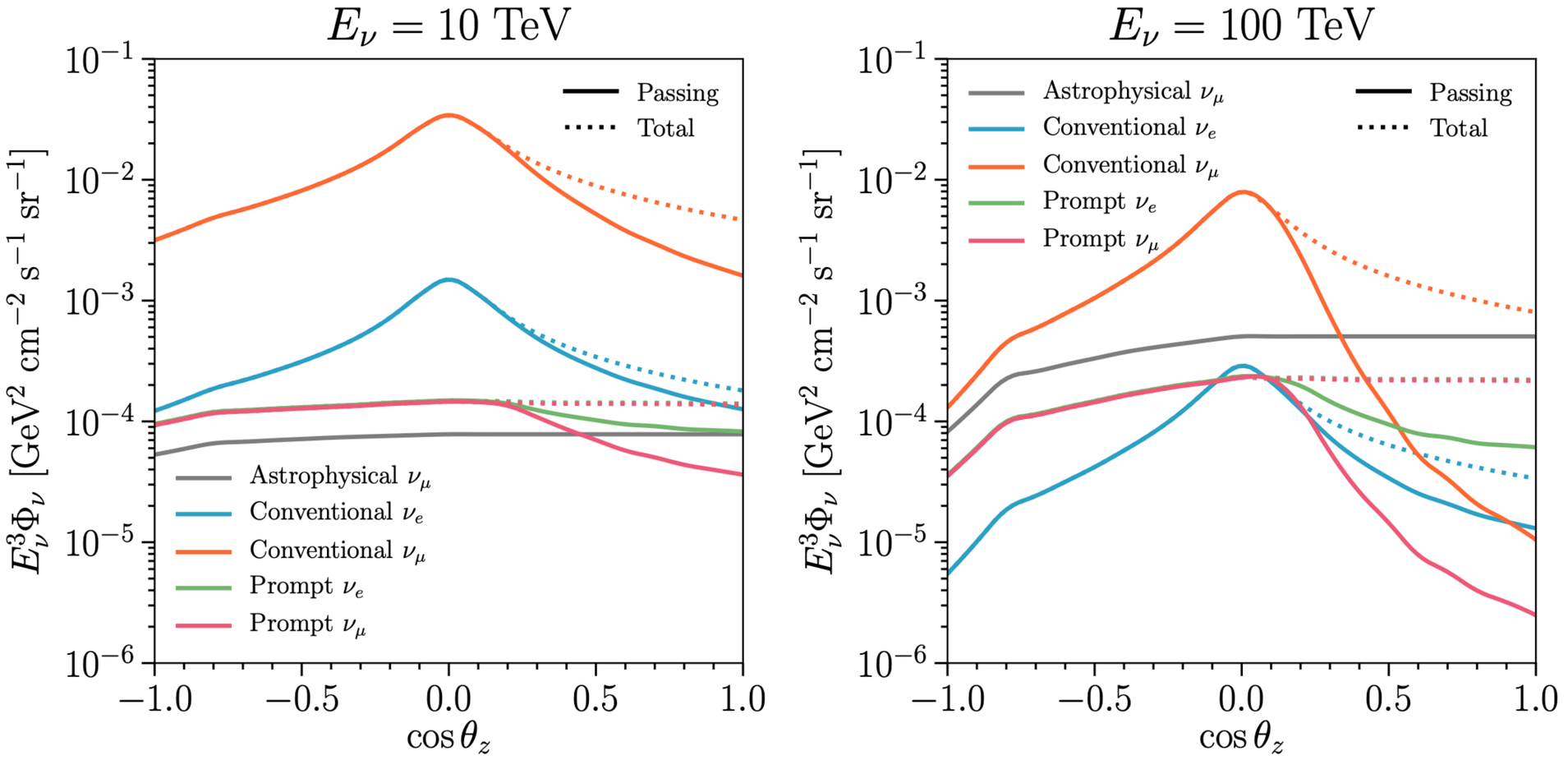
IceCube South Pole Neutrino Observatory
icecube.wisc.edu

Summary

- Neutrino astronomy is a young field and many things are still to be discovered
- Measurements of neutrino flavor composition and particle/anti-particle ratio are a unique possibility to study source environments
- Real time alerts are contributing to Multi-Messenger efforts
- The first promising neutrino source candidates have been identified
- IceCube Gen2 can advance neutrino astronomy to understand the sources of neutrinos, gamma rays and cosmic rays faster

Angular distributions and atmospheric self veto effect



Arguelles et al., JCAP 2018

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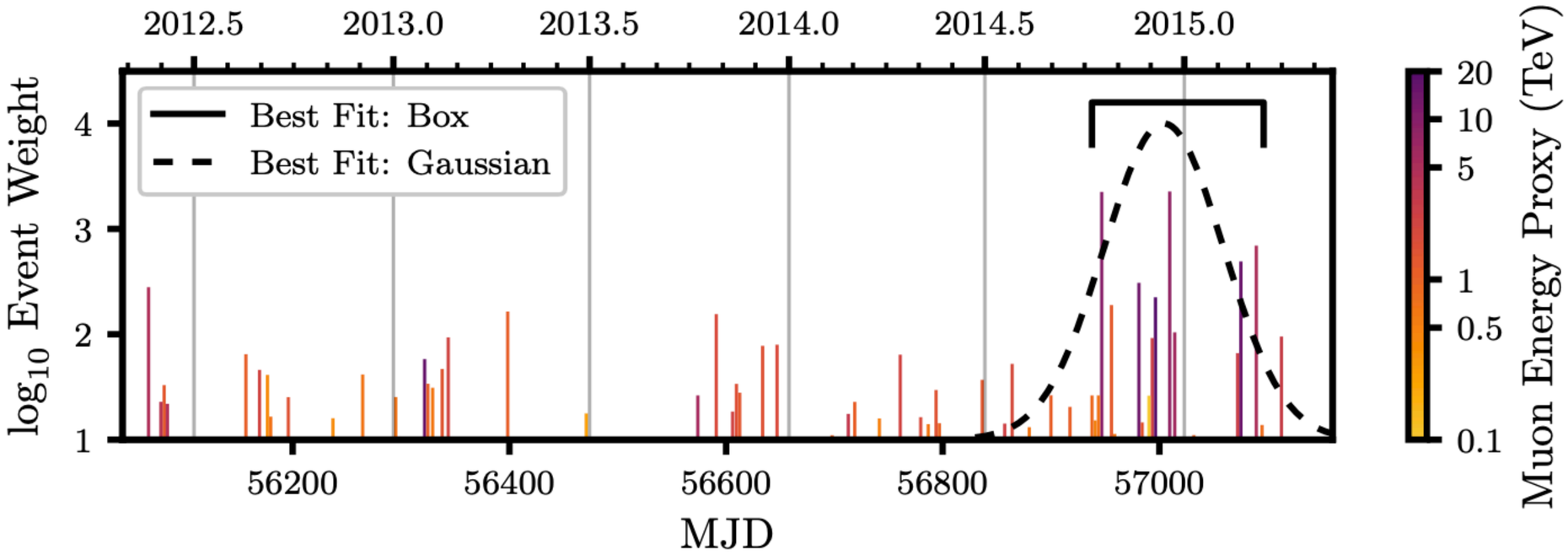

Aartsen et al., Science 2018

Point source searches with cascades

- New neural network based reconstruction
- Improved angular resolution for cascade events

Aartsen et al., ApJ 886 2019