Millimeter-Bright AGN as Astrophysical Neutrino Sources

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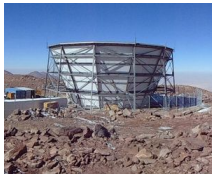
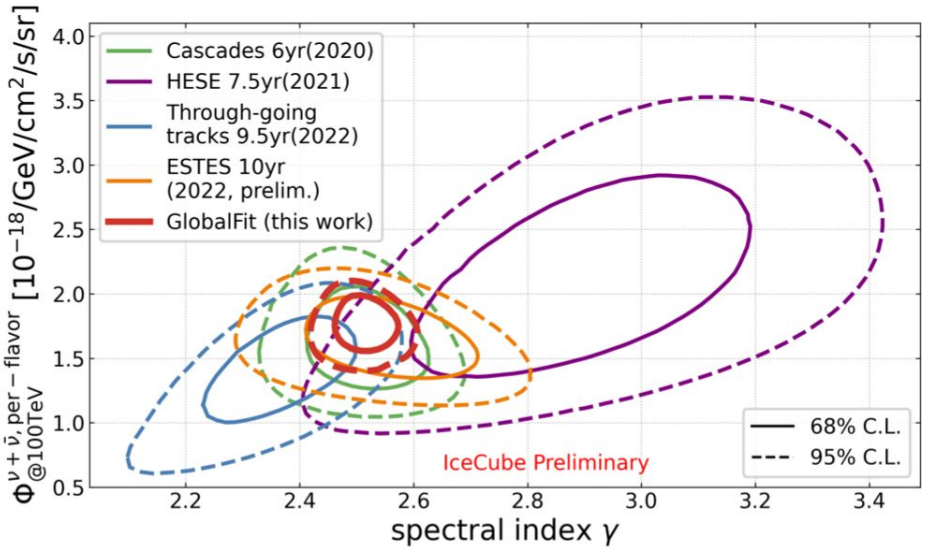
for the IceCube and ACT Collaborations

September 12th, TeVPA 2023

High-Energy Astrophysical Neutrinos



arXiv:2308.00191



- Approximate power-law astrophysical spectrum
  - Spectral index of ~2.5
- ***Diffuse intensity exceeds*** that predicted from extragalactic gamma-ray observations
  - ***GeV gamma-rays interact or lose energy in their source environments***
- Partially resolved components have softer spectra – Seyfert galaxies and galactic emission
- What source class produces these higher energy neutrinos (50 TeV – 10 PeV)?

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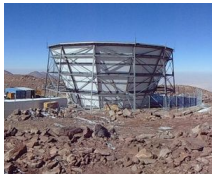

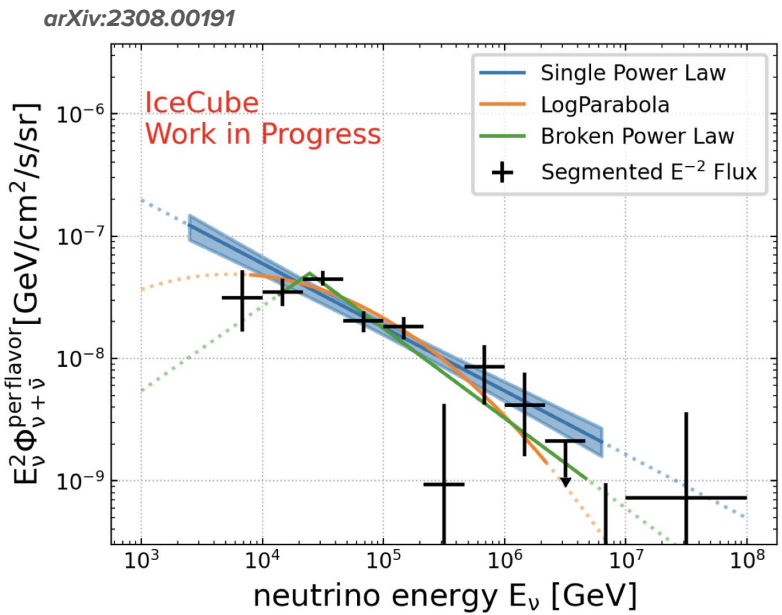

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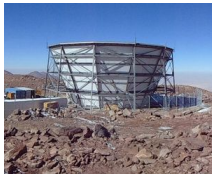
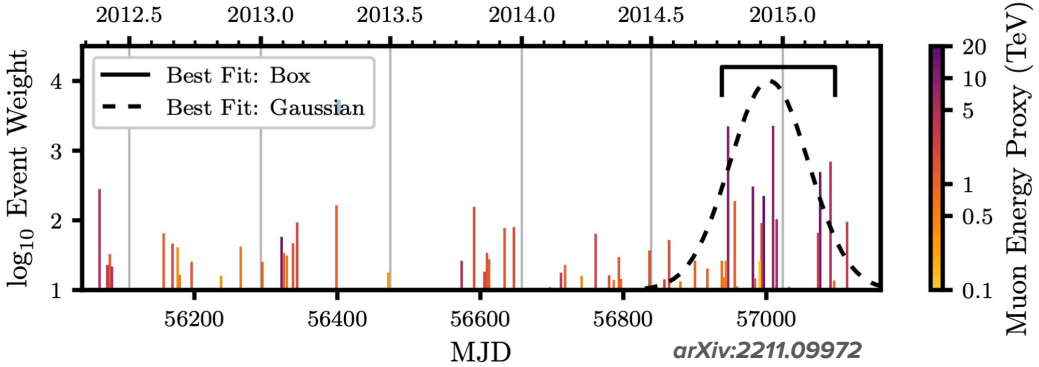
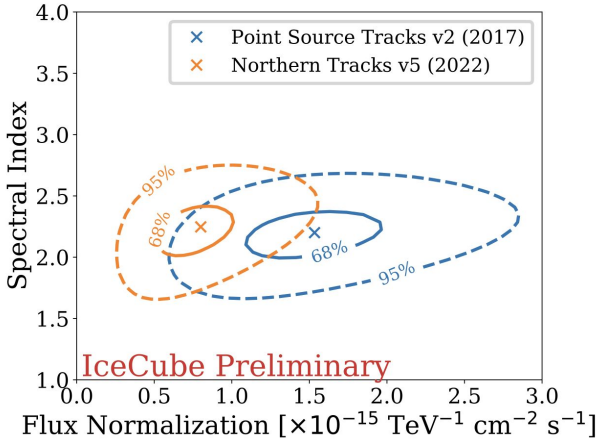


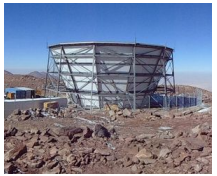
- ~300 TeV muon neutrino from blazar, TXS 0506+056 (2017)
  - 6-month accompanying gamma-ray flare
- Archival search reveals 5-month neutrino flare (September 2014–)
  - No associated gamma-rays
- ***A time-variable, blazar AGN hosting a potential gamma-ray opaque environment. Our high-energy neutrino source class?***



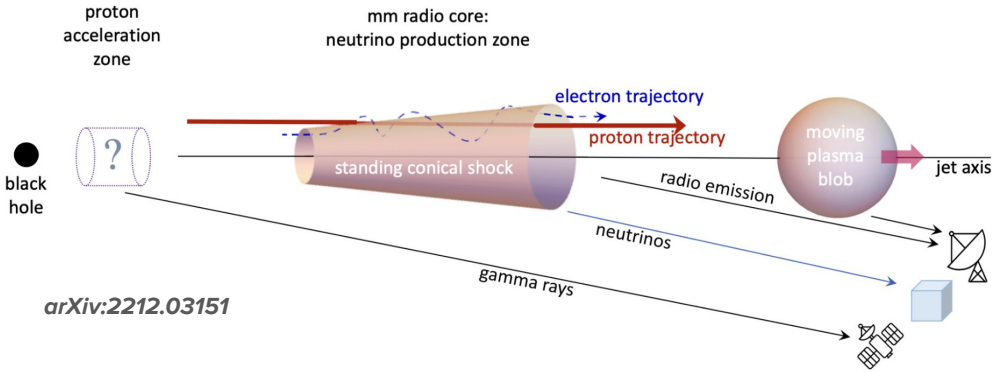


How can we study production sites which might account for the 2014–2015 intensity?

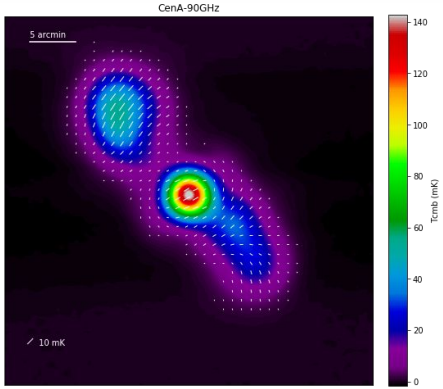
Millimeter and Radio-Bright AGN



- Recent works suggestive of correlation with radio-bright AGN
- Modeling shows the ***radio-millimeter core at the jet base*** to be an efficient environment for p-gamma(SSC) collisions
  - Neutrino power-law spectrum produced



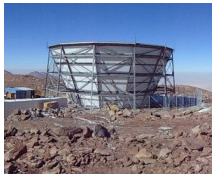
arXiv:2212.03151



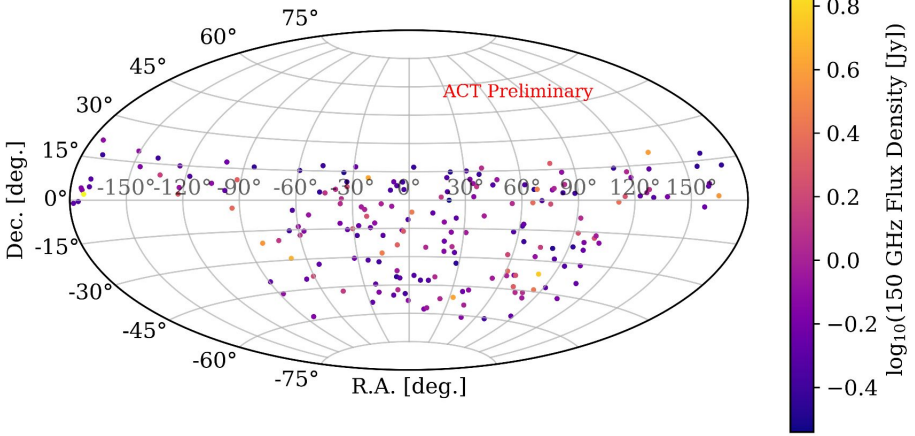
Central core of Cen A imaged at 90 GHz with SPT-3G

- Radio emission impacted by synchrotron self-absorption – larger contributions from kiloparsec-scale structures. ***Millimeter wavelengths best tracer of compact core radiation***

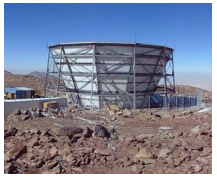
The Atacama Cosmology Telescope



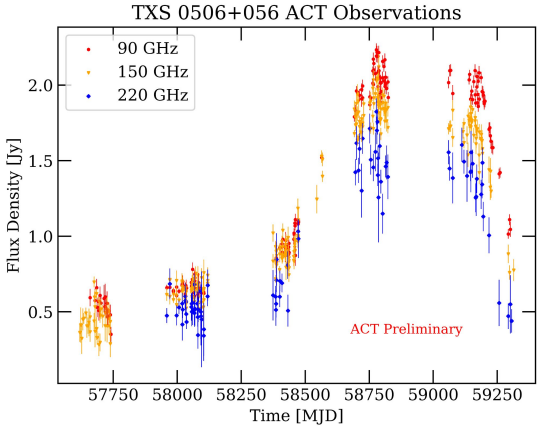
- Located in Chile, ACT is a pointed instrument used to image the cosmic microwave background
- ACT has shared a first catalog of 90, 150, 220 GHz light curves for their ~200 brightest sources (the blend of FSRQ and BL Lacs plotted below) – Ma. et al in prep + Vargas et al in prep
    - 40% sky coverage, daily monitoring of variable, jetted sources similar to TXS 0506+056

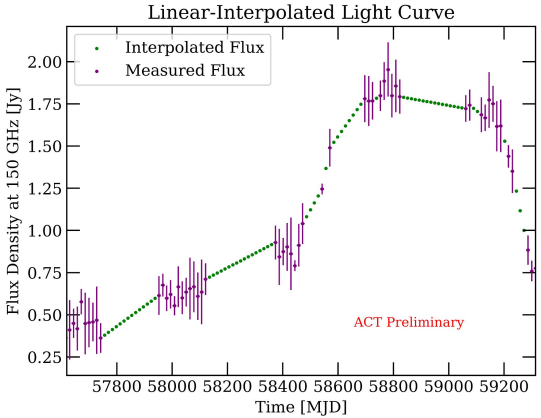


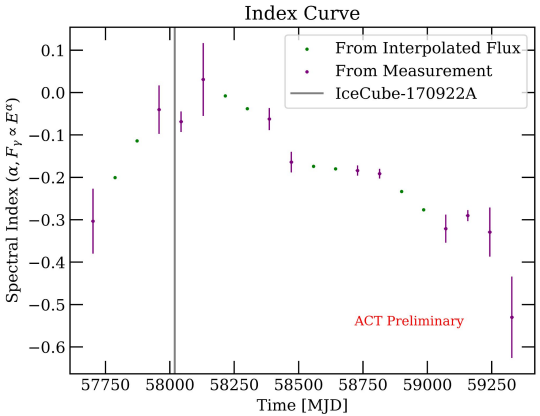
TXS 0506+056 as a Millimeter Source



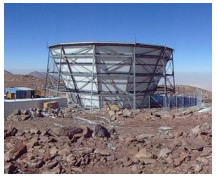
- 150 GHz and 90 GHz curves linearly interpolated, used to construct spectral index curve
- TXS is top ~5% of catalogue in hardness, shows significant increase during IceCube-170922A
- ***Can we associate alert and 2014/2015 flare with different synchrotron signatures?***



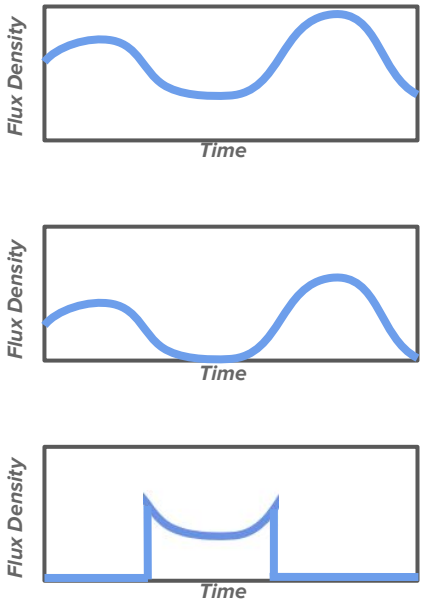


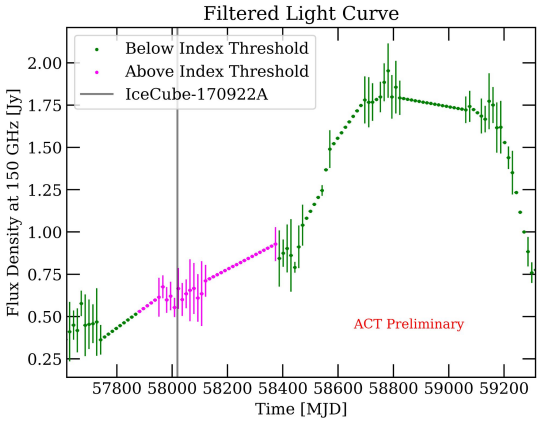


Correlating with Millimeter Activity



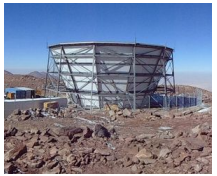
- Utilize light curve information for three phenomenological models:
  - **Direct correlation with an interpolated 150 GHz light curve**
  - **Correlation with the baseline-subtracted light curve** – remove quiescent emission from extended regions
  - **Correlation with the light-curve filtered by source spectral hardness** – trace particle injection at higher energies

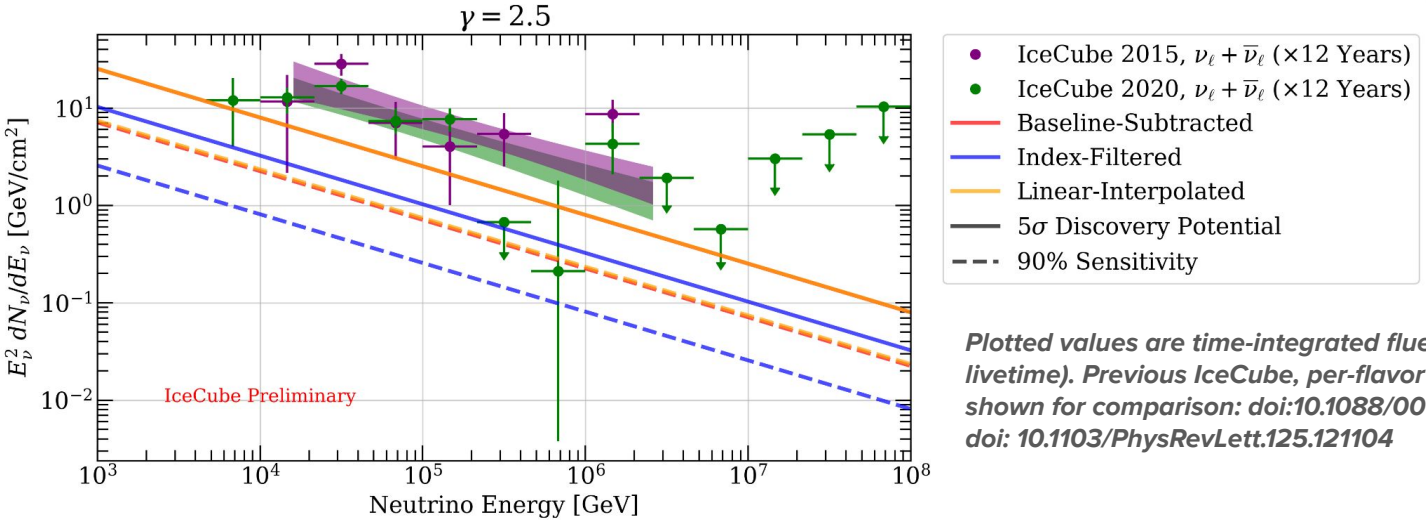




Top 32% of spectral activity (by index) retained with filter. Example for TXS 0506+056 shown above

Emission from the Population

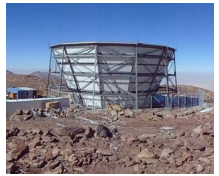


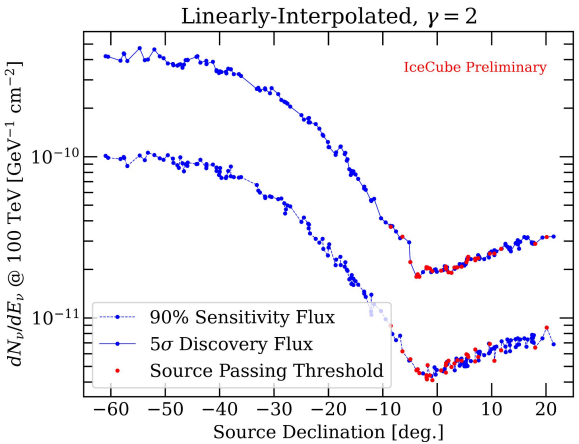


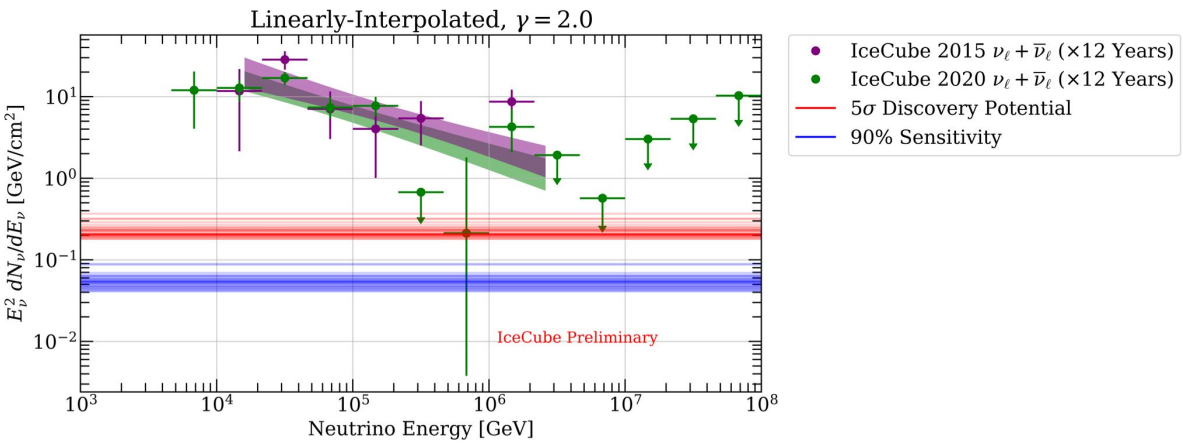
Plotted values are time-integrated fluences (12 year livetime). Previous IceCube, per-flavor diffuse results shown for comparison: doi:10.1088/0004-637X/809/1/98, doi: 10.1103/PhysRevLett.125.121104

- ***Sensitivities*** shown for three time-dependent stacked analyses (track sample @12 years)
  - ~200 blazars considered per search, each with a unique neutrino emission curve assumption
- Decreased time window improves sensitivity for the filtered emission model

Individual Source Searches

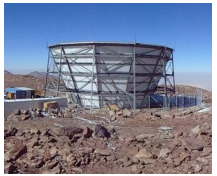






- Time-dependent analyses of individual sources also planned
- Under each emission model, the ratio of expected neutrino brightness to source sensitivity is used to select the top ~10% of likely contributors
  - Roughly 50 unique source locations will be tested

Analysis Outlook

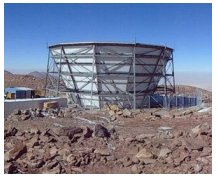


- Results and publication expected in coming months (!)
  - ***There have already been a number of works hinting at such a correlation – IceCube has so far had difficulty corroborating***
  - ***Millimeter wavelengths should give the most robust tracer of core activity – more definitive statement***

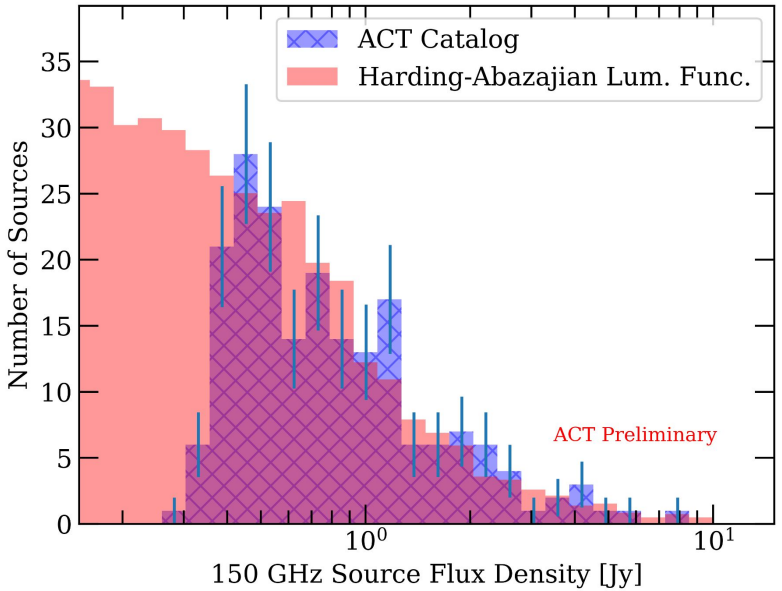
- Numerical modeling will be useful to understand the (multi-zone ?) emission of blazar sources
  - The TXS 0506+056 alert event should be explained in context of (likely associated) millimeter data
  - Whether the millimeter behavior of TXS and other sources is consistent with neutrino production down the jet *and* at the base (core)
  - Intending to share results of modeling in the coming year

Backup Material

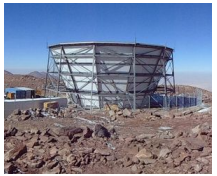
ACT Catalog Completeness



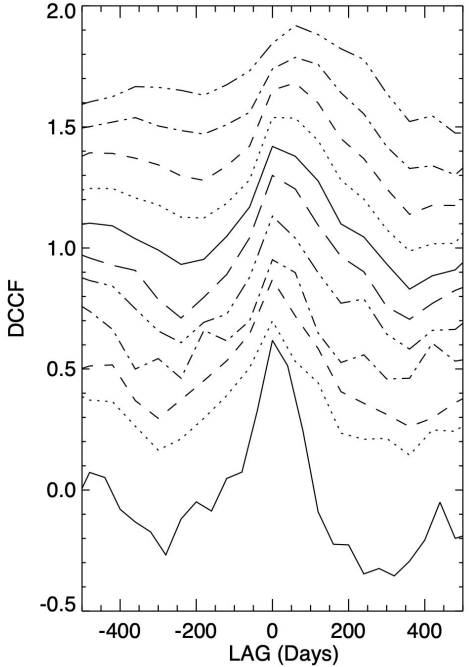
- Catalog completeness is estimated with FIRESONG
- Our completeness correction follows (2.5x) the Harding-Abazajian luminosity-dependent blazar evolutionary model. The evolution of X-ray blazars of luminosity 1E38-1E48 erg/s is considered (arXiv:1012.1247 and arXiv:1206.4734)
- Assuming full-sky coverage, the source class would be 71% complete. As ACT observes 40% of the sky, the final catalog represents 28.4% of the blazar population



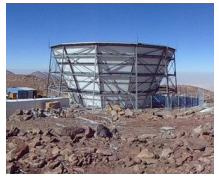
Millimeter Correlation of Fermi Blazars

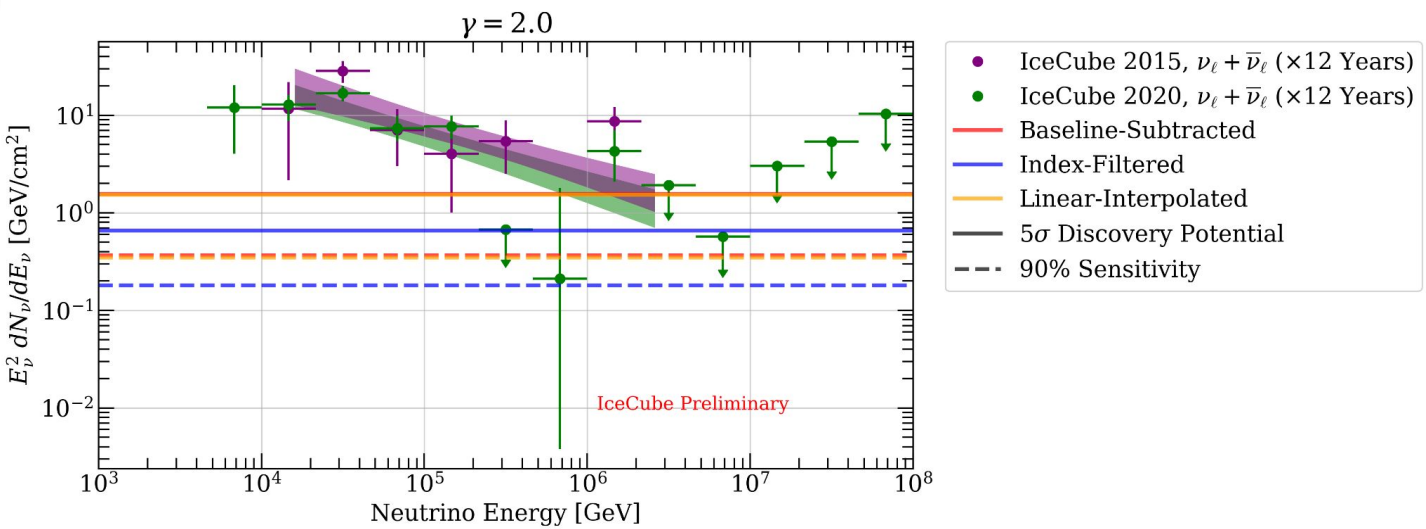


- A 2014 study considered the correlation of Fermi-bright blazars with radio emission of different wavelengths (see arXiv:1403.4170)
- Right shows the result of a discrete cross correlation between Fermi and F-GAMMA program data
  - From top to bottom, wavelengths of 110, 60, 36, 28, 20, 13, 9, 7, 3, 2 and 0.8 mm
  - Shown as a function of relative lag between gamma-ray and radio data
- The relative correlation of gamma-ray-bright sources increases towards millimeter-wavelengths
- *Will we see a similar response with the neutrinos of gamma-ray opaque sources?*



Additional Stacked Sensitivities





- Shown are additional sensitivities, assuming an injected source spectral index of 2.0
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