A follow-up survey of active galactic nuclei at TeV energies with the HAWC γ-ray observatory

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HAWC AGN Survey

1. Active galactic nuclei: extragalactic γ-ray emitters and cosmic-ray accelerators.
2. Pair attenuation by the extragalactic background light: how far can we reach?
3. The HAWC GRO.
4. A 3FHL sample of AGNs: characteristics.
5. Preliminary results.

1. Active galactic nuclei

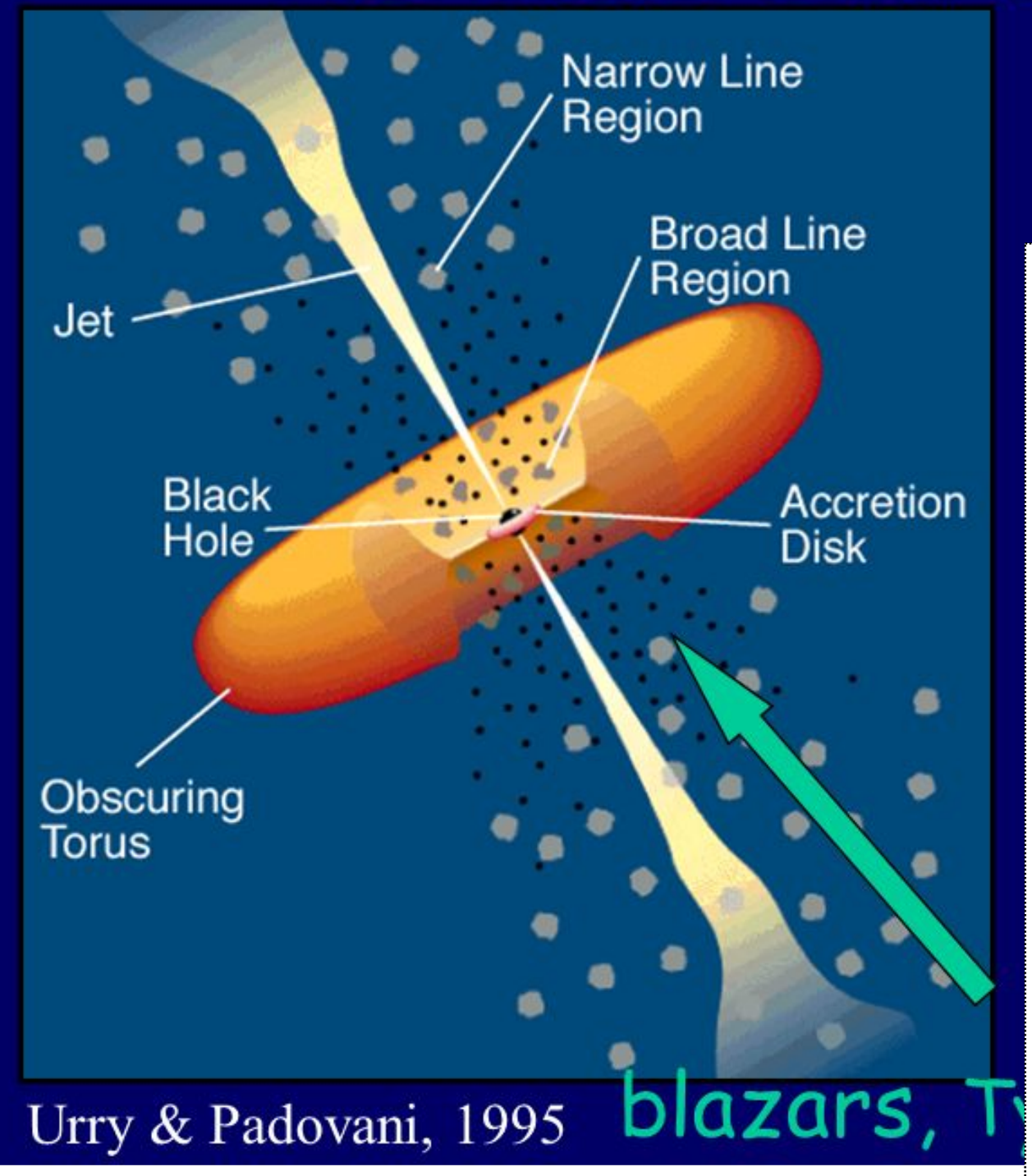
- AGN are unresolved objects that often surpass in luminosity their host galaxies. They also show highly powerful relativistic jets

  → supermassive black hole models.

  → unified model to interpret their differences

- They are the most common type of GeV γ-ray source.
- They are suspected to be extragalactic UHE cosmic ray sources.

The AGN Unified Model



M. Hillas 1984

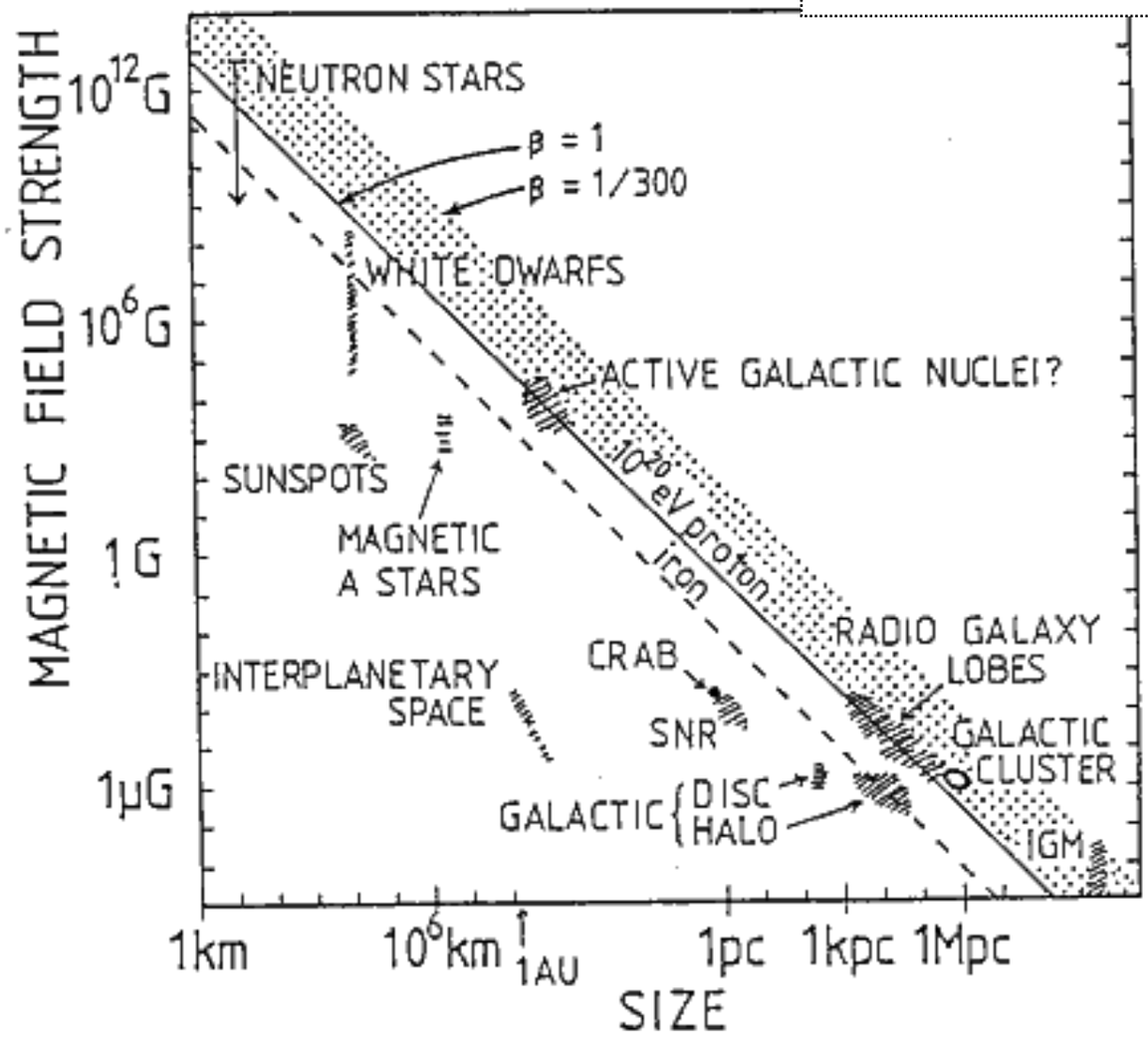
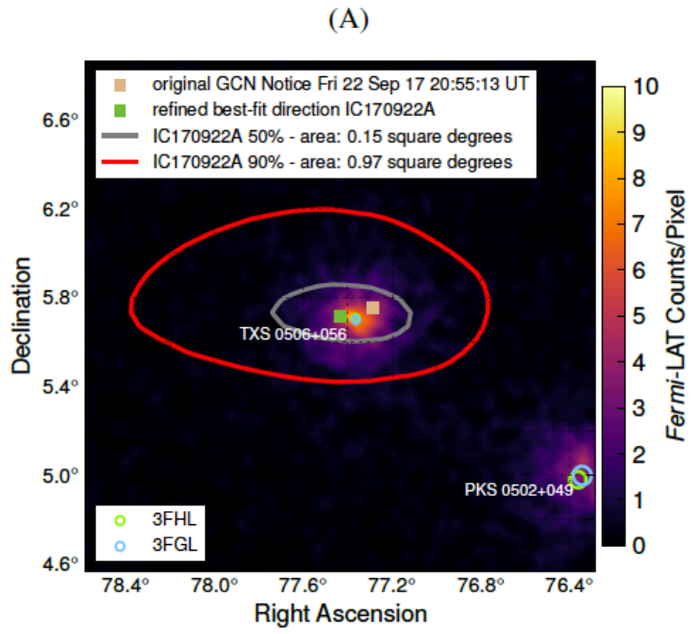
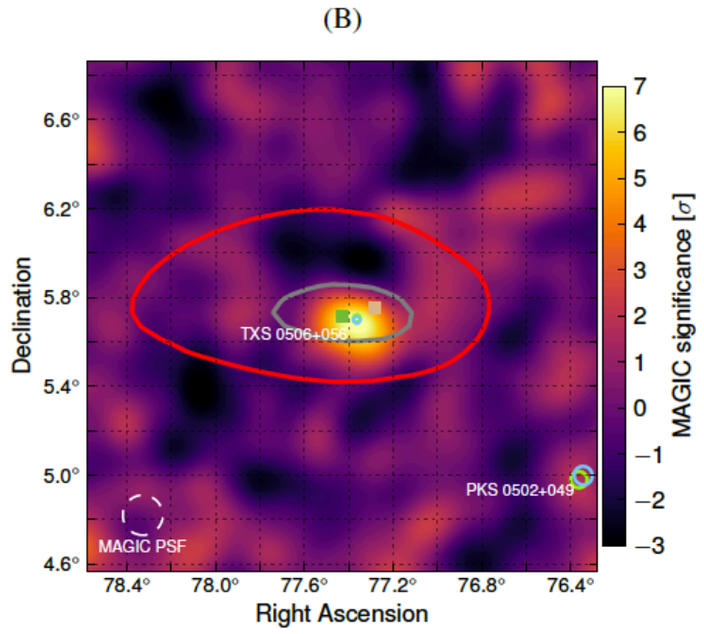


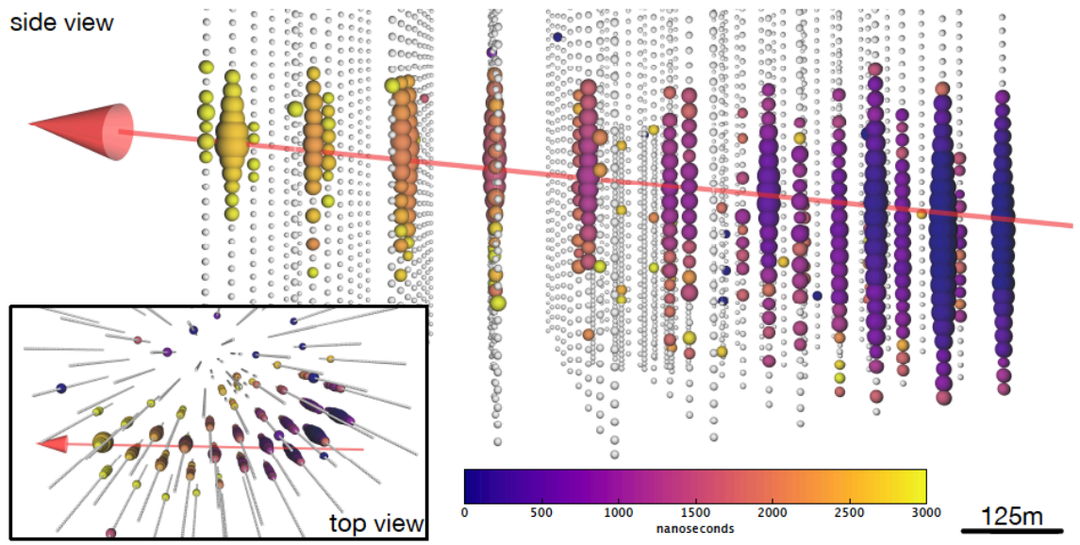
Figure 1. Size and magnetic field strength of possible sites of particle acceleration. Objects below the diagonal line cannot accelerate protons to 10^{20} eV.

TXS 0506+056

- HE (290 TeV) neutrino IceCube-170922A matching 3FHL source TXS 0506+056 @ z=0.3365 (Science 361, 2018).
- Detected by MAGIC: N(E > 90 GeV) ≃ 3.6×10^{-11} $cm^{-2}s^{-1}$.
- HAWC ppper limits (E > 1 TeV) for emission contemporaneous to the event, and in archival data since Nov 2014 (Atel 10802, 2017).







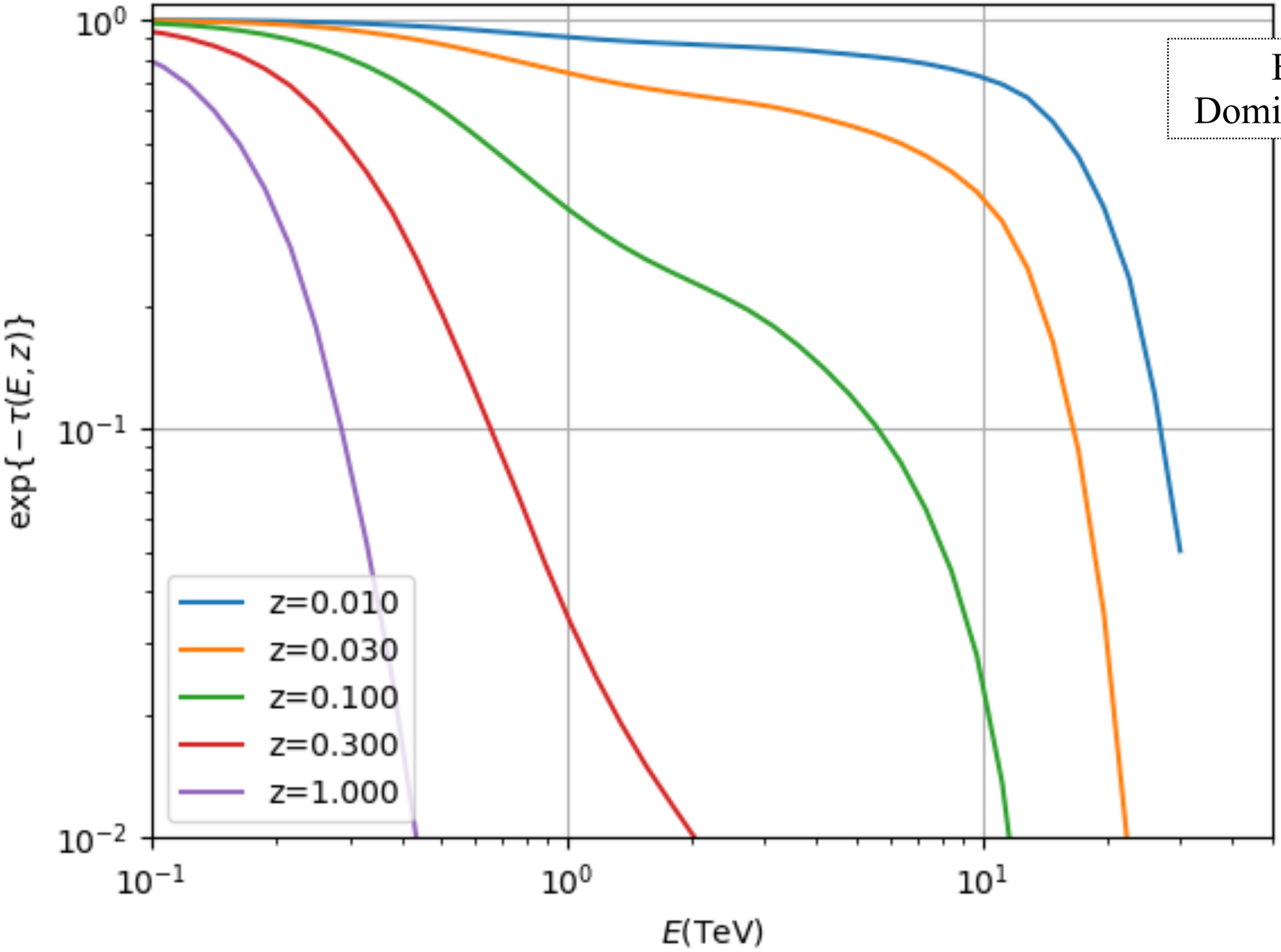
2. Pair attenuation by EBL

- However, we are impeded to look for the highest energy photons as far as we would like…
- Pair production: $\gamma\gamma \rightarrow e^{-}e^{+}$ @ $E_{\gamma}h\nu \gtrsim 0.25$ eV·TeV
  - IR radiation obscures our view of the TeV sky.
  - The CMB does the same, starting at 100s of TeV.

$$\tau(E,z) = \int_0^z \int_0^\infty \int_{0\star}^\pi \sigma(\omega) n_\nu(z') \frac{d\mu}{2} d\nu \left(\frac{d\ell}{dz'}\right) dz'$$

con $\omega = \sqrt{Eh\nu(1-\cos\theta)/2}$, $\mu = \cos\theta$, $d\ell/dz = c/H(z)(1+z)$.
La integración en μ considera el umbral $\omega > mc^2$.

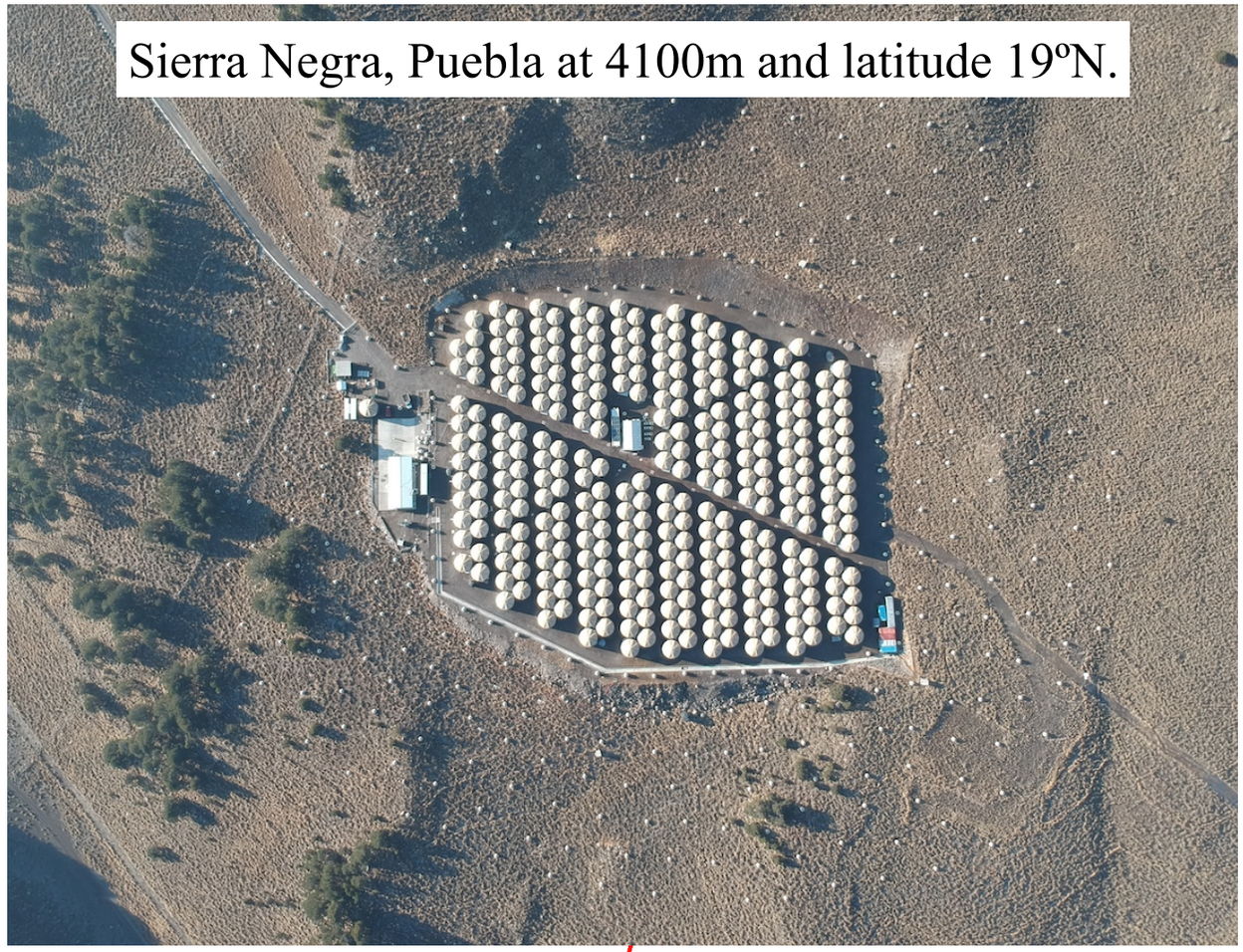
EBL model of Dominguez et al. (2011)

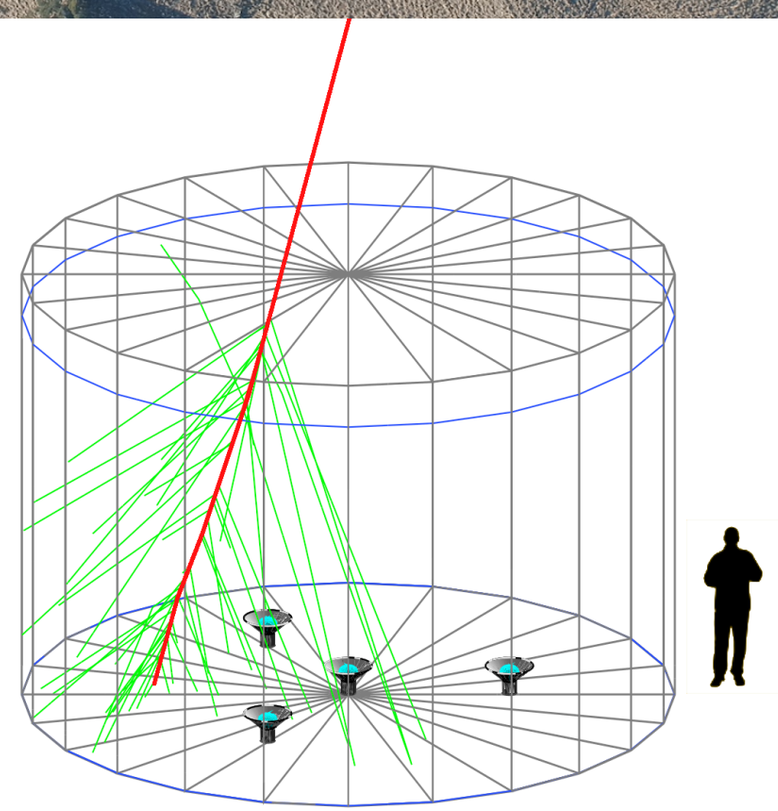


Photon-photon attenuation models rely on Lorentz invariance; they can be affected by physics beyond the SM (like axion coupling to γ).

3. HAWC

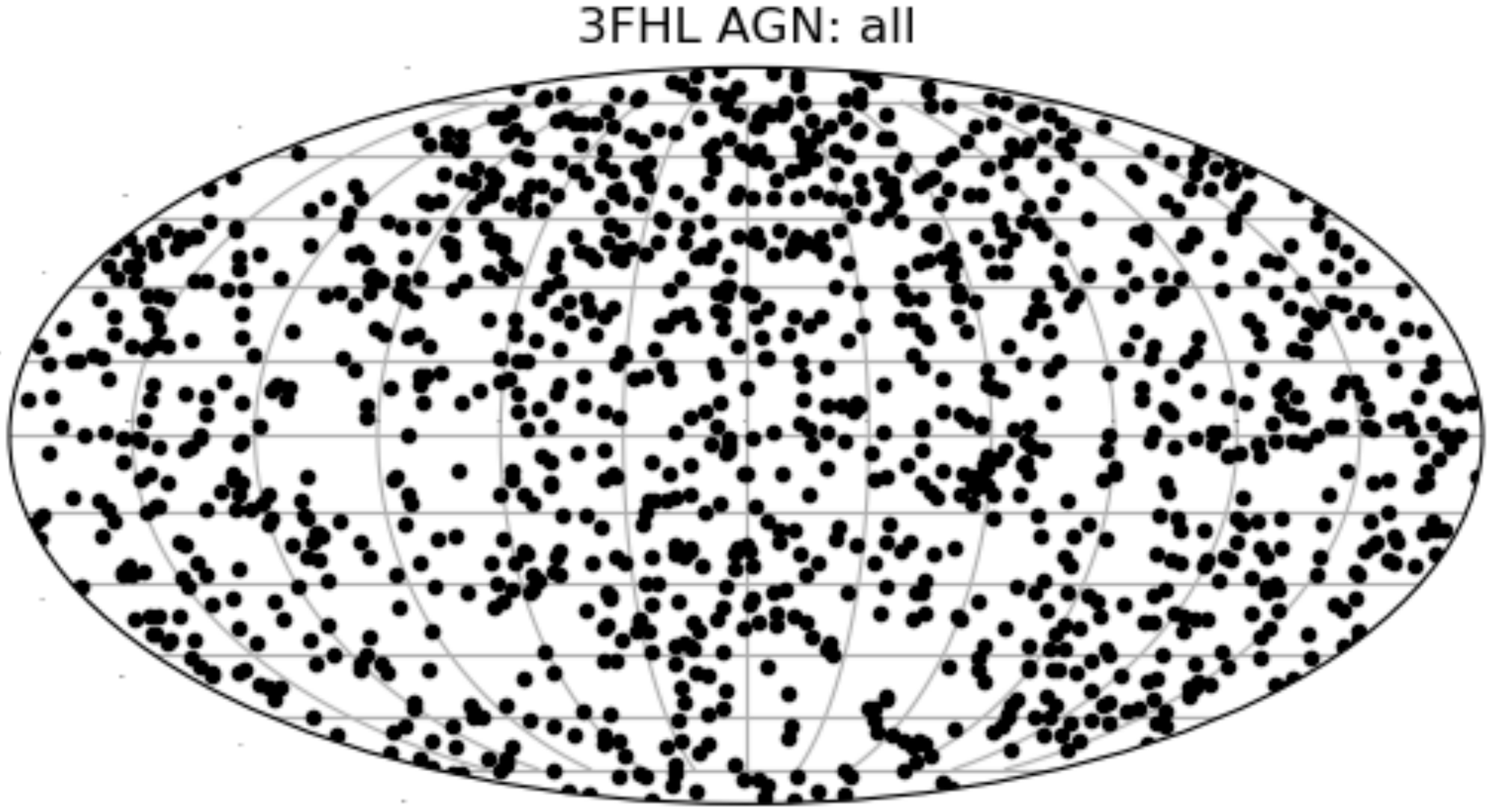
- Air shower array implementing the water Cherenkov technique.
- Array of 300 WCD occupying 22,000 m^2:
  - each WCD is 7.2m in diameter and 5m in height, with 180,000 liters of highly purified water;
  - each WCD instrumented with 3+1 PMTs;
  - started full operation in March 2015.
- HAWC surveys continuously (24/7) 1.8 sr around its zenith; 2/3 of the sky every sidereal day.
- HAWC median photon energy is 7 TeV (Abeysekara et al. 2017a,b).



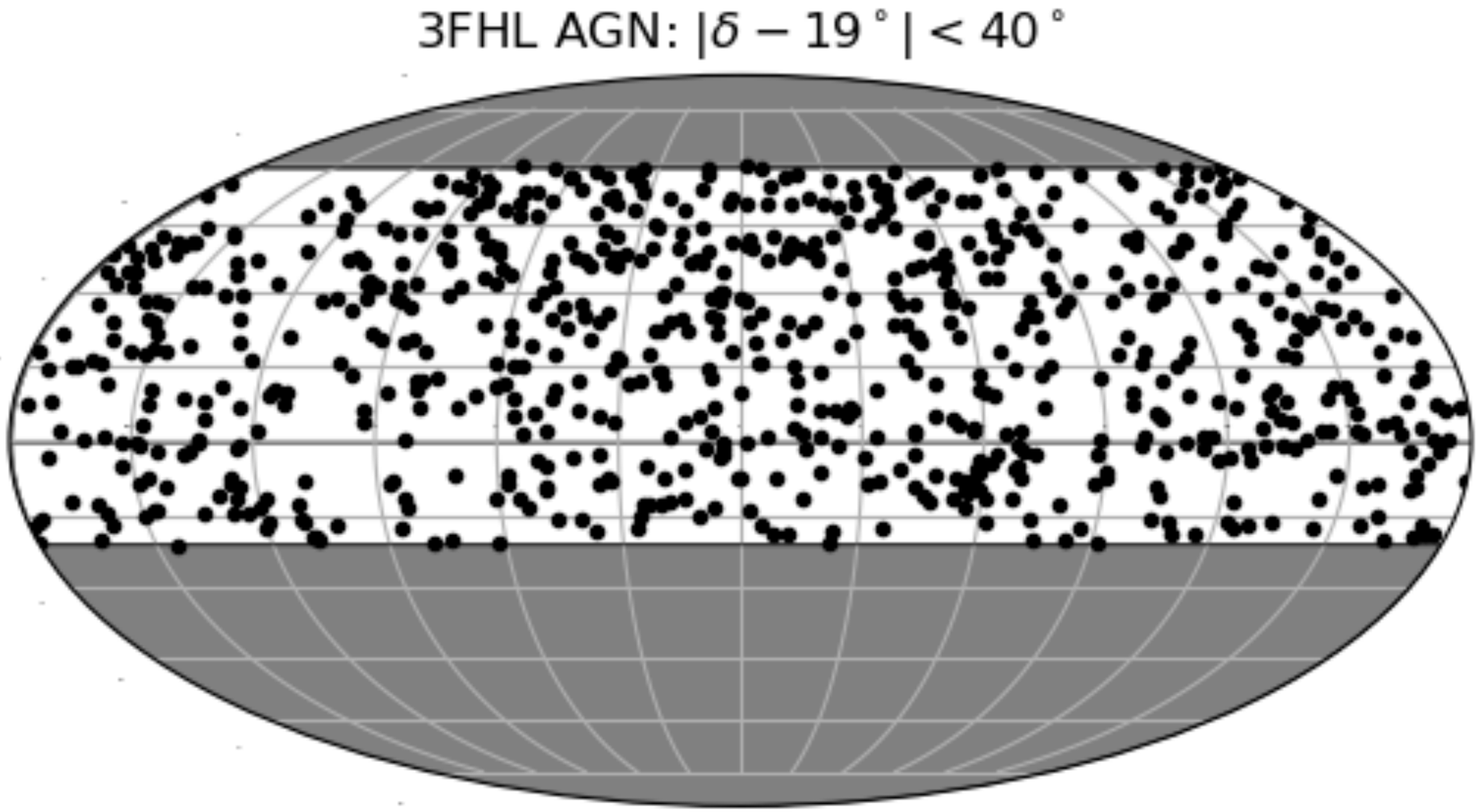


4. 3FHL sample and analysis

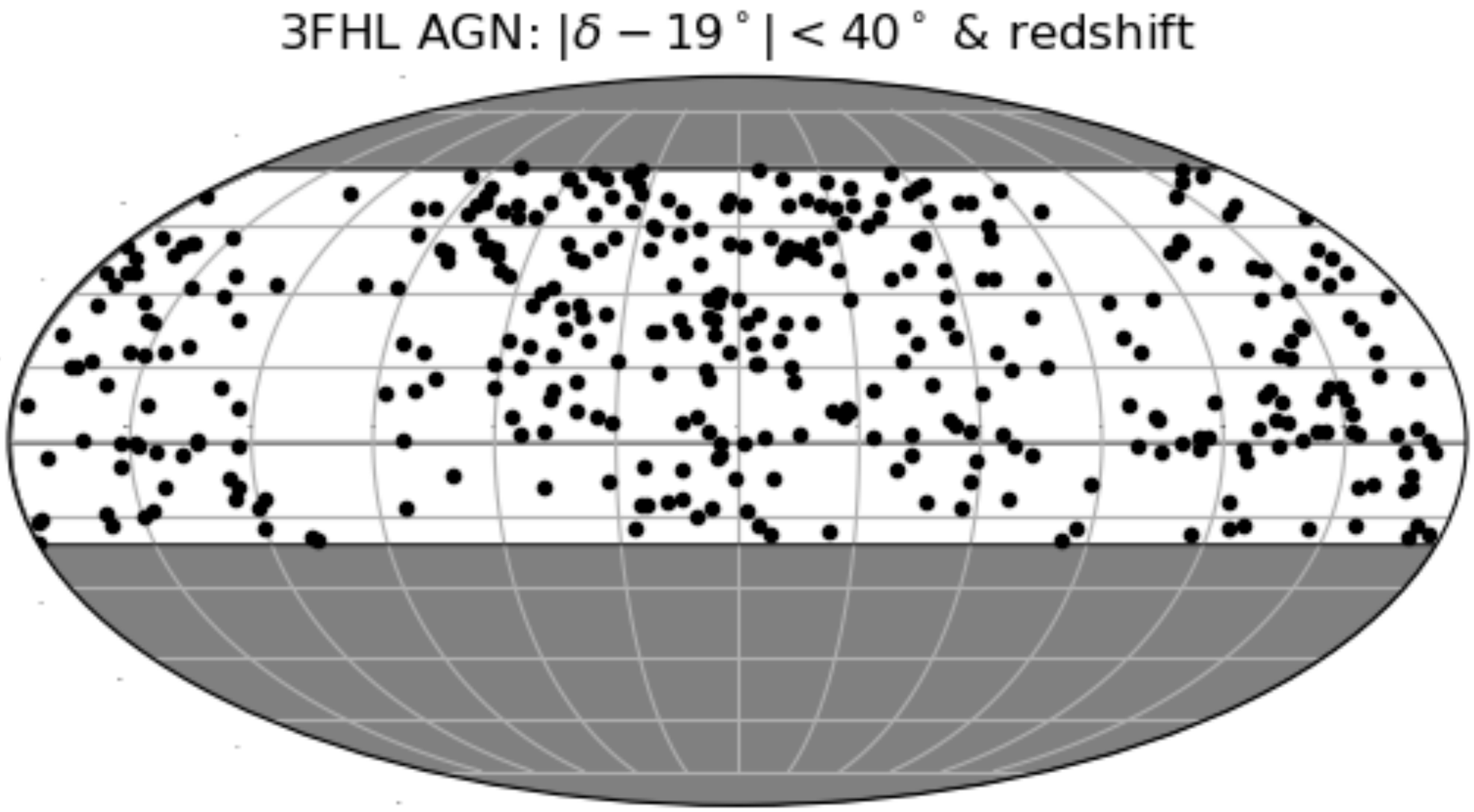
- AGN from the Third Fermi-LAT catalog of HE sources (E>10 GeV); in HAWC FoV (|δ-19º|<40º) & z<0.3.
  - 3FHL data from August 2008 to August 2015.
  - 1017 days of live HAWC data from Nov 2014 to Dec 2017.
- Sources tested for average persistent emission using a Maximum Likelihood point source model at the location of the counterpart, with power law spectra attenuated by the EBL; index and normalization as free fit parameters.
- When undetected, 95% confidence level upper limits were calculated fixing the spectral index to 2.5, fitting only flux normalization.



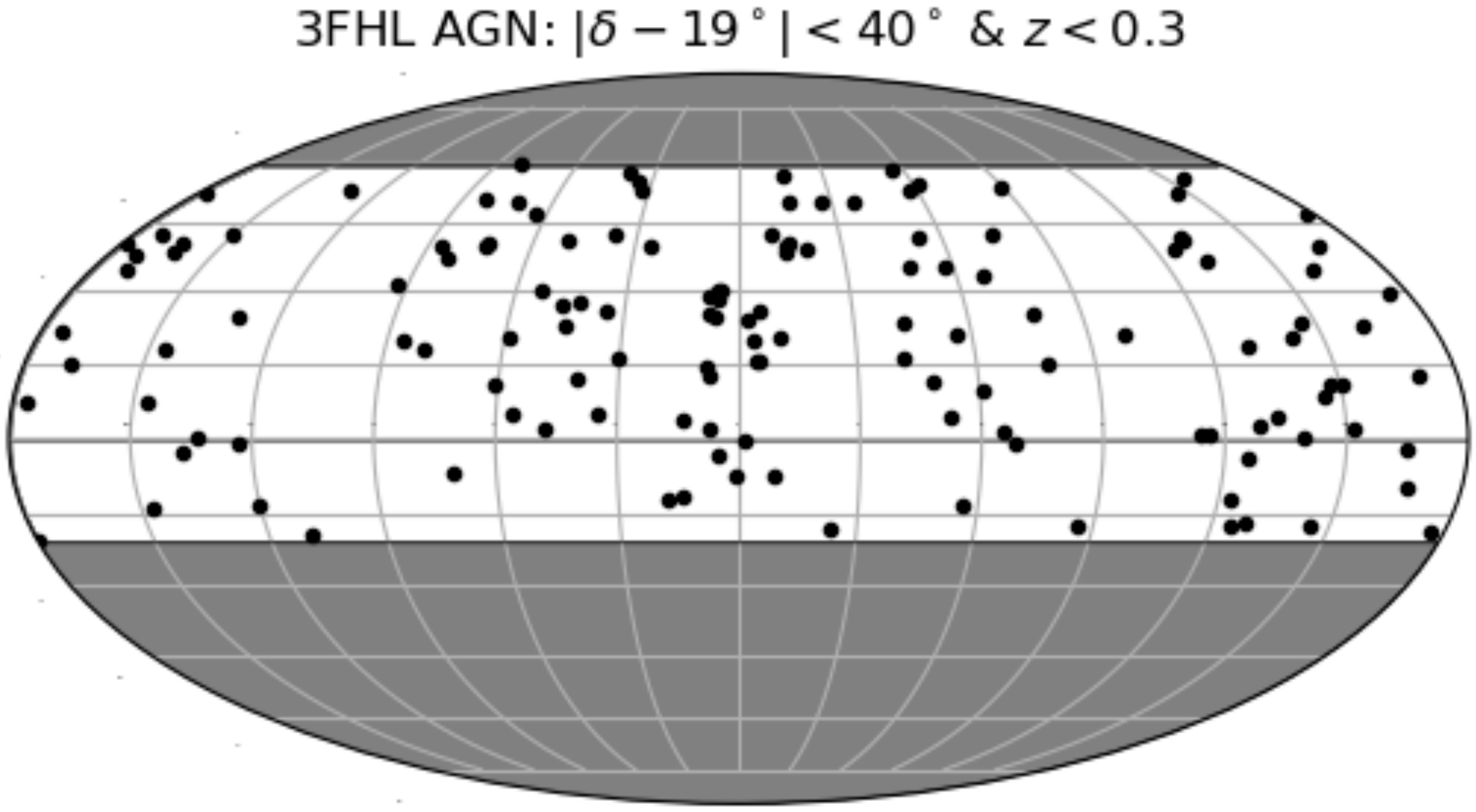
1231 AGN in 3FHL



736 AGN in 3FHL and HAWC FoV

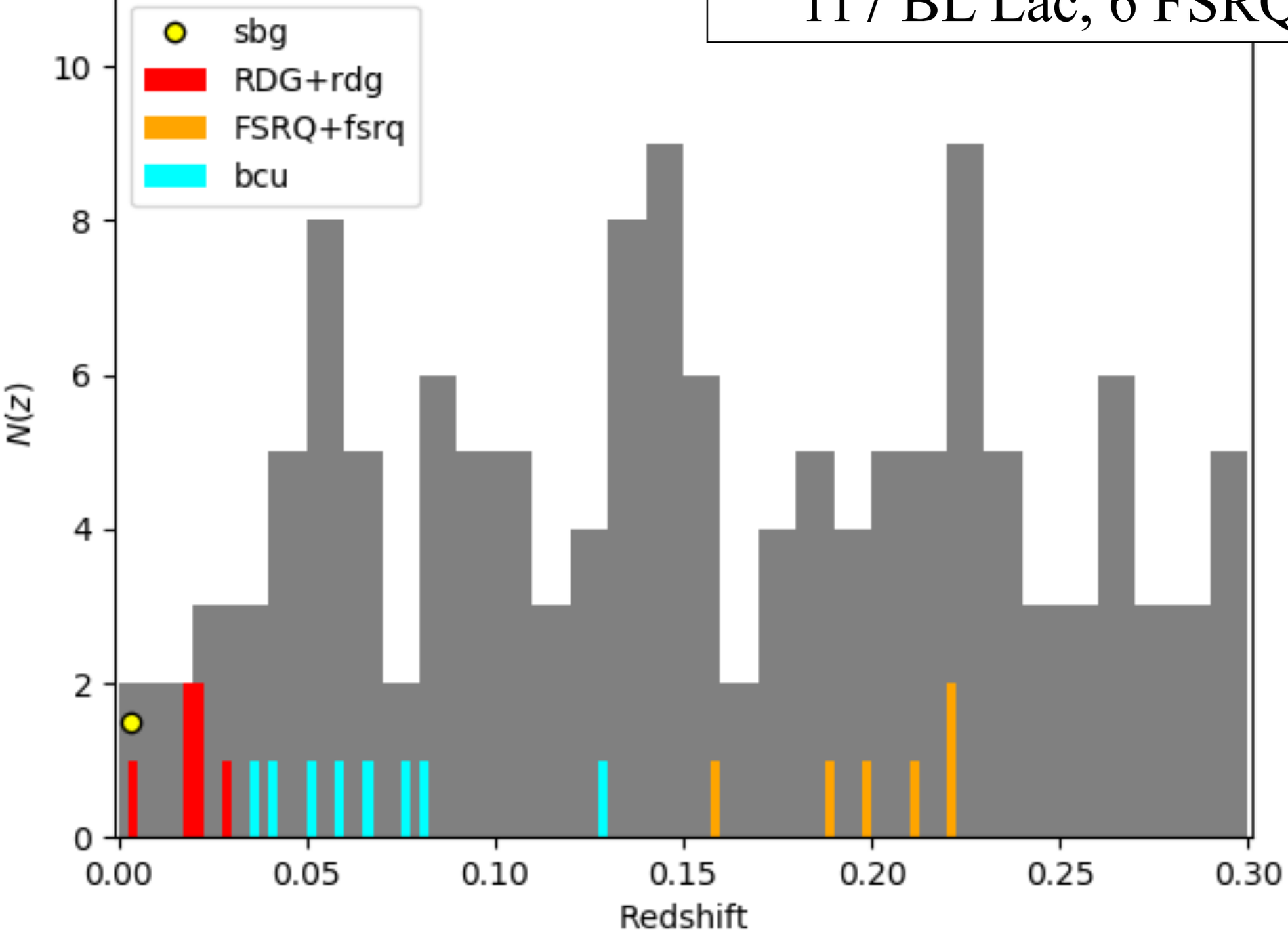


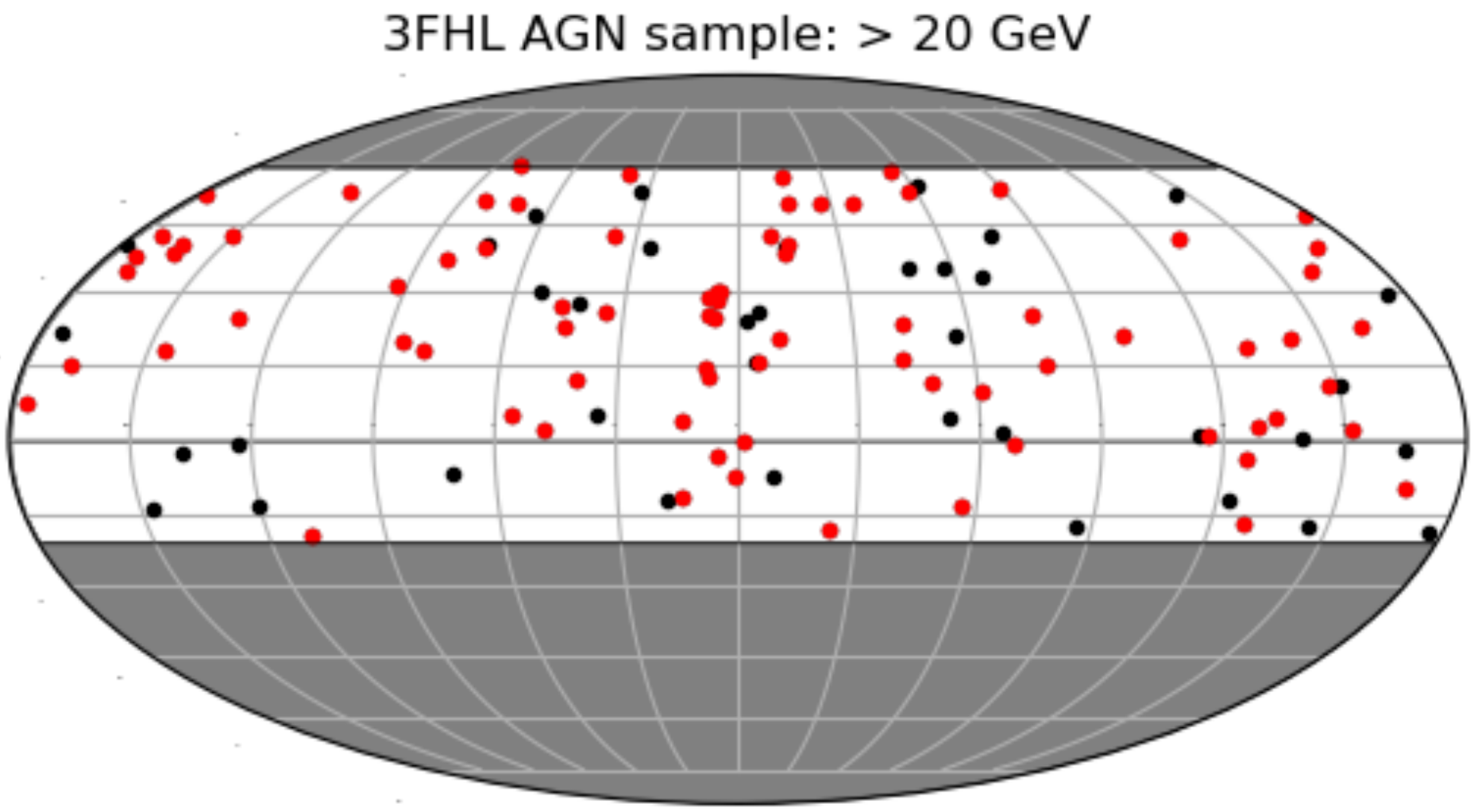
373 AGN in 3FHL and HAWC FoV
with a redshift measure



138 AGN in 3FHL and HAWC FoV
and z<0.3 :: **THIS IS THE SAMPLE**

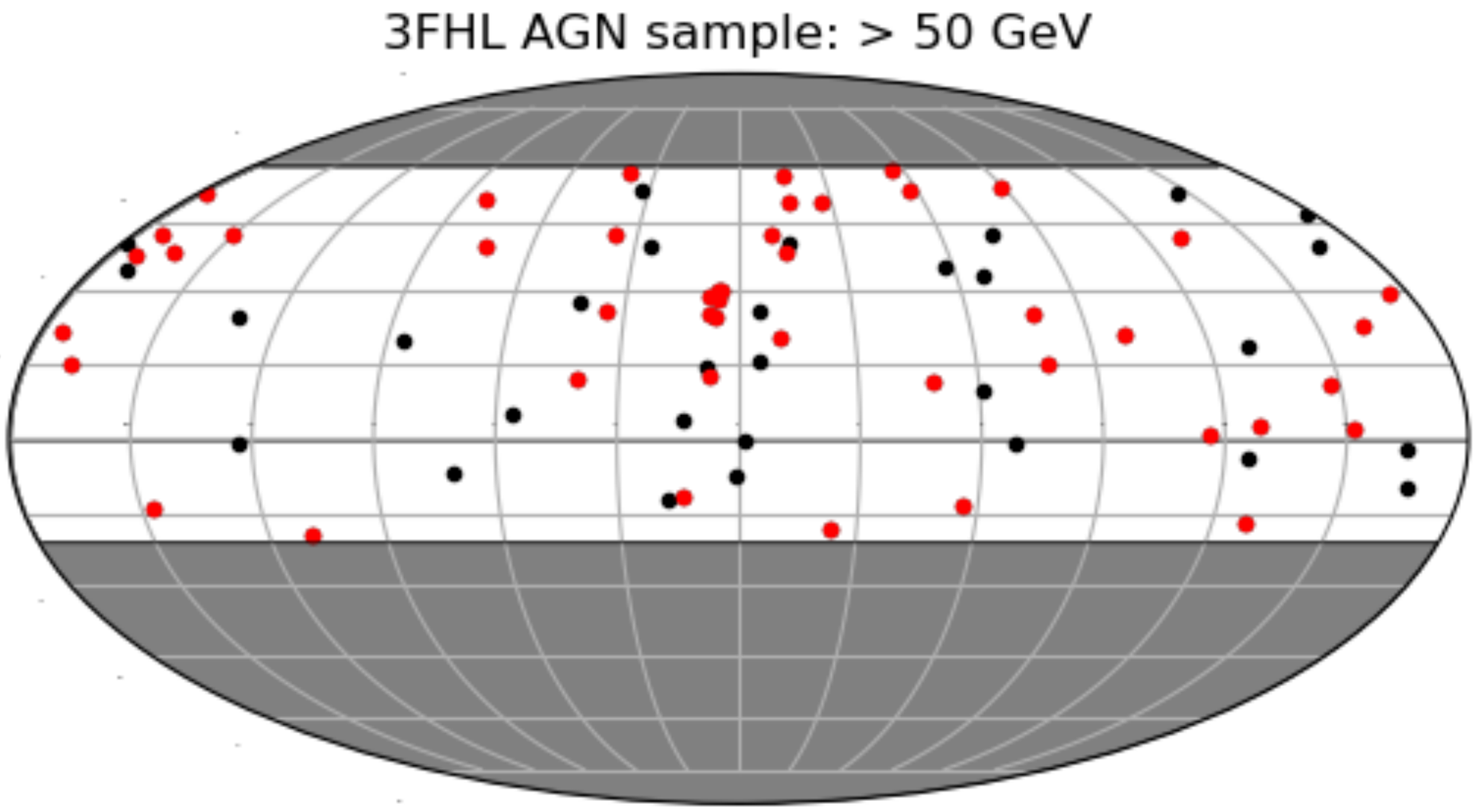
Sample composed of:
1 starburst galaxy, 6 radiogalaxies,
117 BL Lac, 6 FSRQ, 8 bcus





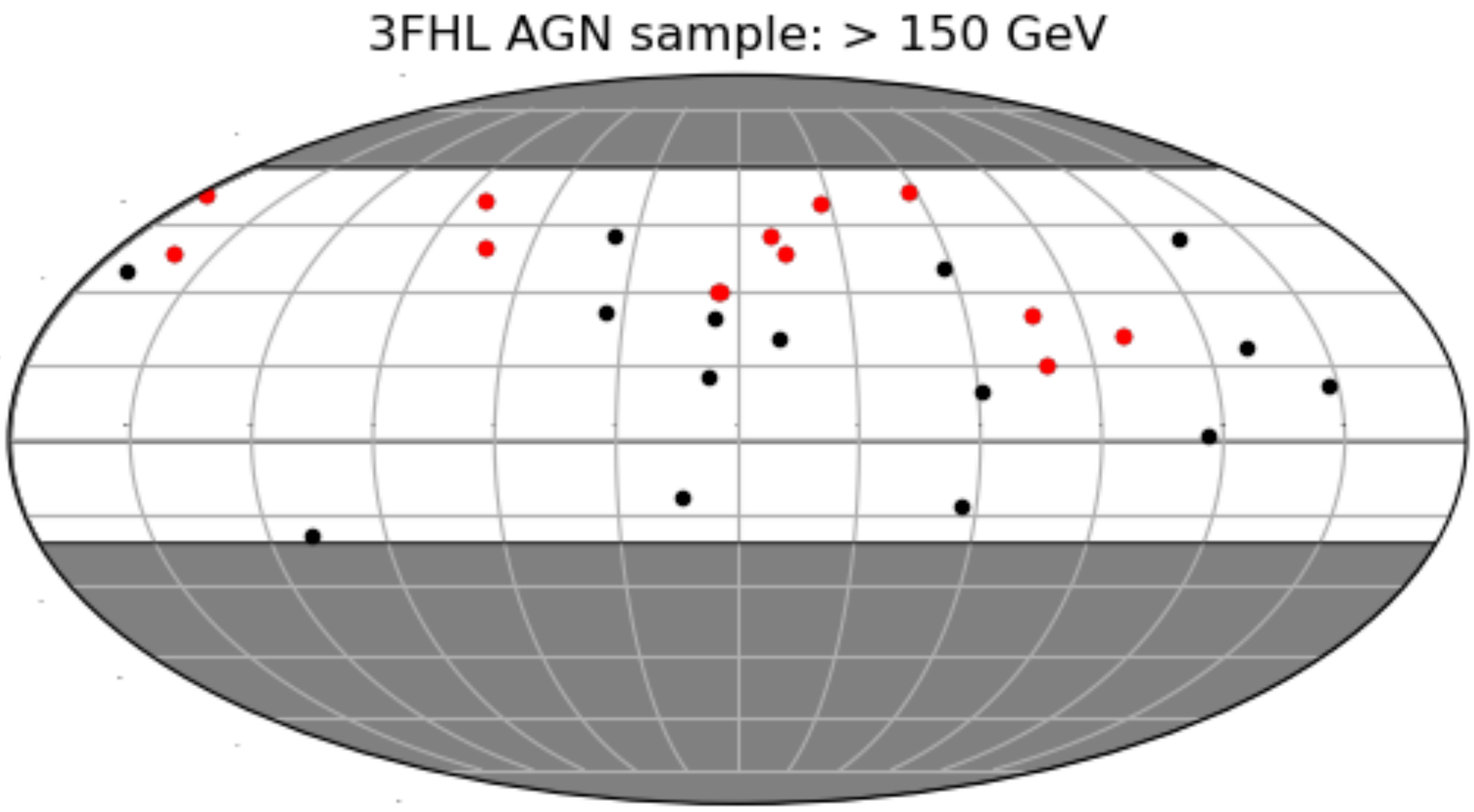
AGN in the sample detected in 20-50 GeV

117 with TS>10 and **79 with TS>25**



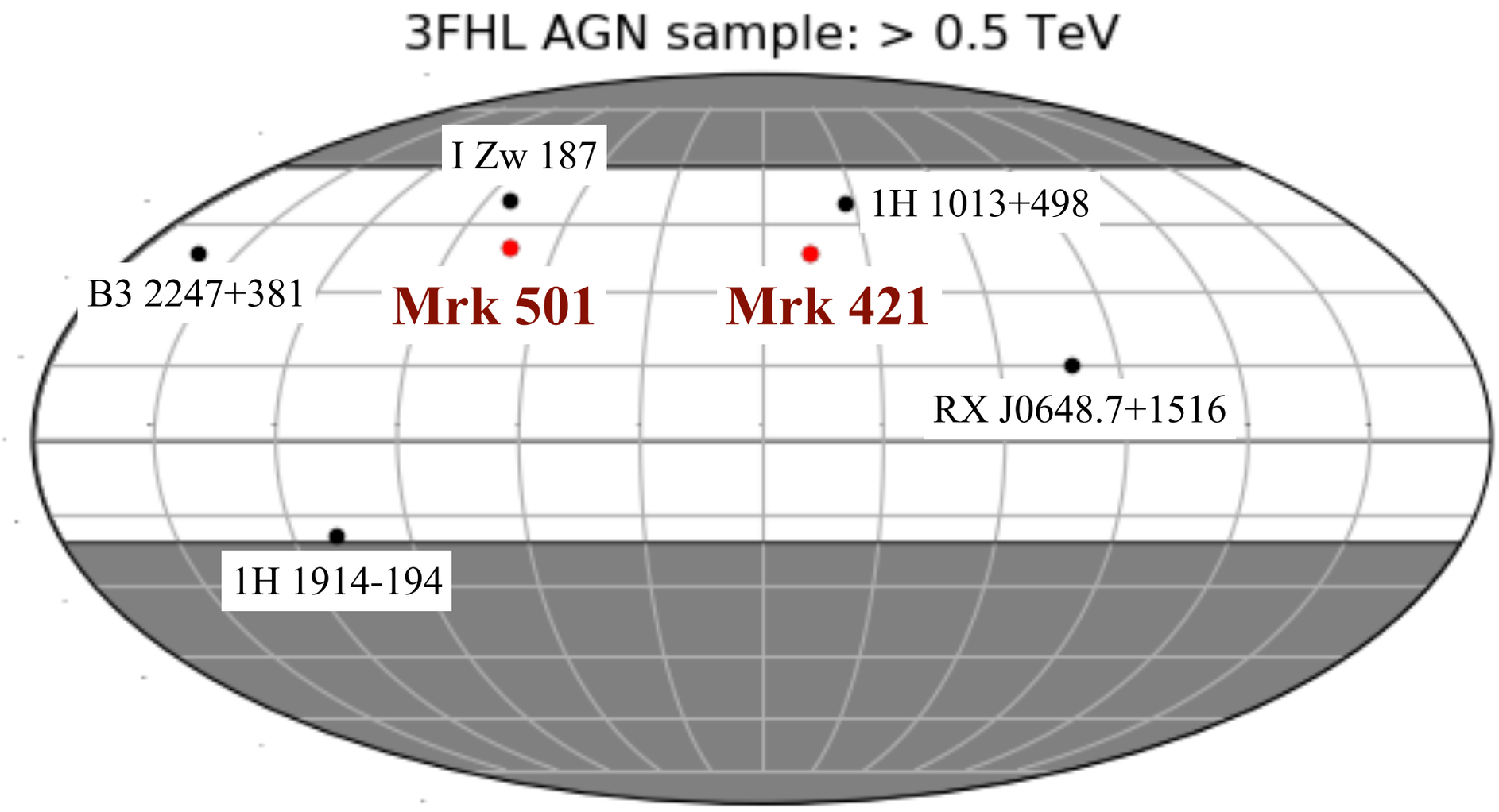
AGN in the sample detected in 50-150 GeV

76 with TS>10 and **43 with TS>25**



AGN in the sample detected in 150-500 GeV

28 with TS>10 and **13 with TS>25**



AGN in the sample detected 0.5-2.0 TeV

7 with TS>10 and **2 with TS>25**

5. HAWC preliminary results

- HAWC detected Mrk 421 at 45.6σ level:
  - $dN/dE = (25.7 \pm 1.2) \times 10^{-12}$ TeV^{-1} cm^{-2} s^{-1} (E/TeV)$^{-2.42 \pm 0.04}$ for E>0.5 TeV
- HAWC detected Mrk 501 at 20.2σ level:
  - $dN/dE = (6.8 \pm 1.2) \times 10^{-12}$ TeV^{-1} cm^{-2} s^{-1} (E/TeV)$^{-1.96 \pm 0.04}$ for E>0.5 TeV
- The other (136) AGN undetected down to 95% UL of about 10^{-12} TeV^{-1} cm^{-2} s^{-1} (30 mCrab), for E>0.5 TeV, assuming EBL attenuated power-law spectra (E/TeV)$^{-2.5}$

5. HAWC preliminary results

- Radiogalaxies { M 87, NGC 1275, IC 310, 4C +39.12, 3C 264 and NGC 1218} undetected.
  - given the distances to RDGs (z=0.0042 to 0.029), HAWC directly tests their emission (up to about 10 to 30 TeV).
  - HAWC limits for M 87, IC 310 are below 3FHL extrapolation.
- BL Lac objects: the two nearest (Mrk 421, Mrk 501) are detected. The remaining 115 are undetected:
  - those with $z > 0.1$ or 0.2 are more difficult for HAWC;
  - limits on VHE reported BL Lac like TXS 0210+515 or VER J0521+211 are below previous fluxes observed during flaring or on intermediate states.
- No evidence for starburst (NGC 1068), FSRQs, or bcus.

Summary

- We used 1017 days of HAWC data to search for AGN in the field of view within $z < 0.3$.
- No AGN other than Mrk 421 and Mrk 501 is detectable at photon energies > 0.5 TeV above an average flux level of about 30 mCrab.
  - The extragalactic IR background obscures the TeV view of the Universe beyond $z>0.1$ to 0.3.
- Results of this survey are summarized in a forthcoming publication.
- More sensitive sub-TeV analysis tools for WCOs are coming on line - keep tuned!