A follow-up survey of Active Galactic Nuclei with the HAWC γ-ray observatory

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HAWC AGN follow-up survey

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2. The HAWC GRO
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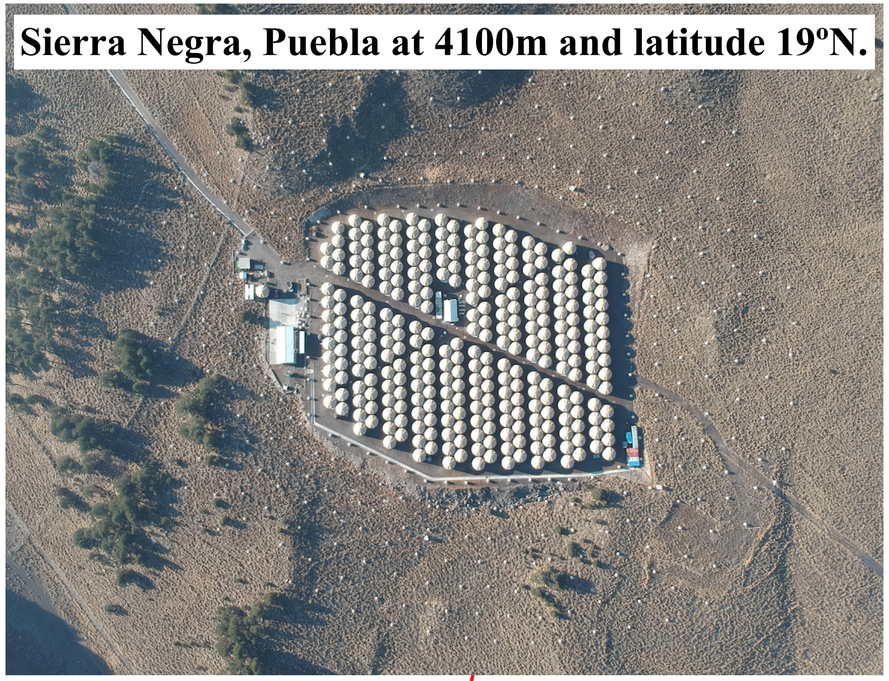
6. Summary

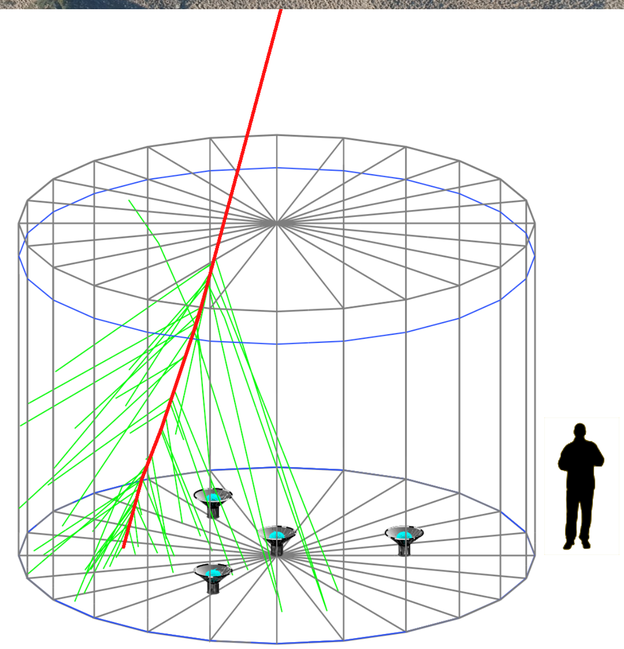
1. Active Galactic Nuclei

- A radio discovery, AGN are strong emitters along all the EM spectrum.
- Compact, energetic, variable, jets $\Longrightarrow$ SMBH model, disk geometry.
  - Blazars as AGN whose axis matches our line of sight
- Multi-messenger nature: AGN are very likely to be cosmic-ray sources, specially at ultra high energies (Hillas 1984), and neutrino sources (TXS 0506+056).
- A detailed long-term view of their TeV behavior can be provided by wide field-of-view γ-ray observatories.
- Photon-photon attenuation by the EBL is an obstacle
  - HAWC survey limited here to $z < 0.3$.

2. The HAWC GRO



- Air shower 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.
  - outrigger expansion to 100,000 m^2 in 2017-2018.
- HAWC surveys continuously1.8 sr around its zenith; it scans 2/3 of the sky every sidereal day in the 0.1-100 TeV band (and above - Malone talk GAI2b).
- HAWC median photon energy is 7 TeV (Crab & 2HWC; Abeysekara et al. 2017a,b).



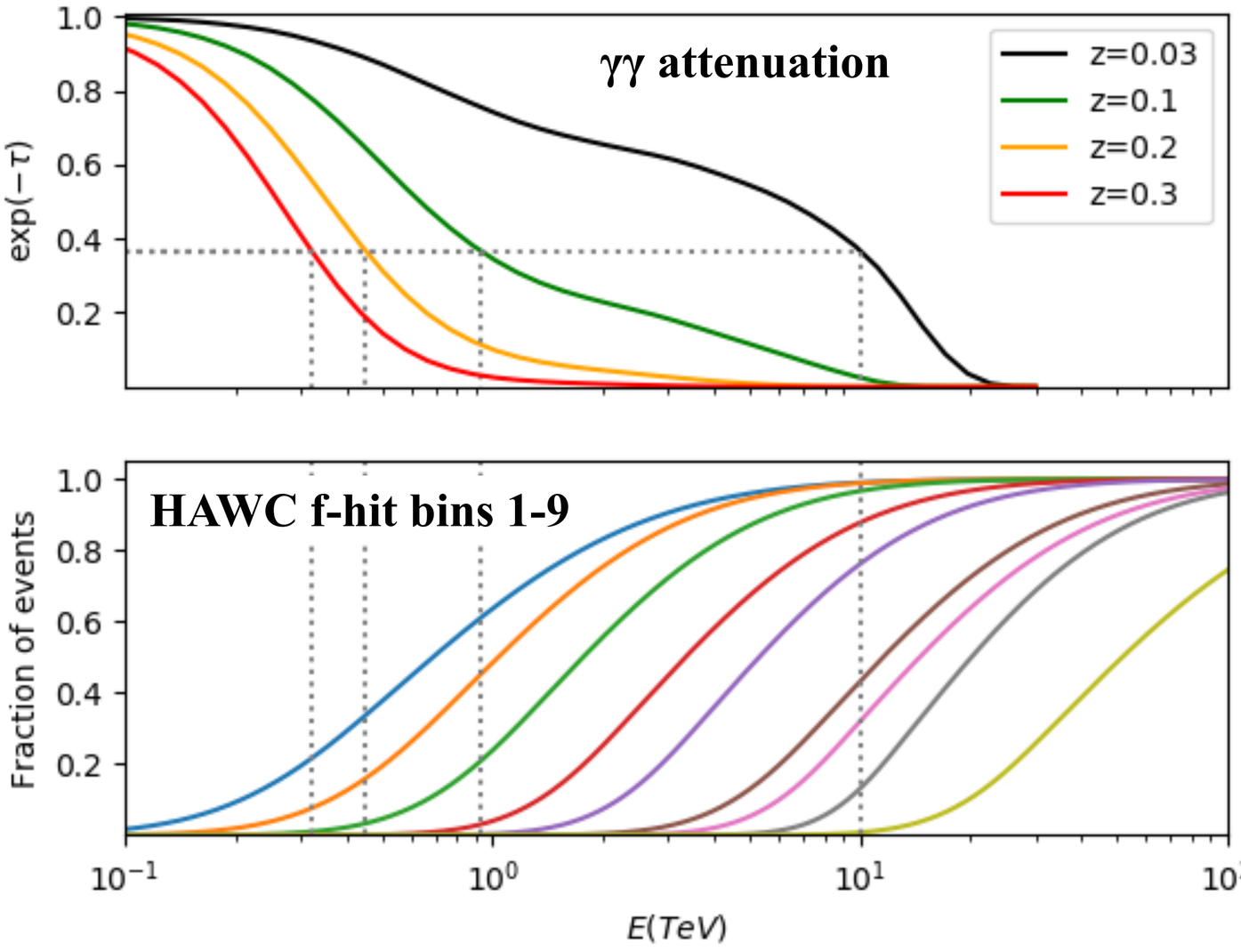
3. Photon photon attenuation by the EBL

- High energy γ rays interact with intervening photons.
- $\gamma\gamma \rightarrow e^- e^+$ process is optimum shortly above threshold:

$$E_\gamma h\nu \gtrsim 0.25 \text{ TeV}\cdot\text{eV}$$

$$[\lambda \lesssim 4.8\ \mu\text{m}\ (E_\gamma/\text{TeV})]$$

- The opacity of the Universe to γ rays, $\tau(E_\gamma,z)$, is calculated using a model of $n_\nu(z)$, the extragalactic background light (EBL), from UV to FIR.



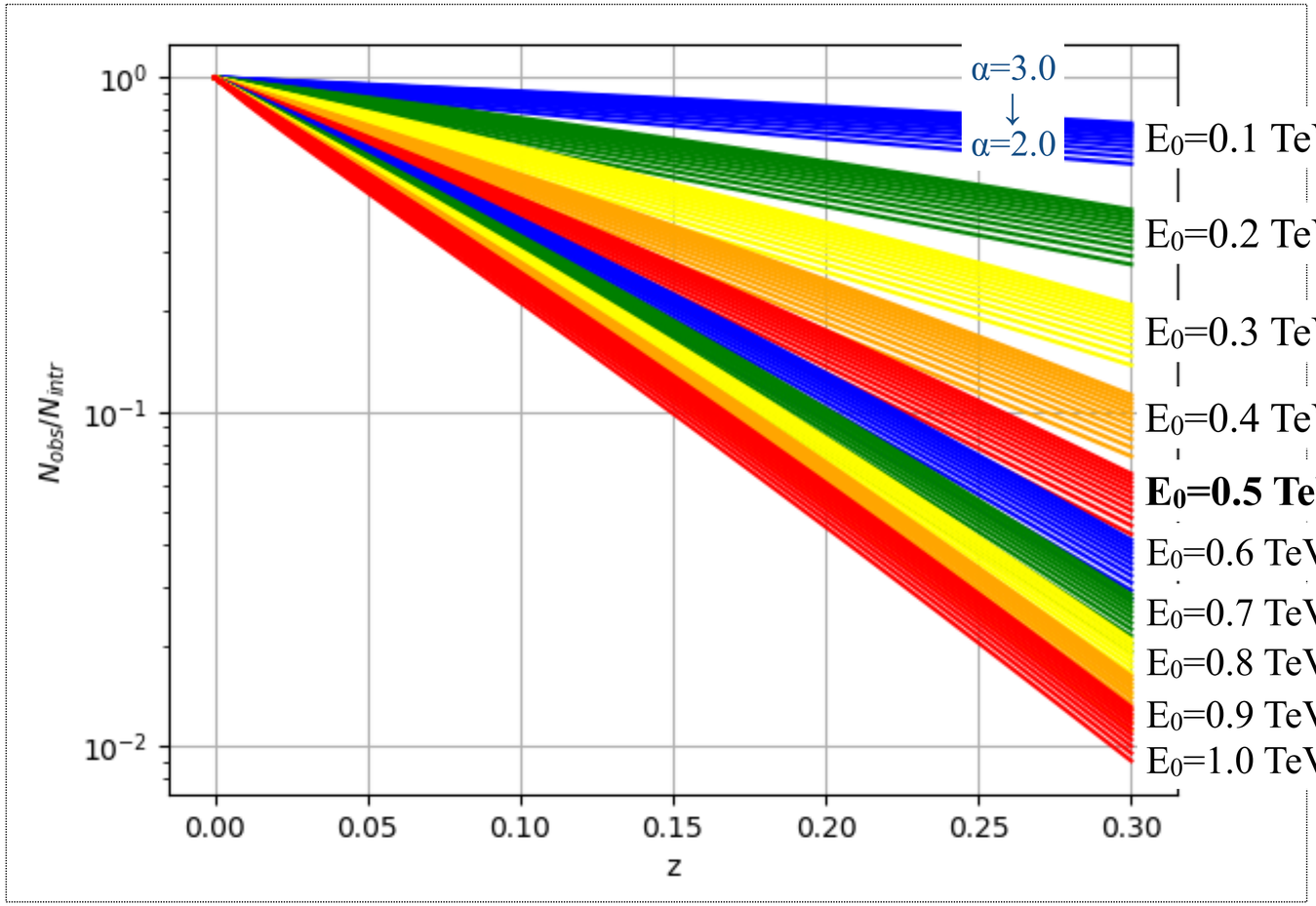
3. Photon photon attenuation by the EBL

- Calculating the attenuation for a distant source with an intrinsic power-law spectrum, observed with a threshold energy E_0, one gets,

  $N_{obs}(>E_0) = N_{intr}(>E_0) \exp(-z/z_h)$,

  where z_h depends strongly on E_0 and weakly on spectral index α.

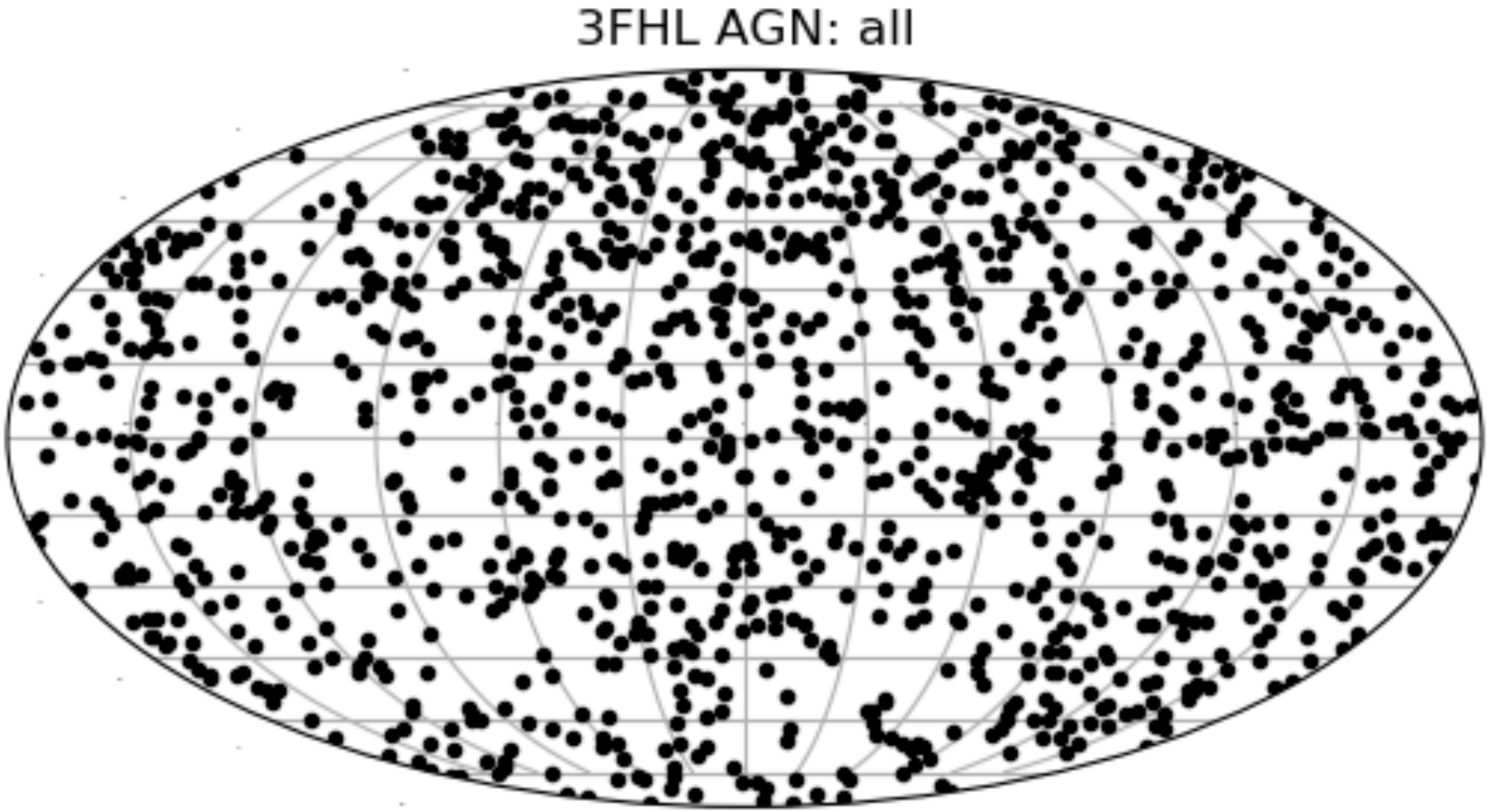
- For E_0=0.5 TeV (maximum of HAWC f_{hit} bin 1) and α=2.5, one gets z_h=0.108.



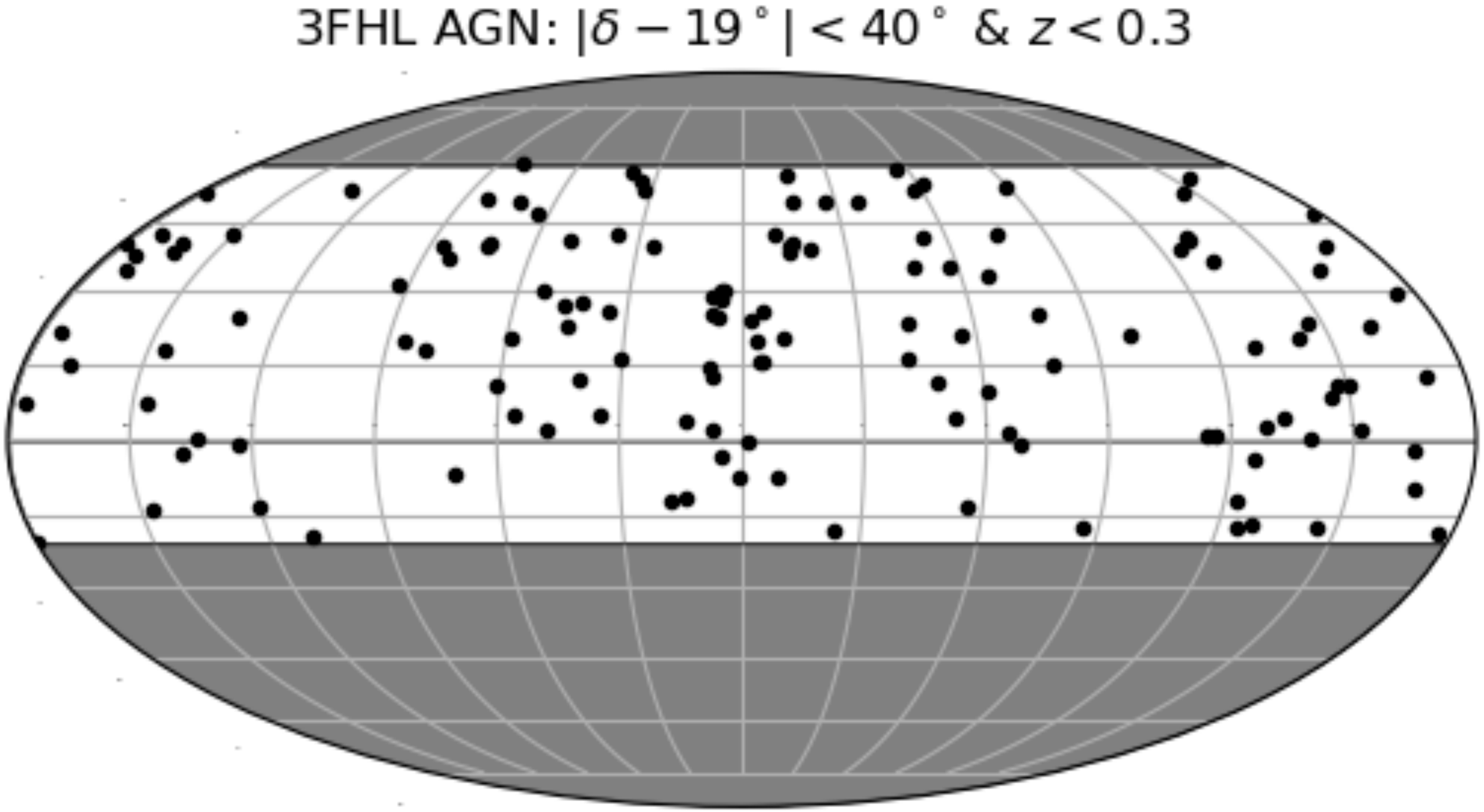
(EBL: Dominguez 2011)

4. The HAWC AGN follow-up survey

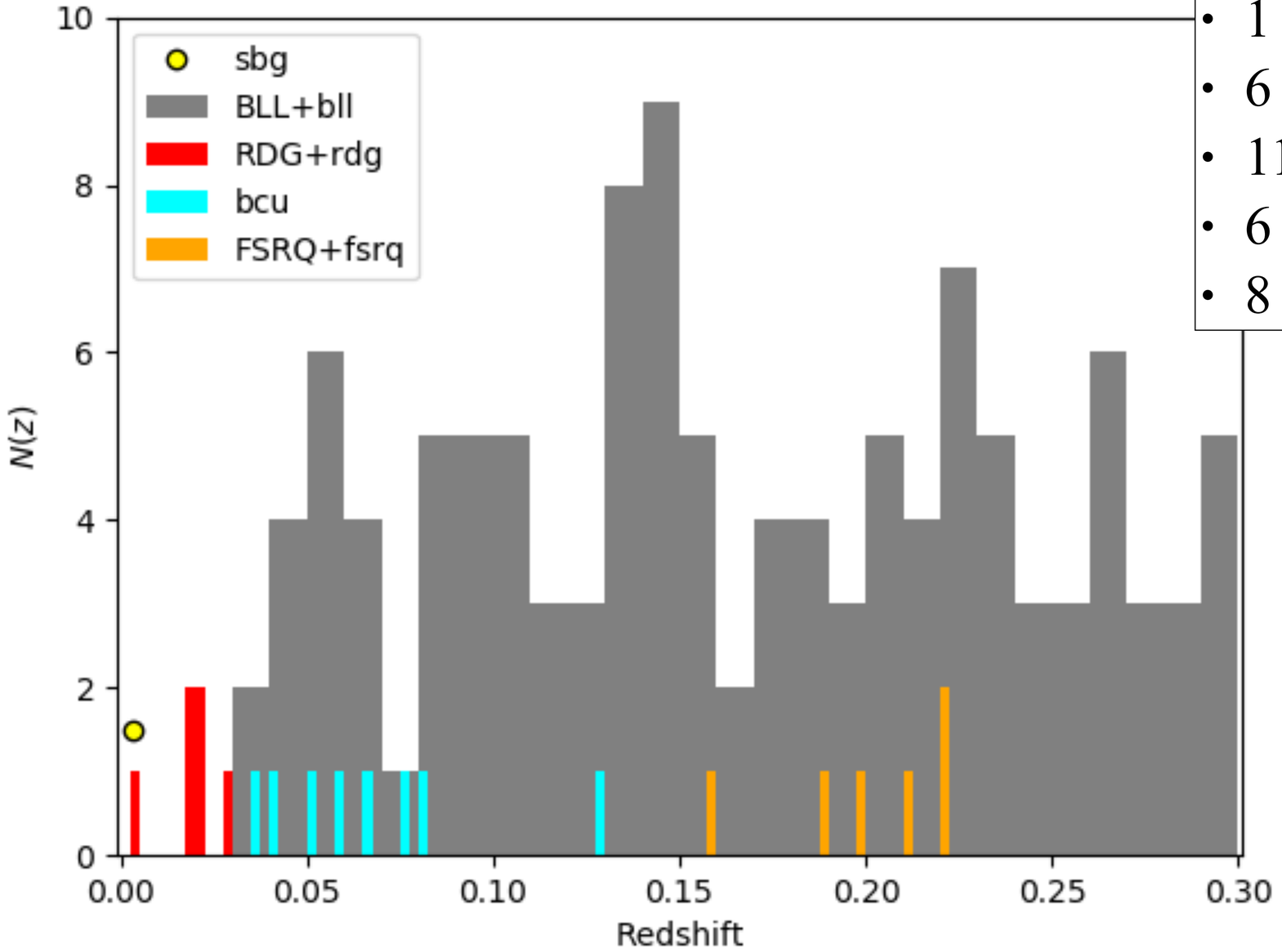
- Survey of AGN in the 3FHL within the FoV of HAWC ($|\delta\text{-}19^{\circ}|<40^{\circ}$) limited to $z<0.3$.
- Uses the HAWC 1017 day dataset: Nov 2014 to Dec 2017
  - 2HWC contains 507 day of data
- Standard HAWC analysis (as in Crab 2017 and 2HWC):
  - Maximum Likelihood testing spectral fits: intrinsic power-law × EBL at the position and redshift of the associated counterpart.
  - TS calculated from log-likelihood ratio between best fit (H_1) and null hypothesis (H_0)
  - EBL model of Dominguez et al. (2011).



1231 AGN in 3FHL

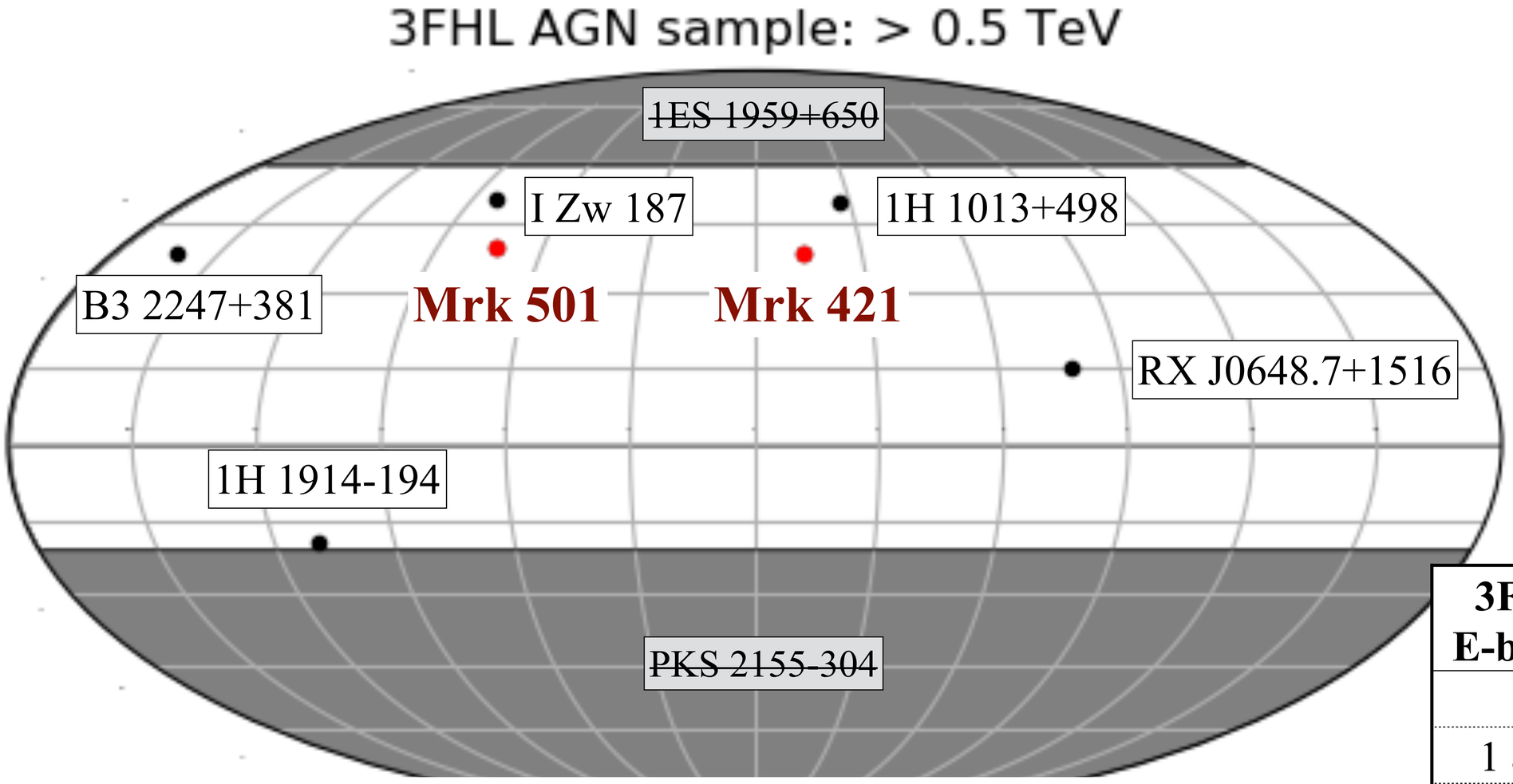


138 AGN in 3FHL & HAWC FoV & z<0.3 :: **THIS IS THE SAMPLE**



The sample is composed of:

- 1 starburst galaxy (NGC 1068)
- 6 radiogalaxies (M 87, IC 310…)
- 117 BL Lac objects
- 6 FSRQ
- 8 bcus



AGN in the sample detected in all Fermi bands

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

3FHL E-bands	N(TS>10)	N(TS>25)
1	127	95
1 & 2	110	68
1 → 3	72	43
1 → 4	28	13
1 → 5	7	2

4. The 3FHL sample

- AGNs in the 3FHL matching $|\delta - 19^{o}| < 40^{o}$ and $z < 0.3$
  - from 1251 total of AGNs to a sample of 138 (of which 117 BL Lacs).
- Finding best targets for HAWC:

  (1) TS>10 up to (0.5-2.0 TeV) in 3FHL ⇒ {**Mrk 421, Mrk 501** @ TS>25}
  + {I Zw 187 = **1ES 1727+502, 1H 1013+498, B3 2247+381, RX J0648.7+1516, 1H 1914–194**}.

  (2) extrapolated N(>0.5 TeV) ≥ 30 mCrab with 3FHL spectral parameters:
  {Mrk 421, Mrk 501, I Zw 187, B3 2247+381} +
  {**M87, IC 310, 1ES 2344+514, TXS 0210+515**}.

  (3) extrapolated N(>0.5 TeV) ≥ 30 mCrab from ACTs:
  + {**H 1426+428**}.

5. Analysis and results

- Description of f_{hit}, fraction of channels hit, as in Crab 2017 and 2HWC.
- HAWC 1017 day data, f_{hit} binned. MaxLik analysis: attenuated power-law fit at location and redshift of counterpart:

  $(dN/dE)_{intr} = \varphi_1 (E/1\ TeV)^{-\alpha} \Leftrightarrow (dN/dE)_{obs} = \varphi_1 (E/1\ TeV)^{-\alpha} \exp\{-\tau(E,z)\}$,

- **Run 1**: LiFF spectral fits with $\{\varphi_1 ; \alpha\}$ free.
- **Run 2**: 95% CL upper limits with Zebra, φ_1 free and α=2.5.
- Upper limits given here as observed photon fluxes:

  $N_{obs}(>0.5\ TeV) \leq \text{sqrt}(32/9)\ \varphi_1^{UL} \exp(-z/z_h)$

Object	Class	Redshift (z)	ϕ_1 (10^{-12}TeV^{-1}cm^{-2}s^{-1})	$N_{obs}(>0.5$ TeV) (10^{-12}cm^{-2}s^{-1})	s
Mrk 421	BL Lac	0.031	28.1 ± 1.3	39.76 ± 1.84	+45.7
Mrk 501	BL Lac	0.033	12.7 ± 1.3	17.64 ± 1.81	+19.9
M 87	RDG	0.004	≤ 0.52	≤ 0.95	+1.55
IC 310	RDG*	0.019	≤ 1.56	≤ 2.47	+1.06
1ES 2344+514	BL Lac	0.044	≤ 5.08	≤ 6.37	+0.70
TXS 0210+515	BL Lac	0.049	≤ 7.71	≤ 9.23	+1.65
1ES 1727+502	BL Lac	0.055	≤ 3.24	≤ 3.67	–0.40
B3 2247+381	BL Lac	0.119	≤ 2.85	≤ 1.78	–0.64
H 1426+428	BL Lac	0.129	≤ 8.83	≤ 5.03	+0.86
1H 1914–194	BL Lac	0.137	≤ 24.8	≤ 1.31	–0.51
RX J0648.7+1516	BL Lac	0.179	≤ 3.56	≤ 1.28	–0.51
1H 1013+498	BL Lac	0.212	≤ 2.48	≤ 0.66	–0.11

Table 1: The twelve best HAWC targets, all fitted assuming $\alpha = 2.5$. The upper panel shows the two detections, which are followed by the non-detections, ranked by redshift. The values for the two Markarians assume $\alpha = 2.5$, which differs from their best fit value. The limits are 95% confidence level.

Crab Nebula
$N_{0.5} \simeq 62.4$

Some of these BL Lac are EHBL (GAI5)

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About Mrk 421 and Mrk 501 with HAWC

Detailed spectral fits for Mrk 421 and Mrk 501	Sara Coutiño poster PS2-52
γ and X-ray correlations for Mrk 421	José Andrés García Talk GAI8h
Search for neutrinos on Mrk 421 and Mrk 501	Mukharbek Organokov NU6h

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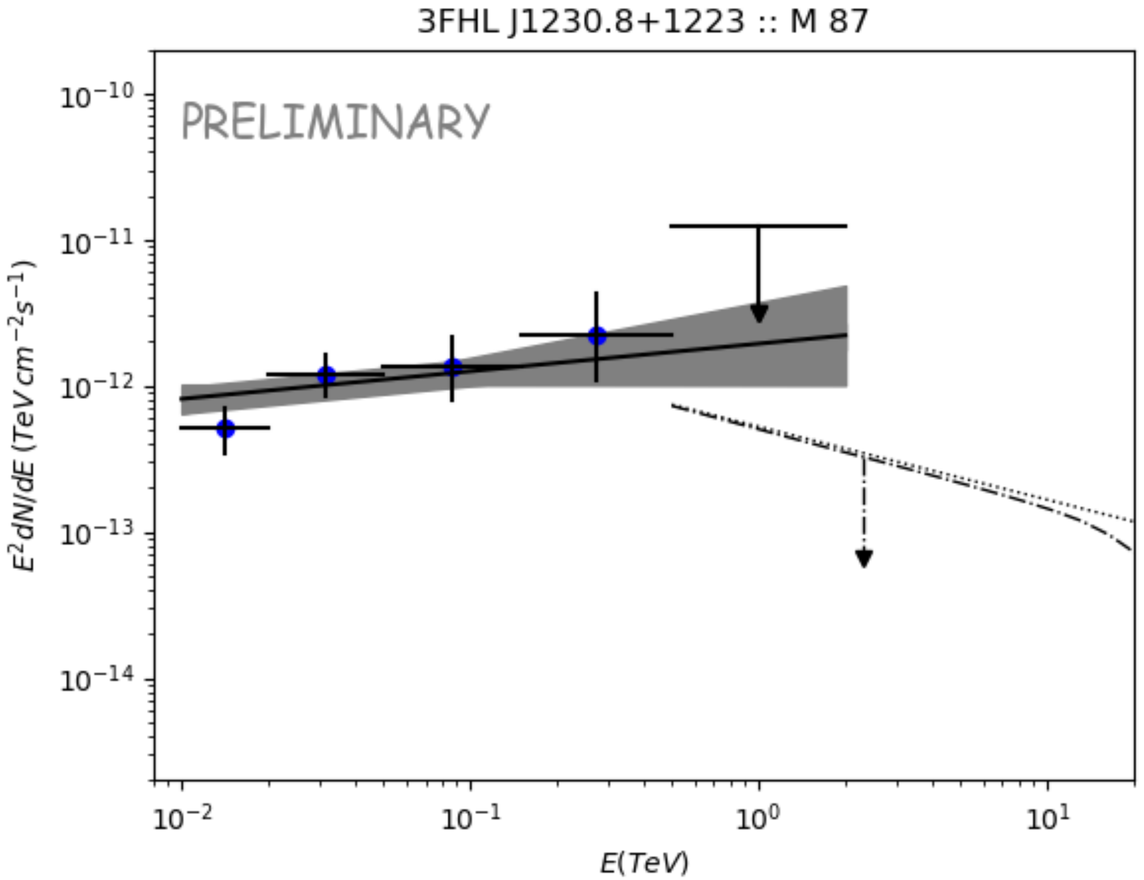
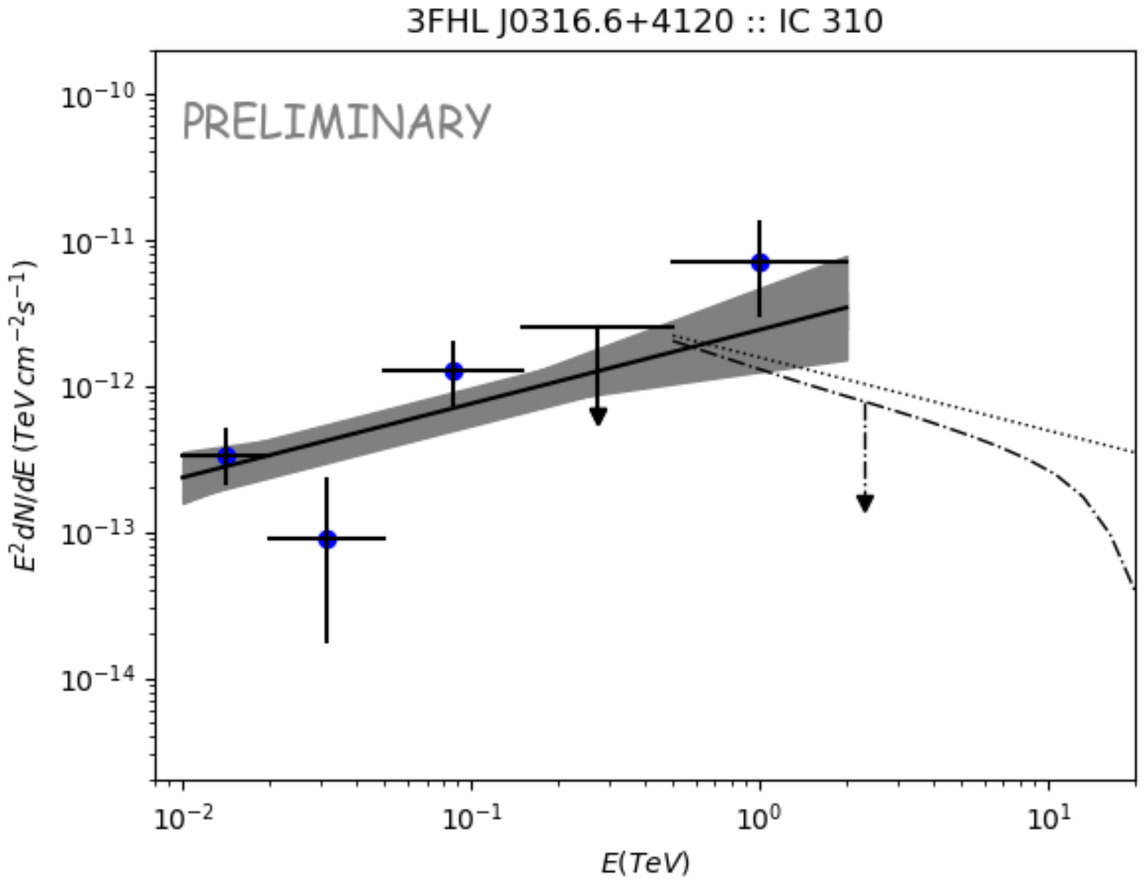
Two radiogalaxies





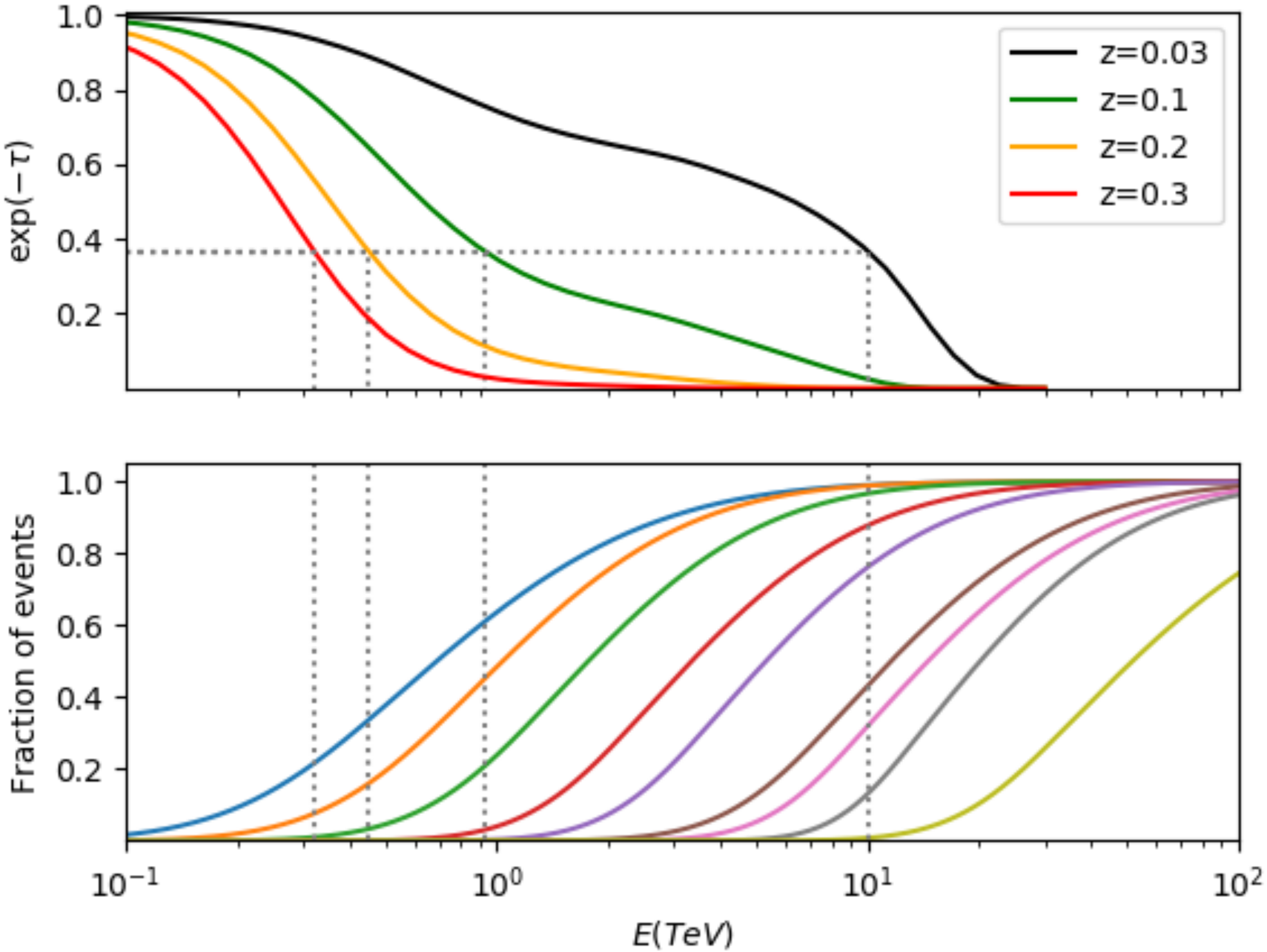
Radiogalaxies are of particular interest as γγ attenuation occurs above 1 TeV.

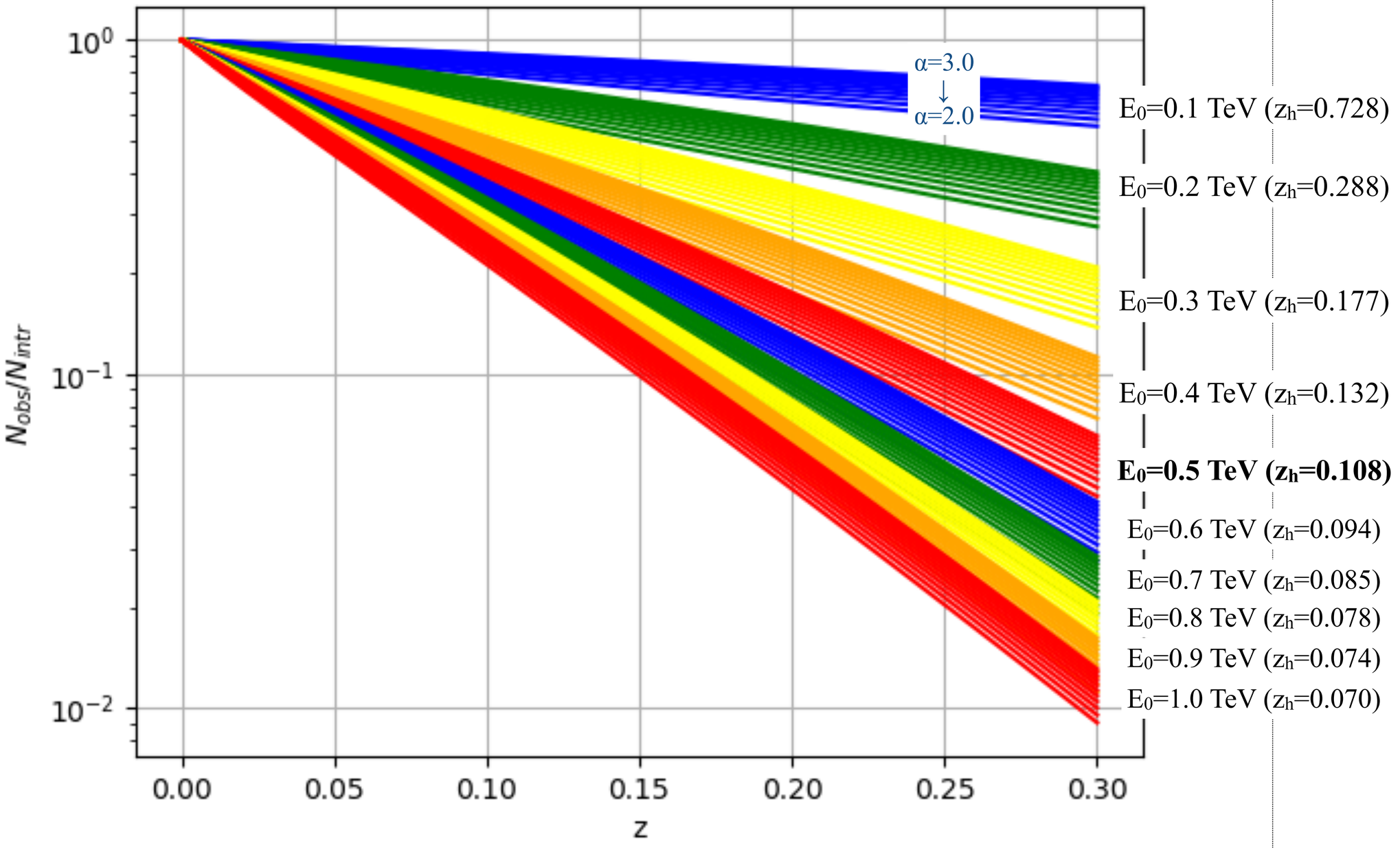
They can provide a more direct diagnostic on the production mechanisms.

For E>10 TeV they can sample the Mid to far IR part of the EBL.

Summary

- HAWC has performed a follow-up of 138 AGN detected above 10 GeV by *Fermi*-LAT; selected as those in its FoV and $z<0.3$.
- The two nearest BL Lac objects known, Mrk 421 and Mrk 501, are detected with high significance.
- Upper limits are set for the rest of the sample:
  - the EBL is an important limiting factor to reach beyond $z \gtrsim 0.1$ with current air shower arrays.
  - long term average TeV emission from radiogalaxies is below 30 mCrab.
  - Full search refereed draft paper in HAWC editorial pipeline.
- Work on development and implementation of low-energy analysis tools.


1.0
0.8
0.6
0.4
0.2
exp(−τ)
z=0.03
z=0.1
z=0.2
z=0.3
Fraction of events
10^{-1}
10^{0}
10^{1}
10^{2}
E(TeV)


10^0
10^{-1}
10^{-2}
N_{obs}/N_{intr}
0.00
0.05
0.10
0.15
0.20
0.25
0.30
z
α=3.0
↓
α=2.0
E_0=0.1 TeV (z_h=0.728)
E_0=0.2 TeV (z_h=0.288)
E_0=0.3 TeV (z_h=0.177)
E_0=0.4 TeV (z_h=0.132)
E_0=0.5 TeV (z_h=0.108)
E_0=0.6 TeV (z_h=0.094)
E_0=0.7 TeV (z_h=0.085)
E_0=0.8 TeV (z_h=0.078)
E_0=0.9 TeV (z_h=0.074)
E_0=1.0 TeV (z_h=0.070)