Observation of radio galaxies with HAWC

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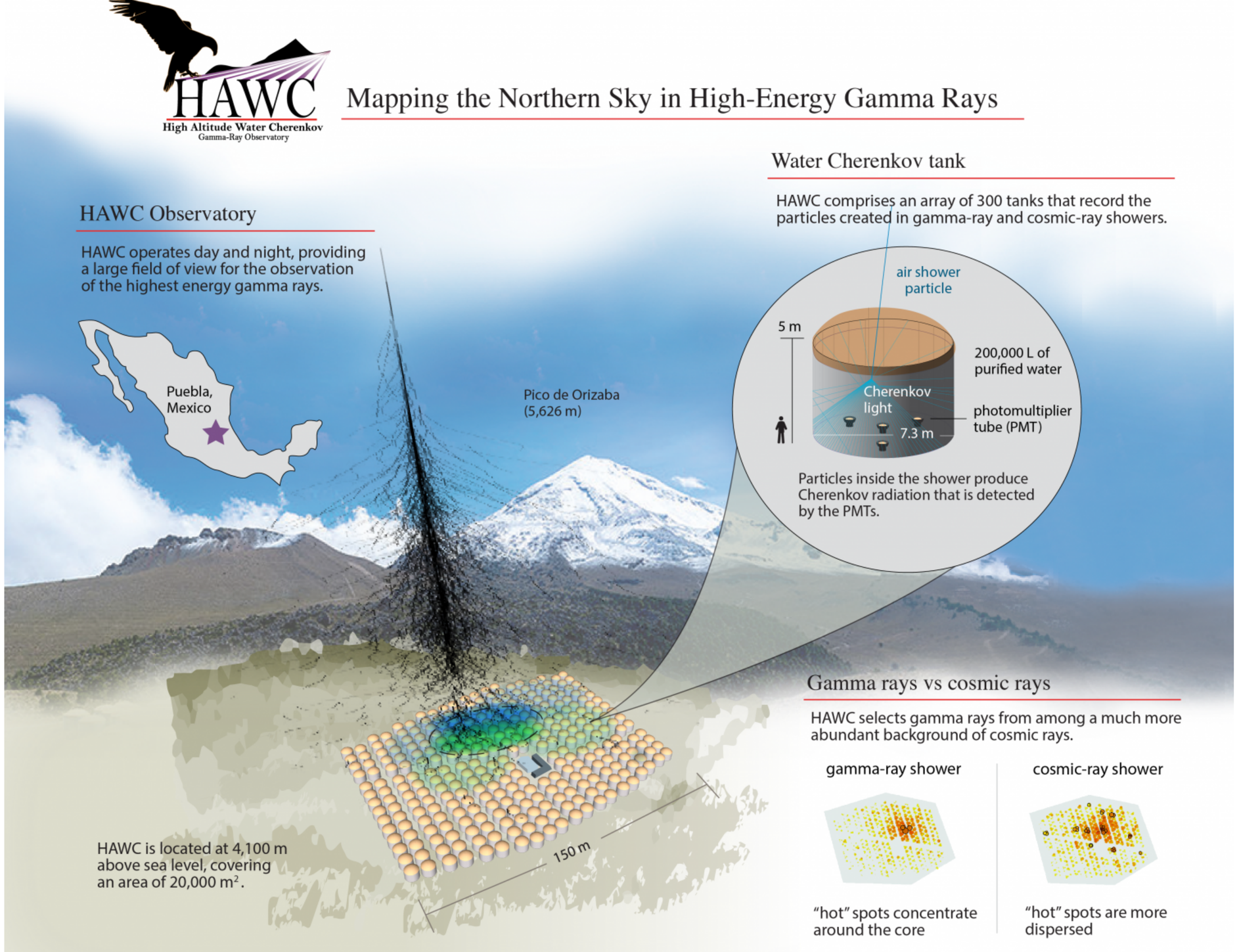


Some characteristics:

- DC > 95%
- Wide F.O.V
- 300 GeV - 100 TeV

=> HAWC is a good experiment to source monitoring.

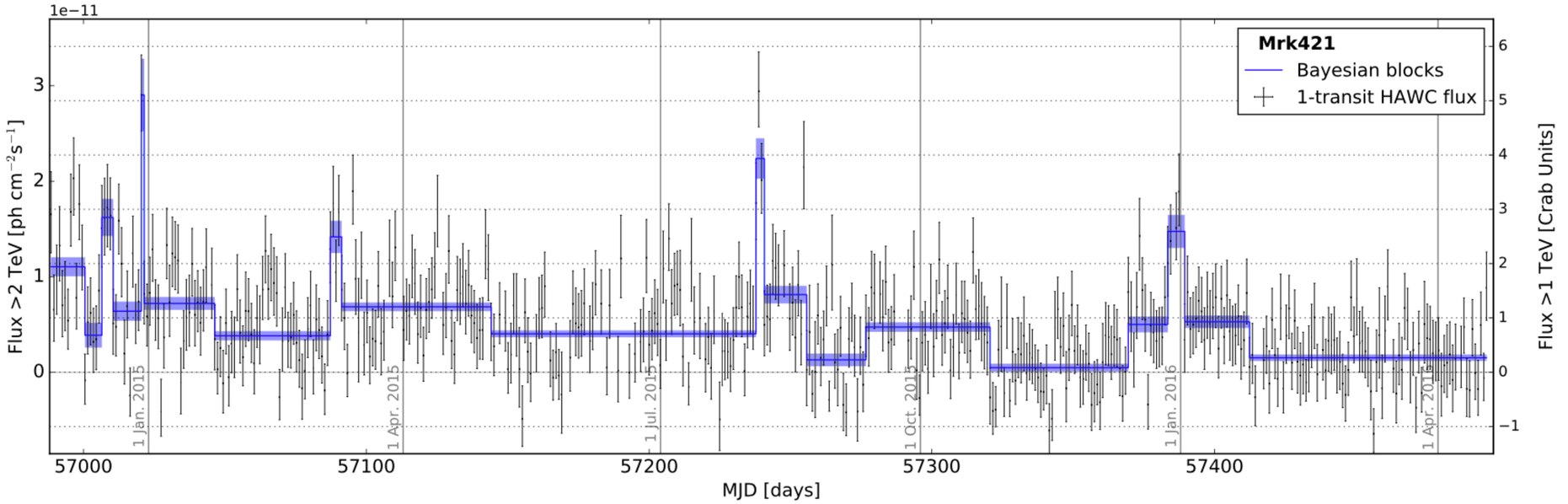


Figure 4. Flux light curve for Mrk 421 with sidereal-day sampling for 471 transits between 2014 November 26 and 2016 April 20. The integrated fluxes are derived from fitting F_i in $dN/dE = F_i\,(E/(1\ \mathrm{TeV}))^{-2.2}\exp(-E/(5\ \ \mathrm{TeV}))$ and converted to Crab Units via dividing by the HAWC measurement of the average Crab Nebula gamma-ray flux. The blue lines show the distinct flux states between change points identified via the Bayesian blocks analysis with a 5% false positive probability.

A. U. Abeysekara (2017) DOI: 10.3847/1538-4357/aa729e

Radio Galaxy (RG)

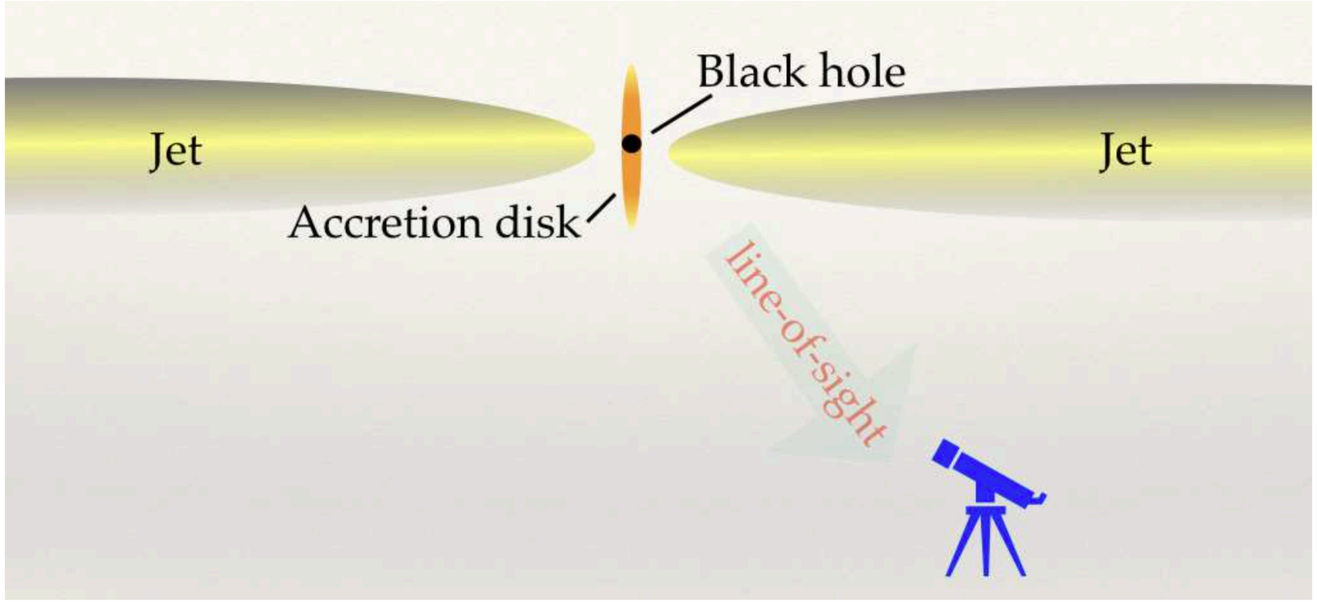


Figure 1. Sketch representing the mis-aligned radio emitting bipolar jets of a radio galaxy (not to scale). Jets typically extend up to a few hundreds of kilo-parsec to mega-parsec scales.

B. Rrani (2018) arXiv:1811.00567

- RG is a class of Active Galactic Nuclei (AGN).
- Host a relativistic jet misaligned with the line of sight.
- Prove the physics of VHE emission process.

Radio Galaxies at TeV

Table 1. 3LAC MAGN: (i) Source name; (ii) 3FGL name; (iii) right ascension; (iv) declination; (v) redshift; (vi) radio classification; (vii) detected TeV counterpart. 3C 120 has been added to the list since it is a confirmed γ-ray source, and also Tol1326-379 and PKS1718-379 recently associated with 3FGL sources.

Source	3FGL Name	RA (J2000)	Dec (J2000)	z	FR type	TeV source
3C 78	3FGLJ0308.6+0408	03 08 26.22	+04 06 39.3	0.02865	FR I	no
IC310	3FGLJ0316.6+4119	03 16 42.97	+41 19 29.61	0.019	FR I	yes
NGC1275	3FGLJ0319.8+4130	03 19 48.16	+41 30 42.1	0.0175	FR I	yes
ForA(lobes)	3FGLJ0322.5-3721	03 21 37.75	-37 12 49.1	0.00587	FR I	no
4C+39.12	3FGLJ0334.2+3915	03 34 18.41	+39 21 24.4	0.02059	FR I	no
Pictor A	3FGLJ0519.2-4542	05 19 49.72	-45 46 43.85	0.03506	FR II	no
PKS0625-35	3FGLJ0627.0-3529	06 27 06.72	-35 29 15.33	0.05494	FR I	yes
3C 189	3FGLJ0758.7+3747	07 58 28.1	+37 47 11.8	0.04284	FR I	no
3C 221	3FGLJ0934.1+3933	09 35 06.63	+39 42 06.7	–	FR II/SSRQ	no
3C 264	3FGLJ1145.1+1935	11 45 05.0	+19 36 22.74	0.02172	FR I	yes
M87	3FGLJ1230.9+1224	2 30 49.42	+12 23 28.04	0.00428	FR I	yes
CenA(core)	3FGLJ1325.4-4301	13 25 27.61	-43 01 08.8	0.0018	FR I	yes
3C 303	3FGLJ1442.6+5156	14 43 02.76	+52 01 37.29	0.14119	FR II	no
NGC6251	3FGLJ1630.6+8232	16 32 31.96	+82 32 16.39	0.02	FR I	no
3C 111	3FGLJ0418.5+3813c	04 18 21.27	+38 01 35.8	0.0485	FR II	no
CenB	3FGLJ1346.6-6027	13 46 49.04	-60 24 29.35	0.01292	FR I	no
TXS0348+013	3FGLJ0351.1+0128	03 50 57.36	+01 31 04.91	1.12	FR II/SSRQ	no
3C 207	3FGLJ0840.8+1315	08 40 47.58	+13 12 23.56	0.681	FR II/SSRQ	no
PKS1203+04	3FGLJ1205.4+0412	12 06 19.92	+04 06 12.04	0.536	FR II/SSRQ	no
3C 275.1	3FGLJ1244.1+1615	12 43 57.64	+16 22 53.39	–	FR II/SSRQ	no
3C 380	3FGLJ1829.6+4844	18 29 31.78	+48 44 46.16	0.695	FR II/SSRQ	no
3C 120	–	04 33 11.1	+05 21 16	0.033	FR I	no
Tol1326-379	3FGL1330.0-3818	13 29 19.2	-38 14 18	0.028	FR 0	no
PKS1718-649	3FGLJ1728.0-6446	17 23 41.0	-65 00 37	0.014	CSO	no

RG detected with TeV counterpart:

1. IC310
2. NGC1275
3. PKS0623-35
4. 3C 264
5. M87
6. CenA(core)

Torresi, E. (2018) DOI: https://doi.org/10.1017/S1743921318007895

Radio Galaxies at TeV

Table 1. Radio galaxies detected at TeV energies

Source	Type	**Redshift (Distance in Mpc)**	$\mathbf{M}_{BH}$ $(\mathbf{M}_{\odot})$	$\mathbf{L}_{VHE}$ **(erg s^{-1})**
Centaurus A	FR1	0.00183 (3.7) [23]	5×10^{7} [24]	10^{40}
M87	FR1	0.0044 (16) [25]	6×10^{9} [26]	10^{41}
3C 84	FR1	0.0177 (71) [27]	$(3\text{-}8)\times10^{8}$ [28,29]	10^{45}
IC 310	FR1	0.0189 (80) [30]	$(1\text{-}7)\times10^{8}$ [24,31]	10^{44}
3C 264	FR1	0.0217 (95) [32]	2.6×10^{8} [33]	6×10^{43}
PKS 0625-35	FR1/BL Lac	0.05488 (220) [34]	3×10^{9} [24]	5×10^{41}

B. Rani (2018) arXiv:1811.00567

The RG are:

- The closest Extragalactic objects.
- Harbors a Super Massive Black Hole ~10^(8-9) solar masses.
- Luminosities up to 10^45 ergs s^-1.
- Classified as Fanaroff and Riley type I (FR1).

Radio Galaxies at TeV

"Like Blazars, TeV radio galaxies exhibit variability on multiple timescale" B. Rani (2018).

There are two state: flaring and quiescent.

A. M87 was the first TeV detected radio galaxy.

   Three active states:

   1. 2005 flare is reported by H.E.S.S.
   2. 2008 flare is reported by MAGIC
   3. 2010 flare is reported by VERITAS

B. NGC1275

   Two active states:

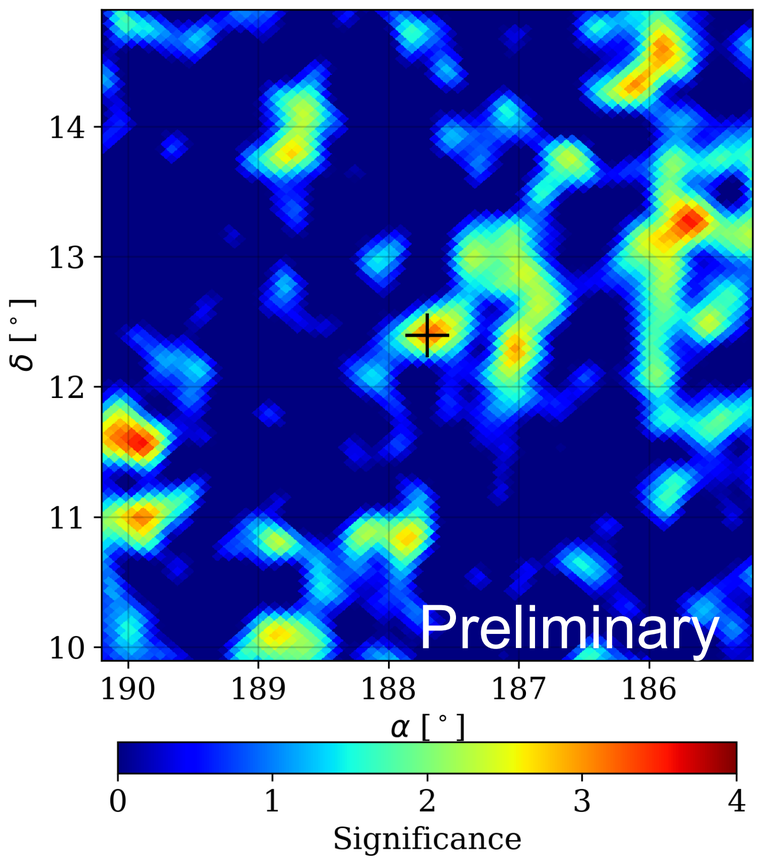
   4. October 2016
   5. Dember 2016

C. 3C 264

Figures

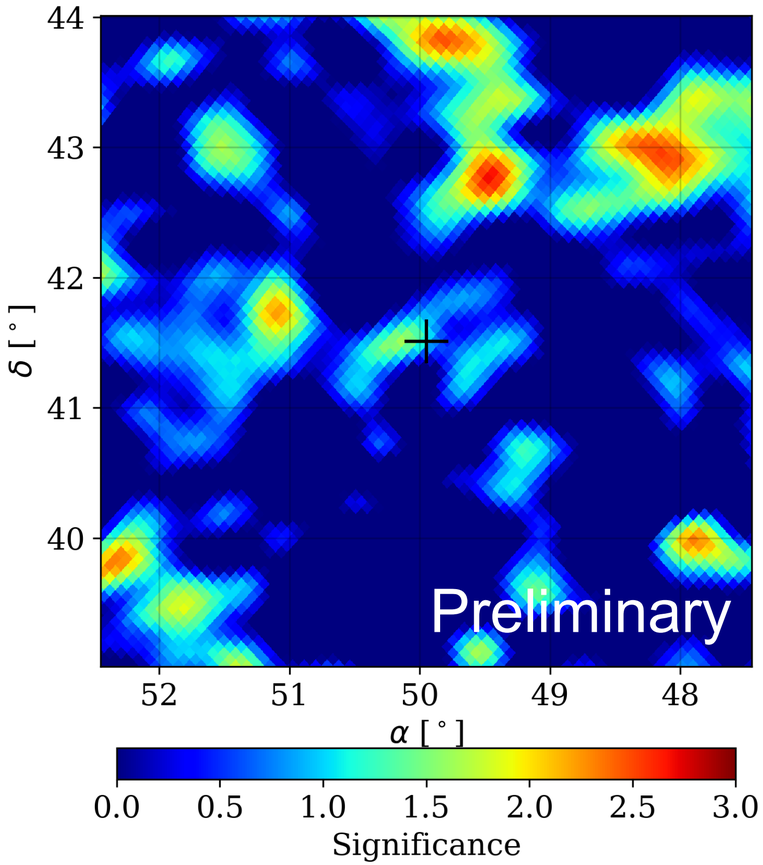
Using 1523 days

M87



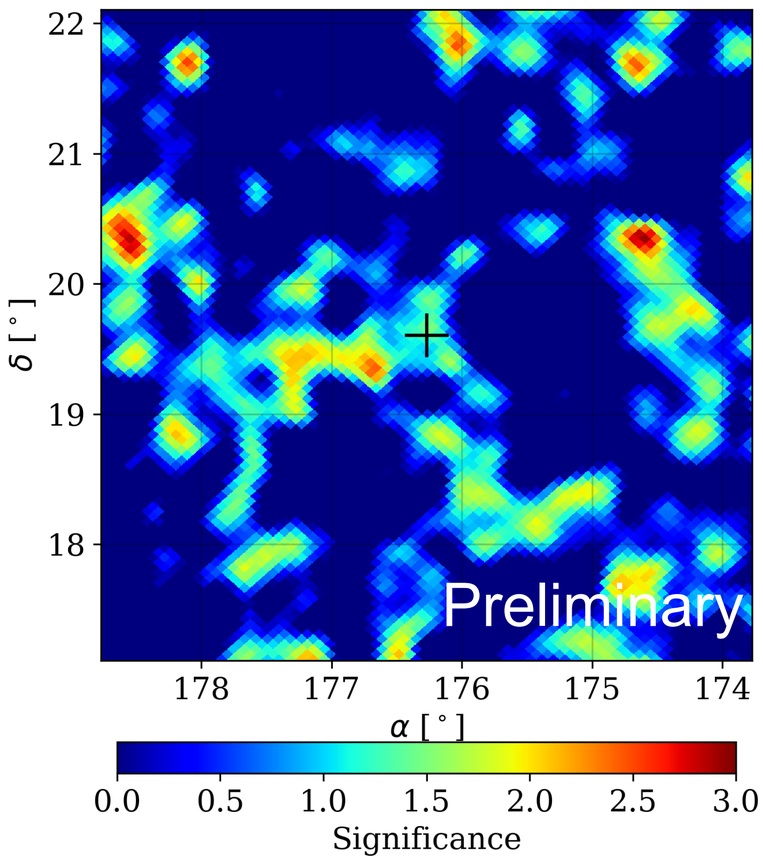
At source: 3.20

NGC1275



At source: 1.15

3C 264

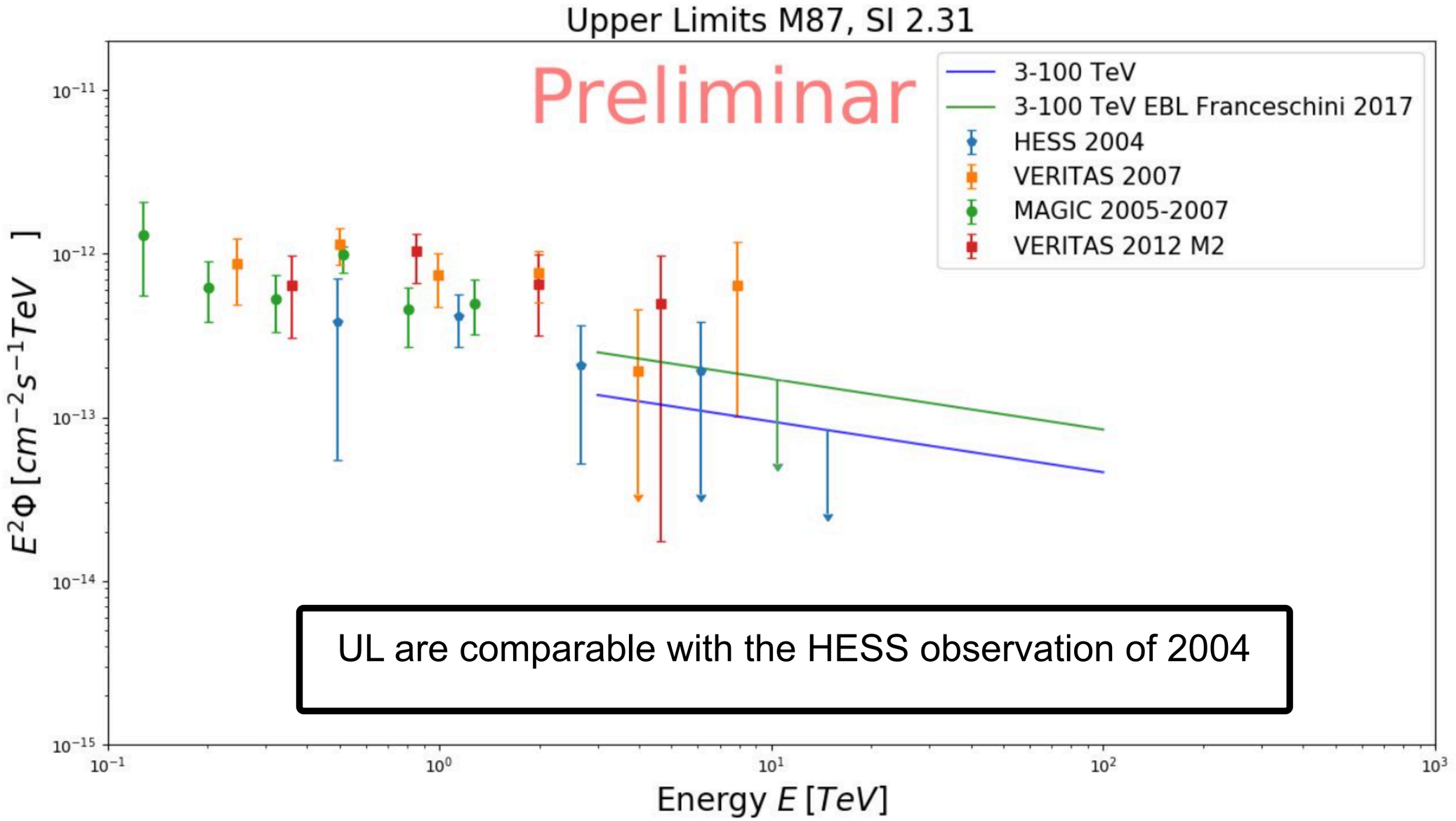


At source: 1.47

Upper Limit

Source	UL with EBL (TeV^-1cm^-2s^-1)	UL without EBL (TeV^-1cm^-2s^-1)	Sigma
M87	2.63E-13	2.63E-13	2.77
NGC1275	1.21E-12	1.05E-11	0.82
3C 264	1.89E-13	2.56E-13	-1.36

EBL Model = Franceschini 2008

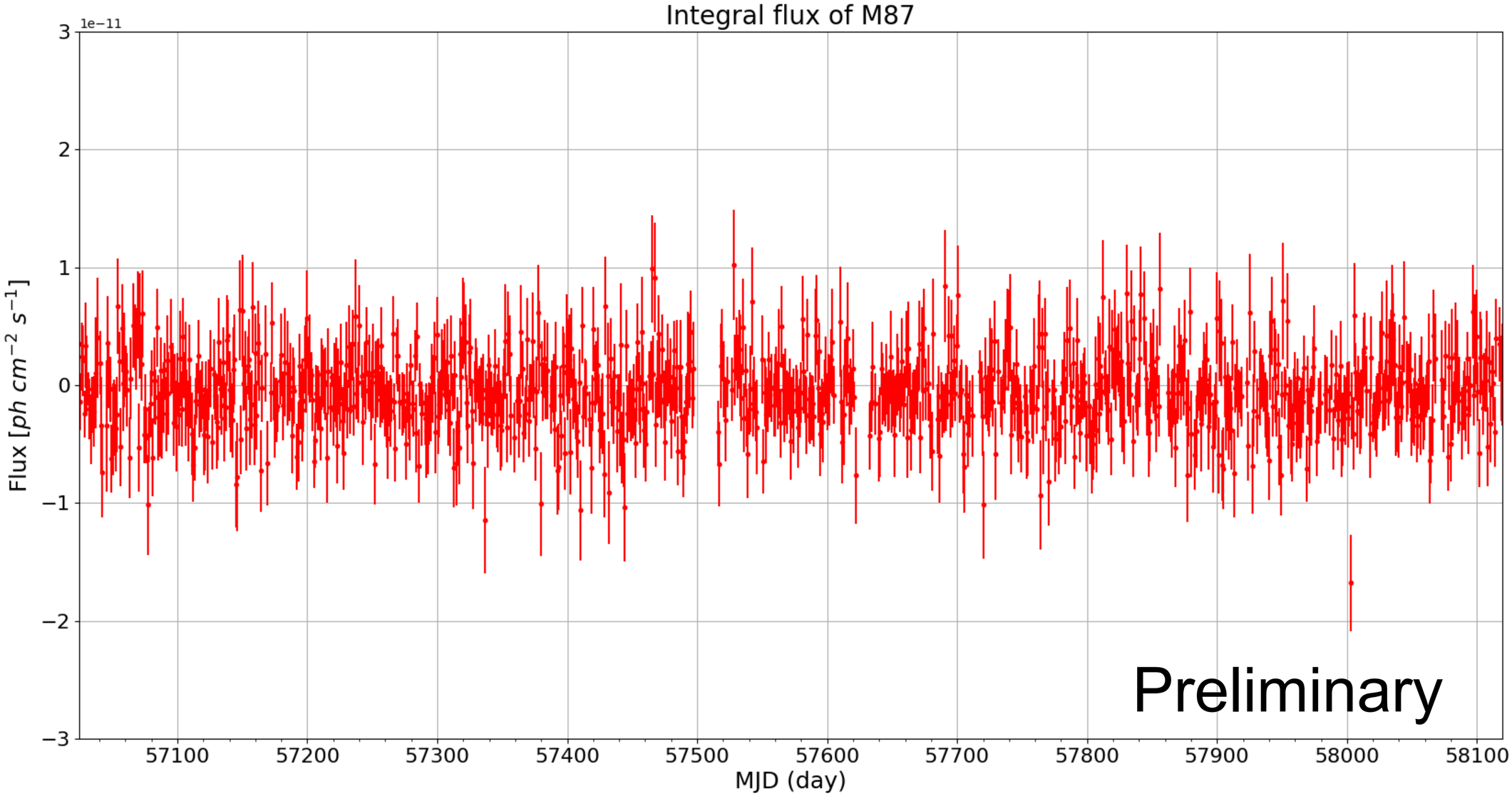


UL are comparable with the HESS observation of 2004

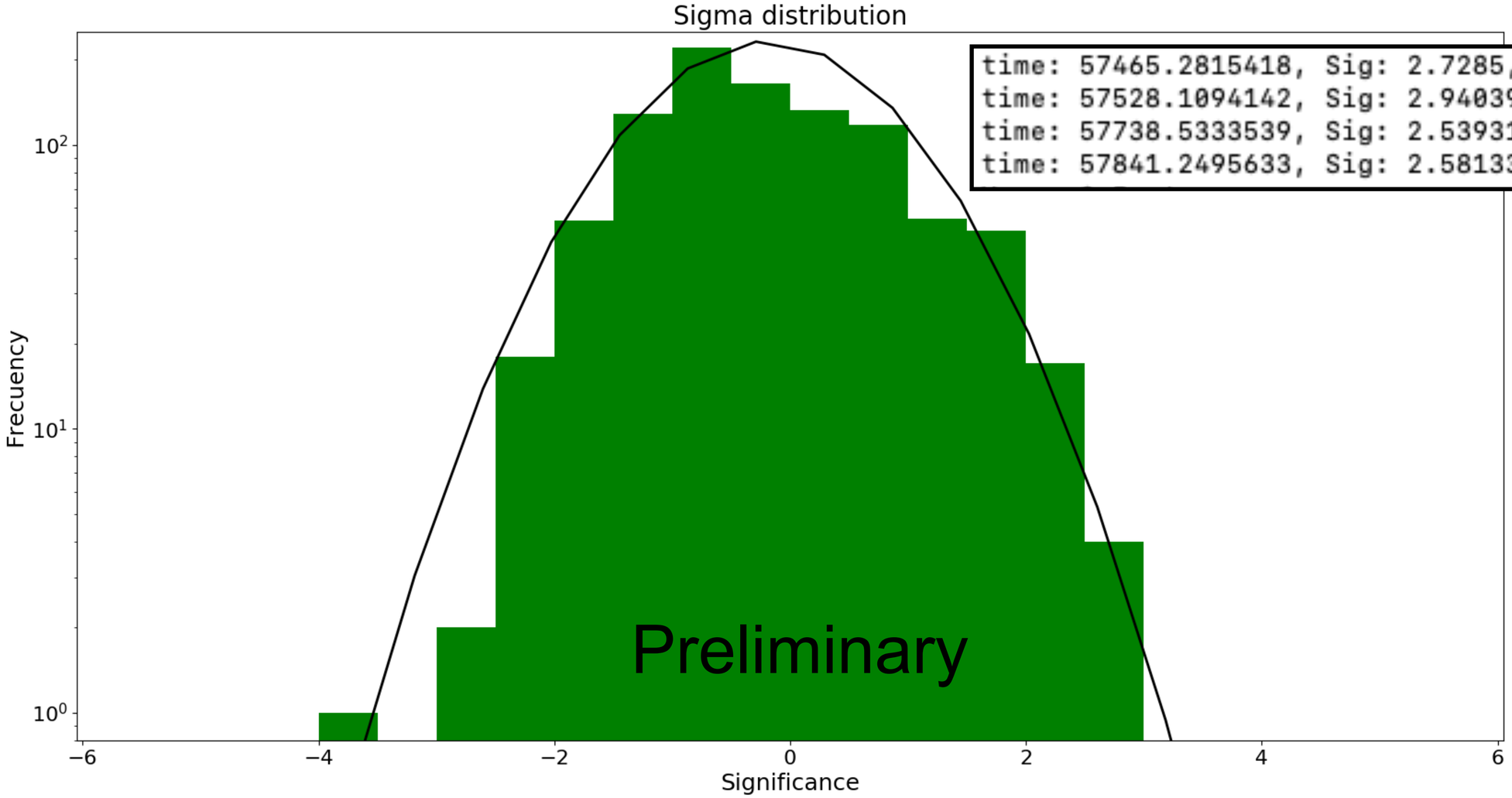
D. Avila (2019) arXiv:1909.00075 & thesis

M87 light curve

Simple Power Law
Index = 2.31
Redshift = 0.0044
Energy pivot = 1 TeV



M87 light curve




```
time: 57465.2815418, Sig: 2.7285, Flux: 9.86778625954e-12
time: 57528.1094142, Sig: 2.94039, Flux: 1.0211221374e-11
time: 57738.5333539, Sig: 2.53931, Flux: 5.06897709924e-12
time: 57841.2495633, Sig: 2.58133, Flux: 7.71160305344e-12
```

```
Fit results: mu = -0.19,  std = 1.02
```

NGC 1275 light curve

CutOff Power Law
Index = 3.0
Redshift = 0.017559
Energy pivot = 1 TeV
Energy cut = 500 GeV

```
time: 57093.2727599, Sig: 2.75227, Flux: 1.47457091373e-11
time: 57404.4481087, Sig: 2.50094, Flux: 1.24323394368e-11
time: 57546.060495, Sig: 2.60842, Flux: 1.3480438653e-11
time: 57854.2164807, Sig: 2.61711, Flux: 1.34898101341e-11
time: 57923.0815373, Sig: 2.53452, Flux: 1.24582842768e-11
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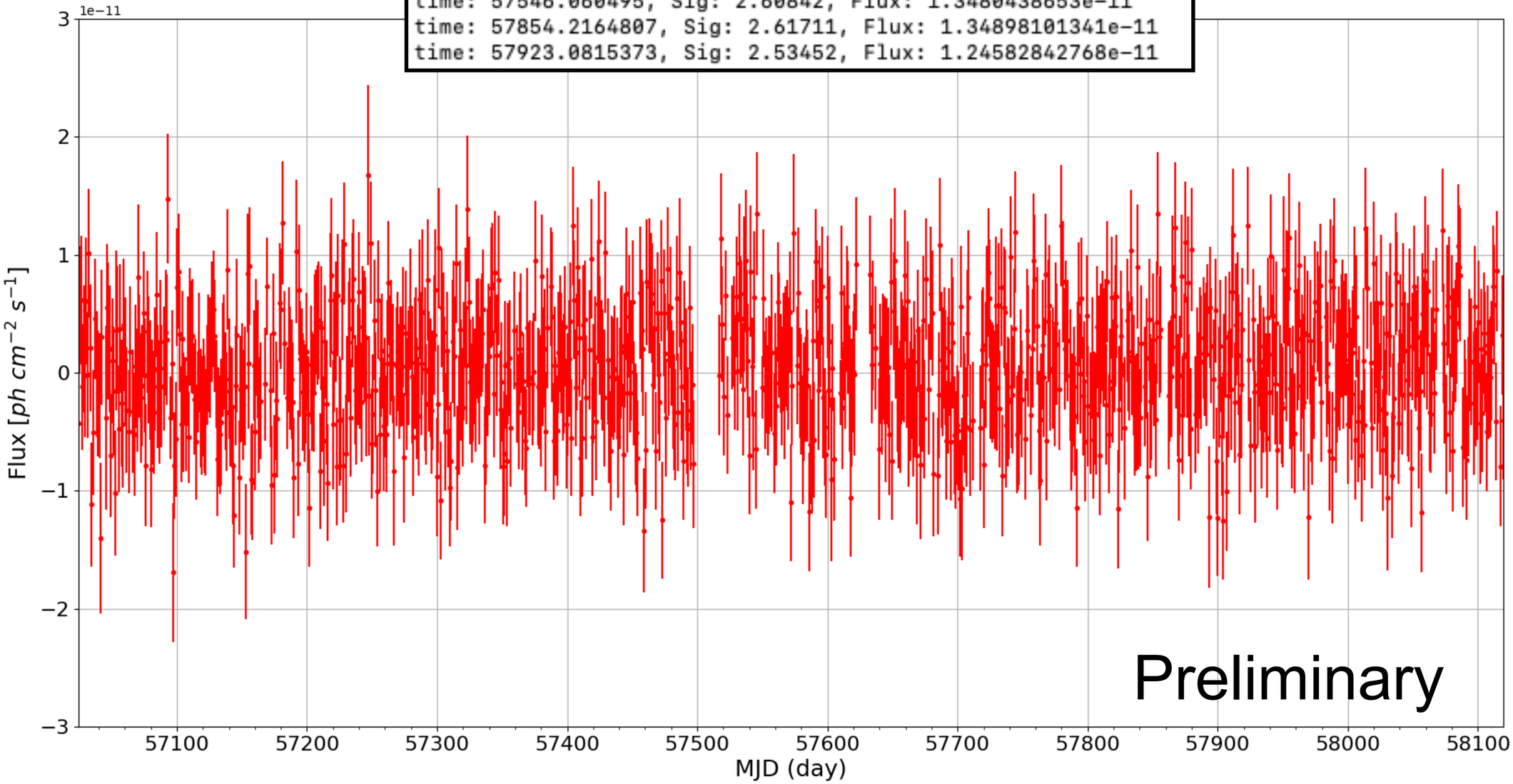
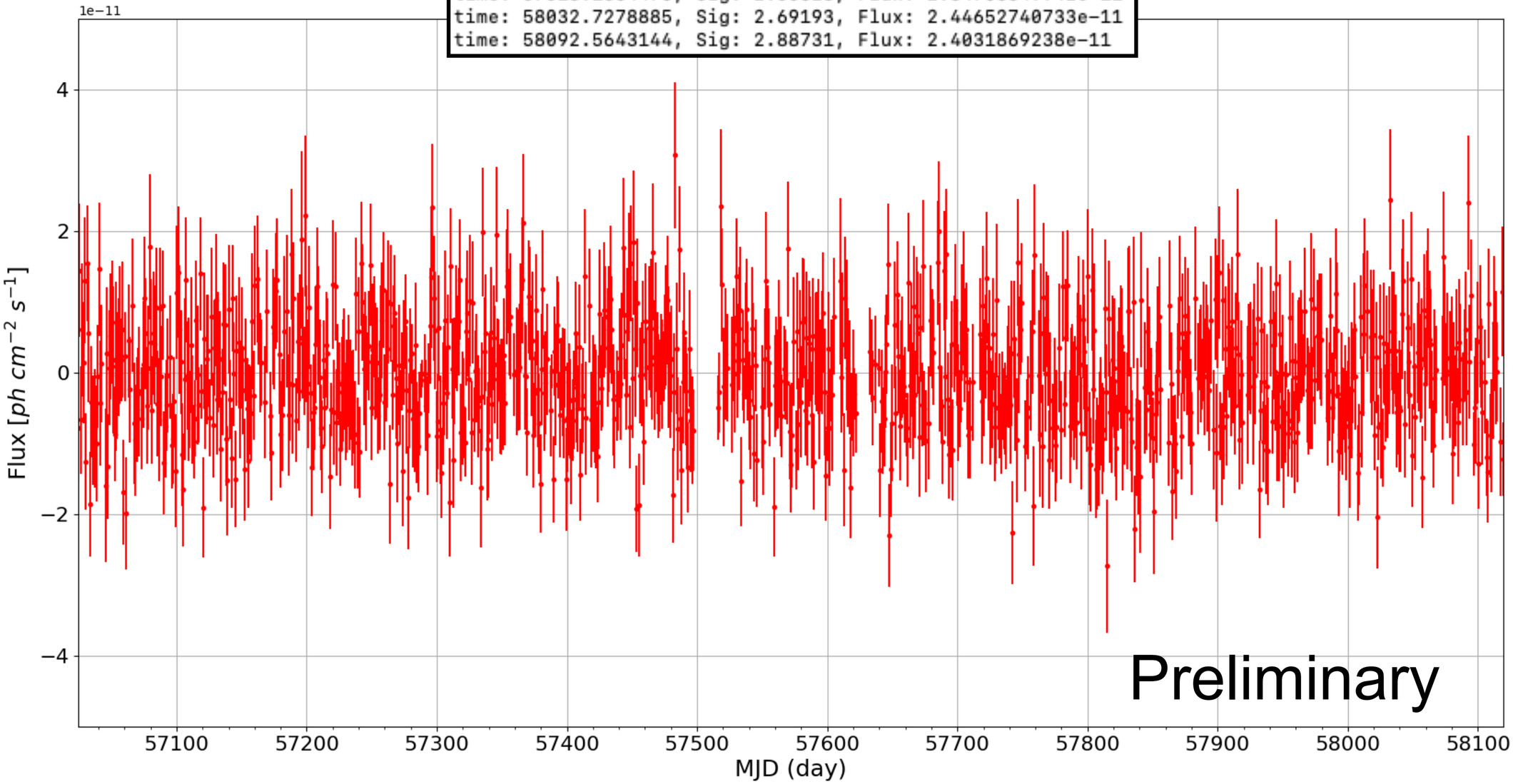


3C 264 light curve

CutOff Power Law
Index = 2.3
Redshift = 0.022
Energy pivot = 1 TeV
Energy cut = 10 TeV

```
time: 57296.7433623, Sig: 2.94752, Flux: 2.33722909339e-11
time: 57483.2325958, Sig: 3.32255, Flux: 3.07200992702e-11
time: 57518.1364476, Sig: 2.53628, Flux: 2.34706349942e-11
time: 58032.7278885, Sig: 2.69193, Flux: 2.44652740733e-11
time: 58092.5643144, Sig: 2.88731, Flux: 2.4031869238e-11
```



Summary

- The significance of the RG are less than 5 sigmas.
- The UL were computed for three radio galaxies.
- The LC were obtained for the three radio galaxies.

Thanks!