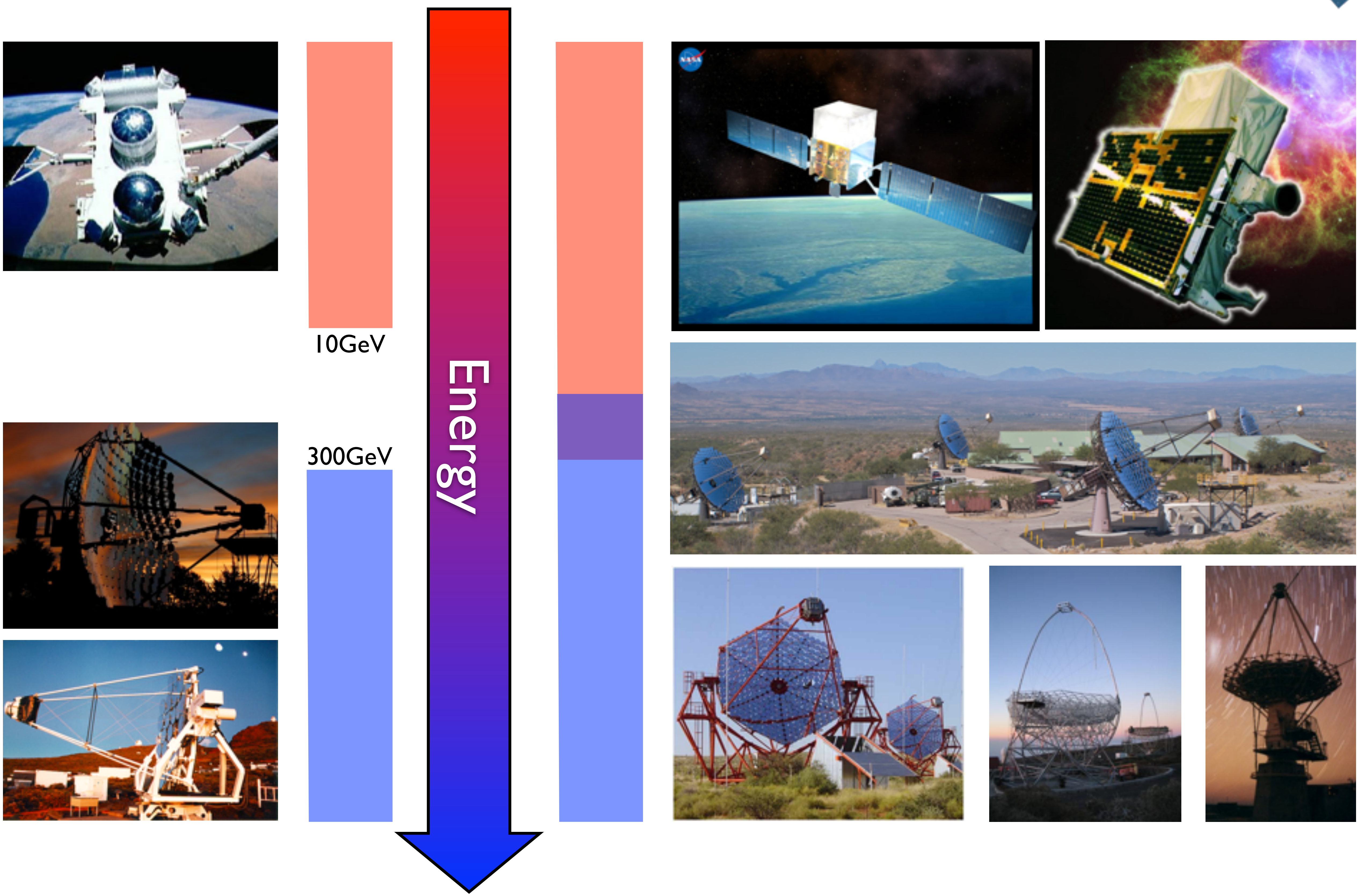
GeV-TeV AGN in the *Fermi* era

Stephen Fegan
(LLR/Ecole Polytechnique)

for the
Fermi-LAT collaboration

GeV-TeV revolution

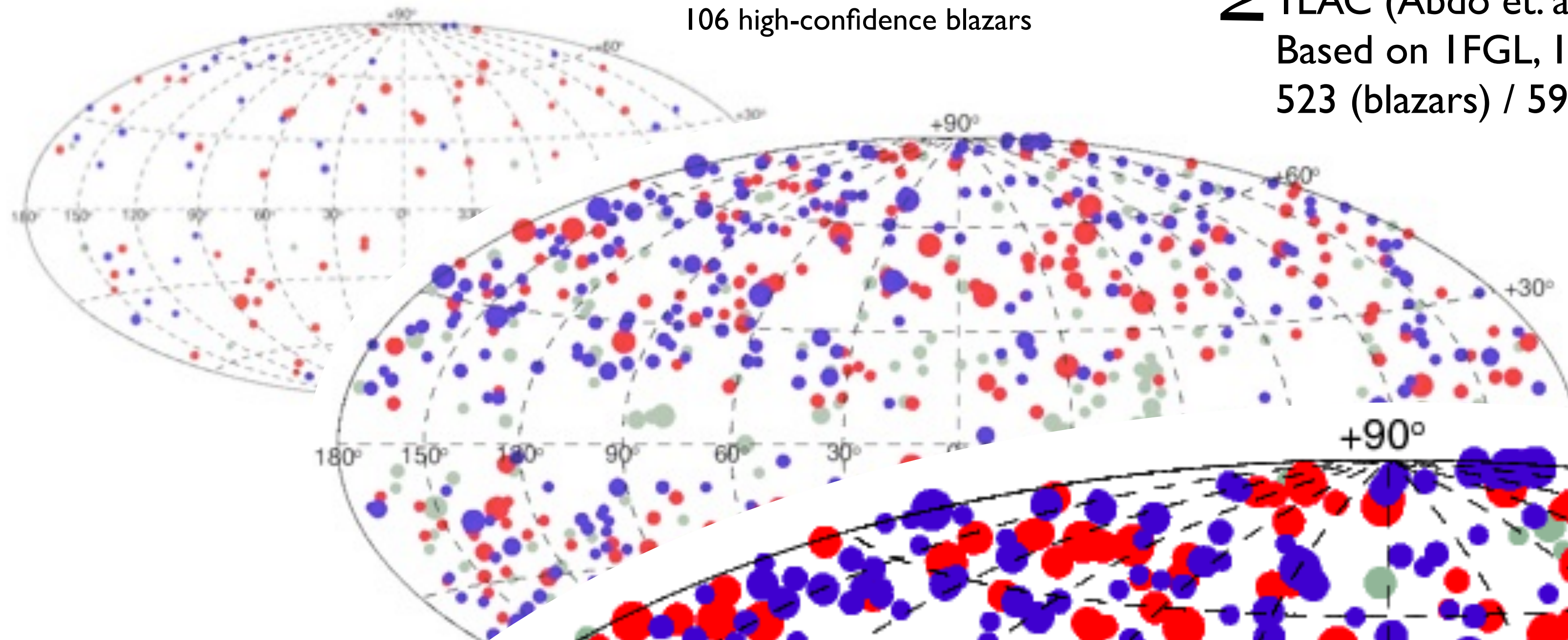


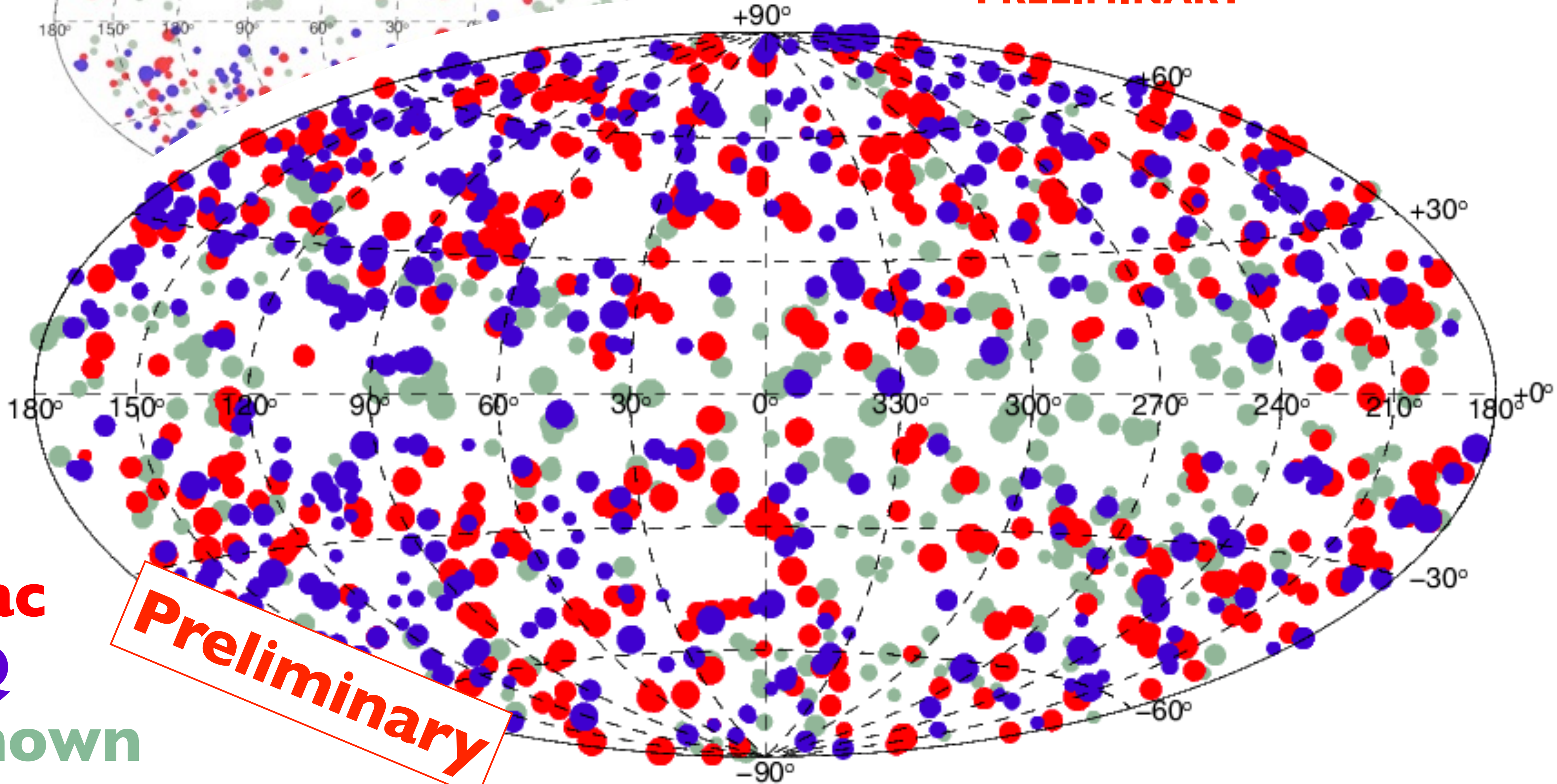
Fermi AGN

1 LBAS (Abdo et. al 2009, ApJ 700, 597)
Based on 0FGL, 3 months data, ~10σ
106 high-confidence blazars

2 1LAC (Abdo et. al 2010, ApJ 715, 429)
Based on 1FGL, 11 months data, ~5σ
523 (blazars) / 599 (total) in clean sample

3 2LAC (Abdo et. al 2011, ApJ in prep.)
Based on 2FGL, 24 months data, ~5σ
863 (blazars) / 885 (total) in clean sample
PRELIMINARY





BL Lac
FSRQ
Unknown

2LAC vs 1LAC

- Longer integration time - 24 months
- Better analysis methodology - Binned
- Improved instrument response - “Pass7”
- Higher resolution Galactic model
- More accurate localization - fewer multiple assoc.
- More sensitive test of source variability
- Three AGN association methods
- Optical follow-up studies of 1LAC sources

AGN populations

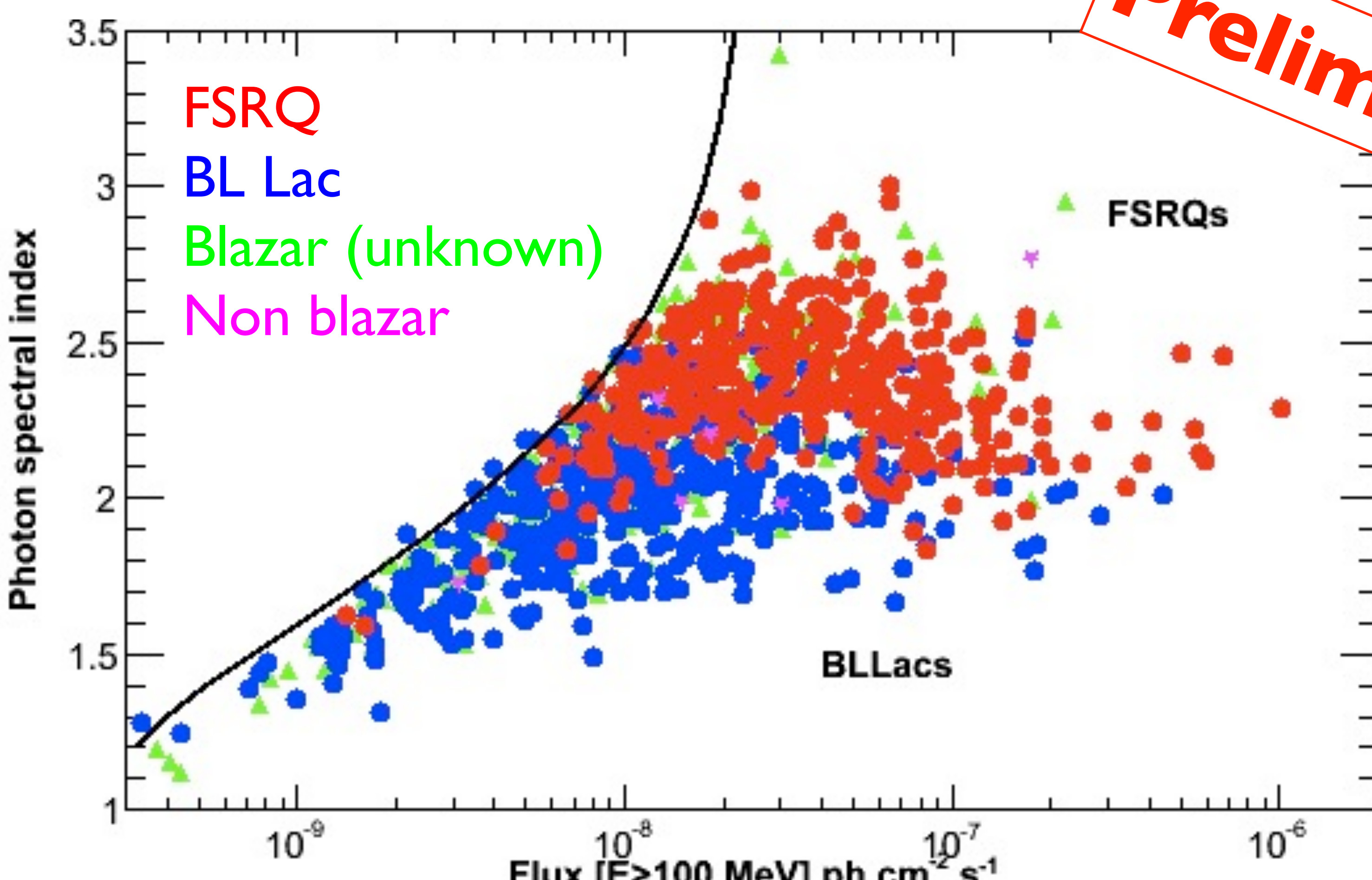
Preliminary

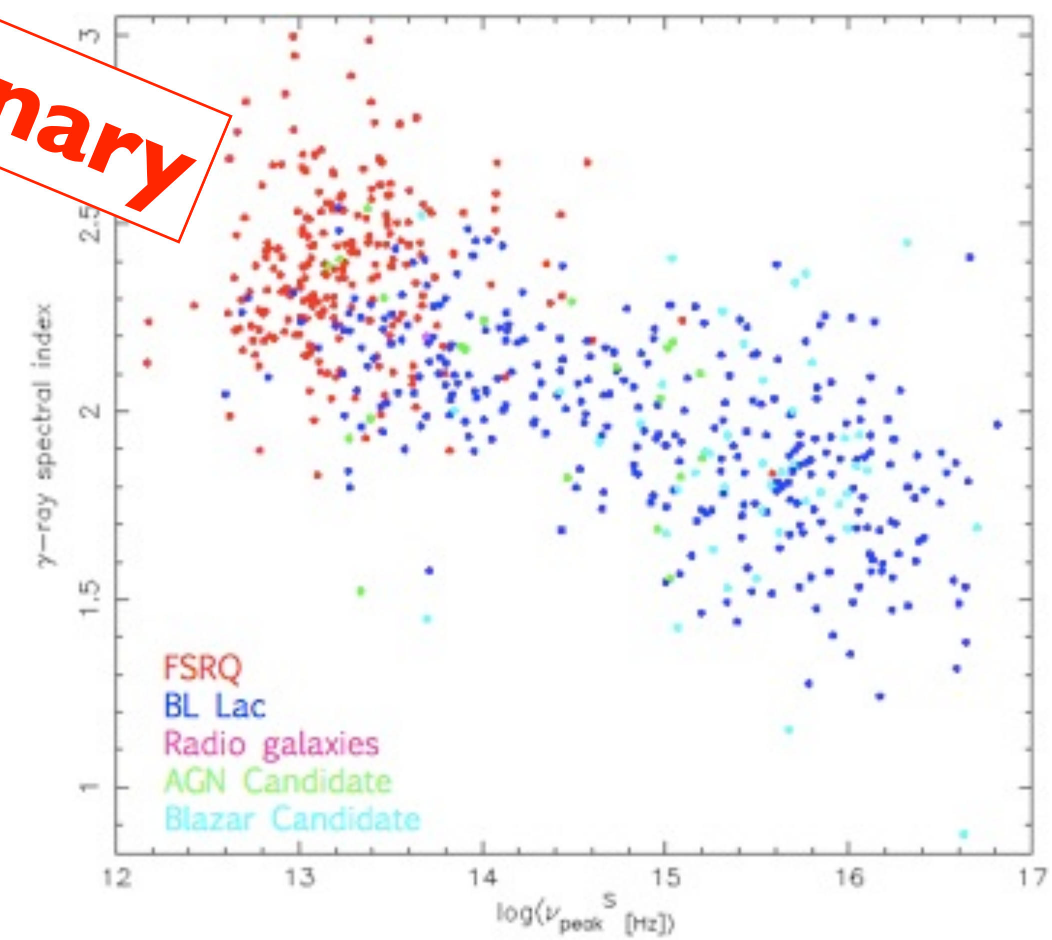
2LAC clean sample: 885 AGN candidates

FSRQ:	35%
BL Lac:	44%
Blazar (unknown):	18%
Other AGN:	2.5%

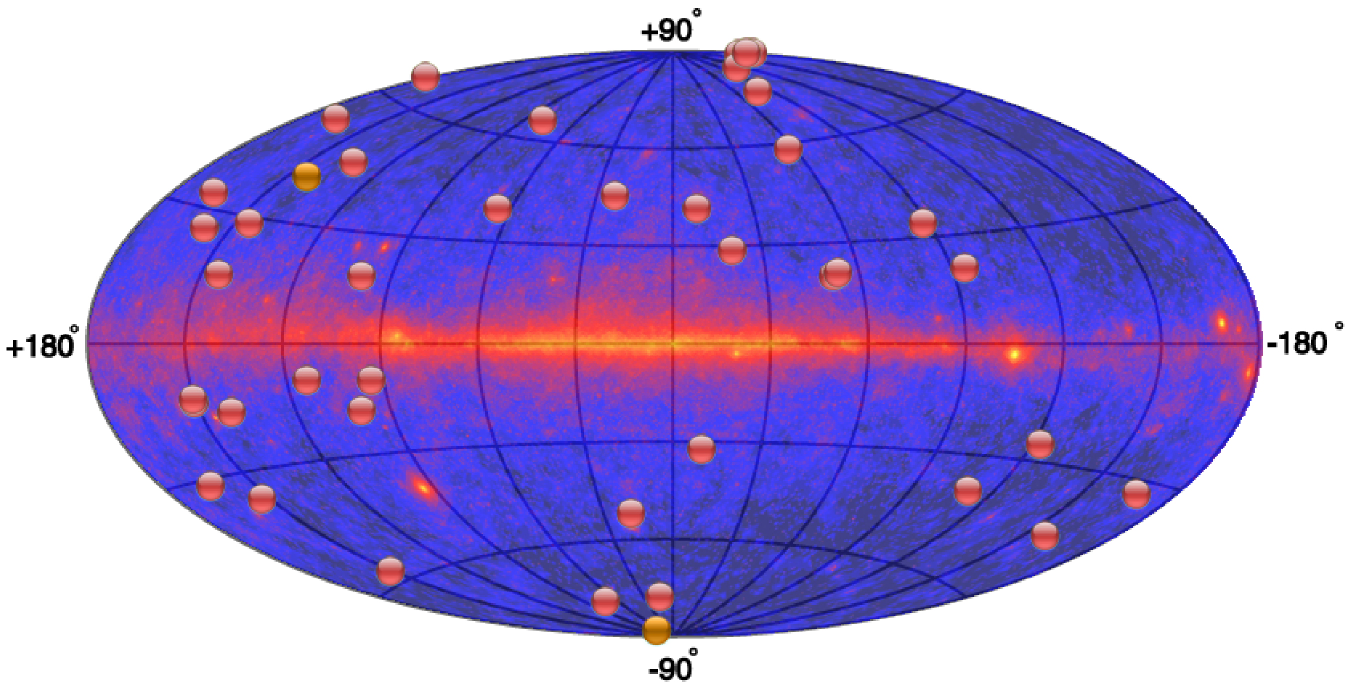
LSP:	35%
ISP:	11%
HSP:	25%
Unclassified:	30%

Preliminary

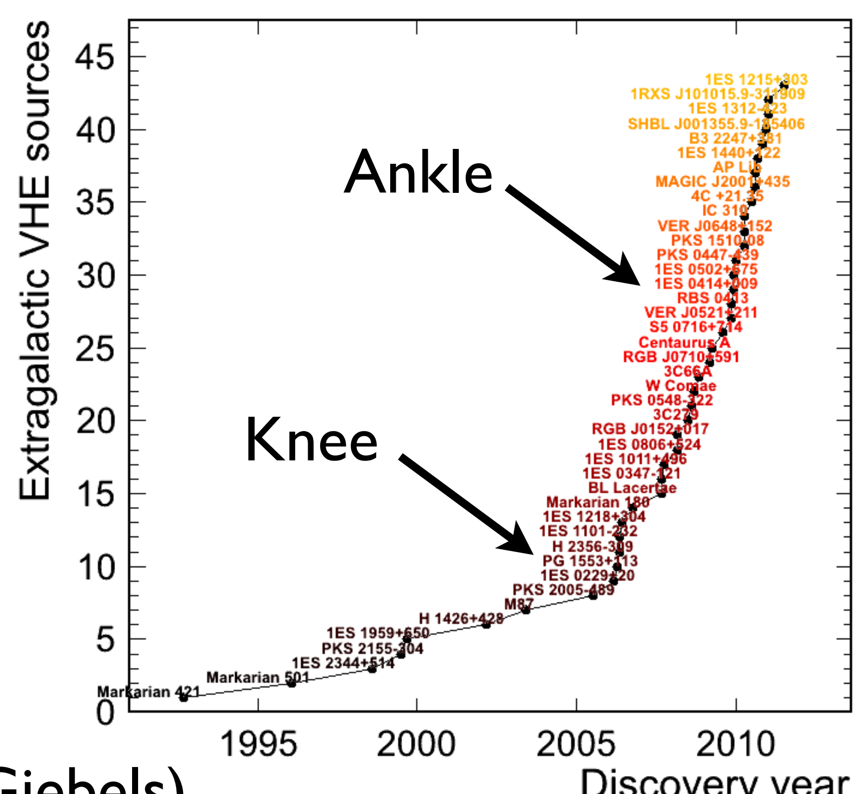




Extragalactic TeV sky



(http://tevcat.uchicago.edu)



(B. Giebels)

- 45 AGN
  - 37 BL Lacs - *29 HBL, 4 IBL and 4 LBL*
  - 3 FSRQ - *3C279, 4C+21.35 and PKS1510-089*
  - 3 FR-I radio galaxies - *M87, NGC 1275, Cen A*
  - 2 unknown - *IC 310 and VER0521+211*
- 2 SBG - *M82, NGC 253*
- *Fermi* implicated in many of the recent TeV discoveries

GeV-TeV AGN

TeV Name	2FGL Name	1FGL Source	R.A. (J2000)	Dec. (J2000)	VHE Index	*Fermi* Index	z	Class
SHBL J001355.9-185406	-	-	00 13 56.0	-18 54 07	-*	-	0.095	HBL
RGB J0152+017	0152.6+0148	-	01 52 33.5	+01 46 40	2.95	1.79	0.08	HBL
3C 66A	0222.6+4302	Y	02 22 41.6	+43 02 35.5	3.64	1.85	< 0.58	IBL
1ES 0229+200	-	-	02 32 53.2	+20 16 21	2.50	-	0.14	HBL
IC 310	0316.6+4119	-	03 16 43.0	+41 19 29	-*	2.1	0.0189	UNK
NGC 1275	0319.8+4130	Y	03 19 48.1	+41 30 42	-*	2.00	0.0176	FRI
RBS 0413	0319.6+1849	Y	03 19 51.8	+18 45 34	-*	1.55	0.19	HBL
1ES 0347-121	-	-	03 49 23.0	-11 58 38	3.10	-	0.188	HBL
1ES 0414+009	0416.8+0105	Y	04 16 52.41	+01 05 24.3	-*	1.98	0.287	HBL
PKS 0447-439	0449.4-4350	Y	04 49 24.7	-43 50 09	4.36	1.86	> 0.176	HBL
1ES 0502+675	0508.0+6737	Y	05 07 56.2	+67 37 24	-*	1.49	0.341	HBL
VER J0521+211	0521.7+2113	Y	05 21 55	+21 11 24	-*	1.93	-	UNK
PKS 0548-322	-	-	05 50 42.9	-32 16 34	2.86	-	0.069	HBL
RGB J0710+591	0710.5+5908	Y	07 10 26.4	+59 09 00	2.69	1.53	0.125	HBL
S5 0716+714	0721.9+7120	Y	07 21 53.4	+71 20 36	3.45	2.01	0.31	LBL
1ES 0806+524	0809.8+5218	Y	08 09 59	+52 19 00	3.6	1.94	0.138	HBL
1RXS J101015.9-311909	1009.7-3123	-	10 10 15.9	-31 19 09	-*	2.34	0.143	HBL
1ES 1011+496	1015.1+4925	Y	10 15 04.1	+49 26 01	4.0	1.72	0.212	HBL
1ES 1101-232	1103.4-2330	Y	11 03 38	-23 29 31	2.94	1.8	0.186	HBL
Markarian 421	1104.4+3812	Y	11 04 27.3	+38 12 32	2.20	1.77	0.031	HBL
Markarian 180	1136.7+7009	Y	11 36 26.4	+70 09 27	3.3	1.74	0.045	HBL
1ES 1215+303	1217.8+3006	Y	12 17 52.1	+30 07 01	-*	2.02	0.13	LBL
1ES 1218+304	1221.3+3010	Y	12 21 21.9	+30 10 37	3.08	1.71	0.182	HBL

TeV Name	2FGL Name	1FGL Source	R.A. (J2000)	Dec. (J2000)	VHE Index	*Fermi* Index	z	Class
WComae	1221.4+2814	Y	12 2					
4C +21.35	1224.9+2122	Y	12 2					
M87	1230.8+1224	Y	12 3					
3C 279	1256.1-0547	Y	12 5					
1ES 1312-423	-	-	13 1					
Centaurus A	1325.6-4300	Y	13					
PKS 1424+240	1427.0+2347	Y	14 2					
H 1426+428	1428.6+4240	Y	14 2					
1ES 1440+122	1442.7+1159	Y	14 4					
PKS 1510-089	1512.8-0906	Y	15 1					
AP Lib	1517.7-2421	Y	15 1					
PG 1553+113	1555.7+1111	Y	15 5					
Markarian 501	1653.9+3945	Y	16 5					
HESS J1943+213	-	-	19					
1ES 1959+650	2000.0+6509	Y	19 5					
MAGIC J2001+435	2001.1+4352	Y	20 0					
PKS 2005-489	2009.5-4850	Y	20 0					
PKS 2155-304	2158.8-3013	Y	21 5					
BL Lacertae	2202.8+4216	Y	22 0					
B3 2247+381	2250.0+3825	Y	22 5					
1ES 2344+514	2347.0+5142	Y	23 47 04.8	+51 42 18	2.95	1.72	0.044	HBL
H 2356-309	2359.0-3037	Y	23 59 09	-30 37 22	3.06	1.89	0.165	HBL

(D. Horan)

GeV-TeV population

Preliminary

- TeV AGN population : 45

  ✓ In 2FGL : 39 (20 HSP, 7 ISP, 5 LSP, 4 UNK, 3 RG)

  ✓ In 2LAC clean sample : 34*

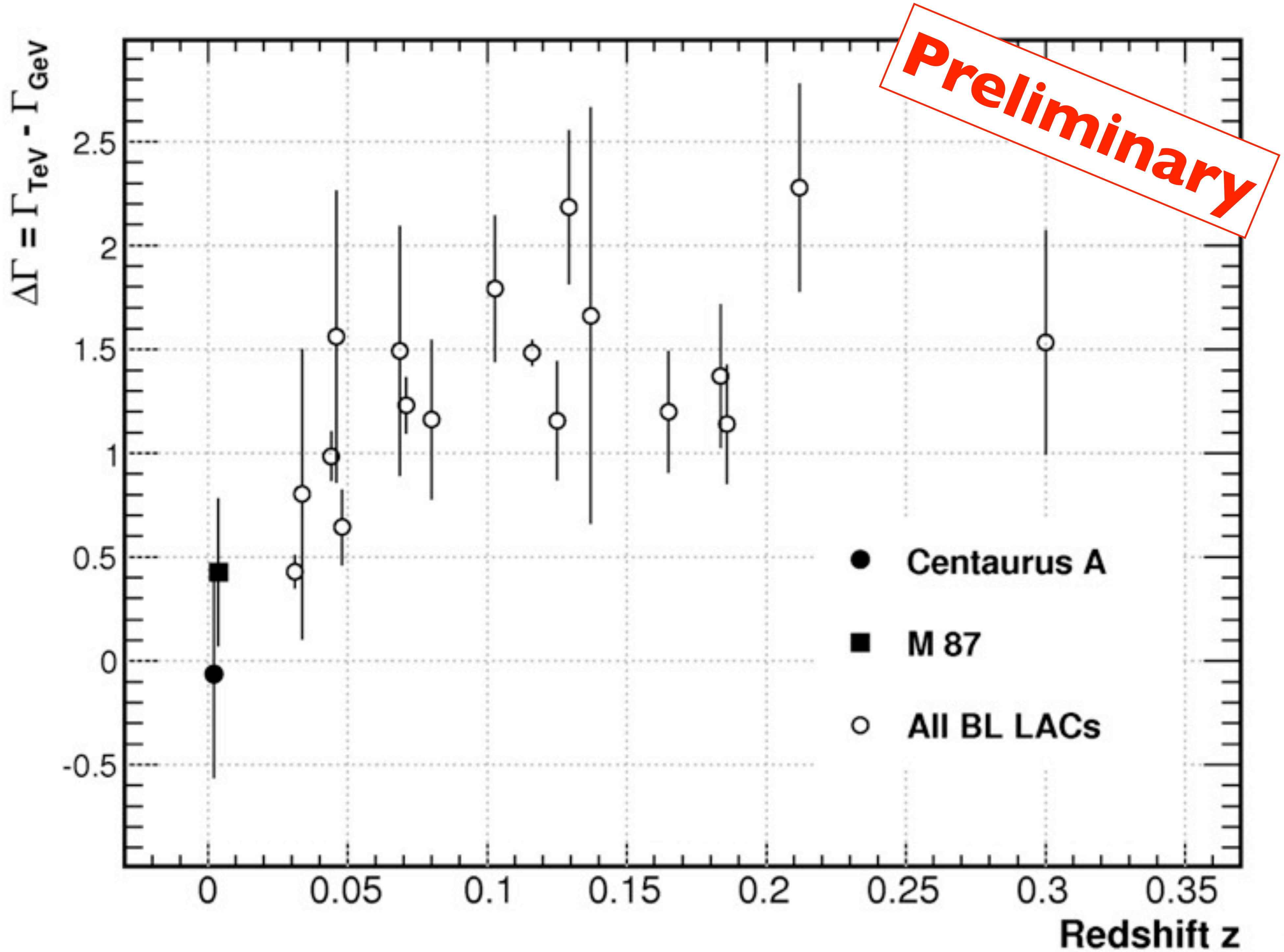
- Missing from 2FGL are,

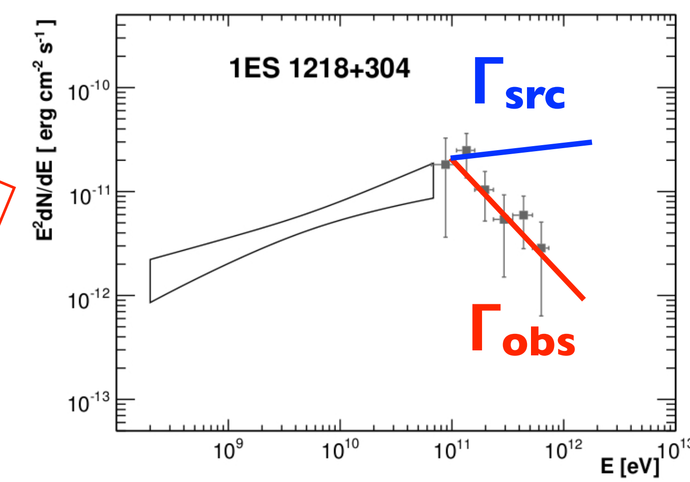
  - SHBL J001355.9-185406
  - 1ES 0229+200
  - 1ES 0347-121
  - PKS 0548-322
  - 1ES 1312-432
  - HESS J1943+213

  all HBL with fluxes 0.4-2% of Crab Nebula flux

* Three sources have |b|<10deg and two are flagged as having possible problems in 2FGL.

Spectral evolution





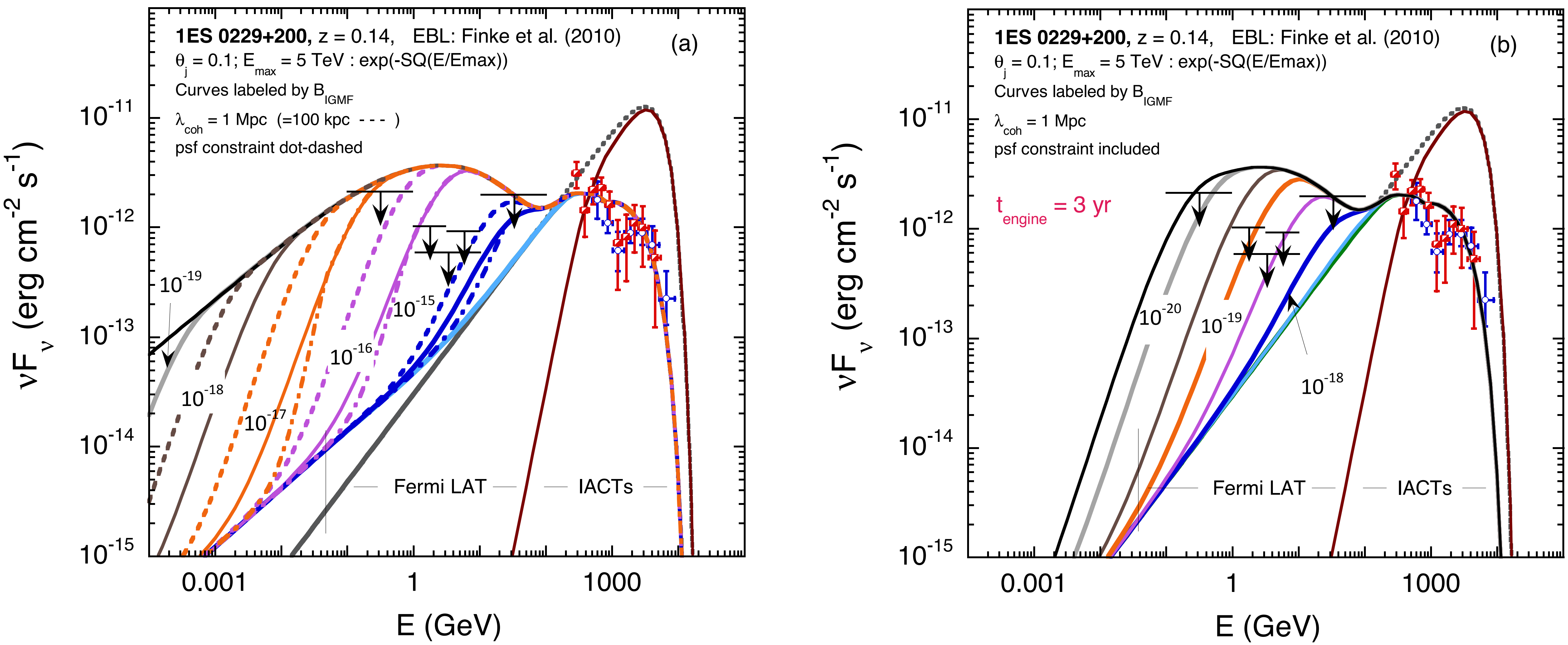
Absorption of γ rays by pair-production with EBL photons produces softening of spectra.

Γ_{obs}-Γ_{src} ~ z + O(z^2)

Fermi spectral index used as a proxy for the intrinsic index in the TeV regime.

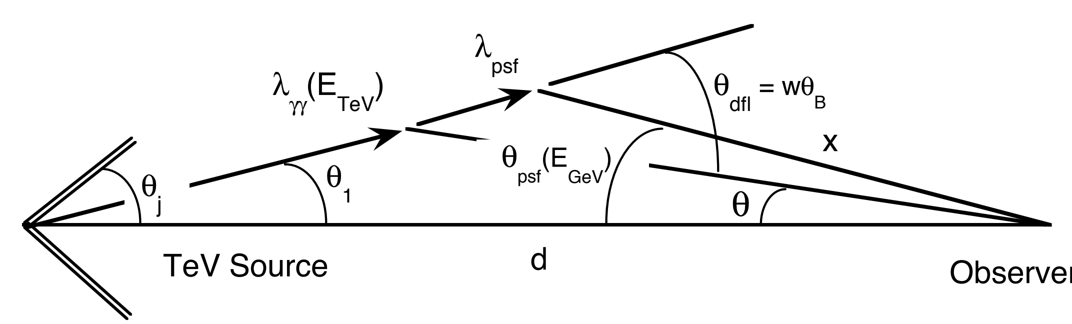
(D. Horan & D. Sanchez)

IGMF constraints



1ES 0229+200 (z=0.14) is a TeV source detected by HESS and VERITAS, in observations separated by 3 years, but not seen by Fermi.

EBL absorption and cascading on CMB produces GeV emission detectable by LAT unless IGMF scatters it away (or AGN engine is short lived).



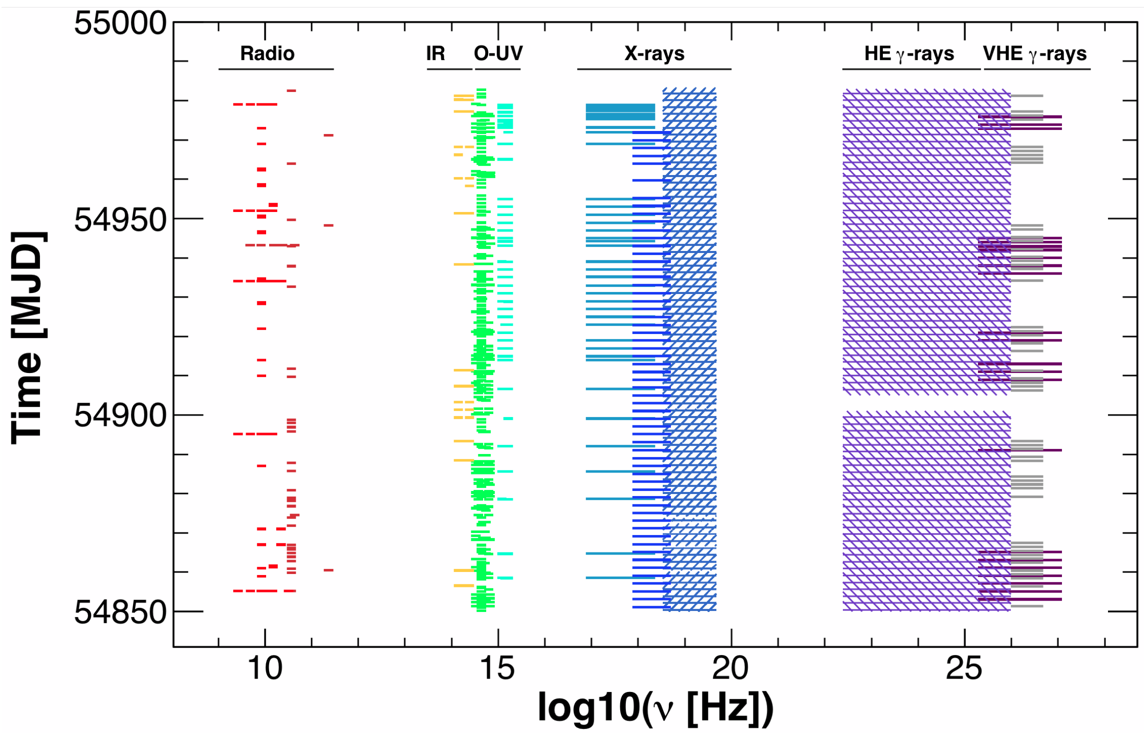
(Dermer et al., 2011, ApJ, 733, 21)

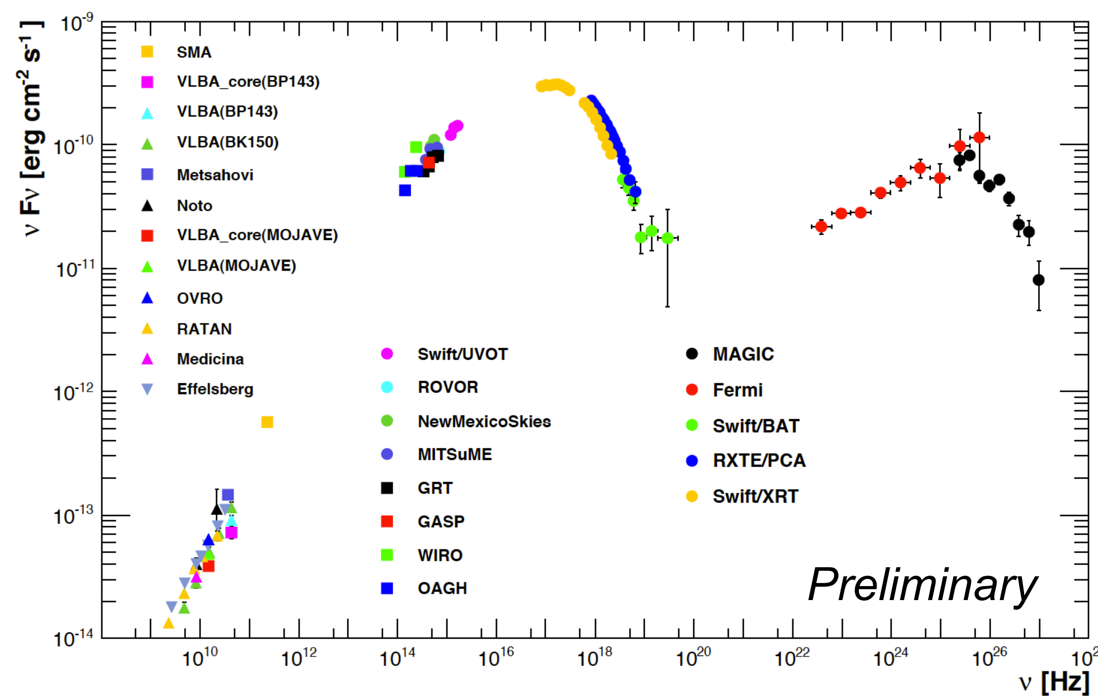
Classical TeV HBL

“Low-state” multi-wavelength observations

Markarian 421

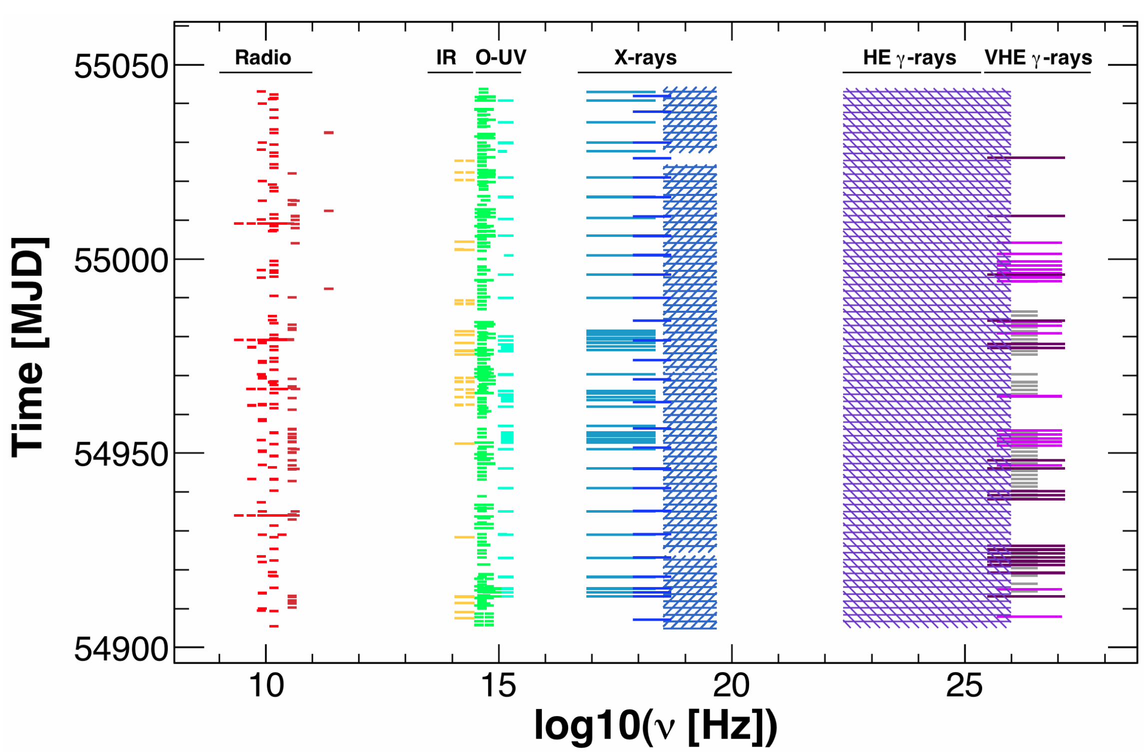
Abdo, A. A. et al. 2011, ApJ, 736, 101

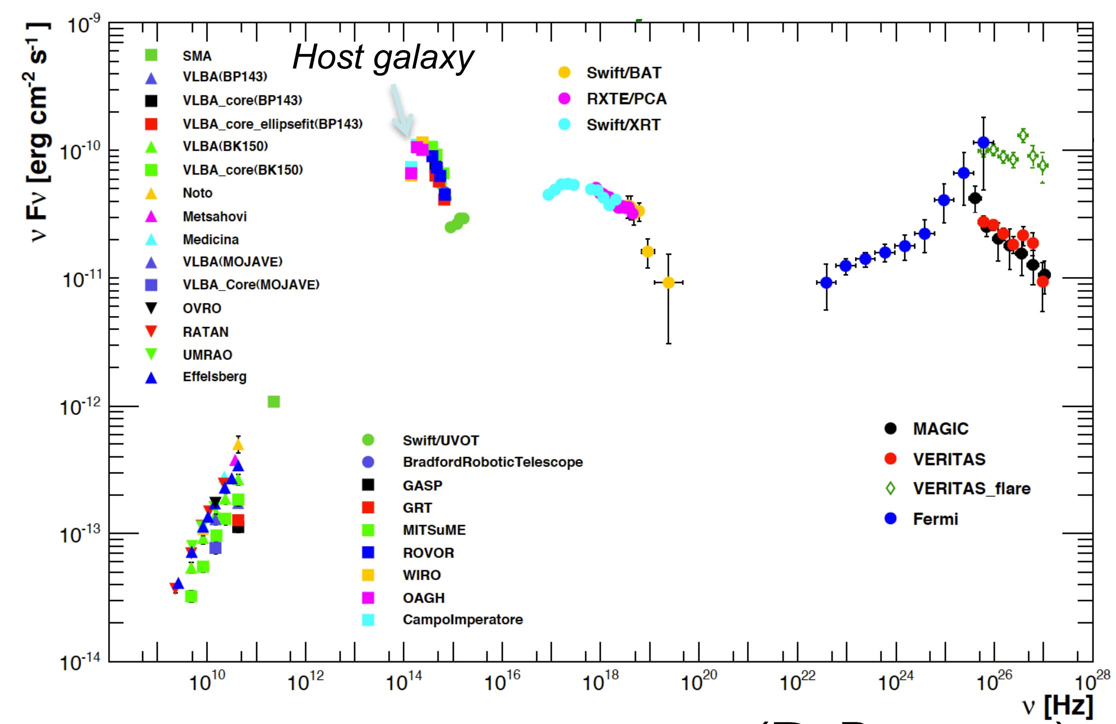




Markarian 501

Abdo, A. A. et al. 2011, ApJ, 727, 129





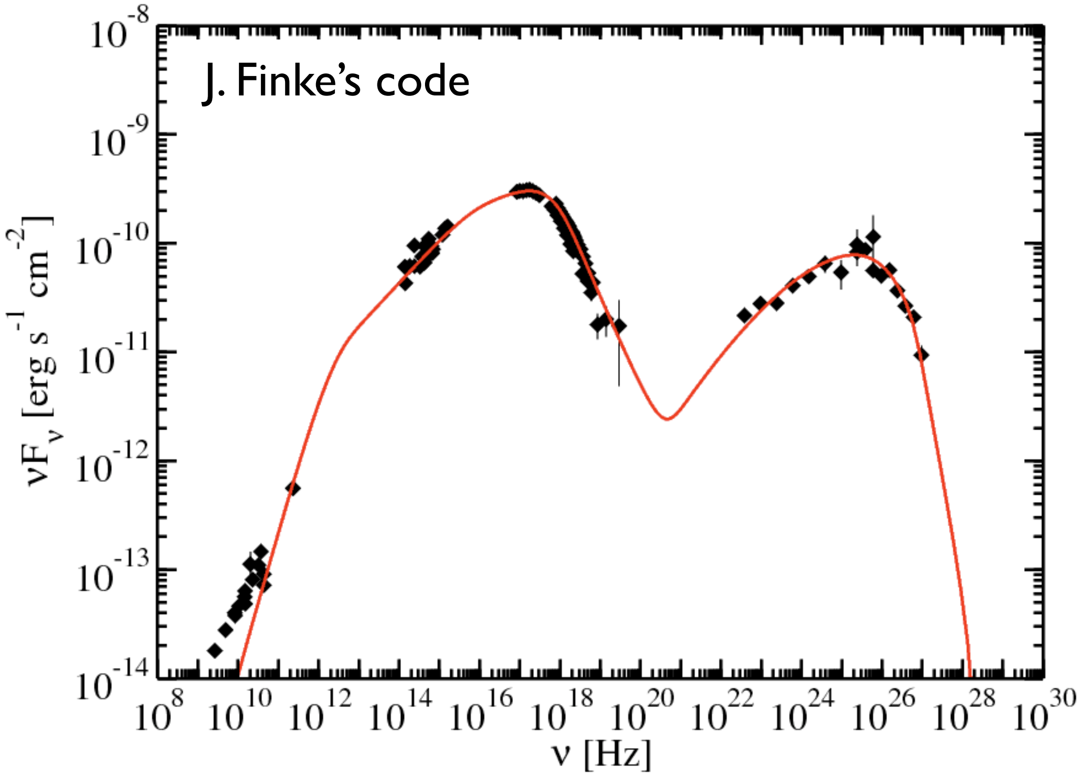
(D. Paneque)

Classical TeV HBL

Synchrotron self-Compton modeling

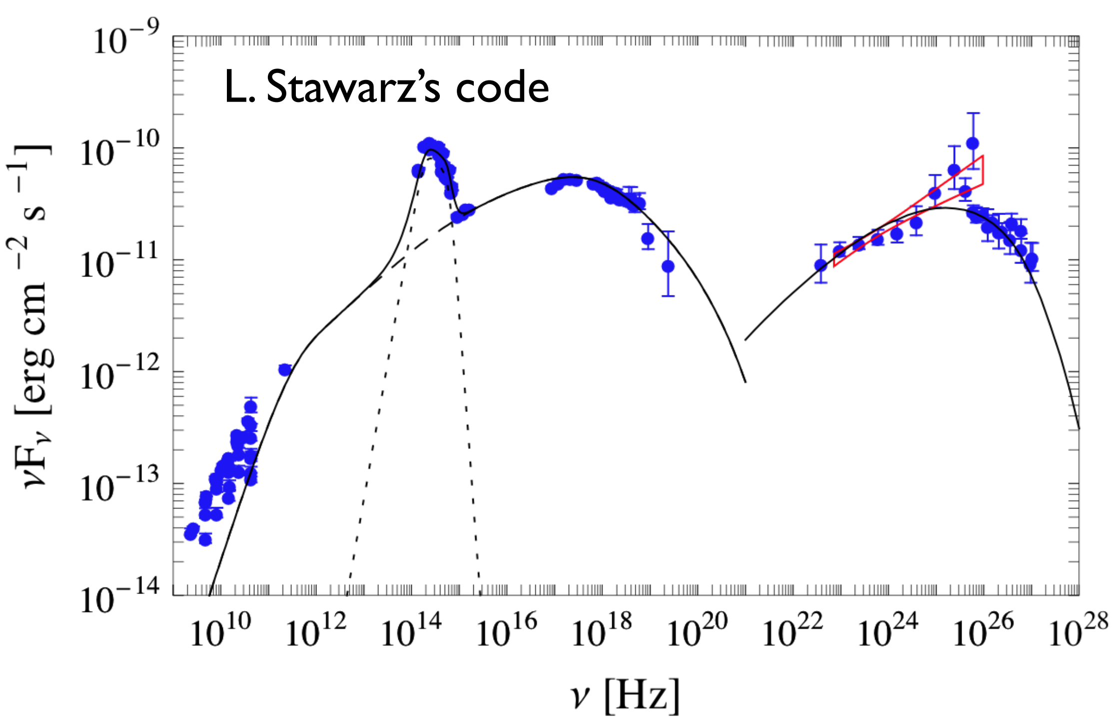
Markarian 421

Abdo, A. A. et al. 2011, ApJ, 736, 101



Markarian 501

Abdo, A. A. et al. 2011, ApJ, 727, 129



Markarian 421

R [cm]	1.3e17
B [G]	1.5e-2
delta	12.0
η_e	56
γ_{min}	600
s1	2.2
γ_{brk_1}	4.e4
s2	2.7
γ_{brk_2}	9.e5
s3	3.7
γ_{max}	1.5e7

Markarian 501

R [cm]	5.2e16
B [G]	3.8e-2
delta	21.0
η_e	10
γ_{min}	800
s1	2.2
γ_{brk_1}	5.e4
s2	2.7
γ_{brk_2}	3.9e5
s3	4.7
γ_{max}	1.0e8

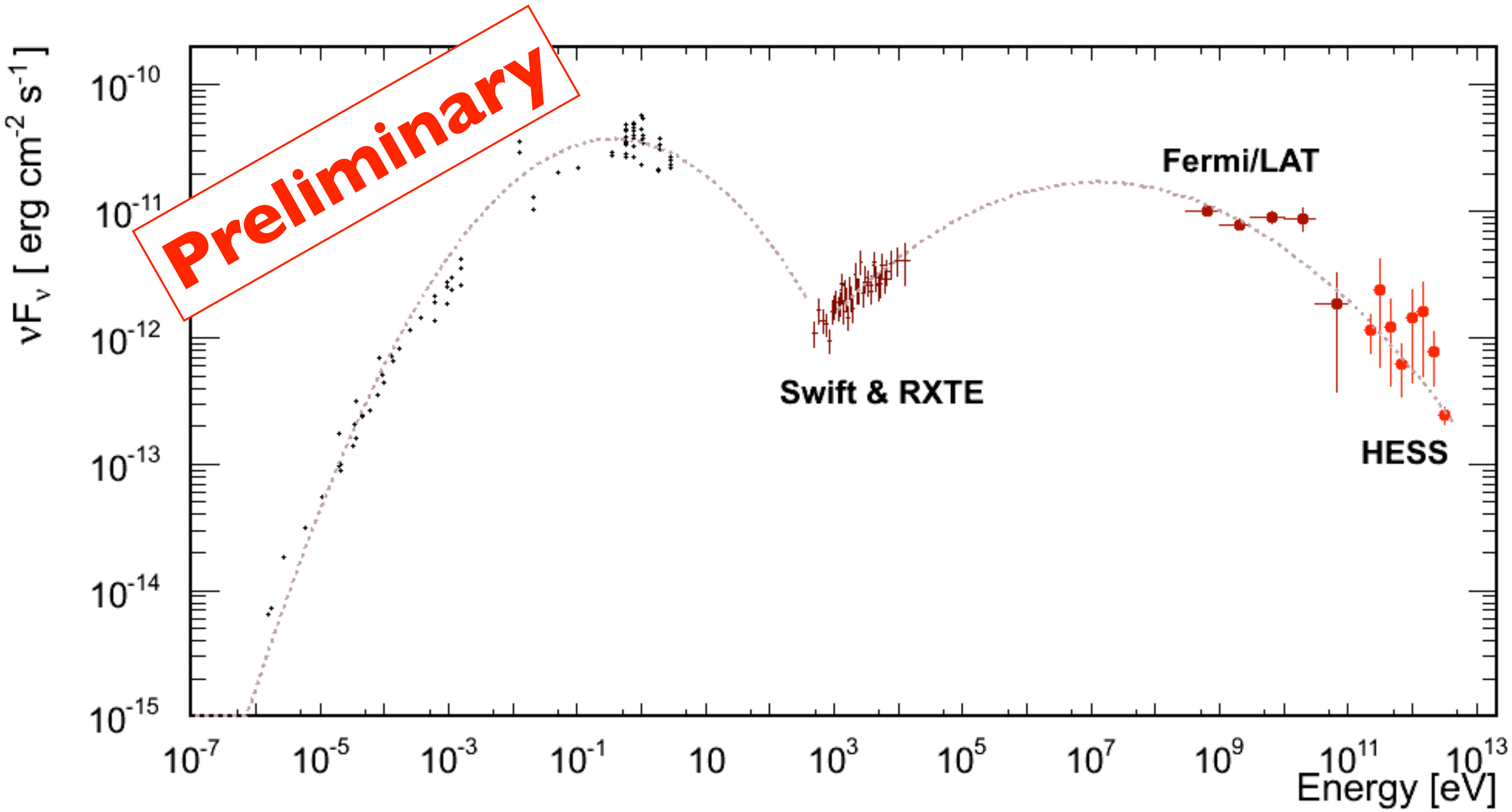
Two breaks in electron spectrum required to fit the data. Has been seen in another bright TeV HBL - PKS2155-304.

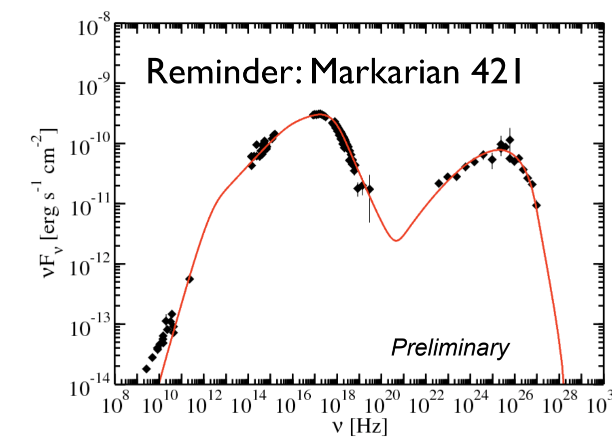
Fit parameters similar between two AGN, is this something fundamental about the bright TeV AGN?

(D. Paneque)

GeV-TeV LBL

Ap Lib (PKS 1414-241, *z*=0.049)





Fermi BSL source, targeted by HESS as potential TeV emitter based on extrapolation of GeV spectrum. Detected at in 11 hours at >7σ.

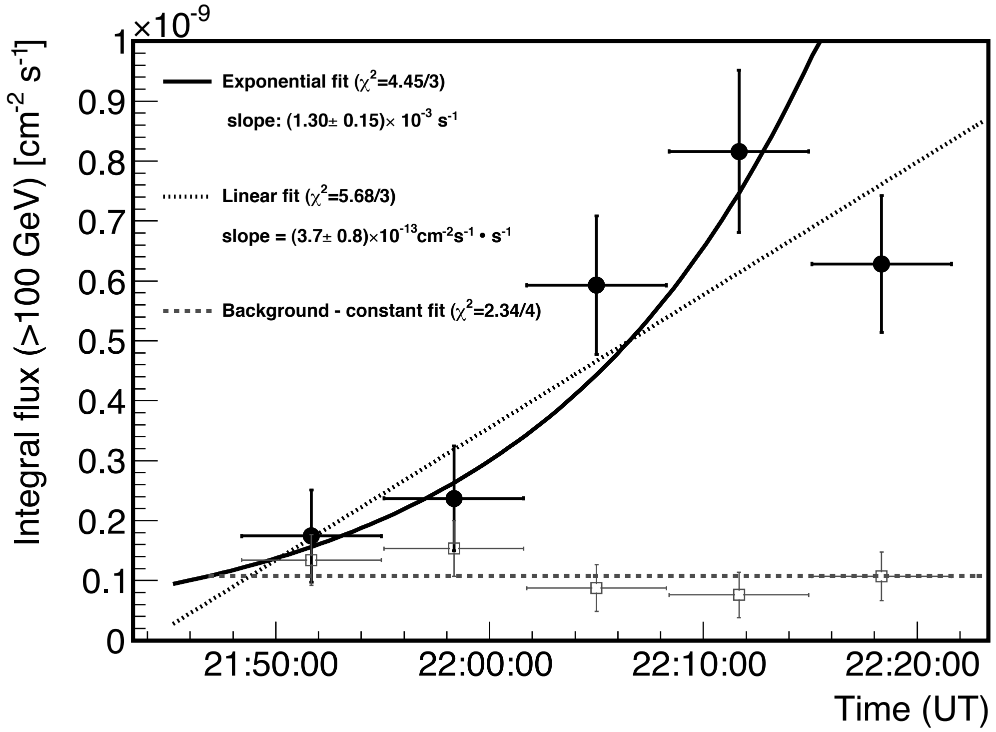
Hard X-ray spectrum, indicates that synchrotron component falls off below X-ray energies. Possibly indicating that HE component dominates for E>0.3keV.

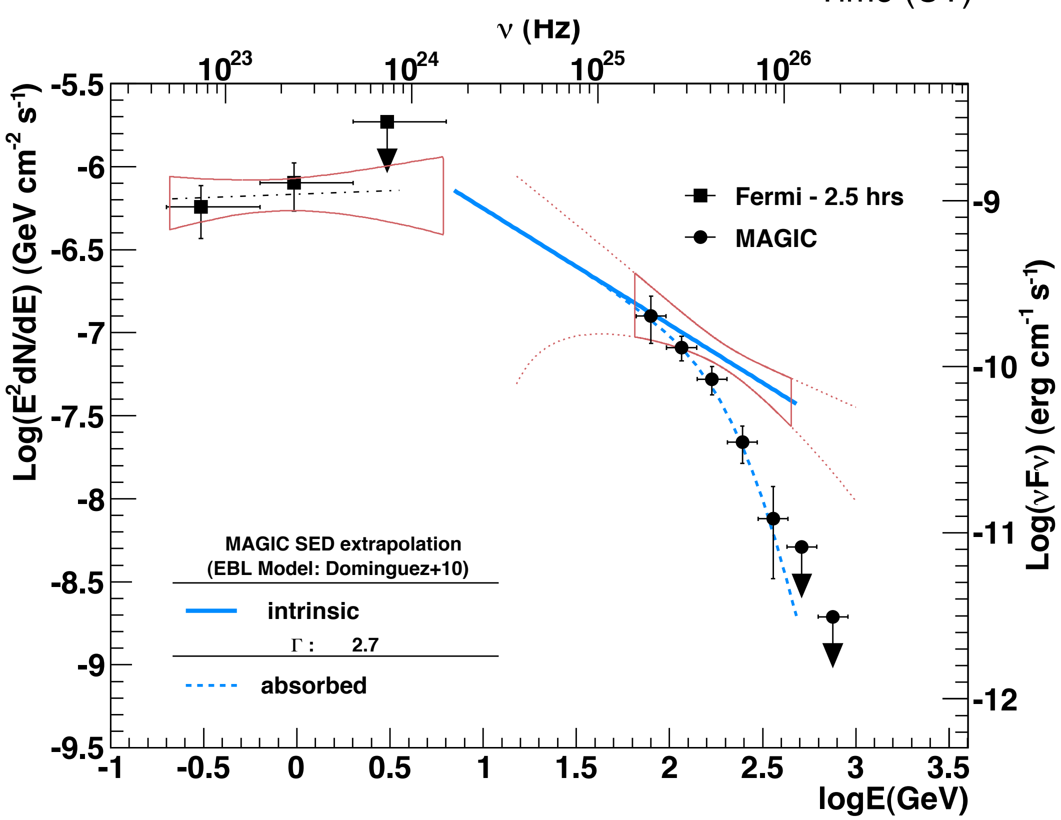
Difficult to explain this with SSC.

(P. Fortin, et al., PoS(Texas2010) 199)

GeV-TeV FSRQ

PKS 1222+21 (4C 21.35, z=0.432)





FSRQ have not generally been detected as TeV emitters in the pre-Fermi era (exception is 3C279 detected by MAGIC during big flare)

MAGIC observations prompted by increasing GeV flux detected and reported rapidly by *Fermi* flare advocate program.

MAGIC report 70-400GeV flux of ~1Crab.

Significant variability: doubling time of 10 minutes compatible with TeV observations

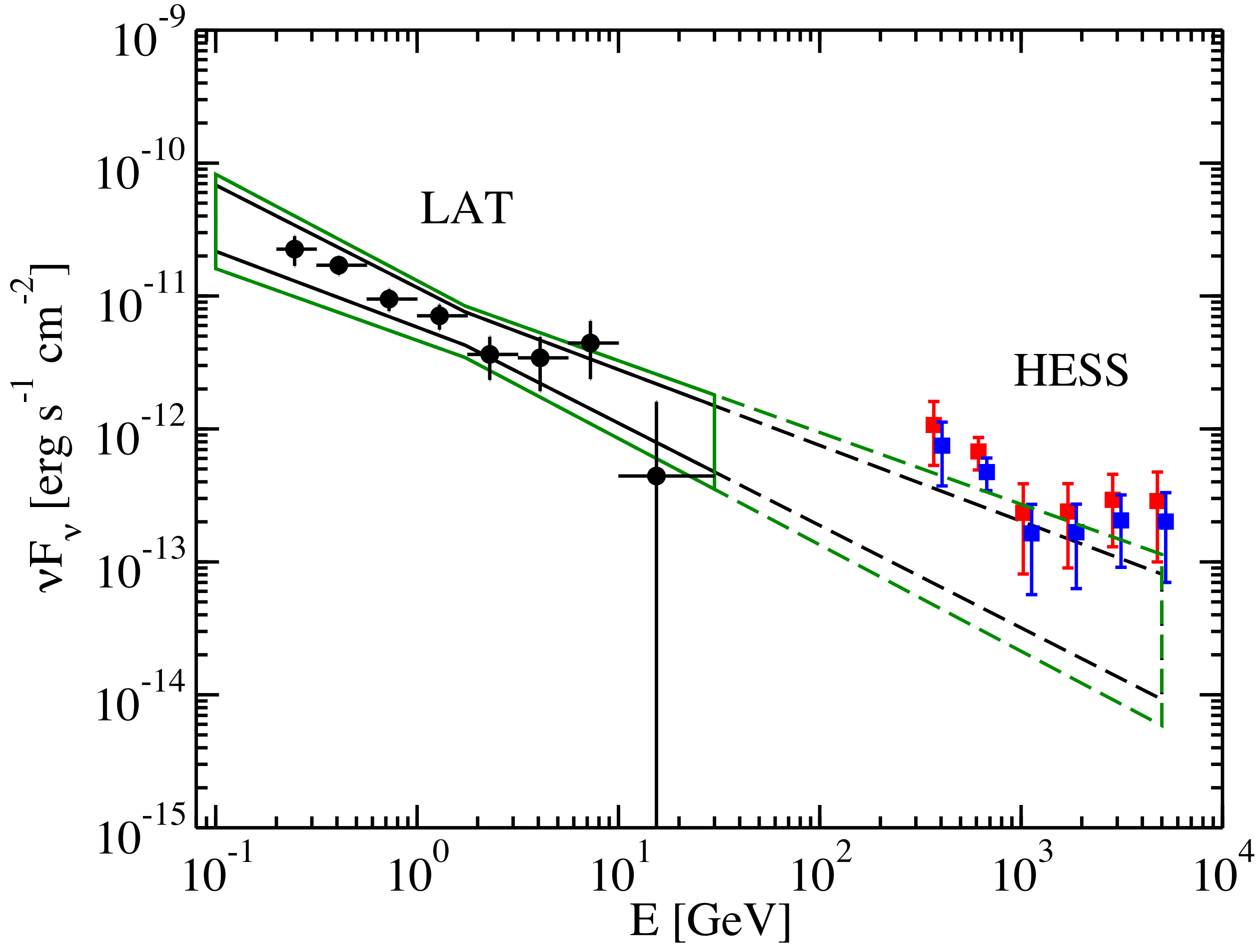
Fermi spectrum “compatible” with extension of MAGIC spectrum, but significant intrinsic hardening observed in spectrum between the two bands.

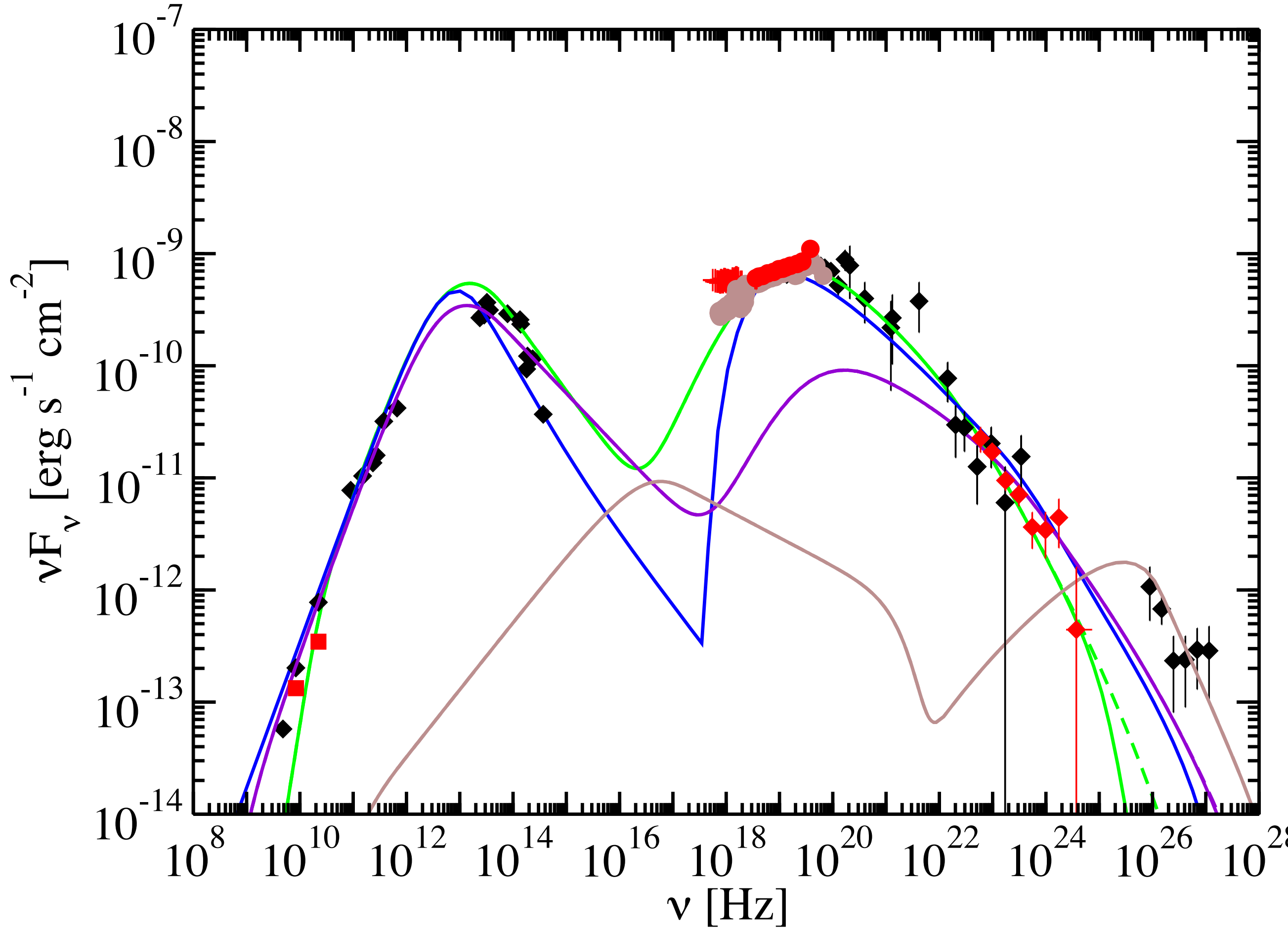
Multi-wavelength studies and modeling are ongoing.

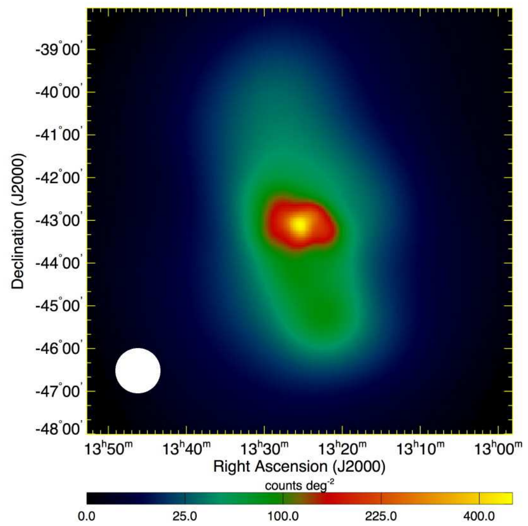
(Aleksić, J. et al. 2011, ApJL, 730, L8)

GeV-TeV non-blazars

Centaurus A (core)







Fermi resolves core and lobe emission from Cen A.

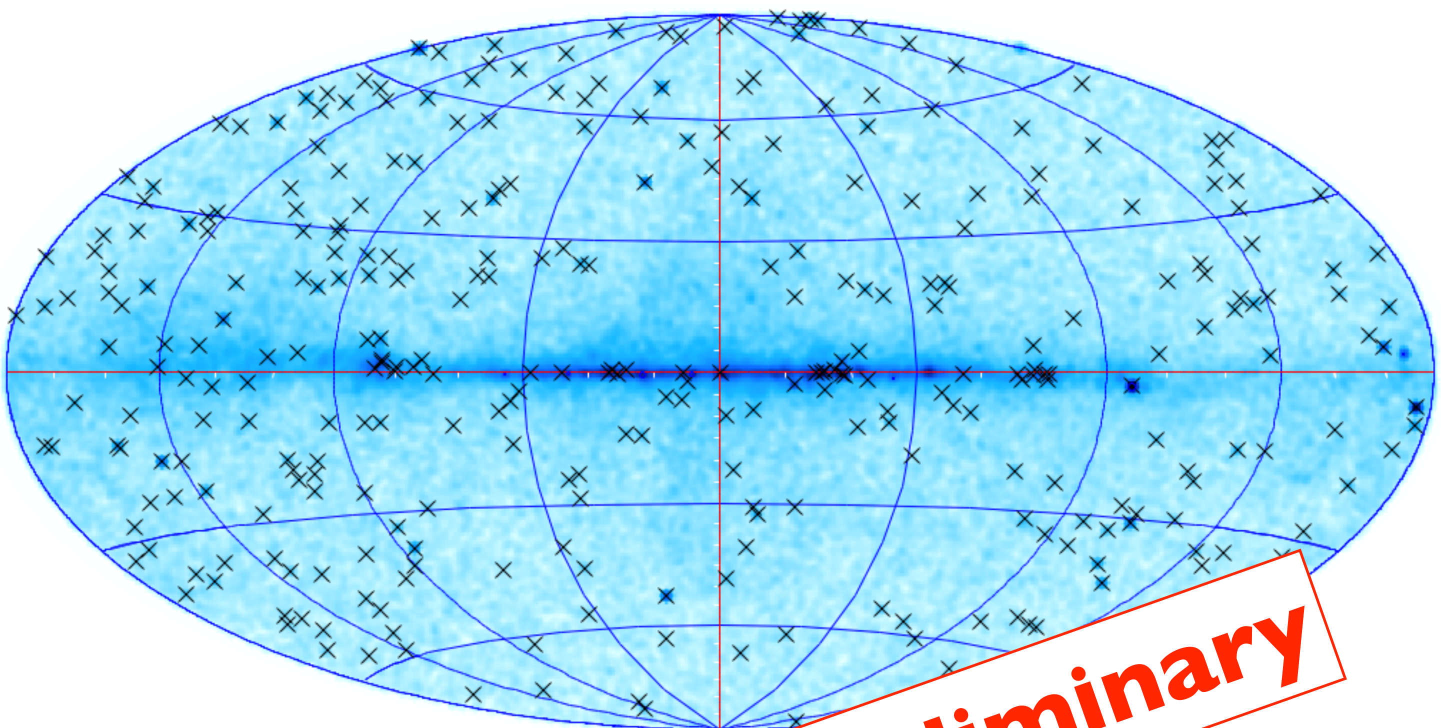
Extrapolation of LAT core spectrum under-predicts HESS emission from Cen A, though spectral indices compatible.

Marginal evidence for additional radiative component.

(Abdo, A. A. et al. 2010, Science 328, 725 & ApJ, 719, 1433)

Future perspectives

Fermi 10GeV catalog



Motivations:

Study highest energy *Fermi* sources.

Identify new spectral components.

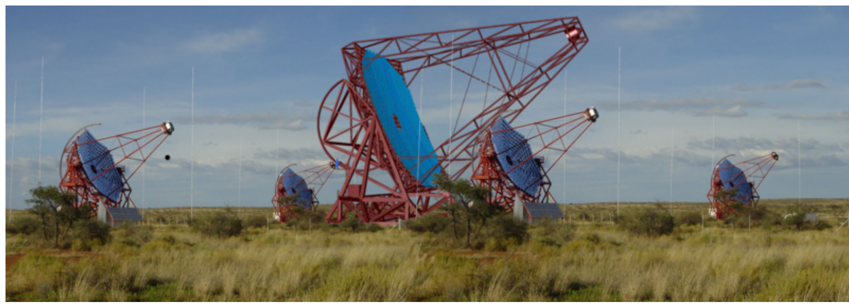
Aid to TeV instruments in choosing good targets for observation.

RA [deg]	DEC [deg]	Association		Type	Flux (E>10 GeV) [10^{-10} ph cm^{-2} s^{-1}]	Photon Index	Flux (E>50 GeV) [10^{-10} ph cm^{-2} s^{-1}]	Flux (E>50 GeV) Crab Nebula units**
166.123	38.207	MRK421	0.031	Blazar	41.2 ± 2.5	1.78 ± 0.07	12.4	1.28
83.626	22.021	CRAB	2 kpc	PWN	71.1 ± 3.3	2.34 ± 0.07	9.7	1
276.13	-13.852	HESSJ1825-137	3.9 kpc	PWN	27.2 ± 3.7	1.90 ± -0.13	6.6	0.68
329.726	-30.21	PKS 2155-304	0.117	Blazar	23.7 ± 2.0	2.01 ± 0.10	4.8	0.49
238.934	11.188	PG1553	0.5	Blazar	21.5 ± 1.9	1.97 ± 0.11	4.7	0.48
253.484	39.756	Mrk501	0.034	Blazar	12.7 ± 1.4	1.72 ± 0.12	4.3	0.44
279.332	-6.991	HESS J1837-069	???	UNID	6.9 ± 1.4	1.45 ± 0.20	4.1	0.42
284.295	2.819	HESS J1857+026	???	UNID	3.9 ± 1.1	1.30 ± 0.28	3.5	0.37
35.657	43.042	3c66a	0.444	Blazar	21.9 ± 1.8	2.15 ± 0.11	3.5	0.36
77.023	67.621	1ES 0502+675	0.341	Blazar	7.6 ± 1.0	1.59 ± 0.13	3.3	0.34
185.34	30.183	1es1218	0.182	Blazar	5.2 ± 0.9	1.53 ± 0.19	3.1	0.32
243.97	-51.982	HESS J1614-518	???	Masive Star Cluster	3.7 ± 1.1	1.41 ± 0.27	2.6	0.27
94.31	22.58	IC443	1.5 kpc	SNR	26.6 ± 2.1	2.61 ± -0.14	2.4	0.25
80.436	21.21	VER J0521+211	???	AGN (unknown type)	8.7 ± 1.2	1.94 ± 0.17	2.4	0.25
216.765	23.802	PKS 1424+240	???	Blazar	15.4 ± 1.6	2.34 ± 0.15	2.0	0.21
72.379	-43.841	PKS 0447-439	0.2	Blazar	10.4 ± 1.3	2.11 ± 0.16	2.0	0.20
240.946	-49.049	J1603-4904	???	???	10.3 ± 1.3	2.12 ± 0.17	1.8	0.19
300.308	43.881	MAGIC J2001+435	???	Blazar	10.0 ± 1.2	2.17 ± 0.17	1.8	0.18
161.247	-59.699	Eta Carinae	???	LBV	5.3 ± 1.1	1.83 ± 0.23	1.5	0.15
248.633	-47.661	???	???	???	5.9 ± 1.5	1.91 ± 0.26	1.4	0.15
266.463	-28.983	TeV Galactic Centre	8.5 kpc	UNID	18.0 ± 2.1	2.59 ± 0.20	1.4	0.14
45.871	-24.114	PKS 0301-243	0.26	Blazar	6.4 ± 1.0	2.00 ± 0.20	1.3	0.14
290.818	14.145	W51C	5 kpc	SNR	14.4 ± 1.7	2.50 ± -0.18	1.3	0.13
278.659	-7.111	SNR G024.7+00.6		SNR	5.5 ± 1.3	1.91 ± 0.28	1.3	0.13
302.365	-48.826	PKS 2005-489	0.071	Blazar	4.9 ± 0.9	1.87 ± 0.22	1.3	0.13
228.507	-59.256	MSH-15-52	5.2 kpc	PWN	5.5 ± 1.0	1.96 ± -0.23	1.2	0.12

(D. Paneque & P. Fortin)

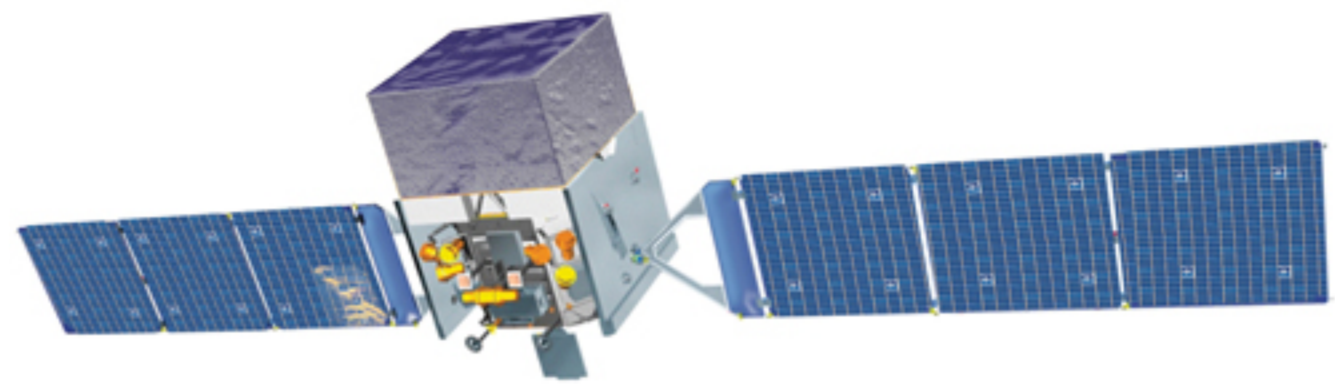
Future perspectives

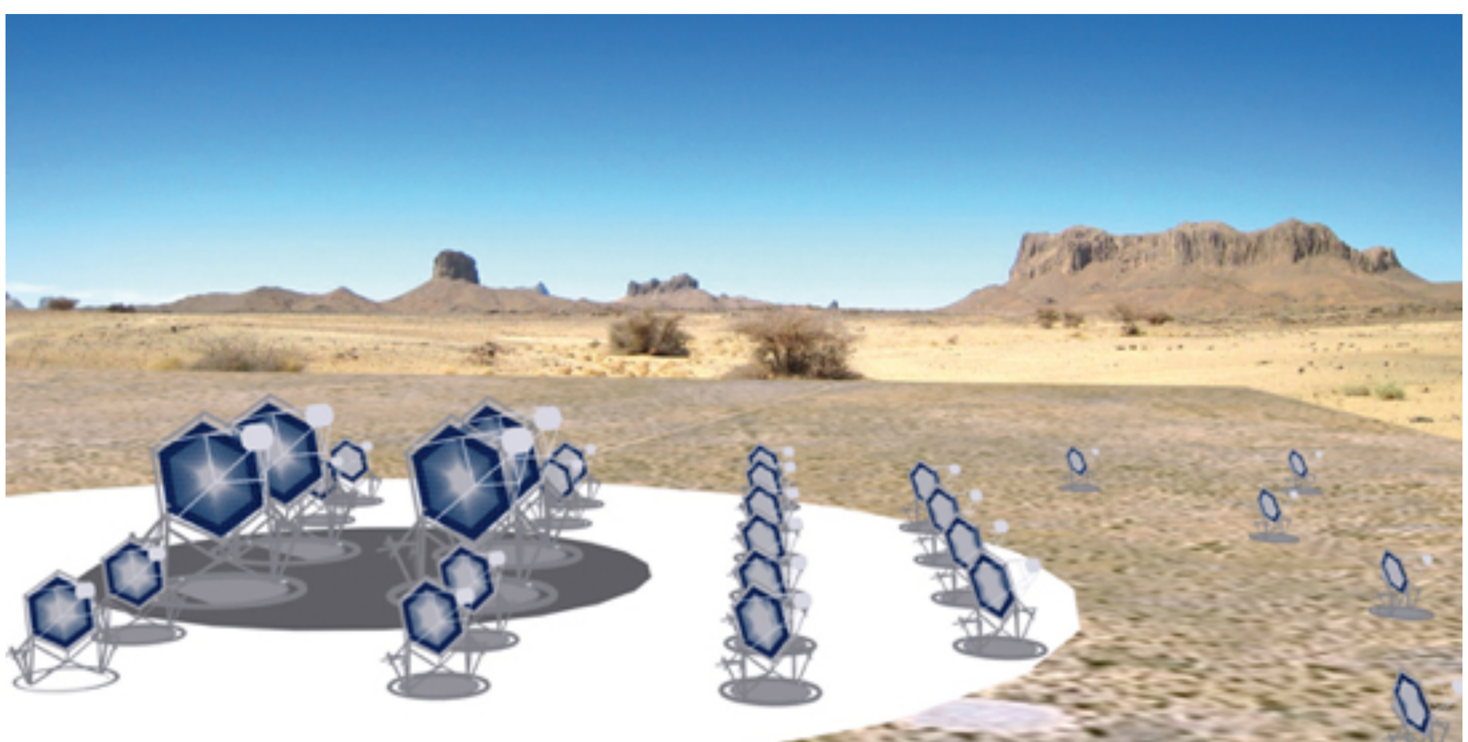
Instruments




HESS - new 28m telescope at center of HESS array
VERITAS - high QE PMTs and new trigger system
MAGIC - second telescope operating now

Fermi's 5-year prime mission extends into 2013. Extended mission possible and would have large impact on future GeV-TeV studies, such as MW campaigns and GeV triggering.





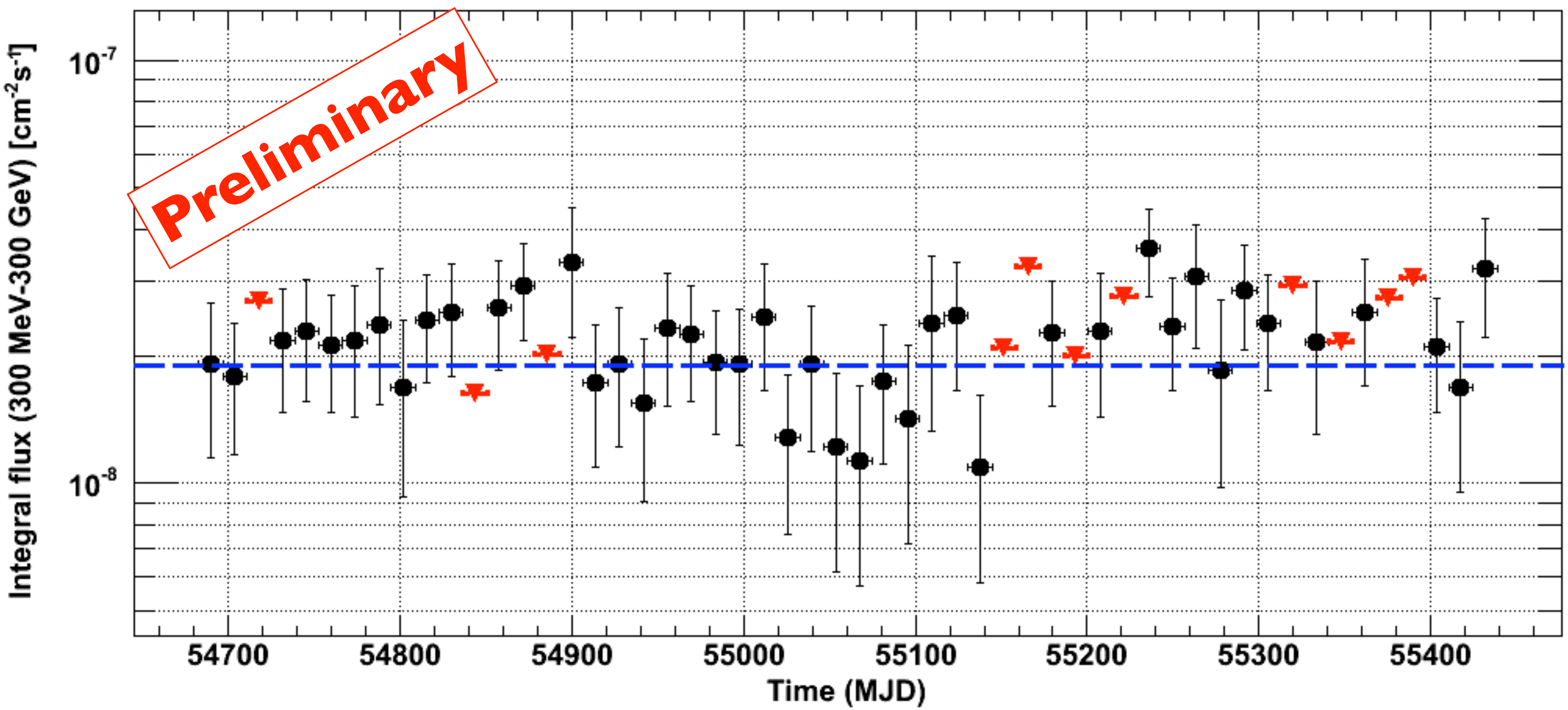
The TeV community is working towards the next-generation HAWC and CTA observatories, which will have vastly improved sensitivity and energy range.

Probe AGN variability on shorter timescales.

Extend GeV-TeV studies of EBL/EMF using more distant sources.

Additional slides

Ap Lib light curve



Cen A

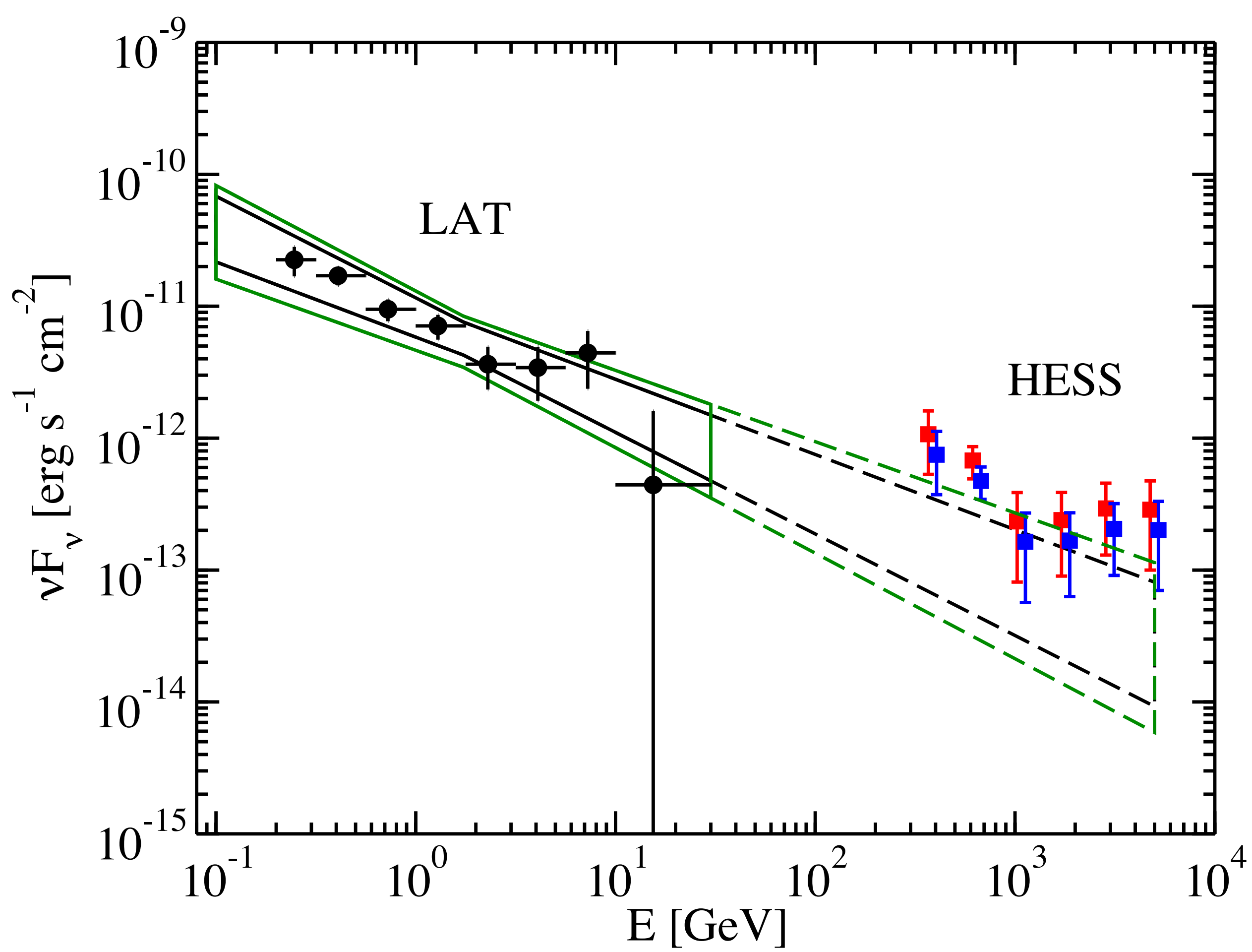


Fig. 3.— Spectrum of the Cen A core from differential fluxes derived for successive energy ranges from model B (black circles). The black bowtie indicates the best fit 0.1 – 30 GeV LAT flux and Γ with statistical errors only, while the green bowtie indicates this with systematic errors as well. The LAT spectrum is extrapolated into the HESS energy range (dashed lines). The HESS data from Aharonian et al. (2009) are shown (red squares) and the HESS data shifted to lower flux by their statistical and systematic normalization error (blue squares). The latter are also shifted in energy by 10% for clarity.

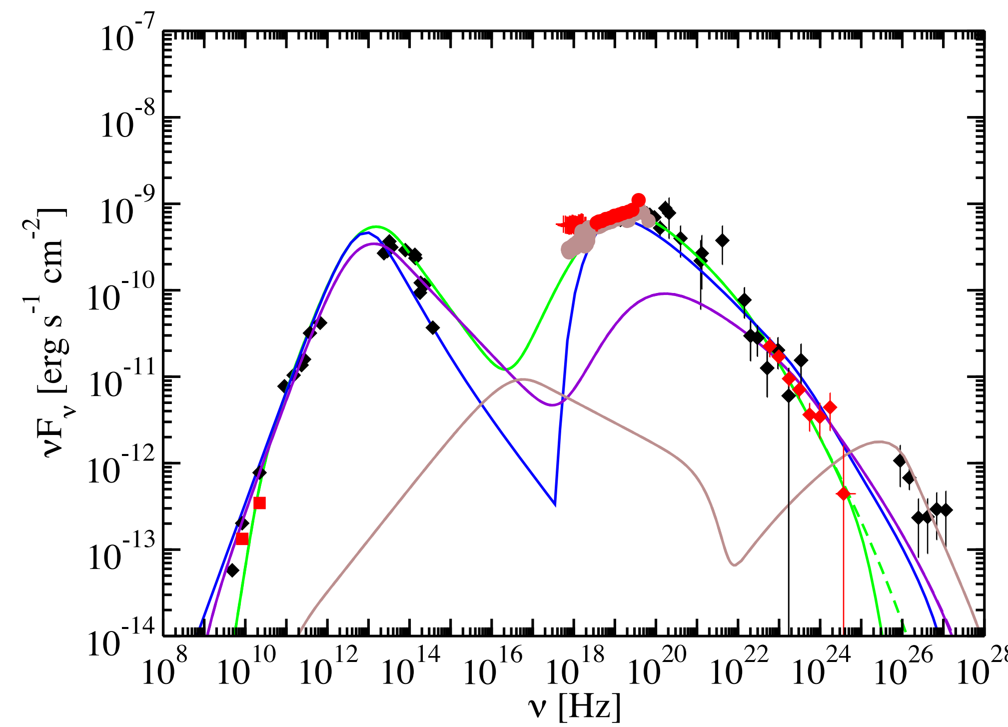


Fig. 5.— The SED of the Cen A core with model fits. Colored symbols are observations between August and May 2009, the epoch of the LAT observations. These include observations of, from low to high frequency: the TANAMI VLBI (red squares), *Swift*-XRT (red crosses), *Suzaku* (brown circles), *Swift*-BAT (red circles), and *Fermi*-LAT (red diamonds). Black symbols are archival data, (Marconi et al. 2000) including HESS observations (Aharonian et al. 2009). Curves are model fits to nuclear region of Cen A. The green curve is a synchrotron/SSC fit to the entire data set. The dashed green curve shows this model without $\gamma\gamma$ attenuation. The violet curve is a similar fit but is designed to under fit the X-ray data, and the brown curve is designed to fit the HESS data while not over-producing the other data in the SED. The blue curve is the decelerating jet model fit (Georganopoulos & Kazanas 2003). See Table 2 for the parameters of these model curves.