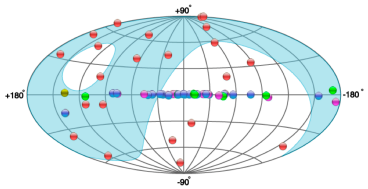
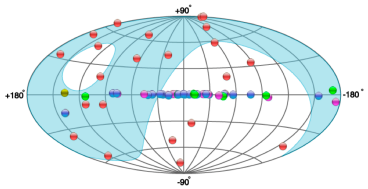


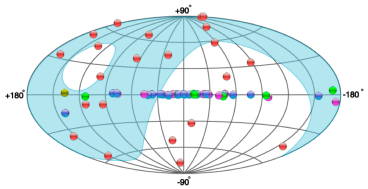
The Extragalactic Sky in TeV Gamma Rays

Frank Krennrich, Iowa State University

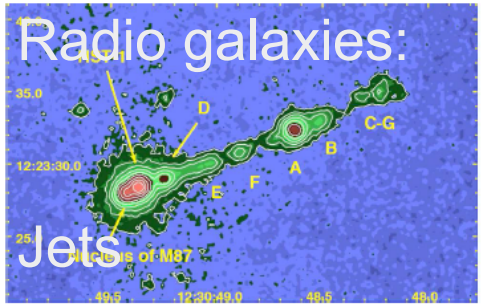


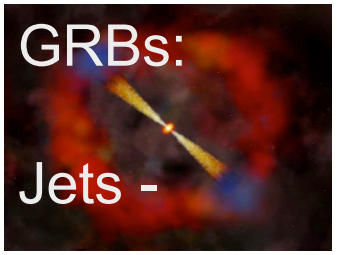
Outline

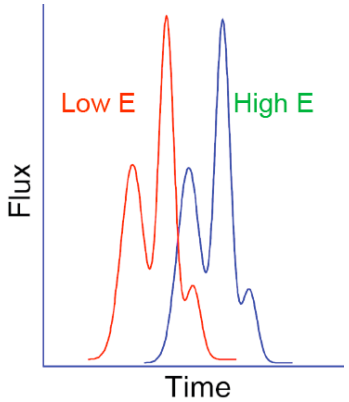
- Overview of extragalactic TeV sources.
- Discovery of starburst galaxies.
- Probing relativistic jets in TeV blazars.
- Intermediate BL Lac objects.
- Cosmology with blazars.
- Quantum gravity tests.
- Radio galaxies.
- Summary.

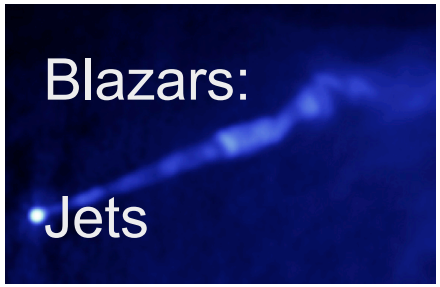


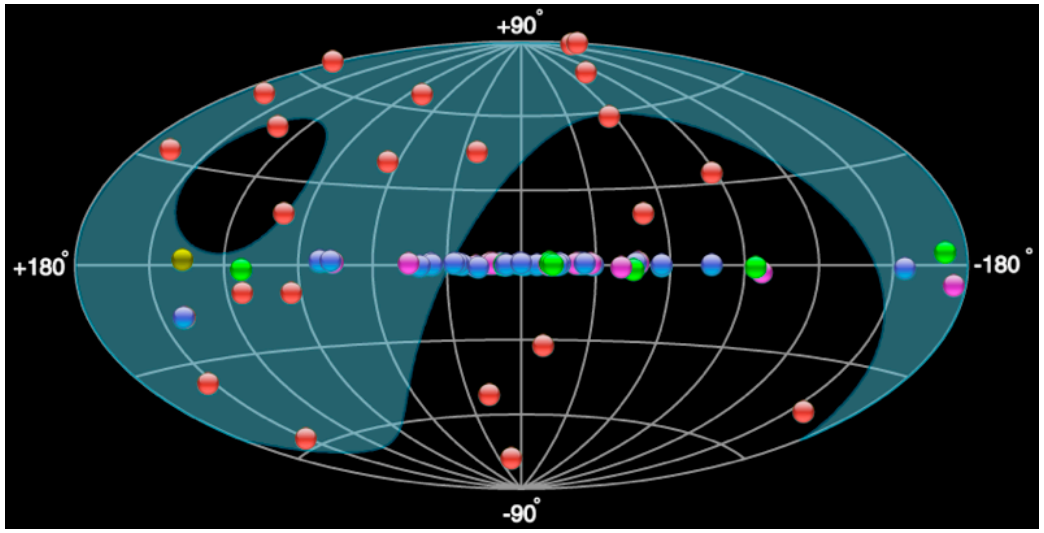
Science Motivations:



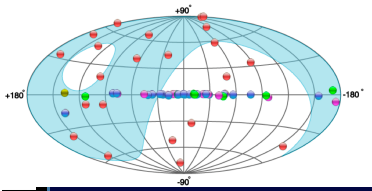








…?



“Telephone Directory”

Name	Type	Date	Dist
3C279	FSRQ	06.01.2008	z = 0.5362
3C66A	LBL	03.01.1998	z = 0.444
PG 1553+113	HBL	03.01.2006	z = 0.35
1ES 1011+496	HBL	09.01.2007	z = 0.212
1ES 0347-121	HBL	08.01.2007	z = 0.188
1ES 1101-232	HBL	04.01.2006	z = 0.186
1ES 1218+304	HBL	05.01.2006	z = 0.182
H 2356-309	HBL	04.01.2006	z = 0.165
1ES 0229+20	HBL	02.01.2006	z = 0.14
1ES 0806+524	HBL	02.01.2008	z = 0.138
H 1426+428	HBL	02.01.2002	z = 0.129
PKS 2155-304	HBL	06.01.1999	z = 0.116
W Comae	IBL	08.01.2008	z = [illegible].02
RGB J0152+017	HBL	02.01.2008	= [illegible]
PKS 2005-489	HBL	06.01.2005	z = 0.071
BL Lacertae	LBL	04.01.2001	z = [illegible].069
1ES 1959+650	HBL	08.01.1999	z = 0.048
Markarian 180	HBL	09.01.2006	z = 0.045
1ES 2344+514	HBL	07.01.1998	z = 0.044
Markarian 501	HBL	01.01.1996	z = 0.034
Markarian 421	HBL	08.01.1992	z = 0.031
M87	FRI	05.01.2003	z = 0.0044

TeVCAT: Courtesy: S. Wakely, UChicago

50!

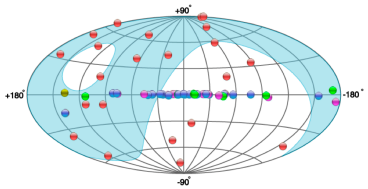
Recent additions:

M82, NGC253
starburst galaxies

Centaurus A, 3C66B
radio galaxies

PKS1424+240,
S5 0716+714,
RGB 0710+591
blazars

LMC
Pulsar wind nebula
outside Milky Way

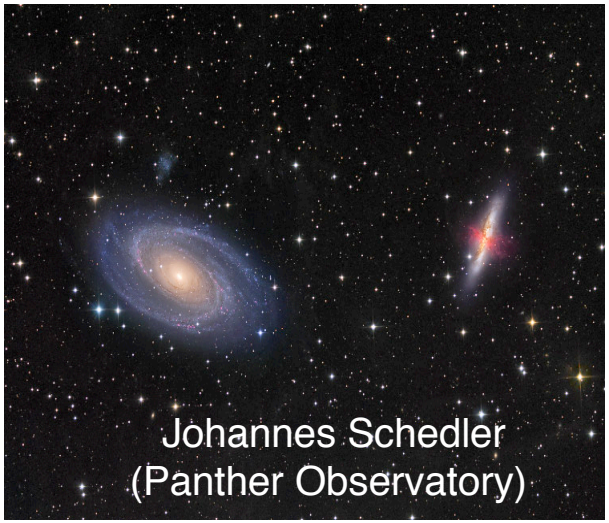


Starburst Galaxies: M82

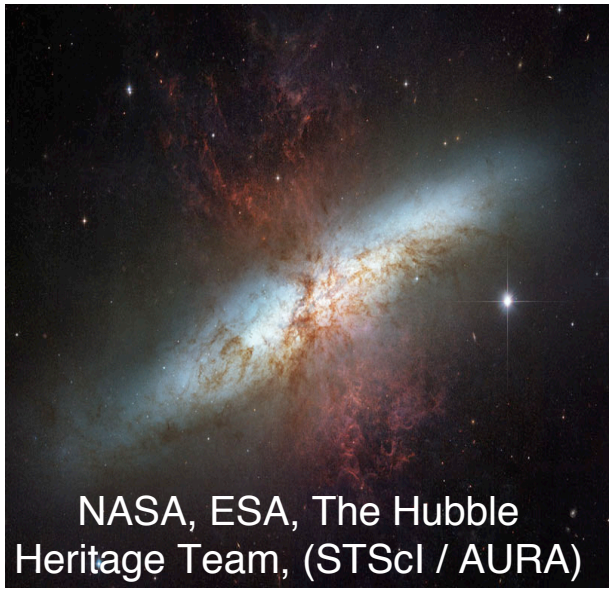
- M82 is the prototype starburst galaxy
- Distance ~ 3.9 Mpc
- Diameter ~ 1’
- SMBH ~ 3 x 10^7 M_{solar}
- Interacts with group of galaxies (M81)
- HST: 200 massive star clusters
- High supernova rate ~ 0.1 - 0.3 per year
- High gas density 150 particles/cm^3

-> excellent candidate for cosmic ray interactions & gamma ray emission.

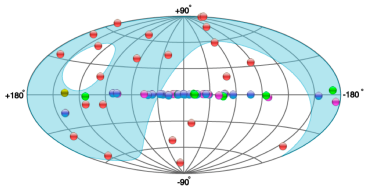
-> probing paradigm that SNRs are the origin of C.R.s.



Johannes Schedler (Panther Observatory)



NASA, ESA, The Hubble Heritage Team, (STScI / AURA)



Starburst Galaxies: M82

- VERITAS data ~ 137 h livetime

  only astronomical dark time, large zenith angle ~ 39°

  increased E_{thres}

  bad weather removed

- Standard VERITAS analysis ("hard cuts")

  Et_{hres} ~ 700 GeV

  cuts a priori optimized on Crab

  hard spectrum expected from theory

  but we count for 3 trials (standard, hard & soft)

- Point-like excess of 91 γ; 5.0 σ (pre-trial)

  3 independent analyses

  many systematic checks performed

- Post-trial: 4.8 σ (7.7×10^{-7})

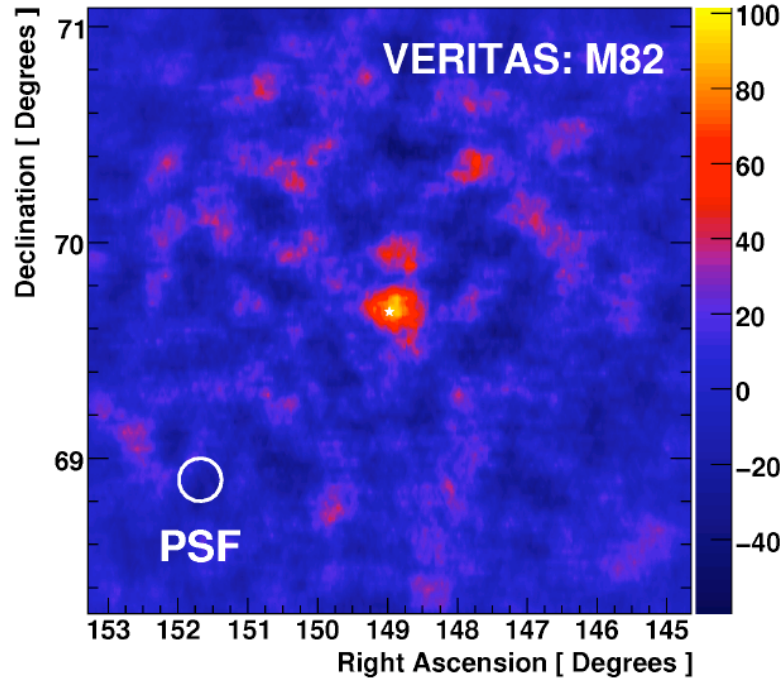
  steady signal

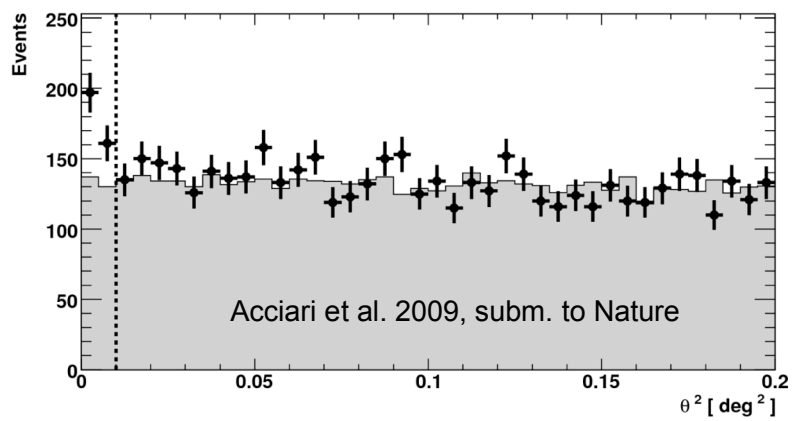
  excess consistent with instrument PSF

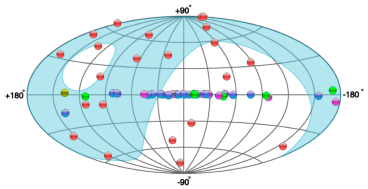
- M82 weakest source ever detected @ VHE

  0.9% of Crab

  Gamma-ray rate: 0.7 γ/hour







Starburst Galaxies: M82

- Spectrum 875 GeV to 5 TeV
- $dN/dE \sim (E / TeV)^{-\Gamma}$

  $\Gamma = 2.5 \pm 0.6$
- VHE flux is close to predictions

  incl. leptonic & hadronic channels
- Origin: hadronic or leptonic?

$$pp \rightarrow \pi^0 \rightarrow \gamma\,\gamma$$

$$pp \rightarrow \pi^{\pm} \rightarrow e^{\pm} \ldots$$

radio

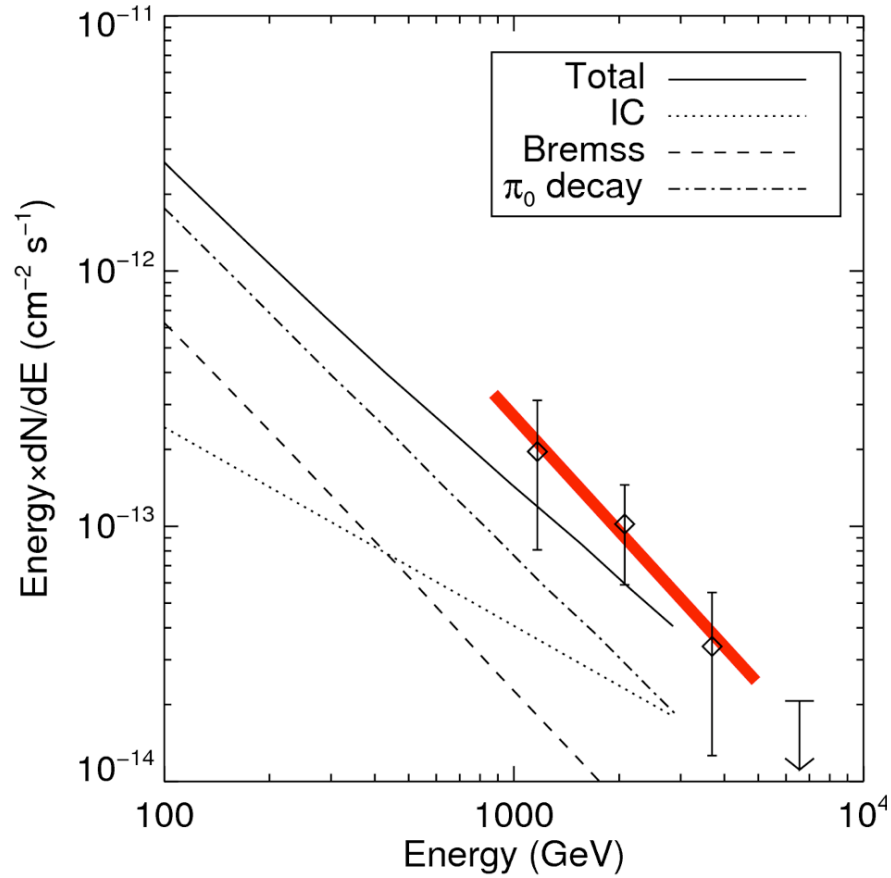
20 GeV

with Γ=2.3, TeV flux OK.

$$e^- \xrightarrow{synchr.} \gamma_{X-ray}$$

$$e^- \gamma_{soft} \rightarrow \gamma_{TeV}$$

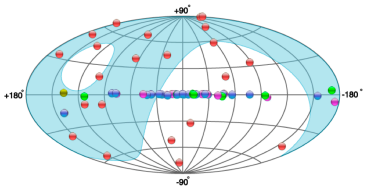
cutoff



Acciari et al. 2009, subm. to Nature

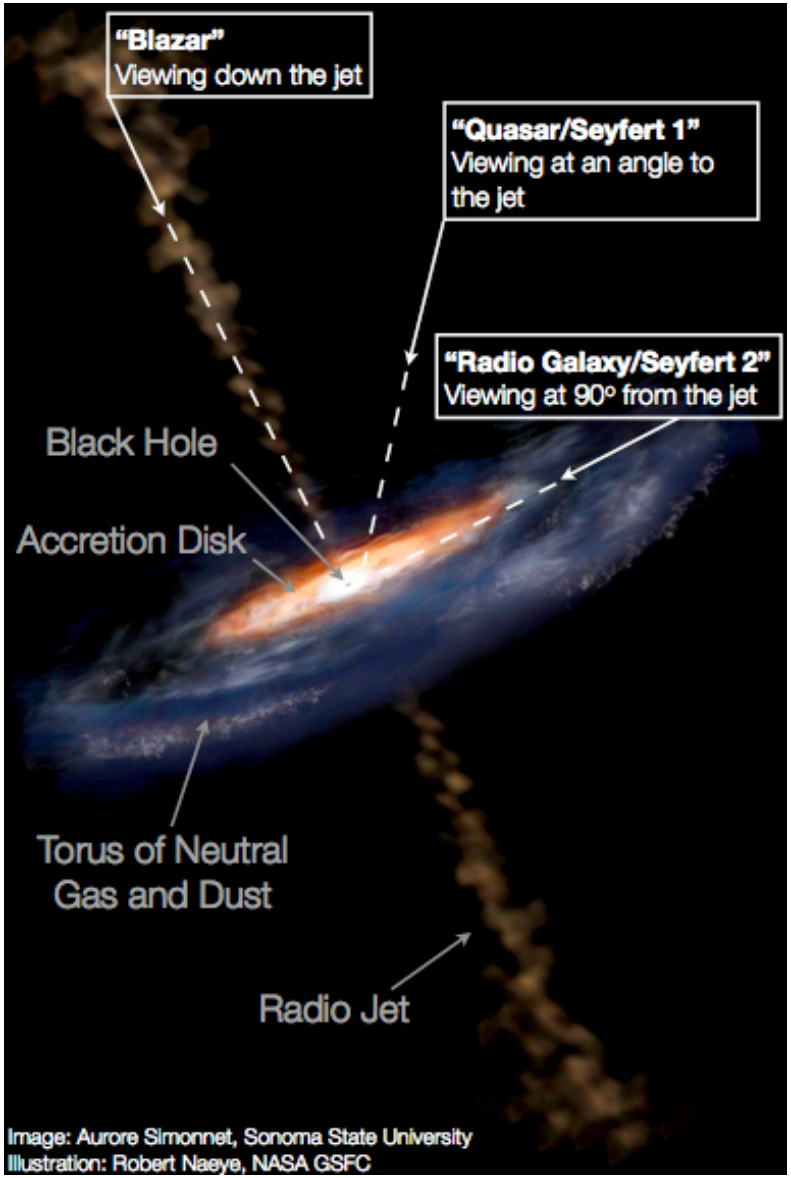
Sensitivity < 1 mCrab needed

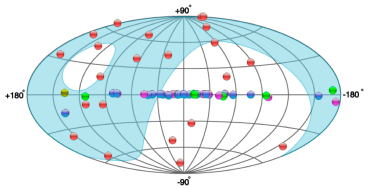
VERITAS: pathfinder for next generation instruments such as AGIS, CTA



Relativistic Jets in Blazars

- “Standard Model” of AGN Physics
  - SMBH
  - Accretion disk
  - Relativistic jet
- Point of view changes appearance
  - Blazar
  - Quasar
  - Radio galaxy
- Physics questions
  - Black hole - jet - connection
  - Acceleration mechanism
  - Emission mechanism
  - Maximum energy
  - hadrons and leptons?
  - UHE cosmic ray connection?
  - Axion emission?





PKS 2155-304

- HBL at z ~ 0.116

  EGRET source

  detected by HESS

- "Gigantic" flare ~ 11 Crab

  HESS: 6.5 hrs of observations July 29-30 2006

  ~ 30,000 photons

  Chandra observations 30 ks

  emission dominated in TeV regime

- TeV/X-ray correlation

  contemporaneous coverage

  correlation, no time lags

  amplitude of variations ~ 22 (TeV),

  ~ 2 (X-ray),

  ~ 1.15 (optical)

  cubic relation between TeV/X-ray variations

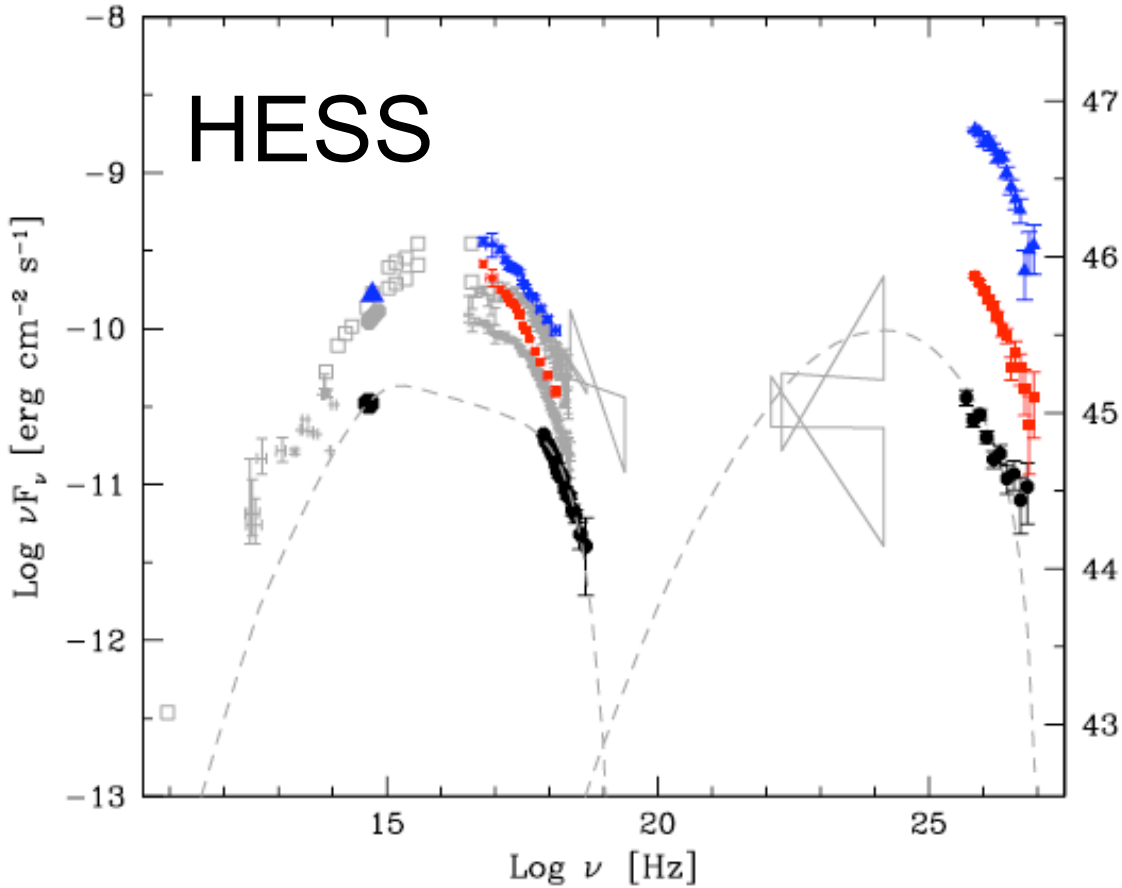
- One-zone SSC Model

  inconsistent with one zone modell

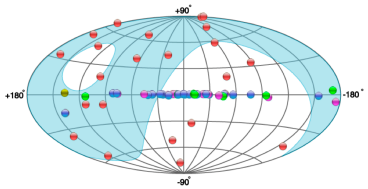
- Conclusions

  Compton dominated emission component

  inconsistent with one-zone SSC



Aharonian et al. 2009, arXiv:0906.2002v1



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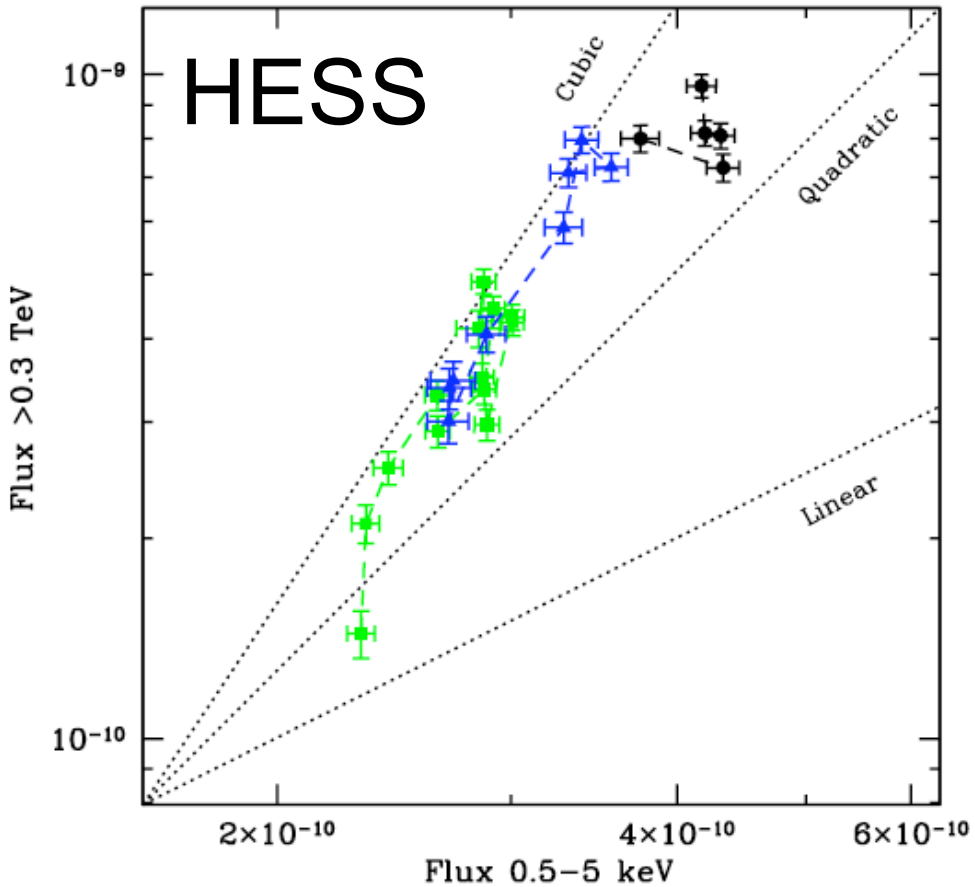

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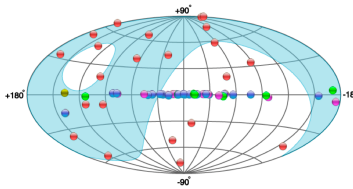


PKS 2155-304 with Fermi+HESS

- HESS,Fermi, RXTE, optical

  11 days, Aug. 2008

  low flux state, but detectable

- SED optical, X-ray, GeV - TeV

  nightly flux variations in optical, X-ray, TeV

  power comparable in X-ray, GeV, TeV

  TeV/optical correlate

  TeV/X-ray do not!

- Interpretation

  one-zone SSC model

  X-ray synchrotron from high energy electrons

  -> IC scattering in Klein Nishina regime

  -> TeV emission not changed

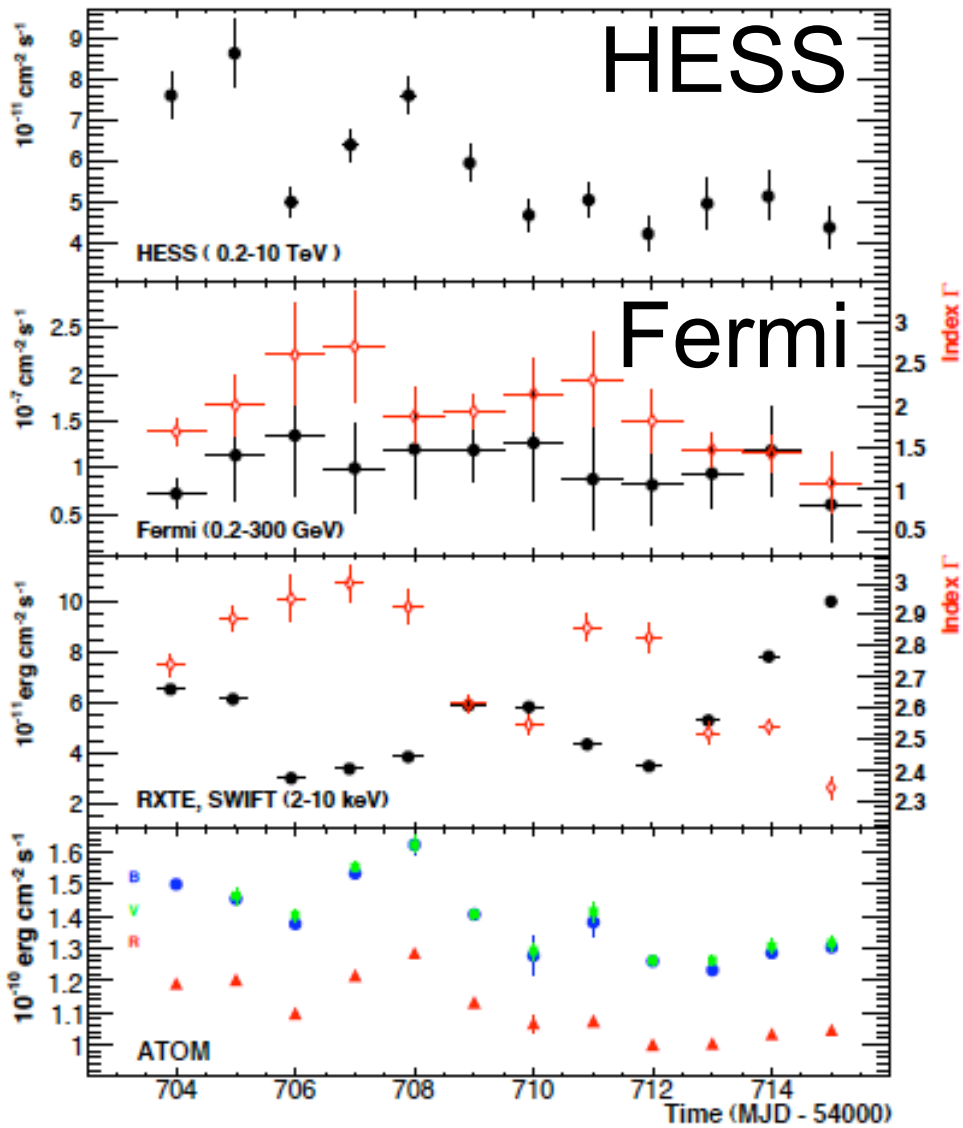
  optical synchr. emission from low E electrons

  -> TeV and optical emission correlated

  -> GeV emission should also correlate but does not!

  one-zone SSC models can explain SED but not the variability pattern!

Aharonian et al. 2009, ICRC, Proc.



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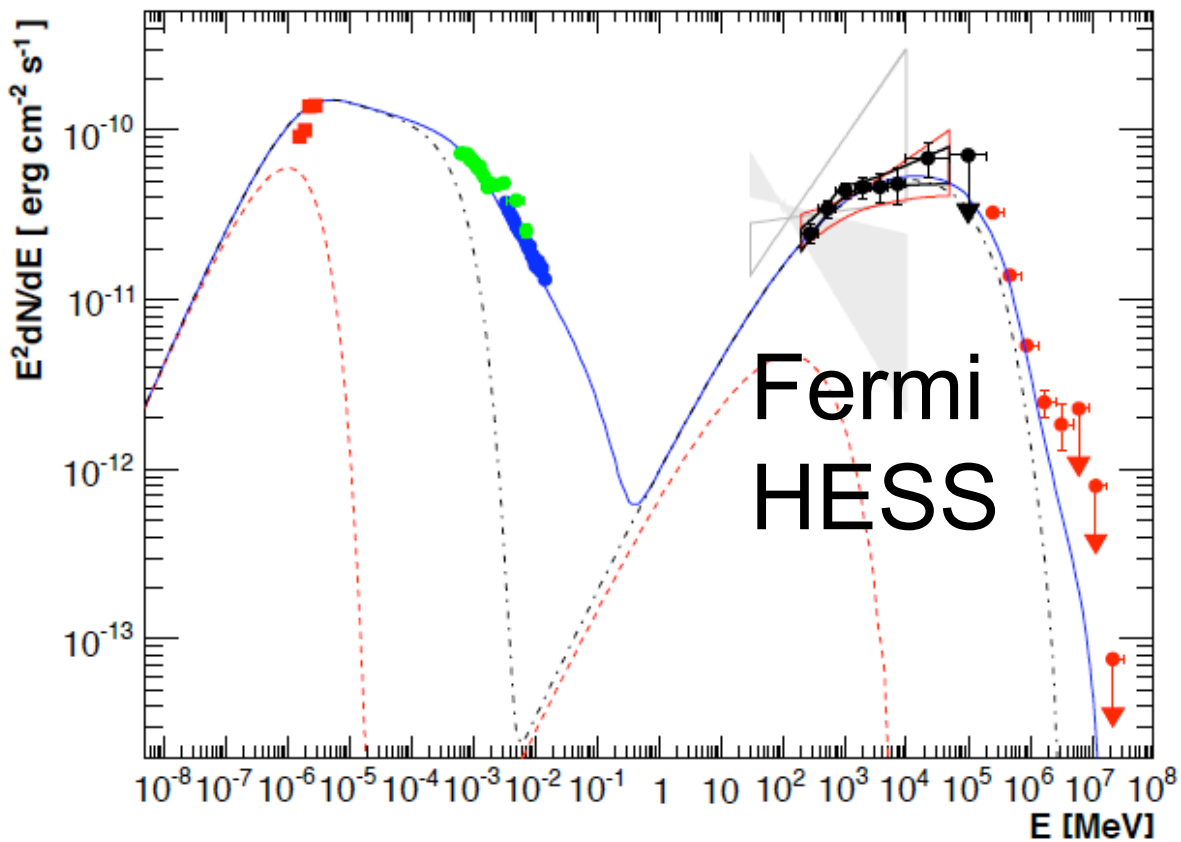
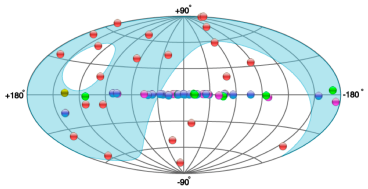
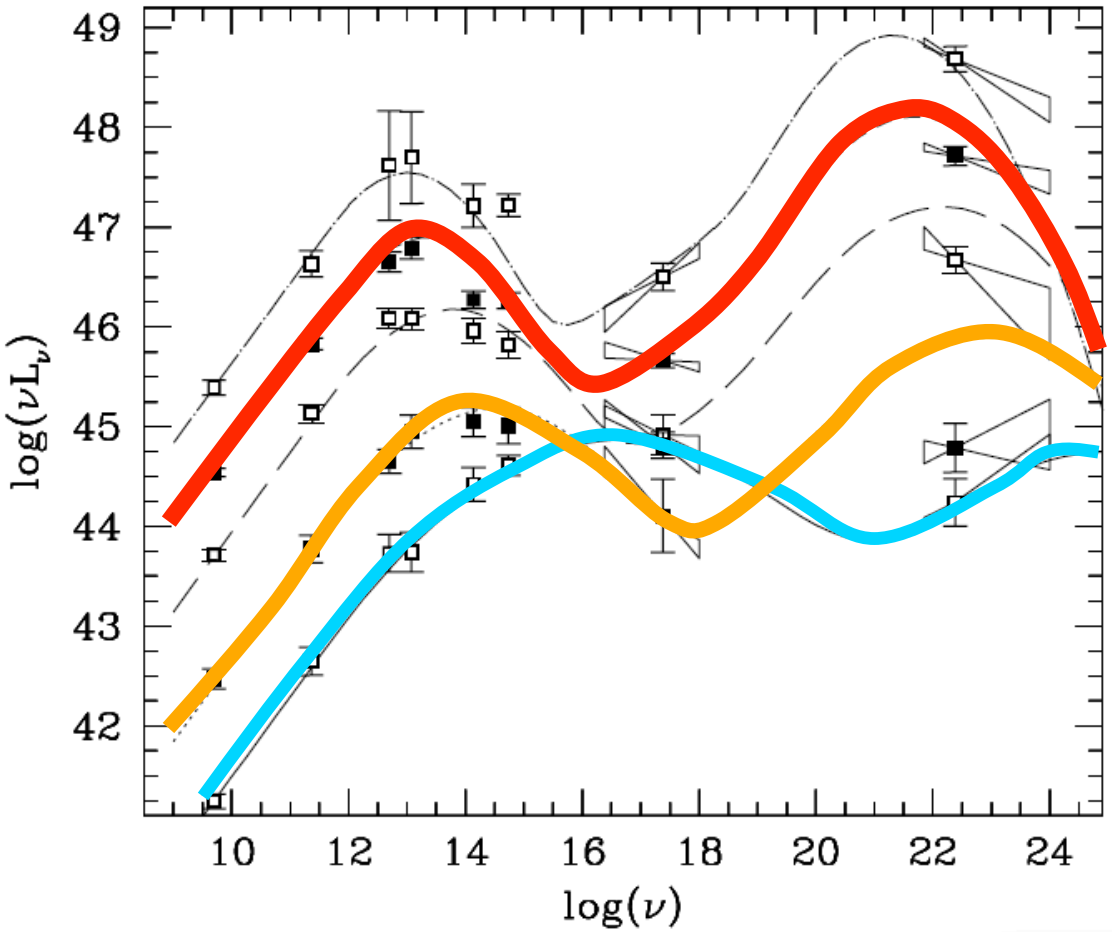




Intermediate BL Lacs

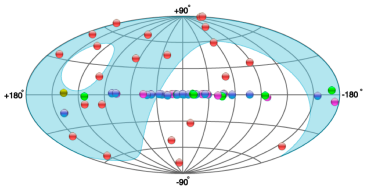
Fossati 1998, MNRAS, 299, 433



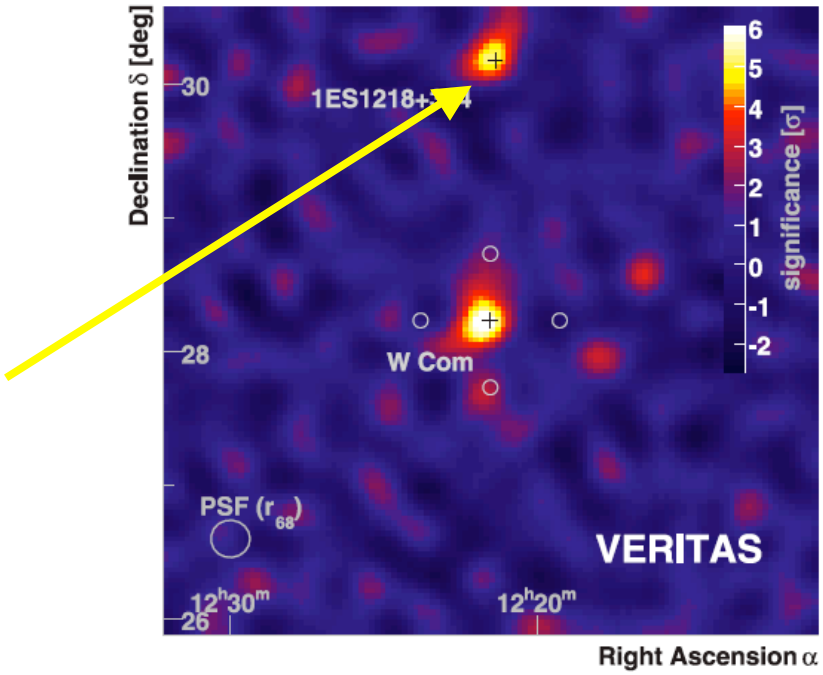
LBL:
powerful, substantial external radiation fields

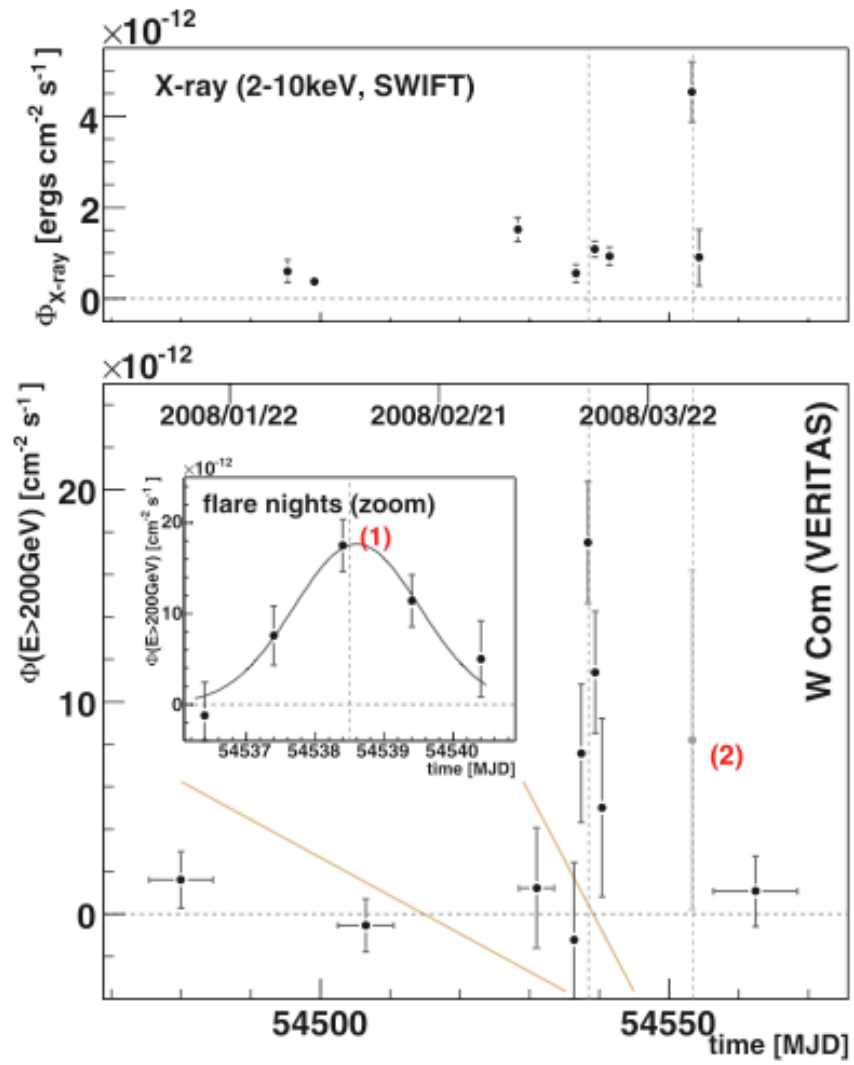
IBL: fall between

HBL:
low power, weak external radiation fields



W Comae





- IBL (intermediate BL Lac)

  discovered in radio (X-rays), 1971 (1980)

  seen by EGRET: 0.1 - 10 GeV

  z = 0.102

  promising candidate for TeV

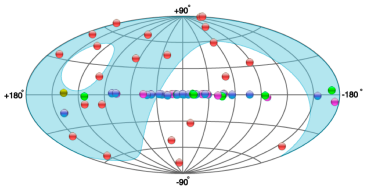
- VERITAS discovery of TeV emission

  4.9 σ in 40 hours

  outburst March 2008 (> 8 σ detection)

  quasi-simultaneous X-ray data

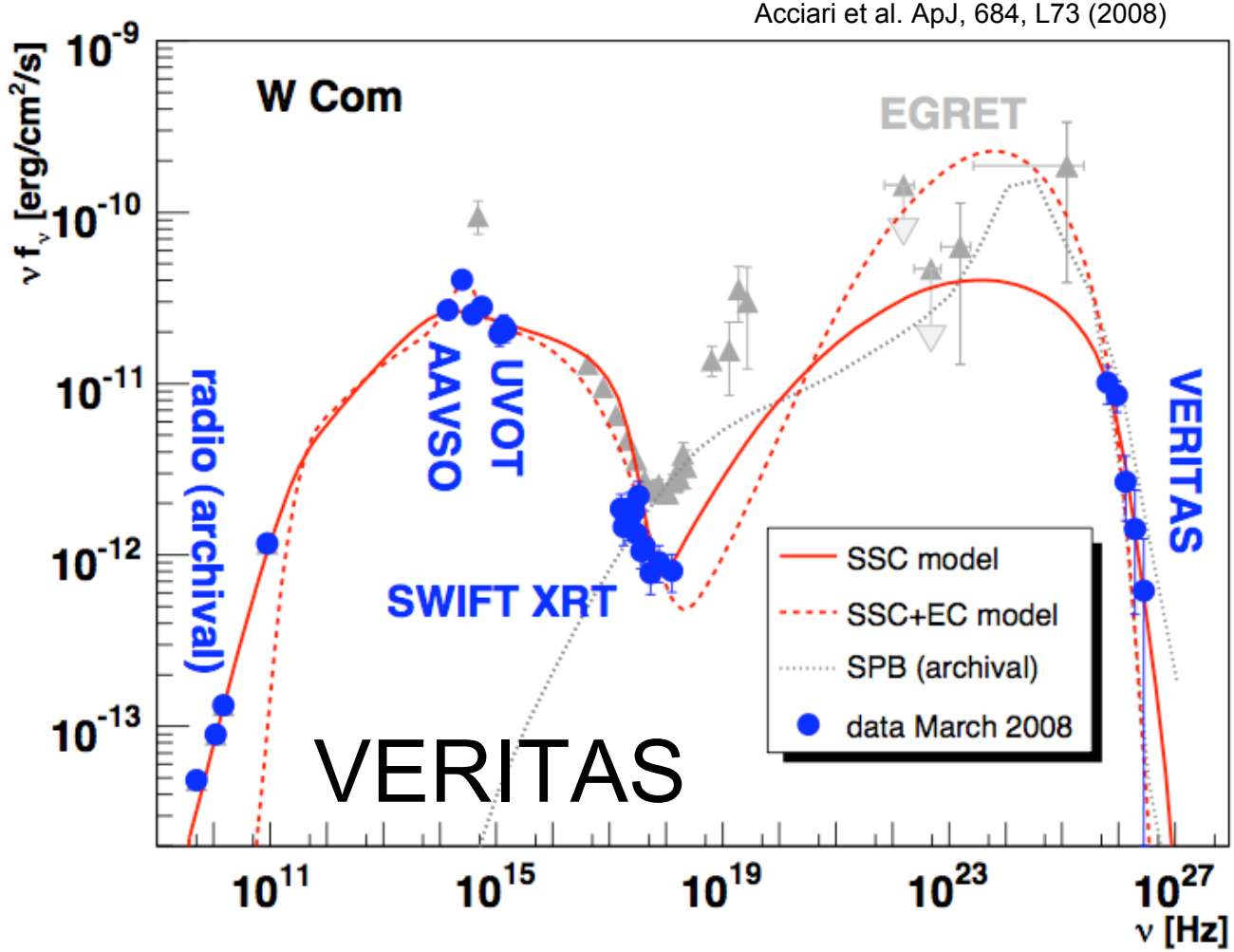
$$\sigma_t = 1.29 +- 0.28 \text{ days}$$

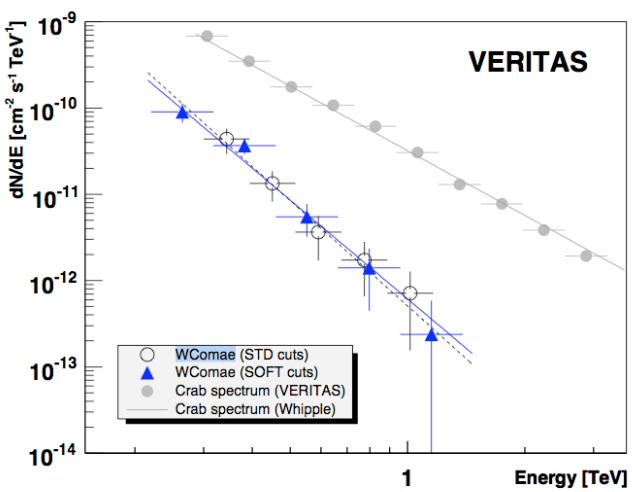


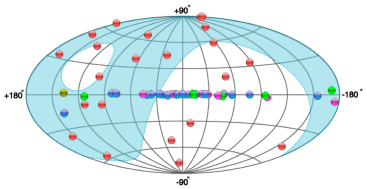
W Comae

- One-zone SSC
  weak magnetic field
- External Compton
  B ~ 0.3 Gauss
- GeV - TeV coverage
  distinghuish between the two

Acciari et al. ApJ, 684, L73 (2008)







3C66A

- **IBL**

  seen by EGRET and Fermi (#1759)

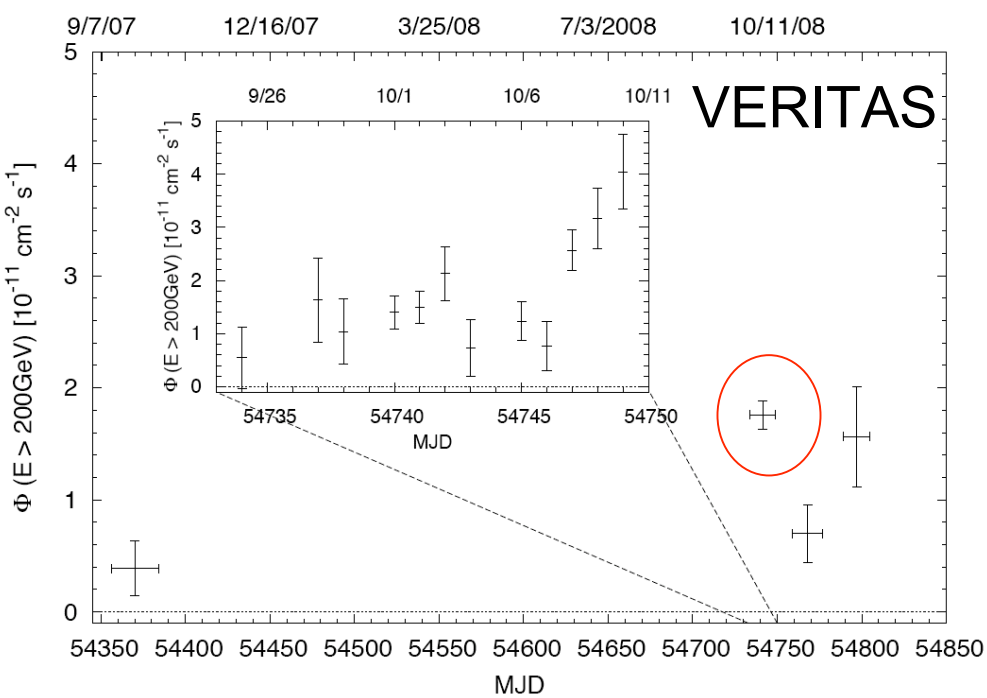
  z = 0.44 (highly uncertain)

  promising candidate for TeV

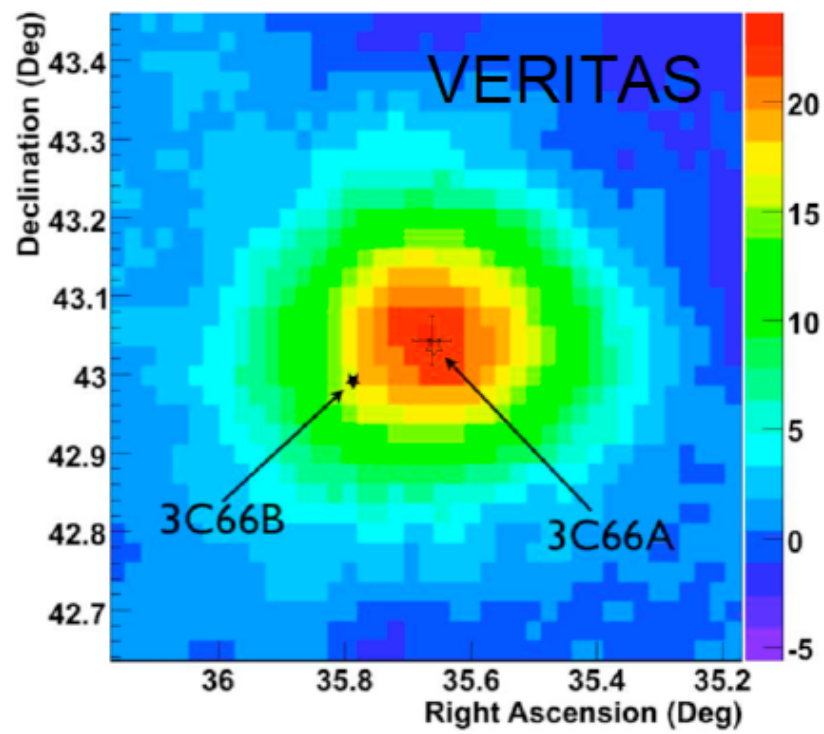
  Crimean group reported 5.1 σ at 1 TeV (1996-98)

- **VERITAS detects TeV emission**

  21 σ in 33 hours, ~ 1800 γ; E_{thres} ~ 120 GeV



Acciari et al. ApJ, 693, L104 (2009)



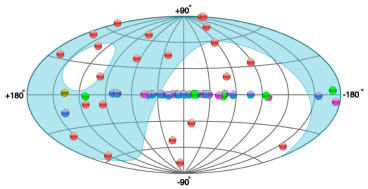
- **MAGIC detects 3C66B (radio galaxy)**

  at 0.12 degree off-set from 3C66A (not contemp.)

- **Two sources or just one?**

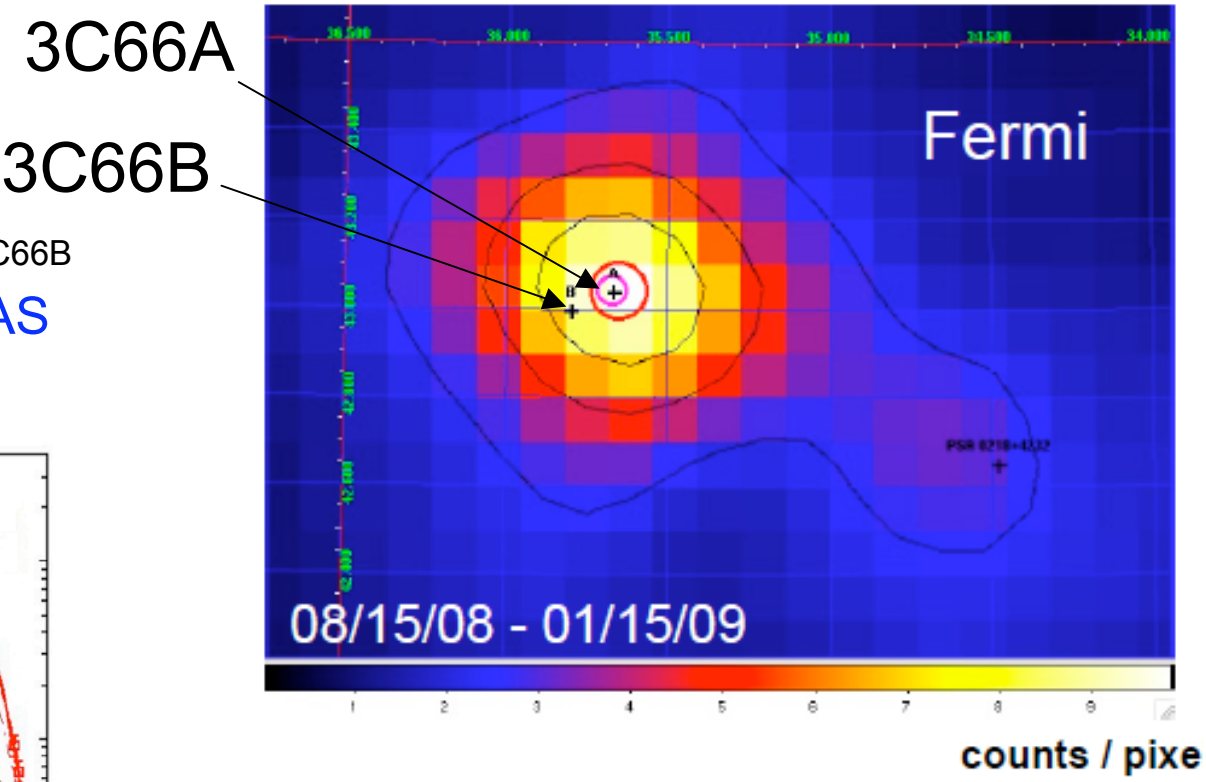
  data is not contemporaneous!

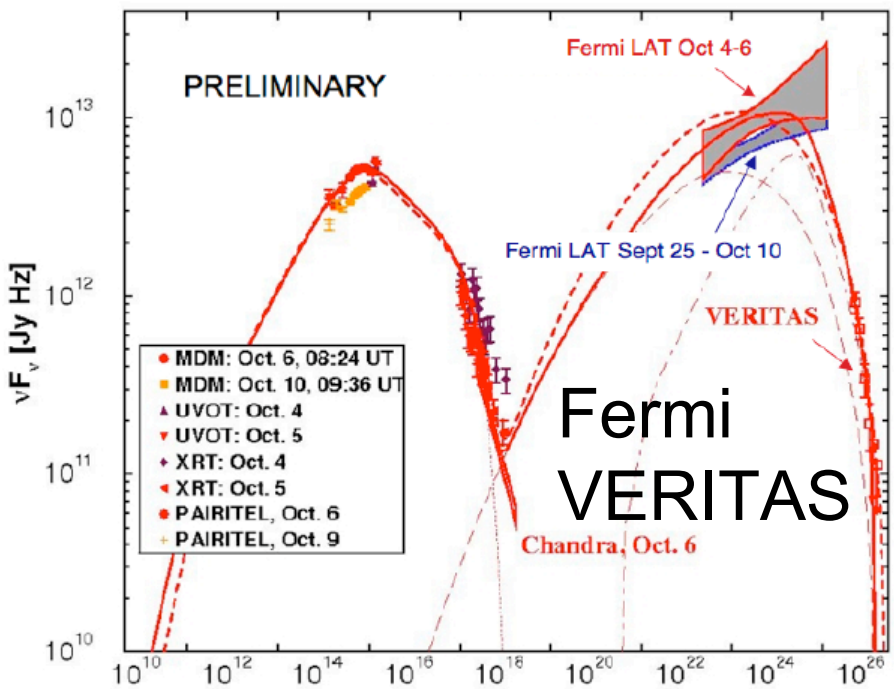
  VERITAS detection is unambiguously 3C66A



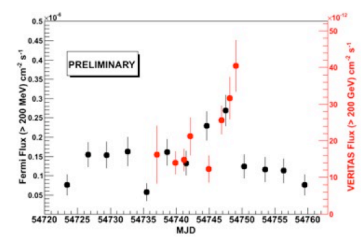
3C66A: Fermi & VERITAS

- **Fermi data**
  Sept. 1 - Dec. 31 2008
  0.1° x 0.1° pixel map
  Fermi & VERITAS identify 3C66A
  Fermi cannot exclude small contribution from 3C66B
- **PAIRTEL/Chandra/Swift/VERITAS**
  SED peaks in GeV regime

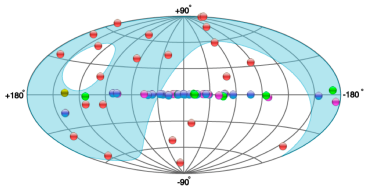




- **SED modeling**
  one-zone SSC model
  EC+SSC
  high ambient seed population in IBLs
  target for IC scattering



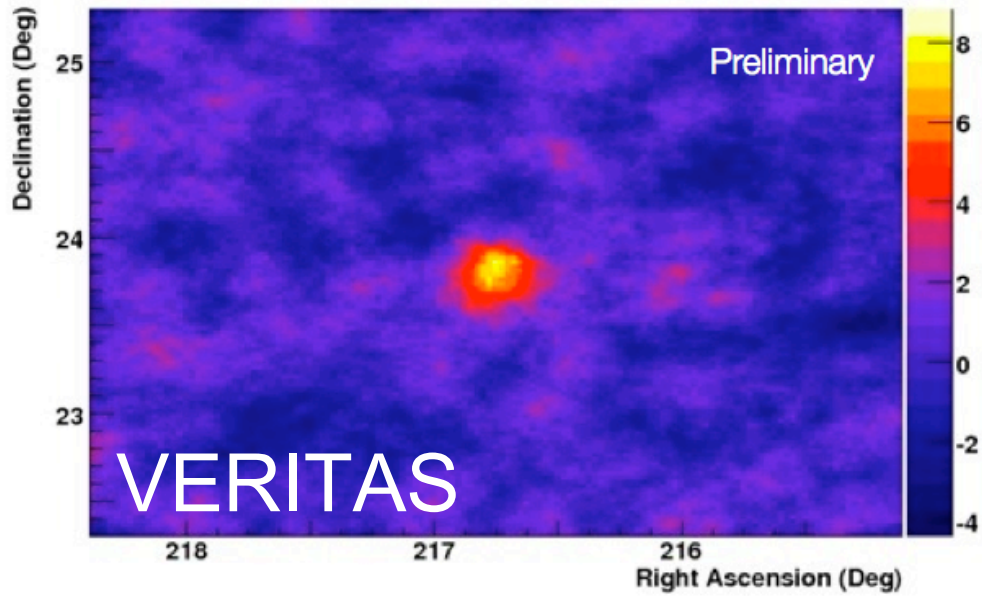
Reyes et al. 2009, ICRC, Proc.

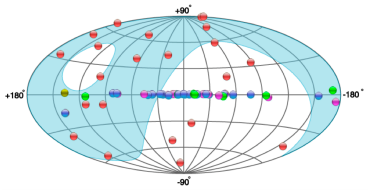


PKS 1424+240

- IBL detected by Fermi
  - 0.2 - 100 GeV
  - Γ = 1.8 +- 0.07
  - promising target for IACTs
  - Fermi & VERITAS identify 3C66A
  - Fermi cannot exclude small contribution from 3C66B
- TeV emission discovered by VERITAS
  - no evidence for variability
  - 7.5 σ in full data set
- First TeV discovery motivated by Fermi
  - E > 1 GeV useful to find new TeV blazars with IACTs
- IBLs: strong link between Fermi/IACTs
  - promising for many more GeV-TeV spectra
  - AGN population studies
  - EBL studies (UV-optical-near IR)

Ong et al., ATEL # 2084





Population Studies

- Blazar discovery program

  X-ray selected BL Lacs

  ~ 60 blazars observed

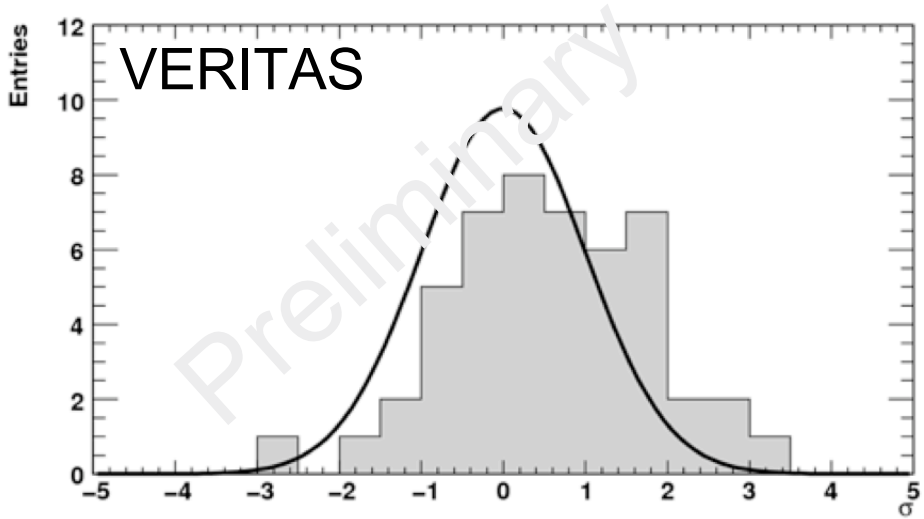
  excluded detections

  remaining objects stacked (120 hours)

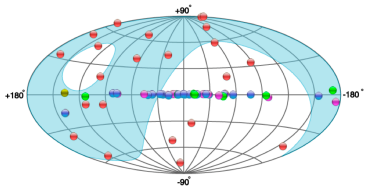
- Combined excess of 49 blazars

  ~ 4.8 σ

  480 events



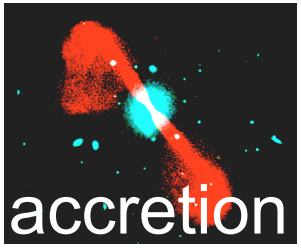
Benbow et al. 2009, ICRC, Proc.



Physics: EBL/Cosmology

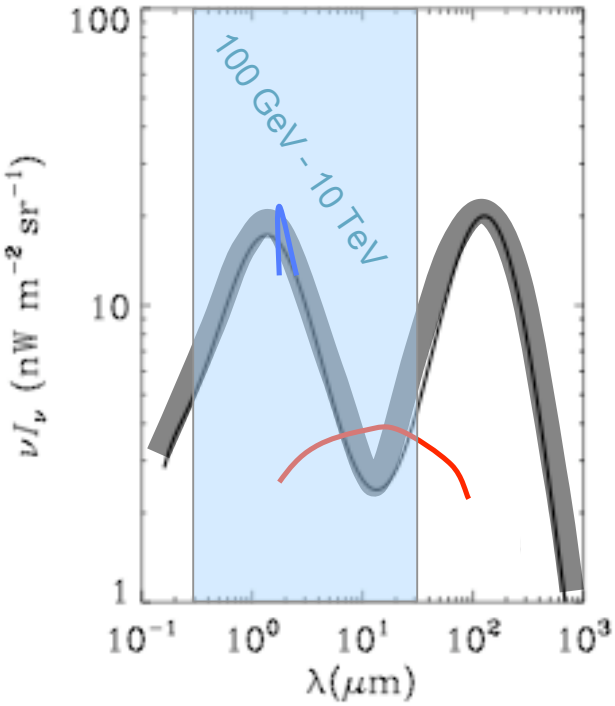
- probe diffuse Cosmic IR-Background
- EBL poorly understood: near - mid IR
- TeV beam: $\gamma + \gamma \rightarrow e^+ + e^-$ interaction
- measure CIRB: absorption(z)

Star/galaxy Formation
z<5



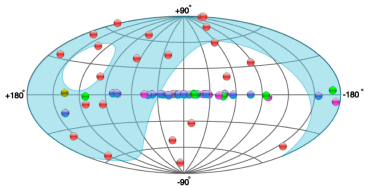
AGNs
z<5

Pop III
z ~ 7 - 30

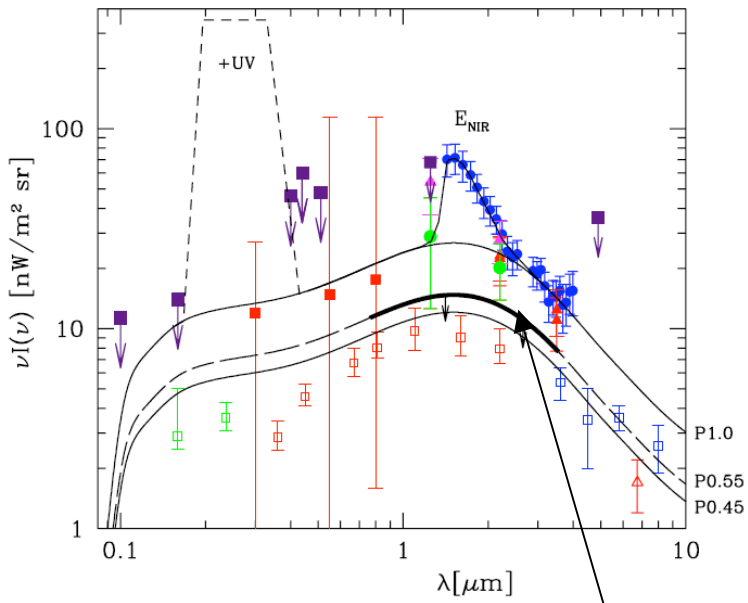


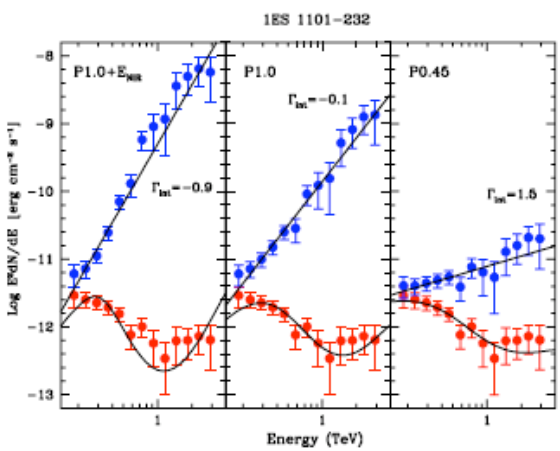
Relics?

Truly diffuse Component?



Upper Limits - Blazar spectra





$\Gamma > 1.5$

Aharonian et al. 2006, Nature, 440, 1018

1ES0347-121

1ES1101-232

1ES1218+30.4

H2356-309

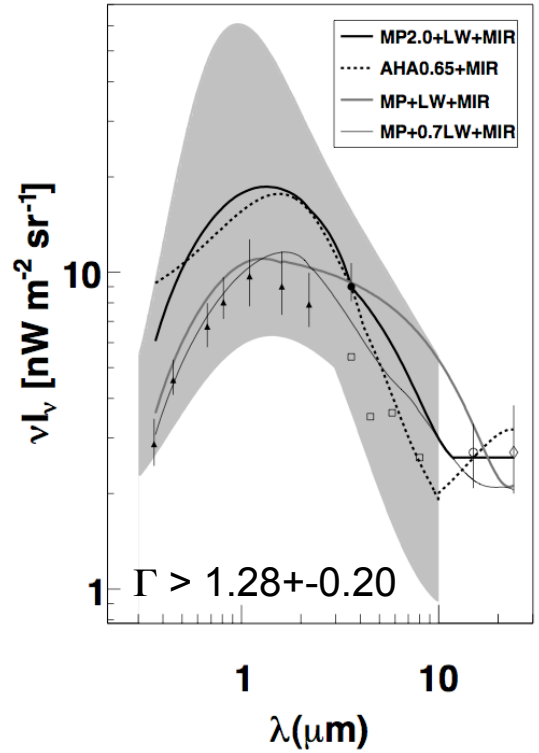
1ES0229+200

1ES0229+200

RGB J0710+591

$\Gamma_{obs} \sim 2.5 - 3.1$

K, Dwek, & Imran, 2008, ApJ, L89, L93



- Hard spectra blazars

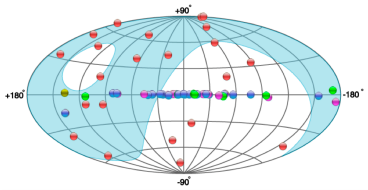
  exhibit unusually hard spectra for given z (0.12 - 0.22)

  intrinsic spectra by considering EBL lower limits

  Γ~1.5 already reached by combining lower limits

  Γ=1.5 not a speed limit, or new physics?

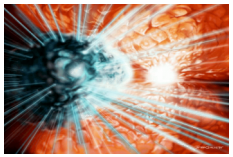
For review of theoretical papers see: Boettcher et al. 2008, ApJ, 679, L9



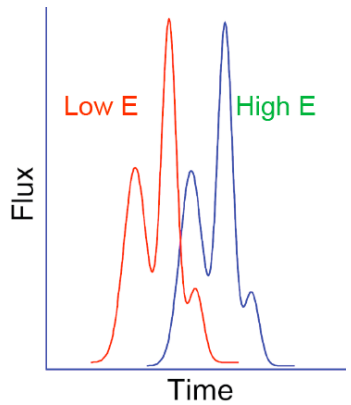
“Time of flight” test: c = const?

E_1

E_2



$E_1 >> E_2$

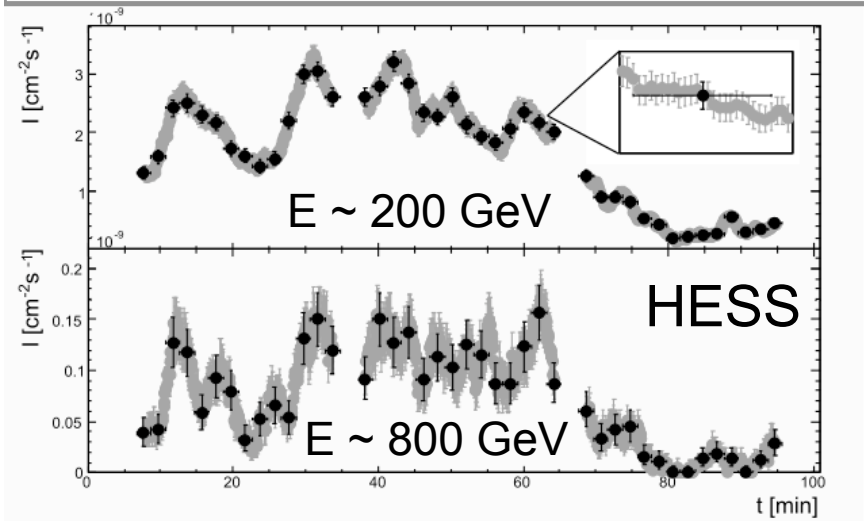


Amelino-Camelia, G., Ellis, J. et al. 1998 , Nature, 395, 525

$$t_1 = \frac{L}{c}\left[1 - \xi \frac{E_1}{E_{QG}}\right]$$

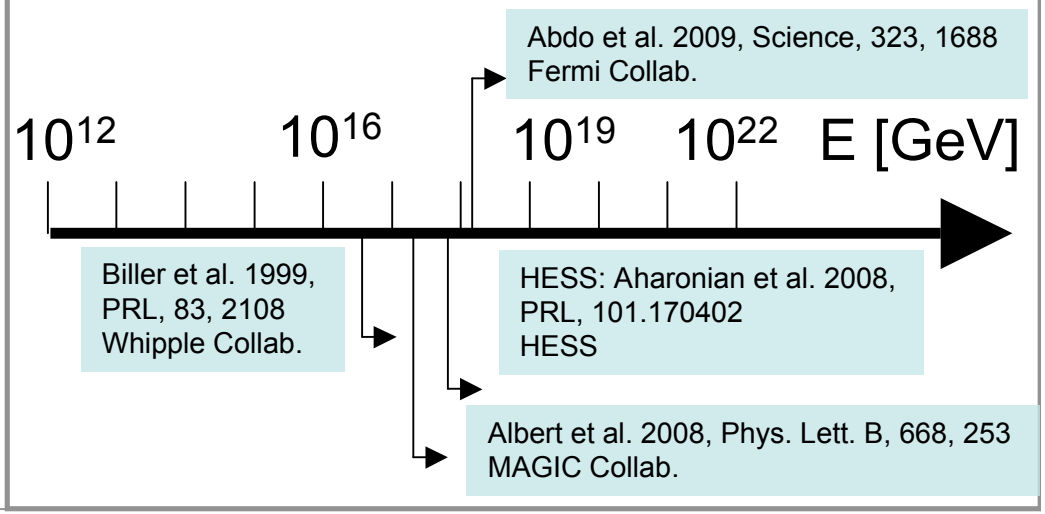
$$t_2 = \frac{L}{c}$$

$$\Delta t \approx \left(\frac{L}{c}\right)\left(\xi \frac{E}{E_{QG}}\right)$$



PKS2155-304

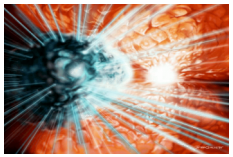
$$E_{QG} > 7.2 \times 10^{17}\, GeV$$



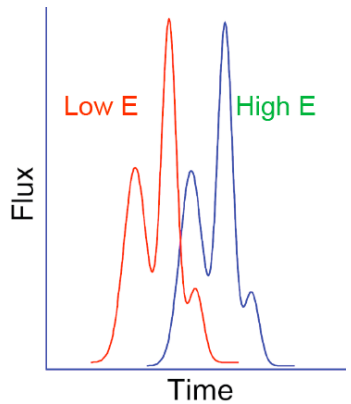
“Time of flight” test: c = const?

E_1

E_2



$E_1 >> E_2$

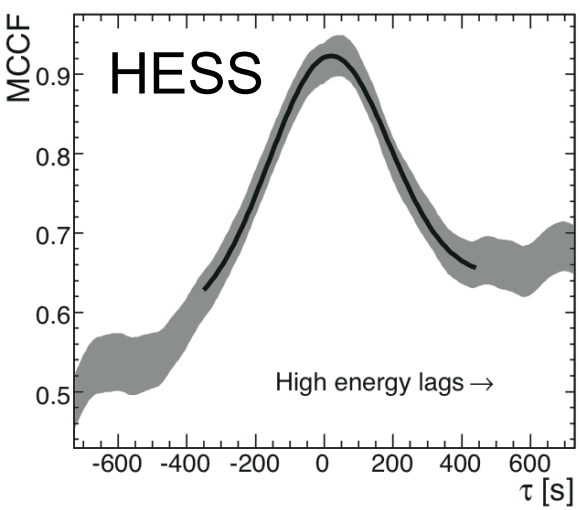


Amelino-Camelia, G., Ellis, J. et al. 1998 , Nature, 395, 525

$$t_1 = \frac{L}{c}\left[1 - \xi \frac{E_1}{E_{QG}}\right]$$

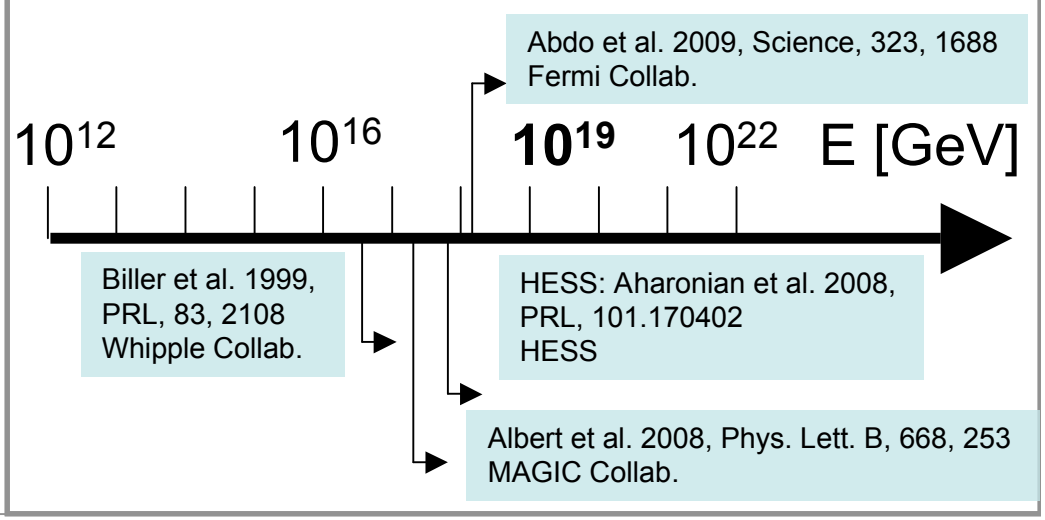
$$t_2 = \frac{L}{c}$$

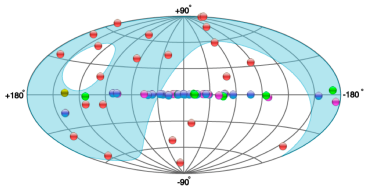
$$\Delta t \approx \left(\frac{L}{c}\right)\left(\xi \frac{E}{E_{QG}}\right)$$



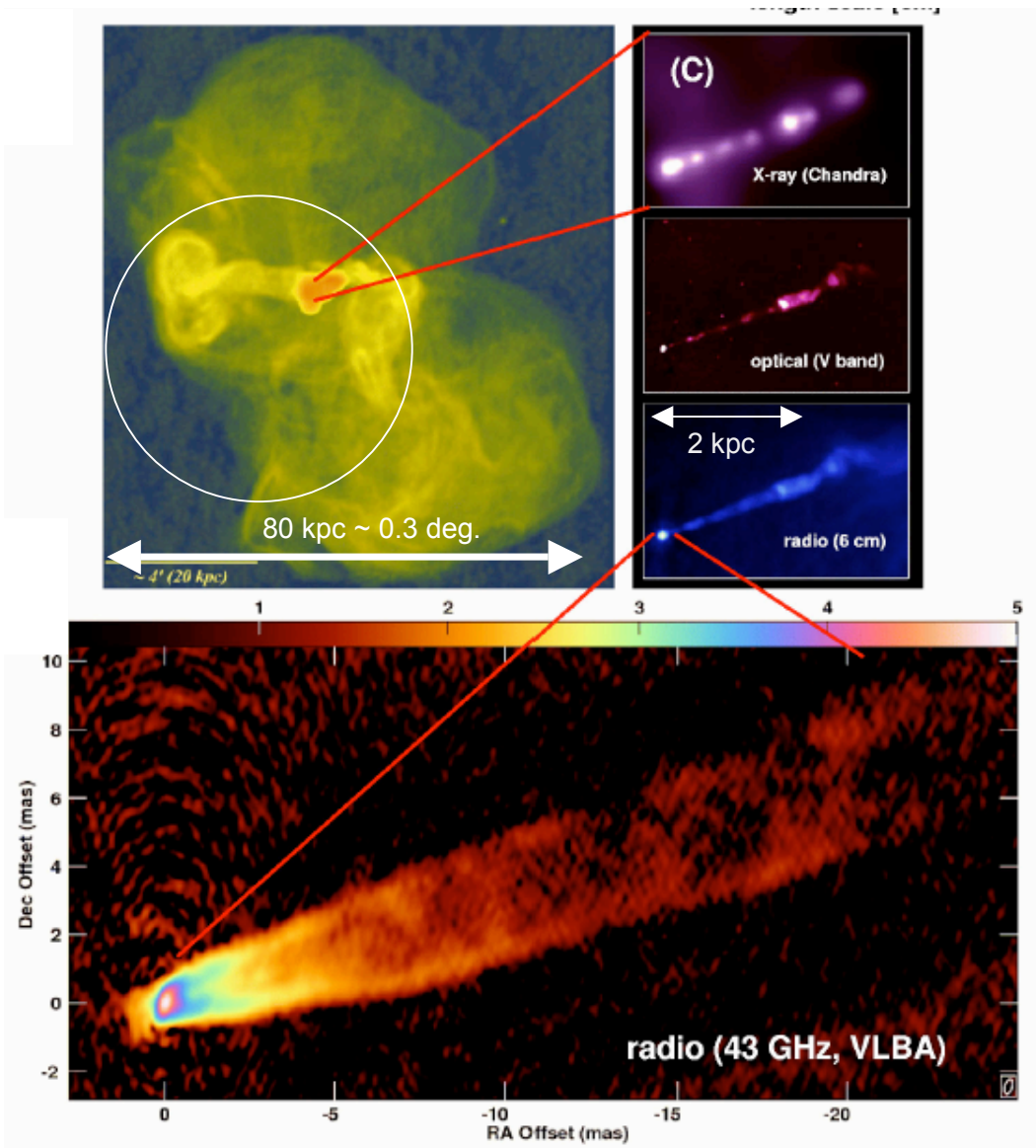
PKS2155-304 no dispersion!

$$E_{QG} > 7.2 \times 10^{17}\, GeV$$

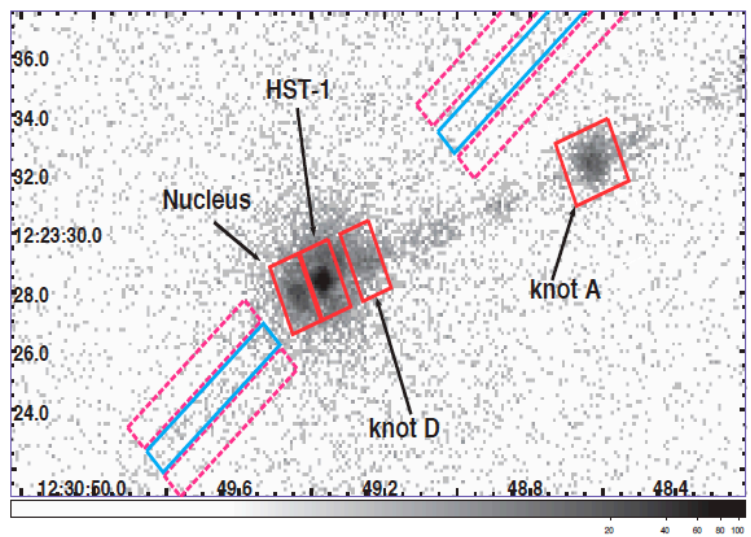


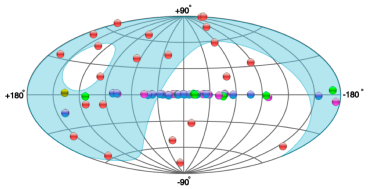


Radio Galaxies: M87



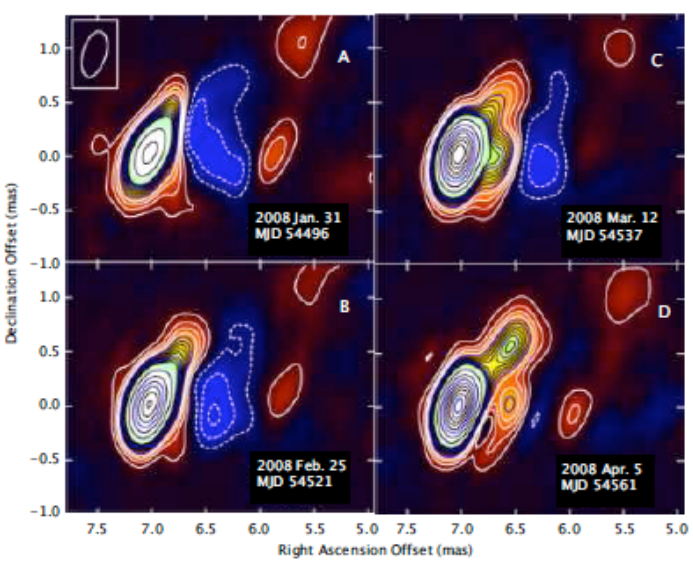
- Nearby giant radio galaxy, 16 Mpc
  - SMBH ~ 6 x 10^9 M_{sun}
  - Jet angle ~ 15 - 30 deg. (not a blazar)
  - resolved jet (radio, optical X-ray)
  - variable emission
- TeV emission
  - Evidence in Hegra data
  - Confirmed by HESS, MAGIC, VERITAS
  - angular resolution of TeV instruments 0.1 deg.
  - TeV emission from where?

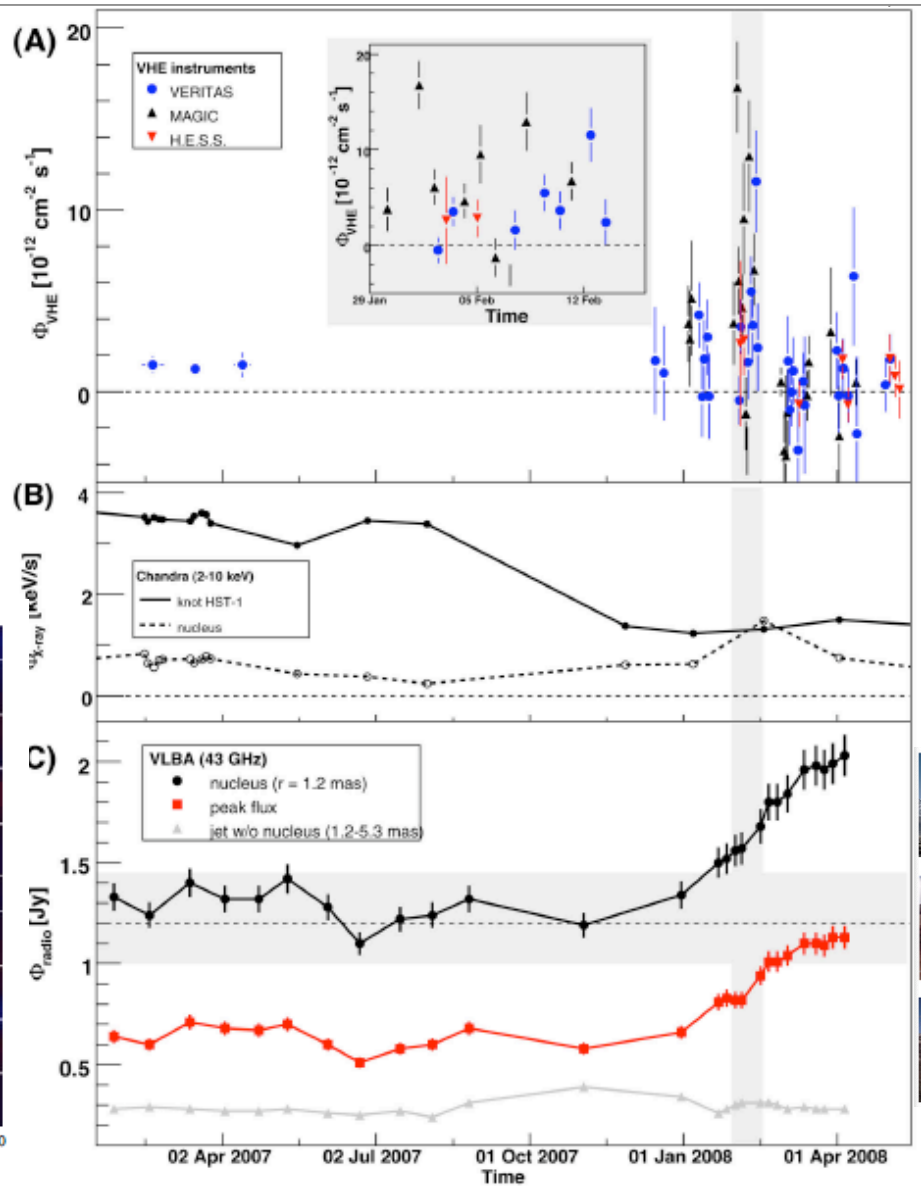


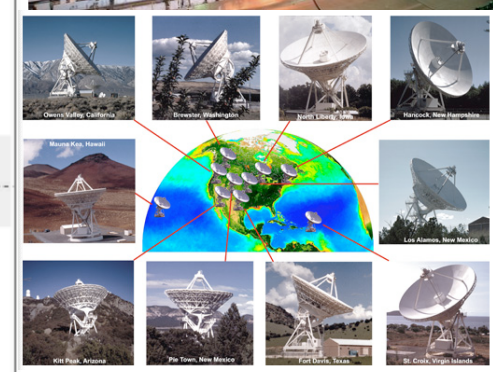


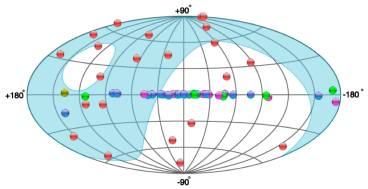
Radio Galaxies: M87

- **Joint TeV campaign:**
  MAGIC, HESS, VERITAS
  Jan. - May 2008
  95 hrs. combined
  MAGIC ToO
- **VLBA movies**
  14 shots in 2008, every 5 days
  ang. resolution 0.2 x 0.4 mas









Radio Galaxies: M87

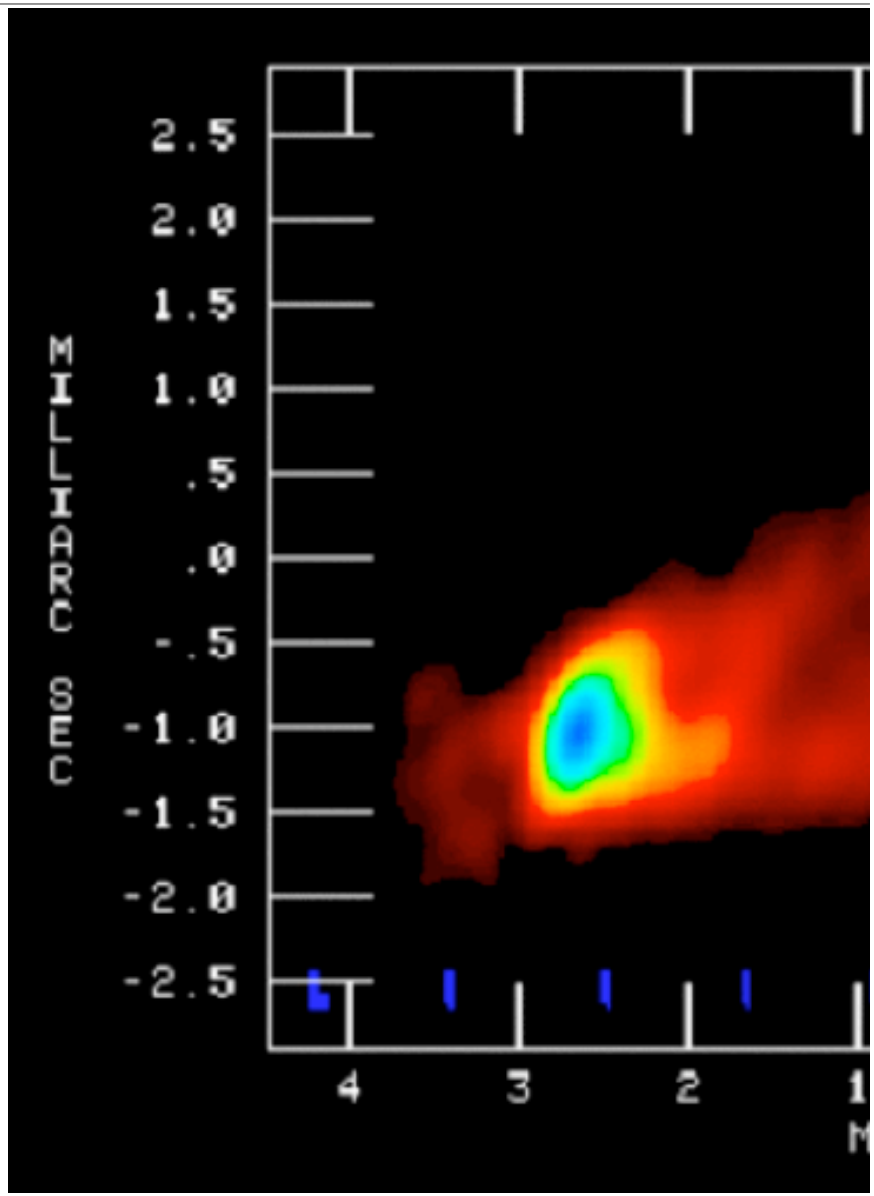
- **Picture?**

  radio, X-ray and TeV flare are likely related (P < 0.5%).
  TeV flares on time scales of 1 day: ~ few R_s
  X-ray quiet at HST-1, but shows a historically high state for core.
  VLBA flare at core (30 x 60 R_s), but slow rise.

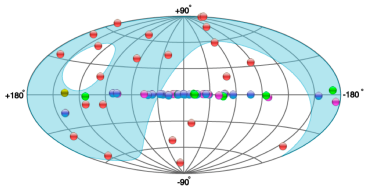
- **What does this mean?**

  Model:
  - we have observed plasma traveling down the jet.
  - transparent at TeV and X-ray energies.
  - region is initially opaque in radio (synchr. Self-absorption). and smoothens the radio flare and a delay in peak.
  - TeV/X-ray emission region well within radio blob.

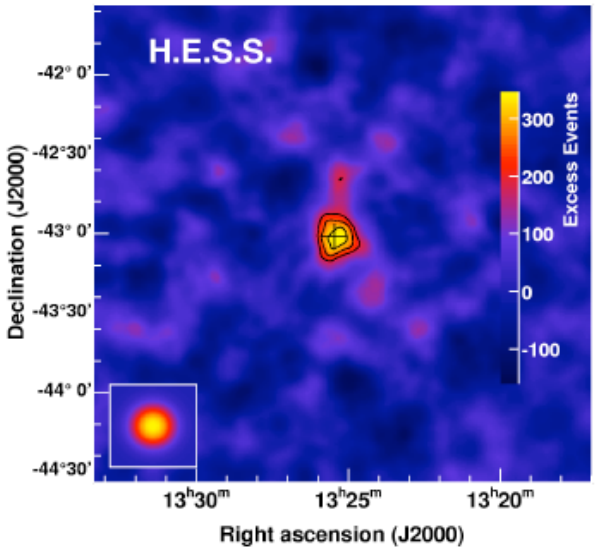
- **TeV emission produced close to the SMBH?**



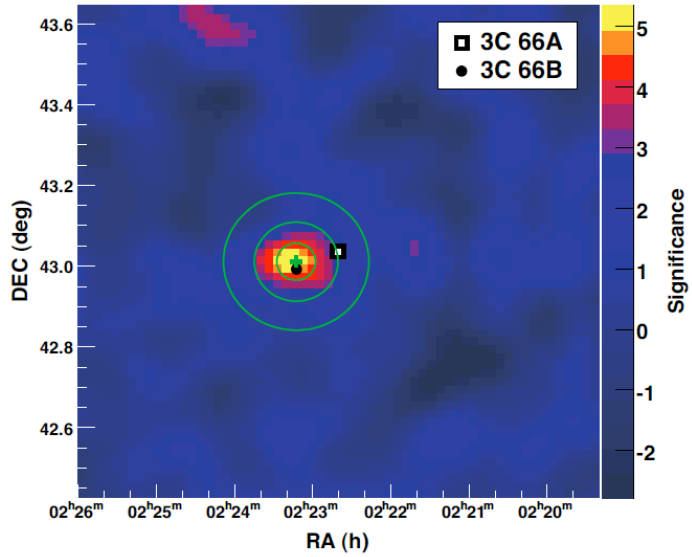
Acciari et al. 2009 (VERITAS Collaboration, VLBA 43 GHz Monitoring team, Hess Collaboration, MAGC Collaboration), Science DOI: 10.1126/science.1175406



Other Radio Galaxies



Aharonian et al. 2009, arXiv:0903.1582



Aliu et al. 2009, ApJ, L692, 29

- Centaurus A
- Closest active radio galaxy, 3.8 Mpc

  Detection by HESS, & Fermi 5 σ

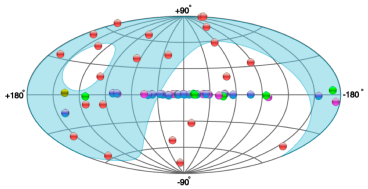
  future multiwavelength coverage: radio, optical, X-ray

- 3C66B?
- ~ 80 Mpc

  Detection by MAGIC 5.4 σ

  but location is within 2 σ of 3C66A

  open question!



Summary

- TeV γ-ray observations provide a window to extragalactic astronomy at the highest energies with > 30 sources.
- Study of cosmic accelerators: relativistic jets, BH-jet connection, …
- Fermi + IACTs are promising to constrain models.
- Probe cosmological radiation fields and Lorentz invariance.
- Discovery of starburst galaxies: role of supernovae in cosmic-ray accel.
- AGIS/CTA is the natural next step following Fermi & present IACTs.