Ten years of TeV observations of M87

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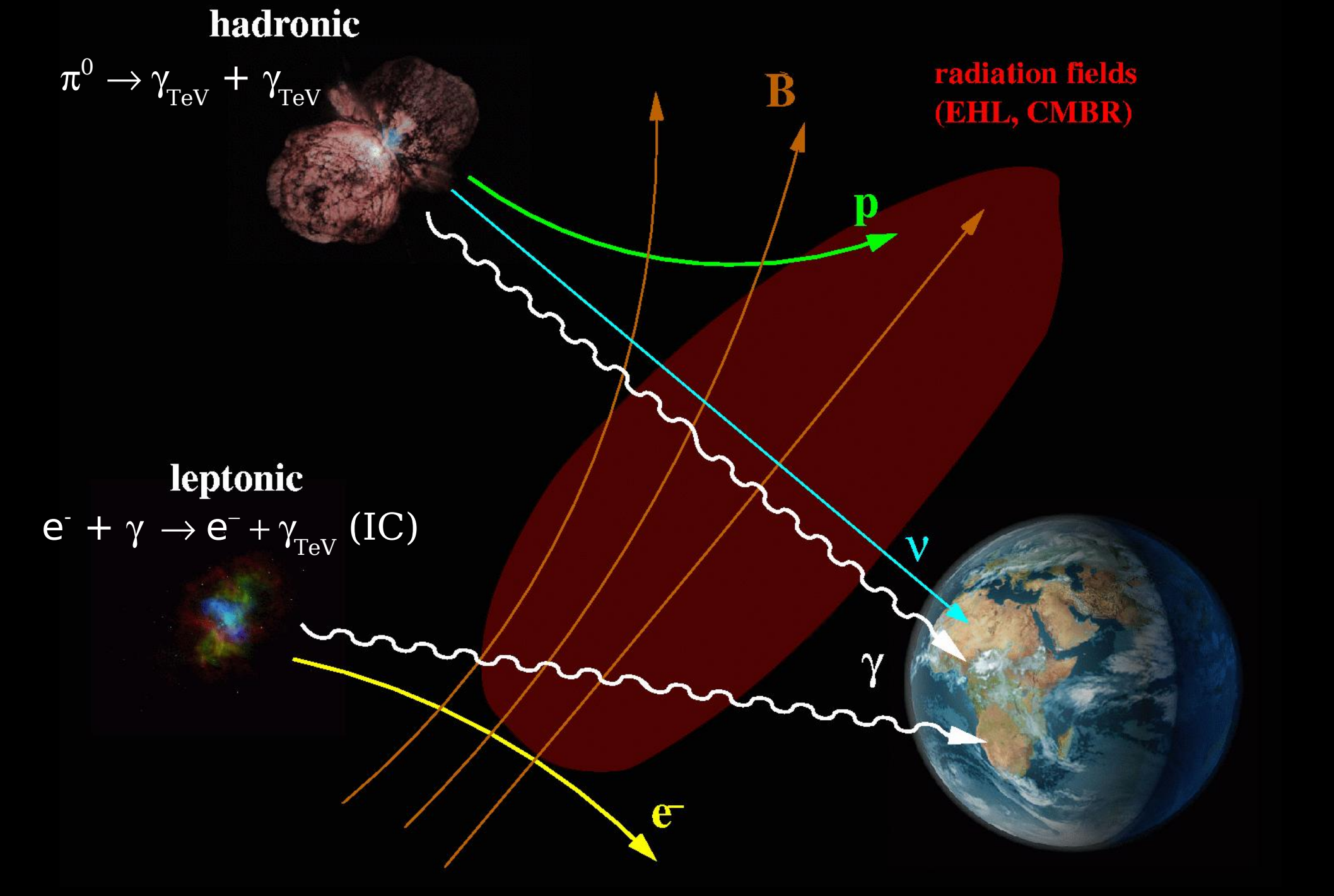
High Energy Phenomena in Relativistic Ooutflows II
(Buenos Aires, Argentina, October 26-30, 2009)

- Astronomy with Cherenkov telescopes
- VHE observations of extragalactic objects
- The giant radio galaxy M87
- M87 seen at very high energies
- Summary and Conclusions

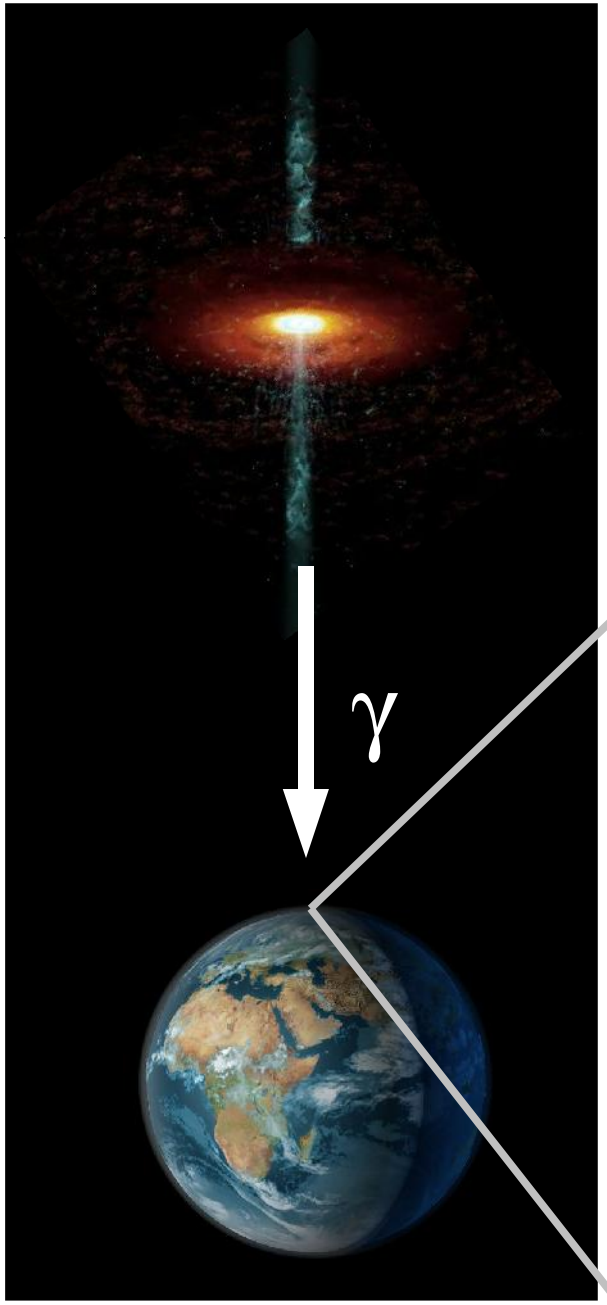
Washington University in St.Louis
Arts & Sciences

Astronomy with Cherenkov telescopes

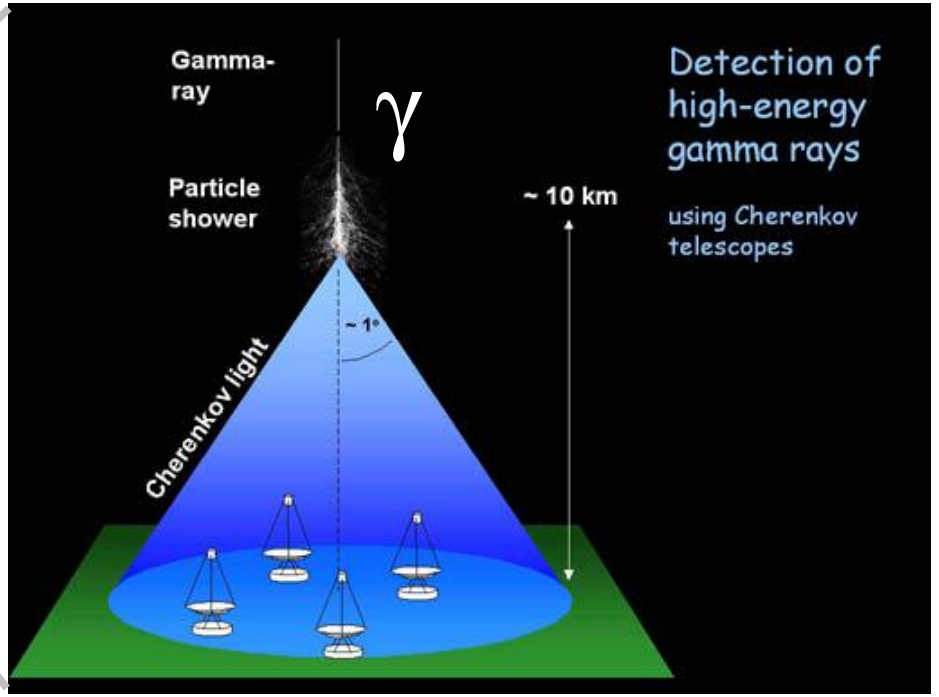
Gamma-ray astrophysics



TeV γ-ray astrophysics with Cherenkov telescopes

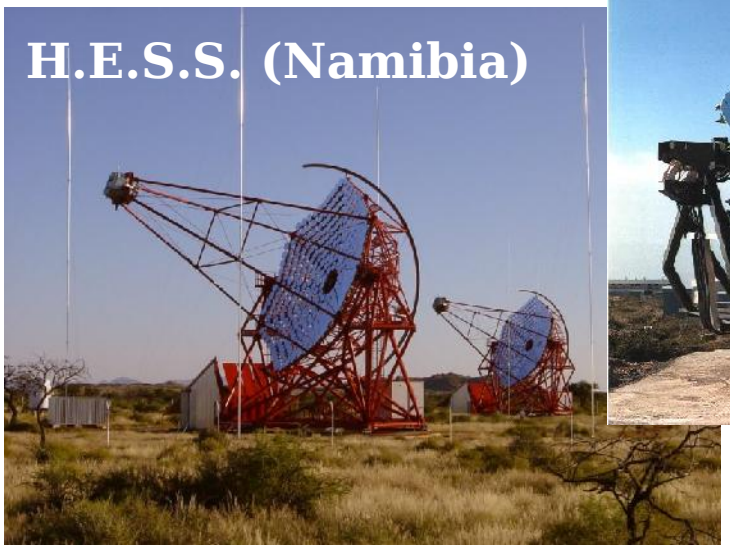


- **Source "produces" high energy γ-rays**
- **Gammas enter earth's atmosphere** and produce air showers & Cherenkov light
- **Imaging** of Cherenkov light with telescopes: reconstruct direction, energy, etc.
- **Reject CR background:** image properties



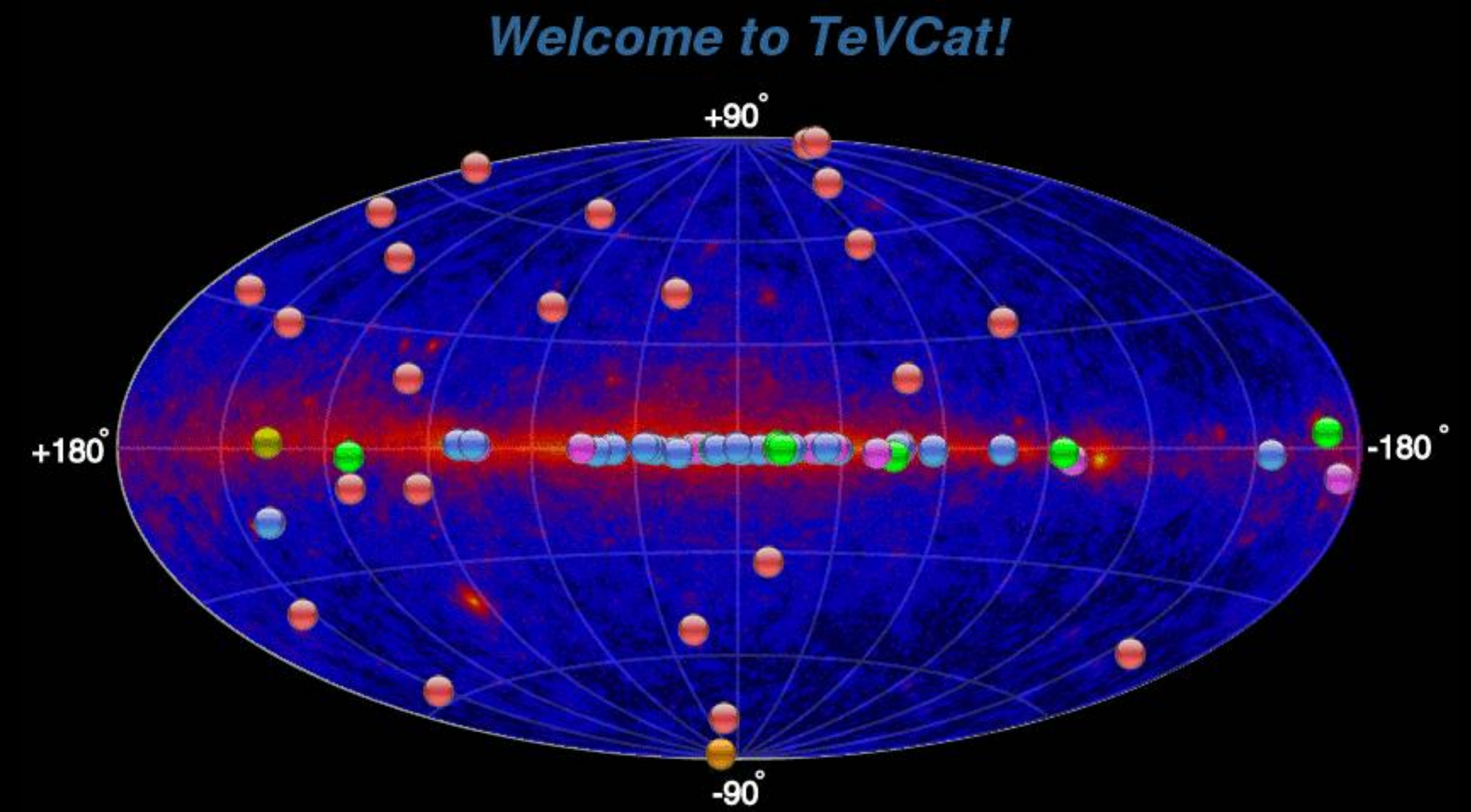
W.Hofmann

Cherenkov Observatories



VHE observations of extragalactic objects

The sky at MeV/GeV/TeV energies

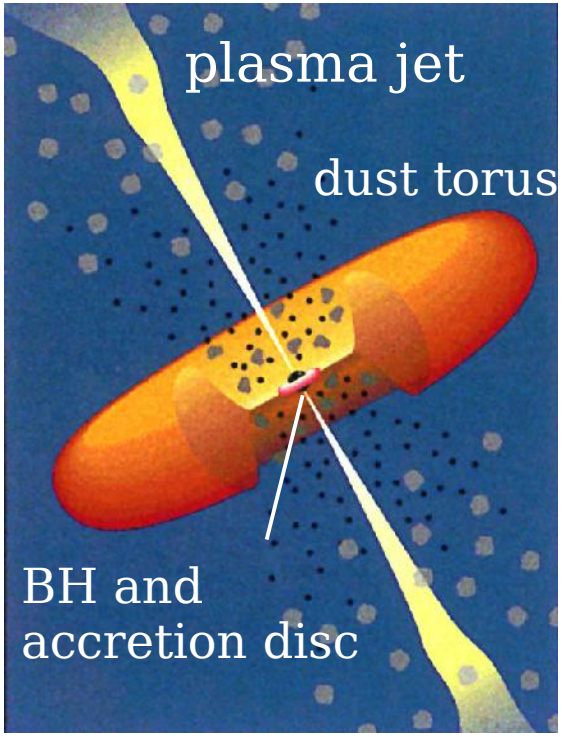


Fermi: http://fermi.gsfc.nasa.gov/ **TevCat: http://tevcat.uchicago.edu**

The Extragalactic VHE sky (Oct. 2009)

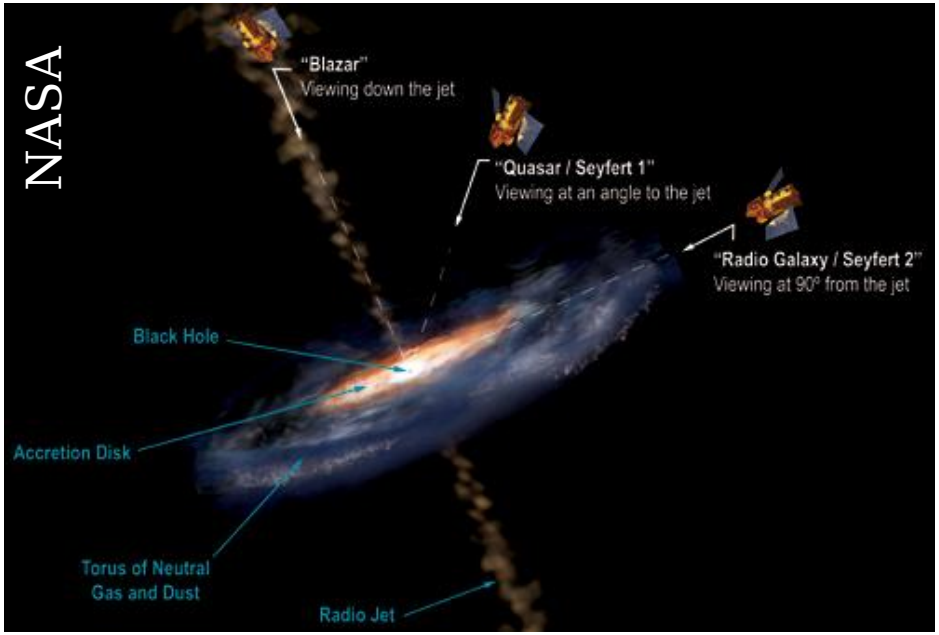
Name	redshift	reference
NGC [illegible]	3.3 Mpc	Aharonian, et al., Science Express (09/2009)
Centaurus A	3.8 Mpc	Raue et al., arXiv0904.2654 (2009)
M [illegible]	4.0 Mpc	Benbow et al., proc of ICRC (2009)
M [illegible]	16.7 Mpc	Aharonian et al., A&A, 403, L1 (2003)
[illegible](?)	[illegible]	Aliu et al., ApJ, 692, L29 (2009)
Markarian 421	[illegible]	Punch et al., Nature, 358, 477 (1992)
Markarian 501	0.034	Quinn et al., ApJ, 456, L83 (1996)
[illegible]	[illegible]	Catanese et al., ApJ, 501, 616 (1998)
Markarian 180	[illegible]	Albert et al., astro-ph/0606630 (2006)
1ES 1959+650	0.047	Nishiyama et al., 29th ICRC, 3, 370 (1999)
PKS [illegible]	[illegible]	Superina et al., Proc. Of ICRC (2007)
BL Lacertae	0.069	Albert et al., astro-ph/0703084 (2007)
PKS 2005-489	0.071	Aharonian et al., A&A, 436, L17 (2005)
W Comae	[illegible]	Swordy et al., ATel #1422 (2008)
PKS 2155-304	0.116	Chadwick et al., ApJ, 513, 161 (1999)
RGB J0710+591	0.125	Ong et al., Atel#1941 (2009)
H 1426+428	0.129	Horan et al., ApJ, 571, 753 (2002)
[illegible]	[illegible]	Swordy et al., ATel #1415 (2008)
[illegible]	[illegible]	Proc. Of ICRC 2007
PKS [illegible]	[illegible](?)	Ong et al., Atel#2084 (2009)
H [illegible]	[illegible]	Aharonian et al., Nature, 440, 1018 (2006)
1ES 1218+304	0.182	Albert et al., ApJ, 642, L119 (2006)
[illegible]	[illegible]	Aharonian et al., Nature, 440, 1018 (2006)
[illegible]	[illegible]	Proc. Of ICRC 2007
[illegible]	[illegible]	Albert et al., ApJ, 667, L21 (2007)
PG [illegible]	> [illegible]	Aharonian et al., A&A, 448, L19 (2006)
[illegible]	???	Teshima et al., Atel #1500 (2008)
[illegible]	> [illegible]	Swordy et al., ATel #1753 (2008)
[illegible]	[illegible]	Errando et al., ArXiv preprint (2008)

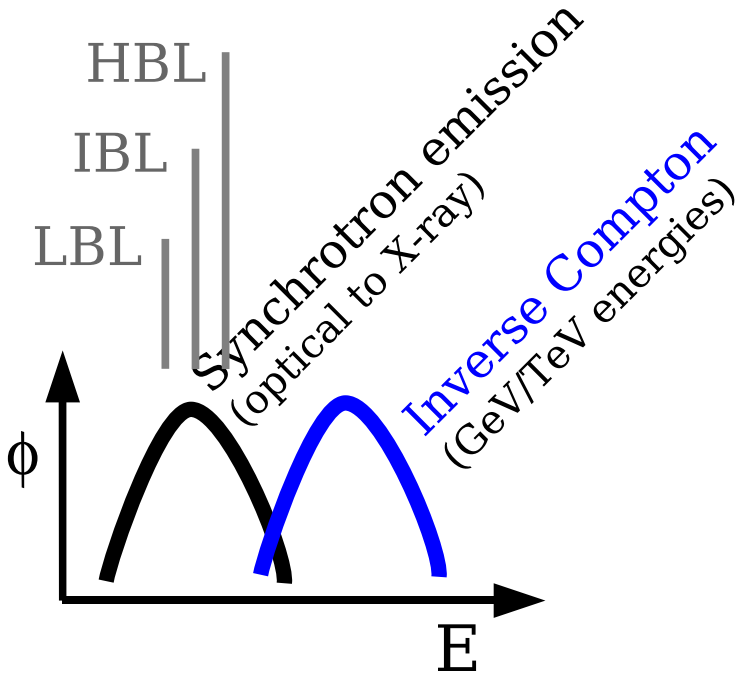
Starburst galaxies
Radio galaxies
Blazars



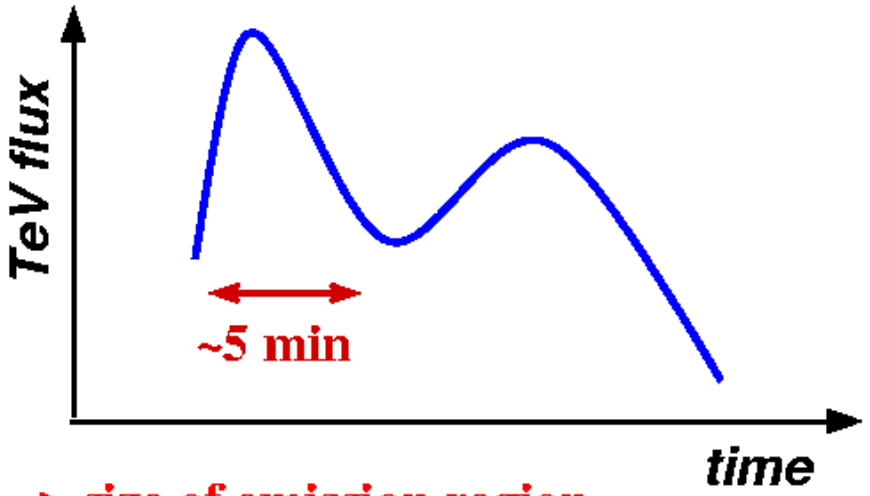
TeV Blazar Observation: Science Motivation

- **AGN:** Black hole and accretion disk power relativistic plasma jets
- **Key questions:**
  (1) Discoveries:
  new blazar types, expand VHE catalog
  (2) Multi-wavelength observations:
  time variability, energy spectra, etc.
  (3) ToO: X-ray, optical, Fermi, ...
- **Science Driver1:** Mechanisms of ultra-relativistic jet production:
  - Particle accel. & emission mechanisms
  - Jet structure & jet formation
  - TeV origin: leptonic or hadronic?
  - Black hole / jet connection
- **Science Driver2:** Blazars as probes of the extragalactic background light (EBL) through pair absorption

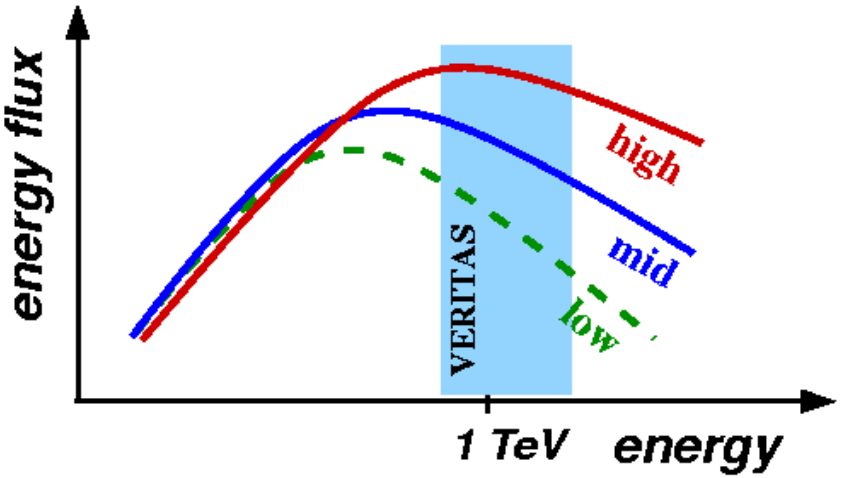




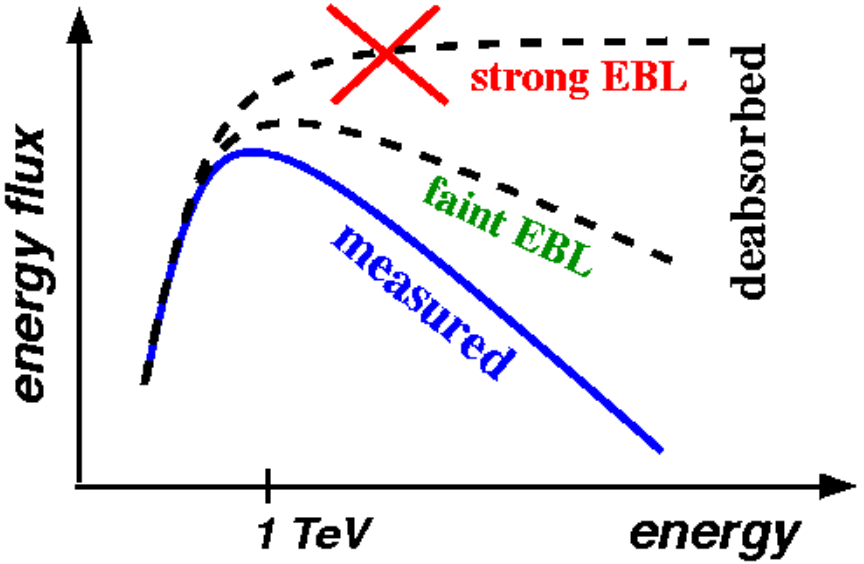
What did we learn from TeV blazars?



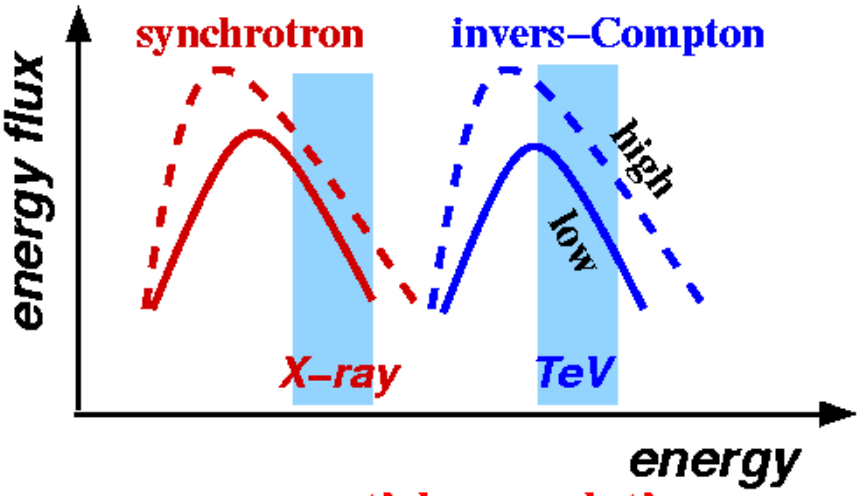
=> size of emission region



=> Γ/flux correlation (mechanism?)



=> strong EBL excluded



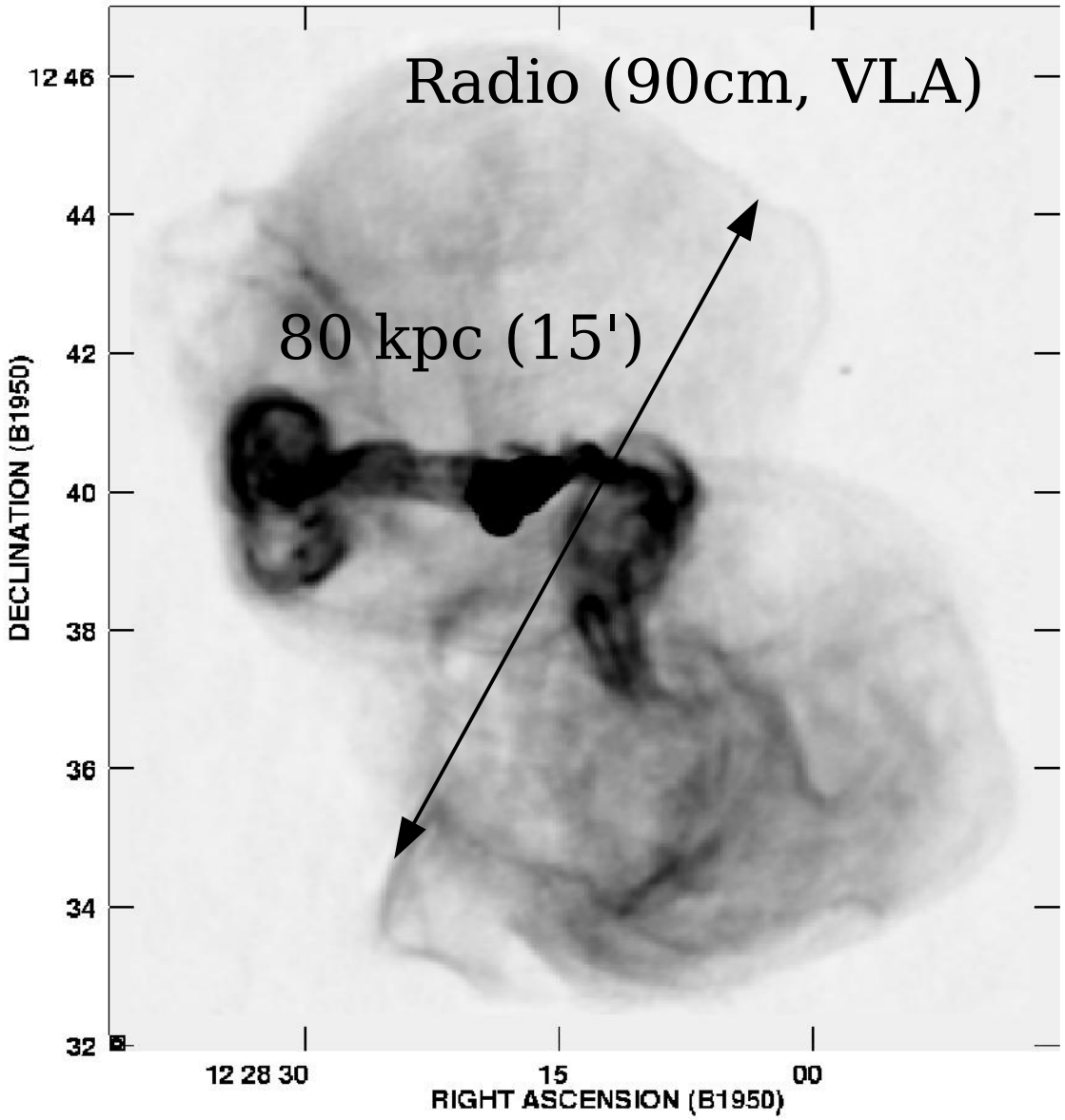
=> same particle population

Open questions: location & exact mechanism => M87?

The giant radio galaxy M87

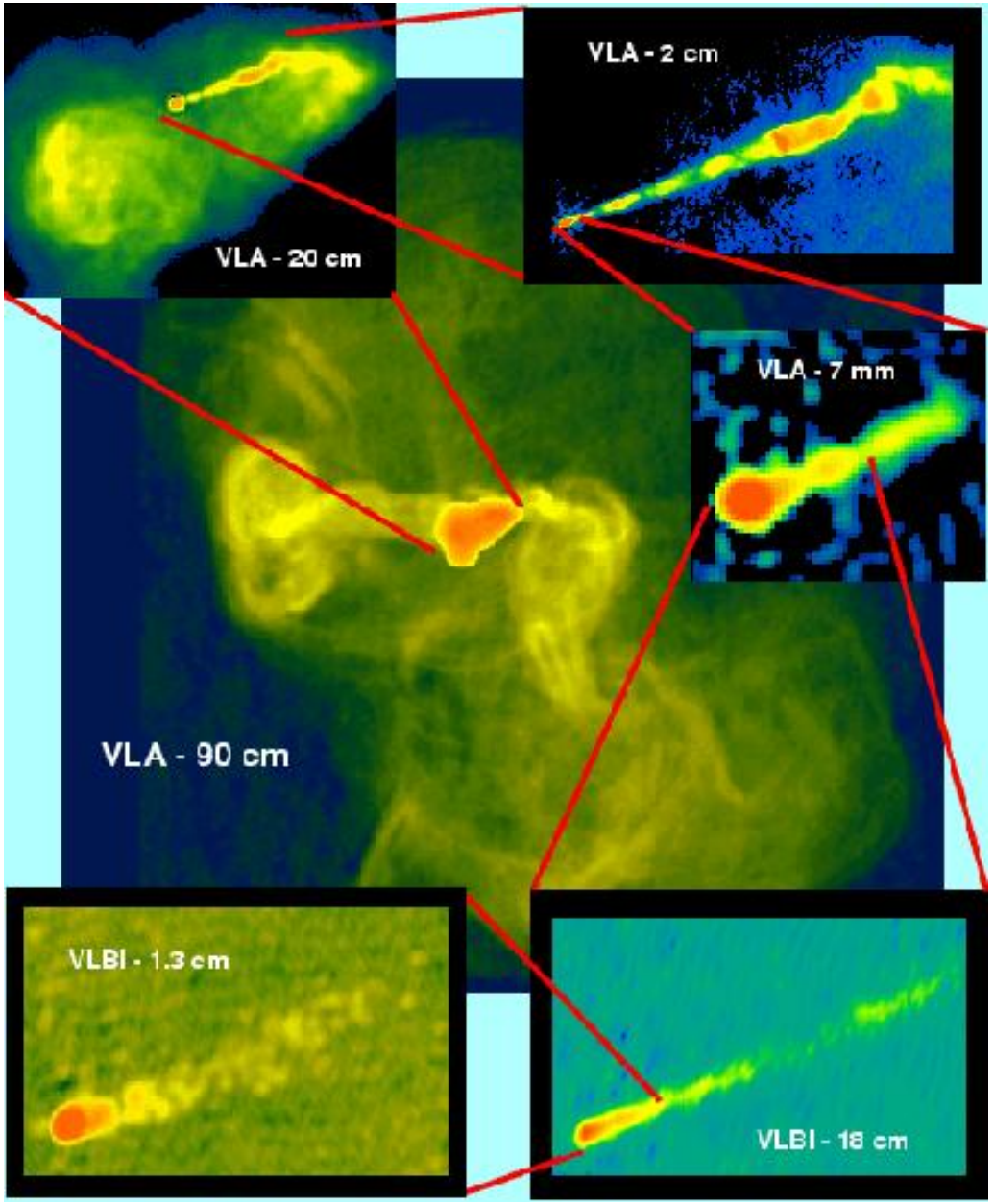
The giant elliptical radiogalaxy M87

Owen et al. (2000), ApJ, 543, 611



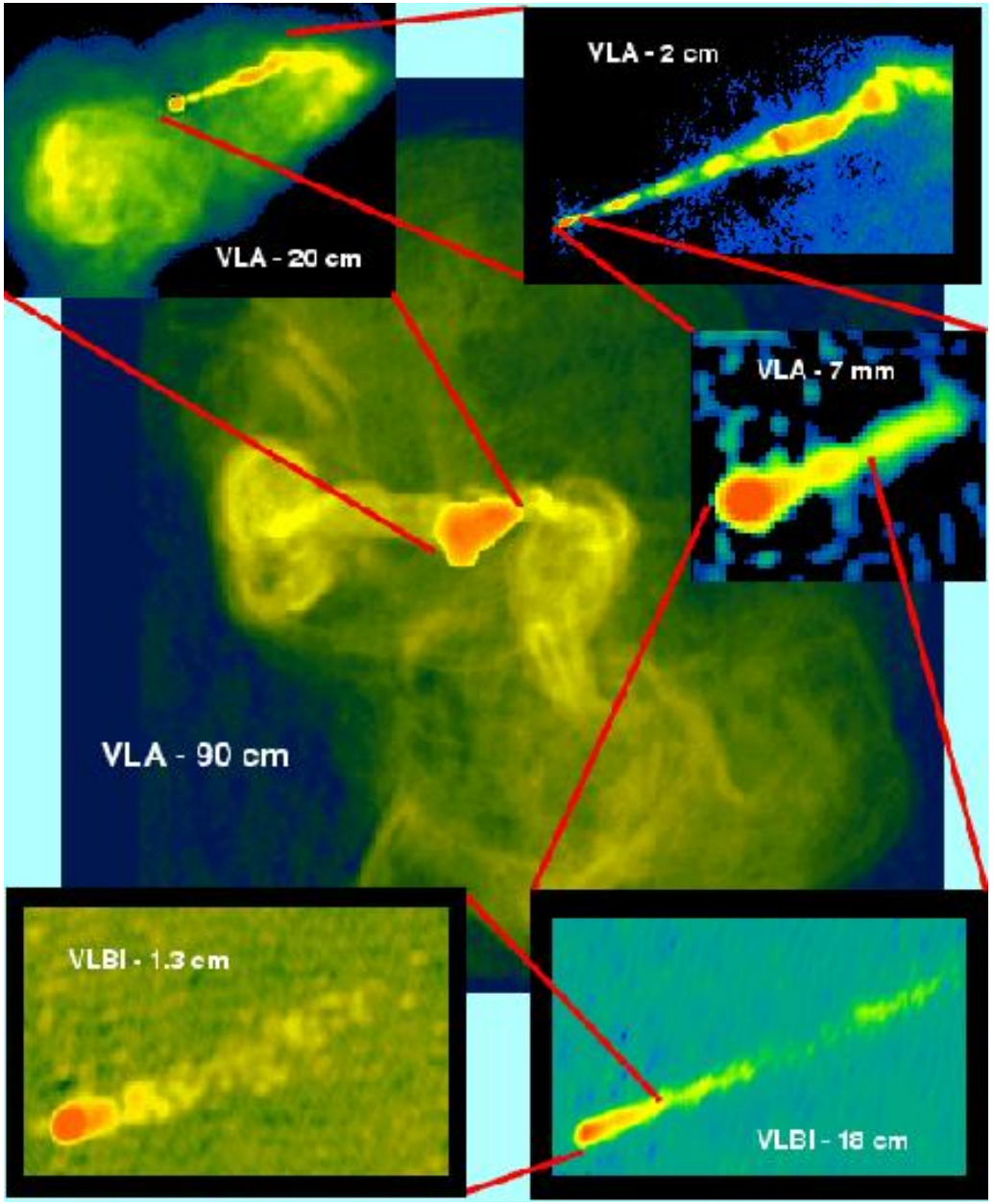
- **Close-by radio galaxy:**
  ~16.7 Mpc (z=0.00436)
- **Radio structure:**
  outflows and halo
  Age_{halo} << Age_{M87}
  => Variable jet activity
- **Jet angle:**
  ~25° ⇒ not a blazar!
- **Central black hole:**
  $M_{BH} \sim 6 \cdot 10^9 M_{sun}$ [Gebhardt & Thomas, ApJ, 700, 1690 (2009)]
- Bondi accretion: 0.1 M_{sun}/yr
  luminosity 10^4 times lower
  => radiatively inefficient or lower

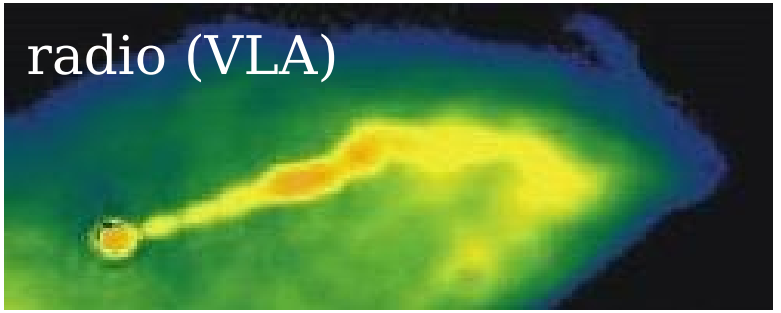
M 87: Seen at radio wavelengths

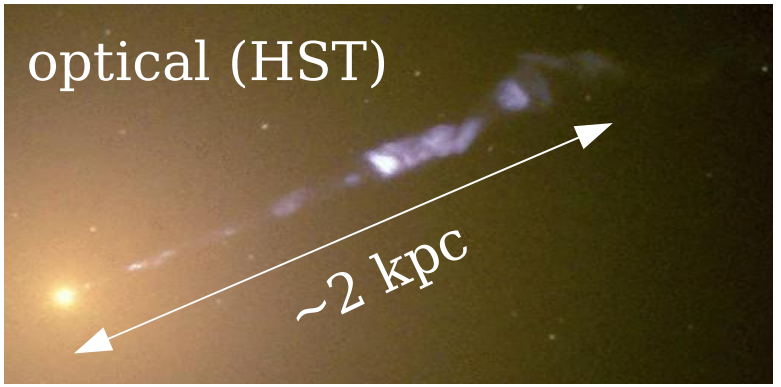


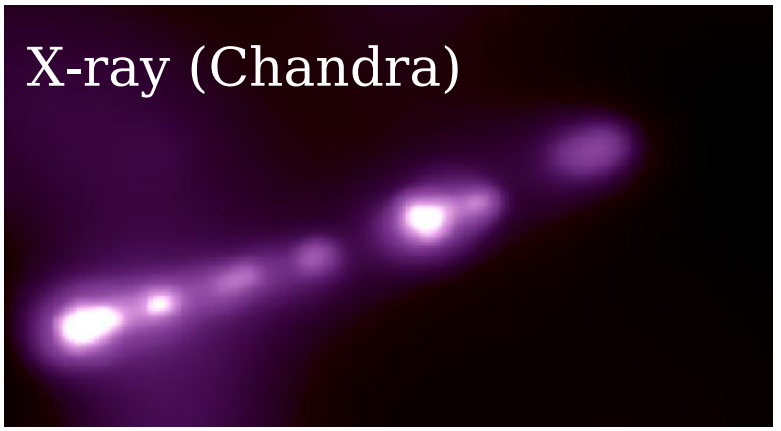
Owen et al. (2000), ApJ, 543, 611

The relativistic plasma jet of M87





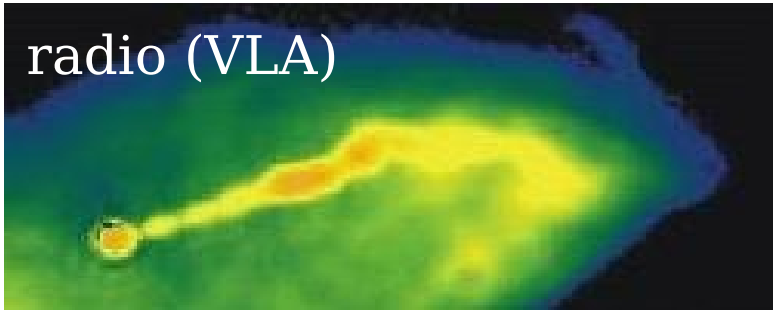


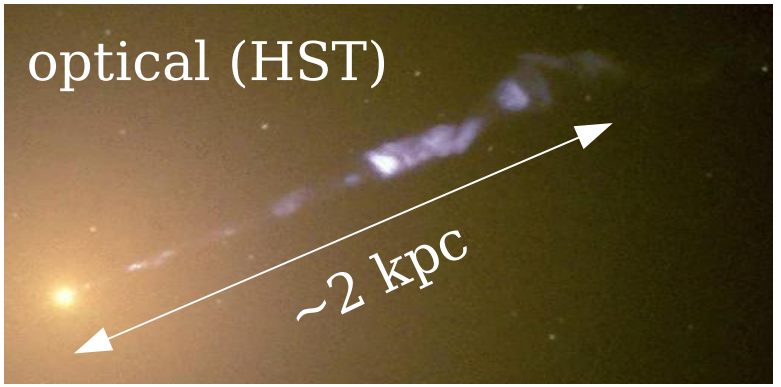


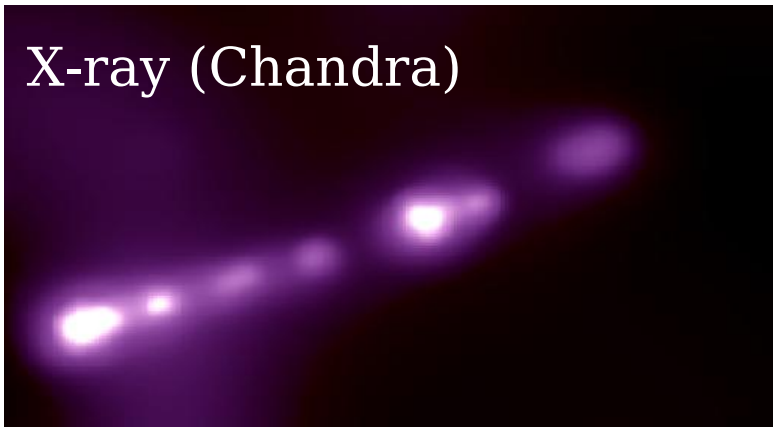
The relativistic plasma jet of M87

- **X-ray/opt:** concentrated structures
  shocks?
- **Radio/opt:** similar polarisation
  synchrotron emission
- **X-ray:** spectrum with α=2.0-2.9
  synchrotron emission?
  Time-scale for synchrotron losses
  => re-acceleration of particles
- **Inner jet:** superluminal motion (~2c)
  => relativistic particle population
- **Variability time-scales:**
  weeks to months

Predictions of VHE γ-ray and UHECR particle emission

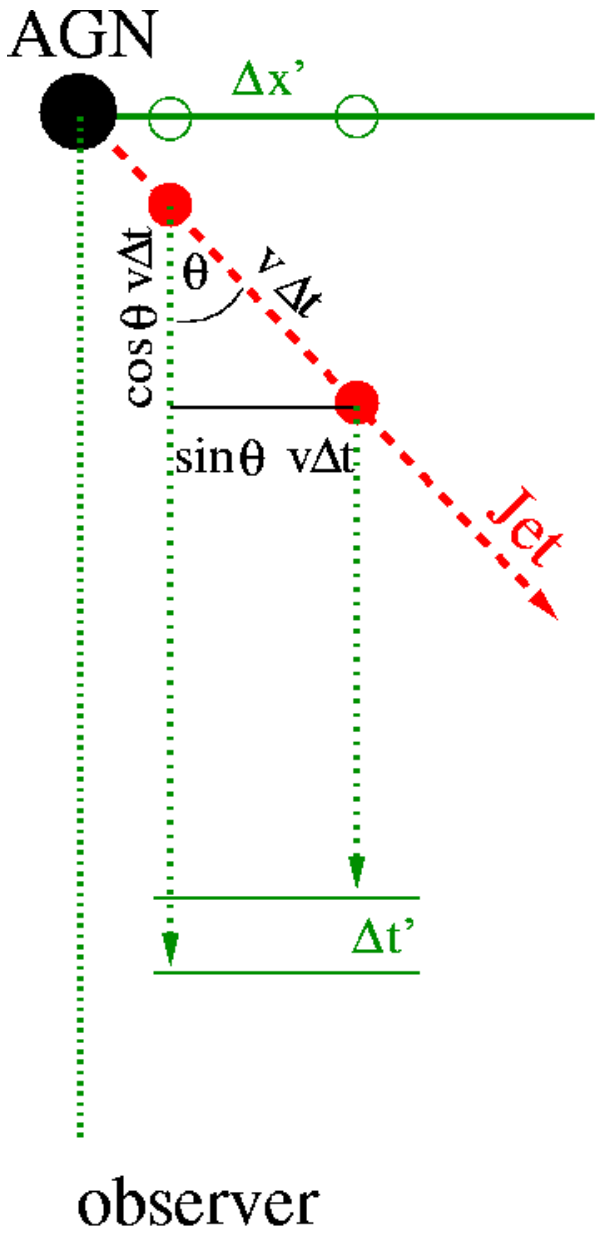


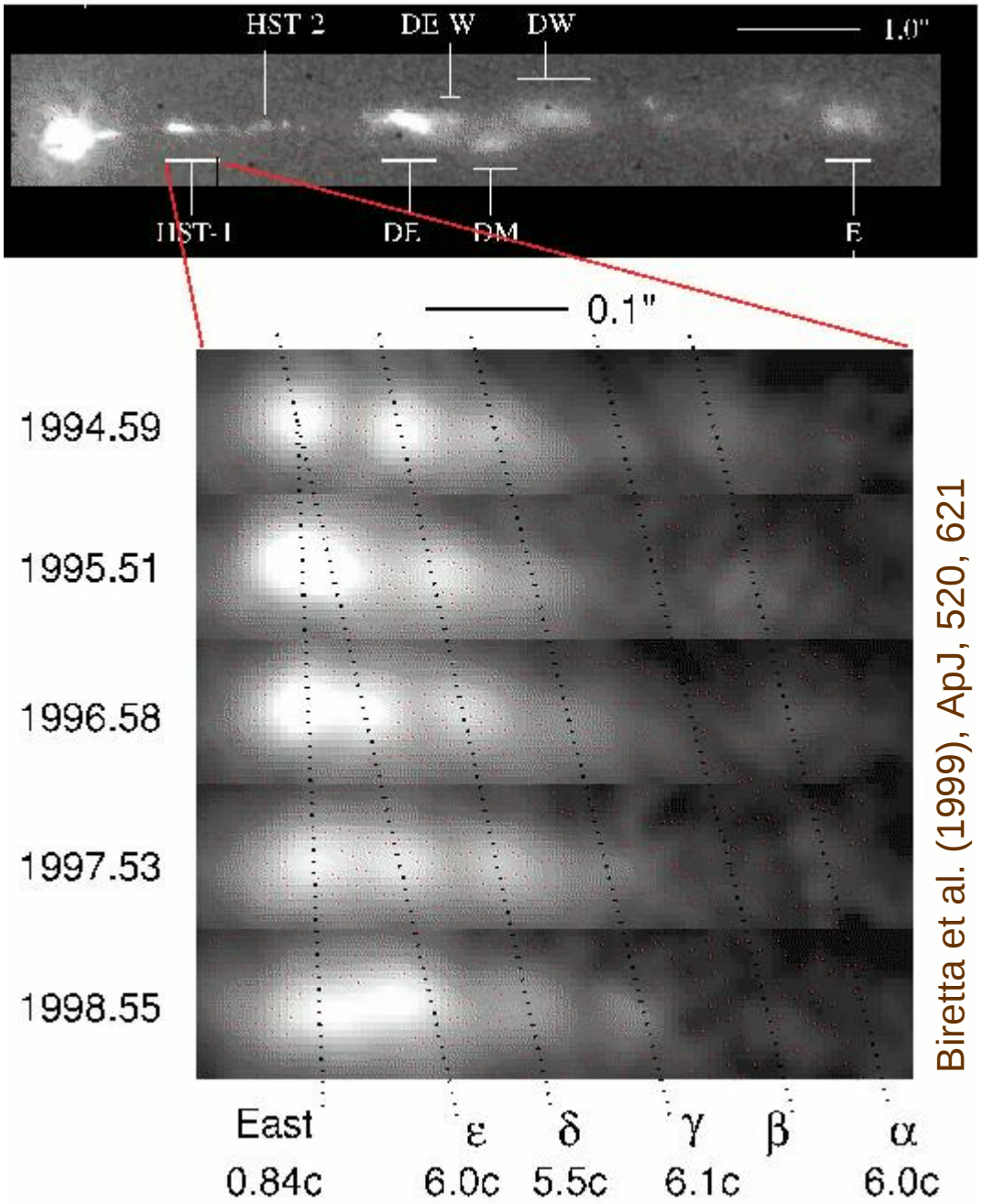




Wilson & Yang (2002), ApJ, 568, 133

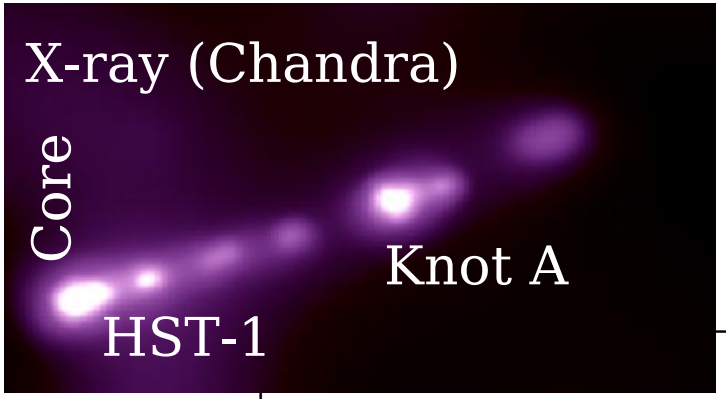
Superluminal motion in the plasma jet of M87

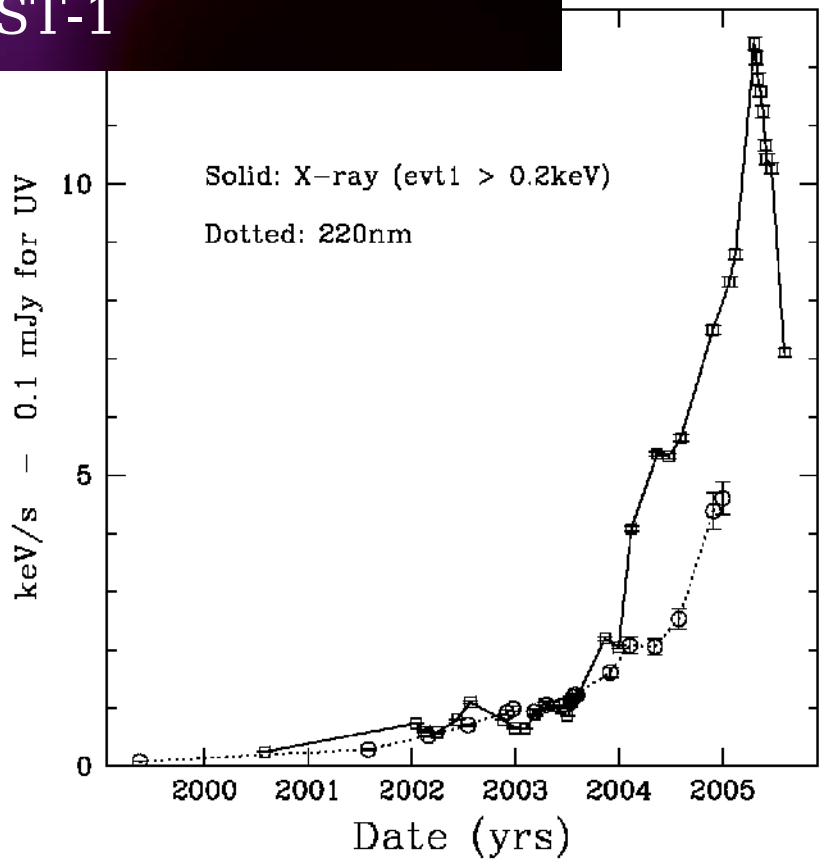


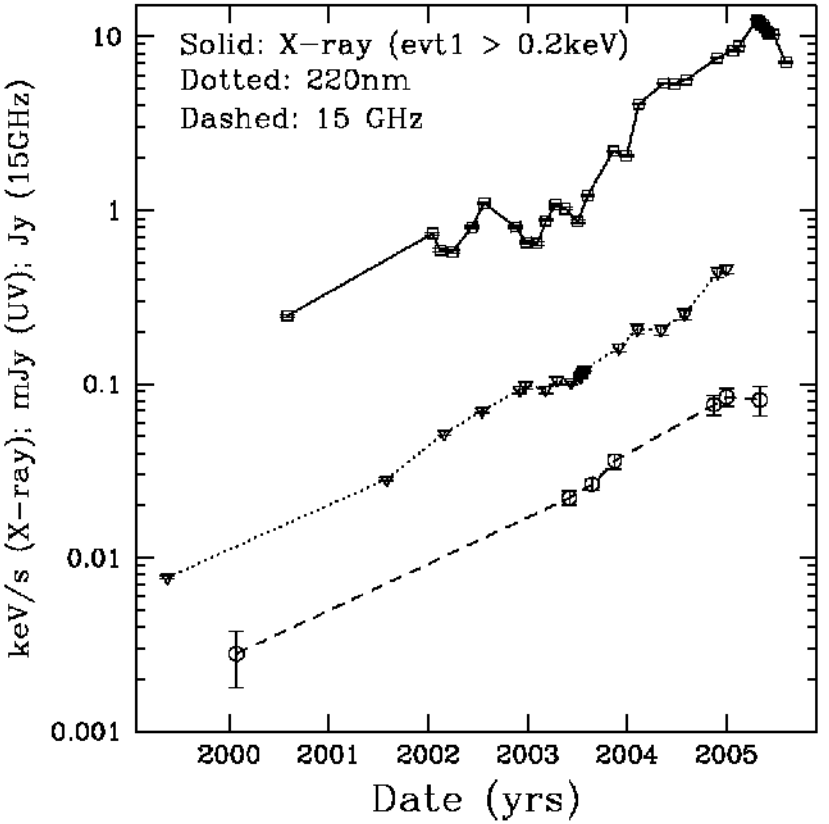


Biretta et al. (1999), ApJ, 520, 621

The strong outburst of HST-1







Harris et al. (2006), ApJ, 640, 211

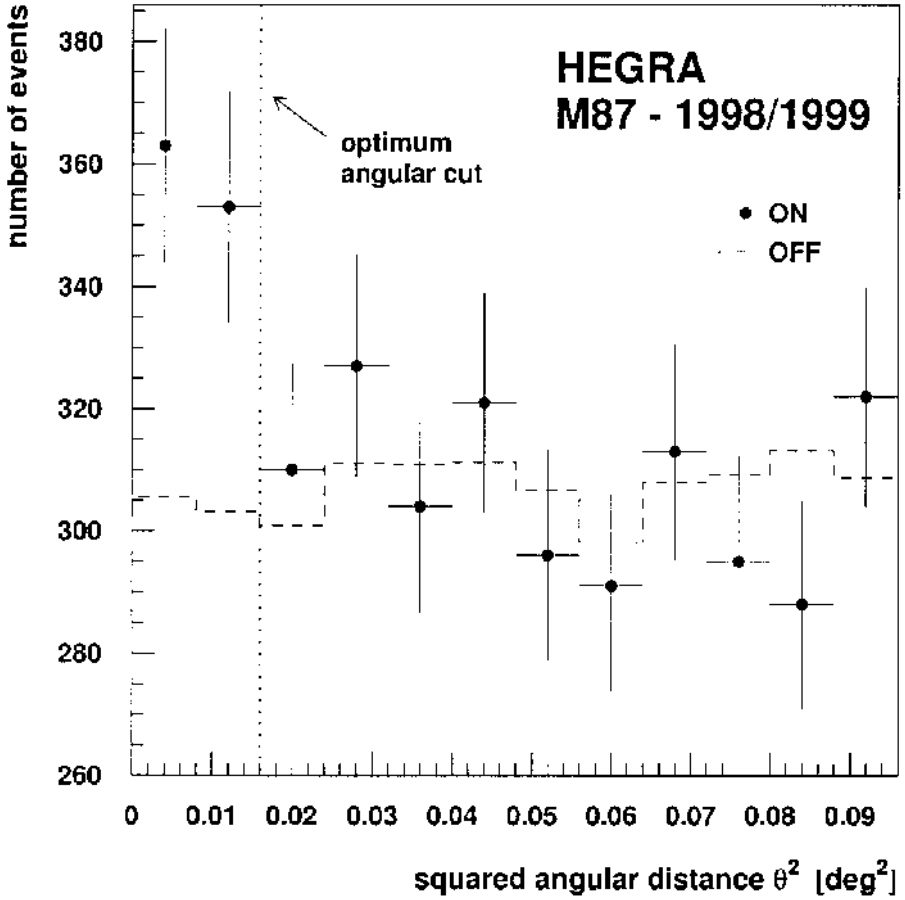
M87 seen at TeV energies

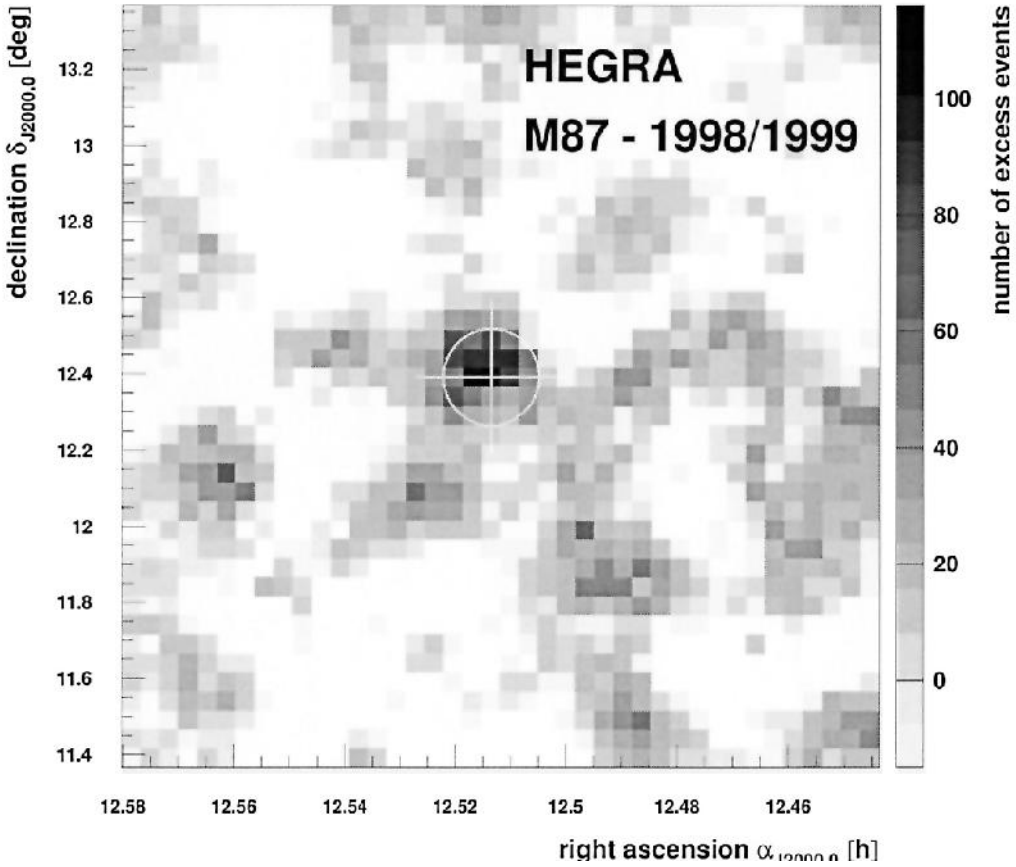
The first hint for TeV emission

In 1998/99 HEGRA asked the question:

Is the giant radio galaxy M 87 a TeV gamma-ray emitter?

[Aharonian et al. 2003, A&A, 403, L1]





First non-blazar AGN emitting TeV gamma-rays

M87: 10 Years of VHE Observations

History:

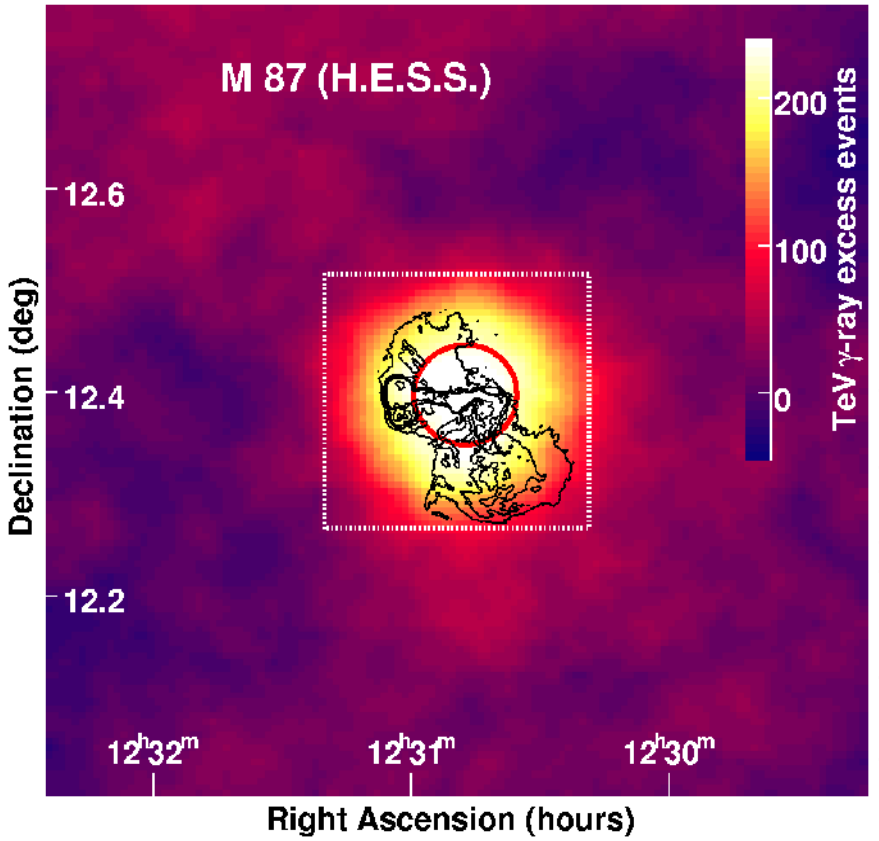
HEGRA (>4σ excess):
[Aharonian et al. 2003]

Whipple (upper limit):
[Lebohec et al. 2003]

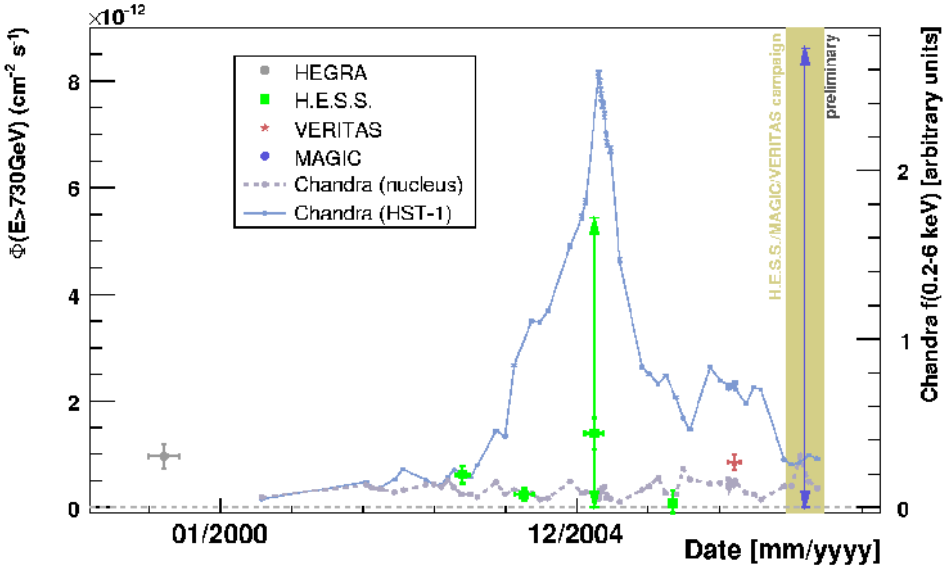
H.E.S.S. (11σ, short-term variability):
[Aharonian et al. 2006]

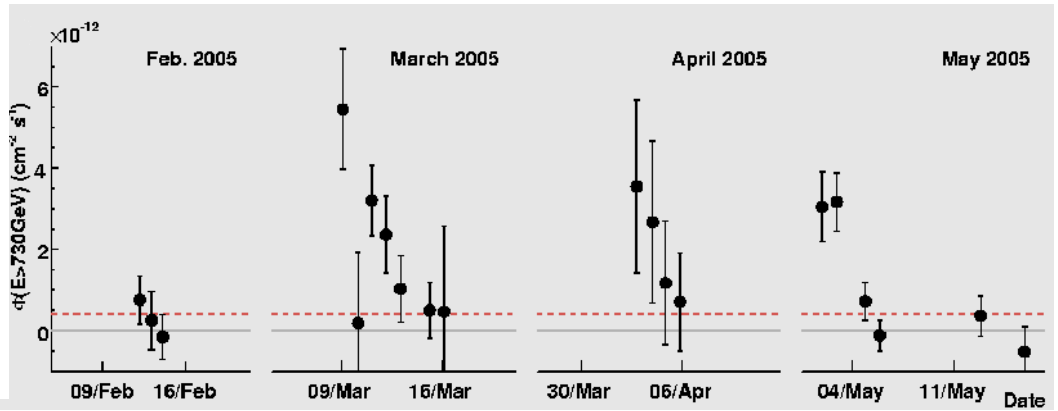
VERITAS (detection):
[Acciari et al. 2008]

MAGIC (confirmation of short-term variability):
[Albert et al. 2008]



Aharonian et al. (2006), Science, 314, 1424

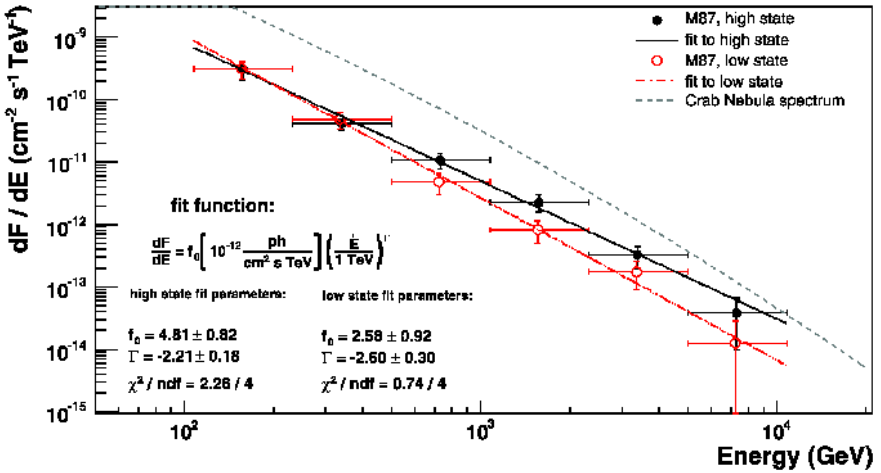




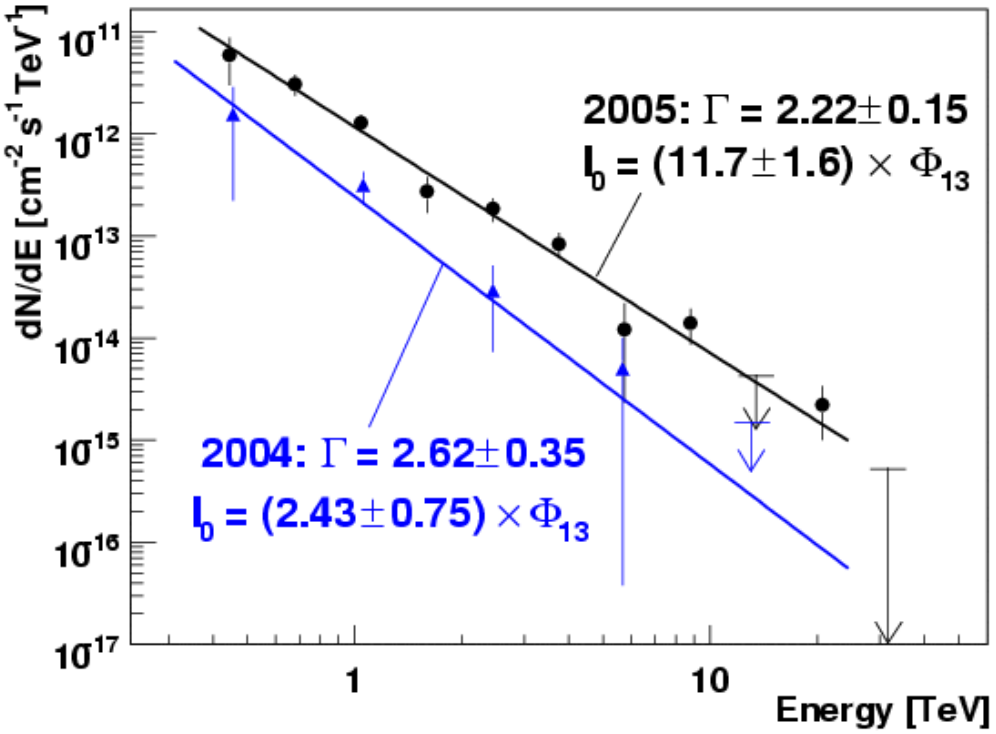
M87 – GeV/TeV energy spectra

- Hard energy spectra
- No significant change in index
  (although hardening with increasing flux might indicate)

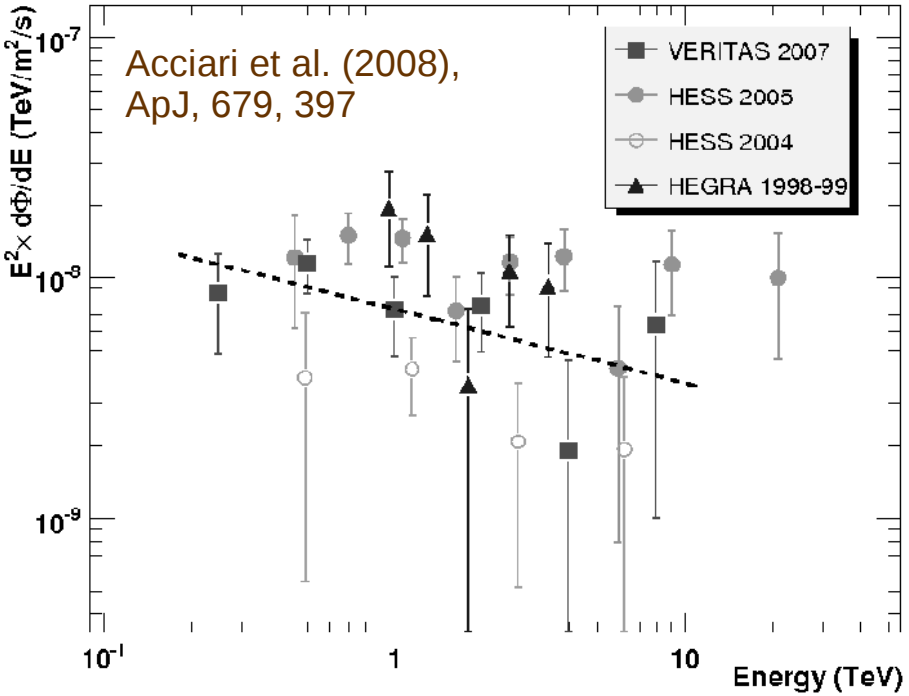
Albert et al. (2008), ApJL, 685, L23



Aharonian et al. (2006), Science, 314, 1424

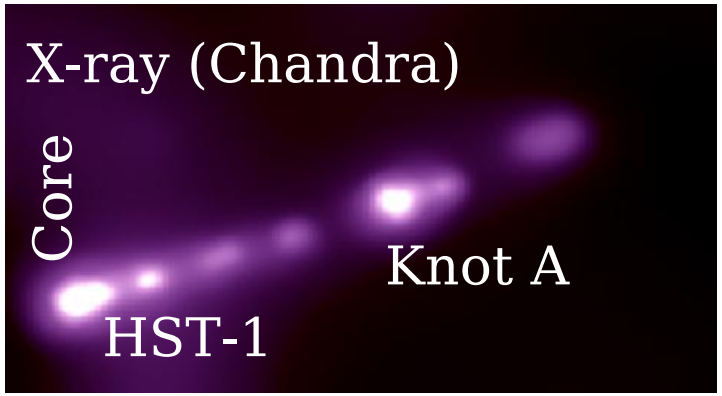


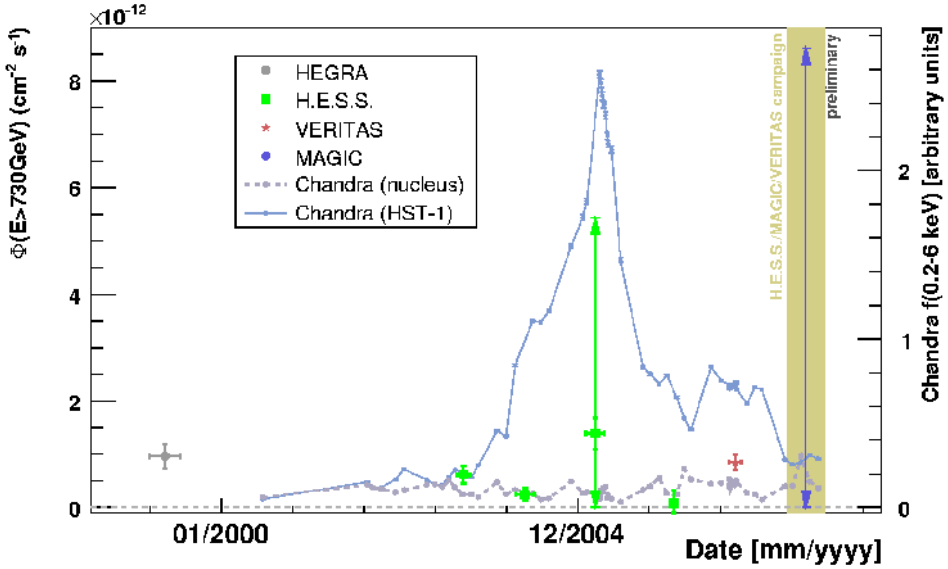
Acciari et al. (2008), ApJ, 679, 397

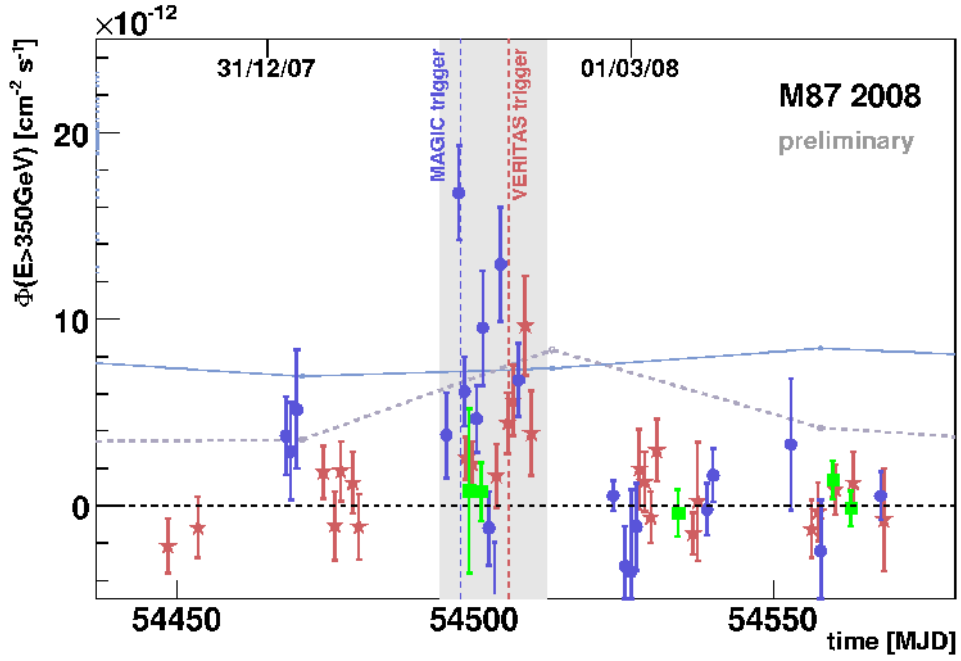


The 2008 VERITAS/MAGIC/H.E.S.S. campaign

- 2008 coordinated observations: VERITAS/MAGIC/H.E.S.S.
- Coverage: 120h, 50 nights
- Outburst in February 2008
  (2 weeks after a MAGIC trigger, X-ray low-state of HST-1)
- Confirmed short-term variability
- 5 Chandra pointings
  [Harris et al., ApJ, 699, 305, 2009]



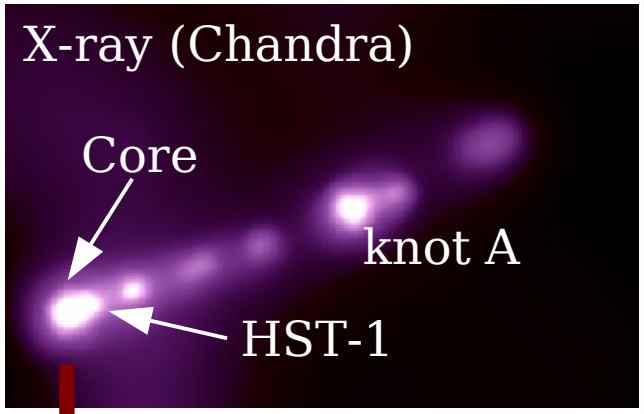


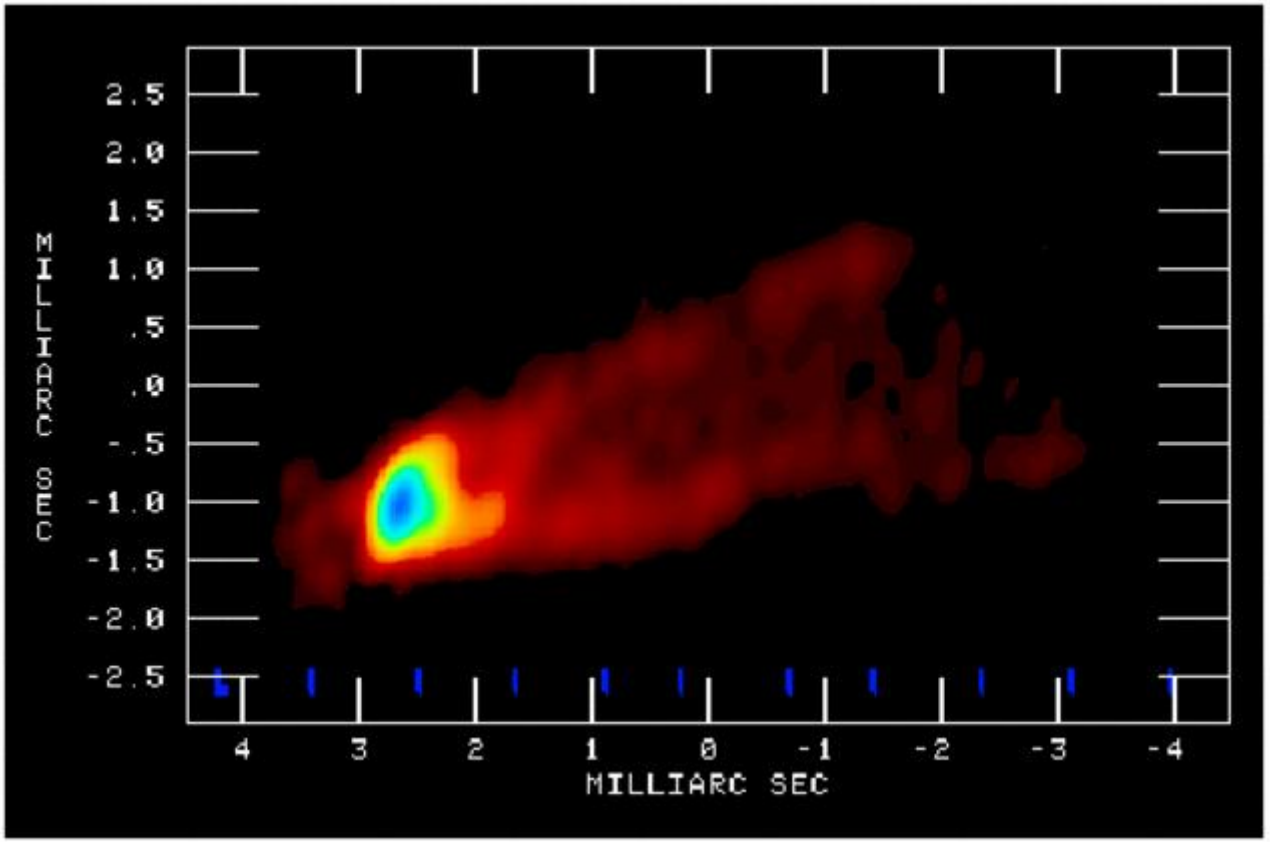


2008: HST-1 unlikely source of VHE emission

The 'radio movie' project by Walker et al.

- Movie of the M87 jet at 43 GHz with the VLBA (2007/2008)
- Craig Walker, Chun Ly, Bill Junor, and Phil Hardee
- Resolution: 0.43x0.21 milli arcsecond (mas)
- 100 Schwarzschild radii = 0.37 mas (1 mas = 0.078 pc)

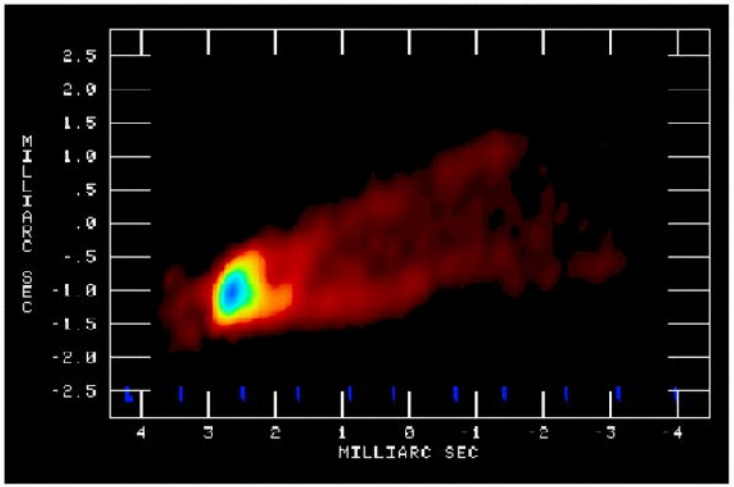




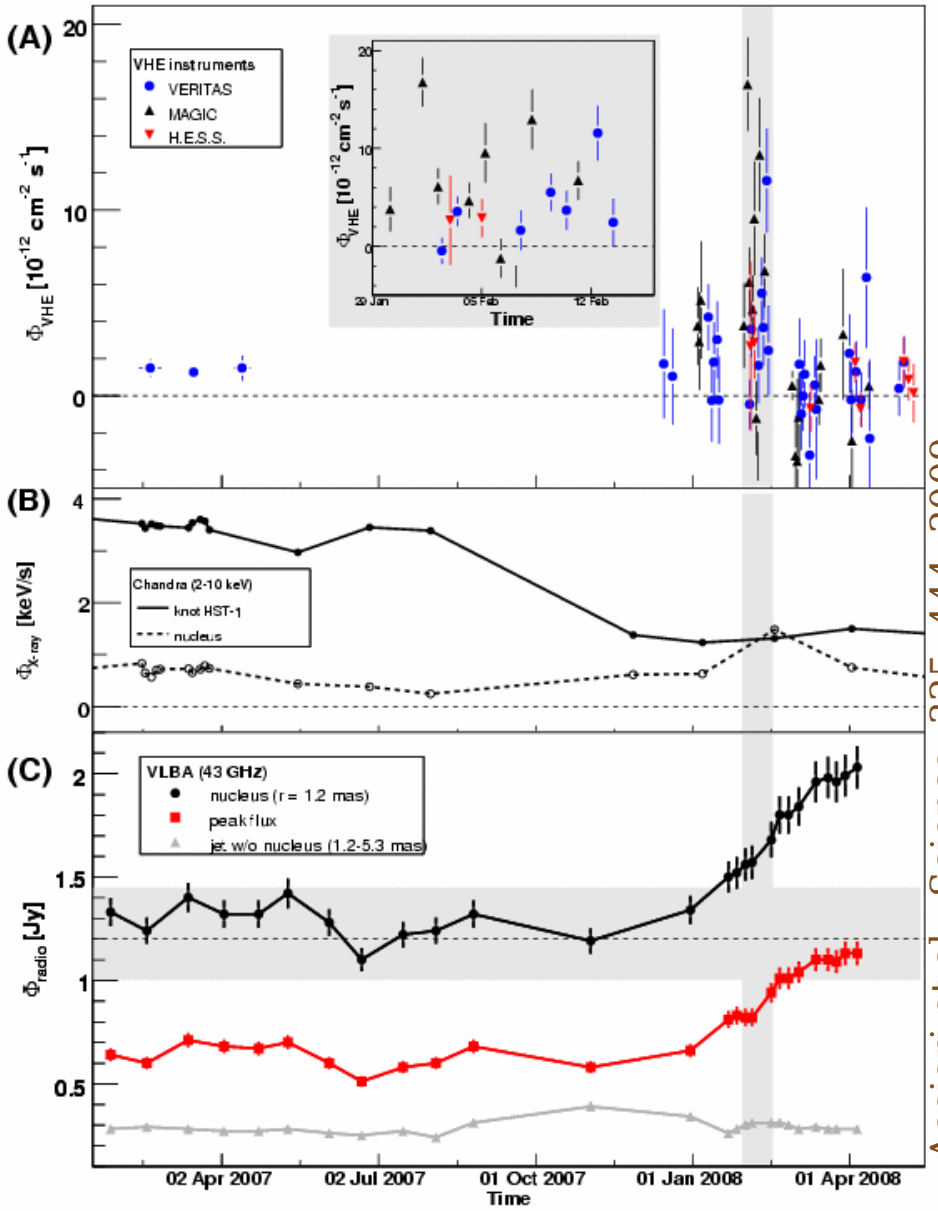
Walker et al., 2007 data

Close cooperation between VLBA, H.E.S.S., MAGIC and VERITAS reveals...

- **VLBA (43GHz, C.Walker et al.):**
  Jet formation @ 30 x 60 R_s
- **VHE: Coordinated campaign:**
  - H.E.S.S./MAGIC/VERITAS
  - More than 120h (>50 nights)
- **VHE flare accompanied by radio flare from BH vicinity**
  [Science, 325, 444, 2009]



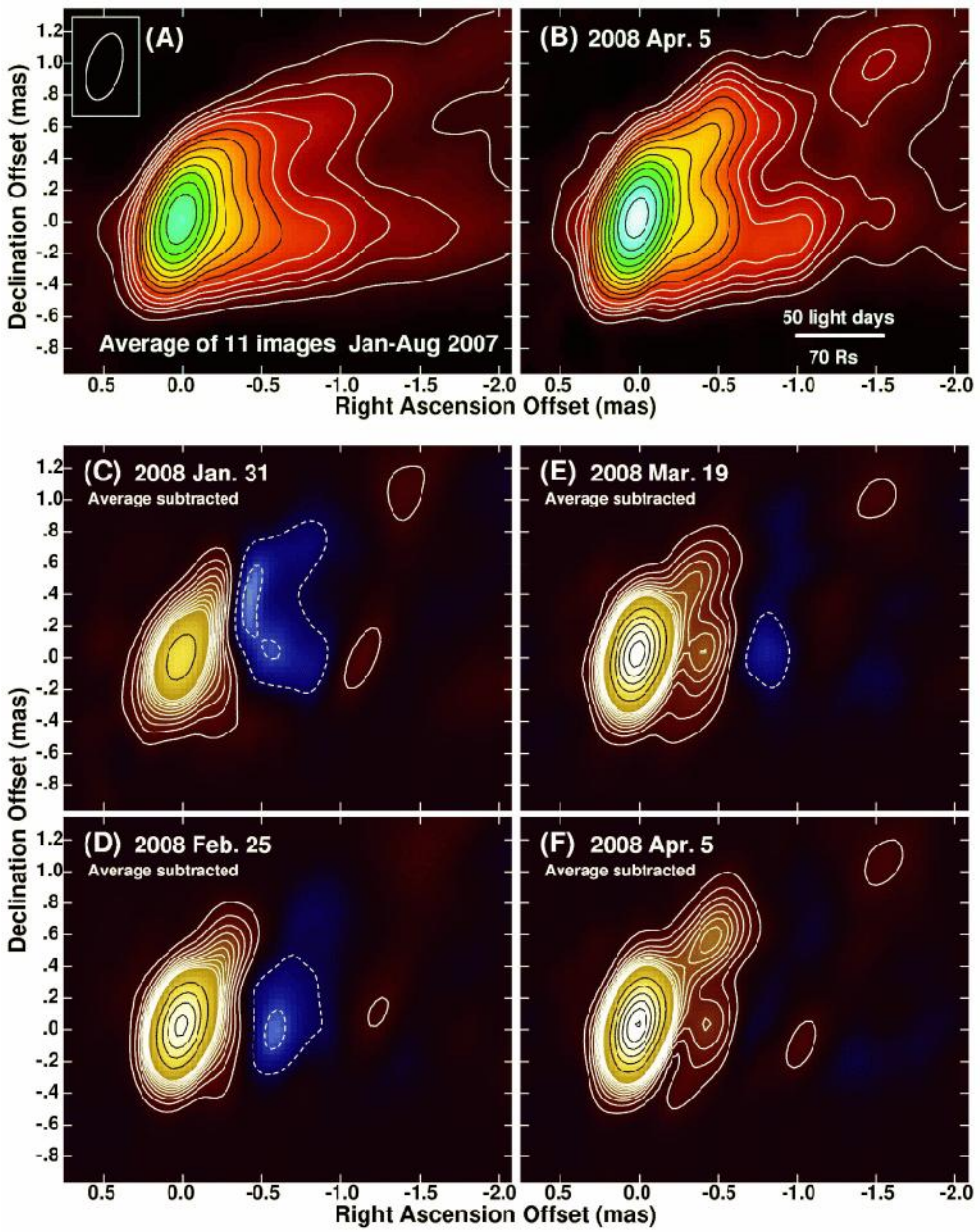
C.Walker et al.

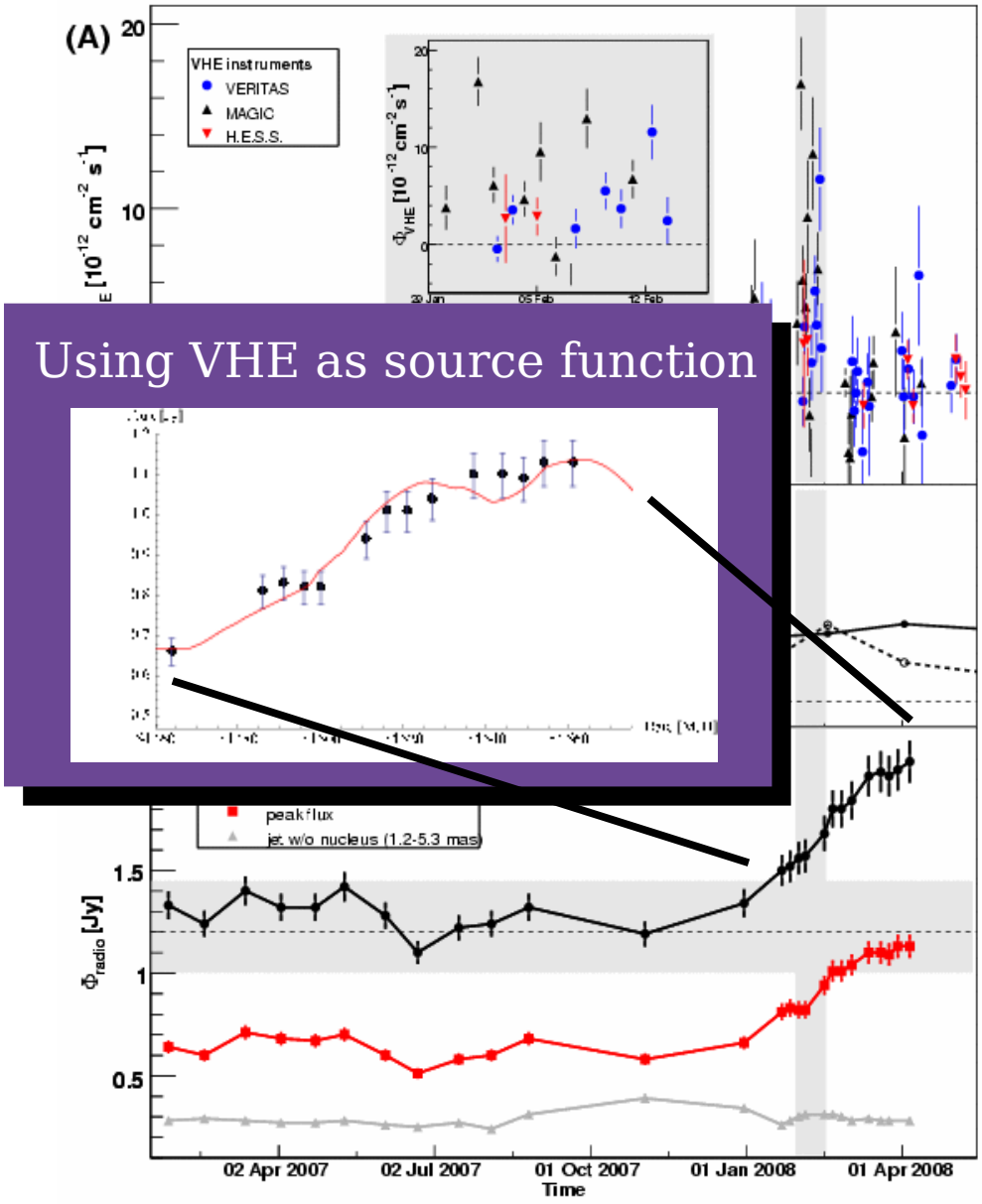


Acciari et al., Science, 325, 444, 2009

Contact: VLBA: C.Walker, F.Davies, P.E.Hardee, B.Junor, C.Ly, H.E.S.S., MAGIC and VERITAS

Close cooperation between VLBA, H.E.S.S., MAGIC and VERITAS reveals...





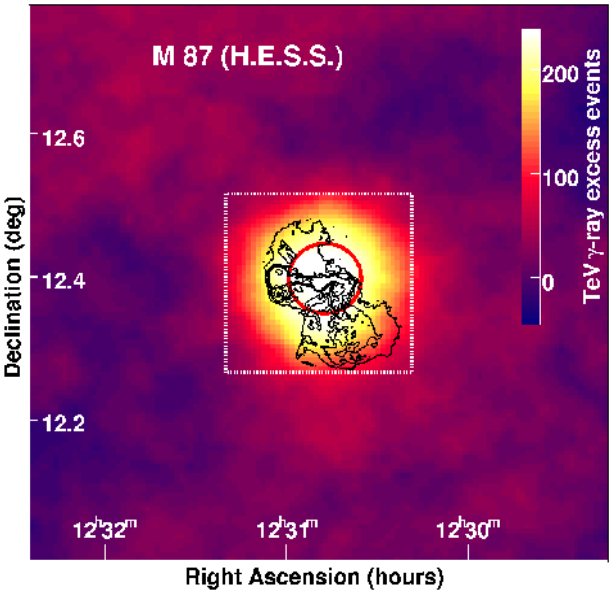
Using VHE as source function

Contact: VLBA: C.Walker, F.Davies, P.E.Hardee, B.Junor, C.Ly, H.E.S.S., MAGIC and VERITAS

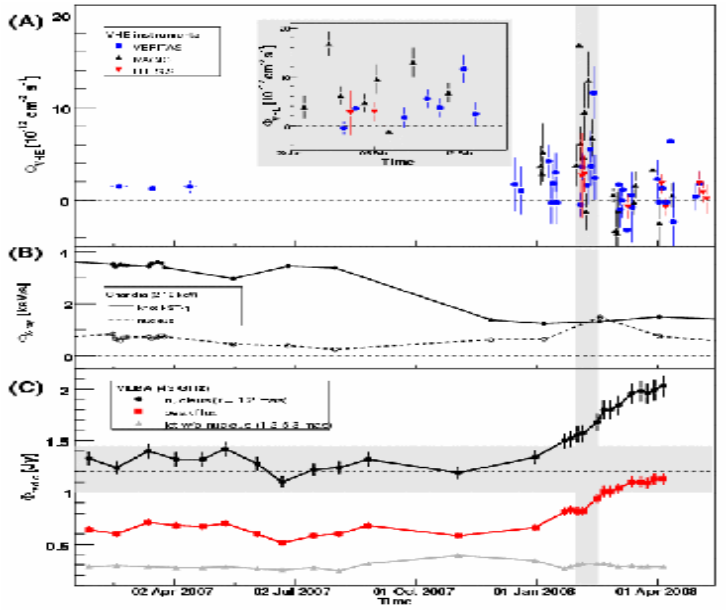
VHE observations of M87 – what did we learn?

- First non-blazar emitting VHE γ-rays:
  Misaligned blazar, AGN unification?
- Short-term variability:
  o) Excludes 'steady' emission models
  o) Constrains size of emitting region
  ($R < 5 \times 10^{15}\ \delta$ cm, ~100 R_{schw})
- Hard energy spectra:
  modeling, emission mechanism
- Radio/TeV connection:
  First experimental evidence: charged particles accelerated in BH vicinity

Key question: origin/(location) of the TeV emission

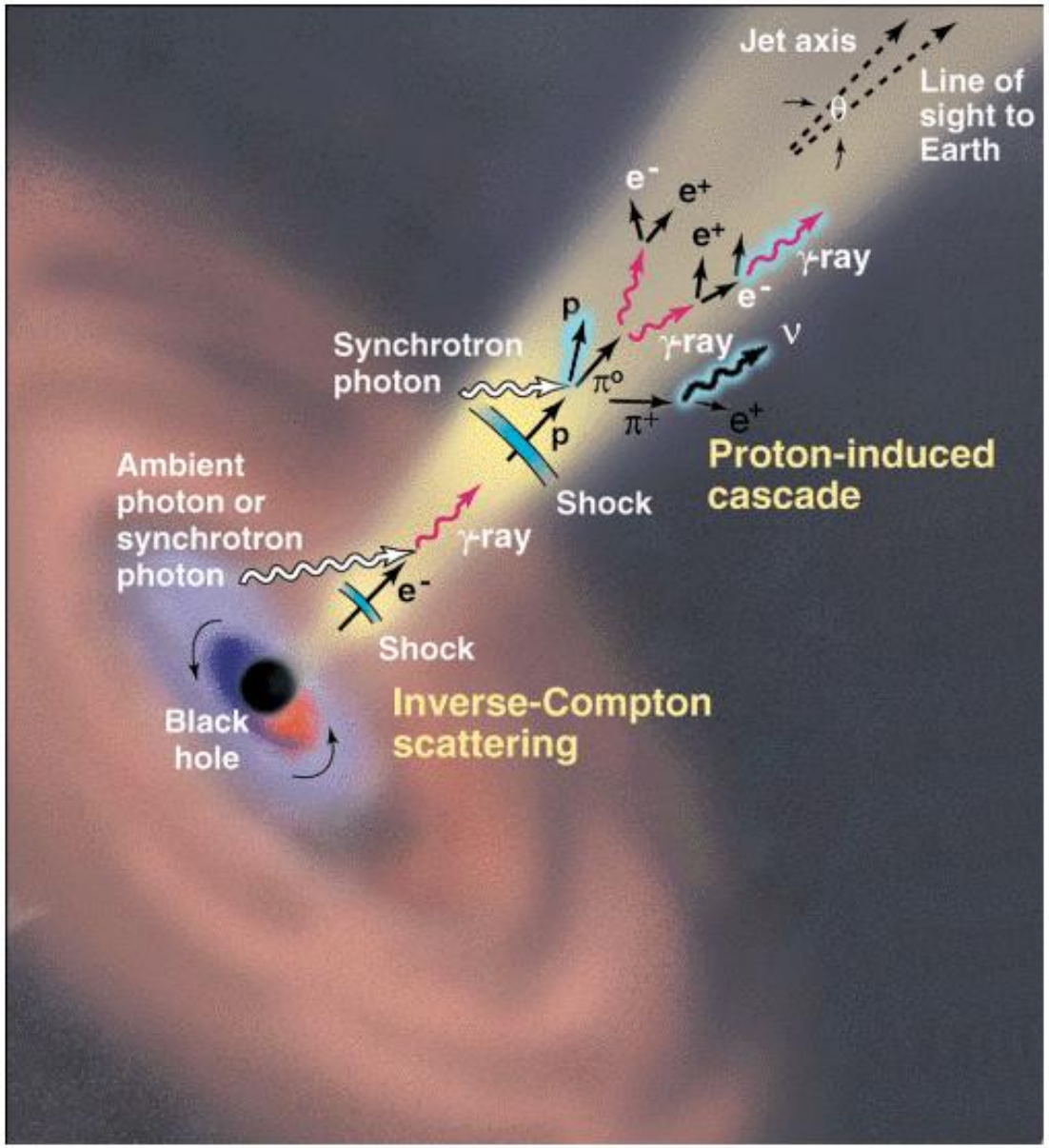


Aharonian et al. (2006), Science, 314, 1424

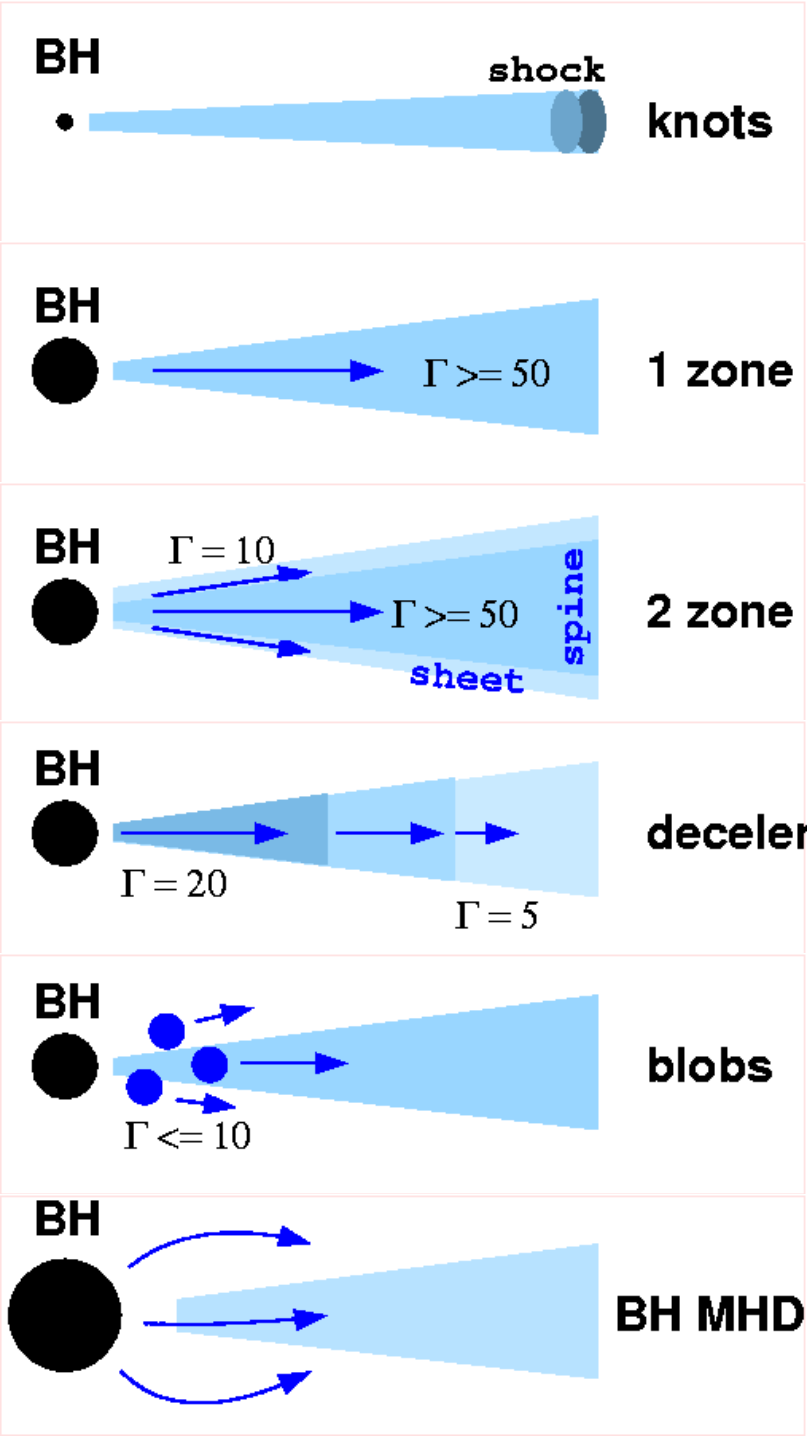


Acciari et al., Science, 325, 444, 2009

VHE jet emission models



Buckley, private communication

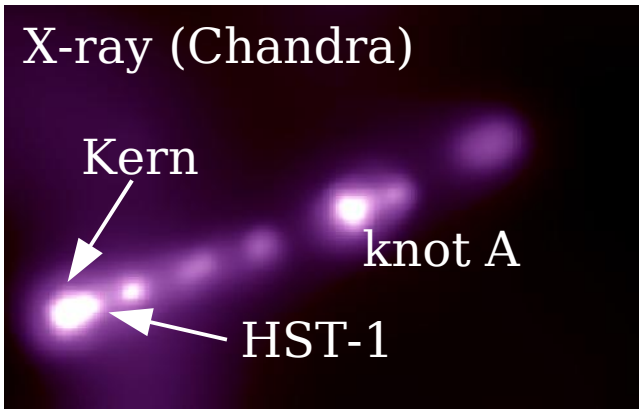


Interpretation: leptonic models 1

Magnetic field in the jet:

[Stawarz et al. (2005), ApJ, 626, 120]

- ➔ IC emission in knots of the jet
- ➔ Problem: TeV γ-ray variability
- ➔ Estimation of the jet magnetic field

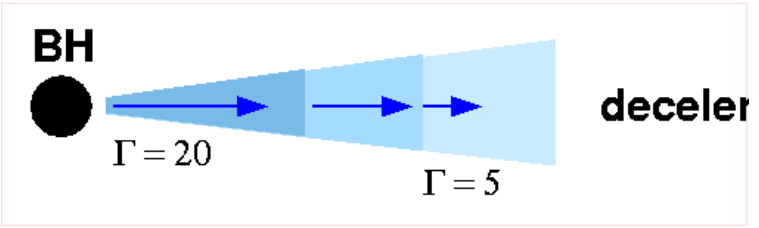


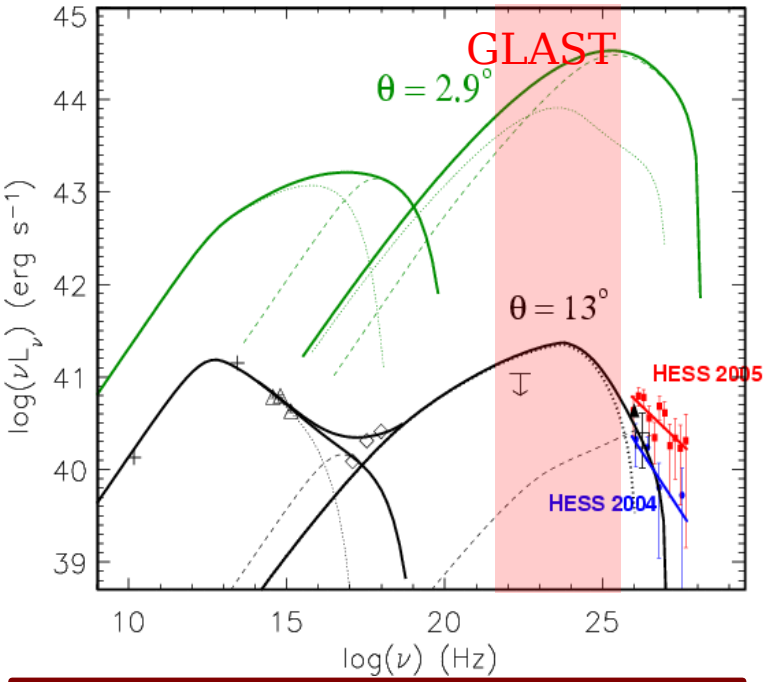
Use TeV UL to constrain magnetic field

Upscatter-Compton-model:

[Georganopoulos (2005), ApJ, 634, L33]

- ➔ Velocity gradient along inner jet
- ➔ Higher intensity in IC peak as SSC





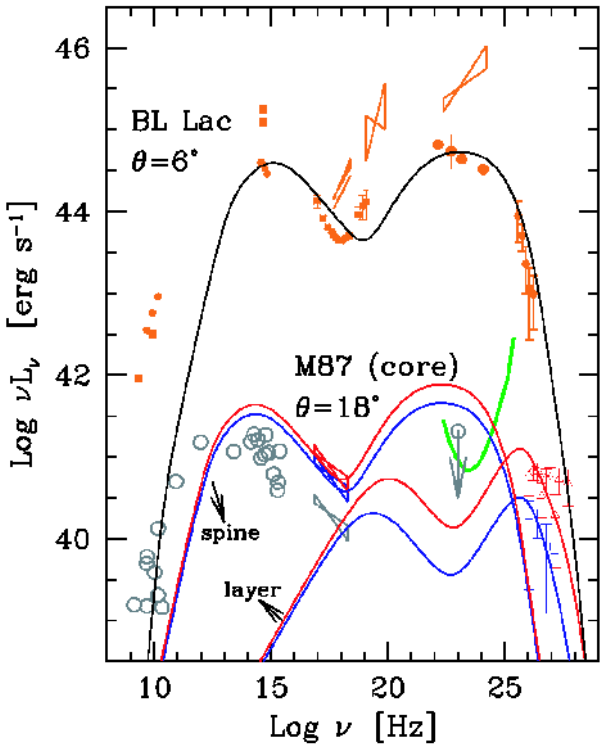
AGN unification?

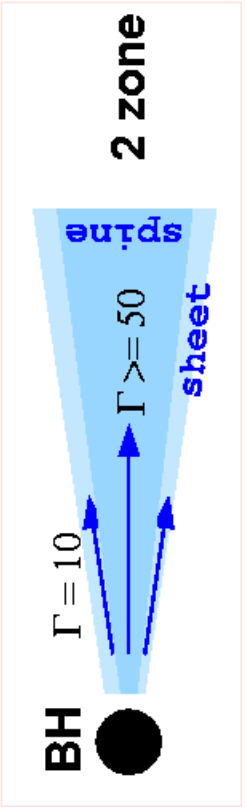
Interpretation: leptonic models 2

Jet spline model:

[Tavecchio & Ghisellini (2008), MNRAS, 385, 98]

- ➔ Photon boost: spline/sheet transition
- ➔ Blazar: spline dominated
- ➔ Radio galaxy: sheet dominated



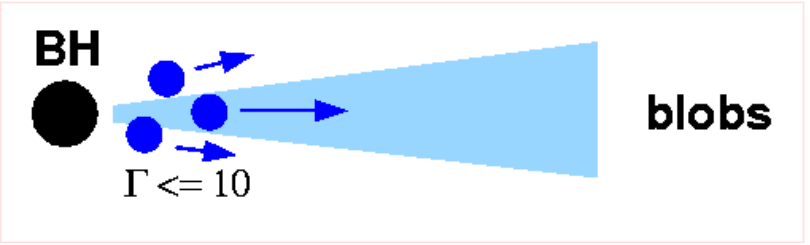


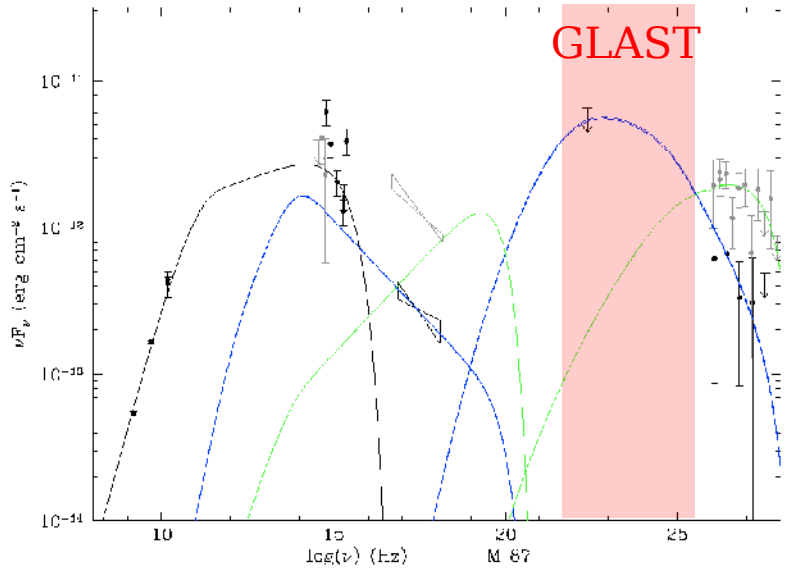
Misalignment, AGN unification

Jet multi-blob SSC model:

[Lenain et al. (2008), A&A, 478, 111]

- ➔ Blobs (10^{14} cm), moderate Γ <10
- ➔ large opening angle, 'before' jet collimation (misaligned blazar)





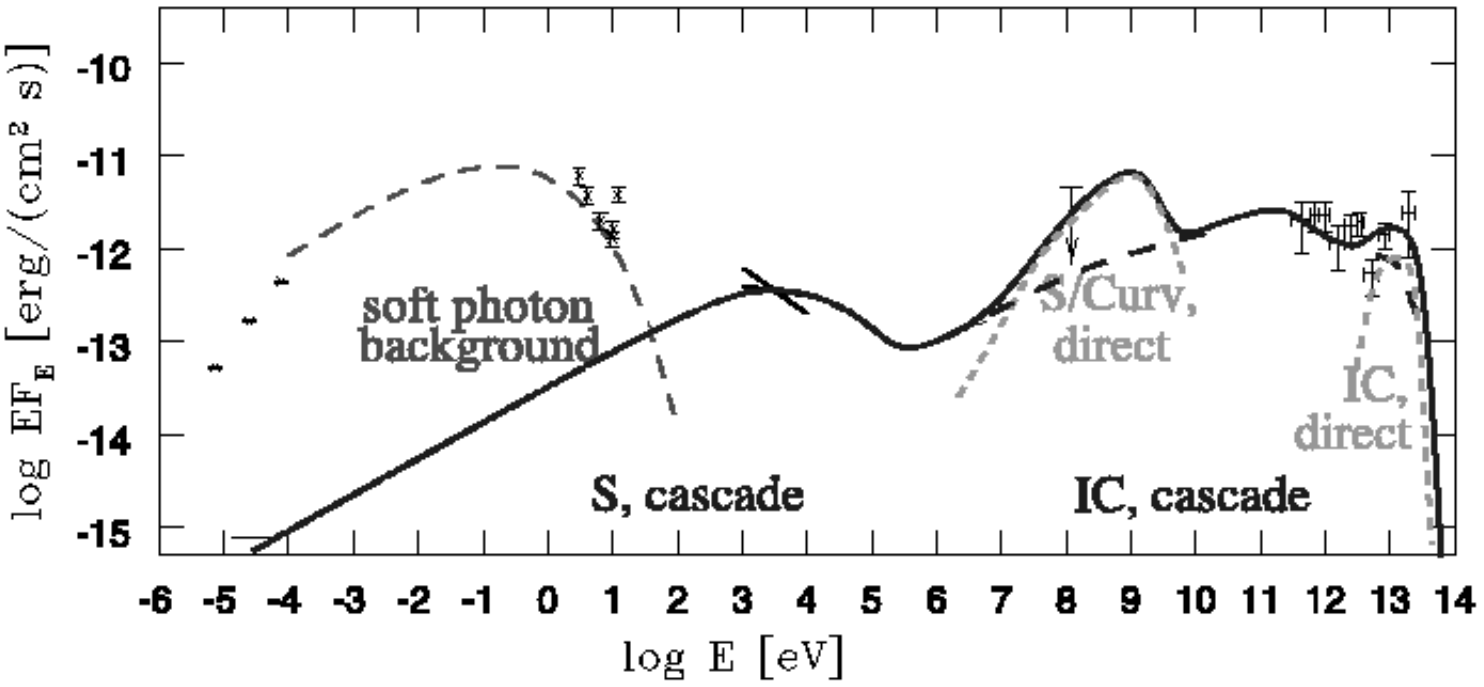
Misalignment, AGN unification

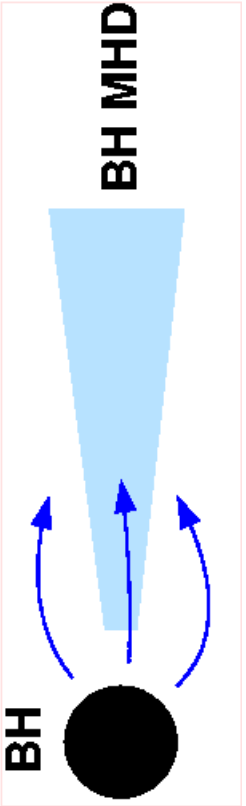
Interpretation: leptonic models 3

Black hole magnetosphere:

[Neronov & Aharonian (2007), ApJ, 671, 85]

- BH horizon/magnetosphere: particle acceleration
  (E field vacuum gaps, rotational induced, similar to pulsars)
  Min. time scale: non-rotating BH (1day), rotating Kerr BH (0.5day)
- Synchrotron, curvature and VHE invers-Compton (anisotropic)
- e^+e^- cascades => isotropic VHE invers-Compton
- Protons: too long cooling times (t_{var})

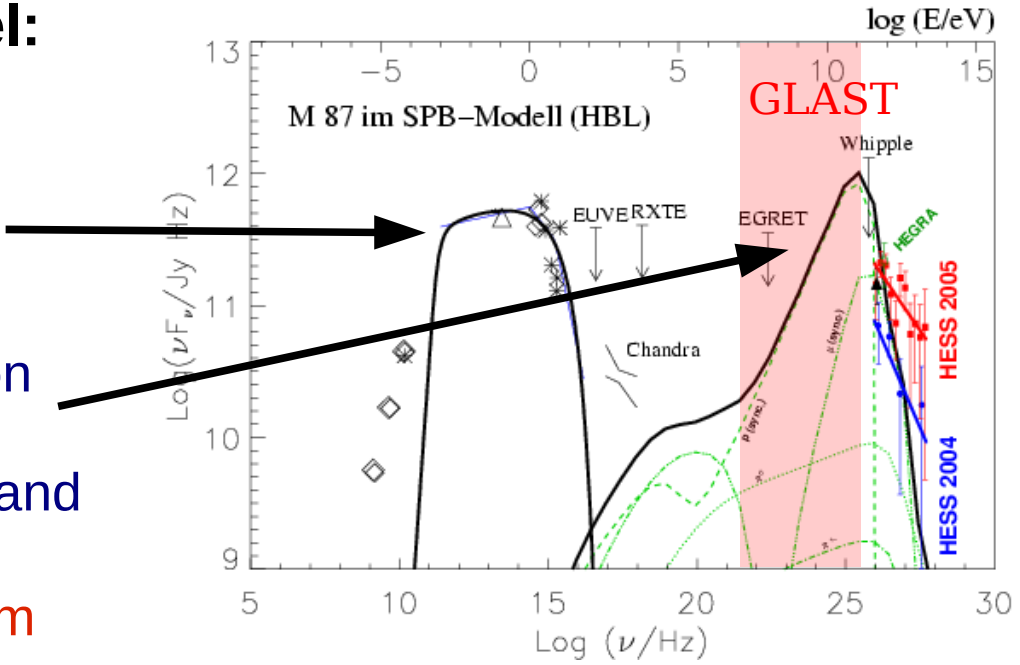


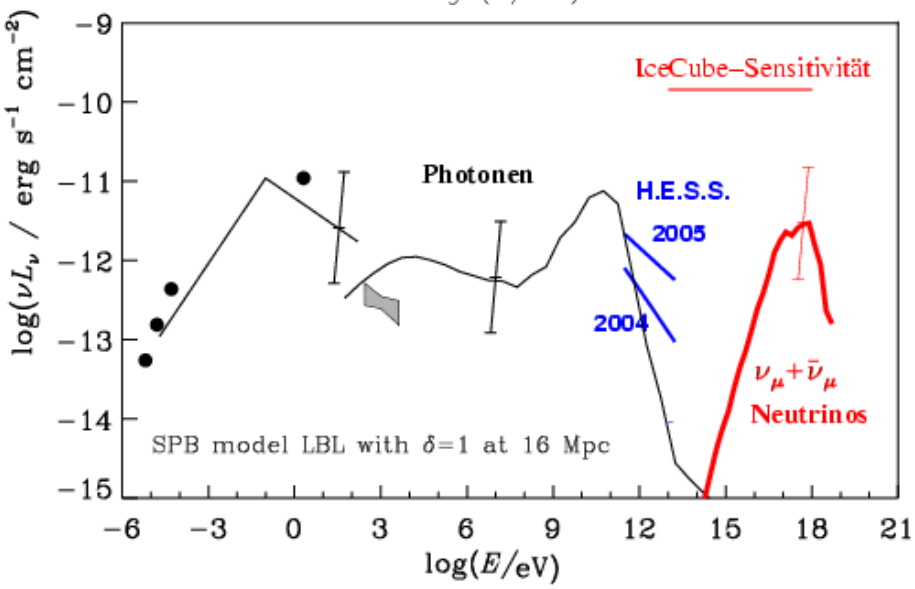


Interpretation: hadronic models

Synchrotron proton blazar model:
[Reimer et al. (2004), A&A, 419, 89]

- High energy particles (core region)
- *Electrons:* Synchrotron radiation (radio- to X-rays)
- *Protons:* scatter with photons (+secondary reactions), synchrotron radiation
- Production of neutrinos (IceCube) and UHECR particles (Auger)
- Model predicts steep γ-ray spectrum (in contrast to TeV measurements)





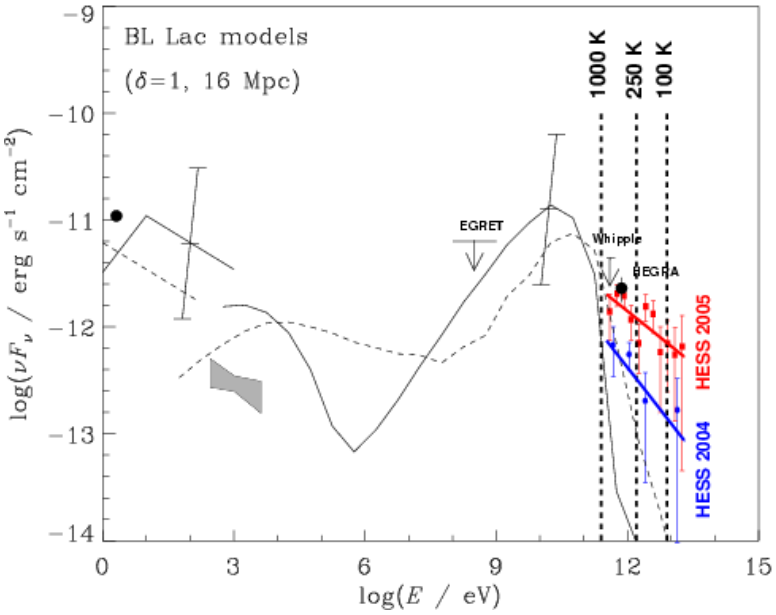
Other hadronic models exist.
Distinguish: neutrinos & UHECR

M87 interpretation: misc models

Central dust torus in M87:

[Donea & Protheroe (2003), PThPS, 151, 186]

- ➔ Temperature dependent infrared radiation field of a dust torus
- ➔ Absorption of the TeV γ-rays
- ➔ Signature in measured spectrum

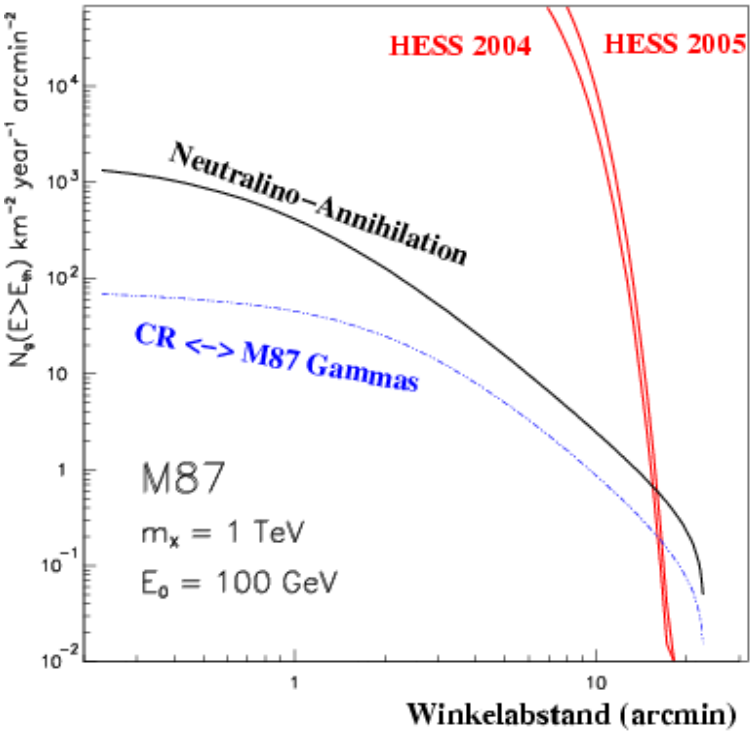


T < 100K or TeV γ-ray emission not originating from center

Neutralino(χ) annihilation:

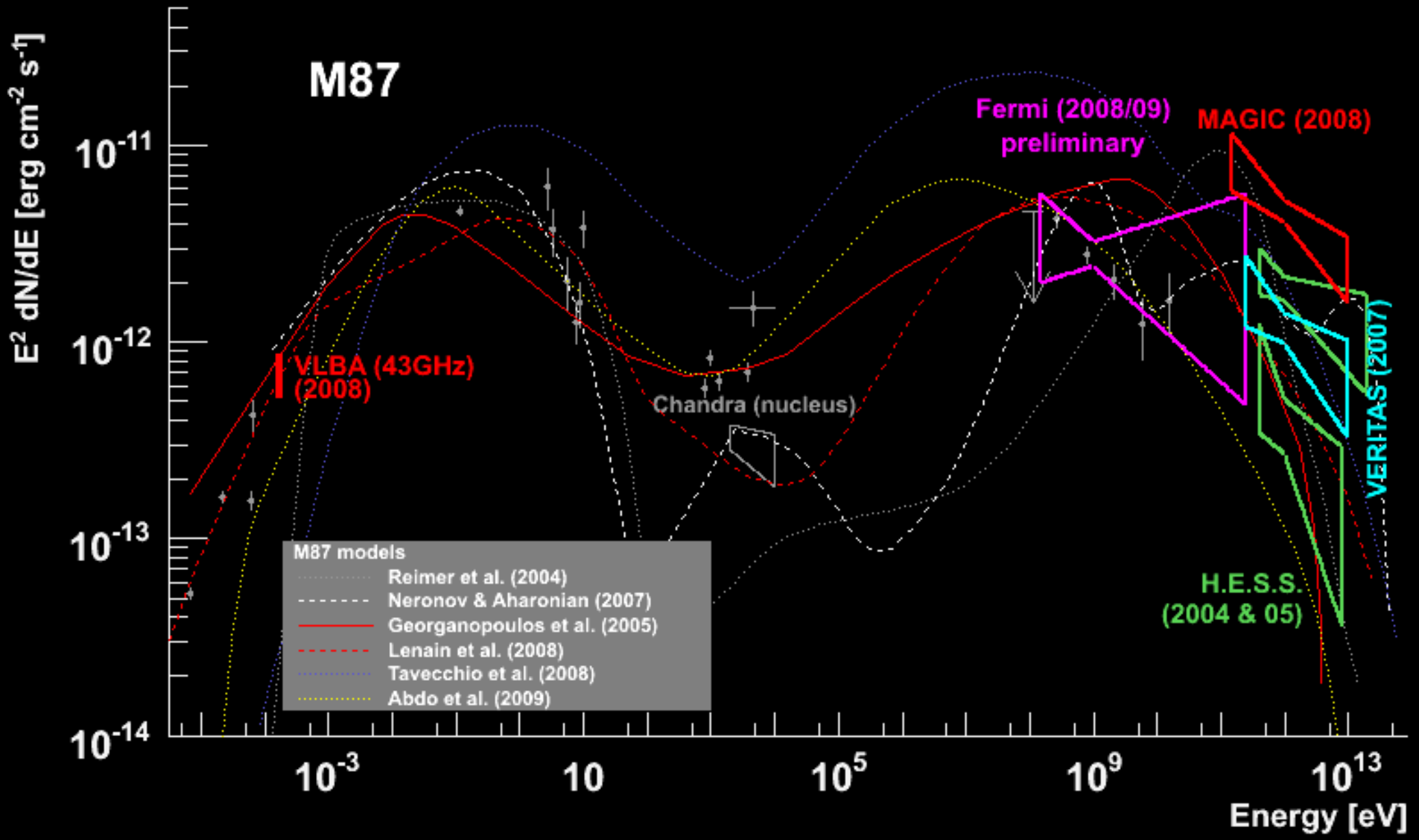
[Baltz et al. (1999), Phys.Rev.D, 61, 023514]

- ➔ Concentration of dark matter in M87
- ➔ Neutralino annihilation →TeV-γ's



Data not explained by (only) χ annihilation (flux level & var.)

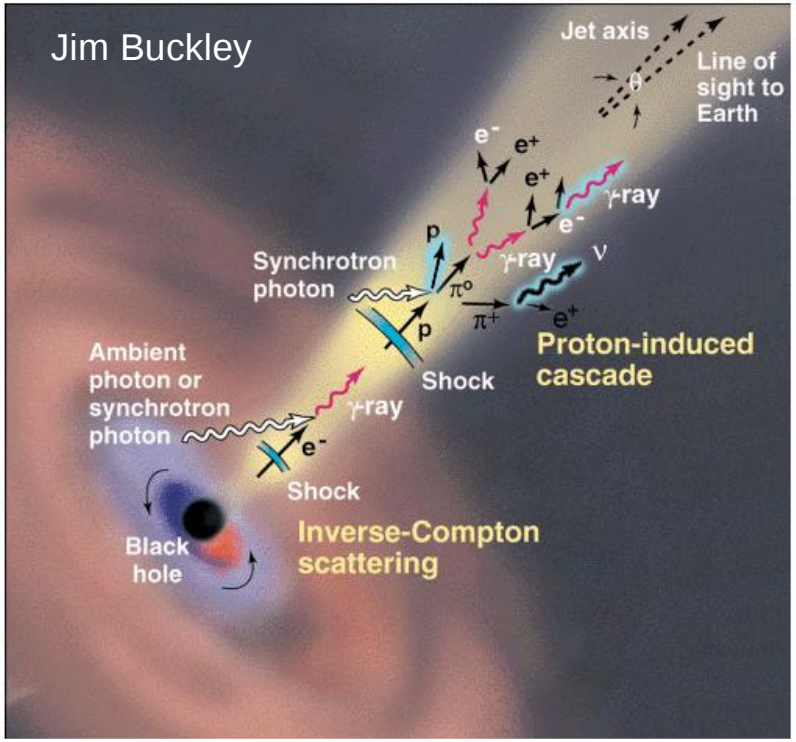
The MWL picture (non-simultaneous)

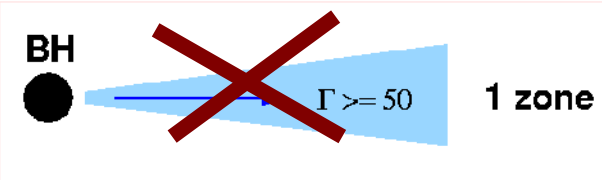


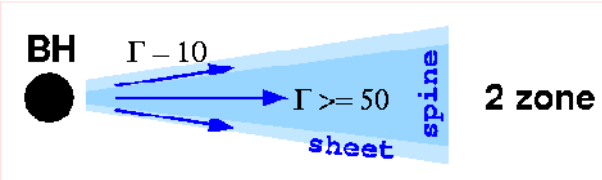
Archival data points taken from Lenain et al (2008) & Abdo et al. (2009)

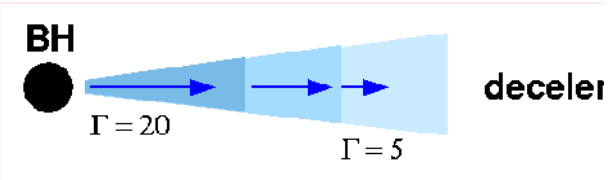
M87: Importance of results & future

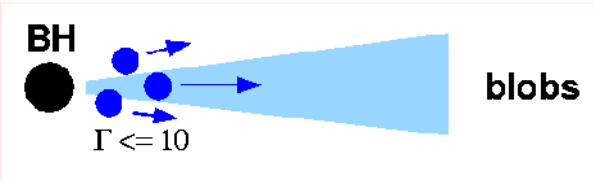
- **TeV/radio connection:**
  - TeV emission from BH vicinity
  - Important input for TeV modeling
  - Accretion & jet formation physics
- **Future questions:**
  - Can pattern be observed repeatedly?
  - TeV emission: How close to BH?
    (how to get TeV photons out w/o absorption?)
  - More detailed sampling of light curves
  - Polarization in radio?
  - Other TeV sources: Similar pattern?

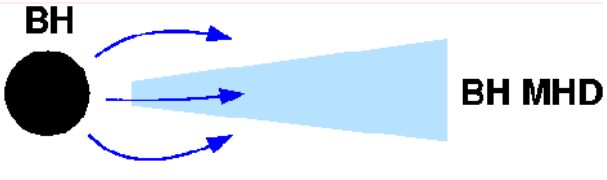












Future TeV/radio cooperation: promising approach!

Summary and Conclusion

Summary and Outlook

- Thanks to the following MWL teams/partners: VLBA, HST, Chandra, Fermi, TeV observatories, ...
- M87: unique laboratory to study jet physics & VHE emission processes