Discovery of fast variability of the TeV γ-ray flux from the radio galaxy M 87 with H.E.S.S.

Matthias Beilicke for the H.E.S.S. collaboration
University of Hamburg, Germany (matthias.beilicke@desy.de)

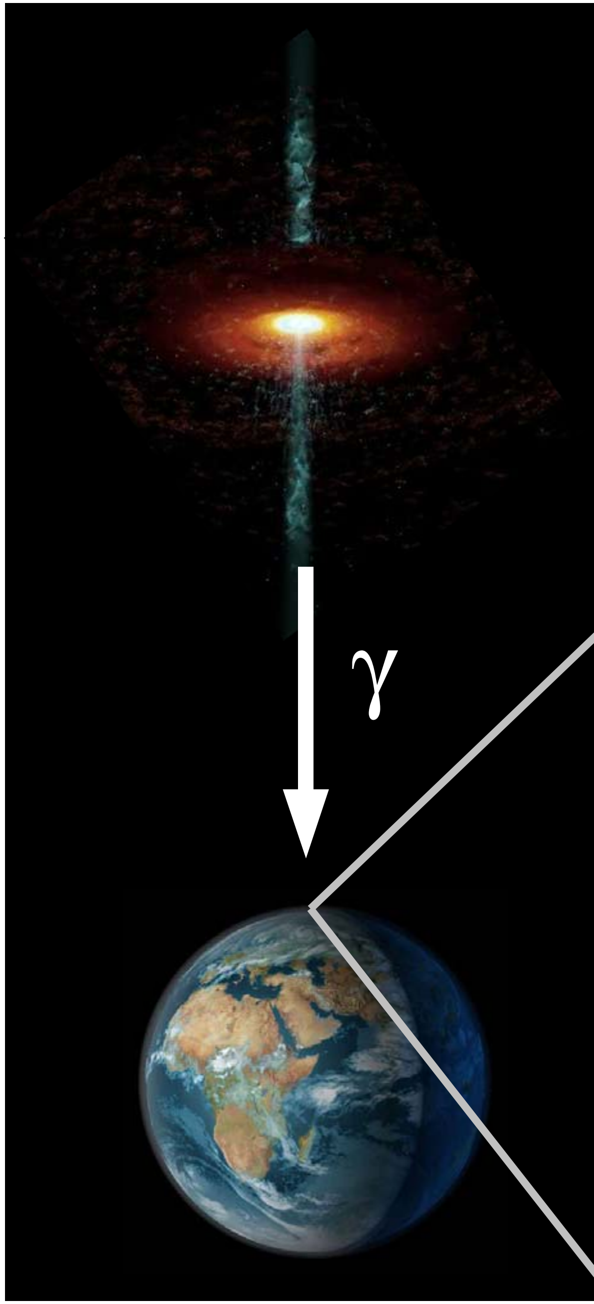
First GLAST Symposium
(Stanford University, 5-8 February 2007)

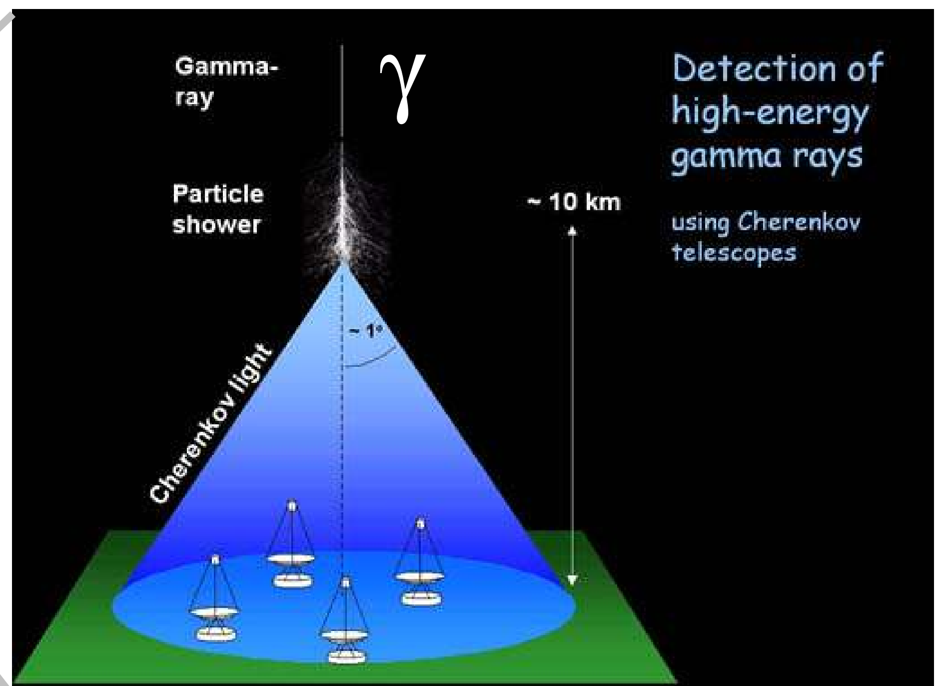
- Introduction
- The radio galaxy M 87
- H.E.S.S. detection of M 87 and implications
- Summary and outlook

bmb+f - Förderschwerpunkt
Astro-Teilchenphysik
Großgeräte der physikalischen Grundlagenforschung

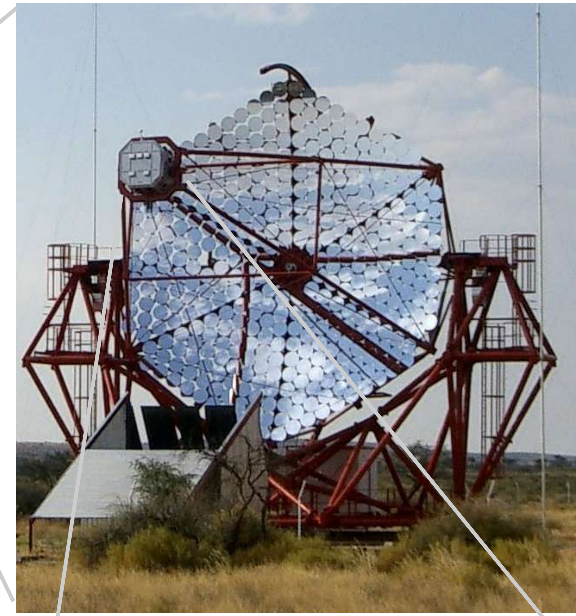
TeV γ-ray astrophysics with Cherenkov telescopes

- **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. of primary particle (stereoscopic obs. pioneered by HEGRA)





The H.E.S.S. Cherenkov telescopes

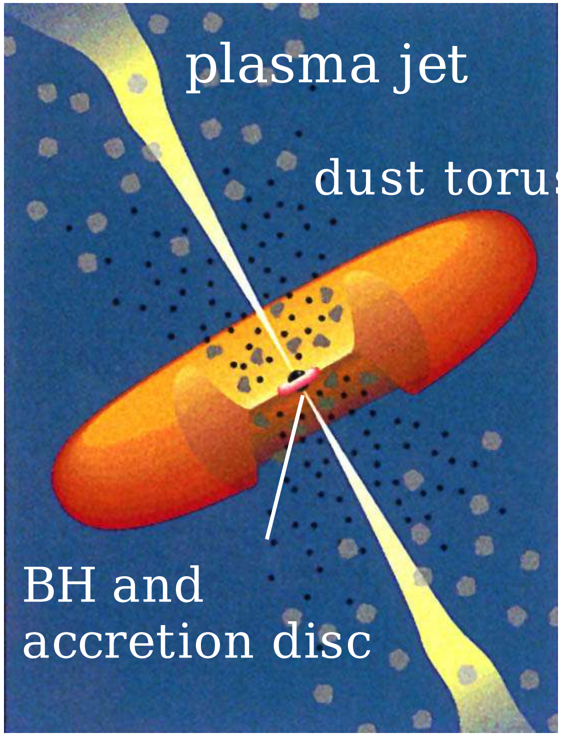


- **H**igh **E**nergy **S**tereoscopic **S**ystem
  (Namibia, stereoscopic observation mode
- Mirror dish (per telescope):
  ~107m^2 mirror surface, 380 facets
- Photomultiplier camera:
  960 PMTs, ~5° field of view (FoV)
- Sensitive energy range:
  100 GeV up to several 10 TeV, ΔE/E ~15%
  1% of Crab: 5 sigma in 25h
- Angular resolution: ~0.1° per event

Extragalactic GeV/TeV γ-ray sky (today)

Name	redshift	reference
M 87	0.004	Aharonian et al, A&A, 403, L1 (2003)
Markarian 421	0.030	Punch et al., Nature, 358, 477 (1992)
Markarian 501	0.034	Quinn et al., ApJ, 456, L83 (1996)
1ES 2344+514	0.044	Catanese et al., ApJ, 501, 616 (1998)
Markarian 180	0.045	Albert et al., astro-ph/0606630 (2006)
1ES 1959+650	0.047	Nishiyama et al., 29th ICRC, 3, 370 (1999)
PKS 548-322	0.067	preliminary!
PKS 2005-489	0.071	Aharonian et al, A&A, 436, L17 (2005)
PKS 2155-304	0.116	Chadwick et al., ApJ, 513, 161 (1999)
H 1426+428	0.129	Horan et al., ApJ, 571, 753 (2002)
1ES 0229+200	0.139	preliminary!
H 2356-309	0.165	Aharonian et al, Nature, 440, 1018 (2006)
1ES 1218+304	0.182	Albert et al., ApJ, 642, L119 (2006)
1ES 1101-232	0.186	Aharonian et al, Nature, 440, 1018 (2006)
1ES 0347-121	0.188	preliminary!
PG 1553+113	>0.25?	Aharonian et al, A&A, 448, L19 (2006)

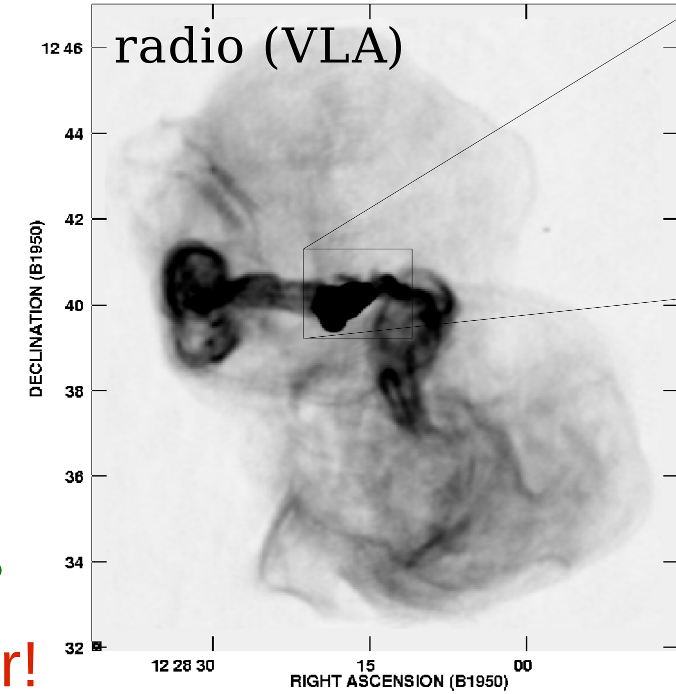
Legend:
discovered by H.E.S.S.
seen by H.E.S.S.

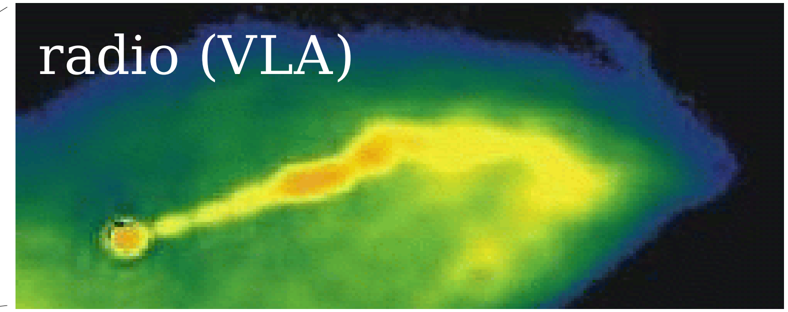


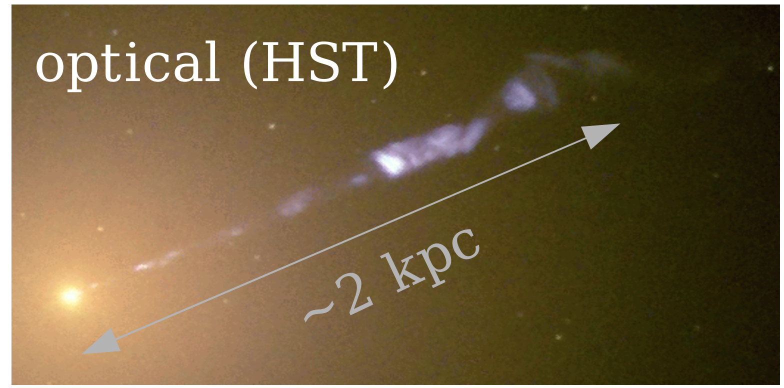
Except for M87, all extragalactic TeV γ-ray sources are blazars

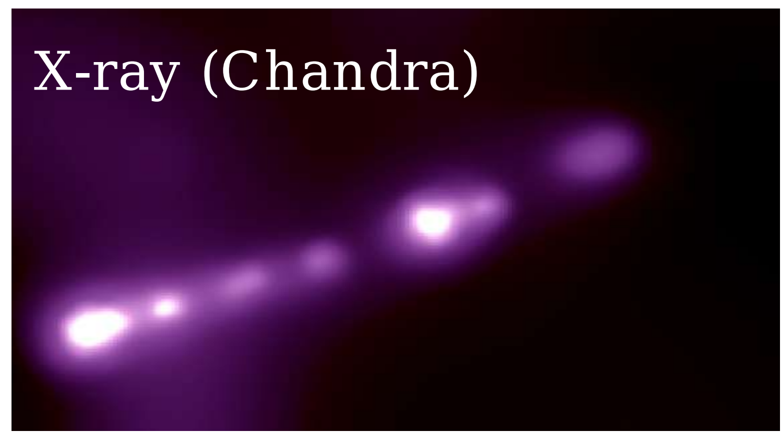
The giant elliptical radiogalaxy M 87

- Distance:
  ~16 Mpc
  (z=0.00436)
- Central BH:
  $M_{BH} \sim 3{\cdot}10^{9}\ M_{sun}$
- Jet angle: ~30°
  ⇒ not a blazar!
- Predictions of TeV γ-ray emission and charged 10^{20} eV particles (UHECR)
- First detection (>4σ) at TeV γ-ray energies by HEGRA in 1998/99
  [Aharonian et al. (2003), A&A, 403, L1]





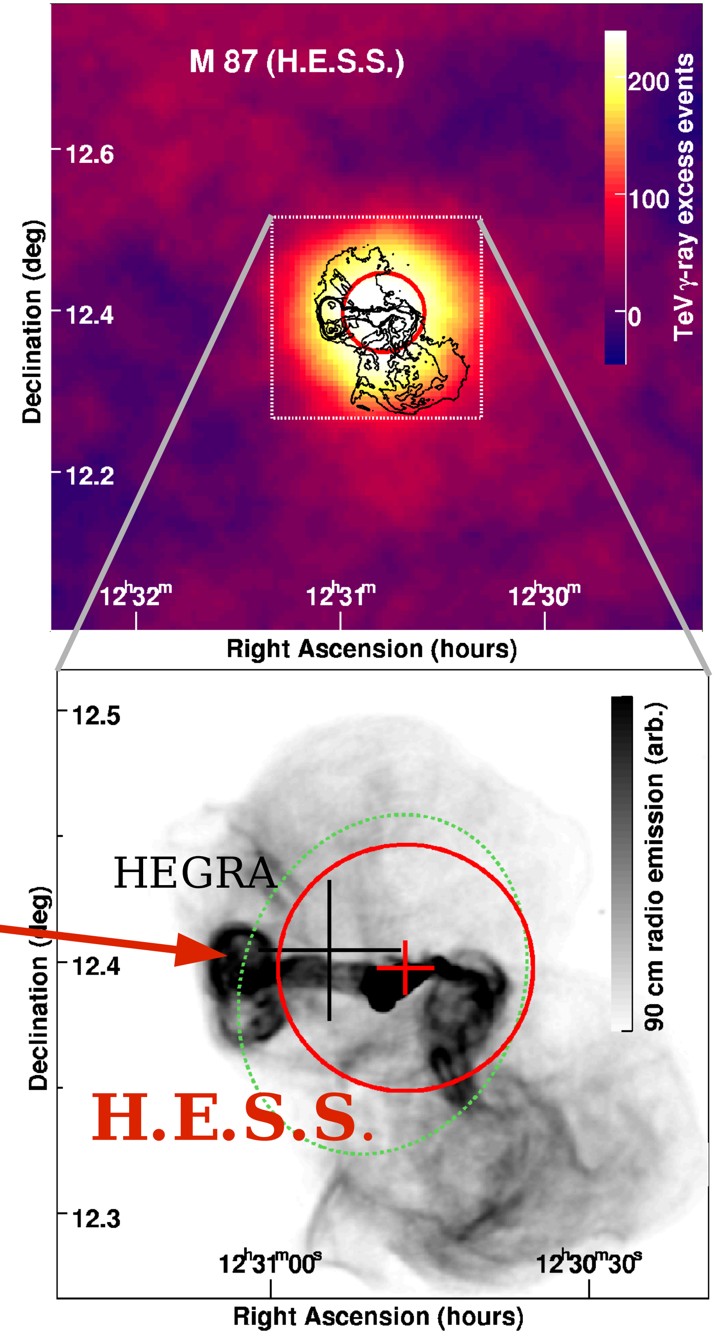




M 87: Interesting candidate for TeV γ-ray observations

M 87: confirmation as TeV γ-ray source by H.E.S.S.

- Observations by H.E.S.S.:
  - 2003 (~19 h, construction phase)
  - 2004-06 (~57 h, 4 telescopes)
- Whole data set (hard cuts):
  243 γ-ray events (13σ)
  ⇒ confirmation as TeV γ-ray source
- Point-source, position compatible with position of M 87 nucleus
- Upper limit for extension (99.9% c.l.):
  3 arc min [14 kpc]



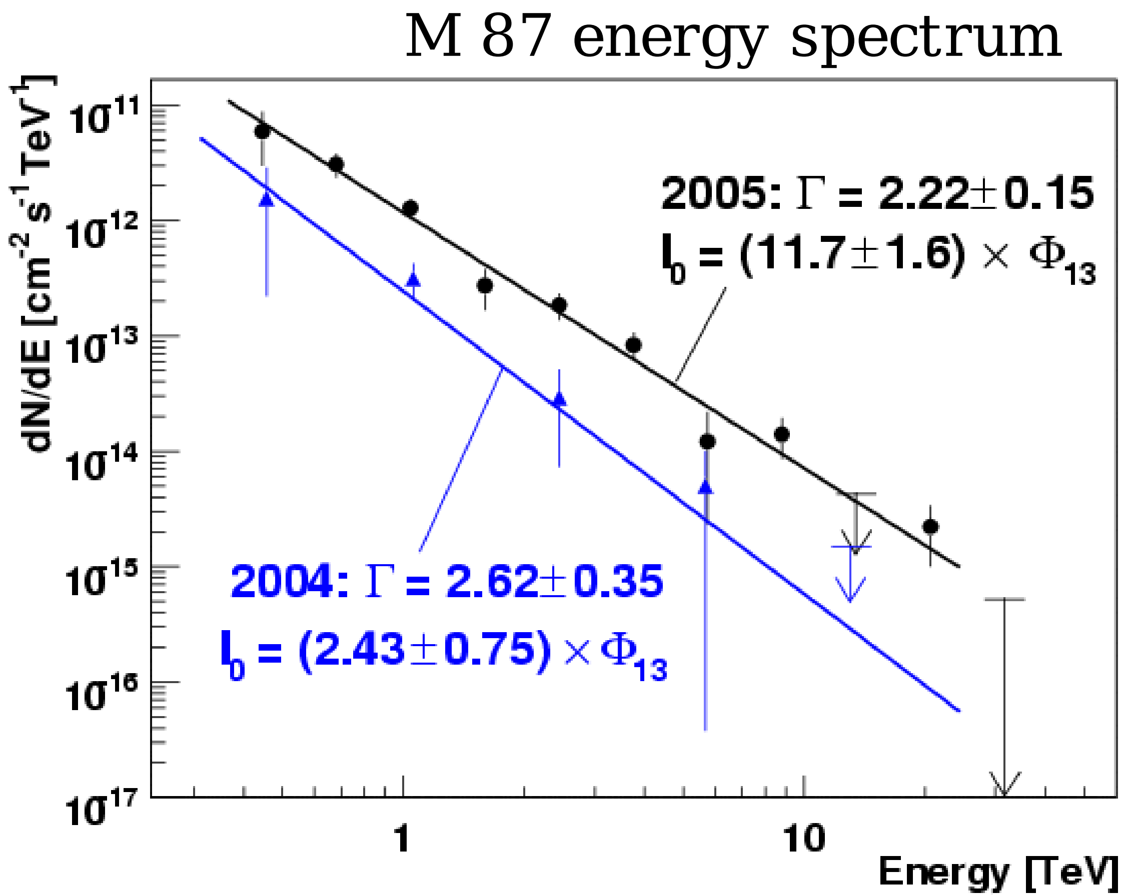
First extragalactic TeV γ-ray source which is not a blazar

M 87: energy spectra

- Separate energy spectra: 2004 (~5σ) & 2005 (~10σ) using standard cuts
- Spectra well described by power-laws:

$$\frac{dN}{dE} = I_0 \cdot \left(\frac{E}{1\,\mathrm{TeV}} \right)^{-\Gamma}$$

- 2004 vs. 2005: photon indexes Γ compatible, but different flux levels

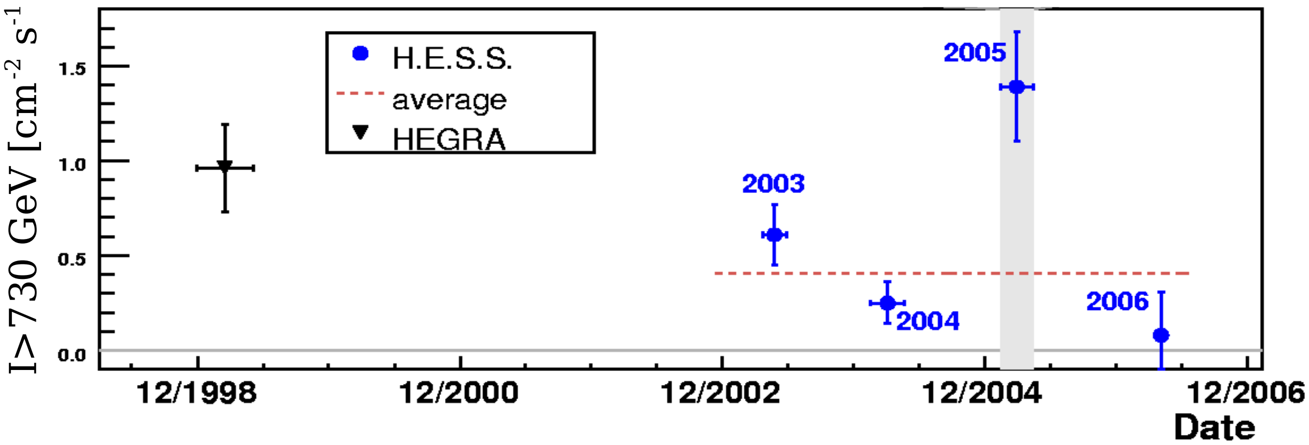


$\Phi_{13} = 10^{-13}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{TeV}^{-1}$

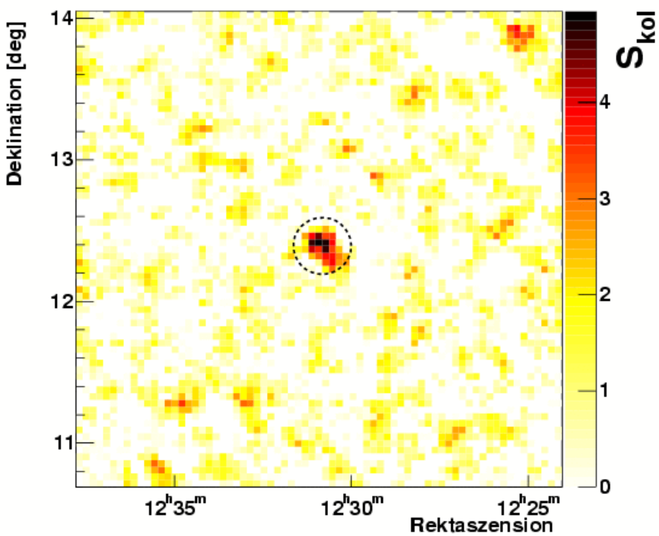
2005: hard energy spectrum beyond 10 TeV

M 87: light curve and long-term variability

- Integral photon flux above 730 GeV (year-by-year)
- Fit of a constant function: variability: 3.2 σ
- Kolmogorov test (applied to distribution of photon arrival times): ~ 4 σ at the sky position of M 87

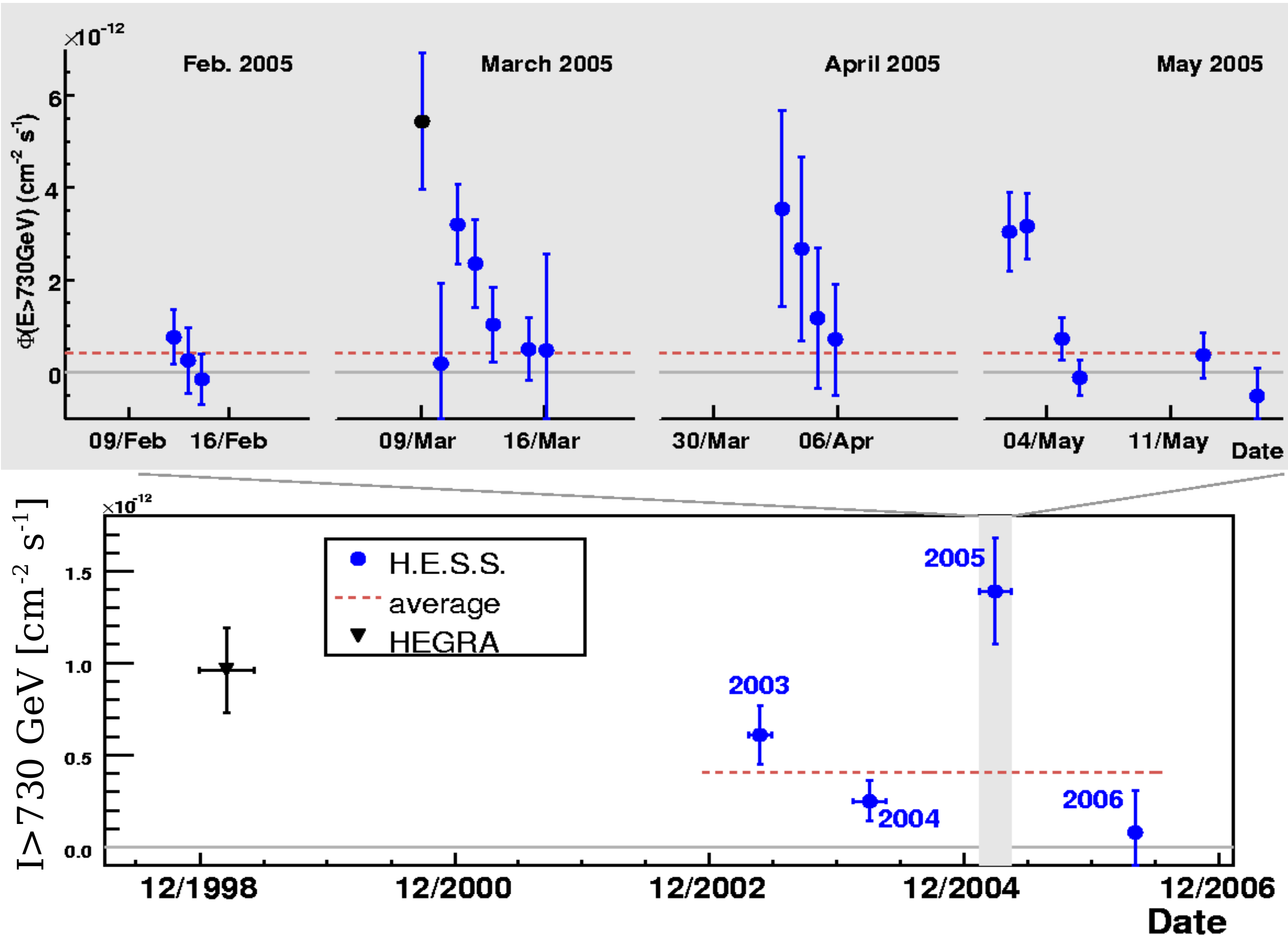


Kolmogorov test



Long-term variability of TeV γ-ray emission from M 87

M 87: light curve and short-term variability

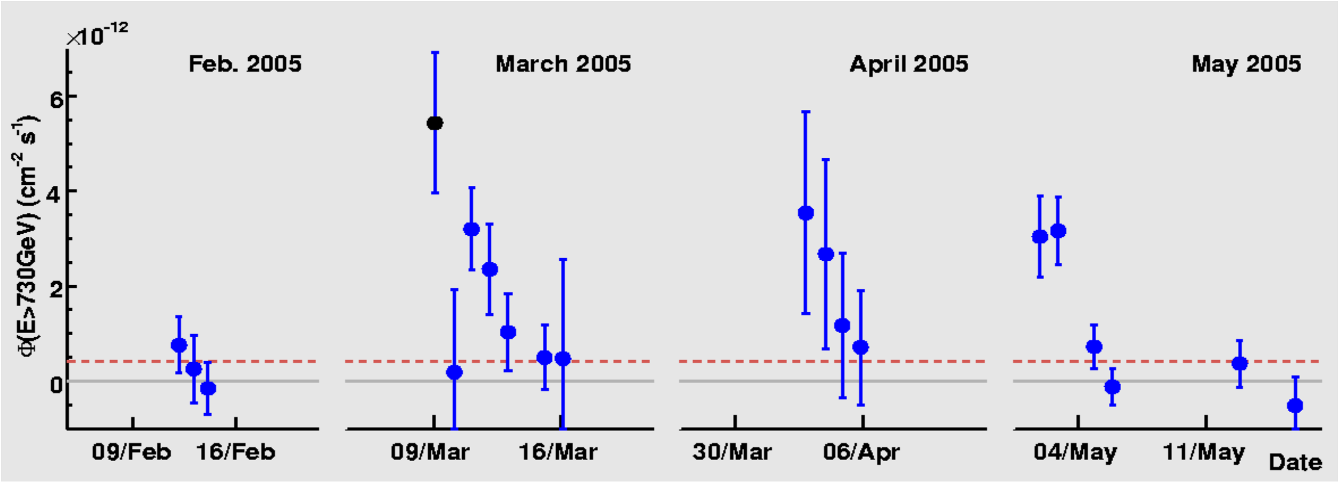


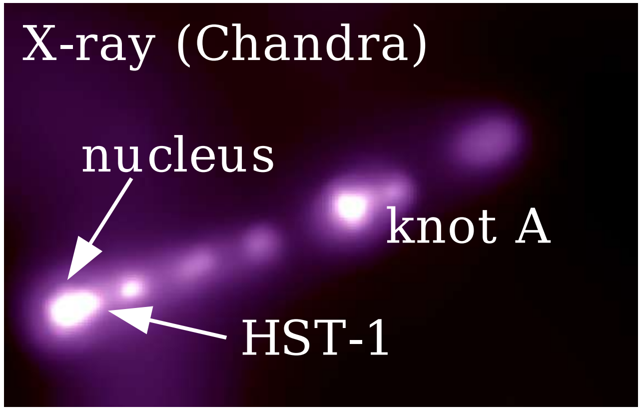
Surprisingly also short-term variability within 2005 (>4σ)

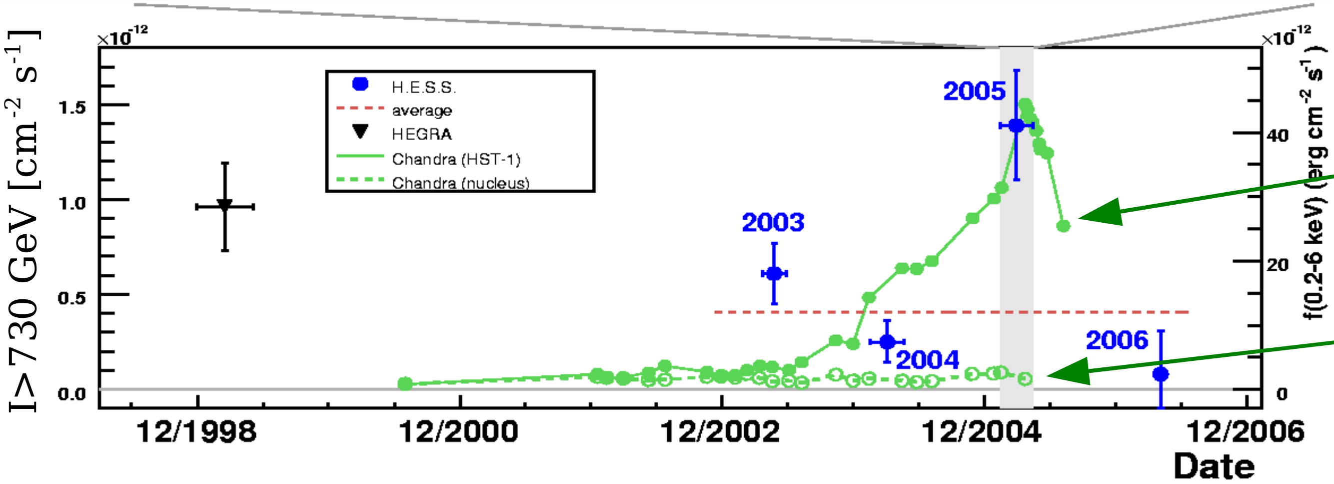
⇒ constrains size of emission region ($R \sim 5\ \delta\ R_s$)

relativistic Doppler factor

M 87: light curve and variability







X-ray emission:

- knot HST-1
  [Harris et al. (2005), ApJ, 640, 211]
- nucleus
  Courtesy to D.Harris (priv. communication)

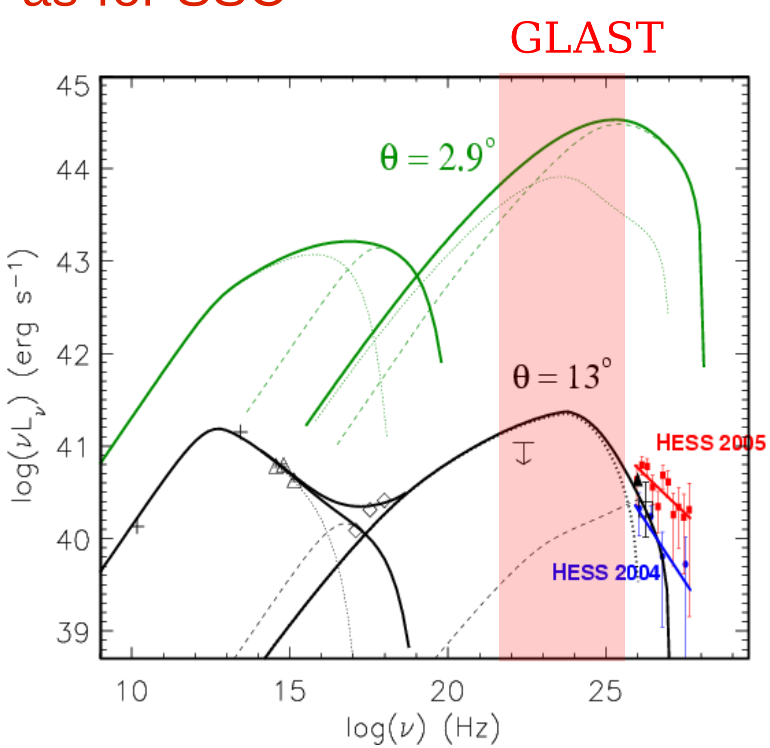
No X-ray/TeV correlation can be derived
⇒ need further MWL observations

Interpretation: leptonic vs. hadronic models

Upscatter-Compton-model:

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

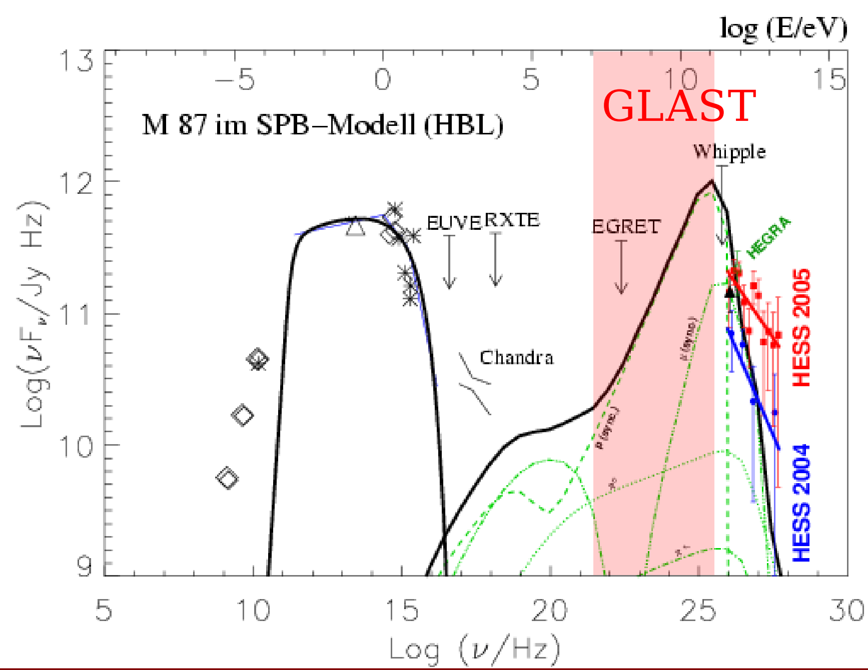
- ➔ Expansion of SSC model: velocity gradient along inner jet
- ➔ Higher energy/intensity in IC peak as for SSC



Synchrotron proton blazar model:

[Reimer et al. (2004), A&A, 419, 89]

- ➔ *Electrons:* Synchrotron radiation
- ➔ *Protons:* scattering with photons (and secondary reactions), synchrotron radiation
- ➔ Production of ν's and UHECR



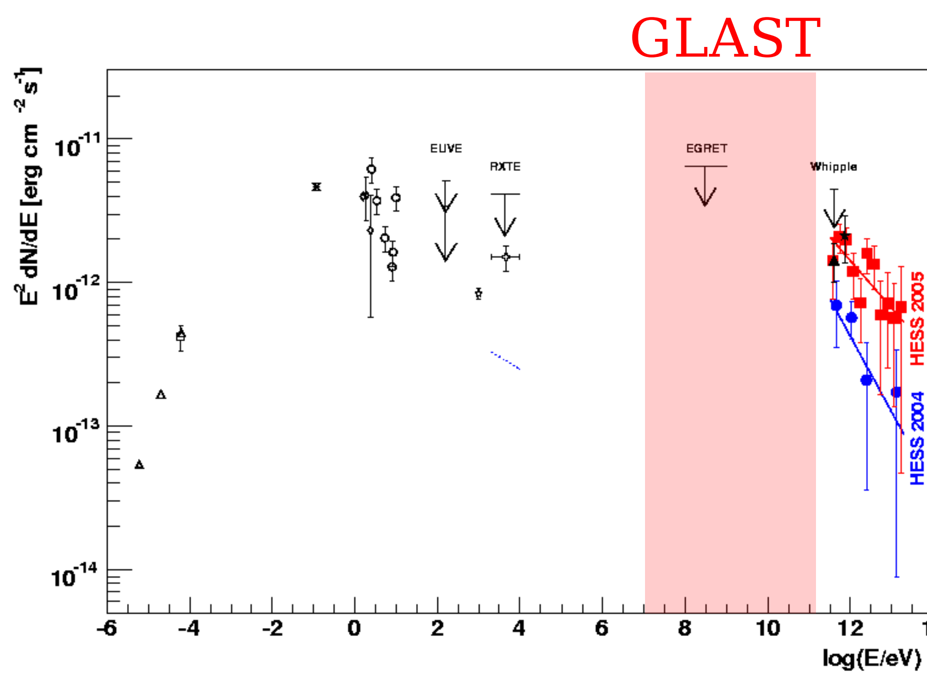
→ Hard energy spectrum challenges both classes of models

M 87: Interpretation and outlook

TeV data (H.E.S.S.)

- M 87 established as first extragal. TeV γ-ray source which is not a blazar
- Variability: $R \sim 5 \times 10^{15}\ \delta$ cm, excludes following models:
  - Dark matter (χ) annihilation
  - CRs in M87, intra cluster gas
  - Large scale jet & knots
- Emission region most likely close to central black hole
- Hard spectrum: Challenges leptonic (SSC) and hadronic (SPB) models
- Alternative mechanisms?
- Aharonian et al., Science,314,1424 (2006)

MWL data & GLAST



- What to expect from GLAST:
  - Position of the VHE peak in SED
  - Variability (time-scales and MWL correlations)?

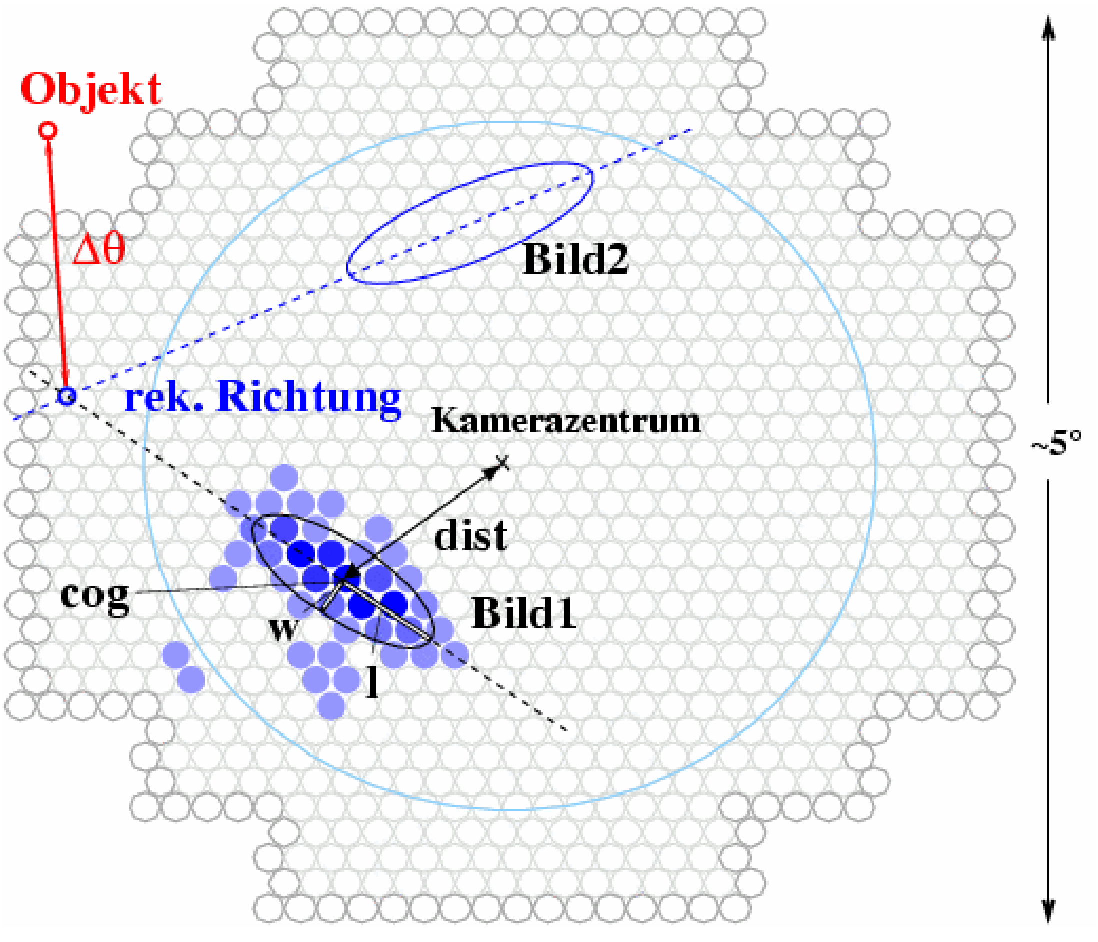
Future MWL observations to constrain the models

Backup transparencies

Backup transparencies

Stereoscopic event reconstruction

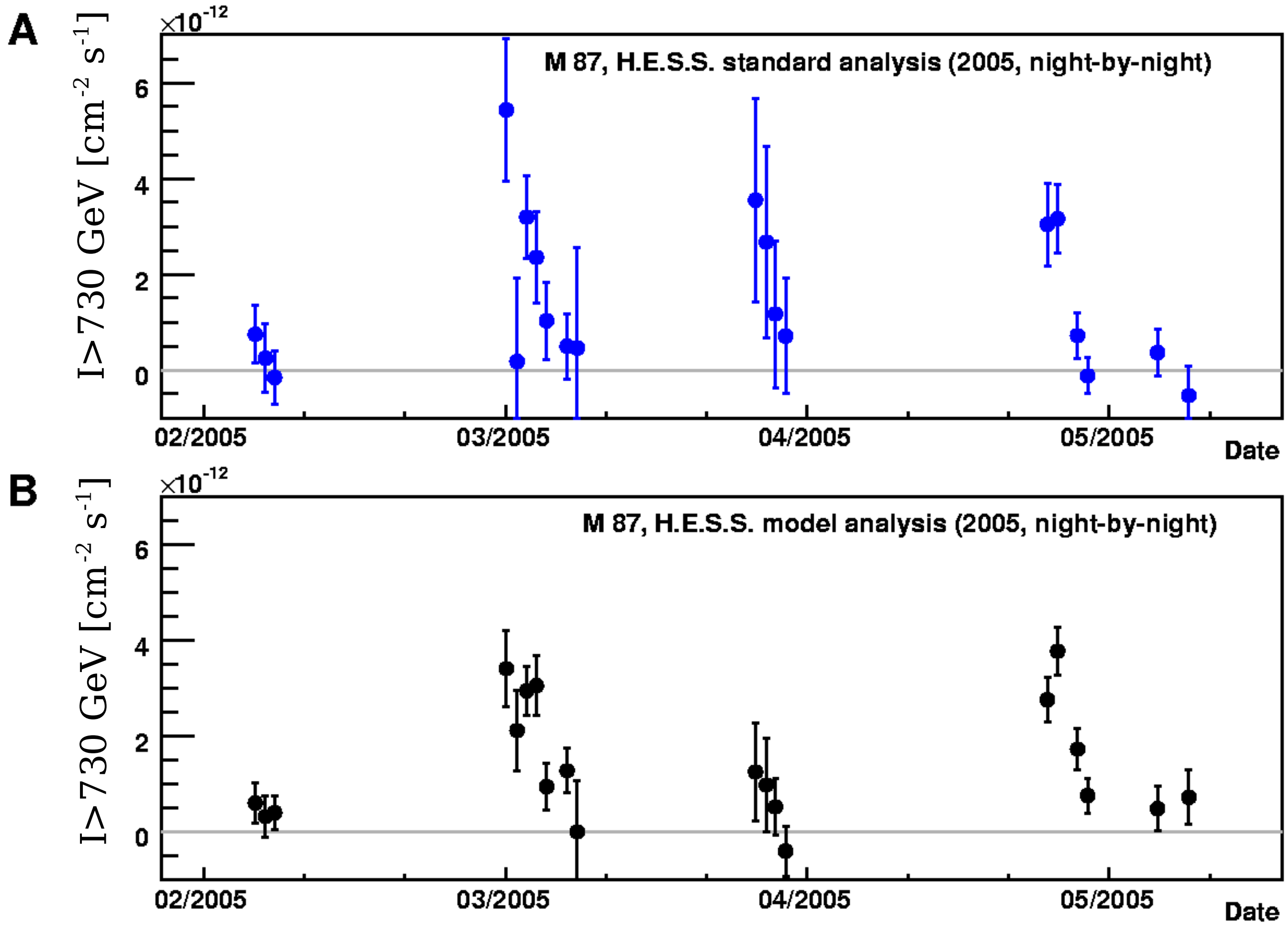
- Image parametrisation:
  Hillas (l, w, Amp, dist, cog)
- Direction:
  Intersection of length axis
- Energy: Image amplitude
  (+ core distance & zenith)
- Type of primary: Statistical
  γ-hadron separation by
  mean scaled image width
  (mscw)



Detector characteristics

➔ *Point spread function* (morphology studies)
➔ *Energy dependent efficiency* (energy spectra)
➔ *FoV dependent acceptance* (background)

M 87: Short-term variability: Model vs. Hillas



Hillas: >4σ

Model: >6σ

Short-term variability in 2005:
confirmed by (more sensitive) model analysis

M 87: interpretation: leptonic models

SSC model (core region):

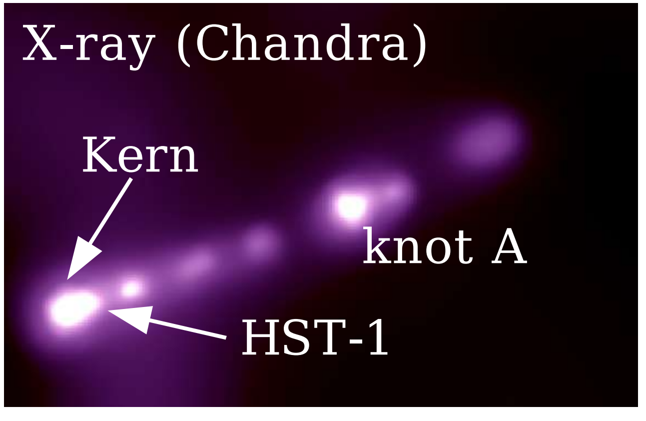
- High energy e⁻-population
- Synchr.- and inv.Compt. radiation
- Requires high Doppler factors
- Modelling for M87 problematic

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

Magnetic field in the jet:

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

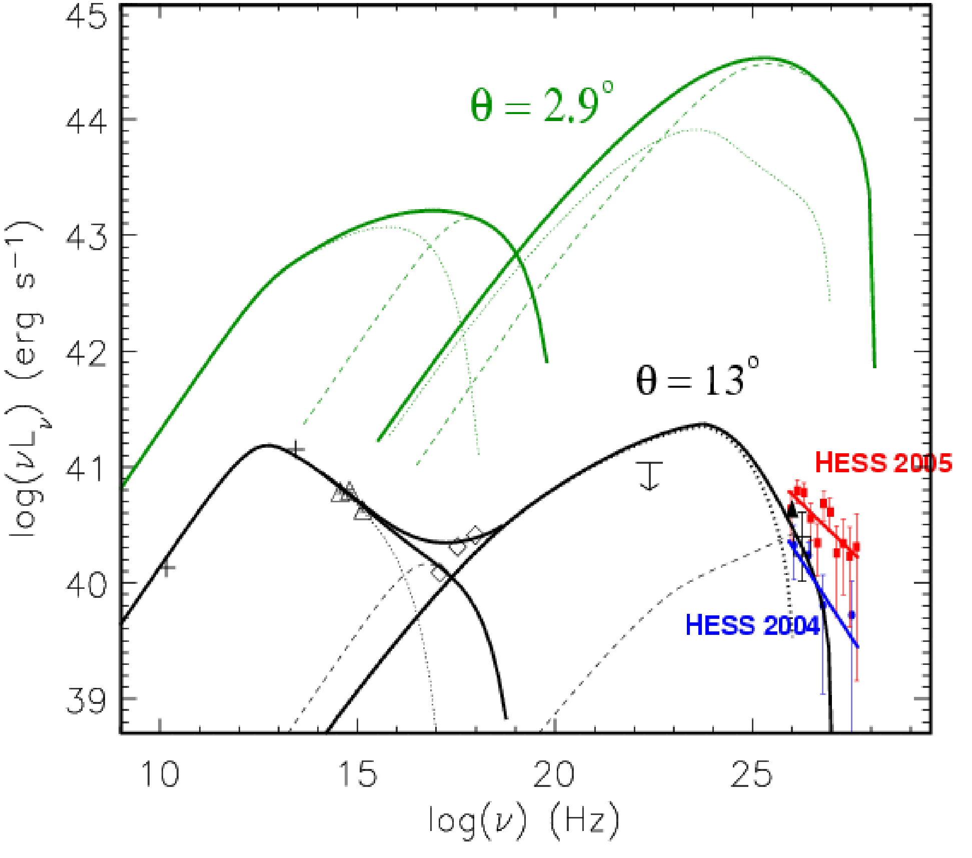
- IC emission in knots of the jet
- Problem: TeV γ-ray variability
- Estimation of the jet magnetic field



Upscatter-Compton-model:

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

- Expansion of the SSC model: velocity gradient along the emission region in the jet
- Higher energies as for Inv. Comp.

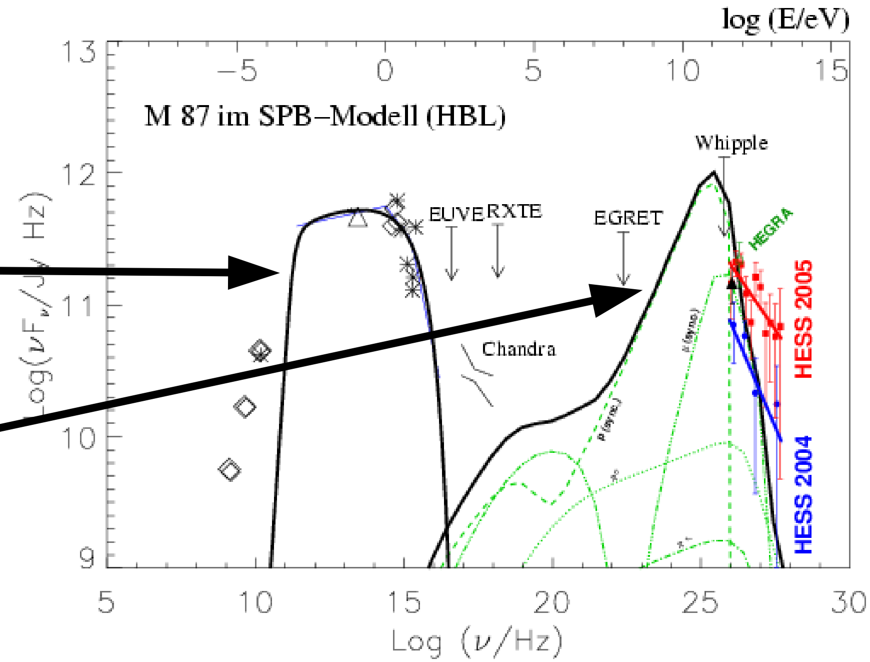


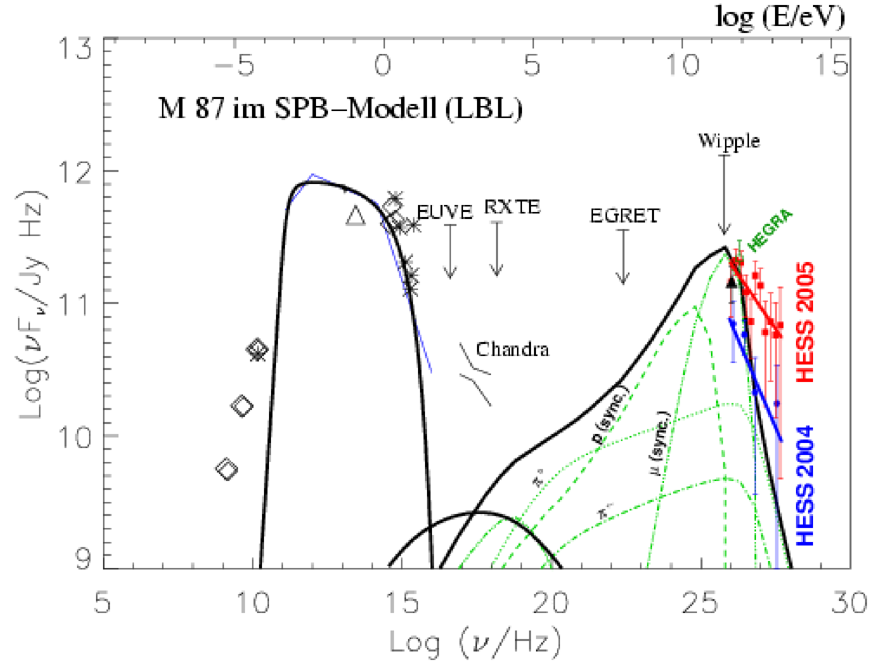
M 87: interpretation: hadronic models

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:* scattering with photons (and secondary reactions), synchrotron radiation
- Production of neutrinos and emission of ultra high energy charged particles (UHECR)
- Model predicts steep γ-ray spectrum (in contrast to H.E.S.S. measurement)





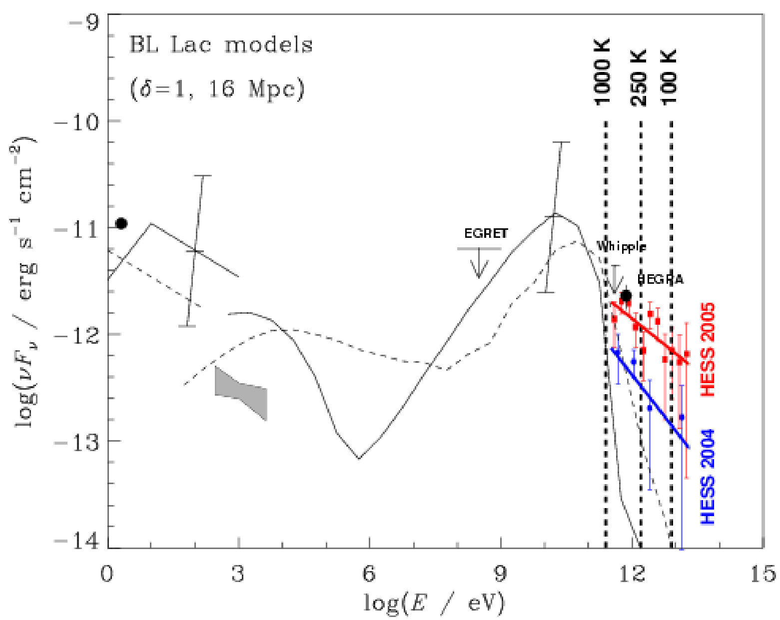
→ SPB model not being confirmed, needs modeling including H.E.S.S. results

M 87: 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

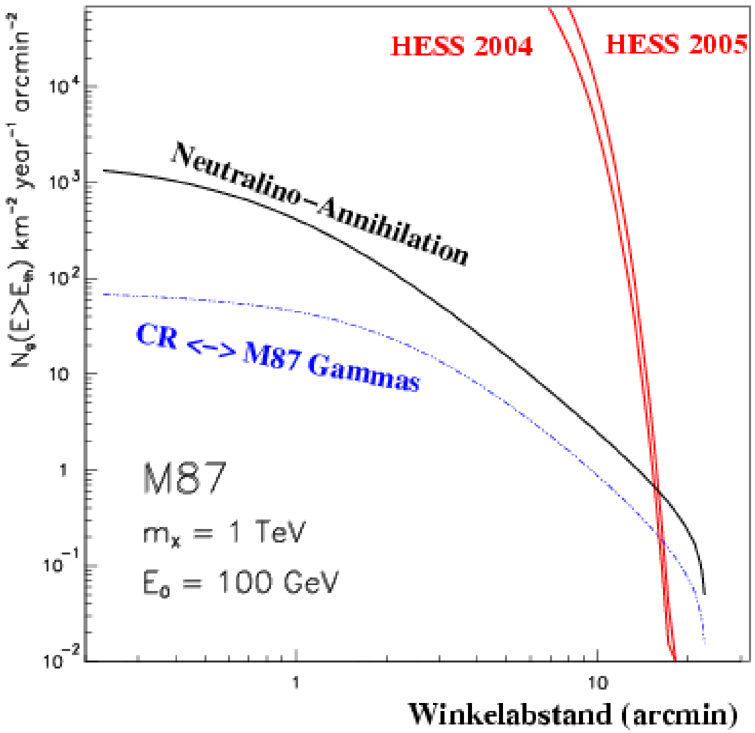


T < 100K or TeV γ-ray emission not originating from centre

Neutralino(χ) annihilation:

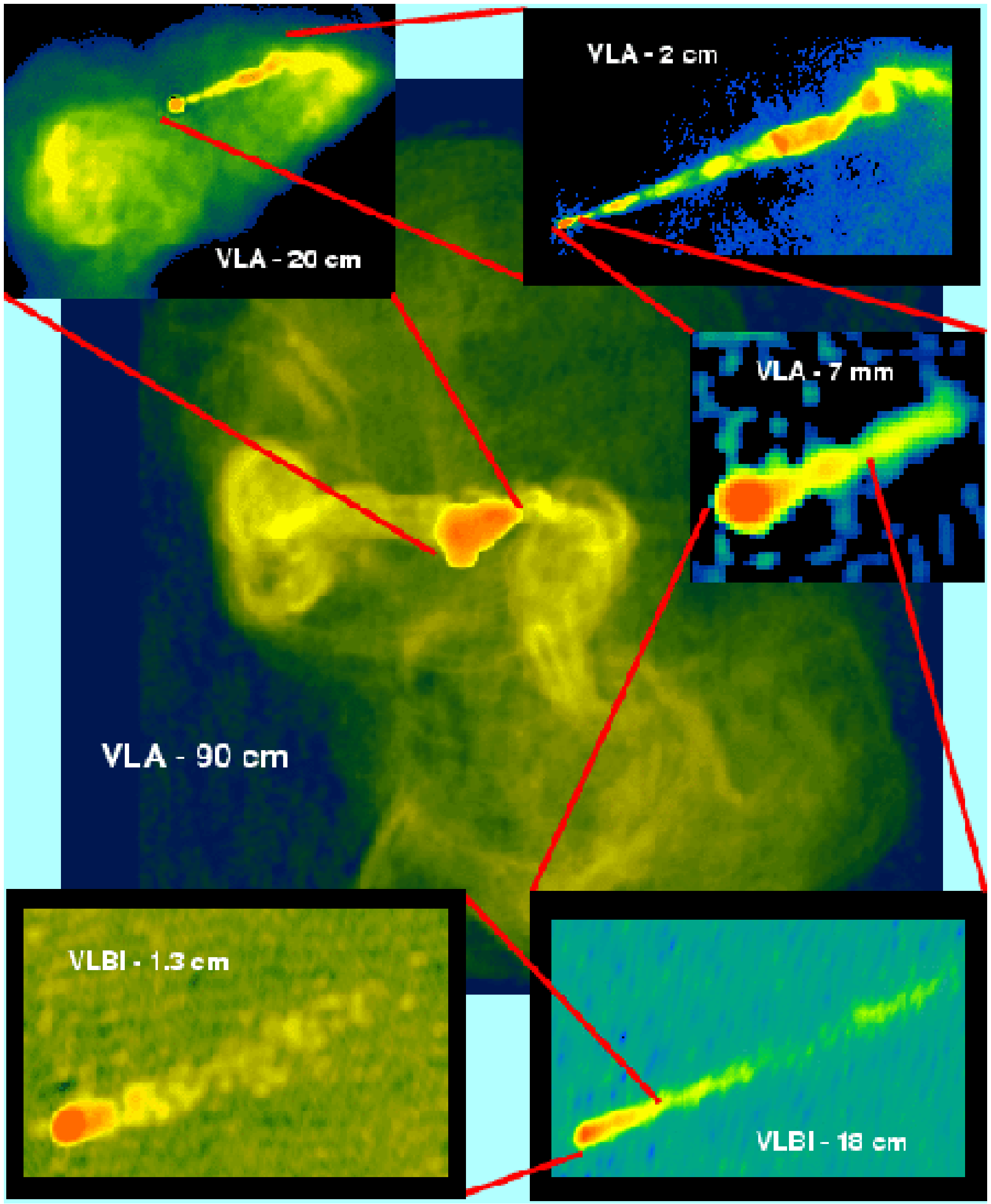
[Baltz et al. (1999), Phys.Rev.D, 61, 023514]

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

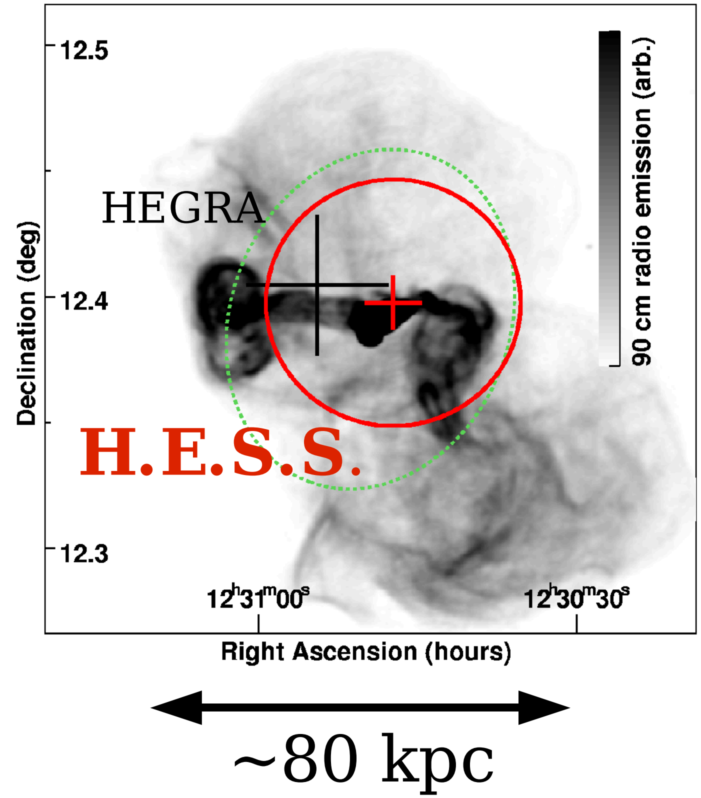


Measured photon flux not being explained by (only) χ annihilation (flux level & var.)

M 87: Seen at radio wavelengths



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



Resolving the kpc jet in the TeV γ-ray regime not possible

Cen A: One of the next possible candidates...

- Distance: 3.4 Mpc (z = 0.0018)
  $\Rightarrow$ even closer than M87!
- Jet angle: ~50° $\Rightarrow$ not a blazar!
- GeV/TeV γ-ray emission:
  - Evidence (>4σ) above 300 GeV
    [Grindlay et al. (1975), ApJ, 197, L9]
  - Predictions [Bai & Lee (2001), ApJ, 549, L173]
- H.E.S.S. observations (2004/2005):
  no signal in ~5h of data
  $I(E>190\ \text{GeV}) < 5.7 \times 10^{-12}\ \text{cm}^{-2}\ \text{s}^{-1}$
  (assuming photon index of $\Gamma = 3.0$)
- H.E.S.S. PSF similar to extension of the kpc jet!