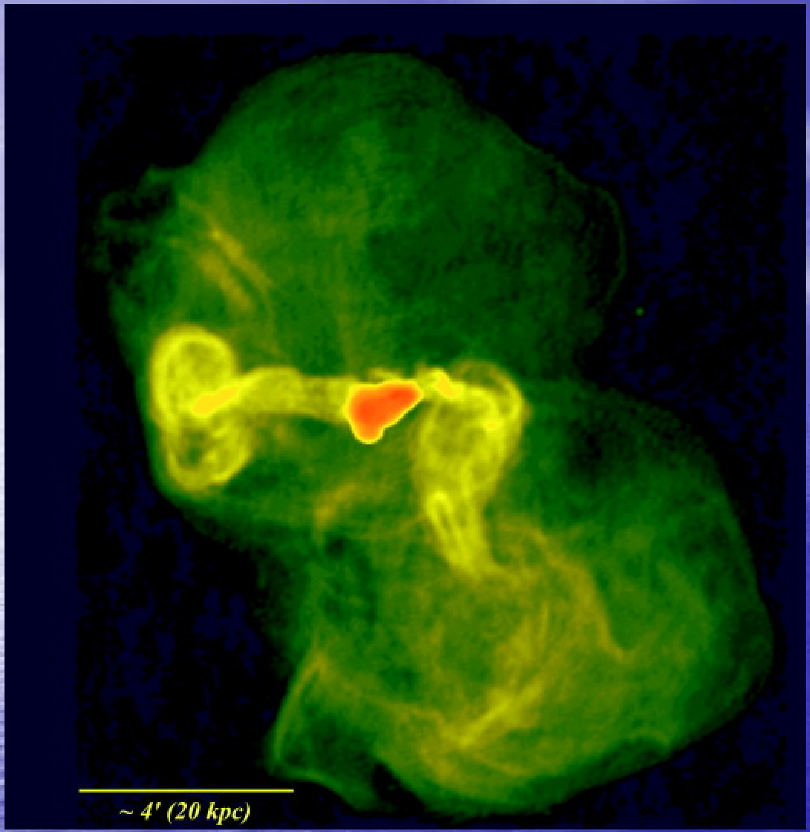
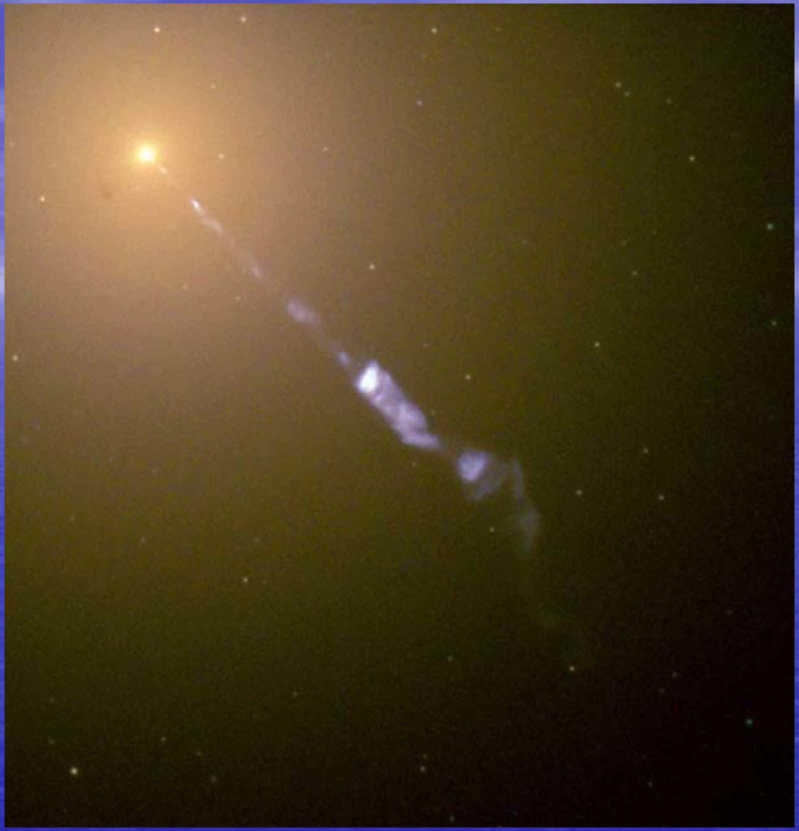


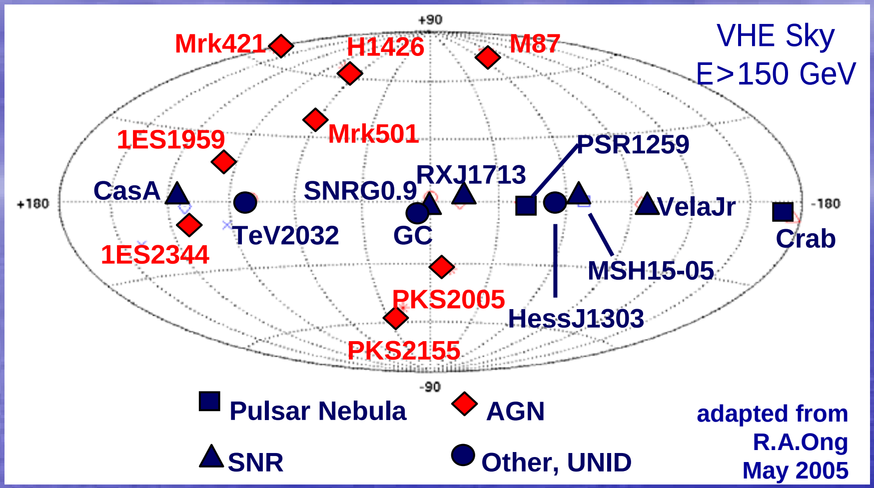


Gamma Rays from the Radio Galaxy M87

Outline

- The uniqueness of M87
- Overview and morphology
- Gamma-ray Observations
- Models for gamma-ray emission
  - Leptonic
  - Hadronic
  - Production of UHECRs
- Observational distinctions between models

What's so special about M87?

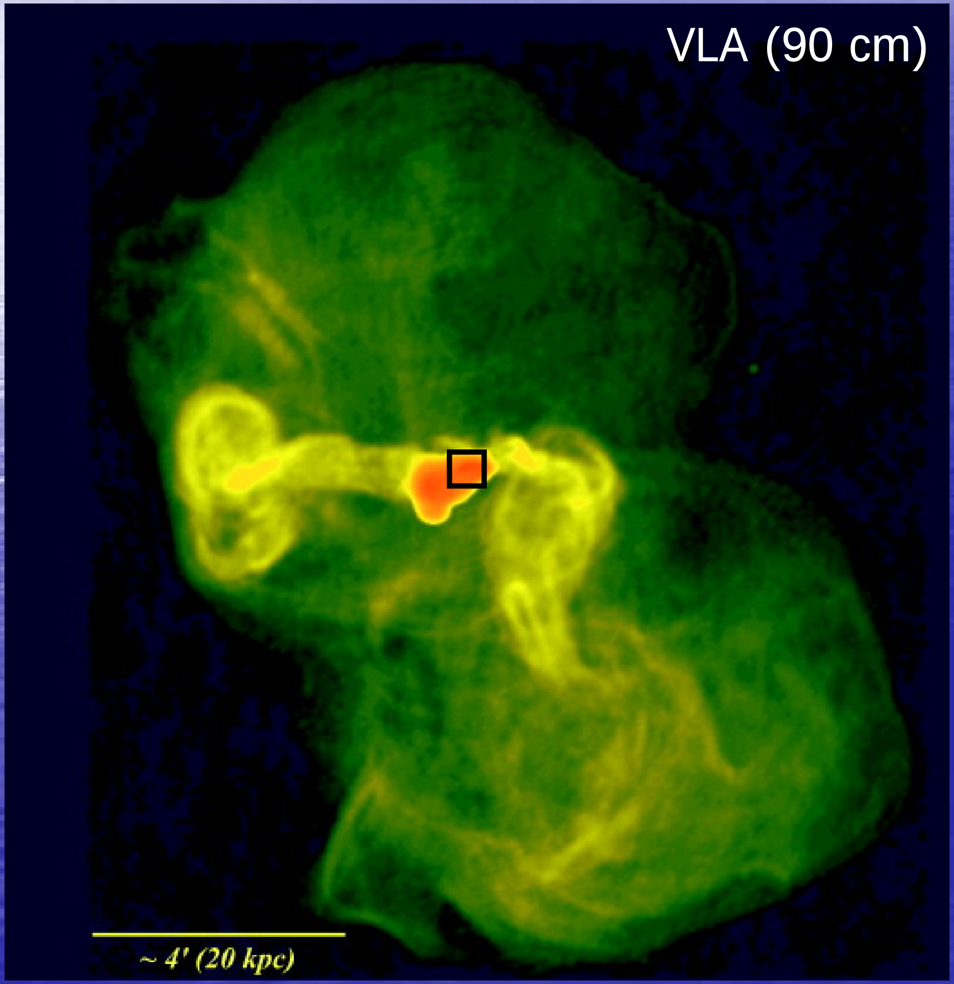


- VHE Cherenkov Telescopes: 8 AGN, 7 blazars + M87
- Doppler boosting intensifies gamma-ray emission in blazars
- What about M87?
  - Jet opening angle ~ 35°
  - Close
  - Low jet luminosity ~ 5×10^{44} erg s^{-1} $\Rightarrow$ less heating to surrounding gas, less γ ray attenuation

Morphology

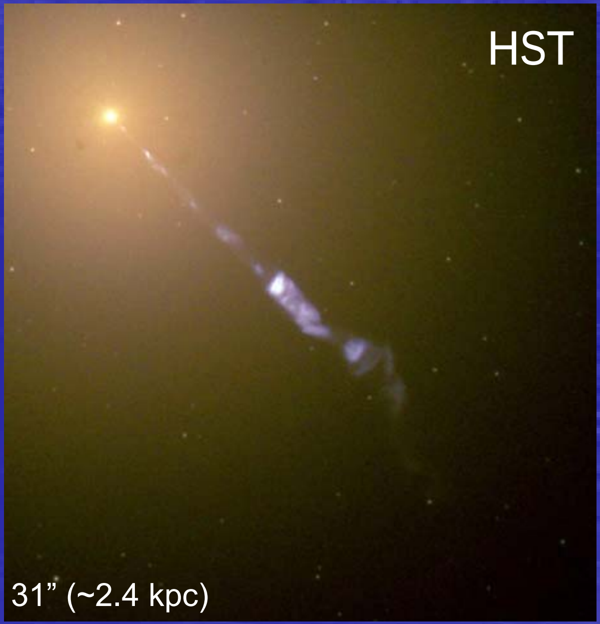
- Center of Virgo cluster
- Distance ~ 16 Mpc
- $M_{BH} = 3 \times 10^9 M_\odot$

Large-scale jets & radio halo



Owen, Eilek, & Kassim 2000

2 kpc jet



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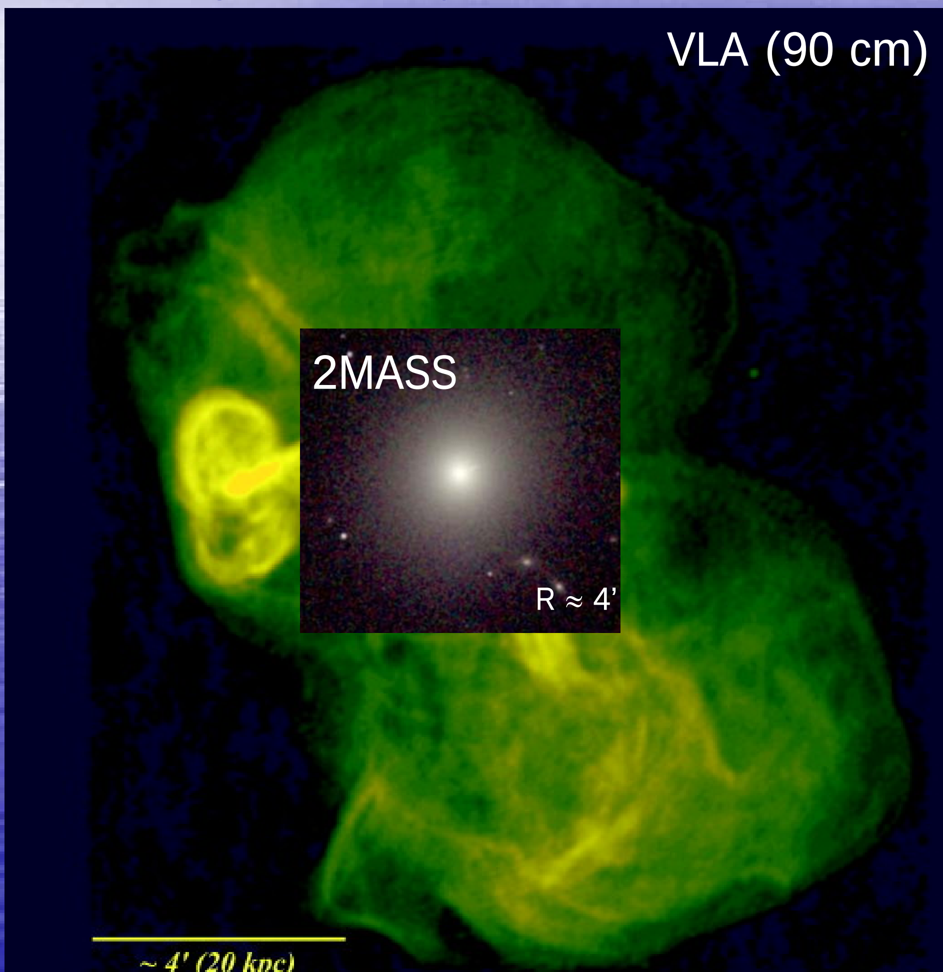

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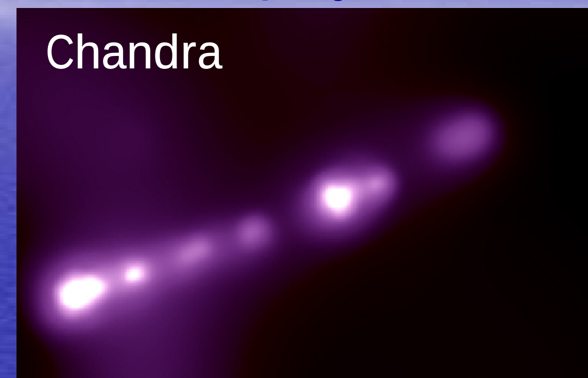
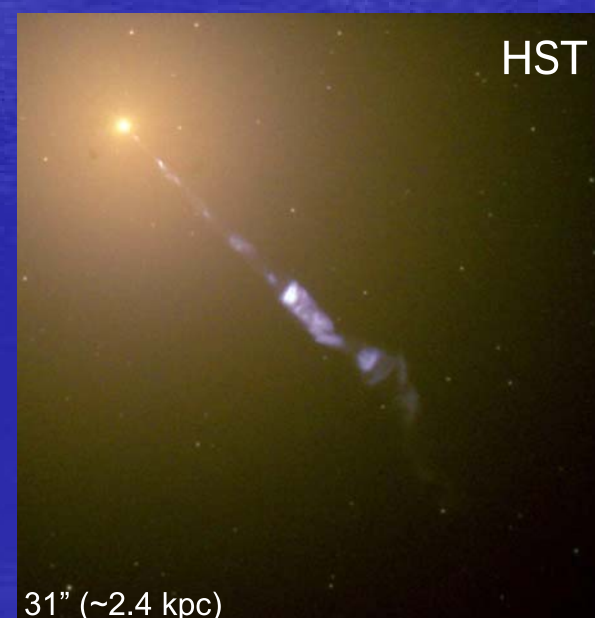
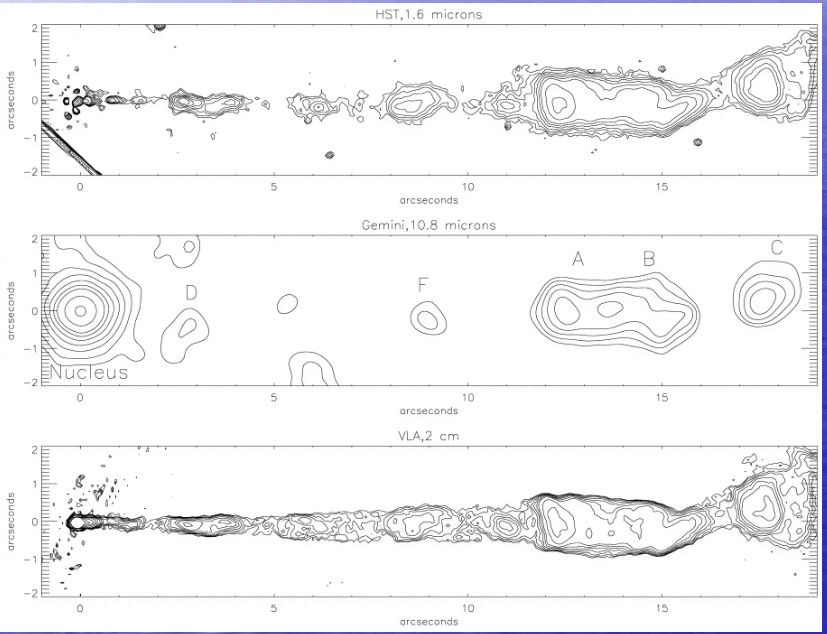
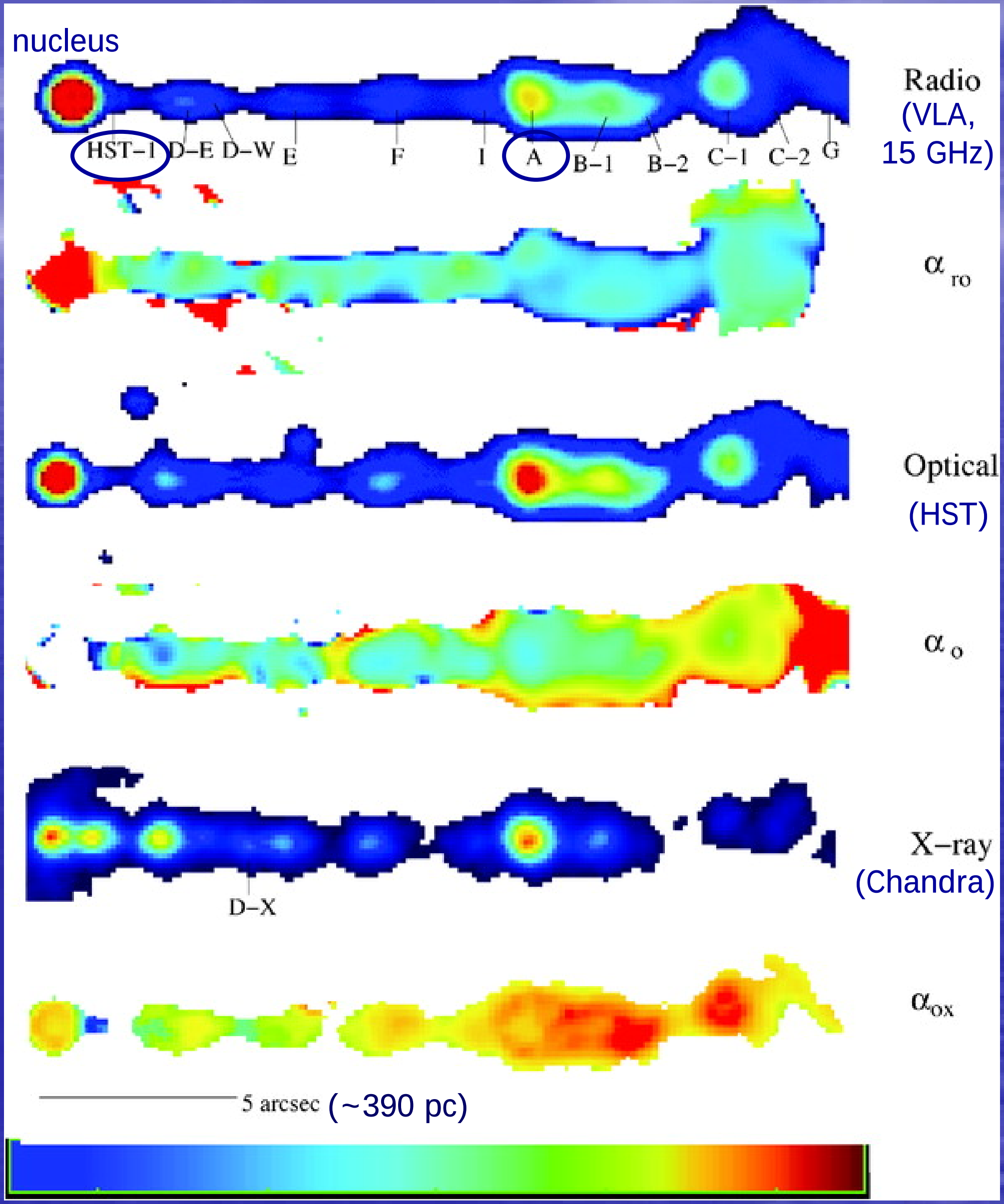




Morphology of central region

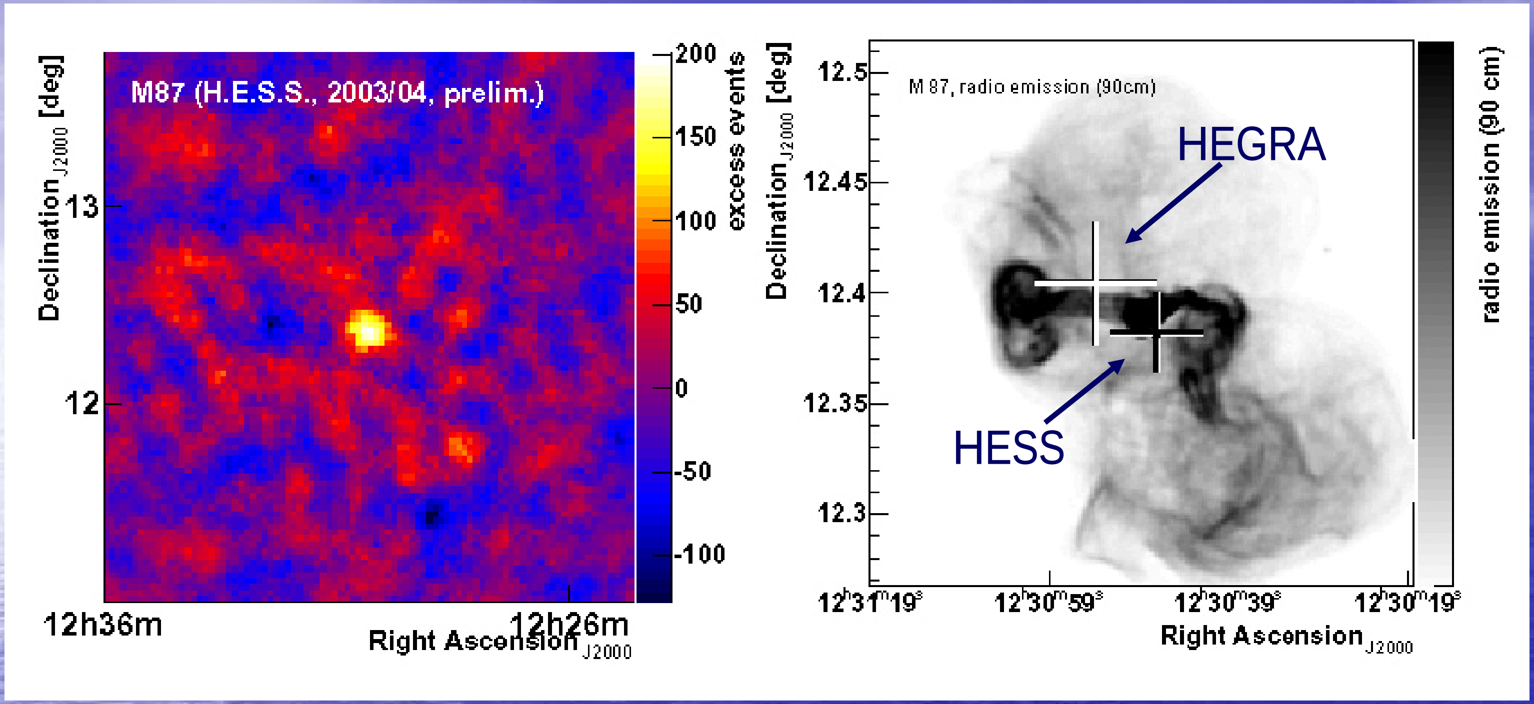




Summary of Gamma-ray Observations

- Upper limits:
  - EGRET: F(> 100 MeV) < 2.2 × 10^{-8} cm^{-2} s^{-1}
  - Whipple 2001-03: F(>250 GeV) < 2.6 × 10^{-11} cm^{-2} s^{-1}
    (Lebohec *et al.* 2001)
- HEGRA 1998-99: F(>730 GeV) = 0.96 × 10^{-12} cm^{-2} s^{-1}
  (Aharonian *et al.* 2003)
- HESS 2003-04:
  - 211 ± 38 events
  - Energy threshold: 160 GeV
  - F(>730 GeV) ~ 0.2-0.5 × 10^{-12} cm^{-2} s^{-1}
  - 2005 data analysis underway, >6σ detection

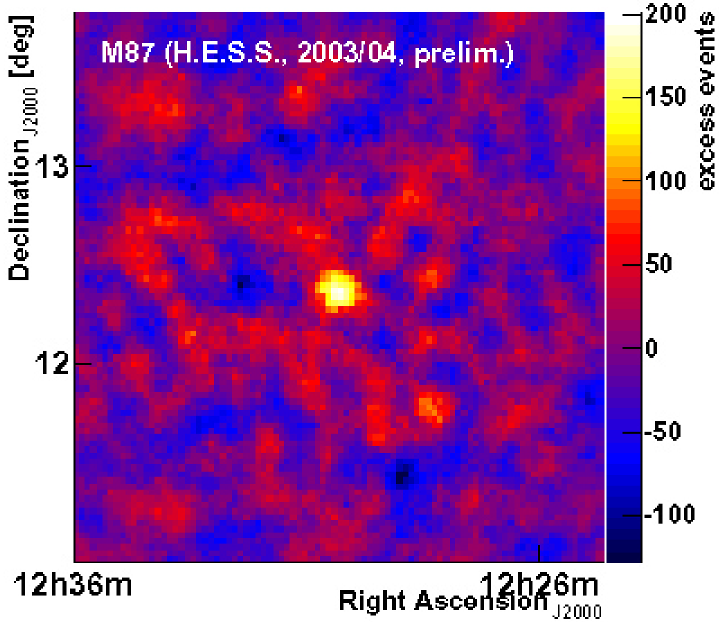
2003-04 HESS Observations

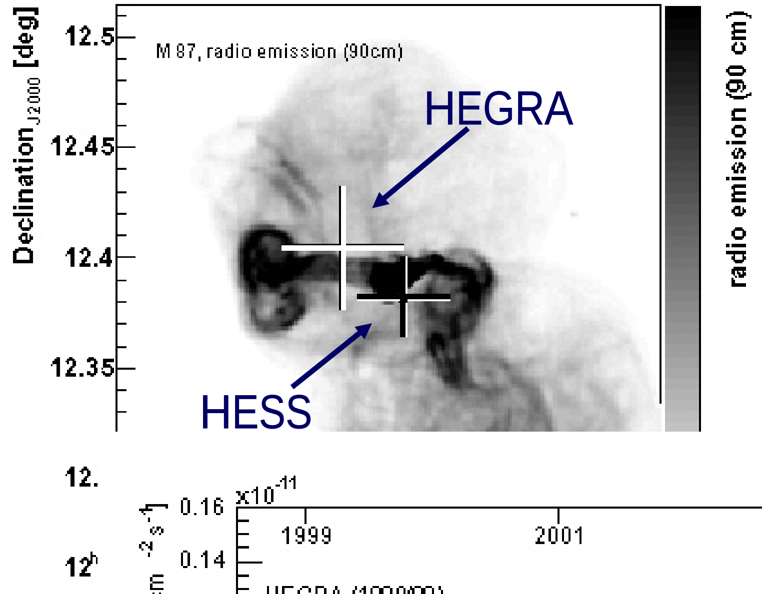


Consistent with point source from nuclear region

Beikicke *et al*. 2005

2003-04 HESS Observations





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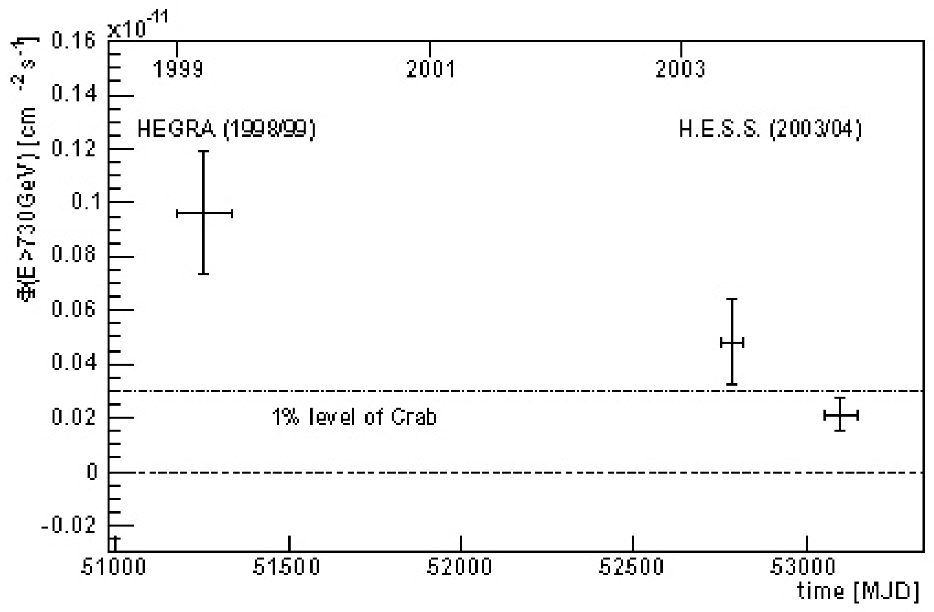
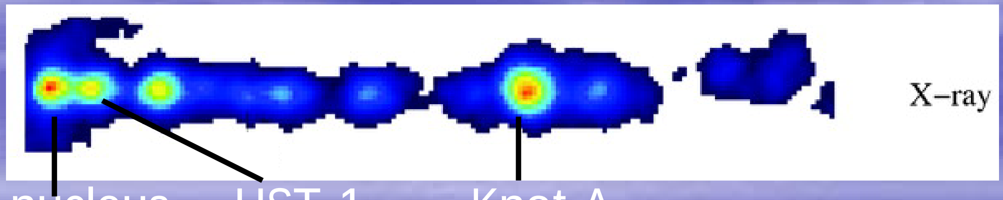


Evidence for variability

Beilicke *et al.* 2005

What is the source of the TeV emission?

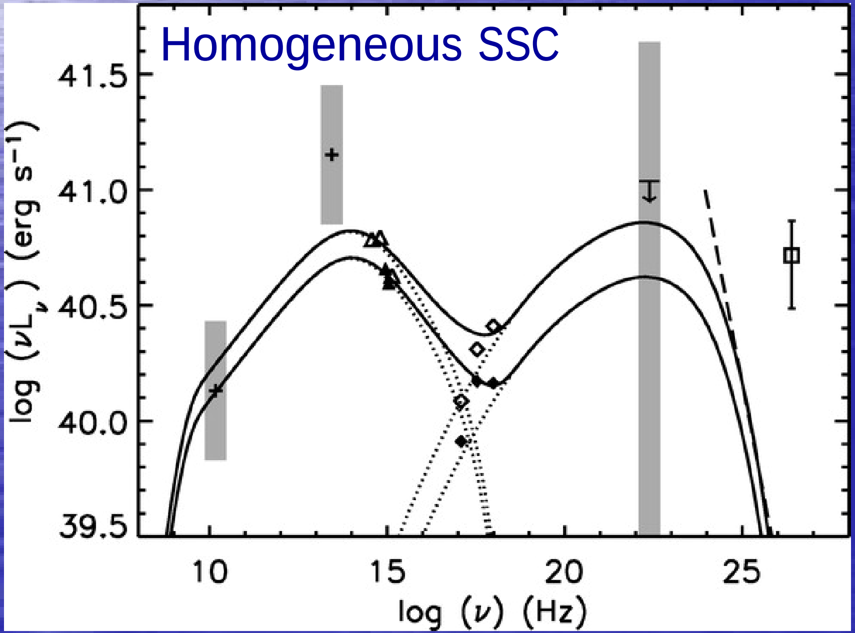


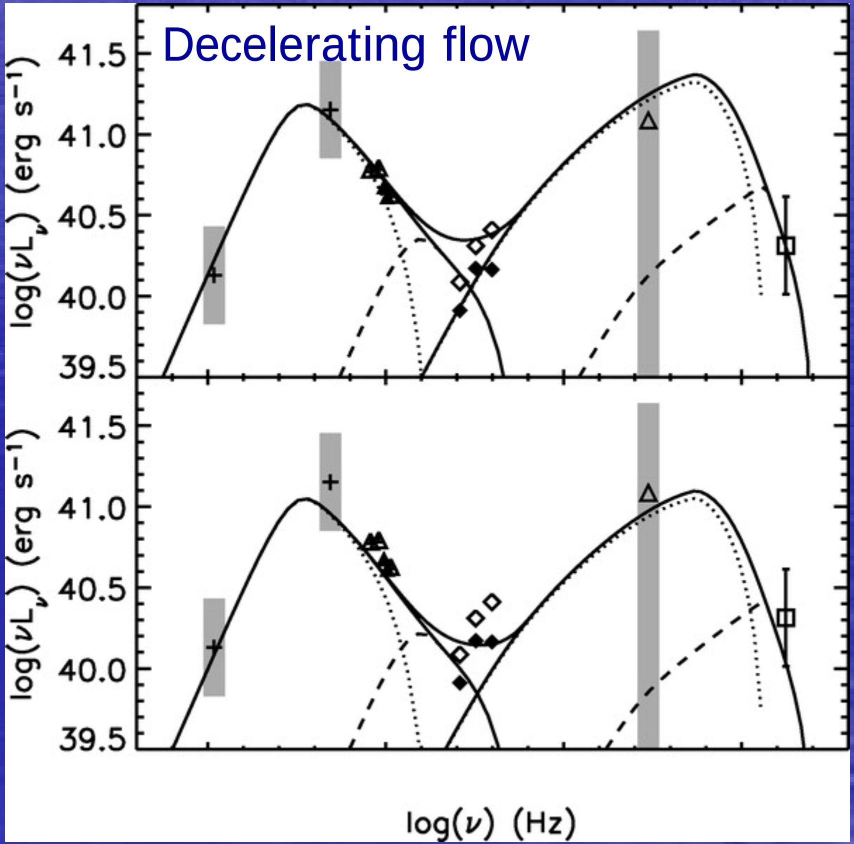
- Variability: flux dropped by factor of ~3 between 1998/99 and 2003/04
- Knot A
  - ~80 pc × 55 pc (projected) ⇒ Δt ~ few hundred years
  - Variability timescale too short
- HST-1
  - Increase in X-ray flux by factor of ~3 in spring of 2004
  - Increase by factor of ~50 between 1999 and 2004 (Harris *et al.* 2005)
  - No evidence for increase in TeV observations
  - Lack of coordinated variability ⇒ no TeV emission
- Leptonic model for nuclear emission...

Georganopoulos, Perlman, & Kazanas 2005

Leptonic Model for Nuclear Emission

- Homogeneous SSC model fails for HE emission
- Decelerating flow model:
  - sub-pc deceleration
  - from Γ_0 = 20 to Γ = 5 over 3 × 10^{17} cm (0.1 pc)
  - Beaming is frequency-dependent
  - "Upstream Compton" scattering





Georganopoulos, Perlman, & Kazanas 2005

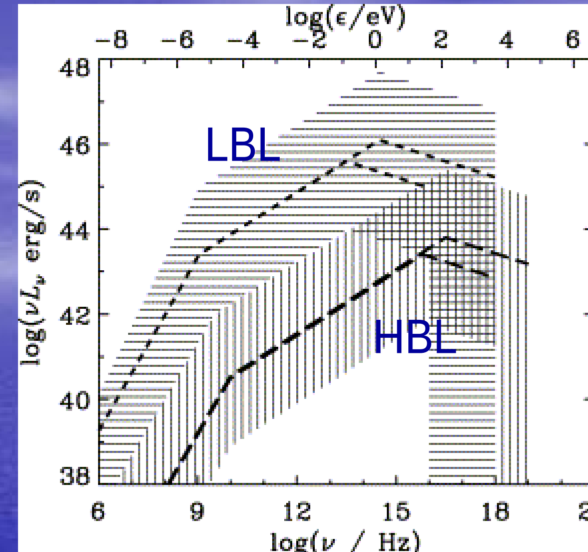
Synchrotron Proton Blazar (SPB) Model

- Blob of material moving relativistically along jet axis
- p & e^- accelerated across shocks
- Power-law distribution of protons in high B (~5-50 G)
- $\gamma_p \sim 10^{10-11} > 10^8 \Rightarrow$ pion production
- Gamma-ray production from:
  - Proton-photon interactions:
    - $\pi^0 \rightarrow 2\gamma$
    - $\pi^\pm \rightarrow \mu^\pm + \nu_\mu$
      - $\mu^\pm \rightarrow e^\pm + \nu_\mu + \nu_e$
  - $e^\pm$ cascades ($2\gamma \rightarrow e^\pm \rightarrow 2\gamma$ ...)
  - $\pi^\pm$ & $\mu^\pm$ synchrotron radiation
  - p synchrotron radiation
- Low-energy hump from e^- synchrotron

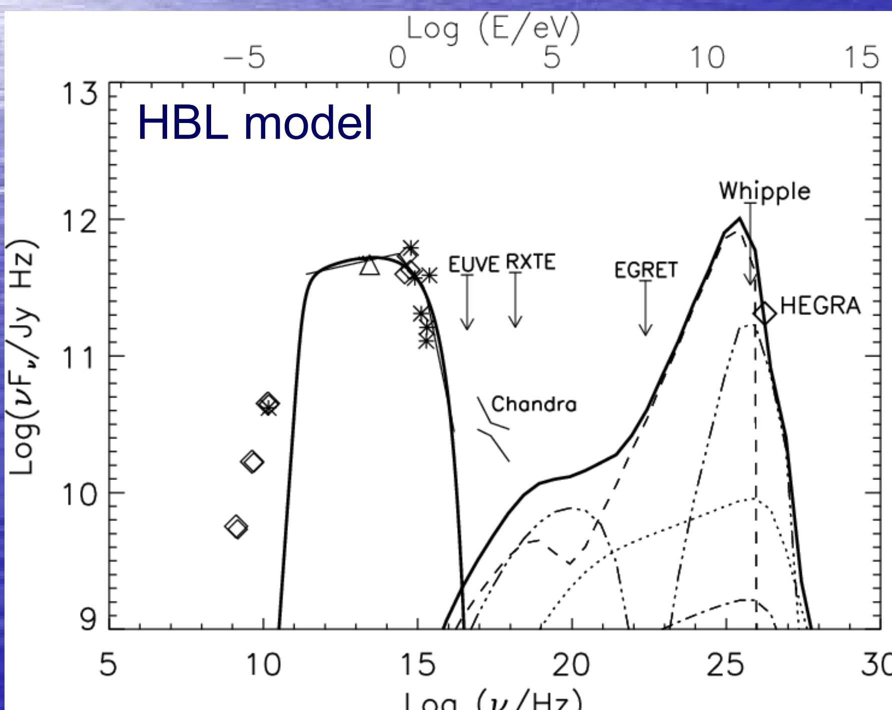
Mücke *et al.* 2003

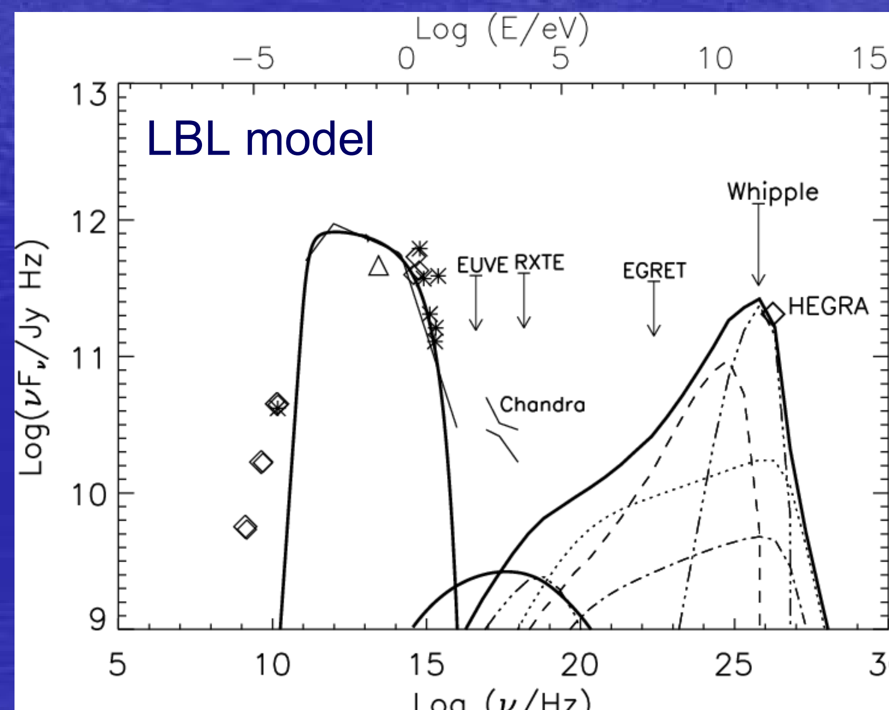
SPB Model Results for M87

Protheroe, Donea, & Reimer 2003
Reimer, Protheroe, & Donea 2004



- Input spectra from average SEDs
- Non-simultaneous data
- HE flux contributors:
  - p synchrotron (dashed)
  - $\mu^{\pm}$ synchrotron (dashed triple-dot)
  - π^{0} cascade (dotted)
  - $\pi^{\pm}$ cascade (dashed-dotted)





A Site for Cosmic Ray Acceleration

- In proton models, ultra-high-energy cosmic ray protons are produced by:
  - Direct acceleration at termination shocks of jets
  - Decay of neutrons produced in jets or accretion shocks outside galaxy: $p\gamma \rightarrow n\pi^+$
- UHECRs ($E > 10^{20}$ eV) attenuated by CMB (GZK cutoff)
  - At 3×10^{20} eV, MFP ~ 5 Mpc, energy loss distance ~ 20 Mpc
- UHECR detections claimed with $E > 10^{20}$ eV
- M87 is close enough to produce them
- Neutrons from M87 can account for observed flux “if the extragalactic magnetic field topology is favorable” (Protheroe, Donea, & Reimer 2003)

Observational Distinctions between Models

- Neutrino flux (difficult to detect!)
- Independent measure of B
- More simultaneous observations
- Larger sample of γ-ray sources
  - Tighter model constraints
  - GLAST?