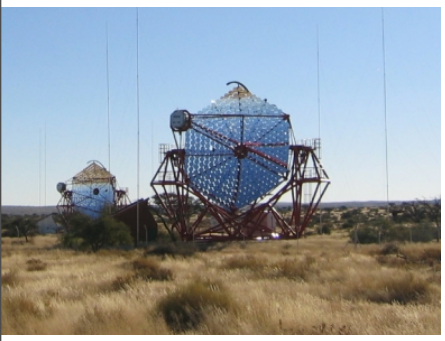
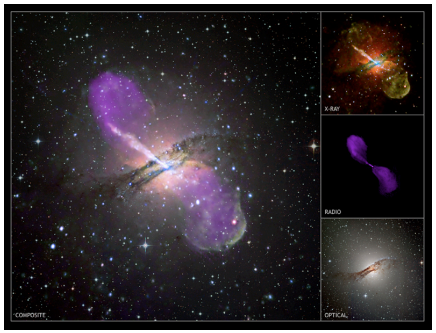
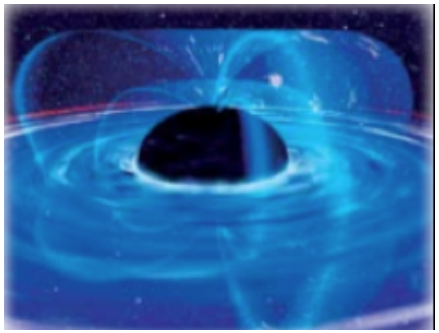
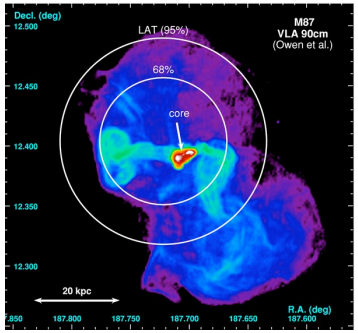
On the origin of VHE gamma-rays from radio galaxies

Frank M. Rieger

Gamma 2012
July 14th, 2012

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Orientation

_Warm-up

- Radio galaxy at HE and VHE

_Radio galaxies @ VHE

- Sources and observed VHE characteristics

_Variable VHE in M87 - theoretical interpretations

- Overview
- Magnetic reconnection & jet-star interactions
- Magnetospheric VHE emission

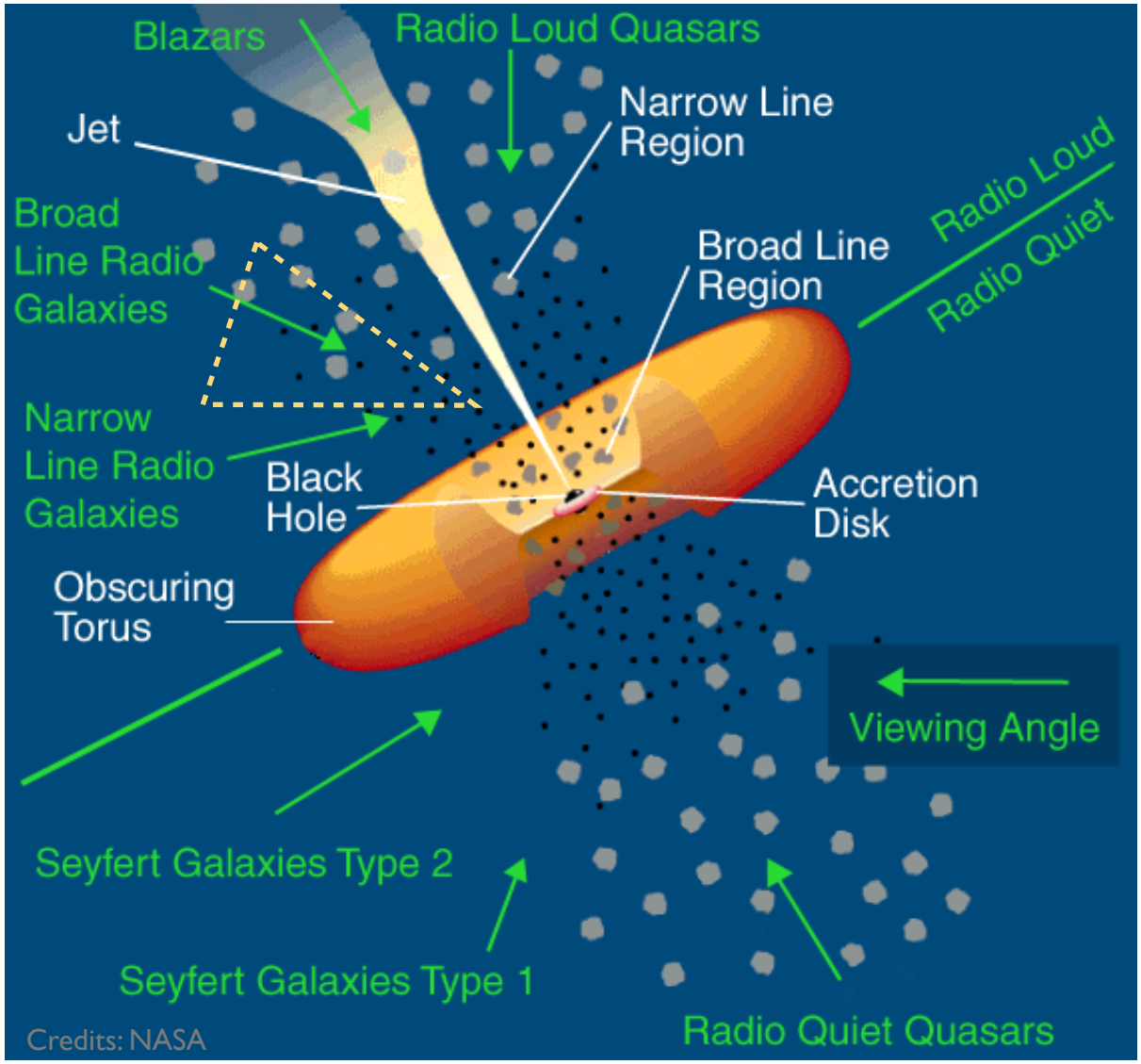
Based on two recent invited review papers:

(1) *Non-thermal Processes in Black-Hole-Jet Magnetospheres*, IJMPD 20 (2011), 1547-1596

(2) *Probing the central black hole in M87 with gamma-rays* (with F. Aharonian) Mod. Phys. Lett. A (2012), to appear

AGN unification - similar central engine

"...the wide variety of AGN phenomena we see is due to a combination of real differences in a small number of physical parameters (like luminosity) coupled with *apparent* differences which are due to observer-dependent parameters (like orientation)." (B. Peterson, AGN, CUP 1997)



TYPICAL PHYSICAL PROPERTIES:

Black Hole

$m \sim 10^8\ M_{sun}$

Accretion disk (SS):

$r \sim (10^{-2} - 10^{-3})$ pc

$n \sim 10^{14}\ r^{-3/2}\ cm^{-3}$

$kT \sim 30\ eV\ r^{-3/4}$

$v \sim 0.4\ c$ *(at inner edge)*

Broad line region (BLR):

$r \sim 0.01\text{-}0.1$ pc

$n \sim 10^{10}\ cm^{-3}$ *(forbidden lines collisional suppressed)*

$v \sim (10^3\text{-}10^4)$ km/s

$T \sim 10^4$ K

Torus:

$r \sim 1$ up to several 10 pc

$n \sim 10^3 - 10^6\ cm^{-3}$

$T \sim$ cold

Narrow Line region (NLR):

$r \sim 100\text{-}1000$ pc

$n \sim 10^3\text{-}10^5\ cm^{-3}$

$v \sim$ a few 100 km/s

$T \sim 10^4$ K

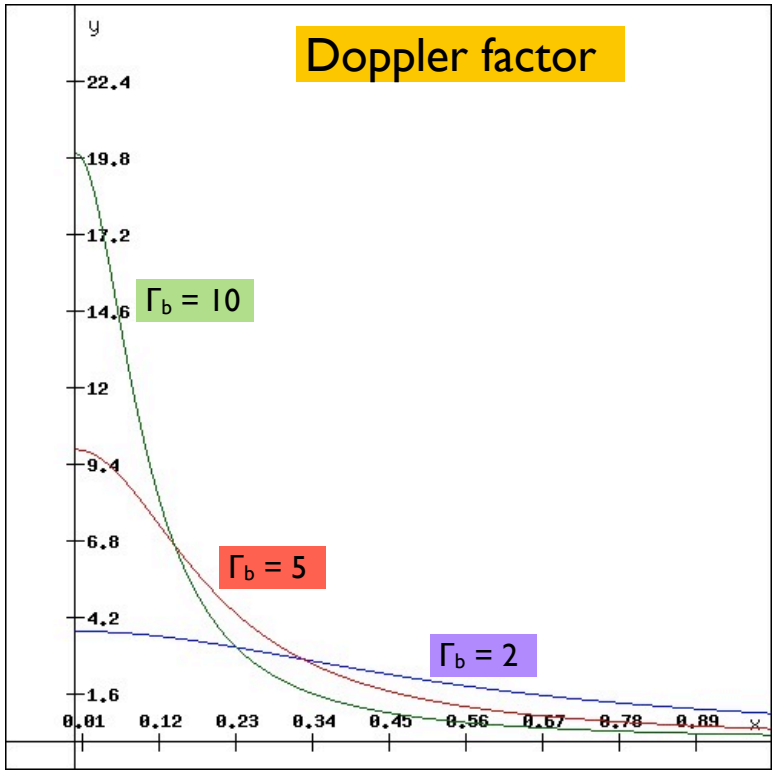
Doppler boosting of emission

If emitting region moves relativistically, observed features appear boosted:

Doppler factor: $$D = \frac{1}{\Gamma_b(1 - \beta_b \cos\theta)}$$

- spectral flux enhancement: $S(\nu) = D^3 S'(\nu')$
- energy/frequency shift: $\nu = D \nu'$
- time variability: $\Delta t = \Delta t' / D$
- ...

may expect to see some radio galaxies in HE with FERMI, but not much in TeV, if emission is (misaligned) BL Lac-type (SSC)



10° 20° 45°

Fermi-LAT & VHE detection of misaligned radio galaxies

out of ≥ 886 AGN ("Clean" sample): ≤ few %

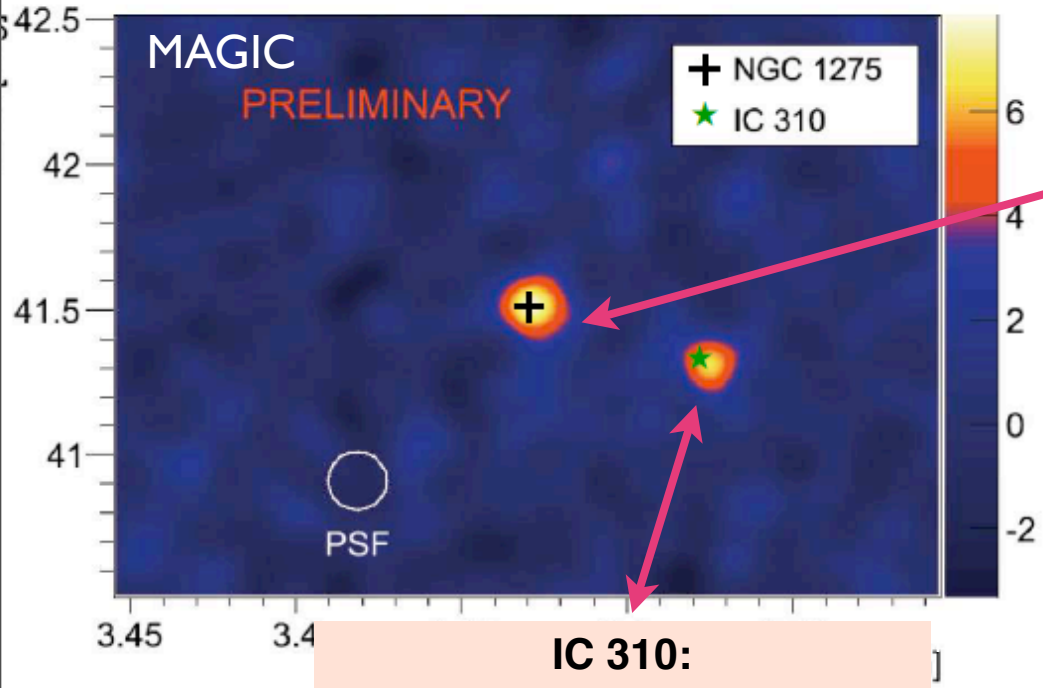
Name	Type	Distance	MeV/GeV detection	**VHE**	Notes
Cen A	FR I	3.7 Mpc	EGRET, LAT 2010	✔	Fermi: Core/lobes
M87	FR I	16 Mpc	LAT 2009	✔	TeV 1d-variability
Fornax A	FR I	18 Mpc	LAT 2011		
Cen B	FR I	56 Mpc	LAT 2011		
NGC 1275	FR I	75 Mpc	LAT 2009	✔	**; jet precession; LAT days-variability***
IC 310	FR1 head-tail	80 Mpc	LAT 2010	✔	Neronov+2010; VHE yr-variability
NGC 6251	FR I	106 Mpc	EGRET, LAT 2010		
3C 78	FR I	124 Mpc	LAT 2010*		
3C 120	FR I	142 Mpc	LAT 2010*		BLRG
3C 111	FR 2	213 Mpc	EGRET, LAT 2010*		BLRG
PKS 0943-76	FR 2	1360 Mpc	LAT 2010		
.....					

Nolan+2012 (Fermi-LAT); Ackermann+2011 (Fermi-LAT); Abdo+ 2010; Cheung 2011 (Fermi Symp.); Neronov+2010, A&A 519

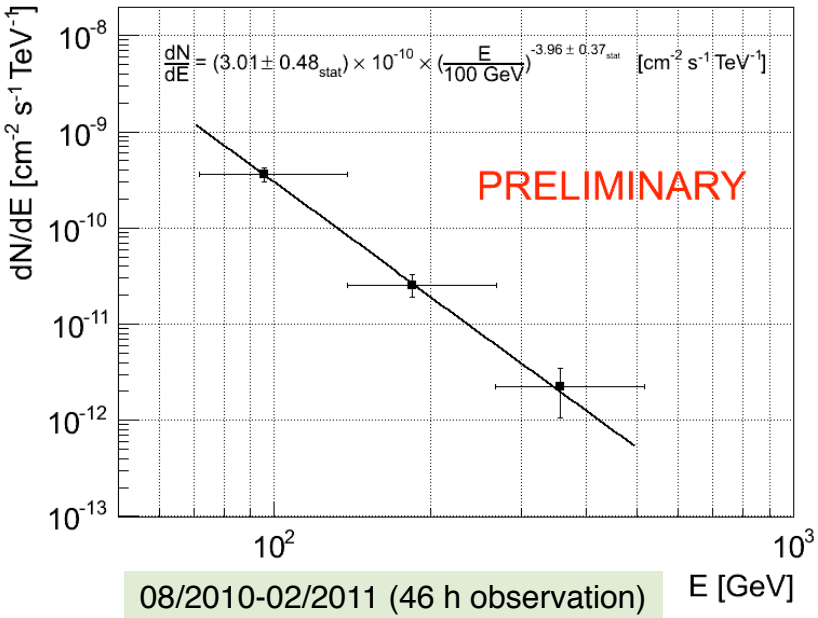
* only in 1st LAT AGN catalog (missing in 2LAC/2FGL)
** Atel #2916 (MAGIC): detected above 100 GeV with 5 σ, steep spectrum, no signal above 400 GeV;
*** Brown & Adams 2011, MNRAS 413: in two yr LAT data

Radio galaxies @VHE

Perseus Cluster Radio Galaxies: *IC 310* and *NGC 1275* (d~75 Mpc)

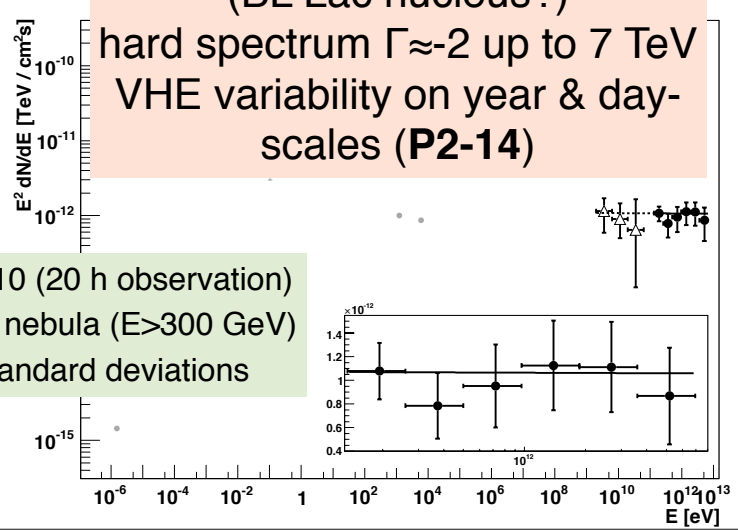


NGC 1275:
VHE seen during enhanced HE LAT activity
Very steep VHE spectrum **Γ** ≈ -4.0
No signal above ~600 GeV



08/2010-02/2011 (46 h observation)
3% Crab nebula (E>100 GeV)
6.6 standard deviations

IC 310:
Head-tail radio galaxy
(BL Lac nucleus?)
hard spectrum Γ≈-2 up to 7 TeV
VHE variability on year & day-scales (**P2-14**)



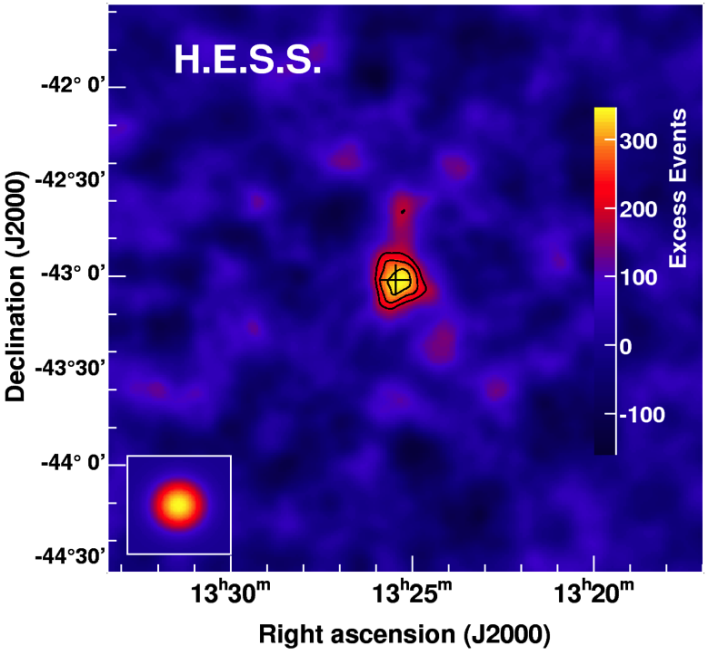
2009/2010 (20 h observation)
3% Crab nebula (E>300 GeV)
7.6 standard deviations

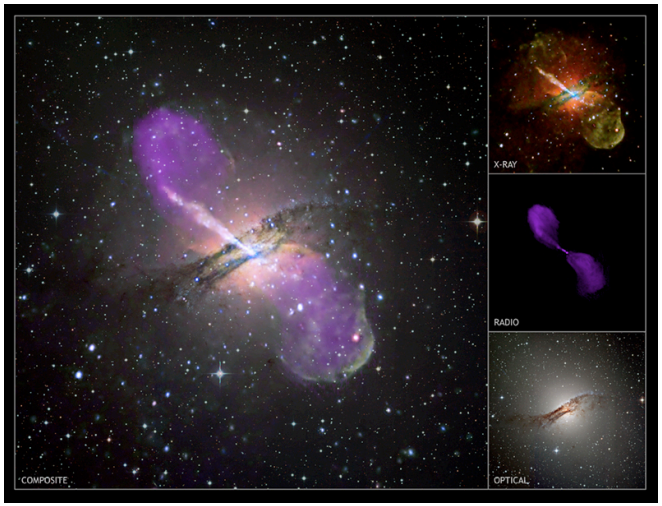
see talk by P. Colin

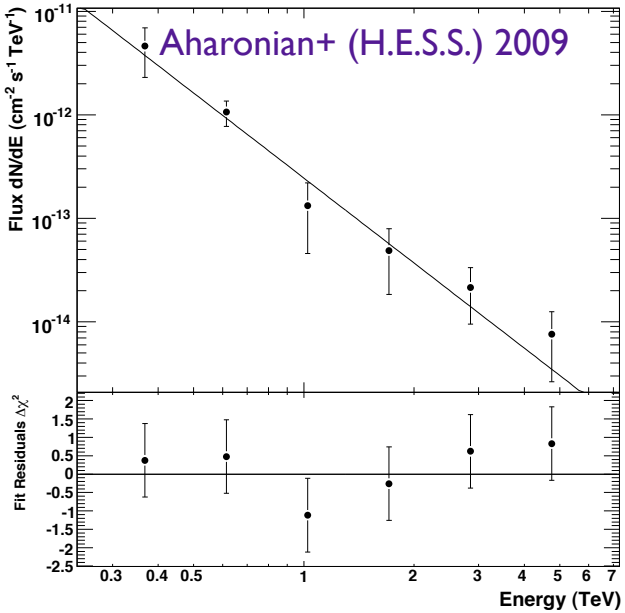
Hildebrandt+ (MAGIC Collab.) ICRC 2011
Aleksic+ (MAGIC) 2010+2012, ApJ

Radio galaxies @VHE

Nearest AGN: *Centaurus A* *(d≈3.7 Mpc)*







Source Properties

BH mass ≈ (0.5-1) x 10^8 M_{sun}

$L_{bol} < 10^{43}$ erg/s << L_{Edd} (quasar SED)

jet velocity ~ 0.5c

jet inclination (VLBI) > 50°, modest beaming!

complex radio morphology (jets, lobes etc)

hybrid disk configuration (no bbb)

H.E.S.S.: TeV γ-rays from the core

2004-2008 (>100h observation), 5σ detection

VHE from 300 GeV - 5 TeV

hard spectrum (Γ≈ -2.7±0.5)

isotropic L(>250 GeV) = 2.6 × 10^{39} erg/s

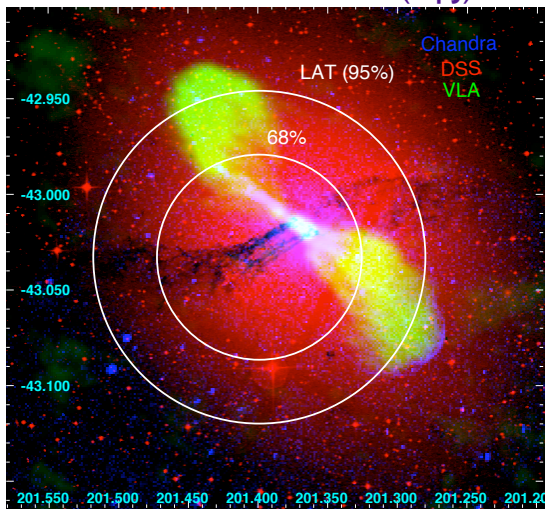
no significant variability detected (low flux)

Recap - Cen A @ high energies

Fermi*: HE** from the ***core* (few kpc) of *Cen A

- detected at 4 σ up to 10 GeV (10 months data)
- step spectra (photon index -2.7)
- isotropic L(>100 MeV) = 4 × 10^{40} erg/s
- light curve consistent with no variability (15d bins)

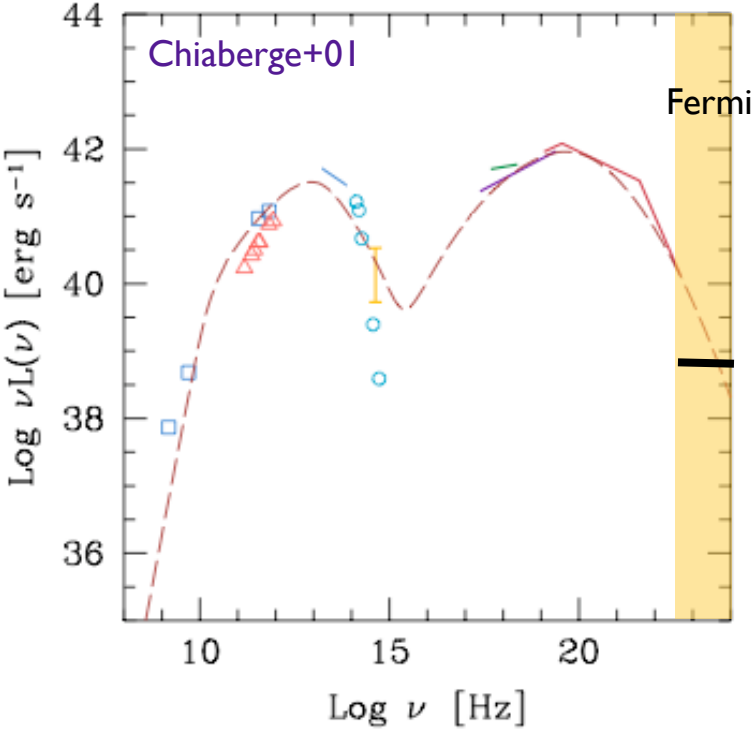
Abdo et al. 2010b (ApJ)



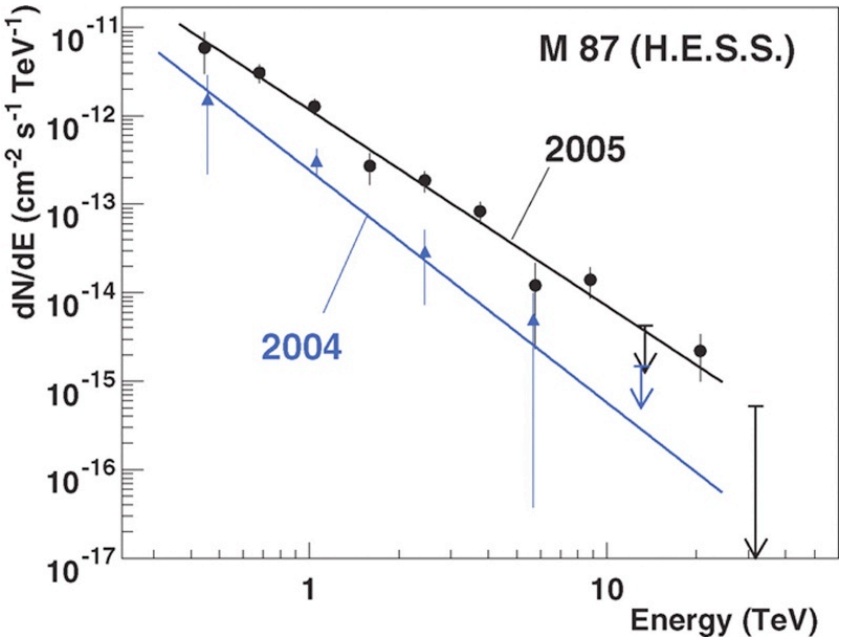
*For HE from **giant radio lobes**, see Yang+2012, A&A 542, poster* **P2-11**

Modeling (misaligned BL Lac)

- radio-GeV can be fitted with one-zone BL Lac type SSC assuming small Doppler factor (D=1.2) viz. large inclination angle (Chiaberge+ 2001)
- under-predicts TeV (even ignoring γγ-absorption)
- emergence of additional component at VHE? R+09, R+11



2nd nearest AGN: ***M87*** (d~16 Mpc)



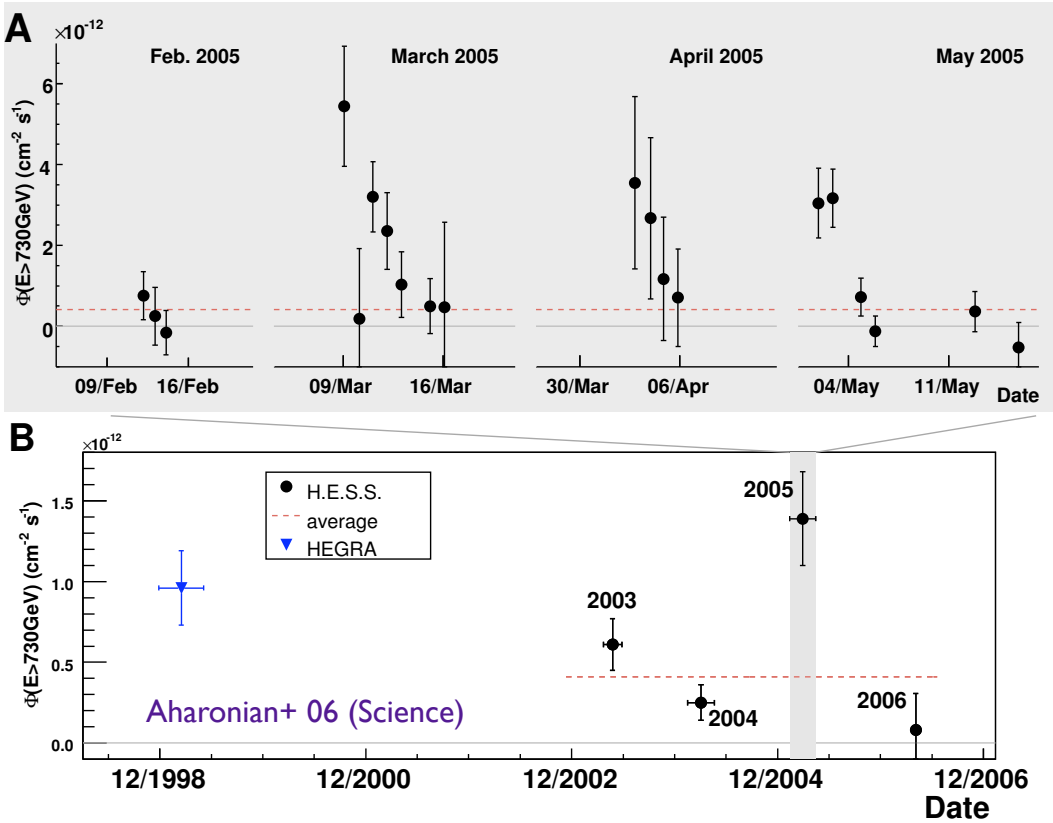
2005 VHE high state:

VHE spectrum beyond 10 TeV

hard spectrum ($\Gamma \approx -2.2$), hardening?

isotropic L(>730 GeV) $\approx 5 \times 10^{40}$ erg/s

rapid variability (timescale 1-2 day)



Source Properties

M_{BH}~ (2-6) $\times 10^9$ M_{sun}

L_{bol} ~10^{42} erg/s << L_{Edd}

L_{jet} ~ 5×(10^{42}-10^{44}) erg/s

one-sided, kpc-scale jet

jet inclination i ~(15-25°)

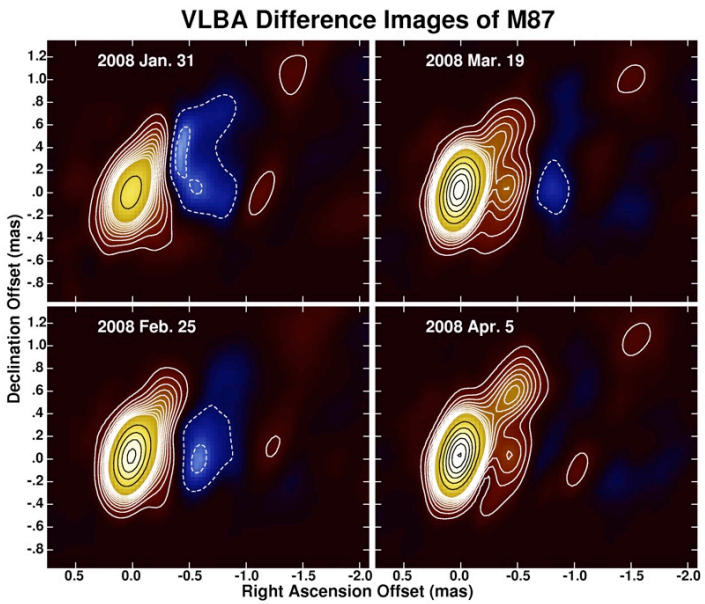
modest Doppler (D ~ 2)

M87 @VHE

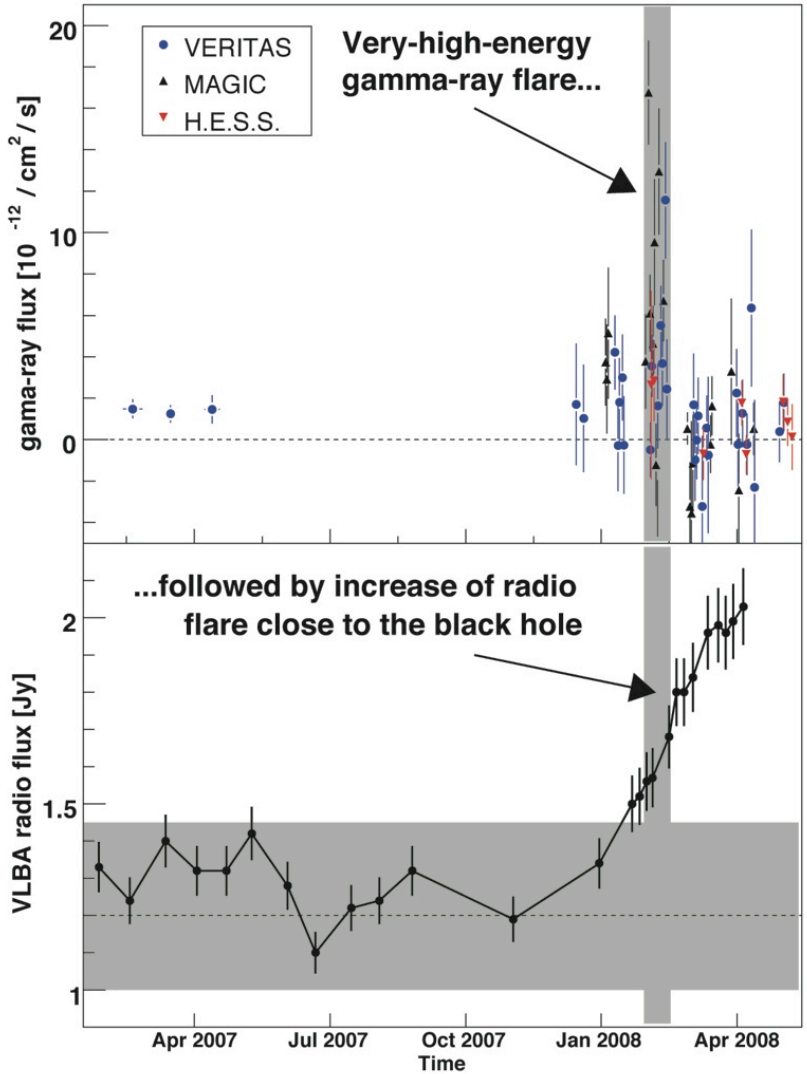
Feb. 2008 VHE flare:

mas radio (43 GHz) nucleus progressively brightened, suggestive of energetic particle injection close to BH

Day-scale activity implies compact zone



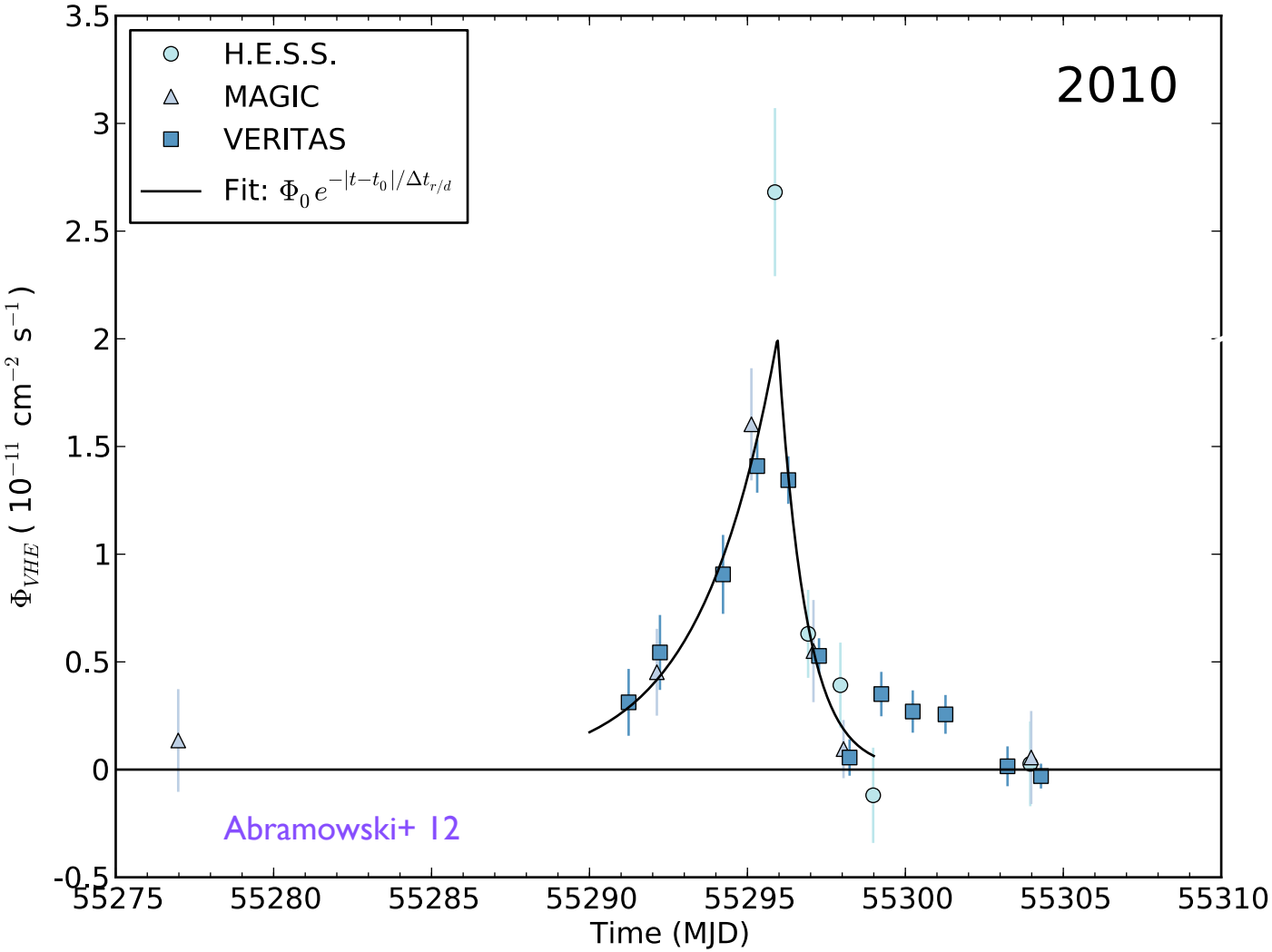
cf. IACT resolution~ 0.1° = 30 kpc



Acciari+ 09, Science 325

M87 @ VHE

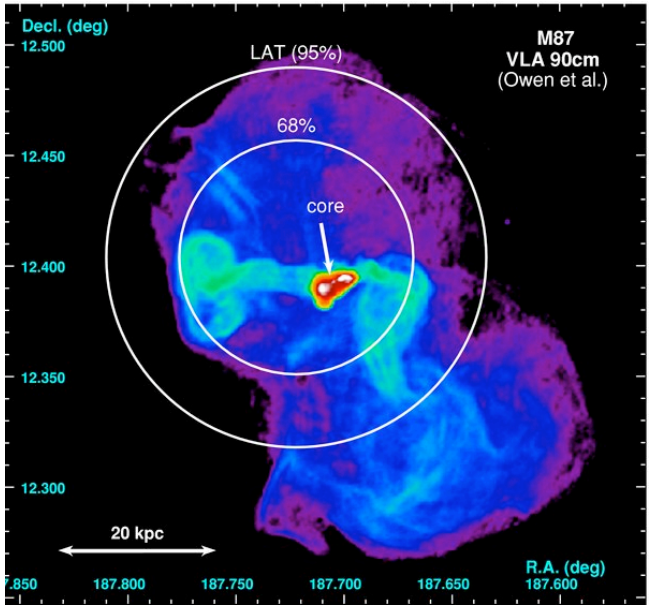
M87 during VHE flare in **April 2010**: well-defined rise and decline

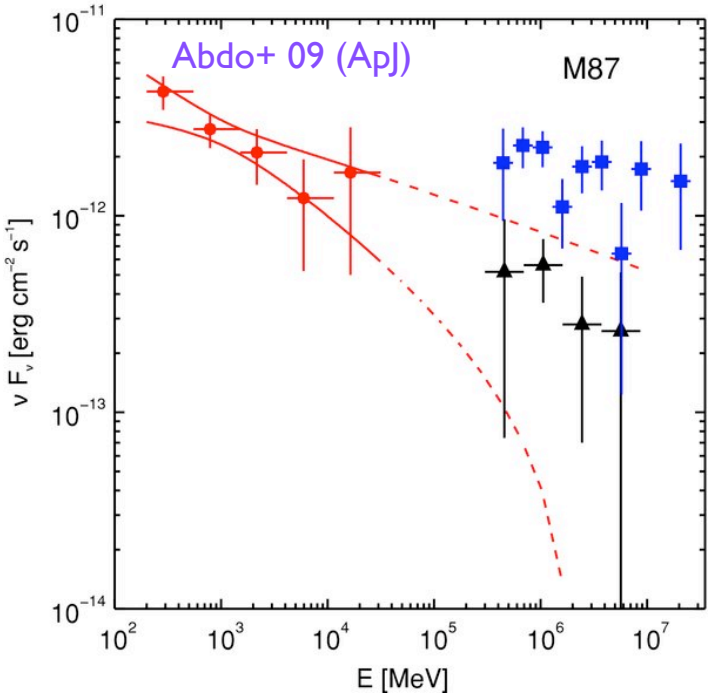


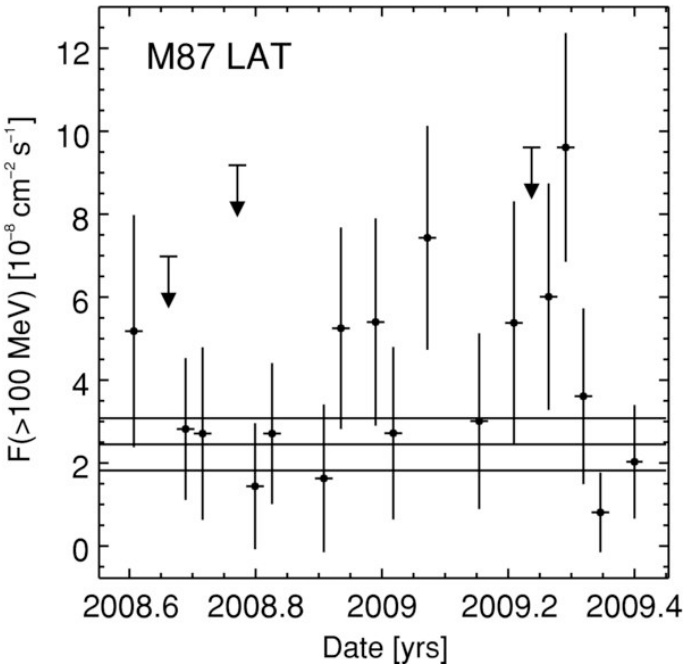
see also VERITAS poster **P2-26**

Recap - M87 @ high energies

- Detected up to 30 GeV in 10 months Fermi data (2008/09)
- Power-law photon index comparable to VHE (-2.2)
- isotropic L(>100 MeV) ≈ 5×10^{41} erg/s
- Detected light curve (10d bins) consistent with no variability



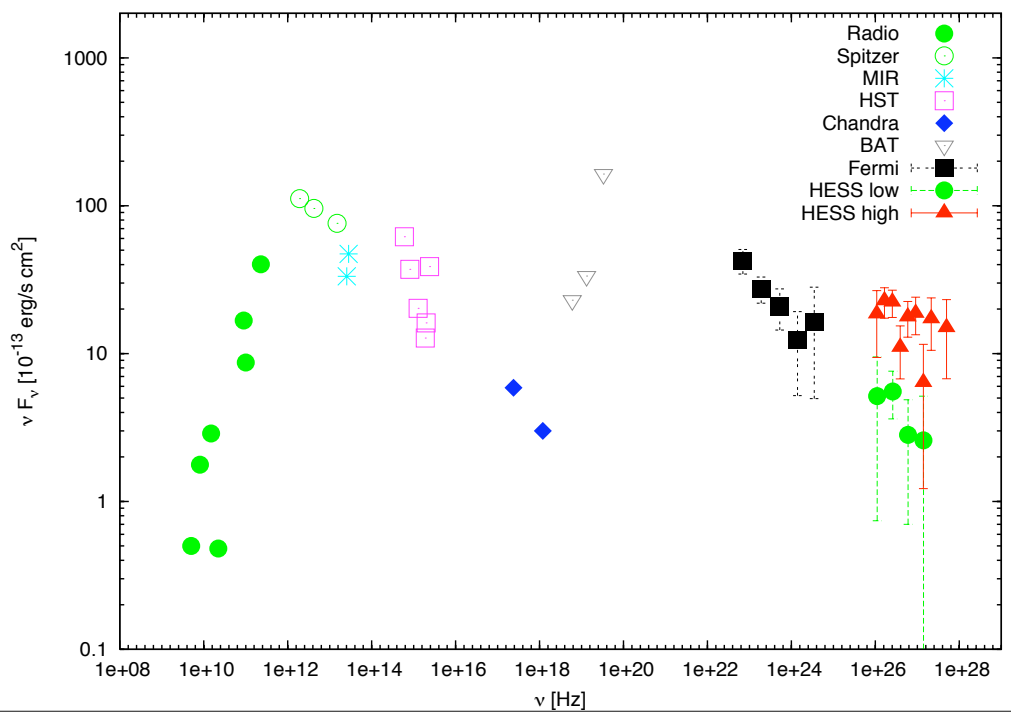


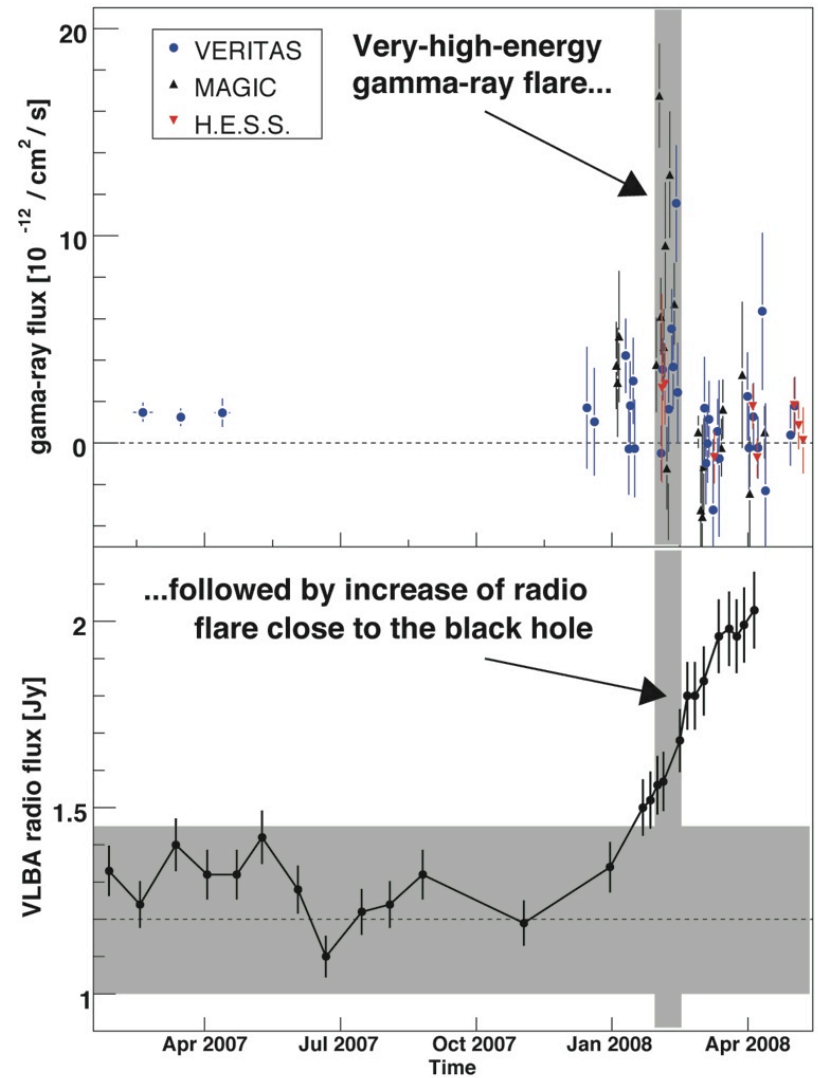


M87 @ VHE - Additional component at TeV?

Heuristic arguments:

- Fermi extrapolation cannot explain high TeV flux
(but perhaps normalization errors + variability)
- one-zone SSC (radio-GeV) cannot fit TeV high state
(also other "conventional" **misaligned** models)
- radio-TeV ('08) link suggests close BH origin
(with day-variability implying compact zone)

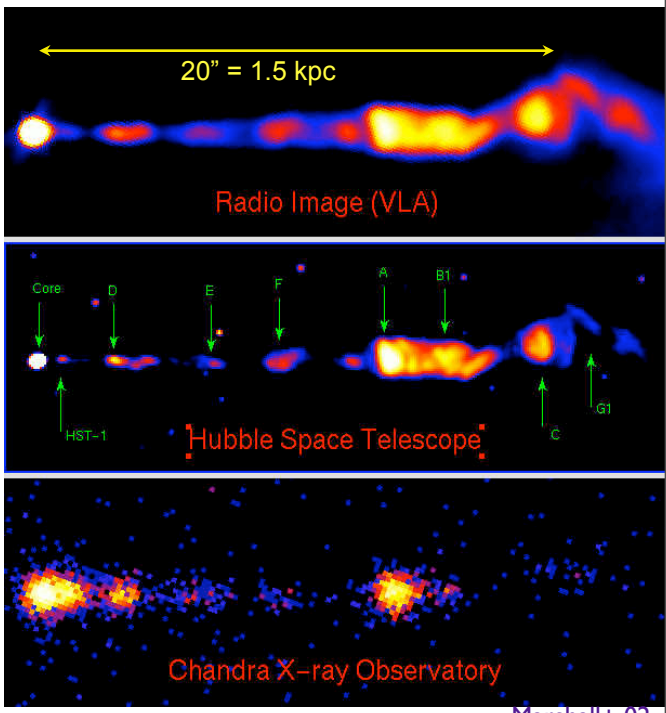




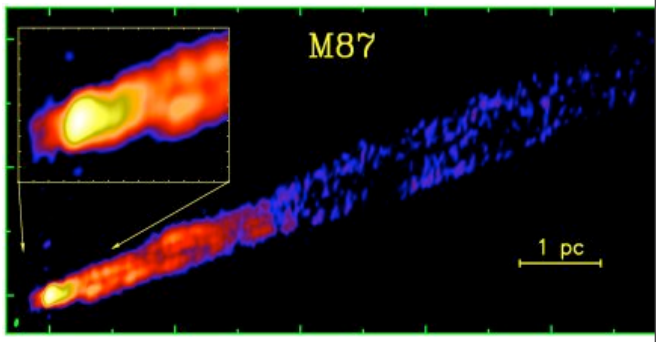
Acciari+ 09, Science 325

Variable VHE from M87 - possible interpretations

HST-1		EC starlight photons (e.g. Stawarz+06)
inner jet (sub-parsec)	leptonic	decelerating flow (e.g. Georganopoulos+05)
		spine-shear (e.g. Tavecchio+08)
		mini/multi-blobs (e.g. Lenain+08)
		reconnection (e.g. Giannios+10)
	hadronic	proton synchrotron & p-γ (e.g. Reimer+04)
		jet-star interactions / pp (e.g. Barkov+12)
		combined lepto-hadronic (e.g. Reynoso+11)
Magneto-sphere		rotational acceleration & IC (e.g. R & Aharonian+08)
		gap-type particle acceleration & IC (e.g. Levinson & R)



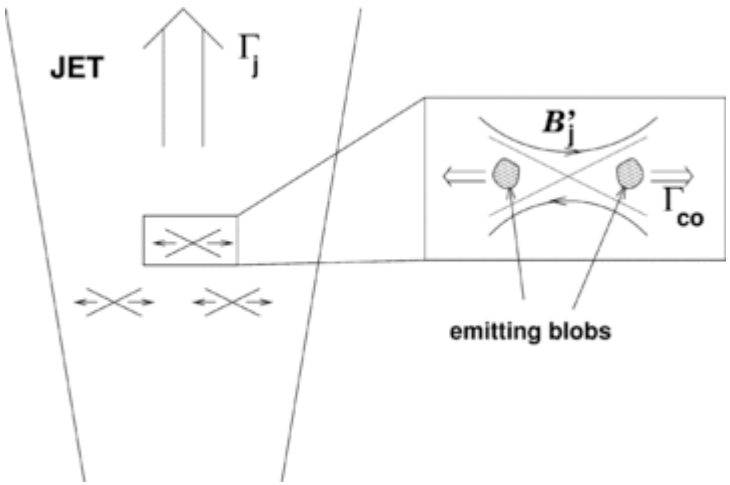
Marshall+ 02



VLBA @ 2cm: Kovalev+ 07

see R & Aharonian 2012 for details

I. Magnetic reconnection origin



Giannios+2009/2010

Jets-in-Jet / Minijets:

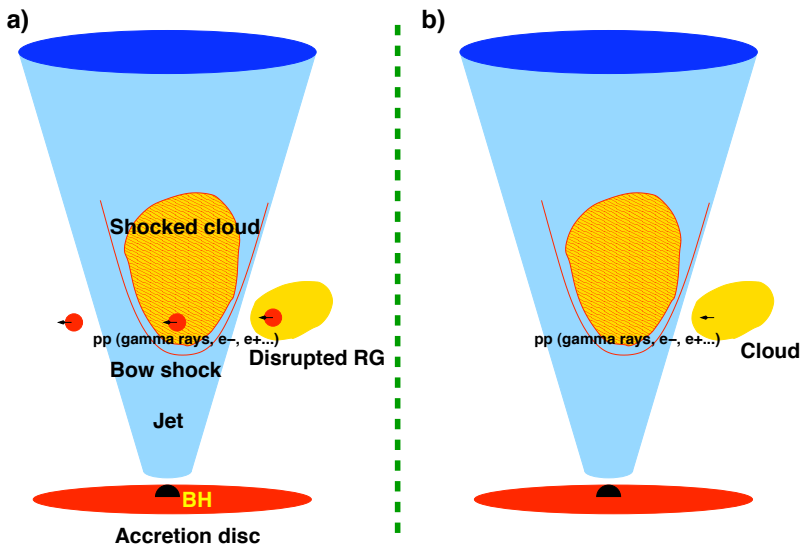
* highly magnetized e-p - jet ($\sigma \sim 100$)
* relativistic (Petschek-type) reconnection
* additional relativistic velocity ($\Gamma_c \approx \sqrt{\sigma}$) wrt mean flow
* *differential (strong) Doppler beaming possible*
* leptonic VHE: EC by accelerated electrons

Potential challenges ?

* lower magnetization for e-p AGN jets ($\sigma \sim 10$)?
* non-negligible guide field/weak dissipation only?
* power-law e-acceleration beyond 10^2-10^3 thermal Lorentz factor $\sqrt{\sigma}\, m_p/2m_e$?

see also talk by B. Cerutti

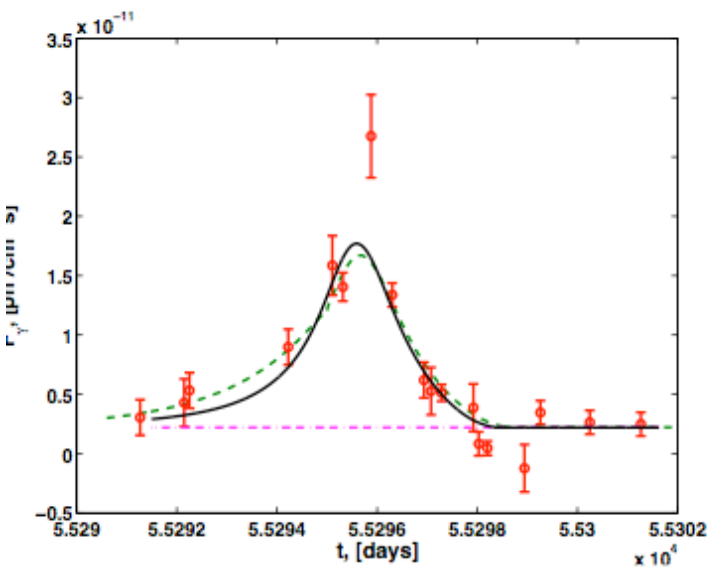
II. Jet-star/cloud (pp) origin



Jet-star/cloud interactions

* VHE due to hadronic/pp-interactions
* high target density introduced by star/cloud
* assume efficient (shock-type) particle acceleration
* explain lightcurve & spectrum

see poster **P2-27**

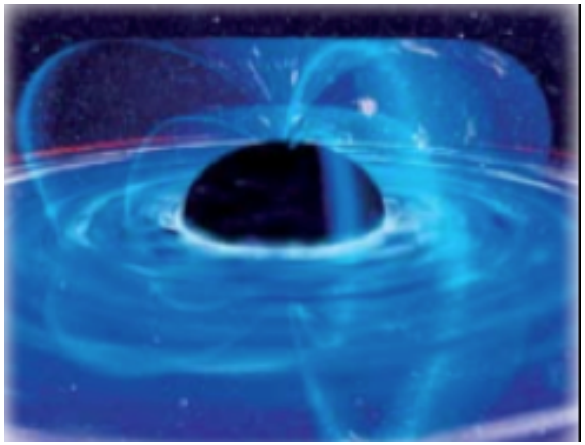


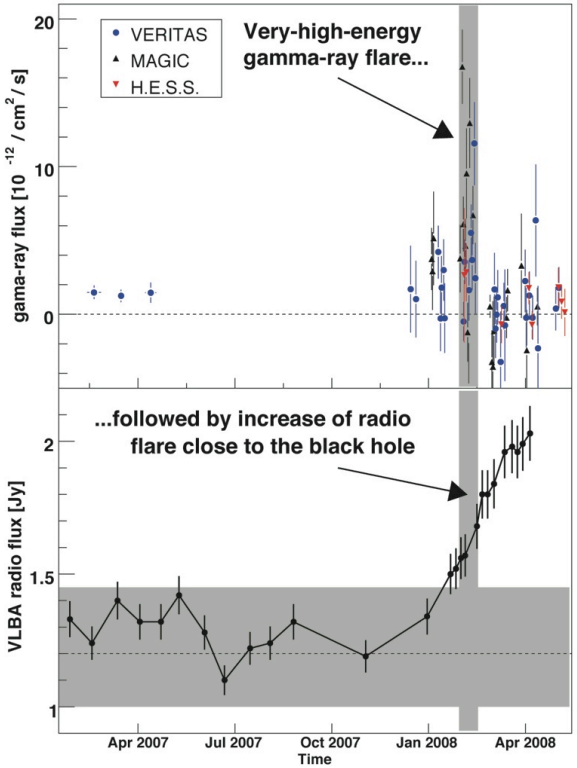
Barkov+2010/2012

Potential challenges ?

* wide observed radio jet opening angle, very large jet power required $L_j \propto L_{VHE} \times (r_j / r_c)^2$?

III. Magnetospheric origin





Possible contribution from BH-magnetosphere:

(Neronov & Aharonian '07; R. & Aharonian '08; Beskin '09; Levinson & R. '11)

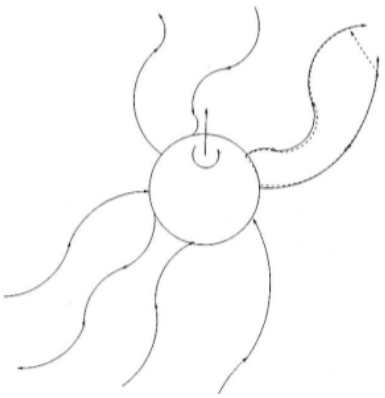
- *Idea:* TeV contribution from close to black hole (< few r_g)
  ➡ variability t_{var} ~ a few (r_g/c) > 0.2 d
- *Requires I:* VHE electrons ($\gamma_e \geq 10^7$) for IC
- *Requires II:* little $\gamma\gamma$-absorption below 10 TeV

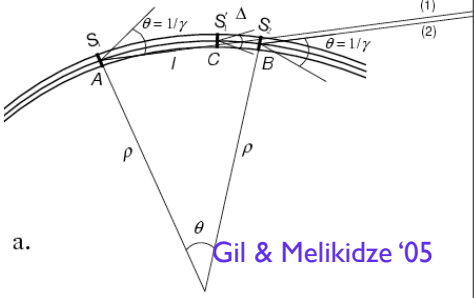
Additional component at TeV energies - HOWTO 1

Example - Gap-type **particle acceleration** in M87

(e.g., Levinson'00; Neronov & Aharonian'07; Levinson & R. '11; R. '11)

- similar to pulsars
- rotating **B** induces **E** = -(**Ω** x **r**) x **B**/c
- **E** supported by local charge density ρ_{GJ} =**∇•E**/4π (Poisson)
- if $\rho<\rho_{GJ}$, unscreened $E_{||}$ components ⇒ particle acceleration
- max. potential drop ~ 3×10^{19} a M_9 B_3 $(h/r_g)^2$ Volts
  - electrons γ_e ~ 10^9-10^{10} possible (given curvature+IC)
  - proton energy < 5×10^{19} eV due to curvature losses or max. potential drop





Gil & Melikidze '05

Potential drawback:

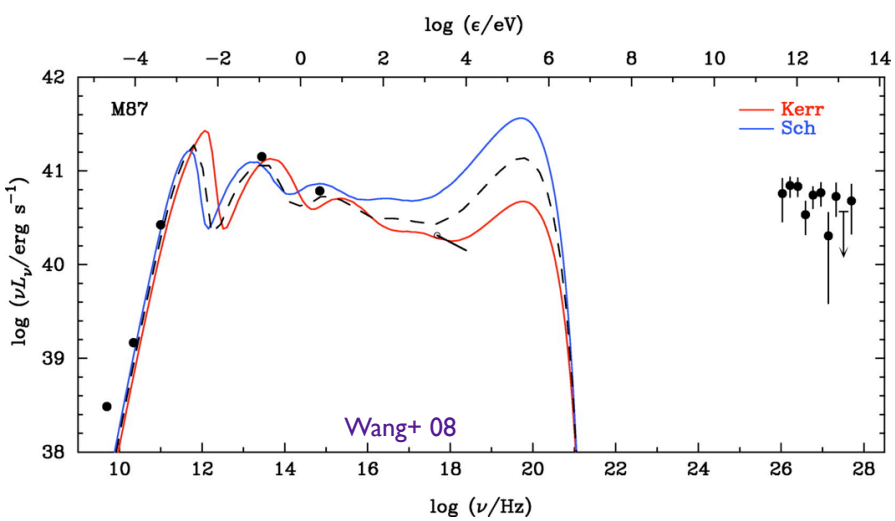
- AGN environs tend to be plasma-rich - enough electric charges/field screening?
  - ➡ pair production in hot ADAF: n_e/n_{GJ} = 10^{13} (accretion rate)$^{3.5}$ (Levinson & R '11)

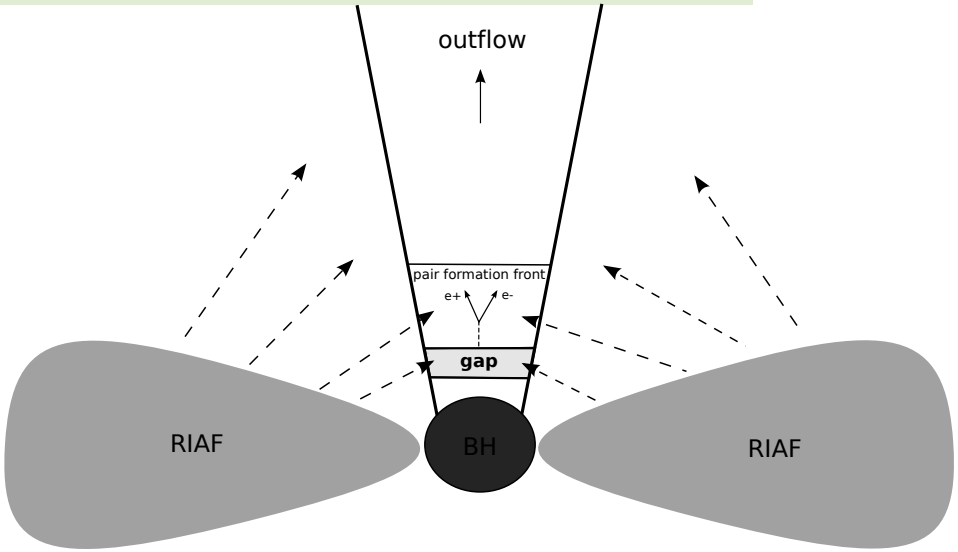
Additional component at TeV energies - HOWTO 2

VHE electrons + IC of ADAF soft photons + elm cascade

How to produce **VHE gamma-rays** in M87: (Levinson & R.'11)

- RIAF/ADAF soft photon field
- primary electron injection via pair-production in hot RIAF/ADAF
- gap-type acceleration of primary electrons up to $\gamma_e \sim 10^{10}$
- direct IC (KN regime) contribution (attenuated above 10 TeV)
- direct curvature contribution below 1 TeV
- elm cascade (initiated by absorption in ambient soft photon field)
- high enough multiplicity to ensure force-free outflow



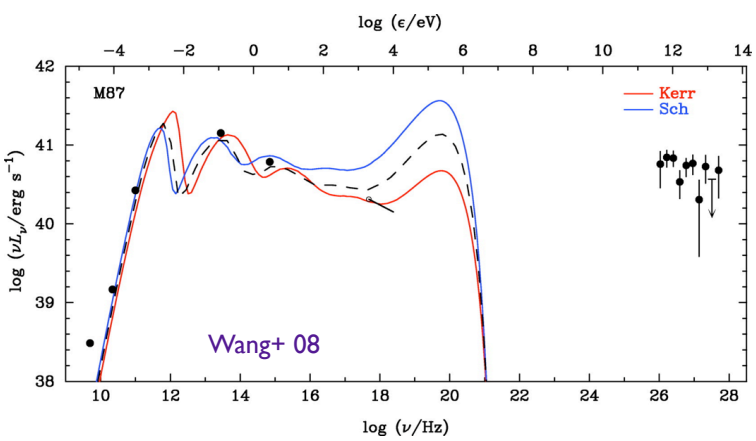


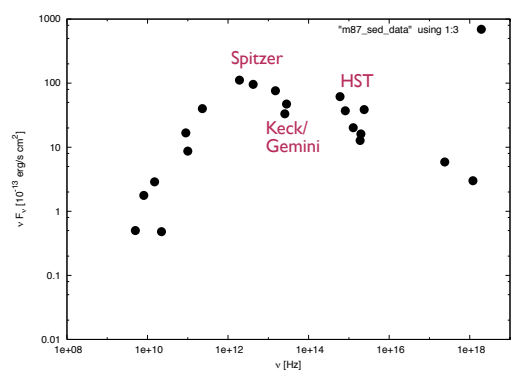
Can TeV gamma-rays escape unabsorbed?

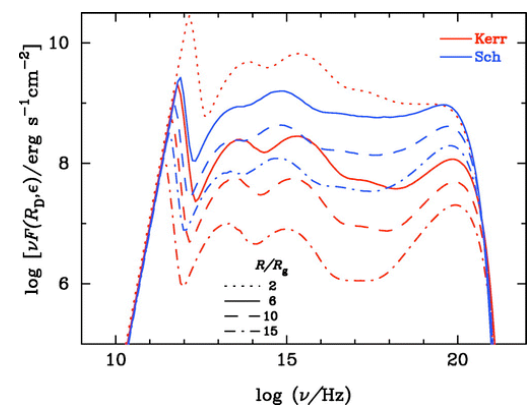
RIAF/ADAF disk with α Bondi rate (Levinson & R. 2011, cf. also Li+ 09)

- consistent with nuclear SED
- Calculate IR target field due to Compton scattering of synchrotron photon:
  - once or twice scattered: $L_c \propto L_s \times \{A\,\tau,\ A^2\tau^2\}$ with $\tau \sim n_e\,\sigma_T\,r << 1$
  - $\tau_{\gamma\gamma} \propto L_c \propto (\textit{accretion rate})^{2\text{-}4} \sim 0.2 - 5$ for α Bondi
  - escape of ≤ 10 TeV photons possible for gap models
  - optical depth highly sensitive on accretion rate!

escape possible



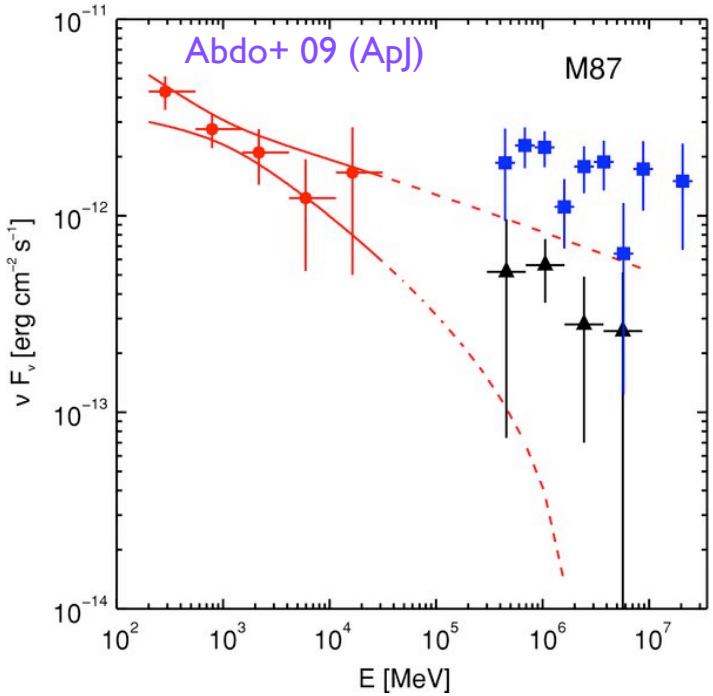


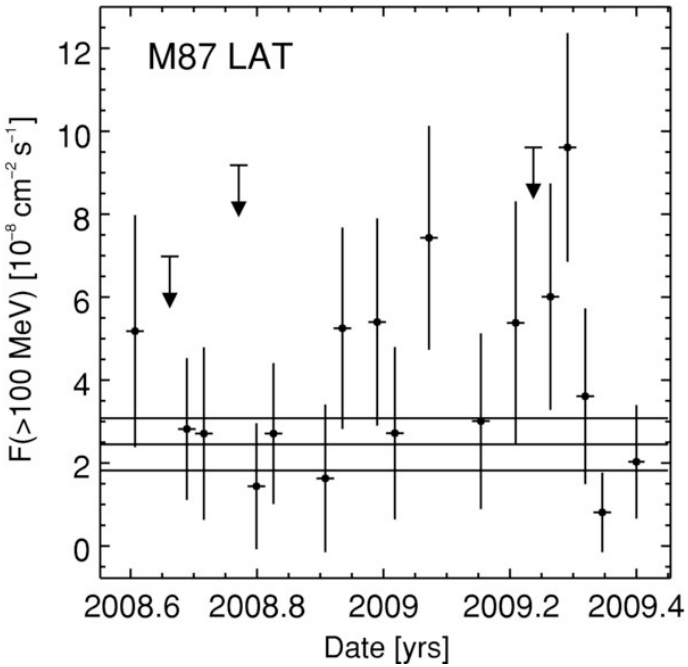


Astrophysical significance of further observations

_The current caveats & source models:

- Weak TeV source @ current IACT sensitivity limit (variability, extension)
- Want better constraints on GeV spectrum (extension?)
- Need better statistics for temporal comparison (correlation?) and short-term analysis (minimum GeV variability timescale?)



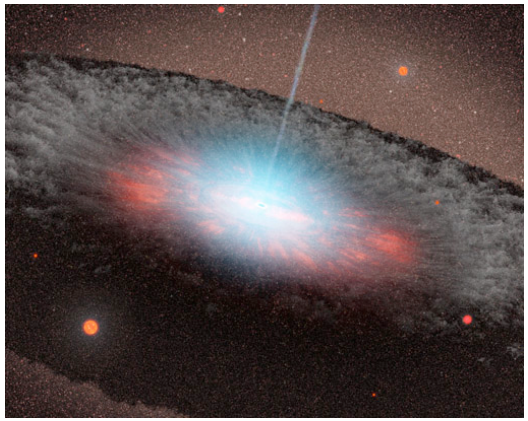


Conclusions

_Astrophysical significance of VHE from misaligned AGN

Fundamental diagnostics of

- acceleration & radiation mechanisms
- near-black-hole environment
- multi-zone models
- ...



THANK YOU!