High-energy emission from RADIO GALAXIES

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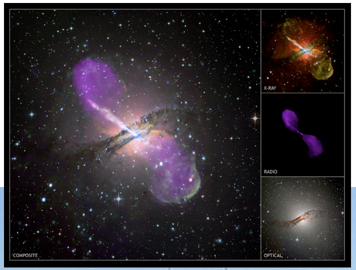
Dublin Summer School 2011
July 14th,



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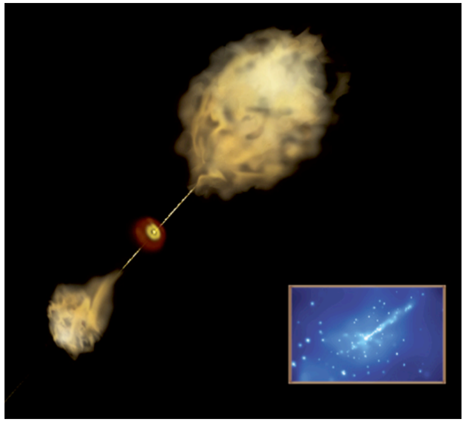
Outline



Credit: NASA E/PO

_Introduction

- the AGN zoo and unification
- radio galaxies - FR I/II dichotomy
- radio galaxies @ high and very-high energies

_Zoom-in I: VHE gamma-ray production in FR I

- VHE emission from non-blazar prototype M87
- particle acceleration and γ-ray production in BH environment
- escape of TeV γ-rays

_Zoom-in II: UHE cosmic-ray production in FR I

- the case of Cen A
- cosmic-ray acceleration sites and efficiencies

_Introduction

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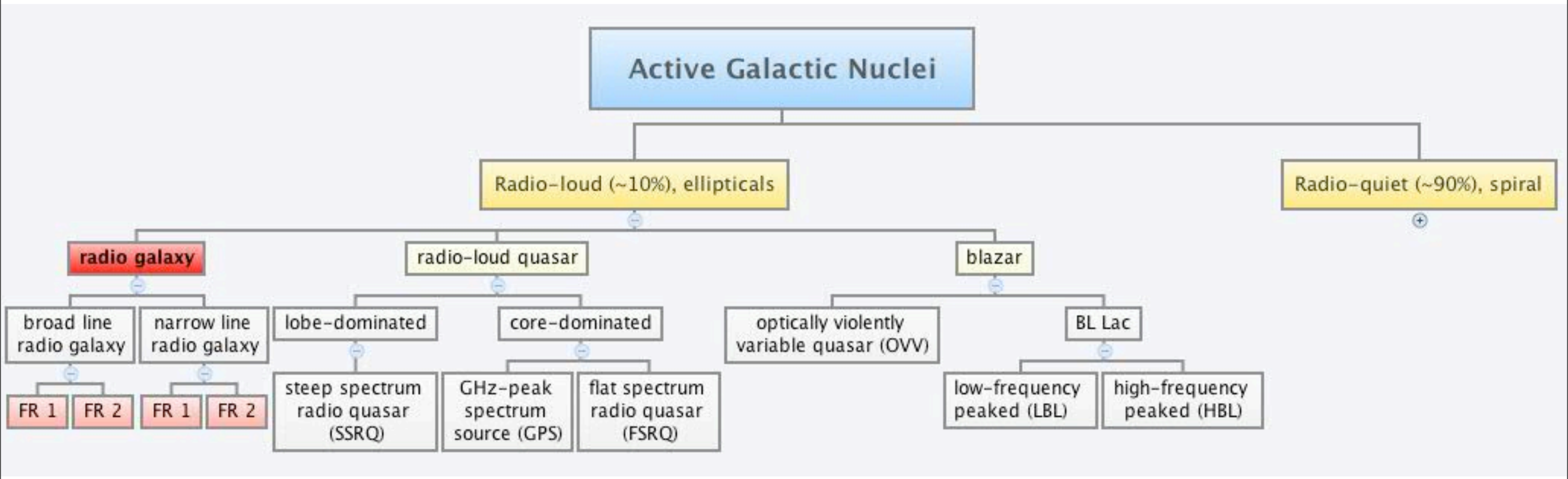
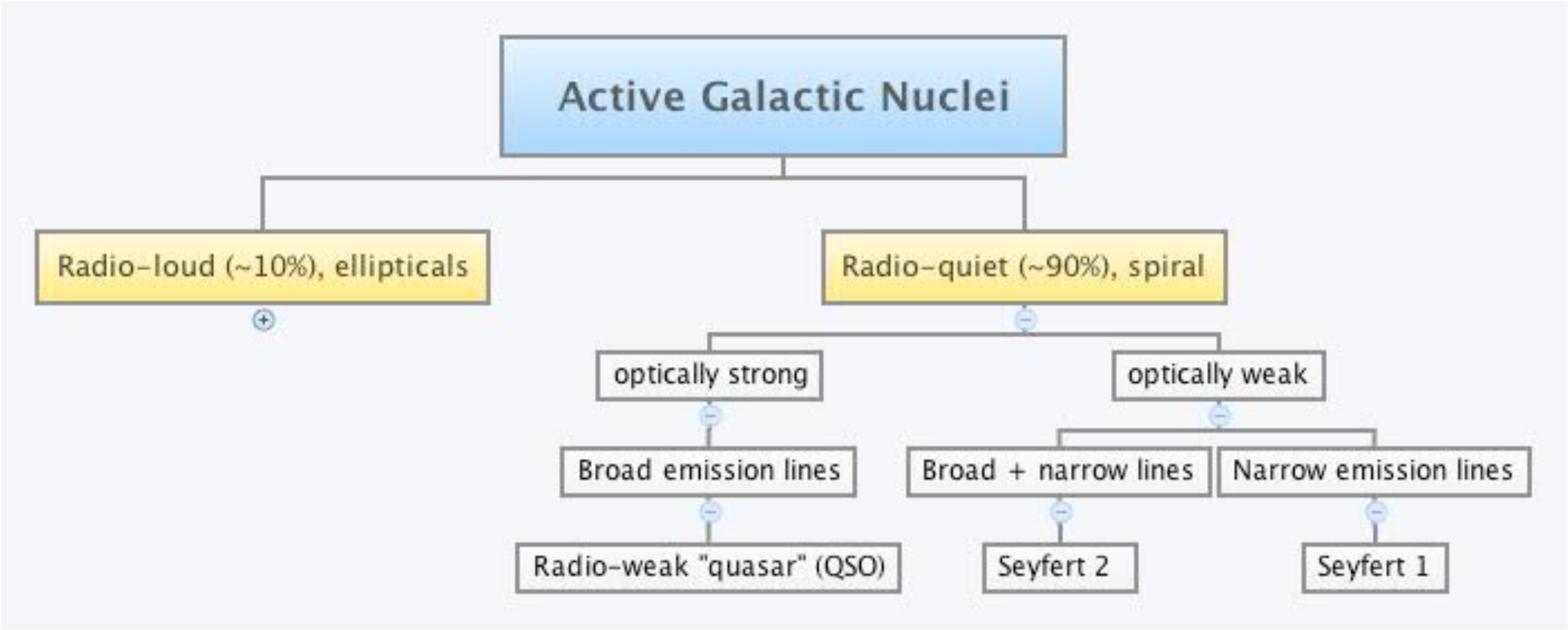
- radio galaxies - FR I/II dichotomy
- radio galaxies @ high and very-high energies

The AGN zoo - classification (attempt)



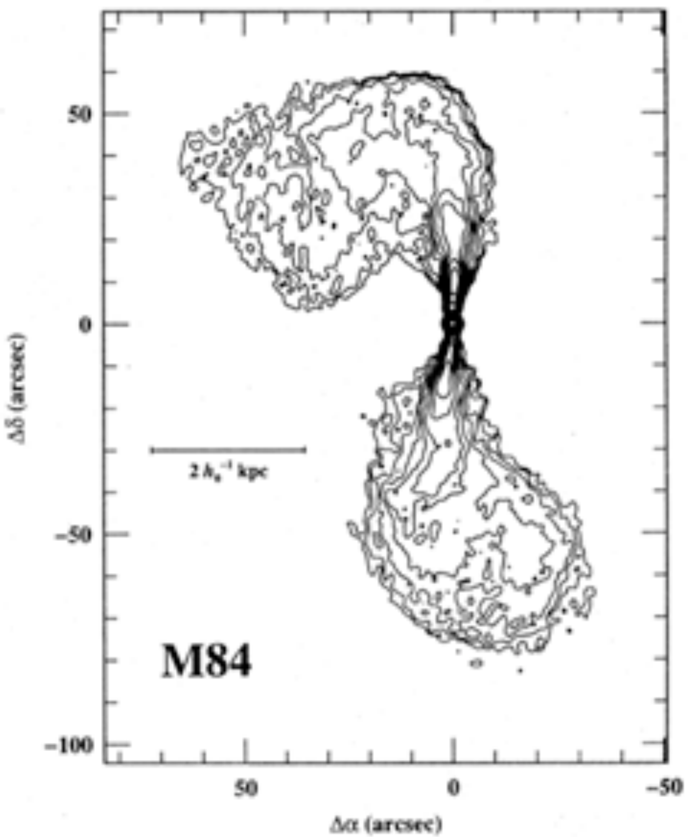
The AGN zoo - classification (attempt)

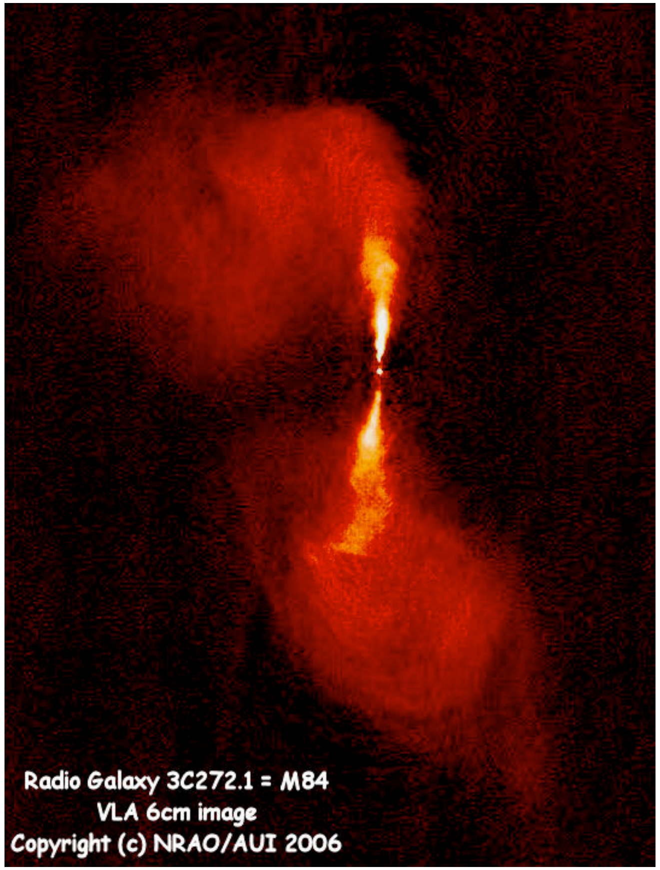


Extended radio sources - morphologies

_Fanaroff & Riley (1974) - **FR I class:**

- lower luminosity radio source $L_{178\,MHz} \lesssim 2x10^{32}$ erg/s/Hz
- edge-darkened (no prominent hot spot)
- only weak optical emission lines
- jet widens & decelerates



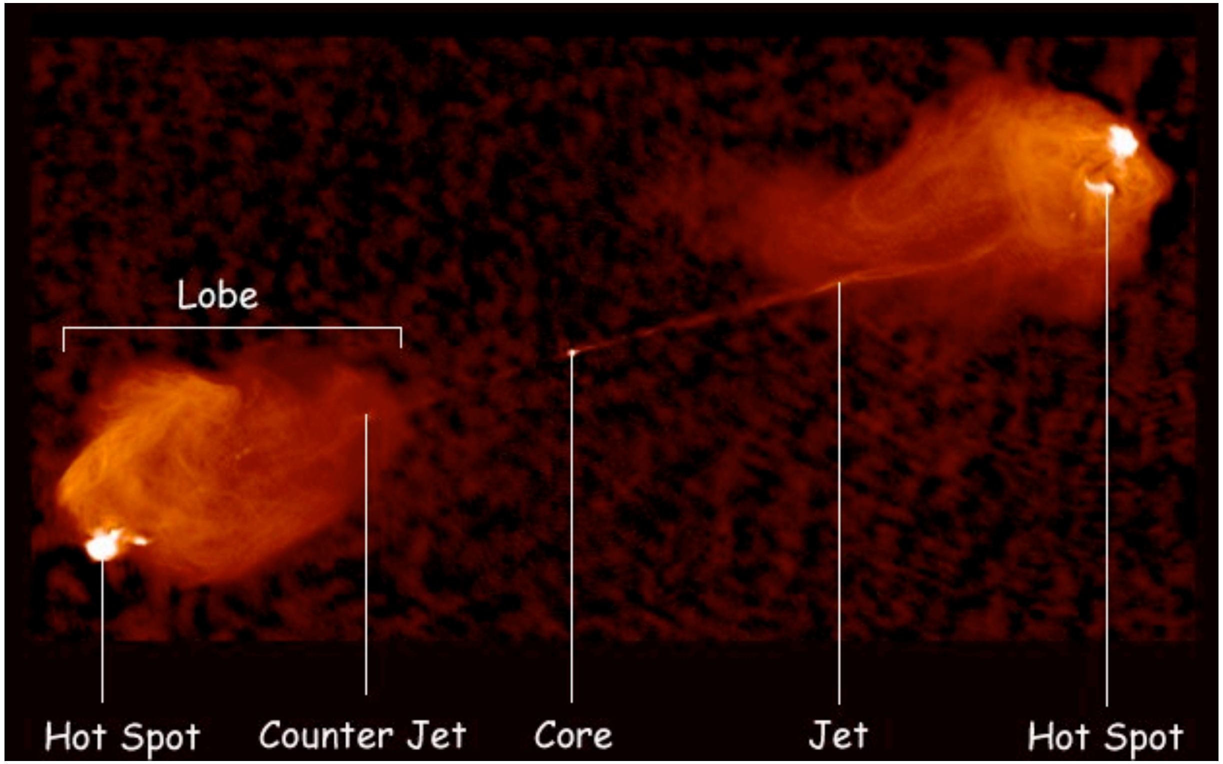


Radio galaxy **M84** (3C272.1, Virgo Cluster) at 5 GHz , d ~ 17 Mpc, size ~ 10 kpc (credits: NRAO/AUI)

Extended radio sources - morphologies

_Fanaroff & Riley (1974) **- FR 2 class:**

- higher luminosity radio source $L_{178\,MHz} \geq 2x10^{32}$ erg/s/Hz
- edge-bright (radio lobes with prominent hot spot)
- strong optical emission lines
- jet remains narrow and relativistic



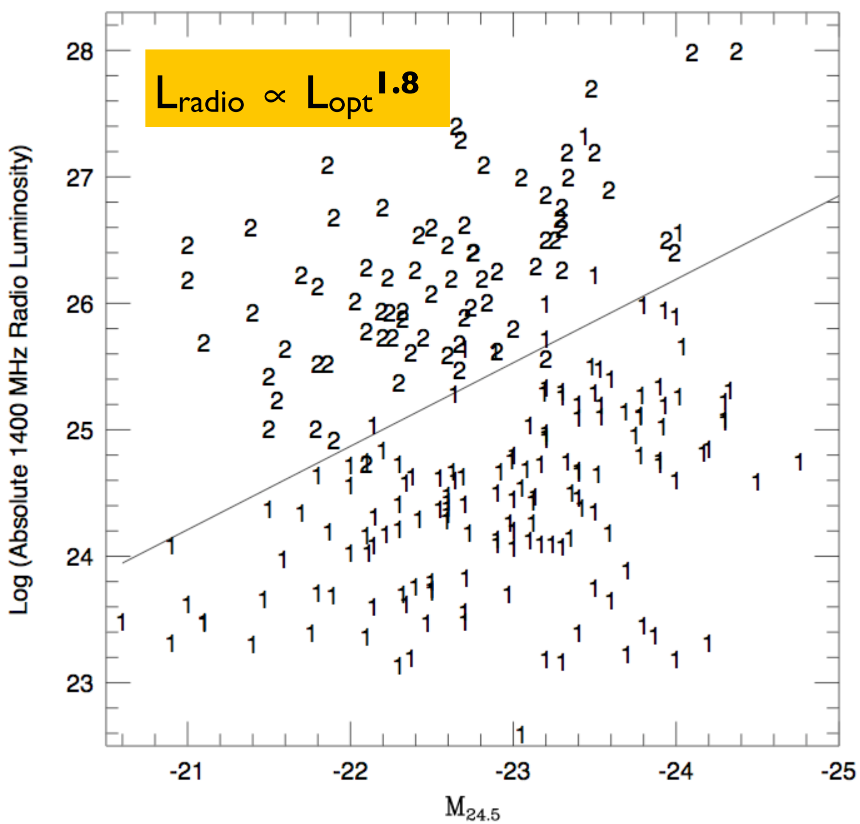
Radio galaxy **Cygnus A** at 5 GHz , d ~ 220 Mpc, (z=0.056), extension ~120 kpc (credits: NRAO/AUI, A. Bridle)

FR1/FR2 transition - dichotomy

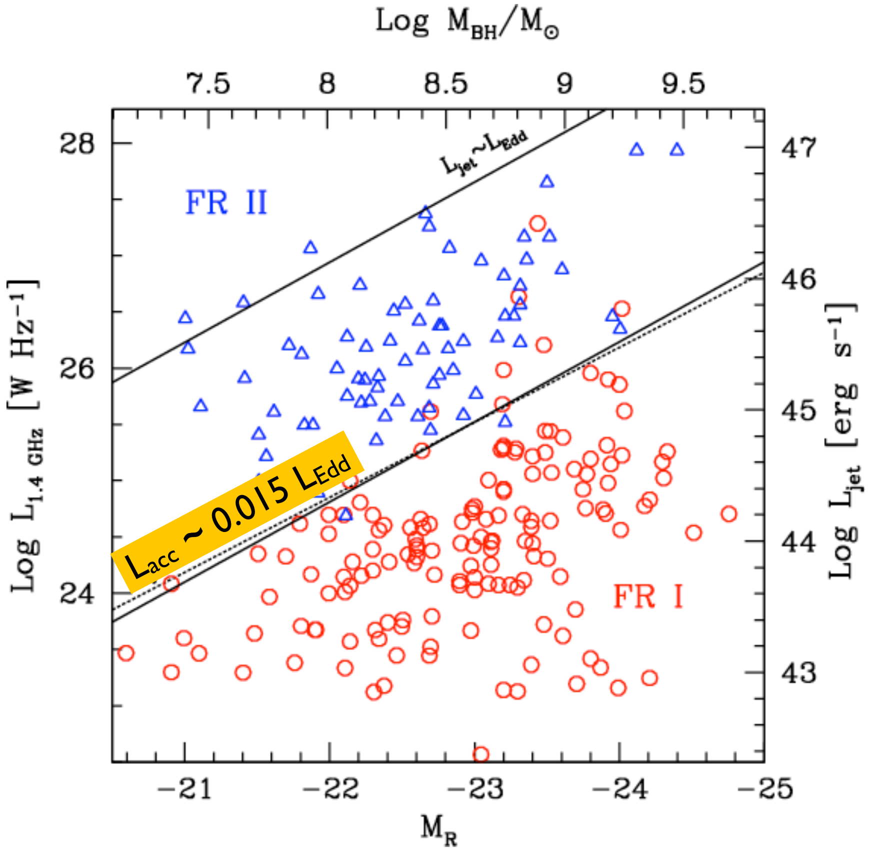
Transition appears at higher L_{radio} for optically more-luminous host galaxies (Owen & Ledlow 1994 etc)

talk by M. Perucho

- *external* cause: interaction with ambient medium (DeYoung '93; Perucho & Marti '07)
- *internal* cause: difference in central engine or jet composition (Baum et al. '95, G&C'01)



Ledlow & Owen 1996, AJ 112



Ghisellini & Celotti 2001, A&A 379

Does FR1/FR2 transition depend on black hole spin?

Idea: use kinetic jet power and BH mass estimates to infer BH spin

$$L_{BZ} \propto a^2 M_{BH}^2 B^2$$

talk by Y. Lyubarsky

- SAMPLE 1:

  analysis suggests difference in spin with FR 1: a≈(0.01-0.4), FR 2: a≈(0.2-1)

  - *"...for AGN with powerful large-scale outflows, beam power is directly related to black hole spin."* (Daly 2011, MNRAS, arXiv:1103.0940)
  - *but*: no difference in accretion considered...

- SAMPLE 2:

  no difference in spin (a>0.9), but in accretion rate (FR 2: SS → FR 1: ADAF)

  - *"Our results suggest that the BHs in FR Is should be rapidly spinning with j ≥ 0.9..."*

    (Wu et al. 2011, ApJ, arXiv:1104.3235)
  - ...

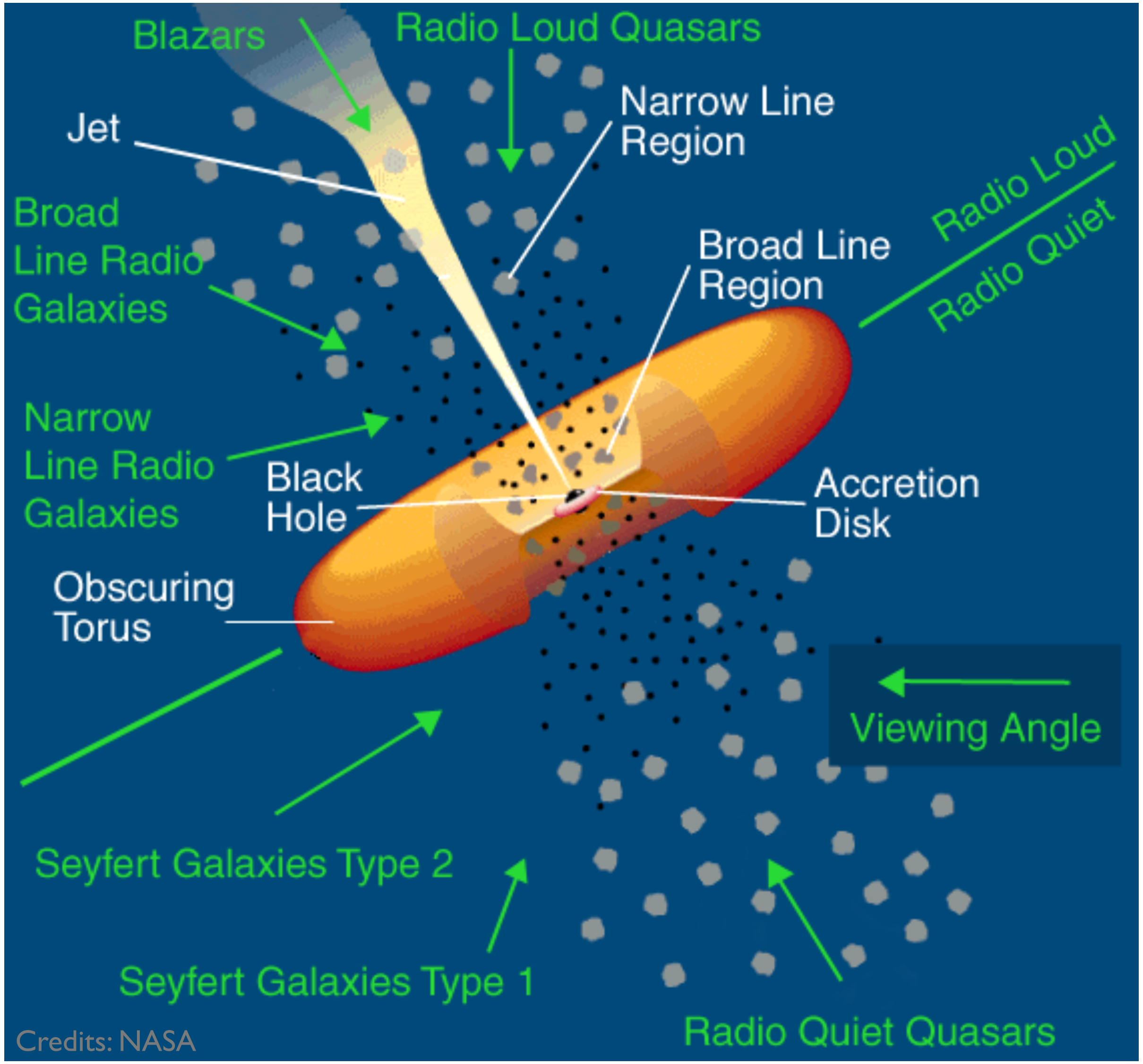
no clear case yet

- Fender+ (MNRAS 2010):

  "No evidence for black hole spin powering of jets in X-ray binaries"

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 ~ 10^8 M_{sun}

Accretion disk (SS):

r ~ (10^{-2} - 10^{-3}) pc

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

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

v ~ 0.4 c *(at inner edge)*

Broad line region (BLR):

r ~ 0.01-0.1 pc

n ~ 10^{10} cm^{-3} *(forbidden lines collisionally suppressed)*

v ~ (10^3-10^4) km/s

T~10^4 K

Torus:

r ~ 1 up to several 10 pc

n ~ 10^3 - 10^6 cm^{-3}

T ~ cold

Narrow Line region (NLR):

r ~ 100-1000 pc

n ~ 10^3-10^5 cm^{-3}

v ~ a few 100 km/s

T ~ 10^4 K

A “possible”, simple unification scheme

Orientation / radio loudness	viewing from the side	viewing face-on
Radio-quiet	Seyfert 2	Seyfert 1
Radio-loud	FR I NLRG FR 2	BL Lac BLRG FSRQ

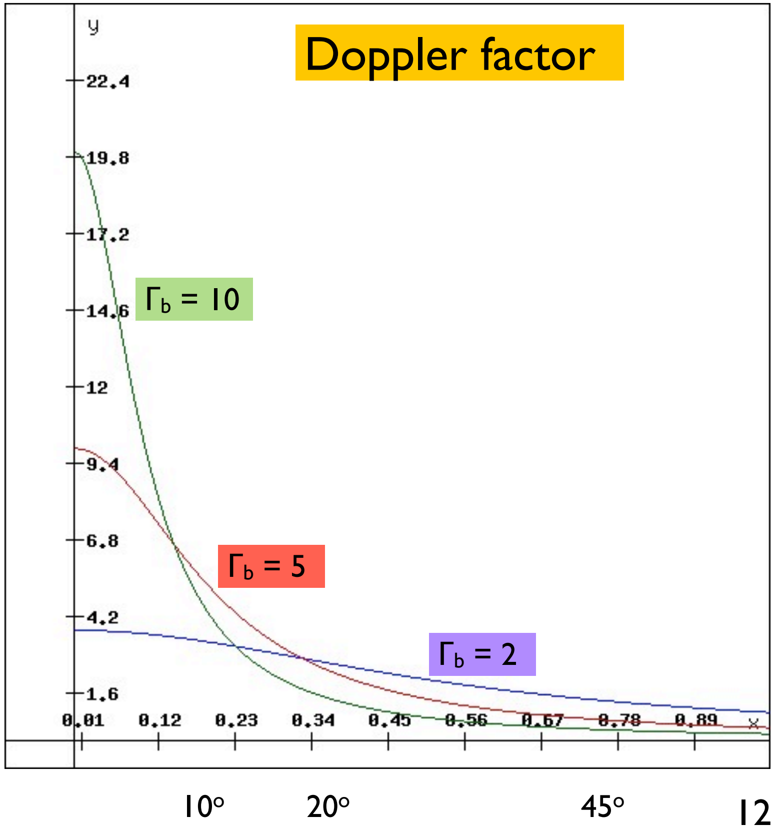
"Everything should be made as simple as possible, but not simpler." — *Albert* ***Einstein***

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: $\Delta t = \Delta t' / D$
- ...



SED of FR 1 Cen A can be well fitted with one-zone BL Lac-type SSC assuming small Doppler factor/large inclination (Chiaberge et al. 2001)

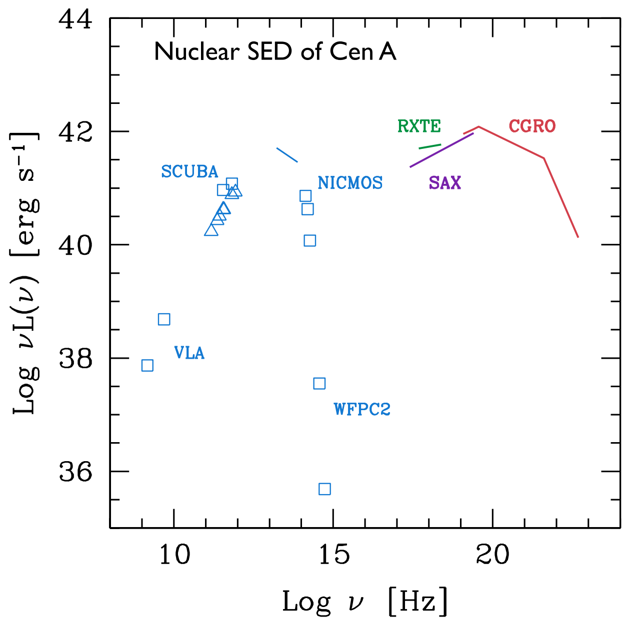
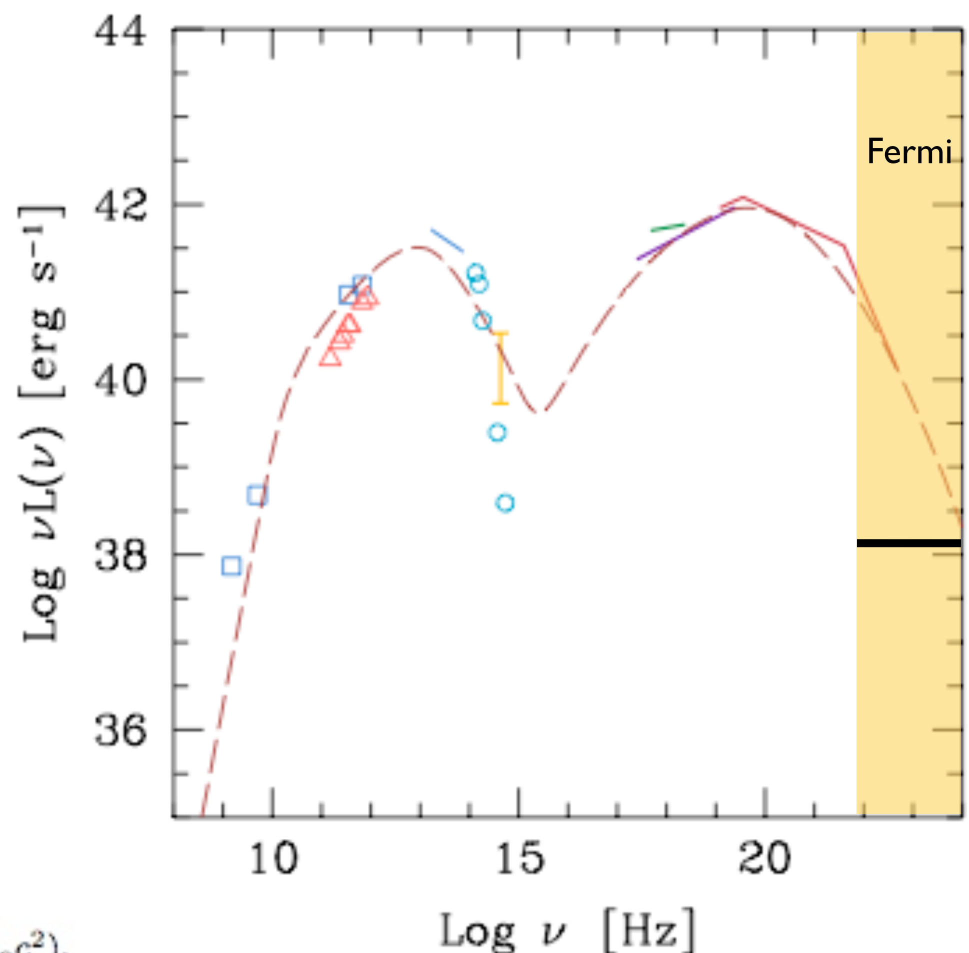


Table 1. Model parameters for the SED of Centaurus A

R	1.2×10^{16} cm	p	3.0
B	0.5 G	γ_{min}	2×10^3
δ	1.2	γ_{max}	1×10^4
L_{inj}	2.7×10^{42} erg s^{-1}	t_{esc}	$10 \times R/c$

$L_{\rm inj}$ is the injected power (in particles of energy equal to $\gamma m_e c^2$).



HE and VHE gamma-ray emission

May expect to see some FR 1-type radio galaxies in the high-energy domain (0.1-10 GeV) with FERMI, but not much in TeV, if emission is (misaligned) BL Lac-type.

Fermi-LAT detection of misaligned radio galaxies

out of > 700 AGN:

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 preliminary*		*preliminary/Cheung*
Cen B	*FR I*	*56 Mpc*	*LAT 2011 preliminary*		*preliminary/Cheung*
3C84	FR I	75 Mpc	LAT 2009	(✔?)*	jet precession; LAT days-variability***
IC 310	FR1 head-tail	80 Mpc	LAT 2010	✔**	Neronov et al. '10; VHE yr-variability
NGC 6251	FR I	106 Mpc	EGRET, LAT 2010		
3C78	FR I	124 Mpc	LAT 2010		
3C120	FR I	142 Mpc	LAT 2010		BLRG
3C111	FR 2	213 Mpc	EGRET, LAT 2010		BLRG
PKS 0943-76	FR 2	1360 Mpc	LAT 2010		
......					

Abdo et al. 2010, ApJ 720; Cheung 2011 (talk @ Fermi Sympos.); Neronov et al. 2010, A&A 519

* Atel #2916 (MAGIC): detected above 100 GeV with 5 σ, steep spectrum, no signal above 400 GeV;
** MAGIC Collab. 2010, hard spectrum up to 7 TeV (photon index ~2);
*** Brown & Adams 2011, MNRAS 413: in two yr LAT data

Radio galaxies II

_Zoom-in 1: VHE gamma-ray production in FR I

- VHE emission from non-blazar prototype M87
- particle acceleration and γ-ray production in BH environment
- absorption and escape of TeV γ-rays

Zoom-in 1: M87 - general properties

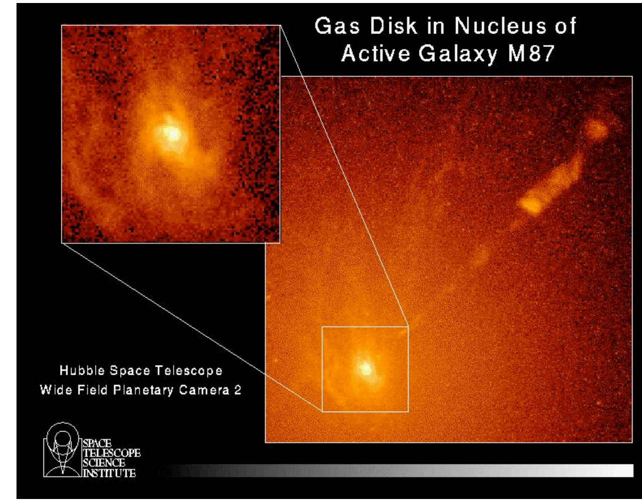
_M87: FR I, non-blazar prototype:

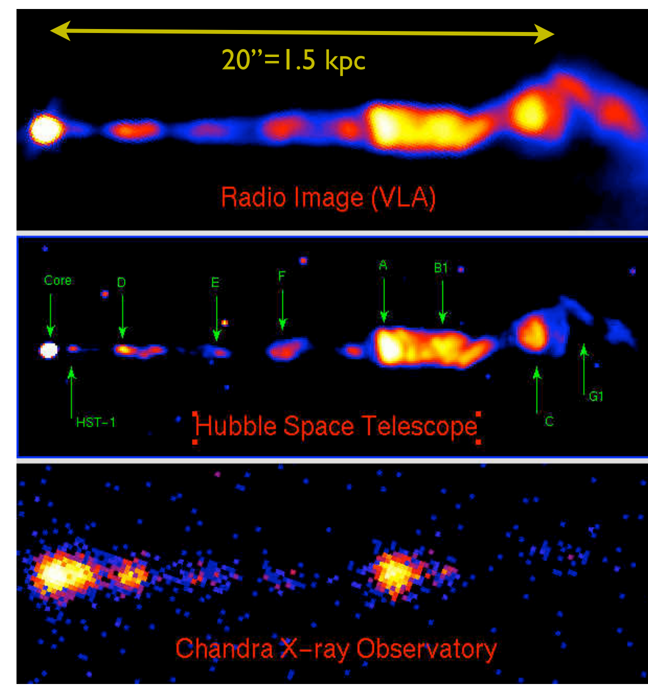
- giant elliptical galaxy (Virgo cluster)
- distance ~16 Mpc
- BH mass (from gas rotation):

$$M_{BH} \sim (3\text{-}6) \times 10^{9}\, M_{sun}$$

- under-luminous $L_{bol} \sim 10^{42}$ erg/s << L_{Edd}
- one-sided, kpc-scale jet
- jet inclination i ~20°,

➡ modest Doppler beaming (D ~ 2)





Marshall et al. 2002

Zoom-in 1: M87 - radio image at different scales

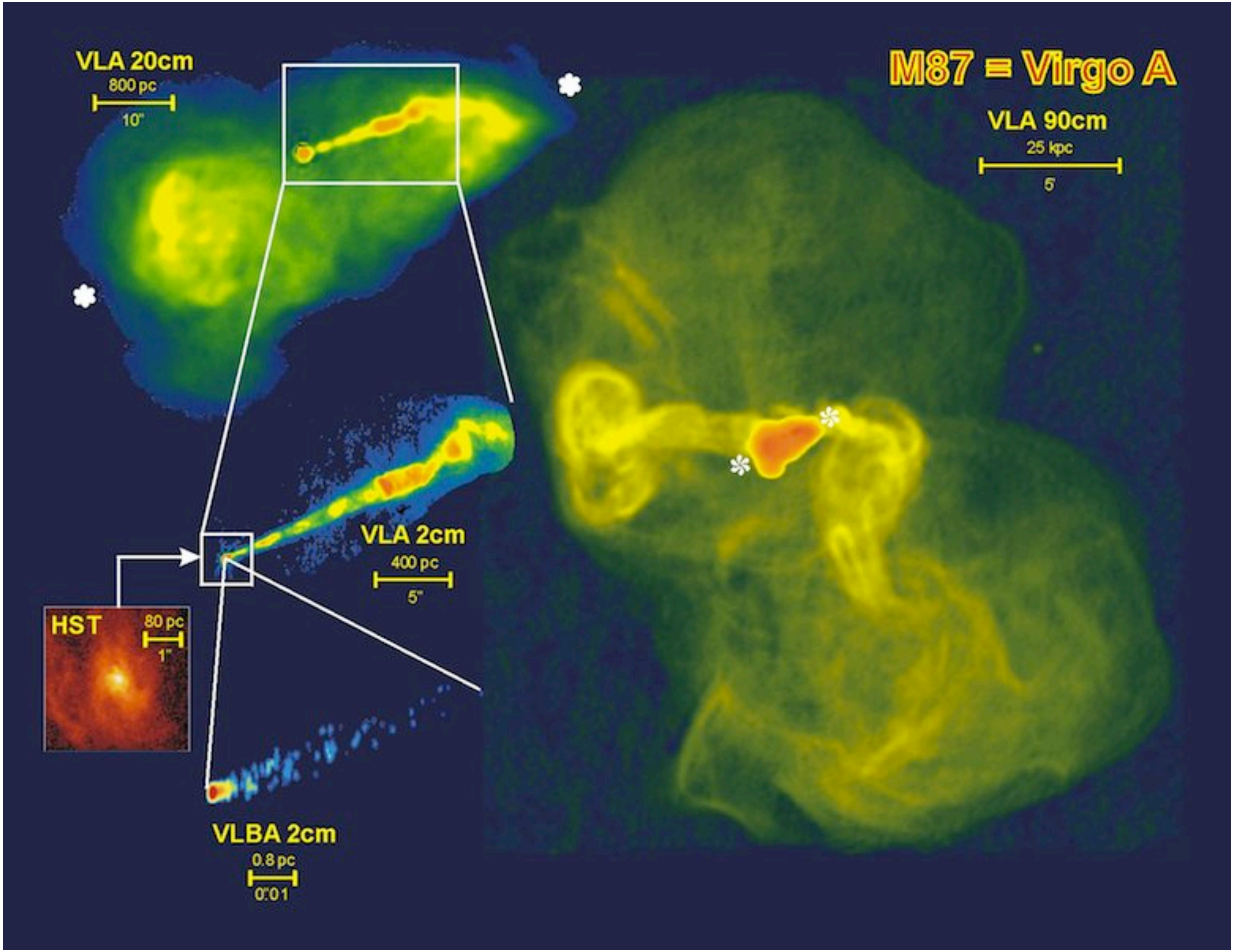


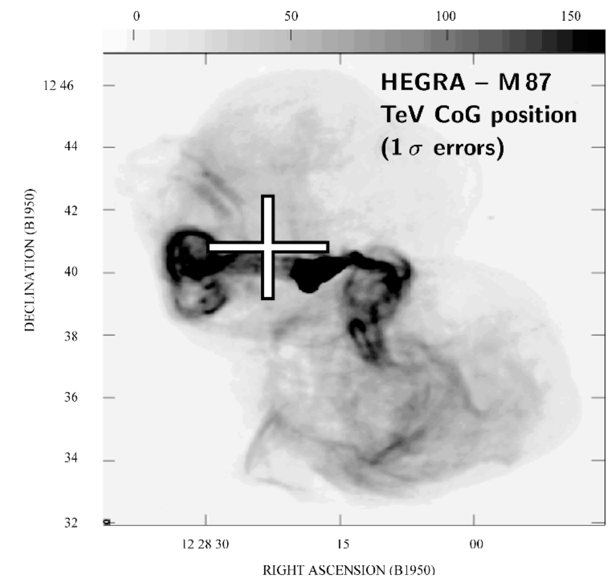
Image courtesy of NRAO/AUI

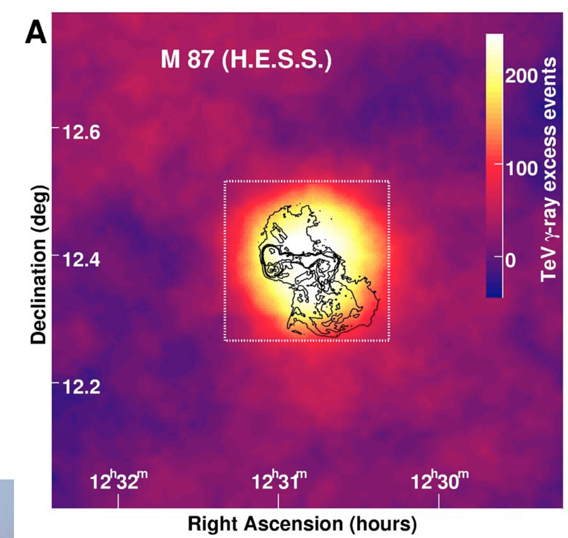
M87 @ very-high energies

_VHE γ-ray history:

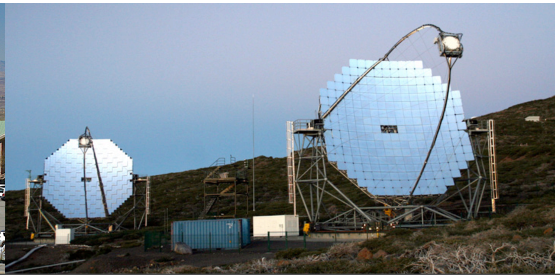
M87 is the first non-blazar extragalactic source known to emit VHE γ-rays

- 1st detection (> 4σ) by **HEGRA** in 1998/99
- **H.E.S.S.**: confirmation (2003-05), VHE variability (long/yr- and short/2d-term) hard spectrum in 2005 (Γ~2.2)
- **VERITAS**: 6σ detection in 2007, no significant short time variability, hard spectrum
- **MAGIC**: 8σ in one night (Jan 08), days-scale variability
- ....





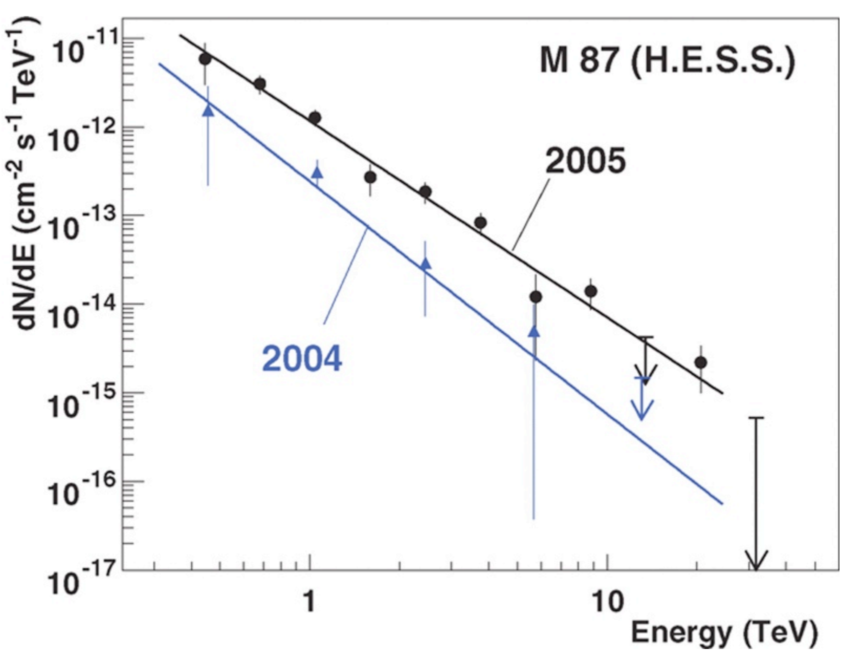
Aharonian et al. 06; Acciari et al. (VERITAS)'08; Albert et al. (MAGIC)'08...

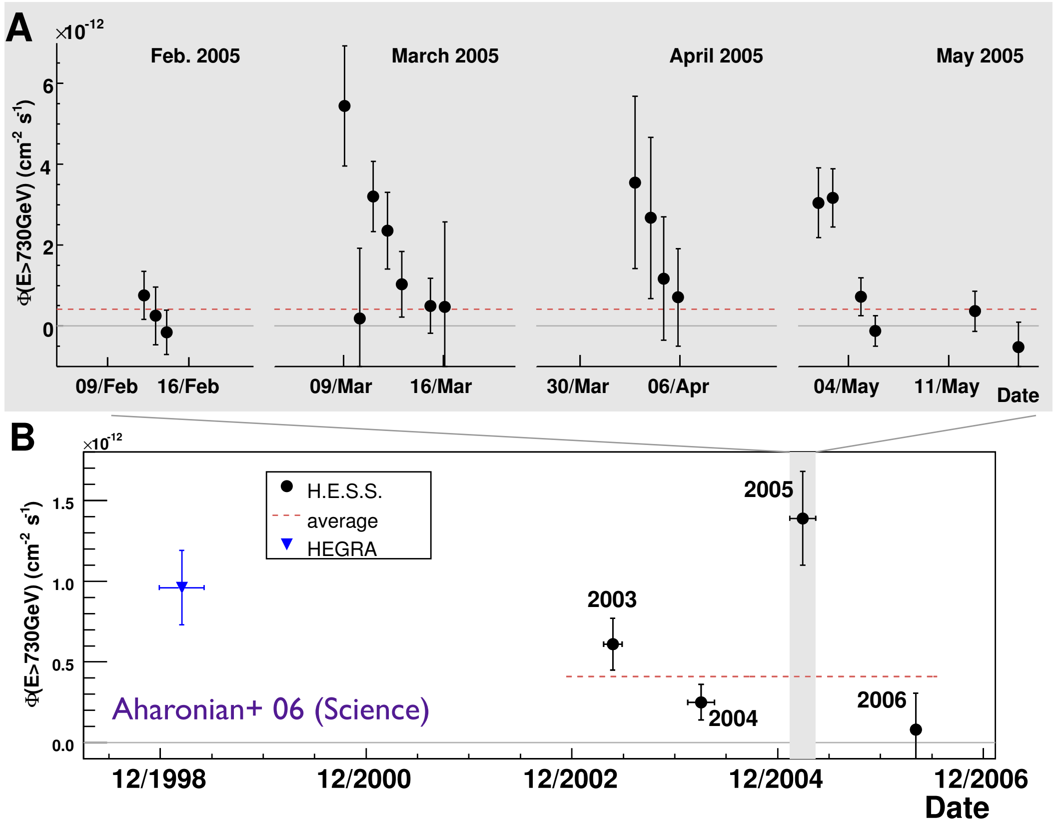


M87 @ very-high energies

_VHE (H.E.S.S.) findings during 2005 high state:

- spectrum extends beyond 10 TeV
- hard VHE spectrum (photon index -2.2)
- isotropic L(>730 GeV) ≈ 5 × 10^{40} erg/s
- evidence for rapid variability (timescale 1-2 days)

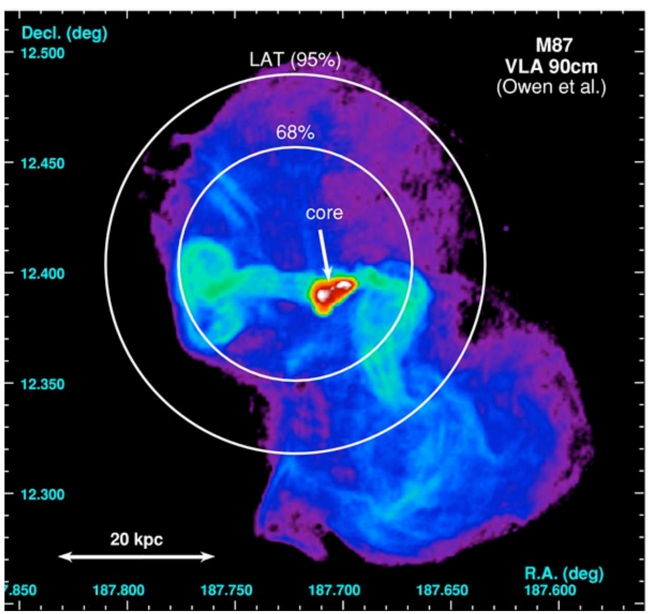


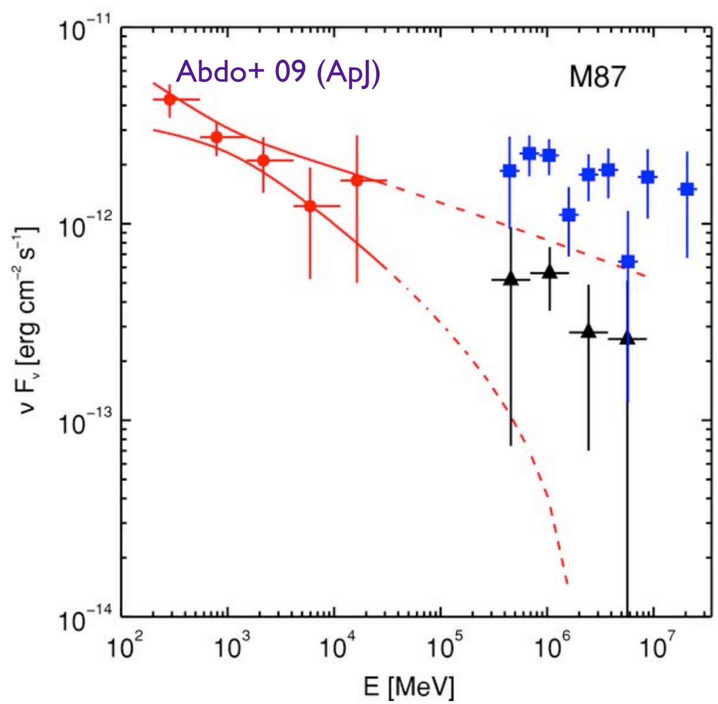


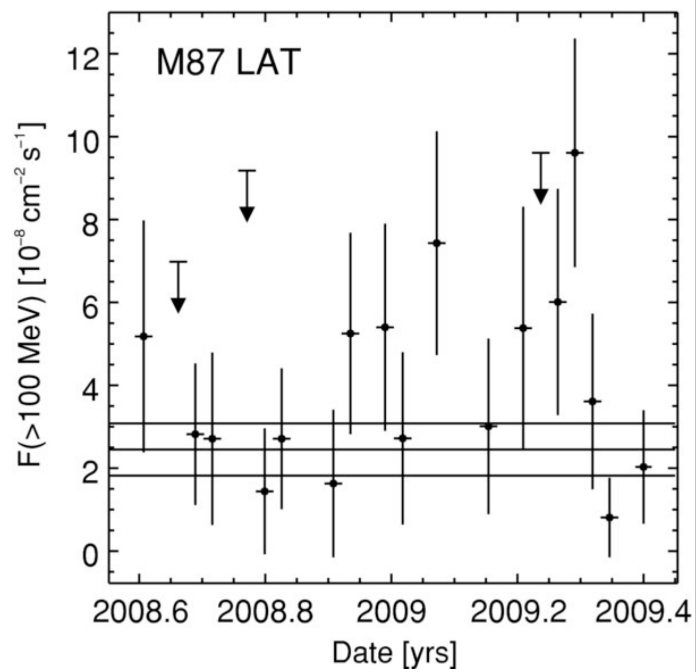
M87 @ high energies

_Fermi (2008/2009) detection of M87:

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







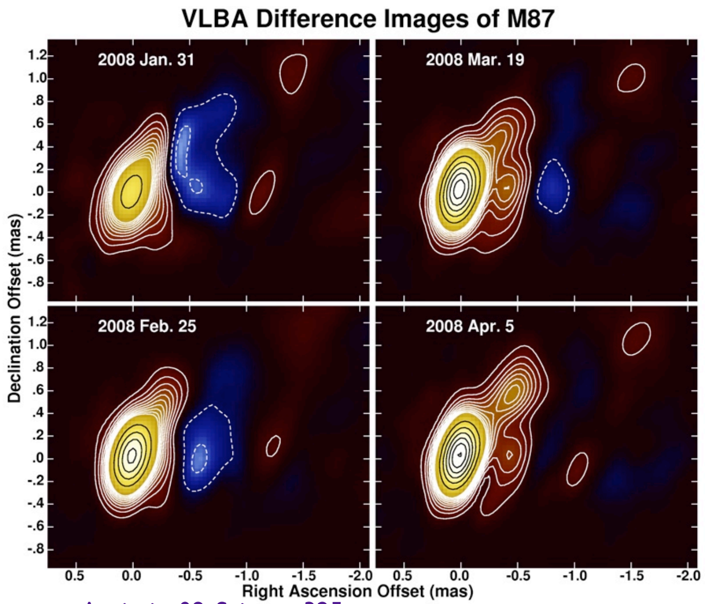
Origin of TeV γ-rays from M87?

_Additional component at TeV energies?

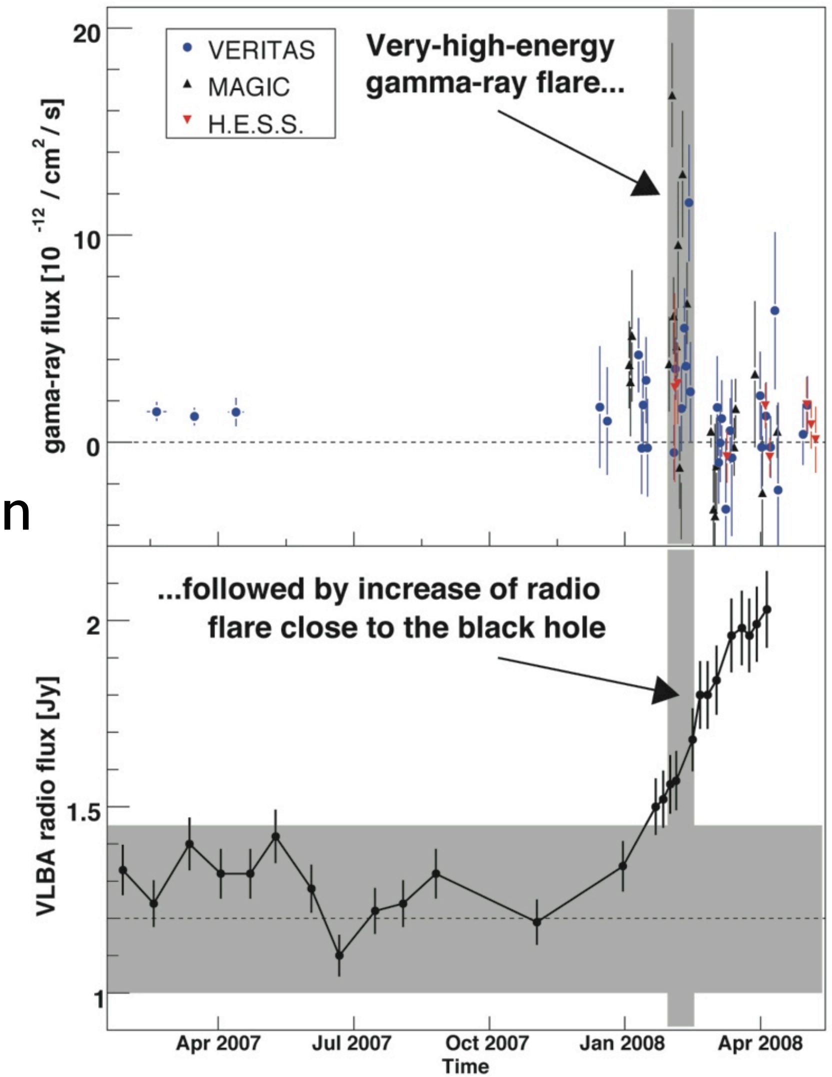
- Fermi extrapolation cannot explain high TeV flux
(but perhaps normalization errors + variability)

- one-zone SSC (radio-GeV) cannot fit TeV high state
(also other "conventional" **misaligned** models)

- radio-TeV ('08) link supports close BH origin
(Note: day-variability implies compact zone)



Acciari+ 09, Science 325

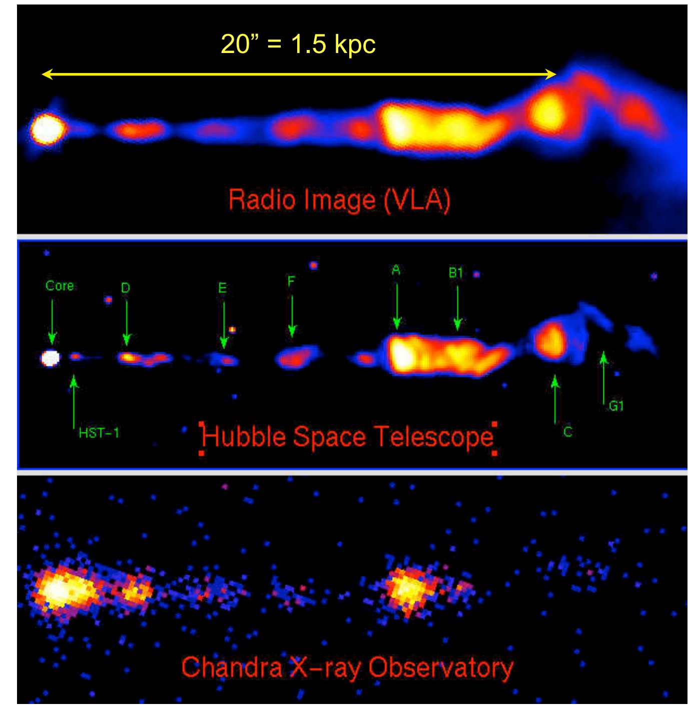


Interlude: On the origin of TeV γ-rays from M87

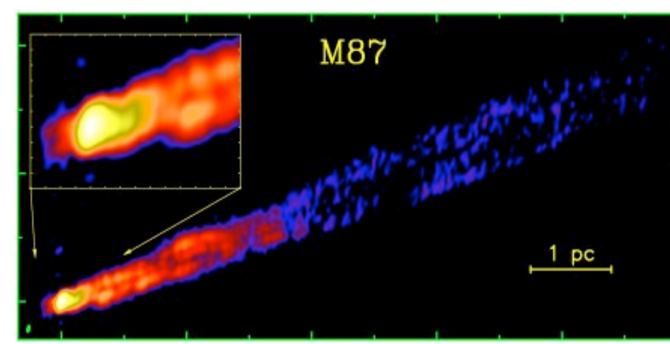
_Challenges to "conventional" jet models without strong Doppler boosting:

- *large-scale* jet (d >>1 pc):
  - Knot A (d ~1 kpc, EC starlight) (Stawarz+ '03)
    => excluded by variability
  - HST-1 (d ~ 100 pc, SSC/EC) (Stawarz+ '06)
    => unlikely (size + TeV variability; cooling break at ~10^{15} Hz, anti-correlation of HST-1 X-ray and VHE light curves)

- *innermost* part of jet (d ~ sub-pc):
  - homogeneous SSC (synchrotron peak in optical)
    ⇒ Compton peak << 1 TeV (cf. Lenain+ '08)
  - proton synchrotron (Reimer+ '03)
    ⇒ no hard TeV spectra, intrinsic cut-off at 0.3 TeV
  - decelerating flow/UC scattering (Georganopoulos+ '05)
    ⇒ cannot explain d-variability and hard TeV spectra
  - Spine/shear interplay (EC) (Tavecchio & Ghisellini '08)
    ⇒ no hard TeV spectrum (due to γγ-absorption)



Marshall+ 02



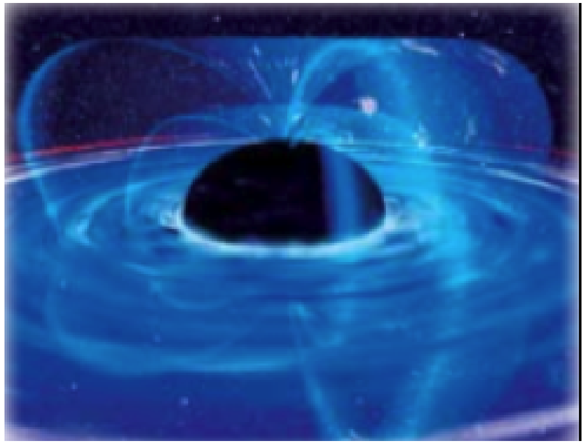
VLBA @ 2cm: Kovalev+ 07

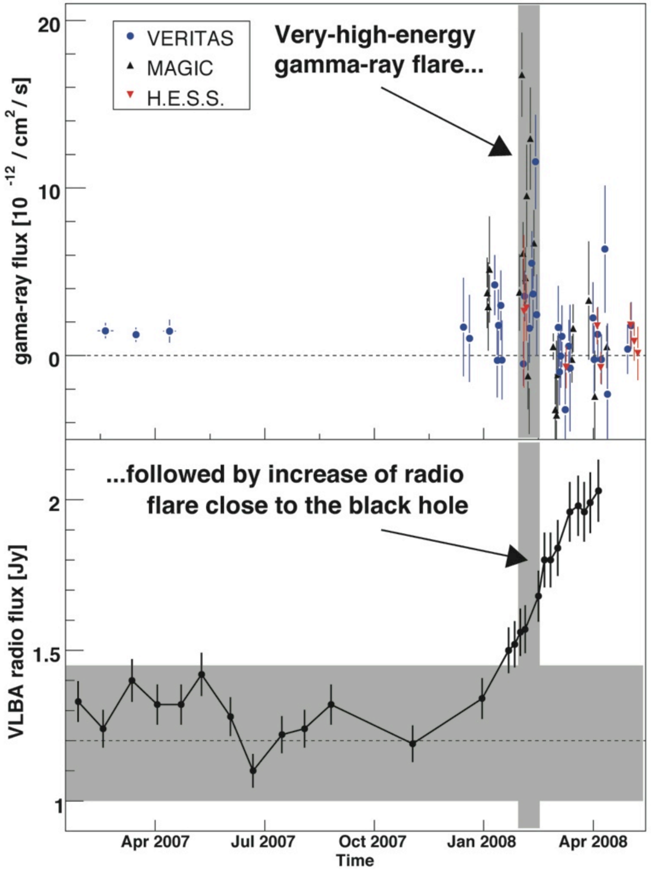
Origin of TeV γ-rays from M87

_BH-magnetosphere models as alternative:

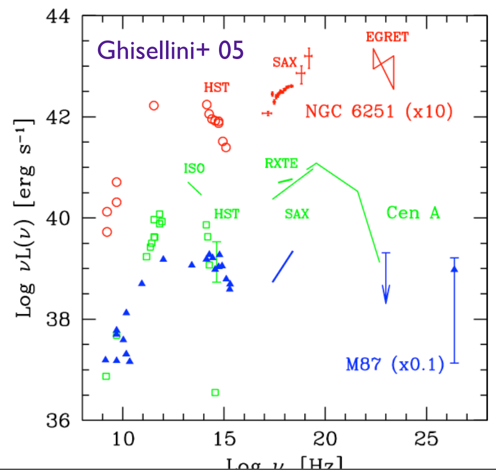
(Neronov & Aharonian '07; R. & Aharonian '08; Beskin '09; Levinson & R. '11)

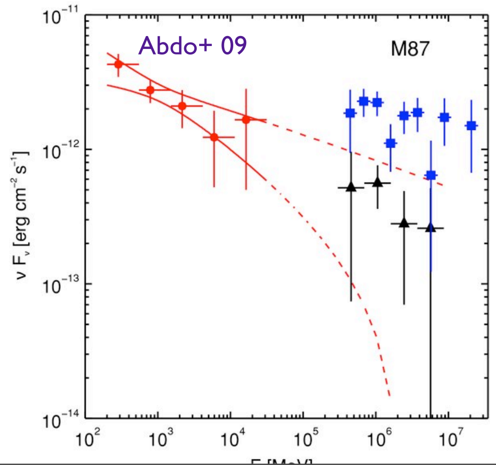
- *Idea:* additional contribution from close to BH ($\sim$ a few r_g)
  - ➡ variability $t_{var} \sim$ a few $(r_g/c) > 0.2$ d
- *Support:* radio and TeV connection
- *Requires I:* VHE electrons ($\gamma_e \geq 10^7$) for IC
- *Requires II:* little $\gamma\gamma$-absorption below 10 TeV





Acciari+ 09, Science 325

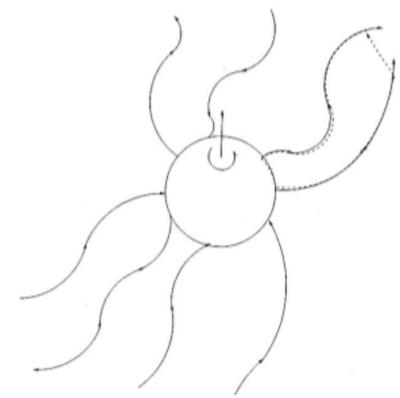




Particle acceleration in rotating BH magnetospheres

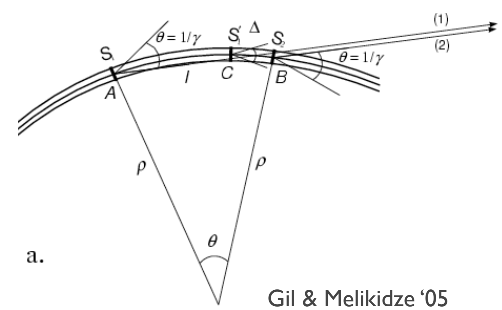
_Example I - Gap-type particle acceleration in M87

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



- similar to pulsars
- rotating **B** induces $\mathbf{E} = -(\boldsymbol{\Omega} \times \mathbf{r}) \times \mathbf{B}/c$
- **E** is supported by local charge density $\rho_{GJ} = \nabla \cdot \mathbf{E}/4\pi$ (Poisson)
- if $\rho < \rho_{GJ}$, we may have unscreened $E_{||}$ components ⇒ particle acceleration
- electrons $\gamma_e \sim 10^8$-10^{10} possible (given curvature+IC)
- proton energy < 5×10^{19} eV due to curvature losses

  or max. potential drop ~ $3\times10^{19}\, a\, M_9\, B_3\, (h/r_g)^2$ Volts



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Gil & Melikidze '05

Potential drawback:

- AGN environs tend to be plasma-rich - enough electric charges?

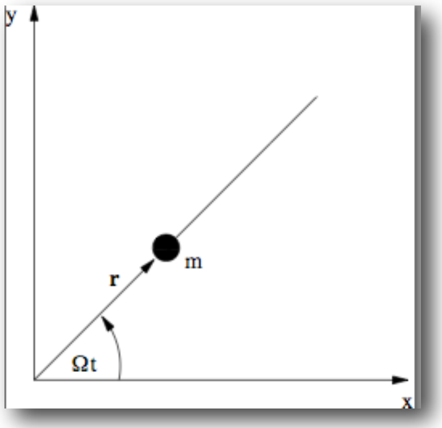
  ➡ pair production in hot ADAF: $n_e/n_{GJ} = 10^{13}$ (accretion rate)$^{3.5}$ (Levinson & R '11)
- $E_{||}$ is screened, acceleration suppressed (but cf. Komissarov'04)

Particle acceleration in rotating BH magnetospheres

_Example II - Centrifugal particle acceleration in M87

(e.g., Gangadhara & Lesch '97; R & Mannheim '00; Osmanov+ '07, R & Aharonian '08)

- plasma-rich environment, $E_{||}$ screened, no gap-type acceleration
- account for inertial (centrifugal) effects close to light surface $r_L = c/\Omega$
- *plasma corotation:*
  - ➡ rotating **B** induces **E**
  - ➡ **E** x **B** drift velocity $\mathbf{v}_D = c\,(\mathbf{E} \times \mathbf{B})/B^2 = \Omega\, r\, \mathbf{e}_\theta$



- *radial motion:*
  - ➡ Hamiltonian is constant of motion

$$H = \gamma\ m_0 c^2 (1 - r^2/r_L^2) = const.$$

- efficient acceleration for $r \rightarrow r_L$
  - ➡ for electrons $\gamma_e \sim 5 \times 10^7$ possible (given IC losses)
  - ➡ proton energy limited by corotation $< 10^{17}$ eV

Potential drawback:

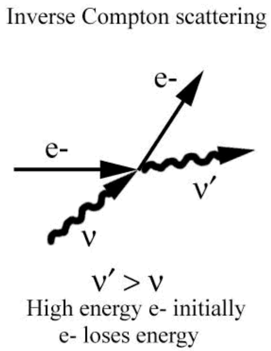
- requires B_Φ/B_P to be small for efficient acceleration

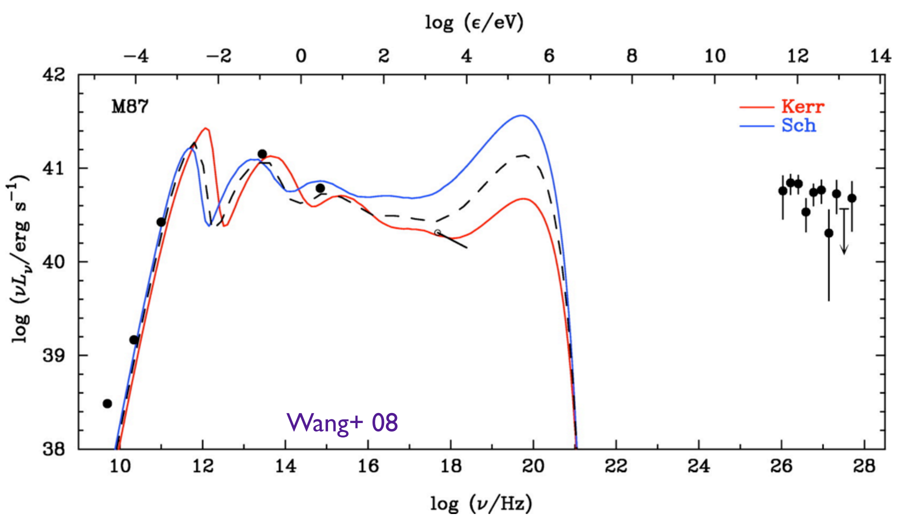
How to produce VHE gamma-rays - Example I

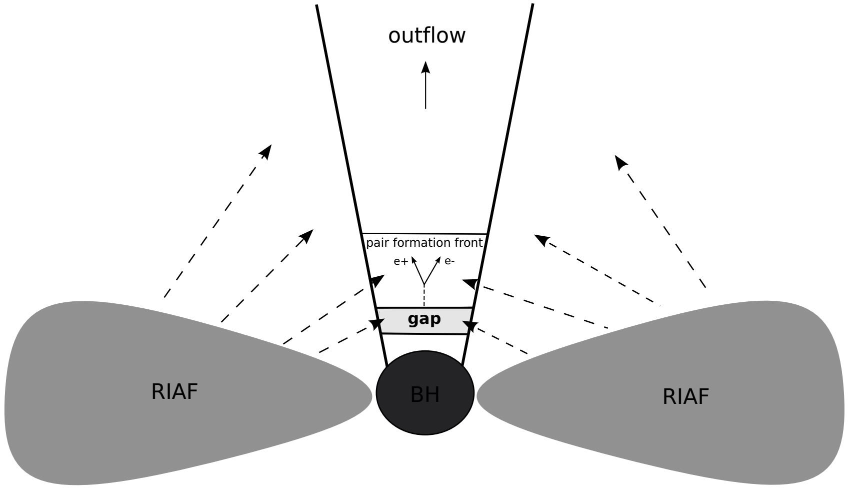
VHE electrons **+** IC of ADAF soft photons + elm cascade

Application to M87: (cf. Neronov & Aharonian'07; 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)





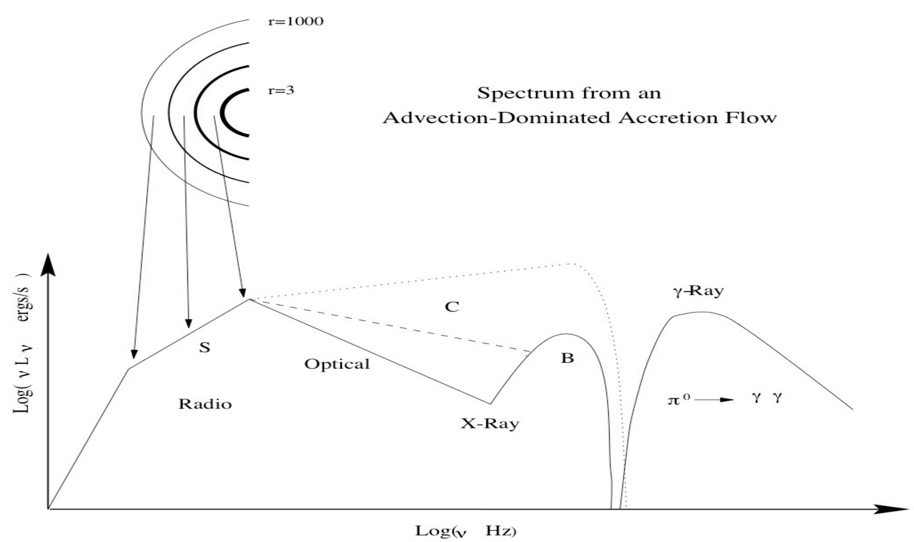


How to produce VHE gamma-rays - Example II

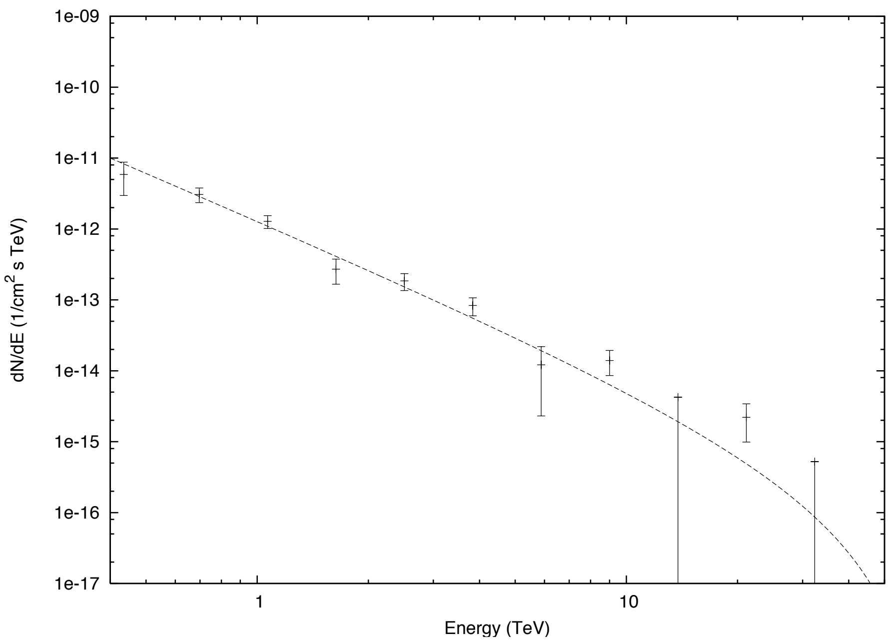
Centrifugal particle acceleration + IC scattering of ADAF photons

(R. & Aharonian'08a,b)

- electron max energies: $\gamma_{max,e} \sim 5 \times 10^7$ (via balance by IC cooling)
- IC (Thomson) off ADAF photons gives VHE emission up to ~ 5 $(\gamma/10^7)$ TeV
- at highest energies sensitive to seed photon spectrum, i.e. disk conditions.



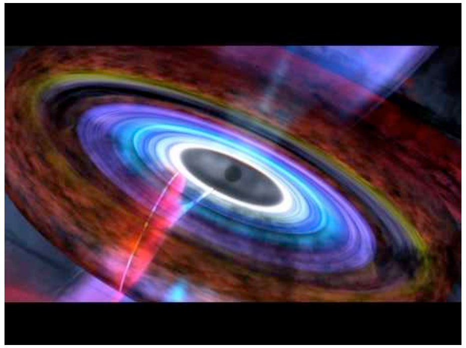
ADAF spectrum: Synchrotron + Comptonized parts
(e.g., Mahadevan '97)



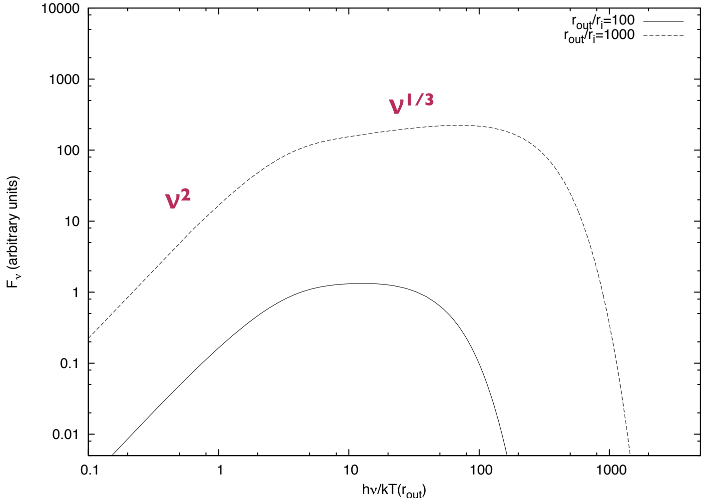
Resultant TeV spectrum for Bondi accretion rate

Can TeV gamma-rays escape unabsorbed?

_**Case I:** Standard (SS) disk (thermal black body)



- $L_{bol} \sim 10^{42}$ erg/s $\geq L_{disk} \Rightarrow$ accretion rate $\sim 10^{-6}\, m_{Edd}$
- Temperature profile $T(r) \sim 7\times10^3\,(r_s/r)^{3/4}$ K
- Disk emission is maximized at frequency $\nu \sim 3\, kT/h \sim 4 \times 10^{14}$ Hz $\Leftrightarrow$ 2 eV
- *Remember:* Photon-photon interaction $\varepsilon_t \sim (1\ \mathrm{TeV}/\varepsilon_\gamma)$ eV
- Disk emission dominated by radius from $r \sim r_s$
- Implies huge target number density $\Rightarrow$ optical depth $\tau_{\gamma\gamma} \sim n_t\, \sigma_{\gamma\gamma}\, r_s >> 1$



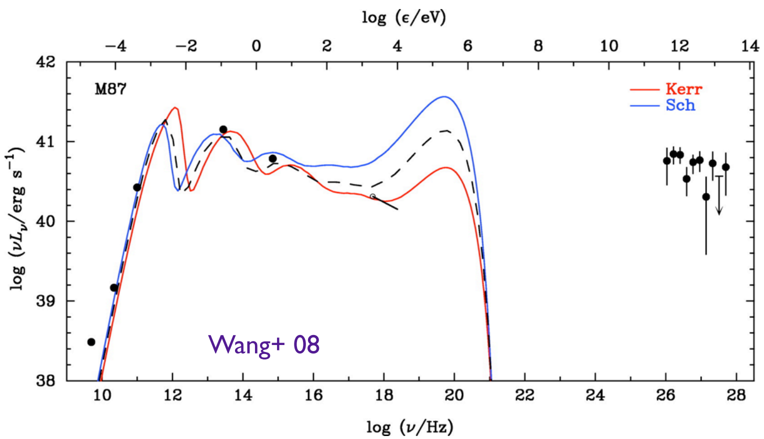
unable to escape

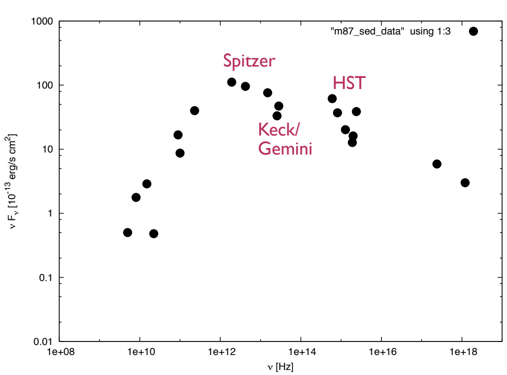
Can TeV gamma-rays escape unabsorbed?

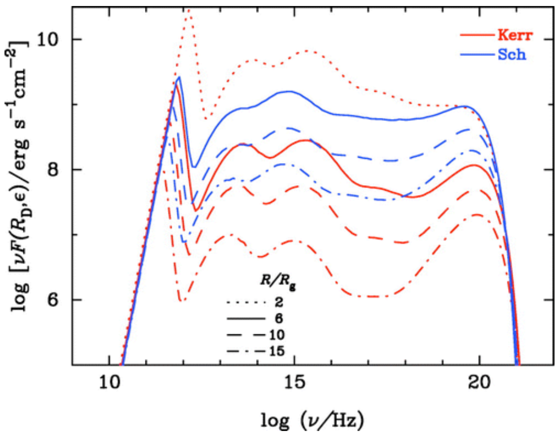
_Case II: RIAF/ADAF disk with α Bondi rate (Levinson & R. 2011, cf. also Li+ 09)

- 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 $\tau \sim n_e \sigma_T r << 1$
  - $\tau_{\gamma\gamma} \propto L_c \propto$ (*accretion rate*)$^{\mathbf{2\text{-}4}}$ ~ 0.2 - 5 for α Bondi
  - escape of ≤ 10 TeV photons possible for gap models, and expected for centrifugal models
  - optical depth highly sensitive on accretion rate!

escape possible



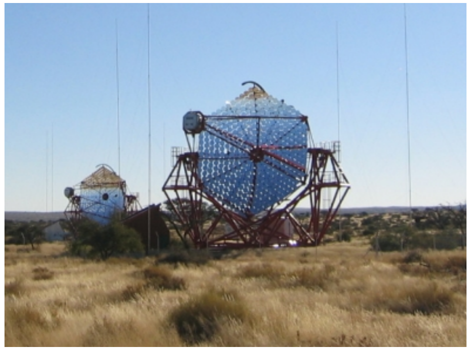


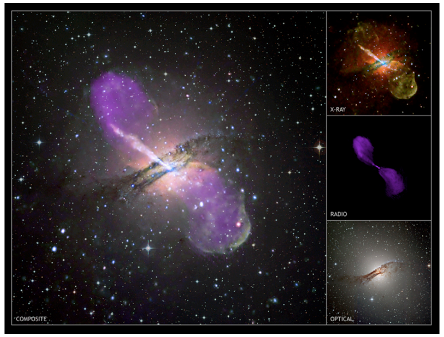


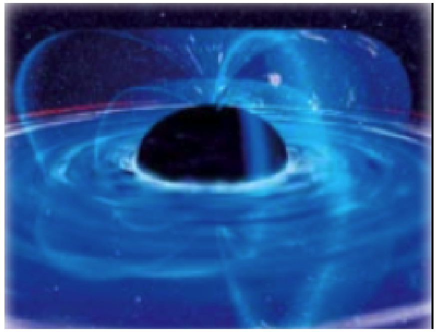
VHE emission from nearby radio galaxies

_Zoom-in I conclusion:

In selected, nearby, low-luminous, non-aligned AGN (e.g., M87, Cen A), VHE processes close to black hole may become observable and allow fundamental diagnosis of its environment.



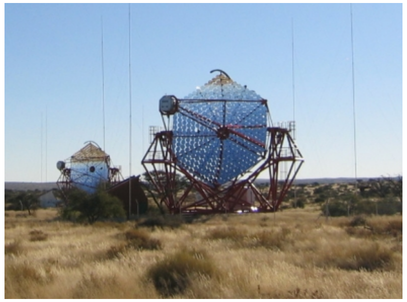




_Zoom-in II: UHE cosmic-ray production in FR I

- the case of Cen A
- cosmic-ray acceleration sites and efficiencies

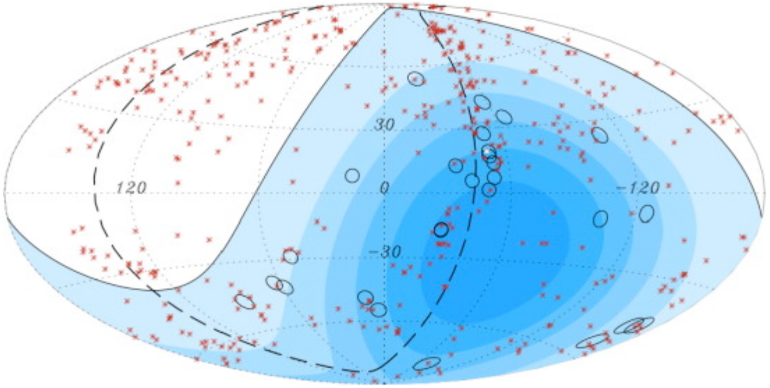
Cen A as a possible UHECR source?



★ **_Cen A is a HE & VHE γ-ray source !**

★ **_Is Cen A an extreme UHECR source ?**

- observational motivation:
  - apparent clustering of arrival directions of UHECR above 57EeV - Cen A (still) has the largest excess relative to isotropic expectations (PAO: Science 318 [2007]; APh 34 [2010])

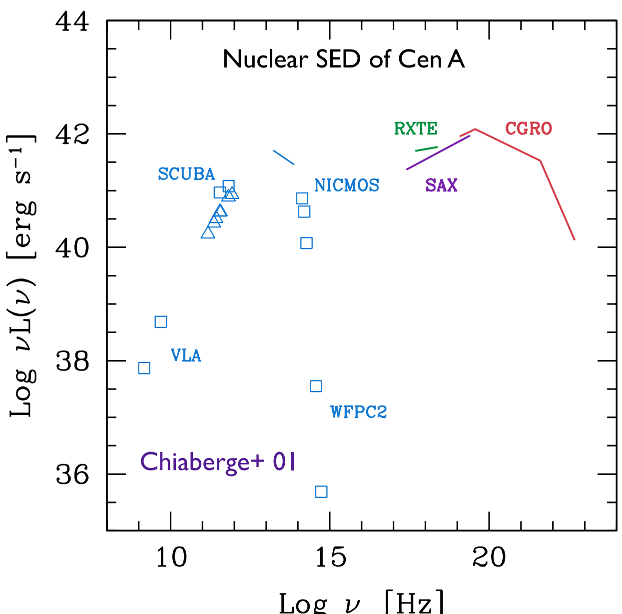


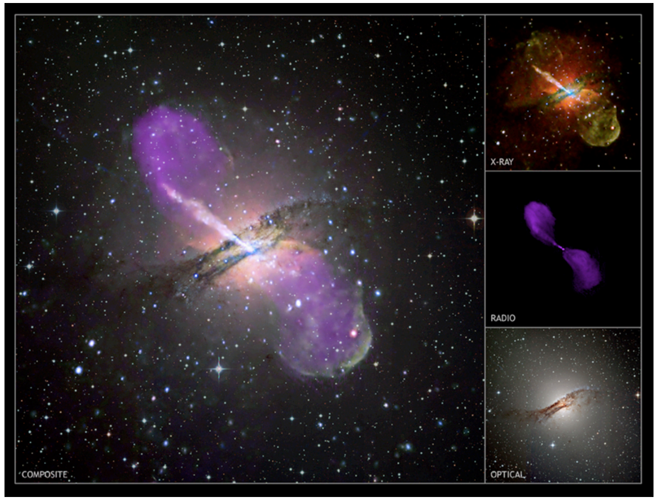
- theoretical question:
  - Does it seem likely that particles might get accelerated to extreme UHECR energies in Cen A?
  - Given what we (seem to) know about Cen A, do existing mechanisms operate efficiently enough?

Cen A - general properties

_Cen A: nearest FR I radio galaxy:

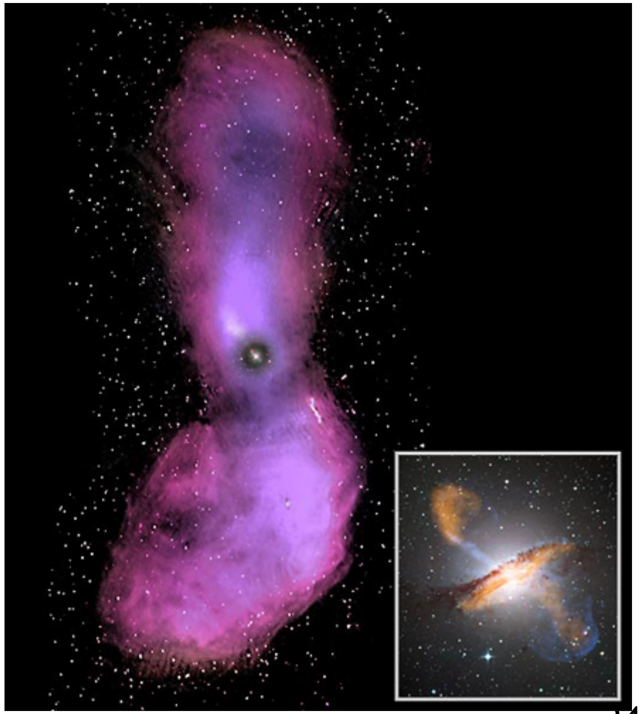
- distance ~ 3.4 Mpc
- central BH mass M_{BH} ~ (0.5-1) x 10^8 M_{sun}
- under-luminous $L_{bol} < 10^{43}$ erg/s (quasar SED)
- jet velocity ~ 0.5c
- jet inclination (VLBI) > 50°, modest beaming!
- complex radio morphology (jets, lobes etc)
- hybrid disk configuration (no bbb)





linear scale ~ 15 kpc

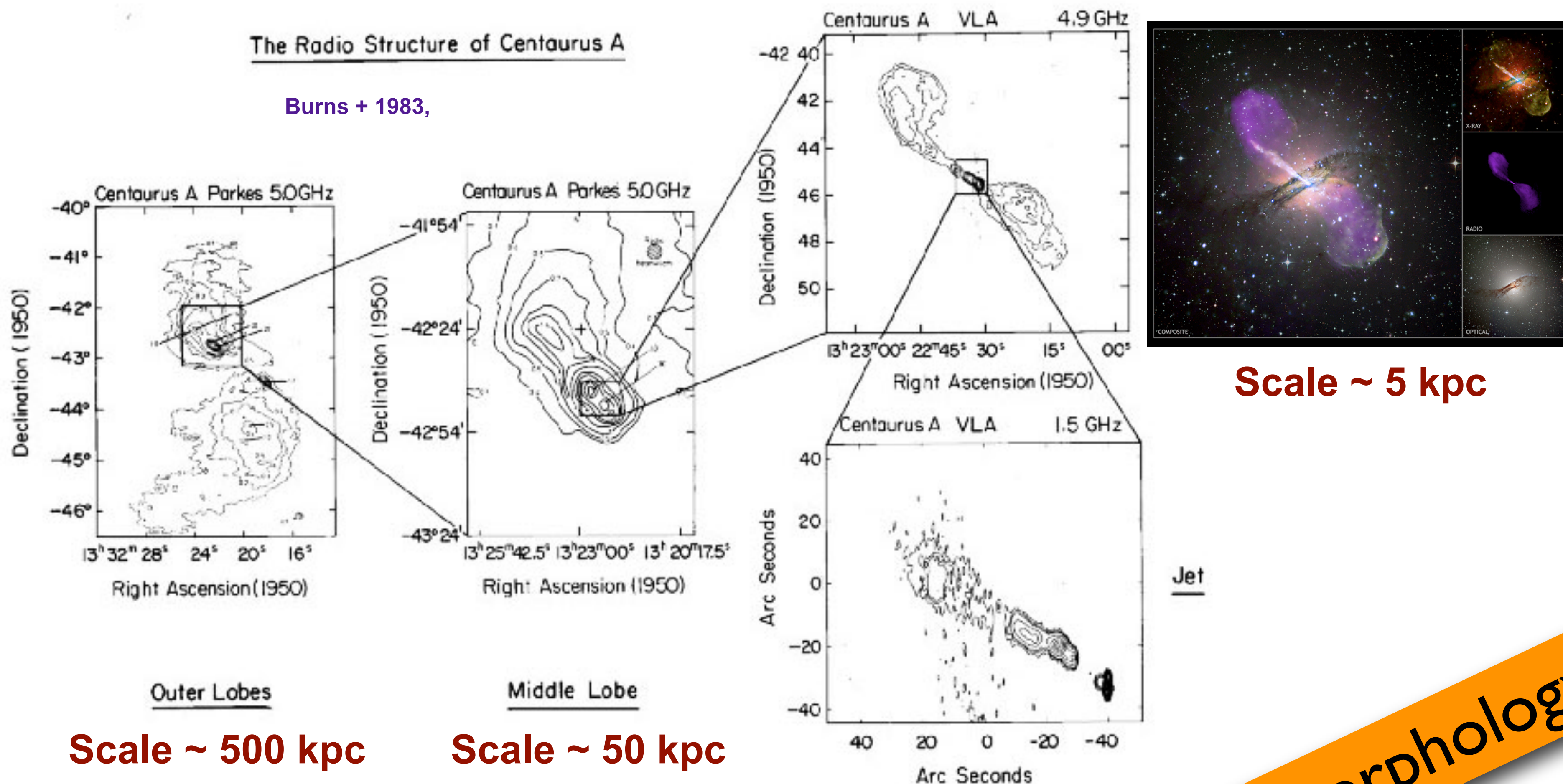
Credit: CSIRO/ATNF; ATCA;ASTRON; Parkes; MPIfR; ESO/WFI/AAO (UKST); MPIfR/ESO/APEX; NASA/CXC/CfA ; see also Feain+ "11



linear scale ~ 500 kpc

Cen A as nearest AGN - radio structure

Burns + 1983,



Scale ~ 500 kpc

Scale ~ 50 kpc

Scale ~ 5 kpc

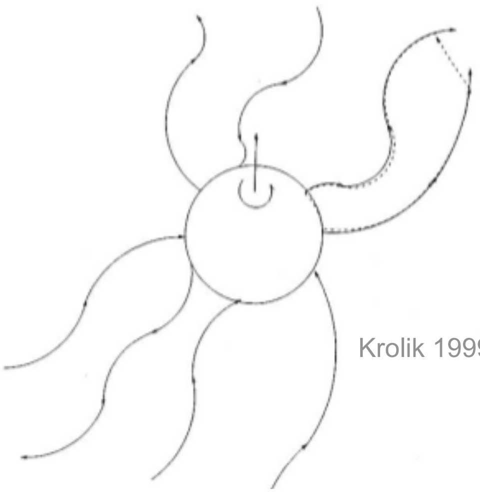
Complex morphology

Cen A as possible UHECR source?

_Efficient acceleration of **protons** close to black hole - ***unlikely***

- rotating BH with $J_{BH} = a\, GM_{BH}^2/c$ embedded in magnetic field (BZ)
  - ➡ **B** rotates with angular velocity of horizon *(membrane paradigm)*
  - ➡ induced electric field **E ~ a B**
  - ➡ available potential $\mathbf{\Phi \sim r_g E}$
  - ➡ maximum achievable CR energy:

$$E_{max} \sim 3 \times 10^{19}\, a\, Z\, M_{BH,8}\, B_{0,4}\, (h/r_g)^2 \text{ eV}$$



Krolik 1999

But: (1) Cen A is not massive enough

(2) Ordered B_0 < equipartition magnetic field < 10^4 G,

(3) Vacuum breakdown ($h<r_g$) is to be expected (Levinson & R 11)

(4) Curvature radiation would otherwise suppress (Levinson '00)

(5) Tendency for low spin ($a \leq 0.5$) in FR I (Daly '11)

?UHECR from quasar remnants?

Boldt & Gosh 1999

_Theory: Blandford & Znajek '77; MacDonald & Thorne '82; Komissarov '04...
_Recent discussion in AGN context: Boldt & Gosh '99; Levinson '00; Neronov+ '05; Kachelrieß+ '08; Levinson & R '11, R'11....

Cen A as possible UHECR source?

_Efficient acceleration of **protons** by shocks-in-jet - ***unlikely***

- non-relativistic shock acceleration timescale:

$$t_{\rm acc} \sim \frac{E}{(dE/dt)} \sim \left(\frac{E}{dE}\right) t_c \sim r_{\rm gyro} \left(\frac{c}{u_s^2}\right)$$

- maximum energy by balance with cross-field diffusion/shock lifetime:

$$\mathbf{E_{max}} \sim Z\, e\, B\, r_t\, \beta_s \leq 2 \times 10^{19}\, Z\, B_{0,4}\, \beta_{s,0.1}\ \mathrm{eV}$$

(using $B(r) \sim B_0\, r_s/r$ with $B_{0,4} = 4\, B_0/10^4$G and $\beta_{s,0.1} = \beta_s/0.1\, c$)

But: (1) expect rather low *internal* shock speeds

➡ low overall bulk flow $\leq$ 0.5c

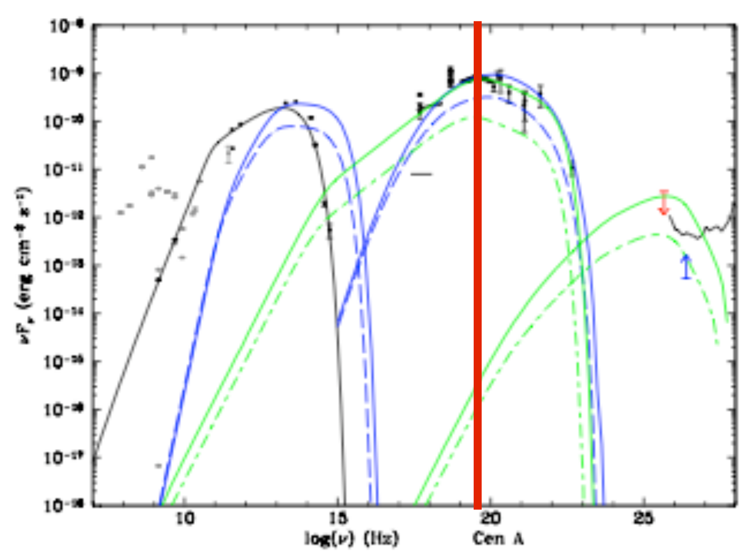
(Tingay+ 01; Hardcastle+ 03)

(2) supported by nuclear SED

➡ synchrotron peak (independent of B):

$\nu_s \sim 2 \times 10^{19}\, (\beta_s/0.1)^2$ Hz

(3) FR I energetics, see following



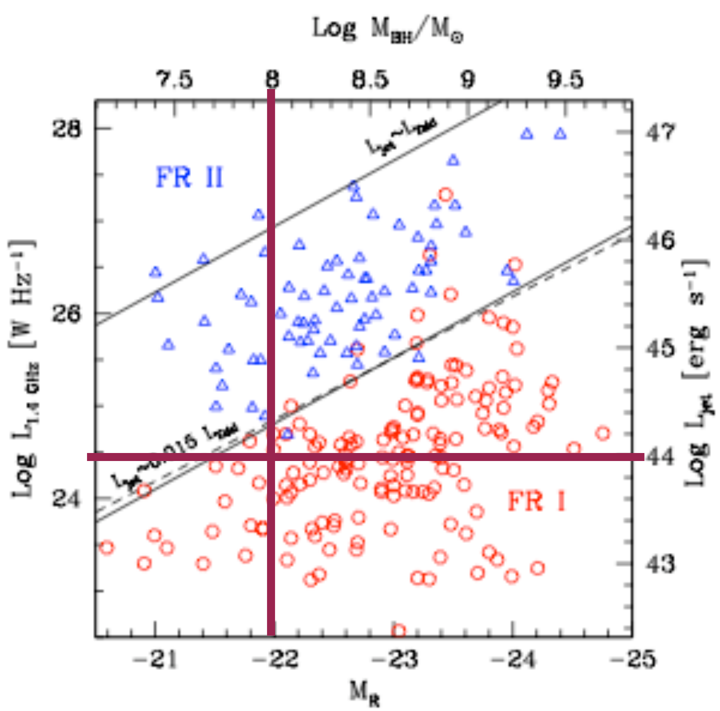
Lenain+ 2008

UHECR from Cen A?

_ Constraints from FR I jet power requirements:

- Magnetic flux carried by the jet: $L_m \sim \pi r^2 (B_p^2/8\pi)\, u_z$
  - from shock acceleration: express B in terms of E_{max}, i.e., $B \propto E_{max} / Z\, \beta_s$
  - minimum jet power $L_j \sim 2\, L_m$

$$L_j \sim 10^{44} \left(\frac{u_z}{0.5c}\right) \left(\frac{0.1}{\beta_s}\right)^2 \left(\frac{E_{\max}}{10^{19} eV}\right)^2 \frac{1}{Z^2} \quad \mathrm{erg/s}$$



No 10^{20}eV protons from shocks in Cen A

Ghisellini & Celotti'01

Cen A as possible UHECR source? (R & Aharonian'09)

_Efficient 2nd order Fermi acceleration in outer lobes? - **unlikely?**

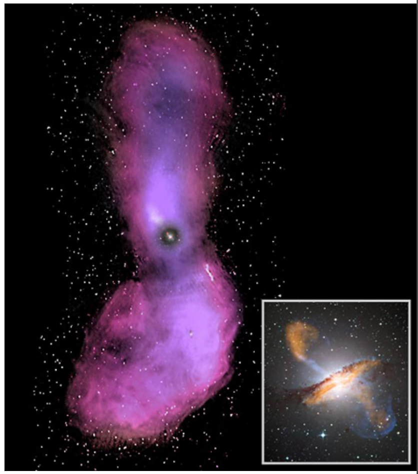
- acceleration timescale:

$$t_{\rm acc} \sim \frac{E}{(dE/dt)} \sim \left(\frac{E}{dE}\right) t_s \sim \left(\frac{c}{v_A}\right)^2 \frac{\lambda}{c}$$

- Maximum when acceleration = escape (cross-field):

$$\mathbf{E_{max} \sim 2 \times 10^{19}}\ Z\ \mathbf{(v_A/0.1c)}\ (R/100\ \mathrm{kpc})\ (B/10^{-6}G)\ \mathbf{eV}$$

may account for PAO events if (!) $v_A > 0.3$ c (Hardcastle+ 09)



linear scale ~ 500 kpc

But: (1) If observed soft X-ray emission is indeed thermal in origin (Isobe+ 01; Marshall & Clark '81)

➡ thermal plasma density of $n_{th} \sim (10^{-5} - 10^{-4})$ cm^{-3}

➡ Alfven speed ~ c/300 << c (cf. also O'Sullivan+ 09)

(2) Faraday RMs suggest densities ~ n_{th} (Feain+ 09)

Cen A as possible UHECR source?

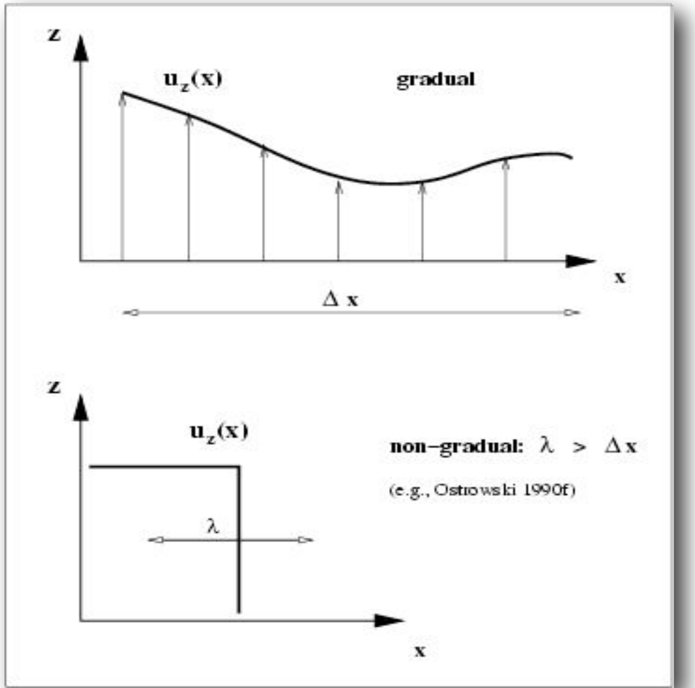
_ Efficient shear acceleration along kpc-jet - perhaps **possible**

Shear acceleration - recap: (Jokipii & Morfill '90; R. & Duffy '04, '06)

- Internal jet stratification (e.g., limb-brightening, polarization, higher energy emission closer to axis)
- Example: one-dim. gradual shear flow with frozen-in scattering centers:

$$\vec{u} = u_z(x)\ \vec{e}_z$$

➡ like 2nd Fermi, stochastic process with average energy gain:



$$\frac{< \Delta\epsilon >}{\epsilon_1} \propto \left(\frac{u}{c}\right)^2 = \left(\frac{\partial u_z}{\partial x}\right)^2 \lambda^2$$

with characteristic effective velocity:

$$u = \left(\frac{\partial u_z}{\partial x}\right) \lambda$$

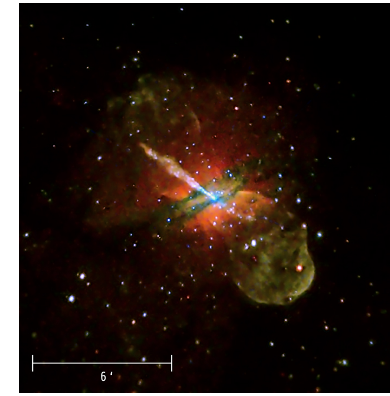
"2nd order Fermi-type"

➡ produces power-law $n(p) \propto p^{-(1+\alpha)}$

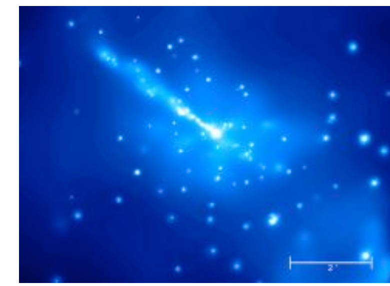
Non-gradual: Ostrowski '90, '98 ; **Gradual shear**: R & Mannheim '02; R & Duffy '04; R+ '07

Cen A as possible UHECR source?

_ On shear acceleration along kpc-jet in Cen A:



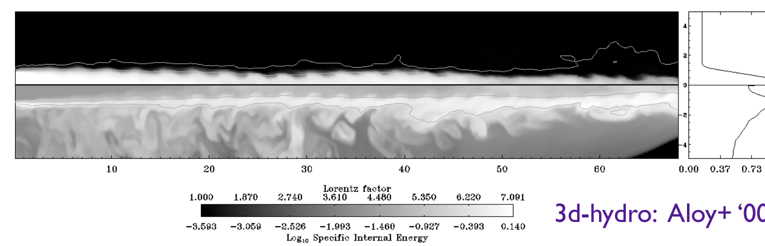
Credit: NASA/CXC/CfA/Kraft et al



- **Advantage:** "distributed" mechanism operating along jet
- **"Disadvantage":** needs high energy seeds $t_{acc} \propto [(\partial u/\partial r)^2\ \lambda]^{-1}$:

  $t_{acc,shear} < t_{adv}$ possible for $\gamma_p \sim 5 \times 10^9$ (using $\Delta r \sim r_j/2$, $\Delta v_z \sim 0.5c$)

  ➡ but: could be provided by shock acceleration in inner part



3d-hydro: Aloy+ '00

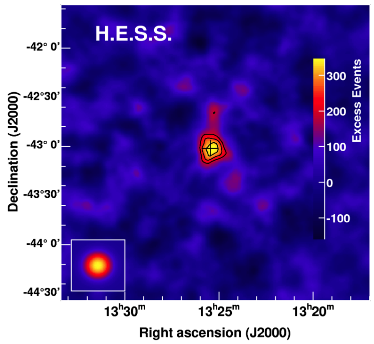
- **Energy boost** by factor ~(10-20) possible

  ➡ constraint by confinement $r_{gyro} < \Delta r$

  ➡ may be more, if B is amplified in shear (Urpin'06; Zhang+ '09)

- **Spectral change** possible due to operation of new mechanisms!

UHECR from nearby FR I radio galaxies



Zoom in II - conclusion:

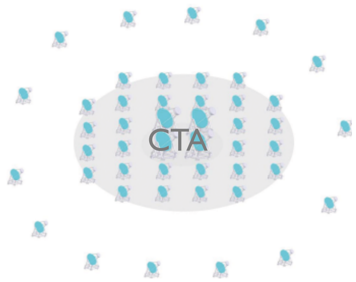
Cen A as possible UHECR source

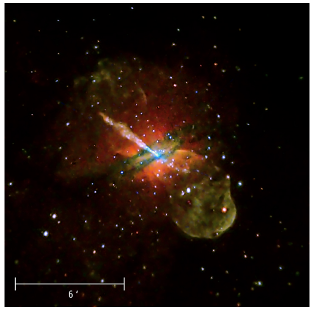
- observationally "motivated", theoretically "possible":
  - if protonic - via shear acceleration along kpc jet
  - if heavier - possibly also via BZ and shocks

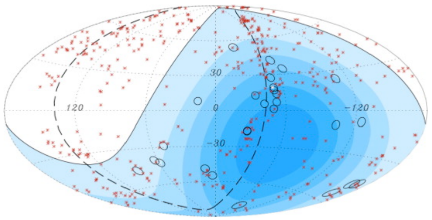
➡ spectral changes might be partly due to operation of different mechanisms

➡ composition heavier towards highest end?

(cf. Abraham et al. '10; Taylor et al. '11)







THANK YOU!

Reading/recommendations:

- B.M. Peterson: An introduction to active galactic nuclei, CUP 1997 *(AGN phenomenology)*
- A. K. Kembhavi; Jayant V. Narlikar: Quasars and Active Galactic Nuclei, CUP 1999 *(FRI/II dichotomy etc)*
- C.M. Urry & P. Padovani 1995: Unified schemes for radio-loud AGN, PASP 107, 803 *(AGN unification)*

- R. Antonucci 2011: Thermal and Nonthermal Radio Galaxies, ARA&A (arXiv:1101.0837)
- F.M. Rieger 2011: Non-thermal processes in black-hole-magnetospheres, IJMPD (arXiv:1107.2119)