Centaurus A as TeV γ-ray and possible UHECR source - Acceleration in context -

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Meudon Workshop
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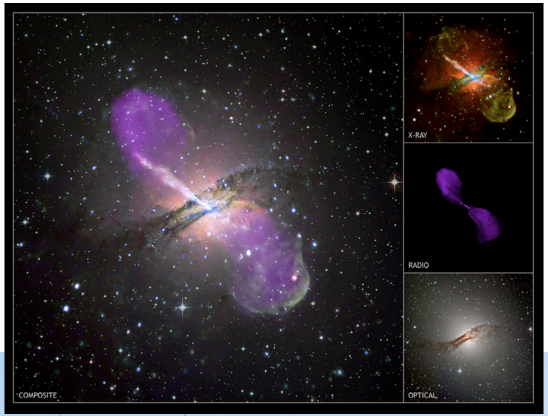

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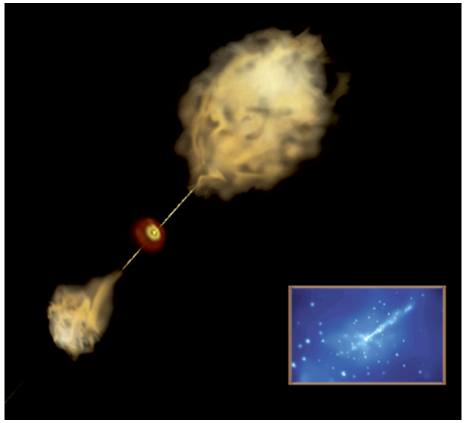
Orientation



Credit: NASA E/PO

★ _VHE gamma-rays from the non-blazar Cen A
- challenge to conventional jet models
- alternative: gamma-rays from vicinity of BH

★ _Accelerating particles in rotating jet magnetospheres
- gap-type acceleration parallel to m.f.
- centrifugal acceleration along rotating field lines

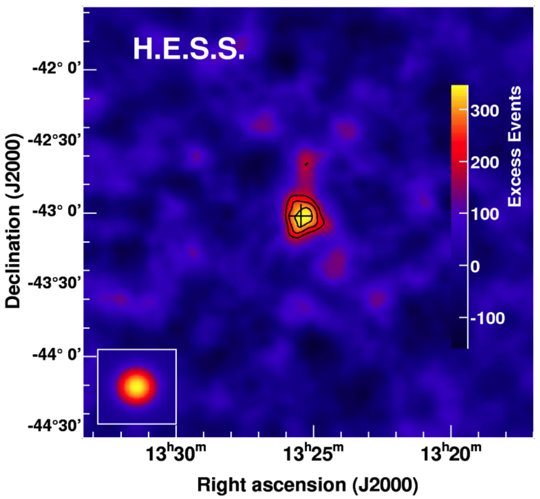
★ _How to produce VHE gamma-rays in Cen A
- IC upscattering of SS disk photons + elm cascade
- IC upscattering of ADAF disk photons

★ _Cen A as a possible UHECR source
- from close to the BH?
- from its giant lobes?
- from its jet?

Recap I - VHE gamma-rays from non-blazar Cen A

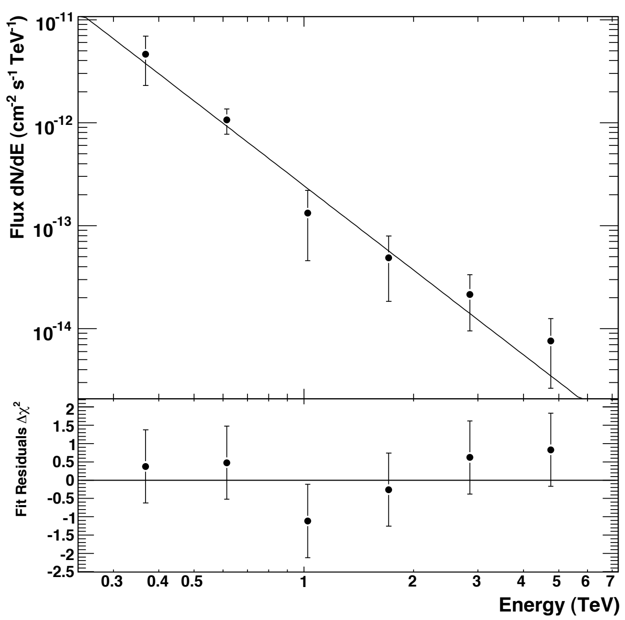
★ _Cen A: FR I radio galaxy, non-blazar prototype:

- distance ~ 3.4 Mpc
- central BH mass $M_{BH} \sim 10^8\ M_{sun}$
- under-luminous $L_{bol} \sim 10^{43}$ erg/s
- jet velocity ~ 0.5c
- jet inclination (VLBI) > 50°, modest beaming



★ _H.E.S.S. detection (more than 100h):

- Emission up to 5 TeV
- relatively hard spectrum (photon index -2.7)
- isotropic L(>250 GeV) = 2.6 $\times 10^{39}$ erg/s
- no variability detected



Aharonian+ 2009; Raue+ 2009

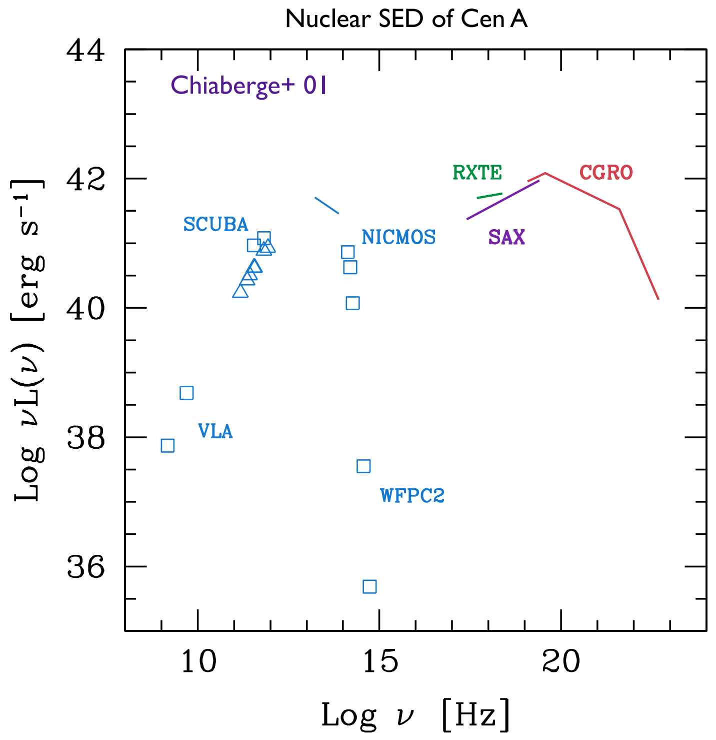
★ _But without strong Doppler boosting:

- intrinsic max. energy not boosted
- absorption not reduced
- ....

Recap II - Origin of VHE γ-rays in Cen A ?

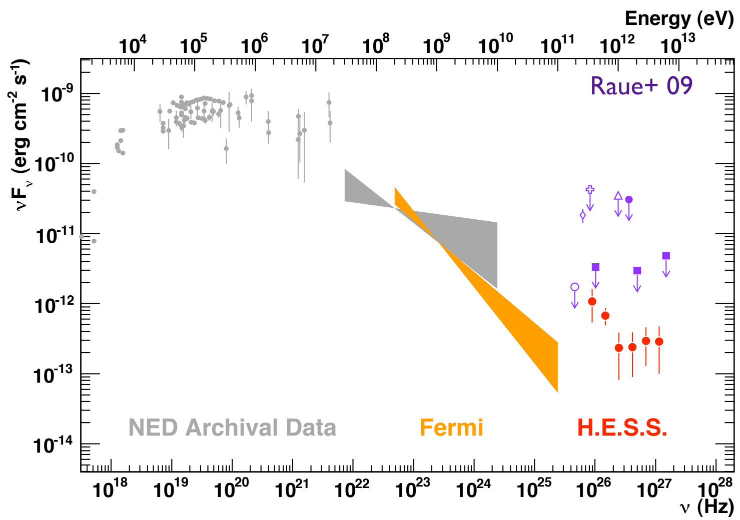
★ _Challenges to conventional jet models:

- **one-zone SSC** (if far-IR peak is synchrotron)
  - unable to account for TeV emission
- **spine-layer** ($\Gamma_s >> \Gamma_l > 1$) (Ghisellini+ 05)
  - less promising (strong de-beaming of spine due to large viewing angle, layer dominates via EC of seed photons from spine...)
- **proton-synchrotron** (Reimer+ '03)
  - intrinsic cut-off < 0.25 TeV
- .....



★ _Evidence for different components?

- Fermi extrapolation ➡ too low TeV flux
  (but variability may occur)
- may need more data to distinguish (variability...)



On the origin of VHE γ-rays in Cen A

★ _Close BH models as alternative:

(e.g., Neronov & Aharonian'07; R. & Aharonian'08, '09; Istomin & Sol'09; Beskin '09)

- Idea: it happens close to the BH (~ a few r_g)

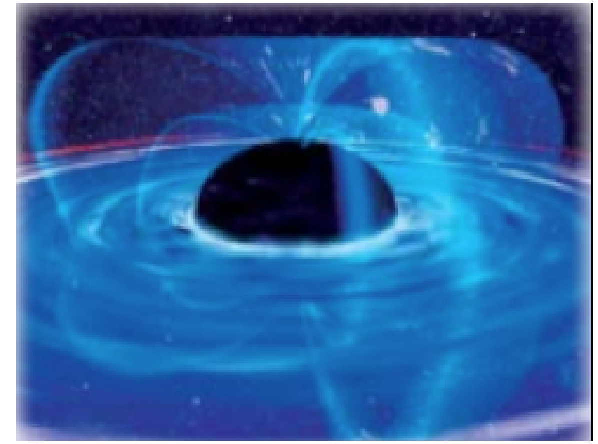
  ➡ variability t_{var} ~ a few (r_g/c)

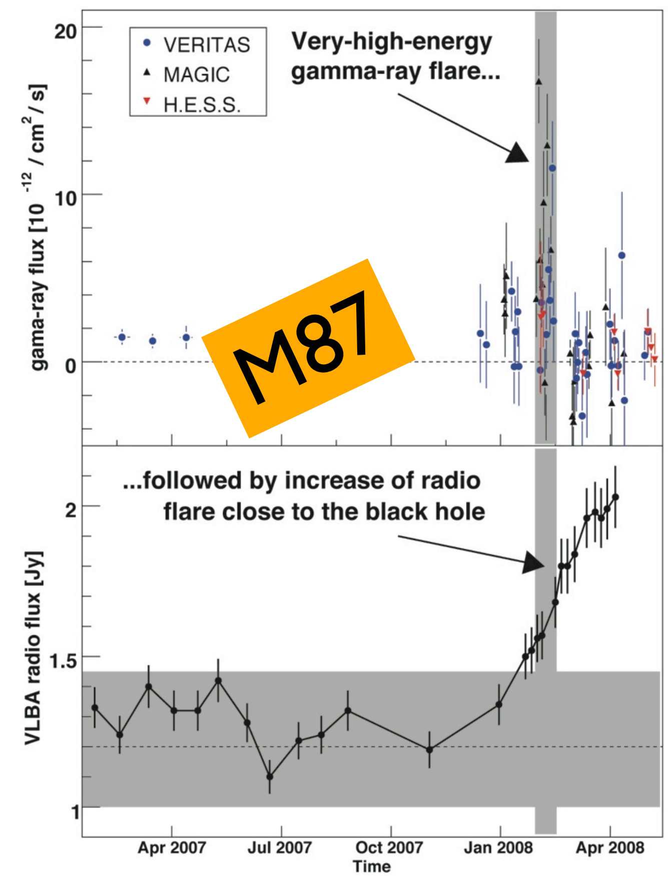
- Claim: can explain VHE facts

  ➡ analog to M87 (support from radio-TeV)

- Requires I: VHE electrons ($\gamma_e \sim 10^7$) for IC

- Requires II: little $\gamma\gamma$-absorption below 5 TeV



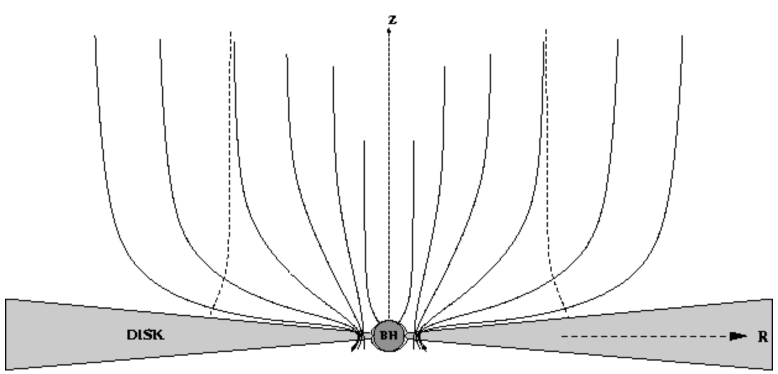


Acciari+ 09, Science 325

Particle acceleration in rotating BH magnetospheres

★_Example I - Gap-type particle acceleration (e.g., Neronov & Aharonian'07 for M87)

- similar to pulsars
- rotating **B** induces **E** = -(Ω x **r**) x **B**/c
- **E** must be supported by local charge density $\rho_{GJ} = \nabla \cdot \mathbf{E}/4\pi$ (Poisson)
- if $\rho < \rho_{GJ}$, we may have unscreened $E_{||}$ components
- electron acceleration $\gamma_e \sim 10^8$ possible (given curvat.+IC losses)
- protons energy limited by potential drop or curvature losses



Potential drawback:

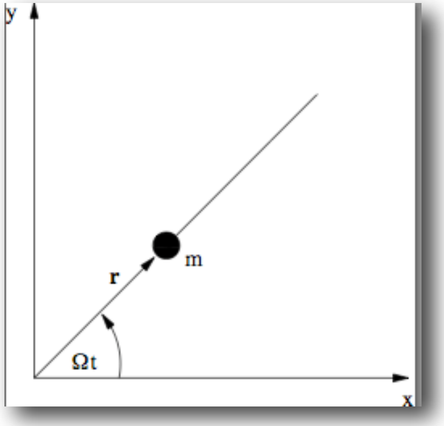
- AGN environment is plasma-rich (enough electric charges)
- $E_{||}$ is screened, acceleration suppressed (but cf. Komissarov'04)
- inertial effects not included

Particle acceleration in rotating BH magnetospheres

★_Example II - Centrifugal acceleration in Cen A (R & Aharonian'09)

- plasma-rich environment, $E_{||}$ screened, no gap-type acceleration
- account for inertial (centrifugal) effects close to light surface

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

Potential drawback:

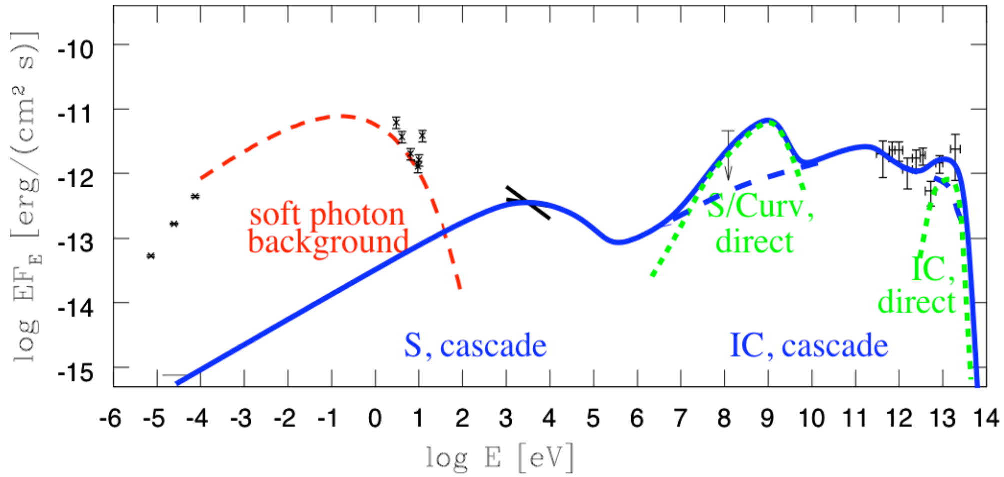
- requires B_ϕ/B_p to be small for efficient acceleration

How to produce VHE gamma-rays - Example I

VHE electrons **+** IC of SS disk photons + elm cascade

In analogy to M87: (Neronov & Aharonian'07)

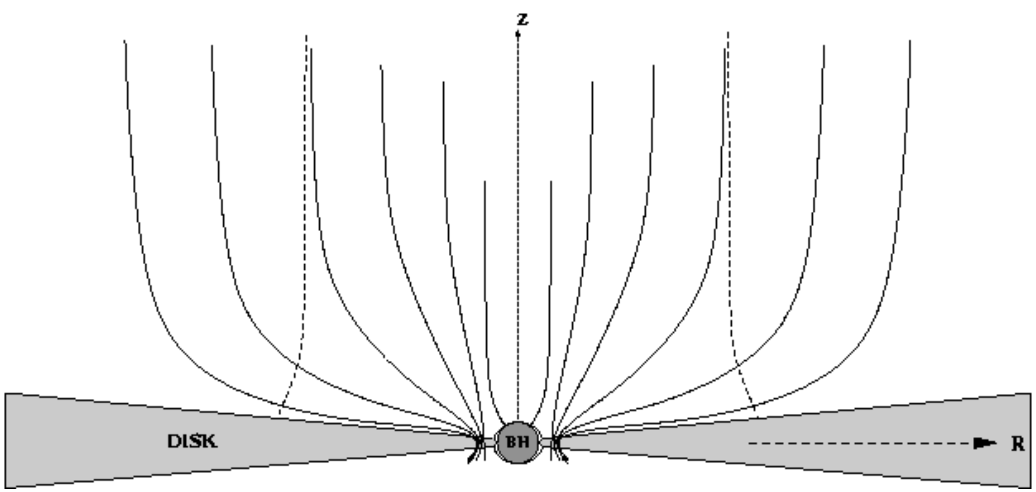
- primary electrons with $\gamma_e \sim 10^8$
- direct IC (KN regime) contribution (attenuated)
- elm cascade (initiated by absorption in ambient photon field)
- secondary IC emission etc.
- GeV and TeV emission could be connected



How to produce VHE gamma-rays - Example II

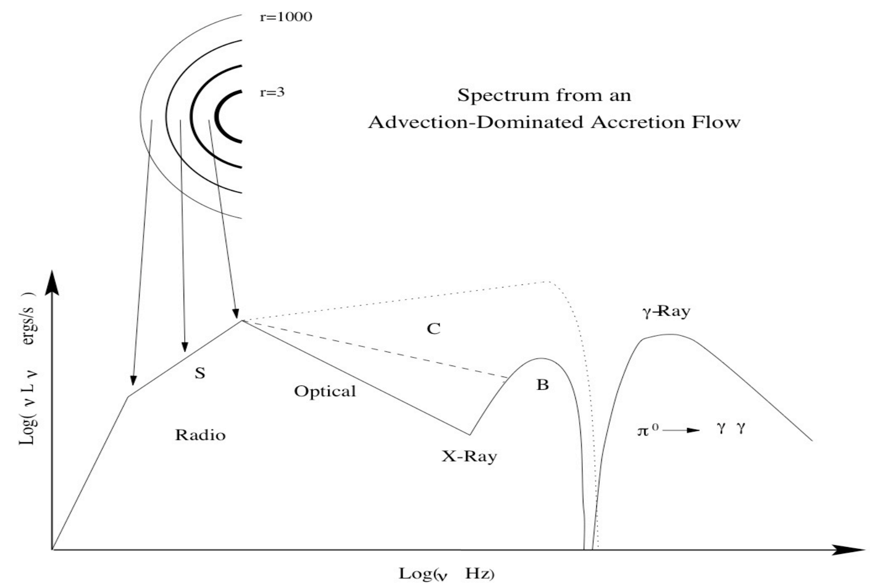
Centrifugal particle acceleration + **IC scattering of ADAF photons**

(R. & Aharonian'08a,b)



Jets as centrifugally accelerated disk wind.

(e.g., Blandford & Payne' 82; Fendt '97)



ADAF disk emission spectrum:

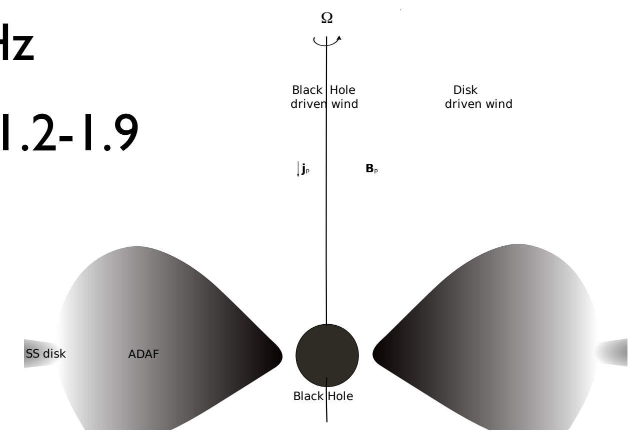
-synchrotron + Comptonized parts

(e.g., Mahadevan '97)

How to produce VHE gamma-rays - Example II

★ _Cen A as hybrid ADAF + SS disk candidate: (Marconi+ 01; Evans+ 04; Meisenheimer+07)

- optically-thin synchrotron emission peaking at ~ 7 x 10^{11} Hz
- Comptonized part with $L_\nu \propto \nu^{-\alpha}$ above peak with $\alpha(m_B) \approx 1.2$-1.9



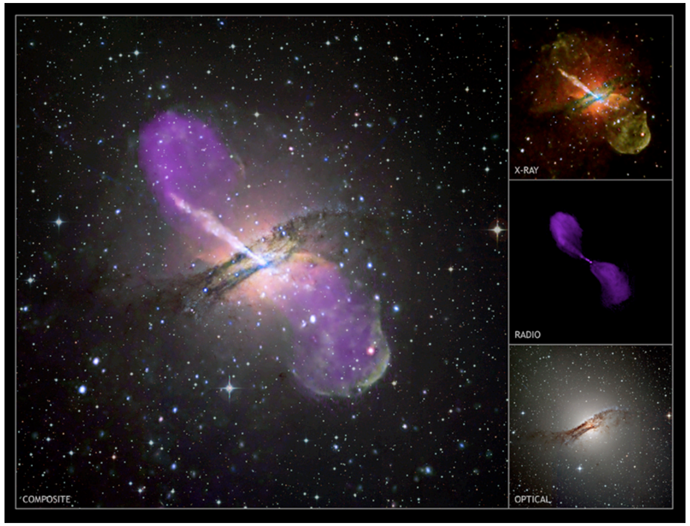
★ _Energetic electrons:

- $\gamma_{max,e} \sim 10^7$ (via centrifugal acceleration = IC cooling)

★ _TeV emission: (R & Aharonian 09)

- IC (Thomson) up-scattering of ADAF photons gives emission up to ~ 5 ($\gamma/10^7$) TeV ✓ o.k.
- at highest energies sensitive to seed photon spectrum ✓ o.k.
- maximum output $L_{TeV} \sim 10^{39}$ erg/s $\propto$ M_{BH} ✓ o.k.
- Minimum variability time ~ 5 r_s/c ~ 1 h

- not sensitive enough yet to probe -



Credit: X-ray: NASA/CXC/CfA/R.Kraft+; Radio: NSF/VLA/Univ. Hertfordshire/M.Hardcastle; Optical: ESO/WFI/M.Rejkuba+)

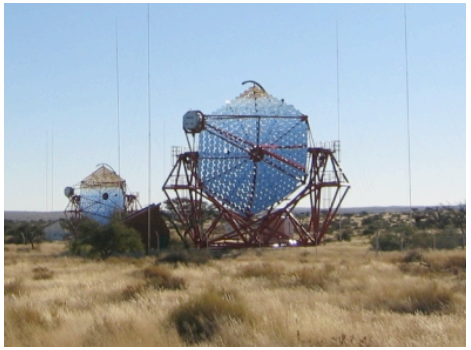
The centrifugal - ADAF IC scenario for Cen A

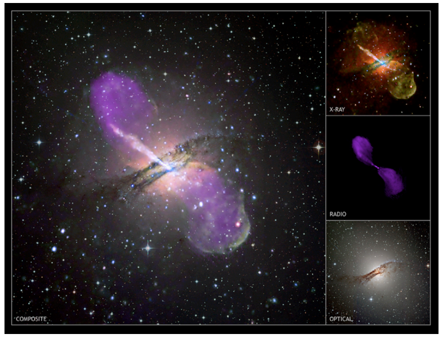
★ _Gamma-gamma absorption? (R & Aharonian 09)

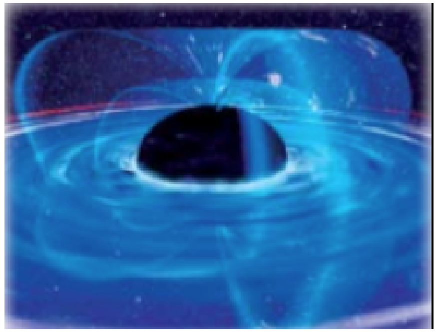
- infrared disk field is low enough to allow escape of TeV photons (for $\alpha \geq 1.4$)
- similar, if nuclear mid-infrared flux is dominated by torus ≥ 0.1 pc (Radomski+ 08)

_Preliminary Conclusion I:

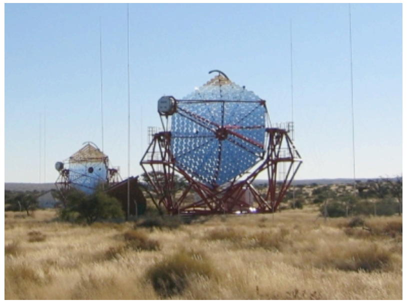
In selected, nearby, low-luminous, non-aligned AGN (e.g., M87, Cen A), VHE processes close to black hole may become observable and allow fundamental diagnosis of its environment.







Cen A as a possible UHECR source?

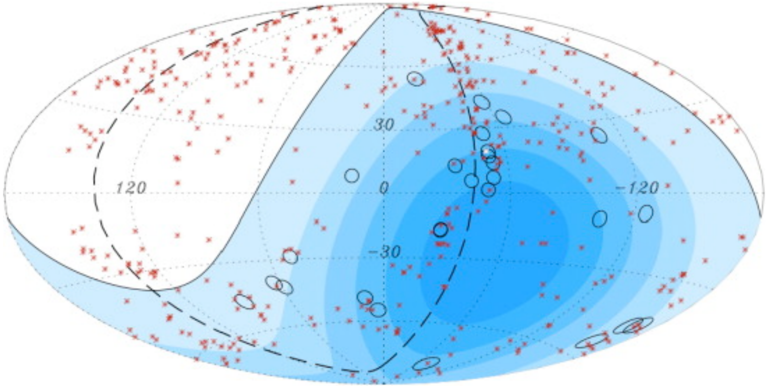


★ _**Cen A is a VHE gamma-ray source !**

★ _**Is Cen A an extreme UHECR source ?**

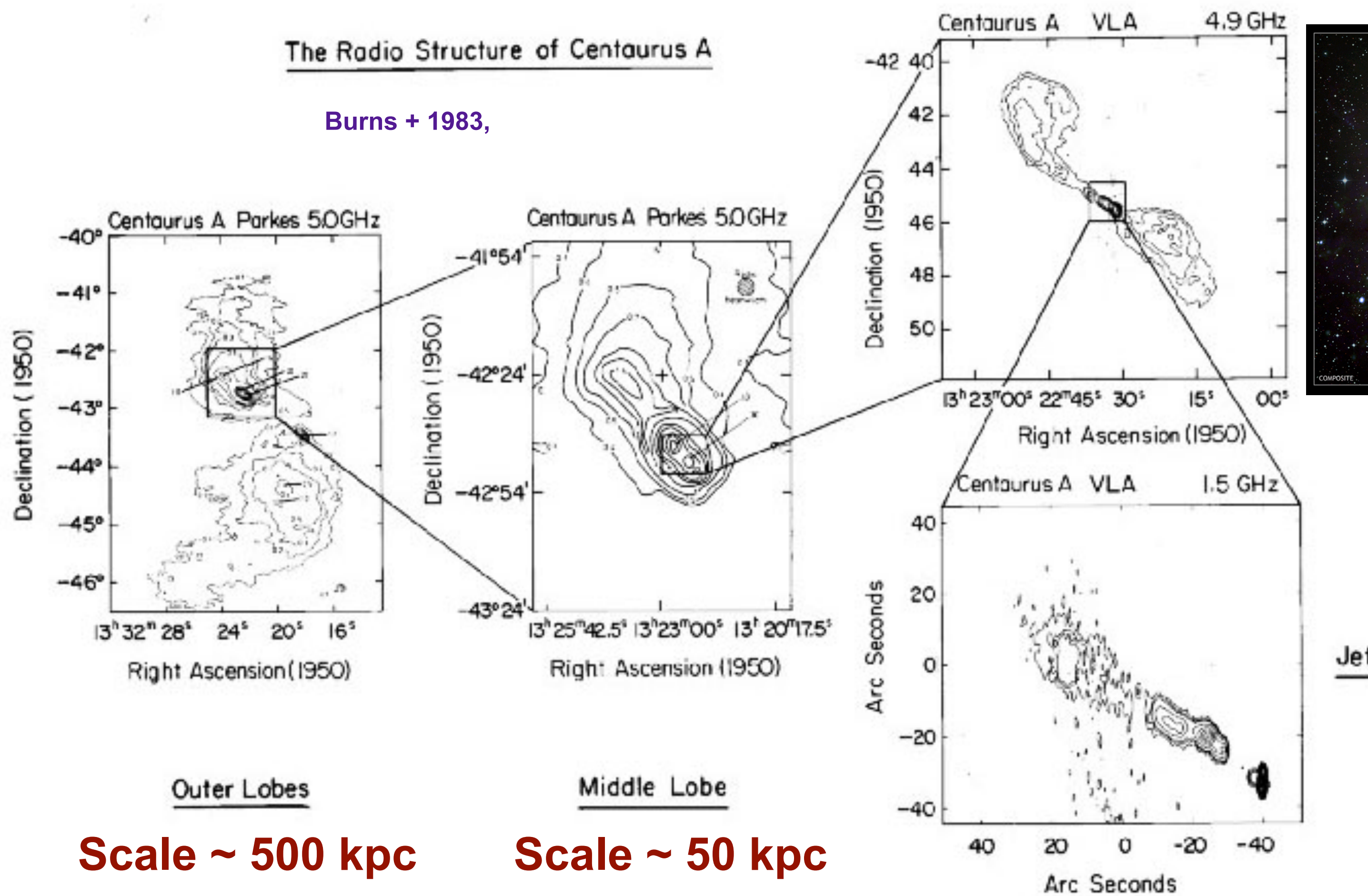
- observational motivation:
  - apparent clustering of arrival directions - up to 4 out of 27 PAO events (>57 EeV) may be associated with Cen A (PAO, Science 318 [2007]; APh 29 [2008])

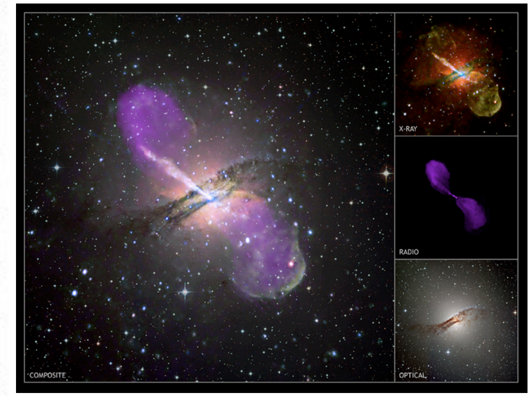
- theoretical question:
  - Does it seem likely that particles might get accelerated to extreme UHECR energies in Cen A?
  - Given what we (seem to) know about Cen A, do mechanisms operate efficiently enough?



Cen A as nearest AGN - radio structure

Burns + 1983,





Scale ~ 5 kpc

Scale ~ 500 kpc

Scale ~ 50 kpc

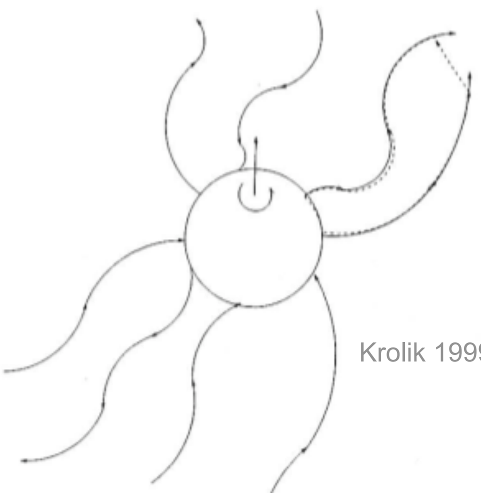
Complex morphology

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

★ _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 **$\Phi \sim r_g E$**
  - ➡ maximum achievable CR energy:

$$\mathbf{E_{max}} \sim 3 \times 10^{19}\ a\ Z\ M_{BH,8}\ B_{0,4}\ \mathrm{eV}$$



But: (1) Cen A is not massive enough

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

(3) Vacuum breakdown is to be expected

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

(5) Tendency for low spin in FR I (Daly '09)

?UHECR from quasar remnants?

Boldt & Gosh 1999

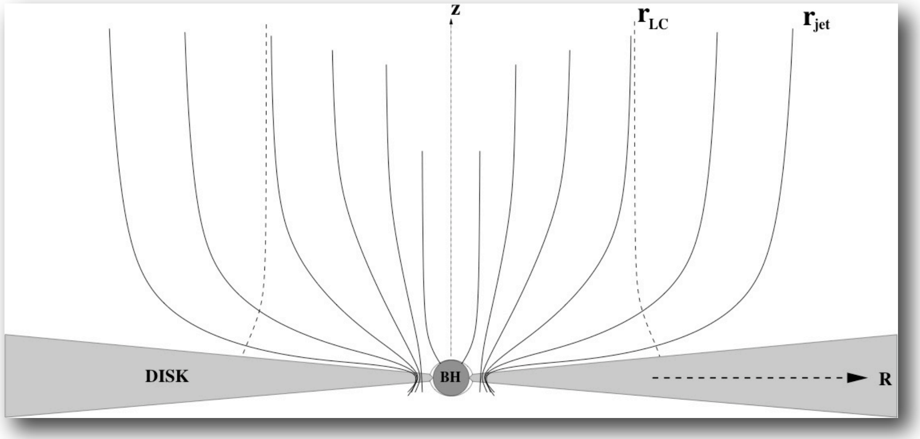
_Theory: Blandford & Znajek '77; MacDonald & Thorne '82; Komissarov '04...
_Recent discussion in AGN context: Boldt & Gish '99; Neronov & Semikoz '03; Neronov, Tinyakov & Tkachev '05; Kachelrieß, Ostapchenko & Tomas '08....

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

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

- Disk magnetosphere - centrifugal acceleration: (R & Aharonian '08b)

But: Breakdown of co-rotation: $E_{max} < 10^{17}$ eV for protons



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

★ _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 $\beta_{s,0.1} = \beta_s/0.1\, c$)

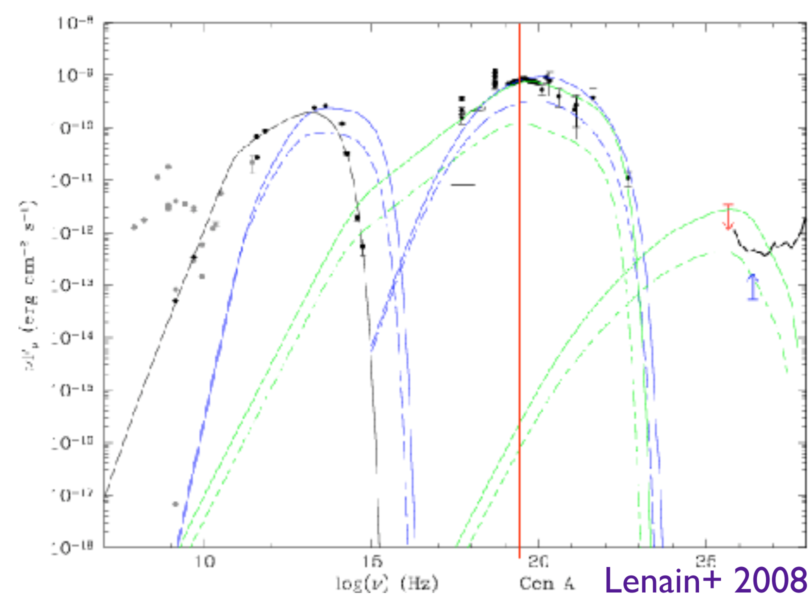
But: (1) expect rather low *internal* shock speeds
➡ low overall bulk flow ≤ 0.5c

(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 later



Lenain+ 2008

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

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

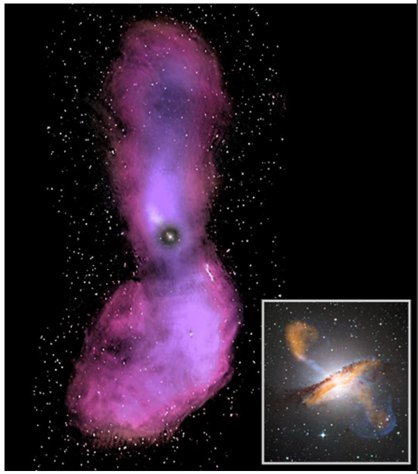
- acceleration timescale:

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

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

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

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



linear scale ~ 500 kpc

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

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

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

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

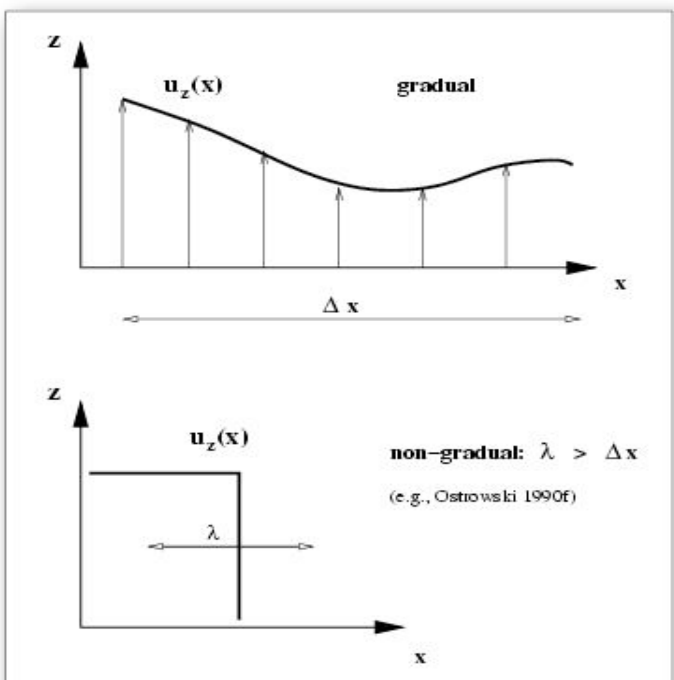
★_ Efficient shear acceleration along kpc-jet - perhaps **possible**

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:



$$\frac{<\Delta\epsilon>}{\epsilon_1} \propto \left(\frac{u}{c}\right)^2 = \frac{1}{c^2}\left(\frac{\partial u_z}{\partial x}\right)^2 \lambda^2$$

with characteristic effective velocity:

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

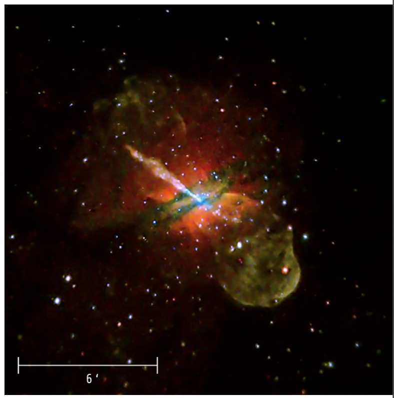
"2nd order Fermi-type"

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

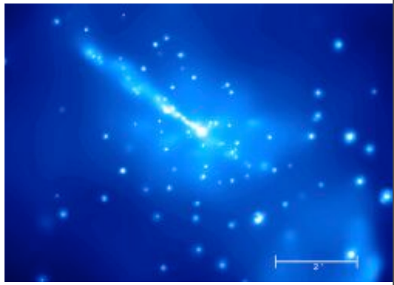
Non-gradual: Ostrowski '90, '98 ; **Gradual shear**: R & Mannheim '02; R & Duffy '04; R+ '07

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

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



Credit: NASA/CXC/CfA/Kraft et al

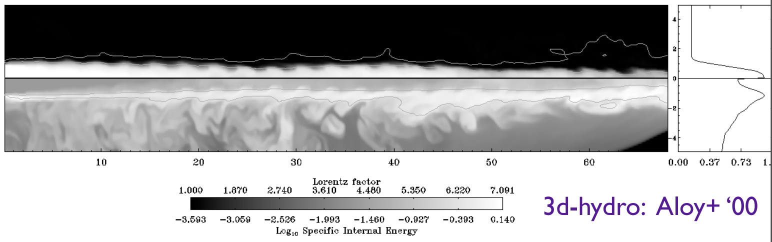


- **Advantage:** "distributed" mechanism operating along jet

- **"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 Cen A? (R'09)

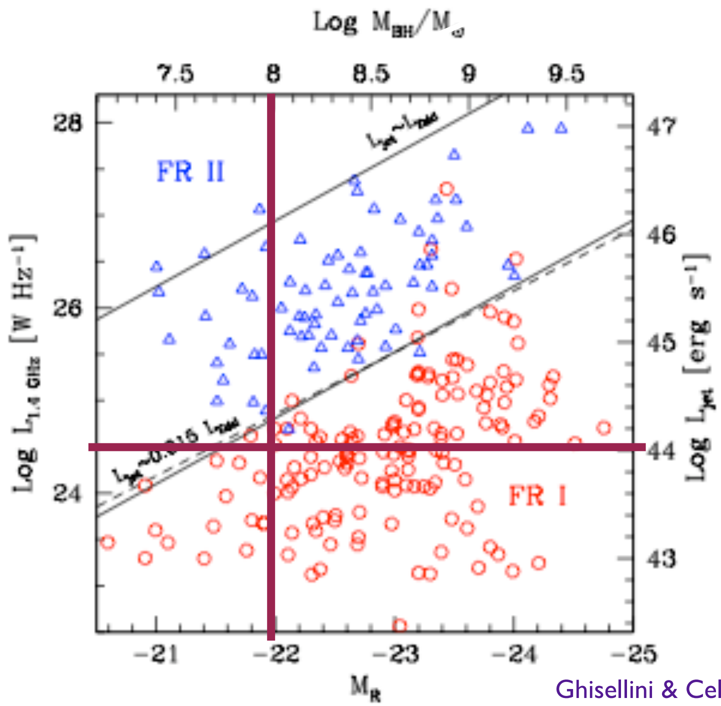
★_ Constraints from FR I jet power requirements:

- 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}: $B \propto E_{max} / Z\, \beta_s$
  - 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

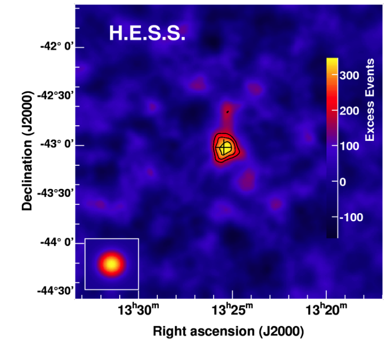
- Do same exercise for shear:
  - o.k. for $E_{max} \sim 10^{20}$ eV
    (e.g., $B \sim 10^{-4}$G, $r \sim 0.5$ kpc, $u_z \sim 0.5c$)



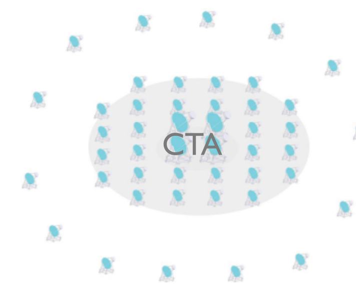
Ghisellini & Celotti'01

Summary

_Cen A is a TeV gamma-ray source (➡ H.E.S.S.)

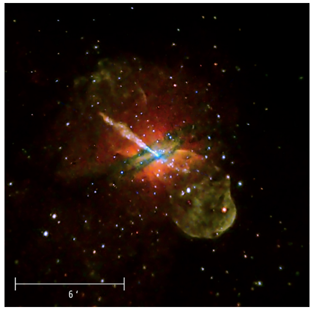


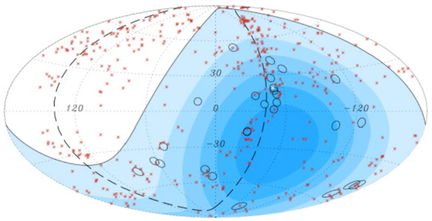
- may allow to probe near-BH environment ...
- need more data ➡ CTA



_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?





THANK YOU!