# Cen A as TeV gamma-ray and possible UHECR source


Frank M. Rieger

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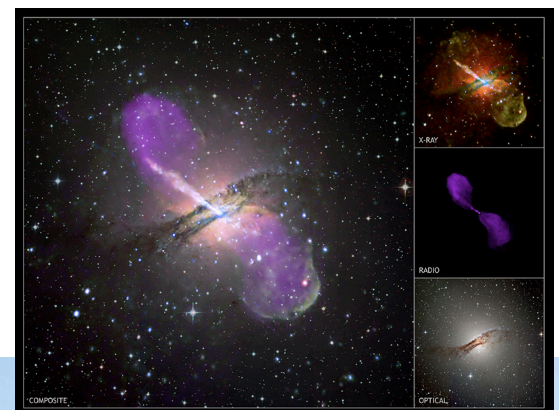






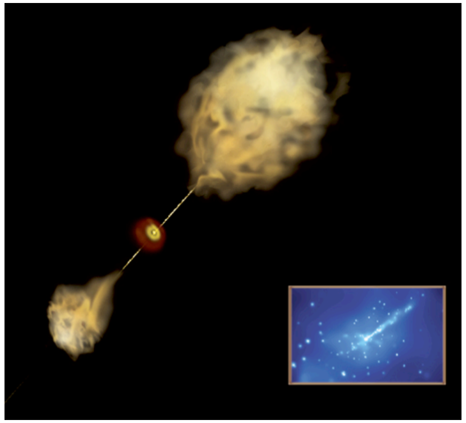
Max Planck Institut
für Kernphysik
Heidelberg, Germany

# Orientation

★ _VHE gamma-rays from the non-blazar Cen A

➡ challenge to conventional jet models

➡ alternative: gamma-rays from vicinity of BH



Credit: NASA E/PO

★ _Accelerating particles in rotating jet magnetospheres

➡ plasma-rich environment - no gap-type acceleration

➡ alternative: centrifugal acceleration along rotating field lines

★ _Application to Cen A

➡ TeV gamma-ray emission via IC up-scattering of disk photons

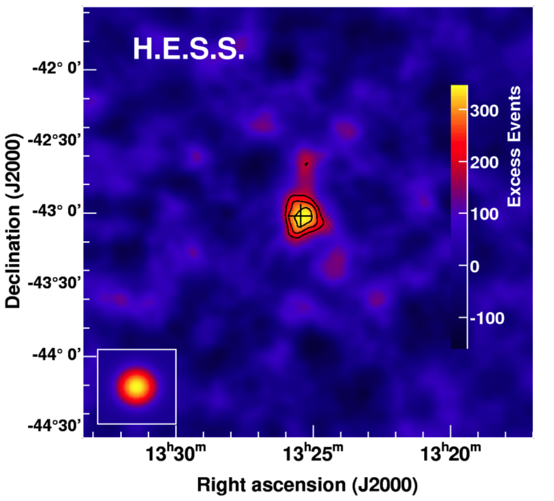
➡ producing UHECRs close to the BH?

➡ producing UHECRs in the 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 $M_{BH} \sim 10^8\ M_\odot$
- under-luminous $L_{bol} \sim 10^{43}$ erg/s
- jet velocity ~ 0.5c
- jet inclination (VLBI) > 50°, modest beaming

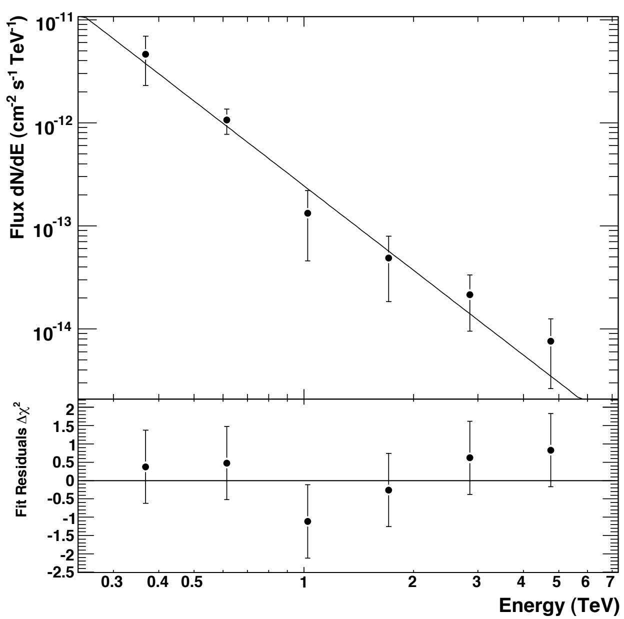



★ _H.E.S.S. detection (more than 100h):

- Emission up to 5 TeV
- relatively hard spectrum (photon index -2.7)
- isotropic L(>250 GeV) = $2.6 \times 10^{39}$ erg/s

★ _But without strong Doppler boosting:

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

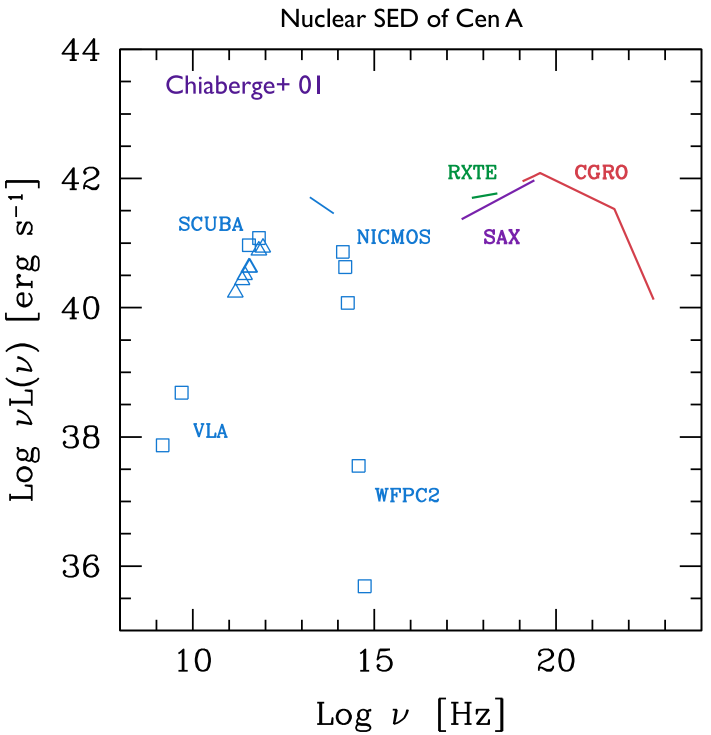



Aharonian+ 2009; Raue+ 2009

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

## ★ _Challenges to conventional jet models:

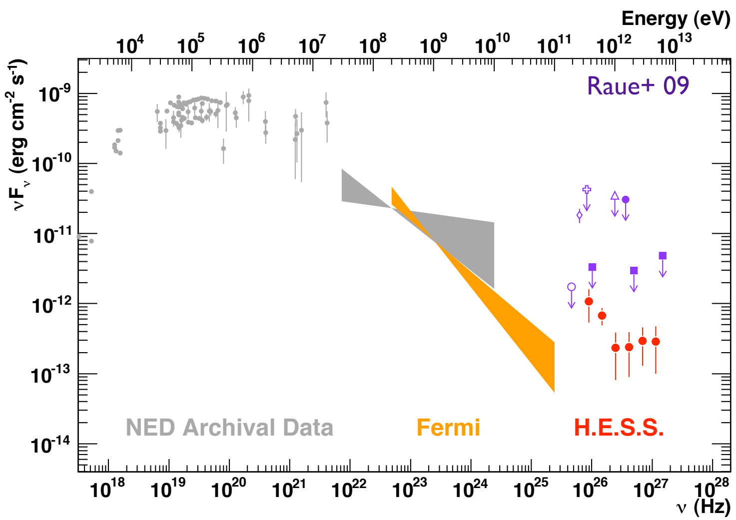
- **one-zone SSC** (if far-IR peak is synchrotron) is unable to account for TeV emission
- **spine-layer** ($\Gamma_s >> \Gamma_l > 1$) less promising (strong de-beaming of spine due to large viewing angle, layer dominates via EC of seed photons from spine) (Ghisellini+ 05)
- **proton-synchrotron** has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




## ★ _Evidence for different components?

- Fermi extrapolation ➡ too low TeV flux

  (but need full spectral info + variability may occur)
- need more data to distinguish (variability...)




## ★_Close BH models as another possibility

# A possible close BH scenario for Cen A

★ _Need energetic particles ⇒ Acceleration in rotating jet magnetopsheres:

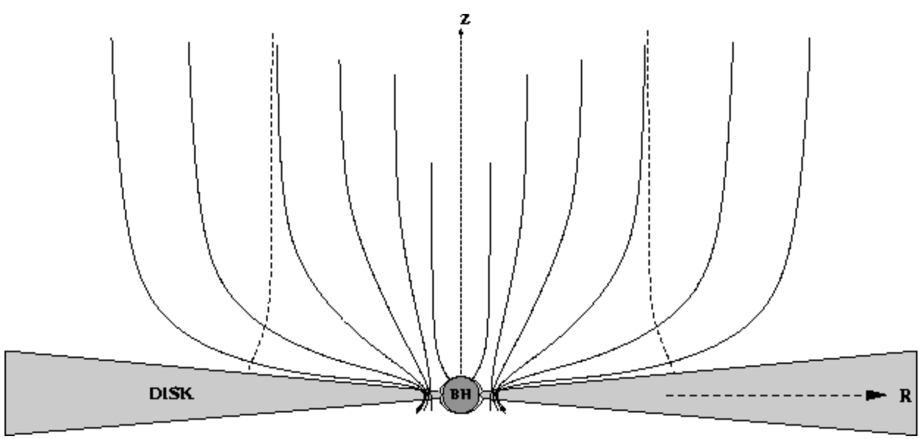
(Machabeli & Rogava ‘94; Gangadhara & Lesch ‘97; R & Mannheim ‘00; Osmanov & R ‘09)

_assume: rotating, monopole-type magnetic field structure
(driven by rotation in inner disk or ergosphere)

_assume: sufficiently plasma-rich environment (enough charges)

➡ electric field II is screened

➡ no efficient gap acceleration




_account for inertial effects

➡ Centrifugal particle acceleration (bead-on-wire) close to light surface

# Accelerating particles in rotating jet magnetospheres

★_Some more details:

_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

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

➡ equation of motion

$$\gamma \frac{\partial^2 r}{\partial t^2} + \frac{\partial r}{\partial t}\frac{\partial \gamma}{\partial t} = \gamma\, \Omega^2 r$$

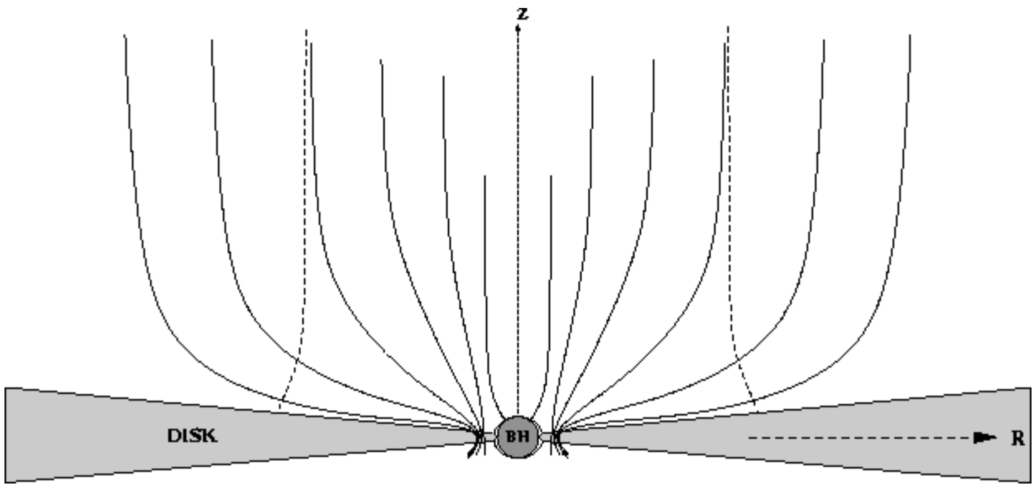
_maximum energy limited by co-rotation or radiative constraints (IC):

$\gamma_e \sim 10^7$ for Cen A parameters

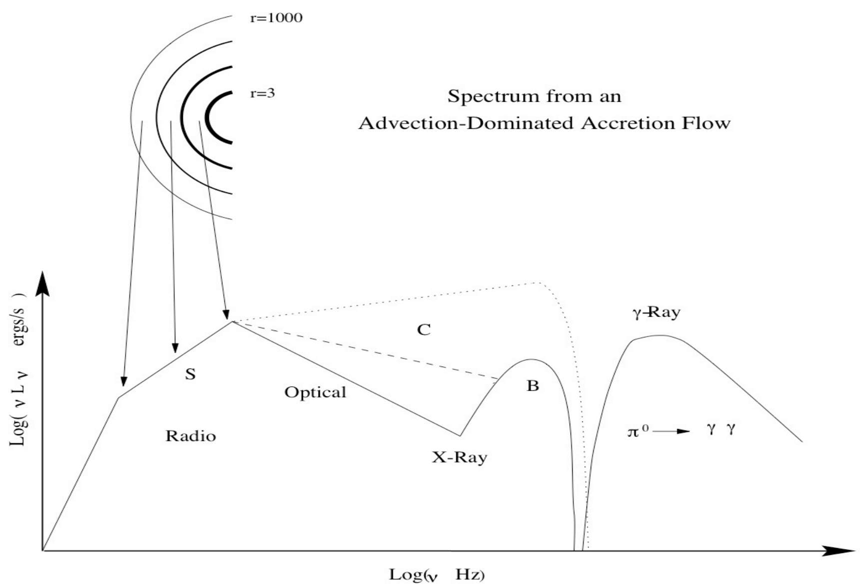
# The centrifugal - ADAF IC scenario

_Putting things together (R & Aharonian '09)

Centrifugal particle acceleration + IC scattering of ADAF photons




Jets as centrifugally accelerated disk wind.
(e.g., Fendt '97)

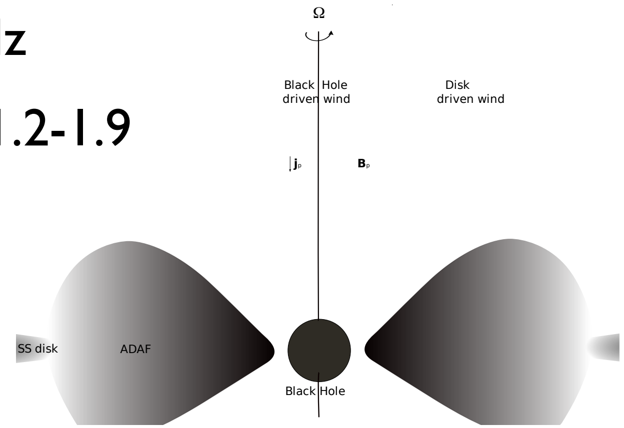



ADAF disk emission spectrum:
-synchrotron + Comptonized parts
(Mahadevan '97)

# The centrifugal - ADAF IC scenario for Cen A

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

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



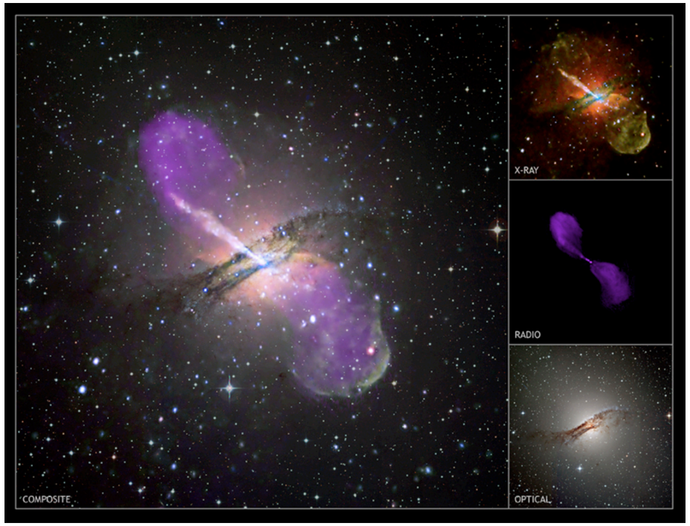

## _Energetic electrons:

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

## _TeV emission: (R & Aharonian 09)

- IC (Thomson) up-scattering of ADAF photons gives emission up to $\sim 5\,(\gamma/10^7)$ 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 $\sim 5\, r_s/c \sim 1$ 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+)

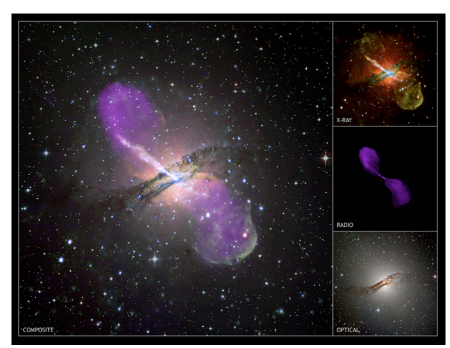
# The centrifugal - ADAF IC scenario for Cen A

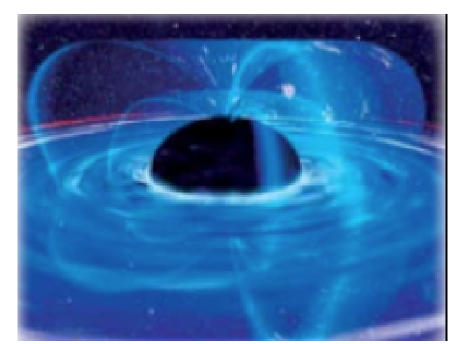
## _Gamma-gamma absorption? (R & Aharonian 09)

- 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 $\geq 0.1$ pc (Radomski+ 08)

## **_Preliminary Conclusion I:**

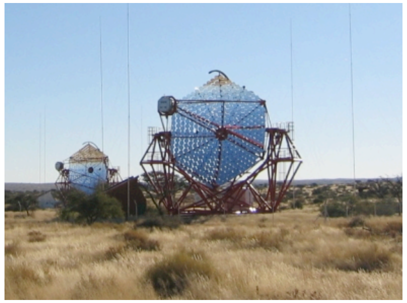
*In selected, nearby, low-luminous, non-aligned AGN (e.g., M87, Cen A), VHE processes close to black hole may become observable and allow fundamental diagnosis of its environment.*



# Cen A as a possible UHECR source?

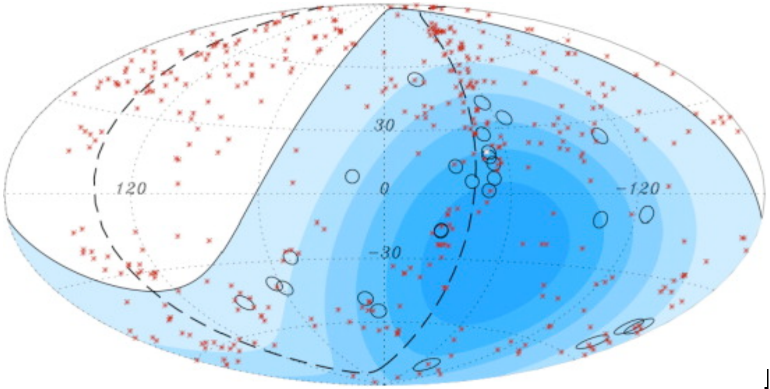
★ **_Cen A is a VHE gamma-ray source !**



★ **_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 existing mechanisms operate efficiently enough?

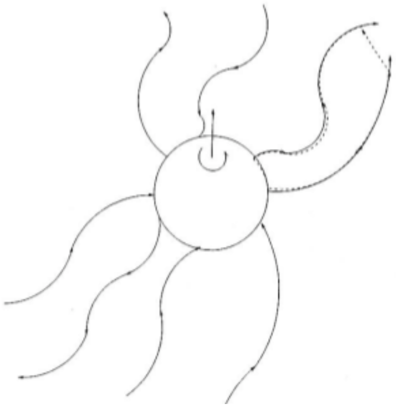


# Cen A as possible UHECR source? (R & Aharonian 09)

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

➡ BH magnetosphere - BZ-type unipolar inductor *(membrane paradigm)*:

$$E_{max} \sim 2 \times 10^{19}\, a\, Z\, M_{BH,8}\, B_{0,4}\ \mathrm{eV}$$



Krolik 1999

**But**: (1) Cen A is not massive enough

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

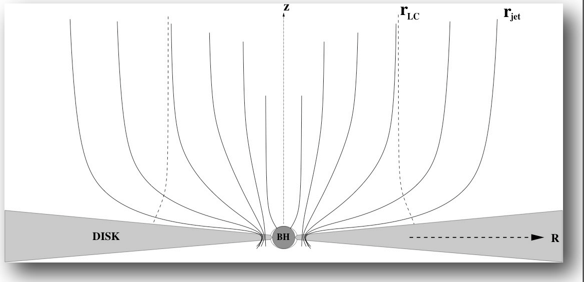
(3) Vacuum breakdown is to be expected

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

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

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

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



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

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

Maximum energy: $\mathbf{E_{max}} \sim e\, B\, r_t\, \beta_s \leq 8 \times 10^{18}\, Z\, B_{0,4}\, \beta_{s,0.1}$ eV

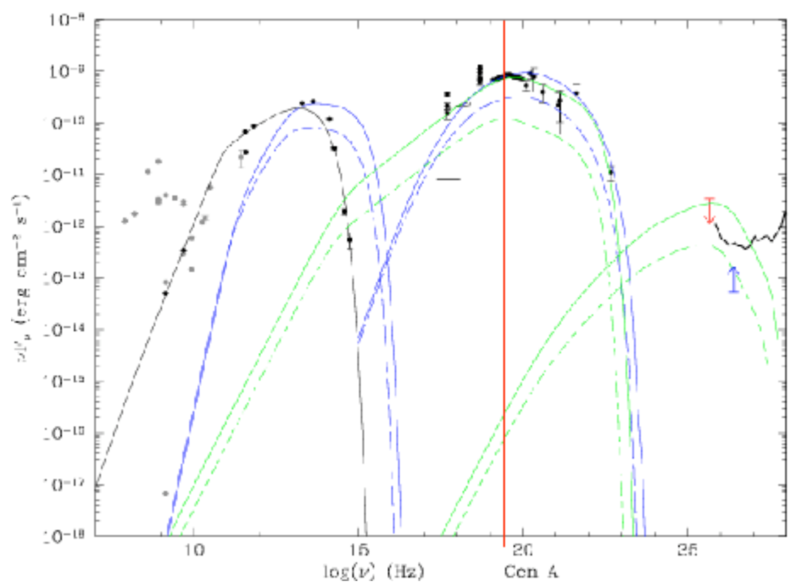
(using $B(r) \sim B_0\, r_s/r$ with $B_{0,4} = B_0/10^4$G and $\beta_{s,0.1} = \beta_s/0.1$ c)

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

➡ internal shocks, 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




Lenain+ 2008

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

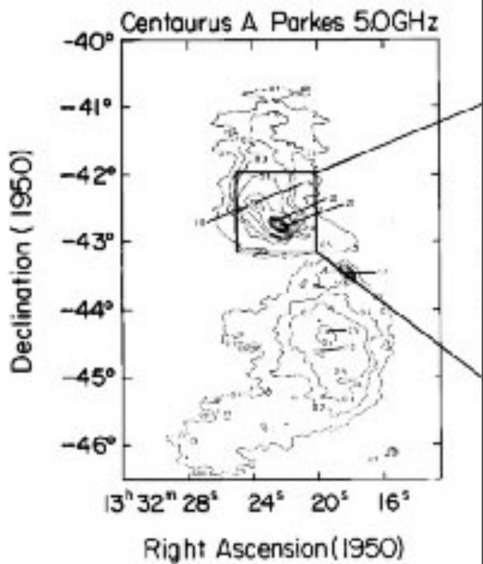
## _Efficient 2nd order Fermi acceleration in outer lobes? - **unlikely ?**

Maximum when acceleration = escape (cross-field):

$$\mathbf{E_{max} \sim 2 \times 10^{20}}\ Z\ \mathbf{(v_A/c)}\ (R/100\ \mathrm{kpc})\ (B/10^{-6}\mathrm{G})\ \mathbf{eV}$$

may account for PAO events if (!) $v_A > 0.3$ c (Hardcastle+ 08)

Burns+ 1983




**Scale ~ 500 kpc**

Outer Lobes

**But:** If (part of the) observed X-ray emission is indeed thermal in origin (Isobe+ 01; Marshall & Clark 1981)

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

➡ Alfven speed ~ c/$10^3$ << c (cf. also O'Sullivan+ 09)

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

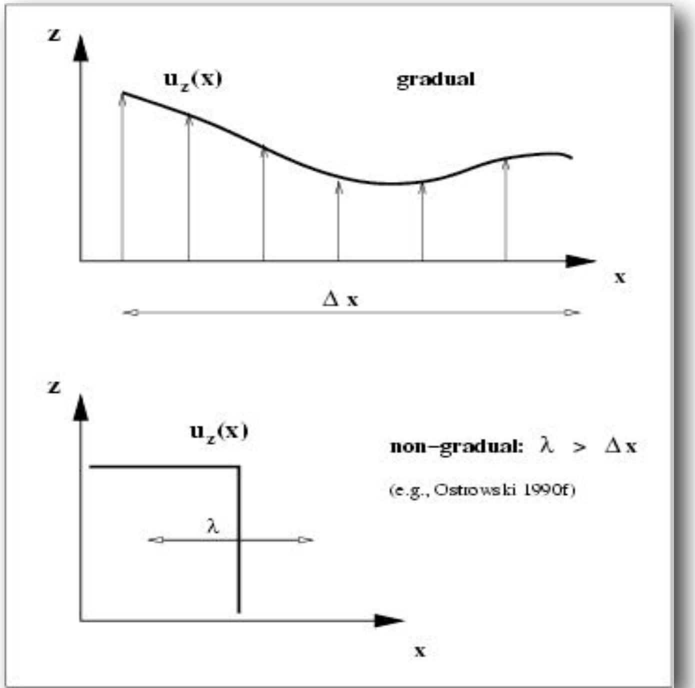
## _ Efficient shear acceleration along kpc-jet - perhaps **possible**

**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:




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

with characteristic effective velocity:

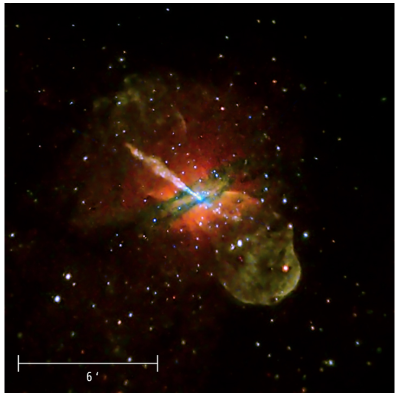
$$u = \left(\frac{\partial u_z}{\partial x}\right) \lambda$$

"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

# Shear acceleration along kpc-jet in Cen A? (R & Aharonian 09)




Credit: NASA/CXC/CfA/Kraft et al

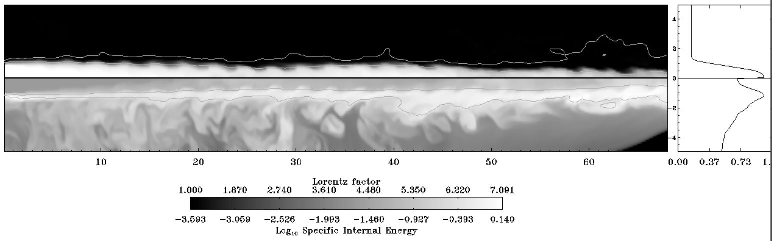
_Advantage: "distributed" mechanism operating along jet

_"Disadvantage": needs high energy seed particles $t_{acc} \propto [(\partial u/\partial r)^2 \lambda]^{-1}$:

$t_{acc,shear} < t_{adv}$ 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+ 2000




_will allow energy boost by factor ~(10-20)

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

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

_spectral change possible due to operation of new mechanisms!

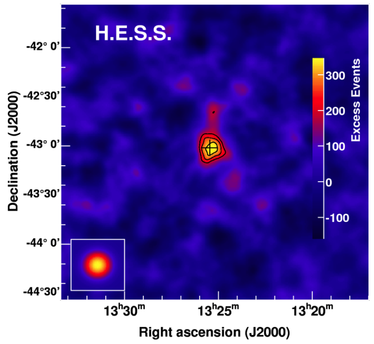
# Summary

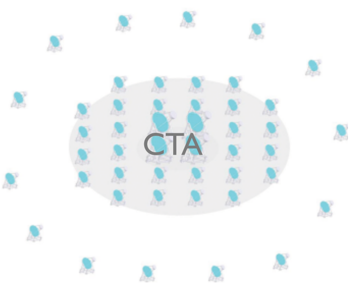
## _Cen A is a TeV gamma-ray source ( ➡ H.E.S.S.)

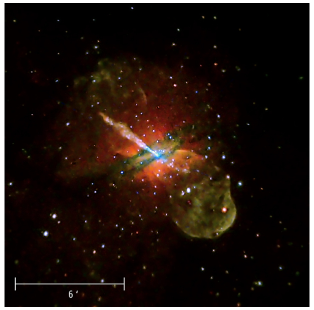
- may allow to probe near-BH environment ...
- need more data ➡ CTA

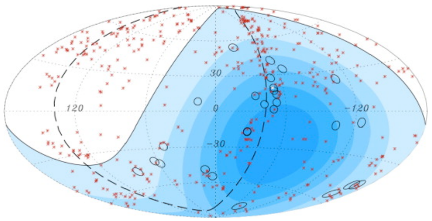
## _Cen A as possible UHECR "proton" source

- observationally "likely", theoretically "possible":
  - via shear acceleration along large-scale jet
  - if, then spectral changes might be partly due to operation of different mechanisms





**THANK YOU!**