Ultra-high-energy Cosmic Ray Contribution from the Spin Down Power of Black Holes

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11 December 2012

OVERVIEW

- Introduction
- Description of the spin-down model for UHECRs
- Prediction for UHECR events and comparison with the Auger data
- Conclusions

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INTRODUCTION

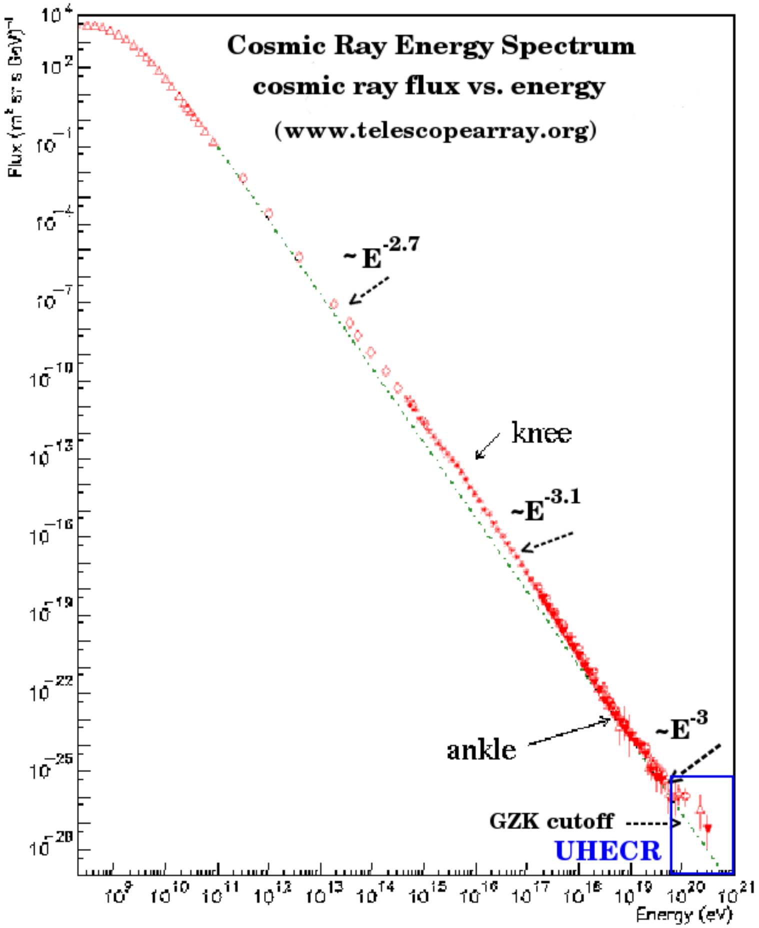
Ultra-high-energy cosmic rays

UHECRs: $E > 50$ EeV
1st UHECR: Linsley (1963)

- cosmic rays are a direct sample of matter from outside the solar system
- they can provide important information on the chemical evolution of the universe or put constraints on Galactic and extragalactic magnetic fields
- secondary particles: principally pions, muons, electrons, neutrinos, gamma rays

UHECR flux: a few dozen particles/km^2/century

Ultra-high-energy cosmic rays



UHECRs: $E > 50$ EeV

1st UHECR: Linsley (1963)

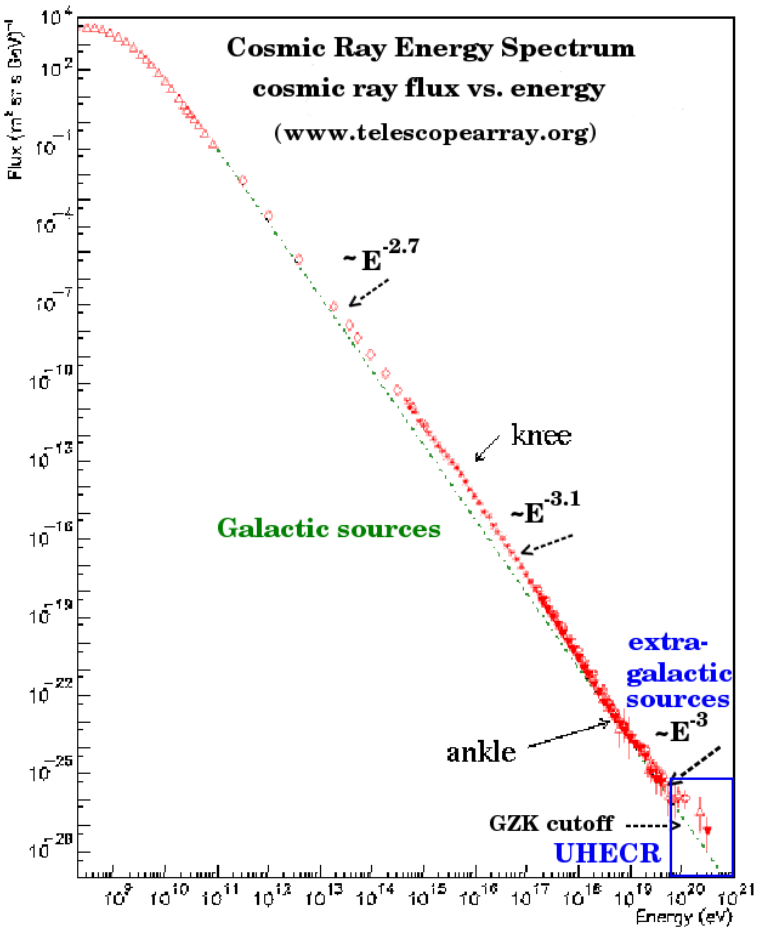
UHECR flux: a few dozen particles/km^2/century

- What are the primary UHECR particles? Is there a (GZK) cutoff in the spectrum? What are the sources of UHECRs?

Ultra-high-energy cosmic rays

Galactic sources (of CRs): e.g., supernova remnants (acceleration of particles in diffuse parallel shocks)

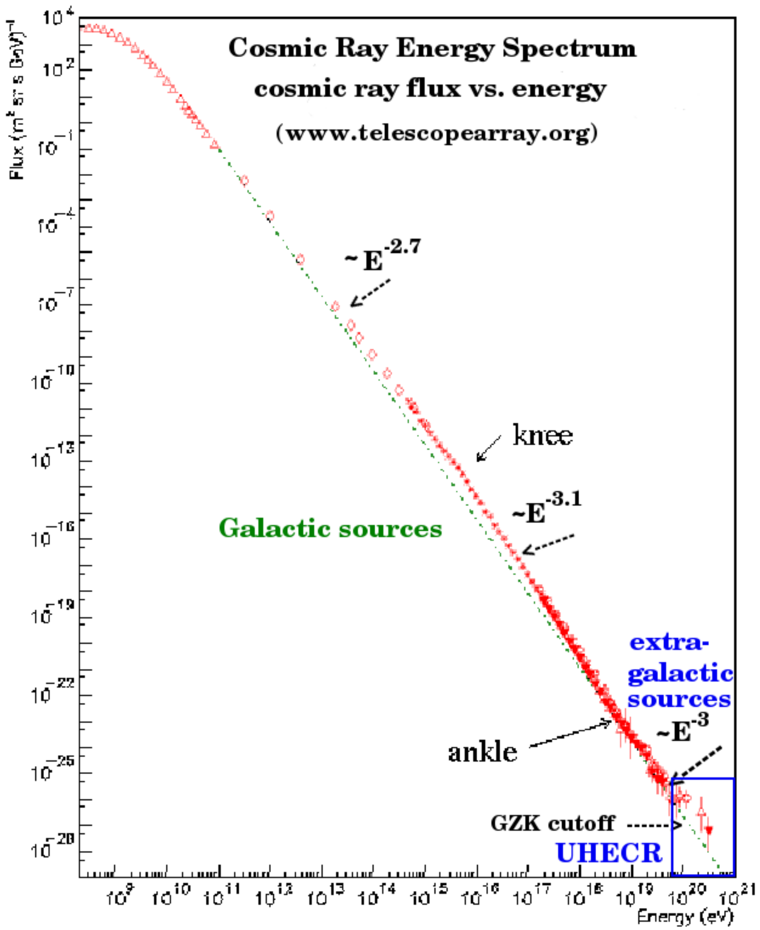
Extra-galactic sources (of UHE-CRs): most probably jets (internal shocks) and lobes (external shocks) in AGN and γ-ray bursts



Ultra-high-energy cosmic rays

GZK cutoff: Greisen (1966) and Zatsepin & Kuzmin (1966) – particles (protons) with $E > 50$ EeV are subject to energy loss by pion photo-production by scattering off of the CMB photons, $p\gamma \rightarrow p\pi^0(n\pi^-) \rightarrow$ sources of UHECR protons should be located within ~ 50 Mpc

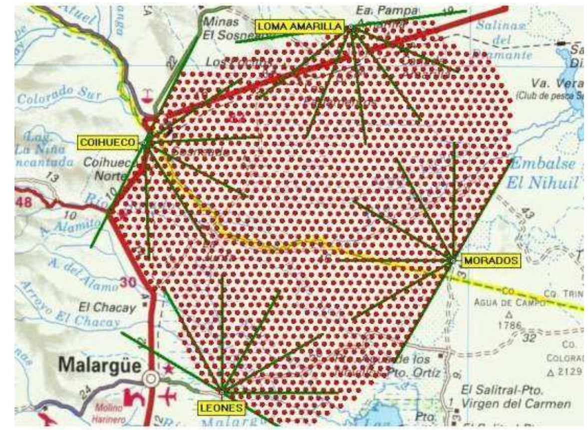
GZK horizon: observed flux above $\sim$ 50 EeV from sources within a $\sim$ 200 Mpc



- arrival direction of the primary UHECRs does not exactly point to their sources (deflection by magnetic fields especially along the galactic plane)

Ultra-high-energy cosmic rays

The Pierre Auger Observatory: Provence of Mendoza, Argentina, air fluorescence and water-Cherenkov detection (1600 tanks) in a hybrid instrument with an aperture of 7000 km^2 sr, on a surface array area $\sim$ 3000 km^2, since 2004 (finished 2008)



www.auger.org

- 31 Dec 2009: 69 UHECR events (55-142 EeV), arrival directions with respect to their correlation with populations of nearby extra-galactic objects in the Véron-Cetty & Véron (VCV) catalog, galaxies in the 2MRS (NIR), and AGN detected by Swift-BAT (hard X-rays)
- blue circles of radius 3.1° centered at the positions of the 318 AGN in the VCV catalog that lie within 75 Mpc; 29 out of 69 events present correlating arrival directions

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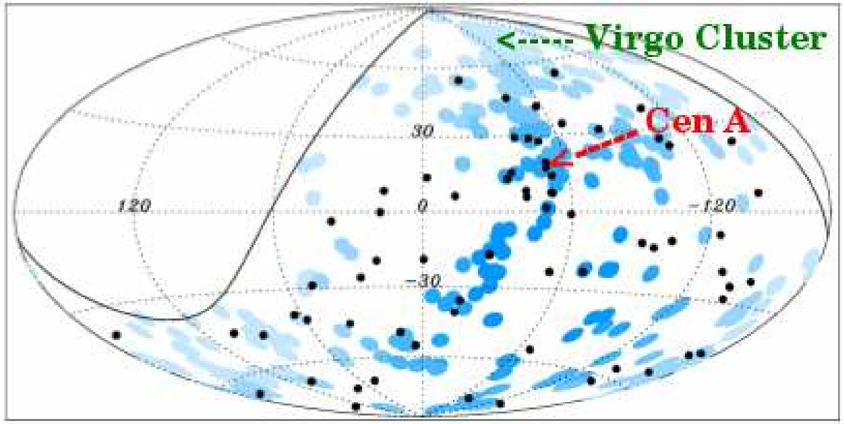

Abreu et al. for Auger Collaboration (2010)

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Ultra-high-energy cosmic rays

OVERVIEW

INTRODUCTION

UHECRs

AGN

Jet formation

Jet emission

Shocks

UHECR MODEL

CONCLUSIONS

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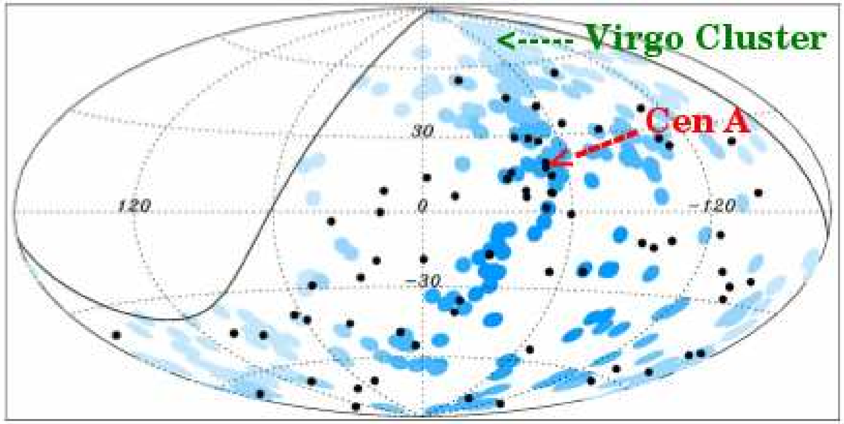


Abreu et al. for Auger Collaboration (2010)

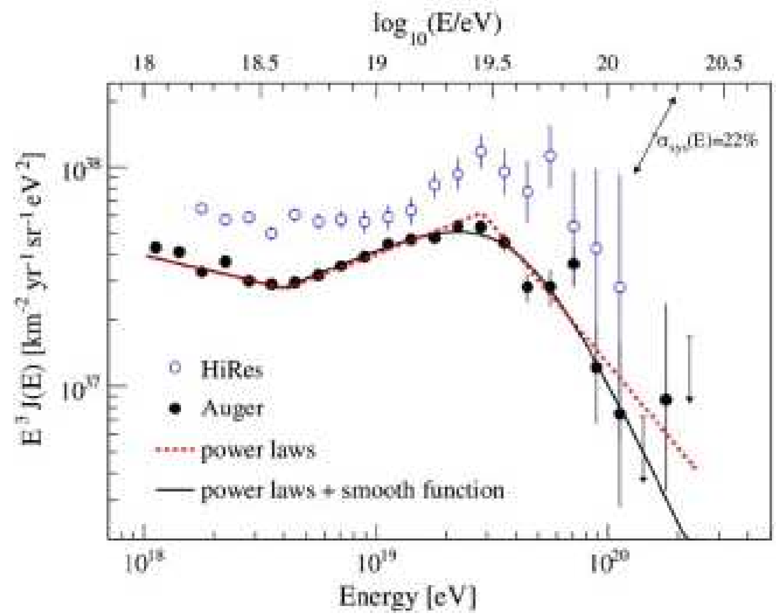
- autocorrelation of arrival directions: the absence of strong clustering at small angles $\rightarrow$ many contributing sources and/or large angular separations between arrival directions from the same source

- 18% from events (with $E > 55$ EeV) lie within 18° of Cen A

- none of the 69 events is within 18° of M87 (which gets 1/3 the exposure that Cen A gets)

Ultra-high-energy cosmic rays

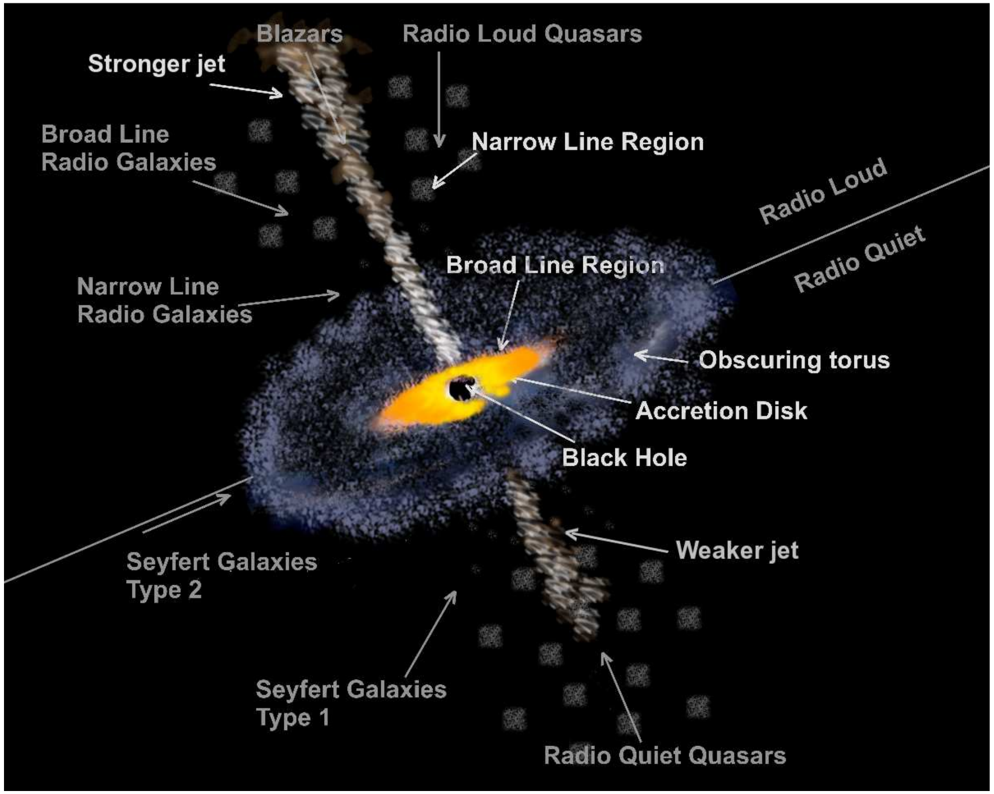
High Resolution – Fly's Eye experiment (HiRes) in Millard County, Utah, USA since 2007; collaboration between universities and institutions in the the United States, Japan, Korea, Russia, and Belgium



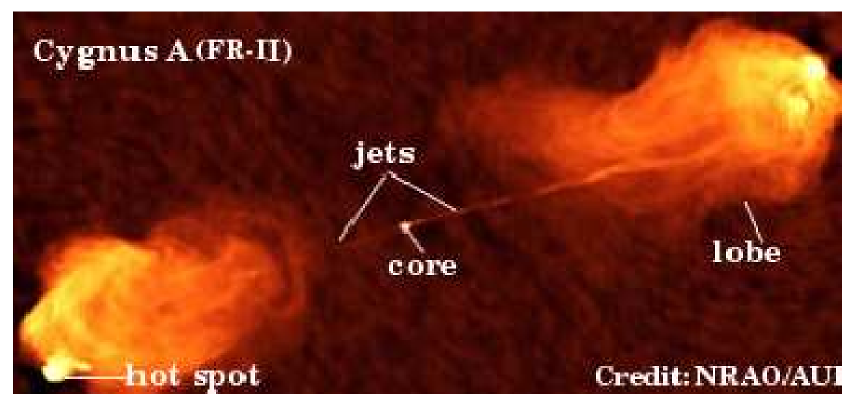
Sommers, P. (2012)

- HiRes data show GZK cutoff and protons as primary particles
- Auger data show trans-GZK; possible heavy nuclei; statistical correlation with AGN
- UHECR sources: possible AGN jets

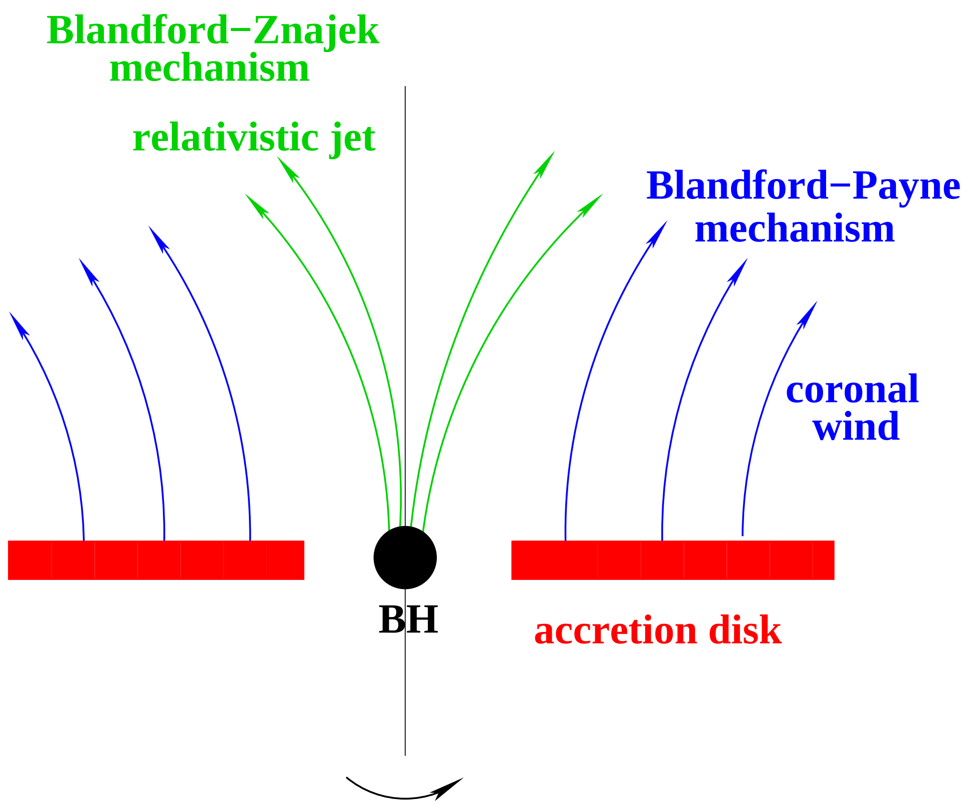
Active galactic nuclei



- galaxies whose nucleus spectrum cannot be explained by standard stellar physics, e.g., a dense stellar cluster of massive stars or a stellar mass BH
- spinning supermassive BH, $M \sim 10^7 - 10^9 M_\odot$, surrounded by an accretion disk
- AGN jets: $v_{\rm jets} \sim 0.9 - 0.995c$ or $\gamma = 2 - 10$ (bulk Lorentz factor)

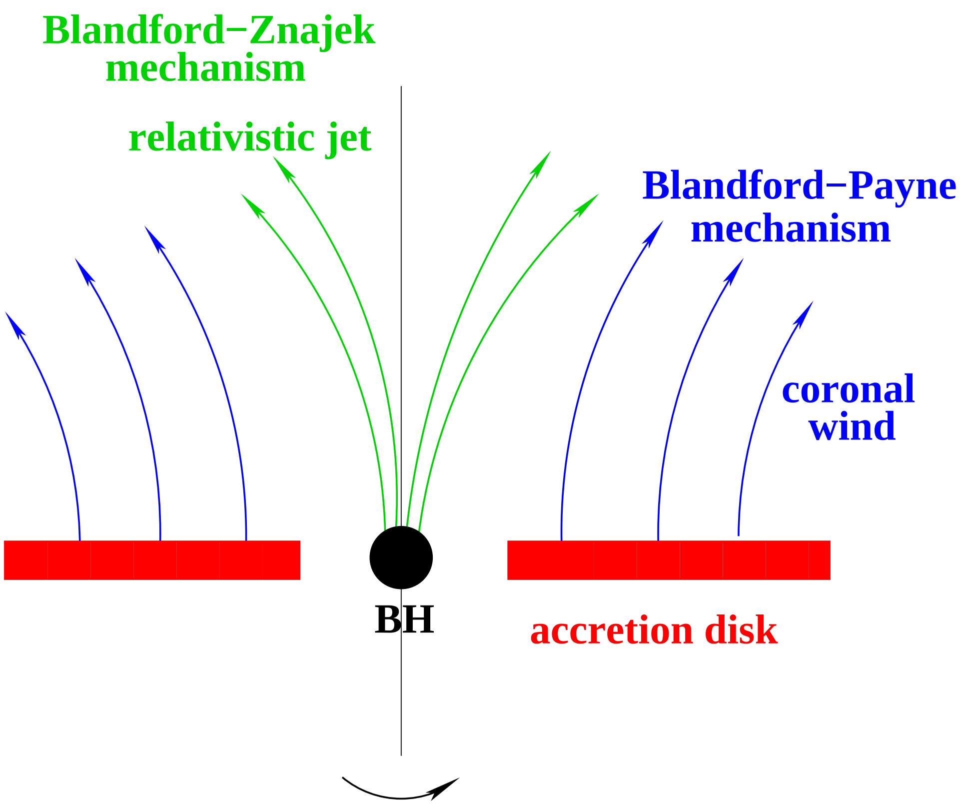


- Blandford-Payne mechanism (1982): MHD flow – the jet can be launched and collimated by centrifugal and magnetic forces – the disk particles are driven upwards by the gradient of the pressure in the disk to fill the corona around the disk and are further accelerated by the gradient of the magnetic pressure

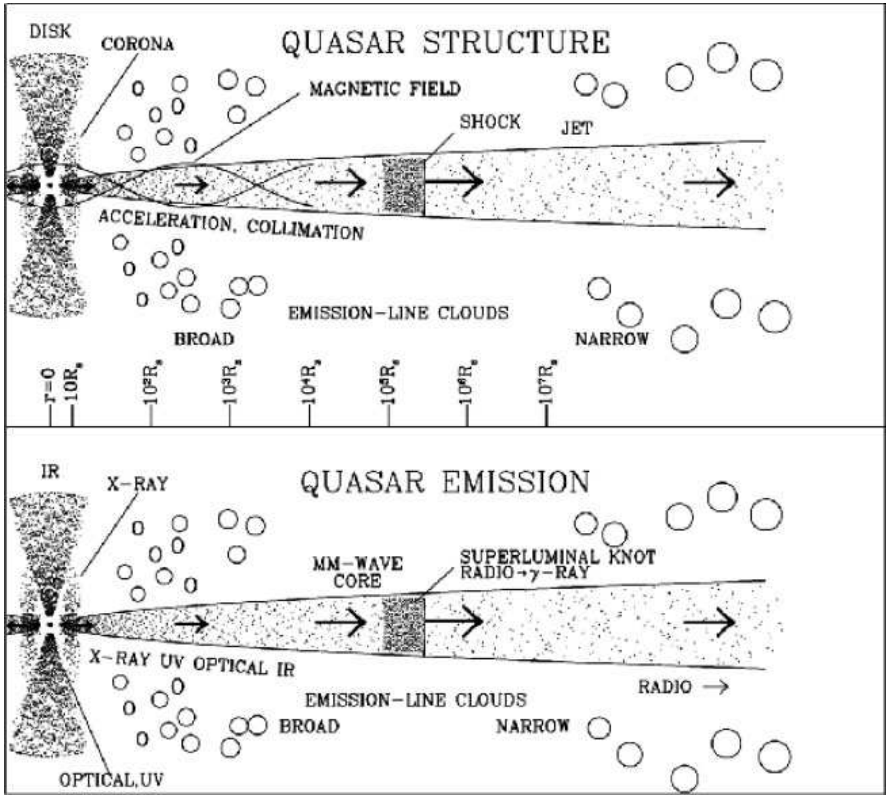


Mechanisms of jet formation

- Blandford-Znajek mechanism (1977): electromagnetically extraction of energy and angular momentum of a BH (“BH dynamo” mechanism) → the energy flux of the jets is provided by conversion of the BH rotational energy into Poynting flux, which is then dissipated at large distances from the BH by current instabilities



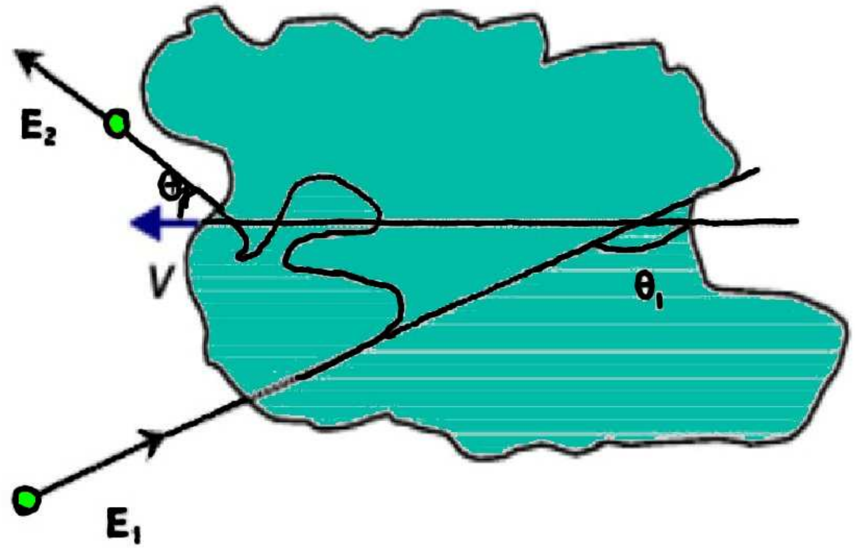
Propagation and emission of the jet



Marscher2000

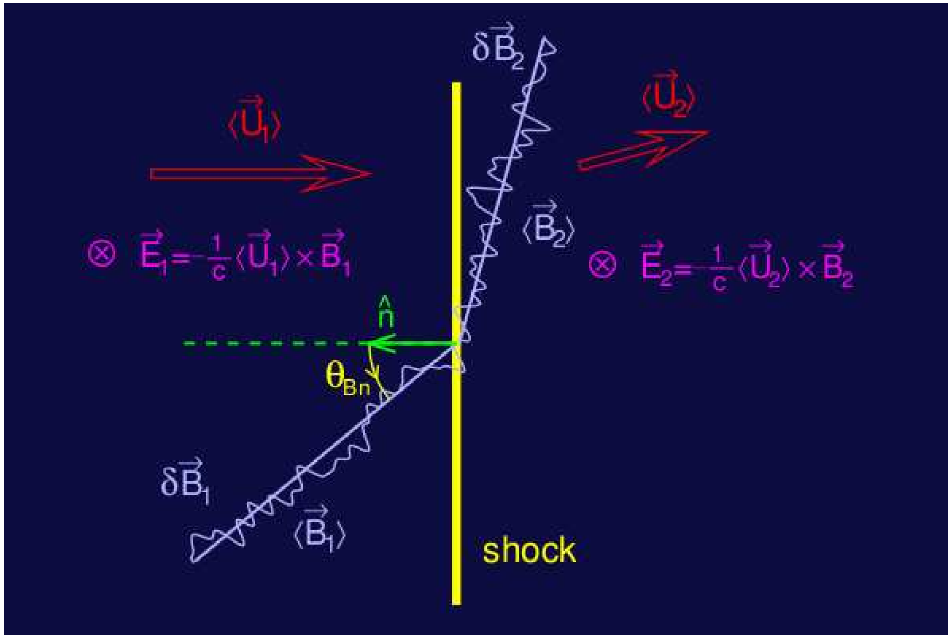
- structure and emission of a radio-loud AGN
- helical magnetic fields
- synchrotron and inverse Compton radiation

Difussive shock acceleration



- collision of a charged particle with a moving magnetic cloud
- acceleration of energetic particles by Fermi processes (i.e., diffusive shock acceleration or second order Fermi acceleration) in AGN jets

Difussive shock acceleration



Giacalone 2003

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- Blandford (2000): acceleration region can be sustain by magnetic energy extraction from spinning black holes

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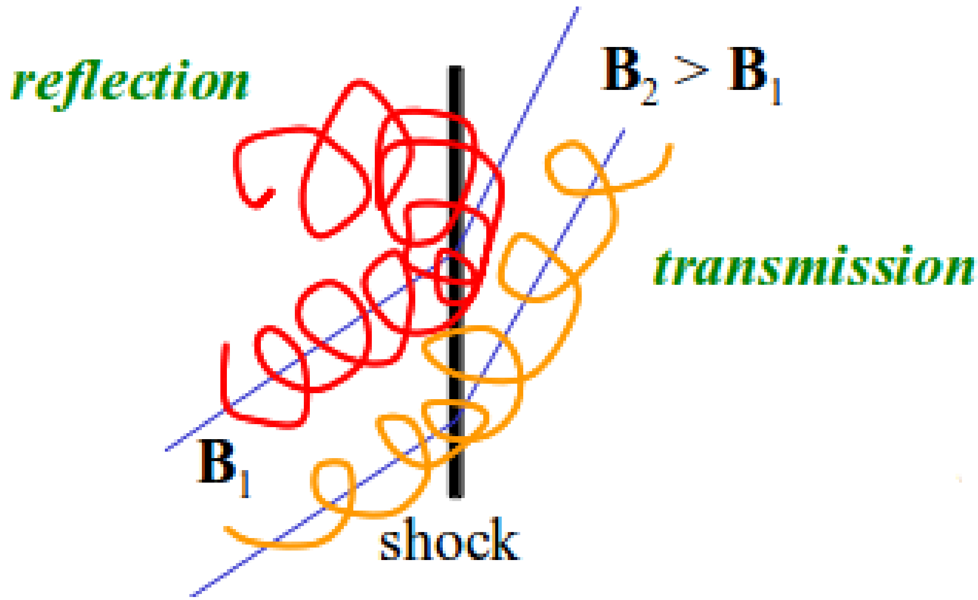

Ostrowski 2003

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SPIN-DOWN MODEL FOR ULTRA-HIGH-ENERGY COSMIC RAYS

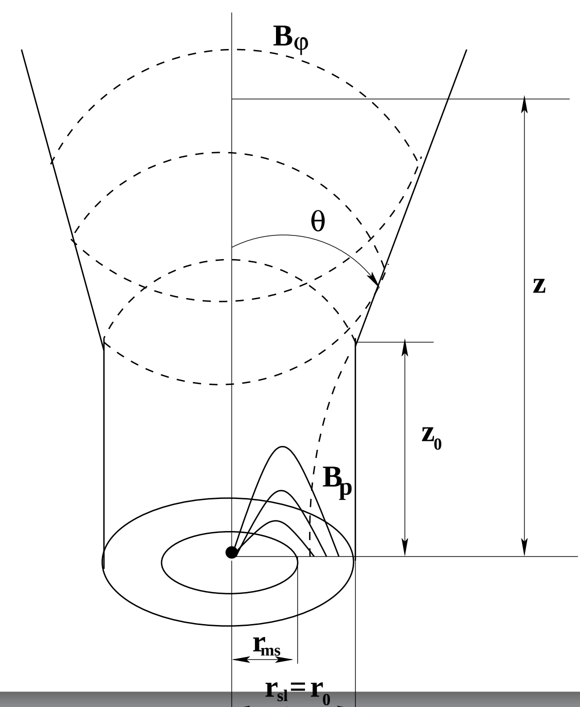
Duţan & Caramete, in preparation

Introduction

- common idea: UHECRs ($E > 50$ EeV) are produced in AGN; Problem: bolometric luminosities of most of the AGN are significantly lower than that required to satisfy the minimum condition for UHECR acceleration in a continuous jet
- scope: to study the possibility of UHECR production in radio jets from low-luminosity AGN (LLAGN), with a jet power $P_{\mathrm{j}} \leqslant 10^{46}$ erg s^{-1}
- we rewrite the equations which describe the synchrotron self-absorbed emission of a non-thermal particle distribution to obtain the observed radio flux density (F_{obs}) from flat-spectrum core sources
- jet power provides the UHECR luminosity and so, its relation to the observed radio flux density
- estimate the particle maximum energy for both spatial and synchrotron loss limits

Model description

- we assume that the UHECRs are accelerated by shocks in AGN jets
- the jet uses the BH spin-down power and then extends into a conical shape with a constant opening angle 2θ, as a consequence of the free adiabatic expansion of the jet plasma. [similar geometry: Markoff et al. (2001)]
- we assume that the UHECRs are proton-dominated (HiRes – protons, Auger – maybe light nuclei)
- in the observer frame, the magnetic field along the jet varies as $B \sim \gamma_j^{-1} z^{-1}$ and the electron number density in the jet scales as $\sim \gamma_j z^{-2}$, where γ_j = bulk Lorentz factor of the jet
- we set the slope of the particle density distribution ($\sim E^{-p} dE$) to $p = 2$ (spectral index $\alpha = 0.5$) and $B \simeq B_H^{max}$



Model description

- frame comoving with the matter in the jet and the (rest) frame of the observer, in which the relativistic jet moves with γ_j
- electron and proton number densities: $f_{ep} \equiv n_e / n_p$ ($n_{e|p}$ measured in a comoving frame)
- comoving density of the jet:
  $nm = n_p m_p + n_e m_e = n_p m_p \left(1 + f_{ep} \frac{m_e}{m_p}\right) \equiv n_p m_p f_0$
- mass flow rate into the jets (in observer frame):

$$\dot{M}_j = \frac{d}{dt}\left(\rho_j V_j\right) = nmv_j(S)_{z=0} = \gamma_j \beta_j c n_p m_p f_0 2\pi r_g^2 k_0$$

GR factor

- proton number density:

$$n_e = f_{ep} \frac{\dot{M}_j}{\gamma_j \beta_j c m_p f_0 2\pi r_g^2 k_0}$$

Model description

- we suppose that a recollimation shock (Sanders 1983) is produced at the jet height $\sim z_0 \rightarrow$ power-law energy distribution of the particles:

$$N(E)dE = CE^{-p}dE \quad \text{or} \quad N(\gamma)d\gamma = C'\gamma^{-p}d\gamma$$

$$C = C'(m_{\mathrm{e}}c^2)^{p-1}$$

- for a conical jet, the normalization of the e^- number density:

$$C' = C'_0 \left(\frac{z}{z_0}\right)^{-2} (\mathrm{cm}^{-3})$$

- self-absorbed synchrotron emission of the jets: spectra from compact radio sources can be explained by self-absorbed synchrotron emission of the jets produced by electrons with a power-law energy distribution

Model description

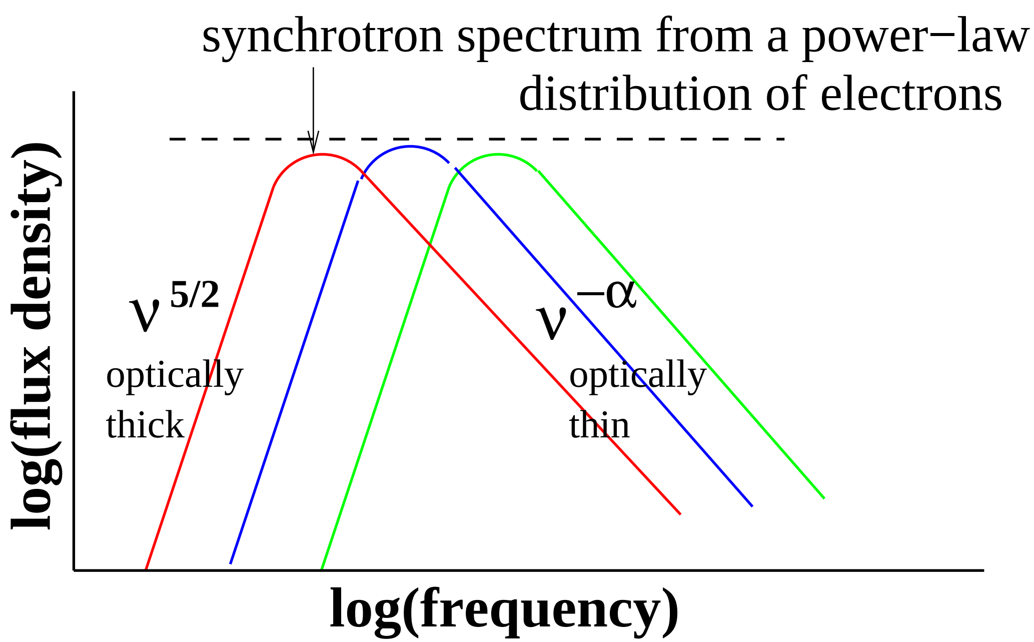
- to calculate the flux density of the synchrotron emission from radio sources with a flat-spectrum core, we rewrite the absorption coefficient, optical depth, synchrotron emissivity and source function (Rybicki & Lightman 1979)

- to obtain the emission spectrum, one needs to solve the equation for the radiative transfer:

$$dF_\nu = S_\nu \left[1 - \exp(-\tau_\nu)\right] d\Omega$$

$$\begin{aligned} S_\nu &= \text{source function (ratio between emission and absorption coeff.)} \\ \tau_\nu &= \text{optical depth} \\ d\Omega &= 2\pi r dz / D_s^2 \\ r &= \text{jet radius} \\ D_s &= \text{distance to the source} \end{aligned}$$

Model description



- intrinsic flux density for $\tau_\nu = 1$, flat-spectrum core sources:

$$F' = K_4 (C_0' l_0)^{\frac{5}{p+4}} r_0^{\frac{2p+13}{p+4}} B_0^{\frac{2p+3}{p+4}} D_s^{-2} (\tan\theta)^{-1}$$

- observed flux density for a continuous jet consisting of uniformly-spaced blobs:

$$F_{obs} = \mathcal{D}_j^{2+\alpha} F'$$

Model description

- UHECR luminosity:

$$L_{\rm CR} = \varepsilon_{\rm CR}\gamma_{\rm j}^2 \dot{M}_{\rm j} c^2$$

$$L_{\rm CR} = K_5 \beta_{\rm j} \mathcal{D}_{\rm j}^{-h} \left(\frac{\gamma_{\rm j}}{5}\right)^{\frac{2p+13}{5}} \left(\frac{\tan\theta}{0.05}\right)^{\frac{p+4}{5}} \left(\frac{r_0}{2r_{\rm g}}\right)^{-\frac{2p+13}{5}} \left(\frac{B_{\rm H}}{B_{\rm H}^{\rm max}}\right)^{-\frac{2p+3}{5}} F_{\rm obs}^{\frac{p+4}{5}} D_{\rm s}^{\frac{2(p+4)}{5}} \left(\frac{M}{10^9 M_\odot}\right)^{-\frac{2p+3}{10}} {\rm erg\,s}^{-1}$$

  - quantities in black color depend on the jet parameters, except for K_5 which depends on p, and quantities in purple depend on the BH and on the launching area
  - for a continuous blob emission: $h = [(p+3)(p+4)]/10$
  - we set $p = 2$ from shock acceleration calculations

- UHECR flux: $F_{\rm CR} = L_{\rm CR}/(4\pi D_{\rm s}^2)$

Model description

- maximum particle energy of UHECR:
  - spatial limit (Falcke & Biermann 1995, Gallant & Achterberg 1999):

$$E_{\rm max}^{\rm sp} = 5\times 10^{20}\left(\frac{B_{\rm H}}{B_{\rm H}^{\rm max}}\right)\left(\frac{r_0}{2r_{\rm g}}\right)\left(\frac{M}{10^9 M_\odot}\right)^{1/2}\ ({\rm eV})$$

  - synchrotron loss limit (Biermann & Strittmatter 1987):

$$E_{\rm max}^{\rm loss} = 4.2\times 10^{18}\left(\frac{\nu_*}{3\times 10^{14}{\rm Hz}}\right)^{1/2}\left(\frac{\gamma_{\rm j}}{5}\right)^{1/2}\left(\frac{z}{z_0}\right)^{1/2}\left(\frac{B_{\rm H}}{B_{\rm H}^{\rm max}}\right)^{-1/2}\left(\frac{M}{10^9 M_\odot}\right)^{1/2}\ ({\rm eV})$$

ν_* = cutoff in the non-thermal emission spectra of AGN

Application to M87 and Cen A

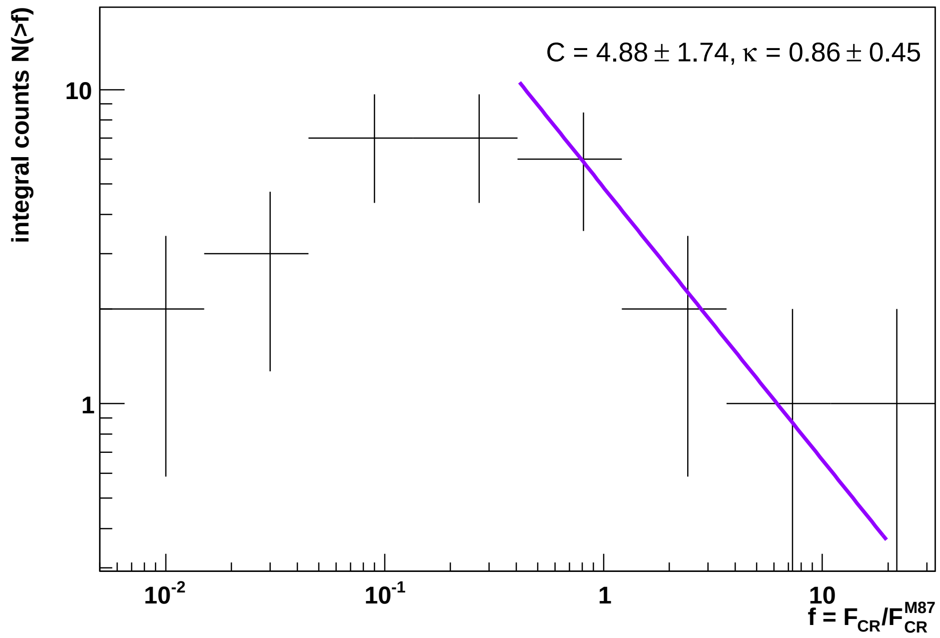
Source	γ_j	φ ($\circ$)	θ ($\circ$)	D_s (Mpc)	M ($\times 10^9 M_\odot$)	F_{core}^{5GHz} (mJy)	E_{max}^{sp} (ZeV)	E_{max}^{loss} (ZeV)	L_{CR} (erg s^{-1})	F_{CR} (erg/s/cm^2)
M87	6	10	19	16	3	2875.1	0.86	0.25	2.03×10^{43}	7.03×10^{-10}
Cen A	2	65	5	3.5	0.055	6984	0.11	0.21	3.16×10^{42}	2.28×10^{-9}

- estimations for the UHECR maximum particle energy, luminosity, and flux in the case of M87 and Cen A, whose jet parameters can be obtained from observational data
- energy along the jet estimated by Whysong and Antonucci (2003): $\sim 10^{45}$ erg s^{-1} and $\sim 10^{43}$ erg s^{-1} for M87 and Cen A, respectively
- the sources have a low power jet, though they are powerful enough to provide the environment for particles to be accelerated to UHEs of ~ 1 ZeV (here, the jet power is supplied by the BH spin-down power)

Predictions for nearby galaxies as UHECRs sources

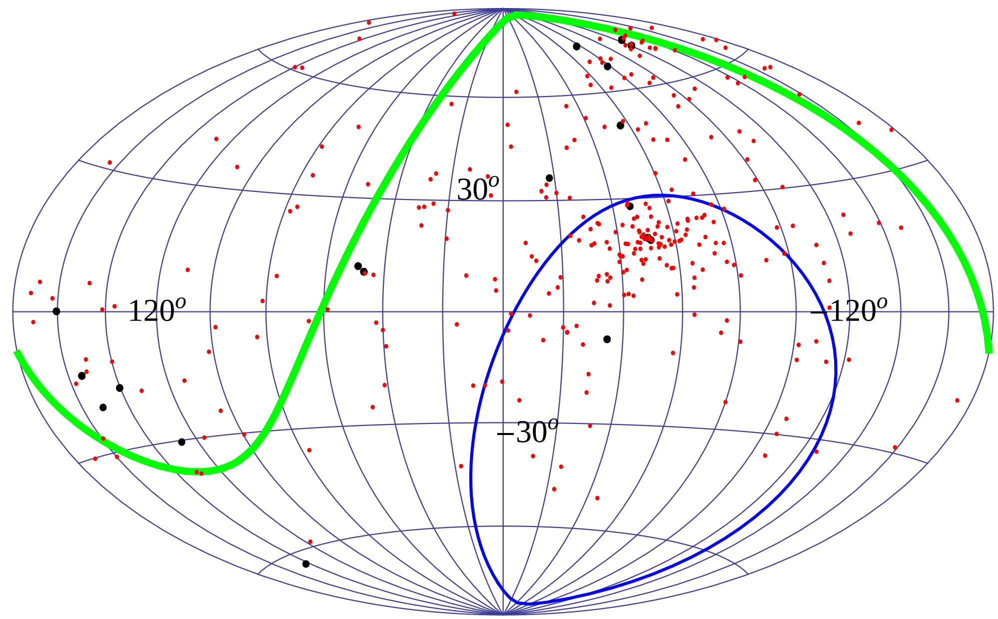
- apply the model to a complete sample of 29 steep-spectrum radio sources (Caramete 2013) at redshift $z < 0.025$ (~ 100 Mpc), with a total radio flux density larger than 0.5 Jy
- jet parameters are assumed to be the same as for M87 $\rightarrow$ the luminosity and flux of UHECRs are only scaled by the BH mass, the radio flux density, and the distance to the AGN
- Cen A, M87, and NGC 3862 are the strongest radio sources of the sample
- all sources have $E_{\rm max} \sim 10^{2}0$ eV
- Cen A, NGC 3862, NGC 3801, CGCG 114-025, UGC 2783 have $F_{\rm CR} > F_{\rm CR}^{\rm M87}$

Predictions for nearby galaxies as UHECRs sources



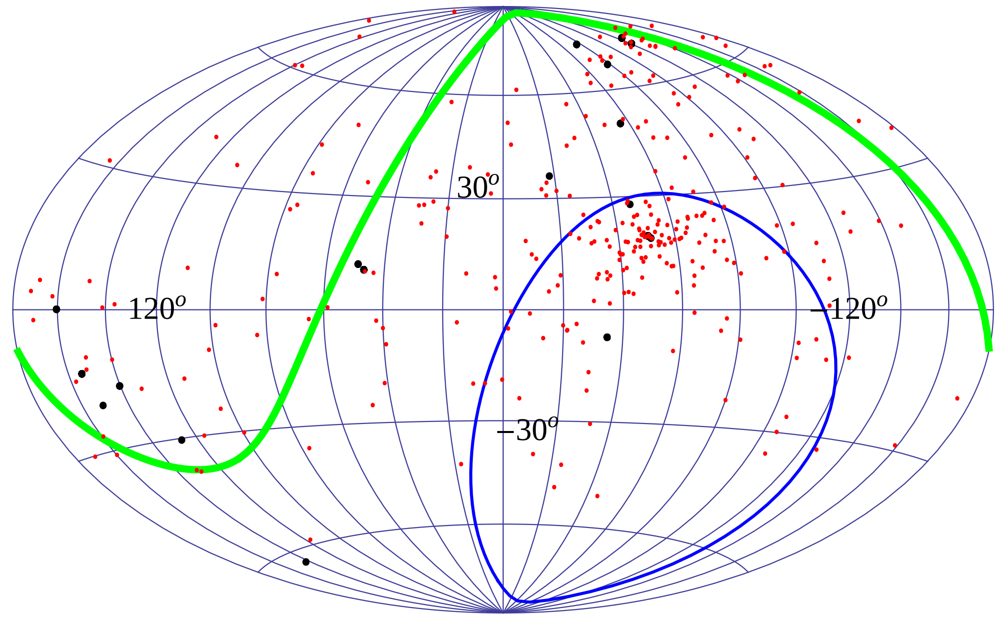
- fit a power-law model ($N = C\, f^{\kappa}$) to the mean values of the data in each bin for $N(> 0.405)$
- a power-law model with $\kappa > 1 \rightarrow$ weak sources can dominate over the strong sources $\rightarrow$ LLAGN (powered by the BH spin down) can make a large contribution to the integrated UHECR flux in the local universe

Predictions for UHECR events

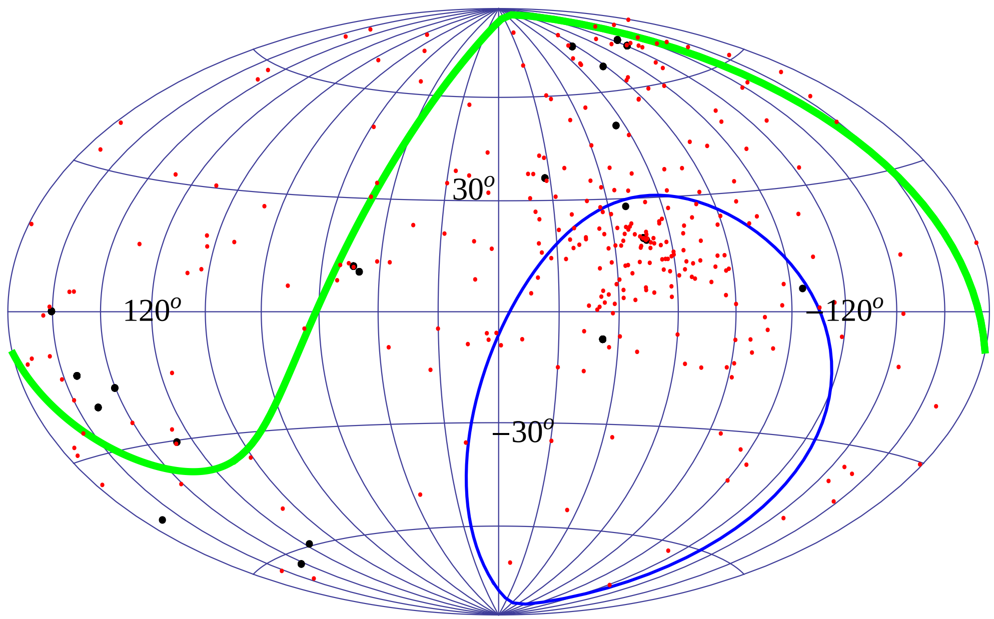


- Aitof projection in galactic coordinate of 300 scattered events (red dots) coming from a selected population of AGN sources (black dots) using the Monte Carlo simulation – same method as in Caramete et al. (2012, submitted)
- model in scattering angles of θ^{-2}, per solid angle, which spreads events evenly into logarithmic rings $\Delta\theta/\theta$= const
- particle acceleration with spatial limit

Predictions for UHECR events



- above the thick line is the area from the sky not seen by the Auger (declinations above than 24.8 degrees)
- thin line surrounds the area from the sky not seen by the HiRes experiment (declinations less then -32 degrees)



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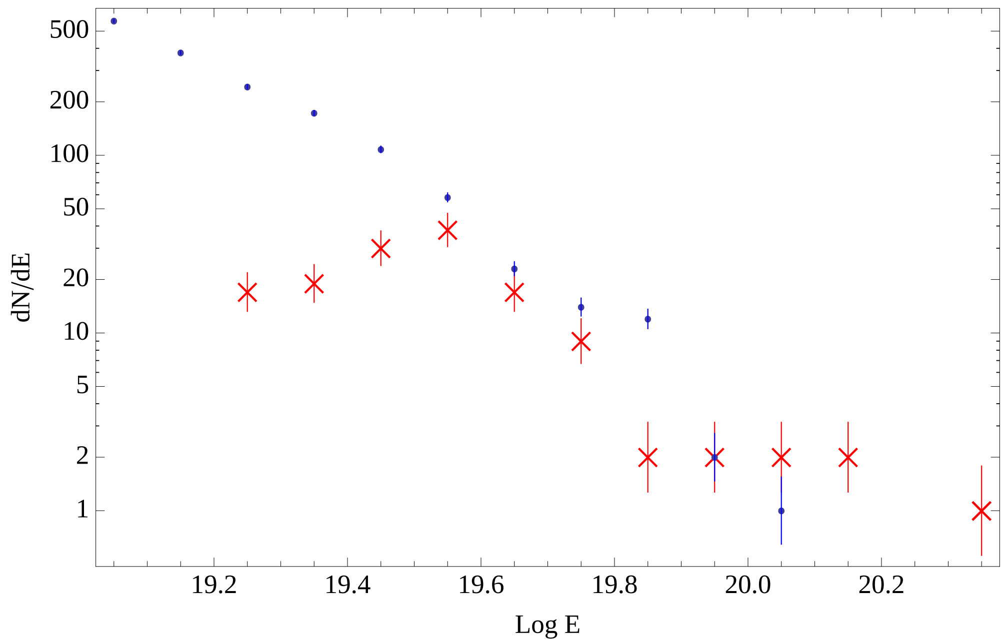

- Preliminary: Energy spectrum of the Pierre Auger Observatory in blue (The Pierre Auger Coll., Phys. Rev. Lett., vol. 101, 6 (2008)) and the corresponding energy spectrum coming from the Caramete's list of sources represented by a star symbol

CONCLUSIONS

Summary and conclusions

- common idea: bolometric luminosities of most of the AGN are significantly lower than that required to satisfy the minimum condition for UHECR acceleration in a continuous jet

- scope: to study the possibility of UHECRs production in radio jets from low-luminosity AGN (LLAGN), with a jet power $P_{\mathrm{j}} \leqslant 10^{46}$ erg s^{-1}

- we rewrite the equations which describe the synchrotron self-absorbed emission of a non-thermal particle distribution to obtain the observed radio flux-density (F_{ν}) from flat-spectrum core sources

- jet power provides the UHECR luminosity and so, its relation to the observed radio flux-density

- we obtain the expressions for the luminosity and flux of the UHECRs as a function of the F_{ν} and jet parameters

Summary and conclusions

- we apply the model to M87 and Cen A, two possible sources of UHECRs whose jet parameters can be inferred from observations
- we use a complete sample of 29 steep-spectrum radio sources Caramete (2013) with a $F_\nu > 0.5$ Jy at 5 GHz to make predictions for the maximum particle energy and flux of the UHECRs
- although the jet power is $\leqslant 10^{46}$ erg s^{-1}, the jet particles can be accelerated to energies $\geqslant 100$ EeV
- make predictions for UHECR events – sky plot
- fit the model predictions to the Auger data
- extend the AGN source sample to obtain better statistical results; main problem: black hole masses are unknown – improved catalog of BH masses (Caramete & Biermann 2010, A&A 521)

Summary and conclusions

- More information on radio data and BH mass from other nearby AGN are required to develop an improved statistical model which may answer the question of whether the flux of the UHECRs is produced by many weak radio galaxies or a few strong radio galaxies