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What does bend jets in galactic halos?

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Evolution of active galactic nuclei jets are analyzed from their origin in accretion disks of active galactic nuclei to their destruction in far halos of galaxies. The model of active galactic nuclei jet deformation in far regions of galactic halos is presented. According to it jets change their shapes due to scattering by black holes in halos. Numerical simulations of jet particle motion in the field of Schwarzschild black holes in a galactic halo are performed to support this model. Simulated shapes of jets are in a good correspondence with observed data. It is shown that any known types of black holes (primordial, stellar, intermediate, and massive) could be responsible for jet deformation because of permissible values of their concentration in galactic halos. Other reasons of jet deformation are considered, and applicability of them are discussed.

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1. Introduction

Jets are observed in various astronomical objects, such as active galactic nuclei (AGNs), X-ray binaries, gamma-ray bursts, and young stellar objects. These astrophysical jets have variety in the linear size. In AGNs, jets extend more than several hundreds kpc and are several times larger than the host galaxies. In X-ray binaries jets are much smaller than those in AGNs. The size of jets ranges from 0.1 pc to 100 pc [1-2]. Astrophysical jets show variety also in the velocity and luminosity [2]. Despite all these varieties in the scale, astrophysical jets have common features. (1) Velocities of jets are of the order of the escape velocity of the source. (2) Jets are well collimated and essentially cylindrical. (3) Jets have complex internal structure, such as jet bodies, cocons, and hotspots. (4) Jets show often S-shaped point symmetry around the source. (5) Jets vary their shapes and directions on short time scales. (6) Jets associate disks of which planes are perpendicular to the jet axis. These similarities suggest that astrophysical jets have common physical mechanisms in the formation and collimation. Many researchers have studied various aspects of astrophysical jets both observationally and theoretically to shed light on the mechanisms of formation and collimation. In observations, jet sources have been studied in wide range of wavelength, from radio to X-ray. In radio region, hundreds of jets have been found in AGNs [1-2]. Their velocities or morphologies are studied statistically. In X-ray region, using spectra and their variabilities, the structure and dynamics of the most inner region of jet sources, at which the jets accelerate, are investigated [3-8]. Recently, data of higher spatial or energy resolution are available with interferometer techniques and space observatories. For examples, in radio, with very long baseline interferometer (VLBI) techniques images of radio jets with resolution of milli-arcsecond are obtained. In infrared and optical, the NASA's Hubble space telescope has taken images of 0.1 arcsecond resolution, which are not available with ground-based telescopes. In X-ray, the ASCA, CHANDRA, and XMM-Newton satellites observe images with KeV energy. Moreover, multiwavelength observations are carried out owing to cooperation of observatories with different target wavelength. In multiwavelength

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observations, targets are observed in different wavelengths simultaneously.

In theories, formation and collimation of jets are investigated in various fields: structure of accretion disks, acceleration and collimation processes of jets with numerical simulations, shock waves in accretions disk, particle acceleration mechanisms at shocks, etc. There are two main branches of accretion disk models: Standard accretion disk model and advection dominated accretion flow (ADAF) model. Although the standard models explain many aspects of observational features of accretion disks, there are still some features that can not be accounted for, e.g., spectra of low luminosity AGNs. Various kinds of jet acceleration, collimation, and deformation mechanisms have been proposed [7-13]. Jets are accelerated by gas pressure, magnetocentrifugal force, magnetic pressure, or radiation pressure. There are some collimation processes proposed: collimation by funnel flow, pinch effect of plasma, or cylindrical environment. Some researchers have found the accretion solution with shock waves. At the shock waves relativistic particles that will cause X-ray or γ-ray flares, are produced by particle acceleration processes, such as Fermi acceleration mechanism.

2. Unresolved Problems

As noted in the previous section, observations have revealed various aspects of astrophysical jets: (1) jets are very fast (relativistic jets are common in AGNs) and are highly collimated (the ratio of length to width ranges from 10 to 100); (2) jets often associates accretion disks perpendicular to the jet axis (e.g., NGC4261, M87, and HH31); (3) jets ejections have close relation to activities of accretion disks. To account for these observations, many theorists have investigated accretion disks and jets therefrom. Accretion disk models have widely succeeded in accounting for many observational aspects of AGNs, e.g., the UV bump in spectra, high and low states. Although accretion disk models succeed in understanding the spectra, they are not effective tools to understand the formation and collimation mechanisms of jets. Jet formation and collimation mechanisms have been intensively investigated with numerical simulations. Mainly by solving hydrodynamical equations numerically, many researchers propose various kinds of jet acceleration and jet collimation mechanisms [9-12].

There are three main problem linked with jets today: (1) what are jets made of, (2) why jets are highly collimated and relativistic, and (3) what is the reason of jet shape changes. In this paper We try to answer the last one. Study of AGN jet destruction is based on the hypothesis: deformation of jets in far halo regions of host galaxies occurs due to their scattering by particles of dark matter. In the proposed model stream of charged particles scatters many times by Schwarzschild black holes of halos. Next sections contain description of performed numerical simulations of jet deformation to support proposed hypothesis. And in the last section the results are analyzed and compared with experimental data.

3. Numerical Simulations of Jet Destruction

In this paper we propose the hypothesis:

- jets are deformed due to the process of frequent scattering by invisible halo particles.

In this paper black holes are considered as the most probable candidate for scatters.

Used numerical method is based on simulation of charged particle motion in Schwarzschild field of black holes. As it will be seen further, the sort of particles in jets does not make any difference for this model.

A particle of jet gets into far halo region of the galaxy. It meets a black hole there and deviates from its initial path at the angle θ (fig. 1). Mean free path of the jet particle:

$$L \simeq \frac{1}{n\sigma}, \qquad (1)$$

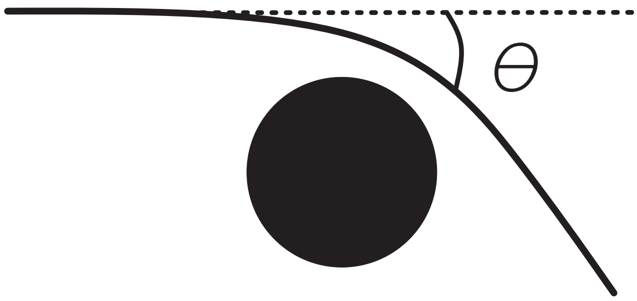

FIG. 1: Scattering of a jet particle by black hole in far halo region of the host galaxy.

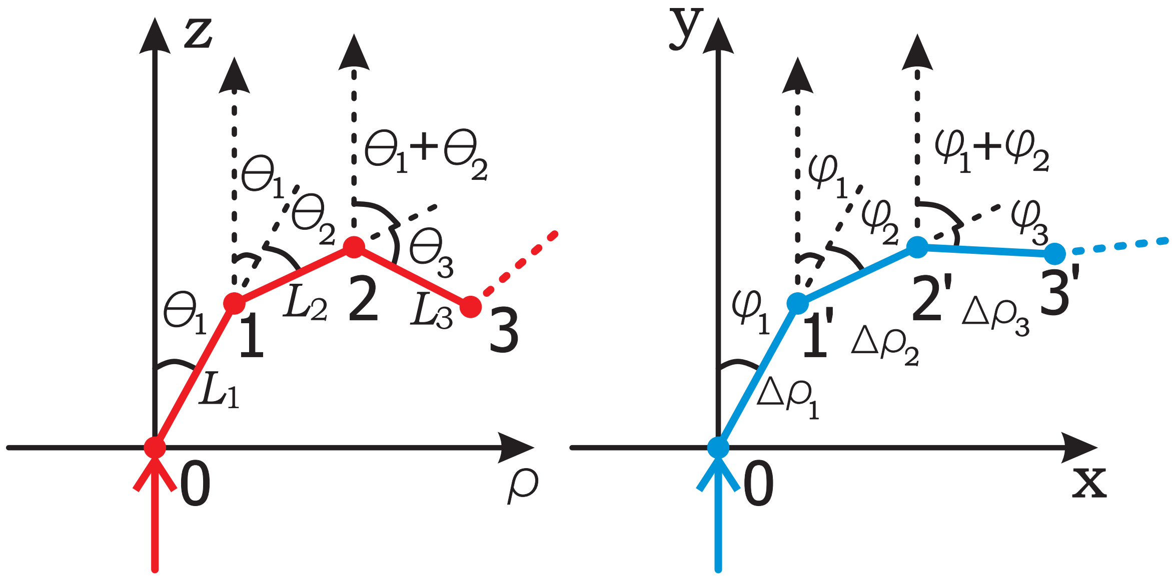

FIG. 2. Motion and scattering of a jet particle in galactic halo. Top: ρ-z plane ($\rho = \sqrt{x^2+y^2}$), bottom: x-y plane.

where n — concentration of black holes in the halo, σ — effective scattering cross section. In Cartesian 3D coordinate system, where axis Z is directed radially to the halo, X and Y axes are arbitrary directed, coordinate shifts of the jet particle between k and $k+1$ scatters can be inferred from the system (fig. 2):

$$\begin{cases} \Delta x_k &= L_k \sin(\theta_1 + \ldots + \theta_k) \cos(\varphi_1 + \ldots + \varphi_k), \\ \Delta y_k &= L_k \sin(\theta_1 + \ldots + \theta_k) \sin(\varphi_1 + \ldots + \varphi_k), \\ \Delta z_k &= L_k \cos(\theta_1 + \ldots + \theta_k), \\ k &= 1 \ldots N, \end{cases} \tag{2}$$

where θ_k and φ_k — projections of deviation angles (fig. 2), N — the total number of scatters per one jet particle. Values of φ_k are uniformly distributed on the interval from 0 to 2π, θ_k are random numbers distributed according to equations of particle motion in Schwarzschild field. To calculate φ_k it is necessary to solve equations of general relativity during each step of simulations. To avoid this equations are solved numerically once for definite sample of points. The result is function $\theta(b)$, where $b = R_g L/\Gamma$, $R_g = 2GM/c^2$ — gravitation radius of a black hole, L is angular momentum and $\Gamma = 1/\sqrt{1 - V^2/c^2}$ — Lorenz-factor of jet particle. To obtain $\theta(b)$ for any value of b piecewise cubic Hermite polynomial interpolating method is used (fig. 3). For function $\theta(b)$ Γ is assumed to be much larger than unity. In reality this assumption is true during the most part of jet trajectory in the halo. Even when $\Gamma \sim 1 - 2$, deviation angle error becomes about 1 degree.

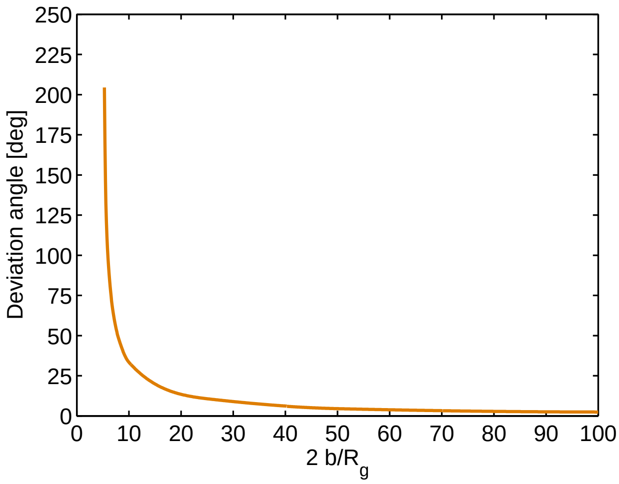

FIG. 3. Interpolated b — deviation angle dependence for jet particle scattered by a black hole in galactic halo; $b = R_g L/\Gamma$, $R_g = 2GM/c^2$ — gravitation radius of a black hole, L and Γ — angular momentum and Lorenz-factor of jet particle.

Using $\theta(b)$ dependence and applying laws of probability theory for sums of random numbers, system (2) can be replaced with:

$$\begin{cases} \Delta x_k &= L_k \sin\Theta_k \cos\Phi_k, \\ \Delta y_k &= L_k \sin\Theta_k \sin\Phi_k, \\ \Delta z_k &= L_k \cos\Theta_k, \\ k &= 1\ldots N. \end{cases} \tag{3}$$

In (3) Θ_k and Φ_k are normally distributed random angles. As Φ_k is distributed as a sum of uniform distributions φ_k its mean M and standard deviation ς:

$$\begin{cases} M[\Phi_k] &= \pi k, \\ \varsigma[\Phi_k] &= \pi\sqrt{k/3}, \\ k &= 1\ldots N. \end{cases} \tag{4}$$

To do the same for Θ_k it is necessary to use function $\theta(b)$ obtained earlier. Assuming value b to be a uniformly distributed random number, distribution of $\theta(b)$ is presented in fig. 4. As angles θ_k have the same distribution,

$$\begin{cases} M[\Theta_k] &= kM[\Theta_1], \\ \varsigma[\Theta_k] &= \sqrt{k}\varsigma[\Theta_1], \\ k &= 1\ldots N. \end{cases} \tag{5}$$

Fig. 4 is plotted in Matlab 7.0 system using its functions and built-in random number generators. Coordinates of a jet particle in defined coordinate system can be inferred from:

$$\begin{cases} x_n &= \sum_{k=1}^{n} \Delta x_k, \\ y_n &= \sum_{k=1}^{n} \Delta y_k, \\ z_n &= \sum_{k=1}^{n} \Delta z_k, \end{cases} \tag{6}$$

where $n \le N$ — number of simulation step. Mean free path L_k depends on k in systems (3) and (6) in general case.

To perform simulations of charged particle motion in galactic halo with black holes, Matlab 7.0 system is used. Initial parameters are: $M = 500$ — number of particles in the jet, $N = 1000$

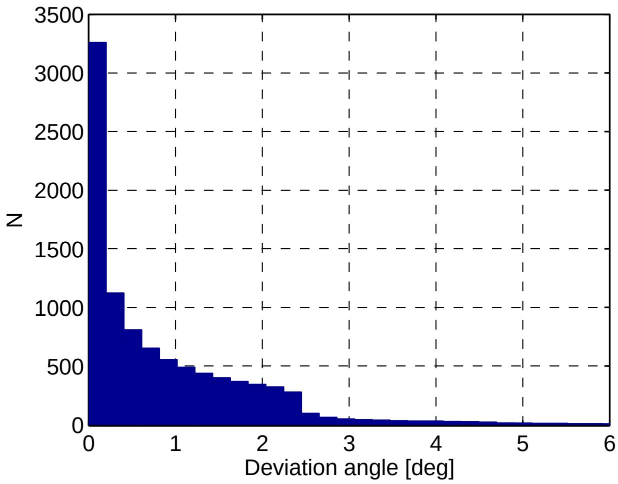

FIG. 4. Distribution of jet particles on deviation angles. Histogram is plotted based on $\theta(b)$ dependence.

— maximal number of scatters per one particle, $L = \text{const} = 10$ kpc. Values of M and N are limited with computing power of used hardware resources. Jet particles move in halo without their deceleration with $\Gamma > 1$ in the model. Numerical algorithm is developed with account of loss of jet particles, because some of them can move in the negative direction of Z axis and leave far halo region. Results of calculations according to (3—6) are presented in fig. 5. It shows positions of jet particles near scattering black holes of a halo. As matter inflow into the halo due to jet is assumed to be constant, this 3D plot illustrates shape of jet in halo in any moment of time. Variation of M and N does not change this shape considerably. Value L is chosen to simulated jet shape size becomes ~ 100 kpc. Variation of N and M parameters shows that such a fit of experimental jet shape depends on only mean free path at large numbers of scatters and jet particles. That means, jet particles move in finite volume at large values of N and M.

4. Concentration and masses of black holes in galactic halos

The next step is estimation of black hole average masses and their concentration in halos of host galaxies. Black hole concentration can be inferred from the expression based on the definition of mean free path (1):

$$n \simeq \frac{1}{L\sigma}, \tag{7}$$

where σ — mean cross section. Assuming that mean value of σ is equal to $(L/4)^2$ and its maximal value is $(L/2)^2$ we have black hole concentration constraint:

$$\varrho > \frac{4 \cdot \langle M \rangle}{\pi L^3} \tag{8}$$

where $\langle M \rangle$ — average black hole mass. Black hole density is plotted in the fig. 6. Analyzing this result it is necessary to note that all known types of black holes (primordial, stellar, intermediate, and supermassive) could be responsible for jet deformation. Characteristic time of jet deformation is defined as:

$$T = \max\left(\sum_{k=1}^{N} L_k\right) \cdot \frac{1}{c} = \frac{LN}{c}. \tag{9}$$

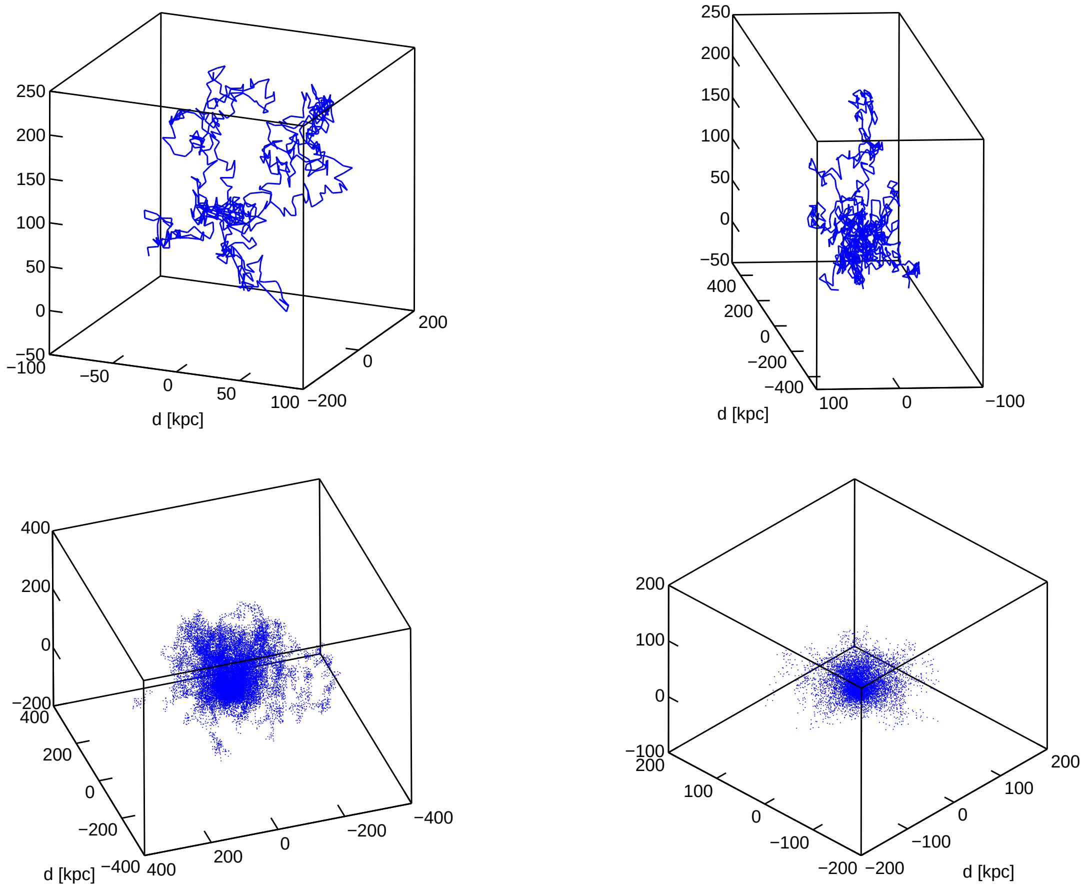

FIG. 5. Position of jet particles near scatters in a galactic halo. Plots illustrate shape of jet and position of $M \times N$ black holes in arbitrary moment of time. Origin of coordinates corresponds to the point where jet gets into the region of halo with black holes. Mean free path of jet particles $L = 10$ kpc. Top-left panel: $M = 1$, $N = 10000$; top-right panel: $M = 10$, $N = 1000$; bottom-left panel: $M = 500$, $N = 1000$; bottom-right panel: $M = 1000$, $N = 100$.

For applied parameters $T \simeq 2.5 \times 10^8$ years.

Created model is used to study average filling of halo by black holes. To do this fractal dimension of black hole cluster is analyzed. Fig. 7 shows distance from coordinate zero point — number of black holes dependence. It can be fitted with law:

$$N(R) \sim R^{1.65}. \tag{10}$$

This result indicate rather leaky filling of halo regions.

5. Discussion and Conclusion

In this paper we propose numerical algorithms and codes for numerical Monte Carlo simulations of scattering of jet electrons by far-halo cold dark matter particles. We simulate final jet evolution stages, their inelastic slowing down and spatial deformation. Simulations are performed with variations of parameters: number of scatters, and mean free path. Proposed model is based on the hypothesis: invisible CDM particles in galactic halos are responsible for the observed deformation. This model is free of the difficulty to explain why jets are deformed essentially only in far regions of halos of the host galaxies. In this paper black holes are considered to be the most appropriate candidates for scatters. Particles of nonbaryonic CDM,

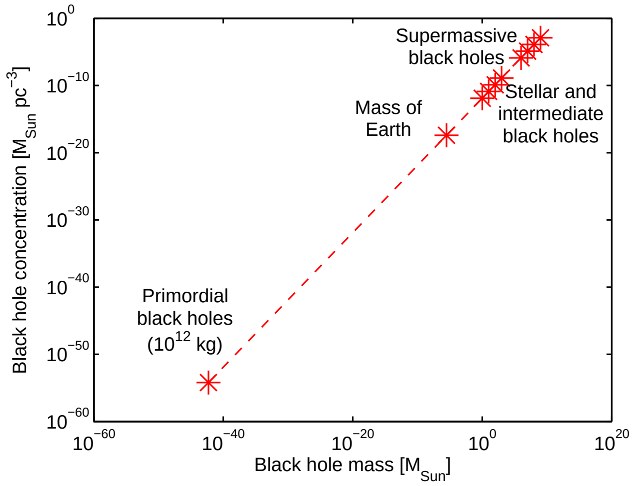

FIG. 6. Average black hole mass — concentration of black holes in a halo dependence. Black holes with masses: 10^{12} kg, 6×10^{24} kg, $1M_\odot$, $10M_\odot$, $100M_\odot$, $1000M_\odot$, $10^6M_\odot$, $10^7M_\odot$, $10^8M_\odot$, $10^9M_\odot$, are marked with asterisks.

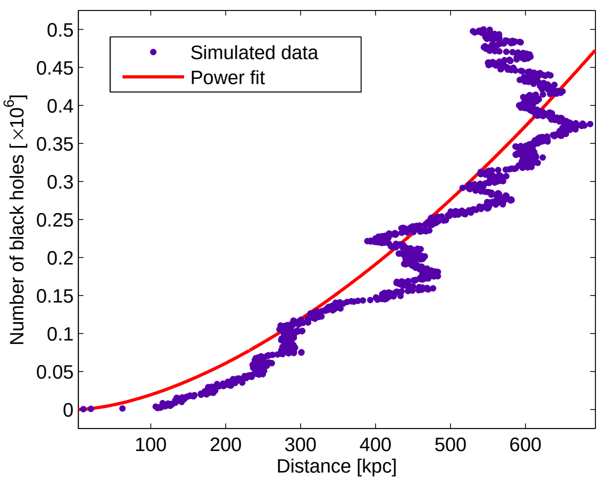

FIG. 7. Distance from coordinate system origin — number of black holes dependence for far region of a galactic halo. Data from the model and its power fit are shown.

such as WIMPs, axions, gravitino et al. [14-17], are not able to deviate jet charged particle trajectories because of weak interaction with them. Neutron stars of stellar mass can reach halo of a galaxy when they get large velocities as a result of asymmetrical supernova explosions or binary system breakup. But strong magnetic fields of neutron stars will capture charged particles of a jet, so it will lose its particles and will not result in observed deformed shape. Moreover, neutron stars as other barionic dark objects (e.g. brown or black dwarves) do not satisfy mass constraint derived in the previous section (fig. 6).

In the proposed model a sample of jet particles move in Schwarzschild field of black holes in halo of a galaxy. When met a black hole jet particle deviates at the angle θ (fig. 1-3), which is calculated on the basis of particle motion equations in general relativity and laws of probability theory. In the model up to 10000 scatters and up to 1000 jet particles with Lorentz factors $\Gamma \gg 1$ are used (fig. 5). After finite number of collisions a jet particle stops. In reality jets decelerate gradually, but this used assumption does not influence the model significantly. Jet particle capture process is neglected in the model in consequence of its low probability. Also, the model is particle independent, the sort of particles (electrons, protons, positrons or something else) does not matter.

Observed jet shapes in far halo regions of galaxies are in a good correspondence with those simulated in this paper (fig. 5).

Concentration constraint of black holes in galactic halos (fig. 6) is derived. Any known types of black holes are capable to cause observed deformed shapes of jets in far halo regions. The origin of such a cluster of black holes in halos needs further investigations.

Calculated fractal dimension of simulated black hole cluster in a galactic halo (fig. 7) shows very leaky filling of far halo by black holes.

Probably, other factors, e.g. interaction with ambient interstellar or intergalactic medium, can also effect jet disruption. But scattering by black hole cluster of a halo seems to be the dominate factor.

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