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On the role of galactic magnetic halo in the ultra high energy cosmic rays propagation.

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ABSTRACT

The study of propagation of Ultra High Energy Cosmic Rays (UHECR) is a key step in order to unveil the secret of their origin. In this article we have focused our analysis on the influence of the magnetic field of the galaxies. We have used the most complete galaxy catalog up to now: the LEDA catalog with 60130 galaxies inside 120 Mpc. In our simulations we assign a Halo Dipole magnetic Field (HDF) to each galaxy. The HDF is a dipole magnetic field with cutoff lower value for $B = 0.1$ nG, which corresponds to a magnetized region of ~ 100 kpc. The code developed is able to retro-propagate a charged particle from the arrival points of UHECR data across our galaxies sample. We have shown that there is a non negligible deviation in the case of protons of 7×10^{19} eV, even if the B value is conservative. We present simulations in case of Virgo cluster and we analyze the case of the AGASA triplet where we find NGC3998 and NGC3992 as possible candidates.

Subject headings: ultra high energy cosmic rays: propagation — magnetic fields: galactic magnetic field, extra-galactic magnetic field

1. Introduction: two puzzles connected

The window of observational astronomy has become broader, firstly in the '70s with the development of the first gravitational wave detectors and in the '90s with the birth of the astroparticle field and the construction of neutrinos telescope. On the other hand, the charged particles, produced abundantly in all astrophysical sources, present the peculiarity that they lose the direction of the source due to diffusion inside galactic magnetic field.

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However, one hope is to use the highest part of the cosmic ray spectrum in order to open a new window in astrophysics. To do this, we must find a path connecting the two fundamental ingredients: the ultra high energy cosmic rays (UHECR) and the intergalactic magnetic field (IGM).

The existence of a $50 \mu\text{G}$ galactic magnetic field was discovered by Schluter & Biermann (1950). Extragalactic magnetic field of order of a few μG were detected by both synchrotron emission and Faraday rotation in the Coma Cluster, and, beyond clusters, in more rarefied regions, surprising magnetic fields of $\sim 0.1\mu\text{G}$ were measured (Kim et al. 1989). A variety of observations suggests that magnetic fields are present in all galaxies and clusters. Even if these fields are small, they are on very large scale and the energy inside could be very huge. More details can be found in Han (2001), Beck (2004) and Vallée (2004).

The importance of magnetic field from the galaxies is well known in the case of radio galaxies where the radio lobes confirm the existence of a large region of magnetic field well outside the galaxy. Kronberg et al. (2001) advanced the idea that the galactic magnetic field, especially in the case of radio galaxies, is a consequence of the presence of a supermassive black hole at the center. Following this view, and using the fact that most probably all galaxies have a massive black hole in their center, we will assume that the existence of the galactic magnetic halo is a general property of galaxies. This has to be modulated by the value of the related field and the size of this halo. In fact the magnetic energy we will put in these halos is quite low by several orders of magnitude compared to the average cosmic rays energy density. There is also observational evidence for the existence of the magnetic halo in the case of spiral galaxy seen edge-on (Krause 2003).

On the other hand, the problem of the origin of the UHECR is a long standing mystery starting with the discovery of a 3×10^{20} eV event (Linsley et al. 1962). This opened the Pandora’s box of a new mystery in physics, unsolved 44 years after. More details can be found in Olinto (2005). Magnetic fields play a vital role in this puzzle, and are a corner stone in order to study the UHECR propagation. As a matter of fact the gyroradius R of a proton of energy E in a magnetic field B is given by $R \sim 100 \text{ kpc} \times E(10^{20}\text{eV})/B(\mu\text{G})$.

The influence of cosmic rays propagation has been underlined in several articles. Alvarez-Muniz & Stanev (2005) scrutinized the influence of galactic magnetic field and they have shown that protons in the range of $10^{18} \div 10^{19}$ eV can be used to probe the large scale structure of the galactic magnetic field. Prouza & Smida (2003) made a study of the influence of the galactic magnetic field, including a magnetic galactic halo in form of dipole given by Han (2001). Medina-Tanco (1998) analyzed the effect of large magnetic field localized in sheets and filaments, while voids are almost free of magnetic field. He has shown that this assumption has dramatic consequences on the cosmic ray propagation. Sigl, Miniati & En-

sslin (2004) analyzed the influence of extragalactic magnetic fields and have shown that for strongly magnetized regions, observers predict considerable large scale anisotropies between 10^{19} eV and 10^{20} eV. Yoshiguchi, Nagataki & Sato (2004) presented numerical simulations of UHECR in a structured intergalactic magnetic field given by IRAS PSCz catalog. They estimated the number of sources in order to explain the AGASA data observations and have found that $\sim 10^{-5} \div 10^{-6} \text{ Mpc}^{-3}$ is the best number of UHECR sources density. Dolag et al. (2004) examined the propagation of UHECR using simulations of large-scale structure formation to study the build-up magnetic field in the intergalactic magnetic medium. They constructed full-sky maps of expected deflection angles of UHE protons.

Cosmic rays propagation in the galaxy is strongly affected by the GMF, where the gyroradius of a proton can be as small as ~ 300 pc. Therefore, for $E < 10^{18}$ eV, cosmic rays diffuse in the GMF. They get isotropized and hence do not reveal the sources where they were accelerated. In the range between 10^{18} and 10^{19} eV, cosmic rays through the magnetic fields are thought to change from heavy to light in composition and from diffusive to ballistic in propagation (Aloisio & Berezhinsky 2005).

It has long been hypothesized that the deviation by galaxies are unlikely or inefficient. In this article we have reconsidered this hypothesis in light of a complete galaxy catalog. With the lack of general data of magnetic halos for all the galaxies of the survey, we will assume this is a general property and use a model similar to our own Milky Way.

In sec. 2 we will detail the code used to retropropagate the charged particles, here assumed to be protons, across our nearby universe (up to ~ 120 Mpc) obtained from the galaxy sample. In sec. 3 we will present the results of simulation in the Virgo cluster and maps of AGASA data, with particular attention to the triplet. In sec. 4 we will finally show that such deviations are not negligible and are to be incorporated in propagation calculations.

2. Calculation technique

In order to study the propagation of UHECR inside a 120 Mpc sphere radius, we looked at the most complete view of our local universe. Recently, Paturel et al. (2005) published a complete catalog of galaxies by merging several catalogs in the aim to realize the catalog of catalogs. LEDA (Lyon-Meudon Extragalactic Database) is a collection of near infrared properties of galaxies, using full resolution images from DENIS measurement survey. This leads to a catalog of 753153 galaxies with I, J, L, K magnitudes. From this, we have extracted a sample of 60130 galaxies inside 120 Mpc. We selected the galaxies for which we have a distance estimator in the catalog. LEDA permits also to have the inclination parameter of

the galaxy axis as well as several other features.

We will use this sample to study the propagation through the galactic magnetic halo. Lacking direct measurement of magnetic field of large sample of galaxies, we will assume a simple model for it: each galaxy is surrounded by a magnetic halo with a dipole structure, oriented as the rotation axis for spiral galaxies and the symmetry axis for elliptic ones. The Halo Dipole magnetic Field (HDF) is, in spherical coordinates,

$$\begin{aligned} B_x &= -3\mu_G \cos \phi \sin \phi \sin \theta / R^3 \\ B_y &= -3\mu_G \cos \phi \sin \phi \cos \theta / R^3 \\ B_z &= \mu_G (1 - 3 \cos^2 \phi) / R^3 \end{aligned}$$

where $\mu_G = 184.2 \mu\text{G kpc}^3$ is the galactic magnetic moment and R is the distance from galactic center. These values are similar to those of Milky Way (Stanev 1997). The inner zone (< 500 pc) is taken as a constant value $B_z = 500$ mG. The magnetic field is considered unimportant for $R > 100$ kpc, where it falls below 0.1 nG. The orientation of the magnetic dipole is chosen with a random number, but is parallel to symmetry axis or rotation axis of galaxies.

According to Longair (1997), the average cosmic ray density in the Milky Way is ~ 0.6 eV cm^{-3} . The total magnetic energy stored inside this halo is $(B^2/2\mu_0)(4\pi r_0^3/3) \sim 10^{55}$ ergs, which is less than the total energy inside cosmic rays estimated as the value 10^{63} ergs for a normal galaxy. Therefore the value of the field in this assumption is conservative and it is much less than the equipartition one, which is reasonable for structured fields. By comparison, under the assumption that the field was adiabatically compressed, Furlanetto & Loeb (2001) found that the intergalactic magnetic field should be at ~ 1 nG, while we are at 0.1 nG at the halo edge.

In order to explain the presence of such magnetized halo, we can follow the arguments proposed by Kronberg et al. (2001) regarding Giant Radio Galaxies (GRG). In their analysis of GRG, they concluded that a large fraction of energy is stored in extended radio source in form of magnetic energy. They noticed that contrary to the case of radiation energy, which is quickly lost, magnetic energy gets confined for a significant fraction of cosmic time. They assumed that gravitational energy lies at the origin of this magnetized energy and proposed a new link between massive black holes and the magnetized universe. Since we have now solid indications that massive black holes are a common feature of all galaxies, we can extend the argument developed by Kronberg to all galaxies: at some level the energy exchanges between gravitational and magnetic energy, through the presence of a massive black hole. This leads naturally to the conclusion that the massive black holes are at the origin of magnetized galaxies. In the case of AGN, the presence of the magnetism is unveiled

by the radio lobes. In case of less active galaxies, it could be associated to some less extended lobe like a magnetized halo. Our assumption is then fully justified in this new scenario.

3. Results and discussions

In our simulation we used the AGASA data, which are the only published (Takeda et al. 1999). We present here a map in galactic coordinates where we have superimposed the AGASA events and the corresponding events after the interaction with Galactic Magnetic Field (GMF) according to the model given by Stanev (1997). The simulation presented on fig. 1, shows clearly an effect of the GMF. The maximum deviation is related to region of high density of matter where the field is more important. The results were consistent with Kachelriess, Serpico & Teshima (2005).

We have then concentrated our analysis to the Virgo Cluster as a test in order to evaluate the influence of the HDF. The result is given on fig. 2. We inject 10000 monochromatic protons distributed in a cone half angle 1° , and study the backward propagation by numerical integration of the equation of motion. The net mean deflection due to HDF is $\Delta\theta \sim 0.71^\circ$ at 30 Mpc for a proton of energy 7×10^{19} . If we add the galactic contribution we obtain a global deviation of $\Delta\theta \sim 1.56^\circ$. In order to evaluate the influence of the field amplitude, we have made another simulation with a greater value. The results are presented in fig. 3.

Finally we have focused on the AGASA triplet. The results are displayed in fig. 4.

Among the galaxies inside the possible sources for the triplet we have isolated NGC3998 and NGC3992 which are at a distance of ~ 25 Mpc. We have noticed that several trajectories are coming from these galaxies and coincide with AGASA triplet event.

NGC3998 is a LINER type I and it has been recently observed by XMM-Newton (Ptak et al. 2004). Several observations have shown an increase of X-ray flux characteristic of an intense activity. They concluded that a jet model may be consistent with the radio and X-ray flux and jet emission may produce also the mid-IR and optical/UV flux. If we follow this conclusion, we can assume the existence of a jet and presumably a shock wave at the end of this jet. In this environment we expect to have UHECR acceleration (Rachen & Biermann 1993). We naturally propose NGC3998 as a solid candidate for the AGASA triplet.

NGC3992 is a giant luminous spiral galaxy located inside a group of galaxies with a large mass to light ratio. Historically this is a known galaxy (M101), and hosted a supernova type I (Zwicky & Karpowicz 1964). This could be interesting in light of the observed connection between supernovae and gamma-ray bursts, which are likely transient UHECR sources (Vietri

1995).

4. Conclusions

We have developed a propagation code of UHECR using the 60130 galaxies within 120 Mpc, with known distance from LEDA catalog, and we put a magnetic halo field around them. In the simulations we assumed that the UHECR are protons. Using AGASA data we have found evidence for deviation that could affect the direction of the source.

The presented results are model dependent and our main objective is to demonstrate the influence of galactic magnetic halos on UHECR propagation. We want to underline that we used a conservative approach: first, in the choice of the B field we took a dipole component with an edge value of the halo of ~ 0.1 nG; second, in our simulation we focused on protons at energy $\sim 7 \times 10^{19}$ eV. Heavier or less energetic particles are more deviated. Despite all this, our work shows clearly that the influence of HDF is not negligible. A next step will be to incorporate in the code the influence of the cluster magnetic field and the intergalactic magnetic field, which has been partially done in fig. 3.

In the case of the AGASA triplet, our results suggest some possible candidates. NGC3998 presents some astrophysical interest: it is an active galaxy at relatively short distance. Therefore we suggest it as a possible UHECR source. The scenario presented here is related to the galactic magnetic halo and answers to the fundamental question of the relation between magnetism and structure formation. This question is addressed from the theoretical part with some possible connection between supermassive black holes and magnetism, as in Kronberg scenario. From the experimental point of view the Square Kilometer Array will surely clarify the picture by mapping the magnetic field of galaxies with more accuracy. UHECR propagation could give us another astrophysical test of this connection.

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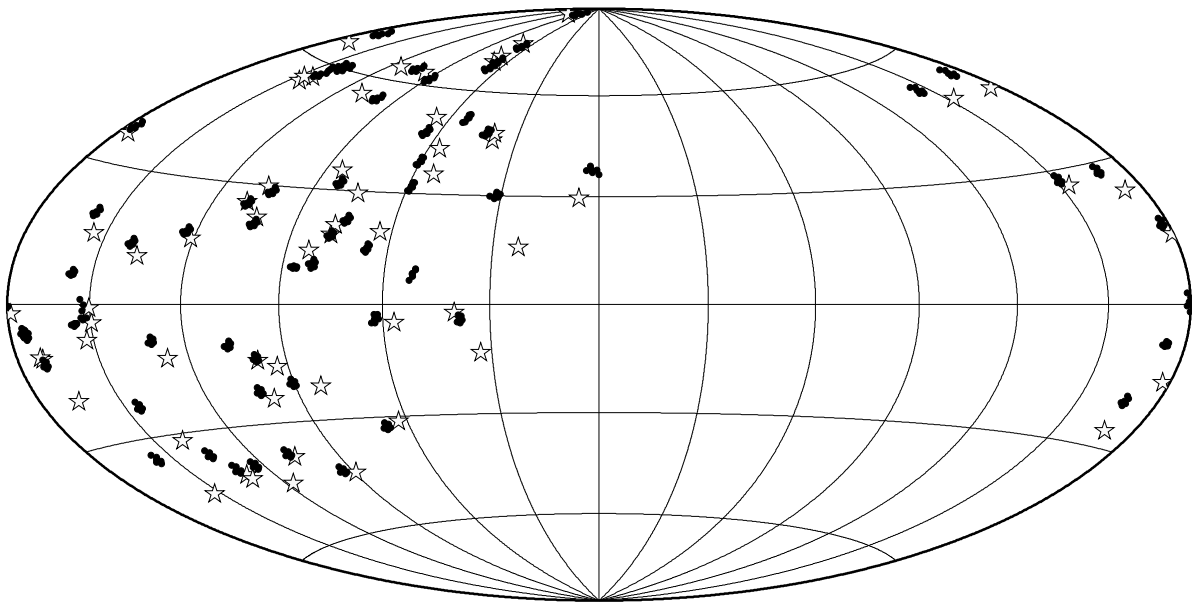


Fig. 1.— Effect of the Milky Way magnetic field on AGASA data (stars). Hammer equal area projection in galactic coordinates. Each simulation has seven points inside a 1° radius spot.

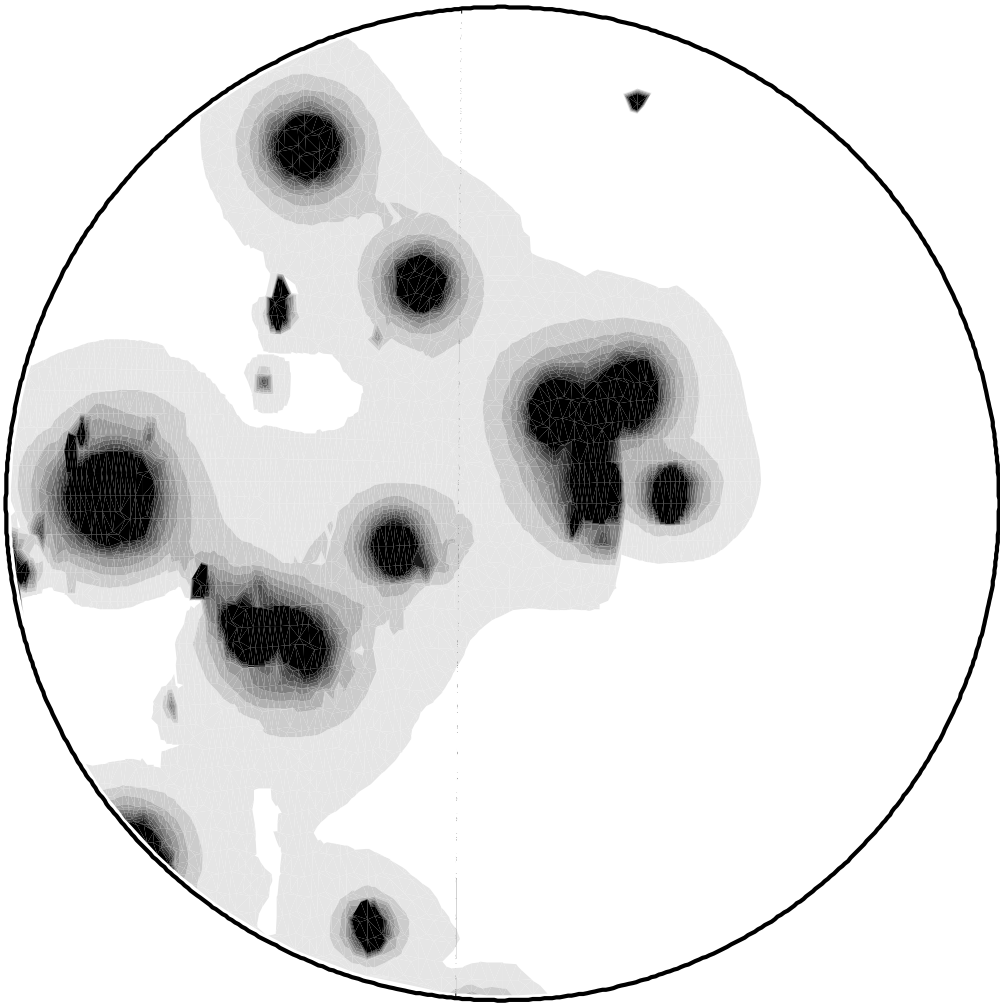


Fig. 2.— Deflection for 10000 trajectories of energy $E = 7 \times 10^{19}$ eV inside a circular spot of half radius 1° towards Virgo Cluster center, considered at 30 Mpc. Black zones are for $\Delta\theta > 1^\circ$

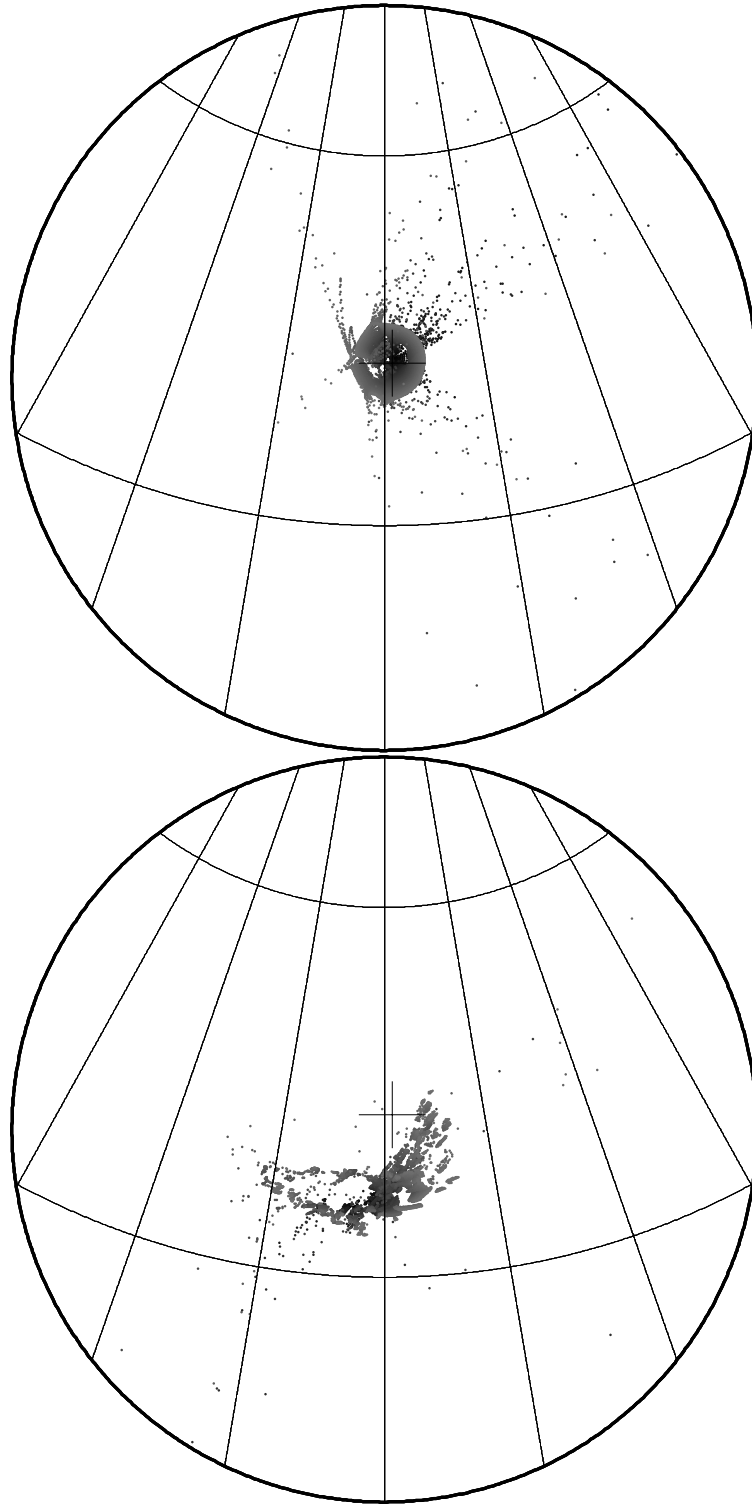


Fig. 3.— The dispersion of trajectories through Virgo galaxies magnetic fields at 30 Mpc in gnomonic projection. 10000 protons at $E = 7 \times 10^{19}$ eV, in a spot of half angle 1° are injected. At start, darker points were closer to center of Virgo nominal coordinates ($l = 279.2$, $b = +74.4$). Upper: a simple dipole field, as described in text; the mean deviation is $\Delta\theta = 0.71^\circ$. Lower: the same, with a radial dipole magnetic field component frozen to 1 nG up to a radius of ~ 300 kpc; the mean deviation is $\Delta\theta = 2.03^\circ$.

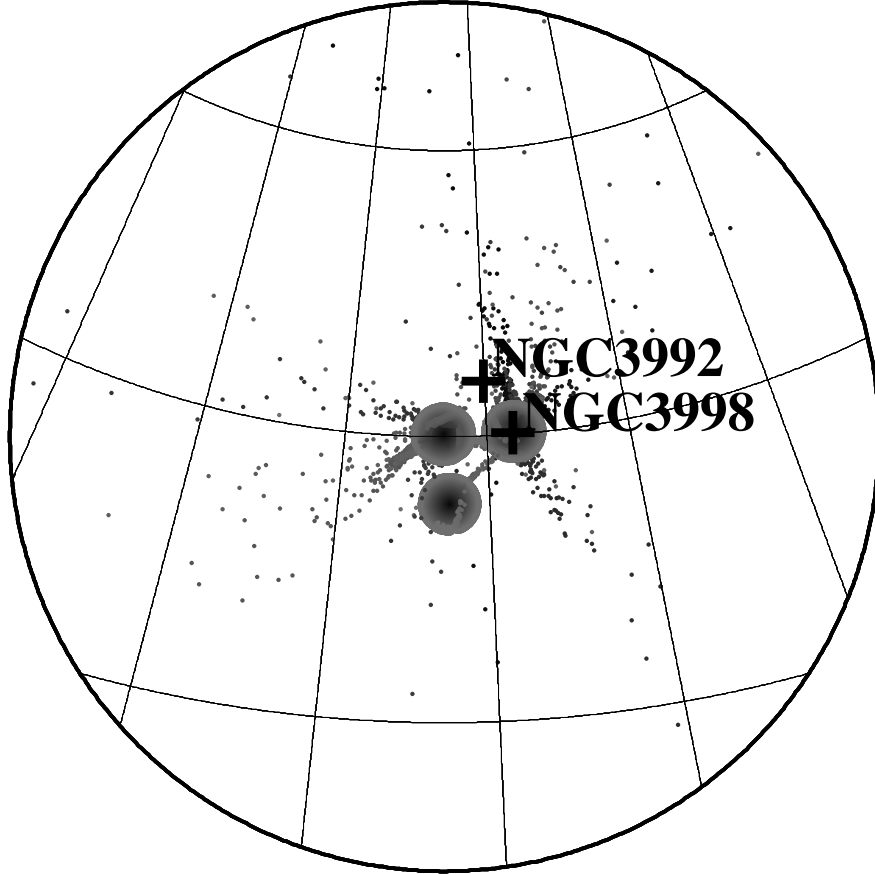


Fig. 4.— Triplet dispersion at 30 Mpc. 40000 protons for each AGASA point (direction and energy) were back-propagated, including Milky Way field and outer galaxy dipole field. At start, darker points were closer to center of AGASA nominal coordinates. Two candidates are shown. To validate a source we choose the presence in at least one trajectory per event.