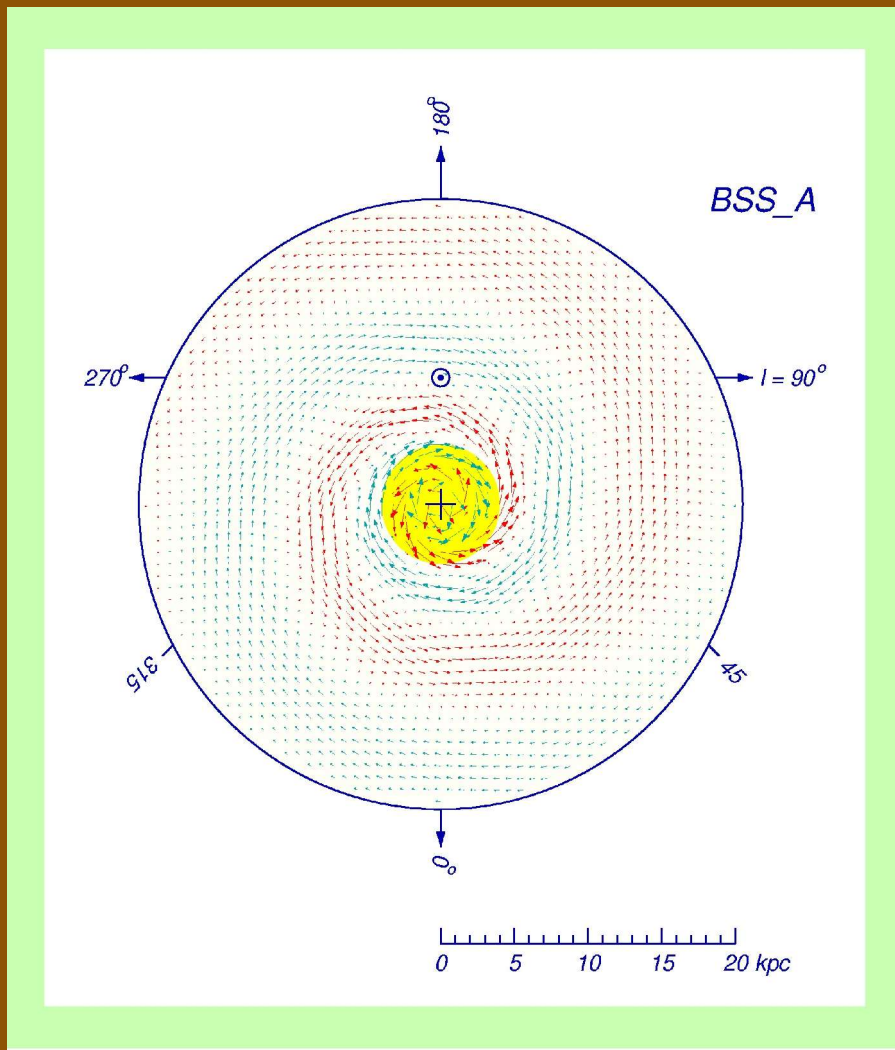


Galactic Transport of Cosmic Rays

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We shall discuss attempts to transport high energy cosmic rays ($E > 10^{16}$ eV) from their sources to different destinations in specific galactic magnetic fields models. The calculations that I will show as examples are done with the Monte Carlo technique, which is very inefficient in this application. Since the cases that we discuss are on the boundary between diffusion and rectilinear propagation we do not have much of a choice. The time consuming techniques requires some simplifications of basic magnetic field features, mostly in the description of its turbulence.



Technique is simple:

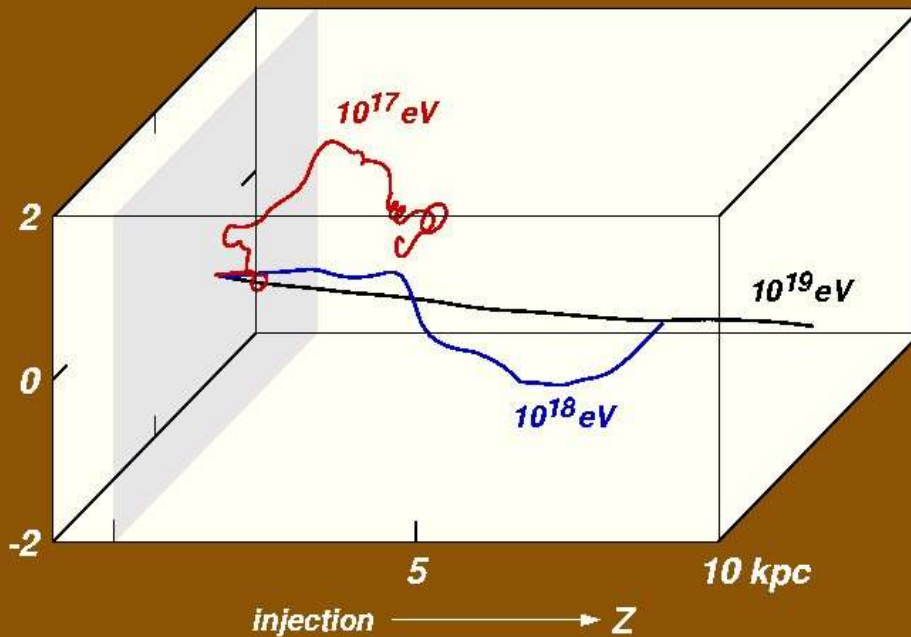
- take a model of the galactic magnetic field. BSS odd parity and ASS even parity fields used here with & without additional halo field. These fields cause minimum and maximum deflection among reasonable models.
- inject particles at the source (usually isotropically) and propagate them by solving the equation of motion in the magnetic field.
- collect the needed information either at the Solar system, or on leaving the Galaxy.

An approach that is often used is to *backtrack* particles of the opposite charge from the field of view of the detector and identify the possible location of their sources.

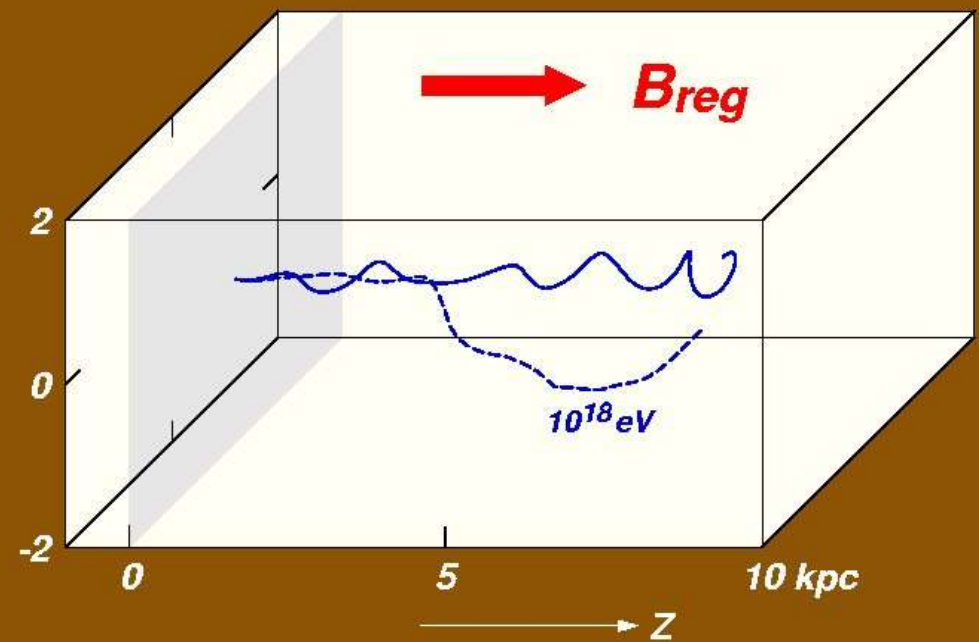
Basic behavior

$$r_g(1 \text{ PeV}, 1 \mu\text{G}) = 1 \text{ pc}$$

Trajectories of particles of different energy injected in the same direction in 1 μG random magnetic field.



When an organized field is switched on, particle trajectories becomes more regular as particles girate around the magnetic field lines.



Magnetic field implementation

Three types of magnetic field are used:

1) Regular field B_{reg} (ASS, BSS, etc) with the solar system at 8.5 kpc from the galactic center. Radial dependence of field strength is $1/r$. Field assumed constant within the 4 kpc circle. Field decreases exponentially above and below the galactic plane.

2) Random component with coherence length of 100 pc and strength of $B_{\text{reg}}/2$ unless otherwise stated.

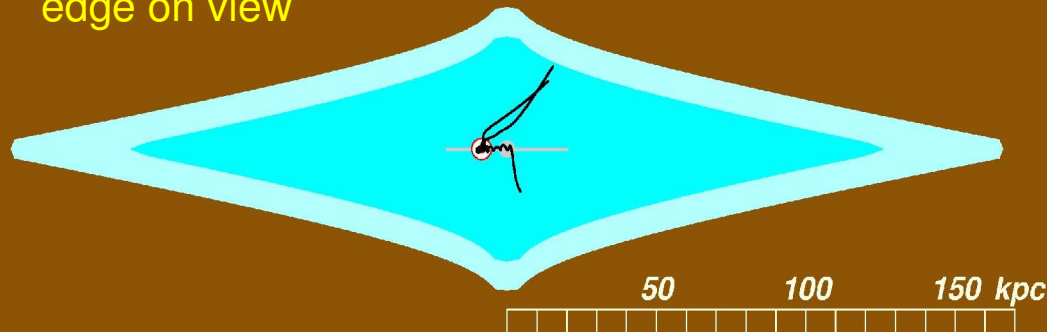
3) A0 dipole field (Han 2002) is occasionally introduced. Its strength decreases as r^{-3} and is only $0.3 \mu\text{G}$ at the solar system.

Cosmic ray problems to address: (all in the non diffusive propagation regime)

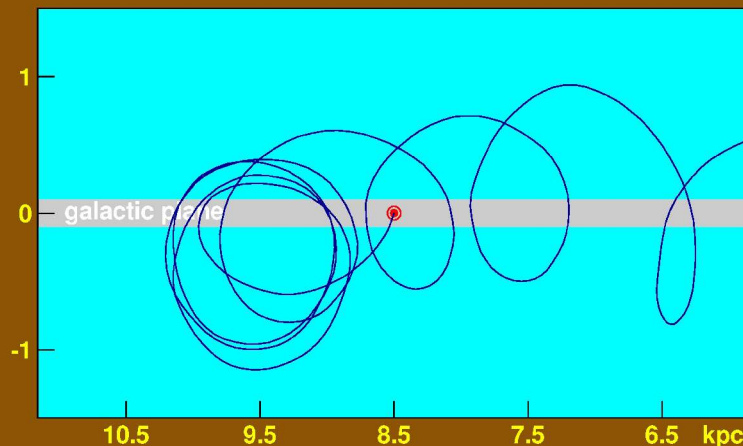
- 1) Leakage out of the Galaxy/penetration of extragalactic cosmic rays into the Galaxy.
- 2) Testing specific acceleration models.
- 3) Anisotropies due to the cosmic ray source distribution and magnetic field topology.

Leakage out of the Galaxy

edge on view



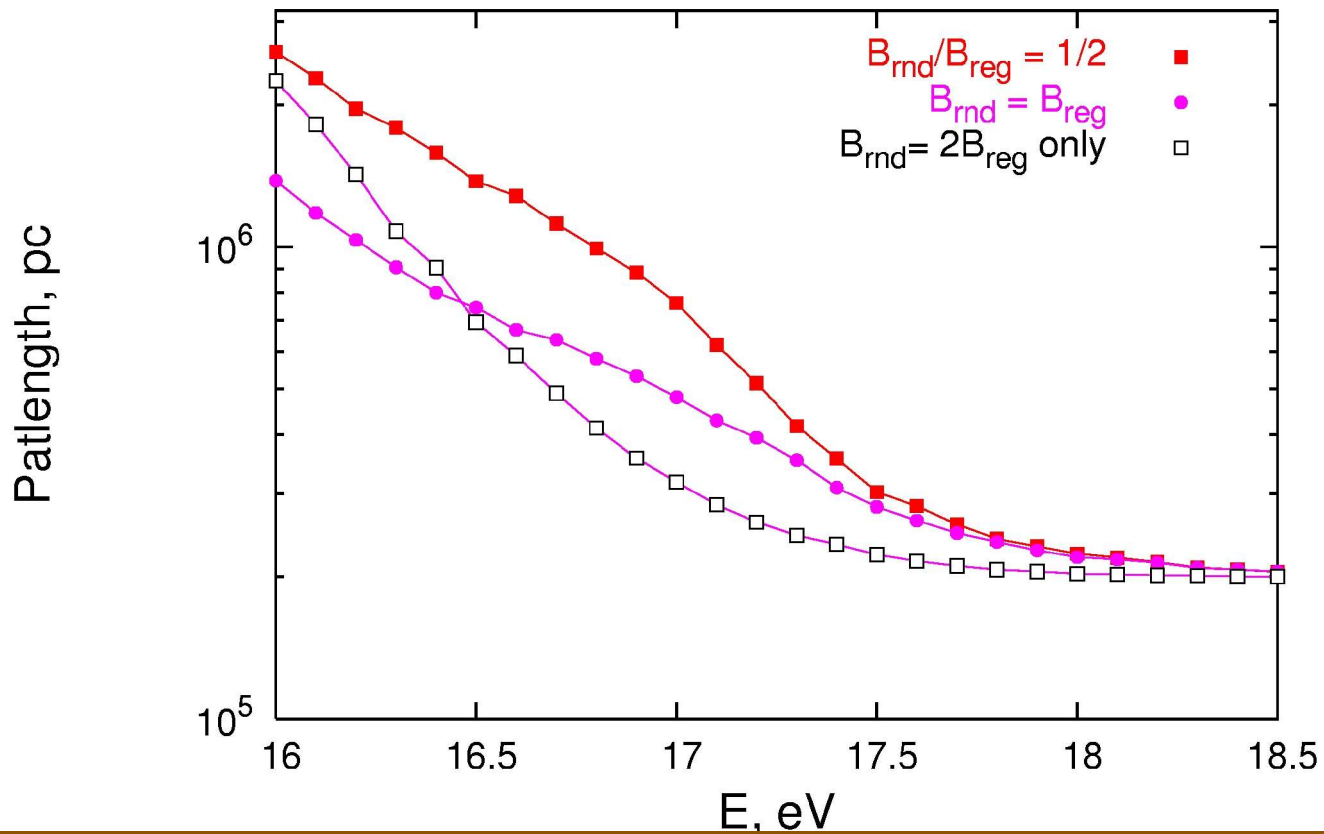
Particles injected from Earth and followed in the volume above. Propagation seems to be straight only because of the large scale – see expanded graph below.



What is the extent of the galactic B field ?
When field strength equals extragalactic field ?
How strong is the extragalactic field?
1 & 0.1 nG shown here.

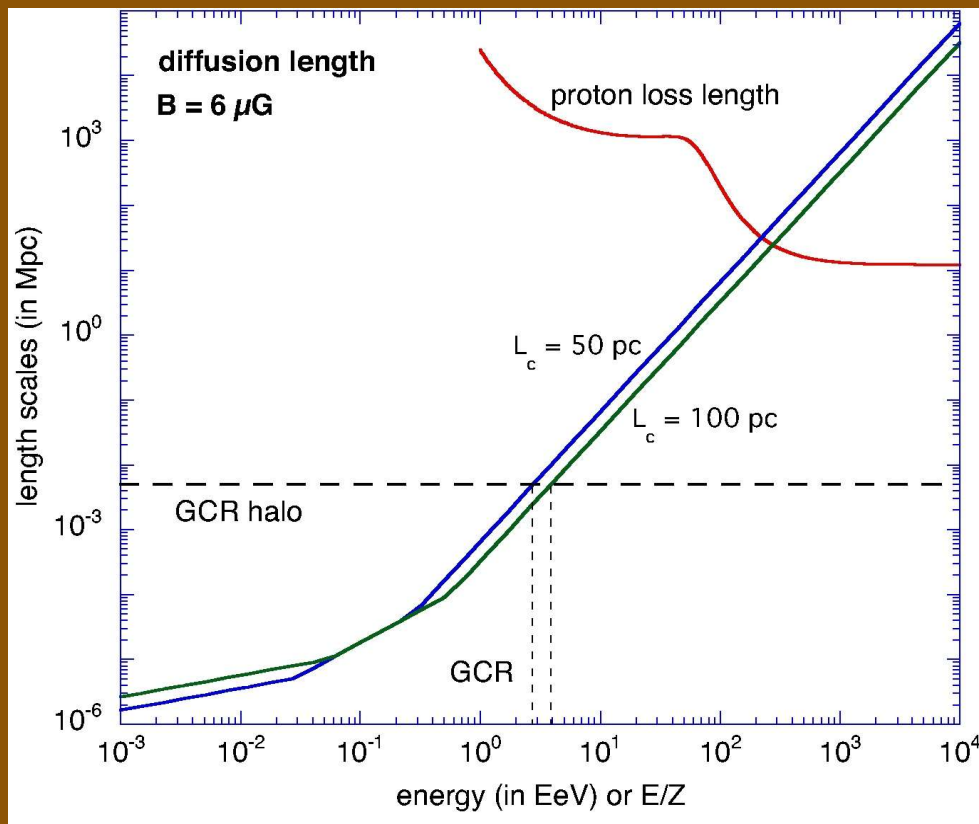
25 kpc exponential field cutoff in galactic plane assumed in this case.

There is a strong anisotropy – particles escape mostly up and down, not along the plane.



Escape time is inconsistent with GeV results since magnetized volume exceeds by orders of magnitude galactic plane. Simplified random field turbulence works in the same direction.

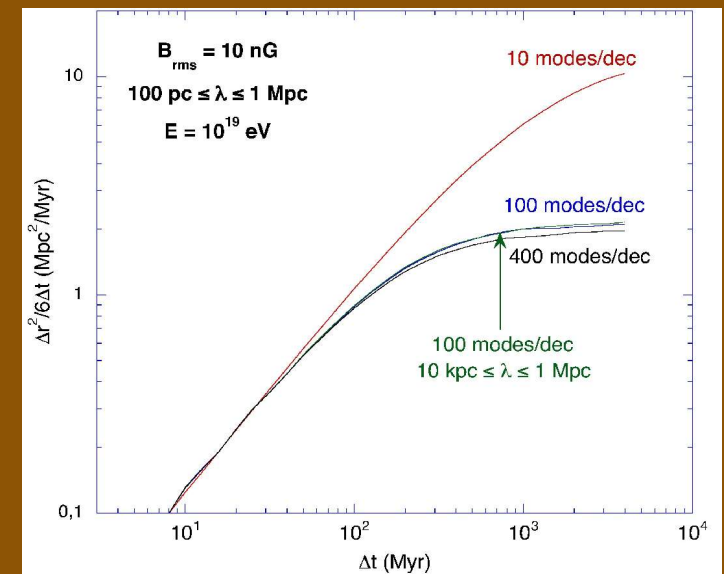
Average pathlength for escape from the Galaxy for three field models. Random field only model shows $1/E$ behavior. Regular field models converge at \sqrt{E} behavior at low enough energy. The range above $\log E = 16.5$ is the transition range between diffusion and straight line propagation. Note higher field causes smaller pathlength, possibly because of easier transverse motion.



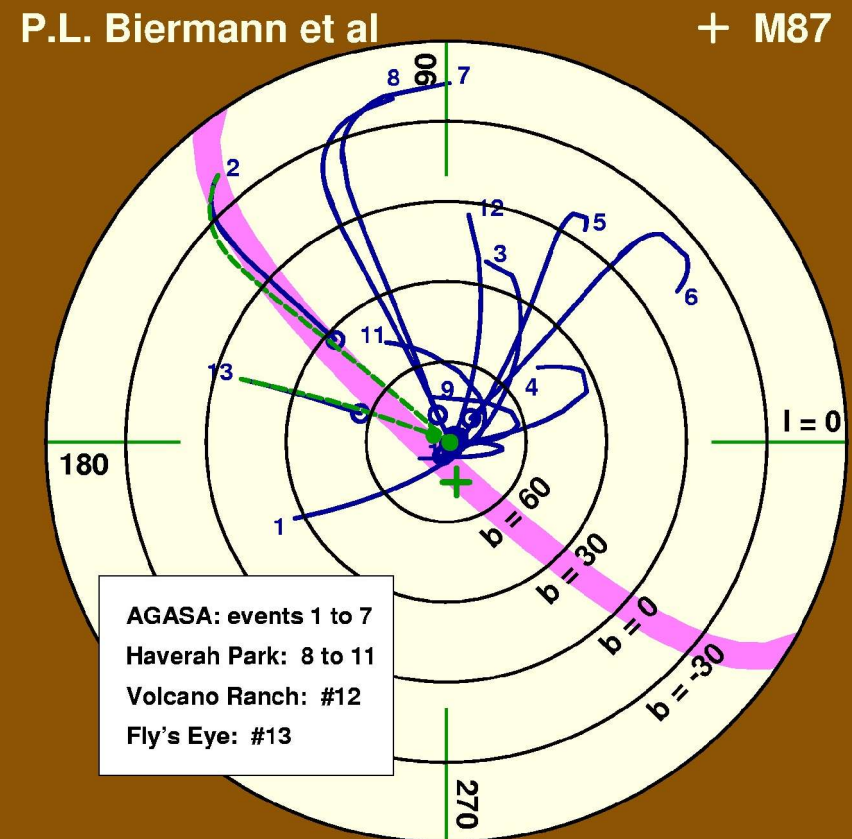
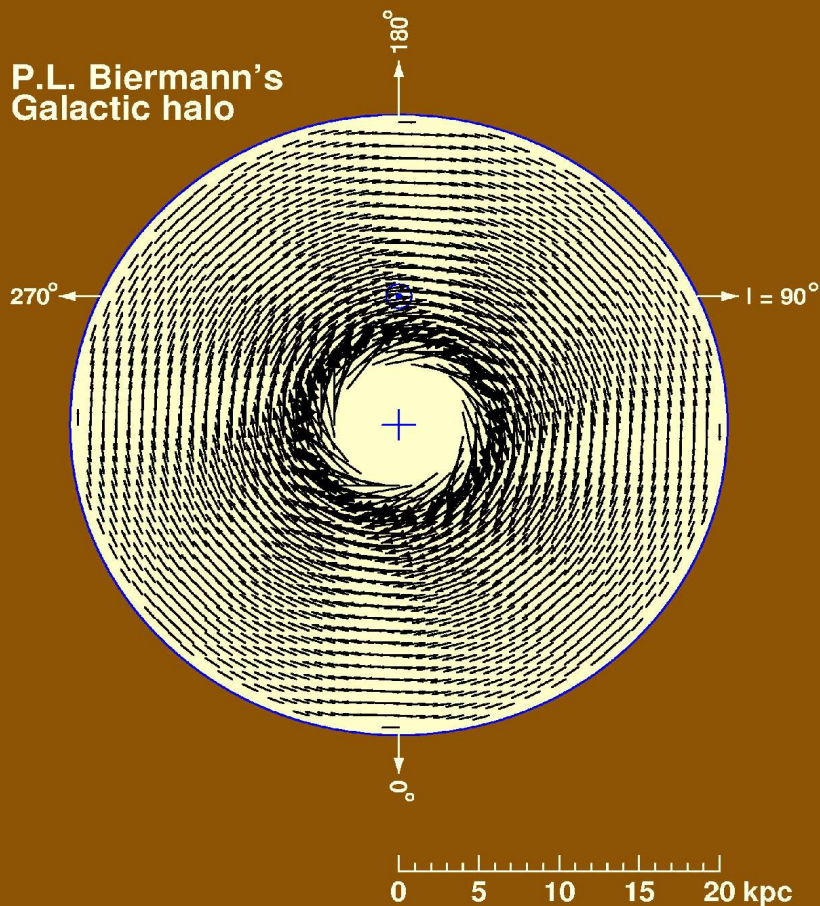
The same energy range is considered by E. Parizot in relation to extragalactic cosmic rays. Parizot studies deflection, diffusion coefficient, and magnetic horizon and does an excellent study of the inaccuracies introduced by not representing correctly the magnetic field turbulence, as shown below.

E. Parizot, *astro-ph/0409129*

a warning

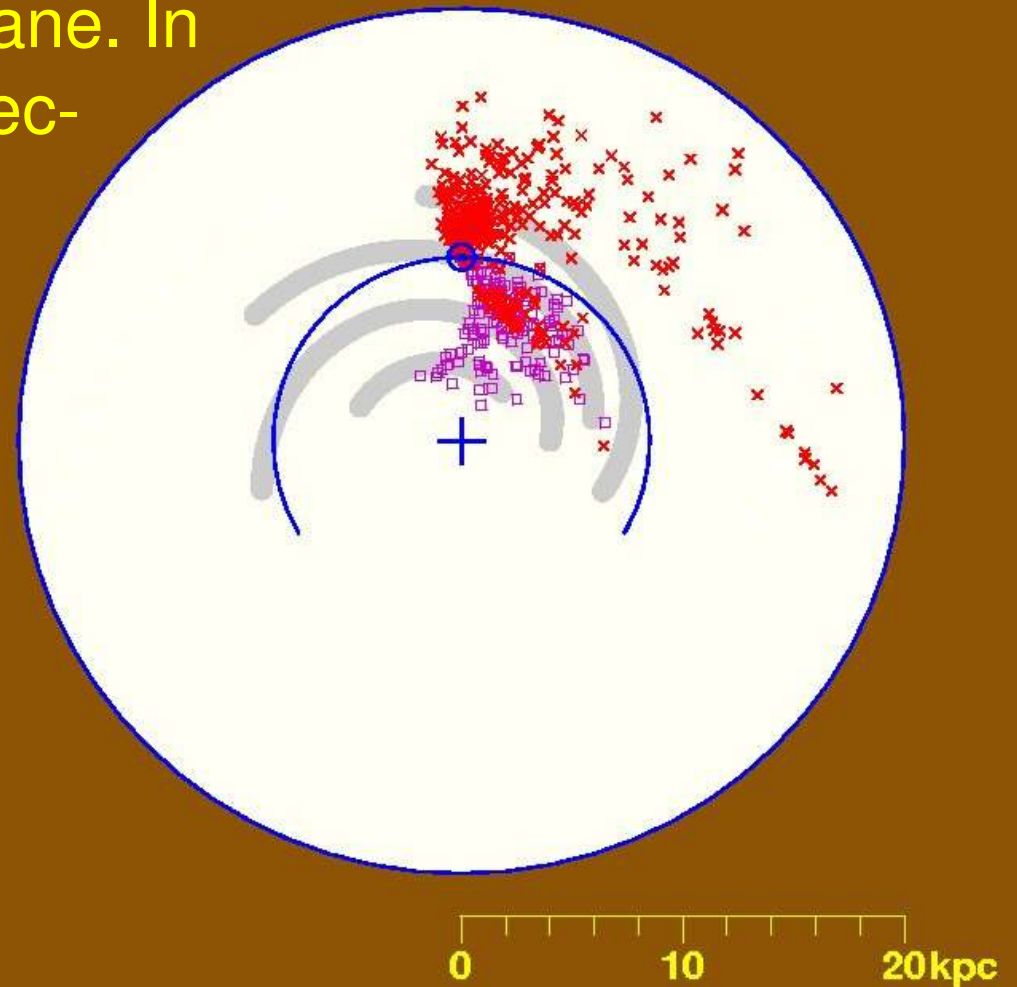


The extreme case is P.L. Biermann's suggestion of a large extended halo (up to 1.5 Mpc) following the observation of identical field direction (inwards along galactic arms) in many galaxies. It is applied here to extragalactic cosmic rays that can only come to us from the NGP.

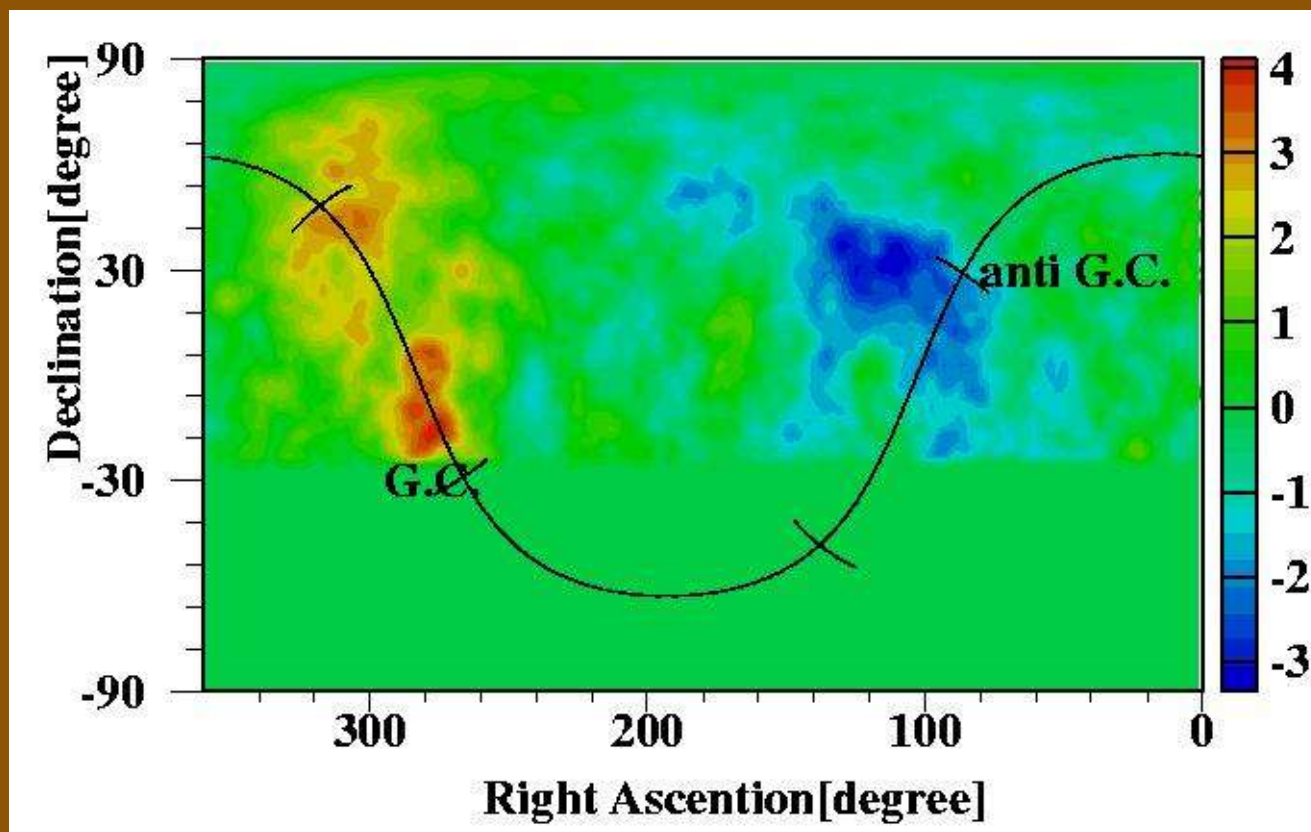


Testing acceleration models: backtrack cosmic rays from the Earth and see where to look for their sources.

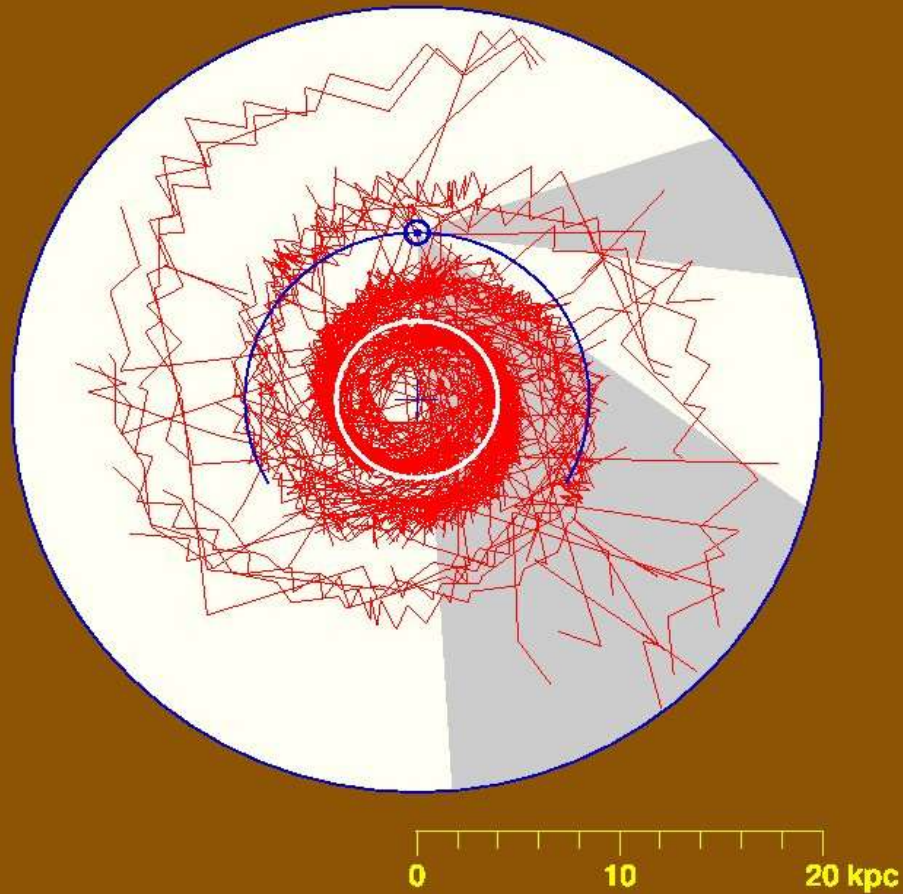
Dots show the positions at which backtracked 10^{20} eV iron nuclei (injected from the field of view of existing air shower arrays) cross the galactic plane. In the ASS model these intersections are in the direction of the galactic center, while in the BSS model they are mostly in direction of the anticenter. The graph also gives us an indication how far from us the sources of such particles can be.



Anisotropies

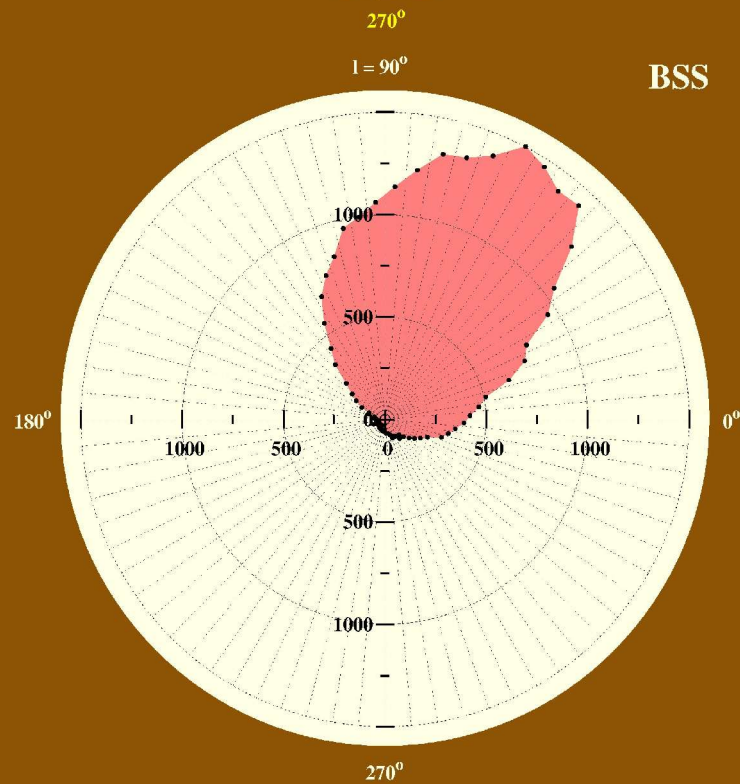
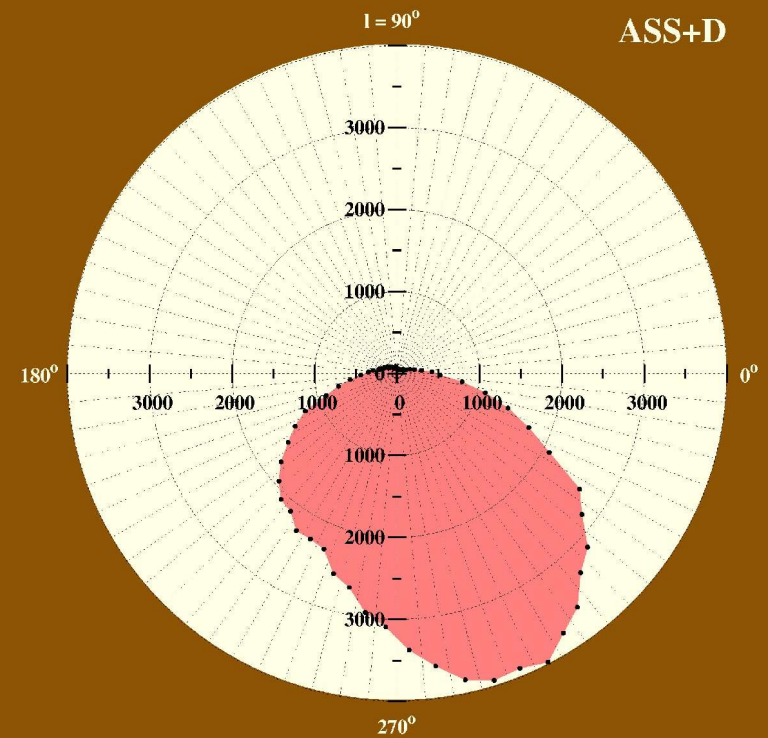
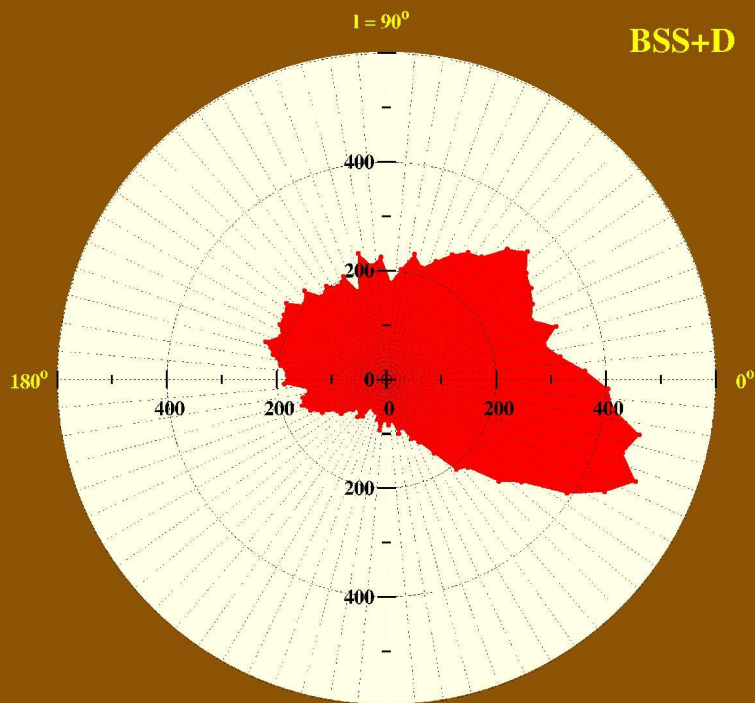


AGASA: More cosmic rays of energy about 10^{18} eV come from the local galactic arm and from direction close to the galactic center. Less particles come from the galactic anticenter. This result has provoked many explanations: the last GRB in the Galaxy, neutrons from Cygnus OB2, neutrons from the galactic center ...



These two directions of excess are shaded. The graph shows the locations where 10^{18} eV protons injected isotropically at the 4kpc circle cross the galactic plane. It is obvious to the eye that the main trend is gyration around the magnetic field lines. It is not obvious what is the anisotropy that this motion will create, as the particle direction is almost normal to the field lines.

In the exercise that follows we inject particles on a $E^{-2.7}$ energy spectrum around 10^{18} eV isotropically from sources at the 4 kpc circle and from $1/r$ galactocentric distribution and follow them in different field models until they intersect 1 kpc sphere around the solar system.

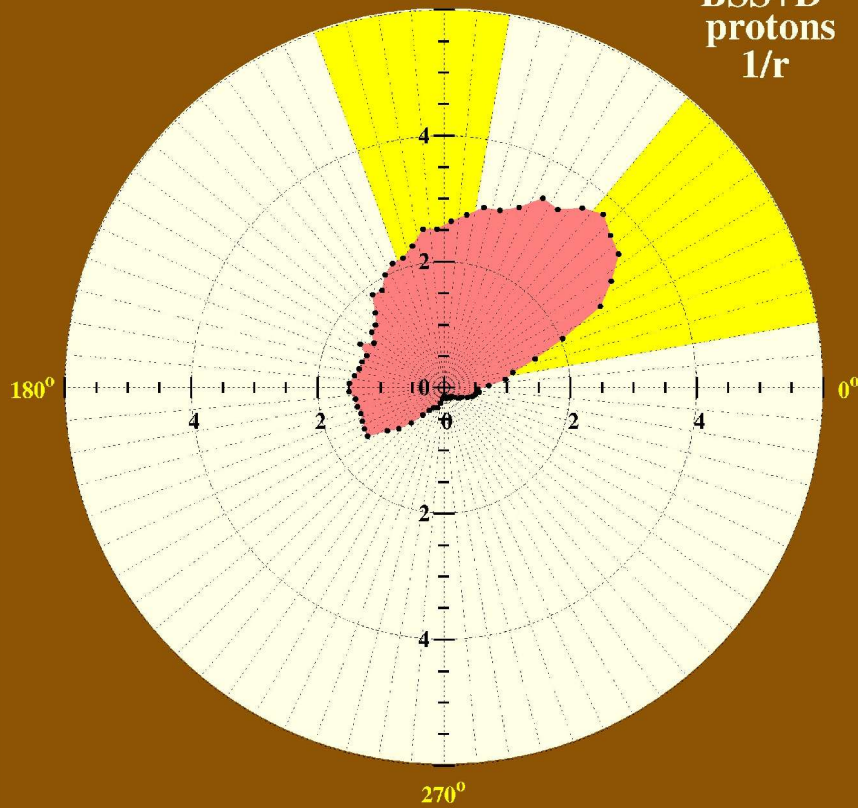


Sensitivity of the anisotropy to the magnetic field model and to the existence of magnetic halo. Han's A0 halo model is used in this exercise.

AGASA field of view

$l = 90^\circ$

BSS+D
protons
 $1/r$

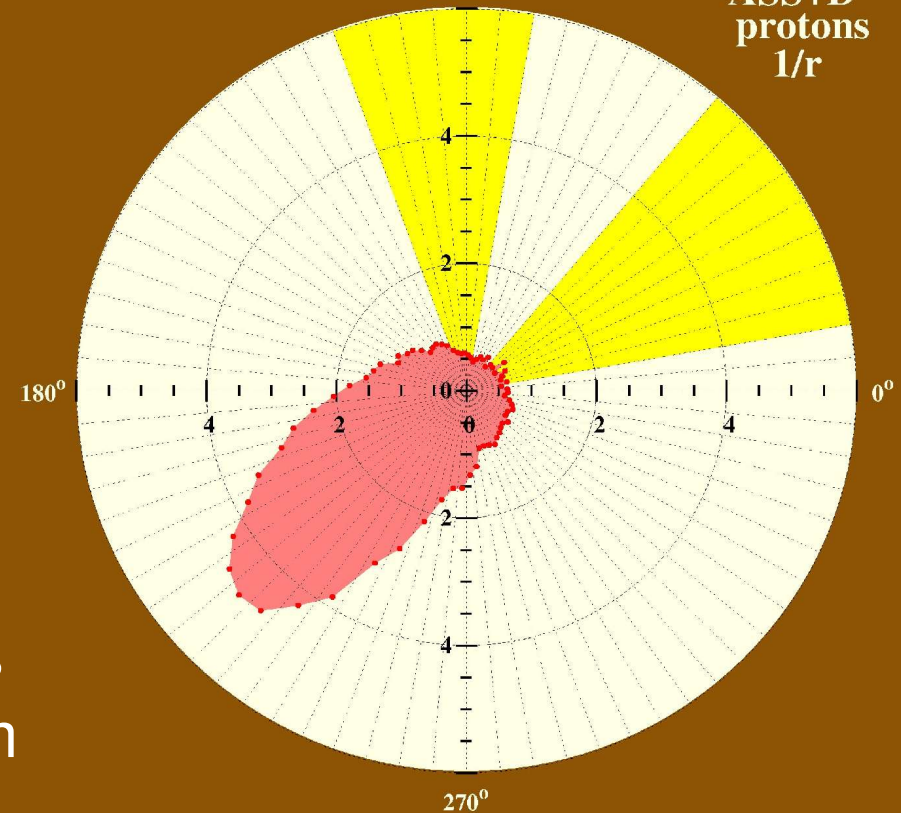


AGASA field of view

AGASA field of view

$l = 90^\circ$

ASS+D
protons
 $1/r$



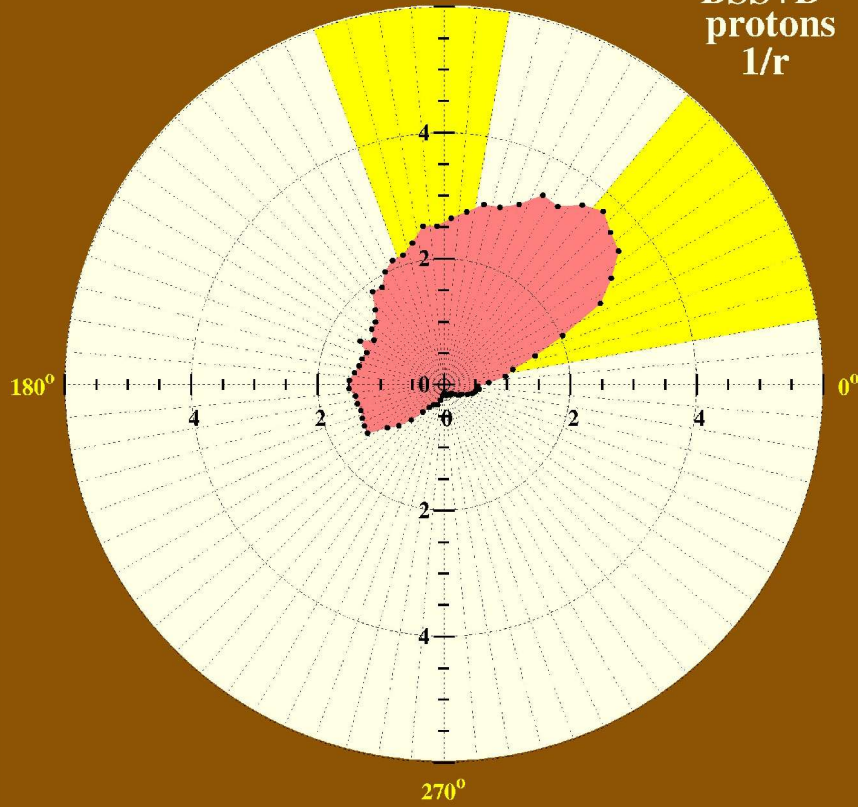
The anisotropies generated by the two magnetic field models have almost exactly the opposite phase. Neither is an exact match but in the BSS model more protons come from galactic center/local arm direction.

Sensitivity to source distribution

AGASA field of view

$l = 90^\circ$

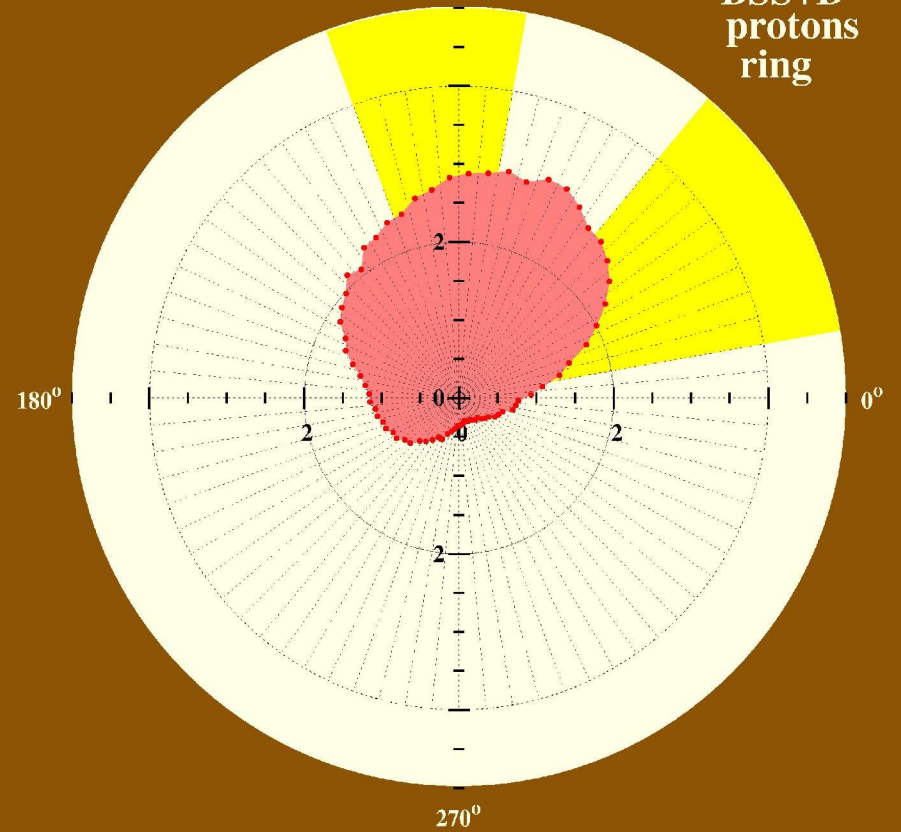
BSS+D
protons
 $1/r$



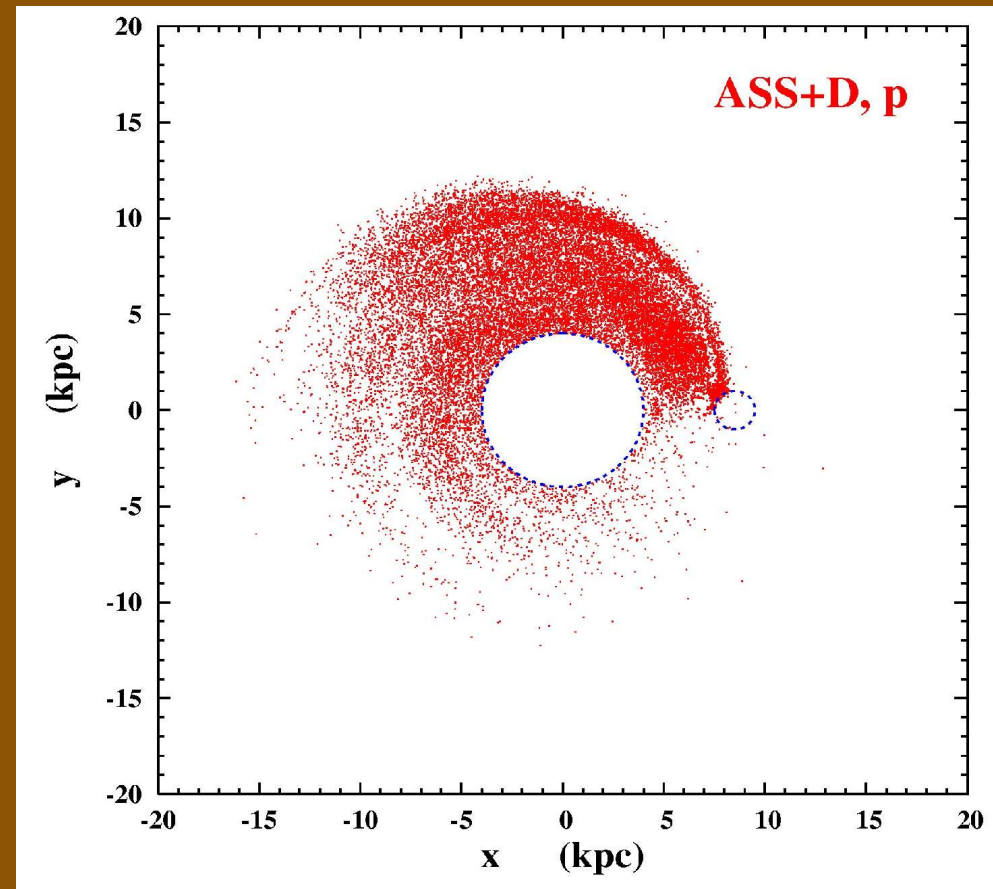
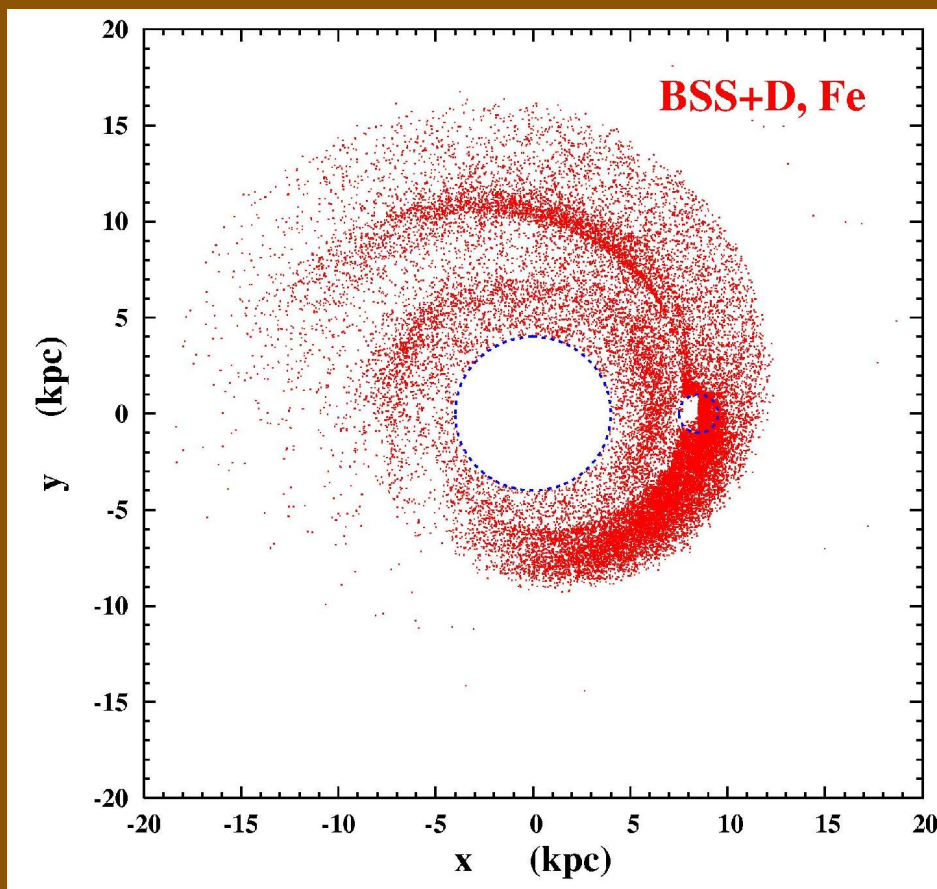
AGASA field of view

$l = 90^\circ$

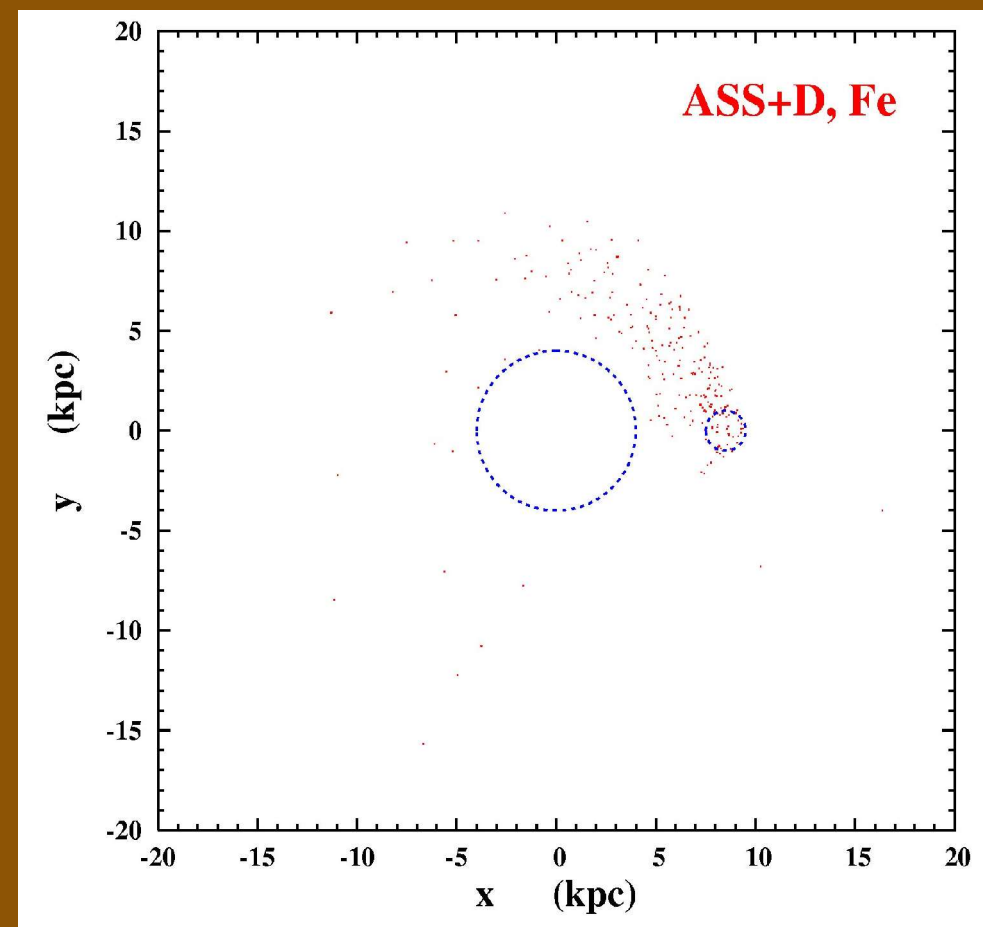
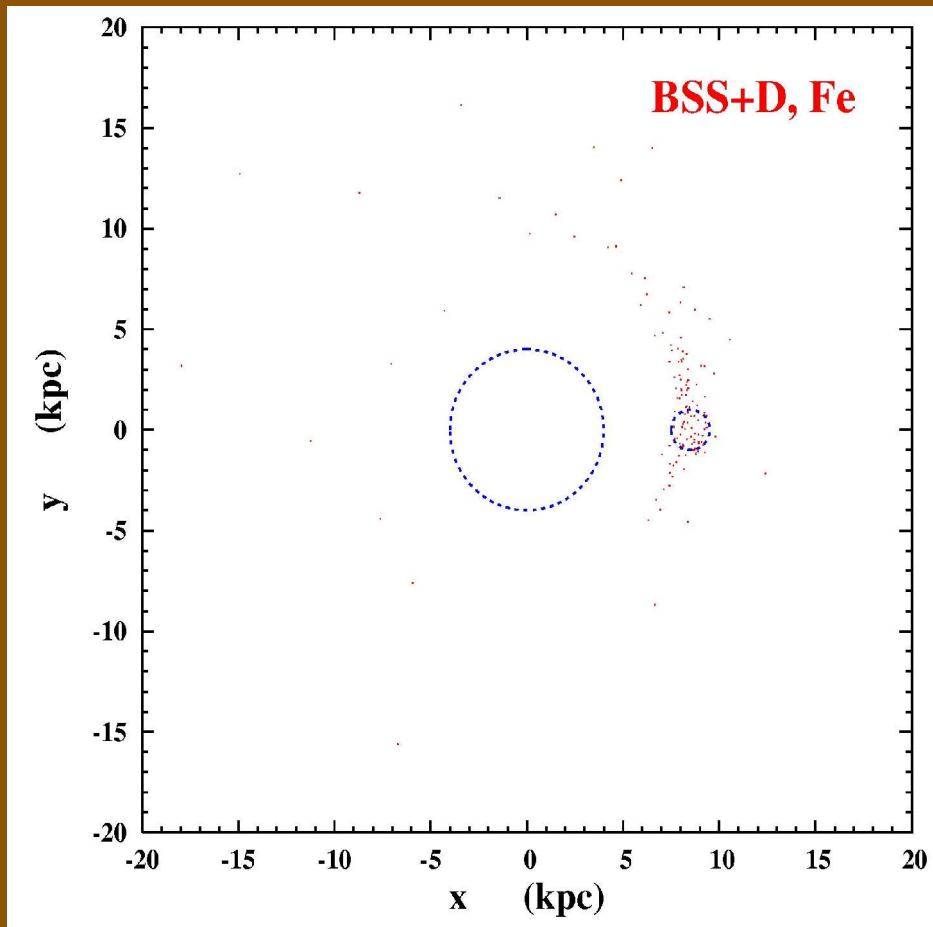
BSS+D
protons
ring



Location of the sources from which *protons* reach the solar system after isotropic injection and propagation in the galactic magnetic field.



One result is very similar in propagation in any field: iron nuclei with total energy of 10^{18} are very inefficient. Very few nuclei could propagate to us for the $1/r$ source distribution as shown below. None did when all sources were at the 4 kpc circle.



Conclusions

At rigidities above $10^{16.5}$ V particle transport in the Galaxy is in the intermediate region between linear propagation and diffusion. Particle trajectories and their containment in the Galaxy are strongly influenced by:

- the model of regular magnetic field
- the ratio between regular and random field strength

Propagation in the galactic magnetic fields creates anisotropies (at high energy) that are a function of the field models and the distribution of cosmic ray sources. The amplitude of the anisotropy may be of order 4-5%, close to the AGASA result. We can not identify a magnetic field model that fits the AGASA result.

If most of the cosmic rays at 10^{18} eV are iron nuclei, they should originate not far from us, as they propagate inefficiently in the galactic fields. **Heavy nuclei CR composition is inconsistent with significant anisotropy at 10^{18} eV.**