The CR anisotropy below the knee: experiments and models of the last decade

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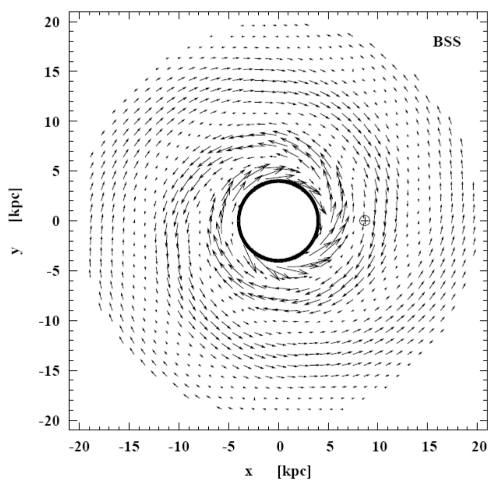
Conference on
Astro-particle
Physics

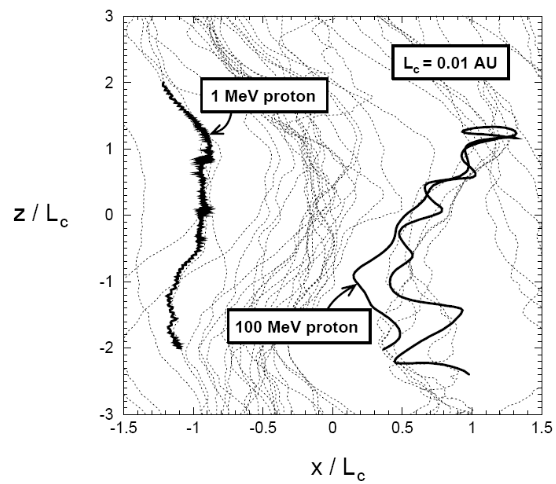
Roma, May 23rd, 2013

GMF for the rigidity range 10^{12}-10^{15} V

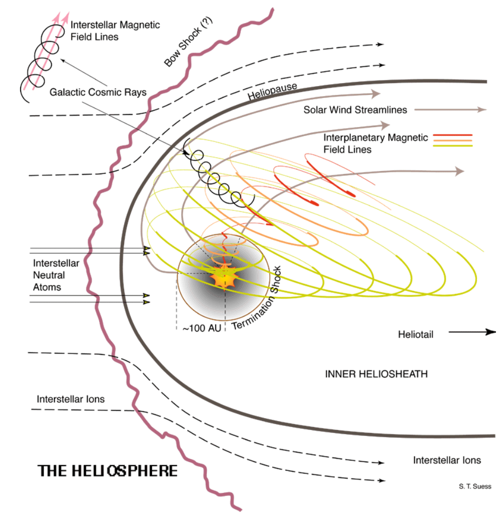
The galactic magnetic field is thought to be the superposition of a “regular” and a “chaotic” component (with intensities B_{reg}~2 μG and B_{ch}~0.5÷5 μG respectively).



Alvarez Muniz J. And Stanev T. 2006 J. Phys.: Conf. Ser. 47 126



J. Giacalone and J. R. Jokipii 1999 *ApJ* 520 204



http://interstellar.jpl.nasa.gov/interstellar/probe/interaction/

The gyroradius of a particle of rigidity R TeraVolt is:

$$r = \frac{p}{ZeB} \approx R[TV] \times 5\,10^{-4}\,pc \approx R[TV] \times 100\,AU.$$

$10^{12} - 10^{13}$ V:
Solar system

$10^{13} - 10^{15}$ V:
Local Interstellar Medium

Particles are expected to scatter on turbulent field modes and to lose memory of their past trajectory on distance scales of the order of the scattering length λ(p).

In the ISOTROPIC DIFFUSION approximation a nearby and recent source is expected to leave a weak dipolar trace in the CR arrival distribution:

$$\vec{\delta}(p) \approx -\frac{3}{c_0}\frac{\vec{j}}{n} = \frac{3D(p)}{c_0}\frac{\vec{\nabla}n}{n}$$

D(p) can be estimated from the B/C abudance ratio as well as from the pbar/p fraction (see for instance Blasi&Amato arXiv:1105.4521 [astroph.HE]):

$$D(p) \approx 10^{28}\left(\frac{p/Z}{3\,\mathrm{GeV}}\right)^{\delta}\ \mathrm{cm}^2\,\mathrm{s}^{-1}$$

with $\delta = 0.45$ instead of $\delta = 2 - \alpha = 1/3$ for a Kolmogorov Spectrum

$$\left|\frac{1}{c_0}\frac{\vec{\nabla}n}{n}\right| \approx \frac{1}{R} \approx \frac{1}{1\,\mathrm{kpc}}$$

is the distance of the closest source, so that

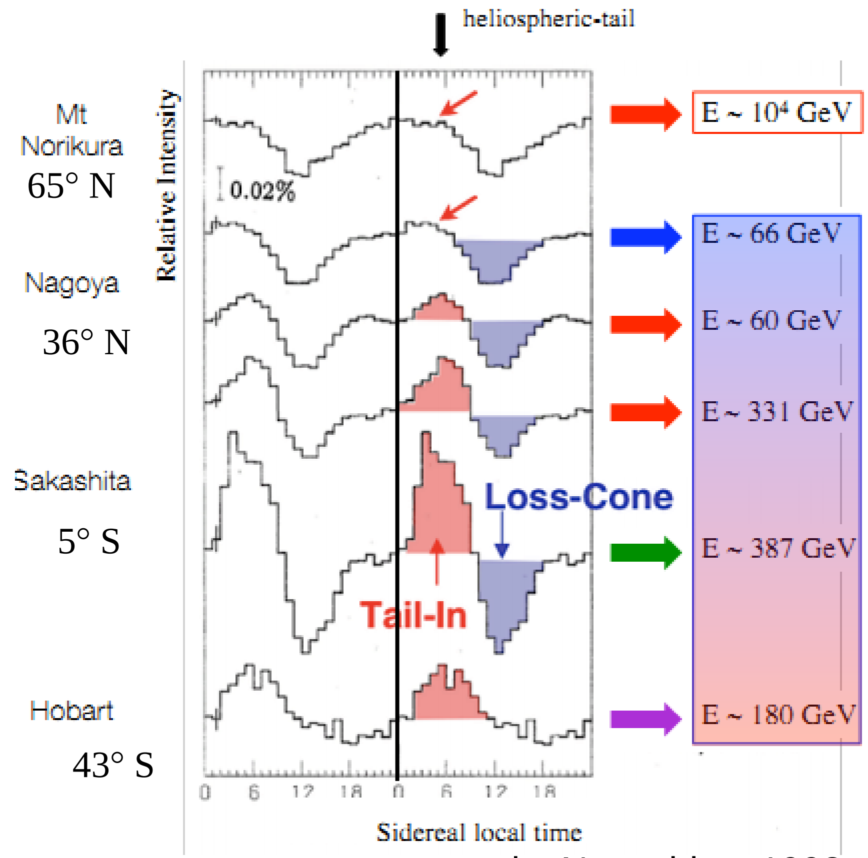
$$\left|\vec{\delta}(p)\right| \approx 10^{-3}\left(\frac{p/Z}{20\,\mathrm{TV}}\right)^{\delta}$$

More than one source? Sum of dipoles → dipole

An-isotropy: a history

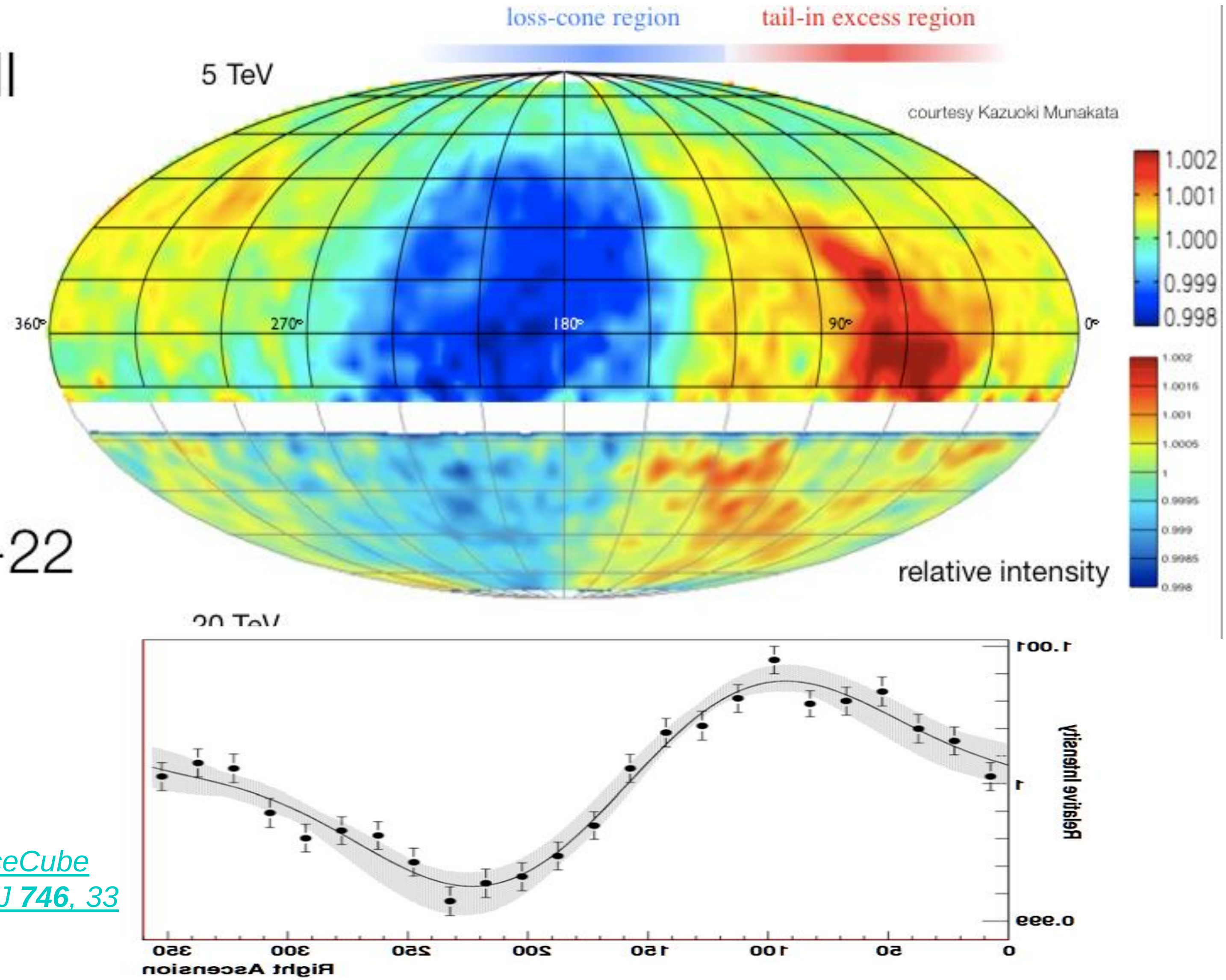
The anisotropy of arrival direction of CRs was observed since 30’s in μ detector, surface arrays and ν detectors; the anisotropy level is 10^{-3} - 10^{-4} in the energy range 10s GeV - 100s TeV

- Tail-in feature directed towards the heliospheric tail peak located at RA ~ 6h (~90˚)
- Amplitude and phase change with latitude
- North-South asymmetry
- Tail-in modulated in time: max in Dec. and min in June



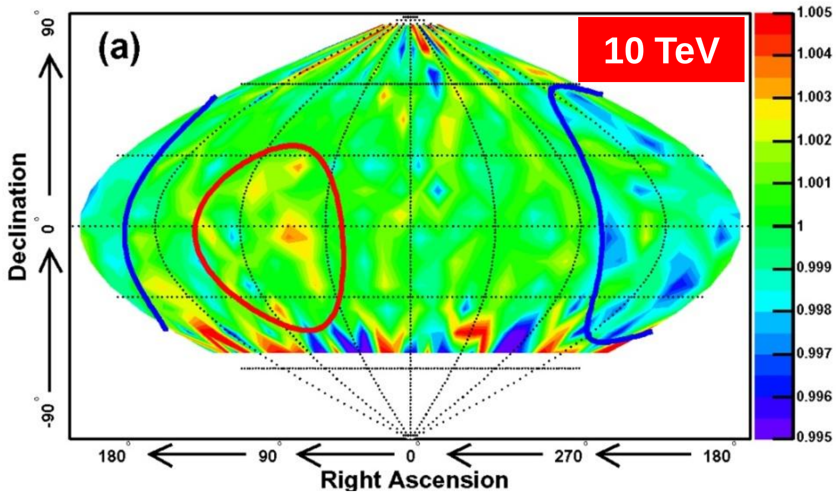
by Nagashima 1998

Cosmic ray anisotropy

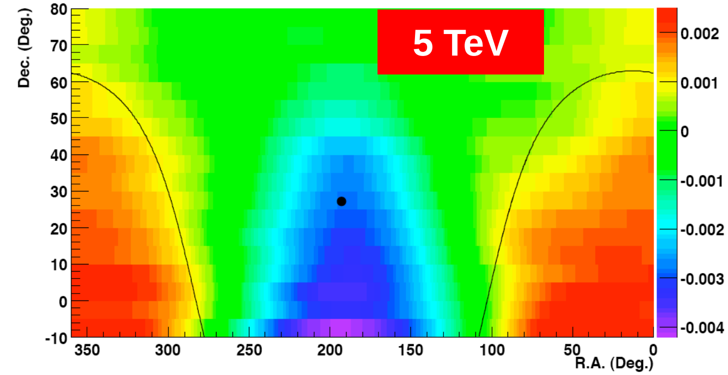


Abbasi R. et al. (IceCube Collaboration), ApJ **746**, 33 (2012)

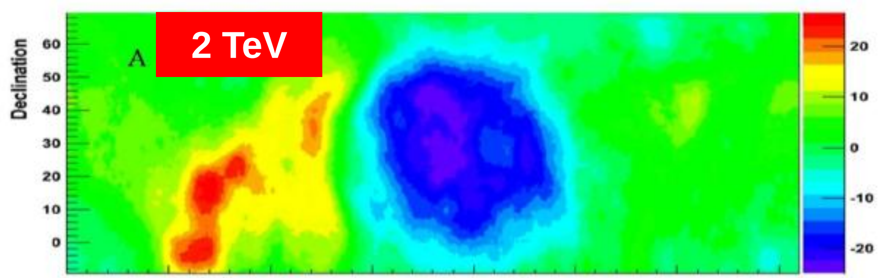
Recent observations of the CR anisotropy



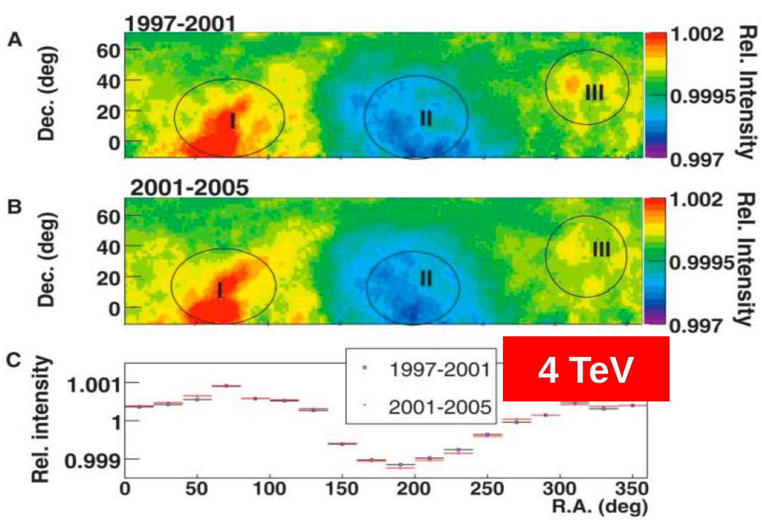
Super-Kamiokande – ICRC 2007 Proceedings



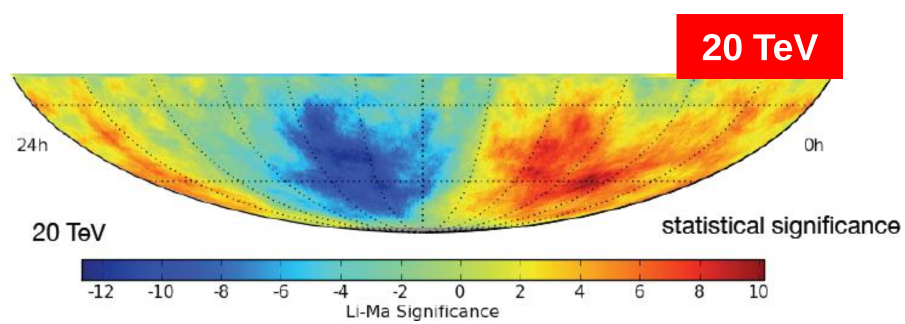
MILAGRO - 2009 *ApJ* **698** 2121



ARGO-YBJ– ICRC 2011 Proceedings



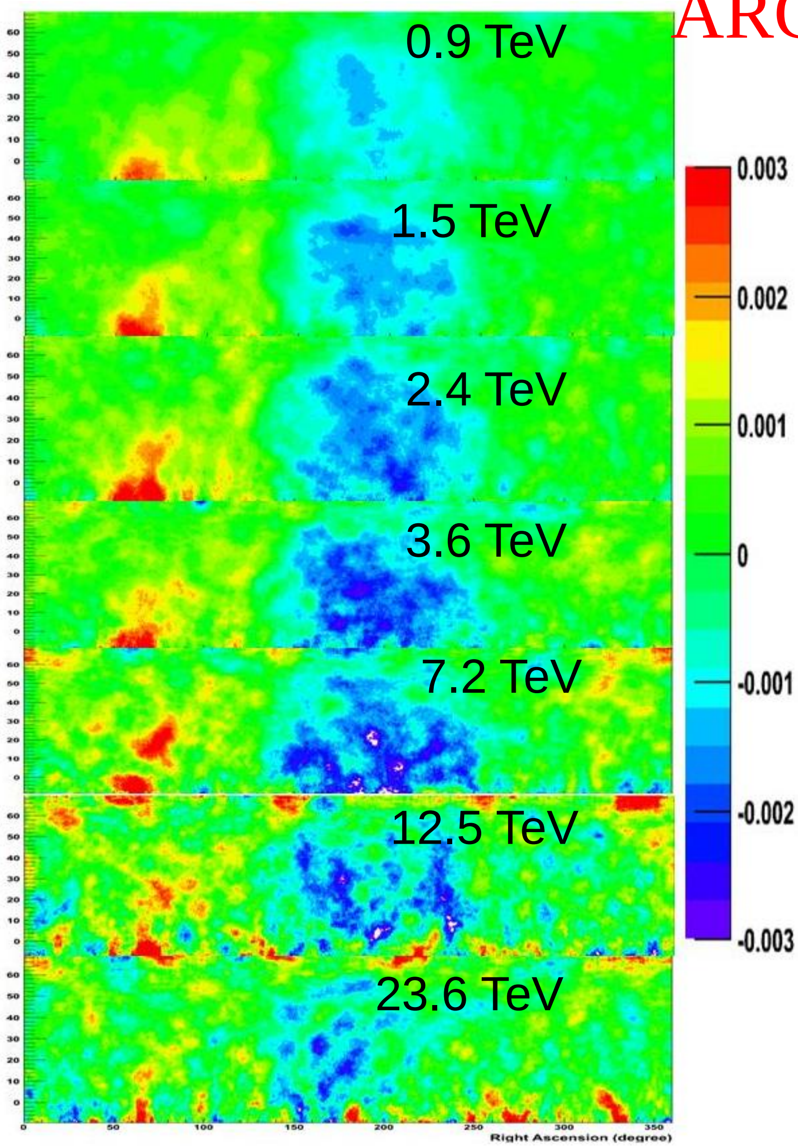
Tibet AS-γ - *Science* 20 October *2006*:
Vol. 314 no. 5798 pp. 439-443



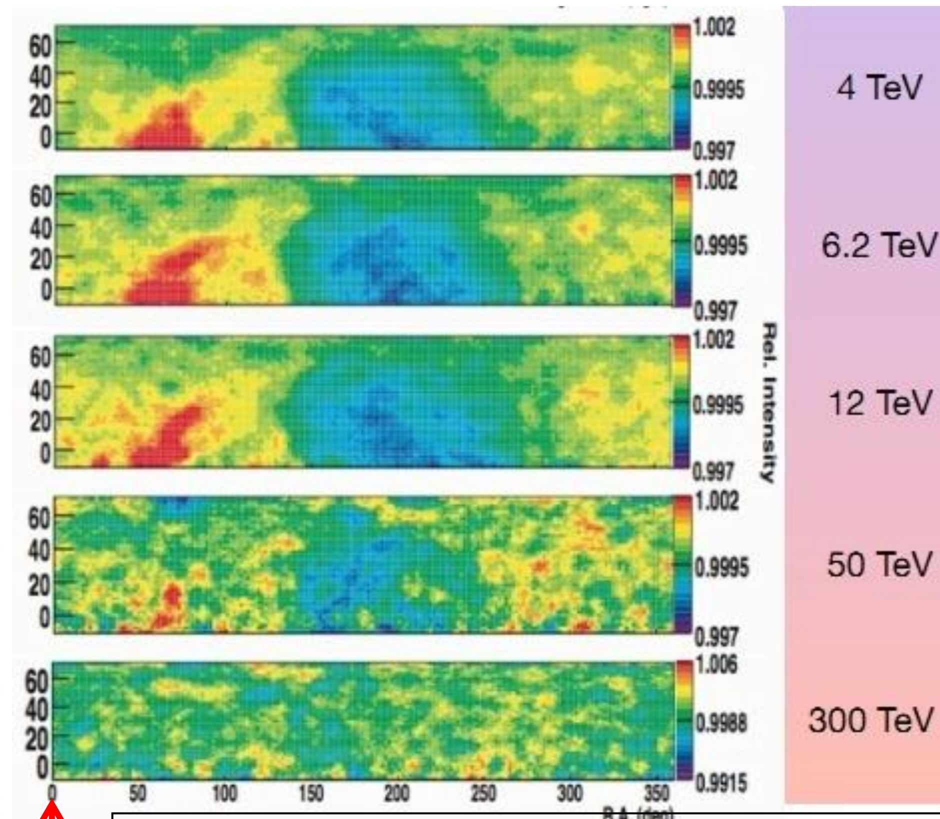
ICE-CUBE - 2010 *ApJ* 718 L194

LSA as a function of the primary energy

ARGO-YBJ



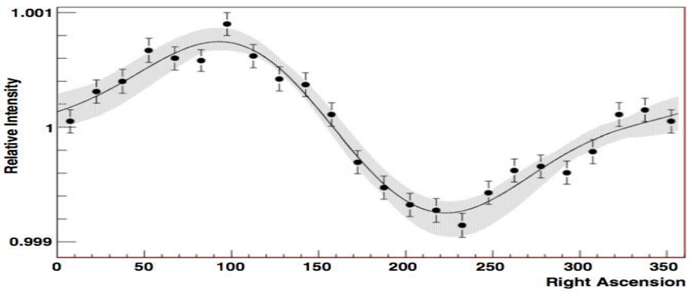
Tibet ASγ



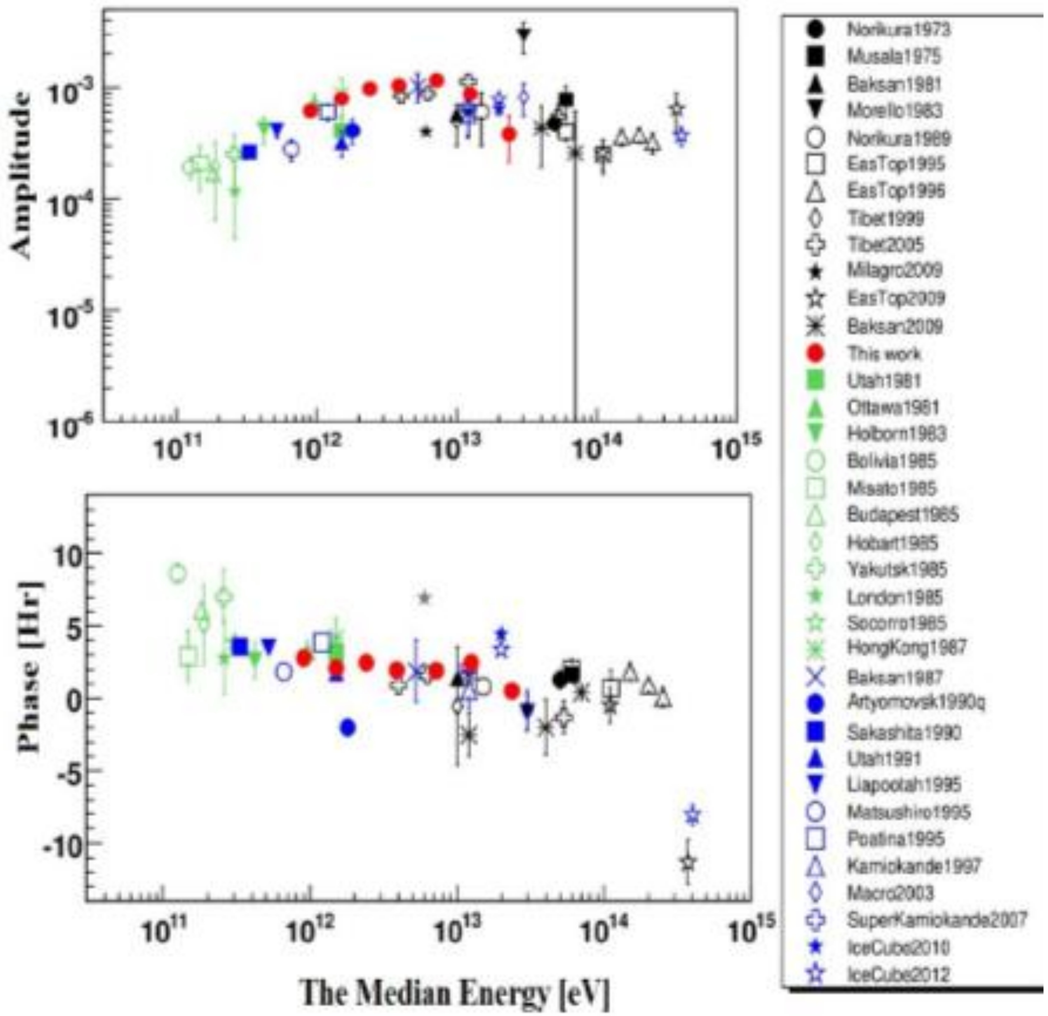
Anisotropy seems to disappear. From the absence of the CG effect they infer the corotation of GCR with the GMF environment

A data compilation

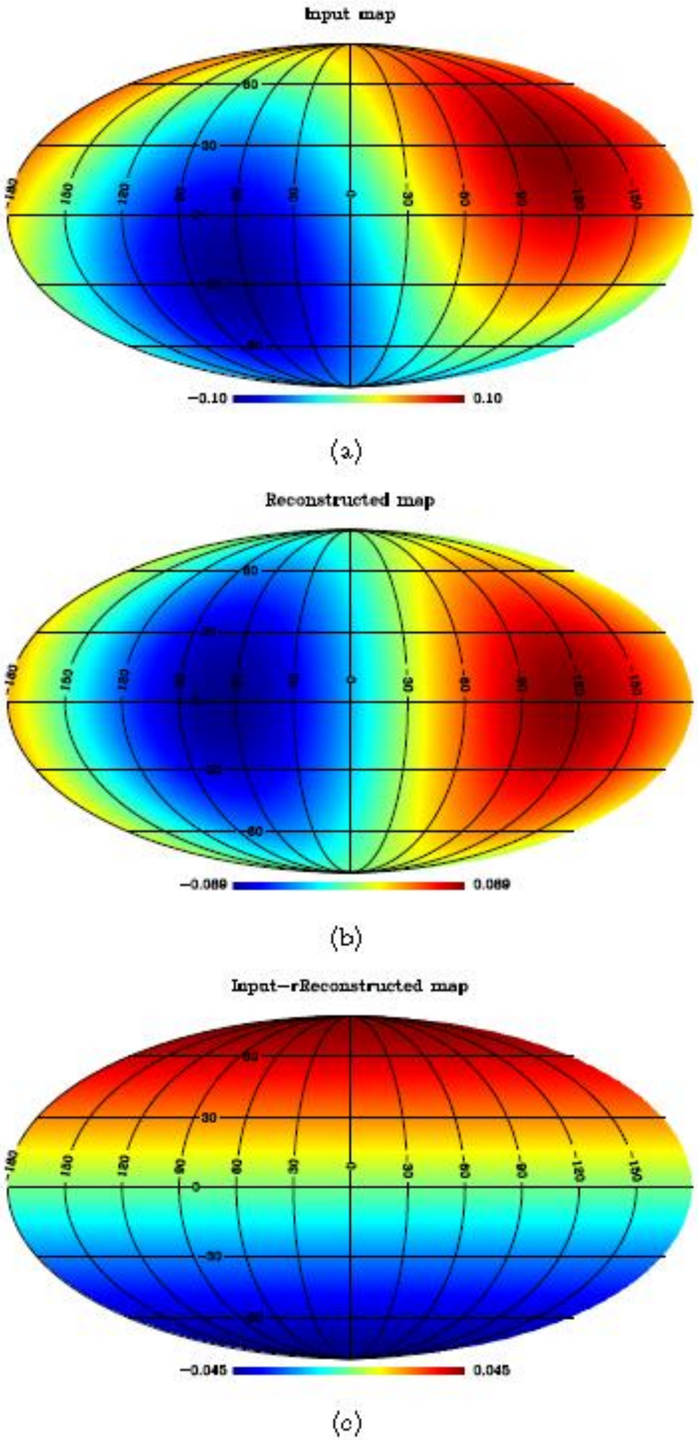
Usually, data are projected along the R.A. projection (e.g. IC22):



Then a 2-harmonics fit is performed and amplitude and phase of the first harmonics are discussed (see the compilation for reference). They are generally interpreted as important signature, as the dipole is a trace of the source distribution.
BUT…



From ARGO-YBJ 32° ICRC contribution



If the signal is looked at as a distribution $f(\theta, \phi)$ on the sphere, the act of normalizing the average content of each declination belt to zero can be written as the operator S:

$$f(\theta, \phi) \xrightarrow{S} f'(\theta, \phi) = f(\theta, \phi) - \frac{1}{2\pi} \int_0^{2\pi} \mathrm{d}\phi\, f(\theta, \phi)$$

where the f' distribution is the measured one, which differs from the "true" f for the average $\langle f \rangle_\theta = 1/2 \int_0^{2\pi} \mathrm{d}\phi\, f(\theta, \phi)$. We can consider the spherical harmonics expansion of the f distribution:

$$f(\theta, \phi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_m^\ell\, Y_\ell^m(\theta, \phi)$$

and considering in a closer detail the effect of the average on the signal. In fact:

$$\int_0^{2\pi} \mathrm{d}\phi\, Y_\ell^m(\theta, \phi) = \begin{cases} 0 & \text{if } m \neq 0 \\ Y_\ell^m(\theta, \phi) & \text{if } m = 0 \end{cases}$$

Using the last result, f' can be rewritten as:

$$f'(\theta, \phi) = f(\theta, \phi) - \sum_{\ell=0}^{\infty} a_0^\ell\, Y_\ell^0(\theta, \phi) \qquad (5)$$

where the degeneracy is made explicit. In fact, all terms with $m = 0$ are suppressed by the experimental technique applied, what is more important as the multipole order ℓ gets lower.

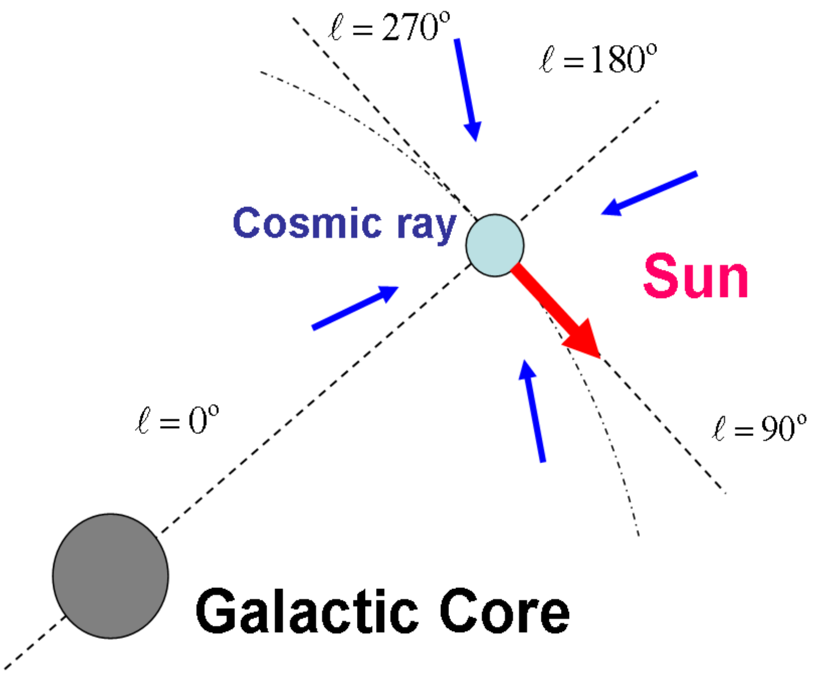
Iuppa&DiSciascio ApJ 766 (2013) 96

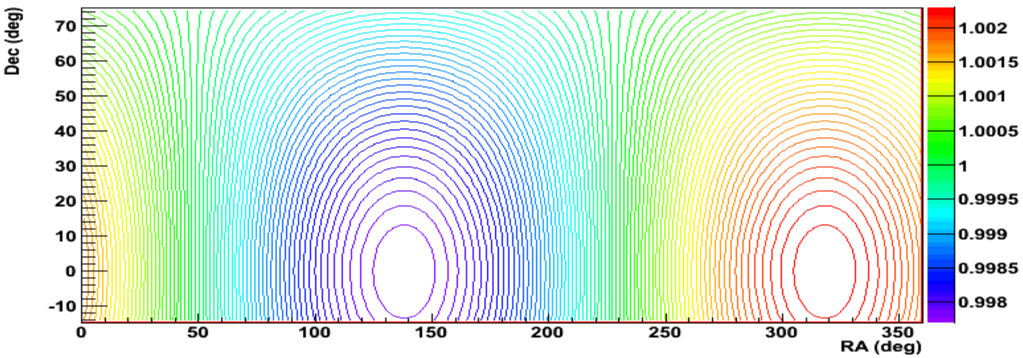
Sidereal Compton-Getting effect

CR flow: $j \propto E^{-\alpha}$ **V=220km/s,** $\alpha = 2.7$

Expected signal:

$$\frac{\Delta I}{I} = (\alpha + 2)\frac{v}{c}\cos\theta$$





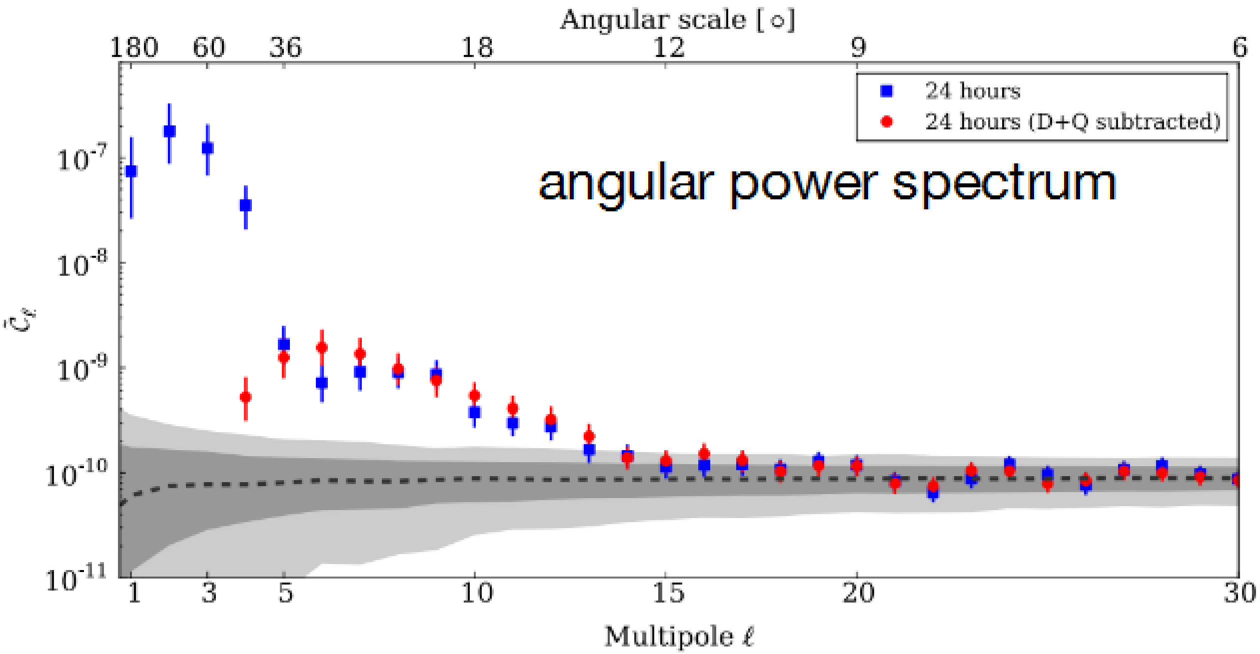
Expected CG for nothern hemisphere experiments

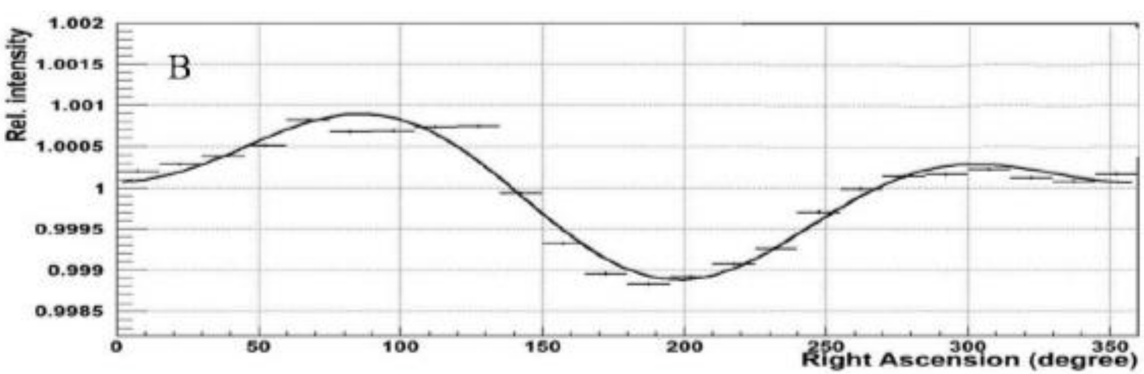
A.H. Compton and I.A. Getting, Phys. Rev. **47**, 817(1935)

It is an effect purely due to kinematics. If the measured signal is not compatible (as it happens), **should it be subtracted anyway?**

The solar CG effect (due to the motion of the Earth around the Sun) was successfully observed by Tibet-ASg, IceCube and ARGO-YBJ. It is nothing more (and nothing less!) than a validation of the analysis.

4-pole, 6-pole and 8-pole (the old 2° harmonics…)





ICECUBE has been the first experiment showing a CL spectrum of the arrival direction distribution. Strong L=2-3-4 components are visible.

There are strong L=2-3-4 components in the CR anisotropy, even below 10^{15} eV. If dipole means sources, what is this power related to?

When a “traditional” 1D R.A. projection is presented, a 2 harmonics function is fot to the experimental distribution (ARGO-YBJ example).

4-pole, 6-pole and 8-pole: an-isotropic diffusion

A dipole (and only a dipole) is expected if isotropic diffusion is assumed. I.e. D(p) is a scalar.

But the diffusion is likely not isotropic, as it should be stronger along field-parallel direction and weaker in the perpendicular directions. D(p) is a tensor.

$$D = \begin{pmatrix} D_\perp & 0 & 0 \\ 0 & D_\perp & 0 \\ 0 & 0 & D_\parallel \end{pmatrix}$$

Effenberger et al.: Anisotropic diffusion of galactic cosmic ray protons

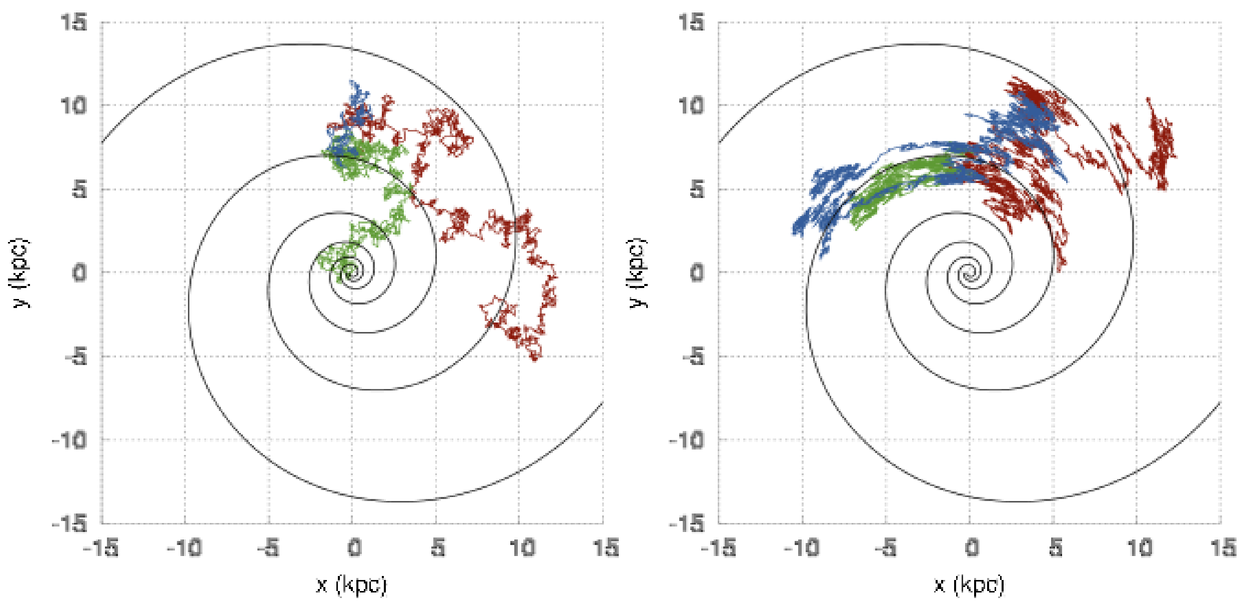


Fig. 3. Sample paths of pseudo-particles in the galactic magnetic spiral field, coloured by three different colours for three particles, each starting at the same point in phase space (i.e. Earth's position at 1 GeV) and projected onto the galactic plane. The black lines show integrated magnetic field lines to illustrate the magnetic field orientation. The left panel shows sample paths for isotropic diffusion, with no visible effect of the magnetic field orientation. The right panel illustrates the preferential diffusion along the magnetic field for a simulation with anisotropy $\epsilon = 0.1$. Note that the exit point of the red particle in the right panel is actually the radial boundary, while the other particles all exit through the halo's z-boundary (not visible).

Isotropic diffusion

$$D_\perp = D_\parallel$$

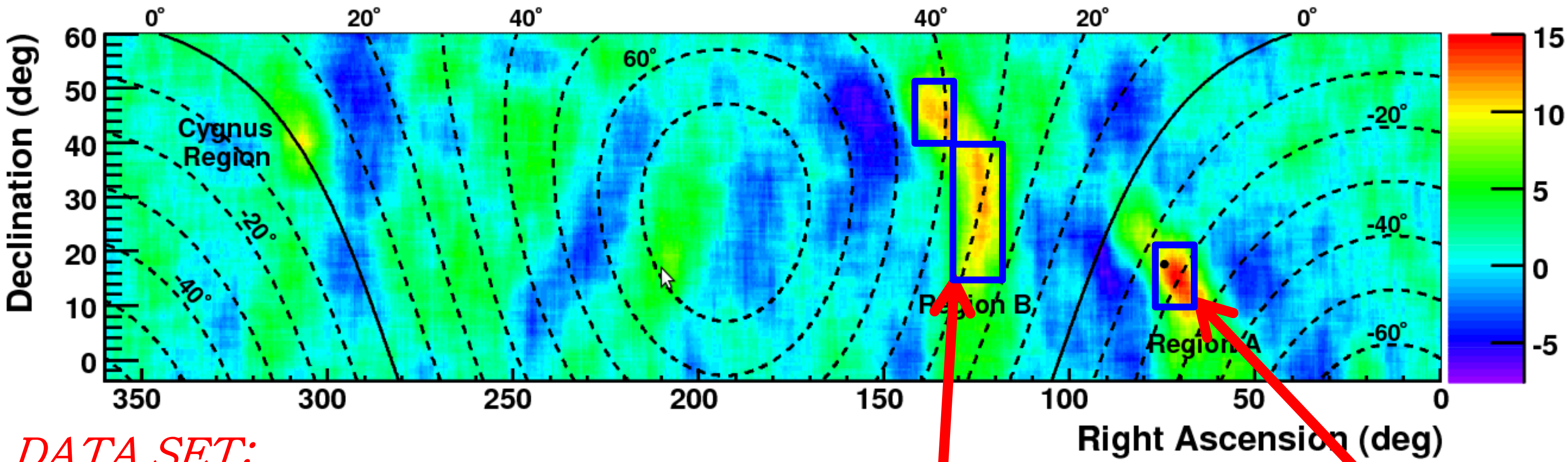
An-isotropic diffusion

$$D_\perp = \varepsilon D_\parallel$$

The "medium" scale anisotropy

MILAGRO: Discovery of Localized Regions of Excess 10-TeV Cosmic Rays

Phys.Rev.Lett.101:221101,2008



DATA SET:
Zenith angle < 45°

2.2 10^{11} events
Median energy 1 TeV
NO GAMMA HADRON DISCRIMINATIN APPLIED

Background estimation technique: direct integration method (2 hours intervals)

Region B
12.4 s.d. pre-trial
Fractional excess:
4 10^{-4}

Ra: 117°–131° | 131°–141°

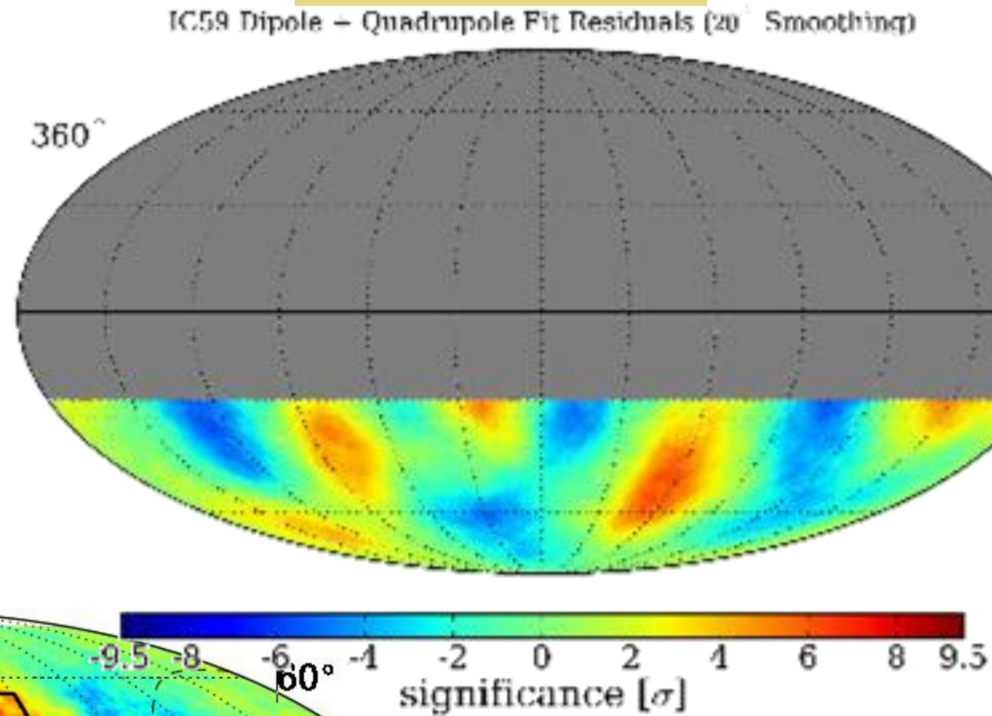
De: 15°–40° | 40°–50°

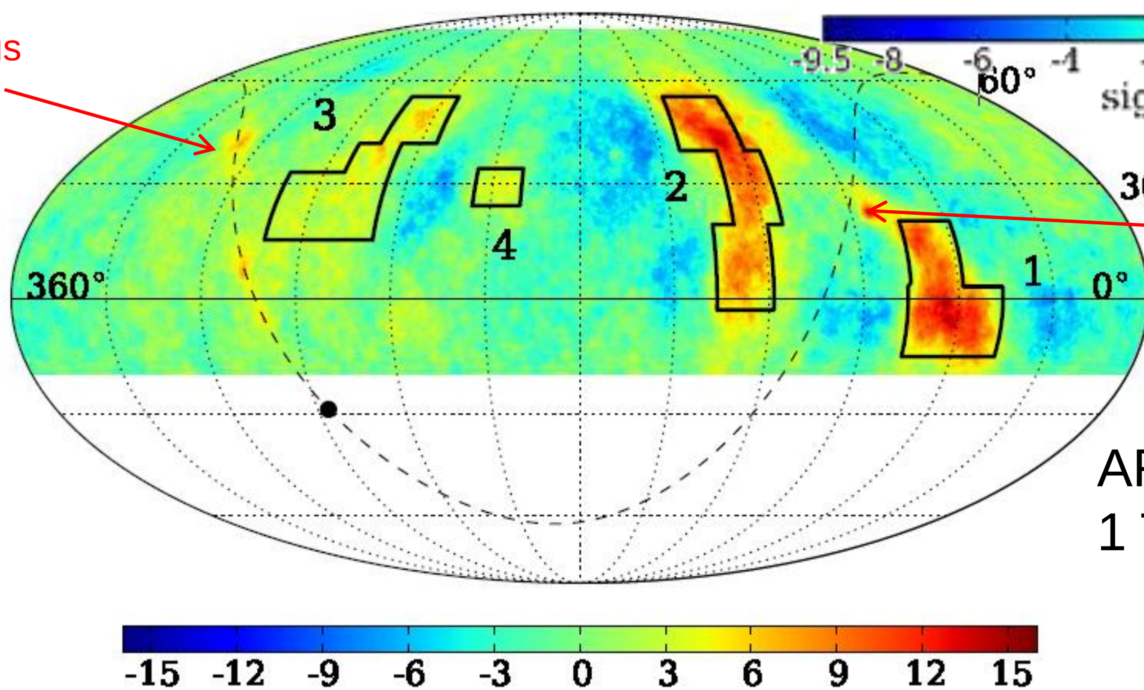
Region A
15 s.d. pre-trial
Fractional excess:
6 10^{-4}

Ra: 66°–76°

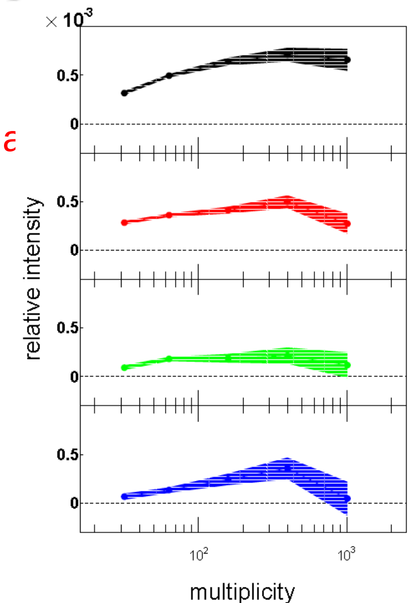
De: 10°–20°

IceCube
20 TeV





ARGO-YBJ
1 TeV



How medium scale anisotropies are obtained? Often Time-Average-based Methods are used.

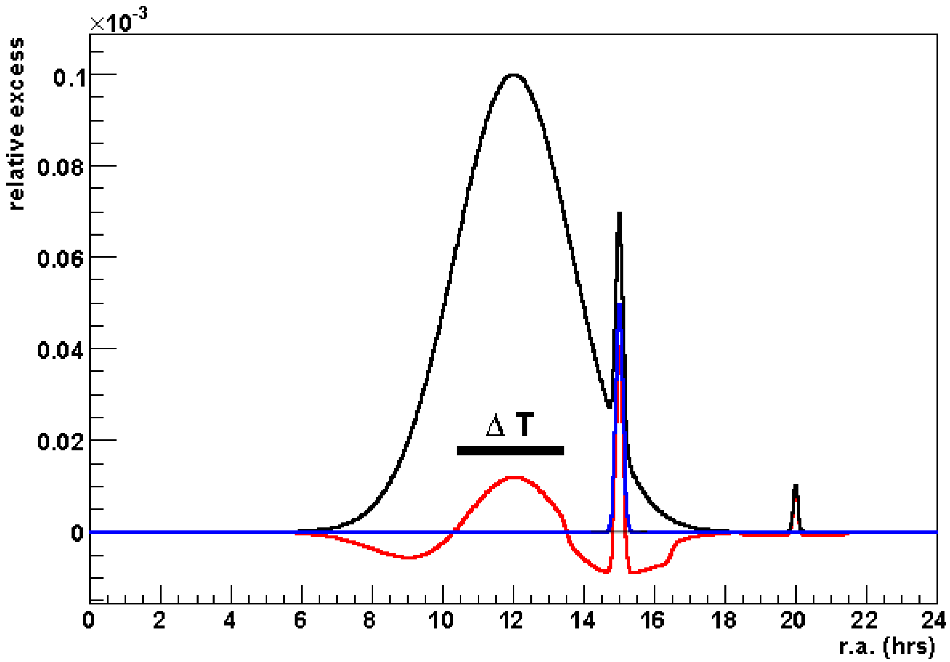
For a given pixel n with content x_n, the background is estimated to be:

$$\xi_n = \frac{1}{N} \sum_{k=n-N/2}^{n+N/2} x_k \quad (N \leq \mathcal{N})$$

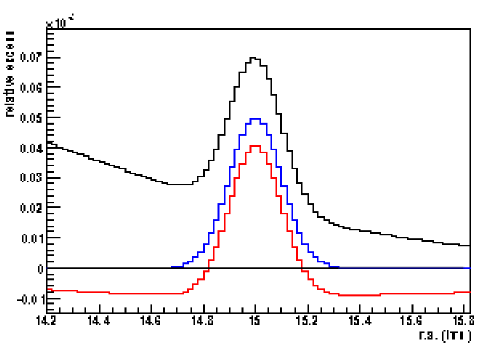
All structures narrower than N will be averaged out in the background, so that the difference events-background will maintain only features narrower than N.
The method acts effectively as a high-pass filter.

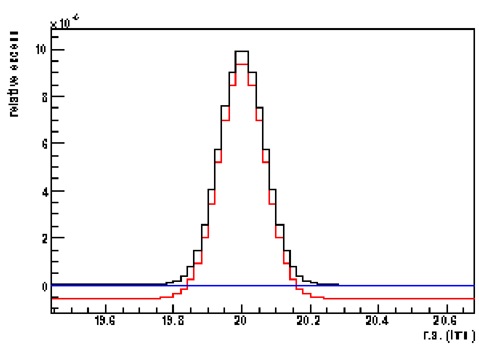
Collateral effects

Underestimation of the intensity



(a)





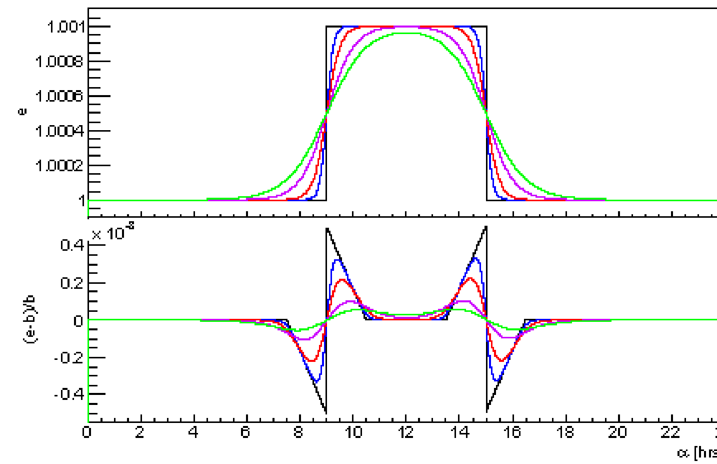


FIG. 4.— Toy-calculation to highlight the relevance of the gradient along the RA direction of the signal under study. *Top panel:* a 6-hrs wide signal as intense as 10^{-3} with respect to the underlying flat background was simulated to rise up with different slope; *bottom panel:* the signal as reconstructed after the TAM-calculated background subtraction (time-window: 3 hrs).

Larger scale suppression dependent on the R.A. gradient

Angle selction dependent on declination

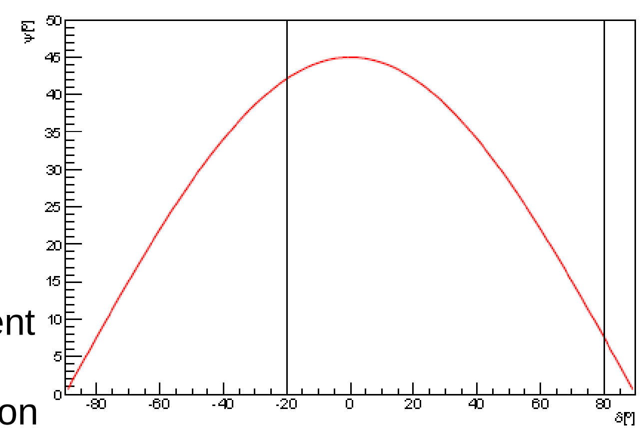


FIG. 6.— Angular distance between two points on the sphere having RA coordinates shifted 45° from each other, as a function of the declination. The vertical lines enclose the declination region for which many computations of this paper were made.

What is behind the intermediate scale anisotropies?

Directional approach

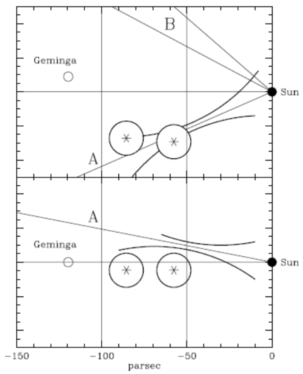


Fig. 1. Projection of the anticenter region on the meridian plane at Galactic longitude 195° (upper panel) and on the Galactic plane (lower panel). See text for details.

Salvati & Sacco, Astronomy&Astrophysics 2008

The excesses are due to **nearby sources** (Geminga, Vela, Monogem…) emitting CR. In any case it looks as **particular features of the local magnetic** *field are needed to bring us the radiation so beamed*. The spectrum and the cut-off are explained with the age of the source.

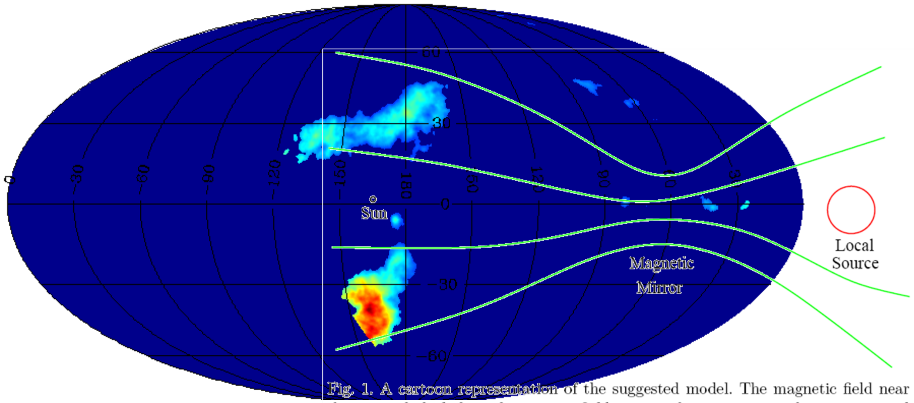
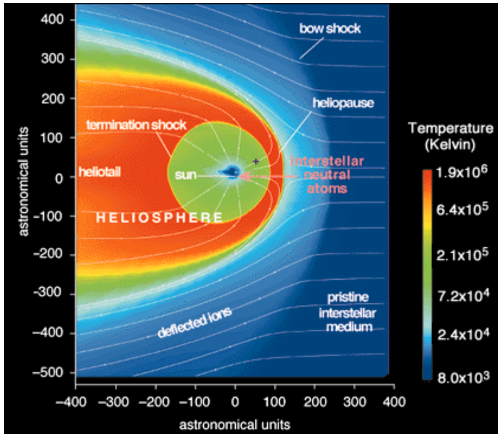
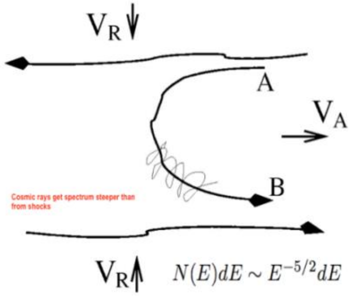


Fig. 1. A cartoon representation of the suggested model. The magnetic field near the sun is linked through a strong field region where most particles are mirrored to a region containing a slightly higher amplitude and harder spectrum of cosmic rays, presumably as a result of a local source event such as a supernova explosion. Only particles with pitch angles closely aligned to the field can penetrate through the mirror and emerge as a field-aligned beam on the other side (another possibility would be to locate the source inside the strong field region itself rather than behind the trap).

Drury & Aharonian, Astroparticle Physics 2008





$N(E)dE \sim E^{-5/2}dE$

$$E_{max} \approx 10^{13}\ eV \cdot \left(\frac{B}{1\ \mu G}\right) \cdot \left(\frac{L_{zone}}{134\ AU}\right)$$

What we see is the effect of the **magnetic reconnection in the heliotail**. The spectrum and the cutoff are due to the efficiency of the process.

Lazarian & Desiati, 2010, arxiv 1008.1981

What is behind the intermediate scale anisotropies?

Stochastic MHD approach

Energy-dependent small scale anisotropies naturally arise from the local concrete realization of the turbulent magnetic field within the cosmic ray scattering length.

Giacinti& Sigl
Phys. Rev. Lett. 109, 071101 (2012)

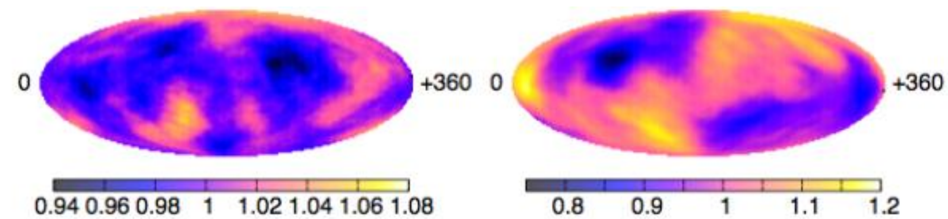


FIG. 1. Renormalized CR flux predicted at Earth for a concrete realization of the turbulent magnetic field, *after subtracting the dipole* and smoothing on 20° radius circles. Primaries with rigidities $p/Z = 10^{16}$ eV (*left panel*) and 5×10^{16} eV (*right panel*). See text for the field parameters and boundary conditions on the sphere of radius $R = 250$ pc.

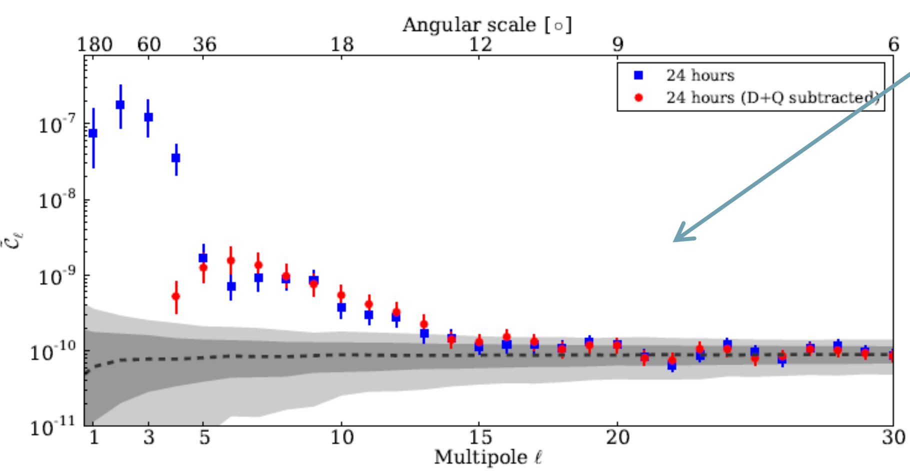
The CR arrival distribution at Earth contains multipoles:

$$a_{lm}(p) = |\delta(\mathrm{p})| \int \mathbf{G}_p(\mathbf{n}) \cdot \mathbf{e}_z Y_{lm}(\mathbf{n}) d^2\mathbf{n}$$

Dipole amplitude

Dipole direction

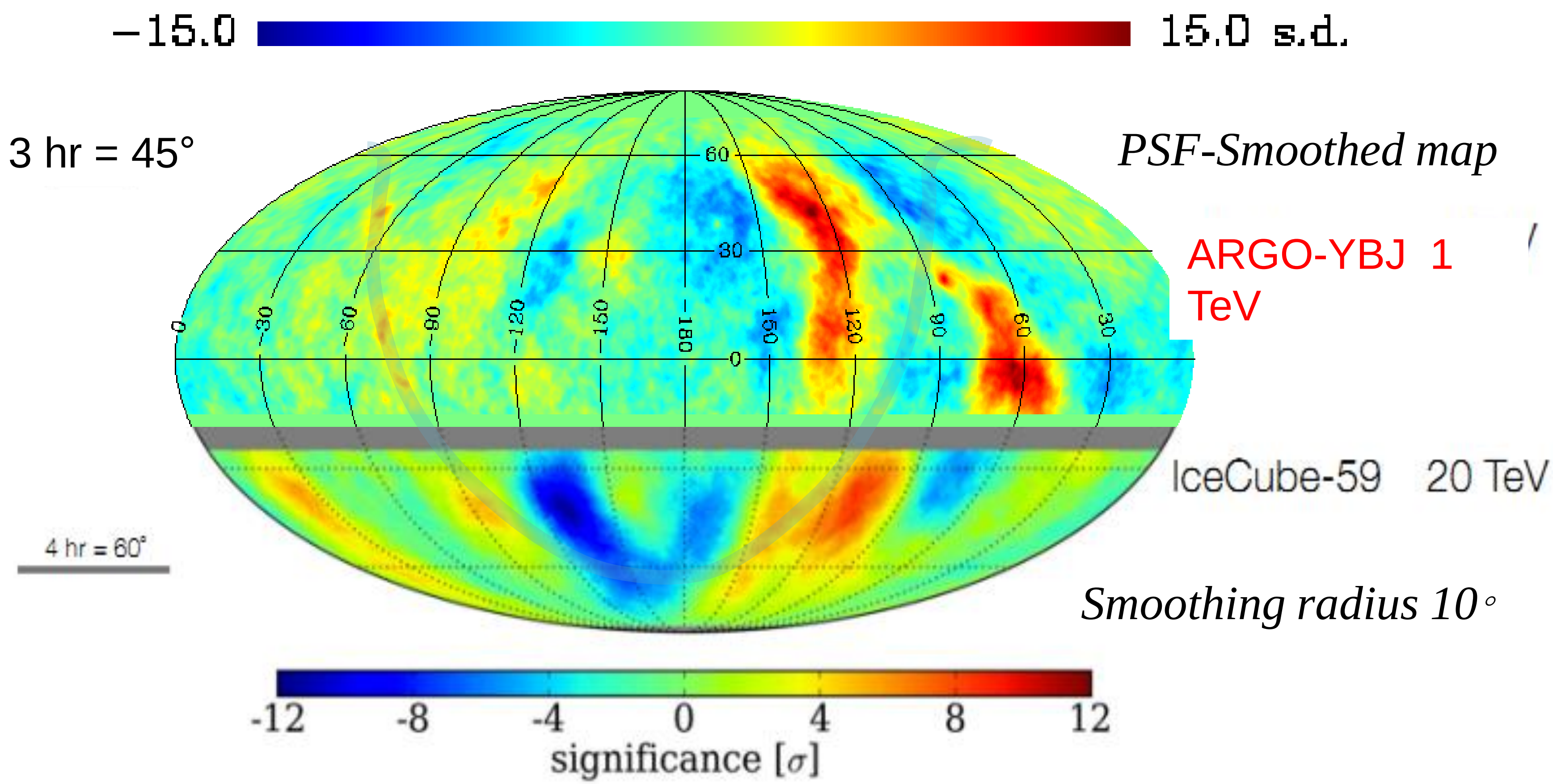
Direction after the propagation of the particle with initial direction **n**. <u>It depends on the magnetic field turbulence spectrum!</u>



There is a connection between the observed angular power spectrum and the magnetic field turbulence spectrum.

Outlook to the future: towards a complete TeV CR sky-map

ARGO-YBJ + IceCube-59



Conclusions

- A CR standard model exists which foresees a dipolar anisotropy due to contributions of nearby sources. Predictions strongly rely on the isotropic diffusion model.
- The CR anisotropy was observed by a number of experiments since 30s. In the last decade 2D maps containing few 10^{11} events were realized.
- All techniques applied to date are not sensitive to the m=0 components of the anisotropy. It translates in a huge uncertainty in determining the dipole (and low-poles) contribution.
- The sidereal CG has not been observed yet. Is it mixed with other signals?
- Low-L contributions to the anisotropy are practically not interpreted to date, although they may be one of the most efficient way to quantify the parallel/perpendicular asymmetry in the local magnetic turbulence.
- Medium scale excesses and deficits have been observed in the last 5 years.
- Detection techniques (Time-average-based methods) often introduce little bias to be accounted for in interpreting results.
- The interpretations of the medium scale anisotropy rely on directional elements or on Stochastic MHD considerations.
- No model of CR propagation in the Local Interstellar Medium exists yet to account for all observations.