SIMULATIONS OF THE COSMIC-RAY ANISOTROPY DOWN TO TeV ENERGIES

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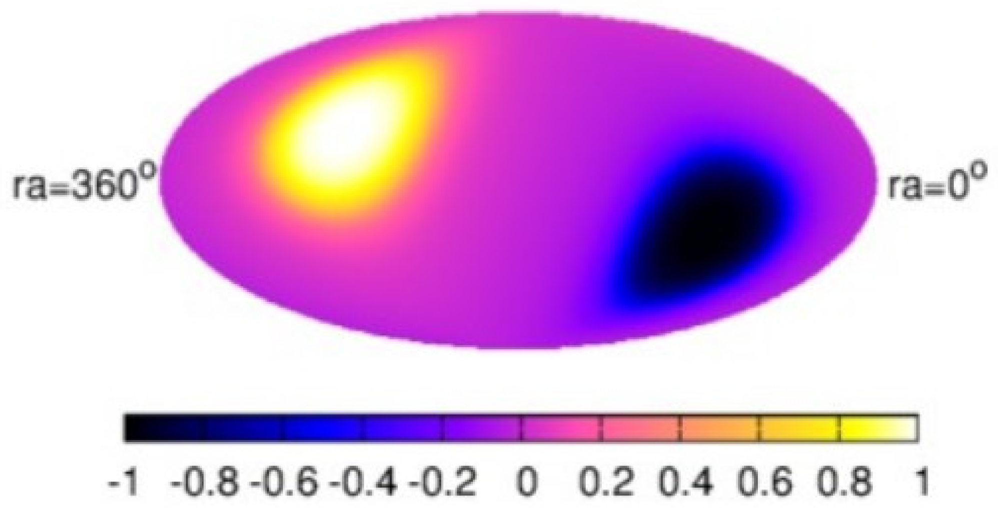
Abstract: We calculate the shape of the TeV-PeV **cosmic-ray** (CR) **anisotropy** in 3D Kolmogorov turbulence. We present the first numerical calculations of the CR anisotropy down to TeV energies, using realistic values for the coherence length of the interstellar turbulence. At these low energies, the large-scale CR anisotropy aligns with the direction of local magnetic field lines around the observer. In this type of turbulence, the cosmic-ray intensity is flat in a broad region perpendicular to magnetic field lines. Even though the CR anisotropy is rather gyrotropic, we show that the local realization of the turbulence around the observer results in the appearance of weak, non-gyrotropic, small-scale anisotropies, which contain important information about the local turbulence level.

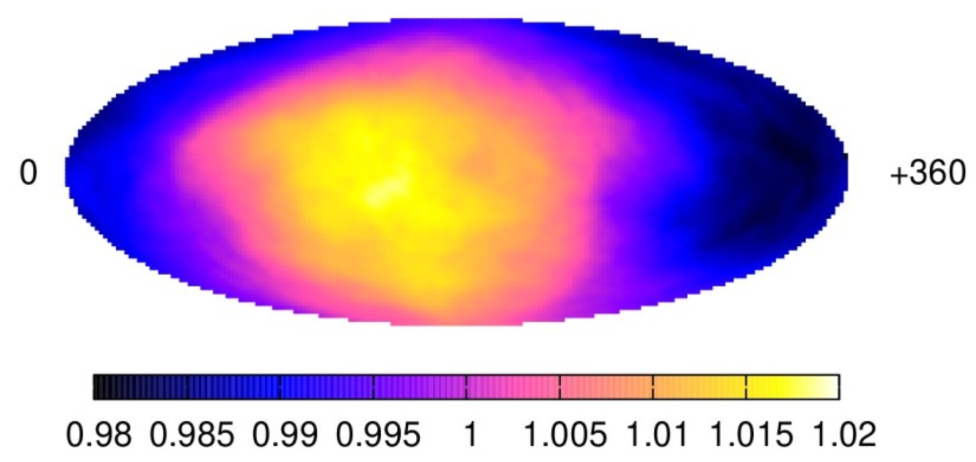
CONTEXT :



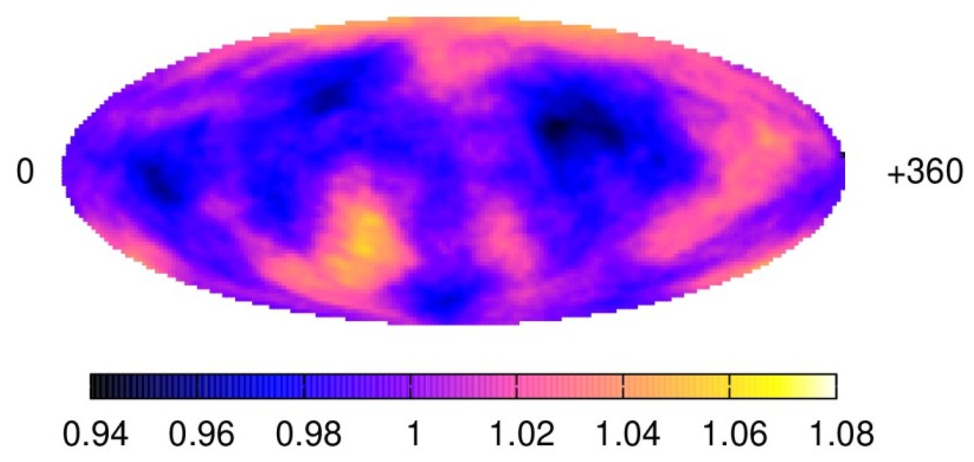
Giacinti & Kirk, ApJ 835, 258 (2017), arXiv:1610.06134

Observations of the TeV CR anisotropy show that the large-scale anisotropy is roughly aligned with local magnetic field lines and is **not a pure dipole**. On top of it, non-gyrotropic, smaller-scale anisotropies also exist. In previous works, we have shown analytically that the large-scale anisotropy is indeed not expected to be a dipole in general (see the left panel). We have also shown numerically that small scale anisotropies appear beyond the dipole anisotropy, and that they are due to the configuration of the local turbulent magnetic fields within a CR mean free path from Earth (see the 2 panels on the right hand side). Those numerical simulations were however made for 10 PeV CRs, and numerical simulations with more realistic (i.e. lower) CR energies are needed...

90°smoothing



20°smoothing - {Dipole}



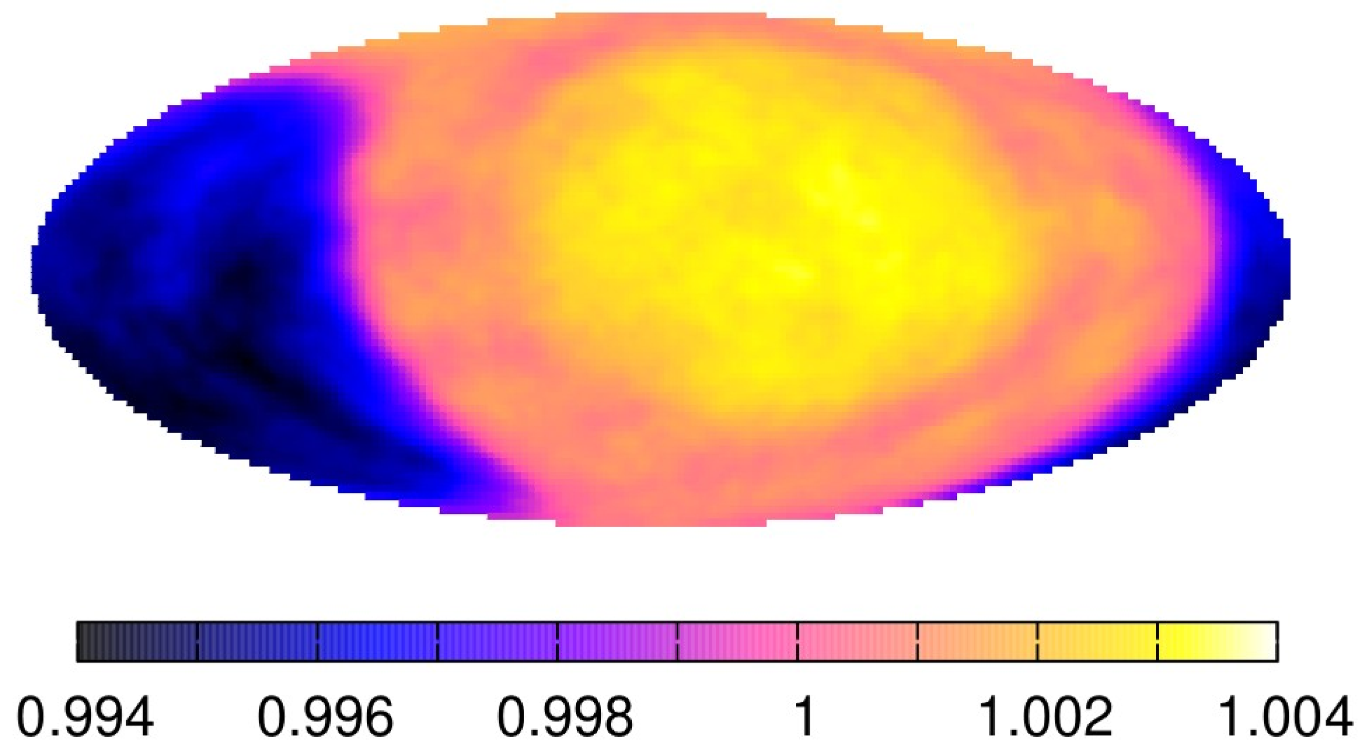
Giacinti & Sigl, Phys. Rev. Lett. (2012), arXiv:1111.2536

NEW SIMULATIONS – RESULTS :

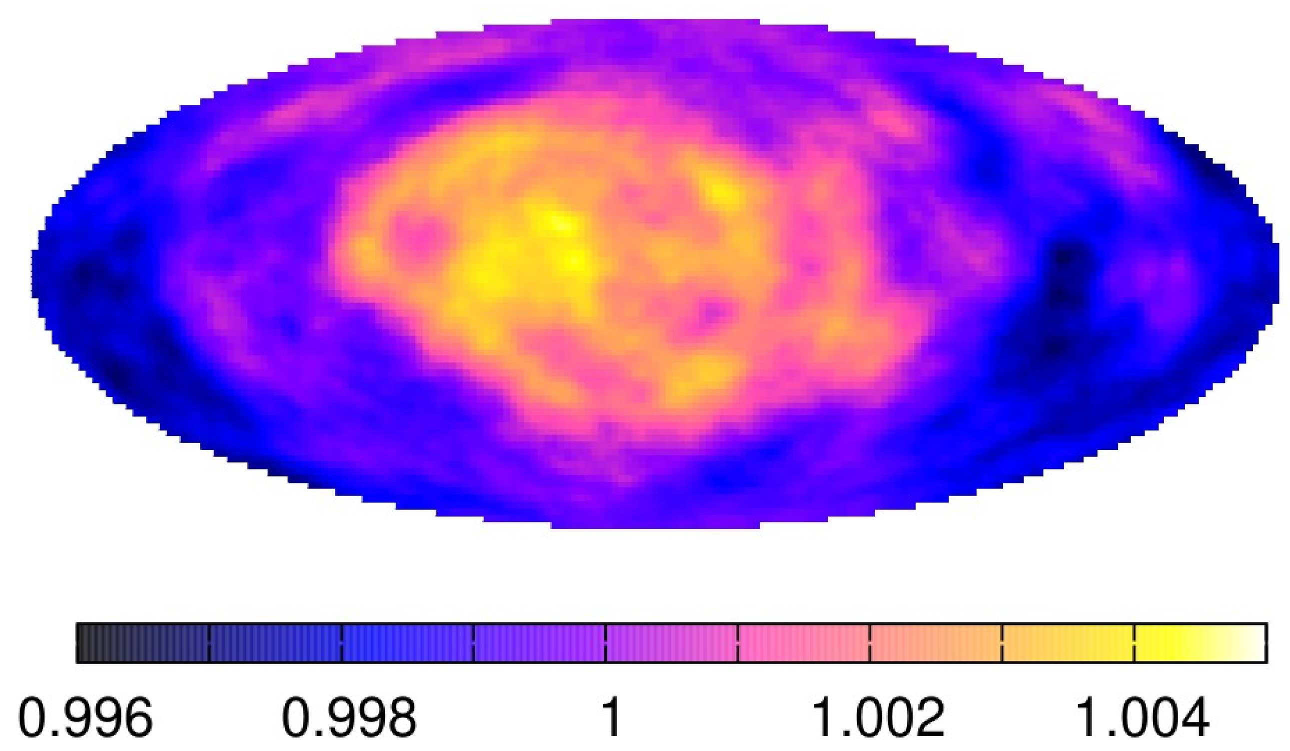
… In the present study, we fill this gap. We propagate individual **~ TeV cosmic-rays in synthetic 3D turbulent magnetic fields**, with a Kolmogorov power spectrum and with realistic values for the outer scale (~ 100 pc). These simulations are the first ones to reach realistically low cosmic-ray energies (3 TeV), while using realistically large outer scales and coherence lengths for the interstellar turbulence.

Numerical calculations of the relative CR flux at 3 TeV in two different realizations of 3D isotropic Kolmogorov turbulence with B_{rms} = 4 μG and l = 150 pc. The CR intensity in these maps is averaged over 10°-radius circles:

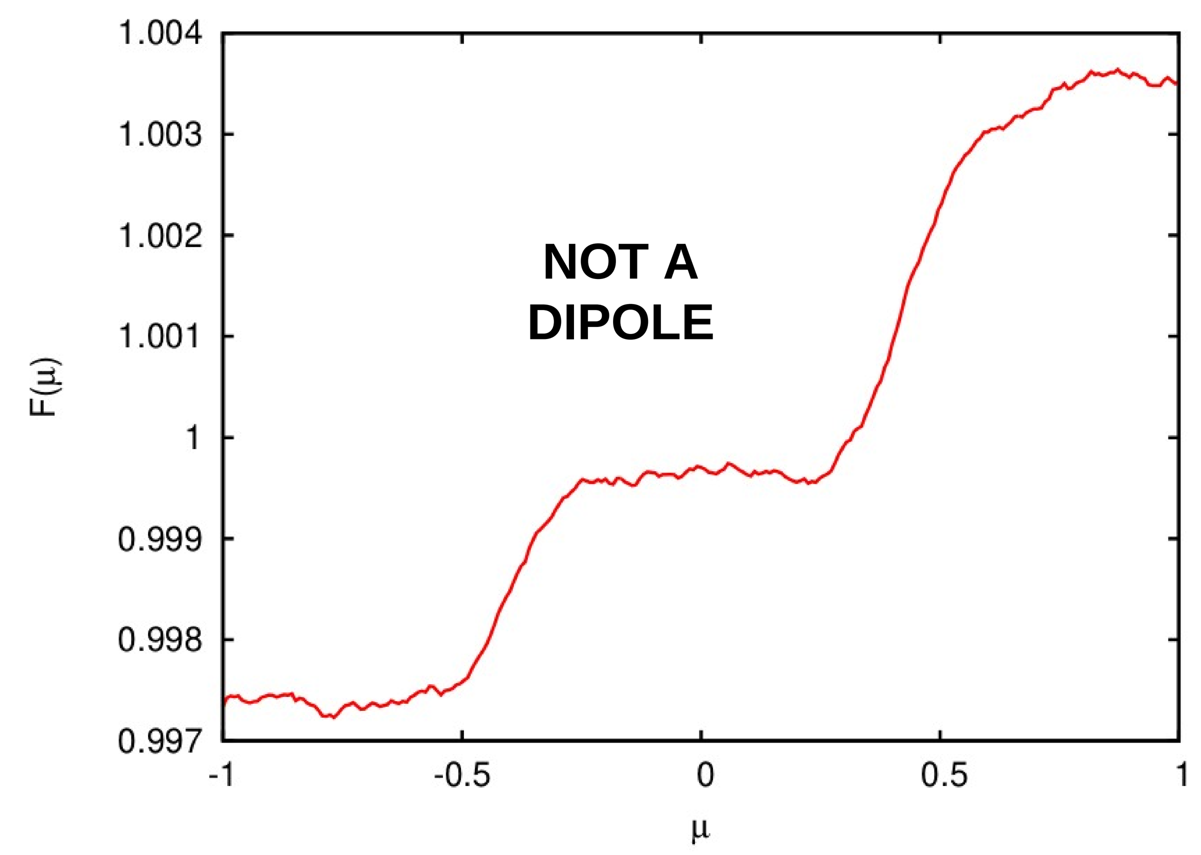
Observer 1 (Low δB/B):



Observer 2 (High δB/B):



Numerical calculation of the gyrophase-averaged relative CR flux F(μ), at 3 TeV, for an observer in a given realization of 3D isotropic Kolmogorov turbulence with B_{rms}=4μG and l=150pc:



(NB: μ is the cosine of the pitch angle)

We find that:
- → The large-scale CR anisotropy aligns with the direction of the local magnetic field line at the observer's location,
- → The large-scale CR anisotropy is not a dipole,
- → "Non-gyrotropic", smaller-scale anisotropies appear too,
- → The relative amplitude of the small-scale anisotropies with respect to the large-scale anisotropy grows with the local value of the turbulence level on gyroresonant scales, δB/B.

Conclusions: The large-scale TeV CR anisotropy at Earth, g(μ), is not consistent with a simple dipole interpretation. We present here the first numerical calculations of the CR anisotropy in 3D isotropic Kolmogorov turbulence down to 3 TeV. We find that g(μ) has a flattening in directions around μ = 0 in this type of turbulence. At these low energies, the CR anisotropy aligns well with the direction of local magnetic field lines around the observer and is quite gyrotropic. Weak, "non-gyrotropic" small-scale anisotropies do nonetheless appear due to the local configuration of the turbulence around the observer at the time of the observations. Their amplitude, which is always much smaller than that of the large-scale anisotropy g(μ), depends on the turbulence level on resonant scales in our local magnetic flux tube, thus providing a unique measure of the local turbulent magnetic field profile, and a valuable test of multi-scale particle transport in turbulent plasmas.