Probing the CMB-cosmic ray connection: ultra-local and extragalactic effects

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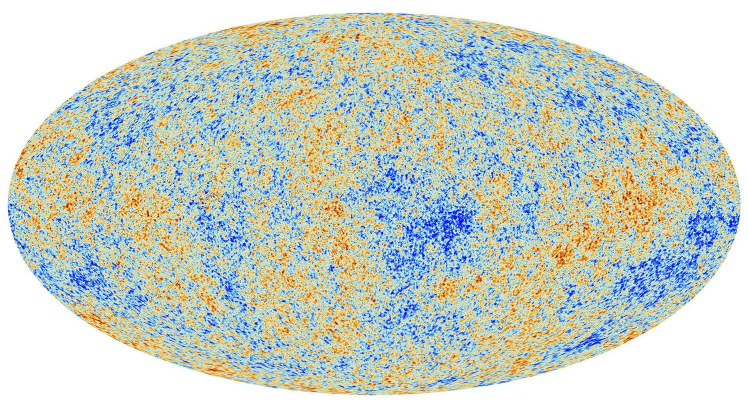
The Cosmic Microwave Background (CMB) was discovered in 1964 [1] and today is one of the most well studied cosmological features. The mean temperature of the CMB and its anisotropies are know with high level of precision thanks to missions such as COBE-FIRAS and Planck [2].

Ultra-high-energy cosmic rays are the most energetic particles known in the universe, reaching above 10^{20} eV. Their mass composition varies with energy, with protons dominating around 10^{18} eV and heavier elements becoming more present as the energy rises [3].



Background-subtracted map of the CMB anisotropies seen by Planck [4]

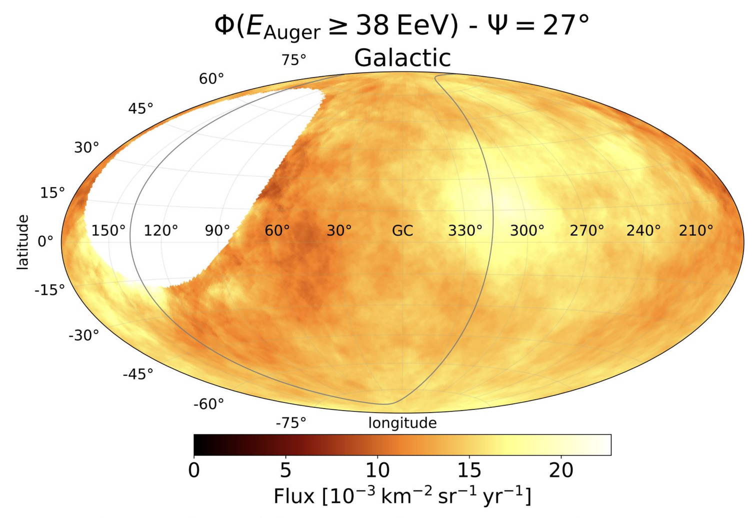
Interactions between UHECRs and the CMB field have been first suggested in 1966 by Greisen, Zatsepin and Kuz'min [6][7]
The interactions **destroy the photon** and occur mainly in two channels:

GZK effect	Bethe-Heitler **Pair production**
$p+\gamma_{CMB} \rightarrow \Delta^+ \rightarrow p+\pi^0$ $p+\gamma_{CMB} \rightarrow \Delta^+ \rightarrow n+\pi^+$	$p+\gamma_{CMB} \rightarrow p+e^+ +e^-$
GZK effect: E_{th}=7e19 eV	Bethe-Heitler **Pair production:** E_{th}=5e17 eV

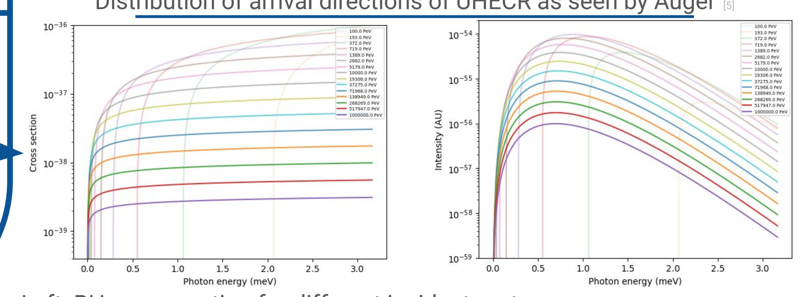
There are analogous interactions for heavy nuclei

CRs lose much more energy in the GZK effect than in BH
The BH has lower energy threshold

BH pair production interactions are by far the most common



Distribution of arrival directions of UHECR as seen by Auger [5]



Left: BH cross section for different incident protons.
Right: convolution of BH cross section and the CMB black body spectrum

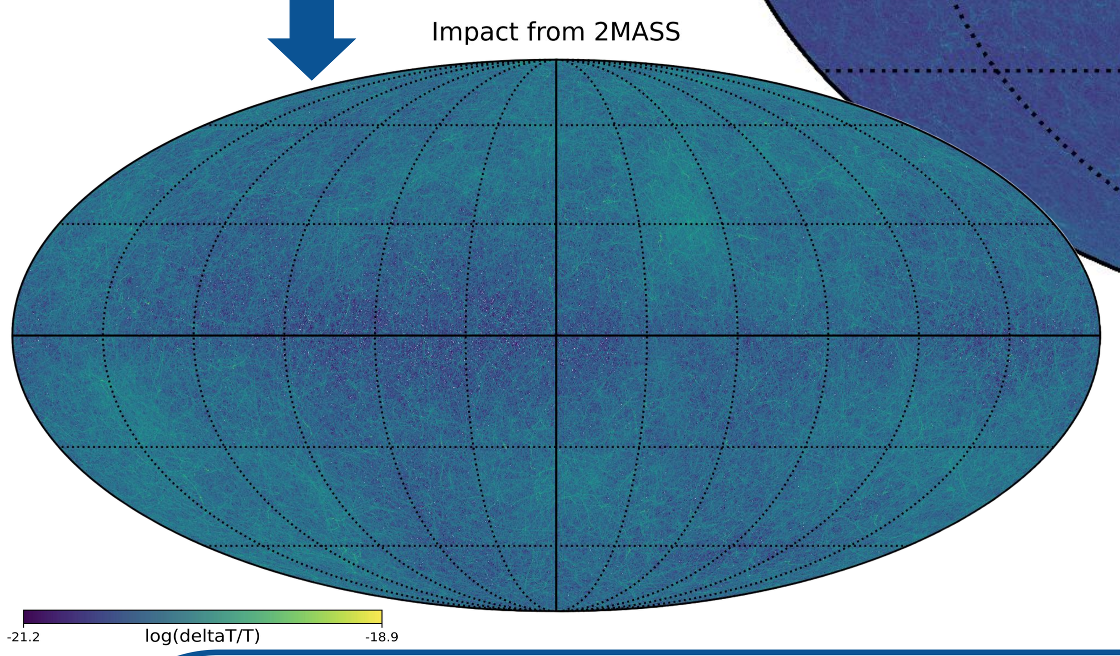
Throughout the years, these interactions have been thoroughly studied from the point of view of the effects on the UHECRs, but here we investigate the opposite side:

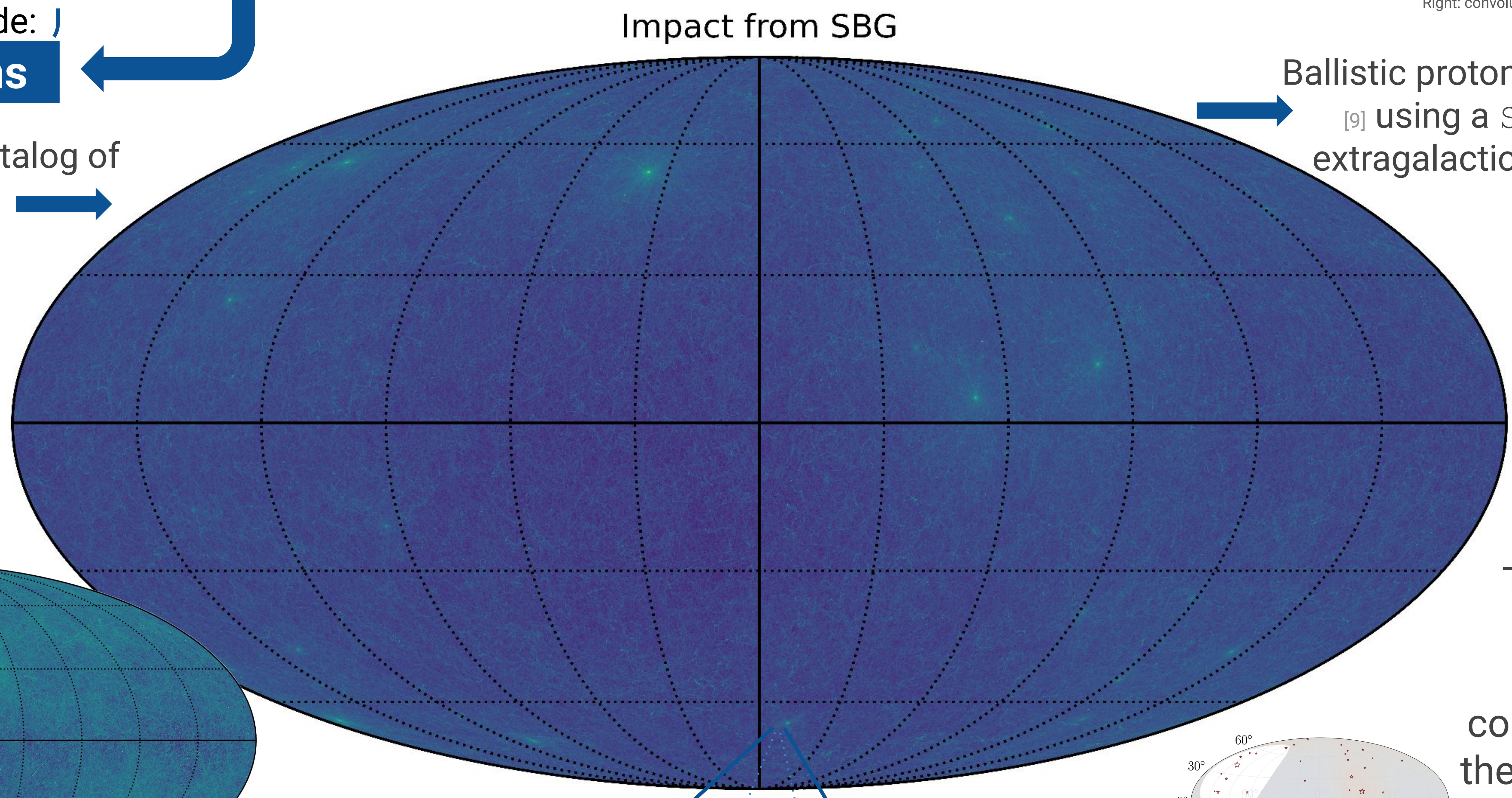
The missing photons

Impact on the CMB from catalog of local SBGs used by Auger [8]

SBGs are probable candidate sources

2MASS traces local matter in general - an alternative simulation

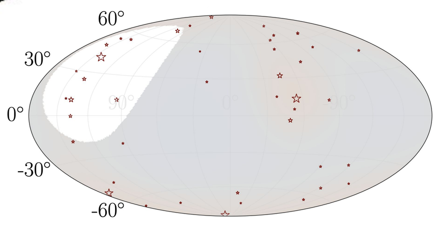




Ballistic protons simulated with CRPropa [9] using a `SimpleGridTurbulence` extragalactic magnetic field (1 nG rms)

Trails of interactions left by propagating UHECRs are visible in simulation - if observed could give insight on the strength and direction of EMFs

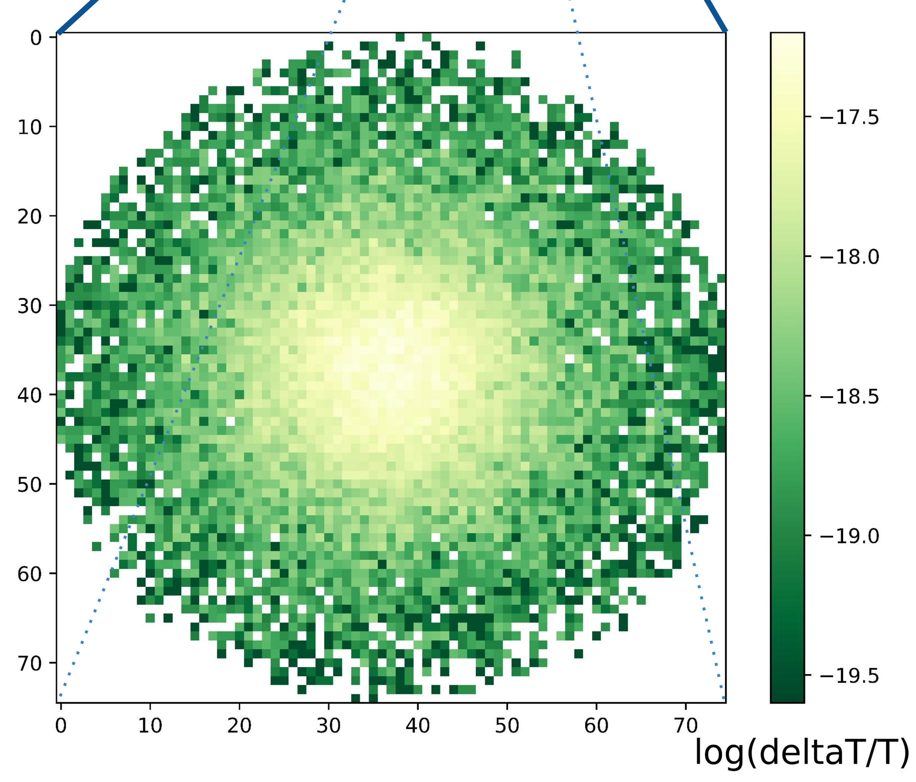
The maximum predicted CMB anisotropy at this resolution is of **O(-18)** concentrated very close to the injected UHECR source galaxies - to know more we have to **zoom into the galaxies** themselves



Map of the location of SBGs in the catalog.[8]

Inside galaxies, local source, such as compact objects, energetic winds, active galactic features, are generally clustered around the galactic center .This results in a higher concentration of interaction close to the center of the host galaxy.

For a diffuse flux of 1E-18 $m^{-2}sr^{-1}s^{-1}GeV^{-1}$ **peak expected effect is of O(-17)**



The bulk of interactions in this simulation are carried out by medium energy protons which are not deflected enough by magnetic fields to leave recognizable trails of interactions inside the galaxy. Heavier elements such as Fe at lower energies are, but current mass composition models do not predict them with large abundance.

Future and conclusions

Possible simulation improvements

Add different atomic species to investigate more realistic species mix, more complex mean free path and magnetic deflection.

Realistically the total effect is the cumulation of all interactions from all cosmological distance - need catalogs more complete in distance

The effects of UHECR-CMB BH interactions are extremely small when compared to the typical CMB anisotropies - by O(-10). While not visible right now, future generations of radio and microwave instrument may be able to observe them, giving incredible insight into UHECR sources far more distant than those accessible with dedicated detectors.

Resources

[1] Penzias, A. A.; Wilson, R. W., 1965, "A Measurement of Excess Antenna Temperature at 4080 Mc/s", The Astrophysical Journal, https://ui.adsabs.harvard.edu/abs/1965ApJ...142..419P/abstract [2] https://lambda.gsfc.nasa.gov/product/cobe/about_firas.html , https://www.cosmos.esa.int/web/planck
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[5] The Pierre Auger Collaboration, 2023, "An update on the arrival direction studies made with data from the Pierre Auger Observatory", PoS ICRC 2023, https://inspirehep.net/literature/2740433 [6] Greisen, K., 1966, "End to the cosmic-ray spectrum?", Physical Review Letters, https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.16.748 [7] Zatsepin, G.T.; Kuz'min, V.A.; 1966, "Upper limit of the spectrum of cosmic rays", Journal of Experimental and Theoretical Physics Letters [8] The Pierre Auger Collaboration, 2024, "Constraining models for the origin of ultra-high-energy cosmic rays with a novel combined analysis of arrival directions, spectrum, and composition data measured at the Pierre Auger Observatory", JCAP01, https://iopscience.iop.org/article/10.1088/1475-7516/2024/01/022

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