Probing the dipole of the diffuse gamma-ray background

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Probing the Dipole of the Diffuse Gamma-Ray Background

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Abstract

We measured the dipole of the diffuse γ-ray background (DGB), identifying a highly significant time-independent signal coincidental with that of the Pierre Auger UHECR. The DGB dipole is determined from flux maps in narrow energy bands constructed from 13 yr of observations by the Large Area Telescope (LAT) of the Fermi satellite. The γ-ray maps were clipped iteratively of sources and foregrounds similar to that done for the cosmic infrared background. The clipped narrow energy band maps were then assembled into one broad energy map out to the given energy starting at $E = 2.74$ GeV, where the LAT beam falls below the sky's pixel resolution. Next we consider cuts in Galactic latitude and longitude to probe residual foreground contaminations from the Galactic plane and center. In the broad energy range $2.74 < E \leqslant 115.5$ GeV, the measured dipoles are stable with respect to the various Galactic cuts, consistent with an extragalactic origin. The γ-ray sky's dipole/monopole ratio is much greater than that expected from the DGB clustering component and the Compton–Getting effect origin with reasonable velocities. At $\simeq$(6.5–7)% it is similar to the Pierre Auger UHECRs with $E_{\rm UHECR} \geqslant 8$ EeV, pointing to a common origin of the two dipoles. However, the DGB flux associated with the found DGB dipole reaches parity with that of the UHECR around $E_{\rm UHECR} \leqslant 1$ EeV, perhaps arguing for a non-cascading mechanism if the DGB dipole were to come from the higher-energy UHECRs. The signal-to-noise ratio of the DGB dipole is largest in the 5–30 GeV range, possibly suggesting the γ-photons at these energies are the ones related to cosmic rays.

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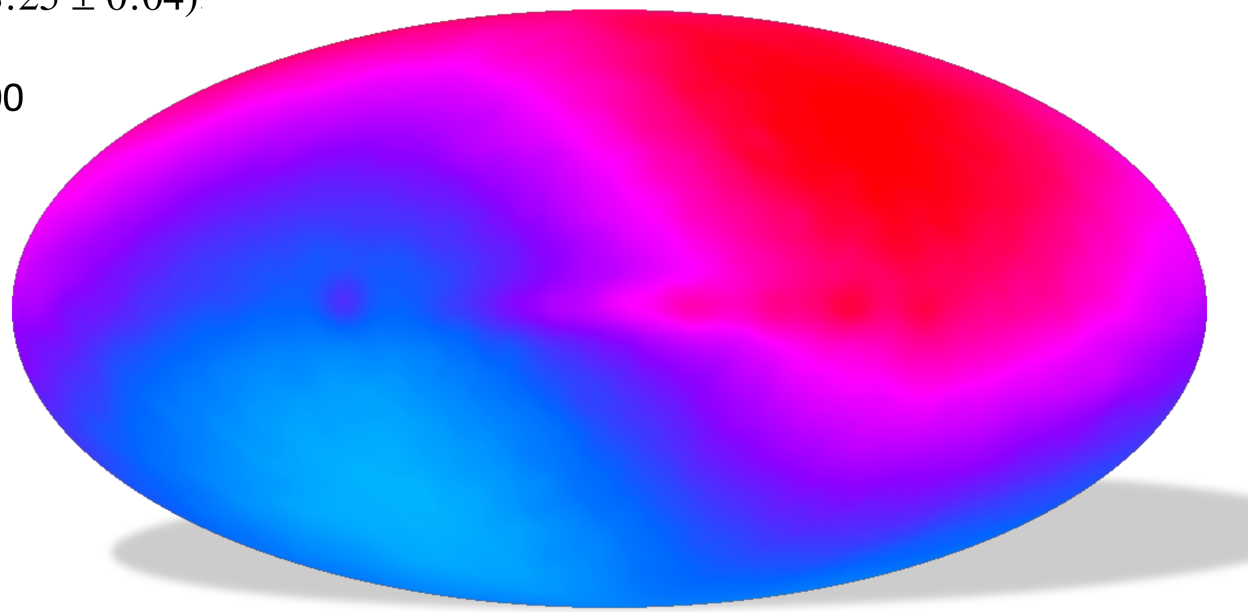
CMB dipole – the gold standard of measurements

- dT/T = 1.23x10^{-3}
- Toward $(l, b)_{\mathrm{CMB}} = (263.°85 \pm 0.°1, 48.°25 \pm 0.°04)$
- Velocity V_{CMB} = 370 km/sec at *S/N*>200
-
- ***Is it fully kinematic though?***
- Most people would say “yes”
- But contrary evidence exists
- This has important implications



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Previous probes of CIB dipole's kinematic nature

- Velocity field vs gravity – Villumsen&Strauss(1987),Gunn(1988),Erdogdu+(2006),..
- Radio counts' dipole – Nodland&Ralston(1997),Jain&Ralston(1999)
- Dark flow – Kashlinsky+(2008),(2009),(2010),(2011),Atrio-Barandela+(2010),(2014)
- Peculiar velocity probes – Mathewson+(1991),Lauer&Postman(1994)
- WISE QSO dipole – Secrest+(2021)
- Anisotropy in X-ray cluster scaling relations – Migkas+(2020)

- See reviews – Kashlinsky+(2012), Kumar-Aluri+(2023)

- Problem: for *S/N*~4–6 probe the directional uncertainty ΔΘ is large

$$\Delta\Theta \simeq \sqrt{2}(S/N)^{-1}\mathrm{rad}$$

CMB dipole and preinflationary remnants

PHYSICAL REVIEW D VOLUME 44, NUMBER 12 15 DECEMBER 1991

Tilted Universe and other remnants of the preinflationary Universe

Michael S. Turner

Inflation does ***not***, in general, makes the observed space-time uniform, homogeneous and isotropic. It rapidly expands the already such small patch to well beyond the current cosmological horizon.

term). *The dipole anisotropy associated with the tilting of the Universe is not observable because it is canceled by a corresponding dipole anisotropy from the potential term (at order kx).* Said another way, in spite of the existence of the density gradient associated with the superhorizon-sized curvature perturbation, the spatial hypersurfaces defined by the isotropy of the CMBR coincide with those defined by the isotropy of the expansion.

Preinflationary remnants – how far can they be?

VOLUME 73, NUMBER 12 PHYSICAL REVIEW LETTERS 19 SEPTEMBER 1994

Microwave Background Anisotropy in Low-Ω_0 Inflationary Models and the Scale of Homogeneity in the Universe

A. Kashlinsky,[1] I. I. Tkachev,[2,3] and J. Frieman,[2,4]

if the size of the homogeneous region is close to the present Hubble radius, such nonlinear inhomogeneities on large scales will induce significant microwave background anisotropy via the Grischuk-Zel'dovich (GZ) effect [12]. In order of magnitude, the quadrupole anisotropy induced by superhorizon-size fluctuations of lengthscale L is $Q_L \simeq (\delta\rho/\rho)_L (LH_0)^{-2}$. The Cosmic Background Explorer (COBE) Differential Microwave Radiometers have measured a quadrupole anisotropy of $Q_{\rm COBE} = (4.8 \pm 1.5) \times 10^{-6}$ from the first year of data and $Q_{\rm COBE} = (2.2 \pm 1.1) \times 10^{-6}$ from the first two years of data [13]. Consequently, assuming order-unity density fluctuations on scales $L \gtrsim L_0$, the size of the inflated patch must be significantly larger than the present Hubble radius, $L_0 > 500 H_0^{-1}$ [14,15]. Cosmic variance can cause the

The Compton-Getting (1935) effect for cosmic backgrounds

PHYSICAL REVIEW VOLUME 174, NUMBER 5 25 OCTOBER 1968

Comment on the Anisotropy of the Primeval Fireball*

P. J. E. Peebles† and David T. Wilkinson†

photons. In the same interval, observer O sees the same number of counts, but expresses it as

$$d\mathfrak{N}=n(\nu)d\nu d\Omega A_0|v+c\cos\theta|dt, \quad (2)$$

where $A_0|v+c\cos\theta|dt$ is the volume swept out by the $d\mathfrak{N}$ photons.

The quantities needed to relate $n'(\nu',\theta')$ and $n(\nu)$ transform as follows[3]:

$$dt'=dt(1-v^2/c^2)^{1/2}, \quad (3)$$

$$\cos\theta'=(\cos\theta+v/c)[1+(v/c)\cos\theta]^{-1}, \quad (4)$$

$$d\Omega'=d\varphi' d\cos\theta'=d\Omega(1-v^2/c^2)[1+(v/c)\cos\theta]^{-2}, \quad (5)$$

$$\nu'=\nu[1+(v/c)\cos\theta][1-(v/c)^2]^{1/2}. \quad (6)$$

Using Eqs. (1)–(6), we have

$$n'(\nu',\theta')=n(\nu)(\nu'/\nu)^2. \quad (7)$$

See eq. 7 in this 1-page paper

The Compton-Getting (1935) effect – cnt'd

Cosmic backgrounds have intensity I_ν:

$I_\nu \propto \nu\, n(\nu)$ – hence: I_ν/ν^3 is Lorentz-invariant

Thus: $I_\nu/\nu^3 = I_{\nu_0}/\nu_0^3$

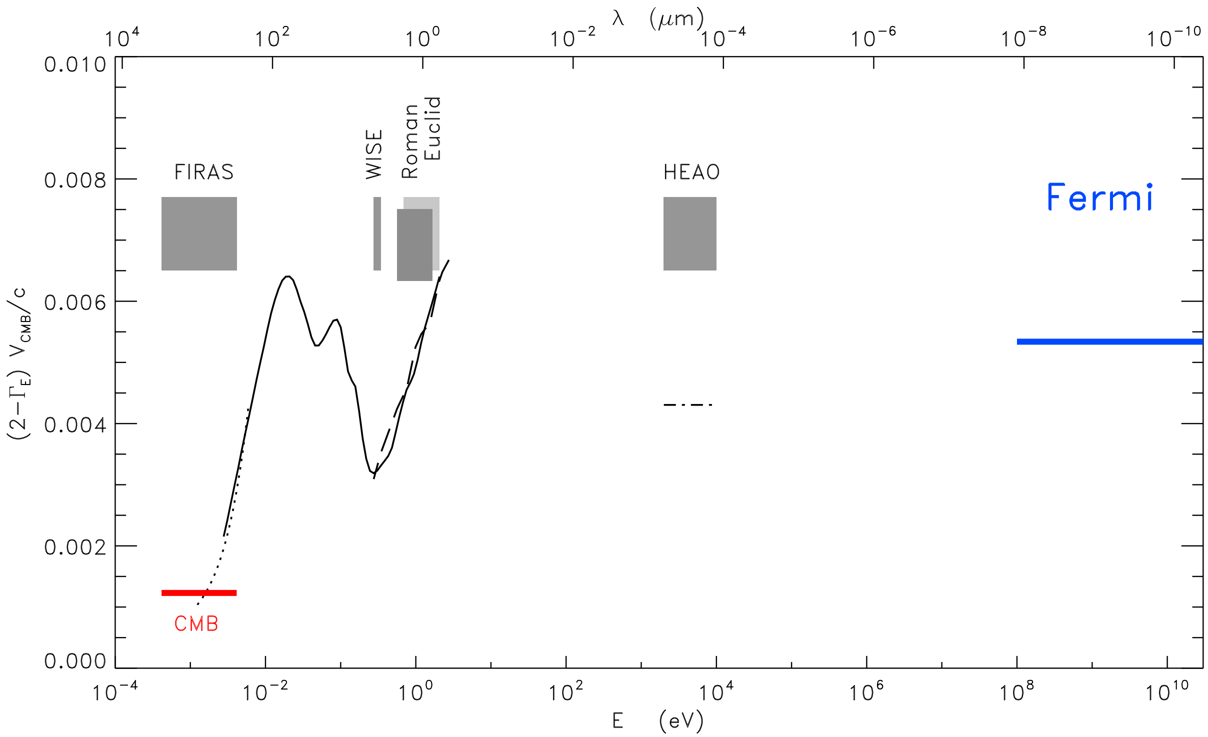
With: $\nu = \nu_0(1 + \frac{V}{c}\cos\Theta)\sqrt{[1 - \left(\frac{V}{c}\right)^2]}$

Which for *V<<c* leads to the dipole in I_ν :

$$\boldsymbol{d}_\nu = (3 - \alpha_{\nu,\infty})\frac{\boldsymbol{V}}{c}\bar{I}_\nu, \quad \text{with} \quad \alpha_{\nu,\infty} = \partial \ln I_\nu / \partial \ln \nu$$

Where $\alpha_\nu<2$ the dipole is *amplified* over that of the CMB

Compton-Getting amplification vs *E*



Hence, 1) the dipole we sought to probe would be ~0.5-0.6%, 2) using ~10^6 photons/sources, 3) thus expecting ~(5—6)σ result if all goes well.

Probing DGB dipole – Fermi LAT maps

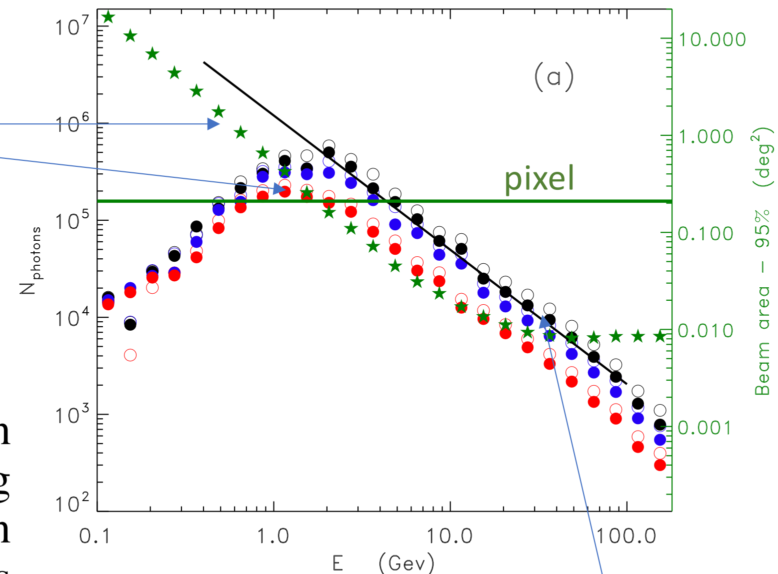
- Selected data taken at the start of scientific operations, continuing through the end of mission Cycle 13, specifically, all the weekly photon files 2008 August 31–2021 September 1
- Used weekly photon files from latest reprocessing, P8R3 & the front-plus-back converting events
- To limit contamination from γ-rays scattered from the Earth's atmosphere, a selection cut was applied to remove data taken when the LAT boresight rocked to >52° with respect to the zenith.
- The selection cuts resulting from this reprocessing significantly reduce the occurrence of CR-induced spurious (i.e., non-photon) events
- We also excluded any time interval when the LAT was not in survey mode
- To minimize potential contamination from CR-induced events in the detector, we selected the "UltraClean" event selection cut and the corresponding instrument-response function
- The diffuse maps at each year were coadded in narrow E-bands from 0.1 to >100 Gev
- The individual narrow E-bands were assembled in HEALPix N_{side}=128 format and then clipped, etc.

Probing DGB dipole – Source removal & clipping

- Fermi LAT beam falls below pixel size at E>2.05 GeV
- Hence concentrate of 2.74 < E(GeV) < 115
- First remove brightest 3000+ sources from the fourth Fermi Gamma-Ray LAT (4FGL) catalog
- Then remove "sources" using CIB developed clipping, i.e.

isolates iteratively the pixels with photons exceeding a given threshold of $N_{\rm phot}(l_{\rm Gal}, b_{\rm Gal}) \geqslant \langle N_{\rm phot}\rangle + N_{\rm cut}\sigma(N_{\rm phot})$, removing here the entire beam at 95% c.l. around the pixels identified in the given iteration and proceeds until no more such excursions are found at the given $N_{\rm cut}$. Typically up to ten iterations were

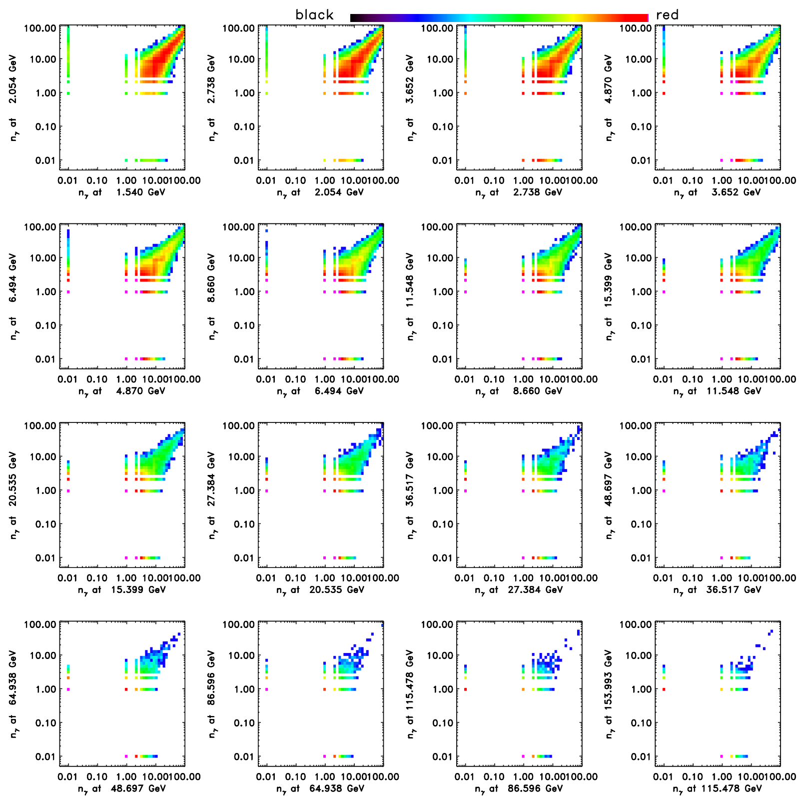
- At different Galaxy cuts, (l, b)



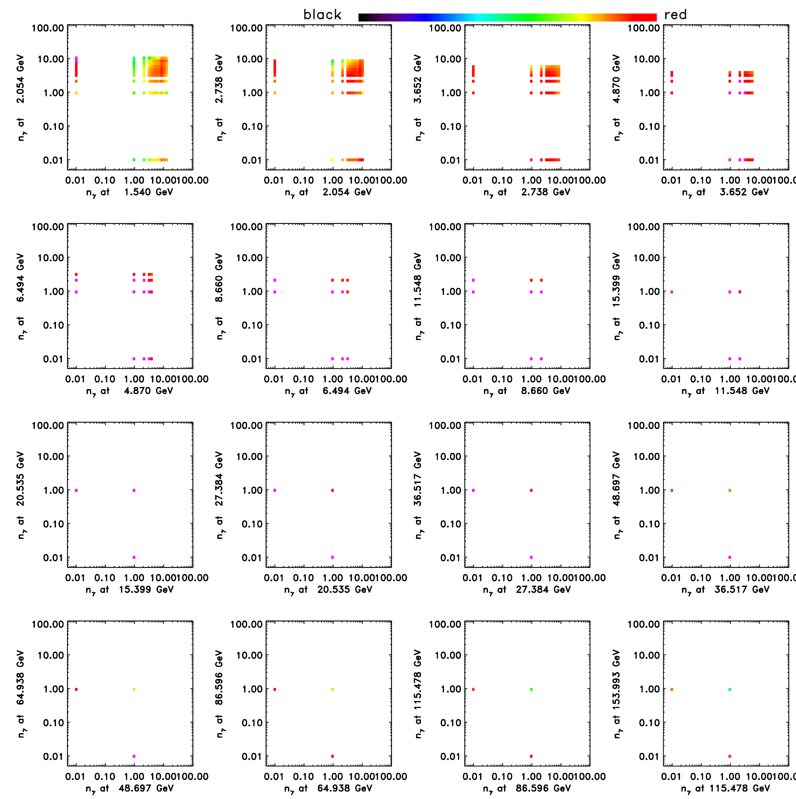
Number of remaining DGB photons at each E-band for the various Galaxy cuts.

DGB flux slope of $E^{-0.34}$

Probing DGB dipole – Clipping of narrow E-maps

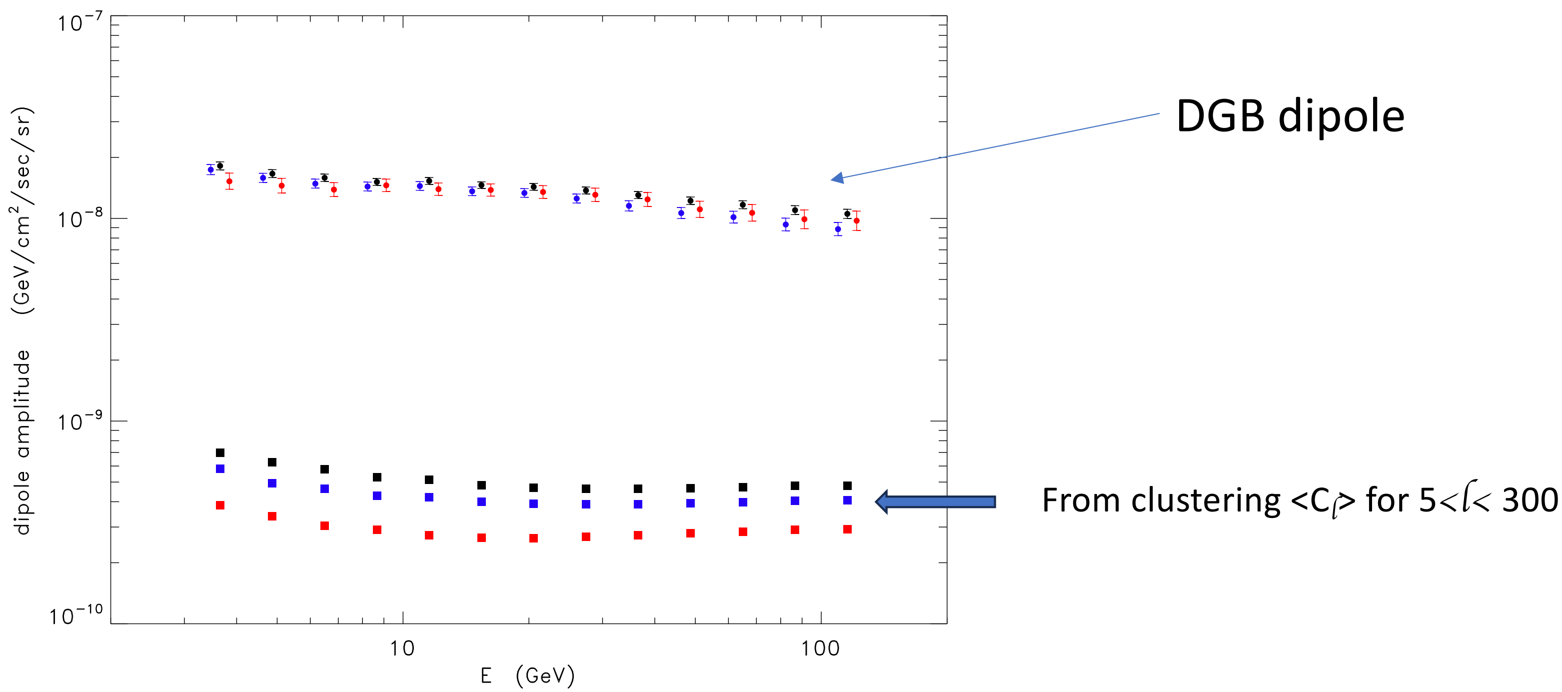


Narrow E vs next E: ***unclipped***



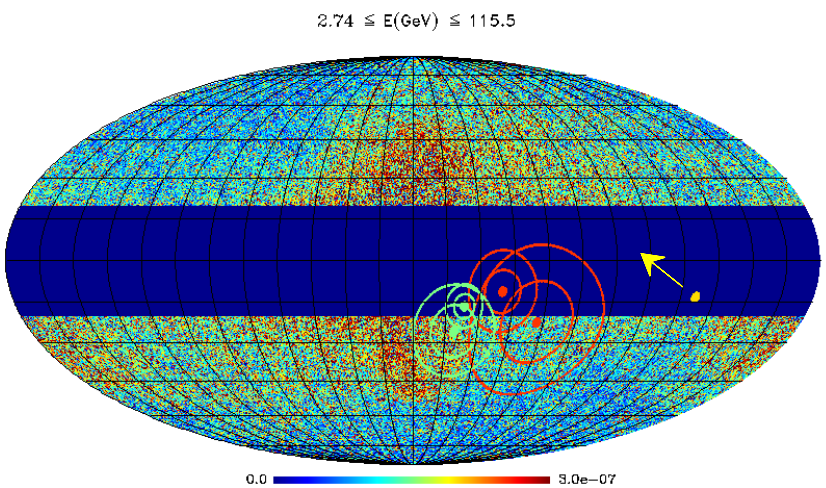
Narrow E vs next E: ***clipped***

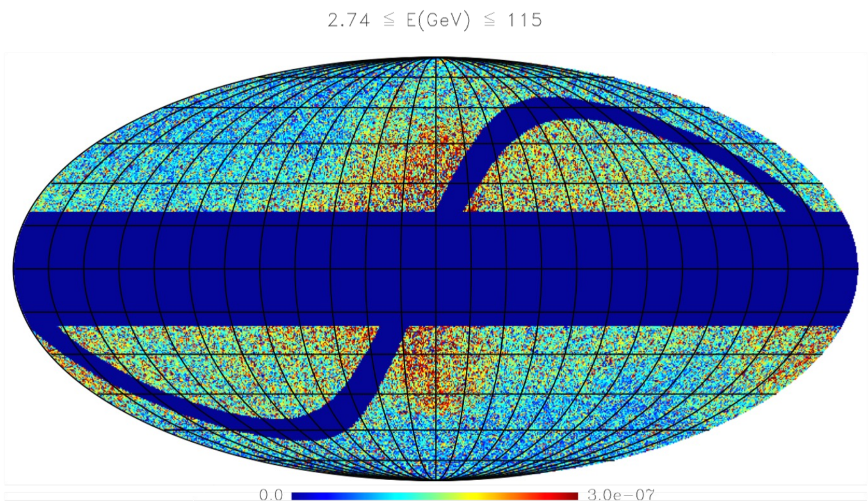
Results:



i) The γ-ray Fermi LAT maps were coadded using 13 years of data. ii) Then clipped off individual sources. iii) Then the remaining Galaxy and Solar System contributions removed. iv) Then dipoles evaluated from 2.05 GeV out to the given γ-ray E and v) their random errors computed from bootstrap.

Results:



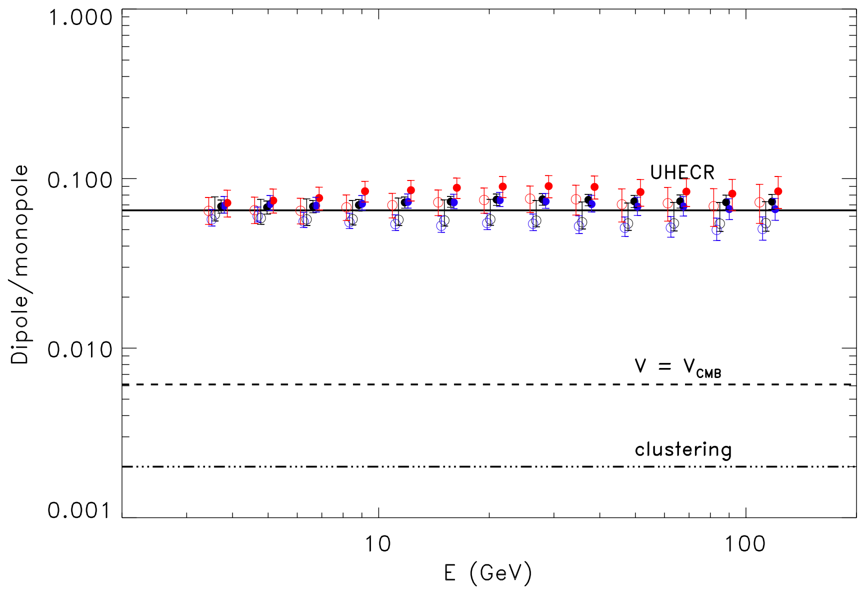


With Ecliptic plane kept in

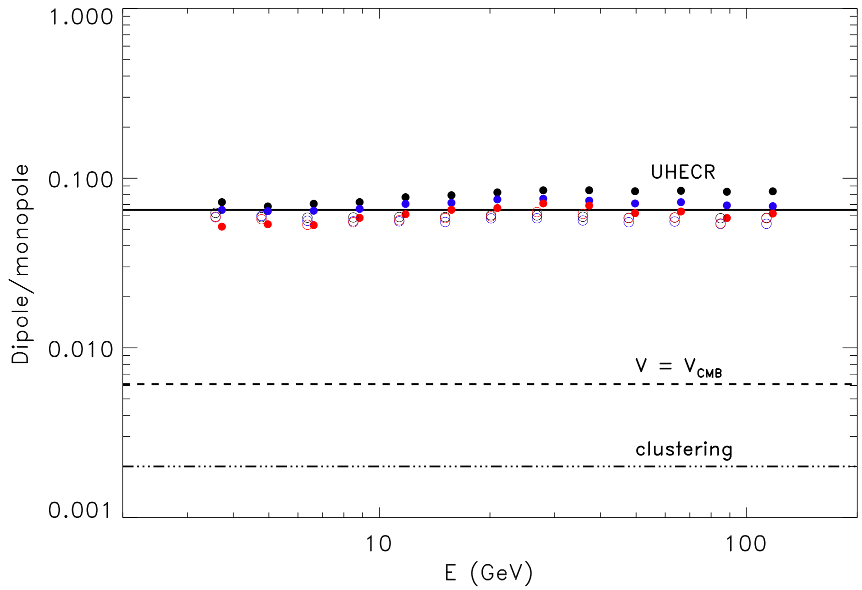
Without Ecliptic plane

Results:

With Ecliptic plane kept in



Without Ecliptic plane



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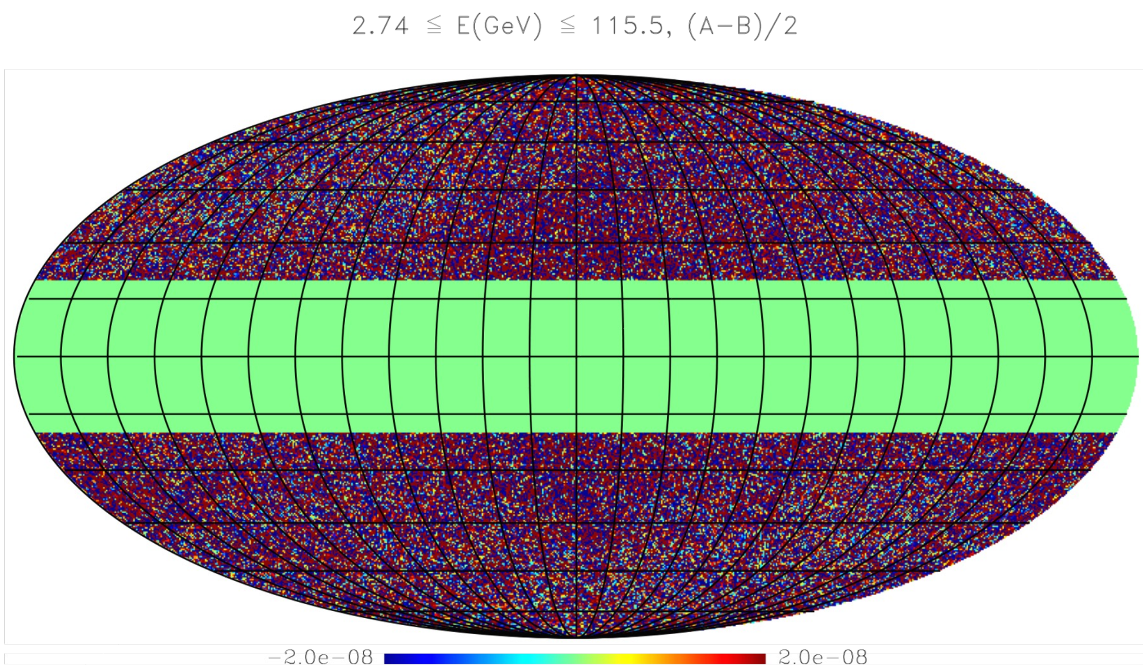
More on errors and systematics



A is years 1 through 6
B is years 7 through 12

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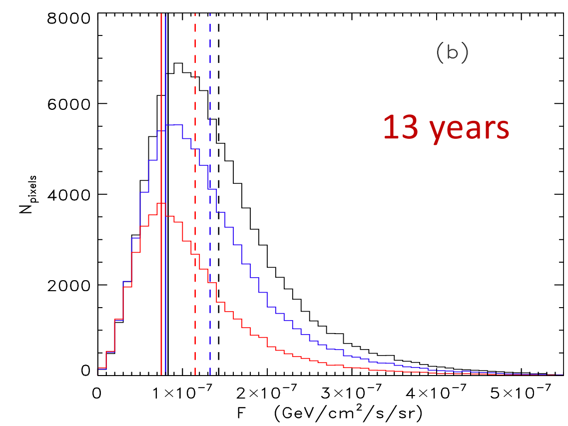

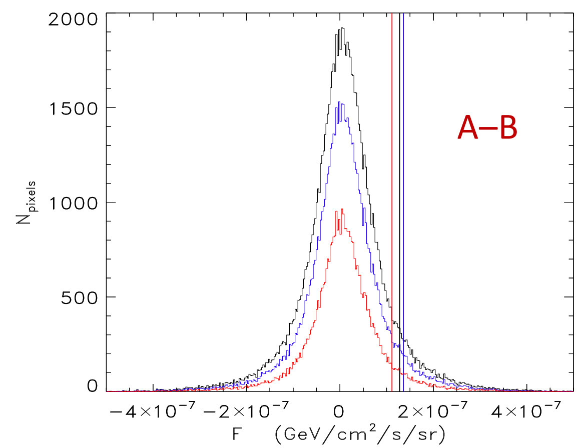

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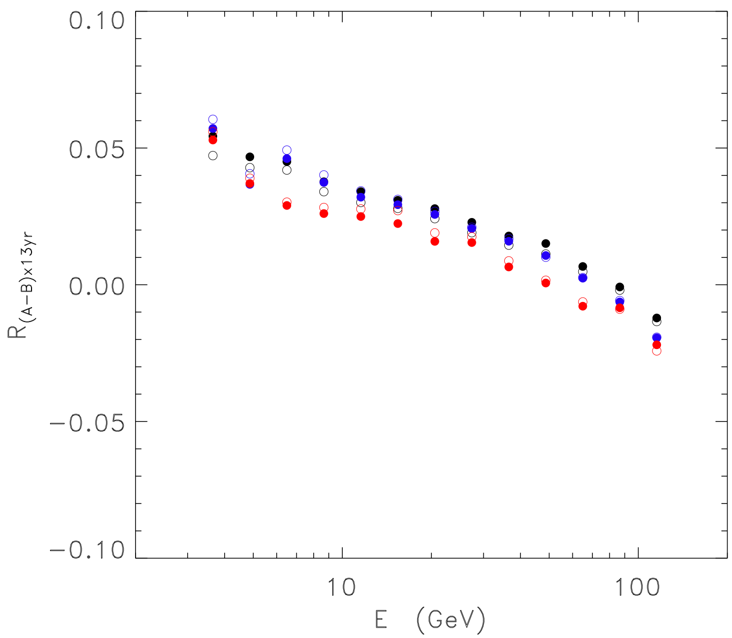
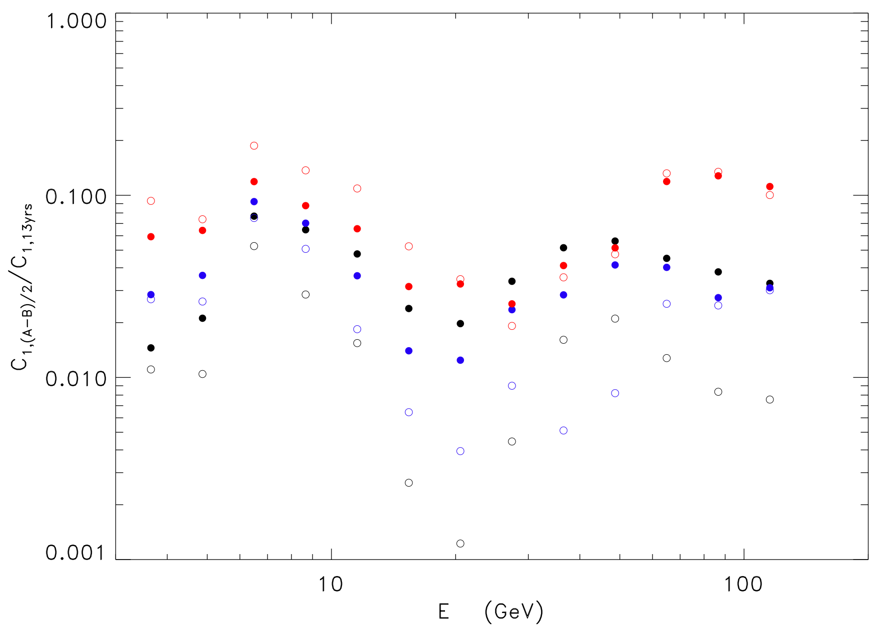
More on errors and systematics – cnt'd



Correlation, R, between (A–B) and 13 yr maps vs E



Ratio of (A–B) to 13 yr maps dipole powers vs E

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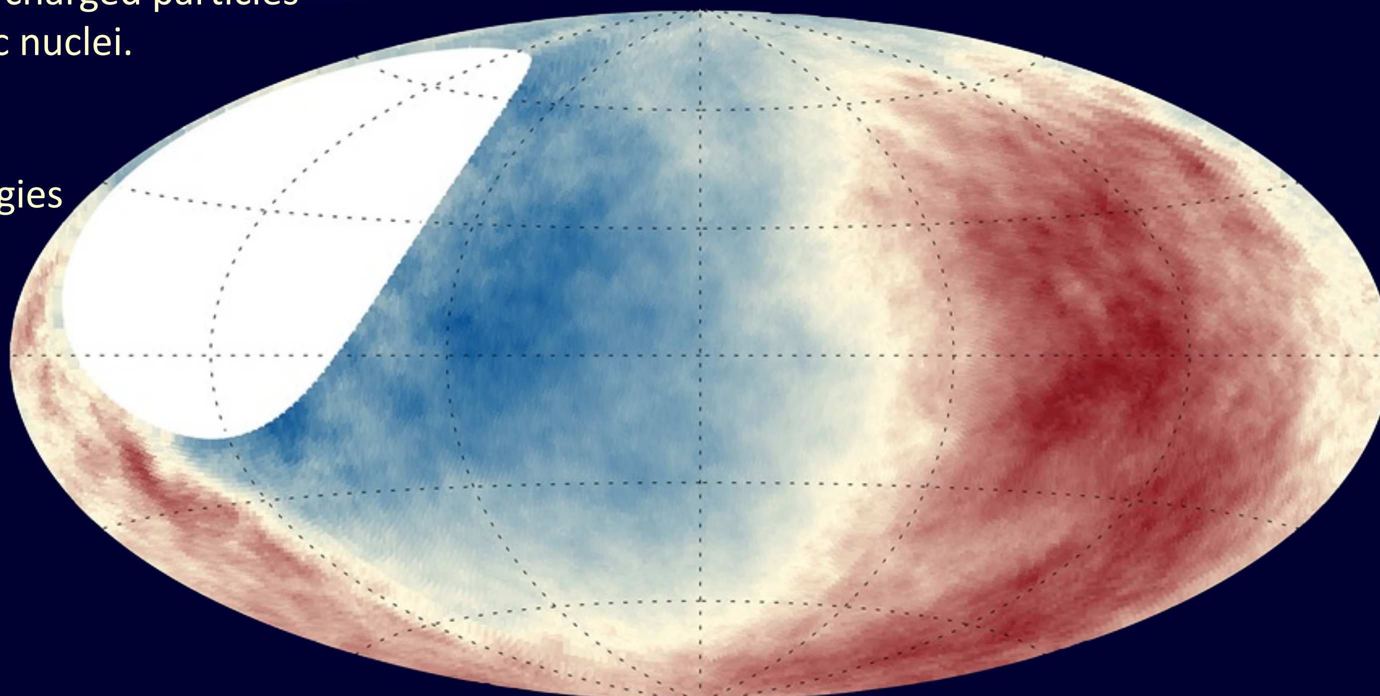
Cosmic ray connection

Cosmic rays are accelerated charged particles – mostly protons and atomic nuclei.

UHECRs: Particles with energies **exceeding a billion times** the energy of gamma rays we studied (> 1 EeV).

Rare: Annual flux > 10 EeV is ~1 per square km

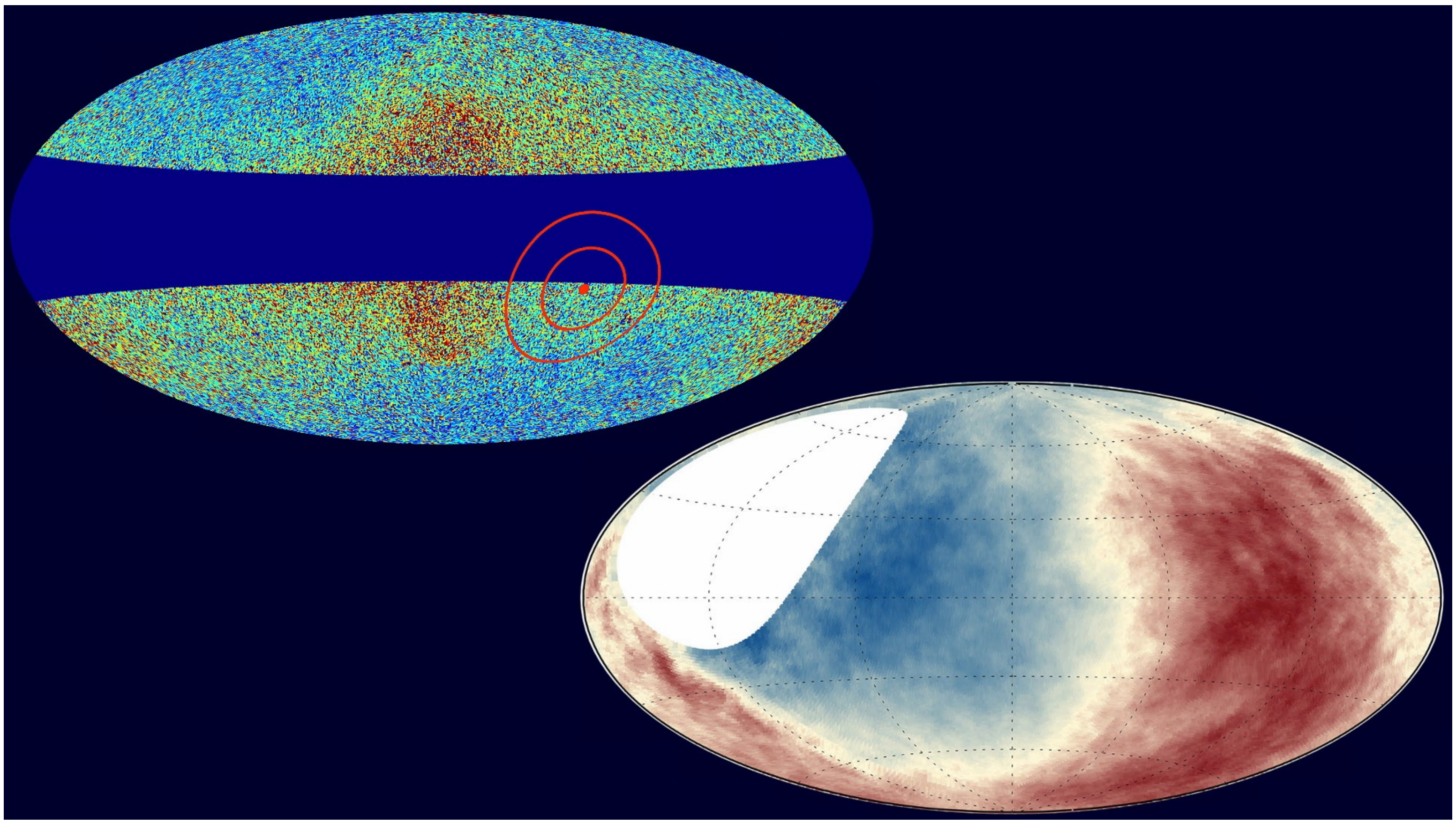
Origins: Unknown



All-sky "heat map" for > 8 EeV cosmic rays with the central plane of our galaxy running across the middle. Redder regions reflect areas with higher rates. Pierre Auger Collaboration (2017)

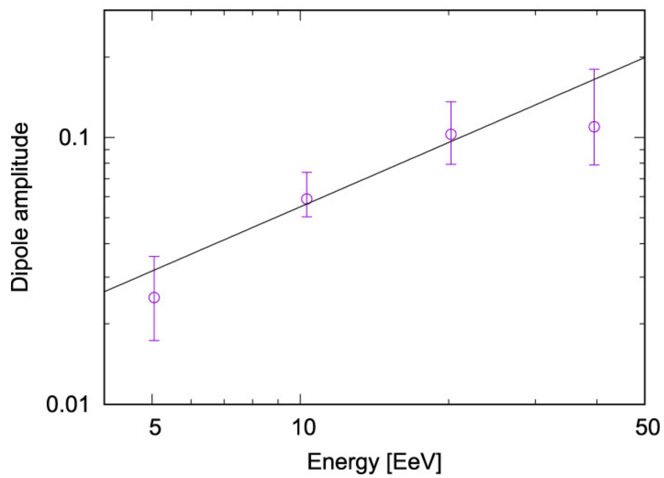
DGB & UHECR at 8 EeV

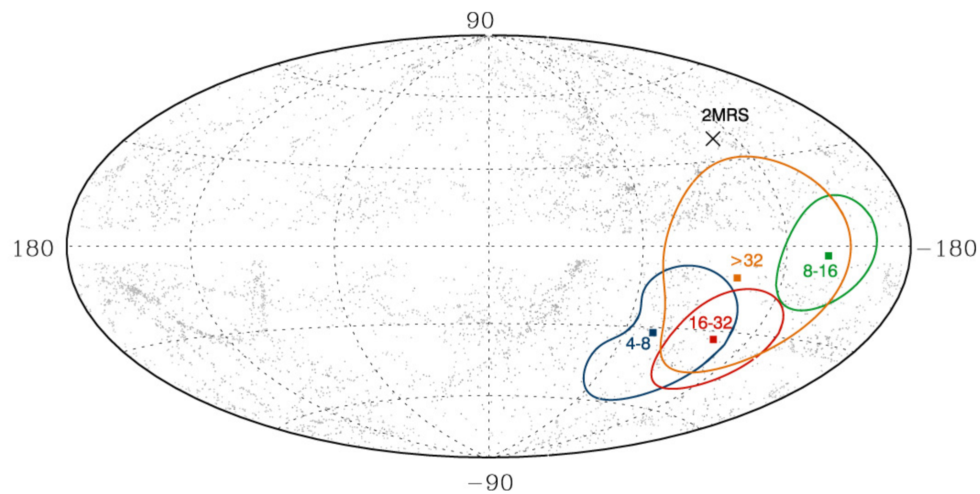
Directional uncertainty: $\Delta\Theta \simeq \sqrt{2}(S/N)^{-1}\mathrm{rad}$



UHECR connection?

- The discovered DGB signal cannot come from motion or clustering.
- Appears coherent with Pierre-Auger UHECR dipole of EeV CRs.





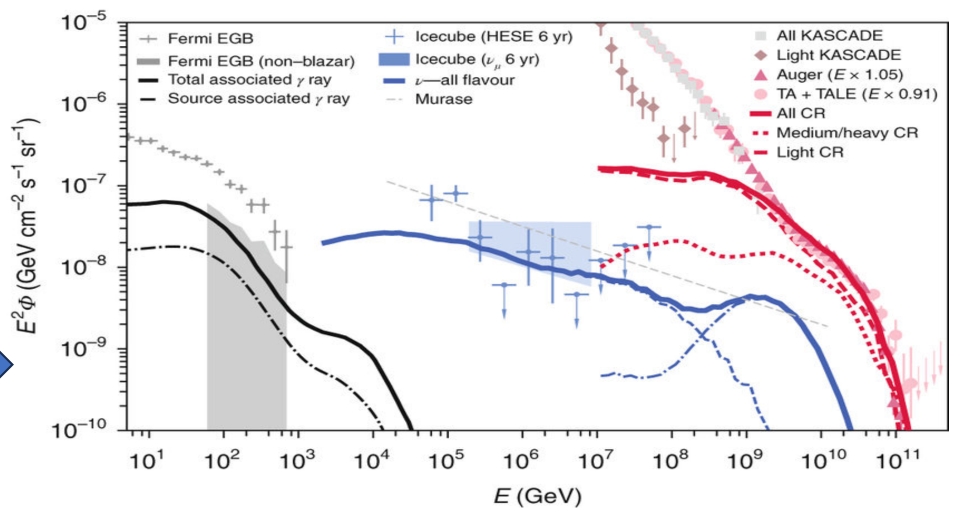
$$\Delta\Theta \simeq \sqrt{2}(S/N)^{-1}\mathrm{rad}$$ ~ 16.2 deg for *S/N*=6

DGB vs UHECR: cascading vs common independent origin

- **Cascading:**
- Possible origin via pions $\pi^0 \rightarrow \gamma\gamma$
- From e.g.
- GZK from the Δ resonance: $p+\gamma_{CMB} \rightarrow \Delta^+ \rightarrow \pi^0 + p$
- Proton decay: $p \rightarrow e^+ + \pi^0$ or $p \rightarrow \mu^+ + \pi^0$

From Fang & Murase (2018)

- **Common origin:**
- Dipole at [3-100] GeV has flux $F_{DGB} \sim 10^{-7}$ Gev/cm^2/s/sr
- Matches UHECR flux at E < 1 EeV



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Interpretation and implications

- The discovered DGB signal cannot come from motion or clustering.
- Appears coherent with Pierre-Auger UHECR dipole of EeV CRs.

- If so, its origin is unlikely from CR cascading via photomesonic production (either GZK effect or proton decay) – not enough CR flux.
- Hence this indicates a common origin of the GeV photons and UHECRs from either same environments or sources.

- Or a new origin not yet proposed with more work required to follow.