Supplemental material to the article

Breaks in gamma-ray spectra of distant blazars and transparency of the Universe

1. The sample construction. The sample includes blazars observed in VHE by various instruments (see Table 1).

Name	Redshift	Class	Instrument	Ref.
1ES 1959+650	0.048	BLL	VERITAS	[1]
PKS 2005−489	0.071	BLL	HESS	[2]
RGB J0152+017	0.080	BLL	HESS	[3]
W Com	0.102	BLL	VERITAS	[4]
1ES 1312−423	0.105	BLL	HESS	[5]
PKS 2155−304	0.116	BLL	HESS	[6]
RGB J0710+591	0.125	BLL	VERITAS	[7]
1ES 1215+303	0.130	BLL	MAGIC	[8]
1ES 0229+200	0.140	BLL	VERITAS	[9]
H 2356−309	0.165	BLL	HESS	[10]
1ES 1101−232	0.186	BLL	HESS	[11]
1ES 0347−121	0.188	BLL	HESS	[12]
1ES 0414+009	0.287	BLL	HESS	[13]
4C +21.35	0.432	FSRQ	MAGIC	[14]
3C 279	0.536	FSRQ	MAGIC	[15]
PKS 0426−380	1.003	FSRQ	LAT	–
PKS 0426−380	1.110	BLL	LAT	–
RGB J1448+361	1.508	BLL	LAT	–
PKS J0730−1141	1.591	FSRQ	LAT	–
B3 1307+433	2.156	BLL	LAT	–

Table 1: **The list of sources.** The table lists the objects contributed to the main result of the paper, Fig. 3. Additional 39 objects which give upper limits only are not listed. References are given in the main text.

We imposed the following requirements:

(1) the source's redshift is known and safely measured spectroscopically (we use the SIMBAD astronomical database [16] for Fermi sources and TeVCat [17] values for other sources);

(2) the mean energy of the last spectral bin E_{last} after deabsorption satisfies $\log_{10}(E_{\text{last}}/E_0) > 0.1$. This last bin may have either a flux measurement or an upper limit but the previous bin is required to have a measurement;

(3) there are at least five energy bins in the measured spectrum.

For atmospheric Cerenkov telescopes, we started from the TeVCat catalog and obtained published measurements in the literature. We use only one spectrum per object and do not stack individual spectral points in order to avoid the potential variability problem.

For Fermi LAT, we preselected a sample of blazars from the 2FGL catalog [18] with measured $z \geq 0.7$, detected at $E > 10$ GeV with the test statistics $TS \geq 16$. For each of these 99 blazars we reconstruct the observed spectrum at $E > 2$ GeV in the bins (2-4) GeV, (4-10) GeV, (10-30) GeV, (30-100) GeV and (100-300) GeV with the standard *gtlike* routine from *Fermi Science Tools v9r27p1*, taking for the input the Pass 7REP (V15) data recorded from 2008 August 4 to 2014 April 19 [19,20]. The lower limit of 2 GeV was chosen to cut away spectral features which often happen at slightly lower energies, so that the remaining spectrum follows a power law reasonably well. Then we applied our criterion (2) to the obtained spectra.

For the additional test discussed below (see Fig. 1), the selection procedure was the same except we did not put the $z \geq 0.7$ condition at preselection and replaced E_0 by 100 GeV in the criterion (2) at selection.

2. Deabsorption. For the main results of the paper, we use the lowest-absorption model available, the "fiducial" model of Gilmore et al. [21]. The optical depth for various energies and redshifts is provided by the authors of Ref. [21] at
`http://physics.ucsc.edu/~joel/EBLdata-Gilmore2012/`.

To account for the absorption, we recalculated integral number flux of photons in each energy bin. We note that the deabsorption not only increases the flux by a $\exp(\tau)$ factor but also shifts the mean energy of the bin because higher-energy photons experience stronger absorption. To account for the latter effect, we use the measured power-law spectral index for the entire spectrum we use (quoted in the referenced papers for the Cerenkov data and returned by *gtlike* for the Fermi LAT data), approximated the observed spectrum within a bin by this power law, applied the $\exp(\tau(E))$ correction to this power law and recalculated the mean energy and the integral flux in the bin for the emitted spectrum.

3. Potential biases and systematic errors. The first suspect to test is the Malmquist bias: faint sources would not be detected at high energies, while bright sources may have harder spectra. To address this potential bias, we included in the sample the blazars which have been detected below E_0 but have not been detected above (the upper limits in Fig. 3 of the main text).

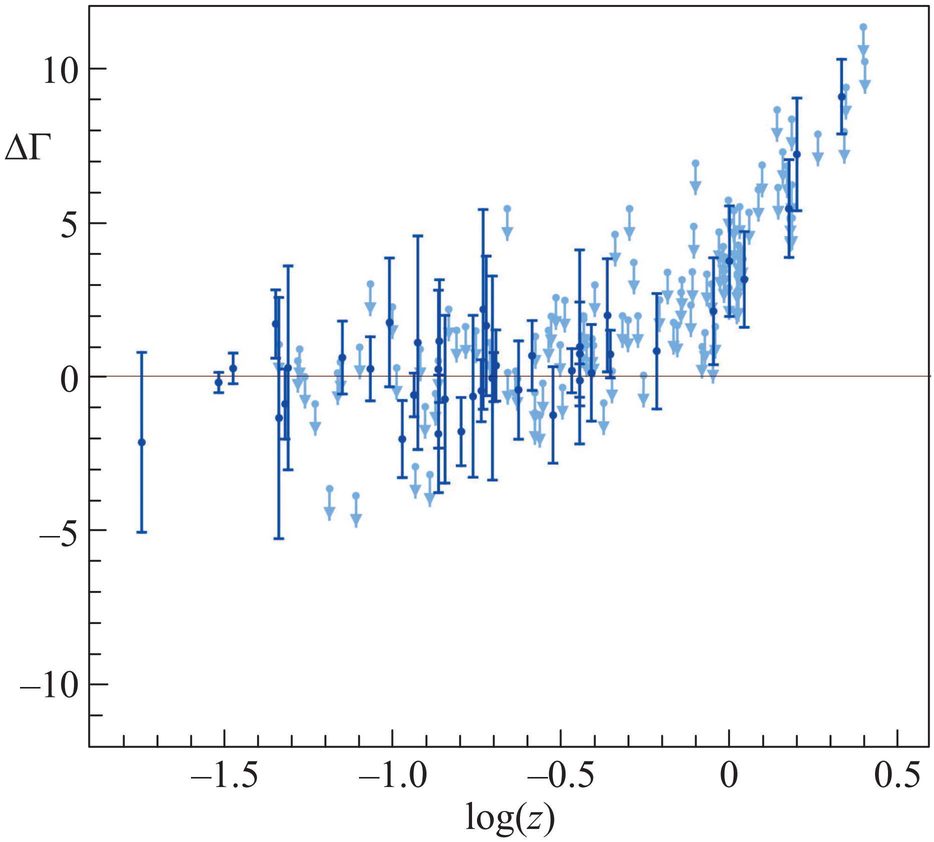

Figure 1: Same as in Fig. 3 of the main text but for the break assumed to happen at $E = 100$ GeV, for the extended sample of Fermi-LAT blazars described in the text. The breaks appear for distant objects only, for which $E_0 \sim 100$ GeV

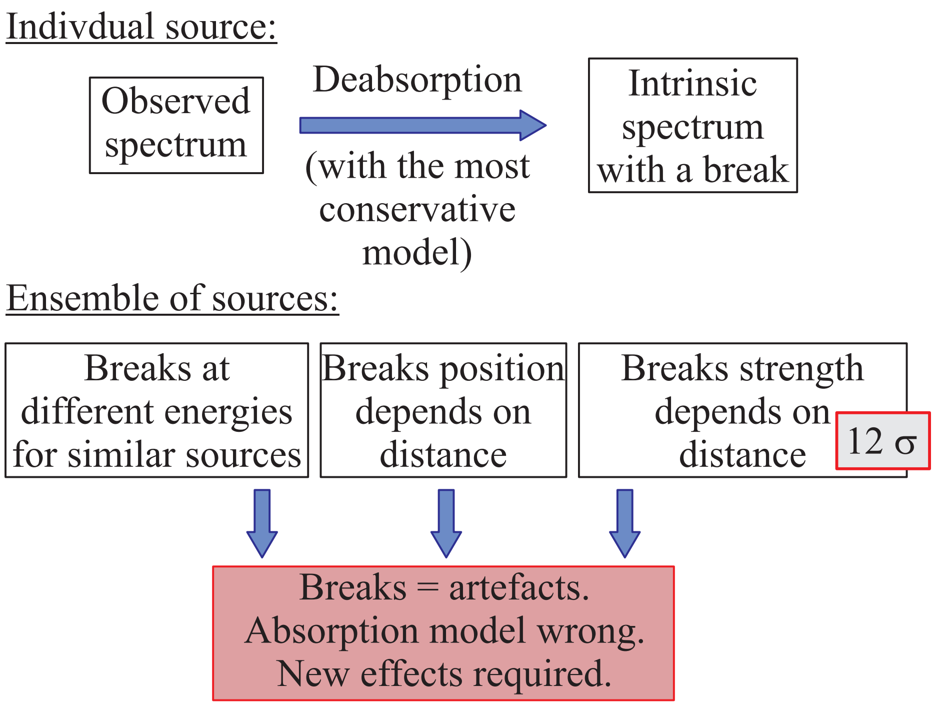

Figure 2: A schematic view of the main result of the paper

We see that their inclusion does not affect our result, thus disfavouring this kind of a bias.

Next, there is a scatter of intrinsic properties of blazars; FSRQs are in general brighter than BLLs, hence detected farther; we see this trend also in our sample. Maybe the break position depends on the class of a blazar and just occasionally correlates with its distance, so that, for instance, all FSRQs have a break at $E \sim 100$ GeV while all BLLs have it at $E > 1$ TeV? This explanation is disfavoured by the presence, in our sample, of a very distant BLL and of a few relatively nearby FSRQs whose spectral breaks perfectly follow the general redshift dependence. A further test is given by Fig. 1 where we searched for a break at 100 GeV in a large sample of all Fermi blazars with known redshift, detected above 10 GeV. The plot suggests that the breaks appear for distant sources only, in agreement with our main result.

The errors of the energy determination for particular photons, combined with a rapidly falling spectrum, may result in an artificial overestimation of the flux in the highest-energy bin. An upward systematic error in the energy determination of all photons may shift the entire spectrum towards higher energies and, therefore, higher opacities, resulting in overestimation of the correction for the pair production. However, since we combine the data from four different instruments, one of which uses a completely different detection method, it is hardly possible that the experimental errors would sum up to a coherent effect. Though in some cases the hardening is observed in the last bin only, this is not so for a number of objects at various distances.

Another potential source of trouble is the redshift measurement: maybe they are incorrect, our sources are not that distant and we therefore overestimate the absorption? The redshift determination is a subtle task and there certainly may be erroneous values because of misidentification of spectral lines. To this end, we selected only objects with firm spectroscopic redshift measurements, so it is hardly possible that *all* their redshifts are significantly overestimated.

To summarize this discussion, it is very unlikely that the effect we see results from a selection bias or from a systematic error.

A schematic view of the main result of the paper is given in Fig. 2.

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