PROCEEDINGS OF SCIENCE

Where are the cascades from blazar jets?

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Blazars are among the most powerful accelerators in the Universe and are expected to produce a strong TeV gamma-ray flux. The gamma-rays from these blazars may produce cascades by inverse-Compton scattering off intergalactic radiation. The GeV gamma-rays produced by these interactions, make up a large contribution to the IGRB. In a previous paper, Blancos et al. [8] showed that this contribution overproduces the IGRB, indicating that something is effectively quenching the cascade component of the IGRB or that blazars have an intrinsic spectral cutoff that is in tension with observations of local blazars.

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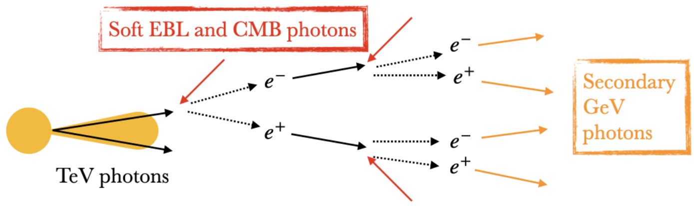

Figure 1: Schematic representation of the attenuation and cascade development of TeV γ-rays emitted from blazars. The TeV γ-rays are attenuated due to pair production with soft EBL and CMB photons. The pairs inver-Compton scatter off the same EBL and CMB photons, leading to the production of a secondary GeV flux, through the process of cascades.

1. The Isotropic γ-ray background and blazars

The isotropic γ-ray background (IGRB) consists of photons from outside the Milky Way that cannot be attributed to any known or resolved point sources. The IGRB is measured by first constructing the extragalactic γ-ray background (EGRB), consisting of all photons from outside the Milky Way, and then masking known sources. Previous studies have shown that the IGRB can be almost entirely accounted for by γ-rays produced by misaligned active galactic nuclei (AGN) and star-forming activity in unresolved galaxies [8, 18, 19]. AGN refers to galactic centers which emit a higher-than-normal luminosity in at least one region of the electromagnetic spectrum. The AGN is theorized to be powered by accretion of matter and energy into the supermassive black hole of the galaxy hosting the AGN. AGN may have jets, which consist of ionized matter and energy that is emitted as beams along the axis of rotation of the galaxy. If the jet is pointed directly towards the Earth, the AGN is classifies as a blazar.
AGN and blazars are powerful γ-ray emitters. There is a component to the IGRB that comes from unresolved blazars, which contributes significantly below ~ 10 Gev and potentially above 100 GeV.

2. Blazar Attenuation and Cascade Development

Observations of both local and distant blazars indicate that blazars are powerful TeV γ-ray emitters that emit photons with energies up to tens of TeV [1, 2, 5, 6, 24]. However, the TeV emission is severely attenuated due to to pair production with background photons in the extragalactic background light (EBL) and the cosmic microwave background (CMB). The electron-positron pairs produced in this process may inverse-Compton scatter off the same EBL and CMB photons, leading to electromagnetic cascades, where the TeV photons give rise to a larger number of GeV photons. These GeV photons may contribute to the IGRB, dependeing on the strength of the intergalactic magnetic field (IGMF).
Since the pairs are charged, they are deflected by the IGMF. However, the amount of deflection depends on the strength of the IGMF. If the IGMF is sufficiently weak (($\lesssim 10^{-14}$ G)), the pairs are only slightly deflected giving rise to diffuse GeV "pair halos" around the positions of bright blazars. Such "pair halos" could be detected in e.g. extended source searches and through searches for time-

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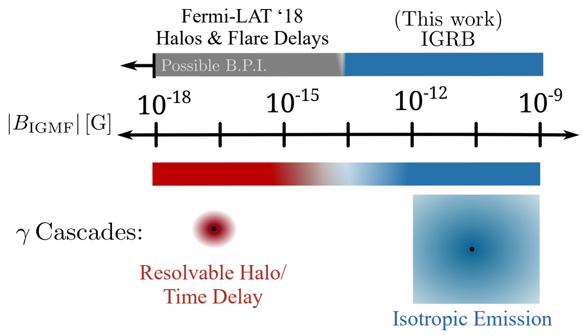

Figure 2: A diagram of the cascaded γ-ray flux from blazars as a function of the IGMF strength at a coherence length taken to be roughly $\lambda \sim 1$ kpc. When the IGMF is weaker than $\sim 10^{-14}$ G, the cascades are detectable as degree-scale halos and as a time delay in flares [3]. When the IGMF is stronger, the cascades are essentially isotropic and contribute to the IGRB. For particularly weak fields, beam-pair instabilities could cool pairs before they generate cascades.

delays in the flux of highly-variable blazars. However, Fermi-LAT has not detected any such pair halos, constraining the IGMF strength to $> 10^{-15}$ for correlation lengths of ~1 kpc [3, 14, 15, 21]. When the IGMF is stronger (($B \gtrsim 10^{-14}$ G)), the pairs are deflected too much to be associated with any blazars and no pair halos are observed. In this case, the GeV photons produced in the cascades contribute entirely to the IGRB.

Thus, we have the following argument for our paper [9]. Recent observations prove that,

1. Local blazars produce a bright TeV flux, and do not generally have sharp spectral cutoffs at O(TeV) energies.
2. The IGMF is too weak to cool e^+e^- pairs and prevent them from producing bright γ-ray emission via ICS.
3. Models of mAGN, SFG, and sub-threshold blazar point source dominate the IGRB, limiting the contribution of diffuse blazar cascade emission to fall below ~10%, which is in strong tension with blazar models.

The only known SM solution is that beam-plasma instabilities cool the electron-positron pairs before inverse-Compton scattering can occur. However, the efficiency of these instabilities depend on a number of factors, such as the IGMF strength and the injected pair spectrum [4, 11, 12, 23].

3. Modeling and Source Selection

We based our source selection on the 2709 Fermi blazars in Ref. [25], which calculate the spectral energy distribution of these blazars. Furthermore, we only included the sources that have a defined redshift and that we found in a cross-check with the 4FGL catalogue [3], leaving us with a total of 1702 sources.
For each source, we refit the spectrum observed by Fermi with one of three spectral models: power-law, log-parabola or power-law with an exponential cutoff, based on the best-fit model in 4FGL. We take the Fermi best-fit spectral parameters as a seed for this fitting, in order to ensure that the fit can

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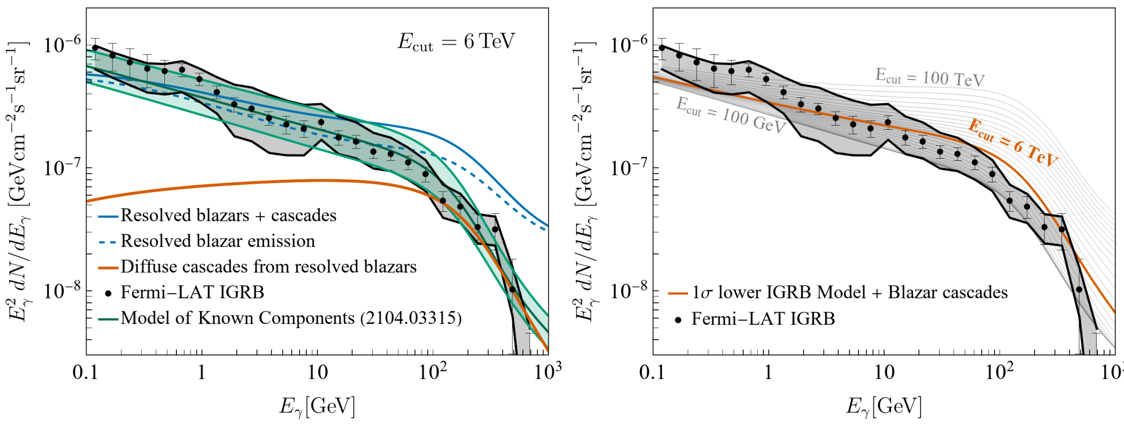

Figure 3: *Left:* All sky flux compared to the measured IGRB, with the maximum allowed cutoff in the blazar intrinsic spectrum. This plot shows the key result of our study, namely that adding the diffuse cascades from resolved blazars overproduces the IGRB unless on adds a intrinsic cutoff in the blazar spectrum at 6 TeV. Note that this is in tension with observations of local blazars, such as MrK 421 and Mrk 501 [5]. *Right:* Expected diffuse γ-rays from the known contributions plus the diffuse cascades from resolved blazars.

reproduce the observed flux.
We account for attenuation in the EBL by dividing the flux with the mean photon survival probability in each energy bin:

$$\langle P_{\gamma\gamma} \rangle = \frac{\int_{\Delta E} \exp[-\tau_{\gamma\gamma}(z, E)]\phi_{\text{obs}}(E)}{\int_{\Delta E} \phi_{\text{obs}}(E)}\,, \tag{1}$$

where $\tau_{\gamma\gamma} \sim \int d\epsilon \sigma_{\gamma\gamma} dn/d\epsilon$ is the optical depth, $\sigma_{\gamma\gamma}$ is the pair-production cross section, $dn/d\epsilon(z)$ is the number density of the target background photons, and $\phi_{\text{obs}}(E)$ is the observed flux (power law, a log parabola, or power law with a super-exponential cutoff). The intrinsic, or de-absorbed, data points are then re-fit to a spectral model in order to extrapolate them above 100 TeV. Note that the majority of the brightest sources were all fit by downward-curving spectra (192/200), and that in total 27% of all the sources were fit by either a log-parabola or a power-law with an exponential cutoff.

The cascade development is calculated using the publicly available code, γ-cascades [7]. Note that we use the EBL model by Ref. [16] and that we also account for the effects of cosmological redshift on the γ-ray propagation.

4. Results

Our main result is that the cascades from resolved blazars overproduce the IGRB unless we add an exponential cutoff to the blazars at E >6 TeV, as shown in figure 3. We add the cutoff, E_{cut}, as an additional parameter in the intrinsic spectra of all blazars, and calculate the line-of-sight and cascaded γ-ray flux as a function of E_{cut}. Note that the expected diffuse γ-ray flux from cascades quickly overproduces the entire IGRB, although the exact value of the maximum E_{cut} may be uncertain.

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5. Beam-plasma Instabilities

The only known SM solution to the emerging tension introduced in this paper, is that beam-plasma instabilities effectively cool the pair beam before inverse-Compton scattering can occur. However, the efficiency of this cooling depends heavily on the strength of the IGMF and the chosen pair-beam distribution function chosen at injection.
The instabilities can be quenched by inhomogeneities in the intergalactic medium or by having weak, tangled IGMF ($> 10^{-18}$ G) with pc scale correlation lengths[4, 17, 22]. Thus, very feeble IGMF are required for the instabilities to effectively cool the pair beams. The efficiency of the cooling is also sensitive to the pair-beam distribution function at injection. For a generic Gaussian distribution function[20], the IGMF must be weaker than 10^{-18} for the cooling to be sufficiently effective, while for a relativistic Maxwellian[10, 11, 13], the IGMF must be weaker than 10^{-14} G. Thus, there is a corresponding sliding scale for the IGMF field strength between $10^{-18} - 10^{-14}$ as critical to stabilize the pair beam.

6. Conclusions

This work has shown that conservative models of blazar spectra, TeV γ-ray cascade physics and IGMF magnitude predict that there is a bright, isotropic GeV γ-ray signal that is ruled out by Fermi-LAT data coming from the observed blazar population. The SM solution to this is that beam-plasma instabilities cool the pairs before ICS can occur, thereby quenching the cascaded GeV signal.

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