LETTERS

A limit on the variation of the speed of light arising from quantum gravity effects

A list of authors and their affiliations appears at the end of the paper

A cornerstone of Einstein's special relativity is Lorentz invariance—the postulate that all observers measure exactly the same speed of light in vacuum, independent of photon-energy. While special relativity assumes that there is no fundamental length-scale associated with such invariance, there is a fundamental scale (the Planck scale, $l_{\mathrm{Planck}} \approx 1.62 \times 10^{-33}$ cm or $E_{\mathrm{Planck}} = M_{\mathrm{Planck}}c^2 \approx 1.22 \times 10^{19}$ GeV), at which quantum effects are expected to strongly affect the nature of space–time. There is great interest in the (not yet validated) idea that Lorentz invariance might break near the Planck scale. A key test of such violation of Lorentz invariance is a possible variation of photon speed with energy[1–7]. Even a tiny variation in photon speed, when accumulated over cosmological light-travel times, may be revealed by observing sharp features in γ-ray burst (GRB) light-curves[2]. Here we report the detection of emission up to ~31 GeV from the distant and short GRB 090510. We find no evidence for the violation of Lorentz invariance, and place a lower limit of $1.2E_{\mathrm{Planck}}$ on the scale of a linear energy dependence (or an inverse wavelength dependence), subject to reasonable assumptions about the emission (equivalently we have an upper limit of $l_{\mathrm{Planck}}/1.2$ on the length scale of the effect). Our results disfavour quantum-gravity theories[3,6,7] in which the quantum nature of space–time on a very small scale linearly alters the speed of light.

On 10 May 2009, at $T_0 = $ 00:22:59.97 UT, both the Gamma-ray Burst Monitor (GBM)[8] and the Large Area Telescope (LAT)[9] onboard the Fermi Gamma-ray Space Telescope triggered on the very bright short GRB 090510 (hereafter all times are measured relative to T_0). Ground-based optical spectroscopy data, taken 3.5 days later[10], exhibited prominent emission lines at a common redshift of $z = 0.903 \pm 0.003$, corresponding to a luminosity distance of $d_{\mathrm{L}} = 1.8 \times 10^{28}$ cm (for a standard cosmology of $[\Omega_\Lambda, \Omega_{\mathrm{M}}, h] = [0.73, 0.27, 0.71]$). The GBM light curve (Fig. 1b, c; 8 keV–40 MeV) consists of seven main pulses. After the first dim short spike near trigger-time, the flux returns to background level; the main GBM emission starts at 0.53 s and lasts $<$0.5 s. The main LAT emission above 100 MeV starts at ~0.63 s and lasts $<$1 s with a decaying tail that extends to ~200 s.

A single 31-GeV photon was detected at 0.829 s, which coincides in time with the last of the seven GBM pulses (Fig. 1b, c, f). The nature of this Fermi/LAT event as a photon (rather than a background cosmic ray) was confirmed with very thorough analysis (see Supplementary Information section 1). We find the directional and temporal coincidence of this photon with GRB 090510 to be very significant, at $>5\sigma$ confidence, and find the 1σ confidence interval for its energy to be 27.97–36.32 GeV.

The known distance[10] ($z = 0.903 \pm 0.003$) of GRB 090510 and the detection of $>$1 GeV photons less than a second from its onset allow us to constrain the possible variation of the speed of light with photon-energy (known as photon dispersion: one form of the Lorentz Invariance Violation, LIV). Some quantum-gravity theories[2,4,5] are consistent with the photon-propagation speed v_{ph} varying with photon-energy E_{ph}, and becoming considerably different from the ordinary (or low-energy limit of) speed of light, $c \equiv v_{\mathrm{ph}}(E_{\mathrm{ph}} \to 0)$, near the Planck scale (when E_{ph} becomes comparable to $E_{\mathrm{Planck}} = M_{\mathrm{Planck}}c^2$). For $E_{\mathrm{ph}} \ll E_{\mathrm{Planck}}$, the leading term in a Taylor series expansion of the classical dispersion relation is $|v_{\mathrm{ph}}/c - 1| \approx (E_{\mathrm{ph}}/M_{\mathrm{QG},n}c^2)^n$, where $M_{\mathrm{QG},n}$ is the quantum gravity mass for order n and $n = 1$ or 2 is usually assumed. The linear case ($n = 1$) gives a difference $\Delta t = \pm(\Delta E/M_{\mathrm{QG},1}c^2)D/c$ in the arrival time of photons emitted together at a distance D from us, and differing by $\Delta E = E_{\mathrm{high}} - E_{\mathrm{low}}$. At cosmological distances this simple expression is somewhat modified (see Supplementary Information section 4).

Because of their short duration (typically with short substructure consisting of pulses or narrow spikes) and cosmological distances, GRBs are well-suited for constraining LIV[2,11,12]. Individual spikes in long[13] (of duration $>$2 s) GRB light-curves (10–1,000 keV) usually show[14] intrinsic lags: the peak of a spike occurs earlier at higher photon-energies. However, there are either no lags or very short lags of either sign for short GRBs[15]. Thus far, intrinsic lags have been seen only on timescales of up to the width of individual spikes in a light curve, which for GRB 090510 are $\sim 10^{-2}$ s. Intrinsic lags have not yet been measured at high energies; if they are also present there, it is reasonable to assume that their behaviour is similar to that at low-energies (at least approximately).

When allowing for LIV-induced time-delays, the measured arrival time, t_{h}, of the high-energy photons might not directly reflect their emission time, t_{em} (which would have been their arrival time if $v_{\mathrm{ph}} = c$). Therefore, we make reasonable and conservative assumptions on t_{em}, constraining it using the observed lower-energy emission (for which LIV-induced time-delays are relatively negligible).

Using the DisCan method[12], we have searched for time delays within the LAT data (actual energy range of the photons used: 35 MeV–31 GeV) in the burst interval with the most intense emission (0.50–1.45 s). This approach extracts dispersion information from all detected LAT photons, and does not involve binning in either time or energy. It moves each photon to the time at which it would have been detected in the absence of any LIV-induced lag, given a trial value of the energy-lag coefficient. The value of this coefficient that maximizes a measure of the sharpness of the resulting light curve is an estimate of the apparent dispersion. Bootstrap error analysis[16] shows that this is not a detection, just an upper limit. For reasons similar to those advanced above (improbability of inherent lags or fortuitous cancellation of quantum gravity and intrinsic dispersion) we take this as an upper limit on LIV-induced dispersion. A similar method was described in ref. 17. We obtain a robust upper limit of $|\Delta t/\Delta E| < 30\ \mathrm{ms\ GeV^{-1}}$ (at the 99% confidence level) on possible linear energy dispersion of either sign, or $\xi_1 \equiv M_{\mathrm{QG},1}/M_{\mathrm{Planck}} > 1.22$ (limit a in Table 1).

Using a different approach, we derive additional limits. To constrain a positive time delay ($v_{\mathrm{ph}} < c$, implying $t_{\mathrm{h}} > t_{\mathrm{em}}$) we do not attempt to associate the relevant high-energy photon with a particular spike in the low-energy light-curve. Instead, we simply assume that it was emitted sometime during the relevant lower-energy emission episode, that is, after its starting time t_{start} ($t_{\mathrm{em}} > t_{\mathrm{start}}$; see Fig. 1).

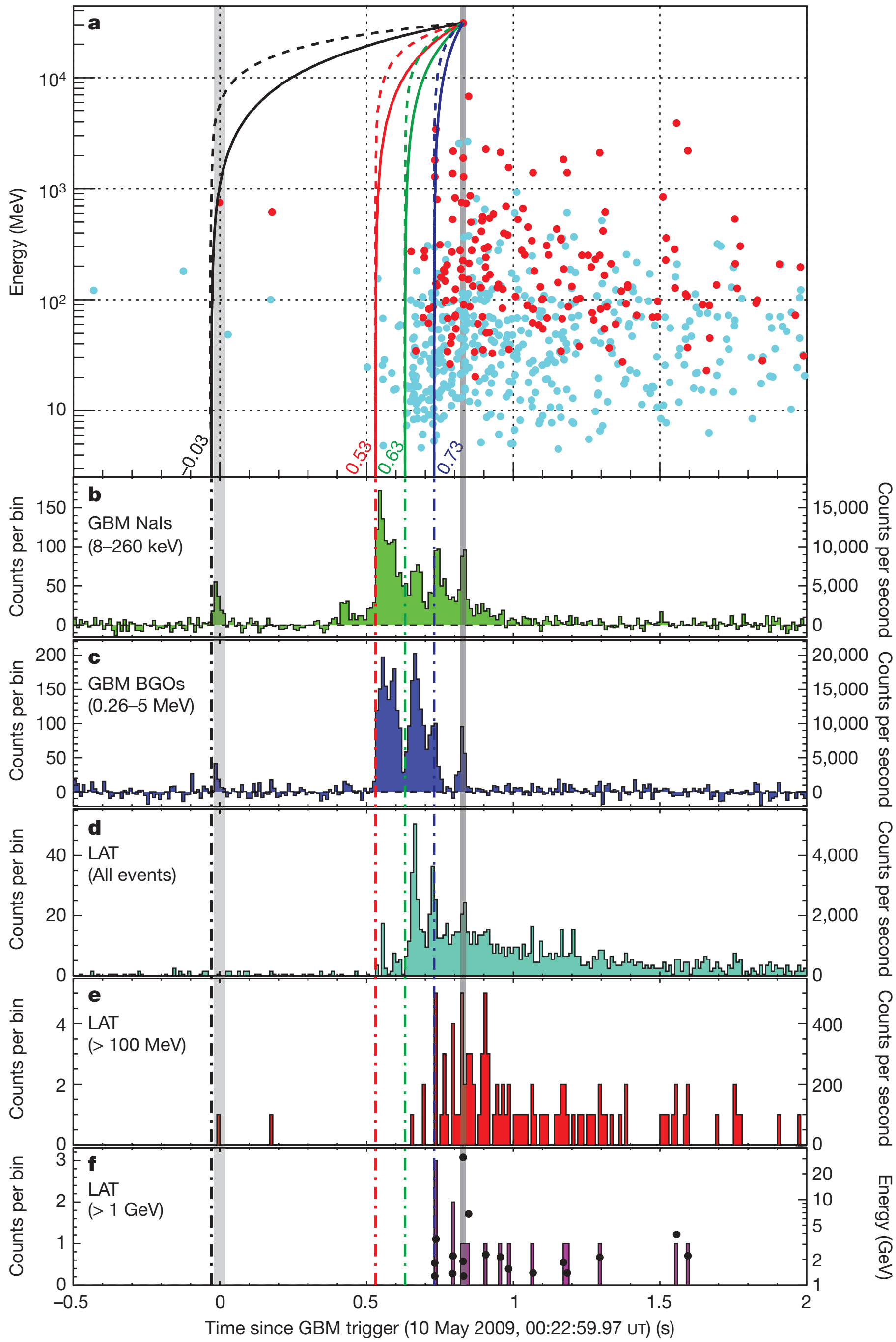

Figure 1 | Light curves of GRB 090510 at different energies. **a**, Energy versus arrival time with respect to the GBM trigger time for the 160 LAT photons that passed the transient off-line event selection (red) and the 161 photons that passed the onboard γ-ray filter (blue), and are consistent with the direction of GRB 090510. The solid and dashed curves are normalized to pass through the highest energy (31 GeV) photon and represent the relation between a photon's energy and arrival time for linear ($n = 1$) and quadratic ($n = 2$) LIV, respectively, assuming it is emitted at $t_{\rm start} = -30$ ms (black; first small GBM pulse onset), 530 ms (red; main <1 MeV emission onset), 630 ms (green; >100 MeV emission onset), 730 ms (blue; >1 GeV emission onset). Photons emitted at $t_{\rm start}$ would be located along such a line owing to (a positive) LIV-induced time delay. **b**–**f**, GBM and LAT light curves, from lowest to highest energies. **f** also overlays energy versus arrival time for each photon, with the energy scale displayed on the right side. The dashed-dotted vertical lines show our four different possible choices for $t_{\rm start}$. The grey shaded regions indicate the arrival time of the 31-GeV photon $\pm$10 ms (on the right) and of a 750-MeV photon (during the first GBM pulse) $\pm$20 ms (on the left), which can both constrain time delays of either sign. **b** and **c** show background-subtracted light curves for GBM NaI in the 8–260-keV band and a GBM BGO in the 0.260–5-MeV band, respectively. **d**, LAT events passing the onboard γ-ray filter. **e**, LAT transient class events with $E > 100$ MeV. **f**, LAT transient class events with $E > 1$ GeV. In all light curves, the time-bin width is 10 ms. In **b**–**e** the per-second count rate is displayed on the right for convenience.

This implies $\Delta t < t_{\rm h} - t_{\rm start}$ and thus sets a lower limit on $M_{\rm QG}$. We have conservatively used the 31-GeV photon, even if another photon gave a stricter limit, because it is less sensitive to the exact choice of $t_{\rm start}$ or to intrinsic lags. In the following, we describe several possible different assumptions along with the astrophysical reasoning behind them and the corresponding lower limits on $M_{\rm QG}$, starting from the most conservative assumption, and ending with the least conservative assumption (which is still very likely, and with good astrophysical motivation).

No high-energy photon has ever been detected before the onset of the low-energy emission in a GRB. Therefore, it is highly unlikely that the 31-GeV photon was emitted before the observed onset of

Table 1 | Limits on Lorentz invariance violation

	Limit on $|\Delta t/\Delta E|$ or $|\Delta t|$	Limit on $M_{QG,1}/M_{Planck}$	Valid for s_n
Limit a:	$|\Delta t/\Delta E| < 30$ ms GeV^{-1}	>1.22	±1
Limit b:	$|\Delta t| < 859$ ms	>1.19	1

Details for the derivations of these limits are given in the main text and Supplementary Information Section 4. Limit a is obtained by testing for an energy-dispersion in the high-energy (LAT all-event) data (that might smear the sharp observed spikes in the light curve); we find an upper limit for a linear dispersion of photons above 30 MeV of $|\Delta t/\Delta E| < 30$ ms GeV^{-1} (at 99% confidence; see Supplementary Information section 3). Limit b relies on the 31-GeV photon, and conservatively uses the 1σ lower limit on its energy (28.0 GeV) and the 1σ lower limit on the redshift ($z = 0.900$). Limit b assumes that the 31-GeV photon was not emitted before the onset of any emission detected by Fermi, so that t_{start} is set to the onset of the first small isolated GRB spike, 30 ms before the GBM trigger time. $s_n = 1$ indicates a positive ($v_{ph} < c$) time-delay and $s_n = -1$ indicates a negative ($v_{ph} > c$) time-delay.

GRB 090510. This implies $\xi_1 > 1.19$ (limit b in Table 1), which we consider our most conservative limit with this method. While the underlying assumption on t_{em} is very reasonable, it is still an assumption; if for some reason t_{em} were to be before t_{start}, this limit would be weakened by a factor of $(t_h - t_{em})/(t_h - t_{start})$.

We stress here that our most conservative limits, a and b in Table 1, rely on very different and largely independent analysis, yet still give a very similar limit, of $\xi_1 > 1.2$. This lends considerable support to this result, and makes it more robust and secure than for each of the methods separately.

Our data can be used to set additional limits, which, although not as secure as the one mentioned above, are still very useful. Using the same approach as for limit b, we note that for a reasonable emission spectrum the 31-GeV photon would be accompanied by a large number of detectable (by either GBM or LAT) lower-energy photons, which suffer a much smaller LIV-induced time-delay, and thus 'mark' its emission time, $t_{em,31}$. If $t_{em,31}$ were during the first isolated GBM spike, then lower-energy photons emitted together with it should have been clustered near the black line in Fig. 1a owing to LIV-induced energy dispersion. Because this is not observed, it is much more likely that $t_{em,31}$ is associated with a later lower-energy emission episode. Setting t_{start} to the onset of the main GBM emission (530 ms) results in $\xi_1 > 3.42$.

Similarly, the expected large number of detectable >0.1-GeV photons emitted together with the 31-GeV photon makes it reasonable to set t_{start} to the onset of the main >0.1-GeV emission (630 ms; see Supplementary Information section 2), resulting in $\xi_1 > 5.12$. Correspondingly, the expected fair number of detectable >1-GeV photons emitted together with the 31-GeV photon makes it reasonable to set t_{start} to the onset of the main >1-GeV emission (730 ms), resulting in $\xi_1 > 10.0$. The $\xi_1 > 10.0$ value might be somewhat affected by the relatively small-number statistics for >1-GeV photons, or by intrinsic spectral lags (such effects are expected to be much smaller for the limit based on >0.1 GeV photons).

Finally, one can also set limits on LIV-induced time-delays of either sign based on the temporal association of the 31-GeV photon with the 7th GBM spike, and by associating the 0.75-GeV photon with the first GBM spike, because these photons arrive near the peak of a very narrow GBM spike (see Fig. 1), which is probably not due to chance coincidences. These associations would imply $\xi_1 > 102$ and 1.33, respectively. It is important to keep in mind, however, that while these associations are most likely, they are not very secure.

Our most secure and conservative new limit, $\xi_1 > 1.2$, is much stronger than the previous best limit of this kind ($\xi_1 > 0.1$ from GRB080916C; ref. 18) and fundamentally more meaningful. Given that in most quantum gravity scenarios $M_{QG,n} \le M_{Planck}$, even our most conservative limits greatly reduce the parameter space for $n = 1$ models[19,20]. Our other limits, and especially our least conservative limit of $\xi_1 > 102$, make such theories highly implausible (models with $n > 1$ are not significantly constrained by our results). Thus, it is unlikely that other predictions of such $n = 1$ models would be observed. These include, for example, a reduction in the absorption of $\geq$10 TeV γ-rays by $\gamma\gamma \to e^+e^-$ interactions with extragalactic infrared photons[21,22], and fuzziness of radio or optical images of distant extragalactic sources[23–25]. Our stringent photon dispersion limit strongly disfavours models of Planck scale physics in which the quantum nature of space–time causes a linear variation of the speed of light with photon energy.

Received 12 August; accepted 12 October 2009.
Published online 28 October 2009.

1. Wheeler, J. A. & Ford, K. W. *Geons, Black Holes, and Quantum Foam: A Life in Physics* (W. W. Norton and Company, 1998).
2. Amelino-Camelia, G., Ellis, J., Mavromatos, N. E., Nanopoulos, D. V. & Sarkar, S. Tests of quantum gravity from observations of gamma-ray bursts. *Nature* **393,** 763–765 (1998).
3. Mattingly, D. Modern tests of Lorentz invariance. *Living Rev. Relativity* **8,** 5–84 (2005).
4. Kostelecky, V. A. & Mewes, M. Astrophysical tests of Lorentz and CPT violation with photons. *Astrophys. J.* **689,** L1–L4 (2008).
5. Amelino-Camelia, G. & Smolin, L. Prospects for constraining quantum gravity dispersion with near term observations. Preprint at ⟨http://arxiv.org/abs/0906.3731⟩ (2009).
6. Jacobson, T., Liberati, S. & Mattingly, D. Lorentz violation at high energy: concepts, phenomena and astrophysical constraints. *Ann. Phys.* **321,** 150–196 (2006).
7. Amelino-Camelia, G. Quantum gravity phenomenology. Preprint at ⟨http://arxiv.org/abs/0806.0339⟩ (2008).
8. Guiriec, S. *et al.* GRB 090510: Fermi GBM detection. *GCN Circ.* **9336** (2009).
9. Ohno, M. *et al.* Fermi LAT detection of GRB 090510. *GCN Circ.* **9334** (2009).
10. Rau, A. *et al.* GRB090510: VLT/FORS2 spectroscopic redshift. *GCN Circ.* **9353** (2009).
11. Rodríguez Martínez, M., Piran, T. & Oren, Y. GRB 051221A and Tests of Lorentz Symmetry. *J. Cosmol. Astroparticle Phys.* **05,** 017–023 (2006).
12. Scargle, J. D., Norris, J. P. & Bonnell, J. T. An algorithm for detecting quantum gravity photon dispersion in gamma-ray bursts: DisCan. *Astrophys. J.* **673,** 972–980 (2008).
13. Kouveliotou, C. *et al.* Identification of two classes of gamma-ray bursts. *Astrophys. J.* **413,** L101–L104 (1993).
14. Norris, J. P. *et al.* Spectral evolution in gamma-ray bursts. *Adv. Space Res.* **6,** 19–22 (1986).
15. Norris, J. P. & Bonnell, J. T. Short GRBs with extended emission. *Astrophys. J.* **643,** 266–275 (2006).
16. Efron, B. & Tibshirani, R. *An Introduction to the Bootstrap* (Chapman and Hall, 1993).
17. Albert, J. *et al.* Probing quantum gravity using photons from a flare of the active galactic nucleus Markarian 501 observed by the MAGIC telescope. *Phys. Lett. B* **668,** 253–257 (2008).
18. Abdo, A. A. *et al.* Fermi observations of high-energy gamma-ray emission from GRB 080916C. *Science* **323,** 1688–1693 (2009).
19. Ellis, J., Mavromatos, N. E. & Nanopoulos, D. V. Derivation of a vacuum refractive index in a stringy space time foam model. *Phys. Lett. B* **665,** 412–417 (2008).
20. Zloshchastiev, K. G. Logarithmic nonlinearity in theories of quantum gravity: origin of time and observational consequences. Preprint at ⟨http://arxiv.org/abs/0906.4282⟩ (2009).
21. Kifune, T. Invariance violation extends the cosmic-ray horizon? *Astrophys. J.* **518,** L21–L24 (1999).
22. Jacob, U. & Piran, T. Inspecting absorption in the spectra of extra-galactic gamma-ray sources for insight into Lorentz invariance violation. *Phys. Rev. D* **78,** 124010 (2008).
23. Christiansen, W. A. Jack Ng, Y. & van Dam, H. Probing spacetime foam with extragalactic sources. *Phys. Rev. Lett.* **96,** 051301 (2006).
24. Jack Ng, Y. Spacetime foam and dark energy. *AIP Conf. Proc.* **1115,** 74–79 (2009).
25. Jack Ng, Y. Spacetime foam: from entropy and holography to infinite statistics and nonlocality. Preprint at ⟨http://arxiv.org/abs/0801.2962⟩ (2008).

Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

Acknowledgements The Fermi LAT Collaboration acknowledges support from a number of agencies and institutes for both the development and the operation of the LAT as well as scientific data analysis. These include NASA and DOE in the United States, CEA/Irfu and IN2P3/CNRS in France, ASI and INFN in Italy, MEXT, KEK, and JAXA in Japan, and the K. A. Wallenberg Foundation, the Swedish Research Council and the National Space Board in Sweden. Additional support from INAF in Italy for science analysis during the operations phase is also acknowledged. J. Granot gratefully acknowledges a Royal Society Wolfson Research Merit Award. The Fermi GBM Collaboration acknowledges the support of NASA in the United States and DRL in Germany. J. Conrad is a Royal Swedish Academy of Sciences Research Fellow, funded by a grant from the K. A. Wallenberg Foundation. E.T. is a NASA Postdoctoral Program Fellow and a Canon Foundation in Europe Fellow. A. J.v.d.H. is a NASA Postdoctoral Program Fellow. We thank J. Ellis for comments.

Author Contributions All authors contributed extensively to the work presented in this paper.

Author Information Reprints and permissions information is available at www.nature.com/reprints. Correspondence and requests for materials should be addressed to J. Granot (j.granot@herts.ac.uk), S. Guiriec (sylvain.guiriec@nasa.gov), M. Ohno (ohno@astro.isas.jaxa.jp) and V. Pelassa (pelassa@lpta.in2p3.fr).

A. A. Abdo[1,2], M. Ackermann[3], M. Ajello[3], K. Asano[4,5], W. B. Atwood[6], M. Axelsson[8,9], L. Baldini[12], J. Ballet[13], G. Barbiellini[14,15], M. G. Baring[16], D. Bastieri[17,18], K. Bechtol[3], R. Bellazzini[12], B. Berenji[3], P. N. Bhat[19], E. Bissaldi[20], E. D. Bloom[3], E. Bonamente[21,22], J. Bonnell[24,25], A. W. Borgland[3], A. Bouvier[3], J. Bregeon[12], A. Brez[12], M. S. Briggs[19], M. Brigida[26,27], P. Bruel[28], J. M. Burgess[19], T. H. Burnett[29], G. A. Caliandro[26,27], R. A. Cameron[3], P. A. Caraveo[30], J. M. Casandjian[13], C. Cecchi[21,22], Ö. Çelik[23,24,31], V. Chaplin[19], E. Charles[3], C. C. Cheung[1,2,24], J. Chiang[3], S. Ciprini[21,22], R. Claus[3], J. Cohen-Tanugi[32], L. R. Cominsky[33], V. Connaughton[19], J. Conrad[9,10], S. Cutini[34], C. D. Dermer[1], A. de Angelis[35], F. de Palma[26,27], S. W. Digel[3], B. L. Dingus[36], E. do Couto e Silva[3], P. S. Drell[3], R. Dubois[3], D. Dumora[37], C. Farnier[32], C. Favuzzi[26,27], S. J. Fegan[28], J. Finke[1,2], G. Fishman[38], W. B. Focke[3], L. Foschini[39], Y. Fukazawa[40], S. Funk[3], P. Fusco[26,27], F. Gargano[27], D. Gasparrini[34], N. Gehrels[24,25], S. Germani[21,22], L. Gibby[41], B. Giebels[28], N. Giglietto[26,27], F. Giordano[26,27], T. Glanzman[3], G. Godfrey[3], J. Granot[42], J. Greiner[20], I. A. Grenier[13], M.-H. Grondin[37], J. E. Grove[1], D. Grupe[43], L. Guillemot[44], S. Guiriec[19], Y. Hanabata[40], A. K. Harding[24], M. Hayashida[3], E. Hays[24], E. A. Hoversten[43], R. E. Hughes[45], G. Jóhannesson[3], A. S. Johnson[3], R. P. Johnson[6], W. N. Johnson[1], T. Kamae[3], H. Katagiri[40], J. Kataoka[4,46], N. Kawai[4,47], M. Kerr[29], R. M. Kippen[36], J. Knödlseder[48], D. Kocevski[3], C. Kouveliotou[38], F. Kuehn[45], M. Kuss[12], J. Lande[3], L. Latronico[12], M. Lemoine-Goumard[37], F. Longo[14,15], F. Loparco[26,27], B. Lott[37], M. N. Lovellette[1], P. Lubrano[21,22], G. M. Madejski[3], A. Makeev[1,49], M. N. Mazziotta[27], S. McBreen[20,50], J. E. McEnery[24], S. McGlynn[9,11], P. Mészáros[43], C. Meurer[9,10], P. F. Michelson[3], W. Mitthumsiri[3], T. Mizuno[40], A. A. Moiseev[25,23], C. Monte[26,27], M. E. Monzani[3], E. Moretti[14,15], A. Morselli[51], I. V. Moskalenko[3], S. Murgia[3], T. Nakamori[4], P. L. Nolan[3], J. P. Norris[53], E. Nuss[32], M. Ohno[54], T. Ohsugi[40], N. Omodei[12], E. Orlando[20], J. F. Ormes[53], M. Ozaki[54], W. S. Paciesas[19], D. Paneque[3], J. H. Panetta[3], D. Parent[37], V. Pelassa[32], M. Pepe[21,22], M. Pesce-Rollins[12], V. Petrosian[3], F. Piron[32], T. A. Porter[6], R. Preece[19], S. Rainò[26,27], E. Ramirez-Ruiz[7], R. Rando[17,18], M. Razzano[12], S. Razzaque[1,2], A. Reimer[3,55], O. Reimer[3,55], T. Reposeur[37], S. Ritz[6], L. S. Rochester[3], A. Y. Rodriguez[56], M. Roth[29], F. Ryde[9,11], H. F.-W. Sadrozinski[6], D. Sanchez[28], A. Sander[45], P. M. Saz Parkinson[6], J. D. Scargle[57], T. L. Schalk[6], C. Sgrò[12], E. J. Siskind[58], D. A. Smith[37], P. D. Smith[45], G. Spandre[12], P. Spinelli[26,27], M. Stamatikos[24,45], F. W. Stecker[24], M. S. Strickman[1], D. J. Suson[59], H. Tajima[3], H. Takahashi[40], T. Takahashi[54], T. Tanaka[3], J. B. Thayer[3], J. G. Thayer[3], D. J. Thompson[24], L. Tibaldo[13,17,18], K. Toma[43], D. F. Torres[56,60], G. Tosti[21,22], E. Troja[4,24], Y. Uchiyama[3,54], T. Uehara[40], T. L. Usher[3], A. J. van der Horst[38], V. Vasileiou[24,23,31], N. Vilchez[48], V. Vitale[51,52], A. von Kienlin[20], A. P. Waite[3], P. Wang[3], C. Wilson-Hodge[38], B. L. Winer[45], K. S. Wood[1], X. F. Wu[43,61,62], R. Yamazaki[40], T. Ylinen[9,11,63] & M. Ziegler[6]

[1]Space Science Division, Naval Research Laboratory, Washington, District of Columbia 20375, USA. [2]National Research Council Research Associate, National Academy of Sciences, Washington, District of Columbia 20001, USA. [3]W. W. Hansen Experimental Physics Laboratory, Kavli Institute for Particle Astrophysics and Cosmology, Department of Physics and SLAC National Accelerator Laboratory, Stanford University, Stanford, California 94305, USA. [4]Department of Physics, [5]Interactive Research Center of Science, Tokyo Institute of Technology, Meguro City, Tokyo 152-8551, Japan. [6]Santa Cruz Institute for Particle Physics, Department of Physics and Department of Astronomy and Astrophysics, University of California at Santa Cruz, [7]UCO/Lick Observatories, Santa Cruz, California 95064, USA. [8]Department of Astronomy, Stockholm University, [9]The Oskar Klein Centre for Cosmoparticle Physics, [10]Department of Physics, [11]Department of Physics, Royal Institute of Technology (KTH), AlbaNova, SE-106 91 Stockholm, Sweden. [12]Istituto Nazionale di Fisica Nucleare, Sezione di Pisa, I-56127 Pisa, Italy. [13]Laboratoire AIM, CEA-IRFU/CNRS/Université Paris Diderot, Service d'Astrophysique, CEA Saclay, 91191 Gif-sur-Yvette, France. [14]Istituto Nazionale di Fisica Nucleare, Sezione di Trieste, [15]Dipartimento di Fisica, Università di Trieste, I-34127 Trieste, Italy. [16]Rice University, Department of Physics and Astronomy, MS-108, P. O. Box 1892, Houston, Texas 77251, USA. [17]Istituto Nazionale di Fisica Nucleare, Sezione di Padova, [18]Dipartimento di Fisica "G. Galilei", Università di Padova, I-35131 Padova, Italy. [19]CSPAR, University of Alabama in Huntsville, Huntsville, Alabama 35899, USA. [20]Max-Planck Institut für extraterrestrische Physik, 85748 Garching, Germany. [21]Istituto Nazionale di Fisica Nucleare, Sezione di Perugia, [22]Dipartimento di Fisica, Università degli Studi di Perugia, I-06123 Perugia, Italy. [23]Center for Research and Exploration in Space Science and Technology (CRESST), [24]NASA Goddard Space Flight Center, Greenbelt, Maryland 20771, USA. [25]University of Maryland, College Park, Maryland 20742, USA. [26]Dipartimento di Fisica "M. Merlin" dell'Università e del Politecnico di Bari, [27]Istituto Nazionale di Fisica Nucleare, Sezione di Bari, I-70126 Bari, Italy. [28]Laboratoire Leprince-Ringuet, École polytechnique, CNRS/IN2P3, F-91128 Palaiseau, France. [29]Department of Physics, University of Washington, Seattle, Washington 98195-1560, USA. [30]INAF-Istituto di Astrofisica Spaziale e Fisica Cosmica, I-20133 Milano, Italy. [31]University of Maryland, Baltimore County, Baltimore, Maryland 21250, USA. [32]Laboratoire de Physique Théorique et Astroparticules, Université Montpellier 2, CNRS/IN2P3, 34095 Montpellier, Cedex 5, France. [33]Department of Physics and Astronomy, Sonoma State University, Rohnert Park, California 94928-3609, USA. [34]Agenzia Spaziale Italiana (ASI) Science Data Center, I-00044 Frascati (Roma), Italy. [35]Dipartimento di Fisica, Università di Udine and Istituto Nazionale di Fisica Nucleare, Sezione di Trieste, Gruppo Collegato di Udine, I-33100 Udine, Italy. [36]Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA. [37]Université de Bordeaux and CNRS/IN2P3, Centre d'Études Nucléaires Bordeaux Gradignan, UMR 5797, Gradignan 33175, France. [38]Space Science Office, VP62, NASA/Marshall Space Flight Center, Huntsville, Alabama 35812, USA. [39]INAF Osservatorio Astronomico di Brera, I-23807 Merate, Italy. [40]Department of Physical Sciences, Hiroshima University, Higashi-Hiroshima, Hiroshima 739-8526, Japan. [41]Jacobs Technology, Huntsville, Alabama 35806, USA. [42]Centre for Astrophysics Research, University of Hertfordshire, College Lane, Hatfield AL10 9AB, UK. [43]Department of Astronomy and Astrophysics, Pennsylvania State University, University Park, Pennsylvania 16802, USA. [44]Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany. [45]Department of Physics, Center for Cosmology and Astro-Particle Physics, The Ohio State University, Columbus, Ohio 43210, USA. [46]Waseda University, 1-104 Totsukamachi, Shinjuku-ku, Tokyo, 169-8050, Japan. [47]Cosmic Radiation Laboratory, Institute of Physical and Chemical Research (RIKEN), Wako, Saitama 351-0198, Japan. [48]Centre d'Étude Spatiale des Rayonnements, CNRS/UPS, BP 44346, F-30128 Toulouse cedex 4, France. [49]George Mason University, Fairfax, Virginia 22030, USA. [50]University College Dublin, Belfield, Dublin 4, Ireland. [51]Istituto Nazionale di Fisica Nucleare, Sezione di Roma "Tor Vergata", [52]Dipartimento di Fisica, Università di Roma "Tor Vergata", I-00133 Roma, Italy. [53]Department of Physics and Astronomy, University of Denver, Denver, Colorado 80208, USA. [54]Institute of Space and Astronautical Science, JAXA, 3-1-1 Yoshinodai, Sagamihara, Kanagawa 229-8510, Japan. [55]Institut für Astro- und Teilchenphysik and Institut für Theoretische Physik, Leopold-Franzens-Universität Innsbruck, A-6020 Innsbruck, Austria. [56]Institut de Ciencies de l'Espai (IEEC-CSIC), Campus UAB, 08193 Barcelona, Spain. [57]Space Sciences Division, NASA Ames Research Center, Moffett Field, California 94035-1000, USA. [58]NYCB Real-Time Computing Inc., Lattingtown, New York 11560-1025, USA. [59]Department of Chemistry and Physics, Purdue University Calumet, Hammond, Indiana 46323-2094, USA. [60]Institució Catalana de Recerca i Estudis Avançats (ICREA), 08193 Barcelona, Spain. [61]Joint Center for Particle Nuclear Physics and Cosmology (J-CPNPC), [62]Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210008, China. [63]School of Pure and Applied Natural Sciences, University of Kalmar, SE-391 82 Kalmar, Sweden.