First Analysis of Jupiter in Gamma Rays and a New Search for Dark Matter

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We present the first dedicated γ-ray analysis of Jupiter, using 12 years of data from the *Fermi* Telescope. We find no robust evidence of γ-ray emission, and set upper limits of $\sim 10^{-9}$ GeV cm^{-2} s^{-1} on the Jovian γ-ray flux. We point out that Jupiter is an advantageous dark matter (DM) target due to its large surface area (compared with other solar system planets), and cool core temperature (compared with the Sun). These properties allow Jupiter to both capture and retain lighter DM, providing a complementary probe of sub-GeV DM. We therefore identify and perform a new search for DM-sourced γ-rays in Jupiter, where DM annihilates to long-lived particles, which can escape the Jovian surface and decay into γ rays. We consequently constrain DM-proton scattering cross sections as low as about 10^{-40} cm^2, showing Jupiter is up to 10 orders of magnitude more sensitive than direct detection. This sensitivity is reached under the assumption that the mediator decay length is sufficient to escape Jupiter, and the equilibrium between DM capture and annihilation; sensitivities can be lower depending on the DM model. Our work motivates follow-up studies with upcoming MeV telescopes such as AMEGO and e-ASTROGAM.

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Introduction.—The king of the Roman gods, Jupiter, commanded lightning, thunder, and storms. Analogous to the Greek god Zeus, he exerted his power with lightning bolts as weapons. His luminous wrath won his name one of the brightest objects in the sky, *Iovis Stella* (the star of Jupiter). Today, it is known as Jupiter, which is the heaviest and largest planet in our Solar System.

For the first time, we perform a dedicated search for Jupiter's lightning bolts (γ rays) with the *Fermi* γ-ray Space Telescope. These γ rays could potentially be produced through the active acceleration of cosmic rays in Jovian magnetic fields [1], through the passive interaction of Galactic cosmic rays with Jupiter's atmosphere (similar to solar models [2]), or from dark matter (DM) annihilation. Using 12 years of *Fermi* Large Area Telescope (LAT) γ-ray data, we perform a novel analysis that has been optimized for studies of Solar System objects, such as the Sun [3,4]. This is the first ever measurement of Jupiter in γ rays, with important implications for our understanding of Jovian properties; see the Supplemental Material [5] for discussion of the astrophysical implications.

Detecting, or ruling out, Jovian γ-ray emission would also have important implications for DM. DM in the Galactic halo can be captured by Jupiter if it scatters with Jovian matter, loses sufficient kinetic energy, and becomes gravitationally bound. Jupiter is an advantageous DM detector for several reasons. First, compared with the Sun, it has a much cooler core. This low core temperature means that less kinetic energy is transferred to the DM, making it easier to capture and retain DM after the initial scattering. While DM evaporation inhibits Solar DM limits below a few GeV, studies of Jupiter can probe lighter DM. Second, compared with other planets, Jupiter is heavier and has a larger radius. This means it can capture more DM, and consequently has a larger DM annihilation rate.

Figure 1 illustrates the DM scenario we study; to detect DM annihilation inside Jupiter, the γ rays must escape its atmosphere. Captured DM particles annihilate to long-lived mediators that subsequently decay outside of the Jovian surface, producing a new source of γ rays that can be detected by the *Fermi* Telescope. This is the first proposed detectable signature of DM from Jupiter. We will use our new Jovian gamma-ray measurements to search for this signal for the first time.

Long-lived particles are theoretically well motivated [6–11]. They are currently extensively searched for in fixed-target and collider experiments [12–14], as well as

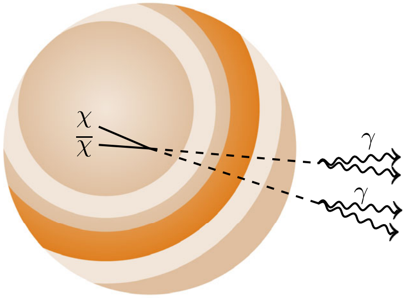

FIG. 1. Schematic of DM annihilation to long-lived particles in Jupiter. The long-lived particles can decay outside the Jovian surface, producing a new source of γ rays.

astrophysical settings [15–32]. Dark sectors with long-lived mediators have previously been constrained using celestial bodies such as the Sun [10,33–53], Earth [40], and recently with large populations of brown dwarfs and neutron stars [32]. In this Letter, we complement this existing parameter space, showing that Jovian γ-ray searches provide a MeV-scale cross section sensitivity that significantly exceeds previous efforts. In light-mediator scenarios, our results are far superior to direct detection experiments.

Fermi γ-ray data analysis.—To study Jupiter in γ rays, we perform a novel *Fermi*-LAT analysis optimized for Solar System objects that move with respect to the astrophysical background. The key to our method is the production of a fully *data-driven* background model. We first calculate the γ-ray flux in a 45° region of interest (ROI) surrounding Jupiter. While this ROI vastly exceeds the $\sim 1°$ point-spread function (PSF) of *Fermi*-LAT photons at ~ 1 GeV, such a large ROI is necessary to study Jupiter at energies near 10 MeV, where the 95% containment angle can approach 30°. We assign every γ ray a "Jovian" coordinate by calculating its deviation in right ascension (RA) and declination (DEC) from the simultaneous Jupiter position. We then produce a background model by calculating the γ-ray flux at each position in equatorial coordinates during periods when Jupiter was more than 45° away. Finally, we determine the equatorial exposure at every pixel in the Jovian coordinate system and subtract the background flux. This produces an "on" and "off" map that isolates Jupiter's flux and automatically accounts for astrophysical uncertainties that plague standard γ-ray analyses.

Our dataset includes all γ rays with recorded energies between 10 MeV and 10 GeV and zenith angles below 90°. This significantly expands on previous *Fermi*-LAT studies that adopted a minimum energy of 100 MeV. Owing to the large point-spread function and energy dispersion of *Fermi*-LAT events between 10 and 100 MeV, this adds significant modeling complexity, which we address below.

For each recorded γ ray, we calculate its offset (in RA, DEC) from the simultaneous positions of Jupiter, the Sun, and the moon. We bin the data into 60 energy bins (20 logarithmically spaced bins per decade), and calculate the exposure across the entire sky in 1 h (3600-second) increments. Over this period, Jupiter moves only 0.003° with respect to the equatorial coordinate system, while the Sun moves ~0.04° and the moon moves 0.5°. These shifts are small compared with our ROIs and the instrumental PSF, justifying our treatment of each source as stationary *within* each time bin.

To build our background model, we remove all photons recorded within 45° of Jupiter (our "on" region), within 40° of the Sun (which has an extended halo [54]), and within 20° of the moon (which produces only disk emission). While the solar and lunar flux could be modeled and fit in the analysis (this approach was taken for lunar emission in Ref. [4]), this adds significant complexity because the Sun and moon are much brighter than Jupiter. In this analysis, we simply mask these sources, losing only $\sim 15\%$ of the total Jupiter exposure. We also remove bright flares that approach too close to Jupiter; see the Supplemental Material [5] for details.

Using this background model we calculate the γ-ray photon count at each RA-DEC during periods when Jupiter is not present. This is possible because Jupiter is far from any single RA-DEC most of the time. Because we have also calculated the exposure in equatorial coordinates in fine

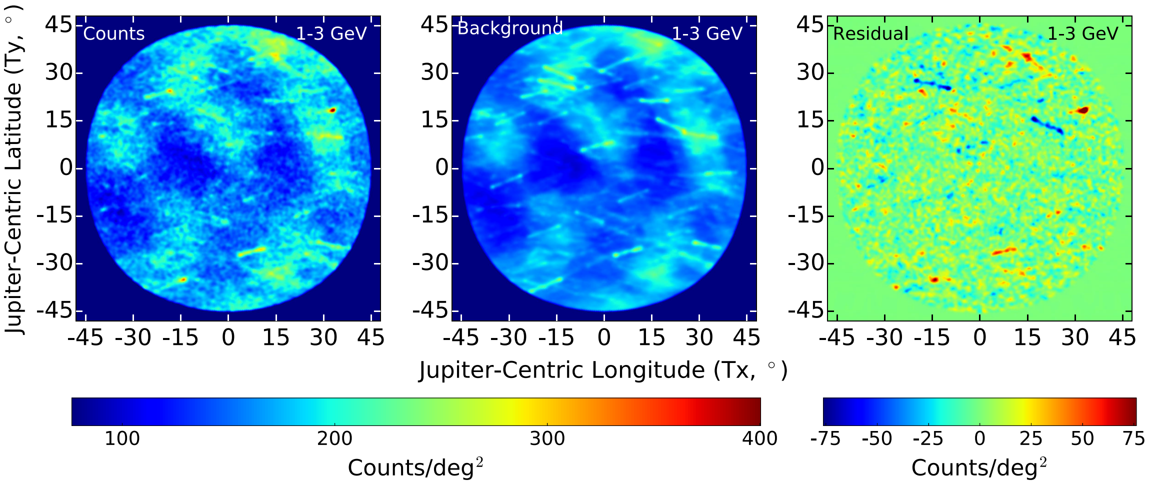

FIG. 2. *Fermi*-LAT γ-ray data utilized in our analysis. For the visualization of this figure, we combine all energy bins between 1–3.16 GeV, and smear all results with a 1° Gaussian, choices that are not made in the analysis of our data. *Left:* Counts map produced by all events recorded within 45° of the position of Jupiter. *Middle:* The background map, which is produced from observations of events calculated by examining identical regions in RA/DEC when Jupiter is not present. *Right:* The residual calculated by subtracting the model from our data.

temporal bins, we can translate the photon count into a background γ-ray flux. Finally, in every 3600-second window, we convert each point in equatorial coordinates to its simultaneous position in Jovian coordinates, producing an entirely data-driven background model at each point in Jovian coordinates. Finally, we model Jupiter itself. Because the spatial extent of Jupiter is much smaller than the *Fermi* PSF at any energy, we treat Jupiter as a point source; details are in the Supplemental Material [5].

Figure 2 shows our model at energies between 1 and 3 GeV, including the γ-ray flux within 45° of Jupiter, the γ-ray flux predicted by our background model, and the resulting residual. Bright lines across the ROI correspond to bright sources moving through the Jovian coordinate system. The residuals are generally only a few percent, with maximum values near 20%. These primarily stem from flaring sources that we did not remove. The scale of Jupiter in this 1–3 GeV energy bin is about 1/45th of the image width. The contribution from Jupiter will cover a much larger region in the lowest-energy bins, justifying our usage of a full 45° ROI.

Upper limits on the Jovian γ-ray flux.—We utilize IMINUIT to calculate the simultaneous fit of our background model and the Jupiter flux in each energy bin. In this case, we utilize a simple two-parameter fit, where the normalization of the Jupiter flux, and the normalization of the overall background template, are allowed to float independently in each energy bin. We note two important details. First, the normalization of the background template should equal 1, as the normalization of background sources should be independent of the position of Jupiter. Indeed, we find only very small deviations (on the order of 1–2%) from unity, verifying the accuracy of our techniques. Small errors may stem from variable sources, or instrumental exposure corrections that are correlated with the Jupiter position.

We allow the normalization of Jupiter to assume both positive or negative values. This is important, because constraining the Jupiter flux to be positive (and binning the data finely in energy) may make upward fluctuations appear overly significant. However, this choice can add complexity in the high-energy regime, because Poisson statistics are ill defined when the total model expectation is negative in any pixel. Here, we follow Ref. [55], calculating the Poisson statistic from its absolute value in bins where the observed number of counts is 0, but ruling out negative fluctuations in bins where the number of observed photons is nonzero. This choice is numerically important, but has no practical impact on our results.

Figure 3 shows the Jovian γ-ray flux in our analysis. We note several important results. First, the overall flux of Jupiter is consistent with 0. For an E^{-2} γ-ray spectrum we obtain a 95% confidence upper limit on the Jovian energy flux of 9.4×10^{-10} GeV cm^{-2} s^{-1} between 10 MeV and 10 GeV, while for a cosmic-ray motivated spectrum of $E^{-2.7}$ we obtain an upper limit of 3.2×10^{-9} cm^{-2} s^{-1}. For power-law spectra between $E^{-1.5}$ and $E^{-3.0}$, the significance of Jovian emission never exceeds 1.5σ. Second, we note that the error bars in our analysis are highly correlated. This is due to the significant energy-dispersion of low-energy *Fermi*-LAT data, which smears the true Jovian energy flux between multiple energy bins. This effect decreases, from ~30 to 50% in the lowest energy bins, to near 15% at GeV energies. Third, we note that there is a statistically significant excess in the lowest energy bins (below 15 MeV). The local significance of this excess is 4.6σ in the energy bin between 10 and 11.2 MeV, 2.3σ in the bin between 11.2 and 12.6 MeV, and 1.3σ in the bin between 12.6 and 14.1 MeV. Combined, these provide a 5σ local excess. This is a potentially exciting result, pointing to the possibility that Jupiter may be capable of accelerating cosmic rays to MeV energies in its strong electromagnetic fields. However, significant caution is warranted. Firstly, this analysis severely pushes the limits of the *Fermi*-LAT. To our knowledge, no other study of steady-state emission has taken place in such a low-energy regime. Numerous systematic effects may be present in the low-energy bins that would be difficult to control in any analysis, and a detailed study of systematics in this region (which lies beyond the scope of this paper), would be necessary. Secondly, the *Fermi*-LAT effective area rises rapidly with

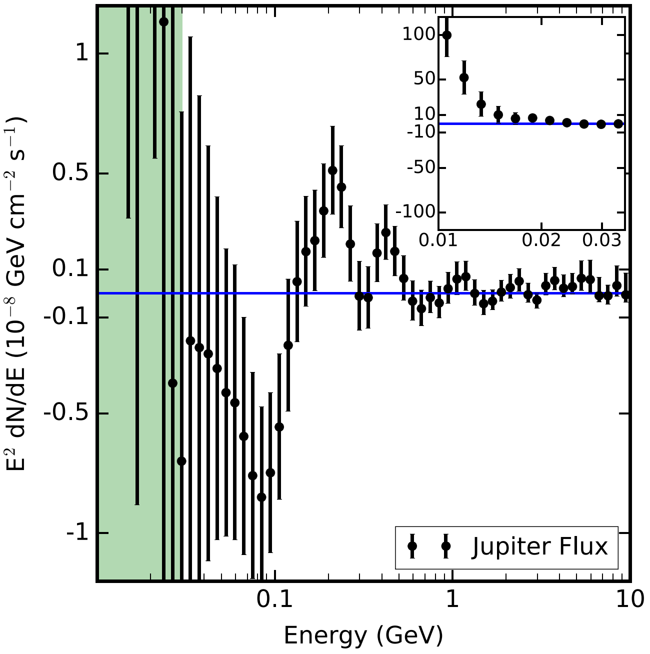

FIG. 3. The γ-ray flux from Jupiter obtained in our analysis. The blue horizontal line depicts no γ-ray flux. The significant energy dispersion (especially at low energies) makes the flux in nearby energy bins highly correlated. Through most of the energy range, we find no evidence for Jovian γ-ray emission. In the inset (green region), we enlarge to show the bright emission in the lowest energy bins.

energy in this regime. The exposure at 20 MeV is 50 times larger than at 10 MeV. The fact that no excess is observed in the 20 MeV energy bins strongly constrains the spectrum of any 10 MeV excess. Effectively, any power-law emission at 10 MeV (with spectra harder than ∼E^{-3}) is ruled out, and the emission observed at 10 MeV must have a spectrum that is strongly exponentially suppressed. Fourth, we find a low-significance excess (2σ local), best fit by the annihilation of a DM particle of mass 493 MeV into long-lived particles which decay directly into γ rays. However we do not consider this sufficiently statistically significant.

Dark matter in Jupiter.—DM from the Galactic halo can fall into Jupiter, scattering and losing energy. Once the kinetic energy of the DM is less than the gravitational potential, the DM particle is captured. DM capture can occur via single or multiple scatters with Jovian matter [41,56–58]. The DM capture rate for N required scatters is given by [56]

$$C_N = \pi R_{♃}^2 p_N(\tau) \frac{\sqrt{6} n_\chi}{3\sqrt{\pi}\bar{v}} \times \left[(2\bar{v}^2 + 3v_{\rm esc}^2) - (2\bar{v}^2 + 3v_N^2) \times \exp\left(-\frac{3(v_N^2 - v_{\rm esc}^2)}{2\bar{v}^2} \right) \right], \tag{1}$$

where $v_{\rm esc} = \sqrt{2GM_{♃}/R_{♃}} \sim 60$ km/s is Jupiter's escape velocity with G as the gravitational constant, and $M_{♃} = 1.9 \times 10^{27}$ kg and $R_{♃} = 69,911$ km are the mass and radius of Jupiter, respectively. $\bar{v}$ is the DM velocity dispersion, $n_\chi(r)$ is the DM number density at the Jupiter position, related to the mass density via $n_\chi(r) = \rho(r)/m_\chi$, and $v_N = v_{\rm esc}(1 - \beta_+/2)^{-N/2}$ with $\beta_+ = 4m_\chi m_n/(m_\chi + m_n)^2$. Note that here we have assumed that a scattering variable $z = \sin^2(\theta_{\rm CM}/2)$, where $\theta_{\rm CM}$ is the c.m. scattering angle, takes its average value of $\langle z_i \rangle = 1/2$, which is not a perfect assumption for the single scatter limit, but is accurate within a factor of a few in our case. The probability of a single DM particle undergoing N scatters is

$$p_N(\tau) = 2 \int_0^1 dy \frac{y e^{-y\tau} (y\tau)^N}{N!}, \tag{2}$$

where y is the cosine of the incidence angle of DM entering Jupiter, and τ is the optical depth,

$$\tau = \frac{3}{2} \frac{\sigma}{\sigma_{\rm sat}}, \tag{3}$$

and $\sigma_{\rm sat}$ is the saturation cross section of DM capture onto nucleons given by $\sigma_{\rm sat} = \pi R^2/N_n$, where N_n is the number of Jovian nucleons. We assume for simplicity that Jupiter is 100% hydrogen. The total capture rate of DM in Jupiter $C_{♃}$ is then given by

$$C_{♃} = \sum_{N=1}^{\infty} C_N. \tag{4}$$

Assuming that equilibrium between capture and annihilation of DM within Jupiter is reached, the annihilation rate ($\Gamma_{\rm ann}$) is simply $\Gamma_{\rm ann} = C_{♃}/2$.

We assume that DM annihilates into two mediators ϕ that have a sufficiently long lifetime τ or large boost factor $\gamma \approx m_\chi/m_\phi$ such that the decay length L exceeds the radius of Jupiter $R_{♃}$, as

$$L = \gamma\beta\tau \simeq \gamma c\tau > R_{♃}. \tag{5}$$

The total flux at Earth from long-lived particles in Jupiter is given by [44]

$$E^2 \frac{d\Phi}{dE} = \frac{\Gamma_{\rm ann}}{4\pi D_\oplus^2} \times E_\gamma^2 \frac{dN_\gamma}{dE_\gamma} \times \mathrm{BR}(X \to \mathrm{SM}) \times P_{\rm surv}, \tag{6}$$

where $D_\oplus$ is the average distance of Jupiter to Earth, and $\mathrm{BR}(X \to \mathrm{SM})$ is the branching ratio of the mediator to a given standard model (SM) final state. The probability of the signal surviving to reach the detector near Earth, $P_{\rm surv}$, provided the decay products escape Jupiter is [44]

$$P_{\rm surv} = e^{-R_{♃}/\gamma c\tau} - e^{-D_\oplus/\gamma c\tau}. \tag{7}$$

In Eq. (6), the $E_\gamma^2 dN_\gamma/dE_\gamma$ term corresponds to the γ-ray energy spectrum. The relevant DM annihilation process is $\chi\bar{\chi} \to \phi\phi \to 4\mathrm{SM}$. DM annihilation to two mediators is dominant over DM annihilation to one mediator, as it is not phase-space suppressed. This yields the characteristic γ-ray box spectral shape [59]. As we consider mediators at least a factor few lighter than the DM, the highest energy γ rays always peak close to the DM mass. This means that our results are approximately independent of the mediator mass (provided it is sufficiently boosted or long-lived to escape Jupiter).

Figure 4 shows our new cross section constraints on DM annihilation to long-lived particles using Jovian γ rays at 95% C.L., for mediator decay to γ rays, via $\chi\chi \to \phi\phi$, $\phi \to 2\gamma$. In this plot we take the mediator to decay at the Jovian surface. We show for comparison, limits from direct detection (DD) [60–63], which loses sensitivity with lower DM masses as the recoils become increasingly weak. Jupiter on the other hand, is optimized to search for DM particles with masses of around the proton mass, providing up to 10 orders of magnitude stronger sensitivity than DD. While we only show limits for direct decay to gamma rays, our search is also sensitive to other final states, which produce gamma rays via electromagnetic bremsstrahlung or hadronic decays. As we show constraining power of up

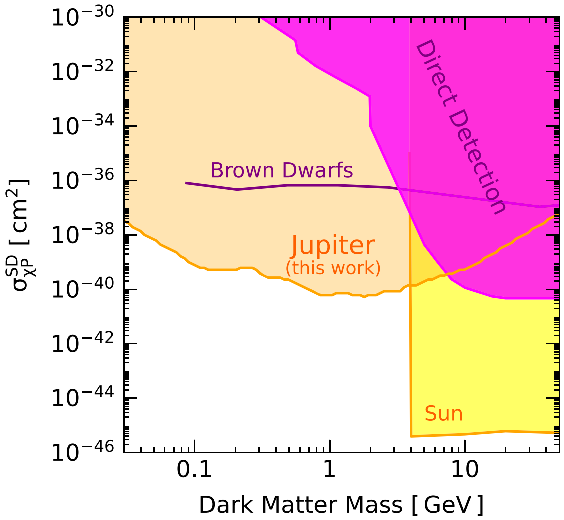

FIG. 4. 95% C.L. DM-proton scattering cross section limits as a function of DM mass m_χ, arising from DM annihilation to long-lived particles, from our new Jovian γ-ray search. We show complementary constraints from direct detection [60–63], as well as DM annihilation to long-lived particles in the Sun [44,46], and brown dwarfs in the Galactic Center [32].

to 10 orders of magnitude higher than previous limits, we expect that while other final states can produce weaker limits, there should still be significant constraining gain. Note that compared with the Jupiter limits, the DD limits do not require any minimum annihilation cross section. We also show complementary searches for DM and long-lived particles in the Sun [44,46], and the Galactic Center (GC) population of brown dwarfs (BDs) [32]. Compared with GC BDs, Jupiter is only one object in a comparably low DM density; however it is very close to Earth, leading to superior sensitivities. Compared with solar DM results as calculated in Refs. [44,46], the solar limits extend to much lower cross sections, owing to the Sun being much larger than Jupiter and closer to the Earth. The Jupiter limits extend to lower DM masses, because Jupiter's cooler core in part can more easily prevent evaporation of sub-GeV DM. However, depending on the specific DM model of interest, we emphasize that the low-mass end of the sensitivity can substantially change. In the case of only heavy mediators, the DM evaporation mass is about 200 MeV–1 GeV for Jupiter depending on the scattering cross section. In the case of light mediators, the DM evaporation mass can be instead at least sub-MeV [64]. We therefore show the sensitivity of Fermi assuming no evaporation, but the exact lower bound where the sensitivity truncates will depend on the DM model. Discussion of some example models is given in Sec. III F of the Supplemental Material [5].

Conclusions.—We produced the first ever measurement of Jupiter in γ rays, using 12 years of data from the *Fermi* γ-ray Space Telescope. Our results are important for understanding Jupiter's atmospheric properties and magnetic fields, and furthermore applying to a new DM signature. We designed a new analysis framework that led to the first *Fermi* steady-state analysis down to 10 MeV. This was made possible as all instrumental uncertainties (point-spread function, energy dispersion, effective area) are directly accounted for in our data-driven background model. This unlocks the power of our low-energy data, where these uncertainties become particularly acute.

Across most γ-ray energies, we found no γ-ray flux in excess of background expectations, setting the first upper limits on the Jovian γ-ray flux. At lower γ-ray energies, we find statistically significant evidence for Jovian γ-ray emission below 15 MeV at 5σ local. While this emission has an extremely soft spectrum and is not well fit by any DM model, it may provide significant evidence of primary cosmic-ray acceleration within the Jovian atmosphere. However, this analysis pushes the envelope of *Fermi*-LAT's sensitivity as an MeV γ-ray detector, and should not yet be taken as robust. We emphasize the need for new, and robust analyses for MeV Jovian γ rays, which can be provided by proposed MeV telescopes such as AMEGO or e-ASTROGAM.

We pointed out that Jupiter is an ideal DM detector. Compared with the nearby Sun, Jupiter has a cooler core, which can prevent the evaporation of lighter DM particles, allowing new sensitivity to sub-GeV DM. Compared with other Solar System planets, Jupiter is much larger, allowing a larger capture and consequent annihilation rate. We showed that if captured DM annihilates to sufficiently long-lived or boosted mediators, the mediators can escape the Jovian surface, and decay into γ rays that are detectable by the *Fermi* Telescope. We find a low-significance excess, best fit by the annihilation of a DM particle of mass 493 MeV into long-lived particles which decay directly into γ rays. However, the local significance of this excess only slightly exceeds 2σ. We therefore used our new upper limits on the Jovian flux to constrain, for the first time, the annihilation of DM to long-lived mediators in Jupiter, for DM with masses above a few tens of MeV, with DM-proton scattering cross sections down to about 10^{-40} cm^{-1}. This is up to 10 orders of magnitude more sensitive than DD. We emphasize, however, that the lower end of the DM mass sensitivity and cross section limits can weaken, particularly in the context of specific particle models. These limits should instead be interpreted as demonstrating the strong constraining power of this search, rather than generic, robust constraints. Our results motivate model-dependent studies of the DM parameter space that can be constrained using Jovian γ rays.

For additional results for our Jovian gamma-ray analyses, additional discussion of the astrophysical implications of our Jovian gamma-ray measurement, and additional discussion on Jovian DM, see the Supplemental Material [5], which includes Refs. [3,4,10,32–53,64–134].

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[5] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.131.071001 for additional results for our Jovian gamma-ray analyses, additional discussion of the astrophysical implications of our Jovian gamma-ray measurement, and additional discussion on Jovian DM.

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