Probing the Pulsar Explanation of the Galactic-Center GeV Excess Using Continuous Gravitational-Wave Searches

Andrew L. Miller[1,2,3,*] and Yue Zhao[4,†]
[1]Université catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium
[2]Nikhef—National Institute for Subatomic Physics, Science Park 105, 1098 XG Amsterdam, The Netherlands
[3]Institute for Gravitational and Subatomic Physics (GRASP), Utrecht University, Princetonplein 1, 3584 CC Utrecht, The Netherlands
[4]Department of Physics and Astronomy, University of Utah, Salt Lake City, Utah 84112, USA

(Received 6 February 2023; revised 3 April 2023; accepted 12 July 2023; published 25 August 2023)

Over 10 years ago, *Fermi* observed an excess of GeV gamma rays from the Galactic Center whose origin is still under debate. One explanation for this excess involves annihilating dark matter, another requires an unresolved population of millisecond pulsars concentrated at the Galactic Center. In this work, we use the results from LIGO and Virgo's most recent all-sky search for quasimonochromatic, persistent gravitational-wave signals from isolated neutron stars, which is estimated to be about 20%–50% of the population, to determine whether unresolved millisecond pulsars could actually explain this excess. First, we choose a luminosity function that determines the number of millisecond pulsars required to explain the observed excess. Then, we consider two models for deformations on millisecond pulsars to determine their ellipticity distributions, which are directly related to their gravitational-wave radiation. Lastly, based on null results from the O3 frequency-Hough all-sky search for continuous gravitational waves, we find that a large set of the parameter space in the pulsar luminosity function can be excluded. We also evaluate how these exclusion regions may change with respect to various model choices. Our results are the first of their kind and represent a bridge between gamma-ray astrophysics, gravitational-wave astronomy, and dark-matter physics.

DOI: 10.1103/PhysRevLett.131.081401

Introduction.—A tantalizing excess of GeV gamma rays was observed by *Fermi* over 10 years ago coming from the Galactic Center, and yet its origin has remained elusive. While early studies suggested that the almost spherically symmetric Galactic-Center excess spatial morphology was well fit by dark-matter models [1–7], and that recent cosmic-ray burst events in our Galaxy could also explain this excess [8–10], an astrophysical explanation of unresolved millisecond pulsars also appears consistent with the observed excess [11–15]. The debate between these two explanations is intense: some studies claim that the spatial morphology of the Galactic-Center excess matches better with the mass distribution of the Galactic bulge [16–19], while other studies indicate a preference for a spherically symmetric distribution [20,21]. There have also been potential detections of gamma rays from point sources in the inner Galaxy [22–24], but it was shown recently that systematic biases favoring individual sources may exist in these works [25–27]. Furthermore, predictions for the fraction of the Galactic-Center excess explained by millisecond pulsars range from a few percent [28,29] to 100% [30], depending on the luminosity function chosen.

The general theme behind these studies is to devise a luminosity function to fit the observed Galactic-Center excess, based on minimal assumptions [17,31] or astrophysics, e.g., assuming luminosity functions identical to those from known millisecond pulsars in globular clusters [29], asserting that accretion-induced collapse is responsible for creating a millisecond pulsar population [32], or allowing emissions from low-mass x-ray binaries to compose the Galactic-Center excess [33,34]. However, since these choices are required to generate the same observed excess, only some studies of x rays [35], TeV gamma rays [36], and radio observations [37] have allowed us to actually exclude luminosity functions.

Another approach is thus needed to test the viability of the millisecond pulsar hypothesis. In this Letter, we show that all-sky searches for continuous waves, i.e., quasimonochromatic, persistent signals from isolated, asymmetrically rotating neutron stars concentrated around the Galactic Center, can constrain the millisecond pulsar hypothesis for a chosen luminosity function and provide a complementary probe of the Galactic-Center excess.

Gravitational waves could be emitted by neutron stars with deformations on their surfaces, which would then cause a "spin down," a decrease in the rotational frequency of the star over time, of $\mathcal{O}(< 10^{-9})$ Hz/s. The size of this deformation is *a priori* unknown and could vary among neutron stars [38]; however, contrary to *Fermi*, advanced LIGO [39], Virgo [40], and KAGRA [41] do not rely on electromagnetic emissions, meaning they could potentially detect gravitational waves from sources *Fermi* may not see.

In fact, the strength of a superposition of signals from a stochastic gravitational-wave background of isolated millisecond pulsars in the Galactic Center was calculated in Ref. [42], assuming a fixed ellipticity and moment of inertia for the population. However, the authors did not systematically try to exclude the luminosity function, nor test robustness of their calculations against different modeling assumptions for the millisecond pulsar population. Furthermore, a stochastic gravitational-wave background was actually searched for in the Galactic Center recently [43], resulting in constraints on the ellipticity of millisecond pulsars there; however, this search was conducted independently of any knowledge of the GeV excess. In contrast, here we consider millisecond pulsars emitting individually detectable signals, directly link gravitational-wave searches and the observed luminosity of the GeV excess, and put data-driven constraints, while testing the robustness of our modeling choices.

To address the Galactic-Center excess problem using gravitational waves, we will use results from one of the most recent all-sky searches of the latest LIGO-Virgo-KAGRA data, O3, that targeted isolated neutron stars with gravitational-wave frequencies between [10, 2048] Hz and spin downs between $[-10^{-9}, +10^{-8}]$ Hz/s [44] with the frequency-Hough method [45]. We will specifically consider the portion of the sky that contains the Galactic Center. Additionally, we choose to use upper limits from searches for isolated neutron stars because these searches can reach the Galactic Center (~8 kpc), which cannot yet be reached by all-sky searches for neutron stars in binary systems [46], thus our results only constrain isolated millisecond pulsars that could comprise ~20% of the population [48], and some binary systems with particular orbital parameters [49].

Millisecond pulsars.—Gravitational waves from an isolated neutron star could be emitted due to a deviation from axial symmetry, which can be written in terms of a dimensionless equatorial ellipticity ϵ, defined in terms of the star's principal moments of inertia [54] $\epsilon \equiv |I_{xx} - I_{yy}|/I_{zz}$. The value of I_{zz} is at $\mathcal{O}(10^{38}\text{–}10^{39})$ kg m^2, depending on the unknown neutron star equation of state [55,56]. In this study, we choose three representative values $(10^{38}, 5\times 10^{38}, 10^{39})$ kg m^2. The gravitational-wave amplitude h_0 is directly proportional to the ellipticity [54]:

$$h_0 = \frac{16\pi^2 G}{c^4}\frac{I_{zz}\epsilon f_{\rm rot}^2}{d}, \tag{1}$$

where d is the star's distance from Earth and $f_{\rm rot}$ is the star's rotational frequency. In this study, we adopt the strategy in Ref. [57] and assume this distribution of frequencies is representative of the unknown rotational frequencies of millisecond pulsars [49].

It is also useful to introduce the spin-down limit ellipticity $\epsilon^{\rm sd}$. This is the maximum allowed ellipticity of a neutron star, assuming that all of the rotational energy lost by a millisecond pulsar is converted into gravitational waves [58]:

$$\epsilon^{\rm sd} = \sqrt{\frac{5c^5}{2G}}\frac{1}{16\pi^2}\sqrt{\frac{|\dot f_{\rm rot}|}{I_{zz} f_{\rm rot}^5}}. \tag{2}$$

In the following study, we consider two models to determine the ellipticity distribution of millisecond pulsars. The first is to model the deformation as being caused by a strong internal magnetic field misaligned with the star's rotational axis [59–61]. The second is to require that the gravitational-wave radiation of millisecond pulsars is a fixed fraction of the total energy loss [62,63].

Model 1: Deformation caused by magnetic field: Neutron stars cannot remain spherical in the presence of a strong *internal* magnetic field $B_{\rm int}$ [64,65]. If this field does not align with the rotational axis, it could sustain a deformation on the surface. Specifically, assuming a superconducting core, the ellipticity is related to $B_{\rm int}$ as [66] $\epsilon \approx 10^{-8}(B_{\rm int}/10^{12}\ \text{Gs})$.

The internal magnetic field of a pulsar is not directly observable. We have to derive its value using the pulsar's measured external magnetic field $B_{\rm ext}$. In this study, we consider a range of ratios when calculating the probability of gravitational-wave detection based on O3 search results, but we take a benchmark value as $B_{\rm int} = 150 B_{\rm ext}$, motivated by Refs. [67,68], when applying our results to exclude portions of the luminosity function parameter space (see below). We also assume millisecond pulsars near the Galactic Center follow the same $B_{\rm ext}$ distribution given in the Australian Telescope National Facility (ATNF) catalog [69]. However, the internal magnetic field could even be 10^4 times larger than the external one [49,70,71].

Model 2: Fixed fraction of gravitational-wave energy loss: Rather than relying on specific models to estimate the ellipticity distribution, we also employ ellipticities that are inferred from the ATNF catalog at ~5% or ~10% of the spin-down limit. Such a choice is motivated by recent constraints on the gravitational-wave equatorial ellipticities of millisecond pulsars, in which the spin-down limit has been slightly surpassed for some known millisecond pulsars [66]. We note that our assumed values are smaller with respect to the constraints on millisecond pulsars in Refs. [49,66].

Luminosity function for Galactic-Center GeV emission.—The luminosity function is directly related to the number of millisecond pulsars needed to explain the observed GeV excess, and is one of the dominant contributions to astrophysical uncertainties. In this Letter, we use two well accepted benchmarks. The first is a luminosity function following a log-normal distribution [29]:

$$\frac{dN}{dL} \propto \frac{dP(L)}{dL} = \frac{\log_{10} e}{\sigma_L\sqrt{2\pi}L}\exp\left(-\frac{\log_{10}^2(L/L_0)}{2\sigma_L^2}\right), \tag{3}$$

where L is the luminosity and L_0 and σ_L are two free parameters [49].

The second benchmark has a general power-law dependence on energy cut ($E_{\rm cut}$), magnetic field (B), and the spin-down power ($\dot{E}$) [30,49]:

$$L\frac{dP(L)}{dL} = \eta E_{\rm cut}^{a_\gamma} B^{b_\gamma} \dot{E}^{d_\gamma}. \quad (4)$$

We note that our results can easily be generalized to different luminosity functions, since the result from the gravitational-wave search simply translates to a constraint on the total number of millisecond pulsars detectable via gravitational waves, i.e., $N_{\rm GW}$. For a different choice of the pulsar luminosity function, one simply needs to compare $N_{\rm GW}$ with the number of pulsars needed to explain the GeV excess to obtain a constraint on the luminosity function parameters.

Following the discussion in Ref. [72], we first calculate the total luminosity contributed by millisecond pulsars in the Galactic Center:

$$L_{\rm GCE} = N_{\rm MSP}\int_{L_{\rm min}}^{\infty} LP(L)dL. \quad (5)$$

Here $N_{\rm MSP}$ is an overall normalization parameter, characterizing the number of millisecond pulsars, and $L_{\rm min}$ is the minimum detectable luminosity by *Fermi*. For $L_{\rm GCE} \approx 10^{37}$ erg/s [49], we compute $N_{\rm MSP}$ for various choices of L_0 and σ_L, which will influence the number of detectable gravitational-wave sources in O3.

Method.—A search for quasimonochromatic gravitational-wave signals originating from anywhere in the sky was performed using data from the third observing run of advanced LIGO-Virgo-KAGRA [44]. One algorithm, the frequency-Hough [45] algorithm, tracks linear frequency evolution over time by mapping points in the time-frequency plane of the detector to lines in the frequency-frequency derivative plane of the source [45,73]. Though all outliers were vetoed, competitive upper limits were set on the degree of deformation that neutron stars could have [49].

In this study, we apply the results obtained in the frequency-Hough all-sky search to calculate the number of detectable millisecond pulsars at the Galactic Center. We note that this search and the one that specifically targets a single sky pixel that completely covers the Galactic Center [74] are complementary to each other, and we will comment on the future optimization later. The Galactic-Center search can obtain a better sensitivity than the all-sky one, since it only looks at one pixel, significantly reducing the computational cost of the search, and can therefore use longer Fourier transforms to look for quasimonochromatic signals. Here, however, we would like to consider a larger spatial extent than that covered in the Galactic-Center search, i.e., greater than 150 pc from the Galactic Center, which is why we use the all-sky search results. We therefore apply a correction factor to "specialize" the all-sky search results to the Galactic Center [49].

In our study, we assume particular ellipticity distributions described above. Furthermore, we apply the rotation frequency distribution measured in the ATNF catalog [69] to determine the gravitational-wave frequency from these millisecond pulsars [49]. We provide details on the conversion from the direct output of the gravitational-wave search h_0 to the ellipticity ϵ [49].

Let us calculate the probability for a millisecond pulsar to be detectable through gravitational-wave measurements $P_{\rm GW}$. The gravitational-wave search leads to upper limits of the ellipticity as a function of the frequency, i.e., $\epsilon_{\rm UL}(f)$, at a given confidence level (here, 95%). These limits mean that if there is one millisecond pulsar whose rotation frequency is $f_{\rm rot}$ and ellipticity is larger than $\epsilon_{\rm UL}(f)$, it should have been detected by the search.

From the frequency-Hough all-sky upper limits [49], we first calculate the probability that a neutron star has an ellipticity above the minimum detectable one for a given frequency. This is obtained by integrating the ellipticity distribution [49] over the value above $\epsilon_{\rm UL}(f)$. We then integrate this quantity over the frequency distribution [49]. This gives

$$P_{\rm GW} = \int_{\log_{10}f_{\rm min}}^{\log_{10}f_{\rm max}} d\log_{10}f\, P(\log_{10}f) \times \int_{\log_{10}\epsilon_{\rm UL}}^{0} d\log_{10}\epsilon\, P(\log_{10}\epsilon), \quad (6)$$

where $P(\log_{10} f)$ and $P(\log_{10}\epsilon)$ are the probability density functions for gravitational wave frequency and ellipticity, respectively, and f has units of Hz. Also, we take $f_{\rm min} = 120$ Hz and $f_{\rm max} = 2000$ Hz, which is in the range of frequencies analyzed in the all-sky search [74] with a cutoff at $f_{\rm rot} = 60$ Hz to ensure we are targeting millisecond pulsars. The distributions over ellipticity and frequency are normalized to one and assumed to be independent.

At last, the number of millisecond pulsars detectable with gravitational waves $N_{\rm GW}$ can be easily determined as $N_{\rm GW} = P_{\rm GW}N_{\rm MSP}$, where $N_{\rm MSP}$ is obtained above. If a set of luminosity function parameters L_0 and σ_L leads to $N_{\rm GW} \geq 1$, it indicates that the frequency-Hough all-sky search should have observed at least one millisecond pulsar in the population if those L_0 and σ_L did explain the GeV excess. Consequently, such a set should be excluded.

Results.—$P_{\rm GW}$ is fixed by the frequency and ellipticity distributions that we choose, as well as the upper limits on ellipticity from the frequency-Hough all-sky search. It is therefore *independent* of the luminosity function model considered to explain the GeV excess. Thus, we first present our results in terms of $P_{\rm GW}$ which can be directly applied to probe the parameter space of *any* luminosity

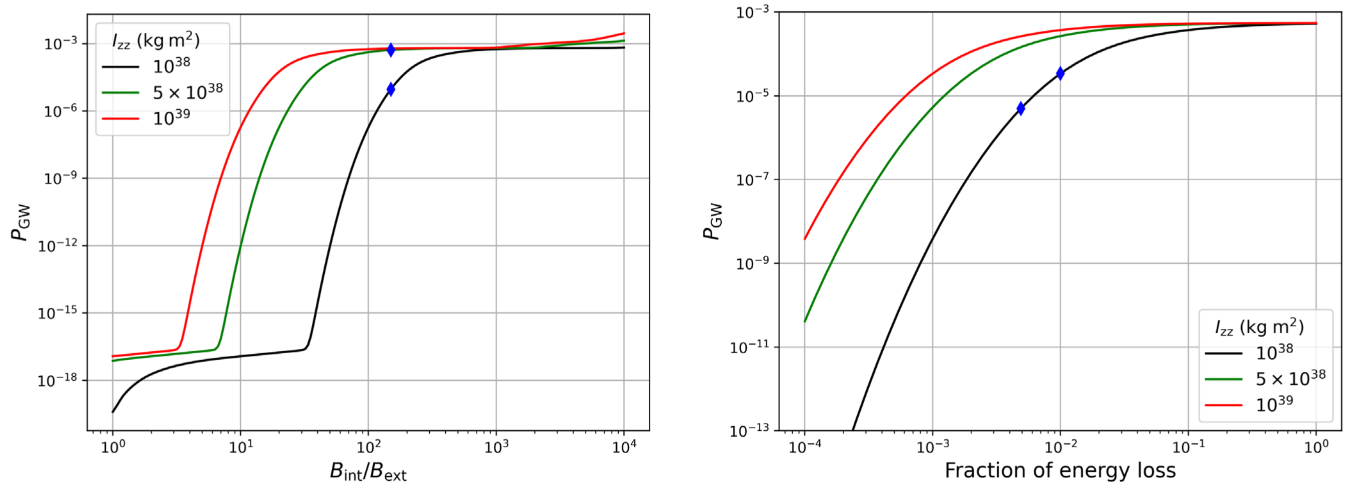

FIG. 1. Probability to detect a gravitational-wave signal obtained through Eq. (6), as a function of the internal/external magnetic field ratio (left), and the fraction of rotational energy that we allow to be emitted as gravitational waves (right). The blue diamonds denote the benchmarks that we used to perform concrete analyses with the chosen pulsar luminosity function; see Fig. 2 and Ref. [49]. $d = 8$ kpc.

function. Here, we provide, in the left- and right-hand sides of Fig. 1, P_{GW} as a function of the ratio of internal and external magnetic fields, and of the percentage of rotational energy responsible for gravitational-wave emission, respectively, for different choices of the moment of inertia.

In the left-hand panel of Fig. 1, we see a smooth increase in P_{GW} as the internal magnetic field strength grows, which corresponds to the peak in the first ellipticity probability density function (PDF) [49], shifting more and more to the right and thus allowing more support for higher ellipticites. There is little difference beyond $B_{int}/B_{ext} = 10^3$ because at this value the small "bump" in this PDF (at 10^{-8}) already contributes to P_{GW}, and the upper limits themselves are not sensitive enough to reach the peak ellipticity in the PDF. Our results are very sensitive to the tail of the distribution of the ellipticity PDF, since the upper limits tend to only comprise the two small bumps at 10^{-8} or 10^{-6}. Furthermore, at $B_{int}/B_{ext} = 10^4$, only a factor of ~ 6 separates the black and red curves, because even with the order of magnitude improvement in the upper limits when allowing $I_{zz} = 10^{39}$ kg m^2 versus $I_{zz} = 10^{38}$ kg m^2, the highest peak in the ellipticity PDF still does not contribute to P_{GW}.

In the right-hand panel of Fig. 1, when all rotational energy goes into gravitational waves, the moment of inertia does not play any role in determining P_{GW}. An order of magnitude increase in the moment of inertia only increases the possible ellipticity by a factor of $\sqrt{10} \sim 3$, which does

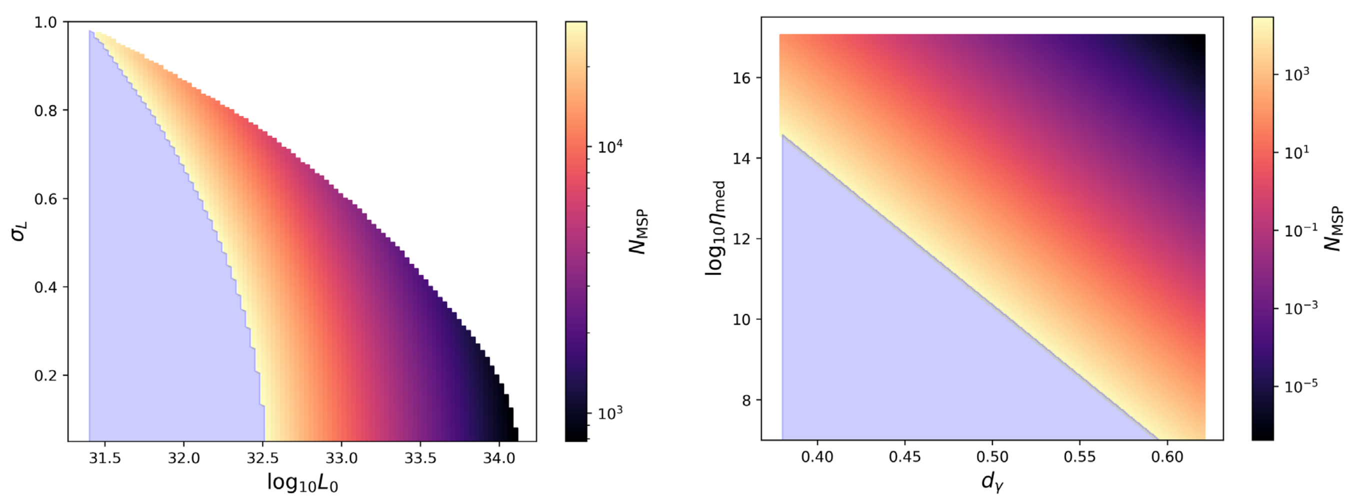

FIG. 2. Exclusion regions (light blue) based on the upper limits of the O3 freuquency-Hough all-sky search for the log-normal (left) and power-law (right) luminosity functions, employing a probability density function for the ellipticity that assumes 1% of the rotational energy loss of the star goes into gravitational waves. We take $d = 8$ kpc and $I_{zz} = 10^{38}$ kg m^2 in this analysis. The upper right white region on the left-hand plot has been excluded by *Fermi*.

not alter much the second ellipticity PDF [49]. Furthermore, allowing less and less rotational energy to be converted into gravitational waves has a sizable effect, since the ellipticity PDF [49] scales linearly with this fraction. Again, due to the sensitivity of P_{GW} to the tail of the ellipticity PDF, I_{zz} matters more for lower fractions than for higher ones.

As an example of what one can do with specific values of P_{GW}, we present our results in terms of exclusion regions in the parameter space of a pulsar luminosity function that explains the GeV excess given in Eqs. (3) and (4), in the left- and right-hand panels of Fig. 2, respectively. Here, we consider as a benchmark the "fixed fraction of gravitational-wave energy loss" model, in which 1% of the star's rotational energy is converted into gravitational waves, given by a blue diamond in Fig. 1. If a pair of luminosity function parameters [e.g., L_0, σ_L in Eq. (3), left-hand panel, and η_{med}, d_γ in Eq. (4), right-hand panel] results in to too many millisecond pulsars in the Galactic Center, such that at least one of them would have been detected in the O3 frequency-Hough all-sky search, we can rule out that point in the luminosity function parameter space. The benchmarks of a chosen set of parameters are labeled as blue diamonds in the Fig. 1 [49].

Conclusions.—In this Letter, we have, for the first time, presented gravitational-wave constraints on the millisecond pulsar hypothesis to explain the observed GeV excess by *Fermi* using LIGO-Virgo-KAGRA data. We used upper limits from the most recent frequency-Hough all-sky search to calculate the number of detectable millisecond pulsars for various luminosity function parameters, integrating over physically motivated distributions of rotational frequency and ellipticity. We considered two models for neutron-star deformation, one in which an internal magnetic field sustained the deformation, and another in which we were agnostic to the mechanism of deformation and instead assumed a fixed fraction of rotational energy loss via gravitational waves. For these two models, we computed the probability of detecting a gravitational-wave signal in a search of O3 data, and then excluded portions of the luminosity function parameter space for both models on the basis of null observations for particular parameter choices.

Our exclusion regions depend on (1) the ellipticity distributions we calculate, which themselves are functions of the external magnetic field or the fraction of the rotational energy we assume goes into gravitational waves, (2) the gravitational-wave frequency distribution we use, and (3) the moment of inertia. Furthermore, our results are valid for isolated neutron stars, which comprise about half of all known pulsars (the other half are in binary systems) [49].

In the future, all-sky gravitational-wave searches will be able to dig deeper into the noise at all frequencies; thus our constraints could be greatly improved. A factor of 5–10 improvement in the upper limits, expected in third-generation detectors [75,76], would allow us to almost completely exclude this luminosity function under the assumptions presented in this work. Furthermore, we plan to devise a template-based method to search for the GeV excess in the Galactic Center by weighting sky pixels by the expected spatial distribution of millisecond pulsars in each one. This approach should improve the sensitivity to millisecond pulsars, and would allow us to incorporate other aspects of millisecond pulsar astrophysics into our work, such as frequency or ellipticity distributions as a function of location. Our future work would also require using finer-resolution sky pixels to explore the inner parsec regions of the Galactic Center, which would add to the computational cost of such gravitational-wave searches and thus needs to be studied.

We also plan to combine the constraints inferred by *Fermi* and gravitational-wave detectors to probe more portions of the luminosity function parameter space. Furthermore, we could employ correlated frequency or ellipticity probability density functions, e.g., Ref. [77], that should be more representative of the underlying physics of gravitational-wave emission from millisecond pulsars. Our work therefore represents a major connection between neutron stars, gravitational waves, dark matter, and the Galactic-Center excess.

This material is based upon work supported by NSF's LIGO Laboratory which is a major facility fully funded by the National Science Foundation. We thank Bryn Haskell, Ian Jones, and Graham Woan for helpful discussions regarding how to construct ellipticity distributions from known millisecond pulsars. We also acknowledge the LIGO-Virgo-KAGRA continuous-wave group for helpful feedback on this project, including Rodrigo Tenorio for questions regarding the application of these results to millisecond pulsars in binary systems. All plots were made with the PYTHON tools MATPLOTLIB [78], NUMPY [79], and PANDAS [80,81]. A. L. M. is supported by a FSR Incoming Postdoctoral Fellowship. Y. Z. is supported by the U.S. Department of Energy under Award No. DESC0009959.

[*]andrew.miller@nikhef.nl
[†]zhaoyue@physics.utah.edu

[1] L. Goodenough and D. Hooper, arXiv:0910.2998.
[2] D. Hooper and L. Goodenough, Phys. Lett. B **697**, 412 (2011).
[3] D. Hooper and T. Linden, Phys. Rev. D **84**, 123005 (2011).
[4] C. Gordon and O. Macias, Phys. Rev. D **88**, 083521 (2013); **89**, 049901(E) (2014).
[5] T. Daylan, D. P. Finkbeiner, D. Hooper, T. Linden, S. K. N. Portillo, N. L. Rodd, and T. R. Slatyer, Phys. Dark Universe **12**, 1 (2016).
[6] F. Calore, I. Cholis, C. McCabe, and C. Weniger, Phys. Rev. D **91**, 063003 (2015).
[7] K. N. Abazajian, N. Canac, S. Horiuchi, and M. Kaplinghat, Phys. Rev. D **90**, 023526 (2014).

[8] J. Petrović, P. D. Serpico, and G. Zaharijaš, J. Cosmol. Astropart. Phys. 10 (2014) 052.
[9] E. Carlson and S. Profumo, Phys. Rev. D **90**, 023015 (2014).
[10] I. Cholis, C. Evoli, F. Calore, T. Linden, C. Weniger, and D. Hooper, J. Cosmol. Astropart. Phys. 12 (2015) 005.
[11] K. N. Abazajian, J. Cosmol. Astropart. Phys. 03 (2011) 010.
[12] F. Calore, I. Cholis, and C. Weniger, J. Cosmol. Astropart. Phys. 03 (2015) 038.
[13] Q. Yuan and B. Zhang, J. High Energy Astrophys. **3–4**, 1 (2014).
[14] J. Petrović, P. D. Serpico, and G. Zaharijas, J. Cosmol. Astropart. Phys. 02 (2015) 023.
[15] C. S. Ye and G. Fragione, Astrophys. J. **940**, 162 (2022).
[16] O. Macias, C. Gordon, R. M. Crocker, B. Coleman, D. Paterson, S. Horiuchi, and M. Pohl, Nat. Astron. **2**, 387 (2018).
[17] R. Bartels, E. Storm, C. Weniger, and F. Calore, Nat. Astron. **2**, 819 (2018).
[18] O. Macias, S. Horiuchi, M. Kaplinghat, C. Gordon, R. M. Crocker, and D. M. Nataf, J. Cosmol. Astropart. Phys. 09 (2019) 042.
[19] M. Pohl, O. Macias, P. Coleman, and C. Gordon, Astrophys. J. **929**, 136 (2022).
[20] M. Di Mauro, Phys. Rev. D **103**, 063029 (2021).
[21] I. Cholis, Y.-M. Zhong, S. D. McDermott, and J. P. Surdutovich, Phys. Rev. D **105**, 103023 (2022).
[22] S. K. Lee, M. Lisanti, and B. R. Safdi, J. Cosmol. Astropart. Phys. 05 (2015) 056.
[23] S. K. Lee, M. Lisanti, B. R. Safdi, T. R. Slatyer, and W. Xue, Phys. Rev. Lett. **116**, 051103 (2016).
[24] M. Buschmann, N. L. Rodd, B. R. Safdi, L. J. Chang, S. Mishra-Sharma, M. Lisanti, and O. Macias, Phys. Rev. D **102**, 023023 (2020).
[25] R. K. Leane and T. R. Slatyer, Phys. Rev. Lett. **123**, 241101 (2019).
[26] R. K. Leane and T. R. Slatyer, Phys. Rev. Lett. **125**, 121105 (2020).
[27] R. K. Leane and T. R. Slatyer, Phys. Rev. D **102**, 063019 (2020).
[28] D. Hooper, I. Cholis, T. Linden, J. M. Siegal-Gaskins, and T. R. Slatyer, Phys. Rev. D **88**, 083009 (2013).
[29] D. Hooper and T. Linden, J. Cosmol. Astropart. Phys. 08 (2016) 018.
[30] H. Ploeg, C. Gordon, R. Crocker, and O. Macias, J. Cosmol. Astropart. Phys. 12 (2020) 035; 07 (2021) E01.
[31] F. List, N. L. Rodd, and G. F. Lewis, Phys. Rev. D **104**, 123022 (2021).
[32] A. Gautam, R. M. Crocker, L. Ferrario, A. J. Ruiter, H. Ploeg, C. Gordon, and O. Macias, Nat. Astron. **6**, 703 (2022).
[33] I. Cholis, D. Hooper, and T. Linden, J. Cosmol. Astropart. Phys. 06 (2015) 043.
[34] D. Haggard, C. Heinke, D. Hooper, and T. Linden, J. Cosmol. Astropart. Phys. 05 (2017) 056.
[35] J. Berteaud, F. Calore, M. Clavel, P. D. Serpico, G. Dubus, and P.-O. Petrucci, Phys. Rev. D **104**, 043007 (2021).
[36] O. Macias, H. van Leijen, D. Song, S. Ando, S. Horiuchi, and R. M. Crocker, Mon. Not. R. Astron. Soc. **506**, 1741 (2021).
[37] F. Calore, M. Di Mauro, F. Donato, J. W. T. Hessels, and C. Weniger, Astrophys. J. **827**, 143 (2016).
[38] G. Woan, M. D. Pitkin, B. Haskell, D. I. Jones, and P. D. Lasky, Astrophys. J. Lett. **863**, L40 (2018).
[39] J. Aasi *et al.* (The LIGO Scientific Collaboration), Classical Quantum Gravity **32**, 074001 (2015).
[40] F. Acernese, M. Agathos, K. Agatsuma, D. Aisa, N. Allemandou, A. Allocca, J. Amarni, P. Astone, G. Balestri, G. Ballardin *et al.*, Classical Quantum Gravity **32**, 024001 (2015).
[41] Y. Aso, Y. Michimura, K. Somiya, M. Ando, O. Miyakawa, T. Sekiguchi, D. Tatsumi, and H. Yamamoto (The KAGRA Collaboration), Phys. Rev. D **88**, 043007 (2013).
[42] F. Calore, T. Regimbau, and P. D. Serpico, Phys. Rev. Lett. **122**, 081103 (2019).
[43] D. Agarwal, J. Suresh, V. Mandic, A. Matas, and T. Regimbau, Phys. Rev. D **106**, 043019 (2022).
[44] R. Abbott *et al.* (LIGO Scientific, VIRGO, and KAGRA Collaborations), Phys. Rev. D **106**, 102008 (2022).
[45] P. Astone, A. Colla, S. D'Antonio, S. Frasca, and C. Palomba, Phys. Rev. D **90**, 042002 (2014).
[46] The O3a all-sky binary SkyHough search [47] only analyzed gravitational-wave frequencies up to 300 Hz, and did not consider a frequency derivative term in the gravitational-wave waveform, which limits the search sensitivity to, at best, 1–2 kpc for $\epsilon = 10^{-4}$, and to much lower distances for smaller ellipticities, which are expected for millisecond pulsars.
[47] R. Abbott *et al.* (LIGO Scientific and Virgo Collaborations), Phys. Rev. D **103**, 064017 (2021).
[48] L. Jiang, N. Wang, W.-C. Chen, X.-D. Li, W.-M. Liu, and Z.-F. Gao, Astron. Astrophys. **633**, A45 (2020).
[49] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.131.081401 to understand which binary millisecond pulsar systems our results apply to; for the distribution of gravitational-wave frequencies and ellipticities that were used, the former of which comes from the Australian Telescope National Facility catalog; for the probability distribution of ellipticity, assuming an external magnetic field distribution reported in the ATNF catalog and a fixed fraction of energy loss; for more information about the luminosity functions used in this work; for more information about how we specialize all-sky upper limits to the Galactic Center, as well as how we convert strain amplitude to neutron-star ellipticity; and for more information about how our exclusion regions vary as a function of different parameter choices, which includes Refs. [50–53].
[50] T. M. Tauris *et al.*, Astrophys. J. **846**, 170 (2017).
[51] B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), Phys. Rev. D **100**, 024004 (2019).
[52] Z. Botev, Kernel density estimation, https://www.mathworks.com/matlabcentral/fileexchange/17204-kernel-density-estimation (2023).
[53] P. Jaranowski, A. Królak, and B. F. Schutz, Phys. Rev. D **58**, 063001 (1998).
[54] M. Maggiore, *Gravitational Waves: Theory and Experiments* (Oxford University Press, New York, 2008), Vol. 1.

[55] A. W. Steiner, S. Gandolfi, F. J. Fattoyev, and W. G. Newton, Phys. Rev. C **91**, 015804 (2015).

[56] C. Breu and L. Rezzolla, Mon. Not. R. Astron. Soc. **459**, 646 (2016).

[57] F. De Lillo, J. Suresh, and A. L. Miller, Mon. Not. R. Astron. Soc. **513**, 1105 (2022).

[58] R. Abbott *et al.* (LIGO Scientific, Virgo, and KAGRA Collaborations), Astrophys. J. **913**, L27 (2021).

[59] S. K. Lander, N. Andersson, and K. Glampedakis, Mon. Not. R. Astron. Soc. **419**, 732 (2012).

[60] A. Mastrano and A. Melatos, Mon. Not. R. Astron. Soc. **421**, 760 (2012).

[61] S. K. Lander, Mon. Not. R. Astron. Soc. **437**, 424 (2014).

[62] G. Ushomirsky, C. Cutler, and L. Bildsten, Mon. Not. R. Astron. Soc. **319**, 902 (2000).

[63] C. J. Horowitz and K. Kadau, Phys. Rev. Lett. **102**, 191102 (2009).

[64] M. Maggiore, *Gravitational Waves: Astrophysics and Cosmology* (Oxford University Press, New York, 2018), Vol. 2.

[65] S. Chandrasekhar and E. Fermi, Astrophys. J. **118**, 116 (1953); **122**, 208(E) (1955).

[66] R. Abbott *et al.* (LIGO Scientific and Virgo Collaborations), Astrophys. J. Lett. **902**, L21 (2020).

[67] R. Ciolfi and L. Rezzolla, Mon. Not. R. Astron. Soc. **435**, L43 (2013).

[68] B. Haskell, M. Priymak, A. Patruno, M. Oppenoorth, A. Melatos, and P. D. Lasky, Mon. Not. R. Astron. Soc. **450**, 2393 (2015).

[69] R. N. Manchester, G. B. Hobbs, A. Teoh, and M. Hobbs, Astron. J. **129**, 1993 (2005).

[70] M. Vigelius and A. Melatos, Mon. Not. R. Astron. Soc. **395**, 1985 (2009).

[71] M. Priymak, A. Melatos, and D. J. B. Payne, Mon. Not. R. Astron. Soc. **417**, 2696 (2011).

[72] J. T. Dinsmore and T. R. Slatyer, J. Cosmol. Astropart. Phys. 06 (2022) 025.

[73] O. J. Piccinni, P. Astone, S. D'Antonio, S. Frasca, G. Intini, P. Leaci, S. Mastrogiovanni, A. Miller, C. Palomba, and A. Singhal, Classical Quantum Gravity **36**, 015008 (2019).

[74] R. Abbott *et al.* (KAGRA, VIRGO, and LIGO Scientific Collaborations), Phys. Rev. D **106**, 042003 (2022).

[75] M. Punturo, M. Abernathy, F. Acernese, B. Allen, N. Andersson, K. Arun, F. Barone, B. Barr, M. Barsuglia, M. Beker *et al.*, Classical Quantum Gravity **27**, 194002 (2010).

[76] D. Reitze, R. X. Adhikari, S. Ballmer, B. Barish, L. Barsotti, G. Billingsley, D. A. Brown, Y. Chen, D. Coyne, R. Eisenstein *et al.*, Bull. Am. Astron. Soc. **51**, 035 (2019).

[77] B. Haskell, M. Antonelli, and P. Pizzochero, Universe **8**, 619 (2022).

[78] J. D. Hunter, Comput. Sci. Eng. **9**, 90 (2007).

[79] C. R. Harris *et al.*, Nature (London) **585**, 357 (2020).

[80] Wes McKinney, in *Proceedings of the 9th Python in Science Conference*, edited by Stéfan van der Walt and Jarrod Millman (2010), pp. 56–61, https://conference.scipy.org/proceedings/scipy2010/mckinney.html.

[81] T. Pandas Development Team, pandas-dev/pandas: PANDAS (2020), https://zenodo.org/record/8092754.