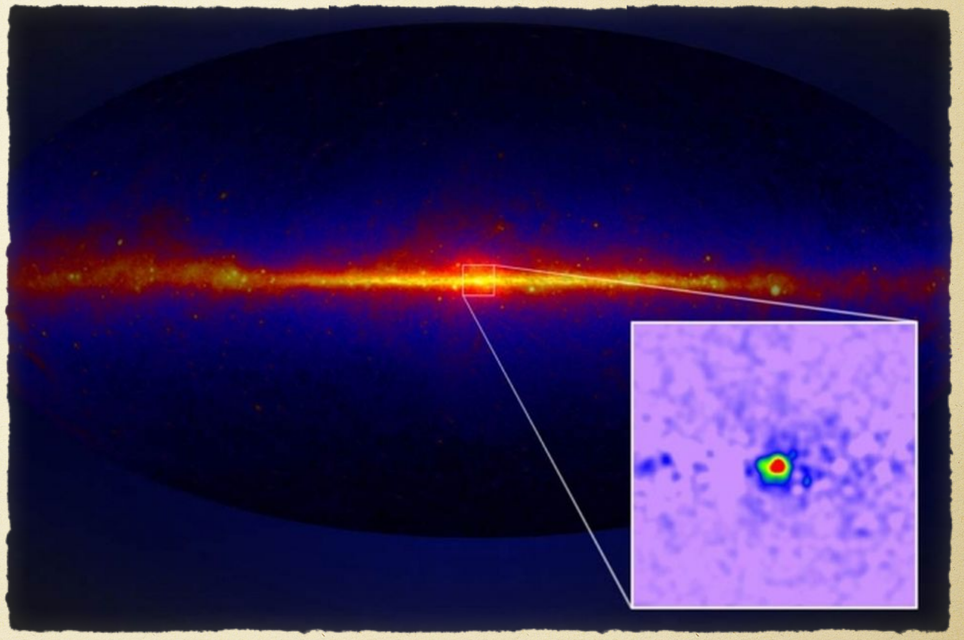
Gravitational-wave constraints on the GeV excess in the galactic center

Andrew L. Miller and Yue Zhao

What is the GeV excess?

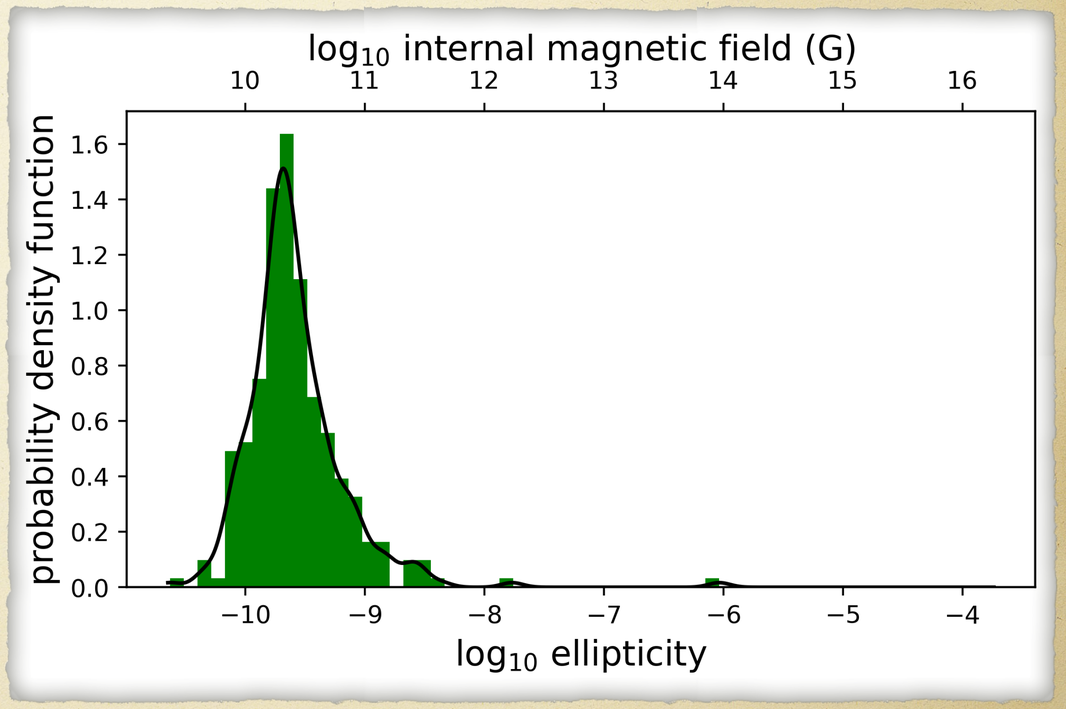
- Fermi-LAT saw a "Galactic Center Gamma-Ray Excess": more γ-rays in the galactic center (center circle)
- Generated by cosmic rays interacting with interstellar medium (gas and radiation field)
- One possible explanation: unresolved population of MSPs
  - But if so, how many?



- Fermi-LAT map (in galactic coordinates), 2009-2013, showing energies > 1 GeV

If MSPs exist in galactic center…

- Continuous gravitational waves, quasi-monochromatic, persistent signals, could be emitted from deformed MSPs
  - Internal magnetic field, buried through accretion, breaks the crust, resulting in small deformations (relative to those in young pulsars)
- $\epsilon \approx 10^{-8} \left(\frac{B_{\rm int}}{10^{12}\,{\rm G}} \right)$ [LVK: ApjL 902.1 (2020): L21]



- Ellipticity PDF for deformations sustained by a magnetic field from ATNF catalog, $B_{\rm int} = 100 B_{\rm ext}$

Modeling the MSP GeV excess

- We use a log-normal distribution, with central value L_0 and width σ_L for the luminosity function of MSPs that could explain the GeV excess
  [Hooper et al. Journal of Cosmology and Astroparticle Physics 2016.03 (2016): 049.]

- Varying these two parameters allows one to obtain the number of MSPs needed to explain the GeV excess

$$P(L) = \frac{\log_{10} e}{\sigma_L \sqrt{2\pi} L} \exp\left(-\frac{(\log_{10} L - \log_{10} L_0)^2}{2\sigma_L^2} \right)$$

$$N_{\mathrm{MSP}} = \frac{L_{\mathrm{GCE}}}{\int_{L_{\mathrm{min}}}^{\infty} L P(L) dL}$$

$$L_{\mathrm{GCE}} \approx 10^{37} \mathrm{erg/s}$$

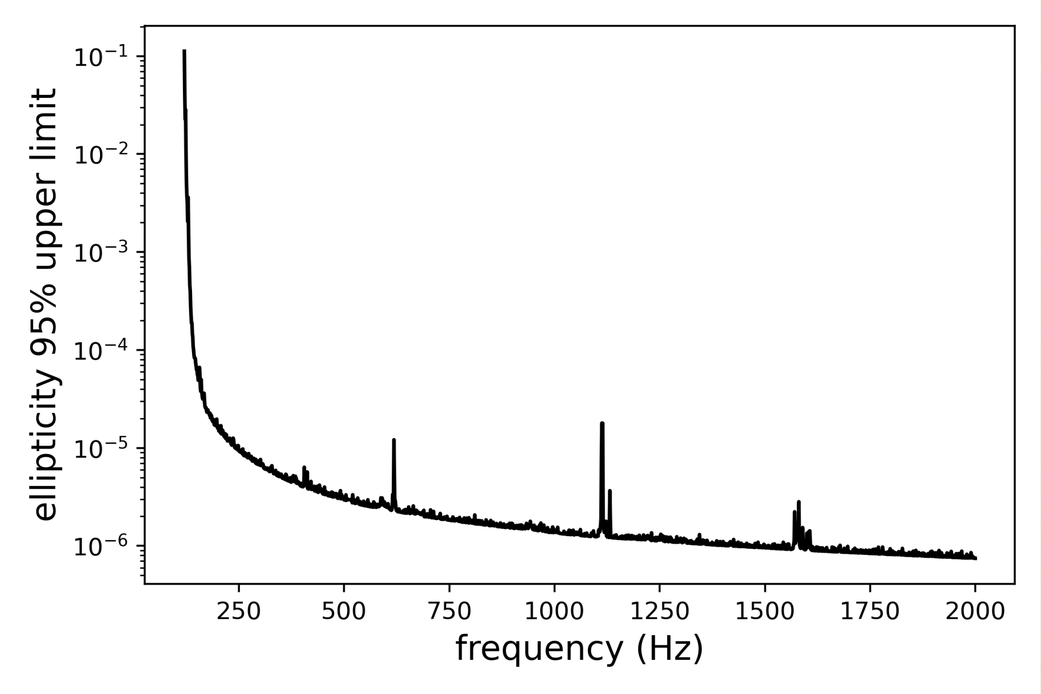
Based on Fermi flux measurements and model for number density of MSPs

Method: Calculate how many MSPs we could have seen in O3?

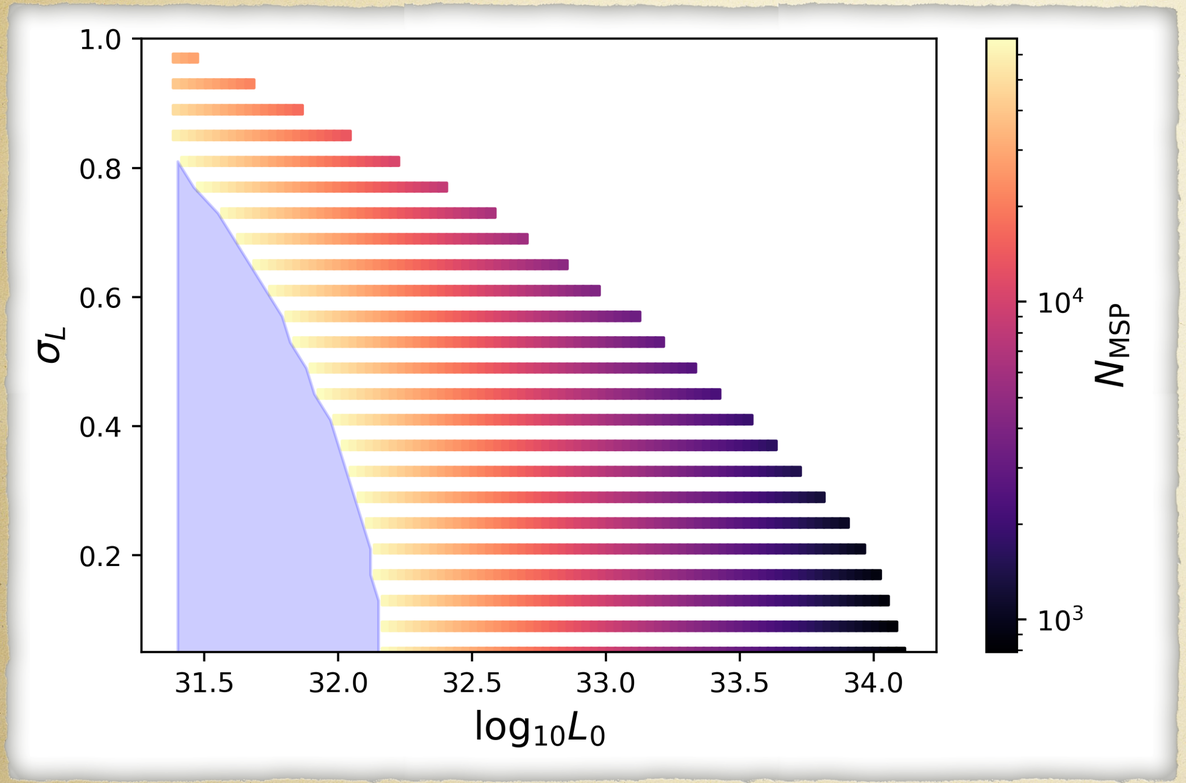
- Choose L_0 and $\sigma_L \rightarrow N_{\mathrm{MSP}}$
- Calculate probability of detecting GWs from a MSP in the galactic center using upper limits from searches for neutron stars in the galactic center and integrating over known frequency distribution of MSPs and ellipticity distribution due to magnetic strains, derived from ATNF catalog parameters:

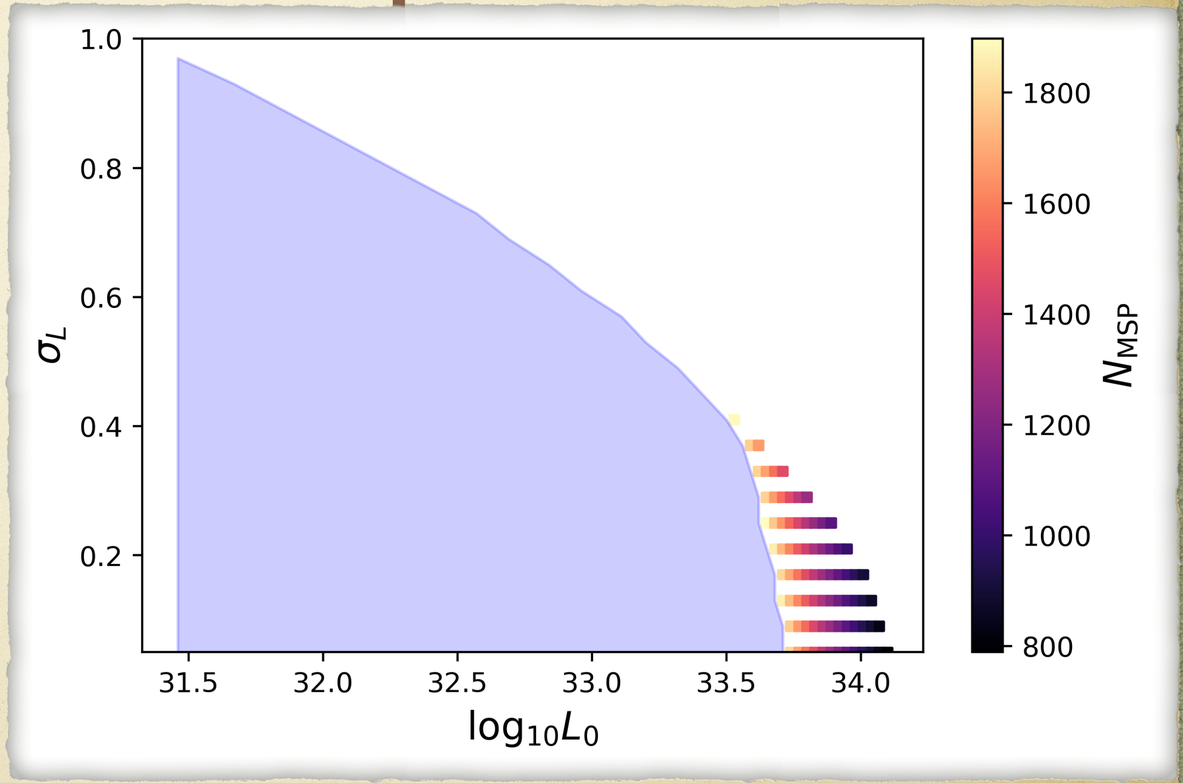
$$P_{\mathrm{GW}} = \int_{\log_{10} f_{\mathrm{min}}}^{\log_{10} f_{\mathrm{max}}} d\log_{10} f P(\log_{10} f) \times \int_{\log_{10} \epsilon_{\mathrm{UL}}}^{0} d\log_{10} \epsilon P(\log_{10} \epsilon)$$

- Exclude a certain choice of L_0 and σ_L if $N_{\mathrm{GW}} = P_{\mathrm{GW}} N_{\mathrm{MSP}} > 1$



Results: exclusion plots





- For $B_{\rm int} = 100 B_{\rm ext}$; $I_{zz} = 10^{38}$ kg m^2 and $I_{zz} = 5 \times 10^{38}$ kg m^2
- Fermi constraints are the white portions of this parameter space

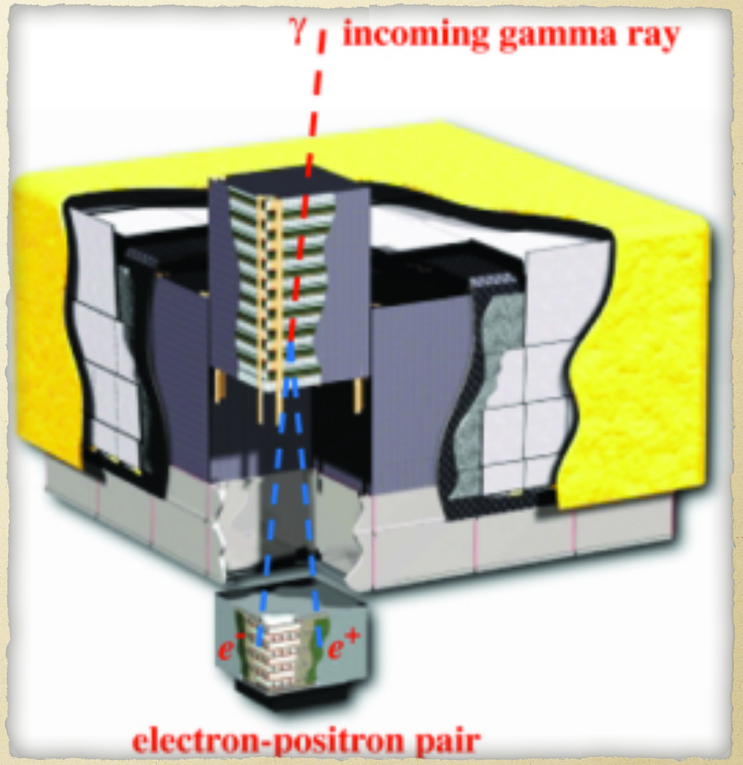
Conclusions

- Searches for CWs can provide insight into whether MSPs can explain the GeV excess, and can actually exclude large portion of the parameter space that is inaccessible to Fermi
- Constraints are conservative: only $\mathcal{O}(1\%)$ of neutron star's rotational energy needs to be converted to GWs for our constraints to be valid
- Method assumes *known* pulsar frequency and magnetic field distributions are indicative of the 10^9 *unknown* pulsars in the galaxy
- Constraints calculated from all-sky search vary by less than $\mathcal{O}(1)$

Back-up slides

Fermi-LAT

- Pair conversion gamma-ray telescope, in range ~[20 MeV, 300 GeV]
- Incoming γ-ray interacts with tungsten —> $e^{\pm}$ pair
- Silicon strips track $e^{\pm}$ in the detector —> direction of γ-ray
- Calorimeter stops $e^{\pm}$—> energy of γ-ray
- Angular resolution varies with γ-ray energy, [3.5°,0.15°] at [0.1,10] GeV

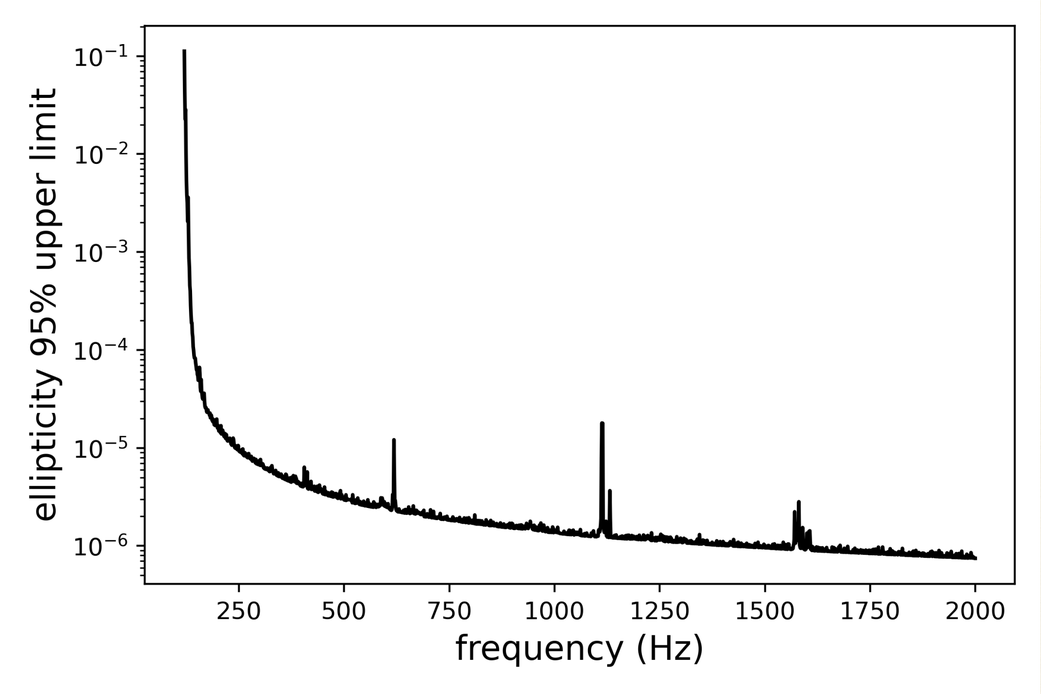


Possible causes of GeV excess

- Generated by cosmic rays interacting with interstellar medium (gas and radiation field)
- Bremsstrahlung of cosmic ray electrons with the interstellar gas
- Pion production from cosmic-ray protons colliding with the interstellar gas
- Inverse Compton scattering of cosmic-ray off interstellar radiation field

Galactic center (GC) O3 search

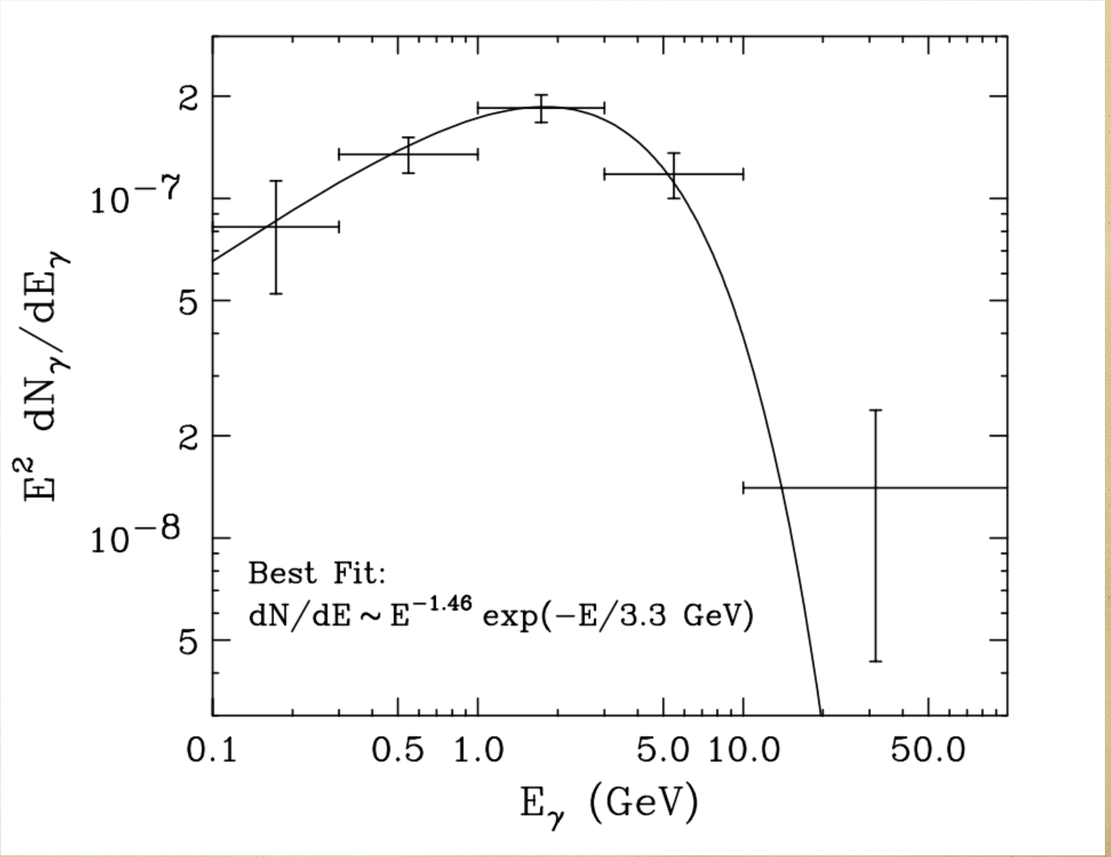
- MSPs residing in the galactic center could be detected via their GW emission
- The strength of their internal magnetic fields could determine the size of their deformations, which would result in GWs
- We could use O3 Galactic center upper limits to contribute to the GeV excess debate. To do this, we assume an ellipticity distribution of GC MSPs
  - In this work, we take ellipticities derived from MSP parameters in the ATNF catalog
- Search has very fine sky resolution: ~25-150 pc



[LVK: arXiv:2204.04523]

Spectrum of MSPs seen at Fermi

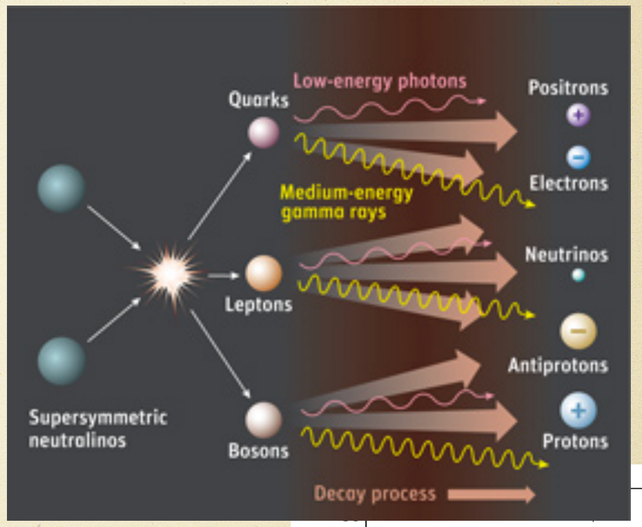
- Gamma-ray spectrum for 37 MSPs observed by Fermi
- Best fit to data standard for pulsars
- Initially: MSPs can't account for >10% of the GeV excess, since their spectra are too soft at sub-GeV energies, despite model fine-tuning (varying magnetic field, spatial distribution of MSPs, etc.)
- But, when accounting for distance uncertainties of MSPs to galactic center, MSP hypothesis can't be ruled out

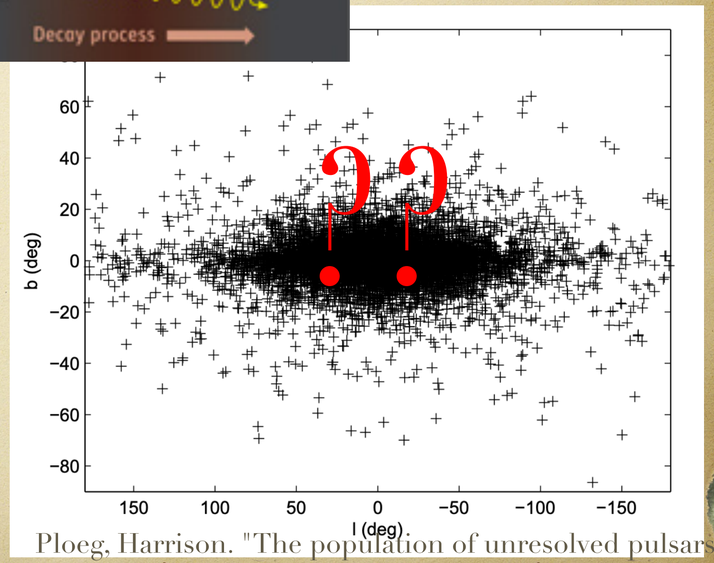


Hooper, et al. Physical Review D 88.8 (2013): 083009.

Explanations for the GeV excess

- Annihilating dark matter
  - Observed flux spectra could be explained by a WIMP with a mass of [30,60] GeV, with dark matter —> leptons, quarks, or mixtures
- Unresolvable population of millisecond pulsars in binary systems
  - One photon pair production —> $e^{\pm}$ that are accelerated along $\vec{E}$ field lines; $e^{\pm}$ follow $\vec{B}$ field lines and therefore lose energy along the track —> γ-rays in Fermi
  - Spectra of γ-rays detected from pulsars in 4 out of 8 globular clusters studied consistent with Fermi-LAT's spectra (Abazajian, Kevork N. Journal of Cosmology and Astroparticle Physics 2011.03 (2011): 010.)
  - Inverse Compton scattering of $e^{\pm}$

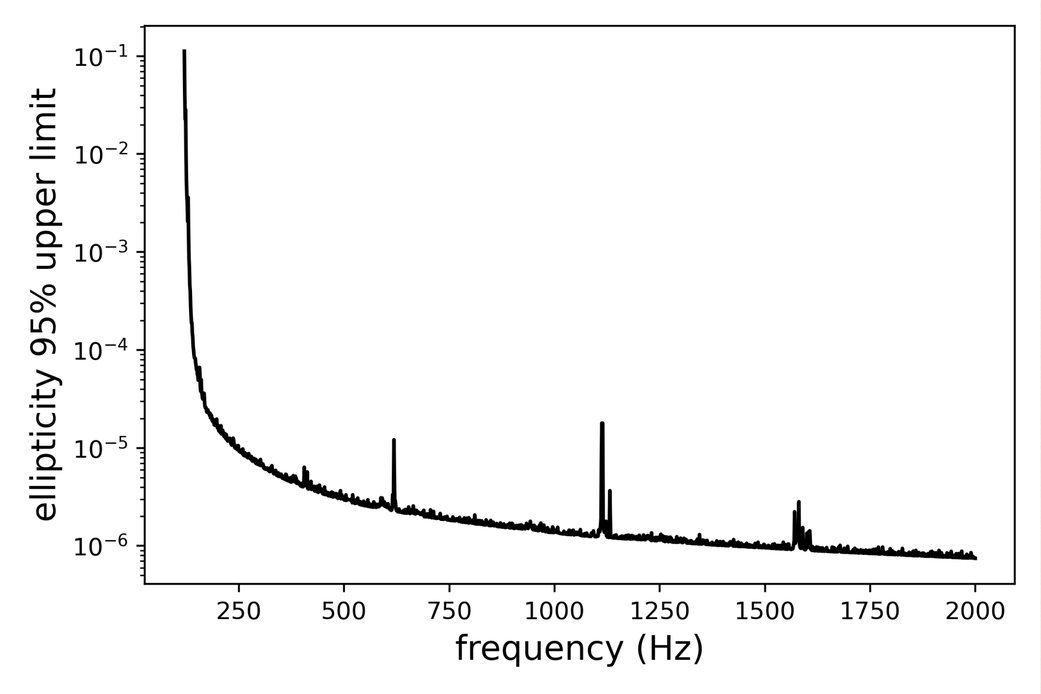




Ploeg, Harrison. "The population of unresolved pulsars explanation of the Galactic Center excess." (2017).

Galactic center (GC) O3 search

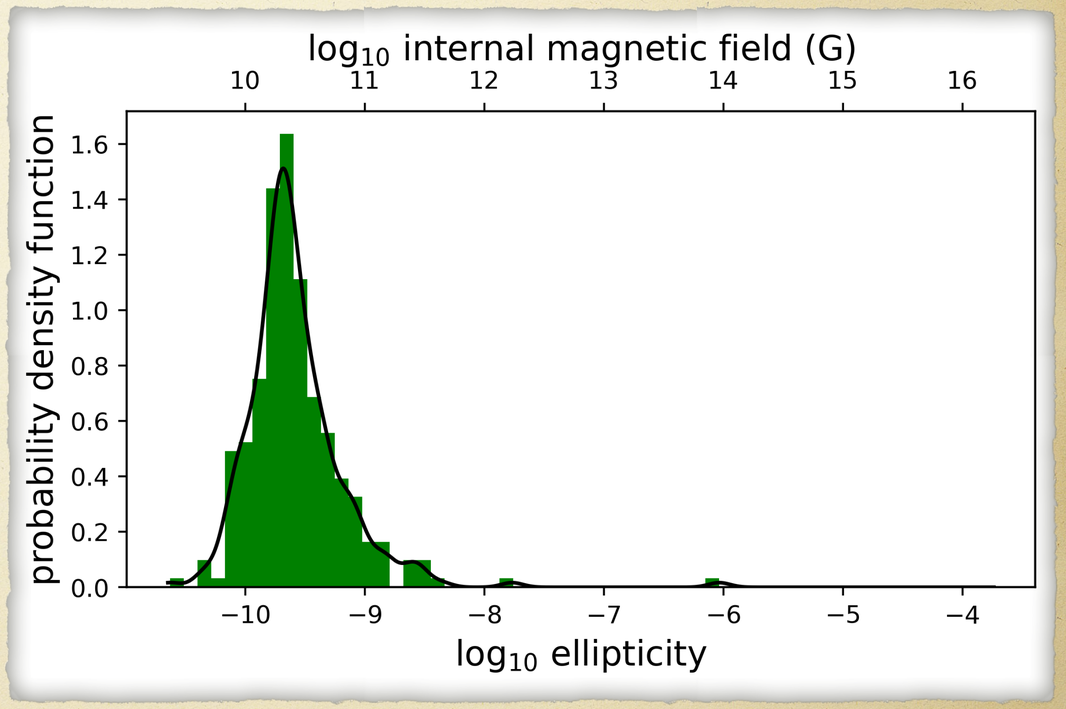
- MSPs residing in the galactic center could be detected via their GW emission
- The strength of their internal magnetic fields could determine the size of their deformations, which would result in GWs
- We could use O3 Galactic center upper limits to contribute to the GeV excess debate. To do this, we assume an ellipticity distribution of GC MSPs
  - In this work, we take ellipticities derived from MSP parameters in the ATNF catalog
- Search has very fine sky resolution: ~25-150 pc



[LVK: arXiv:2204.04523]

Assuming magnetic strains

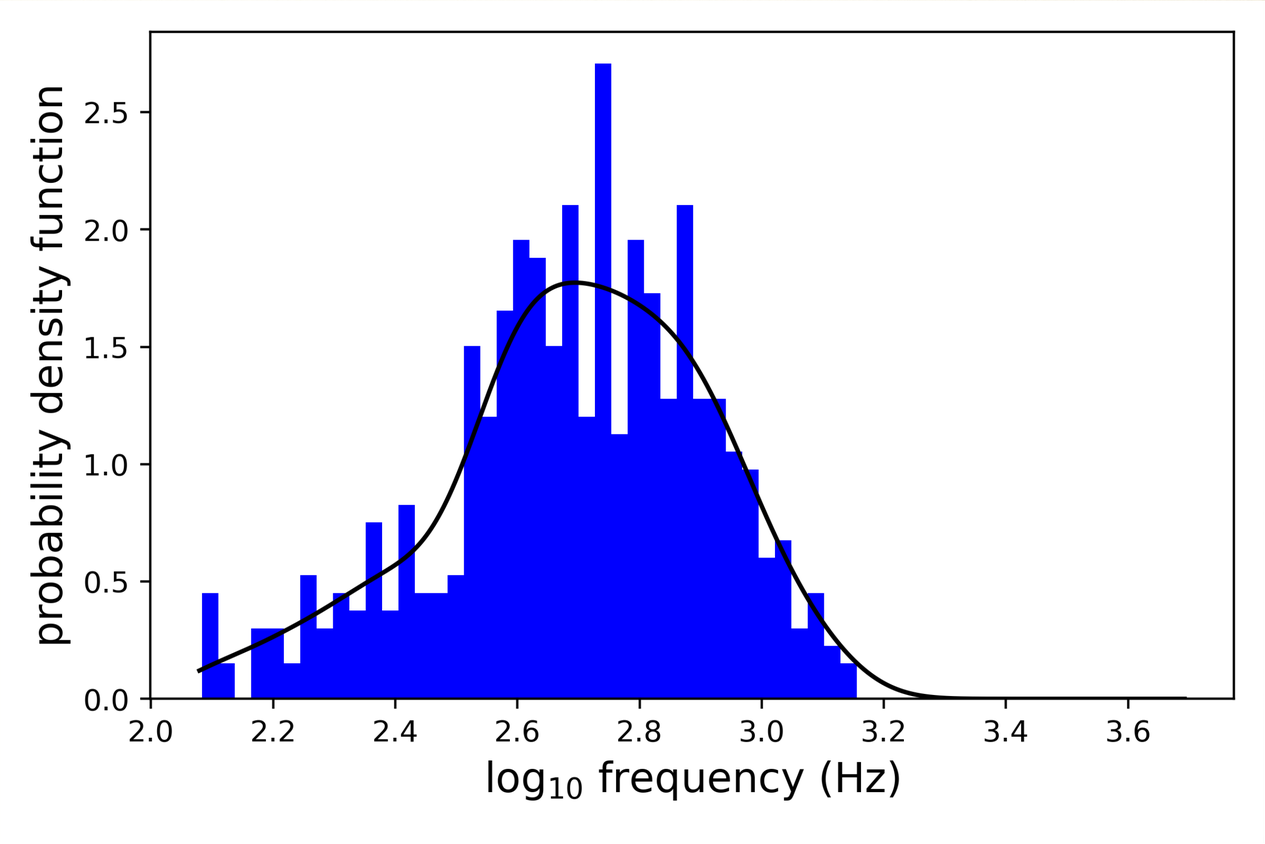
- Internal magnetic field, buried through accretion, breaks the crust, resulting in small deformations (relative to those in young pulsars)
- We know the upper limits on ellipticity, the number of expected MSPs Fermi should have seen, and the ellipticity distribution
- $\epsilon \approx 10^{-8} \left(\frac{B_{\rm int}}{10^{12}\,{\rm G}} \right)$ [LVK: ApjL 902.1 (2020): L21]



- Ellipticity PDF for deformations sustained by a magnetic field, $B_{\rm int} = 100 B_{\rm ext}$

Integrating over frequency

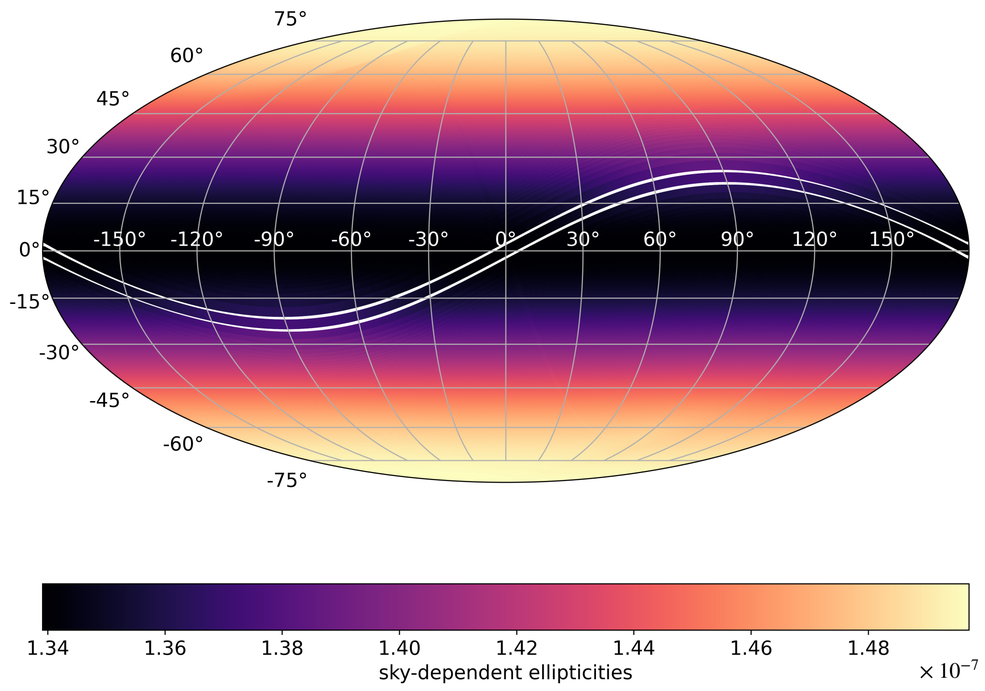
- Frequency distribution comes from ATNF catalog, in which we have selected only rotational frequencies above 60 Hz



Sky-dependence

- If we consider upper limits from the O3 all-sky search, we can, at a fixed frequency, create a skymap of the ellipticity distribution [Limits from LVK: arXiv: 2201.00697]
- In the future, we could perform a template-weighted search according to an MSP distribution function to improve sensitivity
- Equal footing as GC search - directional vs. all-sky constraints are comparable - definitely don't change by order of magnitude

- $f = 2000$ Hz, $d = 1$ kpc, $\epsilon_{\mathrm{UL}} = 1.4 \times 10^{-7}$, $I_{zz} = 10^{38}$ kg $\cdot$ m^2



- Upper limits averaged over polarization & inclination angles