Estimating the gamma-ray pulsar population with the Fermi-LAT blind search sensitivity

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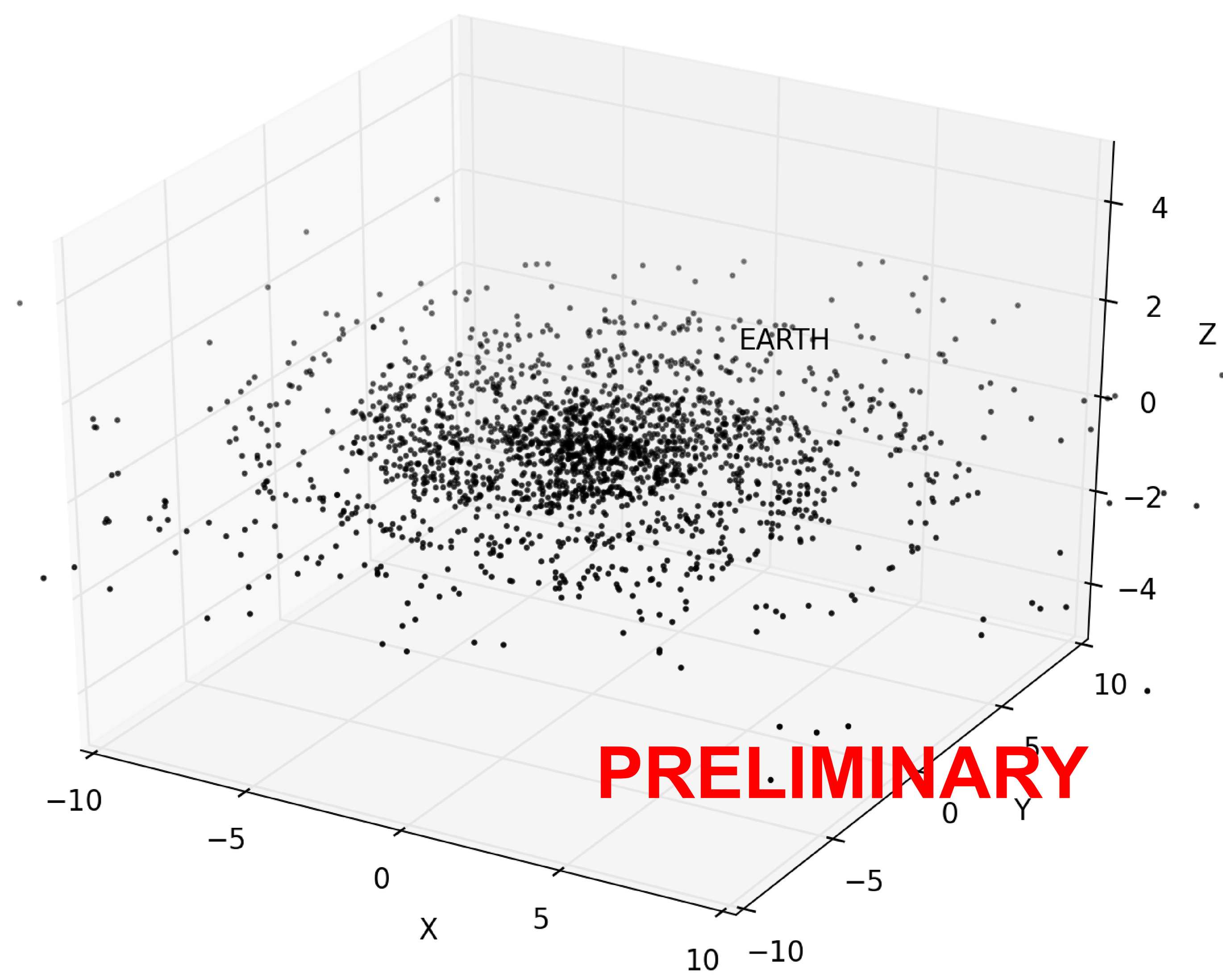

Figure 1: Birth distribution of a simulated pulsar population, with the Solar System located at (0, 8.5, 0) kpc. Only 5,000 pulsars are plotted to illustrate the spiral-arm structure, which is still present in the young pulsars that have not moved far.

Abstract

The number of gamma-ray pulsars discovered in blind frequency searches of Fermi-LAT photon data raises the question of how many pulsars are in our Galaxy, as well as the pulsars' underlying energy and spatial distribution. By using a Galactic pulsar distribution[1] and assuming a pulse profile and spectrum similar to those previously detected in blind searches, along with an understanding of the Fermi-LAT blind search sensitivity[2], we can estimate the underlying birth characteristics of pulsars. We present results on this pulsar population study, including estimations of population size and initial spin-down energy distribution. Assuming a magnetic field distribution sampled according to the known blind search pulsars, we can rule out a birth distribution of $\dot{E} < 10^{37}$ erg s^{-1} and $\dot{E} > 10^{40}$ erg s^{-1} at $p < 0.05$.

Galactic pulsar population

Isolated neutron stars are thought to be formed in core-collapse supernova events where Population I stars lying in the arms of spiral galaxies die. We expect birth locations of pulsars to be highly correlated with the Galactic spiral arms[3] (see figure 1). We use a right-handed Cartesian frame, and model the spatial distribution of the birth locations by four major arm centroids whose loci are described analytically by[1,4]:

$$\theta(r) = k \ln\left(\frac{r}{r_0}\right) + \theta_0 \qquad \rho(r) = A\left(\frac{r+R_1}{R_\odot + R_1}\right)^a e^{-b\left(\frac{r-R_\odot}{R_\odot+R_1}\right)}$$

We evolve the pulsars according to the Galactic potential[5]:

$$\phi_{dh}(r,z) = \frac{-GM_{dh}}{\sqrt{\left(a_G + \sum_{i=1}^{3}\beta_i\sqrt{z^2+h_i^2}\right)^2 + b_{dh}^2 + r^2}} \qquad \phi_{b,n}(r) = \frac{-GM_{b,n}}{\sqrt{b_{b,n}^2 + r^2}} \qquad -\nabla\phi_G(r,z) = -\frac{\partial\phi_G}{\partial r}\hat{r} - \frac{\partial\phi_G}{\partial z}\hat{z}$$

The pulsars are aged to a random time between birth and the radio death line[6], below which pulsars are no longer energetic enough to power the radio emission. This extension is to explore the possible *gamma-ray death line*.

Pulsar spin evolution

A pulsar is born with a large non-infinite spin frequency which decreases due to magnetic braking via:

$$\frac{1}{2f^2} - \frac{1}{2f_0^2} = B_0^2 \frac{3c^3}{32\pi^4}\frac{I}{R^6} = \frac{B_0^2}{(3.2\times10^{19})^2}t$$

Here we assume a constant magnetic field due to most decay constants being larger than the age of most gamma-ray pulsars[7]. We calculate the flux above 100 MeV and luminosity assuming the L ~ Ė$^{1/2}$ according to the following equations[8]:

$$F_{100} = \frac{L}{4\pi d^2} = \frac{C\sqrt{10^{33}\times\dot{E}}}{4\pi d^2} \qquad L \simeq w\dot{E} = C\left(\frac{\dot{E}}{10^{33}\ \mathrm{erg\ s^{-1}}}\right)^{\frac{1}{2}} \times 10^{33}\ \mathrm{erg\ s^{-1}}$$

We assume a spectral model distribution & pulse profile drawn from the detected gamma-ray pulsar distribution[9] and use the blind search sensitivity[2] to estimate the probability of detection.

Population comparison

We sampled birth Ė populations in a grid of ($36 \le \log_{10}\dot{E} \le 41$), ($0.1 \le \sigma \le 1.1$) and compared the present-day spin-down energy (Ė), frequency (f), and frequency spin-down (f1) populations with those of the known blind search populations using the Kolmogorov-Smirnov test (KS-test)[10] (figure 2). We can rule out $\dot{E} < 10^{37}$ erg s^{-1} and $\dot{E} > 10^{40}$ erg s^{-1} as viable birth models (probability < 0.05). Since pulsars are aged to the radio death line, many less energetic pulsars are detected in the blind search, and many highly energetic pulsars are detected, even though their spin-down energy is far above the Crab pulsar ($\dot{E} = 4 \times 10^{38}$ erg s^{-1}) (see figure 3).

Radio populations use pulsar birth models with low birth periods compared to those detected in gamma-rays. Using a typical model of μ_P = 300 Ms and σ_P = 150 ms[1], we detect a population that we can reject as the birth distribution of gamma-ray pulsars (see figure 4). Finally, we estimate the number of Galactic pulsars to be about 2 x 10^6, larger than previous radio studies[1,4].

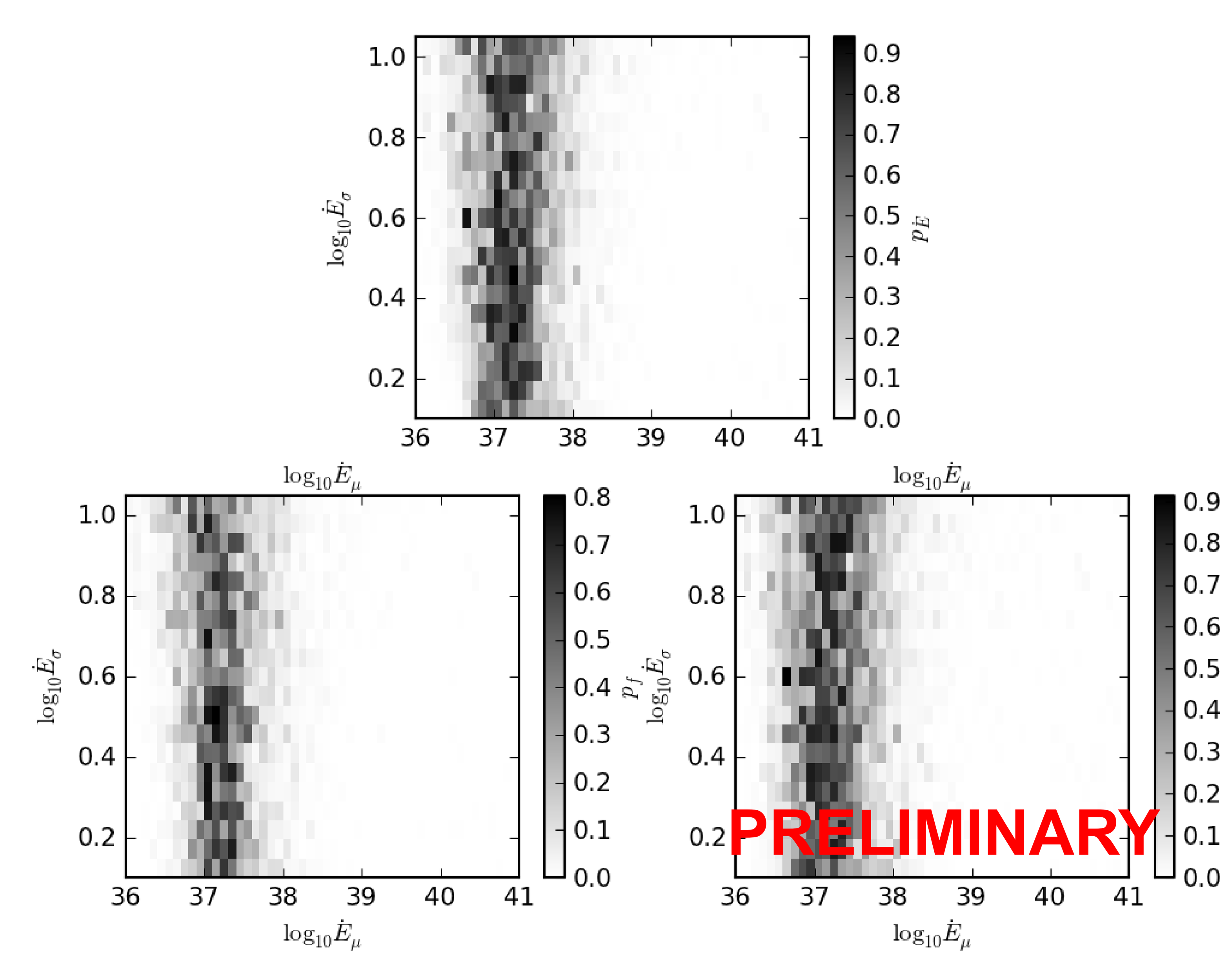

Figure 2: Kolmogorov-Smirnov (KS) p-value distribution of different pulsar birth models in a grid of $\log_{10}\dot{E}$: ($36.0 \le \log_{10}\dot{E} \le 41.0$), ($0.1 \le \sigma \le 1.0$). Here, we can reject pulsar birth models that are very low ($\dot{E} < 10^{37}$ erg s^{-1}) and very high ($\dot{E} > 10^{40}$ erg s^{-1}) with high significance ($p < 0.05$). The B-fields (upper right) were sampled according to the known blind search pulsar distribution, and have very high p-values, as expected.

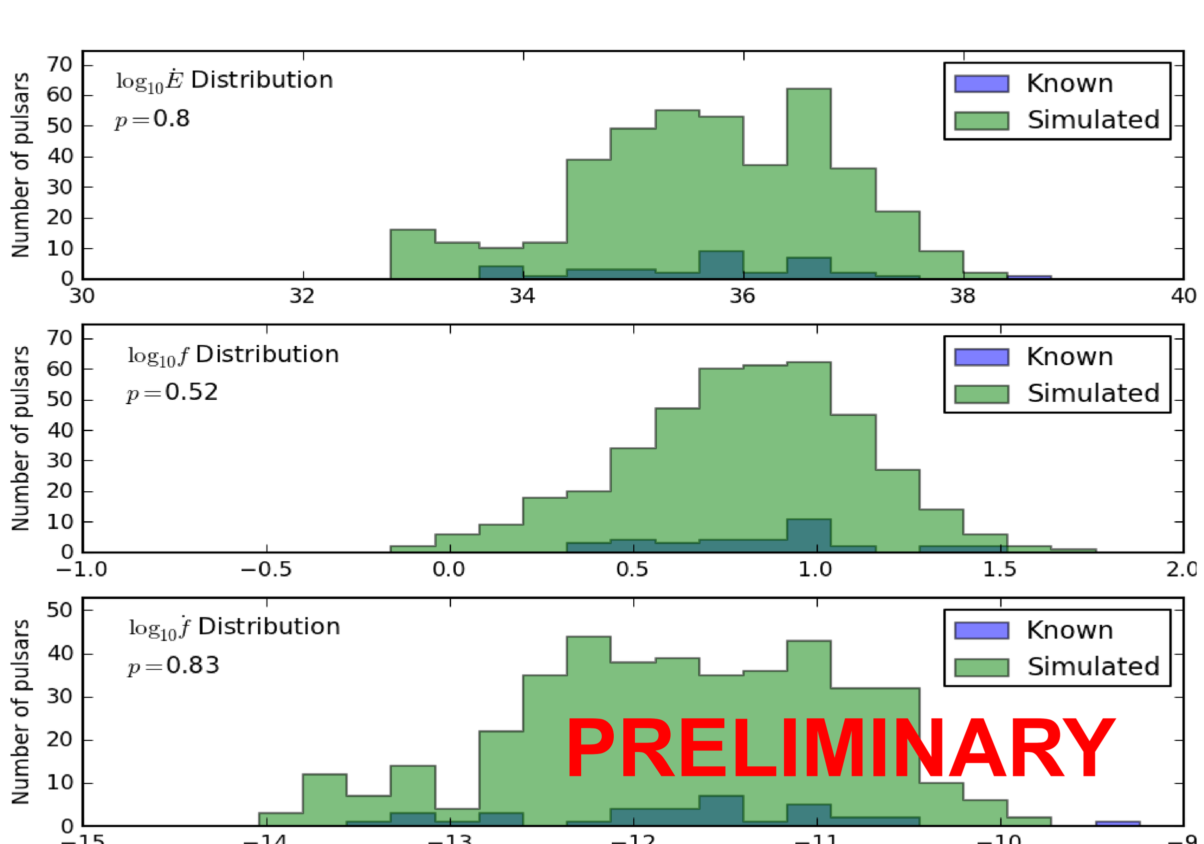

Figure 3: Example comparison of known blind search pulsar distribution with simulated pulsar distribution of $\log_{10}\dot{E}$ (μ, σ) = (37.5, 0.6) for Ė, f, and f1. The p-values for all three parameters are $p > 0.05$ meaning we cannot reject this pulsar birth model.

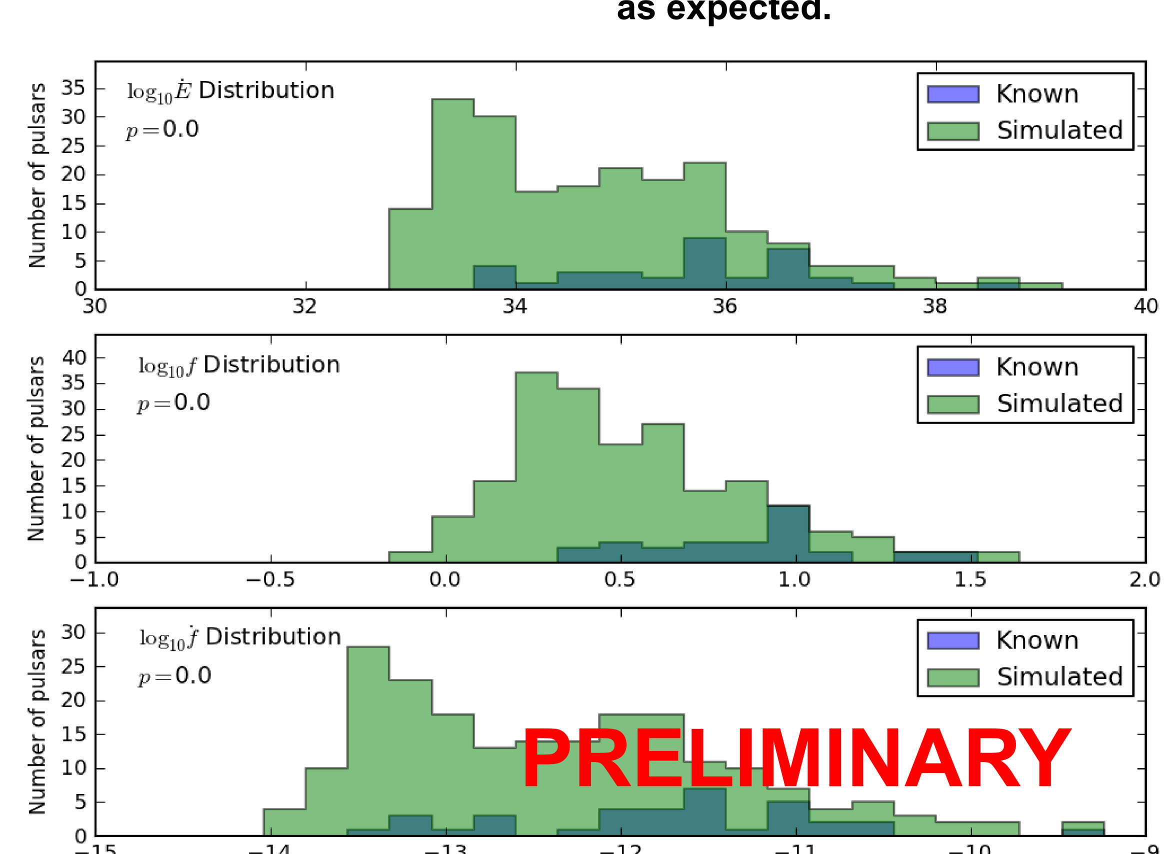

Figure 4: Example comparison of known blind search pulsar distribution with simulated pulsar distribution of P_0 = 300 ms and σ_P = 150 ms for Ė, f, and f1[1]. The p-values for all three parameters are $p < 0.05$, meaning we can reject this pulsar birth model.

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