Is Gamma-ray Burst 221009A Really a Once-in-10,000 Year Event?

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Abstract: Extrapolation of the gamma-ray burst fluence distribution to the fluence of gamma-ray burst (GRB) 221009A, the brightest ever detected, leads to the conclusion that GRBs brighter than this burst should occur approximately once per 10,000 years. It would be a large coincidence if such a GRB occurred in the approximately 50 years that humanity has had the ability to detect such bursts. Here we propose that GRB 221009A is part of a separate, nearby population of narrow-jet GRBs. This population can allow GRBs as bright or brighter than 221009A to occur as often as once every 200 years without over-producing the observed rate of other GRBs. We explore observational implications of this model.

QR Code below links to the paper!

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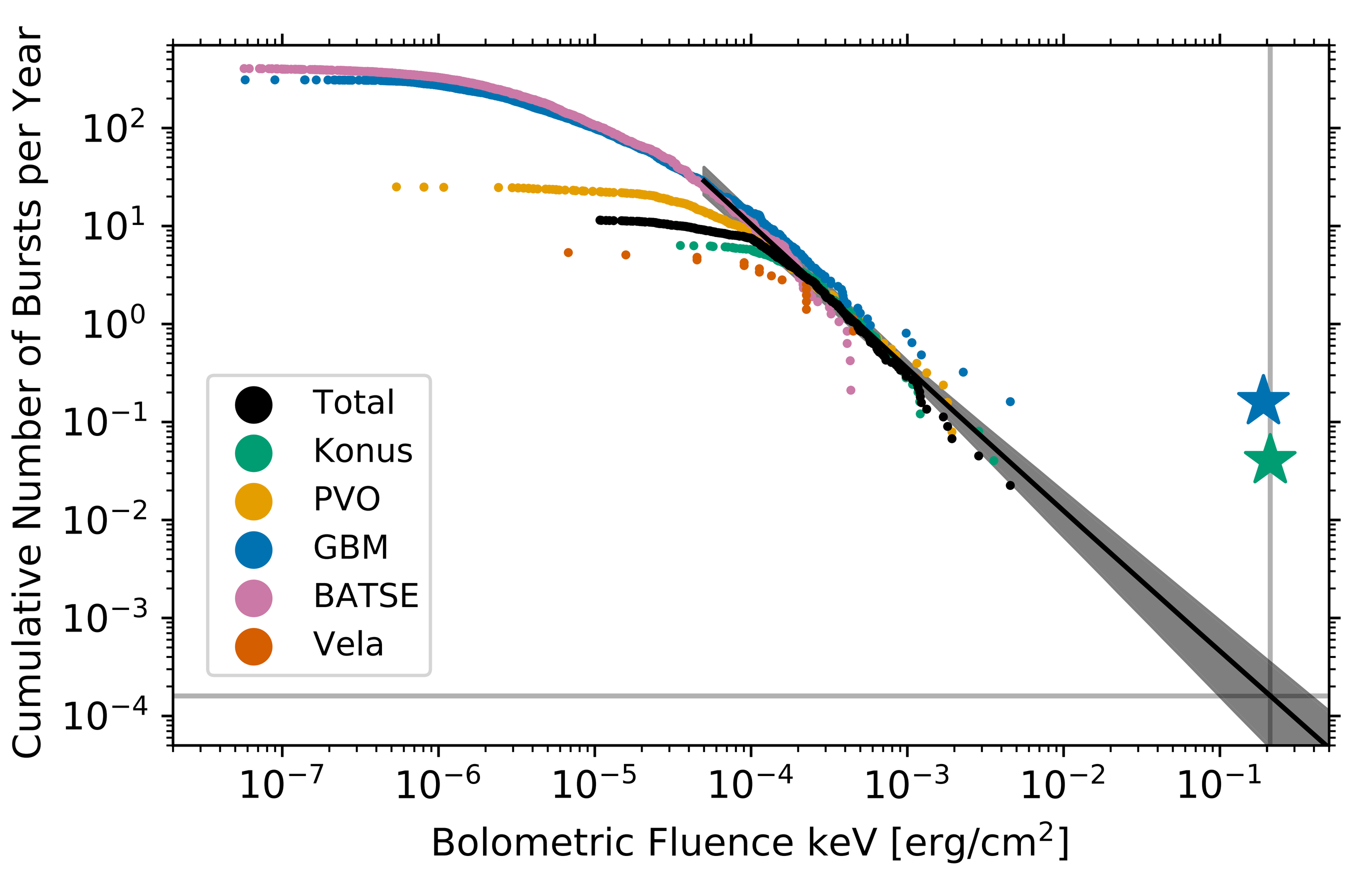
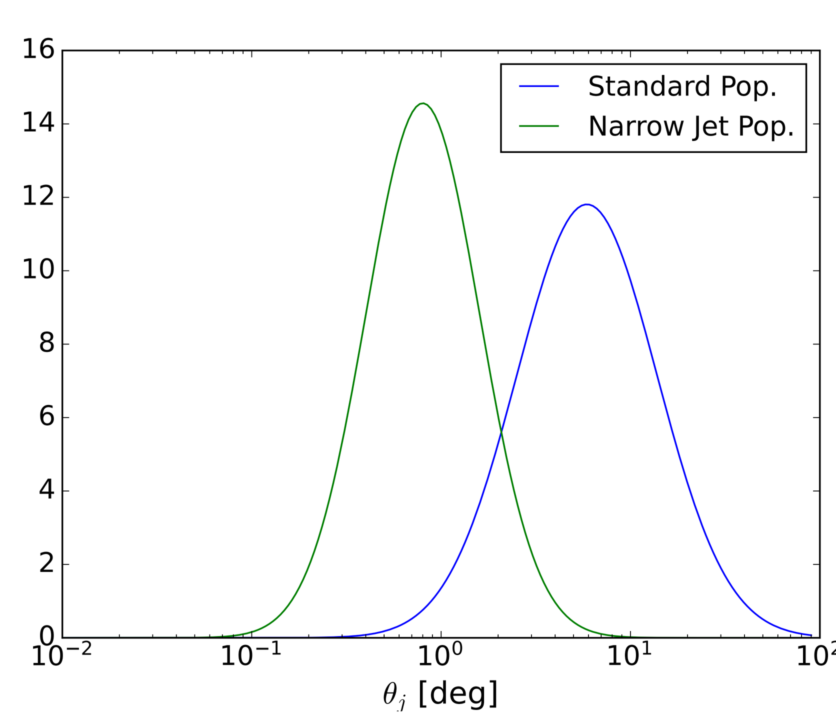
I. GRB 221009A

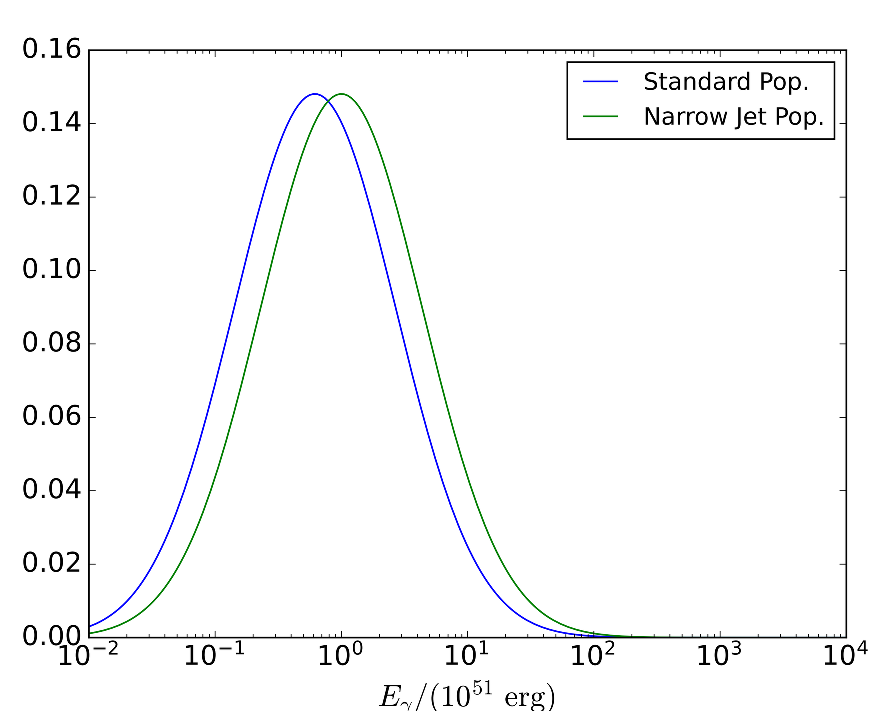


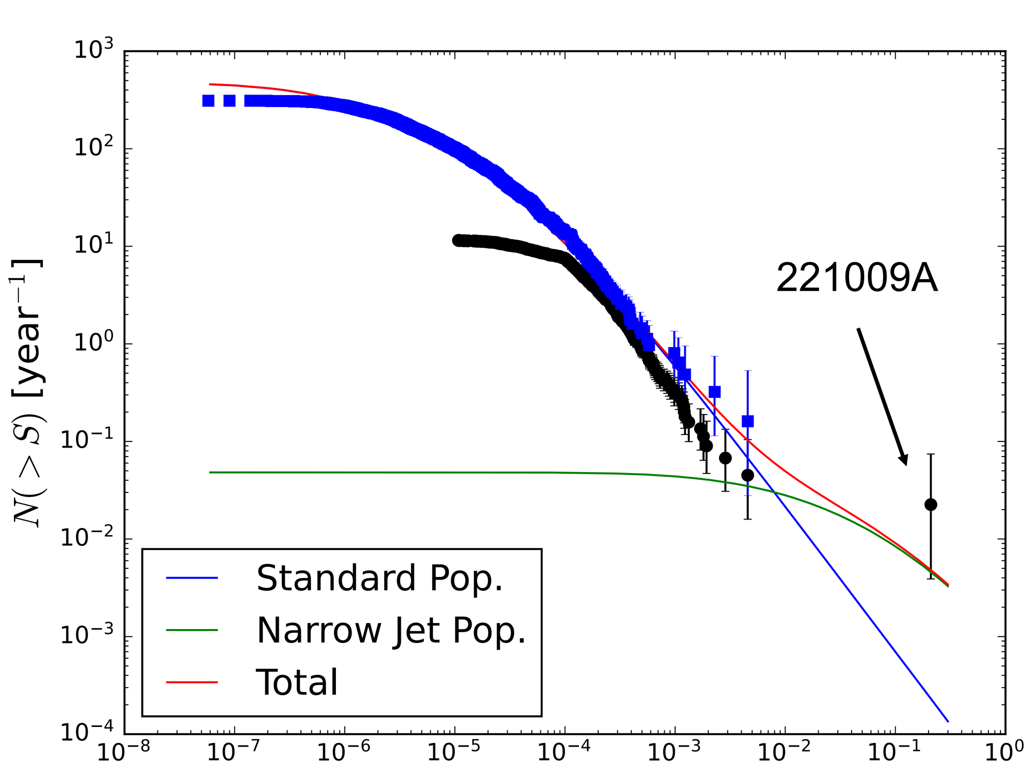
Right: Taken from Burns et al. (2023). The cumulative rate of long GRBs versus fluence, i.e., the "logN-logS distribution". A simple extrapolation of this distribution to the fluence measured of GRB 221009A (represented as stars on the plot) indicates bursts brighter than the BOAT should occur at a rate of once every 10,000 years, at odds with how long humanity has been able to detect GRBs. But what if there is another explanation?

II. Another population of GRBs

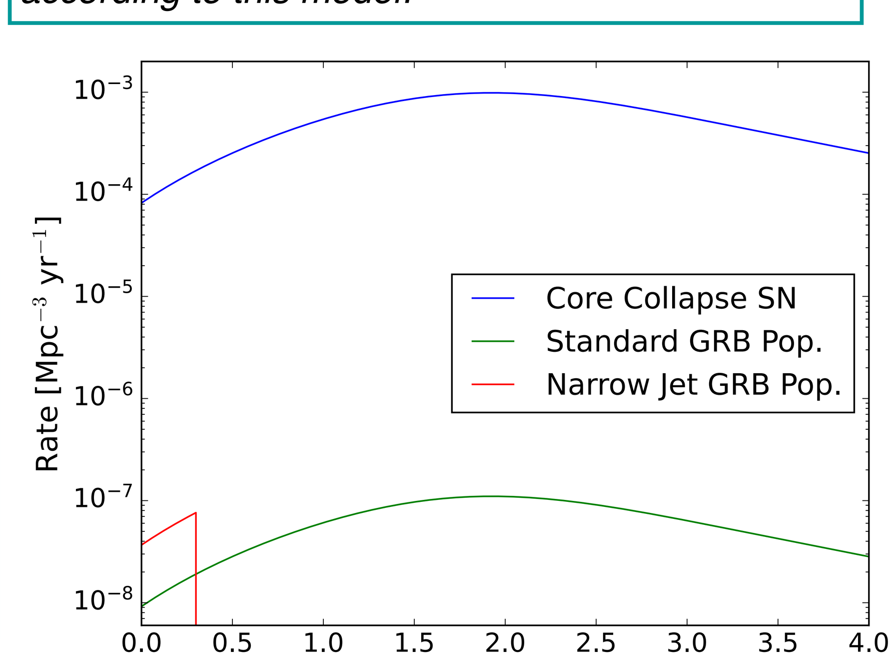
We suppose that there are two populations of GRBs! One has a jet opening angle (θ_j) and distribution of energy released in gamma-rays ($E_\gamma = (1-\cos\theta_j)E_{iso}$, where E_{iso} is the isotropic equivalent energy released, consistent with the distributions found by Goldstein et al. (2016), and follows the star formation rate. The other has much narrow θ_j, with a distribution centered on θ_j=0.8^O, consistent with modeling the LHAASO emission for 221009A (Cao et al. 2023). The narrow jet population must be restricted to redshifts $z < 0.38$ to avoid over-producing the observed distribution of standard GRBs. ***Below left:*** distribution of θ_j. ***Below right:*** distribution of E_γ.





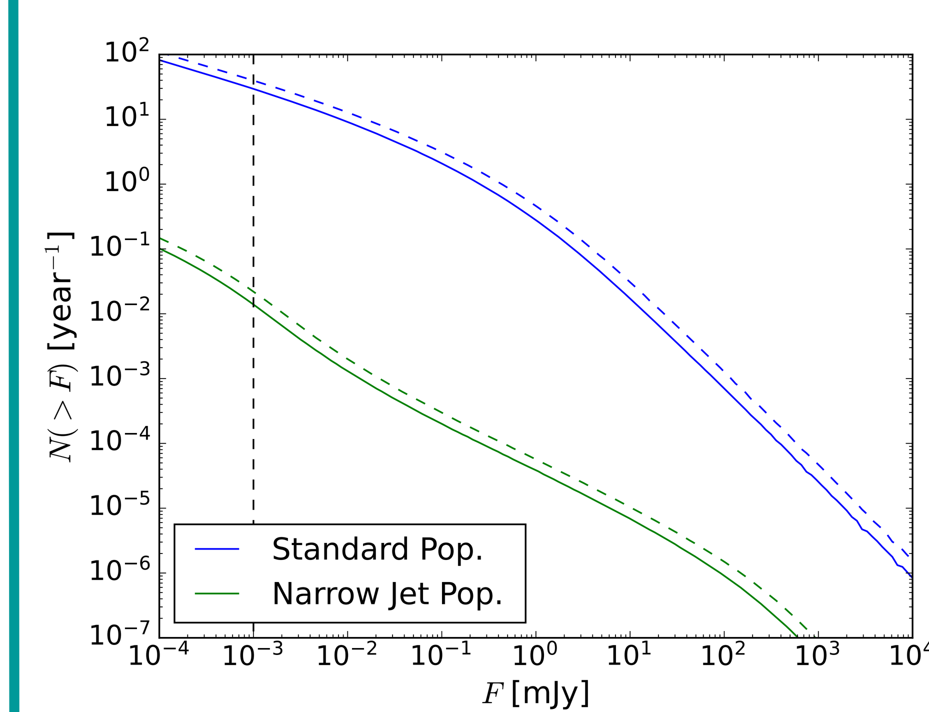


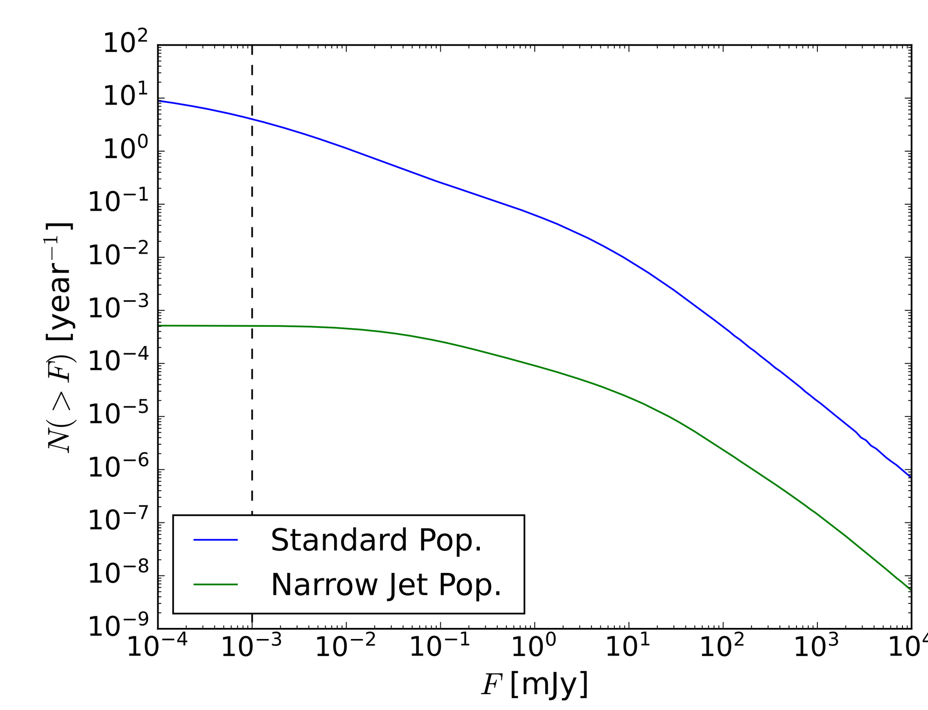
Left: GRB populations, taken from Burns et al. (2023), for GBM (blue squares) and all other instruments (black circles), including Poisson uncertainties. Our standard population of GRBs (blue curve), based on E_γ and θ_j distributions from Goldstein et al. (2016), does a good job describing the GRB population, except for 221009A. The addition of the narrow jet population (green curve) is able to explain this burst, within the Poisson uncertainties! *GRBs brighter than 221009A should then occur about once per 200 per year, according to this model!*



Right: The total rate of core-collapse supernovae (CCSNe), and the rate of standard and narrow jet GRBs (including those not pointed at the Earth) as a function of redshift. The GRB rates are substantially below the CCSN rate, as expected. The narrow jet GRB population must be restricted to redshifts $z <\sim 0.4$ in order to avoid over-producing the rate of standard GRBs. At $z<\sim0.4$, the narrow jet GRBs outnumber the standard GRBs!

III. Afterglows





We can estimate the number of orphan afterglows expected to be observed from these two populations, using the afterglow model by van Eerten et al. (2010). Since off-axis GRB afterglows can brighten over time, and the narrow jet GRBs outnumber the standard GRBs, one might expect there to be a substantial number of afterglows from the narrow jet population. However, a detailed estimate shows that in all cases, the narrow jet population will be outnumbered by the standard population. ***Above left:*** Expected number of optical afterglows that will be observed by *Vera Rubin Observatory/LSST* above a flux density F. Solid curves include dust extinction (Covino et al. 2013), dashed curves do not. *Rubin* flux sensitivity limit is shown by the vertical dashed line. ***Above right:*** Expected number of radio afterglows that will be observed by the Square Kilometer Array (SKA) above a flux density F. SKA survey solid angle is not totally clear; this assumes 1 deg^2 per night. SKA flux sensitivity is also not totally clear, but an estimate of Phase 1 sensitivity is shown by the vertical dashed line.

IV. Cosmic Rays

GRBs have long been considered possible sources of ultra-high energy cosmic rays (UHECRs). Could the narrow jet population of GRBs be a substantial source of UHECRs?

If the UHECRs are Fe nuclei, they will be completely isotropized within the GZK radius of ~100 Mpc before arriving at Earth. In this case, all GRBs within this radius would produce UHECRs observable on Earth, not just ones pointed at the Earth. In the nearby universe, the narrow jet population will outnumber the standard population of GRBs (see Section II). Since the sources of the highest energy UHECRs must be at <~ 100 Mpc, and the narrow jet GRBs outnumber the standard GRBs within this radius, if UHECRs are predominantly made of Fe nuclei, the narrow jet population (including GRB 221009A) is more energetically favorable to be the source of UHECRs!

V. Life on Earth and in the Milky Way

Detailed simulations indicate that GRBs more fluent than ~10^8 erg cm^{-2} can cause a mass extinction of life (e.g., Thomas et al. 2005; Piran & Jimenez 2014). GRBs as bright or brighter than 221009A (S=0.21 erg cm^{-2}; z=0.151) can cause an extinction event out to distance d=32 kpc, which is about the diameter of the Milky Way. This is a much larger distance than typically assumed, typically a few kpc. A *GRB like 221009A could cause an extinction event on Earth if it exploded anywhere in the Milky Way and it was pointed at the Earth!*

Given the expected number of narrow jet GRBs for a given star formation rate from our model, and given the star formation rate in the Milky Way (~2 $M_\odot$/yr; Licquia & Newman 2015; Elia et al. 2022), one can estimate that an extinction of life on Earth will occur from a GRB at a rate of approximately once per 500 Myr. The end-Ordovician mass extinction occurred 440 Myr ago, and has been suggested to have been caused by a GRB (Melott et al. 2004). It is plausible that the extinction event was caused by a GRB similar to 221009A.

Not just the Earth will suffer a GRB extinction event with a rate of one per 500 Myr from the narrow jet population, but everywhere in the Milky Way will. This has significant implications for the Galactic Habitability Zone (Lineweaver et al. 2004), and the survival of life in the Milky Way. These GRBs may make life in the Galaxy much less likely than previously thought. This has implications for the search for life on exoplanets by Habitable Worlds Observatory. Understanding the rate of GRBs like 221009A is essential for understanding how common or rare life is in the Milky Way.

References:
Burns, E., et al., 2023, ApJ, 946, L31
Cao, Z., et al., 2023, Science, 380, 1390
Covino, S., et al., 2013, MNRAS, 432, 1231
Elia, D., et al., 2022, ApJ, 941, 162
Goldstein, A., et al., 2016, ApJ, 181, 18
Licquia, T. C., & Newman, J.A., 2015, ApJ, 806, 96
Lineweaver, C. H., et al., 2004, Science, 303, 59
Melott, A. L., et al., 2004, IJoA, 3, 55
Piran, T., & Jimenez, R., 2014, PRL, 113, 231102
Thomas, B., et al., 2005, ApJ, 634, 509
Van Eerten, H., et al., 2010, ApJ, 722, 235

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