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Determining the Mass and Spin of the Black Hole in GRB 220101A Using 0.1-100 GeV Data Observed by Fermi/LAT

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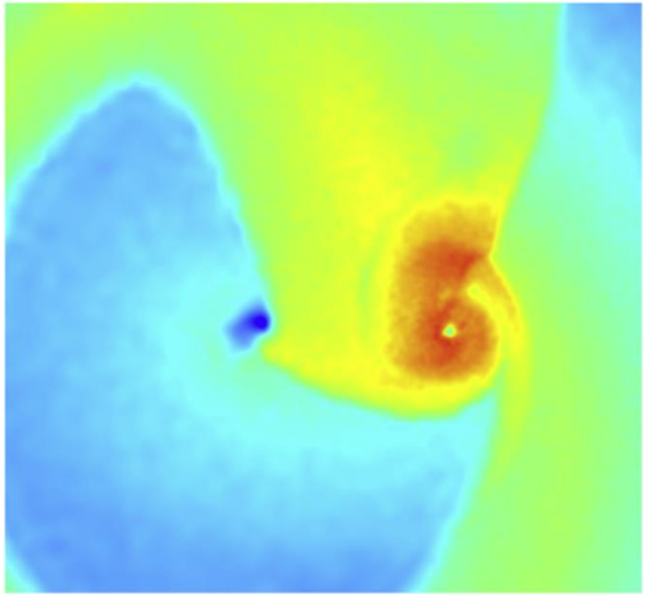
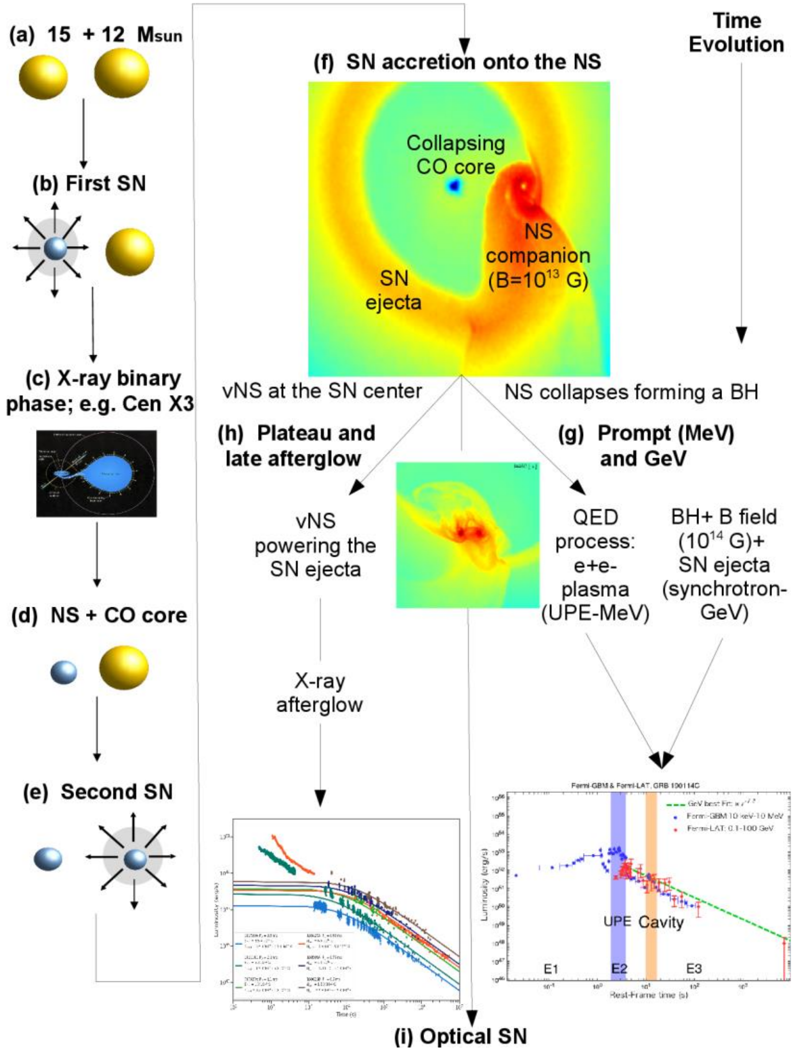
Introduction



- the progenitors of long gamma-ray bursts
- the observational details of GRB 220101A
- configuration of the electric field around the black hole
- Necessary conditions

BDHN, suggested progenitor for long GRBs

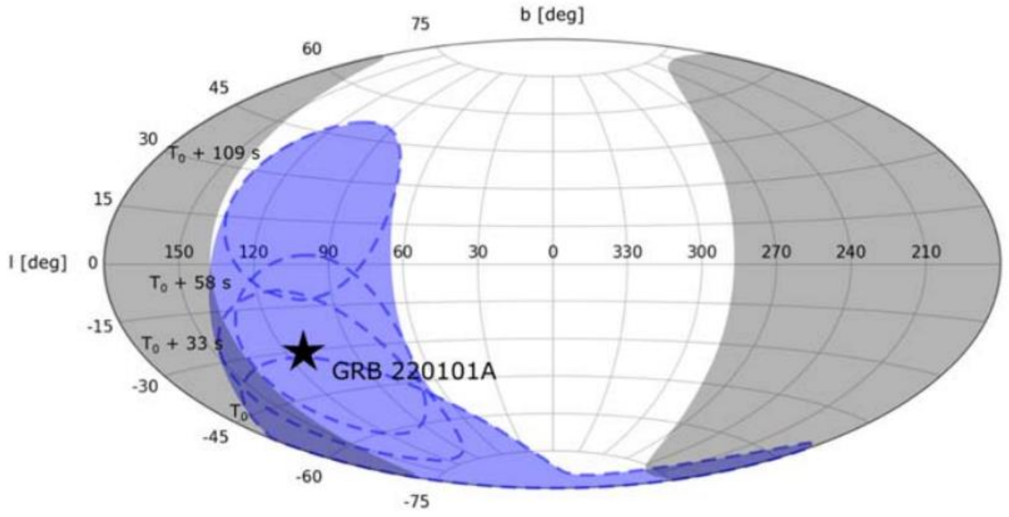


Observation of GRB220101A

trigger time: 2022-01-01 05:11:13 (UT)

redshift: z = 4.61

Isotropic energy: $E_{iso} = 4 \times 10^{54}\ erg$

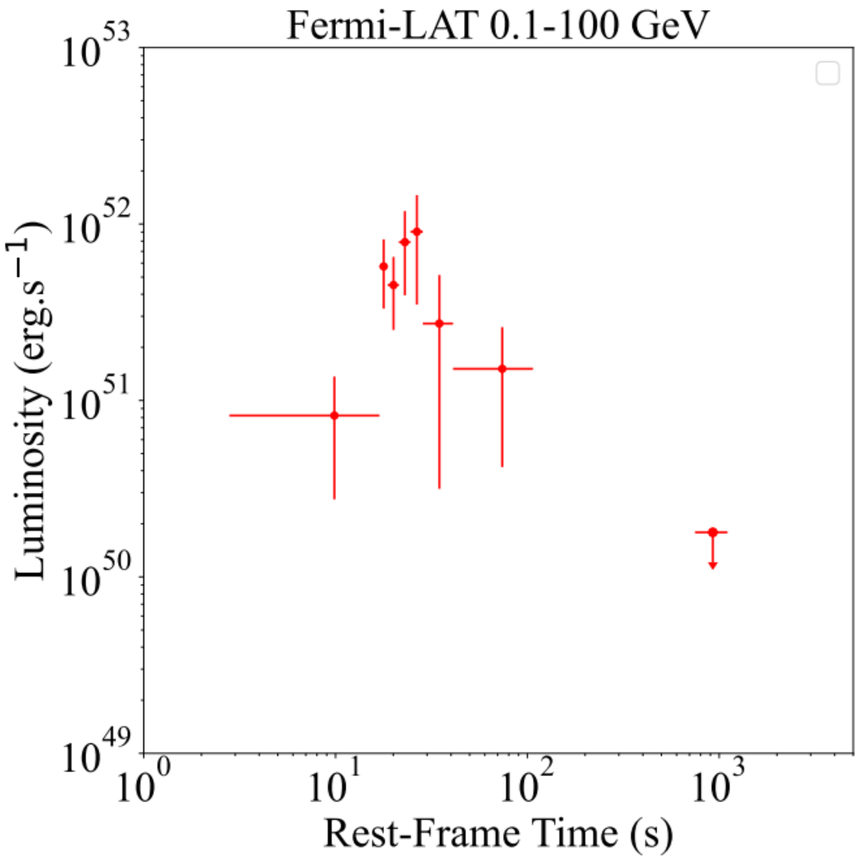


SuperAGILE 40° field of view (blue shaded region) in galactic coordinates, in the time interval from T0 to T0 + 109 s.

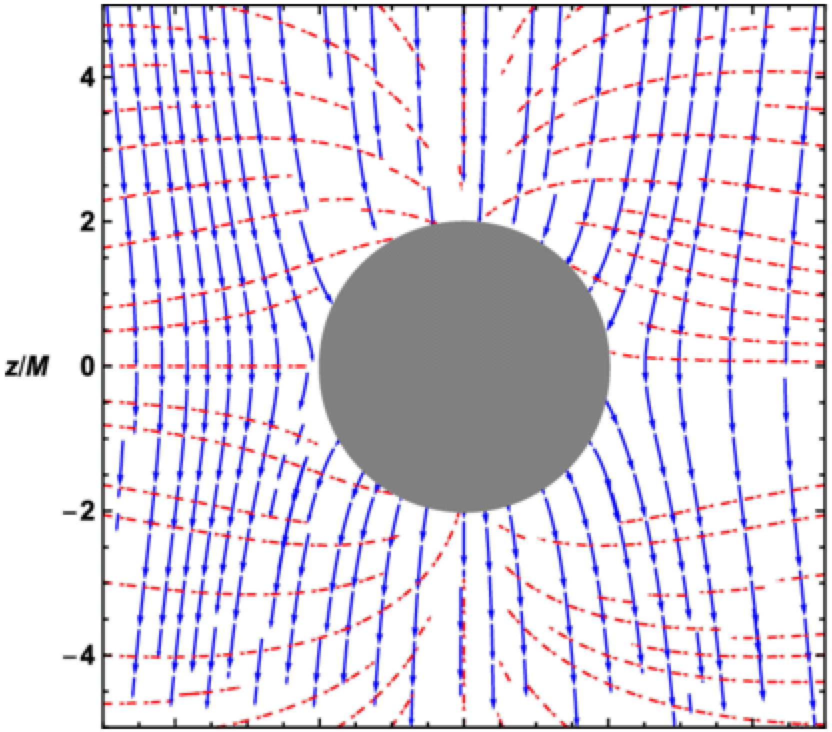
spectral analysis of each time bin

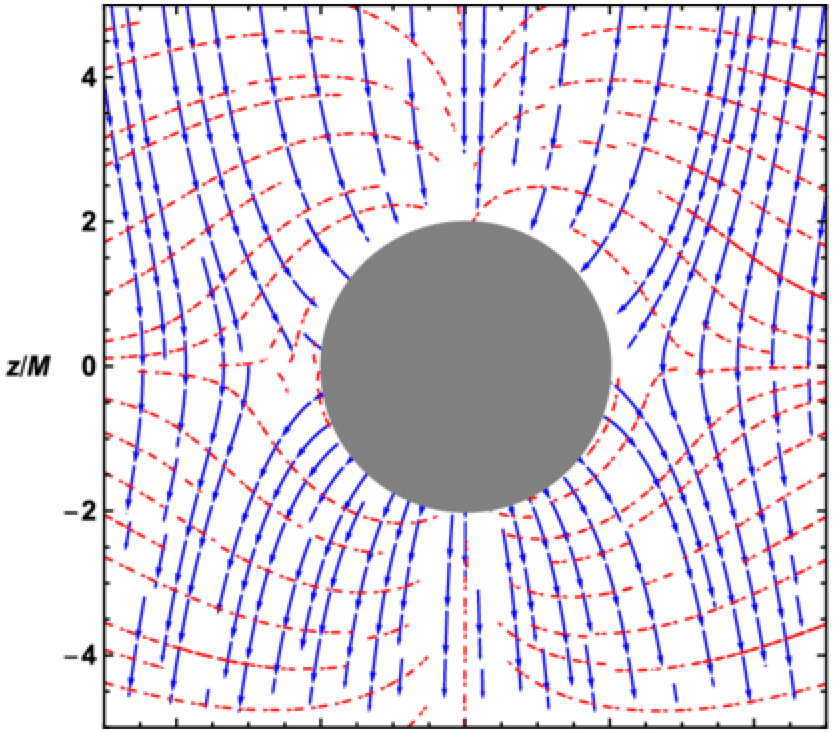
Start time (s)	End time (s)	Time-Error (s)	Alpha -	Luminosity (erg/s)	Luminosity Error (erg/s)
15.69	95	55.345	-2.65 ± 0.766	8.2×10^{50}	5.46×10^{50}
95	105	100	-4.78 ± 1.45	5.8×10^{51}	2.4×10^{51}
105	120	112.5	-3.82 ± 1.08	4.5×10^{51}	2.0×10^{51}
120	138	129	-2.56 ± 0.517	7.9×10^{51}	3.9×10^{51}
138	160	149	-2.06 ± 0.418	9.1×10^{51}	5.5×10^{51}
160	230	195	-1.67 ± 0.47	2.7×10^{51}	2.4×10^{51}
230	600	415	-2.08 ± 0.543	1.5×10^{51}	1.1×10^{51}
4200	6200	5200	-	1.8×10^{50}	-

Overall behavior of luminosity



Electric and Magnetic Fields Around Black Holes





$$E_{\hat{r}} = -\frac{2B_0 J\, G}{c^3}\frac{(r^2 - \hat{a}^2)}{(r^2 + \hat{a}^2)^2}, \tag{1}$$

$$E_{\hat{\theta}} = 0, \tag{2}$$

$$B_{\hat{r}} = \frac{B_0\left(-\frac{4\, G\, J^2 r}{M(r^2+\hat{a}^2)} + a^2 + r^2\right)}{(r^2 + \hat{a}^2)}, \tag{3}$$

$$B_{\hat{\theta}} = 0. \tag{4}$$

substituting the effective charge into the charge of the Kerr-Newman solution, Eq. (1)

$$E_{\hat{r}} \approx -\frac{2B_0 J\, G}{c^3}\frac{(r^2 - \hat{a}^2)}{(r^2 + \hat{a}^2)^2} \approx -\frac{1}{2}\alpha B_0 \frac{r_+^2}{r^2}. \tag{5}$$

where $r_+ = (\hat{M} + \sqrt{\hat{M}^2 - \hat{a}^2})$ is the (outer) event horizon, $\hat{M} = GM/c^2$, and $\hat{a} = a/c = J/(M\, c)$, being M and J the mass and angular momentum of the Kerr BH


Acceleration in polar axis
UHECRs

Acceleration in non-polar axis

Synchrotron radiation

for γ ≫ 1: (γ is the Lorentz factor)

$$m_e c^2 \frac{d\gamma}{dt} = e\frac{1}{2}\alpha B_0 c - \frac{2}{3}e^4 \frac{B_0^2 \sin^2\langle\chi\rangle}{m_e^2 c^3}\gamma^2$$

$$\epsilon_\gamma = \frac{3e\hbar}{2m_e c} B_0 \sin\langle\chi\rangle\,\gamma^2 = \frac{3}{2} m_e c^2 \beta \sin\langle\chi\rangle\,\gamma^2$$

$$\gamma_{\max} = \frac{1}{2}\left(\frac{3}{e^2/(\hbar c)}\frac{\alpha}{\beta \sin^2\langle\chi\rangle}\right)^{\frac{1}{2}}$$

And synchrotron cooling time for the maximum critical energy of photon obtained from :

$$t_c = \frac{\hbar}{m_e c^2}\frac{3}{\sin\langle\chi\rangle}\left(\frac{e^2}{\hbar c}\alpha\beta^3\right)^{-\frac{1}{2}}$$

Inner engine parameters inference

Condition 1

$$E_{\text{extra}} \geq E_{\text{GeV}}$$

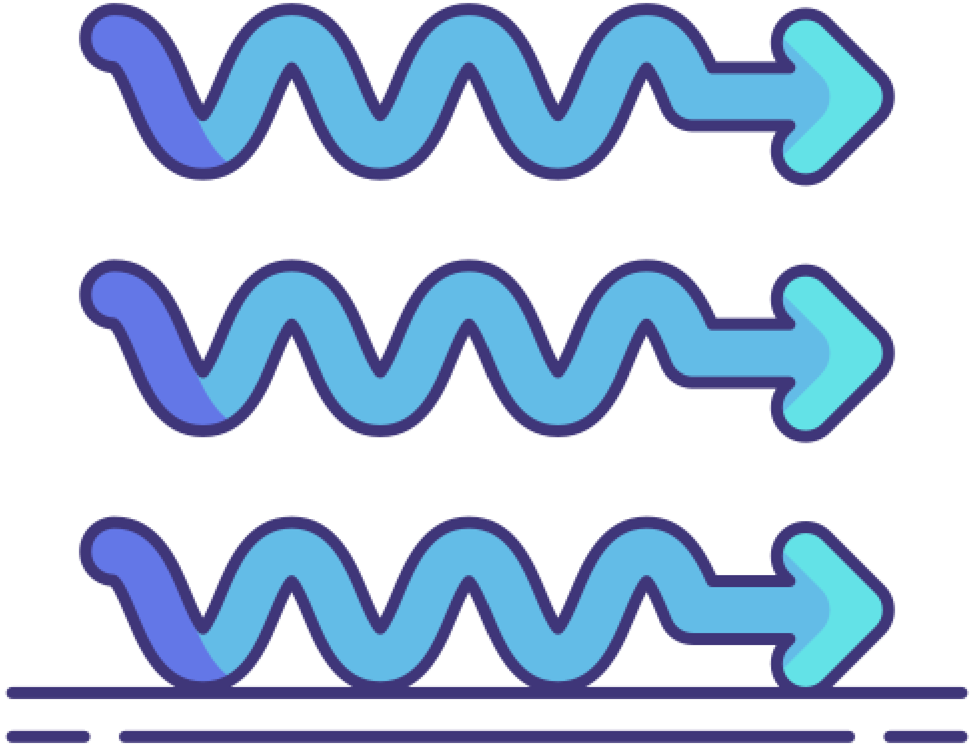
$$M \geq \frac{1}{\eta}\frac{E_{\text{GeV}}}{c^2}, \quad \eta \equiv 1 - \sqrt{\frac{1+\sqrt{1-\alpha^2}}{2}}$$

η(max) ≈ 0.293 and α(max) = 1

obtaining a lower limit for the mass and spin of the black hol

Condition 2

The necessary transparency for photons to escape. The attenuation coefficient for this process is equal to:



$$\beta \ll \frac{16}{9}\frac{e^2}{\hbar c}\frac{1}{\alpha} \approx \frac{1.298 \times 10^{-2}}{\alpha}, \quad B_0 \ll \frac{5.728 \times 10^{11}}{\alpha}\,\mathrm{G}$$

$$\overline{R} \approx 0.23\frac{e^2}{\hbar c}\left(\frac{\hbar^2}{m_e c}\right)^1 \beta \sin\langle\chi\rangle \exp\left(-\frac{4/3}{\psi}\right)$$

getting the upper limit of the magnetic field.

Condition 3

duration of synchrotron radiation or cooling time

$$\tau_{\mathrm{rad},1} = \frac{\mathcal{E}_1}{L_{\mathrm{GeV},1}}$$

$$t_c\left(\langle\chi\rangle, \alpha, \beta\right) = \tau_{\mathrm{rad},1}\left(\mu, \alpha, \beta, L_{\mathrm{GeV},1}\right)$$

Final values:

We obtain the following expression for β as a function of α, observable luminosity and energy, E(GeV) and L(GeV):

$$\beta\left(\epsilon_\gamma, E_{\rm GeV}, L_{\rm GeV,1}, \alpha\right) = \frac{1}{\alpha}\left(\frac{64}{9}\sqrt{3\frac{e^2}{\hbar c}}\frac{\epsilon_\gamma}{B_c^2 r_+(\mu,\alpha)^3}\frac{L_{\rm GeV,1}}{eB_c c^2}\right)^{2/7}$$

So the final values are:

$\beta = 6.8 \times 10^{-4}$
$\alpha = 0.546$
$M = 3.94\ M_\odot$
$M_{irr} = 3.78\ M_\odot$

In conclusion:

The analysis of GRB 220101A supports the Binary Driven Hypernova model, showing a strong link between the observed GeV emission and the properties of a newborn Kerr black hole.
The study found a correlation between the emission characteristics and the black hole's mass (3.94 solar masses) and spin (0.546), aligning with theoretical predictions.
This research enhances our understanding of gamma-ray bursts and the role of black holes in cosmic events, while also suggesting future studies on radiation types and transparency conditions.

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Thank You

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