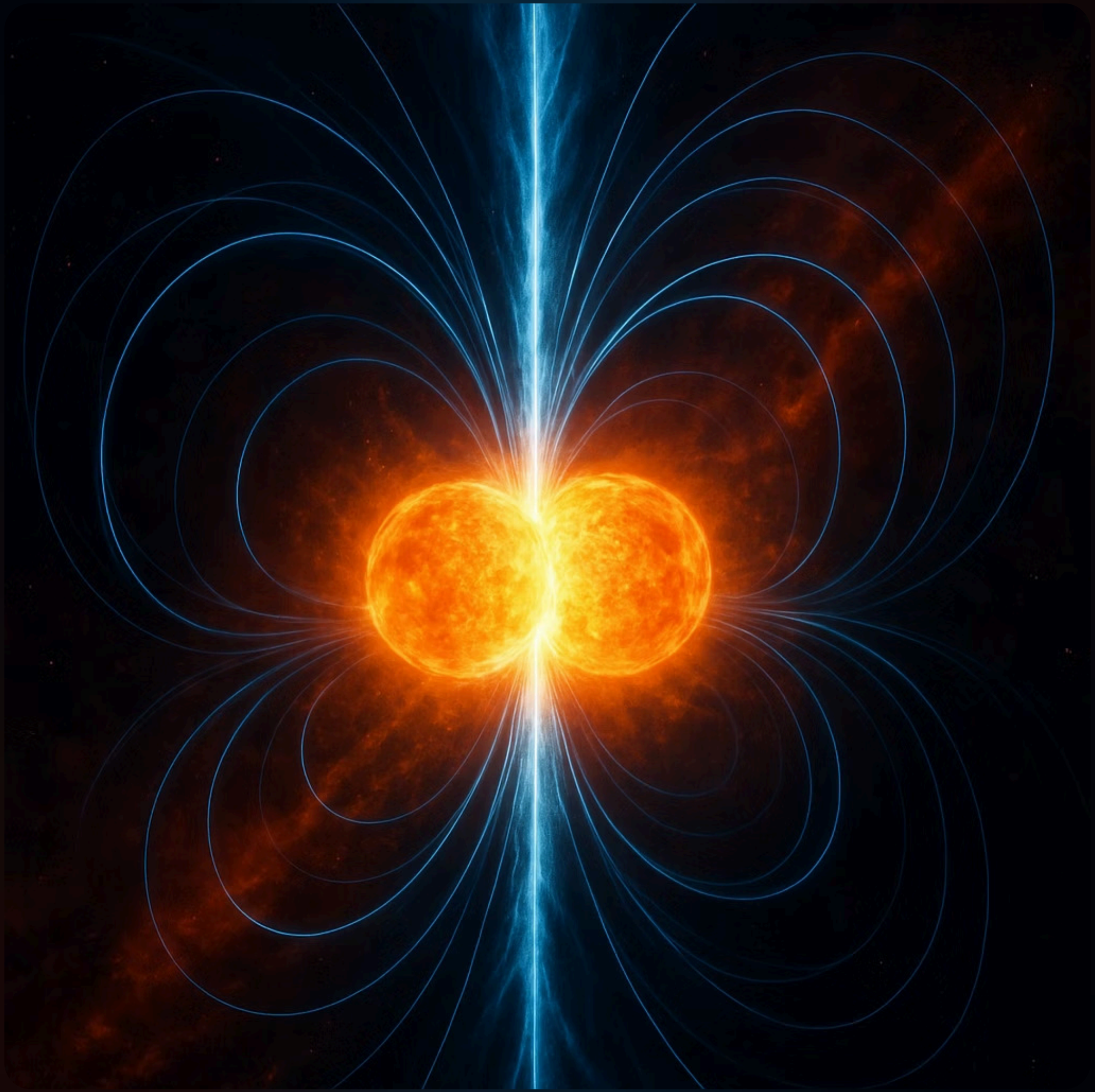

GRB 090510: a magnetized NS-NS merger leading to a black hole

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GRB 090510 (z= 0.903):

NS-NS merger timeline

1 Inspiral up to merger

Mainly driven by GWs

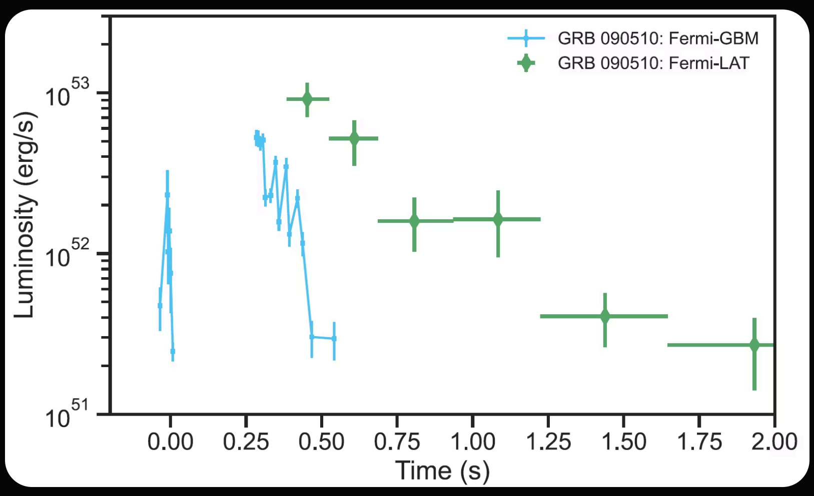
High EM fields could play a role in the approach to and merger dynamics

2 Merger

Mainly EM emission (precursor + prompt emission of the short GRB)

EM configuration: rotating magnetic field (e.g., dipole) + induced electric field + surface charge that minimizes the energy of the electromagnetic field configuration (Ruffini & Treves 1973)

3 Precursor



Emission before the main peak of the prompt emission.

Fermi-GBM mainly in the 0.3-10 MeV energy band

Rest-frame time **dt = -0.06 - 0.06 s**

Eiso = 2.28E51 erg

Powered by magnetic energy: giant-flare like emission

B = few 1E16 G (+ possible 10-30 degrees beaming?)

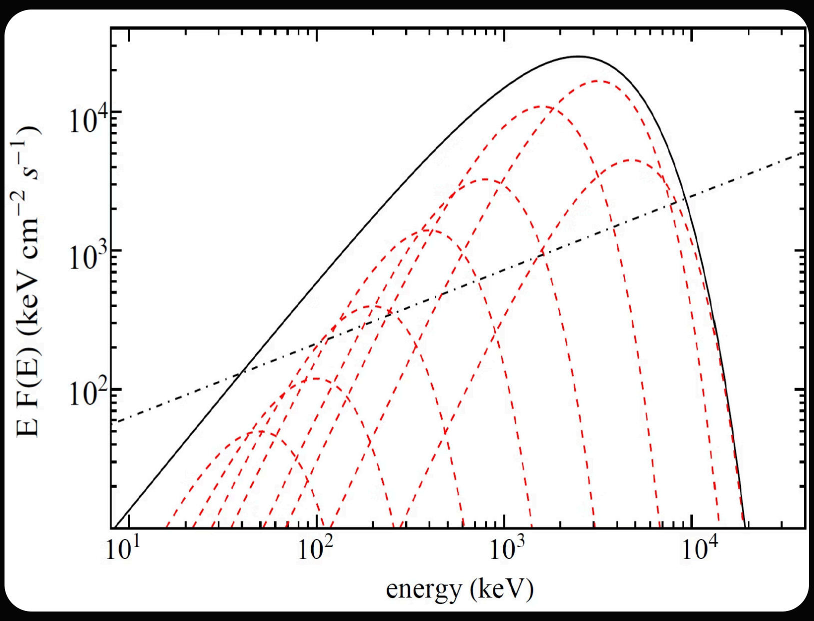
4 Ultrarelativistic Prompt Emission (UPE)

Fermi-GBM energy band: 8 keV - 40 MeV

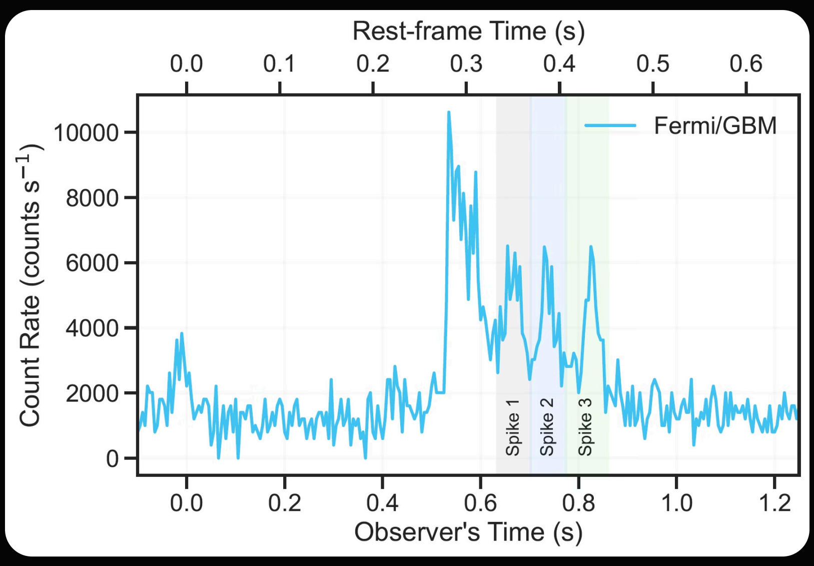
Rest-frame time: **dt=0.25-0.35 s**

Eiso = 3.95E52 erg

Overcritical induced E-field: e+e- pair plasma is formed around the merged object. The plasma dynamics and transparencies lead to thermal MeV photons observed as blackbodies in the UPE spectrum.



5 Post-UPE spikes



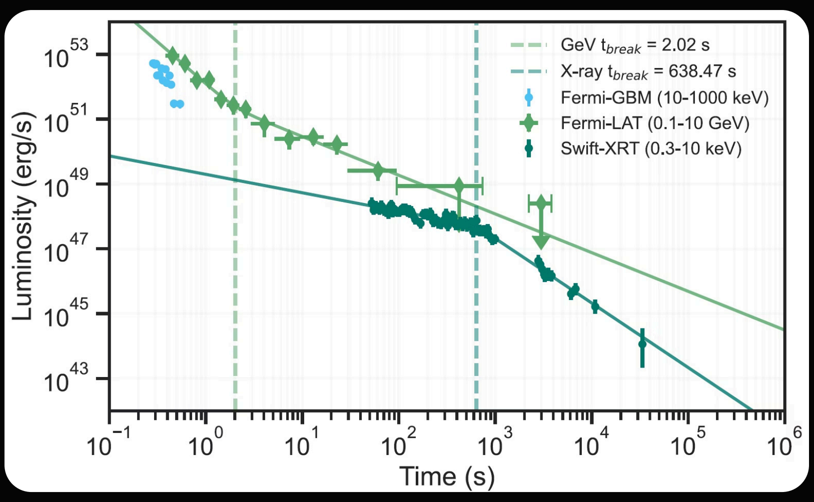
Fermi-GBM energy band: 8 keV -40 MeV

Rest-frame time **dt = 0.35-0.43 s**

Esp1 + Esp2 + Esp3 = 1.70E51 erg

Advanced hypothesis: quasi-periodic oscillations of material in accretion disk around the merged object (before the GeV emission-BH formation)

6 The GeV emission



100 MeV-100 GeV band of Fermi-LAT

Rest-frame time **dt = 0.5 - 200 s**

Eiso = 5.09E52 erg

Starts when the Kerr BH forms, so when the merged object reaches the critical mass.

Powered by the BH extractable energy, mediated by the radiation of electrons accelerated by the induced E-field.

B → has turned undercritical

E → consequently undercritical

7 The X-ray afterglow

Swift-XRT 0.3-10 keV energy band

Rest-frame time **dt= 50-30,000 s**

Eiso =8.23E50 erg

Powered by accretion onto the newborn Kerr BH

Precursor

Electric and magnetic field of a perfectly conducting, rotating magnetic dipole endowed with surface charge (Ruffini and Treves, Astron. J. 1973)

$$(B_r, B_\theta, B_\phi) = \begin{cases} (\cos\theta, -\sin\theta, 0)\,\tilde{B}, & r < R, \\ (2\cos\theta, \sin\theta, 0)\,\dfrac{\tilde{B}}{2}\dfrac{R^3}{r^3}, & r \geq R. \end{cases}$$

$$(E_r, E_\theta, E_\phi) = \begin{cases} \left(-r\sin^2\theta\dfrac{\Omega}{c}, -r\sin\theta\cos\theta\dfrac{\Omega}{c}, 0\right)\tilde{B}, & r < R \\ \left(\dfrac{Q}{r^2} - P_2(\cos\theta)\dfrac{R^4}{r^4}\tilde{\Omega}\tilde{B}, -2\sin\theta\cos\theta\dfrac{R^4}{r^4}\tilde{\Omega}\tilde{B}, 0\right), & r \geq R \end{cases}$$

$$\tilde{B} = B_p + \frac{2\tilde{\Omega}}{3}\frac{Q}{R^2}$$

$$\tilde{\Omega} \equiv \Omega R/c$$

"Observable" magnetic field: notice the magnetic field is a dipole of this strength!

Rotation parameter: it is of order 0.1 for the merged object, so the solution can be presented as an expansion in series of it ("slow" rotation regime).

Surface charge density:

$$\sigma R^2 = Q - \tilde{\Omega} B_p R^2 [P_2(\cos^2\theta) - \sin^2\theta] + \mathcal{O}(\tilde{\Omega}^2)$$

Notice that the Faraday-induced electric field contributes with an "effective charge", which on the pole is

$$Q_{\rm eff} = -\tilde{\Omega} B_p R^2$$

Energy stored in the electromagnetic field

$$W = W_{\rm in} + W_{\rm ext} = \frac{1}{4}\int_0^\pi \int_0^R (E^2 + B^2) r^2 \sin\theta dr d\theta + \frac{1}{4}\int_0^\pi \int_R^\infty (E^2 + B^2) r^2 \sin\theta dr d\theta = \frac{Q^2}{2R} + \frac{\tilde{B}^2 R^3}{4}\left(1 + \frac{2}{5}\tilde{\Omega}^2\right)$$

$$Q = -\frac{1}{3}\tilde{\Omega}\tilde{B}R^2 = -\frac{1}{3}\tilde{\Omega}B_p R^2 + \mathcal{O}(\tilde{\Omega}^2)$$

$$Q = -\frac{1}{3\,k\,\mathcal{C}}\frac{c^3}{G} J B_p + \mathcal{O}(\tilde{\Omega}^2)$$

Minimizes the electromagnetic field energy

How large is this charge?

M = 2.4 Msun, R = 12 km (C=0.29), k=2/5 (rigid sphere):

|Q| = 2.82 J B (c = G = 1)

For B = 2E14 G → |Q|/M=1.3E-5

$$\tilde{B} = \frac{B_p}{1 + \frac{2}{9}\tilde{\Omega}^2} = B_p\left(1 - \frac{2}{9}\tilde{\Omega}^2\right) + \mathcal{O}(\tilde{\Omega}^2)$$

$$W_{\rm min} = \frac{B_p^2 R^3}{4}\left(1 + \frac{28}{45}\tilde{\Omega}^2\right) + \mathcal{O}(\tilde{\Omega}^2)$$

$$\Delta\tilde{W} \equiv \frac{W_{\rm min} - W(Q=0)}{B_p^2 R^3/4} = \frac{2}{9}\tilde{\Omega}^2 + \mathcal{O}(\tilde{\Omega}^2)$$

The charge contributes to the observable magnetic field appears only at second order in the rotation parameter. Up to first order, it is the bare field.

The same applies to the electromagnetic field energy. The charge contribures less than 1% to the electromagnetic energy!

The energy is dominated by the energy of the magnetic dipole

If it powers the precursor:

$$W \approx W_{\rm mag} = \frac{1}{4}B_p^2 R^3$$

$$B_p = 2R^{-3/2}\sqrt{E_{\rm prec}(1 - \cos\theta_{\rm prec})}$$

8.5E15 G - 2.7E16 G for a beaming angle of 10-30 degrees.

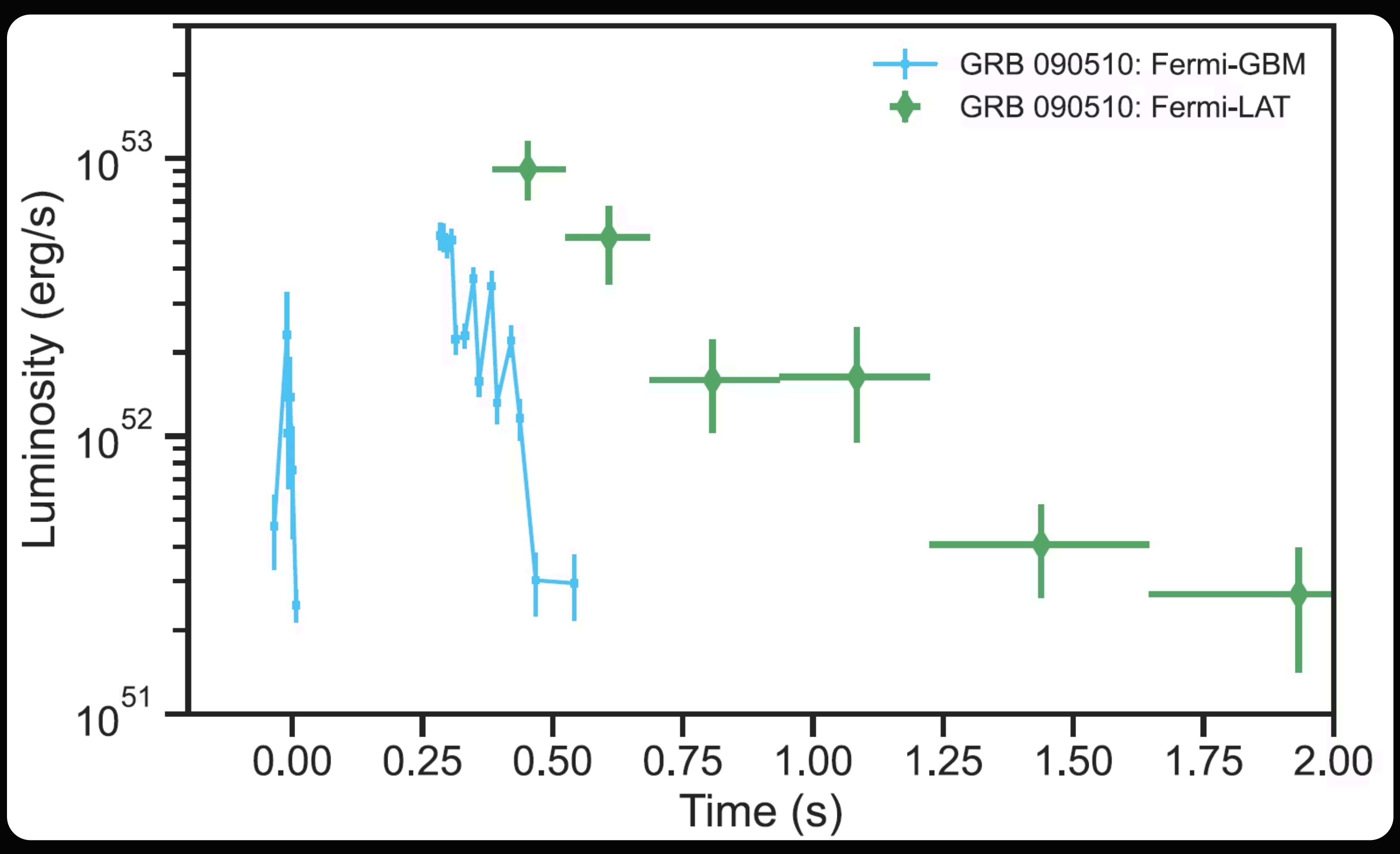
Estimate of the luminosity as magnetic flux crossing the region of open field lines:

$$L_{\rm prec} \sim \frac{\Omega^2}{6\pi^2 c}\Phi_{\rm open} = \frac{\Omega^2}{6\pi^2}B_p S_{\rm open} = \frac{1}{6}B_p^2 R^2 c\left(\frac{\Omega R}{c}\right)^4$$

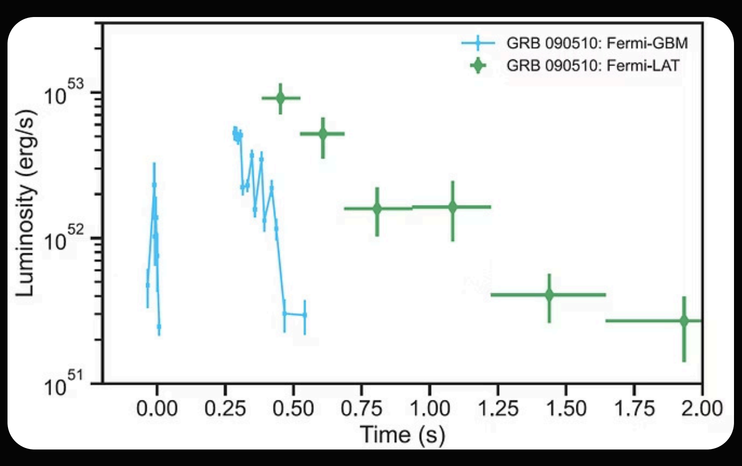
At merger, it approaches a radius-independent value:

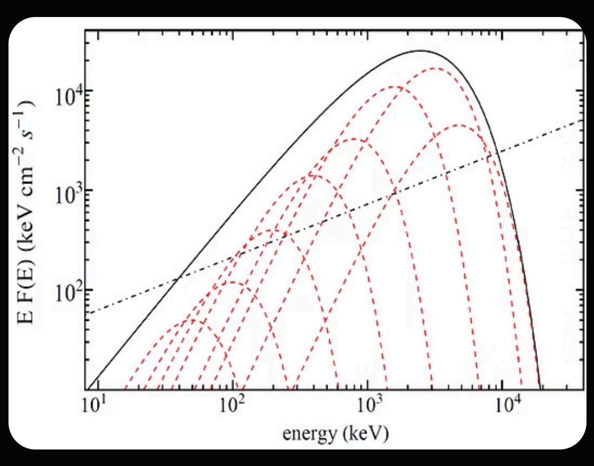
$$L_{\rm prec,mgr} = \frac{G^2}{384 c^3}(B_p M)^2 \approx 9.78 \times 10^{50}\left(\frac{B_p}{10^{16}\,{\rm G}}\frac{M}{2.4 M_\odot}\right)^2 \ {\rm erg\ s^{-1}}$$

For the above beaming angles, it leads to a luminosity as the one observed in the precursor 1E51-1E52 erg!



UPE Phase





The UPE spectrum was shown in Ruffini et al. ApJ 2016 as a convolution of blackbodies, there associated with the transparency of e+e- plasma formed around a newborn BH. However, the field should be overcritical before the BH formation! The merged object, while reaching the critical mass, has an overcritical electric field.

Schwinger's electron-positron creation rate (density per unit time):

$$\dot{n} = \frac{e^2 \tilde{E}\tilde{B}}{4\pi^2\hbar^2 c}\sum_{n=1}^{\infty}\frac{1}{n}\coth\left(n\pi\frac{\tilde{B}}{\tilde{E}}\right)e^{-\frac{n\pi E_c}{\tilde{E}}}$$

$$\tilde{E} = [(\mathcal{F}^2+\mathcal{G}^2)^{1/2}-\mathcal{F}]^{1/2}, \quad \tilde{B} = [(\mathcal{F}^2+\mathcal{G}^2)^{1/2}+\mathcal{F}]^{1/2}$$

$$\mathcal{F} \equiv \frac{1}{4}F_{\mu\nu}F^{\mu\nu} = \frac{1}{2}(\mathbf{B}^2-\mathbf{E}^2)$$

$$\mathcal{G} \equiv \frac{1}{4}F_{\mu\nu}{}^{*}F^{\mu\nu} = \mathbf{E}\cdot\mathbf{B}$$

Dyadoregion (region around the object where pairs are created):

$$\tilde{E}(r,\theta) = E_c$$

This is an implicit equation for the surface of the dyadoregion

$$\tilde{E} \approx E|\cos\theta|$$

Cherubini et al. 2025 (to be submitted) show this approximation is accurate enough for our purpose.

$$r_d(\theta) = \sqrt{\frac{\mathcal{R}+\mathcal{D}}{2}}$$

$$\Delta_d \equiv r_d(\theta) - R$$

$$\beta \equiv B_p/B_c$$

$$r_d(\theta=0) = R\sqrt{\frac{\beta\tilde{\Omega}}{6}\left(1+\sqrt{1+\frac{36}{\beta\tilde{\Omega}}}\right)}$$

$$\beta_{\rm min} = \frac{B_{p,\rm min}}{B_c} = \frac{3}{4\tilde{\Omega}}$$

$$\mathcal{R} = \sqrt{z+2a_2/3}$$

$$\mathcal{D} = \sqrt{-\mathcal{R}^2+2a_2+2a_1/\mathcal{R}}$$

$$z = -2\sqrt{\frac{p}{3}}\sinh\left[\frac{1}{3}\text{arcsinh}\left(\frac{3q}{2p}\sqrt{\frac{3}{p}}\right)\right]$$

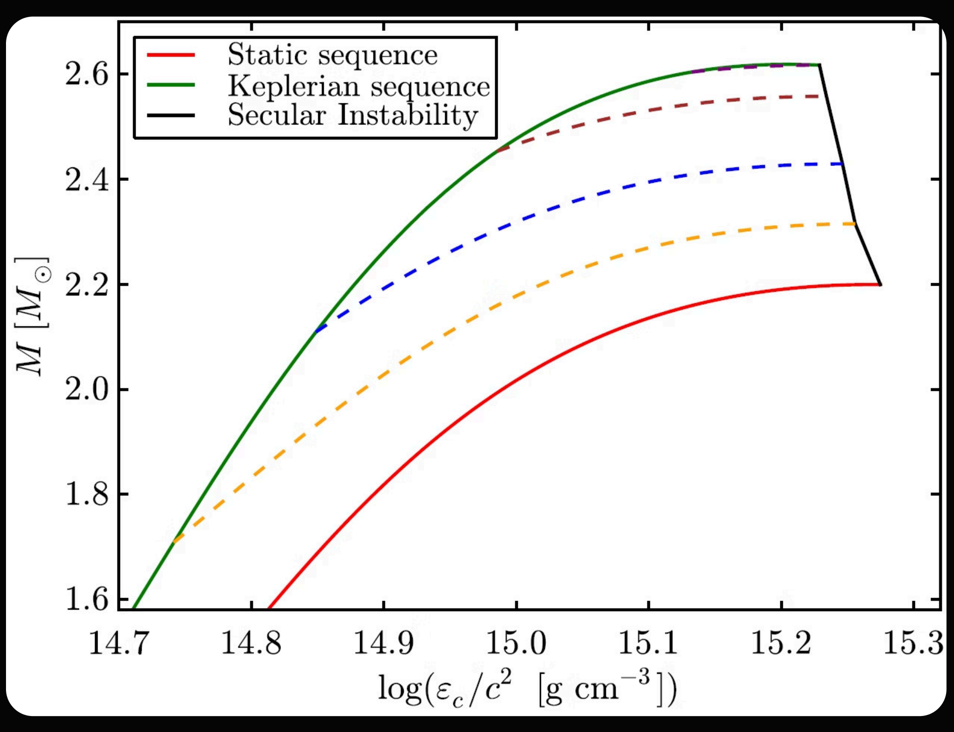
$$p = (3c-b^2)/3,\ q = (2b^3-9bc+27d)/27,\ b = a_2,\ c = 4a_0,\ d = 4a_0a_2-a_1^2$$

$$a_0 = \frac{1}{4}(\beta\tilde{\Omega})^2[(3\cos^2\theta-1)^2+\sin^2 2\theta]\cos^2\theta,$$
$$a_1 = \frac{1}{3}(\beta\tilde{\Omega})^2(3\cos^2\theta-1)^2\cos^2\theta,$$
$$a_2 = \frac{1}{9}(\beta\tilde{\Omega})^2\cos^2\theta.$$

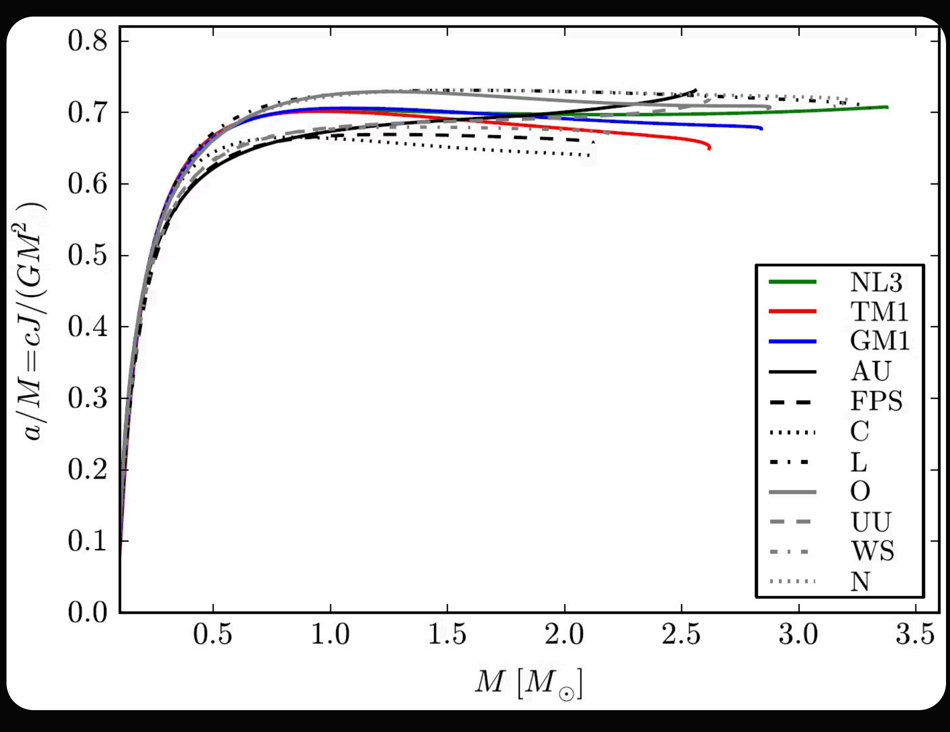
Electromagentic energy stored in the dyadoregion, so available for the pairs:

$$\mathcal{E}_{e^+e^-} = \frac{1}{4}\int_0^{\pi}\int_R^{r_d(\theta)}(E^2+B^2)r^2\sin\theta\, dr\, d\theta$$

To compute this energy, we need the magnetic field and the rotation parameter. The latter sets the minimum magnetic field for the induced electric field to create pairs.



Neutron star mass vs. central density. Taken from Cipolletta et al., PRD 0215.



Dimensionless angular momentum along the Keplerian (mass-shedding) sequence (Cipolletta et al., PRD 2015).

We request that, at the time of BH formation:

$$\Omega = \Omega_{\rm crit},\ \Delta_d \to 0,\ \text{or equivalently},\ \tilde{E}(R) \to E_c$$

Minimum magnetic field for the induced electric field to create pairs:

$$B_{p,\rm min} = \frac{3}{4}\left(\frac{\Omega_{\rm crit}R}{c}\right)^{-1} = 2.04\times 10^{14}\ \mathrm{G}$$

From the GeV emission (a few slides below), the BH spin parameter at birth is a/M= 0.22. Thus, we constrain the merged object at the end of the UPE has:

$$\Omega_{\rm crit} = J_{\rm crit}/I \approx 0.22GM^2/(cI)$$

$$\Omega_{\rm crit} < \Omega_K$$

From Cipolletta et al. PRD 2015:

$$\Omega_K = 0.7GM^2/(cI)$$

So, we estimate:

$$\mathcal{E}_{e^+e^-} = 7.92\times 10^{44}\ \mathrm{erg}$$

$$\Delta_d(\theta=0) \approx 0.41R \approx 4.92\ \mathrm{km}$$

$$E_{\rm UPE} = 3.95\times 10^{52}$$

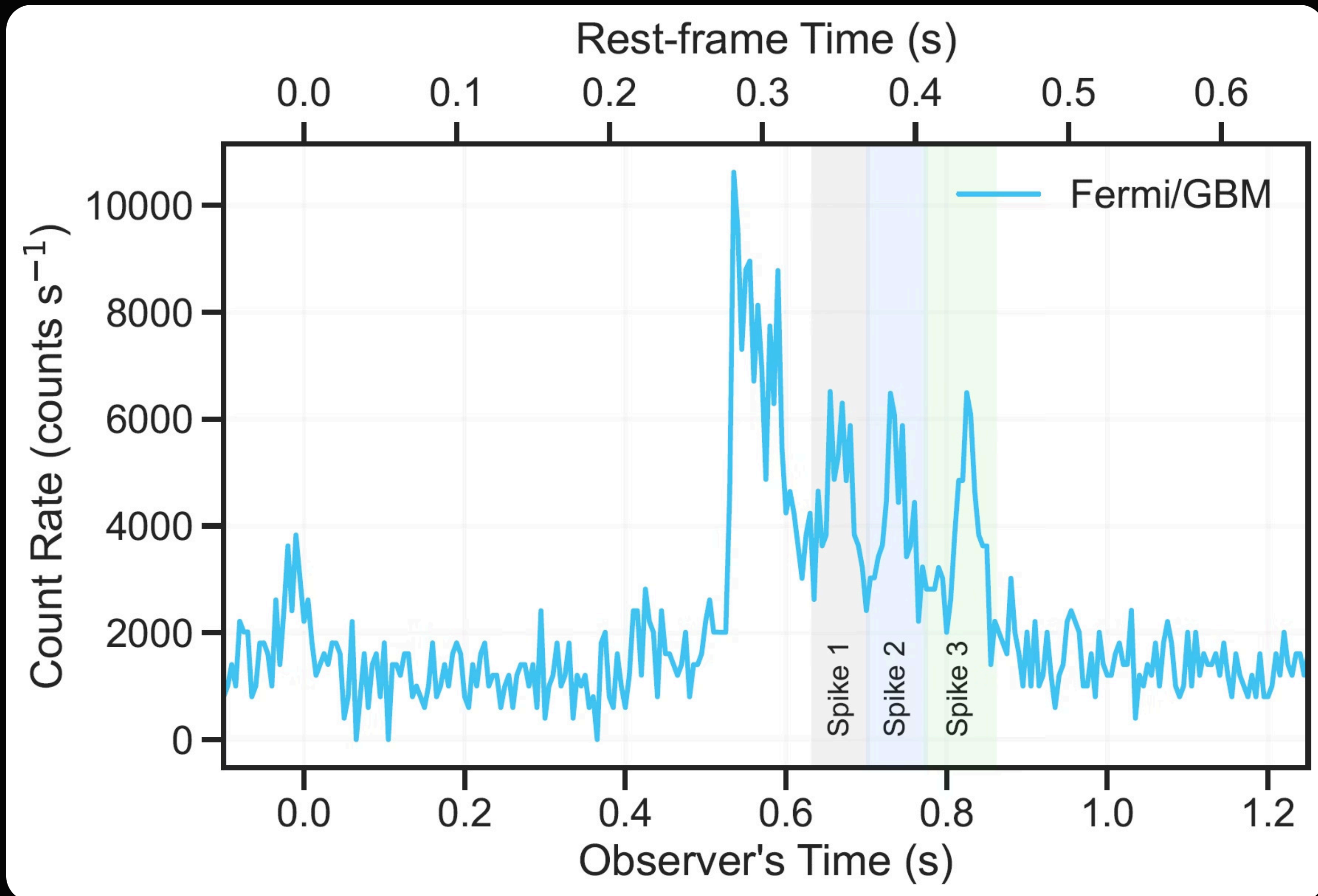
$$N \approx E_{\rm UPE}/\mathcal{E}_{e^+e^-} \approx 5\times 10^7\ \text{impulses}$$

We approximate the pair dynamics to that of a self-accelerating, spherically symmetric ultra-relativistic e+e- photon plasma in a poorly baryon-contaminated medium (Ruffini, Salmonson, Wilson, Xue, A&A 1999; Ibid. A&A 2000, Moradi, et al. PRD 2021; Rastegarnia, et al., EPJC 2022). ***We derive the plasma transparency parameters from the blackbodies observed in the UPE by:***

$$\Gamma \approx \left(\frac{aT_{\rm obs}^4\sigma_T\Delta_d}{16m_Nc^2}\frac{1-\epsilon_{\rm BB}}{\epsilon_{\rm BB}}\right)^{1/3}, \quad \mathcal{B} \equiv \frac{M_Bc^2}{\mathcal{E}_{e^+e^-}} = \frac{1-\epsilon_{\rm BB}}{\Gamma-1} \quad R_{\rm tr} = \sqrt{\frac{\sigma_T}{8\pi}\frac{\mathcal{B}\mathcal{E}_{e^+e^-}}{m_Nc^2}}$$

i-th event	$k_BT_{\mathrm{obs},i}$ (keV)	Γ_i	$\mathcal{B}_i$ (10^{-2})	$R_{\mathrm{tr},i}$ (10^{10} cm)
1	1216	1785.61	0.032	0.21
2	811	1040.49	0.056	0.28
3	405	412.24	0.14	0.44
4	203	164.14	0.36	0.70
5	101	64.71	0.91	1.13
6	51	26.02	2.32	1.80
7	25	10.06	6.40	2.99
8	13	4.21	18.09	5.02

Post-UPE spikes



$$\Omega_{\rm LT} = -\frac{g_{t\phi}}{g_{\phi\phi}} = \frac{2\hat{a}\hat{M}r}{A}c$$

$A = (r^2 + \hat{a}^2)^2 - \Delta\hat{a}^2$

$\Delta = r^2 - 2\hat{M}r + \hat{a}^2$

$\hat{M} = GM/c^2$

$\hat{a} = J/(Mc) = \alpha\, GM/c^2$

Rest-frame time interval between spikes:

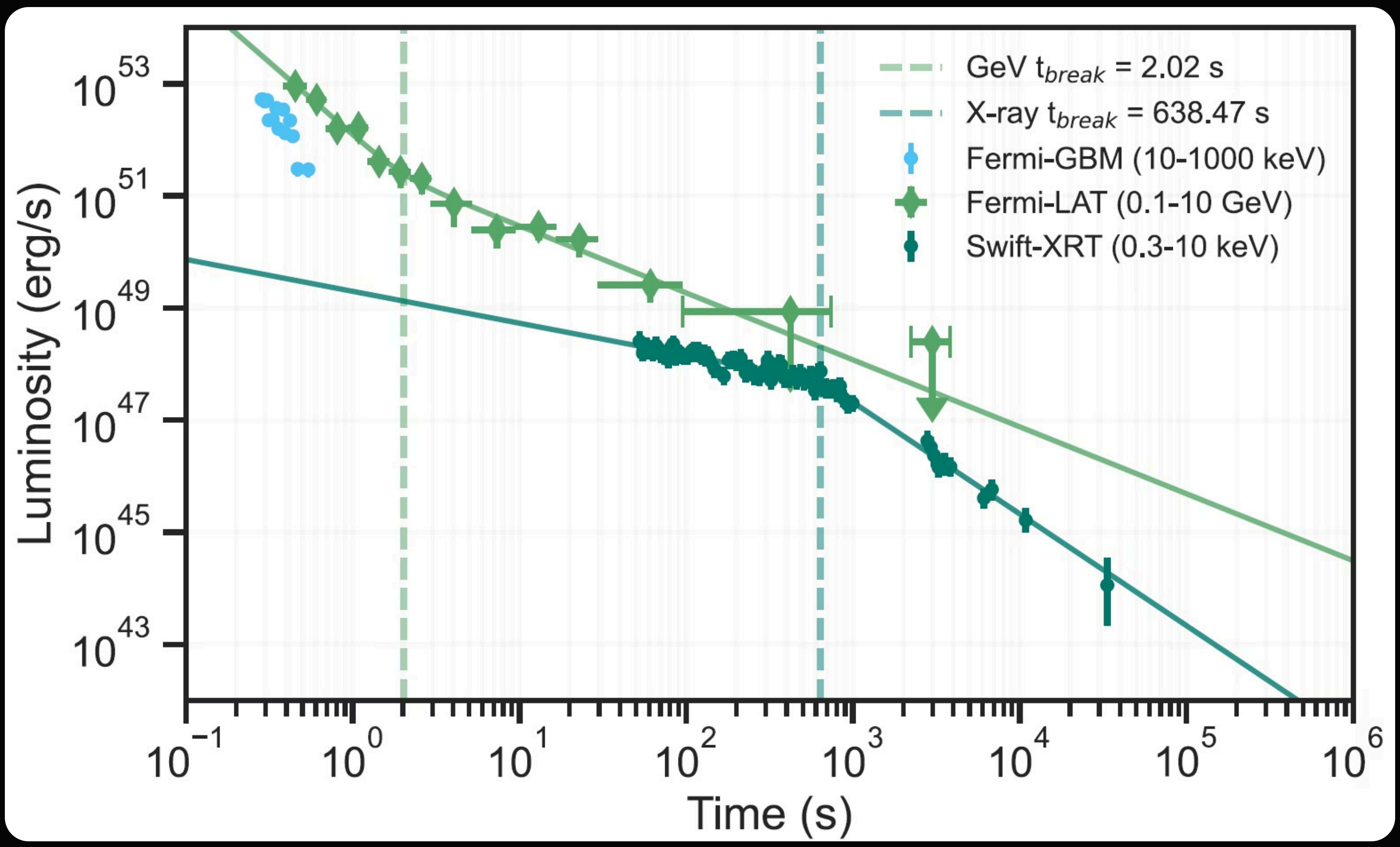
$\Delta t_{\rm sp} \approx 40 \;\; {\rm ms}$

We obtain a QPO period of this value for:

$r = 1.28 R_{\rm LCO} = 6.20 M = 21.60 \;\; {\rm km}$

It is suggestive they are similar to those inferred from QPO data in some low-mass X-ray binaries.

The GeV emission



Christodoulou-Ruffini-Hawking mass-energy formula

$$M^2 = M_{\rm irr}^2 + c^2 J^2/(4G^2 M_{\rm irr}^2)$$

Extractable energy of the Kerr BH

$$E_{\rm ext} \equiv (M - M_{\rm irr})c^2 = E'_{\rm GeV}$$

Assuming the extractable energy powers the GeV emission:

$$M = M_{\rm irr} + E'_{\rm GeV} c^2$$

$$\alpha = 2\frac{M_{\rm irr}}{M}\sqrt{1 - \left(\frac{M_{\rm irr}}{M}\right)^2}$$

Lower limit to the critical mass set by the mass of PSR J0952-0607 (Romani et al., ApJ 2022):

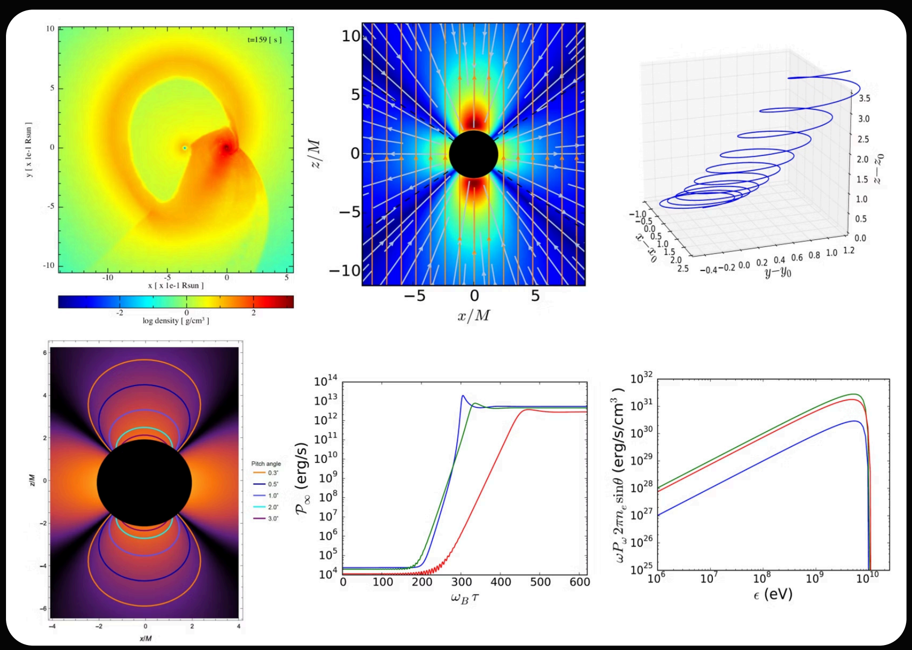
$$M_{\rm irr} = 2.35 M_\odot$$

Intrinsic GeV emission energy from accelerated electrons, using the beaming angle of 60 degrees:

$$E'_{\rm GeV} = 2.54 \times 10^{52} \text{ erg}$$

The BH mass and spin (at birth) are:

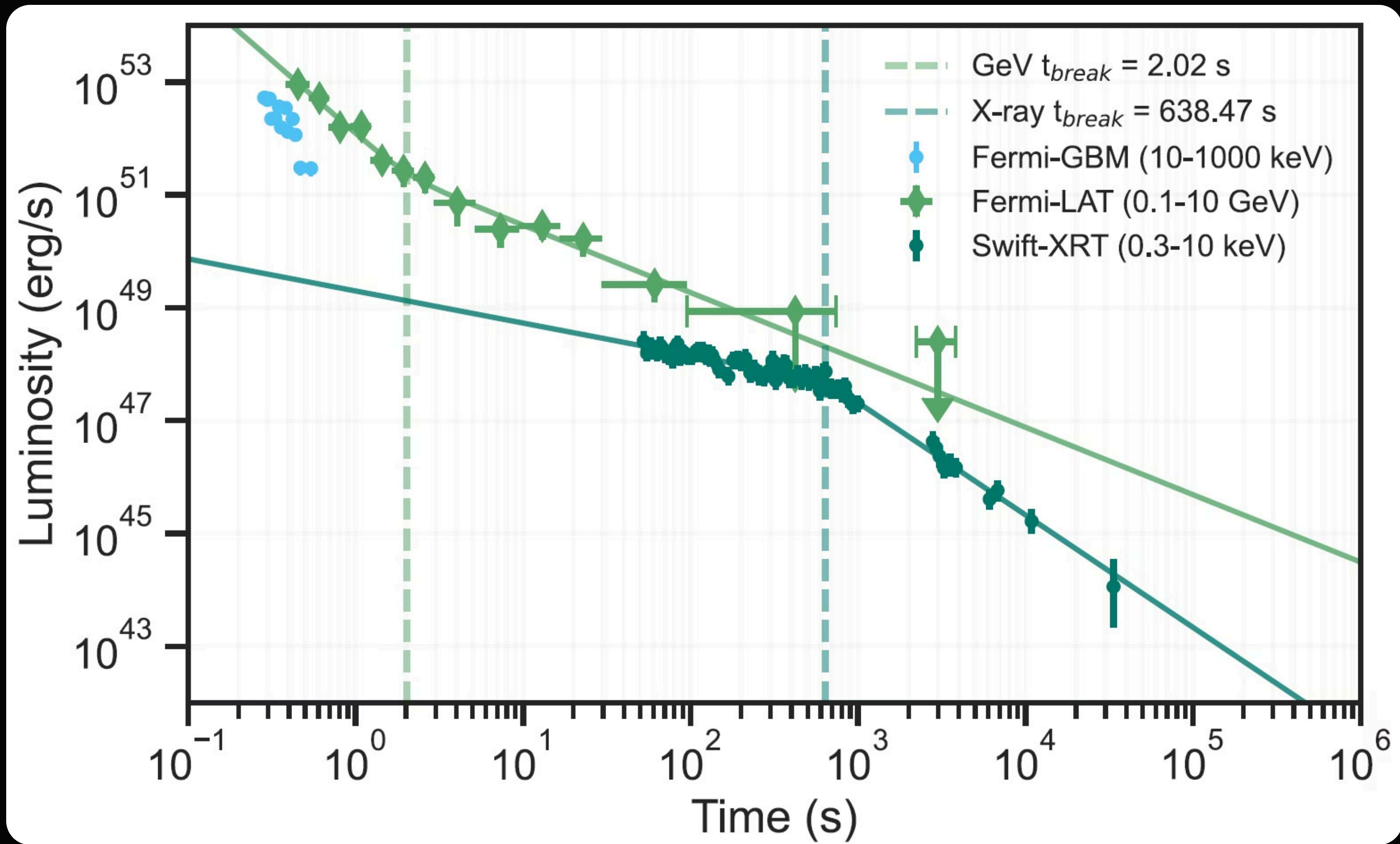
$$M = 2.36 M_\odot \text{ and } \alpha = 0.22$$



The GeV emission from a Kerr BH in a magnetic field.The induced electric field accelerate electrons which radiate at GeV energies:

Ruffini et al., ApJ 2019; Rueda & Ruffini, EPJ 2020; Moradi et al., A&A 2021; Rueda, Kerr, Ruffini, ApJ 2022; Rueda & Ruffini; EPJC 2023; Ibid. EPJC 2024

The X-ray afterglow



Evolution of the BH mass and spin

$$\dot{M} = \frac{\epsilon}{1-\epsilon}\frac{L_{\rm acc}}{c^2}$$

$$\dot{\alpha} = \left(\frac{l}{\epsilon} - 2\alpha\right)\frac{\dot{M}}{M}$$

$$L_{\rm acc} = L_X(t)$$

$$m_{\rm acc} = \int \frac{\dot{m}}{\epsilon}dt = 0.0089 M_\odot$$

The small mass is consistent with the merger being mass symmetric (q=1).

Gravitational-wave emission

Angular momentum conservation:

$$J_{\mathrm{bin,mgr}} = J_{\mathrm{BH}} + J_d + \Delta J_{\mathrm{rad}}$$

Binary angular momentum at merger:

$$J_{\mathrm{bin,mgr}} = \mu\sqrt{GM_{\mathrm{bin}} r_{\mathrm{mgr}}}$$

BH angular momentum:

$$J_{\mathrm{BH}} = \alpha GM^2/c$$

Disk angular momentum:

$$J_d \approx l(\alpha) GM m_d/c$$

Therefore, we infer:

$$\Delta J_{\mathrm{rad}} = 0.302 GM^2/c$$

This is mostly radiated by GWs. The associated energy carried away by the GWs is:

$$\Delta E_{\mathrm{GW,mgr}} \sim \Omega_{\mathrm{mgr}} \Delta J_{\mathrm{GW}}$$

$$\approx 0.007 Mc^2 = 2.96 \times 10^{52}\ \mathrm{erg}$$

where we have used the angular frequency is:

$$\Omega_{\mathrm{mgr}} \approx \Omega_K \approx 0.023 c^3/(GM)$$

These numbers imply we can approximate M = 2 m (1% error), so the mass of the merging components was **1.2 solar masses.**

Summary

$E_{\rm prec}$	2.28×10^{51} erg
$E_{\rm UPE}$	3.95×10^{52} erg
$E_{\rm GeV}$	5.09×10^{52} erg
E_X	8.23×10^{50} erg
M	$2.36 M_\odot$
α	0.22
$M_{\rm irr}$	$2.35 M_\odot$
$m_1 = m_2$	$1.19 M_\odot$
B_p	$\gtrsim 2.04 \times 10^{14}$ G
$\Delta E_{\rm GW,insp}$	$< 0.018 Mc^2 = 7.60 \times 10^{52}$ erg
$\Delta E_{\rm GW,mgr}$	$\sim 0.007 Mc^2 = 2.96 \times 10^{52}$ erg
$\Delta J_{\rm GW,mgr}$	$0.30\, GM^2/c$
$m_d = m_{\rm acc}$	$0.0089 M_\odot$

Inferred properties of the NS-NS merger leading to the short GRB 090510.

Salient points

1. ***Strong magnetic and electric fields are involved***

   The precursor and UPE phase suggest the NS-NS merger develops strong magnetic fields well above 1E14 G and could be up to 1E16 G.

   These fields can have a role in the dynamics of the system approaching the merger, suggesting a revision of GW emission models of NS-NS mergers.

2. ***The induced electric field around the merged object is overcritical***

   The presence of a BH is not mandatory to produce pairs from vacuum breakdown. The electric field induced by the rotating strong magnetic field is able to produce pairs before the object reaches the critical for BH formation.

   The UPE can be therefore powered by the strongly magnetized, fast-rotating object while approaching the critical mass for BH formation.

3. ***The BH mass and spin can be inferred from GeV emission and heaviest pulsar mass***

   The BH mass-energy formula, the extractable energy concept, and the constraint to the BH irreducible mass from the critical mass of a NS (Romani et al., 2022), allow to determine the mass and spin of the newborn Kerr BH.

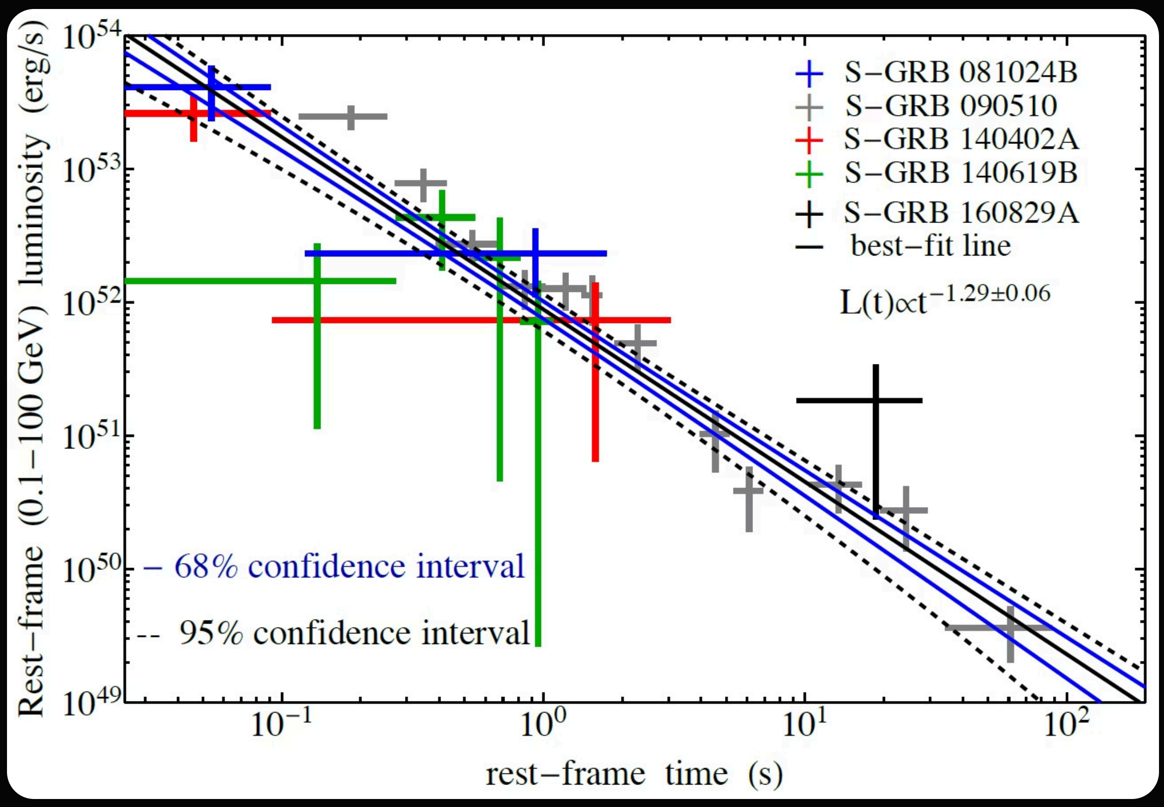
4. ***The X-ray afterglow implies small disk around the BH***

   This result suggest the merger was mass-symmetric, in agreement with the mass distribution of binary NSs

5. ***The GW emission is much less than the EM emission***

   This result suggest the EM fields can have a relevant role in the dynamics of the system in the approach to and duyring the merger. More numerical simulations of this process including electrodynamical effects in NS-NS mergers are needed to assess it.

6. ***GRB 090510 seems not to be unique, so our conclusions general for energetic short GRBs:***



GeV emission of known short GRBs.

Some prospects

1. ## BH masses - NS critical mass

   Inference of the BH mass constraint the NS critical mass and vice versa, as well as the subsequent BH early accretion from bound ejecta. ***What other short GRBs tell about?***

2. ## Not all short GRBs form BHs

   The relative population of short GRBs that ***form and do not form a BH*** has information on how easy or difficult is to form a BH in the merger. Such analysis constraint the NS critical mass, so the nuclear EOS, and the NS-NS mass distribution. Simulations + population synthesis models are needed.

3. ## Pair creation and evolution in highly-magnetized, fast-rotating, massive NS

   Modeling of the pair-creation process around highly-magnetized, fast rotating NS. Thermodynamic properties of the plasma and subsequent evolution to transparency, accounting for the angular dependence in the dynamics.

4. ## Particle motion, collissions, and opacity in the merged object and newborn BH surroundings

   Modeling of photon-photon, photon-matter, photon-magnetic field interaction is needed in MeV, GeV and higher energies. Proton-proton and proton-electron interactions can also lead to high-energy.

5. ## Magnetic field feedback

   Additional modeling of the feedback of e+e- pairs onto the magnetic field (e.g., screening) is needed. Evolution of the magnetic field surrounding the merged object in the transition to the newborn BH.

6. ## Magnetic field geometry

   We have explored a rotating magnetic dipole. What about more complex electromagnetic field geometries? Quadrupole field? Inclined field?

7. ## BH feedback

   The efficiency of extracting the BH energy must be accurately estimated accounting for the BH interaction with particles and fields. How much increase the irreducible mass must be assessed (Rueda & Ruffini, EPJC 2023, 2024; Ruffini et al. PRL 2025; PRR 2025).