Gravitomagnetic interaction of a Kerr black hole with a magnetic field as the source of GRB high-energy radiation

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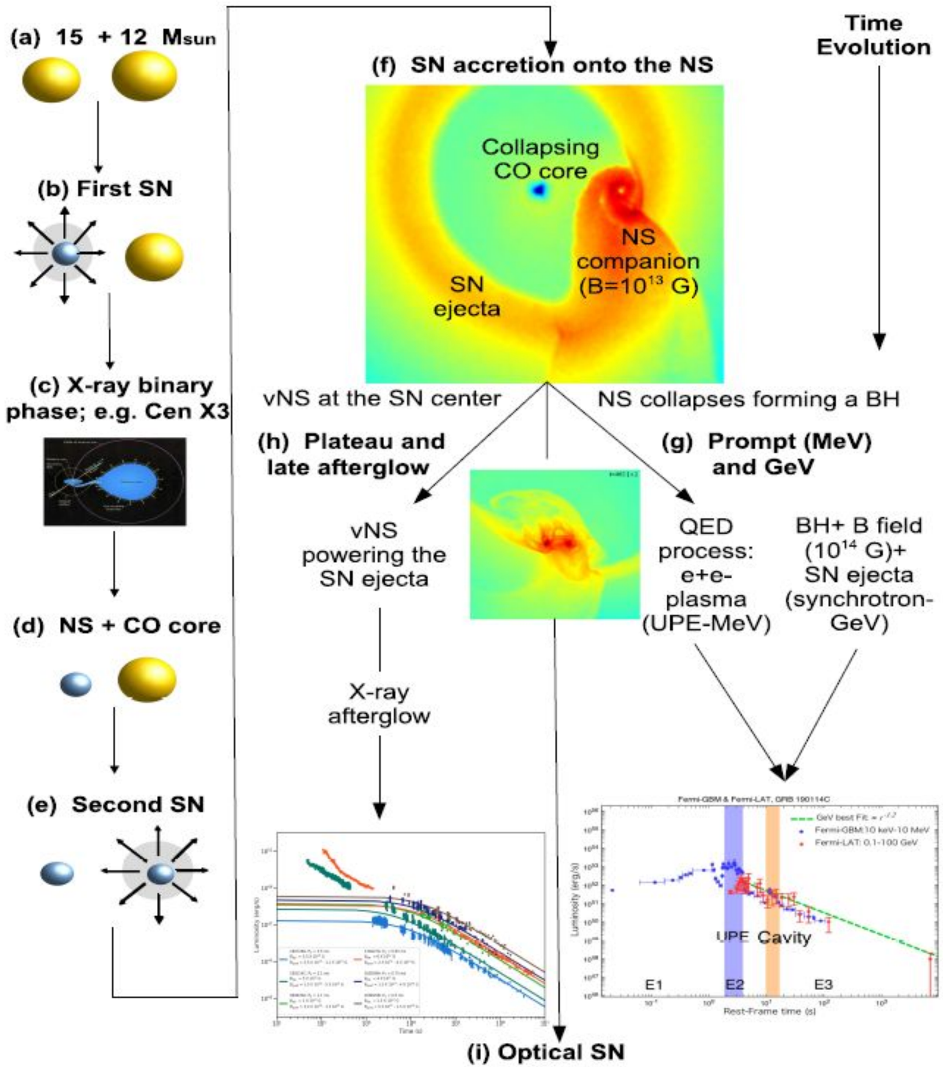
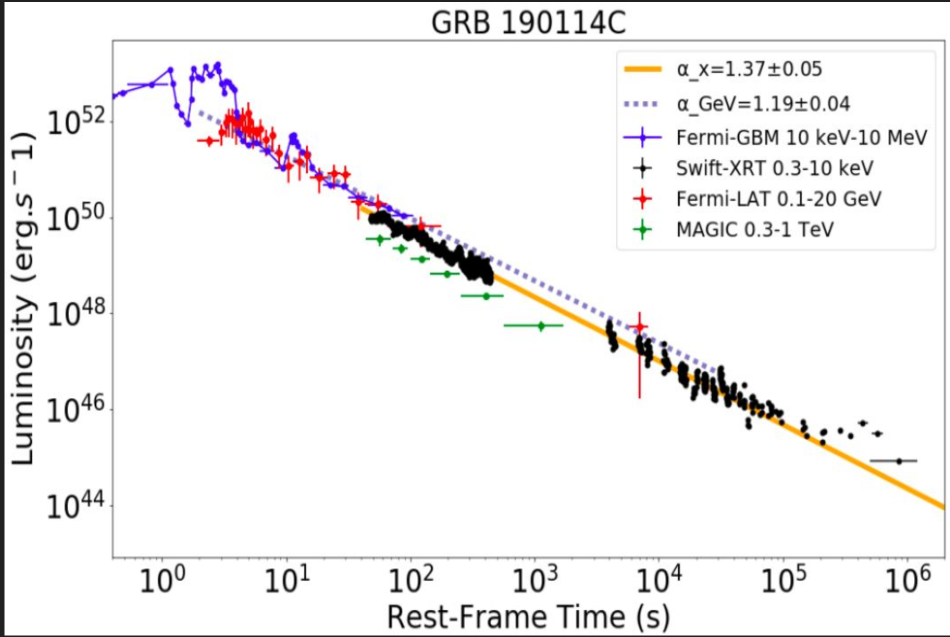
- Can we use an electromagnetic (EM) process to extract energy from a rotating BH?
- What kind of emission does it generate in a GRB and/or an AGN?
- Can we give specific examples of it?

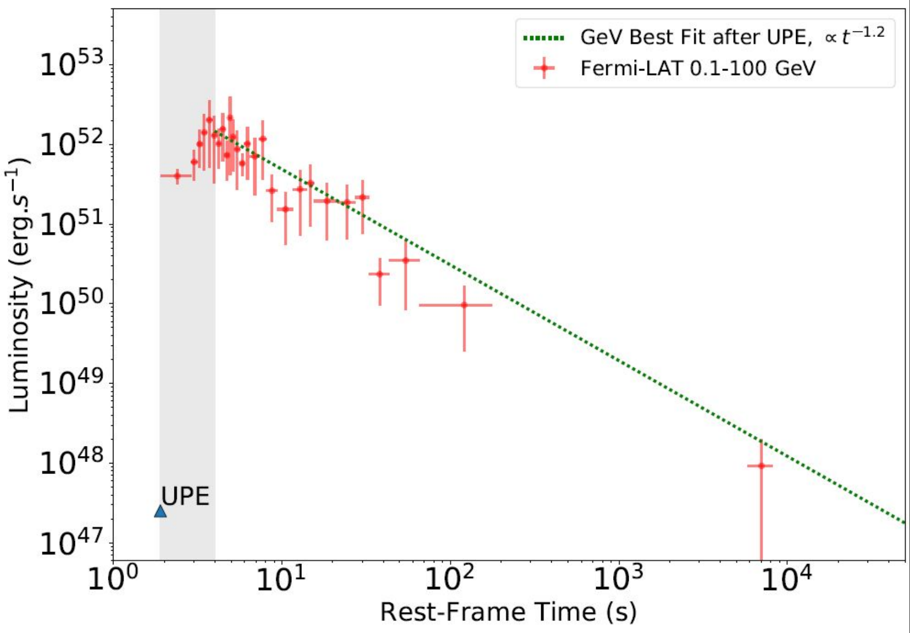
Binary evolutionary path: the BdHN is triggered by the second SN event

Moradi, et al., A&A 2021
Rueda, et al., ApJ 2020
Rueda & Ruffini, EPJC 2020
Ruffini, et al., ApJ 2019
Becerra, et al., ApJ 2019
Becerra, et al., ApJ 2018
Ruffini, et al., ApJ 2018
Cipolletta, et al., PRD 2017
Becerra, et al., ApJ 2016
Fryer, et al., PRL 2015
Becerra, et al., ApJ 2015
Fryer, et al., APJL 2014
Rueda & Ruffini, APJL 2012



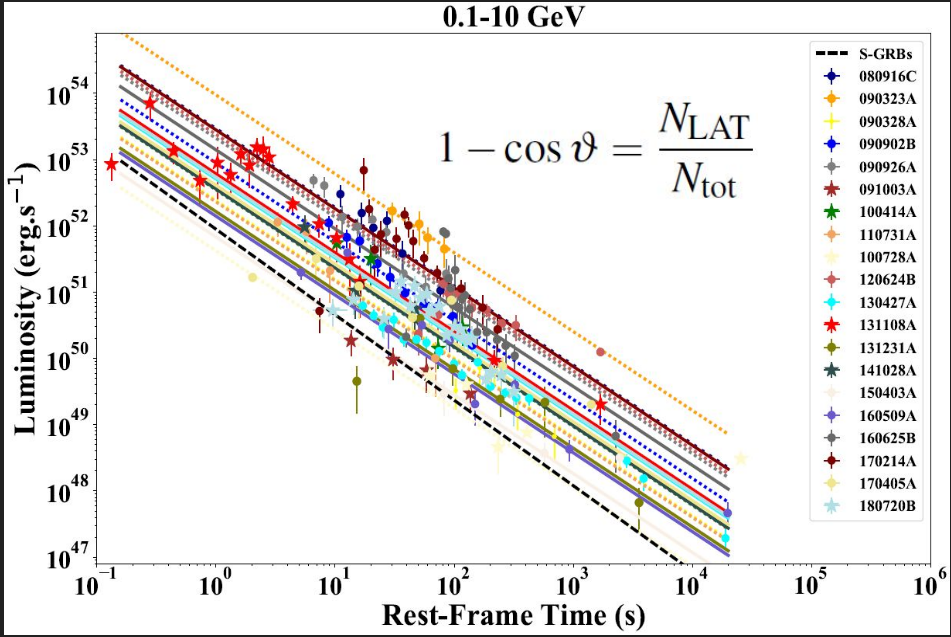
High-energy (GeV) emission of GRB 190114C





Taken from Moradi, Rueda, Ruffini, A&A 2021

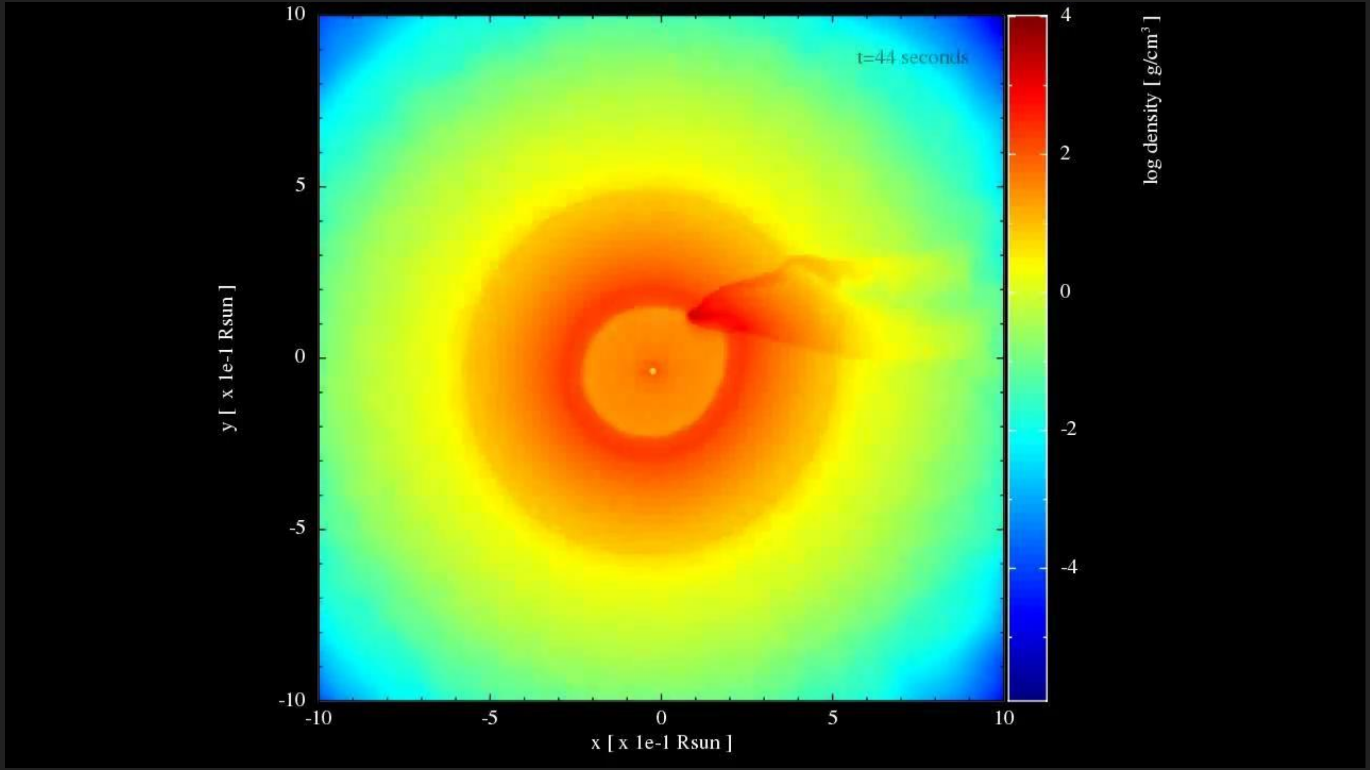
High-energy (GeV) emission of long GRBs



Source	α	$M(\alpha)$ ($M_\odot$)	M_{irr} ($M_\odot$)	B_0 10^{10} G
BdHN I 080916C	0.87	8.9	7.6	1.9
BdHN I 090902B	0.59	5.3	5	2.8
BdHN I 090926A	0.76	8.4	7.7	2.1
BdHN I 110713A	0.37	4.7	4.6	4.5
BdHN I 130427A	0.40	2.3	2.24	4.1
BdHN I 130518A	0.50	2.5	2.4	3.3
BdHN I 131108A	0.56	4.7	4.4	2.9
BdHN I 160509A	0.41	2.4	2.3	4
BdHN I 170214A	0.80	2.8	2.5	2.1
BdHN I 170405A	0.45	3.4	3.3	3.7
BdHN I 180720B	0.27	2.3	2.29	6

Analysis of 480 long GRBs from Ruffini, et al., MNRAS 2021. N_{tot}=54 sources are within the LAT boresight angle and of them N_{LAT}=25 have GeV emission detected, The ratio N_{LAT}/N_{tot} = 25/54 implies that the GeV radiation is emitted within a cone of half-opening angle of about 60 degrees from the normal to the orbital plane.

A simulation of a BdHN of type I



Courtesy: Becerra, et al. ApJ 2019

EM field around a Kerr BH immersed in a magnetic field

$$A_\mu = \frac{B_0}{2}\,\psi_\mu + a\,B_0\,\eta_\mu \qquad E_{\hat{i}} = E_\mu\,\vec{e}^{\mu}{}_{\hat{i}} = F_{\hat{i}\hat{t}} \qquad B_{\hat{i}} = B_\mu\,\vec{e}^{\mu}{}_{\hat{i}} = \epsilon_{\hat{i}\hat{j}\hat{k}}F^{\hat{j}\hat{k}}$$

$$E_{\hat{r}} = \frac{B_0\hat{a}\hat{M}}{\Sigma^2 A^{1/2}}\left[2r^2\sin^2\theta\,\Sigma - (r^2+\hat{a}^2)(r^2-\hat{a}^2\cos^2\theta)(1+\cos^2\theta)\right]$$

$$E_{\hat{\theta}} = B_0\hat{a}\hat{M}\,\frac{\Delta^{1/2}}{\Sigma^2 A^{1/2}}2\,r\,\hat{a}^2\sin\theta\cos\theta\,(1+\cos^2\theta)$$

$$B_{\hat{r}} = \frac{B_0\cos\theta}{\Sigma^2 A^{1/2}}\left\{(r^2+\hat{a}^2)\Sigma^2 - 2\hat{M}r\hat{a}^2[2r^2\cos^2\theta + \hat{a}^2(1+\cos^4\theta)]\right\}$$

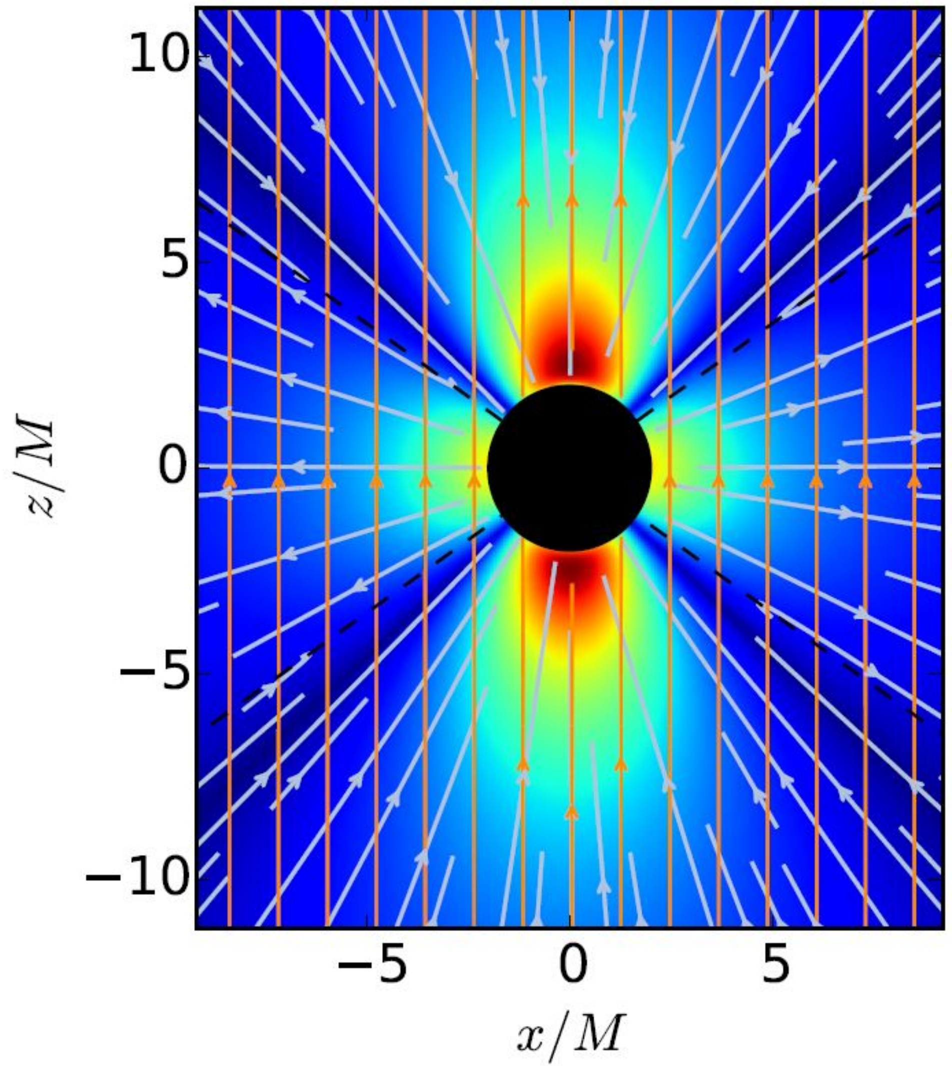
$$B_{\hat{\theta}} = -\frac{\Delta^{1/2}}{\Sigma^2 A^{1/2}}B_0\sin\theta\,[\hat{M}\hat{a}^2(r^2-\hat{a}^2\cos^2\theta)(1+\cos^2\theta) + r\Sigma^2]$$

EM field of the Wald solution (1074) as seen by the ZAMO. Taken from Moradi, Rueda, Ruffini, A&A 2021

Inner engine components:

- The Kerr metric describing the rotating BH;
- An asymptotically uniform magnetic field around the Kerr BH;
- A very low density ionized plasma 10^{-14} - 10^{-6} g cm^{-3}.

Taken from Moradi, Rueda, Ruffini, A&A 2021



“*Surface charge*” on the BH horizon

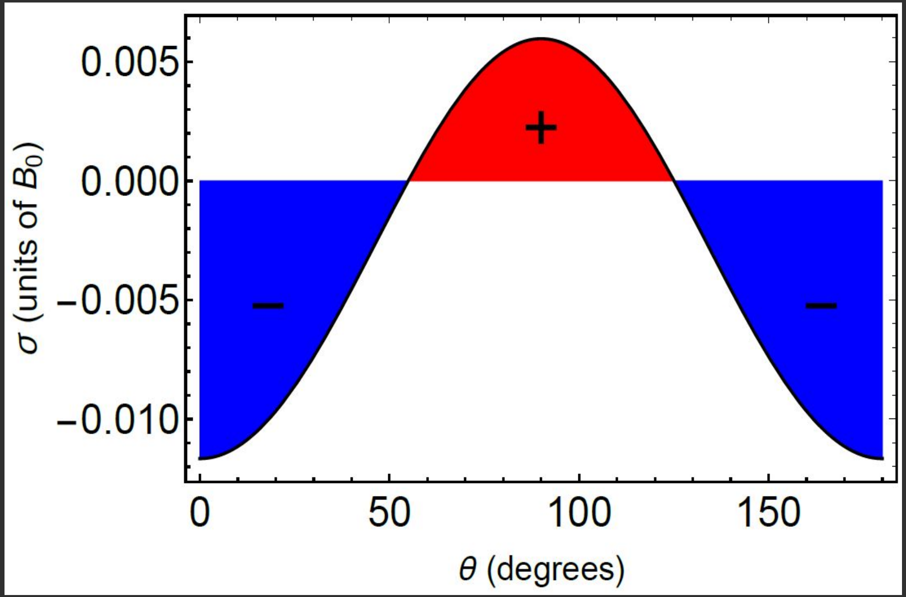
$$\sigma = \frac{1}{4\pi} B_0 a r_+ (r_+ - M) \frac{r_+ \sin^4\theta - M\cos^2\theta(1+\cos^2\theta)}{(r_+^2 + a^2\cos^2\theta)}$$

$$Q_{\rm patch} = \iint \sigma \sqrt{|h_{ij}|}\, dx^i dx^j$$

$$Q_\pm = \pm\frac{2\sqrt{3}}{9} M^2 B_0 \frac{a}{M} = \pm\frac{2\sqrt{3}}{9} B_0 J$$

Taken from Rueda, Ruffini, Kerr (in preparation)

Thorne, Price and MacDonald (1986); Miniutti & Ruffini (2000)



The induced E-field is quadrupolar: two patches are positively charged, and two are negatively charged. The net charge is zero. The B-field and the BH spin are parallel, so the E-field points inward around the polar axis up to nearly 60 degrees. Then, it reverses direction. There is reflection symmetry with respect to the equator.

EM field energetics

$$\mathcal{E} \approx \frac{1}{2} E_{\hat{r}}^2 r_+^3 \approx \frac{G}{c^4} \frac{B_0^2 J^2}{M}$$

Total electric energy available to be emitted

$$\Delta\Phi = \frac{1}{c} e\, a\, B_0$$

Maximum particle energy attainable

BH energetics

$$E_{\rm extr} \equiv (M - M_{\rm irr})c^2$$

Extractable BH energy

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

Christodoulou-Ruffini-Hawking BH mass formula

Equations of motion: Kerr metric in EM field, radiation reaction, ZAMO

$$\frac{Du^{\hat{a}}}{d\tau} = \frac{du^{\hat{a}}}{d\tau} + \omega_{\hat{c}}{}^{\hat{a}}{}_{\hat{b}} u^{\hat{b}} u^{\hat{c}} = \frac{q}{m} F^{\hat{a}}{}_{\hat{b}} u^{\hat{b}} - \mathcal{F}^{\hat{a}}$$

$$\mathcal{F}^{\hat{a}} = \frac{2}{3}\left(\frac{q}{m}\right)^2 \frac{q^2}{m}\left(F_{\hat{c}\hat{d}} F^{\hat{d}}{}_{\hat{e}} u^{\hat{c}} u^{\hat{e}}\right) u^{\hat{a}} + \frac{2}{3}\left(\frac{q}{m}\right)^2 \frac{q^2}{m} F^{\hat{a}}{}_{\hat{b}} F^{\hat{b}}{}_{\hat{c}} u^{\hat{c}} + \frac{2}{3}\left(\frac{q}{m}\right)^2 q \frac{DF^{\hat{a}}{}_{\hat{b}}}{dx^{\hat{c}}} u^{\hat{b}} u^{\hat{c}}$$

$$\approx \frac{2}{3}\left(\frac{q}{m}\right)^2 \frac{q^2}{m}\left(F_{\hat{c}\hat{d}} F^{\hat{d}}{}_{\hat{e}} u^{\hat{c}} u^{\hat{e}}\right) u^{\hat{a}} = -\frac{\mathcal{P}}{m} v^{\hat{a}}$$

$$\mathcal{P} \equiv \frac{2}{3}\left(\frac{q}{m}\right)^2 q^2 \hat{\gamma}^3 \left[(\vec{E} + \vec{v} \times \vec{B})^2 - (\vec{v} \cdot \vec{E})^2\right]$$

Taken from Rueda, Ruffini, Kerr (in preparation)

EOM in the *slow-rotation* regime

$$\frac{d\hat{\gamma}}{d\tau} = -\frac{e}{m}E^{\hat{r}}v^{\hat{r}}\hat{\gamma} - \frac{\mathcal{P}}{m} + \left[\frac{M}{r^2\sqrt{1-2M/r}} - \frac{6Ma\sin\theta}{r^3}v^{\hat{\theta}}\right]\hat{\gamma}v^{\hat{r}}$$

$$\begin{aligned}
\frac{dv^{\hat{i}}}{d\tau} = &-\frac{e}{m}\left[(E^{\hat{r}} - v^{\hat{\phi}}B^{\hat{\theta}})\delta^{\hat{i}}{}_{\hat{r}} + v^{\hat{\phi}}B^{\hat{r}}\delta^{\hat{i}}{}_{\hat{\theta}} + (v^{\hat{r}}B^{\hat{\theta}} - v^{\hat{\theta}}B^{\hat{r}})\delta^{\hat{i}}{}_{\hat{\phi}} - E^{\hat{r}}v^{\hat{r}}v^{\hat{i}}\right] \\
&- \frac{\mathcal{P}}{m\hat{\gamma}}v^{\hat{i}} - \left(\frac{M}{r^2\sqrt{1-2M/r}} - \frac{6Ma\sin\theta}{r^3}v^{\hat{\theta}}\right)\hat{\gamma}v^{\hat{r}}v^{\hat{i}} \\
&- \left[\frac{6Ma\sin\theta}{r^3}v^{\hat{\phi}} + \frac{M\,(v^{\hat{\theta}})^2}{r^2(1-2M/r)^{5/2}} + \frac{\sqrt{1-2M/r}}{r}(v^{\hat{\phi}})^2\right]\hat{\gamma}\,\delta^{\hat{i}}{}_{\hat{r}} \\
&+ \left[\frac{M}{r^2(1-2M/r)^{5/2}}v^{\hat{r}}v^{\hat{\theta}} - \frac{\cos\theta}{r\sin\theta}(v^{\hat{\phi}})^2\right]\hat{\gamma}\,\delta^{\hat{i}}{}_{\hat{\theta}} \\
&- \left[\frac{6Ma\sin\theta}{r^3}v^{\hat{r}} - \frac{\sqrt{1-2M/r}}{r}v^{\hat{r}}v^{\hat{\phi}} - \frac{\cos\theta}{r\sin\theta}v^{\hat{\theta}}v^{\hat{\phi}}\right]\hat{\gamma}\,\delta^{\hat{i}}{}_{\hat{\phi}}.
\end{aligned}$$

Taken from Rueda, Ruffini, Kerr (in preparation)

Photon four-momentum at infinity

$$k^{\mu} = e^{\mu}{}_{\hat{b}}\, \Lambda^{\hat{b}}{}_{(a)}\, k^{(a)}$$

$$k^0 = k^{(0)} \hat{\gamma} e^{-\nu} [1 + v_{\hat{i}}\, n^{(i)}]$$

$$n^r = \frac{k^{(0)}}{k^0} e^{-\mu_1} \left[\hat{\gamma} v^{\hat{r}} + n^{(1)} + \frac{\hat{\gamma}^2}{\hat{\gamma}+1} v^{\hat{r}} v_{\hat{j}} n^{(j)} \right]$$

$$n^\theta = \frac{k^{(0)}}{k^0} e^{-\mu_2} \left[\hat{\gamma} v^{\hat{\theta}} + n^{(2)} + \frac{\hat{\gamma}^2}{\hat{\gamma}+1} v^{\hat{\theta}} v_{\hat{j}} n^{(j)} \right]$$

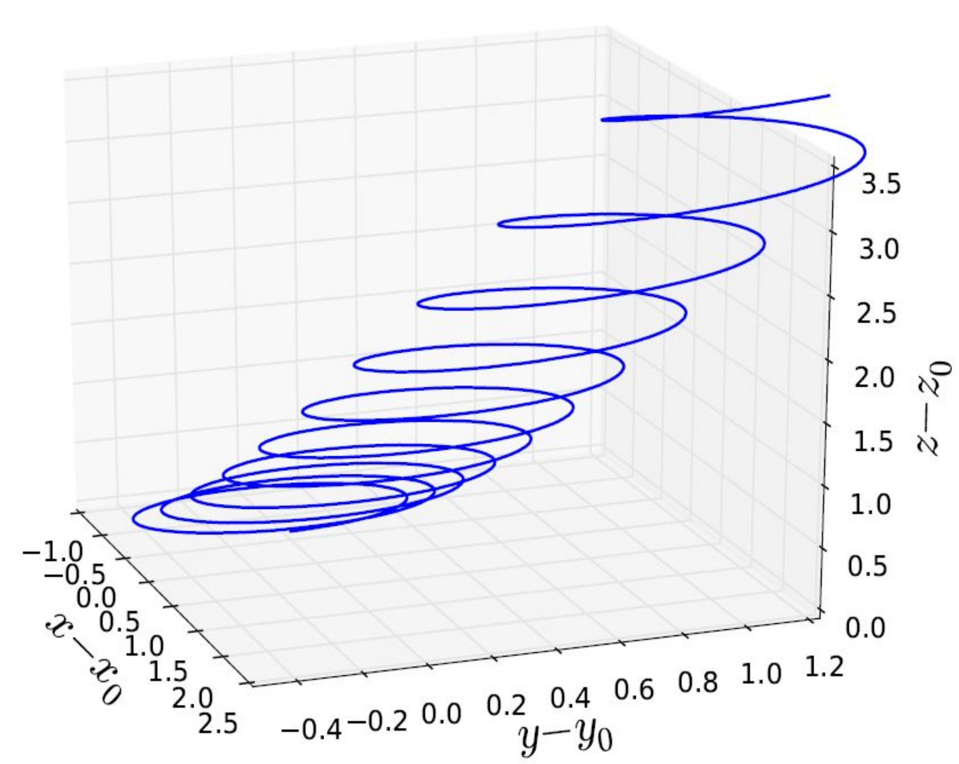
$$n^\phi = \frac{k^{(0)}}{k^0} e^{-\Psi} \left\{ e^{\Psi-\nu} \omega \hat{\gamma} [1 + v_{\hat{j}}\, n^{(j)}] + \hat{\gamma} v^{\hat{\phi}} + n^{(3)} + \frac{\hat{\gamma}^2}{\hat{\gamma}+1} v^{\hat{\phi}} v_{\hat{j}} n^{(j)} \right\}$$

	$\Phi = 0$: plane $\vec{e}_{(z)}$-$\vec{e}_{(x)}$			$\Phi = \pi/2$: plane $\vec{e}_{(z)}$-$\vec{e}_{(y)}$		
	$\Theta = 0$	$\Theta = \pi/2$	$\Theta = \pi$	$\Theta = 0$	$\Theta = \pi/2$	$\Theta = \pi$
k^0	$\frac{k^{(0)}}{\sqrt{1-2M/r}}\sqrt{\frac{1+\hat{\beta}}{1-\hat{\beta}}}$	$k^{(0)}\gamma$	$\frac{k^{(0)}}{\sqrt{1-2M/r}}\sqrt{\frac{1-\hat{\beta}}{1+\hat{\beta}}}$	$\frac{k^{(0)}}{\sqrt{1-2M/r}}\sqrt{\frac{1+\hat{\beta}}{1-\hat{\beta}}}$	$k^{(0)}\gamma$	$\frac{k^{(0)}}{\sqrt{1-2M/r}}\sqrt{\frac{1-\hat{\beta}}{1+\hat{\beta}}}$
n^r	$1-2M/r$	$(1-2M/r)\,\hat{\beta}$	$-(1-2M/r)$	$1-2M/r$	$(1-2M/r)\,\hat{\beta}$	$-(1-2M/r)$
n^θ	0	$(1/\gamma)(1/r)$	0	0	0	0
n^ϕ	$2Ma/r^3$	$2Ma/r^3$	$2Ma/r^3$	$2Ma/r^3$	$2Ma/r^3 + (1/\gamma)(1/r\sin\theta)$	$2Ma/r^3$

Taken from Rueda, Ruffini, Kerr (in preparation)

Inner engine **operation**

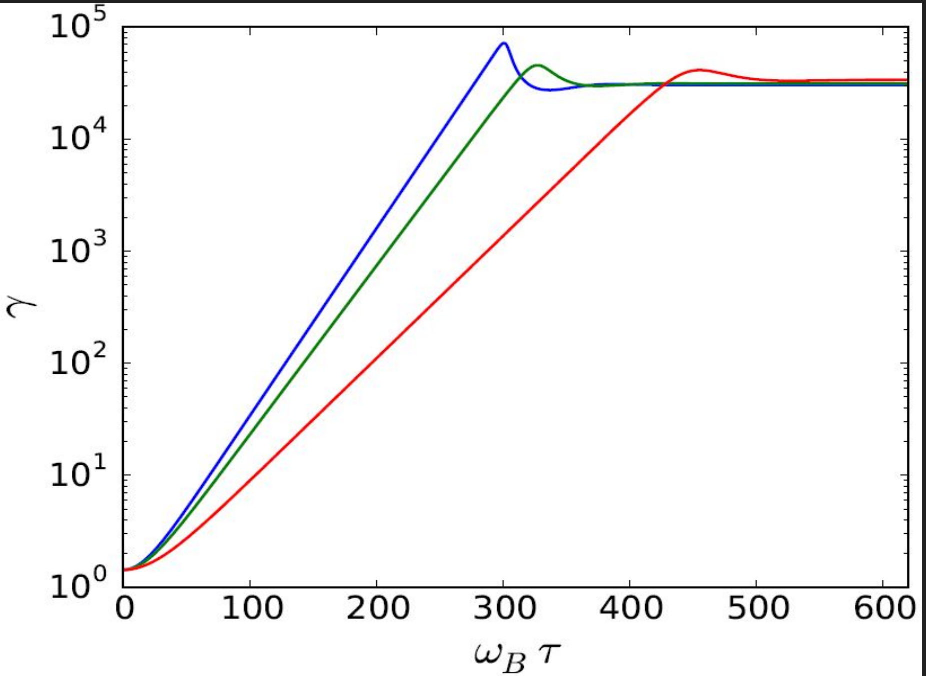
- B-field + BH spin → E-field;
- E-field accelerates e^- (and/or e^+, p) as allowed by the ***EM energy***;
- Along θ=0: UHECRs;
- At $\theta\neq0$: synchrotron radiation is emitted with τ= 10^{-15} s and ϵ_γ= GeV
- Total energy emitted = ***EM energy***. The process restarts $\boldsymbol{J = J_0 - dJ}$, being $\boldsymbol{dJ}$ the BH angular momentum extracted.



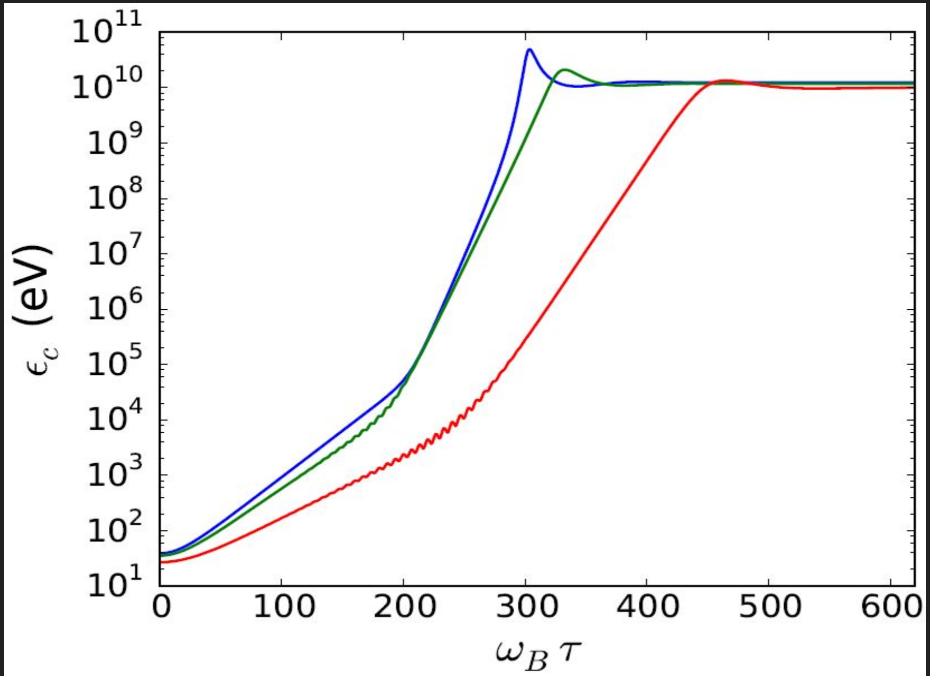
Electron motion around a BH of M = 4 $M_\odot$ and spin a/M = 0.3, in a magnetic field of 10^{10} G. The electron initial position is r= 4 M, θ=20 degrees. Figure taken from Rueda, Ruffini, Kerr (in preparation).

Taken from
Rueda & Ruffini, EPJC 2020;
Moradi, Rueda, Ruffini, A&A 2021

Electron Lorentz factor



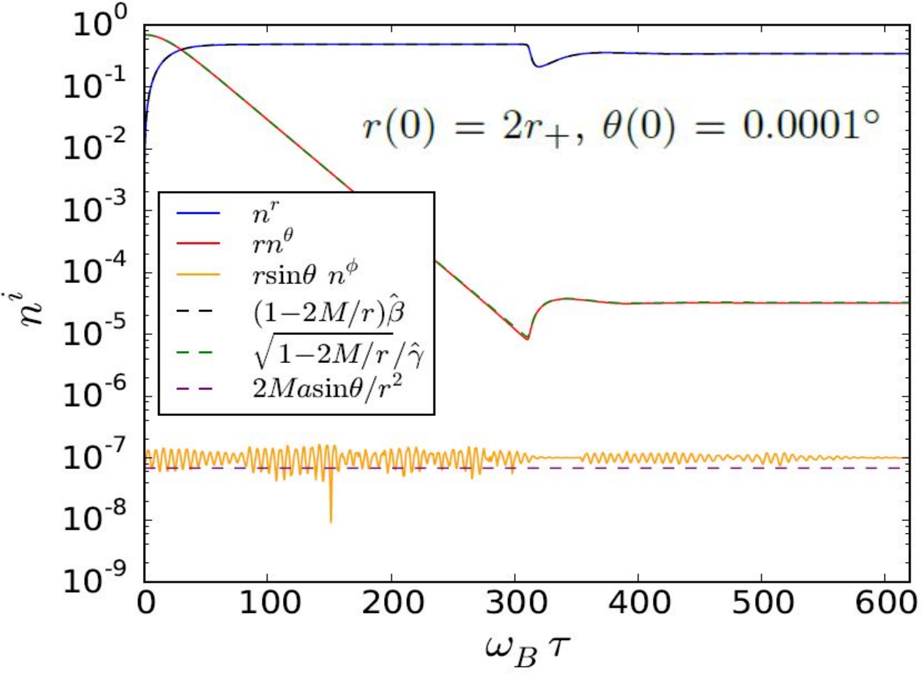
Characteristic photon energy

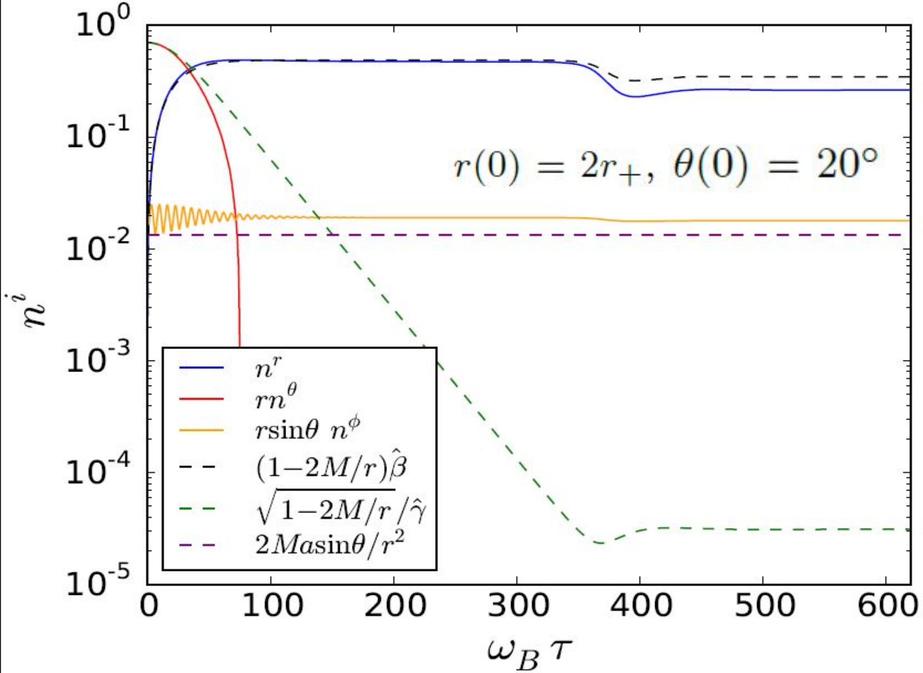


Lorentz factor and critical energy of the photons emitted by an electron at an initial position r= 4 M and θ=1 (blue), 14 (green) and 27 degrees, accelerated in the EM field of a BH of M = 4 $M_{\odot}$ and spin a/M = 0.3, immersed in a magnetic field of 10^{10} G.

Taken from Rueda, Ruffini, Kerr (in preparation)

Spatial components of the photon four-momentum

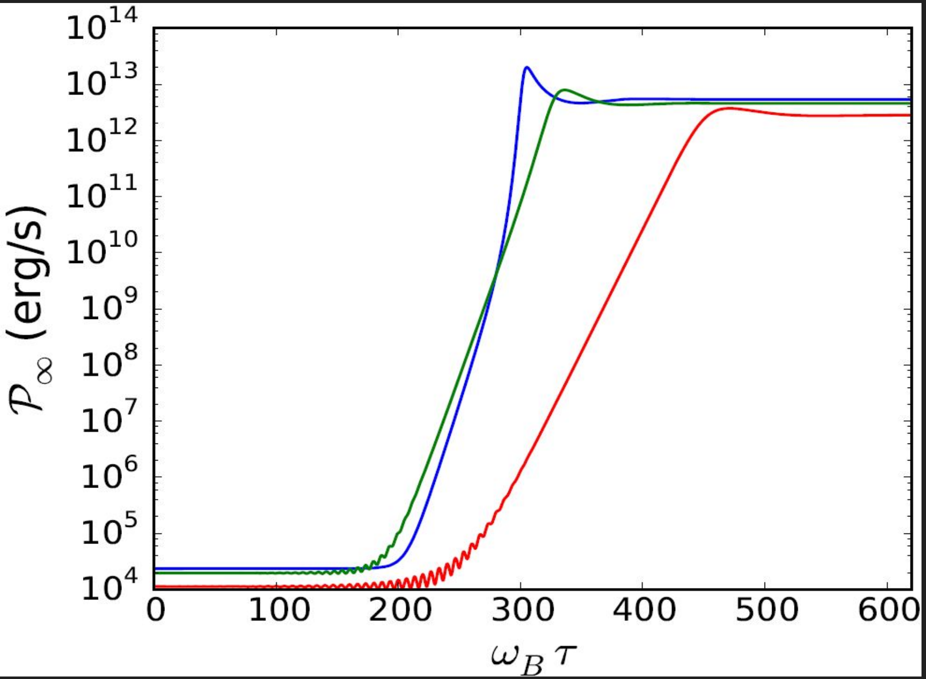




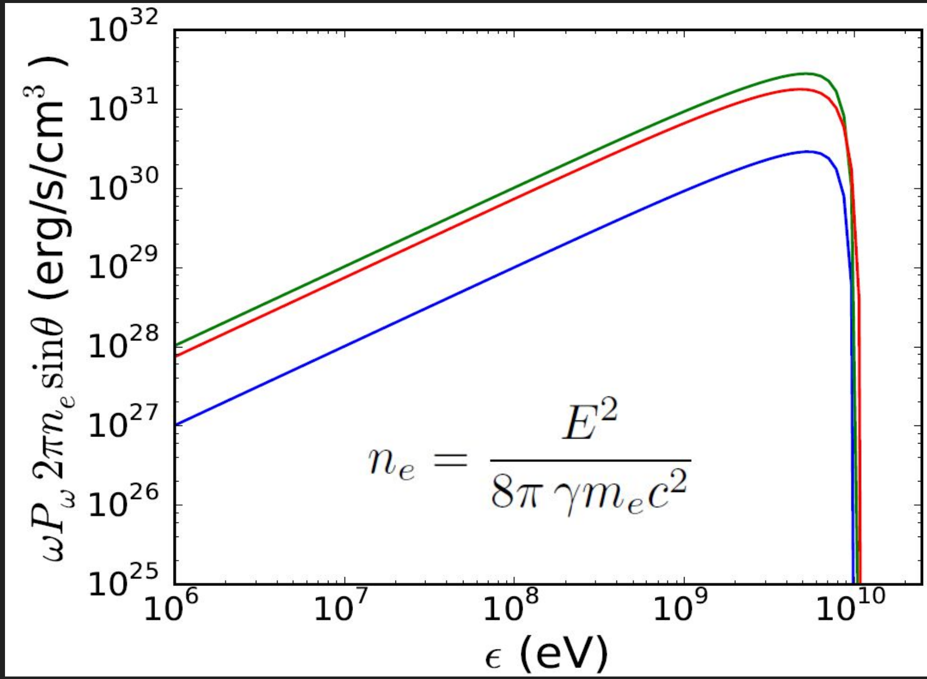
Spatial components of the four-momentum of photons emitted by an electron at an initial position r= 4 M and selected polar angle positions, accelerated in the EM field of a BH of M = 4 $M_\odot$ and spin a/M = 0.3 immersed in a magnetic field of 10^{10} G.

Taken from Rueda, Ruffini, Kerr (in preparation)

Bolometric power



Spectrum



Bolometric power and spectrum of the radiation emitted by an electron at an initial position r= 4 M and θ=1 (blue), 14 (green) and 27 degrees, accelerated by the EM field of a BH of M = 4 $M_\odot$ and spin a/M = 0.3 immersed in a magnetic field of 10^{10} G.

Taken from Rueda, Ruffini, Kerr (in preparation)

Off-polar emission: radiation timescale

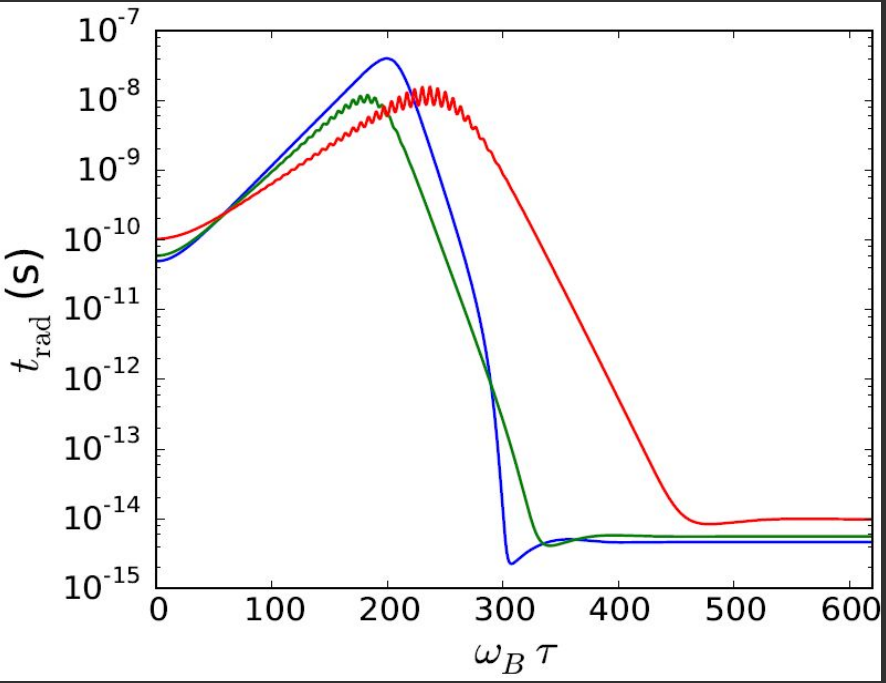
$$t_{\rm rad} = -\frac{p_\mu \eta^\mu}{\mathcal{P}_\infty}$$

Back-of-the-envelope estimate:

Asymptotic Lorentz factor of the order of 10^4
Electron energy is of the order of 10^{11} eV = 10^{-1} erg,
Radiation power of the order of 10^{13} erg/s.

This implies a radiation timescale of 10^{-14} s.

Taken from Rueda, Ruffini, Kerr (in preparation)



Radiation timescale associated with an electron accelerated from an initial position r= 4 M and θ=1 (blue), 14 (green) and 27 degrees. The inner engine is a BH of M = 4 $M_\odot$ and spin a/M = 0.3, immersed in a magnetic field of 10^{10} G.

Polar emission: UHECRs

$$\Delta\Phi \sim 10^{18}\,\text{eV}$$

$$N_{\text{pole}} = \frac{\mathcal{E}}{\Delta\Phi} = \frac{\Omega_{\text{eff}}}{\omega_{\text{eff}}} \sim 10^{31}$$

$$\tau_{\text{pole}} \equiv \frac{\Delta\Phi}{eE_{\hat{r}}\,c} \approx \frac{r_+}{c} = \frac{\alpha}{2\Omega_+} \approx 10^{-5}\,\text{s}$$

$$\dot{N}_{\text{pole}} \equiv \frac{N_{\text{pole}}}{\tau_{\text{pole}}} \sim 10^{36}\,\text{s}^{-1}$$

$$\dot{\mathcal{E}}_{\text{pole}} = \dot{N}_{\text{pole}}\Delta\Phi \sim 10^{54}\,\text{eV}\,\text{s}^{-1} \approx 10^{42}\,\text{erg}\,\text{s}^{-1}$$

Example: Numbers for a BH of $M = 4\,M_\odot$ spin $a/M = 0.3$, magnetic field 10^{11} G. Figure taken from Rueda, Ruffini, Kerr (in preparation). See also Moradi, Rueda, Ruffini, A&A 2021.

$$\frac{dN_{\text{pole}}}{d\epsilon dt} \approx \frac{\dot{\mathcal{E}}_{\text{pole}}}{(\Delta\Phi)^2_{\text{em}}} = \frac{N_\pm}{\Delta\Phi_{\text{em}}\tau_{\text{em}}} \approx \frac{\sqrt{3}}{9}\frac{1}{e^2}$$

→ A "standard candle"?

Taken from Rueda, Ruffini, Kerr (in preparation)

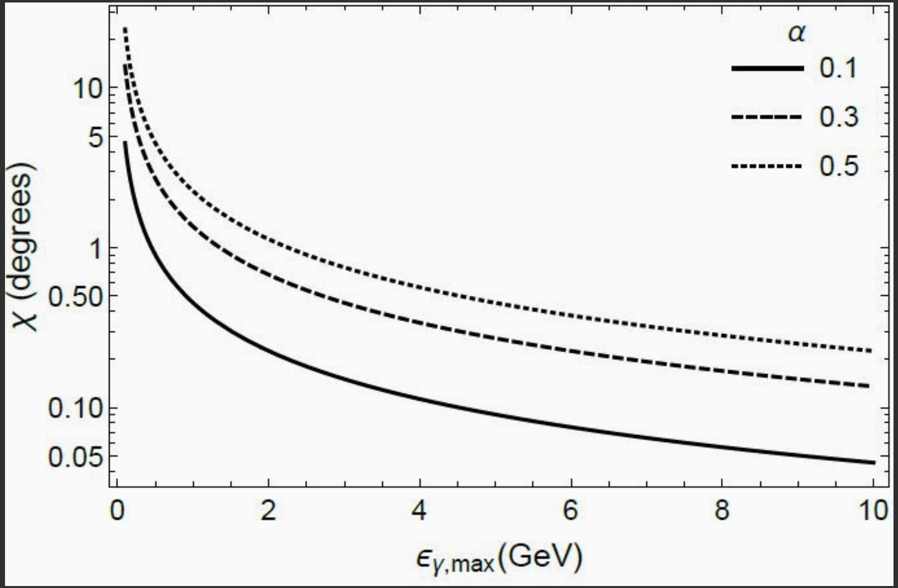
Off-polar emission: synchrotron radiation, pitch angles, photon energy, radiation timescale

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

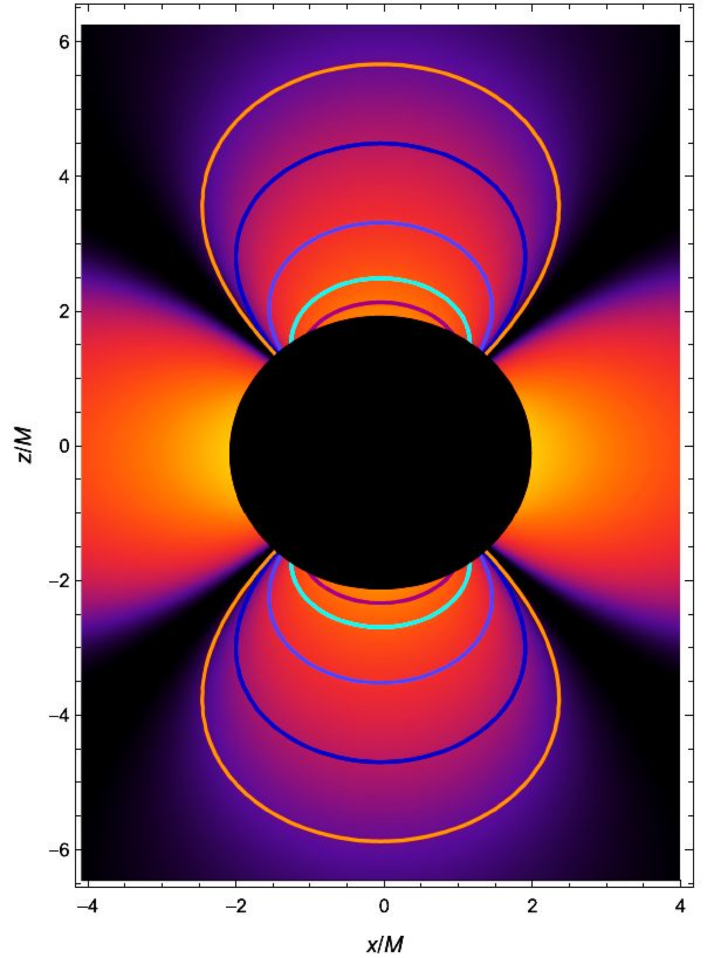
$$\epsilon_\gamma = \frac{3e\hbar}{2m_e\, c} B_0 \sin\langle\chi\rangle\,\gamma^2 = \frac{3}{2} m_e c^2 \beta \sin\langle\chi\rangle\,\gamma^2$$

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

Taken from Moradi, Rueda, Ruffini, A&A 2021



Example: BH spin a/M = 0.5, magnetic field 10^{11} G. Photons of energy 0.1-10 GeV (e.g. Fermi-LAT) are emitted by electrons with pitch angles 0.23-23 degrees.



Taken from Moradi, Rueda, Ruffini, A&A 2021

Examples of *inner engine parameters for GRBs and AGN*

	GRB 190114C	AGN (M 87*-like)
M ($M_\odot$)	4.4	6.0×10^9
α	0.4	0.1
B_0 (G)	4.0×10^{10}	10
$\tau_{\rm pole}$	4.33×10^{-5} s	0.68 d
$\Delta\Phi$ (eV)	3.12×10^{18}	2.66×10^{17}
$\mathcal{E}$ (erg)	7.02×10^{37}	6.96×10^{44}
$\dot{\mathcal{E}}_{\rm pole}$ (erg s^{-1})	1.62×10^{42}	1.18×10^{40}
χ (°)	0.1805–18.05	0.0451–4.51
t_c (s)	1.45×10^{-16}–1.45×10^{-14}	0.2939–29.39
$L_{\rm GeV}$ (erg s^{-1})	4.83×10^{51}–4.83×10^{53}	2.37×10^{43}–2.37×10^{45}

BH mass and spin, magnetic field, acceleration timescale along the poles, maximum particle energy attainable, blackholic quantum, UHECR power, pitch angle of GeV radiation, synchrotron radiation time scale, GeV luminosity.

BH energy extraction process

$$L_{\rm GeV} = \frac{dE_{\rm GeV}}{dt} \leq \frac{dE_{\rm extr}}{dt} \approx \frac{\mathcal{E}}{t_{\rm rad}}$$

$$c^2 dM = dE_{\rm extr} \approx dE_{\rm GeV} \approx \mathcal{E}$$

$$dJ = \frac{c^2 dM}{\Omega_+}$$

$$\frac{\Delta M}{M} = 1 - \frac{M_{\rm irr}}{M}$$

$$\frac{\Delta J}{J} = \left(1 + \frac{M_{\rm irr}}{M}\right)^{-1}$$

Taken from Rueda, Ruffini, Kerr (in preparation)

Conclusions I

- ***Inner engine***: Kerr BH + magnetic field + ionized plasma.
- ***The EM energy*** in the ***inner engine*** is radiated in high-energy (GeV) photons.
- Thus, it sets how many particles can be accelerated
- Quantitatively, the ***EM energy*** scales with the ***M***, ***a***, and ***B***.
- The BH energy extraction is operated by "***elementary processes***". Each of them emits a definite amount of EM energy (= BH extracted energy), and a fraction of ***J***. Each new process starts with a lower ***J***, likewise of ***EM energy***.
- Since ***J*** and the ***EM energy*** decrease with time, the full extraction process tends to last for infinite time → the BH can radiate forever!

Conclusions II

- The radiation mechanism sets the timescale and characteristic energy: polar: ***UHECRs***; off-polar: ***synchrotron radiation***.
- ***UHECRs.*** The high-energy particles accelerated per unit time per unit energy is a fixed, universal value that depends only on the elementary charge → are we in presence of a ***"standard candle"***?
- ***Synchrotron radiation***. Accelerated e^- emit GeV photons in 10^{-15} s. Together with the value of the the ***EM energy,*** it leads to GeV radiation of up to a few 10^{52} erg/s!
- Outward acceleration (so GeV radiation) occurs around the polar axis up to nearly ***60 degrees*** (with equatorial symmetry). This strikingly coincides with GRB observations by Fermi-LAT! (Ruffini, *et al.*, MNRAS 2021)