General features of energy extraction from black holes through charged particle production

Filip Hejda

Centro de Astrofísica e Gravitação, Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Portugal

CEICO, Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic

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Penrose process and its improvements

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Outline of the setup

- First-order EOM for a test particle with mass m in an axially symmetric, stationary spacetime can be written using function X

$$\frac{\mathrm{d}t}{\mathrm{d}\lambda} \equiv p^t = \frac{X}{N^2} \qquad \frac{\mathrm{d}r}{\mathrm{d}\lambda} \equiv p^r = \frac{\sigma}{N\sqrt{g_{rr}}}\sqrt{X^2 - N^2\left(m^2 + \frac{p_\varphi^2}{g_{\varphi\varphi}}\right)}$$

- Function X has the physical meaning of "locally measured energy redshifted to spatial infinity": $NE_{\mathrm{LNRF}} = X = -p_t - \omega p_\varphi$
- For Schwarzschild, X is just the conserved energy, i.e. $X \equiv E$; Penrose process is possible only when X has spatial dependence
- $p^r \in \mathbb{R} \implies$ function X cannot change sign (assuming $g_{\varphi\varphi} > 0$)

$$|X| \geqslant N\sqrt{m^2 + \frac{p_\varphi^2}{g_{\varphi\varphi}}} > 0$$

- Hence, there must be a turning point between two points with different signs of function X (we selected $X > 0$ to preserve causality)

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Collisional process with uncharged initial particles

- Let us consider a model process in which a collision of two uncharged particles gives rise to two oppositely charged particles
- For uncharged particles, $-p_t \equiv E$ and $p_\varphi \equiv L$ are conserved; function X is given by $X = E - \omega L$; only ω spatially dependent
- Provided the asymptotics is healthy (no Melvin!) $|\omega_\mathrm{H}| \geqslant |\omega| > 0$
- Considering only particles that can get close to the black hole leads to restrictions on angular momentum L, e.g.:
- Marginally bound particles ($E \approx m$) with l (defining $L = lm$) in a certain range $l_\mathrm{min} < l < l_\mathrm{max}$ won't get reflected; hence $X \leqslant f_\mathrm{mb}(m)$
- Photons ($m = 0$) with impact parameter b (defining $L = bE$) in a certain range $b_\mathrm{min} < b < b_\mathrm{max}$ won't get reflected; hence $X \leqslant f_\mathrm{ph}(E)$
- Function X is additive and conserved at the instant of collision:
- Bound on the total value: $X_3^\mathrm{C} + X_4^\mathrm{C} = X_0 = X_1^\mathrm{C} + X_2^\mathrm{C} \leqslant f_\mathrm{in}(E_1, E_2)$
- Since X must be positive, bound works individually: $X_{3,4}^\mathrm{C} \leqslant f_\mathrm{in}(E_1, E_2)$

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Producing realistic charged particles

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- Spatial dependence of X gets a contribution proportional to q: $X = X_\mathrm{C} + \Delta X = X_\mathrm{C} - \Delta\omega p_\varphi^\mathrm{C} - q\xi$
- For realistic particles, $|q| \gg m$ in geometric units (an electron has $q \approx -2 \cdot 10^{21} m$)
- Close to the black hole $\xi \sim \frac{Q}{M}\left(1 - \frac{r}{r_\mathrm{C}}\right)$
- N.B. For uncharged initial particles we have bounds on X_C (and p_φ^C)
- If we assume $|Q| \ll M$, but $|Qq| \gg Mm$, the ξ term will dominate and force a turning point just inside/outside the point of inception
- One of the produced particles is hopelessly captured, the other one guaranteed to escape (and extract energy)
- Didn't assume extremality anywhere, generic conclusion
- Limit of infinitesimal coordinate distance from the horizon not suitable for this kind of process (but fine in the uncharged case!)

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A more detailed look

- Unless unreasonably close to the horizon, production of oppositely charged particles will extract energy. But how much?
- Classical works parametrised the outcome of an event using relative three-velocity, Lorentz factor and the scattering angle
- An alternative parametrisation using function X avoids the three-velocity: O. B. Zaslavskii, PRD **108**, 084022 (2023)
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- E_{cm} controls width of the range: $E_3^{\max} - E_3^{\min} \approx \sqrt{g_{tt}} E_{\mathrm{cm}}$
- For the BSW effect (in the extremal case) $E_{\mathrm{cm}}^2 \sim (r_{\mathrm{C}} - r_{\mathrm{H}})^{-1}$
- In the subextremal case, E_{cm} is bounded
- In both cases the width is negligible compared to the mean!
- N.B. Test particle approximation holds because of scale separation $M \gg |Q| \gg |q| \gg m$; electromagnetic back-reaction is the problem!
- N.B. No exotic particles in subextremal case due to $m_3 + m_4 < E_{\mathrm{cm}}$

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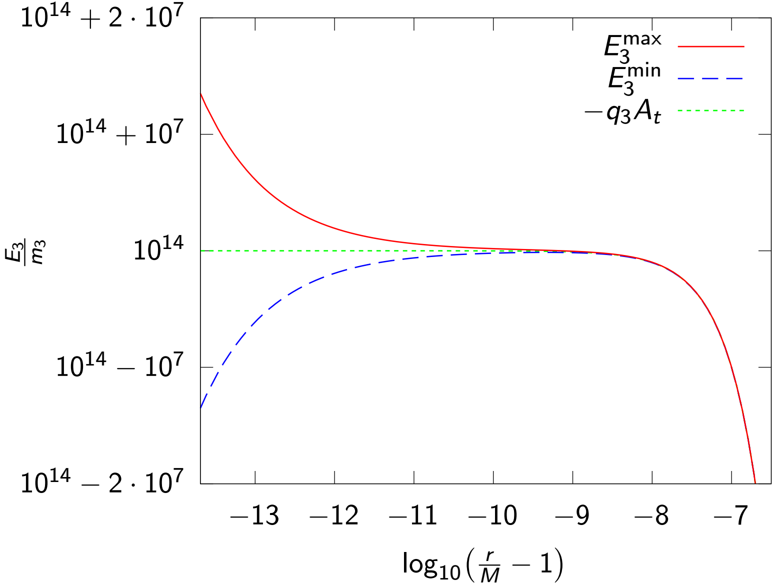
extremal Kerr-Newman $Q = 0.5 \cdot 10^{-7} M$, $q_3 = 2 \cdot 10^{21} m_3$



Conclusions

- The simple model of pair creation close to an electrovacuum black holes shows that it can lead to ejection of highly energetic particles
- Key ingredients are the constraints on the momentum of the centre-of-mass frame, can also work for other (quantum) models
- The general argument holds regardless of extremality; previously studied $r_C \to r_H$ limit gives non-generic results for this model
- Thus, the BSW effect does not seem to be an important ingredient, which is great w.r.t. the BSW effect haters
- Conventional wisdom is that black holes should be largely neutral due to discharge channels; the point is that pair creation is *one of them*!
- Stay tuned for a more detailed treatment of the subextremal case

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