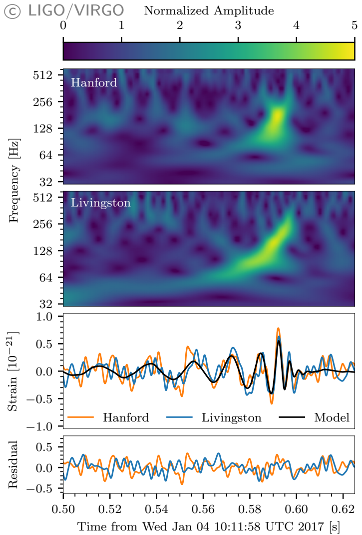
Summary of progress in generalising the BSW effect

Filip Hejda

Centro Multidisciplinar de Astrofísica, Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa

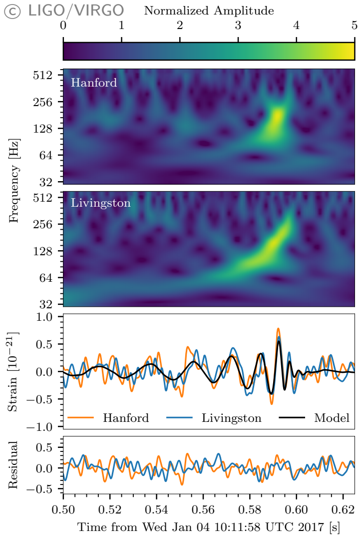
5th IDPASC Students Workshop

Motivation



- "Direct observations" give us more certainty about existence of black holes
- Important to understand how black hole can exchange energy with surroundings
- Many ways: Blandford-Znajek process, superradiance… Penrose process

The ultimate motivation!



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Background of the topic

- Penrose process: a particle splits into two close to a black hole, one fragment falls inside, the other can extract energy due to reduction of the angular momentum/charge of the black hole
- Not very practical, more possibilities with particle collisions
- Arbitrarily high centre-of-mass energy possible for collisions of fine-tuned particles close to extremal black holes (with zero temperature)
- Why consider such oversimplified setup?
- Best case scenario, generalise one step at a time (Don't throw rocks!)
- There were two variants of this so-called BSW effect:
- Centrifugal: particles with fine-tuned angular momentum around an extremally rotating black hole, strongly limited energy extraction
- Electrostatic: particles with fine-tuned charge close to an extremally charged black hole, no bounds on extracted energy found
- Effective potential V, analogy of a classical potential $\varepsilon \geqslant V(l, \tilde{q})$

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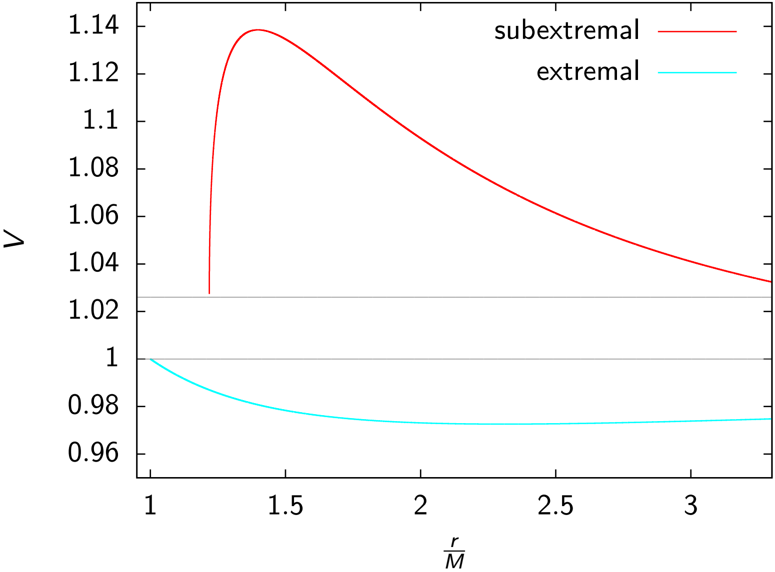
Curves of the effective potential for Kerr-Newman black holes



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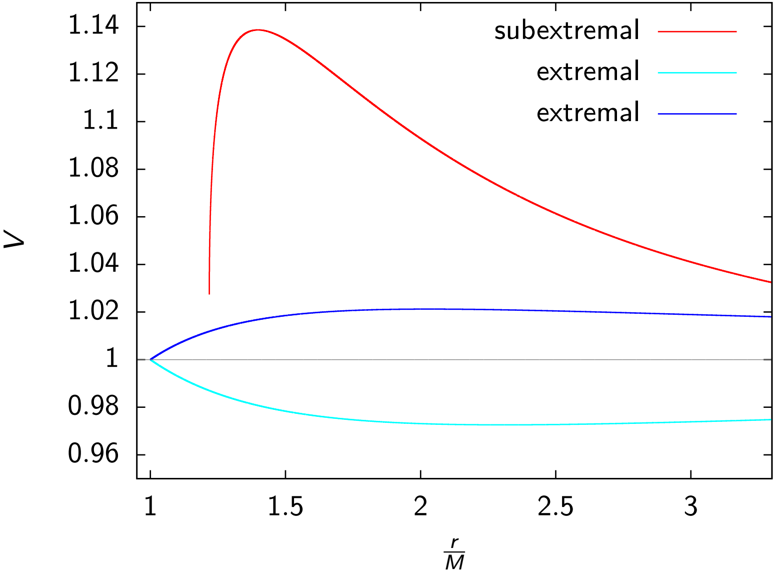

Approach phase (equatorial case)

- One variant of the BSW effect requires particles corotating with the black hole, the other with the same sign of charge as the black hole
- But what happens when we consider charged particles moving around extremal Kerr-Newman black holes that have both angular momentum ($J = aM$) and charge (Q)?
- For particles moving in the equatorial "plane", let us take (specific) angular momentum l and charge $\tilde{q}$ as their relevant parameters, energy ε is determined by the fine tuning
- Let us find a curve that divides regions of parameters with opposite trends (increasing/decreasing) of the effective potential
- See details in: FH, J. Bičák, PhysRevD.95.084055, arXiv:1612.04959
- Further problem is the energy extraction: how do the bounds for the uncharged case appear?

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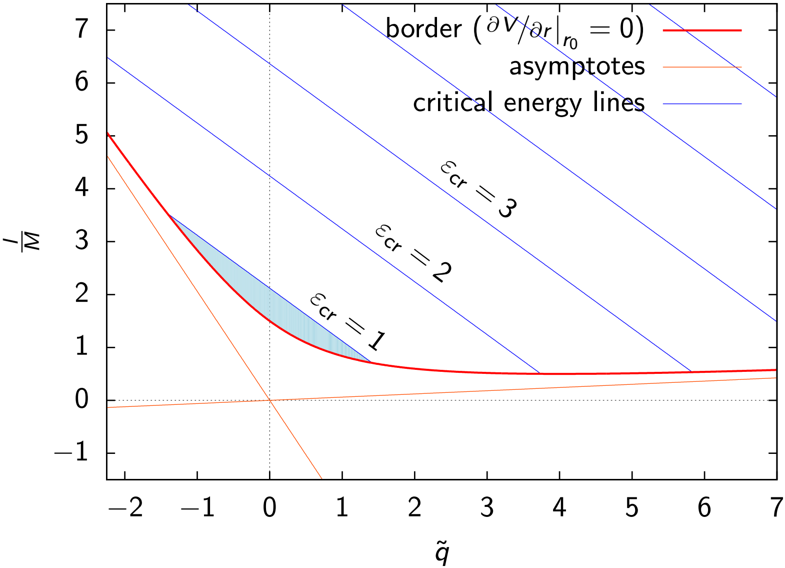
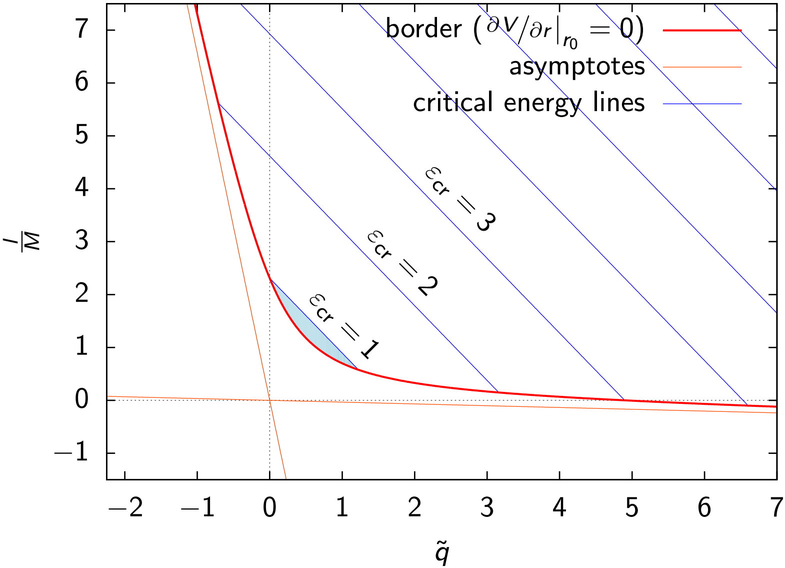
Extremal Kerr-Newman solution with $a = \frac{1}{\sqrt{2}}$, $Q = \frac{1}{\sqrt{2}}$



Extremal Kerr-Newman solution with $a = \frac{1}{\sqrt{3}}$, $Q = \frac{\sqrt{2}}{\sqrt{3}}$



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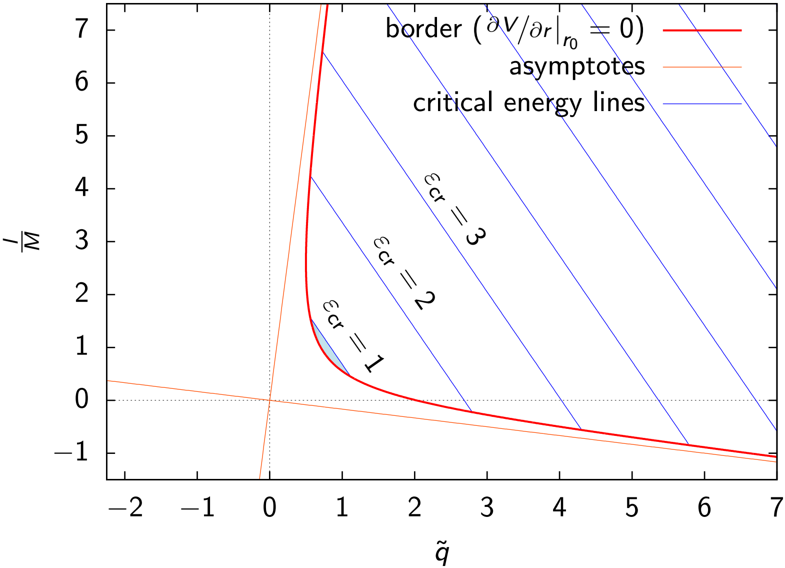
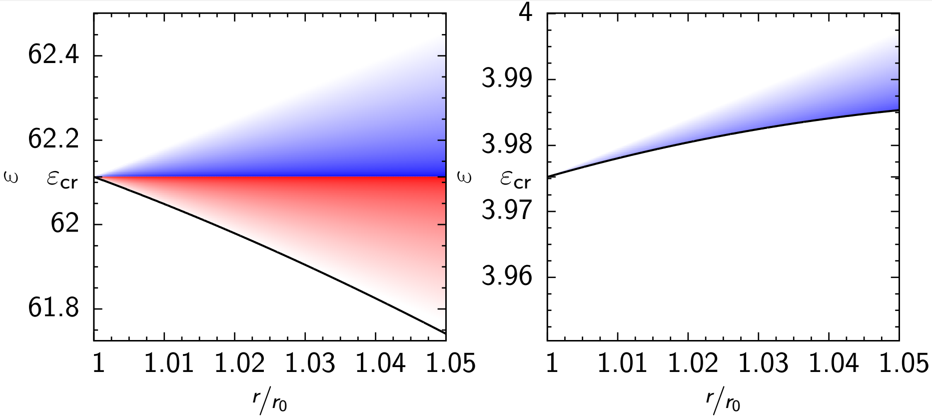


Energy extraction



- Four ways to produce a particle: +/− combined with IN/OUT
- Electrostatic variant of the BSW effect works for collisions at the symmetry axis even when Q is small, also without bounds on extracted energy: FH, J. Bičák, O. B. Zaslavskii, arXiv:1904.02035
- However, $q_3 > q_1$ required, what about the equatorial case?

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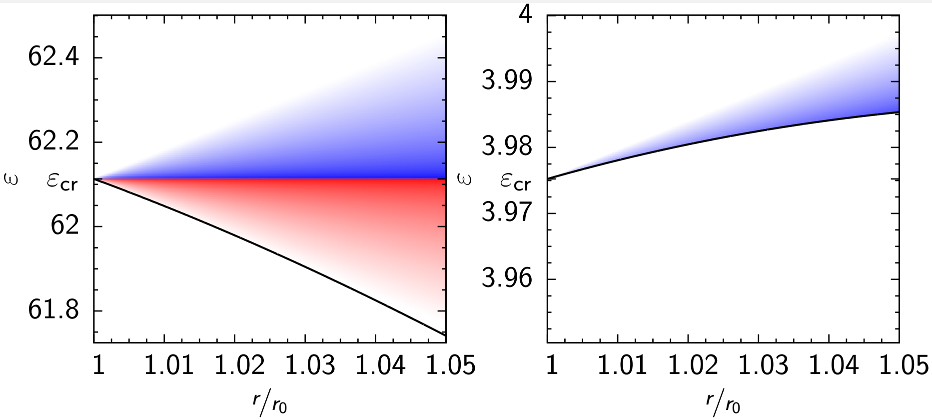

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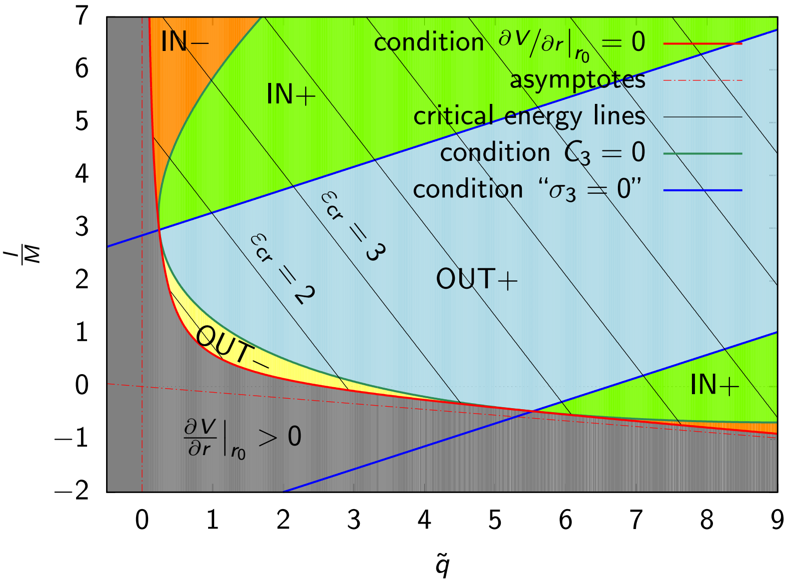
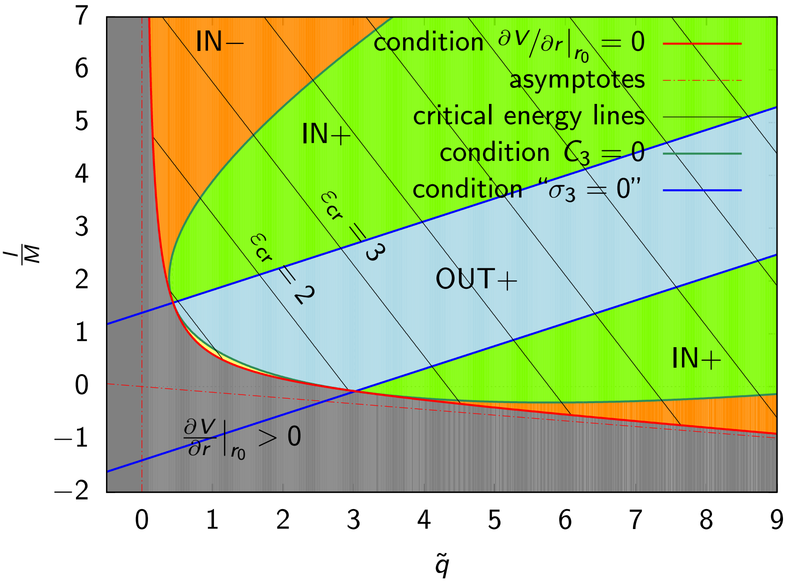
Extremal Kerr-Newman with $\frac{a}{M} = \frac{1}{2}$, $\frac{Q}{M} = \frac{\sqrt{3}}{2}$; process with $\mathfrak{A}_1 = 2.5 m_3$



Extremal Kerr-Newman with $\frac{a}{M} = \frac{1}{2}$, $\frac{Q}{M} = \frac{\sqrt{3}}{2}$; process with $\mathfrak{A}_1 = 1.5m_3$



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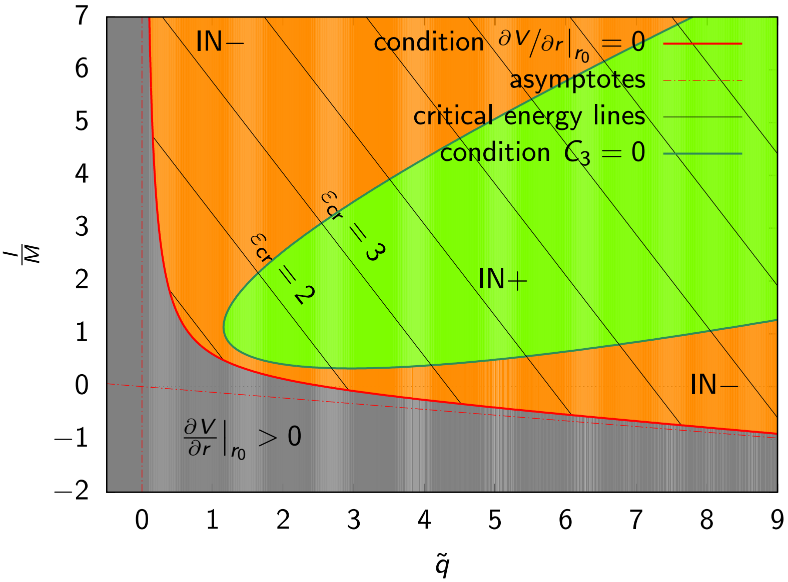
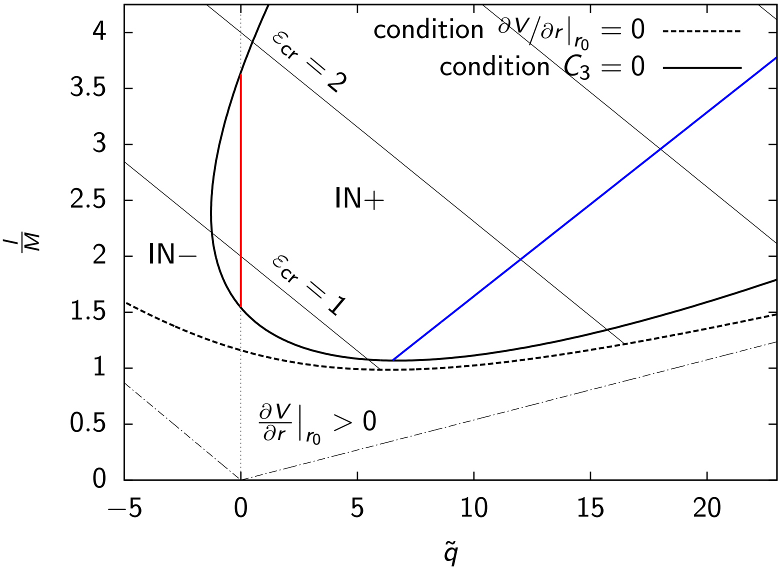


Extremal Kerr-Newman with $\frac{a}{M} = \frac{\sqrt{35}}{6}$, $\frac{Q}{M} = \frac{1}{6}$; process with $3\mathfrak{A}_1 = 2m_3$



Approach phase (general case)

- On the symmetry axis, the electrostatic variant of the BSW effect works for arbitrarily small Q
- In the equatorial "plane", there is a transition to the centrifugal version when Q is below some value
- What happens for general particles that do not follow the symmetry?
- The motion can be chaotic in general. However, Kerr-Newman solution has full separability
- We do not want to care about the motion in latitude ϑ
- All particles with $l \neq 0$ must have turning points in ϑ
- Because of the separability, all the latitudinal turning points occur at the same (two) latitudes (denoted ϑ_{T})
- Therefore, ϑ_{T} can be used as a "constant of motion"
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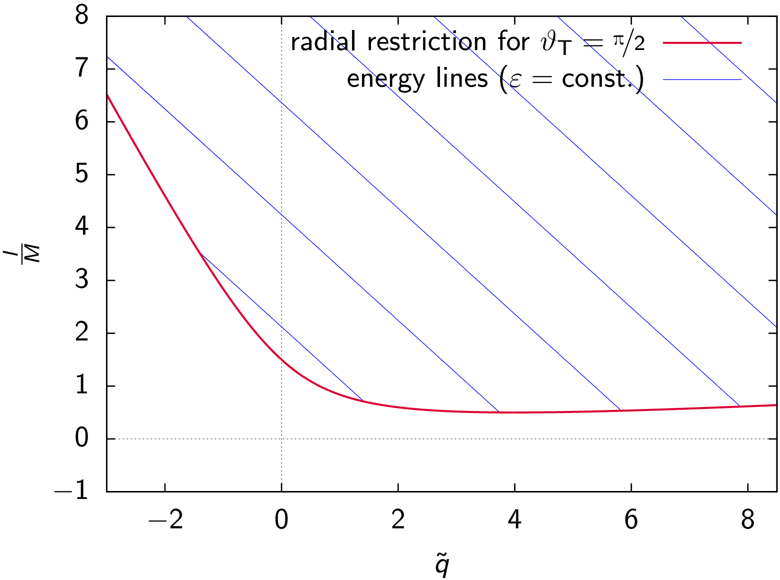
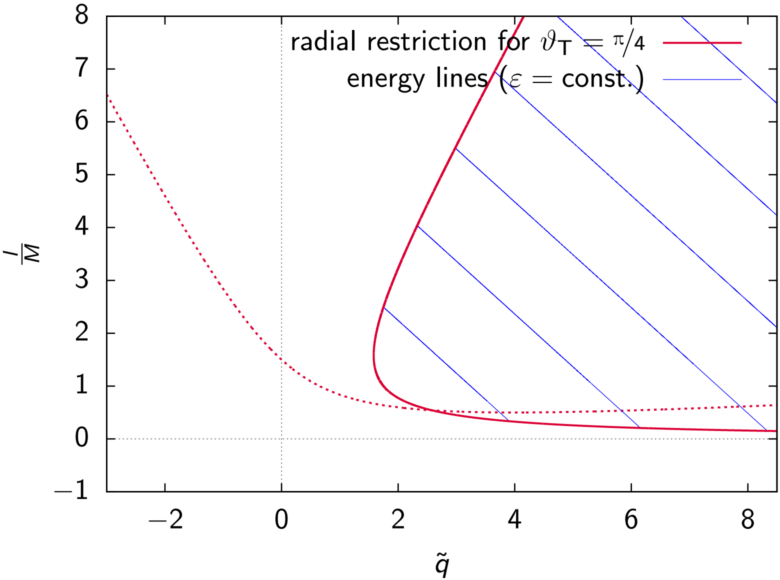
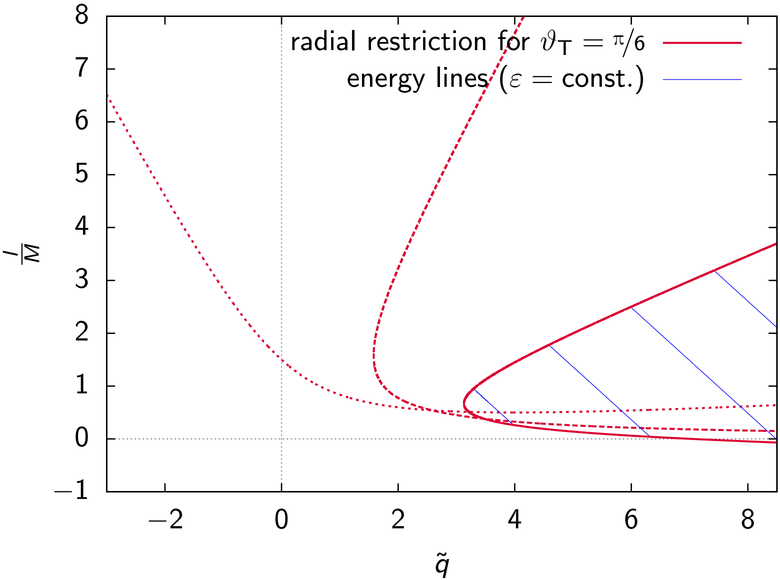
Extremal Kerr-Newman with $\frac{a}{M} = \frac{Q}{M} = \frac{1}{\sqrt{2}}$, equatorial particles



Extremal Kerr-Newman with $\frac{a}{M} = \frac{Q}{M} = \frac{1}{\sqrt{2}}$, particles with $\vartheta_\mathrm{T} = \frac{\pi}{4}$



Extremal Kerr-Newman with $\frac{a}{M} = \frac{Q}{M} = \frac{1}{\sqrt{2}}$, particles with $\vartheta_T = \frac{\pi}{6}$



Acknowledgements

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