Title: Electromagnetic self-force as a cosmic censor

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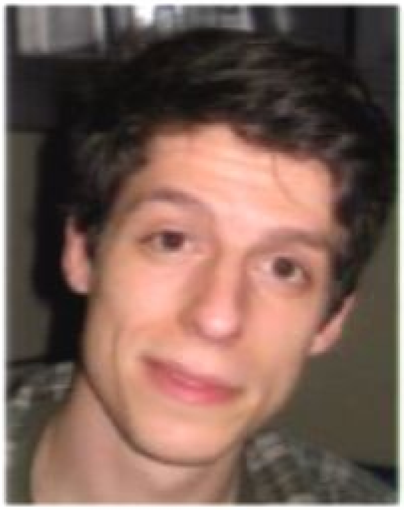
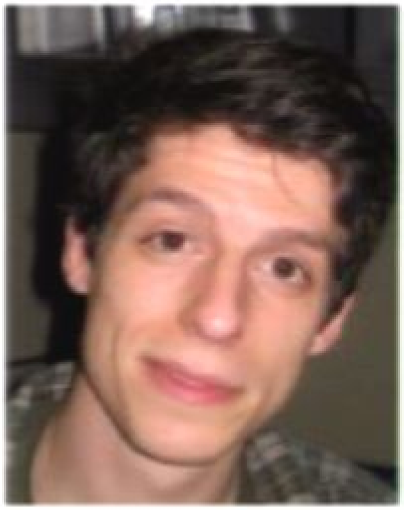
Abstract: Hubeny identified a scenario in which a charged particle falling toward a near-extreme Reissner-Nordstrom black hole can penetrate the black hole and drive it beyond the extremal limit, thereby giving rise to an apparent violation of cosmic censorship. A version of this scenario, relevant to a Kerr black hole and involving a particle with orbital and/or spin angular momentum, was recently examined by Jacobson and Sotiriou (following up on earlier work by Hod); here also the black hole is driven beyond the extremal limit. The Hubeny analysis was inconclusive, however, because in her scenario the particle crosses the horizon with a near-vanishing acceleration; the test-body acceleration is of the same order of magnitude as the acceleration produced by the particle's own electromagnetic self-force, which was not fully incorporated in the analysis. In this talk we report on our computation of the electromagnetic self-force acting on a charged particle falling radially toward a Reissner-Nordstrom black hole, and we reveal whether the self-force acts as a cosmic censor by preventing the particle from reaching the event horizon.



Electromagnetic self-force as a cosmic censor

Peter Zimmerman, Ian Vega, Roland Haas, and Eric Poisson
University of Guelph

Colloquium, Perimeter Institute, May 25, 2011



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Outline

- Cosmic censorship
- Electromagnetic self-force
- Self-force in curved spacetime
- Self-force in Reissner-Nordström spacetime
- Conclusion

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Progress report: no punch line!

Violations of cosmic censorship

- Critical collapse

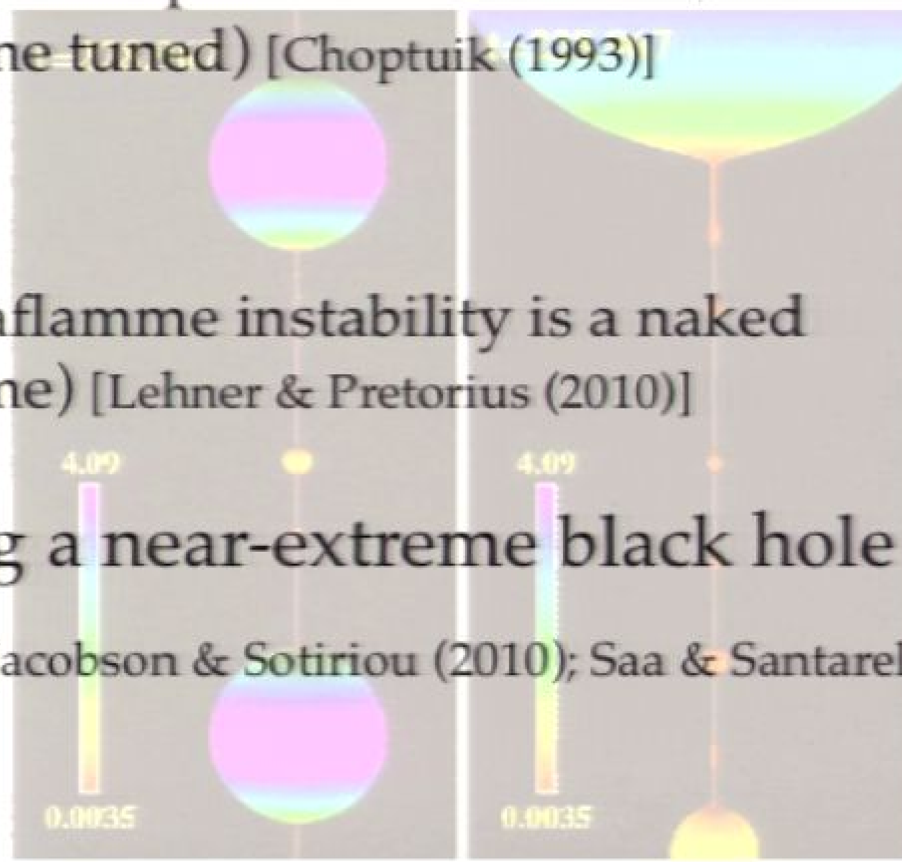
  Choptuik's critical solution represents a massless, naked singularity (infinitely fine-tuned) [Choptuik (1993)]

- Black string

  Endpoint of Gregory-Laflamme instability is a naked singularity (5D spacetime) [Lehner & Pretorius (2010)]

- Overcharging / overspining a near-extreme black hole

  [Hubeny (1999); Hod (2002); Jacobson & Sotiriou (2010); Saa & Santarelli (2011)]



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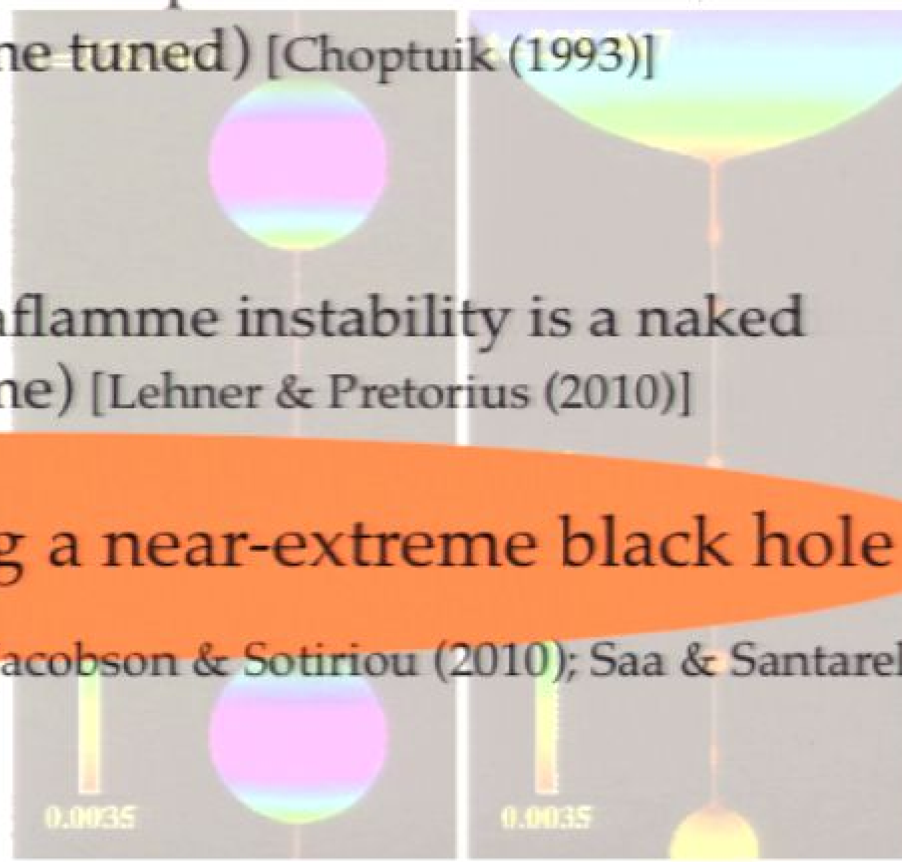
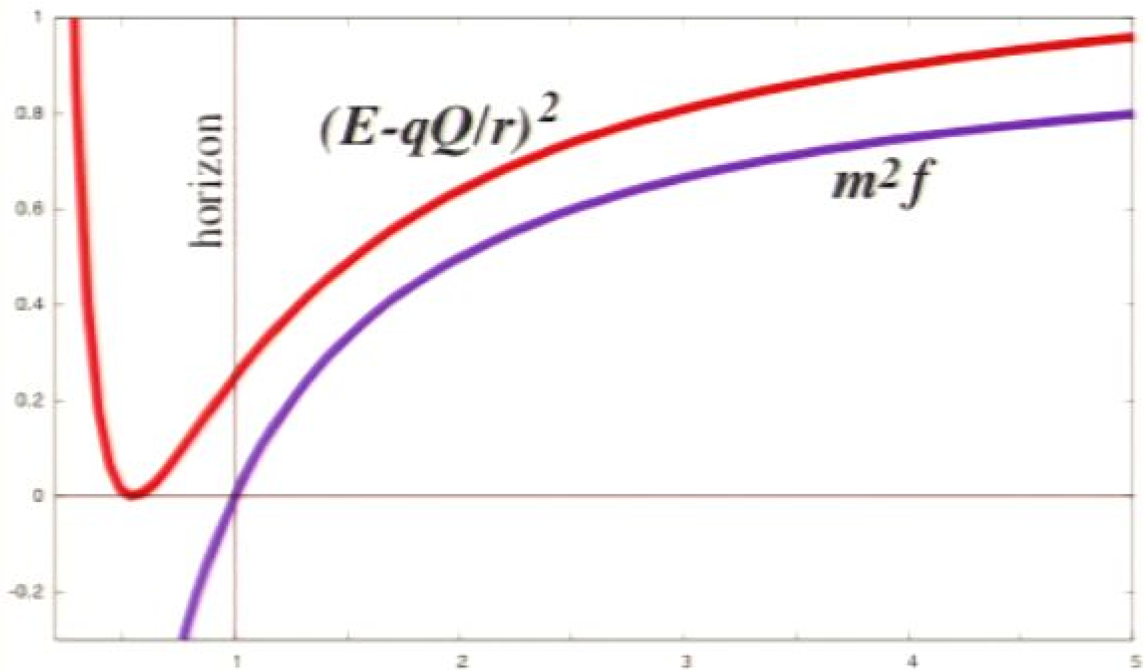


Hubeny scenario

A charged particle falls toward a near-extreme, Reissner-Nordström black hole...



$$M = 1$$
$$Q = 1 - 2\epsilon^2$$
$$q = a\epsilon \qquad a > 1$$
$$E = a\epsilon - 2b\epsilon^2 \qquad 1 < b < a$$
$$m = c\epsilon \qquad c < \sqrt{a^2 - b^2}$$

Final state is overcharged:

$$Q + q > M + E$$

$$(m\dot{r})^2 = \left(E - \frac{qQ}{r}\right)^2 - m^2\left(1 - \frac{2M}{r} + \frac{Q^2}{r^2}\right)$$

Hubeny scenario

This analysis ignores the **electromagnetic self-force** acting on the falling particle; the argument is inconclusive.

Incorporating the self-force is important. (This was only partially attempted by Hubeny, based on incomplete information.)

For the Hubeny scenario,

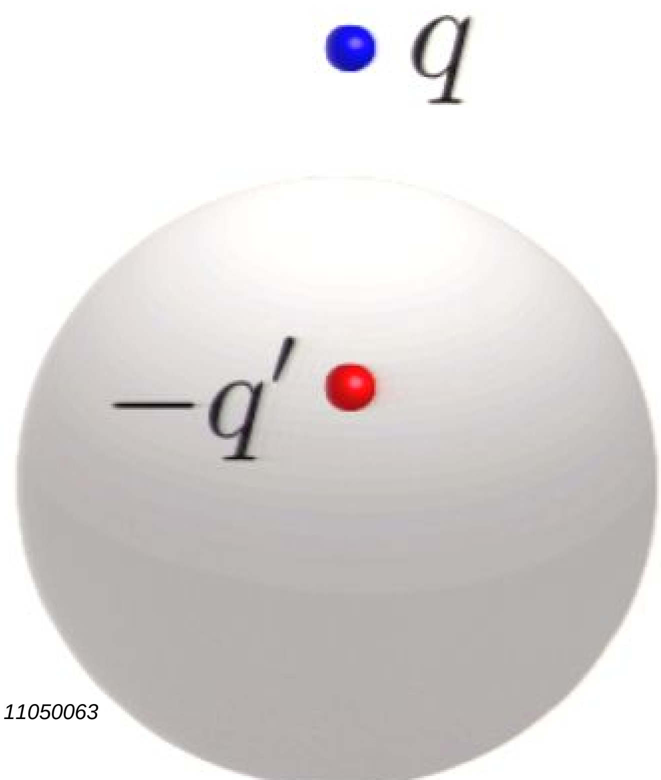
$$m \frac{d^2 r}{d\tau^2}\bigg|_{\text{horizon}} \sim \epsilon^2$$

This is the same scaling as the self-force.

Electromagnetic self-force

There is nothing intuitive about the self-force.

Consider a static charge outside a Schwarzschild hole...



Grounded conductor:

$$f \sim -\frac{q^2 M}{r^3}$$

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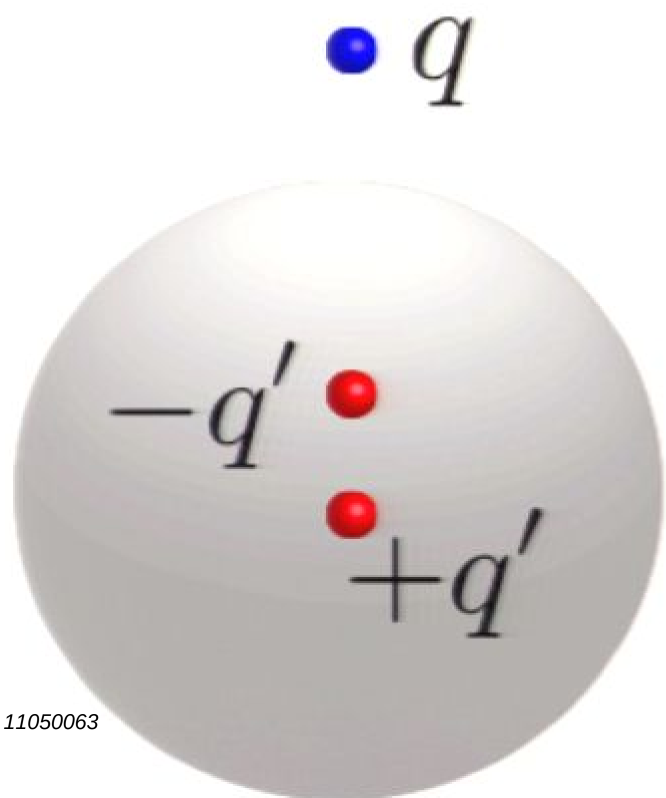

Uncharged conductor:

$$f \sim -\frac{q^2 M^3}{r^5}$$

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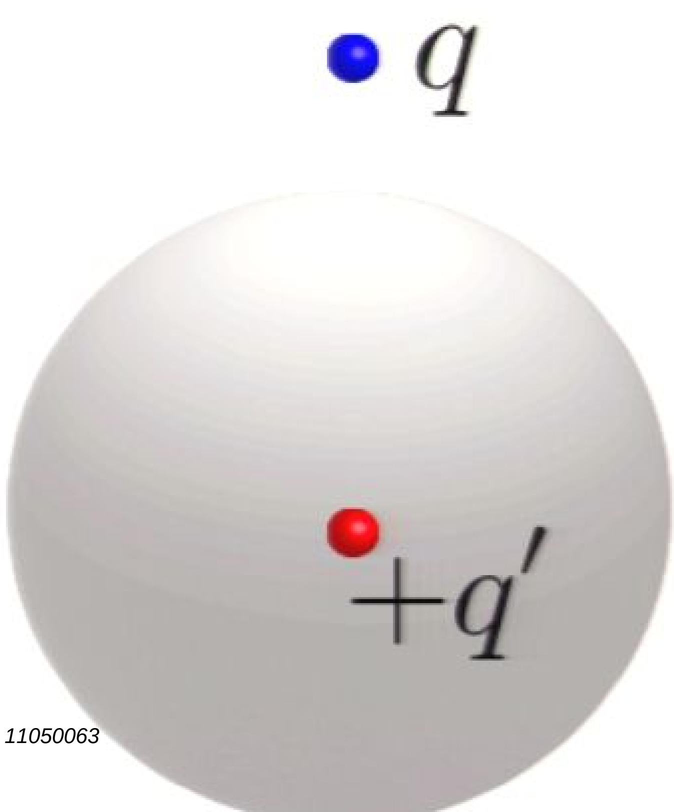

Black hole:

[Smith & Will (1980); Zelnikov & Frolov (1982)]

$$f \sim +\frac{q^2 M}{r^3}$$

Against all expectations, the self-force is **repulsive**.

Electromagnetic self-force

There is nothing intuitive about the self-force.

Consider a nonrelativistic point charge falling radially toward another charge...

$$\boldsymbol{F}_{\text{ext}} = -\frac{qQ}{r^2}\,\hat{\boldsymbol{r}}$$

$$\begin{aligned}\boldsymbol{f}_{\text{self}} &= \frac{2}{3}\frac{q^2}{m}\frac{d\boldsymbol{F}_{\text{ext}}}{dt} \\ &= \frac{4}{3}\frac{q^3 Q}{mr^3}\,\boldsymbol{v}\end{aligned}$$

The self-force **pushes** on the falling charge.

Electromagnetic self-force

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The self-force **pushes** on the falling charge.

$$\boldsymbol{f}_{\text{self}} \cdot \boldsymbol{v} = \frac{2}{3}q^2\,\dot{\boldsymbol{a}} \cdot \boldsymbol{v} = -\frac{2}{3}q^2\,|\boldsymbol{a}|^2 + \frac{2}{3}q^2\,\frac{d}{dt}(\boldsymbol{a} \cdot \boldsymbol{v})$$

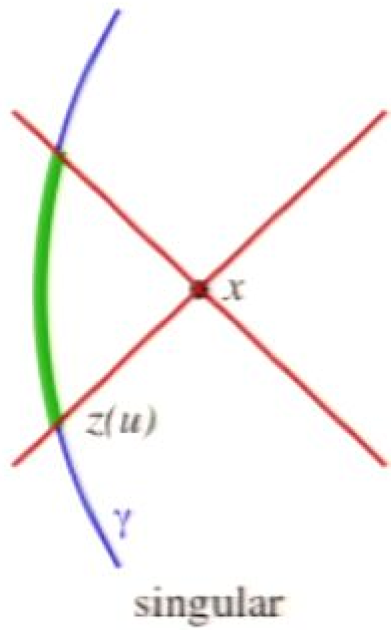
Self-force in curved spacetime

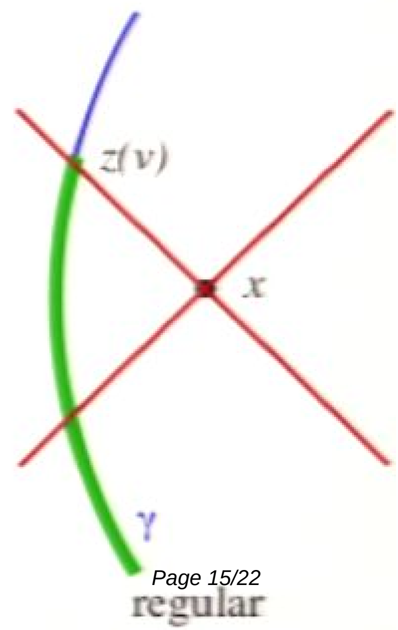
DeWitt & Brehme (1960):

$$ma^\mu = f^\mu_{\rm ext} + q^2 \left(\delta^\mu{}_\nu + u^\mu u_\nu\right)\left(\frac{2}{3m}\frac{Df^\nu_{\rm ext}}{d\tau} + \frac{1}{3}R^\nu{}_\lambda u^\lambda\right)$$
$$+ 2q^2 u_\nu \int_{-\infty}^{\tau^-} \nabla^{[\mu} G_{\rm ret}{}^{\nu]}{}_{\lambda'}\left(z(\tau), z(\tau')\right) u^{\lambda'}\, d\tau'$$

Detweiler & Whiting (2003):

$$F^{\alpha\beta}_{\rm ret} = F^{\alpha\beta}_{\sf S} + F^{\alpha\beta}_{\sf R}$$
$$\nabla_\beta F^{\alpha\beta}_{\sf S} = 4\pi j^\alpha$$
$$\nabla_\beta F^{\alpha\beta}_{\sf R} = 0$$
$$ma^\alpha = qF^{\alpha\beta}_{\sf R} u_\beta$$





Regularization

The **singular field** is known locally as an expansion in powers of the distance to the particle.

It can easily be subtracted from the **retarded field**, which is obtained numerically.

The result is a **regular field** that is entirely responsible for the self-force.

Self-force in Reissner-Nordström

- We compute the Maxwell field for a point particle falling radially toward a Reissner-Nordström black hole.

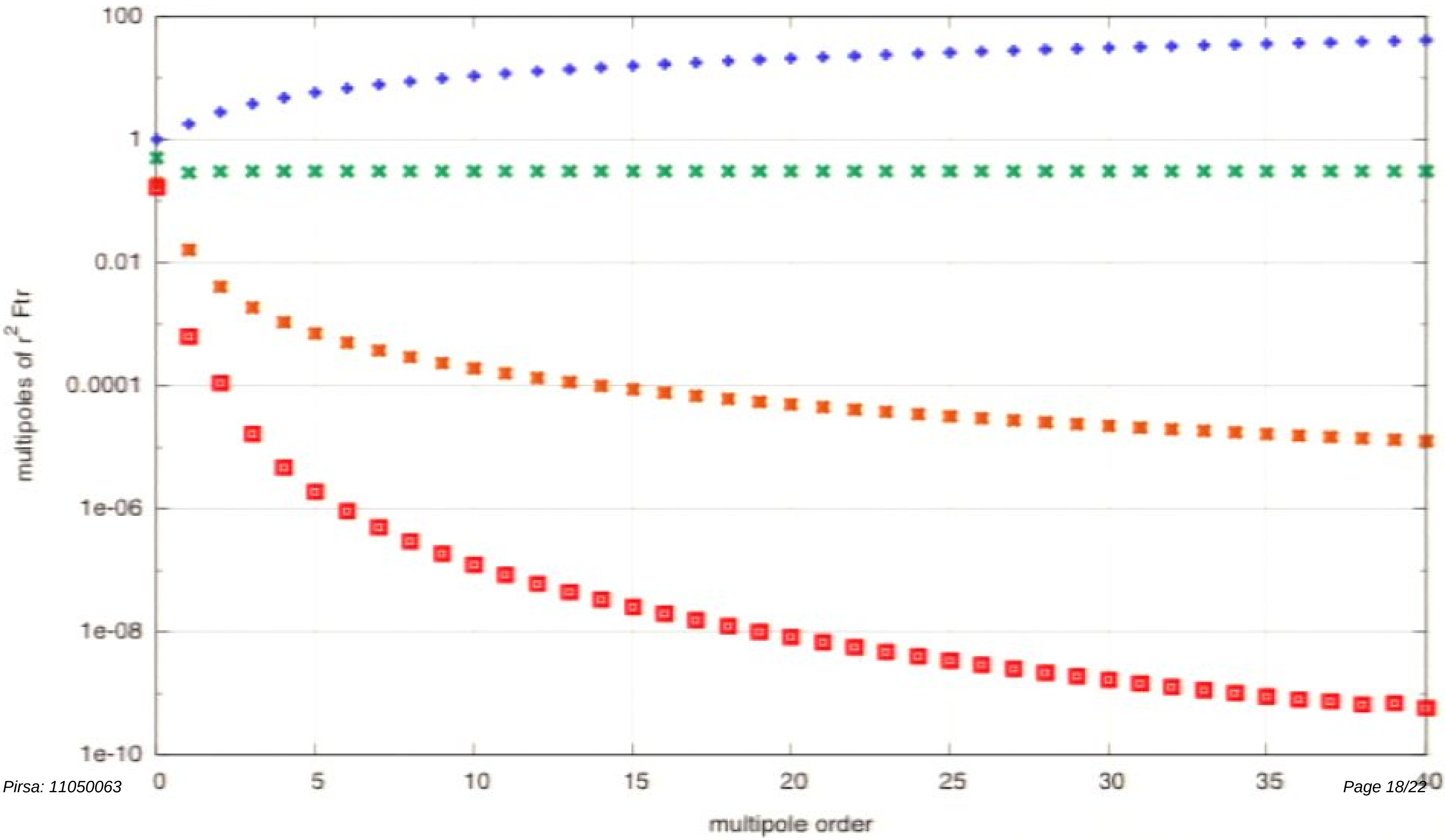
- The field is decomposed into spherical harmonics, and the reduced equations are integrated with a time-domain, finite-difference code that accounts exactly for the delta-function source.

- Each spherical-harmonic mode contains a contribution to a **singular field** which exerts no force, and a contribution to a **smooth field** which is entirely responsible for the self-force; the singular contribution is removed (mode-sum regularization).

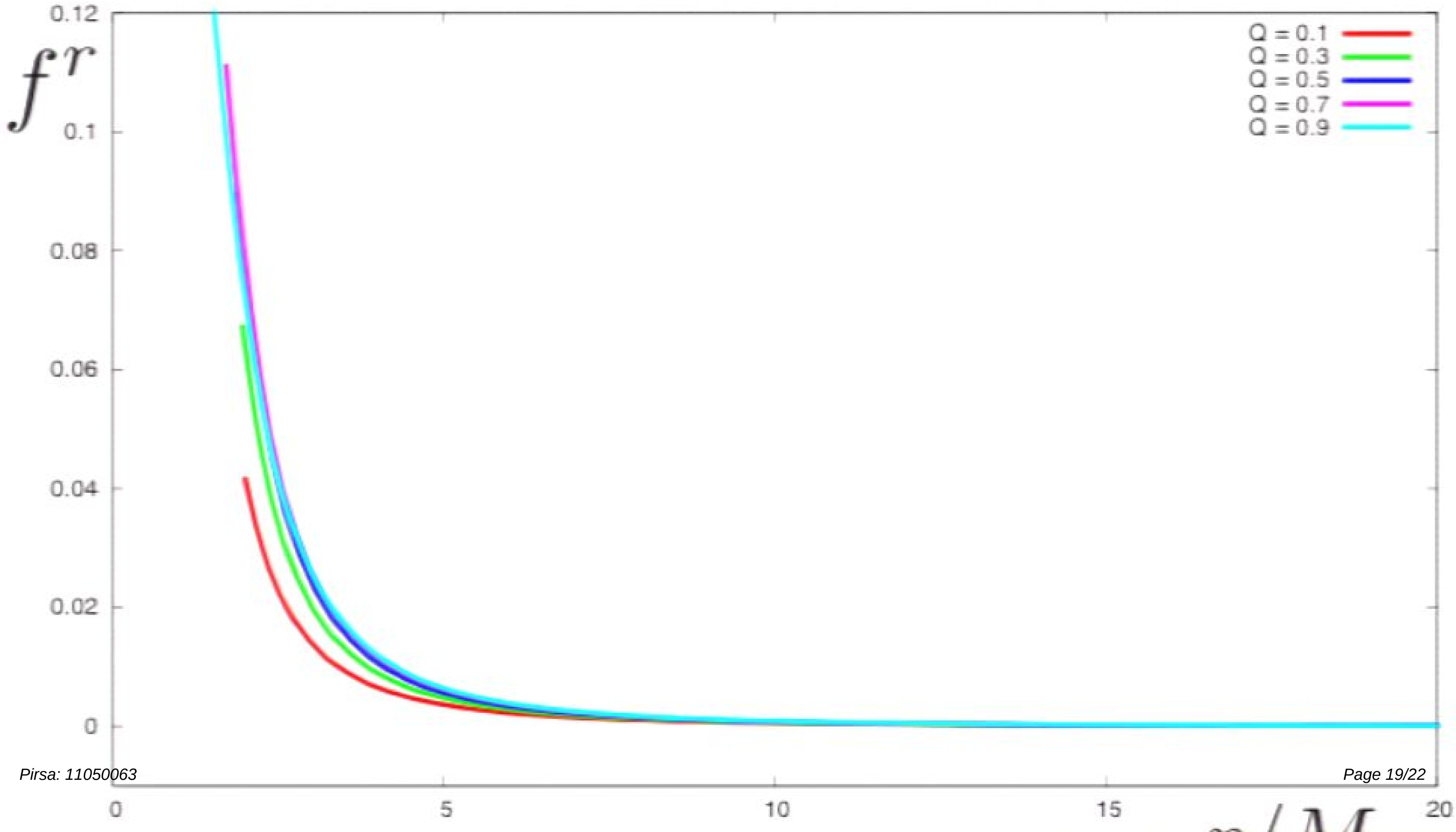
- The self-force is computed by summing over all computed modes up to a maximum value of l; the large-l tail can be estimated analytically.

- Mode-sum regularization acts as a robust check on the numerics.

Mode-sum regularization



Results



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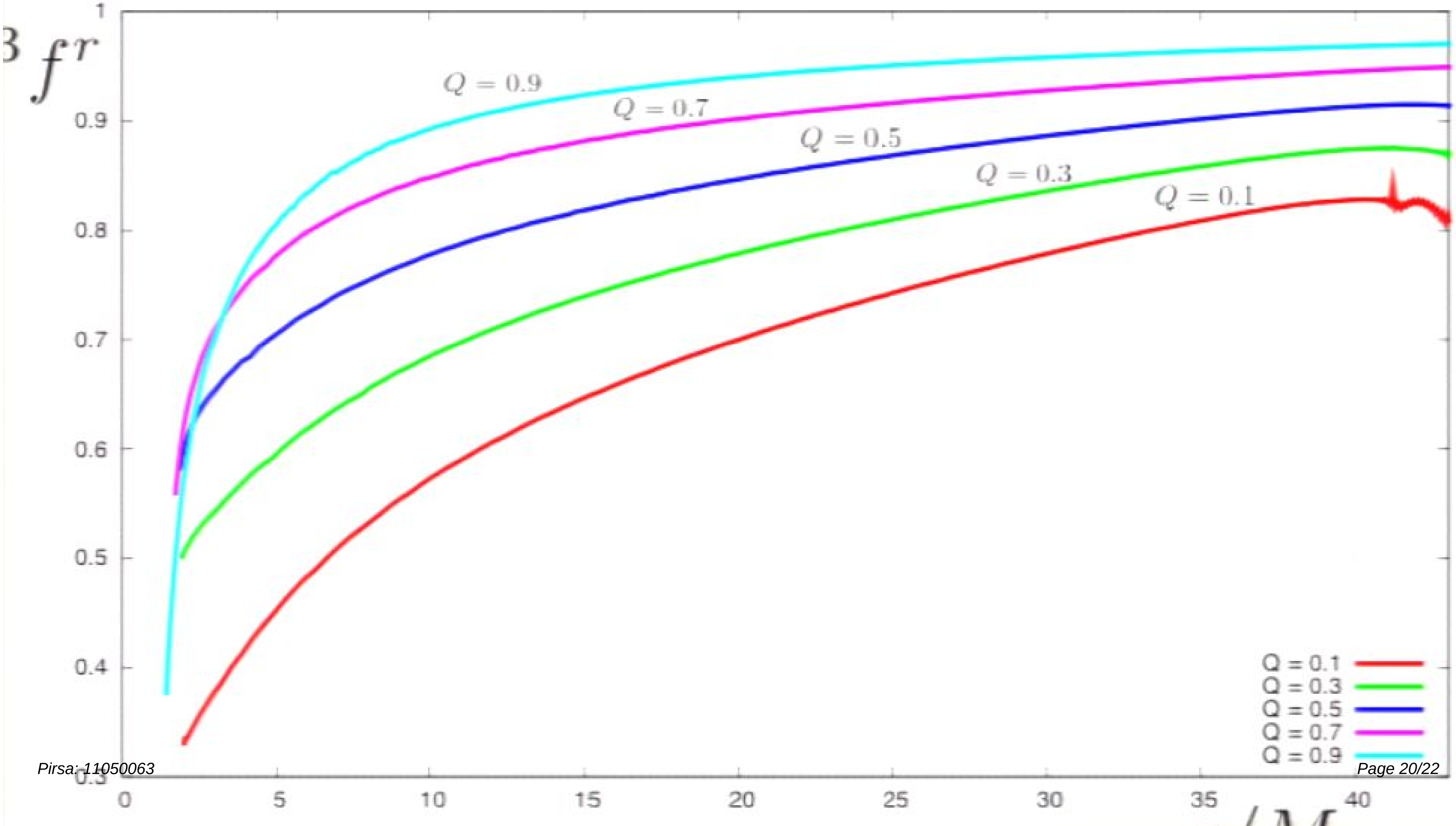
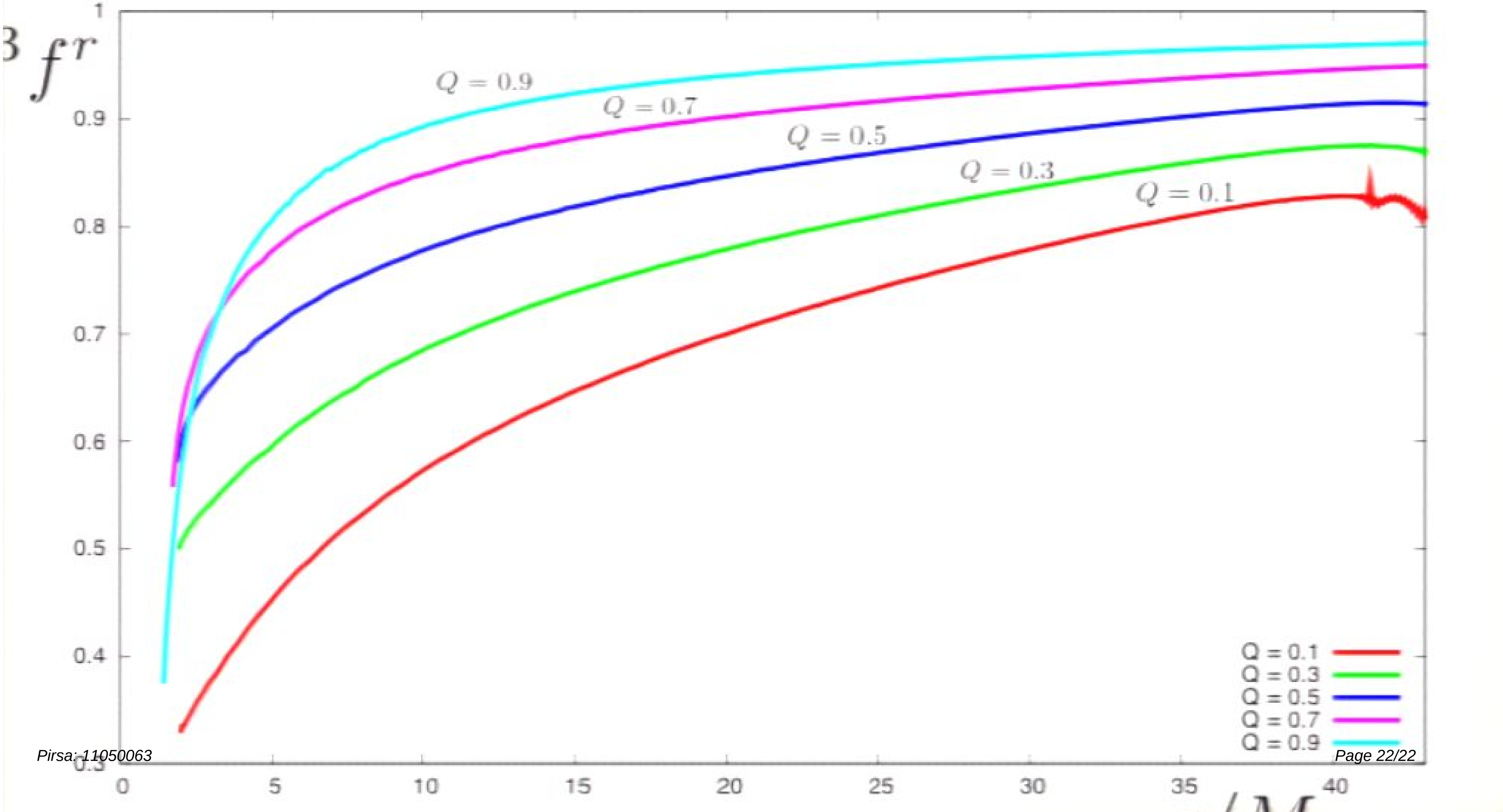


f^r
$Q = 0.9$
$Q = 0.7$
$Q = 0.5$
$Q = 0.3$
$Q = 0.1$
Q = 0.1
Q = 0.3
Q = 0.5
Q = 0.7
Q = 0.9
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0
5
10
15
20
25
30
35
40

Conclusion

- For a point charge falling radially toward a Reissner-Nordström black hole (**starting from rest** --- not a Hubeny trajectory), the electromagnetic self-force is **repulsive and increases with the black-hole charge.**
- This gives us reason to expect that the self-force may act as a **cosmic censor** to invalidate the Hubeny overcharging scenario (but we are cautious: self-force is not intuitive).
- Work is currently underway to calculate the self-force for Hubeny trajectories.

Results



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