Floating Orbits, Superradiant Scattering and the Black-hole bomb: 50 years after

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WILLIAM H. PRESS & SAUL A. TEUKOLSKY

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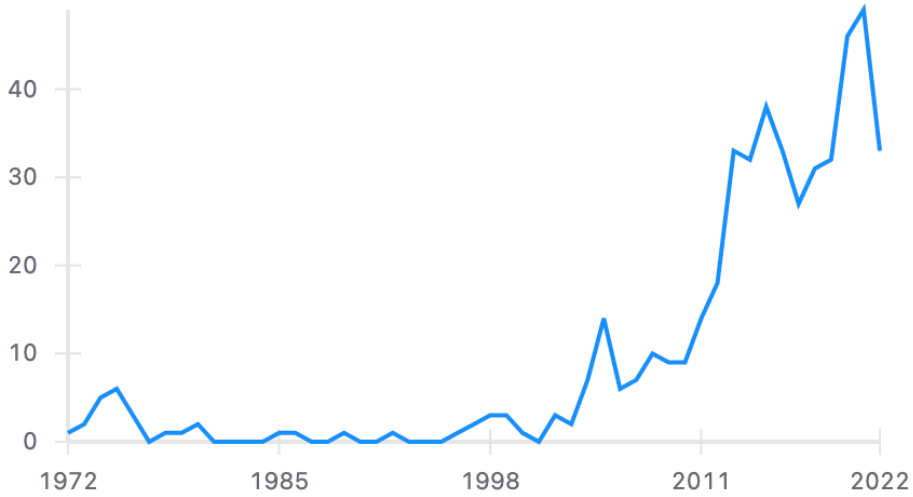
Interesting trends in citations to this paper:

Citations per year



(taken from INSPIRE database)

Vitor Cardoso	47
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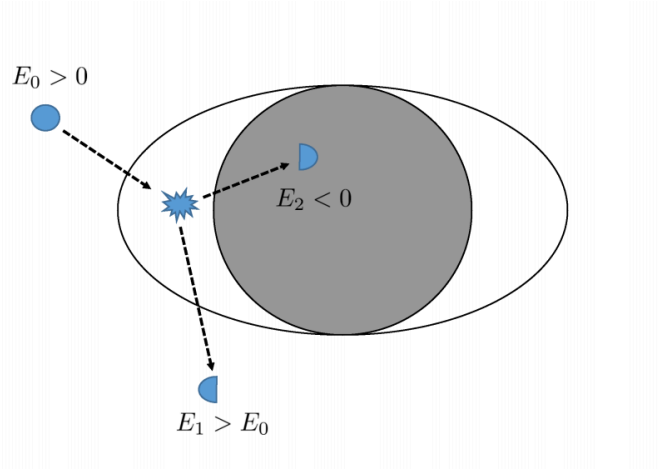
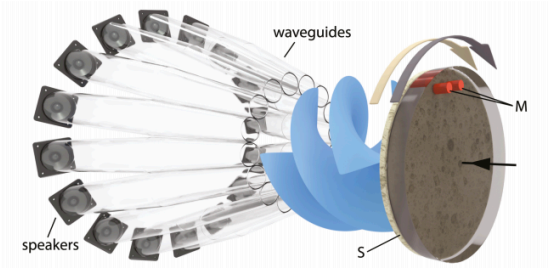
Historical background

A short list of references, but what a remarkable list…

1 Penrose, R., *Revista Del Nuovo Cimento*, **1**, 252 (1969).
2 Christodoulou, D., *Phys. Rev. Lett.*, **25**, 1596 (1970).
3 Misner, C. W., *Phys. Rev. Lett.*, **28**, 994 (1972).
4 Carter, B., *Phys. Rev.*, **174**, 1559 (1968).
5 Boyer, R. H., and Lindquist, R. W., *J. Math. Phys.*, **8**, 265 (1967).
6 Zel'dovich, Ya. B., *JETP Lett.*, **14**, 270 (1971).

- **Ref. 1 (1969):** Penrose process introduced, existence of an ergoregion allows to extract energy and angular momentum from a Kerr black hole (BH).
- **Ref. 2 (1970):** irreducible BH mass introduced. BH energy and angular momentum can be extracted but irreducible mass never decreases.
- **Ref. 6 (1971):** rotating absorbing bodies can amplify incident waves. Suggestion that a similar situation can arise for rotating black holes.
- **Ref. 3 (1972):** mentions that Kerr black holes can amplify (scalar) waves but amplification is small. (fun fact: this paper was trying to explain Weber's gravitational-wave "observations"…)

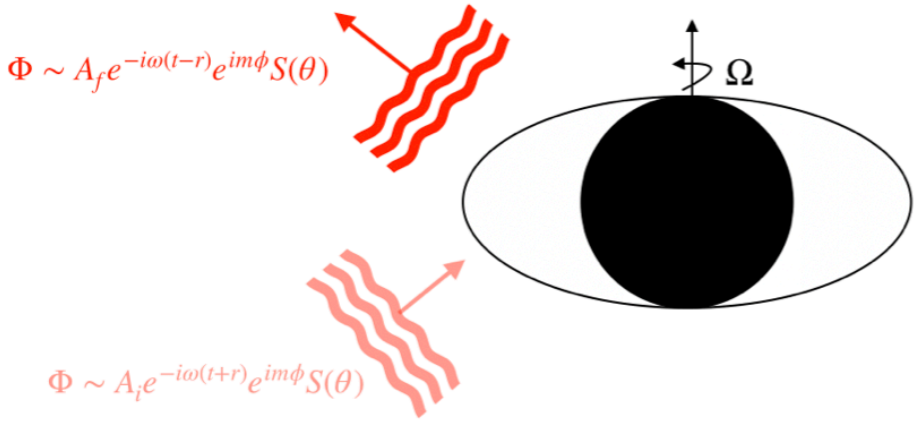




Cromb *et al*, Nature Phy. 16 (2020) 1069-1073

Black-hole superradiance

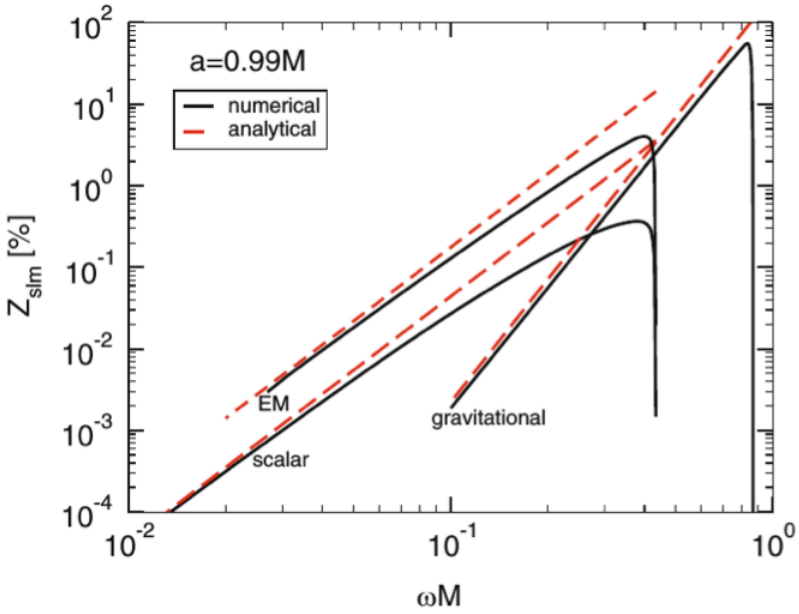
Zel'dovich, '71; Misner '72; Press and Teukolsky ,'72-74
Review: RB, Cardoso & Pani "Superradiance" Lect. Notes Phys. 971 (2020), 2nd ed.



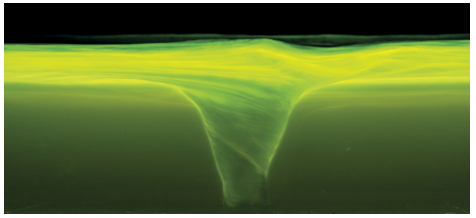
$$\omega/m < \Omega_{\rm H}$$

Amplification of scattered wave through **extraction** of energy and angular momentum from the black hole

$$Z_{slm} = \frac{dE_{\rm out}/dt}{dE_{\rm in}/dt} - 1$$



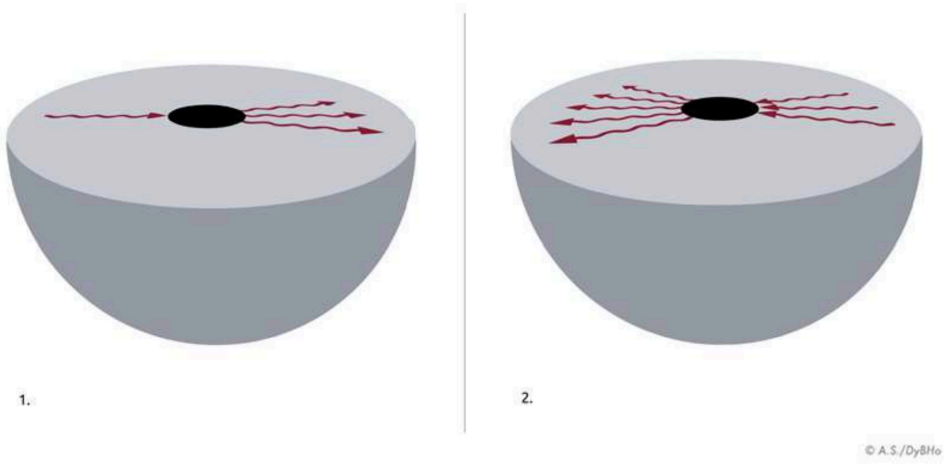
- BH perturbation theory results **confirmed** in full numerical relativity simulations. (East, Ramazanoglu & Pretorius, 2014)
- **Observed** in the lab for an analogue BH system. (Torres, *et al*, 2017)



Torres, *et al*, Nature Phy. 13 (2017) 833-836

Black-hole bomb and superradiant instabilities

Press & Teukolsky '72; Cardoso, Dias, Yoshida & Lemos '04



Surround a Kerr black hole with a **reflecting mirror**.

System is **unstable** when cavity supports waves with frequencies:

$$\omega/m < \Omega_{\rm H}$$

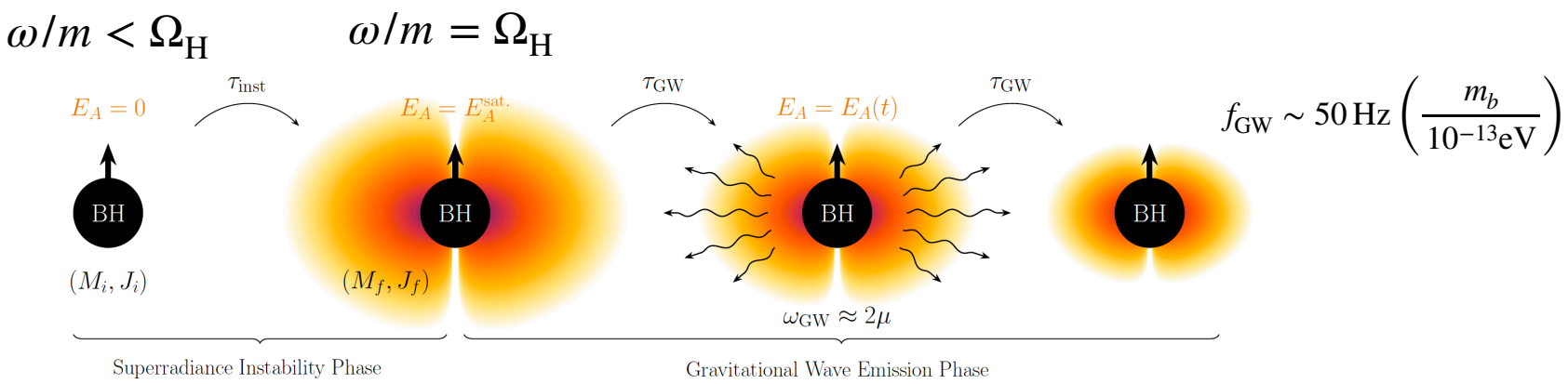
- Plasma around BHs as a mirror for photons? Probably not. (Press&Teukolsky '72; Pani&Loeb '13; Conlon&Herdeiro '18; Blas&Witte '20; Cardoso *et al* '21)
- Boundary of AdS boundary as a mirror: small Kerr AdS black holes are unstable. (Cardoso & Dias '04; Cardoso *et al* '14; Green *et al* '15; Dold '16) Linked to non-uniqueness of Kerr-AdS BHs. (Dias, Santos & Way '15)
- Full numerical simulations of "charged" BH bomb (P. Bosch, S. Green & L. Lehner, '16; Sanchis-Gual et al '16) and Kerr-AdS BH bomb (Chesler&Lowe '18; Chesler '21) shows rich dynamics, however final state of Kerr-AdS instability still an open problem.

From black-hole bombs to particle physics

Massive bosonic fields around Kerr black holes admit **superradiantly unstable** (quasi-)bound state modes.

(Damour '76; Gaina '78; Zouros & Eardley '79; Detweiler '80; Cardoso&Yoshida, '05; Dolan '07; Pani *et al* '12; Witek *et al* '12 RB, Cardoso & Pani '13; Baryakthar, Lasenby & Teo '17; East '17; Cardoso *et al* '18; Frolov *et al* '18; Dolan '18, ...)

Most efficient when $\left(\frac{M}{10M_\odot}\right)\left(\frac{m_b c^2}{10^{-12}\text{eV}}\right) M_{\text{Pl}}^{-2} \sim \mathcal{O}(1)$



- Existence of Kerr black holes with (complex) boson hair satisfying $\omega/m = \Omega_{\text{BH}}$
  (Herdeiro & Radu '14; Herdeiro, Radu & Rúnarsson '16)
- Numerical simulations of superradiant instability evolution confirm picture above.
  (East&Pretorius '17; East '18)
- Can be used to detect/constrain ultralight bosons in the mass range $\sim [10^{-20}, 10^{-10}]\,\text{eV}$ through black-hole and gravitational-wave observations.
  (see review: RB, Cardoso & Pani "Superradiance")

Conclusions

50 years after its introduction, the *black-hole bomb* idea found (direct and indirect) applications in areas unforeseen when the idea was first proposed, such as implications for the dynamics of **black holes in AdS** to the possibility of searching for **new particles** with black-hole and gravitational-wave observations.

"We propose the *black-hole bomb*: locate a rotating black hole and construct a spherical mirror around it … a port hole in the mirror can be periodically opened and the resultant radio flux rectified and used as a **source of electric power**."

Press and Teukolsky , Nature 238, 211-212 (1972)