XXV SIGRAV Conference on General Relativity and Gravitation
Trieste - September 7th, 2023

Nonlinear photon-plasma interaction and the black-hole superradiant instability

Enrico Cannizzaro, **Fabrizio Corelli**, and Paolo Pani

Based on Cannizzaro+, arXiv:2306.12490 [gr-qc] (2023)

SAPIENZA
UNIVERSITÀ DI ROMA

European Research Council
Established by the European Commission

INFN
Istituto Nazionale di Fisica Nucleare

Superradiant Amplification and the Black Hole Bomb

Black holes (BHs) can amplify low-frequency waves thanks to superradiance.

$$\omega < m\Omega$$

[Zel'dovich *Pis'ma Zh. Eksp. Teor. Fiz.* (1971), Zel'dovich *Zh. Eksp. Teor. Fiz* (1972), Brito-Cardoso-Pani *Lecture Notes in Physics* (2020)]

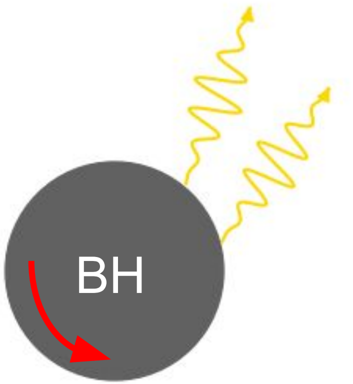
Superradiant Amplification and the Black Hole Bomb

Black holes (BHs) can amplify low-frequency waves thanks to superradiance.

$$\omega < m\Omega$$

[Zel'dovich *Pis'ma Zh. Eksp. Teor. Fiz.* (1971), Zel'dovich *Zh. Eksp. Teor. Fiz* (1972), Brito-Cardoso-Pani *Lecture Notes in Physics* (2020)]

Superradiant Amplification and the Black Hole Bomb

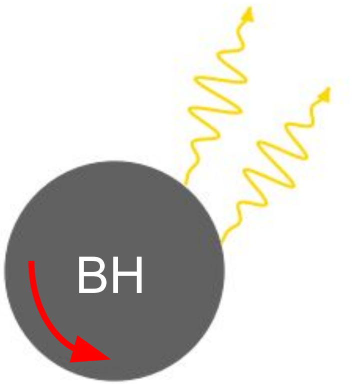


Black holes (BHs) can amplify low-frequency waves thanks to superradiance.

$$\omega < m\Omega$$

[Zel'dovich *Pis'ma Zh. Eksp. Teor. Fiz.* (1971), Zel'dovich *Zh. Eksp. Teor. Fiz* (1972), Brito-Cardoso-Pani *Lecture Notes in Physics* (2020)]

Superradiant Amplification and the Black Hole Bomb



Black holes (BHs) can amplify low-frequency waves thanks to superradiance.

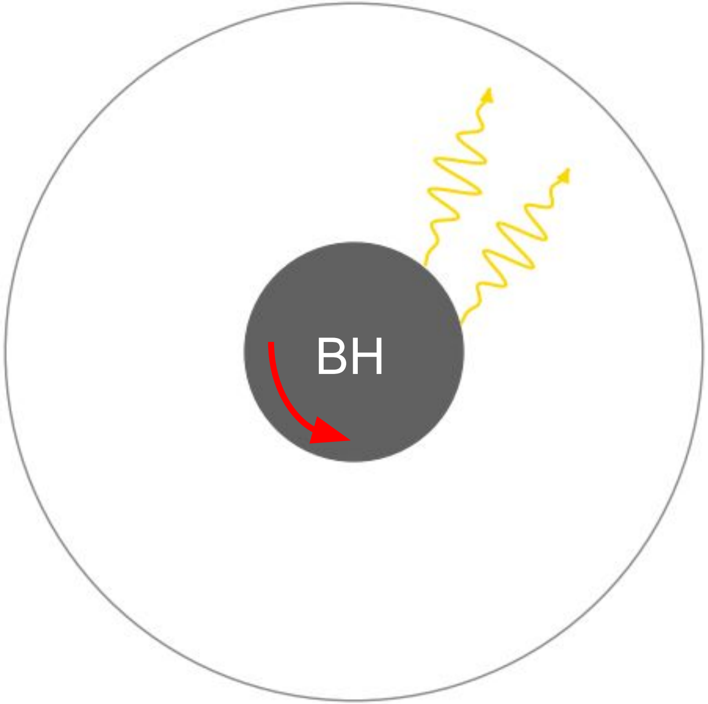
$$\omega < m\Omega$$

[Zel'dovich *Pis'ma Zh. Eksp. Teor. Fiz.* (1971), Zel'dovich *Zh. Eksp. Teor. Fiz* (1972), Brito-Cardoso-Pani *Lecture Notes in Physics* (2020)]

If the BH is surrounded by a mirror, this process can lead to an instability.

[Press-Teukolsky *Nature* (1972)]

Superradiant Amplification and the Black Hole Bomb



Black holes (BHs) can amplify low-frequency waves thanks to superradiance.

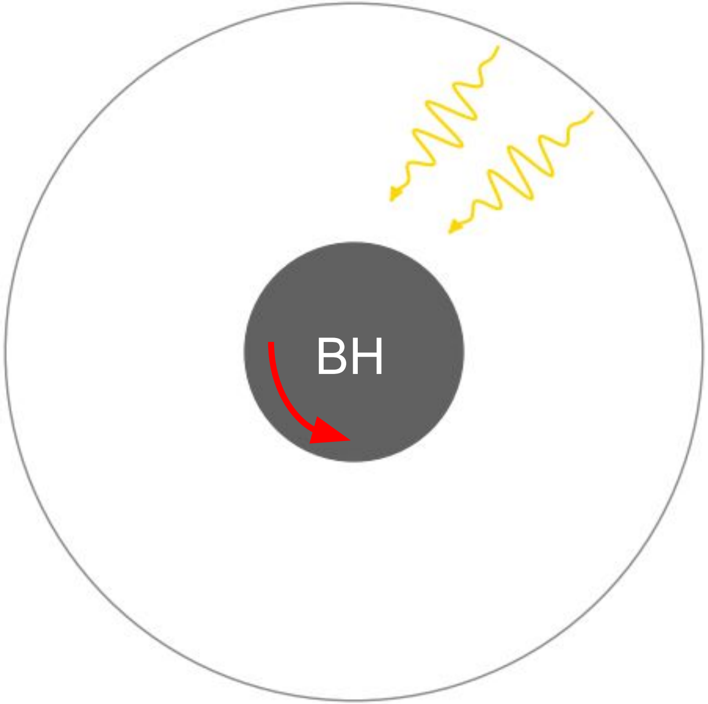
$$\omega < m\Omega$$

[Zel'dovich *Pis'ma Zh. Eksp. Teor. Fiz.* (1971), Zel'dovich *Zh. Eksp. Teor. Fiz* (1972), Brito-Cardoso-Pani *Lecture Notes in Physics* (2020)]

If the BH is surrounded by a mirror, this process can lead to an instability.

[Press-Teukolsky *Nature* (1972)]

Superradiant Amplification and the Black Hole Bomb



Black holes (BHs) can amplify low-frequency waves thanks to superradiance.

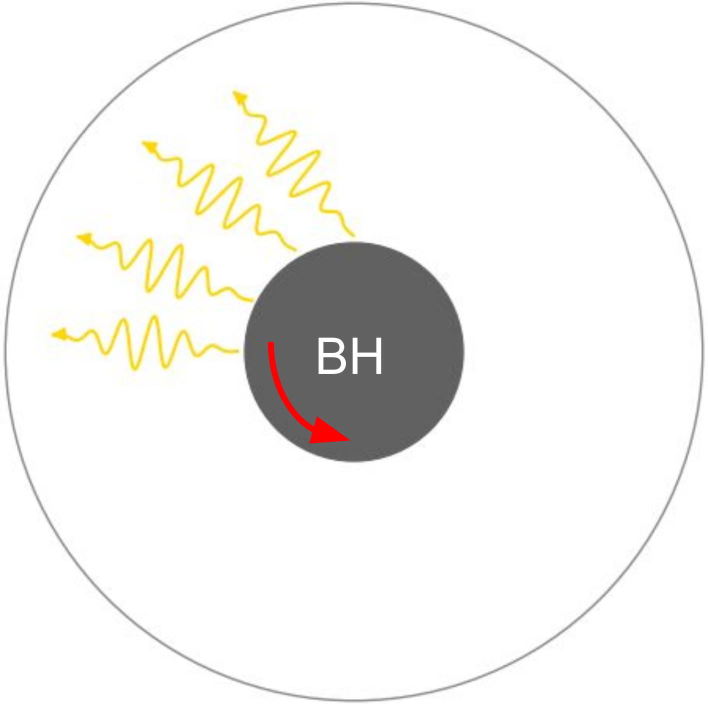
$$\omega < m\Omega$$

[Zel'dovich *Pis'ma Zh. Eksp. Teor. Fiz.* (1971), Zel'dovich *Zh. Eksp. Teor. Fiz* (1972), Brito-Cardoso-Pani *Lecture Notes in Physics* (2020)]

If the BH is surrounded by a mirror, this process can lead to an instability.

[Press-Teukolsky *Nature* (1972)]

Superradiant Amplification and the Black Hole Bomb



Black holes (BHs) can amplify low-frequency waves thanks to superradiance.

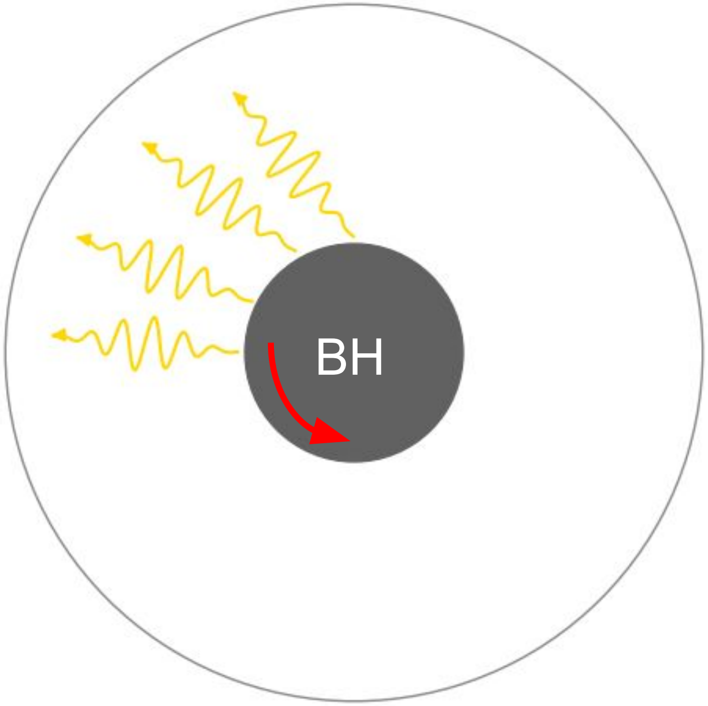
$$\omega < m\Omega$$

[Zel'dovich *Pis'ma Zh. Eksp. Teor. Fiz.* (1971), Zel'dovich *Zh. Eksp. Teor. Fiz* (1972), Brito-Cardoso-Pani *Lecture Notes in Physics* (2020)]

If the BH is surrounded by a mirror, this process can lead to an instability.

[Press-Teukolsky *Nature* (1972)]

Superradiant Amplification and the Black Hole Bomb



Black holes (BHs) can amplify low-frequency waves thanks to superradiance.

$$\omega < m\Omega$$

[Zel'dovich *Pis'ma Zh. Eksp. Teor. Fiz.* (1971), Zel'dovich *Zh. Eksp. Teor. Fiz* (1972), Brito-Cardoso-Pani *Lecture Notes in Physics* (2020)]

If the BH is surrounded by a mirror, this process can lead to an instability.

[Press-Teukolsky *Nature* (1972)]

Interestingly, nature can provide its "mirrors":

➔ Massive bosonic fields

[Damour+ *Lett. Nuovo Cim.* (1976), Detweiler *Phys. Rev. D* (1980)]

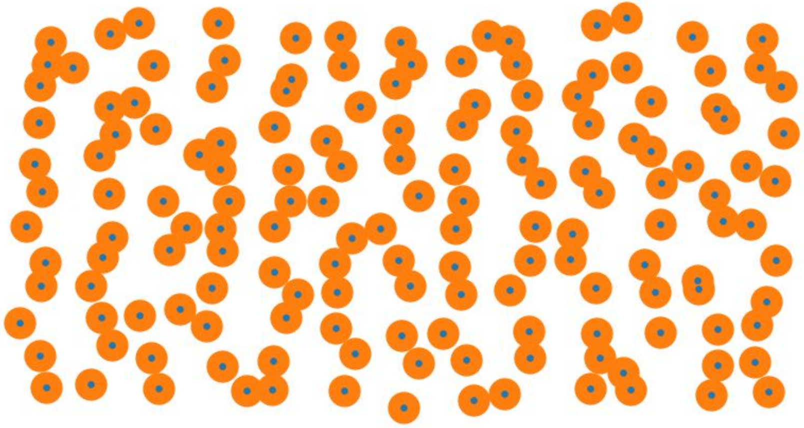
➔ Plasma

[Pani-Loeb *Phys. Rev. D* (2013), Conlon-Herdeiro *Phys. Lett. B* (2018)]

Plasma Frequency

Plasmas are characterized by a typical frequency

$$\omega_p = \sqrt{\frac{n_e e^2}{m}}$$

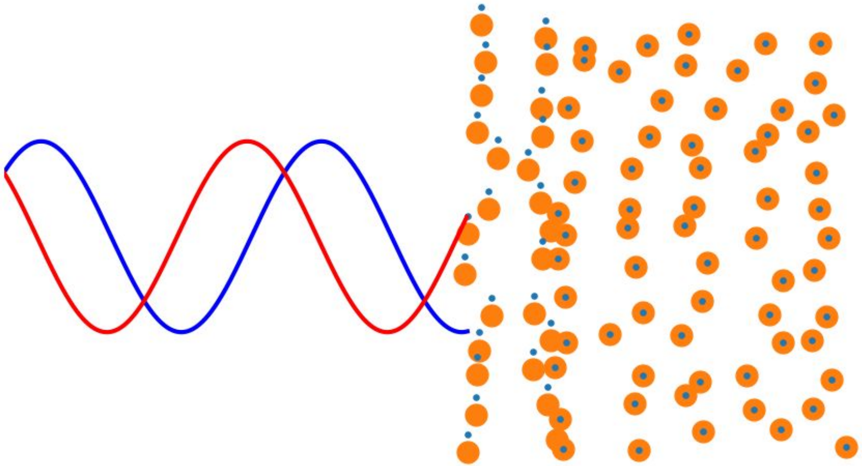


Plasma frequency acts as an effective mass for the photon, providing the mechanism that can trigger the instability.

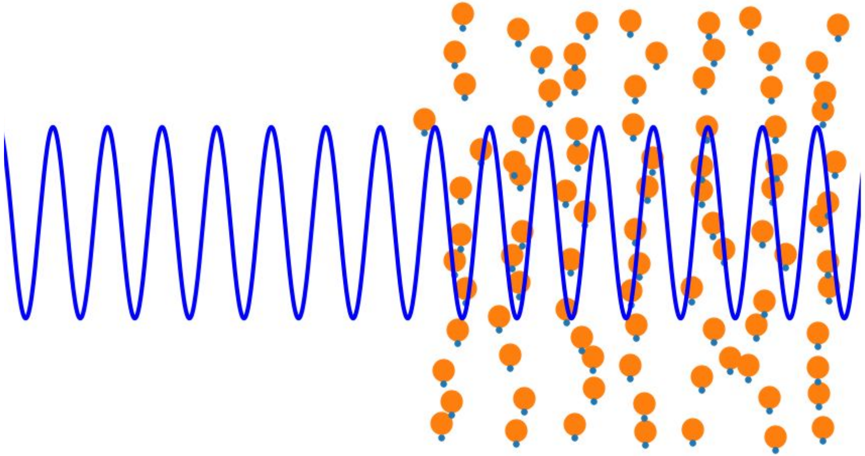
$$\omega^2 = k^2 + \omega_p^2$$

Propagation in the Linear Regime

$\omega < \omega_p$



$\omega > \omega_p$



Plasma Transparency

However, in order to understand whether plasma gives the confinement mechanism that sustains the instability, it is necessary to consider nonlinear effects.

If the electric field becomes large, the relativistic mass of electrons increases, reducing the plasma frequency.

[Kaw-Dawson *Physics of Fluids* (1970), Cardoso+ *MNRAS (2021)*]

$$\omega_p = \sqrt{\frac{ne^2}{m\sqrt{1+\frac{e^2E^2}{m^2\omega^2}}}}$$

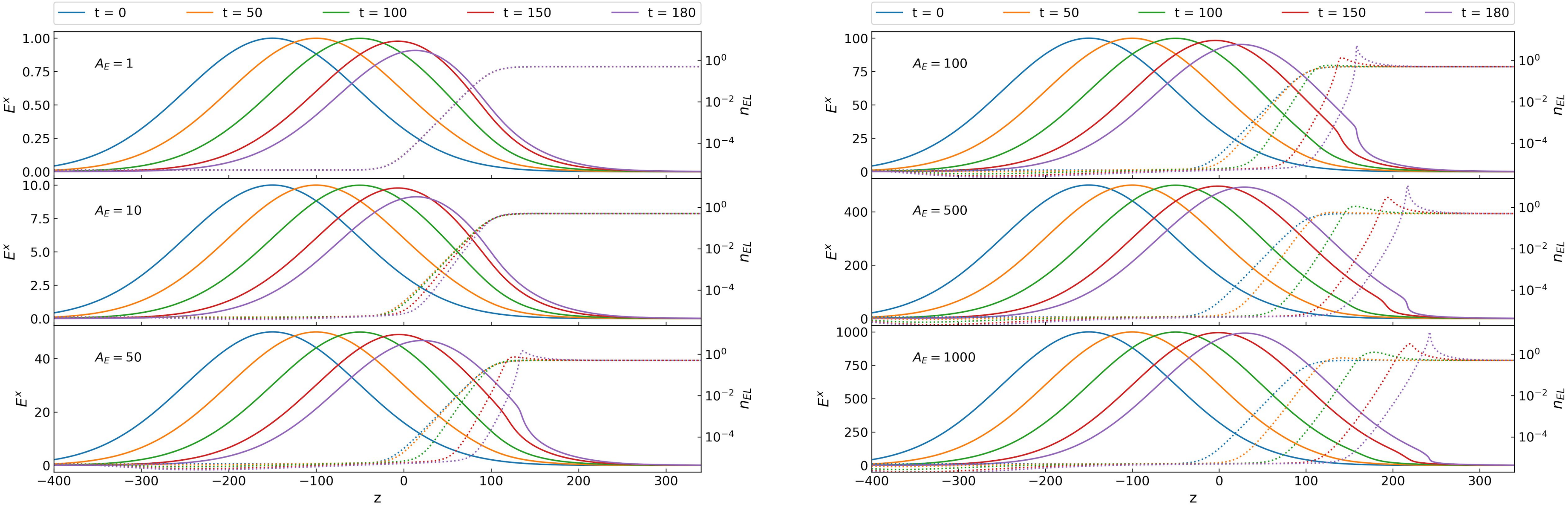
This would let the electromagnetic field propagate through plasma (**transparency**).

Caveat	Assumption of circularly polarized plane waves in a homogeneous plasma.

And for more realistic scenarios?

Numerical Simulations: Qualitative Behavior

Our project: We simulated the nonlinear interaction between an electromagnetic wave packet and a barrier of plasma in a flat spacetime 3+1 setup.



Collective Behavior of Plasma

Velocity dispersion of plasma:

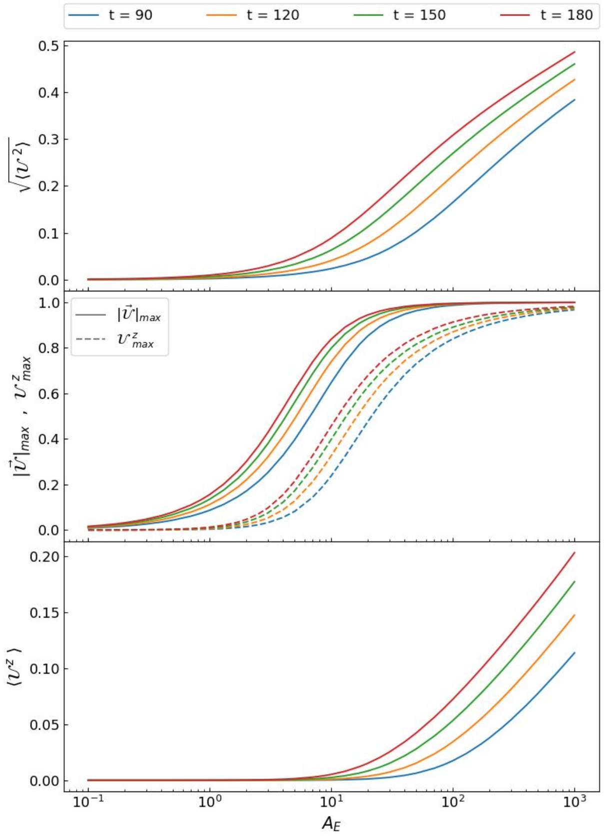
$$\sqrt{\langle \mathcal{U}^2 \rangle} = \sqrt{\frac{\int_V d^3x \, n_{EL} \, \mathcal{U}_i \mathcal{U}^i}{\int_V \, d^3x \, n_{EL}}}$$

Longitudinal collective velocity:

$$\langle \mathcal{U}^z \rangle = \frac{\int_V d^3x \, n_{EL} \, \mathcal{U}^z}{\int_V d^3x \, n_{EL}}$$

Three regimes:

Linear	$A_E \lesssim 1$
Nonlinear	$1 \lesssim A_E \lesssim 10$
Blowout	$A_E \gtrsim 10$



Possible scenarios

Three possible scenarios:

$$\omega_p = \sqrt{\frac{n_e e^2}{m}}$$

The electromagnetic wave destroys the plasma barrier

↓

Superradiance is quenched

Electrons reach a relativistic speed, ω_p drops down, and the EM wave propagates

↓

Superradiance is quenched

The strong peaking of electrons increases ω_p, and the wave is reflected

↓

Superradiance is likely quenched

Take-home messages:

1. Nonlinear effects likely render superradiant instability ineffective.
2. Phenomenology heavily depends on a large number of factors (vorticity, polarization, etc.). A detailed modeling is required to draw definitive conclusions on plasma-driven superradiant instability.

Thank You!