Plasma, Photons and Black Hole Bombs

Enrico Cannizzaro
Advisor: Paolo Pani

PhD Seminars

Work done in collaboration with:

Andrea Caputo

Tel Aviv University and Weizmann Institute of Science

Laura Sberna
Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Potsdam

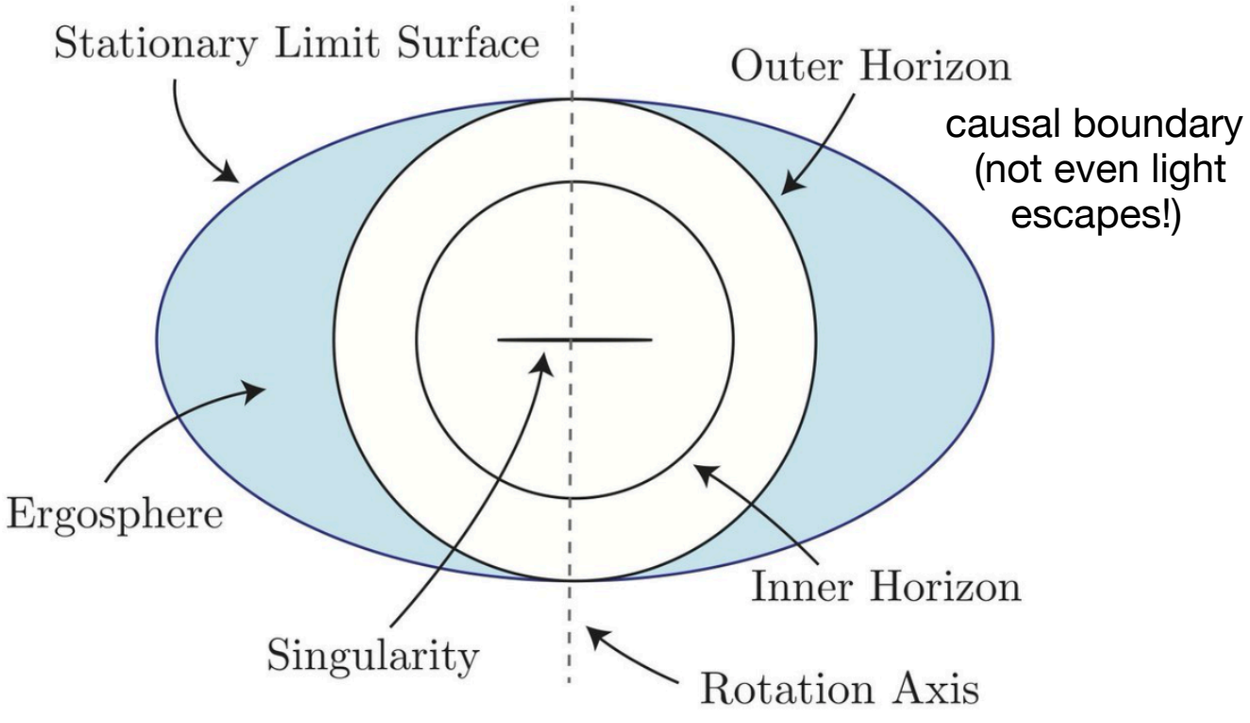
Anatomy of spinning black holes

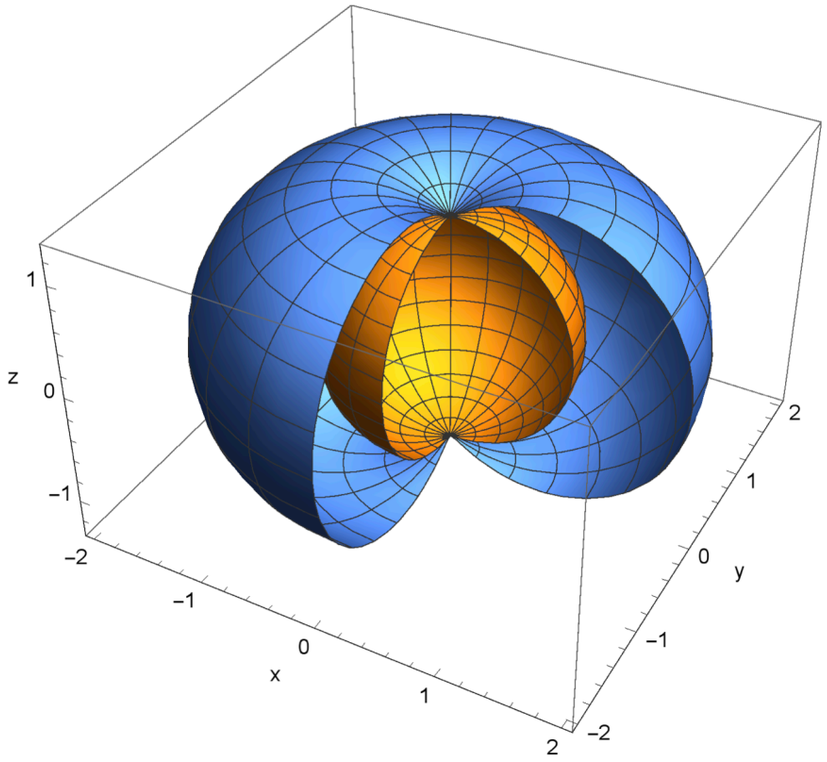
- Black Holes (BHs) are vacuum solutions of Einstein's General Theory of Relativity

- BHs are simple objects: they can be described by only three parameters (no-hair theorem):

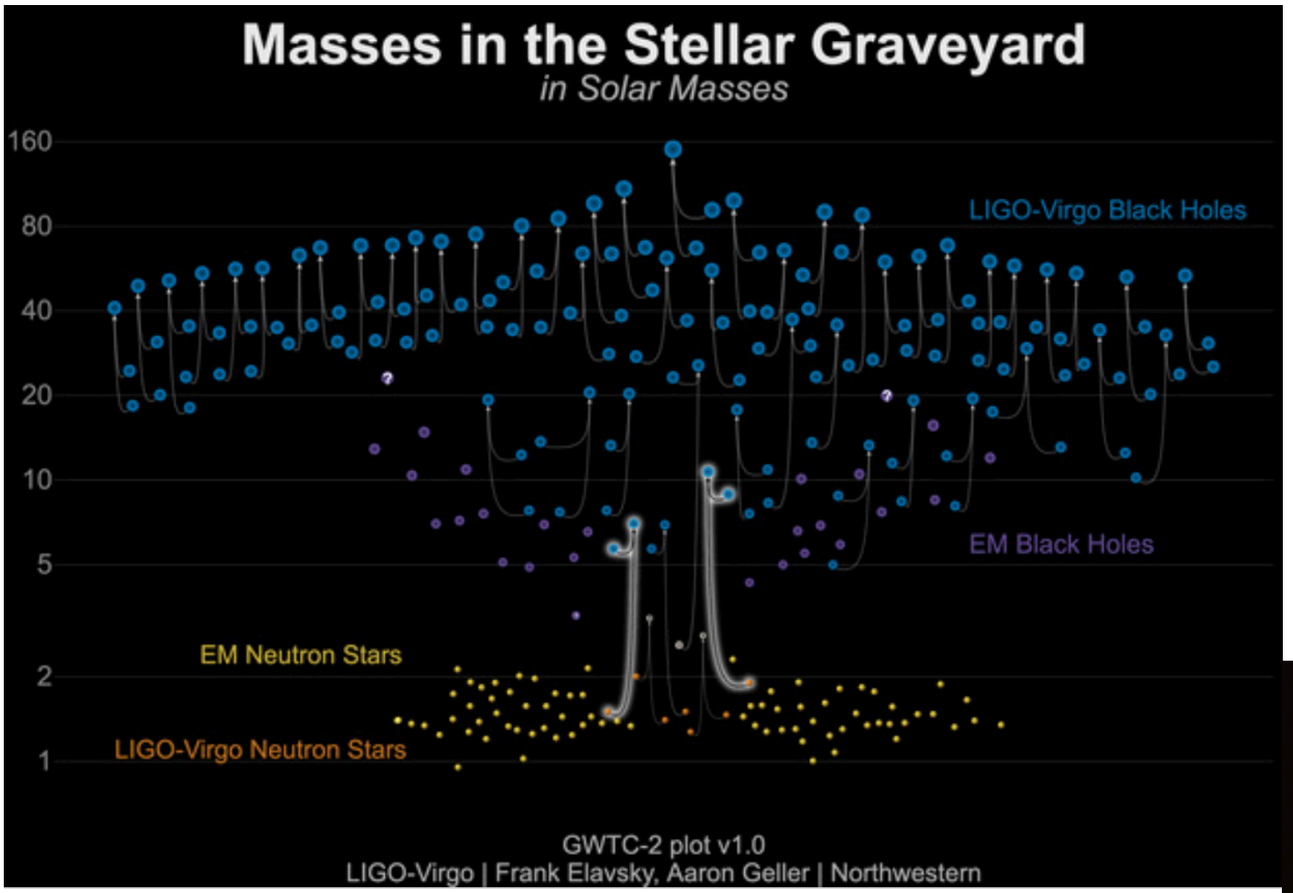
- **Mass**
- **Spin**
- **Charge**

→ Astrophysical BHs are neutral (plasma, pair production, Hawking radiation..)
So they are described only by mass and spin





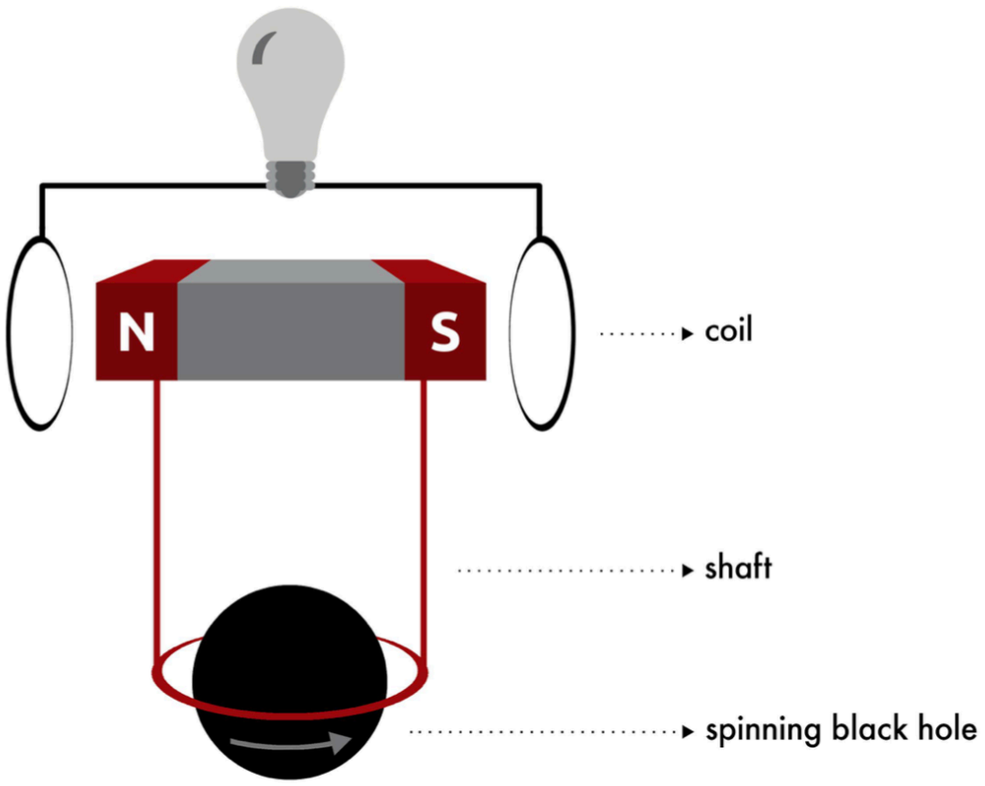
Black Holes in the Universe

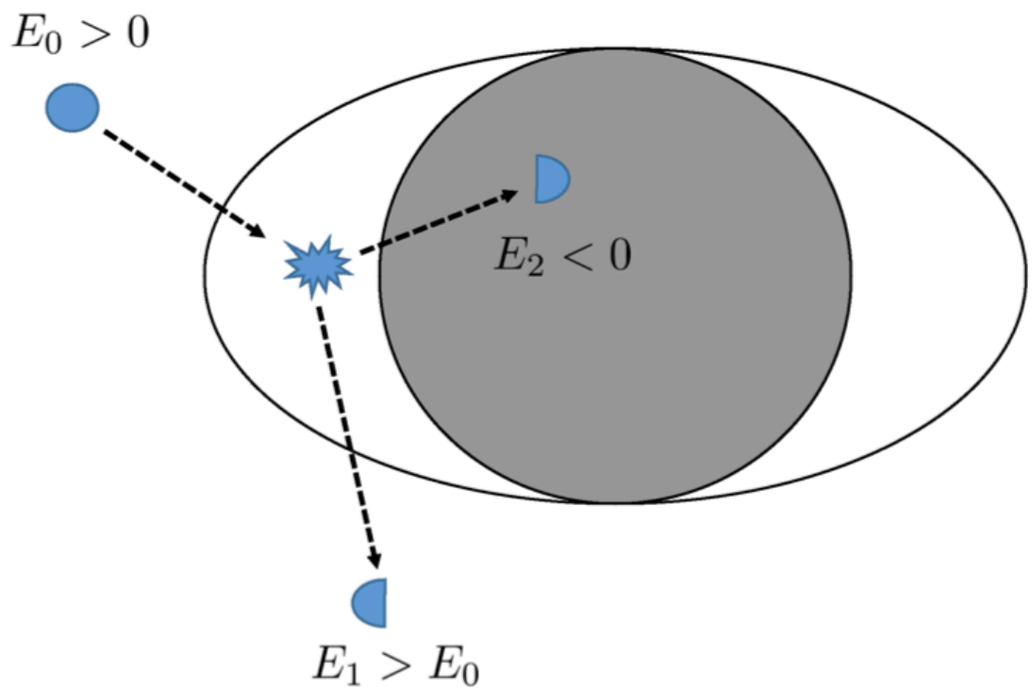


Ligo-Virgo collaboration

EHT collaboration

Energy Extractions from spinning BHs: Two gendankenexperiments



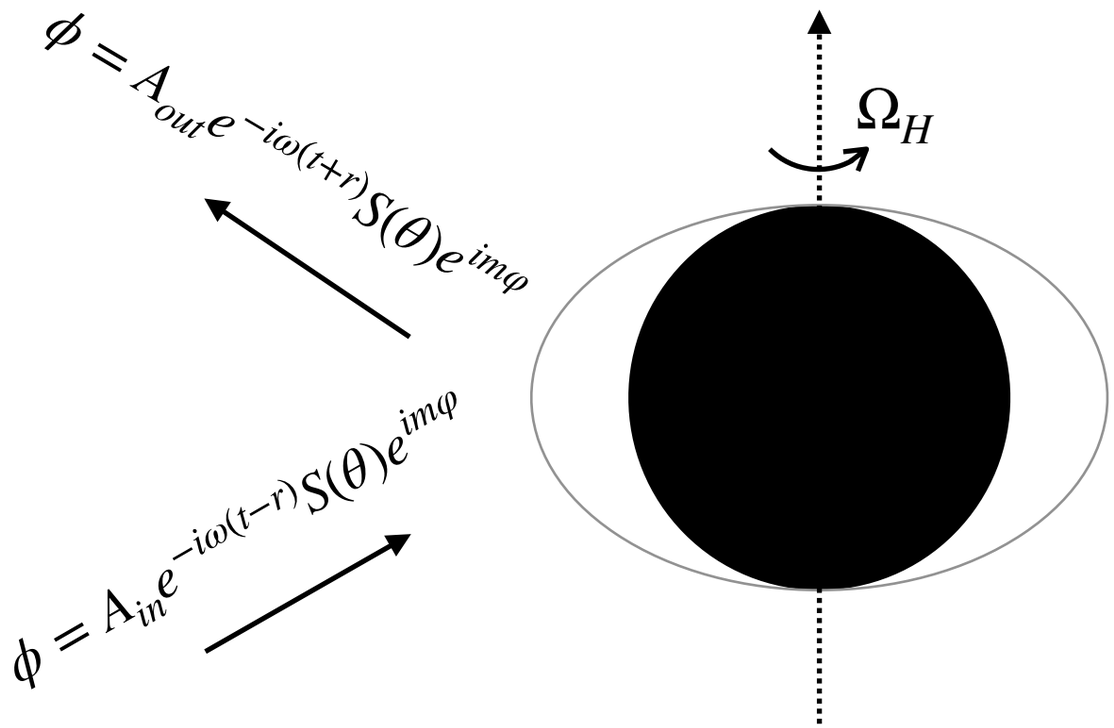


BH powered circuit:
ring and shafts are forced to spin with BH, turn the magnet over and produce a current

Penrose process:
particle decay inside ergoregion.
The particle that escapes at infinity has more energy that the original one (conservation of energy)

Superradiant Scattering

Bosonic waves scattering off spinning BHs can be amplified via superradiance



$$|A_{out}|^2 > |A_{in}|^2$$

$$\omega < m\Omega_H$$

Rotational superradiance Condition

Extraction of energy and angular momentum from the BH

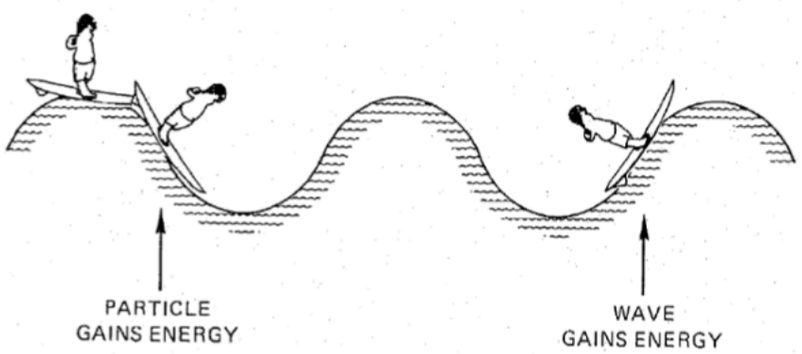
R. Brito, V. Cardoso, and P. Pani "Superradiance: New Frontiers in Black Hole Physics", 2015

A physical interpretation: surfing bosons

$\omega/m < \Omega_H$ ω/m : Angular phase velocity of the wave

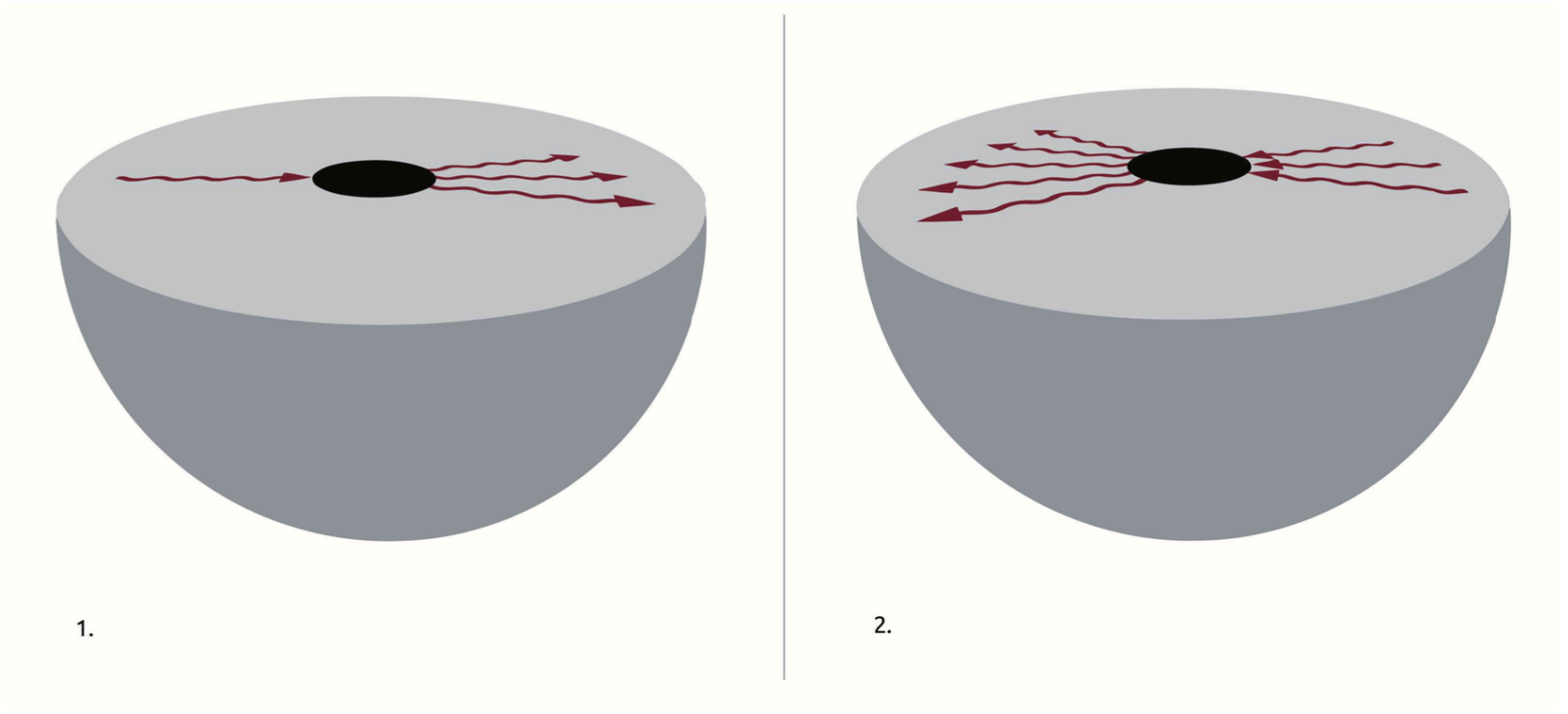
If the angular phase velocity of the wave<angular velocity of BH, energy extraction!

If the surfer is slower than the wave, is accelerated by it. Otherwise, it loses energy



Superradiant Instability: The role of confinement

If superradiance is supported by confinement of the modes, an instability arises.



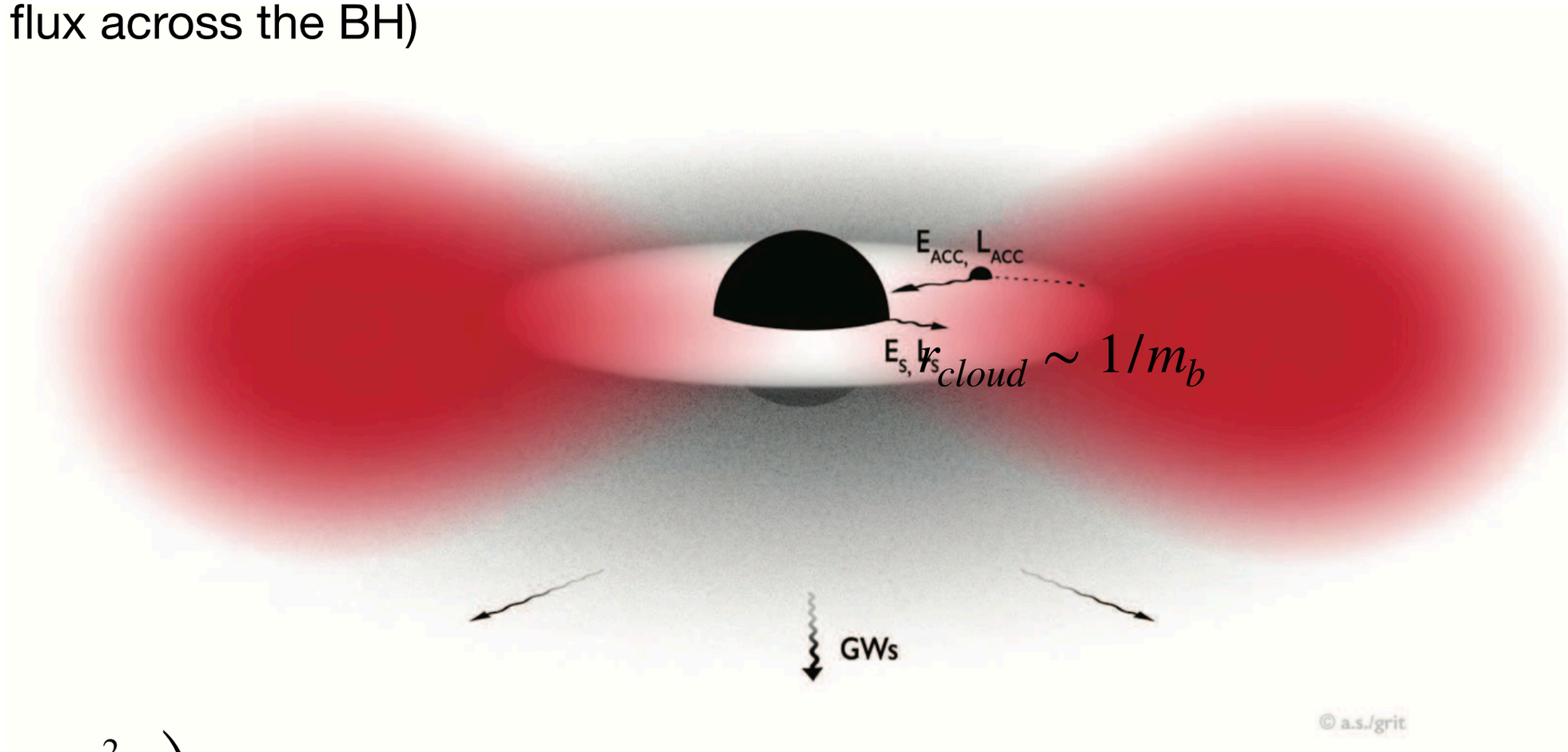
Realistic Confinement can be provided by:

- A mass naturally confining low energy modes

Gravitational Atom

Bosons populates (quasi) bound states around a BH just like a “gravitational atom”, but..

- No Fermi principle!
- Dissipation (GWs, flux across the BH)



$r_{cloud} \sim 1/m_b$

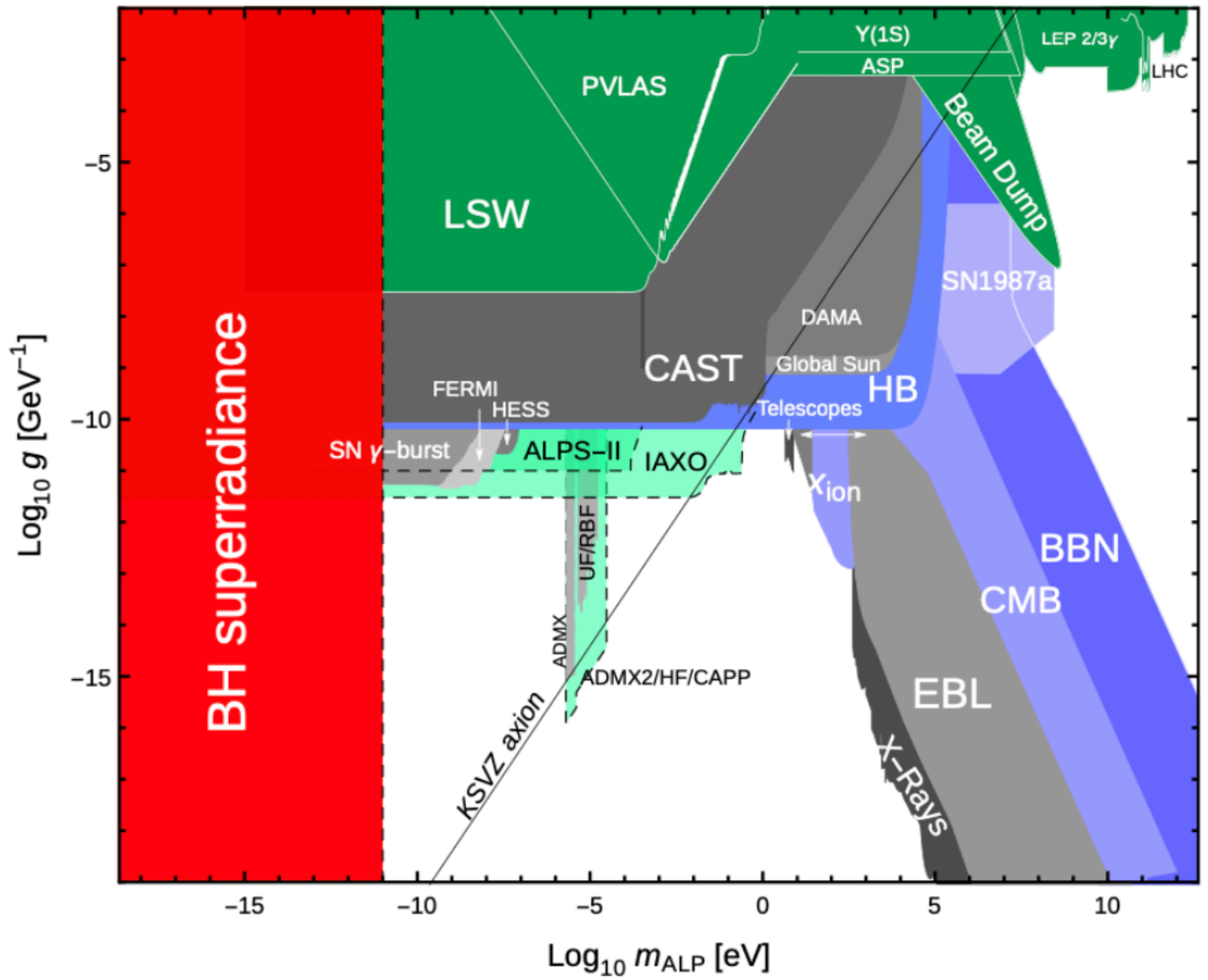
Efficient for:

$$M\mu = \left(\frac{M}{10M_\odot}\right)\left(\frac{m_b c^2}{10^{-12}eV}\right)M_{pl}^{-2} \sim 1 \longrightarrow m_b c^2 \sim 10^{-19} - 10^{-10}eV$$

The cloud can extract up to 29% (10%?) of the BH mass

BHs as particle detectors

8 orders of magnitude in the boson's mass



Ultralight bosons can be probed ONLY via their gravitational interaction

Cardoso+, *JCAP, 2018*

Plasma: The fourth state of matter

Another possibility: Standard Model photons Problem: photons are massless

However, sometimes, nature provides its own mirrors: plasma

Plasma is a ionised gas, composed of positive ions and dissociated, free electrons.

- Is globally neutral, but several electric and magnetic field can characterise plasma at different scales of length.

Why is it important?

The 99% of the visible universe (excluding Dark Matter and Dark Energy) is in the plasma state (fourth state of matter). Is therefore crucial in cosmology and astrophysics!

Why in BH Physics?

Astrophysical BHs are surrounded by plasma! (accretion disks, interstellar medium)

Collective Behaviors in a Plasma: Perturbation theory

What happens if a plasma is subject to a small charge perturbation?

- Ions (heavy) stay fixed
- Electrons are displaced

Electric field created by displacement: $$E = -\frac{en\delta x}{\epsilon_0}$$

Newton's law: $$m_e a = m_e \frac{d^2\delta x}{dt^2} = eE = -\frac{e^2 n\delta x}{m}$$

Electrons behave as a system of coupled oscillators!

The frequency of oscillations is the plasma frequency $$\omega_p = \sqrt{\frac{n_e e^2}{m_e}}$$

The Photon-Plasma system

Photons propagating in a plasma are dressed with an effective mass equal to the plasma frequency

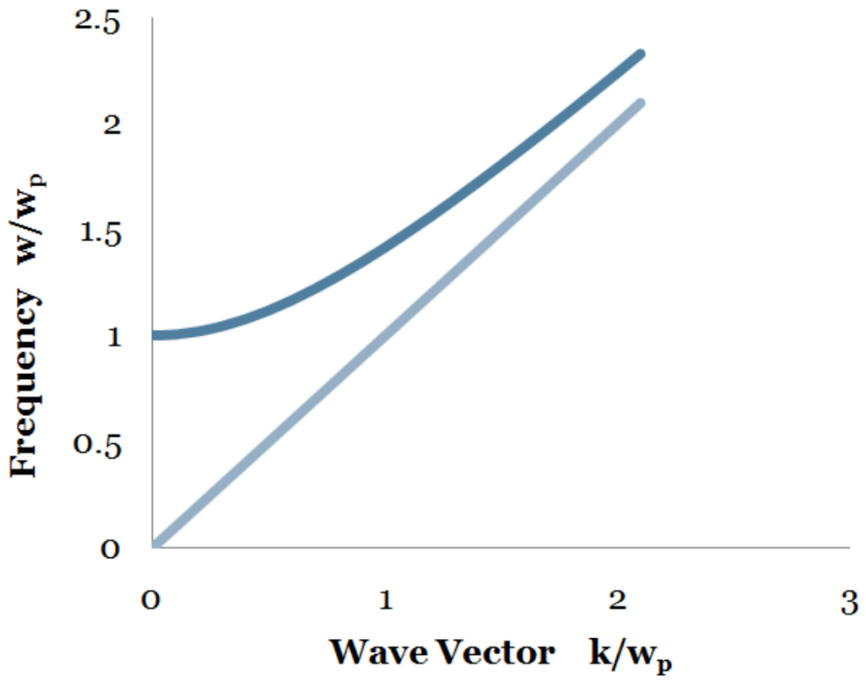
"Effective Mass":

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

Modified dispersion relation: $\omega^2 = k^2c^2 + \omega_p^2$

If $\omega < \omega_p$ the wave is confined by plasma (plasma is opaque)

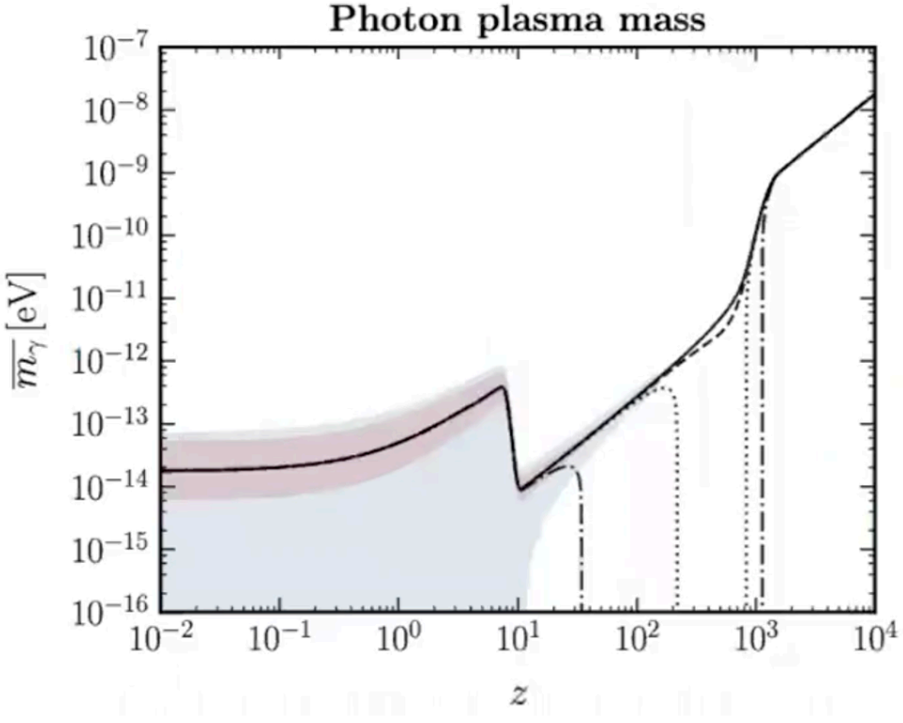
If $\omega > \omega_p$ the wave propagates (plasma is transparent)



This is a cutoff!

Plasma can confine radiation and behave as a mirror!

The Instability: Interstellar medium

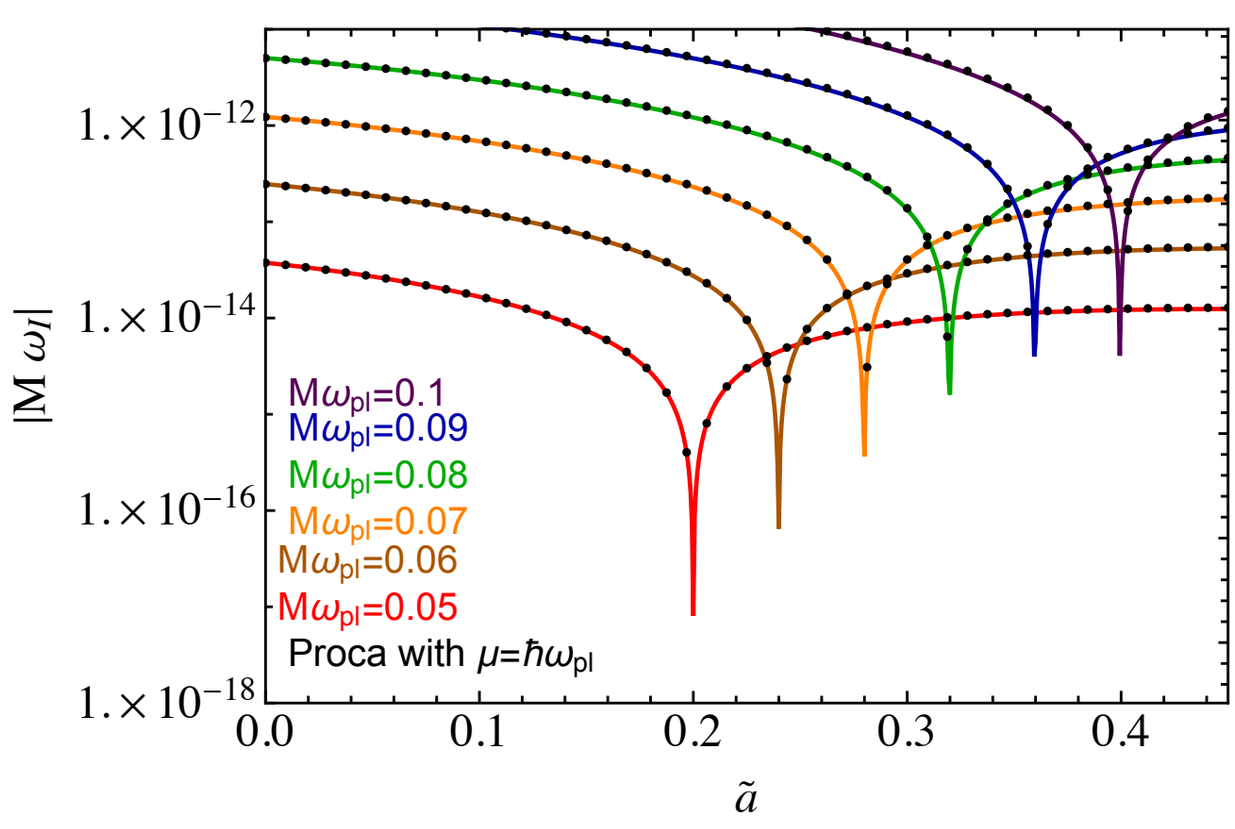


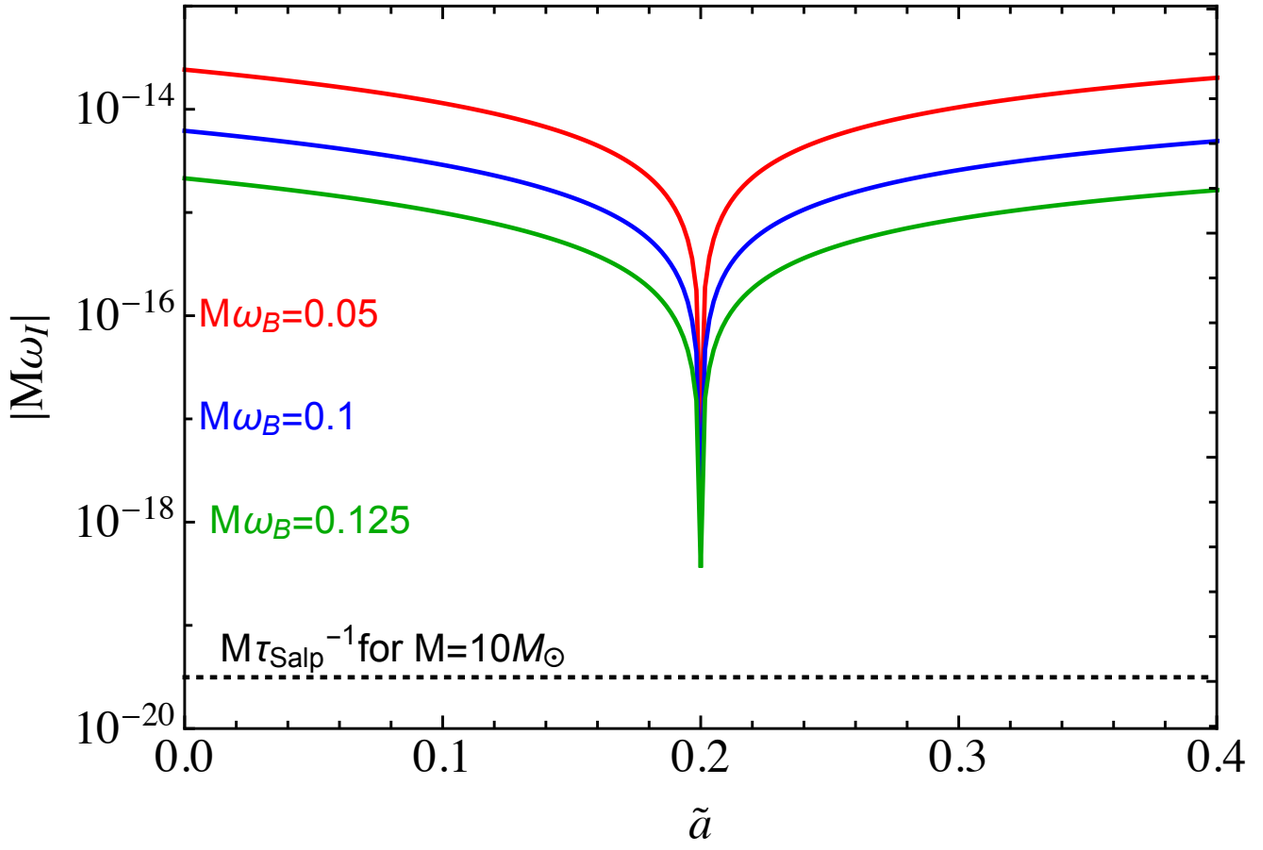
Is exactly in the right range
for Superradiance!

Eigenfrequencies are complex due to dissipation channels in the system:

$$A^\mu \sim A_0 e^{-i\omega t} \sim A_0 e^{-i\omega_R t} e^{\omega_I t}$$

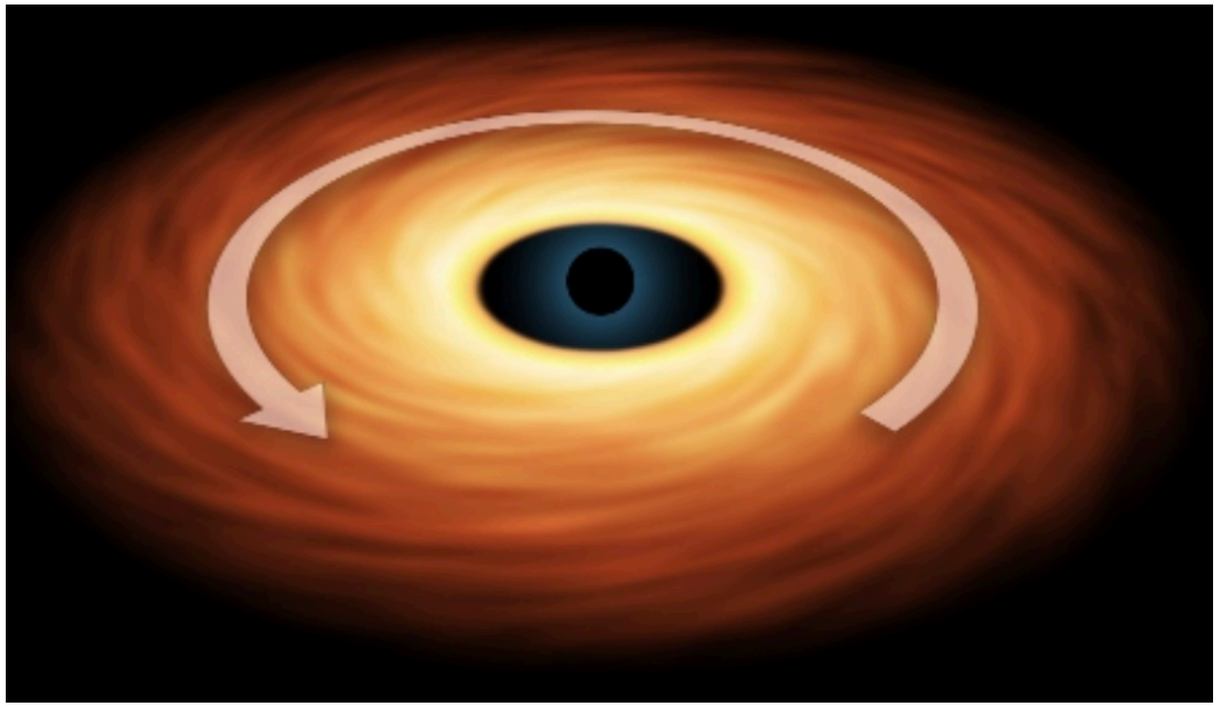
$$\omega_I > 0 \qquad \omega_R < m\Omega_H$$

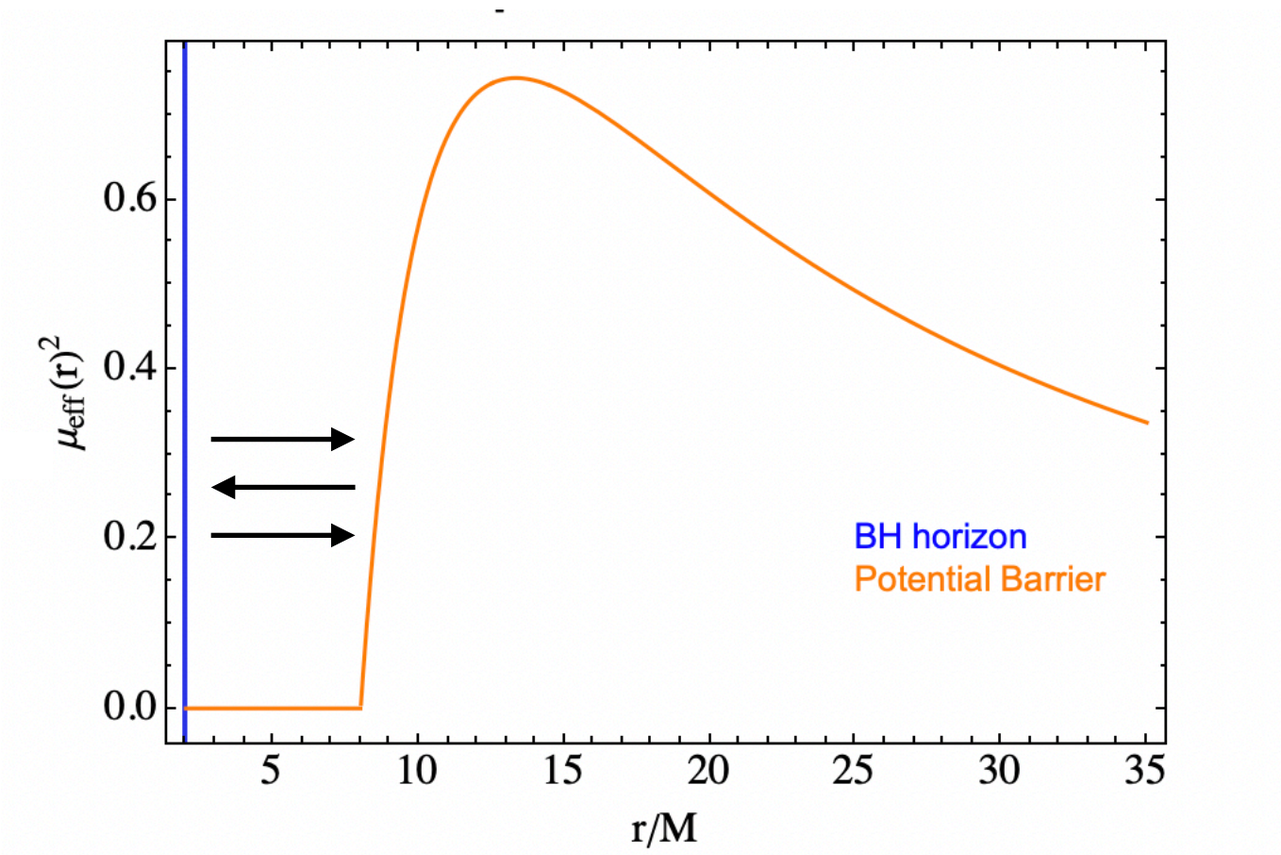




Cannizzaro+, *PRD, 2020* *Cannizzaro+, PRD, 2021*

Accretion disk: Black Hole Bombs





Astrophysical BHs accrete plasma at extreme densities in their vicinities. The accretion disks are truncated at a certain radius and are able to confine radiation near the BH, in a similar way to a BH bomb.

Dima+, CQG, 2020

Ongoing Research

- **Relativistic effects can hamper the instability**

$$\omega_p = \sqrt{\frac{ne^2}{m}} \longrightarrow \omega_p = \sqrt{\frac{ne^2}{m\gamma}} = \sqrt{\frac{ne^2}{m(1+\frac{e^2E_{SR}^2}{m^2\omega^2})}}$$

Is it true? If yes the alternatives:

Analyse plasma BH bomb system where you circumvent the obstacle

Spontaneous Superradiant Instabilities

by accretion disk in scalar tensor theories

, In Preparation

Generalise to plasma effects in Dark photon superradiance