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BLASTs

Black hole Lasers powered by Axion SuperradianT instabilities

João G. Rosa

Aveiro University

with **Tom Kephart** (Vanderbilt University)

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[arXiv:1709.06581 [gr-qc]]

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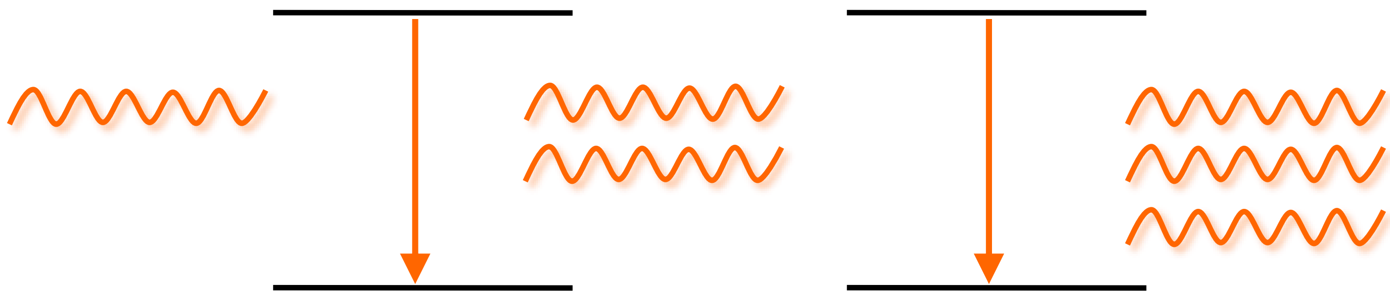
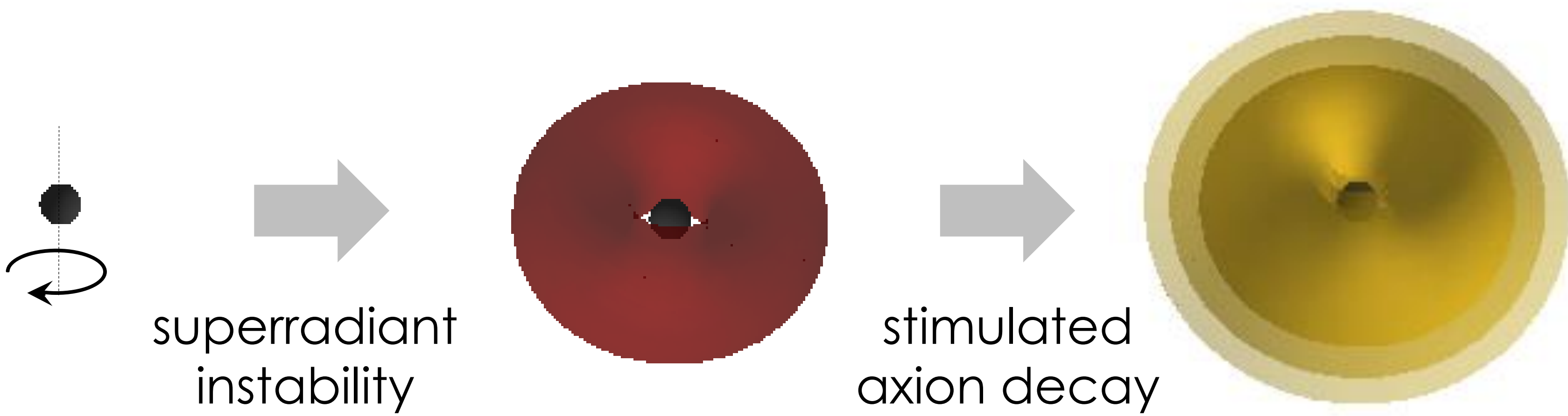
Lasers and stimulated emission



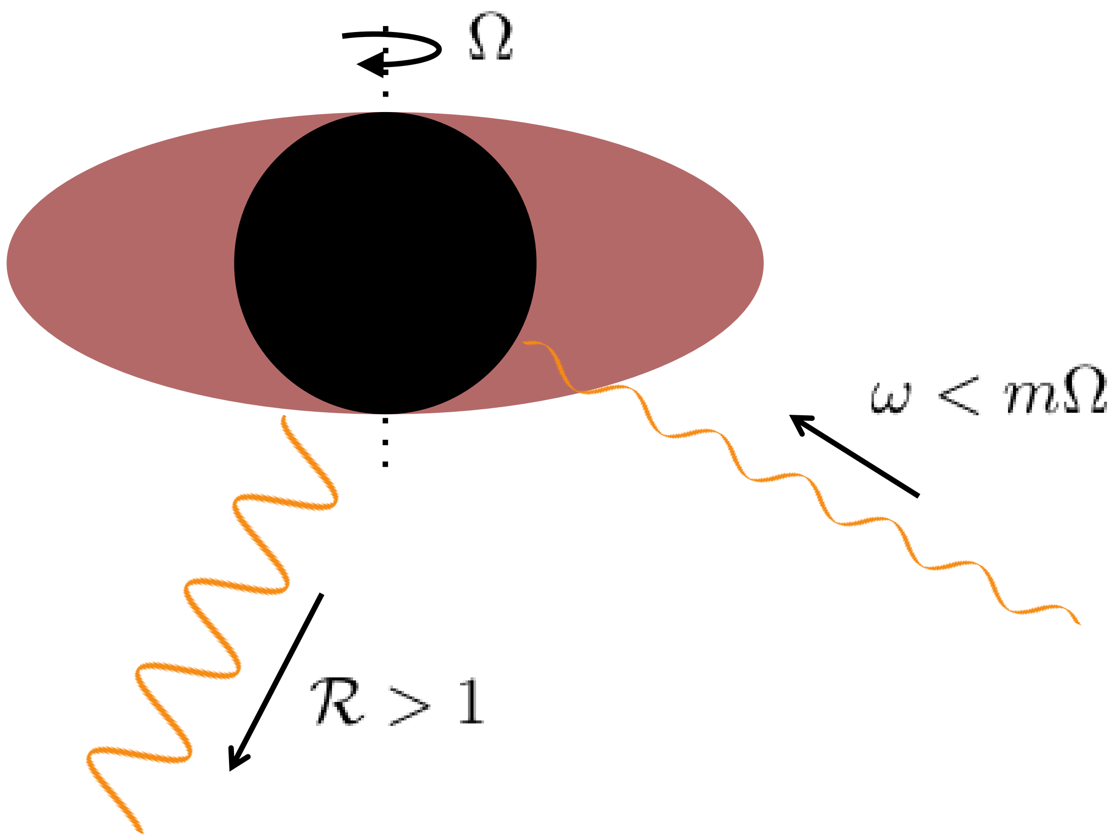
Kerr black hole having a BLAST:



Black hole superradiance

[Zeldovich (1966)]

Low frequency waves can be amplified by scattering off a Kerr black hole, extracting its energy and spin:



Superradiance for scalar waves

Klein-Gordon equation in Kerr space-time:

$$g^{\mu\nu}\nabla_\mu\nabla_\nu\Phi = 0$$

Separation of variables:

$$\Phi(t,r,\theta,\phi) = e^{-i\omega t}e^{im\phi}S(\theta)R(r)$$

stationary and axisymmetric

spheroidal harmonics

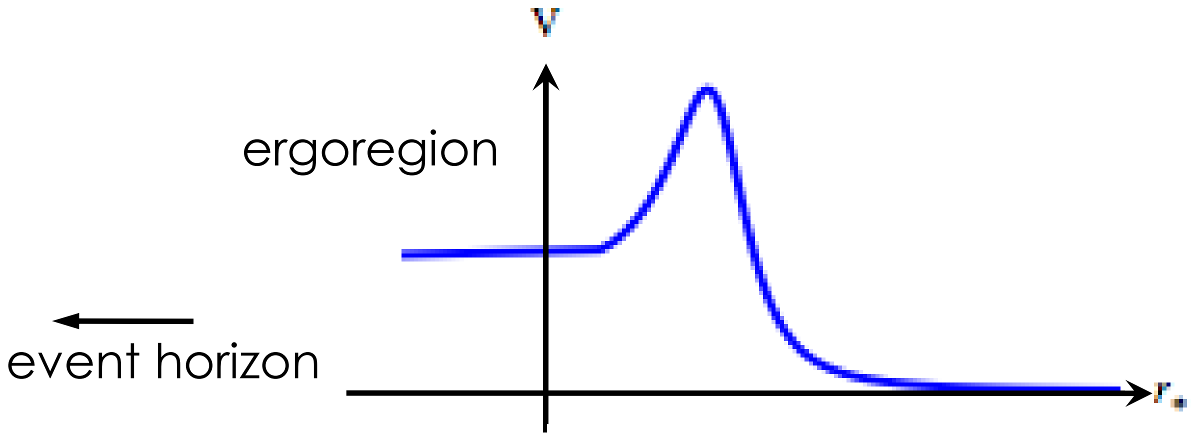
Superradiance for scalar waves

Schrodinger-like radial equation:

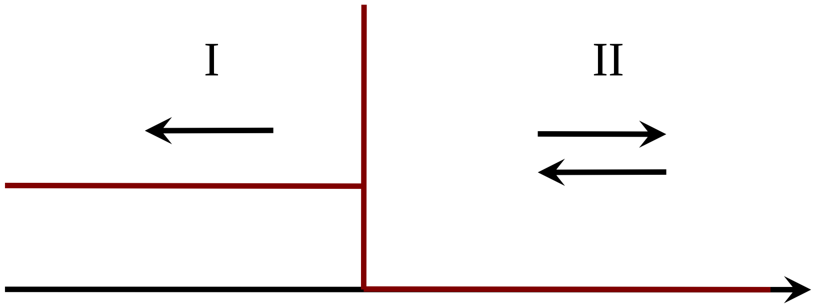
$$\frac{d^2\psi}{dr_*^2} + \left[\omega^2 - V(\omega)\right]\psi = 0$$

where

$$\psi = \sqrt{r^2 + a^2}R\,, \qquad dr_* = \frac{(r^2 + a^2)}{\Delta}dr$$



Toy model for superradiance



$$V(\omega) = \alpha\delta(x) + m\Omega(2\omega - m\Omega)(1 - \Theta(x))$$

General solutions:

$$\psi_I = e^{-i(\omega - m\Omega)x} \ , \qquad \psi_{II} = Ae^{-i\omega x} + Be^{i\omega x}$$

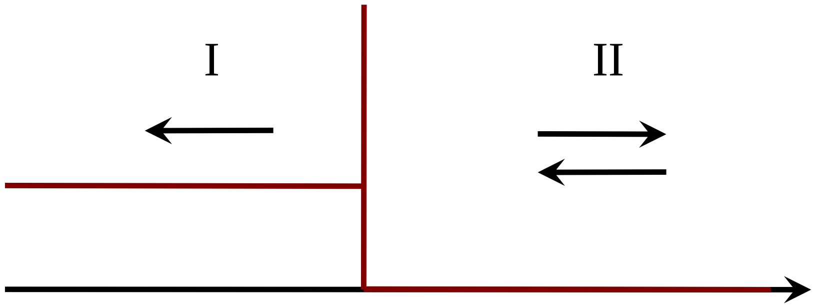
Boundary conditions:

$$\psi_I(0) = \psi_{II}(0) \ , \qquad \psi'_I(0) - \psi'_{II}(0) = \alpha\psi_I(0)$$

Reflection coefficient:

$$\mathcal{R} = \left|\frac{B}{A}\right|^2 = \frac{\alpha^2 + m^2\Omega^2}{\alpha^2 + (2\omega - m\Omega)^2} > 1 \quad \Rightarrow \quad \omega < m\Omega$$

Toy model for superradiance



$$V(\omega) = \alpha\delta(x) + m\Omega(2\omega - m\Omega)(1 - \Theta(x))$$

In the superradiant regime:

- negative phase velocity: $k_I = \omega - m\Omega < 0$
- positive group velocity: $v_g = d\omega/dk_I = 1$

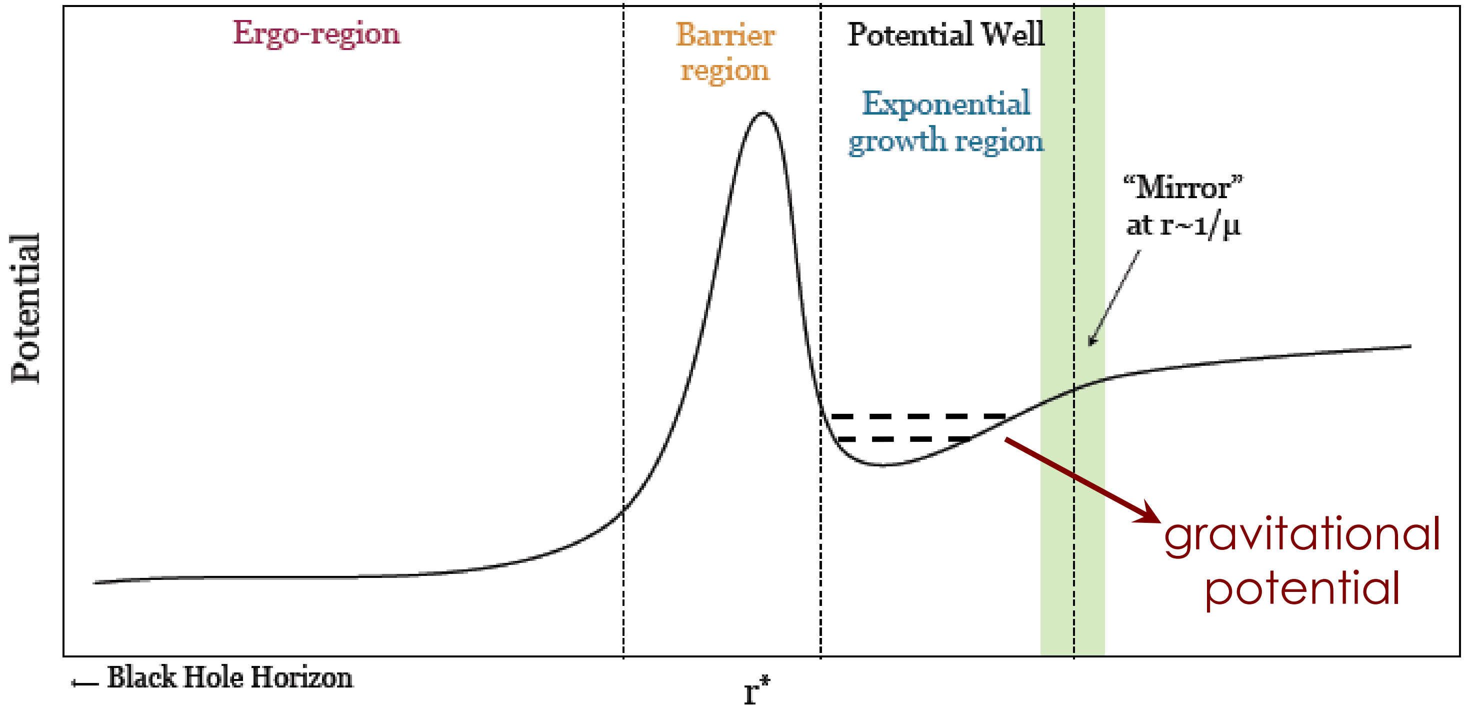
Waves carry negative energy into the BH

Energy and spin extraction from BH

Massive black hole bombs

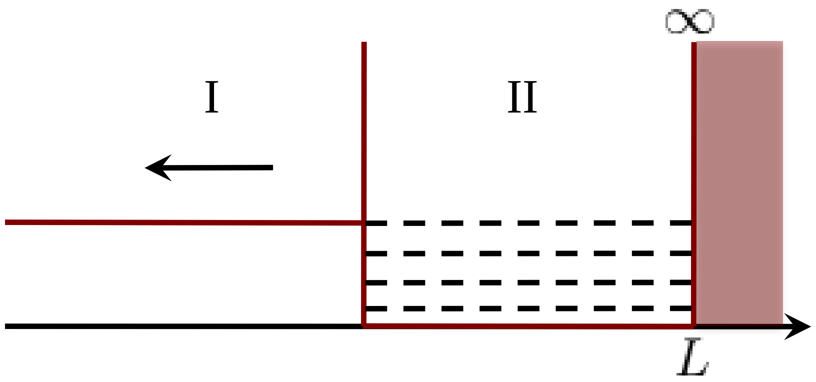
Massive fields can become bound to the black hole:

"gravitational atoms"



[Arvanitaki et al. (2009)]

Toy model for superradiant instabilities



$$\psi_I = e^{-i(\omega - m\Omega)x}$$

$$\psi_{II} = A \sin(\omega x)$$

Bound states satisfy: $\omega \cot(\omega L) + \alpha = i(\omega - m\Omega)$

In the limit $\alpha \gg \omega$: $\omega = \omega_R + i\Gamma$

$$\omega_R \simeq \frac{n\pi}{2L} \qquad \Gamma \simeq -\frac{\omega_R(\omega_R - m\Omega)}{\alpha}$$

$\Phi \propto e^{-i\omega_R t} e^{\Gamma t}$ ➡ Superradiant instability

Superradiant instability

Massive scalar fields form Hydrogen-like bound states in Kerr BH:

$$\hbar\omega_n \simeq \mu c^2 \left(1 - \frac{\alpha_\mu^2}{2n^2}\right) \qquad \alpha_\mu \equiv \frac{G\mu M_{BH}}{\hbar c}$$

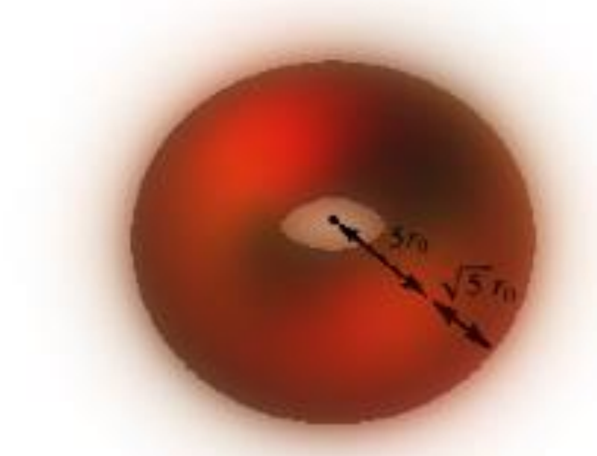
Exponentially growing field for $\omega_n < m\Omega$ leads to scalar cloud

$$\Gamma_s \simeq \frac{\tilde{a}}{24}\alpha_\mu^9 \left(\frac{c^3}{GM}\right) \simeq 4 \times 10^{-4}\tilde{a}\left(\frac{\mu}{10^{-5}\ \mathrm{eV}}\right)\left(\frac{\alpha_\mu}{0.03}\right)^8 \ \mathrm{s}^{-1}\ ,$$

Main cloud properties:

$$r_0 = \frac{\hbar}{\mu c \alpha_\mu} \gg r_+$$

$$\sqrt{\langle v^2 \rangle} \simeq (\alpha_\mu/2)c$$



$n = 2, l = m = 1$

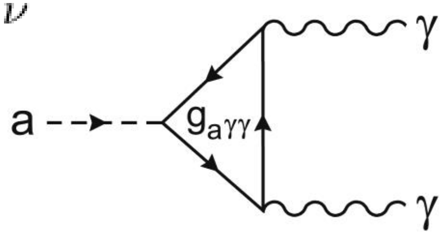
[see review by Brito, Cardoso & Pani (2015)]

QCD axion

Pseudo-scalar particle predicted by the Peccei-Quinn solution to the strong CP problem

$$\mu \simeq 10^{-5} \left(\frac{6 \times 10^{11}\ \mathrm{GeV}}{F_\phi} \right)\ \mathrm{eV}$$

Decays into photon pairs: $\mathcal{L}_{\phi\gamma\gamma} = \frac{\alpha K}{8\pi F_\phi} \phi F_{\mu\nu} \tilde{F}^{\mu\nu}$



$$\tau_\phi \simeq 3 \times 10^{32} K^{-2} \left(\frac{\mu}{10^{-5}\ \mathrm{eV}} \right)^{-5}\ \mathrm{Gyr}$$

Can account for cold dark matter (coherent oscillations, etc)

$$10^{-12}\ \mathrm{eV} \lesssim \mu \lesssim 10^{-2}\ \mathrm{eV}$$

Axionic lasers

Stimulated decay important in dense axion clusters

[Tkachev (1987); Kephart & Weiler (1987,1995)]

Boltzmann equation for axion decay/inverse decay:

$$\begin{aligned}\frac{dn_\lambda(\mathbf{k})}{dt} &= \int dX_{LIPS}\big[f_\phi(\mathbf{p})(1+f_\lambda(\mathbf{k}))(1+f_\lambda(\mathbf{k}'))\\ &- f_\lambda(\mathbf{k})f_\lambda(\mathbf{k}')(1+f_\phi(\mathbf{p}))\big]|\mathcal{M}|^2\end{aligned}$$

where:

$$n_i = \int \frac{d^3k_i}{(2\pi)^3} f_i(\mathbf{k_i})$$

BH-axion-photon system

Simplified model:

- toroidal axion cloud (non-relativistic, flat space)
- homogeneous and isotropic phase space distributions

$$p_\phi \lesssim \frac{\alpha_\mu}{2}\mu c\,, \qquad p_\gamma \simeq \frac{\mu c}{2}\,, \qquad \Delta p_\gamma \simeq \frac{\alpha_\mu}{2}\mu c$$

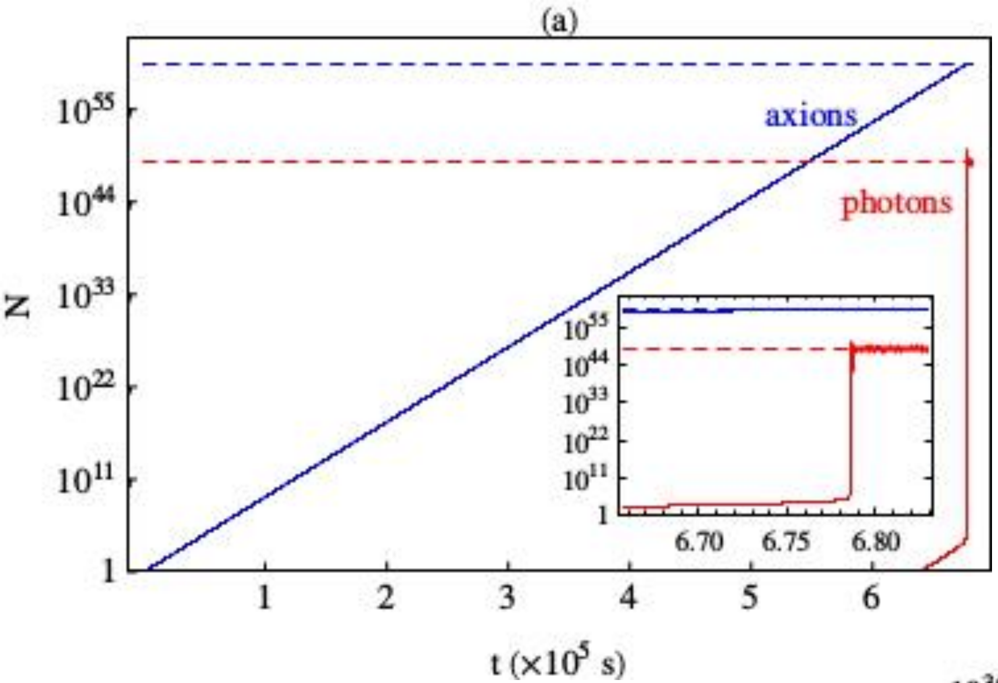
superradiance ↓ spontaneous decay ↓

$$\frac{dN_\phi}{dt} = \Gamma_s N_\phi - \Gamma_\phi\left[N_\phi(1+AN_\gamma) - B_1 N_\gamma^2\right]\,,$$

$$\frac{dN_\gamma}{dt} = -\Gamma_e N_\gamma + 2\Gamma_\phi\left[N_\phi(1+AN_\gamma) - BN_\gamma^2\right]\,,$$

↑ photon escape ↑ stimulated decay ↑ photon annihilation

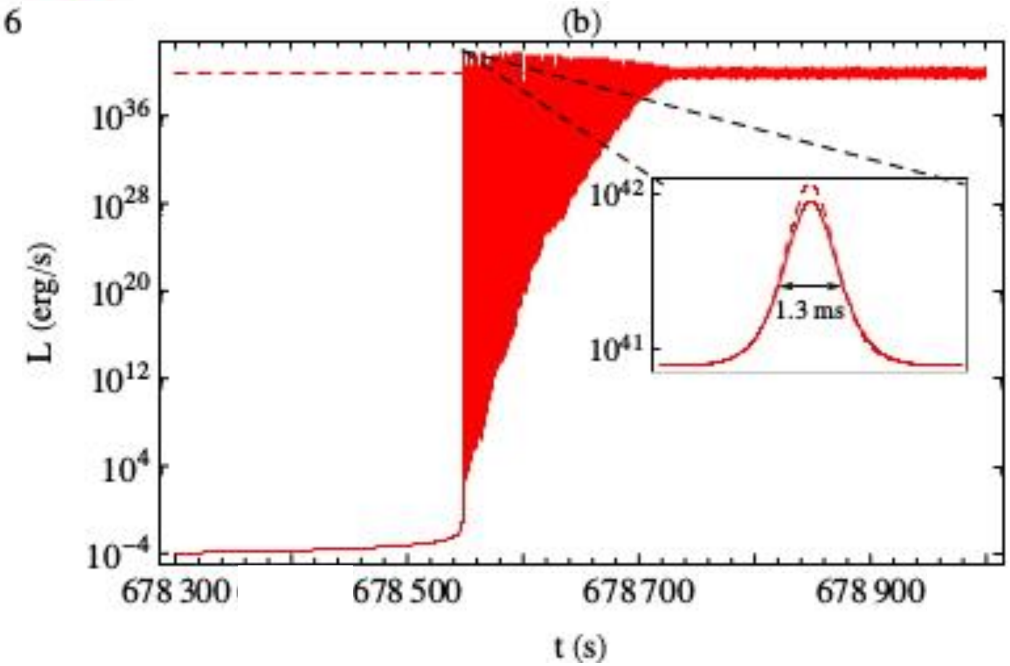
Numerical solution



$$N_\phi^c = \frac{\Gamma_e}{2A\Gamma_\phi}$$

$$N_\gamma^c = \frac{\Gamma_s}{A\Gamma_\phi}$$

$$\mu = 10^{-5}\ \mathrm{eV}$$
$$K = 1$$
$$M_{BH} = 8\times 10^{23}\ \mathrm{kg}$$
$$\tilde{a} = 0.7$$
$$\alpha_\mu \simeq 0.03$$



Constraints

1. Critical cloud mass/spin for lasing:

$$\frac{J_\phi^c}{J_{BH}} \simeq \frac{0.06}{\tilde{a}\alpha_\mu^3 K^2}\left(\frac{\mu}{10^{-8}\ \mathrm{eV}}\right)^{-2} \lesssim 1$$

$\mu \gtrsim 10^{-8}\ \mathrm{eV}$ ➡ $M_{BH} \lesssim 10^{-2} M_\odot$ ➡ Primordial BHs (dark matter?)

<u>PBHs born with no spin but can merge into spinning PBHs</u>

2. Non-linear self-interactions quench instability ('bosenova')

$\phi^c \lesssim F_\phi$ ➡ $\alpha_\mu \lesssim 0.03K$

[Kodama & Yoshino (2012-2015)]

BLAST phenomenology

Schwinger electron-positron pair production increases photon plasma mass and quenches BLAST:

$$|\mathbf{E}| \sim E_c \left(\frac{\mu}{10^{-5}\ \mathrm{eV}}\right)\left(\frac{\alpha_\mu}{0.03}\right)\left(\frac{L}{10^{43}\ \mathrm{erg/s}}\right)^{1/2}$$

We should expect single lasing bursts:

$$L_B \simeq \frac{2\times 10^{42}}{K^2}\tilde{a}\left(\frac{10^{-5}\ \mathrm{eV}}{\mu}\right)^2\left(\frac{\alpha_\mu}{0.03}\right)^7\left(\frac{\xi}{100}\right)\ \mathrm{erg/s}$$

$$\tau_B \simeq \frac{1}{\sqrt{\tilde{a}}}\left(\frac{10^{-5}\ \mathrm{eV}}{\mu}\right)\left(\frac{\alpha_\mu}{0.03}\right)^{-9/2}\left(\frac{\xi}{100}\right)^{-1/2}\ \mathrm{ms}$$

$$\nu_B \simeq 1.2\left(\frac{\mu}{10^{-5}\ \mathrm{eV}}\right)\ \mathrm{GHz}$$

Fast Radio Bursts?
[e.g. Chatterjee *et al.* (2017)]

BLAST phenomenology

Primordial BH merger rates (clustered scenario):

$$\Gamma_{\rm capt}^{\rm total} \simeq 3 \times 10^{-9} f_{\rm DM} \delta^{\rm loc}\ {\rm yr}^{-1} {\rm Gpc}^{-3}$$

[Garcia-Bellido & Clesse (2016)]

May have up to a few new BLASTs formed per year in the sky!

BLASTs repeat every few hours after e^+e^- annihilation, yielding up to 10^8 FRBs before superradiance shuts down

Up to 10^4-10^5 active BLAST FRBs per day across the sky

Other astrophysical signatures:

- e^+e^- annihilation/ positronium afterglows
- GWs from bosenova collapse in between bursts

Look for 10^{-5} eV QCD axion dark matter in the laboratory

➡ ADMX, X3, CULTASK, MADMAX, ORPHEUS, …

+ DM axion-photon conversion in galactic B-field @ SKA
[Kelley & Quinn (2017)]

Thank you!