Lighthouses in the sky – Superradiant instabilities in astrophysical systems

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HW, V. Cardoso, A. Ishibashi, U. Sperhake, Phys. Rev. D 87, 043513 (2013),
H. Okawa, HW, V. Cardoso, (work in progress)

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Outline

1. Motivation
2. Massive scalar fields in BH background
3. Lighthouses in the sky – scalar clouds around black holes
4. Summary and Outlook

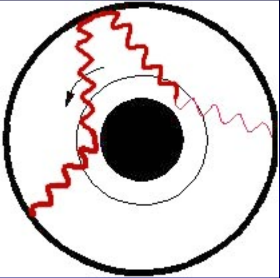
Superradiant scattering and the BH bomb

- superradiant scattering (Misner '72, Zeldovich '71):
  - scattering of wave packet off Kerr BH
  - superradiance condition

$$0 < \omega_R < m\Omega_H = m\frac{a}{2Mr_+}$$

$\Rightarrow$ amplification of wave packet

$\Rightarrow$ extraction of energy and angular momentum off BH



credit: A. Sousa

- "Black Hole bomb"
  (Press & Teukolsky '72, Zeldovich '71, Cardoso et al '04, Rosa '10, Dolan '12, ...)
  - Kerr BH enclosed by mirror
  - multiple scattering

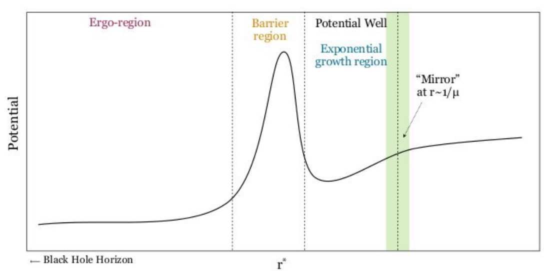
  $\Rightarrow$ exponential growth of modes

  $\Rightarrow$ destruction of mirror – "BH bomb"

Superradiant instability in physical systems

natural mirror provided by

- anti-de Sitter spacetimes (Hawking & Reall '00, Cardoso & Dias '04, ...)
- fields with mass μ (Damour et al. '76, Detweiler '80, Zouros & Eardley '79, ...)
  $\Rightarrow$ "mirror" if: $\omega_R \lesssim \mu$



Arvanitaki & Dubovsky '11

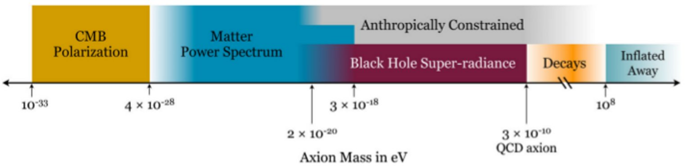
- most promising mass coupling: $M\mu \sim 1/2$
- for astrophysical BHs and known standard-model particles: $M\mu \sim 10^{18}$

$$\tau \sim 10^7 \exp(1.84 M\mu) \left(\frac{GM}{c^3}\right) \quad \text{(Zouros \& Eardley '79)}$$

$\Rightarrow$ insignificant for astrophysical systems?

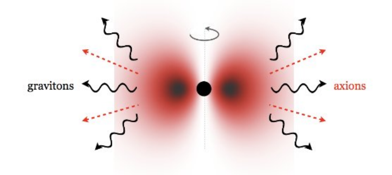
Superradiance instability in physical systems

- candidates:
  - QCD axion with $\mu_a \sim 6 \cdot 10^{-10} eV \left(\frac{10^{16}\mathrm{GeV}}{f_a}\right)$
    (proposed to solve stong CP problem in QCD (Peccei & Quinn '77))
  - ultralight bosons emerging in string theory compactification
    $\Rightarrow$ plethora of ultralight axion-like particles
    $\Rightarrow$ "string axiverse" with $10^{-33} eV \leq \mu \leq 10^{-10} eV$
    (Arvanitaki & Dubovsky '10, '11, Kodama & Yoshino '11)
- bosonic clouds around BHs ($3M_\odot \lesssim M \lesssim 10^9 M_\odot$) if $10^{-21} eV \leq \mu \leq 10^{-8} eV$



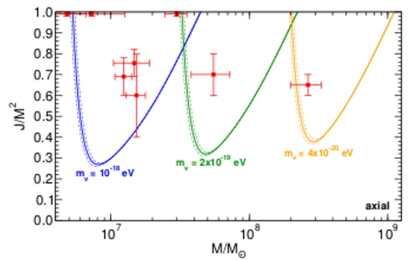
(Arvanitaki et al '10)

Superradiance instability in physical systems



- formation of bound states around BHs
  $\Rightarrow$ "gravitational atom"
- graviton emission from axion cloud
- modified gravitational wave emission
- "gravitational wave pulsar"

- gaps in Regge plot
  $\Rightarrow$ probe of photon mass:
  upper bound $\mu_\gamma \sim 10^{-20} eV$
  (Pani et al'12)
- non-linear self-interaction
  $\Rightarrow$ "bosenova"-like particle bursts
  (Yoshino & Kodama '12)



Pani et al '12

$\Rightarrow$ study beyond-SM particles by precision BH physics

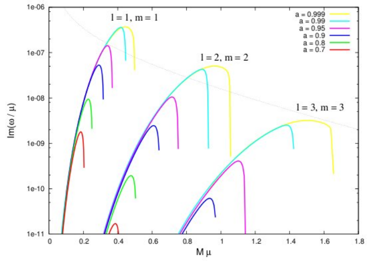
Scalar clouds around black holes

Massive scalar fields - what do we know?

- Klein-Gordon equation (in fixed Kerr background)

$$(\Box - \mu^2)\Phi = 0\,, \quad \text{with} \quad \Phi = \exp(-\imath\omega t)\exp(\imath m\phi) S_{lm}(\theta) R_{lm}(r)$$

solutions: quasi-normal modes or bound states



Dolan '07

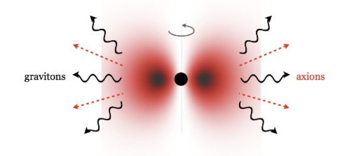
- frequency domain:
  maximum instability growth rate for bound states with
  (Dolan '07, Cardoso & Yoshida '05, Berti et al '09)

$$l = m = 1\,, \quad a/M = 0.99\,, \quad M\mu = 0.42:$$

$$\frac{1}{\tau} = \omega_I \sim 1.5 \cdot 10^{-7} \left(\frac{GM}{c^3}\right)^{-1}$$

- time domain:
  - Strafuss & Khanna '05 (Gaussian initial data): $M\omega_I \sim 2 \cdot 10^{-5}$
  - Kodama & Yoshino '12 (bound state initial data): $M\omega_I \sim 3.2 \cdot 10^{-7}$
  - Dolan '12, Witek et al '12 (Gaussian initial data): $M\omega_I \sim 1.5 \cdot 10^{-7}$, beating and space dependent mode excitation

Scalar clouds around black holes



Arvanitaki et al '10

- in dynamical regime – final state?
- "BH bomb" vs. gravitational atom?
- emission of scalar and gravitational waves?
  $\Rightarrow$ include backreaction onto spacetime

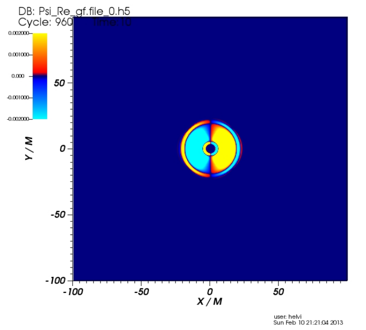
- consider full GR - scalar field system

$$^{(4)}G_{\mu\nu} + 4\pi\left[g_{\mu\nu}\left(\Phi^{*}_{,\lambda}\Phi^{,\lambda} + \mu_S^2\Phi^*\Phi + 2V\right) - 2\partial_{(\mu}\Phi^*\partial_{\nu)}\Phi\right] = 0\,,$$
$$(\Box - \mu_S^2)\Phi = 0$$

- formulation as time evolution problem $\Rightarrow$ solve numerically

Scalar cloud around Schwarzschild – Setup

- consider Schwarzschild BH and scalar field with $\mu = 0.0$ or $\mu = 0.42$
- initialize scalar field as Gaussian wave packet
  $\Pi_0 \sim \exp\left(-\frac{(r-r_0)^2}{w^2}\right) \sum_{lm} Y_{lm}(\theta, \varphi)$

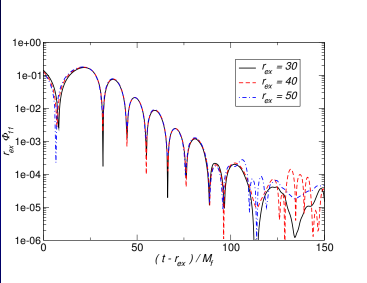


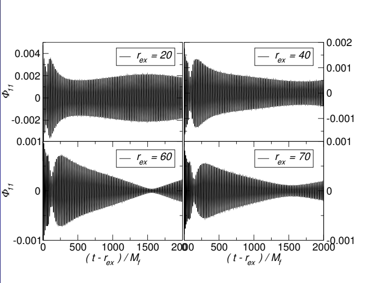
Evolution of a scalar field with $\mu = 0.42$, $r_0 = 12$, $w = 0.5$, $Y = Y_{1-1} - Y_{11}$

Scalar cloud around Schwarzschild – Results I

Time evolution of $l = m = 1$ mode of scalar field Φ

$\mu = 0.0$, $(M\omega_{11} = 0.291 - \imath 0.095)$ $\mu = 0.42$





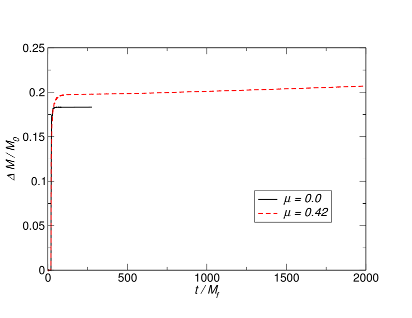
- beating between overtone modes $\omega_{R,1} = \omega_{R,0} + \delta_{10}$, $\delta_{10} \ll 1$

$$\psi \sim (A_0 - A_1)\sin(\omega_{R,0} t) + A_1 \sin(\omega_{R,0} t)\cos(\delta_{10}/2t)$$

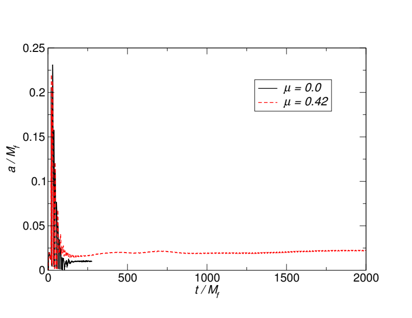
- variation of modulation with location of measurement
  $\Rightarrow$ space dependent excitation of modes
- good agreement with linear evolutions (Dolan '12, Witek et al '12)

Scalar cloud around Schwarzschild – Results II

relative AH mass



spin a/M



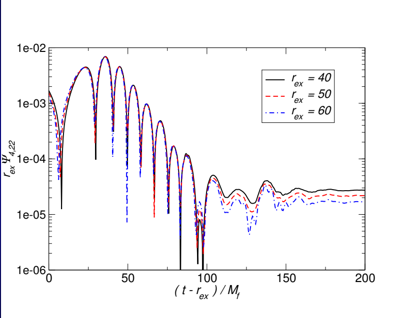
- increase in AH horizon mass
- $\mu = 0.0$: $\Delta M/M_0 = 18.3\%$
- $\mu = 0.42$: $\Delta M/M_0 = 20.9\%$ (after $t \sim 2000M$)

- $\mu = 0.0$: $a_{\max}/M \sim 0.20$
  $\mu = 0.42$: $a_{\max}/M \sim 0.19$
- settles down to Kerr BH with larger mass and small spin

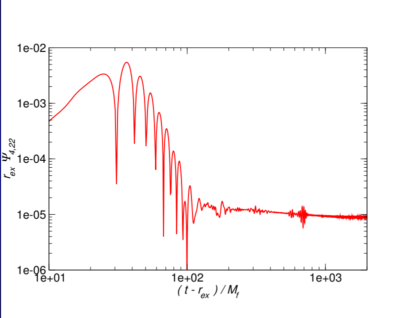
Scalar cloud around Schwarzschild – Results III

time evolution of $l = 2, m = 2$ mode of Newman Penrose scalar Ψ_4

$\mu = 0.0$



$\mu = 0.42$



- quasi-normal ringdown with $M\omega = 0.361 - \imath 0.083$
- settles down to Schwarzschild BH

- quasi-normal ringdown with $M\omega = 0.371 - \imath 0.084$
- long-lived GW emission with $\Psi_{4,22} \sim t^{-0.25} \sin(0.823t)$

Summary and Outlook

- access beyond SM particle physics through precision BH physics
- consider Schwarzschild BH and scalar field with $\mu = 0$
  - absorption of SF by BH
  - QN ringdown measured in GW and scalar field
- consider Schwarzschild BH and scalar with $\mu = 0.42$
  - scalar cloud around BH
  - long-lived, slowly decaying scalar modes
  - beating and space dependent mode excitation
  - long-lived GW with $\omega \sim \mathit{const}$.
- "final" state: Kerr BH with larger mass and small spin

ToDo:

- extension to Kerr BH coupled to scalar field
- final state of superradiant instability in dynamical regime
- astrophysical implications?

Thank you

http://blackholes.ist.utl.pt