Title: Geons, black holes, and all that Jazz

Date: May 02, 2015 02:00 PM

URL: http://pirsa.org/15050144

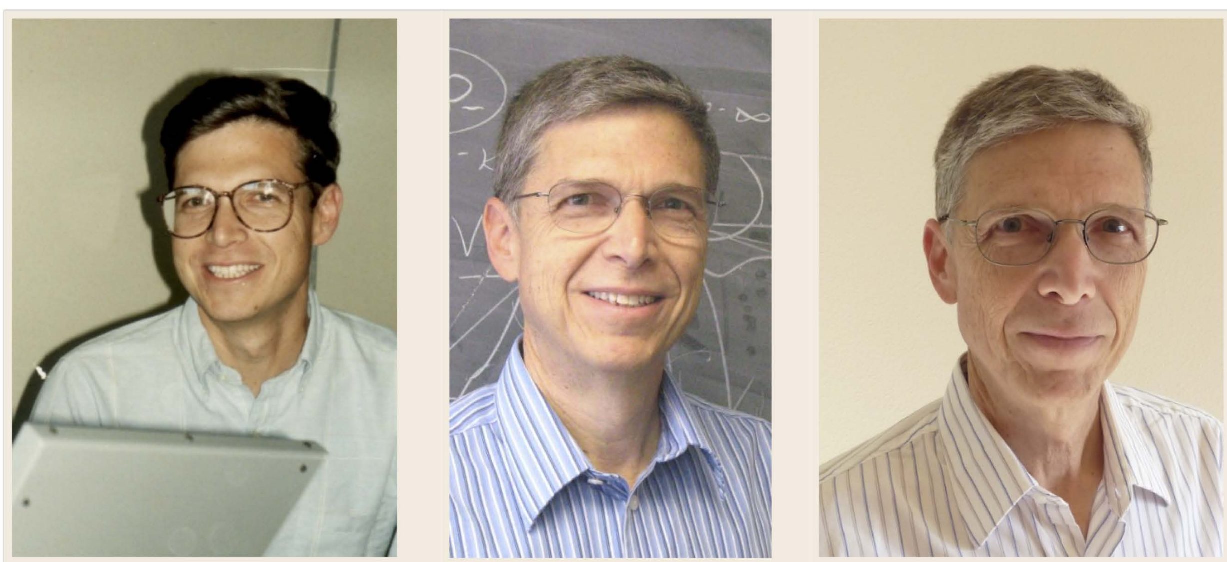
Abstract:

Geons, black holes, and all that Jazz

Jorge E. Santos

Cambridge University - DAMTP

GaryFest - Adventures with G



In collaboration with

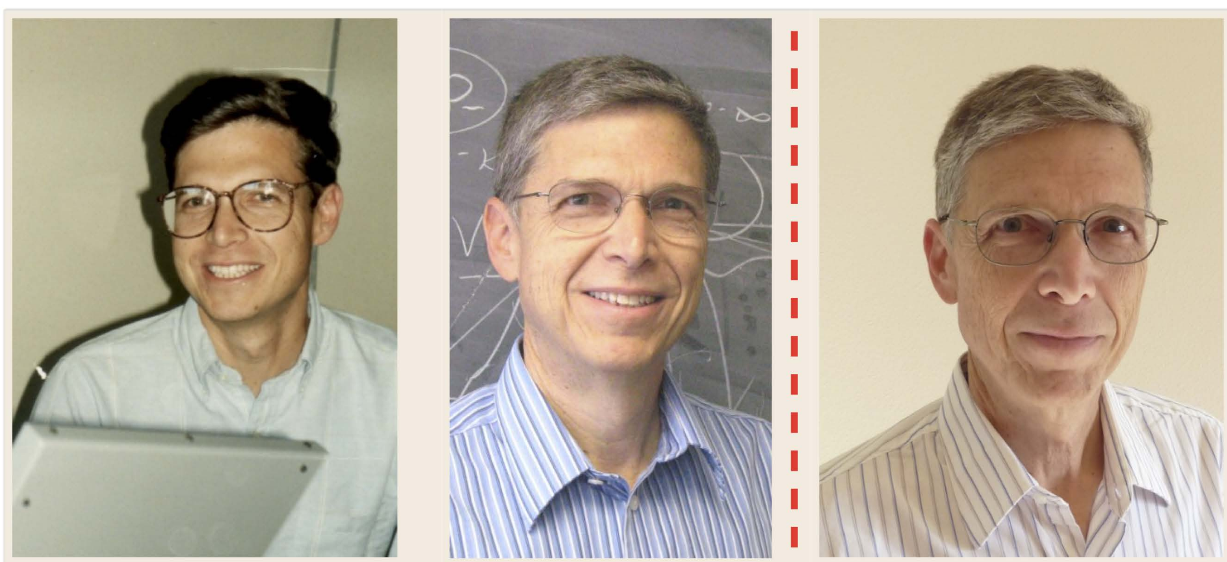
Óscar J. C. Dias (Southampton), and Benson Way (DAMTP)

Geons, black holes, and all that Jazz

Jorge E. Santos

Cambridge University - DAMTP

GaryFest - Adventures with G



In collaboration with

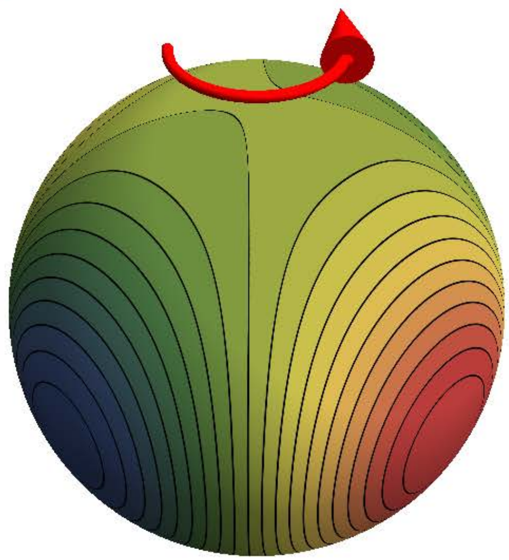
Óscar J. C. Dias (Southampton), and Benson Way (DAMTP)

Geons, black holes, and all that Jazz

Jorge E. Santos

Cambridge University - DAMTP

GaryFest - Adventures with G



In collaboration with

Óscar J. C. Dias (Southampton), and Benson Way (DAMTP)

Motivation

1. Spoiler alert:

Motivation

1. Spoiler alert:
   a. Construct novel black holes solutions in AdS_4.

Motivation

1. Spoiler alert:
   - a. Construct novel black holes solutions in AdS_4.
   - b. Evade Hawking's rigidity theorem - Hollands and Ishibashi 12' - only have one KVF.

Motivation

1. Spoiler alert:
   a. Construct novel black holes solutions in AdS_4.
   b. Evade Hawking's rigidity theorem - Hollands and Ishibashi 12' - only have one KVF.
2. The AdS/CFT correspondence maps asymptotically AdS solutions of the Einstein equation to states of a dual conformal field theory.

Motivation

1. Spoiler alert:

   a. Construct novel black holes solutions in AdS_4.
   b. Evade Hawking's rigidity theorem - Hollands and Ishibashi 12' - only have one KVF.

2. The AdS/CFT correspondence maps asymptotically AdS solutions of the Einstein equation to states of a dual conformal field theory.

   - Since these new solutions contain gravity only, they lie in the universal sector of the correspondence:

Motivation

1. Spoiler alert:
   - a Construct novel black holes solutions in AdS_4.
   - b Evade Hawking's rigidity theorem - Hollands and Ishibashi 12' - only have one KVF.
2. The AdS/CFT correspondence maps asymptotically AdS solutions of the Einstein equation to states of a dual conformal field theory.
   - Since these new solutions contain gravity only, they lie in the universal sector of the correspondence:

$$R_{ab} = -\frac{3}{L^2} g_{ab} \,.$$

Motivation

1. Spoiler alert:
   - a Construct novel black holes solutions in AdS_4.
   - b Evade Hawking's rigidity theorem - Hollands and Ishibashi 12' - only have one KVF.
2. The AdS/CFT correspondence maps asymptotically AdS solutions of the Einstein equation to states of a dual conformal field theory.
   - Since these new solutions contain gravity only, they lie in the universal sector of the correspondence:

$$R_{ab} = -\frac{3}{L^2} g_{ab}\,.$$

Gary has done extensive work on this subject in the past, and we are celebrating his birthday!

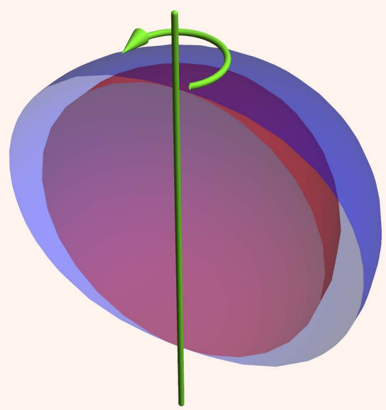
Superradiance

Superradiance - 1/2

- Rotating black holes can have ergoregions, which can act as negative energy reservoirs for particles.

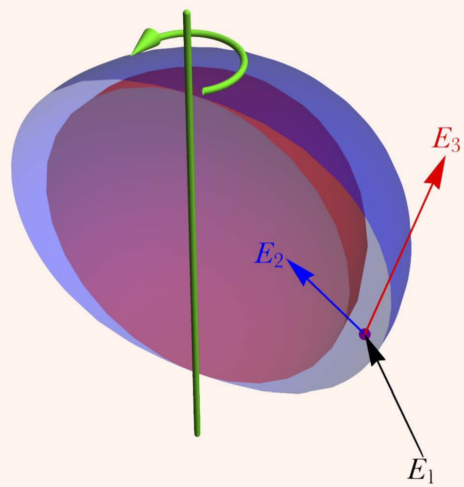
Superradiance - 1/2

- Rotating black holes can have ergoregions, which can act as negative energy reservoirs for particles.



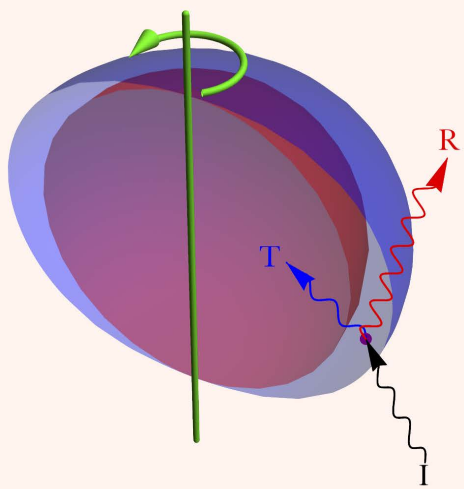
Superradiance - 1/2

- Rotating black holes can have ergoregions, which can act as negative energy reservoirs for particles - Penrose Process (*aka* the Santa-Horowitz triality) - $E_3 > E_1$.



Superradiance - 1/2

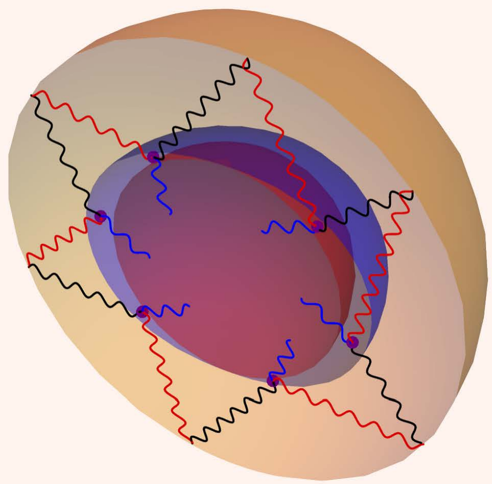
- Rotating black holes can have ergoregions, which can act as negative energy reservoirs for particles.



- The wave analog is coined Superradiance : $|R| > |I|$.

Superradiance instability - 1/3

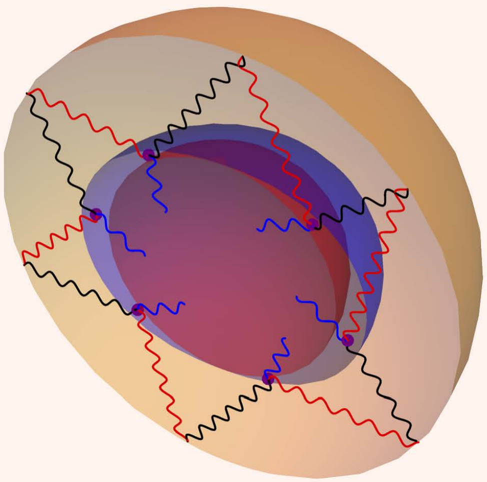
- Rotating black holes can have ergoregions, which can act as negative energy reservoirs for particles.



- The wave analog is coined Superradiance : $|R| > |I|$.
- In AdS, or inside a closed Dirichlet-Wall, the waves bounce back and the process repeats itself ad eternum.

Superradiance instability - 1/3

- Rotating black holes can have ergoregions, which can act as negative energy reservoirs for particles.



- The wave analog is coined Superradiance : $|R| > |I|$.
- In AdS, or inside a closed Dirichlet-Wall, the waves bounce back and the process repeats itself ad eternum.

Superradiance instability

Superradiance Instability - 2/3:

- The Kerr-AdS$_4$ black hole (aka Carter solution):

$$ds^2 = -\frac{\Delta_r}{r^2+x^2}\left[dt-(1-x^2)d\phi\right]^2+\frac{\Delta_x}{r^2+x^2}\left[dt-(1+r^2)d\phi\right]^2 + (r^2+x^2)\left(\frac{dr^2}{\Delta_r}+\frac{dx^2}{\Delta_x}\right),$$

where

$$\Delta_r = (1+r^2)\left(1+\frac{a^2}{L^2}r^2\right)-\frac{2M}{a}r\,, \quad \Delta_x = (1-x^2)\left(1-\frac{a^2}{L^2}x^2\right).$$

Superradiance Instability - 2/3:

- The Kerr-AdS$_4$ black hole (aka Carter solution):

$$ds^2 = -\frac{\Delta_r}{r^2+x^2}\left[\mathrm{d}t-(1-x^2)\mathrm{d}\phi\right]^2+\frac{\Delta_x}{r^2+x^2}\left[\mathrm{d}t-(1+r^2)\mathrm{d}\phi\right]^2 + (r^2+x^2)\left(\frac{\mathrm{d}r^2}{\Delta_r}+\frac{\mathrm{d}x^2}{\Delta_x}\right),$$

where

$$\Delta_r = (1+r^2)\left(1+\frac{a^2}{L^2}r^2\right)-\frac{2M}{a}r,\quad \Delta_x=(1-x^2)\left(1-\frac{a^2}{L^2}x^2\right).$$

- 2 parameters: (M,a).

Superradiance Instability - 2/3:

- The Kerr-AdS$_4$ black hole (aka Carter solution):

$$ds^2 = -\frac{\Delta_r}{r^2+x^2}\left[dt-(1-x^2)d\phi\right]^2+\frac{\Delta_x}{r^2+x^2}\left[dt-(1+r^2)d\phi\right]^2 + (r^2+x^2)\left(\frac{dr^2}{\Delta_r}+\frac{dx^2}{\Delta_x}\right),$$

  where

$$\Delta_r=(1+r^2)\left(1+\frac{a^2}{L^2}r^2\right)-\frac{2M}{a}r\,,\quad \Delta_x=(1-x^2)\left(1-\frac{a^2}{L^2}x^2\right).$$

- 2 parameters: $(M,a)\Leftrightarrow(R_+,\Omega_H)$.

Superradiance Instability - 2/3:

- The Kerr-AdS$_4$ black hole (aka Carter solution):

$$ds^2 = -\frac{\Delta_r}{r^2+x^2}\left[dt-(1-x^2)d\phi\right]^2+\frac{\Delta_x}{r^2+x^2}\left[dt-(1+r^2)d\phi\right]^2 + (r^2+x^2)\left(\frac{dr^2}{\Delta_r}+\frac{dx^2}{\Delta_x}\right),$$

  where

$$\Delta_r = (1+r^2)\left(1+\frac{a^2}{L^2}r^2\right)-\frac{2M}{a}r,\quad \Delta_x=(1-x^2)\left(1-\frac{a^2}{L^2}x^2\right).$$

- 2 parameters: $(M, a) \Leftrightarrow (R_+, \Omega_H)$:
  - $T_H \geq 0 \Rightarrow |\Omega_H L| \leq \sqrt{\frac{L^4+4L^2R_+^2+3R_+^4}{2L^2R_+^2+3R_+^4}} \underset{R_+\to+\infty}{\longrightarrow} 1.$

Superradiance Instability - 2/3:

- The Kerr-AdS$_4$ black hole (aka Carter solution):

$$ds^2 = -\frac{\Delta_r}{r^2+x^2}\left[dt-(1-x^2)d\phi\right]^2+\frac{\Delta_x}{r^2+x^2}\left[dt-(1+r^2)d\phi\right]^2 + (r^2+x^2)\left(\frac{dr^2}{\Delta_r}+\frac{dx^2}{\Delta_x}\right),$$

where

$$\Delta_r=(1+r^2)\left(1+\frac{a^2}{L^2}r^2\right)-\frac{2M}{a}r,\quad \Delta_x=(1-x^2)\left(1-\frac{a^2}{L^2}x^2\right).$$

- 2 parameters: $(M,a)\Leftrightarrow(R_+,\Omega_H)$:
  - $T_H\geq 0\Rightarrow|\Omega_H L|\leq\sqrt{\frac{L^4+4L^2R_+^2+3R_+^4}{2L^2R_+^2+3R_+^4}}\xrightarrow[R_+\to+\infty]{}1.$
- ∂_t and ∂_ϕ are commuting Killing fields; decompose perturbations in Fourier modes: $e^{-i\omega t+im\phi}$.

Superradiance Instability - 2/3:

- The Kerr-AdS$_4$ black hole (aka Carter solution):

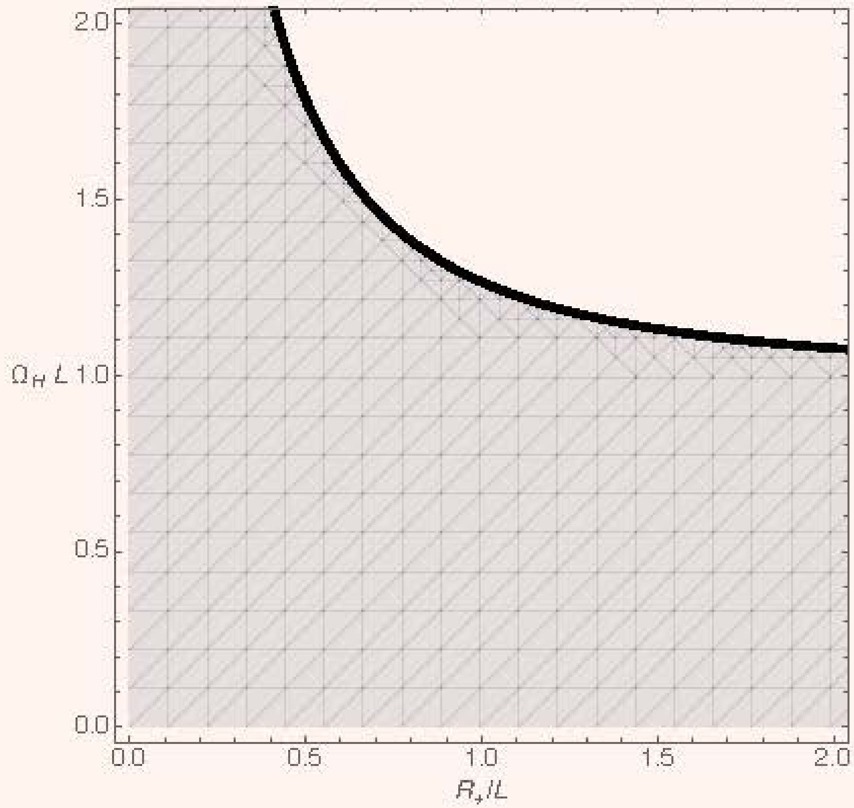
$$ds^2 = -\frac{\Delta_r}{r^2+x^2}\left[dt - (1-x^2)d\phi\right]^2 + \frac{\Delta_x}{r^2+x^2}\left[dt - (1+r^2)d\phi\right]^2 + (r^2+x^2)\left(\frac{dr^2}{\Delta_r} + \frac{dx^2}{\Delta_x}\right),$$

where

$$\Delta_r = (1+r^2)\left(1+\frac{a^2}{L^2}r^2\right) - \frac{2M}{a}r\,,\quad \Delta_x = (1-x^2)\left(1-\frac{a^2}{L^2}x^2\right).$$

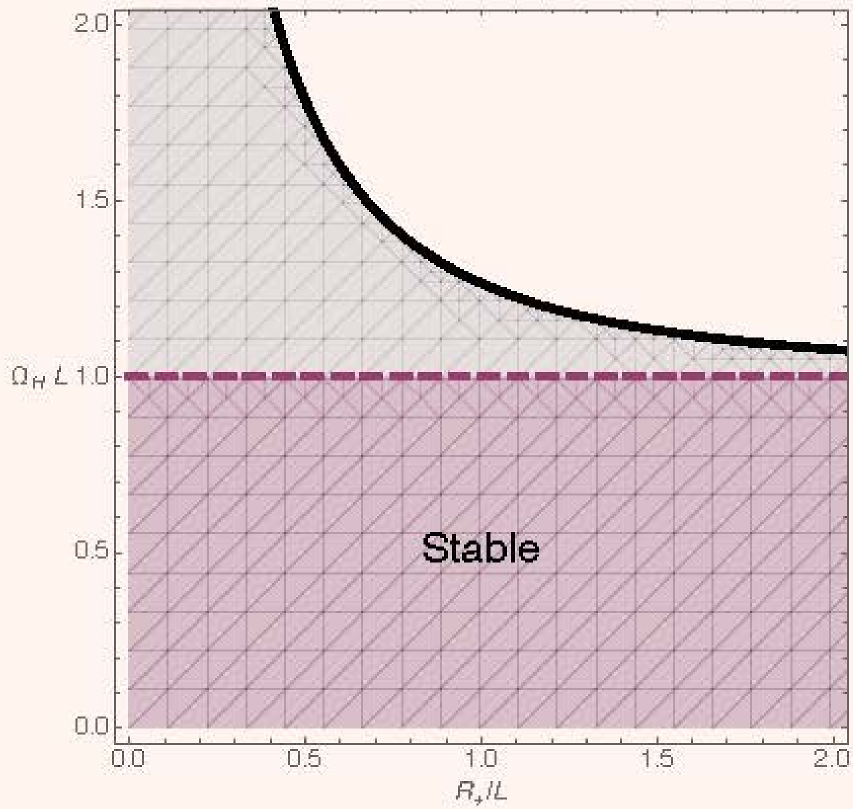
- 2 parameters: $(M, a) \Leftrightarrow (R_+, \Omega_H)$:
  - $T_H \geq 0 \Rightarrow |\Omega_H L| \leq \sqrt{\frac{L^4+4L^2R_+^2+3R_+^4}{2L^2R_+^2+3R_+^4}} \underset{R_+\to+\infty}{\longrightarrow} 1.$
- ∂_t and ∂_ϕ are commuting Killing fields; decompose perturbations in Fourier modes: $e^{-i\omega t + i m\phi}$.
- Unstable if quasi-normal modes with $\mathrm{Im}(\omega) > 0$ exist.

Superradiance Instability - 3/3:



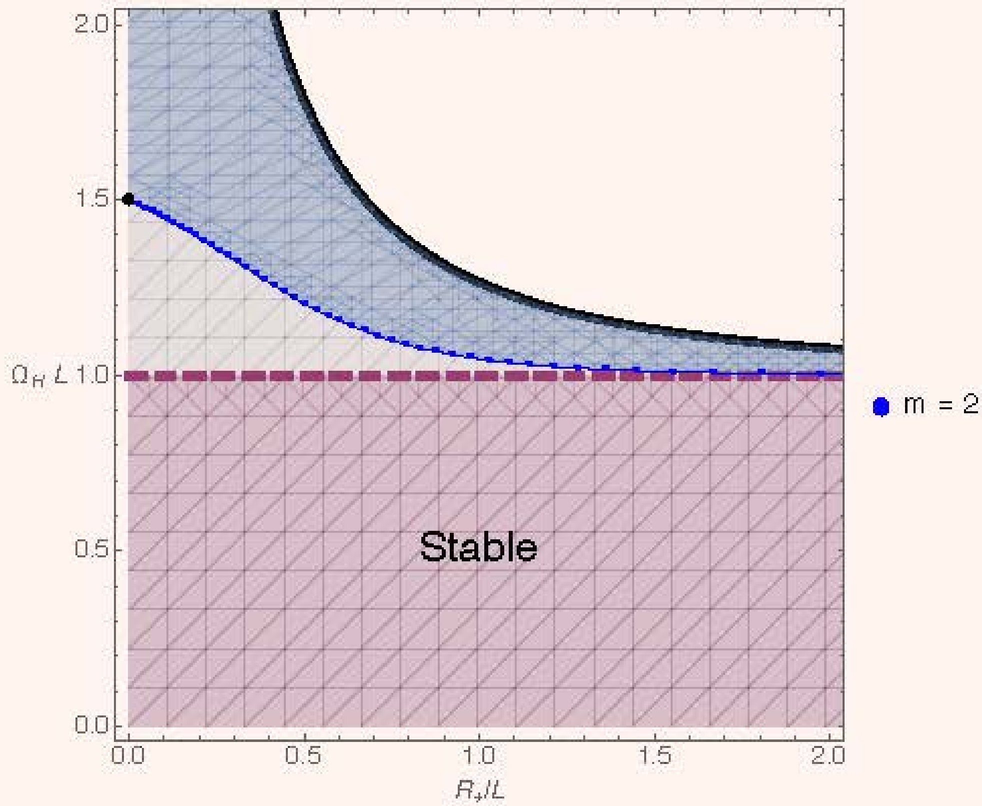
Phase Diagram for Kerr-AdS black holes

Superradiance Instability - 3/3:



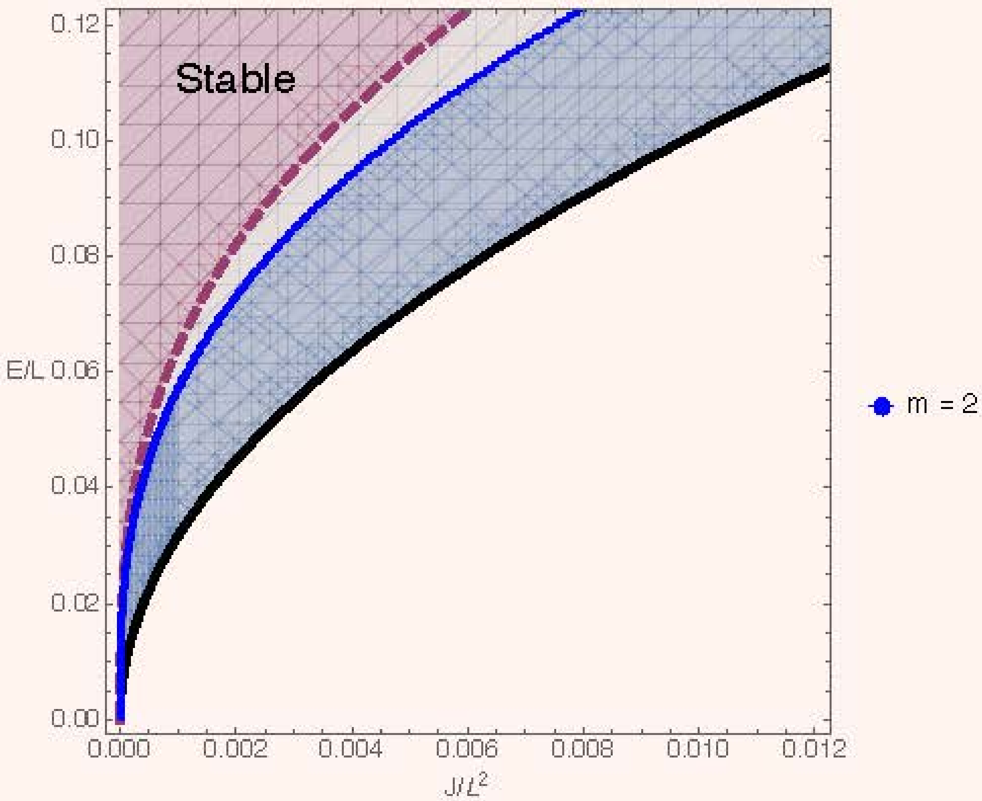
Kerr-AdS with $|\Omega_H L| \leq 1$:
likely to be stable - Hawking and Reall '00.

Superradiance Instability - 3/3:



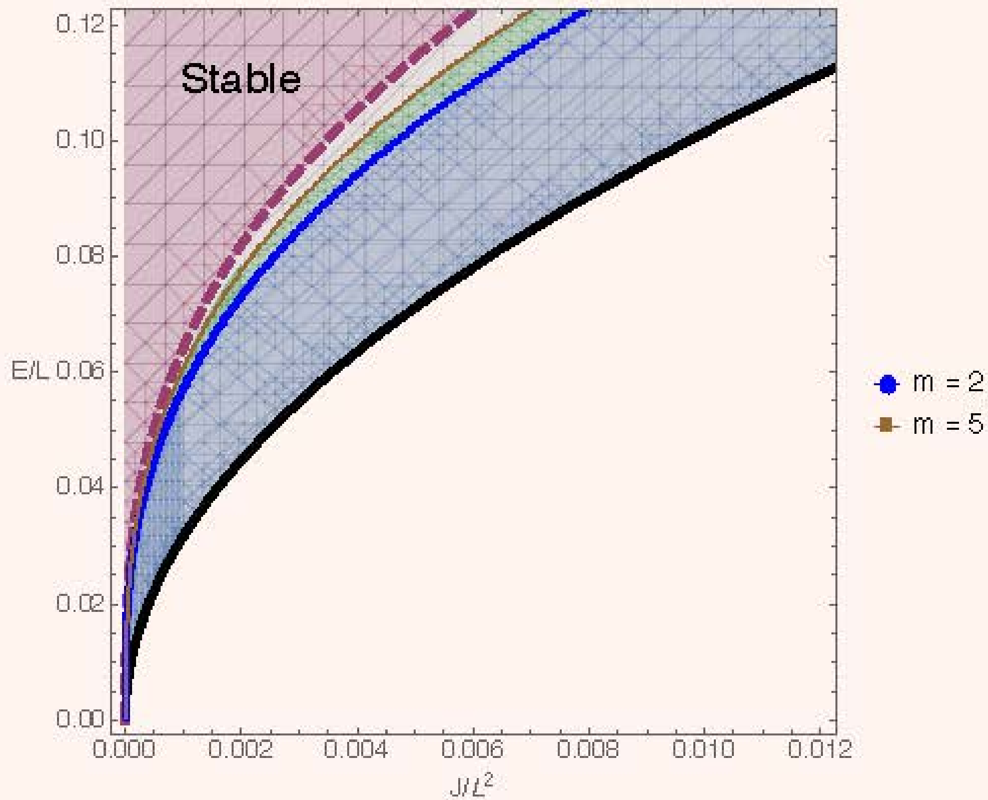
Perturbations with $m \neq 0$ are unstable if $\mathrm{Re}(\omega) \leq m\Omega_H$: onset saturates inequality - Cardoso et al. '14.

Superradiance Instability - 3/3:



In the microcanonical ensemble:
natural variables are (J, E).

Superradiance Instability - 3/3:



Higher m modes appear closer to $\Omega_H L = 1$:
$\Omega_H L = 1$ is reached $m \to +\infty$ - Kunduri et. al. '06.

The nonlinear stability of AdS

The stability problem for spacetimes in general relativity

The question

Consider a spacetime $(\mathcal{M}, g)$, together with prescribed boundary conditions $\mathcal{B}$ if timelike boundary exists.

The stability problem for spacetimes in general relativity

The question

Consider a spacetime $(\mathcal{M}, g)$, together with prescribed boundary conditions $\mathcal{B}$ if timelike boundary exists.

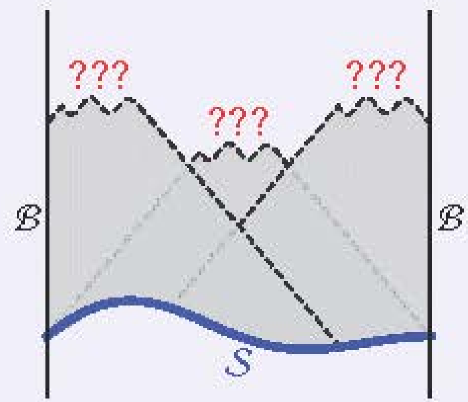
- Take small perturbations (in a suitable sense) on a Cauchy surface $\mathcal{S}$.

The stability problem for spacetimes in general relativity

The question

Consider a spacetime $(\mathcal{M}, g)$, together with prescribed boundary conditions $\mathcal{B}$ if timelike boundary exists.

- Take small perturbations (in a suitable sense) on a Cauchy surface $\mathcal{S}$.
- Does the solution spacetime $(\mathcal{M}, g')$ that arises still has the same asymptotic causal structure as $(\mathcal{M}, g)$?

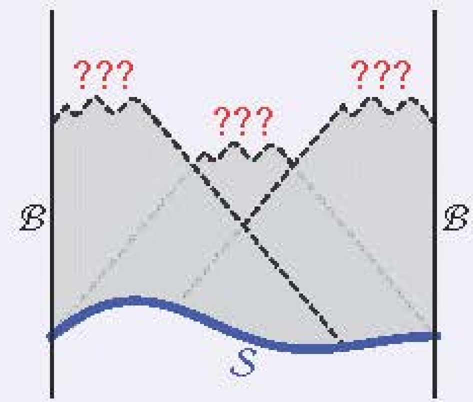


The stability problem for spacetimes in general relativity

The question

Consider a spacetime $(\mathcal{M}, g)$, together with prescribed boundary conditions $\mathcal{B}$ if timelike boundary exists.

- Take small perturbations (in a suitable sense) on a Cauchy surface $\mathcal{S}$.
- Does the solution spacetime $(\mathcal{M}, g')$ that arises still has the same asymptotic causal structure as $(\mathcal{M}, g)$?
- If so, can we bound the "difference" between the asymptotic form of g and g' in terms of initial data defined on $\mathcal{S}$?

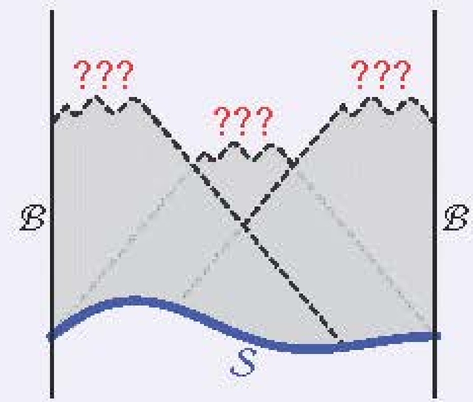


The stability problem for spacetimes in general relativity

The question

Consider a spacetime $(\mathcal{M}, g)$, together with prescribed boundary conditions $\mathcal{B}$ if timelike boundary exists.

- Take small perturbations (in a suitable sense) on a Cauchy surface $\mathcal{S}$.
- Does the solution spacetime $(\mathcal{M}, g')$ that arises still has the same asymptotic causal structure as $(\mathcal{M}, g)$?
- If so, can we bound the "difference" between the asymptotic form of g and g' in terms of initial data defined on $\mathcal{S}$?



In particular, if a geodesically complete spacetime is perturbed, does it remain "complete"?

Minkowski, dS and AdS spacetimes

- At the linear level, Anti de-Sitter spacetime appears just as stable as the Minkowski or de-Sitter spacetimes.

Minkowski, dS and AdS spacetimes

- At the linear level, Anti de-Sitter spacetime appears just as stable as the Minkowski or de-Sitter spacetimes.
- For the Minkowski and de-Sitter spacetimes, it has been shown that small, but finite, perturbations remain small - D. Christodoulou and S. Klainerman '93 and Friedrich '86.

Minkowski, dS and AdS spacetimes

- At the linear level, Anti de-Sitter spacetime appears just as stable as the Minkowski or de-Sitter spacetimes.
- For the Minkowski and de-Sitter spacetimes, it has been shown that small, but finite, perturbations remain small - D. Christodoulou and S. Klainerman '93 and Friedrich '86.
- Why has this not been shown for Anti de-Sitter?

Minkowski, dS and AdS spacetimes

- At the linear level, Anti de-Sitter spacetime appears just as stable as the Minkowski or de-Sitter spacetimes.
- For the Minkowski and de-Sitter spacetimes, it has been shown that small, but finite, perturbations remain small - D. Christodoulou and S. Klainerman '93 and Friedrich '86.
- Why has this not been shown for Anti de-Sitter?
  - It is just *not* true!

Minkowski, dS and AdS spacetimes

- At the linear level, Anti de-Sitter spacetime appears just as stable as the Minkowski or de-Sitter spacetimes.
- For the Minkowski and de-Sitter spacetimes, it has been shown that small, but finite, perturbations remain small - D. Christodoulou and S. Klainerman '93 and Friedrich '86.
- Why has this not been shown for Anti de-Sitter?
  - It is just *not* true!

Claim:

Some generic small (but finite) perturbations of AdS become large and eventually form black holes.

Minkowski, dS and AdS spacetimes

- At the linear level, Anti de-Sitter spacetime appears just as stable as the Minkowski or de-Sitter spacetimes.
- For the Minkowski and de-Sitter spacetimes, it has been shown that small, but finite, perturbations remain small - D. Christodoulou and S. Klainerman '93 and Friedrich '86.
- Why has this not been shown for Anti de-Sitter?
  - It is just *not* true!

Claim:

Some generic small (but finite) perturbations of AdS become large and eventually form black holes.

- The energy cascades from low to high frequency modes in a manner reminiscent of the onset of turbulence.

Heuristics

- AdS acts like a confining finite box. Any generic finite excitation which is added to this box might be expected to explore all configurations consistent with the conserved charges of AdS - including small black holes.

Heuristics

- AdS acts like a confining finite box. Any generic finite excitation which is added to this box might be expected to explore all configurations consistent with the conserved charges of AdS - including small black holes.
- Special (fine tuned) solutions need not lead to the formation of black holes.

Heuristics

- AdS acts like a confining finite box. Any generic finite excitation which is added to this box might be expected to explore all configurations consistent with the conserved charges of AdS - including small black holes.
- Special (fine tuned) solutions need not lead to the formation of black holes.
  - Some linearized gravitational *modes* will have corresponding nonlinear solutions - Geons - Dias, Horowitz and JES.

Heuristics

- AdS acts like a confining finite box. Any generic finite excitation which is added to this box might be expected to explore all configurations consistent with the conserved charges of AdS - including small black holes.
- Special (fine tuned) solutions need not lead to the formation of black holes.
  - Some linearized gravitational *modes* will have corresponding nonlinear solutions - Geons - Dias, Horowitz and JES.
  - These solutions are special since they are exactly periodic in time and invariant under a single continuous symmetry.

Heuristics

- AdS acts like a confining finite box. Any generic finite excitation which is added to this box might be expected to explore all configurations consistent with the conserved charges of AdS - including small black holes.
- Special (fine tuned) solutions need not lead to the formation of black holes.
    - Some linearized gravitational *modes* will have corresponding nonlinear solutions - Geons - Dias, Horowitz and JES.
    - These solutions are special since they are exactly periodic in time and invariant under a single continuous symmetry.
    - Geons are analogous to nonlinear gravitational plane waves.

Heuristics

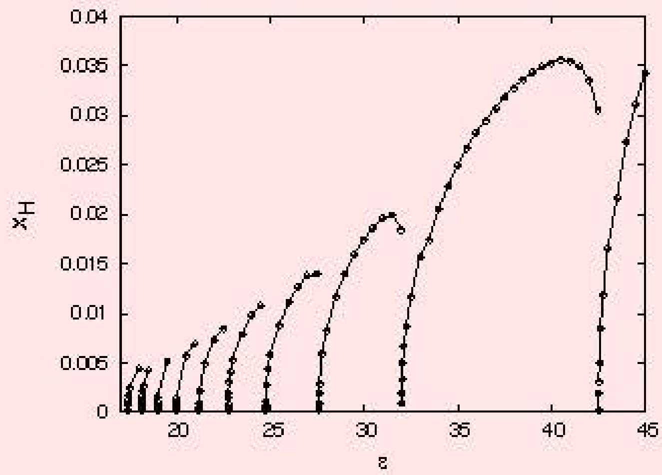
- AdS acts like a confining finite box. Any generic finite excitation which is added to this box might be expected to explore all configurations consistent with the conserved charges of AdS - including small black holes.
- Special (fine tuned) solutions need not lead to the formation of black holes.
  - Some linearized gravitational *modes* will have corresponding nonlinear solutions - Geons - Dias, Horowitz and JES.
  - These solutions are special since they are exactly periodic in time and invariant under a single continuous symmetry.
  - Geons are analogous to nonlinear gravitational plane waves.
- This Heuristic argument has been observed numerically for certain types of initial data, but fails for other types.

What has been observed:

- Spherical scalar field collapse in AdS - Bizon and Rostworowski.

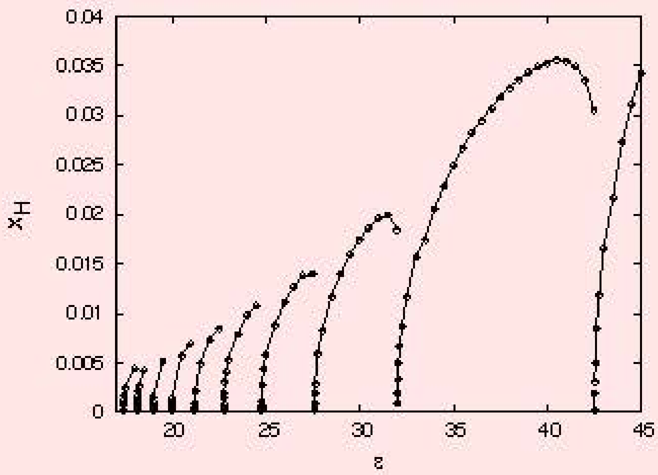
What has been observed:

- Spherical scalar field collapse in AdS - Bizon and Rostworowski.
- No matter how small the initial energy, the curvature at the origin grows and eventually forms a black hole.



What has been observed:

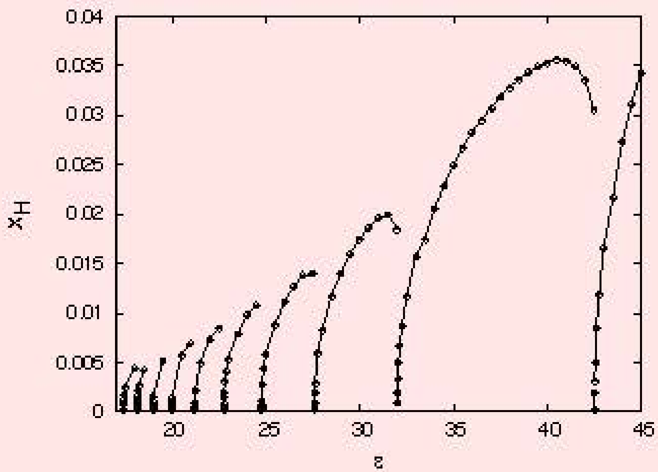
- Spherical scalar field collapse in AdS - Bizon and Rostworowski.
- No matter how small the initial energy, the curvature at the origin grows and eventually forms a black hole.



- Black holes form: $\Delta t \propto \varepsilon^{-2}$, matches naïve KAM intuition and $3^{\rm rd}$ order calculation - Dias, Horowitz and JES.

What has been observed:

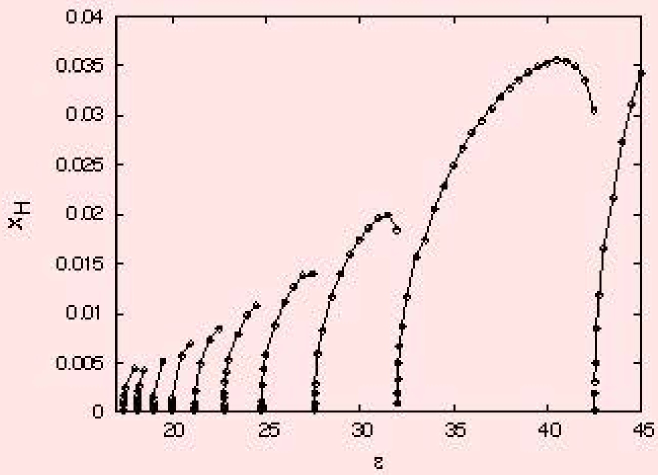
- Spherical scalar field collapse in AdS - Bizon and Rostworowski.
- No matter how small the initial energy, the curvature at the origin grows and eventually forms a black hole.



- Black holes form: $\Delta t \propto \varepsilon^{-2}$, matches naïve KAM intuition and $3^{\rm rd}$ order calculation - Dias, Horowitz and JES.
- Certain types of initial data do not do this: do not seem to form black holes at late times! - Balasubramanian et. al.

What has been observed:

- Spherical scalar field collapse in AdS - Bizon and Rostworowski.
- No matter how small the initial energy, the curvature at the origin grows and eventually forms a black hole.



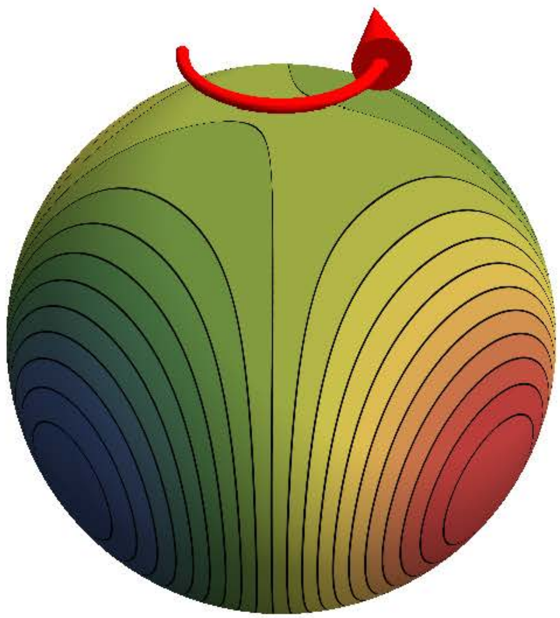
- Black holes form: $\Delta t \propto \varepsilon^{-2}$, matches naïve KAM intuition and 3^{rd} order calculation - Dias, Horowitz and JES.
- Certain types of initial data do not do this: do not seem to form black holes at late times! - Balasubramanian et. al.
- Understand why special fine tuned solutions - Geons - exist.

Geons - Horowitz and Santos 2014

- Geons are regular horizonless solutions of the Einstein equation, which from the QFT perspective do not seem to thermalize.

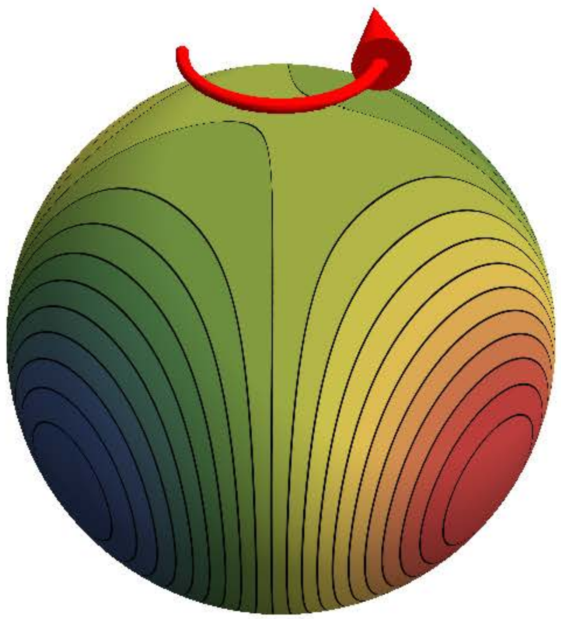
Geons - Horowitz and Santos 2014

- Geons are regular horizonless solutions of the Einstein equation, which from the QFT perspective do not seem to thermalize.
- The boundary stress-tensor contains regions of negative and positive energy density around the equator:



Geons - Horowitz and Santos 2014

- Geons are regular horizonless solutions of the Einstein equation, which from the QFT perspective do not seem to thermalize.
- The boundary stress-tensor contains regions of negative and positive energy density around the equator:



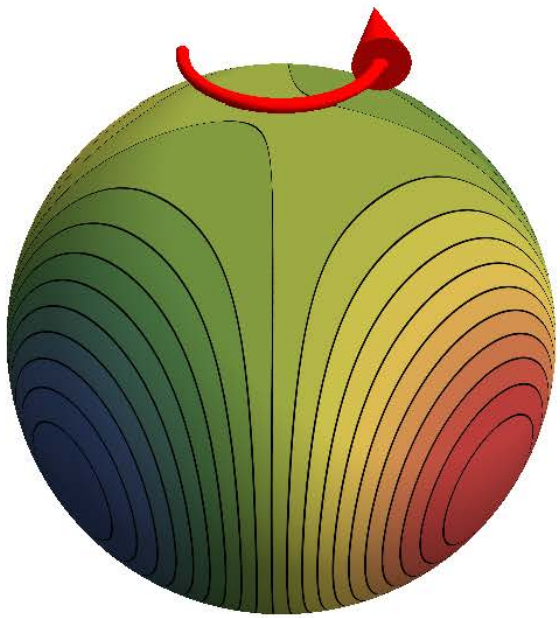
- It is invariant under

$$K = \frac{\partial}{\partial t} + \frac{\omega}{m}\frac{\partial}{\partial \phi},$$

which is timelike near the poles but spacelike near the equator.

Geons - Horowitz and Santos 2014

- Geons are regular horizonless solutions of the Einstein equation, which from the QFT perspective do not seem to thermalize.
- The boundary stress-tensor contains regions of negative and positive energy density around the equator:



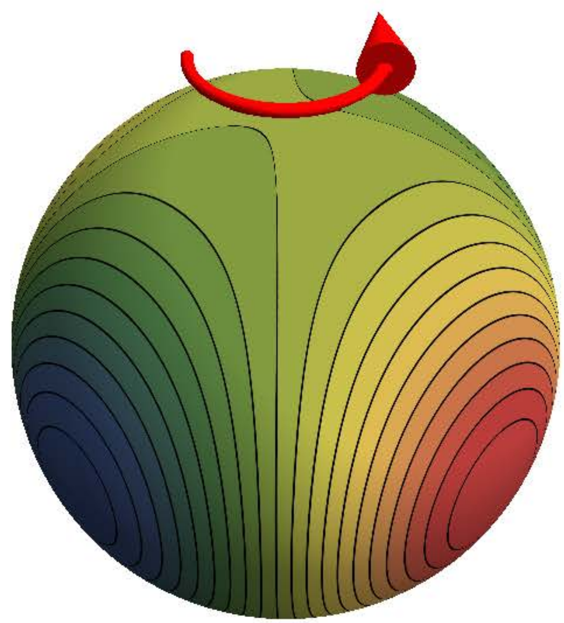
- It is invariant under

$$K = \frac{\partial}{\partial t} + \frac{\omega}{m}\frac{\partial}{\partial \phi},$$

  which is timelike near the poles but spacelike near the equator.
- It satisfies the first law $m\,\mathrm{d}E = \omega\,\mathrm{d}J$.

Geons - Horowitz and Santos 2014

- Geons are regular horizonless solutions of the Einstein equation, which from the QFT perspective do not seem to thermalize.
- The boundary stress-tensor contains regions of negative and positive energy density around the equator:



- It is invariant under

$$K = \frac{\partial}{\partial t} + \frac{\omega}{m}\frac{\partial}{\partial \phi},$$

which is timelike near the poles but spacelike near the equator.

- It satisfies the first law $m\,\mathrm{d}E = \omega\,\mathrm{d}J$.

Unclear if they can have the same energy, *i.e.* coexist, with large AdS black holes!

One black hole to interpolate them all and in the darkness bind them

Surfing the Geon:

- Since Geons rotate rigidly, one can ask whether small black holes can surf the Geon!

Surfing the Geon:

- Since Geons rotate rigidly, one can ask whether small black holes can surf the Geon!
- This is possible if the black hole rotates rigidly with angular velocity $\Omega_H = \omega/m$, ensuring zero flux across the horizon.

Surfing the Geon:

- Since Geons rotate rigidly, one can ask whether small black holes can surf the Geon!
- This is possible if the black hole rotates rigidly with angular velocity $\Omega_H = \omega/m$, ensuring zero flux across the horizon.
- If such solutions exist, we have a black hole with a single Killing vector field - black resonator - conjectured by Reall '03!

Surfing the Geon:

- Since Geons rotate rigidly, one can ask whether small black holes can surf the Geon!
- This is possible if the black hole rotates rigidly with angular velocity $\Omega_H = \omega/m$, ensuring zero flux across the horizon.
- If such solutions exist, we have a black hole with a single Killing vector field - black resonator - conjectured by Reall '03!

Evades rigidity theorem because the only Killing field is the horizon generator!

Surfing the Geon:

- Since Geons rotate rigidly, one can ask whether small black holes can surf the Geon!
- This is possible if the black hole rotates rigidly with angular velocity $\Omega_H = \omega/m$, ensuring zero flux across the horizon.
- If such solutions exist, we have a black hole with a single Killing vector field - black resonator - conjectured by Reall '03!

Evades rigidity theorem because the only Killing field is the horizon generator!

- We have constructed these solutions: ten coupled 3D nonlinear partial differential equations of Elliptic type.

Black resonators 1/3:

- One helical Killing field: $\partial_T = \partial_t + \Omega_H \partial_\phi$.

Black resonators 1/3:

- One helical Killing field: $\partial_T = \partial_t + \Omega_H \partial_\phi$.
- Their line element can be adapted to ∂_T:

$$ds^2 = \frac{L^2}{(1-y^2)^2}\Bigg[-y^2 A \Delta_y (\mathrm{d}T + y\,\chi_1 \mathrm{d}y)^2 + \frac{4y_+^2\,B\mathrm{d}y^2}{\Delta_y} + \frac{4y_+^2 S_1}{2-x^2}\left(\mathrm{d}x + yx\sqrt{2-x^2}\chi_3\mathrm{d}y + y^2x\sqrt{2-x^2}\chi_2\mathrm{d}T\right)^2 + (1-x^2)^2 y_+^2 S_2\left(\mathrm{d}\Psi + y^2\Omega\mathrm{d}T + \frac{x\sqrt{2-x^2}\chi_4\mathrm{d}x}{1-x^2} + y\,\chi_5\mathrm{d}y\right)^2\Bigg]$$

Black resonators 1/3:

- One helical Killing field: $\partial_T = \partial_t + \Omega_H \partial_\phi$.
- Their line element can be adapted to ∂_T:

$$
\begin{aligned}
ds^2 = \frac{L^2}{(1-y^2)^2}\Bigg[&-y^2 A \Delta_y (dT + y\,\chi_1 dy)^2 + \frac{4y_+^2\, B dy^2}{\Delta_y} \\
&+ \frac{4y_+^2 S_1}{2-x^2}\left(dx + yx\sqrt{2-x^2}\chi_3 dy + y^2 x\sqrt{2-x^2}\chi_2 dT\right)^2 \\
&+ (1-x^2)^2 y_+^2 S_2 \left(d\Psi + y^2 \Omega dT + \frac{x\sqrt{2-x^2}\chi_4 dx}{1-x^2} + y\,\chi_5 dy\right)^2 \Bigg]
\end{aligned}
$$

- 2D moduli space:

$$
T \equiv \frac{1+3y_+^2}{4\pi y_+} \quad \text{and} \quad \varepsilon \equiv \int_0^\pi d\phi \chi_4(0,1,\phi)\sin(m\,\phi)\,.
$$

Black resonators 1/3:

- One helical Killing field: $\partial_T = \partial_t + \Omega_H \partial_\phi$.
- Their line element can be adapted to ∂_T:

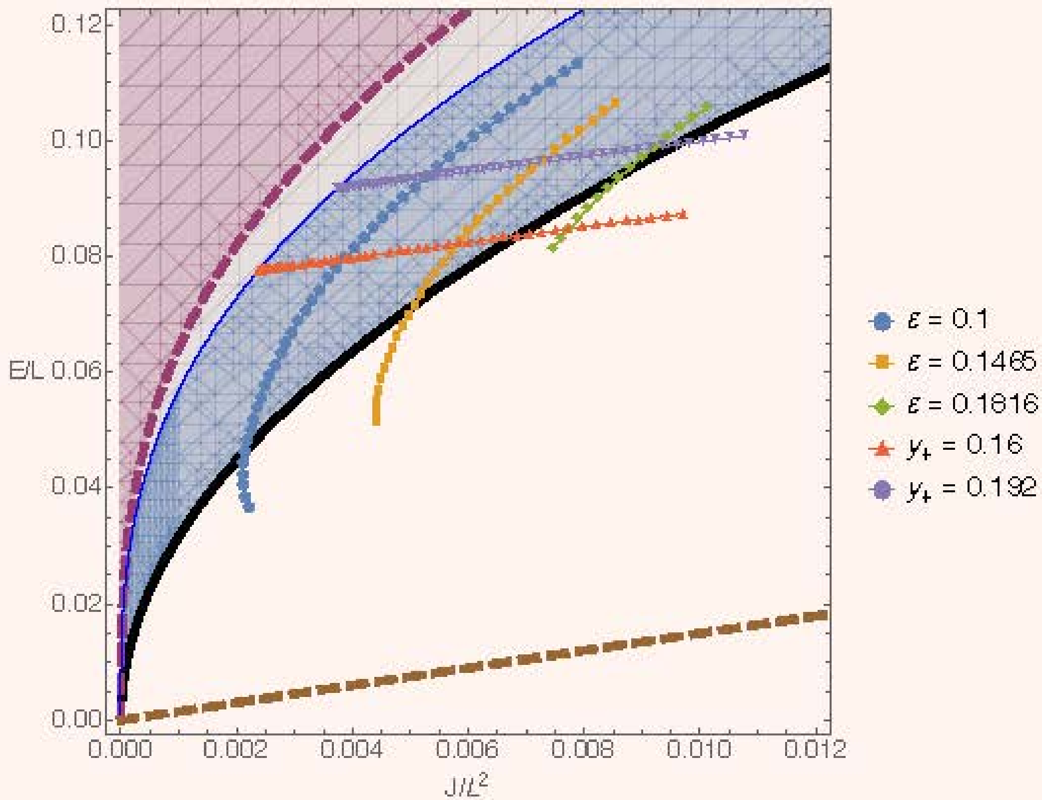
$$ds^2 = \frac{L^2}{(1-y^2)^2}\Bigg[-y^2 A \Delta_y (\mathrm{d}T + y\,\chi_1 \mathrm{d}y)^2 + \frac{4y_+^2\, B \mathrm{d}y^2}{\Delta_y} + \frac{4y_+^2 S_1}{2-x^2}\left(\mathrm{d}x + yx\sqrt{2-x^2}\chi_3 \mathrm{d}y + y^2 x\sqrt{2-x^2}\chi_2 \mathrm{d}T\right)^2 + (1-x^2)^2 y_+^2 S_2 \left(\mathrm{d}\Psi + y^2 \Omega \mathrm{d}T + \frac{x\sqrt{2-x^2}\chi_4 \mathrm{d}x}{1-x^2} + y\,\chi_5 \mathrm{d}y\right)^2\Bigg]$$

- 2D moduli space:

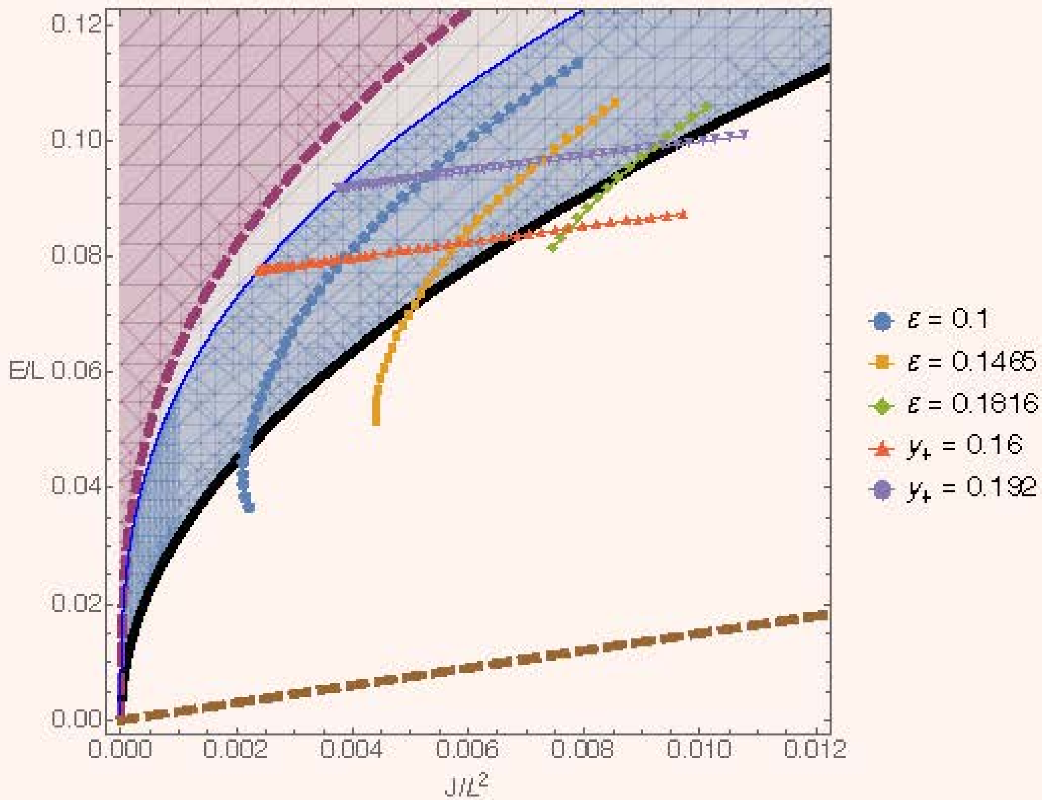
$$T \equiv \frac{1+3y_+^2}{4\pi y_+} \quad \text{and} \quad \varepsilon \equiv \int_0^{\pi} \mathrm{d}\phi \chi_4(0,1,\phi)\sin(m\,\phi)\,.$$

- Bifurcating Killing sphere - Killing horizon generated by ∂_T.

Black resonators 2/3:

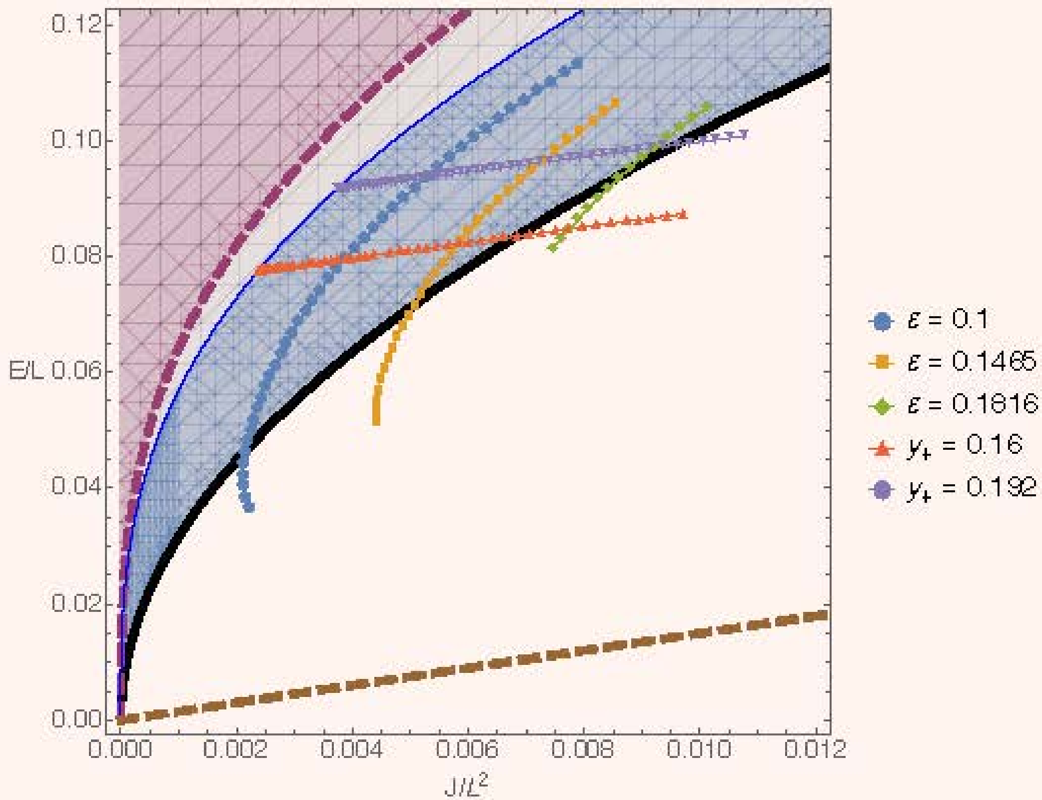


Black resonators 2/3:



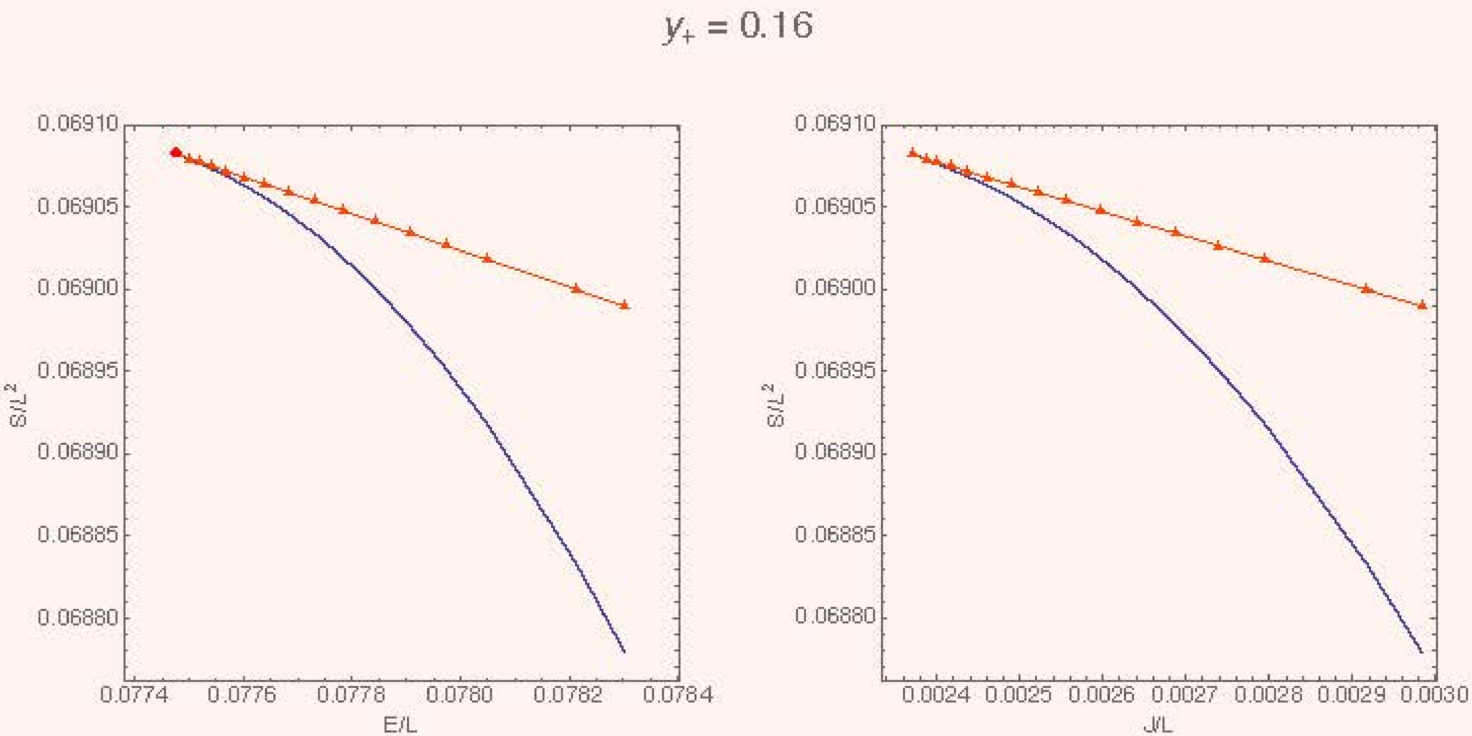
- Black resonators extend from the onset of superradiance instability to the Geons ('onset of turbulent instability').

Black resonators 2/3:



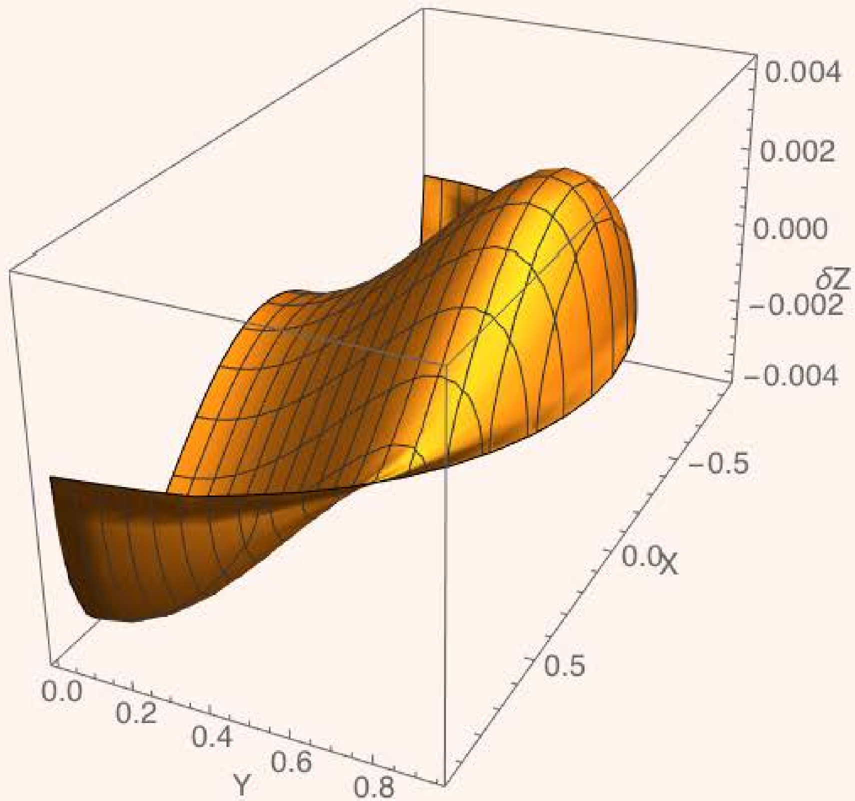
- Black resonators extend from the onset of superradiance instability to the Geons ('onset of turbulent instability').
- Black resonators exist in regions where the Kerr-AdS solution is beyond extremality.

Black resonators 3/3:



- When black resonators coexist with Kerr-AdS solutions, they have higher entropy - 2^{nd} order phase transition.

Black resonators 3/3:



- When black resonators coexist with Kerr-AdS solutions, they have higher entropy - 2^{nd} order phase transition.
- Their horizon is deformed along the ϕ direction along which they rotate - embedding in 3D spacetime - $\delta Z \equiv Z - \bar{Z}$.

Possible Endpoint of the Superradiance Instability?

- If the dynamics was restricted to specific values of m, say $m = 2$, then this would be likely...

Possible Endpoint of the Superradiance Instability?

- If the dynamics was restricted to specific values of m, say $m = 2$, then this would be likely...
- However, recall that $m = 2$ becomes stable in a region where Kerr-AdS is unstable to perturbations with $m > 2$!

Possible Endpoint of the Superradiance Instability?

- If the dynamics was restricted to specific values of m, say $m = 2$, then this would be likely...
- However, recall that $m = 2$ becomes stable in a region where Kerr-AdS is unstable to perturbations with $m > 2$!
- In addition, the cloud of gravitons - hair - never backreacts very strongly on the geometry - central black hole really looks like Kerr-AdS.

Possible Endpoint of the Superradiance Instability?

- If the dynamics was restricted to specific values of m, say $m = 2$, then this would be likely...
- However, recall that $m = 2$ becomes stable in a region where Kerr-AdS is unstable to perturbations with $m > 2$!
- In addition, the cloud of gravitons - hair - never backreacts very strongly on the geometry - central black hole really looks like Kerr-AdS.
- Finally, higher m black resonators seem to have increasing entropy with increasing m.

Possible Endpoint of the Superradiance Instability?

- If the dynamics was restricted to specific values of m, say $m = 2$, then this would be likely...
- However, recall that $m = 2$ becomes stable in a region where Kerr-AdS is unstable to perturbations with $m > 2$!
- In addition, the cloud of gravitons - hair - never backreacts very strongly on the geometry - central black hole really looks like Kerr-AdS.
- Finally, higher m black resonators seem to have increasing entropy with increasing m.
- From Bob's talk yesterday, it is clear that these solutions are all unstable given that K is spacelike in certain regions!

Possible Endpoint of the Superradiance Instability?

- If the dynamics was restricted to specific values of m, say $m = 2$, then this would be likely...
- However, recall that $m = 2$ becomes stable in a region where Kerr-AdS is unstable to perturbations with $m > 2$!
- In addition, the cloud of gravitons - hair - never backreacts very strongly on the geometry - central black hole really looks like Kerr-AdS.
- Finally, higher m black resonators seem to have increasing entropy with increasing m.
- From Bob's talk yesterday, it is clear that these solutions are all unstable given that K is spacelike in certain regions!

Conjecture: there is no endpoint -
Dias, Horowitz and Santos '11

Conclusions:

- We have constructed black holes with a single Killing field.
- They interpolate between superradiance onset and geons.
- New phase dominates microcanonical ensemble.

Conclusions:

- We have constructed black holes with a single Killing field.
- They interpolate between superradiance onset and geons.
- New phase dominates microcanonical ensemble.

What to ask me after the talk:

- Infinite non-uniqueness for Kerr-AdS?
  - How large is it?
- What is the story in the canonical and grand-canonical ensembles?

Conclusions:

- We have constructed black holes with a single Killing field.
- They interpolate between superradiance onset and geons.
- New phase dominates microcanonical ensemble.

What to ask me after the talk:

- Infinite non-uniqueness for Kerr-AdS?
  - How large is it?
- What is the story in the canonical and grand-canonical ensembles?

Outlook:

- What is the field theory interpretation of this phenomenon?
- Can we make a connection with glassy physics?
- ...

Happy Birthday Gary!