QNMs of exotic compact objects

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Outline

1. **Introduction**
2. **Exotic Compact Objects and their QNMs**
3. **QNMs of simplest fuzzballs**
4. **Our recent paper**
5. **Summary**

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- The standard paradigm is that of black holes. Alternatives are a host of exotic compact objects.
- Gravitational wave observations can probe differences.

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- For a class of fuzzballs, a details study of QNMs has been recently performed.
- I will present these results and their implications and some D1-D5 string theory discussion.

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$$\phi(t, r, \theta\,) = \sum_{lm} e^{-i\omega t}\,\frac{\Psi(r)}{r}\,Y_{lm}\,, \tag{2}$$

- Variable Ψ satisfies Schrödinger equation

$$\frac{d^2\Psi}{dr_*^2} + \left(\omega^2 - V\right)\Psi = 0\,, \tag{3}$$

where r_* is the tortoise coordinate $r_* \to -\infty$ at the horizon and $r_* \to +\infty$.

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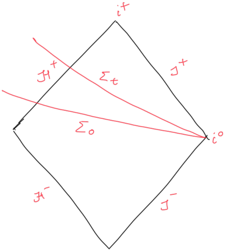
- Mode stability of linearised gravitational perturbations of Schwarzschild and Kerr black holes Regge, Wheeler, Vishweshwara, . . .
- no unstable modes
- However, this is not enough to establish linear stability. Many open issues: completeness of mode solutions, infinite superpositions, Vishweshwara, cf. ICTS talk 2017

The issue of linear stability is different

- Prescribe initial data: ϕ, $\dot{\phi}$ on some initial surface Σ_0 that intersects the future horizon $\mathcal{H}^+$ and infinity with $\phi \to 0$ at infinity.



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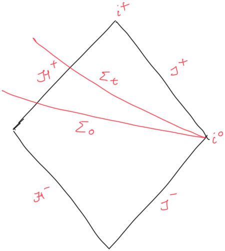

- Theorem: $\phi|_{\Sigma_t} = \mathcal{O}(t^{-\alpha})$, for some positive α, everywhere on and outside the horizon. All derivatives of ϕ also decay. Dafermos and Rodnianski, 2005

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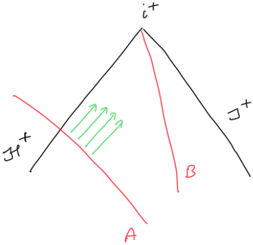
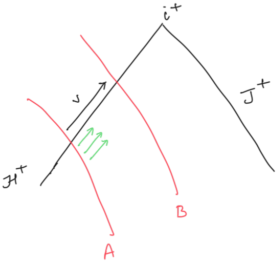
- Redshift factor along the horizon $\mathcal{H}^+ \sim e^{-\kappa v}$.
- Suppose two observers, *A* and *B* are such that *A* crosses the event horizon and B does not. If *A* emits a signal at constant frequency as he measures it, then the frequency at which it is received by *B* is "shifted to the red".





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- It took decades for the community to overcome individual prejudice – BHs became the *only* acceptable solution to the collapse problem.
- BHs is the standard paradigm. Any observation otherwise would indicate beyond the standard physics.
- So far, no observation that cannot be explained by the Kerr black hole physics.

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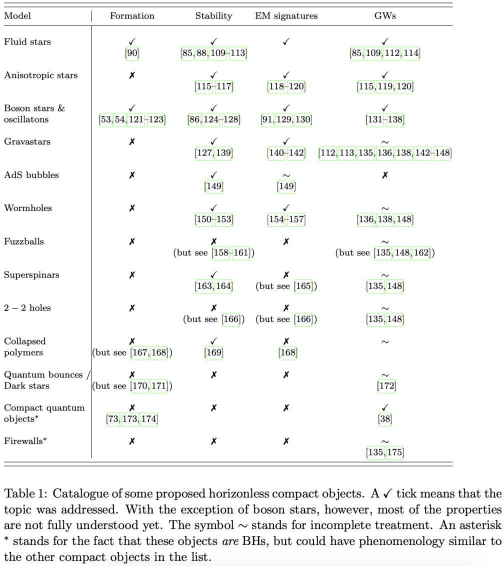
- I wish to draw a parallel: by questioning GR in the weak field we have the PPN paradigm.
- Such a paradigm can only be developed by entertaining the possibility of exotic compact objects and finding quantitative differences.
- Currently, a calculational route is taken: construct horizonless compact objects, ask questions about formation, stability, QNM spectrum, etc.

Catalogue



Model	Formation	Stability	EM signatures	GWs
Fluid stars	✓ [90]	✓ [85, 88, 109–113]	✓	✓ [85, 109, 112, 114]
Anisotropic stars	✗	✓ [115–117]	✓ [118–120]	✓ [115, 119, 120]
Boson stars & oscillatons	✓ [53, 54, 121–123]	✓ [86, 124–128]	✓ [91, 129, 130]	✓ [131–138]
Gravastars	✗	✓ [127, 139]	✓ [140–142]	∼ [112, 113, 135, 136, 138, 142–148]
AdS bubbles	✗	✓ [149]	∼ [149]	✗
Wormholes	✗	✓ [150–153]	✓ [154–157]	∼ [136, 138, 148]
Fuzzballs	✗	✗ (but see [158–161])	✗	∼ (but see [135, 148, 162])
Superspinars	✗	✓ [163, 164]	✗ (but see [165])	∼ [135, 148]
$2-2$ holes	✗	✗ (but see [166])	✗ (but see [166])	∼ [135, 148]
Collapsed polymers	✗ (but see [167, 168])	✓ [169]	✗ [168]	∼
Quantum bounces / Dark stars	✗ (but see [170, 171])	✗	✗	∼ [172]
Compact quantum objects*	✗ [73, 173, 174]	✗	✗	✓ [38]
Firewalls*	✗	✗	✗	∼ [135, 175]

Table 1: Catalogue of some proposed horizonless compact objects. A ✓ tick means that the topic was addressed. With the exception of boson stars, however, most of the properties are not fully understood yet. The symbol ∼ stands for incomplete treatment. An asterisk * stands for the fact that these objects *are* BHs, but could have phenomenology similar to the other compact objects in the list.

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    - Gravastars and AdS bubbles: negative pressure inside. Thin shell models with de Sitter core also capture much of the same physics.
    - “2 – 2 holes” and geons: thin shell objects in higher derivative theories, or some objects in infinite derivative theories.

General structure

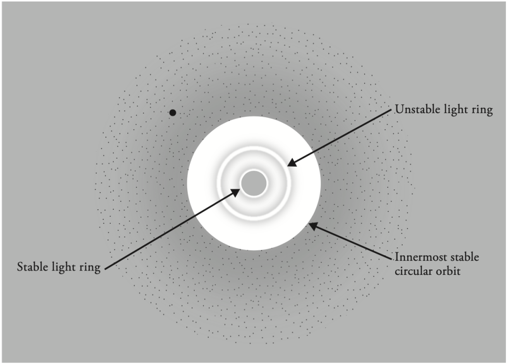

Figure: Stable planetary orbits, Inner most stable circular orbit: $6M$, Photon sphere: $3M$, Typically for exotic objects there is a second *stable* light ring.

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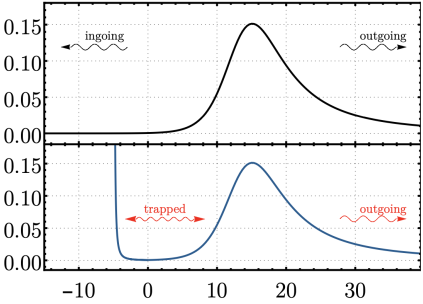

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- If the "hard" surface is at $r = 2M(1+\epsilon)$ then in the small ϵ expansion,

$$\omega_R \sim M^{-1} |\ln \epsilon|^{-1}, \qquad \omega_I \sim -M^{-1} |\ln \epsilon|^{-2l-3} \tag{4}$$

which are very different from black hole.

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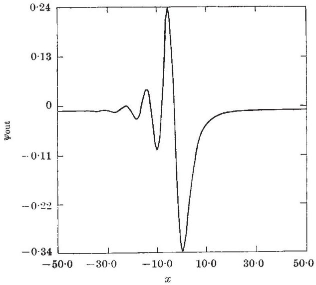

Figure: From Vishveshwara's 1970 paper.

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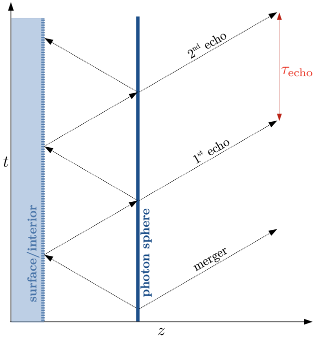

Figure: GW echos from an exotic compact object.

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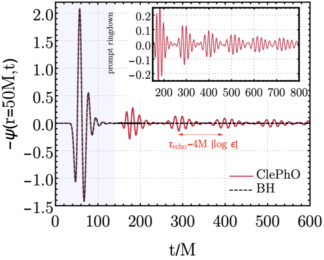

Figure: Expected GW signal from an exotic compact object.

- Since we don't see such a signal, it put constraints on the nature of exotic compact object and on the possible boundary conditions.

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- Rotating exotic compact objects are expected to suffer from ergoregion instability, i.e., negative energy excitation is trapped in the ergo-region but has no place to “fall”.
- Since all exotic compact objects have slowly decaying QNMs they are expected to be non-linearly unstable, crudely speaking perturbation builds up in time.

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- In particular, decay properties of a scalar field on a black hole should have an understanding from the fuzzball proposal.
- Eperon, Reall, and Santos argued that this does not seem to be the case. There is a debate. In this talk I will stick myself to only the QNM computation.

Bena Warner microstate geometries

In 5d supergravity a large class of supersymmetric solutions exist that are:

- Asymptotically flat
- Stationary: $\frac{\partial}{\partial t}$ Killing vector, timelike at infinity
- Geodesically complete, with topology $\mathbb{R} \times \Sigma$ where Σ have non-trivial two cycles – bubbling solutions
- Rotating, and have no horizon

For simplicity I will focus on the 5d perspective. Often it is better to work in 6d.

Evanescent Ergo-surface, Gibbons and Warner 2005

- Killing vector $\frac{\partial}{\partial t}$ is timelike everywhere except at a timelike hypersurface $\mathcal{S}$ where it is null. Infinite redshift.
- This surface is an ergo-surface but has no ergo-region.
- Norm of $V = \frac{\partial}{\partial t}$, i.e., $-V^2$, is minimised there.
- That is $\nabla_a(-V^2) = 0$.

Evanescent ergo-surface are ruled by zero energy null geodesics

- Consider on $\mathcal{S}$

$$V^b \nabla_b V_a = -V^b \nabla_a V_b = \frac{1}{2} \nabla_a (-V^2) = 0. \tag{5}$$

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- V^a is tangent to a geodesic. In fact, to a null geodesic. In fact, to a zero energy null geodesic. Recall $E = -P \cdot V$.
- A timelike surface ruled by null geodesics. cf. photon sphere of Schwarzschild.

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- Using Geometric optics/WKB methods one can determine real and imaginary parts of QNMs of Kerr. Yang et al 2012.

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- This is very peculiar. It does not happen typically.
- Using Geometric optics/WKB methods one can determine real and imaginary parts of QNMs. The real part is expected to be close to zero and imaginary part is expected to be very small.

QNMs

- Eperon, Reall, Santos calculated QNMs for the simplest 2 and 3 charge microstate geometries and showed that (in the large l limit)

$$\omega_R \sim \mathcal{O}(l^0), \qquad \omega_I \sim -\exp\left[-2l \log l\right] \tag{6}$$

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- Festuccia and Liu pointed out large AdS black holes have slow QNMs

$$\omega_R \sim \mathcal{O}(l), \qquad \omega_I \sim -\exp\left[-\beta l\right] \tag{7}$$

- QNMs for microstate geometries are much slower.

ERS Nonlinear Instability?

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- For microstate geometries the situation is much worse; stable trapping is in a compact region of space and hence even slower decay. This strongly suggests non-linear instability of a very large class of microstate geometries.

Contrasting with black holes

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- There are clear qualitative differences between decay properties of scalars on fuzzballs and black holes.

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Our recent paper

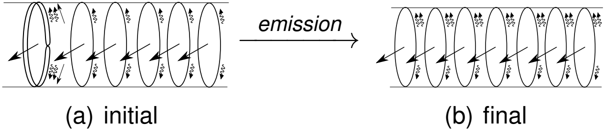
- Most of the previous authors were concerned about the non-linear instability per se.
- With Bidisha Charkrabarty and Debodirna Ghosh we were concerned about the slow decaying modes, and the spectral problem.
- I will only present a broad brush discussion, detailed can be asked to Bidisha and Deb.

Near decoupling limit

- We focus on the computation of QNMs in the decoupling limit, where AdS/CFT is expected to be valid (D1-D5 orbifold CFT).
- The dual CFT description of the simplest SUSY fuzzballs is very well understood. Scalar excitations are also well understood. We ask where are the slow decaying QNMs.

QNMs spectrum from the D1-D5 CFT

- Using certain results of Avery, Chowdhury, Mathur 2008 we can compute the transition.



(a) initial (b) final

Figure: The scalar emission.

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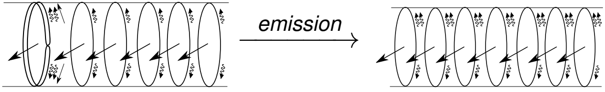

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Figure: The scalar emission.

- This gives the full QNMs spectrum. The decoupling limit faithfully captures ERS physics; there are indeed low energy modes with large l, i.e.,

$$\omega_R \sim \mathcal{O}(l^0). \tag{8}$$

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- The set-up we are interested in is different. The three-charge microstate geometries discussed above have an inner AdS region glued to an asymptotically flat region.
- The quansinormal modes are determined via the outgoing boundary conditions in the asymptotically flat region. Therefore, we are interested in the emission of a scalar quanta leaving to infinity of the asymptotically flat region. This requires coupling of CFT to flat space modes.
- Fortunately, this physics was also worked out by Avery, Chowdhury, Mathur 2008.

QNMs spectrum from the D1-D5 CFT: Imaginary part

- Avery, Chowdhury, Mathur gave a formula for the emission rate to infinity

$$\omega_I = -\frac{2\pi}{2^{2l+2}(l!)^2}\frac{(Q_1 Q_5)^{l+1}}{R^{2l+3}}(\omega^2 - \lambda^2)^{l+1}|\langle f|\mathcal{V}|i\rangle|^2. \qquad (9)$$

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- Computing the transition amplitude $|\langle f|\mathcal{V}|i\rangle|^2$ for the above process and taking the large l limit precisely gives ERS results in the decoupling limit.

Outline

1. Introduction
2. Exotic Compact Objects and their QNMs
3. QNMs of simplest fuzzballs
4. Our recent paper
5. **Summary**

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- I emphasised the need to study them further, not because we make like any of these objects, but to develop a quantitative paradigm to test BH nature of compact objects.
- In the QNM spectrum of these objects, boundary conditions play the key role. In many situations correct boundary conditions are not understood.

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- A main ingredient in the arguments of ERS was slow decaying QNMs. We have shown that all such details can be reproduced from a D1-D5 CFT analysis.
- One can do a detailed fuzzball debate at this point, but due to lack of sleep [and my own sanity] I did not go into that.

Thank You!