Vorticity in black holes

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Conjecture. Vorticity is an intrinsic property of close-to-maximally spinning black holes.

If true, macroscopic consequences can follow.

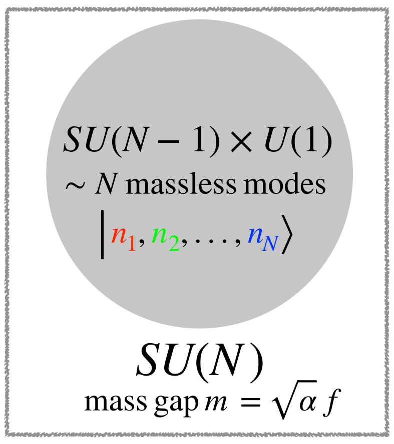
Motivation. The idea is supported by two separate lines of argument.
1) There exists a microscopic description of black holes in terms of a Bose-Einstein condensate of N-marginally bounded gravitons [1]. In this picture, it makes sense that, when rotating, these configurations display vortices analogously to their laboratory counterparts.
2) Unitarity imposes an upper bound on the entropy of a localised-self-sustained configuration. This corresponds to the area measured in units of Goldstone decay constant associated to the symmetries broken by the configuration itself. Configurations saturating this bound are called *saturons* [2]. Black holes belong to this class. However, saturons can also be found in renormalizable field theories. These configurations are found to possess, universally, the key-essential properties observed in black holes such as: thermal emission (Hawking spectrum), information time retrieval (Page's time), an information horizon. This suggests the possibility to use these calculable systems as prototypes for understanding the microscopic structure of black holes as well as predicting novel phenomena. One instance of this is given by vorticity [4].

Prototype Model. Consider a bubble interpolating between two distinct vacua of a global SU(N)-symmetric theory explicitly built out of an adjoint field Φ

$$\mathcal{L} = \mathrm{Tr}\,\partial_\mu \Phi \partial^\mu \Phi - \alpha\, \mathrm{Tr}\left(f\,\Phi - \Phi^2 + \frac{1}{N}\mathrm{Tr}\Phi^2\right)^2$$

- α is coupling, f the symmetry breaking scale (Goldstone decay const.)
- Unitarity implies $\alpha N \lesssim 1$
- The model is renormalizable
- We work in the double scaling limit $N \to \infty, \quad \alpha N \sim 1$

Consider a bubble interpolating between the vacua $SU(N)$ and $SU(N-1)\times U(1)$ symmetric vacuum stabilised by charge Q:



$$\Phi(x) \to U^\dagger \Phi(x)\, U$$

$$U = \exp\left\{ i\left(t\omega + n\varphi/\sqrt{2}\right)\frac{\omega_j}{\omega}T^j \right\}$$

$$R_0 = \frac{2}{3}\frac{m}{\omega^2}$$

$$E_0 = \frac{\omega}{\alpha}\frac{m^5}{\omega^5}\left(\frac{40\pi}{81}\right)$$

Where ω_j is the frequency of the goldstone corresponding to the T_j the broken generator, n the winding number. For simplicity, take all frequencies to be equal to ω.
The bubble is stabilised by a charge Q, measuring the occupation number of flavoured Goldstone in the bubble interior. This configuration has a large degeneracy (due to reshuffling of Goldstone in flavour modes)

$$Q = \sum_i^N n_i = \frac{16\pi}{81\alpha}\frac{m^5}{\omega^5} \qquad n_{\text{states}} = \binom{Q}{N} \simeq \left(1+\frac{Q}{N}\right)^N \left(1+\frac{N}{Q}\right)^Q$$

For $m \simeq \omega, \quad Q \sim N \sim 1/\alpha$, entropy area law is recovered [2,3]

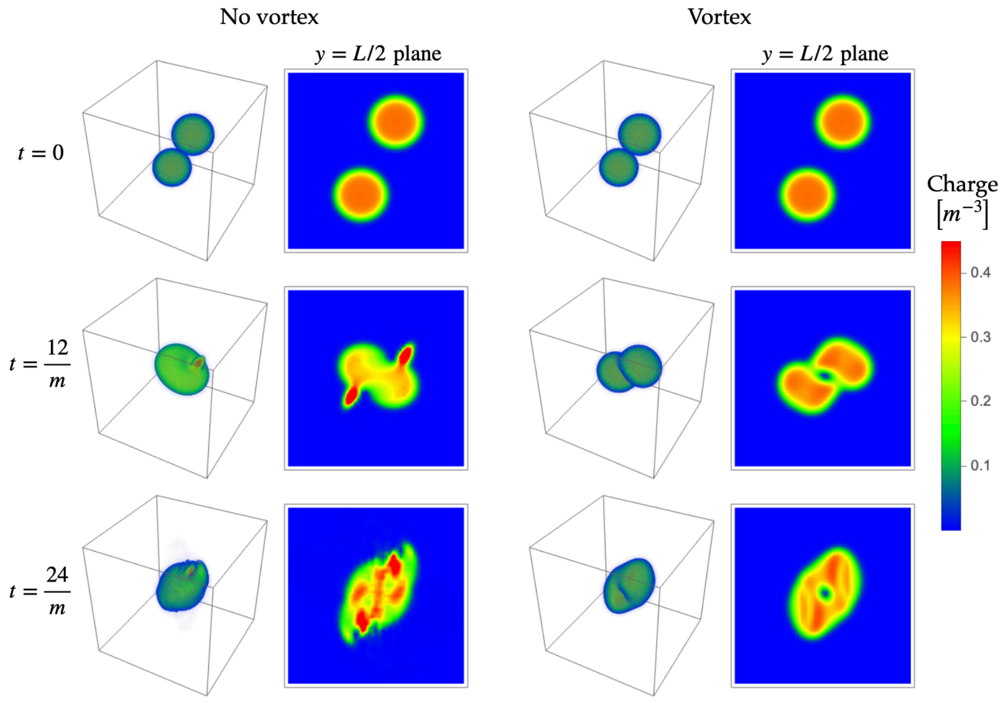
$$S \simeq \log n_{\text{states}} \simeq R_0^2 f^2 \simeq N \simeq Q \simeq E_0 R_0 \simeq 1/\alpha$$

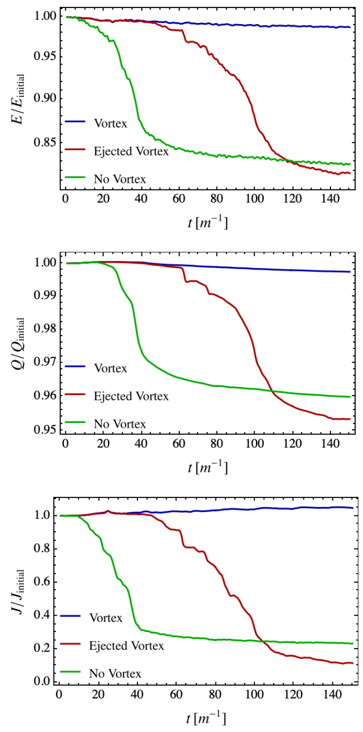
In the spinning case, $n \geq 1$, the configuration has spin [4]

$$J \simeq nQ \simeq nS$$

- To maintain saturation, $n \sim \mathcal{O}(1)$
- Same bound as extremal black holes emerges $J^{\max} \leq S$
- Microscopic interpretation of the bound in terms of vorticity
- Topological understanding of absence of Hawking radiation: soft quanta emission is forbidden by macroscopic nature of the vortex

Merger dynamics. What is the impact of vorticity in soliton mergers?

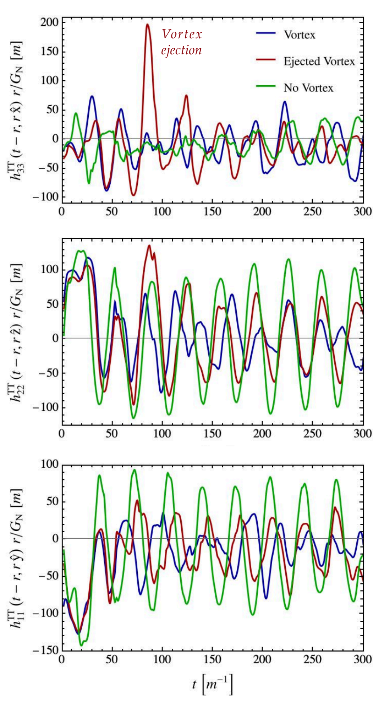


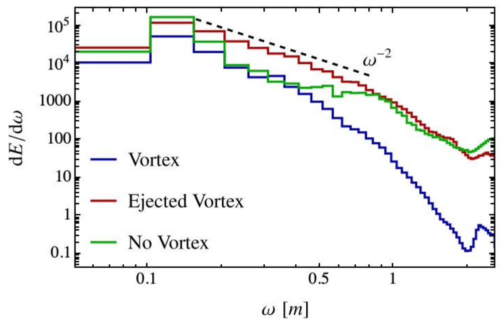


- *No Vortex:* the solitons simply merge
- *Ejected Vortex:* the resulting soliton possesses a vortex for a while. Eventually it is ejected resulting in a close-to-zero spin configuration
- *Vortex:* almost no emission takes place in this case. The energy and angular momentum are invested in vortex formation

Charge is conserved in the mergers - presence of information horizon.
If vorticity is an intrinsic property of highly-spinning black holes, a similar interference could lead to macroscopic deviations in the gravitational radiation of mergers [5].

Analogous behaviours are confirmed by the gravitational-wave signal [6]





- Around wavelengths of size of the vortex, the GW radiation is suppressed (blue curve in UV)
- This energy is, instead, emitted at the merger (green) or at the vortex ejection (red) giving similar amplitude
- General infrared source due to the asymptotic mass gap, leading to pulsating configuration

Take-home message. We characterized the impact of vorticity in black hole prototypes constructed in renormalizable field theory. If black holes admit such a substructure, macroscopic suppressions are expected in mergers around wavelength of the black hole radius, potentially accompanied by delayed bursts due to the vortex ejection.

References.
[1] Dvali, Gomez "Black Hole's Quantum N-Portrait", 2013
[2] Dvali, "Entropy Bound and Unitarity of Scattering Amplitudes", 2021
[3] Dvali, Bermudez, **MZ**, "Memory burden effect in black holes and solitons", 2024
[4] Dvali, Kuhnel, **MZ**, "Vortices in black holes", 2022
[5] Dvali, Kaikov, Kuhnel, Bermudez, **MZ**, "Vortex Effects in Merging Saturons", 2023
[6] **MZ**, in progress