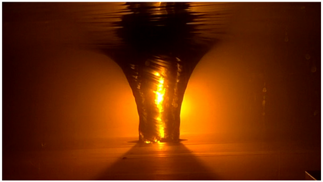
Universidade Federal do ABC

Analogue Gravity

Verão Quântico, 2025



Maurício Richartz

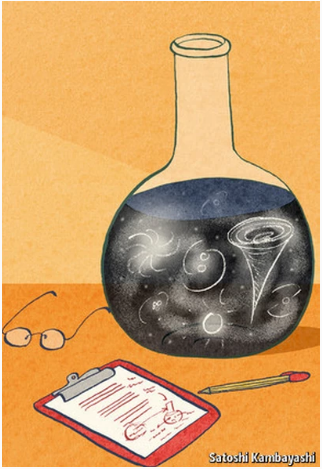
Universidade Federal do ABC (UFABC)

CNPq FAPESP

Outline

- Introduction: analogue gravity
- Surface waves in fluids and superfluids
- Superradiance and quasinormal ringing in fluids
- Superradiance and quasinormal ringing in superfluids
- Conclusion

Introduction



– Some processes in the Universe (specially when gravity and quantum physics are both important) are extremely hard to observe.
– Can we set up experiments to rebuild the Universe in the laboratory?
– Can we study fundamental processes (like Hawking radiation and cosmic inflation) using analogue classical or quantum simulators?

Analogue models of gravity

Analogue models of gravity are systems that can mimick curved space-time effects (both classical and quantum), e.g. Hawking radiation and superradiance, leading naturally to questions like "Can we see black hole evaporation in a laboratory?"

PHYSICAL REVIEW LETTERS

VOLUME 46 25 MAY 1981 NUMBER 21

Experimental Black-Hole Evaporation?

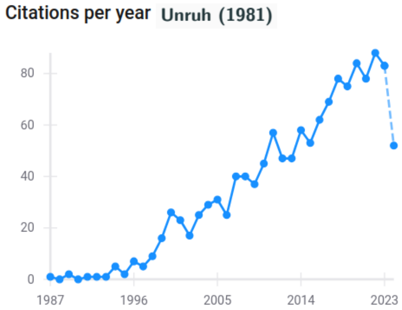
W. G. Unruh

Department of Physics, University of British Columbia, Vancouver, British Columbia V6T 2A6, Canada

(Received 8 December 1980)

It is shown that the same arguments which lead to black-hole evaporation also predict that a thermal spectrum of sound waves should be given out from the sonic horizon in transsonic fluid flow.

Fluids ↔ Gravity



PHYSICAL REVIEW D VOLUME 44, NUMBER 6 15 SEPTEMBER 1991

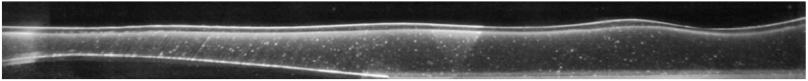
Black-hole evaporation and ultrashort distances

Theodore Jacobson
Department of Physics, University of Maryland, College Park, Maryland 20742
(Received 28 March 1991)

The role played by ultrahigh frequencies or ultrashort distances in the usual derivations of the Hawking effect is discussed and criticized. The question "would a black hole radiate if there were a Planck scale cutoff in the rest frame of the hole?" is posed. Guidance is sought from Unruh's fluid-flow analogue of black-hole radiation, by taking into account the atomic nature of the fluid. Two arguments for black-hole radiation are given which assume a Planck length cutoff. One involves the response of static accelerated detectors outside the horizon, and the other involves conservation of the expectation value of the stress tensor. Neither argument is conclusive, but they do strongly suggest that, in spite of reasonable doubt about the usual derivations of black-hole radiation, a "safe" derivation which avoids our ignorance of ultrashort-distance physics can likely be formulated. Remaining open questions are discussed.

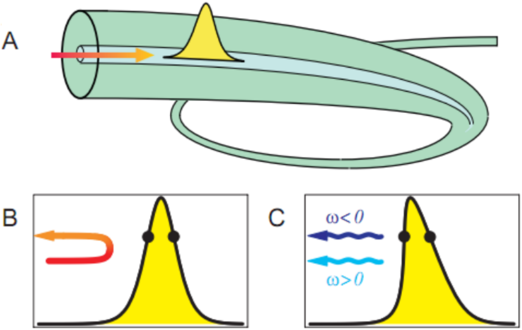
Experimental realizations (some examples)

Surface Waves



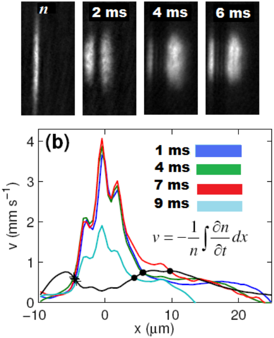
Ref.: Physics in Canada (Unruh, 2010), Weinfurtner et al (PRL, 2011)

Fiber Optics



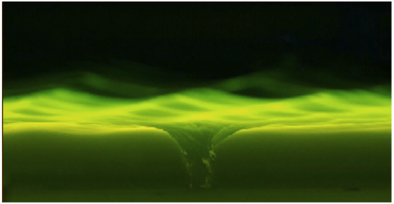
Ref.: Philbin et. al (Science, 2008)

BEC



Ref.: Lahav et. al (PRL, 2010)

Fluids and superfluids



Rotational superradiant scattering in a vortex flow

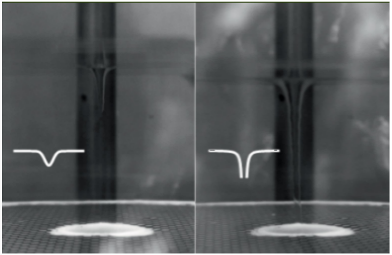
Theo Torres, Sam Patrick, Antonin Coutant, Maurício Richartz, Edmund W. Tedford & Silke Weinfurtner

Nature Physics **13**, 833–836 (2017) | Cite this article

Quasinormal Mode Oscillations in an Analogue Black Hole Experiment

Theo Torres, Sam Patrick, Maurício Richartz, and Silke Weinfurtner

Phys. Rev. Lett. **125**, 011301 – Published 1 July 2020



Rotating curved spacetime signatures from a giant quantum vortex

Patrik Švančara, Pietro Smaniotto, Leonardo Solidoro, James F. MacDonald, Sam Patrick, Ruth Gregory, Carlo F. Barenghi & Silke Weinfurtner

Nature **628**, 66–70 (2024) | Cite this article

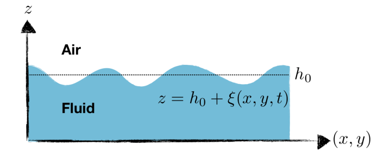
Black-hole spectroscopy from a giant quantum vortex

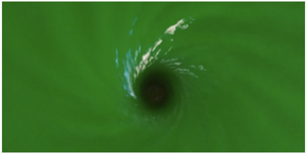
Pietro Smaniotto,[1,2,*] Leonardo Solidoro,[1,2] Patrik Švančara,[1,2] Sam Patrick,[3] Maurício Richartz,[4] Carlo F. Barenghi,[5] Ruth Gregory,[3,6] and Silke Weinfurtner[1,2,6,7,†]

arXiv:2502.11209v1 [gr-qc]

Black hole bomb in a gravity simulator (work in progress)

Theory: background flow



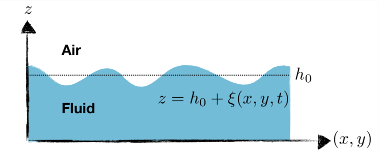


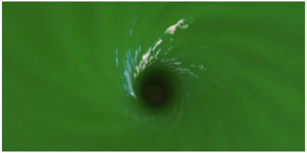
- Flow: constant density, inviscid, irrotational, and axisymmetric.

$$\nabla \cdot \vec{v} = 0, \quad \rho(\partial_t + \vec{v} \cdot \nabla)\vec{v} = -\nabla P, \quad \nabla \times \vec{v} = 0$$

- Free boundary problem: depth h is unknown a priori.
- The simplest solution is the **irrotational vortex ("draining bathtub"):** $\vec{v} = -\frac{D}{r}\hat{\mathbf{r}} + \frac{C}{r}\hat{\phi}$
- If surface waves propagate with velocity c(r), an analogue event horizon will be present where $c(r) = D/r$.

Theory: wave propagation





- Surface waves with frequency ω and wavenumber k satisfy the dispersion relation

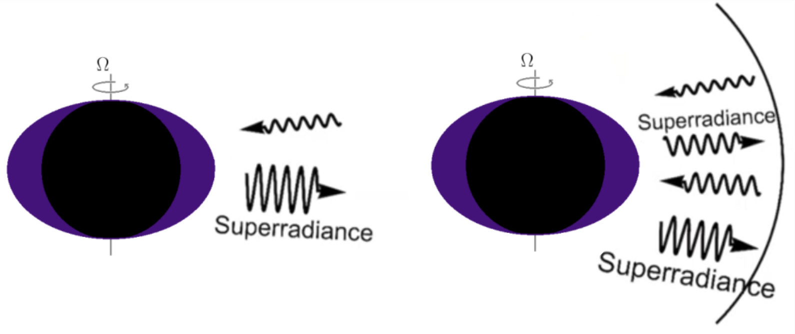
$$\left(\omega - \vec{v} \cdot \vec{k}\right)^2 = \left(gk + \frac{\sigma}{\rho} k^3\right) \tanh(kh).$$

- For long wavelengths ($kh << 1$) and no surface tension ($\sigma = 0$), the dispersion relation is linear $\omega - \vec{v} \cdot \vec{k} = \sqrt{gh}k$, and we can see that $c = \sqrt{gh}$ is the wave speed.

Analogy (linear dispersion):

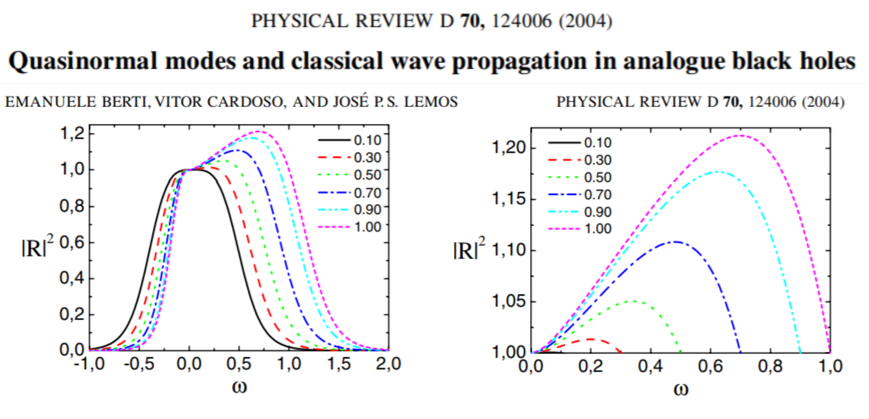
$$\left(\partial_t + \vec{v} \cdot \nabla\right)^2 \delta h = gh\nabla^2 \delta h \;\leftrightarrow\; \partial_\mu \left(\sqrt{-g} g^{\mu\nu} \partial_\nu \psi\right) = 0$$

Superradiance in fluids



- **Superradiance:** scattering process in which rotational energy is extracted from the black hole
- **Black hole bomb:** reflection of superradiant radiation back into the BH leads to an exponentially growing instability.
- **Ergoregion instability:** the absence of the horizon results in the accumulation of negative energy waves.

Superradiance in fluids


PHYSICAL REVIEW D **70**, 124006 (2004)

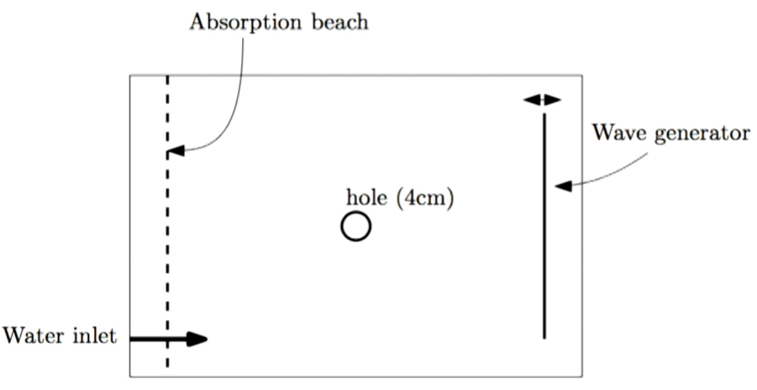
Quasinormal modes and classical wave propagation in analogue black holes

EMANUELE BERTI, VITOR CARDOSO, AND JOSÉ P. S. LEMOS

PHYSICAL REVIEW D **70**, 124006 (2004)

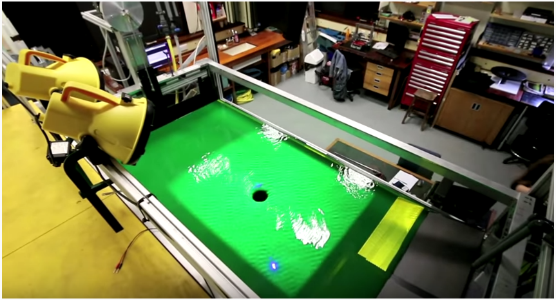
- Corotating waves ($m = 1$, $\omega > 0$) can be amplified.
- Counterrotating waves ($m = 1$, $\omega < 0$) are never amplified.

Superradiance in fluids

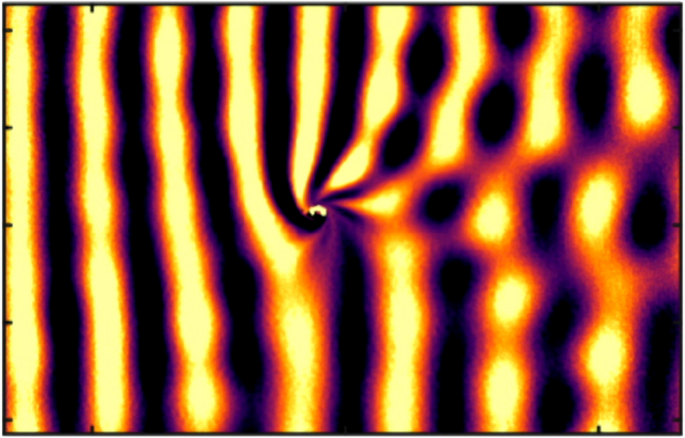


- Water tank: $\sim$ 1,5 m $\times$ 3,0 m.
- Closed circuit, water pumped from auxilliary tank (below main tank). Stationary rotating flow obtained.
- Cameras and detector placed above the tank (close to the ceiling).

Superradiance in fluids



Superradiance in fluids



- Plane wave (created by the wave generator) propagates and scatters off the vortex. We work in the frequency range 2,9 Hz - 4,1 Hz. The fluid is 6.25 cm deep.
- The observed pattern is a mixture: incident + scattered waves.

Superradiance in fluids

- The data acquired by the detector gives us the surface of the fluid as a function of time and position. We fourier transform the signal in time and filter out the excitation frequency f_0. Higher harmonics ($2f_0$, $3f_0$, ...) and background flow ($f = 0$) are eliminated.

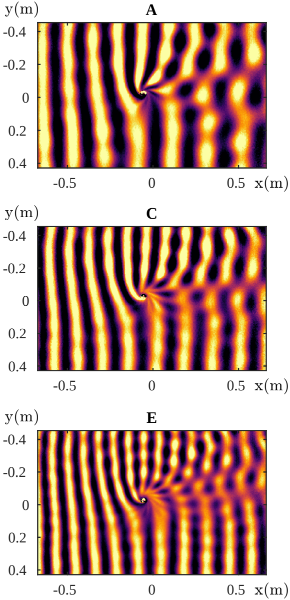
- We decompose the signal into azimuthal waves:

$$\varphi_m(r) = \frac{\sqrt{r}}{2\pi} \int_0^{2\pi} \phi(r, \theta) e^{im\theta} d\theta$$

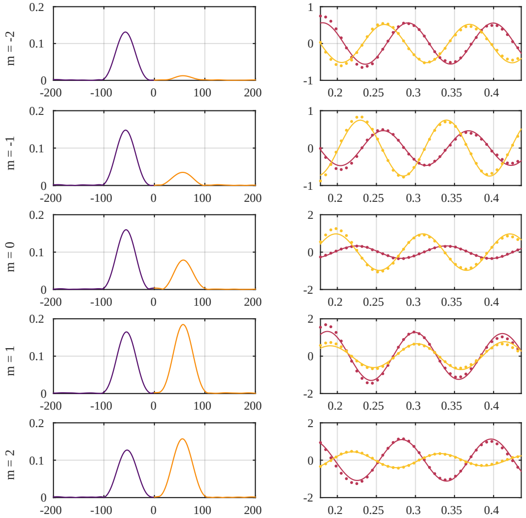
  For each m, we write radial profile as: $\varphi_m = A_m^{\mathrm{in}} e^{-ikr} + A_m^{\mathrm{out}} e^{+ikr}$

- By comparing the ingoing and outgoing parts, we extract the reflection coefficients.

Superradiance in fluids



Superradiance in fluids



Right side

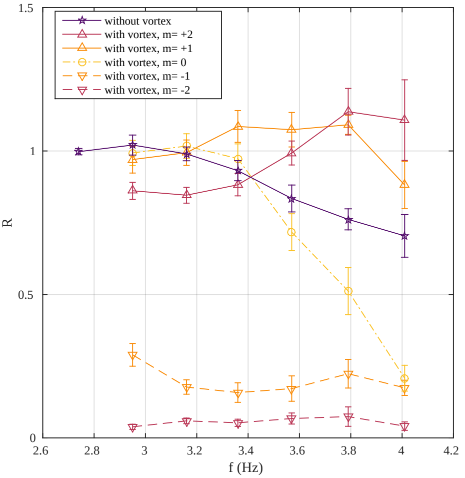
- Dots: signal
- Lines: fit to

$$A_{\text{in}} e^{-ikr} + A_{\text{out}} e^{ikr}$$

Left side

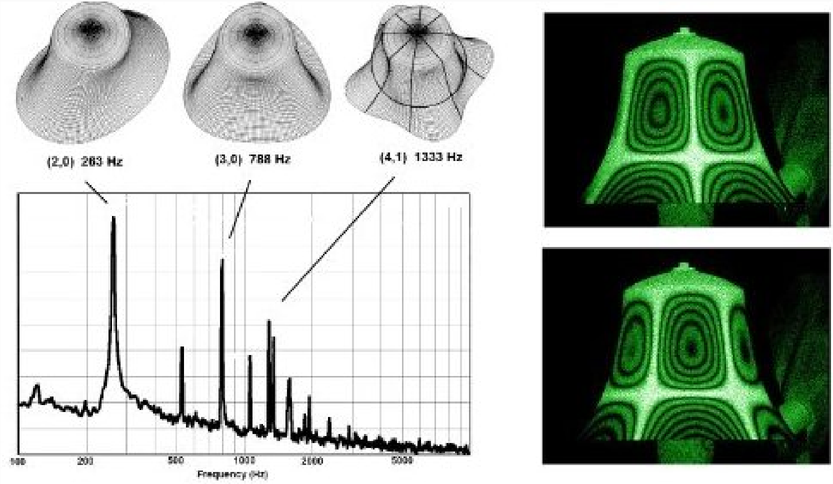
- Fourier profiles

Superradiance in fluids



Counterrotating modes are absorbed, while corotating modes can be amplified.

Quasinormal ringing in fluids



Characteristic modes of a bell: Pseudo-Degeneracy in Hand bell Modes, arXiv: 1004.0491

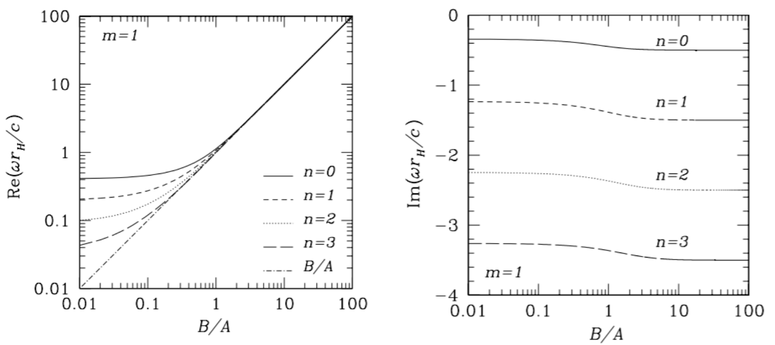
Quasinormal ringing in fluids

PHYSICAL REVIEW D **70,** 124032 (2004)

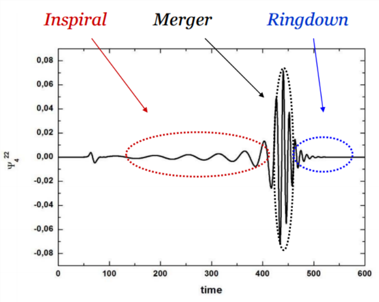
Quasinormal modes and stability of the rotating acoustic black hole: Numerical analysis

VITOR CARDOSO, JOSÉ, P. S. LEMOS, AND SHIJUN YOSHIDA

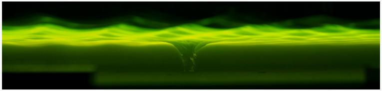
PHYSICAL REVIEW D **70,** 124032 (2004)



Quasinormal ringing in fluids



BH spectroscopy: to identify a black hole by observing the spectrum of its characteristic waves (their oscillation frequencies and decay times).



Vortex spectroscopy: can we identify a hydrodynamical vortex by observing the spectrum of its characteristic waves? I.e. can we determine C and D in $\vec{v} = -\frac{D}{r}\hat{\mathbf{r}} + \frac{C}{r}\hat{\phi}$ using waves?

Quasinormal ringing in fluids

- The characteristic spectrum can be approximated using the properties of lightrings (LRs):

$$\omega_{\mathrm{QNM}}(m) \approx \omega_\star(m) - i\Lambda(m)\left(n + \frac{1}{2}\right),$$

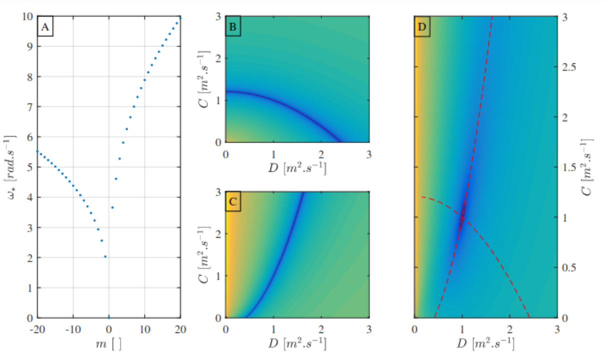
where $\omega_\star(m) = 2\pi f_\star(m)$ is the angular frequency of an m-mode orbiting on the LR, $\Lambda(m)$ is the *Lyapunov exponent* of the orbit for this specific m-mode, and n is the overtone number.

- The LR properties can be deduced from the hamiltonian

$$\mathcal{H} = \omega - \vec{v}\cdot\vec{k} = \pm\sqrt{\left(gk + \frac{\sigma}{\rho}k^3\right)\tanh(kh)}$$

by looking for the critical point $\mathcal{H} = 0, \frac{\partial\mathcal{H}}{\partial r} = 0, \frac{\partial\mathcal{H}}{\partial k_r} = 0.$

Quasinormal ringing in fluids



T.Torres, S.Patrick, MR, S.Weinfurtner, CQG 36, 194002 (2019)

A: Critical points of the hamiltonian when $C = D = 1\,\mathrm{m}^2 \cdot \mathrm{s}^{-1}$.

B: Recovering C and D from the spectrum A using only $m < 0$ modes*.

C: Recovering C and D from the spectrum A using only $m > 0$ modes*.

D: Recovering C and D from the spectrum A using all modes*.

* Darker colors represent smaller errors.

Quasinormal ringing in fluids

- We set up a vortex flow out of equilibrium to observe the emission of characteristic modes during its relaxation. Our experiment was conducted in a 3 m long and 1.5 m wide rectangular tank with a 2 cm-radius sink hole at the centre. Water is pumped continuously from one corner at a flow rate of 15 ± 1 ℓ/min.

- The sink-hole is covered until the water raises to a height of 10.00 ± 0.05 cm. Water is then allowed to drain, leading to the formation of a draining vortex. We recorded the perturbations of the free surface when the flow was in a quasi-stationary state at a water depth of 5.55 ± 0.05 cm. The entire procedure was repeated 25 times.

- The data acquired by the detector gives us the surface of the fluid as a function of time and position.

- The resulting vortex is axisymmetric to a good approximation, allowing us to perform an azimuthal decomposition to study the characteristic modes:

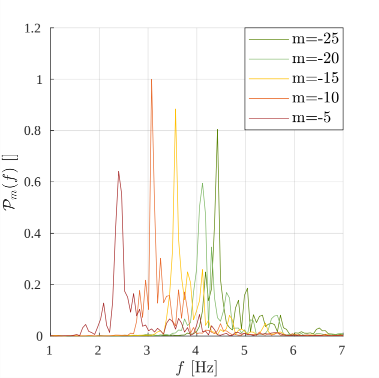
$$\delta h(t, r, \theta) = \mathrm{Re}\left[\sum_{m\in\mathbb{Z}} \delta h_m(t, r) e^{im\theta}\right]$$

- We select specific azimuthal modes by performing a polar Fourier transform and we extract the associated radial profiles $\delta h_m(t, r)$. Azimuthal modes with $m > 0$ are co-rotating with the flow while modes with $m < 0$ are counter-rotating with the flow.

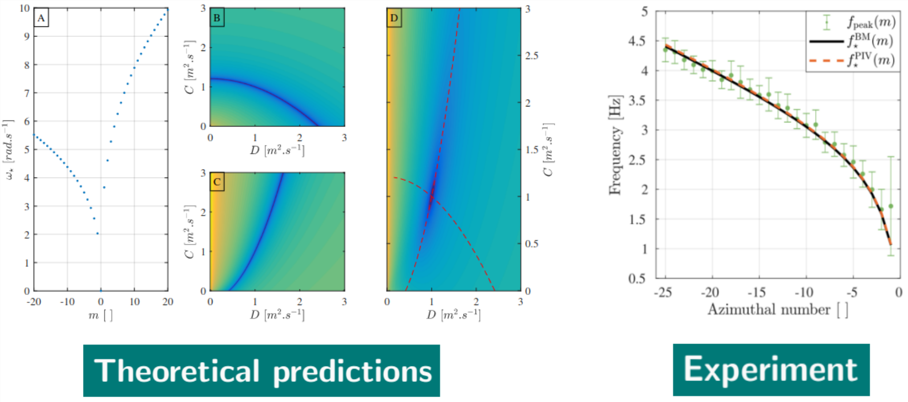
- By calculating the time Fourier transform of $\delta h_m(t, r)$, we estimate the *Power Spectral Density* (PSD) of each m-mode for $r \in [7.4\,\mathrm{cm}, 25\,\mathrm{cm}]$.

Quasinormal ringing in fluids

The PSDs are finally averaged over the radius in order to look at the r-independent frequency content, i.e. the oscillation frequency of the LR modes. For each averaged PSD, corresponding to a different m, the location of the peak, $f_{\mathrm{peak}}(m)$, is obtained.



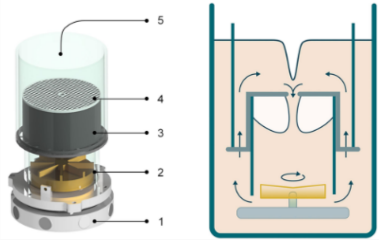
Quasinormal ringing in fluids



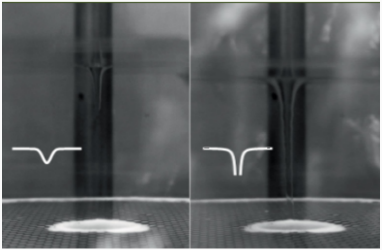
T.Torres, S.Patrick, MR, S.Weinfurtner, CQG 36, 194002 (2019)

T.Torres, S.Patrick, MR, S.Weinfurtner, PRL 125, 011301 (2020)

Quasinormal ringing in superfluids

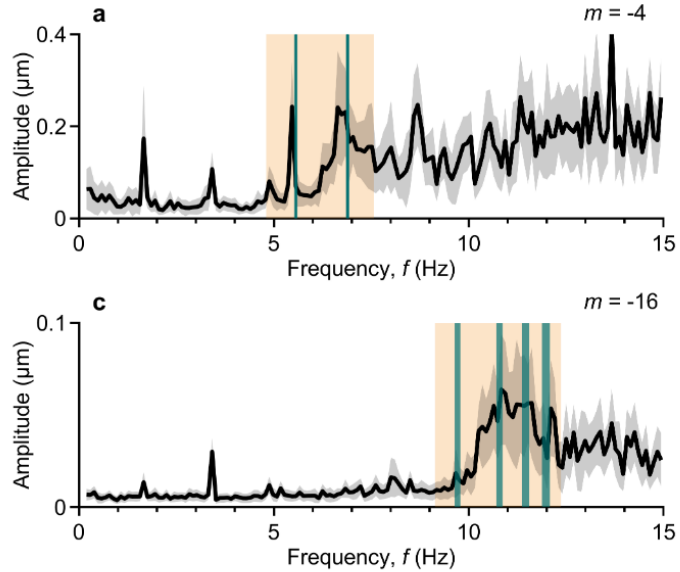


Experimental setup: The flow is driven by a spinning propeller (centrifugal pump). Superfluid helium flows along the outer cylindrical boundary and then towards the central drain hole, forming a draining (bath-tub) vortex.

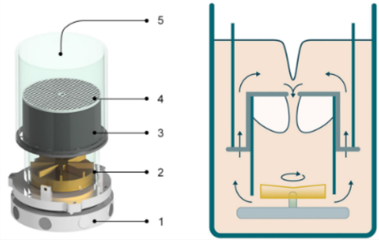


Experiments to observe quasinormal modes and the effect of the boundaries on the overtones.

Quasinormal ringing in superfluids



Superradiant instabilities in superfluids (work in progress)



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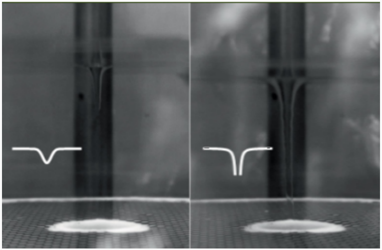
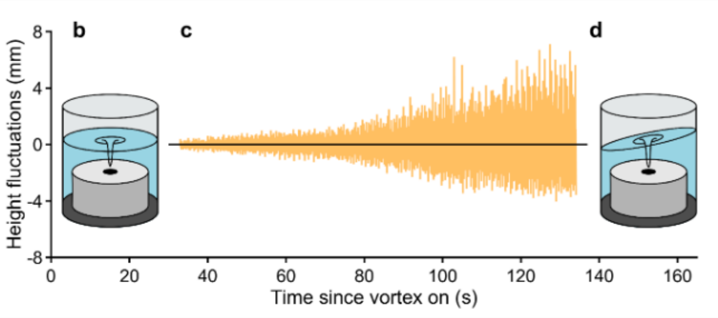
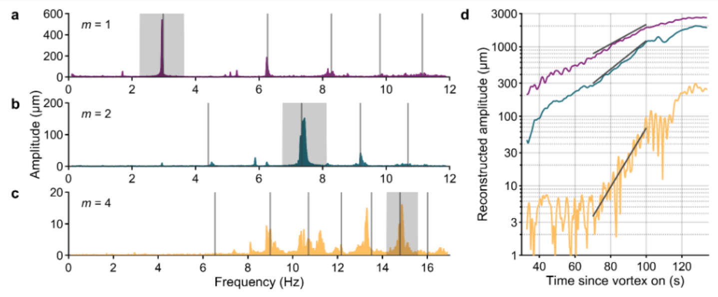


Experiments to observe superradiant instabilities. What is the origin of such instabilities?

Superradiant instabilities in superfluids (work in progress)



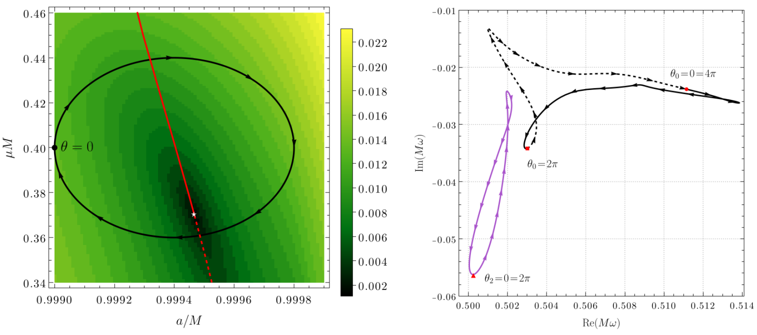


Final Remarks

- Analogue models of gravity have been around for more than 40 years. Experimental realizations began approximately 15 years ago. Most experiments so far are based on 1D systems, so we want to improve and explore more possibilities in 2D systems.
- Physicists have been able to observe several phenomena through analogue models of gravity, including the Hawking effect, superradiant scattering and the characteristic oscillation frequency of a vortex.
- Active area of research: other systems and other phenomena are being investigated.

Future prospects

- Non-hermitian physics: exceptional points in QNM ringing of analogues (induced by vorticity or other degrees of freedom)?
- Recent work (2407.20850, 2408.13964): degeneracy of QNMs and associated geometric phases in Kerr black holes:



- See also works by O. Dias, J. Santos and collaborators [2205.13072 and 2305.11216] and by H. Motohashi [2407.15191].