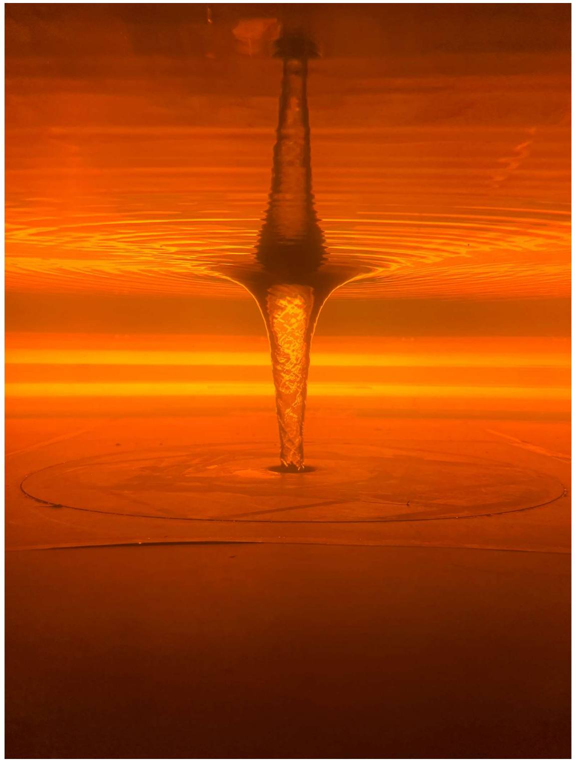
Rotating black holes in the lab



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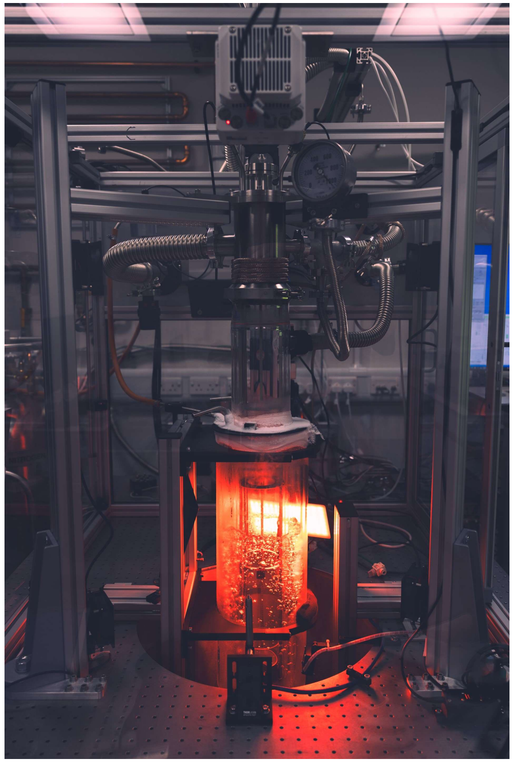
QSimFP



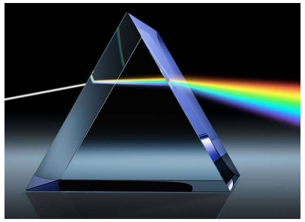
Overview

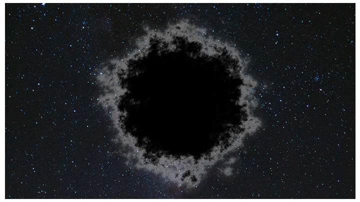
1. Analogue spacetimes
2. Black hole ringdown
3. Superradiance
4. Summary

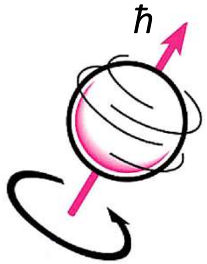
Motivation

1. Study possible signatures of quantum gravity, for example...

- Lorentz violations (string theory, LQG, modified gravity)
- Modified boundary conditions (echoes, fuzzballs, compact objects)
- Quantised charges (black hole mass/area, angular momentum)

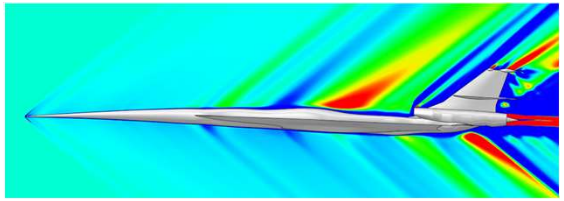


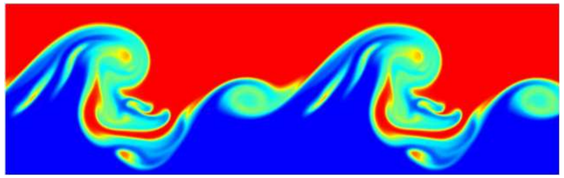




2. Use gravity analogue to study fluid behaviour, for example...

- Stability of supersonic flows (relation to horizon physics)
- Vortex dynamics (connected to superradiance)
- Import techniques (and insights) from gravity





Overview

1. **Analogue spacetimes**
2. Black hole ringdown
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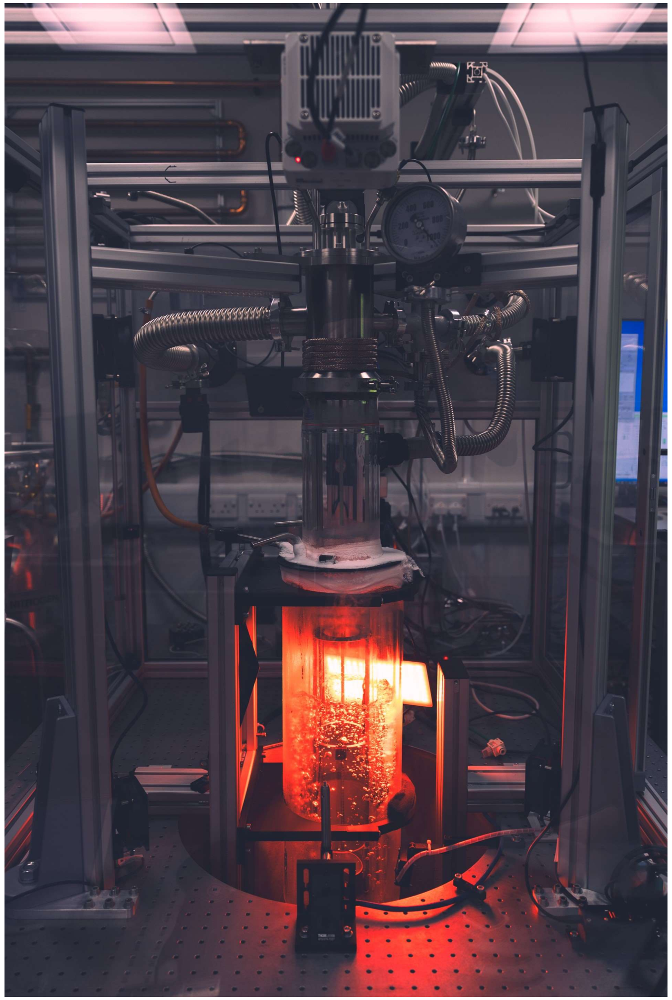


Analogue spacetimes

A massless scalar field ϕ in curved spacetime obeys:

$$\Box\phi \equiv \frac{1}{\sqrt{-g}}\partial_\mu\left(\sqrt{-g}\,g^{\mu\nu}\partial_\nu\phi\right)=0$$

ϕ = waves, $g_{\mu\nu}$ = metric fixed by background

1. Surface waves in water

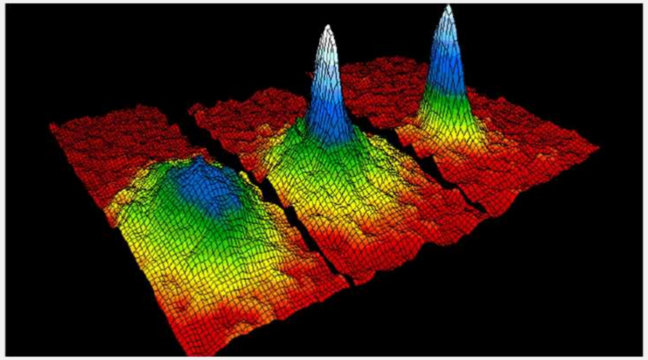
$$\delta v = \nabla\phi$$

$$(\partial_t + v\cdot\nabla)^2\phi - c^2\nabla^2\phi = 0$$

$c=\sqrt{gh}$ wave speed

$$g_{\mu\nu} = \begin{bmatrix} -(c^2-v^2) & -\vec{v} \\ -\vec{v} & \mathbb{1} \end{bmatrix}$$

2. Sound waves in BECs



GPE) $i\hbar\partial_t\Psi = \frac{-\hbar^2}{2M}\nabla^2\Psi + \lambda|\Psi|^2\Psi$

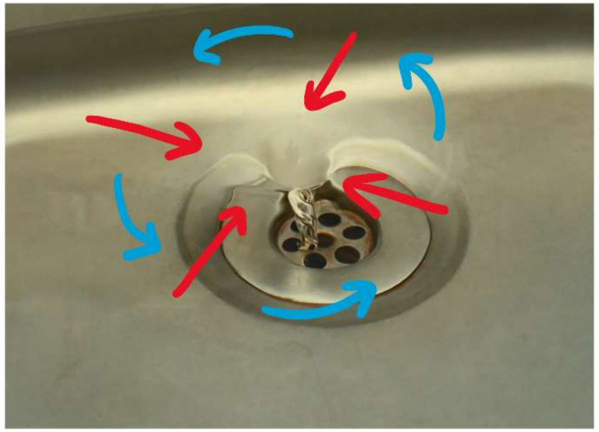
Fluid) $\Psi = \sqrt{n}\,e^{iS - i\mu t/\hbar}$, $\vec{v} = \frac{\hbar}{M}\nabla S$

$$\partial_t v + v\cdot\nabla v + \frac{\nabla P}{\rho} = \nabla\left(\frac{\hbar^2}{2M}\frac{\nabla^2\sqrt{n}}{\sqrt{n}}\right)$$

$$\partial_t n + \nabla\cdot(nv) = 0, \quad P = \frac{\lambda}{2}n^2$$

Sound) $n \to n_0 + \delta n$, $S \to S_0 + \frac{M}{\hbar}\phi$ $\quad c = \sqrt{\frac{\lambda n_0}{M}}$

Rotating black hole analogues



$\vec{V} = V_r \hat{e}_r + V_\theta \hat{e}_\theta$

$V_r = -D/r$ draining flow

$V_\theta = C/r$ circulating flow

$$ds^2 = -c^2dt^2 + \left(dr + \frac{D}{r}dt\right)^2 + \left(rd\theta - \frac{C}{r}dt\right)^2$$

horizon: $r_h = D/c$

ergosphere: $r_e = \frac{\sqrt{C^2+D^2}}{c}$

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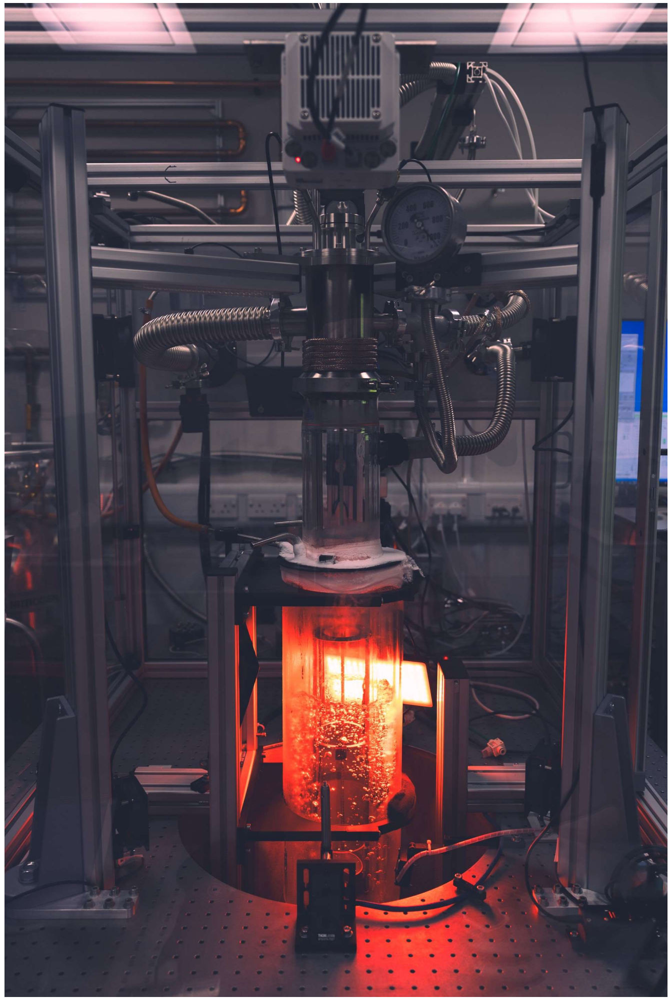
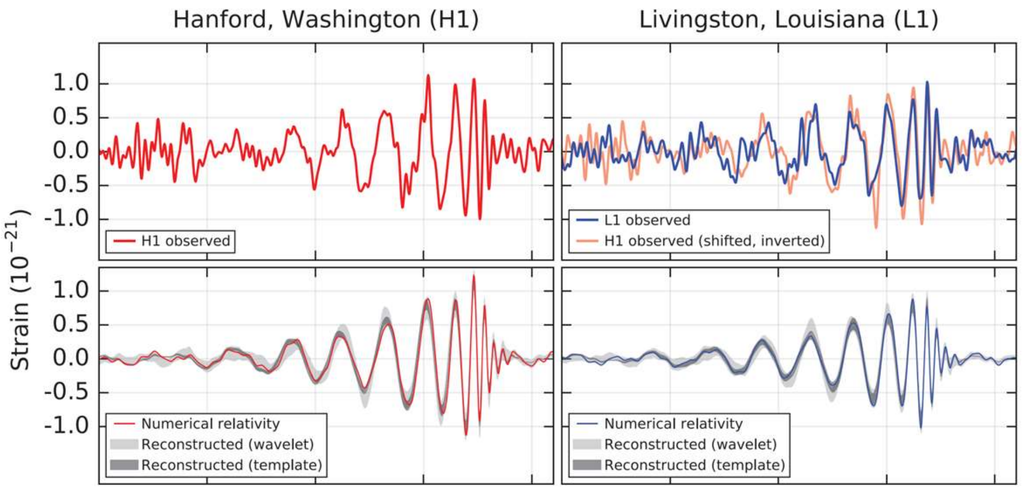


Black hole ringdown

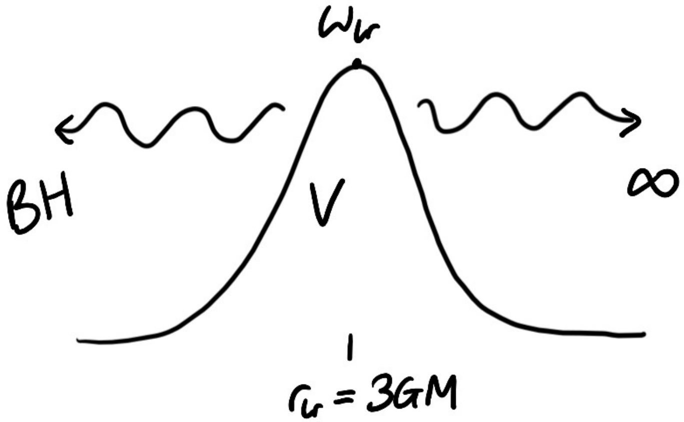
- Effect in linear field theory which probes strong field regime.
- Measured by LIGO/VIRGO



Phys. Rev. Lett. **116** 061102 (2016)

e.g. for Schwarzschild

$$-\partial_x^2\psi + (-\omega^2+V)\psi = 0$$

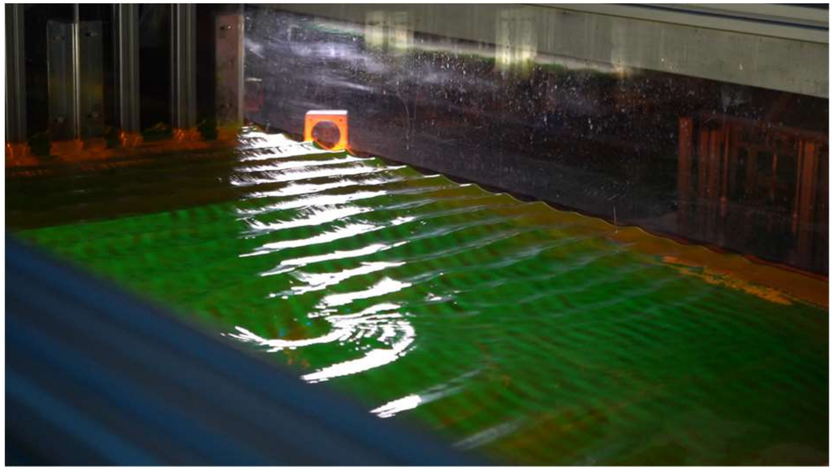


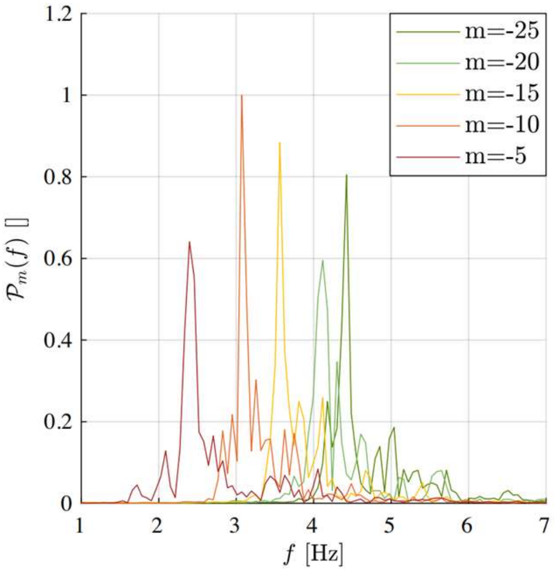
$$\omega_{QNM} \simeq \omega_{lr} - i\frac{\sqrt{-2V''_{lr}}}{2\omega_{lr}}\left(n+\tfrac{1}{2}\right)$$

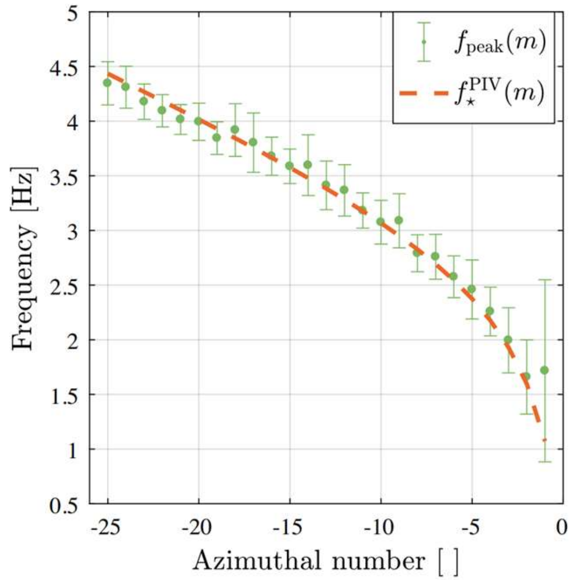
overtones $n = 0, 1, \ldots$

Ringdown experiments (2017)

Phys. Rev. Lett. **125** 011301 (2020)





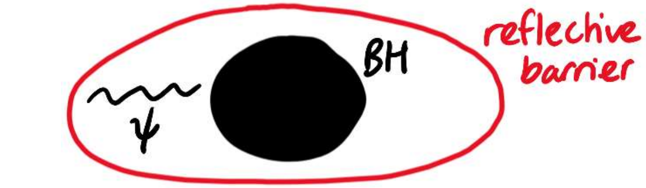


- Boundary reflections obscure ringdown signal
- Each m-mode has distinct spectral peak in the noise
- These peaks are located at the light-ring frequency

TAKEAWAY: suggests "*finite-size* + *noise* = *QNMs*" ?!

Finite-size effects

Based on work in
arXiv:2406.11013

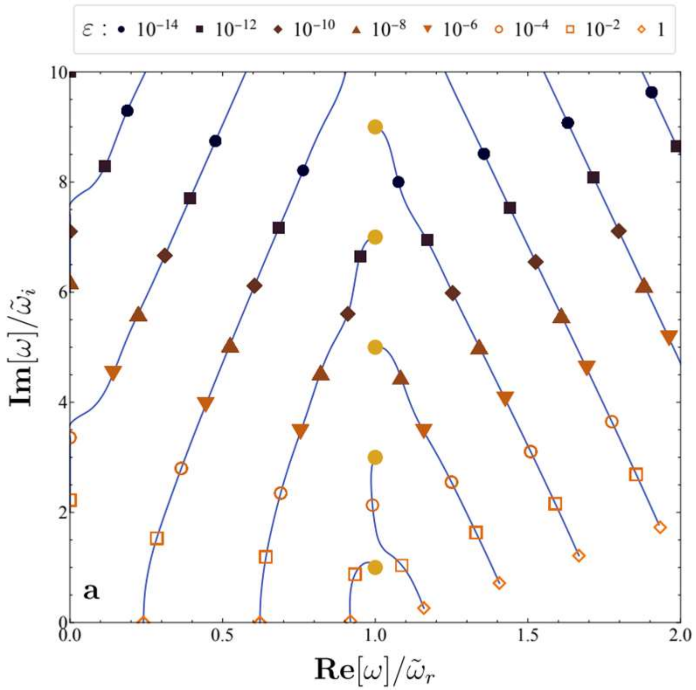


$$-\partial_x^2\psi + (-\omega^2+V)\psi = 0$$

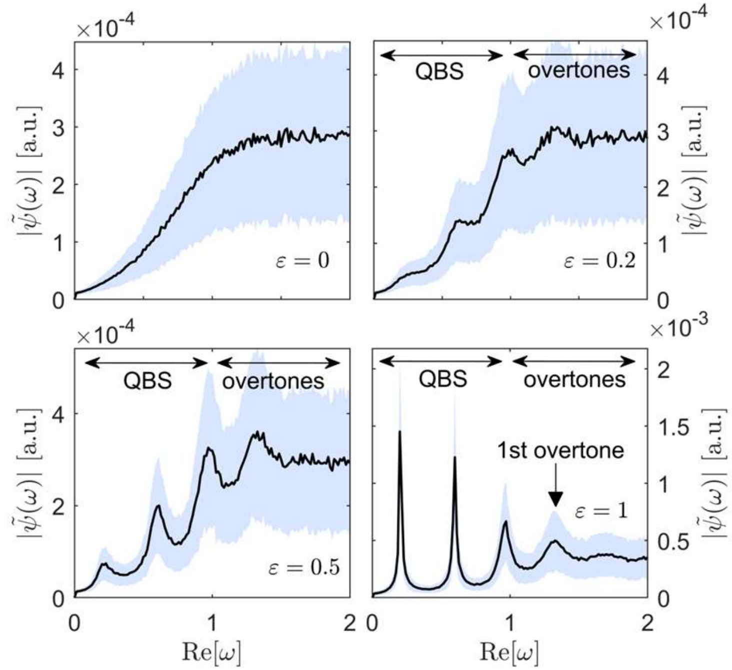
Pöschl-Teller model

$$V = \mathrm{sech}^2\,\alpha x$$

- Varying ε determines a **spectral flow**



- For large ε, QNMs emerge as **peaks in the noise**

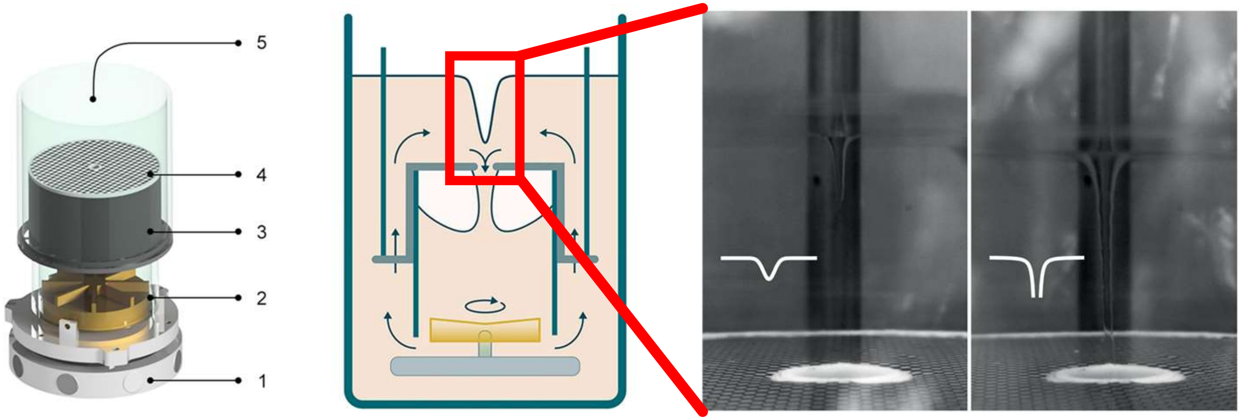


TAKEAWAY: finite size effects *increase overtone lifetime* and *enable QNM excitation by noise*

Superfluid experiments (2025)

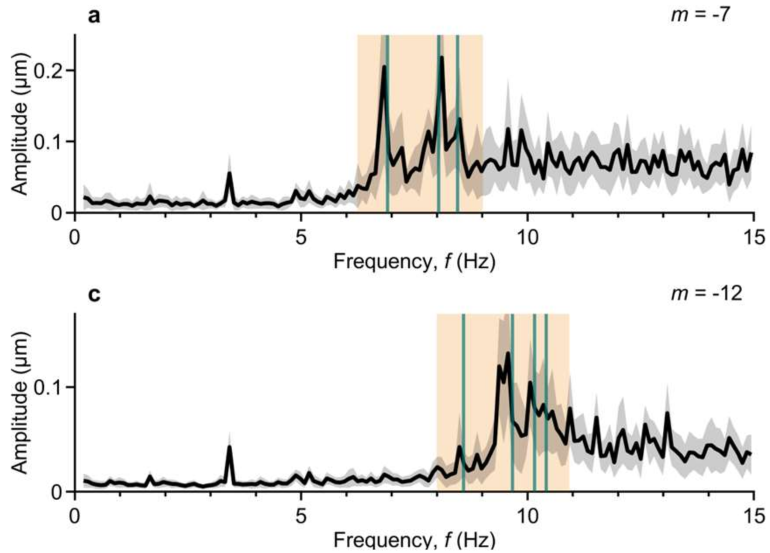
Based on work in
arXiv:2502.1109

- ➢ Experimental schematic
- ➢ Side profile



Nature **628** 66 (2024)

- ➢ Results for $m = -7, -12$



Consistent with…

- Reflecting BCs at the wall
- Absorbing BCs in the core

TAKEAWAY

- ➢ Proof of principle that noise in finite size analogues can be used to measure overtones
- ➢ Use to investigate (a) spectral stability, (b) overtones vs. nonlinearities

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4. Conclusion

Rotational superradiance

- Amplified wave extracts rotational energy from system
- Allows rotating BHs to shed their angular momentum

$|v|^2 > c^2$

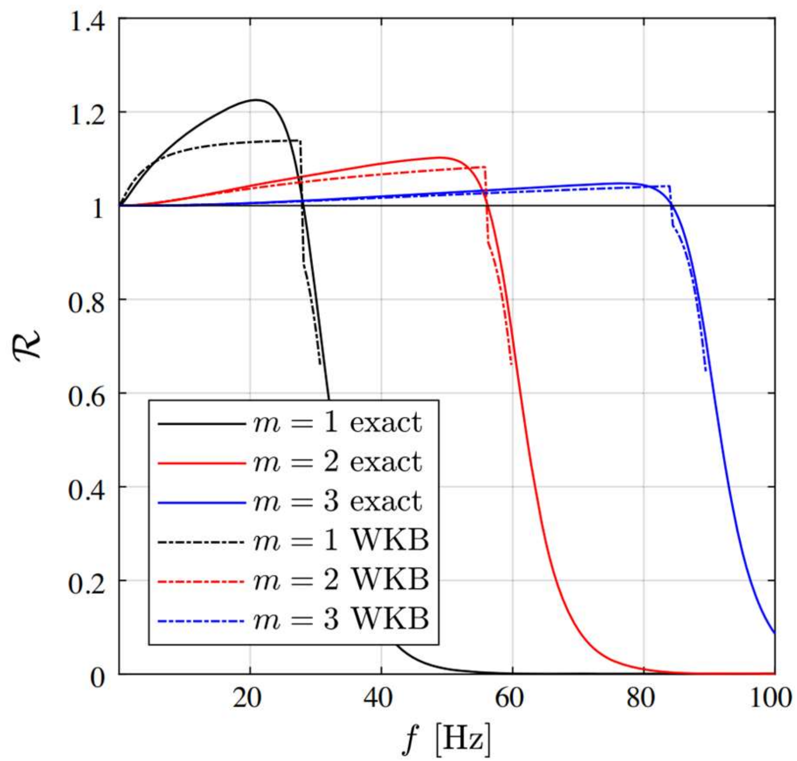
ergosphere

$E < 0$ waves

energy conservation

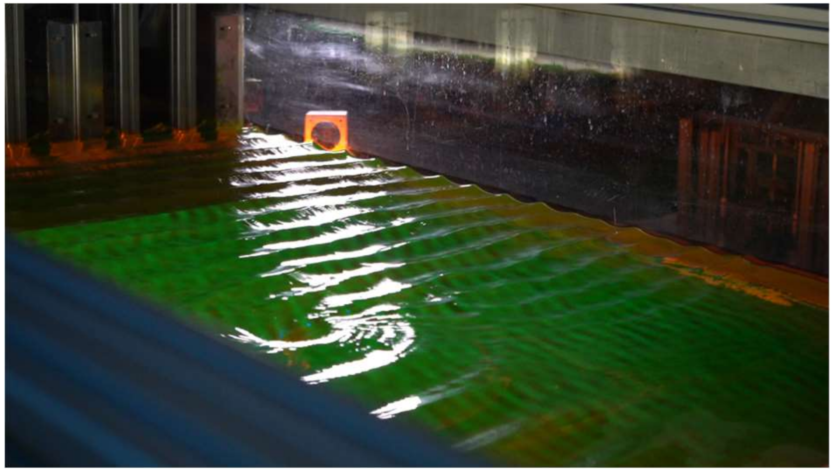
$$|R|^2 + \frac{\omega - m\Omega_h}{\omega}|T|^2 = 1$$

$$\omega < m\Omega_h \Rightarrow |R| > 1$$

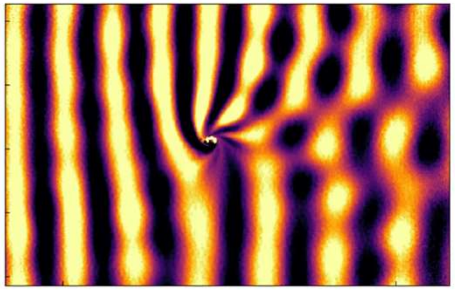


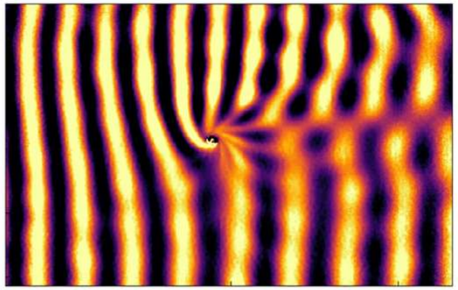
Nature Physics **9** 833 (2017)

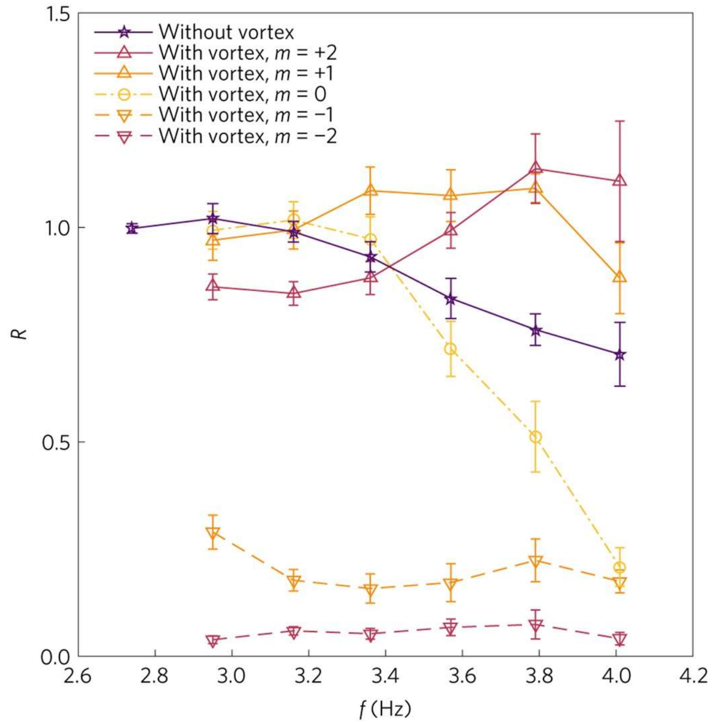
Superradiance experiments (2016)



- ➢ Monochromatic wave of different frequencies







- ➢ Amplification of corotating waves

Deep water - Phys. Rev. D **102**, 084041 (2020)
Capillary-gravity - Phys. Rev. D **110** 124068 (2024)
Sound in BEC - Class. Quant. Grav. **38** 095010 (2021)

Superradiance with LV

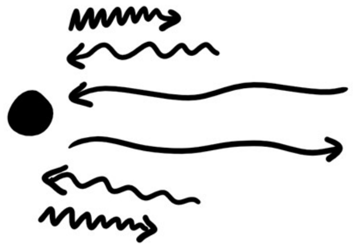
$$(\omega - v\cdot k)^2 = F(k)$$

$$F_{surf}(k) = \left(gk + \frac{\sigma}{\rho}k^3\right)\tanh(hk)$$

$$F_{BEC}(k) = c^2(k^2 + \xi^2 k^4)$$

- Relativistic at low k

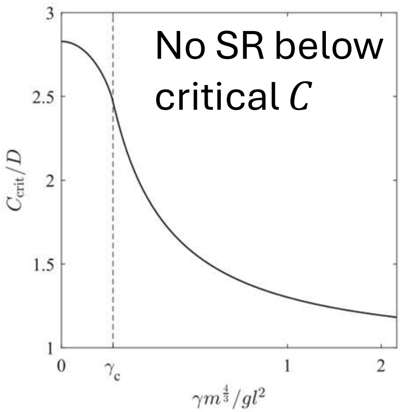
- More modes at high k



- How do extra modes scatter?
- When does core absorb negative energy?

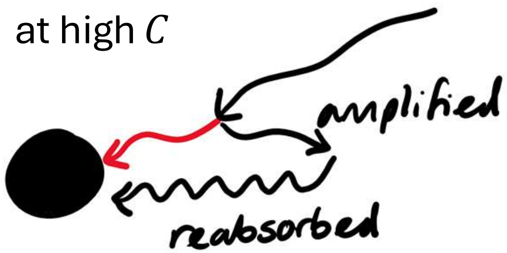
Surface waves

$$0 < \omega < \left(\frac{g^2}{D}\right)^{\frac{1}{3}} \frac{m^{1/3}}{2^{2/3}3}\left(\frac{C}{D} - 2^{3/2}\right)$$



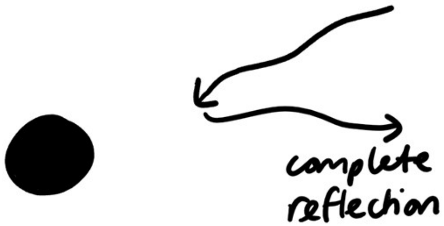
No SR below critical C

SR modes reabsorbed at high C



Sound waves (BEC)

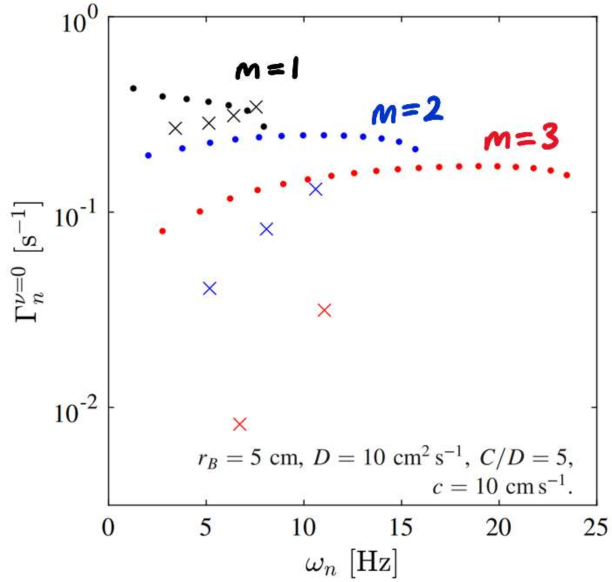
$$0 < \omega < m\Omega_h / 1 + m\xi^2/r_h^2$$



No SR for high m and low C

TAKEAWAYS
- LV alters SR threshold
- LV can stop SR for certain modes

Black hole bomb



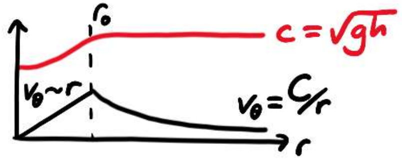
- Black hole bomb (Press & Teukolsky)
- Occurs for ultra-light scalars (e.g. axions)

$$S(\omega_n) = \pi(n + \tfrac{1}{4})$$

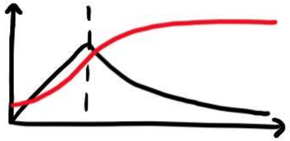
$$\Gamma_n = \frac{\log|R|}{T} - \langle \nu k^2 \rangle_T$$

Phys. Rev. D **110** 124068 (2024)

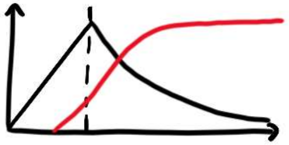
Vorticity leads to extra degrees of freedom!



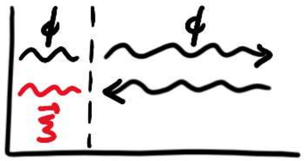
- Core with $\nabla\times v \neq 0$



- Ergoregion intermediate C



- No rotational core for large C



- φ has $E < 0$ in ergoregion
- ξ has $E < 0$ with no ergoregion

TAKEAWAYS:
- Amplification + confinement = instability!
- BHB dominates a rapid rotations

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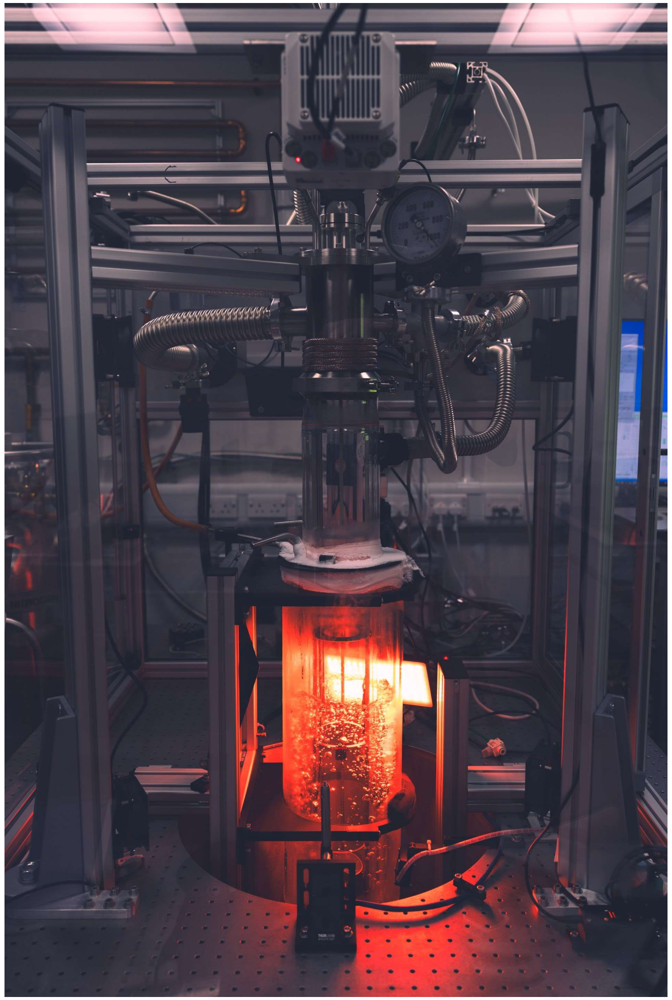
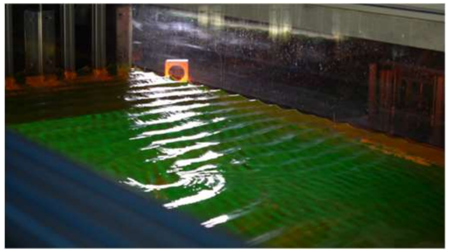
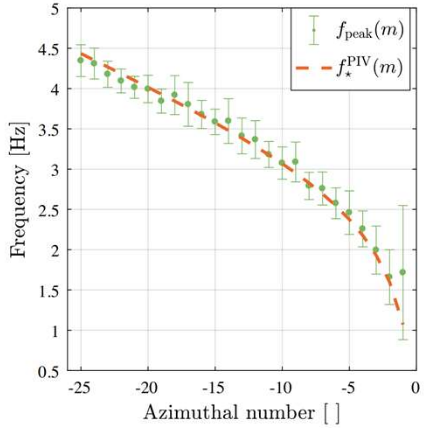
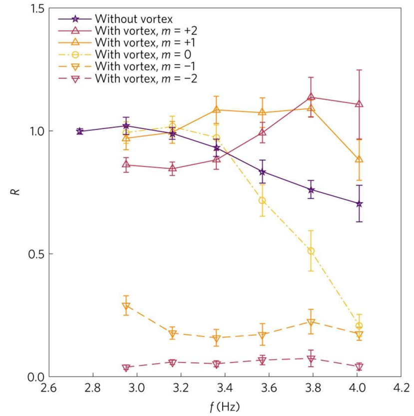
4. **Summary**



Summary

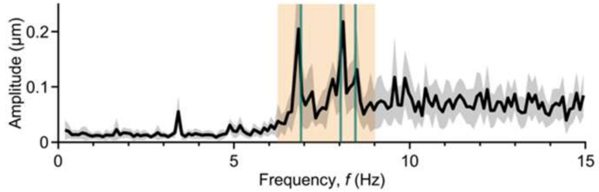






- Waves see draining vortex as a rotating BH

- Measured QNMs and superradiance in water



- Finite size + noise → QNM overtones

- Finite size + superradiance → BH bomb instability

- LV effects lead to spectral modifications of QNMs and SR (can suppress both)

- Next: study effect of quantised angular momentum.