Title: Simulating a quantised black hole

Speakers: Ruth Gregory

Collection/Series: Quantum Gravity

Subject: Quantum Gravity

Date: January 30, 2025 - 2:30 PM

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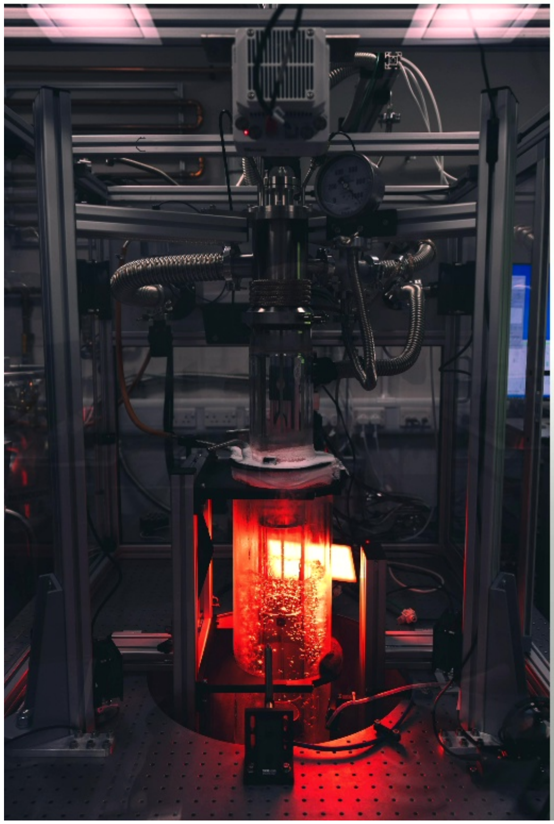
Abstract:

Horizons can occur in a wide range of physical situations, many of which we can construct in the lab. Most gravity simulators observe features, like super-radiance, that are analysed as a continuum effect in gravity, whereas many interesting "beyond GR" features theorise about the impact of quantised aspects of the black hole.

In this talk, I will describe recent experimental work on a liquid helium giant vortex that naturally has quantisation, and how we hope to explore "black hole" phenomena in a broader context.

Based on [arXiv:2308.10773 [gr-qc]]
with: Patrik Svancara, Pietro Smaniotto, Leonardo Solidoro, James MacDonald, Sam Patrick, Carlo Barenghi and Silke Weinfurtner

QSimFP | Quantum Simulators for Fundamental Physics



GRAVITY LABORATORY

Simulating a Quantised Black Hole

“Rotating Curved Spacetime Signatures from a Giant Quantum Vortex”

Nature **628** 66-70 (2024) arXiv:2308.10773 [gr-qc]

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University of Nottingham, UK

Sam Patrick and **Ruth Gregory**
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Newcastle University, UK

KING'S College LONDON

QG/PI SEMINAR – 30/1/25

Outline

- QSimFP
- Fluid analogs: an introduction.
- Quantum systems - the experiment
- Different dispersions – the theory
- Where next?

Why Experiment?

While we are increasingly confident of our theories of General Relativity and the Standard Model, there are gaps and puzzles.

One of the core issues is defining a vacuum. How sure are we of the classical / quantum split?

Non-perturbative processes in QFT and gravity are far less well tested than the controlled environment of a collider.

Black holes do not sit well with QFT – eg unitarity. Can we explore from a different direction?

Much speculation around the quantum nature of black holes involves assumptions about how physics changes at high energies, or if boundary conditions change – we can do this with analogs!

The team

QSimFP

- St Andrews
- Newcastle
- KCL
- Nottingham
- Cambridge
- UCL
- RHUL

External partners
- J. Braden (CA)
- S. Erne (AU)
- M. Johnson (CA)
- J. Schmiedmayer (AU)
- R. Schuetzhold (DE)
- W.G. Unruh (CA)

Gravity simulators
Silke Weinfurtner
(PI, Nottingham)

Science & Technology Facilities Council

EPSRC Engineering and Physical Sciences Research Council

Cosmology & black holes
- Ruth Gregory
- Jorma Louko
- Ian Moss
- Hiranya Peiris
- Andrew Pontzen

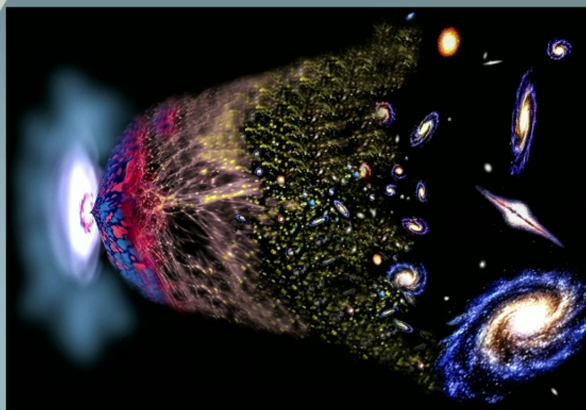
Ultracold atoms
- Thomas Billam
- Zoran Hadzibabic

Superfluids & optomechanics
- Carlo Barenghi
- Anthony Kent
- John Owers-Bradley
- Xavier Rojas
- Viktor Tsepelin

Quantum circuits
- Gregoire Ithier

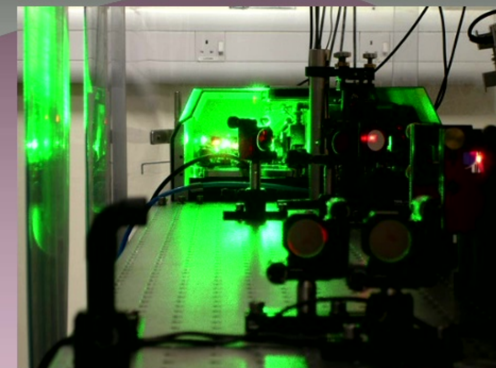
Quantum optics
- Friedrich Koenig

QSimFP



Quantum Vacuum:
- False Vacuum Decay
- Observer dependence

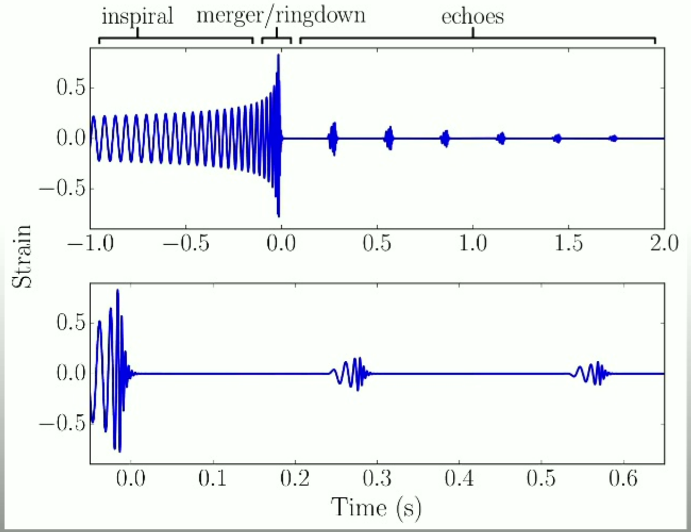
<u>Quantum Black Holes:</u>
- <u>Black hole ring-down</u>



SW

Discretizing a Black Hole: M / S

One of the most common, yet controversial, phenomena associated to discretising the properties of a black hole is that of Echoes.



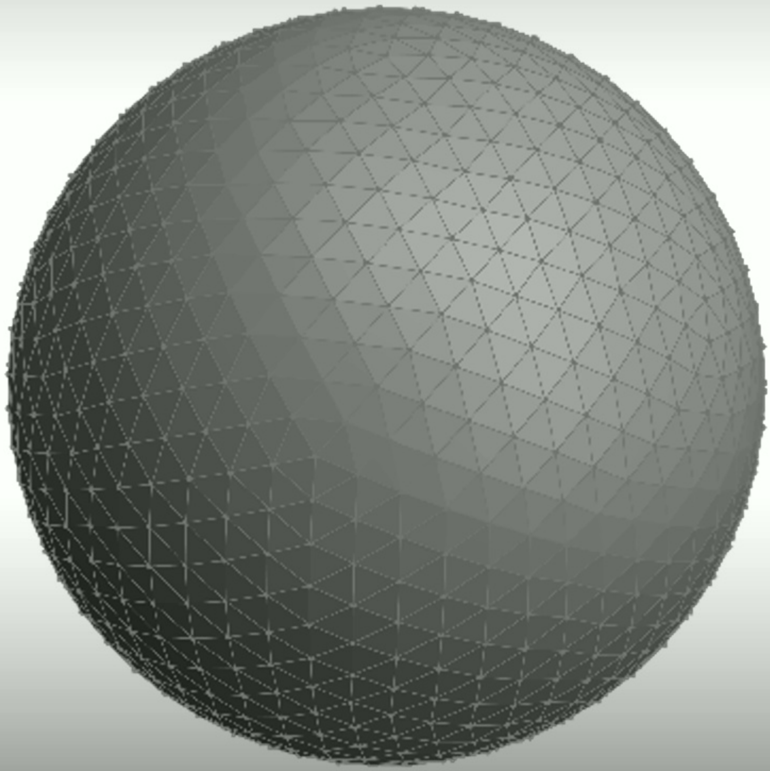


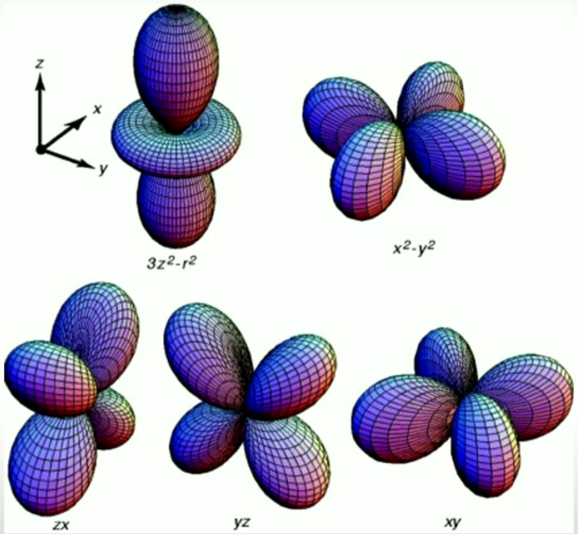
Image credit: B Knispel

Discretising a Black Hole: J

But we can also imagine that black holes carry discrete angular momentum. How is that shed or accreted?

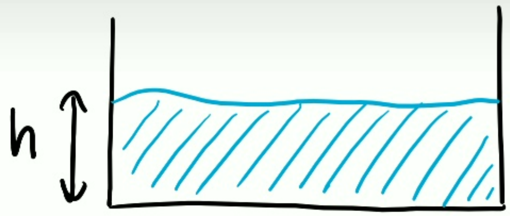
Does a similar quantisation occur in superradiance?

To explore, want to build a quantized fluid "hole".



Basic Analogs – Fluid Simulators

Basics – The Bathtub



$$(\partial_t + \mathbf{v}\cdot\nabla)\,\mathbf{v} + \frac{\nabla p}{\rho} - \mathbf{g} - \nu\nabla^2\mathbf{v} = 0$$

$$\nabla\cdot\mathbf{v} = 0$$

Navier-Stokes

Irrotational

$$\nabla\times\mathbf{v} = 0 \Rightarrow \mathbf{v} = \nabla\phi$$

Coupled system for surface waves:

$$F(k) = k\tanh(hk)$$

$$(\partial_t + \mathbf{v}\cdot\nabla)\phi + g\delta h - \gamma\nabla^2\delta h - 2\nu\nabla^2\phi = 0$$

Integrating out bulk

$$(\partial_t + \nabla\cdot\mathbf{v})\delta h - F(-i\nabla)\phi = 0$$

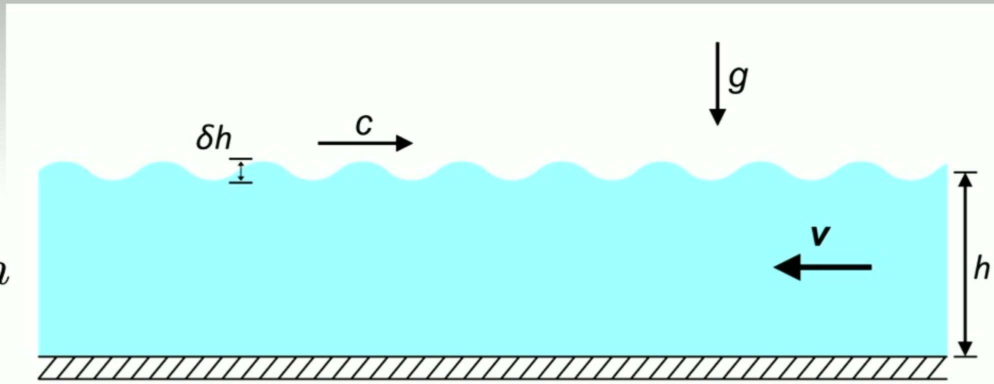
$$\gamma = \sigma/\rho$$

Simple Surface Gravity Waves

Long wavelength:

$$(\partial_t + \mathbf{v}\cdot\nabla)^2\,\phi - c^2\nabla^2\phi = 0\,, \qquad c^2 = gh$$

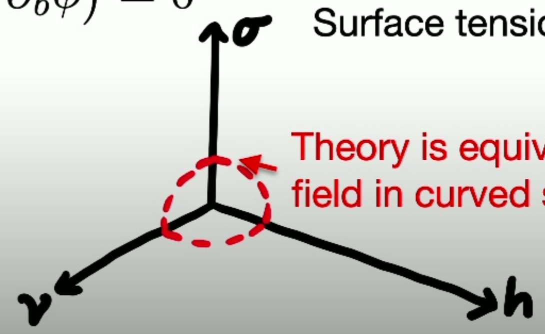
$$\delta h = -\frac{1}{g}\left(\partial_t + \mathbf{v}\cdot\nabla\right)\phi$$



These can be recast in "geometric" form: $\frac{1}{\sqrt{g}}\partial_a\left(\sqrt{g}\,g^{ab}\partial_b\phi\right) = 0$

where

$$g_{ab}dx^a dx^b = c^2\left[c^2dt^2 - (d\mathbf{x} - \mathbf{v}dt)^2\right]$$



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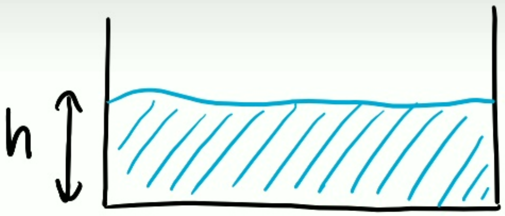

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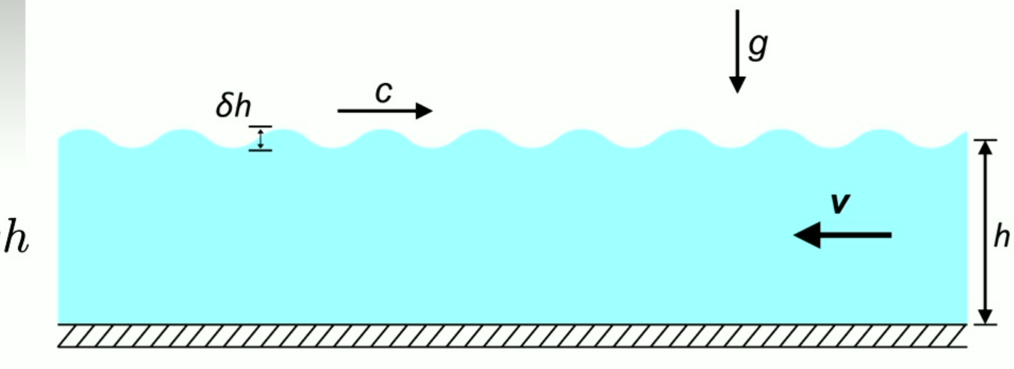

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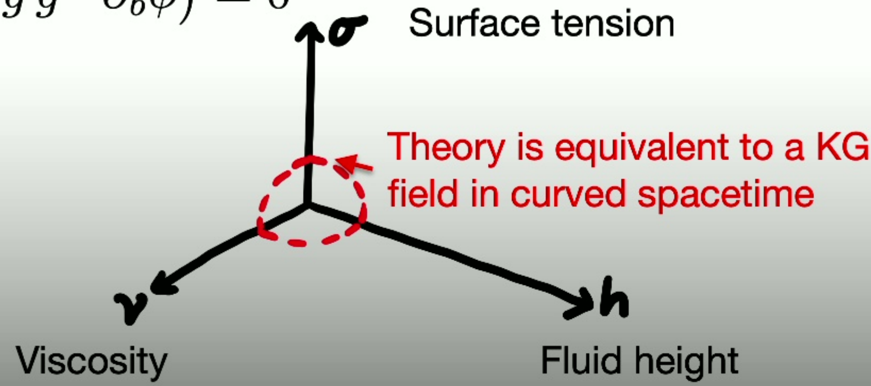
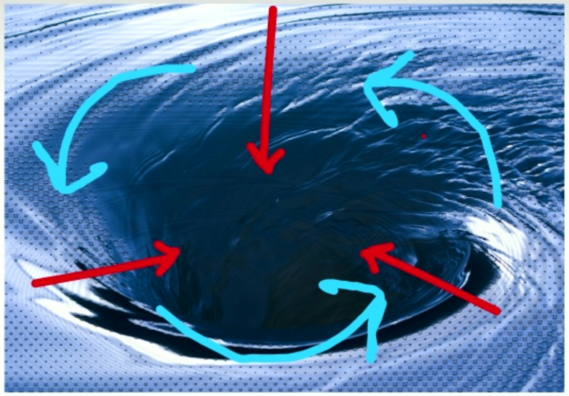


Draining Vortex

$$\mathbf{v} = v_r \mathbf{e}_r + v_\theta \mathbf{e}_\theta$$



$$v_r = -\frac{D}{r} \quad \text{draining flow}$$

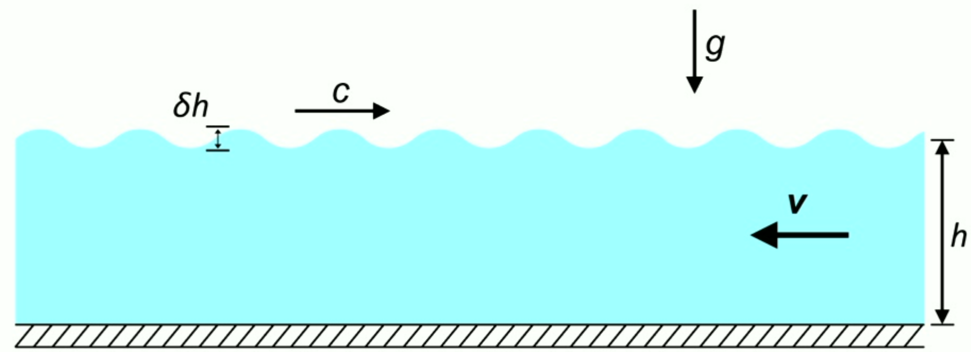
$$v_\theta = \frac{C}{r} \quad \text{circulating flow}$$

The draining vortex simulates a rotating black hole

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

Simple Surface Gravity Waves

Long wavelength:



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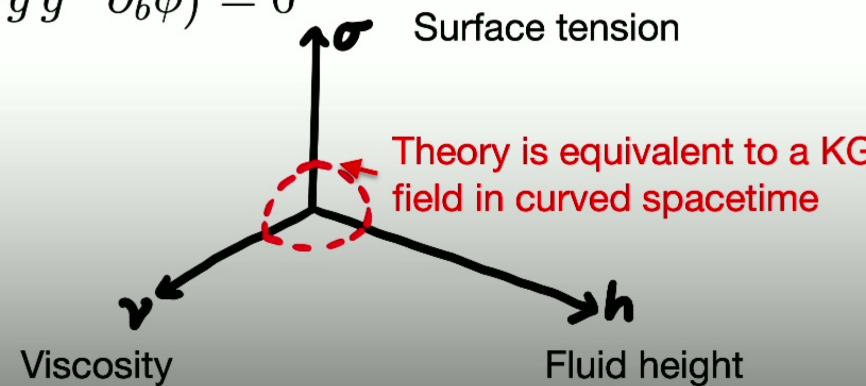
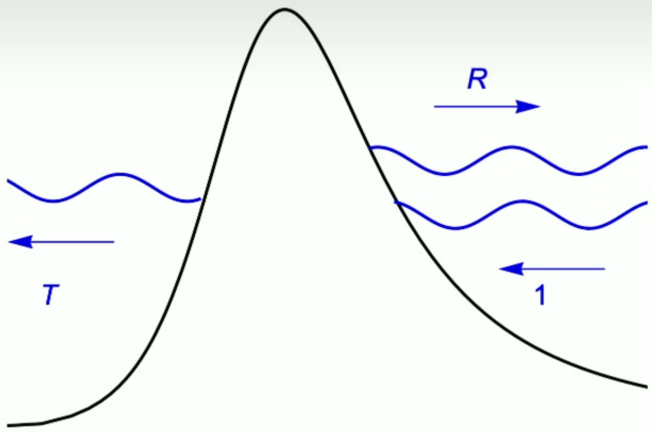
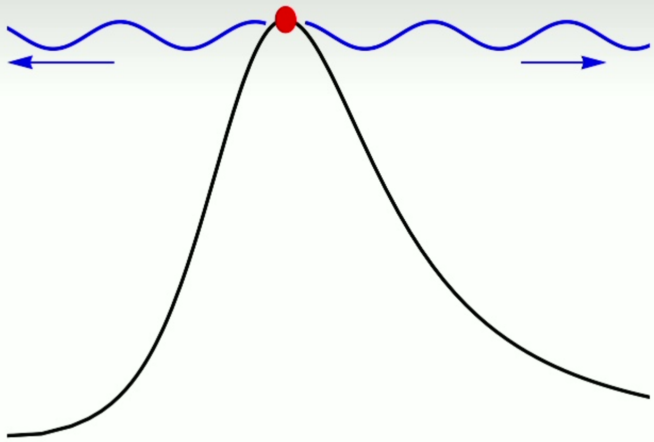


Looking For:
Super-Radiance & Ringdown



$$|R| > 1\,, \quad \omega < m\Omega_h$$



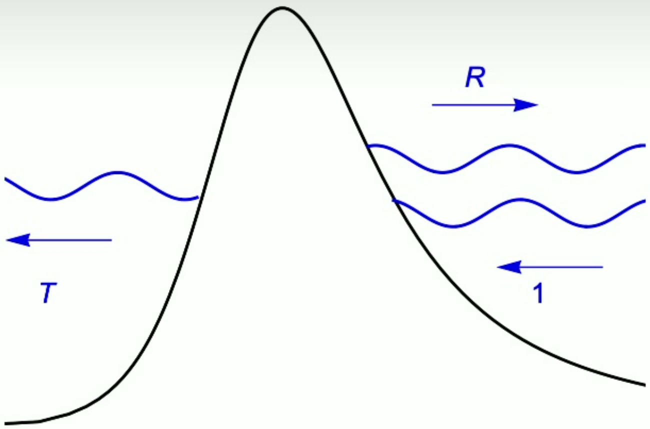
$$\omega_{\rm QNM} \sim \omega_\star - i(n + 1/2)|\lambda|$$

Superradiance is the amplification of low frequency waves by picking up energy from the rotation.

Ringdown is the decay of an excited state around the black hole / vortex

*Cardoso et al. Phys. Rev. D **79** 064016 (2009)*

Super-Radiance



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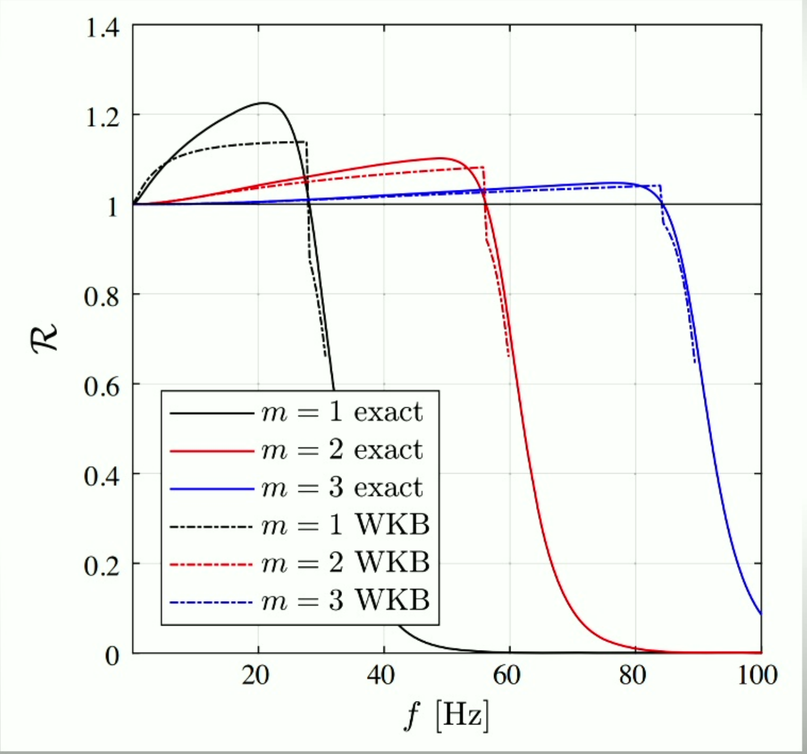
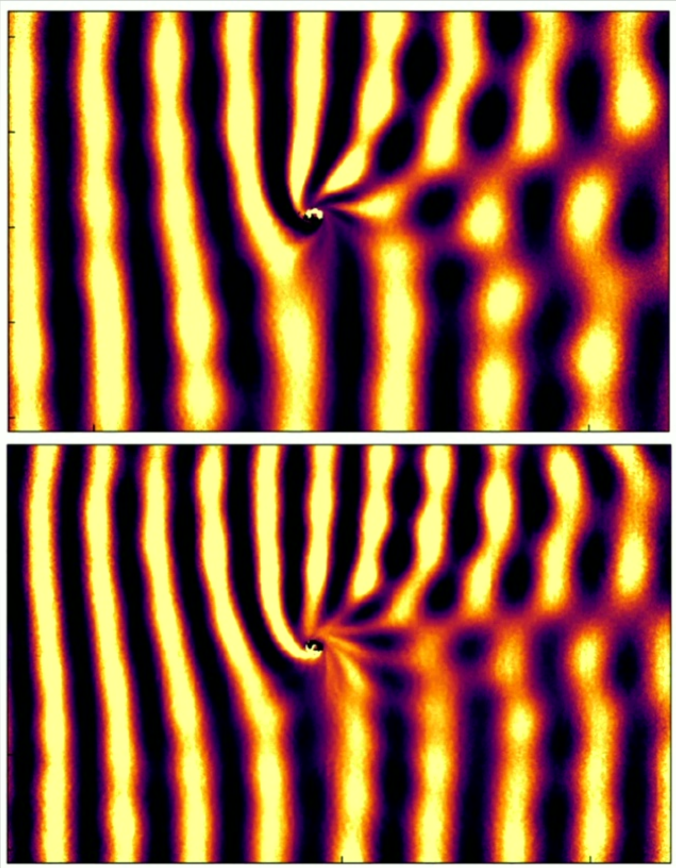
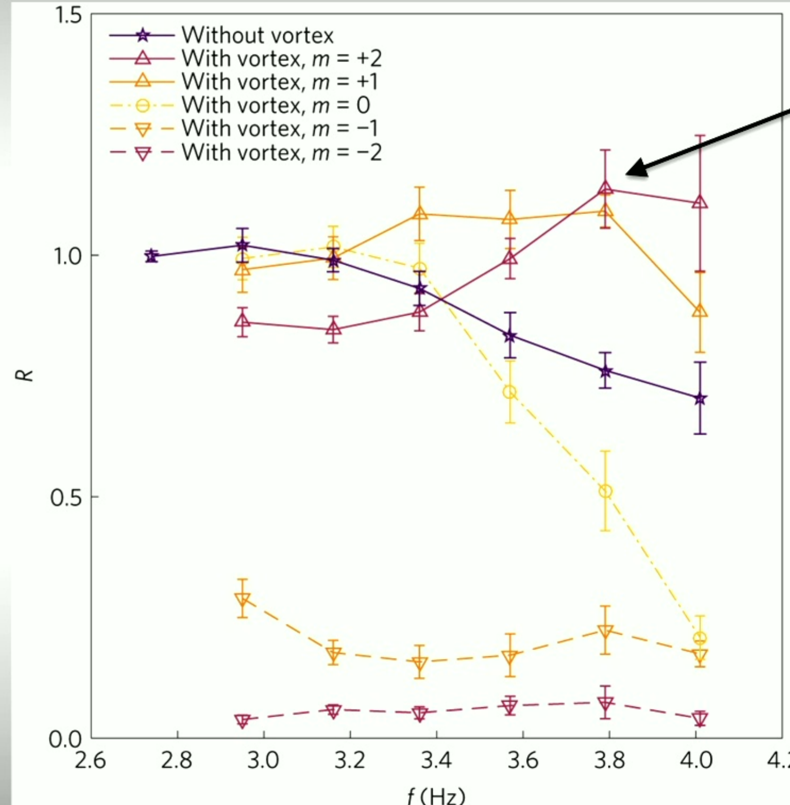


Superradiance



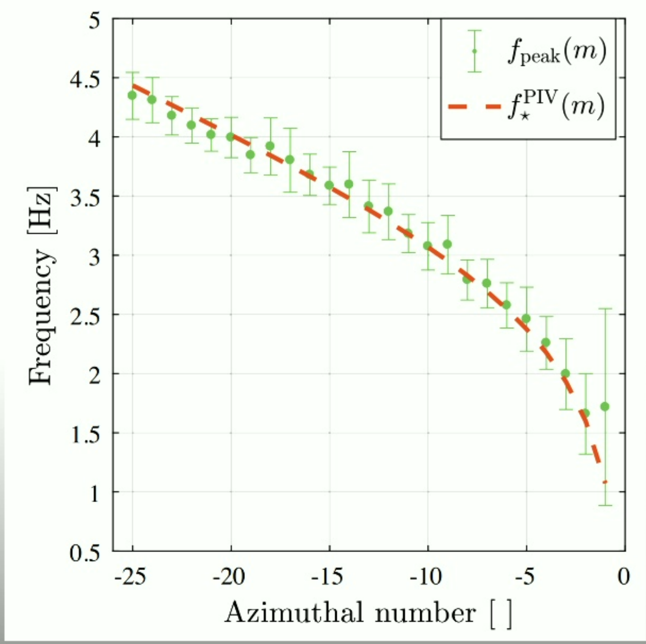


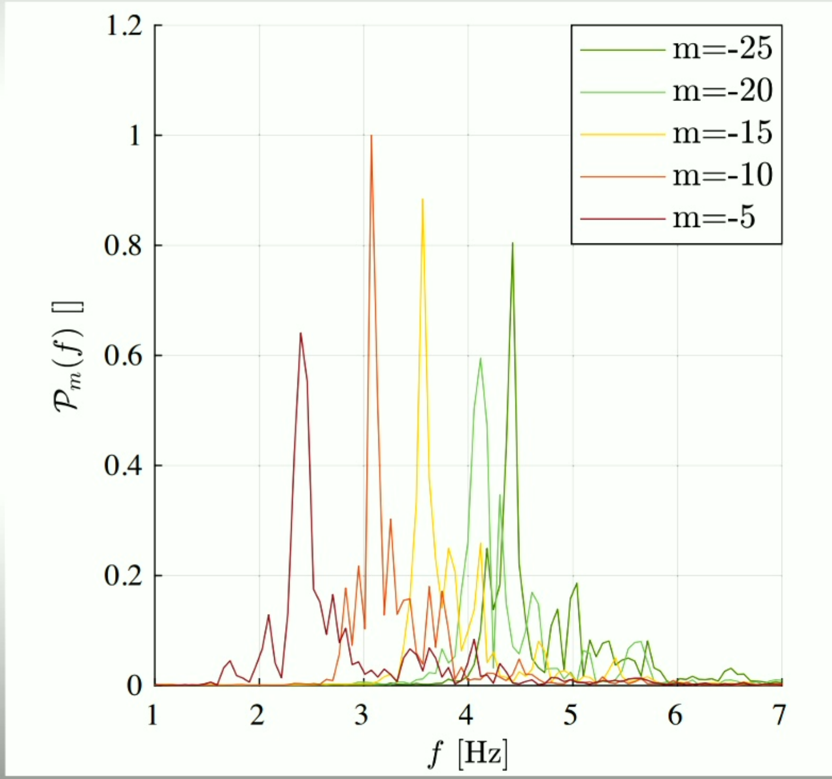
Amplification of corotating modes is consistent with superradiance

Torres et al. Nature Physics **9** 833 (2017)

Ring-down/-ing

Ringing at characteristic frequencies associated to lightring observed.





A Quantum Fluid

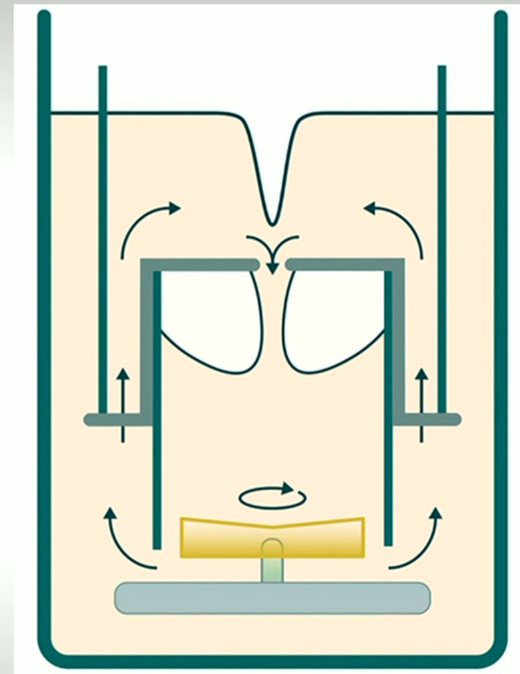
Fluid “black hole” exhibits same phenomena as GR black hole within constraints of experiment.

What happens if we have a less classical set-up?

From Classical to Quantum Fluids

Uses Helium-4,
can't lean over to
stir liquid He!

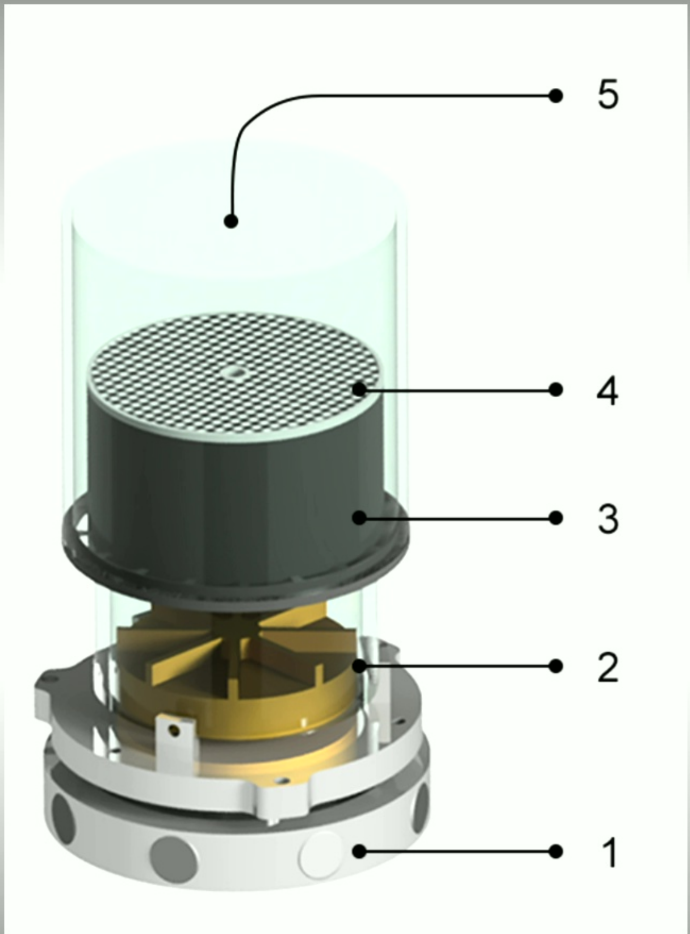
Magnetically coupled
propellor spins to
give circulation.



Based on – Osaka suction vortex
experiment (H Yano et al 2018 J.
Phys. Conf. Ser. 969 012002)

Add draining cavity
for "bathtub" effect.

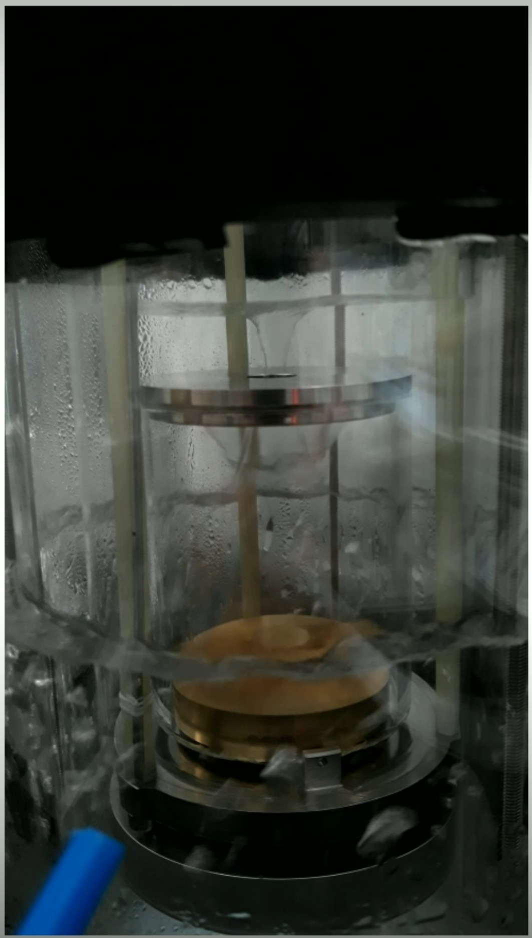
Vortex generator



Experimental area – diameter 75 mm, 40 mm height

1. **Rotation** provided by magnetic coupling
2. **Rotating propeller** acts as a centrifugal pump
3. **Bespoke** 3D printed flow conditioner & draining hole
4. **Patterned disc** provides imaging for ripple detection
5. **Draining vortex** forms in centre

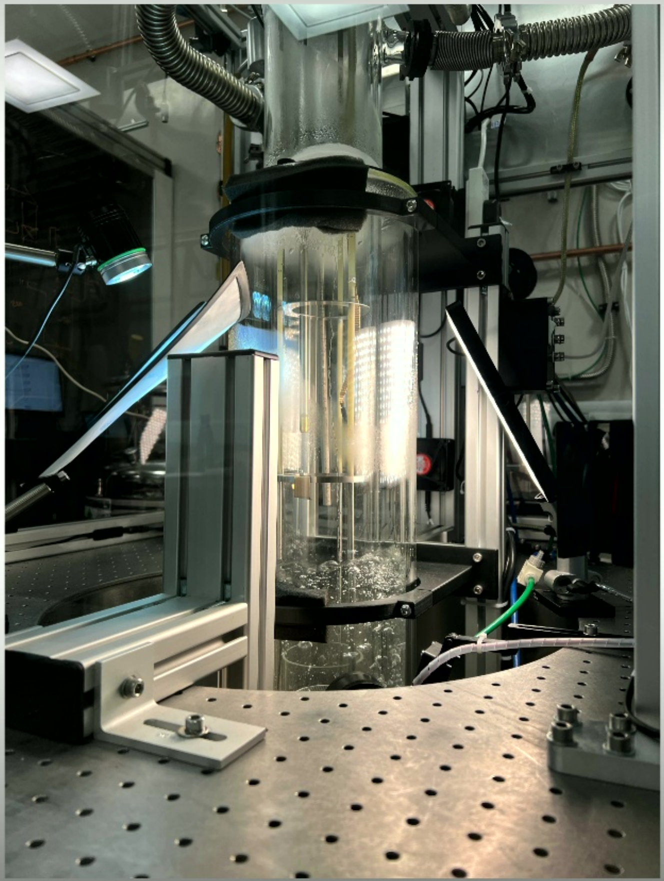
Set-up



Fully transparent - custom glass Dewars without silvering

Experiments at 1.6-1.95 K so far

Propeller speed range 0.5 – 3.5 Hz



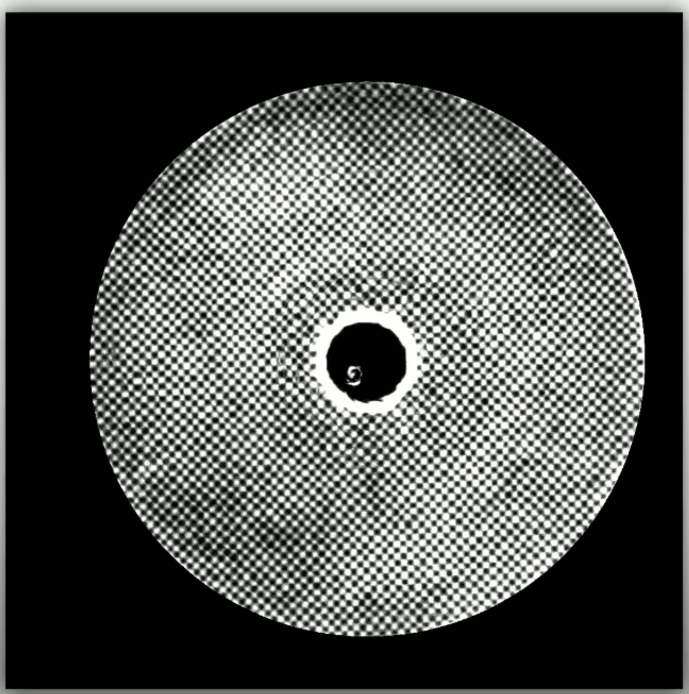
Surfing the Wave

Once a vortex has been formed, it is the surface waves that we want to measure and test.

The patterned disc has a very specific FT, distorted by surface waves.

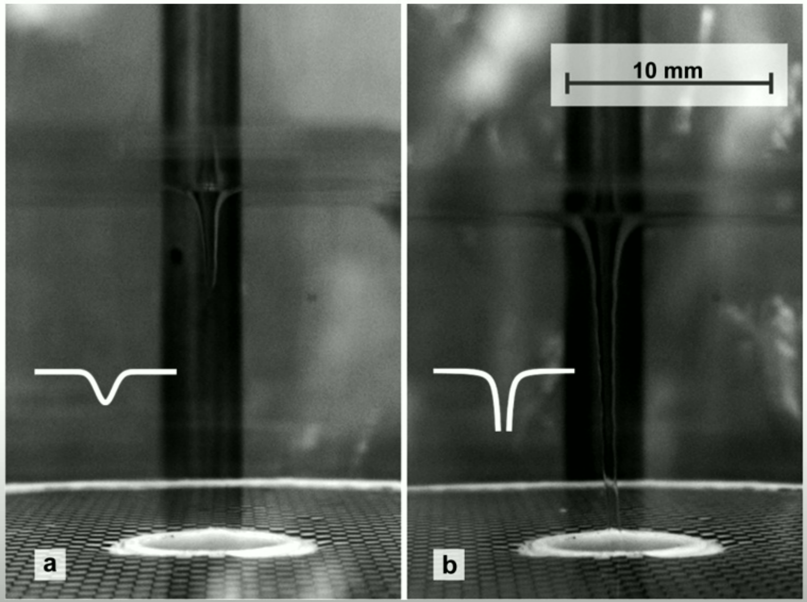
Fourier Transform Profilometry

(high resolution in space and time)

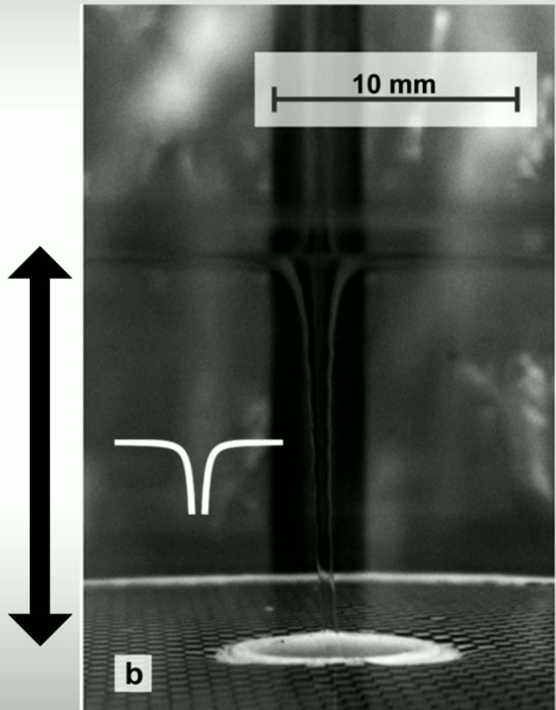


More Messy Modelling!

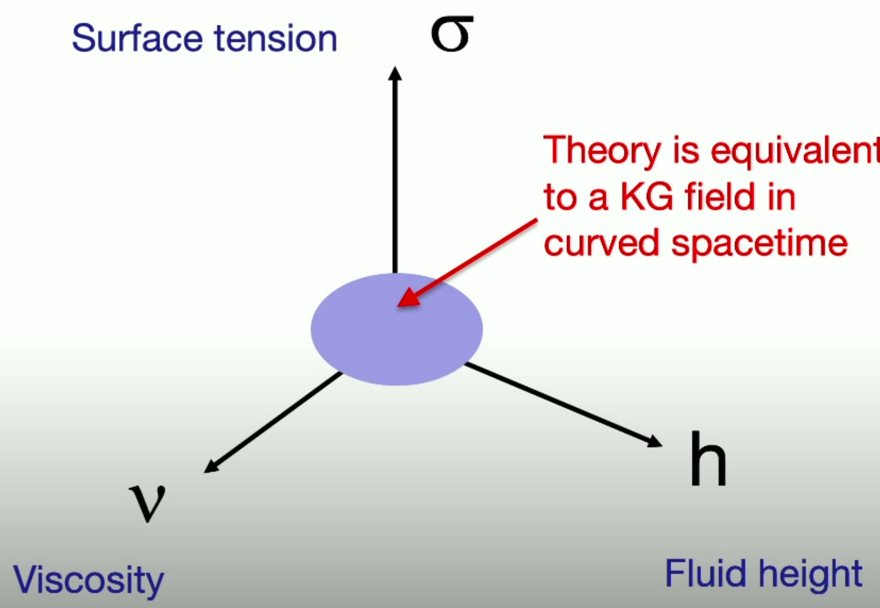
The experiment places constraints on the set-up; have to be more realistic about modelling.



Parameter space



To understand the experiment, need to model properly. Waves in our system aren't long, so need to understand parameter space.



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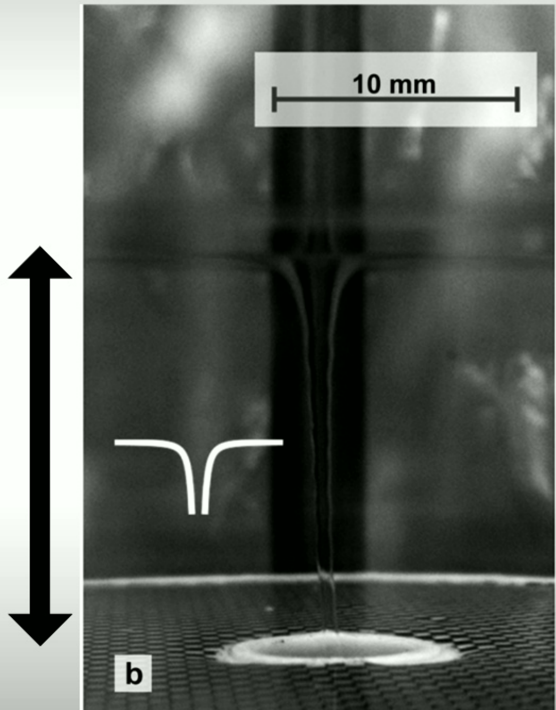

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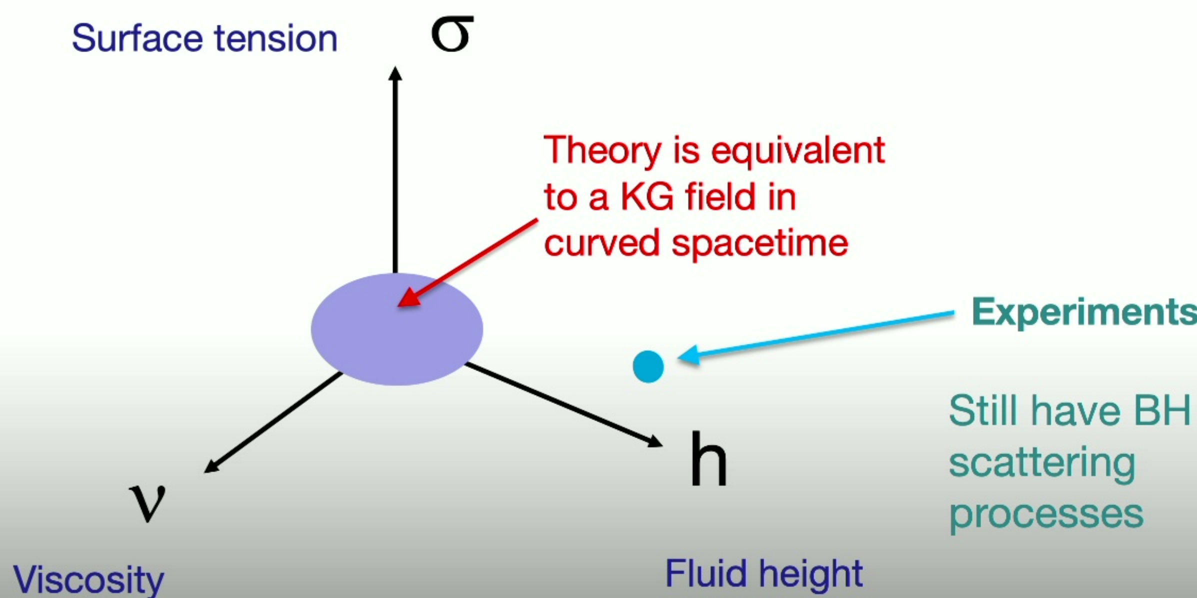
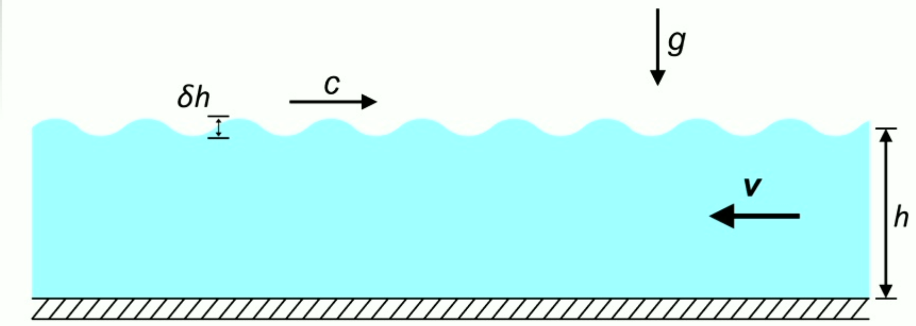


Dispersion, Dispersion, Dispersion

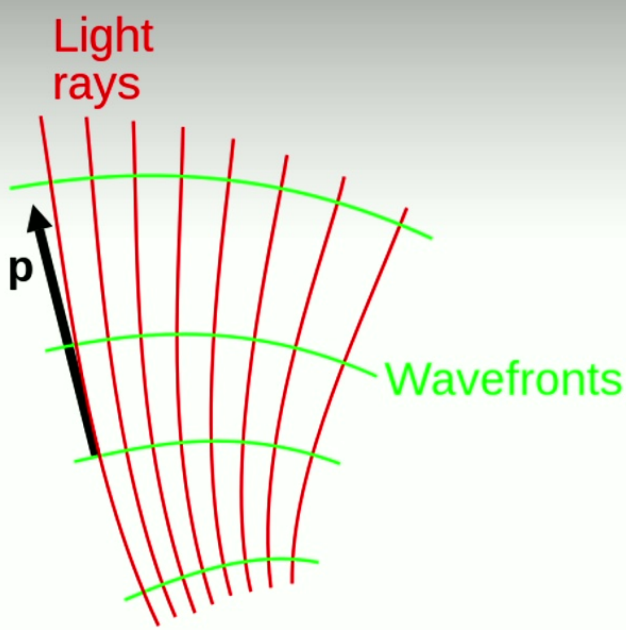
In the absence of spatial flow dependence, plane waves have the dispersion relation:



$$\omega = -i\nu k^2 + \mathbf{v}\cdot\mathbf{k} \pm \sqrt{(gk+\gamma k^3)\tanh(hk) - \nu^2 k^4}$$

Use plane wave intuition to build more general flow via WKB analysis

Wave Structure



To solve wave equations assume the dependence will be largely oscillatory, with some slowly varying amplitude:

$$\begin{bmatrix} \phi \\ \delta h \end{bmatrix} = \begin{bmatrix} \mathcal{A}(\mathbf{x}, t) \\ \mathcal{B}(\mathbf{x}, t) \end{bmatrix} e^{i\mathcal{S}(\mathbf{x},t)}$$

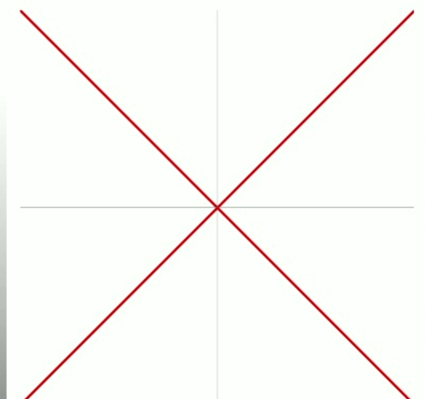
Ignoring viscosity get a dispersion relation:

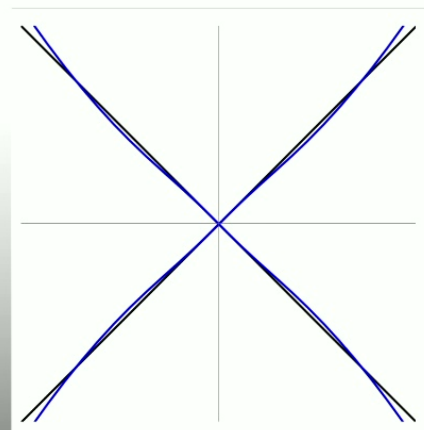
$$(\omega - \mathbf{v} \cdot \mathbf{k})^2 = (g + \gamma k^2) k \tanh(hk)$$

More General Dispersion

$$(\omega - \mathbf{v}\cdot\mathbf{k})^2 = (g + \gamma k^2)k\tanh(hk)$$

$$k_c = \sqrt{g/\gamma}$$



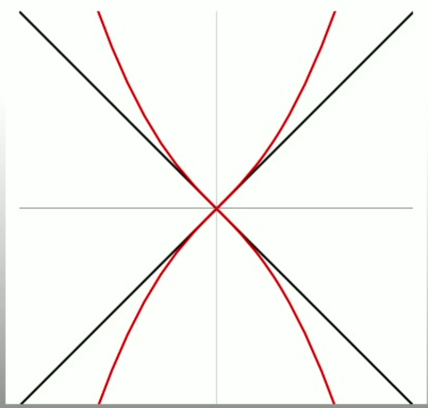


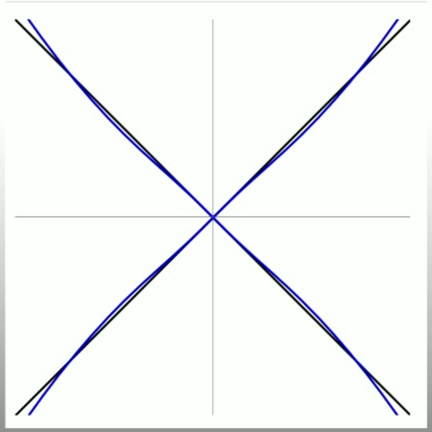
More General Dispersion

$$(\omega - \mathbf{v}\cdot\mathbf{k})^2 = (g + \gamma k^2)k\tanh(hk)$$

Ratio of surface tension to gravity determines scale at which quartic dispersion terms relevant (1.7cm)

$$k_c = \sqrt{g/\gamma}$$





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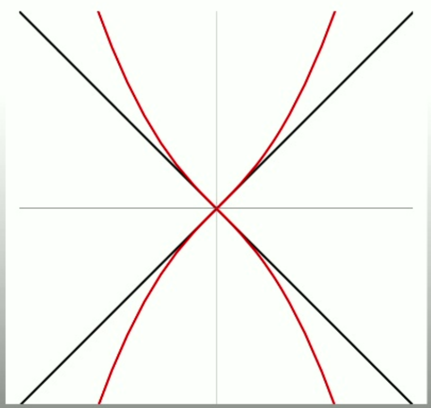
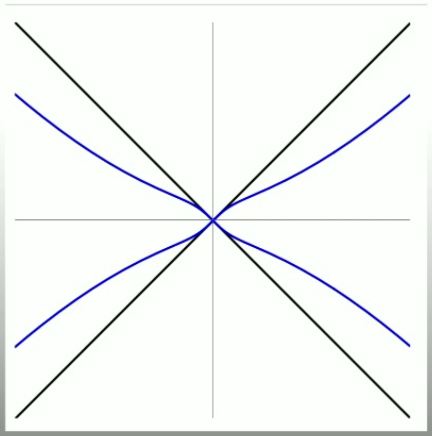
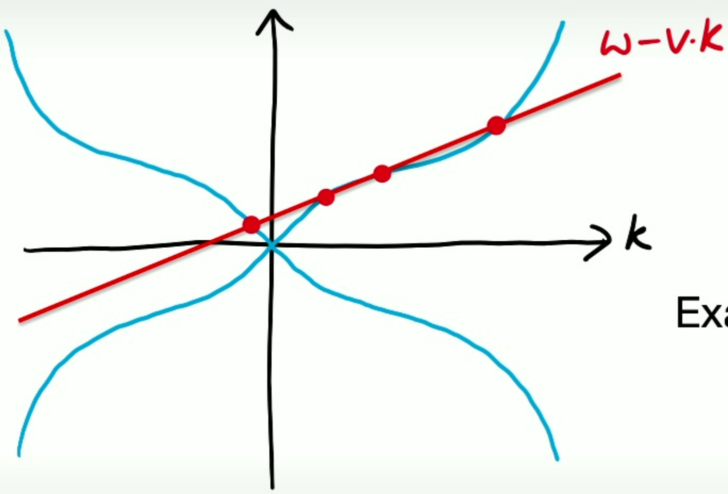
$$k_c = \sqrt{g/\gamma}$$

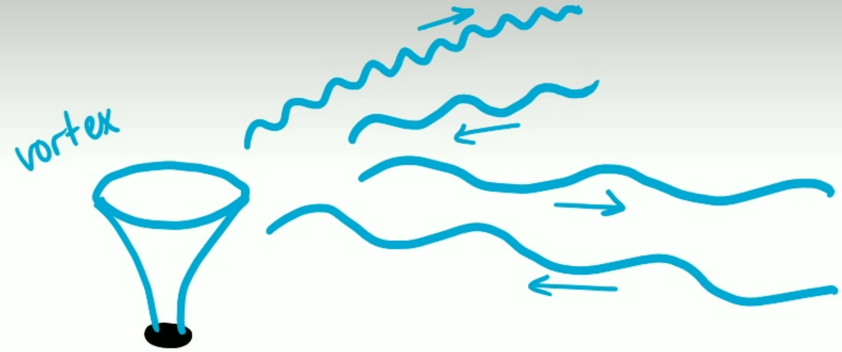
1/h determines the scale of flattening of the dispersion curve.





General Scattering





Example: superradiance with Bogoliubov dispersion

$$(\omega - \mathbf{v}\cdot\mathbf{k})^2 = c^2 k^2 + \xi^2 k^4/4$$

Amplification for $\omega < \dfrac{m\Omega_h}{1 + m\xi/r_h}$

Usual condition

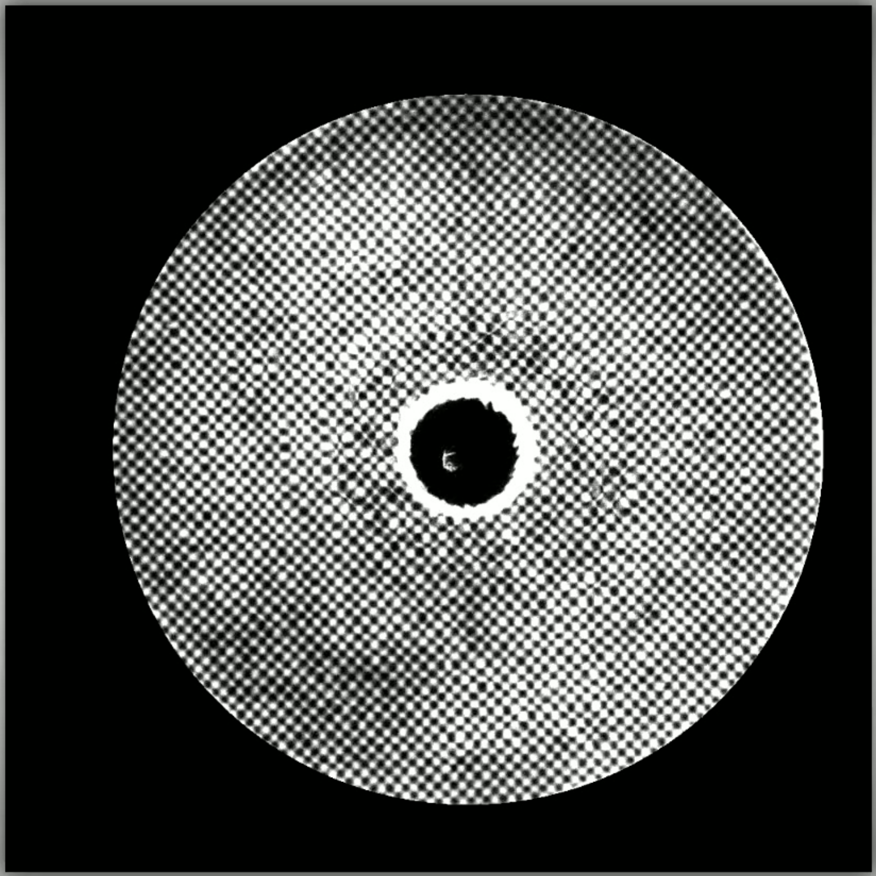
$$\omega < m\Omega_h$$

We understand how to study "black hole" scattering beyond the "relativistic" regime of the original analogy

S. Patrick Class. Quant. Grav. **38** 095010 (2020)

The Wave

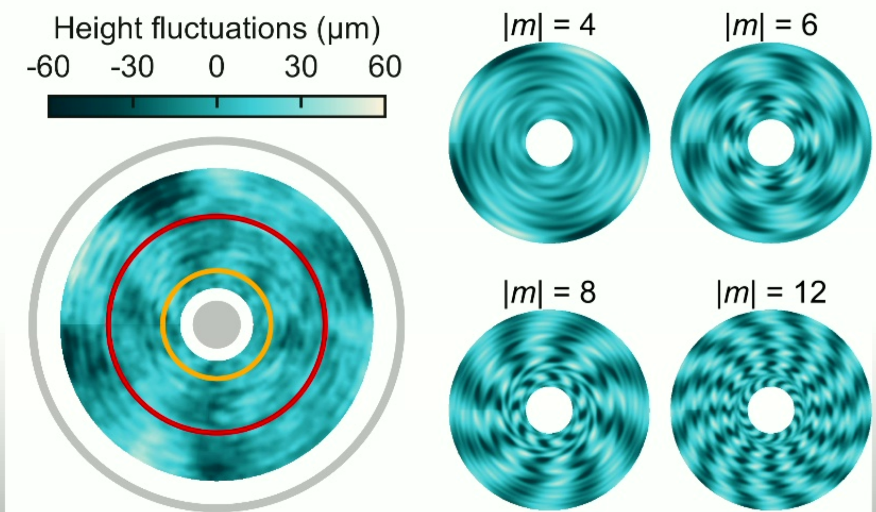
Now we go back to the experiment and test our understanding.

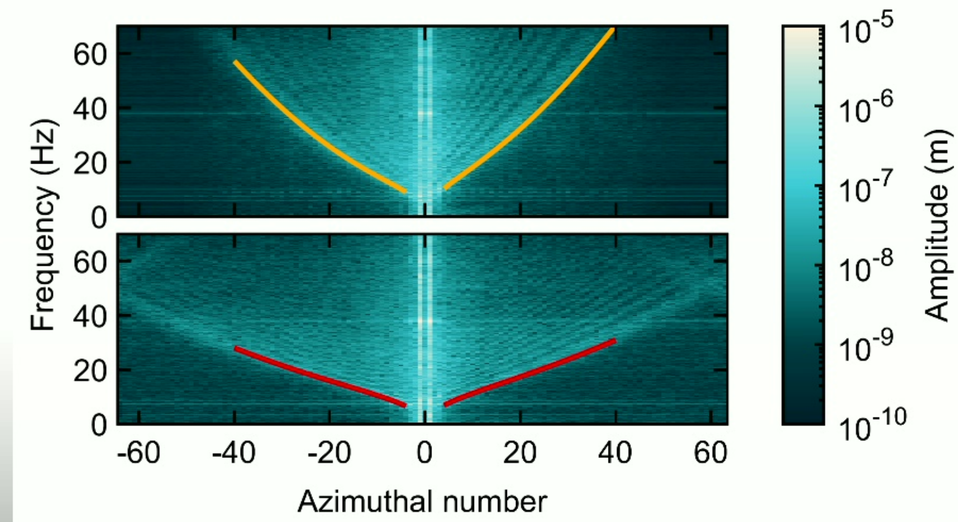


Superfluid Interface Reconstruction

Reconstruct the waves from the profile distortion. Azimuthal number m: number of crests/troughs around the vortex

Plot the dispersion relation w.r.t. angular m eigenvalue. Clear threshold frequency, also greater spectral tilt nearer vortex.





r = 11.2 mm (yellow), r = 22.1 mm (red line)

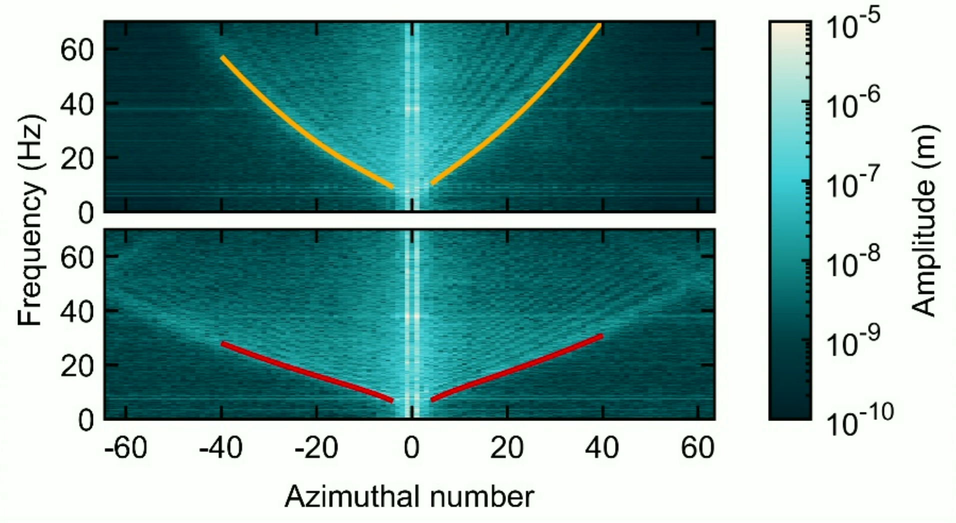
Superfluid Interface Modelling

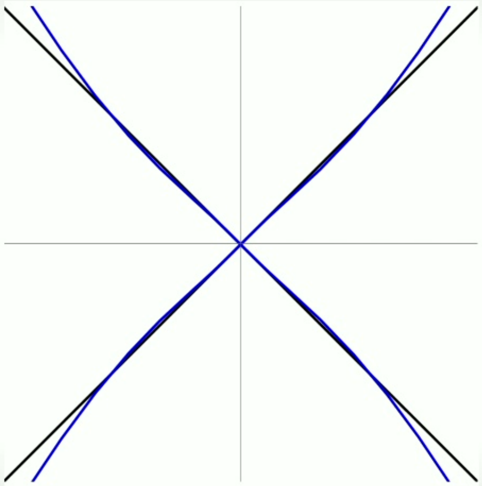
Lifting the dispersion relation from earlier, (deep regime) see the effect of v clearly on yellow plot

$$v_\theta = \Omega r + \frac{C}{r}$$

$$\mathbf{k} = p_r \mathbf{e}_r + \frac{m}{r}\mathbf{e}_\theta$$

$$v_r \approx 0$$





$$\omega_+ \simeq \frac{mC}{r^2} \pm \sqrt{gk + \gamma k^3}$$

Radial Flow Profile

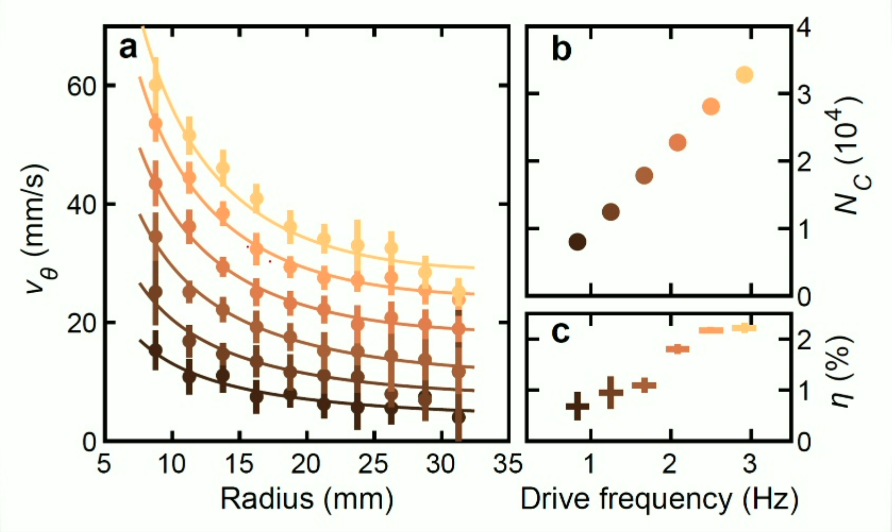
$$\omega_+ \simeq \frac{mC}{r^2} + p_r + \sqrt{gk + \gamma k^3}$$

Minimum frequency stationary w.r.t. p_r

Consistently find $p_r = 0$

Circulation from azimuthal velocity,

$N_C = C/\kappa$ circulation quanta inside core

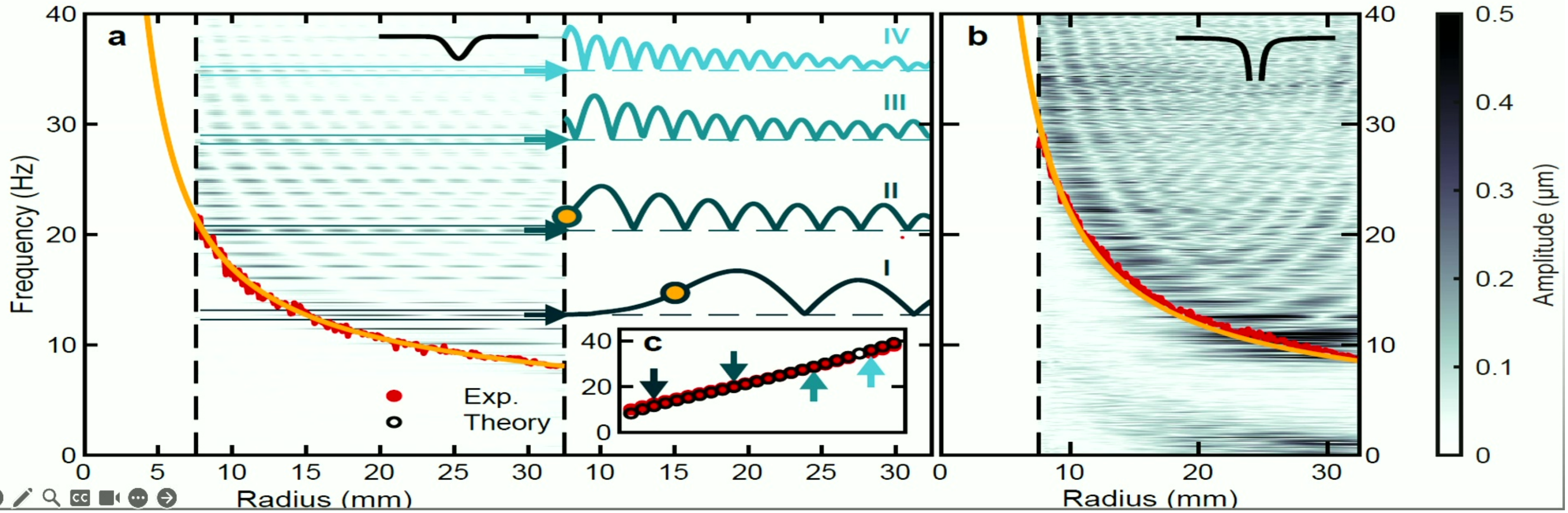


Most extensive quantum vortex flows observed in He II

$N_C \sim 10^4$

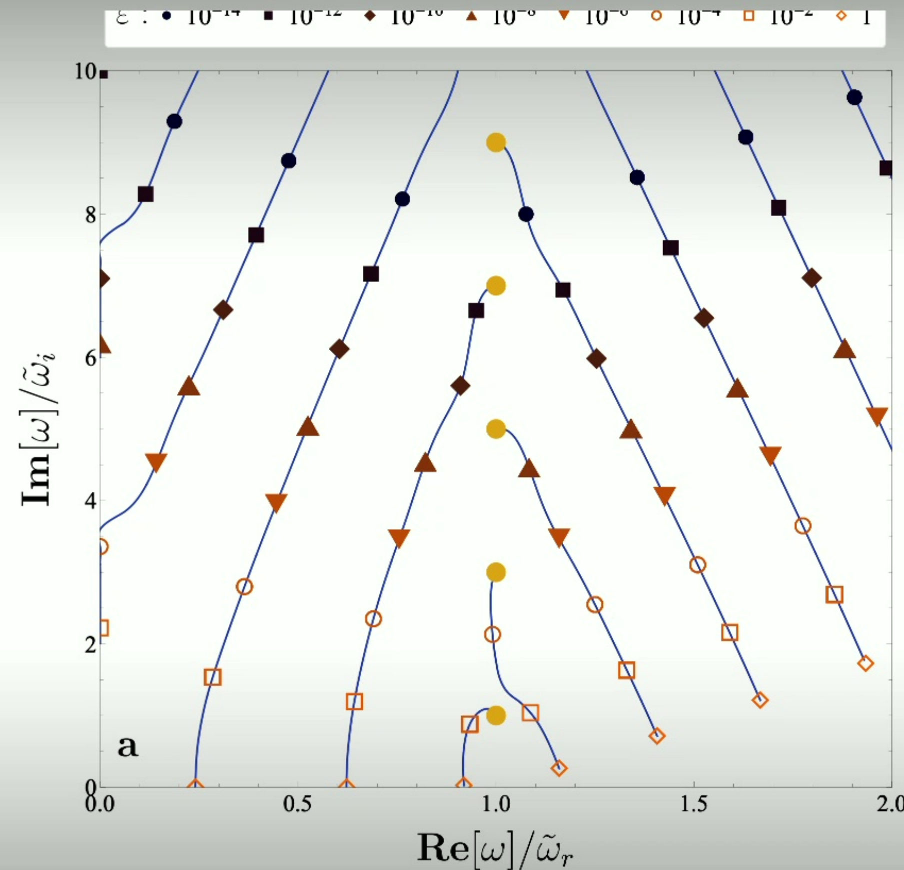
Standing Waves

Picking out an m (+8) and plotting radially shows clear evidence of modes. Minimum frequency provides inner potential barrier, flow confined at outer wall. (L: Solid core, R: Hollow core, Middle: Modelling. Red is measured effective inner barrier, yellow modelled barrier.)

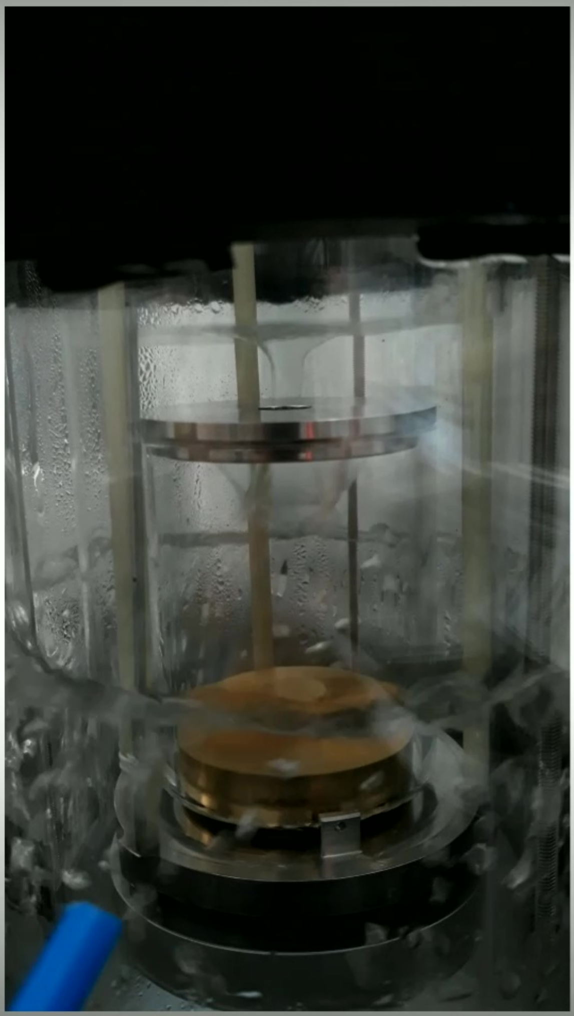


Ringdown

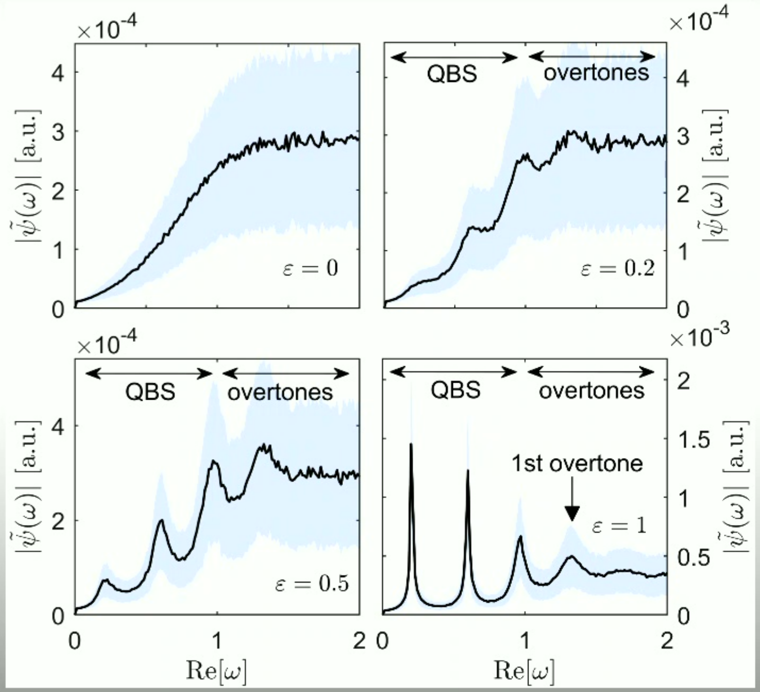
Checking ringdown properties is more messy as experiment is “small” and the boundary acts as a mirror. QNM’s migrate into two categories – quasi-bound states confined near boundary, and genuine QNM’s near vortex core.



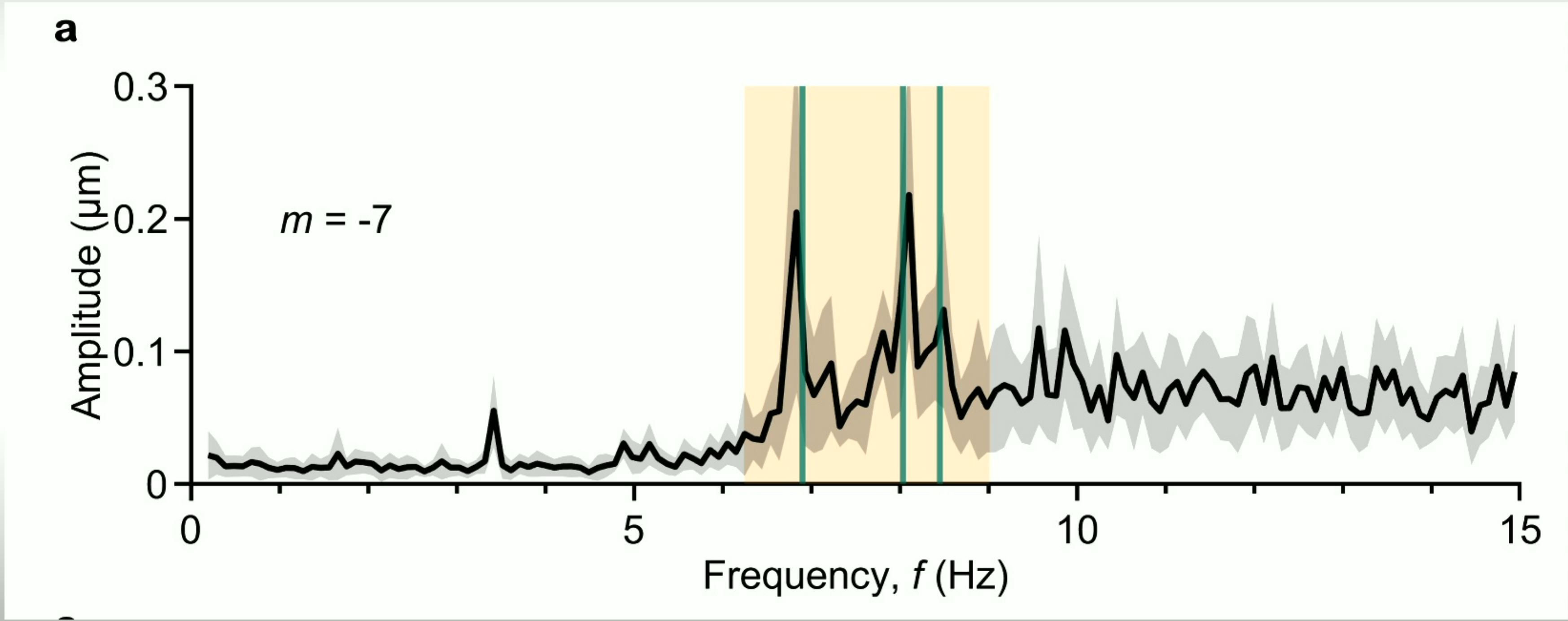
Leonardo Solidoro, Sam Patrick, RG, Silke Weinfurtner; arXiv:2406.11013 [gr-qc]



However – experimental noise now becomes an asset in detecting ringdown modes!

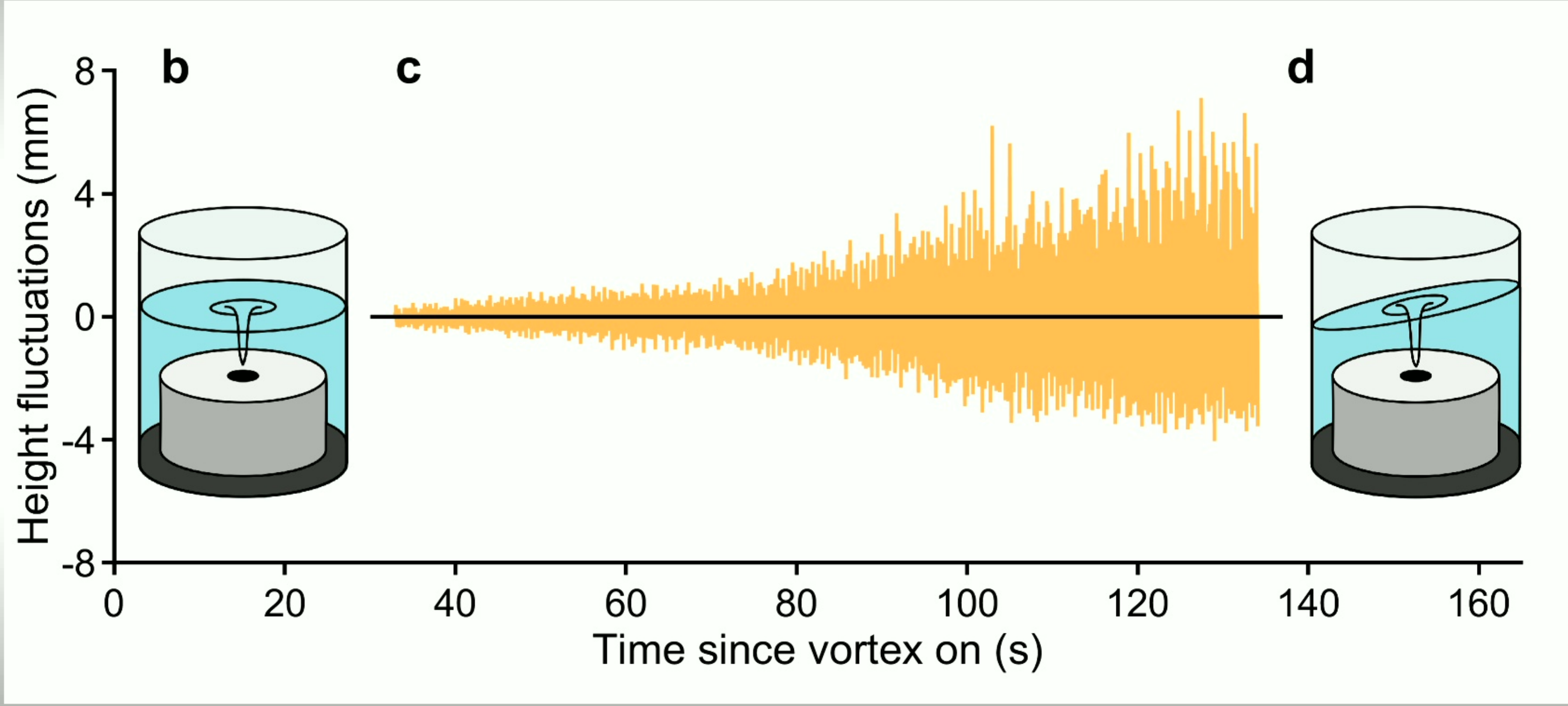


Seeing evidence of ringdown:

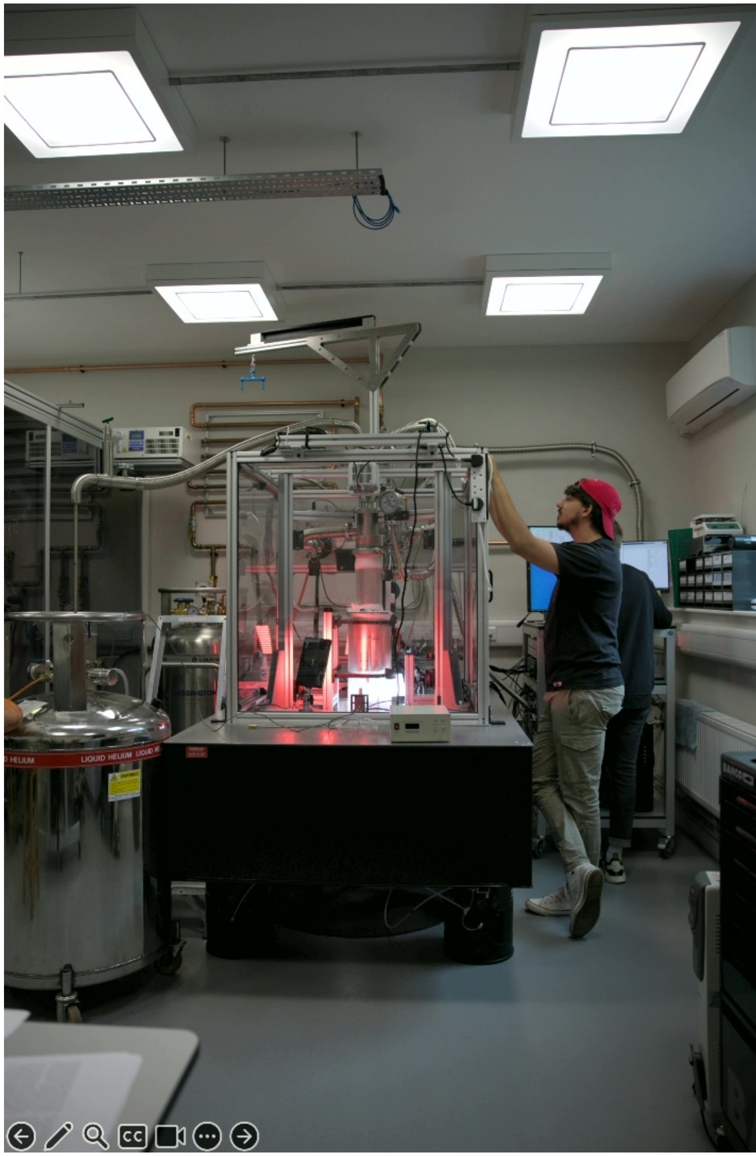


Smaniotto, Solidoro, Svancara, Patrick, Richartz, Barenghi, RG, Weinfurtner; coming soon…

Black Hole Bomb?



Svancara, Smaniotto, Solidoro, Patrick, Richartz, RG, Weinfurtner; in preparation



SUMMARY

- **Proof-of-principle** experiment for a new class of simulators
- Complementary to well established systems, e.g. BECs
- Specific advantages of a quantum liquid interface, e.g. **high-precision simultaneous readout in time and space**
- Looking at **black hole ringing, bombs,** and **superradiance**

OUTLOOK

Analog systems allow general features of wave propagation on various backgrounds to be explored Many properties such as ringdown & superradiance are universal.

- Extremal / near extremal behaviour
- Phenomena of a quantized black hole
- Echoes?