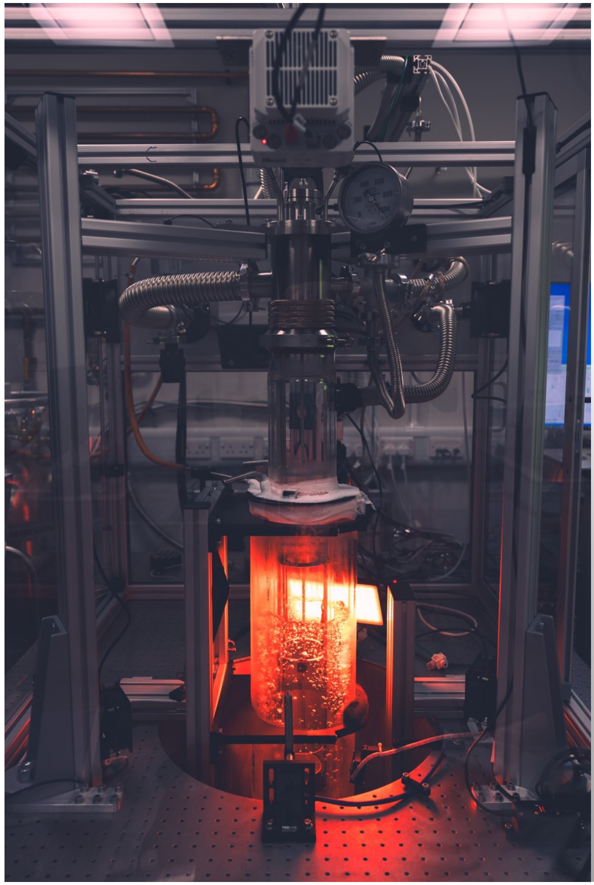
QSimFP | Quantum Simulators for Fundamental Physics



GRAVITY LABORATORY

Towards a Quantum Black Hole Simulator

“Rotating Curved Spacetime Signatures from a Giant Quantum Vortex”

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

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CERN-HET – 29/4/24

Outline

- Some background on QSimFP
- Basic analogs
- More messy modelling
- Quantum systems - the experiment
- Where next?

Why Simulate?

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?

Why Analogs?

- The basic idea of analogy is to construct a system that has the same type of behaviour as the system you want to test. We all know how to do the maths, but does Nature follow the same rules, and what happens when you push the boundaries of your approximation?
- 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!

"Growth comes through analogy; through seeing how things connect, rather than only seeing how they might be different."

….Albert Einstein

The team

QSimFP

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

External partners
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Gravity simulators
Silke Weinfurtner
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Science & Technology Facilities Council

EPSRC
Engineering and Physical Sciences Research Council

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

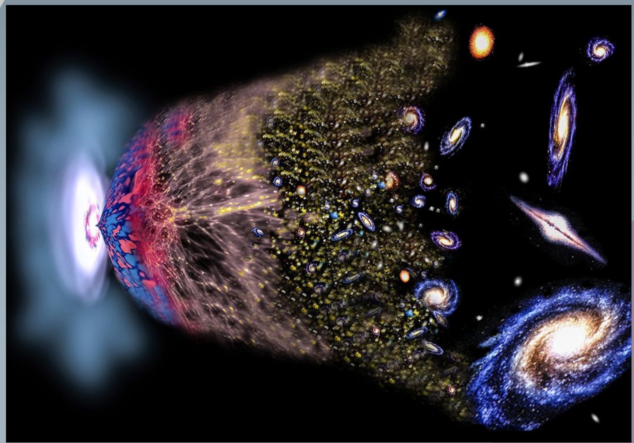
Ultracold atoms
- Thomas Billam
- Zoran Hadzibabic

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

Quantum circuits
- Gregoire Ithier

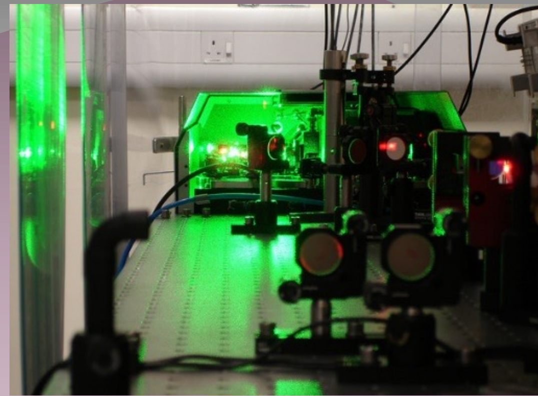
Quantum optics
- Friedrich Koenig

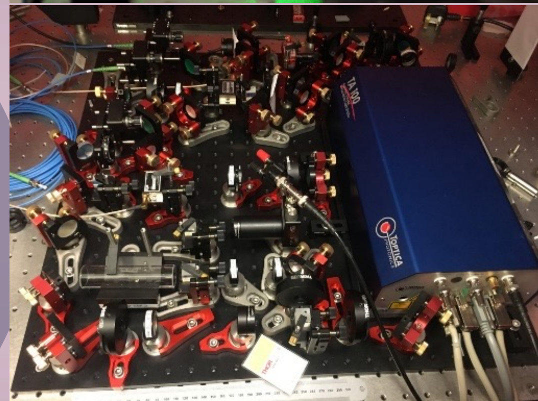
Objectives



Quantum Vacuum:
- False Vacuum Decay
- Observer dependence

Quantum Black Hole:
- Black hole ring-down





SW

Black Holes Discretization: M / S

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

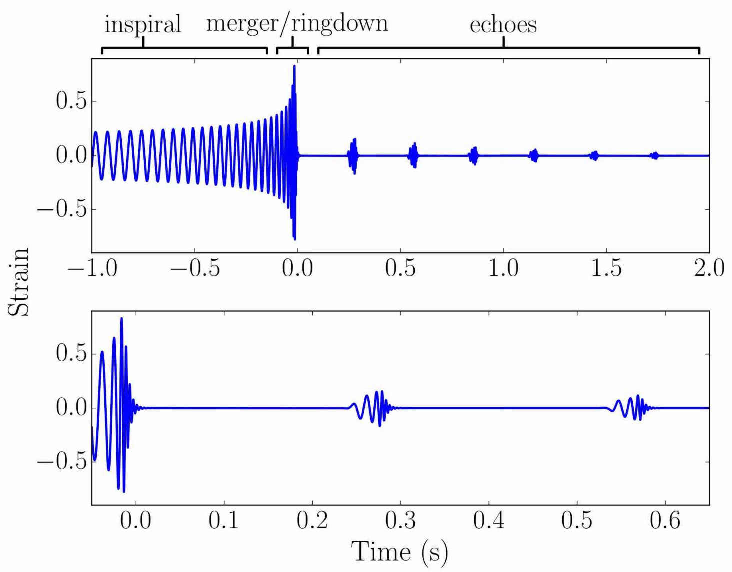
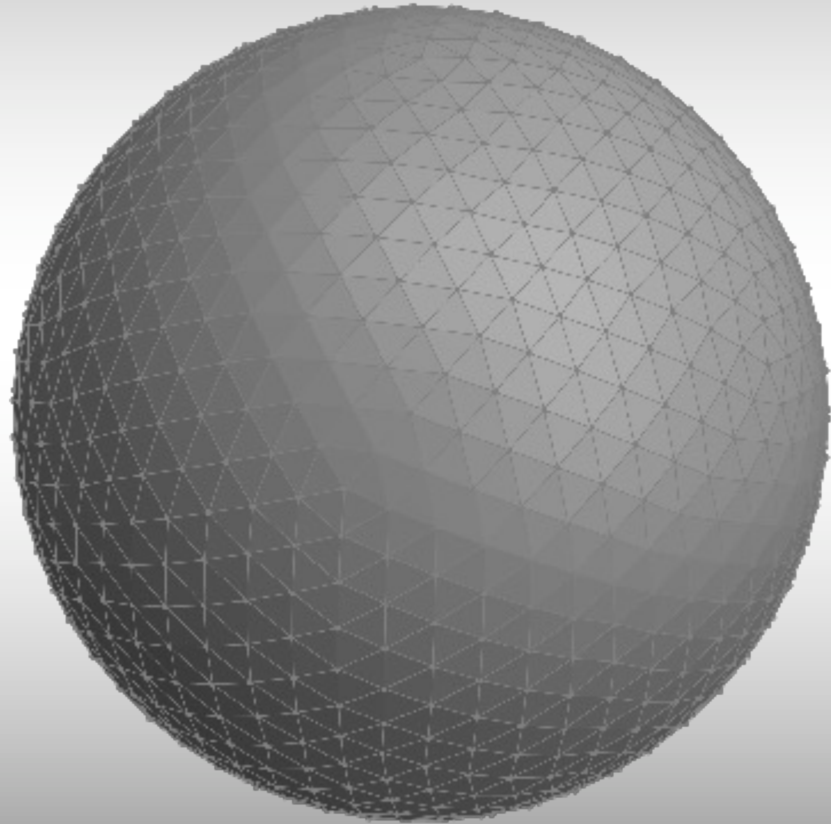


Image credit: B Knispel

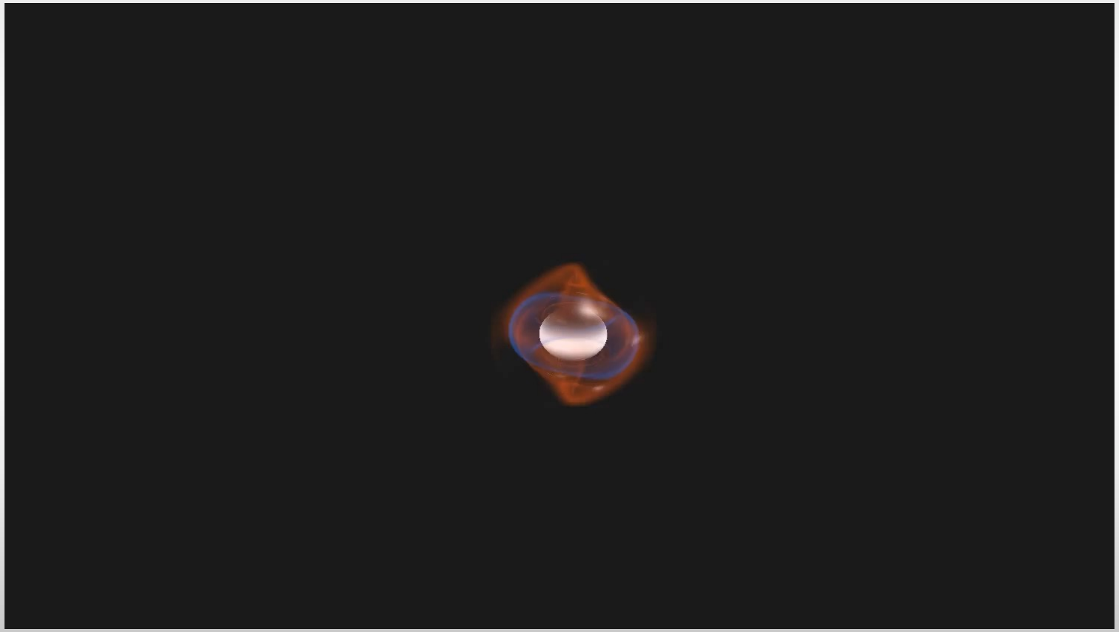


Discretising a Black Hole: J

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, we aim to build a quantized fluid “hole”.



Animation: Will East & Ralf Kahler

Basic Analogs – Fluid Simulators

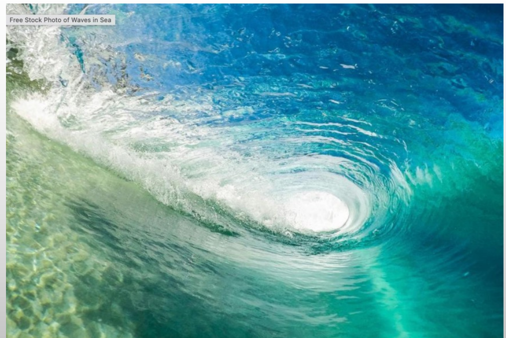
3 × 1.5 m tank with dyed water
Exchangeable central drain
Recirculation pump
Custom wave generator

Bathtub vortex flow in Nottingham (classical)

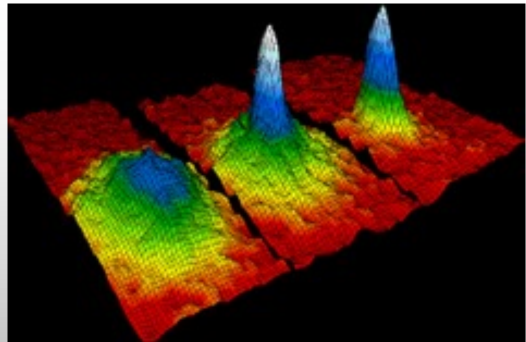
Curved “Spacetimes” in the Lab

- Generally, a gravity simulator is one where the fluctuations are described by an effective field theory in a curved spacetime. The “wave” equation of the perturbations can be cast as a Klein-Gordon type of equation.

$$\partial_a \left(\sqrt{-g} g^{ab} \partial_b \psi\right) = 0$$



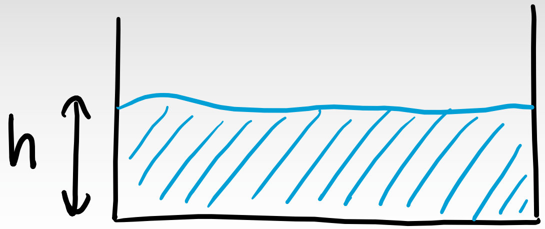
Navier-Stokes



Gross-Pitaevski

HVBK *(finite T superfluid)*

Basics – The Bathtub



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

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

The "bathtub" experiment measures surface waves, involves analysis of Navier-Stokes. Integrating out the bulk and assuming an irrotational flow gives a coupled system for surface waves:

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

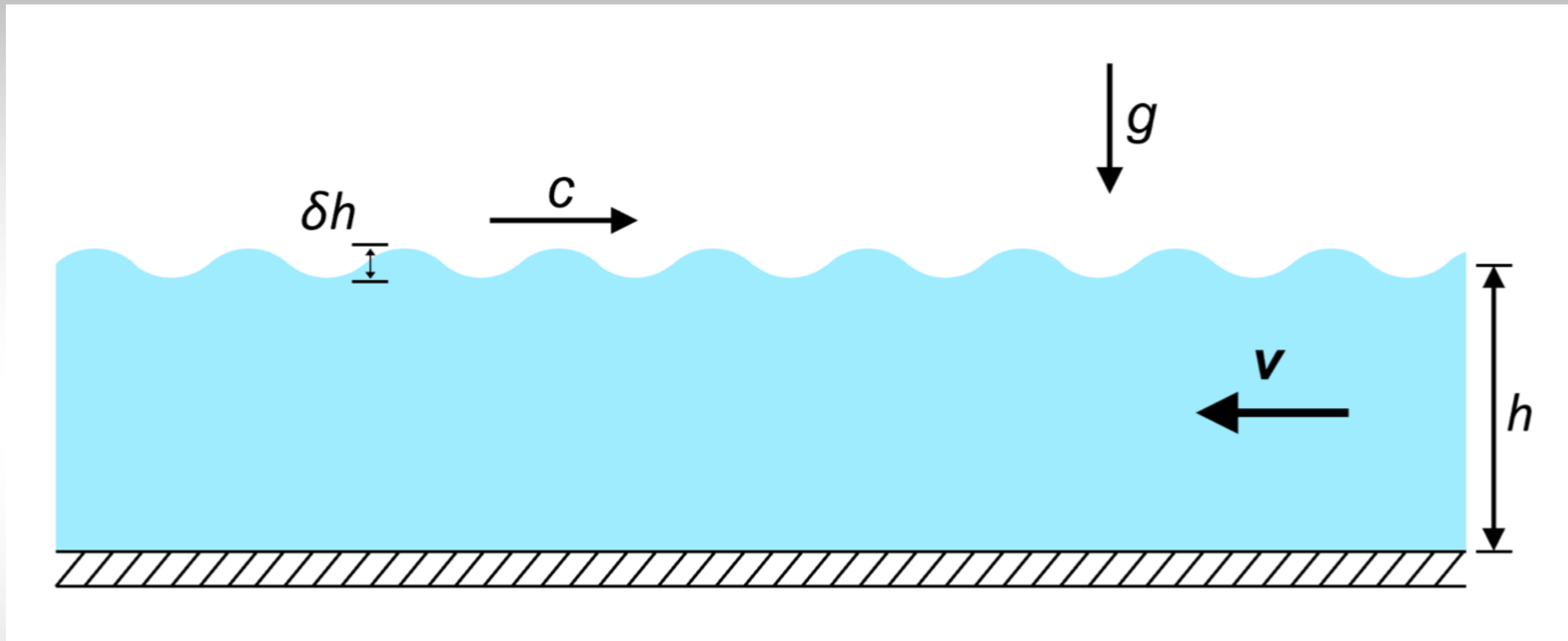
$$(\partial_t + \mathbf{v}\cdot\nabla)\phi + g\delta h - \gamma\nabla^2\delta h - 2\nu\nabla^2\phi = 0$$

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

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

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

Simple Surface Gravity Waves



Equations of motion: $$(\partial_t + \mathbf{v}\cdot\nabla)^2\,\phi - ig\nabla\tanh\left(-ih\nabla\right)\phi = 0\,, \qquad \delta h = -\frac{1}{g}\left(\partial_t + \mathbf{v}\cdot\nabla\right)\phi$$

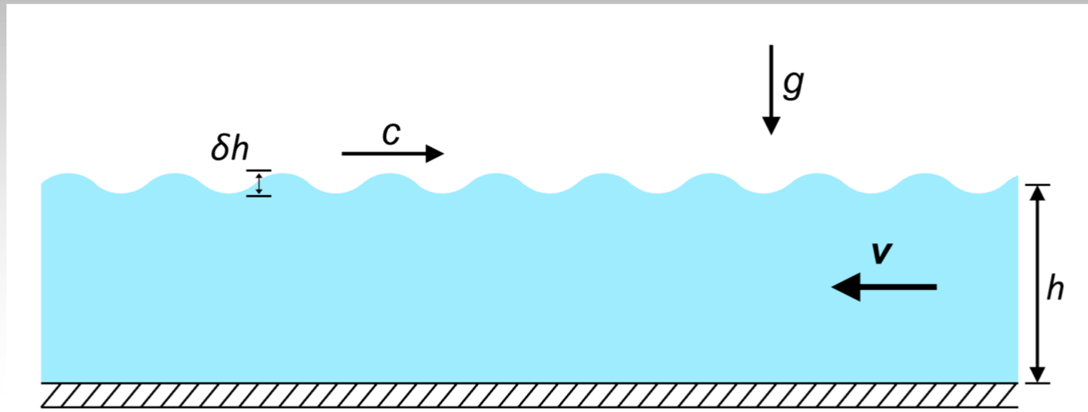
Long wavelength: $$(\partial_t + \mathbf{v}\cdot\nabla)^2\,\phi - c^2\nabla^2\phi = 0\,, \qquad c^2 = gh$$

No viscosity
No surface tension

Simple Surface Gravity Waves

Long wavelength:

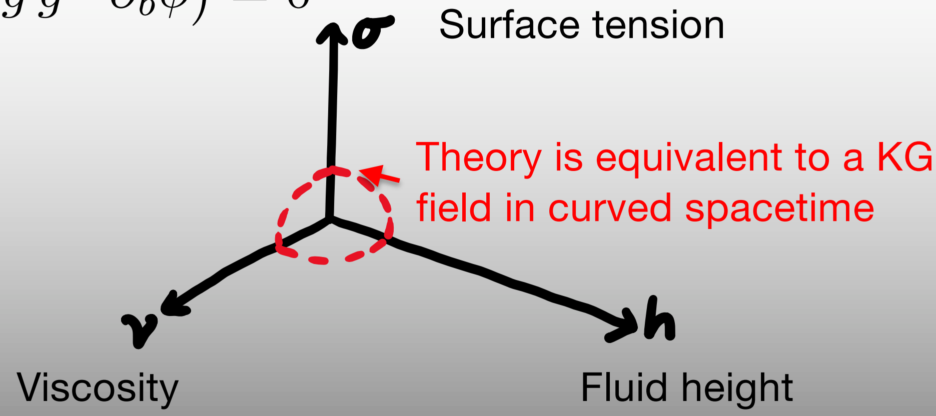
$$(\partial_t + \mathbf{v}\cdot\nabla)^2\phi - c^2\nabla^2\phi = 0\,, \qquad c^2 = gh$$



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

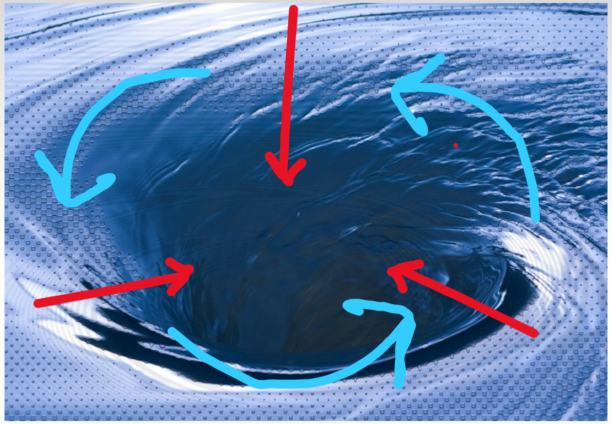
where

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



Draining Vortex

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



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

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

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

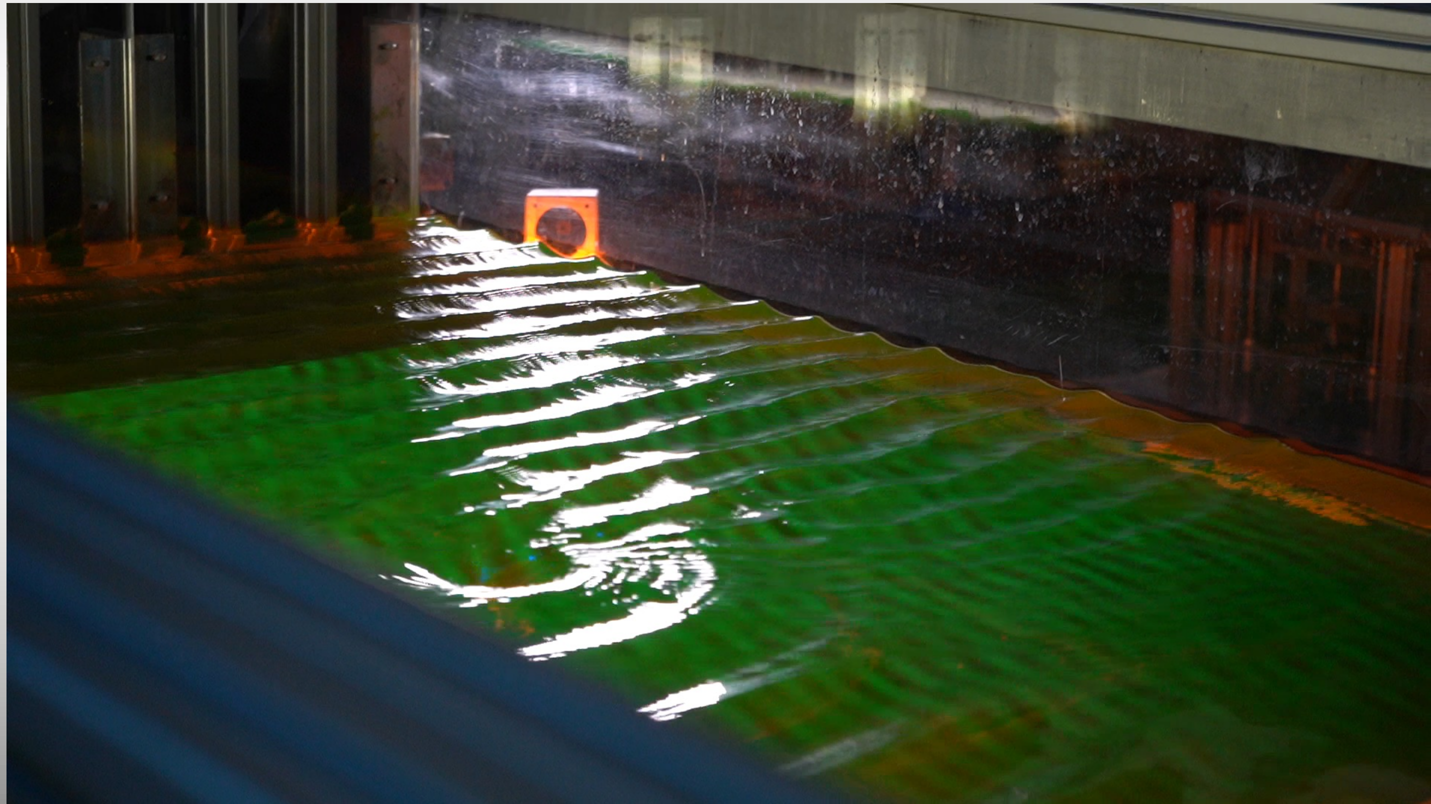
$$r_s = D/c$$

$$r_e = \sqrt{C^2 + D^2}/c$$

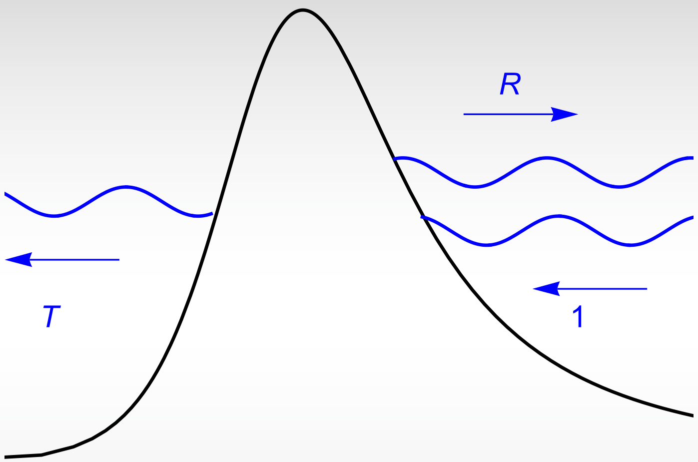
The draining vortex simulates a rotating black hole with both a horizon and an ergoregion

The Bathtub Black Hole

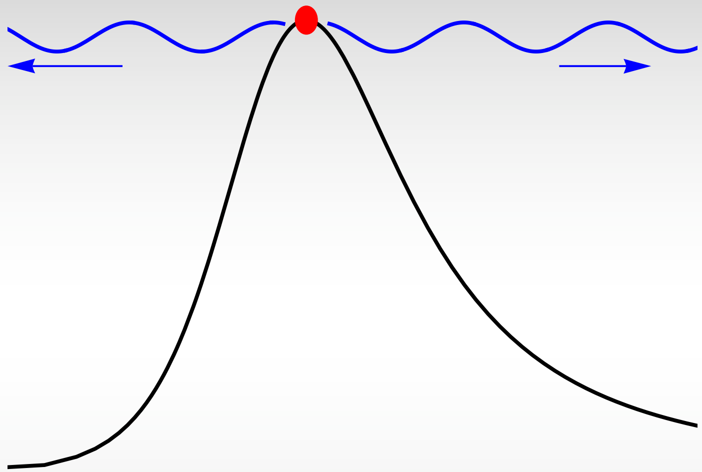
Can input waves for controlled scattering or allow to drain for ringdown.



Super-Radiance & Ringdown



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



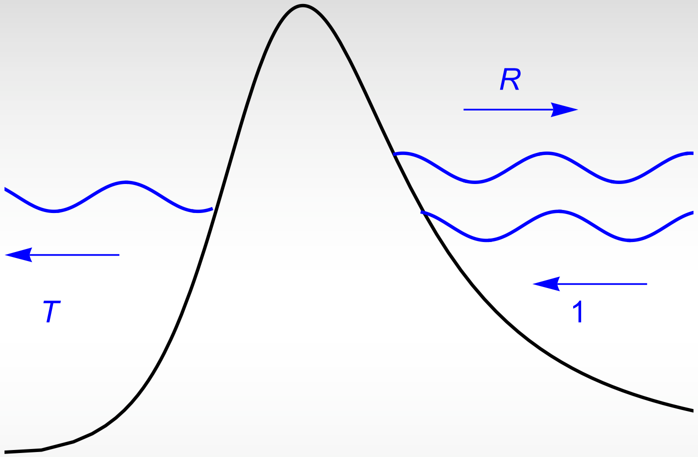
$$\omega_{\rm QNM} \sim \omega_\star - i(n+1/2)|\lambda|$$

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

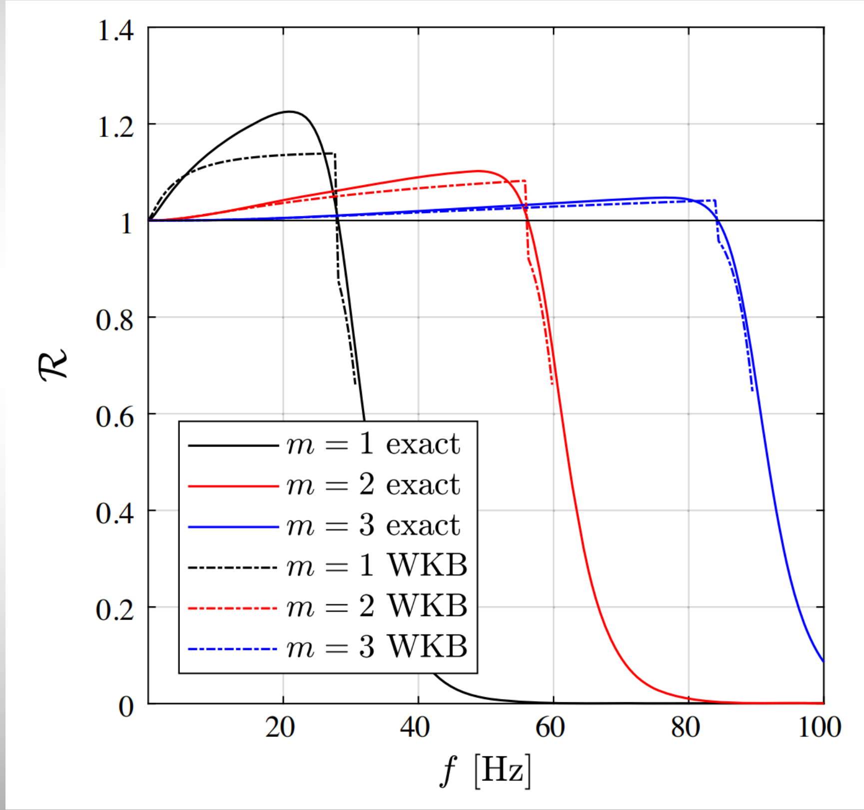
Ringdown is the decay of an excited state around the black hole / vortex

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

Super-Radiance

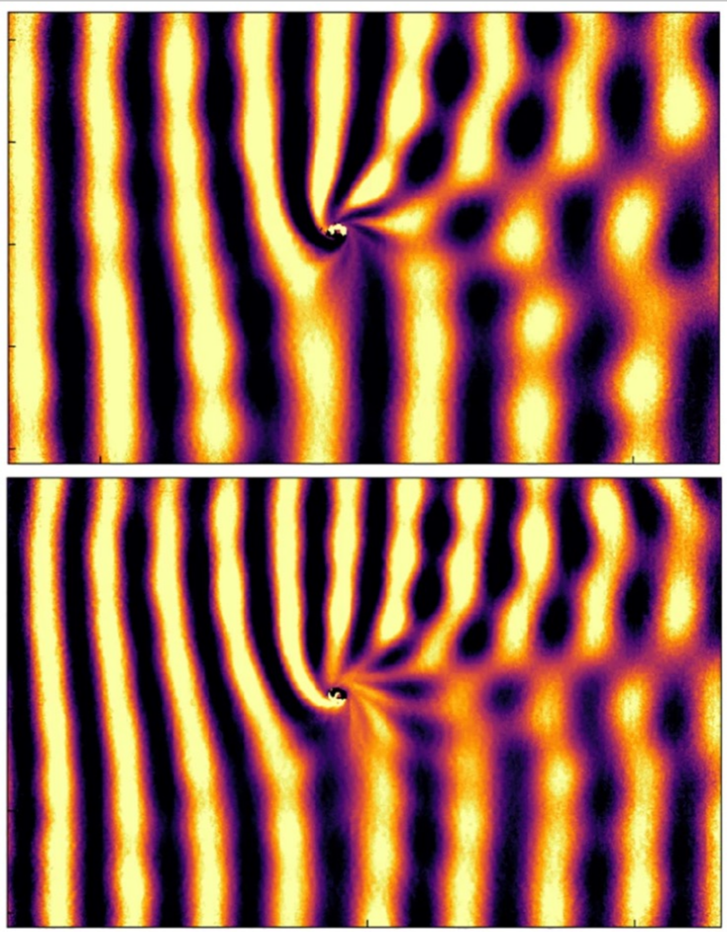


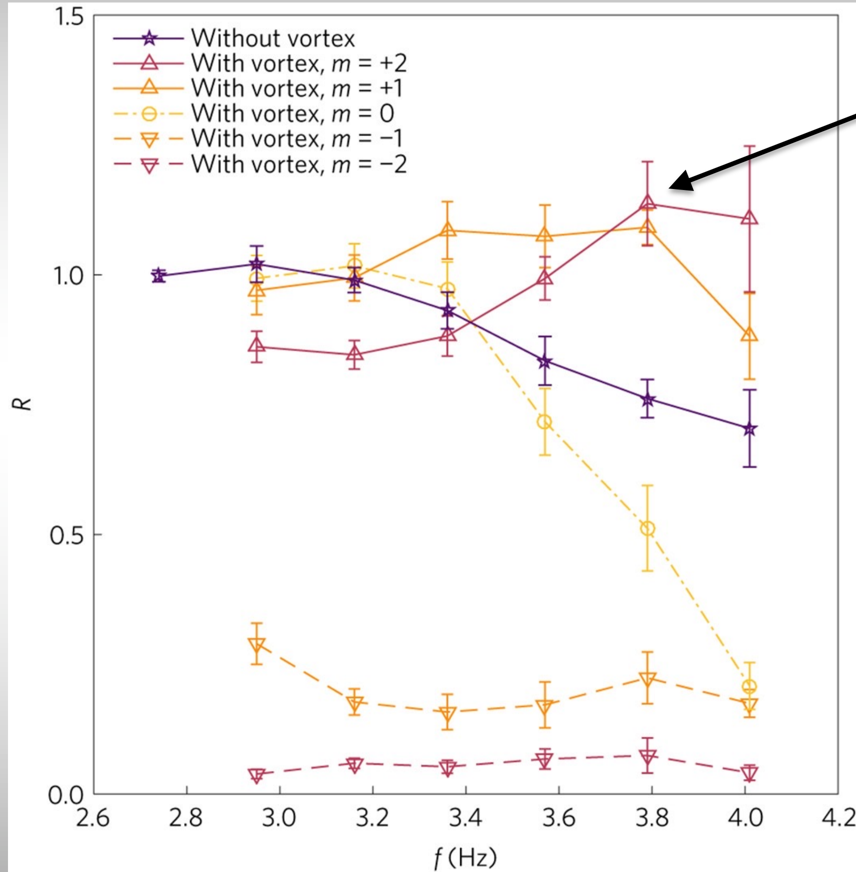
$$|R| > 1\ , \quad \omega < m\Omega_h$$



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

Superradiance



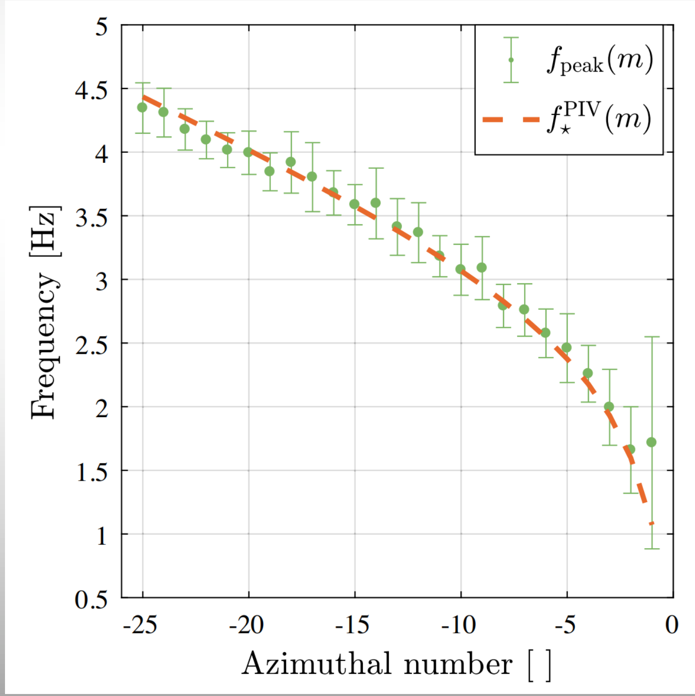


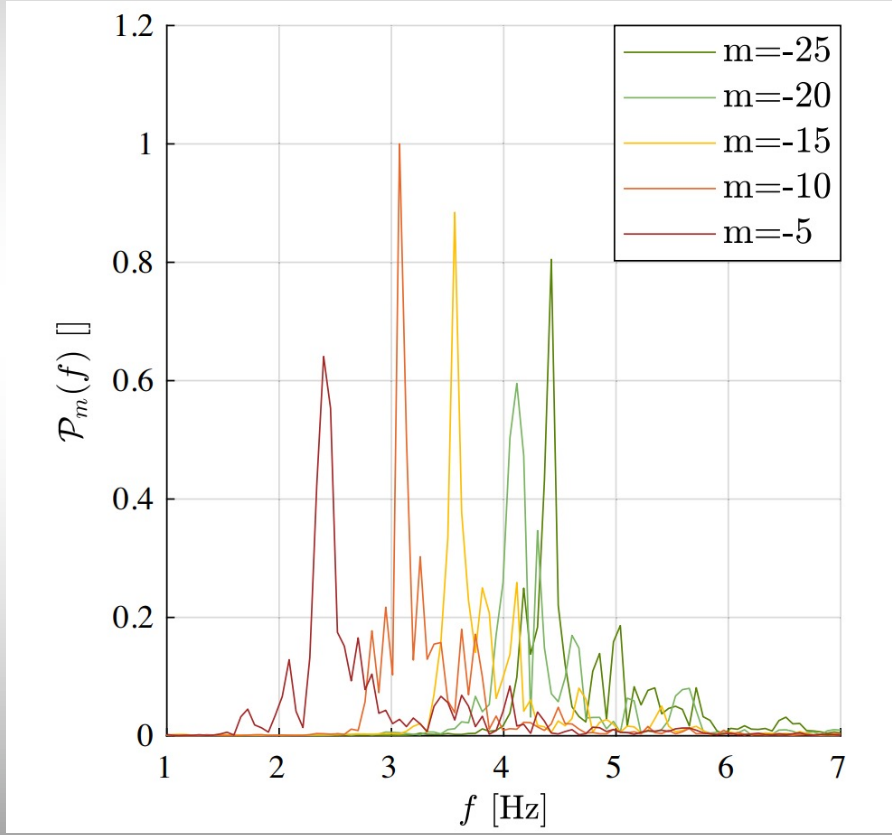
Amplification of corotating modes is consistent with superradiance

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

Ring-down/-ing

Ringing at characteristic frequencies associated to lightring observed.





Parameter space

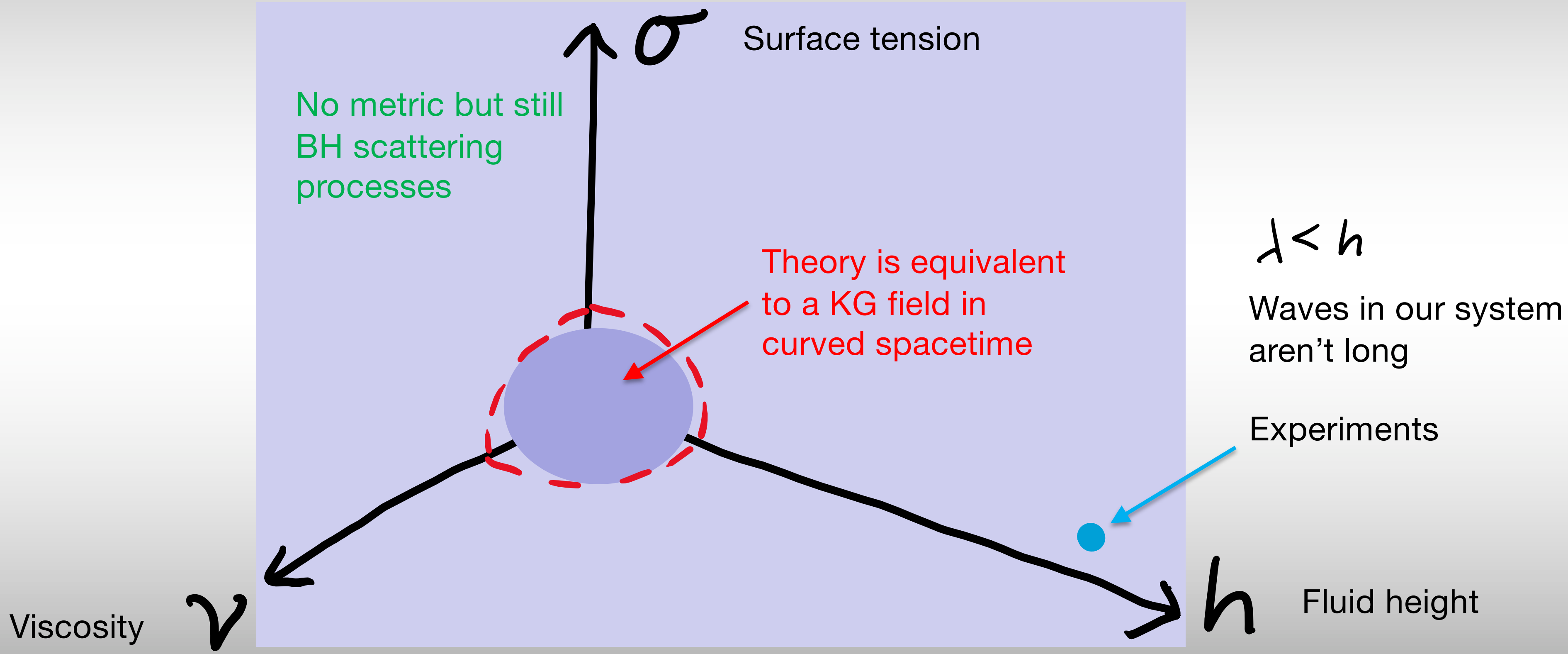
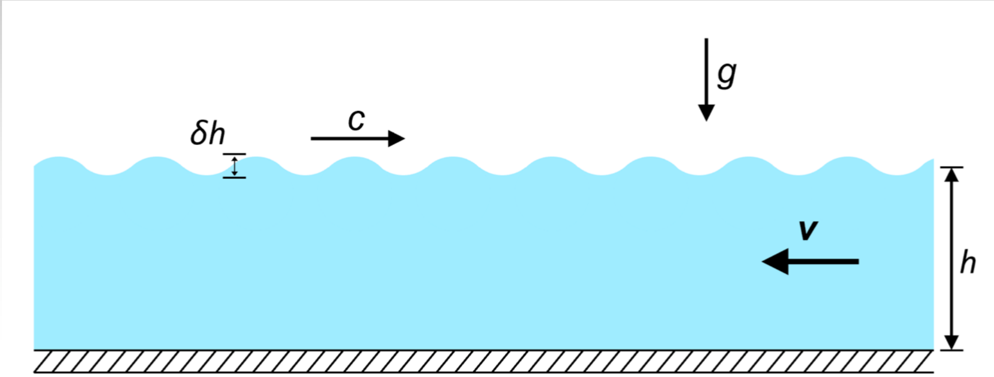


Image credit: Sam Patrick

More Messy Modelling

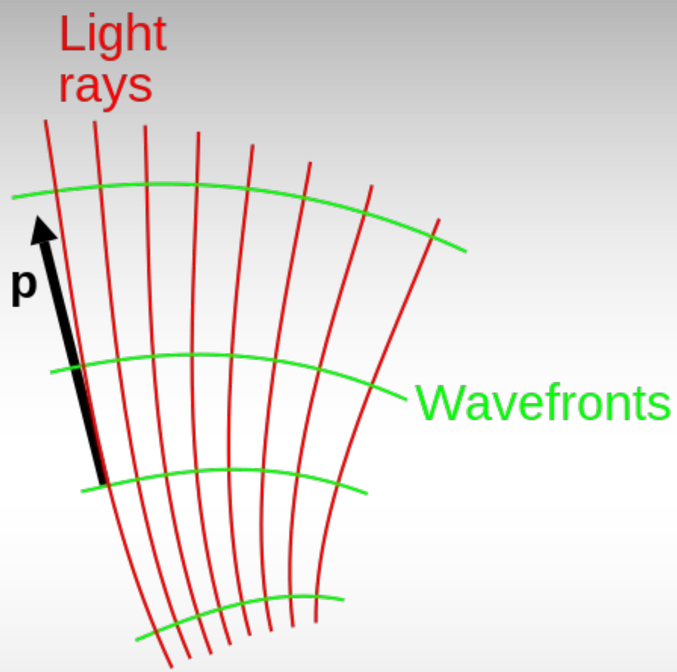
In the absence of spatial flow dependence, plane waves have the dispersion relation:



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

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:

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

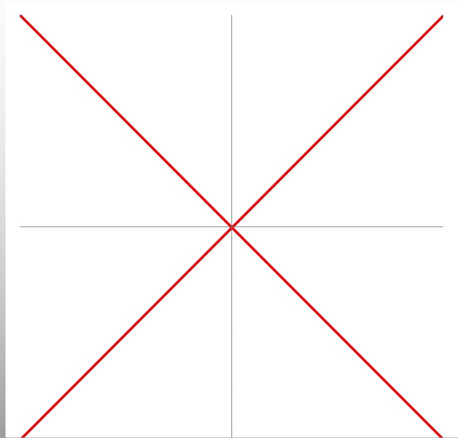
More General Dispersion

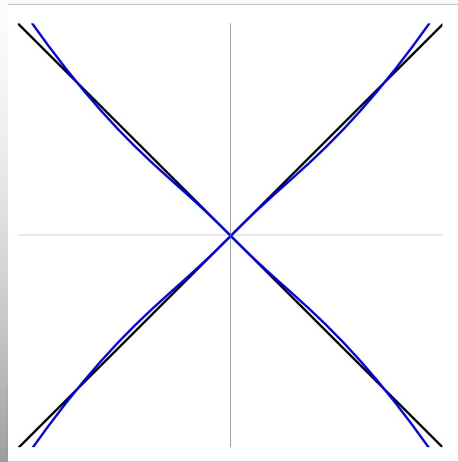
$$(\omega - \mathbf{v}\cdot\mathbf{k})^2 = (g + \gamma k^2)k\tanh(hk)$$

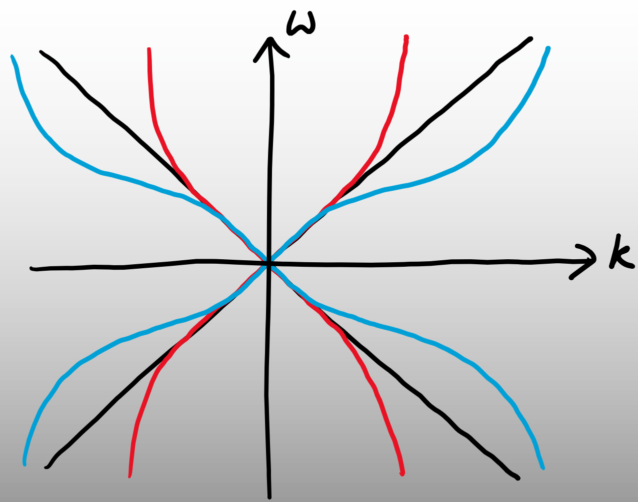
Ratio of surface tension to gravity determines scale at which quartic dispersion terms relevant (1.7cm)

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

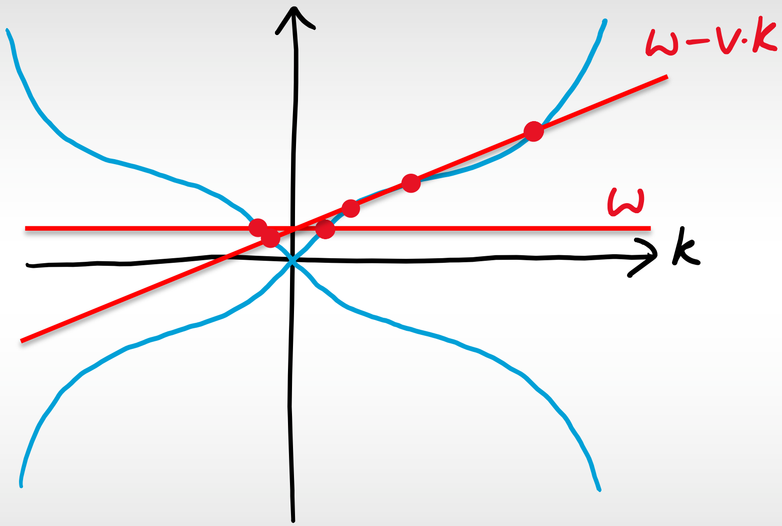
1/h determines the scale of flattening of the dispersion curve.



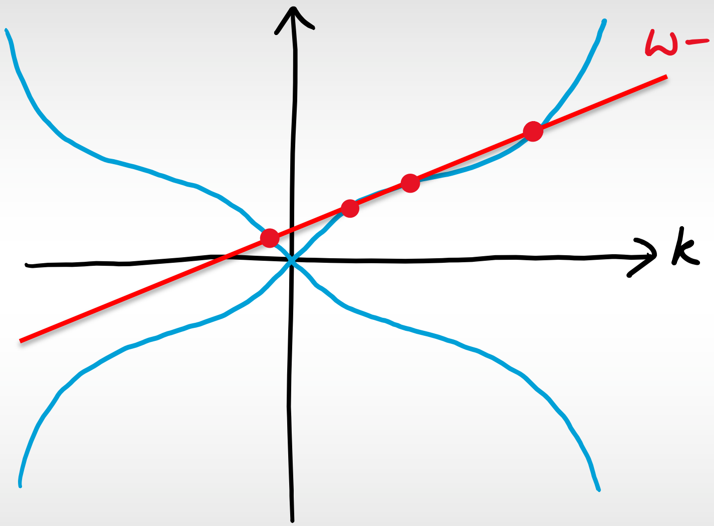


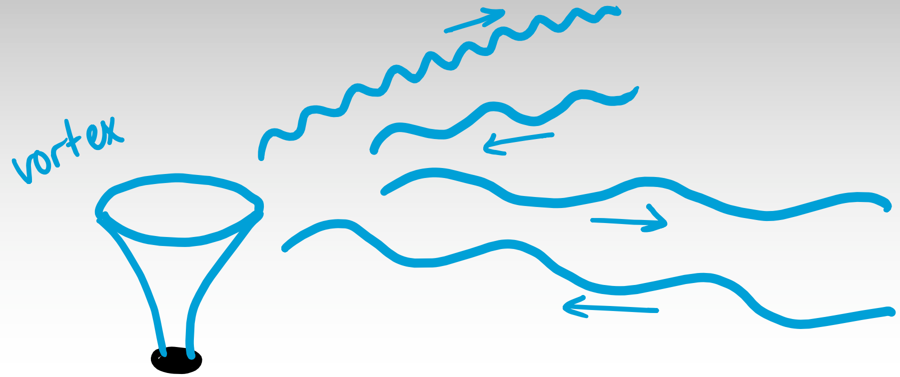


General Scattering



General Scattering





Example: superradiance with Bogoliubov dispersion

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

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

Usual condition

$\omega < m\Omega_h$

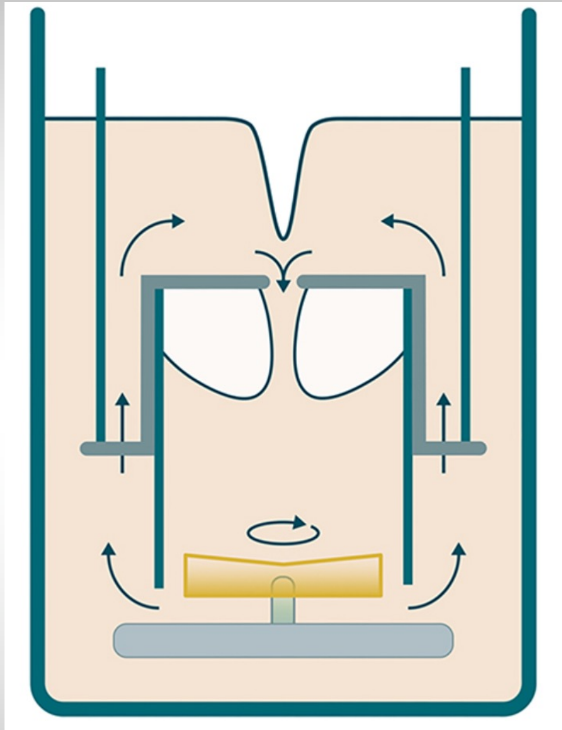
We understand how to study "black hole" scattering beyond the regime of the original analogy

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

From Classical to Quantum Fluids

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

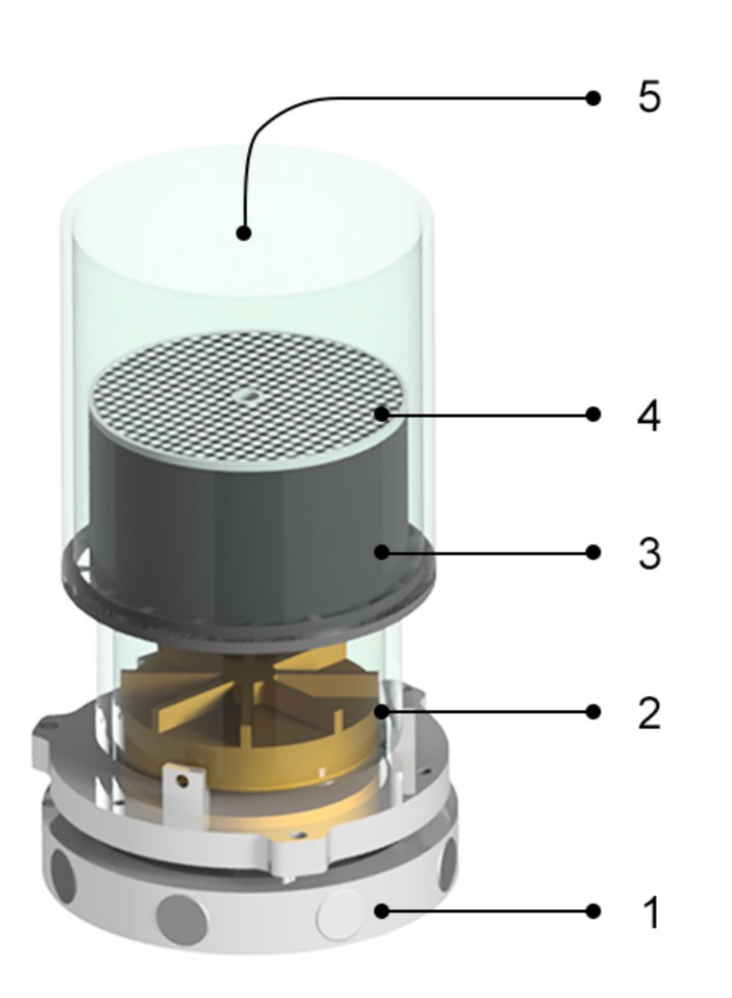
Magnetically coupled propellor spins to give circulation.



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

Add draining cavity for "bathtub" effect. Free surface ripplons.

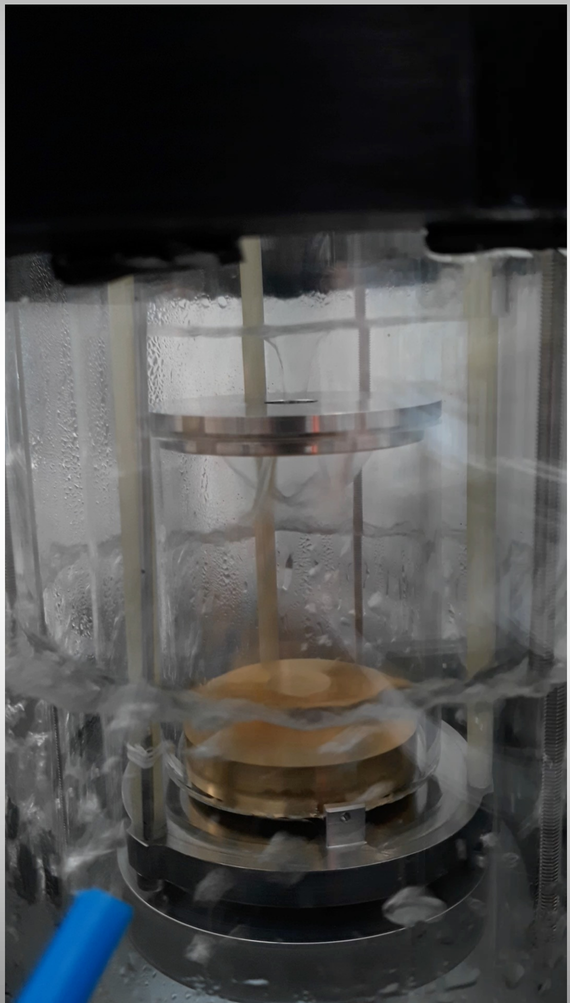
Vortex generator



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

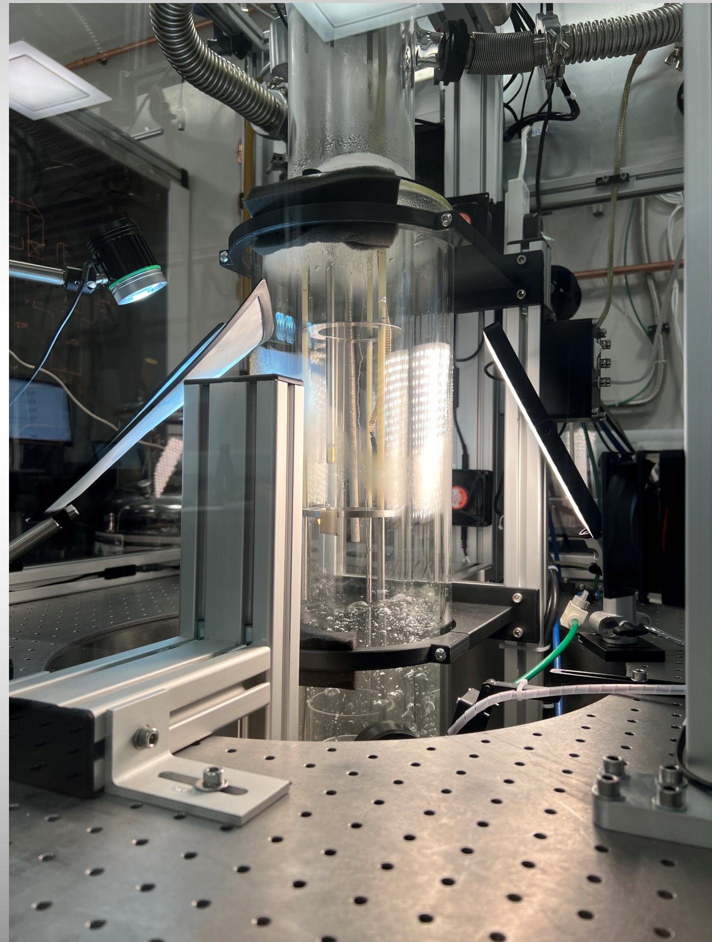
Set-up



Fully transparent - custom glass Dewars without silvering

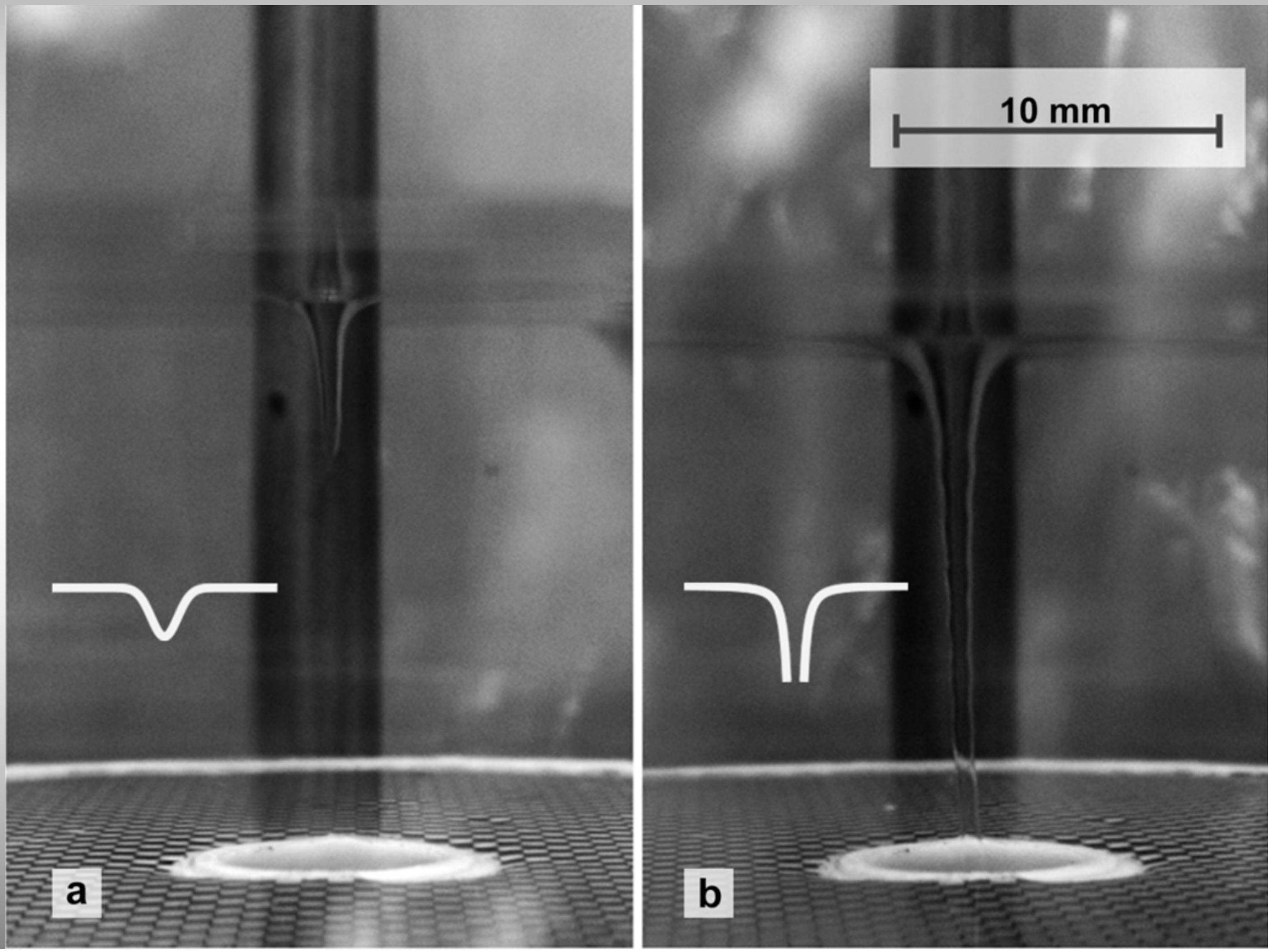
Experiments at 1.95 K in paper (1.7K)

Propeller speed range 0.5 – 3.5 Hz



Low propeller speeds – **Surface depression (solid core)**

Higher propeller speeds – **Hollow core**



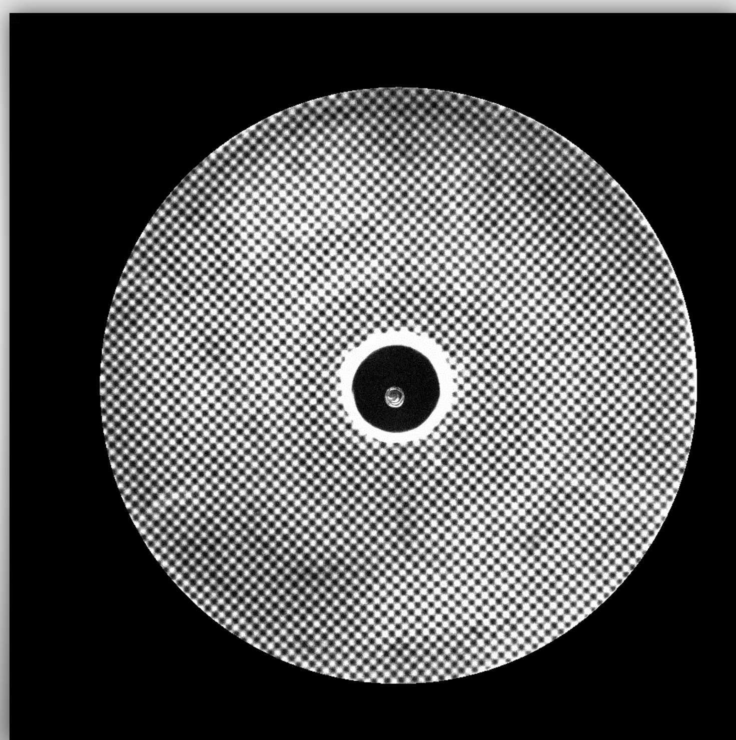
Surfing the Wave

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

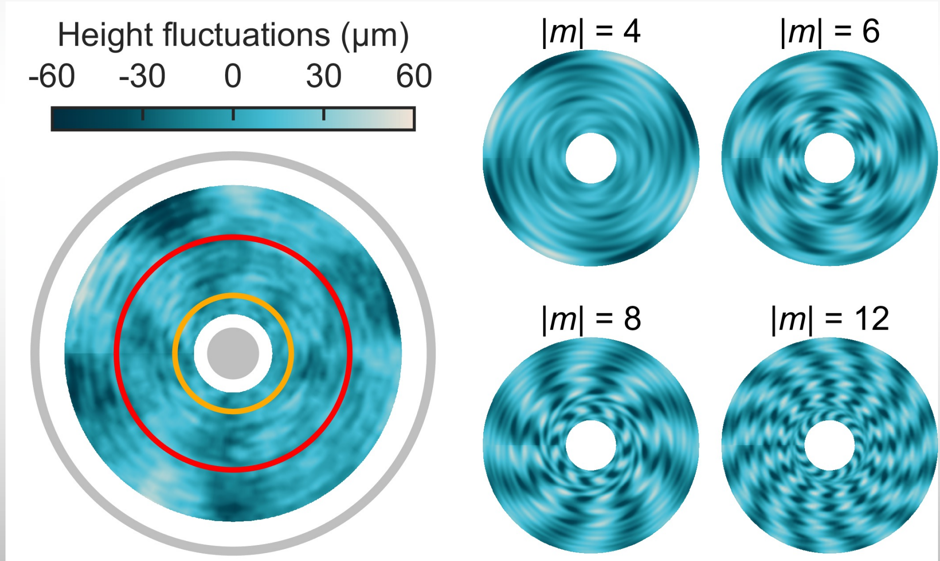
(high resolution in space and time)

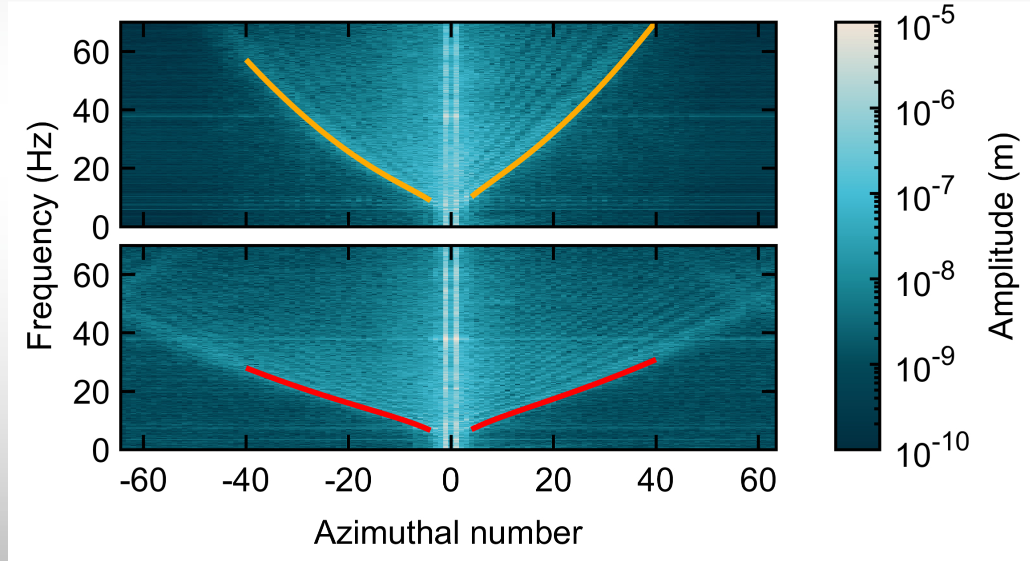


Superfluid Interface Reconstruction

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)

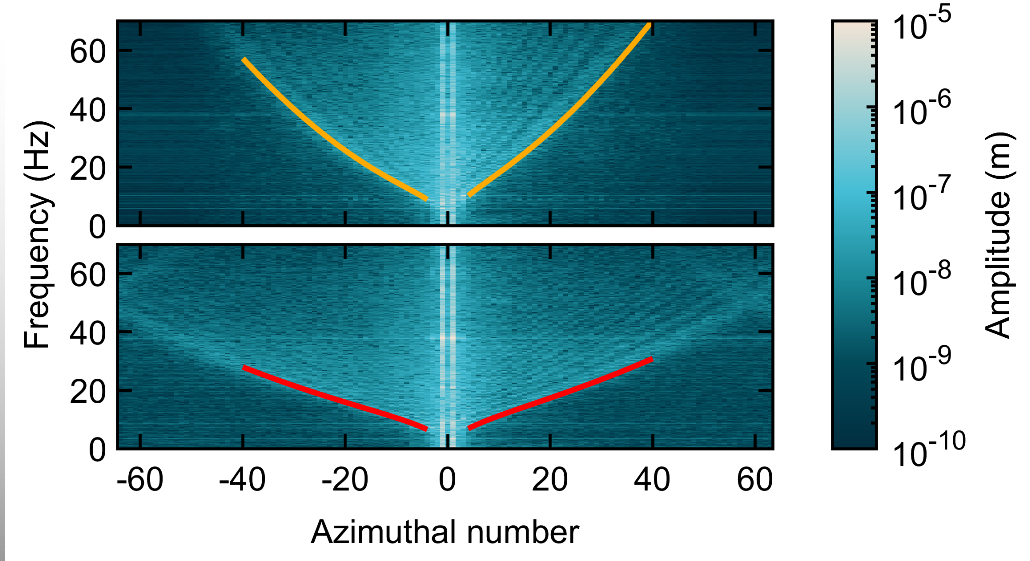
Superfluid Interface Modelling

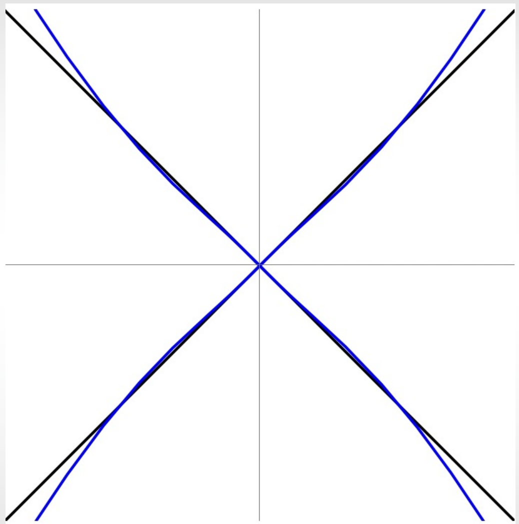
Lifting the dispersion relation from earlier, (deep regime) see the effect of v clearly on yellow plot

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

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

$$v_r \approx 0$$

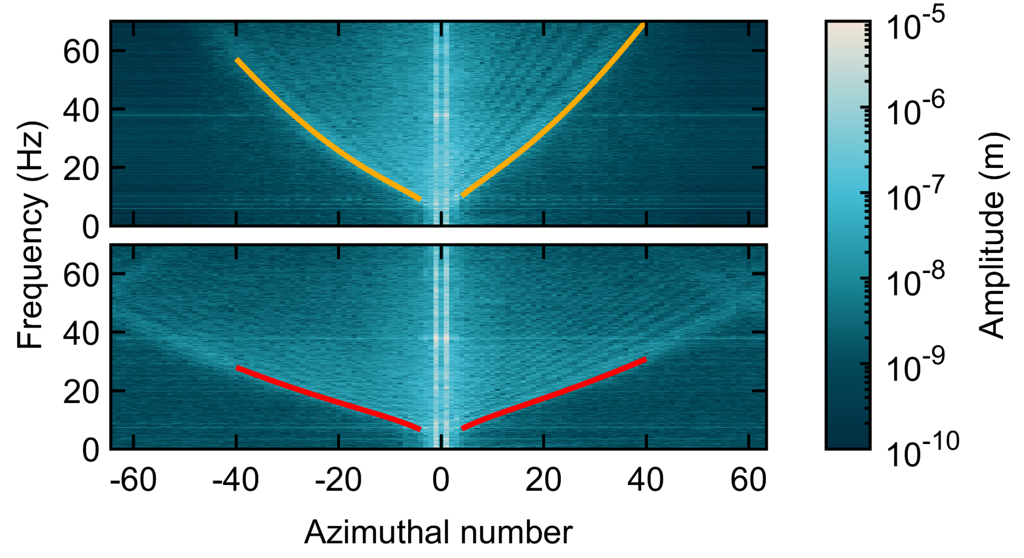


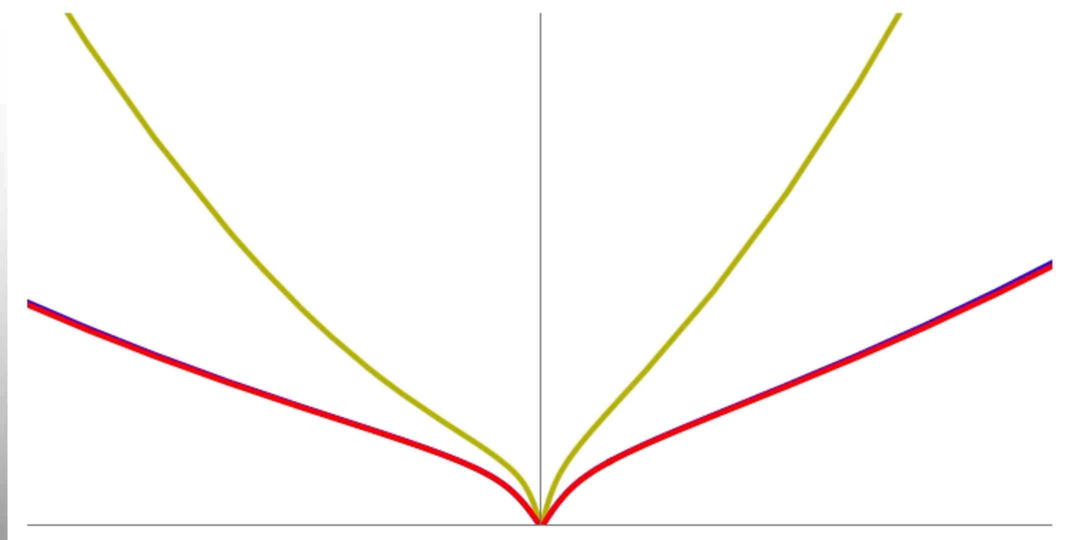


$$\omega_+ \simeq \frac{mC}{r^2} \pm \sqrt{gk + \gamma k^3}$$

Superfluid Interface Modelling

$$\omega_{+} \simeq \frac{mC}{r^2} \pm \sqrt{g\frac{m}{r} + \gamma\left(\frac{m}{r}\right)^3}$$





Radial Flow Profile

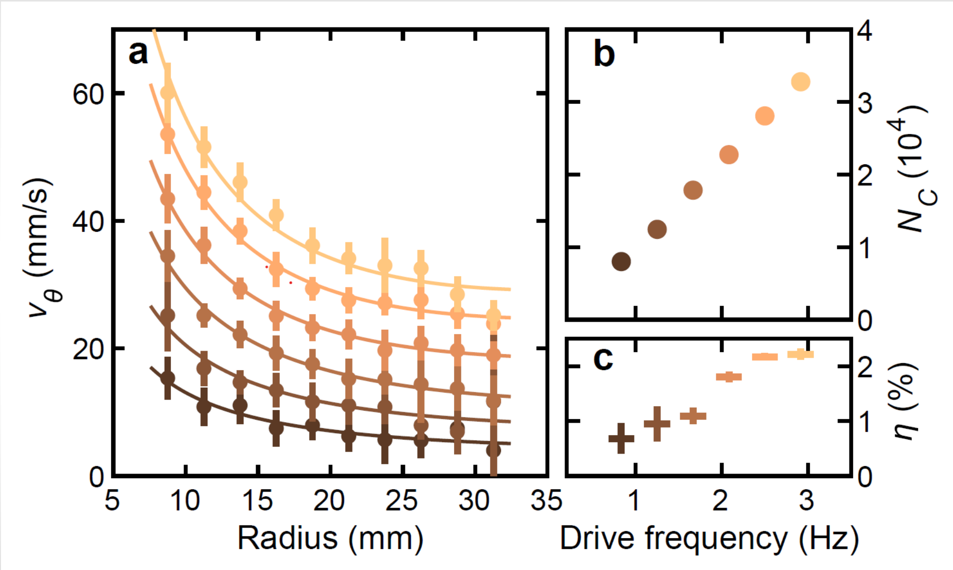
$$\omega_+ \simeq \frac{mC}{r^2} + p_r + \sqrt{gk + \gamma k^3}$$

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

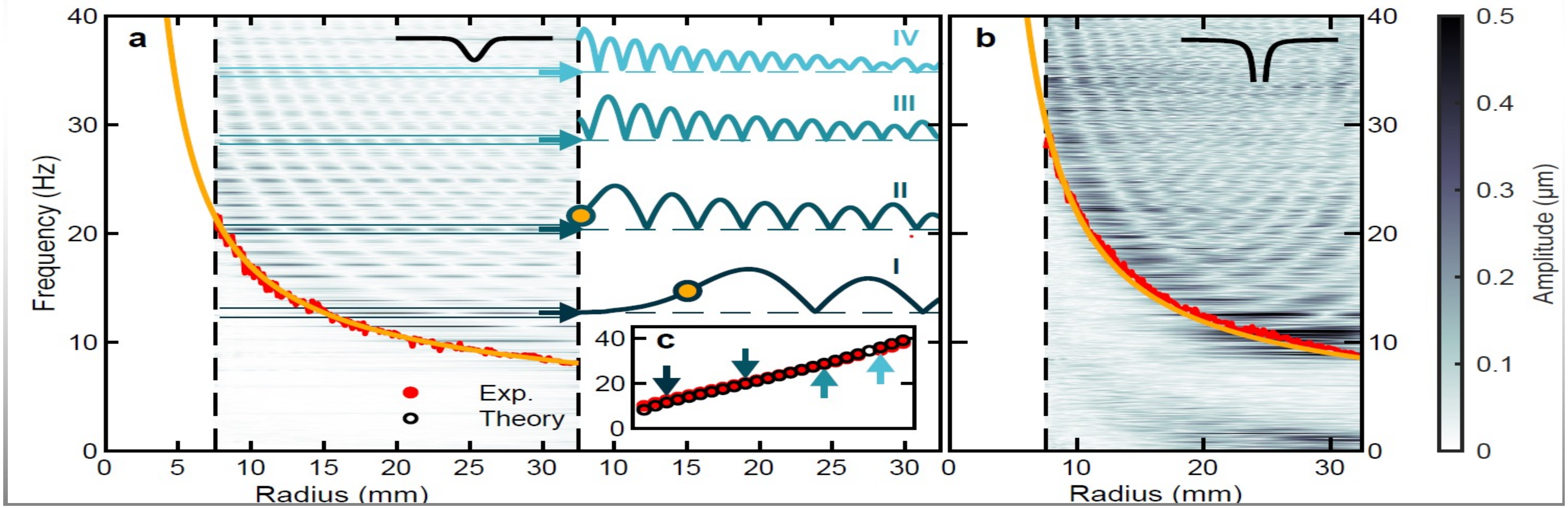


Most extensive quantum vortex flows observed in He II

$N_C \sim 10^4$

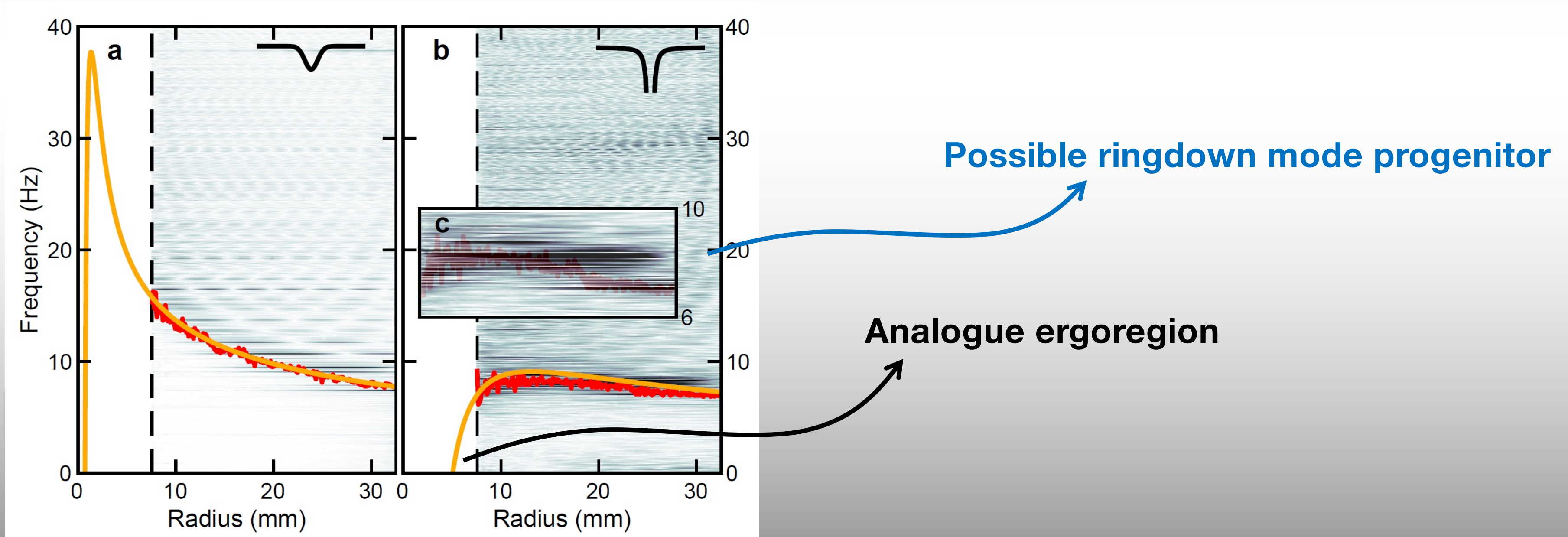
Standing Waves

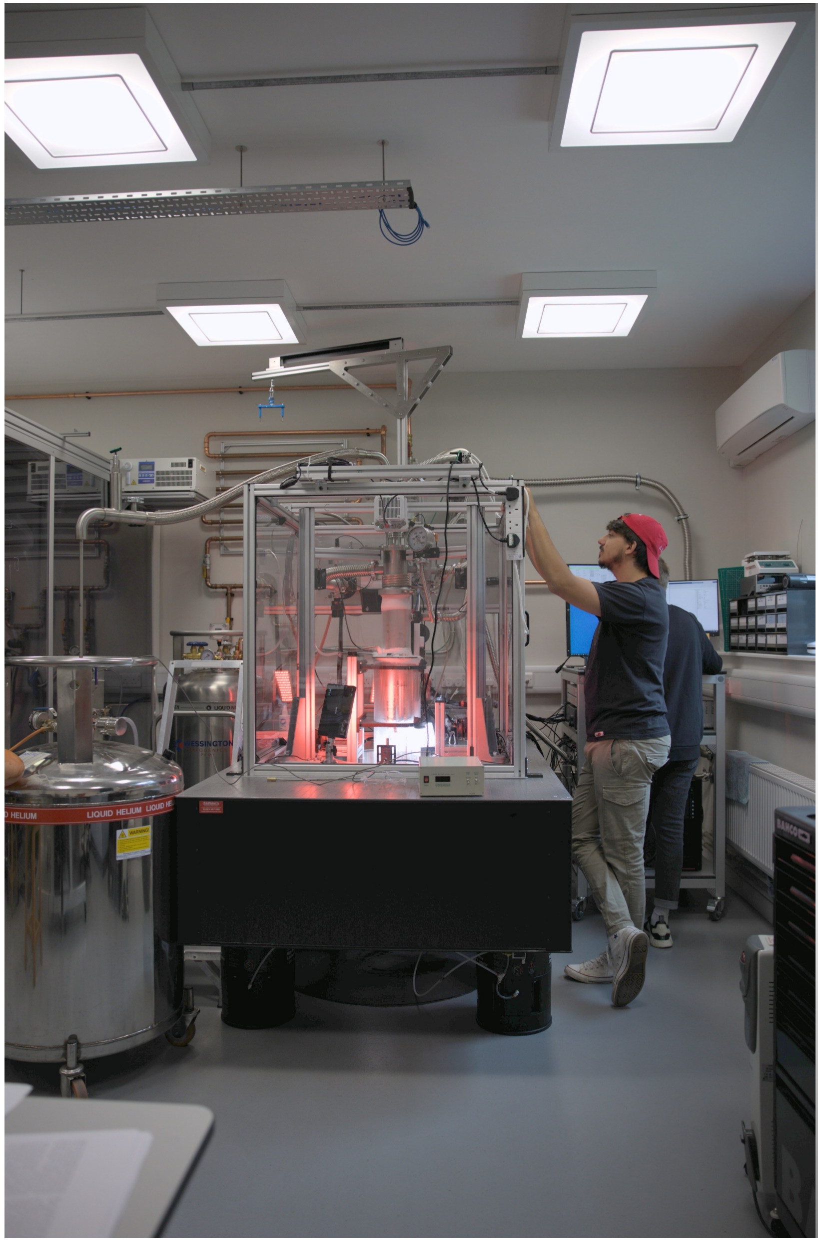
Picking out an *m* (+8) and plotting radially shows clear evidence of modes. Minimum frequency provides inner potential barrier, flow confined at outer wall. (L: Solid core, R: Hollow core, Middle: Modelling. Red is measured effective inner barrier, yellow modelled barrier.)



Counter-rotating waves

For m =-8 picture is a bit different. Solid core shows bound states at lower frequency, but no bound states for hollow core. Instead, evidence of excitations near "light ring" (local maximum of effective potential)



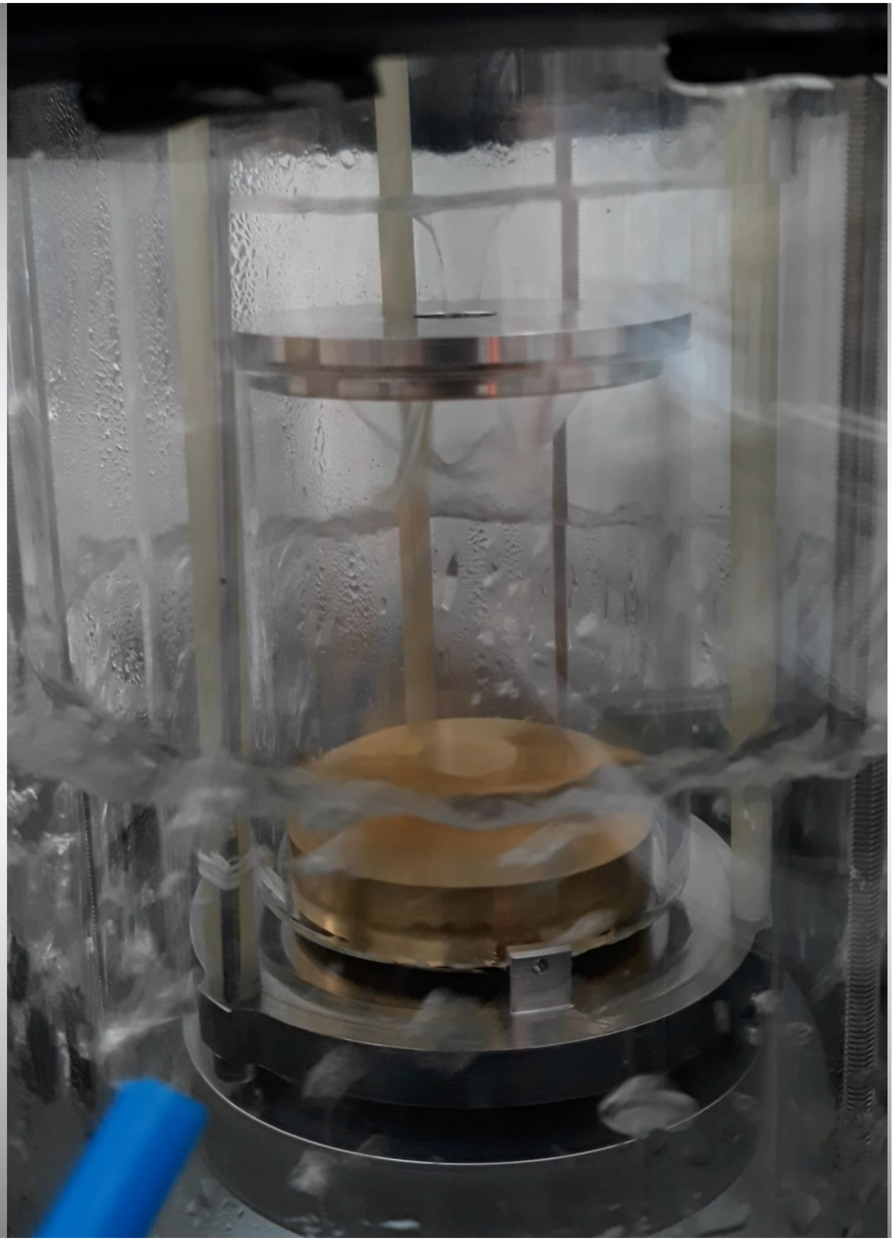


What is next?

- **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**
- Minor refinements to capture **black hole ringing** and **superradiance**

Black Hole Bombs

Superradiant instabilities seem to be a generic feature of these systems. Different fluids have different nonlinearities, but the boundary acts as a mirror and instabilities grow.



Summary

- Analog systems allow general features of wave propagation on various backgrounds to be explored
- Many properties such as ringdown & superradiance are universal
- He II experiment now operating and refinable
- "UV" effects are tunable and observable….
- We can directly tune non-GR black holes.