Curved spacetimes and accelerated observers in experimental analogues

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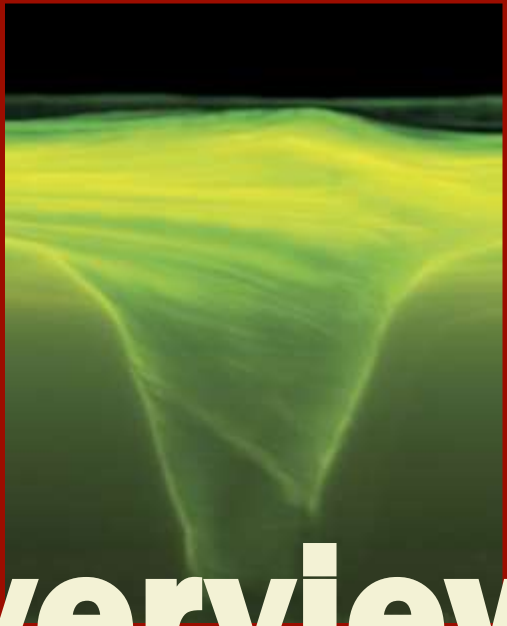
Fluid excitations <-> Scalar field in curved spacetime

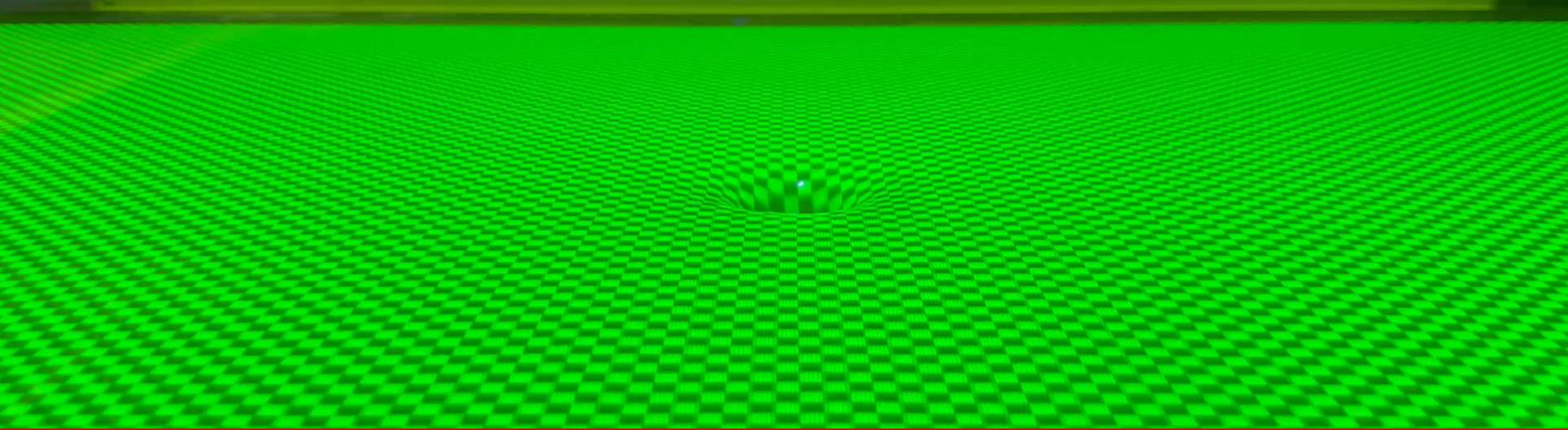
Water vortex



He-II vortex

He-II thin film

Overview




‘Black Hole’ in Classical Fluid

10.1038/nphys4151

ROGER PENROSE

R. Penrose, "Gravitational Collapse: The Role of General Relativity," Rivista del Nuovo Cimento Numero Speziale I, 257–276 (1969).

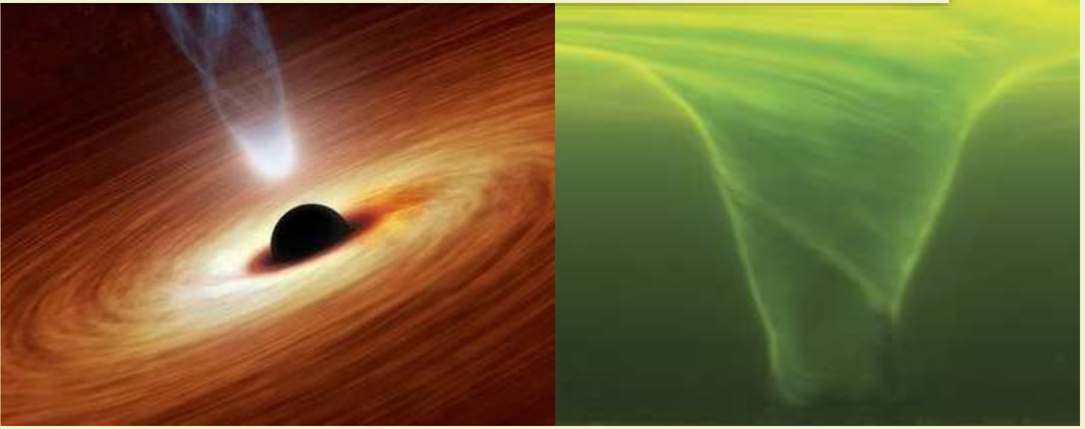
Zel’dovich effect in experiment:
M. Cromb et al. ‘Amplification of Waves from a Rotating Body’. *Nat Phys (*2020)
10.1038/s41567-020-0944-3

Waves should also do this. And scattering from any absorber – not just black holes!

Ya.B. Zel’dovich. *JETP Lett.* 14, 180 (1971)

Ya.B. Zel’dovich. *JETP* 35.6, 1085 (1972)

‘Black Hole’ in Classical Fluid



Amplification condition:

$$\omega_D = \omega - m\Omega(r) < 0$$

ω_D: frequency in fluid frame m: angular momentum number
ω: frequency in lab frame $\Omega(r)$: fluid rotation rate

Decomposing into different angular momentum modes amplification of m=1,m=2 modes was observed.

Theo Torres, Sam Patrick, Antonin Coutant, Maurício Richartz, Edmund W. Tedford, and Silke Weinfurtner. 2017. Rotational superradiant scattering in a vortex flow. *Nature Physics*, *13*(9), 10.1038/nphys4151

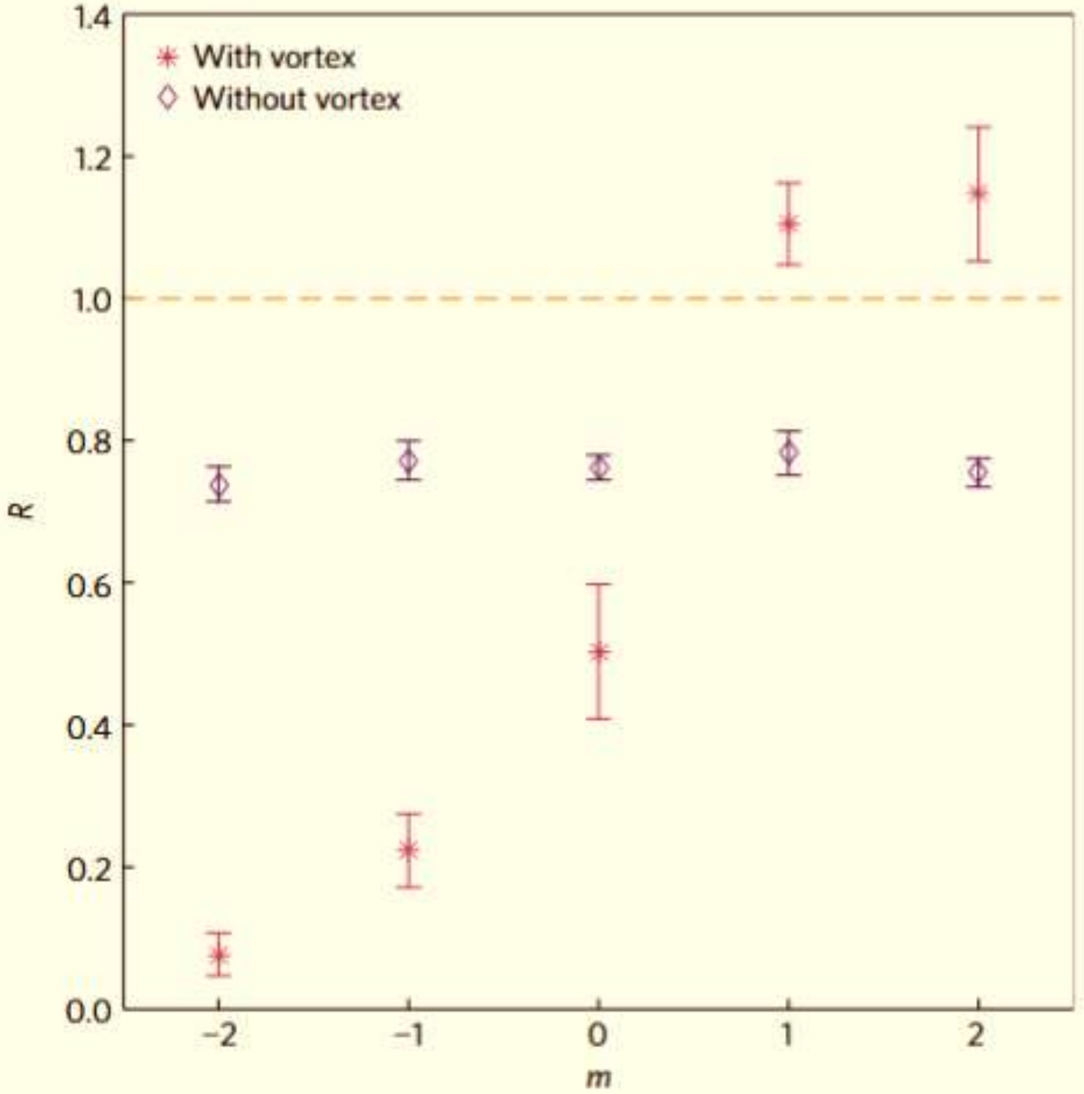
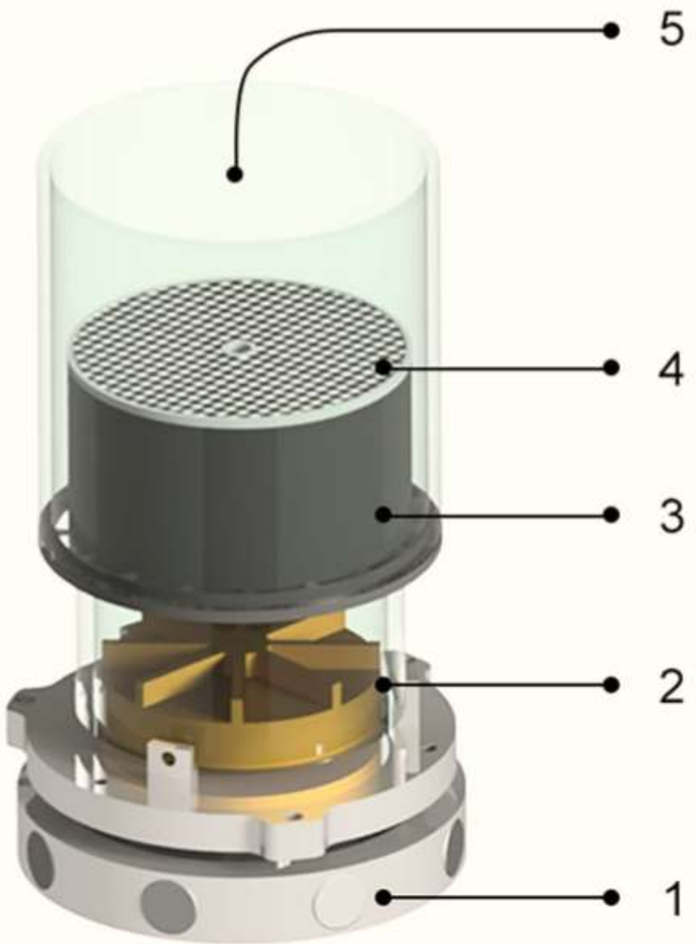
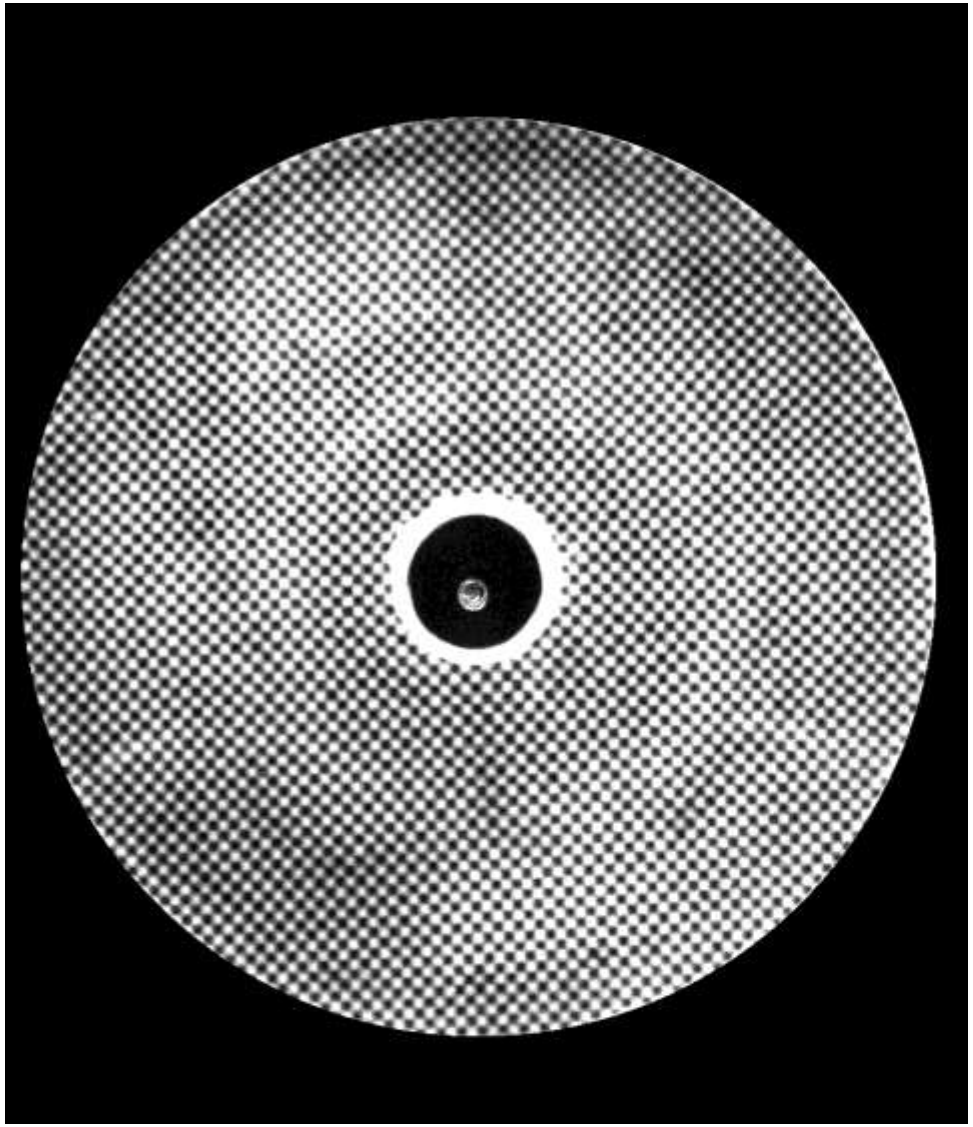


Figure 3 | Reflection coefficients for different values of *m*, for the frequency *f*=3.70 Hz (stars). We have also shown the reflection coefficients for plane waves without a flow, at the same frequency and water height (diamonds). We see that the plane wave reflection coefficients are identical for all *m* values, and all below 1 (within error bars).

Macroscopic Superfluid ^4He Vortex



Patrik Švančara, Pietro Smaniotto, Leonardo Solidoro, et al. 2024. ‘Rotating Curved Spacetime Signatures from a Giant Quantum Vortex’. *Nature* 10.1038/s41586-024-07176-8.



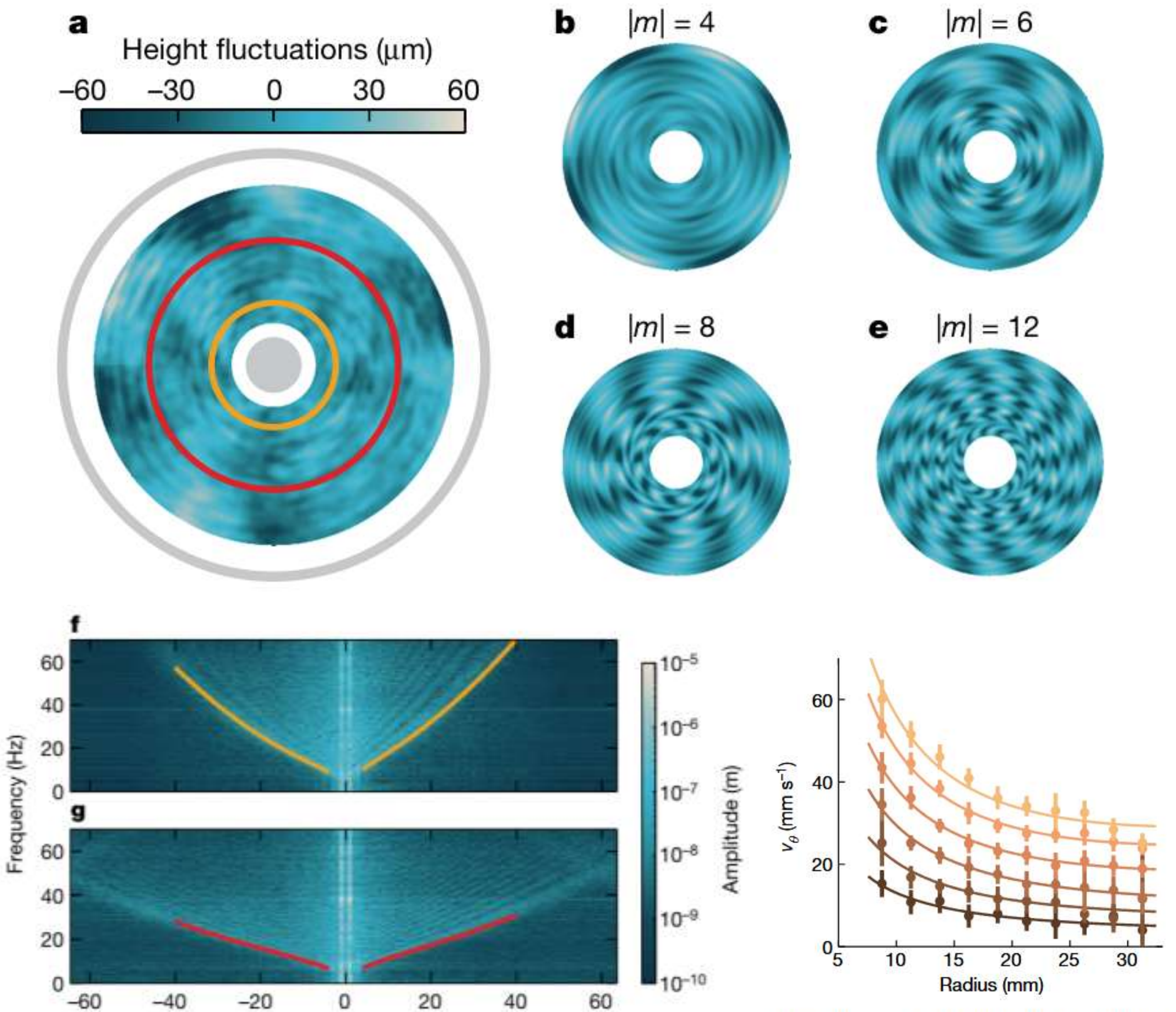
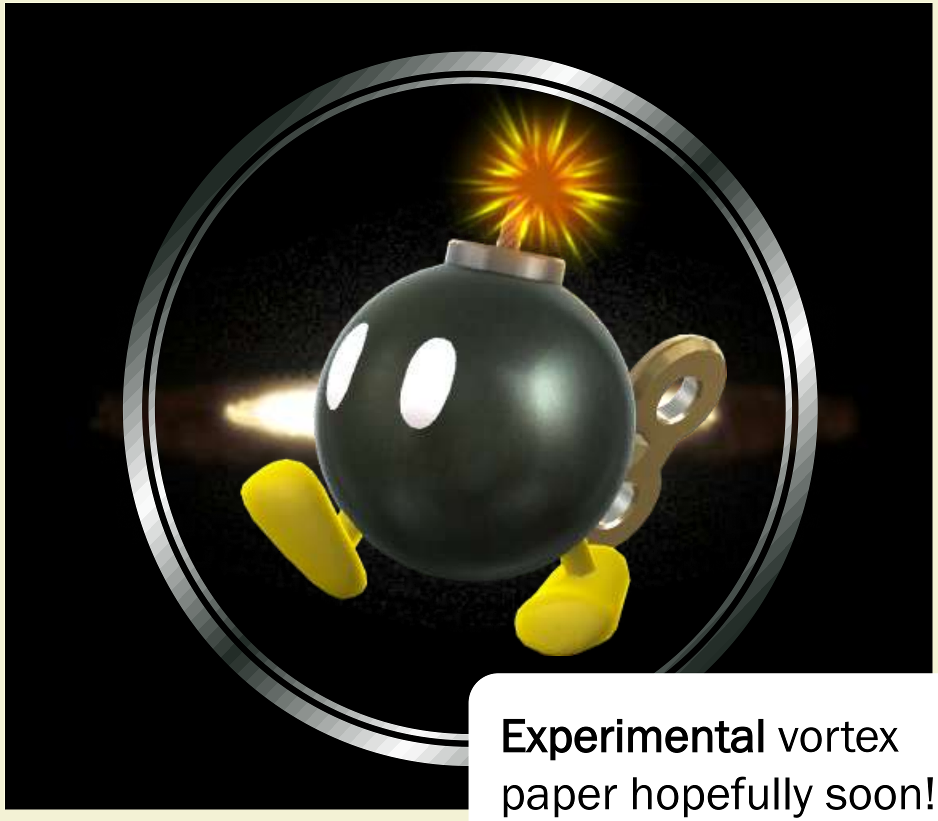


Fig. 3 | Reconstructed velocity distribution

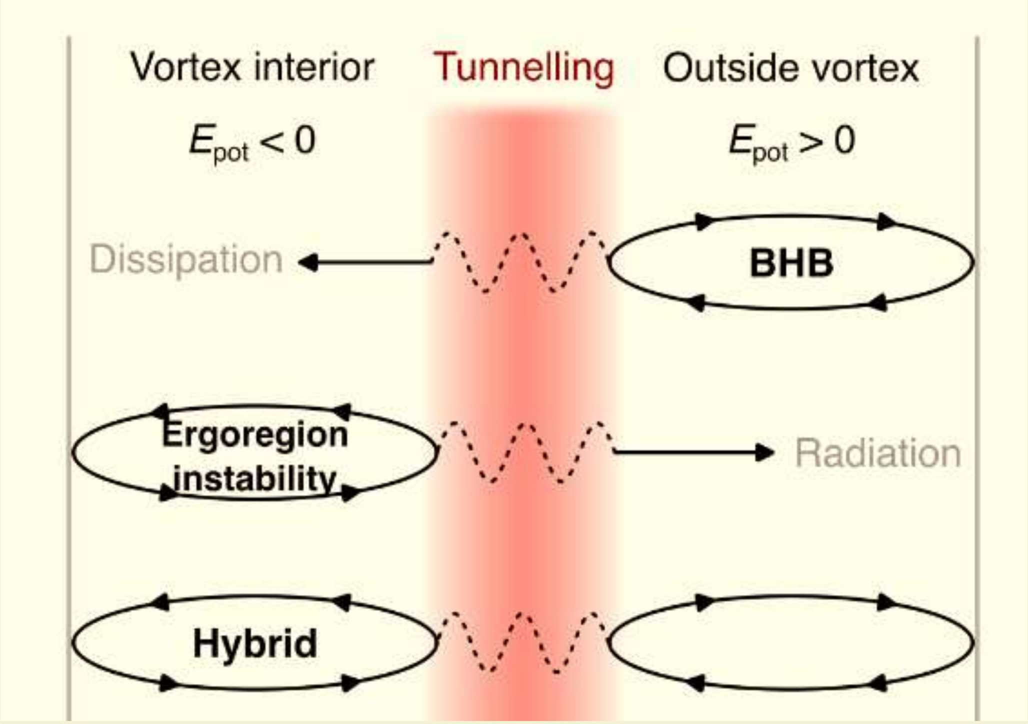
Patrik Švančara, Pietro Smaniotto, Leonardo Solidoro, et al. 2024. 'Rotating Curved Spacetime Signatures from a Giant Quantum Vortex'. *Nature* 10.1038/s41586-024-07176-8.

Black hole bombs and vortex instabilities

Prev post-doc experiment:
M. Cromb, M. C. Braidotti, A. Vinante, D. Faccio, and H. Ulbricht. ‘Creation of a Black Hole Bomb Instability in an Electromagnetic System’ (2025): 10.1126/sciadv.adz4595



Experimental vortex paper hopefully soon!



Sam Patrick, August Geelmuyden, Sebastian Erne, Carlo F. Barenghi, and Silke Weinfurtner. 2022. ‘Quantum Vortex Instability and Black Hole Superradiance’. *Physical Review Research* 4 (3): 033117. 10.1103/PhysRevResearch.4.033117.

Sam Patrick. ‘Quantum Vortex Stability in Draining Fluid Flows’. *Physical Review A* 110, no. 1 (2024). 10.1103/PhysRevA.110.013327

Sam Patrick, Leonardo Solidoro, Maurício Richartz, et al. ‘When Is a Sloshing Vortex an Analogue Black Hole Bomb?’ (2025) arxiv.org/abs/2511.05351v1

"Unruh Effect"

S. A. Fulling, 'Nonuniqueness of Canonical Field Quantization in Riemannian Space-Time'. *Phys. Rev. D, vol.* 7, no. 10 (1973) 10.1103/PhysRevD.7.2850.
P. C. W. Davies, 'Scalar Production in Schwarzschild and Rindler Metrics'. *J. Phys. A Math. Gen*, vol 8, no. 4 (1975) 10.1088/0305-4470/8/4/022.
W. G. Unruh, 'Notes on black-hole evaporation', *Phys. Rev. D*, vol. 14, no. 4 (1976) 10.1103/PhysRevD.14.870.

- A vacuum in an inertial frame would be seen by an **accelerated observer** as a **thermal bath of particles.**

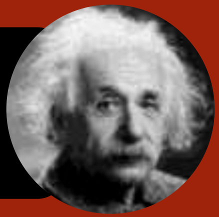
- Related by the equivalence principle to Hawking radiation from the gravitational field of a black hole

$$T = \frac{\hbar a}{2\pi c k_B} \approx 4.06 \times 10^{-21}\ \mathrm{K{\cdot}s^2{\cdot}m^{-1}} \times a$$

- Very small!

Gravity

Curved spacetime
≡
non-inertial motion



~ Acceleration

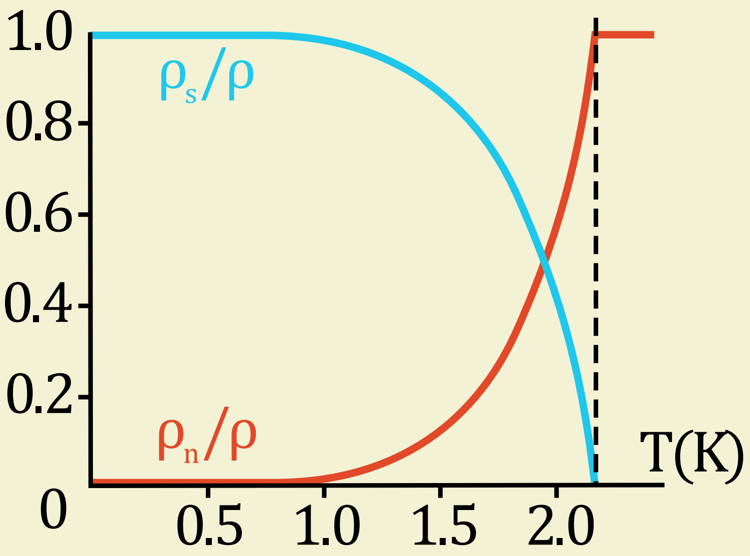
“Unruh Effect”

Unruh effect: accelerated observer sees inertial vacuum as thermal

- Want to compare accelerated vs. inertial measurements of the same quantum field vacuum.
- For our (effective) quantum field: Superfluid thin film ^4He surface waves (‘third sound’).

Our quantum field: 'Third Sound'

- He-4 below T=2.172K becomes a quantum fluid, a 'superfluid'
- 'Two fluid' model of normal liquid component and a pure superfluid component (zero viscosity and zero entropy), ratio depends on the temperature
- 4 types of sound
- The height of the third sound surface waves obey the (2+1)-dimensional Klein–Gordon equation



- First sound: density waves - both components oscillate in phase, like regular sound.
- Second sound: temperature waves - the two components oscillate out of phase. Creates high thermal conductivity

- **Third sound:** occurs in thin films (<100s nm) on a substrate. The normal component sticks to the surface, only the superfluid component moves, oscillating parallel to the surface.
- Fourth sound: occurs in very narrow channels where the normal component is stuck to all sides

“Unruh Effect”

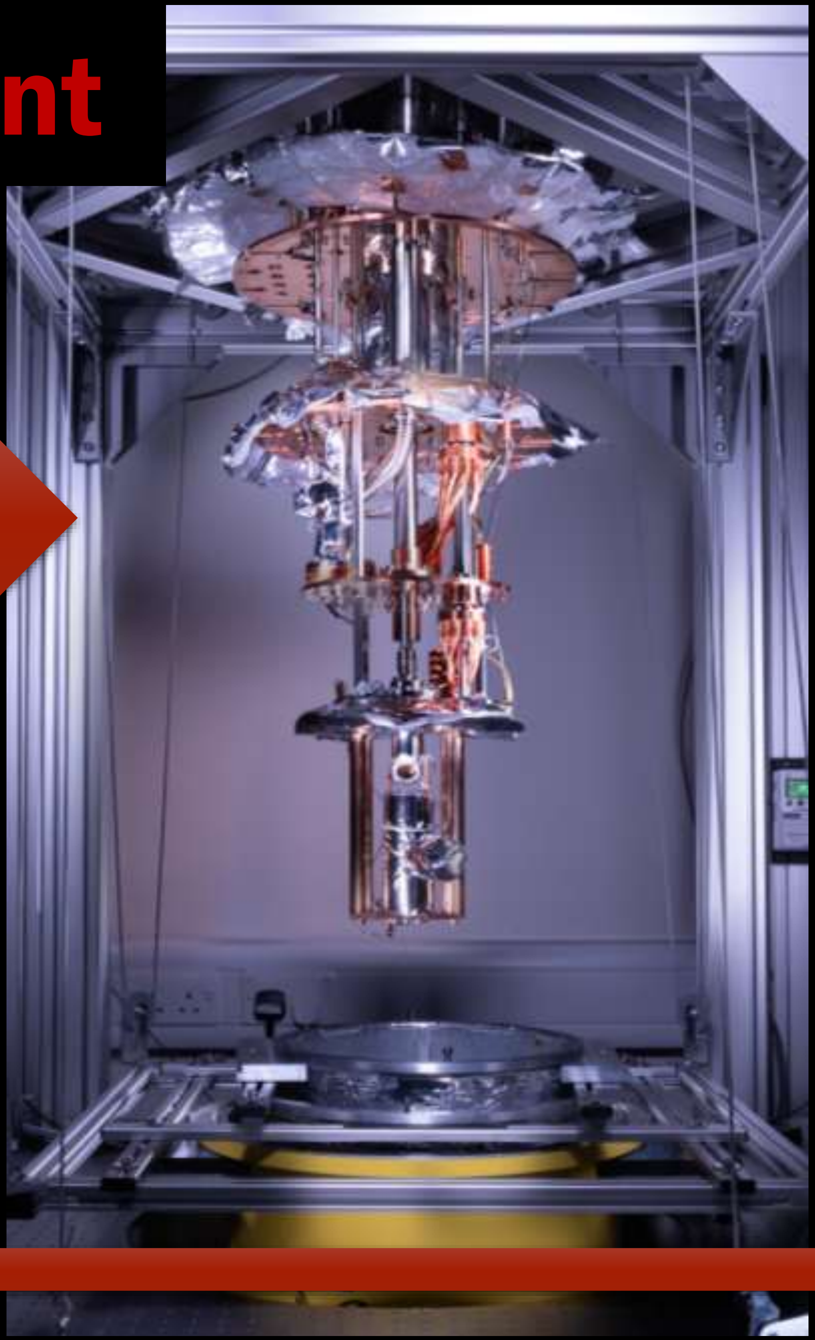
Unruh effect: accelerated observer sees inertial vacuum as thermal

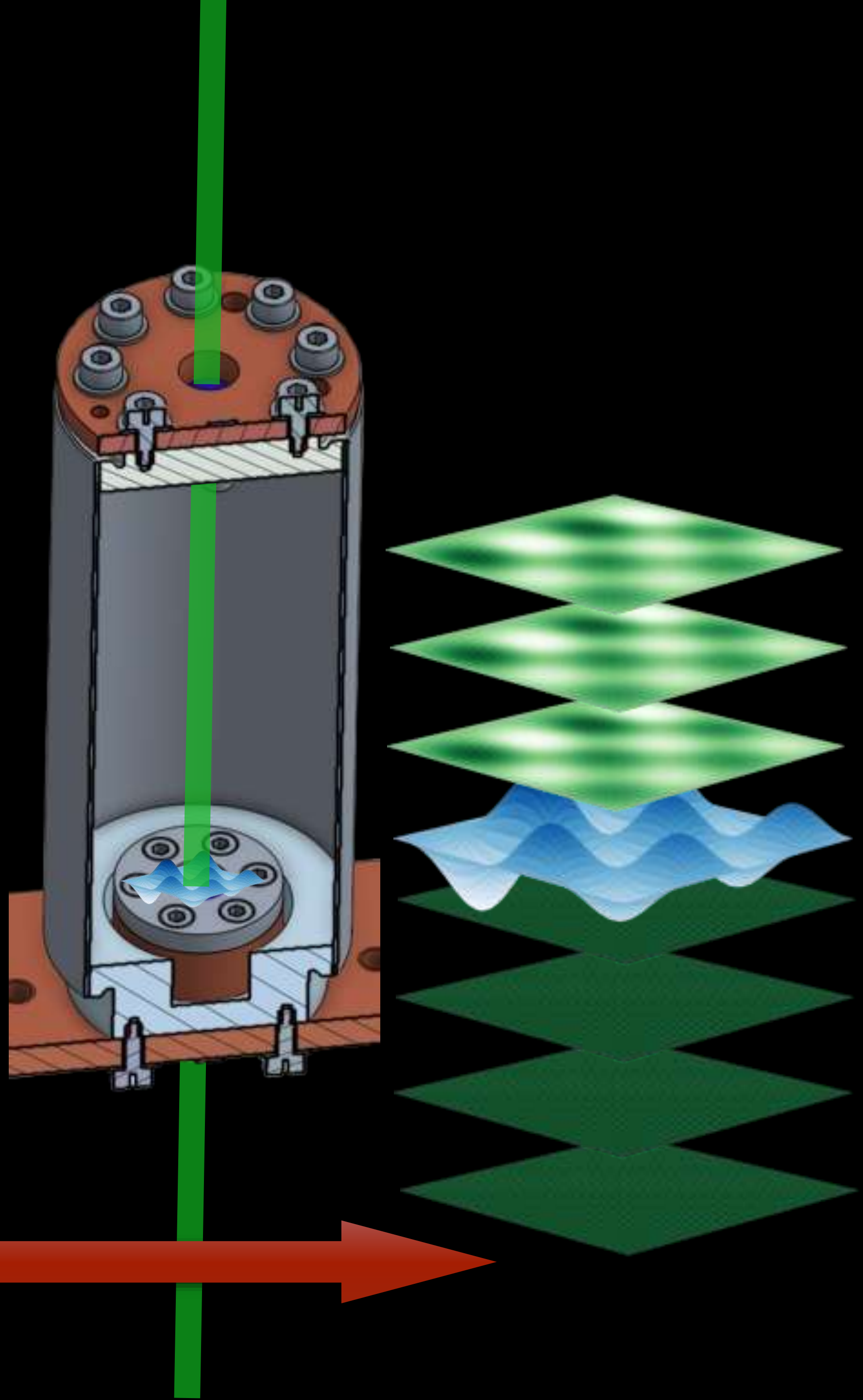
- Want to compare accelerated vs. inertial measurements of the same quantum field vacuum.
- For our (effective) quantum field: Superfluid thin film ^{4}He surface waves (‘third sound’).
- Circular motion is more practical in lab than maintaining linear acceleration.
- Realistically, system not in vacuum state -> velocity effects.
- Subtract the additional velocity-dependent effects to see underlying acceleration effect.

C. R. D. Bunney *et al.*, ‘Third sound detectors in accelerated motion’, *New J. Phys.* (2024) 10.1088/1367-2630/ad5758

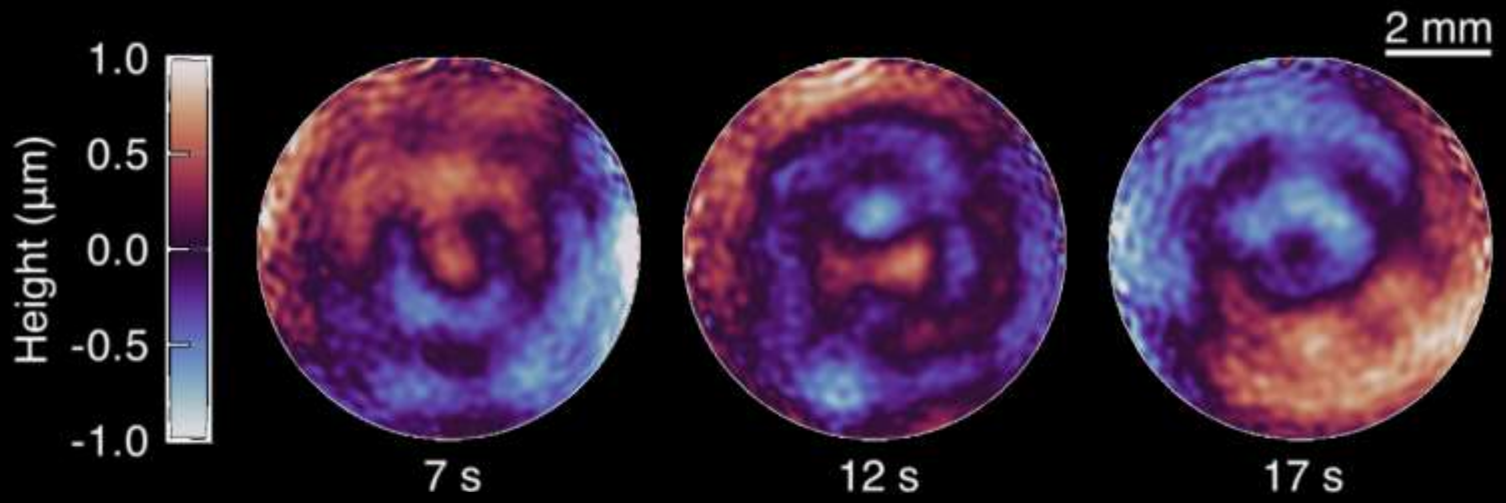
Maciej T. Jarema, Cameron R. D. Bunney, Vitor S. Barroso, Mohammadamin Tajik, Chris Goodwin, and Silke Weinfurtner. ‘Information in Quantum Field Theory Simulators: Thin-Film Superfluid Helium. Preprint, arXiv, 2025. 10.48550/arXiv.2508.07247.

The Experiment

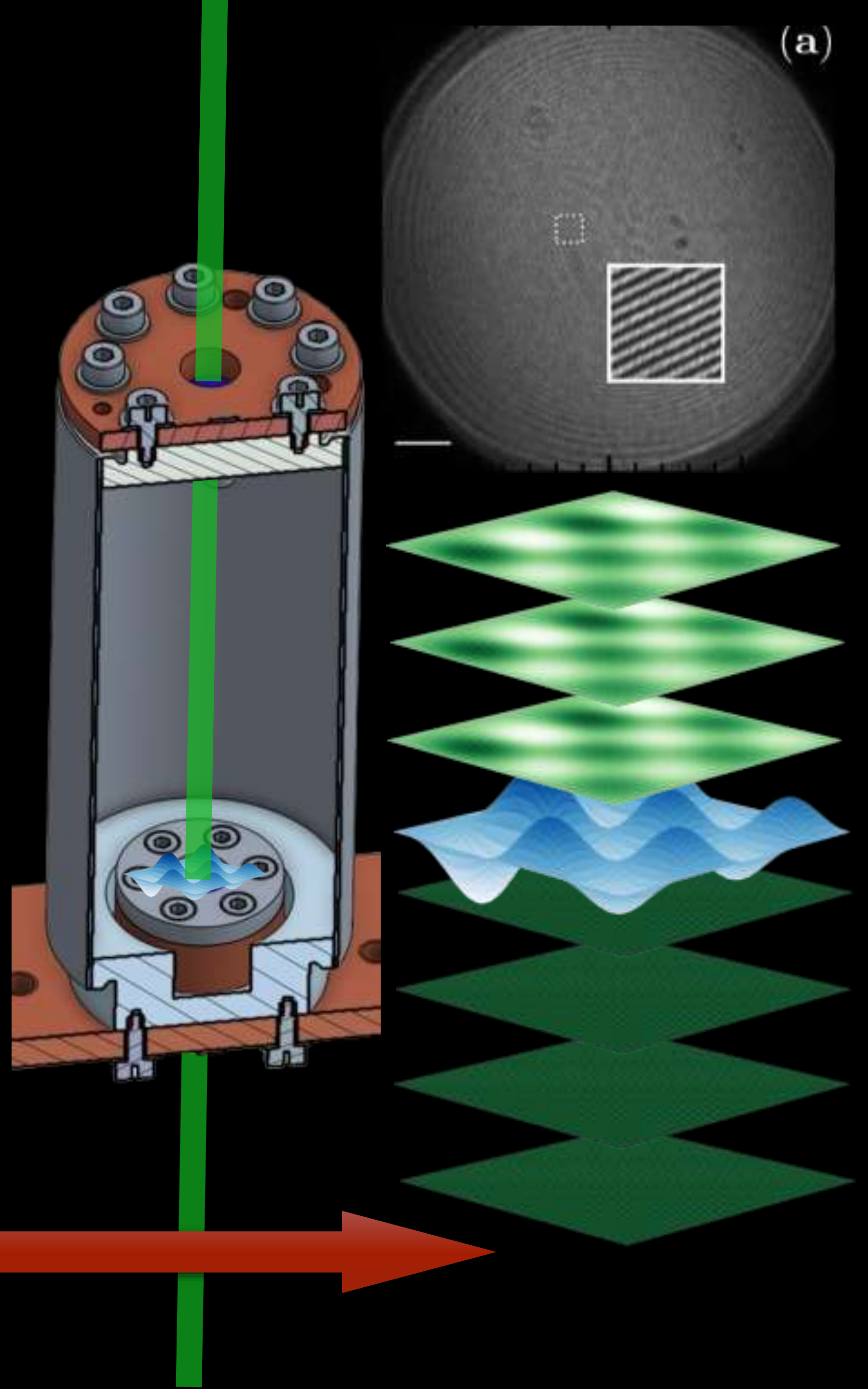




Inertial Observer: Digital Holography

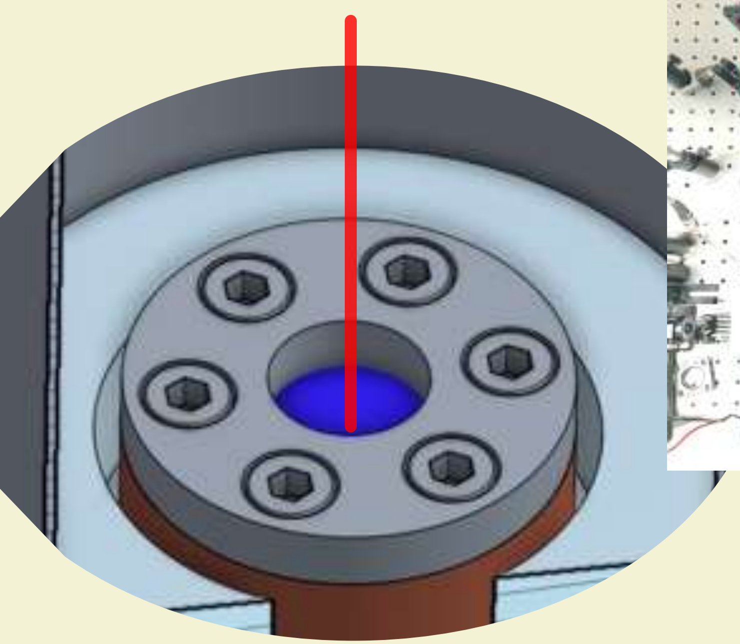


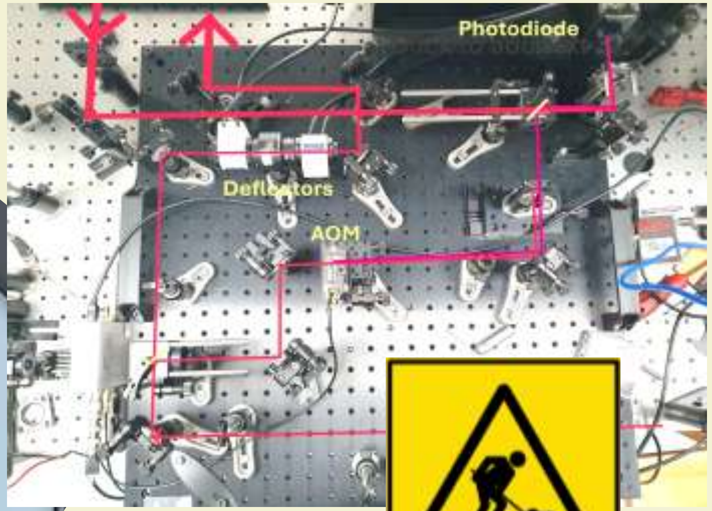
Vitor S. Barroso, Patrik Švančara, Chris Goodwin, *et al.* 'Digital Holographic Imaging for Free Surfaces of Superfluid Helium'. *Physical Review Applied* 26, no. 1 (2026): 014080. 10.1103/dh9b-k6hm

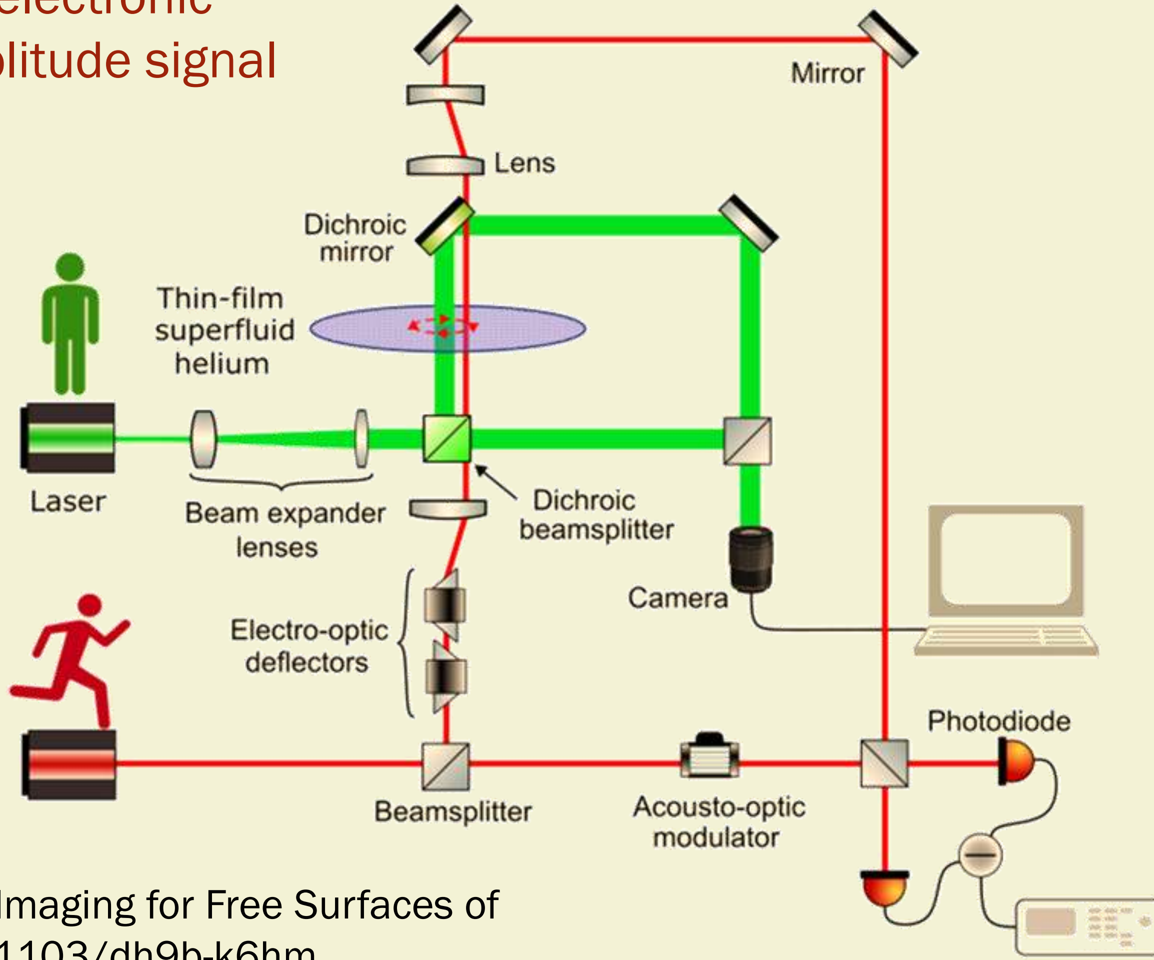


Accelerated Observer: Circular Heterodyne

- Circular path beam: accelerated worldline
- Heterodyne measurement: ref beam is frequency shifted allowing electronic processing of phase & amplitude signal







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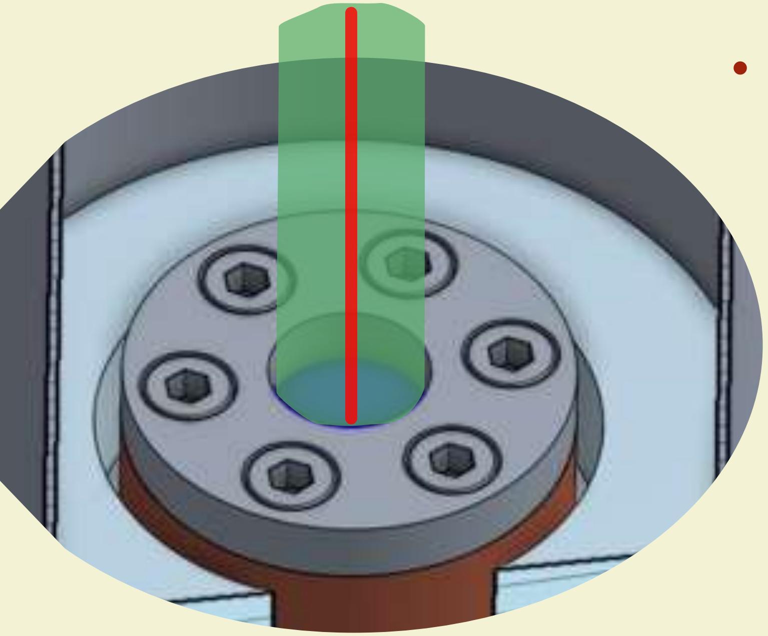
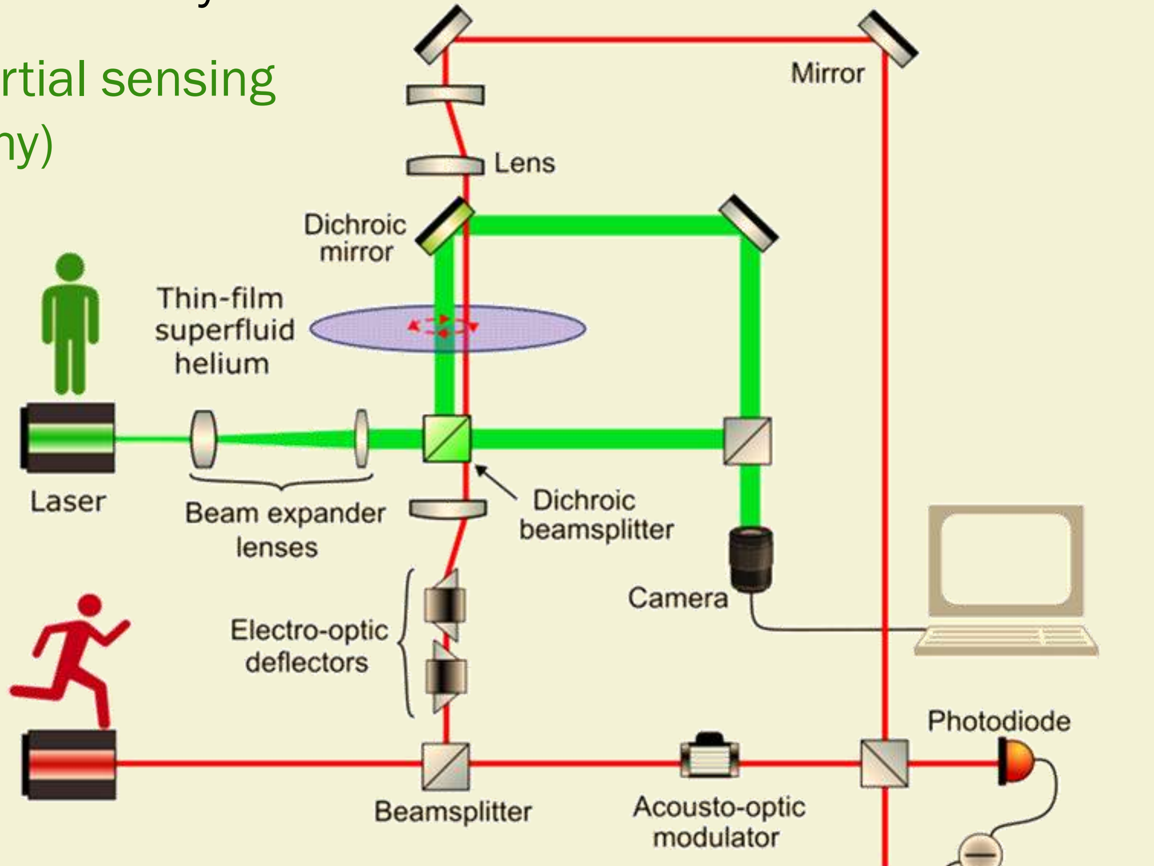
C. R. D. Bunney *et al.*, 'Third sound detectors in accelerated motion', *New J. Phys.* (2024) 10.1088/1367-2630/ad5758

‘Circular Unruh’ experiment

- Laser beams probe the thin film helium ‘quantum field’, height of surface waves imprints laser phase change, measured interferometrically.
  - Expanded stationary beam: inertial sensing of whole field (Digital Holography)
    - Circular path beam: accelerated worldline. (Heterodyne measurement)





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C. R. D. Bunney *et al.*, ‘Third sound detectors in accelerated motion’, *New J. Phys.* (2024) 10.1088/1367-2630/ad5758

A random request

- If anyone knows these papers (CTCs and CTGs from two Perjeons) and can explain them to me, It would be interesting to know if this is something that could feasibly be tested in an experiment with e.g levitated spinning magnets

Gen. Relativ. Gravit. (2005) 37(11): 1833–1844
DOI 10.1007/s10714-005-0163-3

RESEARCH ARTICLE

W. B. Bonnor · B. R. Steadman

Exact solutions of the Einstein-Maxwell equations with closed timelike curves

Received: 24 March 2005 / Published online: 4 November 2005

Abstract We examine two electrovac spacetimes, the Kerr-Newman solution and another due to Perjes, which represent single charged, rotating, magnetic objects. Both contain regions with closed timelike curves (CTC), but these regions would be covered by the sources in any physical realisation of the spacetimes, so the CTC would not be detectable. We then study a stationary solution referring to *two* charged, rotating, magnetic objects. In general there is a region of CTC between the objects no matter how far apart they are. In this case the region would not be covered by the sources, and CTC would be detectable in principle.

Keywords Einstein-Maxwell equation · Spinning charges

1 Introduction

Many solutions of Einstein's equations contain closed timelike curves (CTC): ex-

Gen Relativ Gravit (2009) 41:571–573
DOI 10.1007/s10714-008-0687-4

COMMENT

A comment on Bonnor–Steadman closed timelike curves

Valéria M. Rosa · Patricio S. Letelier

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Physics Letters A 370 (2007) 99–103
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Stability of closed timelike geodesics

V.M. Rosa [a], P.S. Letelier [b,*]

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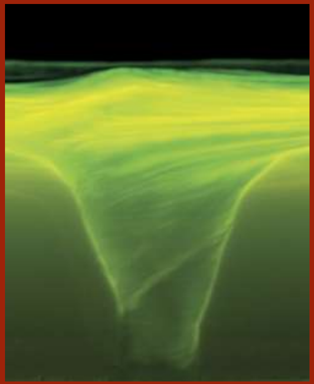
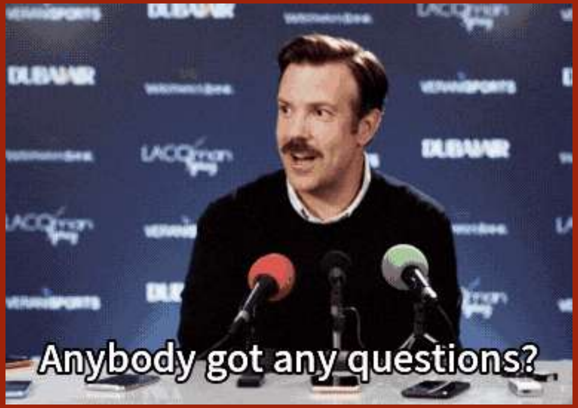
Thanks for listening!



Credit to all the past and present members of the group who worked on these projects!

@gravity_laboratory

no generative ai slop was used in this presentation