# QSimFP Quantum Simulators for Fundamental Physics

## Scientific Goals

Quantum Simulations of Black Hole and Early Universe Processes

## Community

50-50 QT-FP researchers

27 QTFP funded (50 Partners)

## Governance

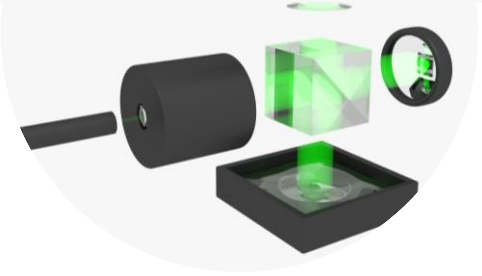
Silke Weinfurtner (PI, Nottingham)

Zoran Hadzibabic (Cambridge)

Ruth Gregory (KCL)

## Outputs (start 2021)

- 1 Patent Application
- 25 Publications
- 6 Preprints
- 4 Feature News Articles
- BBC 'Sky At Night'
- 4 Quantum Simulators



## Experimental Facilities

## Modelling Support

Quantum Simulators
for Fundamental Physics

QSimFP

Thanks to Ian’s summary, I will be focussing entirely on the…

# Scientific Progress Summary

# False Vacuum Decay

**Cambridge**
- Hiranya Peiris

**UCL**
- Andrew Pontzen
- Alex Jenkins

**Newcastle**
- Ian Moss
- Kate Brown

**PI/CITA**
- Matt Johnson
- Jonathan Braden
- Dalila Pirvu

**Zoran Hadzibabic**
- Christoph Eigen
- Konstantinos Konstantinou
- Nishant Dogra

# FVD - Experiment

**Zoran Hadzibabic & team (Cambridge)**

**Completed**

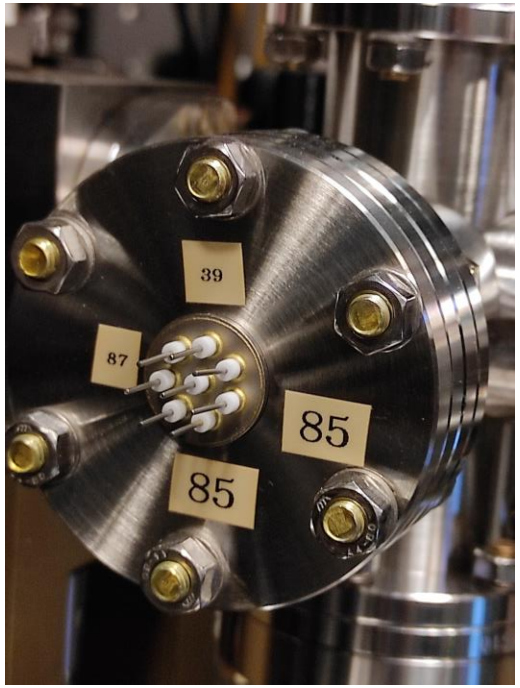
- Large 39K (Potassium) condensates produced
- High-efficiency (>85%) transfer from cooling to science chamber
- Single-component in different hyperfine states (F=1,$m_F$=0,-1)

**Ongoing**

- Optimisations trapping potentials (Box-trap)
- Microscopic detection method (in-Situ, $1\mu\mathrm{m}$ res., cloud $100\mu\mathrm{m}$)

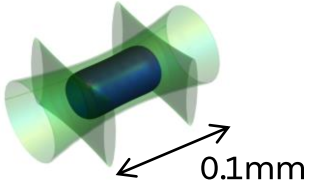
**Next steps**

- Spin-mixture control (percentage of population)

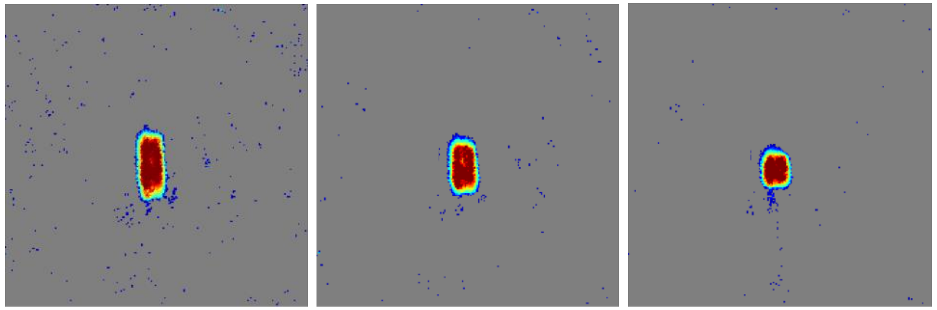


# FVD - Experiment

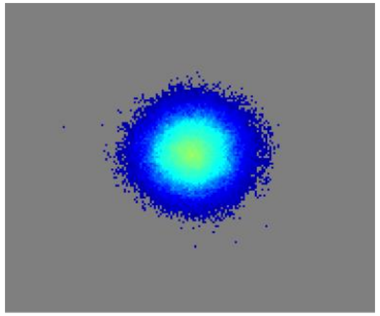
## 3D Box Trap



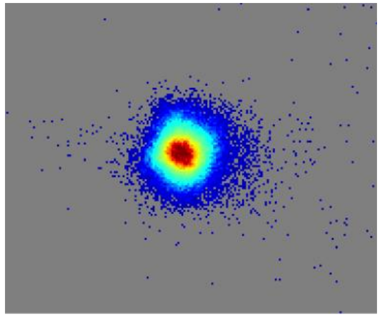
**Optical box**



In-situ 3D boxes of different aspect ratio



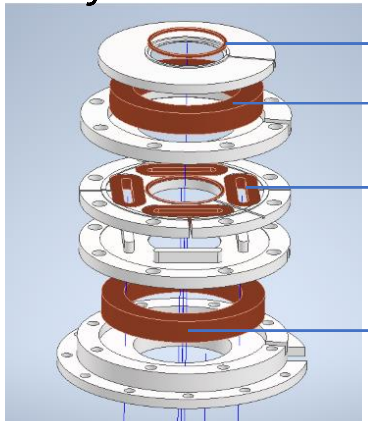
Time-of-flight
of thermal cloud



Time-of-flight
of condensed cloud
600k atoms

## Feshbach Coils

Layout



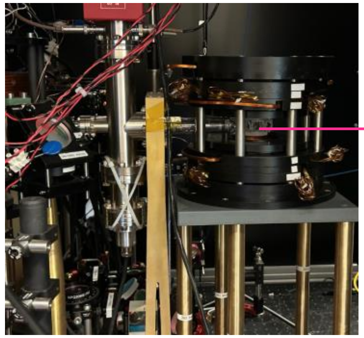
Quench coils

Feshbach coils

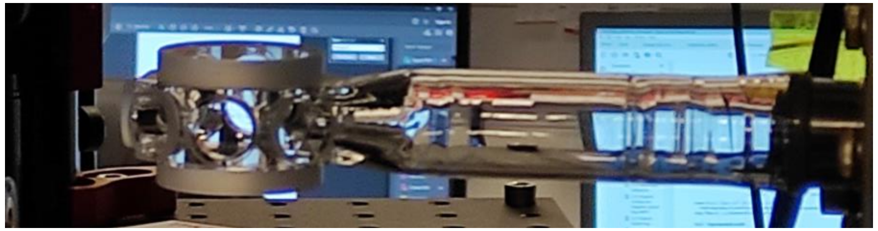
In-plane compensation

Gradient

Coil installation around the science cell:



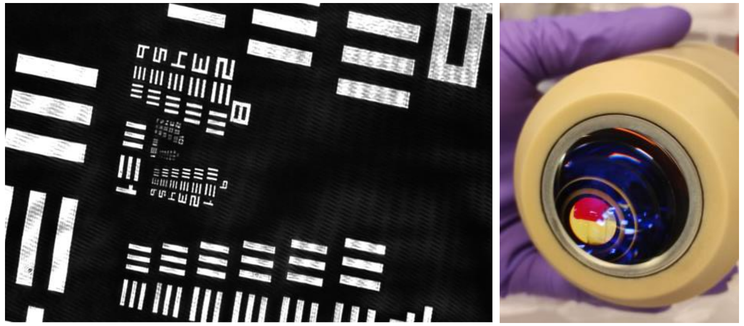
Science cell



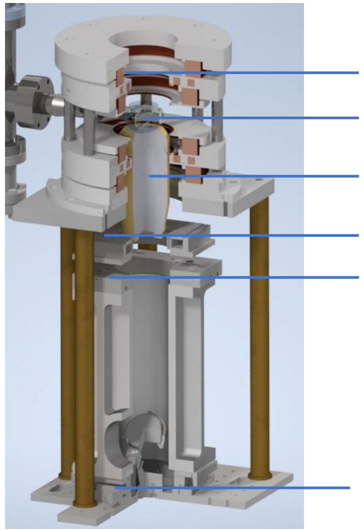
# FVD - Experiment

## Microscope

Testing with USAF target:



<1µm resolution at 767nm



Coils

Science cell

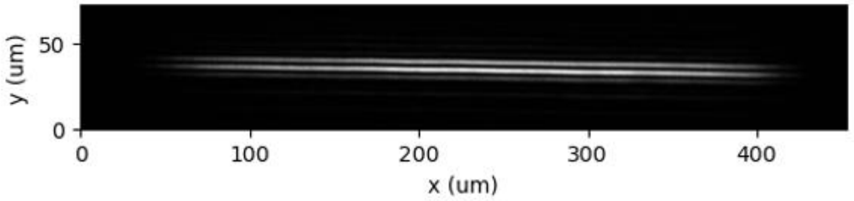
Objective

z-nanopositioner

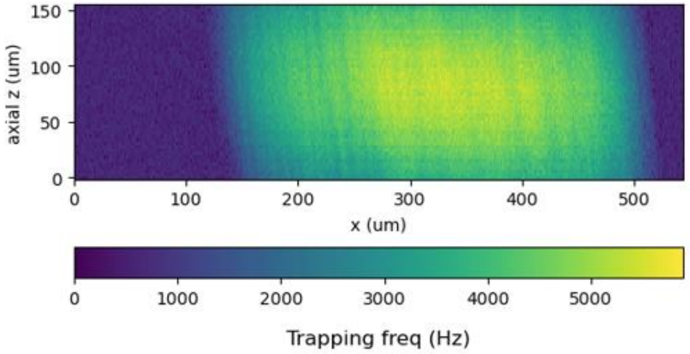
Goniometer

x-y stage

## 2D Confinement



Holographic DMD accordion lattice
Dynamical compression from 3D to 2D

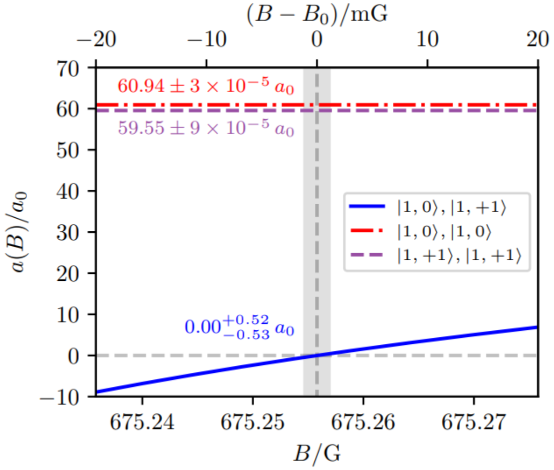


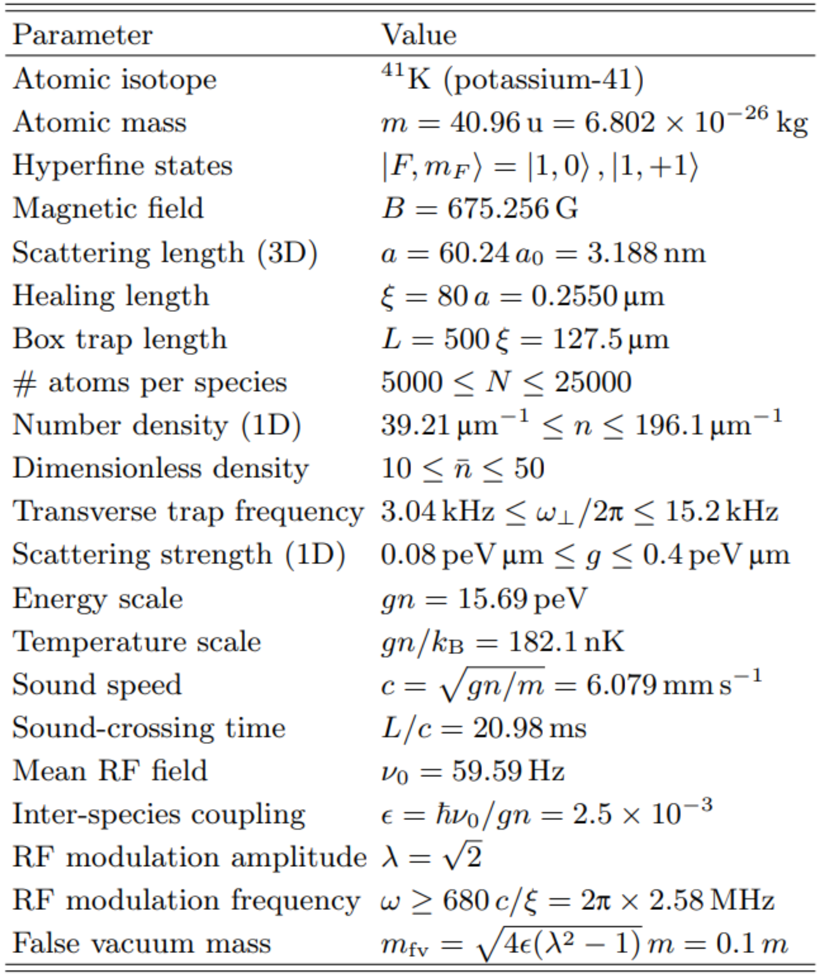
Trapping frequency in-plane profile;
Peaks at 5kHz.

Plans for tighter >20kHz confinement with additional static lattice

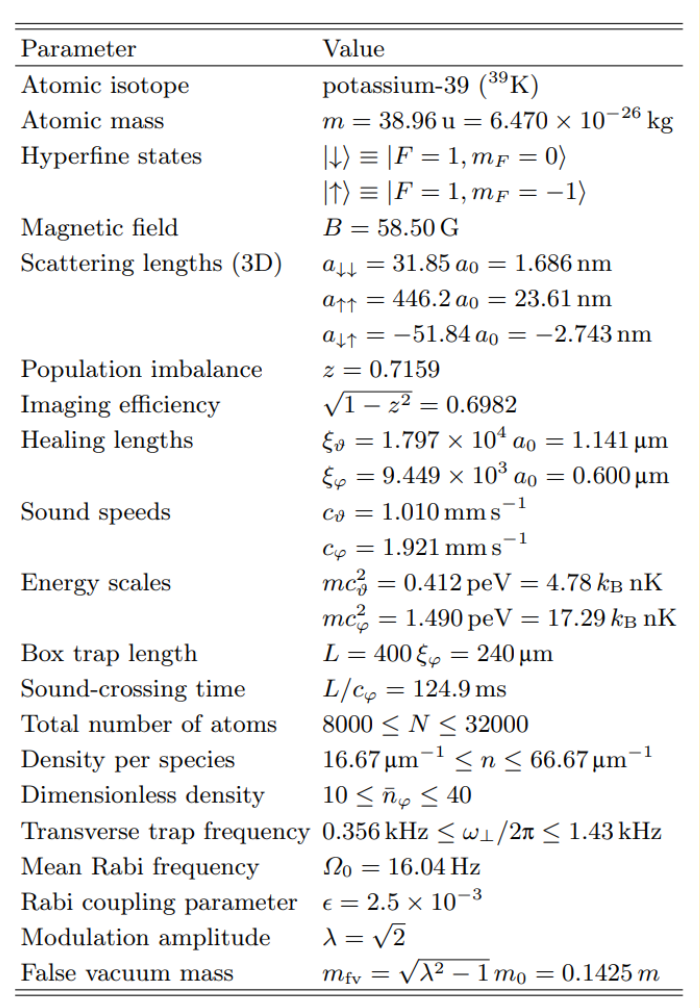
FVD - Theory

# Milestone: identification of viable parameter space

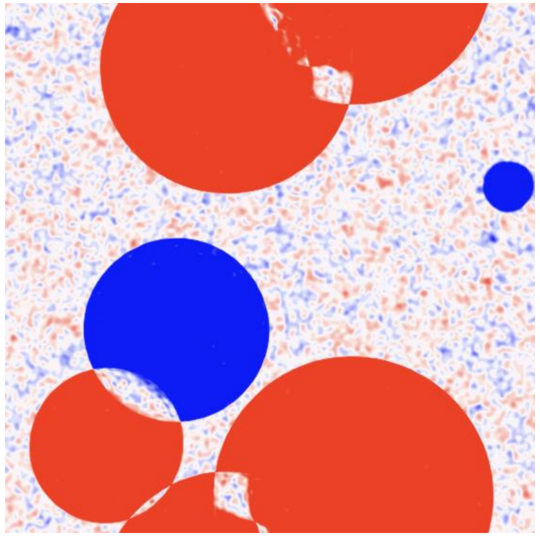




| Parameter | Value |
|---|---|
| Atomic isotope | $^{41}$K (potassium-41) |
| Atomic mass | $m = 40.96\,\mathrm{u} = 6.802 \times 10^{-26}\,\mathrm{kg}$ |
| Hyperfine states | $\lvert F, m_F\rangle = \lvert 1,0\rangle, \lvert 1,+1\rangle$ |
| Magnetic field | $B = 675.256\,\mathrm{G}$ |
| Scattering length (3D) | $a = 60.24\,a_0 = 3.188\,\mathrm{nm}$ |
| Healing length | $\xi = 80\,a = 0.2550\,\mu\mathrm{m}$ |
| Box trap length | $L = 500\,\xi = 127.5\,\mu\mathrm{m}$ |
| # atoms per species | $5000 \le N \le 25000$ |
| Number density (1D) | $39.21\,\mu\mathrm{m}^{-1} \le n \le 196.1\,\mu\mathrm{m}^{-1}$ |
| Dimensionless density | $10 \le \bar{n} \le 50$ |
| Transverse trap frequency | $3.04\,\mathrm{kHz} \le \omega_\perp/2\pi \le 15.2\,\mathrm{kHz}$ |
| Scattering strength (1D) | $0.08\,\mathrm{peV\,\mu m} \le g \le 0.4\,\mathrm{peV\,\mu m}$ |
| Energy scale | $gn = 15.69\,\mathrm{peV}$ |
| Temperature scale | $gn/k_\mathrm{B} = 182.1\,\mathrm{nK}$ |
| Sound speed | $c = \sqrt{gn/m} = 6.079\,\mathrm{mm\,s^{-1}}$ |
| Sound-crossing time | $L/c = 20.98\,\mathrm{ms}$ |
| Mean RF field | $\nu_0 = 59.59\,\mathrm{Hz}$ |
| Inter-species coupling | $\epsilon = \hbar\nu_0/gn = 2.5 \times 10^{-3}$ |
| RF modulation amplitude | $\lambda = \sqrt{2}$ |
| RF modulation frequency | $\omega \ge 680\,c/\xi = 2\pi \times 2.58\,\mathrm{MHz}$ |
| False vacuum mass | $m_\mathrm{fv} = \sqrt{4\epsilon(\lambda^2 - 1)}\,m = 0.1\,m$ |



| Parameter | Value |
|---|---|
| Atomic isotope | potassium-39 ($^{39}$K) |
| Atomic mass | $m = 38.96\,\mathrm{u} = 6.470 \times 10^{-26}\,\mathrm{kg}$ |
| Hyperfine states | $\lvert\downarrow\rangle \equiv \lvert F=1, m_F=0\rangle$ |
|  | $\lvert\uparrow\rangle \equiv \lvert F=1, m_F=-1\rangle$ |
| Magnetic field | $B = 58.50\,\mathrm{G}$ |
| Scattering lengths (3D) | $a_{\downarrow\downarrow} = 31.85\,a_0 = 1.686\,\mathrm{nm}$ |
|  | $a_{\uparrow\uparrow} = 446.2\,a_0 = 23.61\,\mathrm{nm}$ |
|  | $a_{\downarrow\uparrow} = -51.84\,a_0 = -2.743\,\mathrm{nm}$ |
| Population imbalance | $z = 0.7159$ |
| Imaging efficiency | $\sqrt{1 - z^2} = 0.6982$ |
| Healing lengths | $\xi_\vartheta = 1.797 \times 10^4\,a_0 = 1.141\,\mu\mathrm{m}$ |
|  | $\xi_\varphi = 9.449 \times 10^3\,a_0 = 0.600\,\mu\mathrm{m}$ |
| Sound speeds | $c_\vartheta = 1.010\,\mathrm{mm\,s^{-1}}$ |
|  | $c_\varphi = 1.921\,\mathrm{mm\,s^{-1}}$ |
| Energy scales | $mc_\vartheta^2 = 0.412\,\mathrm{peV} = 4.78\,k_\mathrm{B}\,\mathrm{nK}$ |
|  | $mc_\varphi^2 = 1.490\,\mathrm{peV} = 17.29\,k_\mathrm{B}\,\mathrm{nK}$ |
| Box trap length | $L = 400\,\xi_\varphi = 240\,\mu\mathrm{m}$ |
| Sound-crossing time | $L/c_\varphi = 124.9\,\mathrm{ms}$ |
| Total number of atoms | $8000 \le N \le 32000$ |
| Density per species | $16.67\,\mu\mathrm{m}^{-1} \le n \le 66.67\,\mu\mathrm{m}^{-1}$ |
| Dimensionless density | $10 \le \bar{n}_\varphi \le 40$ |
| Transverse trap frequency | $0.356\,\mathrm{kHz} \le \omega_\perp/2\pi \le 1.43\,\mathrm{kHz}$ |
| Mean Rabi frequency | $\Omega_0 = 16.04\,\mathrm{Hz}$ |
| Rabi coupling parameter | $\epsilon = 2.5 \times 10^{-3}$ |
| Modulation amplitude | $\lambda = \sqrt{2}$ |
| False vacuum mass | $m_\mathrm{fv} = \sqrt{\lambda^2 - 1}\,m_0 = 0.1425\,m$ |



FVD - Theory

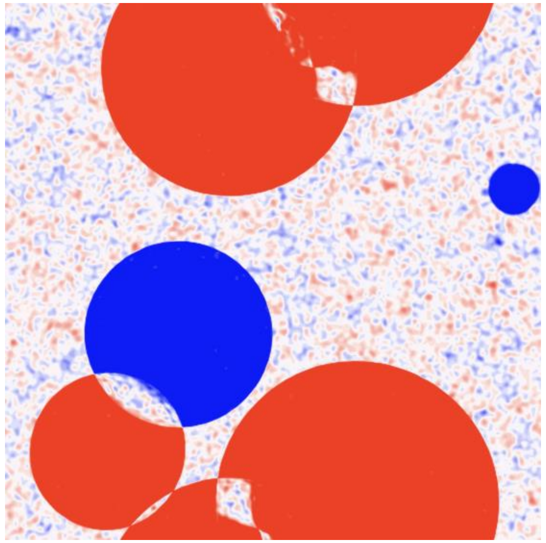
# High-level modelling of multi-component BECs relevant for FVD Experiments

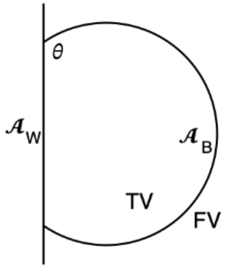
- Expansion of viable parameter space, giving much more favourable experimental prospects

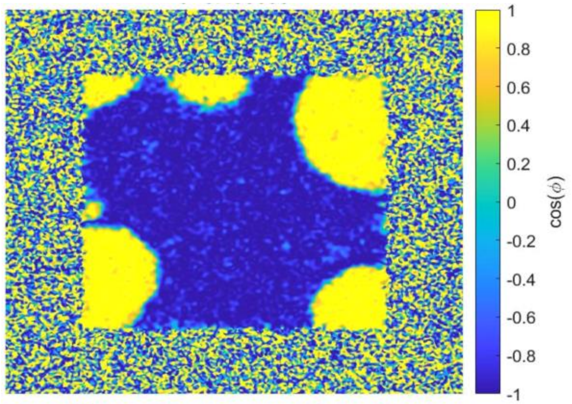
- Paper on initial conditions published in Phys. Rev. D as an *Editor's Suggestion*, recognising "particularly important, interesting, and well written" research

- Continued numerical and theoretical progress in collaboration with Newcastle, Cambridge, and external partners, focused on implementing realistic boundary conditions

- Effect of boundaries on bubble nucleation Instanton theory
  - Numerical simulations at finite temperature (SPGPE)







# Quantum Black Holes

**KCL**
- Ruth Gregory
- Sam Patrick

**Newcastle**
- Carlo Barenghi

**Nottingham**
- Jorma Louko
- Cisco Gooding
- Cameron Bunny

**RHUL**
- Gregoire Ithier

**UBC/Texas AMU**
- Bill Unruh

**Nottingham**
- Silke Weinfurtner
- Anthony Kent
- Patrik Švančara
- Pietro Smaniotto
- Leonardo Solidoro
- Vitor S. Barroso
- Sreelekshmi Ajithkumar

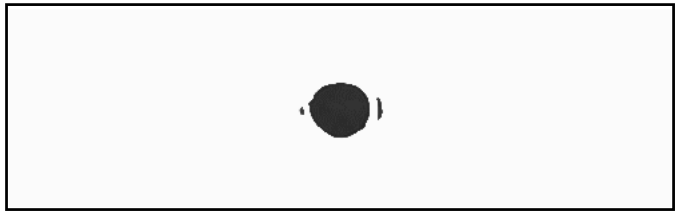
**RHUL**
- Xavier Rojas
- Sumit Kumar

**St. Andrews**
- Friedrich Koenig
- Pavlos Manousiadis
- Christopher Burgess

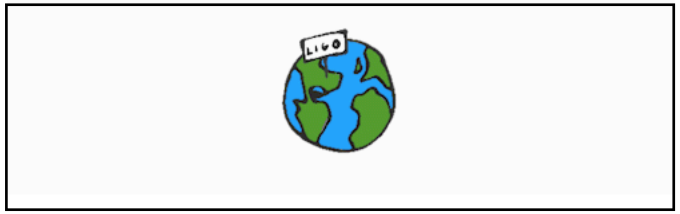
Quantum Black Holes

# Quantum Black Holes

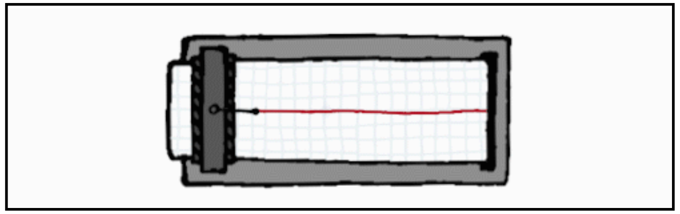
***PERTURBED BLACK HOLE***

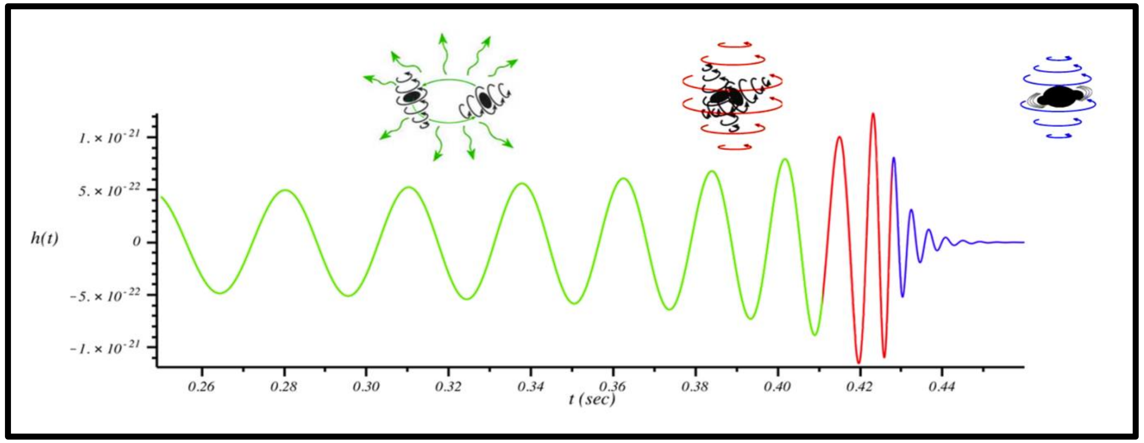


***LIGO DETECTOR***



***LIGO SIGNAL***





- Perturbed black-holes emit characteristic waves
- Recent validation of universality of black hole ring-down in gravity simulators
- Contribution of quantum effects to black hole ringdown dynamics

# Experimental QBH Facilities

**Klein-Gordon equation for a massless scalar field**

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

**Effective metric**

$$g_{ab} \propto \begin{pmatrix} -c^2 + v^2 & -\mathbf{v} \\ -\mathbf{v} & \mathbf{1}_{2x2} \end{pmatrix}$$

**Fibre-optical system:**

- (1+1)-dim. non-rotating geometry
- Quantum correlations from ringdown modes

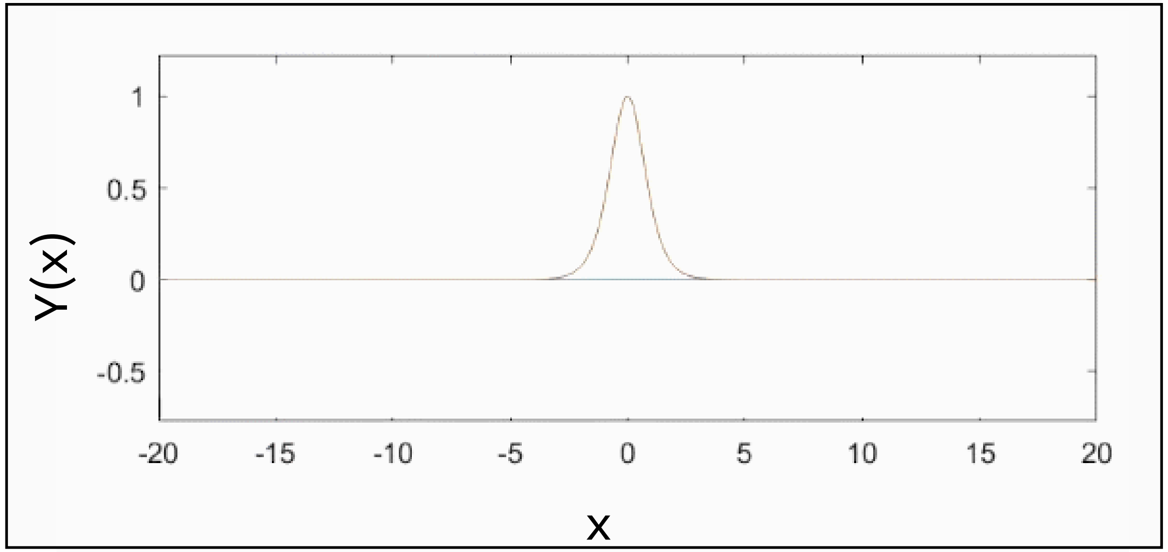
**Superfluid $^4$He** (Xavier Rojas and SW):

- (2+1)-dim. rotating geometry
- BH with quantised circulation

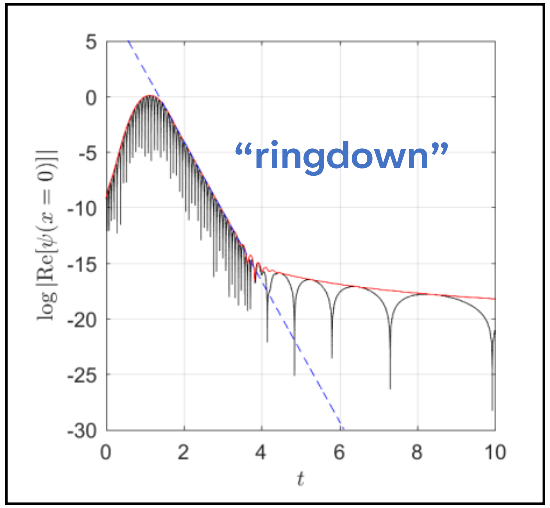
QBH – Modelling

# New black hole analogy – soliton as optical potential

*SCATTERING OF DISPERSIVE WAVE*



*RINGDOWN SIGNAL*



**Formally Equivalent Mode Equations**

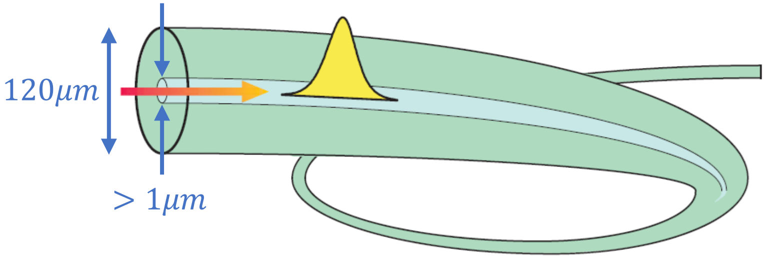
$$\partial_\tau^2 u + \left[ -\frac{2|\beta_{s2}|\Omega}{\beta_{a2}} - \frac{4|\beta_{s2}|}{\beta_{a2}} \operatorname{sech}^2(\tau) \right] u = 0$$

**GVM Soliton QNMs**

$$\Updownarrow$$

$$\partial_\rho^2 \Psi + \left[ \frac{\omega^2}{\alpha^2} - \frac{V_0}{\alpha^2} \operatorname{sech}^2(\rho) \right] \Psi = 0$$

**Black Hole QNMs**

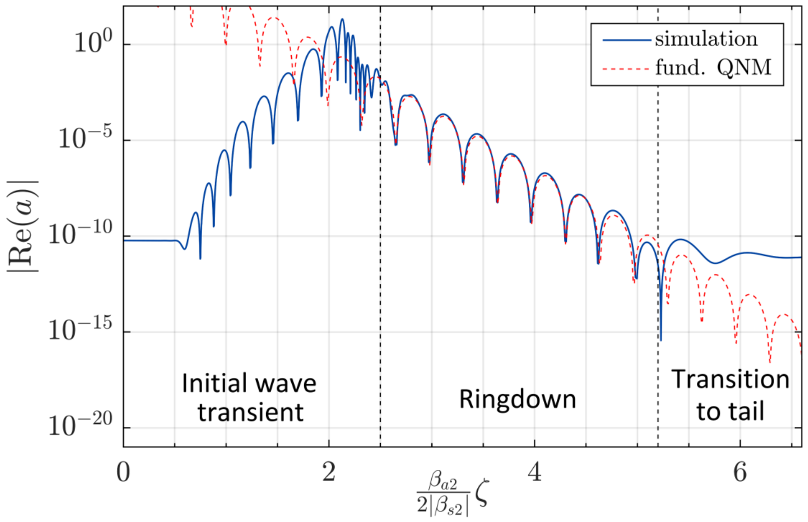


**Phys. Rev. Lett. 132, 053802 2024**

QBH – Modelling

# Numerical simulation and calculation of spectra of fibre-optical relaxations

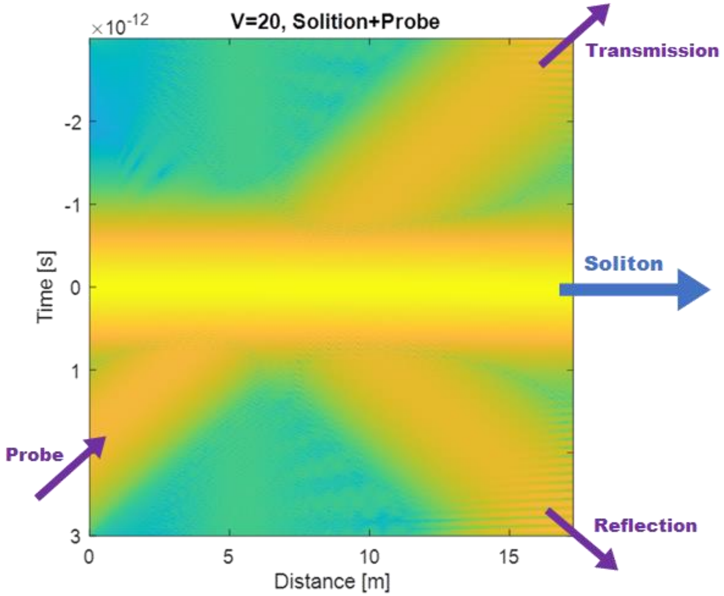
## Linearized Dynamics of Probe Pulse

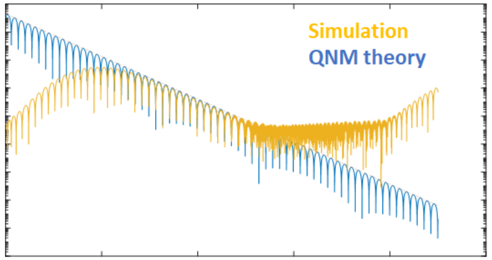


Simulated of linearized probe evolution agrees with theoretical QNM predictions.

**Phys. Rev. Lett. 132, 053802 2024**

## Full Nonlinear Dynamics of Soliton & Probe





Early results

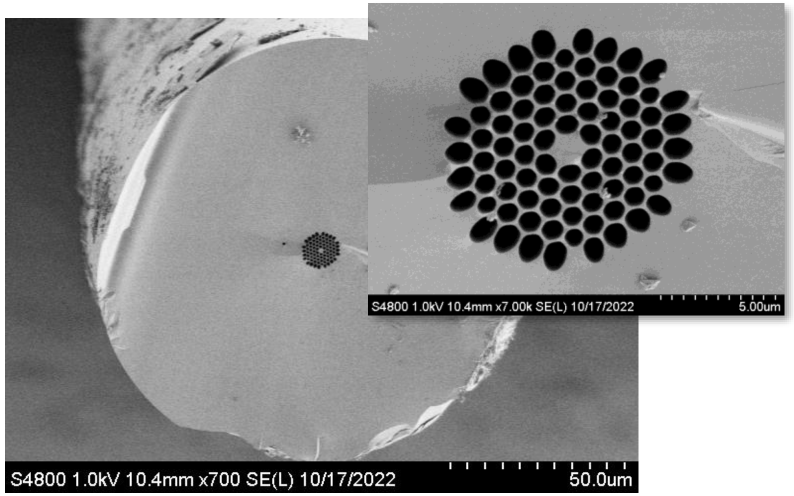
Realistic simulations of light-in-fibre dynamics essential for experimental observation of QNMs.

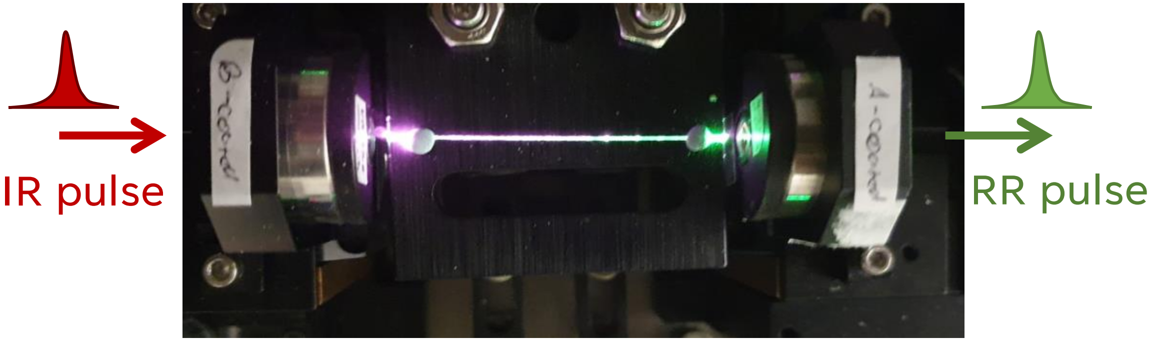
- Split-step Fourier Method
- Integration of generalized NLS

Quantum Black Holes

# Fibre-optical system: (1+1)-dimensional black hole potential

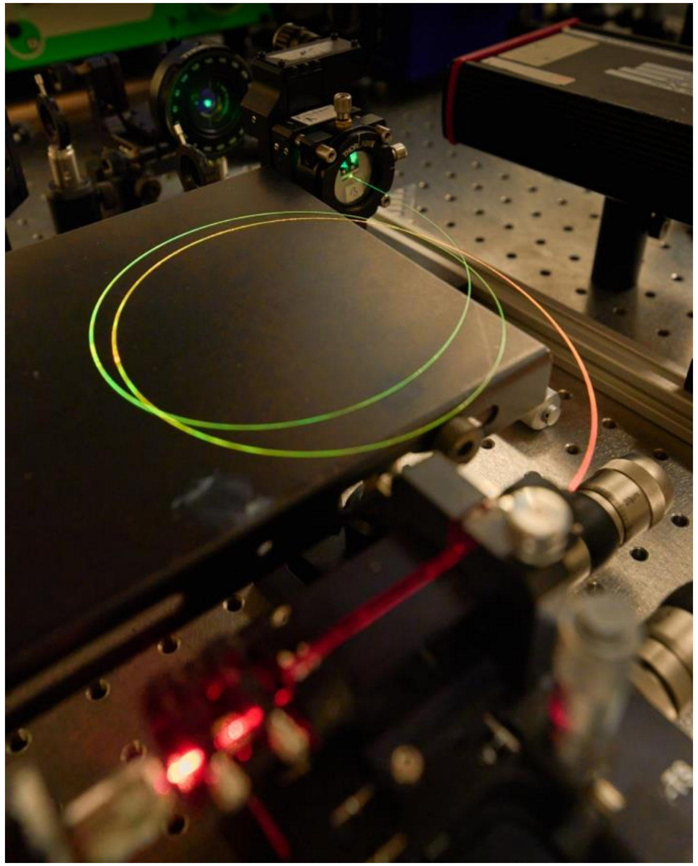
## Generation of Probe Pulses





The probe pulses are generated in non-linear fibres based on the phenomenon of resonance radiation.

## Collision of Soliton & Probe Pulses



The setup for experimental observation of QNMs is being finalized.

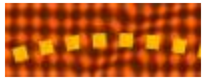
- Frequency-resolved optical gating

# Superfluid helium systems: (2+1)-dimensional rotating geometries

**2+1 dimensions** – rotating (Kerr) black holes are simulated by a **draining (bathtub) vortex**

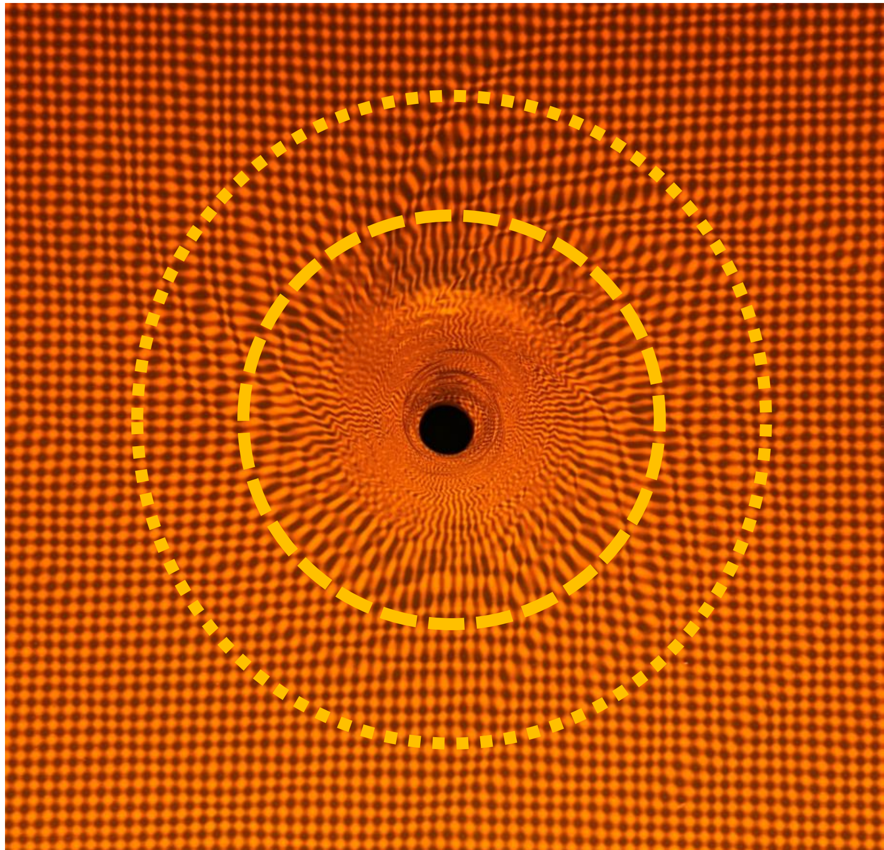
**Radial (draining) velocity** – effective black hole horizon when $\boldsymbol{v_r} = \boldsymbol{c}$

**Azimuthal velocity** – effective ergoregion when $\boldsymbol{v_r^2} + \boldsymbol{v_\vartheta^2} = \boldsymbol{c^2}$



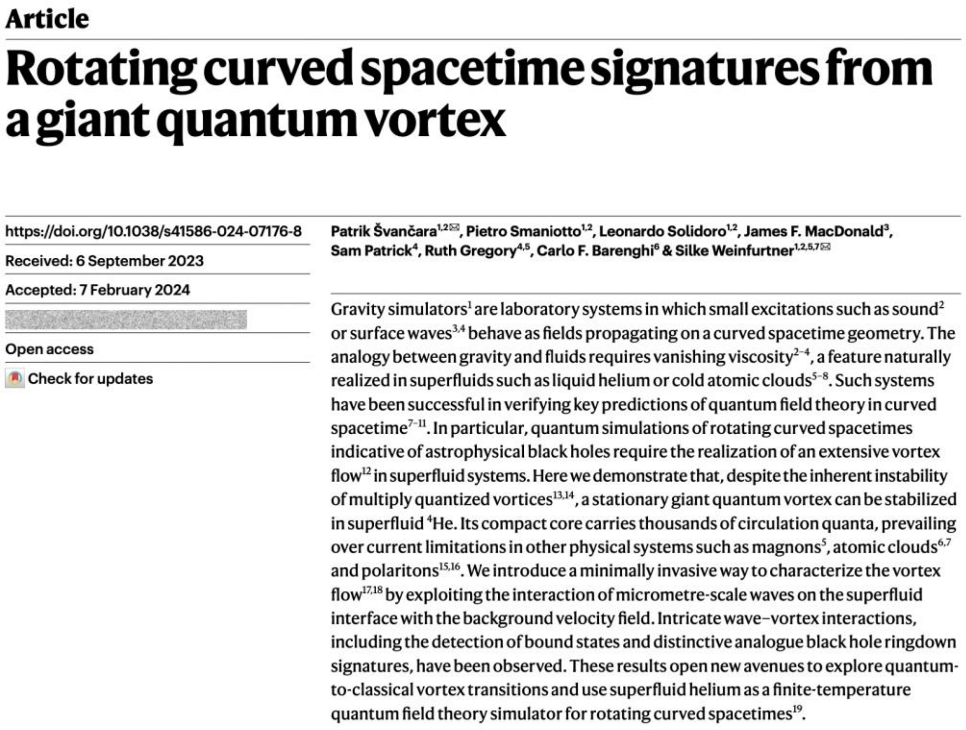
Implementation requires an **irrotational** velocity field:

$$\mathbf{v}(r) = -\frac{D}{r}\boldsymbol{e}_r + \frac{C}{r}\boldsymbol{e}_\vartheta$$



Nottingham - Experiment

# **Giant Quantum Vortex flow** – Nature 20 March 2024



**Article**

## Rotating curved spacetime signatures from a giant quantum vortex

https://doi.org/10.1038/s41586-024-07176-8

Received: 6 September 2023

Accepted: 7 February 2024

[redacted]

Open access

Check for updates

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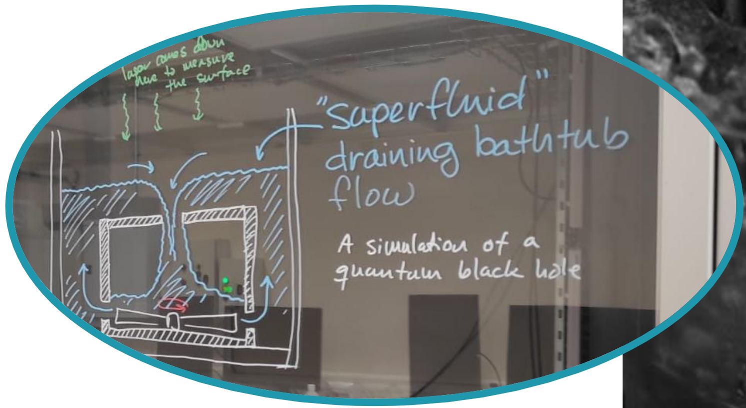
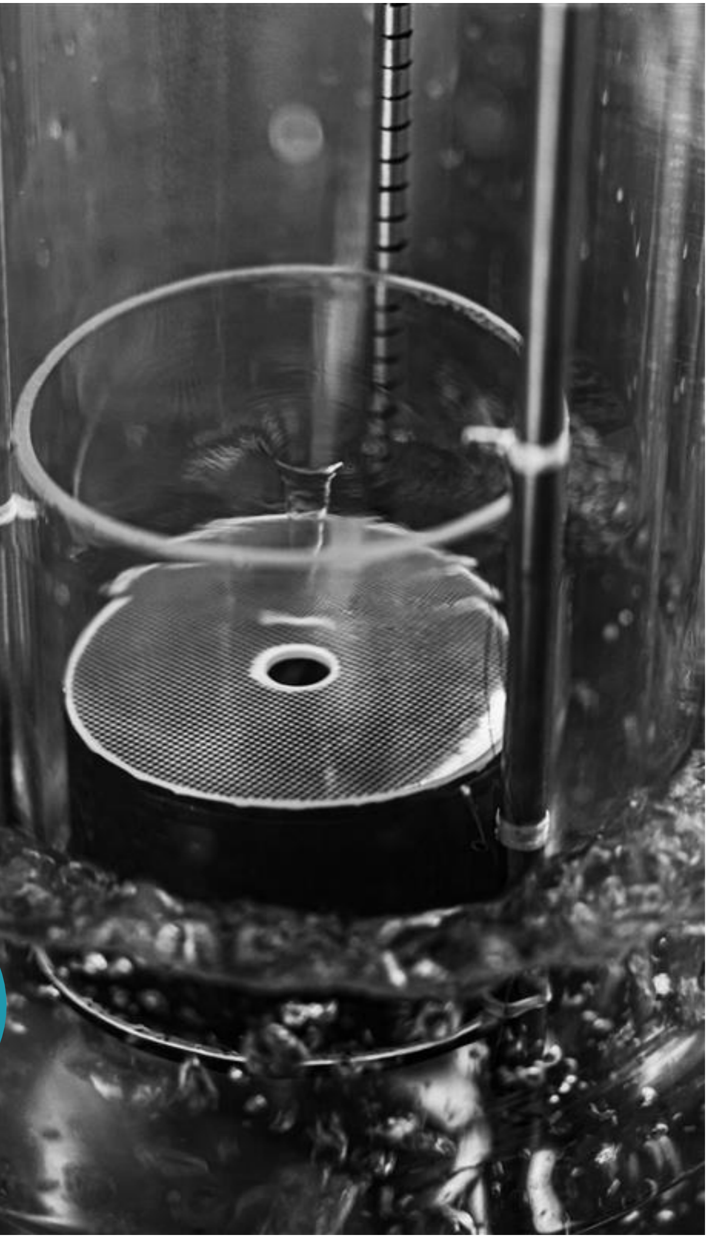
Gravity simulators[1] are laboratory systems in which small excitations such as sound[2] or surface waves[3,4] behave as fields propagating on a curved spacetime geometry. The analogy between gravity and fluids requires vanishing viscosity[2–4], a feature naturally realized in superfluids such as liquid helium or cold atomic clouds[5–8]. Such systems have been successful in verifying key predictions of quantum field theory in curved spacetime[7–11]. In particular, quantum simulations of rotating curved spacetimes indicative of astrophysical black holes require the realization of an extensive vortex flow[12] in superfluid systems. Here we demonstrate that, despite the inherent instability of multiply quantized vortices[13,14], a stationary giant quantum vortex can be stabilized in superfluid $^4$He. Its compact core carries thousands of circulation quanta, prevailing over current limitations in other physical systems such as magnons[5], atomic clouds[6,7] and polaritons[15,16]. We introduce a minimally invasive way to characterize the vortex flow[17,18] by exploiting the interaction of micrometre-scale waves on the superfluid interface with the background velocity field. Intricate wave–vortex interactions, including the detection of bound states and distinctive analogue black hole ringdown signatures, have been observed. These results open new avenues to explore quantum-to-classical vortex transitions and use superfluid helium as a finite-temperature quantum field theory simulator for rotating curved spacetimes[19].





# Giant Vortex Structures

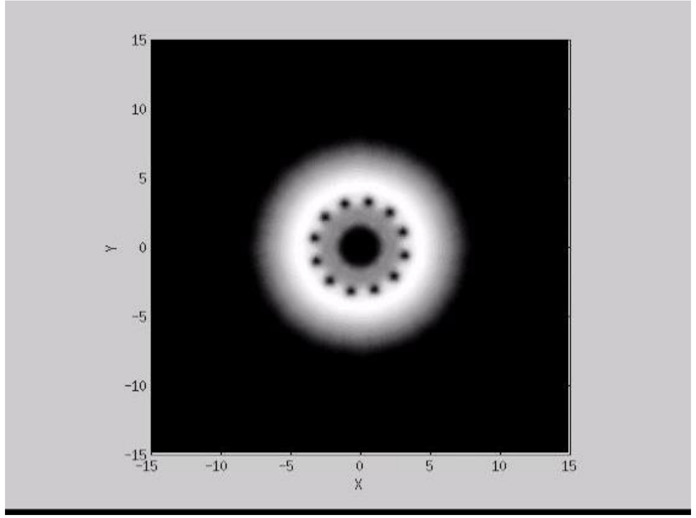
Low viscous dissipation & **potential flow** around **quantised vortices**

Multiply-quantised vortices are **unstable** [Shin 2004, Patrick 2022]

Cluster of singly-wound vortices. How to **confine** them?

How to **stabilise giant vortices?** [Cookson 2021]

- Reducing density in the vortex core [Jheng 2022]
- Draining velocity component [Alperin 2021, Ruffenach 2023]
- Back-action of the normal component [Galantucci 2023]



Video source: Jheng et al. Optics Express (2022)

## Our approach

Large draining vortex in He II with free surface & finite temperature [Inui 2020]

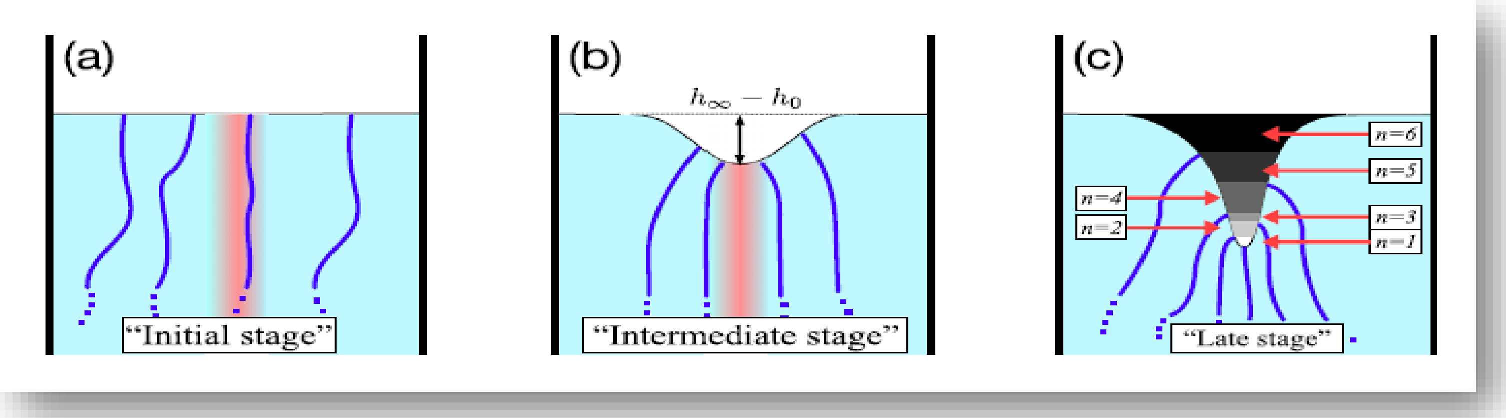
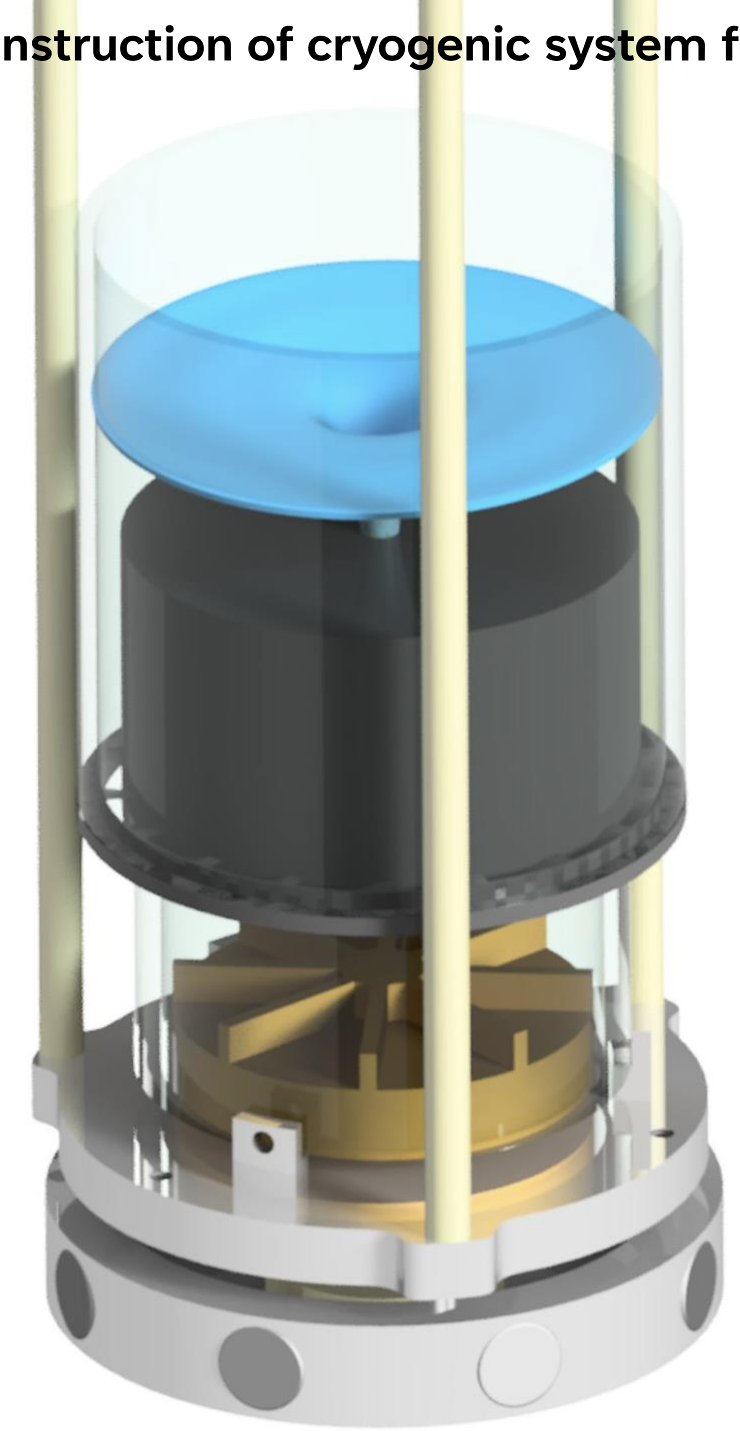


Image source: Inui et al. Physical Review Letters (2020)

Nottingham - Experiment

# Construction of cryogenic system for 0.5-2K study



**Inspiration** – suction vortex experiment from Osaka [Yano 2018]

**Experimental area** – diameter 75 mm, 40 mm height

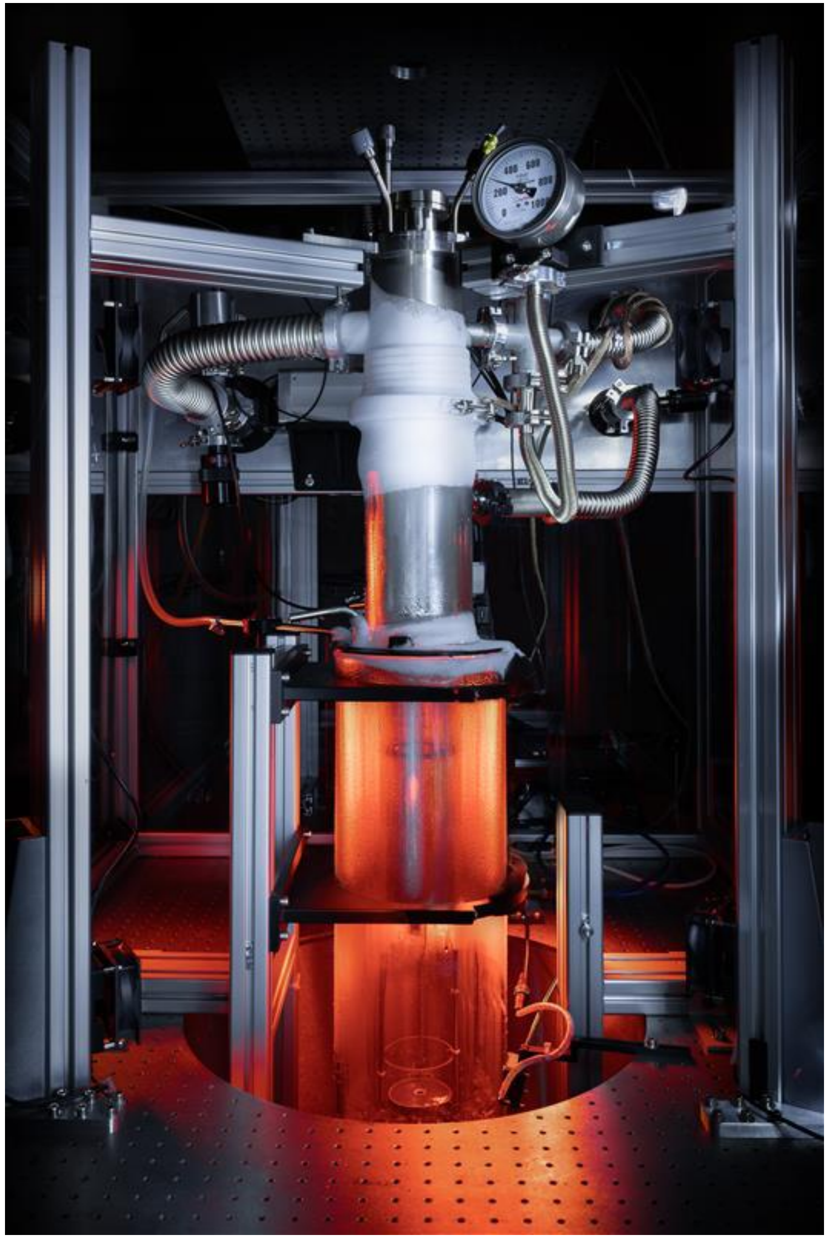
**Bespoke** 3D printed flow conditioner & draining hole

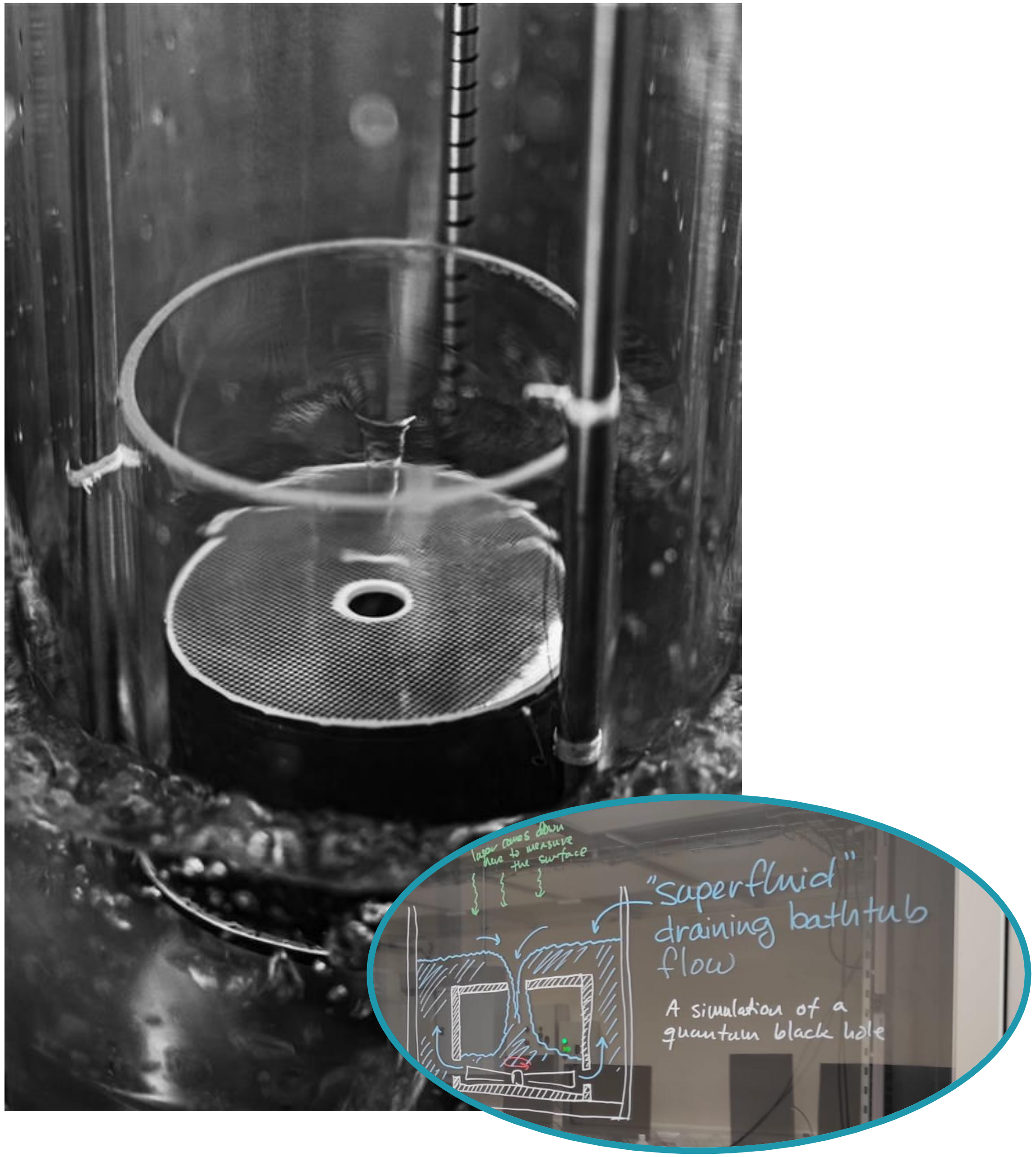
**Rotating propeller** acts as a centrifugal pump

**Rotation** provided by magnetic coupling

Nottingham - Experiment

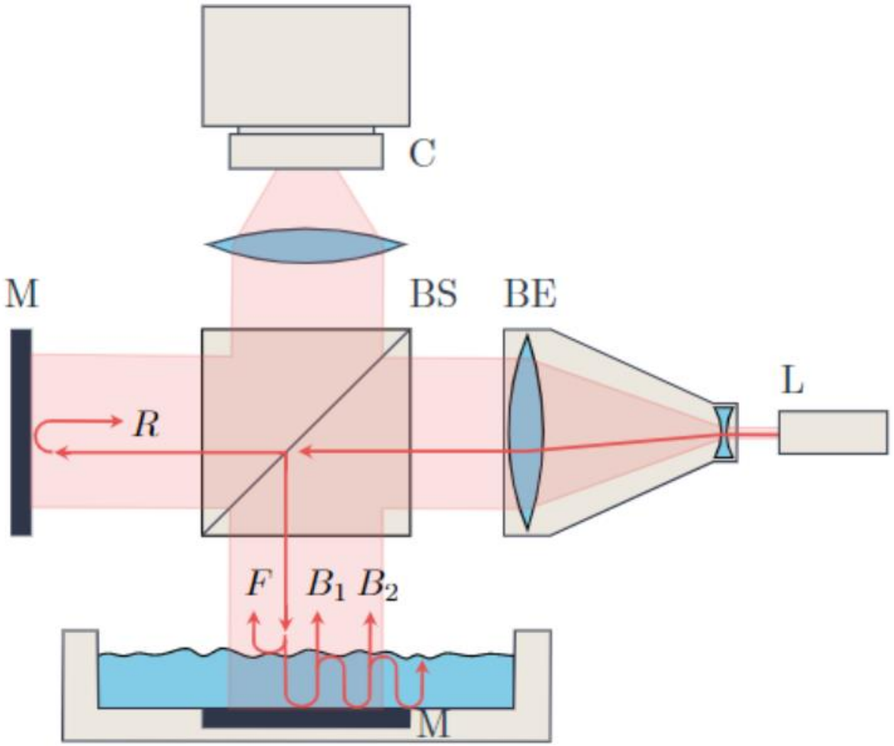
# Construction of cryogenic system

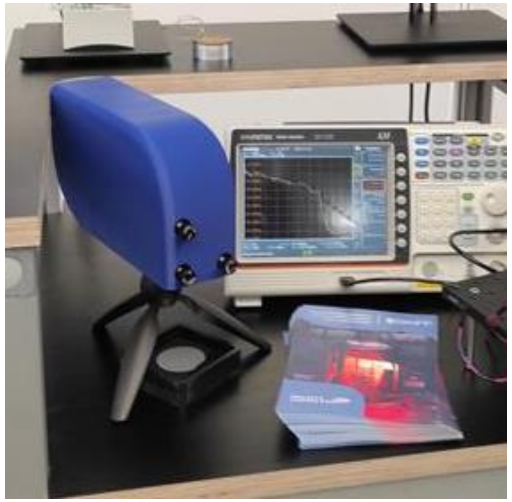




Nottingham - Experiment

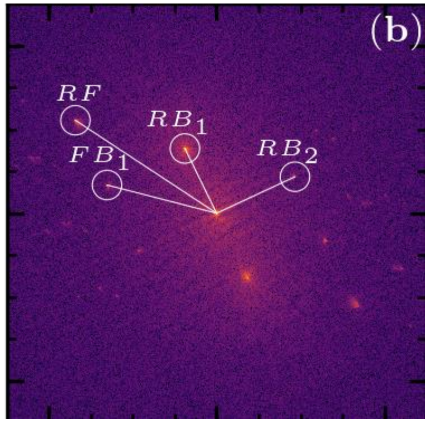
# Interferometric detection scheme for fluid interfaces





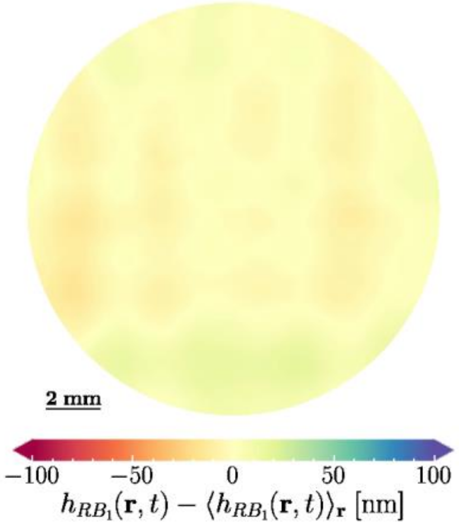
## Industry applications

- Automotive industry
- Aviation industry
- Manufacturing
- Robotic Industry



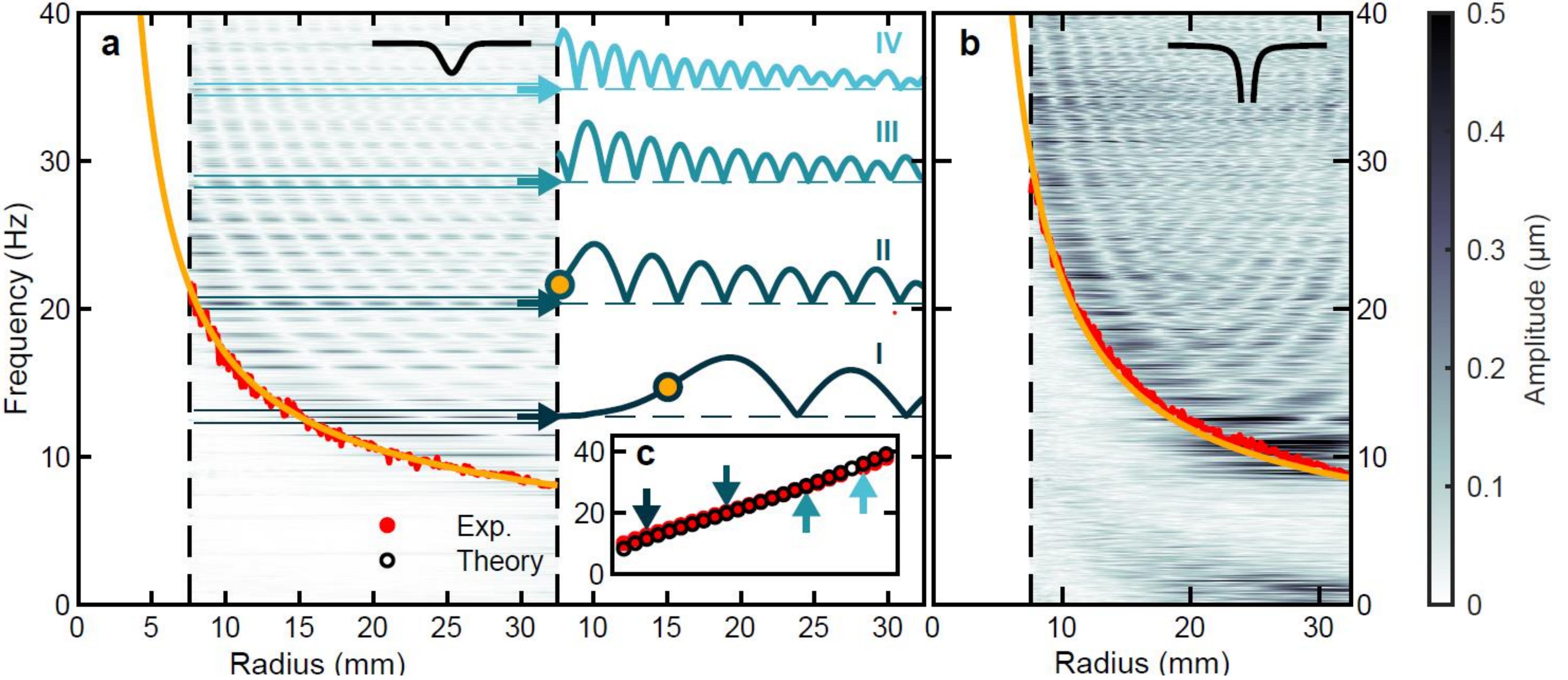
## Patent Application 2214343.2 & Applied Optics, Vol. 62, pp. 7175-7184 (2023)

- Optical Path Length Characterisation
- Real-time monitoring of surface
- Resolution down to 10 nm
- Compact and modular
- Applicable for fluids and gases



Nottingham - Experiment

# Detection of bound states in rotating curved spacetime simulator



**Bound states** between the barrier and boundary

**Propagating** and **Evanescent modes**

**Frequency match –** validity of simplified potential

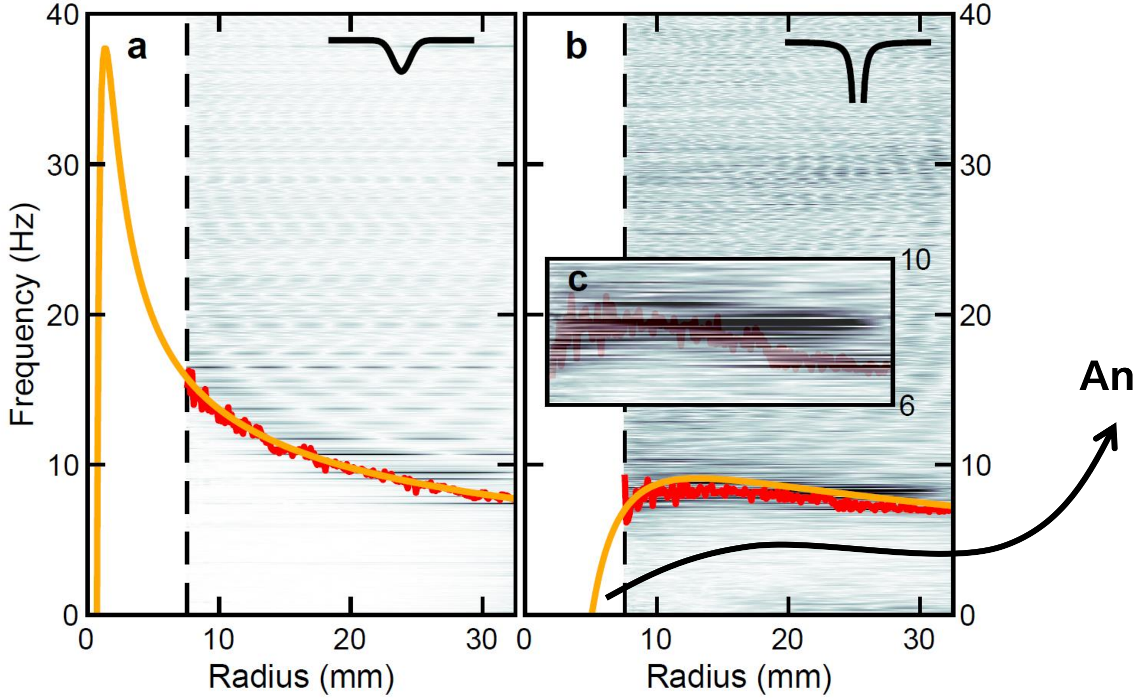
Effective potential (measured velocity)

Effective potential (simplified, $C/r$)

Spectral amplitude

Bound state amplitude

# (Towards) Detection of black hole ringdown in cryogenic system



Analogue ergoregion

**Bound states** up to $30\ \mathrm{Hz}$ in the solid core regime

**Shallow potential well** in the hollow core regime

**Possible black hole ringdown modes**

Effective potential (measured velocity)

Effective potential (simplified, $C/r$)

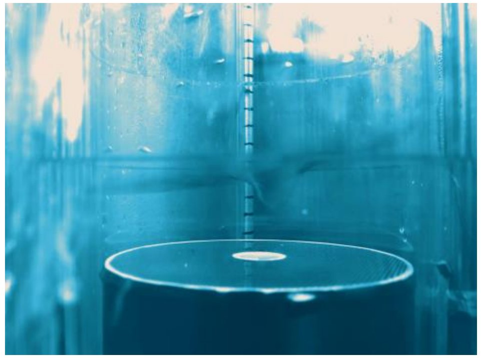
▨ Spectral amplitude

Nottingham - Experiment

## Next steps

Quantum vortex dynamics

- Visualising Quantum Vortex Dynamics through Off-Axis Holography



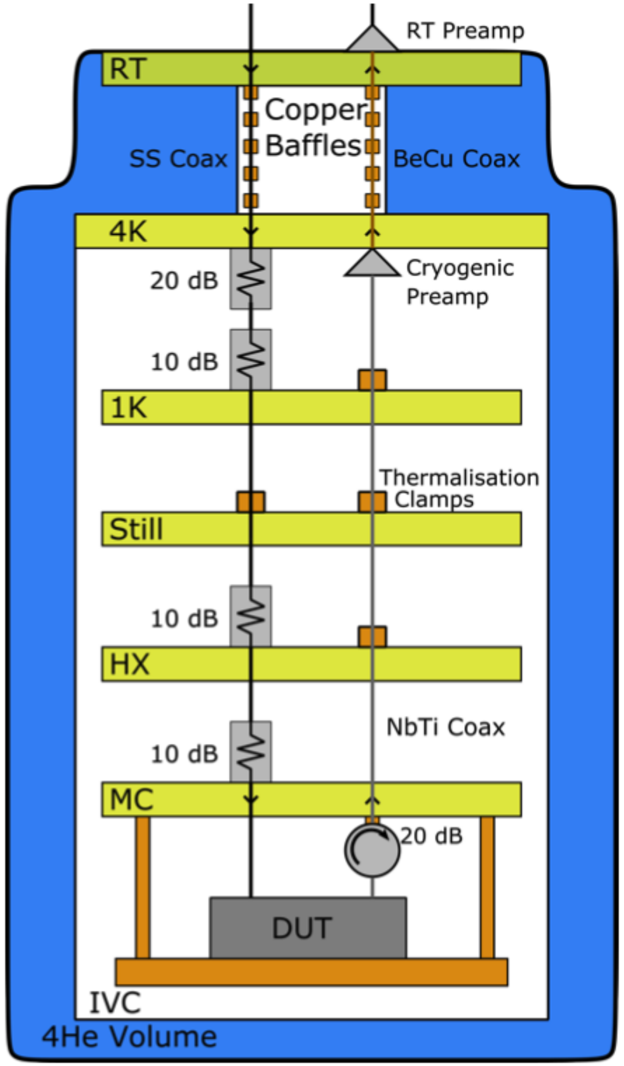
- Experimental exploration of parameter space:
  - Black hole ringing with reflecting boundary conditions
  - Black hole bomb instabilities

- Installation of new cryogenic platform

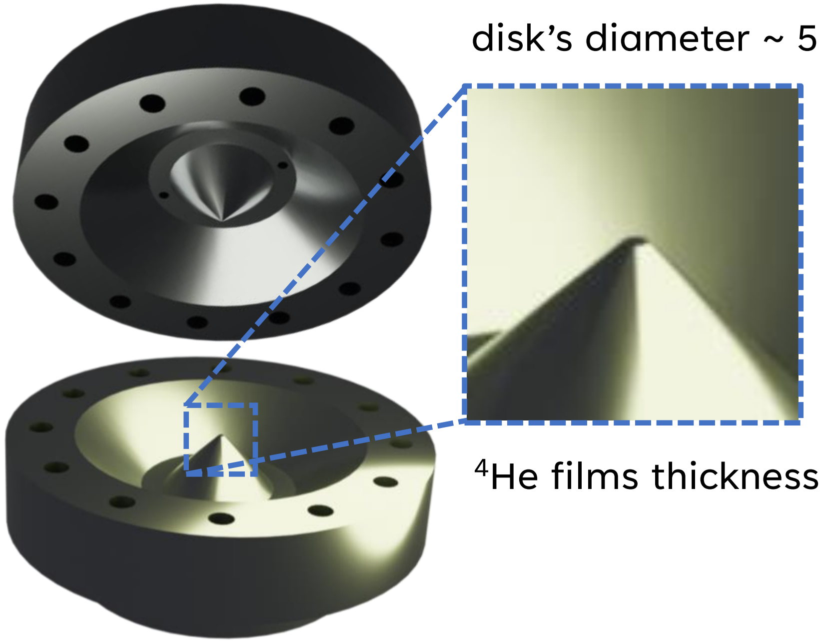
RHUL - Experiment

# Design of sub-100mK platform for ground state superfluid system

## Cryostat



## Microwave Optomechanics with Thin-Films



**Surface wave resonator**

disk’s diameter ~ 500 μm

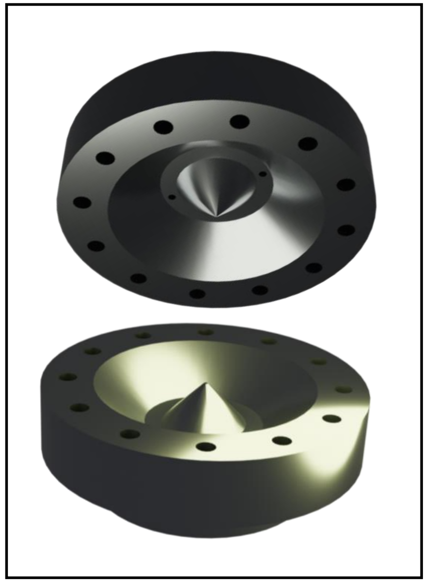
$^4$He films thickness: up to 10 μm

- cavity fabrication
- cavity polishing
- hermetic microwave feedthroughs installation
- characterization at room temperature
- characterization at cryogenic temperature

RHUL - Experiment

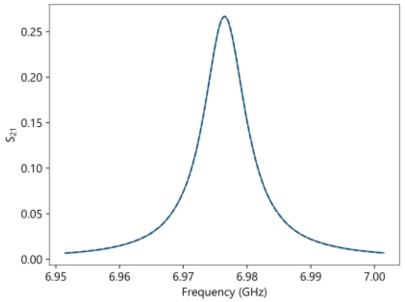
# Design of sub-100mK platform for ground state superfluid system

## Superconducting cavity

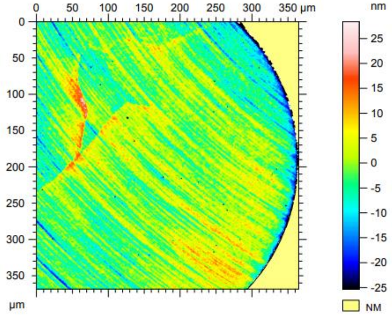


## Experimental progress:

- Re-entrant microwave optomechanics:
  - proof-of-principle, characterization [1,2]
- Development of reliable superfluid leak tight microwave feedthroughs
- Design and fabrication of microwave re-entrant cavities: **μm size gaps**
- Thin-film surface wave resonator walls: **RMS surface roughness ~ 5 nm**



Transmission ($S_{21}$)



Walls surface roughness profile

Low temperature experimental run to start **March 2024**

[1] Optomechanically induced transparency/absorption in a 3D microwave cavity architecture at ambient temperature
S. Kumar, M. Kenworthy, H. Ginn, X. Rojas
AIP Advances **14**, 035107 (2024)

[2] A novel architecture for room temperature microwave optomechanical experiments
S. Kumar, S. Spence, S. Perrett, Z. Tahir, A. Singh, C. Qi, S.P. Vizan, X. Rojas
Journal of Applied Physics **133**, 094501 (2023)

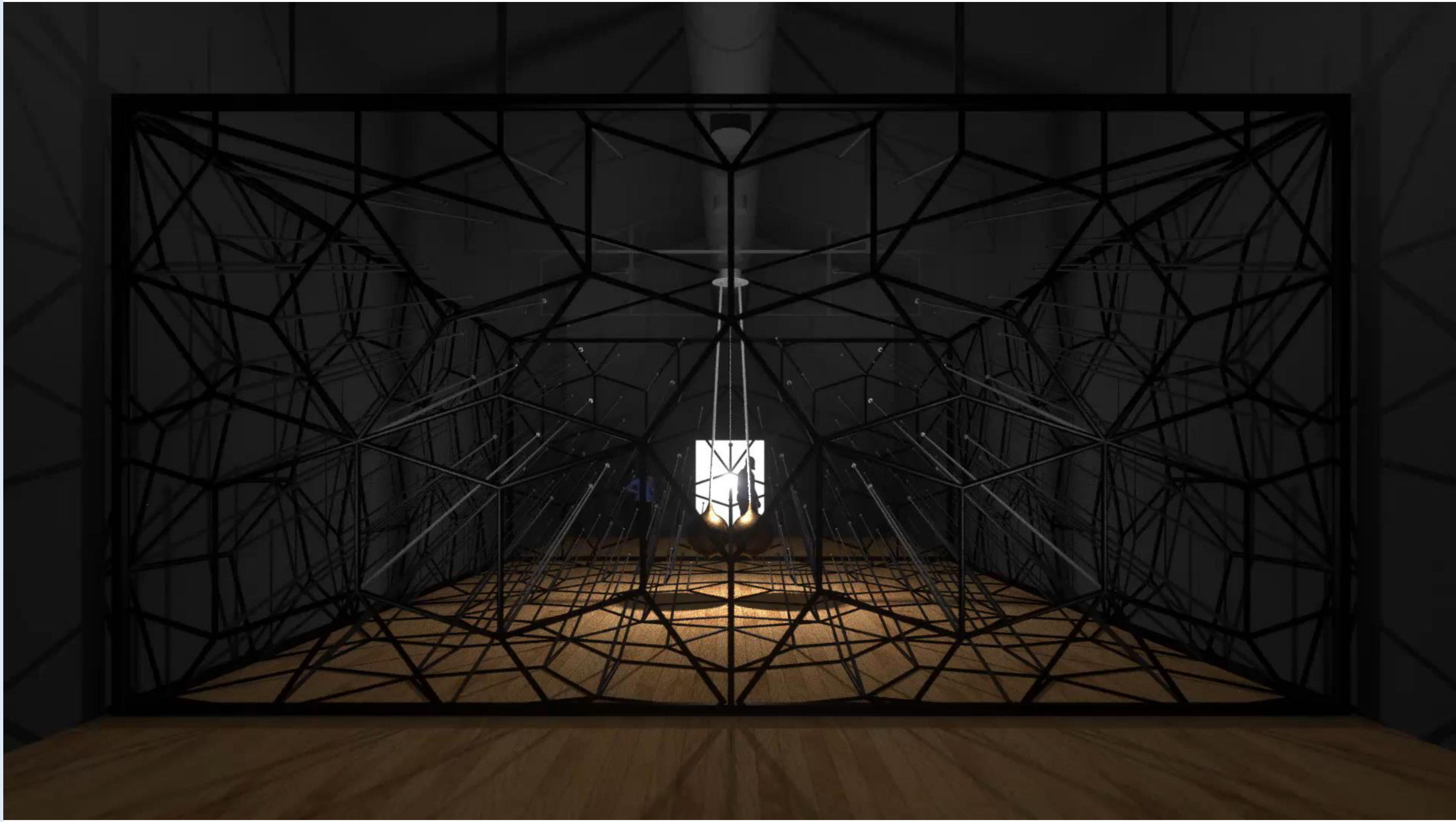
**Join us for the art-science exhibition:**

- Nottingham, Jan-Mar 2025

# Kids on Campus Event

# FVD – Artwork

# QBH – Artwork



# Conrad Shawcross