Quantum simulators of gravitational effects

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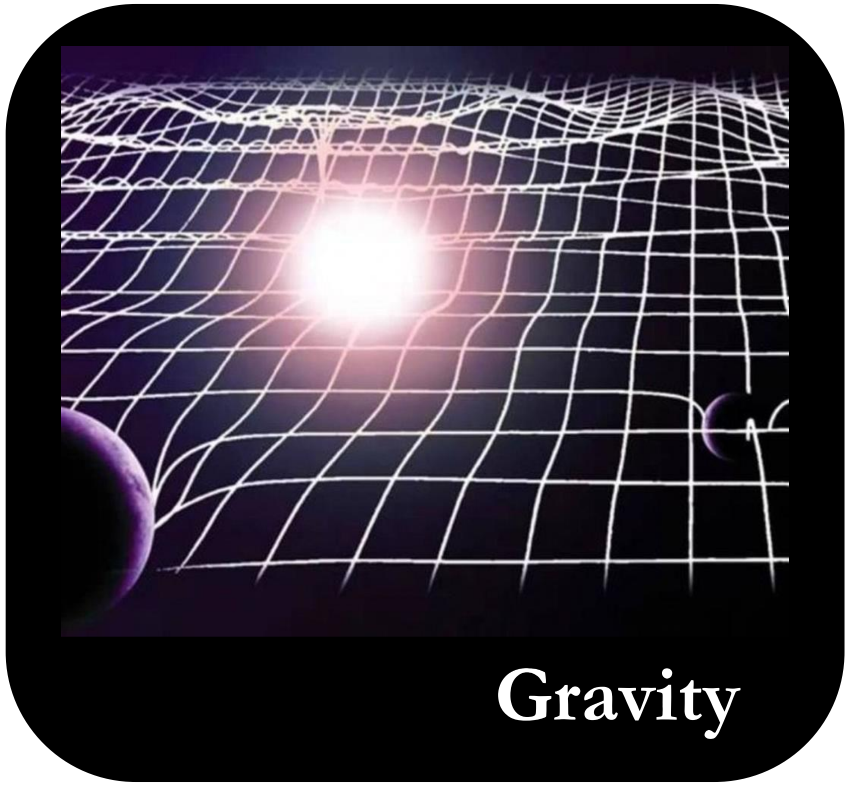
THE ROYAL SOCIETY

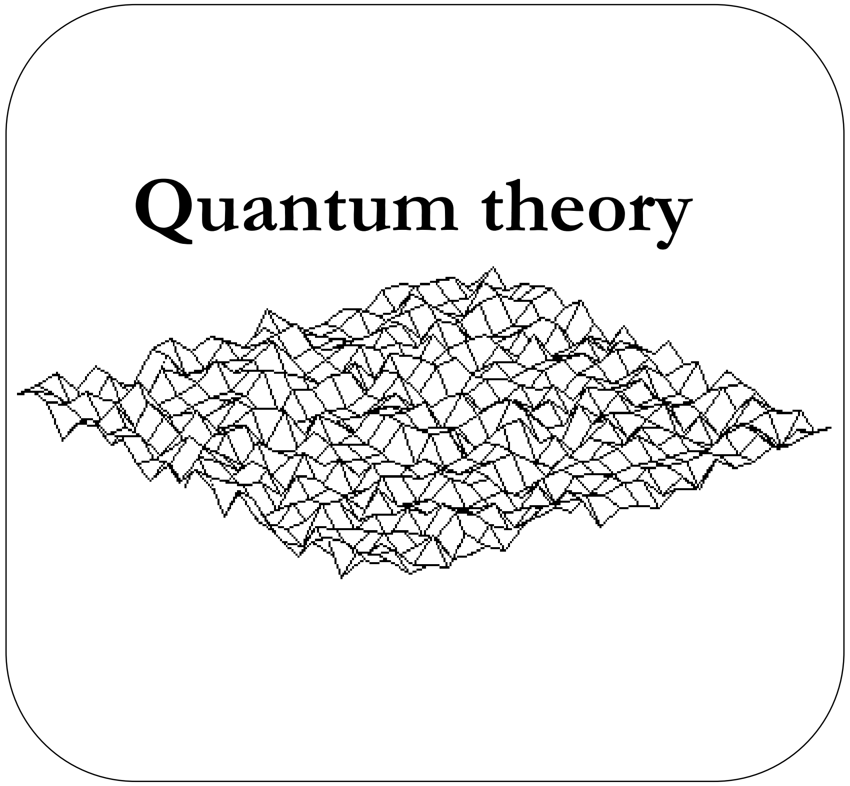
Science & Technology Facilities Council

EPSRC
Engineering and Physical Sciences Research Council

Motivation

- **Deeping our understanding of the dynamics of the early and late Universe** that arise in the interplay between general relativity and quantum fields





- **Focus is on essential processes occurring in situations difficult/impossible to experiment with, and when conventional calculation techniques break down**

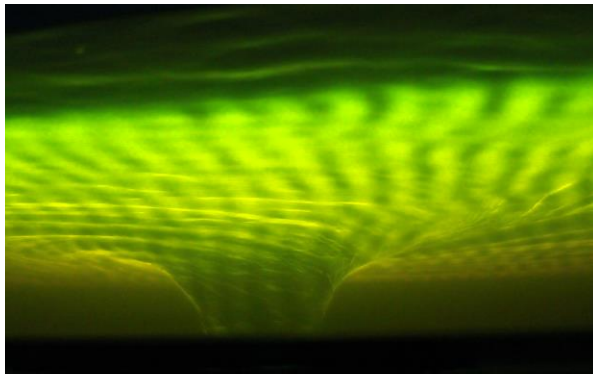
  → gravitational interactions are strong

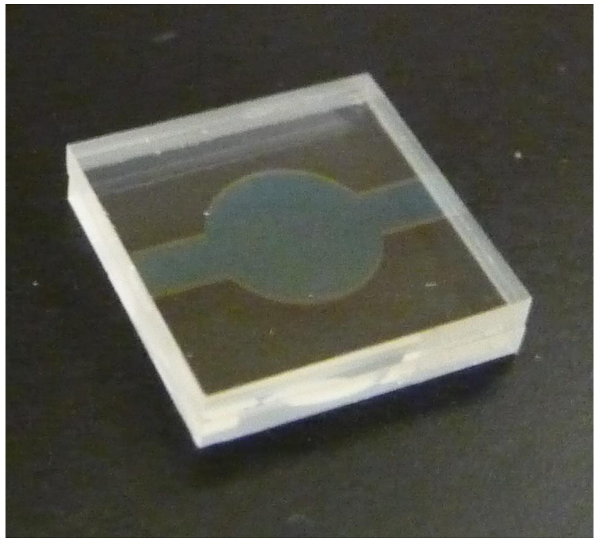
  → quantum effects are important

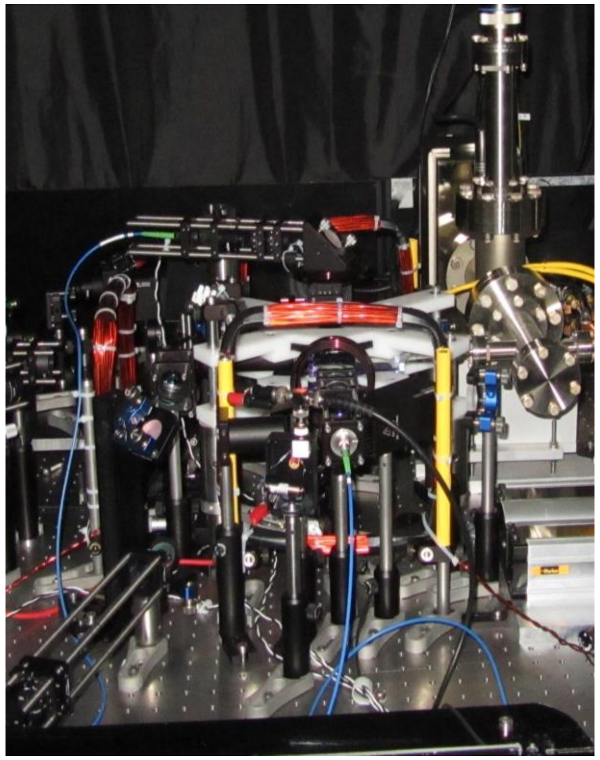
  → length scales stretching beyond the observable Universe

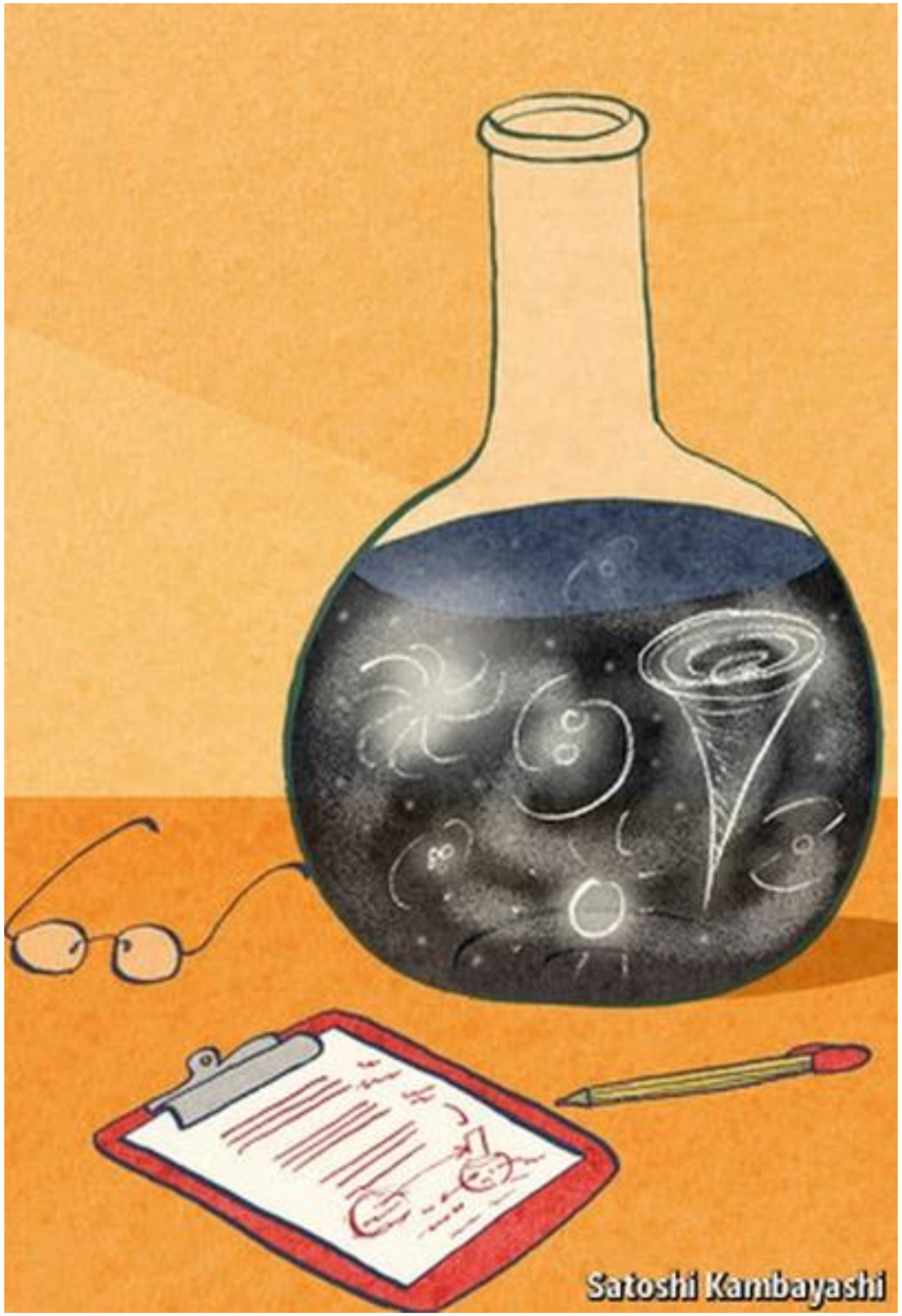
- **Introduce a 'cross-validation' between theory and experiment**

Our approach: Gravity Simulators





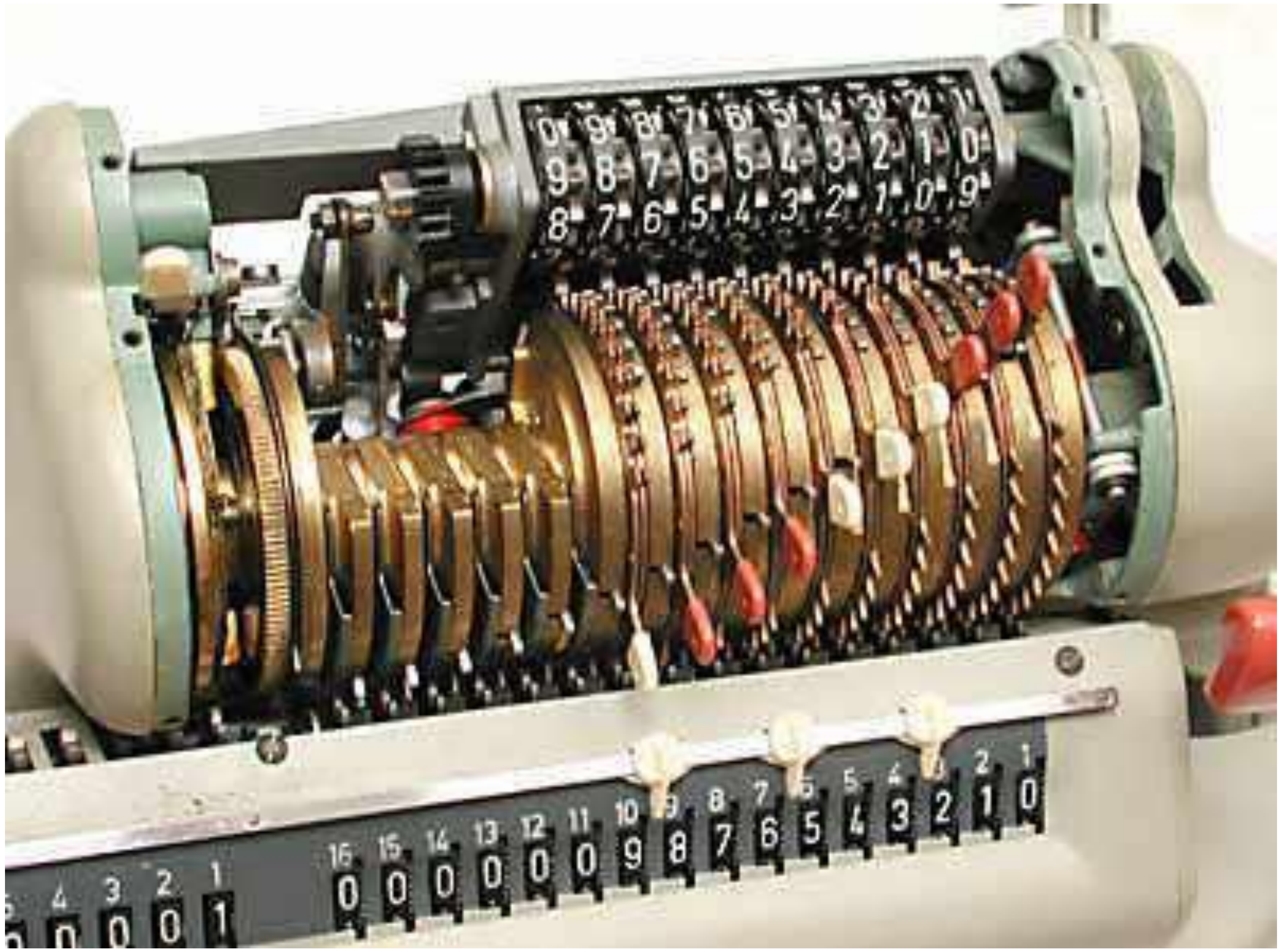




There exists a **broad class of laboratory systems:**

Fluctuations described by an **effective Relativistic Quantum Field Theory** in **flat** or **curved spacetimes**.

Analogue QFT Simulators have a high degree of tunability

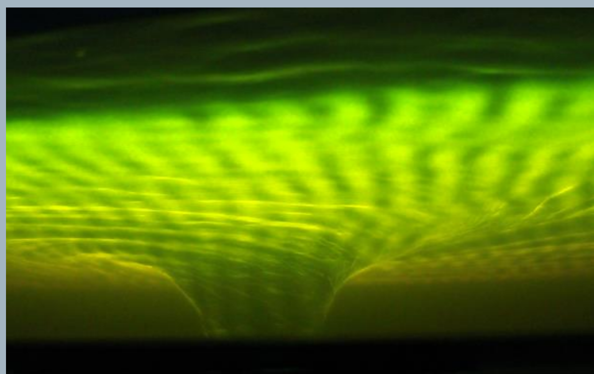


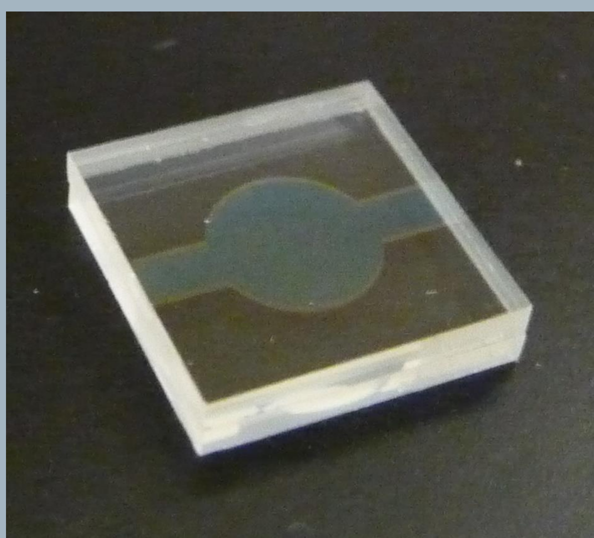
A field of research whose full potential has not yet been reached: **validation → application.**

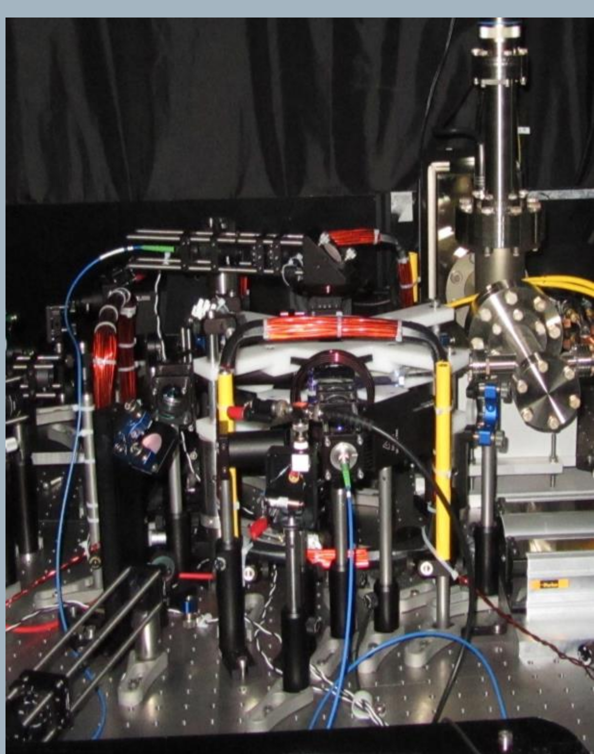
Analogue simulators are versatile, because it is possible to set up and manipulate:

- **Spacetime Geometry**
  → Flat spacetime
  → Black Hole Horizon
  → Cosmological scenarios
- **Signature of Spacetime**
  Euclidean ↔ Lorentzian
- **Effective Mass**
  Stable ↔ Unstable
- **Effective detectors**
  → Unruh radiation

Effective field theories exhibit the same processes







Rotating Black Holes

Superradiance

<u>Ring-down</u>

Black Holes

Hawking radiation

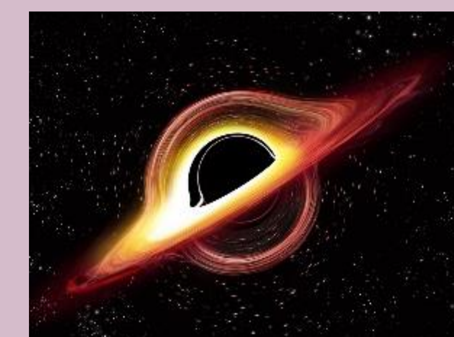
Cosmological spacetimes

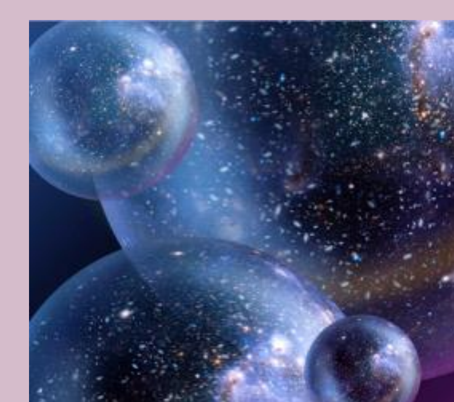
Early Universe Processes

Quantum Vacuum

<u>The False Vacuum Decay</u>

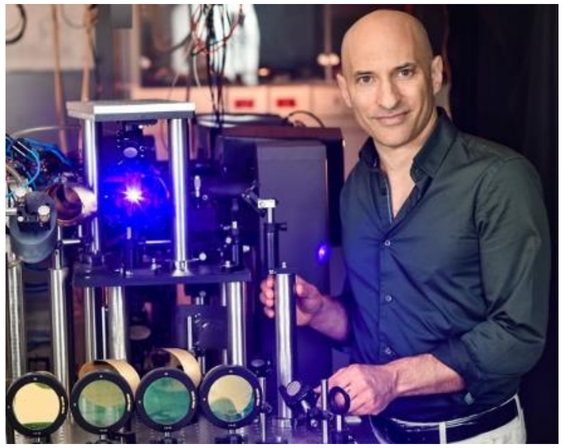
The Unruh Effect





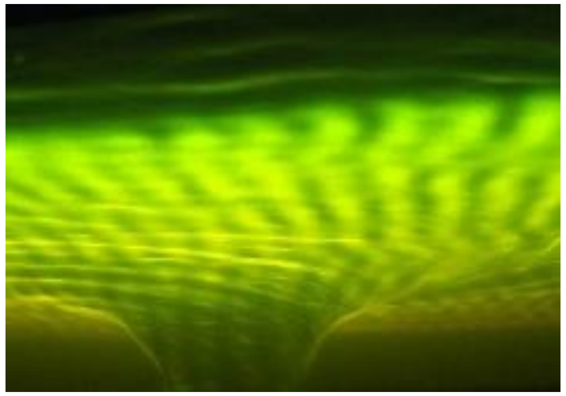
Does this really work?

Black Holes



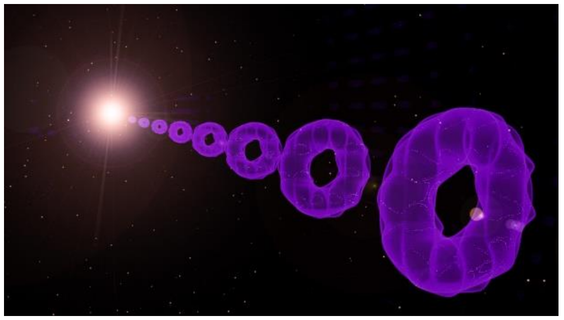
- **Hawking Radiation:**
  Weinfurtner/Unruh 2011
  Rousseoux 2016
  Steinhauer 2016-2019

Rotating Black Holes



- **Superradiance**
  Weinfurtner 2017
- **Light bending**
  Weinfurtner 2018
- **Ring-down**
  Weinfurtner 2018
- **Back-reaction**
  Weinfurtner 2019

Cosmological spacetimes



- **Particle Production**
  Westbrook 2012
- **Hubble Friction**
  Campbell 2018
- **Pair-creation**
  Tobias Schaetz 2019

Observation of thermal Hawking radiation at the Hawking temperature in an analogue black hole Juan Ramón Muñoz de Nova, Katrine Golubkov, Victor I. Kolobov, Jeff Steinhauer
Nature volume **12**, pages 688-691 (2019)

***

See also, Quantum simulation of black-hole radiation, Silke Weinfurtner, Nature 569 (7758), 634

Rotational superradiant scattering in a vortex flow
Theo Torres, Sam Patrick, Antonin Coutant, Mauricio Richartz, Edmund W. Tedford & Silke Weinfurtner
Nature Physics volume **13**, pages833–836 (2017)

A Rapidly Expanding Bose-Einstein Condensate: An Expanding Universe in the Lab
S. Eckel, A. Kumar, T. Jacobson, I. B. Spielman, and G. K. Campbell
Phys. Rev. X 8, 021021 (2018)

Up until now, we only validated the approach…

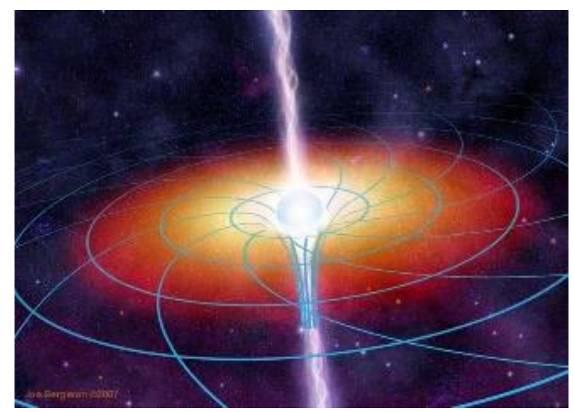
How to build the next generation of quantum simulators?

Technology ⇆ Science

Development of novel quantum systems

⇅

Quantum-sensitive measurements



Quantum Black Holes

- Black Hole Relaxation Process

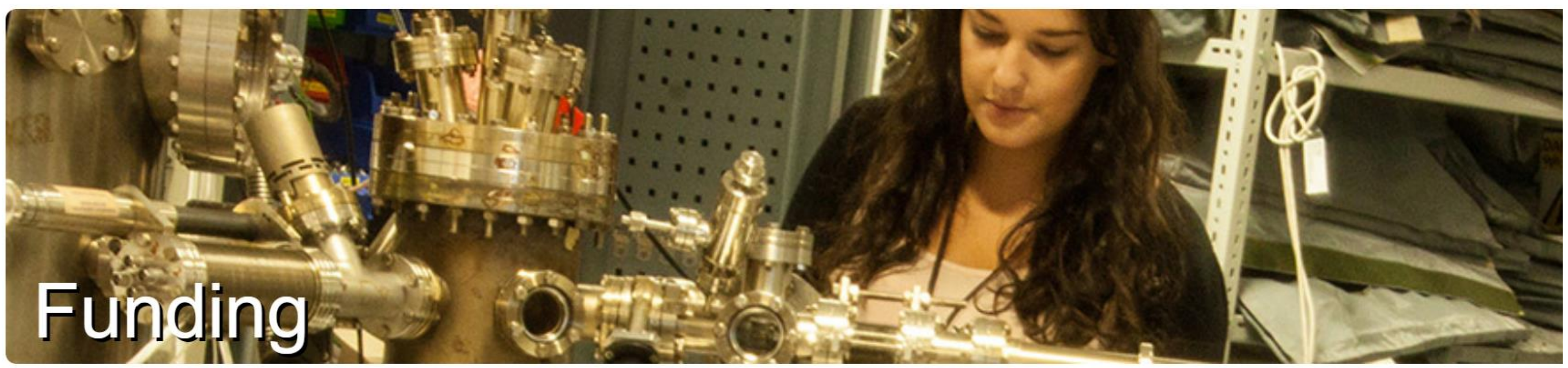
Quantum Vacuum of the Universe

- False Vacuum Decay
- Observer-dependence

To over all expertise you need to collaborate, or you need to build a community!

QSimFP

WP-5 Quantum Simulators of Fundamental Physics



Home / Funding / Research Grants / Funding opportunities / Quantum Technologies for Fundamental Physics (QTFP) Programme

Quantum Technologies for Fundamental Physics (QTFP) Programme

STFC and EPSRC invite applications for research consortia to apply for funding as part of the Quantum Technologies for Fundamental Physics (QTFP) programme. This is a new programme which, building on the investments of the National Quantum Technology Programme, aims to demonstrate how the application of quantum technologies will advance the understanding of fundamental physics questions.

The programme has total funds of up to £40m. The majority of funding (c. £36 million) will be allocated to this research call, which is looking to fund up to seven projects at upwards of £2 million each (at 80% fEC). Applicants wishing to submit a proposal for a large award (>£5 million) should discuss this with STFC (contact details below) ahead of the submission.

Coordination:

Silke Weinfurtner (PI)
The University of Nottingham

Zoran Hadzibabic
University of Cambridge

Hiranya Peiris
UCL

Andrew Pontzen
UCL

QSimFP

External partners
- Bill Unruh (Canada, UBC)
- Joerg Schmiedmayer (Austria, TUV)
- Ralf Schuetzhold (Germany, HZDR)
- Matt Johnson (Canada, PI)
- Jonathan Braden (Canada, CITA)

Cosmology and non-equilibrium field theory and simulations
- Hiranya Peiris (UK, UCL)
- Andrew Pontzen (UK, UCL)
- Ian Moss (UK, Newcastle)
- Ruth Gregory (UK, Durham)
- Jorma Louko (UK, Nottingham)

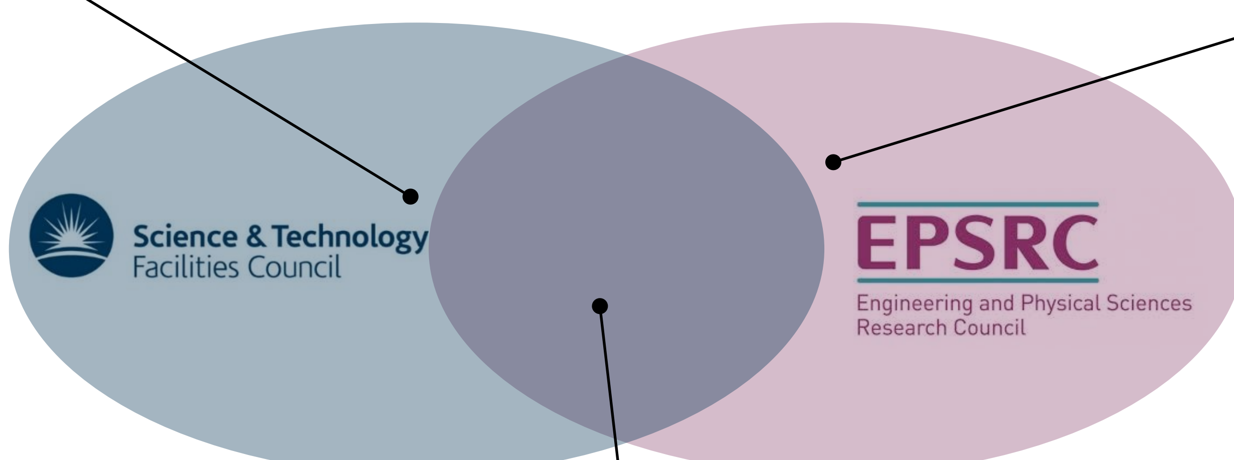
Ultra-Cold Atoms
- Thomas Billam (UK, Newcastle)
- Zoran Hadzibabic (UK, Cambridge)

Superfluid Helium
- John Owers-Bradley (UK, Nottingham)
- Carlo Barenghi (UK, Newcastle)

Superfluid Opto-mechanics
- Xavier Rojas (UK, Royal Holloway)

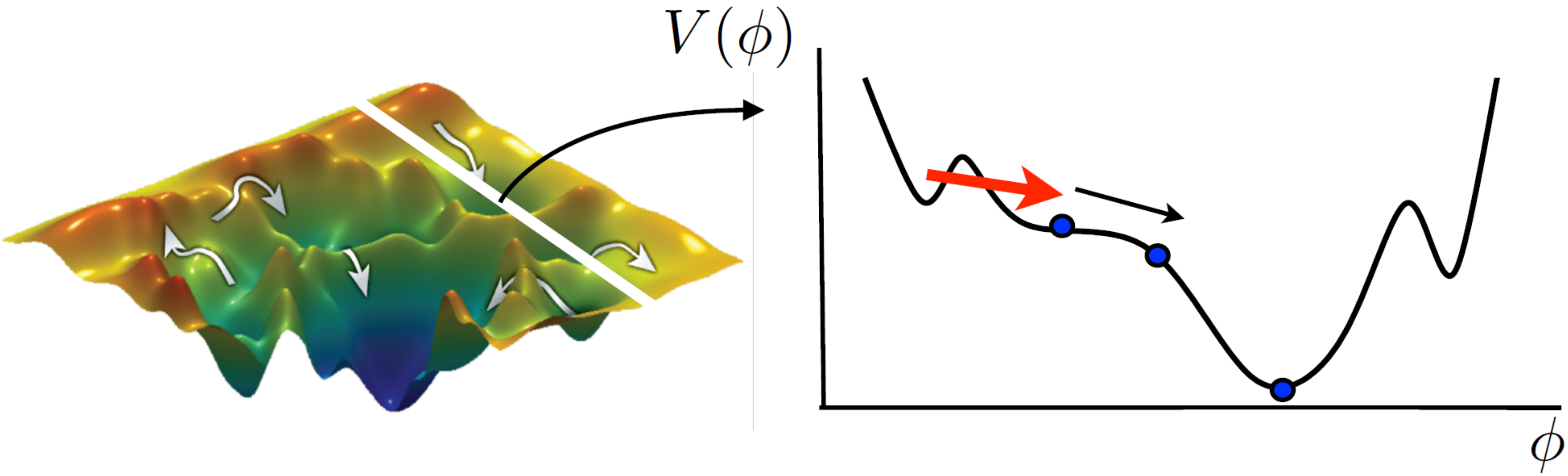
Opto-mechanics
- Pierre Verlot (UK, Nottingham)

Quantum Optics
- Friedrich Koenig (UK, St Andrews)



Gravity Simulators
- Silke Weinfurtner (UK, Nottingham)

Origin of Universe through vacuum decay?



- Particle physics-inspired cosmological theories exhibit **false vacuum decay** via **bubble nucleation**
- Relativistic first-order phase transition: non-perturbative, non-linear, non-equilibrium process
- Understanding dynamics could shed light on origin of Universe

Universe on a table-top?

- Fialko proposal: “emulate” full dynamics in condensed-matter system!
  Fialko, Sidorov, Drummond, Brand, J.Phys.B50 (2017), 024003 [1607.01460

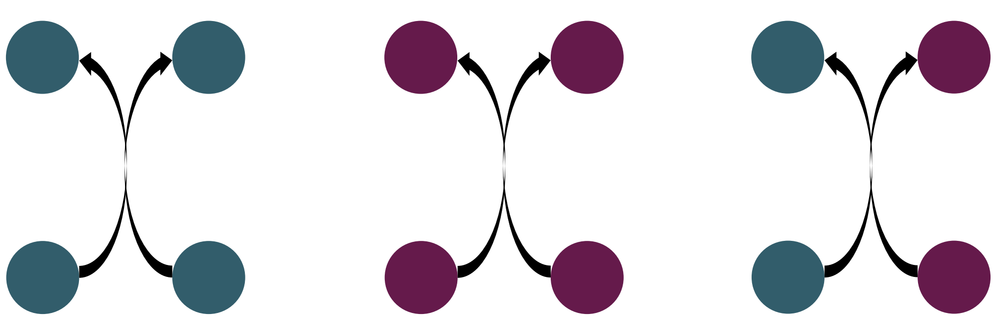
- They propose 2-component coupled Bose-Einstein Condensate (BEC) system (ultra-cold dilute boson gas, in two single-particle states)

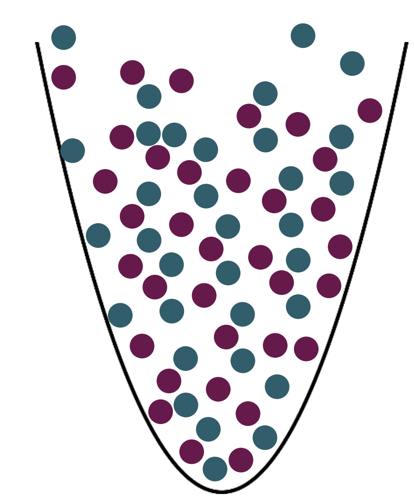
2-component coupled Bose-Einstein Condensates (BECs)

ultra-cold dilute gas of N bosons, in two-single particle states

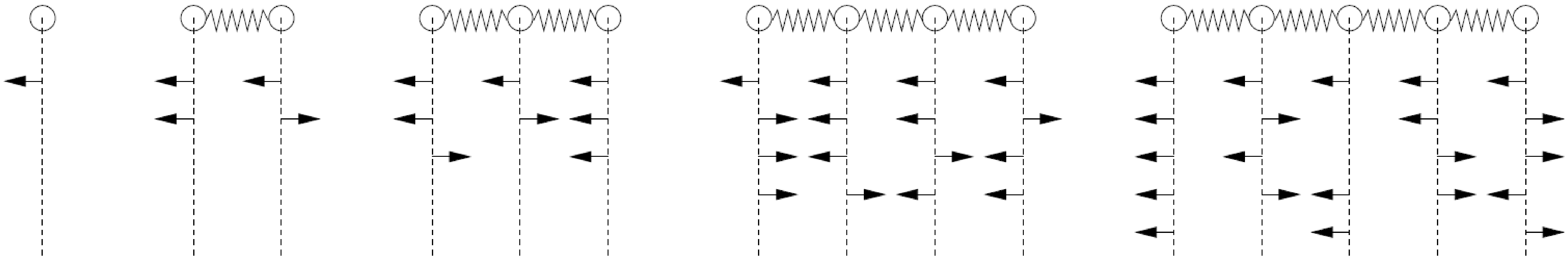
sudo-spinor BEC (e.g. atoms in two different hyperfine states or double-well potential)

$$\hat{\mathcal{H}} = -\hat{\Psi}_i^\dagger \frac{\hbar^2 \nabla^2}{2m_i} \hat{\Psi}_i + \hat{\Psi}_i^\dagger V_{\mathrm{ext},i} \hat{\Psi}_i + \frac{g_{ij}}{2} \hat{\Psi}_i^\dagger \hat{\Psi}_j^\dagger \hat{\Psi}_i \hat{\Psi}_j$$





Condensation: $\hat{\Psi}_i = \sqrt{\hat{\rho}_i}\, e^{i\hat{\phi}_i} \longrightarrow \psi_i = \sqrt{\rho_i} e^{i\phi_i}$



2-component coupled Bose-Einstein Condensates (BECs)

ultra-cold dilute gas of N bosons, in two-single particle states

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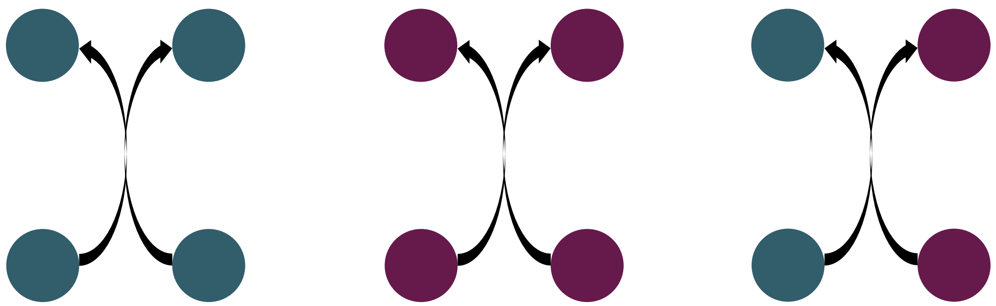

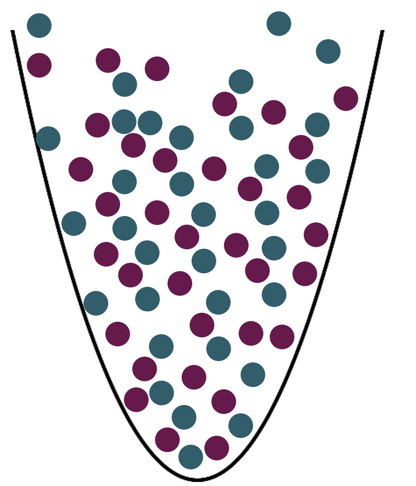

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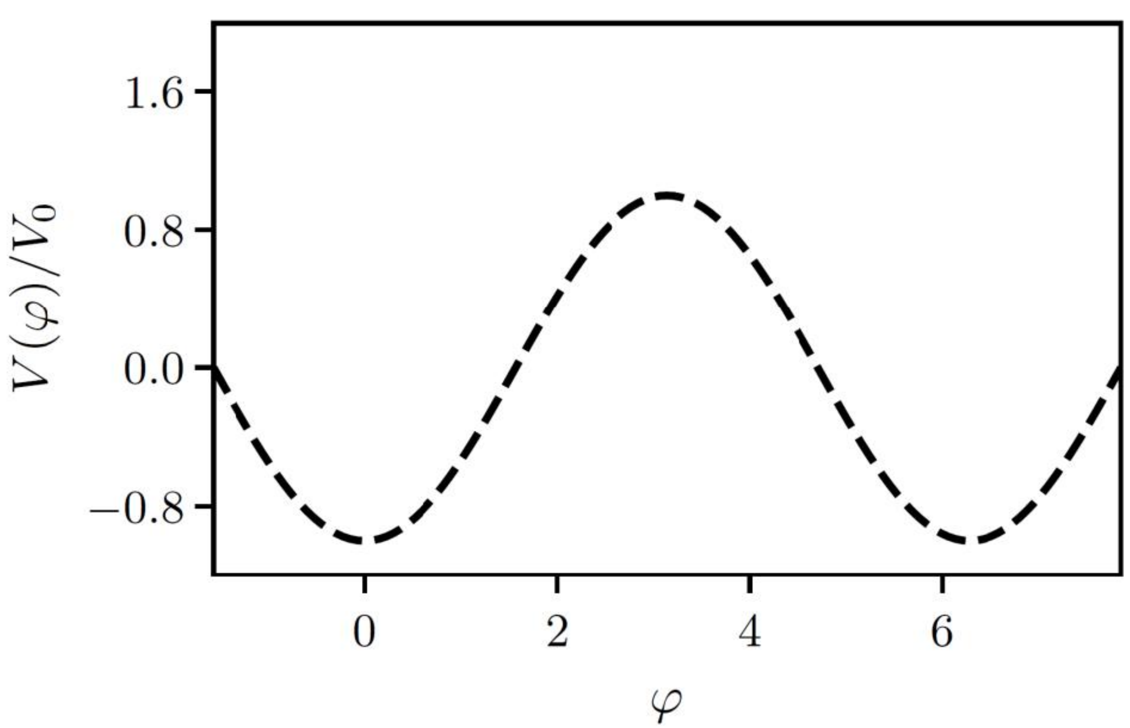
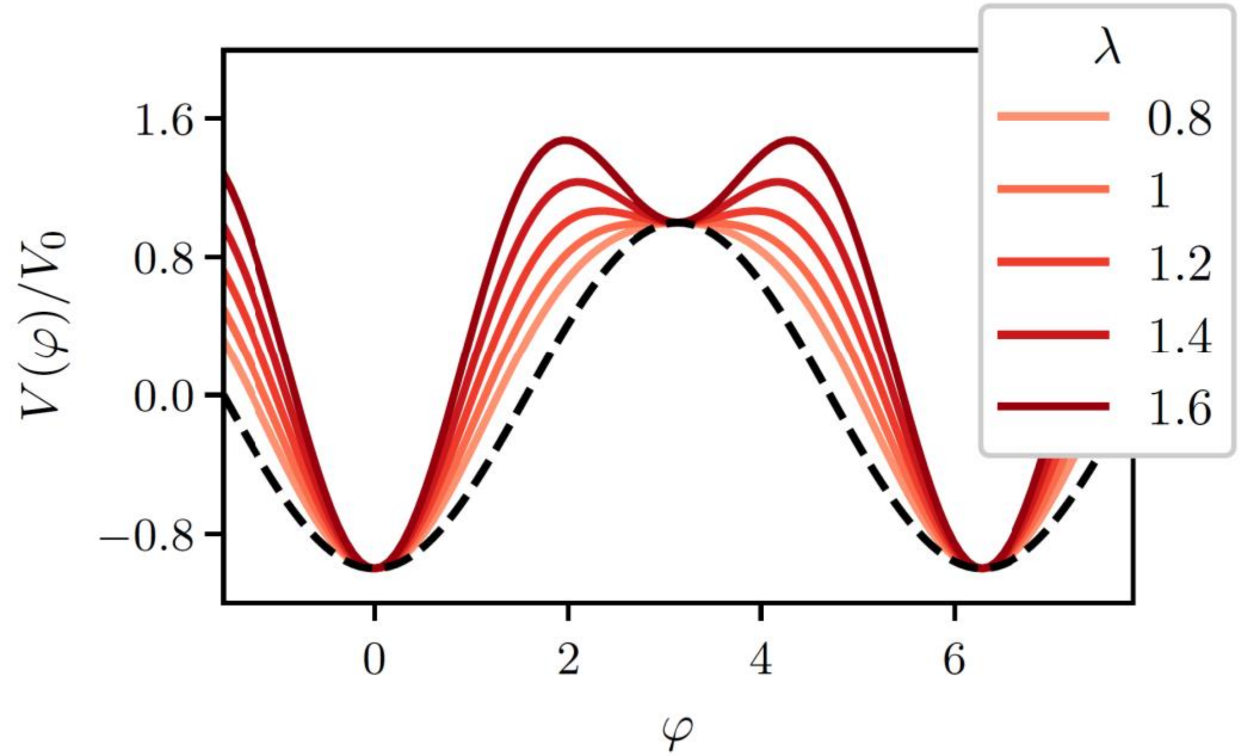
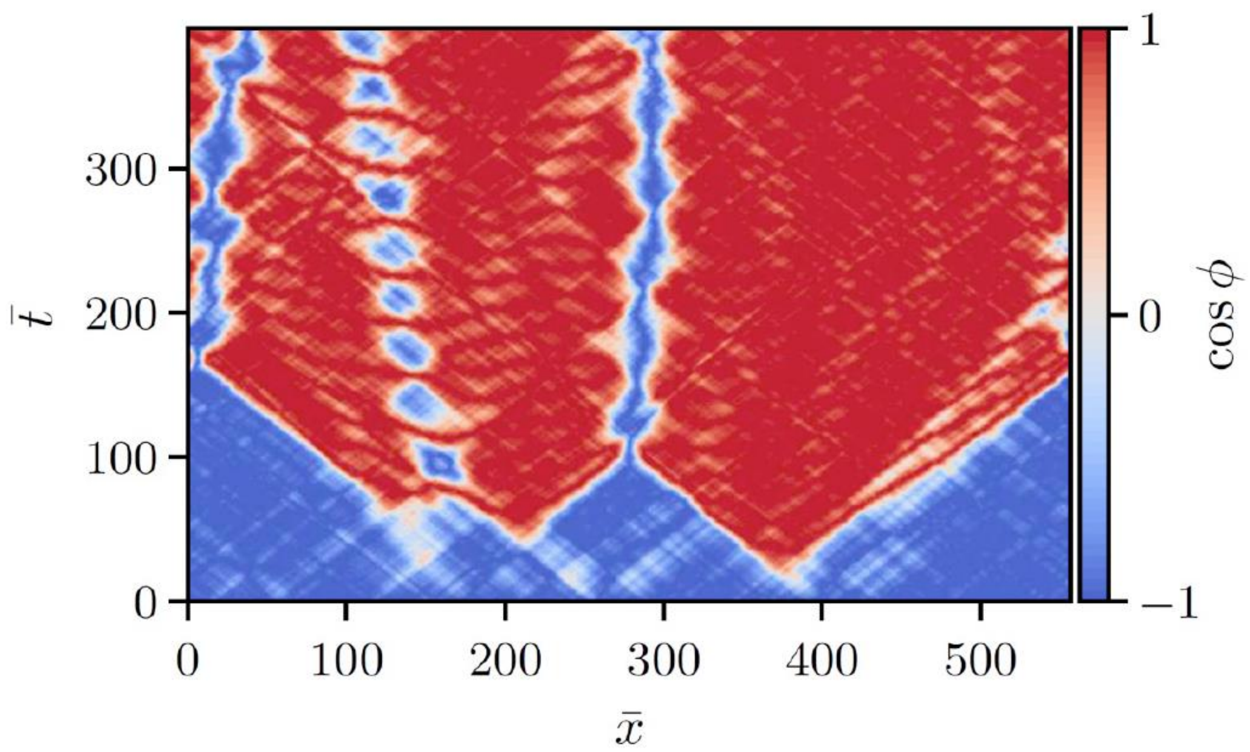




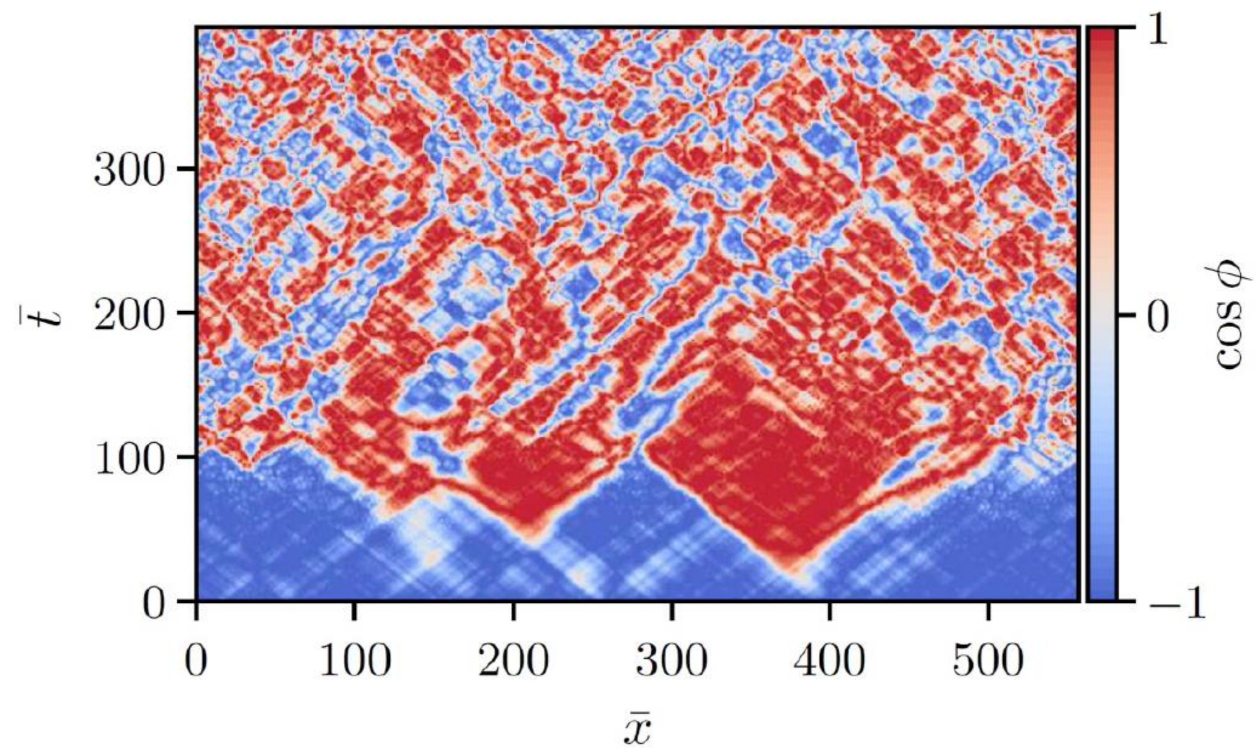
Dynamics of relative phase exhibits Sine-Gordon Lagrangian

Engineer metastable vacuum by adding high-frequency modulation in transition coupling

False vacuum decay



Floquet instability



- Investigated effects that impact validity of analogue if not controlled, feeding back into experimental design.
- Linear stability analysis, confirmed by stochastic lattice simulations.
- Further experimental effects need to be quantified and mitigated.

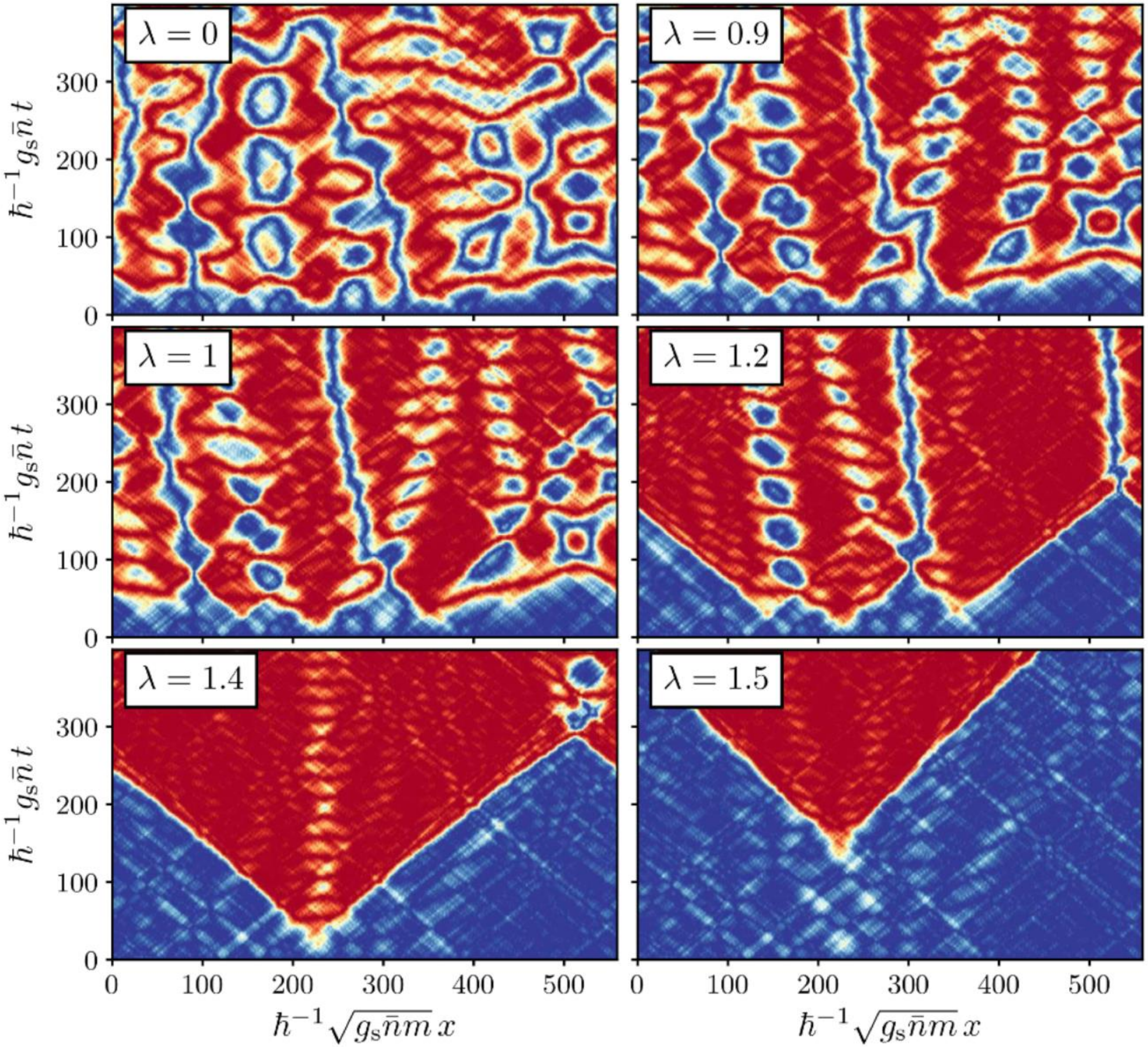
Braden, Johnson, Peiris, Pontzen, Weinfurtner, JHEP (2018), JHEP (2019)

Investigating experimental feasibility

second-order phase transition

rapid nucleation

slower nucleation



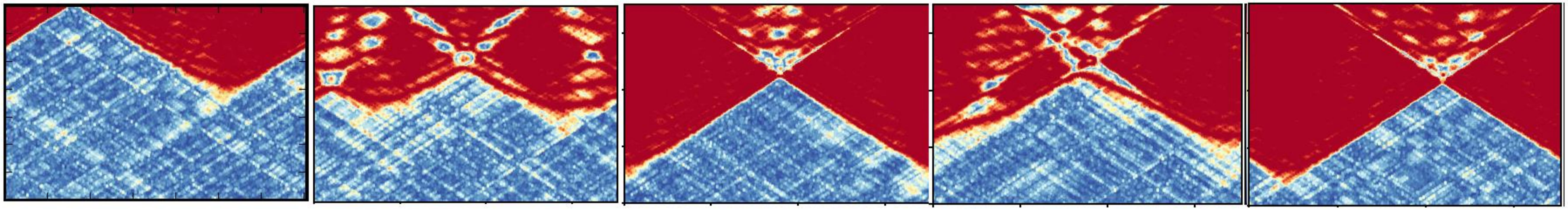
experimentally tunable parameter

λ

Braden, Johnson, Peiris, Pontzen, Weinfurtner, JHEP (2019)

A new description of vacuum decay?

- Can compute decay rates to high precision by stacking many simulations



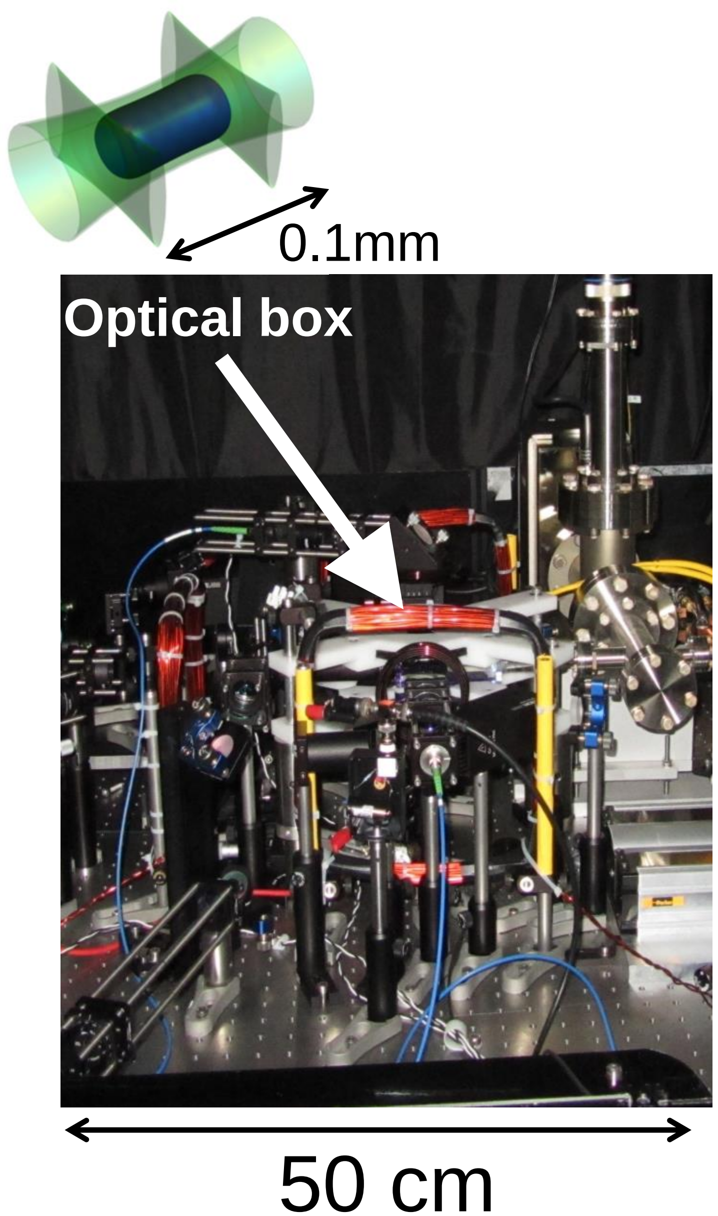
- Compare with "quantum tunnelling" instanton predictions
- Surprise! Rates are very similar (given semiclassical stochastic lattice sims only capture classical decay paths)
- New "real time" semiclassical interpretation of false vacuum decay?
- Technique enables computation of observables inaccessible to instanton formalism

Braden, Johnson, Peiris, Pontzen, Weinfurtner, Phys. Rev. Lett. (2019)
Hertzberg and Yamada (2019), Blanco-Pillado, Deng, Vilenkin (2019)
See also early work on stochastic approach to tunnelling e.g. Linde (1991)

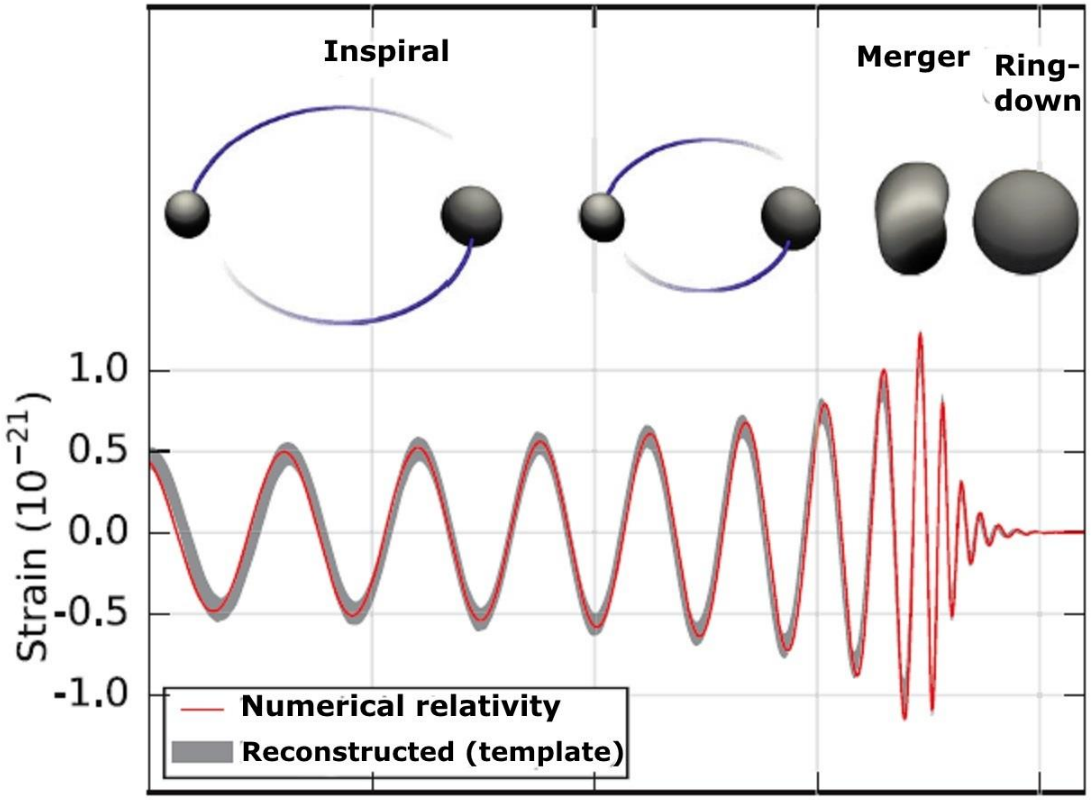
- Working with Zoran Hadzibabic (Cambridge, Quantum Gases) towards experimental implementation! Several other experimental efforts Internationally, e.g. Joerg Schmiedmayer (TU Wien, Atomchip Group)

- Part of “Quantum Simulators for Fundamental Physics” (QSimFP) workpackage and application

Ultra-cold atoms in box trap (Cambridge)

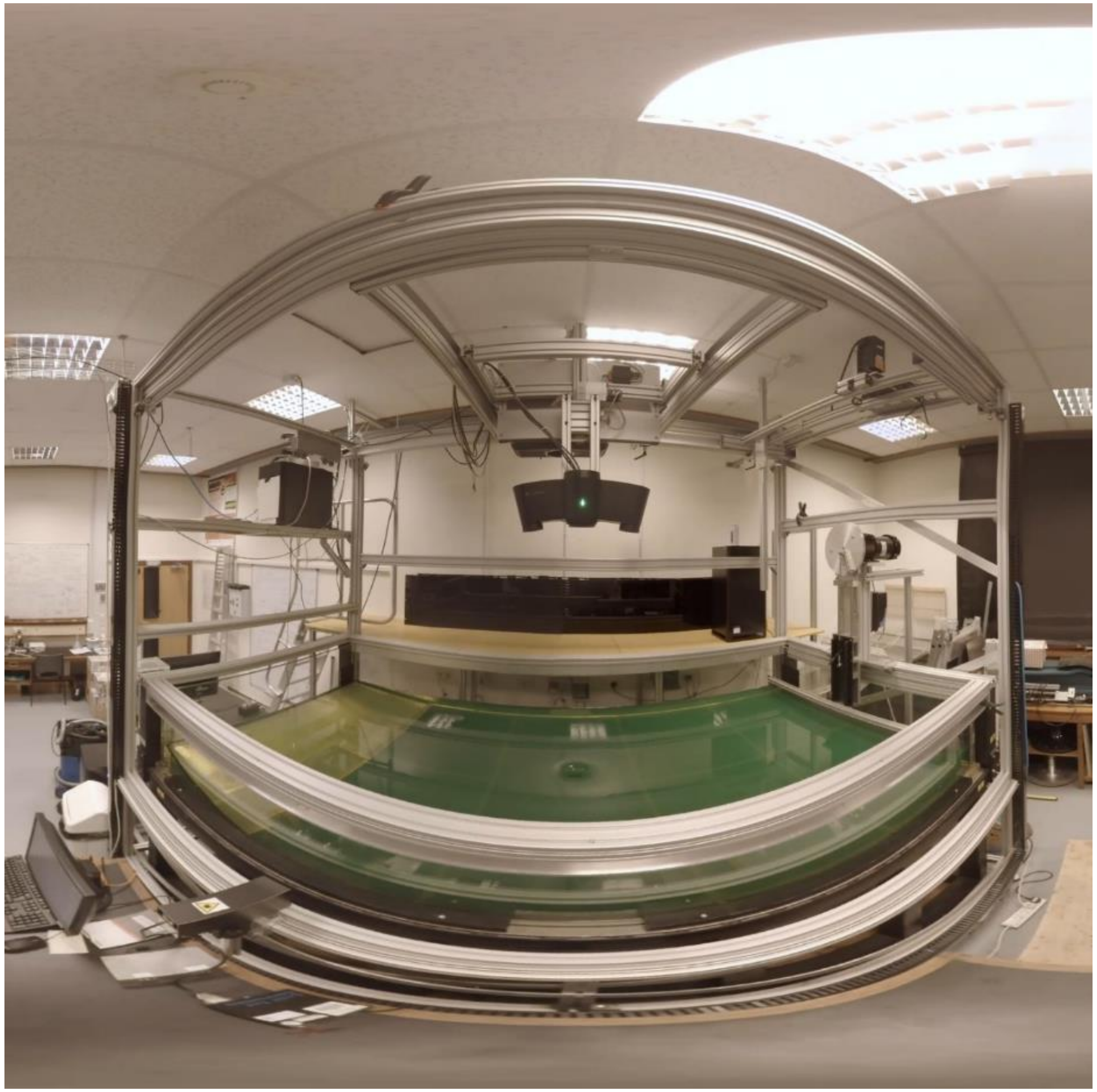


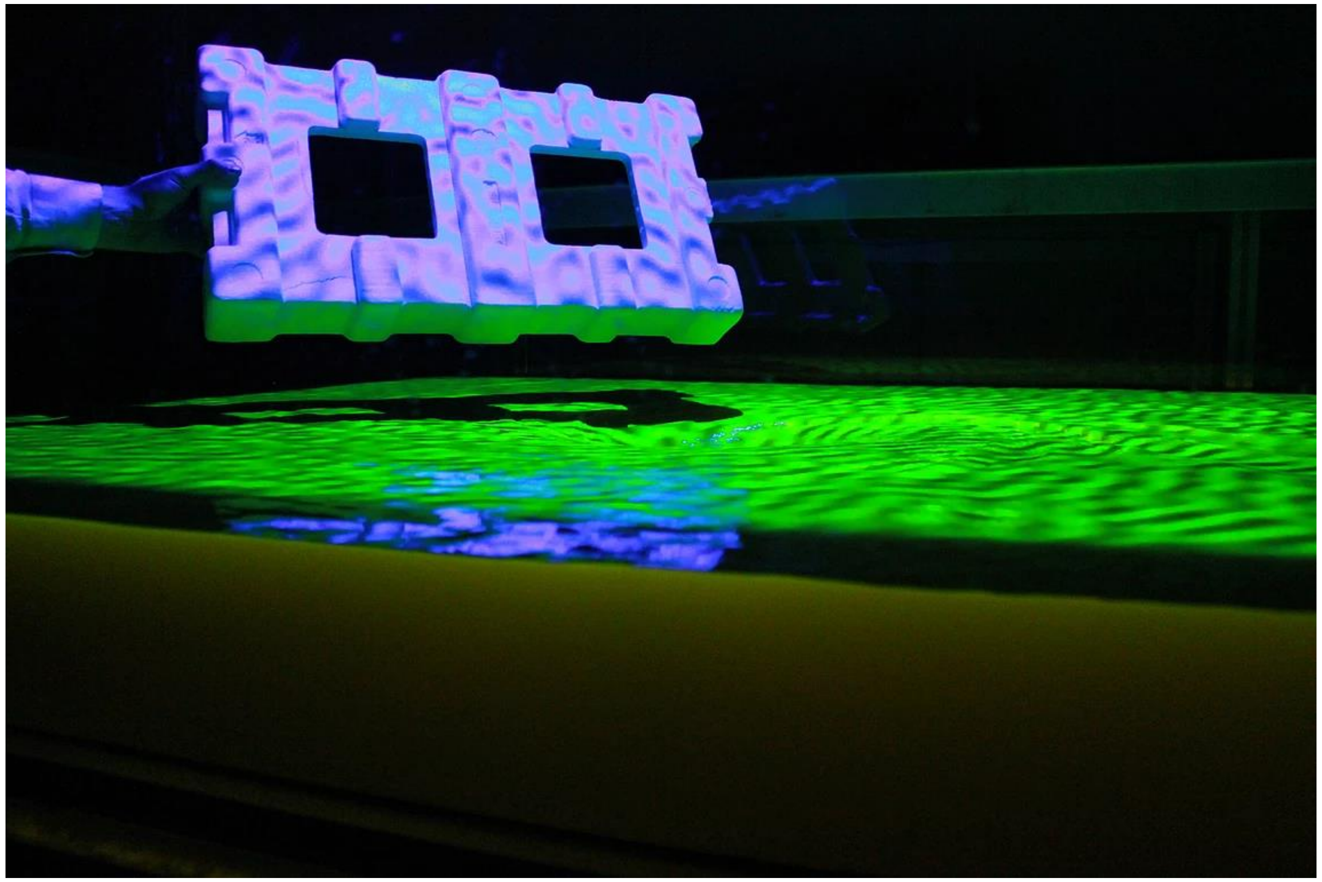
Quantum black hole processes?



- Perturbed black-holes emit characteristic waves, whose frequencies are independent of initial perturbation.
- **Recent validation of universality of black hole ring-down**: ringdown modes naturally excited as part of non-equilibrium process.
- Contribution of quantum effects to black hole dynamics remains open question. Goal is to look for distinctive quantum fingerprints of black hole relaxation process.

The hydrodynamic roatating black hole

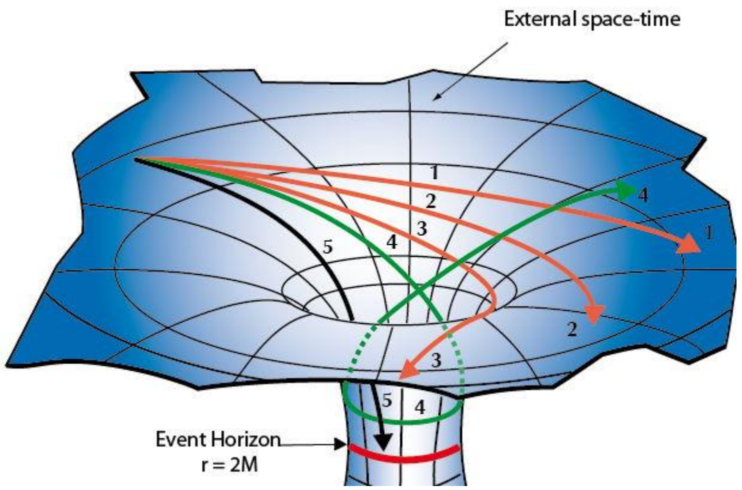


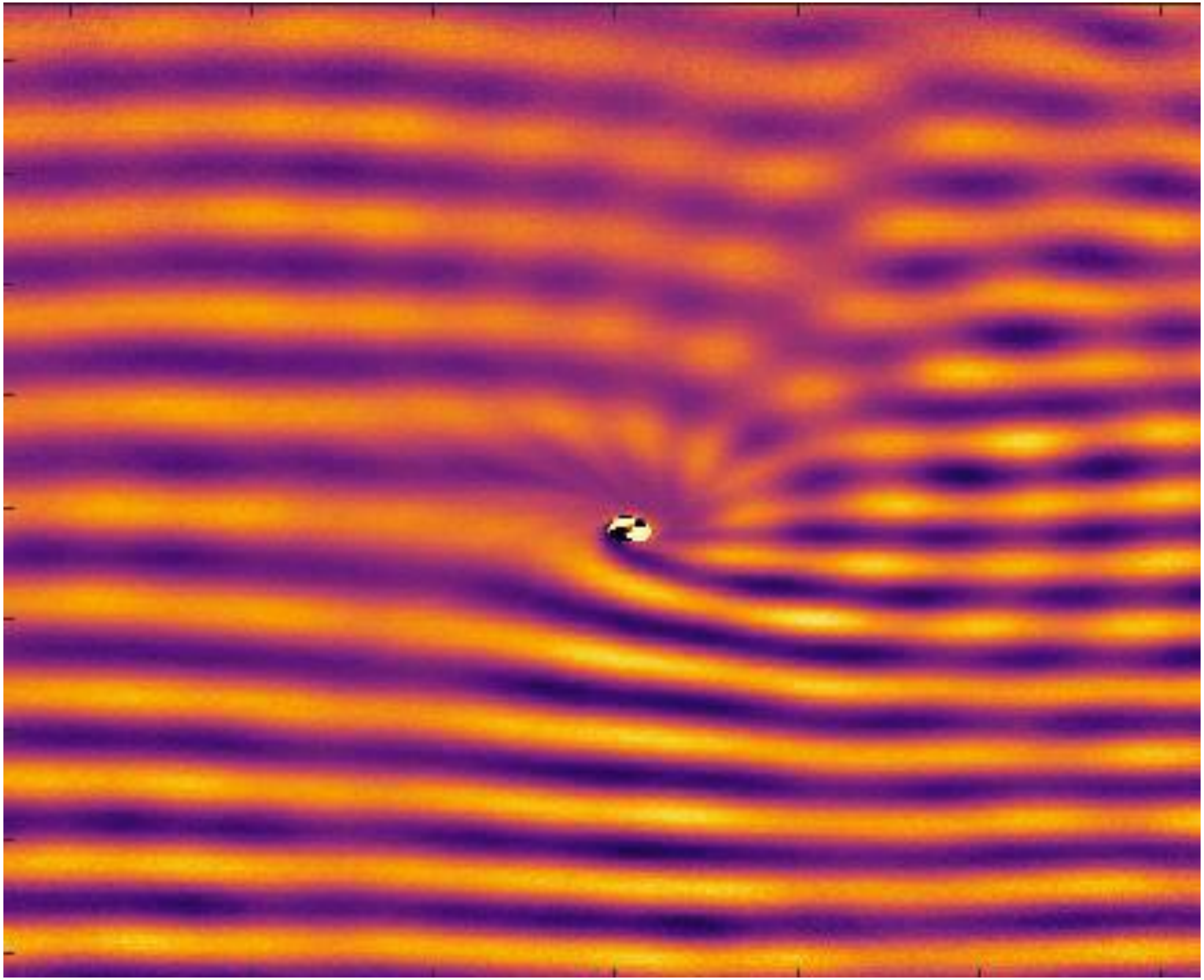


Black Hole Laboratory

The University of Nottingham

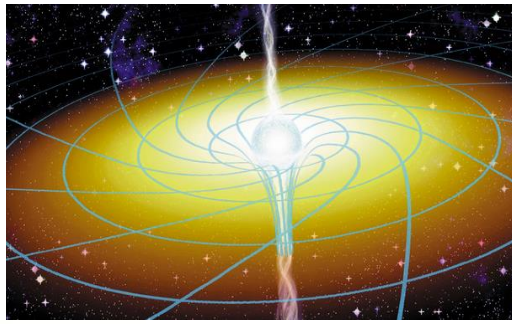
Waves interacting with vortex flow

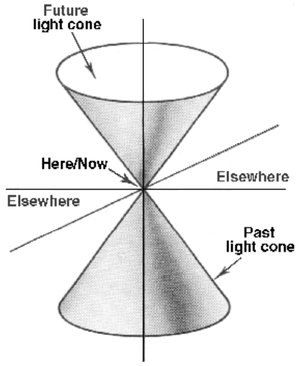




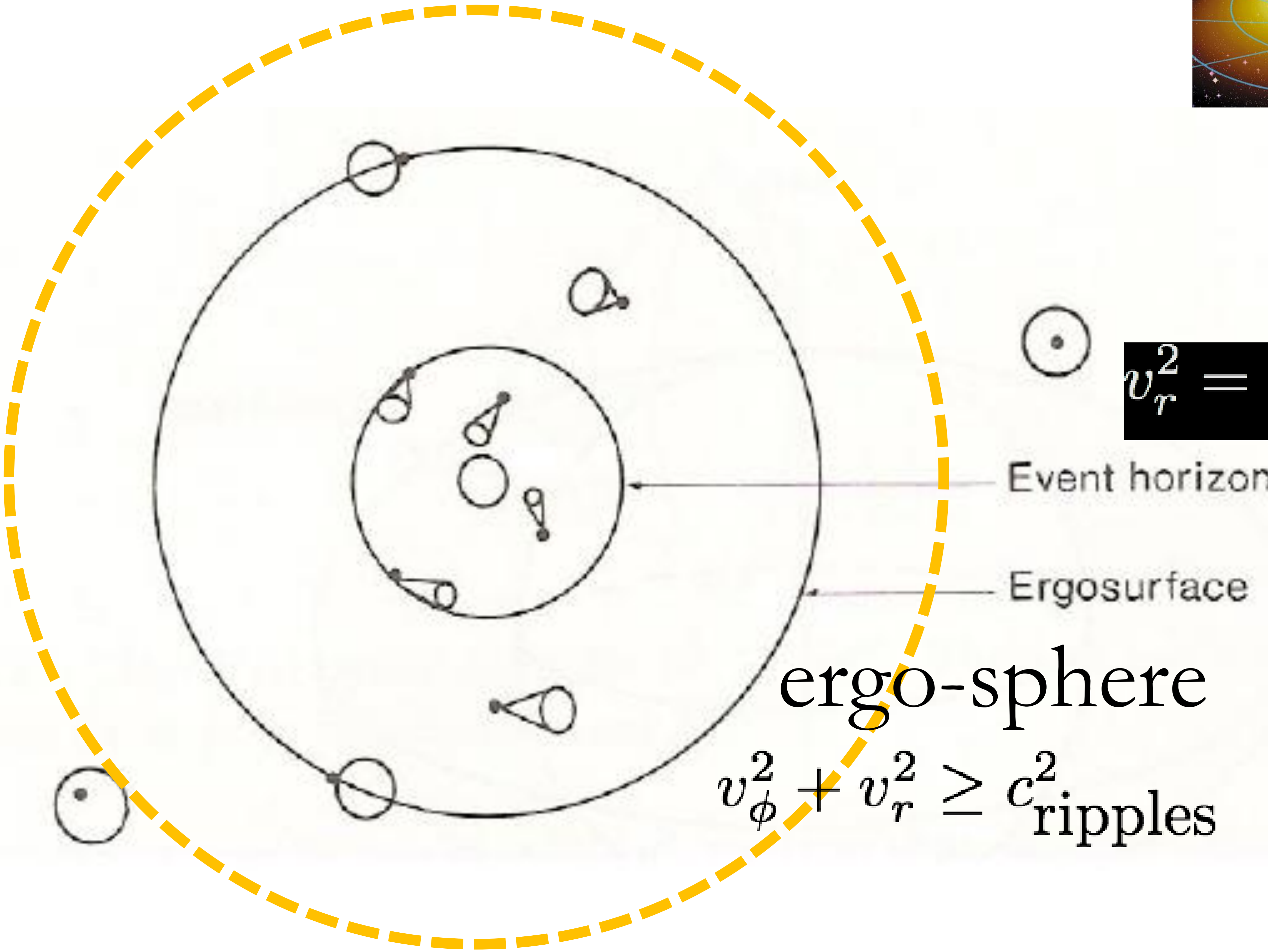
T. Torres, S. Patrick, A. Coutant, M. Richartz, SW, Nature Physics 13, 833-836 (2017)

What is so ‘cool’ about rotating black holes? What can we mimick?





Light Rings Or Circular Orbits



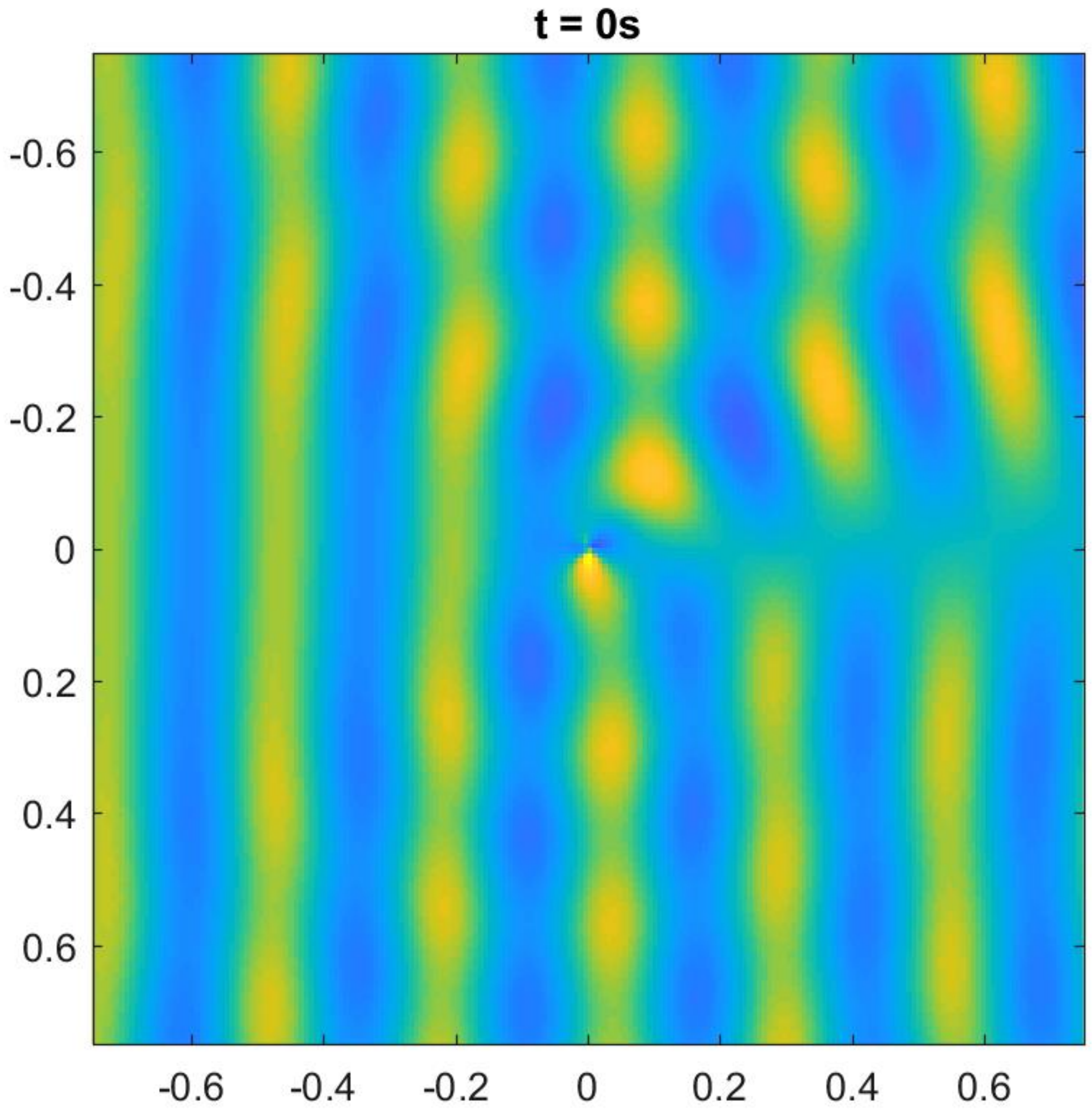
$$v_r^2 = c_{\text{ripples}}^2$$

ergo-sphere

$$v_\phi^2 + v_r^2 \geq c_{\text{ripples}}^2$$

T. Torres, A. Coutant, S. Dolan, SW, J. Fluid Mech. 857 (2018) 291-311

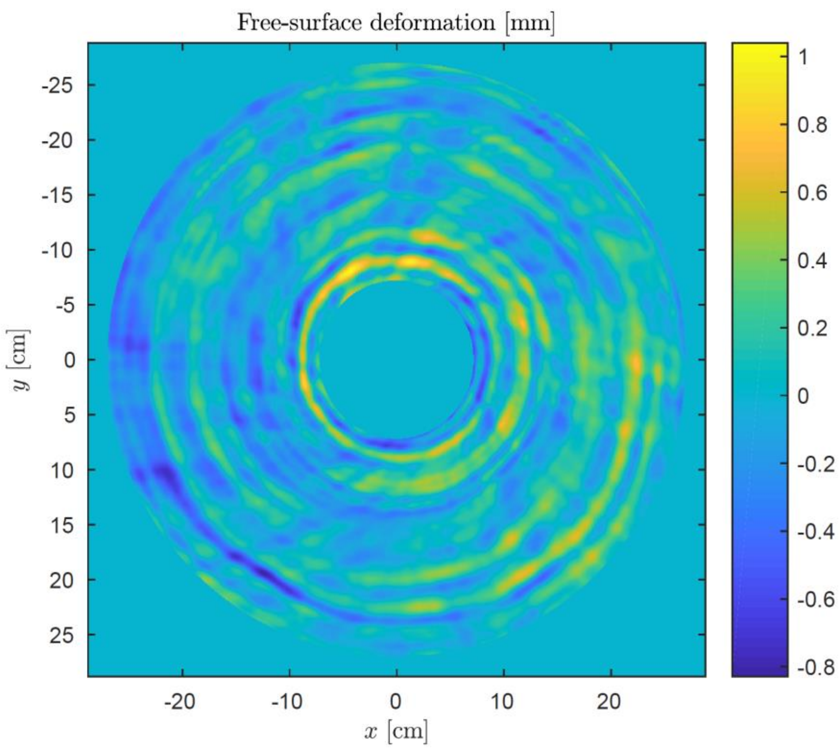
Circular orbits – Light-ring modes

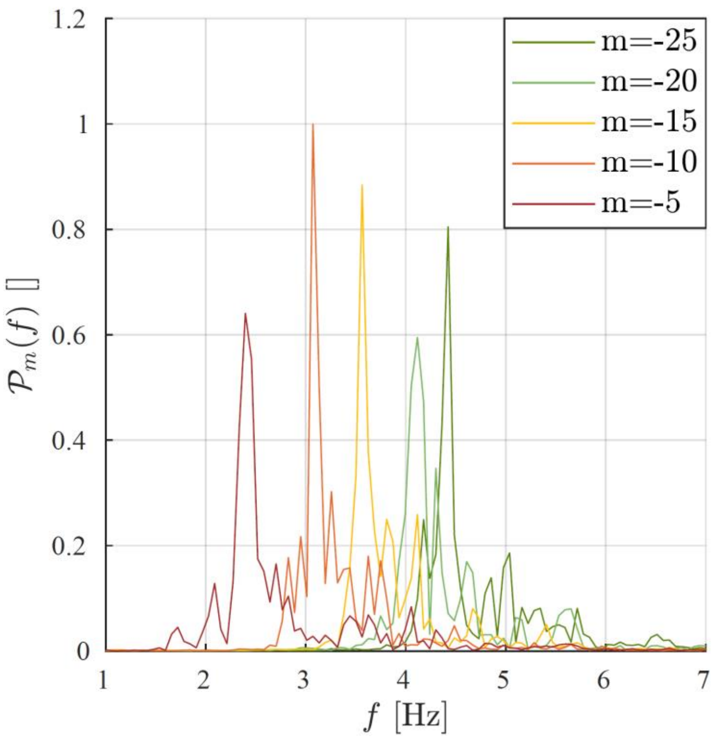


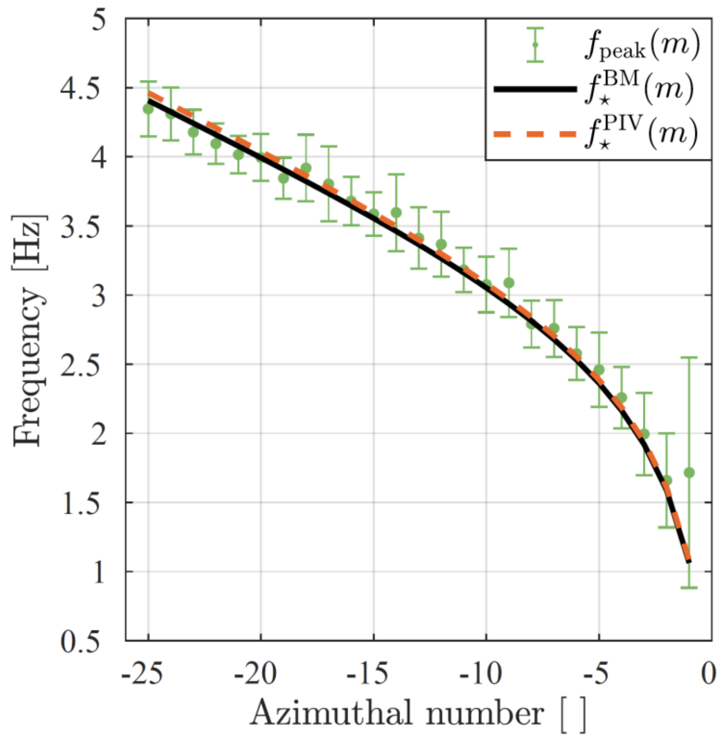
Quasi-normal or ringdown modes:

$$\omega_{\mathrm{QNM}}(m) = \omega_\star(m) - i\Lambda(m)\left(n + \frac{1}{2}\right)$$

The Experiment – Unruh Vortex







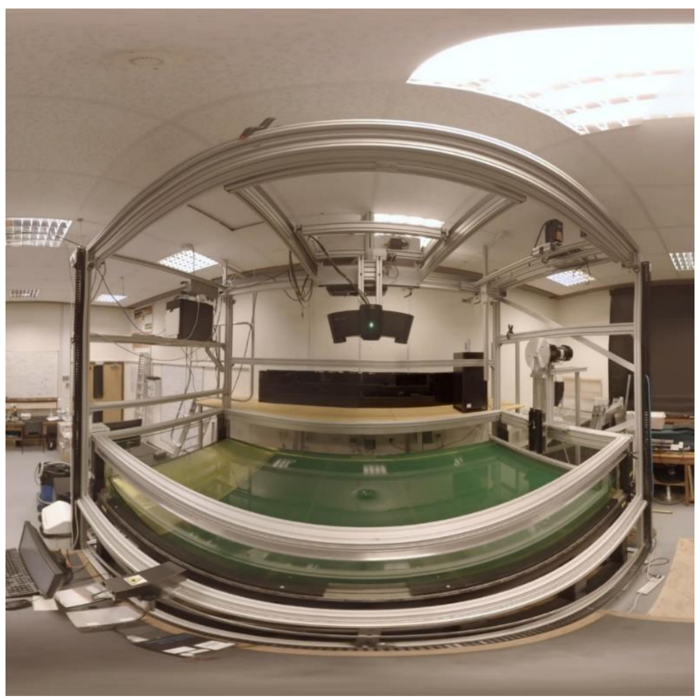
- Counter-rotating light-ring modes are naturally excited as part of non-equilibrium process
- Light-ring modes are the lowest energy modes that can transfer energy across the radial direction
- Effective field theory validation and/or non-invasive fluid flow detection scheme applicable to both fluids and superfluids

T. Torres, S. Patrick, M. Richartz, SW, arXiv:1811.07858

QSimFP

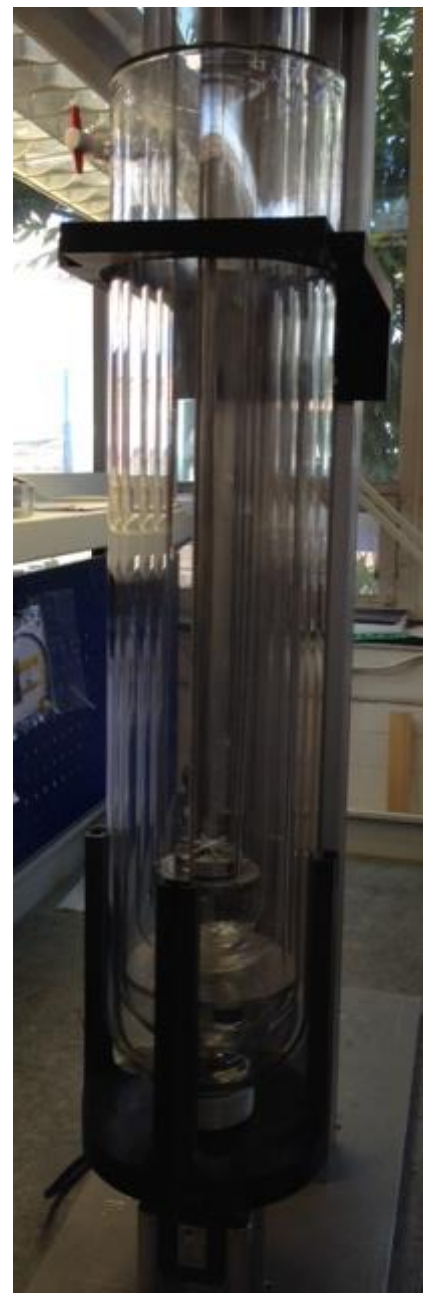
Only assumption: a quantum black hole exhibits quantised angular momentum

Classical angular momentum
Classical surface waves



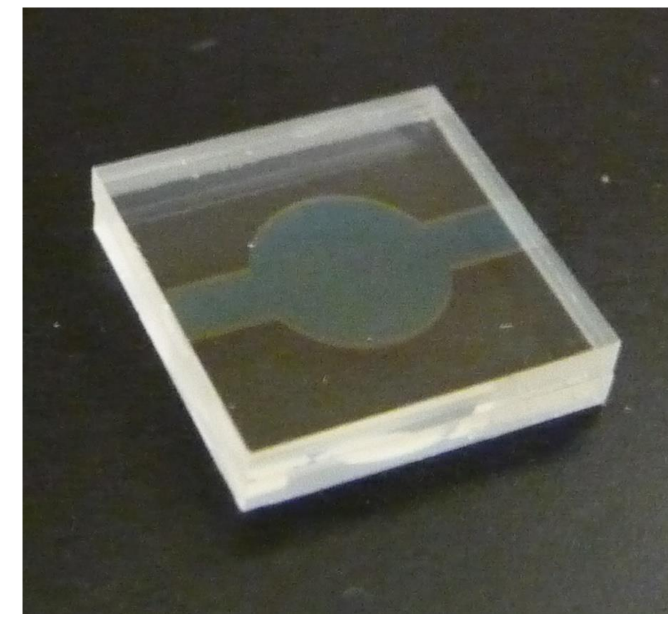
Classical spacetime
Classical relativistic fields

Quantised angular momentum
Classical relativistic ripplons



Quantum spacetime
Classical relativistic fields

Quantised angular momentum
Quantum relativistic ripplons



Experiments: Nottingham
Nano-fabrication: RHUL
My collaborators:
John Owers-Bradly
Pierre Verlot
Xavier Rojas

Quantum spacetime
Quantum relativistic fields

Quantum simulators of gravitational effects

QSimFP

- Continue to build an inter-disciplinary community.
- Construction of novel cryogenic and ultra-cold atoms platforms to explore novel quantum systems: boundary behaviour of stationary draining fluid flows and metastablity of multi-component ultra-cold atom systems.
- Development of novel detection quantum-sensitive detection mechanism.
- Deepening our understanding of effective fields theories (for perturbations in fluids and superfluids).
- Searching for quantum fingerprints of quantum field theory in curved spacetimes where calculations and observations do not offer guidance.