Title: Towards quantum simulators for fundamental physics

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Abstract: Analogue gravity summarises an effort to mimic physical processes that occur in the interplay between general relativity and field theory in a controlled laboratory environment. The aim is to provide insights in phenomena that would otherwise elude observation: when gravitational interactions are strong, when quantum effects are important, and/or on length scales that stretch far beyond the observable Universe. The most promising analogue gravity systems up-to-date are fluids, superfluids, superconducting circuits, ultra-cold atoms and optical systems. While deepening our understanding of the laboratory systems at hand, the long term vision of analogue gravity studies is to advance fundamental physics through interdisciplinary research, by establishing and nurturing a new culture of collaboration between the various communities involved. I will discuss recent efforts to explore the quantum origin of the Universe, accelerated observer radiation, and rotating black hole physics in the laboratory.

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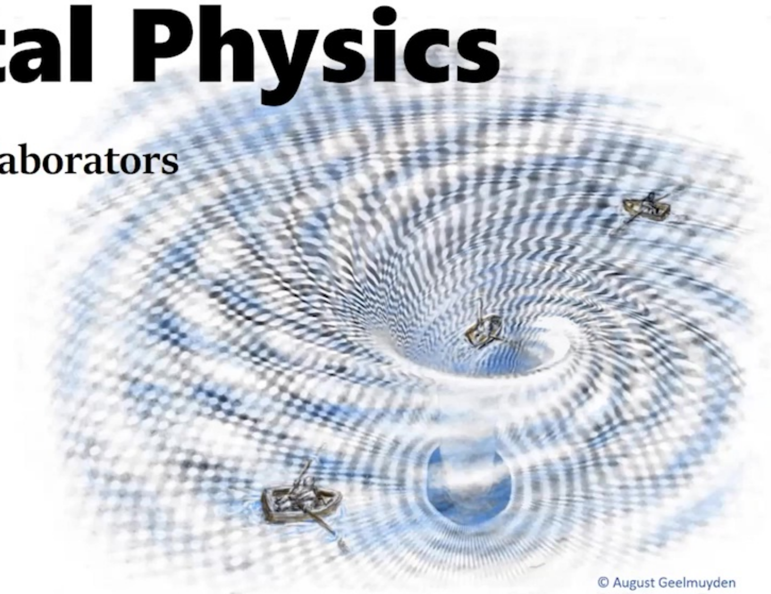
PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Towards
Quantum Simulators for Fundamental Physics

Silke Weinfurtner & **collaborators**



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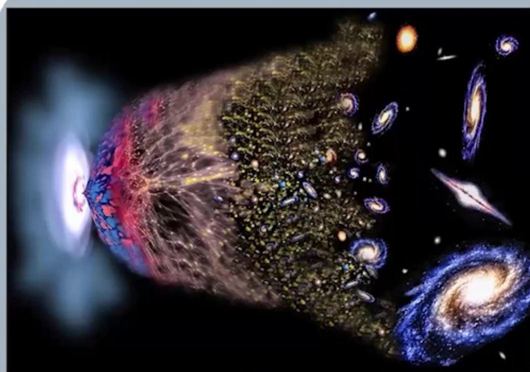
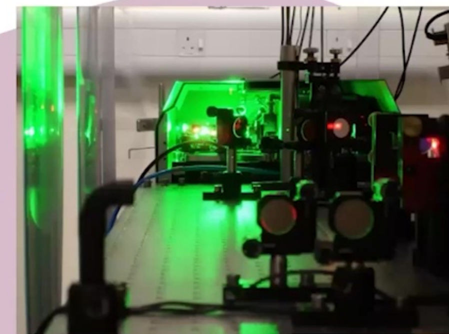
Vision



Quantum Vacuum:
- False Vacuum Decay
- Observer dependence

Quantum Black Hole:
- Black hole ring-down



1st order phase transition in quantum field theory

A toy model for the false vacuum decay in a relativistic setting

Origin of the Universe through vacuum decay?

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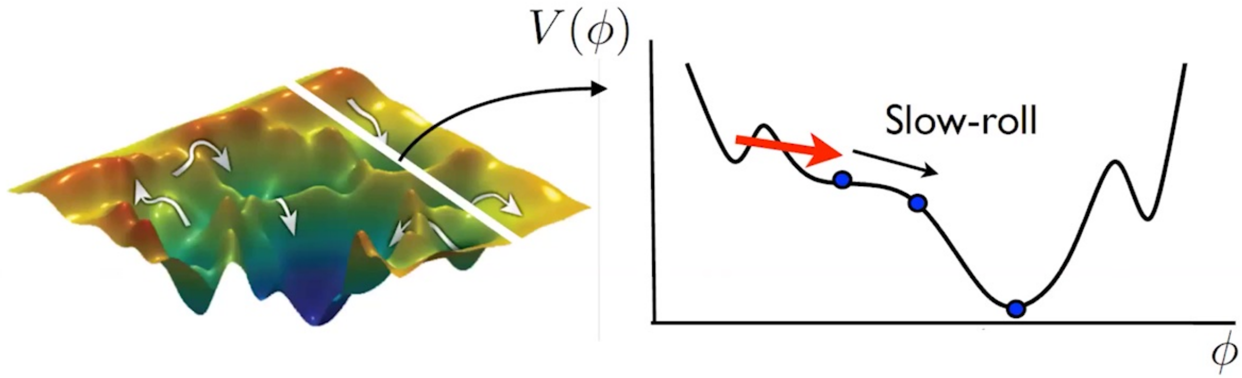

- Particle physics-inspired cosmological theories exhibit **false vacuum decay** via **bubble nucleation**
- Relativistic first-order phase transition: non-perturbative, non-linear, non-equilibrium process
- Understanding dynamics could shed light on origin of Universe

The FVD in the laboratory?

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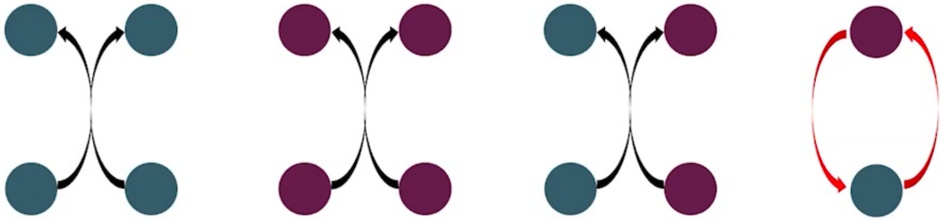
Fialko proposal: "emulate" full dynamics in condensed-matter system!

Fialko, Sidorov, Drummond, Brand, J.Phys.B50 (2017)

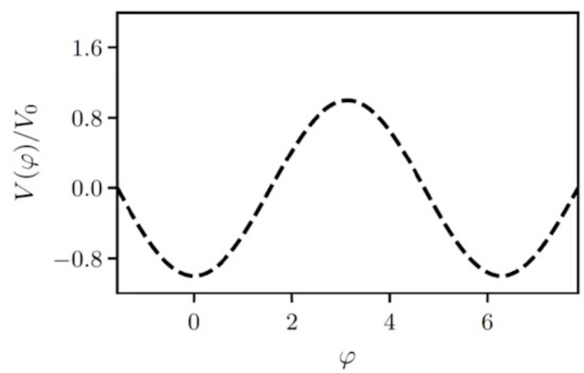
2-component coupled Bose-Einstein Condensates/BECs
ultra-cold dilute gas of N bosons, in two-single particle states
e.g. atoms in two different hyperfine states or double-well potential

$$\hat{\mathcal{H}} = -\hat{\Psi}_i^\dagger \frac{\hbar^2\nabla^2}{2m_i}\hat{\Psi}_i + \hat{\Psi}_i^\dagger V_{\mathrm{ext},i}\hat{\Psi}_i + \frac{g_{ij}}{2}\hat{\Psi}_i^\dagger\hat{\Psi}_j^\dagger\hat{\Psi}_i\hat{\Psi}_j - \frac{\nu}{2}\sigma^{\mathrm{x}}_{ij}\hat{\Psi}_i^\dagger\hat{\Psi}_j \qquad \sigma^{\mathrm{x}} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$



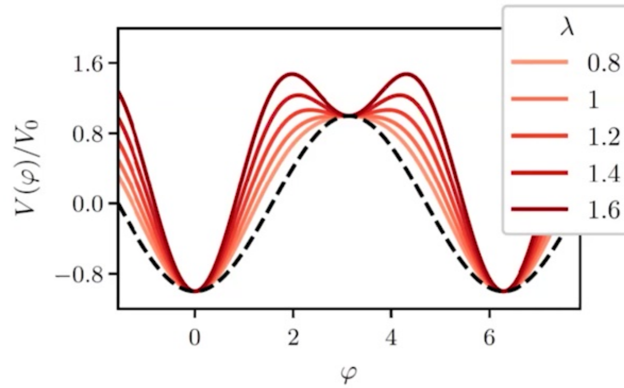
Condensation $\longrightarrow$ $\psi_i = \sqrt{\rho_i}e^{i\phi_i}$

The FVD in the laboratory?



Dynamics of relative phase fluctuations in BEC exhibit Sine-Gordon Lagrangian

$$\mathcal{L}_{\mathrm{eff}}^{\varphi} \propto \frac{\dot{\varphi}^2}{2} - c_{\mathrm{s}}^2 \frac{(\nabla\varphi)^2}{2} - V_0 \left(-\cos\varphi + \frac{\lambda^2}{2} \sin^2\varphi \right)$$



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

Investigating experimental feasibility

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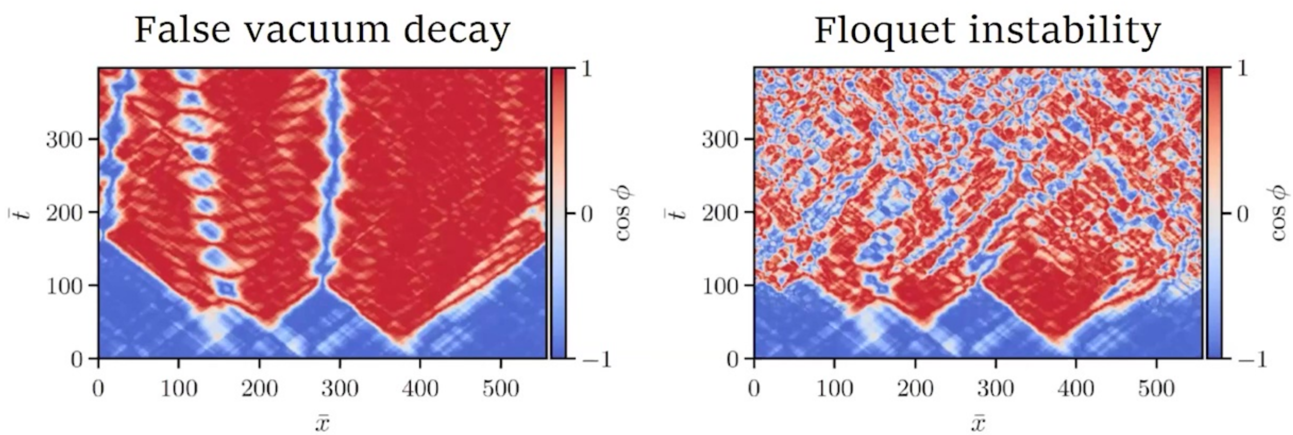

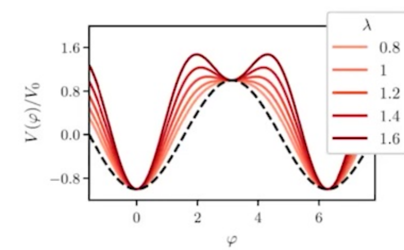

- Investigated effects that impact validity of analogue if not controlled, feeding back into experimental design.
- Linear stability analysis, confirmed by stochastic lattice simulations.
- Further experimental effects need to be quantified and mitigated.

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

Investigating experimental feasibility

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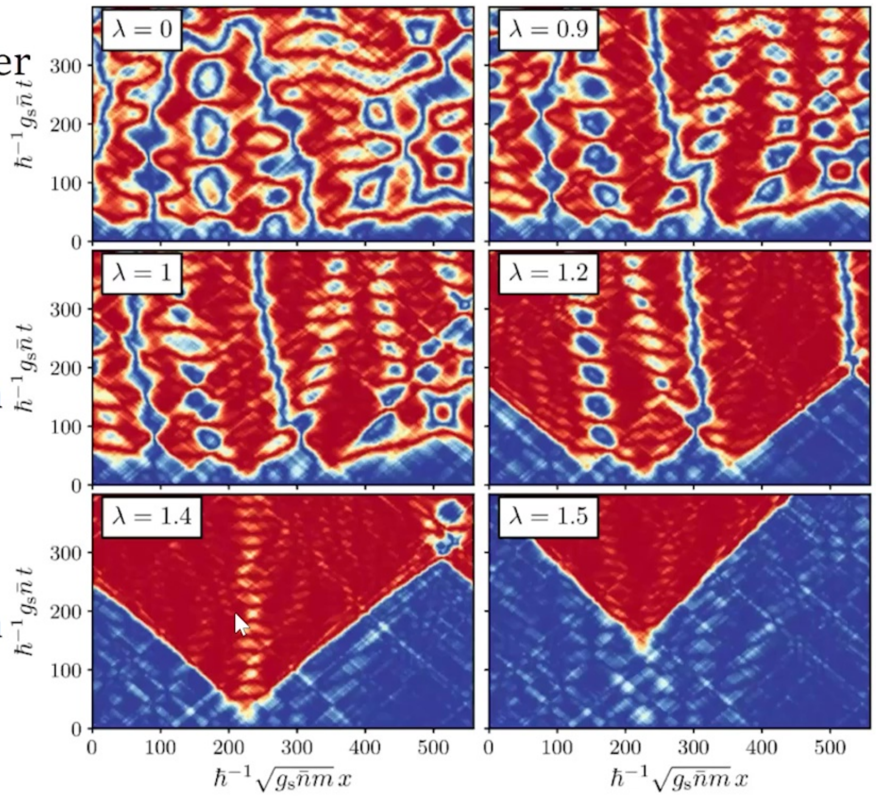
second-order phase transition

rapid nucleation

slower nucleation



experimentally tunable parameter

λ

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

A new description of vacuum decay?

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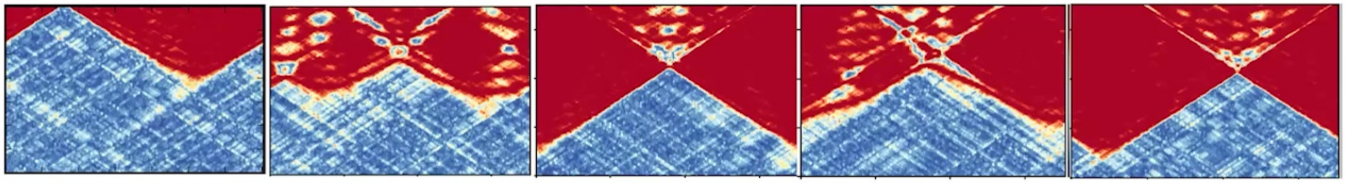
- Can compute decay rates to high precision by stacking many simulations



- 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)

Pathways to experiment

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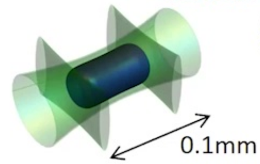
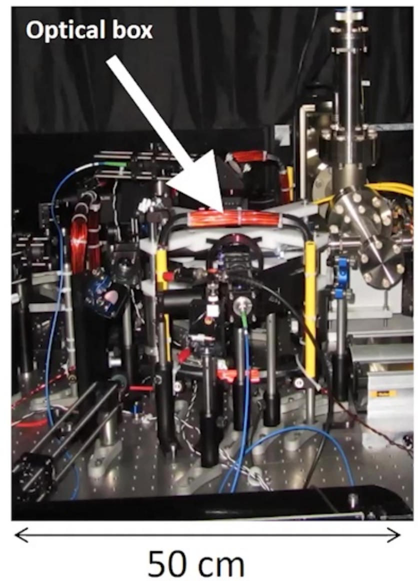
- Experimental implementation possible due to recent developments in quantum technology community

Zoran Hadzibabic, Science 347 (2015)
Zoran Hadzibabic, Nature 563 (2018)
Zoran Hadzibabic, Science 366 (2019)

Ultra-cold atoms
in box trap





Observer dependence

A toy model to investigate ambiguity between particle vs. vacuum state

Observer dependence of quantum vacuum

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$$k_B T_U = \frac{\hbar a}{2\pi c}$$

- A uniformly linearly accelerated observer sees fluctuations of the Minkowski vacuum as a thermal bath with a characteristic temperature [W. G. Unruh, Phys. Rev. D 14, 870 (1976)]
- Unruh-DeWitt detector: 2-level quantum system with an energy gap E, on a smooth time-like trajectory $x(\tau)$, parametrised by proper time τ; and for example the following interaction Hamiltonian: $H_{int} = \alpha \cdot \chi(\tau) \cdot \mu(\tau) \cdot \phi(\tau)$
- The Unruh radiation for an observer with the acceleration a is given by T = 2,5 * 10^(-20) Kelvin/(m/s^2), and hence the effect seems far too small to be detectable.
- As a consequence many of the assumptions that go into qft in cs cannot be tested!

A toy model for particle detectors in a relativistic setting

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Problems to overcome:

- There is no analogue of a relativistic proper time.
  Our solution: circular Unruh effect; proper and coordinate time are related by a time-independent gamma factor [Bell and Leinaas, Nucl. Phys. B 212, 131 (1983)].

- Physical system needed, acting as an effective Unruh-DeWitt detector.
  Our solution: replace 2-level quantum system with an interferometric setup,
  the laser/or any continuous probing field facilitates a suitable particle detector.

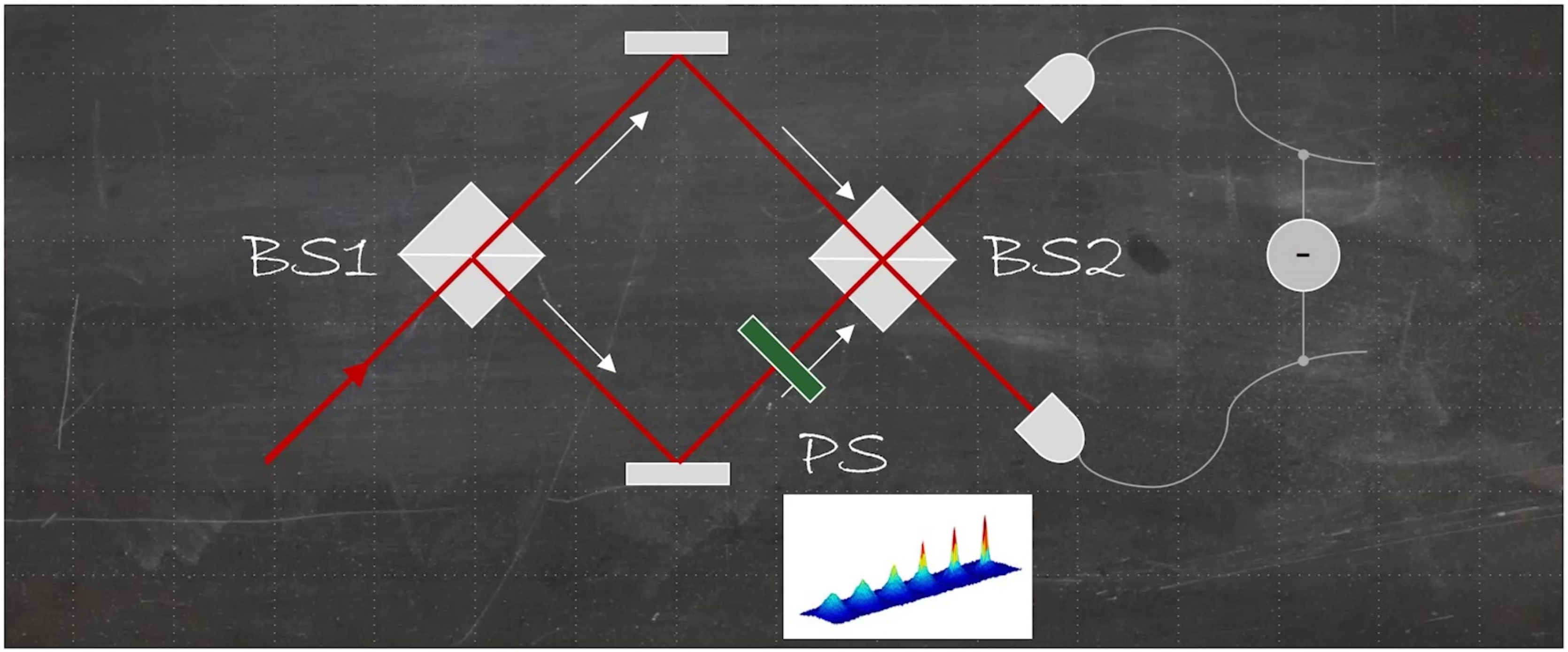
- The Unruh radiation for an observer with the acceleration a is given by
  T = 2,5 * 10^(-20) Kelvin/(m/s^2), and hence the effect seems far too small to be detectable.
  Solution provided naturally: The effective speed of light is lowered by many order (here 11) of magnitude, analogue Unruh effect becomes experimentally feasible!

- **An experimental implementation will allow us to test out mathematical models!**

Interferometric Unruh detectors for Bose-Einstein condensates

FQXi

Basic idea: Quantum fluctuations follow an effective relativistic field theory; coupled laser field acts as an effective Unruh-DeWitt detector: BEC density fluctuation converted to laser phase fluctuation



C. Gooding, S. Biermann, S. Erne, J. Louko, W.G. Unruh, J. Schmiedmayer, SW [arXiv:2007.07160 [gr-qc]]

Circular Unruh radiation in 2+1 dimensions

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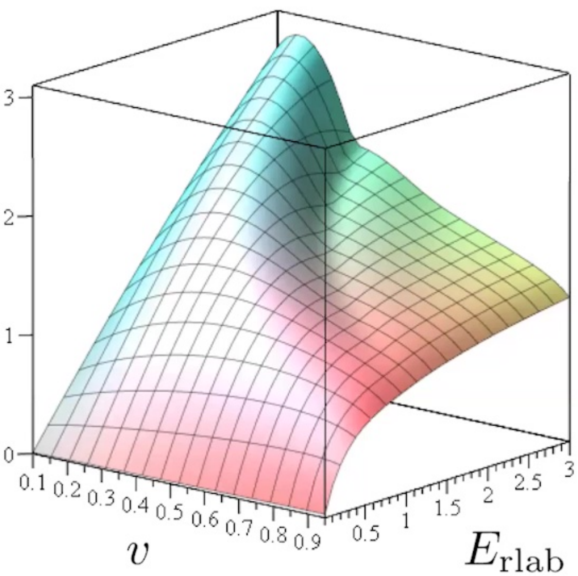
$$T_{\mathrm{rat}} := T_{\mathrm{circ}}/T_{\mathrm{lin}}$$



$$k_B T_{lin} = \frac{\hbar a}{2\pi c}$$

- Circular motion with constant radial acceleration approximately thermal spectrum in 2+1 dimensions and in our system $a_{anlogue} = \frac{v^2}{\sqrt{1-\left(\frac{v}{c}\right)^2} \cdot R}$;

S. Biermann, S. Erne, C. Gooding, J. Louko, J. Schmiedmayer, W.G. Unruh, SW [arXiv:17/07/2020 [gr-qc]]

Mapping: ultra-cold atoms to gravitational system

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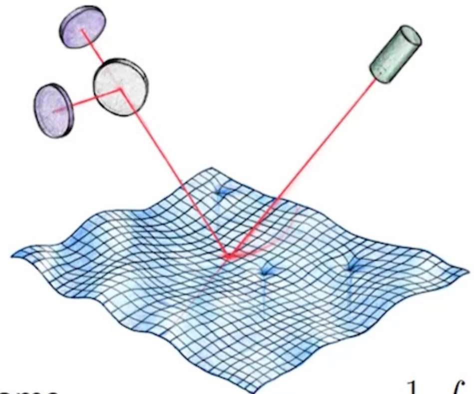
$$\mathcal{L} = \mathcal{L}_{\mathrm{BEC}} + \mathcal{L}_{\mathrm{em}} + \mathcal{L}_{\mathrm{int}}$$



- Laser beam passing through the BEC atoms will react by forming dipoles according to their polarizabilities α.

- If laser is sufficiently detuned from atomic resonance, α real and BEC-light interaction g iven by semiclassical model macroscopic electrodynamics.

$$\mathcal{L}_{\mathrm{int}} \;=\; -\,\alpha\,(\partial_t A)^2\,|\Phi|^2$$

Linearization

$$\begin{aligned} L \;=\; & \frac{1}{2}\int \mathrm{d}z\left(\dot{\psi}^2(t,z) - (\partial_z\psi(t,z))^2\right) \\ & + \frac{1}{2}\int \mathrm{d}\boldsymbol{x}\left(\frac{1}{c_s^2}\dot{\phi}^2(t,\boldsymbol{x}) - (\nabla\phi(t,\boldsymbol{x}))^2\right) \\ & - \varepsilon\int \mathrm{d}\boldsymbol{x}\mathrm{d}z\;\partial_t\psi(t,z)\phi(t,\boldsymbol{x})\delta(\boldsymbol{x}-\boldsymbol{X}(t))\delta(z) \end{aligned}$$

The field theory: a two-dimensional scalar field ϕ(t, x), with x = (x, y), and a one-dimensional 2 probing field ψ(t, z)

Detectability

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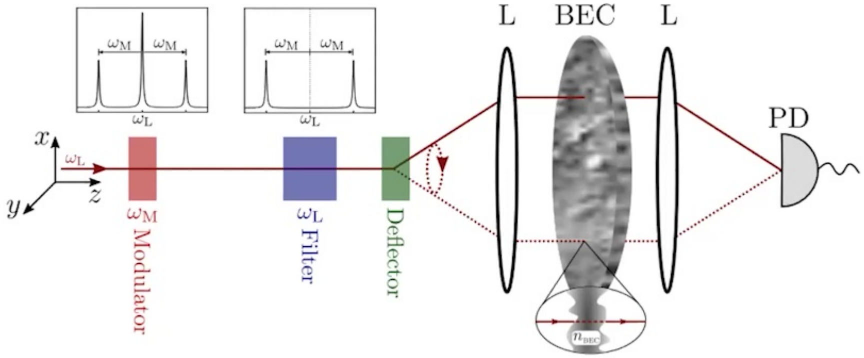

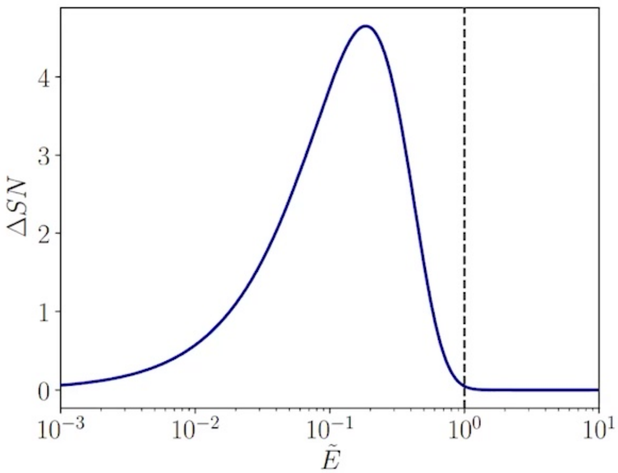

- Detectors response can be extracted from the power spectral density of the phase fluctuations in the laser (unequal time phase-phase correlation functions)
- Signal to noise (shot-noise) calculation for experimentally feasible parameters/setups promising.
- Possibility to test some of the assumptions made to derive the Unruh effect, and beyond...

C. Gooding, S. Biermann, S. Erne, J. Louko, W.G. Unruh, J. Schmiedmayer, SW [arXiv:2007.07160 [gr-qc]]

Black hole ringdown

Analogue gravity simulators of black hole ringdown

Rotating black holes

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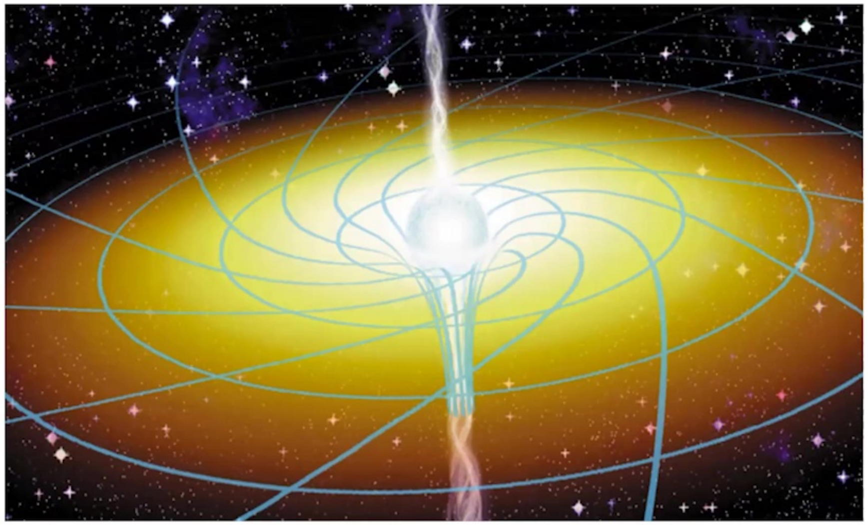

- **Rotating black hole geometries**: apparent/event horizon, ergo-surfaces and light-rings/circular orbits
- Several fundamental physics processes to be explored: Hawking radiation, superradiance, ringdown, ...
- Possibility to explore **quantum effects beyond Hawking radiation**

Rotating black holes

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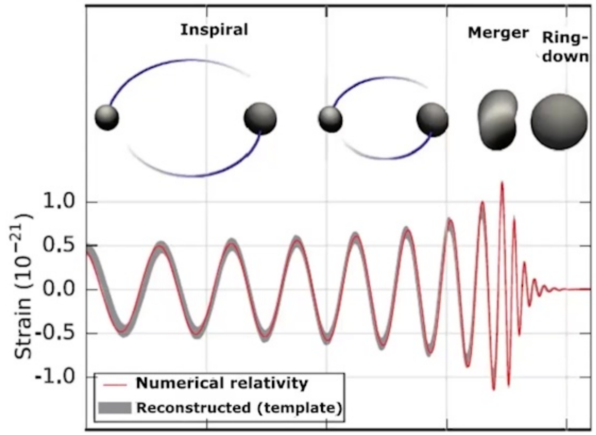

LIGO

- Perturbed black-holes emit characteristic waves, whose frequencies are independent of initial perturbation.
- **Characteristic modes are probes** of the gravitational field surrounding a black hole.
- Contribution of quantum effects to black hole dynamics remains open question.
  Goal is to look for distinctive quantum fingerprints of black hole relaxation process.

Rotating black holes

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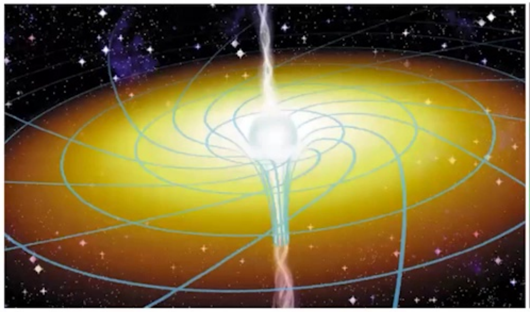

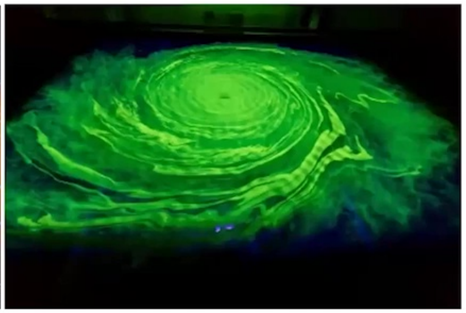

- **Vortex flows exhibit analogue rotating black hole geometries**
  apparent horizons ($v_r^2 = c_{ripples}^2$), ergo-surfaces ($v_\varphi^2 + v_r^2 \geq c_{ripples}^2$)
  and light-rings/circular orbits

- Surface waves (i.e. gravity waves) on shallow water flows: $c^2 = gh$
  Hawking radiation, super-radiance, light-bending, and ring-down

$$g_{\mu\nu} = \left(\frac{h}{g}\right)\begin{pmatrix} -gh + v_\parallel^2\big|_{z=h} & -\vec{v}_\parallel^T\big|_{z=h} \\ -\vec{v}_\parallel\big|_{z=h} & \mathrm{I}_{2\times 2} \end{pmatrix}$$

- Possibility operate simulator in regimes where quantum physics matter

Black hole laboratory

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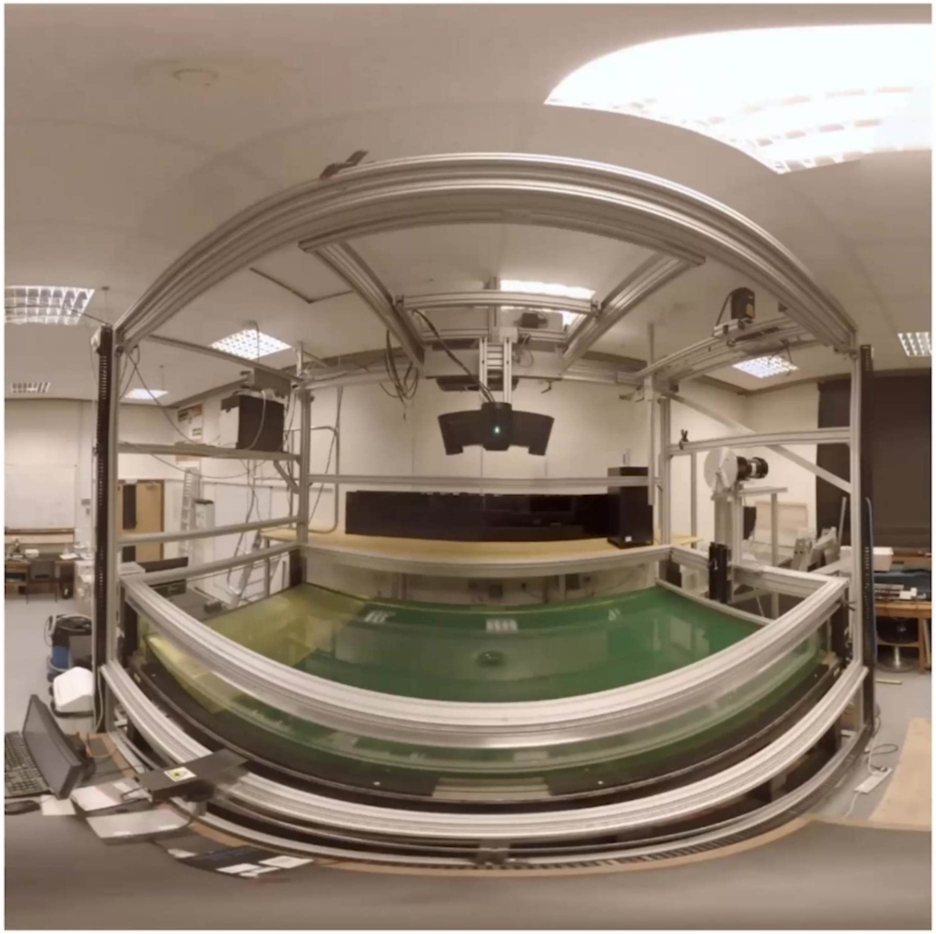

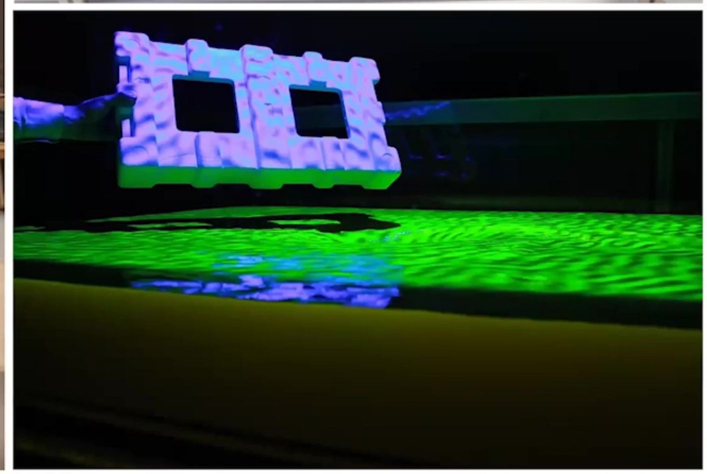

Wave propagation around a hydrodynamic rotating black hole

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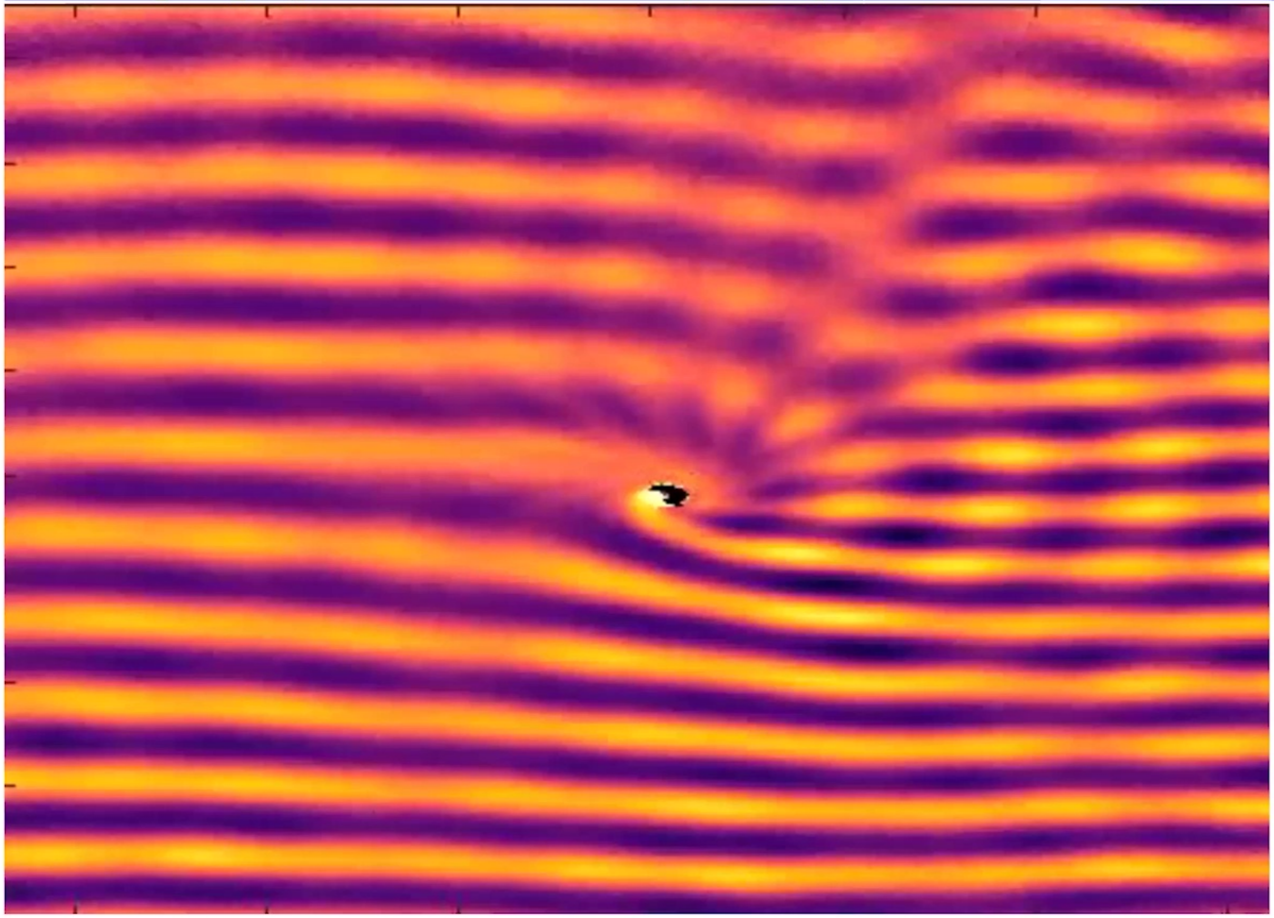

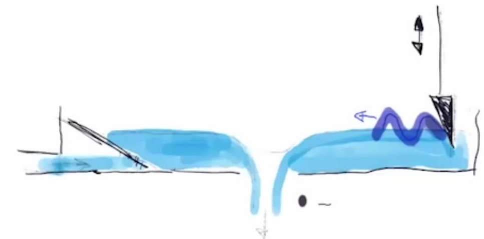

A path on an analogue curved spacetime geometry

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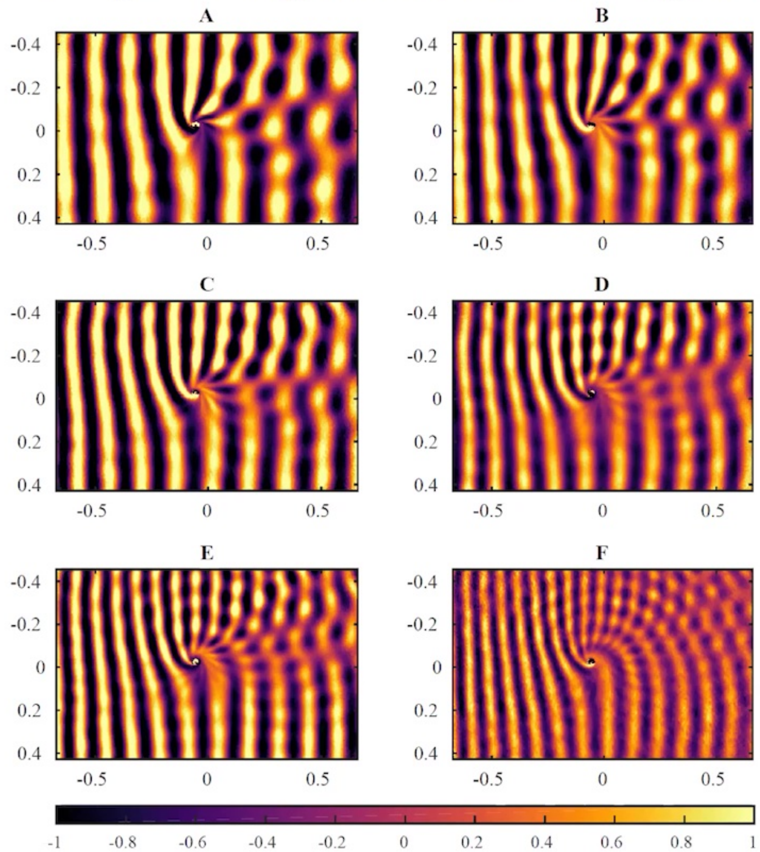
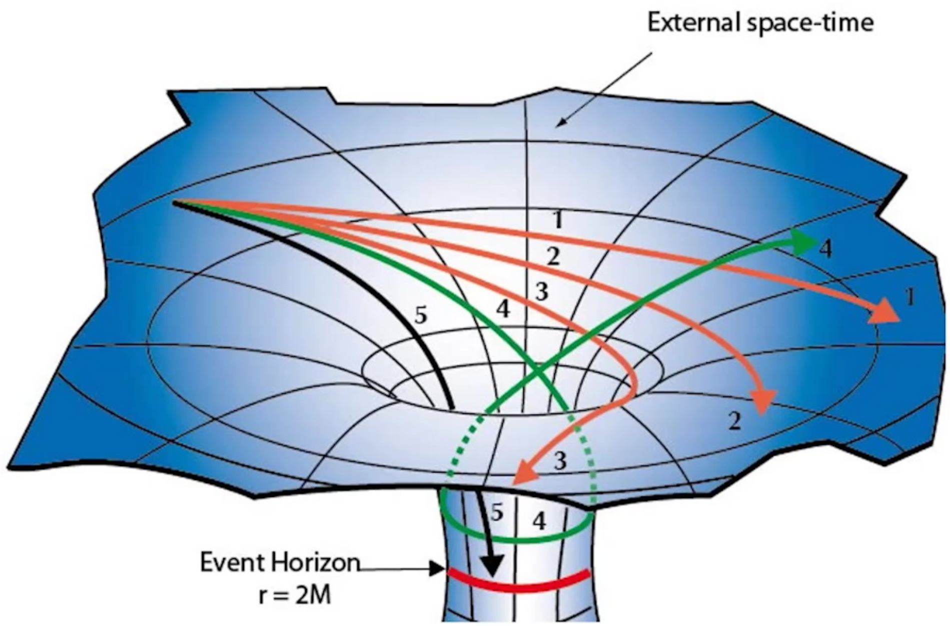
pattern ↔ geodesics (generalisation of a straight line in curved spacetimes)





J. Fluid Mech. 857 (2018) 291-311

Geodesic motion in our system

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$$\mathcal{D}_t^2\phi - i(g\boldsymbol{\nabla} - \gamma\boldsymbol{\nabla}^3)\tanh(-ih_0\boldsymbol{\nabla})\phi + 2\nu\nabla^2\mathcal{D}_t\phi = 0$$

Ray tracing methods:

- gradient expansion valid if the background flow changes over a scale significantly larger than the wavelength;
- Leading order we obtain Hamiltonian for our system
- Hamiltonian equations give characteristics

$$\mathcal{H} = -\frac{1}{2}(\omega - \mathbf{v}\cdot\mathbf{k})^2 + \frac{1}{2}F(\mathbf{k})$$

Quasinormal modes in the analogue gravity system

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Circular orbits

= equilibrium point in radical direction

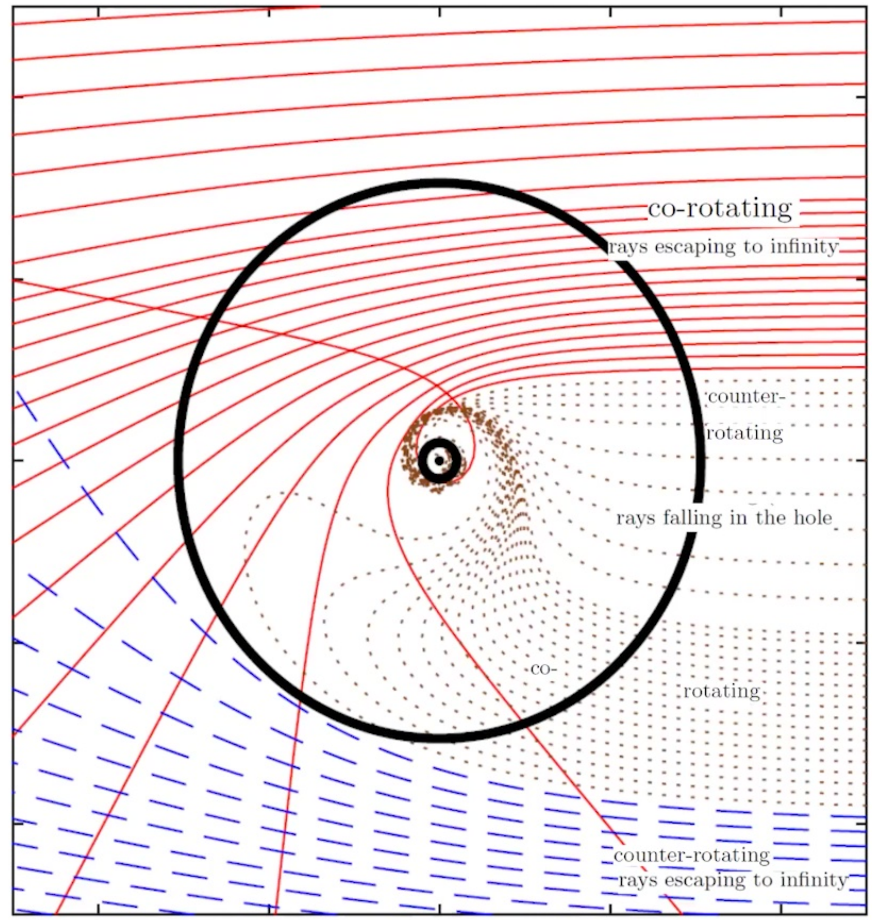
= critical point of Hamiltonian for (r, k_r)

Ringdown modes

Real part → circular orbits

Imaginary part → boundary conductions

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



Wave propagation around a hydrodynamic rotating black hole

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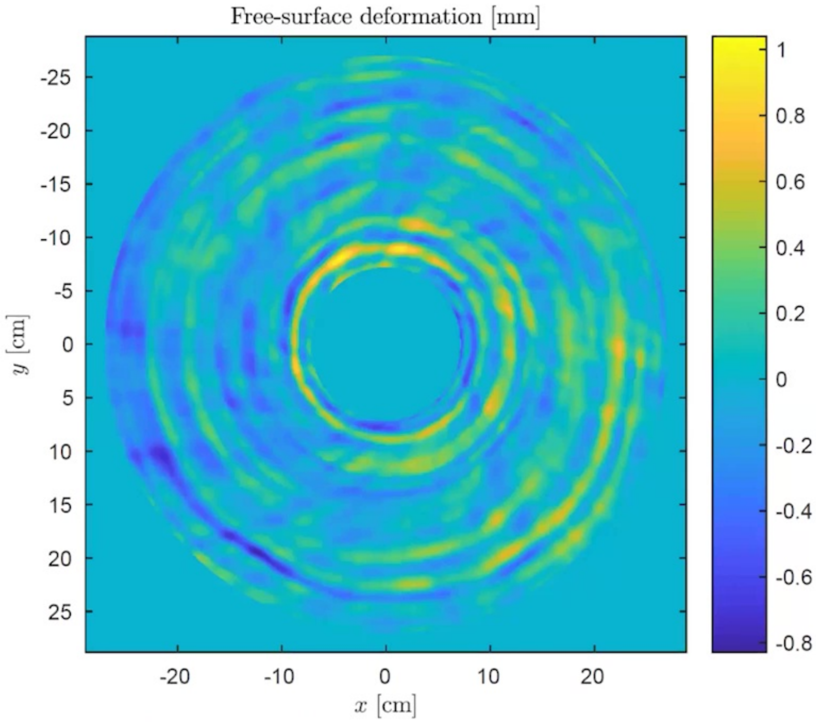

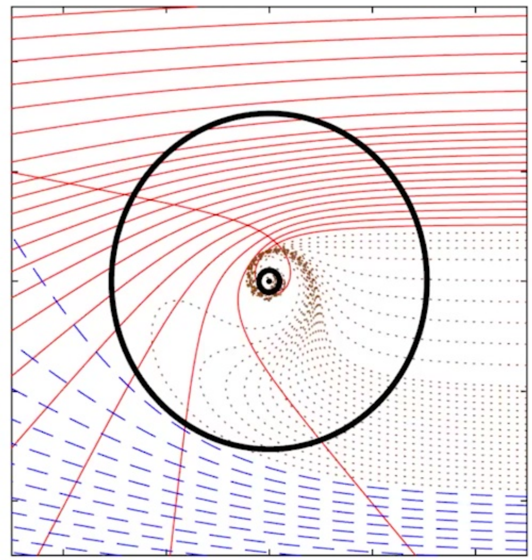

$$\omega_{\mathrm{QNM}}(m) = \omega_{\star}(m) - i\Lambda(m)\left(n + \frac{1}{2}\right)$$

Ringdown modes

Real part → circular orbits

Imaginary part → open boundaries

Wave propagation around a hydrodynamic rotating black hole

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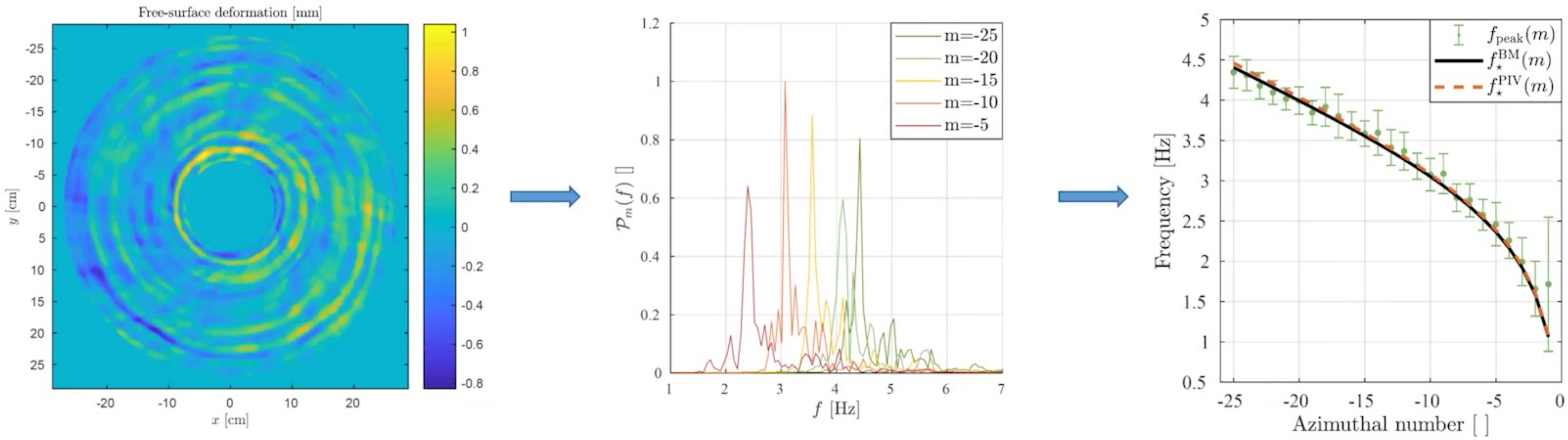

- Light-ring mode calculations extended to higher-spatial derivative field theories agree with experiment; We observer that light-ring modes do not seem to depend on boundary conditions [further tests needed] [Theo Torres, Sam Patrick, Maurício Richartz, Silke Weinfurtner, Phys. Rev. Lett. 125, 011301 (2020)]

- Endpoints of no-equilibrium process, but light-ring modes persistent in non-equilibrium situation [work in progress]

- Effective field theory for improved modelling predicts quasi-bound states [Patrick, Coutant, Richartz, SW, Phys. Rev. Lett. 121, 061101 (2018)]

Pathways to quantum black hole ringdown

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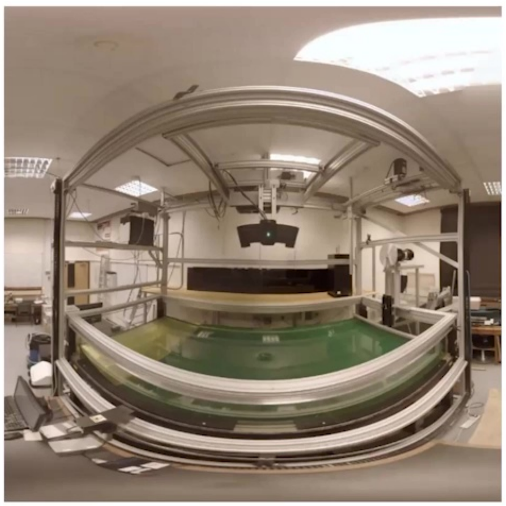
Only assumption: a quantum black hole exhibits quantised angular momentum

Classical angular momentum
Classical surface waves

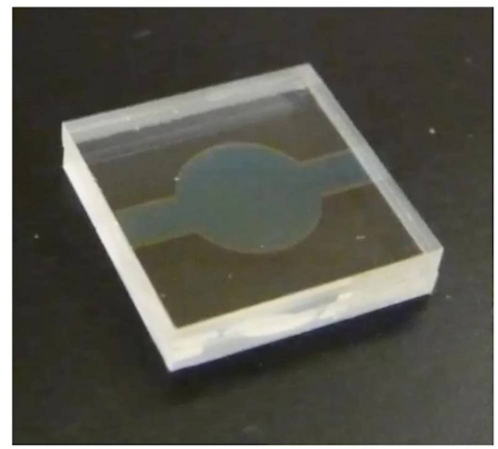


Classical spacetime
Classical relativistic fields

Quantised angular momentum
Classical relativistic ripplons

Quantum spacetime
Classical relativistic fields

Quantised angular momentum
Quantum relativistic ripplons



Quantum spacetime
Quantum relativistic fields

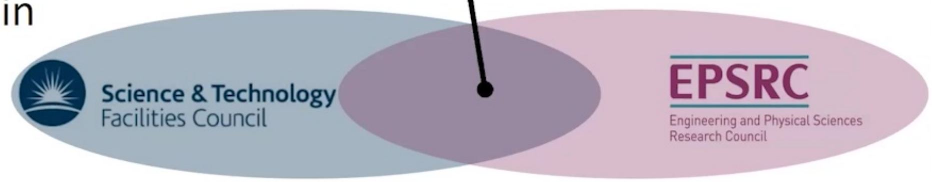
The team

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

QSimFP

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

Gravity simulators
Silke Weinfurtner
(PI, Nottingham)



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

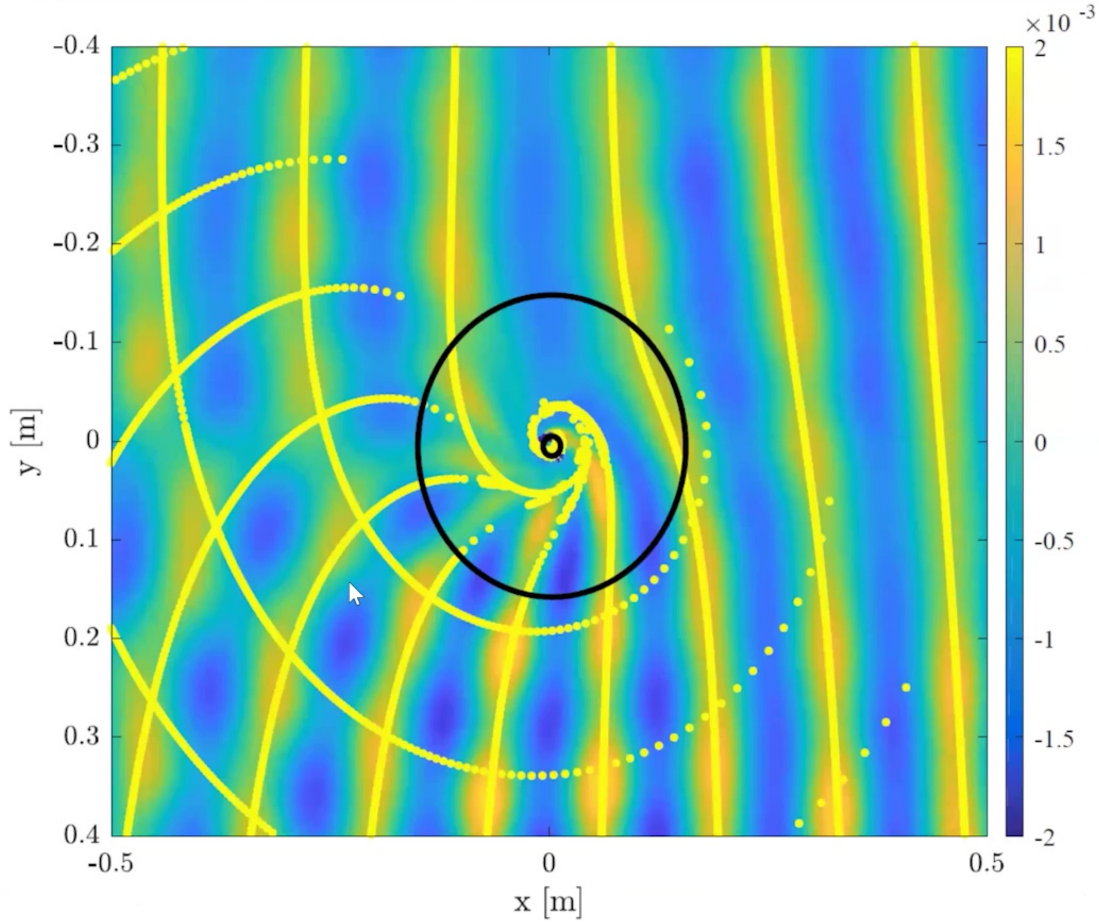
Ultracold atoms
- Thomas Billam
- Zoran Hadzibabic

Superfluids & optomechanics
- Carlo Barenghi
- John Owers-Bradley
- Xavier Rojas
- Pierre Verlot

Quantum circuits
- Gregoire Ithier

Quantum optics
- Friedrich Koenig

Theory versus experiment



Wave propagation around a hydrodynamic rotating black hole

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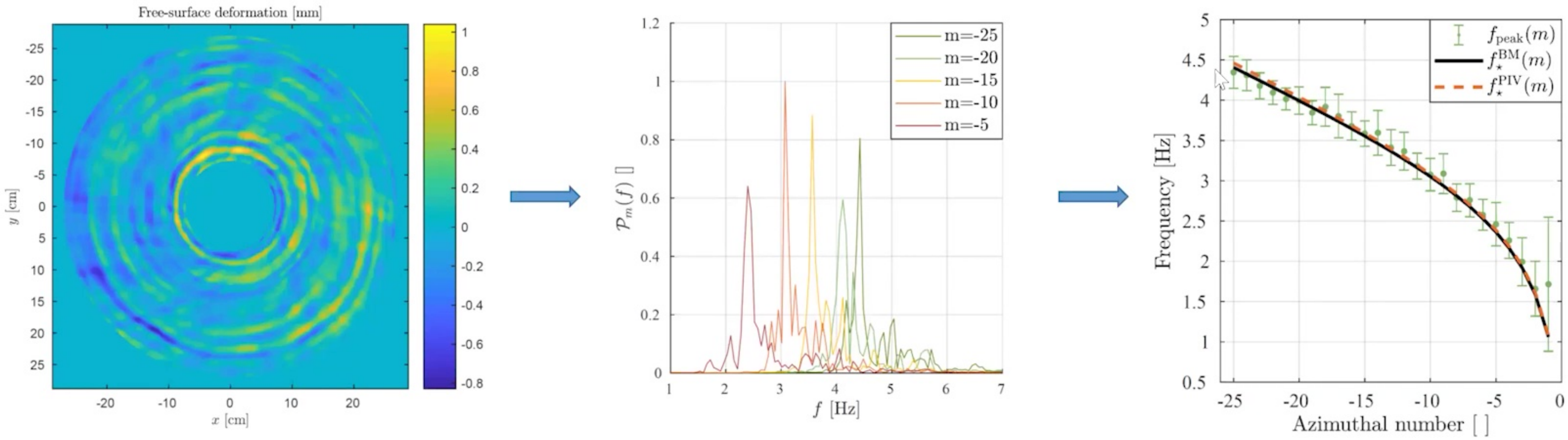

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