# WP5: Quantum Simulators of Fundamental Physics

**Science Goals:** The dynamics of the early universe and black holes are fundamental reflections of the interplay between general relativity and quantum fields. The essential physical processes occur in situations that are difficult to observe and impossible to experiment with: when gravitational interactions are strong, when quantum effects are important, and/or on length scales that stretch far beyond the observable Universe. We propose to study these processes in experiments by employing analogue quantum simulators – systems whose excitations behave like quantum fields in a spacetime background (for example ultra-cold atom systems). Their high degree of tunability, in terms of dynamics, effective geometry, and field theoretical description allows one to emulate a wide range of elusive physical phenomena in a controlled laboratory setting. Studying the dynamics of fields in time-dependent analogue spacetimes will allow us to reproduce in the laboratory some of the most ill-understood processes in our Universe, and make concrete predictions, transferable to cosmology, astrophysics and fundamental physics.

In the very early Universe, it is generally expected that quantum effects play a defining role. For example, within the paradigm of cosmic inflation (a postulated epoch of accelerated expansion), the seeds of large-scale structure in the evolved Universe originate from quantum particle production in a time-dependent spacetime background. Rewinding the clock even further to the Big Bang, the Universe itself must have originated in a strongly quantum regime. Physical scenarios in which quantum mechanical effects are important are the least amenable to direct calculation or computer simulations, and therefore represent a regime where analogue quantum simulators can have the largest scientific impact. We propose to investigate the following processes in a controlled laboratory environment:

A. ***Particle creation in time-dependent spacetimes and cosmic inflation*****:** An effective expansion of the analogue system emulating cosmological inflation will be achieved by changing the propagation speed of excitations, revealing the characteristic features of inflation (e.g., mode freezing, squeezing).

B. ***Black-hole relaxation processes:*** Once black holes are perturbed they relax through the emission of characteristic waves, whose frequency spectrum is independent of the initial perturbation, yielding a "fingerprint" of the black hole. Extending our recent results demonstrating the universality of the black-hole relaxation process to experiments in superfluid Helium and atomic Bose-Einstein condensates (BECs) will allow us to investigate the relaxation of perturbed analogue black hole geometries in the quantum regime.

C. ***False vacuum decay:*** This is a ubiquitous, intrinsically quantum mechanical process that occurs in all theories of particle physics with multiple vacuum states (including the Standard Model of particle physics and most theories beyond it). In cosmology, our observable Universe may have emerged from a bubble nucleation event. We will develop analogue quantum simulators of metastable vacuum state decay via the formation of bubbles which subsequently expand, and use the experimental observations to develop an explicitly time-dependent description of this fundamental process, which does not yet exist.

D. ***Detectors:*** General relativity prevents the unique definition of a vacuum state; consequently, a detector with a constant acceleration through flat space is predicted to observe a thermal bath of

> particles known as Unruh radiation. Within our analogue experiments for spacetime geometries, we will develop the equivalent of detectors in accelerated motion to observe this effect which has strong implications for the early Universe and black hole horizons.

As a consequence, we will establish analogue quantum simulations of cosmological and general relativistic phenomena on a robust foundation.

**Deliverables:**

***Experimental effort.*** We anticipate the following outcomes:

- In Years 1-2 we will create a successful implementation of the characteristic features of inflation (mode freezing, squeezing; **science goal A**) and black hole relaxation processes in quantum simulations **(science goal B)** employing superfluid Helium. The main effort will be to design and set up suitable detection methods/sensors to detect the excitations on a liquid helium-helium vapor interface.
- In Years 1-2 we will initiate a series of ultra-cold atom experiments, with the main focus on false vacuum decay **(science goal C)** and Unruh radiation **(science goal D)**, with the experimental implementation commencing in Years 3-6.

***Theoretical effort.*** We will focus on the emergence and stability of effective field theories in and out of equilibrium in the context of relativistic field theory simulators including:

- creation of effective field theory descriptions of our experiments that are robust in the complex scenarios required, which involve e.g. time-dependent backgrounds and unequal-time (or out-of-time-order) correlations **(all science goals)**;
- simulations of quantum vortex flows from pure superfluids (i.e. BECs) to normal-superfluid mixtures (i.e. superfluid Helium) to study the black hole relaxation process in quantum systems **(science goal B)**;
- simulations of different experimental proposals for quantum false vacuum decay in cold atom systems **(science goal C).** We will determine the extent to which the analogy applies and thus the concrete aspects of physics it is able to probe; and deliver at least one feasible experimental proposal, opening a pathway for its construction;
- development of a feasible experimental implementation for detecting Unruh radiation **(science goal D)** by studying the role of the internal structure and couplings to accelerated observers in cold atom systems.

**Plan and distribution of work:**

***Years 1-2:*** We will begin by hosting a workshop to initiate a series of detailed discussions between experimentalists and theoreticians on the science goals A-D. We will identify a promising set of experimental designs that both capture the relevant physics and could potentially be realized in the laboratory. We will then perform detailed simulations of the proposed experiments in order to verify that they are indeed promising analogue quantum simulators, and to provide a baseline for experimental parameters. The theoretical and simulation work will be carried out with significant connections and feedback from experimentalists, and in collaboration with theoretical and experimental colleagues in Canada and Austria. In parallel we will carry out the superfluid Helium experiments relating to science goals A and B.

***Years 3-6*:** The team will implement any new experimental infrastructure required to undertake the most promising implementations identified in the simulation work from Years 1-2, with a focus on science goals C and D. We plan a second workshop in year 3 to reconnect and coordinate all aspects of the programme and identify the most promising experimental paths on which to focus. Building on the experimental outcomes and insights gained from Years 1-2 studies in superfluid Helium, we will prepare an implementation of science goals A and B in ultra-cold atom experiments, allowing a further reduction of classical thermal noise in the systems. In parallel we will carry out theoretical interpretation and implications for fundamental physics through quantitative comparison to simulations.

**Existing internal infrastructure:** We have an experimental setup for *immiscible diamagnetic quantum 2-fluid systems* available in **Nottingham (Silke Weinfurtner, Richard Hill, John Owers-Bradley)** for use in **Years 1-2** for **science goals A-B**. This employs liquid $^4$He, which undergoes a transition at ~2.2K, where it behaves as a normal fluid and a superfluid. In terms of promising experimental setups for **Years 3-6**, we have established significant connections with experimentalists within the U.K. and Austria covering a rich range of analogue simulators, including: **Lucia Hackemueller, Nottingham (**fermionic Lithium-6 atoms mixture in elongated single or double well potentials); **Zoran Hadzibabic, Cambridge** (Two-component Bose gas, consisting of Rubidium-87 atoms in two different spin states in an optical ring trap and/or potassium atoms trapped in an optical box-trap); **Joerg Schmiedmayer, Vienna** (Bosonic Rubidium-87 in quasi one-dimensional single or double well potentials); **Daniele Faccio, Glasgow** (room temperature photon fluids, also referred to as quantum fluids of light).

All the above systems show a high degree of tunability of the emergent effective relativistic field theory (e.g. using Feshbach resonances, multi-component fluids, or highly tunable trapping potentials), and can be further developed into simulator capable of achieving our objectives.

Simulation work taking place at **UCL** and **Nottingham** are supported by substantial local HPC resources, as well as UCL's institutional HPC facility *Grace*.

**Team and experience:** The WP brings together world-leading researchers in the fields of analogue gravity, cosmology, ultra-cold atoms, superfluid Helium, and magnet physics, many of whom have already established successful collaborations. This combined expertise will allow us to develop a comprehensive understanding of the theory and experimental implementation of analogue relativistic field theory simulators.

- **Silke Weinfurtner, Bill Unruh, Friedrich Koenig** and **Daniele Faccio** are experts in the field of analogue gravity. BU discovered Unruh radiation and the potential of analogue gravity systems and, together with SW was the first to detect Hawking radiation in an analogue gravity system. SW's group was the first to detect superradiance and light-ring modes from an analogue rotating black hole. DF and FK carried out several analogue gravity experiments in optical systems, e.g. Hawking-like radiation (DF, FK), setting up rotating black holes in fluids of light (DF), and the dynamical Casimir effect in meta-materials (DF).
- **Hiranya Peiris, Andrew Pontzen, Matthew Johnson, Jonathan Braden, Ian Moss, Ruth Gregory, Anastasios Avgoustidis, Jorma Louko, Xavier Calmet** and **Ed Copeland** are experts in the fields of cosmology and non-equilibrium quantum field theory and simulations. HP, AP, MJ, JB, and SW have investigated potential analogue quantum simulators of false vacuum decay, in particular coupled multi-species BECs. Through detailed analytical calculations and

sophisticated computer simulations they developed a comprehensive understanding of what is required of an analogue system proposed by Fialkov et al in order to faithfully reproduce the physics of interest. This has paved the way for new experimental designs that could successfully realize an analogue quantum simulator of false vacuum decay. IM and RG have an extensive theoretical programme in laboratory false vacuum decay.

- **Simon Cornish, Sebastian Erne, Thomas Fernholz, Lucia Hackermueller, Zoran Hadzibabic,** and **Joerg Schmiedmayer** are experts in non-equilibrium quantum many-body dynamics. SE has expertise in non-equilibrium quantum field theory and simulations with strong links to cold atom experiments; ZH has a long track record in studying non-equilibrium many-body dynamics yielding interdisciplinary connections between fields. JS has pioneered the experimental investigation of non-equilibrium quantum many-body dynamics and their effective field theory descriptions.
- **John Owers-Bradley** and **Carlo Barenghi** are experts in the field of superfluid Helium.
- **Richard Hill** is an expert in the field of diamagnetic levitation and interdisciplinary science using strong magnetic fields. With AA, SE, and SW, RH has investigated the possibility of mimicking cosmic inflation in 2-fluid systems.

**Approximate Budget:**

| | **Years 1–2** | **Year 3** | **Years 4–6** |
|---|---|---|---|
| **Theory** | £453K | £191K | £634K |
| **Experiment** | £710K | £348K | £1,640K |
| **Total** | £1,163K | £539K | £2,274K |

The estimates above include (a) postdocs (b) PhD students (c) travel for postdocs, students and collaborators (d) laboratory and computing facilities (e) workshops (f) fEC, estates and indirect costs.

**International Context and Pathways to Leadership:** The strong international interest in this area is evidenced by the fact that the funded US QIS programme contained awards investigating quantum analogues of fundamental physics, including the necessary experimental and theoretical work. (https://science.energy.gov/~/media/78921BDAD1894BBF9A686A2125C3B3C0.ashx). This is an area where theoretical development and input is essential for claiming that evidence of fundamental physics processes have been detected in the laboratory. We combine a range of interdisciplinary expertise that does not exist in other efforts to develop analogue quantum simulators of fundamental physics. The theorists involved possess a detailed understanding of both cosmology and ultra-cold atomic physics. Some team members combine experience both in theory and laboratory experiments, bridging the gap with experimentalists who are experts in exploring fundamental physics with cold atom systems.

**Coordination and Governance:** WP5 QSimFP is coordinated by **Silke Weinfurtner** (Nottingham). Within the WP, Weinfurtner coordinates the experimental effort, while **Hiranya Peiris** and **Andrew Pontzen** (UCL) coordinate the theoretical/simulations effort.