Title: Quantum Simulators of Fundamental Physics overview

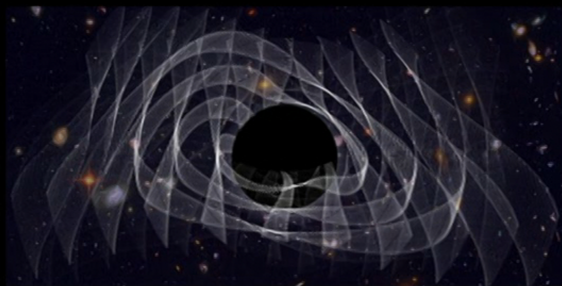
Speakers:

Collection: Quantum Simulators of Fundamental Physics

Date: June 05, 2023 - 9:15 AM

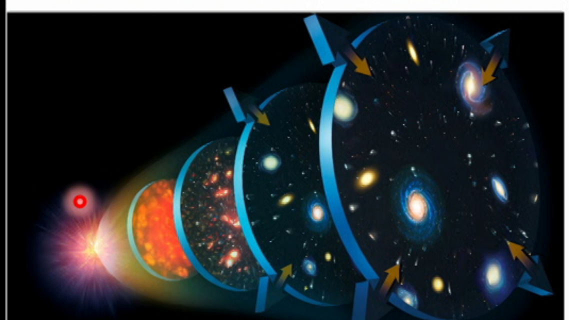
URL: https://pirsa.org/23060001

Abstract: ZOOM: https://pitp.zoom.us/j/95722860808?pwd=REYwSDdiK3pFamRJcjJwOW5FV1RPZz09



UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

Quantum Technology / Simulators for Fundamental Physics



Silke Weinfurtner
The University of Nottingham

Quantum Sciences – Opportunities

Emerging QT to revolutionise life: computing, cryptography, imaging, measurement, sensors and simulations

Quantum Sciences – Opportunities

Emerging QT to revolutionise life: computing, cryptography, imaging, measurement, sensors and simulations

- **UK National Quantum Strategy (2023)**
  - Doubling investment (£1B + £2.5B)
  - 10-year vision plan:
    - Growing knowledge & skills
    - Attract companies & investors
    - Adoption and Use of QT
    - Develop regulatory framework
  - **Investment in QT for Fundamental Physics**
    - Quantum a tool for wider research
    - International partnerships
    - Secure development and employment

Quantum Technology for Fundamental Physics

About QTFP

- £40 million programme to **transform our approach** to understanding the universe and its evolution.

- **QTFP to demonstrate** how quantum technologies could solve some of the greatest mysteries in fundamental physics, e.g.
  - search for dark matter
  - nature of gravity
  - ...

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  - search for dark matter
  - nature of gravity
  - ...

Quantum-enhanced Interferometry for new physics
Principal investigator: Hartmut Grote

A network of clocks for measuring the stability of fundamental constants
Principal investigator: Giovanni Barontoni

Determination of absolute neutrino mass using quantum technologies
Principal investigator: Ruben Saaykan

Quantum sensors for the hidden sector
Principal investigator: Ed Daw

A UK atom interferometer observatory and network
Principal investigator: Oliver Buchmuller

Quantum enhanced superfluid technologies for dark matter and cosmology
Principal investigator: Andrew Casey

Quantum simulators for fundamental physics
Principal investigator: Silke Weinfurtner

QSimFP

Quantum Simulators
for Fundamental Physics

QSimFP | Quantum Simulators for Fundamental Physics

Scientific Goals

Quantum Simulations of Black Hole and Early Universe Processes

Community

50-50 QT-FP researchers

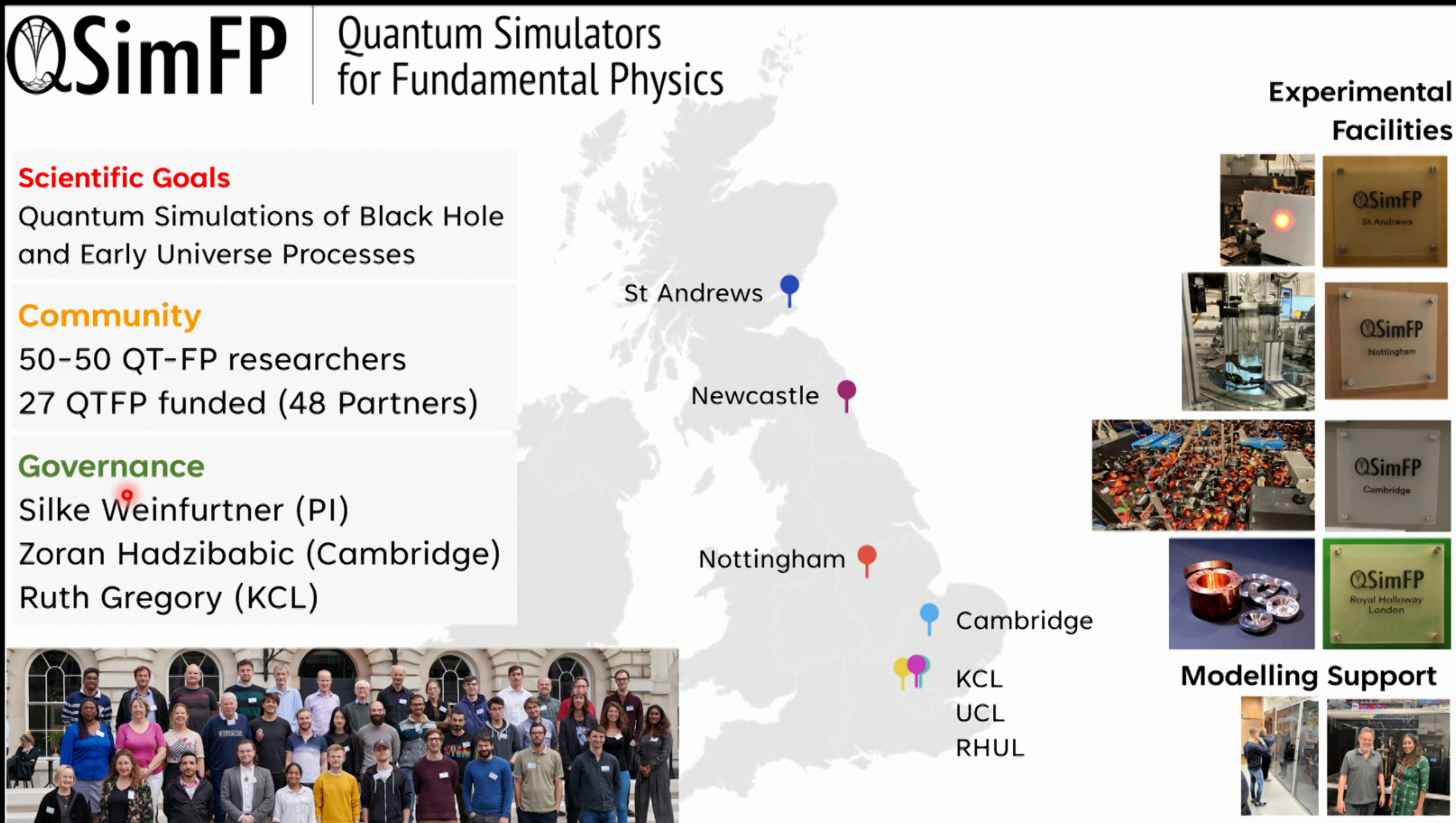
27 QTFP funded (48 Partners)

Governance

Silke Weinfurtner (PI)

Zoran Hadzibabic (Cambridge)

Ruth Gregory (KCL)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Experimental
Facilities
QSimFP
St Andrews
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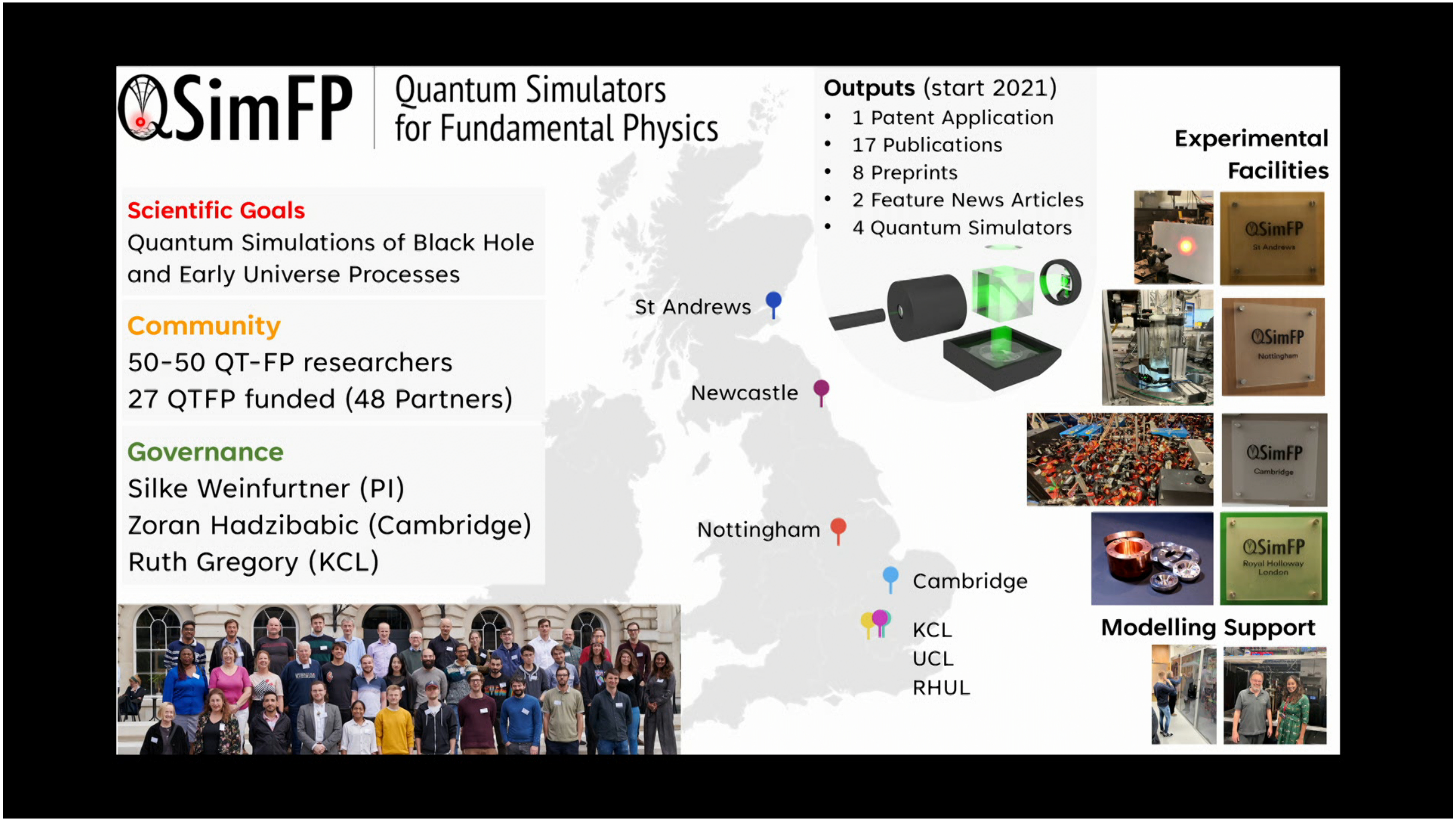
QSimFP
Cambridge
QSimFP
Royal Holloway
London
Modelling Support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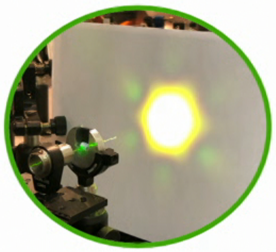
St Andrews
Newcastle
Nottingham
Cambridge
KCL
UCL
RHUL
Outputs (start 2021)
• 1 Patent Application
• 17 Publications
• 8 Preprints
• 2 Feature News Articles
• 4 Quantum Simulators
Experimental
Facilities
QSimFP
St Andrews
QSimFP
Nottingham
QSimFP
Cambridge
QSimFP
Royal Holloway
London
Modelling Support


Experimental Facilities
QSimFP St. Andrews
QSimFP
St Andrews
QSimFP
Nottingham
QSimFP Nottingham
QSimFP Cambridge
QSimFP
Cambridge
QSimFP Royal Holloway
QSimFP
Royal Holloway
London
TU WIEN
TECHNISCHE
UNIVERSITÄT
WIEN
Vienna University of Technology

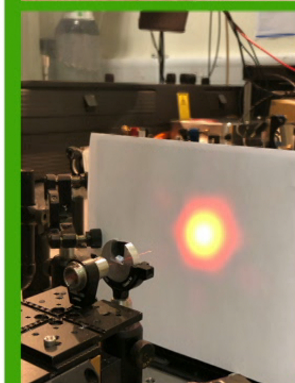
QSimFP St Andrews – Friedrich Koenig



Enabling Technology
- Fibre-optical solitons
- Optical black hole simulator
- Quantum Detectors

Status
- Detectors completed

Quantum fluctuations of light
- MHz frequency range
- Filters out other noises
- 91% quantum efficiency
- Saturation power >20mW
- Single 5V supply



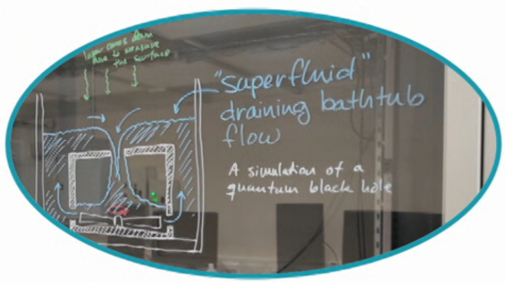
QSimFP Nottingham – Silke Weinfurtner

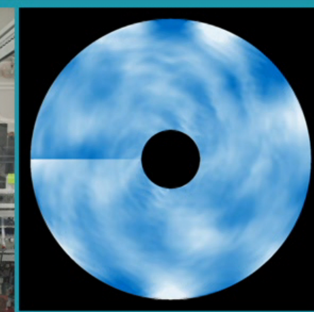
Enabling Technology

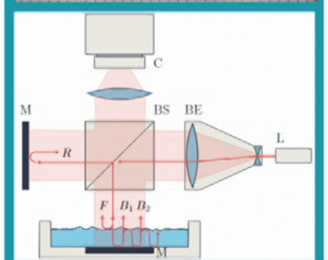
- Ultracold-systems technology
- Flow shaping techniques
- Holographic sensors

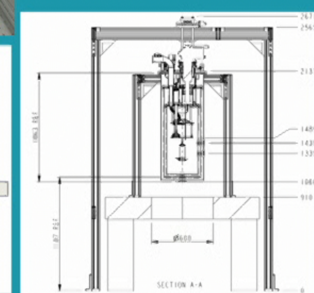
Status

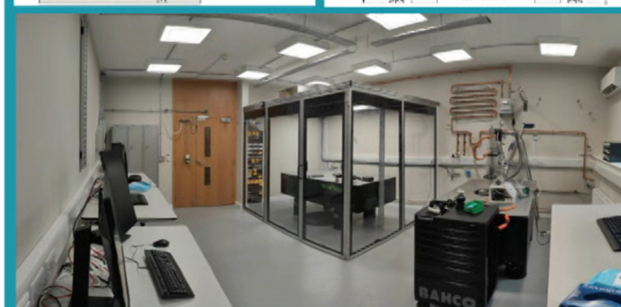
- Superfluid vortex flow
- Irrotational vortex flow May
- Interface detection methods implemented
- Patent application for off-axis holography
- Study of wave-vortex interaction



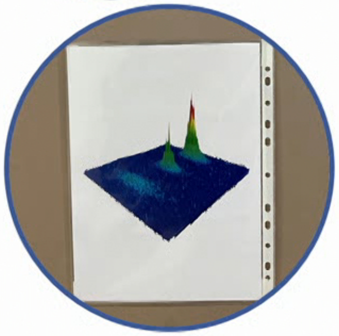








QSimFP Cambridge – Zoran Hadzibabic

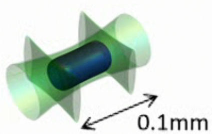


Enabling Technology

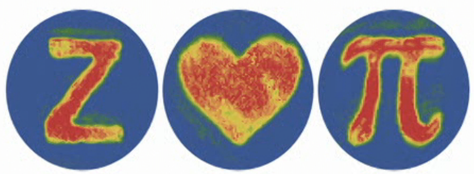
- Ultracold-atoms technology
- Quantum gases in optical box traps
- Holographic light shaping

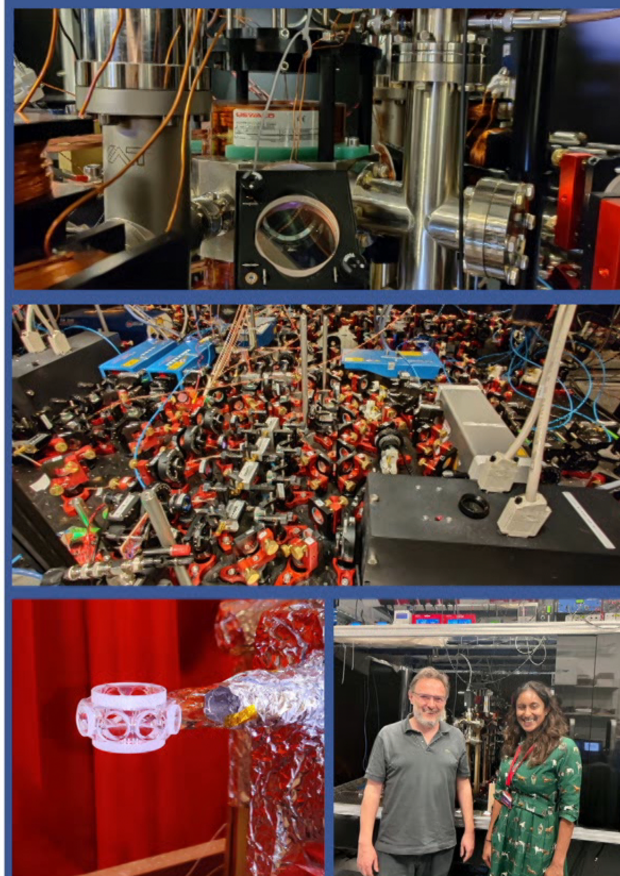
Status

- First BEC achieved on Dec 2022
- Preparation of transport to box trap



Optical box





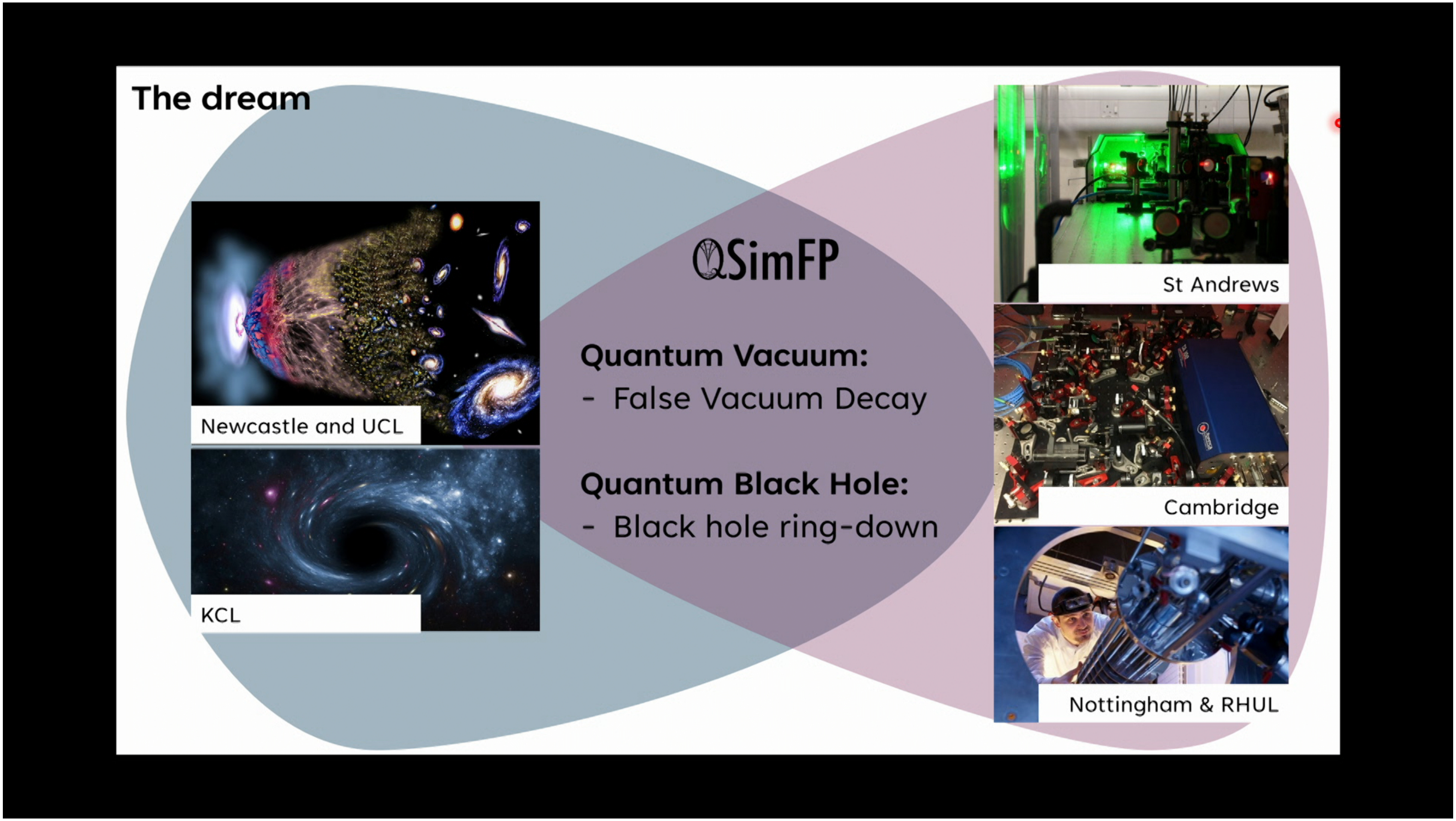
QSimFP RHUL – Xavier Rojas

Enabling Technology

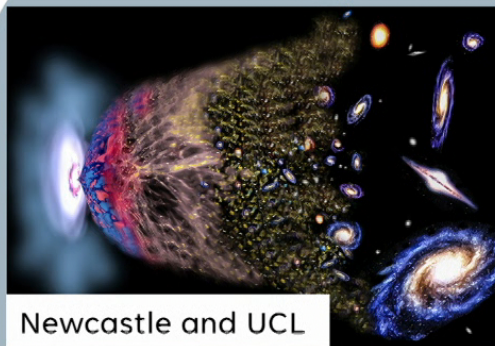
- State-of-the-art nanotechnology facilities
- Nanofluidic devices
- Superconducting microwave micro-structures

Status

- Cryogenic platform up and running
- Design, informed by numerical simulation, of microwave re-entrant cavities coupled to thin superfluid helium films.
- Design of superfluid leak-tight microwave feedthrough couplers.
- Fabrication of a microwave re-entrant cavities using ultra high precision machining


The dream
QSimFP
Quantum Vacuum:
- False Vacuum Decay
Quantum Black Hole:
- Black hole ring-down
Newcastle and UCL
KCL
St Andrews
Cambridge
Nottingham & RHUL

Wonderful modelling support


Newcastle and UCL


KCL

QSimFP

Quantum Vacuum:
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Quantum Black Hole:
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KCL
- Ruth Gregory
- Sam Patrick

UCL
- Hiranya Peiris
- Andrew Pontzen
- Alex Jenkins

Newcastle
- Carlo Barenghi
- Ian Moss

Nottingham
- Jorma Louko
- Cisco Gooding

RHUL
- Gregoire Ithier

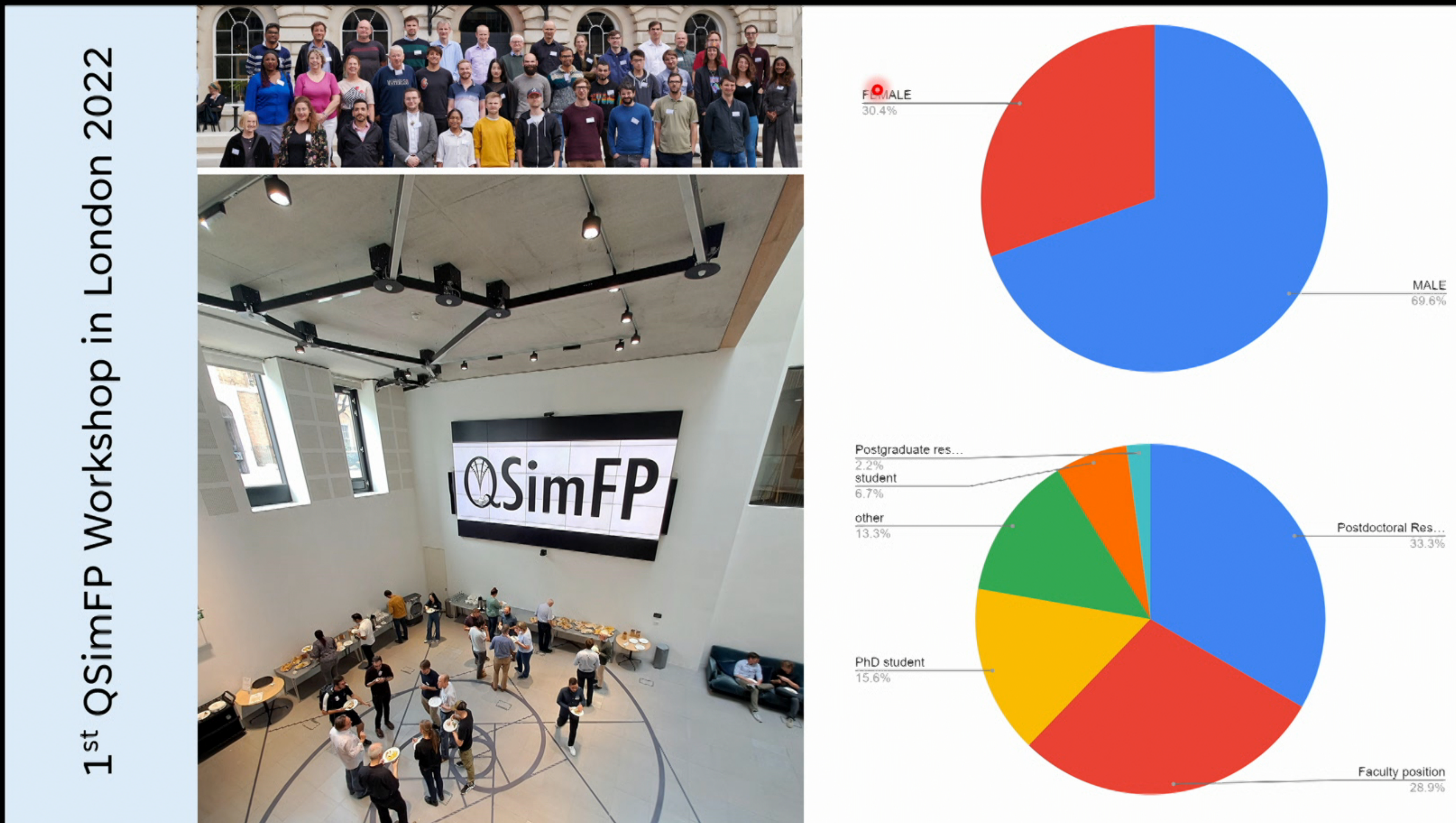
PI/CITA
- Matt Johnson
- Jonathan Braden

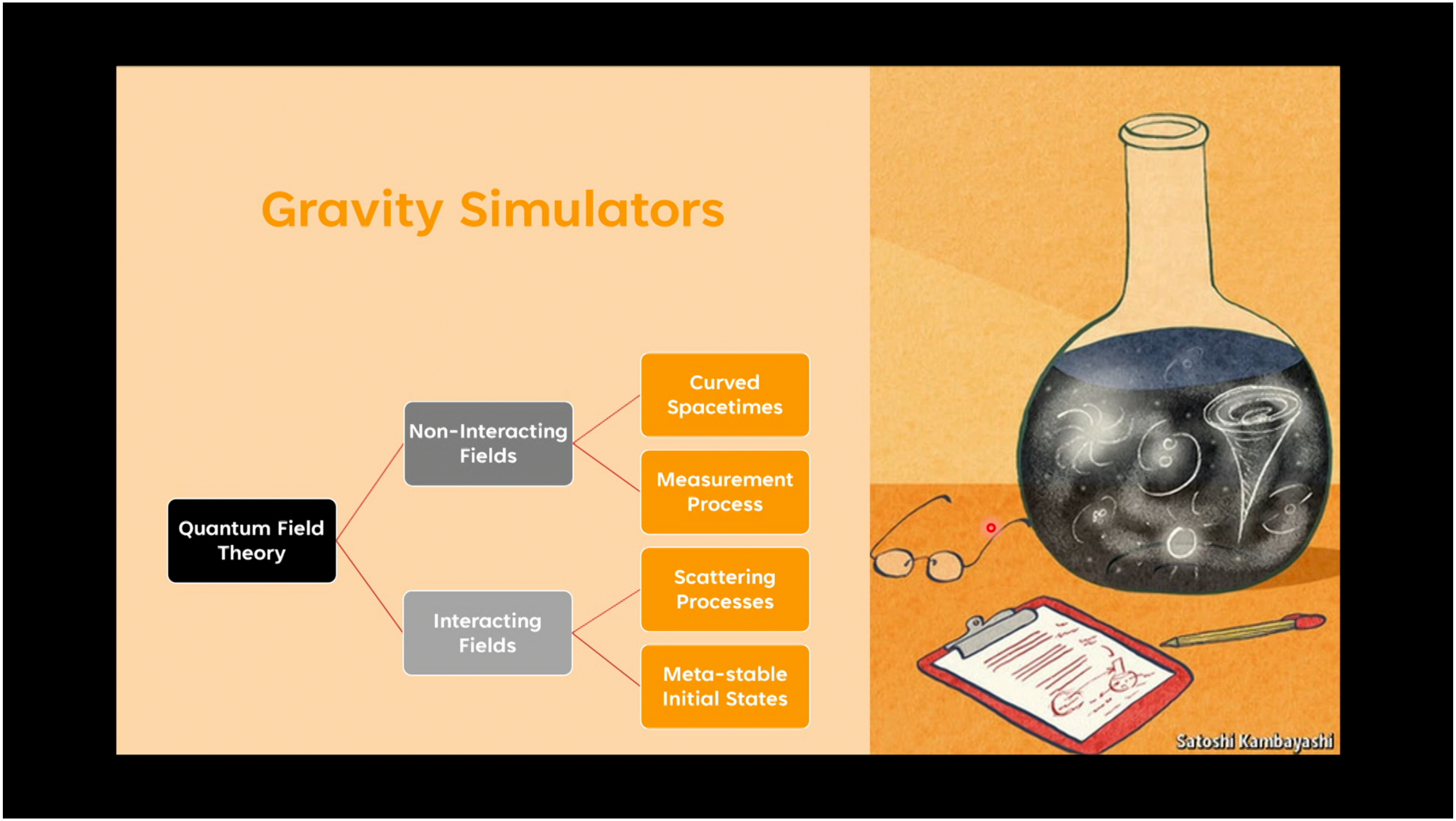
UBC
- Bill Unruh

Dresden
- Ralf Schuetzhold

Impact

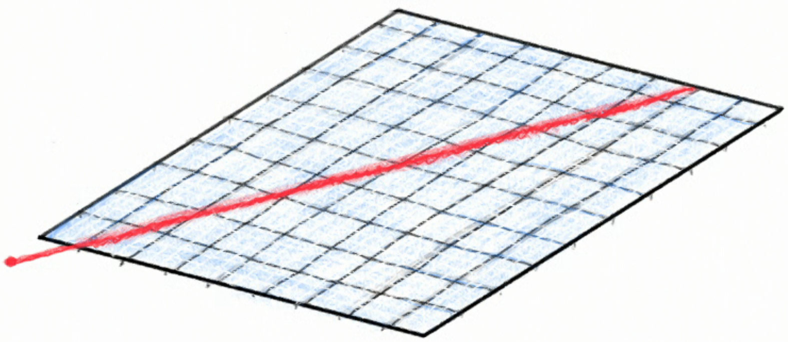
Research Organisations	Journal	Num.
Newcastle + Trento (Italy)	arXiv:2305.05225	(1)
St. Andrews + Nottingham	Theosophical Transaction of Royal Society	1
Newcastle FVD Collaboration	Phys. Rev. A 102, 043324 – 22 Oct 2020 Phys. Rev. A 104, 053309 – 9 Nov 2021 Phys. Rev. A 105, L041301 – 11 Apr 2022 Phys. Rev. D 107, 076027 - 28 April 2023 arXiv:2303.01119	4 (1)
Newcastle + UCL	arXiv:2304.11638	(1)
Newcastle QBH Collaboration	arXiv:2211.09589 – Accepted for publication in J. of Low Temperature Physics	1
Newcastle + Nottingham	Phys. Rev. Research 4, 023099 - 6 May 2022 Phys. Rev. Research 4, 033117 –11 Aug 2022 Phys. Rev. Research 4, 043104 – 14 Nov 2022	3
Nottingham + Sheffield	Phys. Rev. Research 4, 033210 –19 Sep 2022	1
Nottingham	Nature 611, 238-239 – 09 Nov 2022 Patent Application 22-0004 / BB Ref. DJC131594P.GBA arXiv:2305.00226, arXiv:2303.12690	1 (3)
Nottingham + Austria	arXiv:2207.02199 - Under Review in Nature Physics	(1)
Nottingham + RHUL	arXiv:2302.12023 – Under Review in Phys. Rev. Lett.	(1)
Cambridge Collaboration	Phys. Rev. Lett. 129, 190402 – 4 Nov 2022	1
RHUL Collaboration	Applied Phys 133, 094501 - Published 1 March 2023	1
UCL + Nottingham + Canada	Phys. Rev. D 107 (2023) 8, 083509	1
KCL + Nottingham	Phys. Rev. D 106, 045026 – 29 Aug 2022	1
Canada Collaboration	Phys. Rev. D 105, 043510 – 8 Feb 2022	1

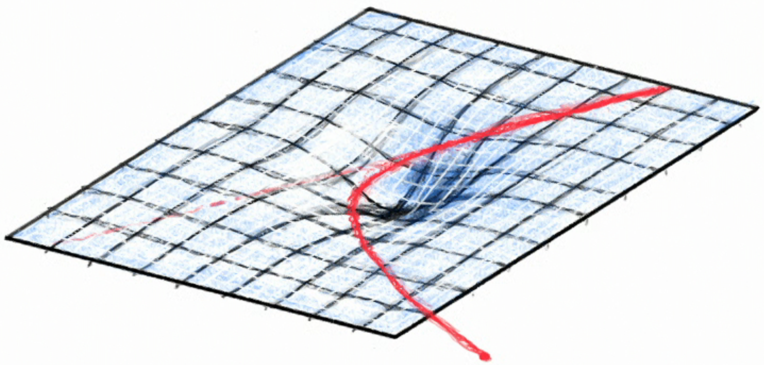

1st QSimFP Workshop in London 2022
QSimFP
FEMALE
30.4%
MALE
69.6%
Postgraduate res…
2.2%
student
6.7%
other
13.3%
PhD student
15.6%
Postdoctoral Res…
33.3%
Faculty position
28.9%


Gravity Simulators
Quantum Field Theory
Non-Interacting Fields
Interacting Fields
Curved Spacetimes
Measurement Process
Scattering Processes
Meta-stable Initial States
Satoshi Kambayashi

Non-interacting Field Dynamics on curved spacetimes (simplified)

$$\frac{1}{c^2}\frac{\partial^2}{\partial t^2}\psi = \nabla^2\psi$$



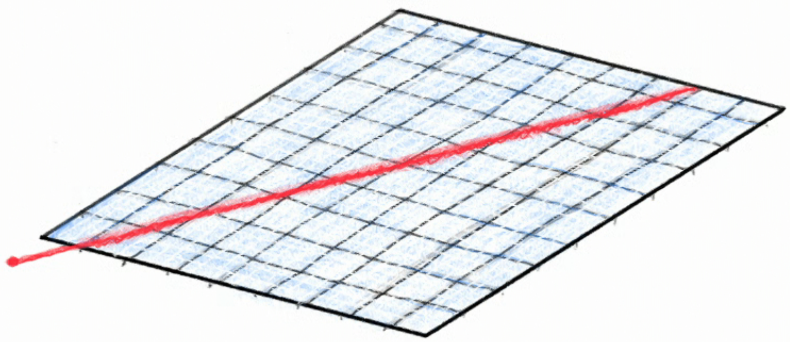


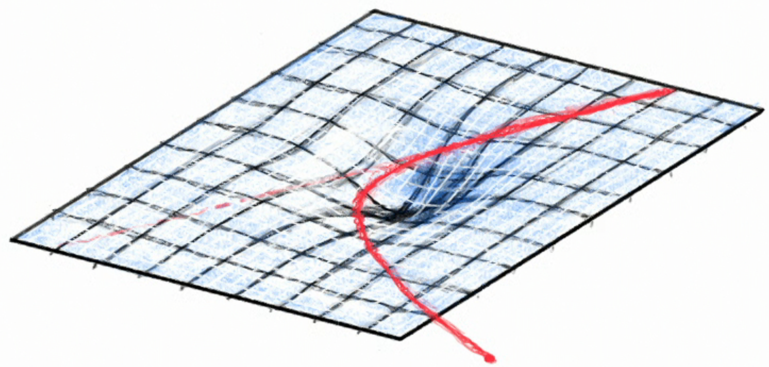
Non-interacting Field Dynamics on curved spacetimes (simplified)

- Wave propagation on **flat spacetime**

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

equivalent to $\dfrac{1}{c^2} \dfrac{\partial^2}{\partial t^2} \psi = \nabla^2 \psi$





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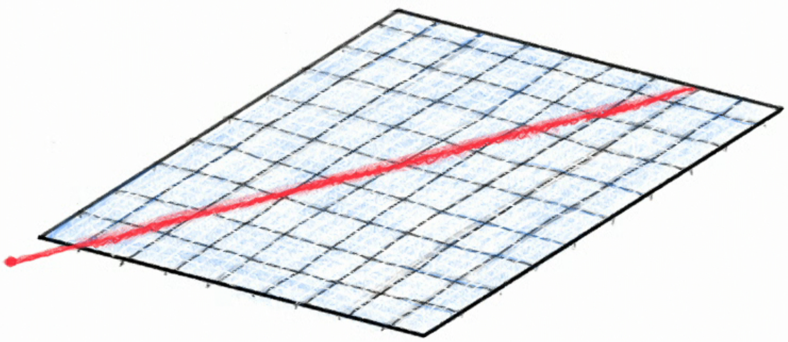
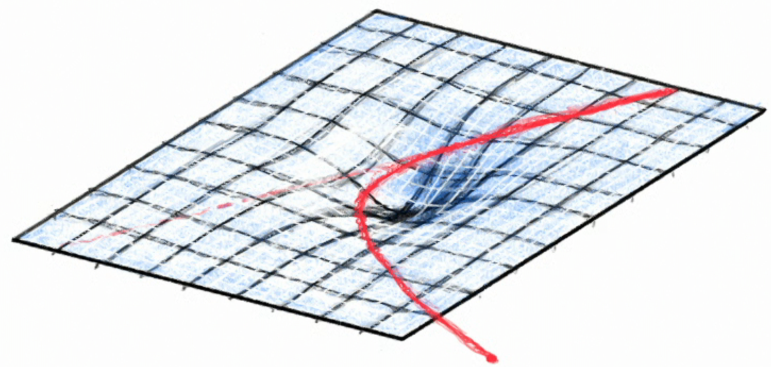
- Wave propagation on **curved spacetime**

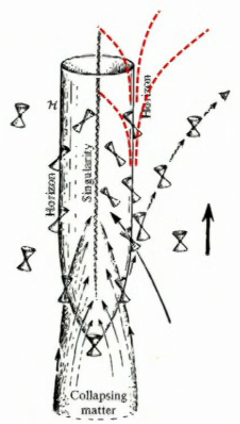
$$\partial_a \left(\sqrt{-g}\, g^{ab} \partial_b \, \psi\right) = 0$$





Classical and Quantum Field Theory on curved spacetimes matters

Black Holes
Hawking radiation



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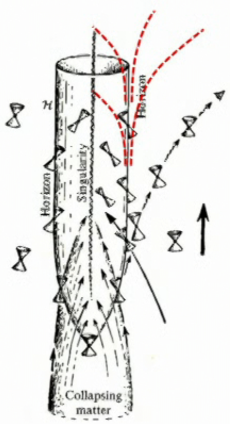
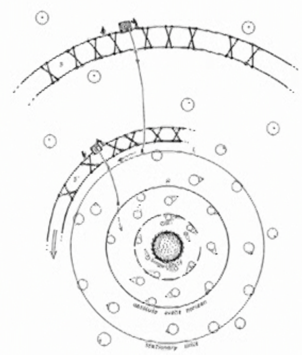


Rotating Black Holes
Superradiance



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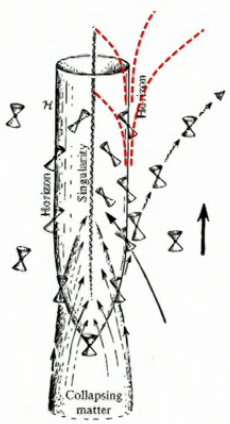

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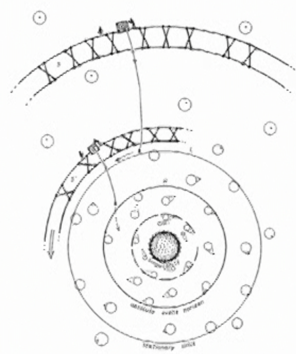
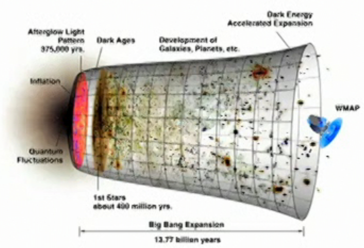
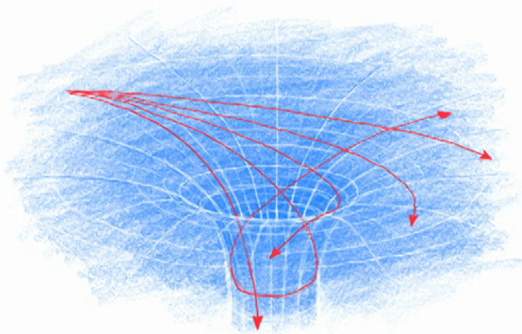


Cosmology
Large-scale structure

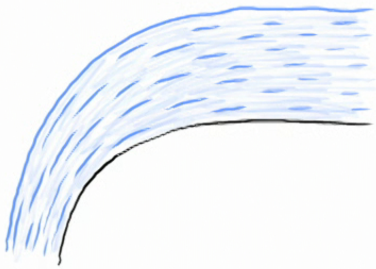


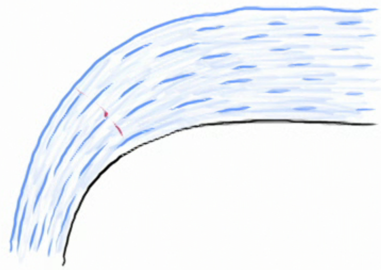
Quantum Vacuum
Unruh effect

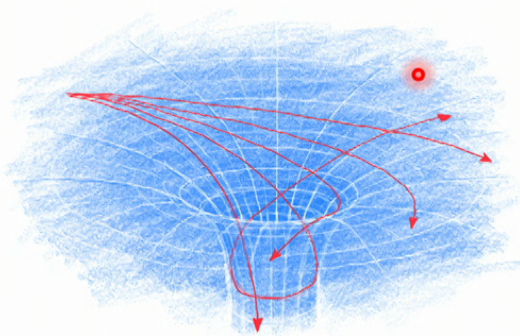
Experimental Black Hole Evaporation? Unruh 1980



Experimental Black Hole Evaporation? Unruh 1980







Broad class of lab systems:

Fluctuations described by an
effective Field Theory
in flat or curved spacetimes:

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

Gravity Simulators Systems

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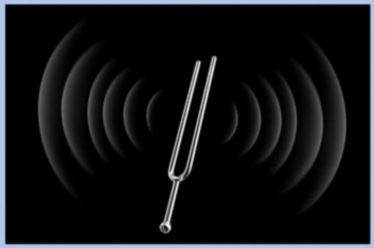
Navier-Stokes Equation



Unruh (1981)
Weinfurtner & Unruh (2020)

Gravity Simulators Systems

Fluctuations described by an **effective Field Theory** in flat or curved spacetimes:

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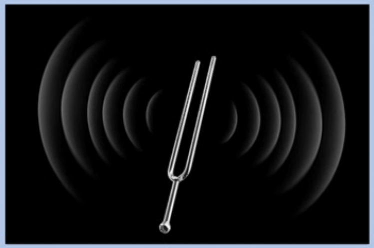
Navier-Stokes Equation

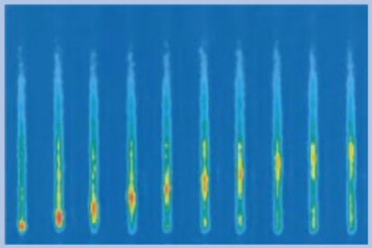


Unruh (1981)
Weinfurtner & Unruh (2020)

Coupled Navier-Stokes

Schützhold & Unruh (2002)
Fifer & Weinfurtner (2019)

Gross-Pitaevskii Equation



Garay & Zoller (2000)
Weinfurtner & Gardiner (2007)

Gravity Simulators Systems

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in flat or curved spacetimes:

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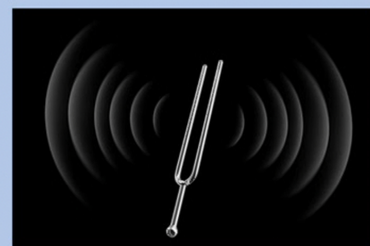
Navier-Stokes Equation

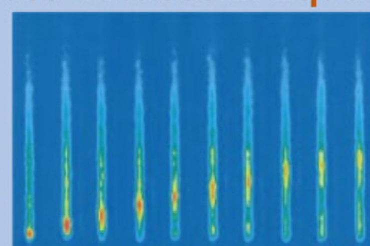


Unruh (1981)
Weinfurtner & Unruh (2020)

Coupled Navier-Stokes

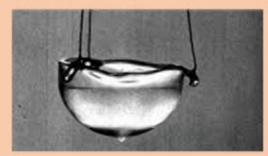
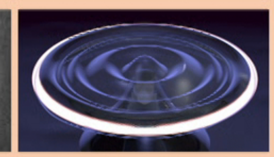
Schützhold & Unruh (2002)
Fifer & Weinfurtner (2019)

Gross-Pitaevskii Equation



Garay & Zoller (2000)
Weinfurtner & Gardiner (2007)

Liquid Helium

Volovic (2003)
Bunny & Weinfurtner (2023)

Gravity Simulators Tunability

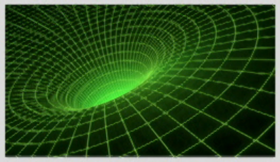
$$g_{ab} \propto \begin{bmatrix} -(c^2 - v^2) & -v_x & -v_y & -v_z \\ -v_x & 1 & 0 & 0 \\ -v_y & 0 & 1 & 0 \\ -v_z & 0 & 0 & 1 \end{bmatrix}$$

Spacetime Geometry

→ Flat spacetime: homogenous, static

→ Black Hole Horizon: stationary flows

→ Cosmology: time-dependent propagation speed



Gravity Simulators Tunability

$$g_{ab} \propto \begin{bmatrix} -c^2 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Signature of Spacetime

→ Euclidean ($c^2 < 0, elliptic\ equations$)

→ Lorentzian ($c^2 > 0, hyperpolic$)

$$\frac{1}{c^2}\frac{\partial^2}{\partial t^2}\psi = \nabla^2\psi$$

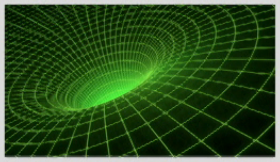
$$g_{ab} \propto \begin{bmatrix} -(c^2 - v^2) & -v_x & -v_y & -v_z \\ -v_x & 1 & 0 & 0 \\ -v_y & 0 & 1 & 0 \\ -v_z & 0 & 0 & 1 \end{bmatrix}$$

Spacetime Geometry

→ Flat spacetime: homogenous, static

→ Black Hole Horizon: stationary flows

→ Cosmology: time-dependent propagation speed



Gravity Simulators Tunability

$$g_{ab} \propto \begin{bmatrix} -c^2 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Signature of Spacetime
→ Euclidean ($c^2 < 0, elliptic\ equations$)
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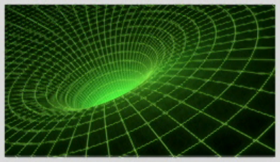


$$\mathcal{L} = \sqrt{-g}\left(-\frac{1}{2}\nabla^\mu\psi\nabla_\mu\psi - \frac{1}{2}m^2\psi^2 + \chi(\tau)\mu(\tau)\left(\lambda_1\psi(\tau) + \lambda_2\partial_\tau\psi(\tau)\right) + \sum_{n=3}^{n}\sum_{i=0}\frac{\alpha_{n,i}}{n!}\binom{n}{i}\psi^{n-i}\pi^i\right)$$

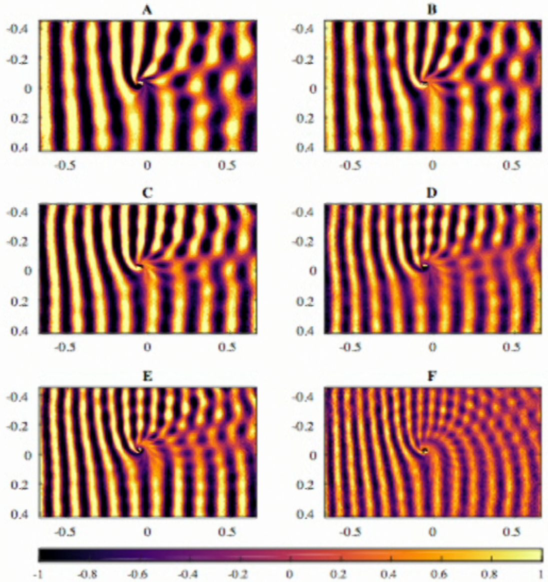
Mass
→ Stable ($m^2 > 0$)
→ Unstable ($m^2 < 0$)
→ Metastable

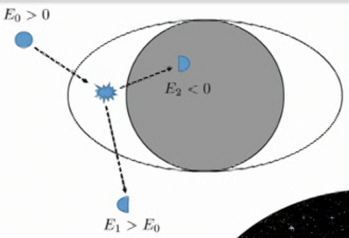
Particle detectors
→ Unruh detectors

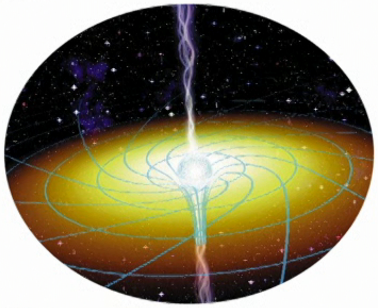
Interacting Fields
→ Scattering
→ Backreaction

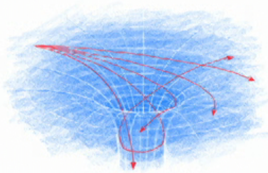
Black Hole Simulators (normal fluid)

Black Hole Superradiance
Nature Physics 2017









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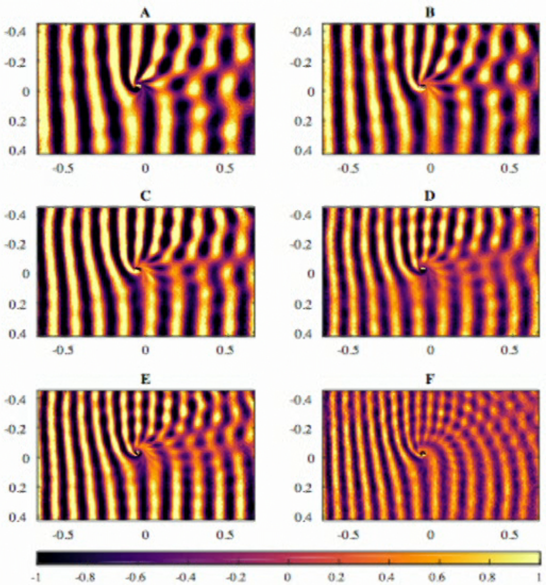
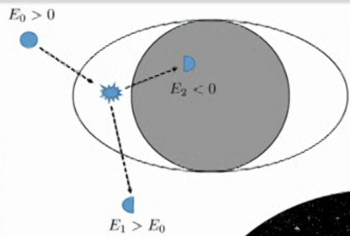
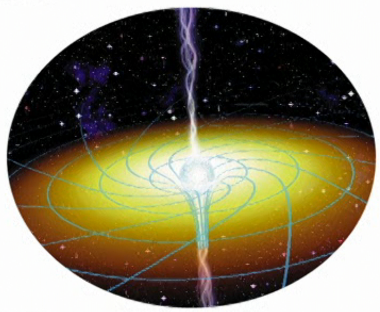
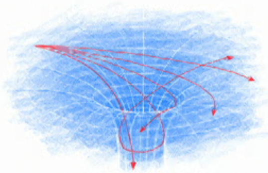
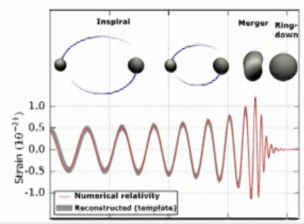




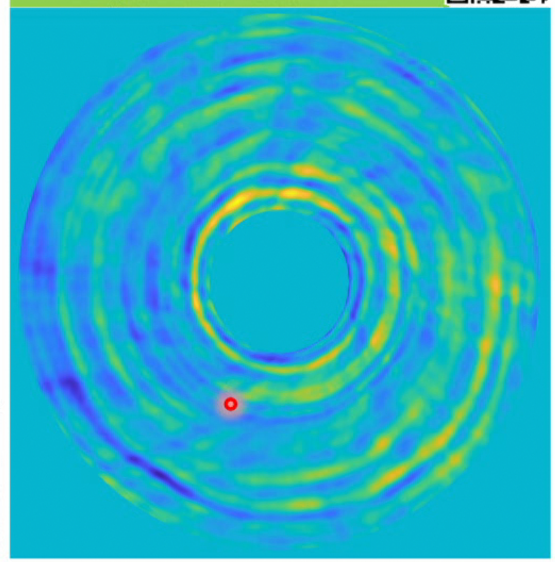




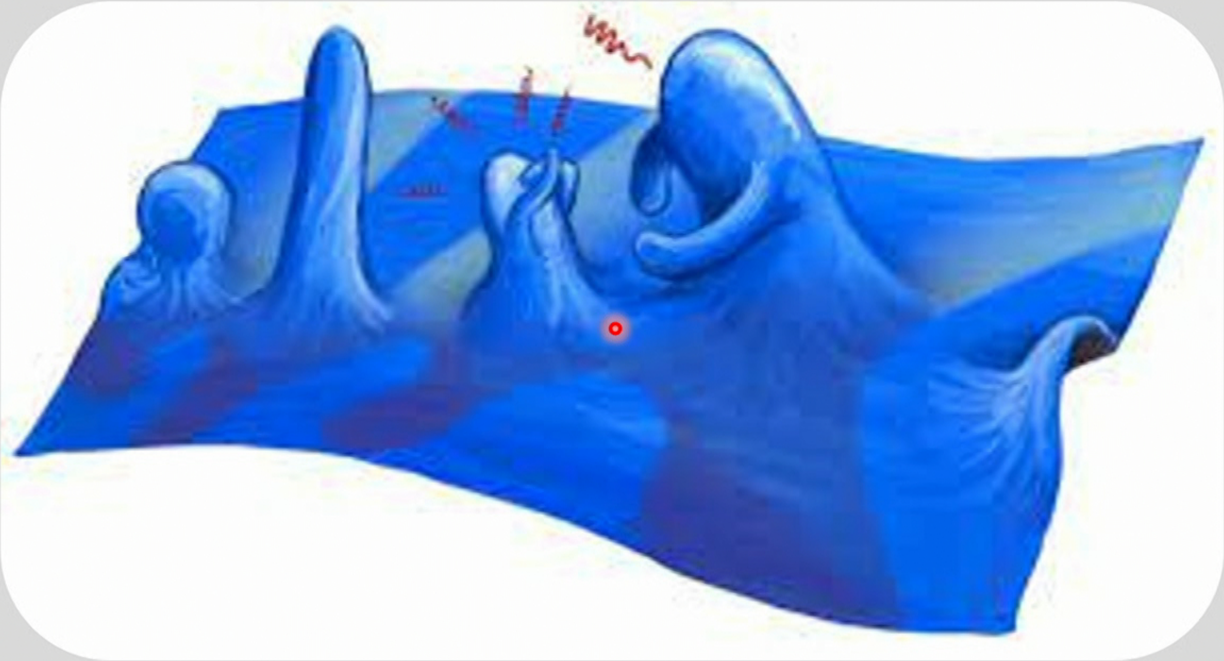


LIGO

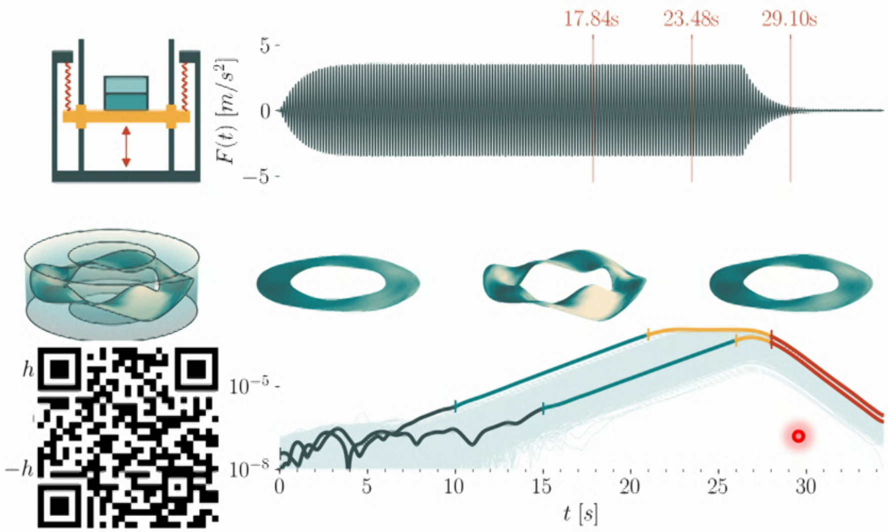
Black Hole Ringdown
Phys. Rev. Lett. 2021



Non-equilibrium Field Theory Simulators

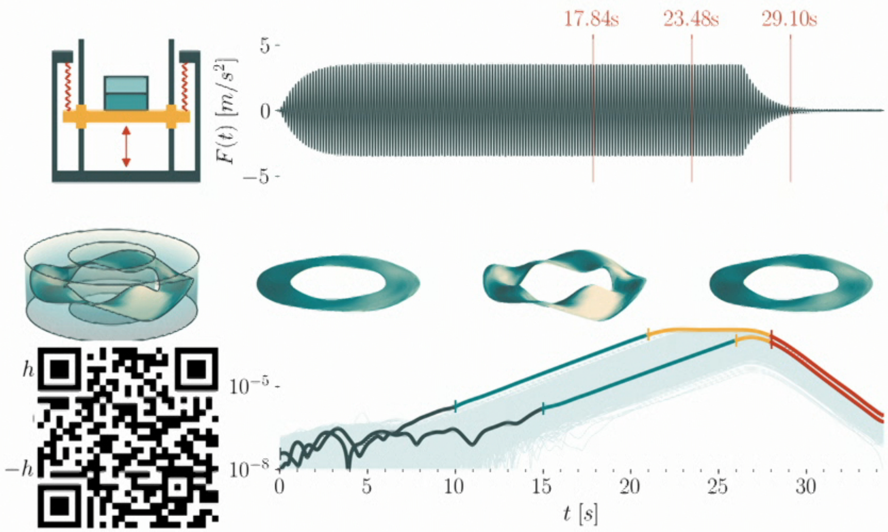


Non-equal time field theory simulator



Erne & Schmiedmayer (2018), Pruefer & Oberthaler (2018)

Non-equal time field theory simulator



Immiscible two-fluid system

- 2 coupled Navier-Stokes eqn.
- Small refractive index 1.015
- Closed and dust free system
- State-of-the-art acceleration platform
- State-of-the-art interface sensor
- Automatized working cycle
- Adapted Fourier Transform Profilometry
- Continuous wavelet analysis

Erne & Schmiedmayer (2018), Pruefer & Oberthaler (2018)

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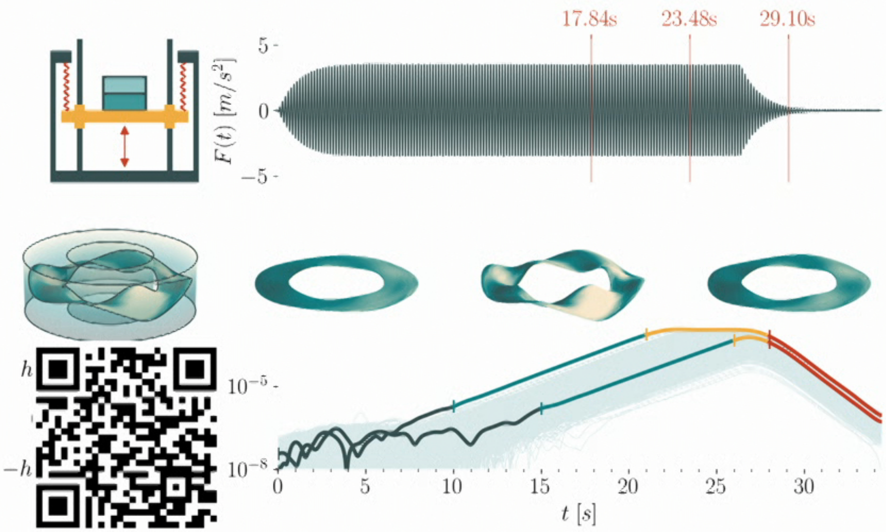

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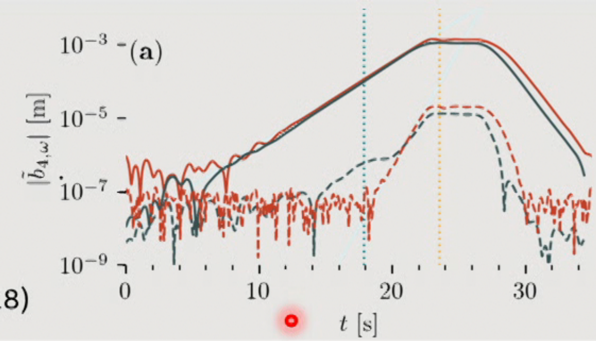
Observables

- Higher-order Unequal time/space correlation functions

Applications to non-equal time field theory

- Pre-turbulence dynamics
- Cosmological particle creation
- Non-linear fluid dynamics
- ...

Erne & Schmiedmayer (2018), Pruefer & Oberthaler (2018)



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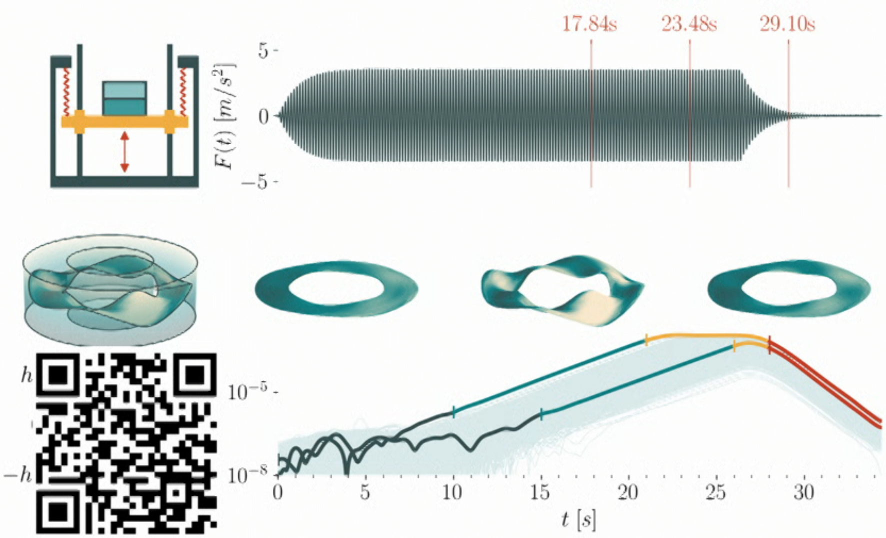

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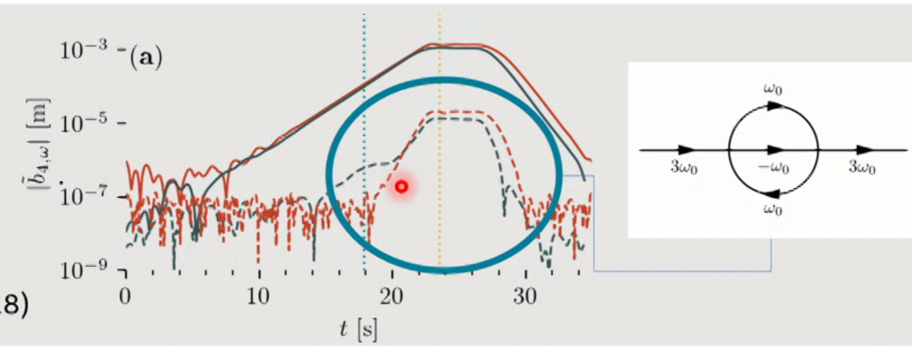


1^{st}-order Phase-Transition in Relativistic Field Theory (proposal)

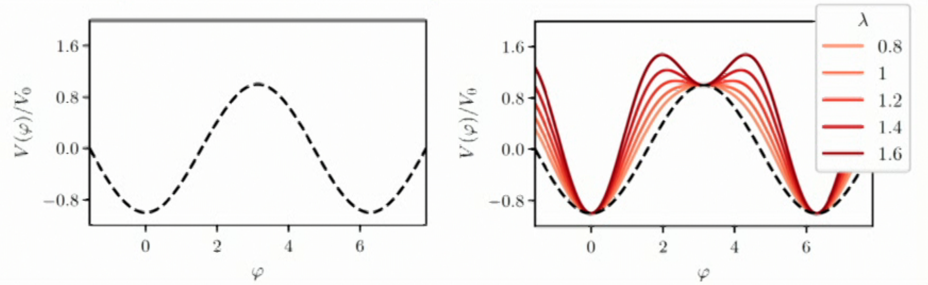
$$\mathcal{L}_{\text{eff}}^{\varphi} \propto \frac{\dot{\varphi}^2}{2} - c_s^2 \frac{(\nabla\varphi)^2}{2} - V_0 \left(-\cos\varphi + \frac{\lambda^2}{2} \sin^2\varphi \right)$$

N-component ultra-cold atoms system

- Spin-1/2 or Spin-1 systems
- Modified Sine-Gordon Lagrangian

Desired observables

- Dynamics of relative phase flections



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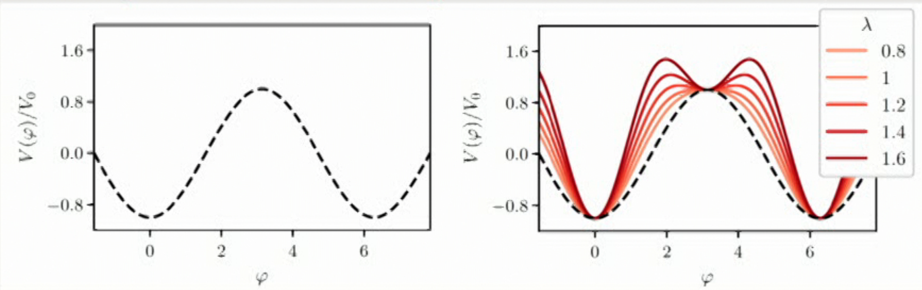

Applications to non-equal time field theory

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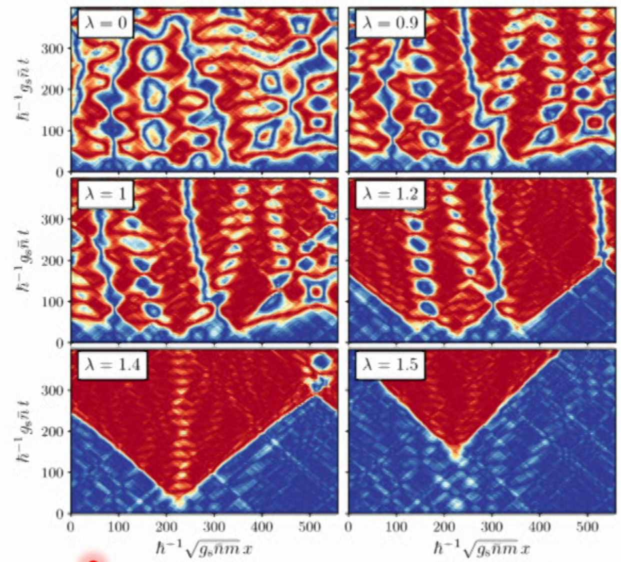
- Gravitational wave analysis

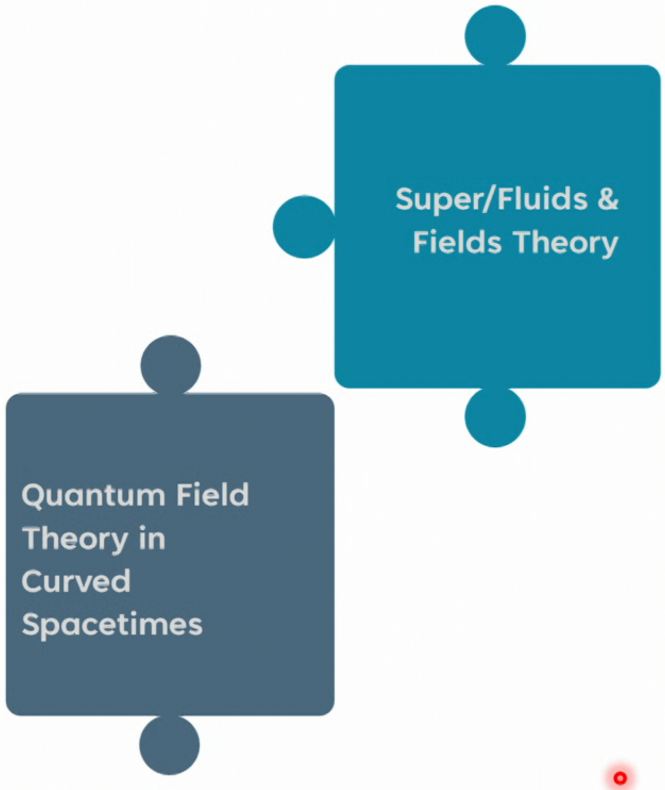
second-order phase transition

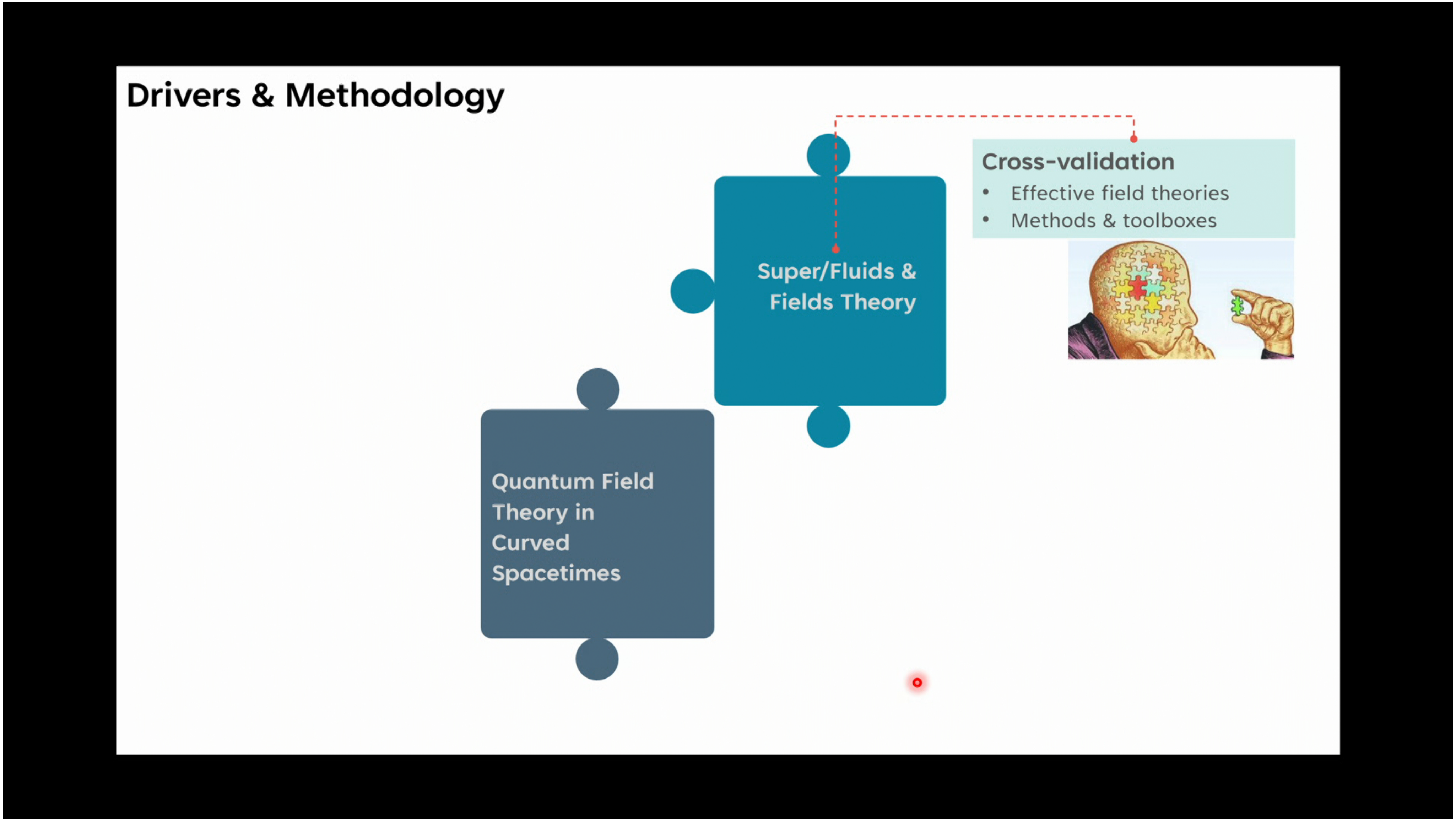
λ

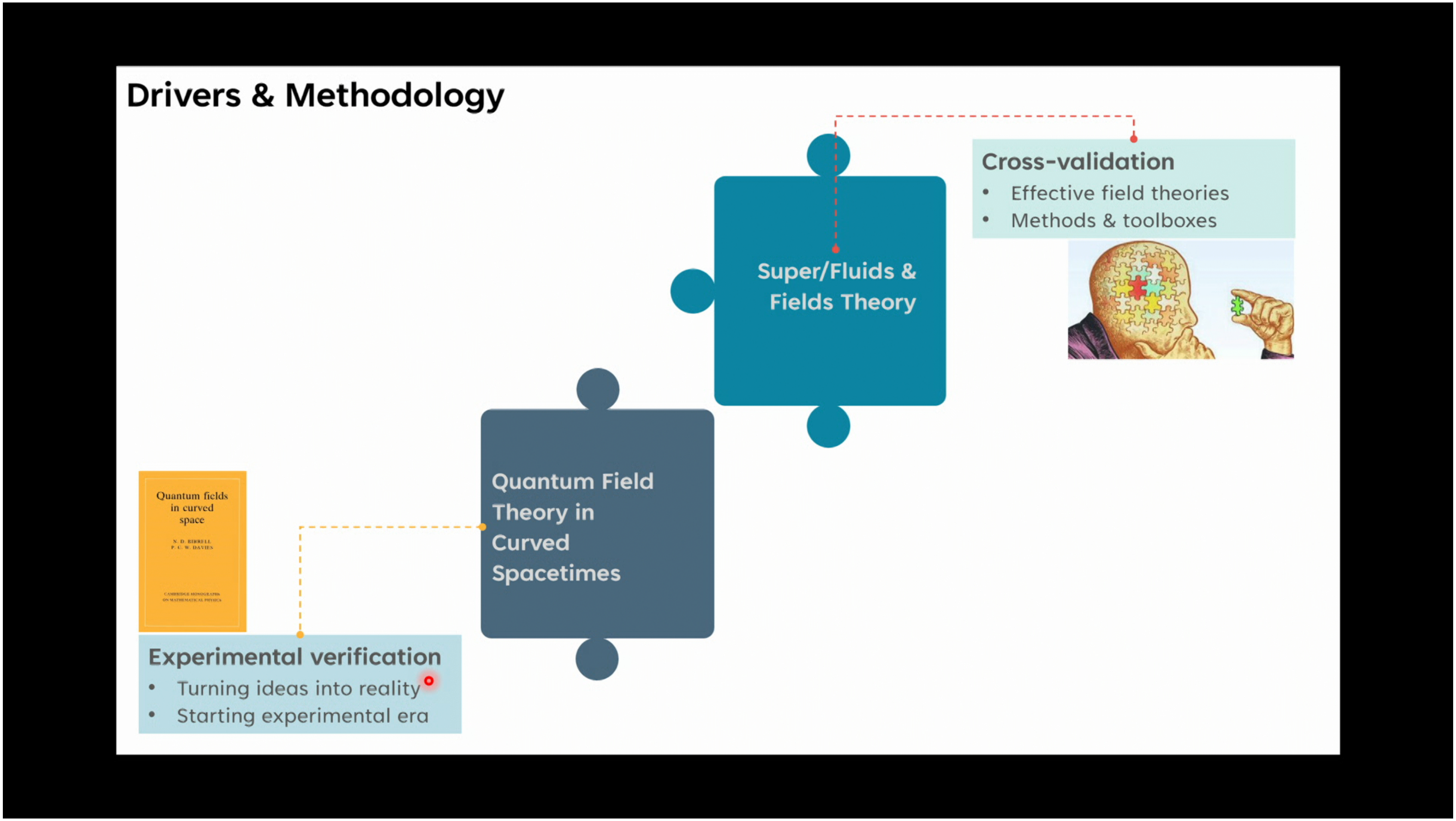


first-order phase transition

Drivers & Methodology




Drivers & Methodology
Cross-validation
• Effective field theories
• Methods & toolboxes
Super/Fluids & Fields Theory
Quantum Field Theory in Curved Spacetimes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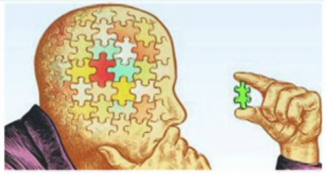
Quantum Field Theory in Curved Spacetimes
Quantum fields in curved space
N. D. BIRRELL
P. C. W. DAVIES
Experimental verification
Turning ideas into reality
Starting experimental era

Drivers & Methodology

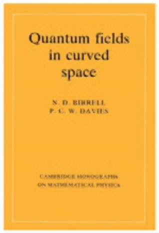
Cross-validation
- Effective field theories
- Methods & toolboxes



Super/Fluids & Fields Theory

Quantum Field Theory in Curved Spacetimes

Field Theory Simulators



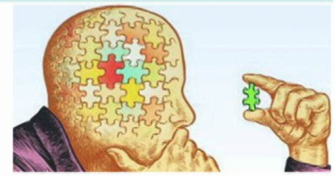
Experimental verification
- Turning ideas into reality
- Starting experimental era

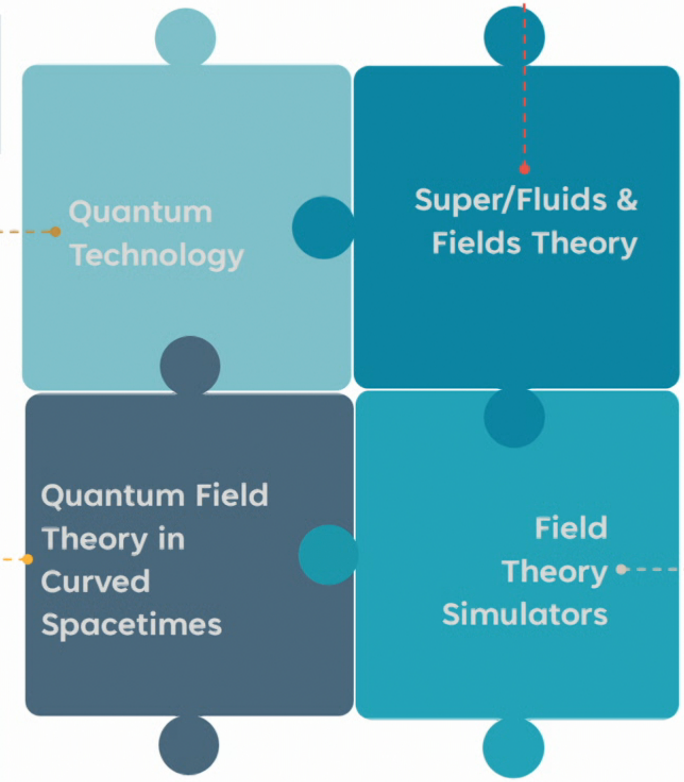
Toolbox
- Simulate the intractable
- Explore parameter space

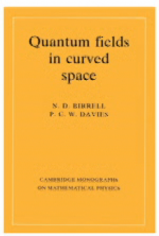
Drivers & Methodology

Development
- Quantum simulators
- Quantum sensing

Cross-validation
- Effective field theories
- Methods & toolboxes







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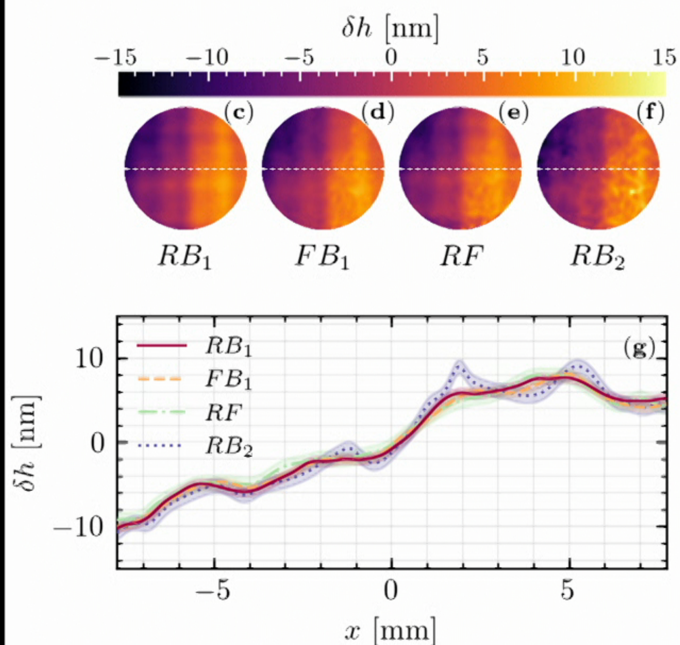
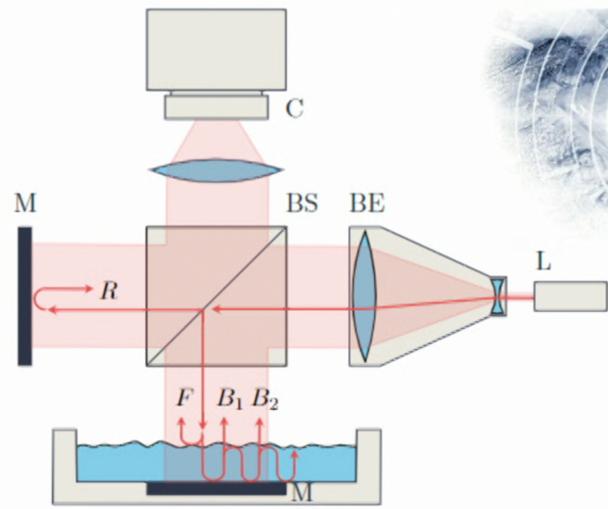
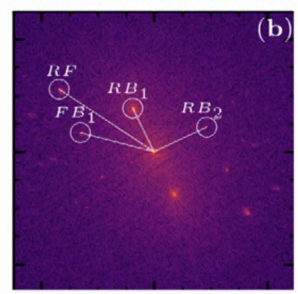
Multiplexed digital holography – partially transparent media



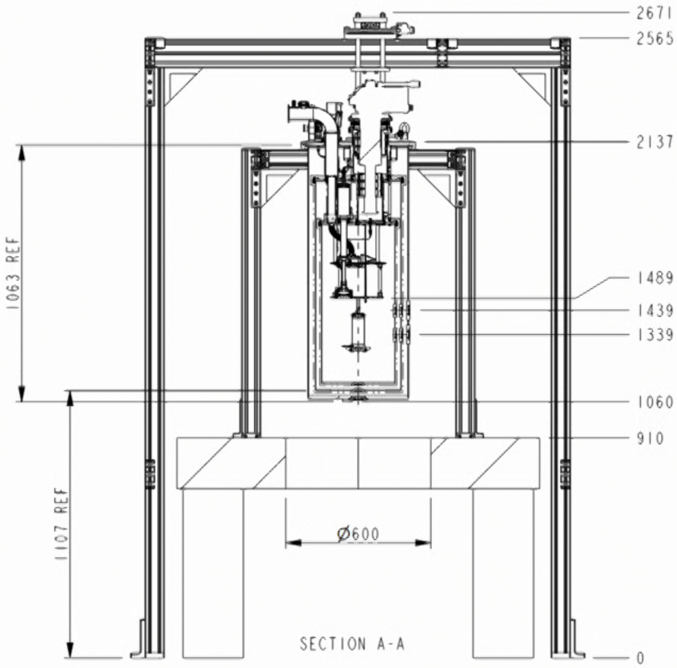




Patent Application 2214343.2

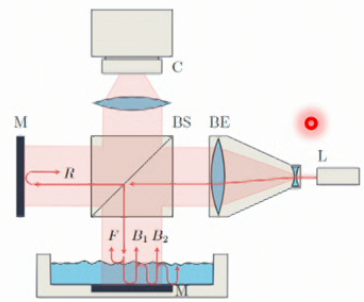
- Optical Path Length Characterisation
- Real-time monitoring of surface
- Resolution down to 10 nm
- Compact and modular
- Applicable for fluids and gases

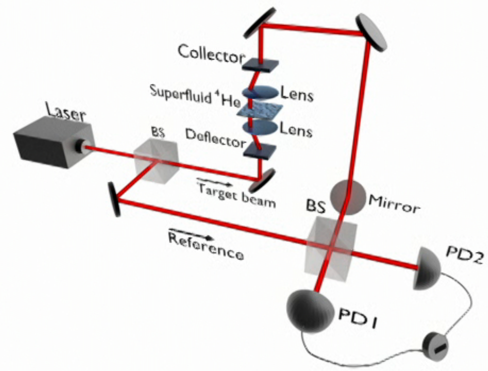
Thin-film superfluid systems with novel interferometric sensors

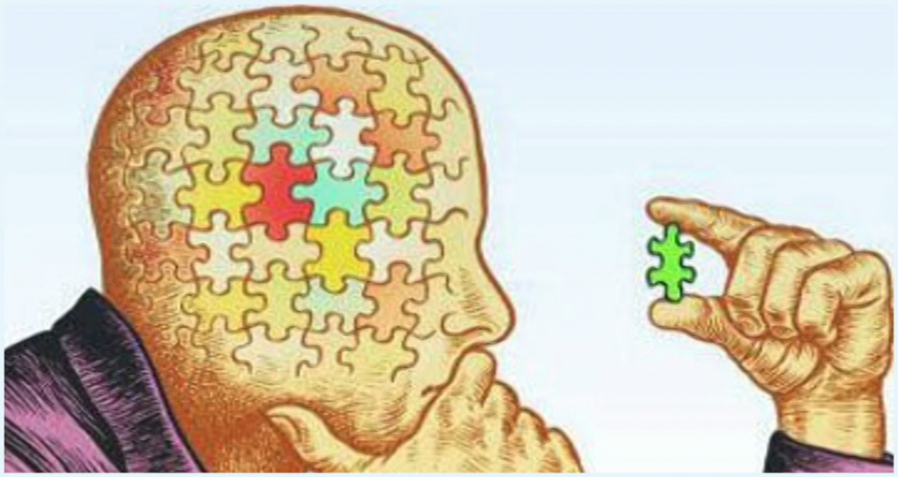


Think-film superfluid helium

- Film thickness (>10nm)
- Dry cryostat (300mK-325K)
- Dual optical access
- Multiple noise-isolation stages
- Tuneable quantum laser system:
  - Focussed beam
  - Expanded beam







Going beyond science:
Making a difference.

The bigger picture

QSimFP unites new communities:

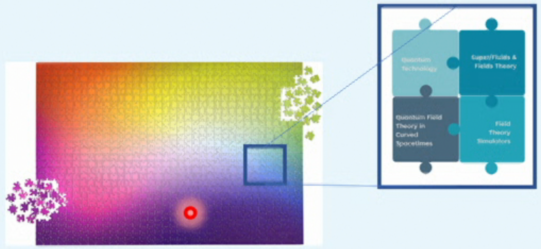
Across the consortia:

- Annual Workshop
- Bi-annual Consortium Meetings
- Bi-weekly Seminar Series

Reporting

- Reporting
- Oversight Committee
- International Advisory Board

The bigger picture



QSimFP part of QTFP

- Annual Winter School
- QTFP Engagement Event
- Stall at NQTP Showcase
- Joint Outreach Event

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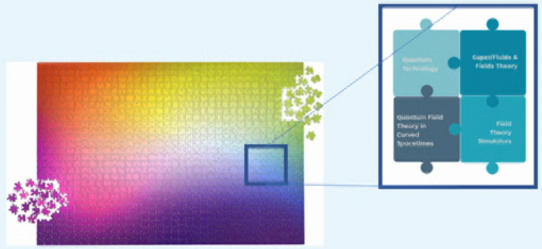
22/23



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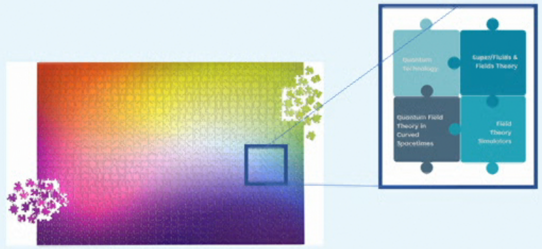
Community Bord

- Regular Meetings
- White Papers
- Joint Engagement Activities

The bigger picture



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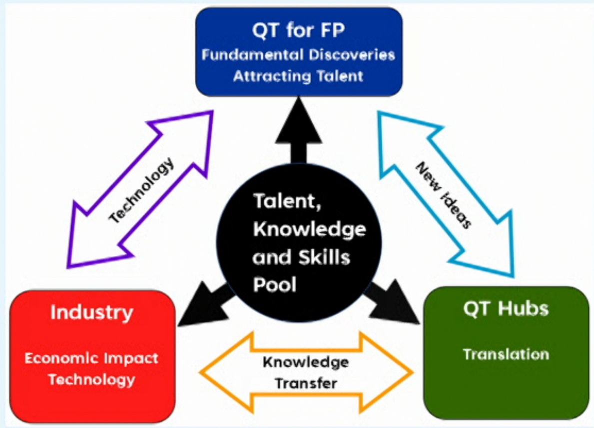
2022 Report from World Economic Forum

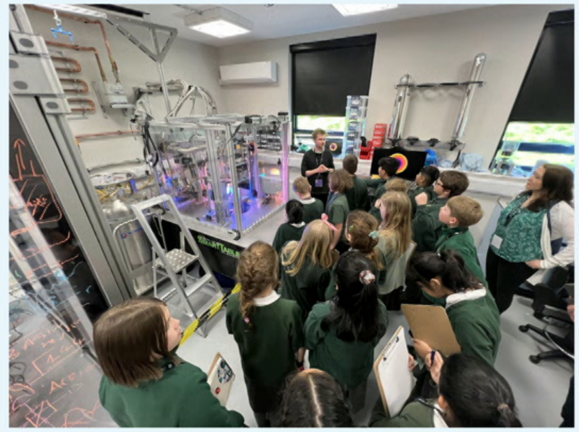
More than half of quantum companies' world- wide are hiring, but talent pool is limited

Unlocking the Quantum Potential

Strategies needed to address the quantum skills gap and build a diverse workforce.

Making a positive difference





Training of Young Scientists
- Schools & Workshops

Inspiring the next generation:
- Kids on Campus Programme
- Virtual QTFP Laboratories

Reaching a wider audience:
- Art-Science Exhibition

Thank you Matt and PI!