Quantum Simulators of Fundamental Physics

Silke Weinfurtner
The University of Nottingham

Sebastian Erne
The University of Nottingham

Theoretical Framework

Quantum Field Theory In Curved-Spacetimes

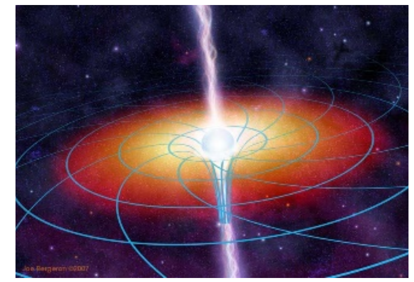
spacetime geometry

Gravity: General Relativity

equivalence principle
dynamical spacetime

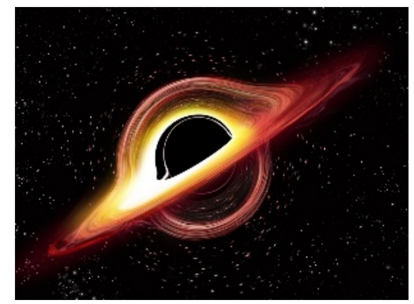
Quantum Field Theory

Fundamental Physical Processes



Rotating Black Holes

e.g. Superradiance



Black Holes

e.g. Hawking radiation

Cosmological spacetimes

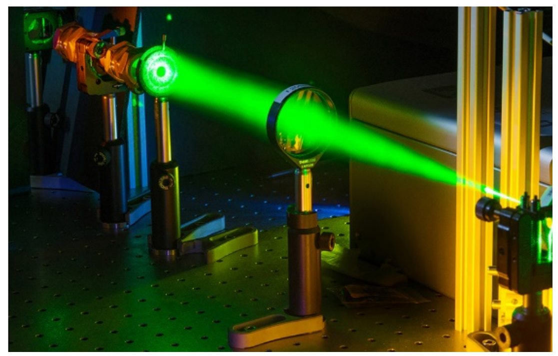
e.g. Early Universe Processes

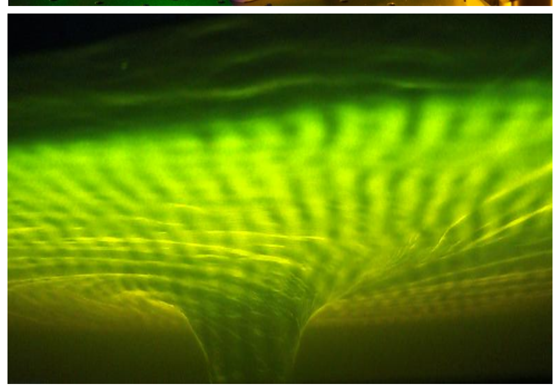
Quantum Vacuum

e.g. The False Vacuum Decay

Analogue Simulators

There exists a **broad class of systems**

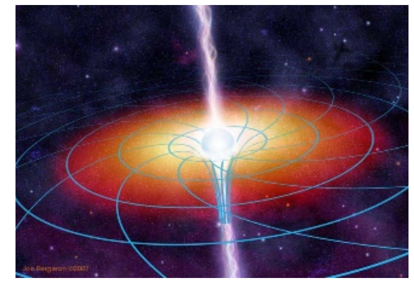




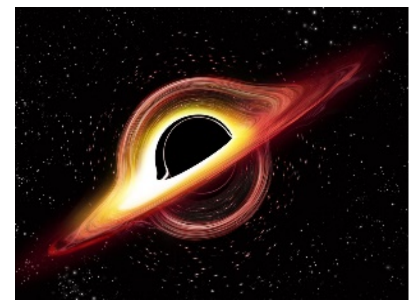
Fluctuations described by an **effective Relativistic Quantum Field Theory** in **flat** or **curved** spacetimes.

EPSRC
Engineering and Physical Sciences Research Council

Fundamental Physical Processes



Rotating Black Holes



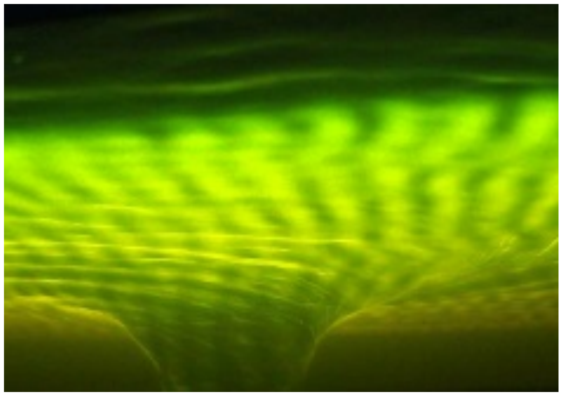
Black Holes

Cosmological spacetimes

Quantum Vacuum

Science & Technology Facilities Council

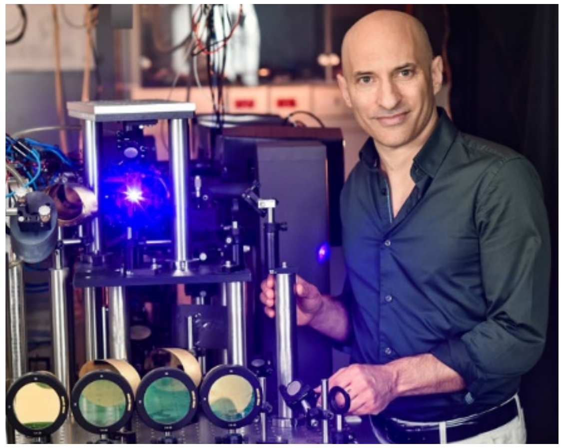
Recent successful examples of Analogue QFT Simulations



Rotating Black Holes

- **Superradiance**
  Weinfurtner 2017
- Light bending
  Weinfurtner 2018
- Quasi-Normal Modes

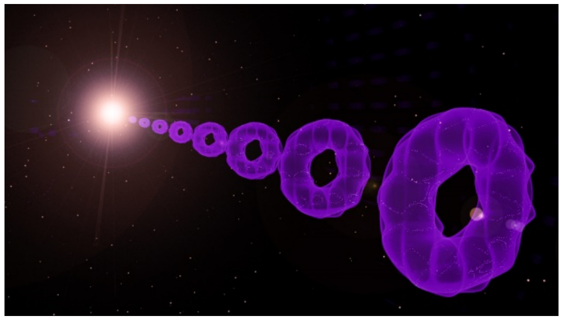
Rotational superradiant scattering in a vortex flow
Theo Torres, Sam Patrick, Antonin Coutant, Mauricio Richartz, Edmund W. Tedford & Silke Weinfurtner
Nature Physics volume **13**, pages833–836 (2017)



Black Holes

- **Hawking Radiation:**
  Weinfurtner/Unruh 2011
  Faccio 2011
  Rousseoux 2016
- Black-Hole Laser:
  Steinhauer 2016

Observation of quantum Hawking radiation and its entanglement in an analogue black hole
Jeff Steinhauer
Nature Physics volume **12**, pages 959–965 (2016)



Cosmological spacetimes

- Particle Production
  Westbrook 2012
- Hubble Friction
  Campbell 2018

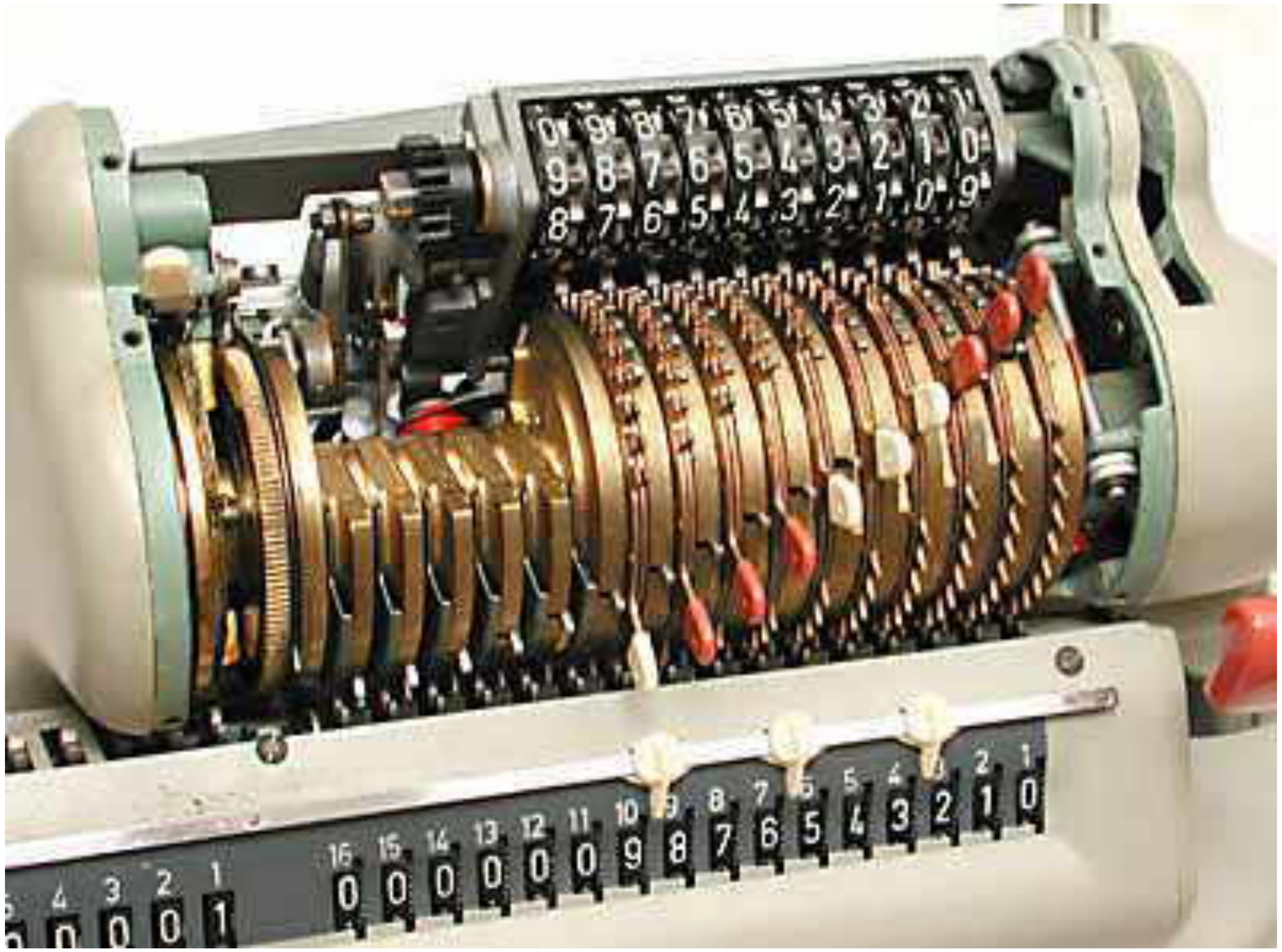
A Rapidly Expanding Bose-Einstein Condensate: An Expanding Universe in the Lab
S. Eckel, A. Kumar, T. Jacobson, I. B. Spielman, and G. K. Campbell
Phys. Rev. X 8, 021021 (2018)

How versatile a tool are these simulators..?
How much more is there to be done..?

Analogue QFT Simulators have a high degree of tunability

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

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



A timely and rapidly growing field of research with many more successes to be expected in the near future…

- Collaborators -

Hiranya Peiris
UCL / Oskar Klein Centre Stockholm

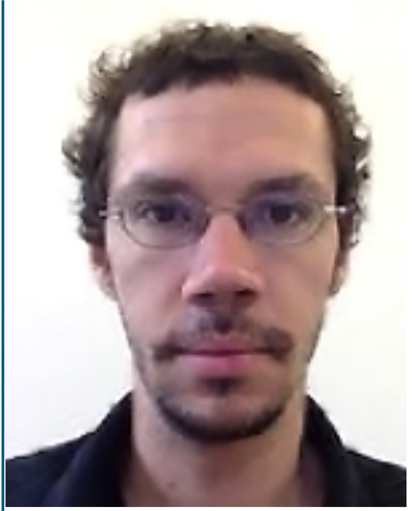
cosmology / early universe phenomenology

Matthew Johnson
Perimeter Institute / York University

theoretical physics / theoretical cosmology

Andrew Pontzen
UCL

cosmology / numerical simulations



Jonathan Braden
Canadian Institute for Theoretical Astrophysics

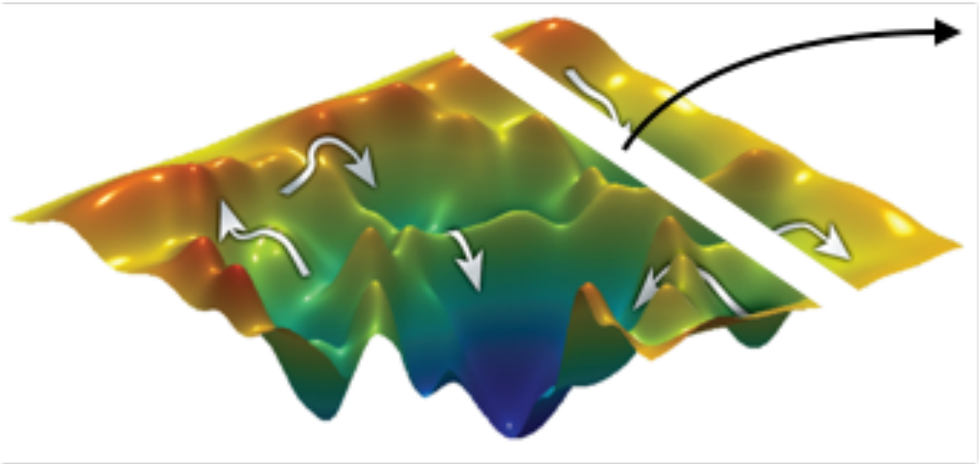
Theoretical physics / non-linear and non-equilibrium dynamics

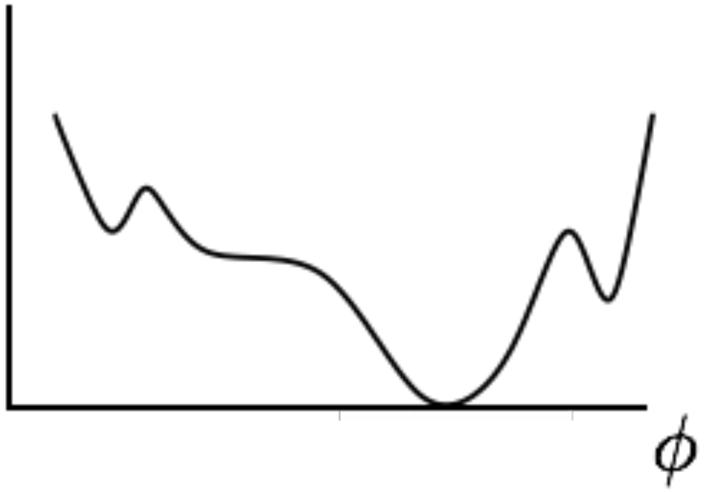
European Research Council
Established by the European Commission

THE ROYAL SOCIETY

Work to date funded by the European Research Council and the Royal Society

The Origin of the Universe through Vacuum Decay?



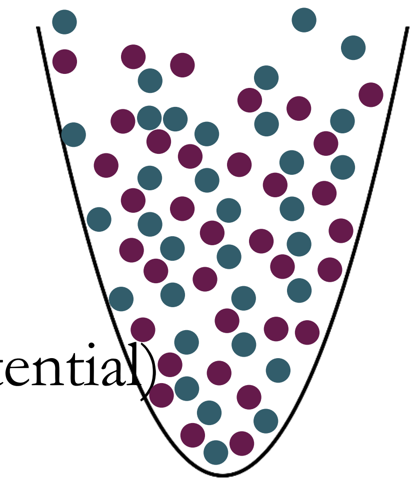


- Cosmological theories inspired by particle physics exhibit vacuum decay
- Vacuum Decay is quantum tunnelling out of the false vacuum via bubble nucleation
- Non-equilibrium physics: relativistic first-order phase transition

→ understanding dynamics of relativistic first-order phase transitions will shed light on the origin of our observable universe

We are building upon the proposal by

O. Fialko, B. Opanchuk, A. I. Sidorov, P. D. Drummond and J. Brand, **The universe on a table top: engineering quantum decay of a relativistic scalar field from a metastable vacuum**, J. Phys. B50 (2017) 024003, [1607.01460].

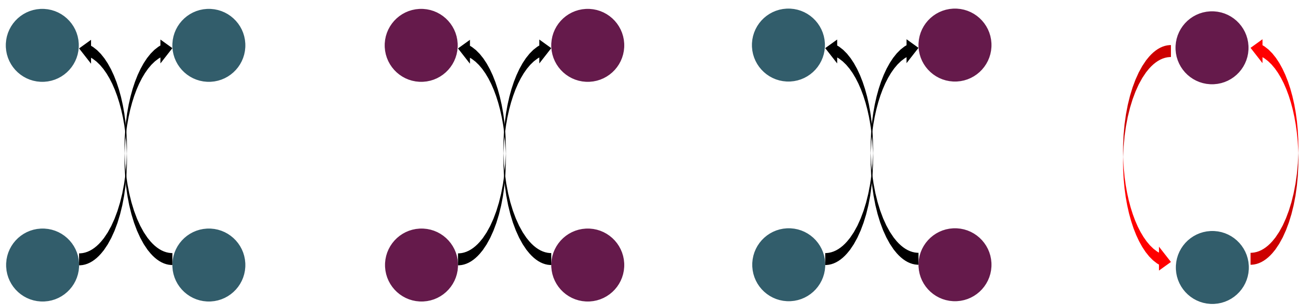


2-component coupled Bose-Einstein Condensates (BECs)

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

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

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



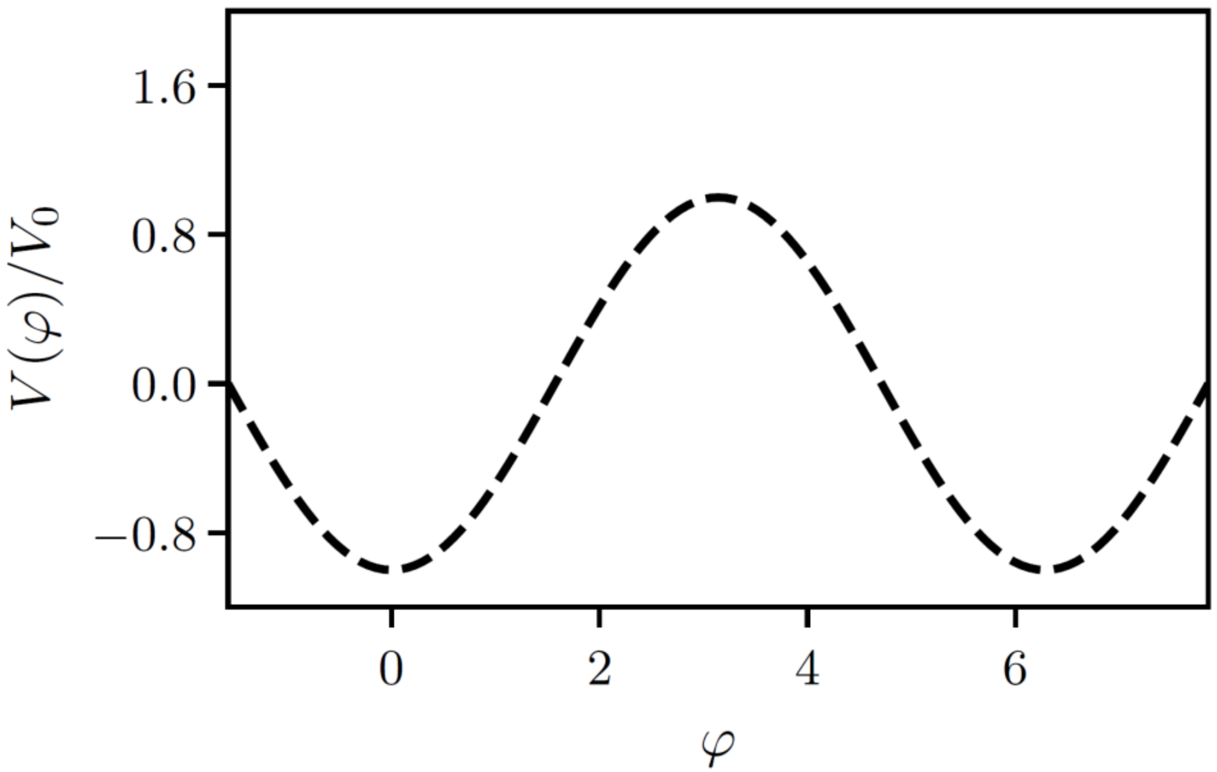
Condensation: $\hat{\Psi}_i = \sqrt{\hat{\rho}_i}\, e^{i\hat{\phi}_i} \longrightarrow \psi_i = \sqrt{\rho_i} e^{i\phi_i}$

Dynamics of relative phase exhibits sine-Gordon Lagrangian

global minima and maxima

minima → **stable**

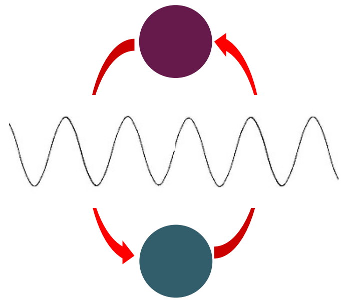
maxima → **unstable**

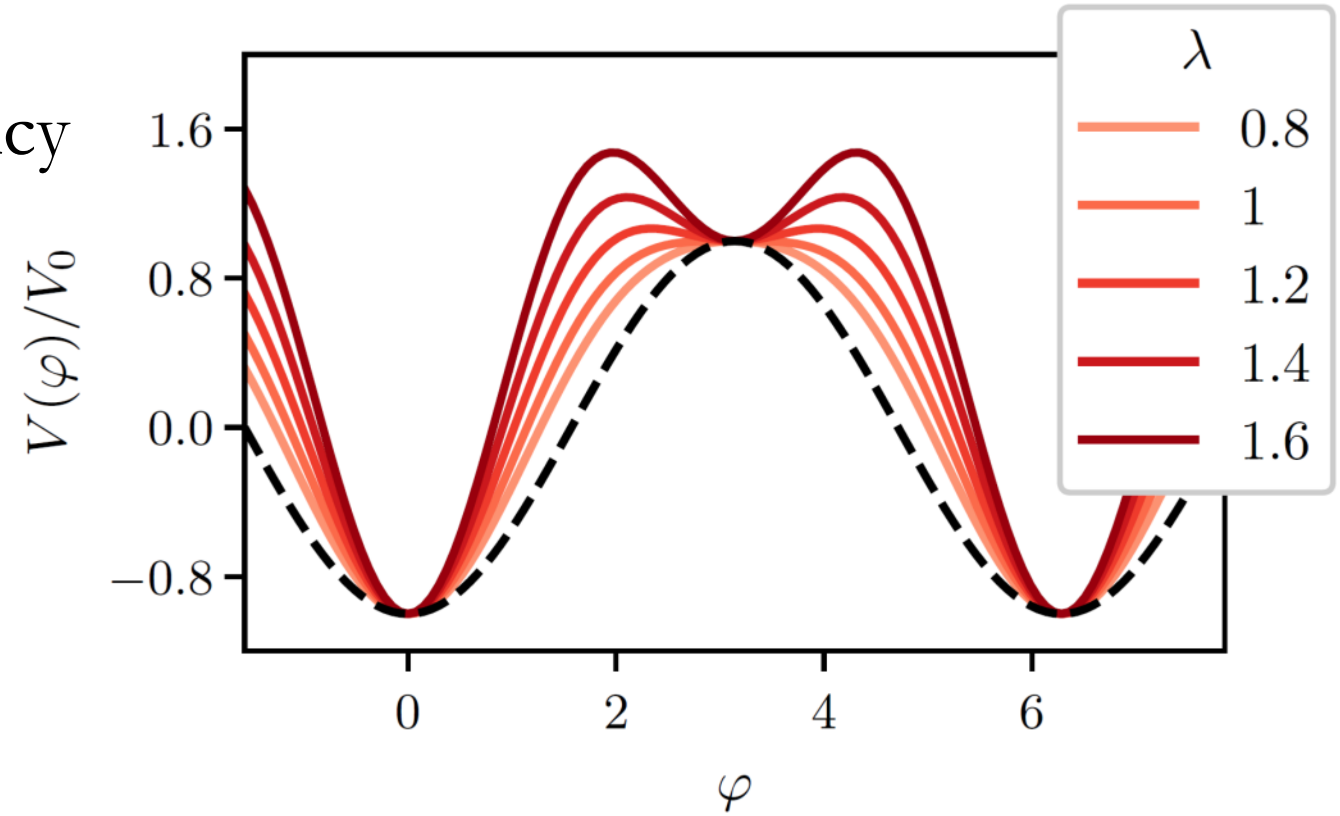


False Vacuum Decay

Fialko et al. suggest to add a high frequency modulation in the transition coupling

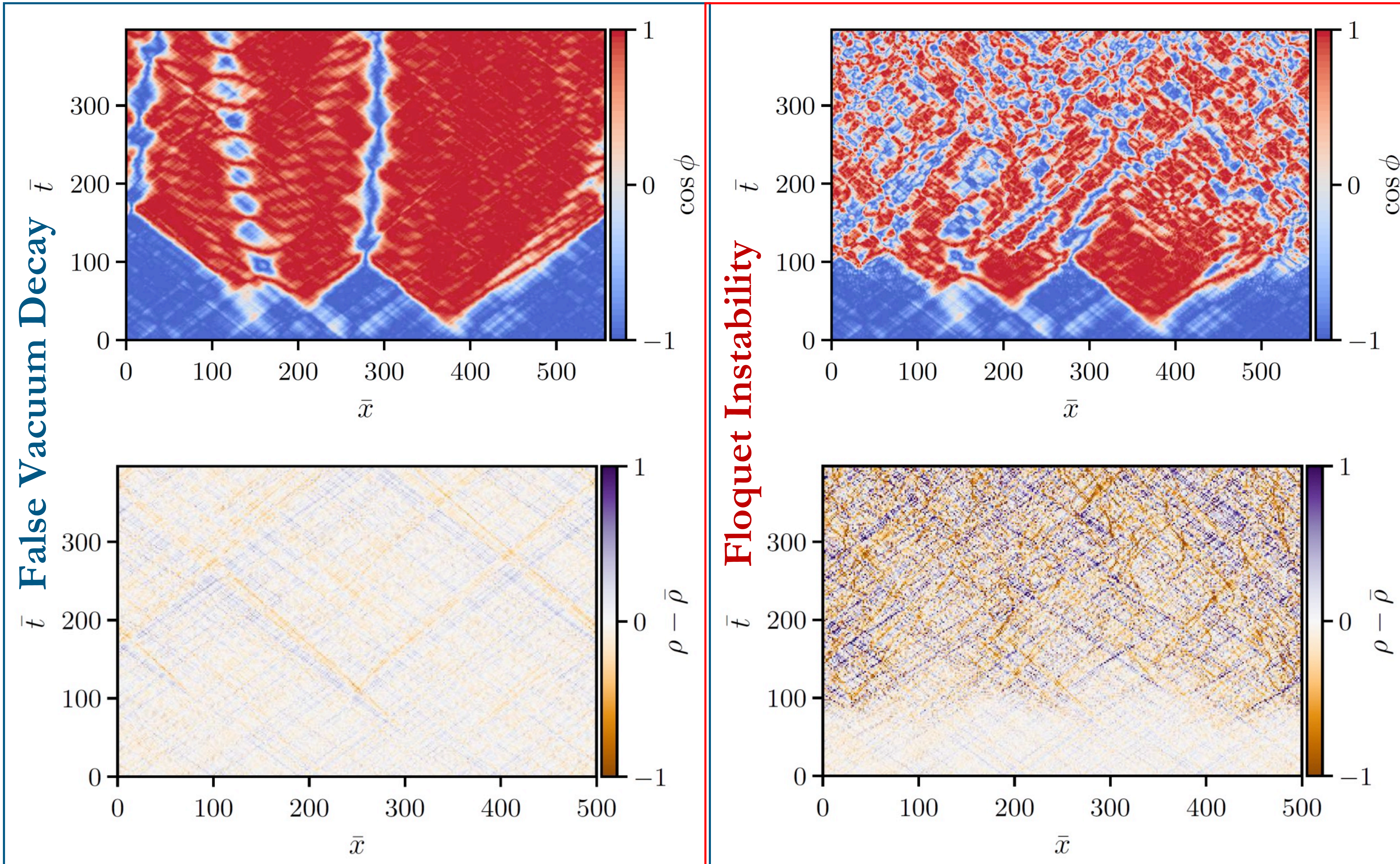
→ **maxima rendered meta-stable**





Our Results on Investigating experimental feasibility

- Feasibility study: Towards the cold atom analog false vacuum; JHEP 07 (2018) 014
- Application to cosmology: A New Semiclassical Picture of Vacuum Decay, under review in PRL
- Lattice simulations: work in progress



Impact

Relativistic simulations of the False Vacuum Decay give insights into:

- the quantum origin of the Universe: emergence of classical bubble from quantum fluctuations;
- true quantum dynamics of first-order phase transitions, e.g. a complete treatment of multi-bubble configurations;
- The effective quantum field theory for small fluctuations in Bose-Einstein Condensates out of equilibrium.

Expression of Interest

The development of Relativistic Field Theory Simulators:

- From theoretical framework to experimental implementation;
- Special emphasis on Early Universe Scenarios, e.g. The False Vacuum Decay;