Alex Jenkins | acj46@cam.ac.uk | 22 Oct 2026
VAST @ Madrid

UNIVERSITY OF CAMBRIDGE

QSimFP

UKRI

Kavli Institute for Cosmology Cambridge KICC

Toward a real-time theory of false vacuum decay

Wang, **ACJ**, **2610.xxxxx**
Hertig, **ACJ**, Peiris, Pontzen, Johnson, **2610.xxxxx**
Zhang *et al.* (inc. **ACJ**), **2608.20311**
Hertig, **ACJ**, Peiris, Pontzen, Johnson, **2607.06680**
Zhang *et al.* (inc. **ACJ**), **2603.08840**
ACJ, Peiris, Pontzen, **2504.02829**
ACJ, Moss, Billam, Hadzibabic, Peiris, Pontzen, **2311.02156**
ACJ, Braden, Peiris, Pontzen, Johnson, Weinfurtner, **2307.02549**

↑↑ **scan for papers**

Collaborators

Cosmology theory

Cold-atom theory

Cold-atom experiments


Jonathan Braden
(CITA → industry)

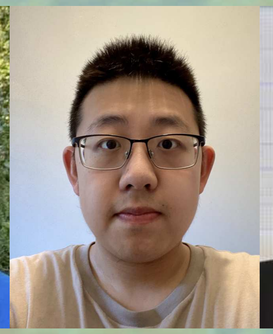

Emilie Hertig
(Cambridge)


Dalila Pîrvu
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Junzhe Wang
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Silke Weinfurtner
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Yansheng Zhang
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Hiranya Peiris
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Matt Johnson
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Andrew Pontzen
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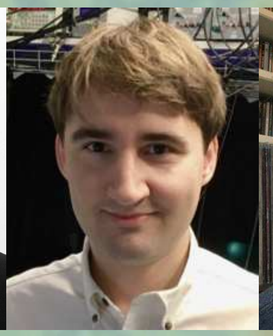

Ian Moss
(Newcastle)


Tom Billam
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Nishant Dogra
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Gehrig Carlse
(Cambridge)


Joseph Thywissen
(Toronto)


Christoph Eigen
(Cambridge)


Zoran Hadzibabic
(Cambridge)

Plan for this talk

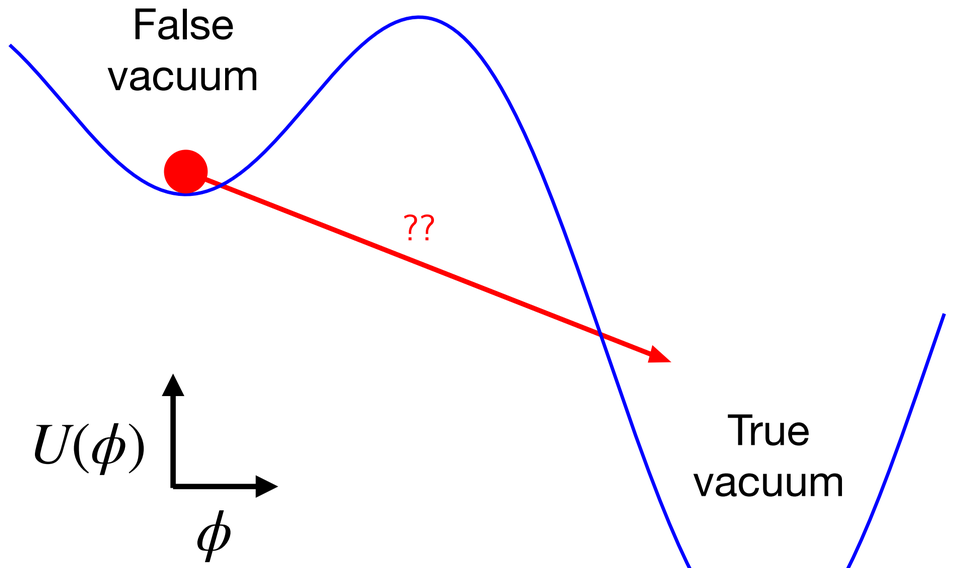
1. **Open problems for vacuum decay**
2. Semiclassical simulations on the lattice
3. Quantum simulations in the laboratory

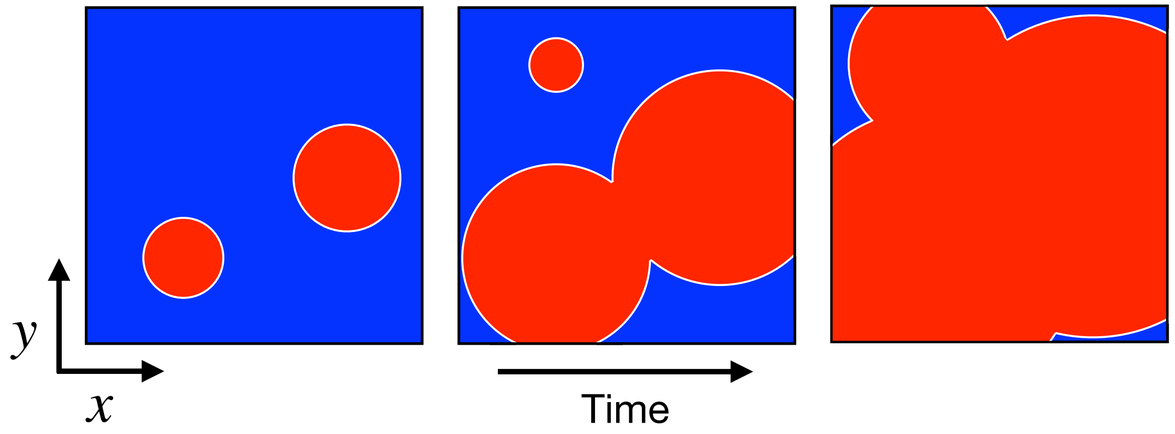
Vacuum decay basics

- We have a relativistic scalar field,

$$\partial_t^2 \varphi - \nabla^2 \varphi + U'(\varphi) = 0$$

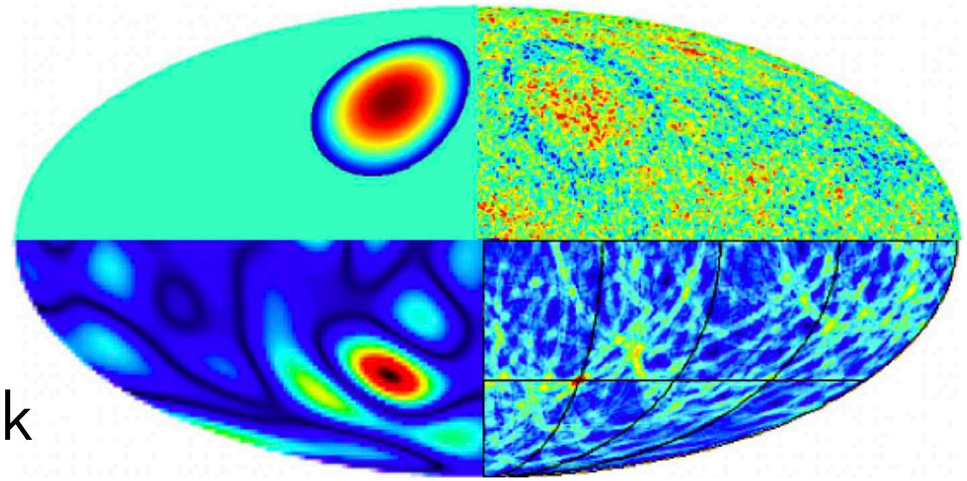
- Field escapes from *local* minimum of potential $U(\varphi)$ to *global* minimum
- Nucleates spatially localised "bubbles" of true vacuum
- Non-perturbative, non-equilibrium QFT process ... *very difficult problem!*





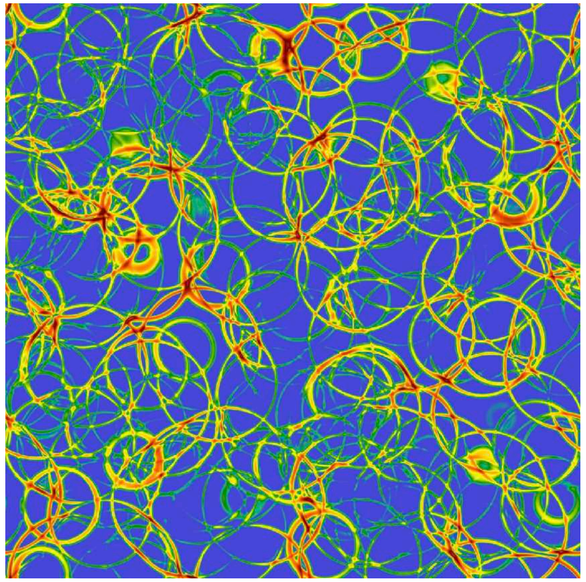
Why do we care?

Feeney+, 1012.1995

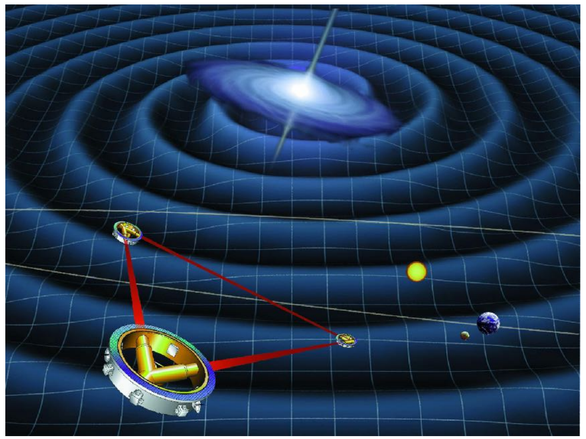


Inflation and the multiverse

Hindmarsh+,1511.04527

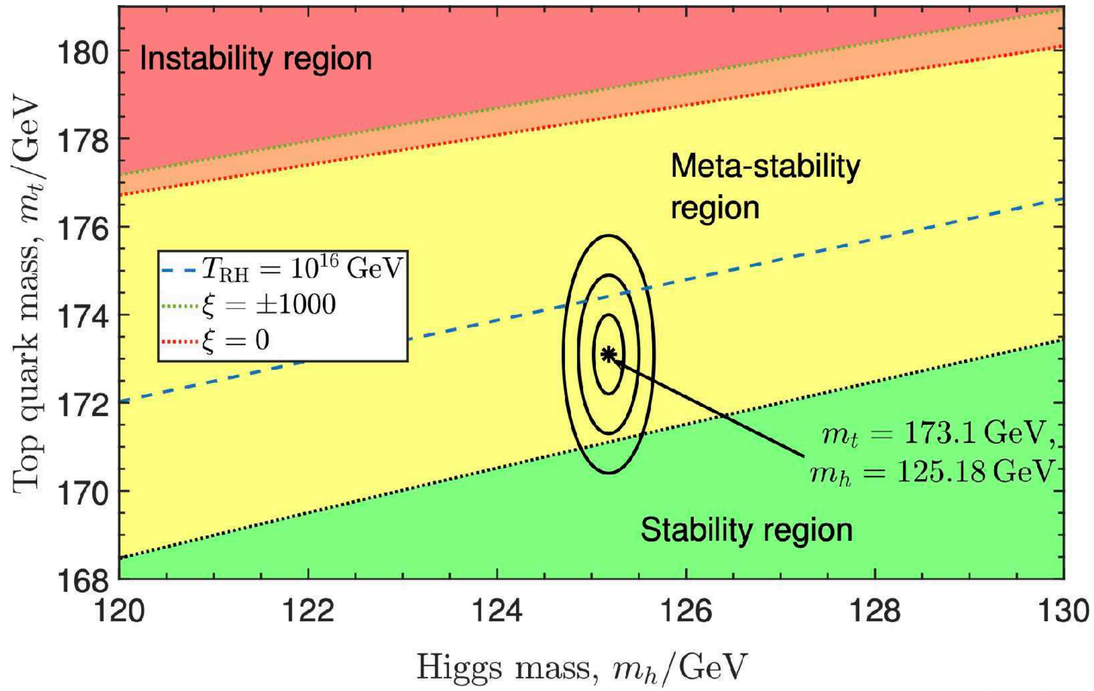


Electroweak Baryogenesis



Gravitational-wave cosmology

Markkanen+, 1809.06923

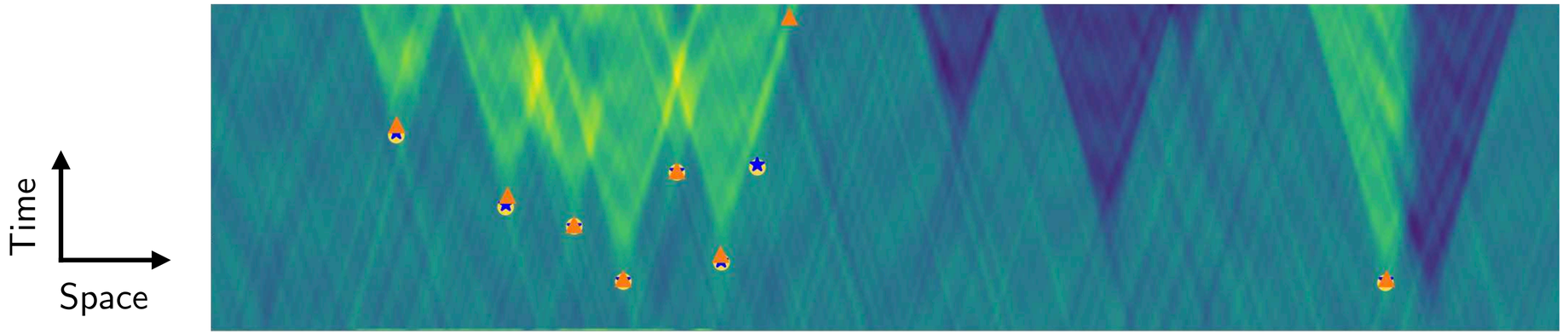


Stability of the Higgs vacuum

Some open questions for vacuum decay

Instanton methods give important insights, *but*,

- What does bubble nucleation look like in *real time*?
- What happens on *dynamical* (cosmological) backgrounds?
- Is the symmetry of the Euclidean solutions *broken* in practice?
- Are there *correlations* between multiple bubbles?

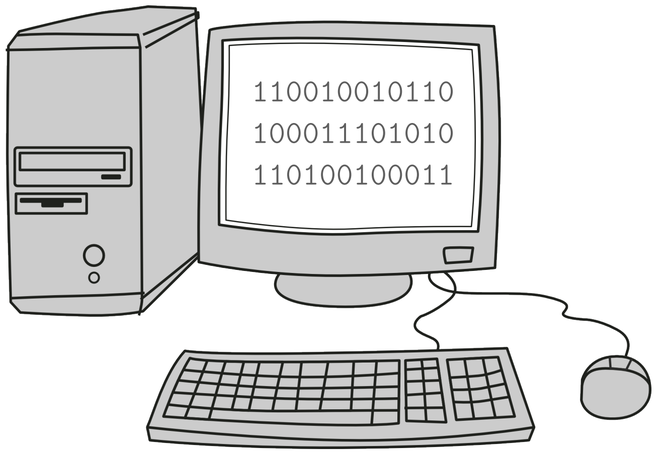


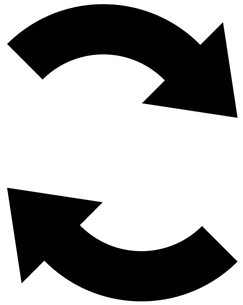
Pîrvu+, 2109.04496

Two routes forward

Real-time lattice simulations

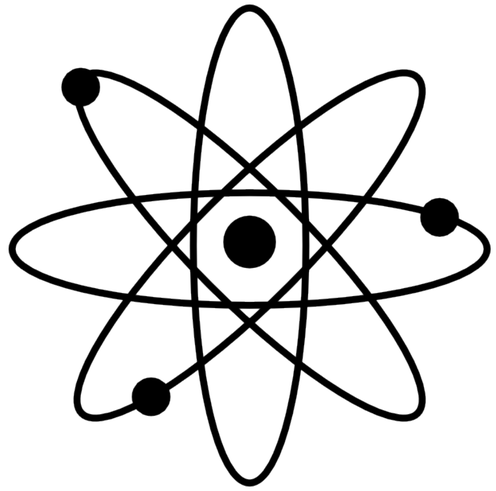
Use a semiclassical approach to study bubble nucleation numerically





Quantum analogue simulations

Engineer a system in the lab which behaves like a relativistic field undergoing vacuum decay



Plan for this talk

1. Open problems for vacuum decay
2. **Semiclassical simulations on the lattice**
3. Quantum simulations in the laboratory

The real-time approach

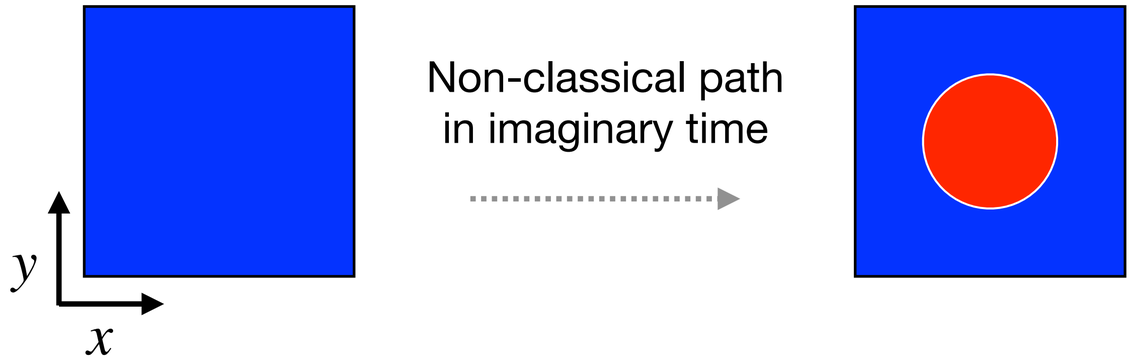
- Instanton picture:
  bubbles appear from "average"
  initial state via *non-classical* paths

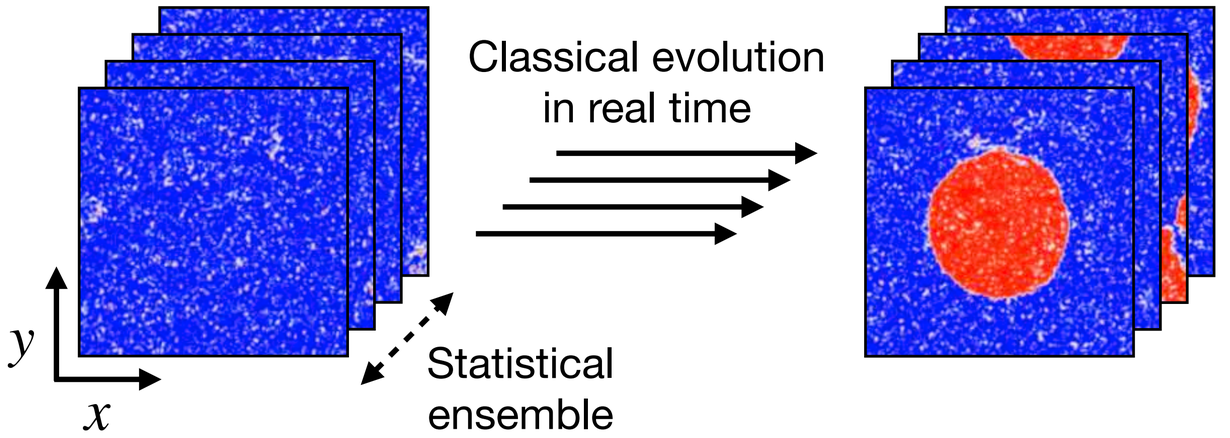
- Real-time picture:
  start with vacuum fluctuations,
  evolve forward *classically*

- Standard approach in inflation,
  preheating, atomic/optical physics, ...
  (truncated Wigner approximation)

Braden+, 1806.06069



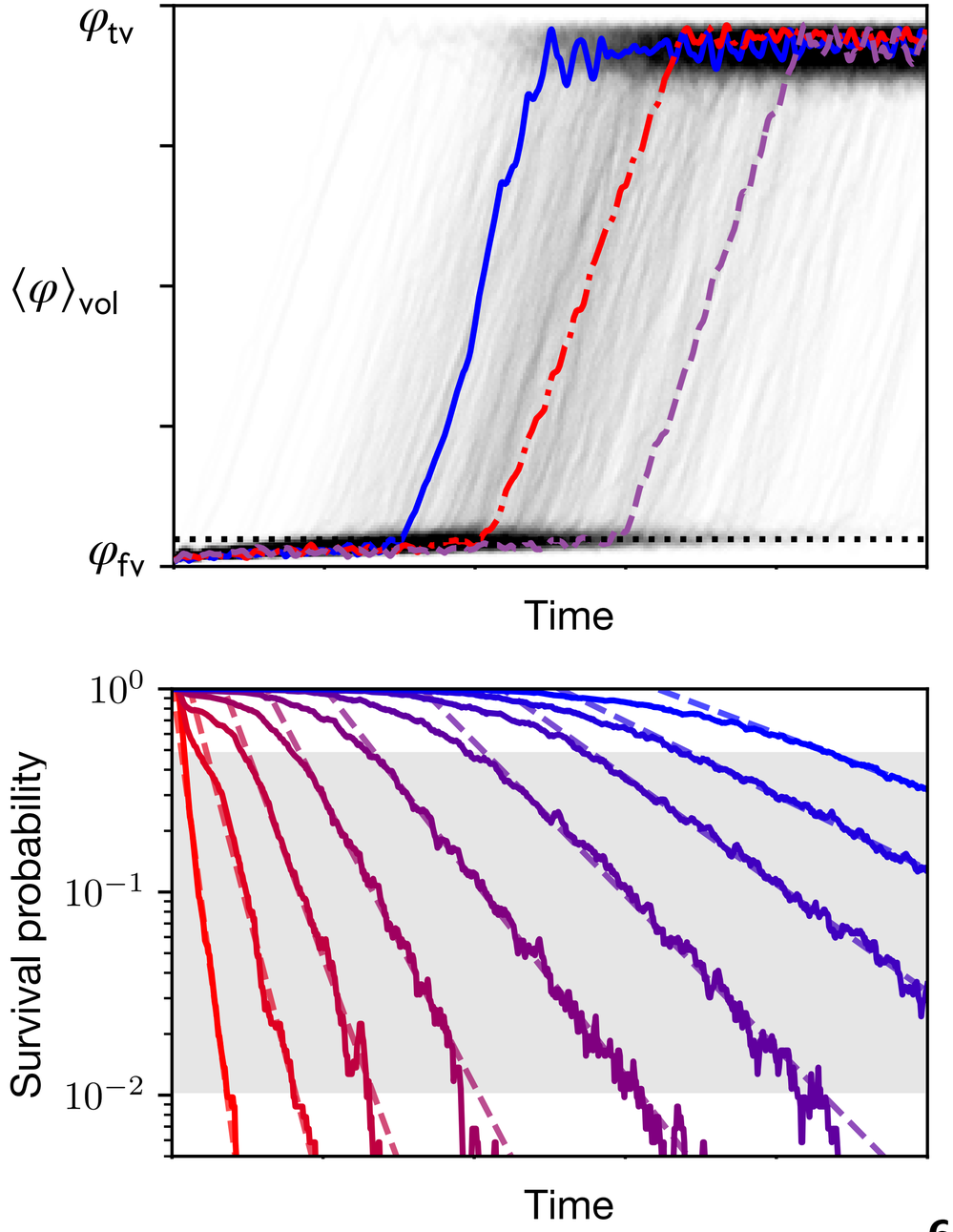




Decay rates on the lattice

- Count how many sims have decayed as a function of time, fit to find decay rate
- Observed rates are *significantly larger* than the instanton prediction — off by many orders of magnitude (!!)
- What's going on here?

Braden+, 1806.06069
ACJ+, 2307.02549



Understanding the discrepancy

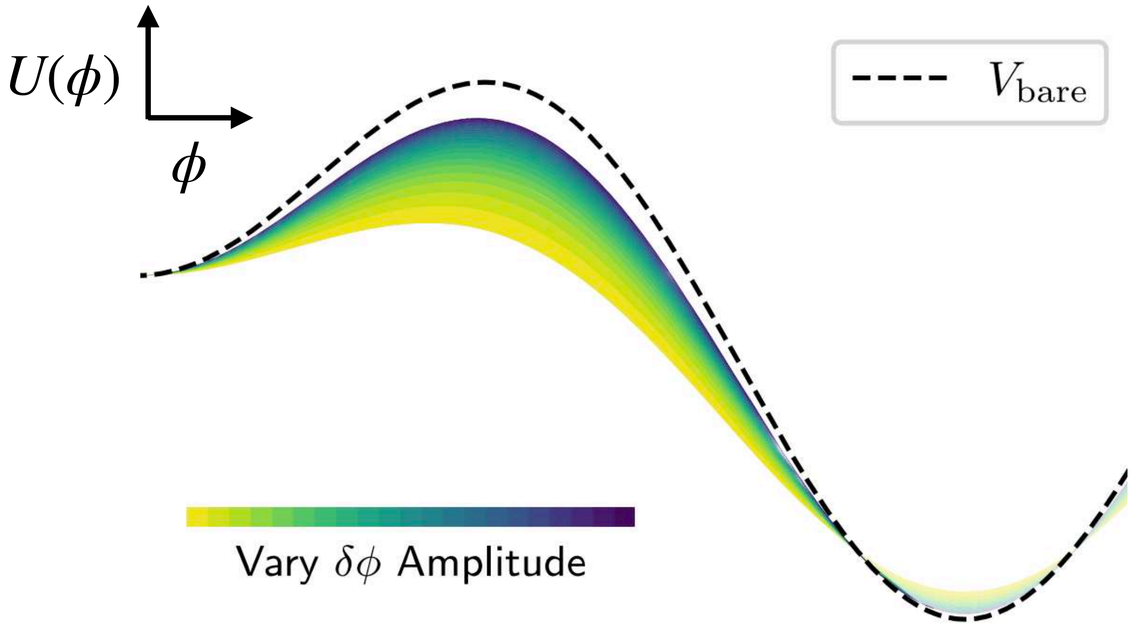


Why do bubbles nucleate so much faster on the lattice than the instanton prediction?

Hypothesis 1: We're seeing a different "decay channel" of the false vacuum. Coleman instantons are not captured with classical time evolution.

Hypothesis 2: We *are* seeing the same process, but are making the wrong comparison. Need to match predictions correctly.

Renormalisation on the lattice

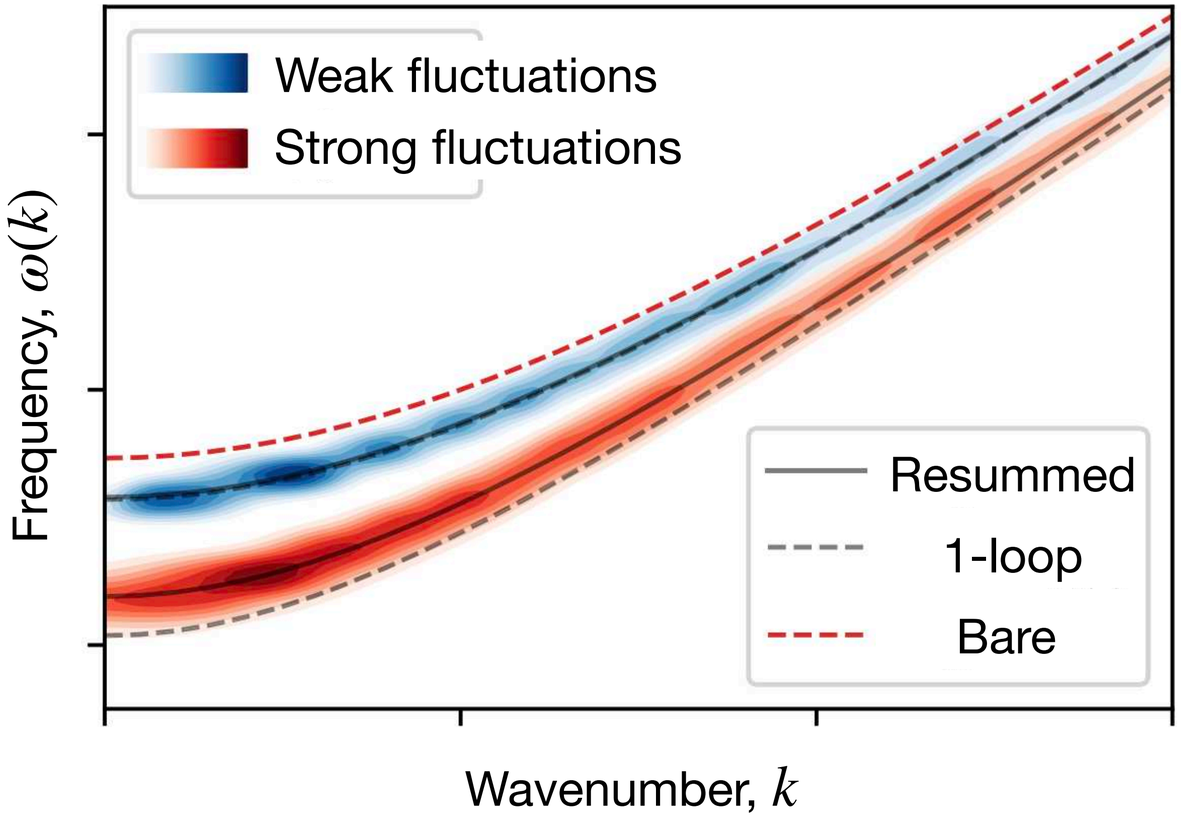


- Potential we put into the code differs from potential felt by modes on the lattice
- Short-wavelength fluctuations *renormalise* the potential felt by long-wavelength modes
- Computed at vacua via Gaussian resummation
- Region between vacua more challenging...

Braden+, 2204.11867



Measuring mass renormalisation



- Renormalised true/false vacuum masses measured with lattice data
- Excellent agreement with Gaussian resummed prediction
- Should be included when comparing against instanton predictions — explanation for enhanced rates?
- Need to extend theory beyond static vacuum states

Braden+, 2204.11867

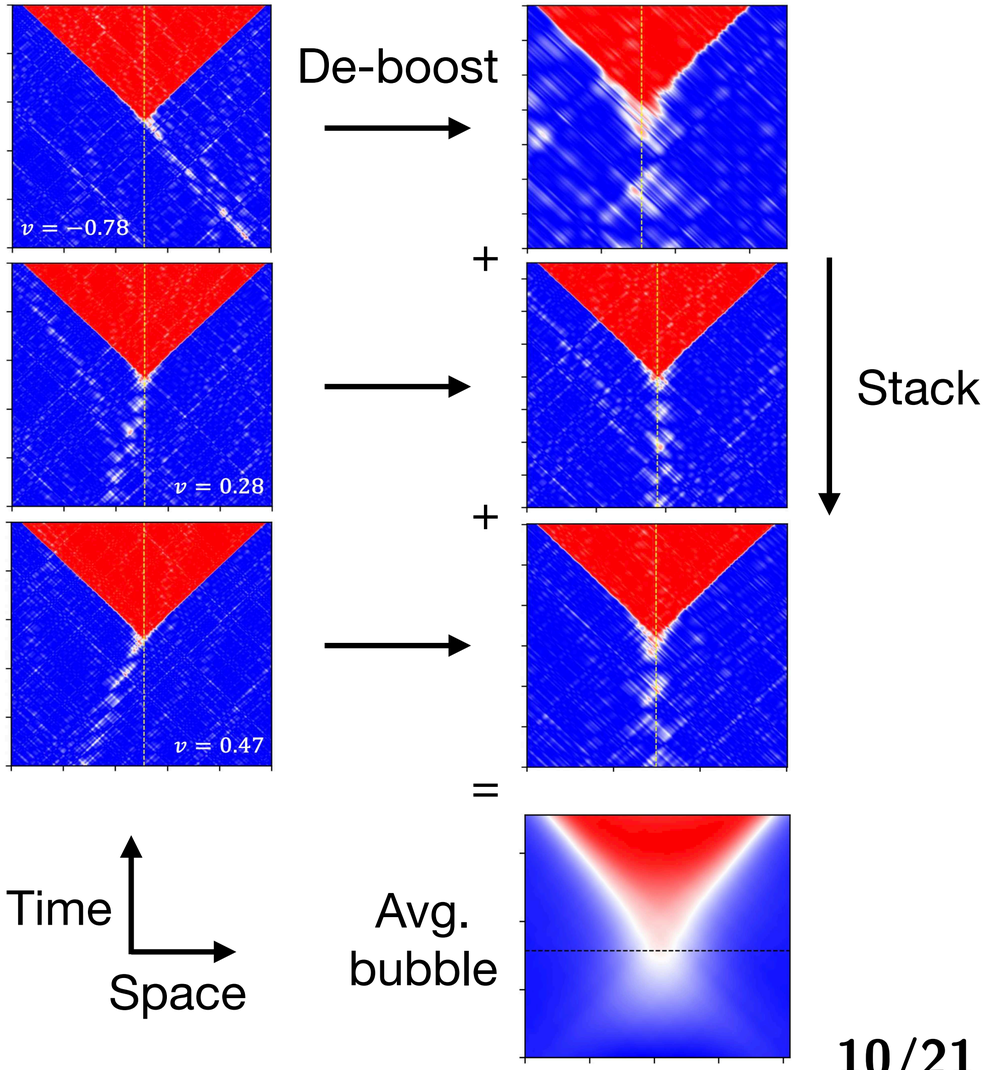


Measuring renormalisation with bubble profiles

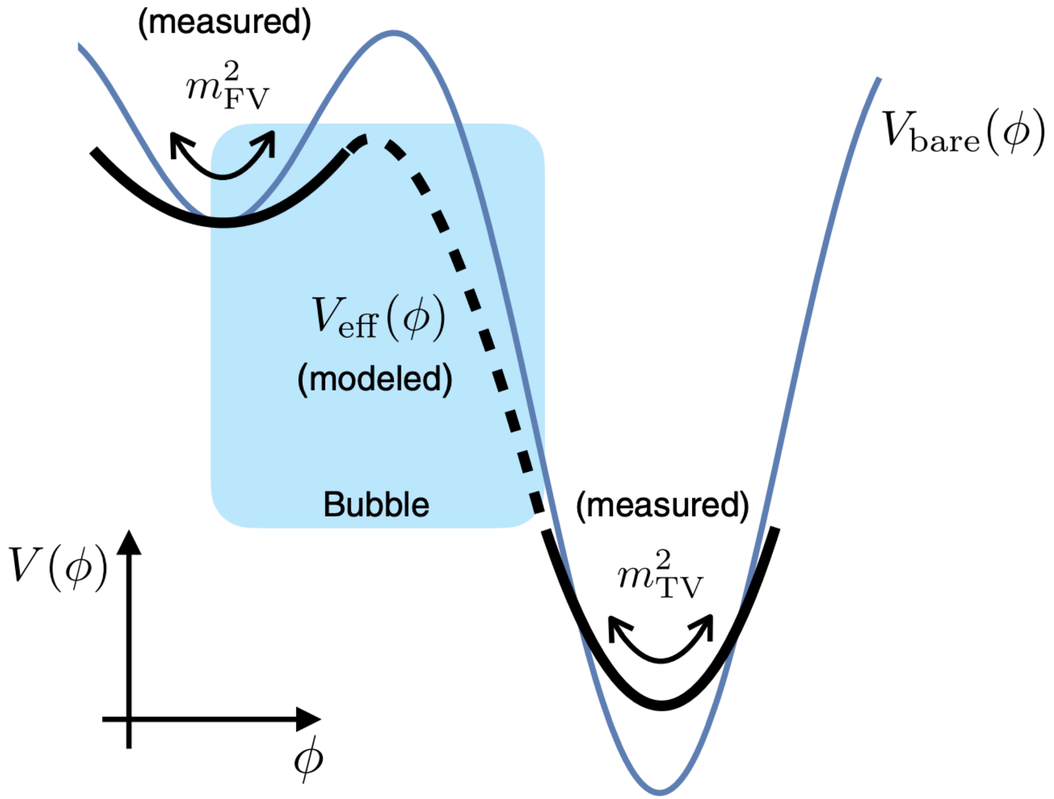
- Field configuration at nucleation uniquely determined by the *renormalised* effective potential $U_{\text{eff}}(\phi)$
- **Key idea:** Measure $U_{\text{eff}}(\phi)$ from bubble profiles observed on the lattice
- Empirical profile found by stacking many bubbles, de-boosted into their rest frames

Hertig, **ACJ**, Peiris, Pontzen, Johnson, 2607.06680



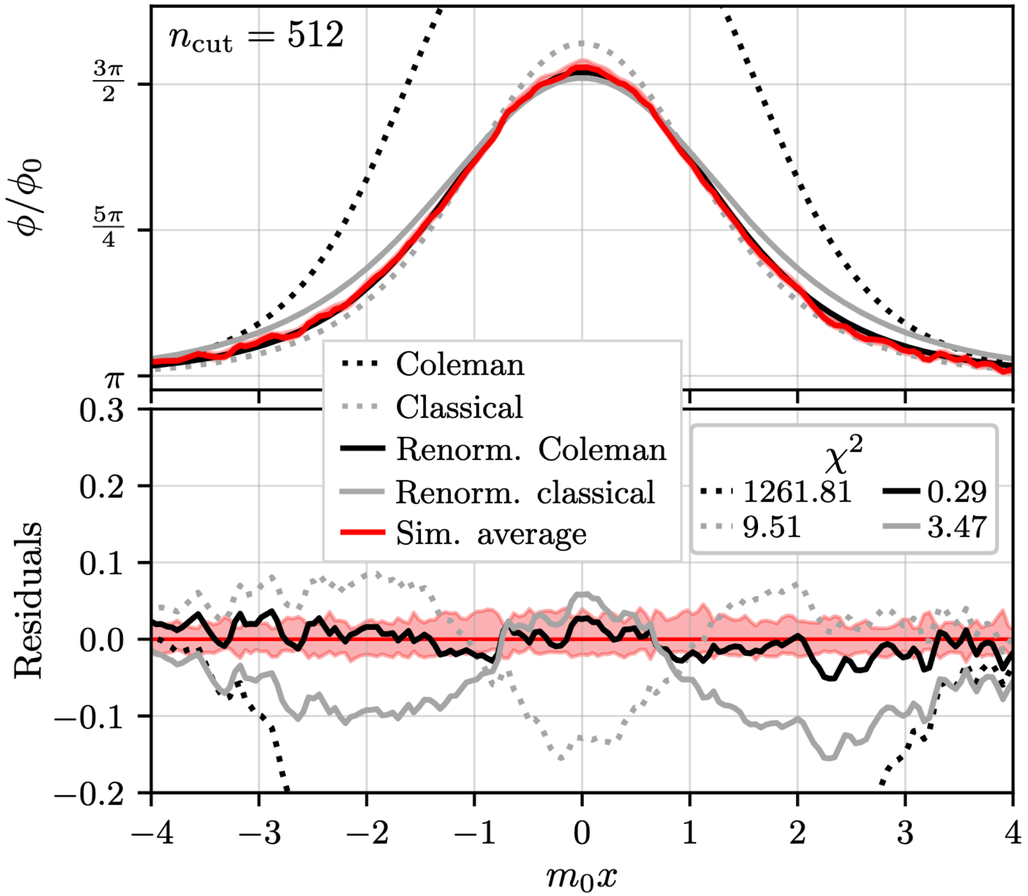


Bubble profile templates



- We consider vacuum (Coleman) and thermal bubbles, with and without renormalisation
- Without renormalisation, we use the bare potential
- With renormalisation, use a 1-parameter family of potentials and fit to the observed bubble profiles

Bubble profile results

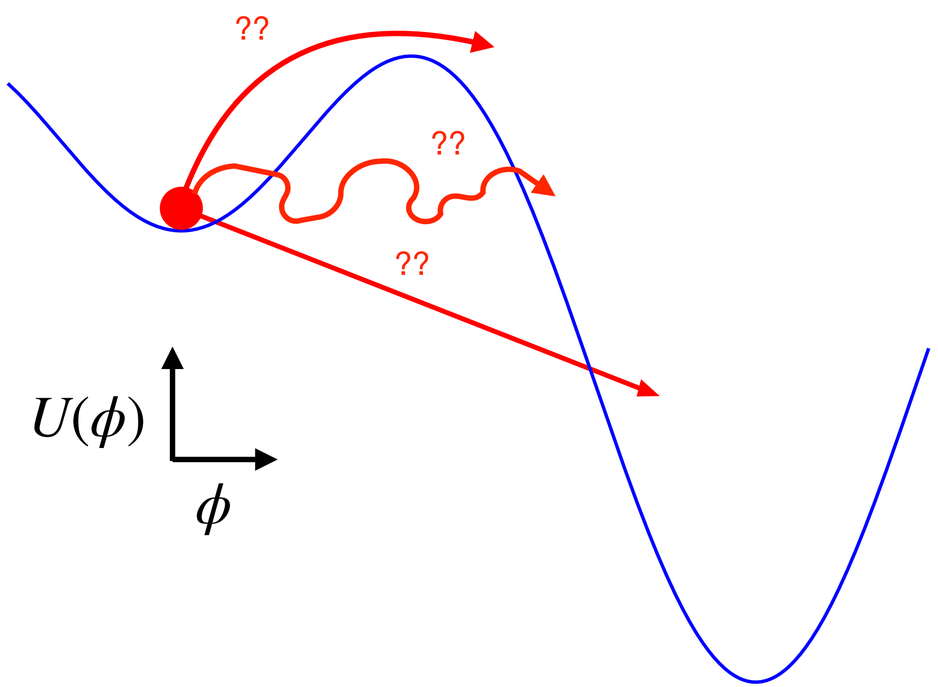


- We find compelling evidence for renormalised Coleman bubbles across all our simulation ensembles
- Running with UV lattice cutoff confirms this is a renormalisation effect
- Instanton decay rate computed with inferred $U_{\rm eff}(\phi)$ matches the lattice rate, resolving long-standing discrepancy

Hertig, **ACJ**, Peiris, Pontzen, Johnson, 2607.06680



Interpretation



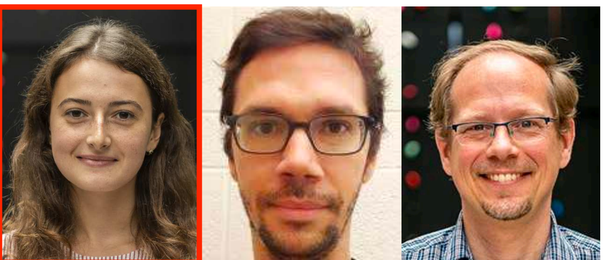
- Is nucleation really "under the barrier"? We recover Coleman bubbles with *purely classical* time evolution
- Usually think of "over the barrier" processes as thermal, but there is no thermalisation here
- In fact, there is no fixed energy barrier in field theory! $U(\phi)$ is an energy *density* which fluctuates, even in vacuum

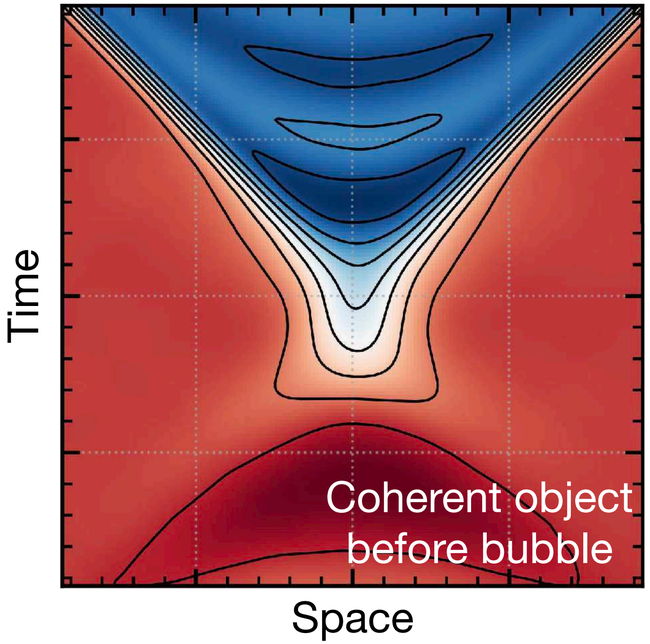
Beyond decay rates

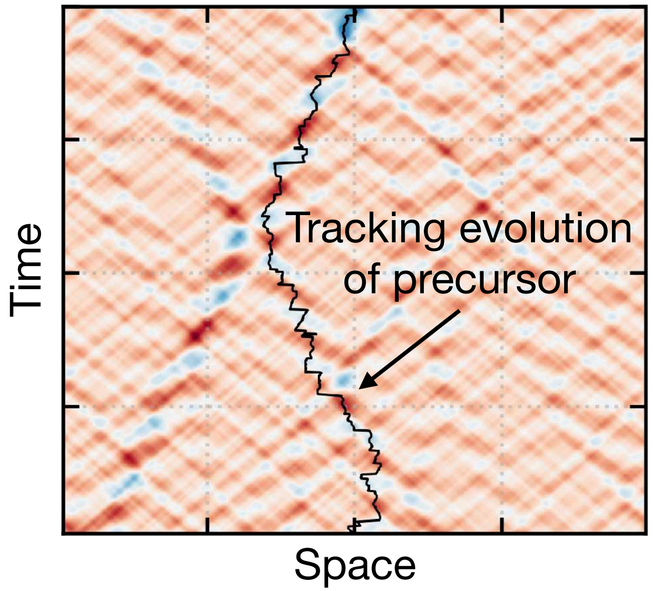
- Many interesting new real-time observables missing from the usual instanton picture:
  - Multi-bubble correlations
  - Peculiar velocities
  - *Oscillon precursors*

  Pîrvu+, 2312.13364, 2109.04496

- These could all have important consequences for the early Universe





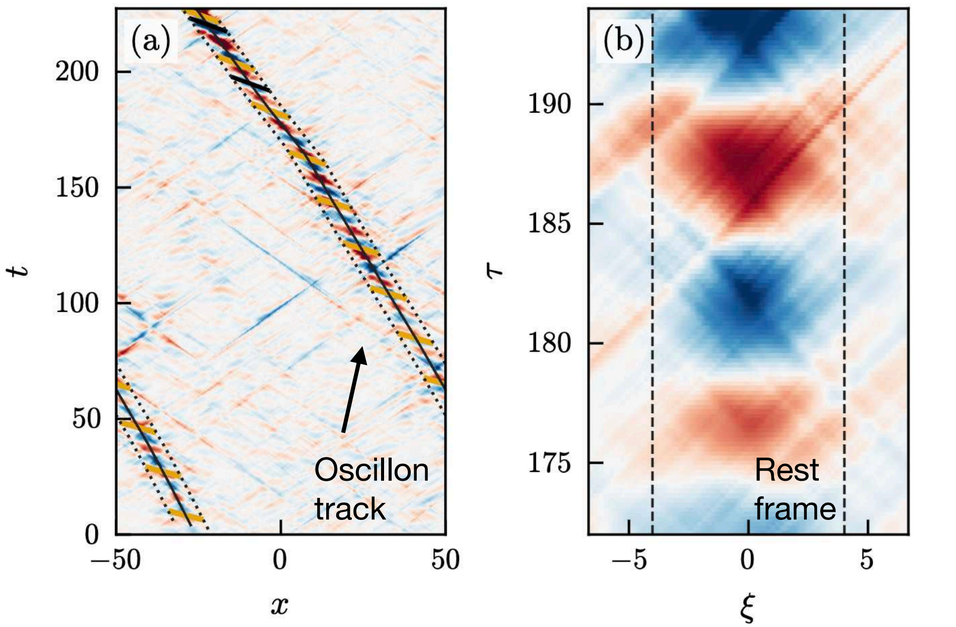


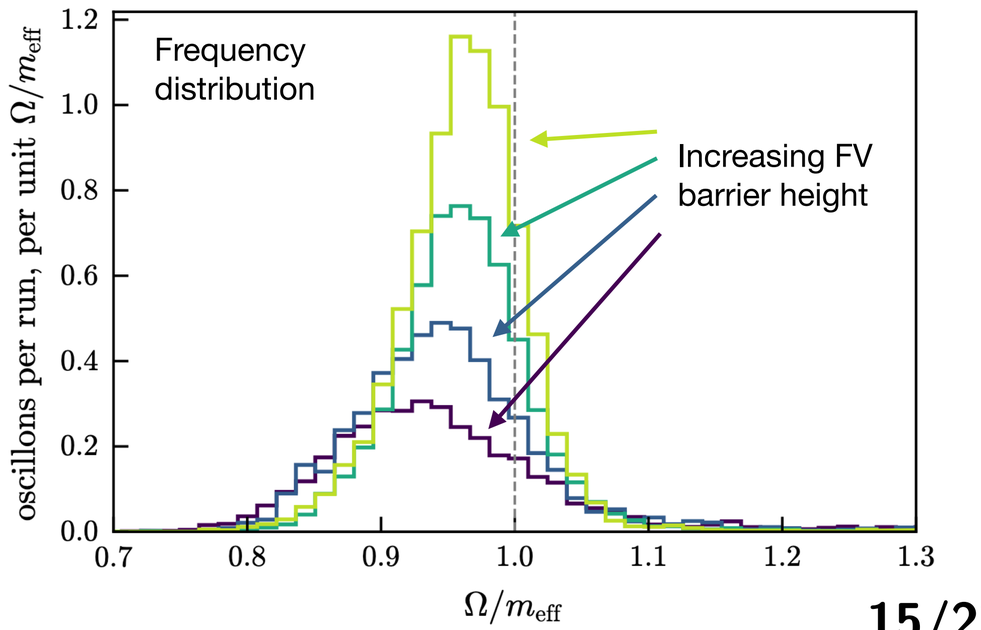
Tracking the precursors

- Tracking oscillons on the lattice is challenging due to fluctuations
- Recently built a numerical framework for extracting oscillons and measuring rest-frame properties (e.g. frequency)
- Next step: pinning down the link between oscillons and bubbles

Wang, Jenkins, 2610.xxxxx





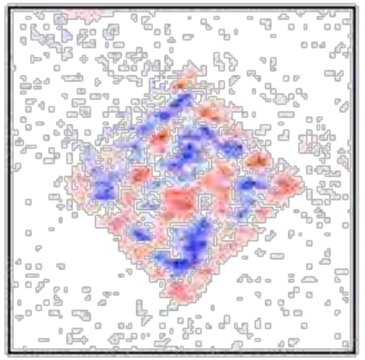


Plan for this talk

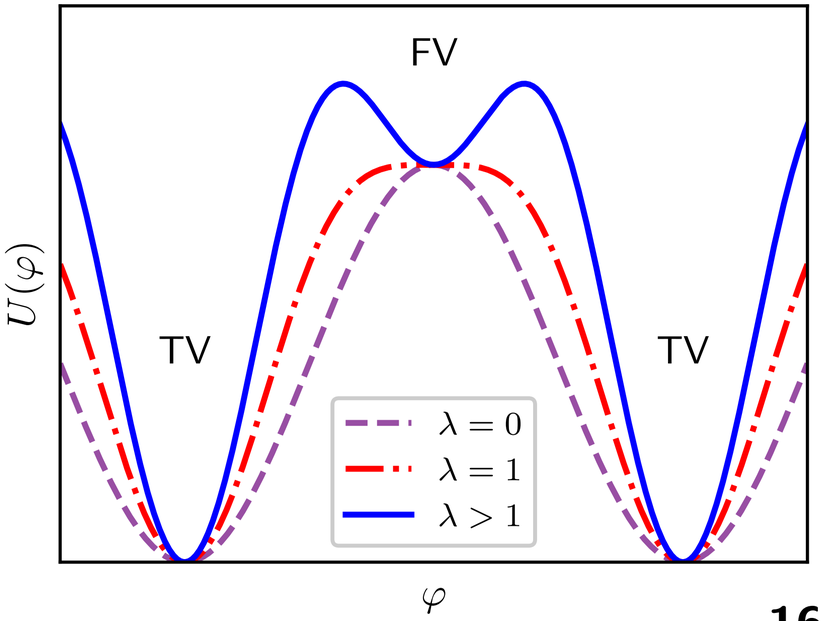
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Our quantum hardware: ultra-cold atoms

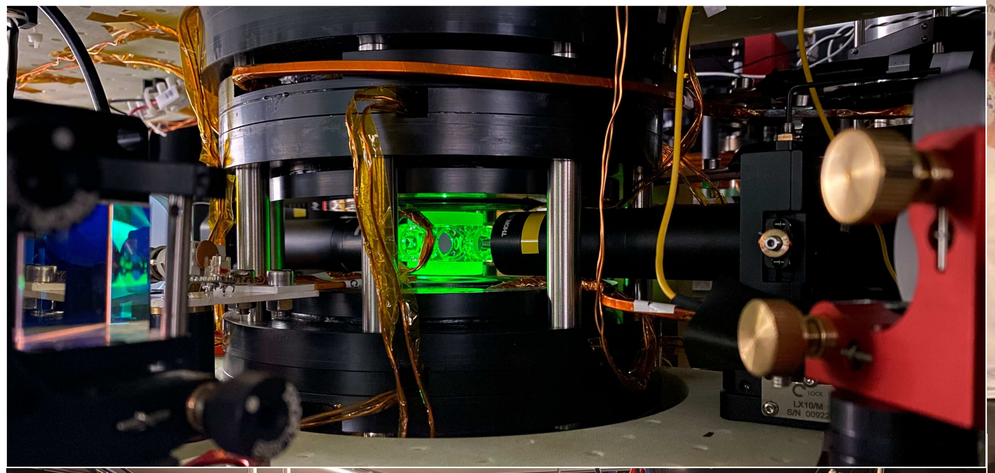
- Cold bosonic atoms form a *condensate* — a quantum field you can take a picture of
- Phase ϕ of the condensate $\psi = \sqrt{n}e^{i\phi}$ behaves like a *relativistic* scalar field on "large" scales ($\gtrsim 1\mu\mathrm{m}$)
- Coupling two condensates ψ_1, ψ_2 gives a potential for the relative phase $\varphi = \phi_1 - \phi_2$
- This can be engineered to produce a metastable false vacuum

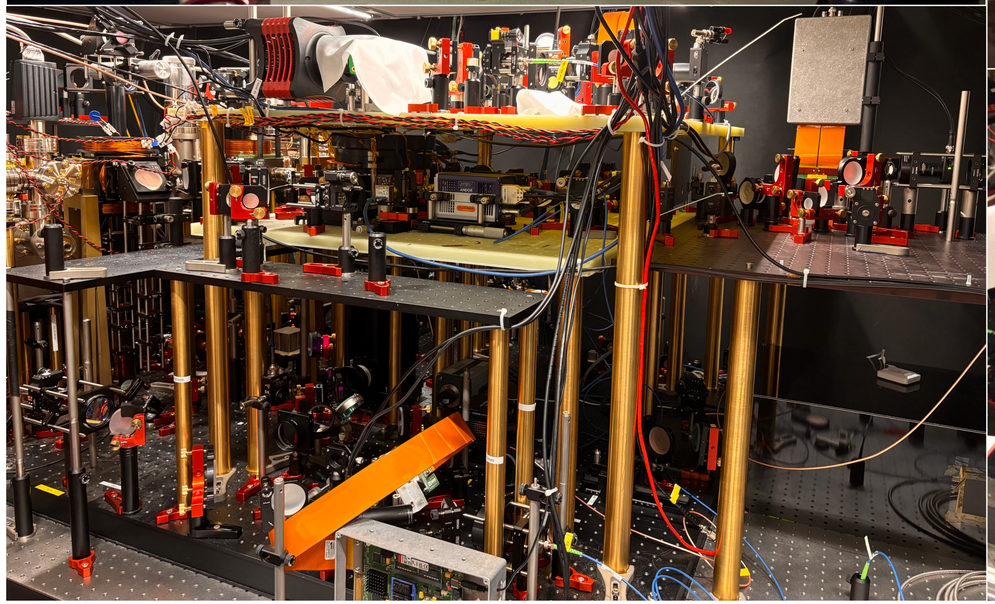


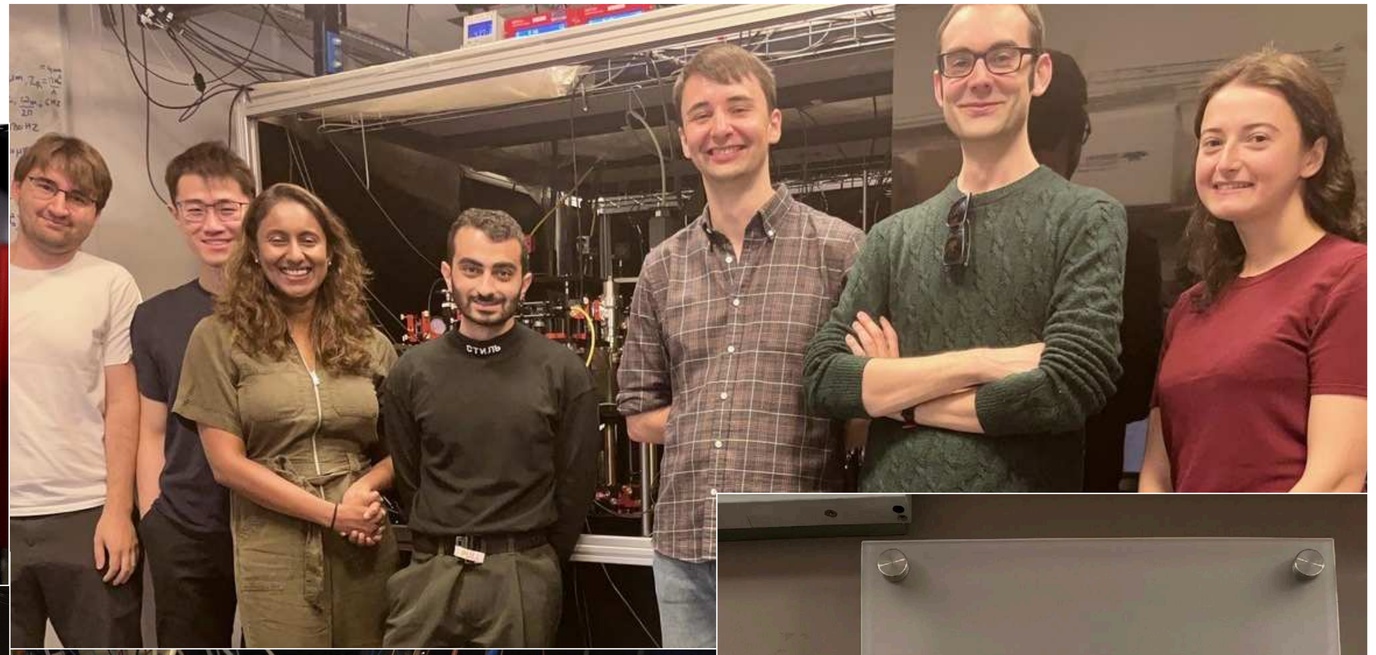


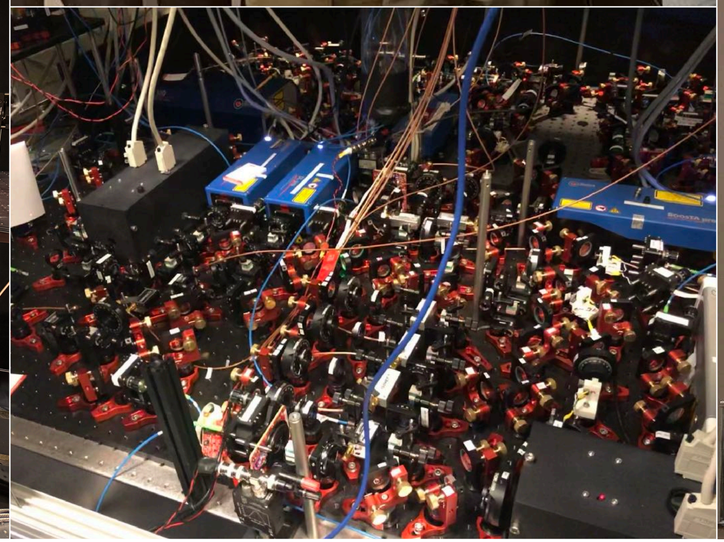


The experiment











Collaborators

Cosmology theory

Cold-atom theory

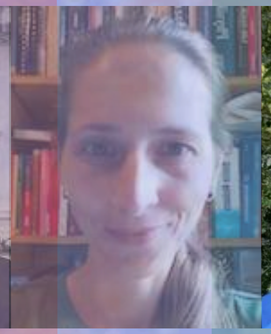
Cold-atom experiments


Jonathan Braden
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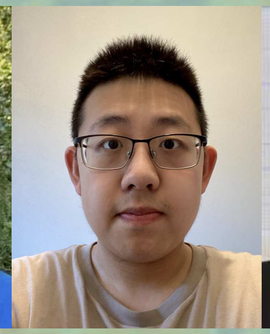

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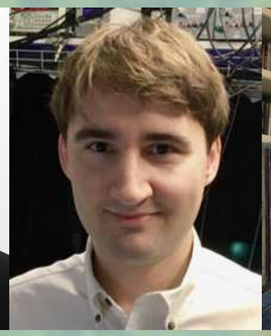

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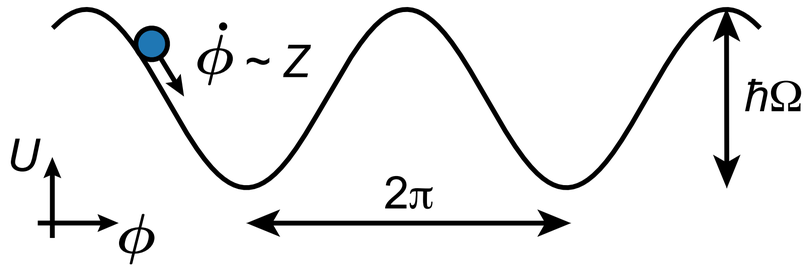

Christoph Eigen
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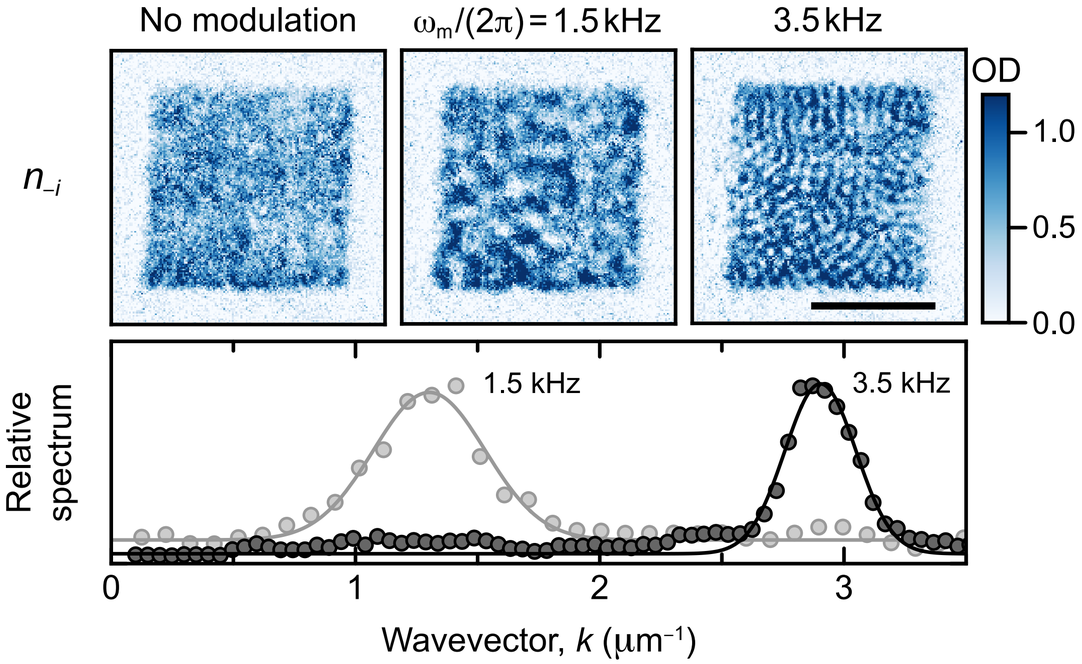

Zoran Hadzibabic
(Cambridge)

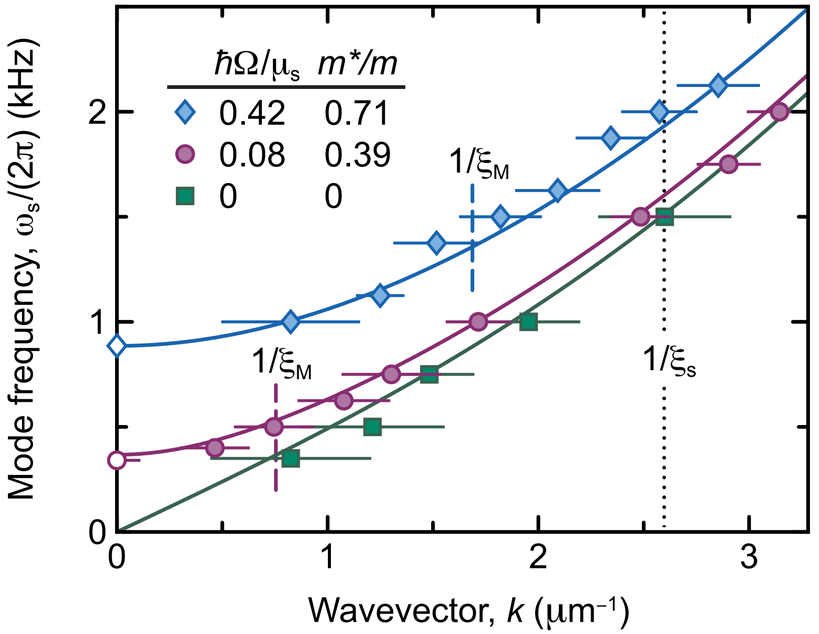
First experimental results

- Uniform two-component condensate *without* false vacuum: Sine-Gordon simulator
- Relativistic dispersion relation with tuneable mass measured by exciting parametric resonances
- Excellent agreement with theory

Zhang *et al.* (inc. **ACJ**), 2603.08840



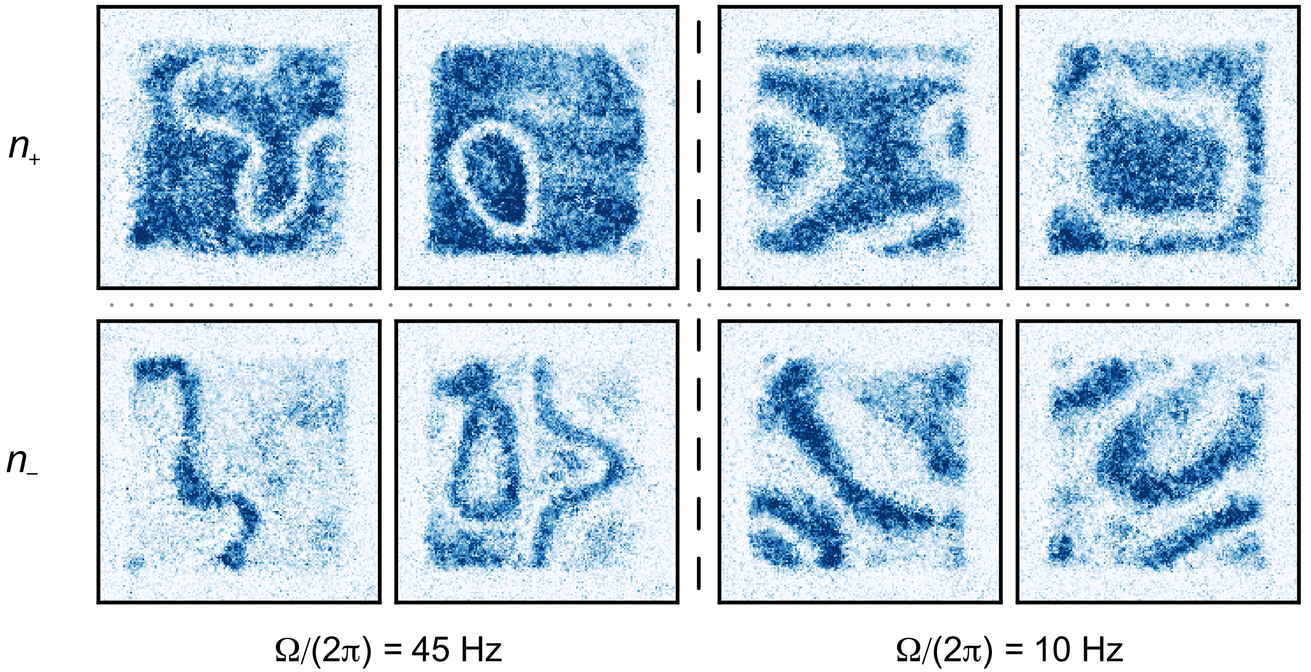


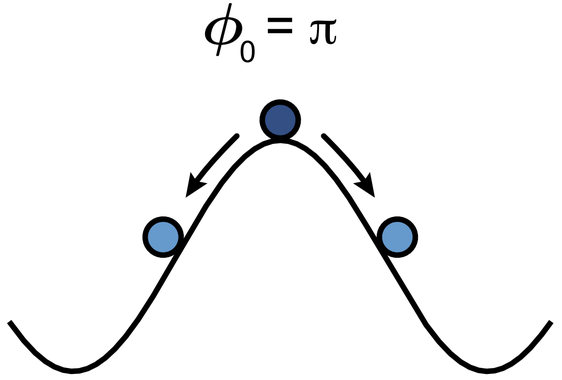


Simulating cosmic domain walls

- Initialising at potential maximum causes defect formation via spontaneous symmetry breaking
- Wall thickness set by the (tuneable) Sine-Gordon mass
- Now working to investigate these objects in detail and compare data with simulations
- Nonperturbative, nonequilibrium quantum field theory in the lab!

Zhang *et al.* (inc. **ACJ**), 2603.08840

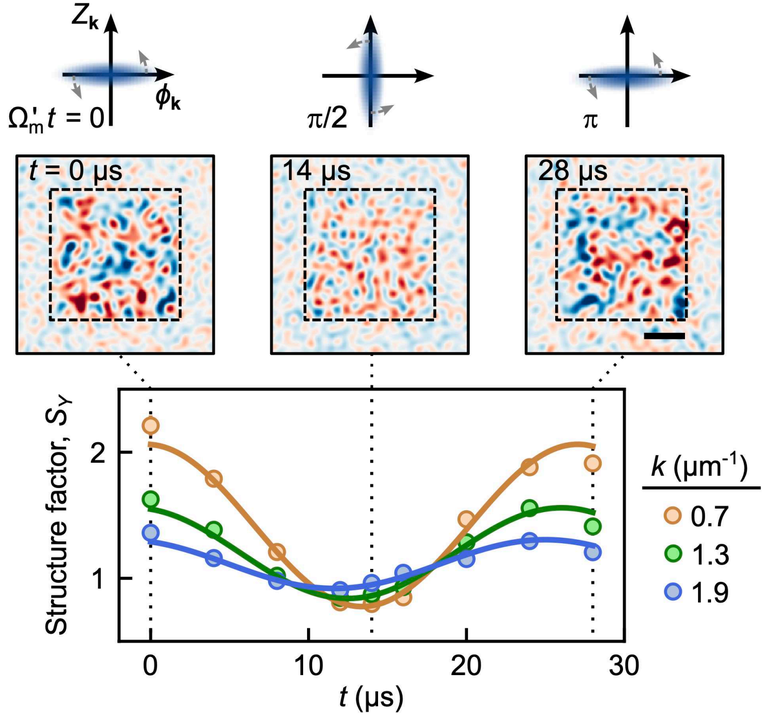


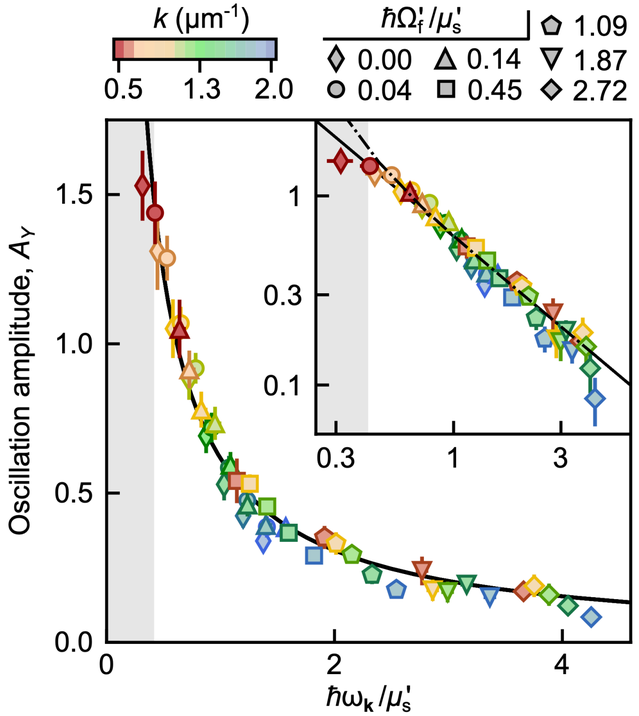


Imaging vacuum fluctuations

- Direct imaging allows us to probe field fluctuations
- Amplitude measured by rotating the squeezed state before imaging
- Resulting scale-dependent amplitude in excellent agreement with zero-temp QFT prediction

Zhang *et al.* (inc. **ACJ**), 2608.20311

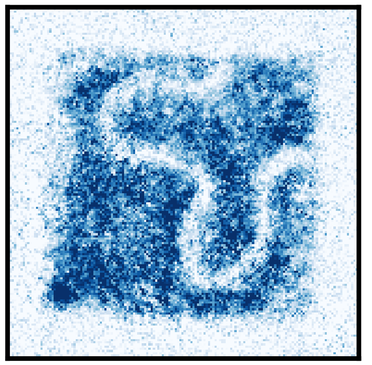


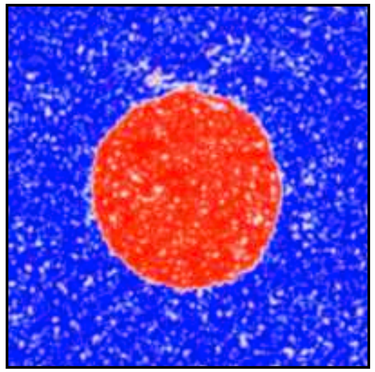


What can we learn with these experiments?

In the near term

- Tests of Kibble-Zurek theory of defect formation
- What are the statistics of the defect network? Do these encode quantum correlations?
- How are the defects renormalised by quantum fluctuations?





In the intermediate term

- Implementing the false vacuum via modulated coupling
- Does the Coleman formalism correctly capture decay rates?
- Do bubbles cluster? Do they have precursors?
- What are the implications for the early Universe?

Unifying theme: Going beyond (semi)classical calculations with a fully quantum simulator

Summary

- *Vacuum decay* is ubiquitous in cosmology, but is poorly understood — we need a *dynamical, real-time* theory
- Quantum analogues offer the *first empirical probes* of this process
- Real-time lattice simulations offer *new conceptual insights* and help us design and interpret the experiments
- Potentially far-reaching implications for our understanding of the early Universe, but much work still to do — stay tuned

Thanks for listening!