Alex Jenkins | acj46@cam.ac.uk | 26 June 2026
PASCOS @ Sheffield

UNIVERSITY OF CAMBRIDGE

Toward a real-time theory of vacuum decay

Based on: **ACJ**, Braden, Peiris, Pontzen, Johnson, Weinfurtner, **2307.02549**
+ **ACJ**, Moss, Billam, Hadzibabic, Peiris, Pontzen, **2311.02156**
+ **ACJ**, Peiris, Pontzen, **2504.02829**
+ Zhang *et al.* (inc. **ACJ**), **2603.08840**
+ Hertig, **ACJ**, Peiris, Pontzen, Johnson, **2606.xxxxx** (in prep.)

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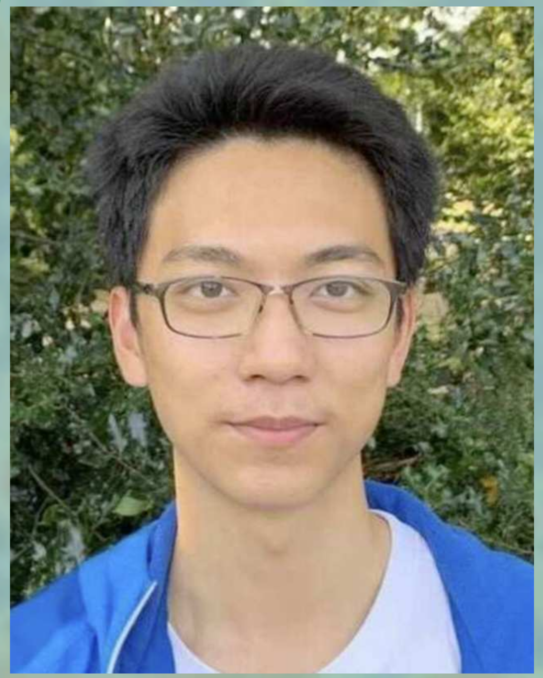
Yansheng Zhang
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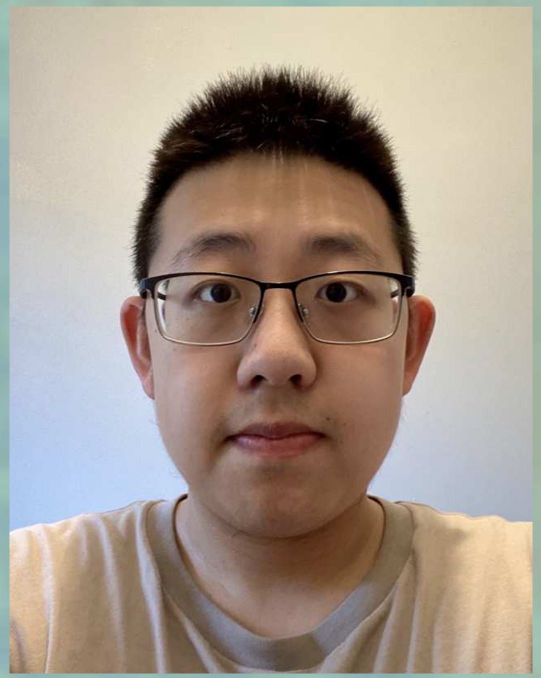
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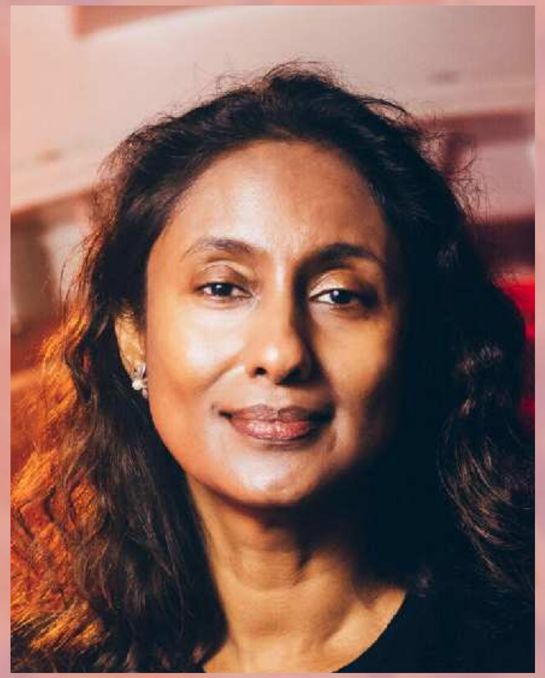
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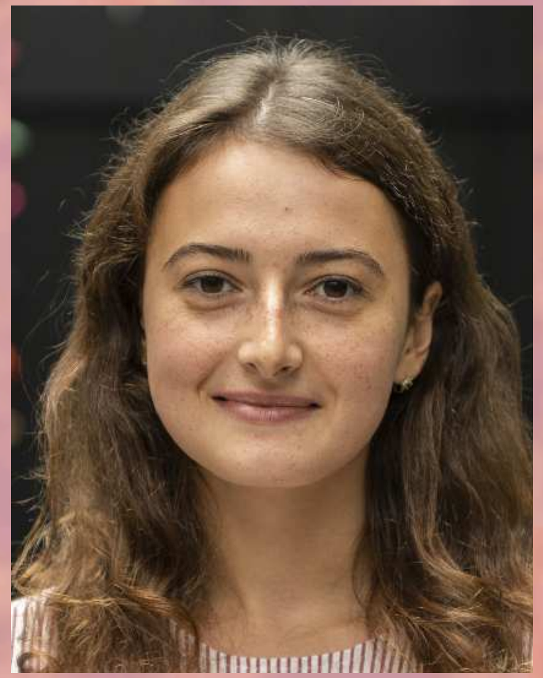
(Cambridge)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(Cambridge)

Cosmology theory

Cold-atom theory

Cold-atom experiments

Plan for this talk

1. **Vacuum decay: standard lore and open problems**
2. Semiclassical simulations on the lattice
3. Quantum simulations in the laboratory

Vacuum decay basics

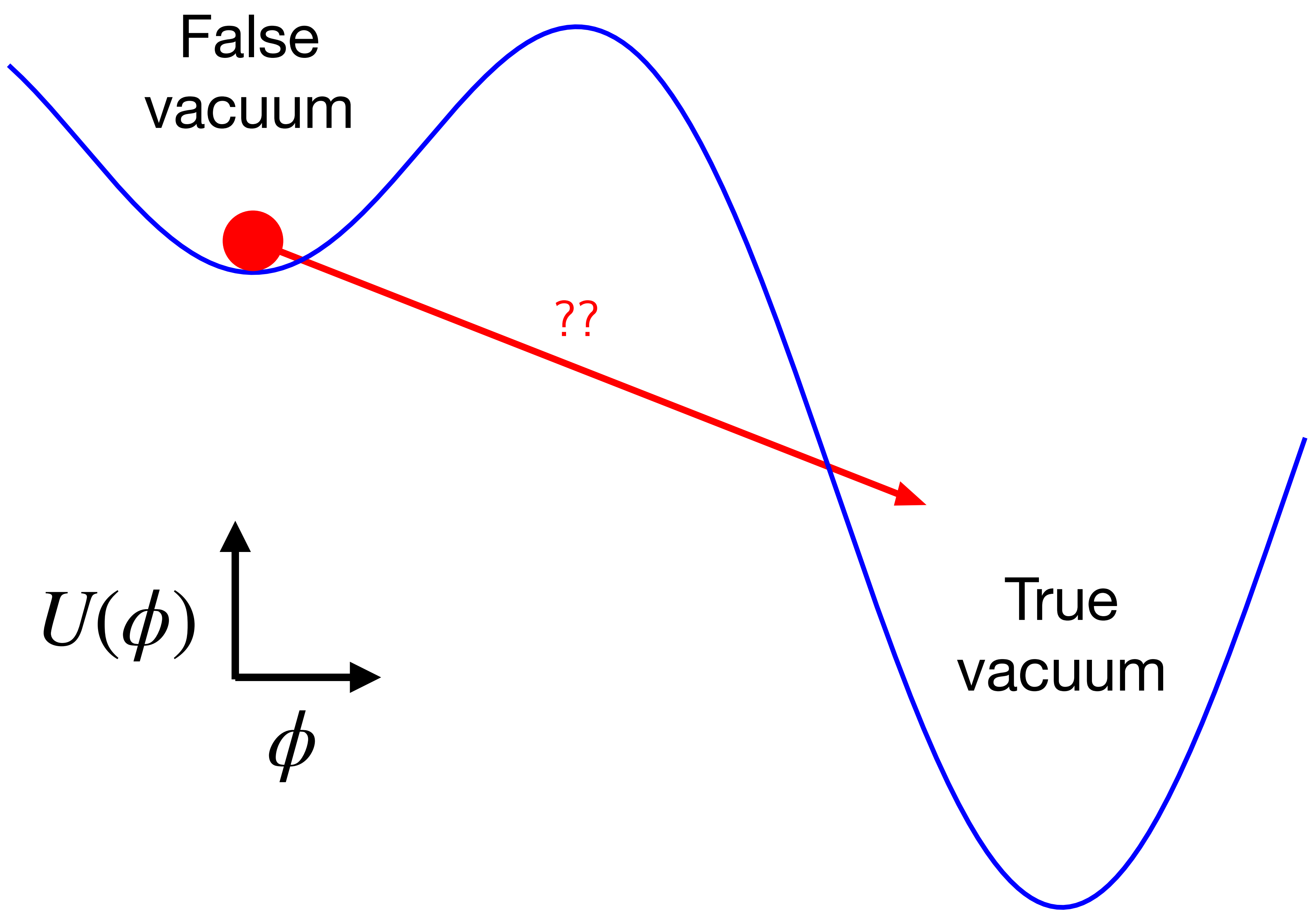
- We have a relativistic scalar field,

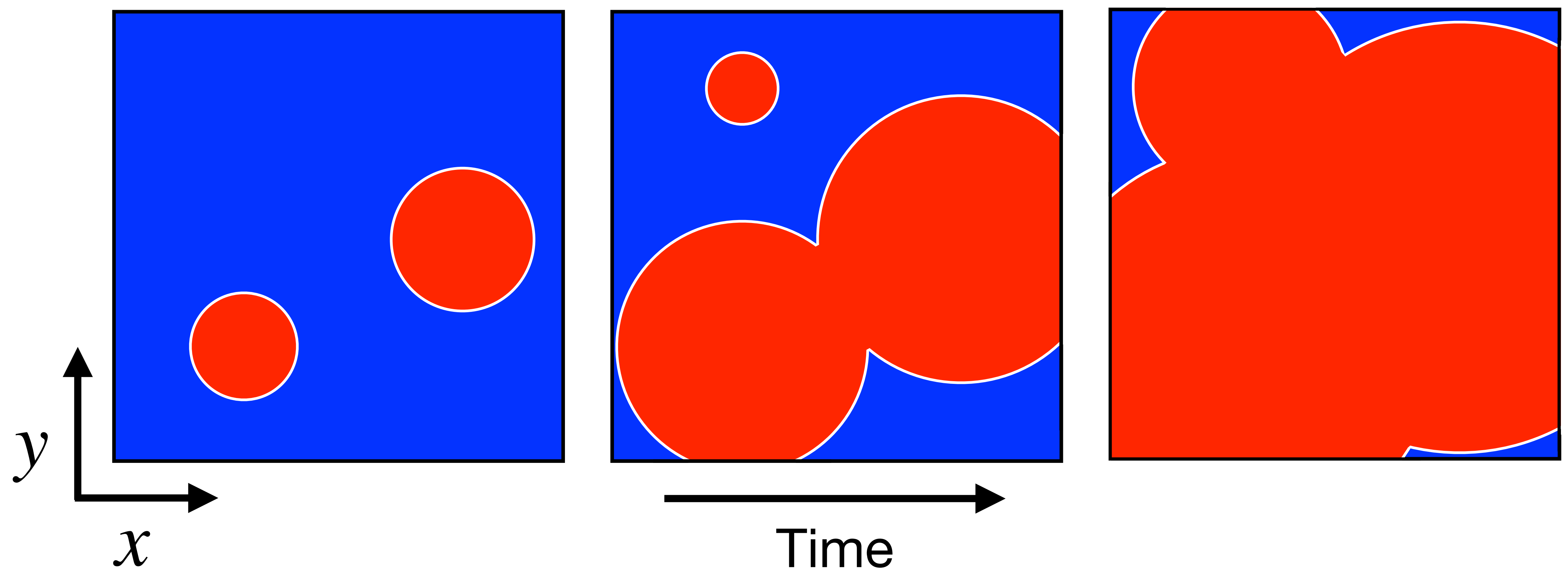
$$\partial_t^2 \varphi - \nabla^2 \varphi + U'(\varphi) = 0$$

- Field escapes from *local* minimum of potential $U(\varphi)$ to *global* minimum

- Nucleates spatially localised "bubbles" of true vacuum

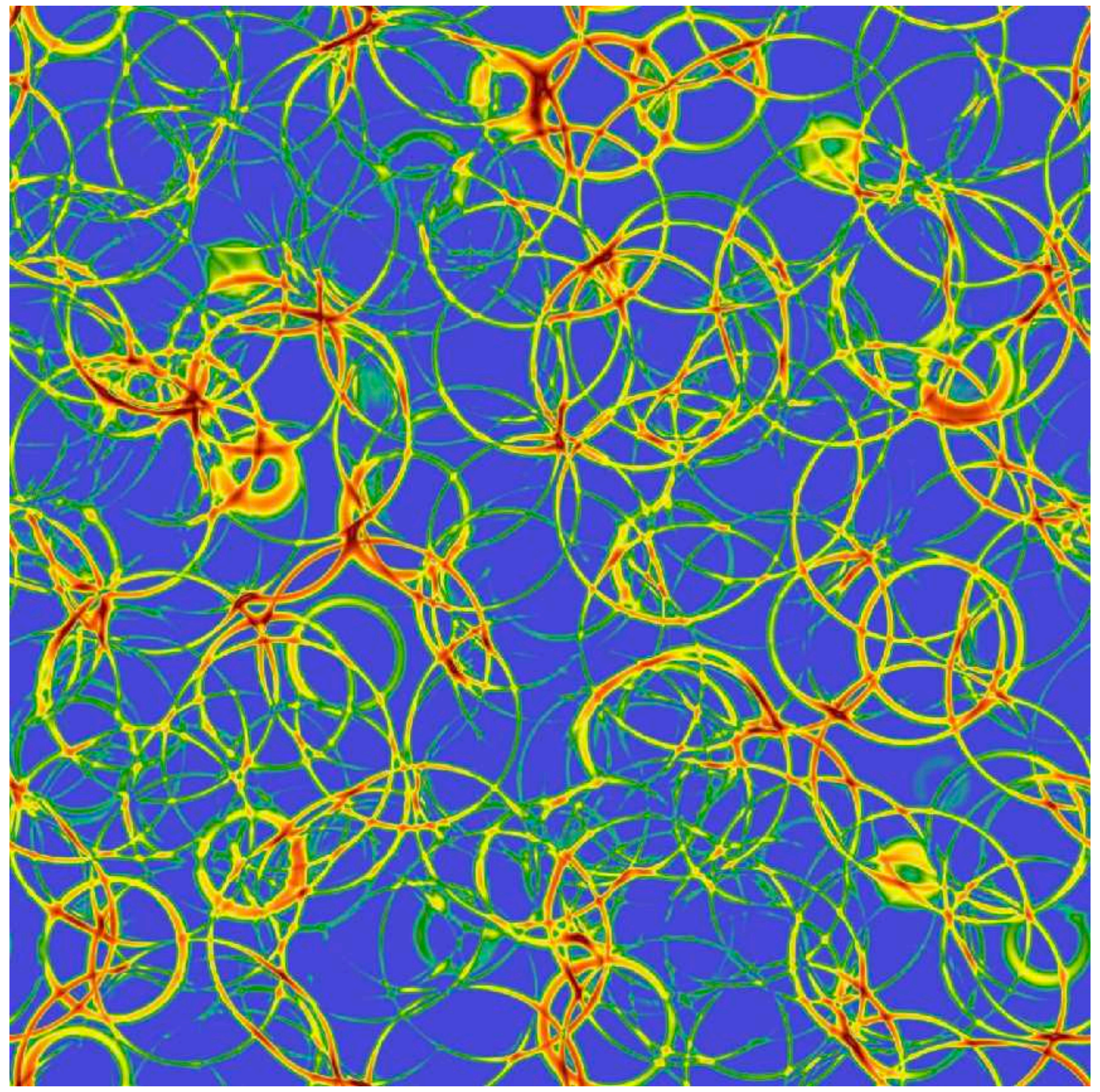
- Non-perturbative, non-equilibrium QFT process … *very difficult problem!*

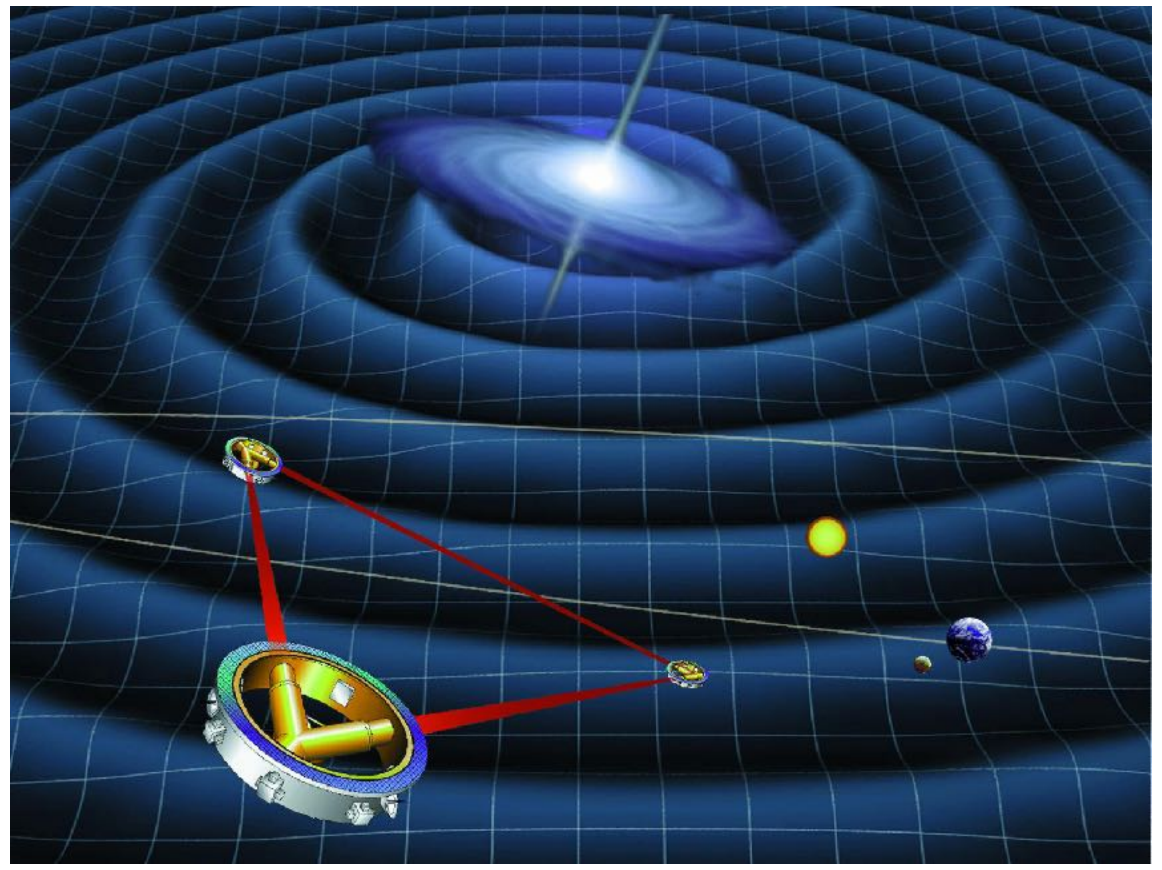




Why do we care?

Hindmarsh+,1511.04527

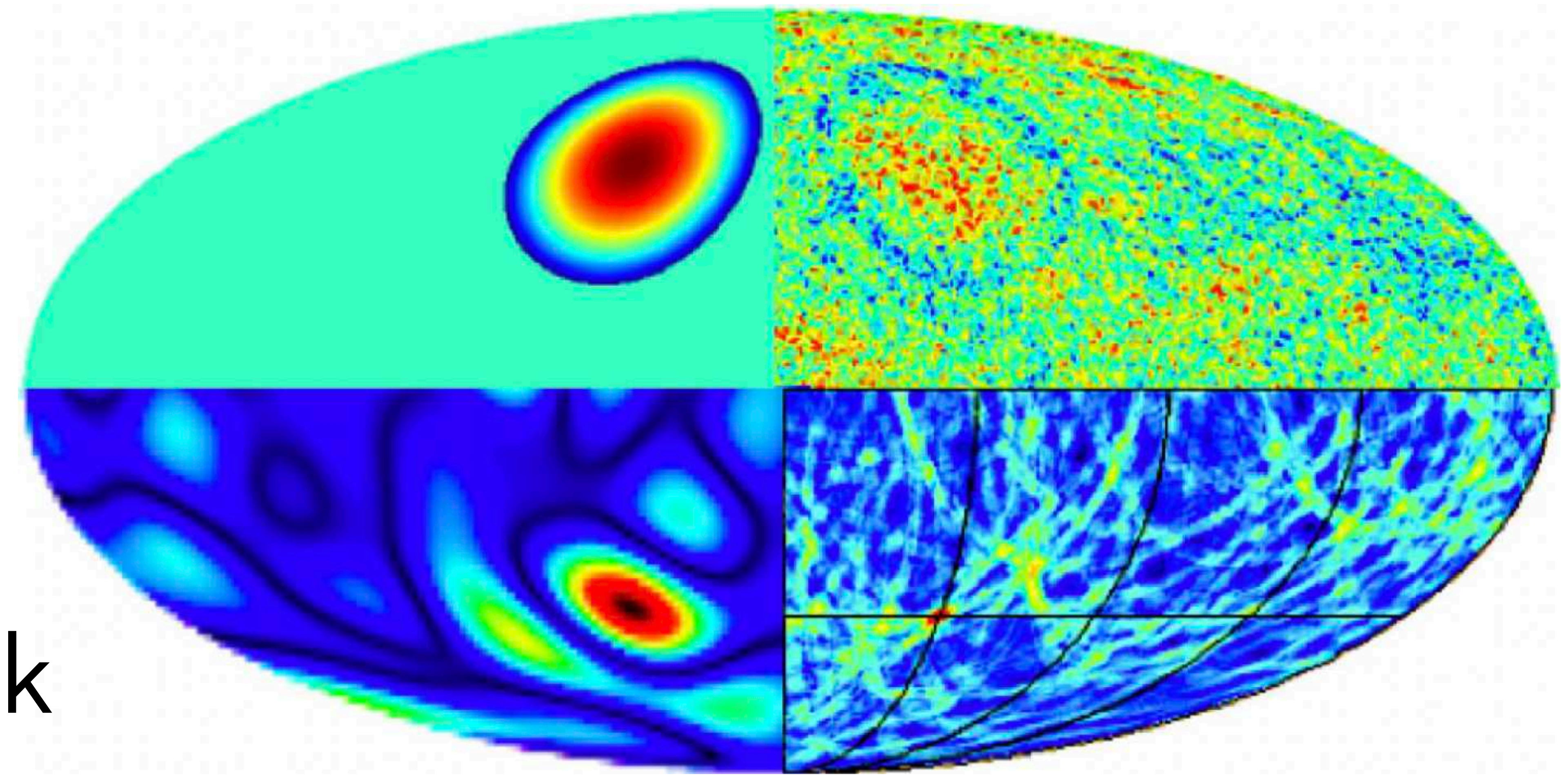




Electroweak Baryogenesis

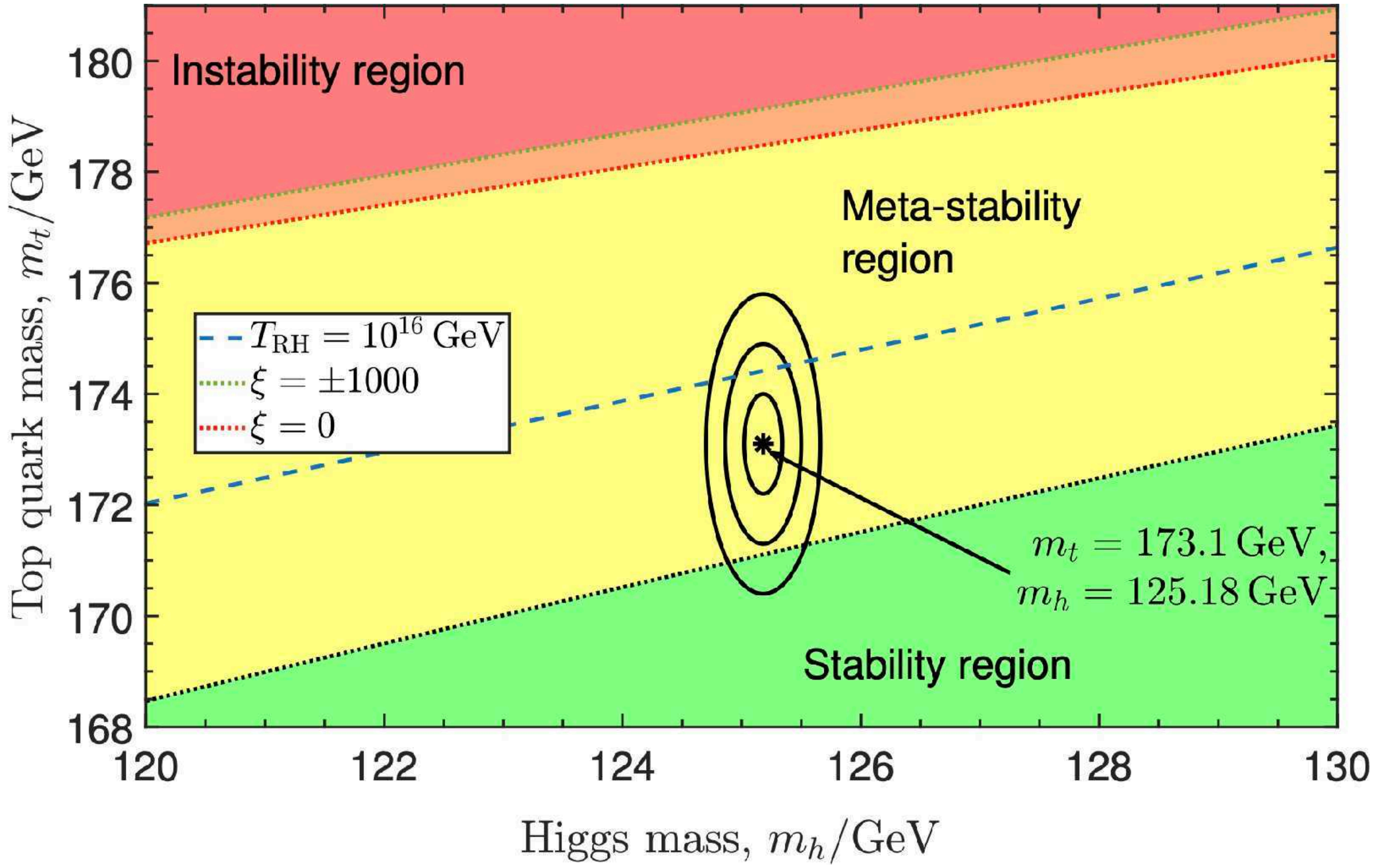
Gravitational-wave cosmology

Feeney+, 1012.1995



Inflation and the multiverse

Markkanen+, 1809.06923

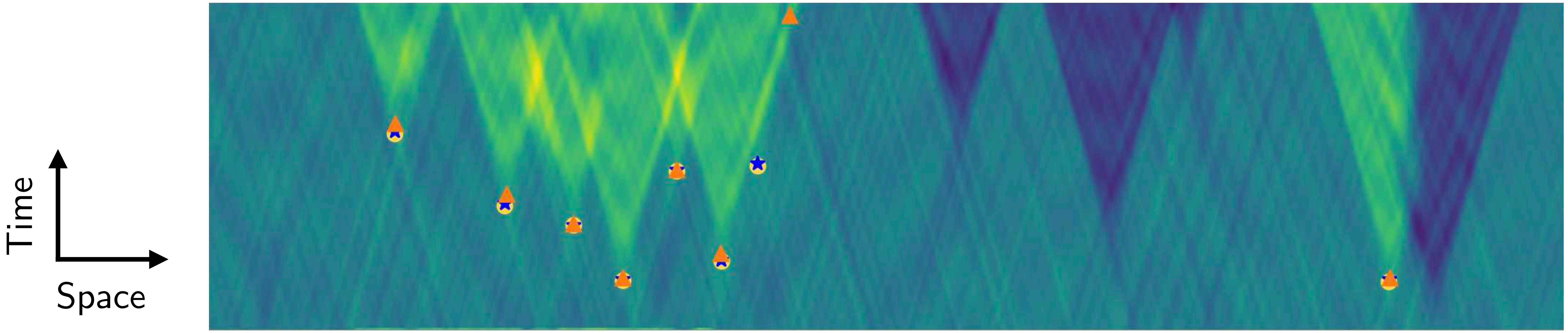


Stability of the Higgs vacuum

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?

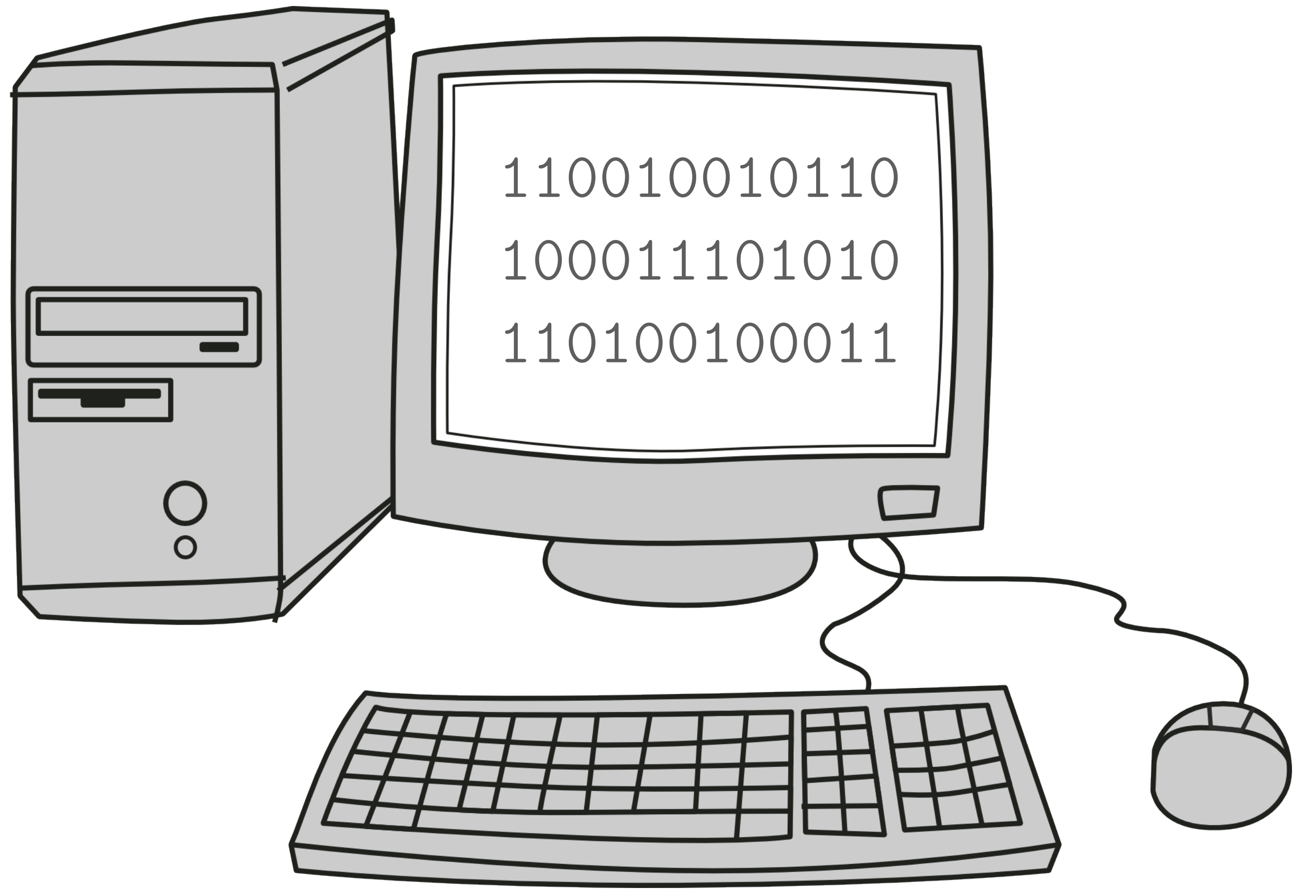


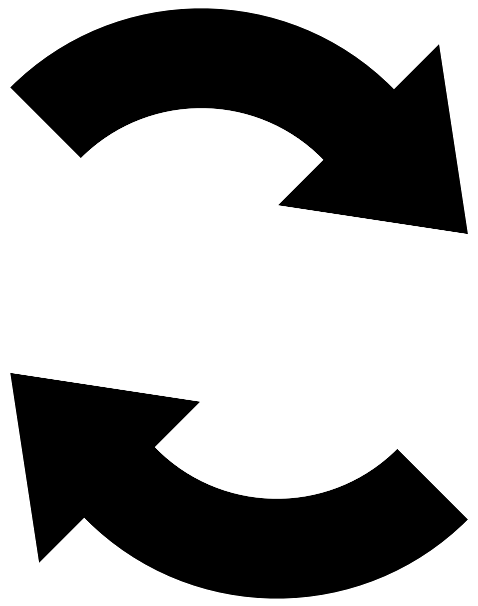
Pîrvu+, 2109.04496

Two routes forward

Real-time lattice simulations

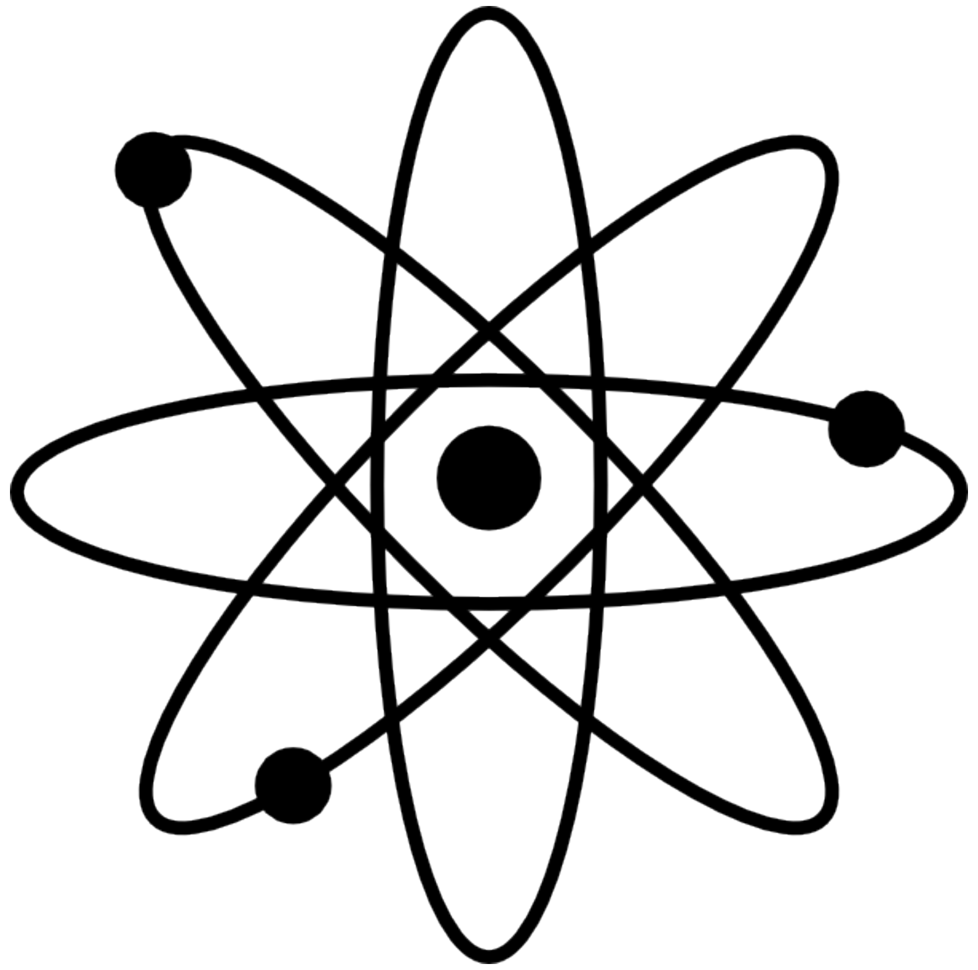
Use a semiclassical approach to study bubble nucleation numerically





Quantum analogue simulations

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



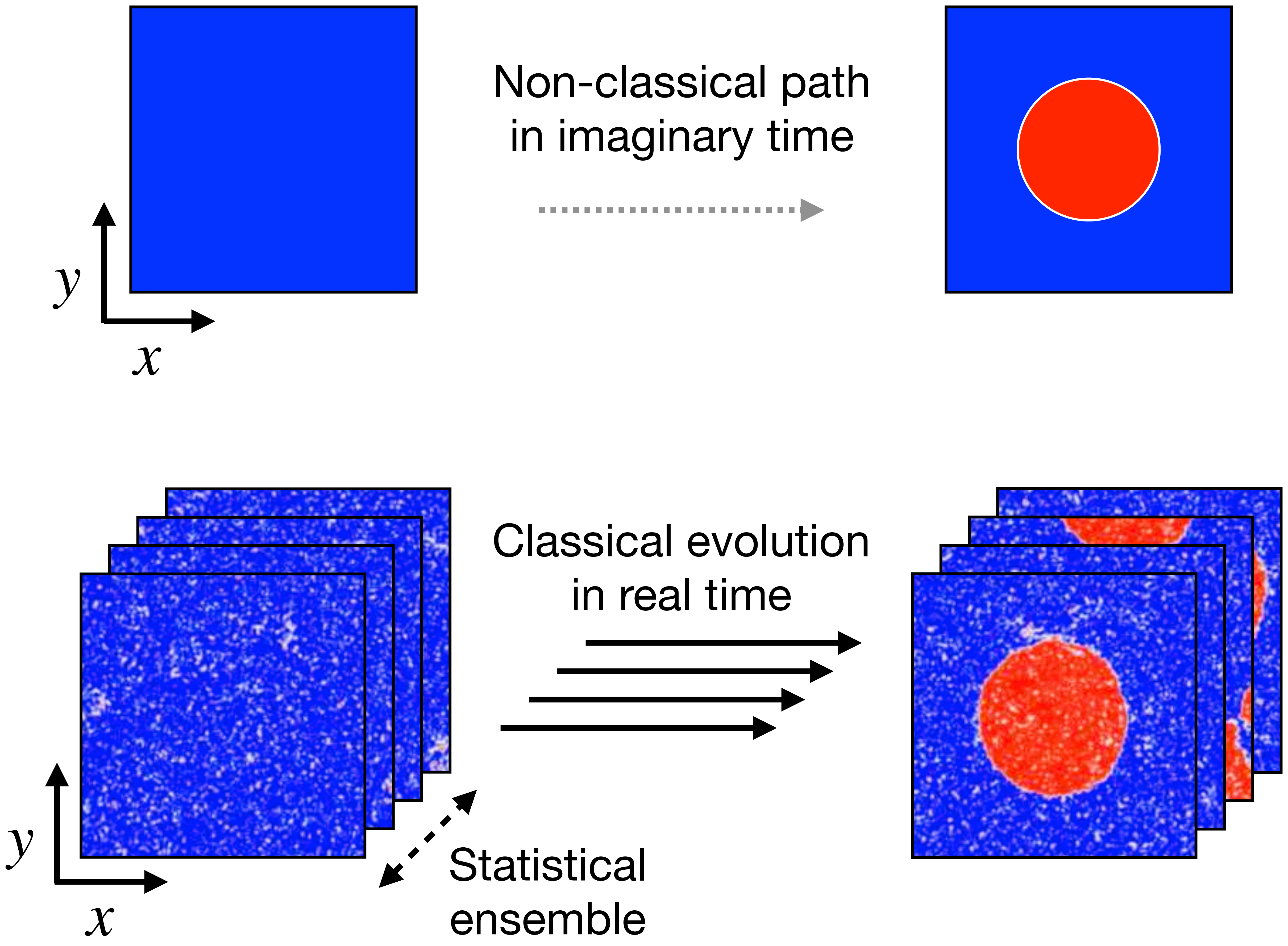
Plan for this talk

1. Vacuum decay: standard lore and open problems
2. **Semiclassical simulations on the lattice**
3. Quantum simulations in the laboratory

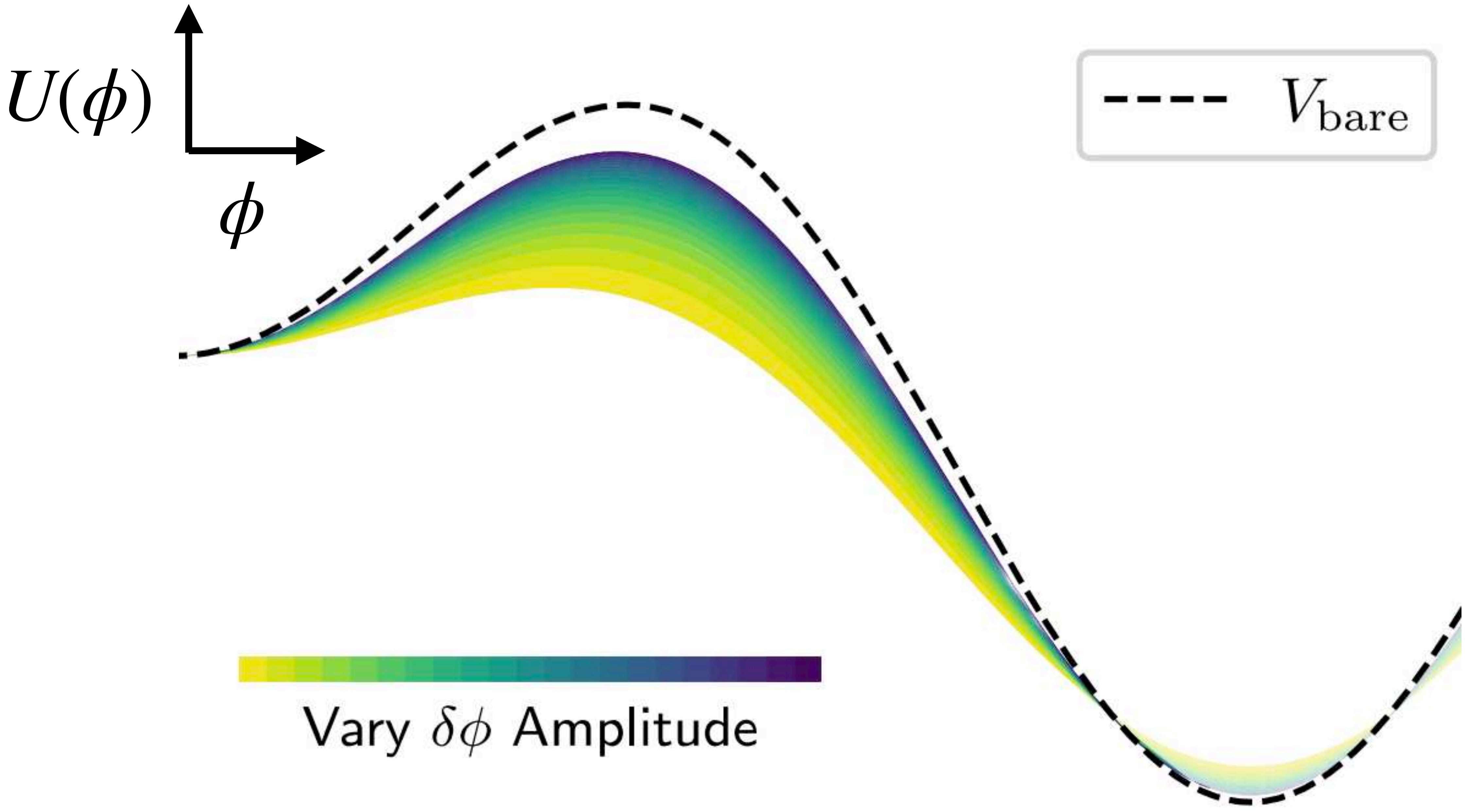
The real-time approach

- Instanton picture: bubbles appear from "average" initial state via *non-classical* paths
- Real-time picture: sample initial state (inc. quantum fluctuations), evolve forward *classically*
- Standard simulation approach in inflation and preheating, also atomic/optical physics (truncated Wigner approximation)

Braden+, 1806.06069



Renormalisation on the lattice



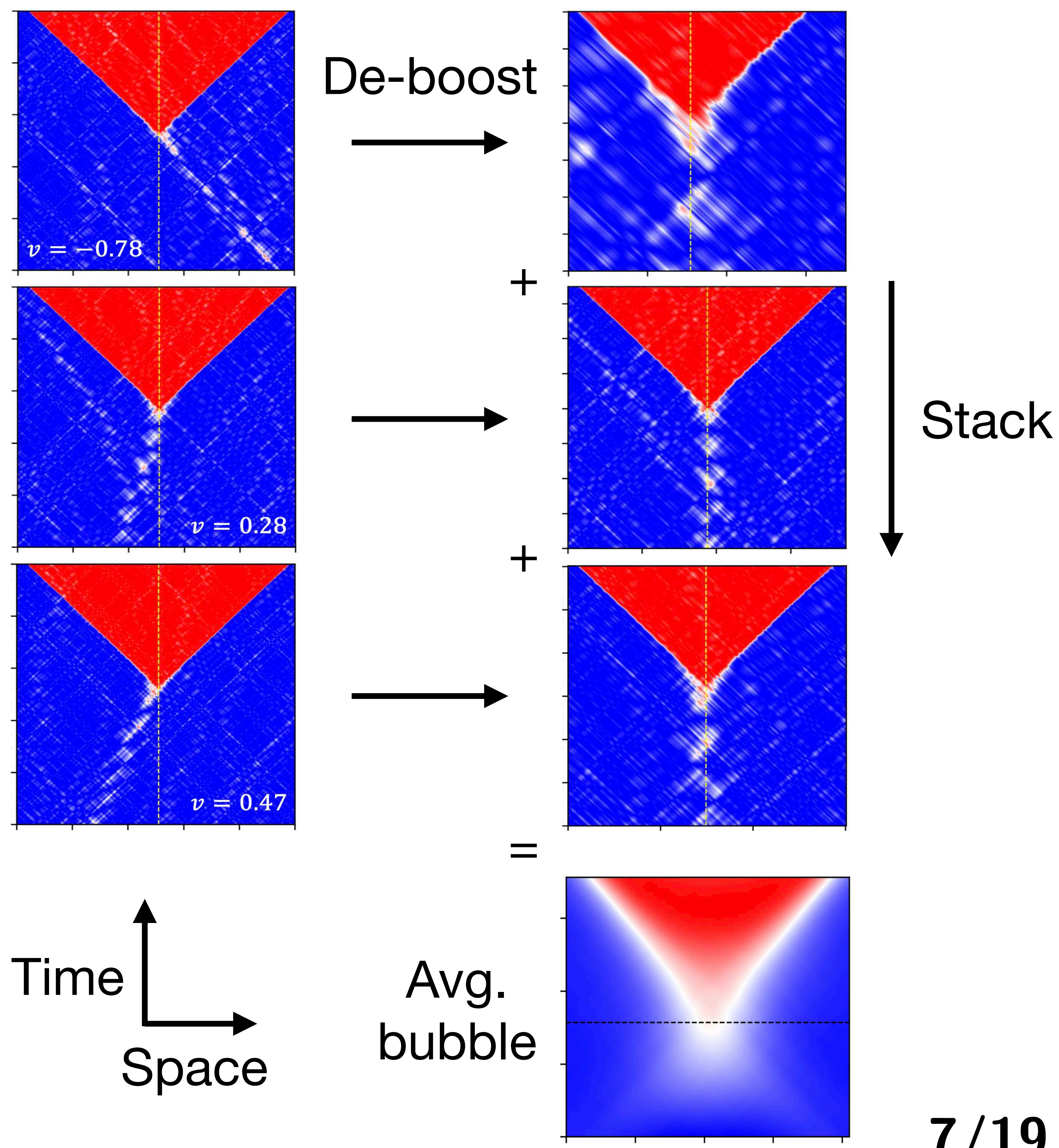
- Potential we put into the code differs from potential felt by modes on the lattice
- Short-wavelength fluctuations *renormalise* the potential felt by long-wavelength modes
- Computed at vacua via Gaussian resummation
- Region between vacua more challenging!

Braden+, 2204.11867

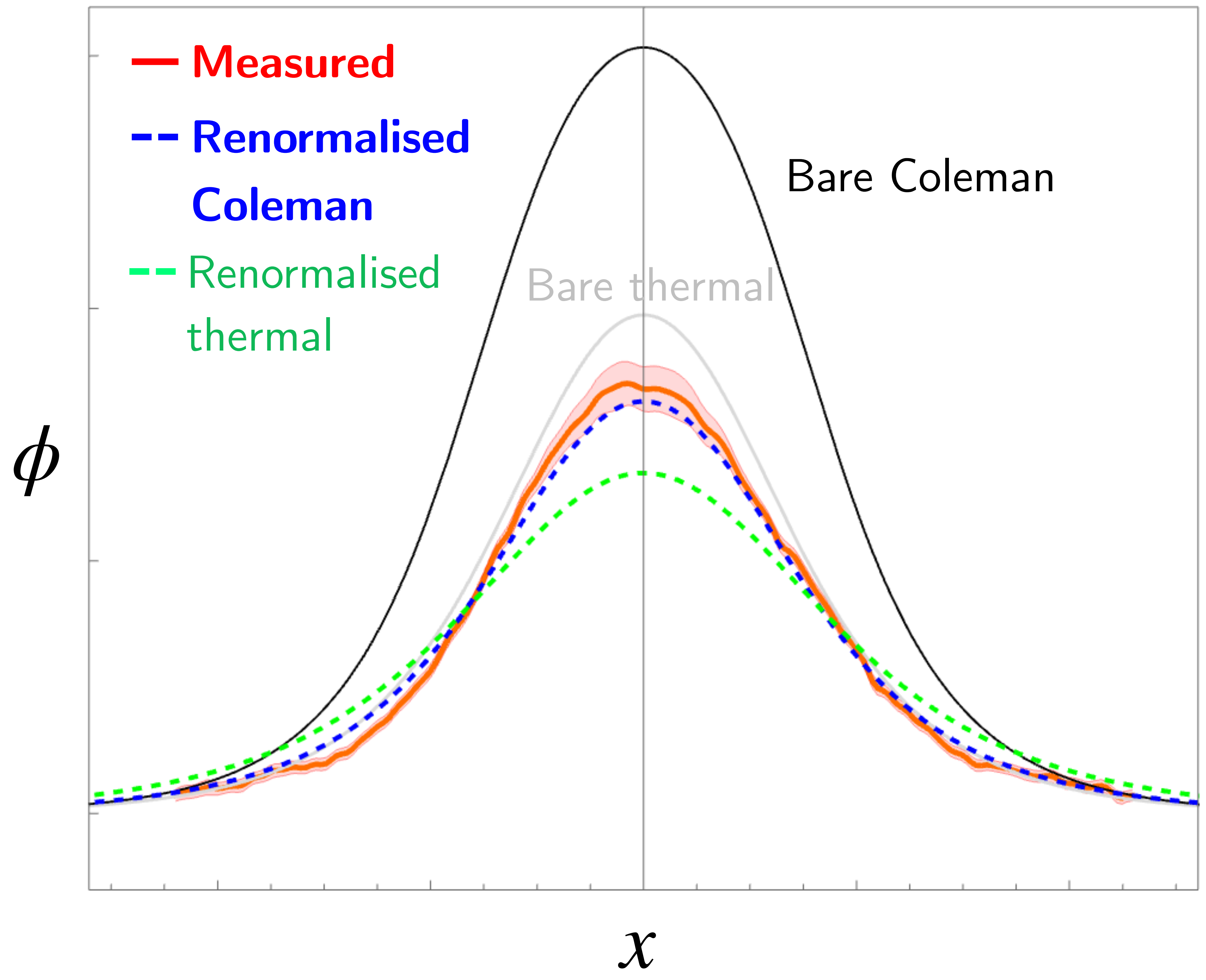
Measuring renormalisation with bubble profiles

- 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, 2606.xxxxx



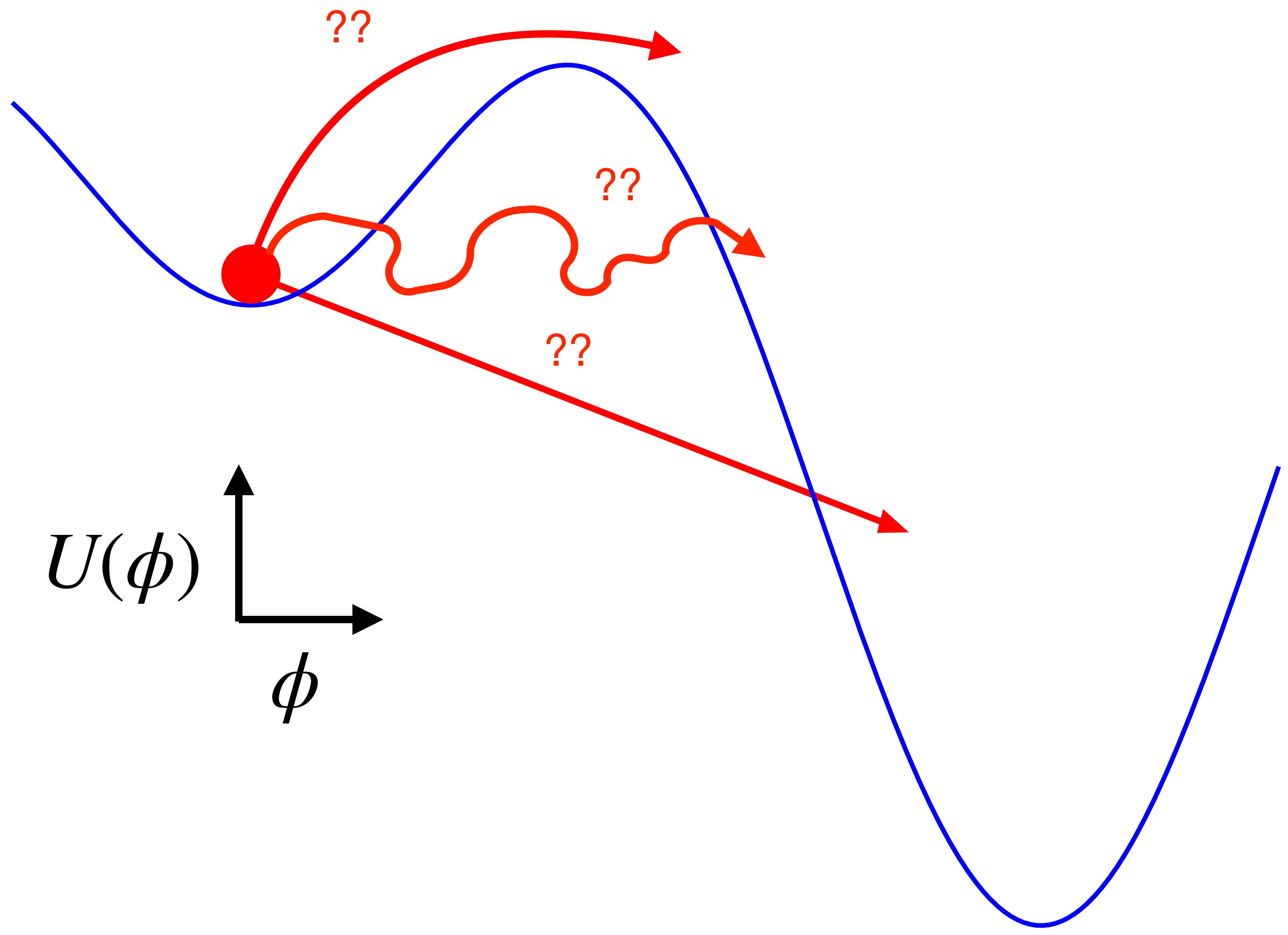
Bubble profile results



- We find compelling evidence for renormalised Coleman bubbles across broad range of simulation ensembles
- Running of profile with UV lattice cutoff confirms this is a renormalisation effect
- Instanton decay rate computed with inferred $U_{\text{eff}}(\phi)$ matches the lattice rate within an order of magnitude, resolving long-standing discrepancy

Hertig, **ACJ**, Peiris, Pontzen, Johnson, 2606.xxxxx

Interpretation



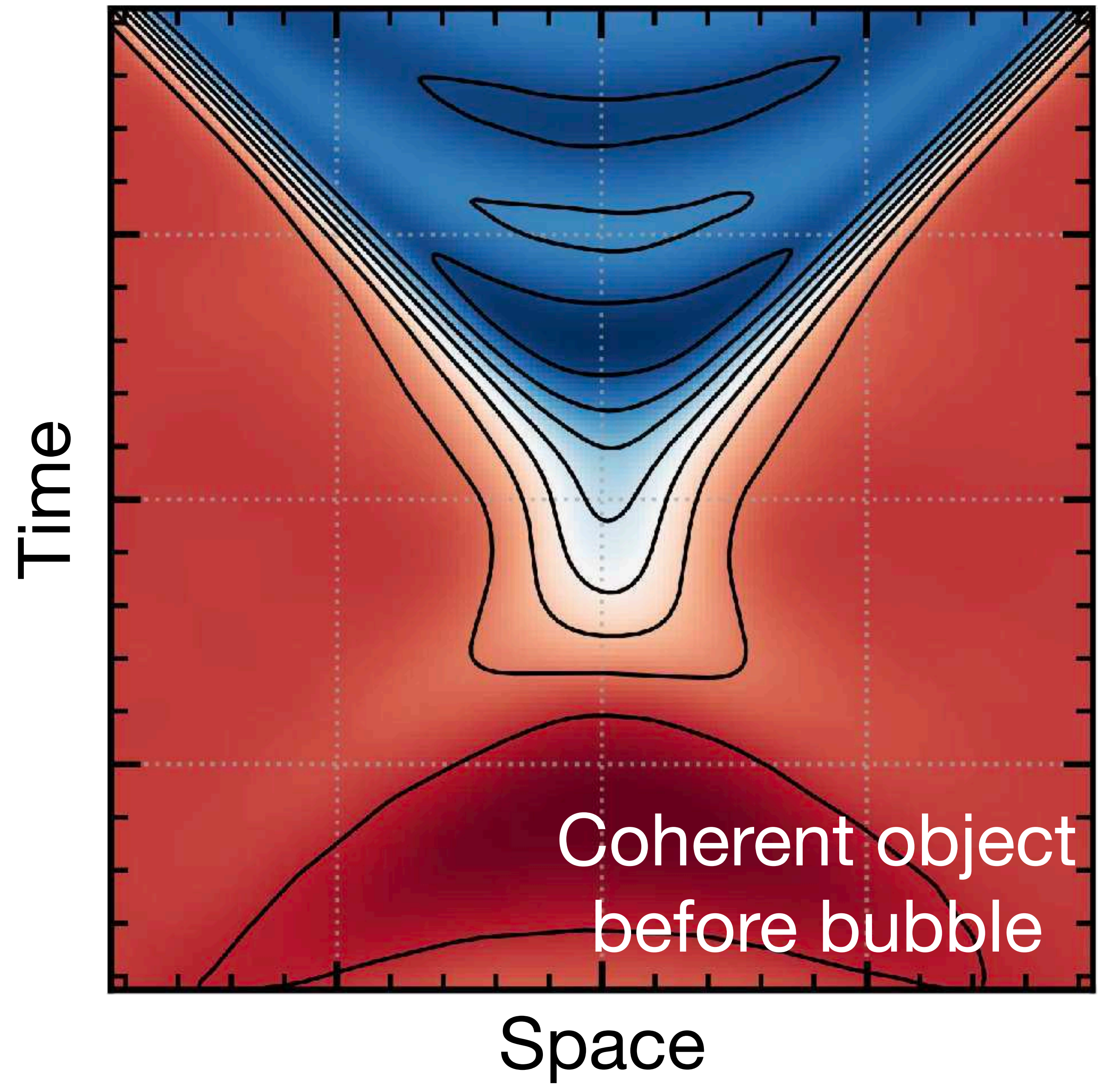
- Our findings challenge the standard lore of nucleation as "under the barrier" — we recover Coleman bubbles with *purely classical* time evolution
- Can think of this as "over the barrier", but *not* thermal
- In fact, there is no fixed energy barrier in field theory! $U(\phi)$ is an energy *density* which fluctuates, even in vacuum
- New, real-time picture of vacuum decay

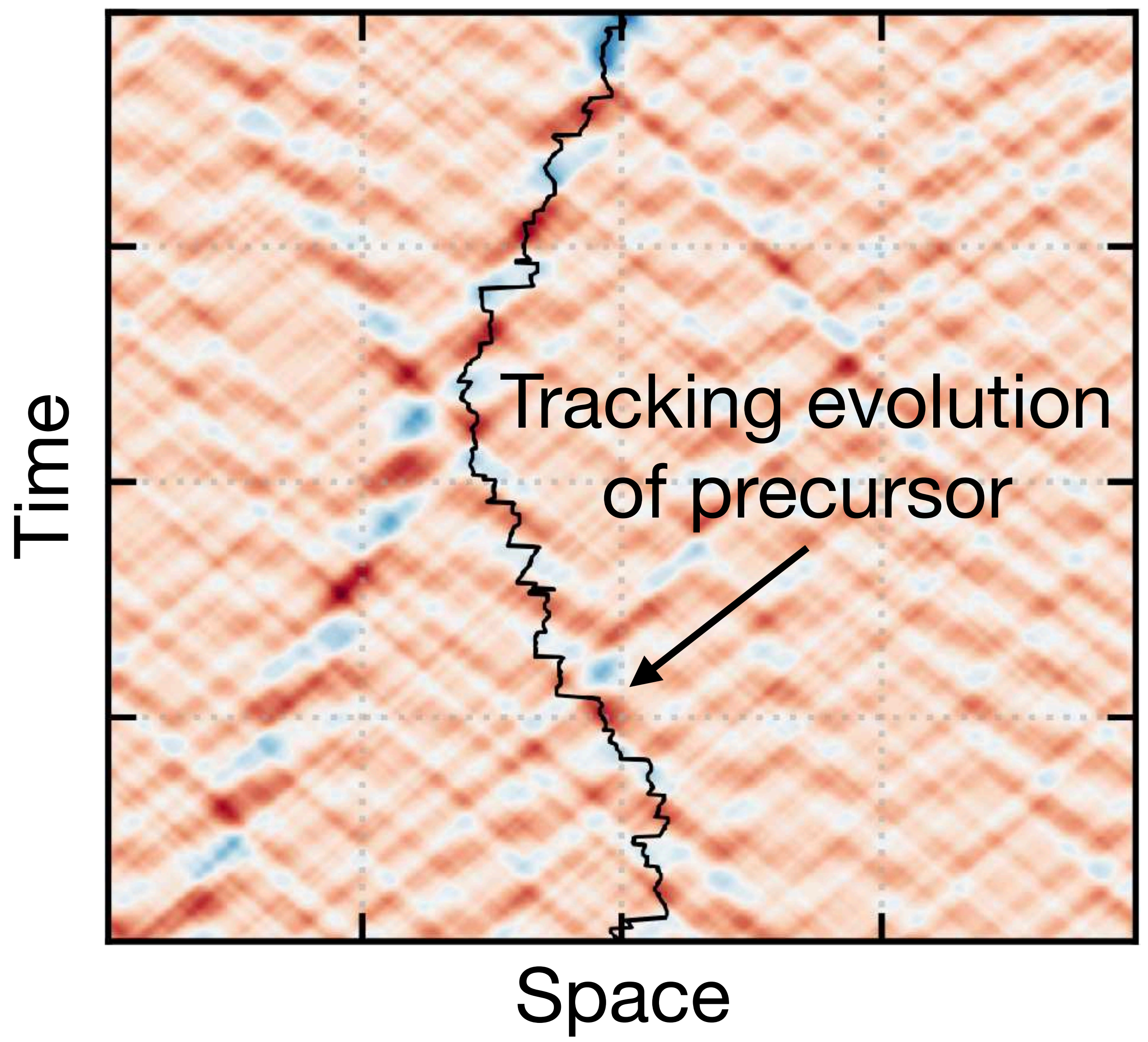
Beyond decay rates

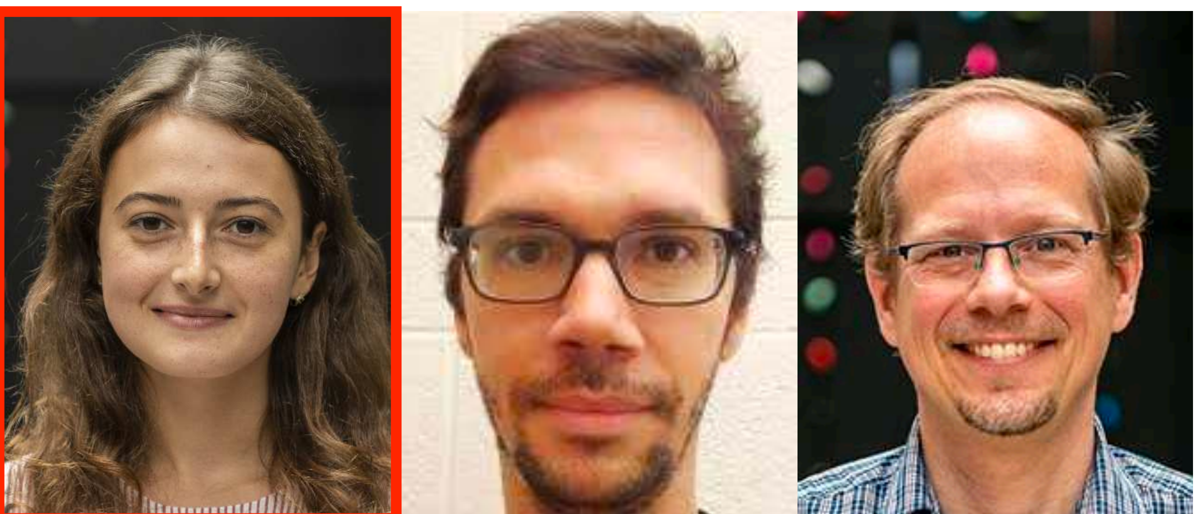
- Many interesting new real-time observables missing from the usual instanton picture:
  - Multi-bubble correlations
  - Peculiar velocities
  - *Oscillon precursors*

Pîrvu+, 2312.13364, 2109.04496

- These could all have important consequences for the early Universe





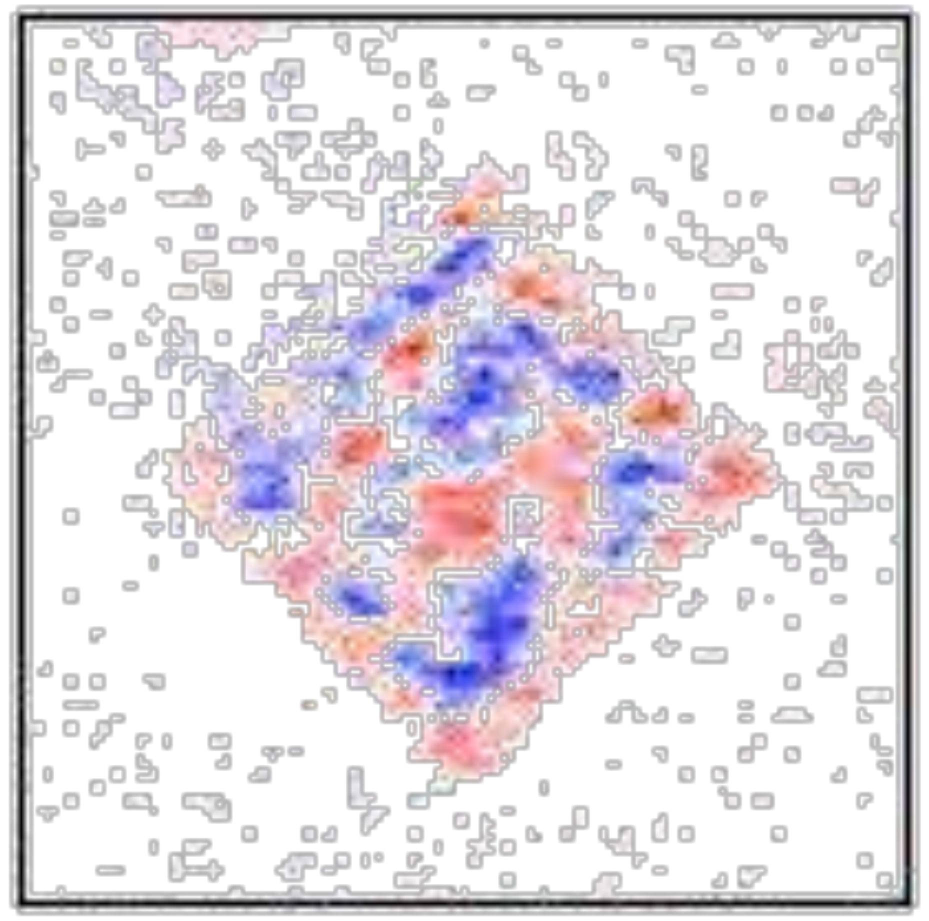


Plan for this talk

1. Vacuum decay: standard lore and open problems
2. Semiclassical simulations on the lattice
3. **Quantum simulations in the laboratory**

Our quantum hardware: ultra-cold atoms

- At ultra-low temperatures, bosonic atoms form a *condensate* — effectively, a quantum field you can take a picture of



- Resulting many-body wavefunction ψ obeys a Gross-Pitaevskii equation

$$i\hbar\frac{\partial\psi}{\partial t} = \left(-\frac{\hbar^2\nabla^2}{2M} + \cancelto{\approx 0}{V_{\mathrm{ext}}(x)} + g|\psi|^2\right)\psi$$

- This is a *non-relativistic* scalar with a $|\psi|^4$ self-interaction potential (no false vacuum)

- How do we get cosmology from this?

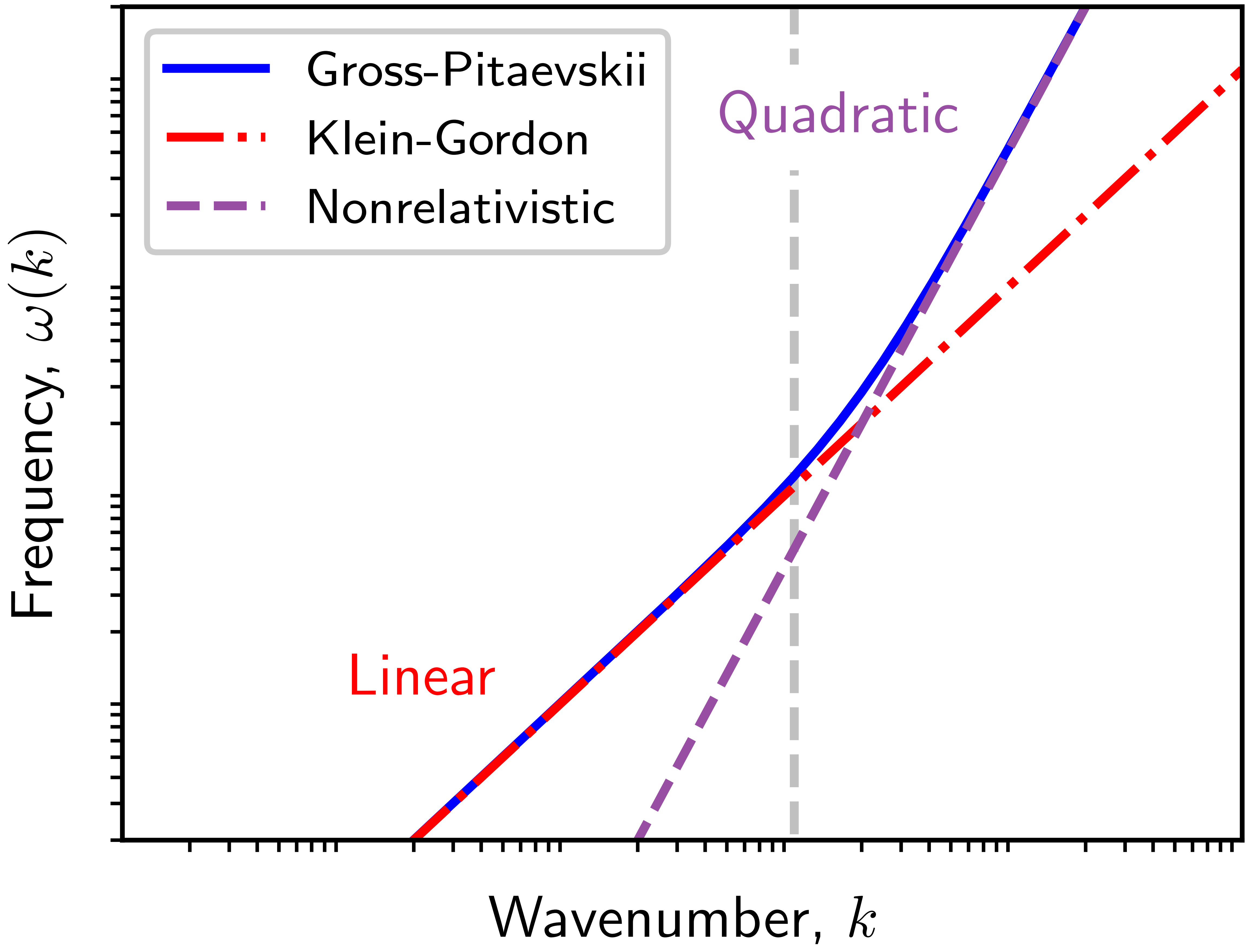
First hint: relativistic dispersion relation

- On small scales, Gross-Pitaevskii reduces to Schrödinger equation, and we get non-relativistic modes

$$\omega(k) \simeq \hbar k^2/(2M)$$

- On large scales, nonlinear self-interactions give rise to massless, *relativistic* phonons

$$\omega(k) \simeq ck$$



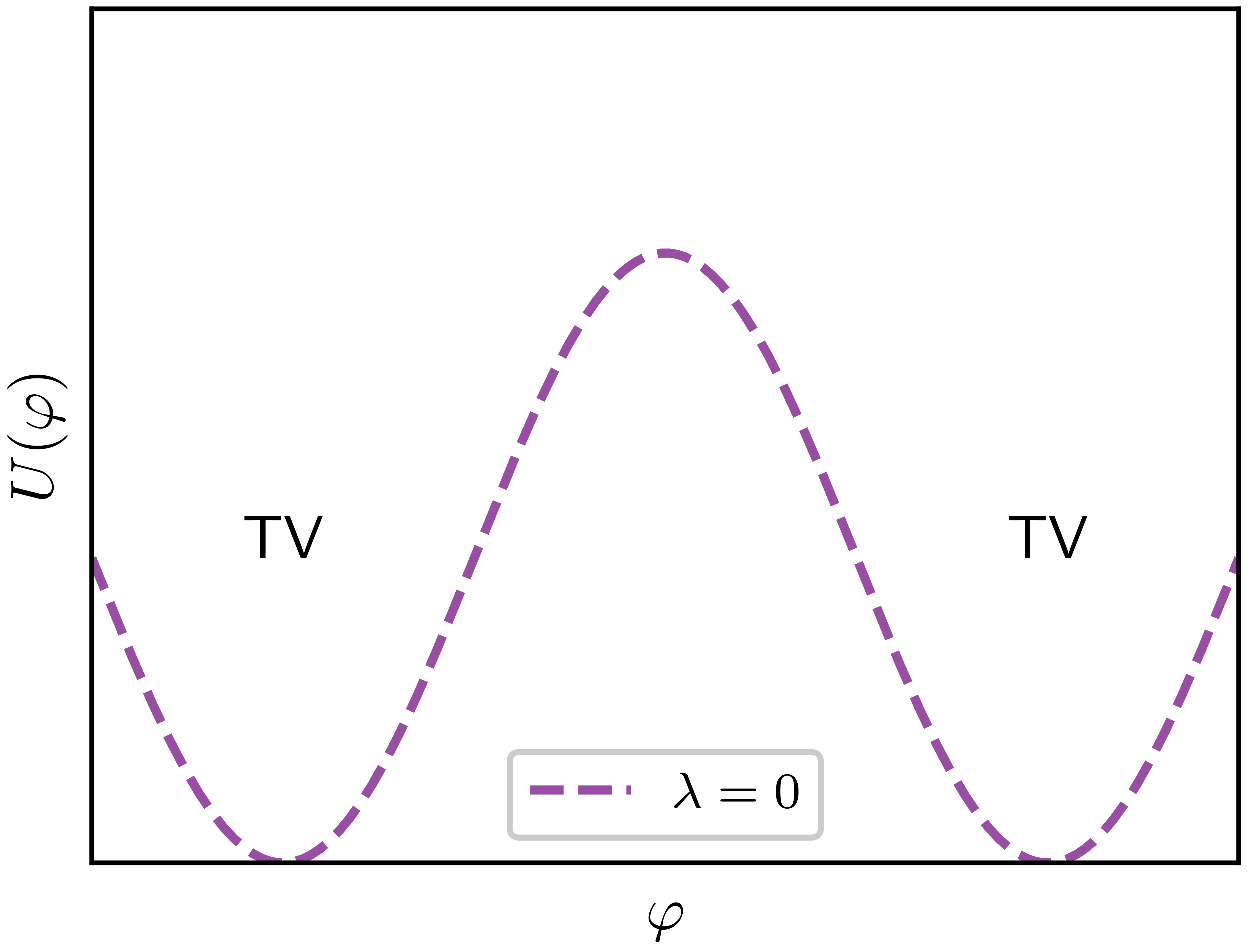
How do we get a potential?

- Consider two atomic states $|\downarrow\rangle$, $|\uparrow\rangle$, coupled by a coherent EM field (Rabi coupling)
- Study the *relative phase* between the two condensates,

$$\varphi = \phi_\downarrow - \phi_\uparrow$$

- Corresponding phonons have a cosine potential due to the coupling

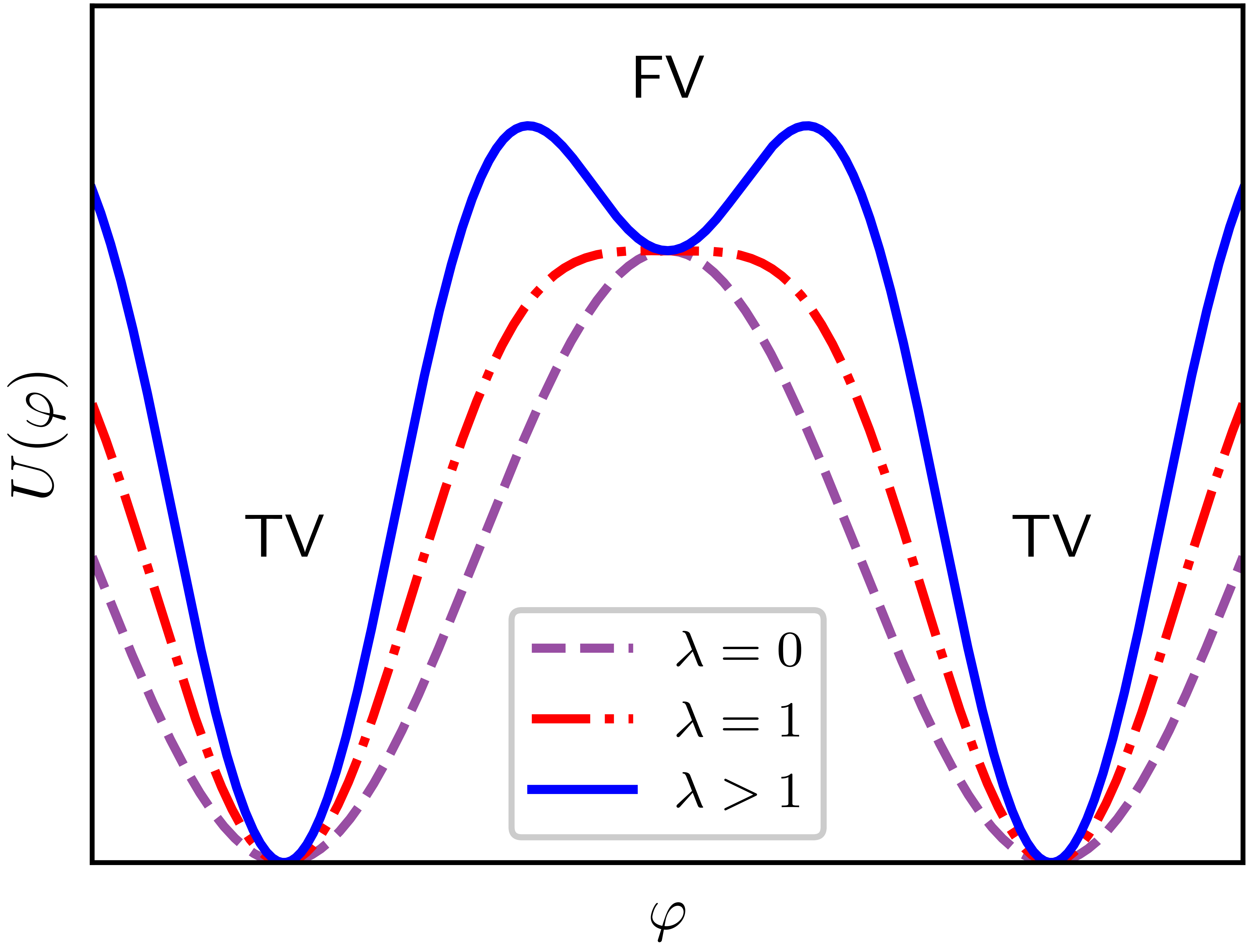
Fischer and Schützhold, cond-mat/0406470
Visser and Weinfurtner, gr-qc/0506029



How do we get a false vacuum?

- Rapid modulation of the Rabi coupling stabilises the false vacuum
- Analogous to a pendulum with an oscillating pivot point

Fialko+, 1408.1163, 1607.01460



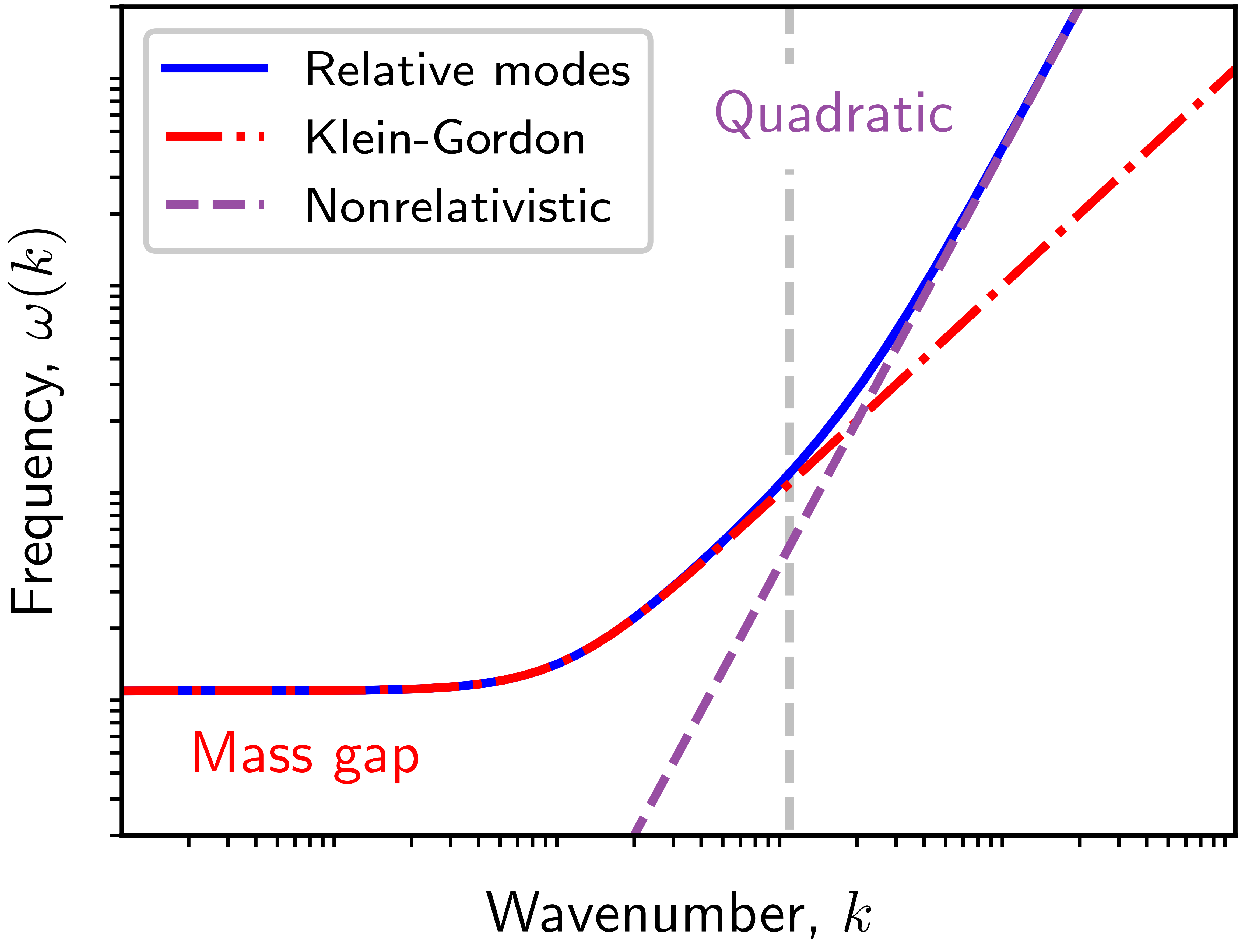
Relative phase dispersion relation

- Modulated coupling gives relative phonons an effective mass, set by false vacuum potential barrier

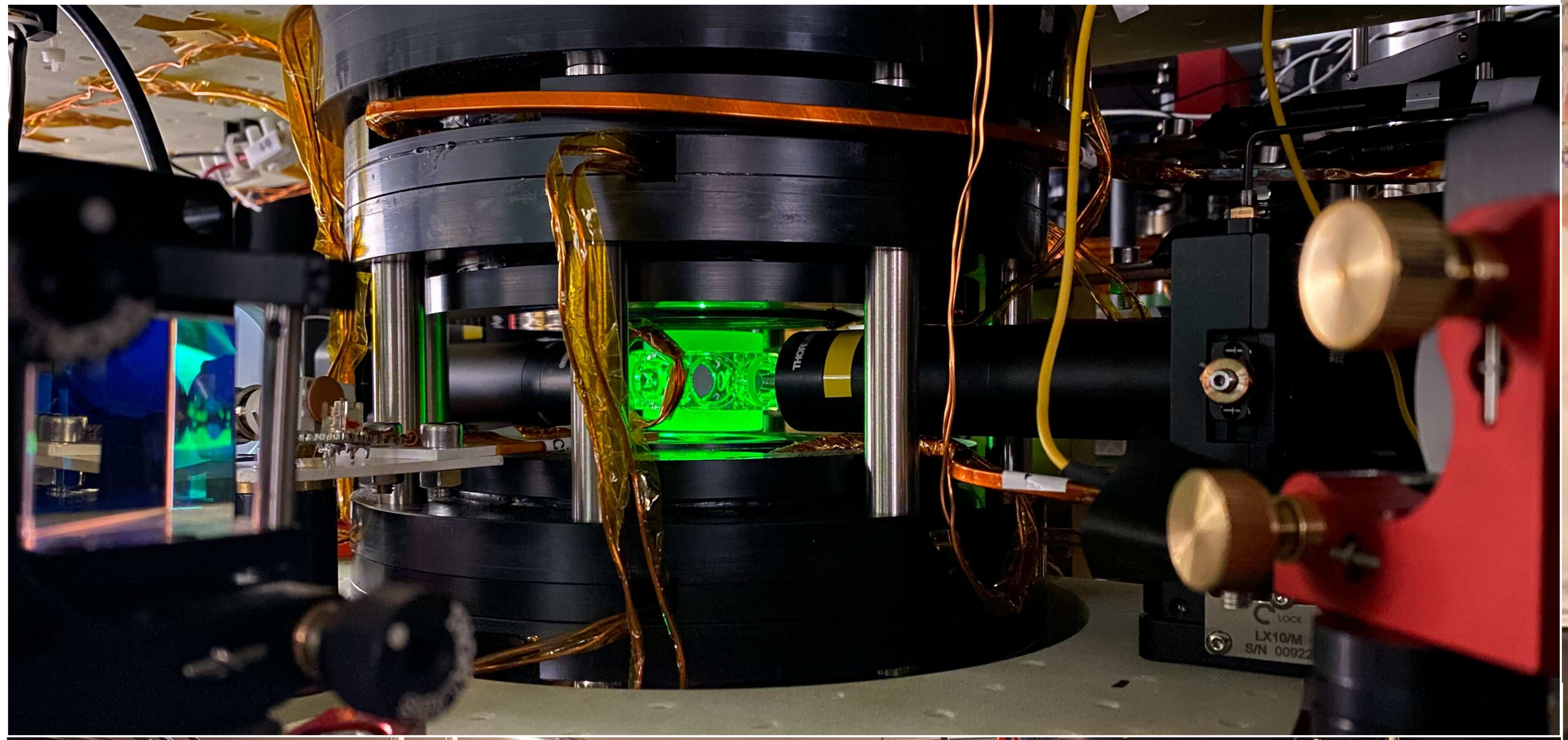
- Matches a massive Klein-Gordon field on large scales

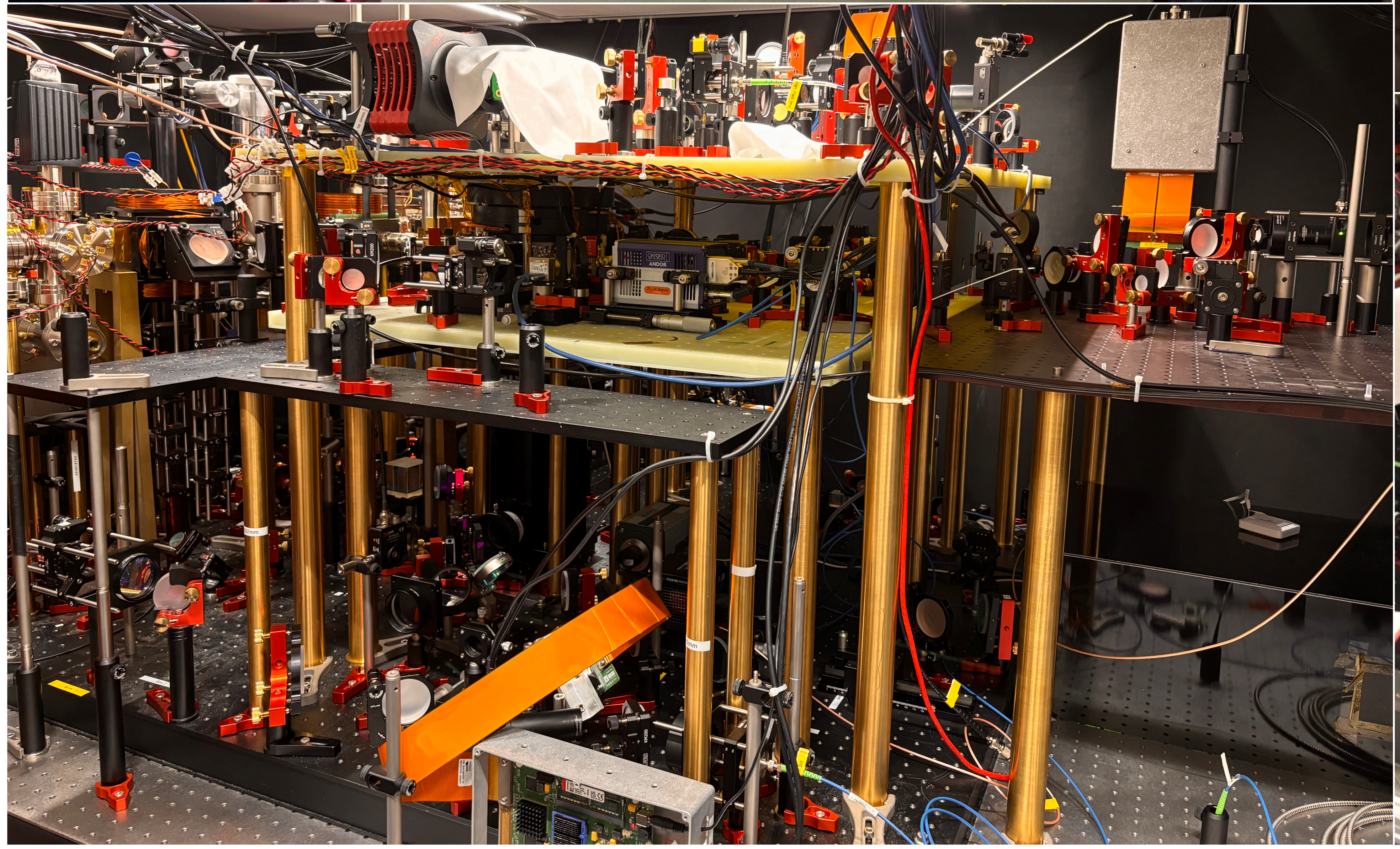
- With more work, one can show this analogy holds *nonperturbatively* and *quantum-mechanically*

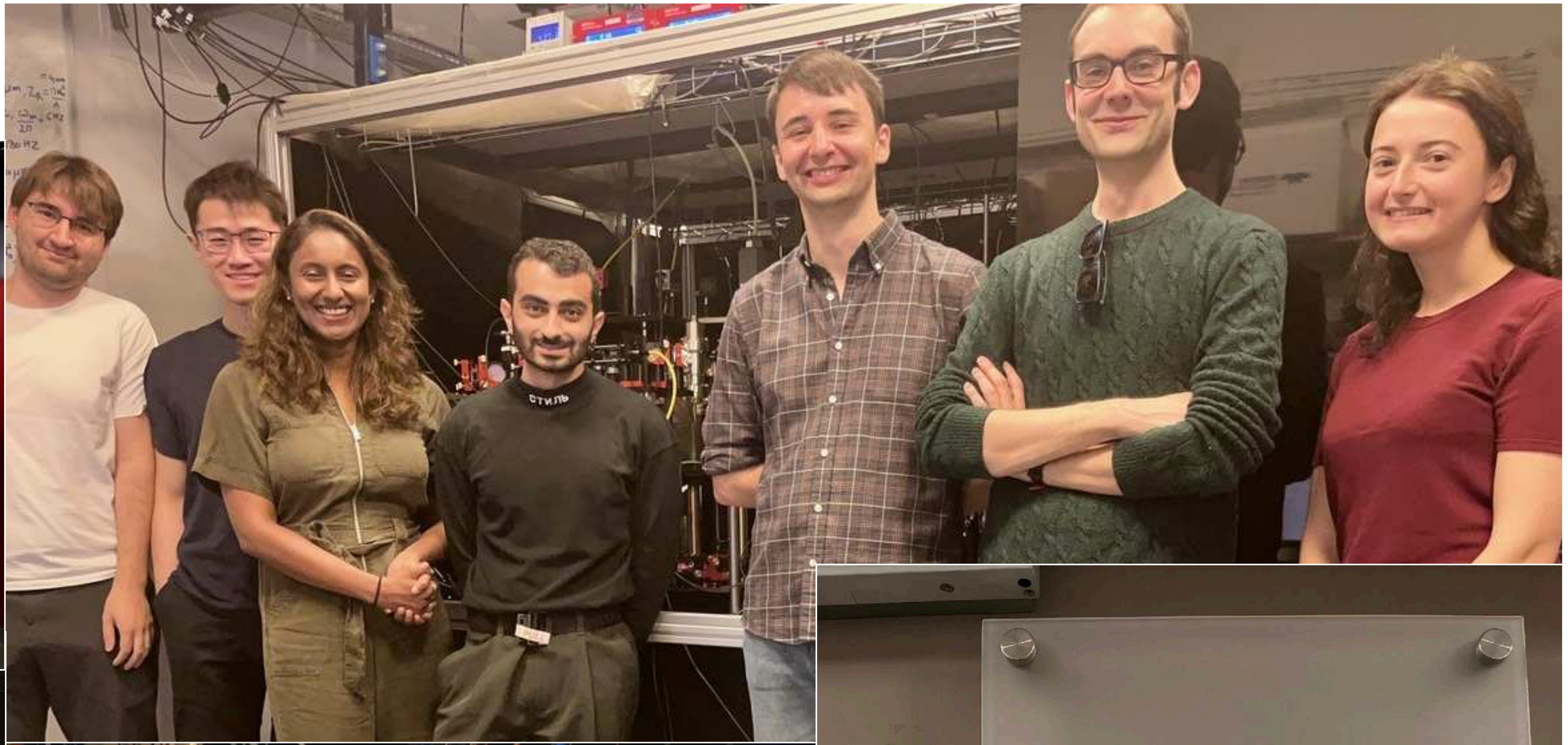
Braden+, 1712.02356, 1904.07873
Billam+, 1811.09169, 2006.09820, 2104.07428
ACJ+, 2307.02549, 2311.02156

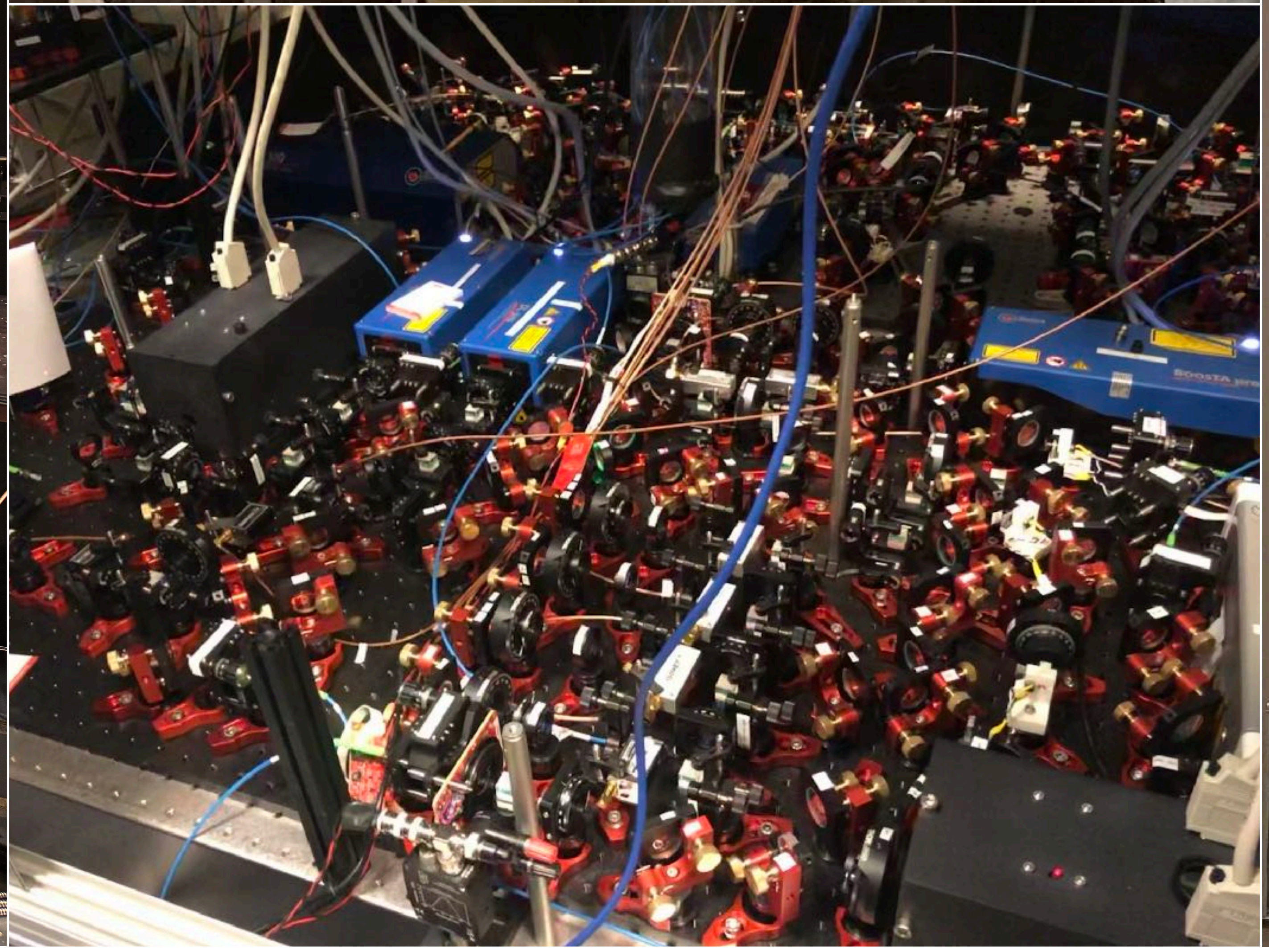


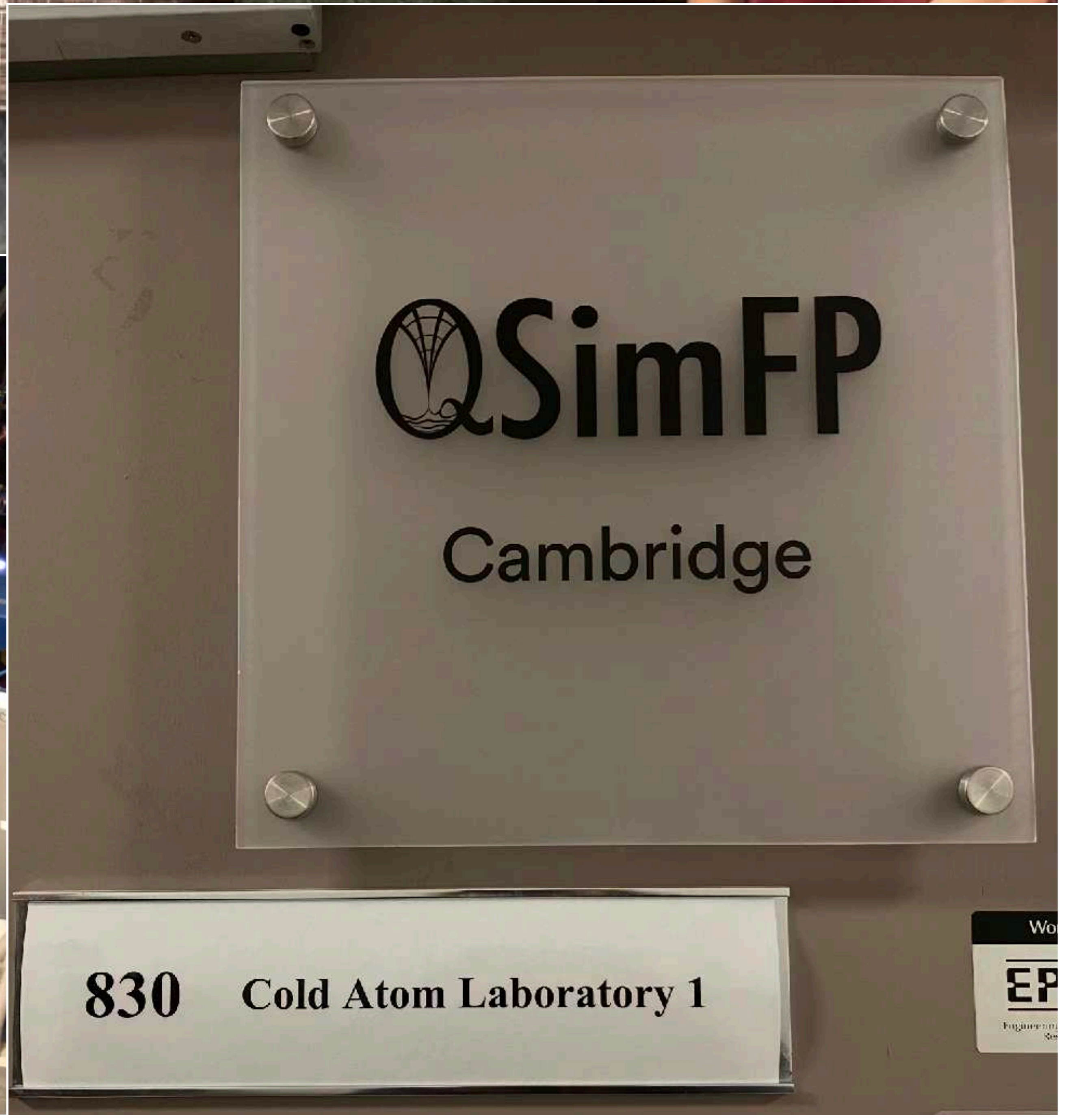
The experiment











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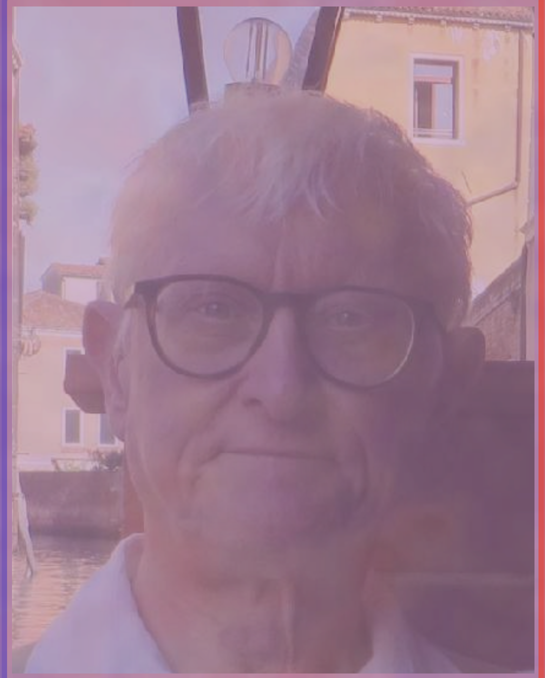

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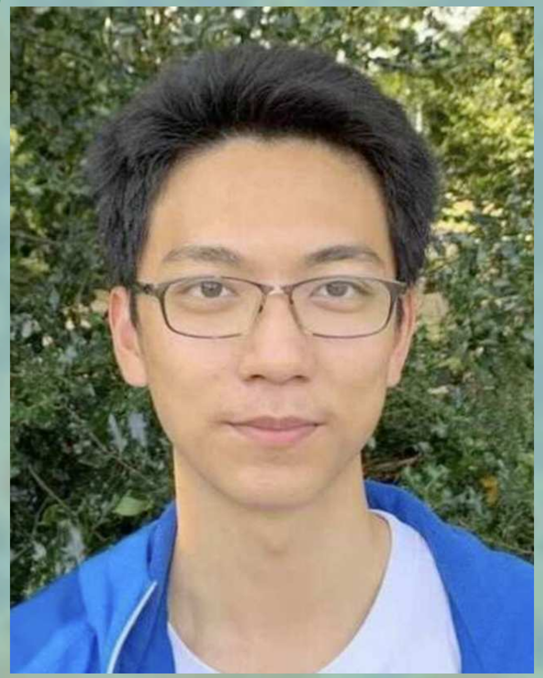

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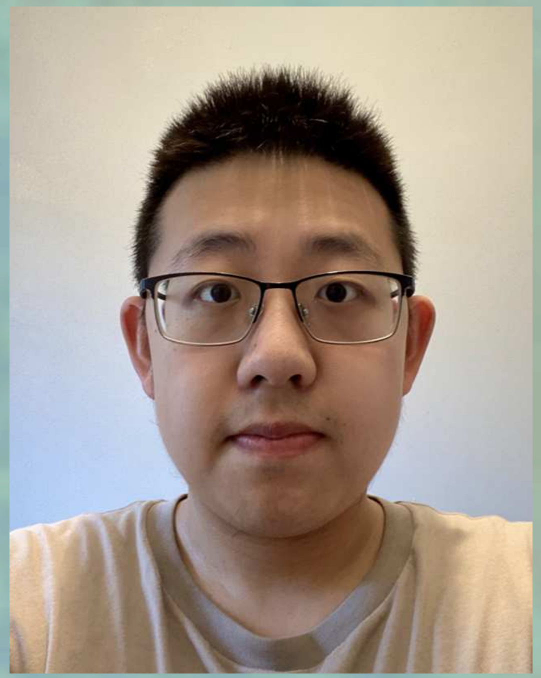

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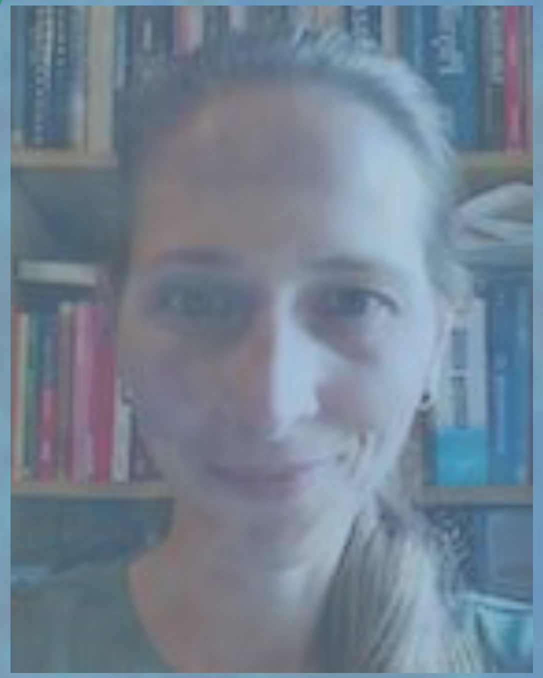

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Christoph Eigen
(Cambridge)

Zoran Hadzibabic
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Cosmology theory

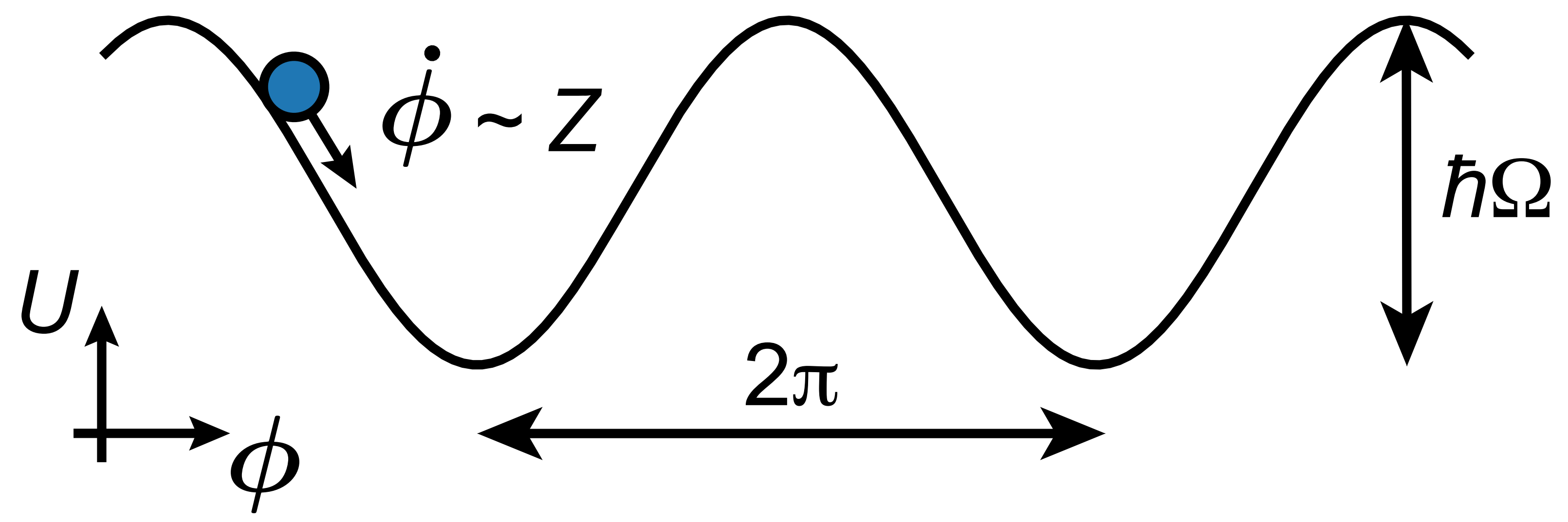
Cold-atom theory

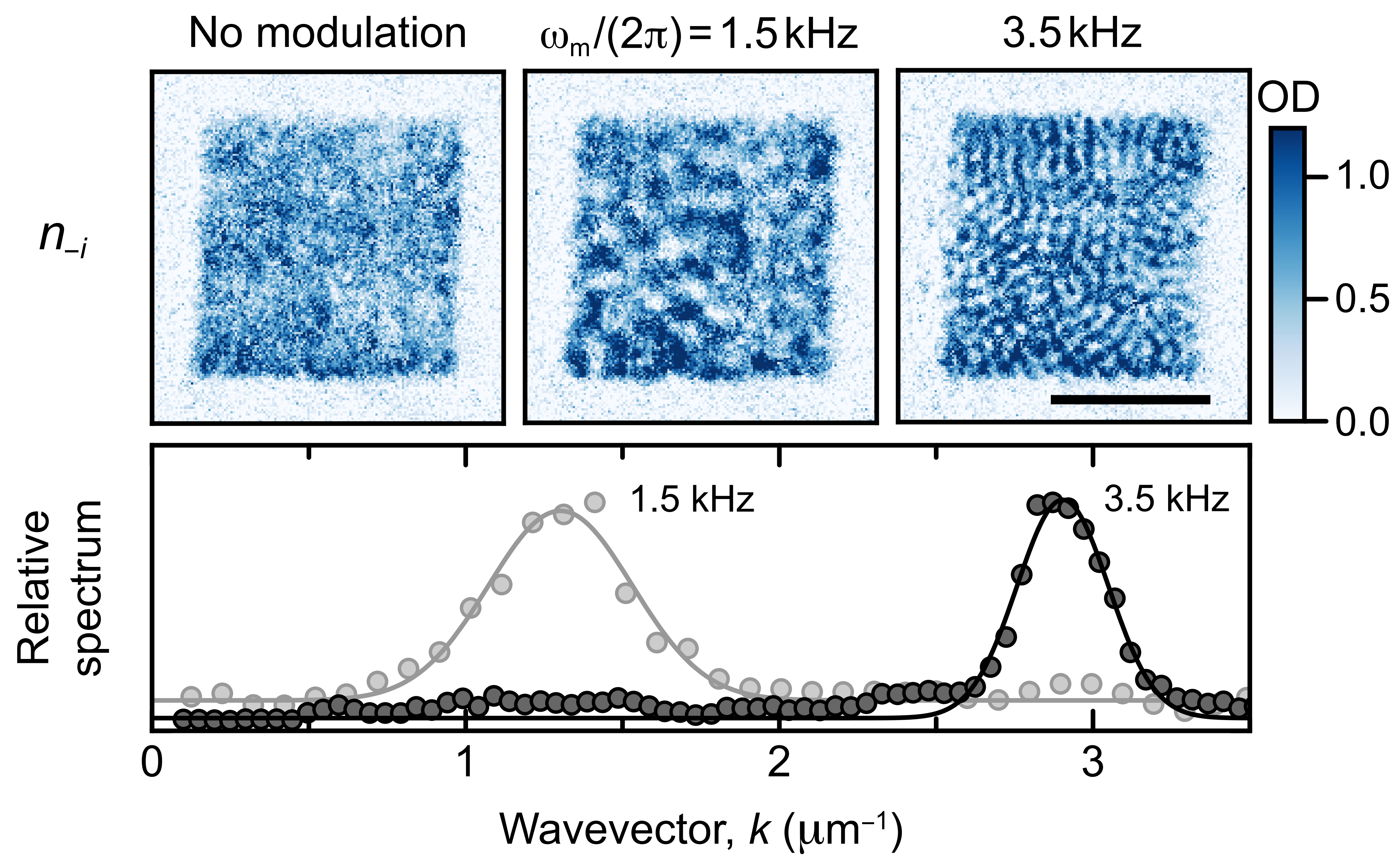
Cold-atom experiments

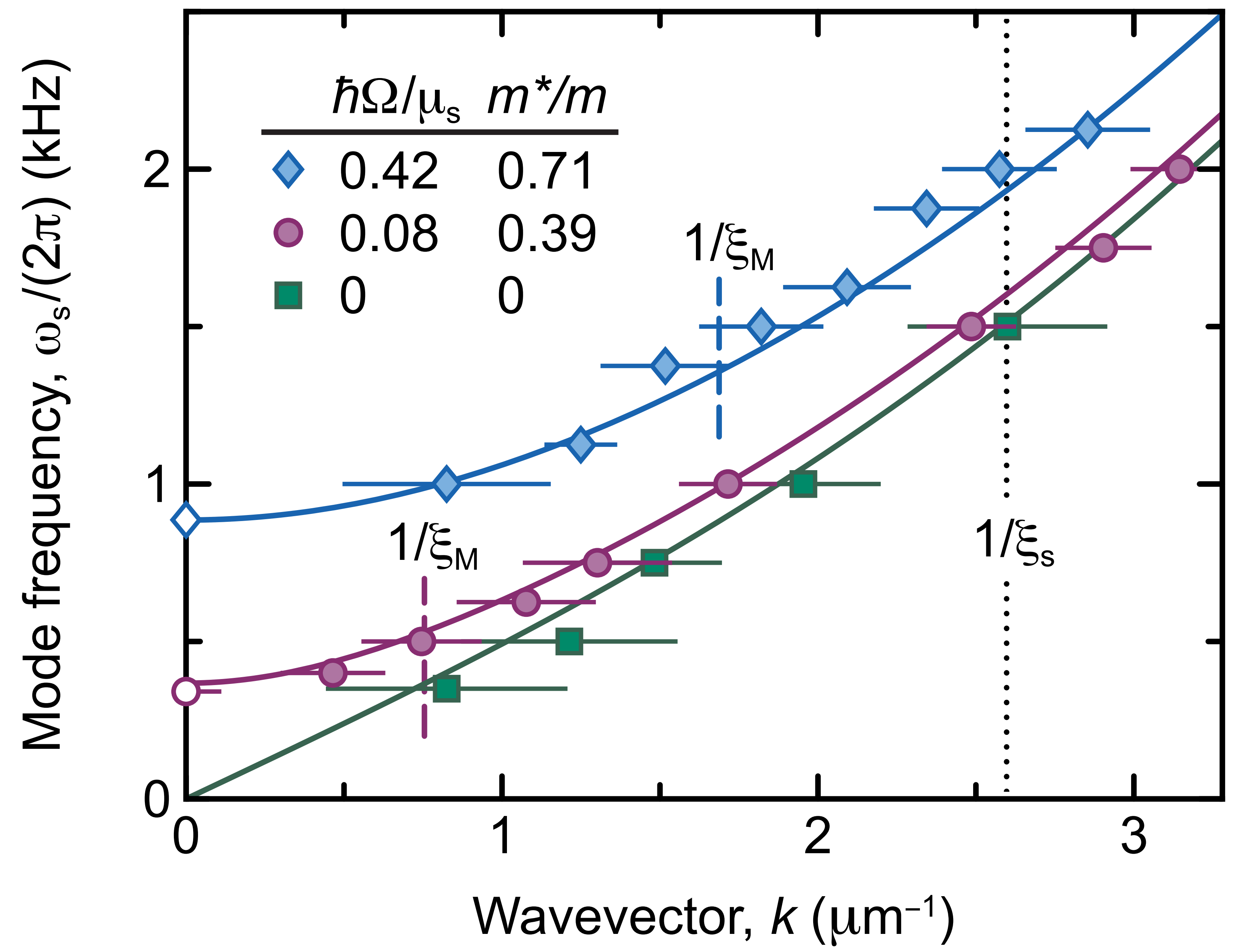
First experimental results

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

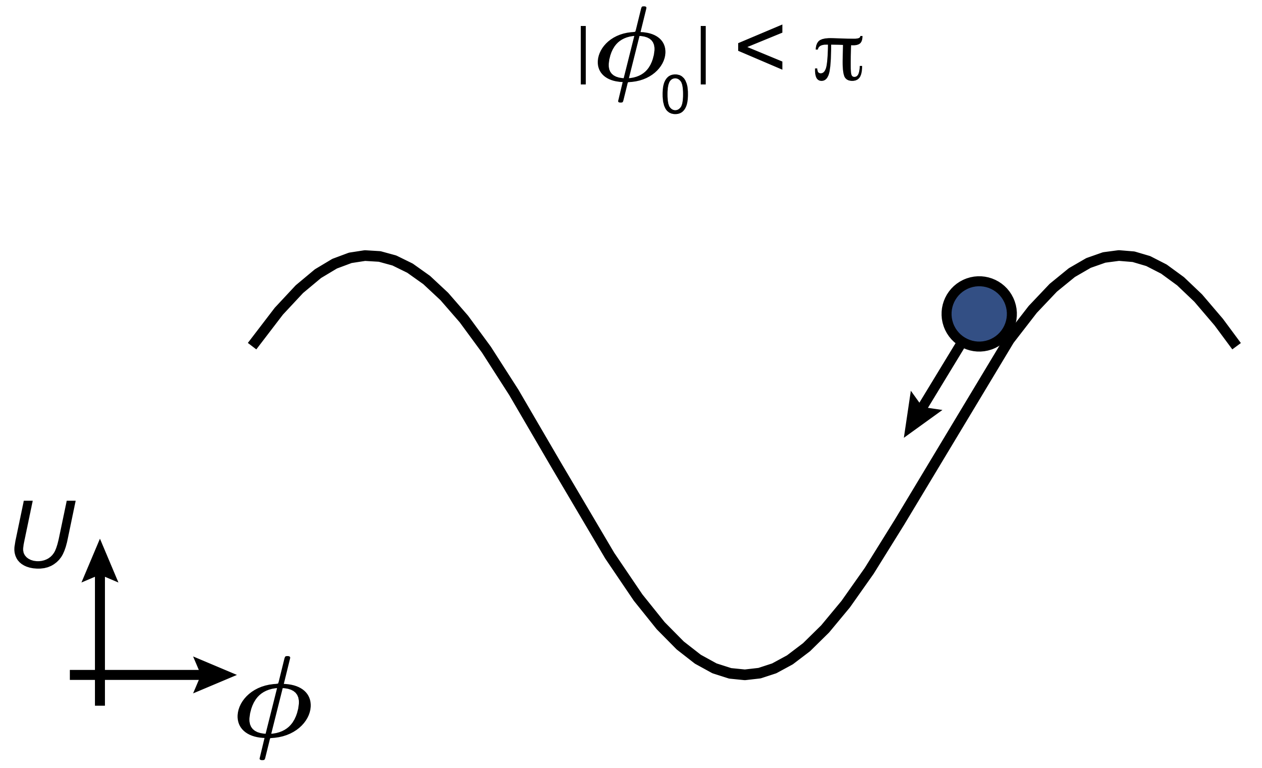
Zhang *et al.* (inc. **ACJ**), 2603.08840







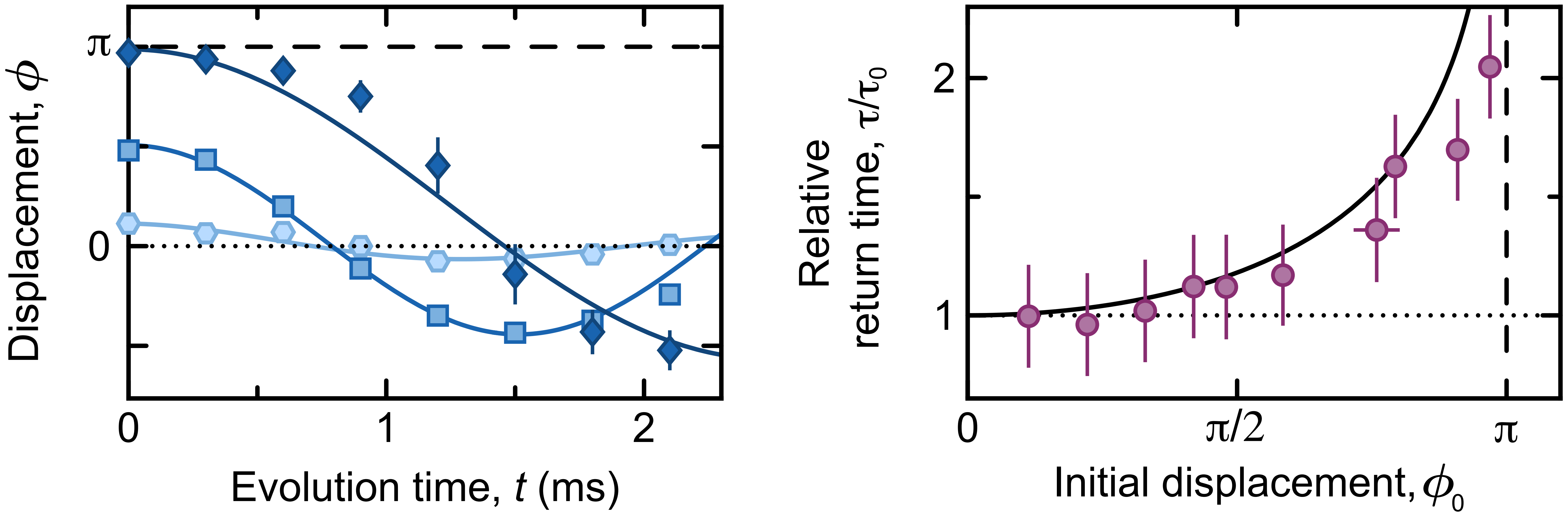
Nonlinear dynamics



- Sine-Gordon behaviour confirmed by homogeneously kicking the field up the potential

- Time taken to return to potential minimum as a function of displacement encodes anharmonic potential

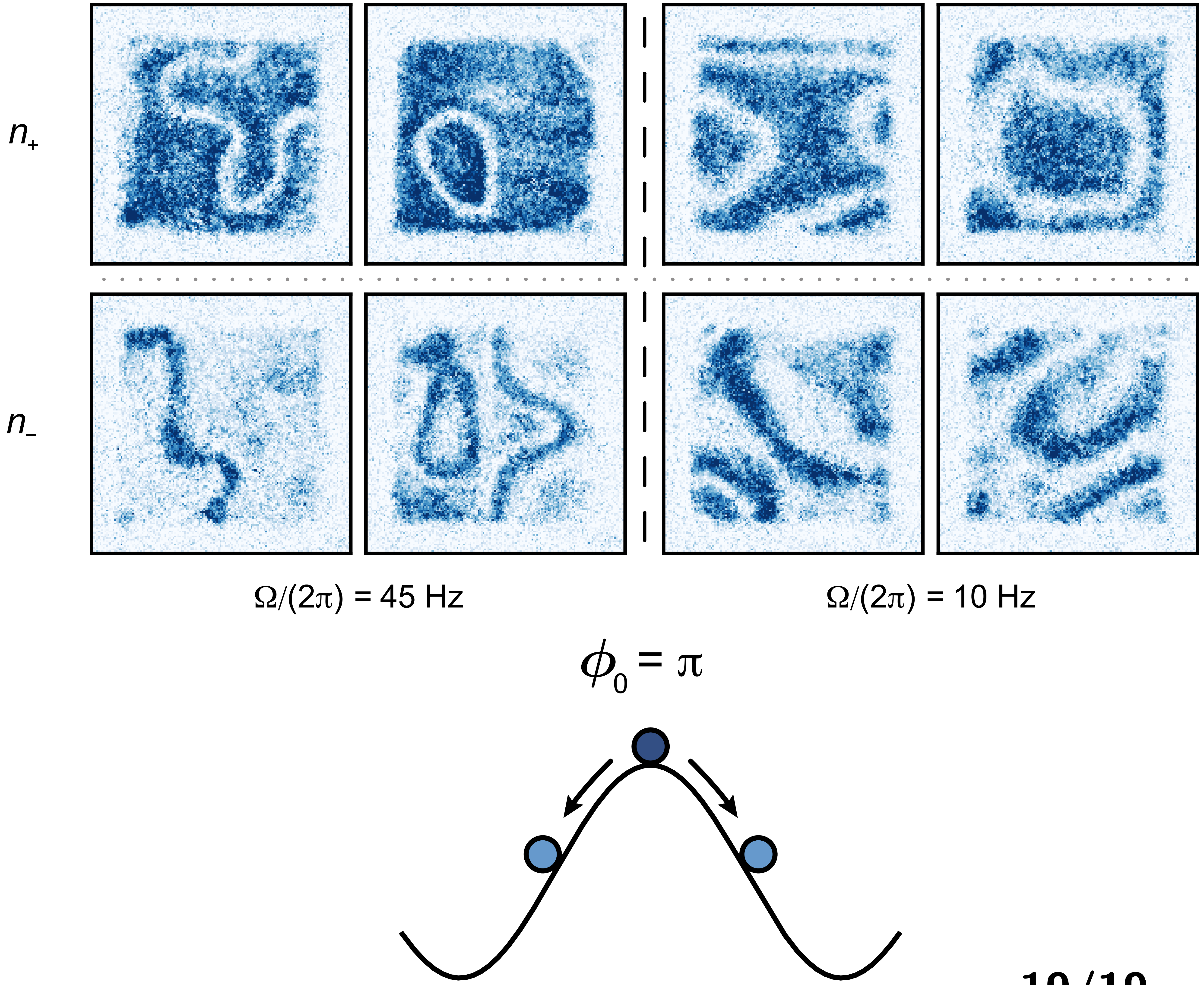
Zhang *et al.* (inc. **ACJ**), 2603.08840



Simulating cosmic domain walls

- Initialising at potential maximum causes defect formation via spontaneous symmetry breaking
- Wall thickness set by the (tuneable) Sine-Gordon mass
- Nonperturbative, nonequilibrium quantum field theory in the lab!
- Potential insights for dark matter production in axion scenarios, plus primordial GW signals

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



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!

Backup Slides

Quantum tunnelling

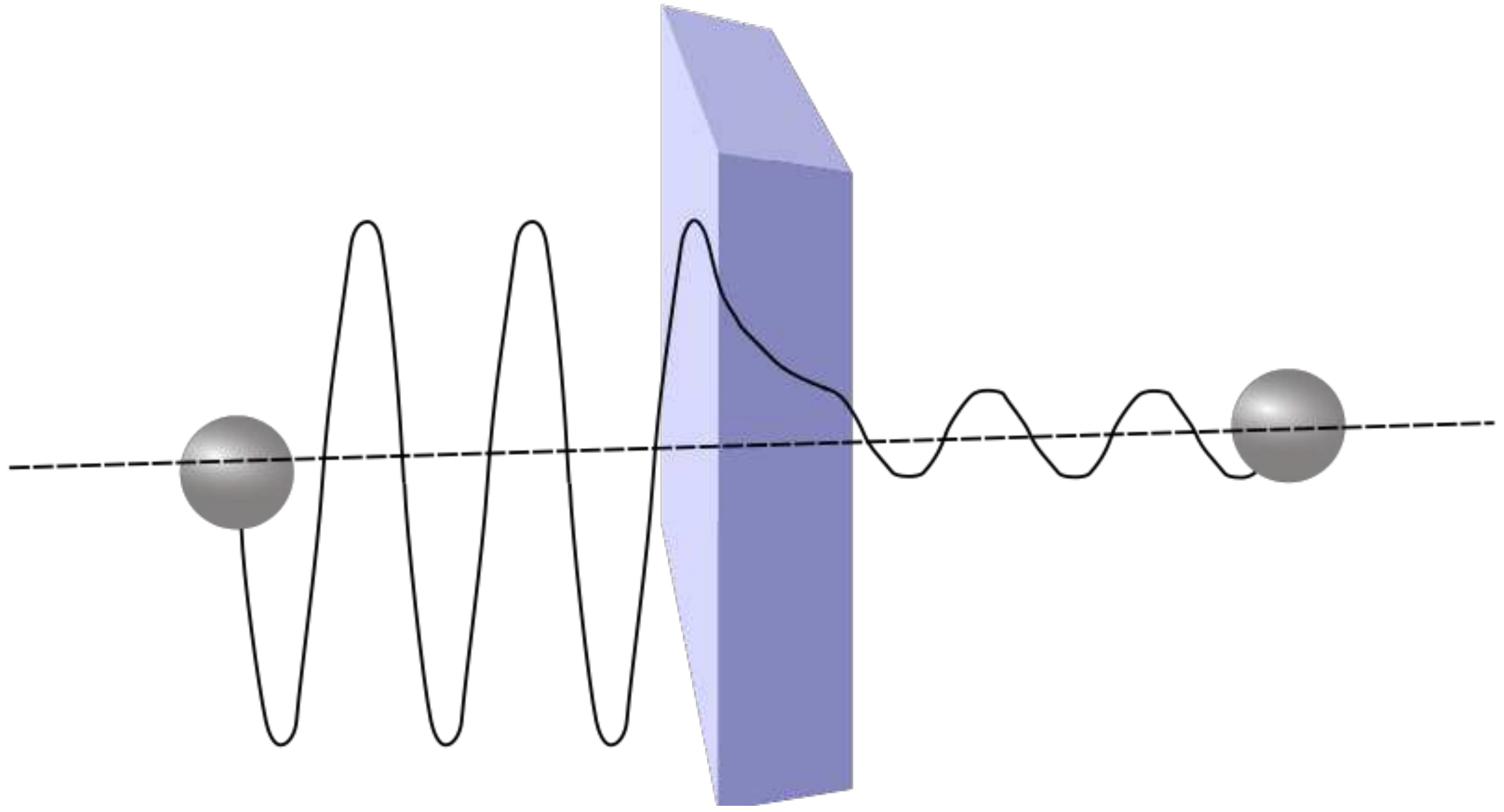
Quantum particles can *tunnel* through a potential barrier $U(x)$

$$\text{decay rate} \sim \exp(-B/\hbar)\,[1 + \mathcal{O}(\hbar)], \quad \text{where} \quad B = \int \mathrm{d}\tau \left(\frac{1}{2}(\partial_\tau x)^2 + U(x) \right)$$

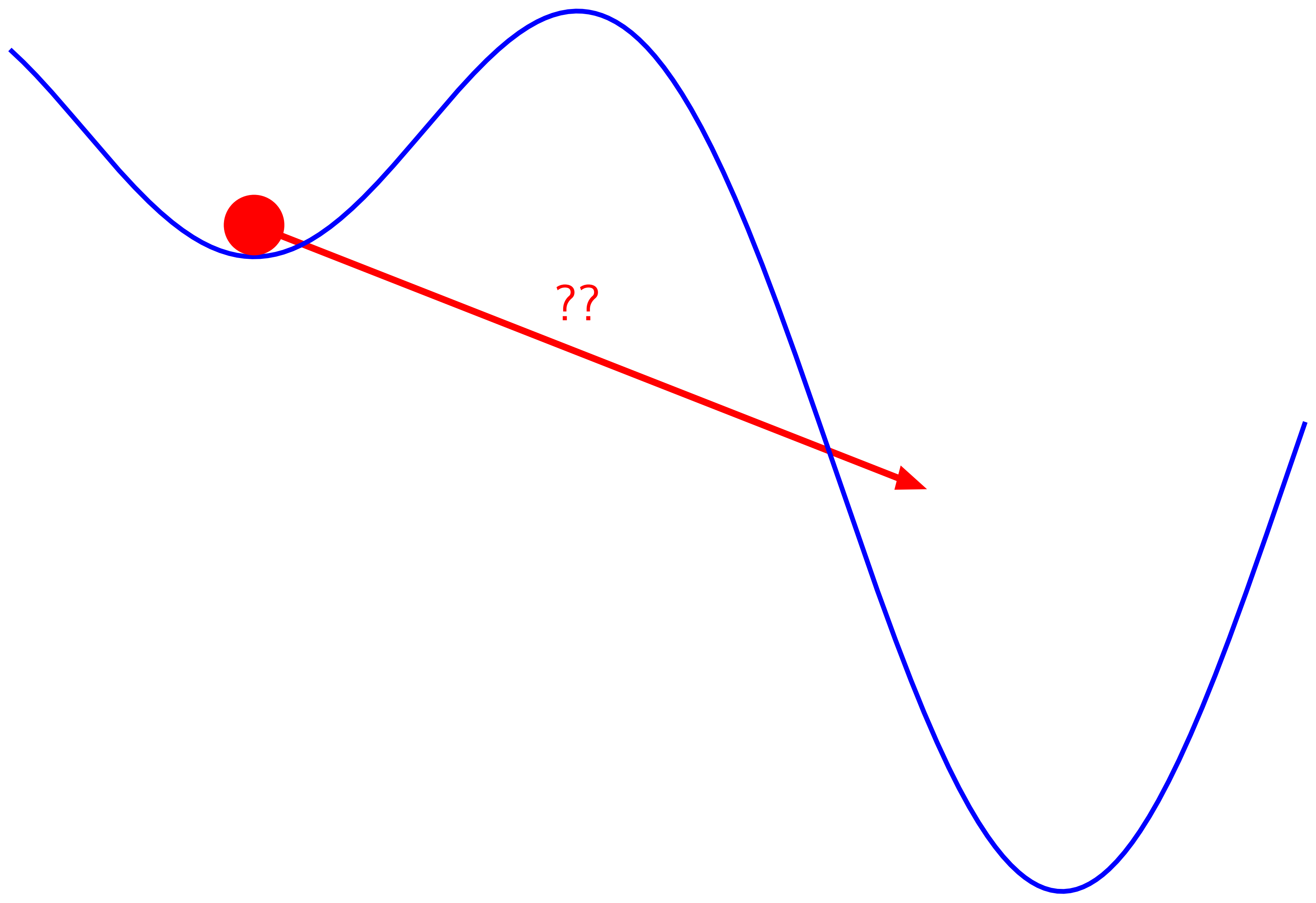
Formally, this is the action S of a trajectory in *imaginary* time $\tau = \mathrm{i}t$

We call it the *Euclidean action*, $B = S_E$

Well-understood theoretically and well-tested experimentally when dealing with a *single* degree of freedom x



Coleman instanton formalism



By analogy with QM, decay rate for a *field* $\phi(t, \mathbf{x})$ is

$$\frac{\text{decay rate}}{\text{unit volume}} \sim \exp(-S_E/\hbar)[1 + \mathcal{O}(\hbar)]$$

$$S_E = \int \mathrm{d}\tau\, \mathrm{d}^3\mathbf{x} \left[\frac{1}{2}(\partial_\tau \phi)^2 + \frac{1}{2}|\nabla \phi|^2 + U(\phi)\right] \quad (\text{where } \tau = \mathrm{i}t)$$

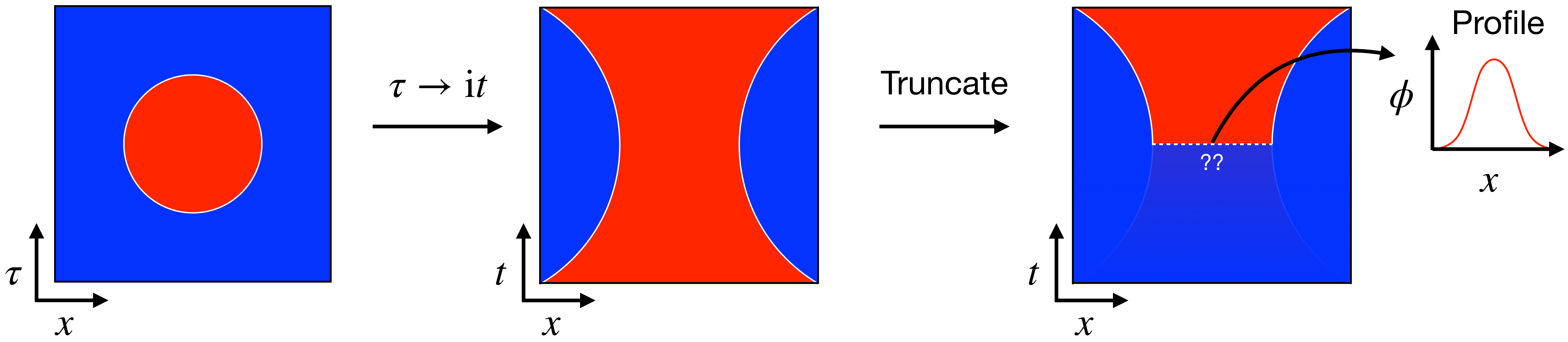
Integral over an imaginary-time field solution called an *instanton*

Note that we've made a conceptual leap to *infinite* degrees of freedom (!!)

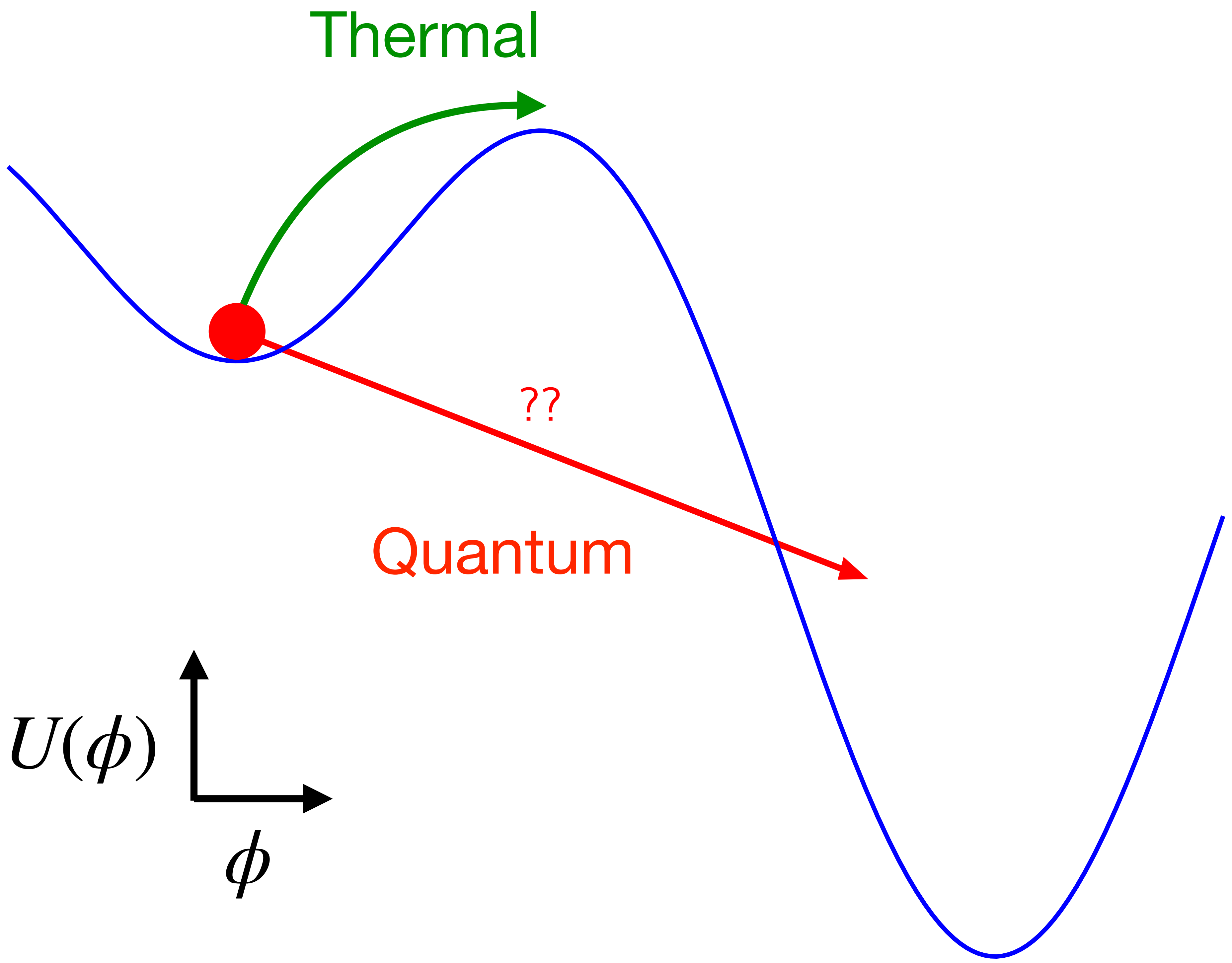
Coleman 1977, Callan and Coleman 1977

Interpreting the Coleman instanton

- To find minimum-action solution, assume symmetry such that $\phi(\tau, \mathbf{x})$ depends only on radial Euclidean distance $\rho = \sqrt{|\mathbf{x}|^2 + \tau^2}$
- Analytically continuing back to real time gives solution as function of $\sqrt{|\mathbf{x}|^2 - t^2}$, including *bubble profile* at $t = 0$
- Clearly nonsensical for $t < 0$ — usually just say the bubble "appears" at $t = 0$



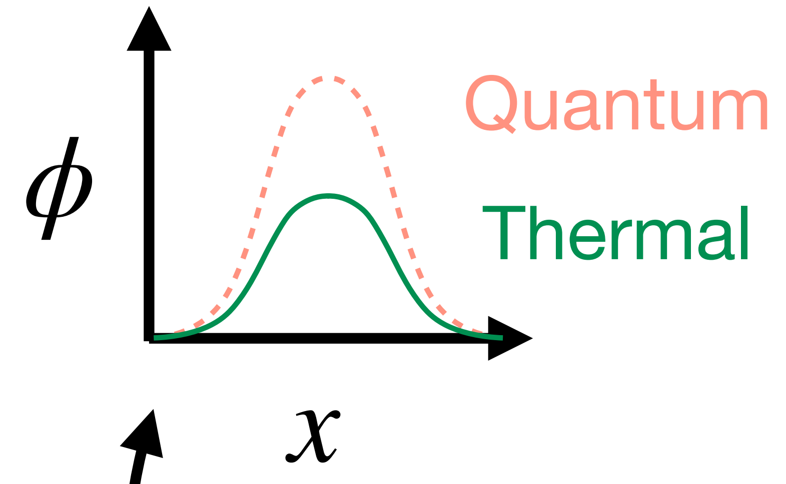
Thermal instantons

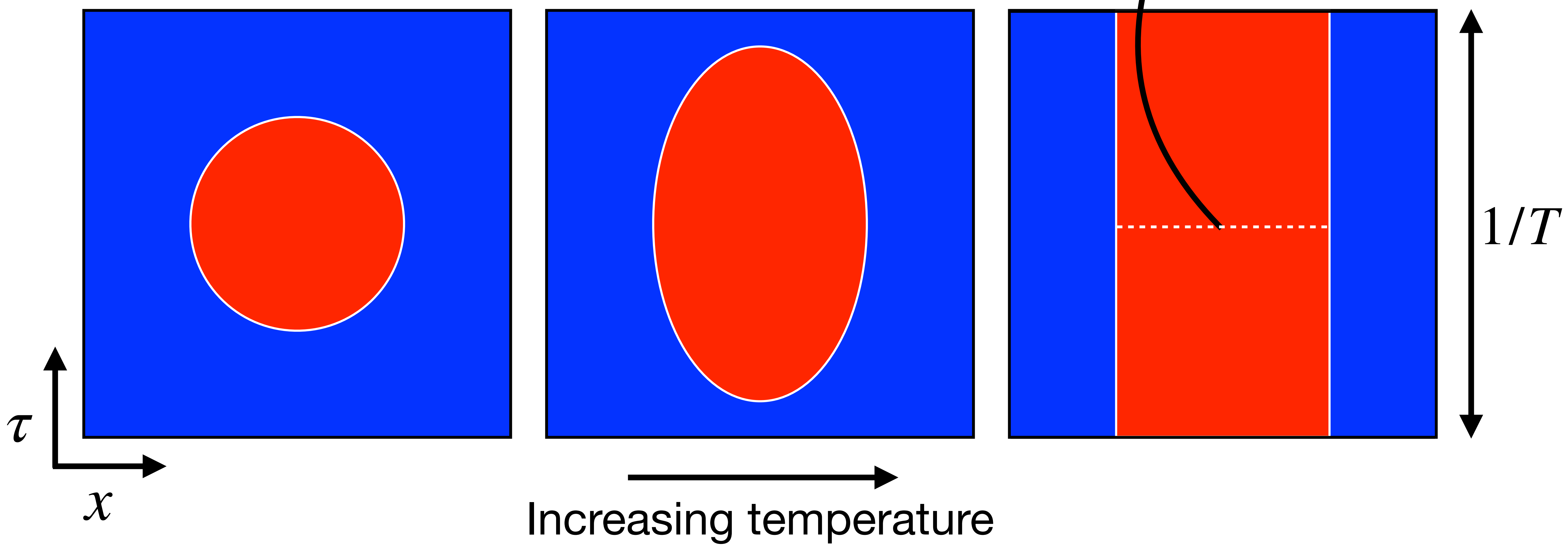


- As well as "under the barrier" vacuum process, can jump to the top of the barrier through thermal excitation

- Distinct decay rate and bubble profile compared to vacuum case, but same Euclidean framework

Linde 1982

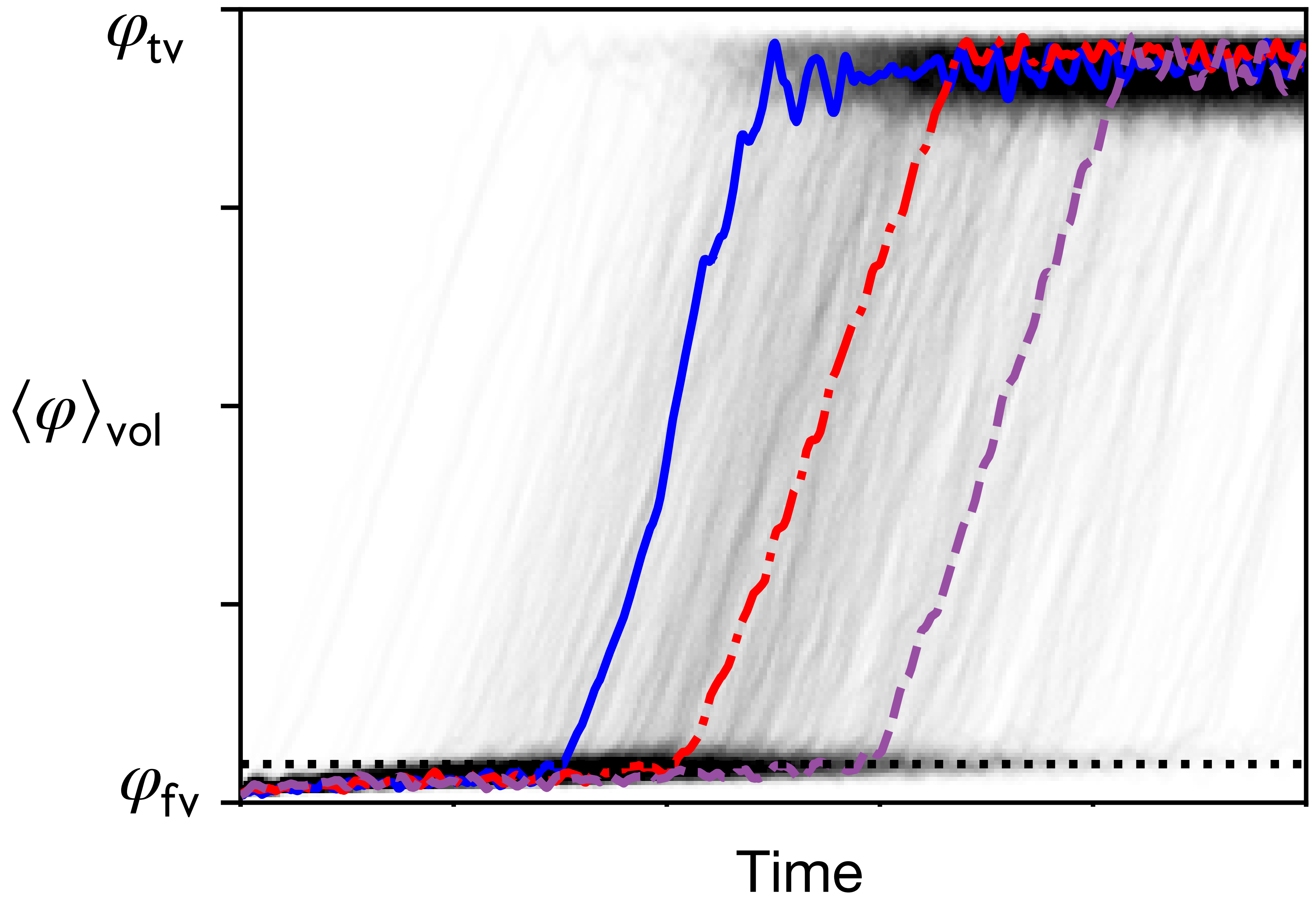


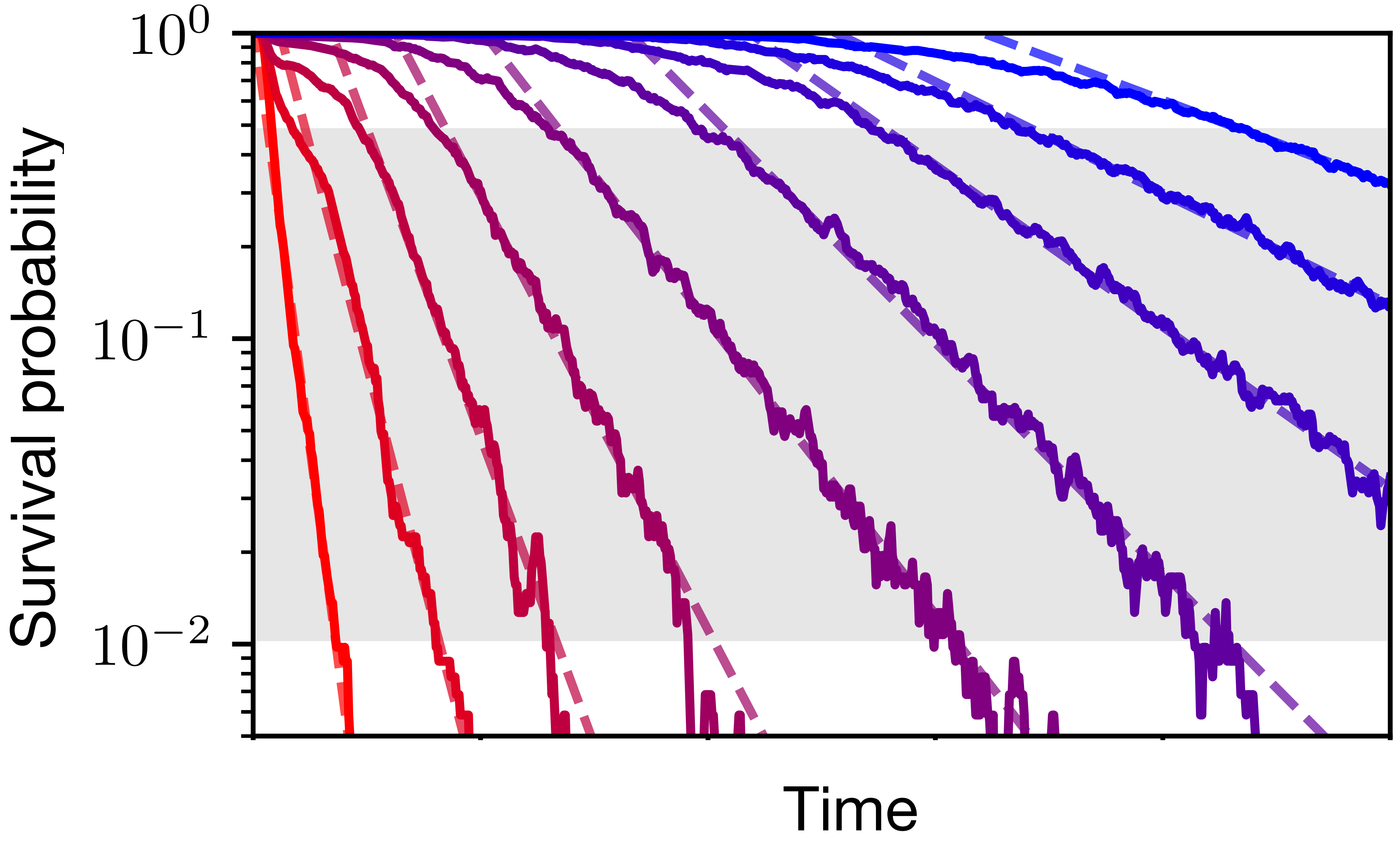


Decay rates on the lattice

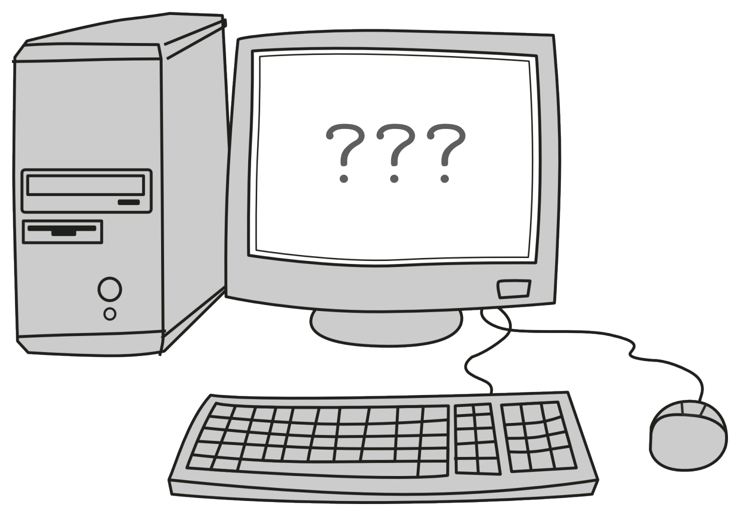
- Run large ensemble of sims, count how many have decayed as a function of time
- Decay rate scales as expected with parameters of the theory
- However, normalisation is *significantly larger* than the instanton prediction — off by many orders of magnitude (!!)

Braden+, 1806.06069
ACJ+, 2307.02549





Understanding the discrepancy

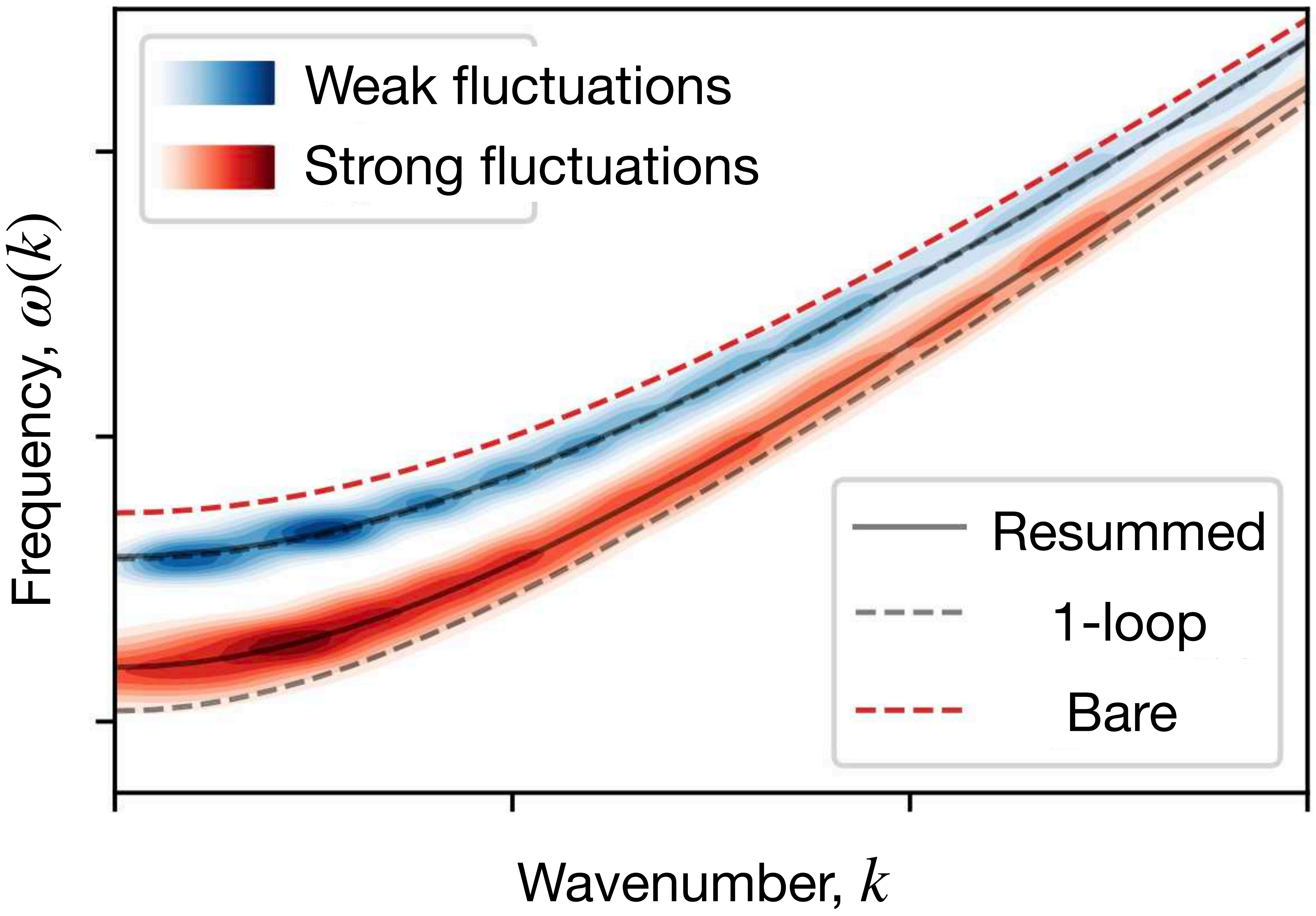


Why do bubbles nucleate so much faster on the lattice than the instanton prediction?

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

Hypothesis 2: We *are* seeing the same process, but are making the wrong comparison. Coleman instantons and real-time simulations are different descriptions of the same process, if you match them correctly.

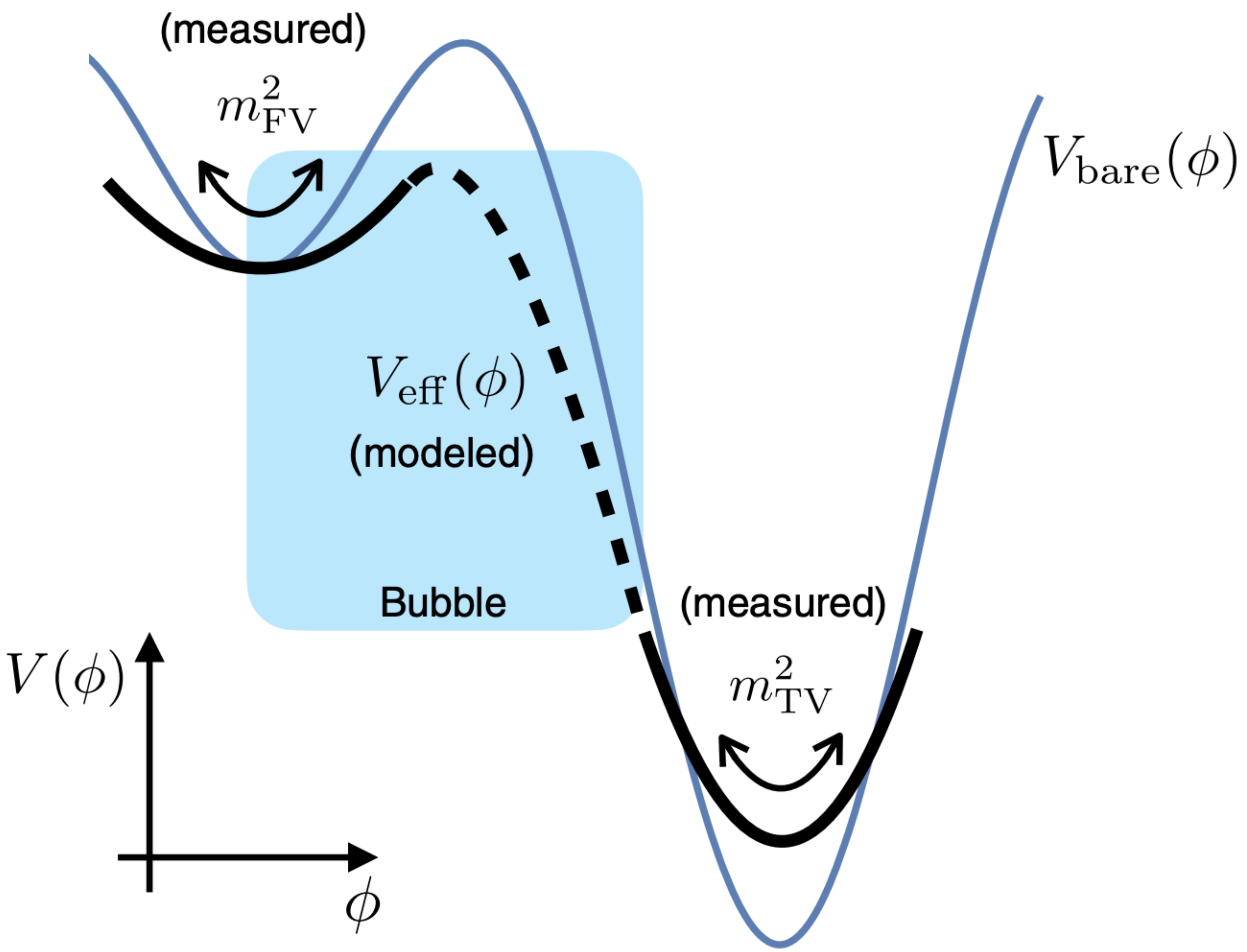
Measuring mass renormalisation



- 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

Bubble profile templates



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

A theorist's wishlist

We want *new cosmological insights*, not just a vague analogy

Minimal criteria we demand for this:

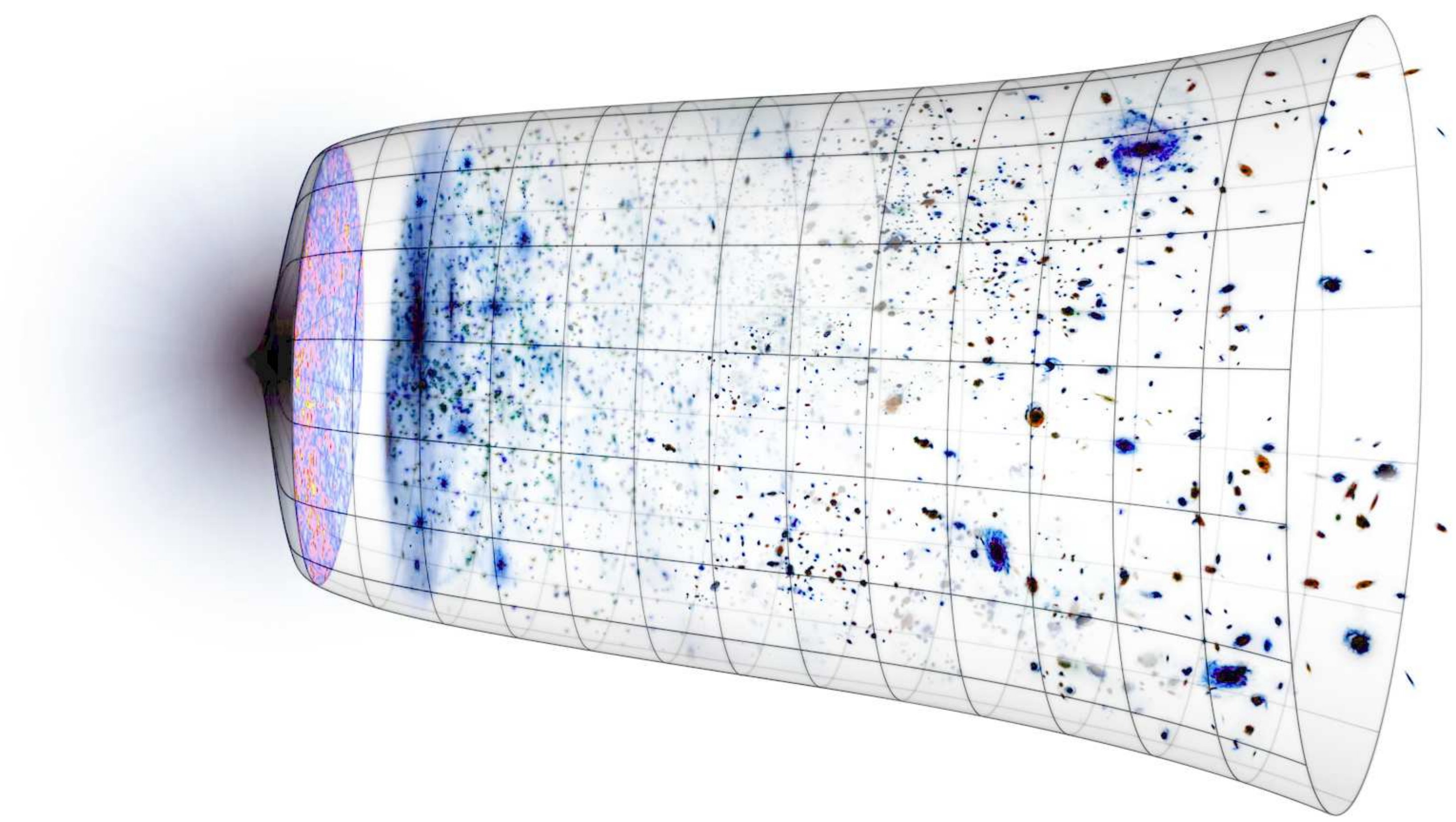
✓ A *metastable state* (not just unstable)

✓ *Homogeneous* in one or more dimensions

✓ *Relativistic* equations of motion

✓ *Relativistic* vacuum fluctuations

✓ *Vacuum* nucleation, not thermal



Things we will *not* demand:

✗ 3+1 dimensions — lower-dimensional analogues already give valuable insights

✗ Hubble expansion or other gravitational effects

✗ Anything beyond a single scalar field (no Standard Model particles)

Simulations for experimental design

- Experiment has a *boundary* that causes rapid nucleation of “edge bubbles”, obscuring the bulk nucleation we’re interested in
- Solution: engineer the trapping potential to create a high-density “trench” around the edge — *completely eliminates boundary nucleation!*
- Real-time simulations provide a powerful check of this idea

ACJ, Peiris, Pontzen, 2504.02829