Title: From the tabletop to the Big Bang: Analogue false vacuum decay from vacuum initial conditions

Speakers:

Collection: Quantum Simulators of Fundamental Physics

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Alex Jenkins | alex.jenkins@ucl.ac.uk | 5 June 2023
QSimFP Workshop | Perimeter Institute

From the tabletop to the Big Bang

Analogue vacuum decay from vacuum initial conditions

Based on work with J. Braden, M. Johnson, H. Peiris, A. Pontzen, S. Weinfurtner
On the arXiv soon! 2306.xxxxx

QSimFP

UCL

Spoilers!

Our three main results:

1. The analogue false vacuum has *the same quantum fluctuations* as the relativistic false vacuum (…in the IR)

2. We've identified *realistic experimental parameters*, and verified with simulations that this system undergoes relativistic vacuum decay

3. We've shown that *quantum* (rather than thermal) decays are accessible with this setup

Plan for this talk

1. What is vacuum decay, and why do we care?
2. How can we simulate vacuum decay in the lab?
3. What theoretical work is needed to exploit these experiments?

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Vacuum decay basics

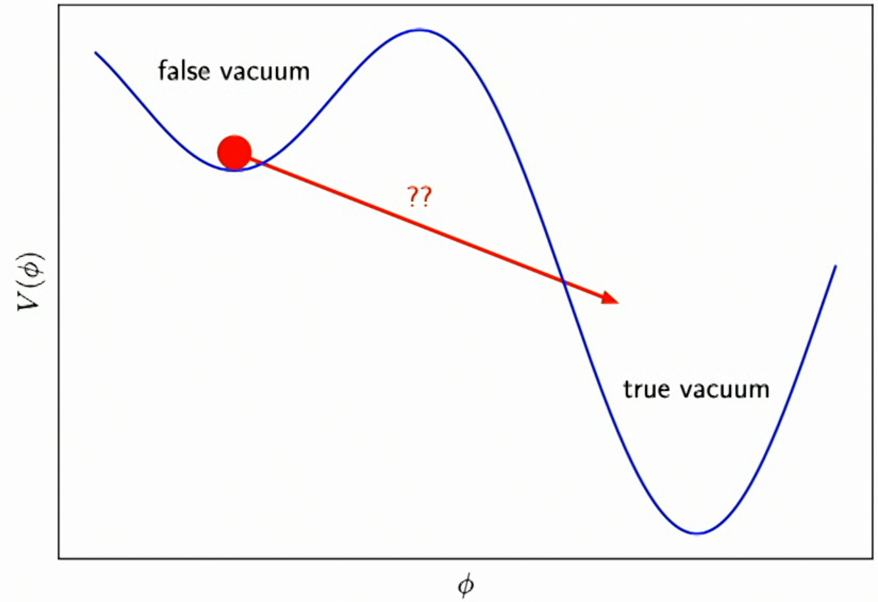
- We have a relativistic scalar field,

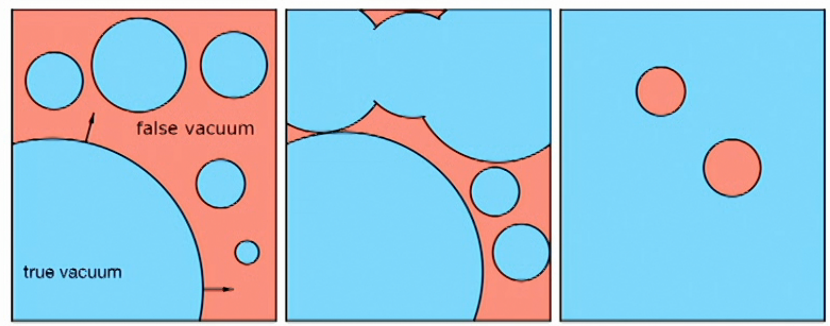
$$\partial_t^2\phi - \nabla^2\phi + V'(\phi) = 0$$

- Field escapes from a *local* minimum of potential $V(\phi)$ to *global* minimum

- Localised "bubbles" of true vacuum expand and collide

- Inherently quantum-mechanical, non-perturbative, non-equilibrium … very difficult problem!





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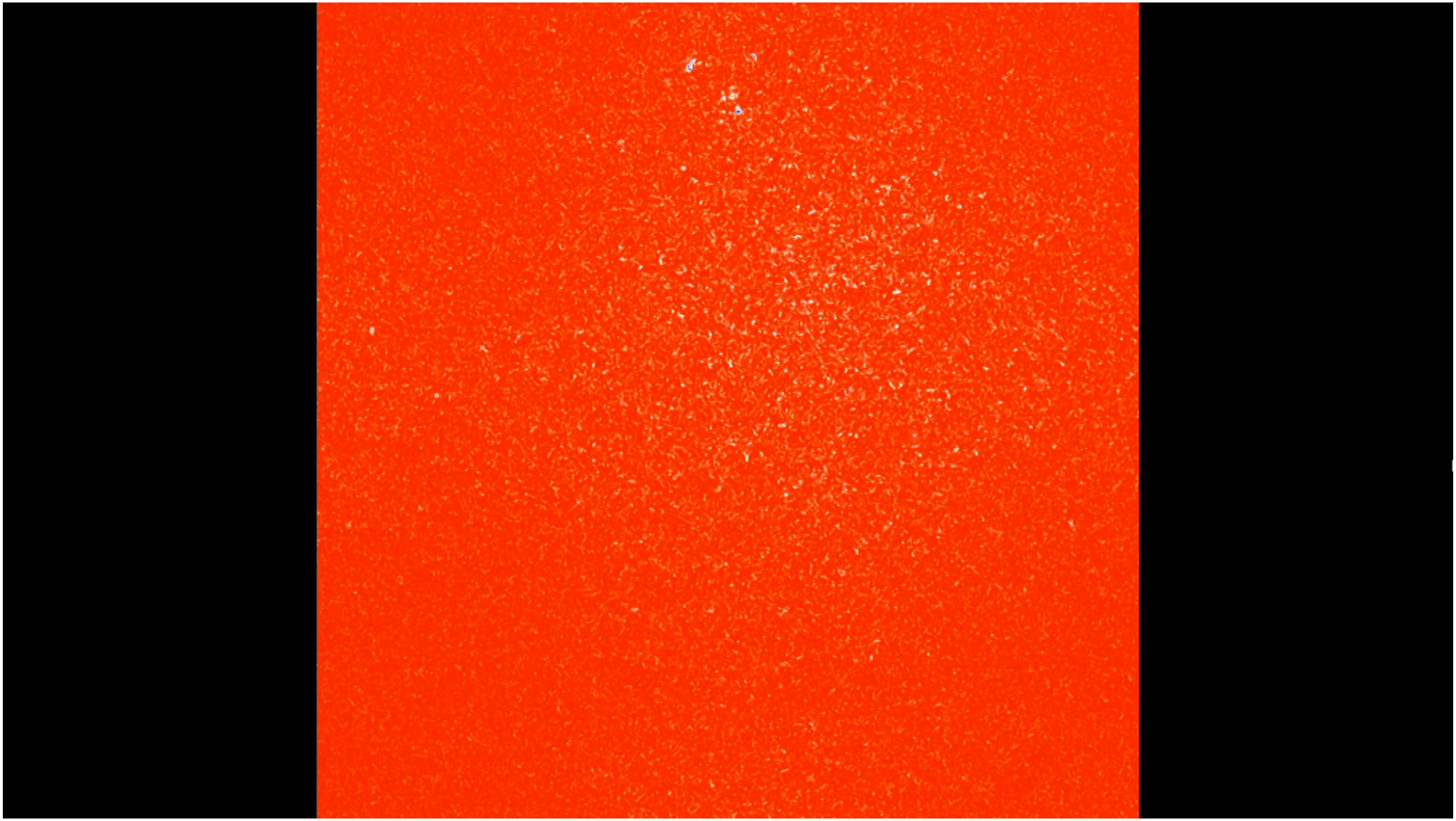
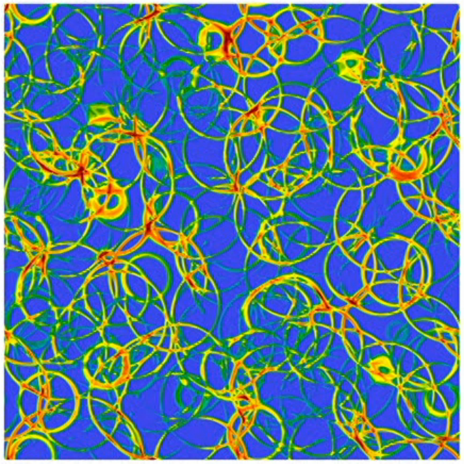


Why do we care?



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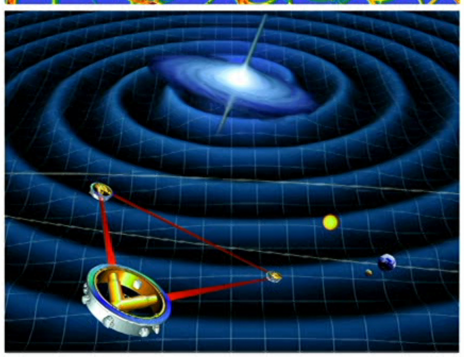
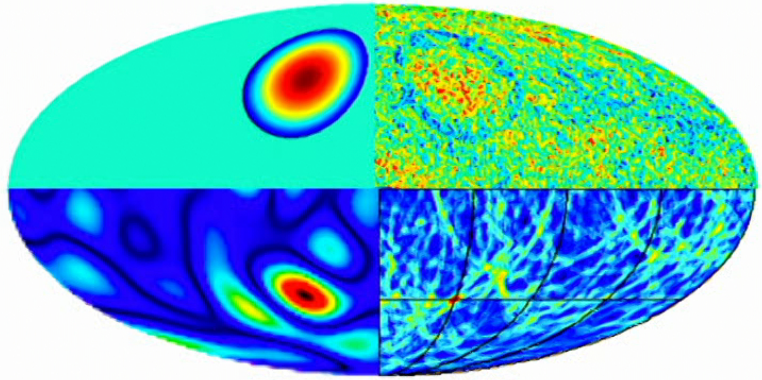


Gravitational-wave cosmology

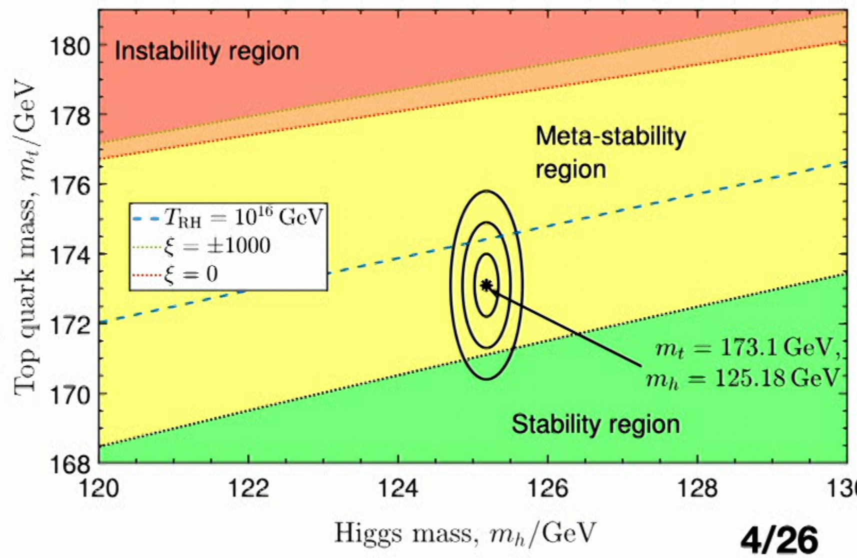


Feeney+, 1012.1995

Inflation and the multiverse

(Meta)stability of the electroweak vacuum

Markkanen+, 1809.06923



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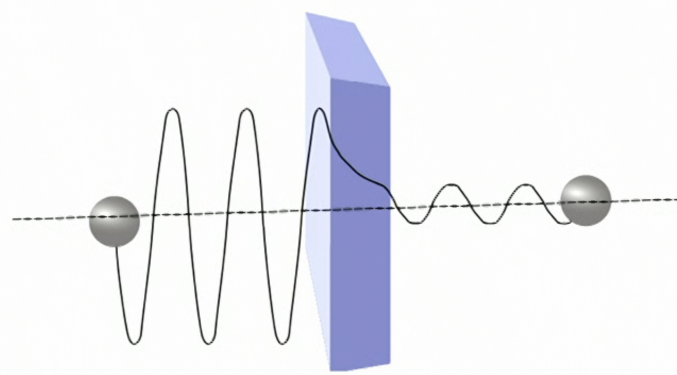
Quantum tunnelling

QM allows non-relativistic particles to *tunnel* through a potential barrier $V(x)$

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

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

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



Instanton formalism

By analogy with QM, the decay rate for a field $\phi(x, t)$ is set by Euclidean action

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

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

This is an integral over an imaginary-time field solution called an *instanton*

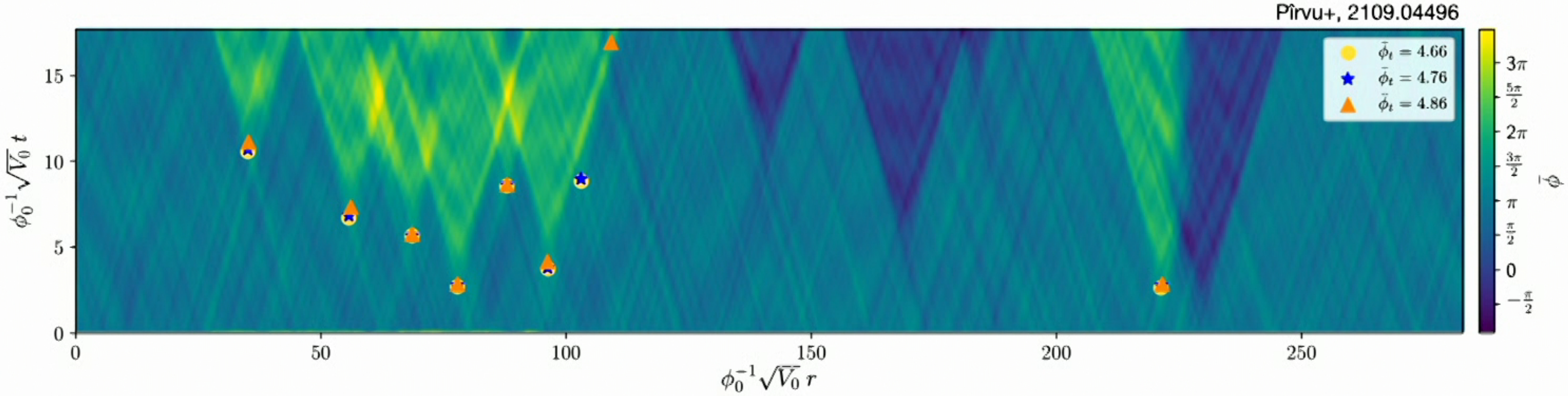
Infinite degrees of freedom, but can find solutions using symmetry assumptions

Works best for deep barriers — the “thin wall” regime

What instantons *can't* tell us

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

Pîrvu+, 2109.04496



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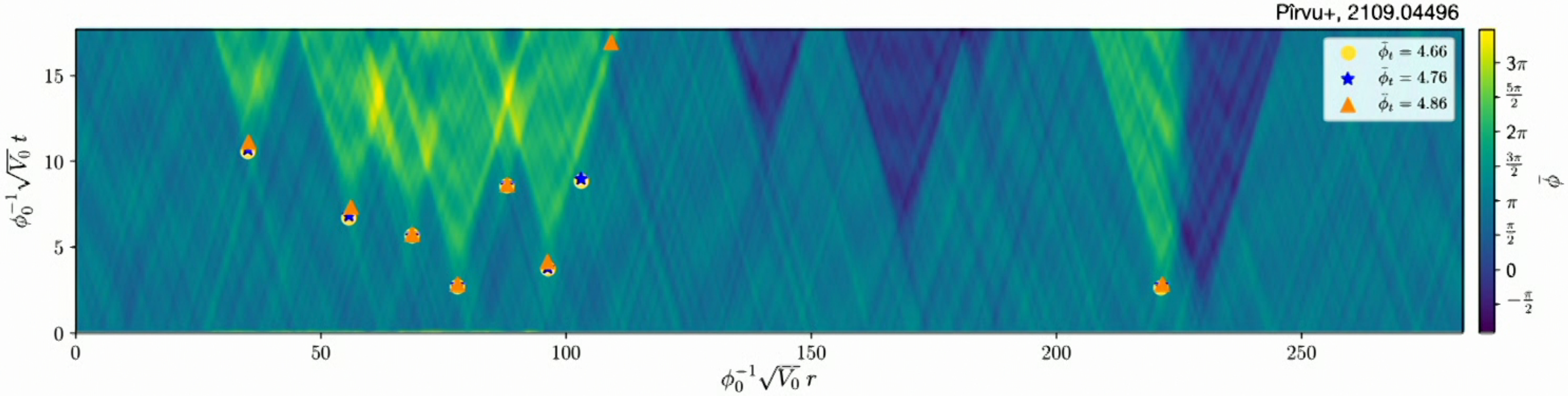
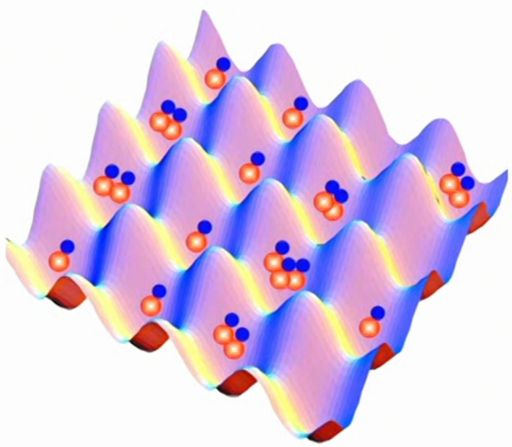


Two routes forward

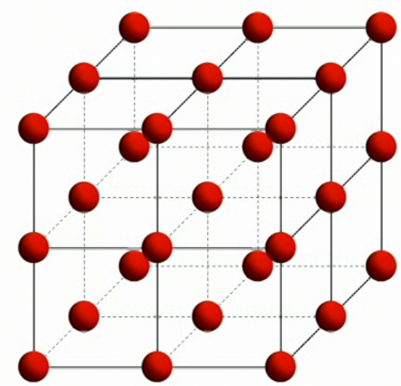
Quantum analogues

Engineer a system in the lab which behaves like a quantum field undergoing FVD



Lattice simulations

Use a semiclassical approach to study bubble nucleation numerically



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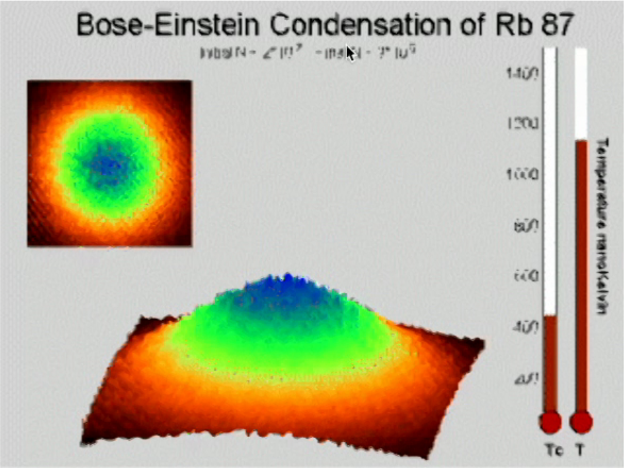
Cold atomic Bose gases

- Highly controllable macroscopic systems with *collective quantum behaviour*
- Why *bosonic*?
  Atoms undergo *Bose-Einstein condensation* to form a diffuse, field-like object
- Why *cold*?
  Quantum excitations of energy ω dominate over thermal effects when $k_B T < \hbar\omega$
- Why *atomic*?
  Can *cool* and *trap* atoms and control their *interactions* very precisely using laser light and magnetic fields
- Why *gases*?
  Low densities mean that the condensate is large enough to be *directly imaged*

Cornell, Wieman, *et al.* — Nobel Prize 2001



Mean-field theory of cold atoms

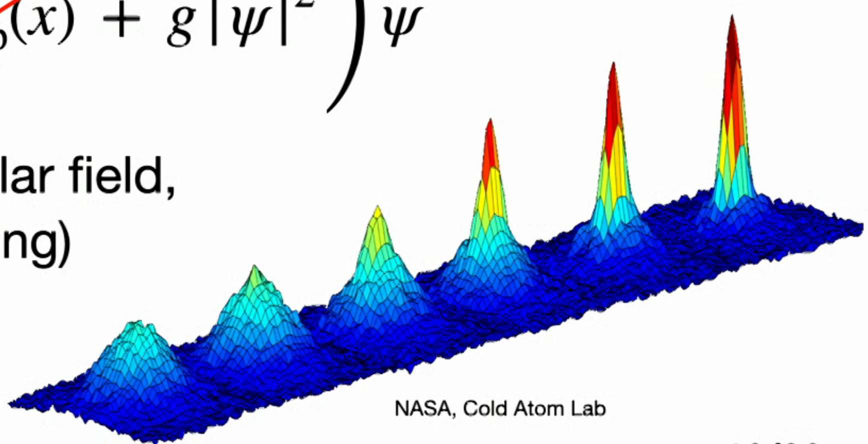
- Atomic field $\hat{\Psi} = \psi + \delta\hat{\psi}$ consists of (highly-occupied, classical) condensate ψ plus small quantum fluctuations $\delta\hat{\psi}$

- Condensate wavefunction obeys the *Gross-Pitaevskii equation* (AKA *nonlinear Schrödinger equation*)

$$i\hbar\frac{\partial\psi}{\partial t} = \left(-\frac{\hbar^2}{2M}\nabla^2 + V_{\text{trap}}(x) + g\,|\psi|^2\right)\psi$$

- Equation of motion for a *non-relativistic* scalar field, with a $|\psi|^4$ potential (no barrier, no tunnelling)

- How do we get cosmology from this??



NASA, Cold Atom Lab

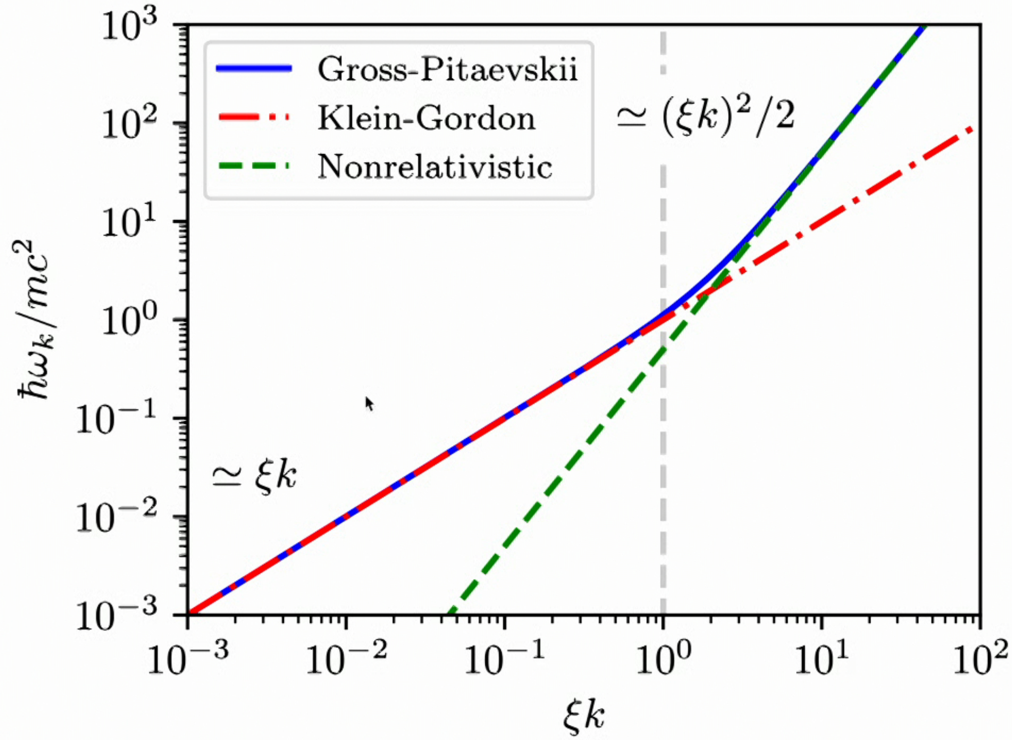
Spectrum of the Hamiltonian

- On small scales, reduces to Schrödinger equation, and we get non-relativistic excitations

$$\omega(k) \simeq k^2/(2m)$$

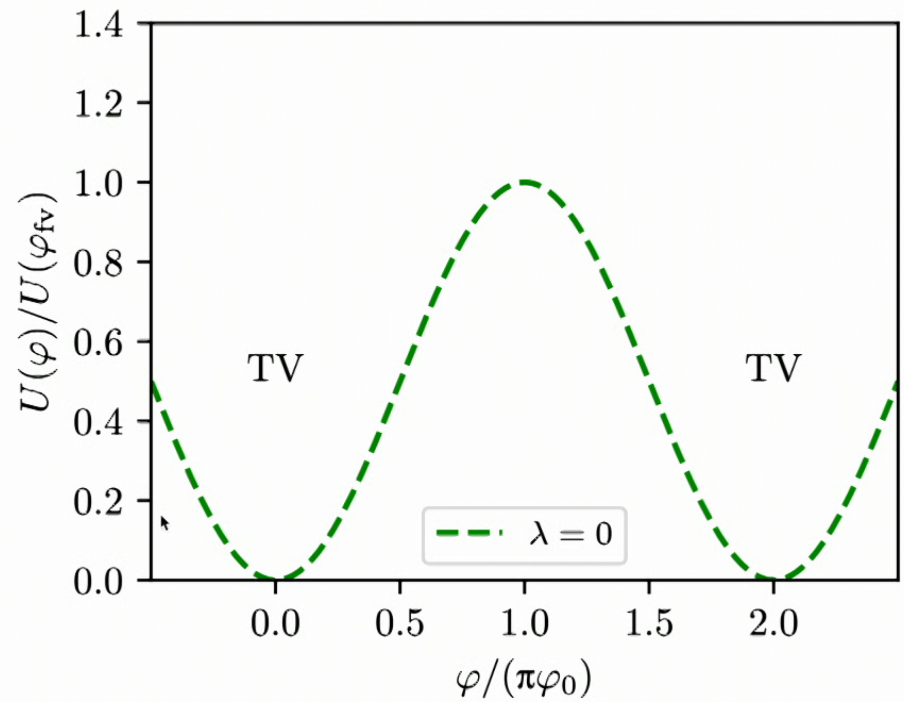
- On large scales, nonlinear interaction gives rise to massless, *relativistic* phonons

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



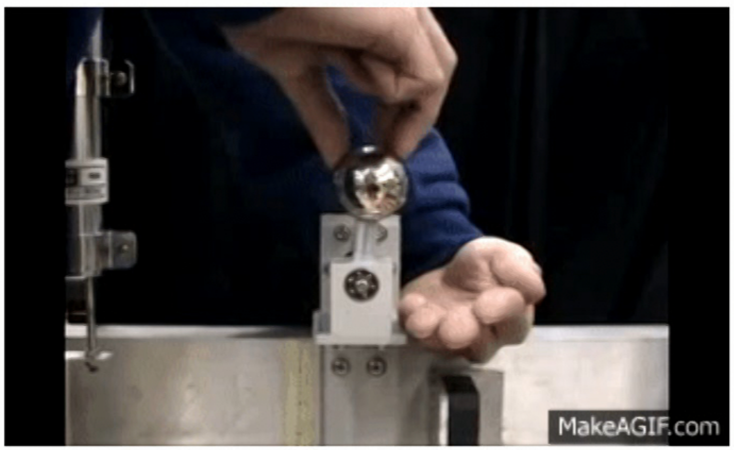
How do we get a potential?

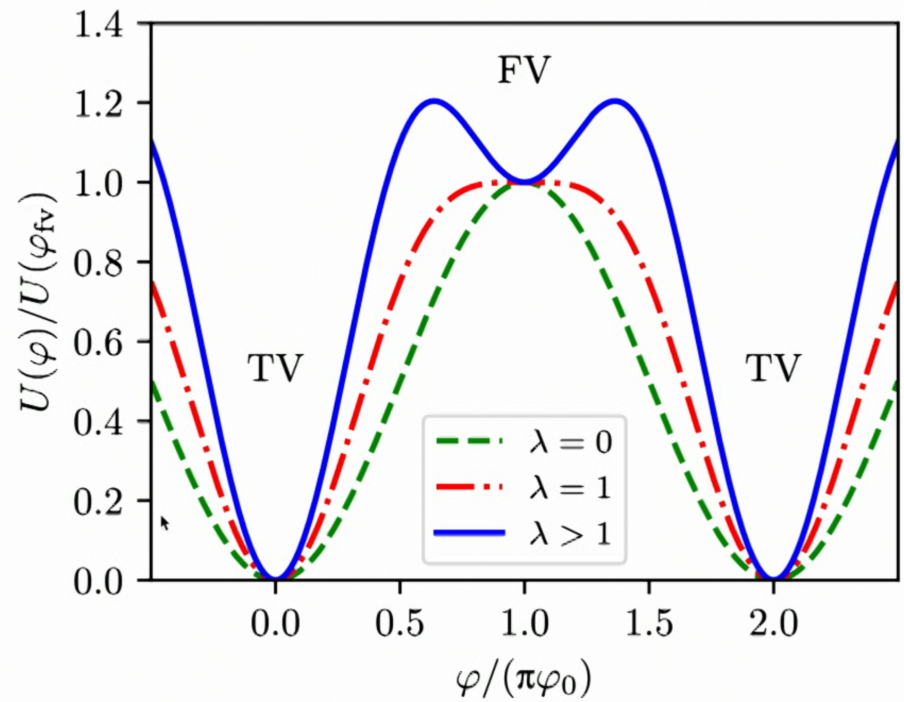
- Consider two identical BECs with an inter-species coupling ν
- Study the *relative* and *total* modes,
$$\delta\hat{\psi}_{\pm} = \delta\hat{\psi}_1 \pm \delta\hat{\psi}_2$$
- The relative phonons have a cosine potential due to the interaction ν



How do we get a false vacuum?

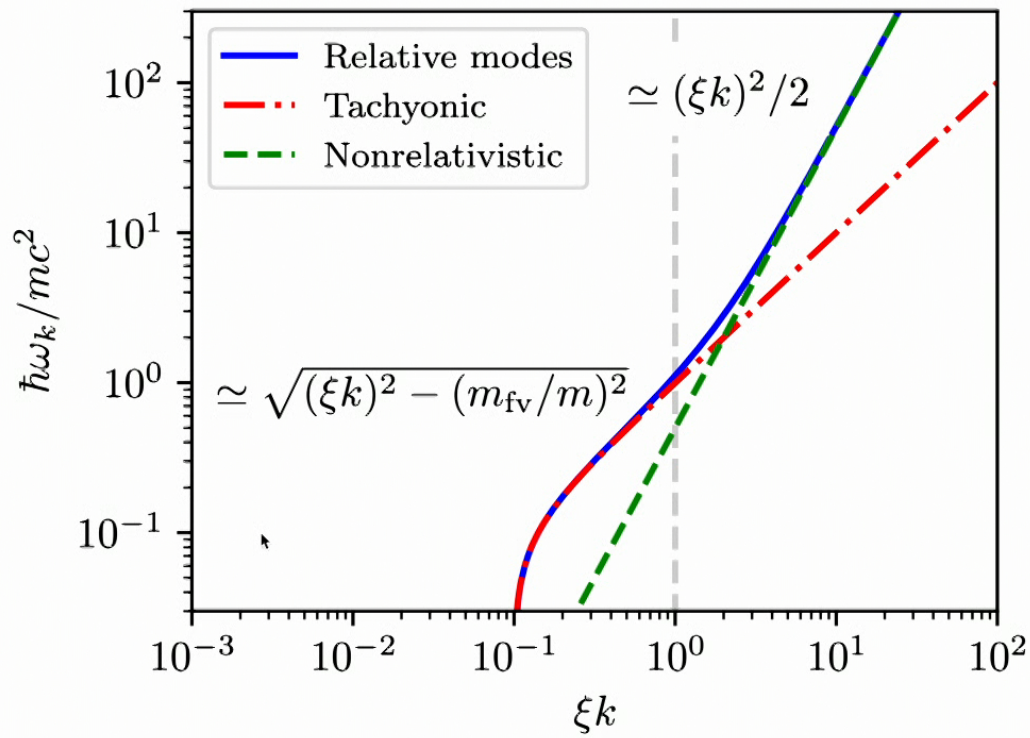
- Rapid oscillations of the coupling ν stabilise the false vacuum
- Analogous to a pendulum with an oscillating pivot point





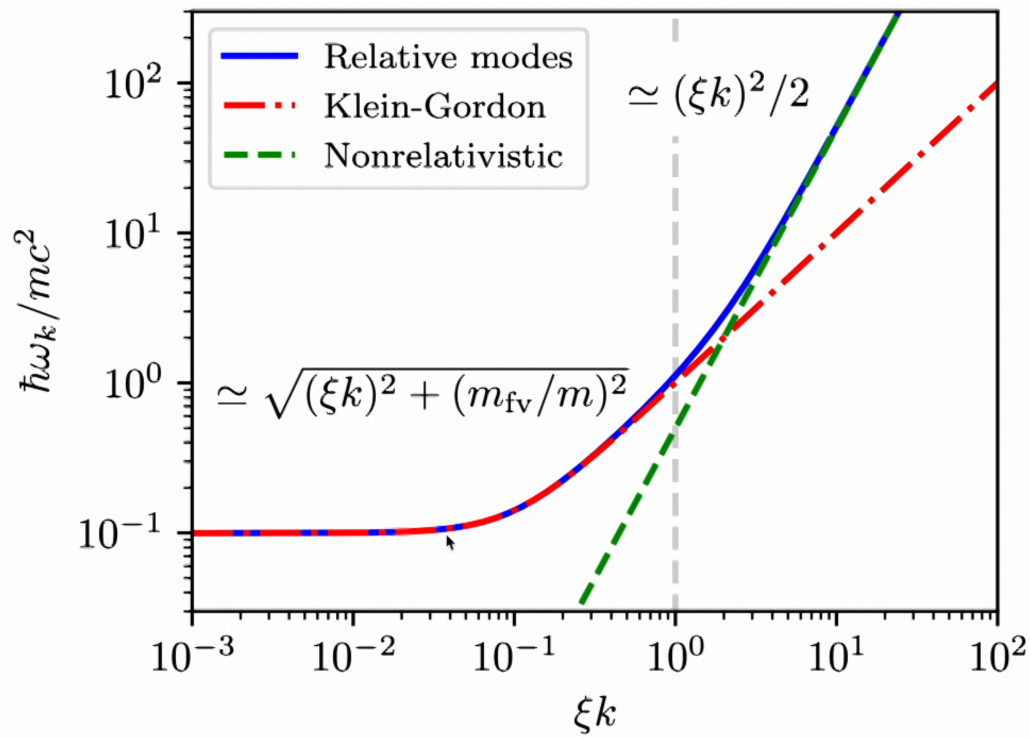
Spectrum of the Hamiltonian (unstable)

- First consider constant coupling ν
- Relative phonons are tachyonic (reflecting the instability)



Spectrum of the Hamiltonian (metastable)

- Now switch on the modulated coupling
- Gives the relative phonons an effective mass, set by the false vacuum potential barrier
- These modes behave like those of a massive Klein-Gordon field on large scales



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BEC parameters

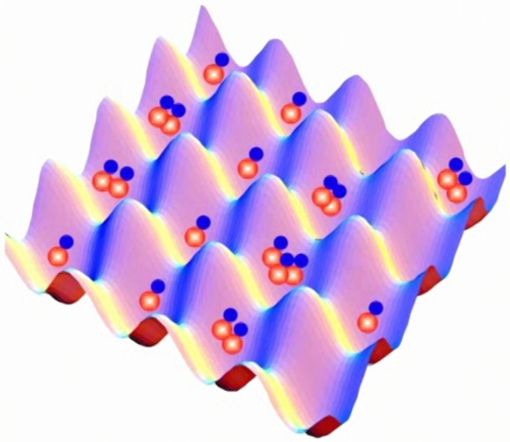
- Our main goal is to maximise the characteristic temperature scale,

$$T_{\rm fv} = \frac{m_{\rm fv}}{m}\frac{gn}{k_{\rm B}}$$

(…subject to experimental/theoretical constraints)

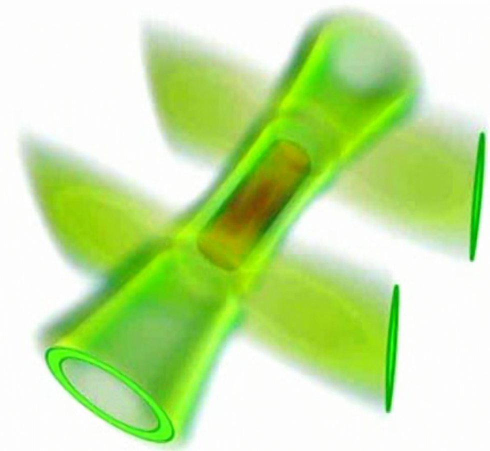
- This makes it easier to achieve $T < T_{\rm fv}$, and thus *quantum* rather than *thermal* decays

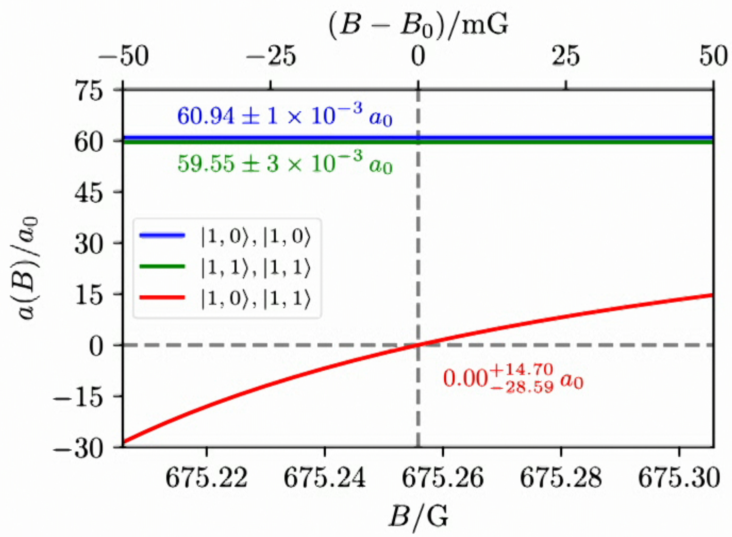
- Once $T_{\rm fv}$ is fixed, we can vary the decay rate via the dimensionless number density $\bar{n}$



BEC parameters

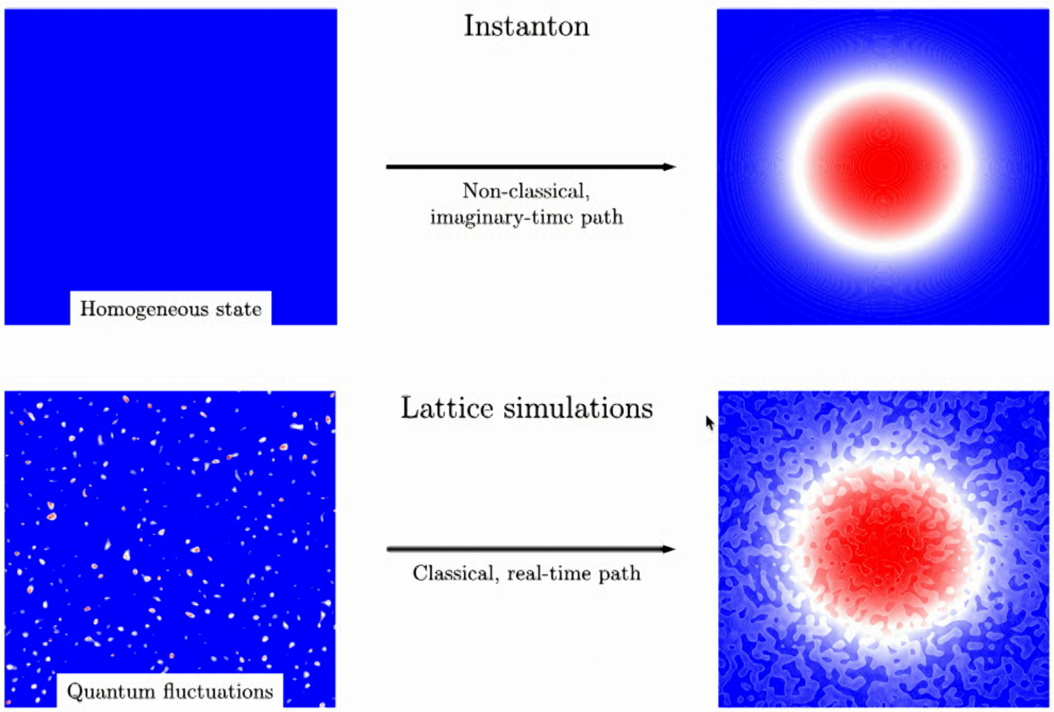
- Potassium-41
- Spin states $|F, m_F\rangle = |1{,}0\rangle, |1, +1\rangle$
- Use Feshbach resonance near $B = 675.26\,\mathrm{G}$
- $L \sim 130\,\mu\mathrm{m}$ effective 1D box trap
- Between $N \sim 8000$ and $\sim 30{,}000$ atoms
- Trapping freq. between $\omega_\perp/2\pi \sim 4\,\mathrm{kHz}$ and $\sim 15\,\mathrm{kHz}$





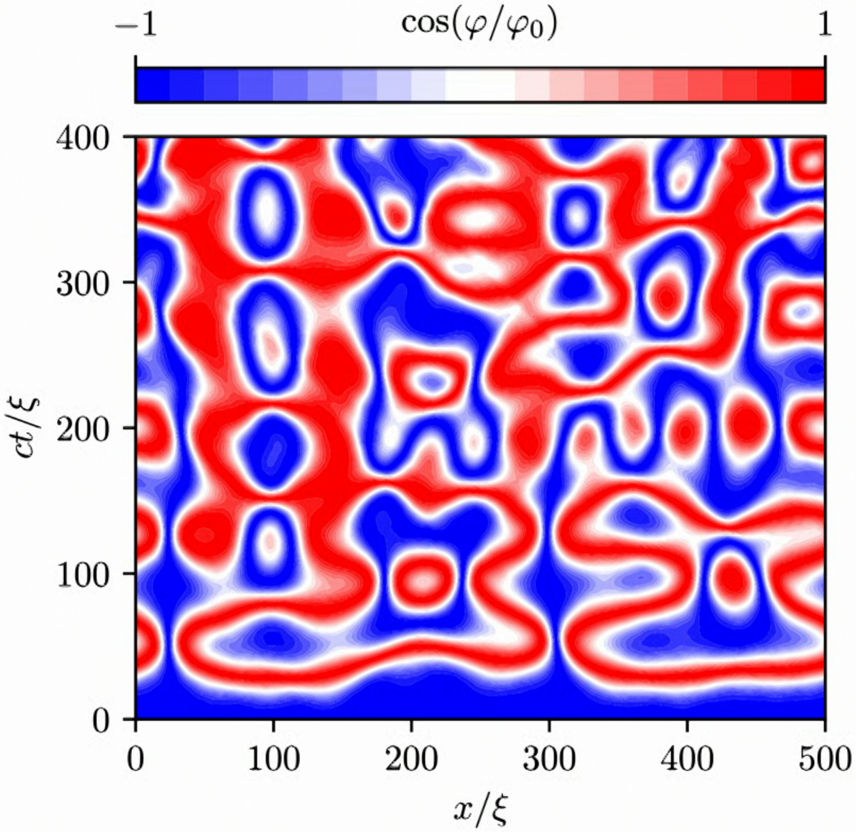
Semiclassical lattice simulations

- Instantons evolve from “classical” initial state via non-classical paths
- Opposite approach: sample initial state (inc. quantum fluctuations), then evolve forward classically
- Used in inflation/preheating sims, also quantum optics/atomic physics (“truncated Wigner approximation”)
- Aim is *not* to replace the experiments, but to guide our understanding

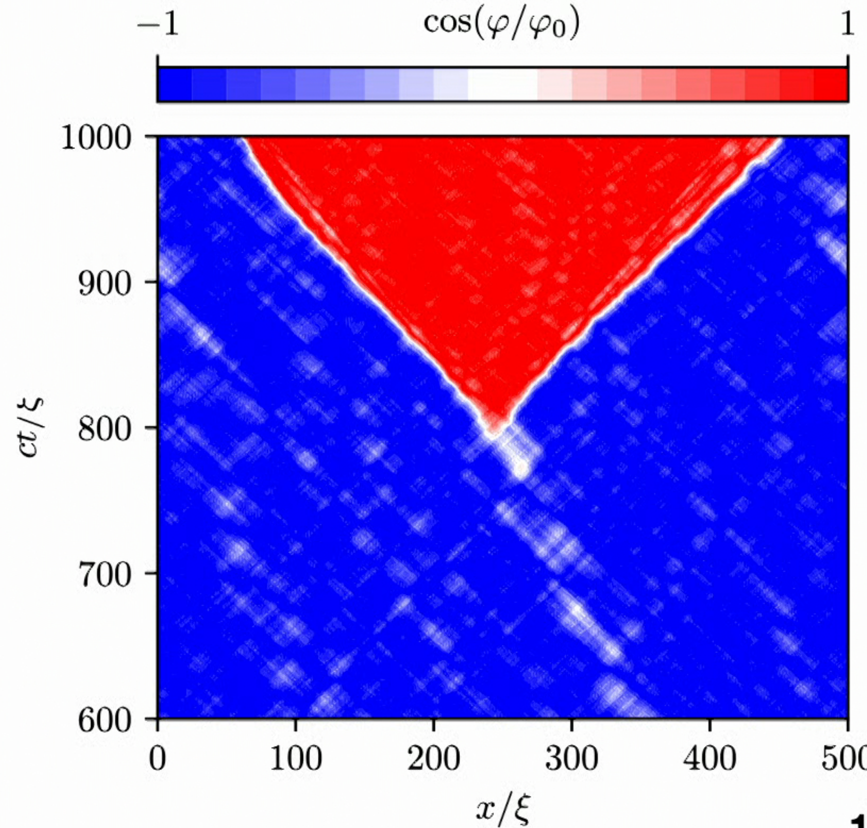


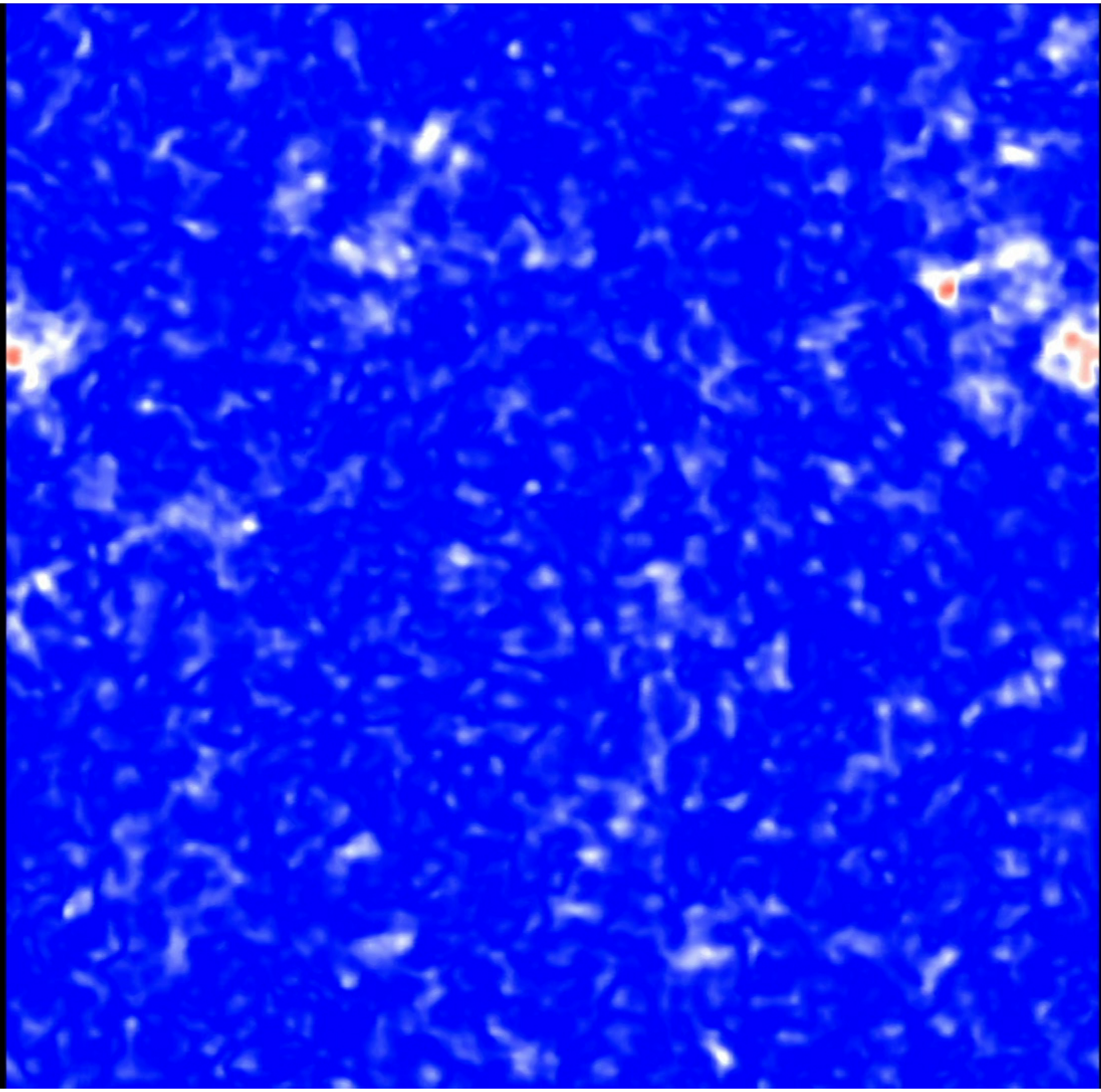
Semiclassical lattice simulations (1D)

Spinodal transition (no potential barrier)



Bubble nucleation (potential barrier)

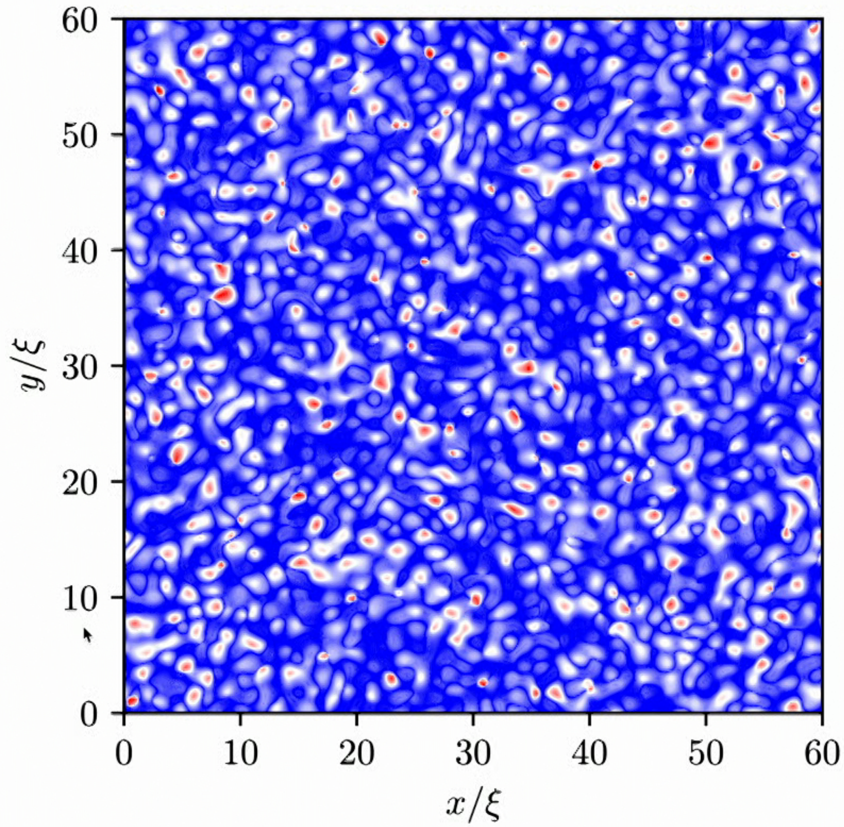




Initial conditions

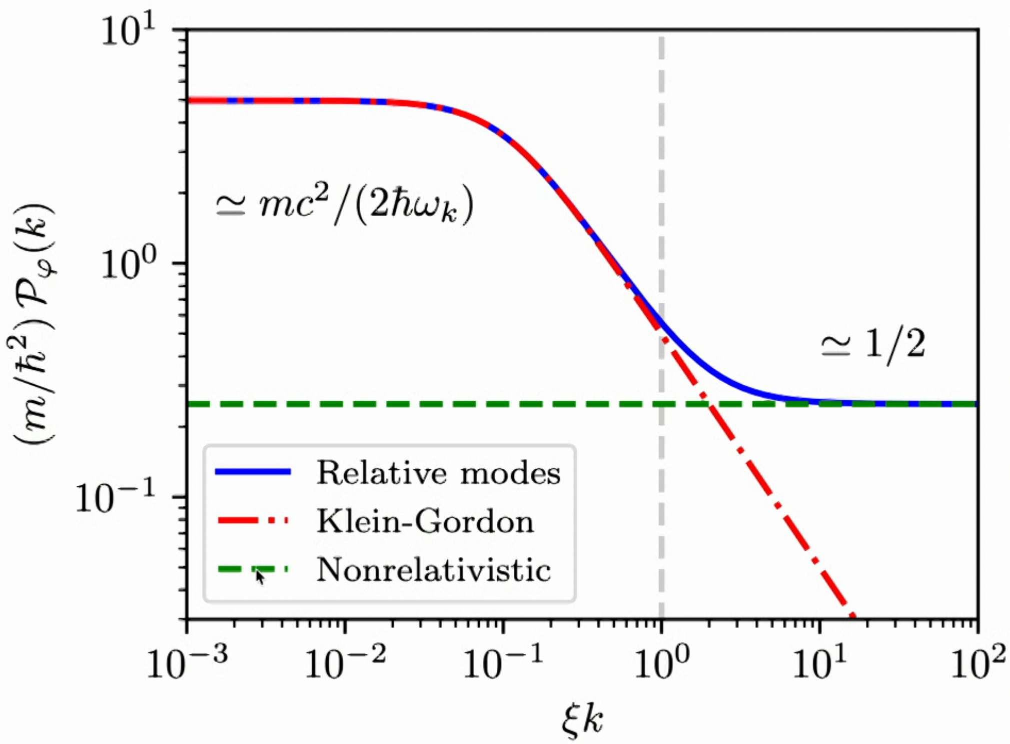
- If we're putting all of the "quantum-ness" into the initial conditions, we'd better make sure they're *robust*
- Most simulations have used *white noise* (only valid for a non-interacting BEC)
- Instead we use Bogoliubov theory to find *power spectra*,

$$\mathscr{P}_\varphi(k) = \langle \Omega \,|\, \hat{\varphi}^\dagger_{\mathbf{k}} \hat{\varphi}_{\mathbf{k}} \,|\, \Omega \rangle$$



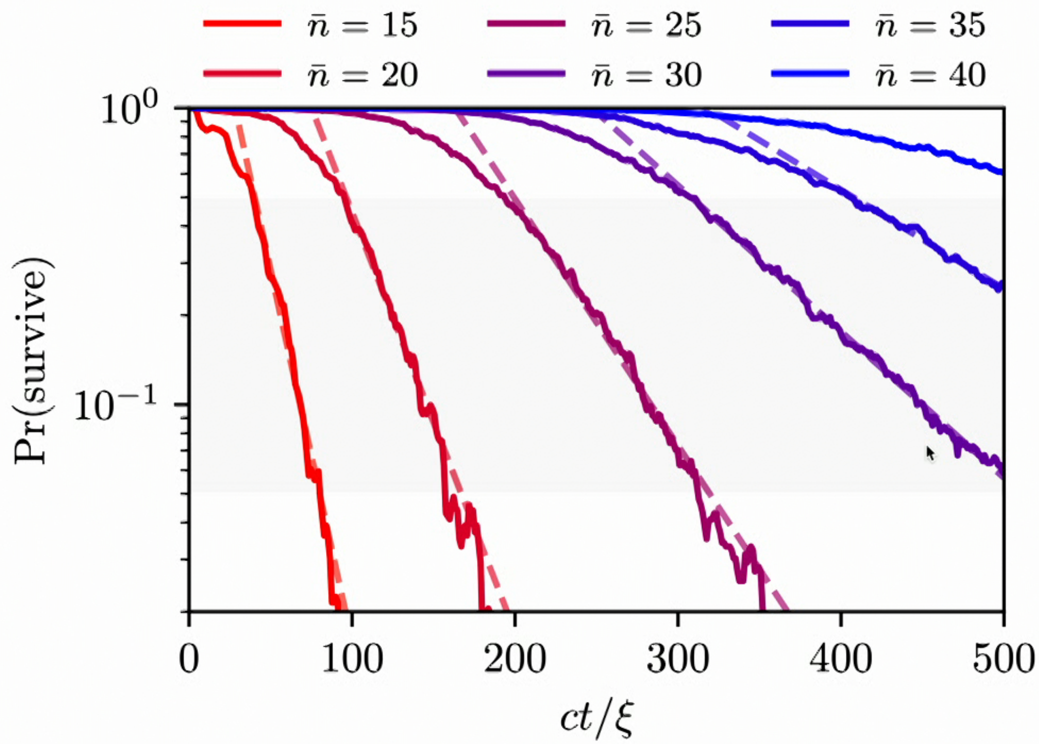
Initial fluctuations in the false vacuum

- We recover the expected Klein-Gordon spectrum in the IR
- Relativistic analogy works *at the level of the quantum fluctuations*, not just the classical equations of motion
- Additional power on small scales due to “shot noise” —excitations of individual atoms



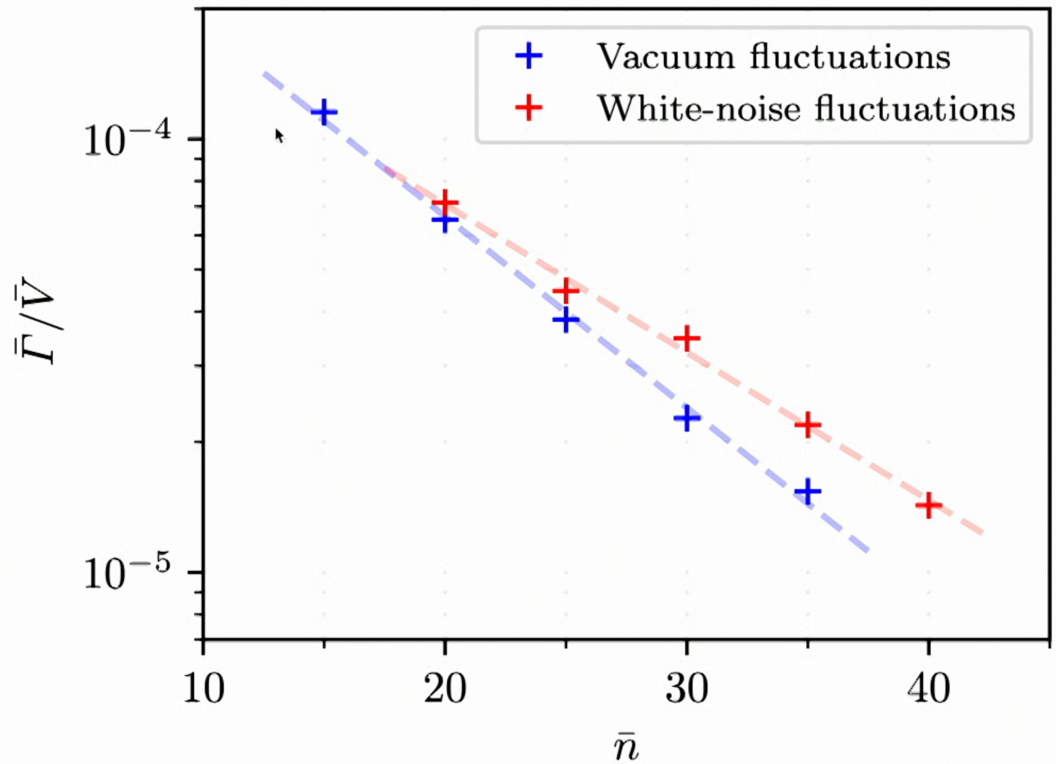
Bubble nucleation rates

- Run large ensemble of sims, count how many haven't decayed as a function of time
- We expect exponential decay, $\mathrm{Pr(survive)} \sim \exp(-\Gamma t)$
- Study decay rate Γ as a function of condensate number density $\bar{n}$ (larger $\bar{n}$, smaller fluctuations, slower decays)



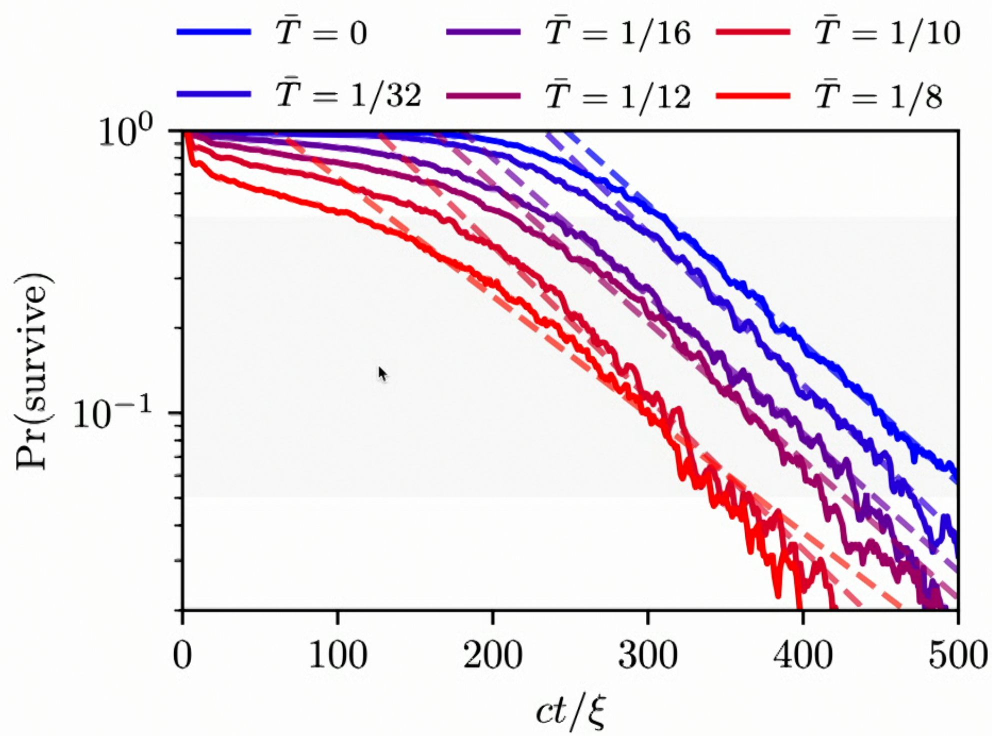
Bubble nucleation rates

- Recover expected linear scaling, $\log \Gamma \propto -\bar{n}$
- White noise leads to faster decays than vacuum, *even though* there is less fluctuation power
- White noise is an *excited state*
- Important to get these details right for reliable predictions



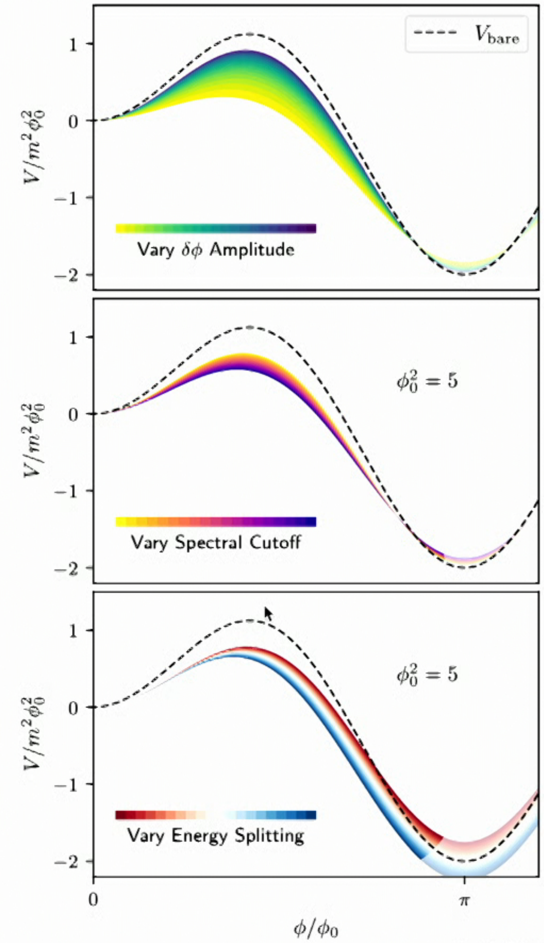
Finite-temperature decay rates

- Real experiment will inevitably be at non-zero temperature
- How high can this be before we deviate from the zero-temperature rate?
- Answer: for our parameters, we need $T \lesssim 18\,\mathrm{nK}$
- Easily accessible with experiments!



Some open problems

- **Boundary effects.** Real experiment has an edge — what effect does this have on bubble nucleation?
- **Renormalisation.** Bare parameters are modified by fluctuations — need to account for this to make reliable predictions / compare with instantons
- **Parametric resonance.** Modulated coupling causes instabilities on small scales — expect this to be damped in practice, but how?



Braden+, 2204.11867

Alex Jenkins | alex.jenkins@ucl.ac.uk | 5 June 2023

Summary

- *Vacuum decay* is a ubiquitous but poorly-understood process in cosmology
- Quantum analogues will enable the *first empirical tests* of this process
- We're using *lattice simulations* to build understanding of these analogues, and have shown they can simulate *quantum, relativistic* bubble nucleation

Thanks for listening!

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