Table-Top Cosmology with a Spinor Bose Gas

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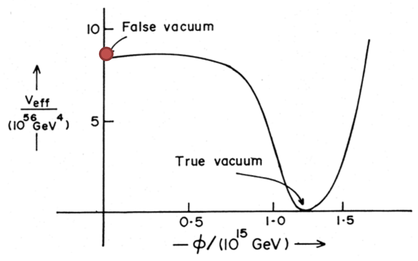
Introduction and Motivation

The quantum decay of a scalar field from a metastable state (**false vacuum decay**) is closely related to the standard theory of the early universe describing the Big Bang as the nucleation of a **bubble** (inflaton), which subsequently leads to a rapid expansion of space inside the bubble (**inflation**).

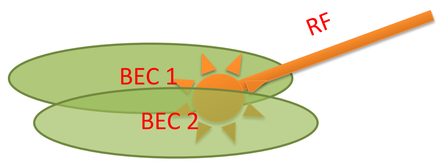
The enormous energy released in the formation of a bubble is converted into an abundance of elementary particles, which later form photons, stars and galaxies [1].



We propose an experimental test of false vacuum decay using an ultracold Bose-Einstein condensate (BEC) of either potassium-41 or lithium-7 [2 - 4].

Our Model

Our model uses:
(i) interacting two-component Bose-Einstein condensate,
(ii) finely engineered coupling between two atomic states and
(iii) the zero inter-state scattering length.



We simulate the quantum dynamics of the coupled Bose fields using the pseudo spin 1/2 notation, relevance to the relativistic Klein-Gordon equation and using the truncated Wigner approximation in solving stochastic Gross-Pitaevskii equations.

The relative phase of two spin components $\phi_a = \phi_2 - \phi_1$ assumes the role of the relativistic scalar field (the inflaton field) and quantum dynamics of the scalar field is described by an equation analogous to the Klein-Gordon equation

$$\partial_t^2\phi_a - c^2\nabla^2\phi_a + \frac{4\nu^2\xi}{\hbar^2 c}\partial_t\phi_a = -\partial_{\phi_a}V(\phi_a)$$

with the effective potential

$$V(\phi_a) = -\omega_0^2\left[\cos(\phi_a) - \frac{\lambda^2}{2}\sin^2(\phi_a)\right],$$

the speed of sound

$$c = \sqrt{g\rho_0/m}$$

the healing length

$$\xi = \hbar/\sqrt{2mg\rho_0}$$

and time-dependent coupling of two components (quantum Kapitza pendulum)

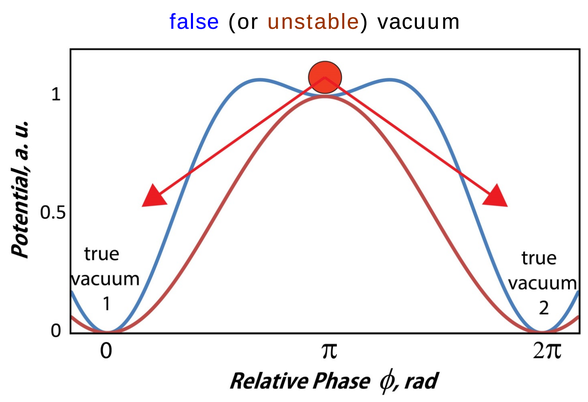
$$\nu + \delta\hbar\omega\cos(\omega t)$$

Here the joint action of atomic interactions ($g\rho_0$) and a modulated RF coupling comes through the parameter

$$\omega_0 = 2\sqrt{\nu g\rho_0}/\hbar$$

and the parameter λ parameterizes the depth of Kapitza modulation

$$\lambda^2 = 2\rho_0 g\delta^2/\nu.$$



Conclusions

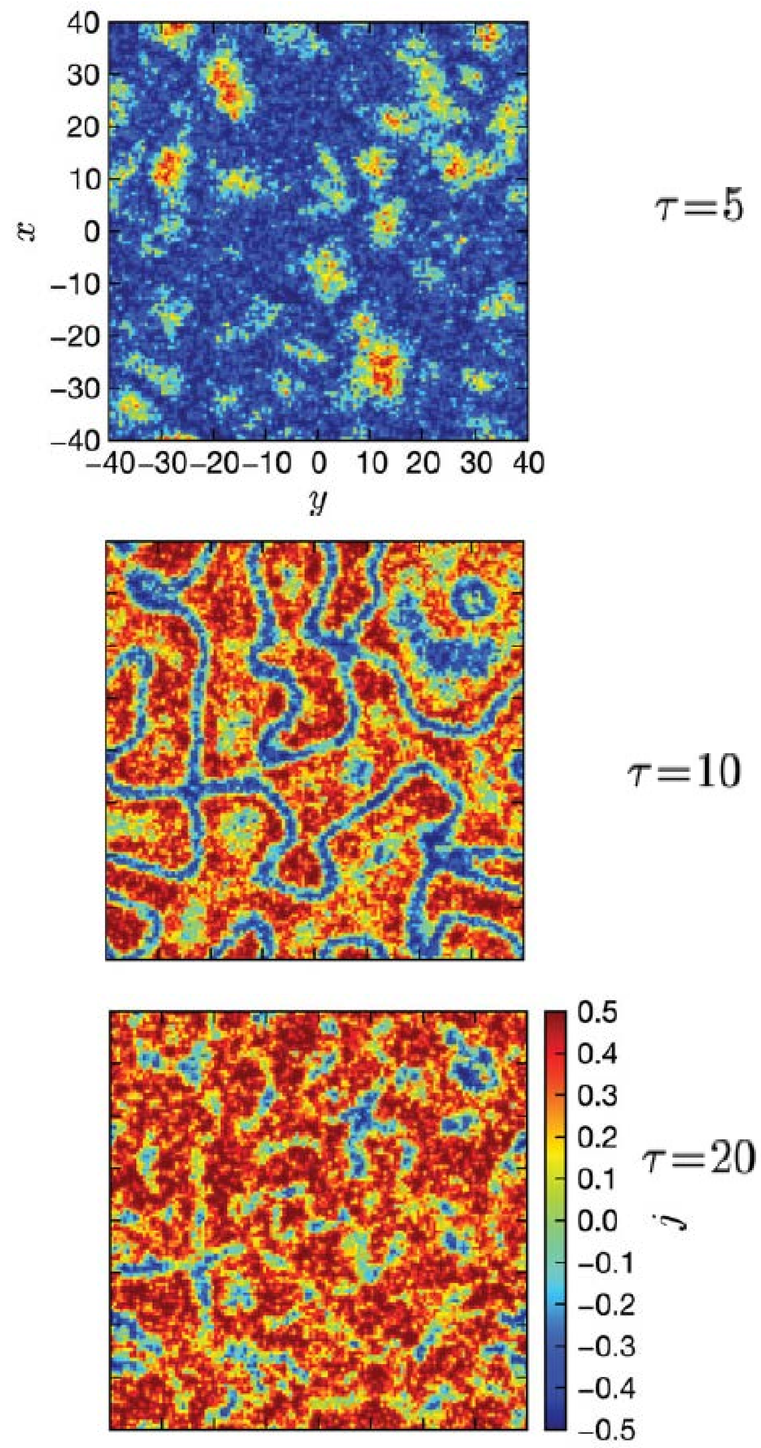
- Demonstrating the **false vacuum decay** by quantum tunneling in a spinor Bose gas will pave the way to analog quantum simulations of a cosmological process that is currently not accessible to exact computer simulation.
- Combined with accurate observational data of the correlations in the Cosmic Microwave Background, a table-top demonstration of the **false vacuum decay** may eventually lead to refined cosmological models of the birth of the Universe.

Unstable Vacuum Decay in 2D

The case of **unstable vacuum** is related to the slow-roll inflation model in cosmology, can be realised for the parameter $\lambda = 0$ in our model and is described by the sine-Gordon equation with a strong influence of quantum fluctuations.

$$\partial_t^2\phi_a - c^2\nabla^2\phi_a + \frac{4\nu g\rho_0}{\hbar^2}\sin\phi_a = 0$$

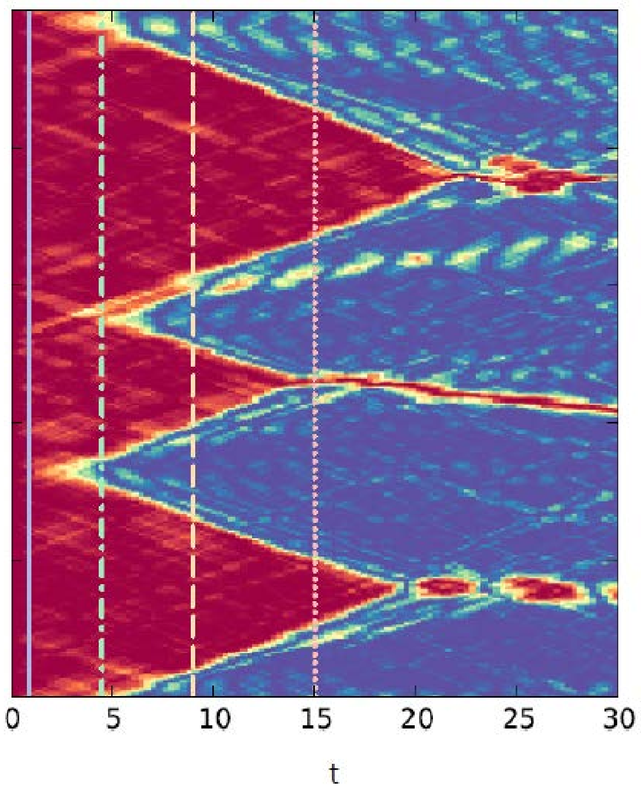
Our simulations of the coupled stochastic Gross-Pitaevskii equations using the truncated Wigner approximation show the appearance of spatial patterns and transient domain walls in the relative phase domain which slowly decay and disappear.



False Vacuum Decay in 1D

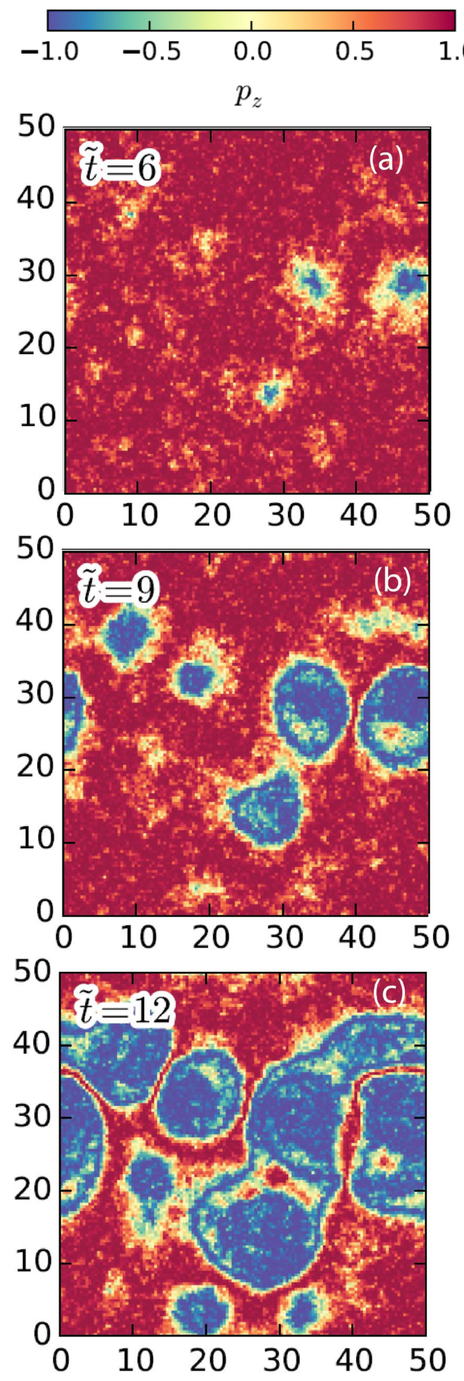
When the parameter λ exceeds the critical value of 1 in the quantum Kapitza regime, **the false vacuum state** is initially trapped in a metastable state of the effective potential $V(\phi_a)$ (blue curve).

The quantum fluctuations enforce tunnelling from the local minimum leading to the nucleation and growth of **bubbles** in the distribution of the relative phase.

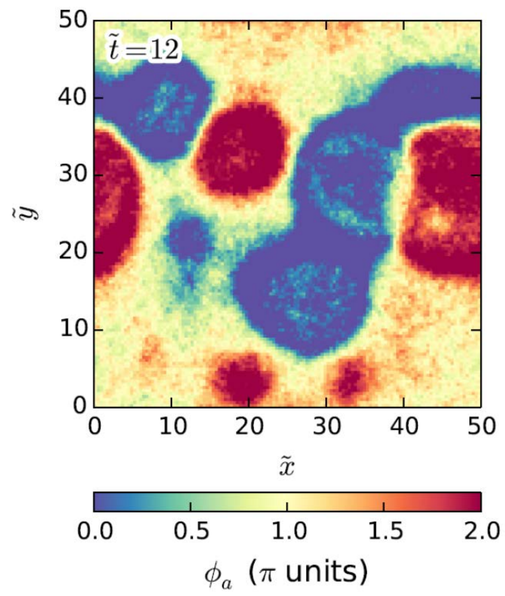


Bubble Nucleation in 2D

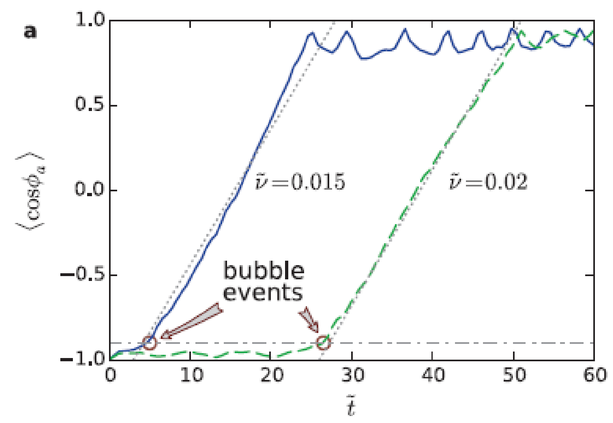
Bubble nucleation and growth in the 2D spatial distribution of the normalised relative density $p_z = (n_1 - n_2)/(n_1 + n_2)$ of two condensates at different evolution times in the **false vacuum** case.



Ramsey interferometry allows to convert the distribution of the relative phase into the spatial distribution of the relative number density $p_z(r)$.



Bubble Nucleation Probability



Bubbles appear via quantum tunnelling ($t = 5$, $\nu = 0.015$ and $t = 26$ $\nu = 0.02$) and grow with the speed of sound.

References

[1] A.H. Guth, *The Inflationary Universe* (1997)

[2] B. Opanchuk, *et al*, *Ann. Physik* **525**, 866 (2013)

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[4] O. Fialko, *et al*, *J. Physics B* **50**, 024003 (2017)