# Quantum simulations of the early universe with cold atoms

P. D. Drummond,[1,*] B. Opanchuk,[1] A. I. Sidorov,[1] O. Fialko,[2] and J. Brand[2]

[1] *Swinburne University of Technology, Melbourne, Australia*
[2] *Massey University, Auckland, New Zealand*

A linearly coupled spinor Bose condensate can be used as a physically accessible laboratory model, or 'quantum simulator' of the cosmological big bang [1]. We show how to engineer this model with either an unstable or metastable vacuum in a relativistic scalar field theory, which is related to models of inflation. There is a relative phase sector whose dynamics correspond to the quantum sine-Gordon equations in one, two or three space dimensions. Simulations of the expected behavior using a truncated Wigner phase-space method show evidence for the dynamical formation of complex domains and expanding 'bubble universes'. The relationship with inflationary models in cosmological theories of the early universe will be explained.

Feshbach resonances in either $^7Li$ or $^{41}K$ are proposed for these simulations, which require a near zero-crossing in the inter-species scattering length, combined with a repulsive intra-species interaction. Topologically distinct universes are found in simulations, characterized by a winding number. Experiments in 1D, 2D or 3D are possible. An externally modulated microwave field is used to engineer the potential. A variety of potentials are possible, thus modeling different inflationary universe scenarios. Regimes of density and coupling are predicted to exist where tunneling takes place on millisecond time-scales. However, the relevant particle loss rates are currently unknown, and this will constrain experiments over longer timescales.

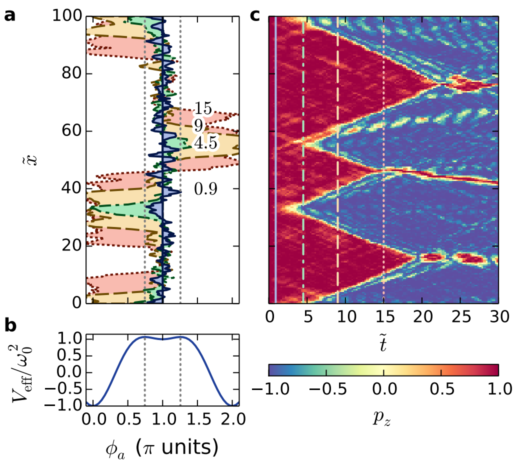


Figure 1. A 1D simulation, with engineered potential energy. Red indicates false vacuum, blue the true vacuum.

An example of one-dimensional simulations demonstrating an analog of relativistic universe formation in the nonlinear regime of the dynamics is given above, with a two-dimensional example in the next column. Here, an initially cold universe (red) with high potential energy spontaneously decays into a hot universe (bue), creating 'matter'. This is in close analogy to the early universe scalar quantum field models of Coleman [2], Guth [3] and others. Despite their seminal nature, there are neither exact solutions nor any previous experimental tests, which creates an exciting opportunity to test these theories. In the BEC quantum simulation proposal the relative phase plays the role of the cosmological scalar field, and the atomic density is nearly uniform. Intriguingly, a Hubble constant appears naturally in Bose gas simulations due to a coupling between the reservoir of phonons and the relative phase field.

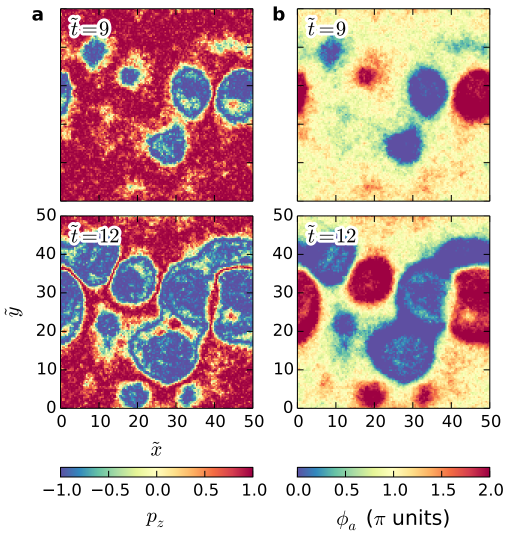


Figure 2. A 2D simulation with universe collisions. The first column shows true and false vacua as before. The second column uses blue and red for topologically distinct vacua, which cannot merge due to domain walls, but instead collide with each other.

This proposal also raises an interesting fundamental question. Is our universe entangled with other universes – and what does this imply for the measurement postulate?

* pdrummond@swin.edu.au

[1] Bogdan Opanchuk, et. al, Annalen der Physik **525**, 866 (2013).
[2] C. Callan and S. Coleman, Phys. Rev. D **16**, 1762 (1977).
[3] A. H. Guth, Phys. Rev. D **23**, 347 (1981).