Title: First observations of false vacuum decay in a BEC

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Collection: Quantum Simulators of Fundamental Physics

Date: June 05, 2023 - 3:30 PM

URL: https://pirsa.org/23060007

Abstract: https://pitp.zoom.us/j/95722860808?pwd=REYwSDdiK3pFamRJcjJwOW5FV1RPZz09

First observations of False Vacuum Decay in a BEC

Ian Moss
June 2023

A Zenesini, A Berti, R Cominotti, C Rogora, IG Moss, TP Billam, I Carusotto, G Lamporesi, A Recati, G Ferrari arXiv:2305.05225

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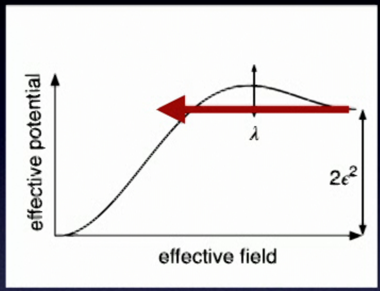
Bubble Taxonomy

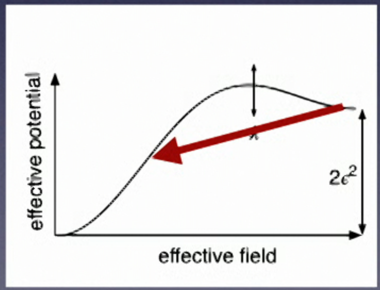
False vacuum decay at finite temperature*

Metastable state non-zero T → Bubbles driven by thermal fluctuations



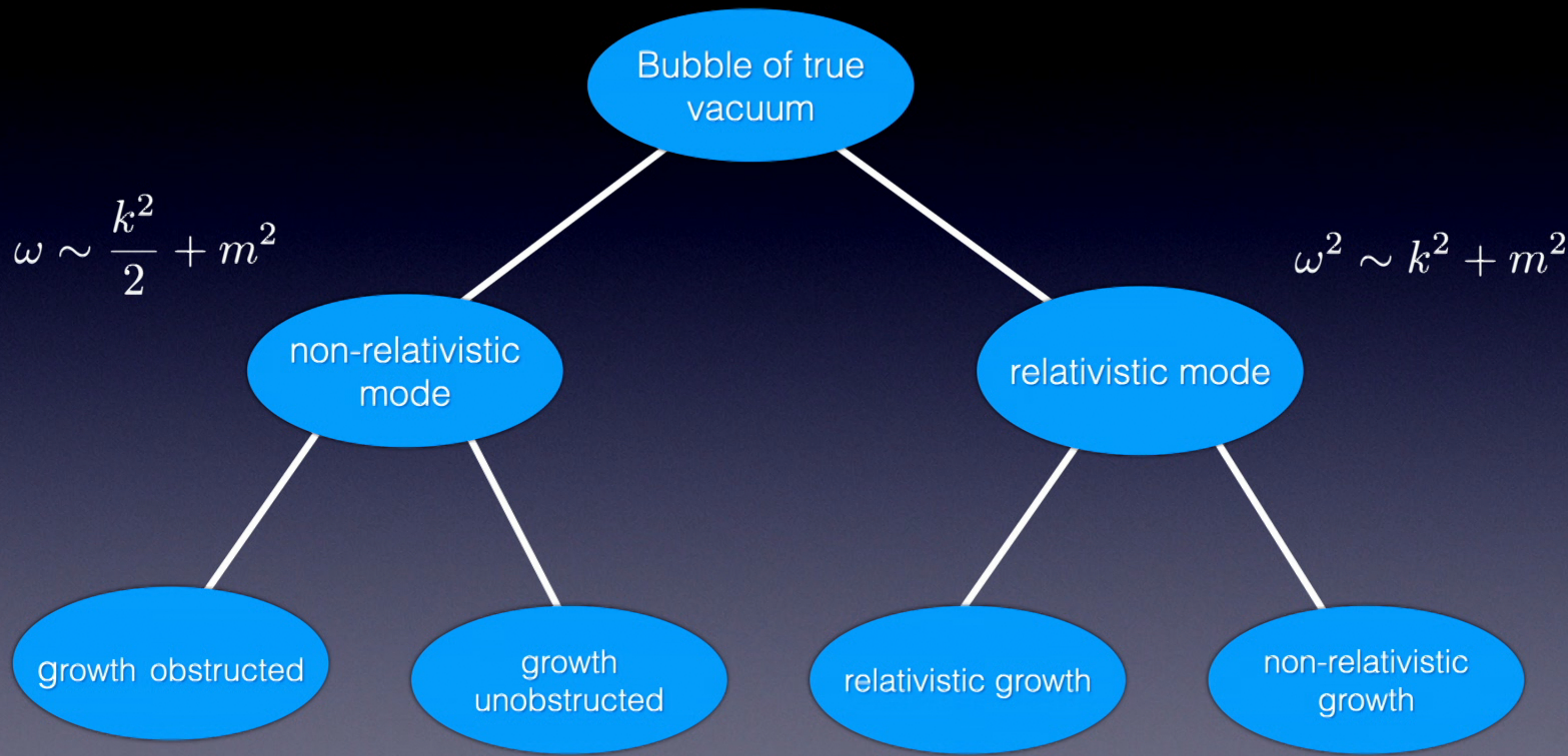
False vacuum decay at zero temperature

Metastable state at T=0 → Bubbles driven by vacuum fluctuations



*AD Linde Nuc Phys B216 1983

Bubble Taxonomy for analogue systems



FVD Observations

Ferromagnetic bubbles in a sodium BEC

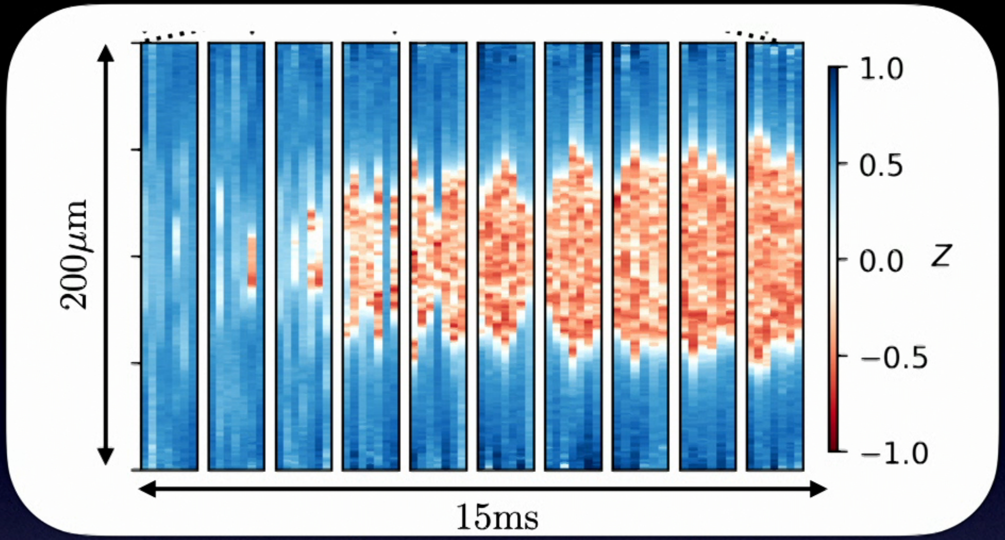
Two Zeeman levels $|\uparrow\rangle = |1, -1\rangle \quad |\downarrow\rangle = |2, -2\rangle$

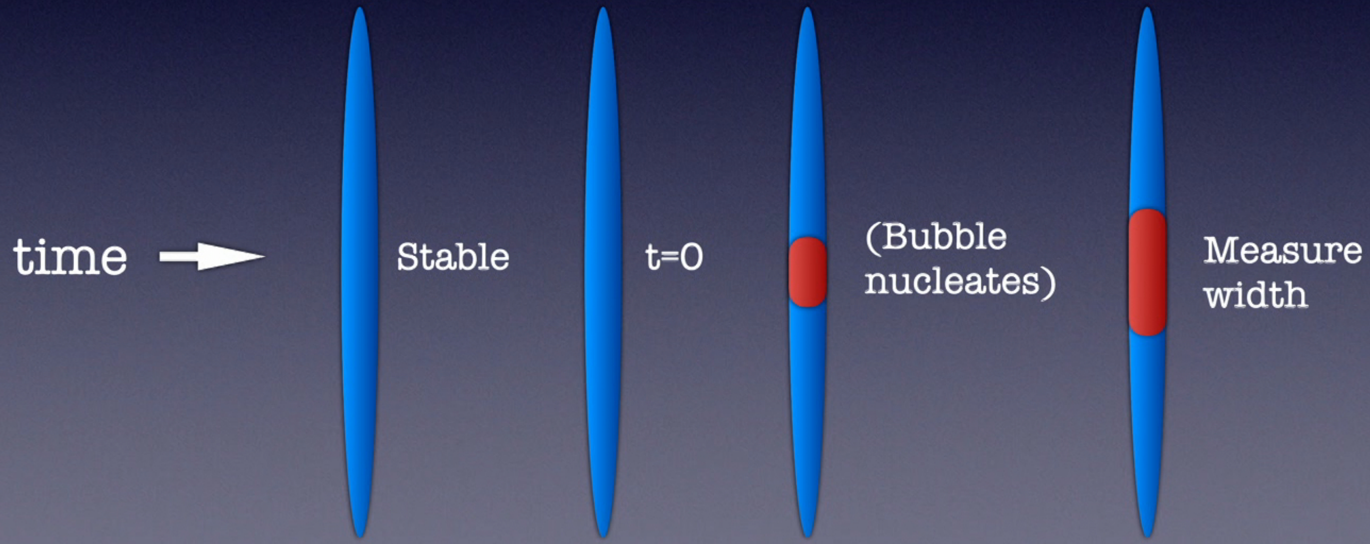
RF mixing $\Omega_R \quad \delta_{\text{eff}}$ (Rabi+detuning)

Collisions $a_{\uparrow\uparrow} \quad a_{\uparrow\downarrow} \quad a_{\downarrow\downarrow}$

Ferromagnetic ground states exist when $\kappa \propto a_{\uparrow\uparrow} + a_{\downarrow\downarrow} - 2a_{\uparrow\downarrow} < 0$

FVD Observations

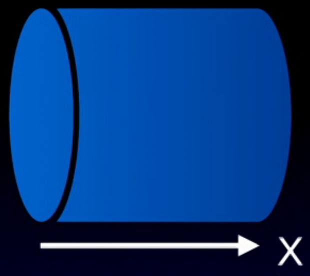




1D Model

Density $n(x)$

Magnetisation $Z = \frac{n_\uparrow - n_\downarrow}{n_\uparrow + n_\downarrow}$

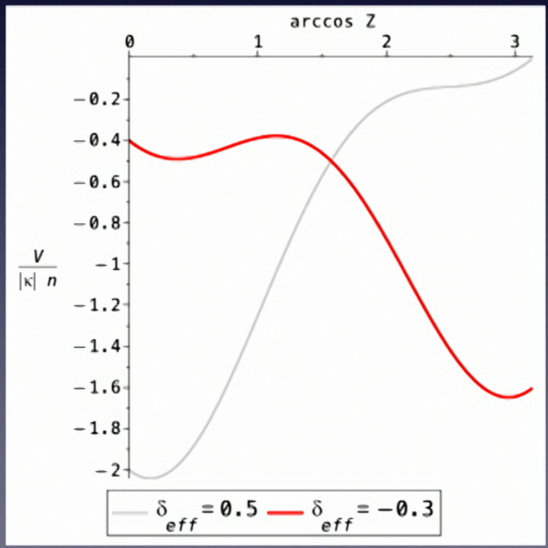


Potential

$$V = -|\kappa| n Z^2 - 2\Omega_R \sqrt{1 - Z^2} - 2\delta_{\text{eff}} Z$$

Depends on x
(1200Hz at centre)

Choose



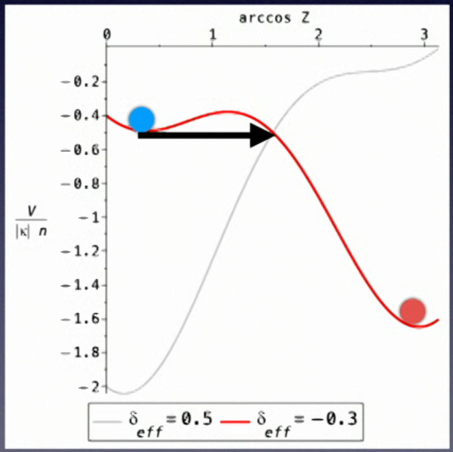
False vacuum decay rate

Thermal rate* $$\Gamma = A \left(\frac{E_c}{k_B T}\right)^{1/2} e^{-E_c/k_B T}$$

$$E_c = \frac{\hbar n}{4} \int \left\{ \frac{n}{2m} \frac{(\nabla Z_c)^2}{1 - Z_c^2} + V(Z_c) \right\} dx$$

Small barrier limit

$$\frac{E_c}{k_B T} \approx 1.77 \frac{n}{T} \left(\frac{\delta_{\rm eff} - \delta_{\rm crit}}{|\kappa| n}\right)^{5/4} \left(\frac{\Omega_R}{|\kappa| n}\right)^{1/6} \left(\frac{|\delta_{\rm crit}|}{|\kappa| n}\right)^{-1/4}$$



*M Hindmarsh, M Ruben, J Lumma 2021

Stochastic GPE simulation

In healing length units

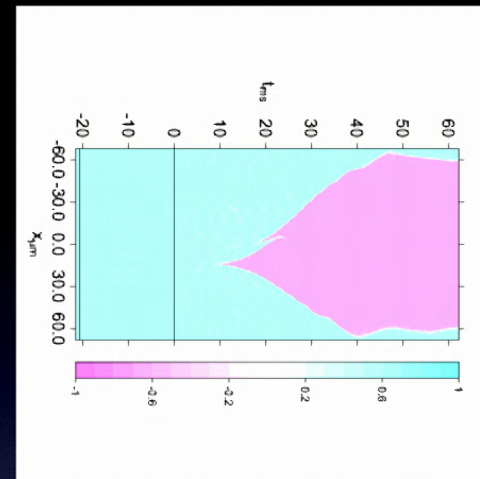
$$i\frac{\partial\psi_m}{\partial t} = \mathcal{P}\left\{(1-i\gamma)\left[-\frac{1}{2}\nabla^2\psi_m + \frac{\partial V}{\partial\psi_m^\dagger}\right] + \eta_m\right\}$$

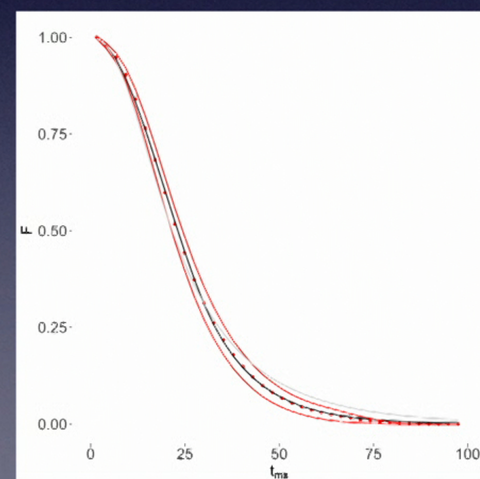
Thermal noise

$$\left\langle \eta_m(x,t)\eta^\dagger_{m'}(x',t')\right\rangle = \frac{2\gamma T}{n}\,\delta(x-x')\delta(t-t')\delta_{mm'}$$

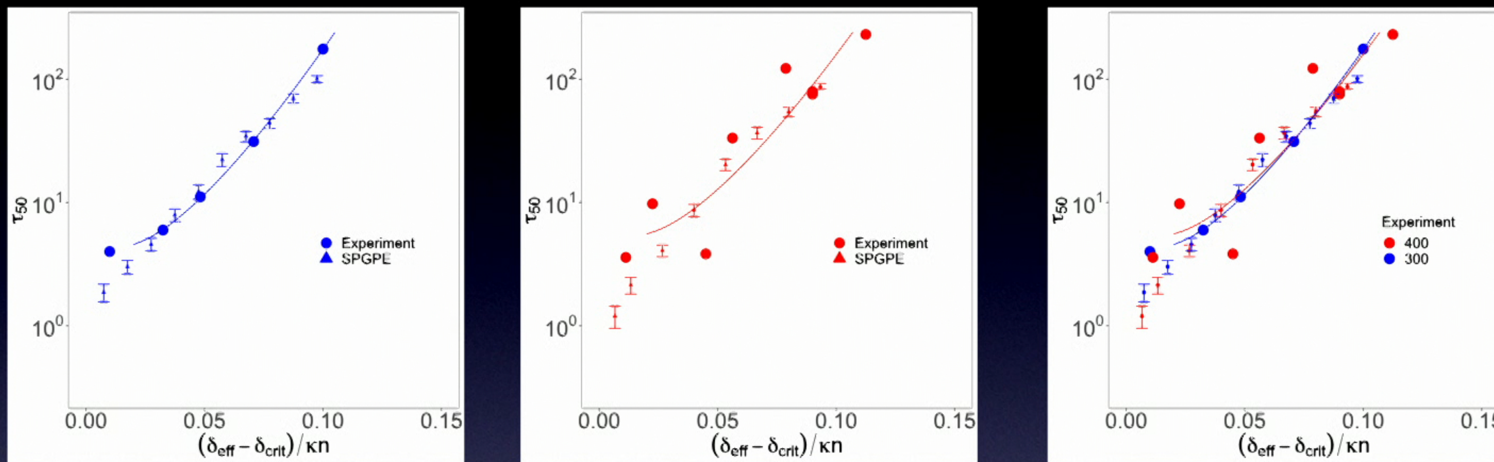
Measure mean nucleation time τ

or vacuum fraction $F(t) = \text{fraction in FV}$





Theory matches experiment



$\Omega_R/2\pi = 300\text{Hz}$ $\Omega_R/2\pi = 400\text{Hz}$

Instanton (line) is a two parameter fit (pre-factor, temperature)

SPGPE data has no free parameters (uses same temperature)

$$\frac{E_c}{k_B T} \approx 1.77 \frac{n}{T} \left(\frac{\delta_{\text{eff}} - \delta_{\text{crit}}}{|\kappa| n} \right)^{5/4} \left(\frac{\Omega_R}{|\kappa| n} \right)^{1/6} \left(\frac{|\delta_{\text{crit}}|}{|\kappa| n} \right)^{-1/4}$$

Summary so far

We see a metastable that state decays by bubble nucleation.

Nucleation timescales show an exponential dependence on the parameters.

Excellent agreement between SPGPE simulations and the instanton decay rate (identical parameters*).

Good agreement between SPGPE simulations, the instanton decay rate and the experiment**.

*The value of $\delta_{\rm crit}$ in the SPGPE is shifted (by fluctuations?).

**The theory value of n/T differs from the experiment (50%).

FVD Fantasies

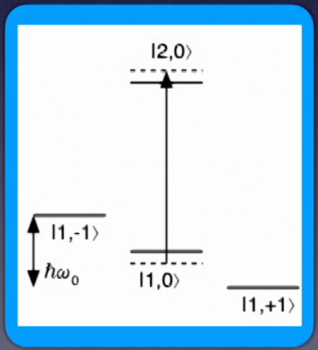
Ferromagnetic bubbles in potassium-41 BEC

2D

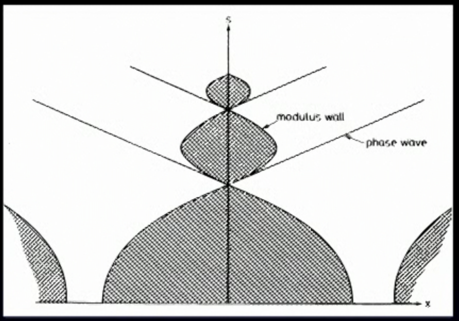
Two Zeeman levels $|\uparrow\rangle = |1,1\rangle \quad |\downarrow\rangle = |1,-1\rangle$

RF (or Raman) mixing $\Omega_R \quad \delta_{\rm eff}$

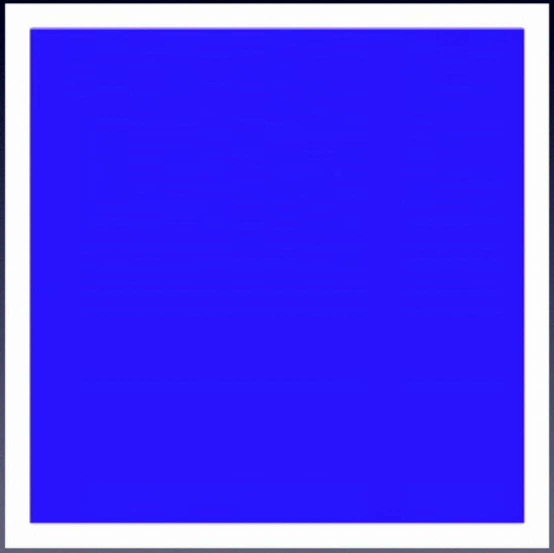
Collisions $a_{\uparrow\uparrow} \quad a_{\uparrow\downarrow} \quad a_{\downarrow\downarrow}$

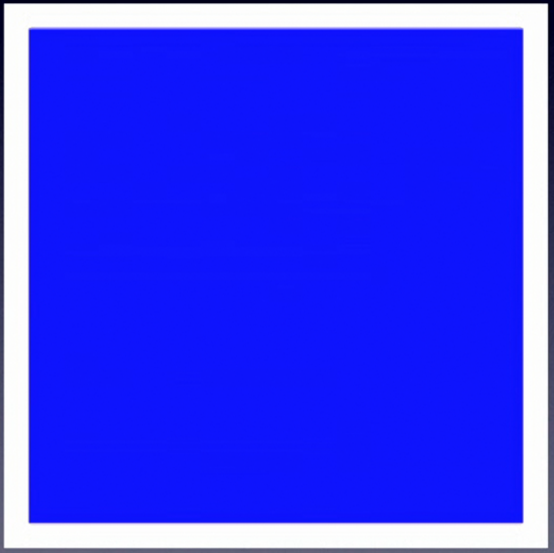


Bubble collisions



Hawking, Moss, Stewart 1982





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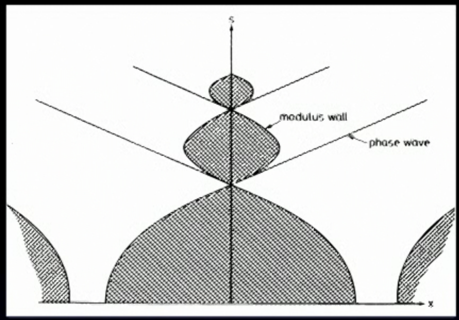

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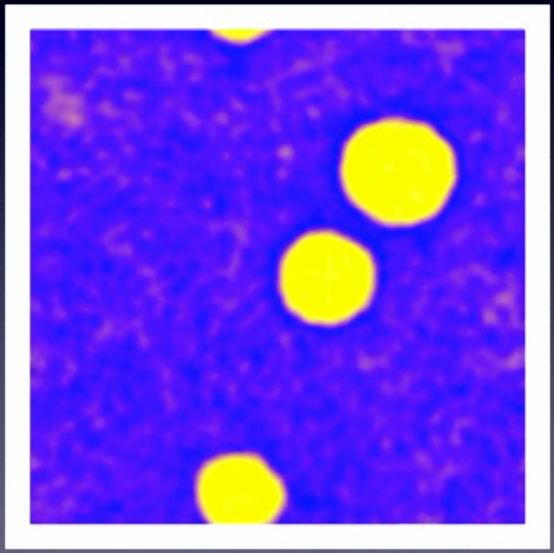
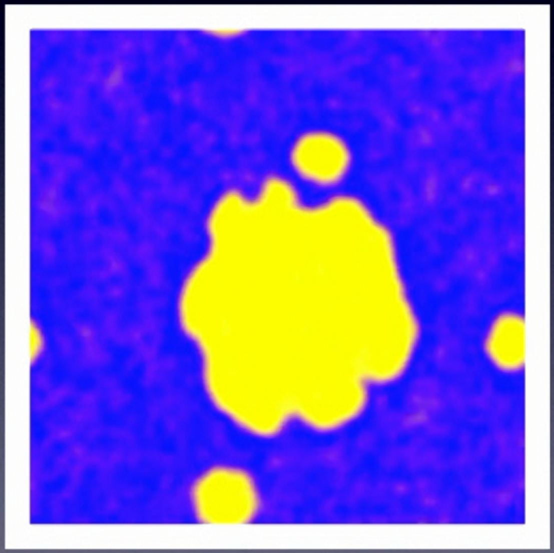
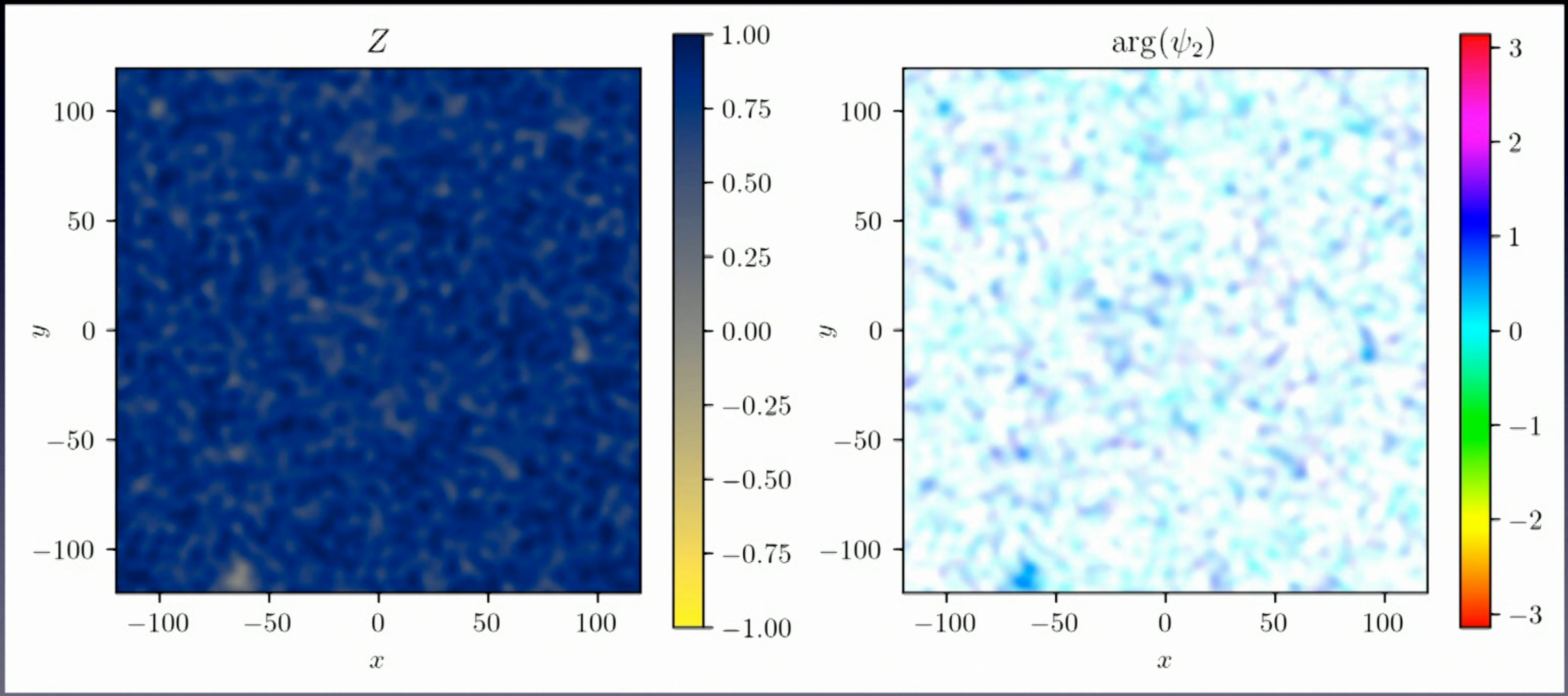




Defect formation

BEC analogue of monopole production in the early universe



Half Quantum Vortices: Wheeler, Salman, Borgh EPL (2021) 30004

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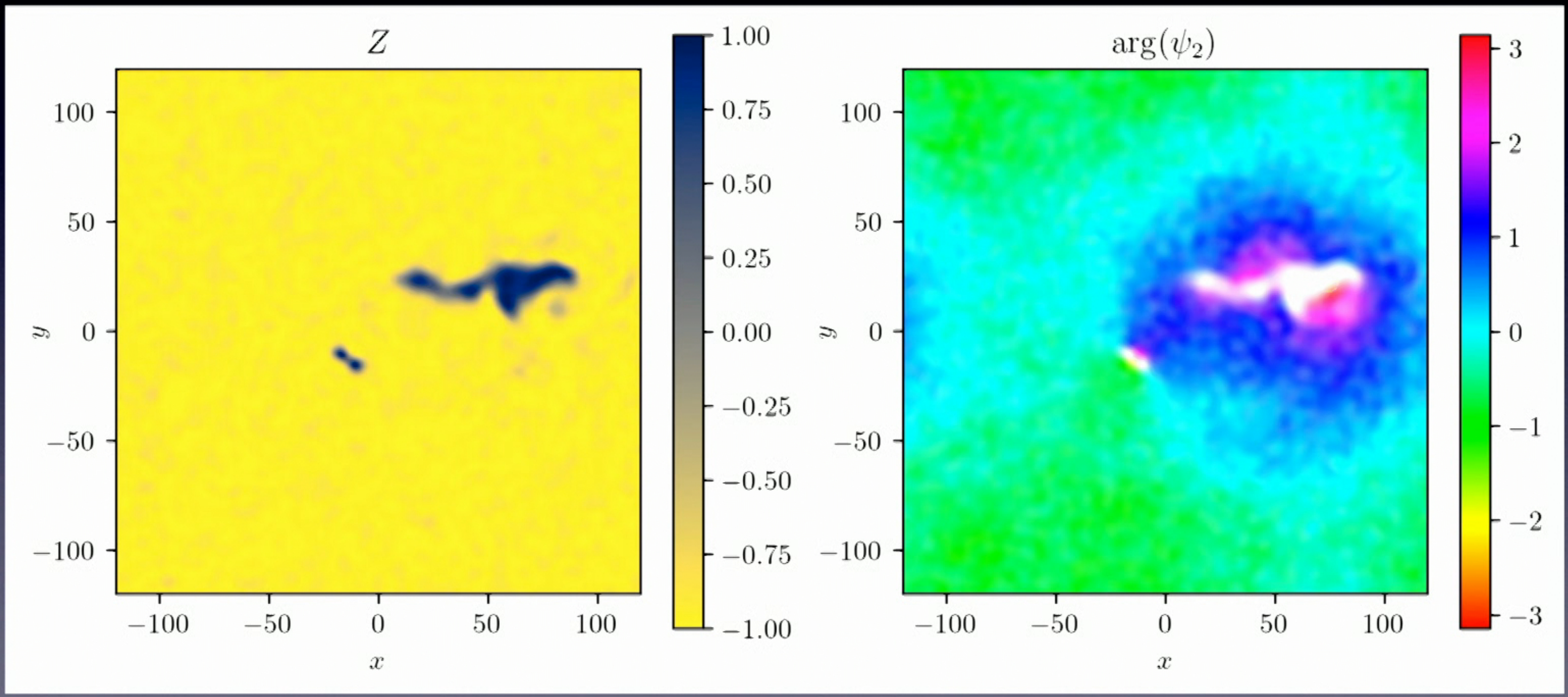

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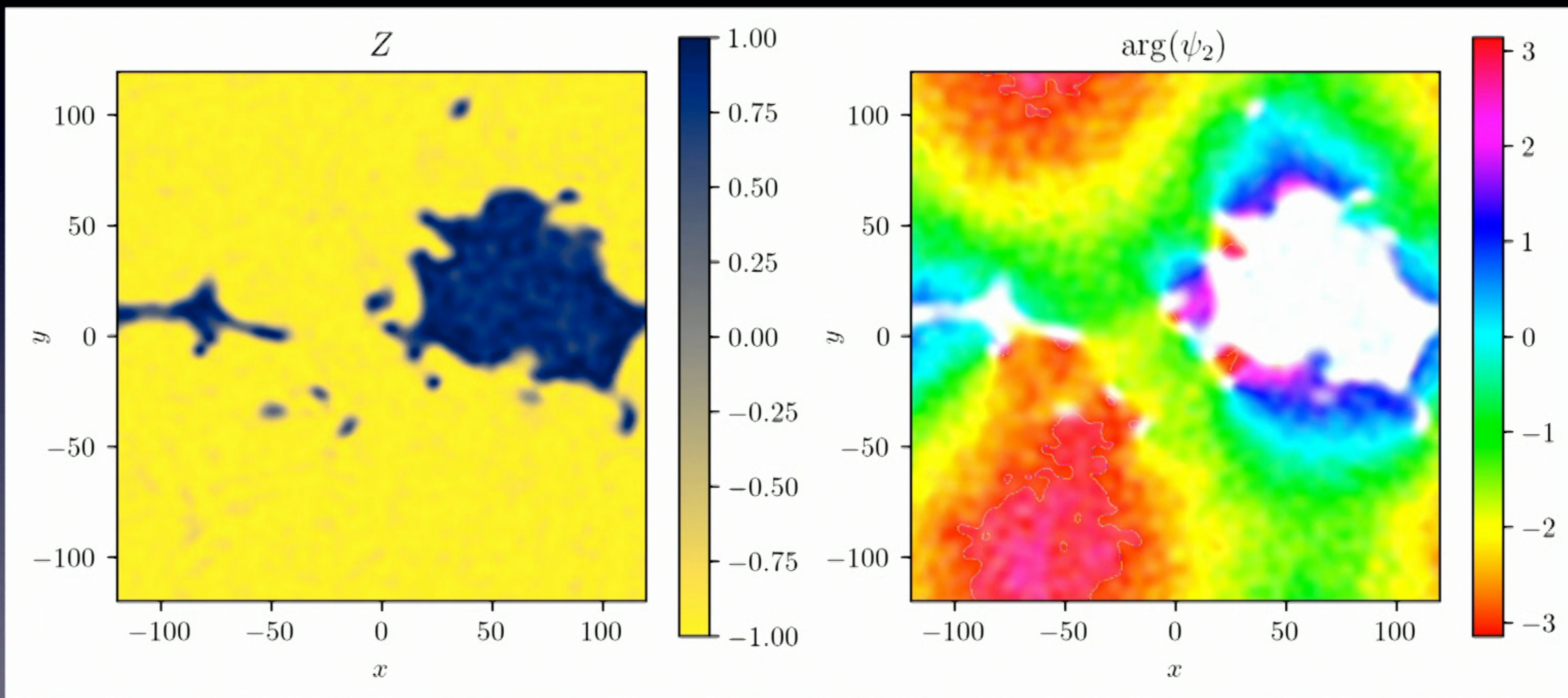

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30004

From fantasy to reality?

This looks like the first experimental demonstration of false vacuum decay at finite temperature in a BEC.

We are on the verge of seeing a whole range of vacuum decay phenomena: zero temperature decay, bubble collisions, defect formation, seeded decay, wave production....