

Title: First observations of false vacuum decay in a BEC

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Collection: Quantum Simulators of Fundamental Physics

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# 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



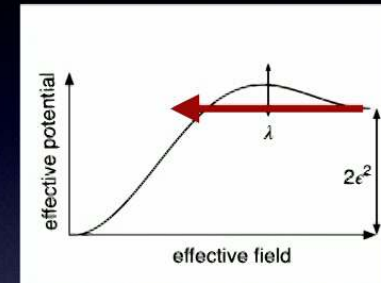
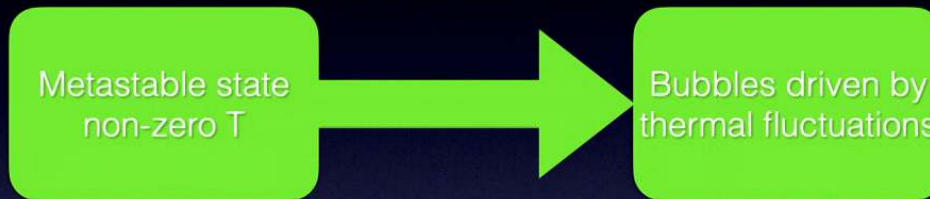
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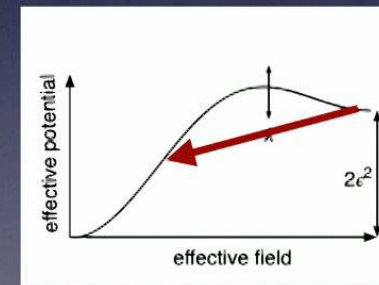
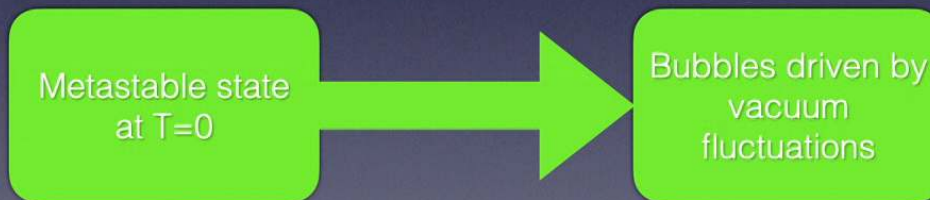


# Bubble Taxonomy

False vacuum decay at finite temperature\*

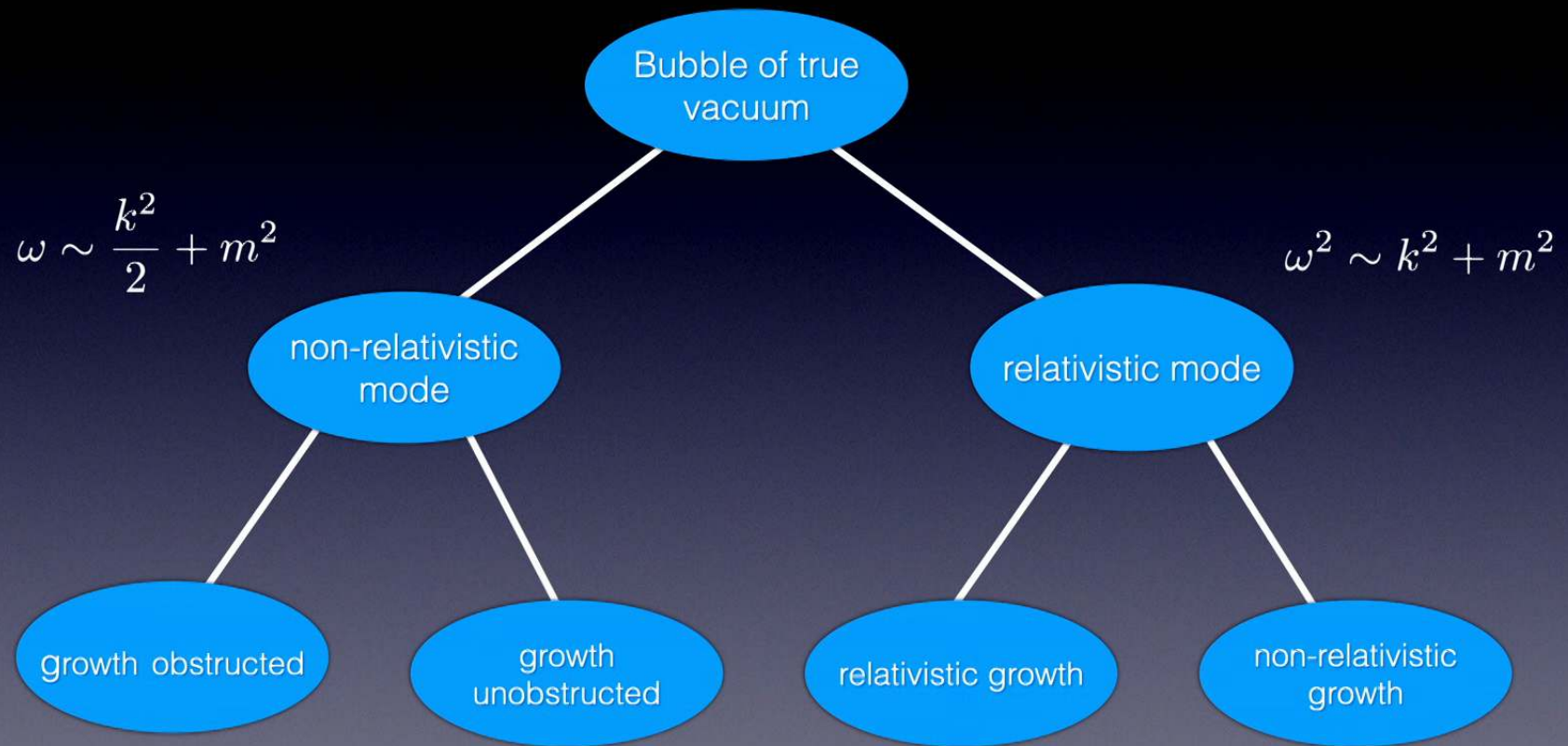


False vacuum decay at zero temperature



\* 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

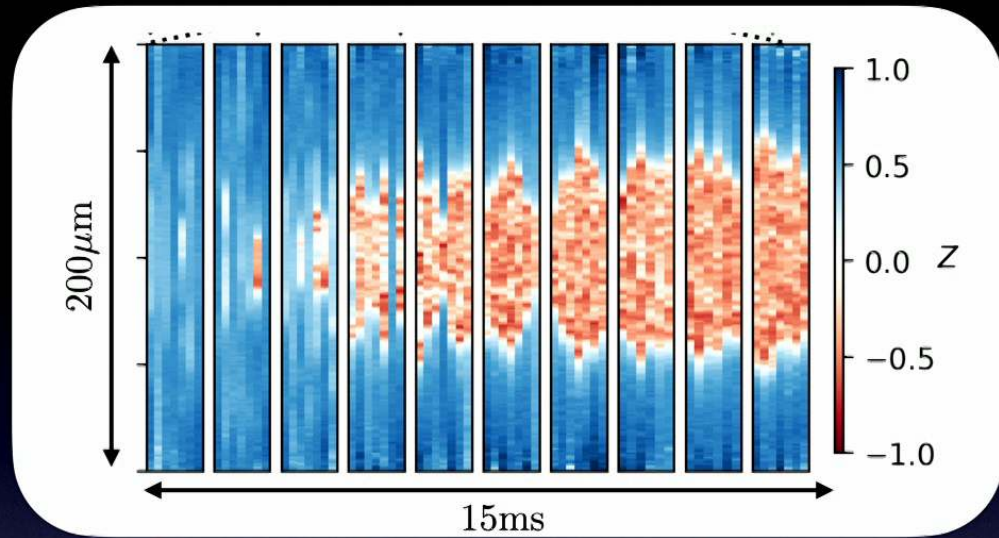
$$\Omega_R \quad \delta_{\text{eff}} \quad (\text{Rabi+detuning})$$

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



time →



Stable



t=0



(Bubble nucleates)



Measure width

# 1D Model

Density

$$n(x)$$

Magnetisation

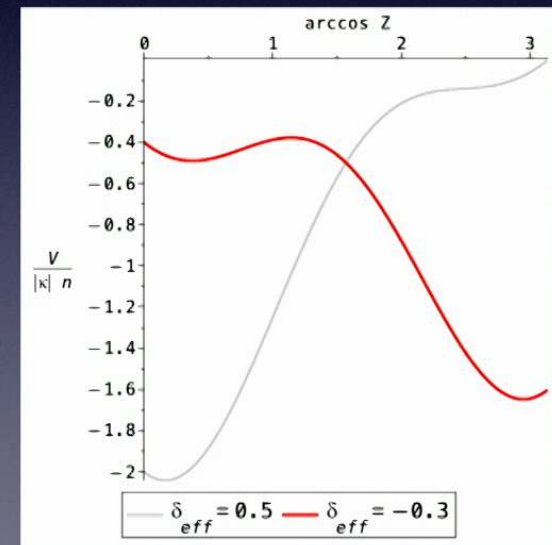
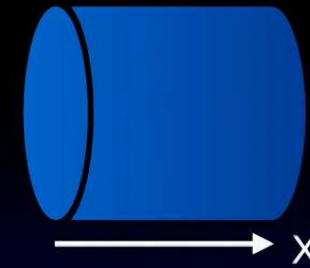
$$Z = \frac{n_{\uparrow} - n_{\downarrow}}{n_{\uparrow} + n_{\downarrow}}$$

Potential

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

Depends on x  
(1200Hz at centre)

Choose



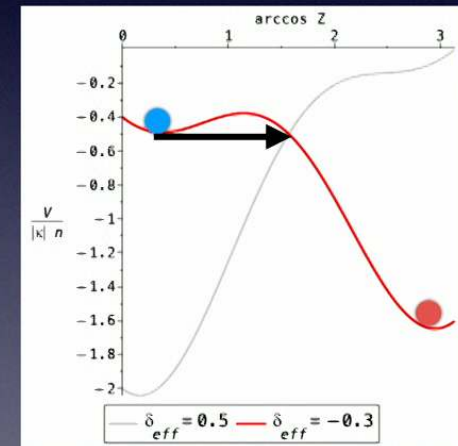
# False vacuum decay rate

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

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



\* M Hindmarsh, M Ruben, J Lumma 2021

# Stochastic GPE simulation

In healing length units

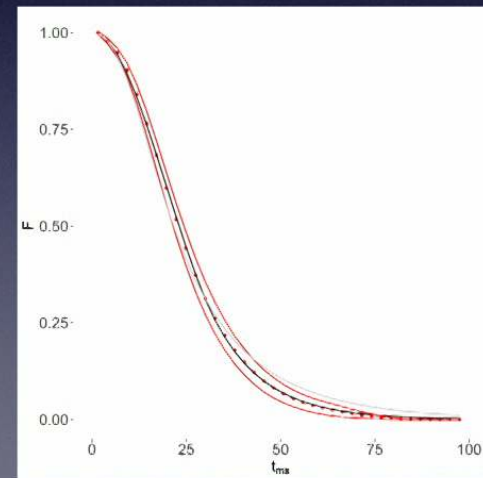
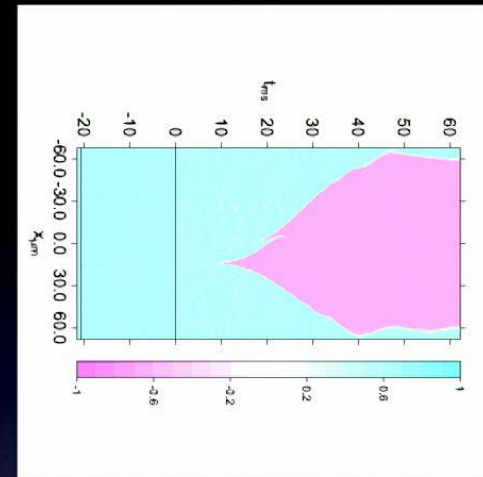
$$i \frac{\partial \psi_m}{\partial t} = \mathcal{P} \left\{ (1 - i\gamma) \left[ -\frac{1}{2} \nabla^2 \psi_m + \frac{\partial V}{\partial \psi_m^\dagger} \right] + \eta_m \right\}$$

Thermal noise

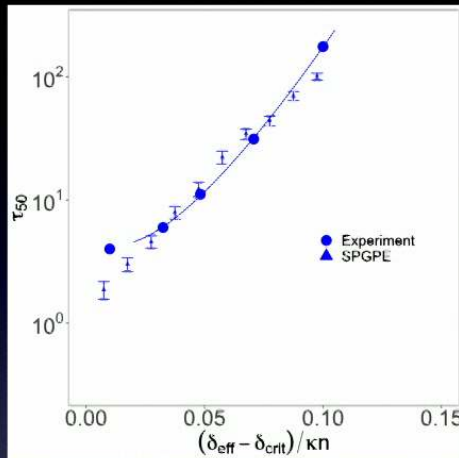
$$\langle \eta_m(x, t) \eta_{m'}^\dagger(x', t') \rangle = \frac{2\gamma T}{n} \delta(x - x') \delta(t - t') \delta_{mm'}$$

Measure mean nucleation time  $\tau$

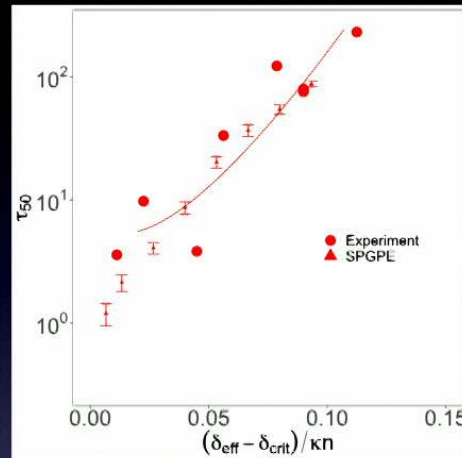
or vacuum fraction  $F(t) =$  fraction in FV



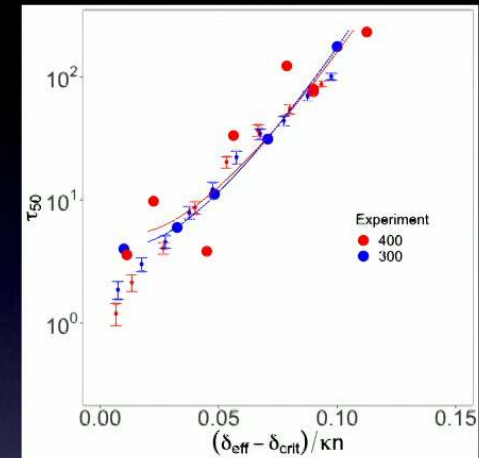
# Theory matches experiment



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



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



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  $\delta_{\text{crit}}$  in the SPGPE is shifted (by fluctuations?).

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

# FVD Fantasies

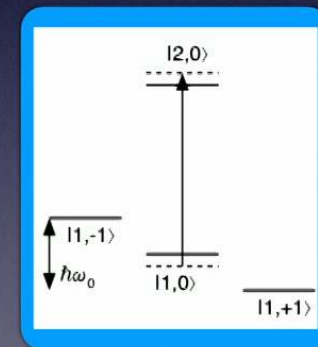
## Ferromagnetic bubbles in potassium-41 BEC

2D

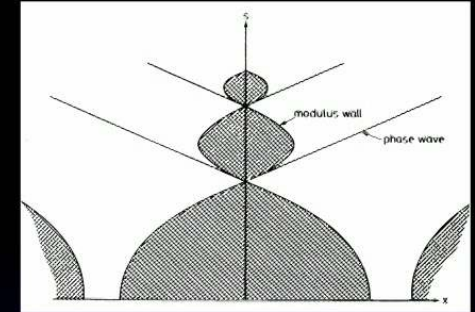
Two Zeeman levels  $|\uparrow\rangle = |1, 1\rangle$   $|\downarrow\rangle = |1, -1\rangle$

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

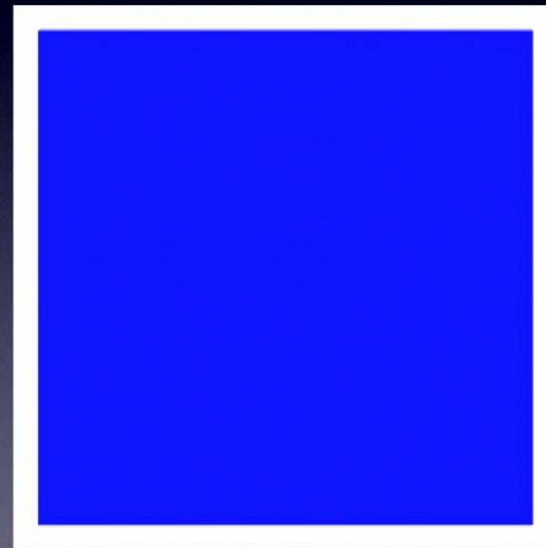
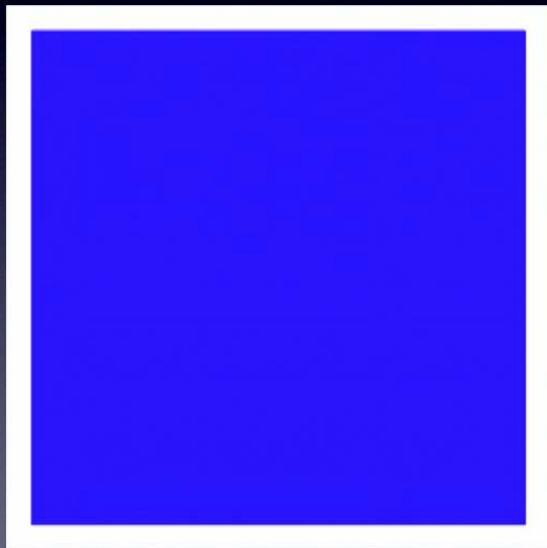
Collisions  $a_{\uparrow\uparrow}$   $a_{\uparrow\downarrow}$   $a_{\downarrow\downarrow}$



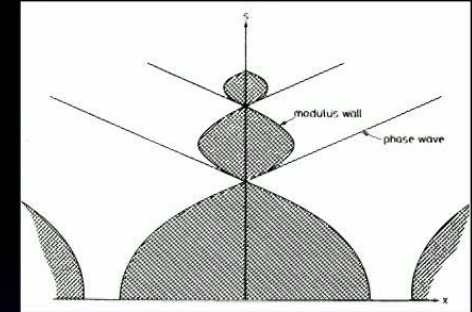
# Bubble collisions



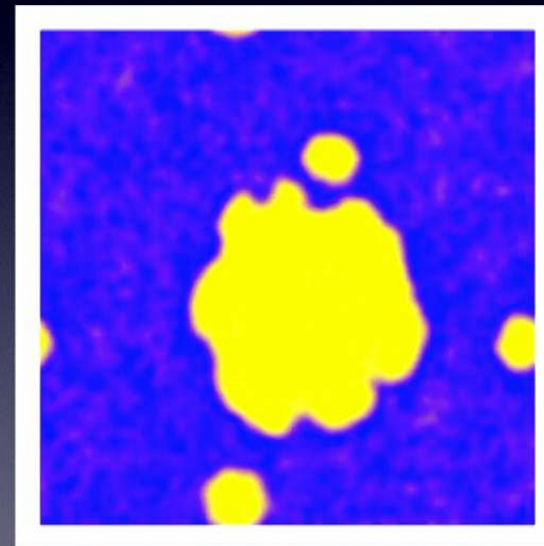
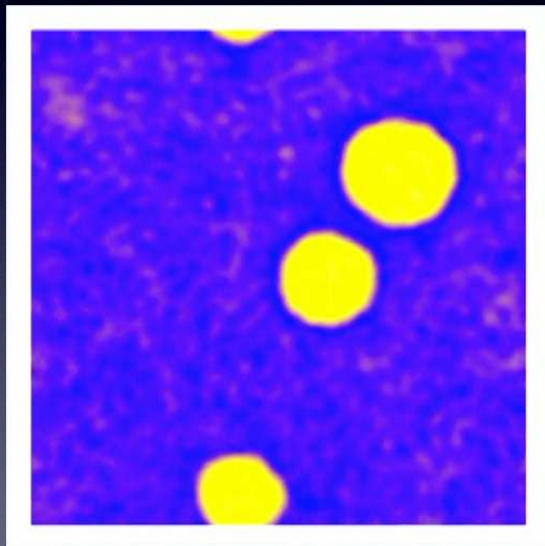
Hawking, Moss, Stewart 1982



# Bubble collisions

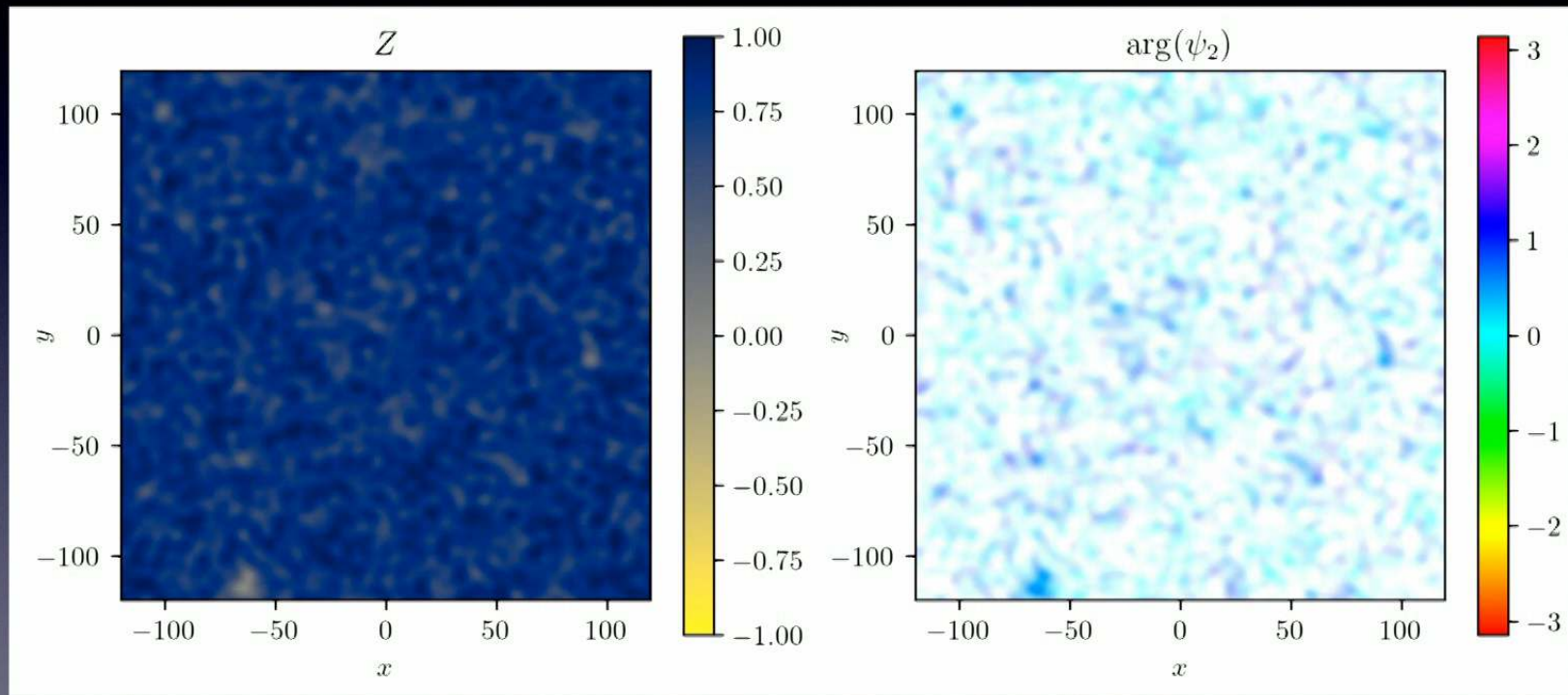


Hawking, Moss, Stewart 1982



# Defect formation

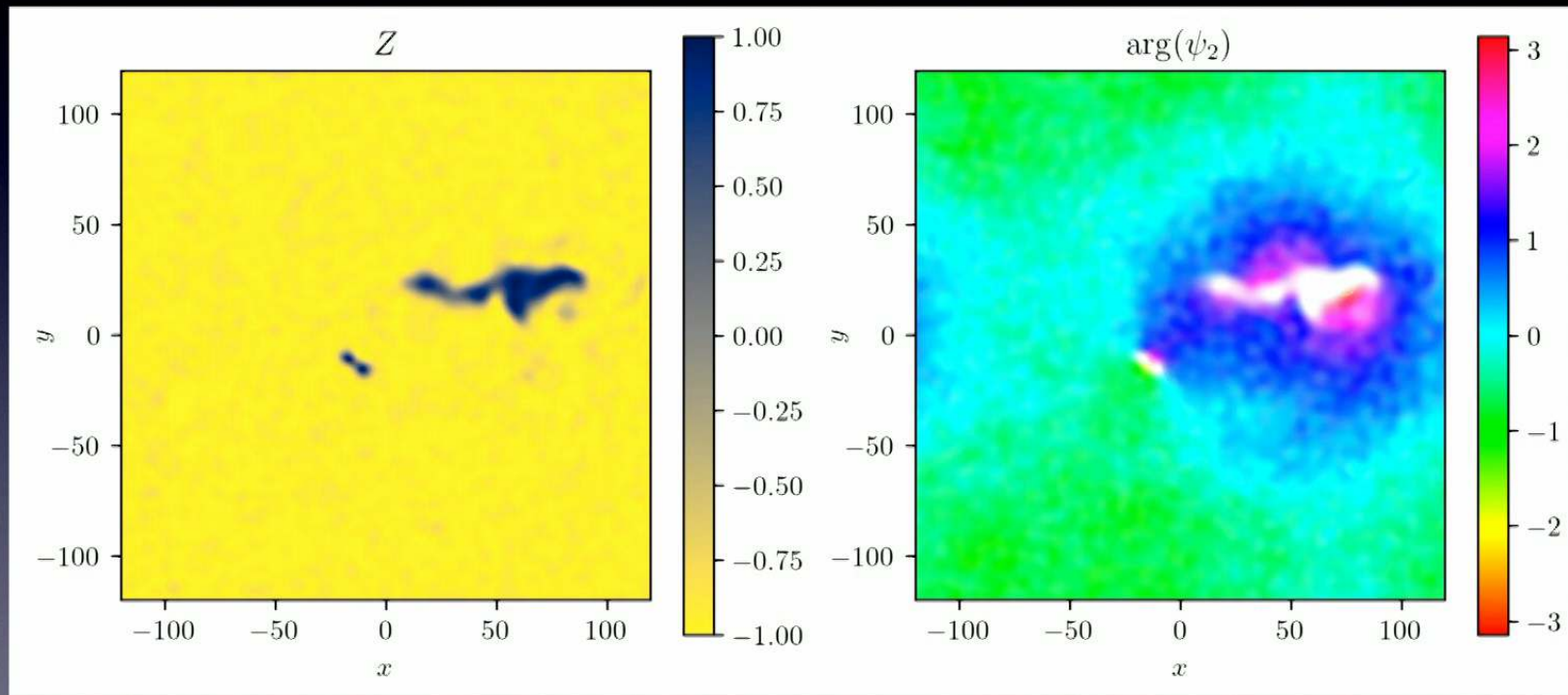
BEC analogue of monopole production in the early universe



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

# Defect formation

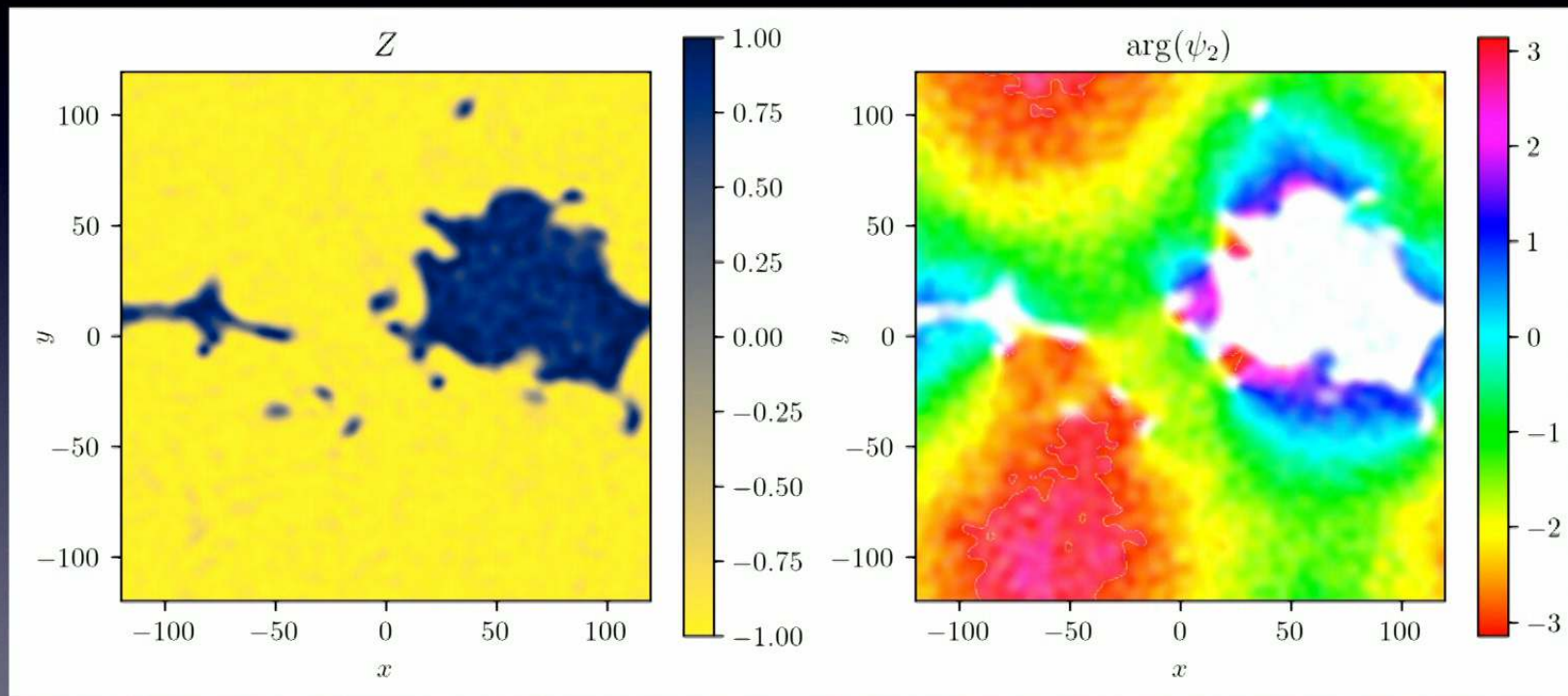
BEC analogue of monopole production in the early universe



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

# Defect formation

BEC analogue of monopole production in the early universe



00:17 00:03

FROM QUANTUM VORTICES: WHEELER, SANNI, D'ORGI ET AL (2017) 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....