Title: Five short talks - see description for talk titles

Speakers: Barbara Soda, Dalila Pirvu

Collection: Quantum Simulators of Fundamental Physics

Date: June 05, 2023 - 2:00 PM

URL: https://pirsa.org/23060004

Abstract: Bubble nucleation in a cold spin 1 gas (Barbara Soda); Bubbles live fast and stick together (Dalila Pirvu); Superfluid helium vortex flow: Experimental realization (Kate Brown); Superfluid helium vortex flow: Surface reconstruction (Leonardo Solidoro); Acceleration-induced effects in stimulated light-matter interactions (Pietro Smaniotto)

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

Acceleration-induced effects in stimulated light-matter interactions

Barbara Šoda, Vivishek Sudhir, Achim Kempf

Quantum Simulators in Fundamental Physics
5 June 2023

Content

- Stimulation of the Unruh effect
- Acceleration-induced transparency

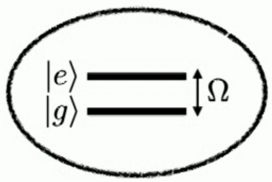
} Improved measurability of Unruh effect in lab

- Stimulation of the Hawking effect
- Gravity-induced transparency

} New gravity-induced phenomena

The standard Unruh effect

- UDW detector:

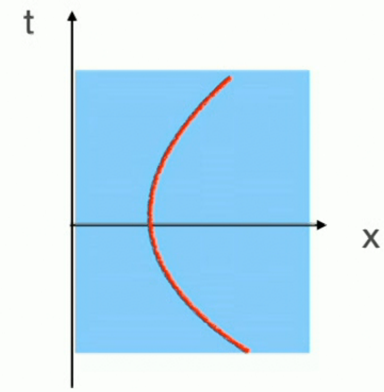


$$H_0^{(D)} = \Omega\, \hat{\sigma}_z$$

- Scalar quantum field:

$$H_0^{(F)} = \int d^3k\, \omega_{\mathbf{k}}\, \hat{a}_{\mathbf{k}}^\dagger \hat{a}_{\mathbf{k}}$$

Trajectory:



- Interaction Hamiltonian: $H_{int} = G\, \hat{\sigma}_x(\tau) \otimes \hat{\phi}(t(\tau), \mathbf{x}(\tau))$

$$H_{int} \propto \int d\mathbf{k} \left(\underbrace{\sigma^- a_{\mathbf{k}}^\dagger + \sigma^+ a_{\mathbf{k}}}_{\text{ROTATING}} + \underbrace{\sigma^- a_{\mathbf{k}} + \sigma^+ a_{\mathbf{k}}^\dagger}_{\text{COUNTER-ROTATING}} \right)$$

- Initial state: $|g\rangle \otimes |0\rangle \to |e\rangle \otimes |1\rangle$

Standard vs. stimulated Unruh effect

	Standard	Stimulated (Fock state)
Transition:	$\|g\rangle \otimes \|0\rangle \to \|e\rangle \otimes \|1\rangle$	$\|g\rangle \otimes \|n_{\mathbf{k}}\rangle \to \|e\rangle \otimes \|(n+1)_{\mathbf{k}}\rangle$
Probability:	$p(\mathbf{k}) = \frac{G^2}{(2\pi)^3\omega_{\mathbf{k}}}\|I_+(\mathbf{k})\|^2$	$p(\mathbf{k}) = \frac{G^2}{(2\pi)^3\omega_{\mathbf{k}}}\left(n\|I_-(\mathbf{k})\|^2 + (n+1)\|I_+(\mathbf{k})\|^2\right)$

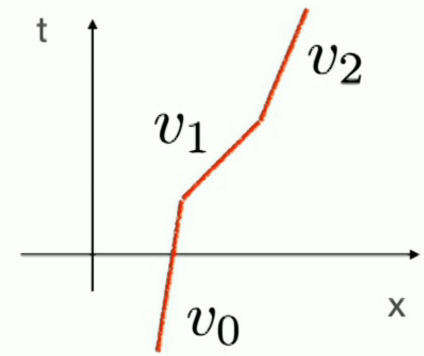
Unruh effect

Probability of excitation enhanced by n!

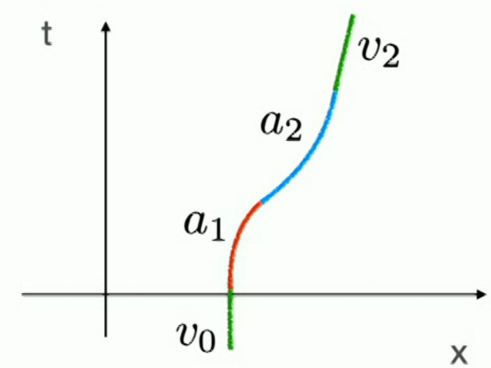
Problem: non-Unruh contribution also enhanced.

Acceleration-induced transparency

- Q: Can we tune the trajectory so that for some Ω the time integral $I_{-}(\Omega, k) = \int \mathrm{d}\tau \, e^{i\Omega\tau - ik^{\mu}x_{\mu}(\tau)} = 0$?



- Yes. Simplest trajectory: moving at three different velocities, with abrupt velocity changes.

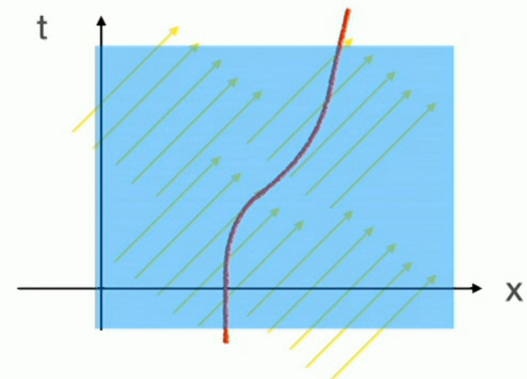


- Also proved existence of a smoother trajectory with the same property.

Stimulated Unruh effect + Acceleration-induced transparency

[1] Stimulate Unruh effect by adding photons,
[2] Acceleration-induced transparency by choosing the trajectory,

Trajectory: specially chosen for acceleration-induced transparency



- -> improved measurability of the Unruh effect.

Stimulated Unruh effect = $n\times$ **Standard Unruh effect**

- E.g. for a 100 mW laser pointer: $n \approx 10^{16}$

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Outlook

Unpublished work on gravity-induced effects:

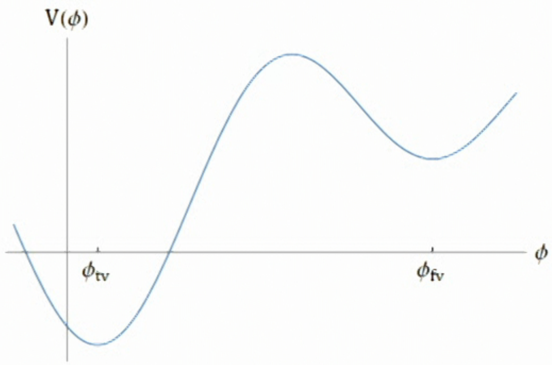
- Resonant terms are potentially strongly affected by gravity, including the possibility of gravity-induced translucency or even transparency.
- Non-resonant terms, e.g. of Hawking and other horizon radiation, can be stimulated (e.g. by accretion disk luminosity?).

Acceleration-Induced Effects in Stimulated Light-Matter Interactions,
Barbara Šoda, Vivishek Sudhir, and Achim Kempf,
Physical Review Letters 128, 163603 (2022)

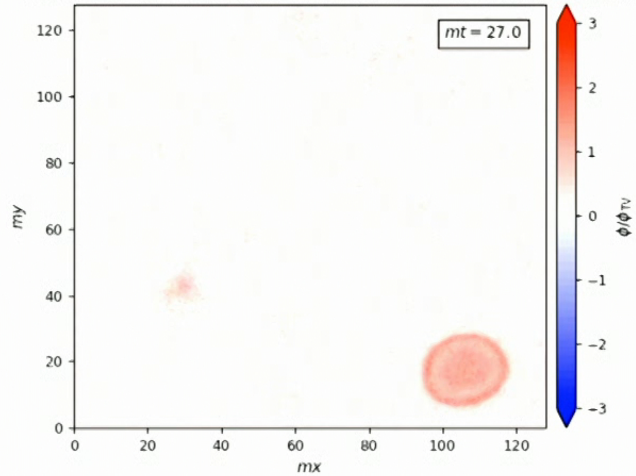
Thank you for your attention!

Relativistic 1st Order PT

- Field theory with associated potential that has 2 non-degenerate minima
- Vacuum zero-point fluctuations trigger nucleations
- Finite regions make the transition, separated by a domain wall



Source: J. Braden; University of Toronto / CITA



Non-pertubative, non-linear, non-equilibrium QFT

Euclidean instanton formalism (eg. Coleman et al. PRD.15.2929, PRD.16.1762):

- Interprets VD in analogy with quantum tunnelling
- Designed to compute observables like decay rates and the bubble profile

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Real-Time Semi-Classical Approach

Braden et al.
PRL 123, 031601 (2019)
PRD 107, 083509 (2023)

Idea: model the phase space evolution of the system using a truncated Wigner approximation

- Stochastically sample realizations of a vacuum state
- Time evolve the initial state classically

$$\left[\frac{\partial}{\partial t} + \int d^dx \left(\dot{\phi}\frac{\delta}{\delta\phi} + \dot{\Pi}\frac{\delta}{\delta\Pi}\right) + \mathcal{O}\left(\hbar^2 V'''(\phi)\frac{\delta^3}{\delta\Pi^3}\right)\right] W\left[\phi(x), \Pi(x); t\right] = 0$$

classical evolution — quantum noise — initial state

Characteristics:

- Real-time evolution of the false vacuum
- Ensemble averages recover classical observables

3

Numerical Implementation

- Initialize the field and momentum around the FV:

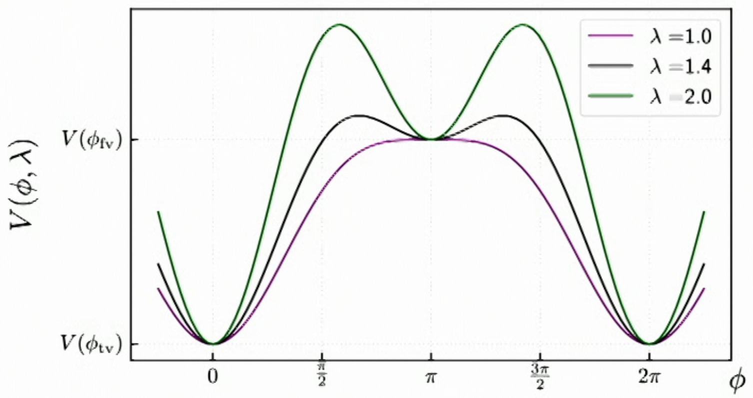
$$\phi(x, t=0) = \phi_{\rm fv} + \delta\phi(x,t), \quad \Pi(x, t=0) = \delta\Pi(x,t)$$

- Model fluctuations according to relativistic theory:

1. Minkowski vacuum: $$\delta\phi = \frac{1}{\sqrt{L}} \sum_j^{n_{\rm cut}} \frac{\hat{\alpha}_j}{\sqrt{2\omega_k}} e^{ik_j x} + \text{ c.c.}$$

2. Thermal bath: $$\delta\phi(T) = \frac{1}{\sqrt{L}} \sum_j^{n_{\rm cut}} \frac{\hat{\beta}_j}{\sqrt{\omega_k}} \frac{1}{\sqrt{e^{\omega_{k_j}/T} - 1}} e^{ik_j x} + \text{ c.c.}$$

- Evolve under potential than has 2 minima



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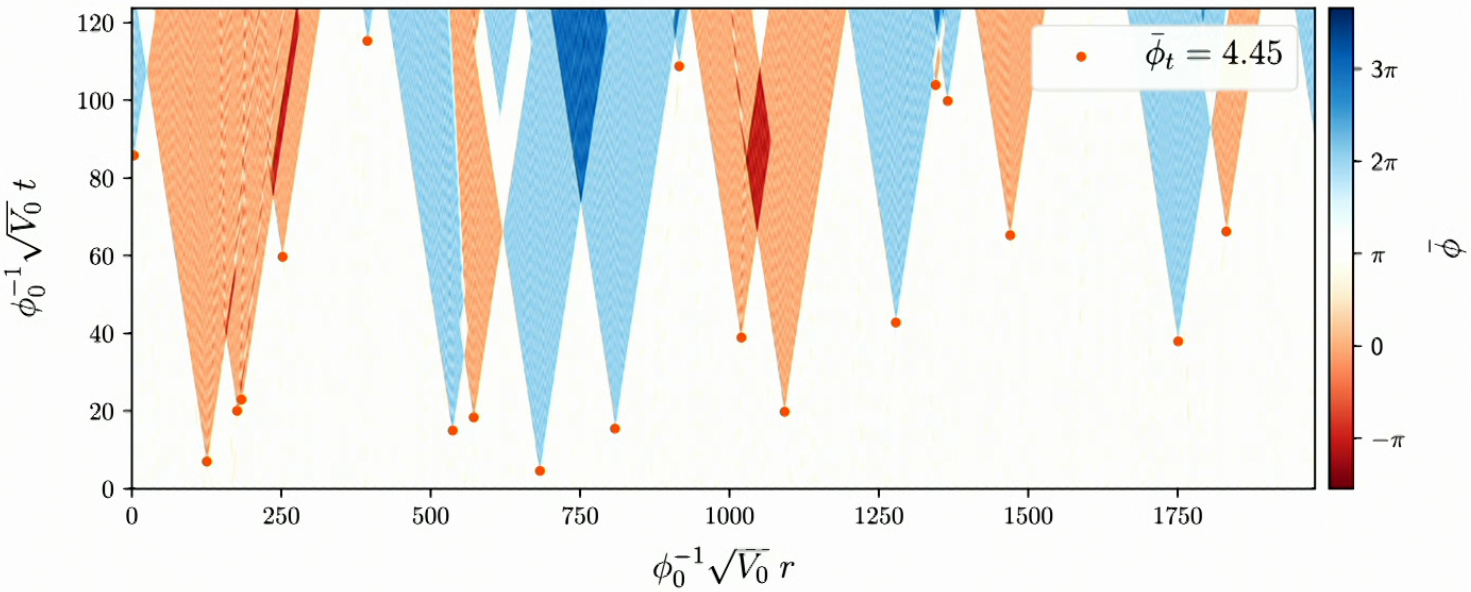
Dynamical Vacuum Decay



- Sometimes, locally, enough energy density accumulates to form a bubble
- Measure how far apart bubbles form from one another:
  - Distribution traces the statistics of the underlying field
  - Similar to: BBKS/Peak theory and galaxy biasing (Bardeen et al. DOI:10.1086/164143)

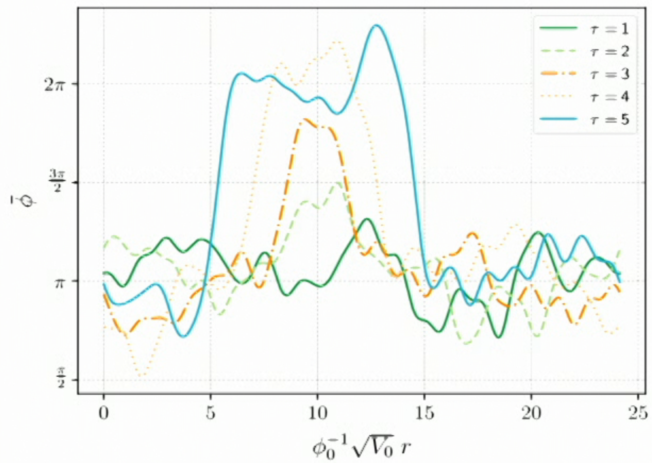
5

First new observable:

- Auto-correlation function between bubble nucleation sites

Next:

- Distribution of bubbles' centre of mass velocity at nucleation



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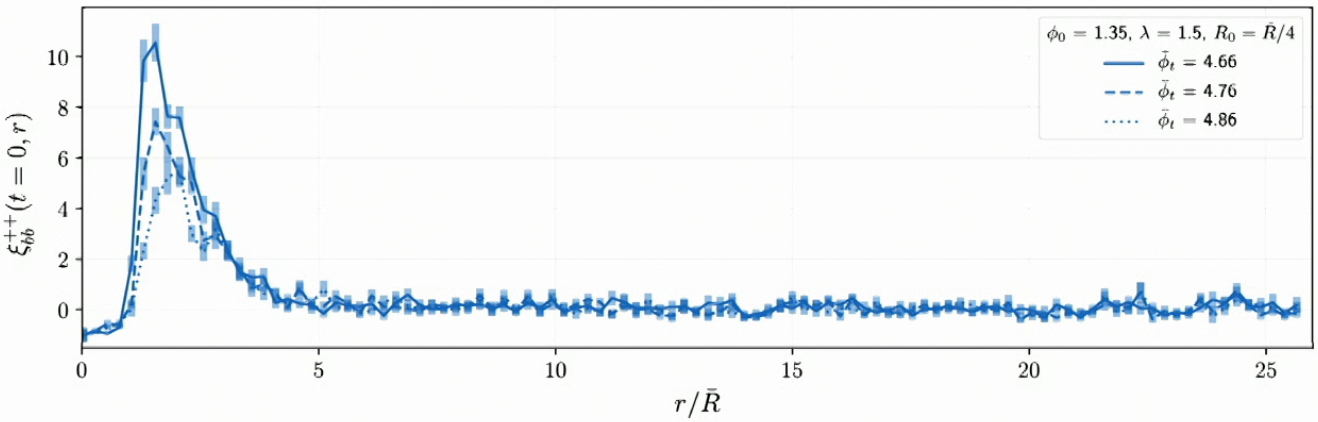
Bubble Auto-Correlation Function

DP et al. PRD 105, 043510 (2022)
De Luca et al. PRD 104, 123539 (2021)



Characteristics:

- Correlation length $\sim mR$
- At finite T, the amplitude scales as $\sim T$, but correlation length is shorter
- Two-point functions are measurable in an experiment!

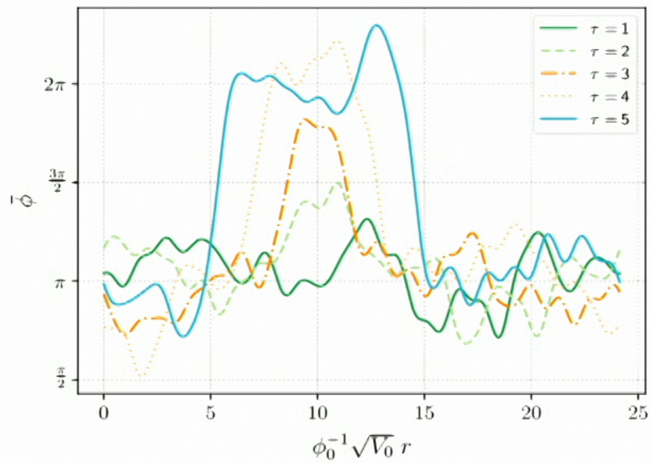
6

First new observable:

- Auto-correlation function between bubble nucleation sites

Next:

- Distribution of bubbles' centre of mass velocity at nucleation



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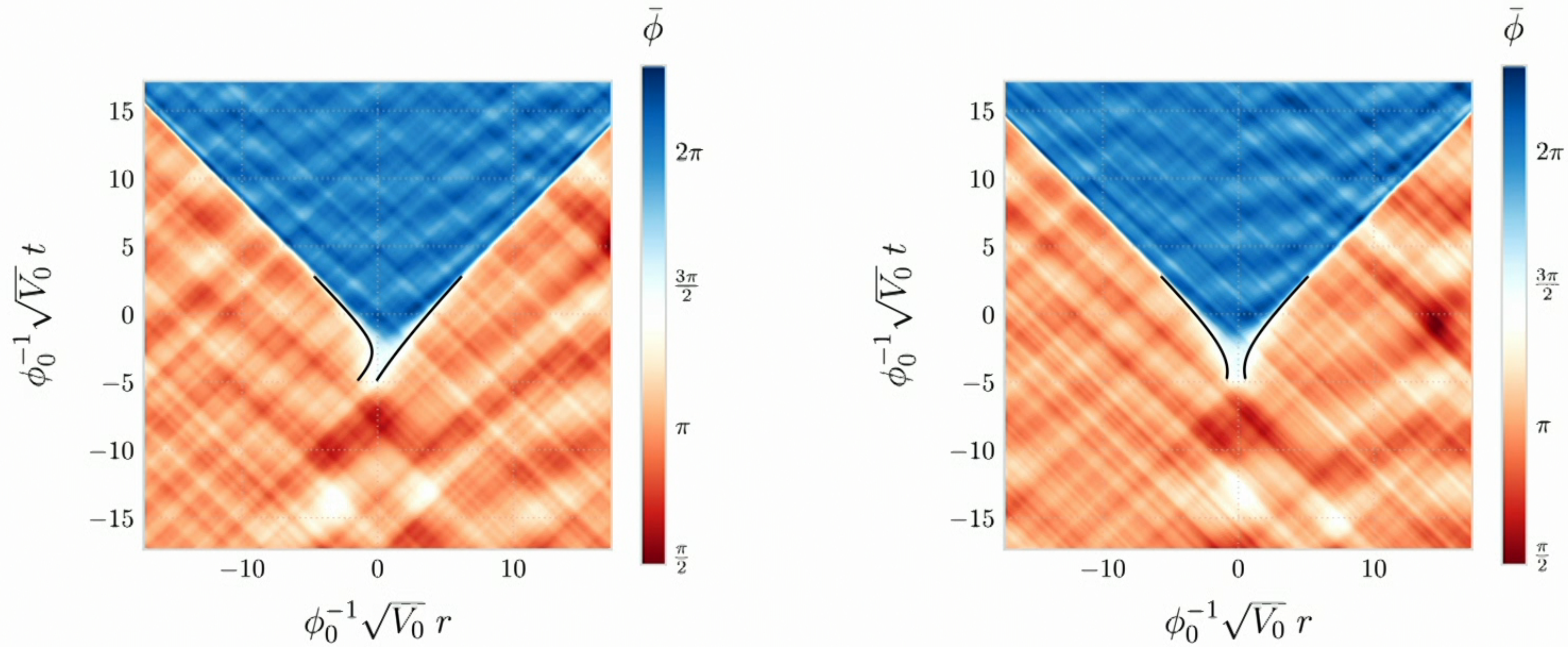
Boosting to Rest Frame

- Walls should expand symmetrically with constant acceleration
- Apply a Lorentz boost on the grid
- The boost factor gives the COM velocity $\gamma(v_{\mathrm{COM}})$



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Thermal Bubbles

- Decay rate proportional to Boltzmann factor

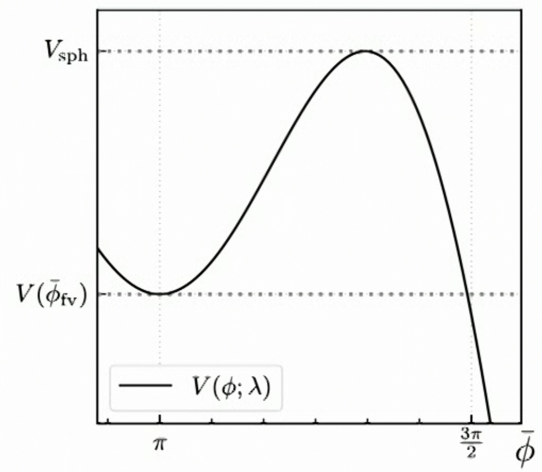
$$\Gamma \sim e^{-\frac{V_{\rm sph}}{T}}$$

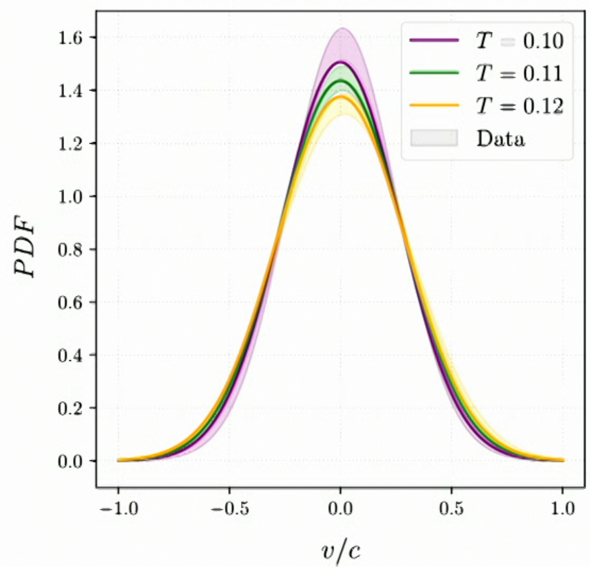
- Deviations from this threshold boost the bubble energy

$$E_{\rm crit} \sim V_{\rm sph}\,\gamma(v) \iff \langle v^2 \rangle \sim \frac{T}{E_{\rm crit}}$$

- Extract v_{COM} from each simulation and measure distribution

- Prediction checks out!





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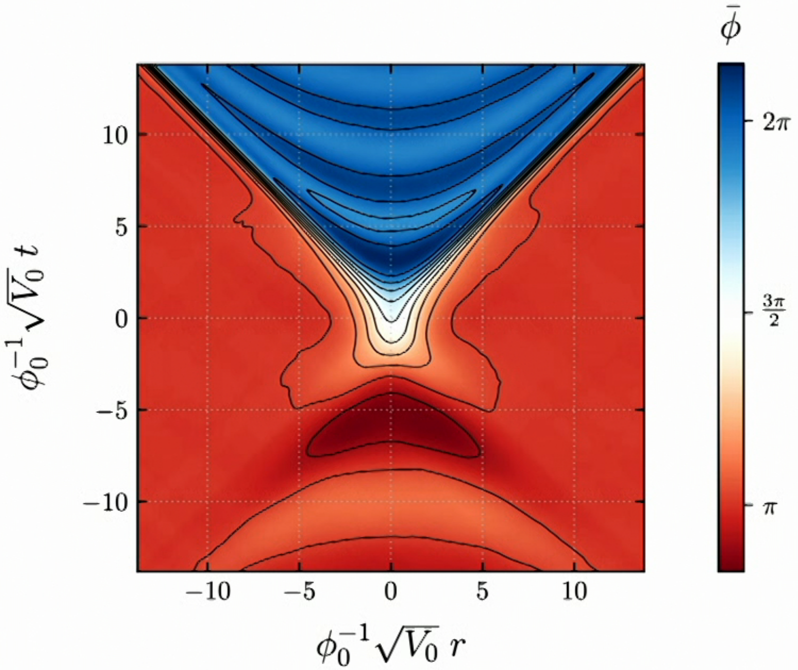
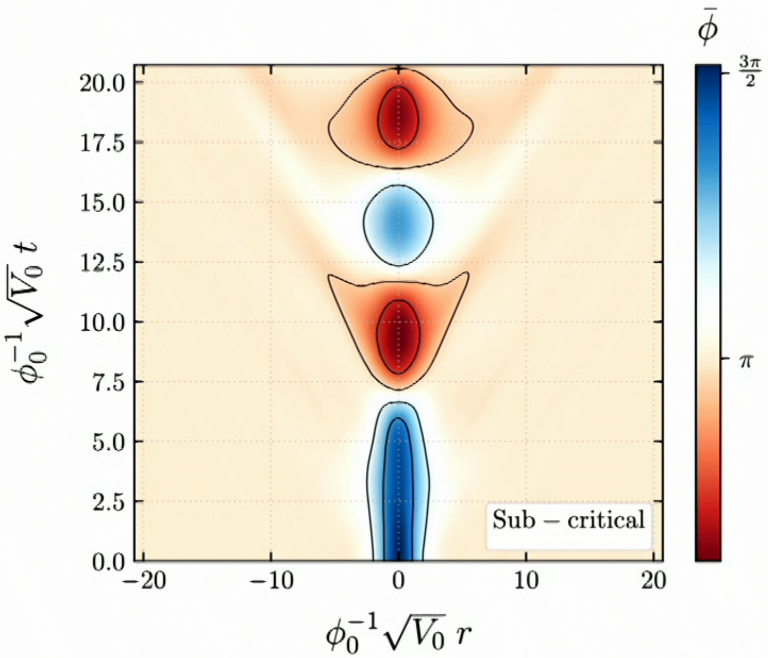
Average Bubble and Precursor

- Stack bubbles now at rest to obtain the average field and momentum profiles
- The sub-critical profile gives a time-dependent bound 'soliton' solution to the EOM
- It is the most likely configuration to yield the expanding bubble





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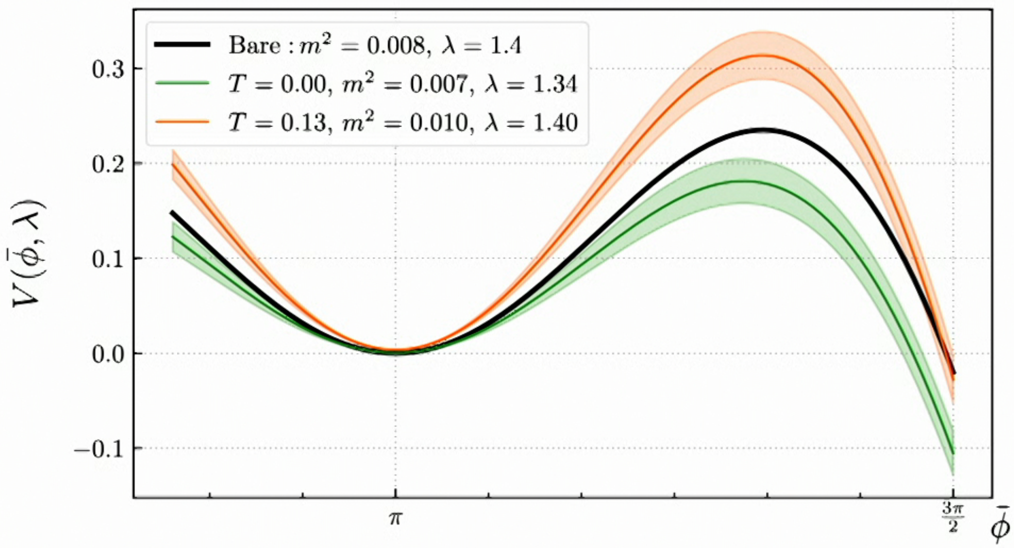
Reconstructing the Potential

- Inverting the equation of motion for the average $\phi_{\rm crit}(x, t \to 0)$, we obtain the one-loop effective potential for the field
- Any changes in the couplings is due to (a sum of) renormalization effects (eg. Braden et al. PRD 107, 083509 (2023))



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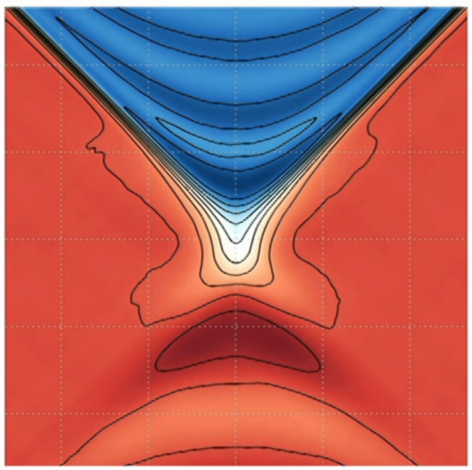
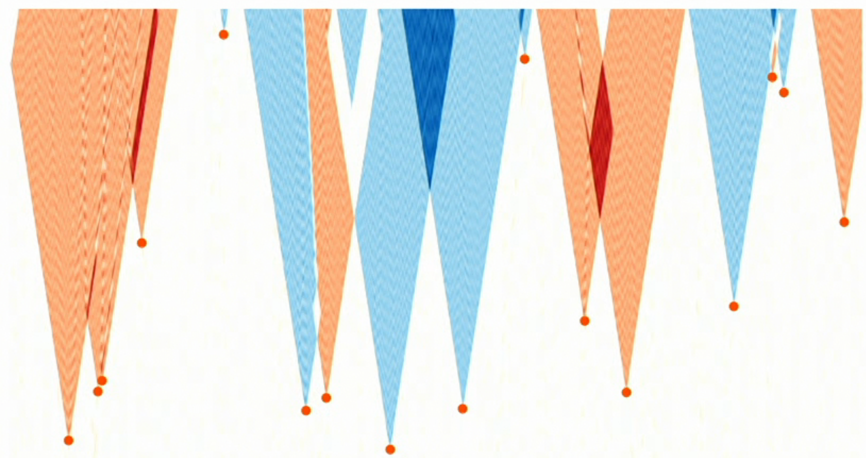
Conclusions

- Introduced two new dynamical observables of bubble nucleation
- If measured:
  - In the Lab: provide a test for the assumptions behind the truncated Wigner approach to understanding vacuum decay
  - Early Universe: give additional information about the initial false vacuum state





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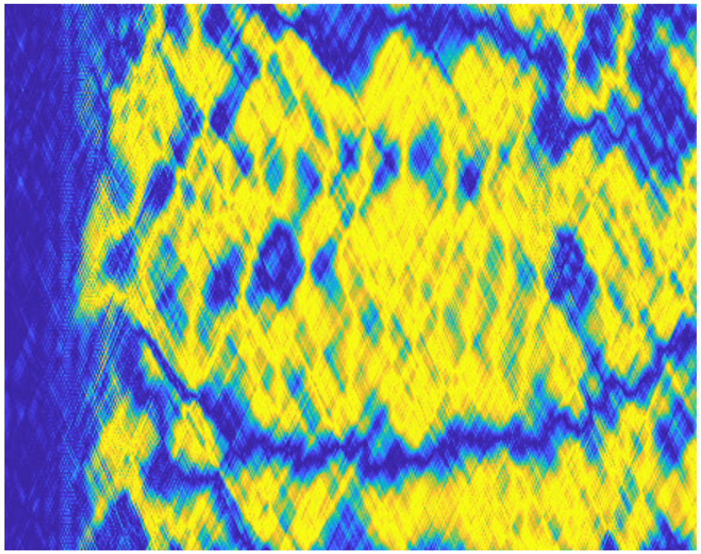
BUBBLE NUCLEATION IN A COLD SPIN-1 GAS

KATE BROWN (She/Her)
Ian Moss & Thomas Billam

arXiv:2212.03621

MOTIVATION

- Lots of (very nice) attempts have been made to model first-order vacuum decay in a 2-component spin-1/2 system
- This system exhibits parametric instabilities ☹
- **Goal:** a system free from instabilities

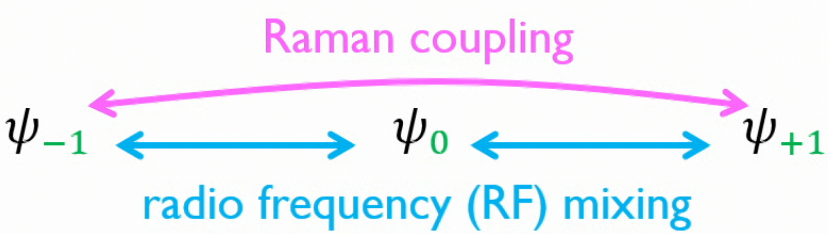


SPIN-1 SYSTEM

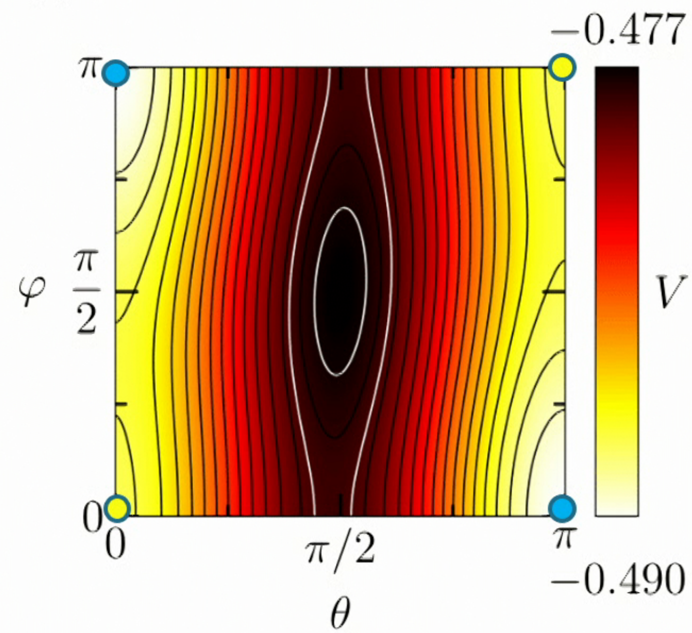
- 3-level, states labelled by $\mathrm{m}_F = \{-1, 0, +1\}$:

$$\psi_{+1} = \sqrt{n_{+1}}e^{i(\theta+\varphi)}, \quad \psi_0 = \sqrt{n_0}, \quad \psi_{-1} = \sqrt{n_{-1}}e^{i(\theta-\varphi)}$$

- Complicated interaction potential, V



- True vacua at $(\theta, \varphi) = (0, \pi)$ and $(\pi, 0)$
- False vacua at $(\theta, \varphi) = (0,0)$ and (π, π)



SPGPE

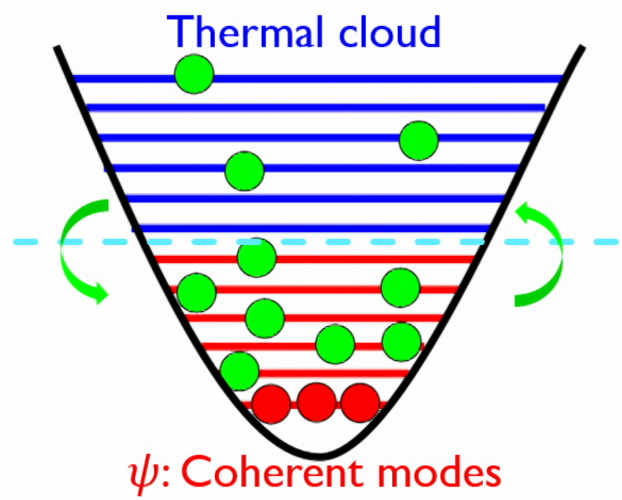
- We use a system of stochastic projected Gross-Pitaevskii equations (SPGPE):

$$i\partial_t \psi_j = P\left[(1 - i\gamma)\left\{-\frac{1}{2}\nabla^2\psi_j + \frac{\partial V}{\partial \psi_j^*}\right\} + \eta_j\right], \qquad j = -1, 0, +1$$

- γ : Damping
- η : Random fluctuations,

$$\langle \eta_i(x,t)\eta_j(x',t')\rangle = 2\gamma T\delta(x - x')\delta(t - t')\delta_{ij}$$

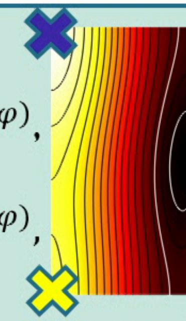
- P : Projector, eliminates high wavelength modes



BUBBLE GROWTH – NO TRAP

Remember:

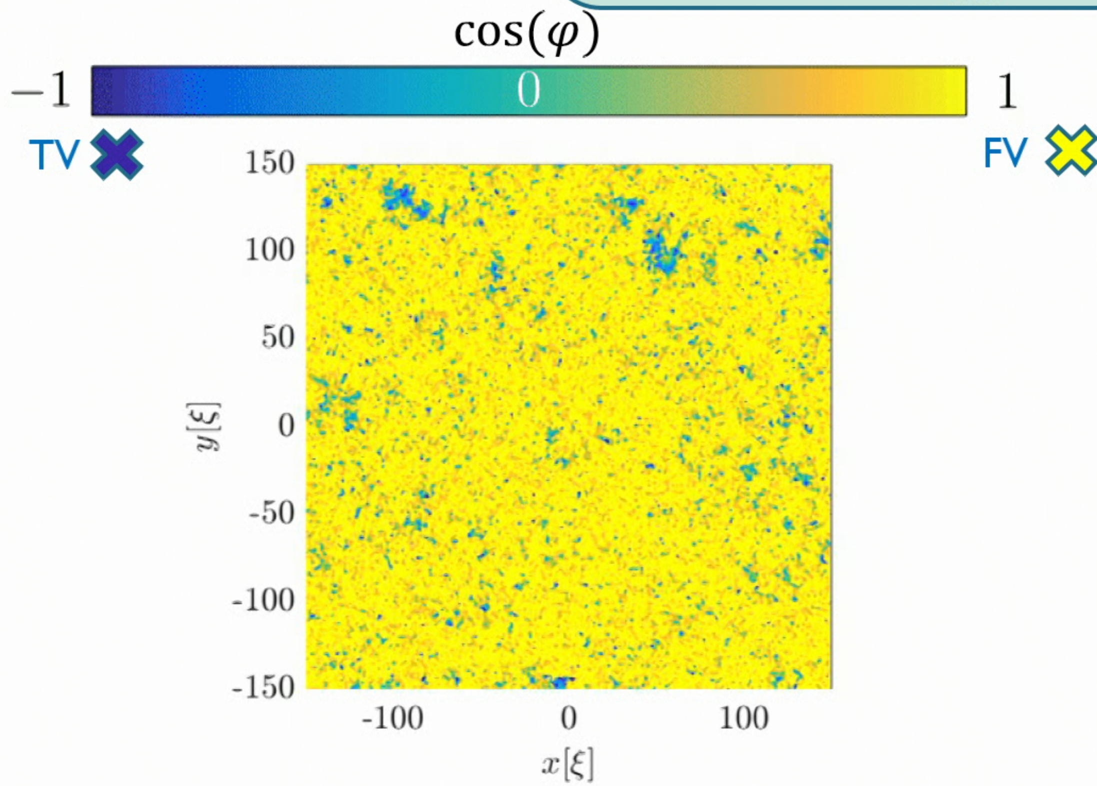
- $\psi_{+1} = \sqrt{n_{+1}} e^{i(\theta+\varphi)}$,
- $\psi_0 = \sqrt{n_0}$,
- $\psi_{-1} = \sqrt{n_{-1}} e^{i(\theta-\varphi)}$,



- 2D uniform system, periodic boundaries
- Initialise in the false vacuum state $(\theta, \varphi) = (0,0)$
- False vacuum:

  $\cos(\varphi) = 1$
- True vacuum

  $\cos(\varphi) = -1$



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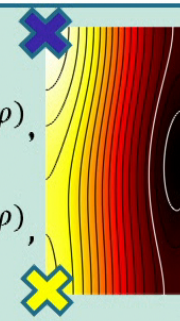

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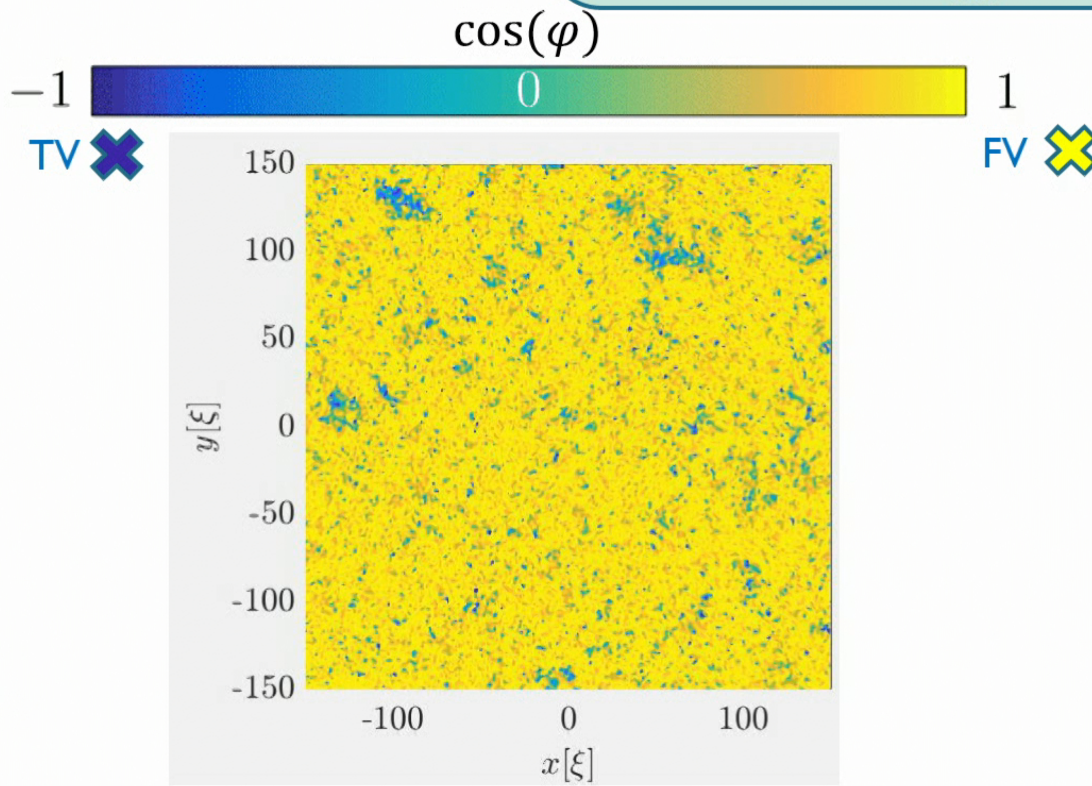
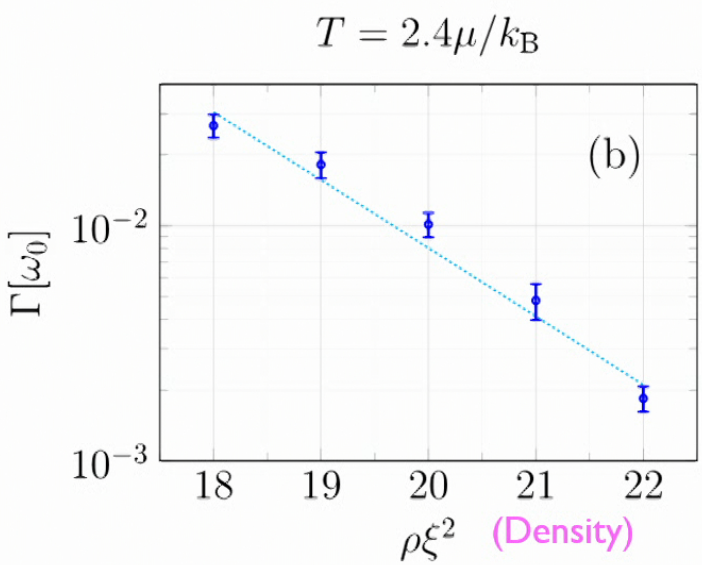
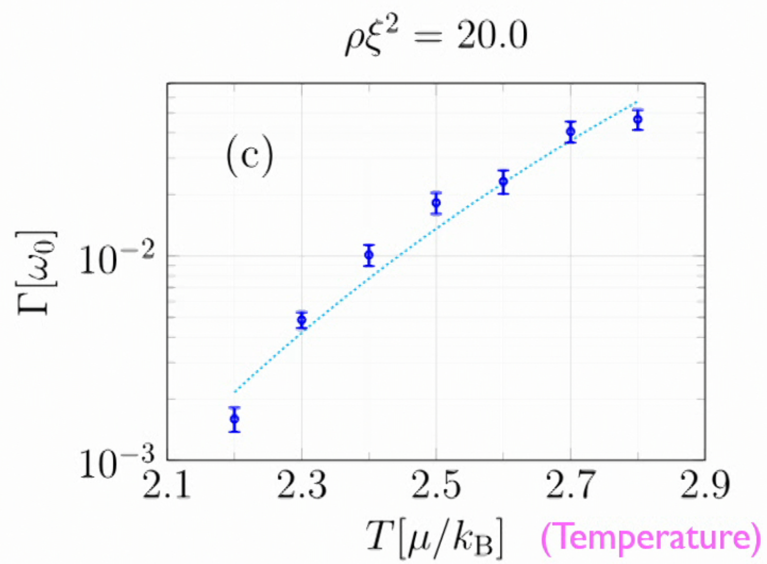


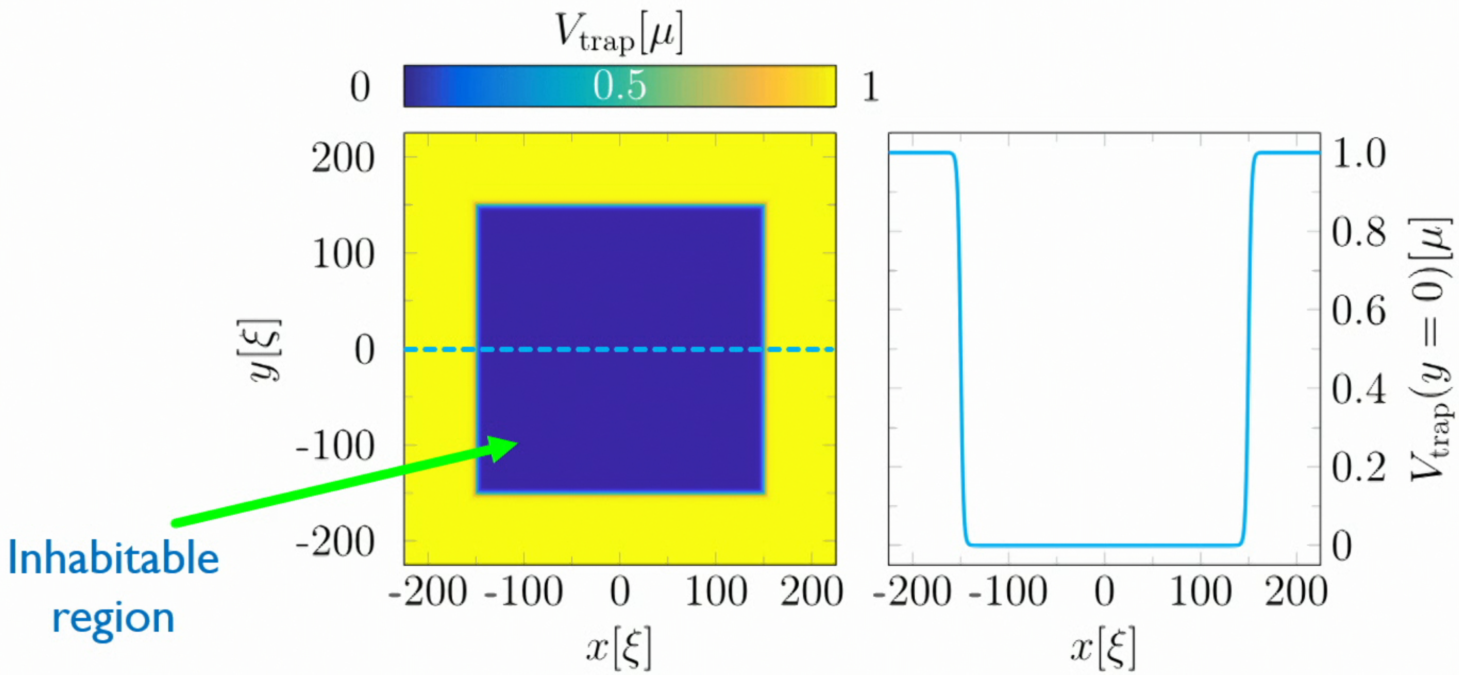
DECAY RATE – NO TRAP

- Rate of false vacuum decay: Γ
- $\Gamma_{\text{instanton}} = A\left(\frac{\rho}{T}\right)\exp\left(-B\frac{\rho}{T}\right)$, freedom in A and B (dotted line)

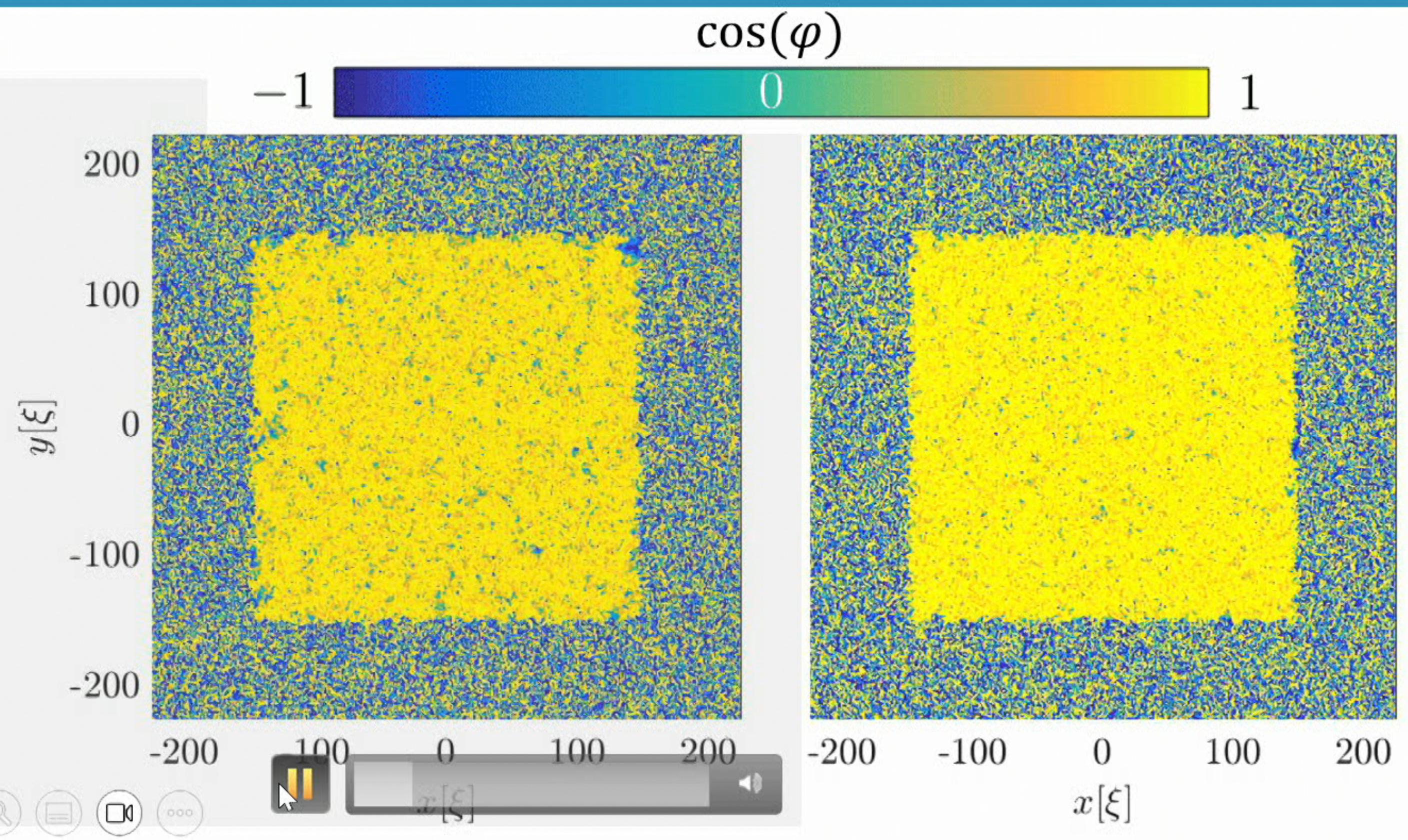




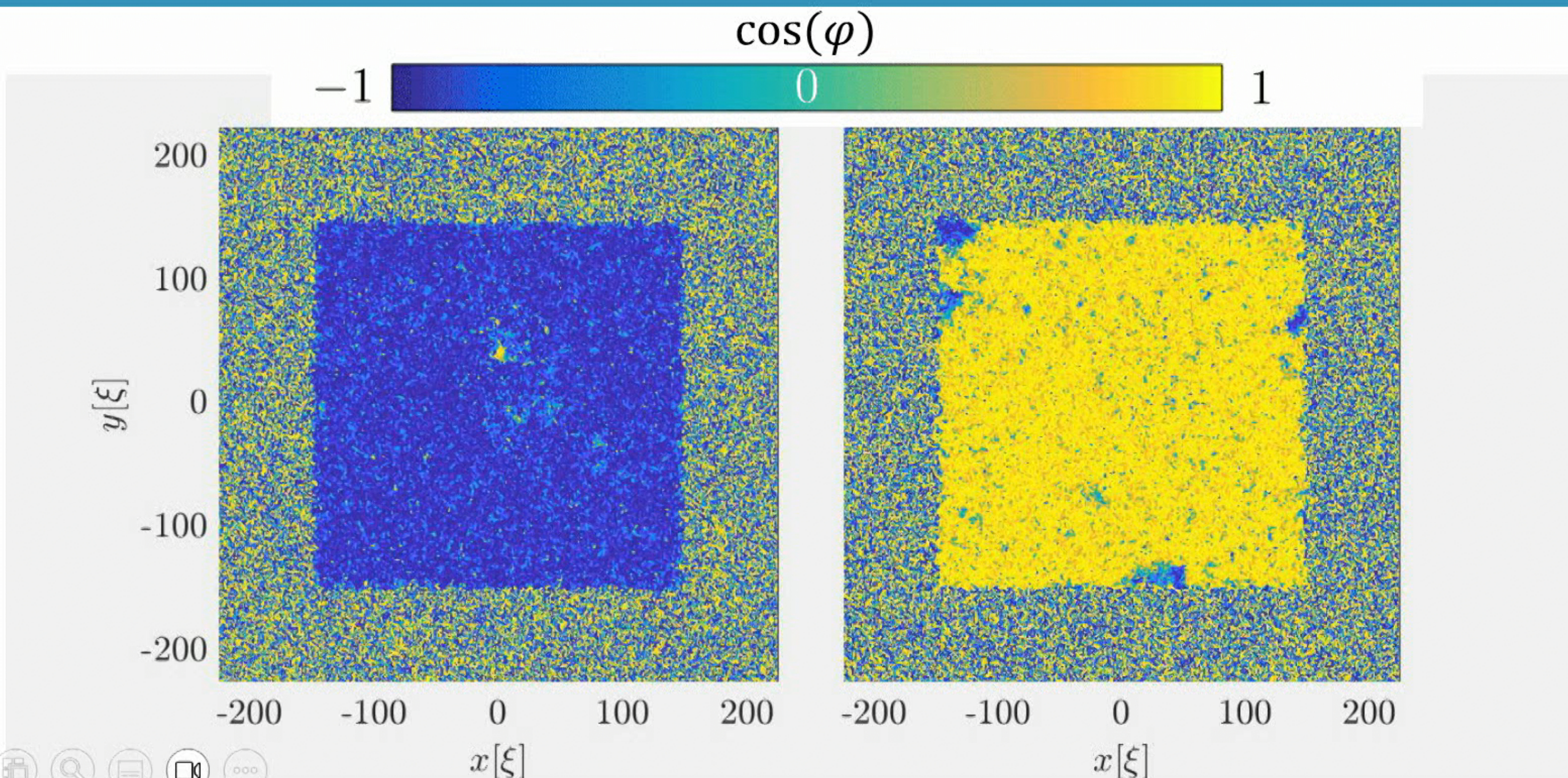
ADDING WALLS



BUBBLE GROWTH - WALLS

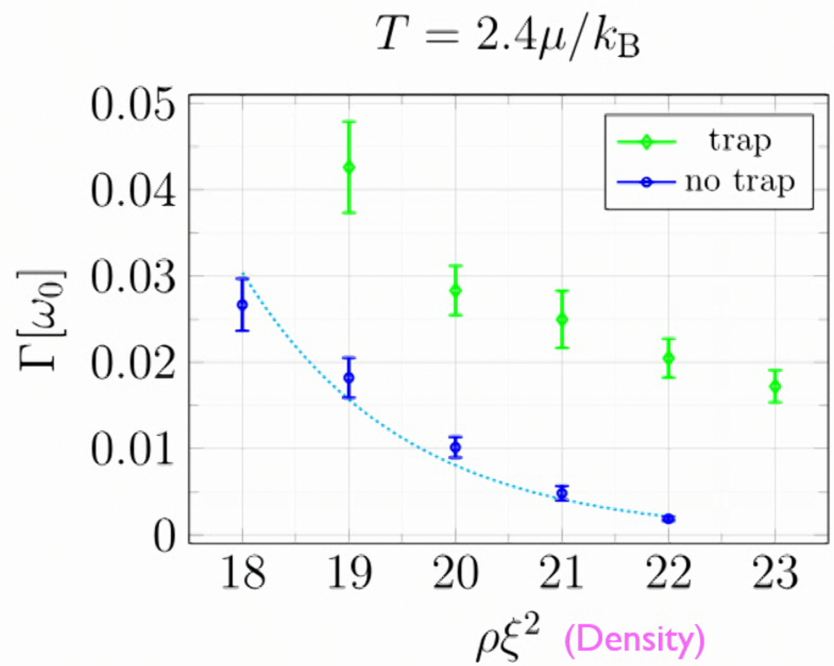


BUBBLE GROWTH - WALLS



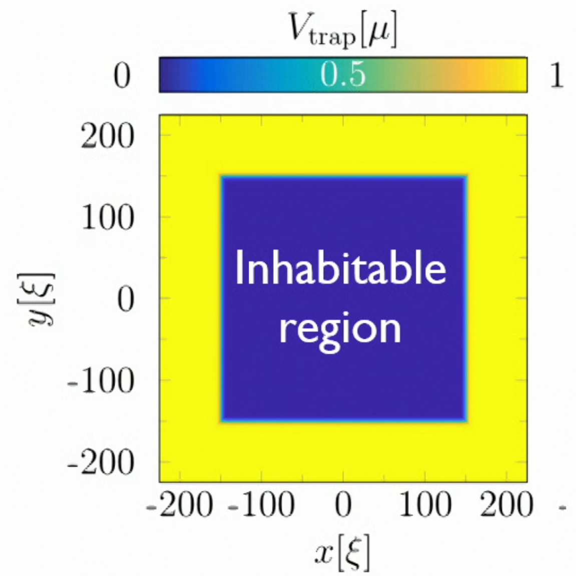
DECAY RATE – TRAP VS NO TRAP

- The addition of boundaries causes a global increase in the rate of false vacuum decay



CONCLUSION

- We have successfully modelled first-order vacuum decay in a spin-1 system
- **Problem!** Walls of trapping potential seed nucleation – false vacuum decays too quickly!
- **Possible solution** – make system bigger! The higher the area-to-perimeter ratio of the inhabitable region, the less impact the walls should have!



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GRAVITY LABORATORY

QSimFP @gravity_laboratory

Superfluid helium vortex flow: Experimental realisation

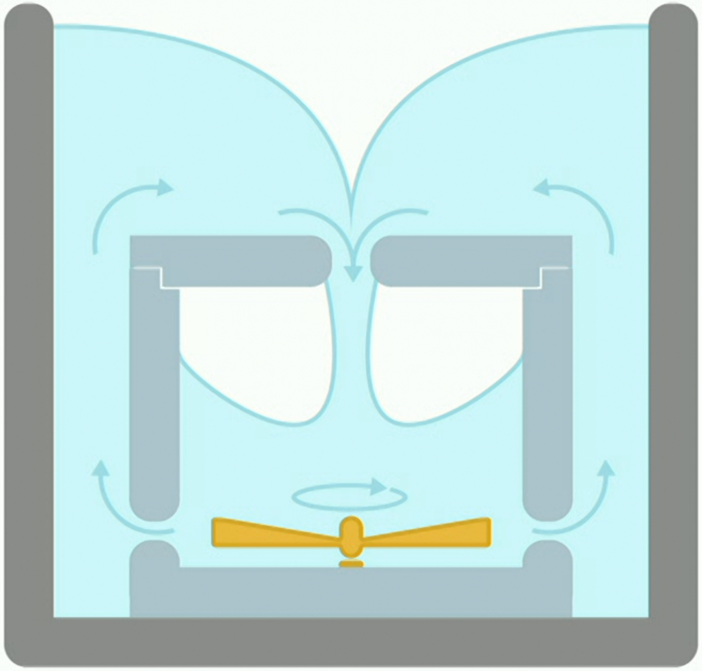
Pietro Smaniotto, Leonardo Solidoro, Patrik Švančara, Silke Weinfurtner
Ruth Gregory, Carlo Barenghi, Sam Patrik

Reach the superfluid transition

Precooling
(ambient 290 K to 77 K) → Transferring liquid helium
(77K to 4.2 K) → Pumping to the transition
(4.2 K to 2.2 K)

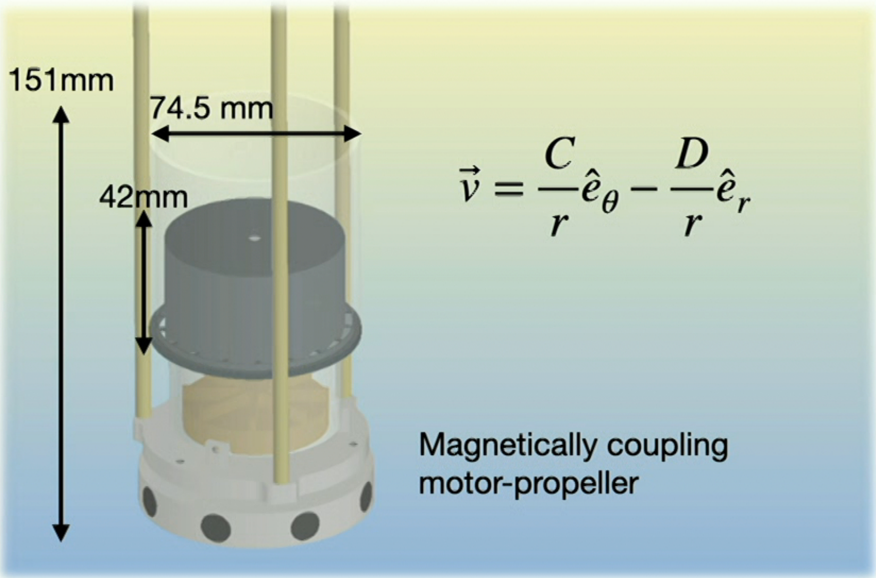
Setting up the vortex flow

- Cylindric cryostat
- Drain hole
- Motor and Propeller
- Flow Conditioner



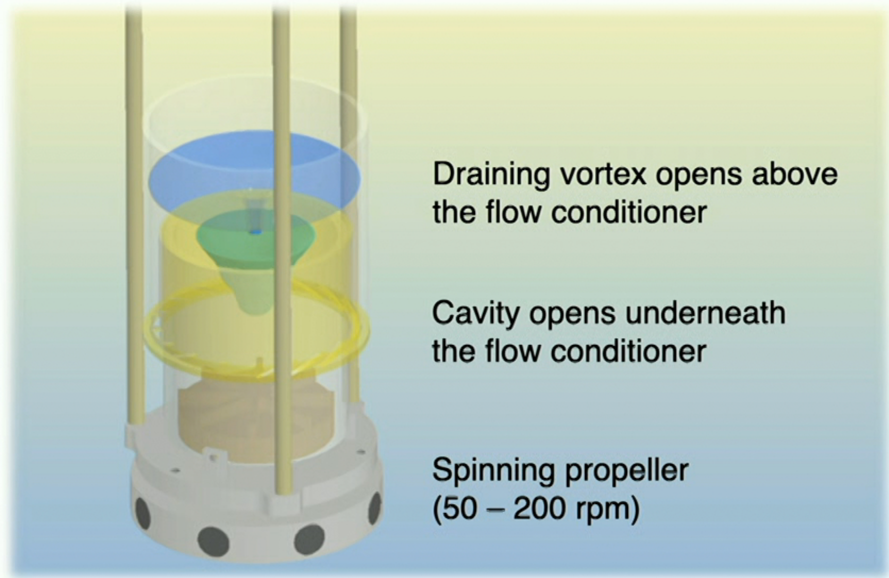
Challenges of the setup

How to make a Rankine vortex?

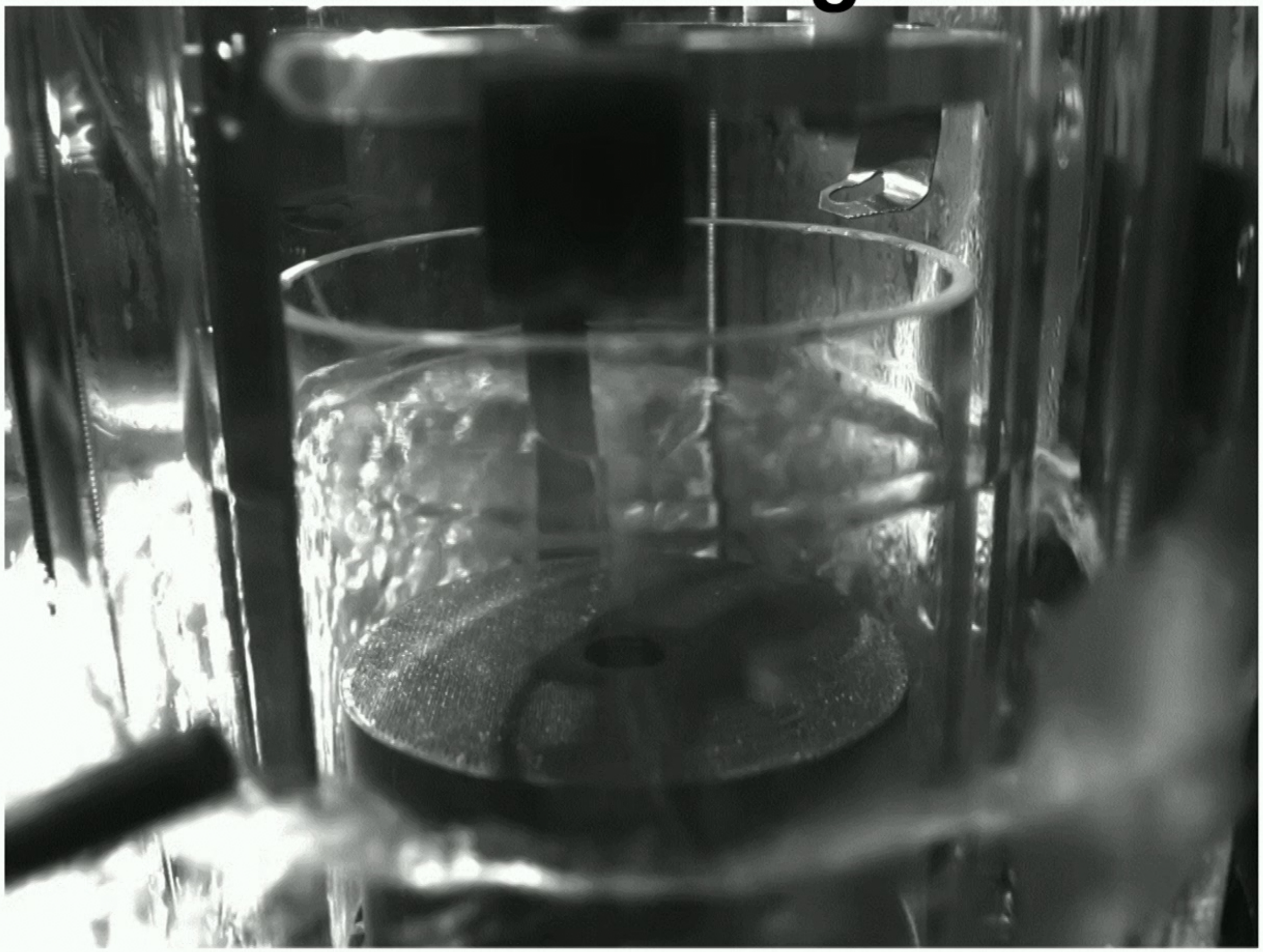


$$\vec{v} = \frac{C}{r}\hat{e}_\theta - \frac{D}{r}\hat{e}_r$$

Pumps, rotating magnetic disk, sources of noise



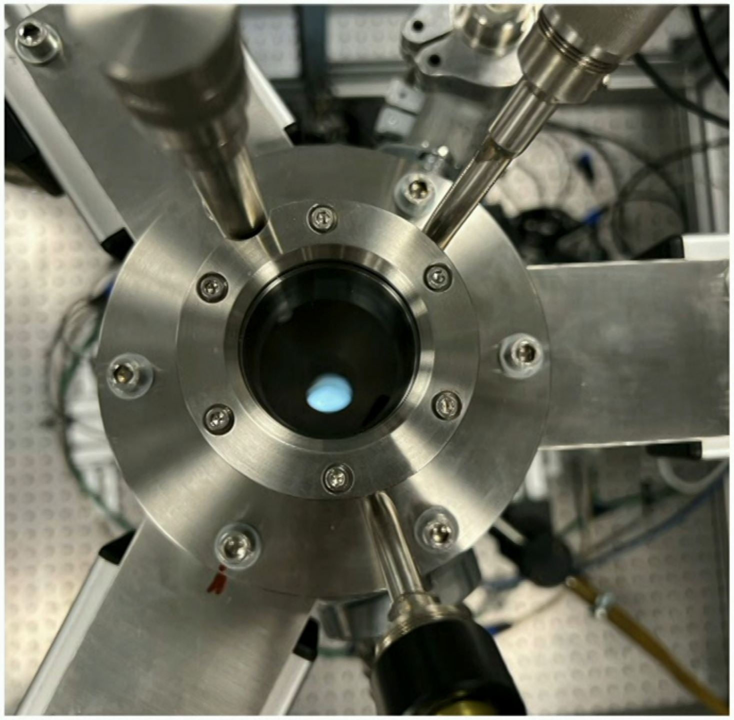
It’s working!



Temperature ca. 2.0 K Propeller frequency ca. 3 Hz

Looking through the window

Phantom camera for surface visualisation



1024x1024 at 200fps

Conclusions and improvements

- Vortex flow in superfluid helium
- Collect videos looking from the top window
- Printed a pattern that can survive low temperatures
- New ways to reduce the shaking
- Patterns printed on metal with no defects

Follow us on Instagram: @gravity_laboratory

Fast Checkerboard Demodulation

Surface Reconstruction in Superfluid Helium Vortex

University of Nottingham
UK | CHINA | MALAYSIA

GRAVITY LABORATORY

Leonardo Solidoro - Pietro Smaniotto - Patrik Švančara - Silke Weinfurtner

What does a wave look like from above?

The passage of a wave produces an apparent distortion on a background below the surface

With Synthetic Schlieren Imaging the distortion is quantified as an effective pointwise displacement and it allows for a non intrusive reconstruction of the fluid's surface

$$I(\mathbf{r}) = I_0(\mathbf{r} - \mathbf{u}(\mathbf{r}))$$

2

What does a wave look like from above?

The passage of a wave produces an apparent **distortion** on a background below the surface

With **Synthetic Schlieren Imaging** the distortion is quantified as an effective pointwise displacement and it allows for a non intrusive reconstruction of the fluid's surface

$$I(\mathbf{r}) = I_0(\mathbf{r} - \mathbf{u}(\mathbf{r}))$$

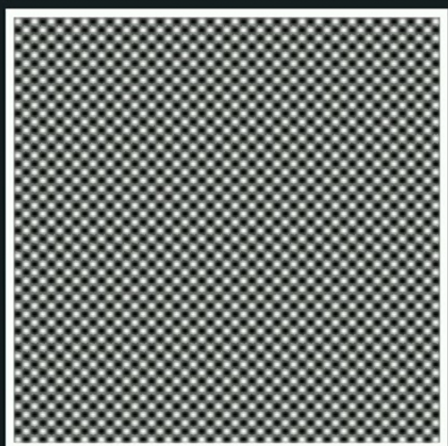
2

Fast Checkerboard Demodulation

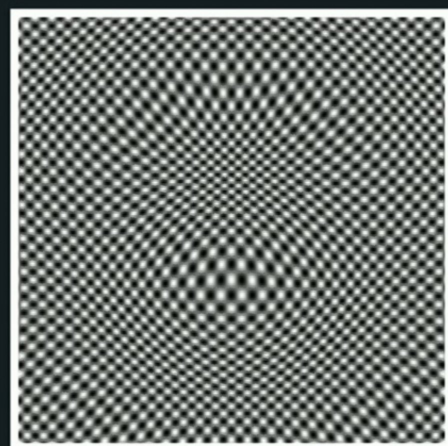
The use of a **periodic 2D pattern** leads to a direct evaluation of the displacement vector

The effect of the distortion is encoded in a **phase modulation** of a carrier signal, as happens in FM radio

S. Wildeman, Exp. Fluids 2018



$$I_0(\mathbf{r}) = \sum a_c e^{-i\mathbf{k}_c \cdot \mathbf{r}}$$



$$I(\mathbf{r}) = \sum a_c e^{-i\mathbf{k}_c \cdot (\mathbf{r} - \mathbf{u}(\mathbf{r}))}$$

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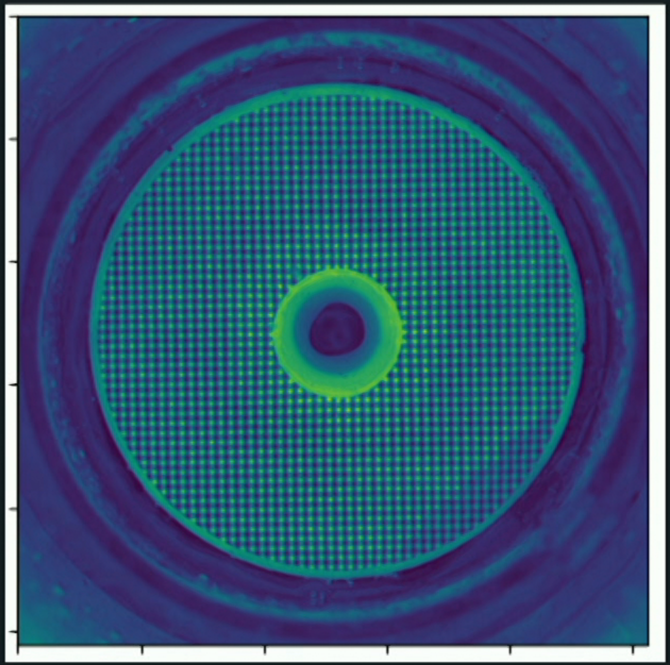
1.

Extract frequencies of the carrier waves

The Fast FT (FFT) of the unperturbed periodic pattern reveals the wavenumber vectors of the carrier waves as peaks in the spectrum

$$g_0(\mathbf{r}) = a_c e^{-i\mathbf{k}_c \cdot \mathbf{r}}$$



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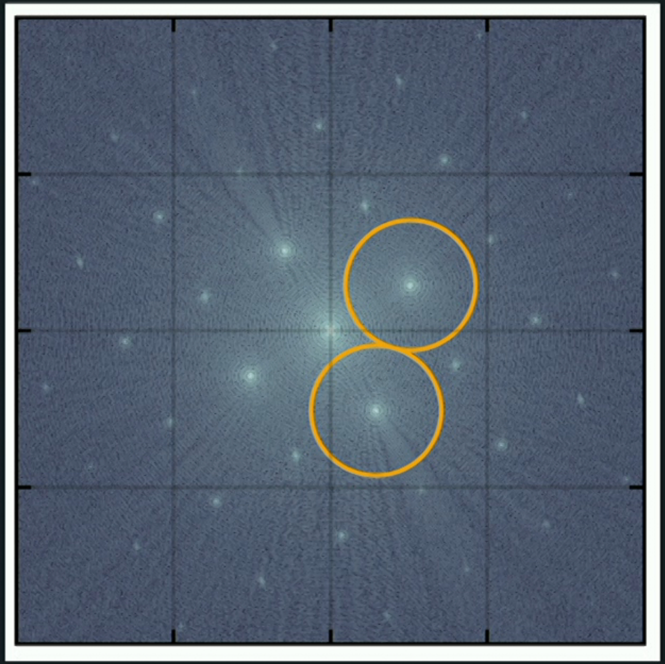
2.

Take the FFT of the distorted frame

The signal caused by the distortion is identified in the spectrum in an area centred at the two carrier peaks

$$g(\mathbf{r}) = a_c e^{-i\mathbf{k}_c\cdot(\mathbf{r}-\mathbf{u}(\mathbf{r}))}$$



5

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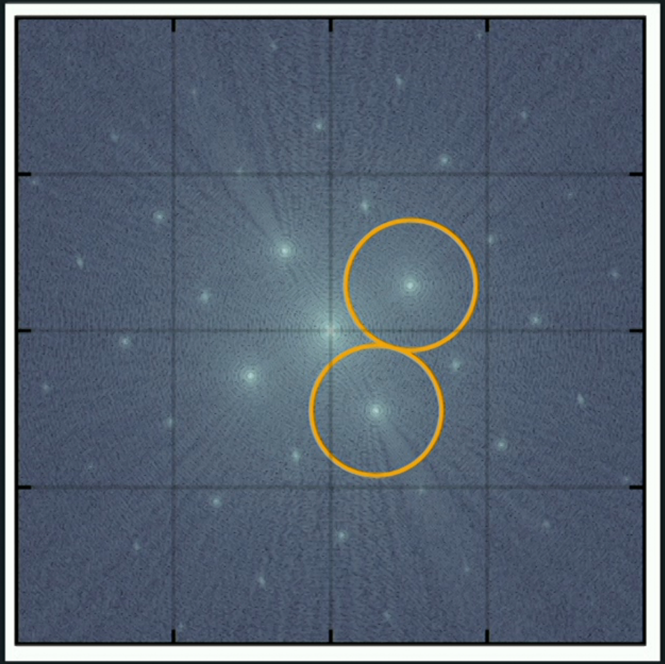

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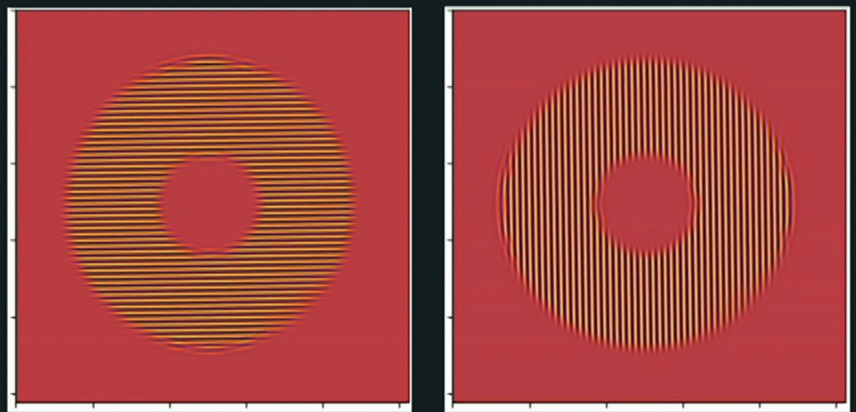
3.

Get the phase and solve

From the spectra one extracts two phases, and therefore two linear equations for the two components of $\mathbf{u}(\mathbf{r})$ for every pixel in the frame



$$\phi_i(\mathbf{r}) = \mathrm{Im}\left(\ln(g_i \cdot g_{0i}^*)\right) = -\mathbf{k}_{ci} \cdot \mathbf{u}$$

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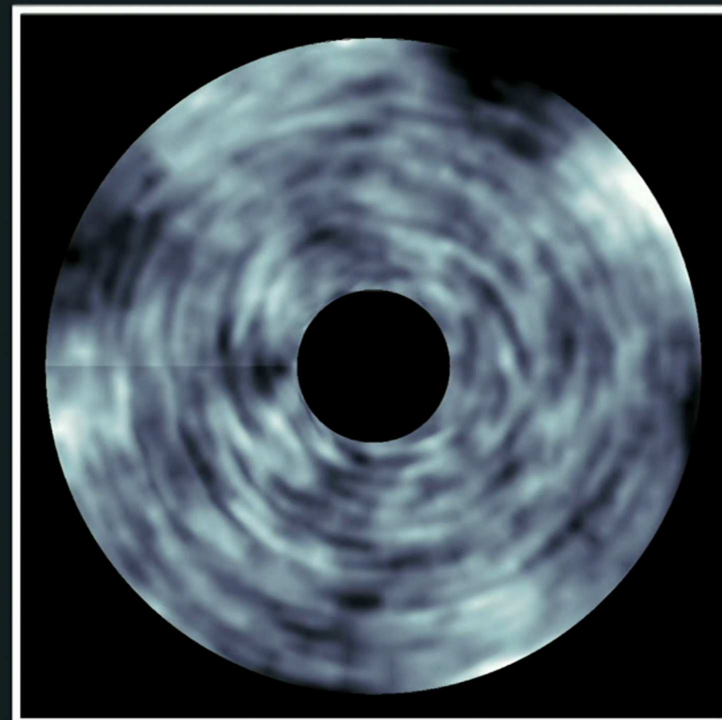
4.

Reconstruct the surface

The displacement vector is proportional to the gradient of the surface height, which can be integrated to reproduce the wave profile

$$\mathbf{u}(\mathbf{r}) \approx -H(1 - n_a/n_l)\nabla h(\mathbf{r})$$



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Conclusions

Why use Fast Checkerboard Demodulation?

Non intrusive method

You only need a pattern and a camera
The sample stays clear and pure, without introducing any external elements

Looking at the surface

The method is sensitive to the surface waves, not the bulk dynamics

Thank you

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