Dynamics of vortex pinning in a 2D superfluid flow

Oliver Stockdale, Matt Reeves, and Matt Davis

The University of Queensland

ARC Centre of Excellence in Future Low-Energy Electronics Technologies

10th International Conference on Spontaneous Coherence in Excitonic Systems, Melbourne

THE UNIVERSITY OF QUEENSLAND AUSTRALIA

January, 2020

StockdaleOliver

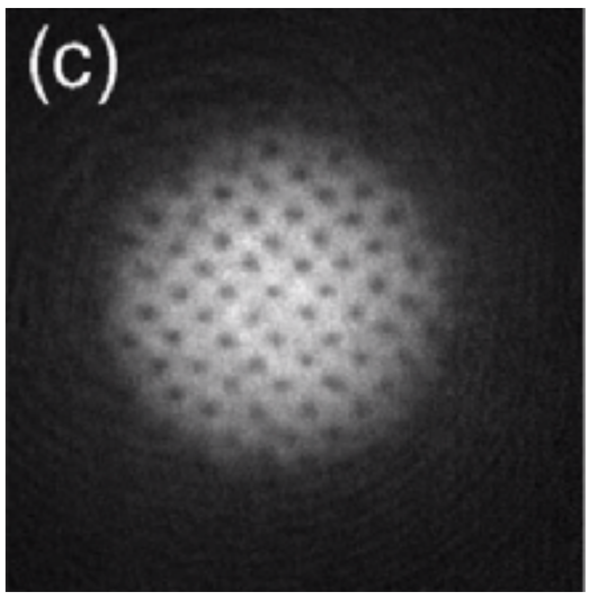
FLEET

ARC CENTRE OF EXCELLENCE IN FUTURE LOW-ENERGY ELECTRONICS TECHNOLOGIES

Vortex Pinning

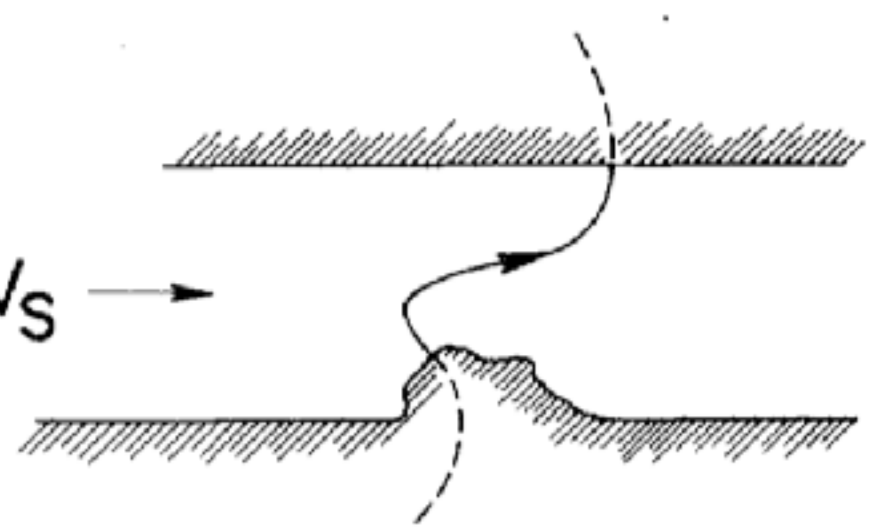
What is vortex pinning? Vortices can become pinned (i.e. trapped) on obstacles in a superfluid due to a local density change

Atomic BEC



S. Tung, V. Schweikhard, and E. A. Cornell, PRL **97**, 240402 (2006)

Superfluid Helium



K. W. Schwarz, PRL **47**, 251 (1981)

Pulsars

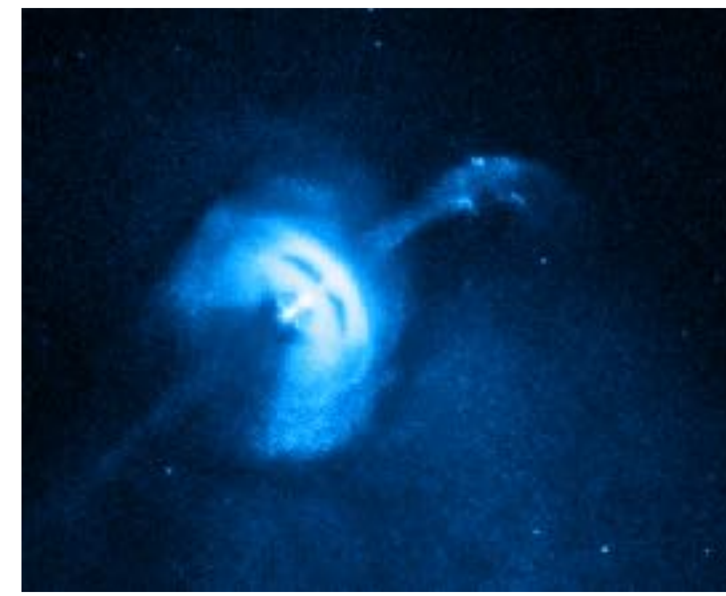
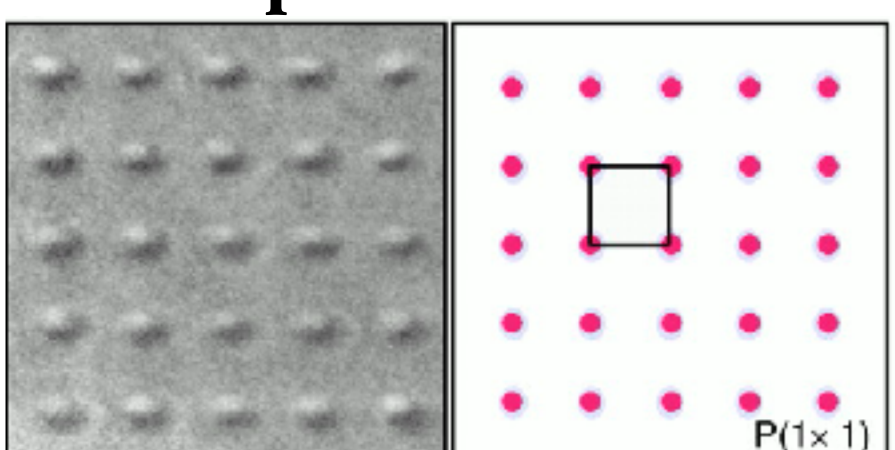


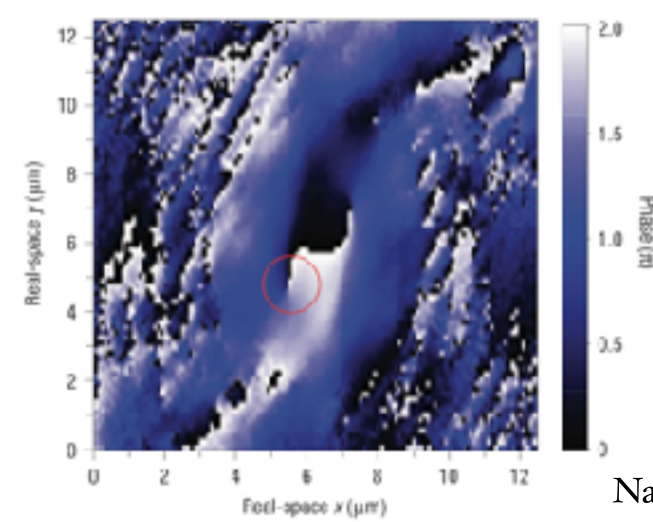
Image of Vela pulsar from NASA's Chandra X-ray observatory

Superconductors



K. Harada, et al, Science **274**, 1167 (1996)

Polariton condensates

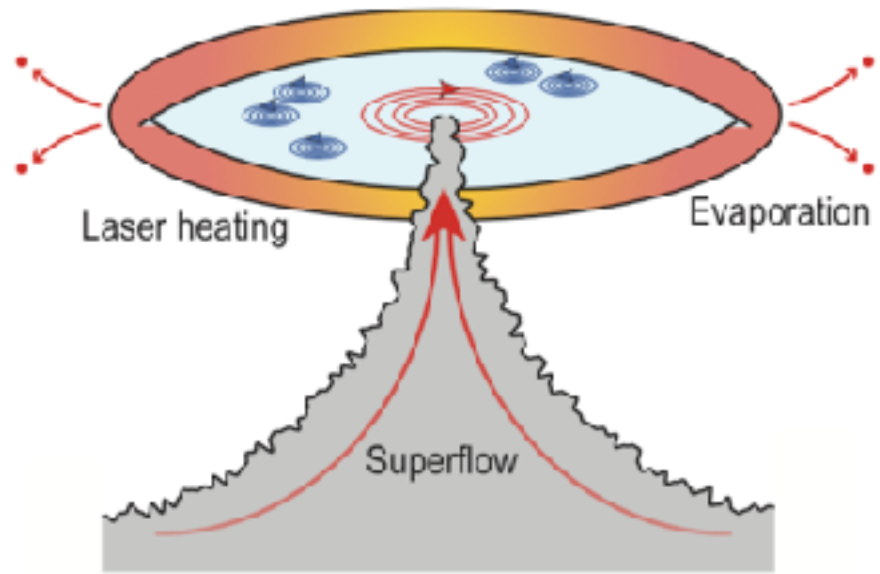


K. F. Lagoudakis, et al, Nature Physics **4**, 706 (2008)

Motivation

UQ superfluid helium experiment

- Motion of quasi-2D vortices cannot be directly imaged
- How do we describe vortex pinning at a microscopic level?

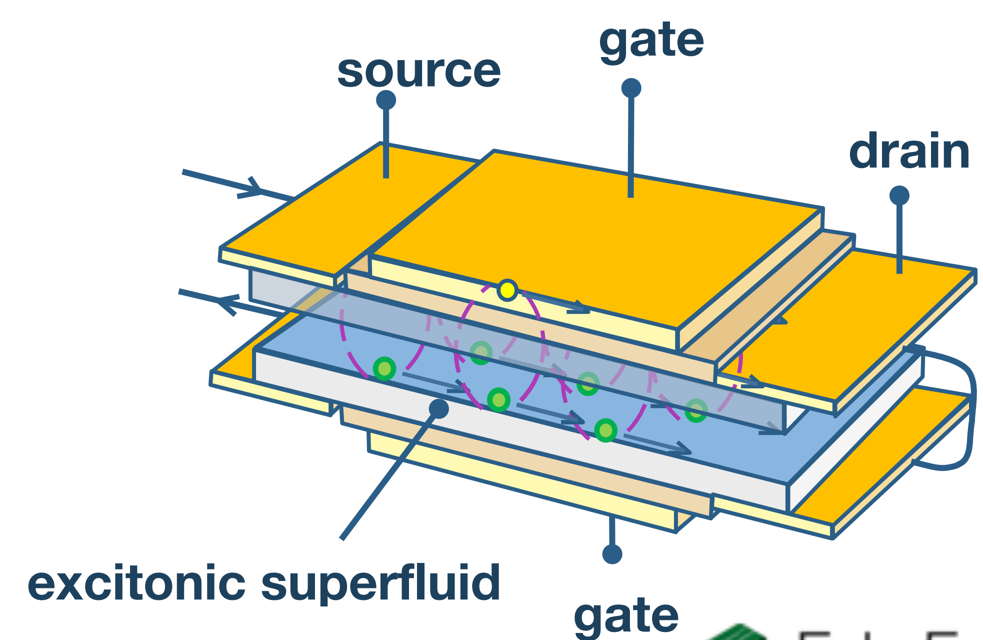


Y. P. Sachkou, C. G. Baker, G. I. Harris, **O.R.S.**, *et al.*, Science **366**, 1480 (2019)

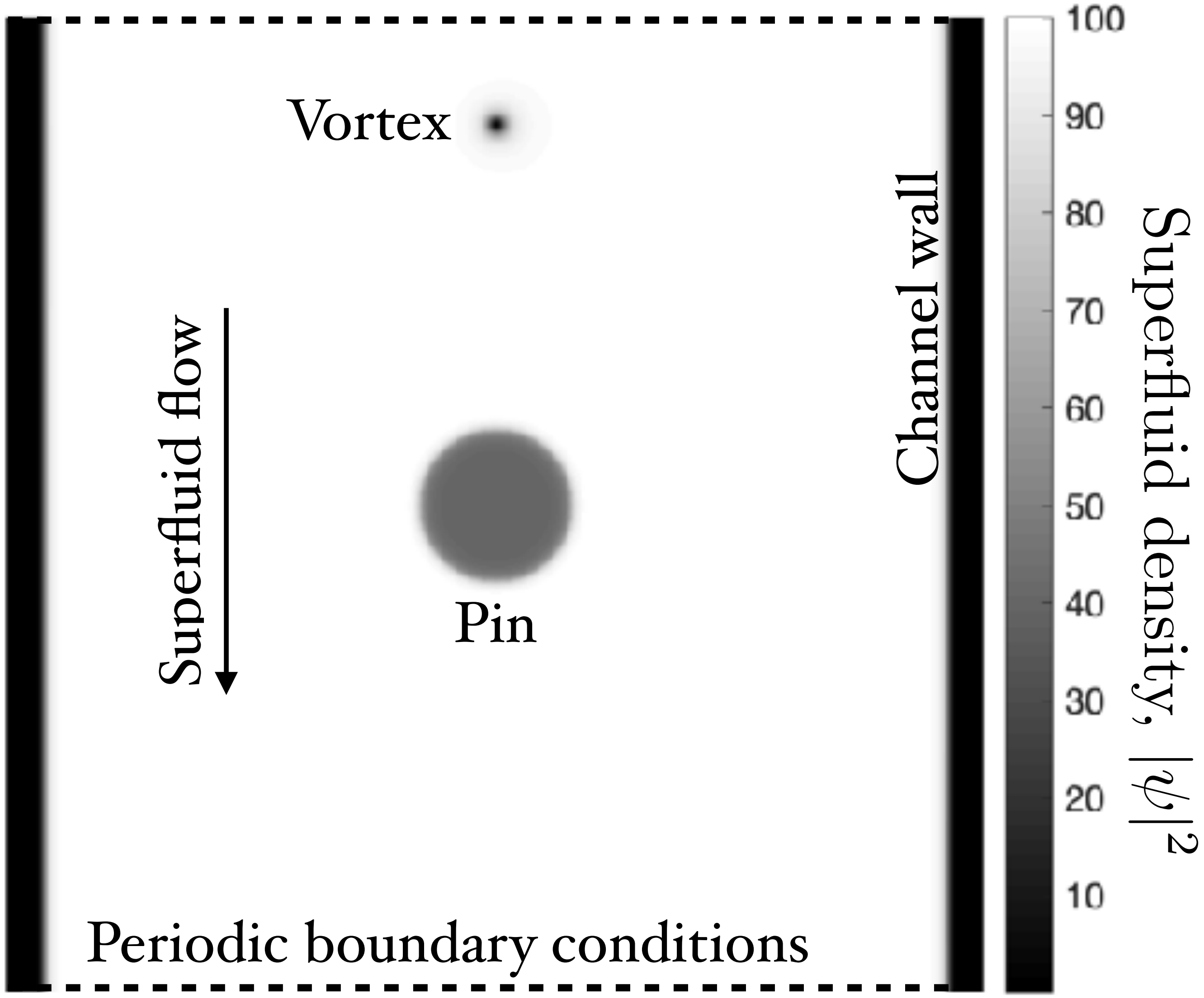
FLEET superfluid transistor

- Superfluids permit zero dissipation - perfect flow without energy loss!
  - Only below a *critical velocity*
  - Above this, vortices can be created

Vortices = turbulence = resistance = low efficiency



The System



Gross-Pitaevskii equation

$$i\partial_t \psi(\mathbf{r},t) = [\mathcal{L} + i v_y \partial_y - \mu]\psi(\mathbf{r},t)$$
$$\mathcal{L} = -\frac{1}{2}\nabla^2 + V(\mathbf{r}) + g|\psi|^2$$

Why simulate an atomic BEC?

- Clean system, easier for us to understand
- We work with experimentalists who could potentially realise these simulations

Easily adaptable to a polariton system: add pumping and loss!

Can we simplify our model?

One can map the Gross-Pitaevskii equation to hydrodynamics, where the velocity of a vortex is well known to depend upon:

Superfluid phase gradients:

$$\mathbf{v}_\Phi = \nabla\Phi; \qquad \psi = \sqrt{\mathbf{n}(\mathbf{r})}e^{i\Phi}$$

Superfluid density gradients:

$$\mathbf{v}_\rho = -\kappa\frac{\hat{\mathbf{z}} \times \nabla\rho}{\rho}; \qquad \kappa = h/m$$

Why bother? Easier to interpret!

Gain qualitative info without much effort

So, how does the vortex move?

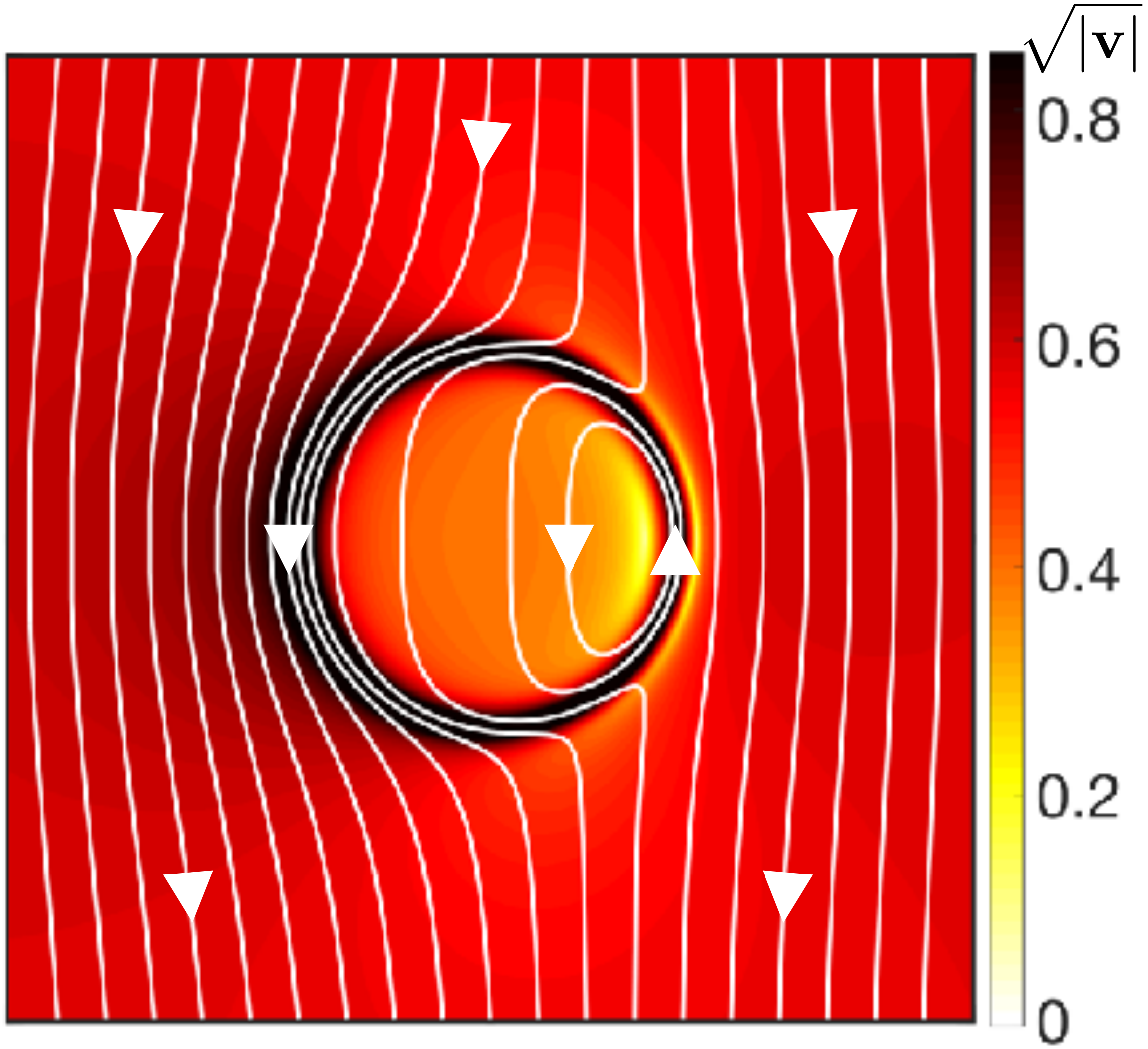
Each white curve is a separate vortex trajectory (arrows denote direction)

Colour represents magnitude of vortex velocity

Two interesting features:

The trajectories are asymmetric

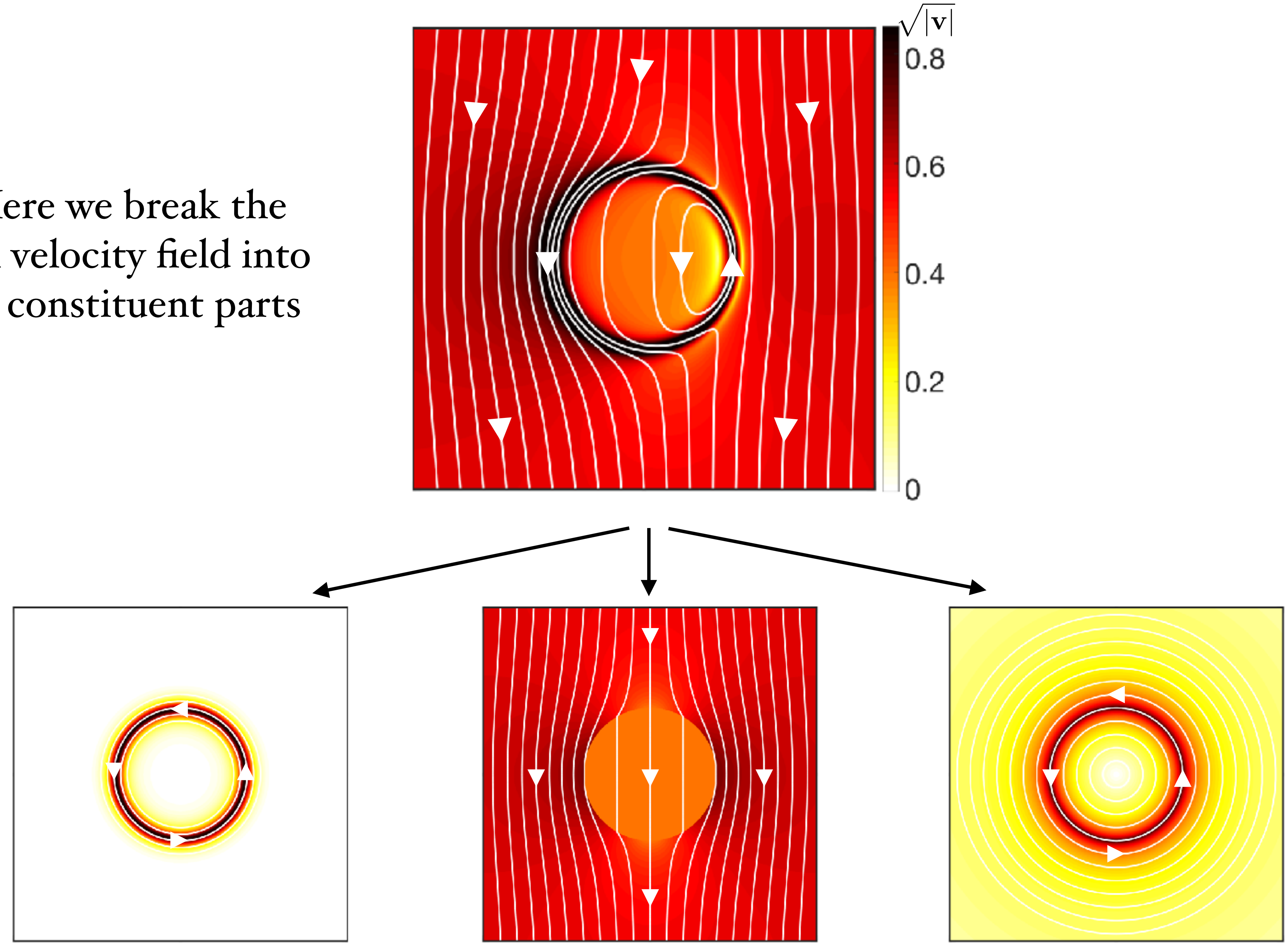
No pinned trajectories begin outside the pinning site



Trajectories change for different superfluid velocities

So, how does the vortex move?

Here we break the full velocity field into its constituent parts



Density Gradient

Background flow

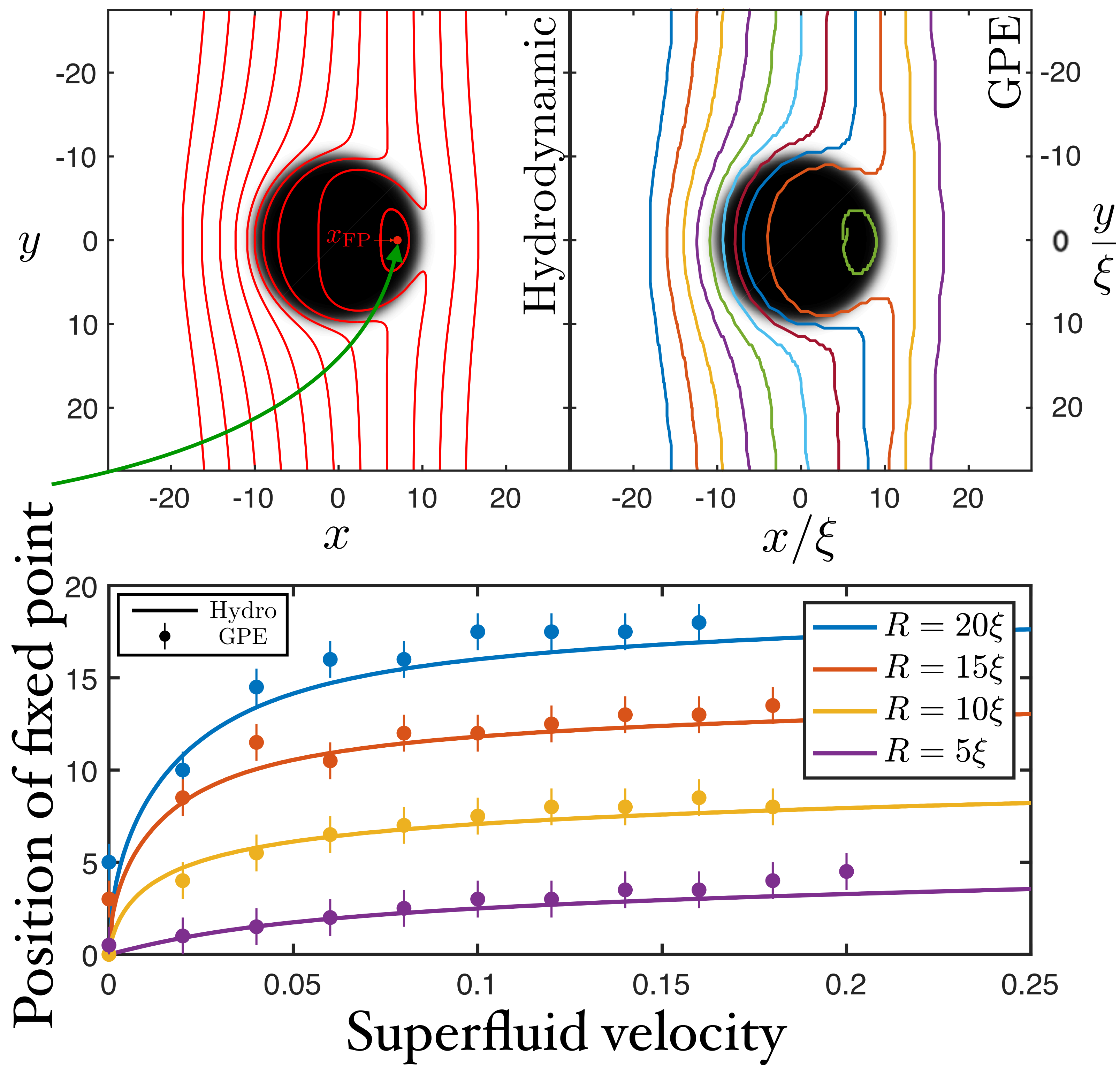
Induced image

Comparison to the full Gross-Pitaevskii equation

Incredibly good approximation to the full model

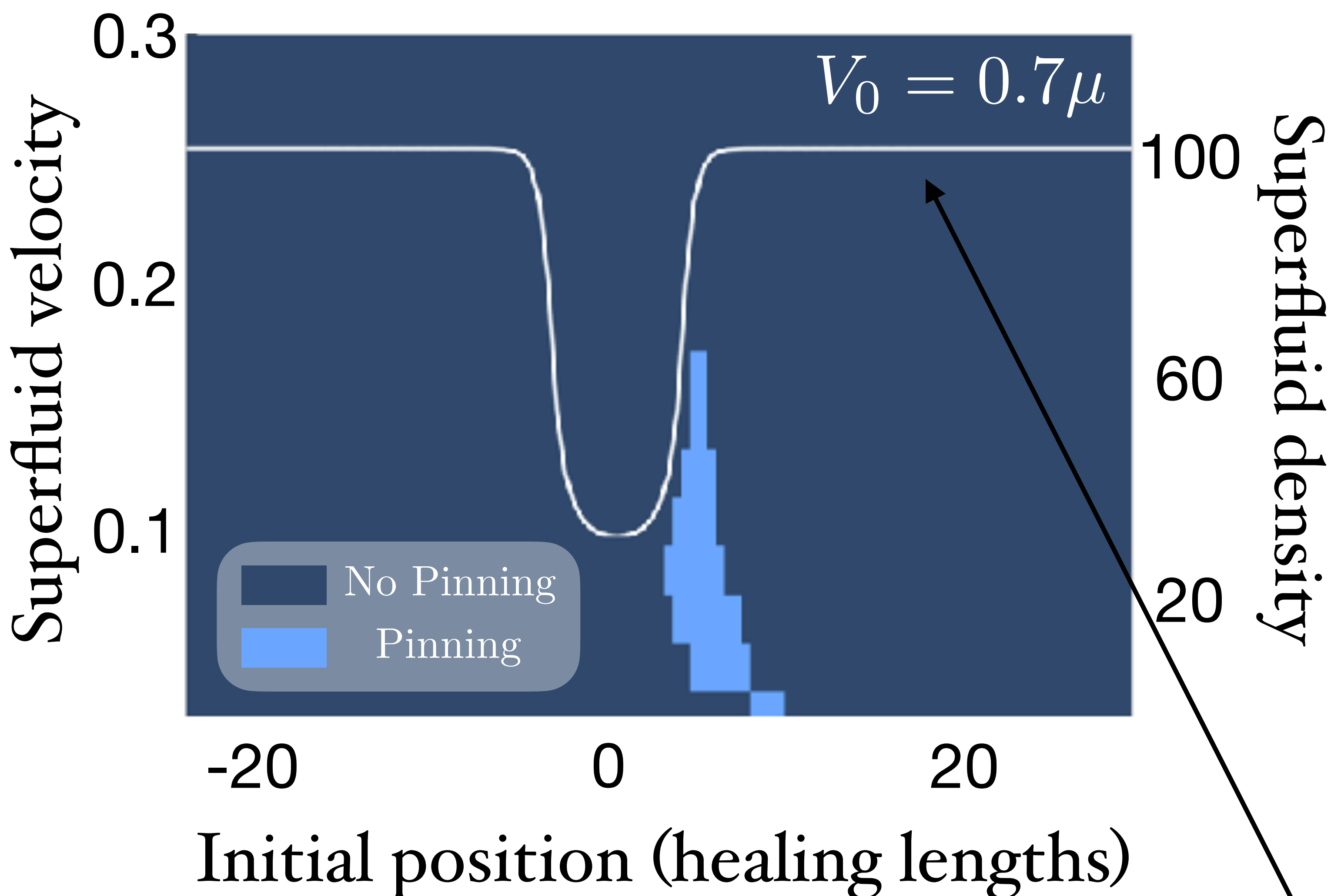
Straight-forward analytical solutions

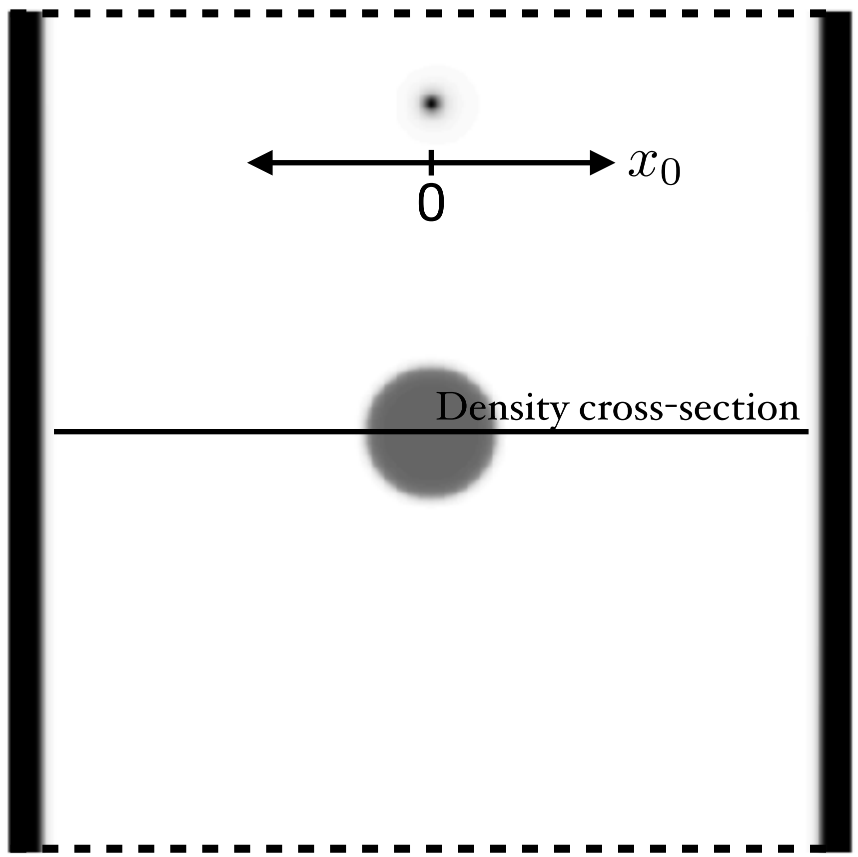
Hydrodynamic model doesn't describe vortex pinning



Full Gross-Pitaevskii Analysis

Phase Diagrams

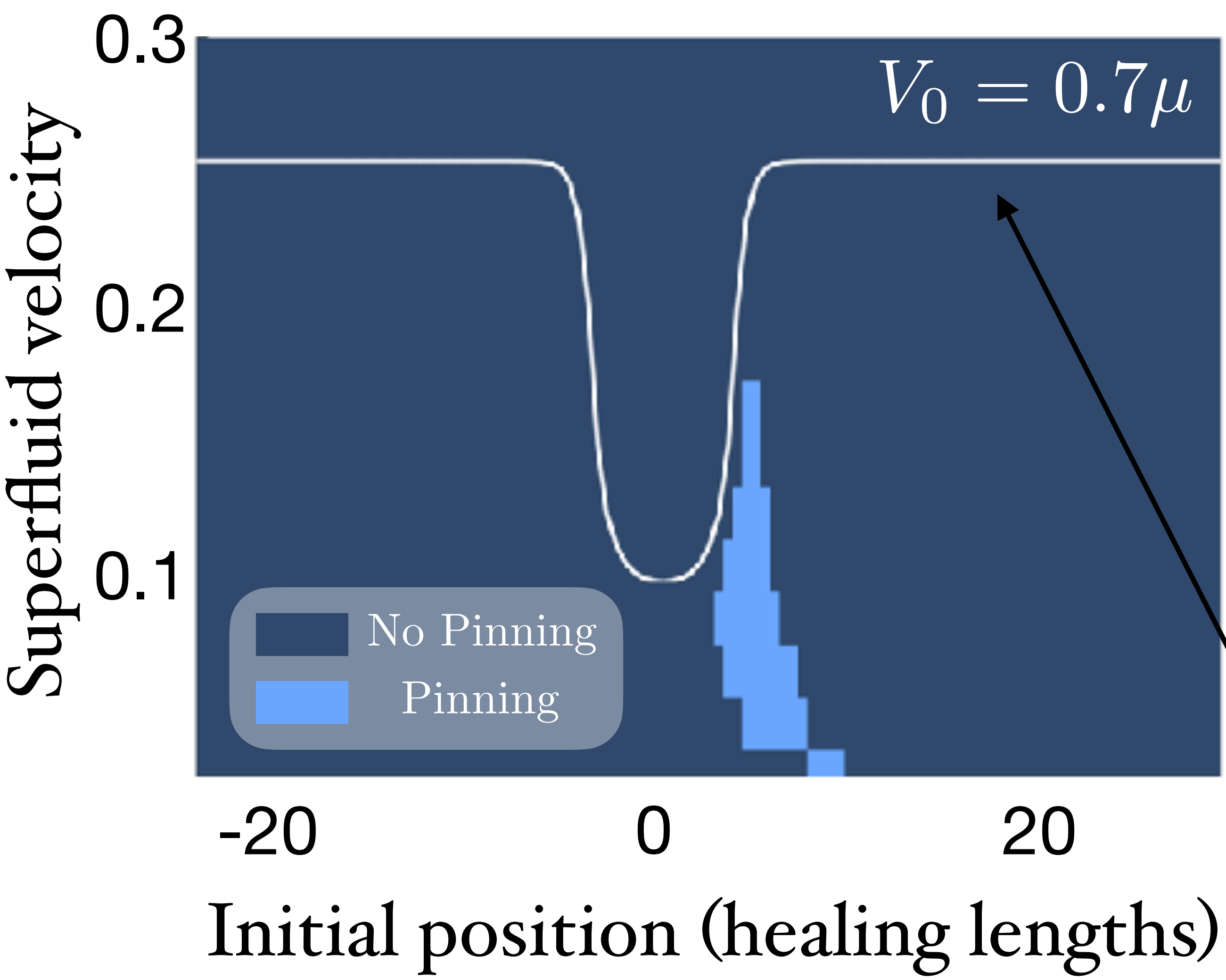




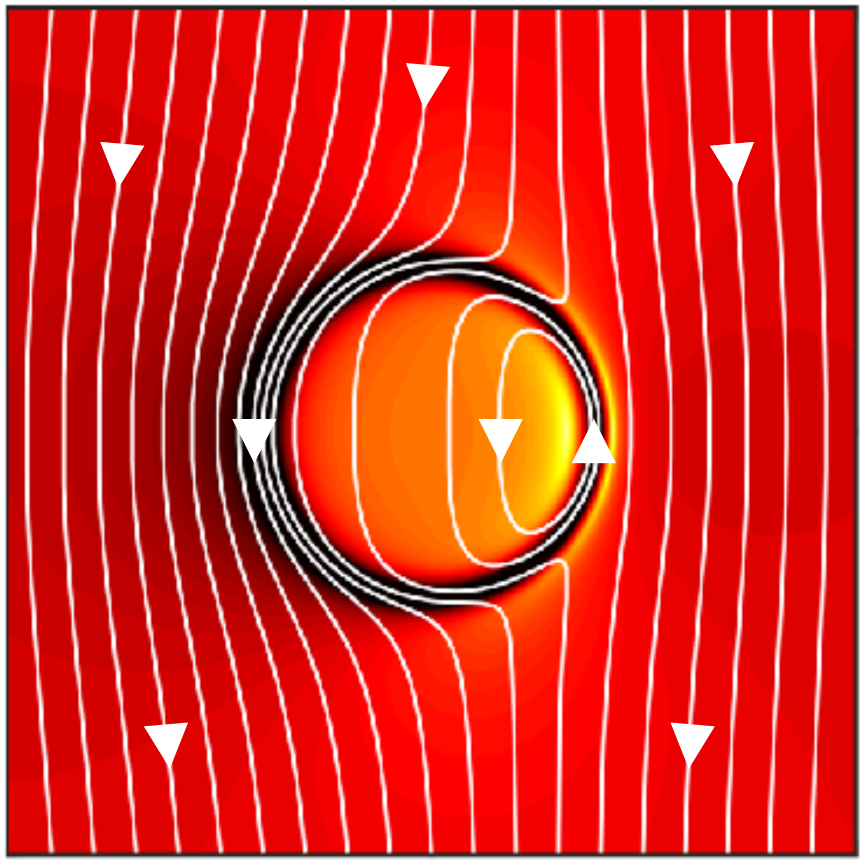
Phase diagram (i.e. pinning/no pinning) corresponds to left axis

White curve: cross section of the superfluid density over the pinning site

Phase Diagrams



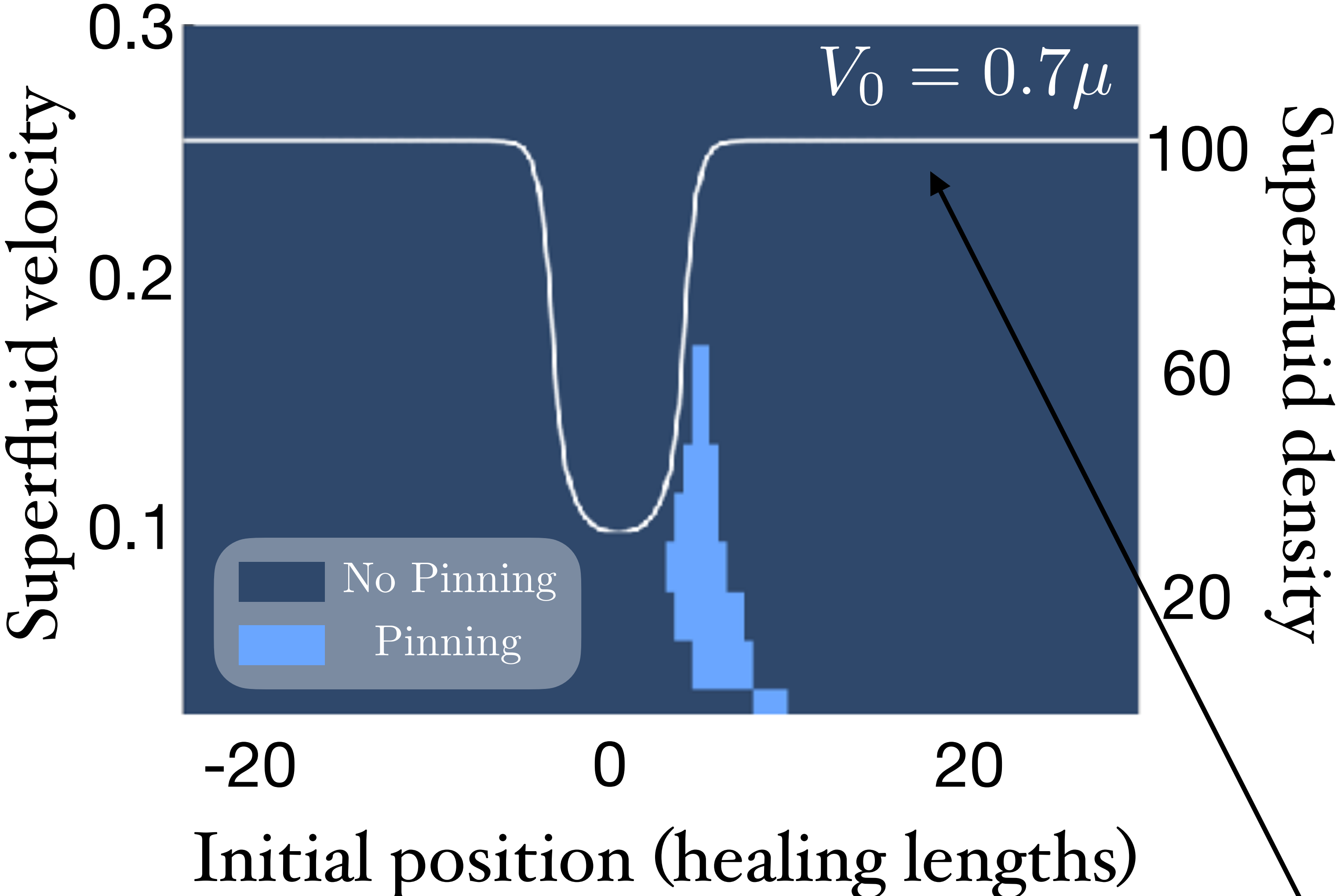
Pinning is dominated by $x_0 > 0$ (would swap for negative circulation)



Phase diagram (i.e. pinning/no pinning) corresponds to left axis

White curve: cross section of the superfluid density over the pinning site

Phase Diagrams



Pinning is dominated by $x_0 > 0$ (would swap for negative circulation)

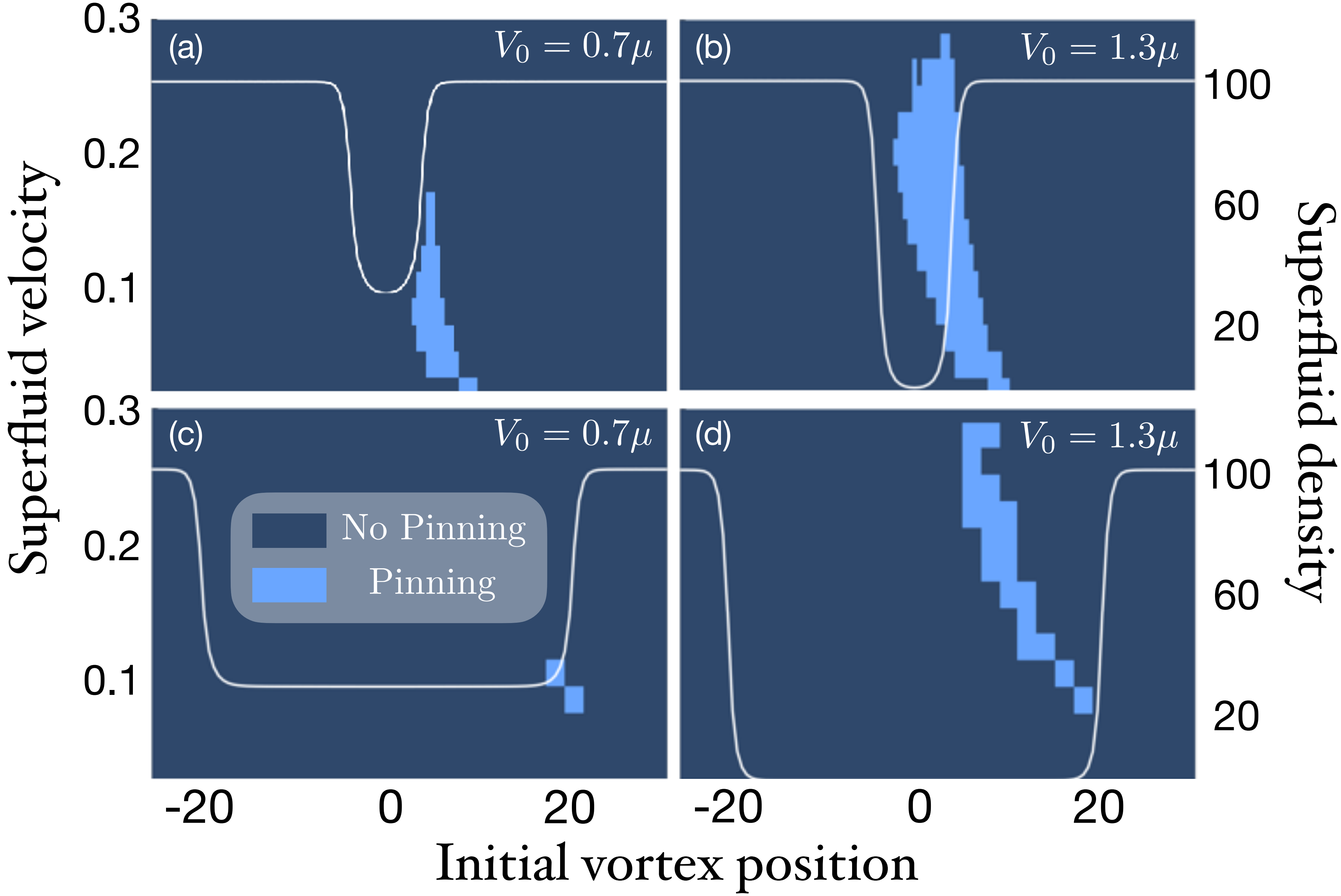
Pinning occurs where acceleration of vortex is largest, leading to emission of sound energy

A window of velocities allow pinning

Phase diagram (i.e. pinning/no pinning) corresponds to left axis

White curve: cross section of the superfluid density over the pinning site

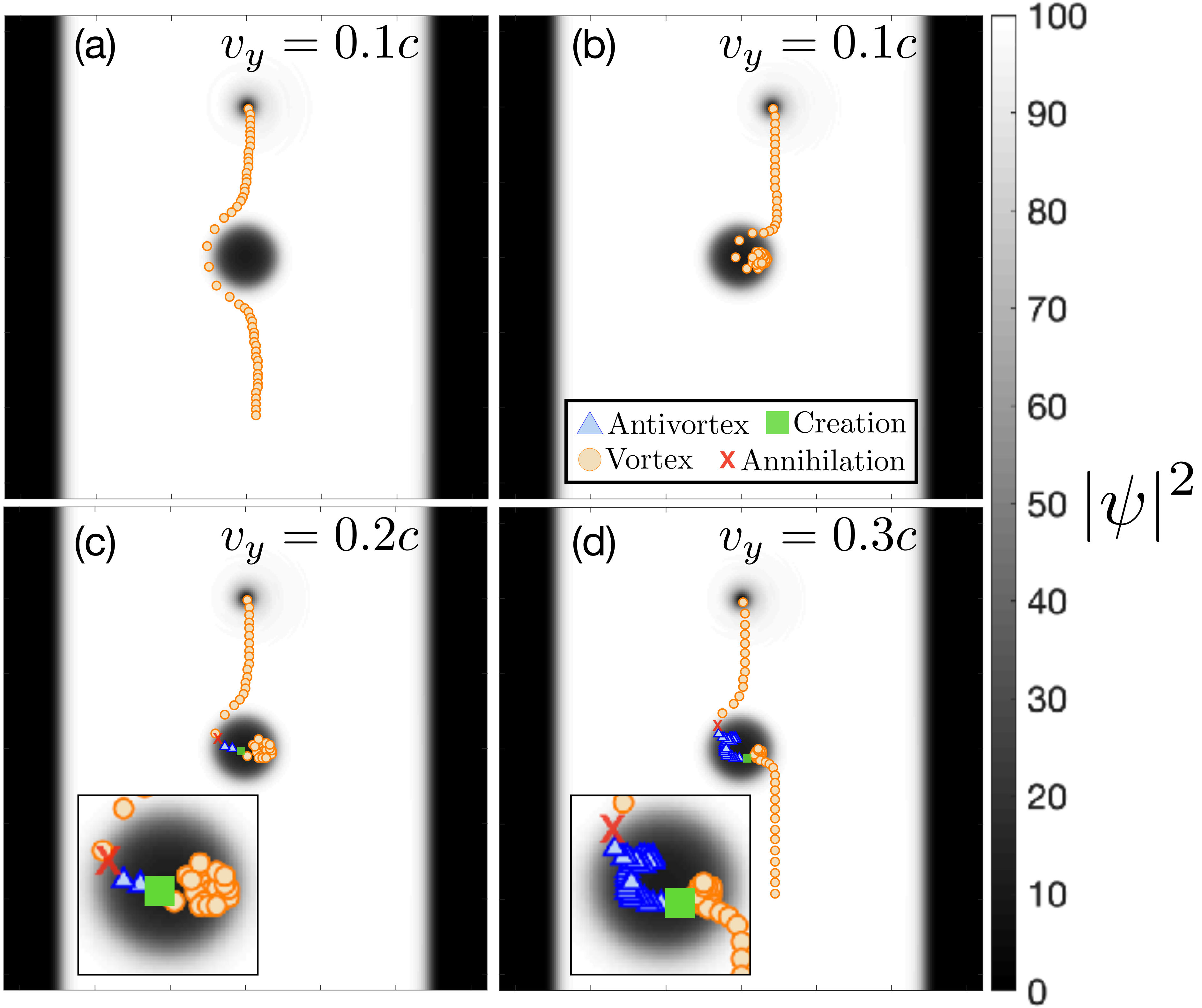
Phase Diagrams



Pinning doesn't scale with *R*

Stronger potential = more pinning (for $V_0 < 1.3\mu$)

Regimes of vortex pinning

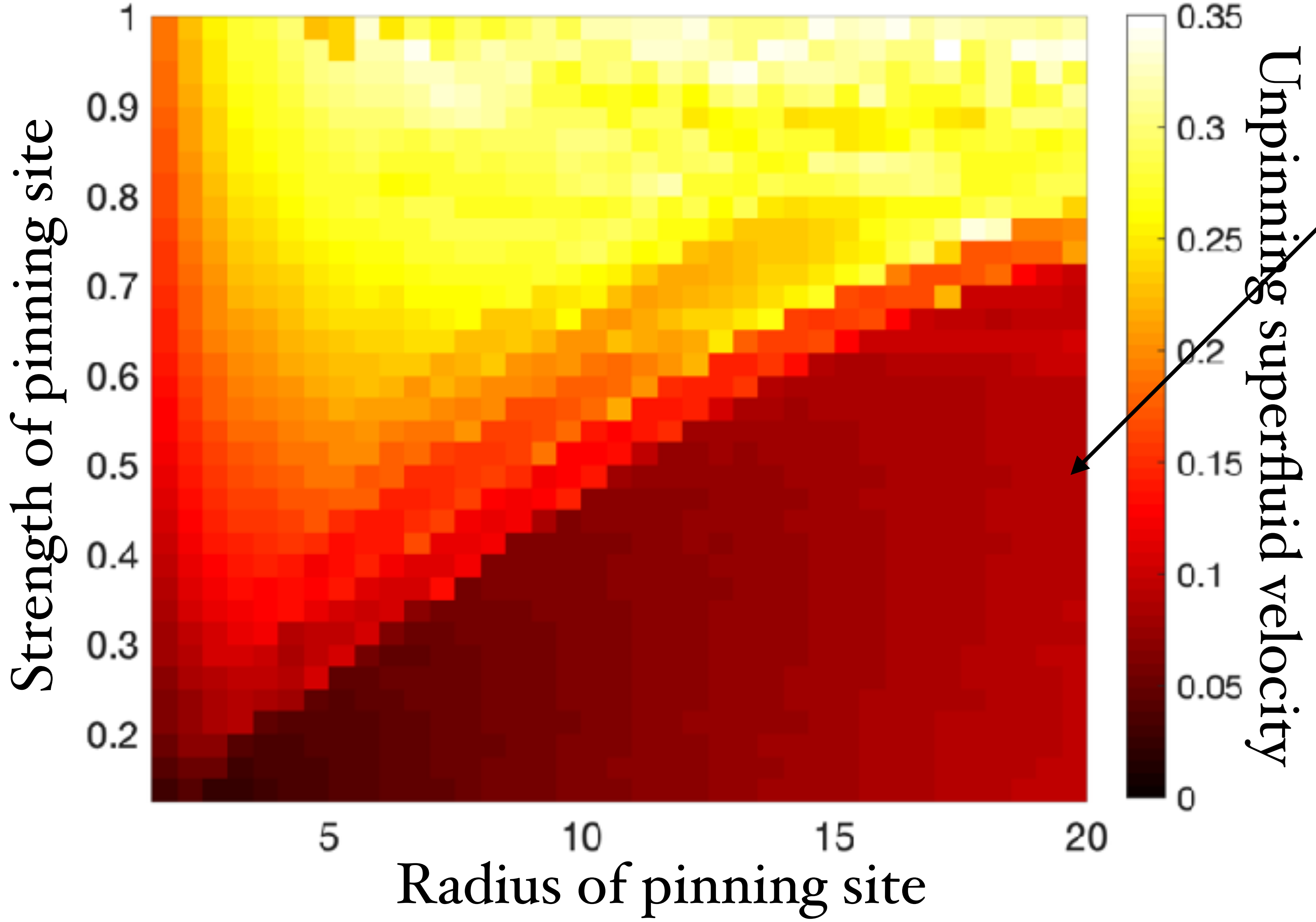


Vortex *Unpinning*

1. Vortex starts pinned

2. Slowly increase superfluid velocity

3. Wait until vortex falls off pinning site



For large R, no change in v_y up to certain point

Smaller pins once again more efficient

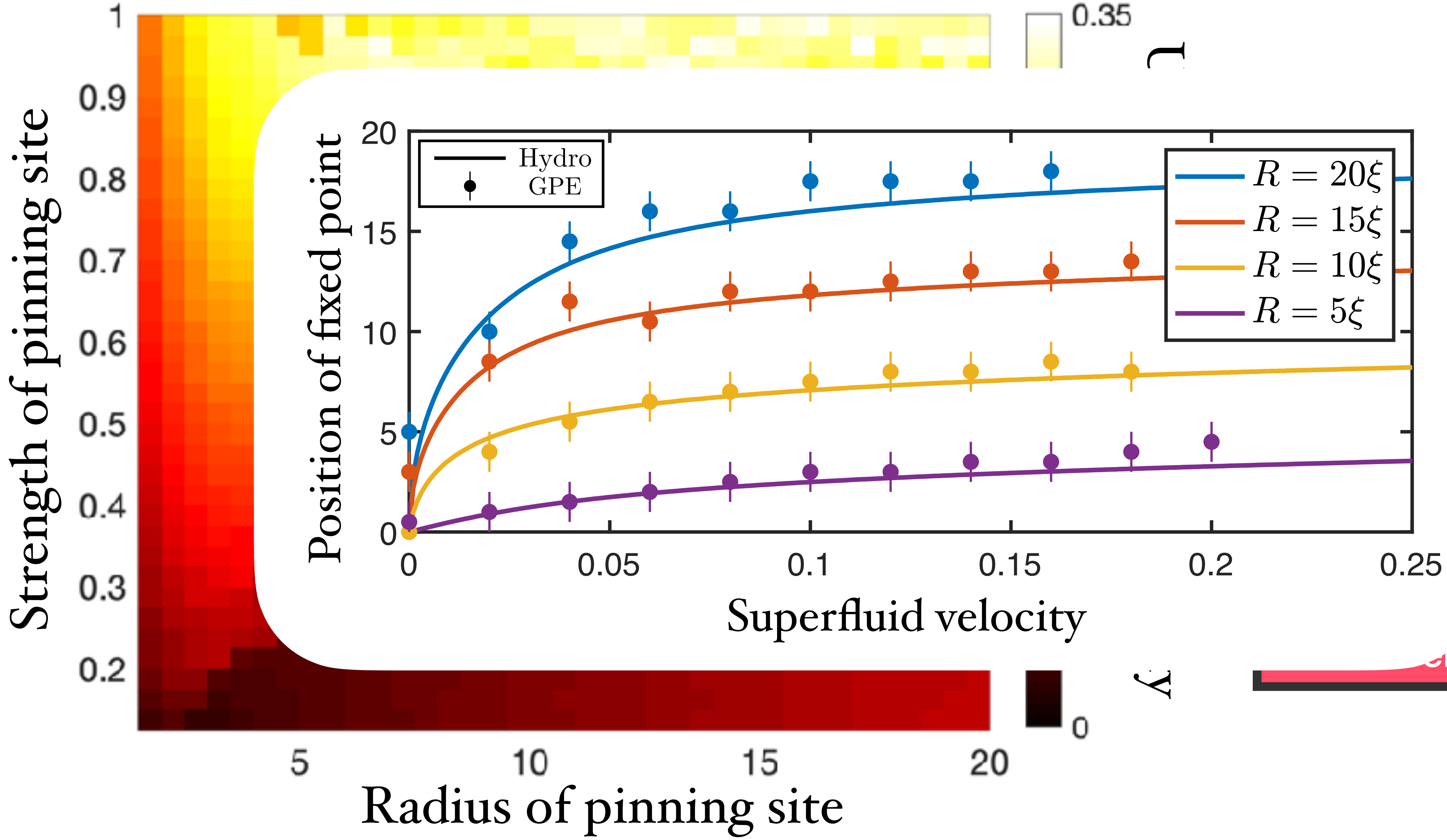
Why does the unpinning dynamics exhibit such behaviour?

Vortex *Unpinning*

1. Vortex starts pinned

2. Slowly increase superfluid velocity

3. Wait until vortex falls off pinning site

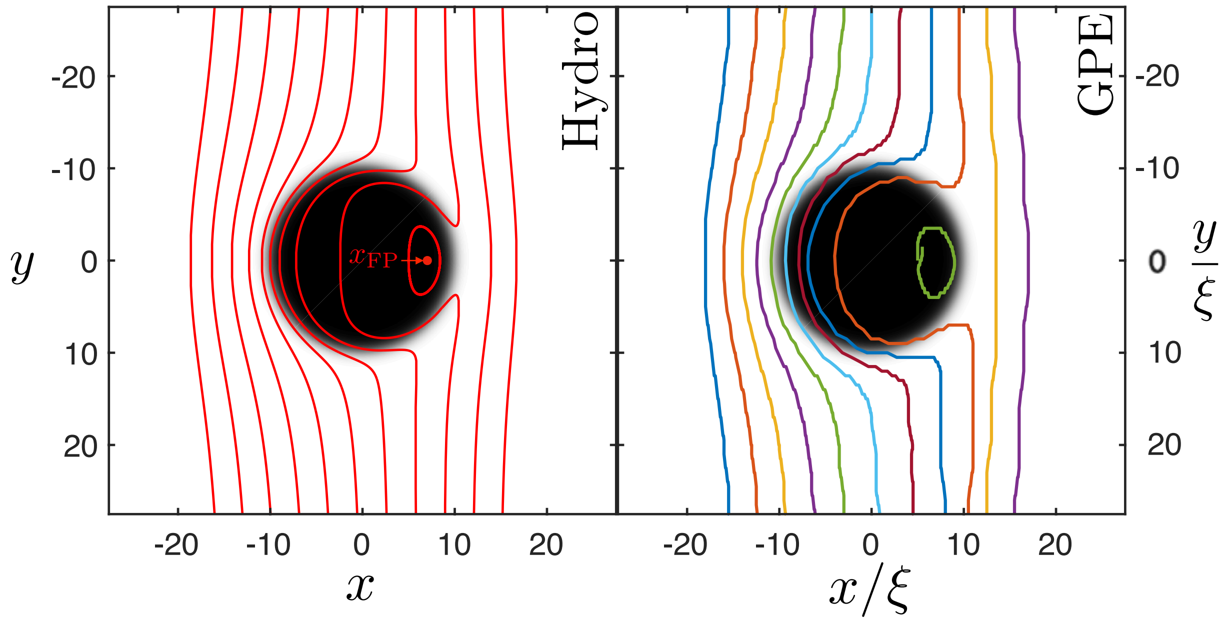


no change in
ertain point

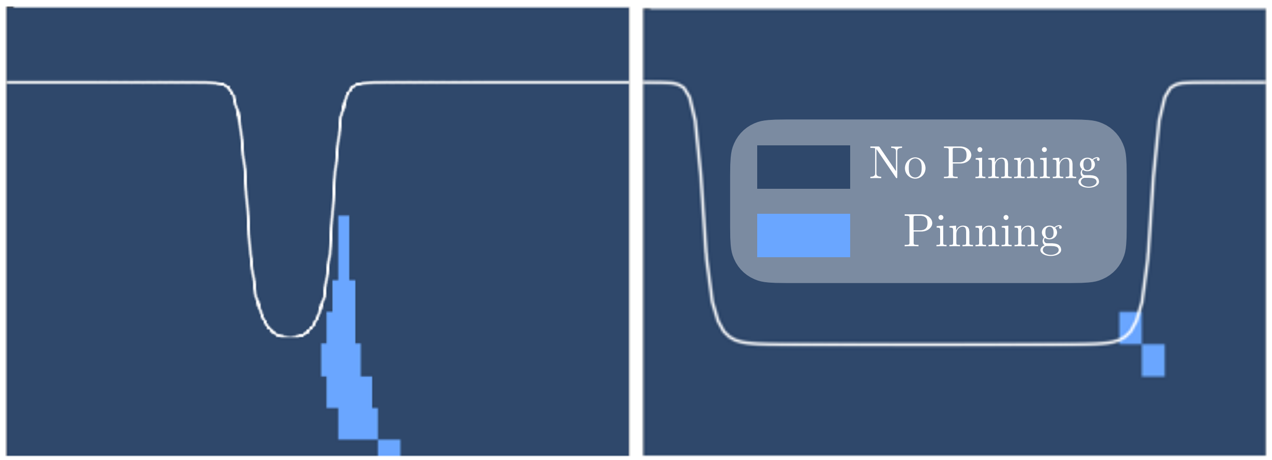
s once again
efficient

he unpinning
exhibit such
ehaviour?

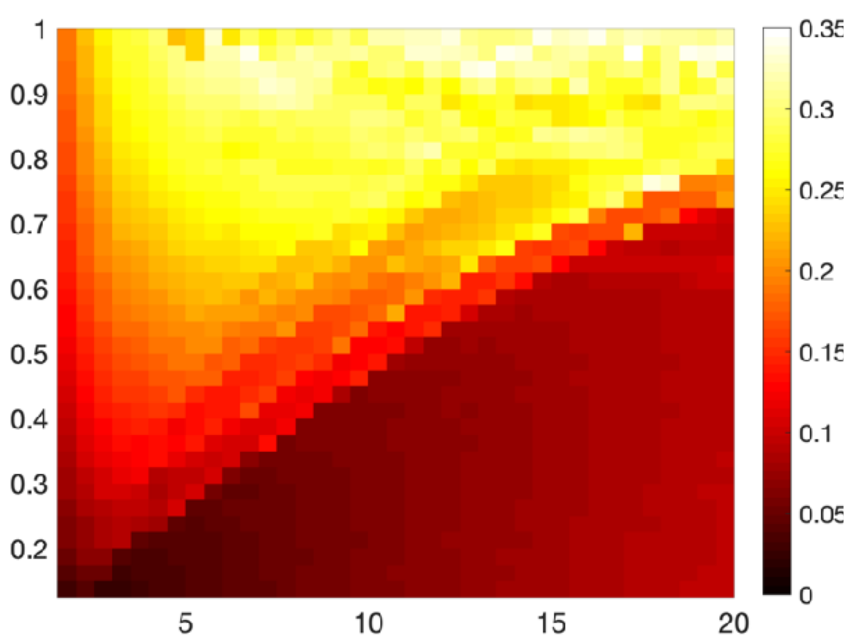
Conclusions



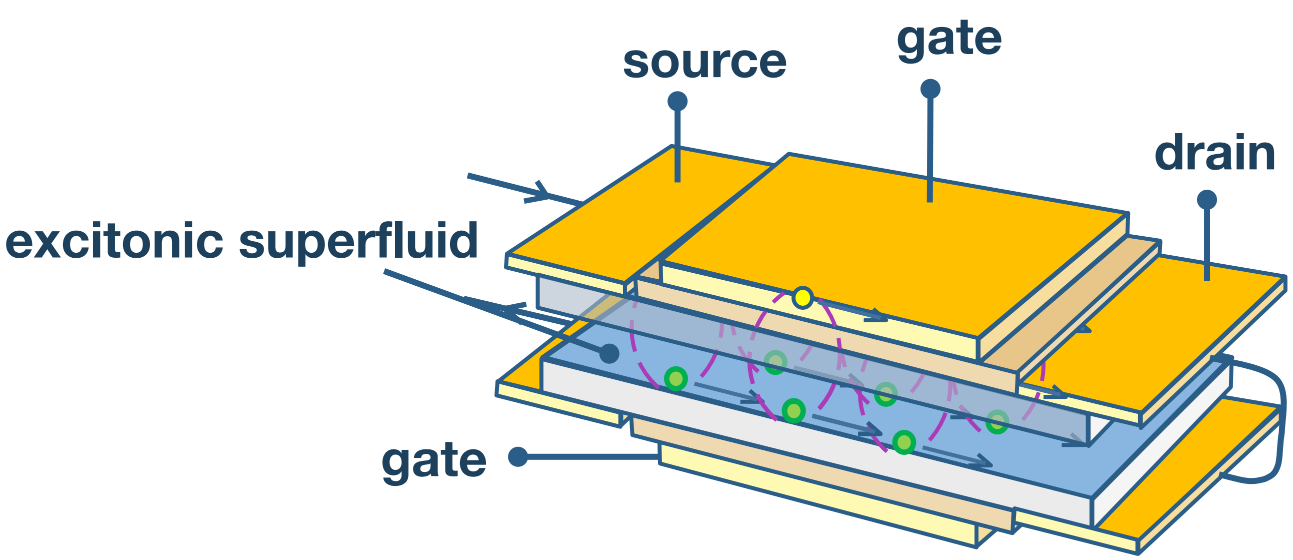
Simple approximations work well



Pinning seems to be best for smaller pins



Unpinning too!



We hope to translate our work to model driven-dissipative superfluid systems

Thank you!