LARGE SCALE FLOWS IN 2D SUPERFLUID TURBULENCE

Andrew Groszek

Atomtronics, Benasque
May 14, 2019

MONASH University

THE UNIVERSITY OF QUEENSLAND
AUSTRALIA

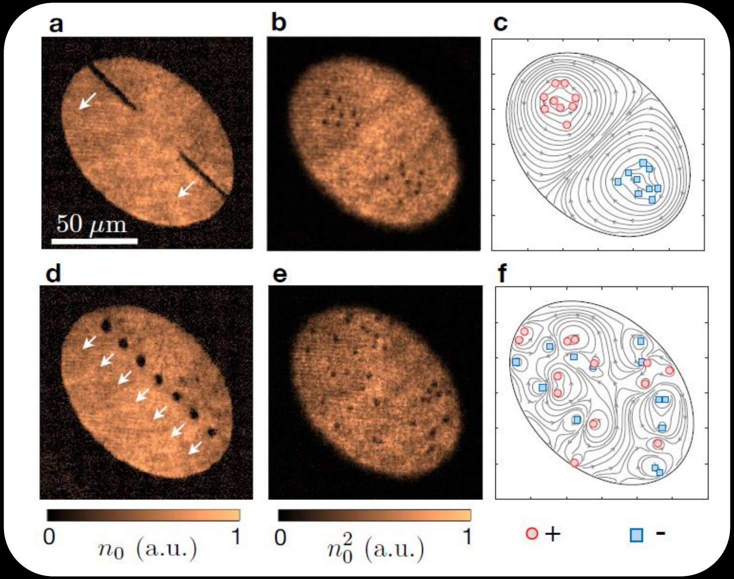
Newcastle University

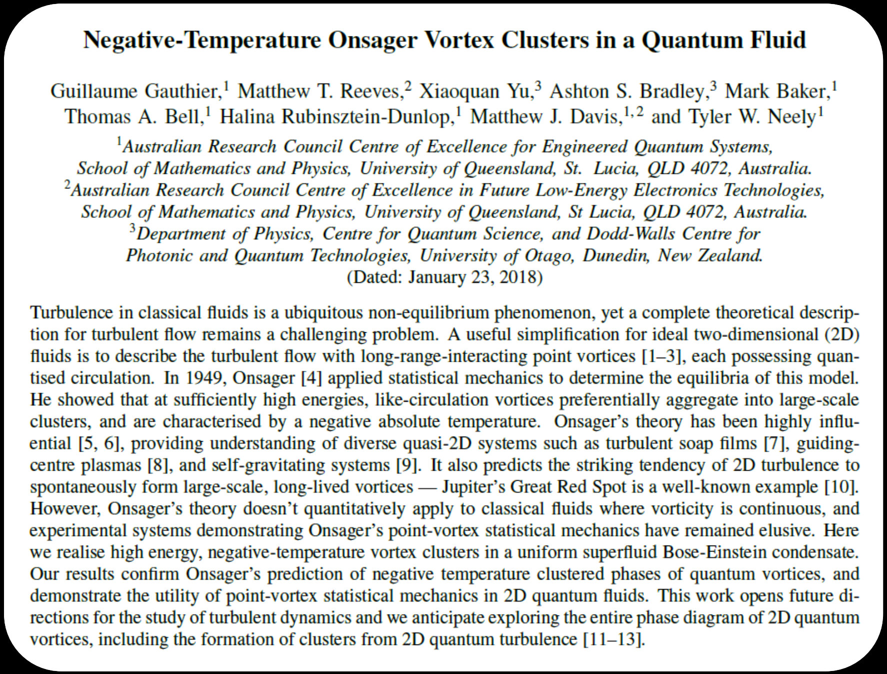
FLEET
ARC CENTRE OF EXCELLENCE IN
FUTURE LOW-ENERGY
ELECTRONICS TECHNOLOGIES

Joint Quantum Centre

UQ EXPERIMENT

- From Ashton Bradley's talk last week:





Negative-Temperature Onsager Vortex Clusters in a Quantum Fluid

Guillaume Gauthier,[1] Matthew T. Reeves,[2] Xiaoquan Yu,[3] Ashton S. Bradley,[3] Mark Baker,[1]
Thomas A. Bell,[1] Halina Rubinsztein-Dunlop,[1] Matthew J. Davis,[1,2] and Tyler W. Neely[1]

[1]*Australian Research Council Centre of Excellence for Engineered Quantum Systems,*
School of Mathematics and Physics, University of Queensland, St. Lucia, QLD 4072, Australia.
[2]*Australian Research Council Centre of Excellence in Future Low-Energy Electronics Technologies,*
School of Mathematics and Physics, University of Queensland, St Lucia, QLD 4072, Australia.
[3]*Department of Physics, Centre for Quantum Science, and Dodd-Walls Centre for*
Photonic and Quantum Technologies, University of Otago, Dunedin, New Zealand.
(Dated: January 23, 2018)

Turbulence in classical fluids is a ubiquitous non-equilibrium phenomenon, yet a complete theoretical description for turbulent flow remains a challenging problem. A useful simplification for ideal two-dimensional (2D) fluids is to describe the turbulent flow with long-range-interacting point vortices [1–3], each possessing quantised circulation. In 1949, Onsager [4] applied statistical mechanics to determine the equilibria of this model. He showed that at sufficiently high energies, like-circulation vortices preferentially aggregate into large-scale clusters, and are characterised by a negative absolute temperature. Onsager's theory has been highly influential [5, 6], providing understanding of diverse quasi-2D systems such as turbulent soap films [7], guiding-centre plasmas [8], and self-gravitating systems [9]. It also predicts the striking tendency of 2D turbulence to spontaneously form large-scale, long-lived vortices — Jupiter's Great Red Spot is a well-known example [10]. However, Onsager's theory doesn't quantitatively apply to classical fluids where vorticity is continuous, and experimental systems demonstrating Onsager's point-vortex statistical mechanics have remained elusive. Here we realise high energy, negative-temperature vortex clusters in a uniform superfluid Bose-Einstein condensate. Our results confirm Onsager's prediction of negative temperature clustered phases of quantum vortices, and demonstrate the utility of point-vortex statistical mechanics in 2D quantum fluids. This work opens future directions for the study of turbulent dynamics and we anticipate exploring the entire phase diagram of 2D quantum vortices, including the formation of clusters from 2D quantum turbulence [11–13].

arXiv:1801.06951, to appear in Science

OUTLINE

Part I – Theory

1. Background – why 2D quantum turbulence?
2. Vortex thermodynamics

Part II – Experiment

1. Background – why now?
2. Monash experiment
3. Results

Summary

OUTLINE

Part I – Theory

1. **Background – why 2D quantum turbulence?**
2. **Vortex thermodynamics**

Part II – Experiment

1. **Background – why now?**
2. **Monash experiment**
3. **Results**

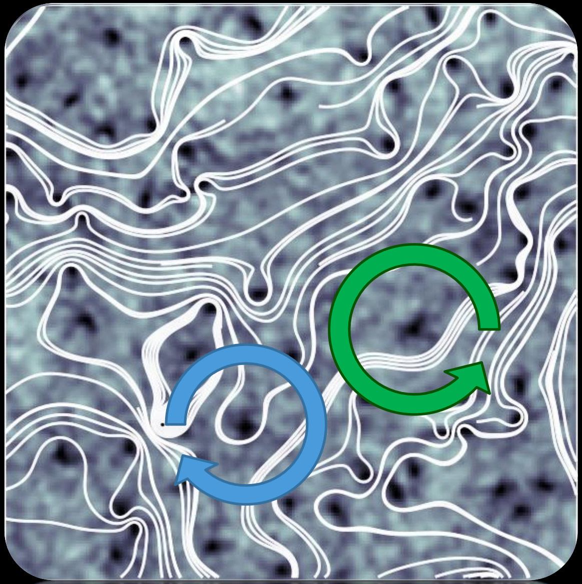
Summary

2D QUANTUM TURBULENCE

“Continuous” vortices

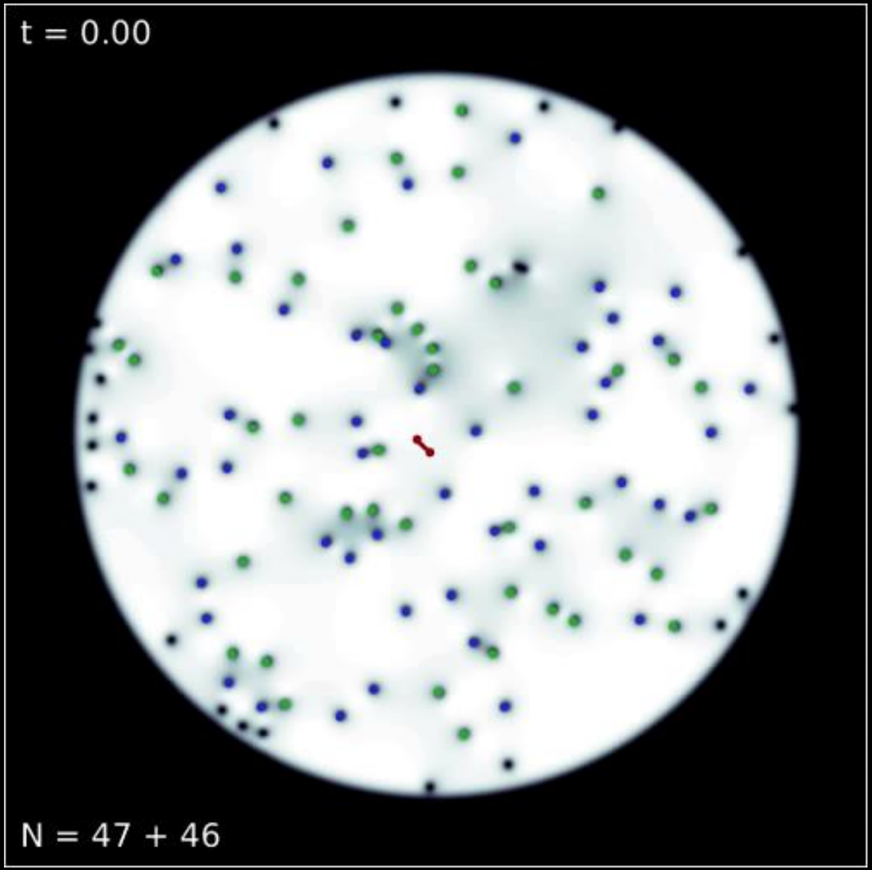
Classical turbulence

Quantum turbulence



Quantised vortices

2D QUANTUM TURBULENCE



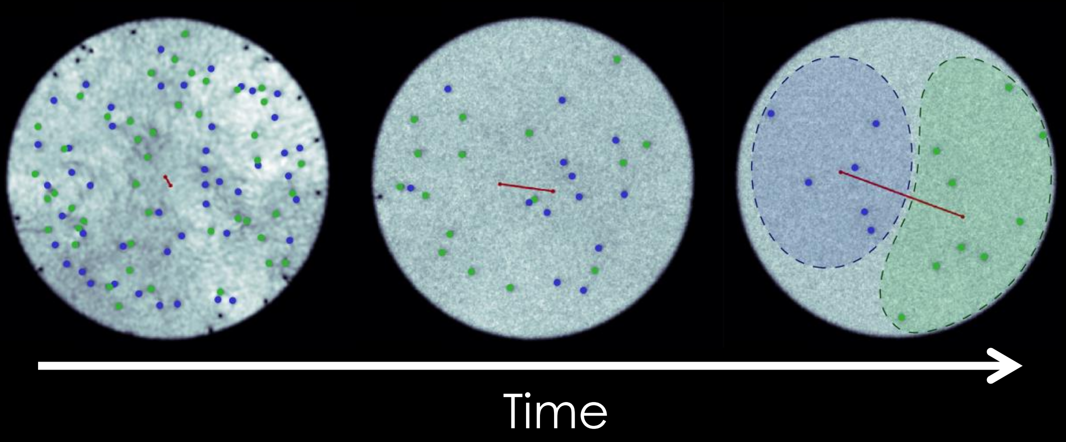
● = vortices

● = antivortices

╲ = dipole moment

For movie, see Supplement of:
Groszek et al., PRA **93**, 043614 (2016)

WHY 2D?



Groszek et al., PRA **93**, 043614 (2016)

OUTLINE

Part I – Theory

1. Background – why 2D quantum turbulence?
2. Vortex thermodynamics

Part II – Experiment

1. Background – why now?
2. Monash experiment
3. Results

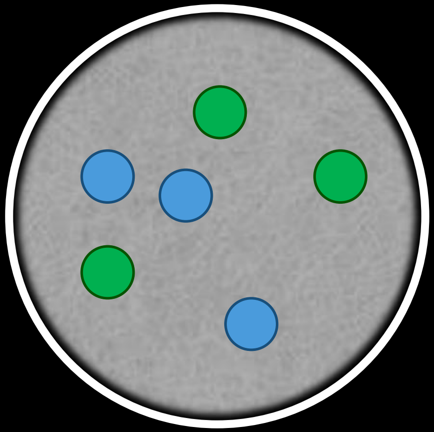
Summary

TEMPERATURE

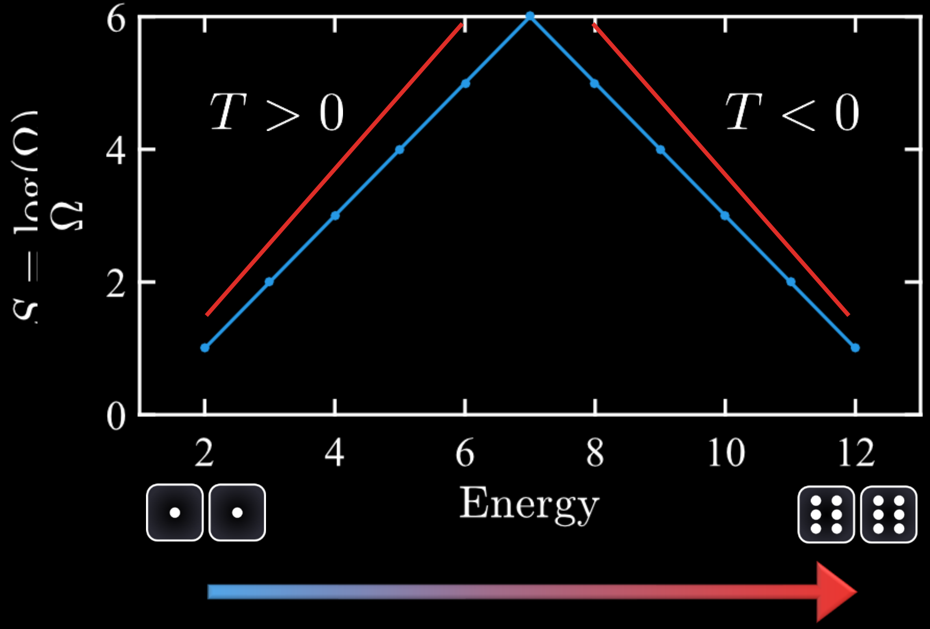
- Vortex temperature (Onsager, 1949):

$$\beta \propto \frac{1}{T} = \frac{\partial S}{\partial E}$$

- Not the temperature of the BEC!



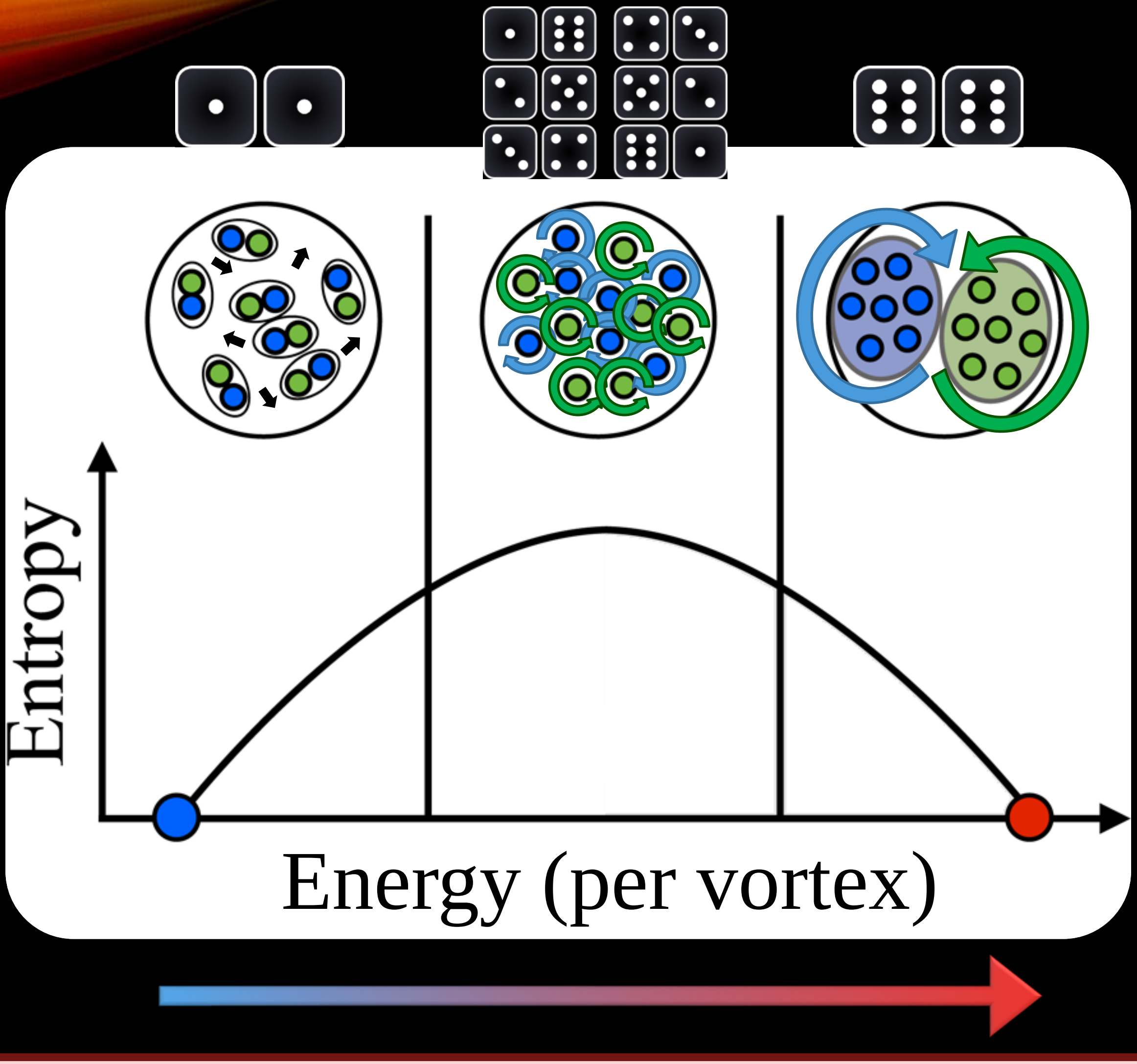
NEGATIVE TEMPERATURES



T:	0K	$+\infty$K	$-\infty$K	-0K
β:	$+\infty$	0		$-\infty$

$$\boxed{\beta \propto \frac{1}{T} = \frac{\partial S}{\partial E}}$$

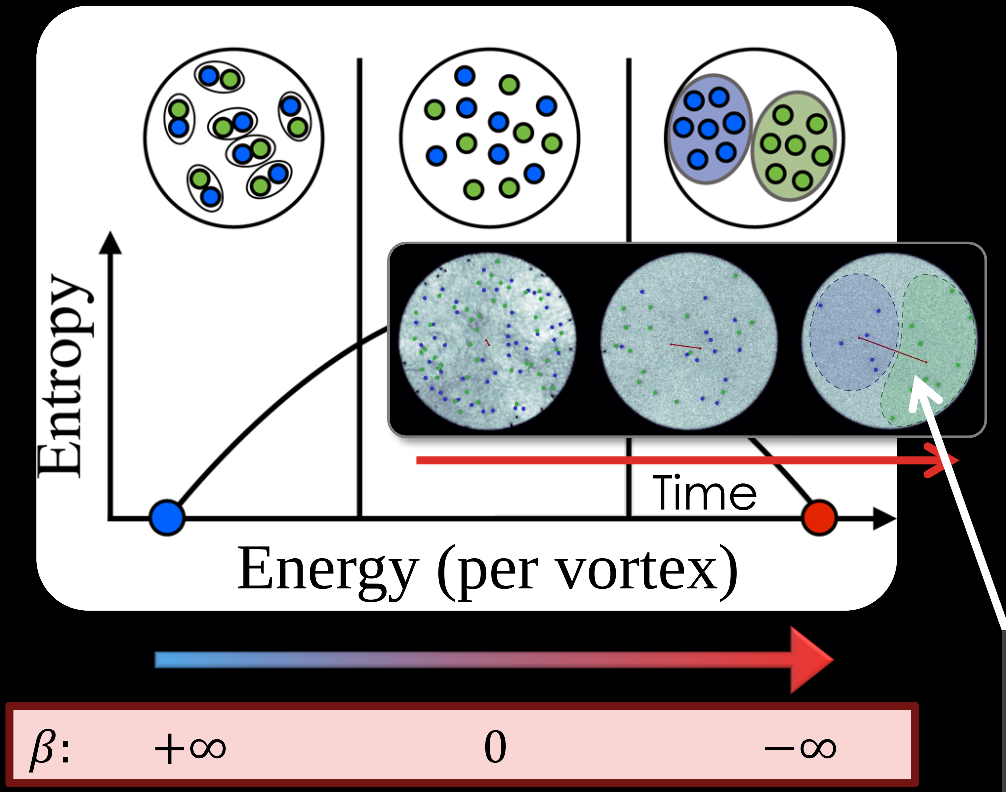
- Roll two dice
  - Sum = energy



β:	$+\infty$	0	$-\infty$

Simula et al., PRL **113**, 165302 (2014)

WHY IS T NEGATIVE?



Simula et al., PRL **113**, 165302 (2014)

- Hamiltonian system:

$$H(x_j, y_j) \sim \sum_{ij} \Gamma_i \Gamma_j \log(|\mathbf{r}_i - \mathbf{r}_j|)$$

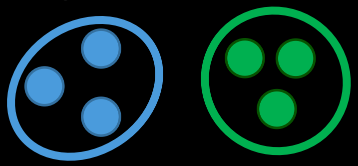
$$\frac{\mathrm{d}x_j}{\mathrm{d}t} \propto \frac{\partial H}{\partial y_j}, \qquad \frac{\mathrm{d}y_j}{\mathrm{d}t} \propto \frac{\partial H}{\partial x_j}$$

- Phase space = real space
- Bounded space → $\beta < 0$ possible

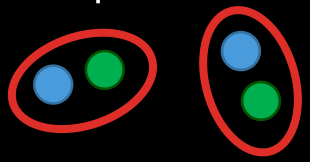
"Evaporative heating": **Coldest** vortices annihilate, remaining vortices **hotter** on average

HOW TO MEASURE T?

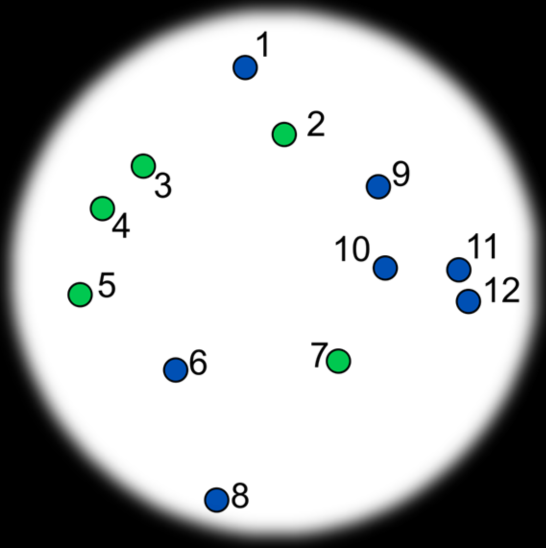
- Split vortices into three groups:
  i. Clusters:



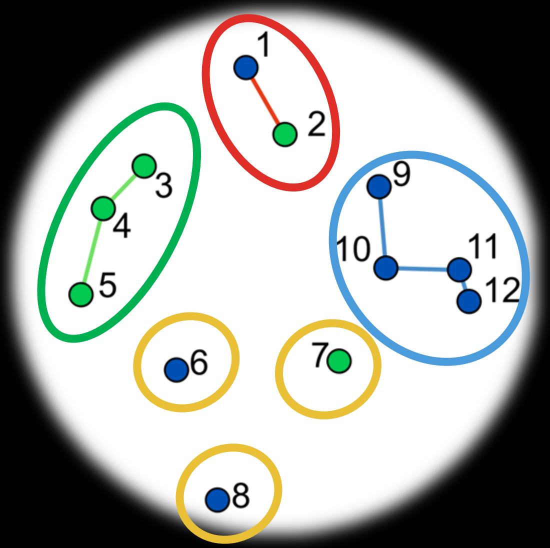
  ii. Dipoles:



  iii. Free vortices:



Before

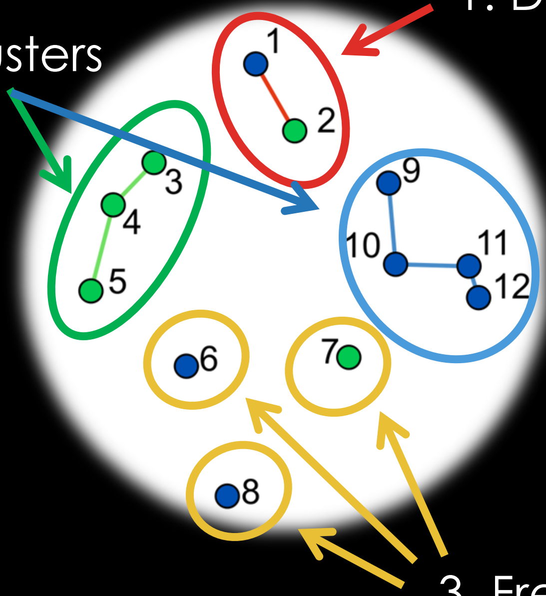


After

Valani et al., NJP **20**, 053038 (2018)

HOW TO MEASURE T?

Vortex classification

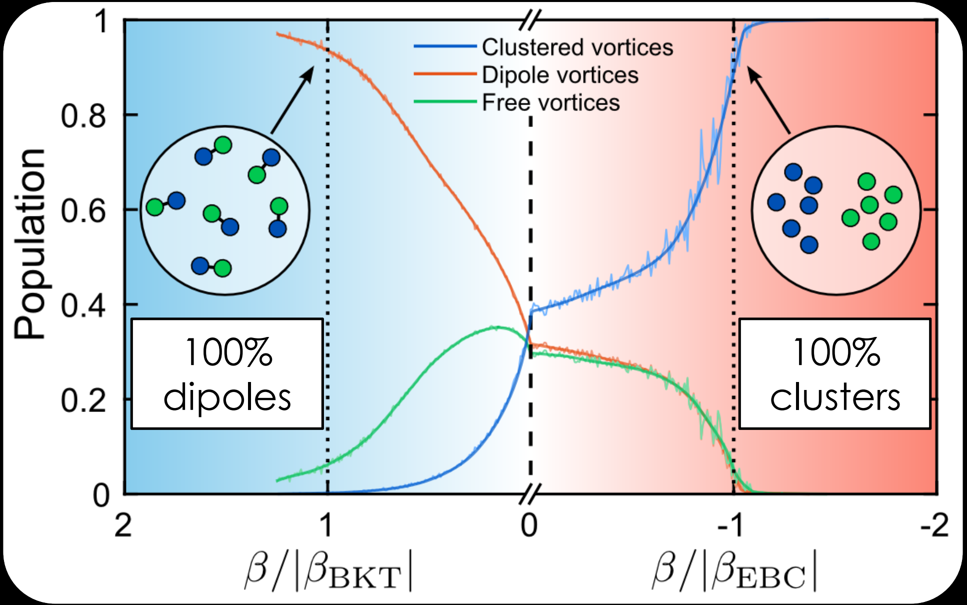


1. Dipoles

2. Clusters

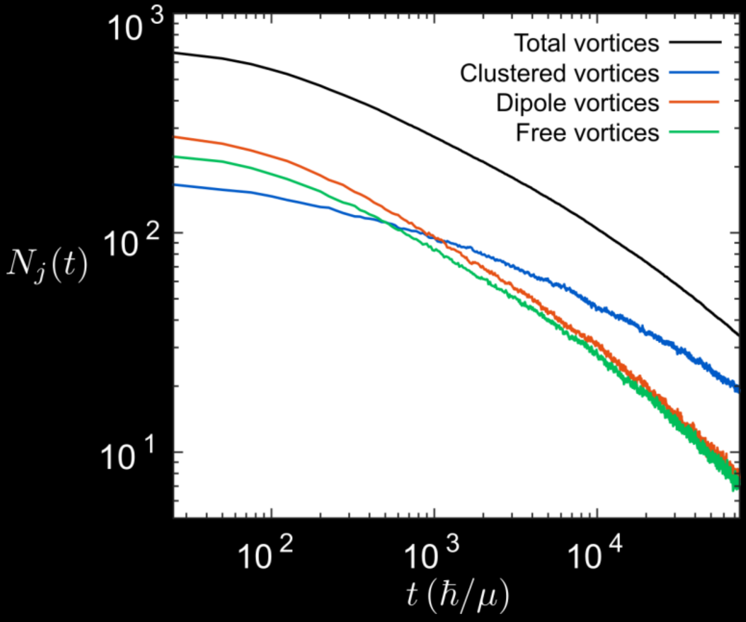
3. Free vortices

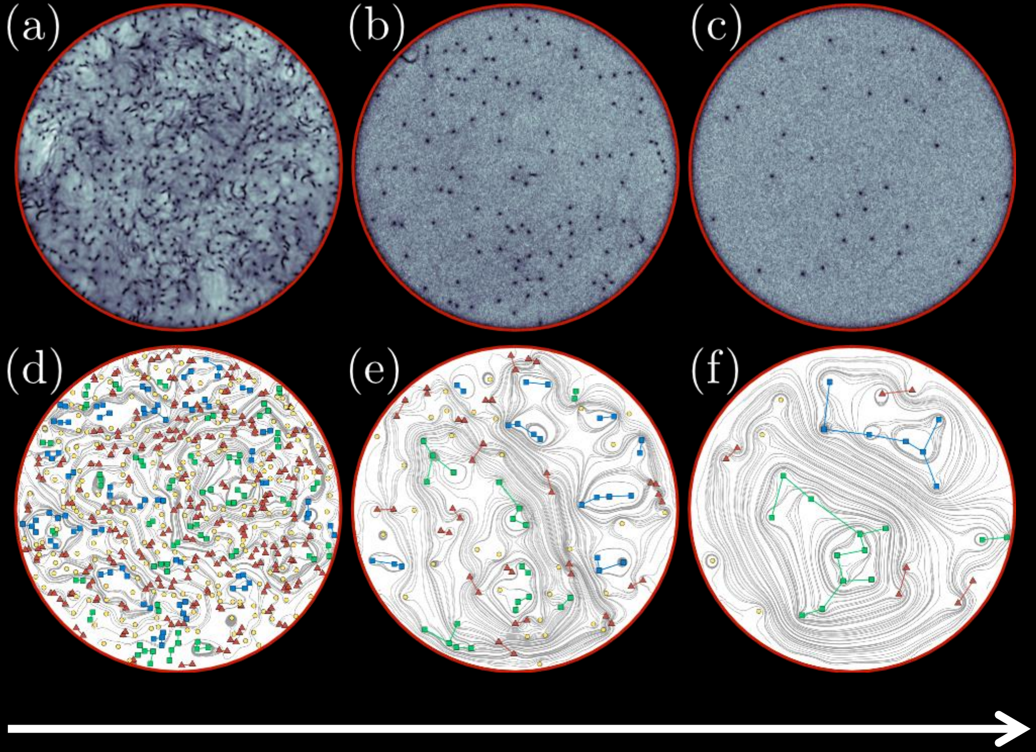
Vortex **thermometers**



Groszek et al., PRL **120**, 034504 (2018)

APPLYING THE THERMOMETER

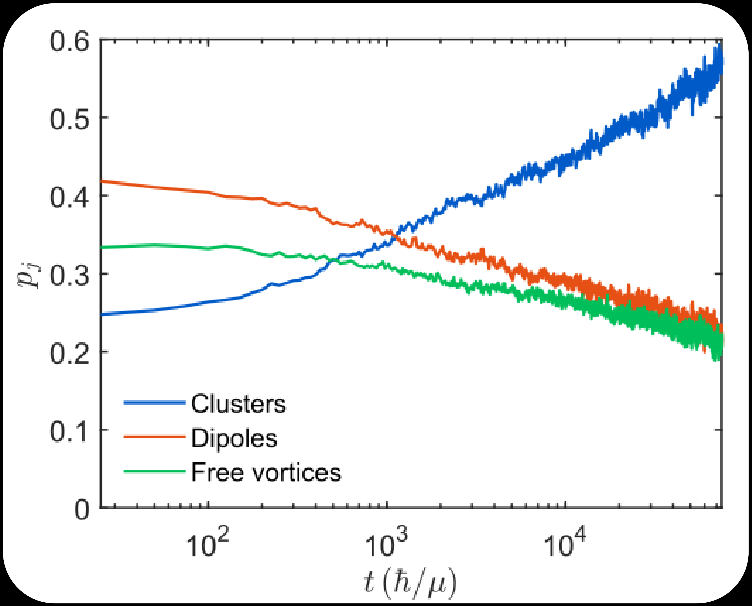


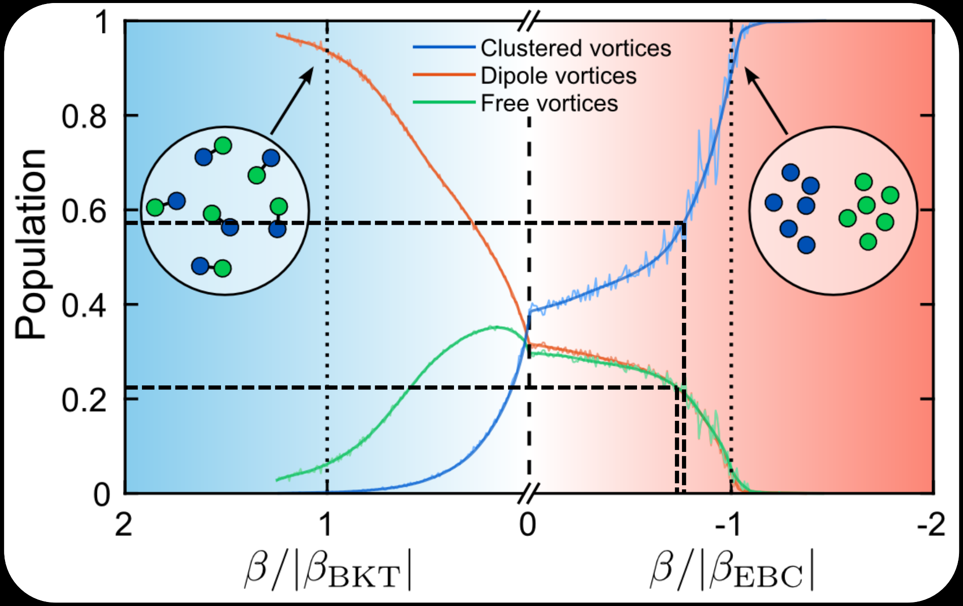


Time

Groszek et al., PRL **120**, 034504 (2018)

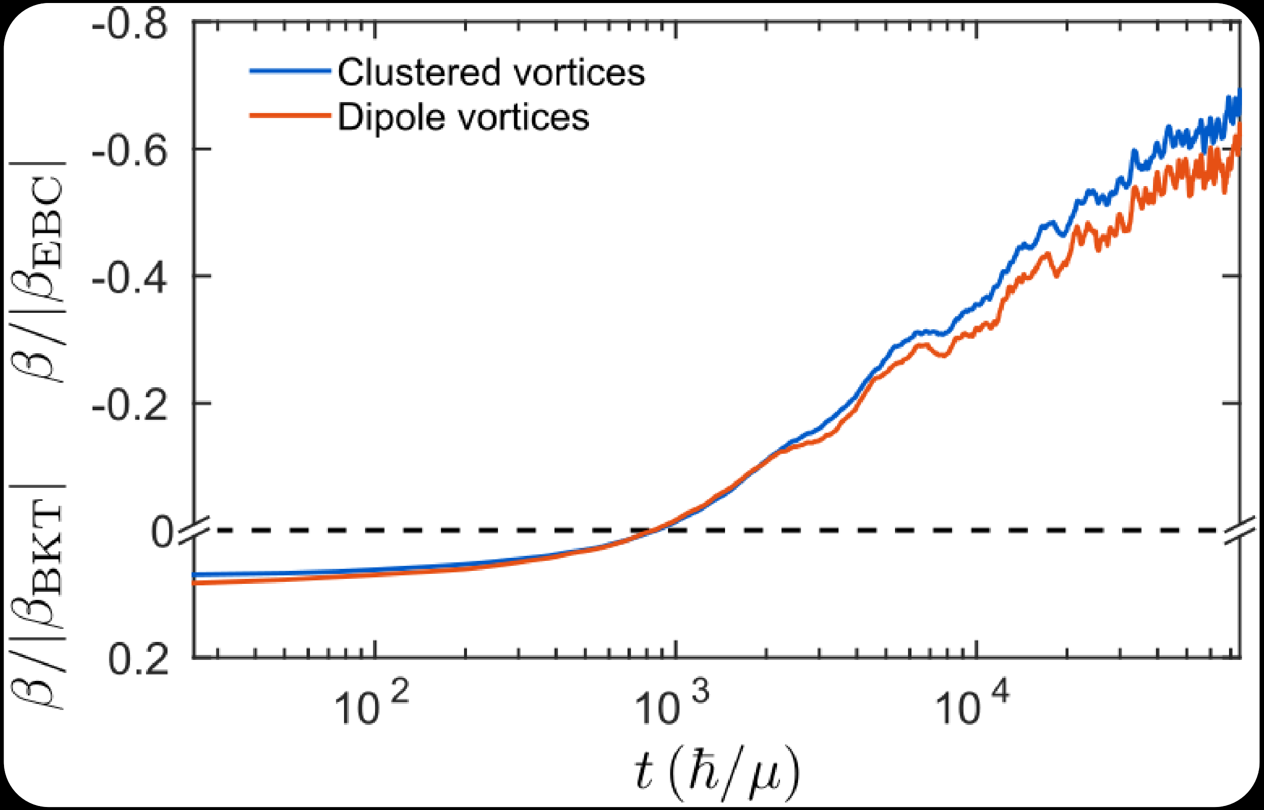
APPLYING THE THERMOMETER





Groszek et al., PRL **120**, 034504 (2018)

APPLYING THE THERMOMETER



Groszek et al., PRL **120**, 034504 (2018)

OUTLINE

Part I – Theory

1. Background – why 2D quantum turbulence?
2. Vortex thermodynamics

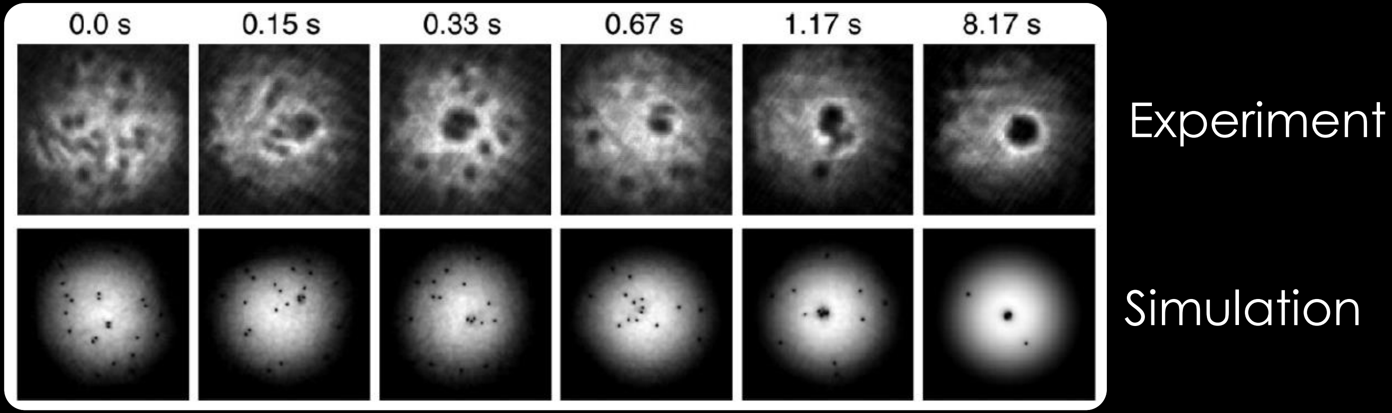
Part II – Experiment

1. Background – why now?
2. Monash experiment
3. Results

Summary

PAST EXPERIMENTS

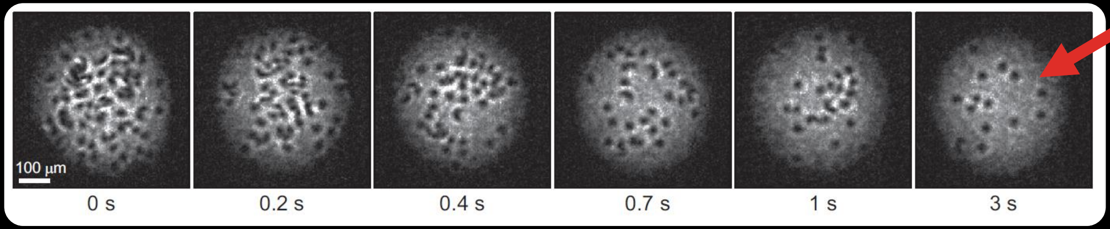
- Neely et al., PRL **111**, 235301 (2013):



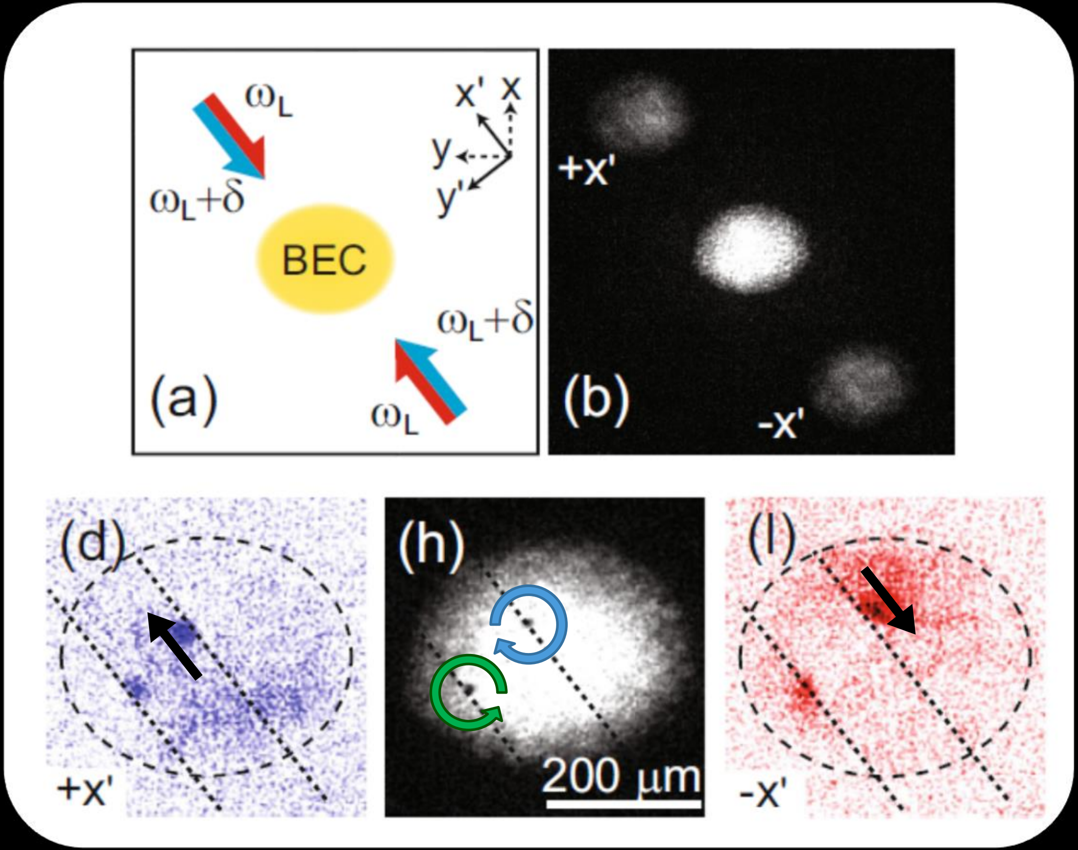
Trapping potential?

- Kwon et al., PRA **90**, 063627 (2014):

Vortex signs?

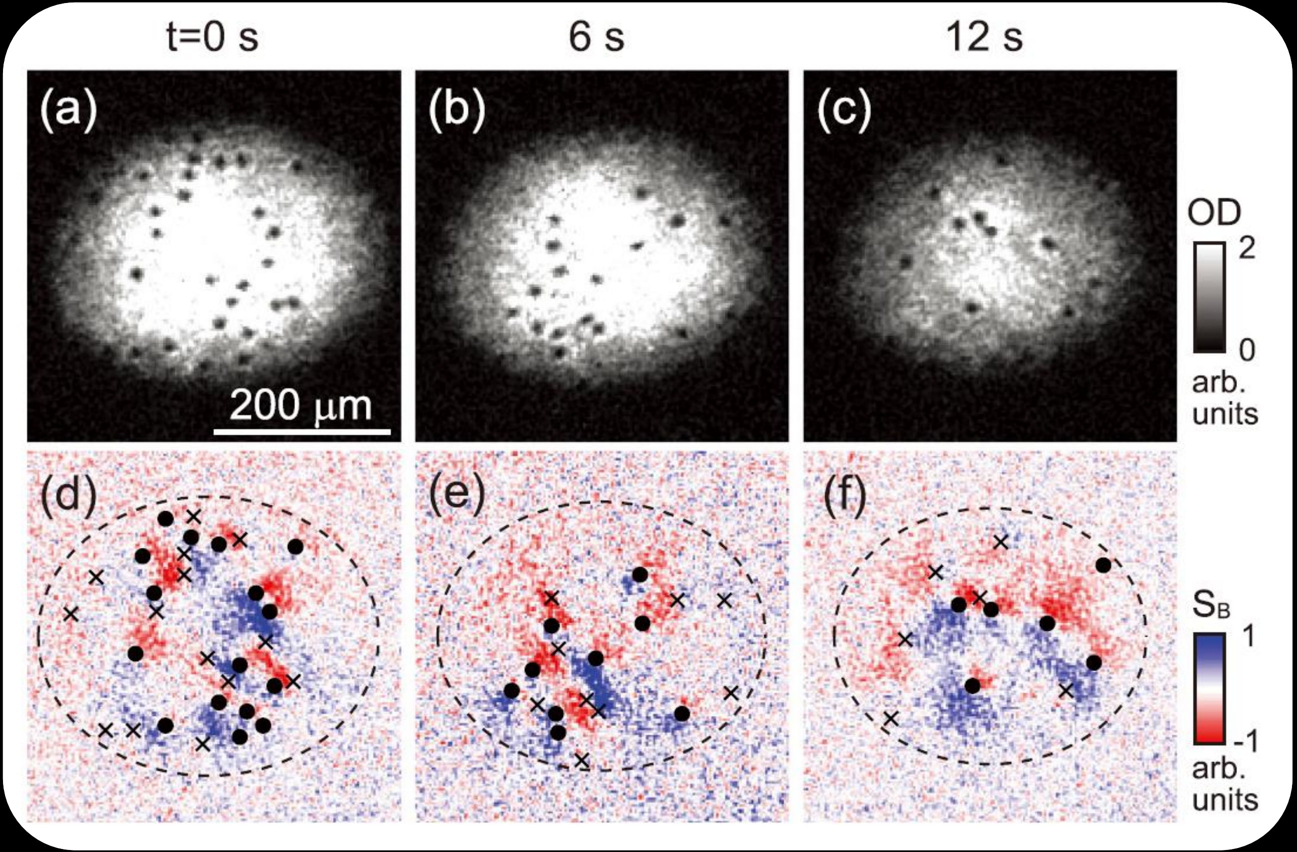


1. SIGN DETECTION



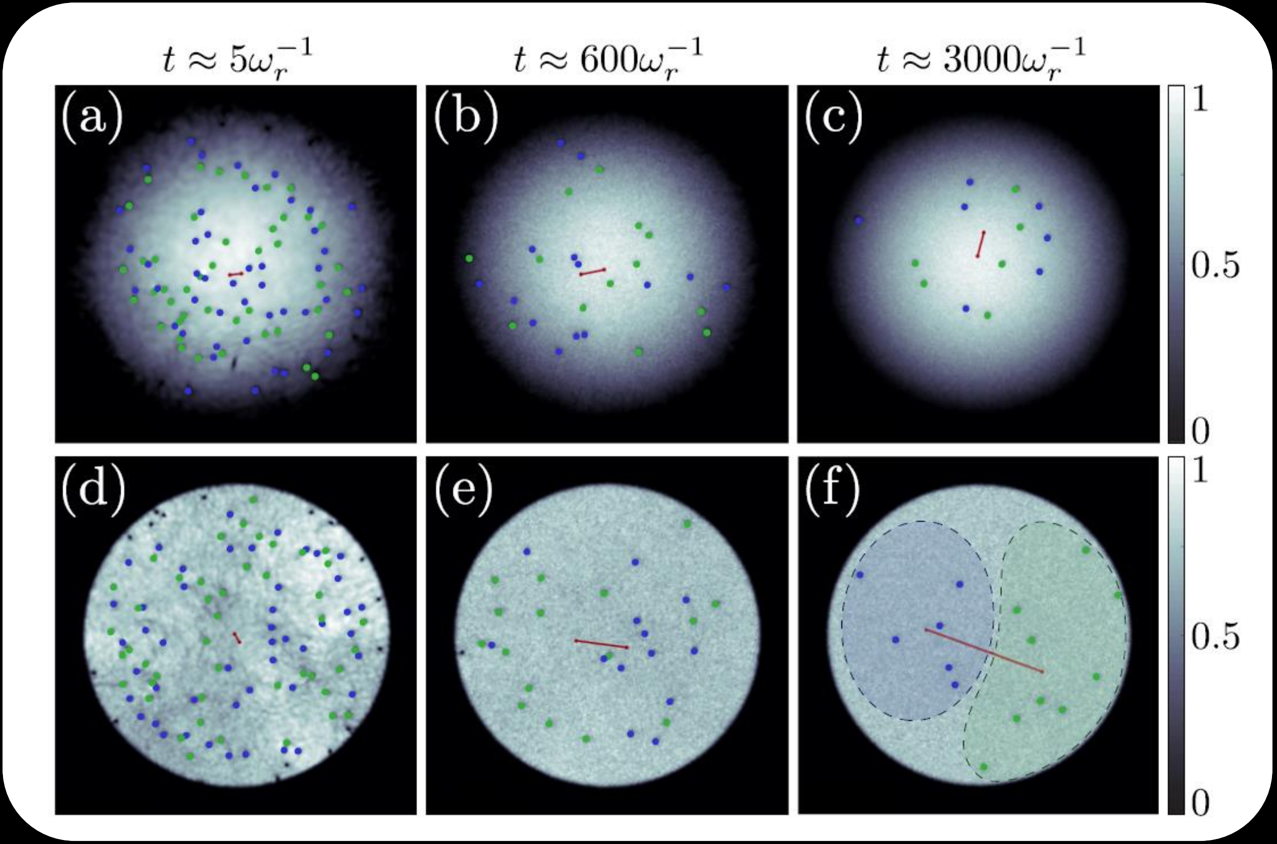
Seo et al., Scientific Reports **7**, 4587 (2017)

1. SIGN DETECTION



Seo et al., Scientific Reports **7**, 4587 (2017)

2. TRAPPING POTENTIAL

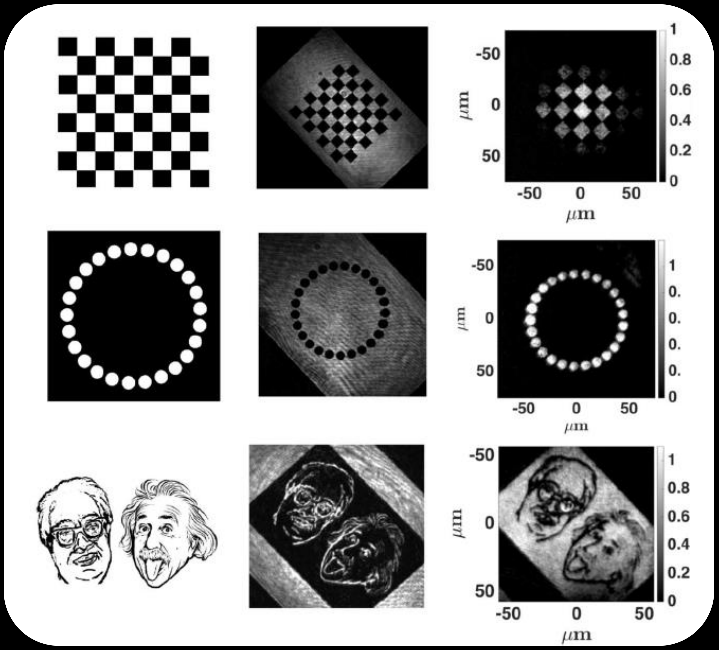


Groszek et al., PRA **93**, 043614 (2016)

2. TRAPPING POTENTIAL

- Solution: Digital micromirror devices (DMDs)

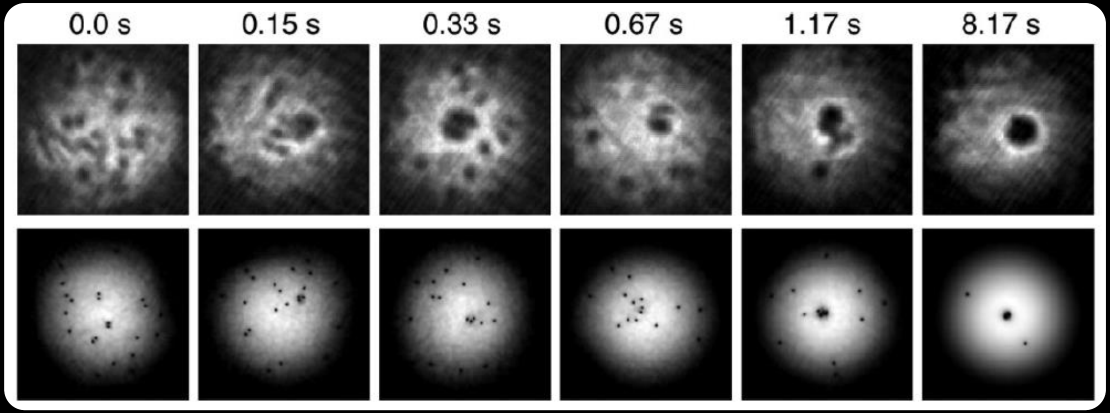
Image Light Atoms



Gauthier et al., Optica **3**, 1136 (2016)

PAST EXPERIMENTS

- Neely et al., PRL **111**, 235301 (2013):



Experiment

Simulation

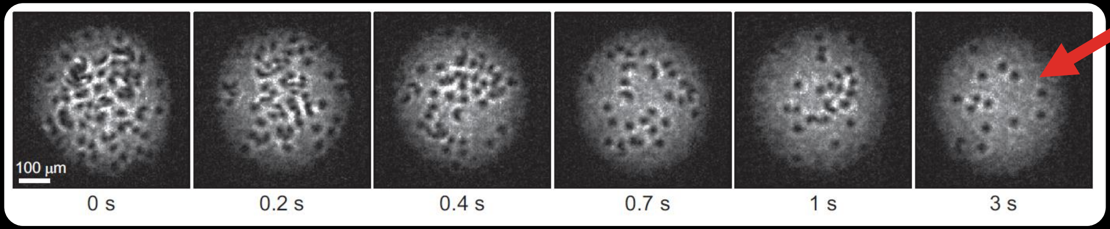
Trapping potential?

✓

- Kwon et al., PRA **90**, 063627 (2014):

Vortex signs?

✓



OUTLINE

Part I – Theory

1. Background – why 2D quantum turbulence?
2. Vortex thermodynamics

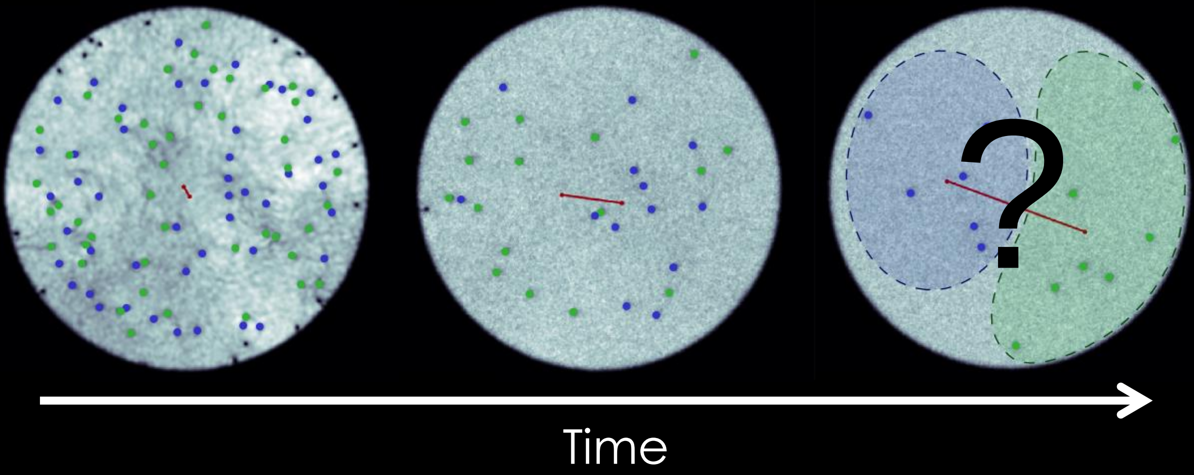
Part II – Experiment

1. Background – why now?
2. **Monash experiment**
3. Results

Summary

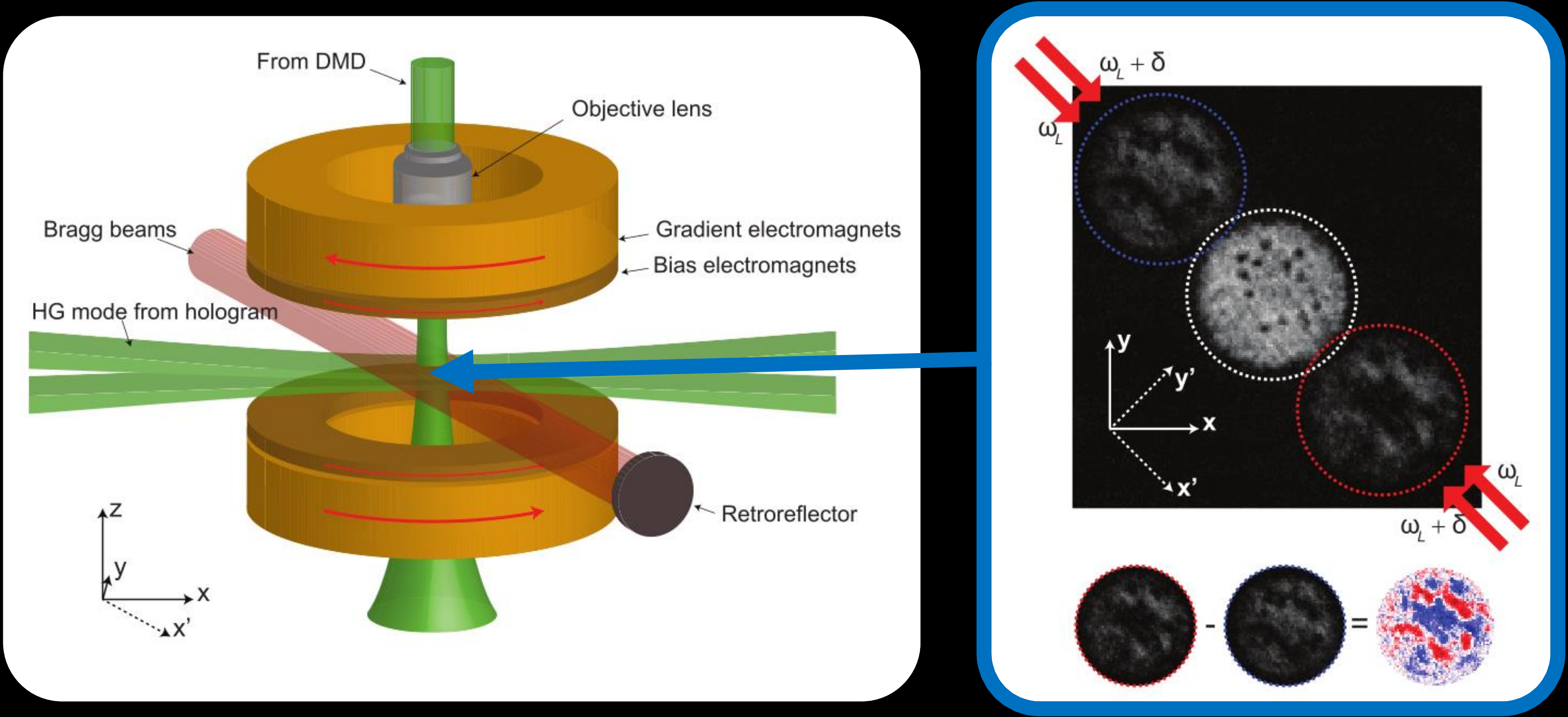
EXPERIMENTAL GOAL

Can we observe negative temperature vortex states in an experiment?



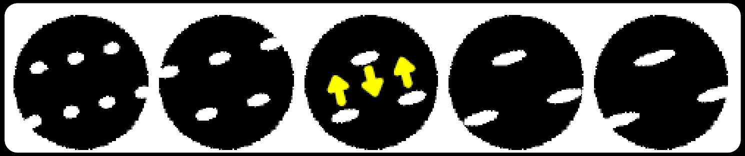
2. Monash experiment

EXPERIMENTAL CONFIGURATION



arXiv:1801.06952

GENERATING VORTICES



2. Monash experiment

OUTLINE

Part I – Theory

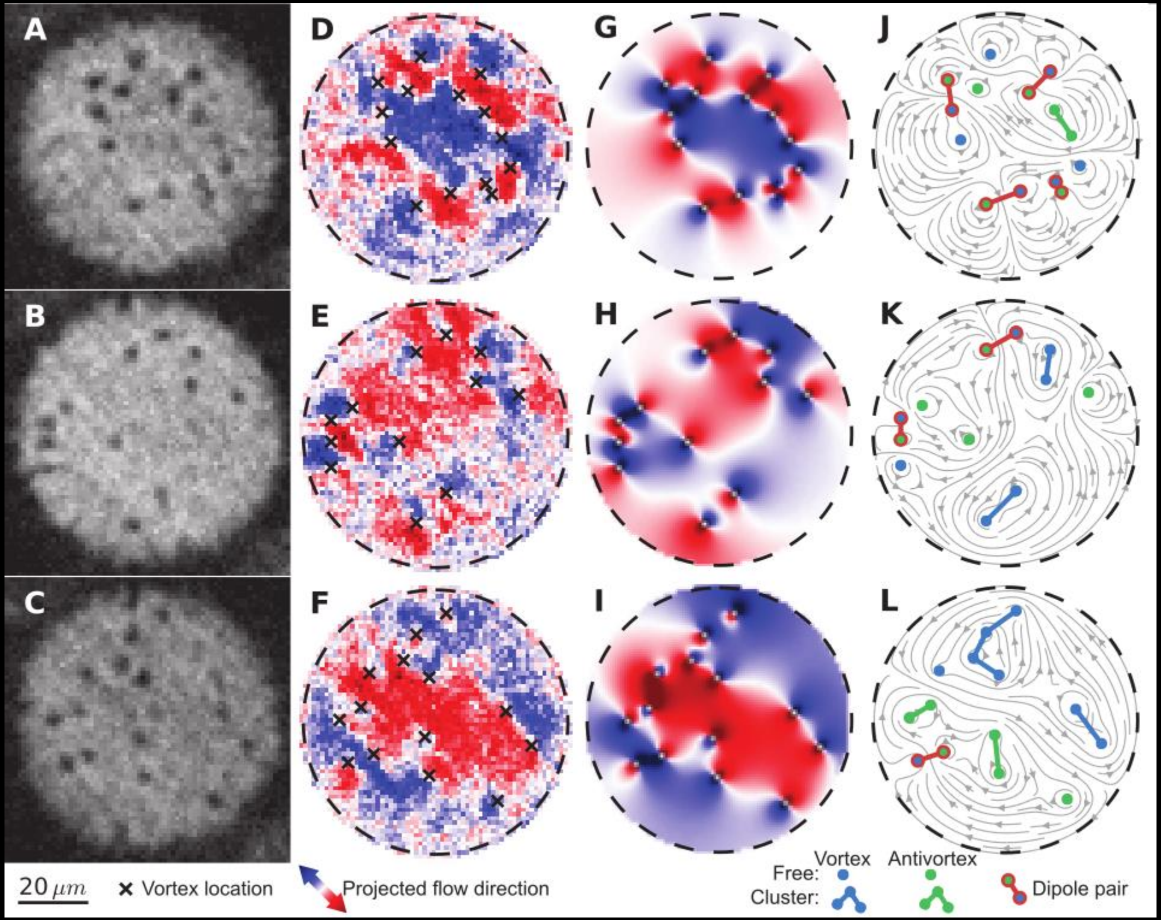
1. Background – why 2D quantum turbulence?
2. Vortex thermodynamics

Part II – Experiment

1. Background – why now?
2. Monash experiment
3. **Results**

Summary

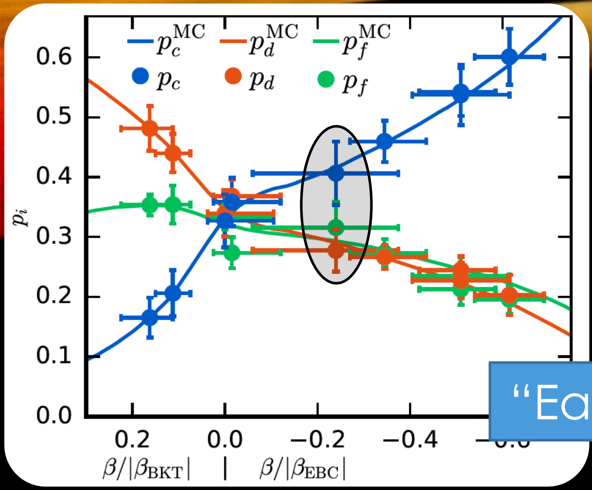
RESULTS: IMAGES

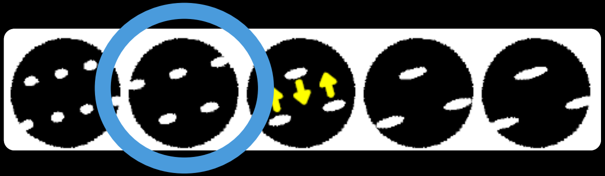


3. Monash experiment results

arXiv:1801.06952

RESULTS: GRID 2

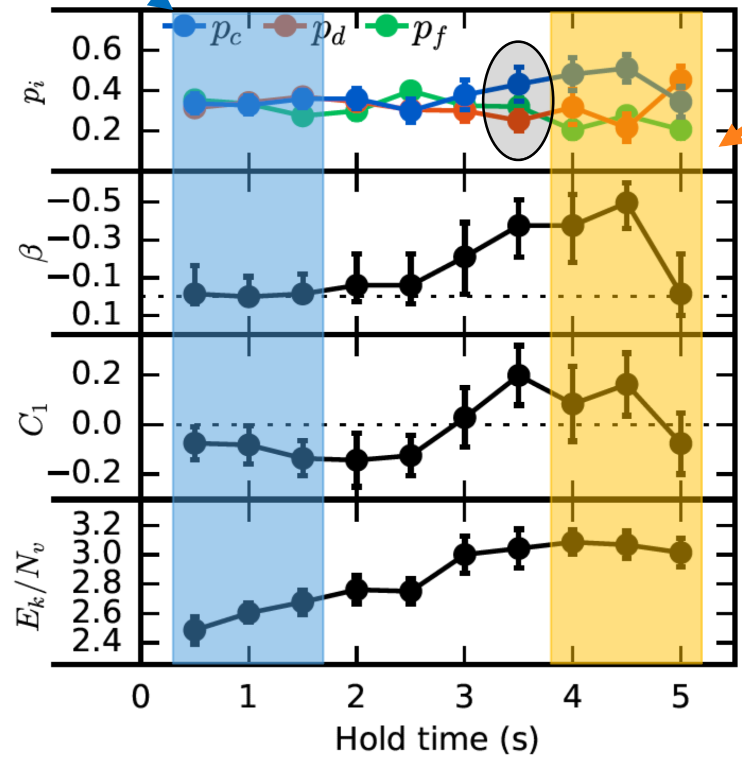




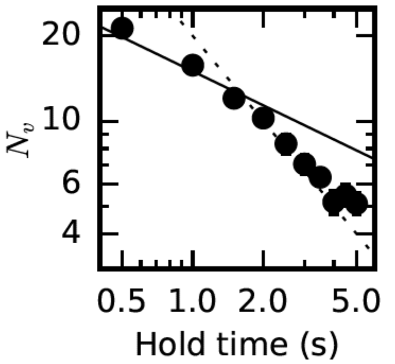
“Early”

“Late”

1. Classified fractions
2. Temperature
3. Correlation function
4. Energy per vortex



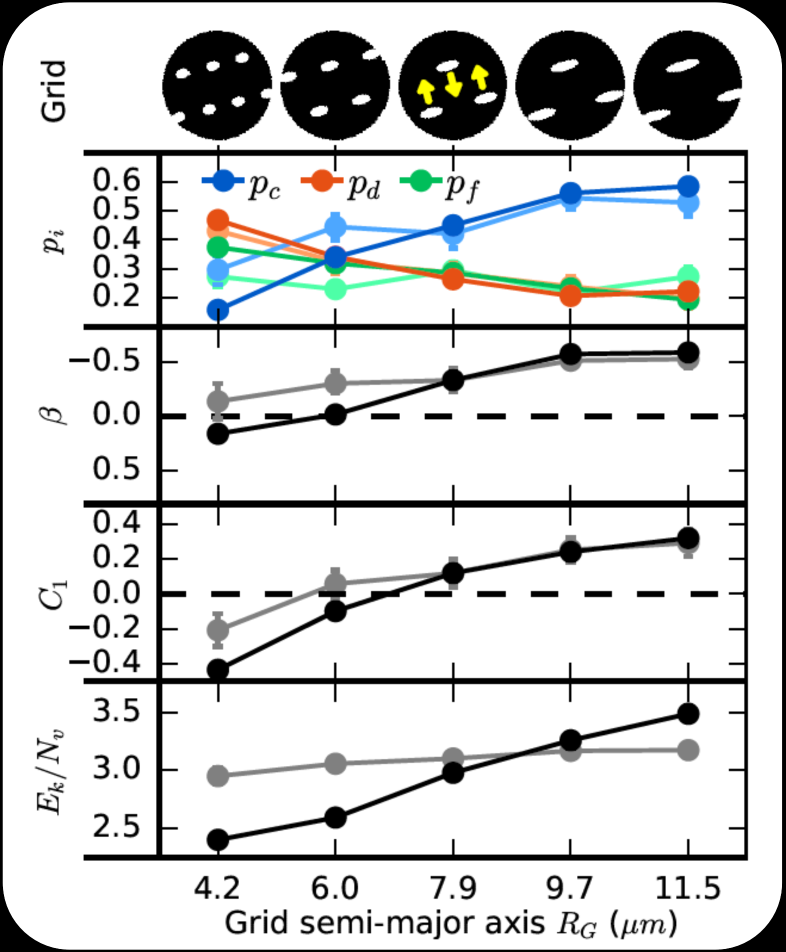
Vortex number



*Averaged over ~20 runs

RESULTS: ALL GRIDS

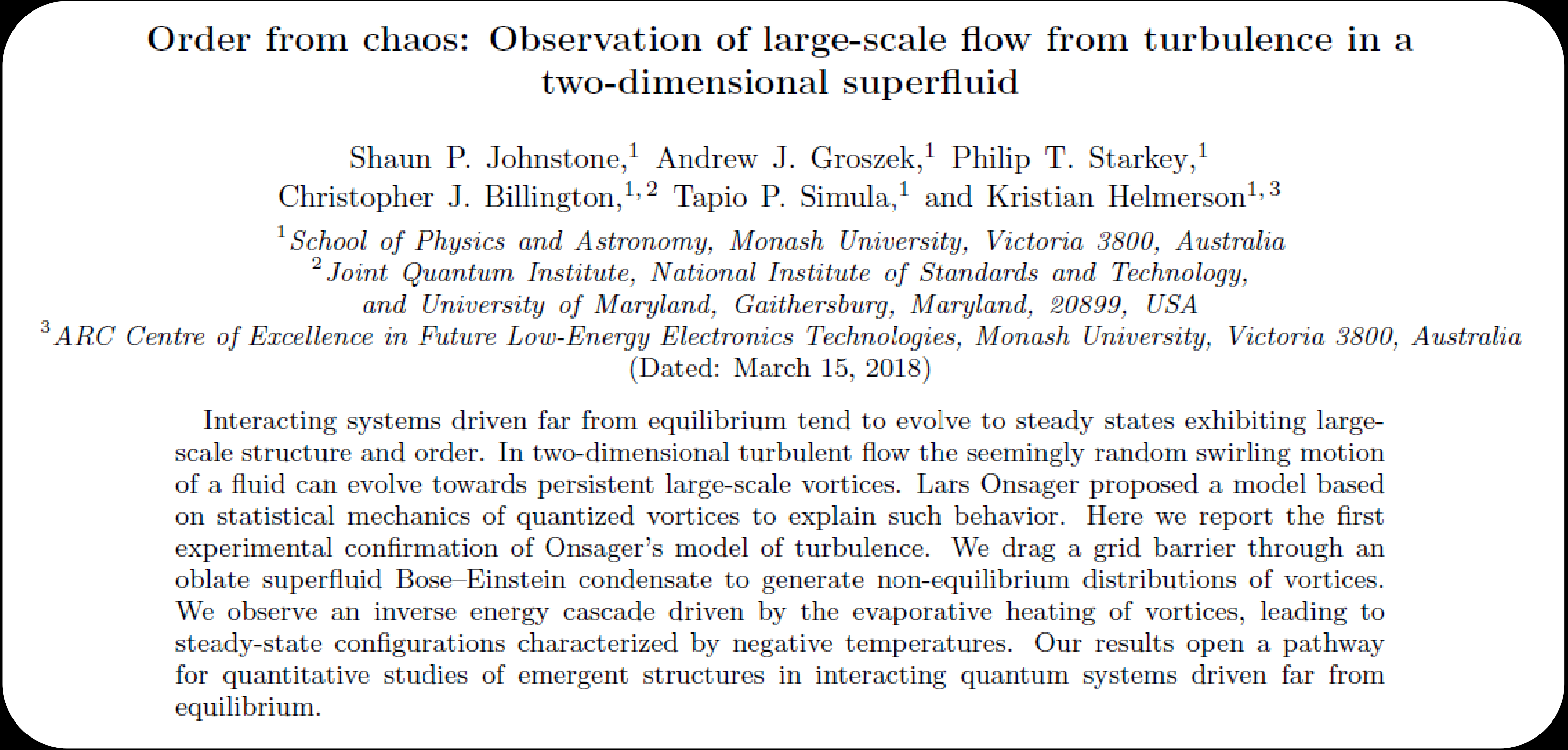
1. Classified fractions
2. Temperature
3. Correlation function
4. Energy per vortex



Dark = early times

Light = late times

3. Monash experiment results



Order from chaos: Observation of large-scale flow from turbulence in a two-dimensional superfluid

Shaun P. Johnstone,[1] Andrew J. Groszek,[1] Philip T. Starkey,[1]
Christopher J. Billington,[1,2] Tapio P. Simula,[1] and Kristian Helmerson[1,3]
[1] *School of Physics and Astronomy, Monash University, Victoria 3800, Australia*
[2] *Joint Quantum Institute, National Institute of Standards and Technology, and University of Maryland, Gaithersburg, Maryland, 20899, USA*
[3] *ARC Centre of Excellence in Future Low-Energy Electronics Technologies, Monash University, Victoria 3800, Australia*

(Dated: March 15, 2018)

Interacting systems driven far from equilibrium tend to evolve to steady states exhibiting large-scale structure and order. In two-dimensional turbulent flow the seemingly random swirling motion of a fluid can evolve towards persistent large-scale vortices. Lars Onsager proposed a model based on statistical mechanics of quantized vortices to explain such behavior. Here we report the first experimental confirmation of Onsager's model of turbulence. We drag a grid barrier through an oblate superfluid Bose–Einstein condensate to generate non-equilibrium distributions of vortices. We observe an inverse energy cascade driven by the evaporative heating of vortices, leading to steady-state configurations characterized by negative temperatures. Our results open a pathway for quantitative studies of emergent structures in interacting quantum systems driven far from equilibrium.

arXiv:1801.06952, to appear in Science

OUTLINE

Part I – Theory

1. **Background – why 2D quantum turbulence?**
2. **Vortex thermodynamics**

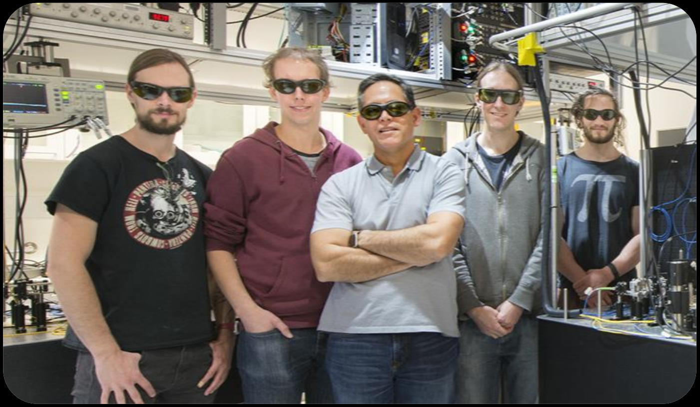
Part II – Experiment

1. **Background – why now?**
2. **Monash experiment**
3. **Results**

Summary

SUMMARY

- Goal: understand + characterise 2D quantum turbulence
  - Vortex clusters / negative temperatures
- **Theory:** now able to measure vortex temperature
- **Experiment:** observed negative temperature vortex states


Kris Helmerson's lab

Tapio Simula


Matthew Davis


David Paganin