Topological quantum matter:

From superfluid ^{3}He to modern materials

November 4-5, 2022, Aalto University

To celebrate 50 years of publication of discovery of superfluid ^{3}He and 80 years anniversary of Matti Krusius, who led world-top-level research on superfluid ^{3}He at Helsinki University of Technology and Aalto University for many years.

Aalto University Department of Applied Physics

Institute Q

EMP

Welcome words

Professor Mika Sillänpää

Vice-head of the Department of Applied Physics,
Aalto University School of Science

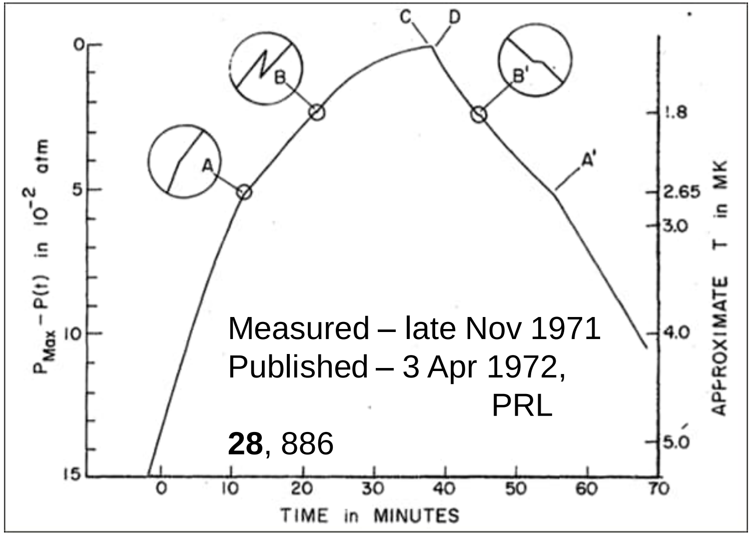
ANNIVERSARY OF DISCOVERY OF SUPERFLUID ^3He

VOLUME 29, NUMBER 14 PHYSICAL REVIEW LETTERS 2 OCTOBER 1972

New Magnetic Phenomena in Liquid He^3 below 3 mK*

D. D. Osheroff,† W. J. Gully, R. C. Richardson, and D. M. Lee
Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, New York 14850
(Received 7 July 1972)

Magnetic measurements have been made on a sample of He^3 in a Pomeranchuk cell. Below about 2.7 mK, the NMR line apparently associated with the liquid portion of the sample shifts continuously to higher frequencies during cooling. Below about 2 mK the frequency shift vanishes, and the magnitude of the liquid absorption drops abruptly to approximately $\frac{1}{2}$ its previous value. These measurements are related to the pressure phenomena reported by Osheroff, Richardson, and Lee.

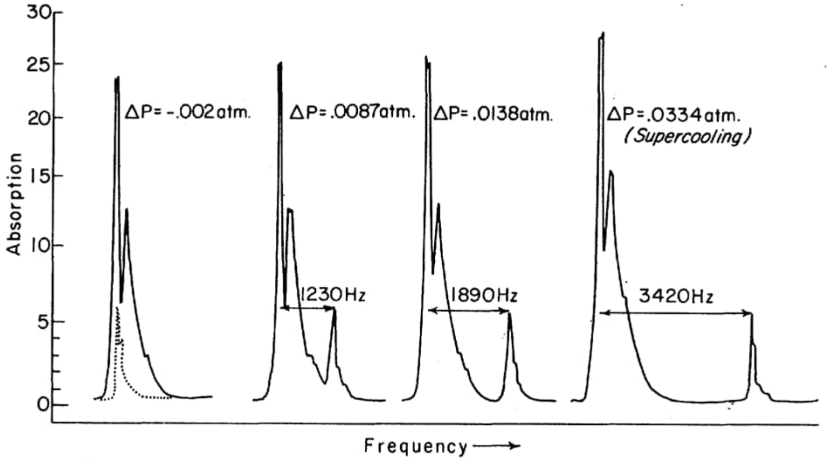


VOLUME 29, NUMBER 18 PHYSICAL REVIEW LETTERS 30 OCTOBER 1972

Interpretation of Recent Results on He^3 below 3 mK: A New Liquid Phase?

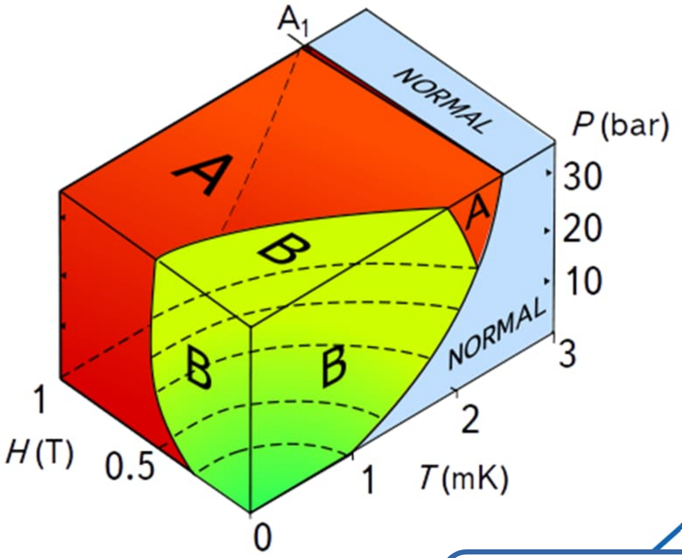
A. J. Leggett
School of Mathematical and Physical Sciences, University of Sussex, England
(Received 5 September 1972)

It is demonstrated that recent NMR results in ^3He indicate that at 2.65 mK, the liquid makes a second-order transition to a phase in which the "spin-orbit" symmetry is spontaneously broken. The hypothesis that this phase is a BCS-type phase in which pairs form with l odd, $S=1$, $S_z=\pm 1$ leads to reasonable agreement with both NMR and thermodynamic data, but involves some difficulties as to stability.

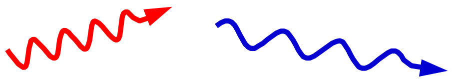


Superfluid ^{3}He – First topological quantum material, Universe in the lab

Topological superfluid with pairing in *L*=1 *S*=1 state: Complex symmetry breaking, structured vacuum, multiple fermionic (quasi)particles and bosonic fields – like the Universe!



- Bosonic excitations

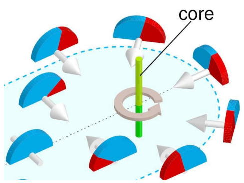


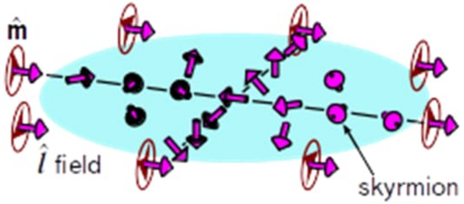
Collective modes: Heavy and light Higgs, sound, spin waves

- Fermionic quasiparticles

Massive and massless: Weyl, Majorana, flat-band …
Synthetic electromagnetic and gravitational fields

- Topological objects





Vortices, skyrmions, solitons… Bound fermionic modes

Topology

in momentum space

in real space

OVERVIEW OF MATTI KRUSIUS SCIENTIFIC CAREER

Oct 12, 1942 – Born in Helsinki

1965 – Comes to the Low Temperature Laboratory as a summer student after 3rd year in TKK

1965-1971 – Experiments on hyperfine interactions in various materials (1967 Master, 1971 PhD)

1972-1975 – Building first "classical" refrigerator for superfluid ^{3}He. (1973-75 Academy research fellow). Measuring phase diagram, NMR on textures.

1975-1977 – University of California at San Diego, USA in the group of J.C. Wheatley. Orbital dynamics, AB transition, zero sound in superfluid ^{3}He.

1977-1982 – Professor at the University of Turku. New field: Atomic hydrogen.

1982-1985 – Return to LTL for rotating superfluid ^{3}He measurements after originating team mostly left. New vortex types in A and B phases.

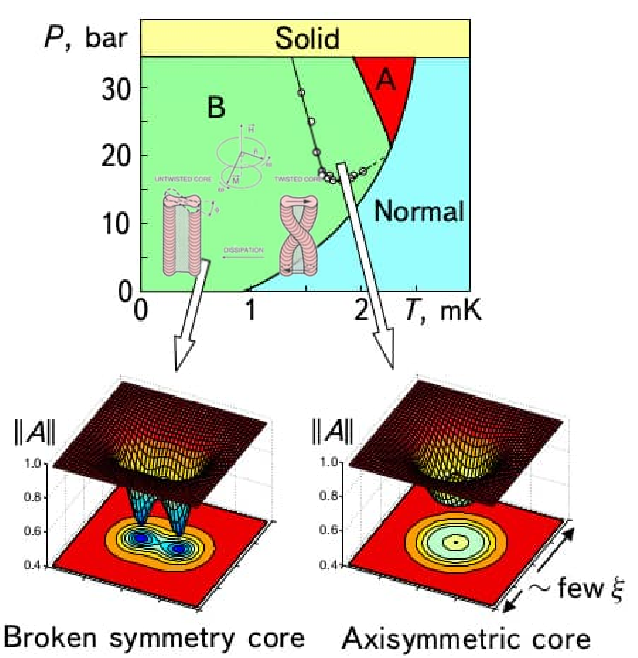
1985-1987 – Back to USA with J.C. Wheatly (at LANL New Mexico) trying to achieve BEC of atomic hydrogen. Figuring out recombination properties and severe difficulties.

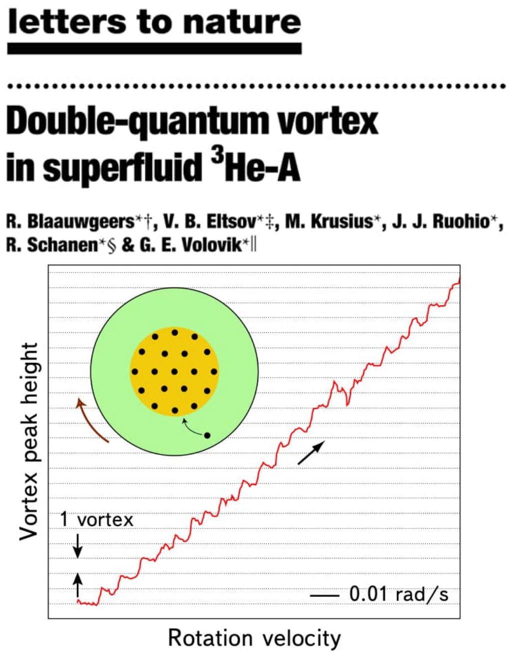
1987 – Final return to LTL to lead rotating superfluid ^{3}He research. (1999-2004 Academy Professor, 2010- emeritus).

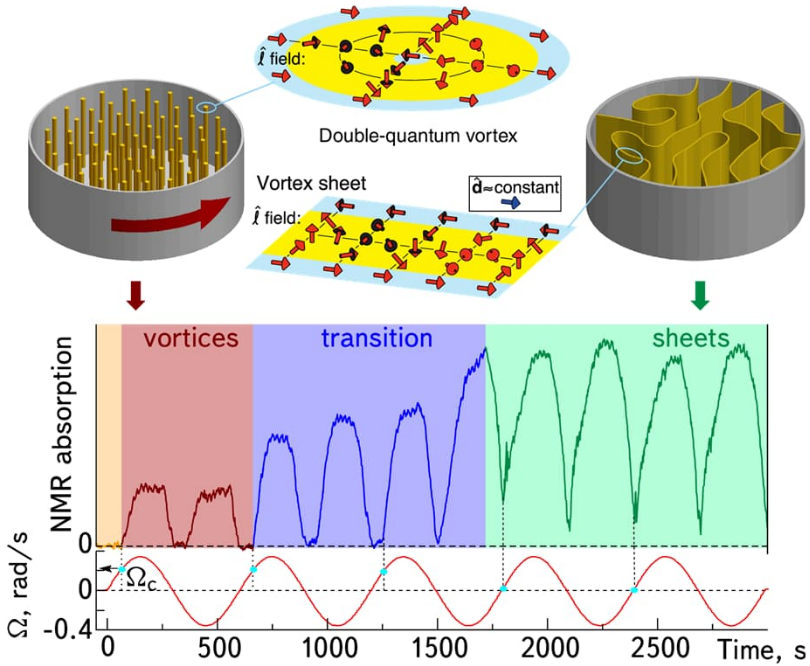
VORTICES AND OTHER TOPOLOGICAL OBJECTS: STRUCTURE AND FORMATION

- Multiple new vortex structures in the A and B phases (non-axisymmetric, double-quantum, combined spin-mass, vortex sheets…) and over objects like topological solitons, identification of their NMR signatures.
- Single-vortex resolution in the NMR measurements in both phases.
- Application of coherent NMR response (HPD, magnon BEC) as a tool.
- Understanding of vortex formation, phase diagrams of various states and critical velocities.
- Close daily collaboration with theoreticians.

Nature, >10 PRLs, >50 other publications





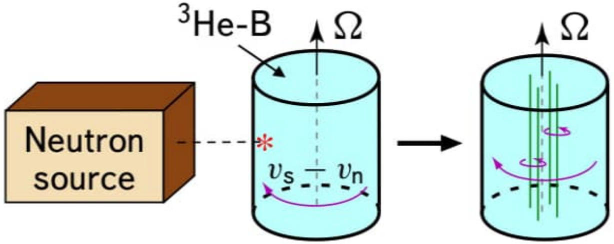


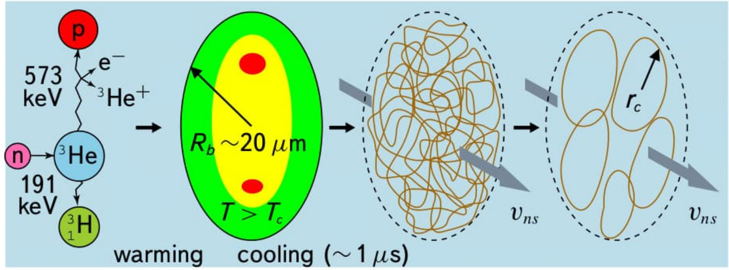
DEFECT FORMATION VIA KIBBLE-ZUREK MECHANIZM

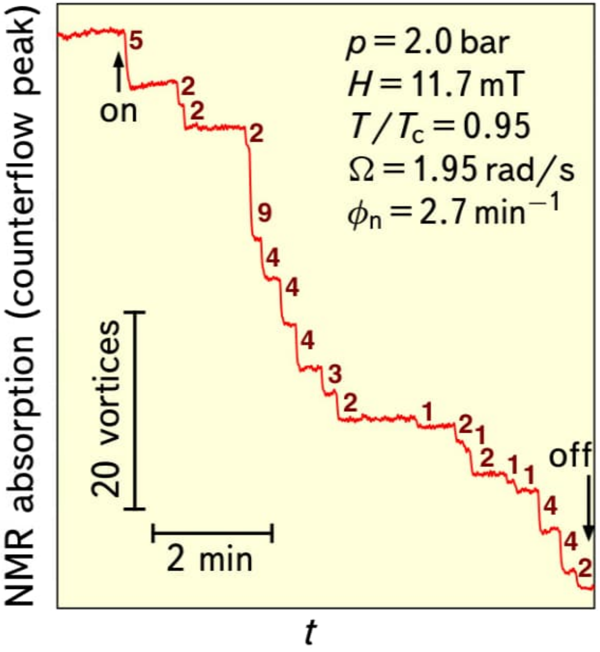
LETTERS TO NATURE

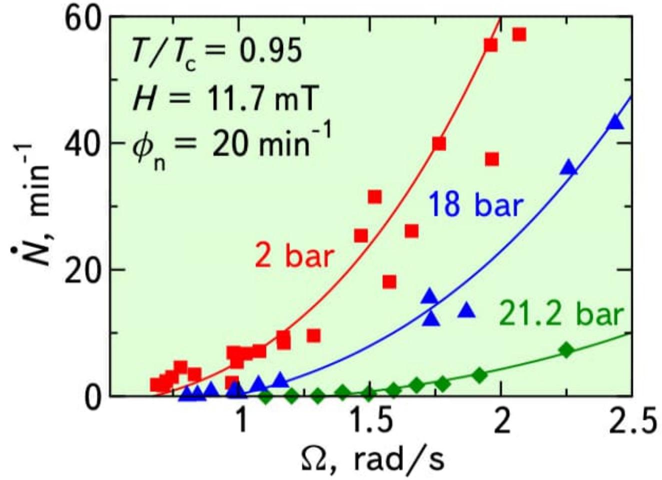
Vortex formation in neutron-irradiated superfluid ^{3}He as an analogue of cosmological defect formation

V. M. H. Ruutu*, V. B. Eltsov*†, A. J. Gill‡§, T. W. B. Kibble‡, M. Krusius*, Yu. G. Makhlin*||, B. Plaçais¶, G. E. Volovik*|| & Wen Xu*





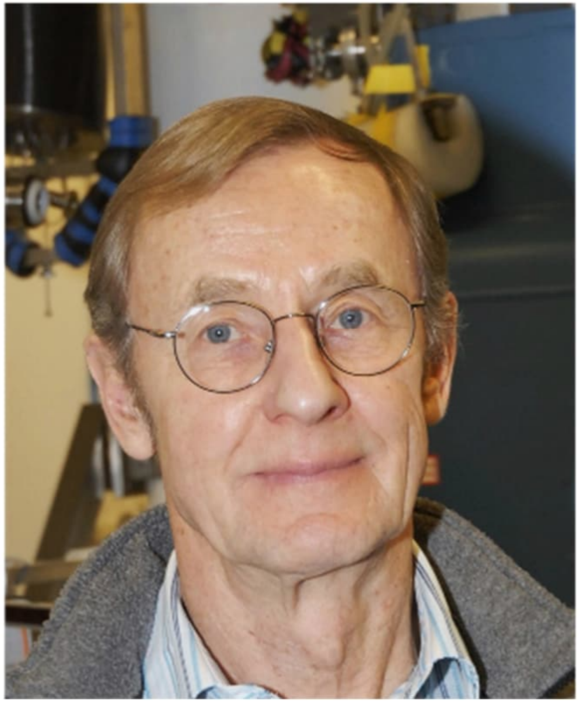




$$\frac{dN}{dt} = \phi_n \mathcal{A}\left[\left(\frac{v_n - v_s}{v_{cn}(p,T,H)}\right)^3 - 1\right]$$

Nature **382**, 344 (1996)
PRL **80**, 1465 (1998)
PRL **85**, 4739 (2000)

FRITZ LONDON MEMORIAL PRIZE 1999

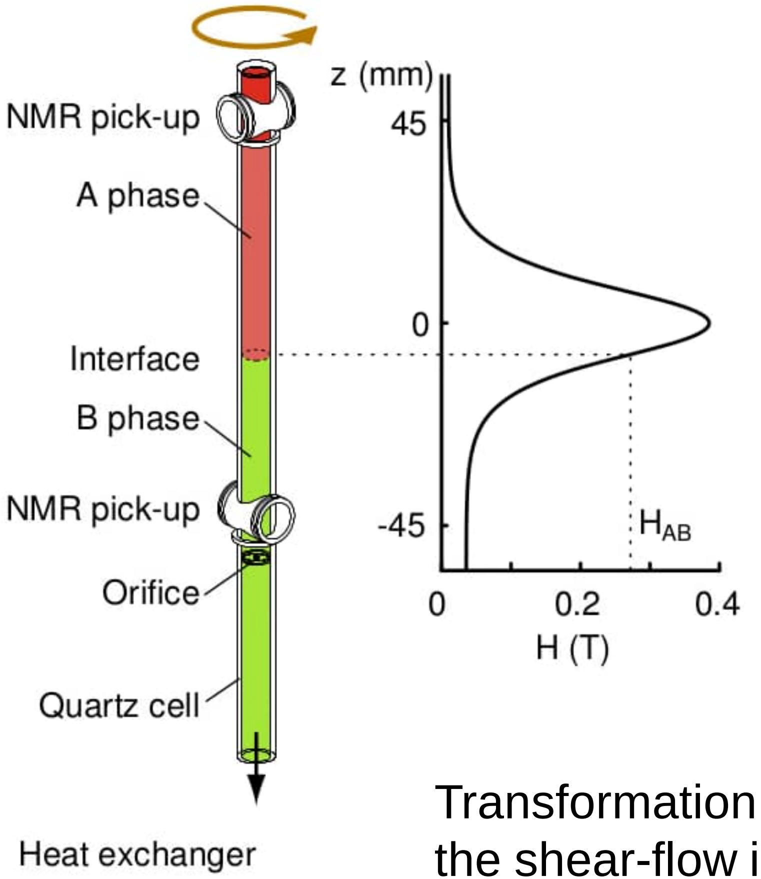


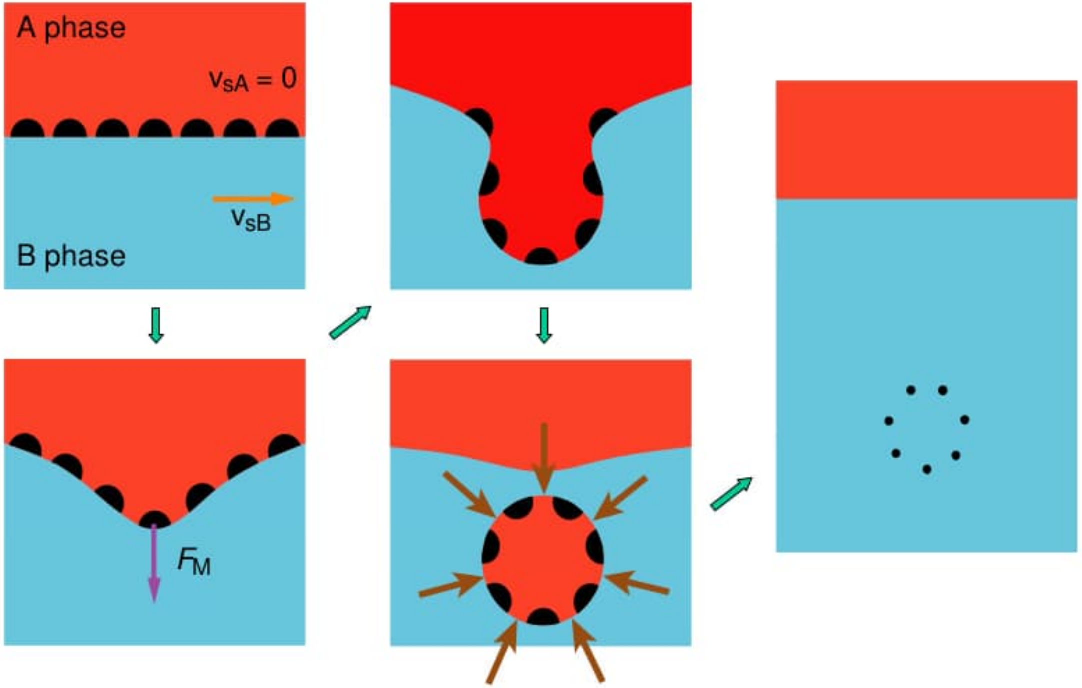
Matti Krusius (Helsinki University of Technology, Finland)

Citation:
"For his imaginative and pioneering use of rotation combined with nuclear magnetic resonance to study various properties of superfluid ^3He, including textures of the order parameter, the structure, pinning and collective behavior of several different types of vortex, the critical velocity under rotation, the effects of motion of the A-B interface and the systematics of nucleation of vorticity by neutron irradiation."

https://physics.duke.edu/sites/physics.duke.edu/files/documents/Krusius1999.pdf

VORTEX FORMATION BY THE AB INTERFACE INSTABILITY





Transformation of vortex structures and controlled injection of vortices by the shear-flow instability of the AB interface.

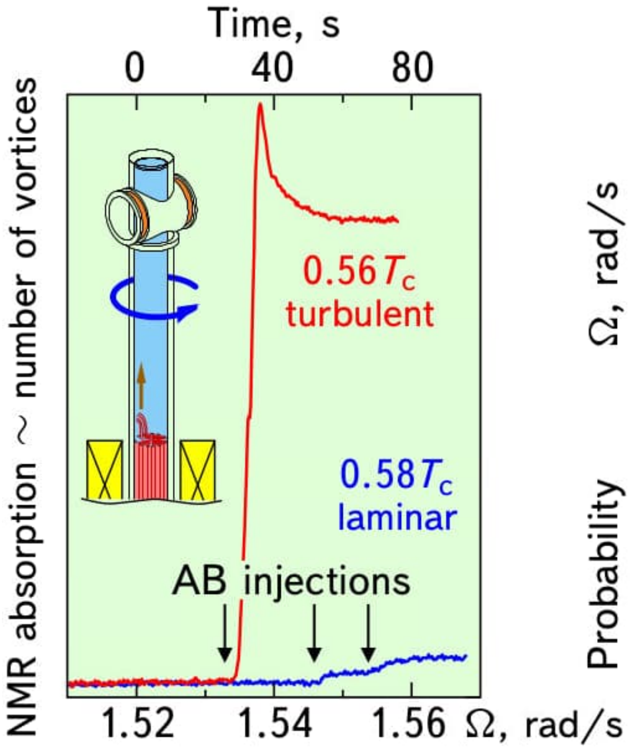
PRL **71**, 2951 (1993); PRL **89**, 155301 (2002); PRL **90**, 225301 (2003)
Rep. Prog. Phys. **69**, 3157 (2006); PRB **99**, 054104 (2019)

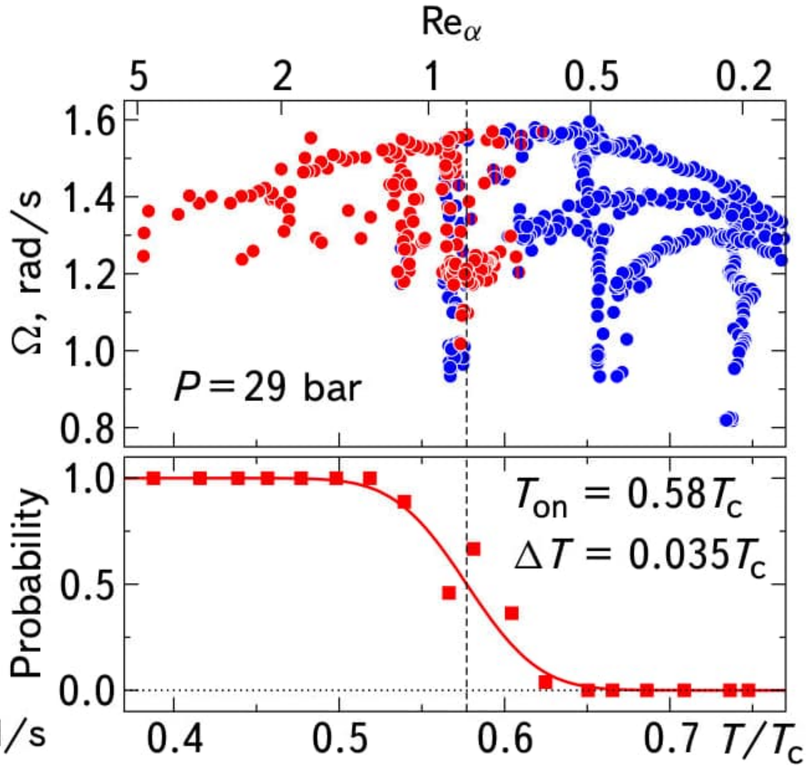
TRANSITION TO SUPERFLUID TURBULENCE

letters to nature

An intrinsic velocity-independent criterion for superfluid turbulence

A. P. Finne[1], T. Araki[2], R. Blaauwgeers[1,3], V. B. Eltsov[1,4], N. B. Kopnin[1,5], M. Krusius[1], L. Skrbek[6], M. Tsubota[2] & G. E. Volovik[1,5]

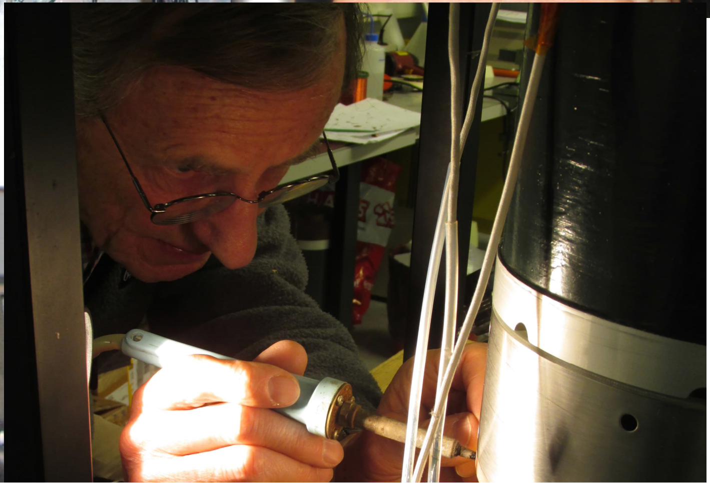




Nature **424**, 1022 (2003)
PRL **96**, 085301 (2006)
PRL **96**, 215302 (2006)
PRL **99**, 265301 (2007)

$$\mathrm{Re}_\alpha = \frac{1-\alpha'}{\alpha} = \frac{\text{inertial}}{\text{viscous}} \text{ terms in HVBK equations}$$

REBUILDING ROTA CRYOSTAT: PUSHING TOWARDS ZERO TEMPERATURE



New ROTA:

T down to 120μK

Ω up to 3.5 rad/s

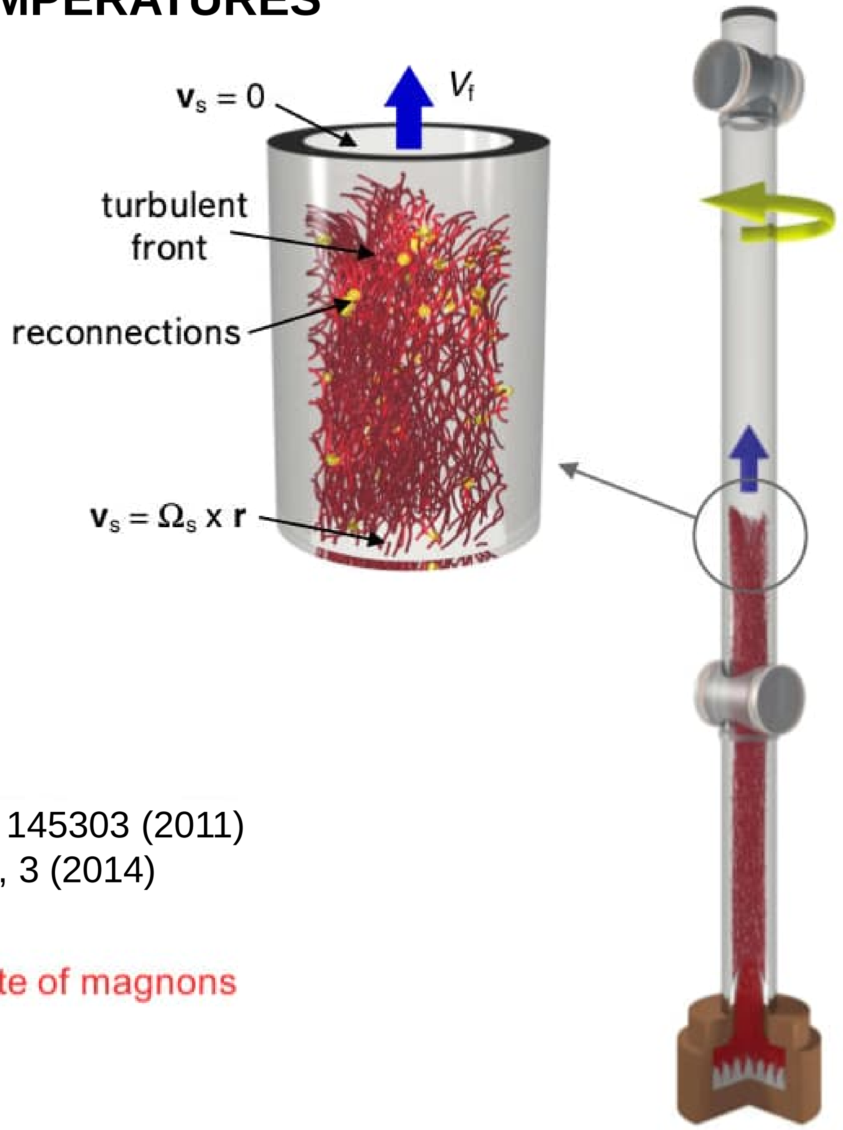
with heat leak

below 20 pW

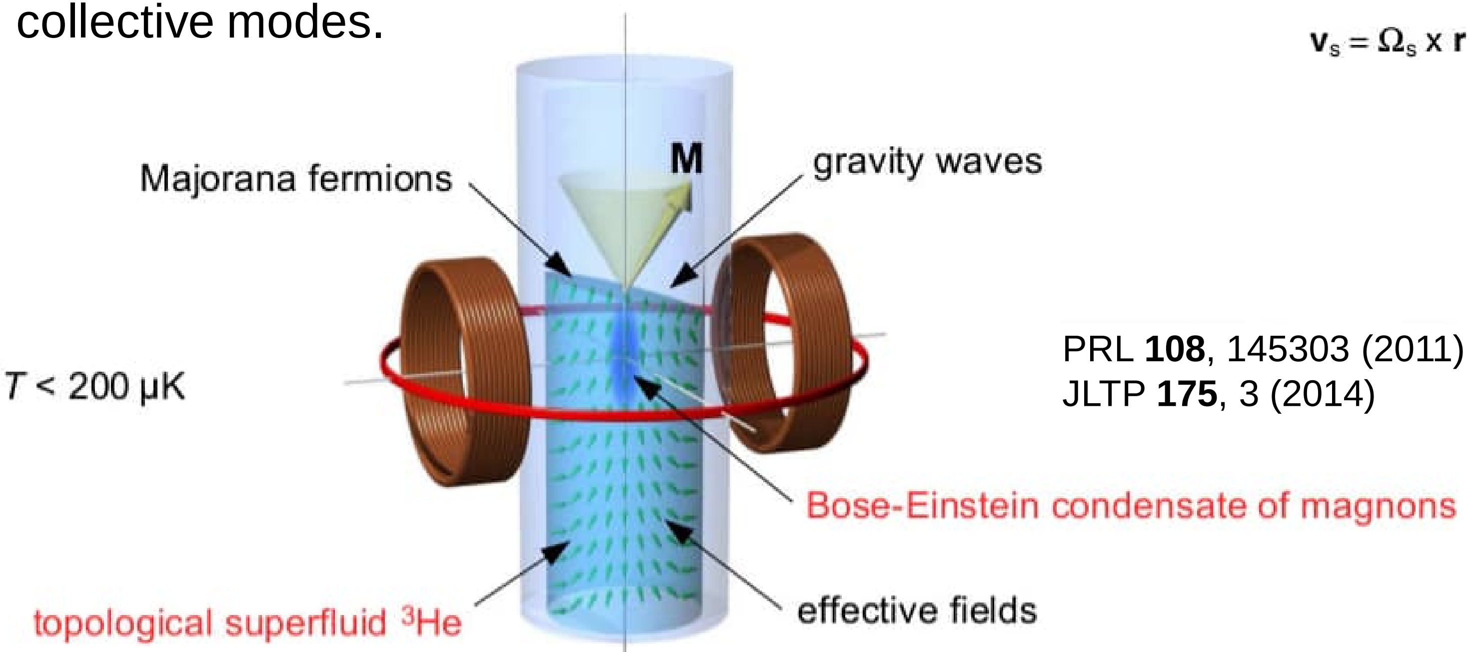
FINDINGS AT ULTRA-LOW TEMPERATURES

New dynamic regime when superfluid loses contact with the container walls.

PRL **105**, 125301 (2010)
PRL **107**, 135302 (2011)
Nature Comm. **4**, 1614 (2013)
PNAS **111**, 4711 (2014)



Magnon condensates as ultra-sensitive, coherent and localized probes of vorticity, fermionic quasiparticles and collective modes.



PRL **108**, 145303 (2011)
JLTP **175**, 3 (2014)

Physics | The Nobel Prize in Physics 1996 | Press Release

https://www.nobelprize.org

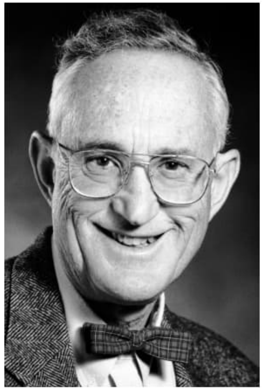


Photo from the Nobel Foundation archive.
David M. Lee


Photo from the Nobel Foundation archive.
Douglas D. Osheroff


Photo from the Nobel Foundation archive.
Robert C. Richardson

A fascinating application of superfluidity in helium-3

The phase transitions to superfluidity in helium-3 have recently been used by two experimental research teams to test a theory regarding how what are termed cosmic strings can be formed in the universe. These immense hypothetical objects, which are thought possibly to have been important for the forming of galaxies, can have arisen as a consequence of the rapid phase transitions believed to have taken place a fraction of a second after the Big Bang. The research teams used neutrino-induced nuclear reactions to heat their superfluid helium-3 samples locally and rapidly. When these were cooled again, balls of vortices were formed. It is these vortices that are presumed to correspond to the cosmic strings. The result, which must not be taken as proof of the existence of cosmic strings in the universe, is that the theory tested appears to be applicable to vortex formation in superfluid helium-3.

Physics | The Nobel Prize in Physics 2003 | Press Release

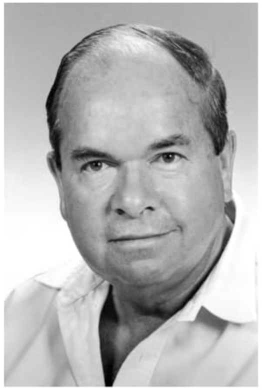


Photo from the Nobel Foundation archive.
Alexei Alexeyevich Abrikosov

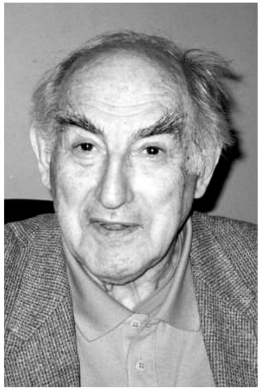


Photo from the Nobel Foundation archive.
Vitaly Lazarevich Ginzburg


Photo from the Nobel Foundation archive.
Anthony J. Leggett

Liquid helium can become superfluid, that is, its viscosity vanishes at low temperatures. Atoms of the rare isotope ^3He have to form pairs analogous with pairs of electrons in metallic superconductors. The decisive theory explaining how the atoms interact and are ordered in the superfluid state was formulated in the 1970s by **Anthony Leggett**. Recent studies show how this order passes into chaos or turbulence, which is one of the unsolved problems of classical physics.


Happy
Birthday