

HOME

Grand Challenges in Quantum Fluids and Solids

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August 7-9, 2015

University at Buffalo



<http://sites.psu.edu/qfs2015/>

GRAND CHALLENGES IN QUANTUM FLUIDS AND SOLIDS

Workshop Motivation

The study of quantum fluids and solids (QFS) has and continues to play a pivotal role in the development of key concepts and ushering paradigm shifts in quantum many body physics in the condensed phases. This workshop aims to build a roadmap to meet the grand challenges of the field and to facilitate the interaction among the QFS and neighboring communities for concerted studies of the many exciting phenomena emerging across these disciplines.

Attendance

68, multi-generational (with 18 post-docs and graduate students) and multi-national (US, Canada, UK, France, Germany, Japan, Korea and China)

Program

SESSION I: Superfluid Helium as Model Systems for Quantum Information and Quantum Computation, Quantum Gases

**Electrons on Helium Surface*: Steve Lyon (docent)

M.I. Dykman , Paul Leiderer, Johannes Pollanen, and David Schuster

Micromechanical Oscillators: John Davis (docent) [Keith Schwab]

Keith Schwab and Eddy Collin

Gold Gases: Jason Ho (docent)

Wolfgang Ketterle, Brian Demarco and David Weiss

SESSION II: One and Two Dimensional Helium Systems

**2D ^3He and ^4He Films*: John Saunders (docent)

Hiroshi Fukuyama and Jan Nyeki

1D Helium Systems: Adrian Del Maestro (docent)

Guillaume Gervais, Peter Taborek and Junko Taniguichi

**Superflow in Solid Helium*: E. Kim (docent)

Bob Hallock, John Beamish and A. Kuklov

SESSION III: Quantum Turbulence and Emergent Phenomena

Quantum Turbulence: George Pickett (docent)

Daniel Lathrop, A. Golov, V.B. Eltsov and Wei Guo

Emergent Phenomena: Frank Gasparini (docent)

Eckhard Krotscheck, Humphrey Maris and Andrey Vilesov

SESSION IV: Superfluid He-3 [Bill Halperin]

Topological Order and Majorana Fermion: Jim Sauls (docent)

Sukbum Chung, A. Vorontsov, and Takeshi Mizushima

Experimental Search for Majorana Fermion in He-3: Bill Halperin (docent)

Ryuji Nomura, Seamus Davis and John Saunders

Effects of Disorder and Confinement: Yoonseok Lee (docent)

Vladimir V. Dmitriev, Richard Haley and Jeevak Parpia

SESSION V: Roadmap to Meet Grand Challenges

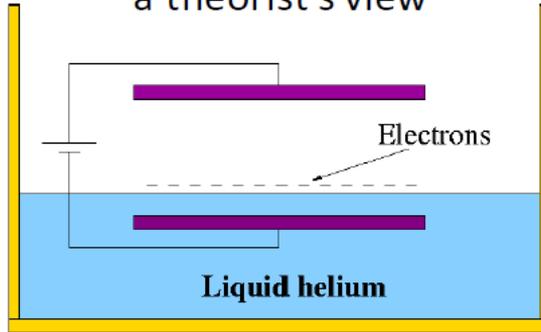
Summary of Scientific Opportunities: Yoonseok Lee (docent)

Wolfgang Ketterle, Tony Leggett, David Lee and George Pickett

Outreach to Stakeholders: Bill Halperin (Coordinator)

John Beamish, Frank Gasparini, Bob Hallock and Jeevak Parpia,

Experimental cell:
a theorist's view

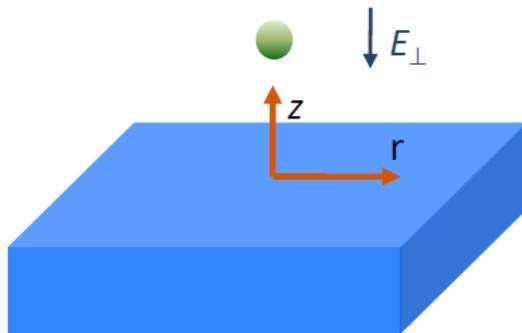


Electrons reside in vacuum. Interelectron distance is $\sim 1\mu\text{m}$. The in-plane mobility is **the highest known**

$$\mu \lesssim 2 \times 10^8 \text{ cm}^2 / \text{V} \cdot \text{s}, \quad \tau \lesssim 10^{-7} \text{ s}$$

GaAs heterostructures: $\mu \lesssim 3.6 \times 10^7 \text{ cm}^2 / \text{V} \cdot \text{s}, \quad \tau \lesssim 10^{-9} \text{ s}$

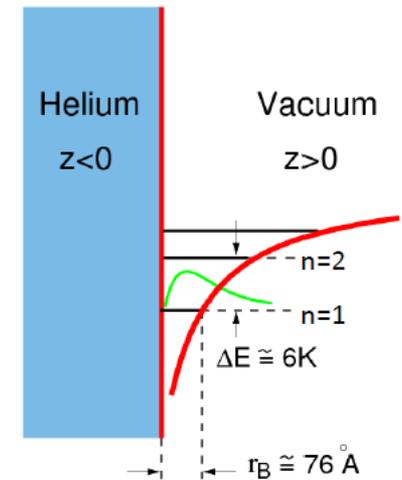
Idealized model: flat surface, infinite barrier, image potential



$$U(z) = -\Lambda/z \quad (z > 0)$$

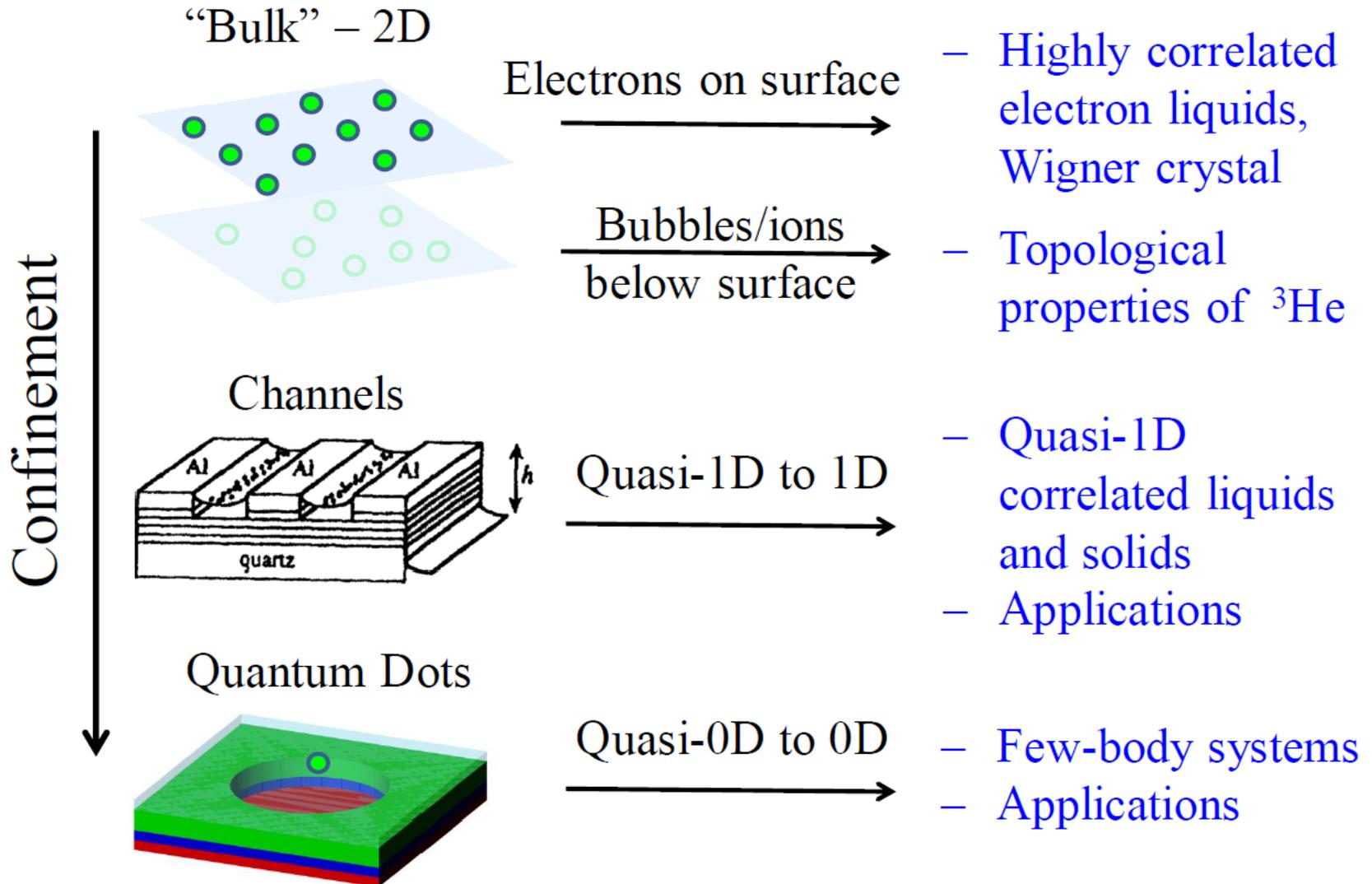
$$\Lambda = (\epsilon - 1) e^2 / 4(\epsilon + 1)$$

$$E_n = -R/n^2, \quad R = m \Lambda^2 / 2\hbar^2$$



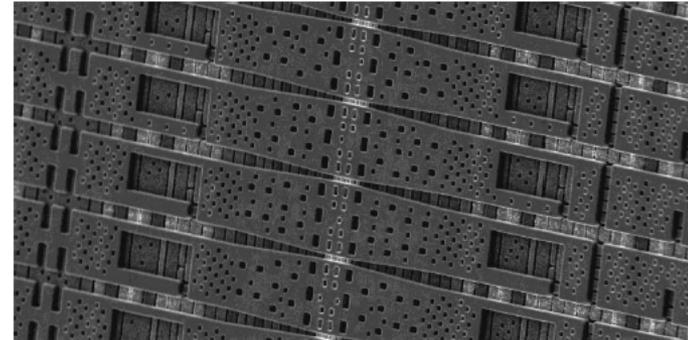
Control: pressing field E_{\perp} , magnetic field, density, temperature

Electrons on Helium – expt'l systems

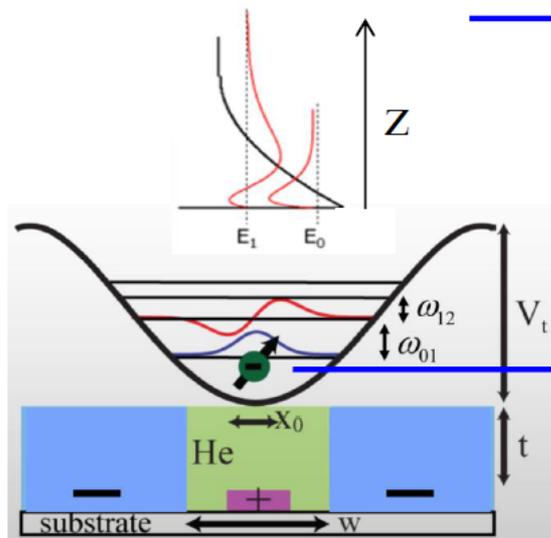


Applications

Moving and manipulating electrons with great precision
(Precision available only to theorists in semiconductors)



Electron “atom” for quantum simulation/computing
Qubits



Vertical transition = hydrogenic potential
Platzman and Dykman, *Science*, **248**, 1967 (1999)

Lateral transition \approx harmonic potential
Schuster, *et al.*, *PRL* **105**, 040503 (2010)

Electron spin – expect long coherence for mobile electrons (very small spin-orbit: $\Delta g < 10^{-7}$ in bubbles $\Rightarrow T_2 \geq 10s$)
Lyon, *PRA* **74**, 052338 (2006)

New Quantum Phases of Monolayers of Helium

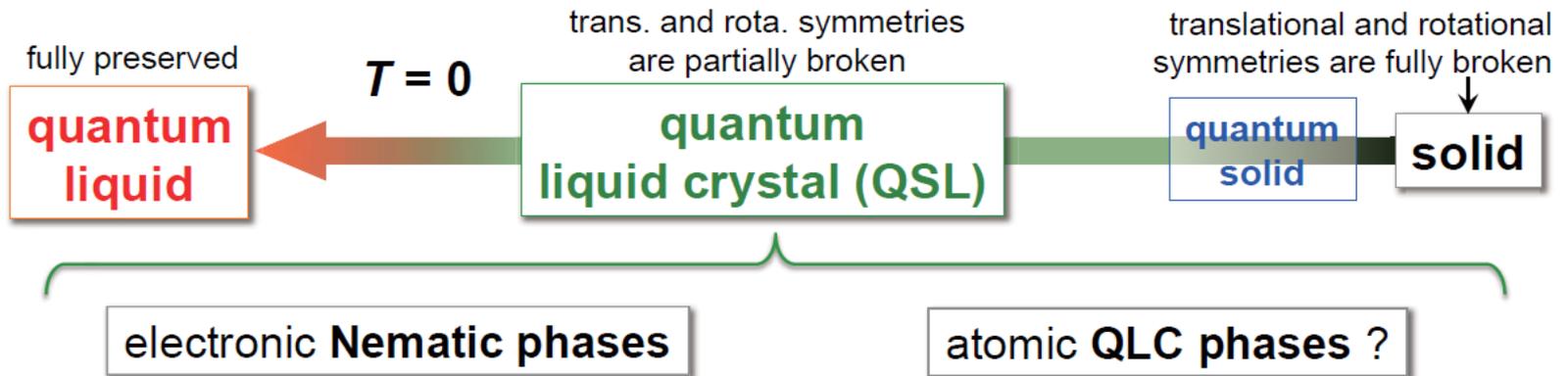
Hiroshi FUKUYAMA

*Department of Physics,
Cryogenic Research Center (CRC),
The University of Tokyo*

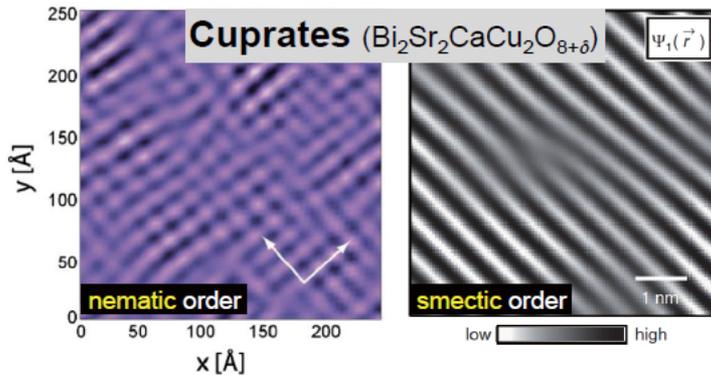
1. New **quantum spin liquid** state in 2D ^3He
2. Search for **supersolidity** in 2D ^4He
3. Liquefaction of ^3He in 2D
4. Search for superfluidity in monolayer liquid ^3He

Quantum Liquid Crystal

New quantum state of matter: Quantum Liquid Crystal



C. Howald et al., PRB **67**, 014533 (2003) A. Meszaros et al., Science **333**, 426 (2011)



Sr₃Ru₂O₇ R.A. Borzi et al. Science **315**, 214 (2007)

2DES in GaAs/GaAlAs M.P. Lilly et al., PRL **82**, 394 (1999)

2D ⁴He • supersolidity ?

2D ³He • gapless quantum spin liquid
• stripe superfluid phase

Q. interplay between superfluid (or spin) and spatial orders?

Q. ubiquitous for strongly correlated 2D quantum systems?

Gapless quantum spin liquid (QSL) state in 2D frustrated magnets

$$\langle S_i \rangle = 0 \text{ without LRO at } T = 0$$

theories

Short range RVB (resonating valence bond)

P.W. Anderson (1973, 1987)

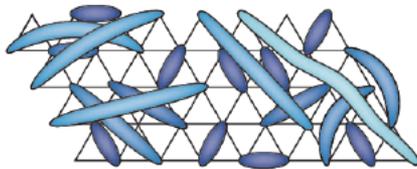
Long range RVB

L.S. Doucot and P.W. Anderson (1988)

$S = 1/2$ Heisenberg n.n. antiferromagnet on a triangular lattice (HAFT) with longer distance interactions



P.W. Anderson



gapless

+ •••

● singlet pair

Fermion fractionalization

C.P. Nave and P.A. Lee (2007)

O.I. Motrunich (2005)

R.R. Biswas, *et al.* (2011)

exotic elementary excitations (spinon, Majorana fermions, ...)

$$C \propto T^{2/3}, \chi = \text{const. or } \chi \propto T^{-1/3}$$

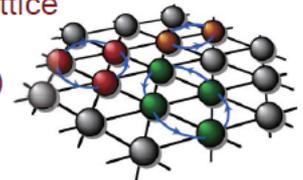
experiments

2D ^3He

First exp. claim of gapless GSL

K. Ishida, HF (1997)

$S = 1/2$ on triangular lattice ring exchanges (4-, 6- spin exchanges)



$$C \propto T?$$

electronic systems

$[\kappa\text{-(BEDT-TTF)}_2\text{Cu}_2(\text{CN})_3]$ $S=1/2$ HAFT

Y. Shimizu *et al.* (2003)

S. Yamashita *et al.* (2008)

M. Yamashita *et al.* (2010)

$\text{EtMe}_3\text{Sb}[\text{Pd}(\text{dmit})_2]_2$ $S=1/2$ HAFT

T. Itou *et al.* (2007)

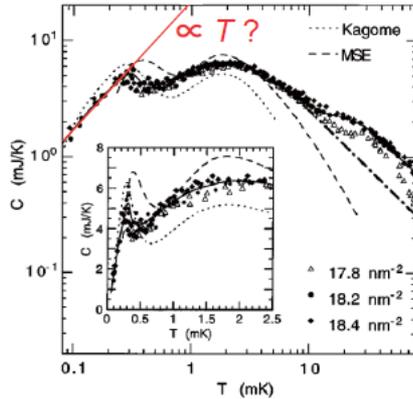
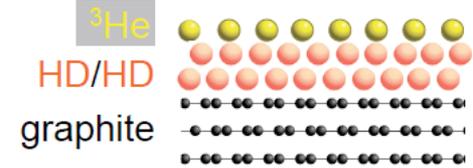
M. Yamashita *et al.* (2010)

S. Yamashita *et al.* (2011)

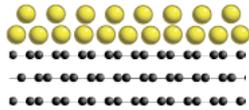
$$C \propto T?, \chi \rightarrow \text{const.}?$$

Recently found **new QSL** phase in 2D ^3He

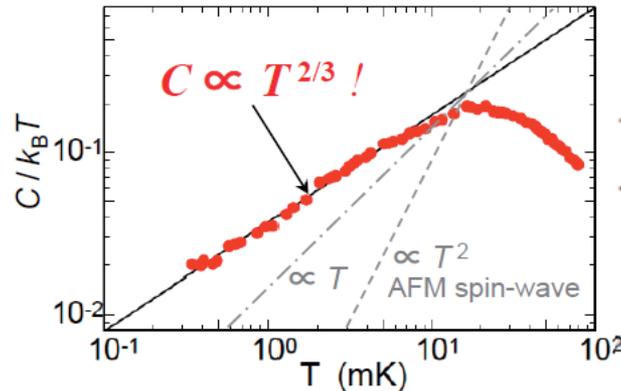
- **Lowest density** (5.25 nm^{-2}) **solid ^3He** ever achieved (pre-plating graphite with a bilayer of HD).
- Both **specific heat (C)** and **magnetic susceptibility (χ)** show **anomalous T -dependencies** at $T \ll J/k_B$.



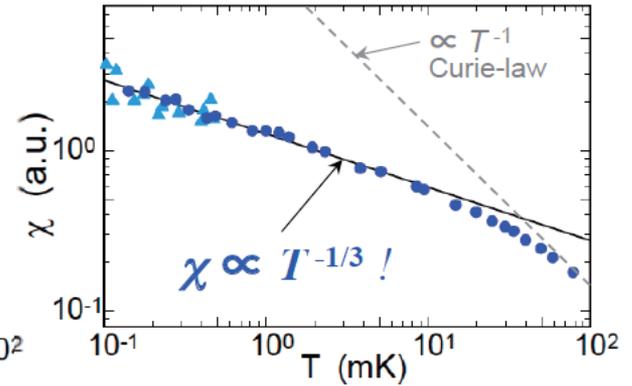
K. Ishida, HF et al. PRL 79, 3451 (1997)



$^3\text{He}/^3\text{He}/\text{gr}$



• M. Kamada, HF et al. (2015)



• H. Ikegami et al., PRL 85, 5146 (2000)
 ▲ R. Masutomi, et al., PRL 92, 025301 (2004)

$$\chi T / C (\propto R_W) = \text{const.}$$

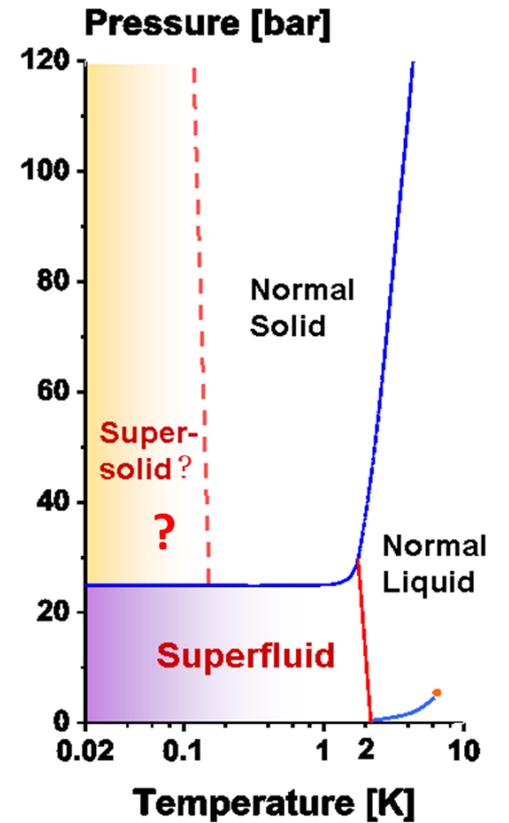
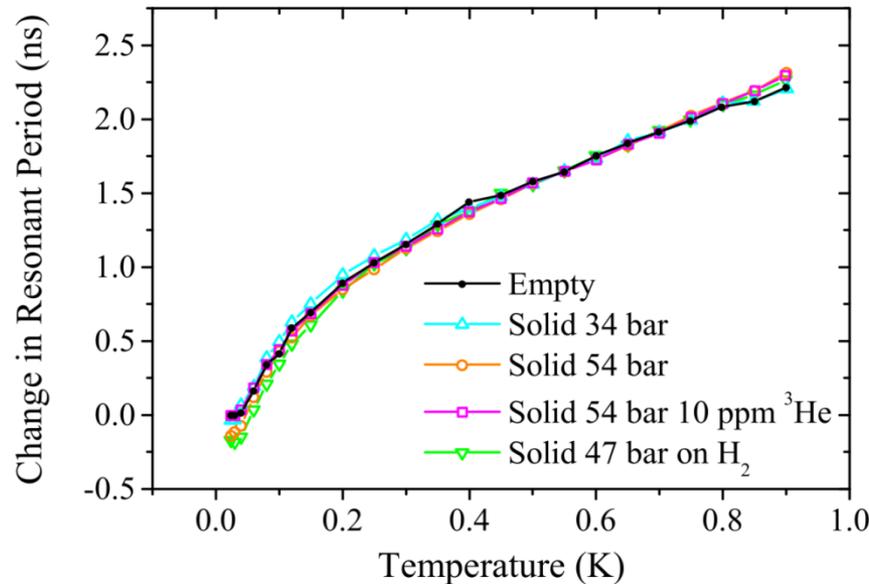
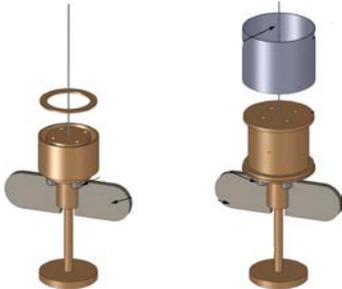
: Can define **Wilson ratio** just as mobile fermion system?!

First experimental confirmation of **Fermion fractionalization !**

Supersolidity in ^4He ?

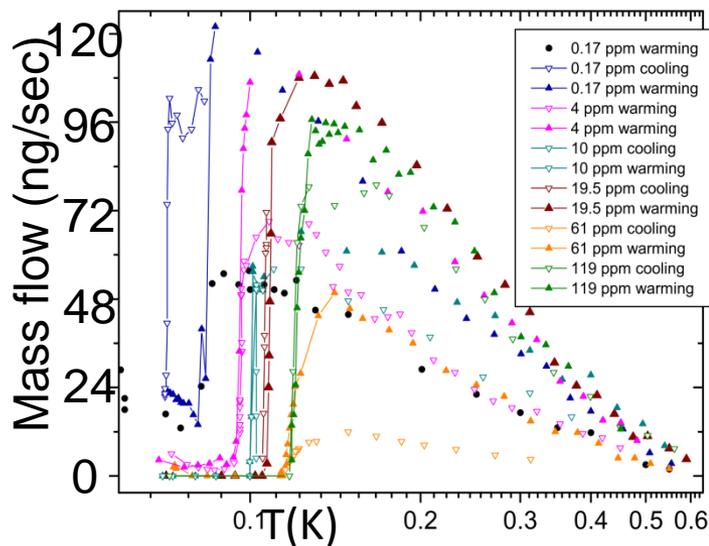
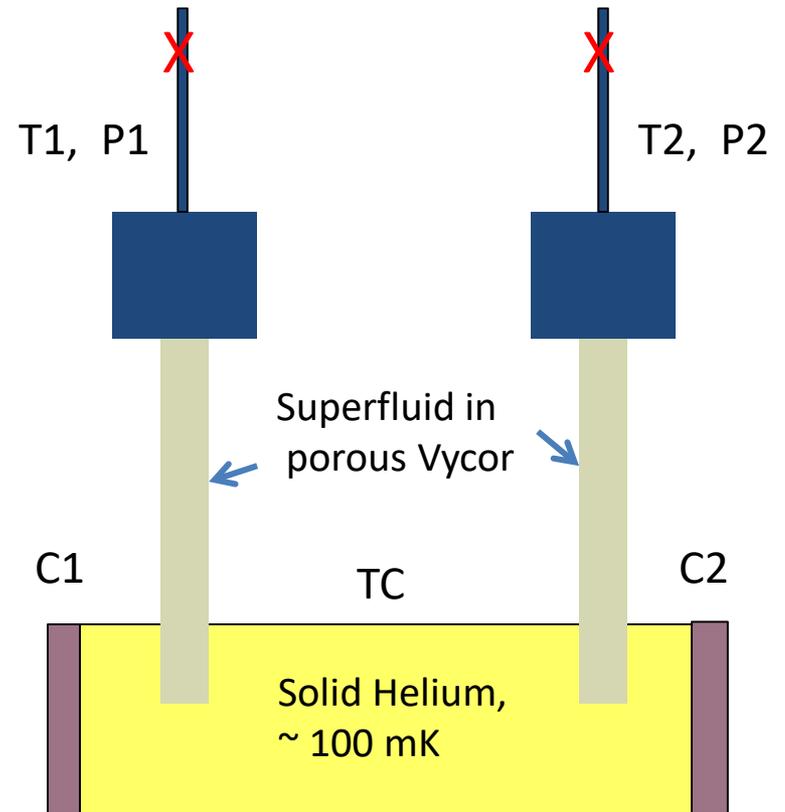
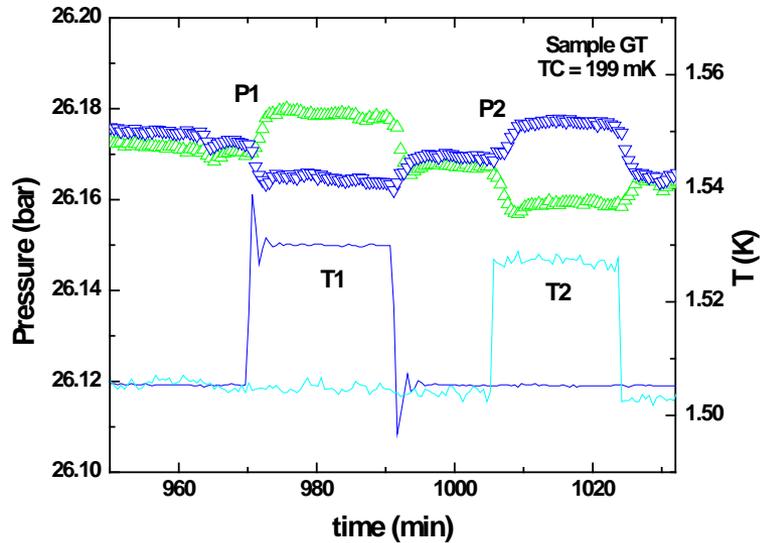
Torsional oscillator experiments between 2004 and 2012 reported possible evidence of superfluid-like behavior in solid helium.

Measurements since 2012 in carefully designed and rigid TOs show that superfluid fraction, if present is less than 1×10^{-5}



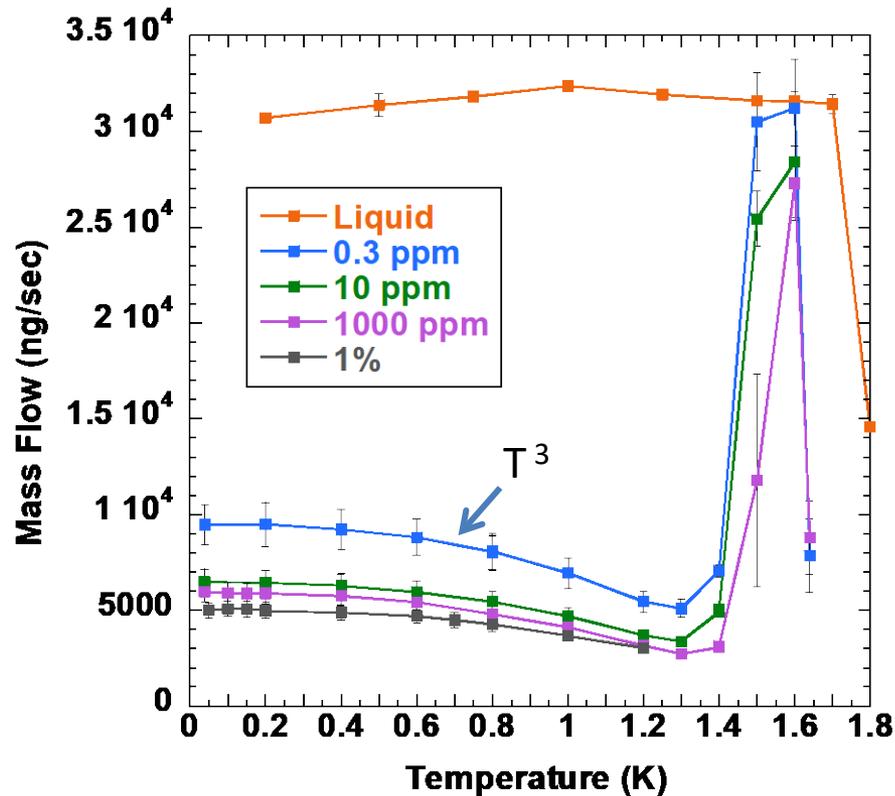
So is this the end of supersolid?

Superfluid fountain effect showing mass flow through solid helium samples



UMass Sandwich

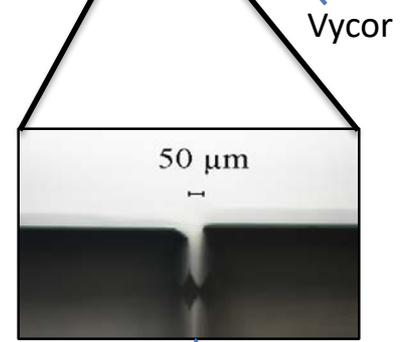
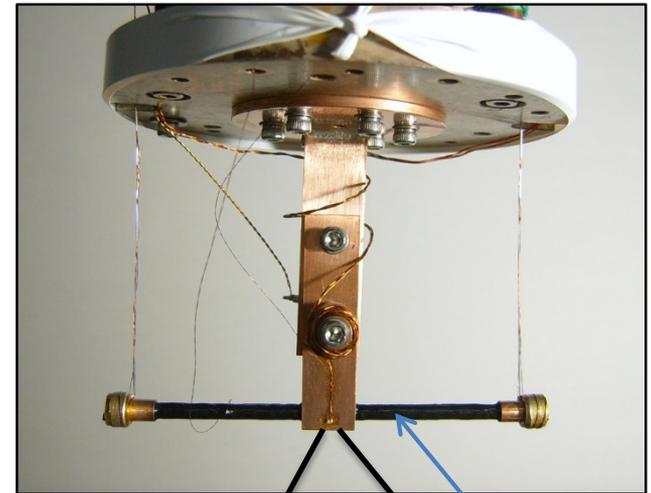
Vekhov and Hallock, *PRL* 113, 035302 (2014)



Reproducible superfluid-like mass flow seen from 50 mK until the melting T. T^3 dependence is seen.
 Note: superfluid density of liquid ^4He shows T^4 dependence.

Flow rate decreases with pressure but measurable up to 31 bar.
 Flow rate is ~ 100 times larger than that found at Umass.

Penn State (thin) Sandwich



Vycor

Space for bulk solid ^4He