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Workshop on Supersolid 2008

18 - 22 August 2008

Probing DC flow and the upper limit of nonclassical rotational inertia in solid Helium-4

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Probing the upper limit of nonclassical rotational inertia and flow in solid ^{4}He

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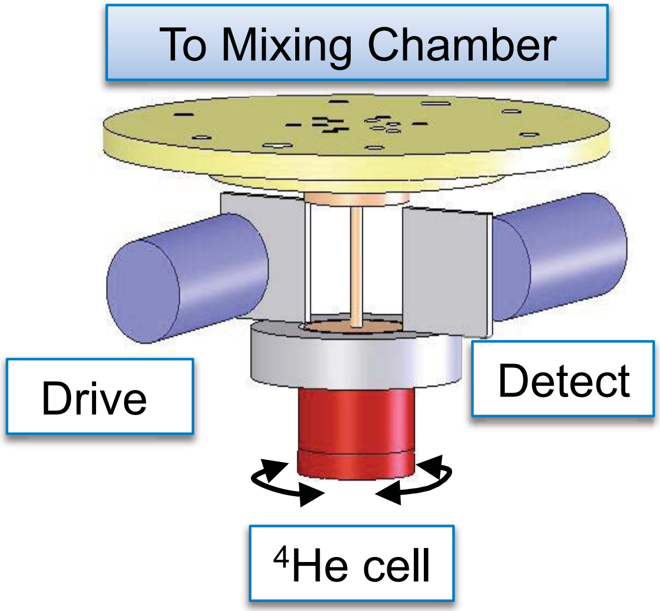
Outline

- Probing the upper limit of NCRI with a torsional oscillator
  - Experimental technique to determine inertia of solid
  - Biggest observed fraction and trend
  - Test of superflow in confined spaces
  - Hysteresis
- Attempt to observe mass flow
  - Setup
  - Mass flow at low pressures
- Conclusion

Motivation

- **Principle**: Measure inertia changes: $P = 2\pi\sqrt{\frac{I}{k}}$
  (P resonance period, k spring constant, I inertia)
- Nonclassical rotational inertia (NCRI or ρ_s/ρ): $\mathrm{NCRI} = \frac{\text{Period drop below } T_c}{\text{Period increase upon filling}}$



Parameters

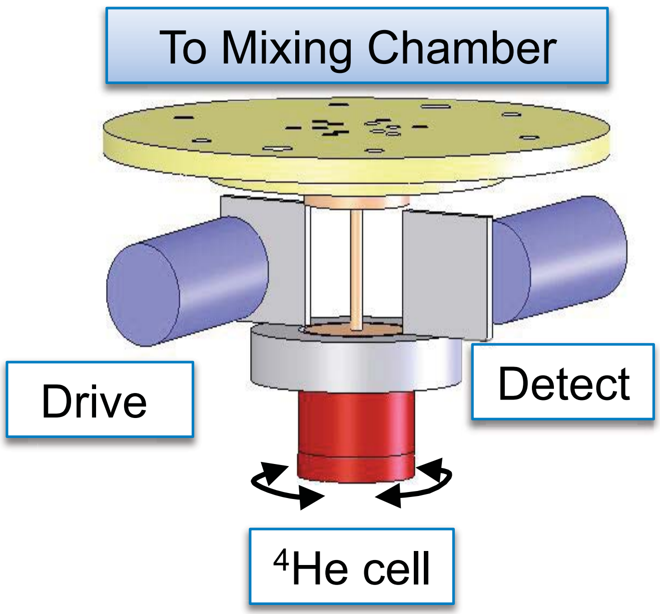
- Velocity
- Frequency
- Sample growth
- Pressure
- Sample geometry
- ^{3}He concentration

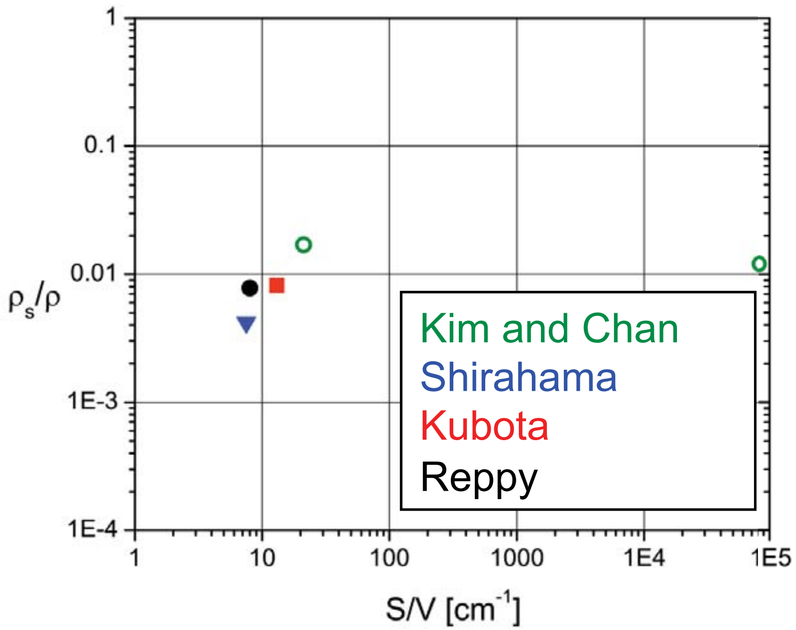
Motivation

- **Principle**: Measure inertia changes:
  (P resonance period, k spring constant, I inertia)

$$P = 2\pi\sqrt{\frac{I}{k}}$$

- **Puzzle**: 0.4 % < ρ_s/ρ < 1.5 %



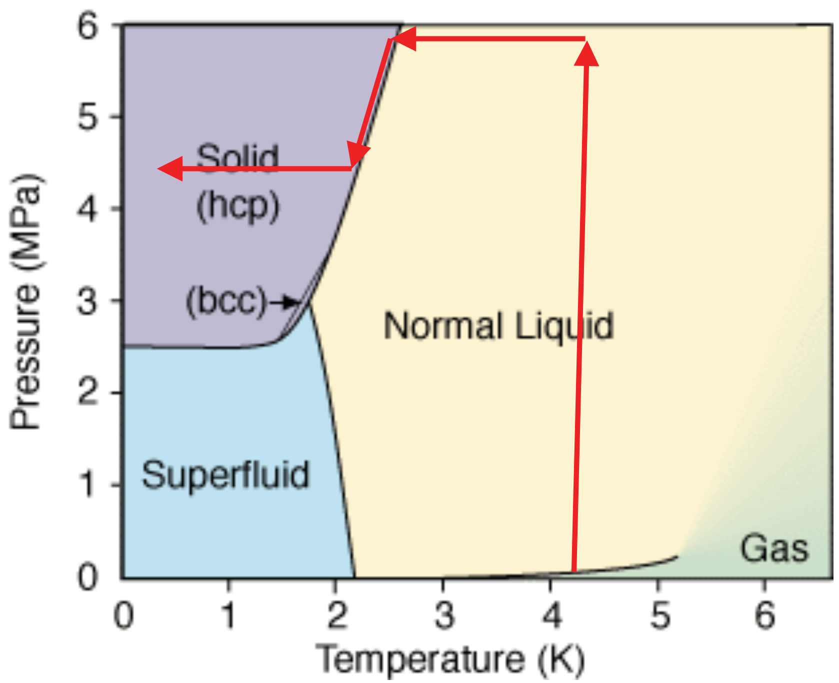


Kim and Chan, Science, **305**, 1941(2004)
Penzev et al., cond-mat/0702632
Kondo et al., cond-mat/0607032 (2006)
Rittner and Reppy, PRL **96**, (2006)

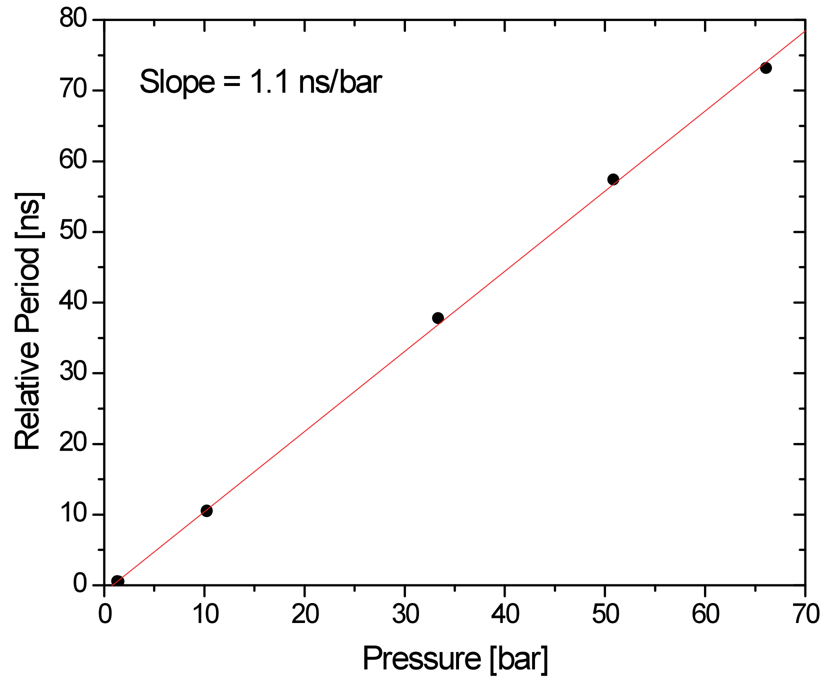
Determination of solid inertia in constant volume growth

- **Problem:** Pressure changes during solidification → period drop

Constant Volume Growth:



Period depends on pressure:



Method 1: reversibly blocked oscillator

f_{res} = 495 Hz

$Q_{4K} = 8 \times 10^5$

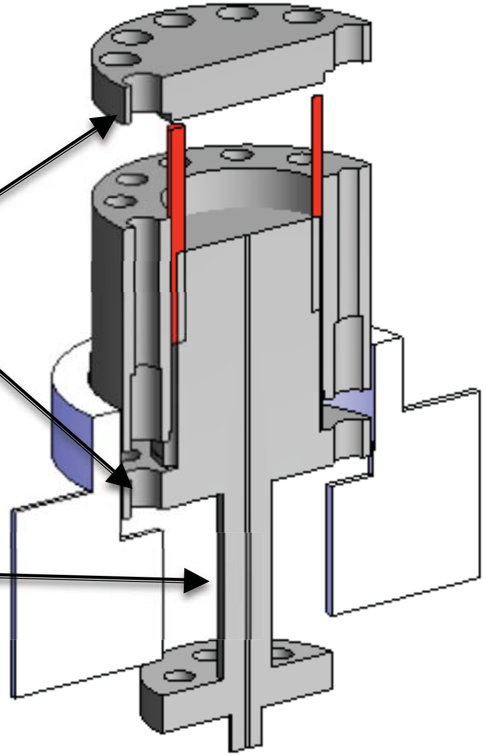
Removable top and bottom attached with screws

Al Torsion Rod:

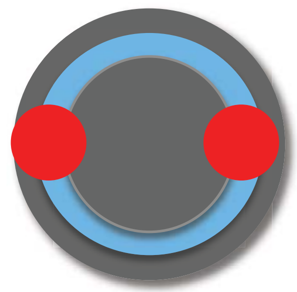
OD = 5.1 mm

ID = 0.76 mm

Length = 1.9 cm

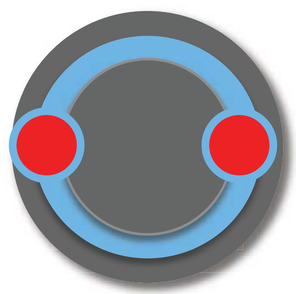


Top view: blocked



→ Solid inertia

Top view: open



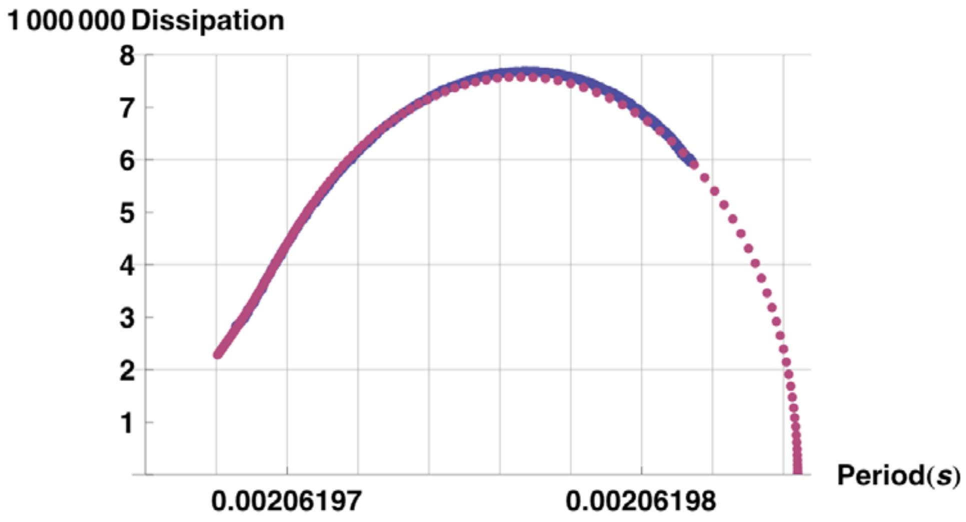
→ NCRI

Method 2: Viscosity of ^{3}He

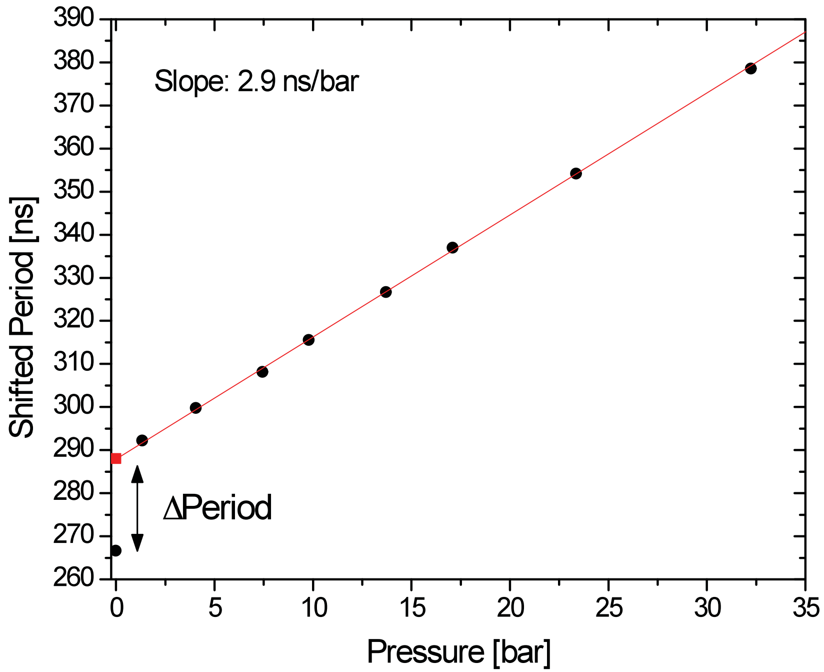
- Liquid ^{3}He: Determine gap from viscosity[1]
- Reversible block in annular cell

error < 5 %

Liquid Helium-3 inertia

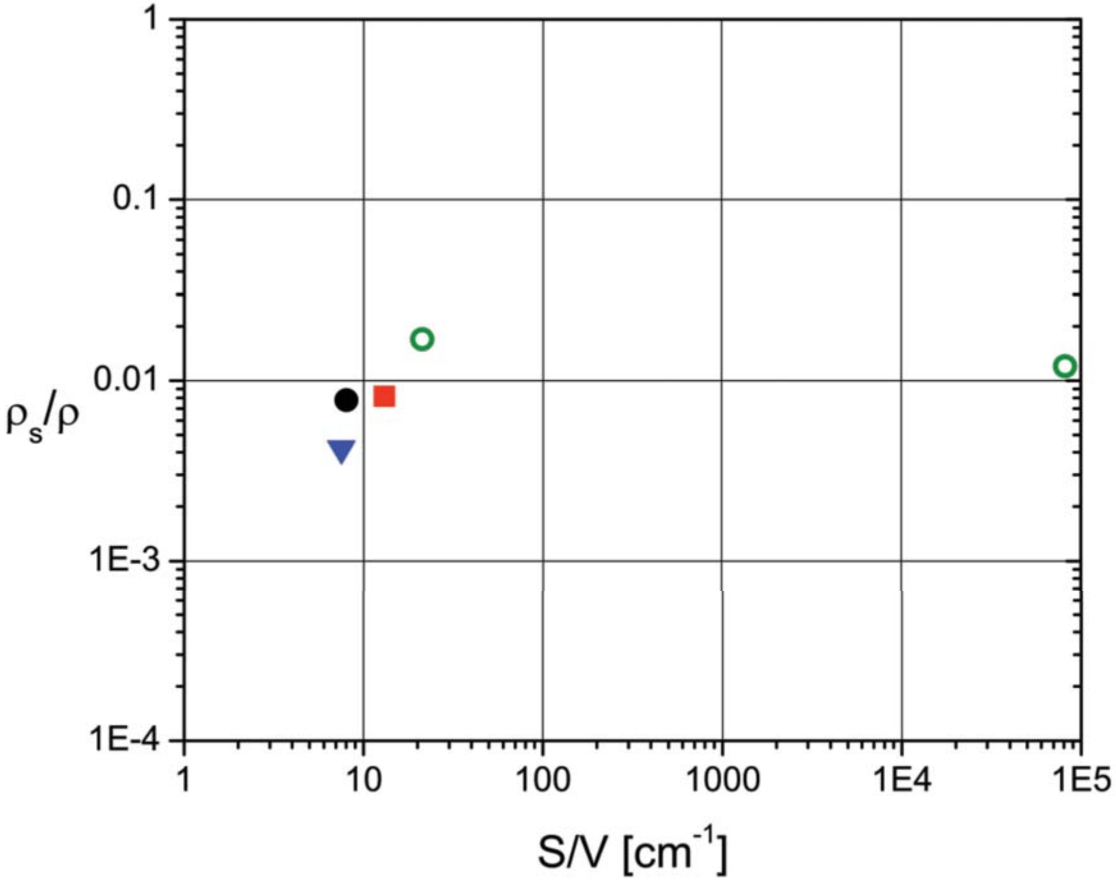


Blocked annulus inertia

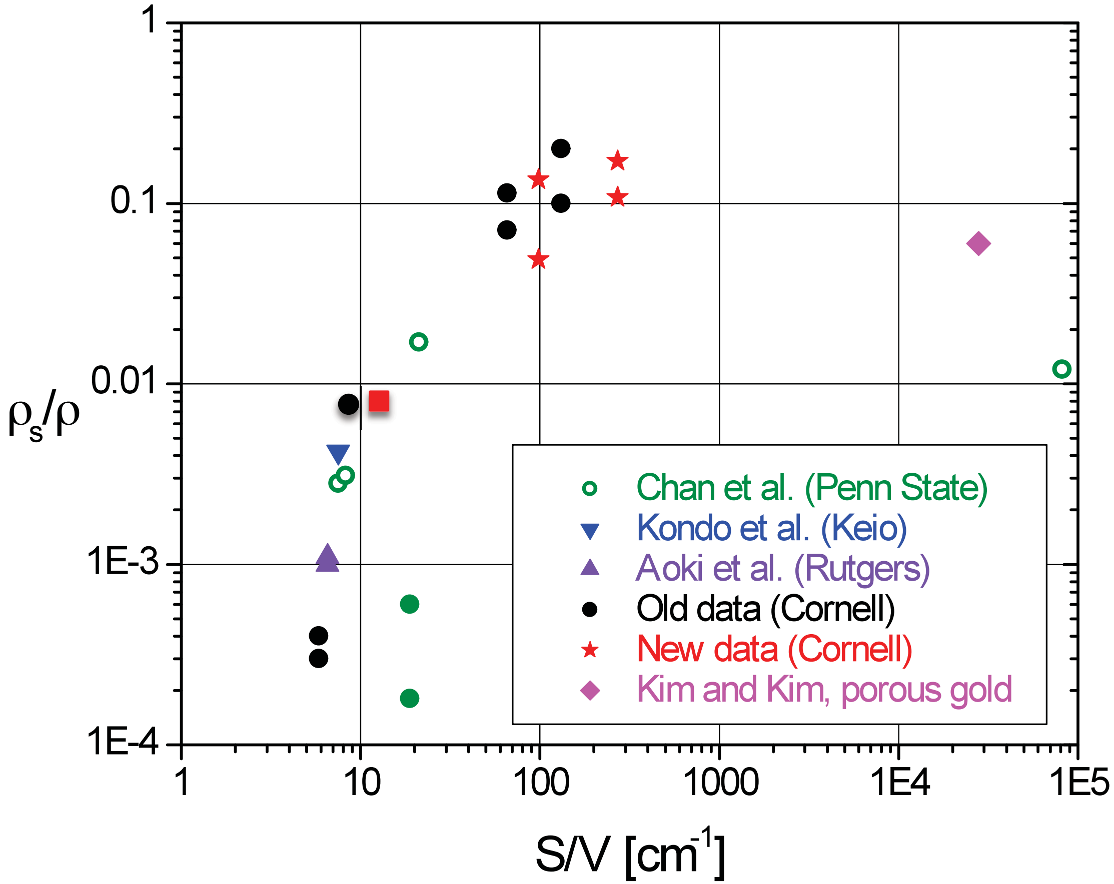


1 Parpia & Reppy, PRL 40, 565 (1978)

NCRI dependence on S/V



NCRI dependence on S/V



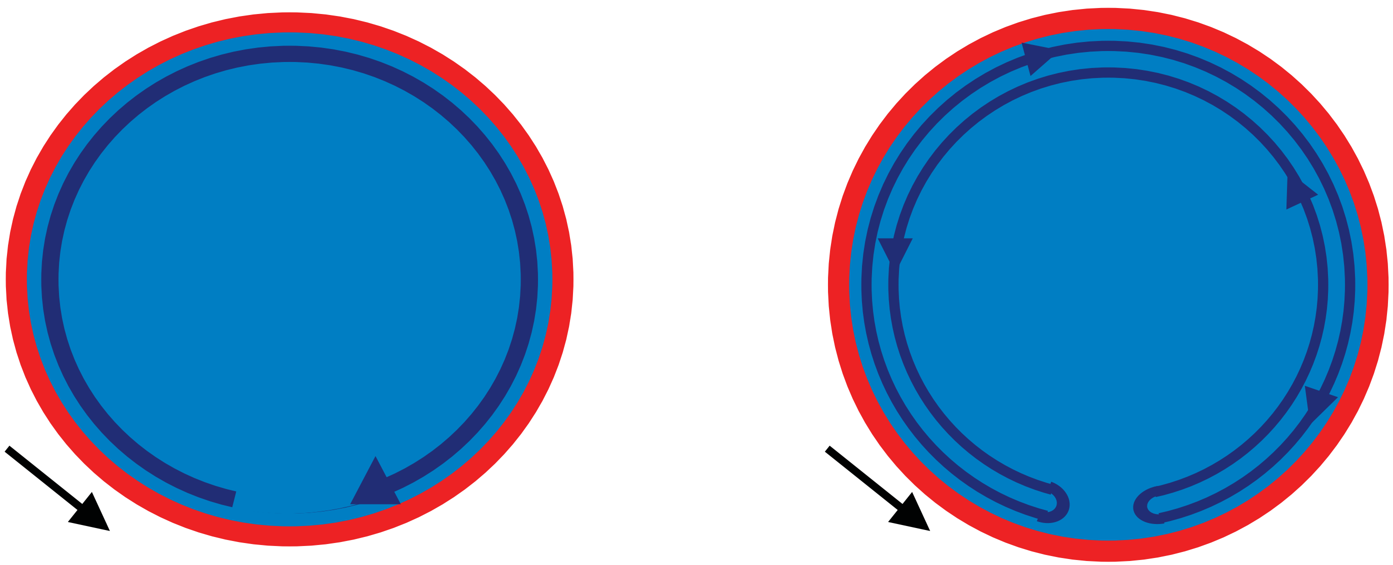
Clark et al., *PRL 99,* 135302 (2007)
M. Kondo et al., cond-mat/0607032 (2006)
Rittner & Reppy, PRL 98, 175302 (2007)

Kim and Chan, Science, 305, 1941(2004)
Aoki et al., PRL 99, 015301 (2007)
Rittner & Reppy, arxiv:0807.2183

Test for superflow

- Superflow is irrotational
- Experimental test: Blocked annulus

Flow in oscillating frame



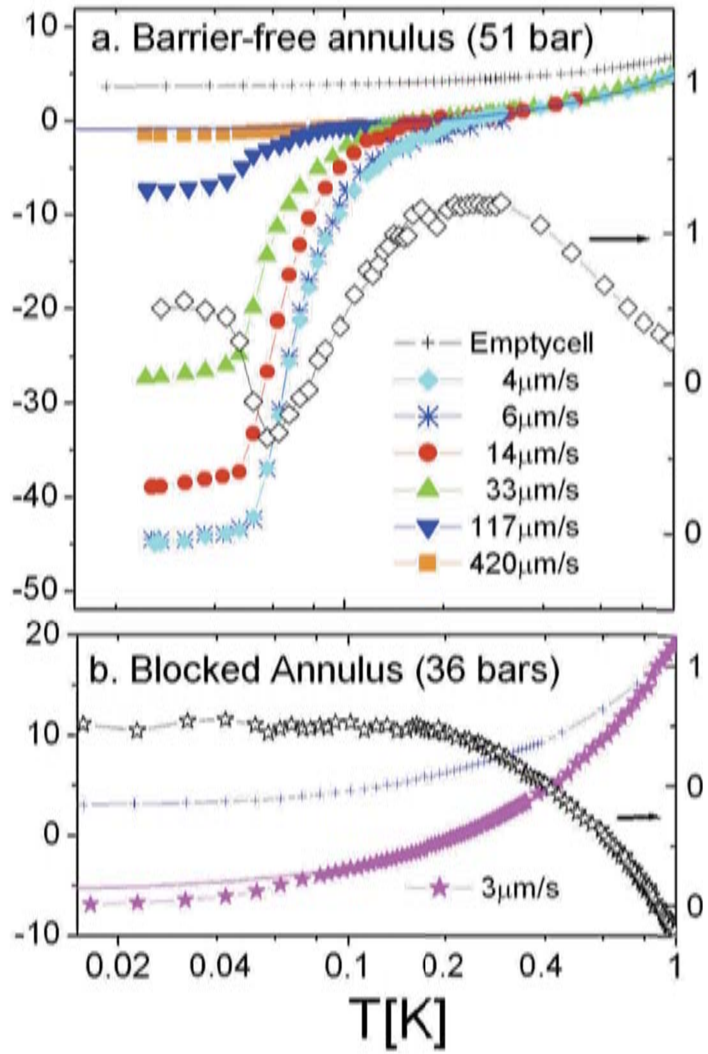
Kim & Chan's blocked annulus[1]

- **Theoretical prediction**:
  100-fold reduction of period drop[2] for 0.63 mm annulus

- **Exp. Observation:**
  45-fold reduction

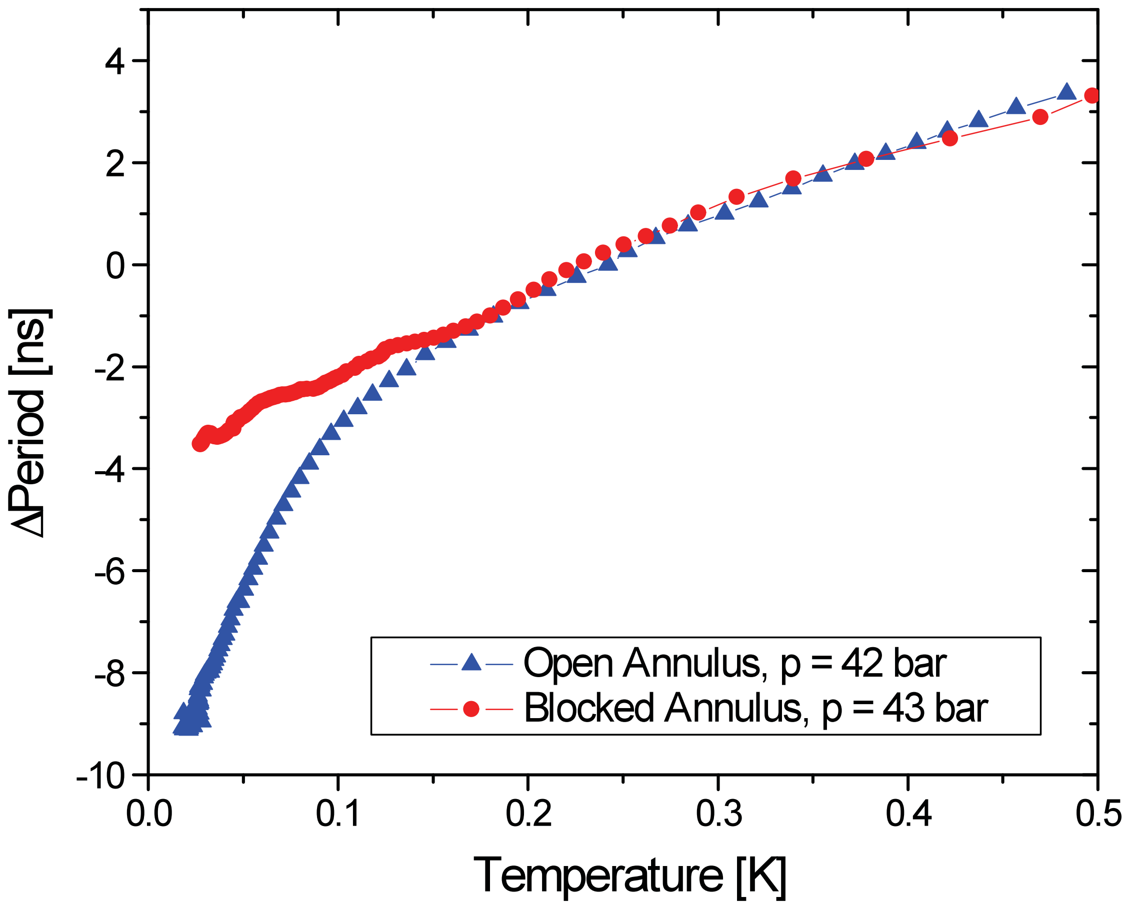
- **Problem**:
  $gap_{open\ annulus} = 0.95$ mm
  $gap_{blocked\ annulus} = 1.1$ mm

- Repeat in narrow annulus



1 Kim & Chan, Science (2004)
2 Mueller, private communication with KC

Blocking a narrow annulus



- Gap 73 μm
- NCRI (open) = 17.1%
  NCRI (block) < 0.8%

  ⬇

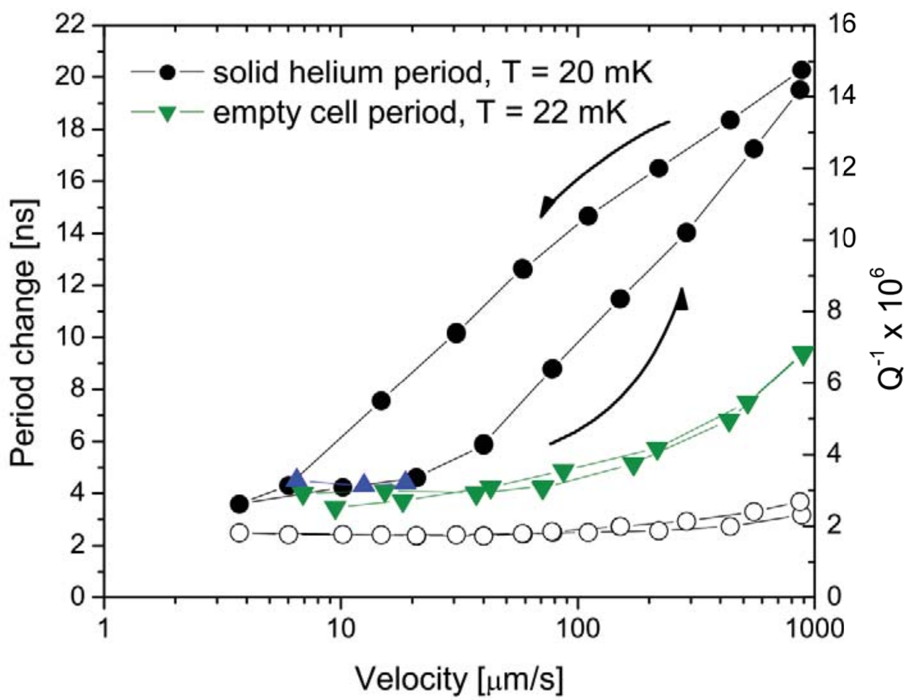
  > 21-fold reduction
- Consistent with **superflow**

Velocity Hysteresis

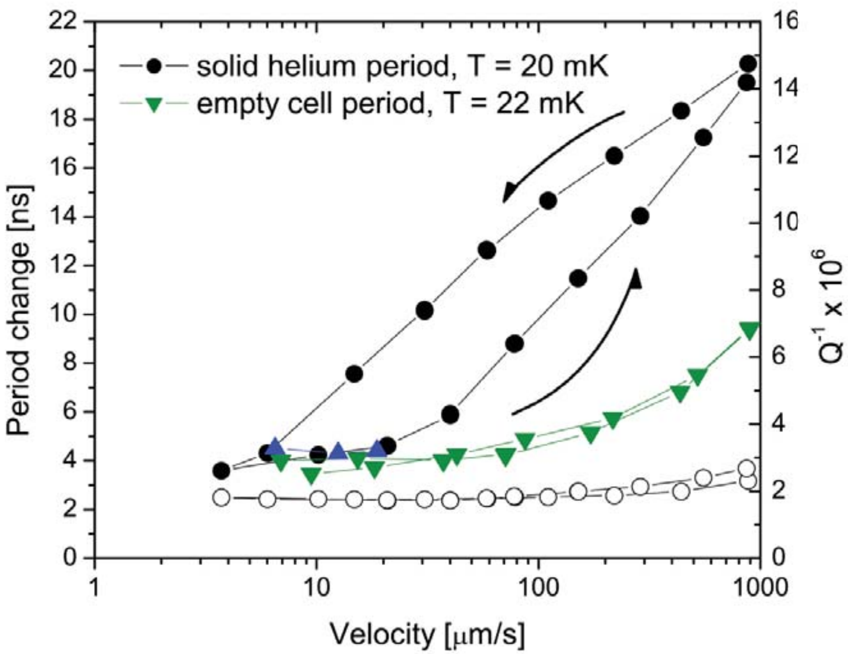
Experimental Procedure

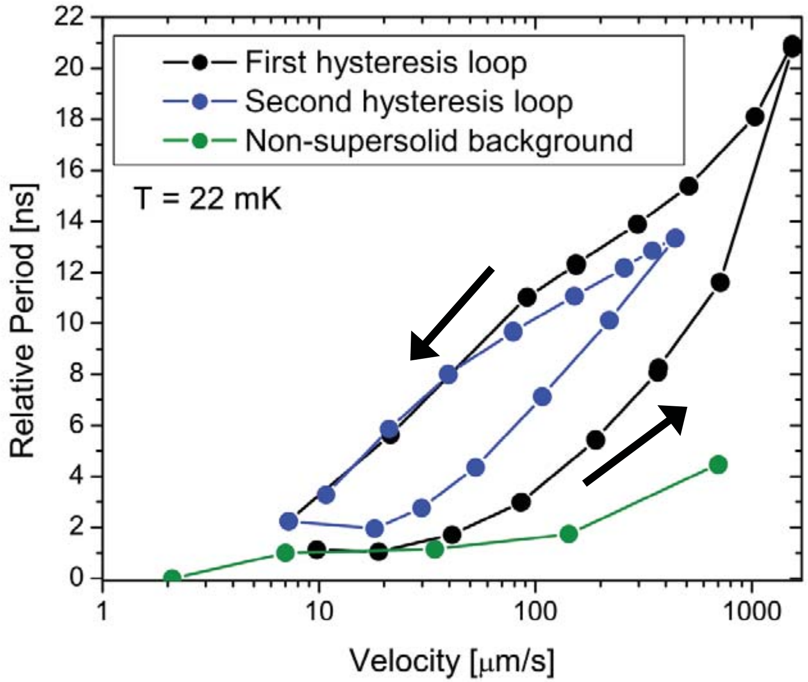
- Fix drive
- Cool to base temperature (18-20 mK)
- Change velocity in steps
- Wait for equilibrium given by Q (~20 min)

Annulus, gap = 148.3 μm



High vs. low velocity cooling





- Critical velocity exists in narrow annular cells (148 μm & 203 μm) → less hysteresis
- No difference between high & low velocity cooling

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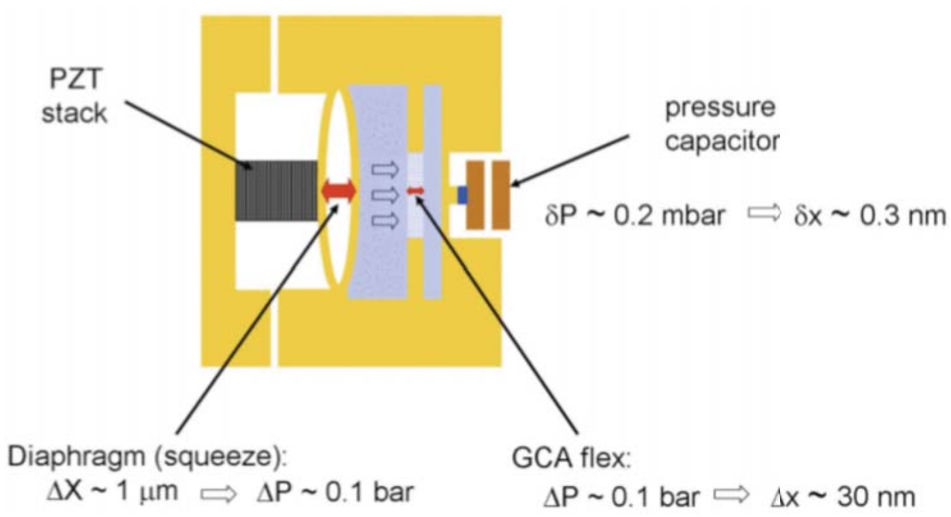
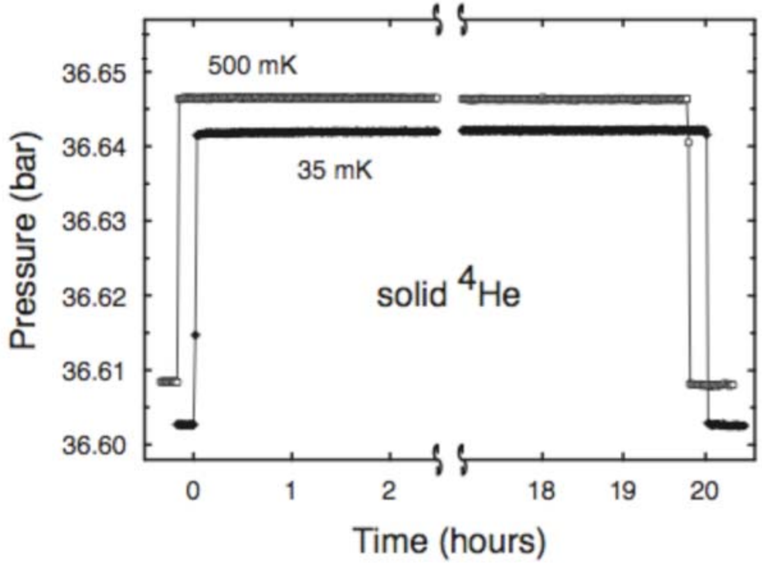
Motivation for flow measurements

Previous DC flow experiments

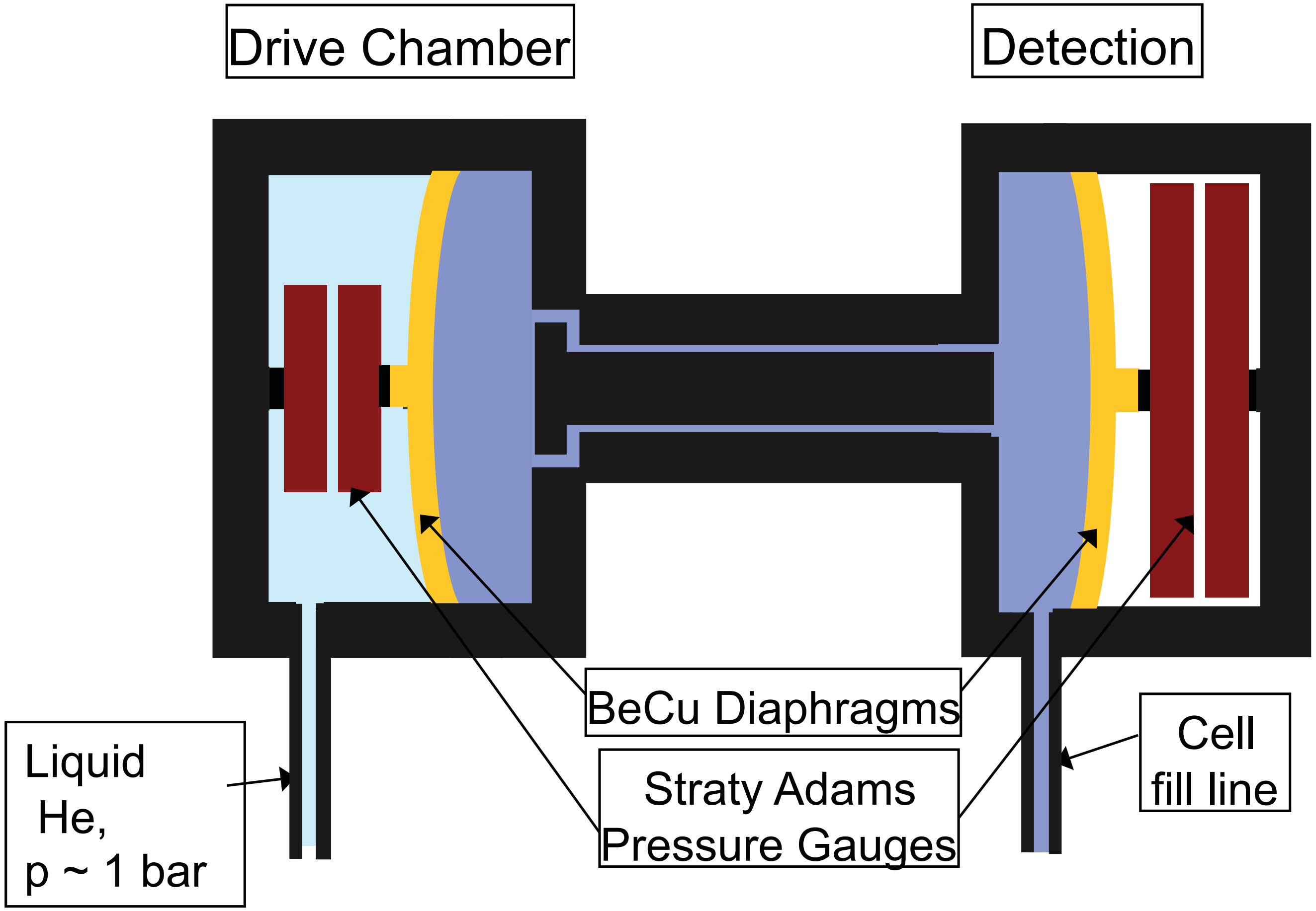




- Eliminate elastic flexing → short term response
- Extend pressure resolution by 100
- Disordered samples

Day & Beamish, PRL **96,** 105304 (2006)

Pressure induced flow



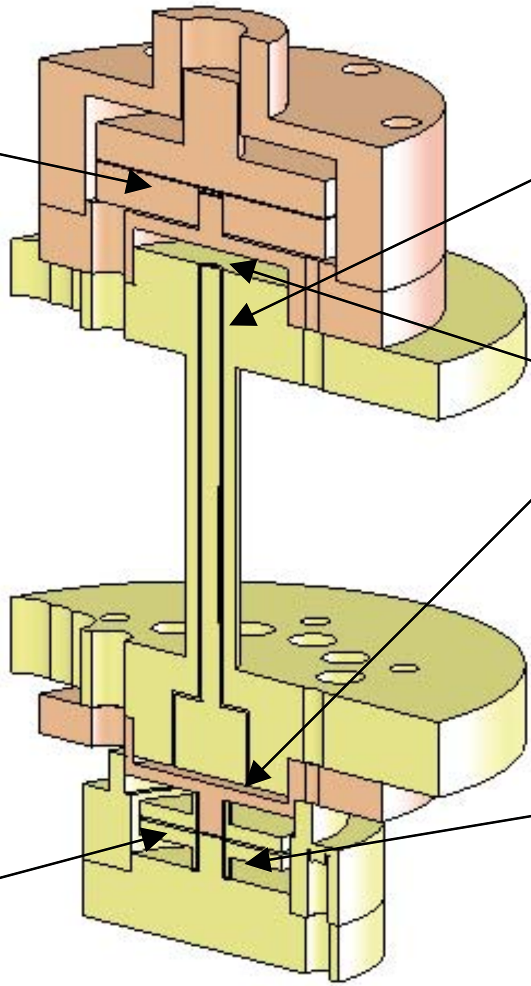
- Apply pressure to solid

Experimental setup

Straty-Adams
Pressure Gauge
$A = 5.0625\ cm^2$
$d \sim 50\ \mu m$
Sensitivity: 2 μbar

Slit:
width = 100 μm
length = 3.8 cm

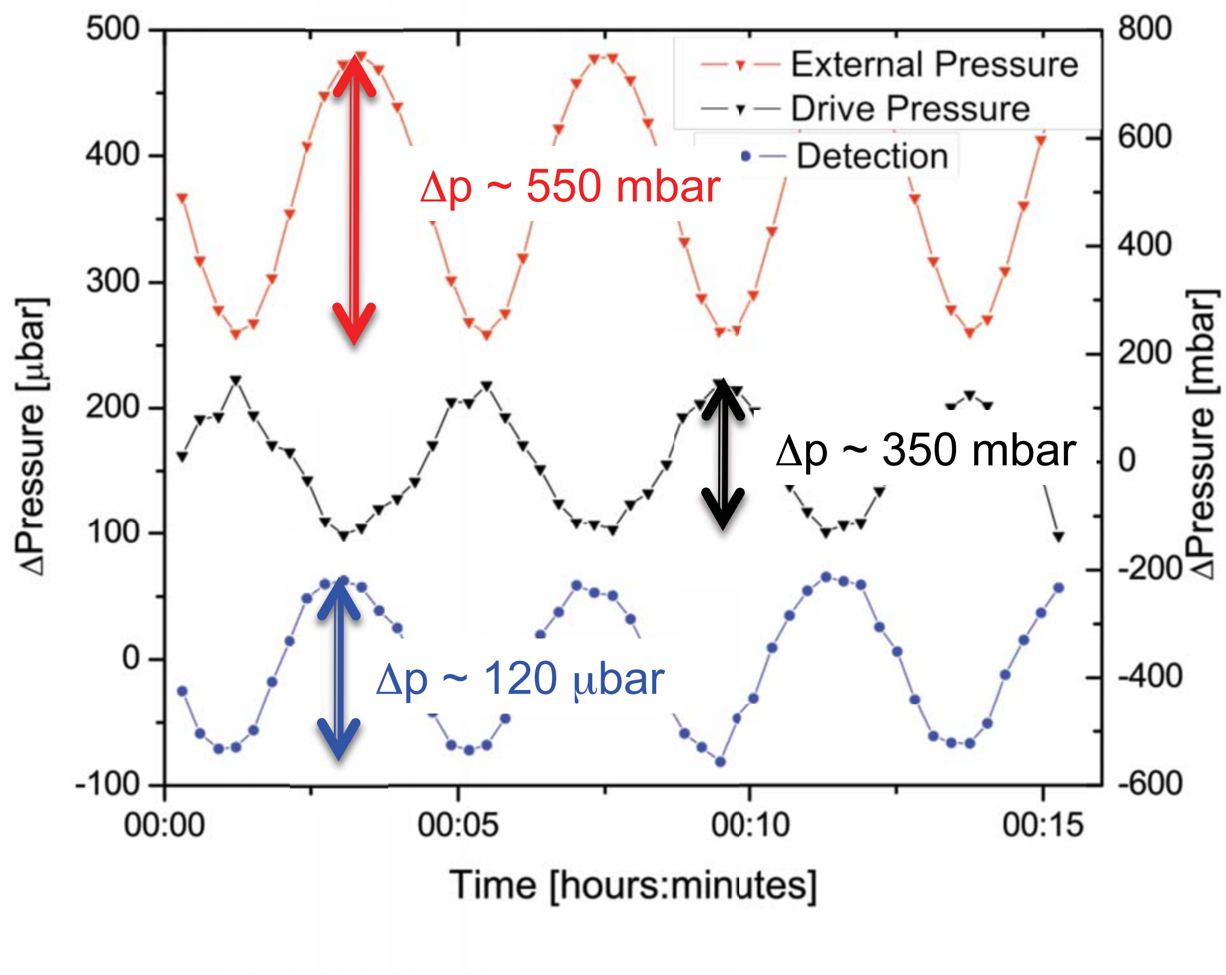
Solid Helium:
gaps = 250 μm
Δp solid ~ 50-100 mbar



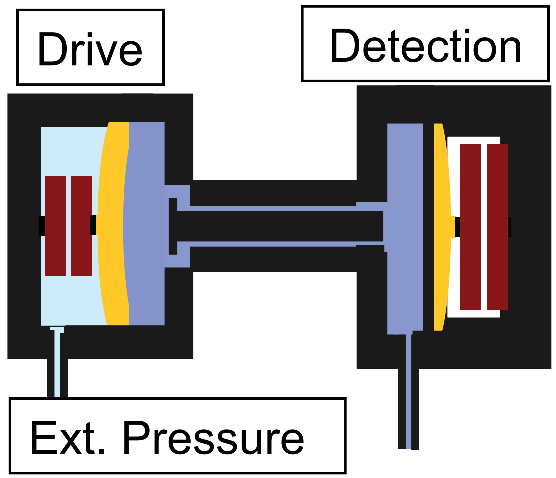
Pressure Gauge
$A = 1.90\ cm^2$
$d \sim 350\ \mu m$
Sensitivity: 1 mbar

Liquid Helium
Drive Chamber,
p ~ 1 bar

Pushing on solid → probable mass flow

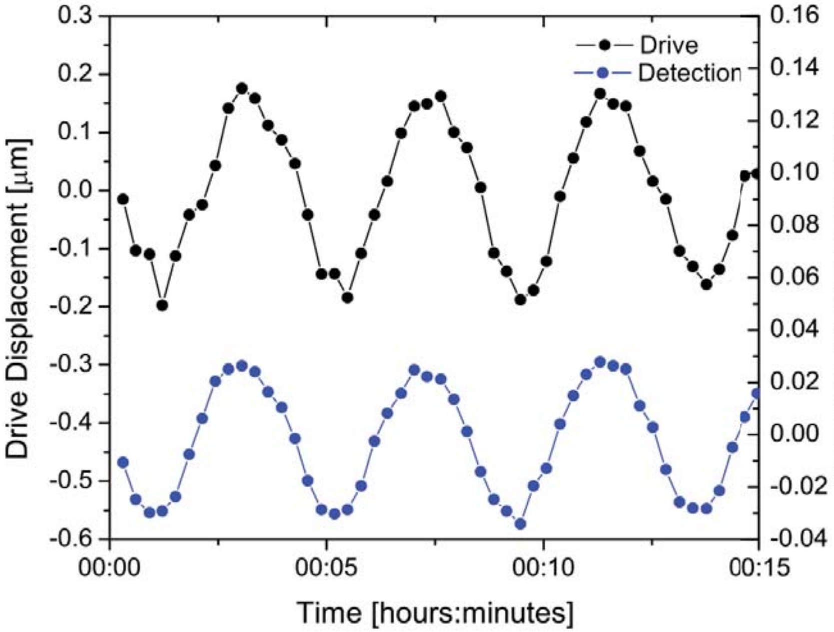


- Frequency = 2 mHz
- p_{Detect} = 25.7 bar
- Δp ~ 50 mbar
- T = 300 mK

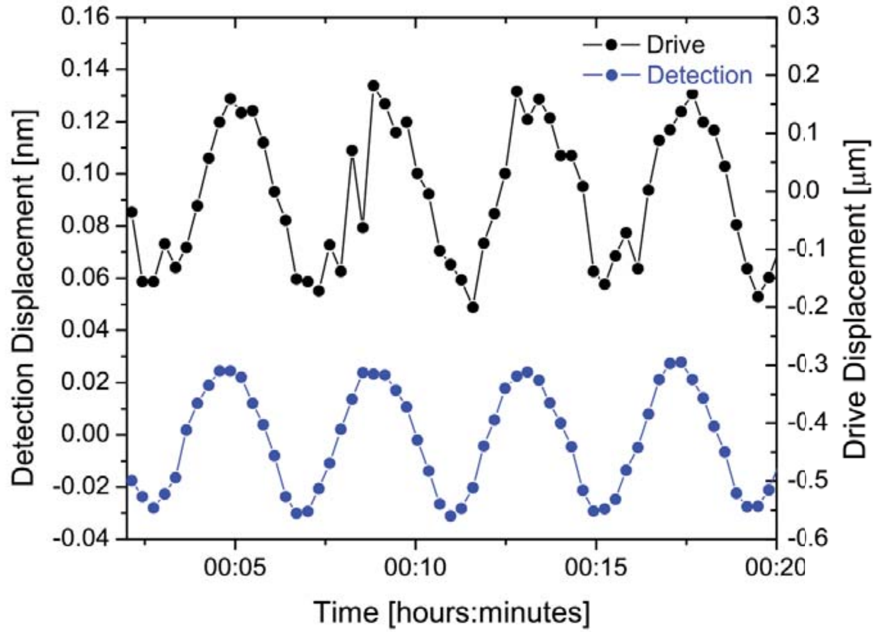


Low temperature mass flow

T = 300 mK



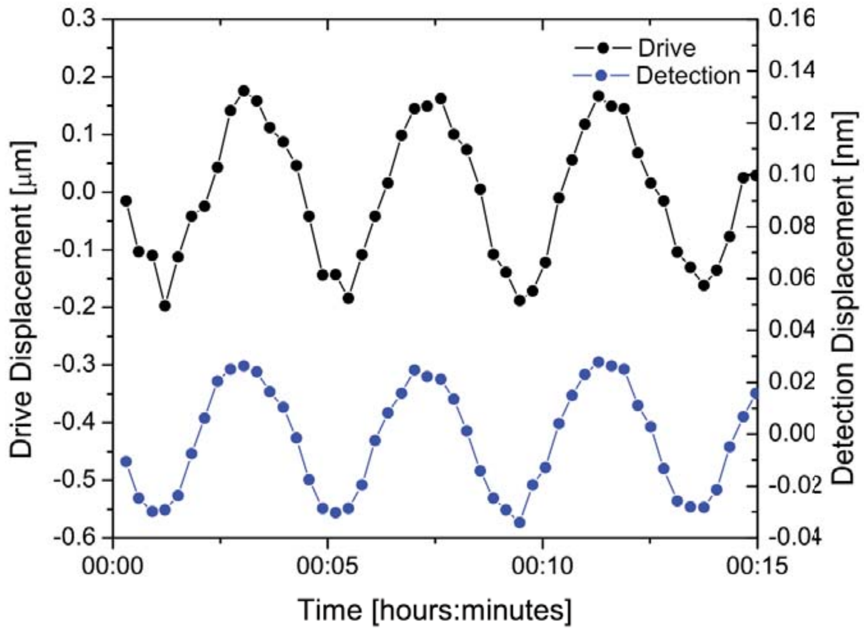
T = 20 mK



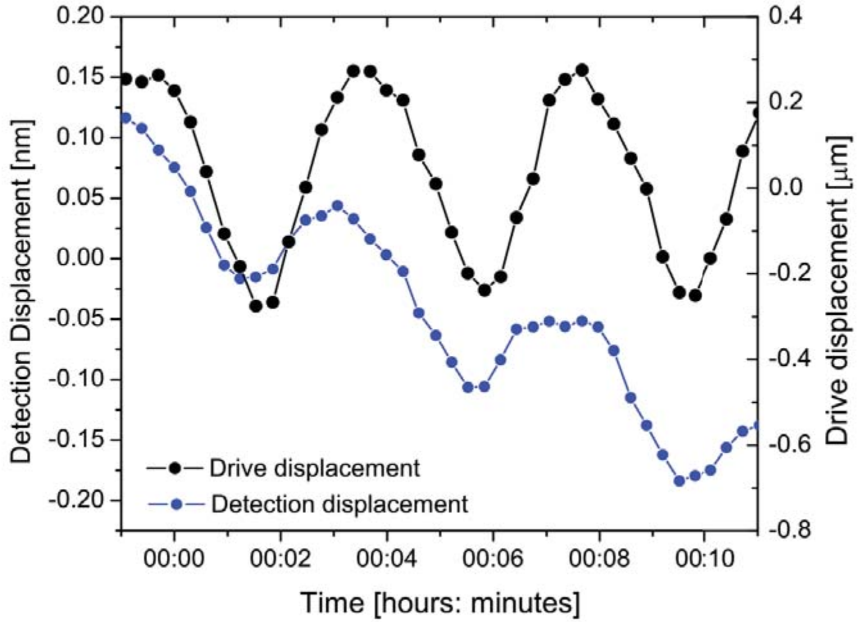
- Ratio of response to drive displacement: ~1 x 10^{-4} → Superfluid Fraction ~ 0.2%

Higher temperature flow

T = 300 mK

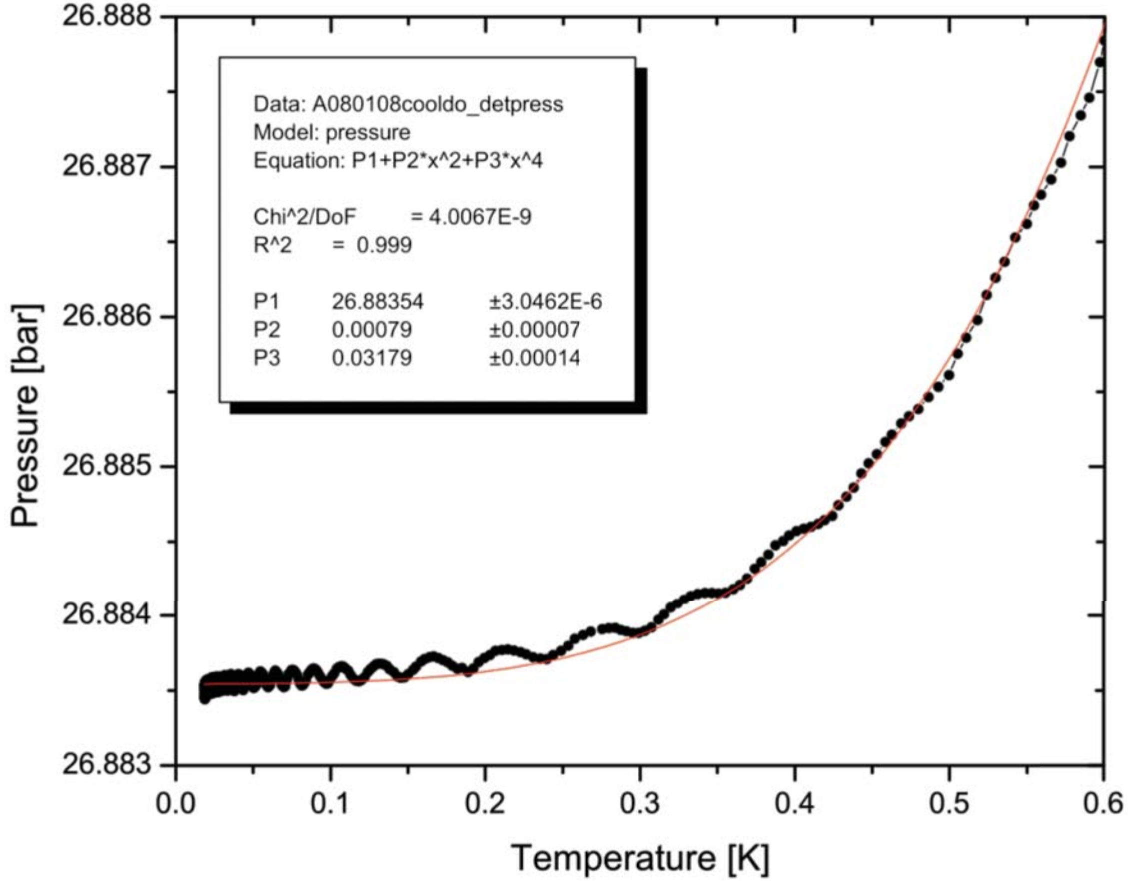


T = 800 mK



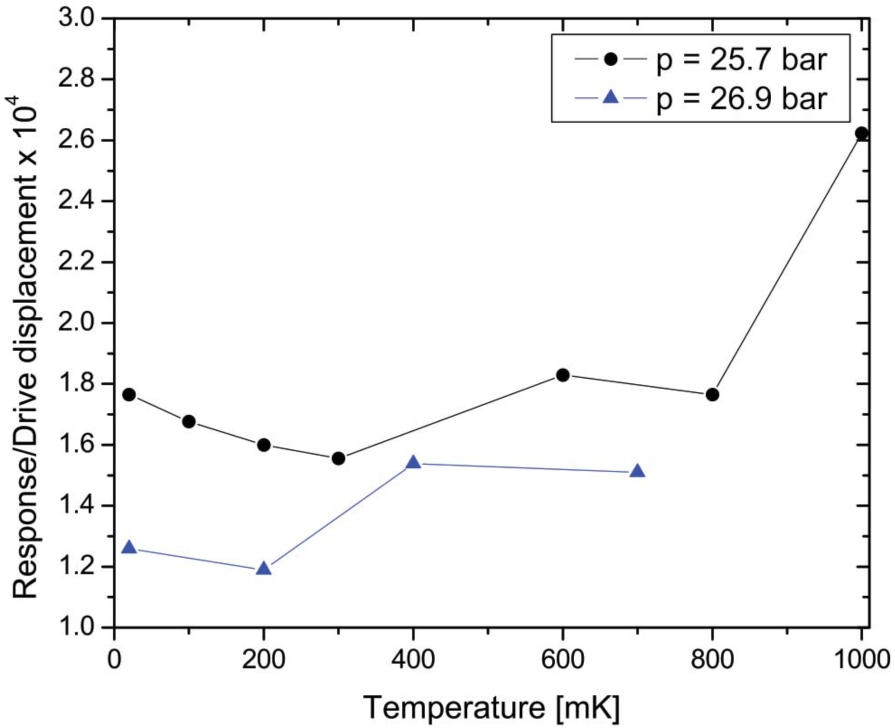
- Signal size temperature independent for 18 mK < T < 1 K

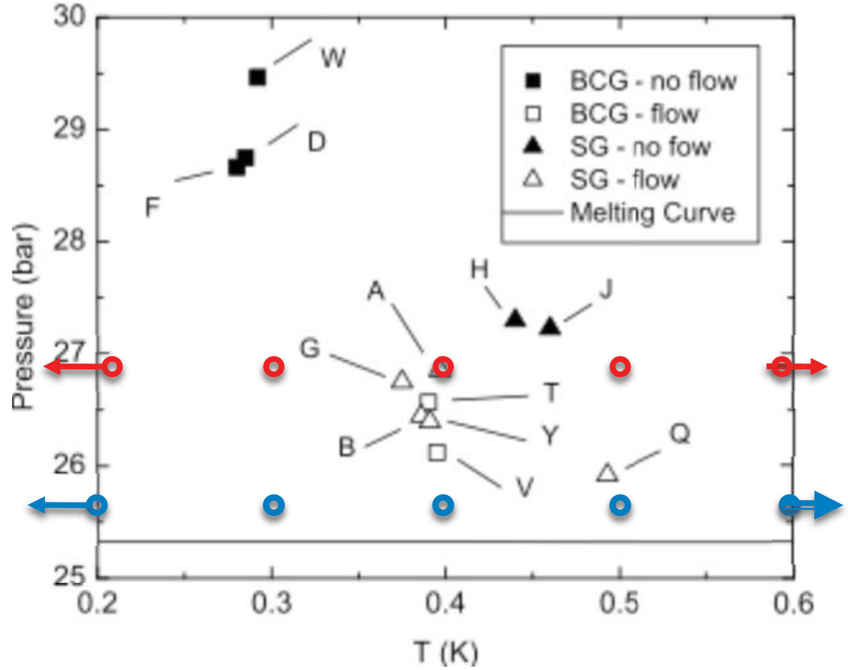
Sample characterization



- Fit detection pressure, $p = p_0+aT^2+bT^4$: a = 0.00079 bar/T^2 → sample disordered

Overview T dependence





- **Interpretation:** Liquid channels

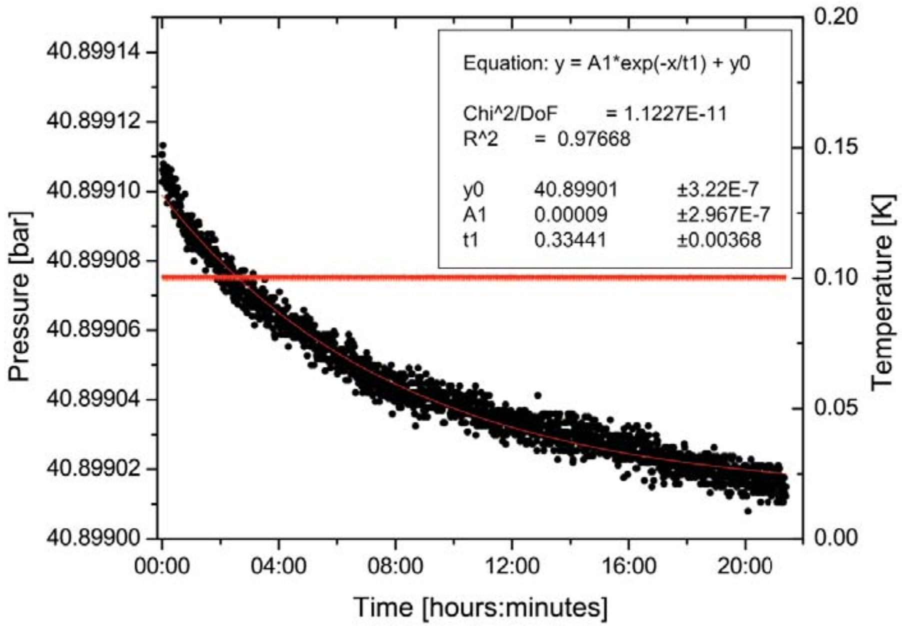
- Related to Ray and Hallock's low pressure mass flow?

Ray & Hallock, PRL 100, 235301(2008)

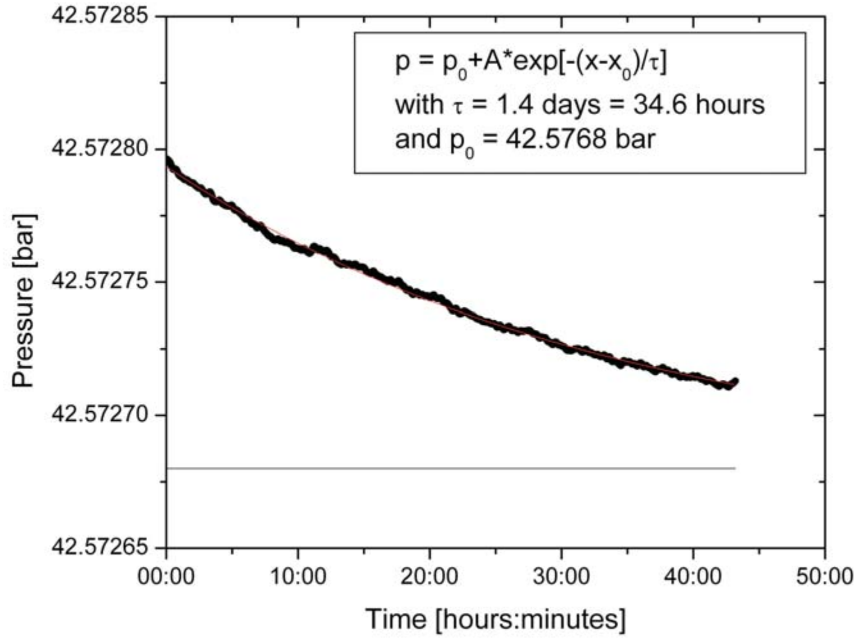
Sasaki et al., PRL **99**, 205301 (2007)

Relaxation processes in helium

T = 100 mK



T = 19 mK

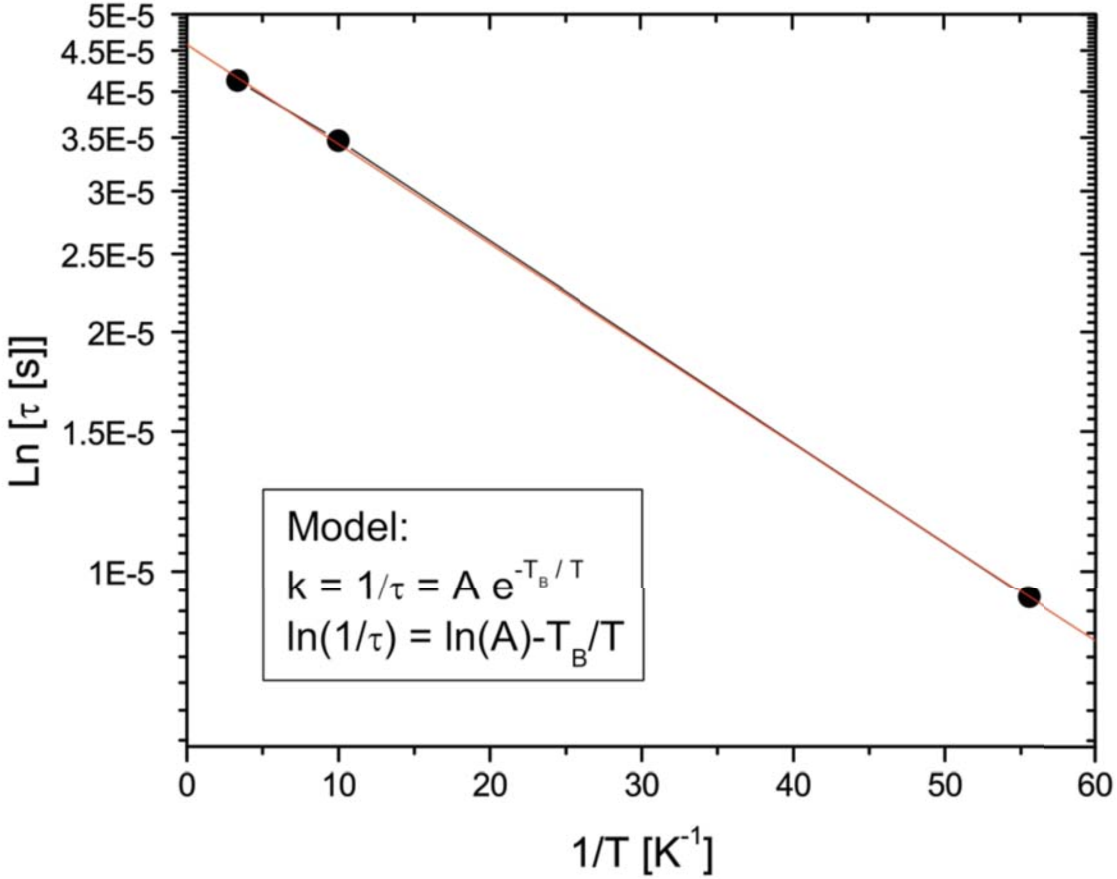


- 100 mK → τ = 8.02 hrs

19 mK → τ = 34.6 hrs

- Plastic flow

Overview Relaxations



- Arrhenius plot, barrier height: T_B = 28 mK

Summary & open questions

- Supersolid fraction levels off at ~ 20% in narrow annuli.
- Blocked annulus experiment consistent with superflow for 17.1 % NCRI.
- Pushing on solid probably results in mass flow at low pressures.

- Superflow?
- Relation to Ray & Hallock's DC flow experiment? Relation to superfluid liquid channels?
- Higher pressure?

1st part: Rittner & Reppy, arXiv:0807.2183 (2008)