Torsion Pendulum Experiments with ^{3}He Confined in Uniaxially Compressed Aerogel

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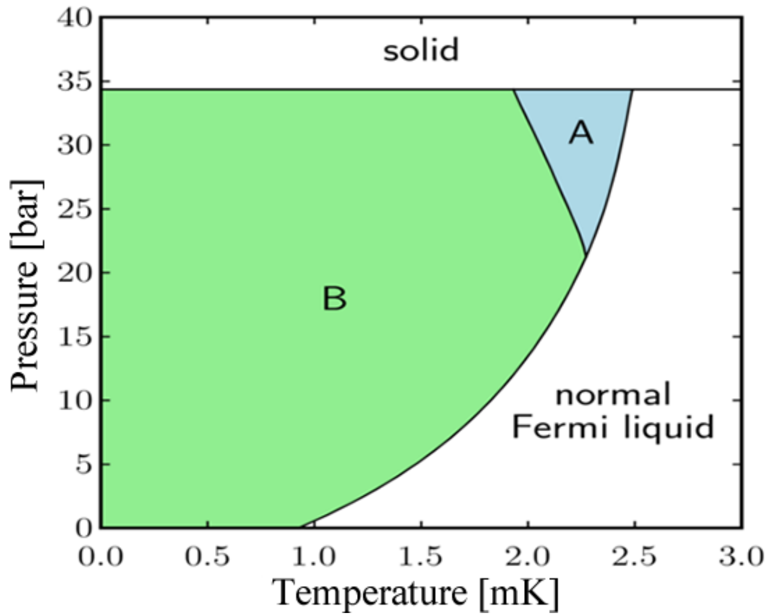
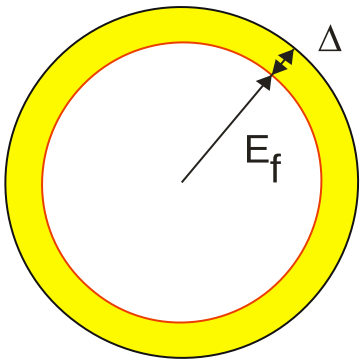
J. Pollanen, W. Halperin at Northwestern

Outline

- Motivation and experimental setup
- Phase Diagram of ^3He in compressed aerogel
- Hydrodynamics of the normal fluid within the aerogel
- Dissipation signatures of the superfluid phases

Bulk Superfluid ^{3}He phases





Isotropic:

B (BW) phase

Preserves Time Reversal Symmetry

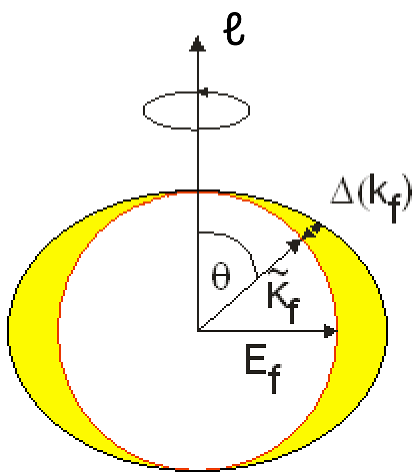
Anisotropic:

A (ABM) phase

Chiral superfluid

Breaks Time Reversal Symmetry

Stabilized by strong coupling at high P

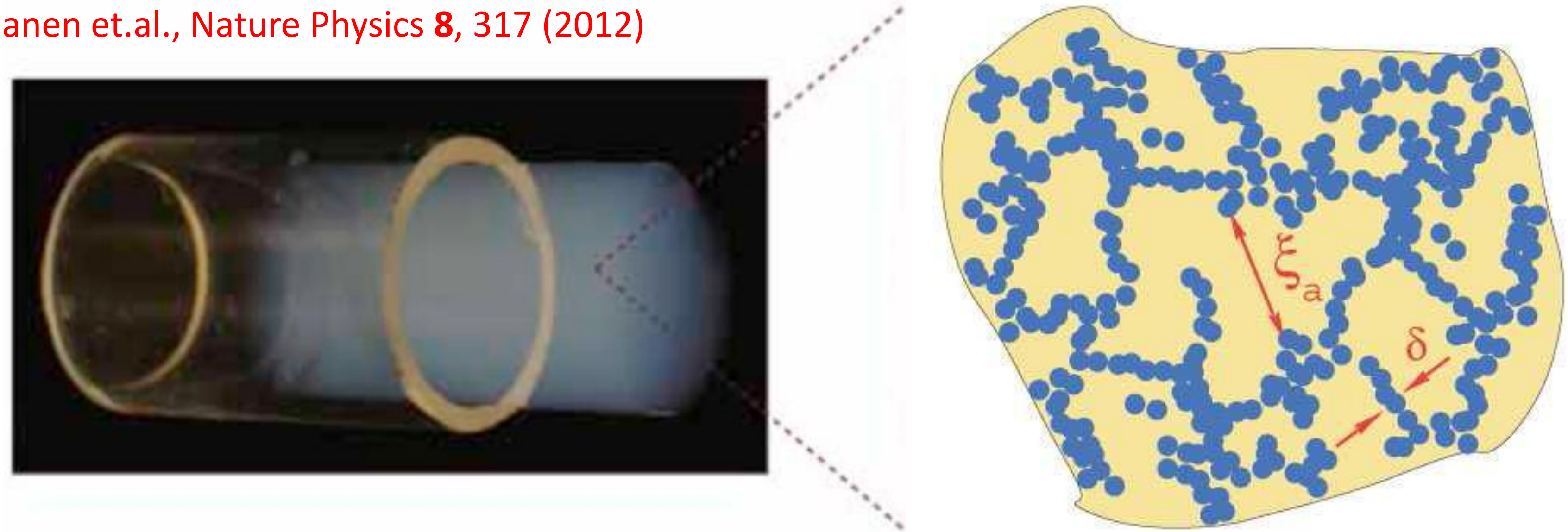


Equal Spin Pairing (ESP) Phase

Bulk ^{3}He is extremely pure – No disorder

Engineer Disorder – Add Aerogel

J. Pollanen et.al., Nature Physics **8**, 317 (2012)



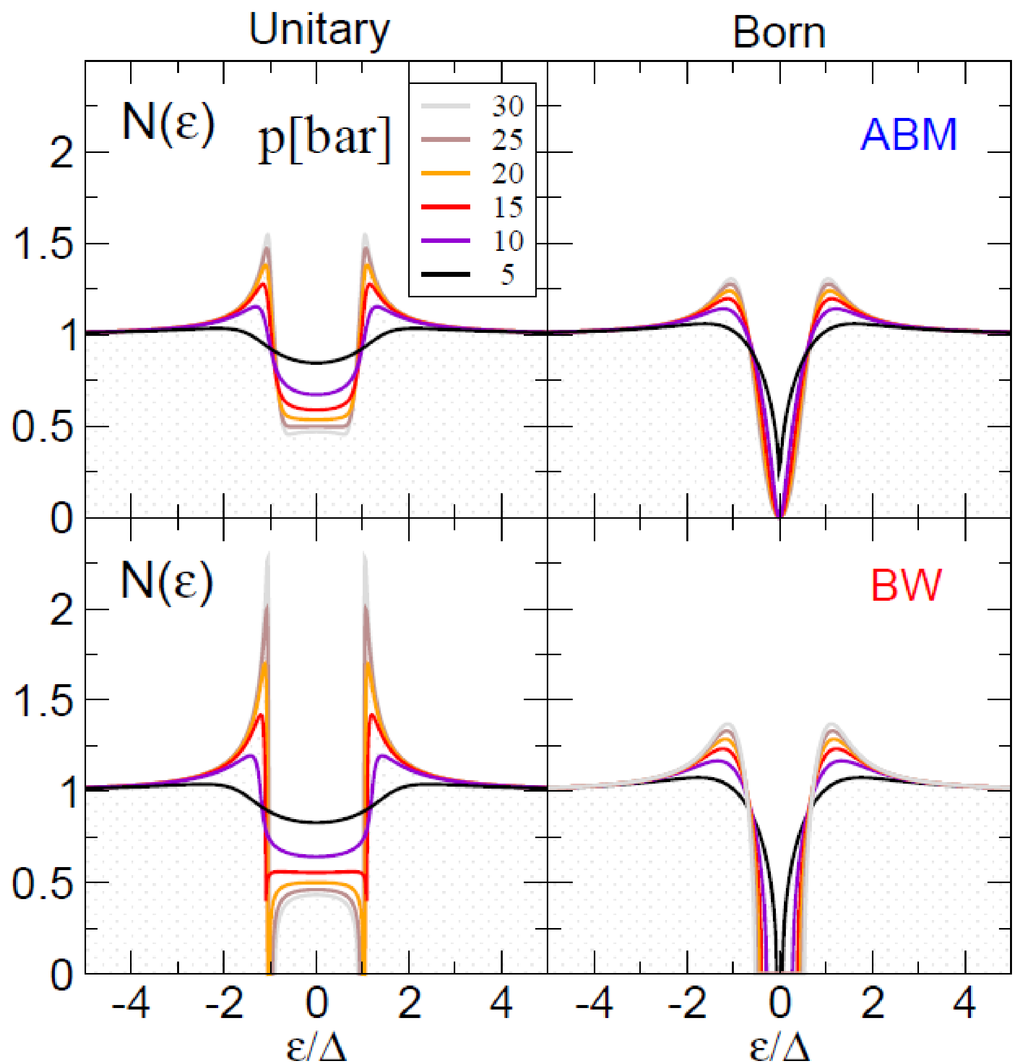
Properties of the aerogel:

- 98% open
- Very Homogenous
- Very Soft: Speed of sound ~ 30 – 50 m/s

- Typical size of the strands: δ ~ 5 nm
- Typical correlation length: ξa ~ 100 nm

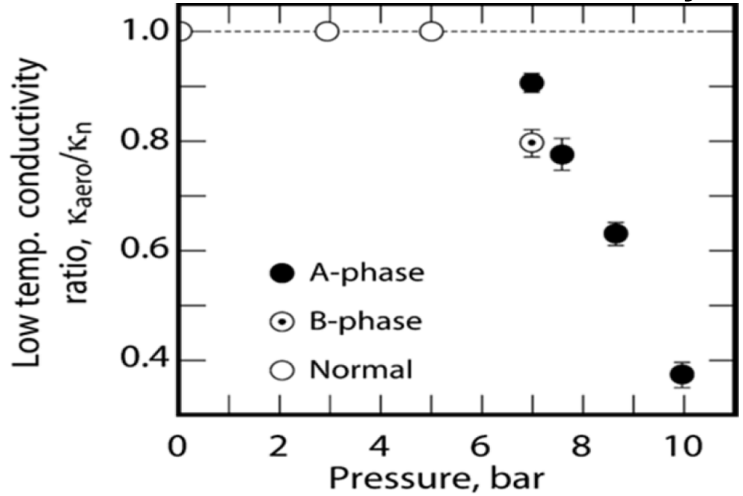
Effects of the Disorder

Density of states above the Fermi surface:



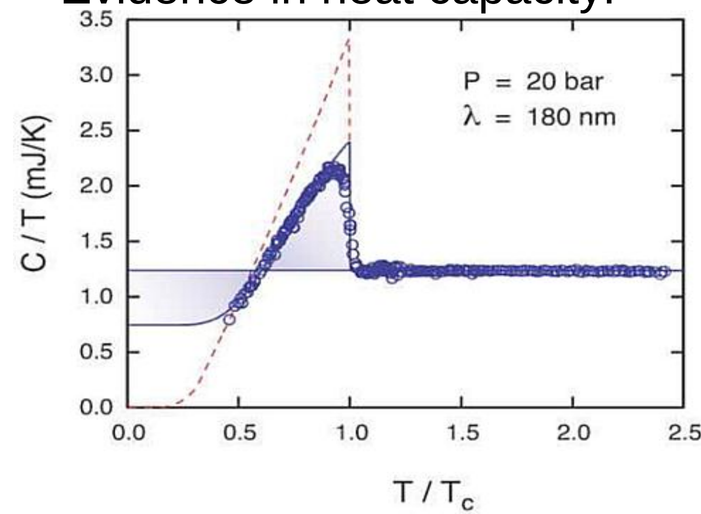
P. Sharma and J. Sauls, Physica B **328**, 313 (2003)

Evidence in thermal conductivity:



S.N. Fisher, et.al., PRL **91**, 105303 (2003)

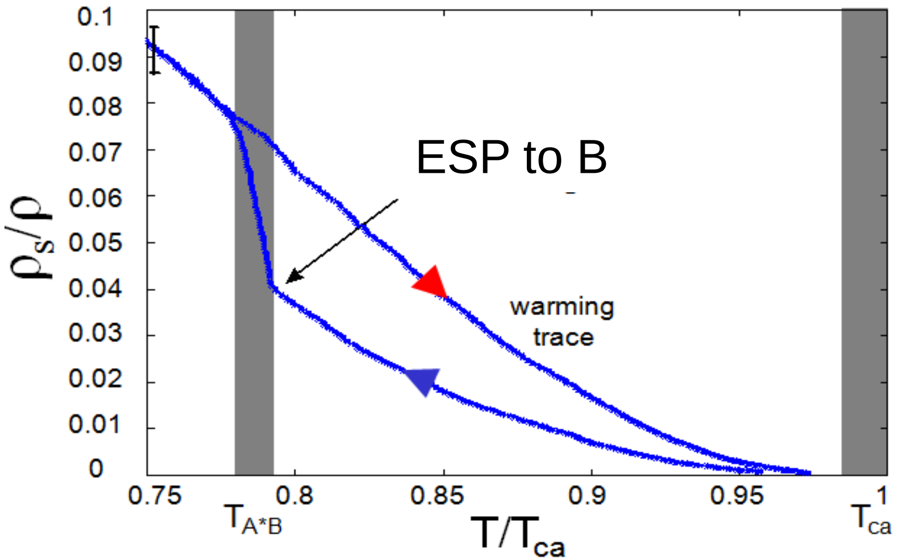
Evidence in heat capacity:



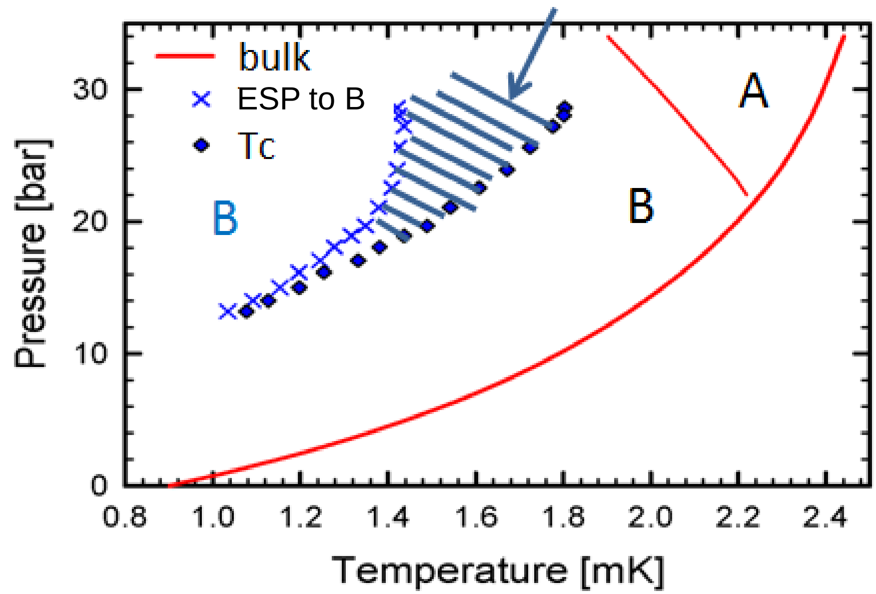
H. Choi et. al., PRL **93**, 145301 (2004)

Data for uncompressed aerogel

Uncompressed Aerogel:



Metastable ESP



Nazaretski, Mulders, Parpia, JETP Lett. **79**, 470 (2004)

No sign of ESP-phase reappearing on warming!

Squeeze The Aerogel

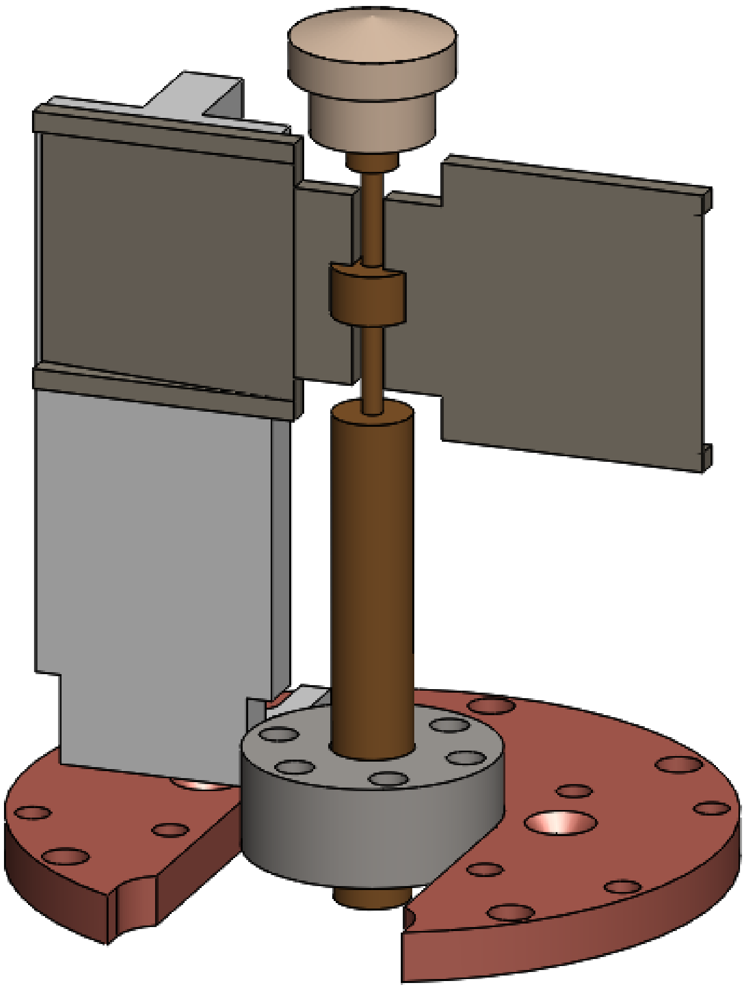
Uniaxial Compression by 10%:

Provide **Anisotropic Disorder**

Expectations:

- Metastability of the ESP phase should be enhanced
- ESP phase could reappear on warming
- Previously expected that compression will orient the ℓ-vector along the axis of anisotropy

Experimental Setup

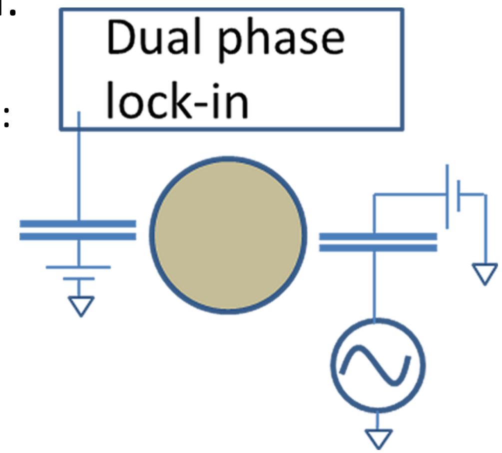


Aerogel is grown in the head of the torsion pendulum, and then compressed by 10%:

Height 440 μm ⟶ 400 μm

Capacitive drive and detection:

Topview:

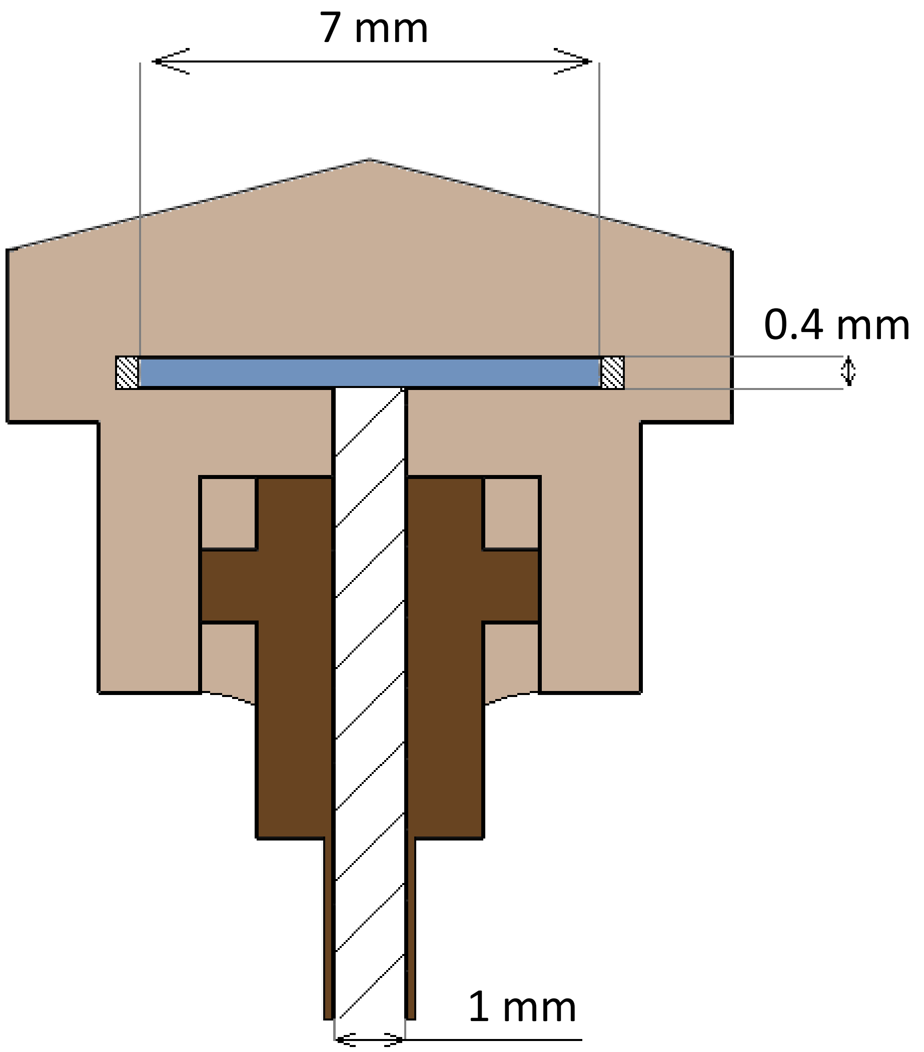


Maintain driving frequency near resonance

Infer **resonant frequency** from the in-phase and quadrature components of the signal

Q is inferred from the amplitude of the response

Bulk Fluid Contribution



Fill line:

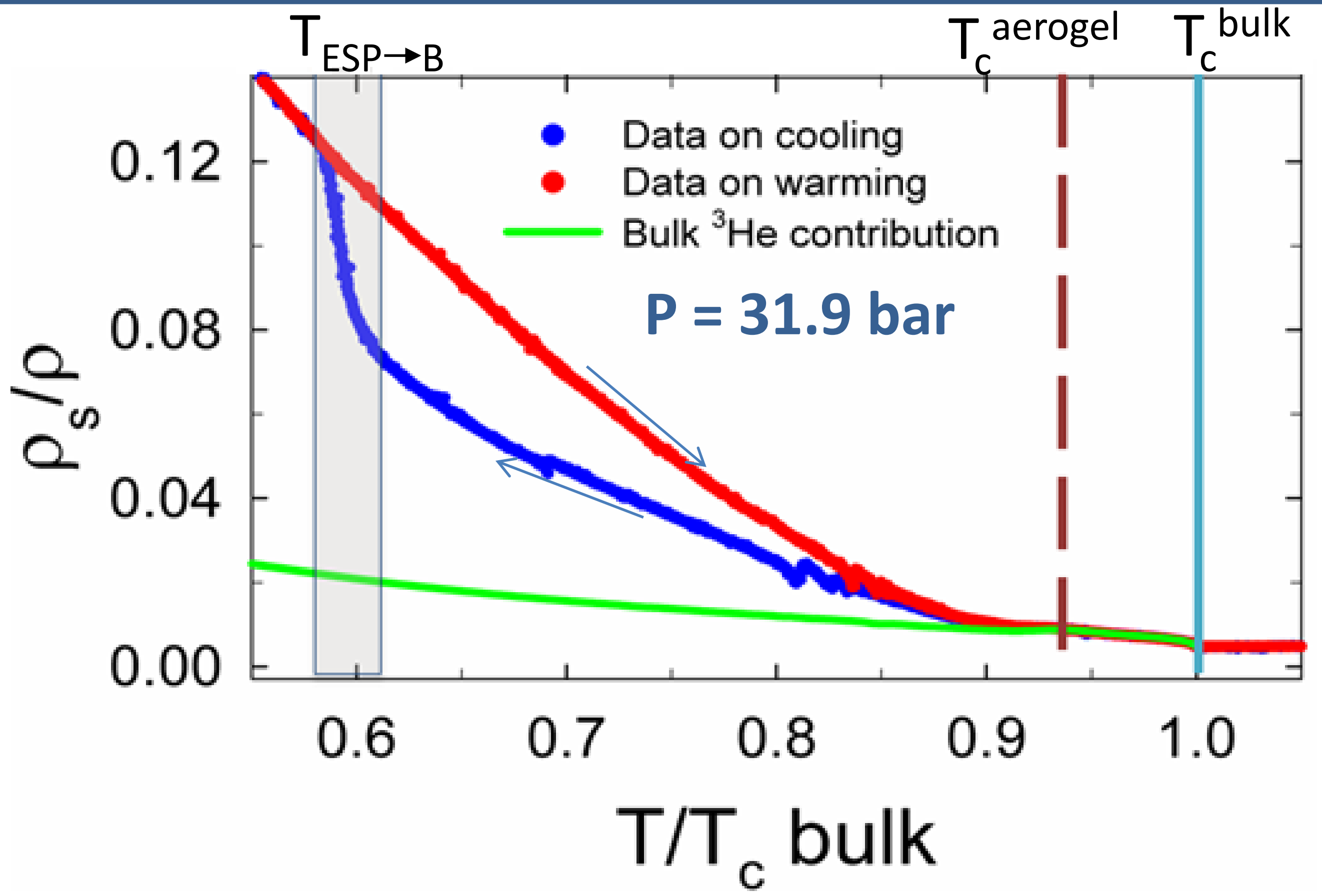
1 mm diameter long cylinder

0.8% of the total moment of inertia

Periphery of the cell:

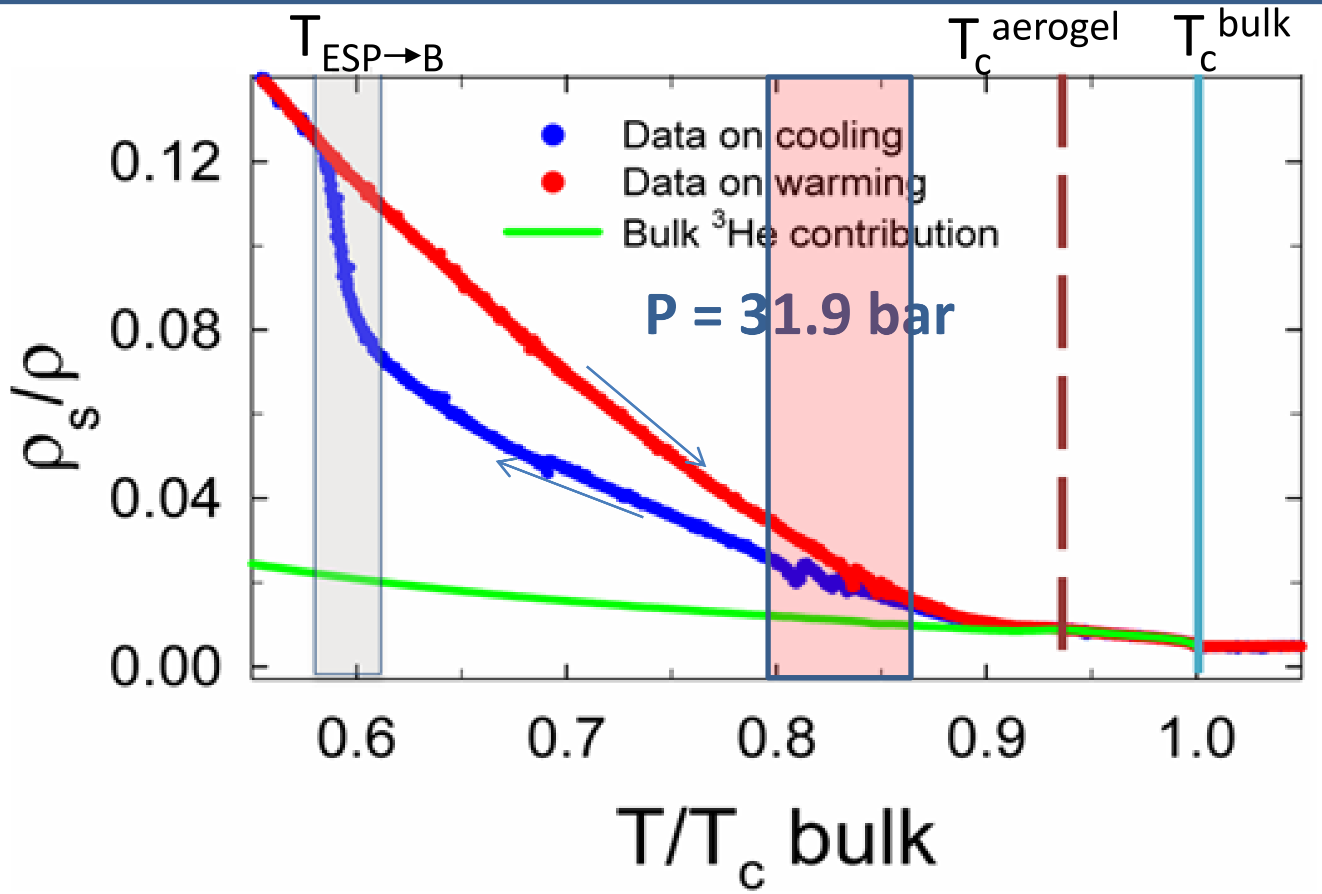
Model as an annulus with thickness of 0.028 μm and 3.2% of the total moment of inertia

Superfluid Data



Determined from the Frequency shift of the pendulum.
T_c suppression of ~ 0.93 T_c^{bulk}
Wide transition between ESP phase and B phase on cooling

Superfluid Data



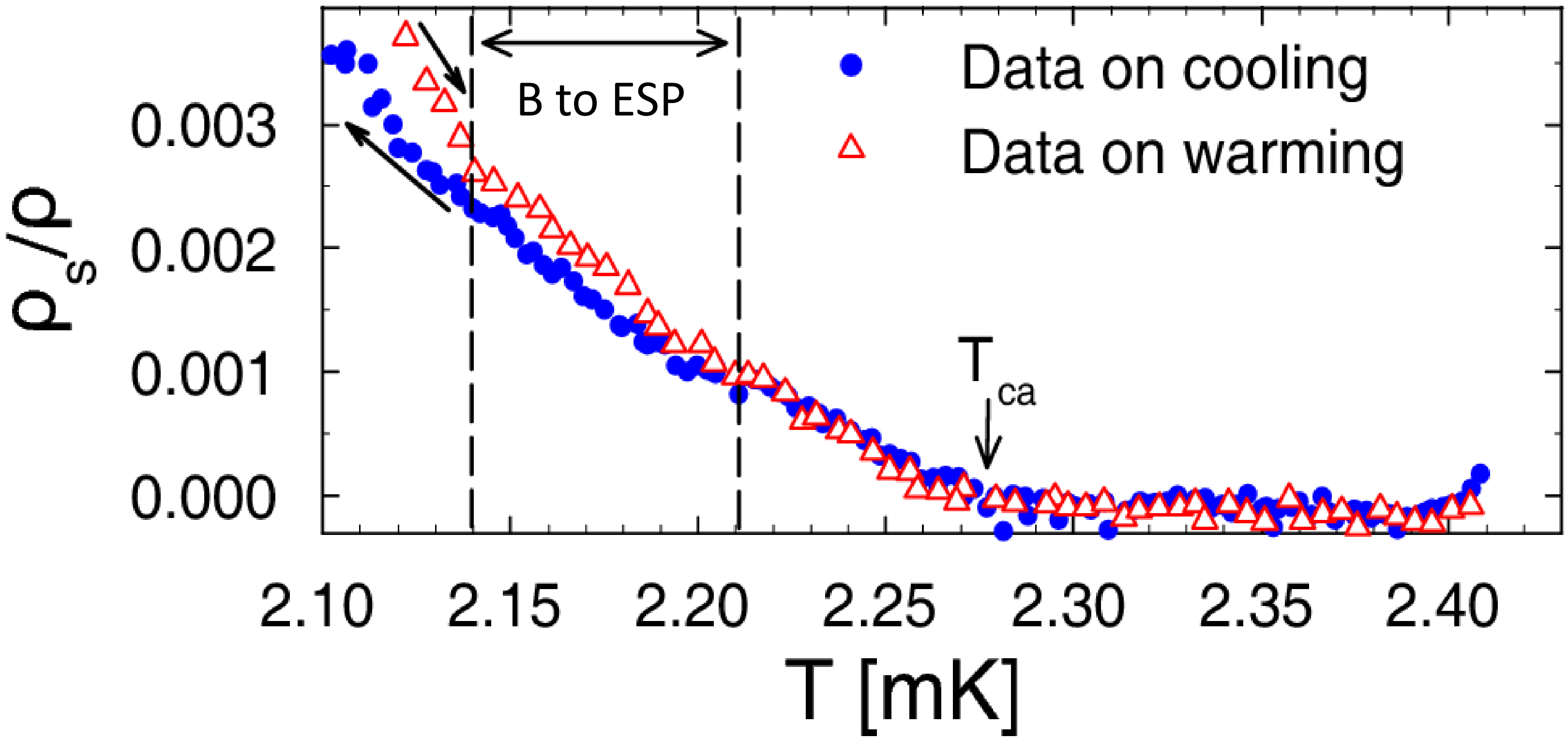
Determined from the Frequency shift of the pendulum.

T_c suppression of ~ 0.93 T_c^{bulk}

Wide transition between ESP phase and B phase on cooling

Region of 4th sound resonance crossings, which we will ignore in the future discussions

Reappearance of the ESP phase

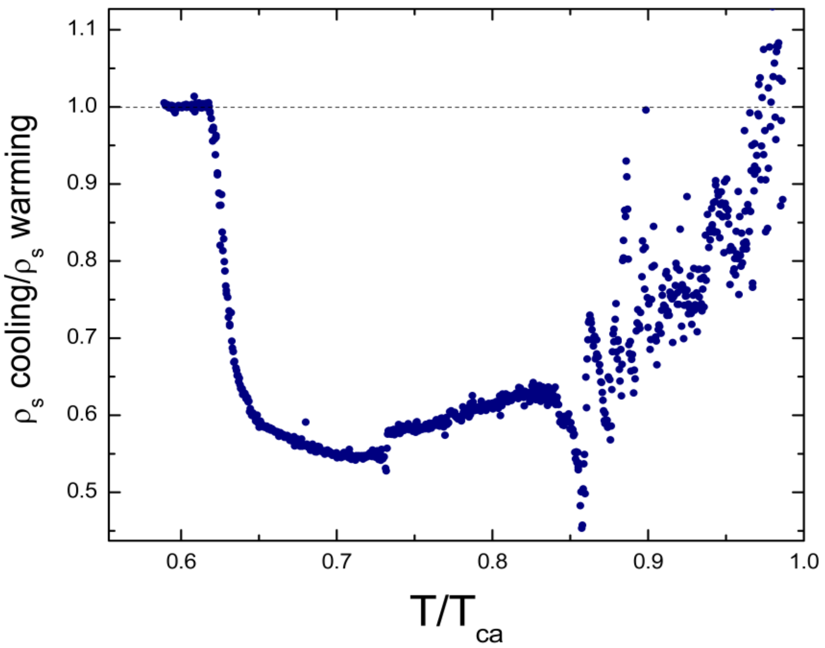


Full transition to ESP state on warming 70 μK below T_c

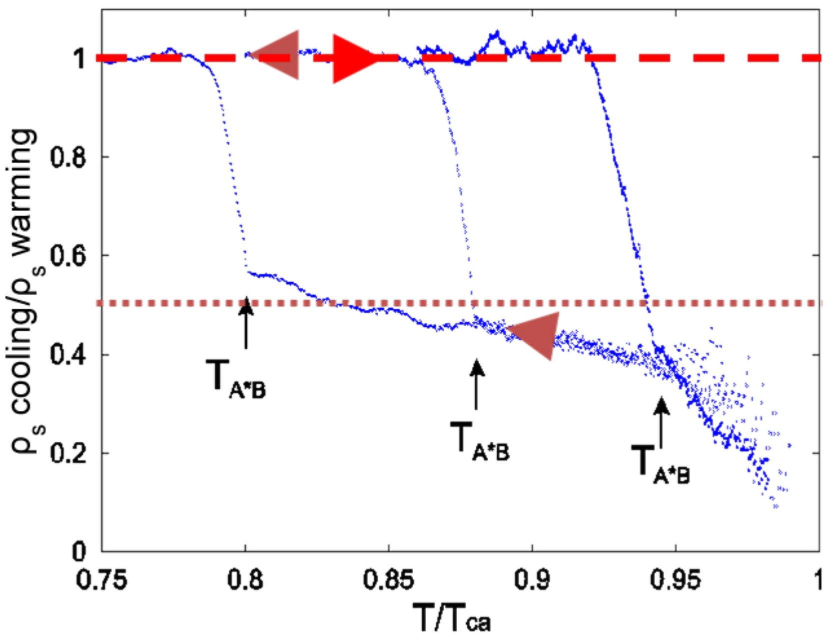
Warming to the partial transition region and immediately cooling allows for coexistence of ESP and B phase at low temperatures

ℓ-vector alignment?

Compressed Aerogel:



Uncompressed Aerogel:



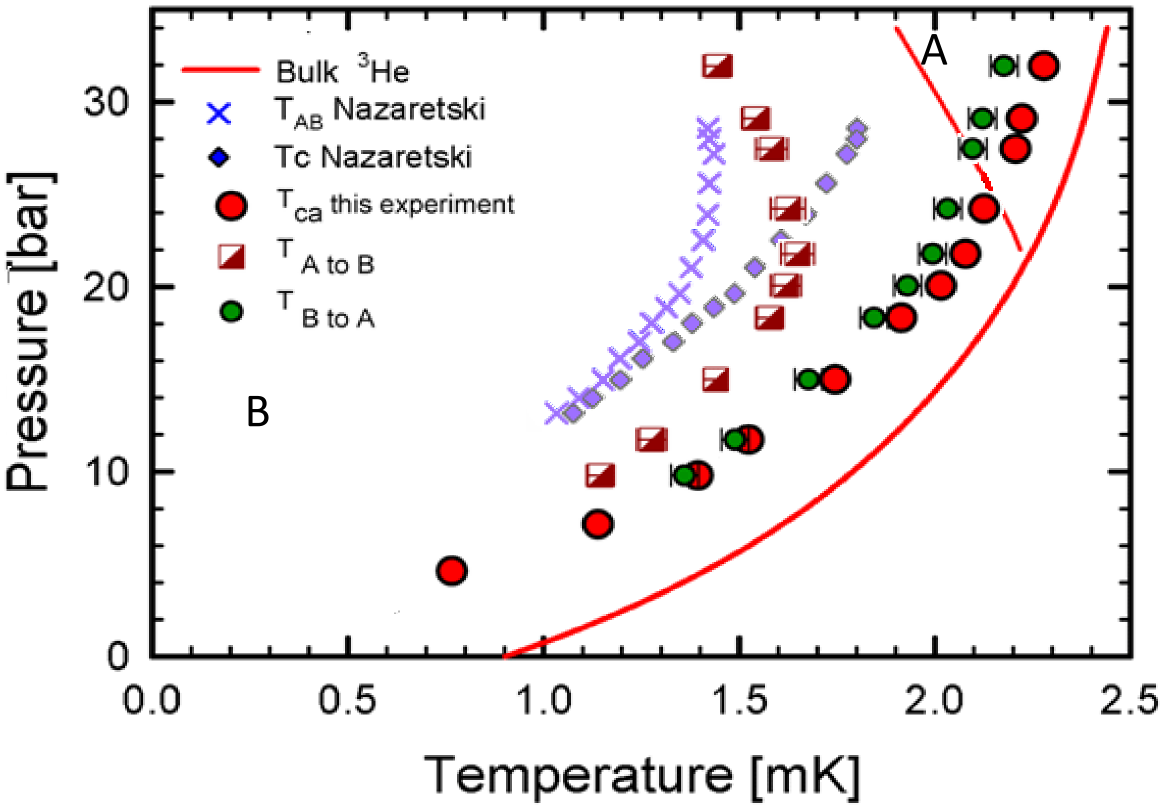
No alignment of ℓ-vector along the anisotropy axis

Instead data consistent with ℓ-vector oriented in the plane of the cell

ρ_s / ρ (ESP phase) shows continuous change with temperature (i.e. power law is different from B phase)

Phase Diagram

Extended region of metastability – allows us to have an extended temperature window in which we have ESP on cooling and B-phase on warming. It is easier to compare the signatures of the two phases

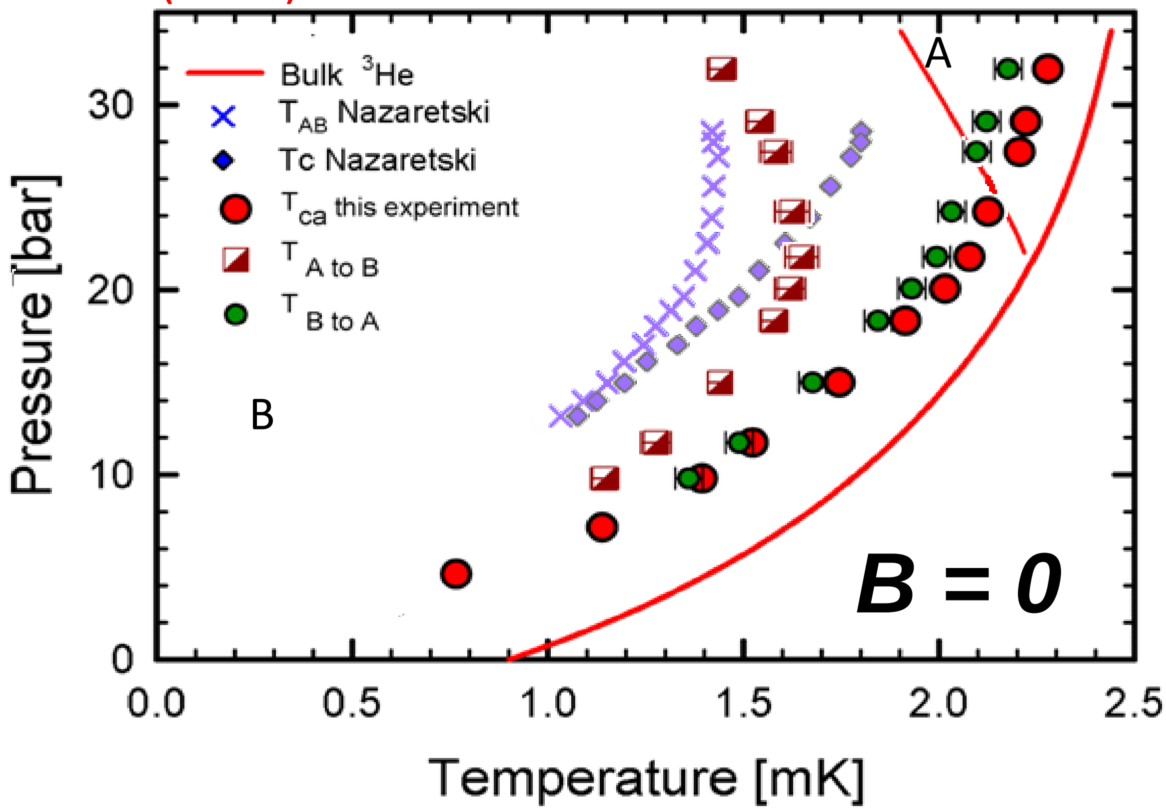


IISM fit to T_c of the aerogel:
mfp = 155nm

Aerogel Disorder = Magnetic Field

Polycritical point is removed

Vicente, et. al., PRB **72** 094519 (2005)

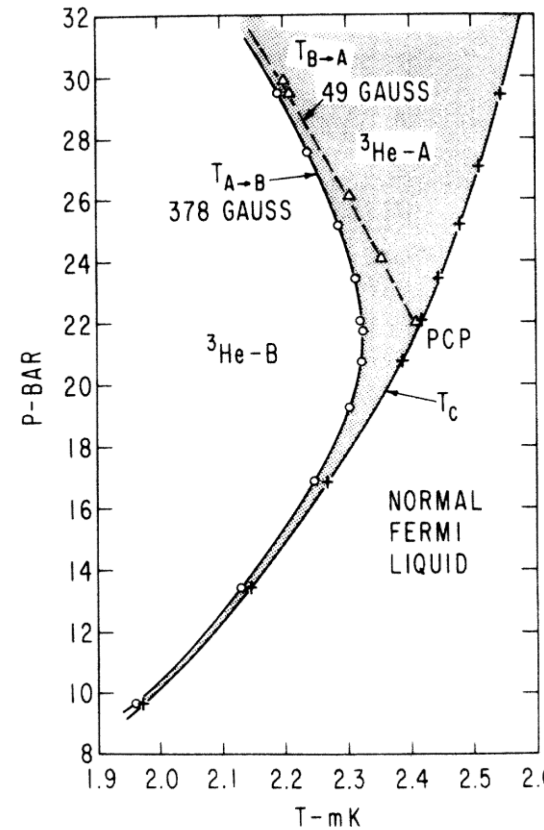


VOLUME 32, NUMBER 20 PHYSICAL REVIEW LETTERS 20 MAY 1974

Profound Effect of a Magnetic Field on the Phase Diagram of Superfluid ^{3}He*

D. N. Paulson, H. Kojima, and J. C. Wheatley
Department of Physics, University of California, San Diego, La Jolla, California 92037

(Received 4 March 1974)



Hydrodynamics of Normal ^{3}He in Aerogel

The fluid is coupled to the aerogel strands through a *friction* force:

$$\mathbf{F} = \frac{\rho}{\tau_f}(\mathbf{v}_{\mathbf{He}} - \mathbf{v}_{\mathbf{a}})$$

Higashitani, et. al. PRB 71, 134508 (2005)

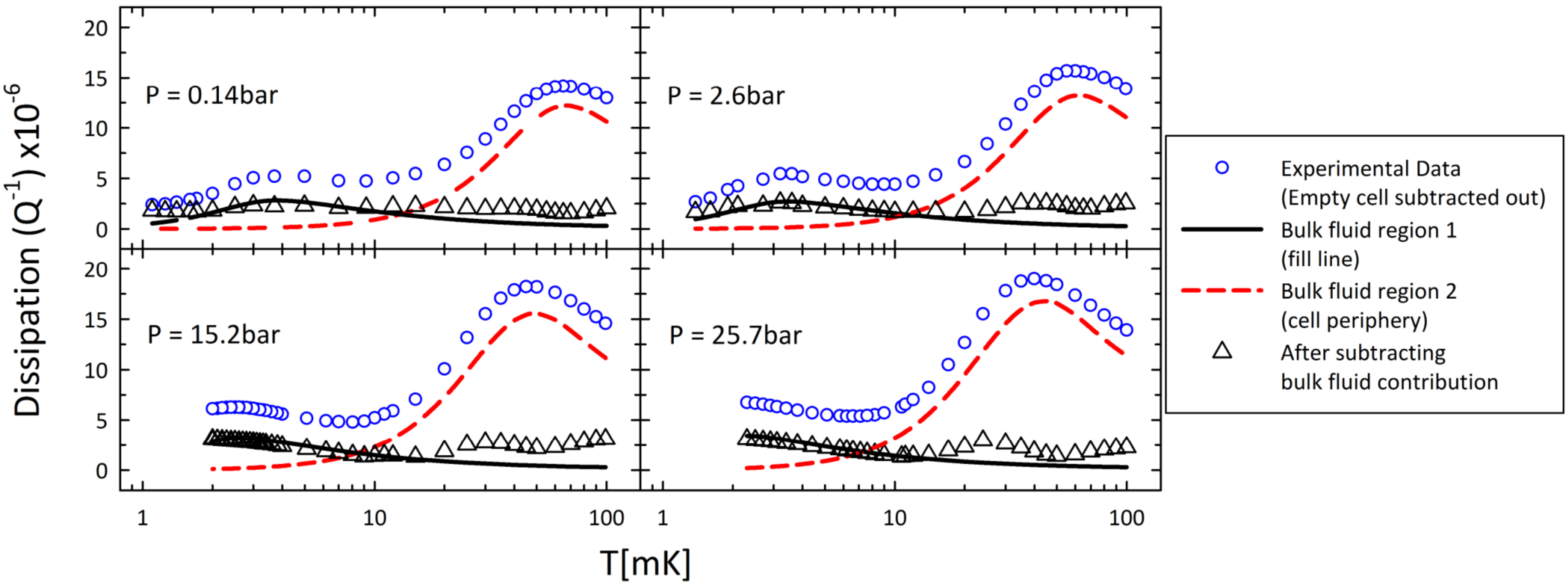
In the normal state, $\tau_f = (\mathrm{mfp}/v_F)(m/m^*) < 10^{-8}\mathrm{s}$

Thus, the equations of motion for the system become:

$$\rho_a \dot{\mathbf{v}}_{\mathbf{a}} = \mu \nabla^2 \mathbf{x}_{\mathbf{a}} + \frac{\rho}{\tau_f}(\mathbf{v}_{\mathbf{He}} - \mathbf{v}_{\mathbf{a}})$$

$$\rho \dot{\mathbf{v}}_{\mathbf{He}} = \eta \nabla^2 \mathbf{v}_{\mathbf{He}} - \frac{\rho}{\tau_f}(\mathbf{v}_{\mathbf{He}} - \mathbf{v}_{\mathbf{a}})$$

Normal State Data



After subtracting bulk:Temperature independent dissipation ~ $2.5x10^{-6}$

Expression for Q^{-1}

Solve the equations of motion in the torsion pendulum geometry:

$$Q^{-1} \approx \boxed{\frac{I_{helium}(P)}{I_{cell}}\omega\tau_f} + \frac{I_{aerogel}}{I_{cell}}\left(1+\frac{\rho_{helium}}{\rho_{aerogel}}\right)^2 \frac{\omega^3 h^2 \eta}{12\mu_{real}^{\;2}} + \frac{I_{aerogel}}{I_{cell}}\left(1+\frac{\rho_{helium}}{\rho_{aerogel}}\right)^2 \frac{\omega^3 h^2}{12\mu_{real}^{\;2}}\frac{\mu_{imag}}{\omega}$$

τ_f in the normal state has to be of the order of 10^{-7}.
Too large!

Expression for Q^{-1}

Solve the equations of motion in the torsion pendulum geometry:

$$Q^{-1} \approx \frac{I_{helium}(P)}{I_{cell}}\omega\tau_f + \boxed{\frac{I_{aerogel}}{I_{cell}}\left(1+\frac{\rho_{helium}}{\rho_{aerogel}}\right)^2 \frac{\omega^3 h^2 \eta}{12\mu_{real}^{\ 2}}} + \frac{I_{aerogel}}{I_{cell}}\left(1+\frac{\rho_{helium}}{\rho_{aerogel}}\right)^2 \frac{\omega^3 h^2}{12\mu_{real}^{\ 2}} \frac{\mu_{imag}}{\omega}$$

Elastic scattering off the aerogel strands imposes an upper limit to the quasiparticle relaxation time, thus the **viscosity *η* is limited to ~ 0.01 Poise**

Expression for Q^{-1}

Solve the equations of motion in the torsion pendulum geometry:

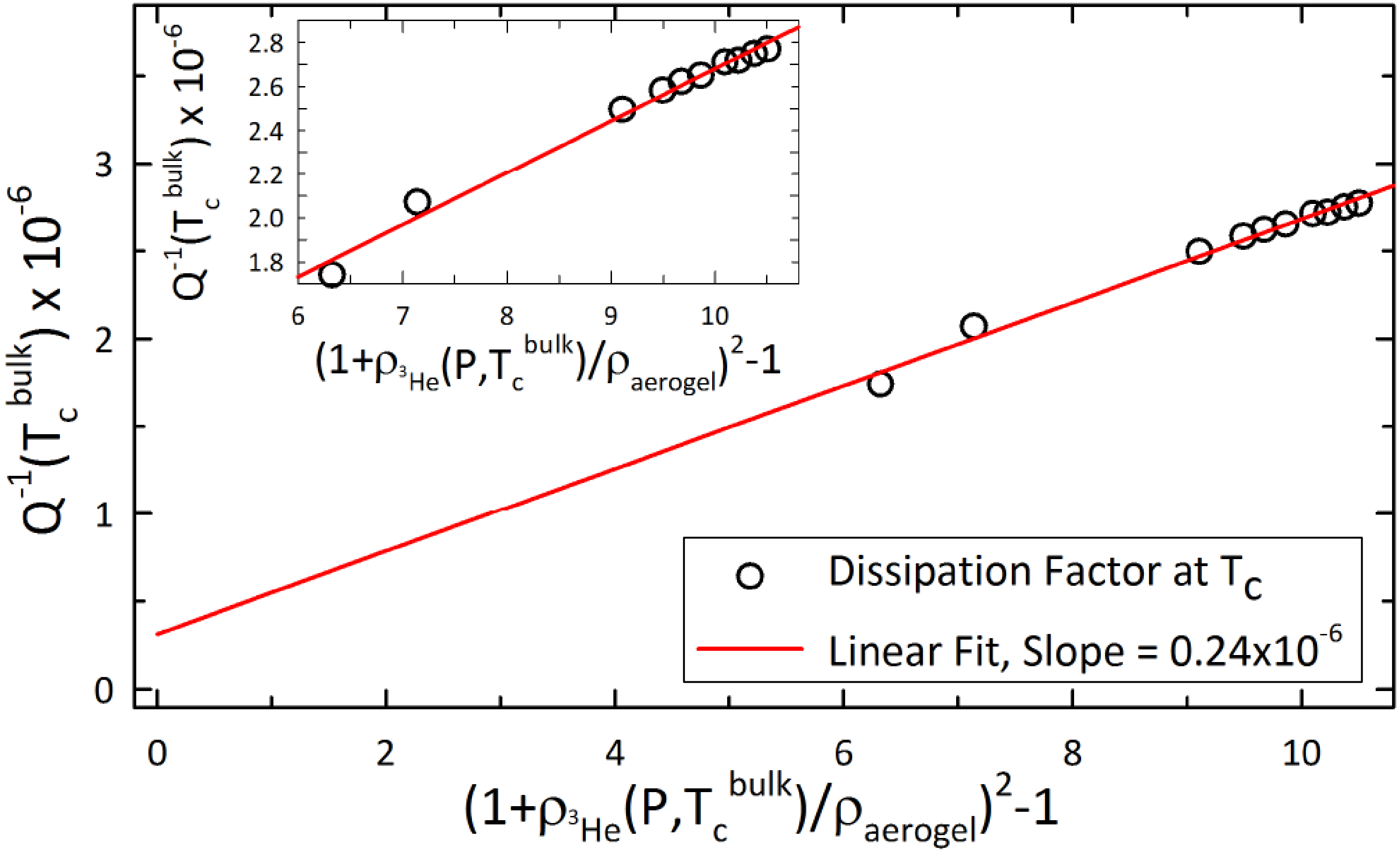
$$Q^{-1} \approx \frac{I_{helium}(P)}{I_{cell}} \omega \tau_f + \frac{I_{aerogel}}{I_{cell}} \left(1 + \frac{\rho_{helium}}{\rho_{aerogel}}\right)^2 \frac{\omega^3 h^2 \eta}{12 \mu_{real}{}^2} + \frac{I_{aerogel}}{I_{cell}} \left(1 + \frac{\rho_{helium}}{\rho_{aerogel}}\right)^2 \frac{\omega^3 h^2}{12 \mu_{real}{}^2} \frac{\mu_{imag}}{\omega}$$

Allow for lossy aerogel by representing the aerogel shear modulus as a complex number:

$$\mu = \mu_{real} - i \mu_{imag}$$

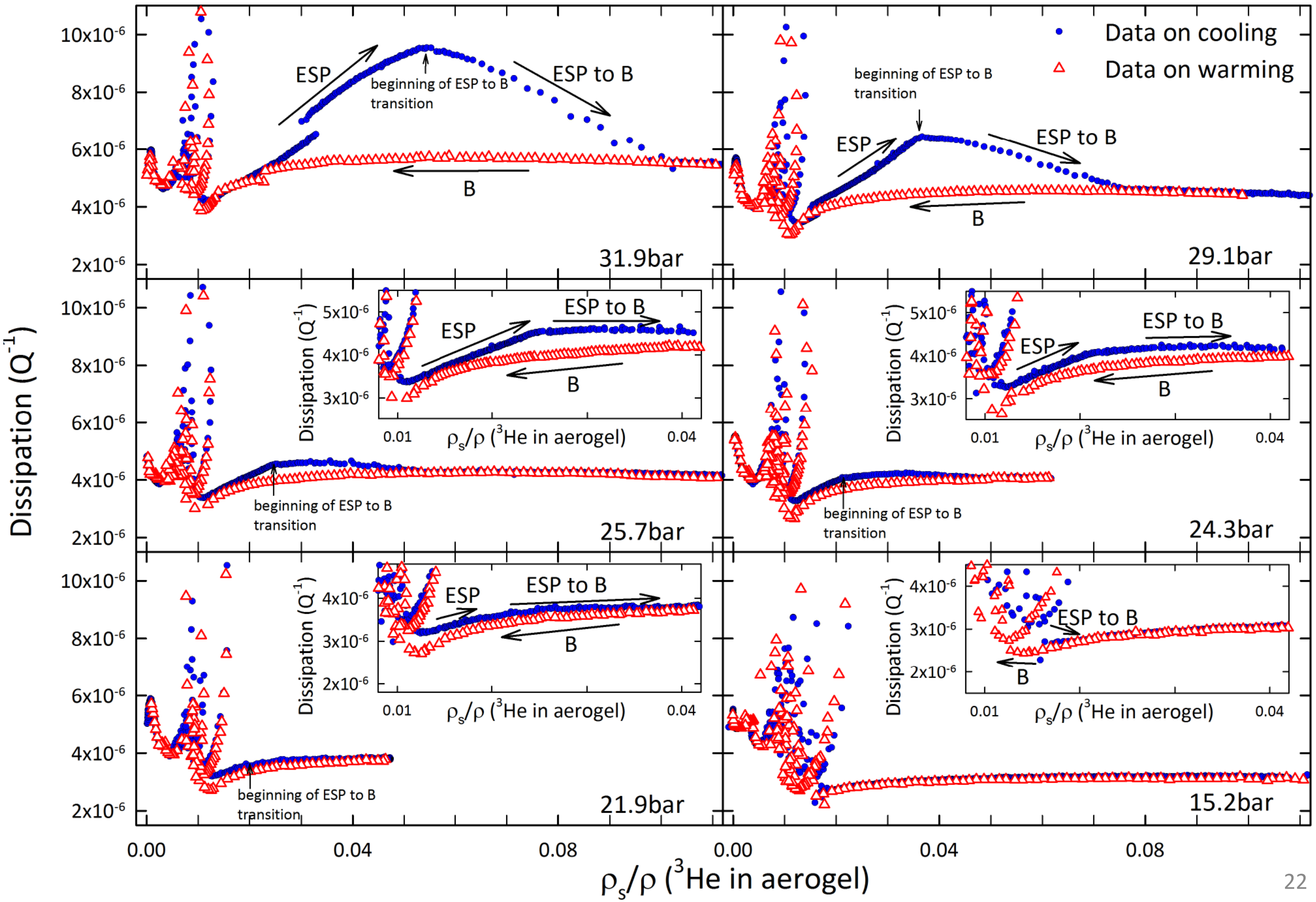
$$Q^{-1} \sim \frac{I_{aerogel}}{I_{cell}} \left(1 + \frac{\rho_{helium}}{\rho_{aerogel}}\right)^2 \frac{\omega^3 h^2}{12 \mu_{real}{}^2} \frac{\mu_{imag}}{\omega} = \left(1 + \frac{\rho_{helium}}{\rho_{aerogel}}\right)^2 Q_{empty}^{-1}$$

Pressure Dependence

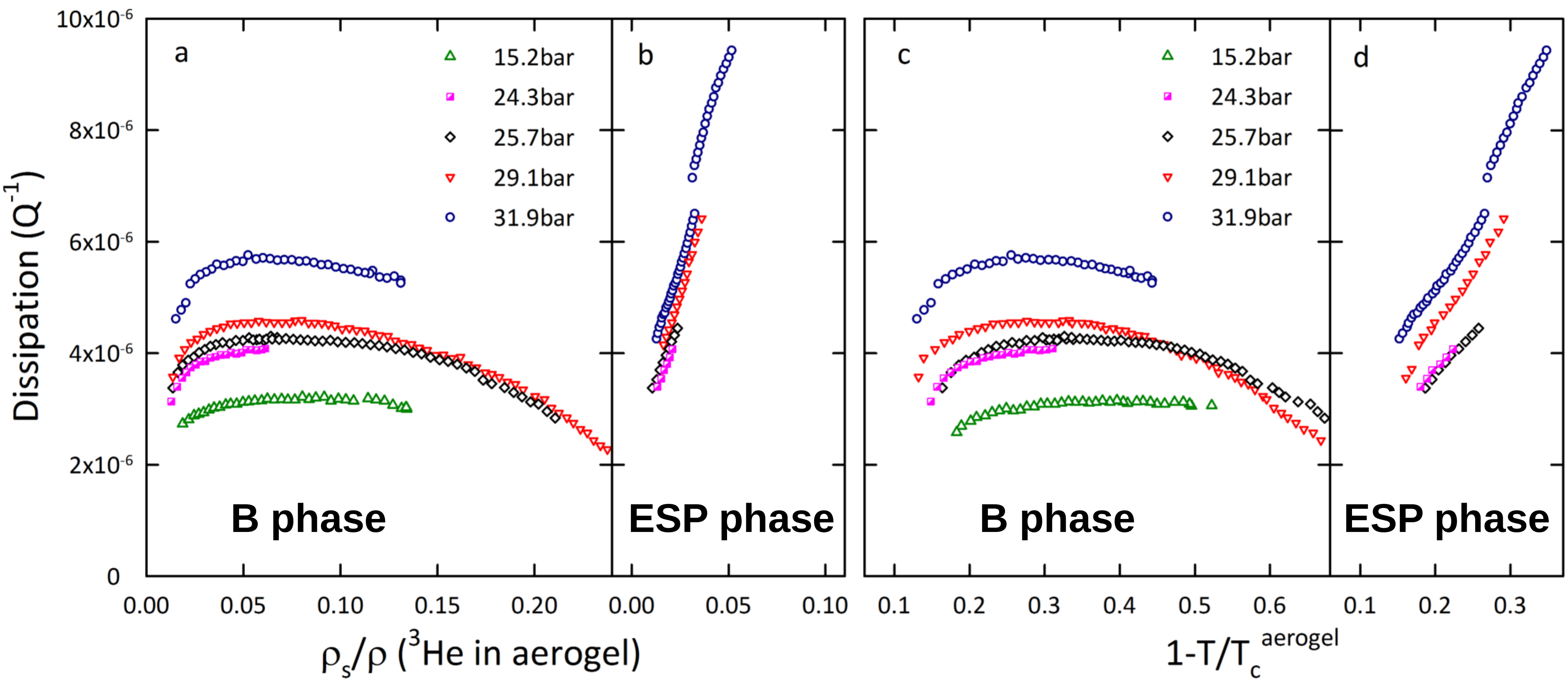


It confirms that the normal state dissipation comes from the intrinsic dissipation of the aerogel

Q^{-1} in the Superfluid State



Q^{-1} in the Superfluid State

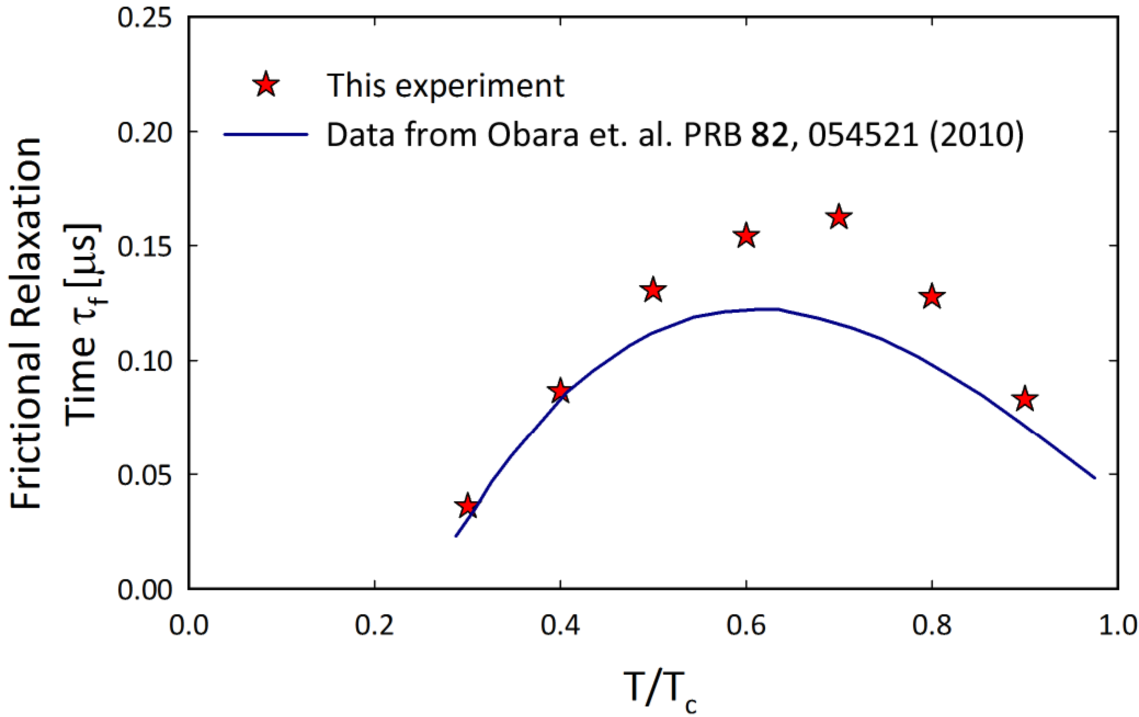


- Very different power laws for the two phases.
- Dissipation scales better with the superfluid fraction than temperature
- Pressure dependence is probably due to the gap suppression at lower pressures

Extract τ_f?

What if we attribute the extra dissipation seen in the superfluid state on rise in τ_f ?

τ_f can increase below T_c compared to the value in the normal state, however, τ_f being of the order of 10^{-7} s **would be unphysical** – this would mean quasi-particle mean free paths of > 3µm.



Compare to the data from Osaka group experiment, which looked at fourth sound propagation of ^3He in aerogel.
The sources of dissipation are probably similar.

Possible Sources of Dissipation

- Low energy excitations from surface states

- Bulk A phase is usually associated with more dissipation due to the nodes in the gap.

- Alignment of the ℓ-vector with the flow; Orbital vicosity.

Bradley et. al., PRL **98**, 075302 (2007)
JLTP **150**, 445 (2008)

Summary

Modification of the phase diagram by aerogel compression:

- Compressed aerogel does increase metastable region of ESP phase, but no alignment of the ℓ-vector
- See ESP phase reappear on warming
- Polycritical point is seen to be removed in the anisotropic disordered system

Bennett et. al., PRL **107** 235504 (2011).

Dissipation signatures of the normal and superfluid phases:

- Aerogel is inherently dissipative – can explain the normal state data
- Larger dissipation as we go deeper in the superfluid state in the ESP phase
- Larger dissipation as we increase the pressure
- Frictional relaxation time τ_f has to be too large to explain the observed effects

Zhelev et. al., accepted at PRB (in production)

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