Superflow in Solid Helium

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Thanks to Michael Ray and Yegor Vekhov

Grand Challenges in Quantum Fluids and Solids Workshop
SUNY - Buffalo
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UMASS AMHERST

Work at UMass
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DMR 12-05217

NATIONAL SCIENCE FOUNDATION

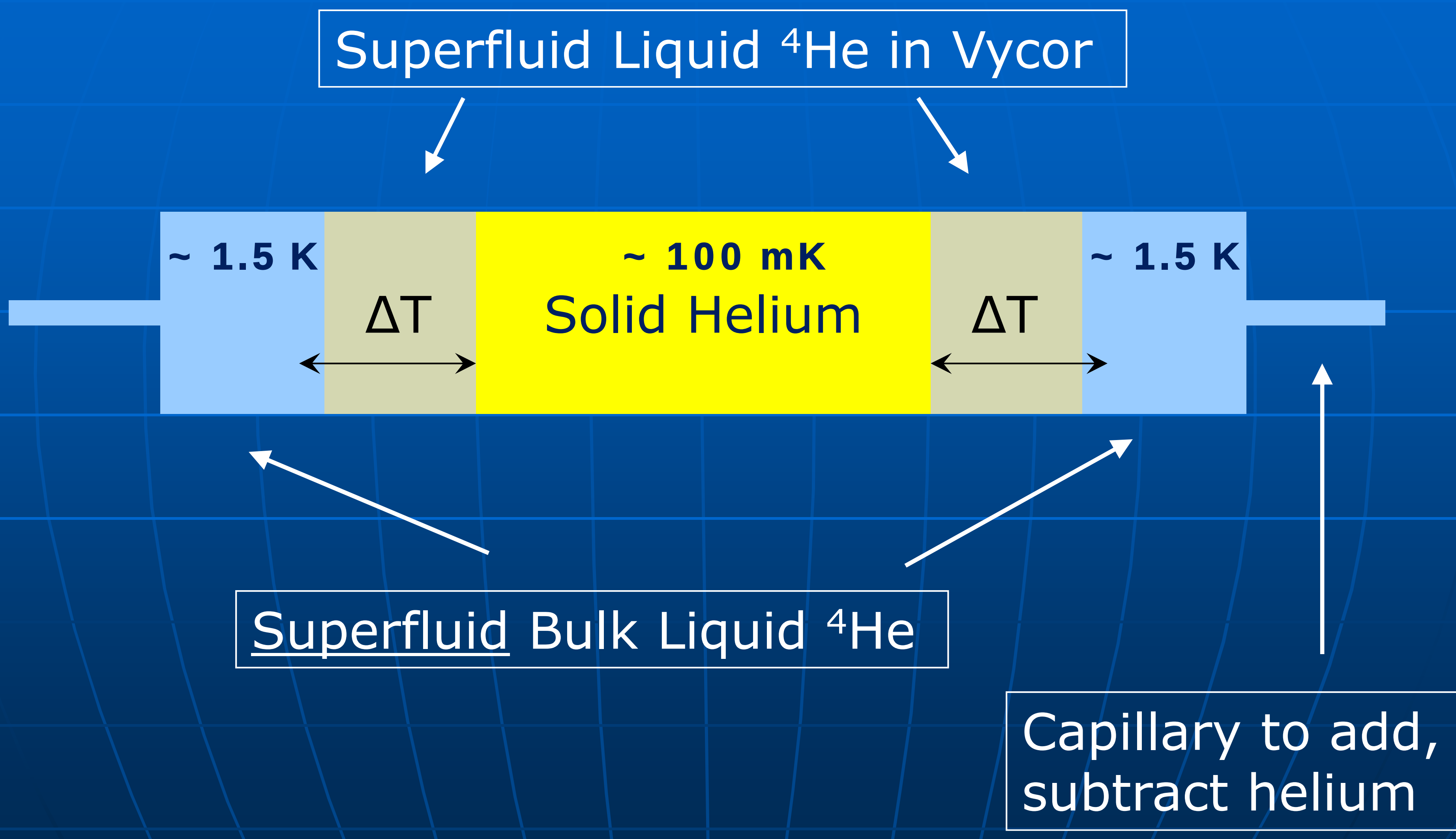
Outline

I. Reminder: Solid Helium (E. Kim)

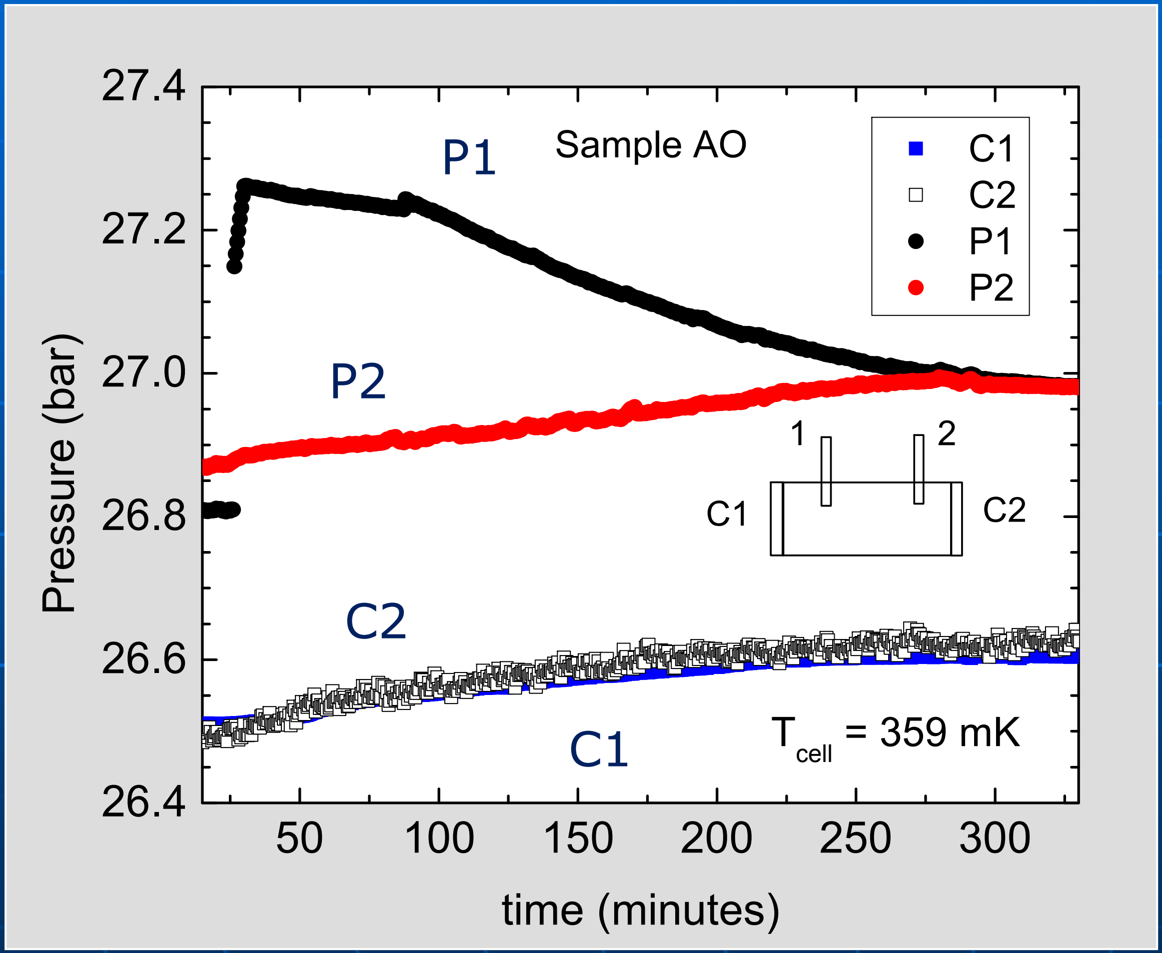
II. Flow Measurements at UMass

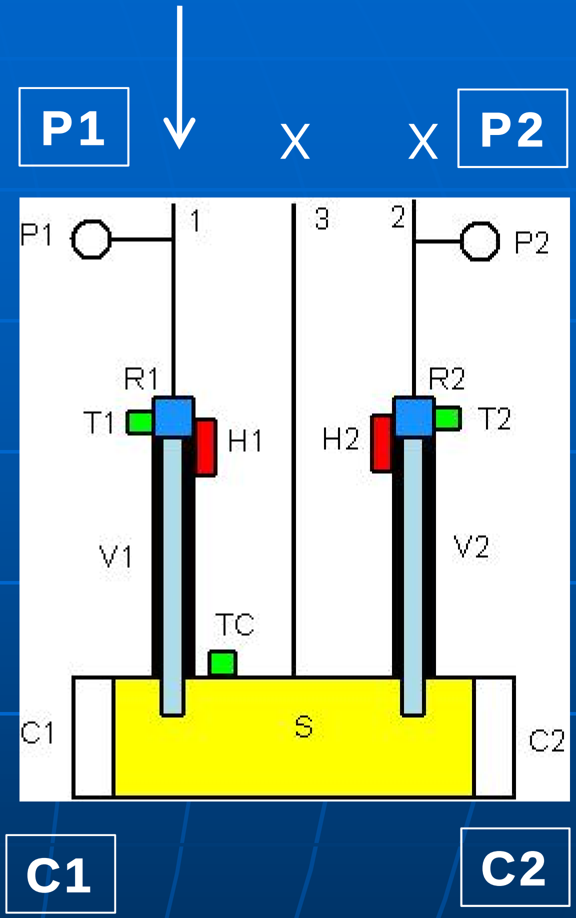
III. Unanswered Questions

A symmetric sandwich:



Early data Interpreted as Evidence for “Flow”





M.W. Ray and R.B. Hallock, Phys. Rev. Lett. 100, 235301 (2008); PRB 79, 224302 (2009).

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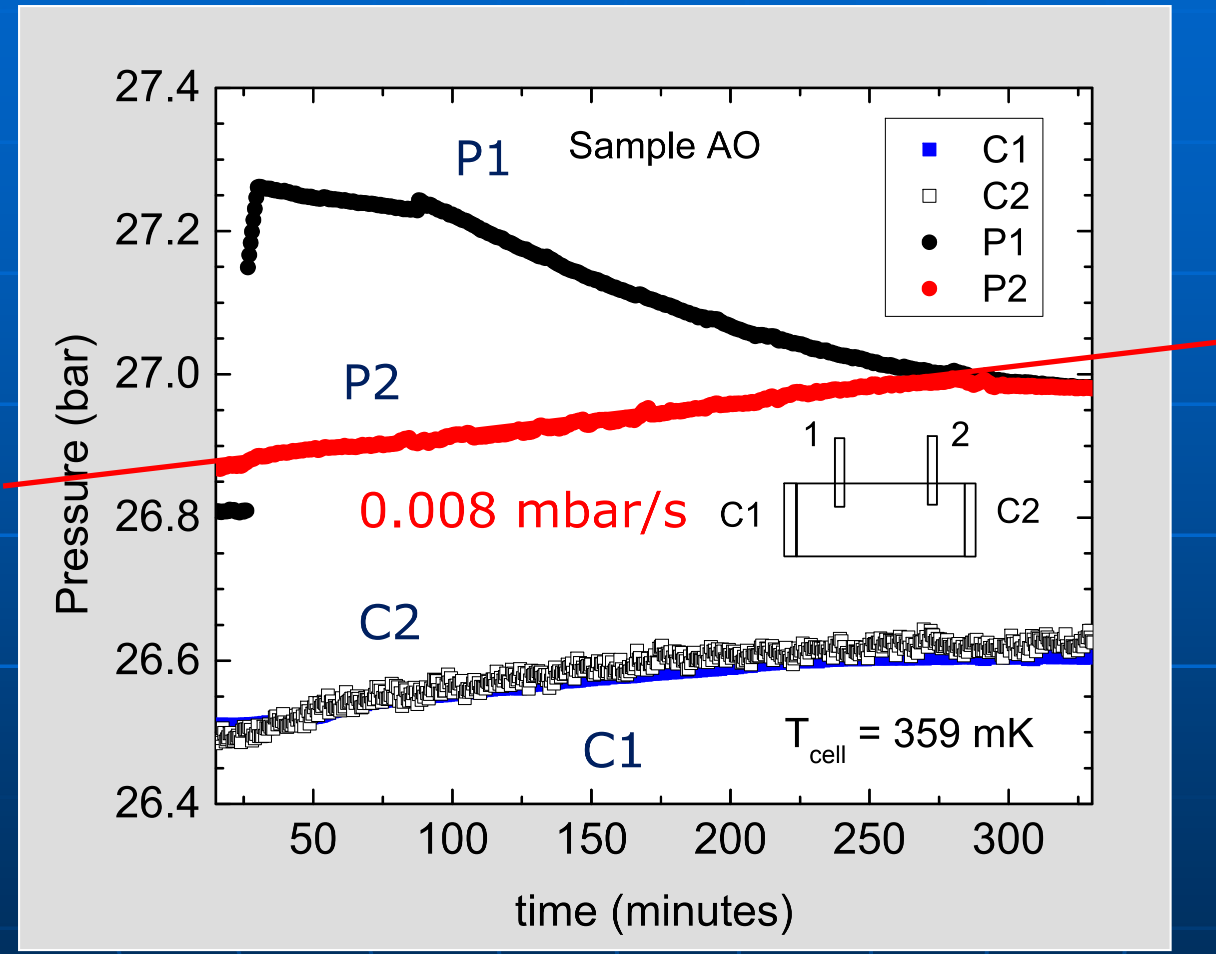
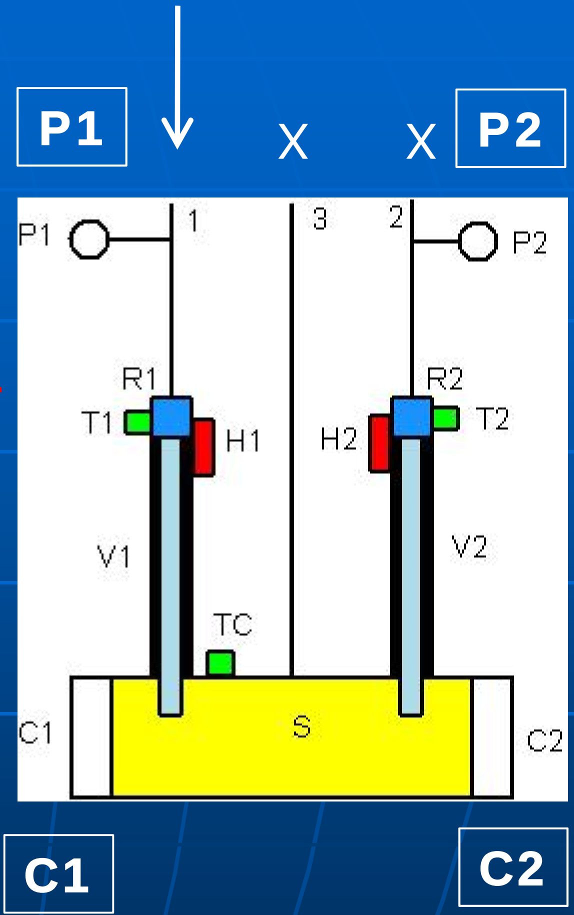




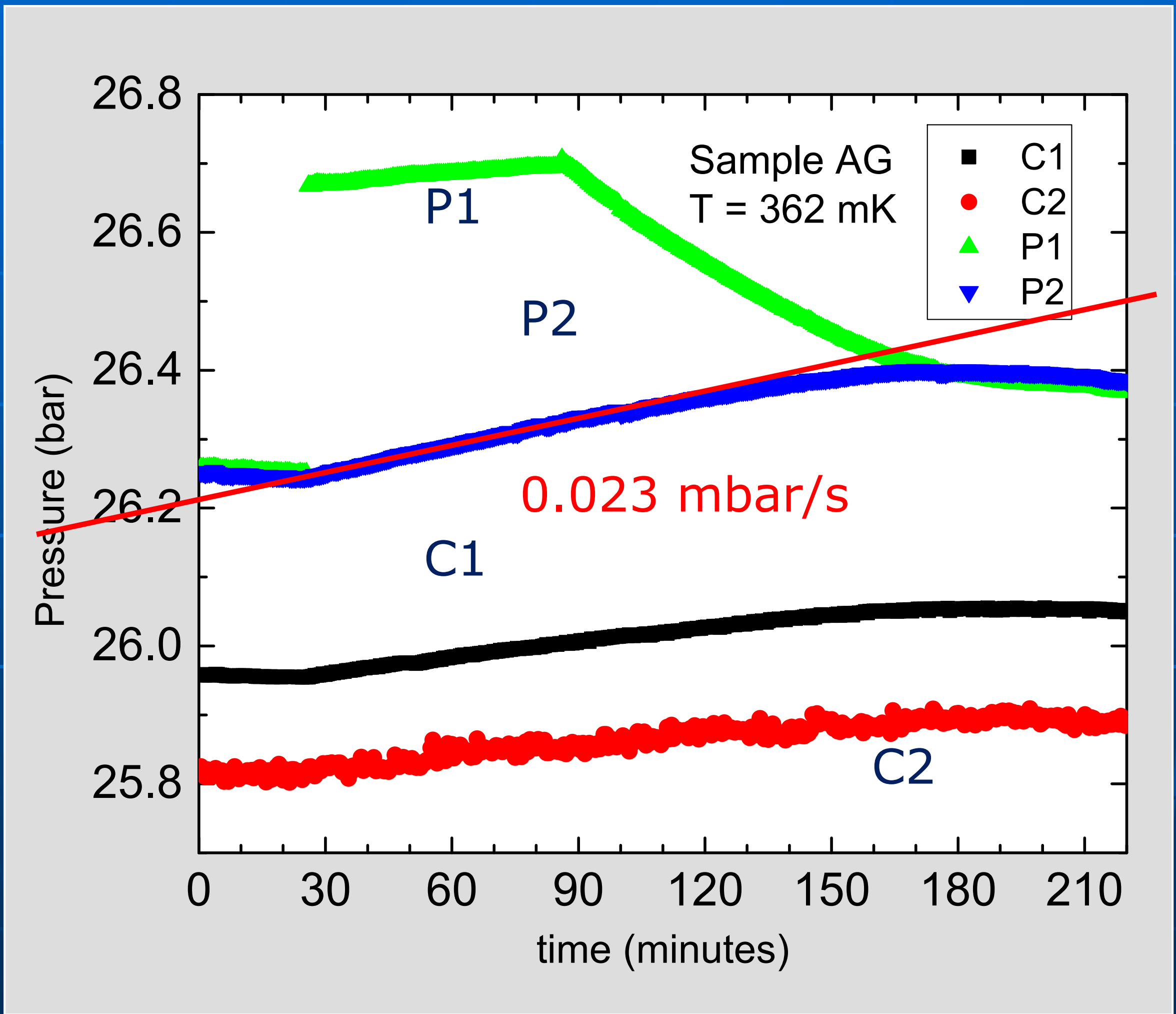
0.1 mbar/s ≈ 5 x 10^{-8} g/s

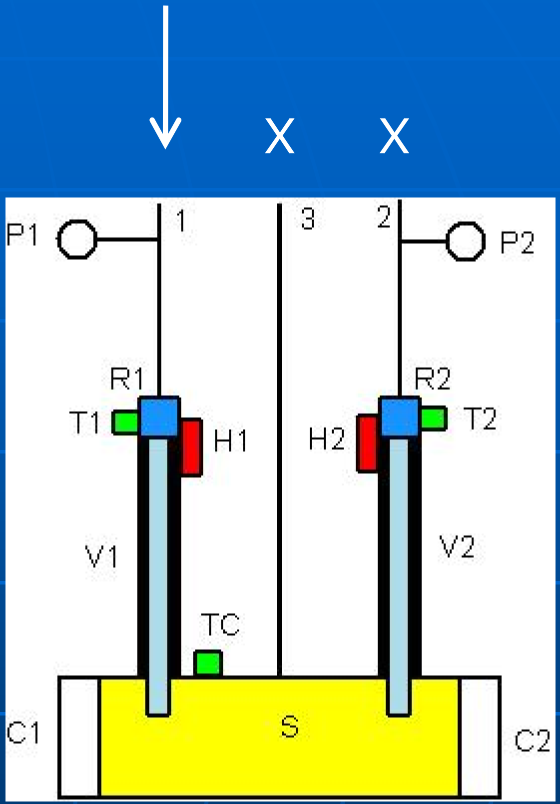
Note C1 and C2 grow similarly

Flux not limited by the Vycor

M.W. Ray and R.B. Hallock, Phys. Rev. Lett. 100, 235301 (2008); PRB 79, 224302 (2009).

Another: Interpreted as Evidence for "Flow"



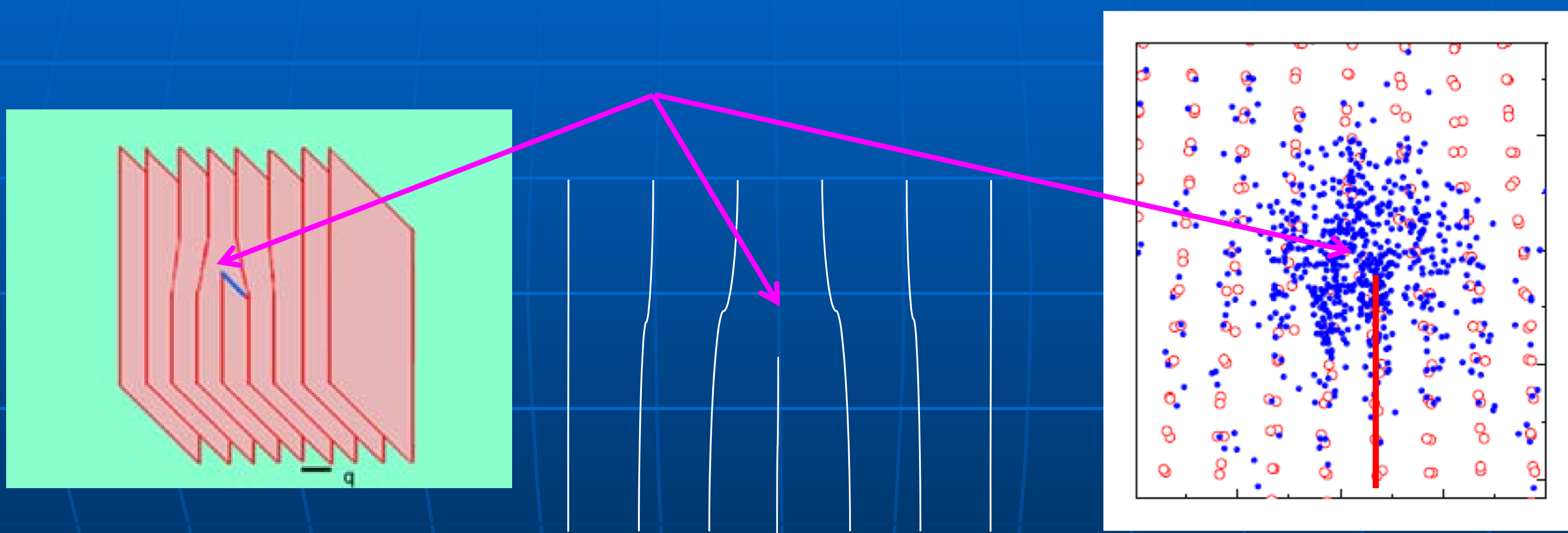


Note: Sometimes C1 and C2, like in this case, show a gradient is present in the cell. (A long-term stable gradient)

Key Question: What carries the flux?

Suggestion**: The"core" of an edge dislocation, which is predicted to have a finite superfluid density. (See A. Kuklov's comments)

The edge can climb while it transports mass; the "superclimb" of edge dislocations*. Mass injection causes a density change.



Alternate scenarios have been proposed, e.g. liquid channels ##, grain boundaries $$, etc..

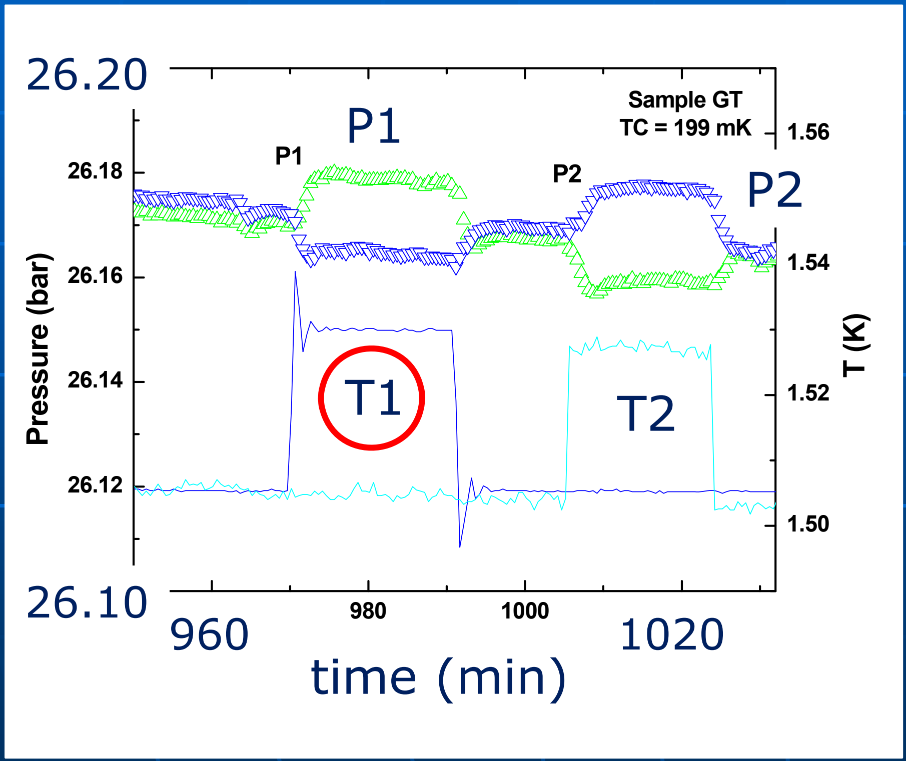
**S.G. Soyler, et al., Phys. Rev. Letters 103, 175301 (2009)
[M. Boninsegni et al., Phys. Rev. Letters 99, 035301 (2007)]

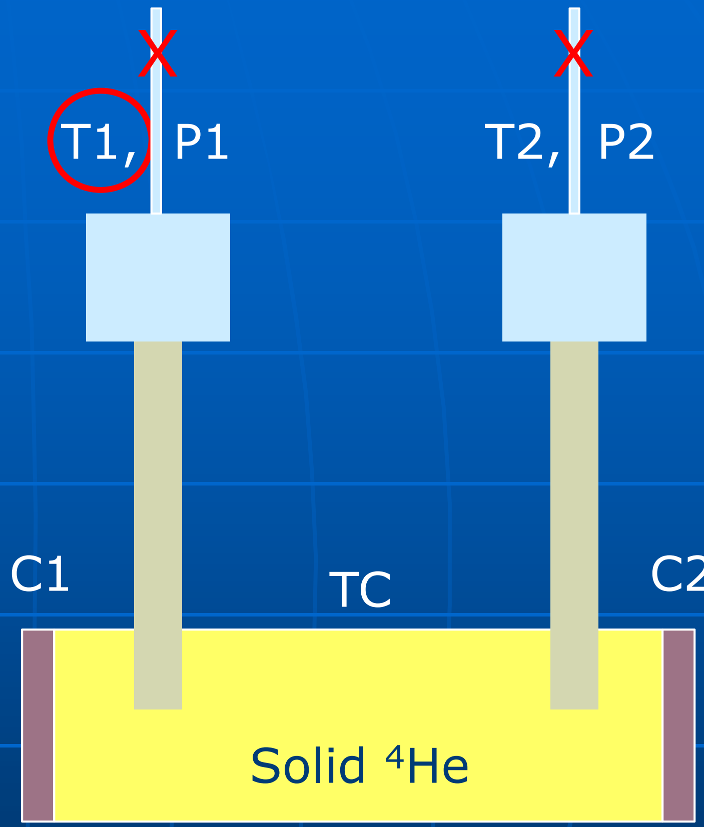
S. Sasaki et al., J. Low Temp. Phys. 153, 43 (2008).

$$ L. Pollet et al., Phys. Rev. Letters 98, 135301 (2007);
S. Sasaki et al., Science 313, 1098 (2006).

Instead of injection of helium, seal the fill lines and apply a temperature difference |T1 - T2| > 0, with solid in the cell:

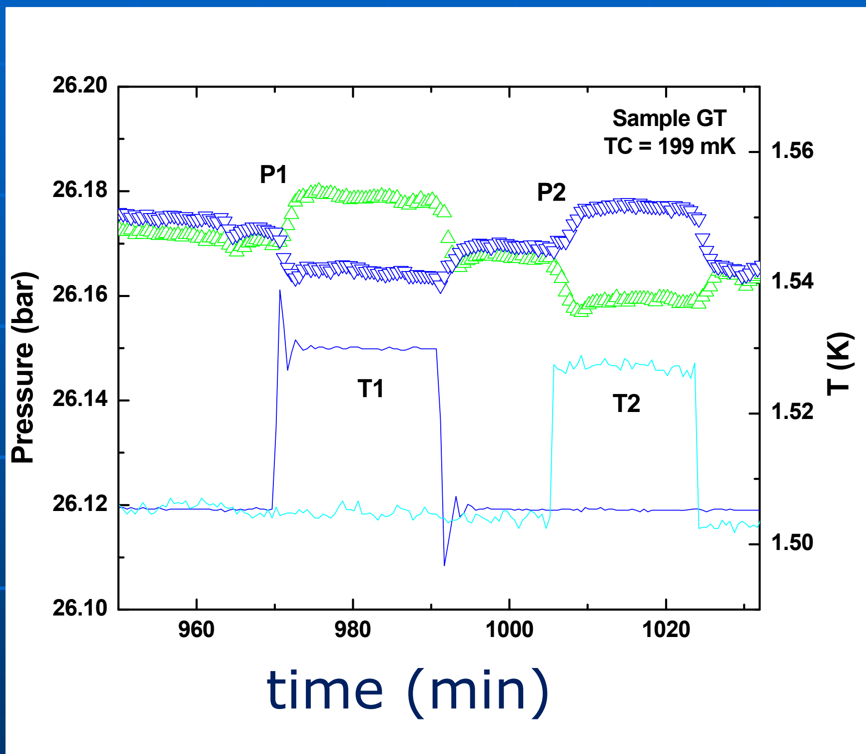
e.g., TC = 199 mK P = ~ 26 bar.



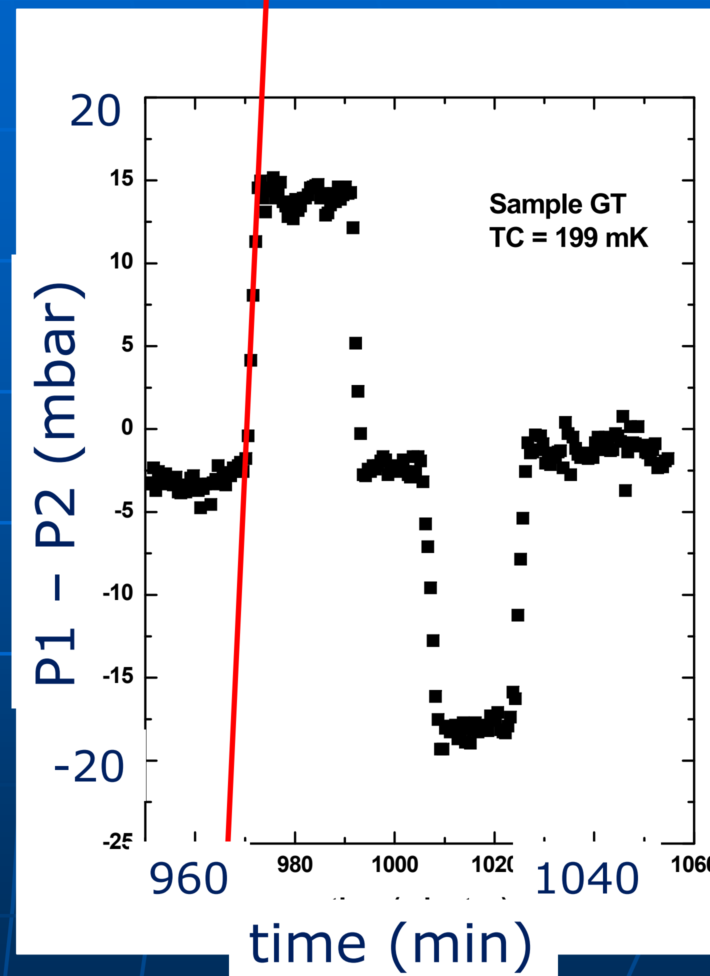


This different approach gives generally consistent results with the previous approach. It has benefits.

T = 199 mK

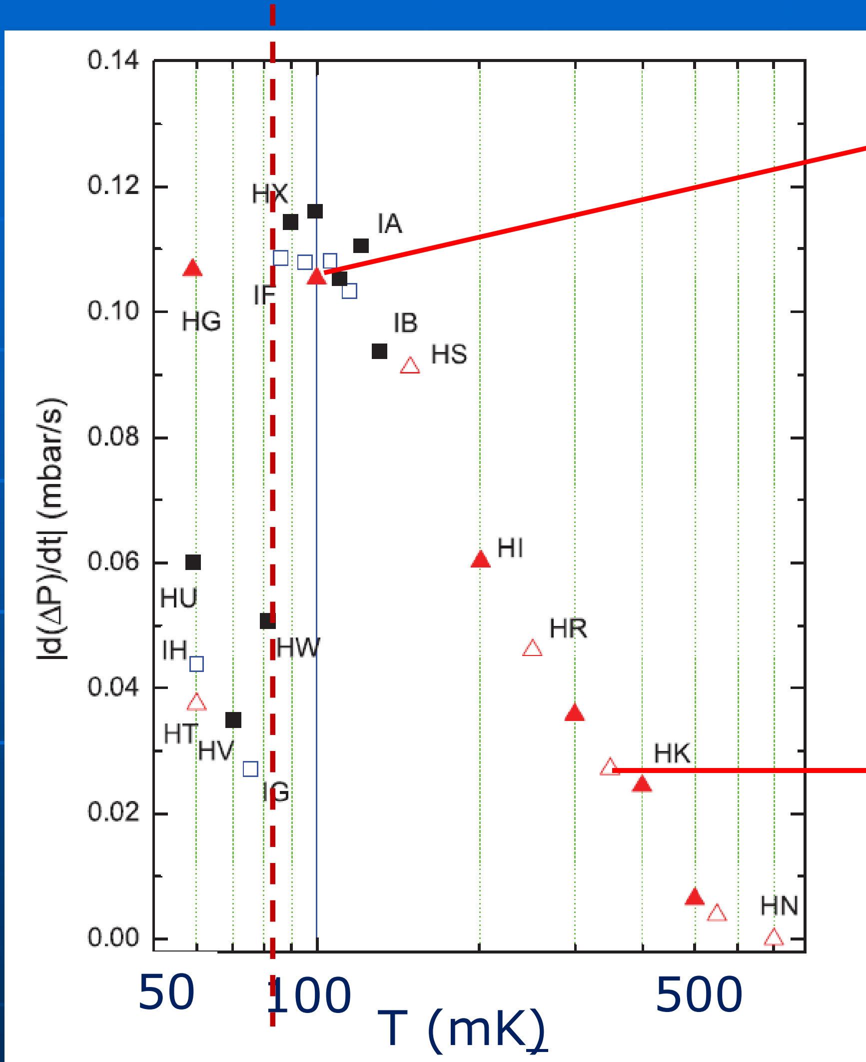


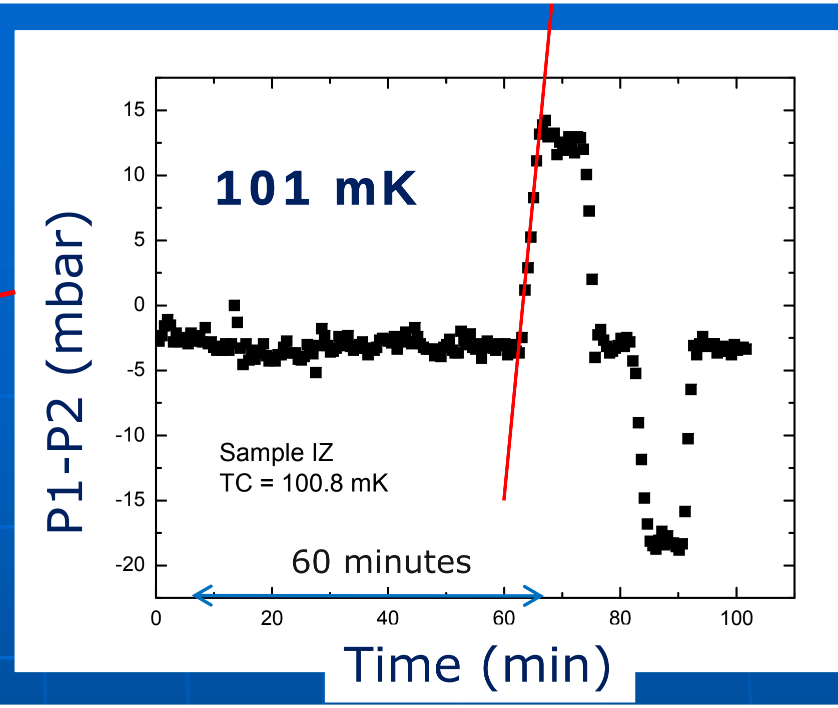
The slope of P1-P2 is related to the flux.

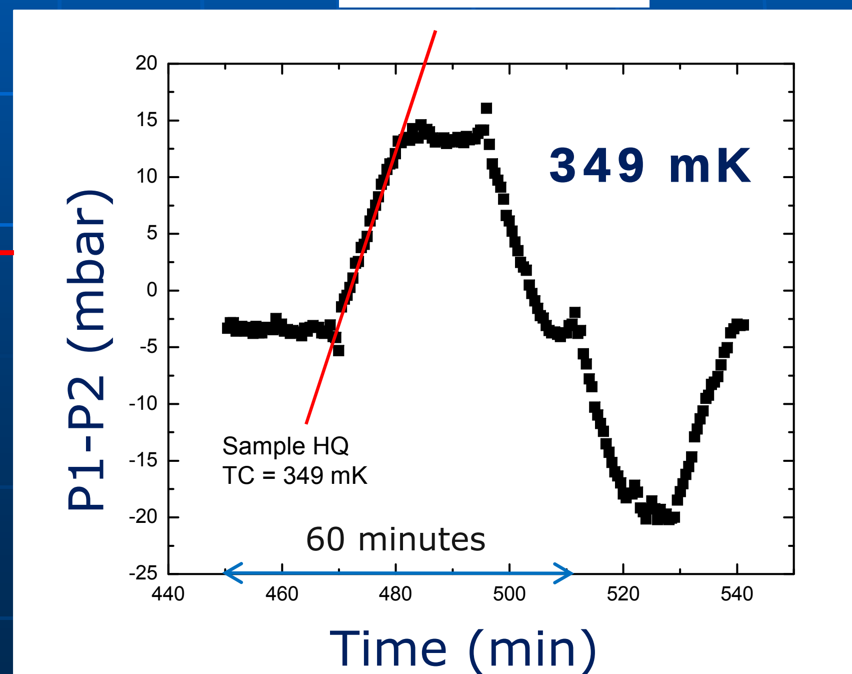


Note: The slope at low temperature is nearly linear.

Slope vs. Temperature:



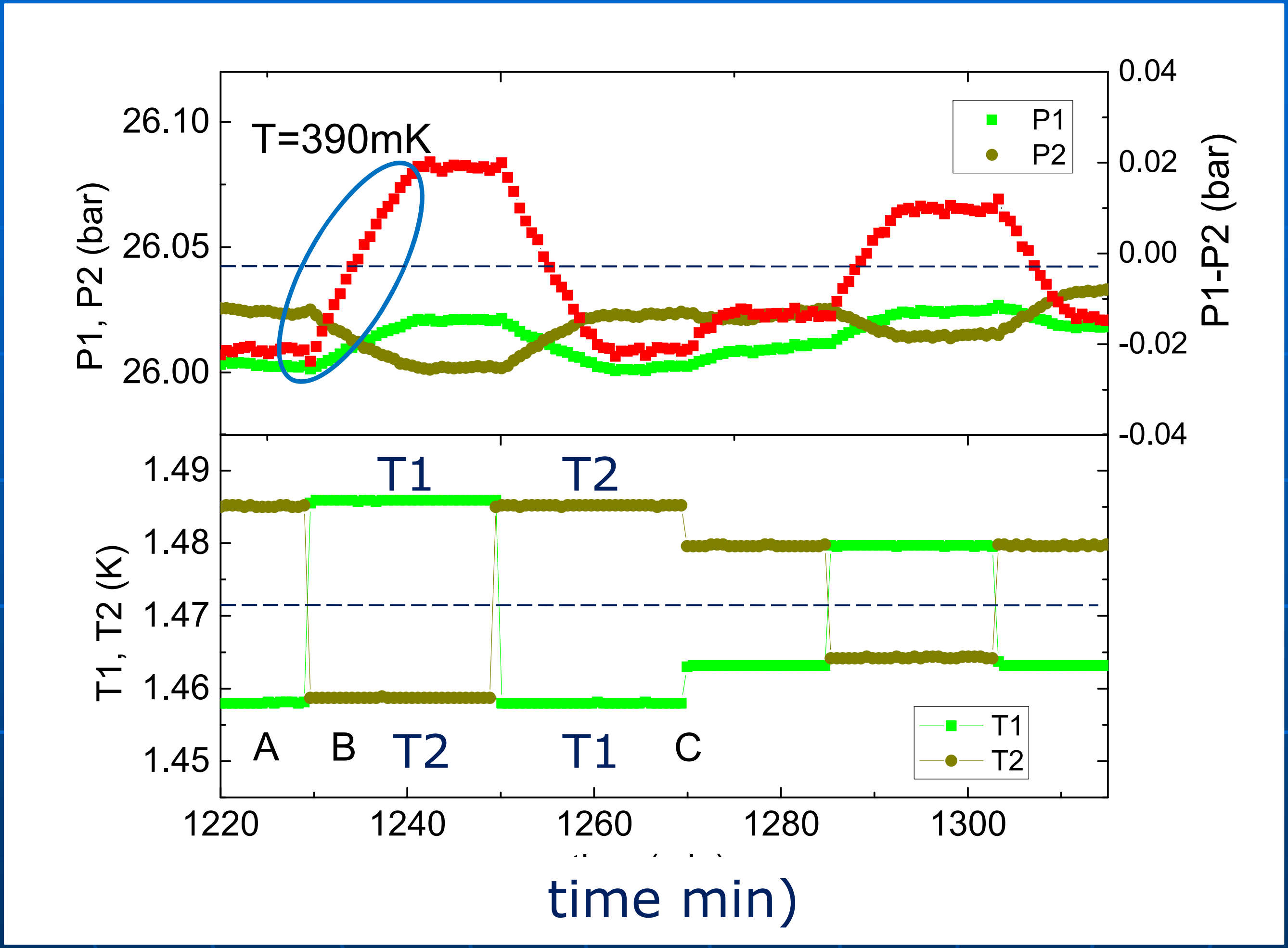


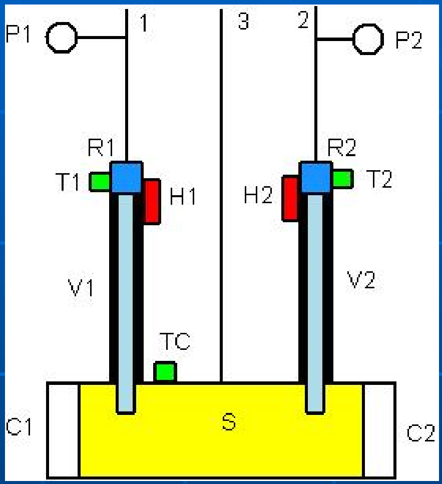


Nominal 300 ppb ^{3}He

M.W. Ray and R.B. Hallock, Phys. Rev. Lett. 105, 145301 (2010); PRB 84, 144512 (2011).

Slope of P1-P2 ~ flux, F



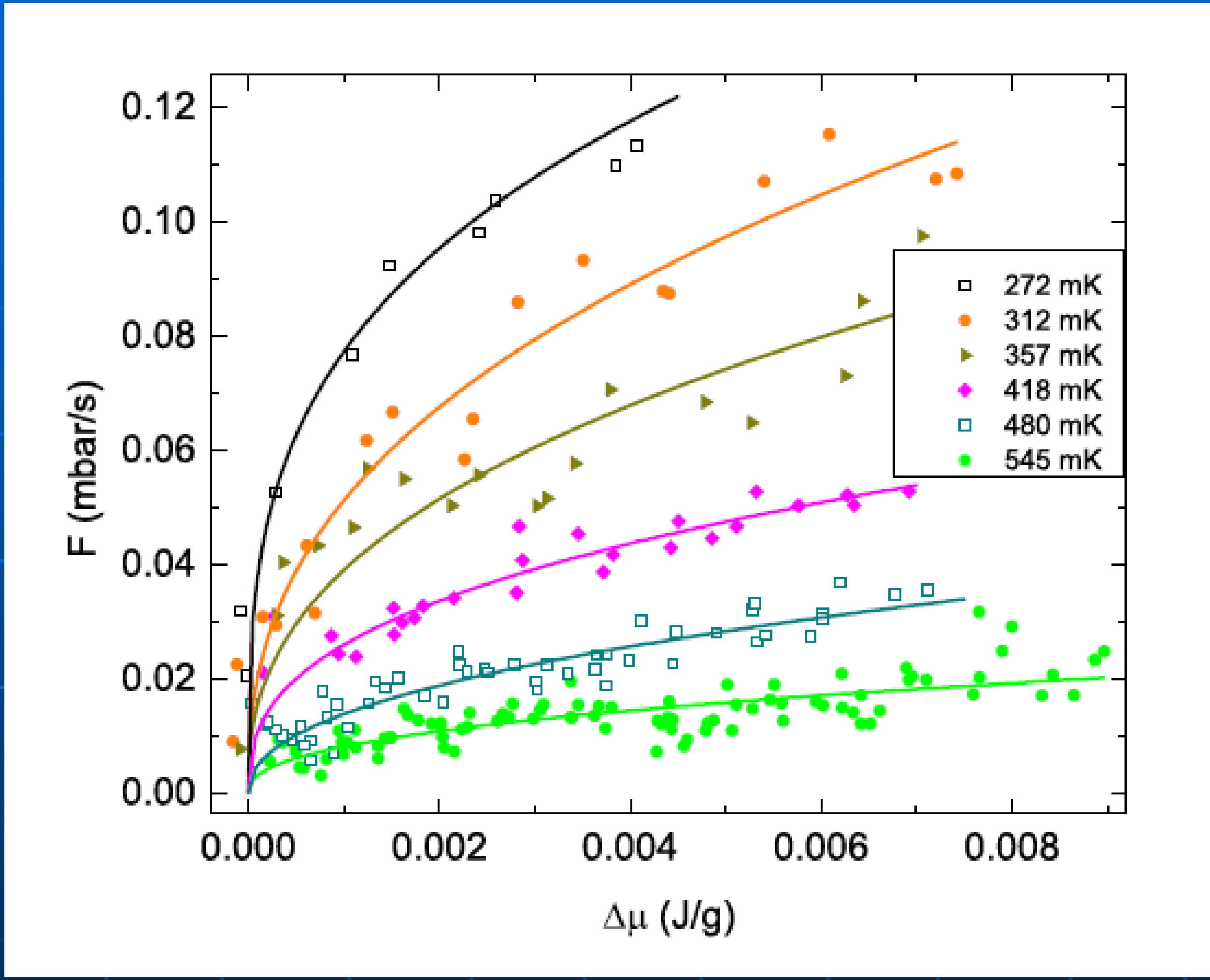


$$F = \frac{d(P1 - P2)}{dt}$$

$$\Delta\mu = m_4[\int(dP/\rho) - \int(sdT)]$$

→ F *vs.* Δμ

$F = A(\Delta\mu)^b$ Note: $b < 1$

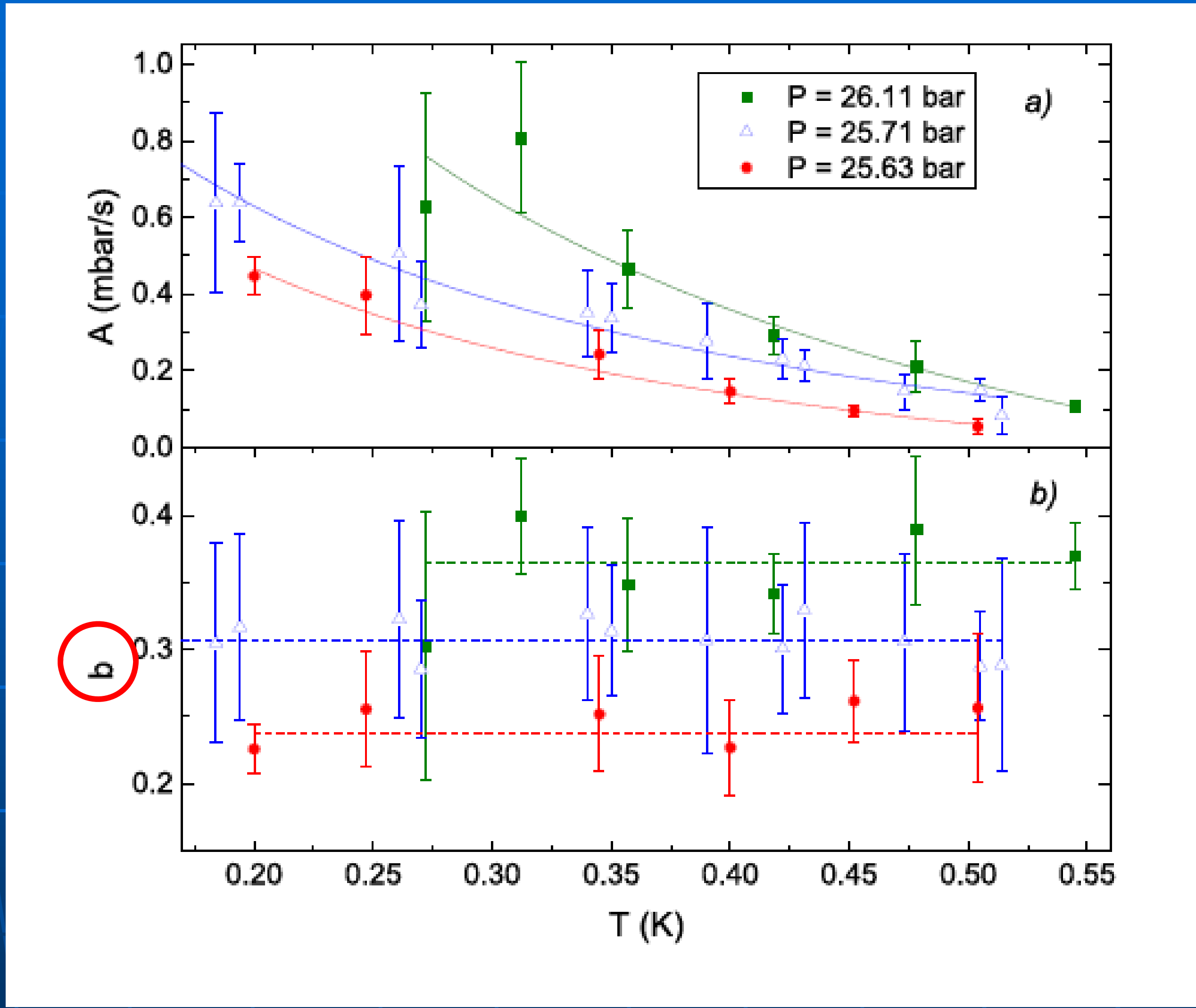


Chemical Potential →

This is not like
$I = (1/R)\ (\Delta V)^1$

$F = A(\Delta\mu)^b$

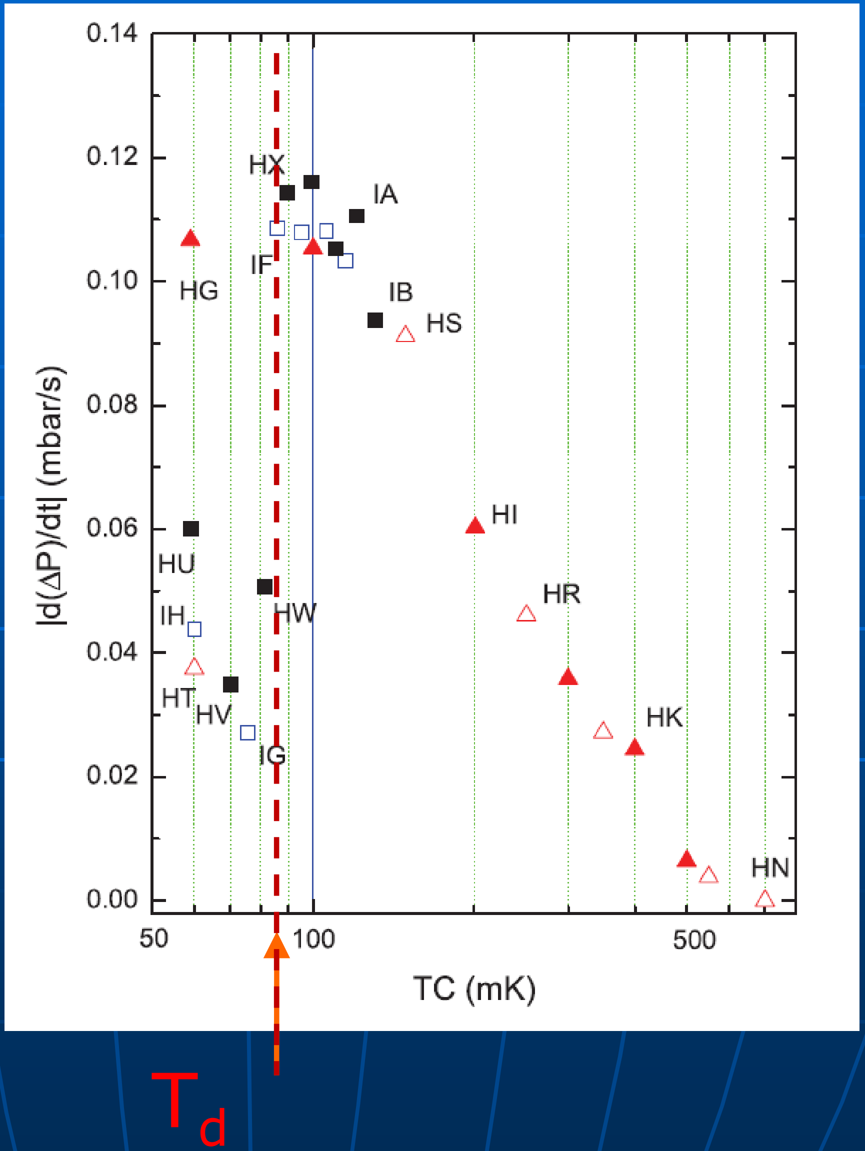
b is a constant, independent of temperature, at a given pressure



Key Question: Is this evidence for the presence of a Tomonaga-Luttinger Liquid – for bosons (i.e. a one dimensional superfluid)?

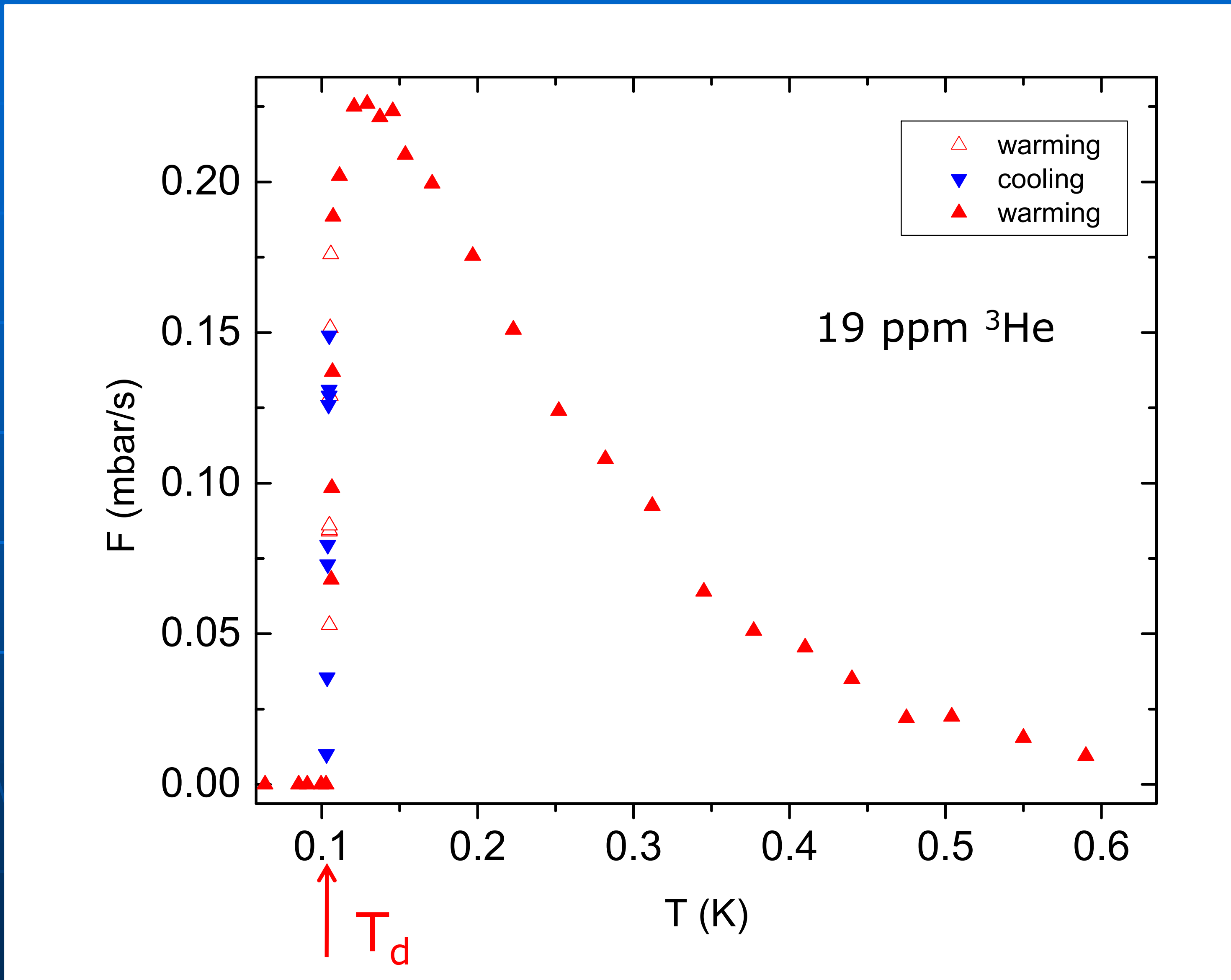
Ye. Vekhov and R.B. Hallock, Phys. Rev. Lett. 109, 045303 (2012); PRB 90, 134511 (2014).

Next, explore the vicinity of the abrupt decrease.



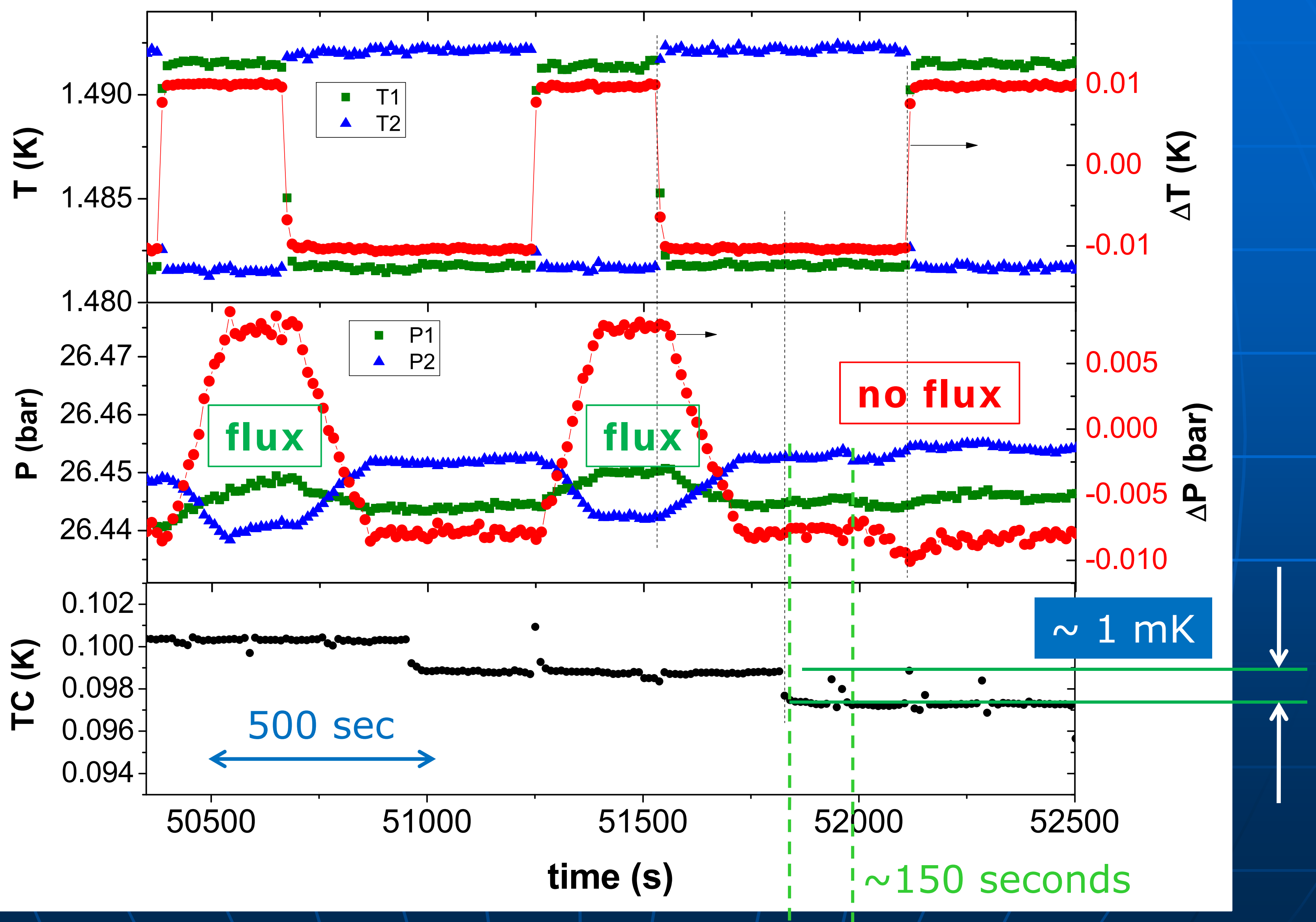
Do this for <u>nominal</u> 300 ppb ^{3}He, but also for other ^{3}He concentrations.

The flux reduction *vs.* temperature is <u>extremely</u> sharp.



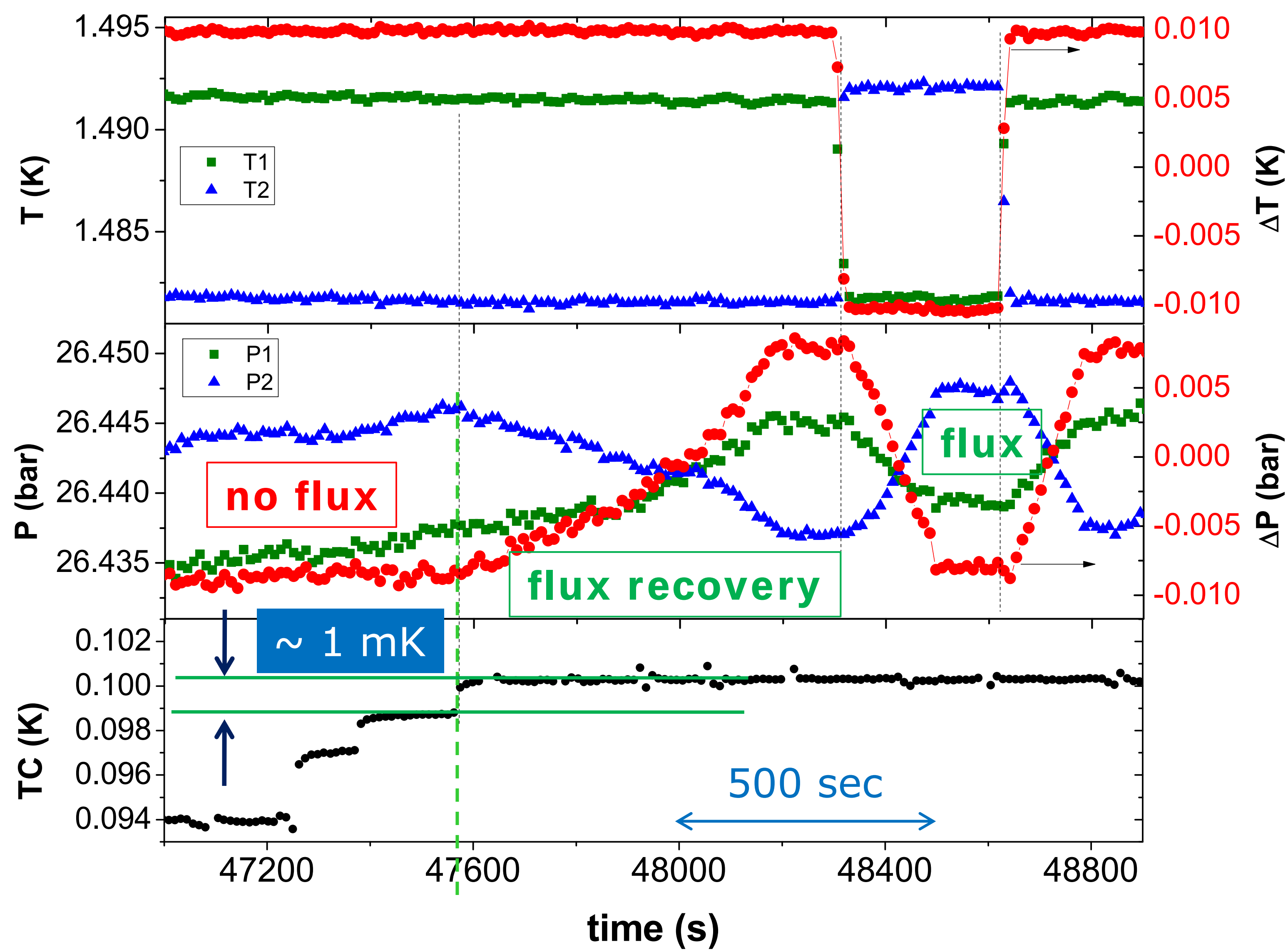
Ye. Vekhov, W.J. Mullin and R.B. Hallock, Phys. Rev. Letters 113, 035302 (2014)

How Sharp? **10ppm ^{3}He** **Cooling**

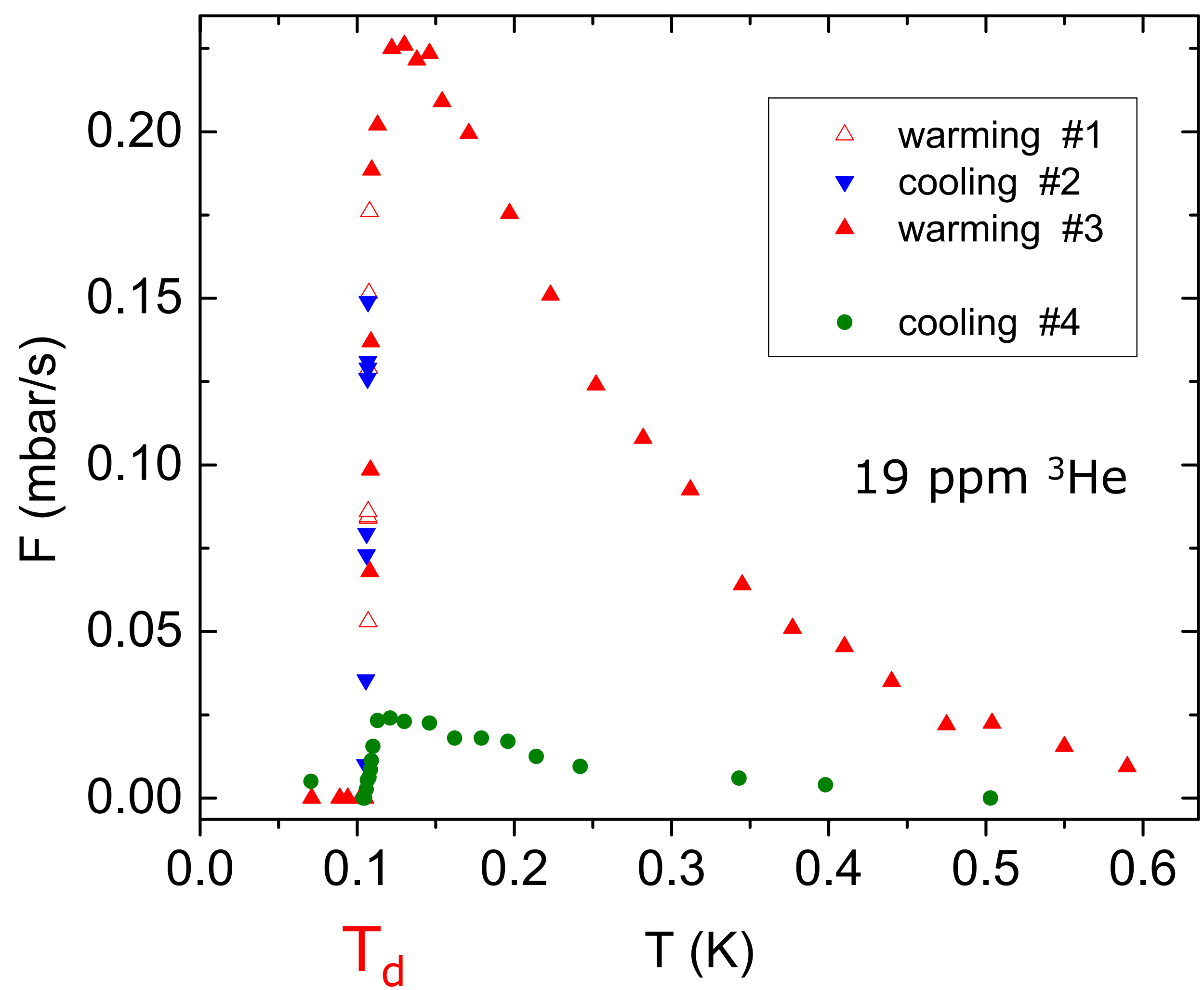


<u>Key Question</u>: What causes the kinetics of recovery?

10ppm ^3He Warming

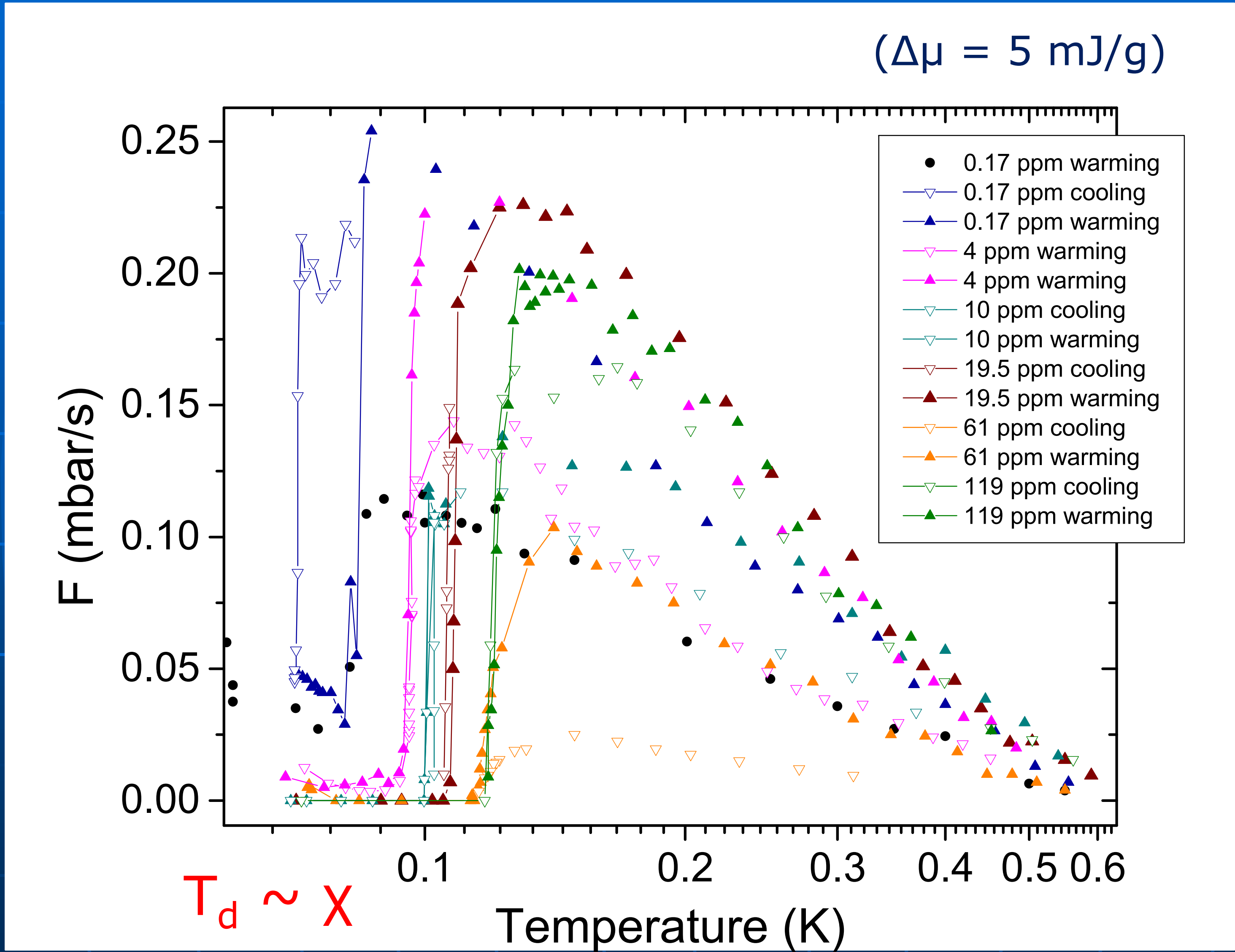


Behavior is sample and history dependent.



Ye. Vekhov, W.J. Mullin and R.B. Hallock, Phys. Rev. Letters 113, 035302 (2014)

Many different samples, different concentrations, different histories:

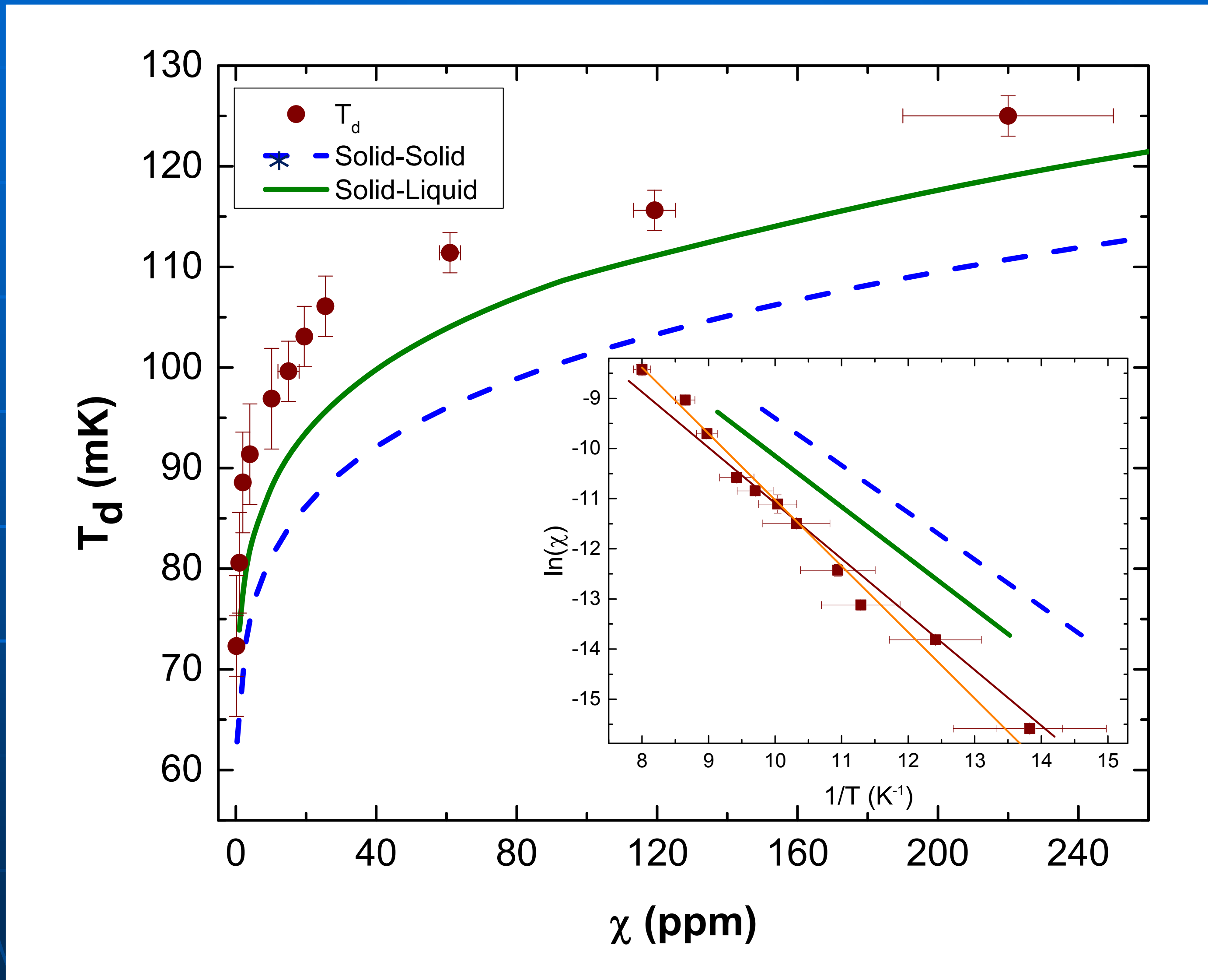


Extinction is somewhat less abrupt at higher concentrations.

Note: High temp (> 0.7 K), kills the flux – it typically does not recover on cooling.

Key Question: Specifically, how does the ^{3}He kill the flux?

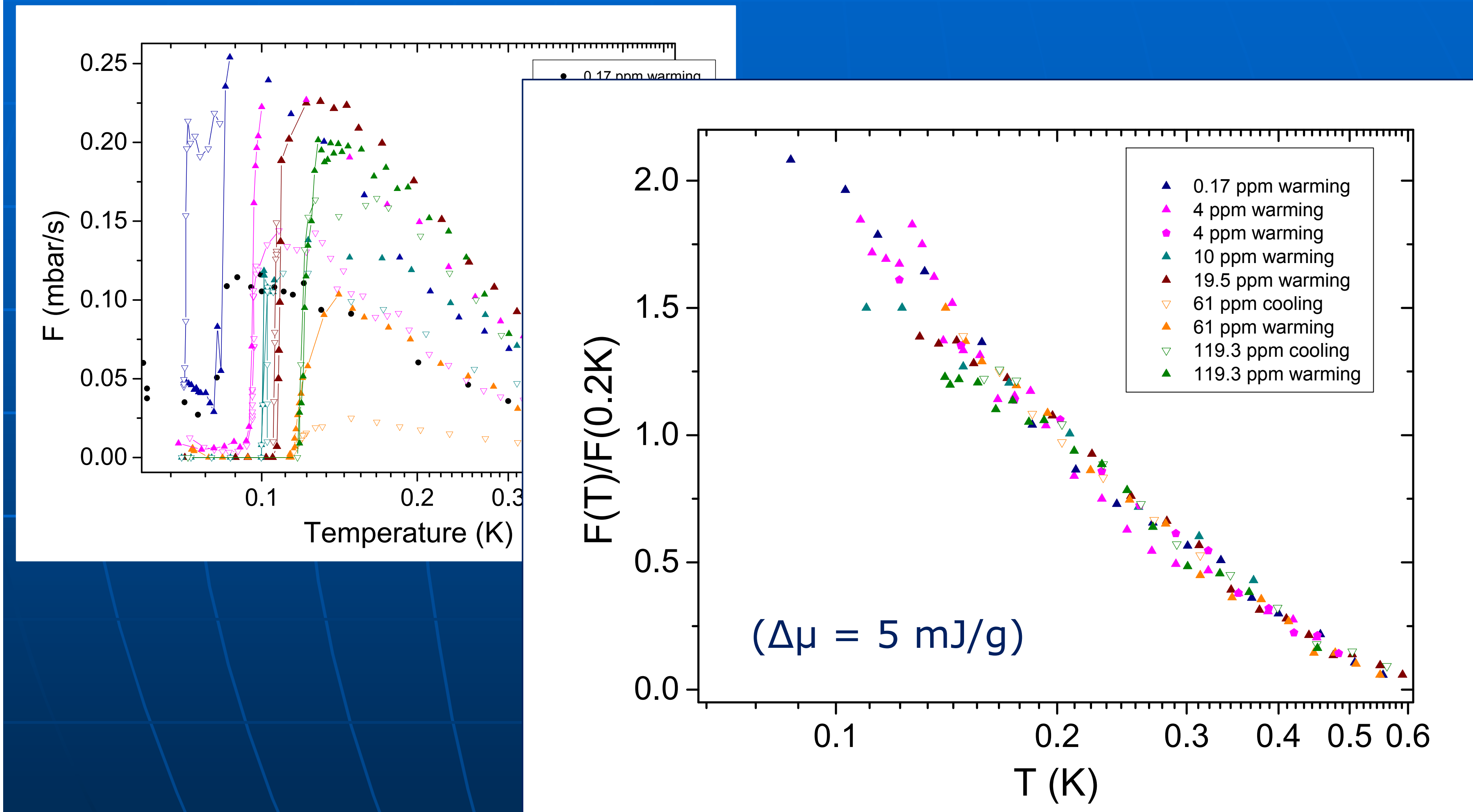
T_d vs. X



Ye. Vekhov, W.J. Mullin and R.B. Hallock, Phys. Rev. Letters 113, 035302 (2014)
*D.O. Edwards and S. Balibar, Phys. Rev. B 39, 4083 (1989)

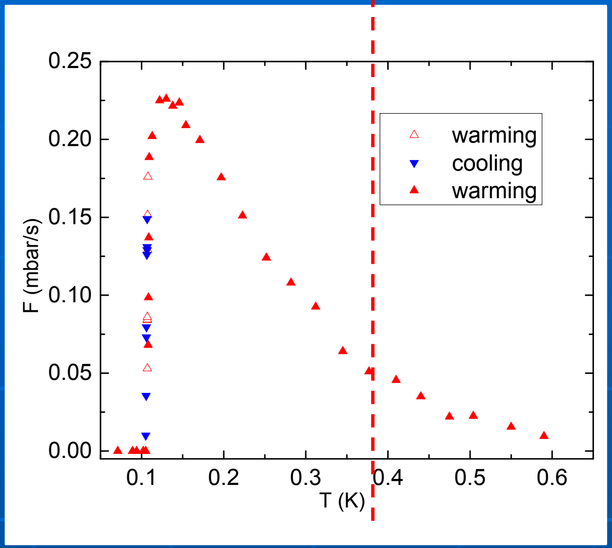
Normalize the flux, pick T = 0.2 K: (for T > T_d)

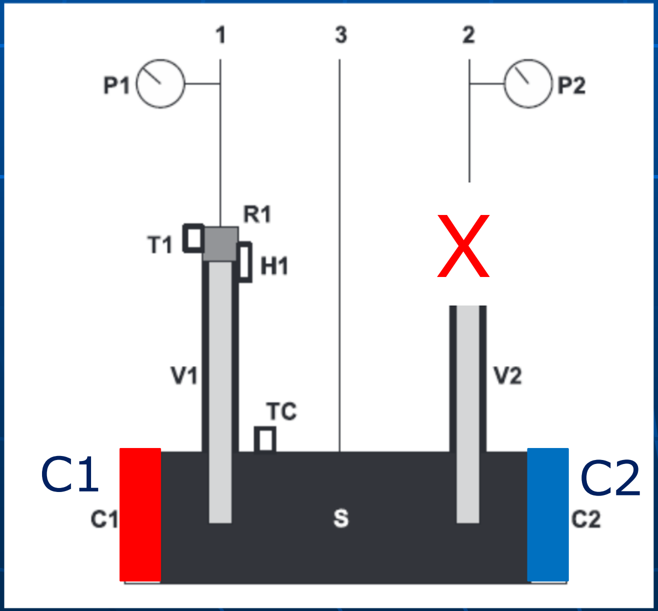
Key Question: That causes the universal behavior?

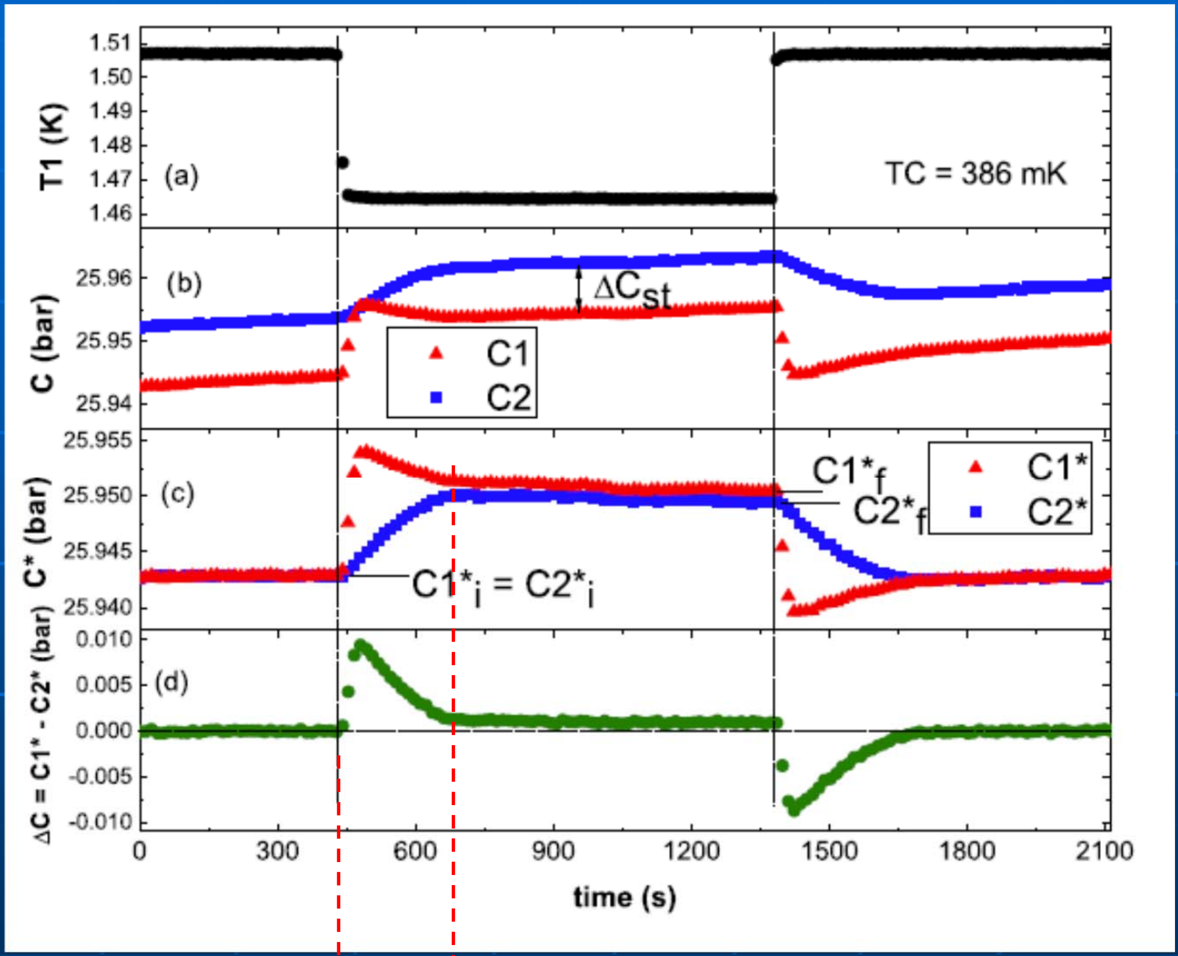


Ye. Vekhov, W.J. Mulllin and R.B. Hallock, Phys. Rev. Lett. 113, 035302 (2014);
Ye. Vekhov and R.B. Hallock, arXiv:1507.00288

Study the syringe effect: inject mass, with no outlet.

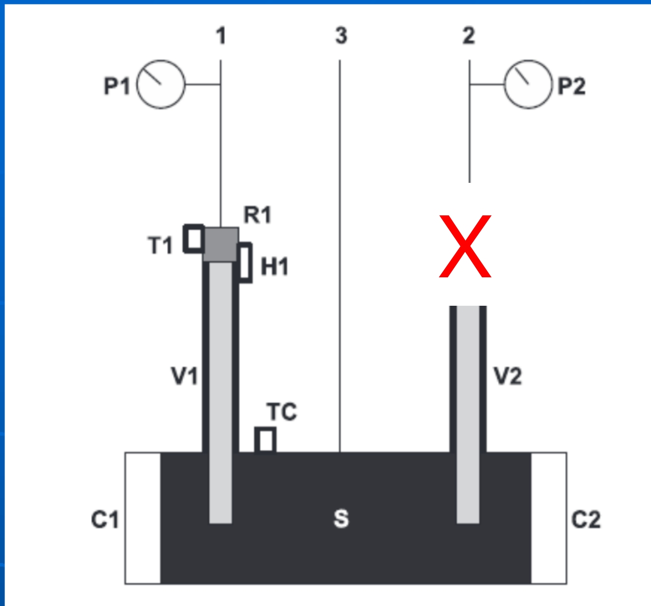


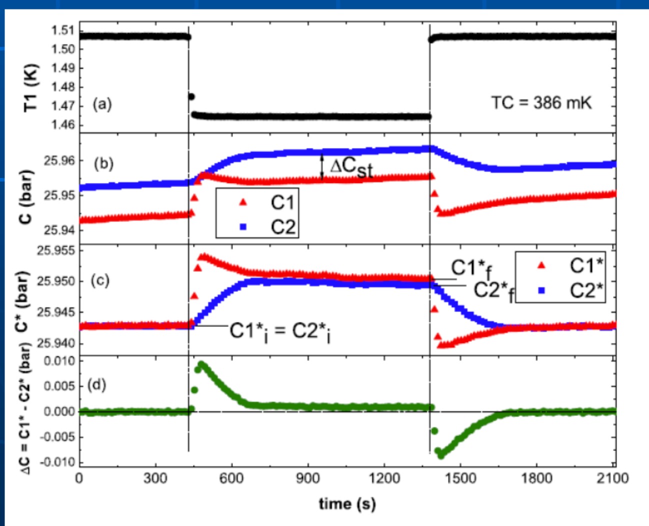


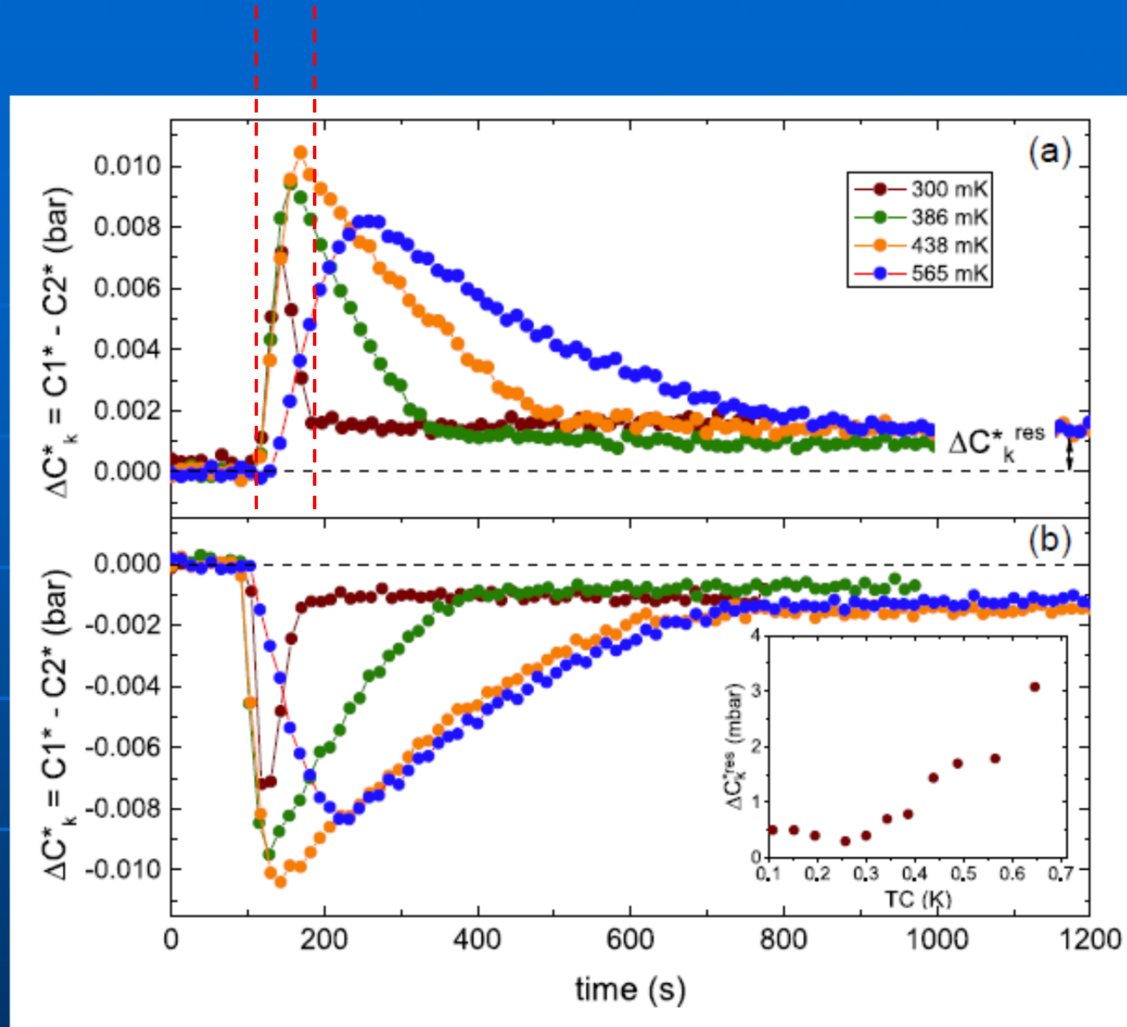


~ 250 sec

~ 70 sec Same ΔT1 in each case:





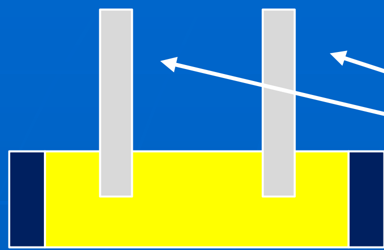


We interpret this to mean that the flux restriction is in the solid itself.

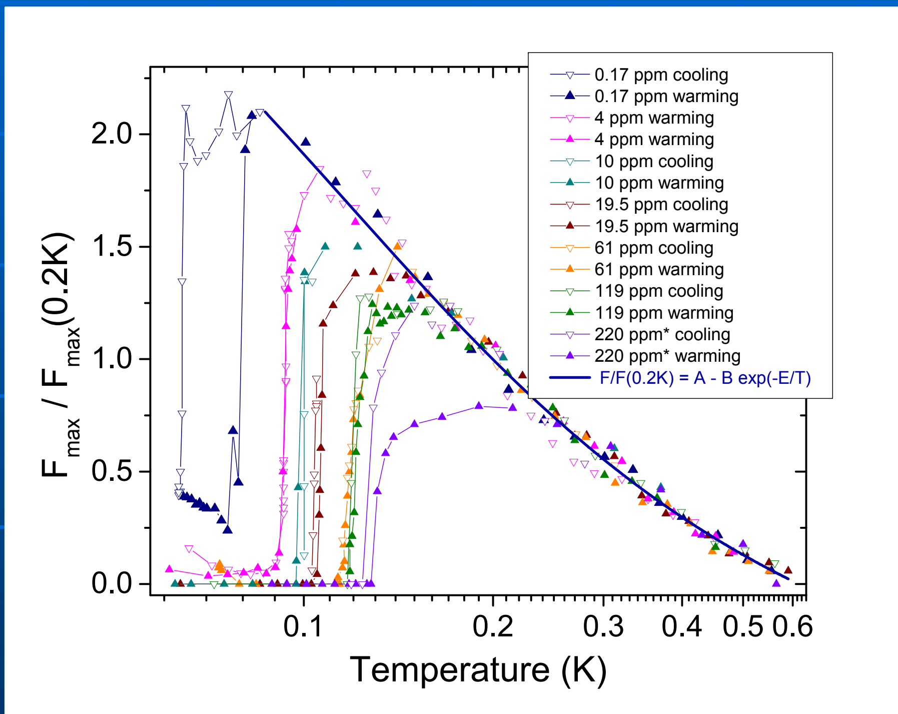
Key Question: What causes this?

Ye. Vekhov and R.B. Hallock, Phys. Rev. 91, 180506(R) (2015).

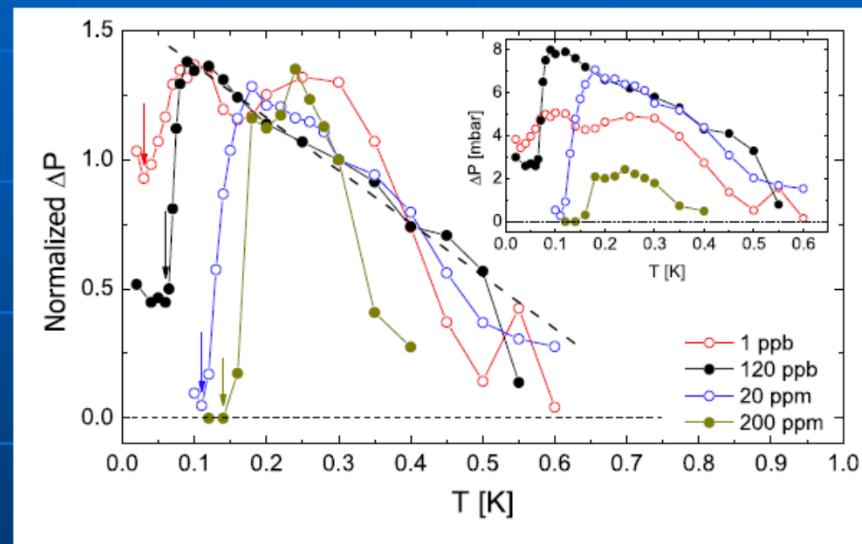
Related Work



Vycor



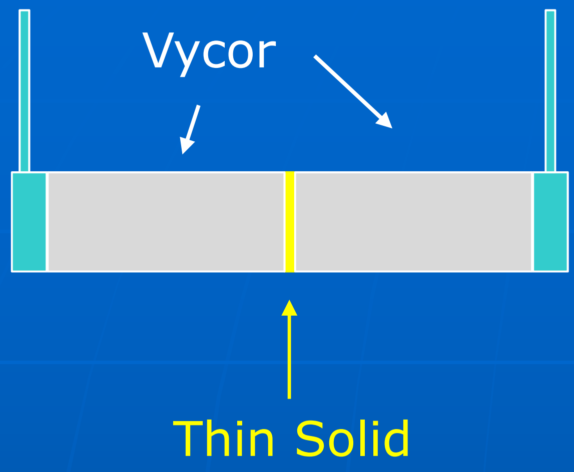
Beamish group*



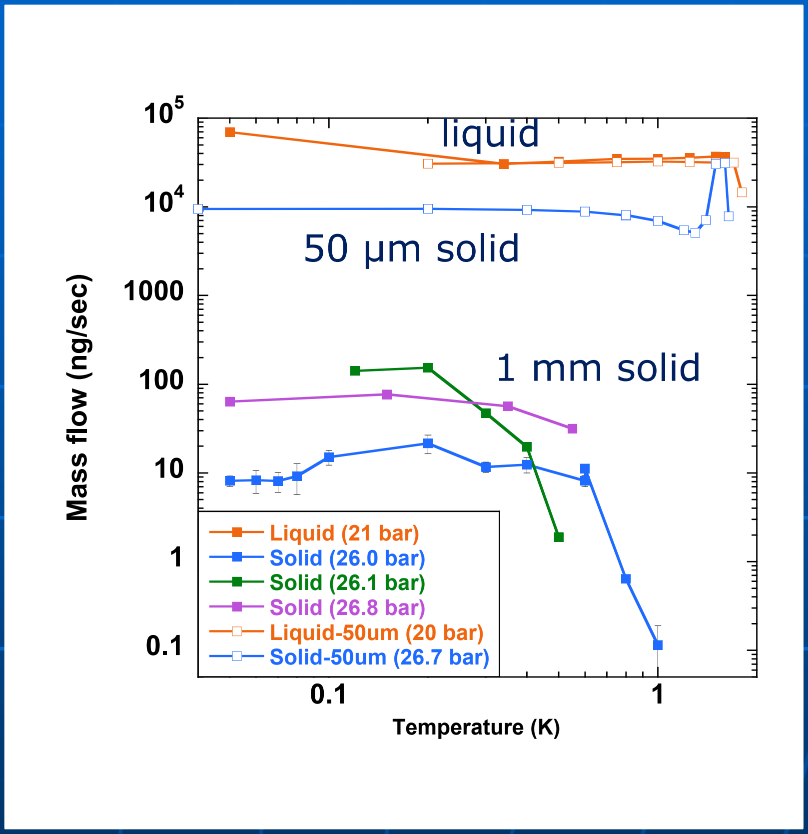
Ye. Vekhov, W.J. Mullin and R.B. Hallock, Phys. Rev. Letters 113, 035302 (2014); Vekhov and Hallock: arXiv:1507:00288

*Z.G. Cheng, J. Beamish, et al. Phys. Rev. Lett. 114, 165302 (2015)

Related Work



Chan group*



*A. Haziot, D. Kim and M.H.W. Chan; APS March +

Outline

I. Reminder: Solid Helium

II. Flow Measurements at UMass

III. Unanswered Questions

Specific Questions:

1. What actually carries the flux?
2. How does the ^{3}He poison the flux?
3. What causes the universal temperature dependence?
4. What governs the kinetics of the flux recovery?
5. What happens if you deform the solid?
6. What causes the flow to stop at about 650 mK?
7. Is this flow really the behavior of a Luttinger Liquid?
8. Can there be a metastable or persistent current?
9. What are the binding energies of ^{3}He to intersections?
10. What is the behavior at the solid-liquid interface?
11. Is there a low temperature limit for the syringe effect?
12. How does the C1, C2 response vary with concentration?

More Broadly:

1. We appear to have quantum dislocations - with low-dimensional superfluidity, plasticity and quantum tunneling.
2. There is an interplay among these new areas that needs to be explored.
3. We need a complete theory of dislocation, impurity interactions.

Comments on issues: S. Balibar, J. Beamish and R.B. Hallock, JLTP 180, 3 (2015)
(created at the time of the Brazil Workshop in 2014)

Thank You

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