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Observation of a supersolid helium phase

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Observation of a supersolid helium phase

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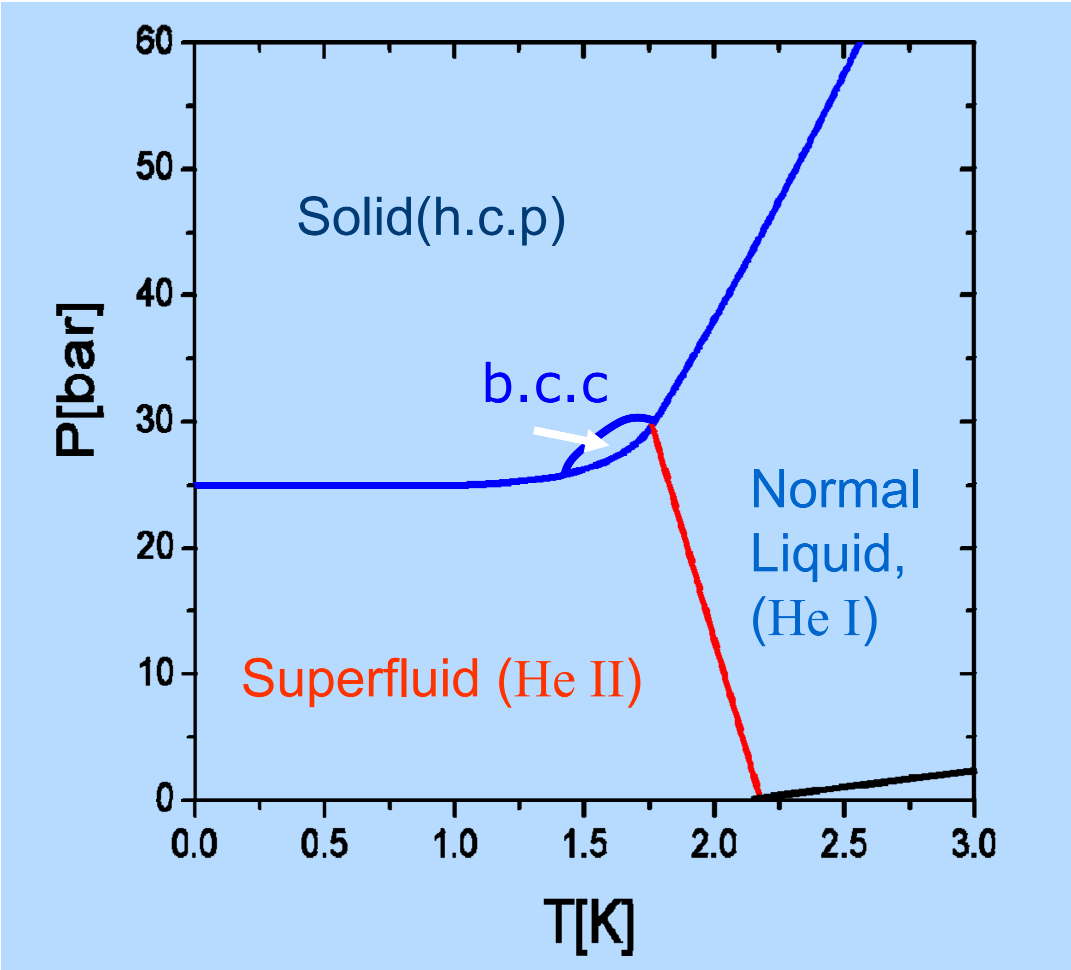
University of Florida

Supported by NSF

Phase diagram of ^{4}He



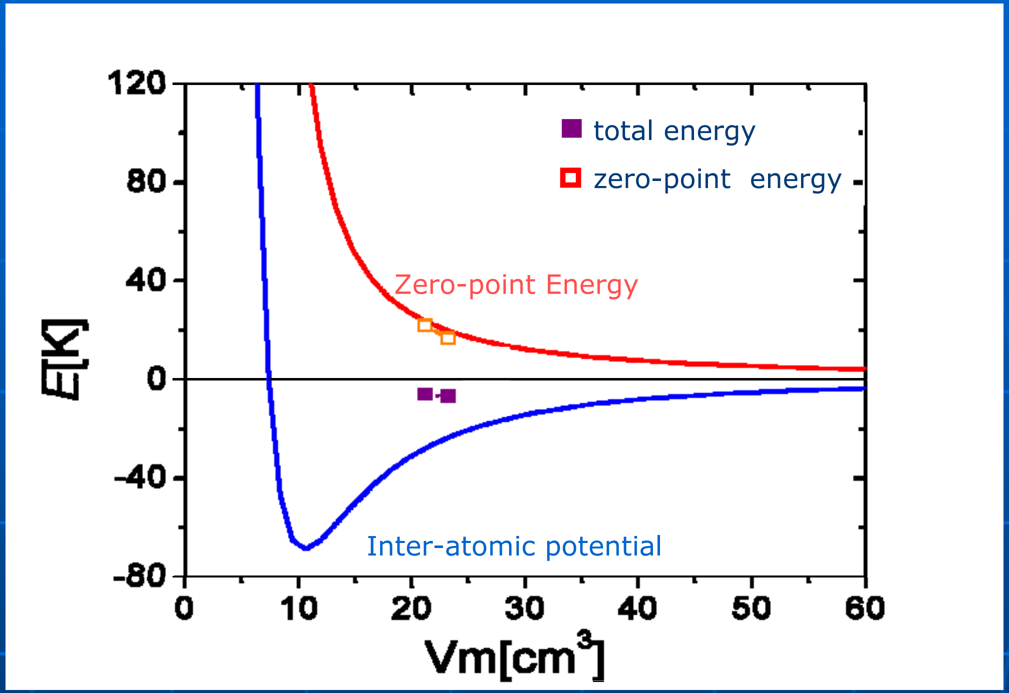
Fritz London is the first person to recognize that superfluidity in liquid ^{4}He is a BEC phenomenon.

Condensation fraction was predicted and measured to be 10% near T=0. Superfluid fraction at T=0, however is 100%.

- Lindemann Parameter

  the ratio of the root mean square of the displacement of atoms to the interatomic distance (d_a)

$$\gamma_L = \frac{\sqrt{<u^2>}}{d_a} = 0.26$$



  exceeding the critical value of Lindemann parameter for melting of a classical solid (0.1~0.15).

- Recently observed Xray measurement at ~0.7K and near melting curve shows 26%
  (Burns et al. *Phys. Rev. B* **55**, 5767(1997))

No experimental evidence of superfluidity in solid helium prior to 2004.

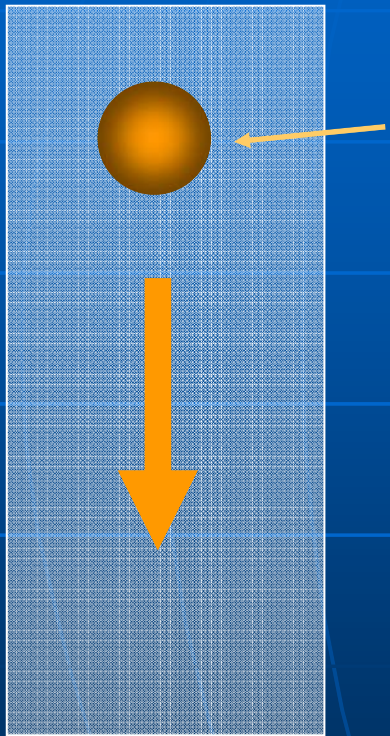
- Plastic flow measurement
  Andreev et al. Sov. Phys. JETP Lett **9**,306(1969)
  Suzuki J. Phys. Soc. Jpn. **35**, 1472(1973)
  Tsymbalenko Sov. Phys. JETP Lett. **23**, 653(1976)
  Dyumin et al.Sov. J. Low Temp. Phys. **15**,295(1989);
  Bonfait, Godfrin and Castaing, J. de Physique 50, 1997(1989)
- Torsional oscillator
  Bishop et al. Phys. Rev. B **24**, 2844(1981)
- Mass flow
  Greywall Phys. Rev. B **16**, 1291(1977)
- $P_V(T)$ measurement
  Adams et al. Bull. Am. Phys. Soc. **35**,1080(1990)
  Haar et al. J. low Temp. Phys. **86**,349(1992)
- However, interesting results are found in
  Ultrasound Measurements at UCSD.
  Goodkind Phys. Rev. Lett. **89**,095301(2002) and
  references therein

Plastic flow

(most experiment carried out above 0.5K)

Measure the displacement of a ball
frozen in solid helium

Andreev et al. Sov. Phys. JETP Lett **9**,306(1969)



Solid helium

A polished ball
(d=1.57mm , Alloy; 75%Pt +25% Co)

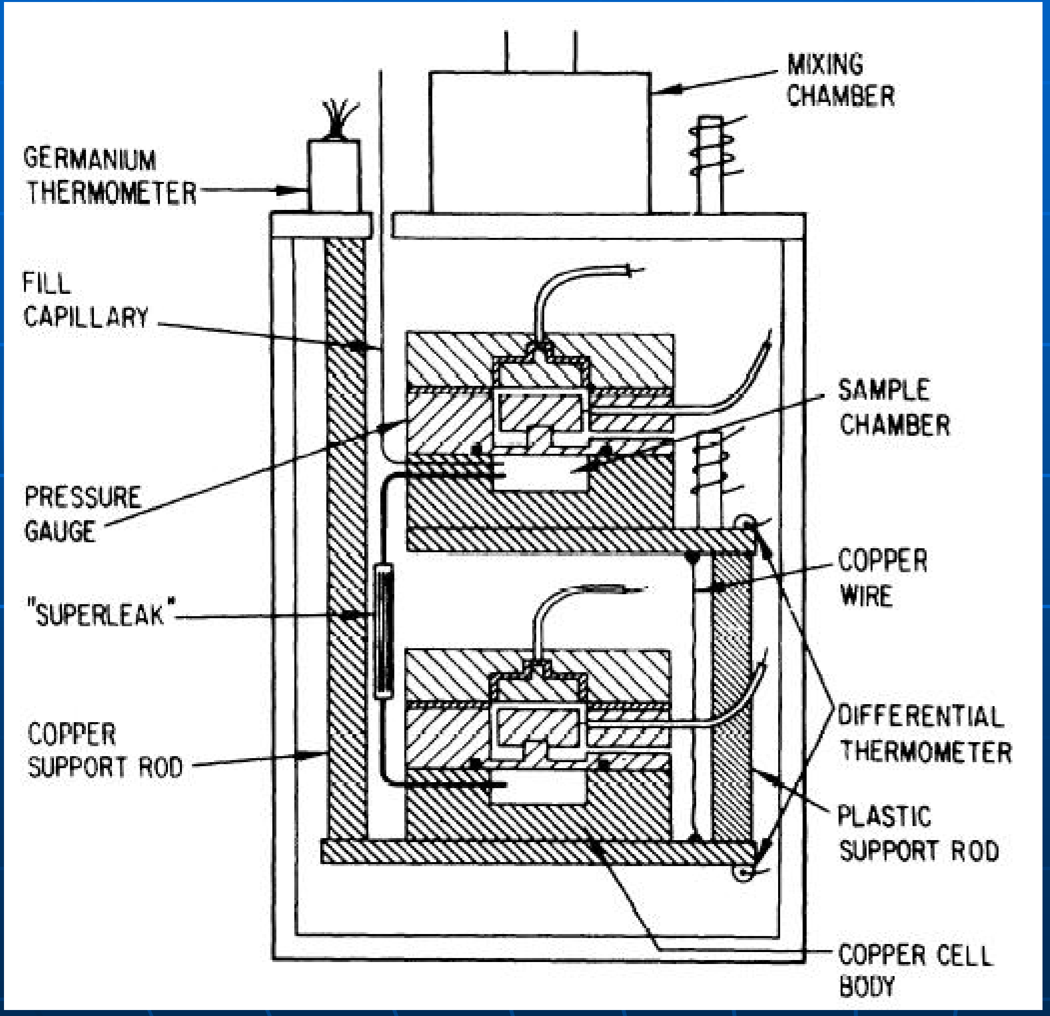
No motion detected at 0.5K

- Suzuki J. Phys. Soc. Jpn. **35**, 1472 (1973)
  (T=1.77K P=32atm,f_c= 6.5×10^5 dyne/cm^2)
- Tsymbalenko Sov. Phys. JETP Lett. **23**,653 (1976)
  (T= 0.6~2.1K, P=25.7~40atm)
- Sanders et al, Phys. Rev. Lett., **39**, 815 (1977)

Mass flow

Search for superfluidity in solid ^{4}He

D. S. Greywall, Phys. Rev. B **16**, 1291 (1977)



ΔP=1~2 bars

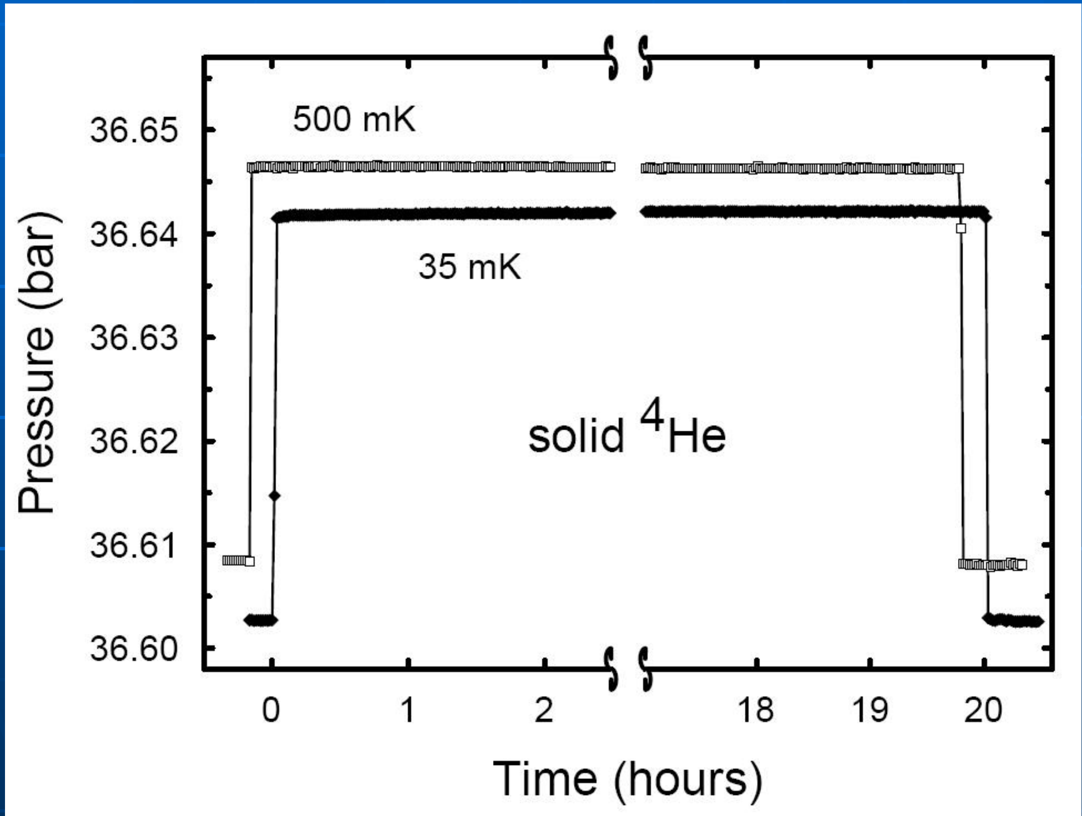
From 25 to 48 bars
No change in the pressure
In both sample chamber

$$\frac{\rho_s}{\rho}|v| \leq 2.5\times10^{-9} cm/s$$

Bonfait et.al. did not see any mass transfer in solid helium in a U-tube down to 4 mK

Pressure driven flow

1. J. Day et. al, Phys. Rev. Lett **95**, 035301 (2005)
2. J. Day and J. Beamish, PRL,96, 105304 (2006)



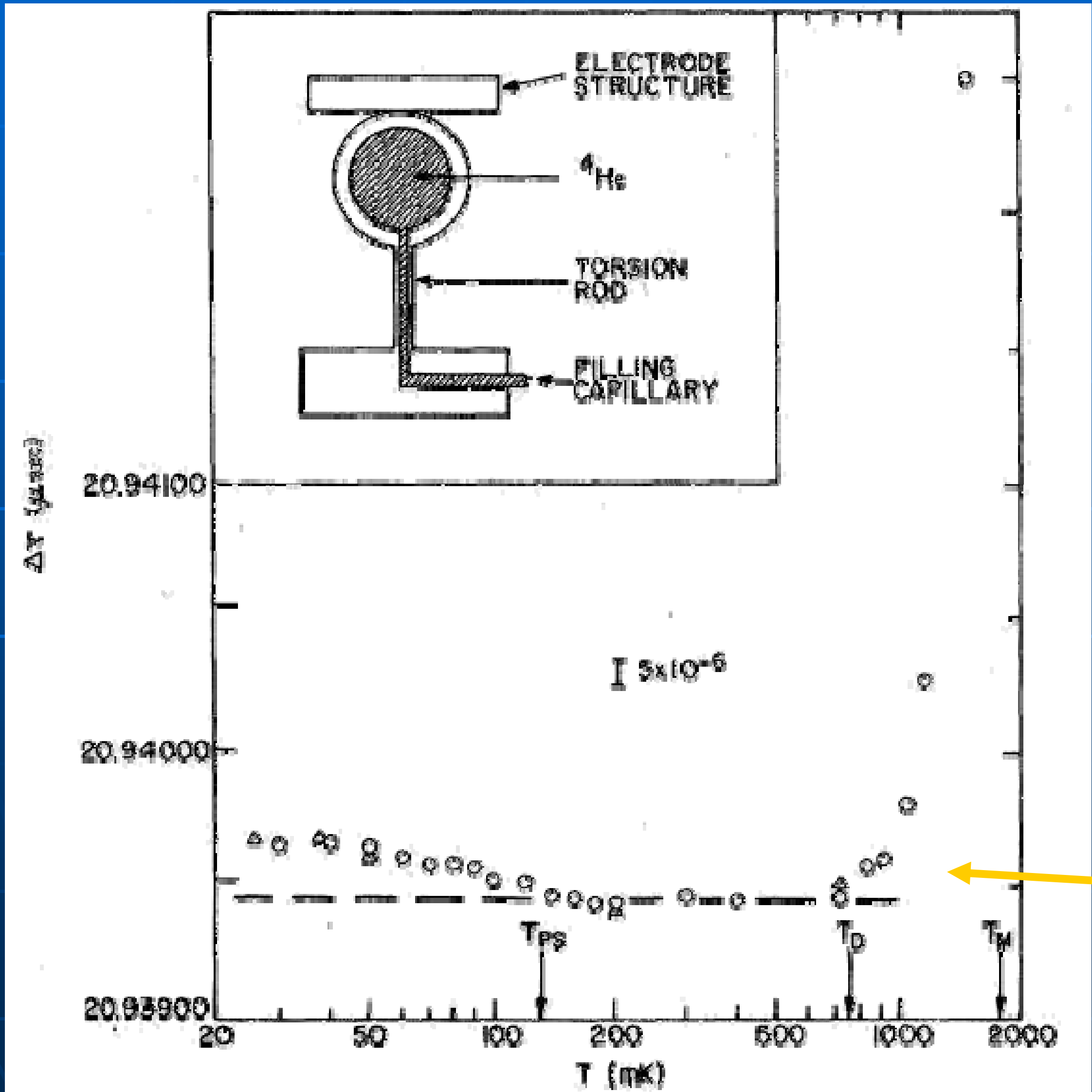
1. No evidence of mass flow from bulk Into vycor
2. Analogous to Greywall

$$\frac{\rho_s}{\rho}|v| \leq 1.5\times 10^{-12} cm/s$$

Diffusive flow of solid helium (T=1.0-1.4K, Ds~10^{-7}cm^2/s)
Dyumin et al. Sov. J. Low Temp. Phys. **15**,295(1989)

Torsion oscillator measurements of bulk solid ^{4}He

Bishop, Paalanen and Reppy, Phys. Rev. B **24**, 2844(1981)



No " NCRI"

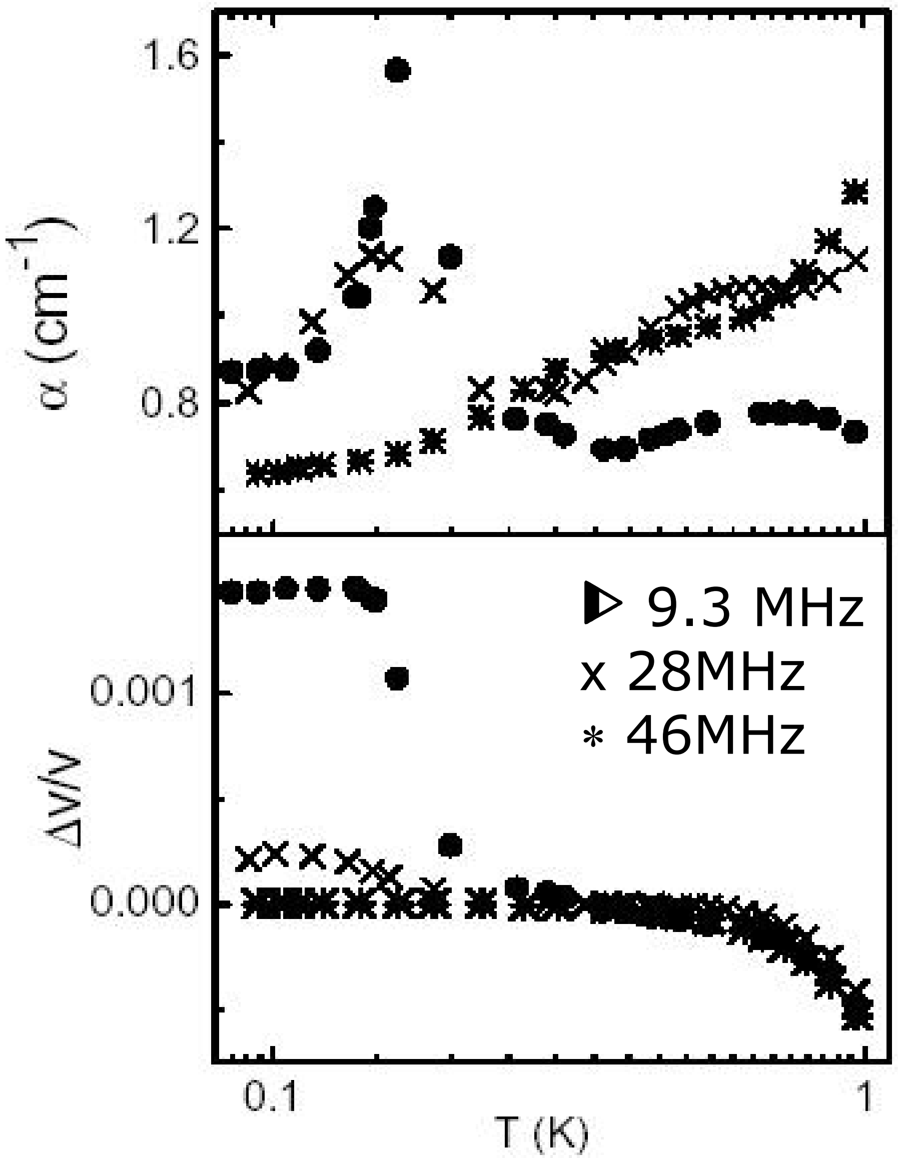
From 25-48bars

ρ_s < 5 parts in 10^6

v_c < 5 μm/sec

^{3}He impurities 411ppm

Ultrasound velocity and dissipation measurements in solid ^4He with 27.5ppm of ^3He



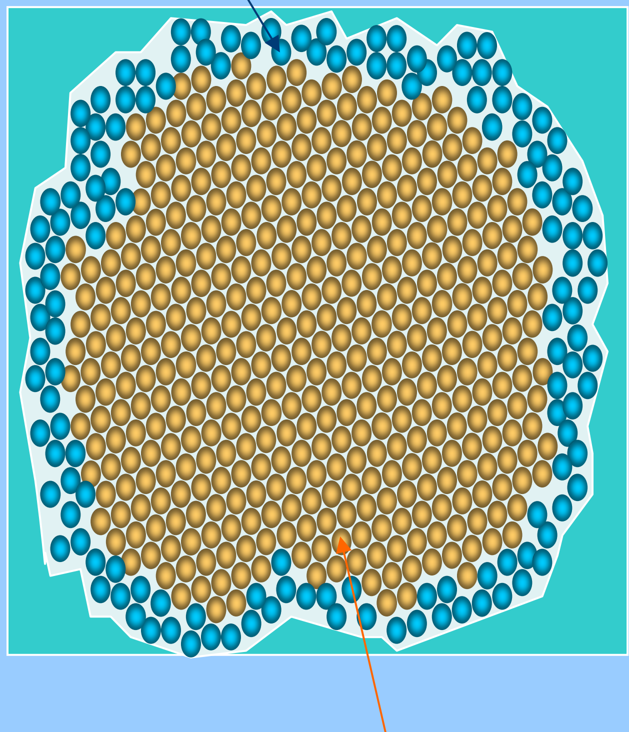
The results are interpreted by the authors as showing BEC of thermally activated vacancies above 200mK.

P.C. Ho, I.P. Bindloss and J. M. Goodkind, *J. Low Temp. Phys.* **109**, 409 (1997)

Goodkind Phys. Rev. Lett. **89**,095301(2002)

TEM of Vycor glass

Solid helium in a porous medium should have more disorder and defects, which may facilitate the appearance of superflow in solid?

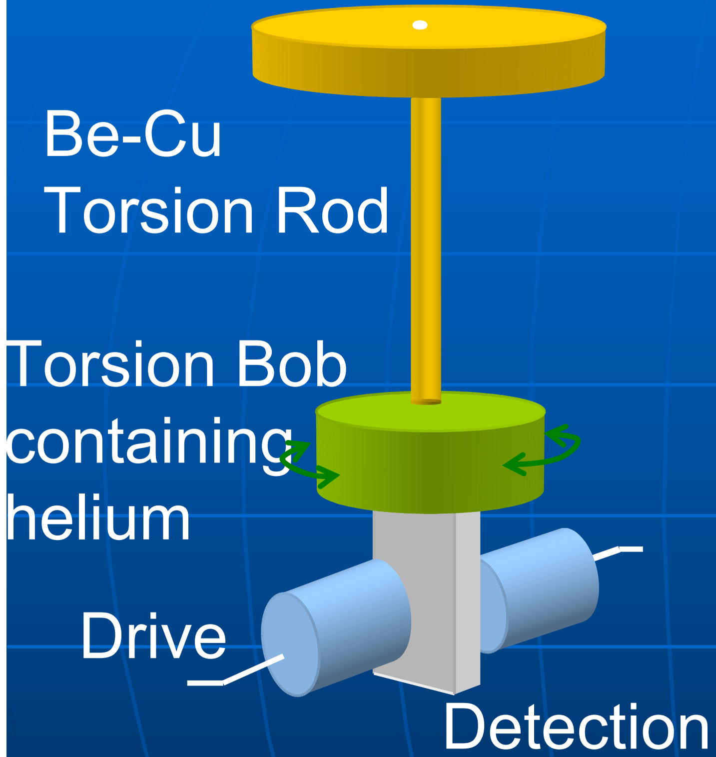


Solidification proceeds in two different directions:

1) In the center of the pore a solid cluster has crystalline order identical to bulk ^4He
2) On the wall of a pore amorphous solid layers are found due to the van der Waals force of the substrate

Elbaum et al. Adams et al. Brewer et al.

Torsional oscillator is ideal for the detection of superfluidity



$$\tau_o = 2\pi\sqrt{\frac{I}{K}}$$

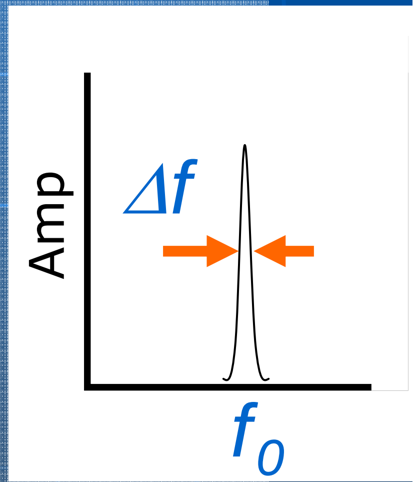
Resolution

Resonant period (τ_o) ~ 1 ms

stability in τ is 0.1ns

$\delta\tau/\tau_o = 5\times10^{-7}$

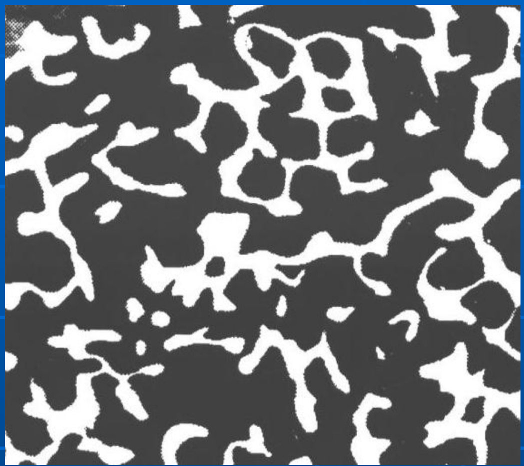
Mass sensitivity ~10^{-7}g

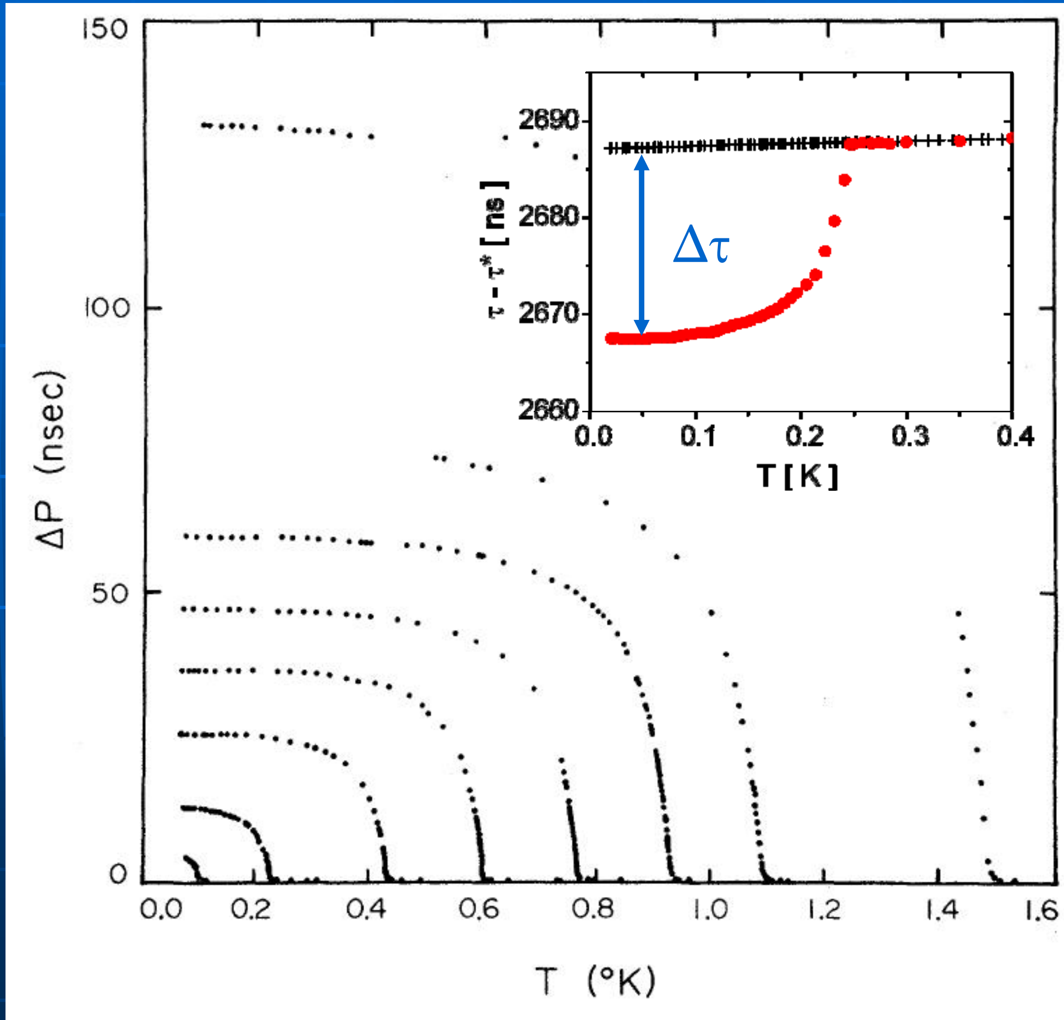


$Q = f_0/\Delta f \sim 2\times10^6$

Torsional oscillator studies of superfluid films

Vycor

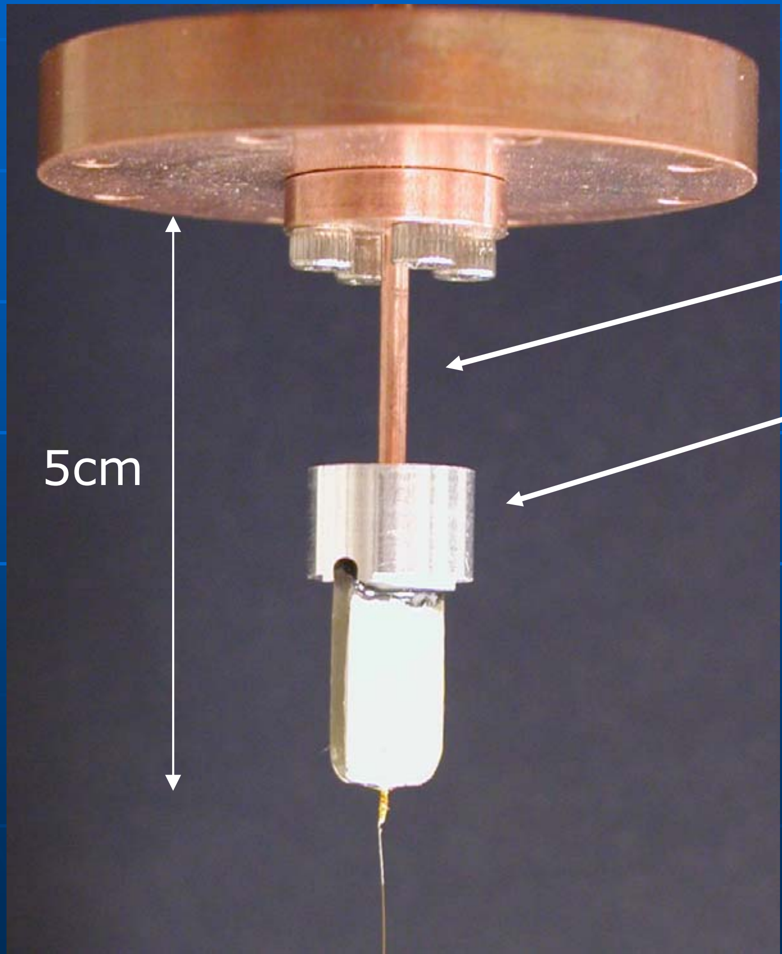




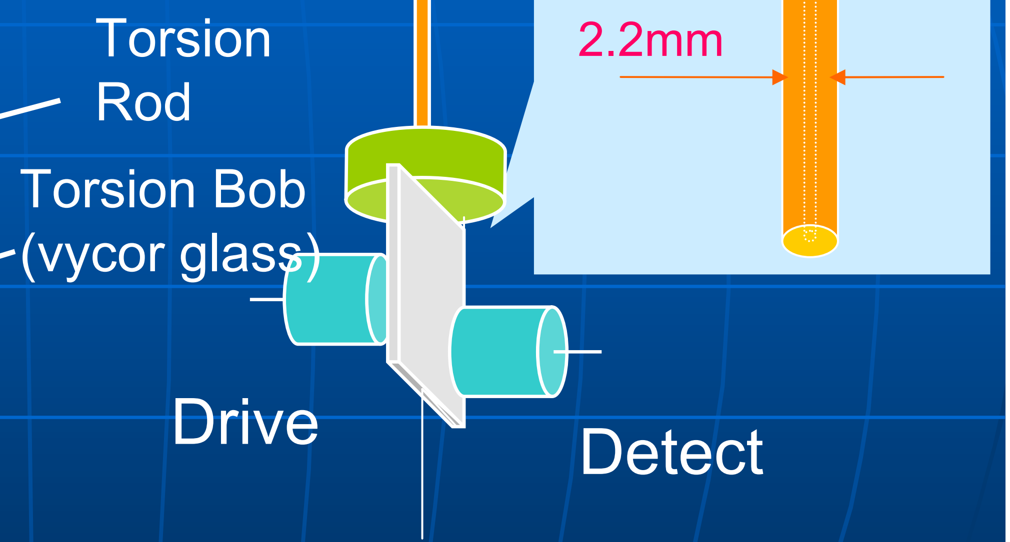
Above Tc the adsorbed normal liquid film behaves as solid and oscillates with the cell, since the viscous penetration depth at 1kHz is about 3 μm.

Berthold,Bishop, Reppy, *PRL* **39**,348(1977)

Solid helium in Vycor glass

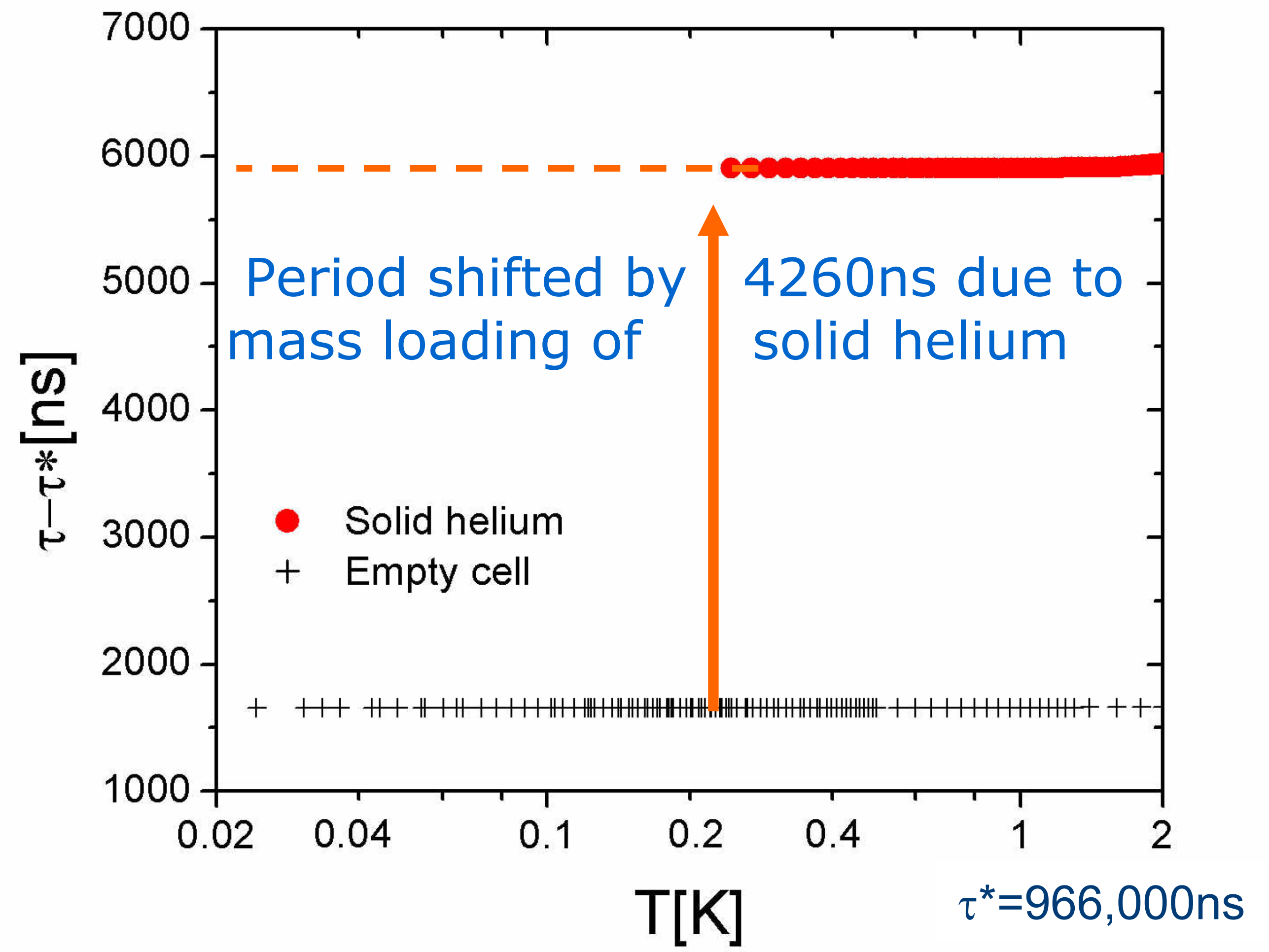


$f_0 = 1024$Hz
$Q \sim 1*10^6$

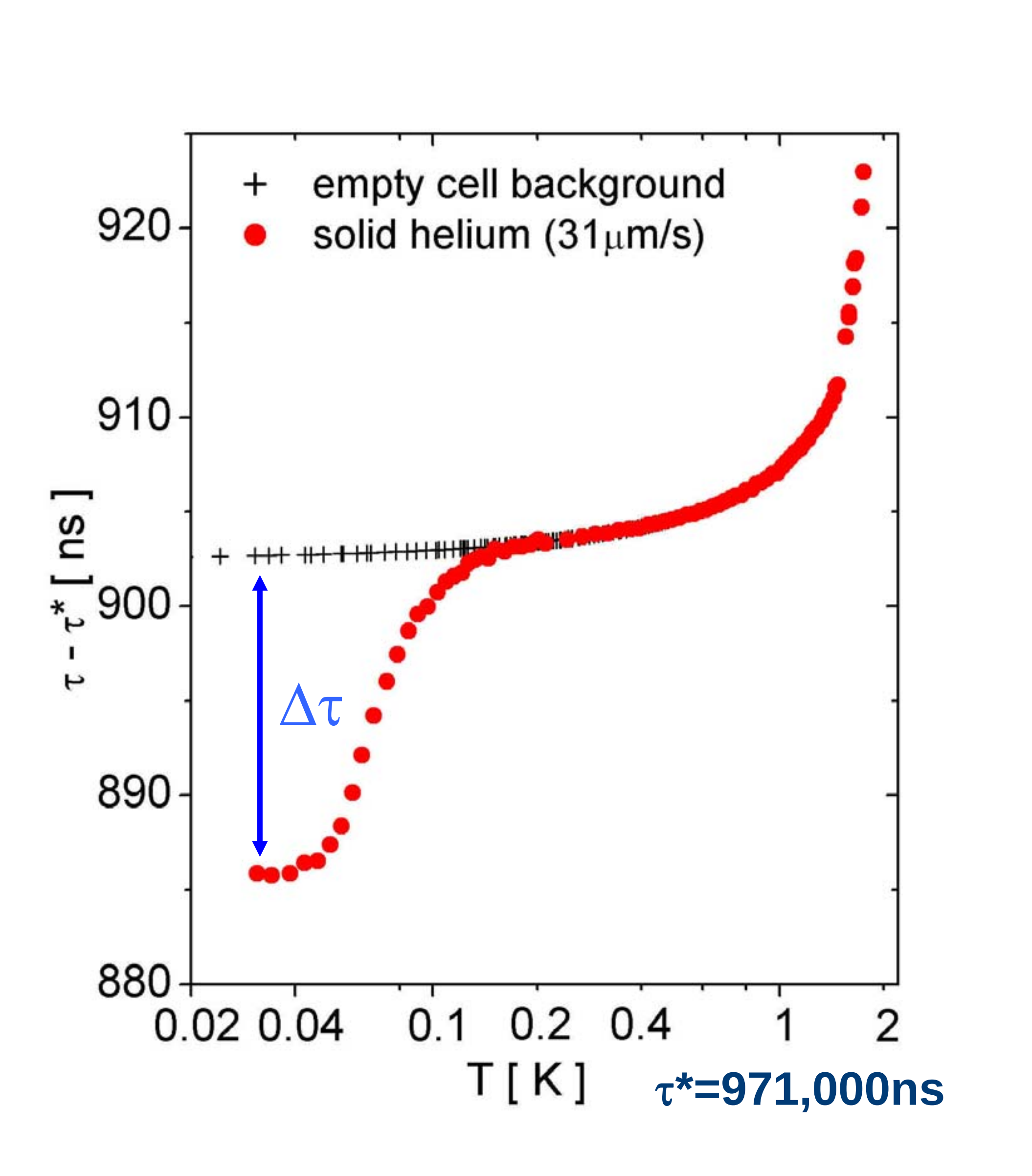


$A = A_0 \sin\omega t$
$v = |v|_{max} \cos\omega t$
$|v|_{max} = rA_0\omega$

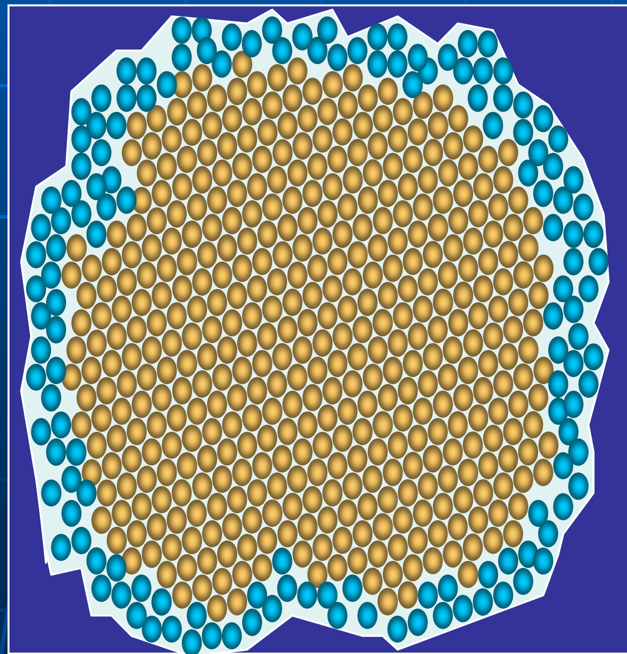
Solid ^{4}He at 62 bars in Vycor glass



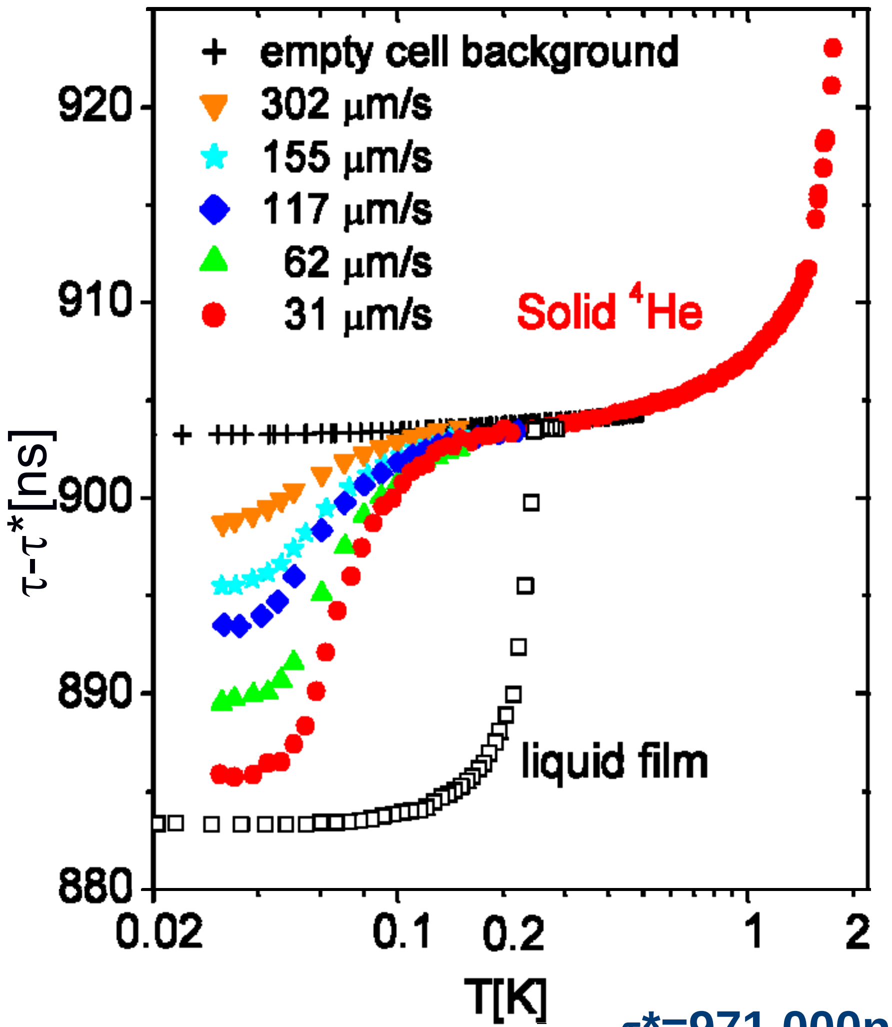
Supersolid response of helium in Vycor glass



- Period drops at 175mK
  → appearance of NCRI
- size of period drop
  -Δτ ~17ns



Superfluid response



τ^*=971,000ns

Total mass loading =4260ns

Measured decoupling

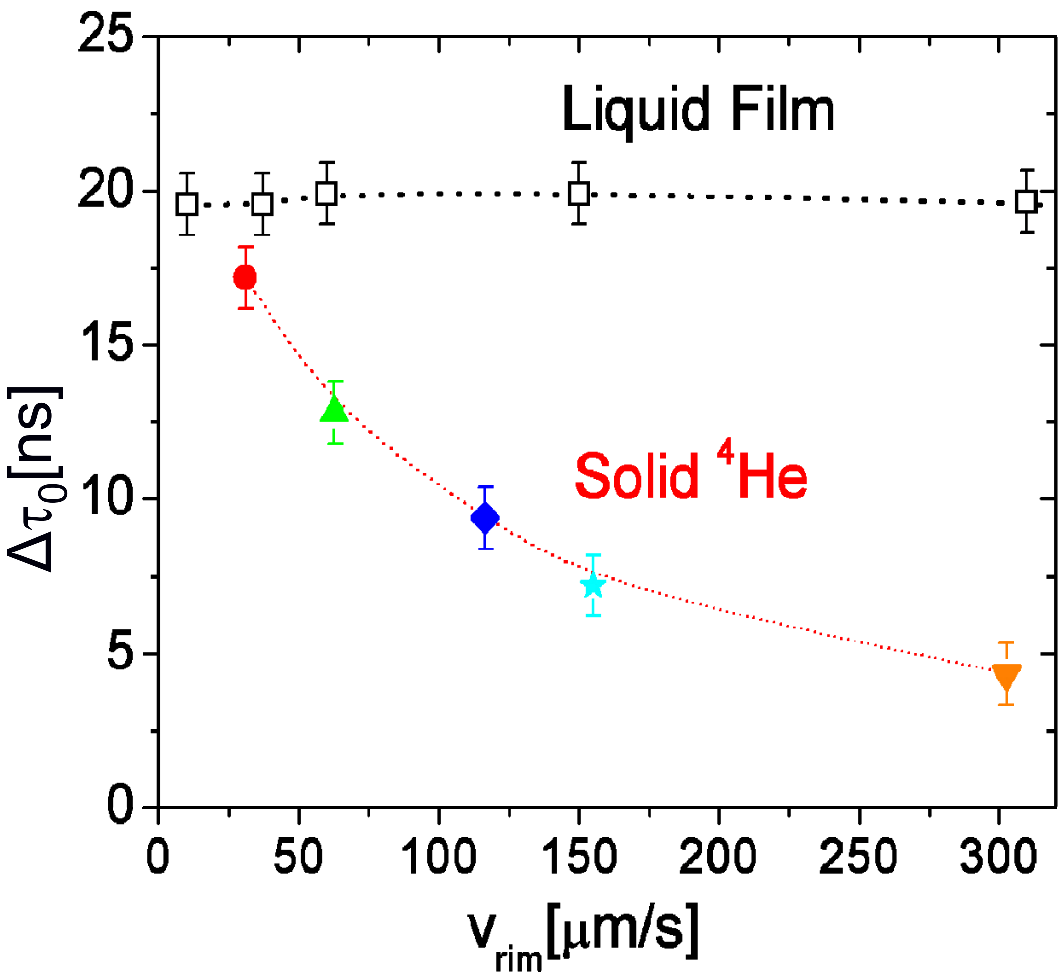
$-\Delta\tau_o$=17ns

" Apparent supersolid fraction"= 0.4%

(with tortuosity correction ρ_s/ρ =2%

Weak pressure dependence

Strong velocity dependence



- For liquid film adsorbed on Vycor glass

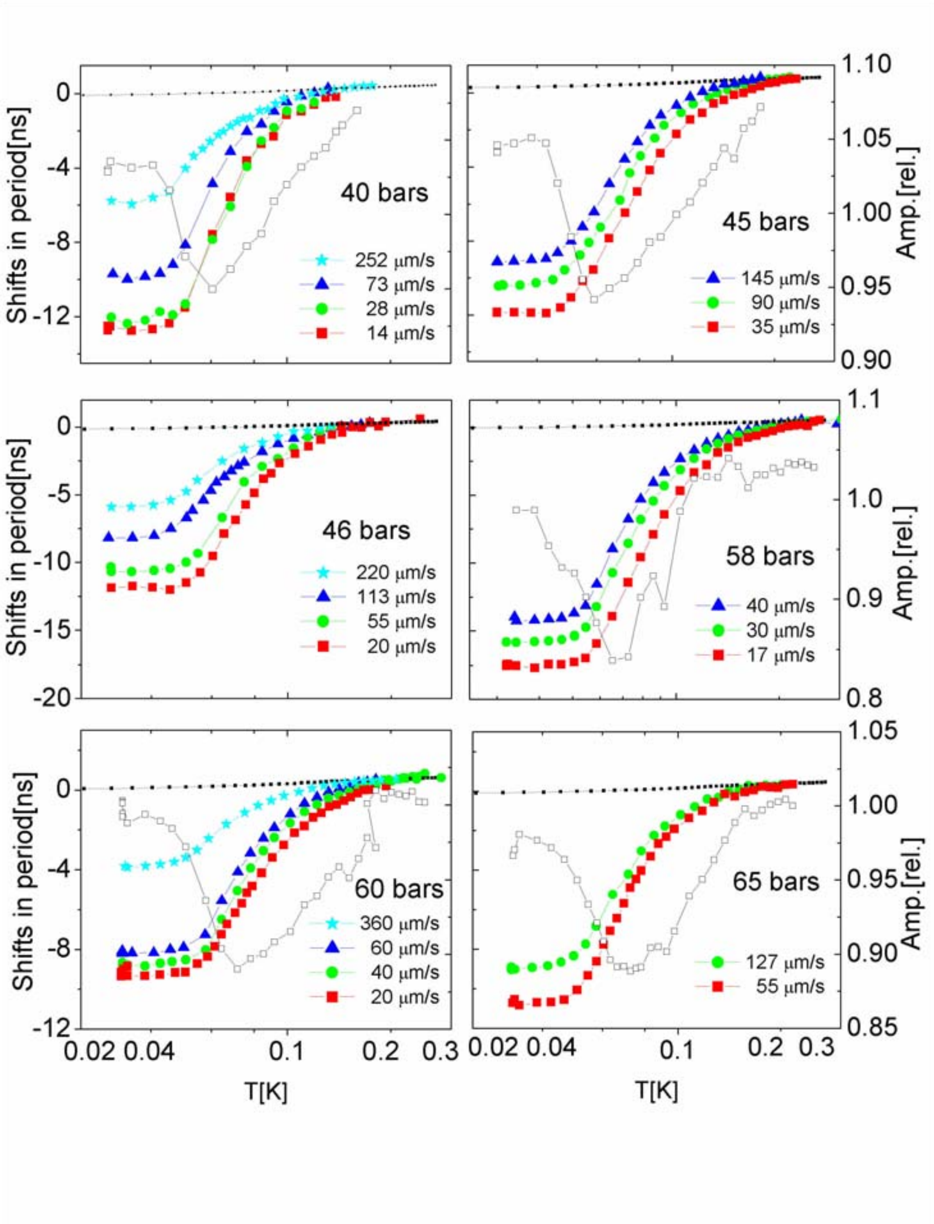
  $v_c > 20$cm/s

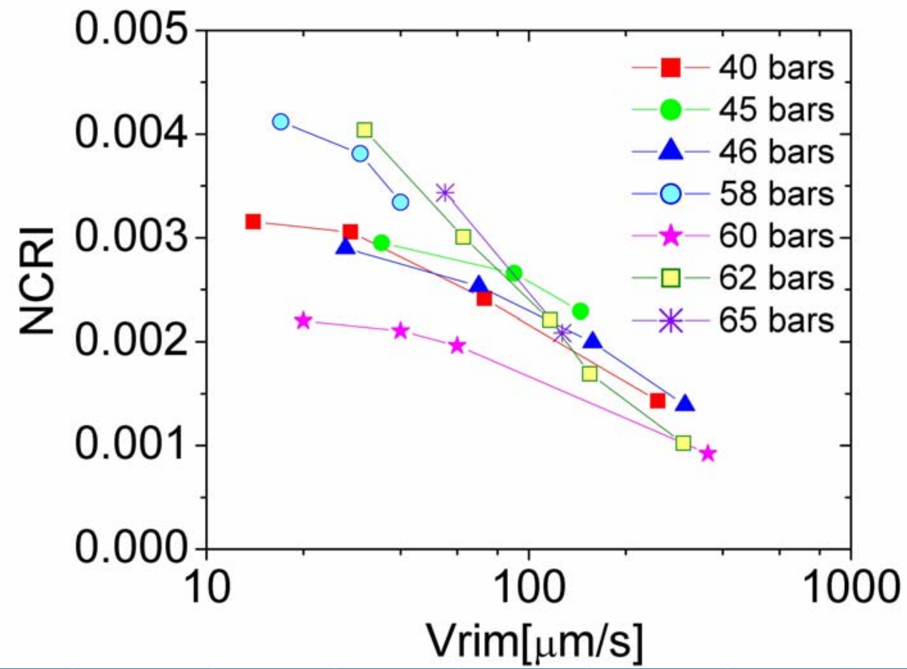
Chan et. al. *Phys. Rev. Lett.* **32**, 1347(1974).

- For superflow in solid ^{4}He

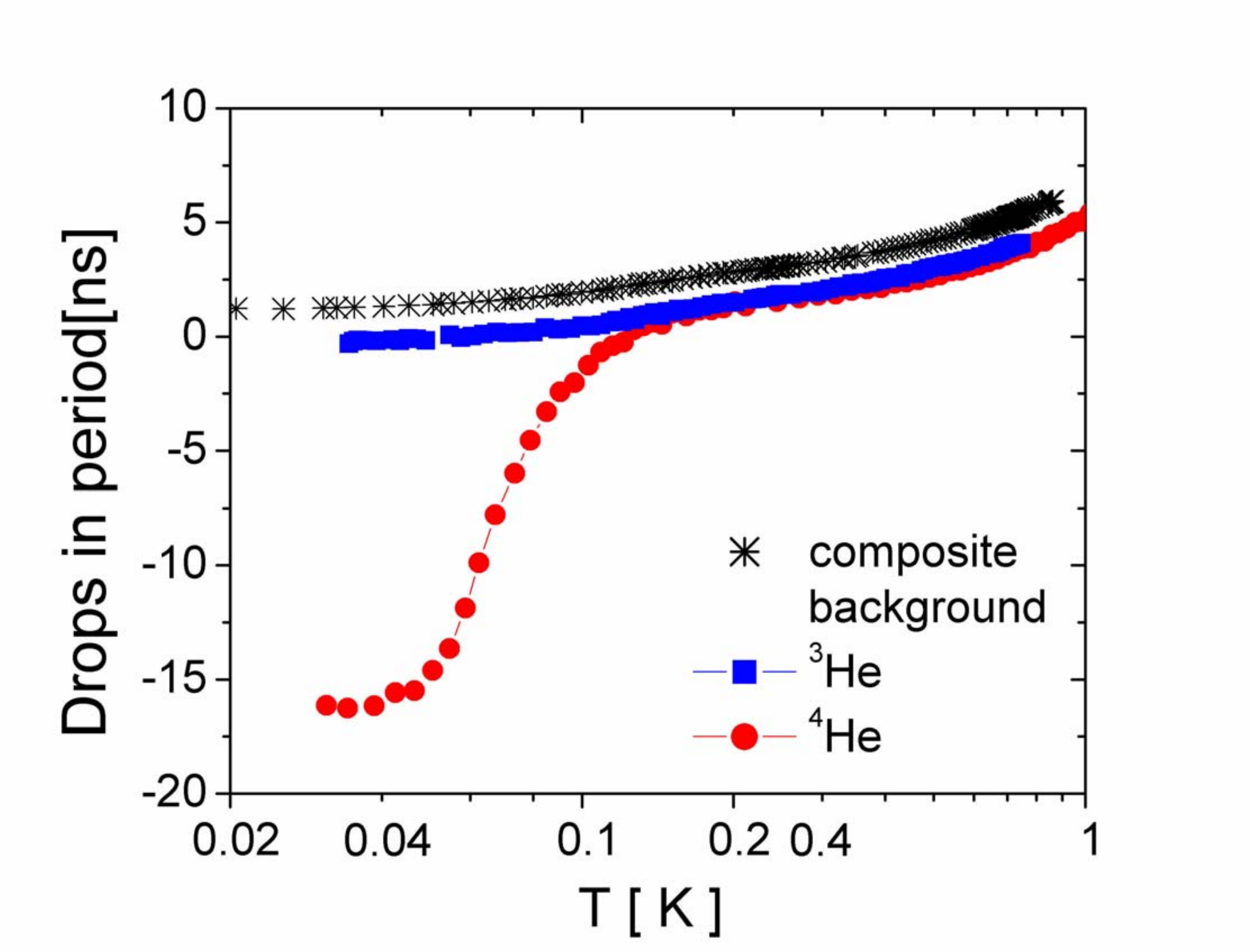
  $v_c < 30$ μm/s

Vycor Results

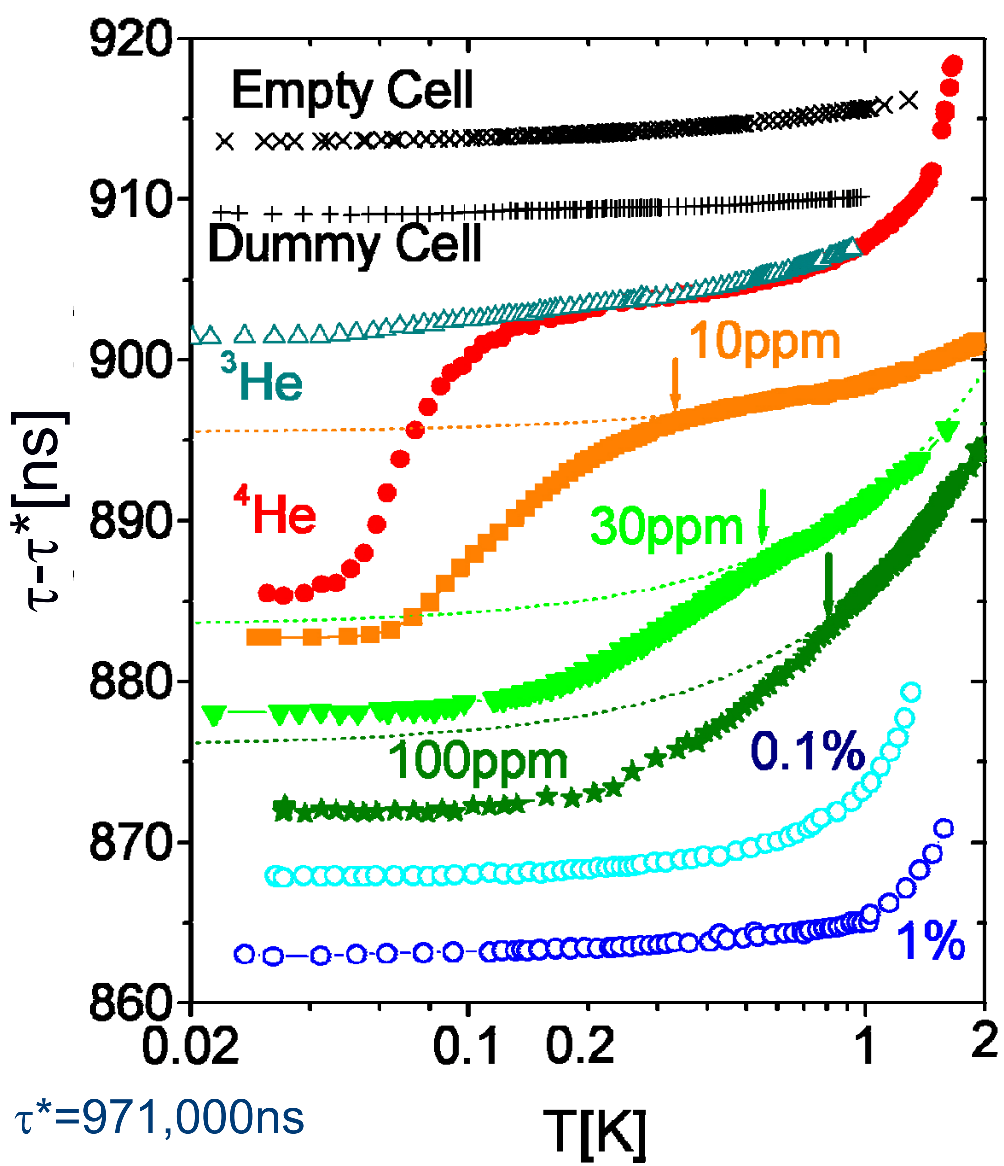




Control experiment 1: Solid ^3He



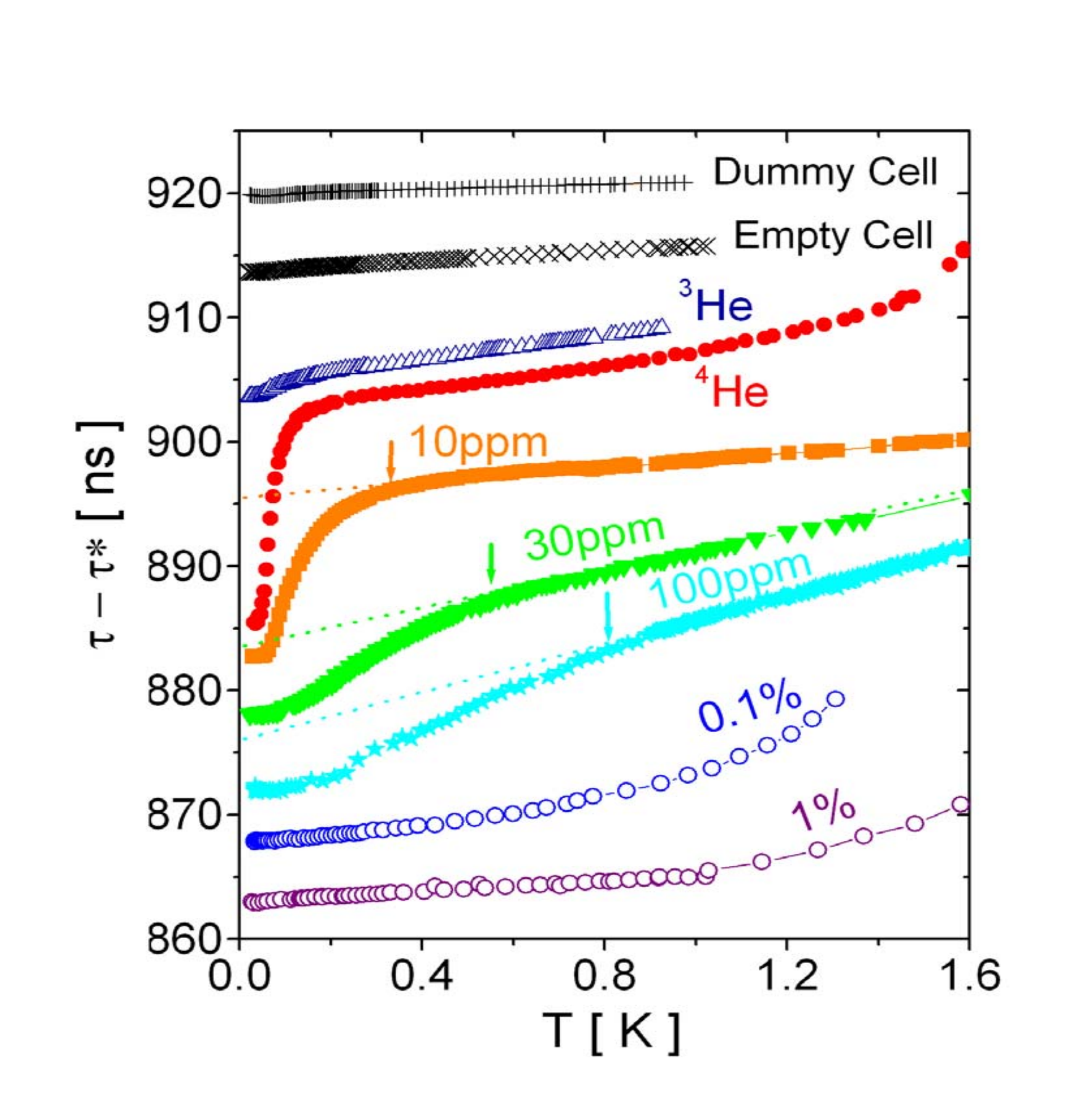
^{4}He solid diluted with a low concentration of ^{3}He



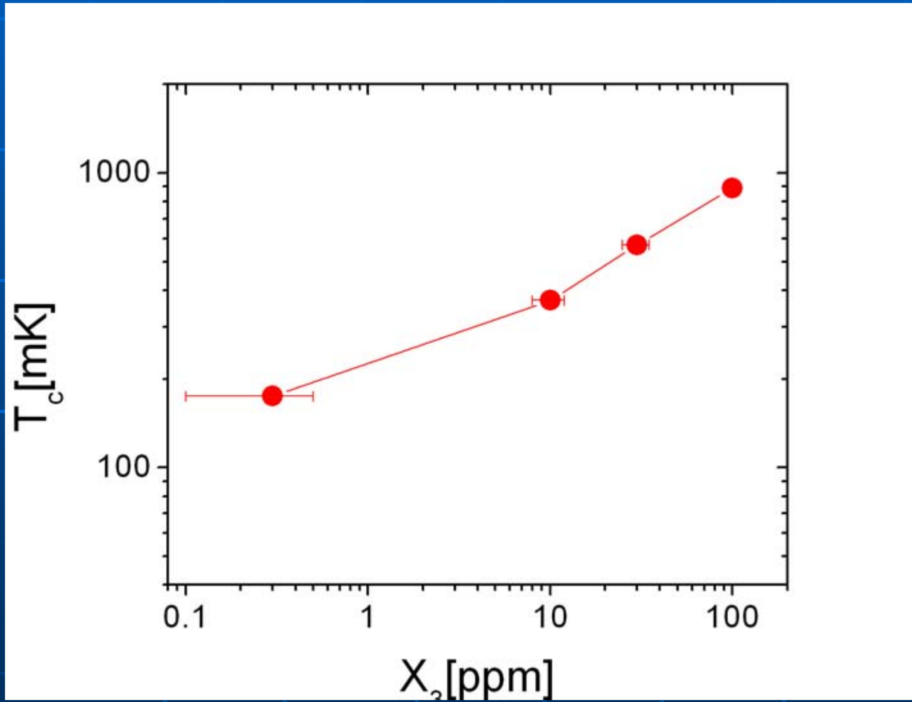
τ^*=971,000ns

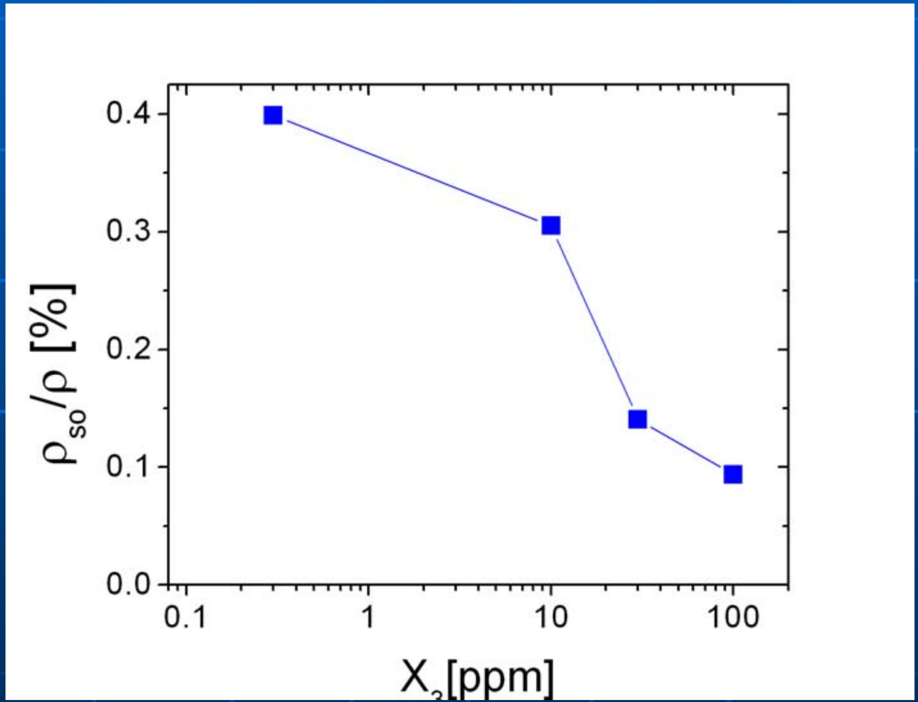
Data shifted vertically for easy comparison

^{4}He solid diluted with a low concentration of ^{3}He



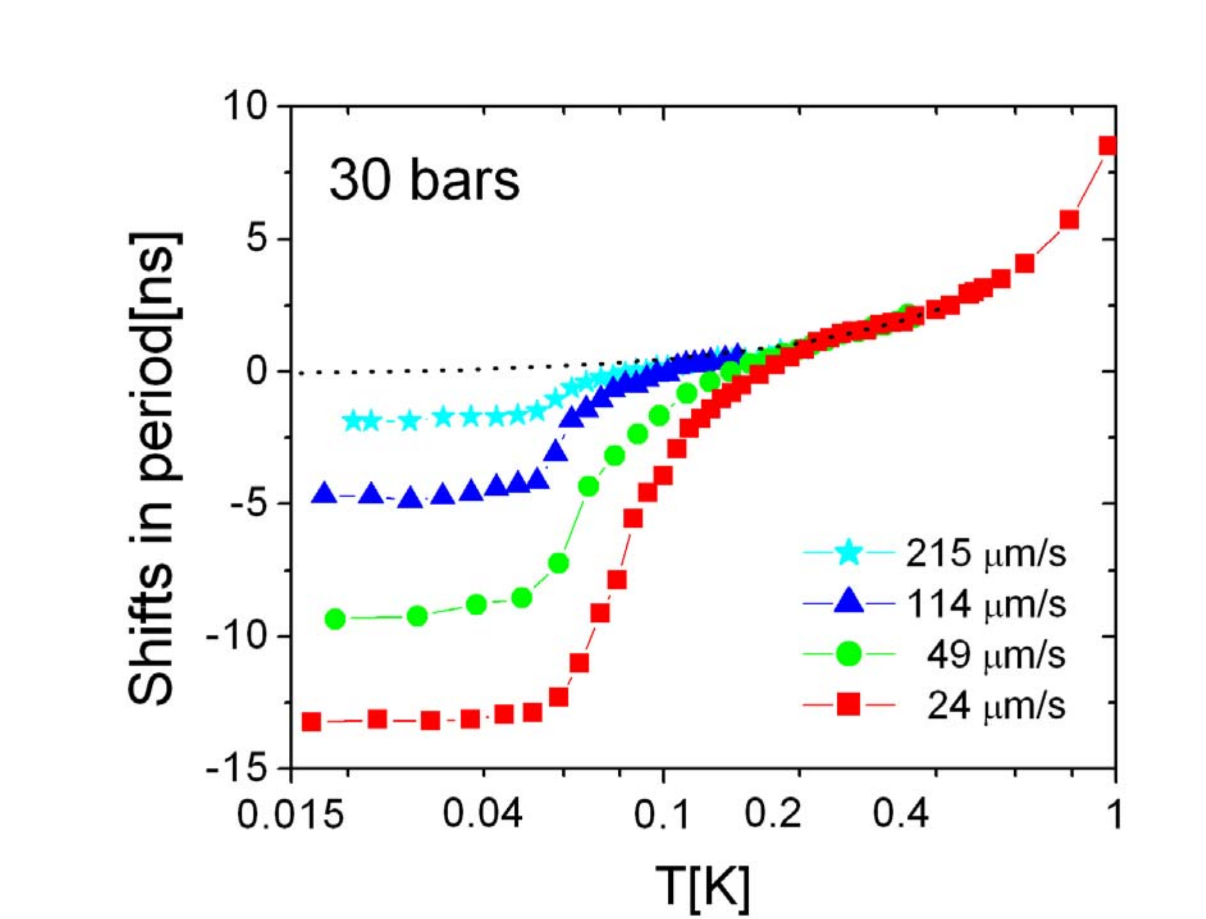
Effect of the addition of ^{3}He impurities

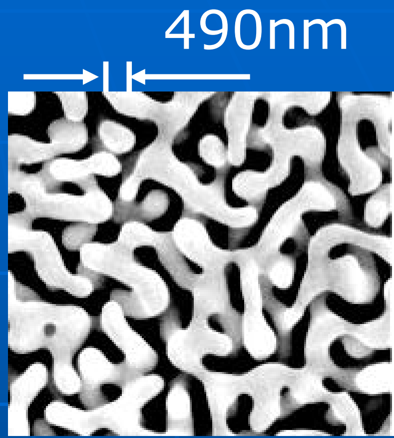




At 0.3ppm, the separation of the ^{3}He atoms is about 450Å

Solid helium in porous gold





Porous Gold

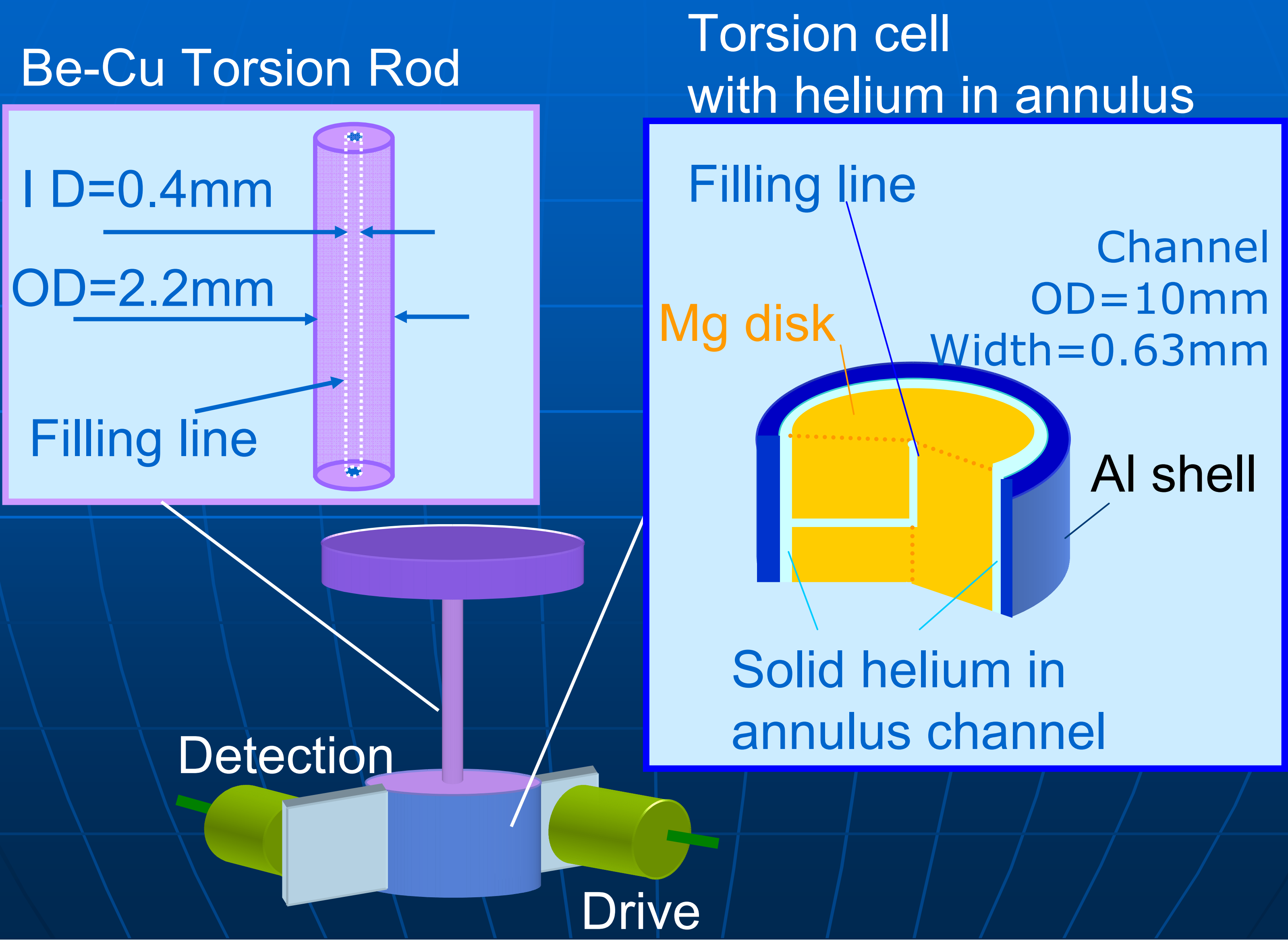
f_0=359Hz

J. Low Temp. Phys. **138**, 859(2005)

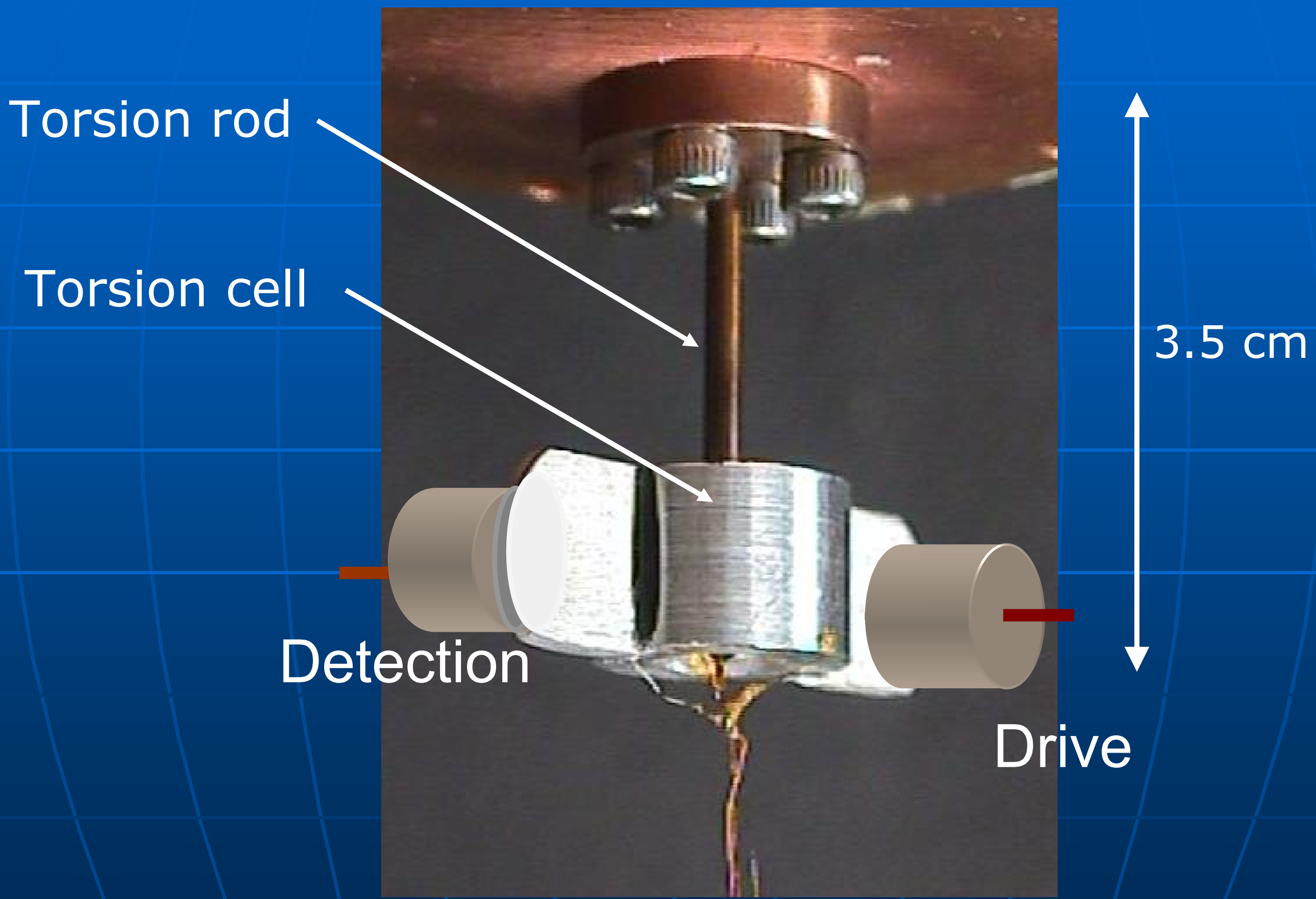
Is a porous matrix crucial for the appearance of the supersolid phase?

	Porous gold	Vycor glass
Pore diameter	490nm	7nm
A/V	$9m^2/cc$	$500m^2/cc$
T_C	~0.2K	~0.2K
ρ_S/ρ (tortuosity)	0.008 (0.012)	0.002~0.005 (0.01~0.025)

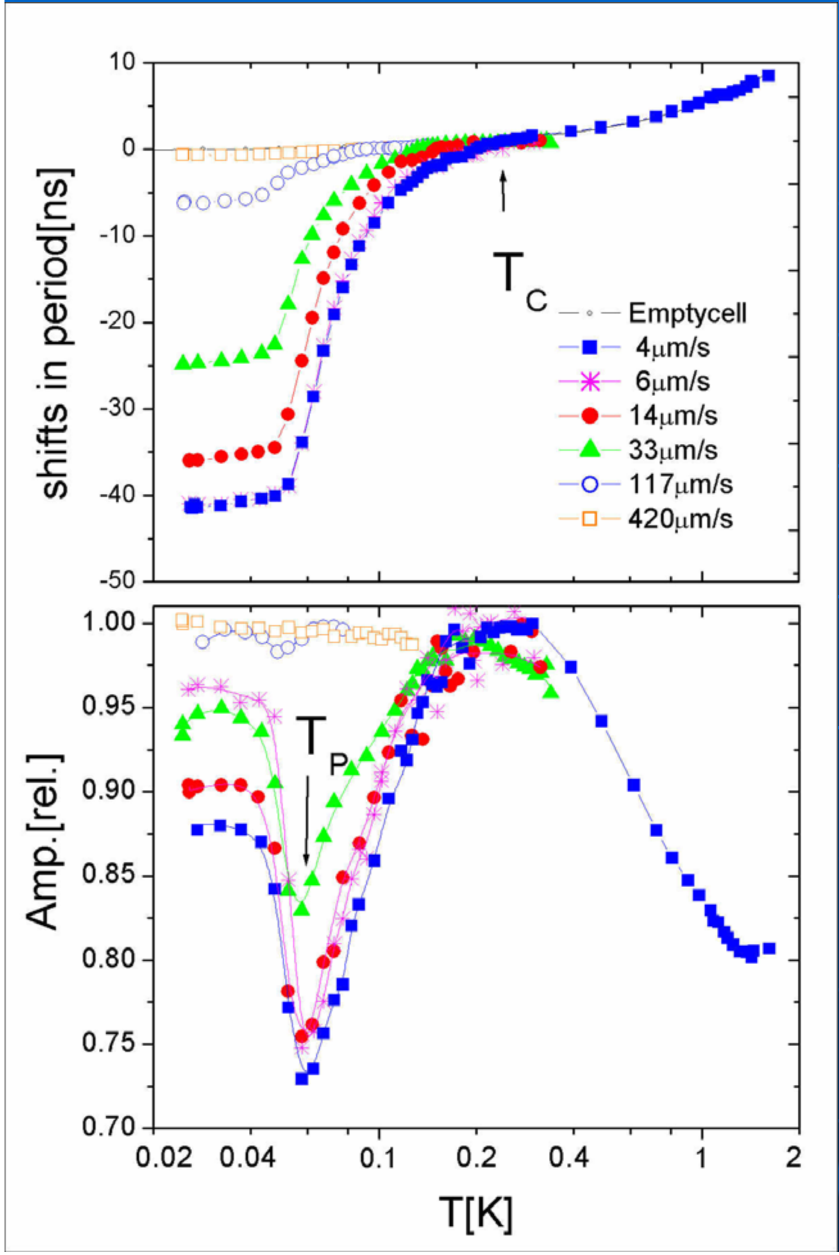
Search for the supersolid phase in the bulk solid ^{4}He.



Torsional Oscillator (bulk solid helium-4)



Porous media are not essential!



Solid ^{4}He at 51 bars

4μm/s corresponds to amplitude of oscillation of 7Å

NCRI appears below 0.25K

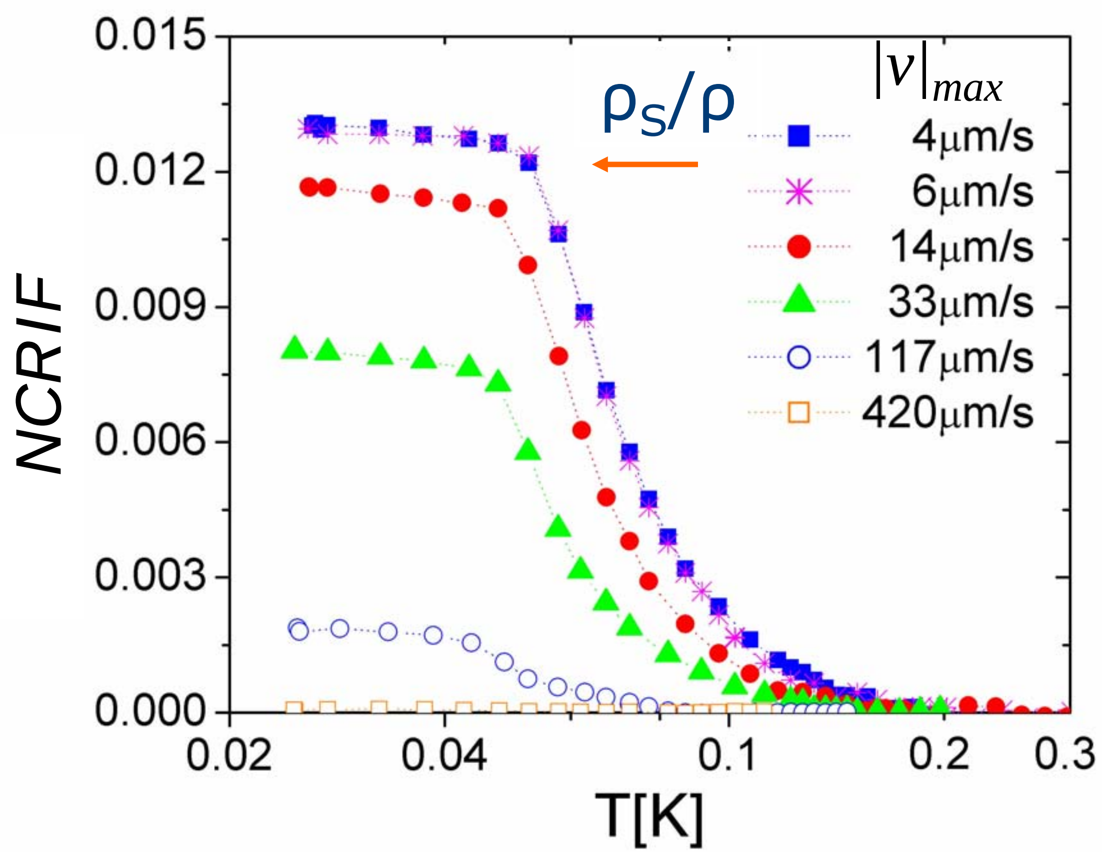
Strong $|v|_{max}$ dependence (above 14μm/s)

Amplitude minimum, Tp

τ_0= 1,096,465ns at 0 bar
1,099,477ns at 51 bars
(total mass loading=3012ns due to filling with helium)

Science **305**, 1941(2004)

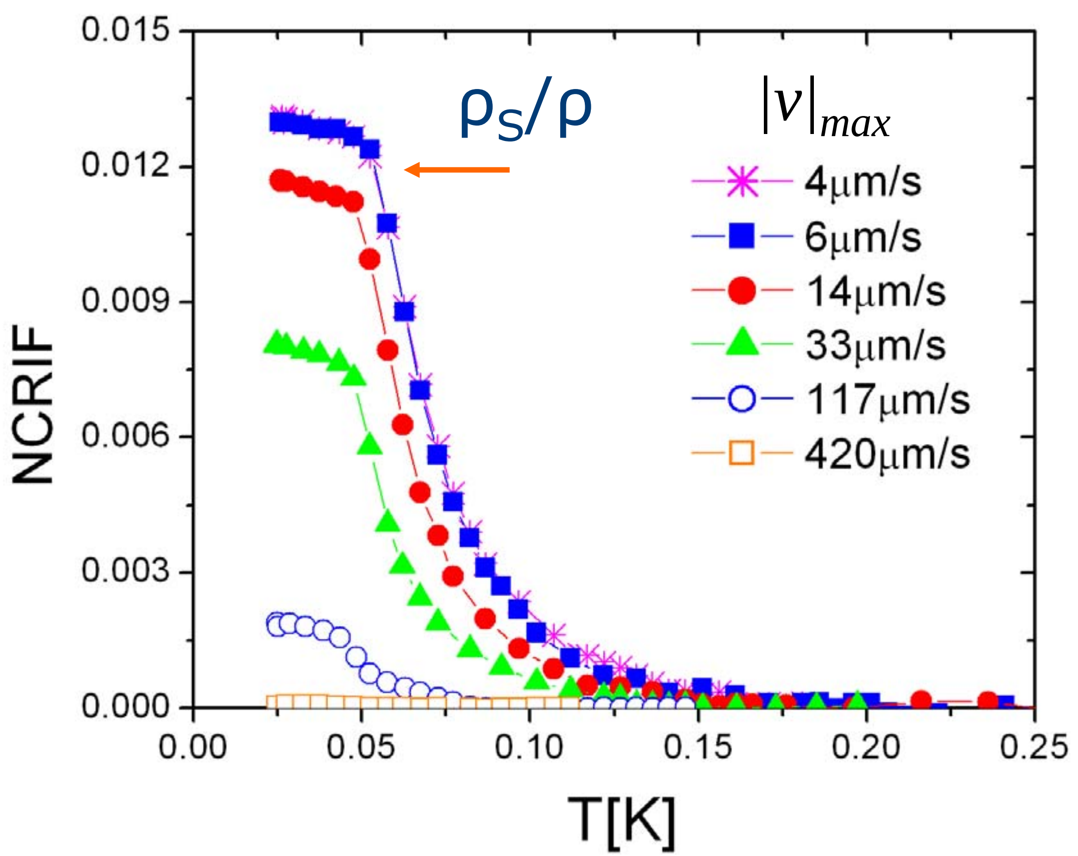
Non-Classical Rotational Inertia Fraction



$$NCRIF = \frac{\Delta\tau}{\text{total mass loading}}$$

Total mass loading
=3012ns at 51 bars

Non-Classical Rotational Inertia Fraction



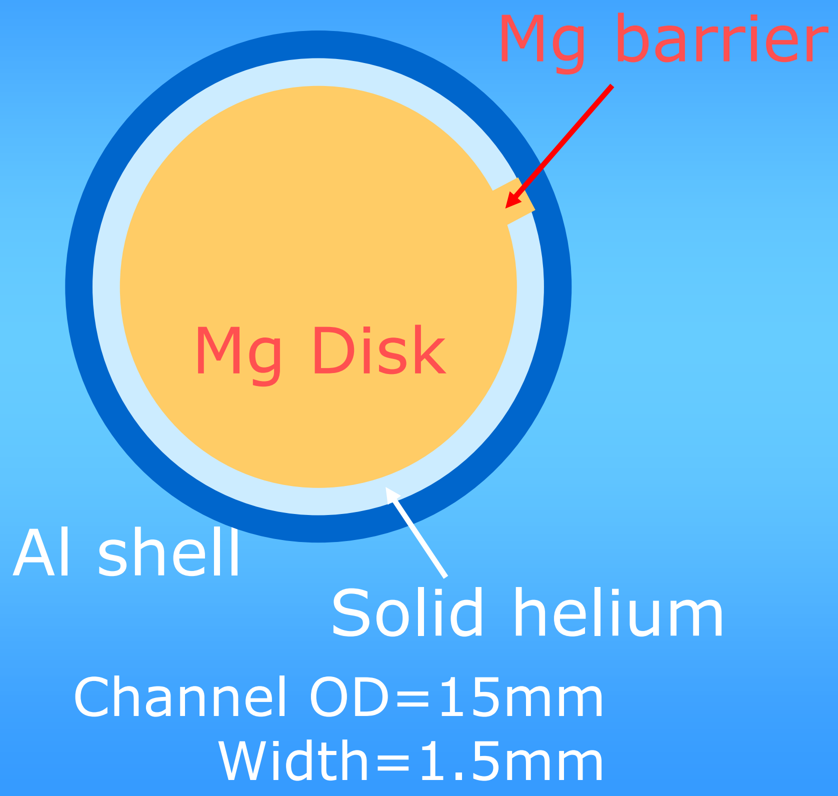
$$NCRIF = \frac{\Delta\tau}{\text{total mass loading}}$$

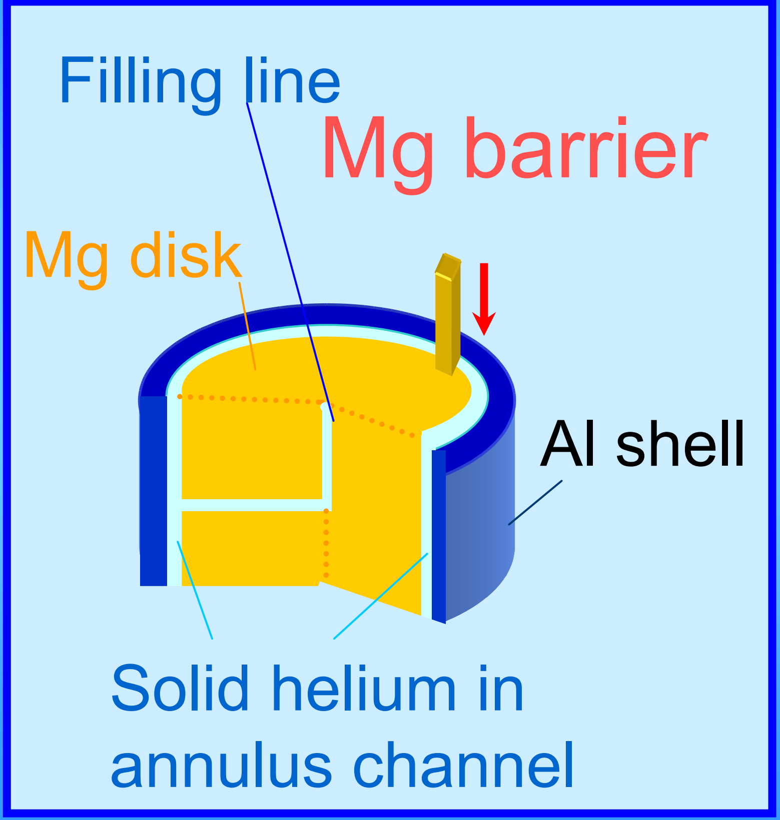
Total mass loading =3012ns at 51 bars

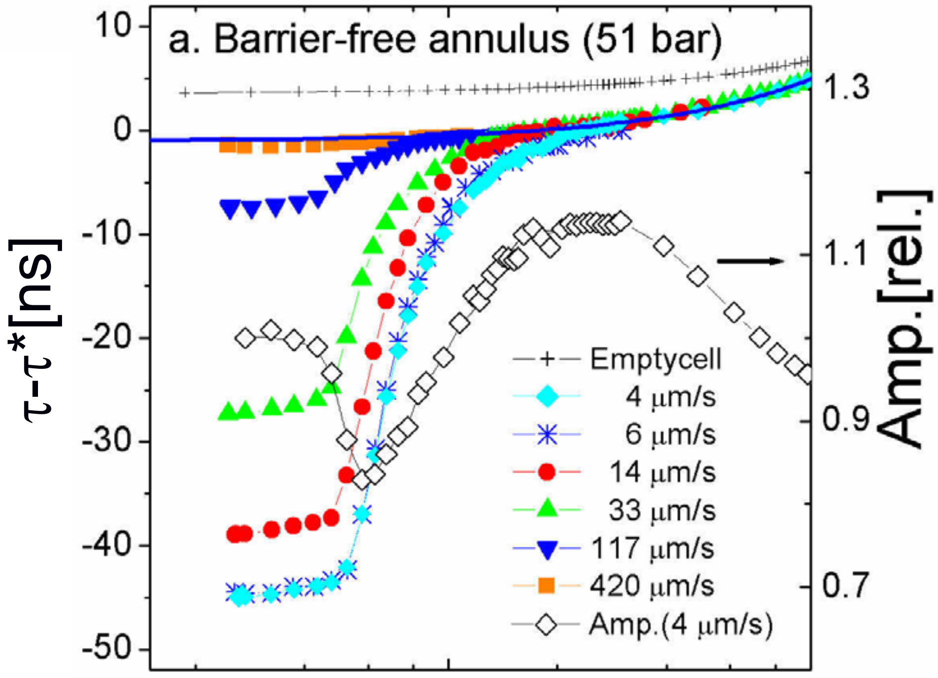
Control experiment

- With a barrier in the annulus, there should be NO simple superflow and the measured superfluid decoupling should be vastly reduced

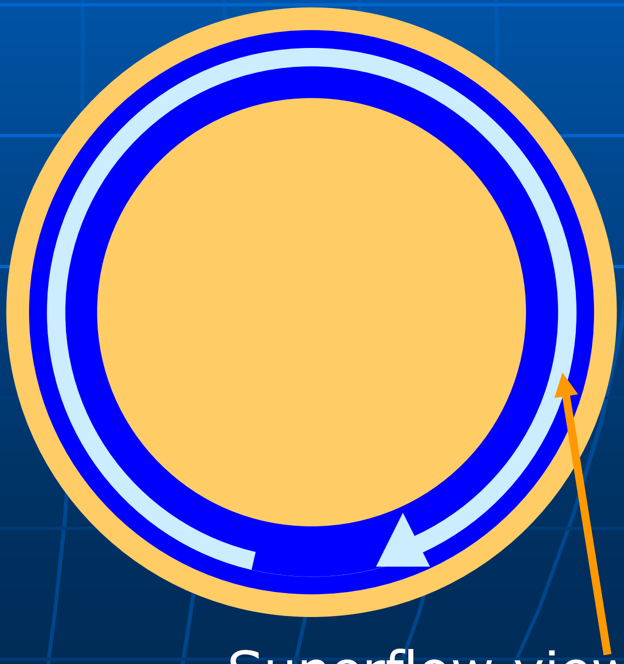
Torsion cell with blocked annulus

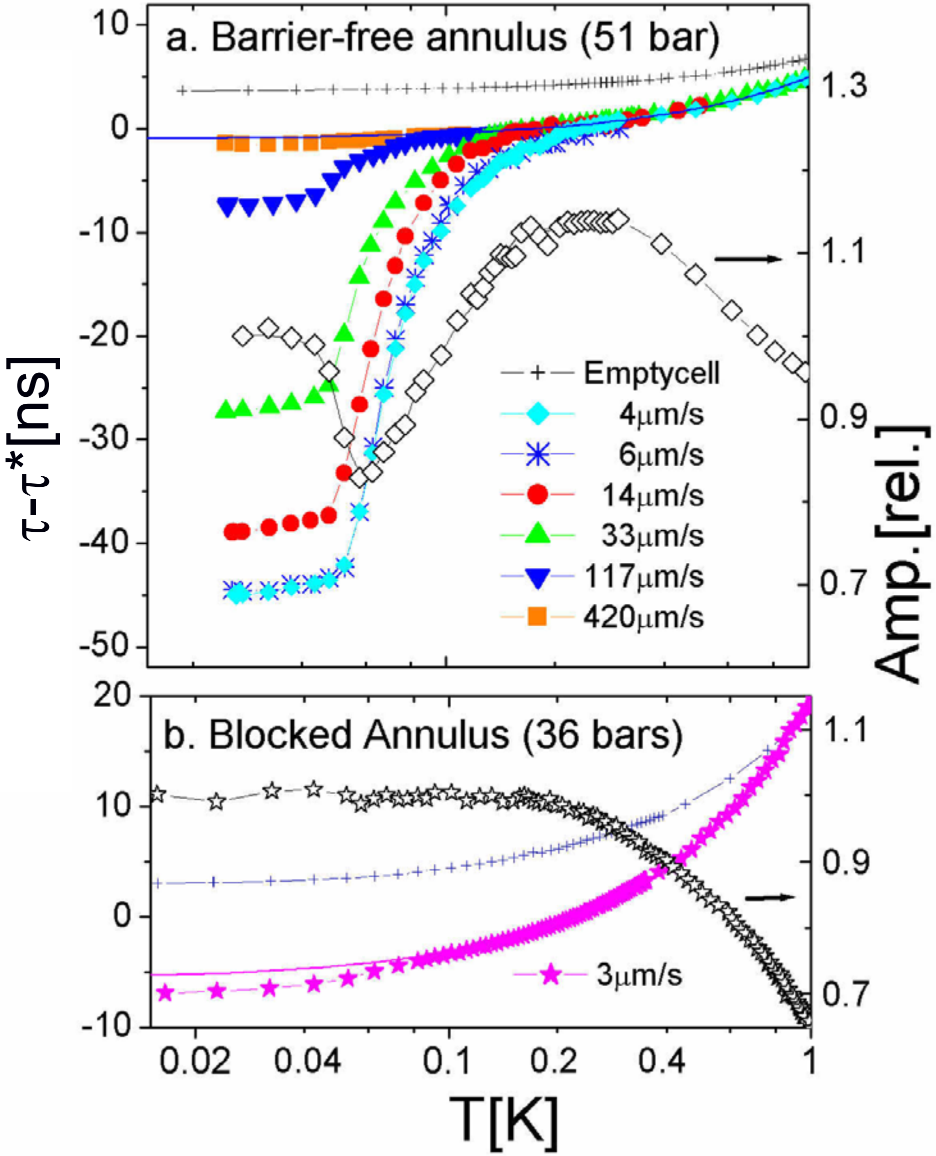






If there is no barrier, then the supersolid fraction appears to be stationary in the laboratory frame; with respect to the torsional oscillator it is executing oscillatory superflow.



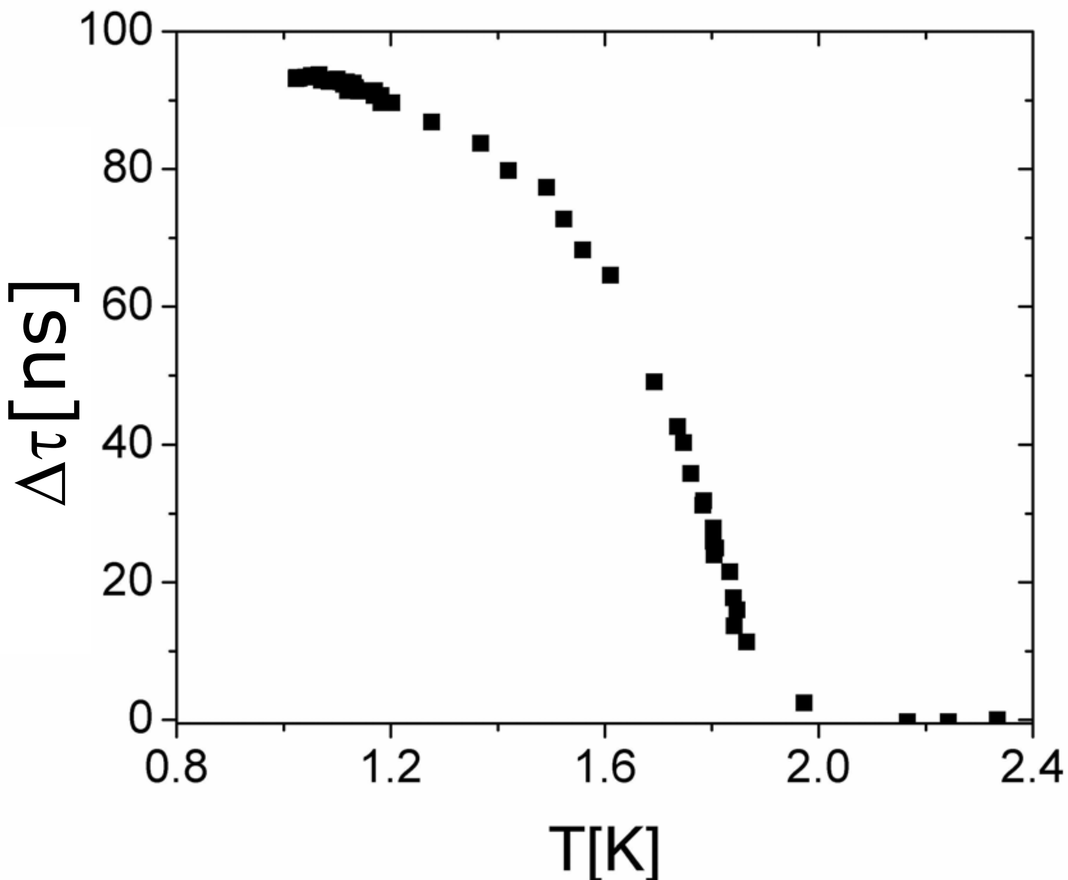


* If no block, the expected Δτ=90ns

With a block in the annulus, irrotational flow of the supersolid fraction contributes about 1% (Erich Mueller) of the barrier-free decoupling.
Δτ~1.5ns

Irrotational flow pattern
in a blocked annular channel
(viewed in the rotating frame)
A. L. Fetter, JLTP(1974)

Similar reduction in superfluid response is seen in liquid helium at 19 bars in the same blocked cell



measured superfluid decoupling in the blocked cell

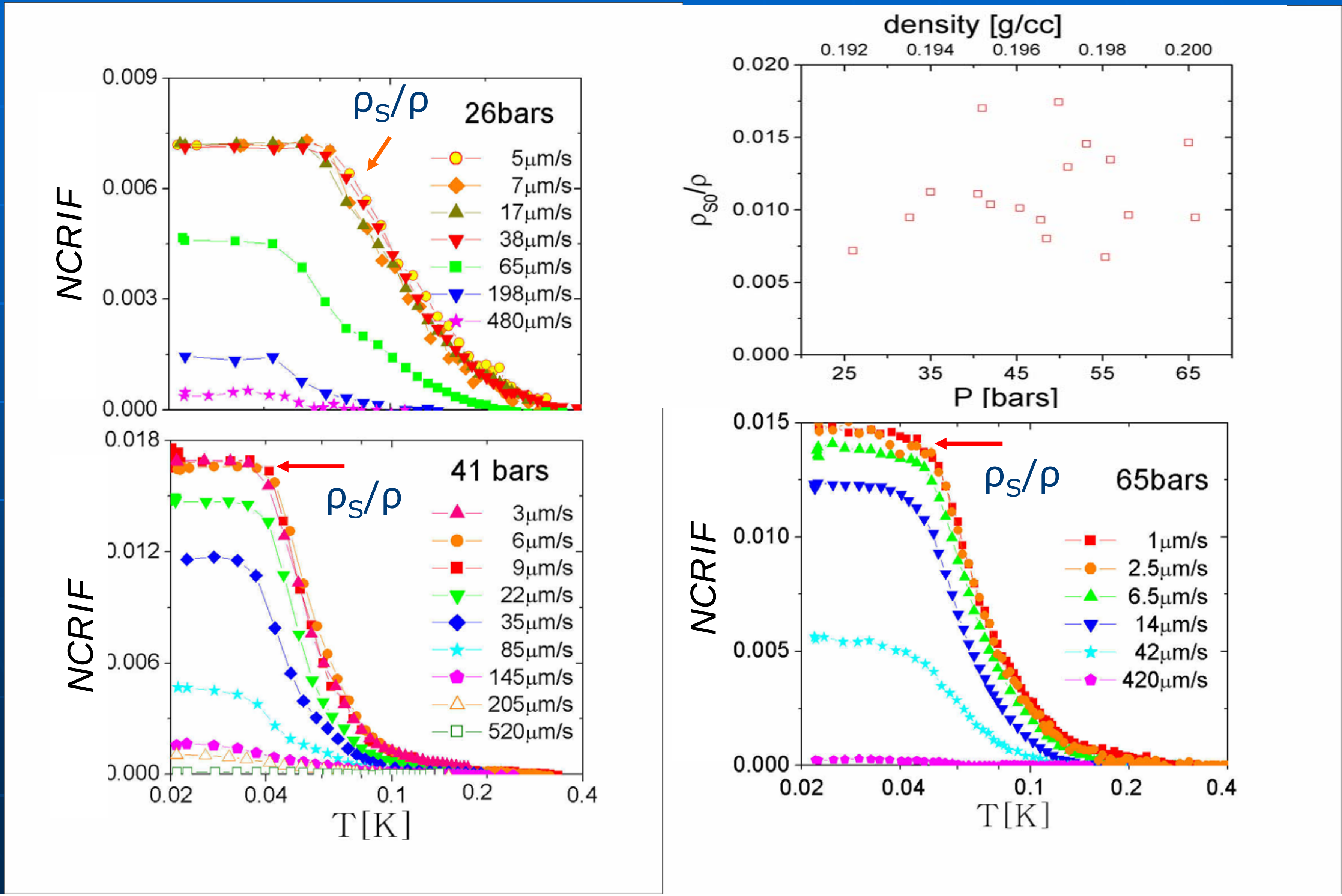
$\Delta\tau(T=0) \approx 93$ns.

While the expected decoupling in unblocked cell is 5270ns.

Hence the ratio is 1.7% similar to that for solid.

Conclusion :
superflow in solid as in superfluid is irrotational.

Solid ^{4}He at various pressures show similar temperature dependence, but the measured supersolid fraction shows scatter with no obvious pressure dependence



What is the reason for the scatters in the supersolid fraction? Crystallinity of the solid sample?

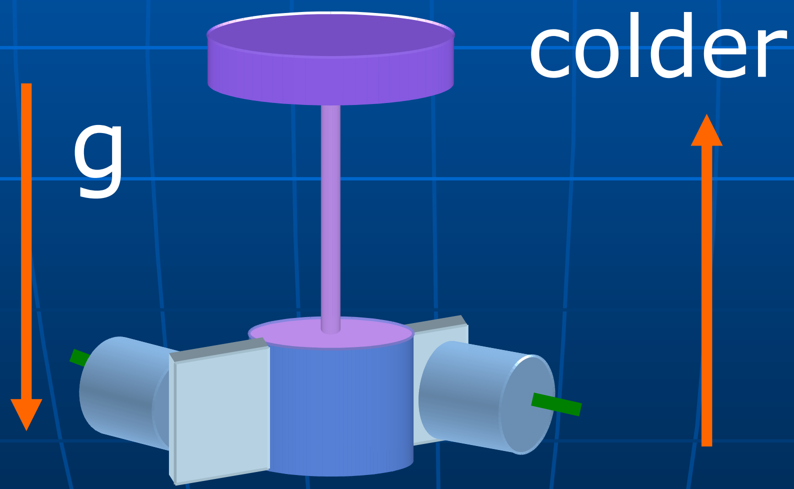
"...helium tends to solidify as a single crystal (or perhaps as a few single crystals) rather than in a polycrystalline form."

The properties of liquid and solid helium, J. Wilks p584 (Clarendon, London, 1967)

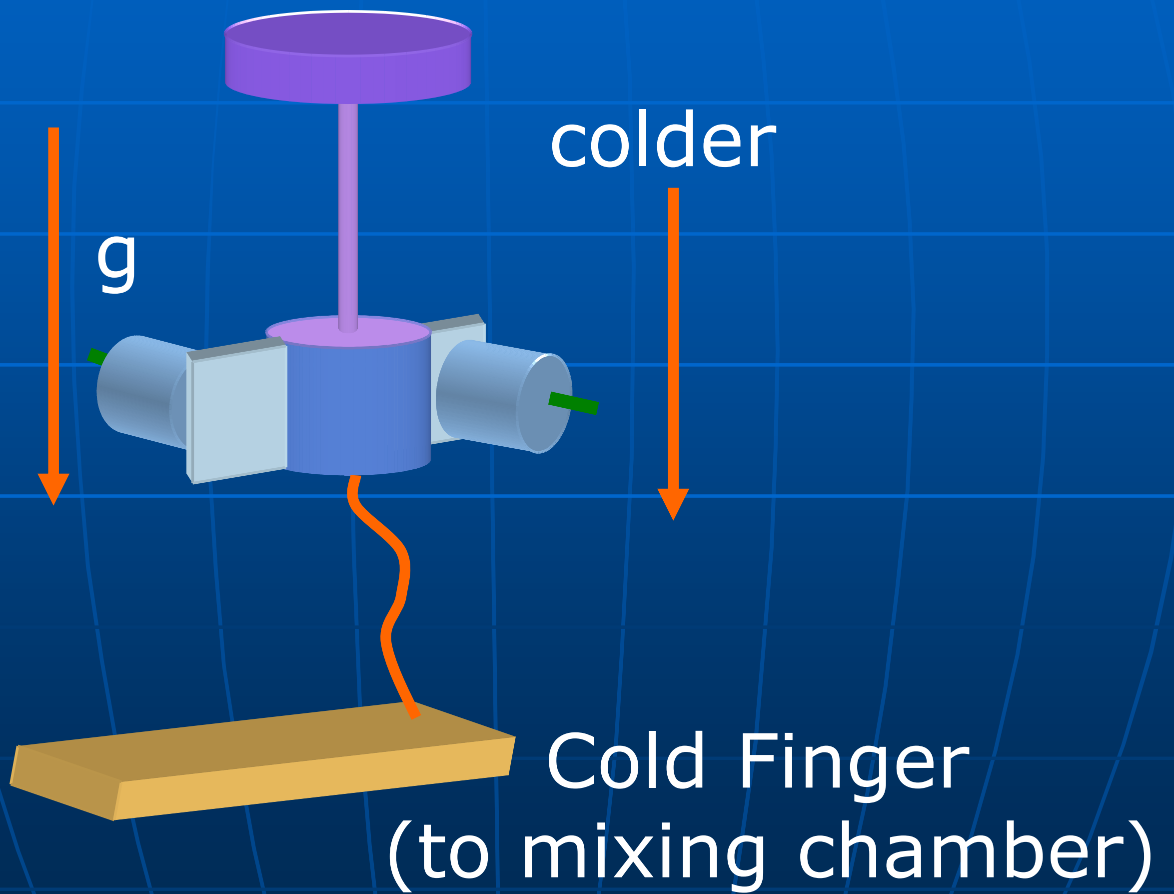
The ^{4}He crystallites inside the 'bulk' torsional cell probably have different orientations with dimensions limited by the channel width of the annulus ~0.63mm or i.d. of torsion rod at 0.4 mm.

Another reason limiting the crystallinity of the solid helium samples is due to the temperature configuration of the cell during the growth of the samples.

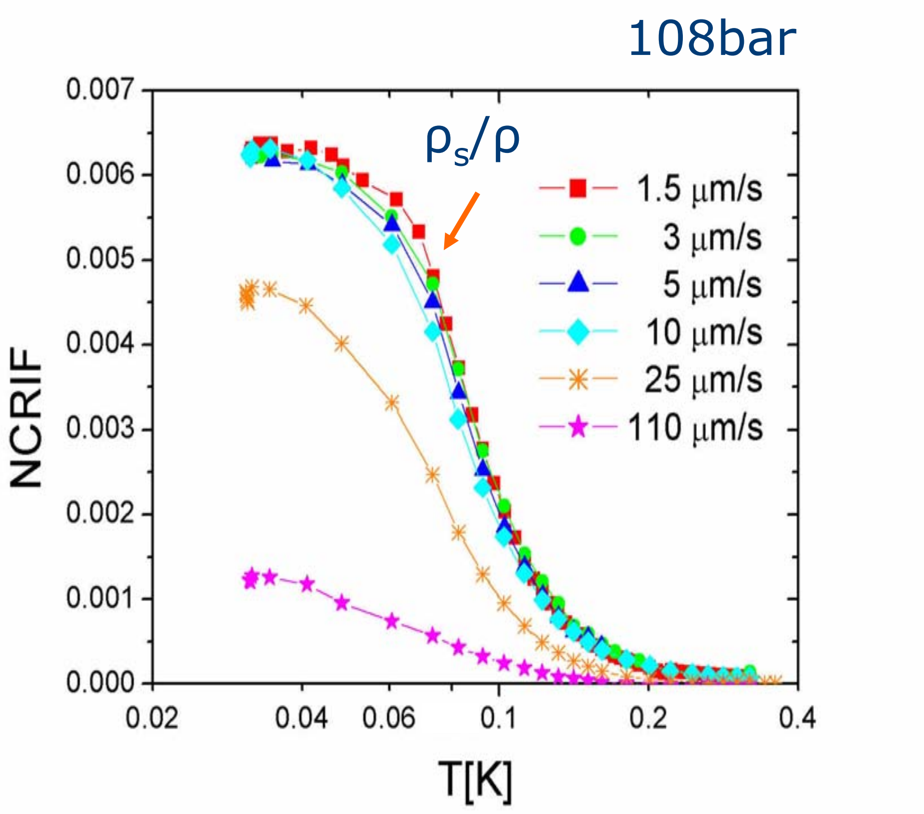
The crystallites were likely nucleated from the torsion rod with dimension of 0.4 mm.

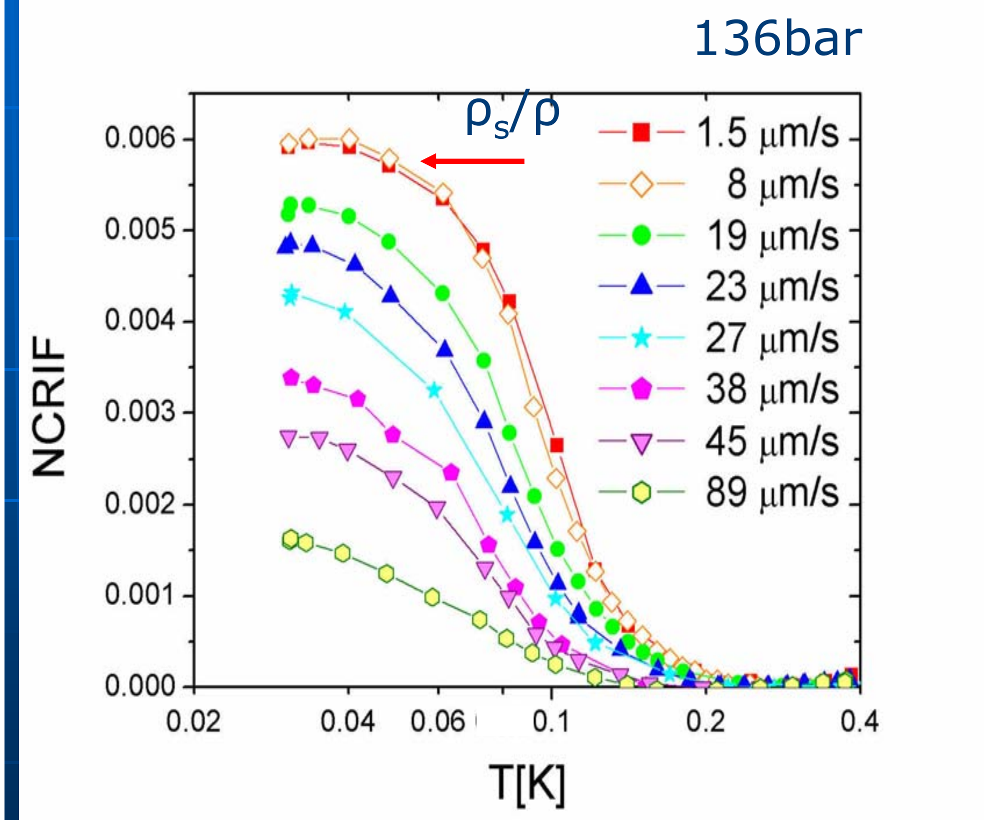


New configuration

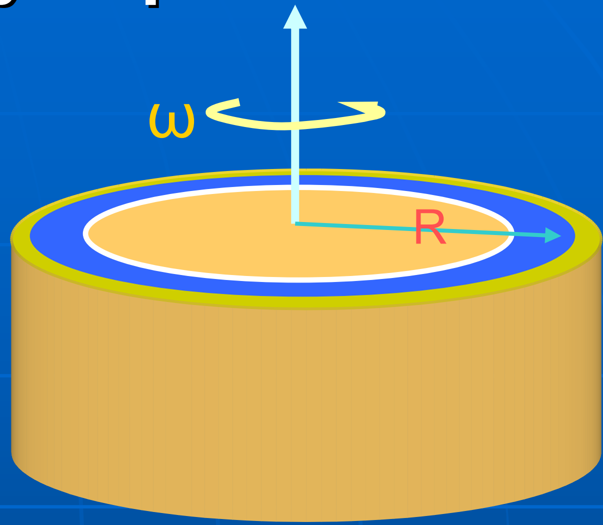


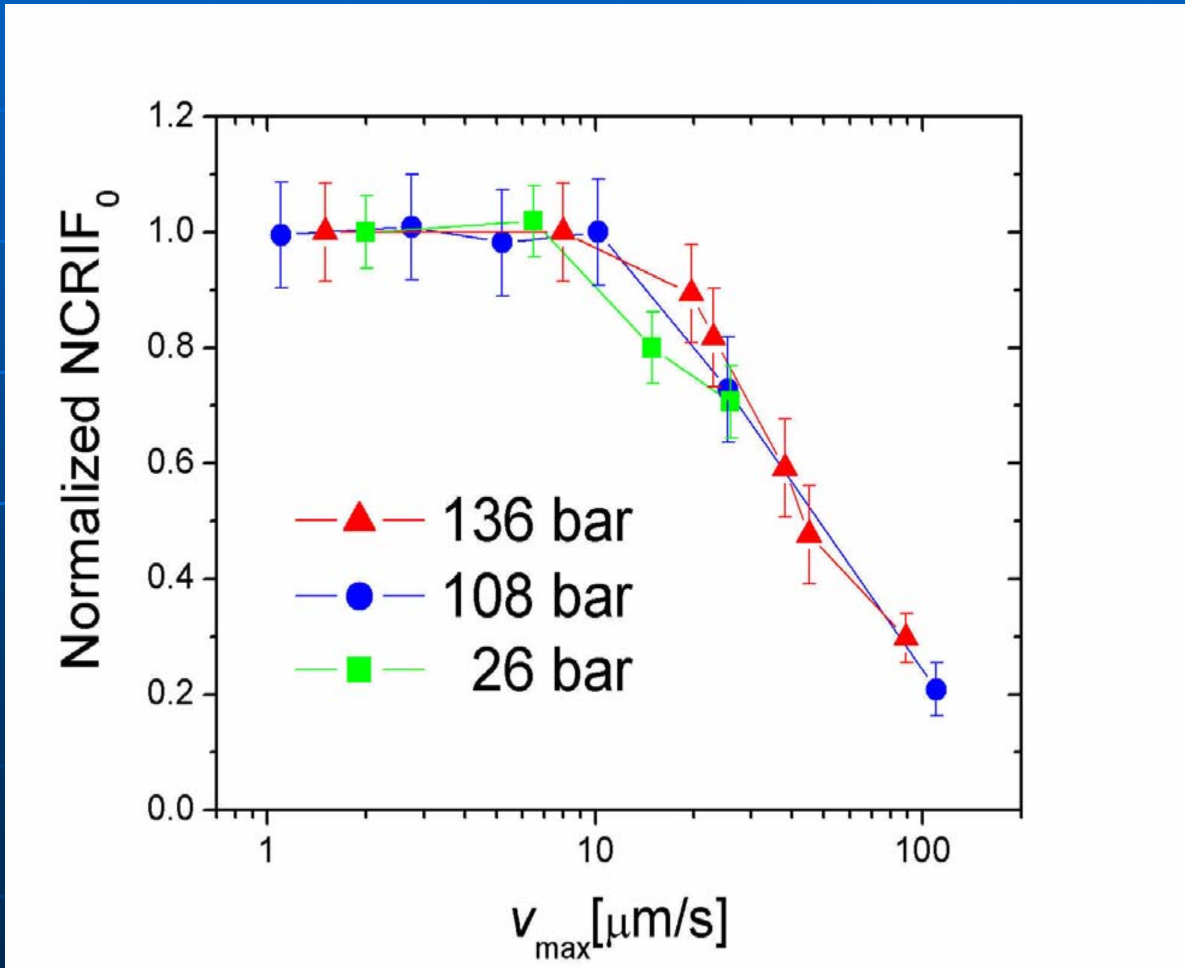
Superflow persists up to at least 136 bars !





Strong and 'universal' velocity dependence in all samples





$v_C \sim 10\mu m/s$

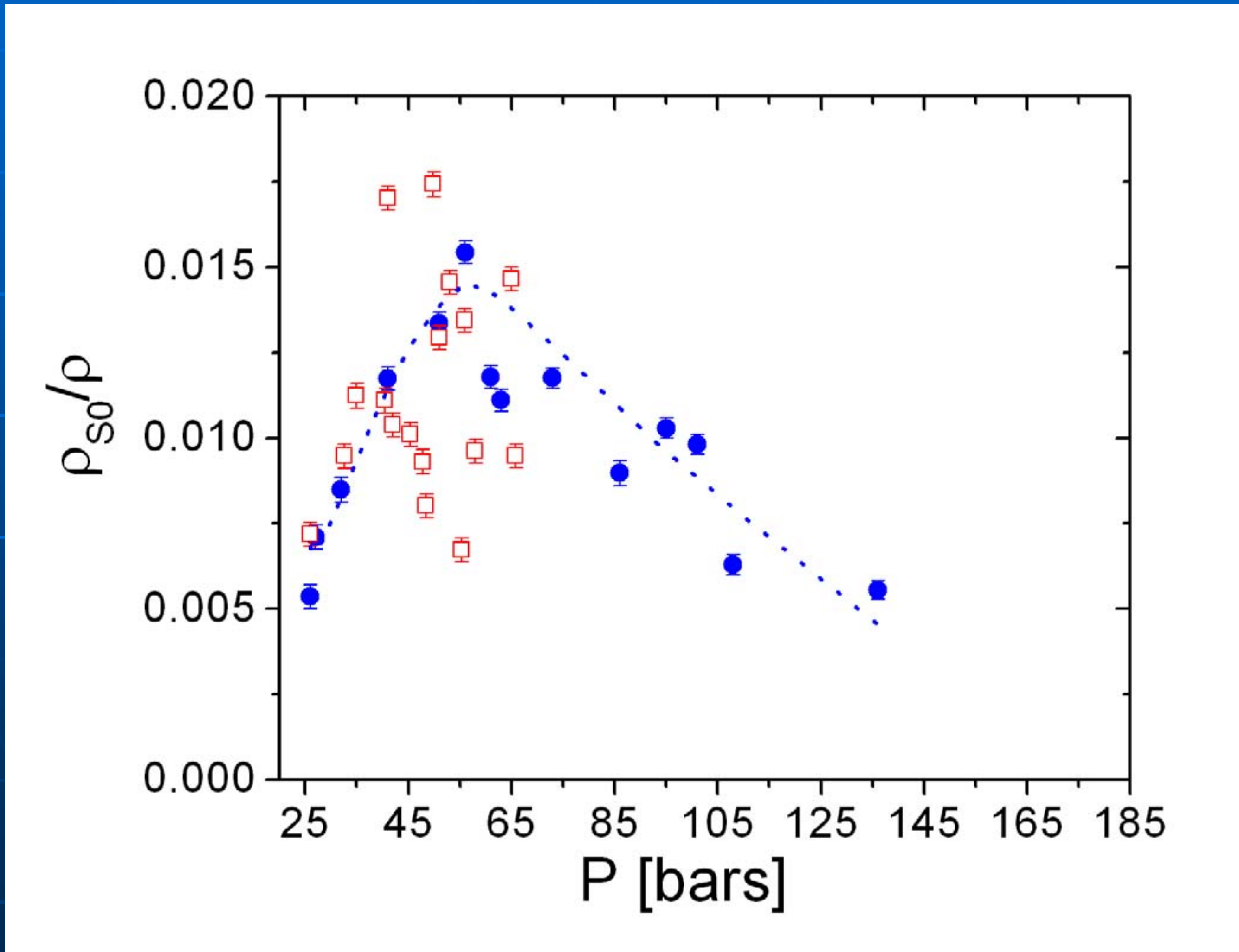
$$\oint v_s dl = \frac{h}{m} \cdot n$$

$$v_s = \frac{h}{2\pi R m} \cdot n$$

$=3.16\mu m/s$

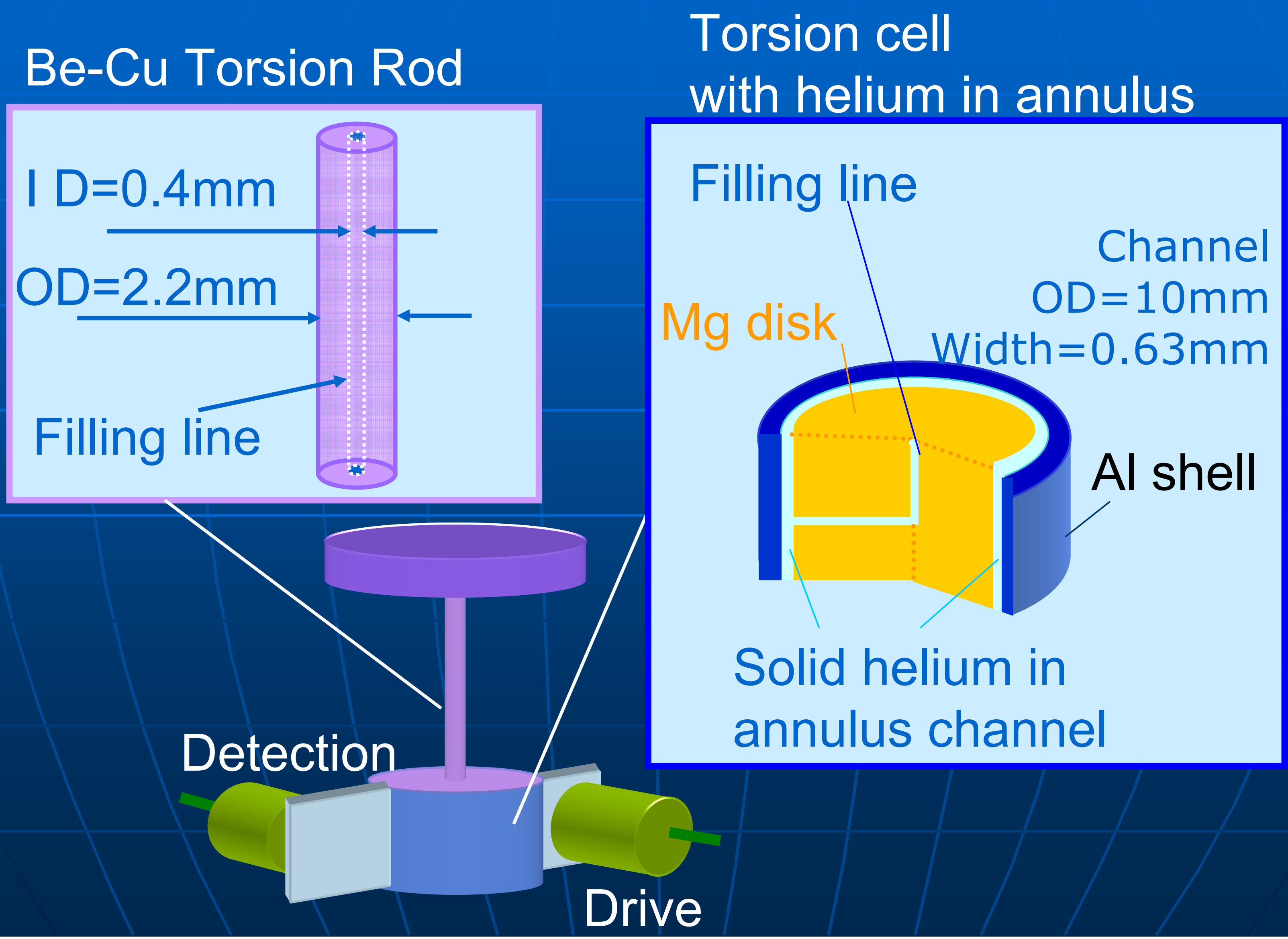
for $n=1$

Pressure dependence of supersolid fraction

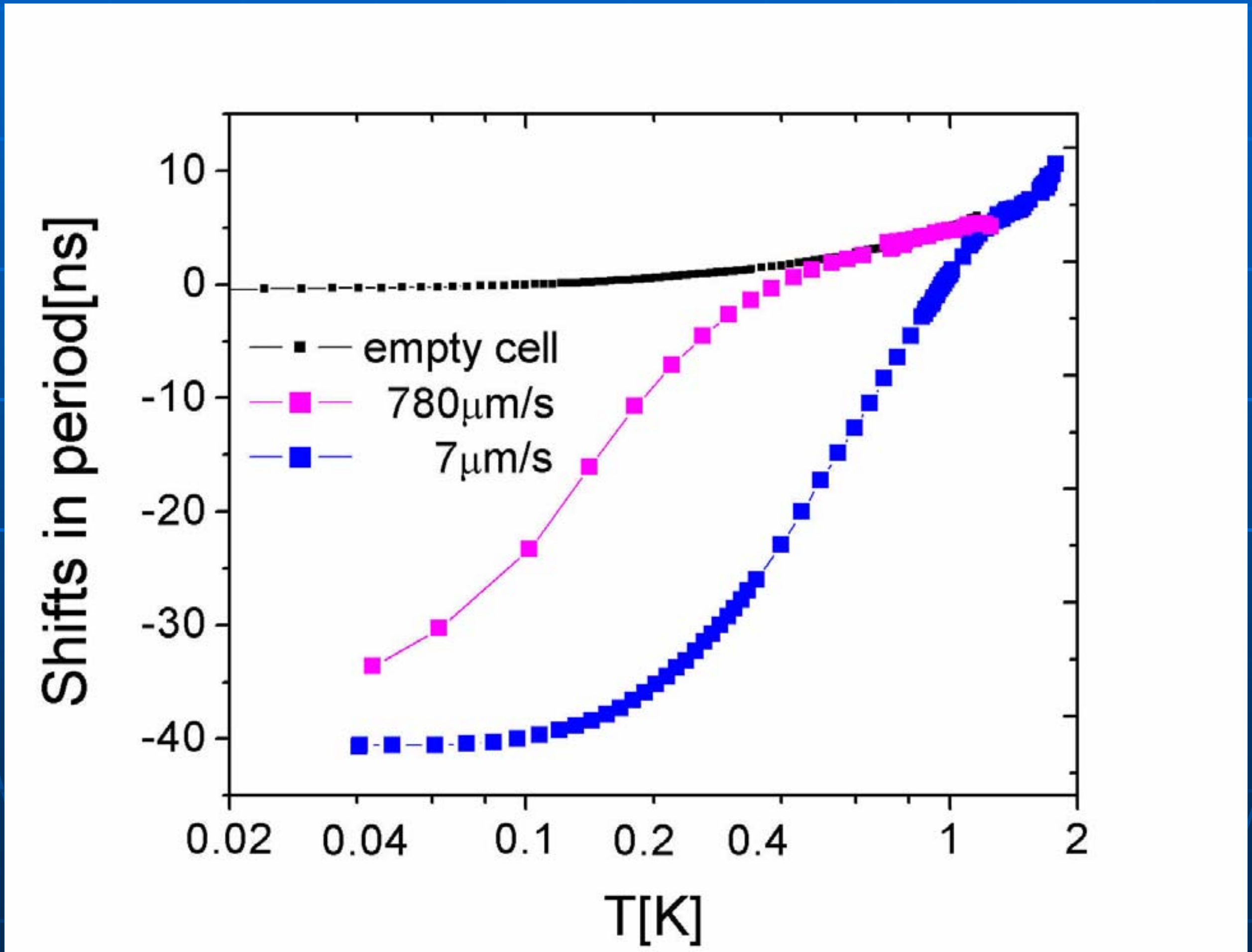


Red data points have the “wrong” temperature gradient in growing the solid helium samples

Search for the supersolid phase in the bulk solid ^{4}He.

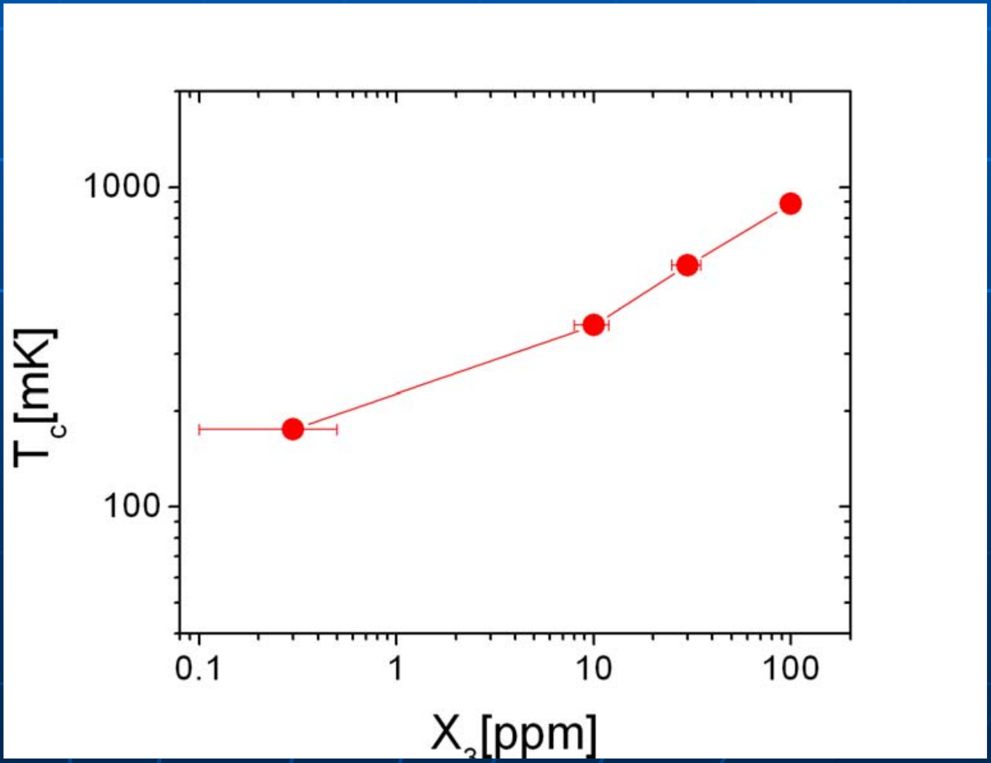


^{4}He solid diluted with a low concentration of ^{3}He (85ppm) at 60 bar

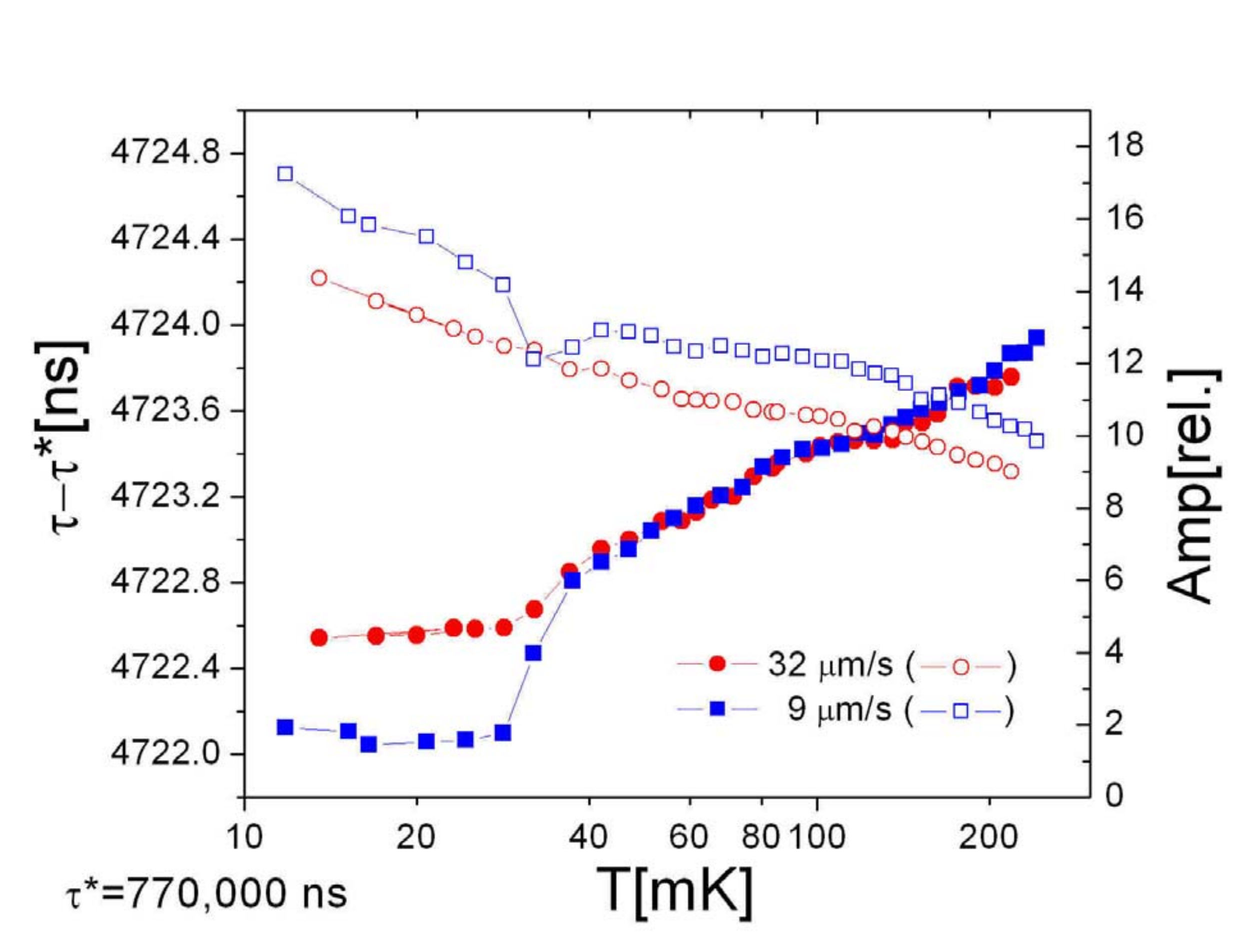


Experiments studying the effects of

- ^3He impurities
- Geometry
- Frequency
- Annealing



Isotopically-pure* ^{4}He (*X_3<1ppb)



Total mass loading due to solid helium $\tau_{He}-\tau_{empty}=3939ns$

Shift in the period $\Delta\tau=1.2ns$

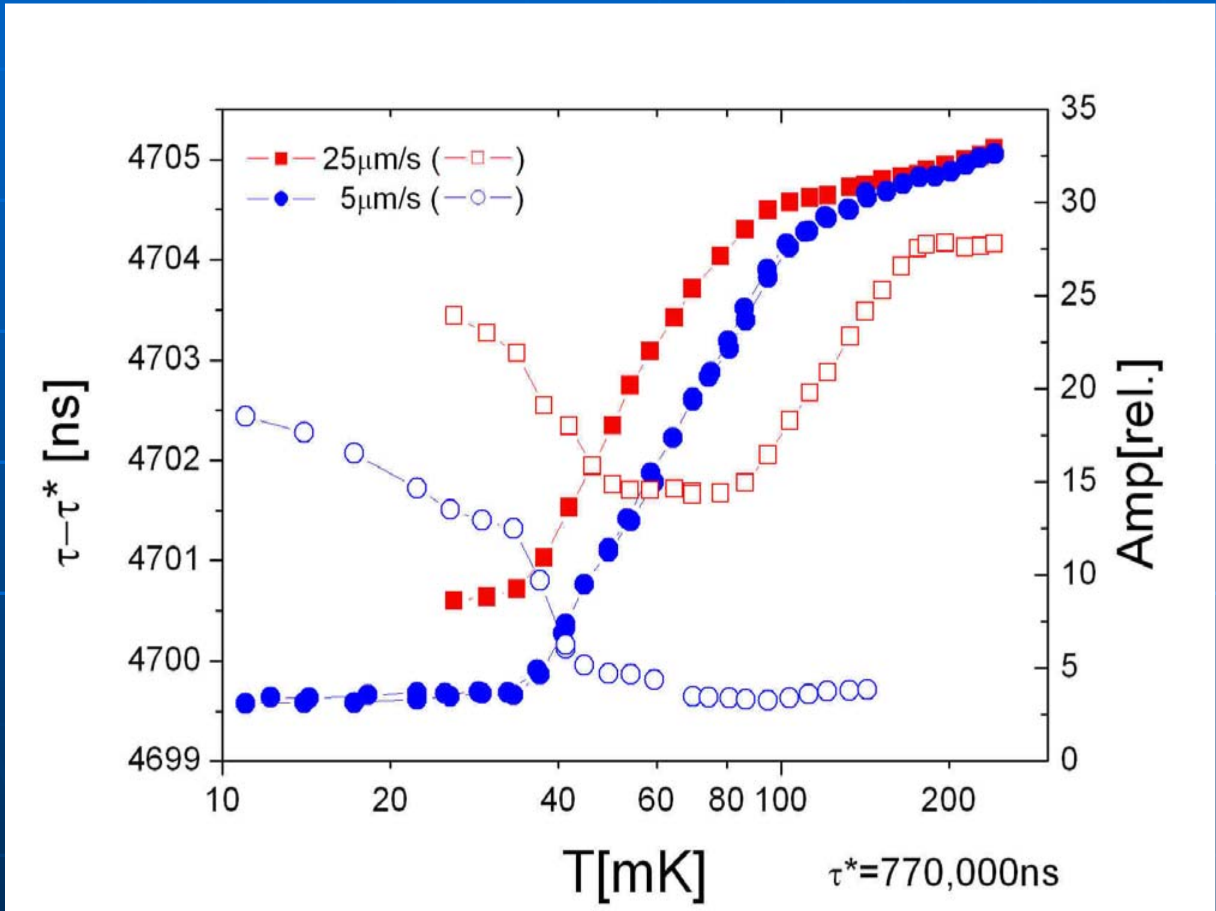
Supersolid fraction ~1.2ns/3939ns ~0.025%

Torsional oscillator
f_0= 1298Hz, Q~1x10^6
Cylindrical Geometry

This work is done at the high B/T facility of the magnet lab.

J.S. Xia (University of Florida)

Solid ^{4}He with X_3~15ppb



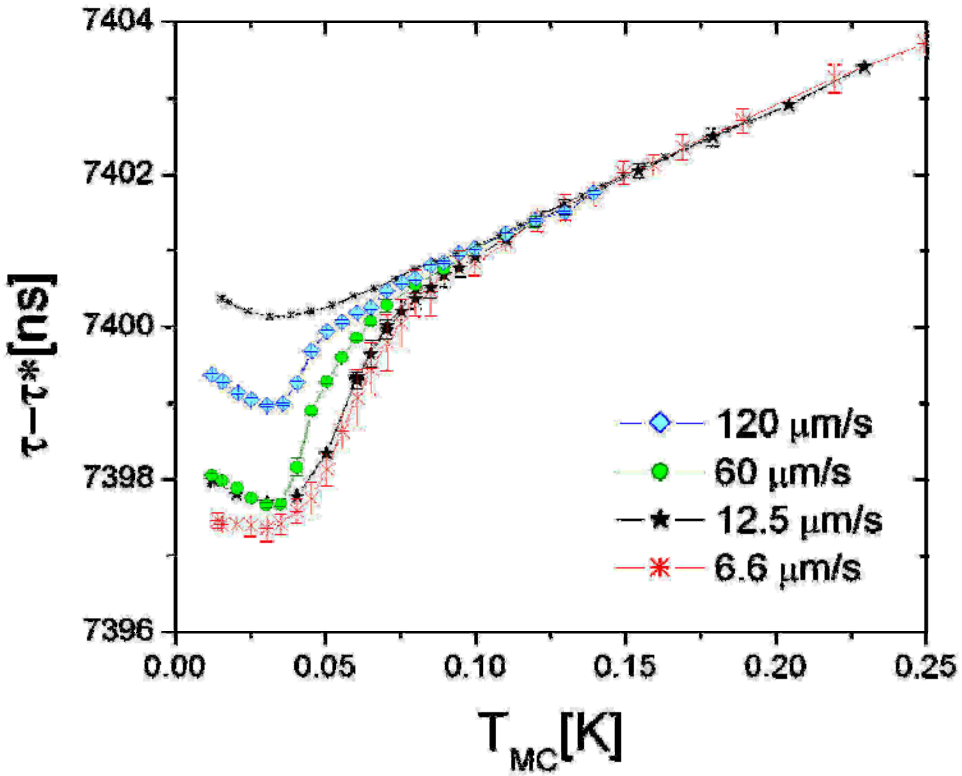
Total mass loading due to solid helium τ_{He}-τ_{empty}=3939ns

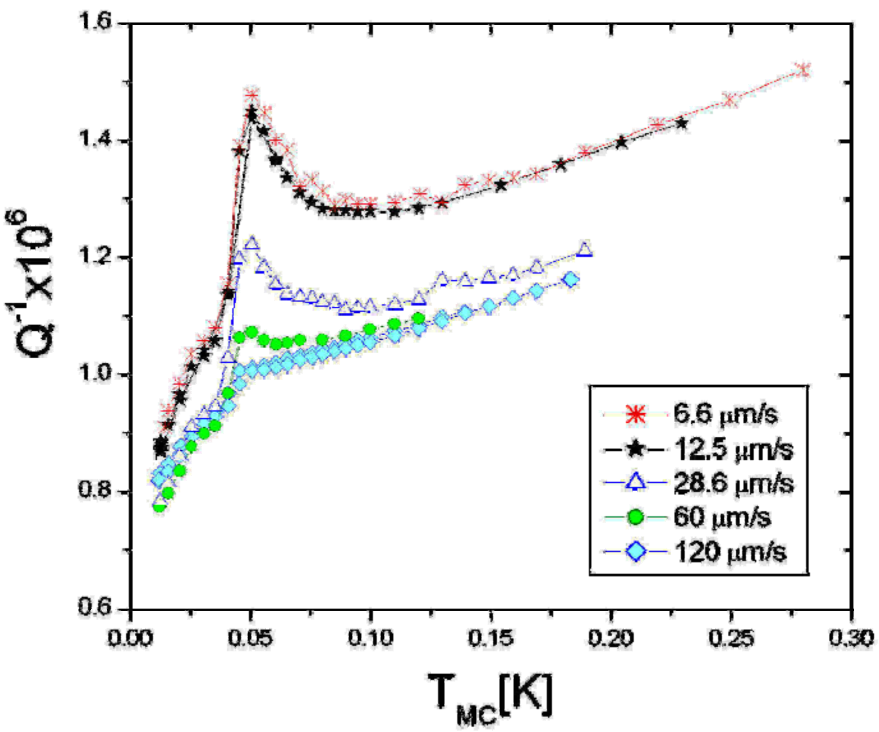
Shift in the period $\Delta\tau$=5ns

Supersolid fraction ~5ns/3939ns ~0.1%

47ppb ^{3}He in solid ^{4}He at 55bars

Resonant frequency:783Hz, Q~1x10^6
Open cylinder (no annular channel)





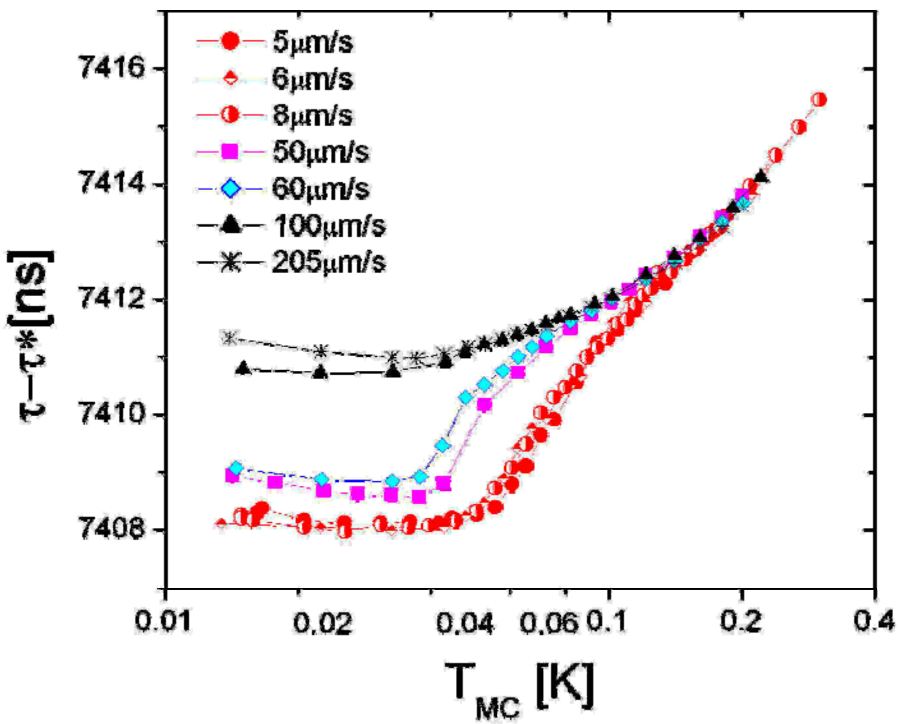
Eunseong Kim and Josh West

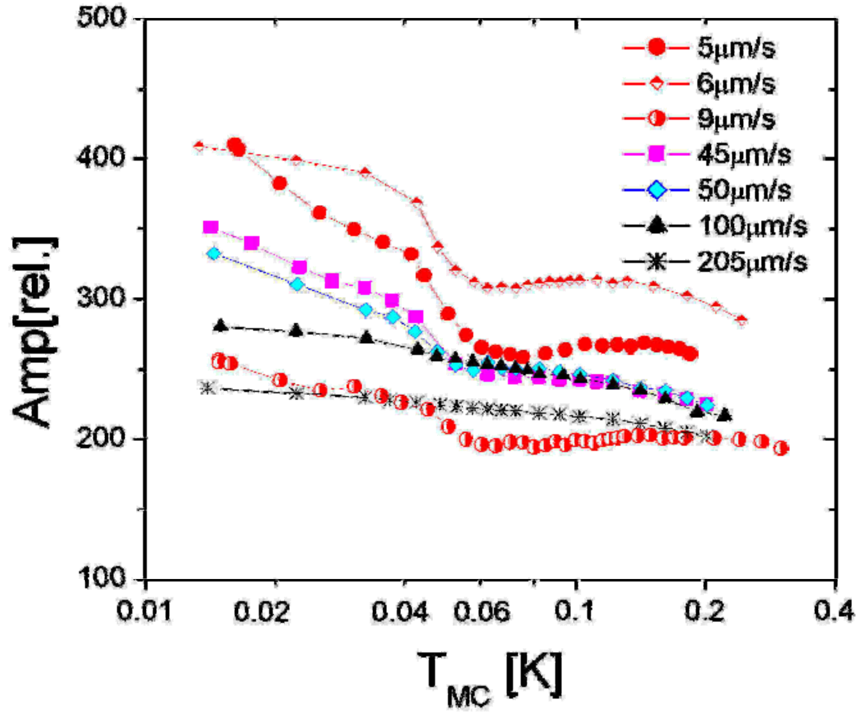
Tc~100mK
Supersolid fraction 2.3ns/1100ns~0.2%

99ppb ^{3}He in solid ^{4}He at 60bars

Resonant frequency:783Hz, Q~1x10^6

Open cylinder (no annular channel)



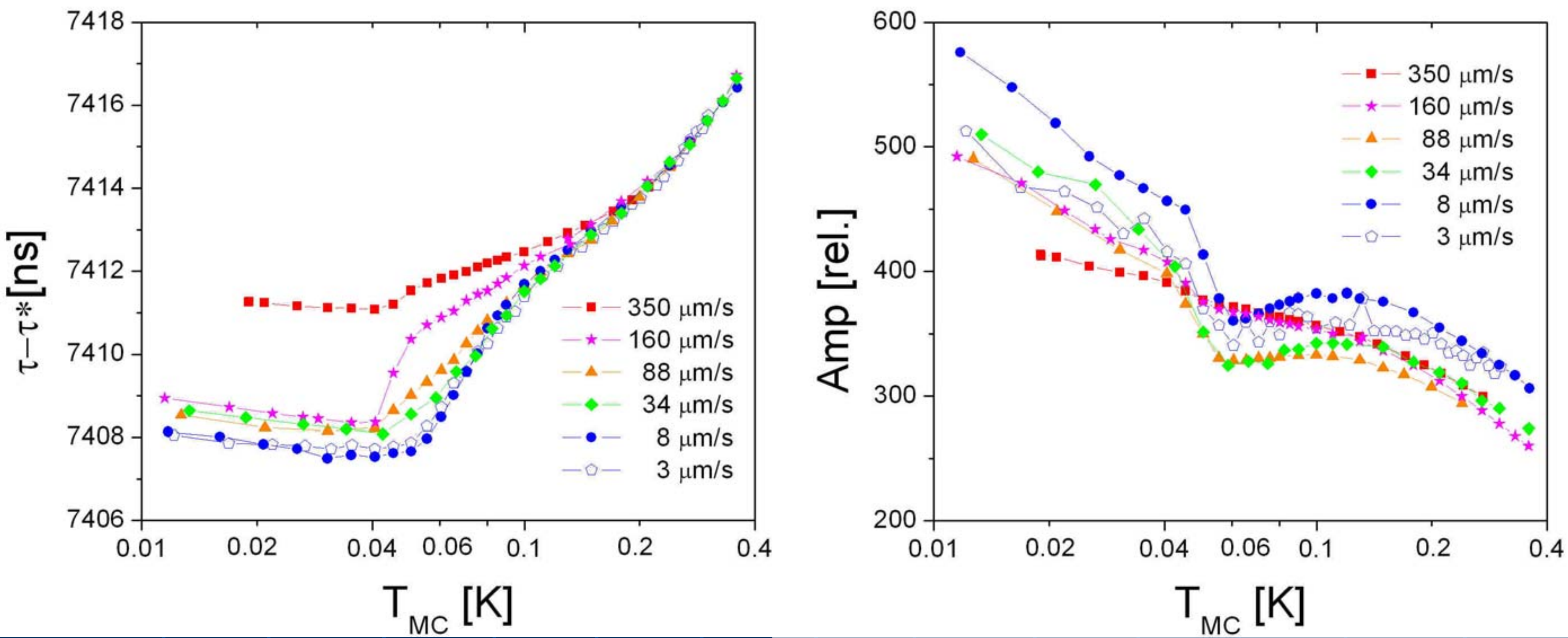


Tc~150mK

Supersolid fraction 3.5ns/1110~0.3%

150ppb ^{3}He in solid ^{4}He at 60bars

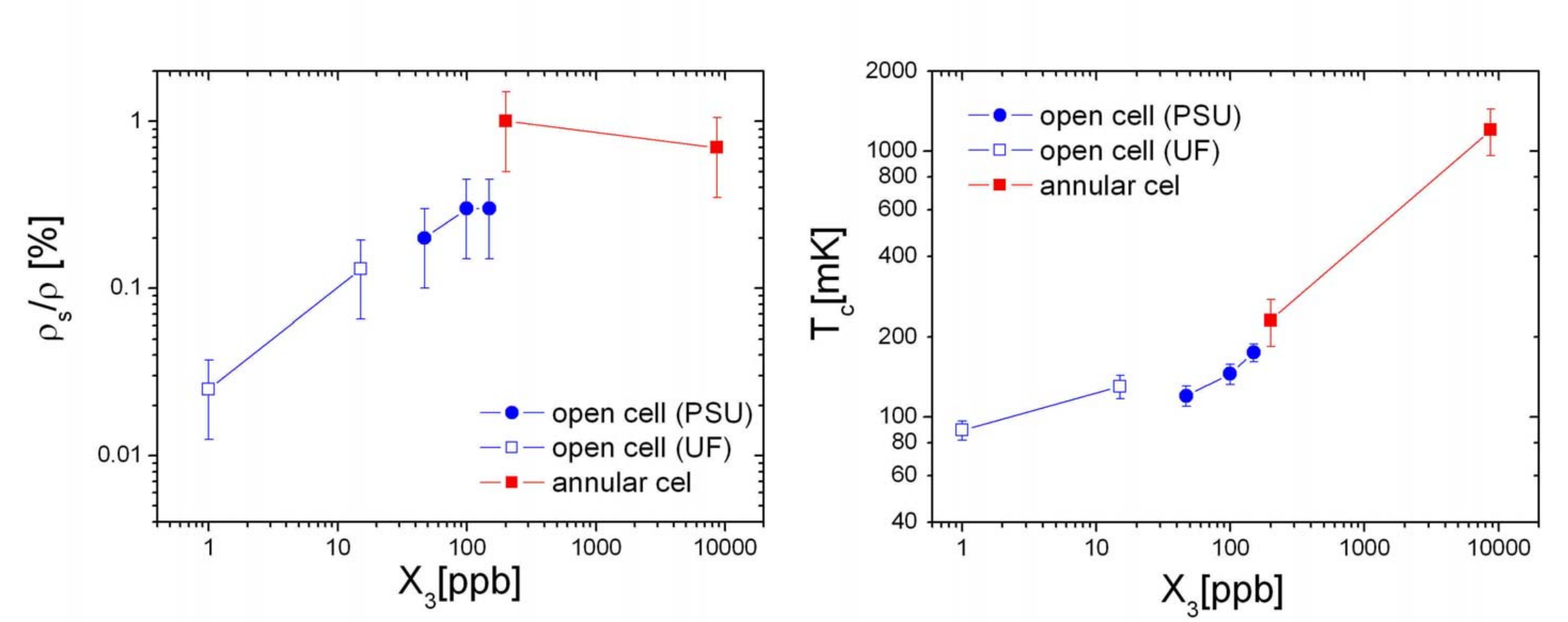
Resonant frequency:783Hz, Q~1x10^6
Open cylinder (no annular channel)



Tc~170mK
Supersolid fraction 3.5ns/1110~0.3%

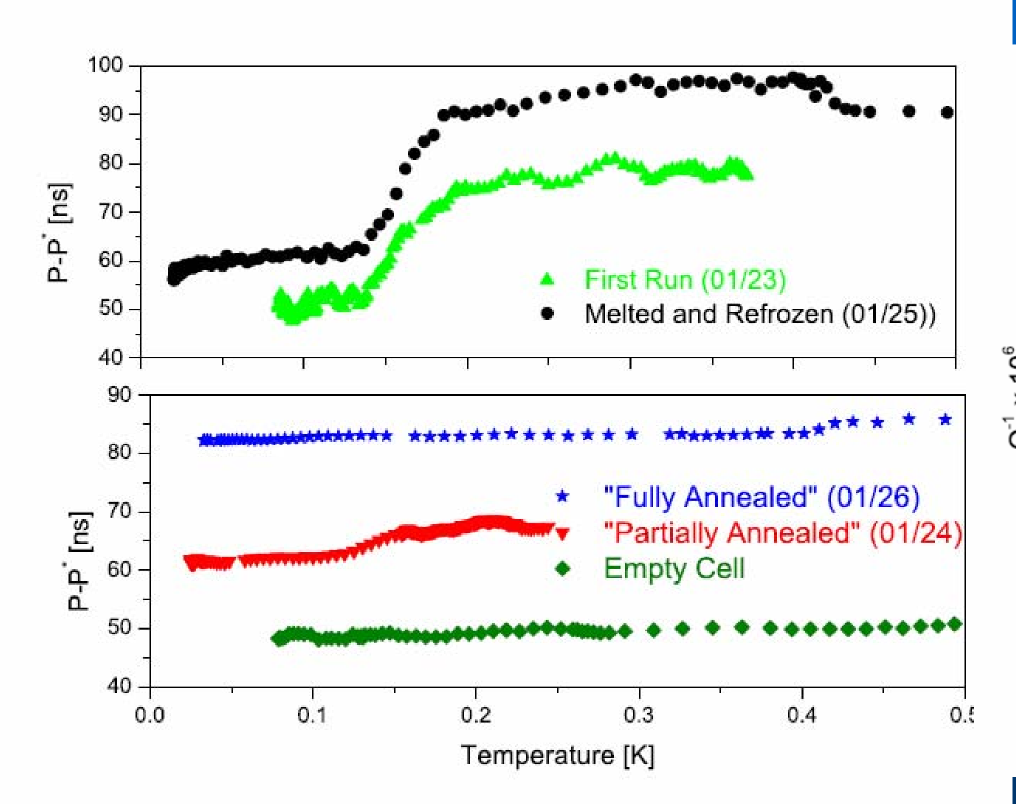
Effect of He-3

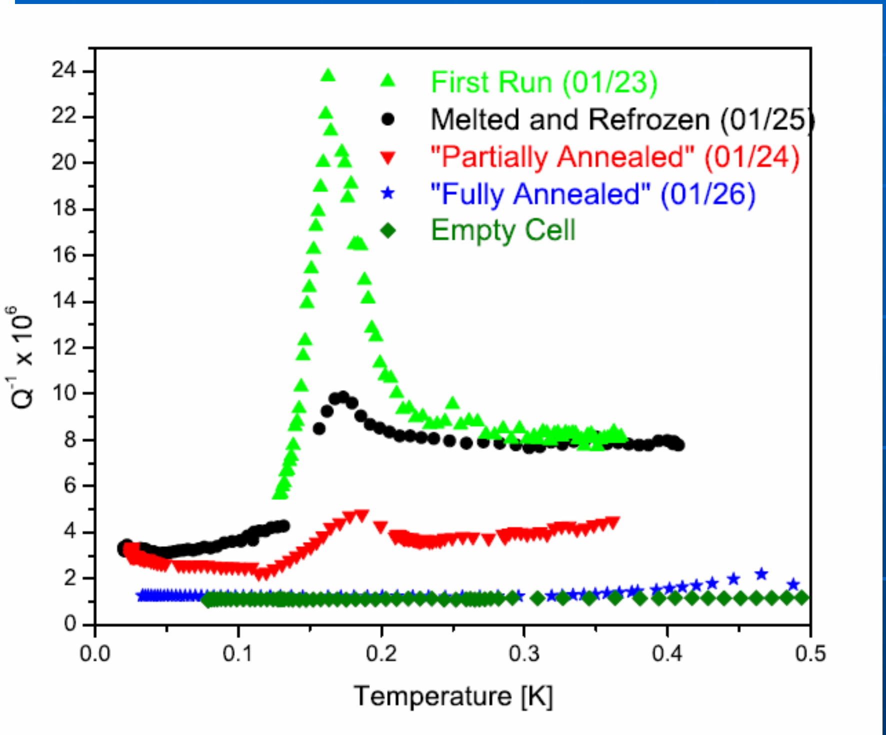
- Tc or onset temperature and supersolid fraction of superflow show strong dependence on concentration of ^3He.



Annealing effect?

A. S. C. Rittner and J. D. Reppy cond-mat/0604528



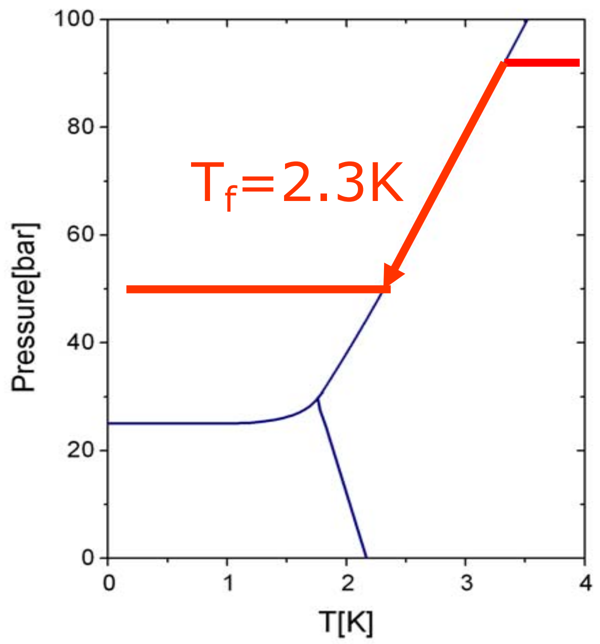


We have looked for the annealing effect and found the supersolid fraction due to different annealing procedure can differ by at most 15%.

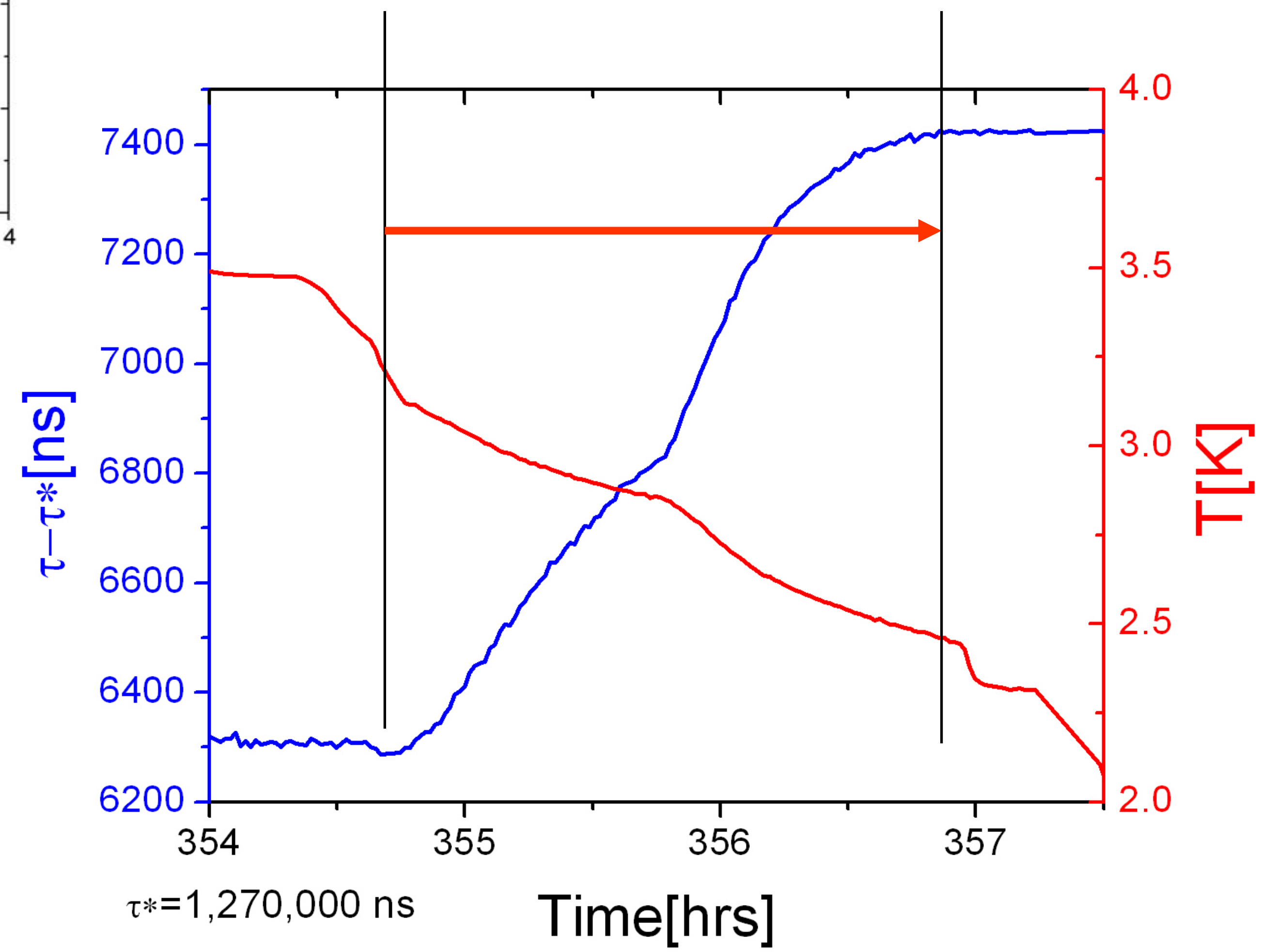
NCRI also observed by Kubota group at Tokyo University, Japan
Shirahama Group at Keio Univerity, Japan

Sample A

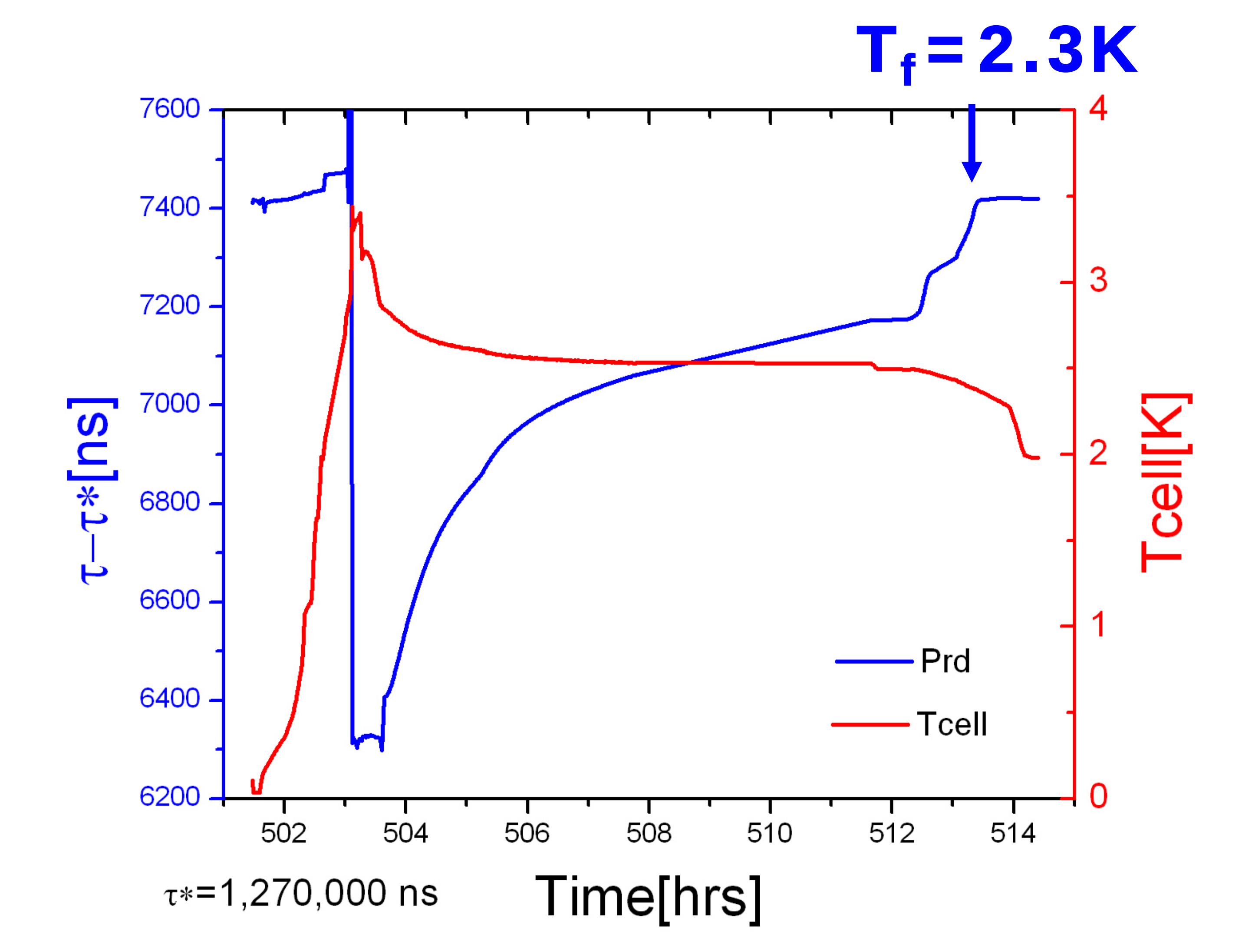
Growing solid helium for 2.3hrs



47 ppb

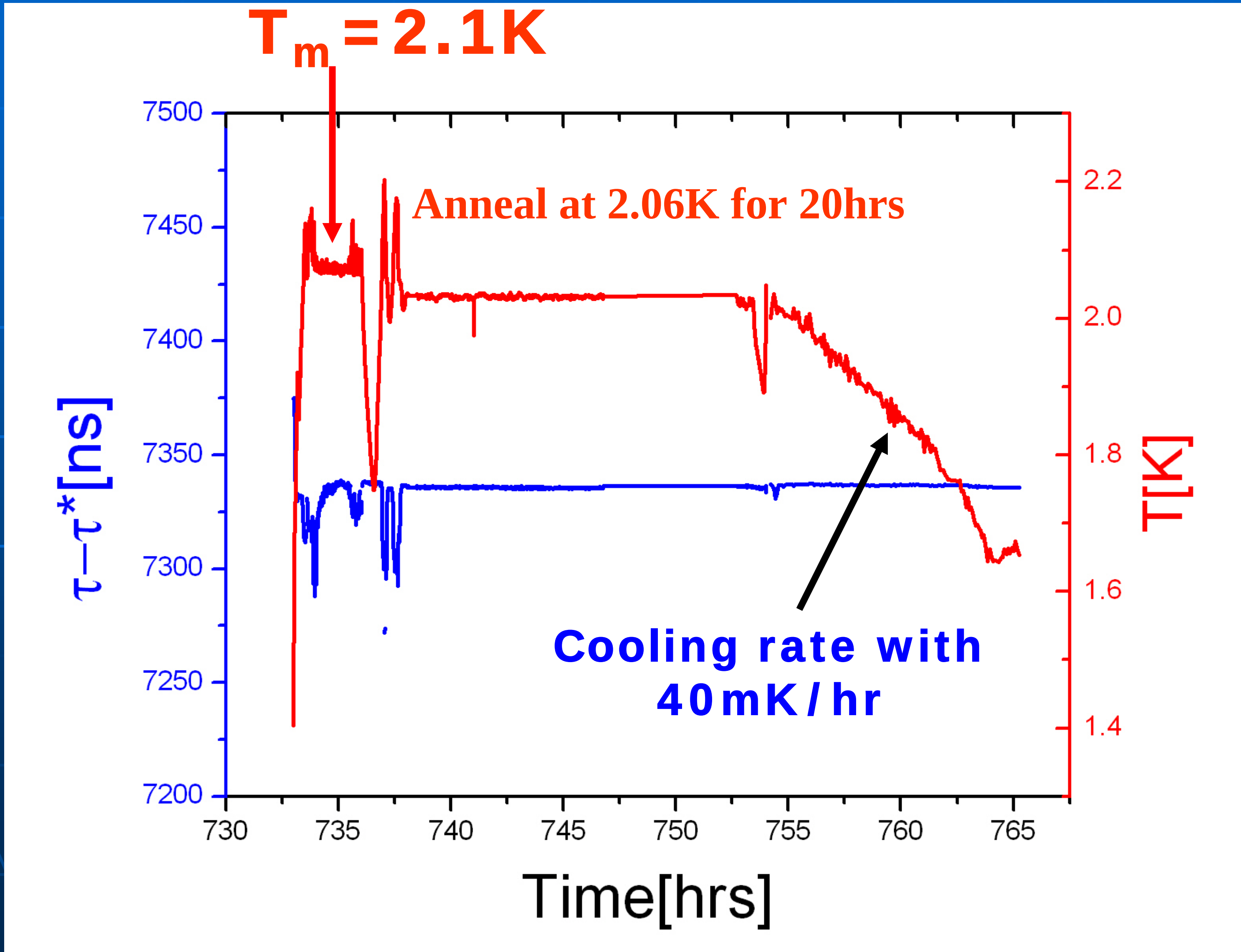


Sample B



$T_f = 2.3K$
7600
7400
7200
7000
6800
6600
6400
6200
τ−τ*[ns]
4
3
2
1
0
Tcell[K]
502
504
506
508
510
512
514
Prd
Tcell
τ*=1,270,000 ns
Time[hrs]

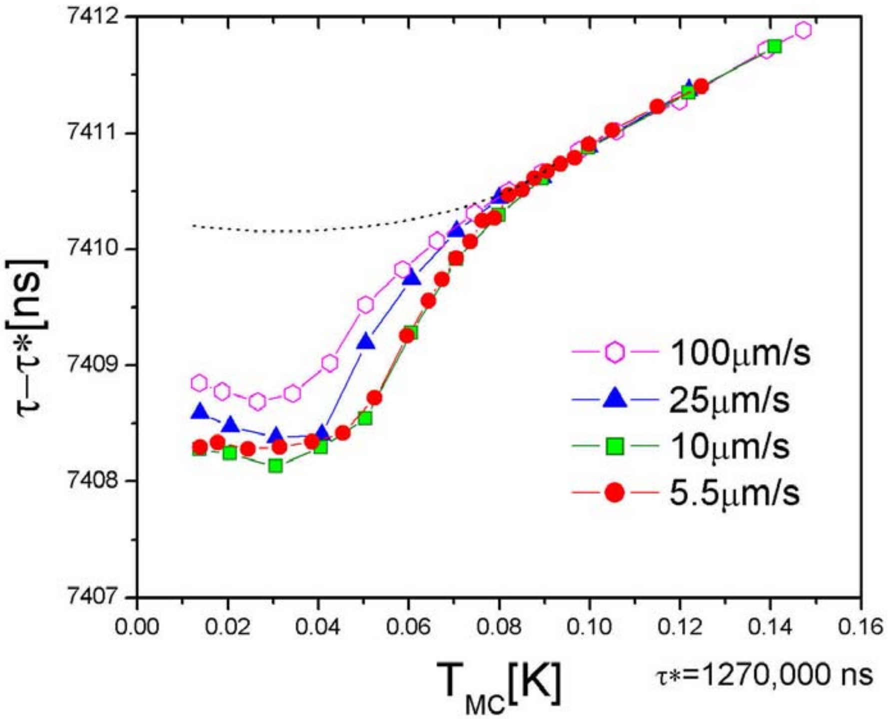
Sample C



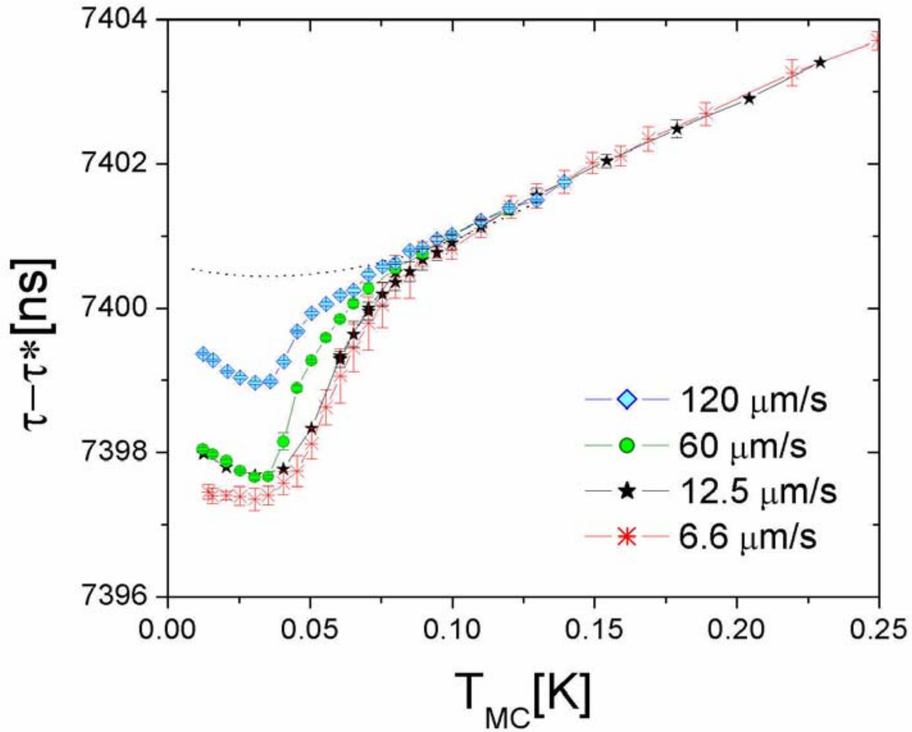
Tm=2.1K
Anneal at 2.06K for 20hrs
Cooling rate with 40mK/hr
7500
7450
7400
7350
7300
7250
7200
τ−τ*[ns]
2.2
2.0
1.8
1.6
1.4
T[K]
730
735
740
745
750
755
760
765
Time[hrs]

47ppb ^{3}He in solid ^{4}He at 50bars

Sample A



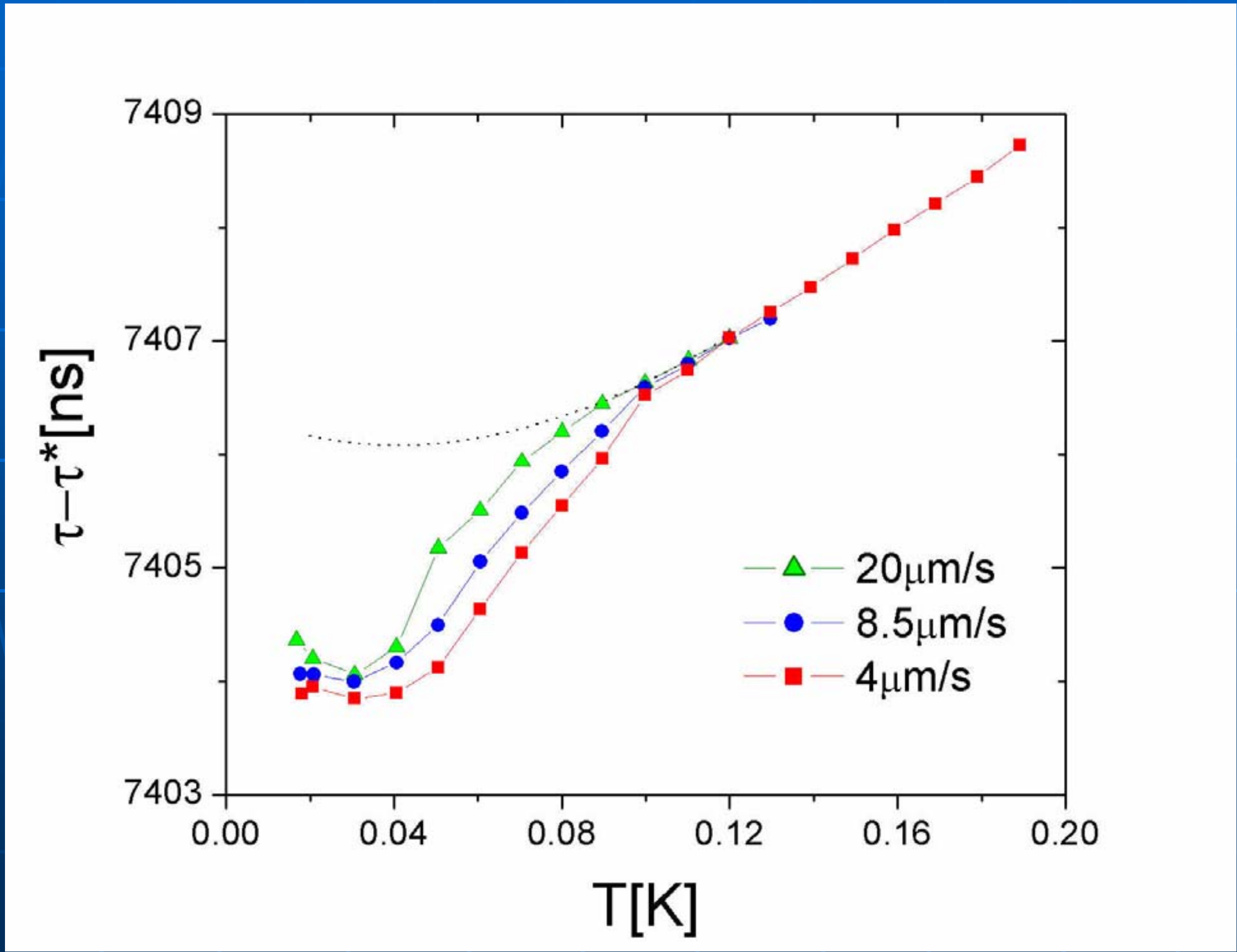
Sample B



Supersolid fraction
2ns/1130ns =0.18%

Supersolid fraction
2.9ns/1130ns =0.25%

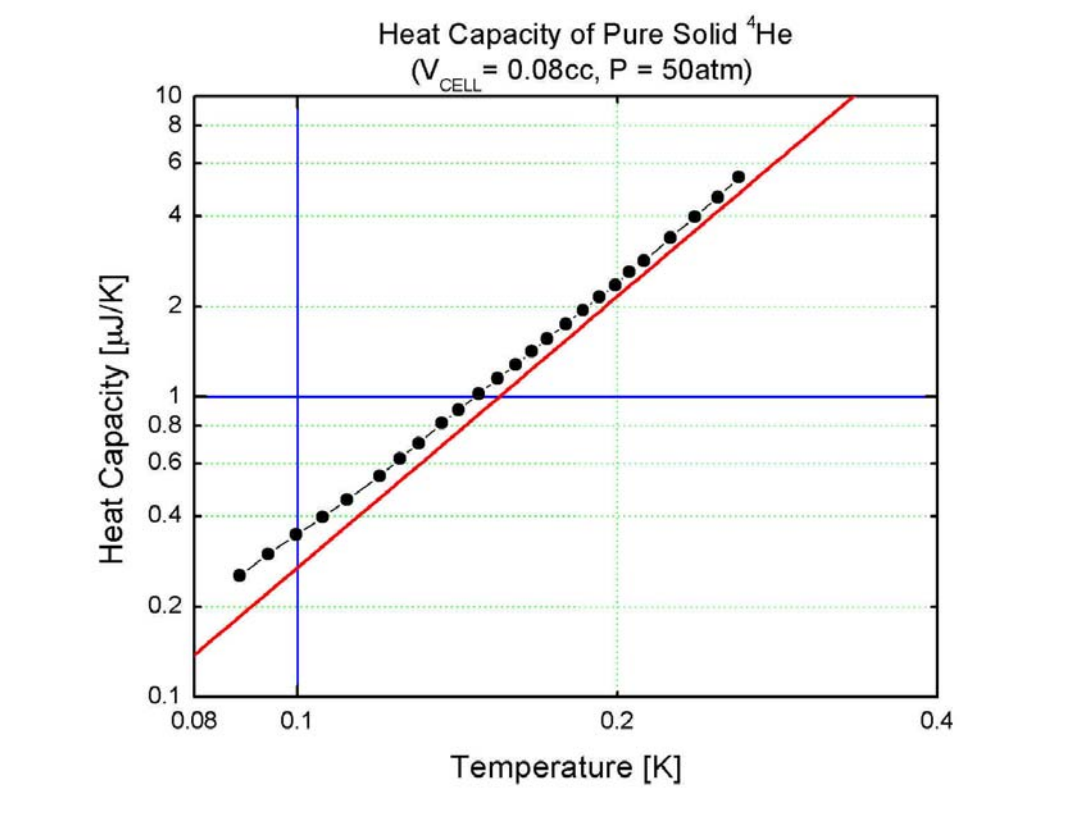
Sample C



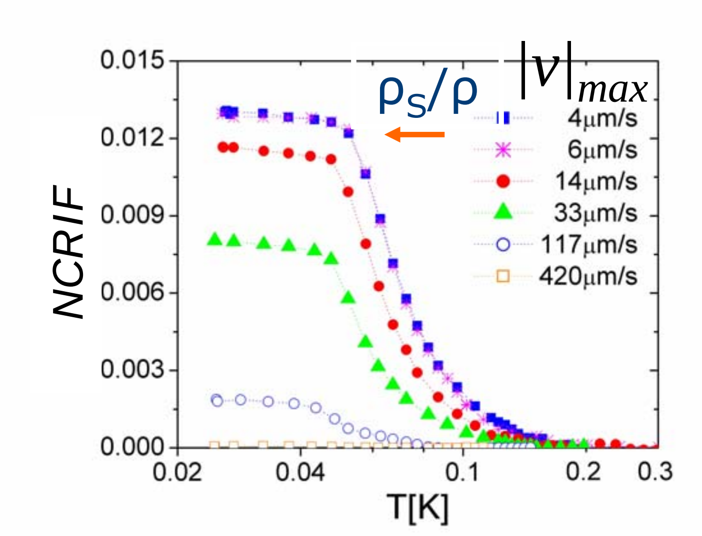
Supersolid fraction

2.2ns/1130ns =0.19%

Heat Capacity signature?



Clark & Chan (2004)



No anomaly in hcp ^{4}He (Vm=20.9cc) down to 100mK in previous studies

Hébral et. al., Castles and Adams, and others

Our experiment

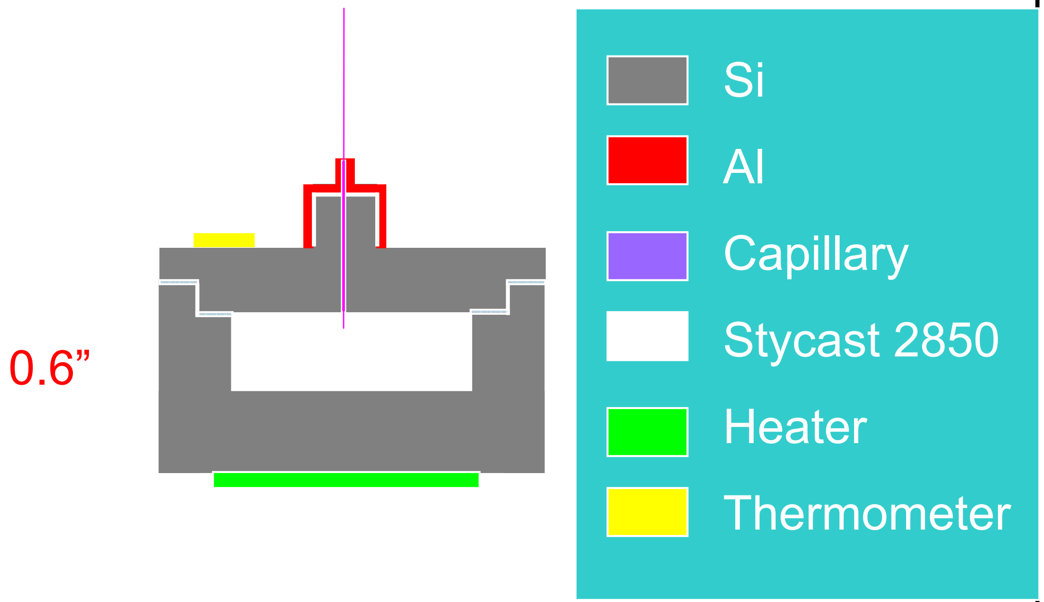
The Silicon cell

- Reasons for Si:

Low heat capacity:

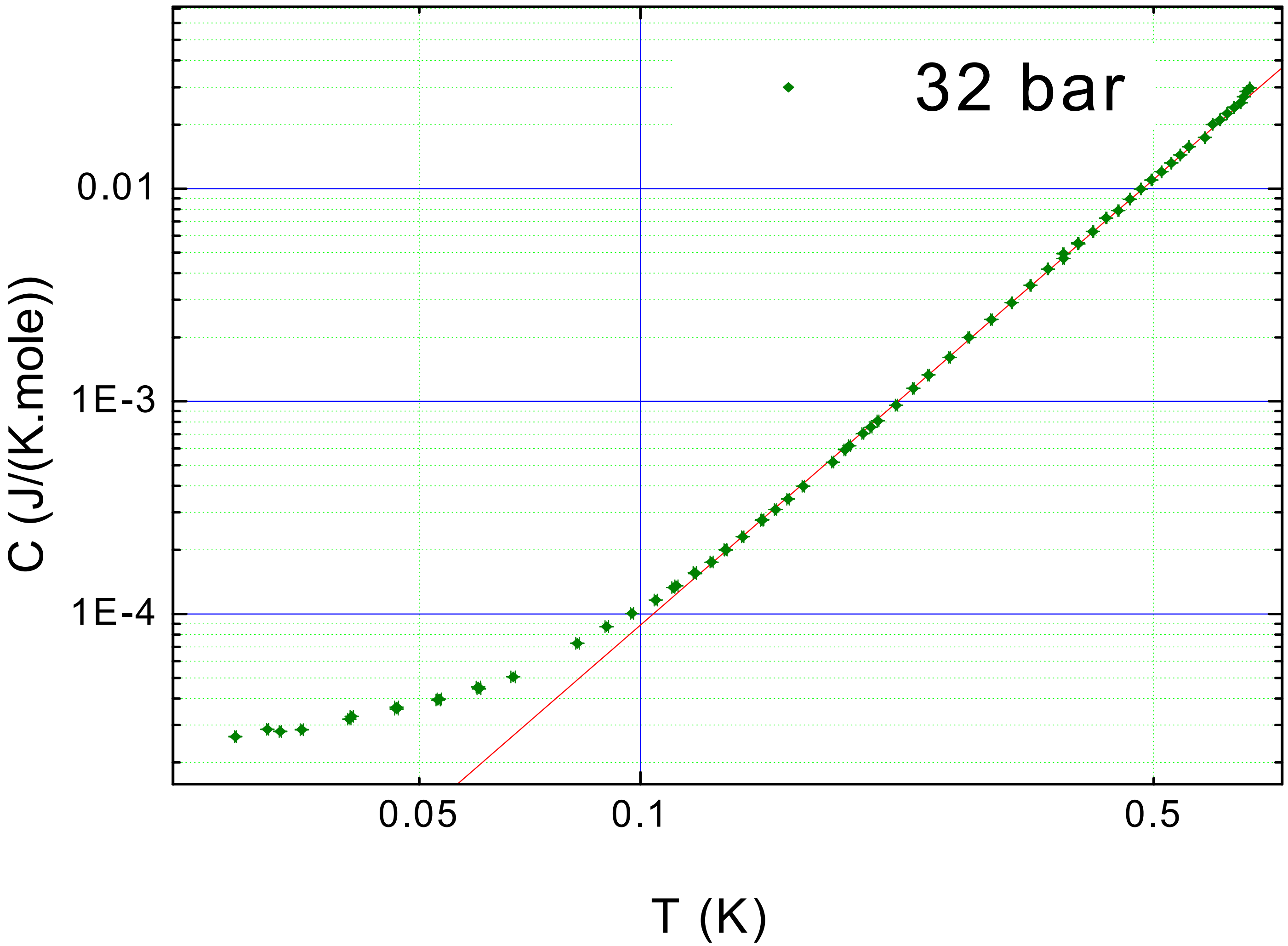
High thermal conductivity:

Helium Volume= 0.926cc



$$\frac{C_{cell}}{C_{He}} = 0.02 \text{ at } 0.1\text{K}$$

Previous measurements: $\frac{C_{cell}}{C_{He}}$ in the order of 10 at 0.1K



Heat Capacity of Solid ^{4}He at 32 bar

Summary and questions:

- "Transition" to supersolid state is found near 200 mK for solid helium with 0.3ppm He-3 in Vycor (7nm),in porous gold(490nm) and in bulk form. Supersolid fractions are found to be around 1 to 2%.
- Near Tc the supersolid density 'fades' away with positive slope. What kind of transition is it? Is the true transition at lower temp. ~60 mK where the supersolid density begins to show a sharp drop?
- Besides the ultra-sound result of Goodkind, there is no signature with other techniques, so far. Are the results from these two techniques consistent?
- Why there is no signature of mass transport in the experiments of Greywall, Beamish and Bonfait?

Summary and questions, II

- In our cell with a narrow annulus (0.6mm) the scatter in the supersolid fraction ranges from 0.5 to 1.6%. When we are more careful in nucleating the solid from the bottom of the cell, rather from the torsion rod, the scatter is reduced by a factor of 4 or 5. A pressure dependence in supersolid fraction is seen. It increases from 0.6% near the melting boundary to 1.5% near 55 bar and then decrease with increasing pressure. Going away near 170 bar.
- What is the origin of the pressure dependence of the supersolid fraction ? If we grow solid under constant pressure condition, will the scatter become even smaller? Or will the supersolid faction goes down and even disappear?
- What is the origin of the small critical velocity that correspond to a few units of quantum circulation?

Summary and questions, III

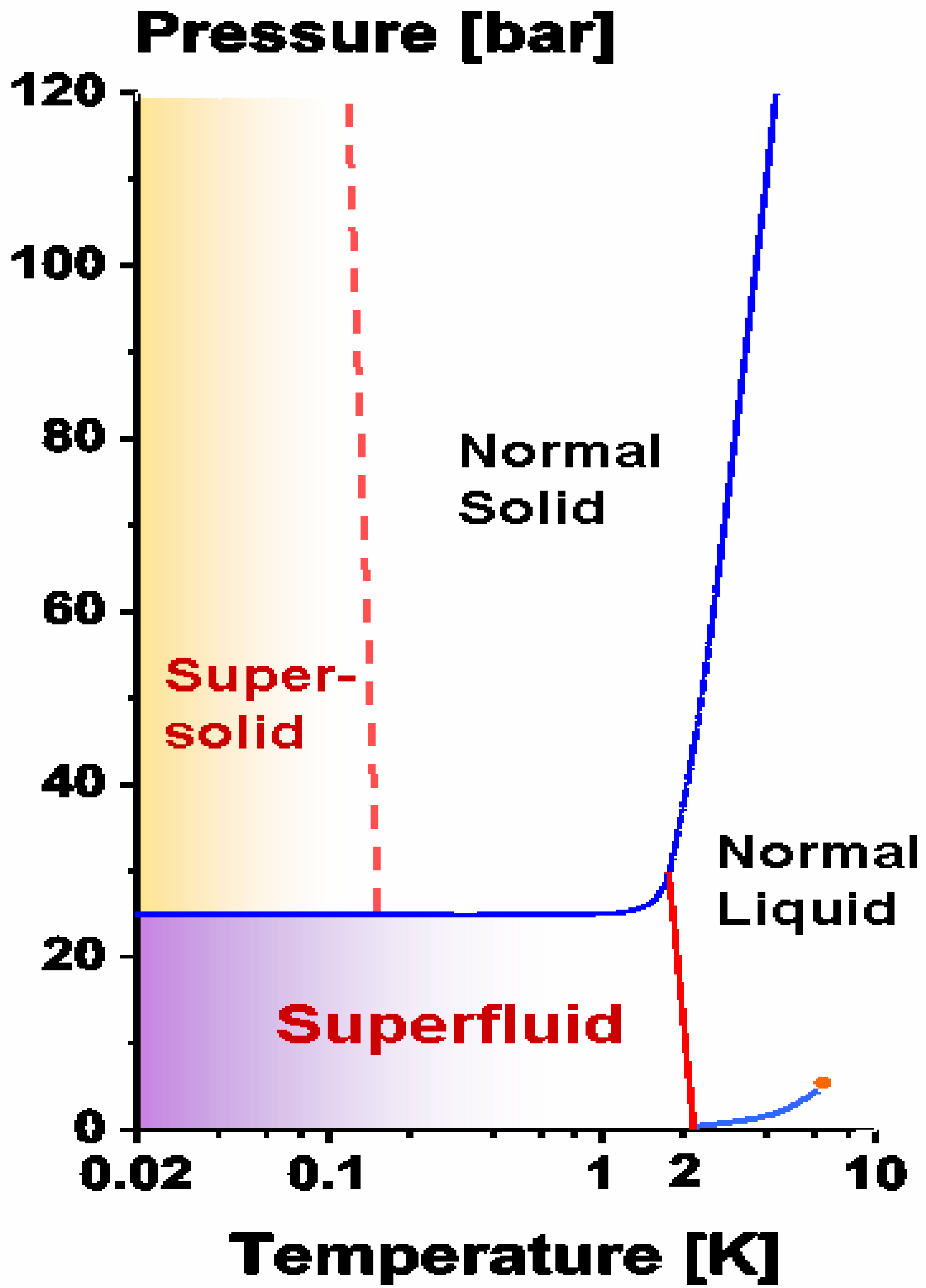
- Supersolid fraction in cell with simple cylindrical geometry appears to be 5 times smaller than that in a cell with annular geometry. [Presumably it is easier to have better quality crystal with a simple geometry]
- Transition temp. increases with He-3 concentration. It is around 50 mK for 1ppb He-3 sample; 200 mK for 300 ppb sample and 1K for 100 ppm sample.
- The supersolid fraction has a maximum with He-3 concentration near 300ppb.
- Frequency dependence on Tc and on supersolid fraction between 160 Hz to 2000 Hz seems quite weak.

- Heat capacity seems to show an anomaly below 120 mK. With an addition to the standard T**3 term. May or may not be related to supersolid , more work is needed.

Summary and questions; IV
effect of annealing

Rittner and Reppy found interesting annealing effect that superflow can be eliminated by annealing. However, we do no see such an effect.

Phase Diagram



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J. R. Beamish,
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A. J. Leggett,
E. Mueller,
M. A. Paalanen,
J. D. Reppy,
W. M. Saslow,
D.S. Weiss,
J.W. Ye