# Summary of Penn State results on supersolids

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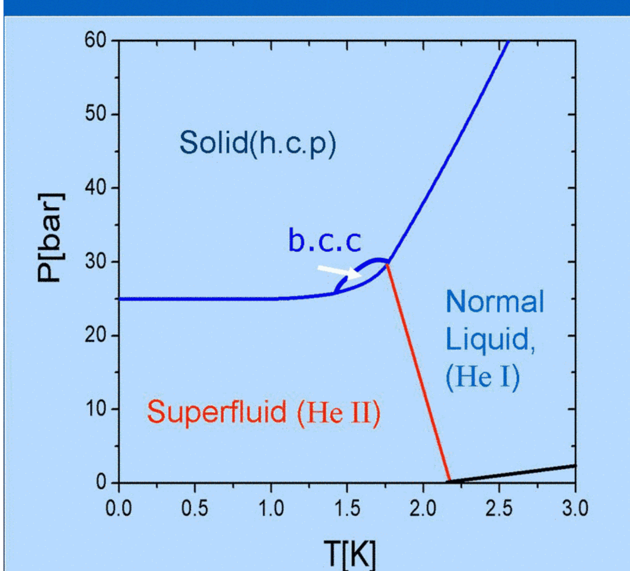
Supported by NSF

## Phase diagram of $^4He$

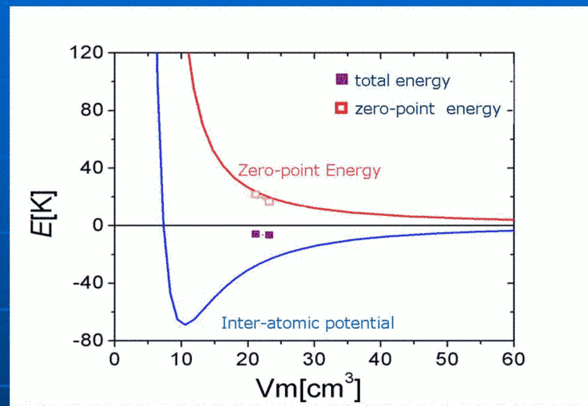



Fritz London is the first person to recognize that superfluidity in liquid $^4He$ is a BEC phenomenon.

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).

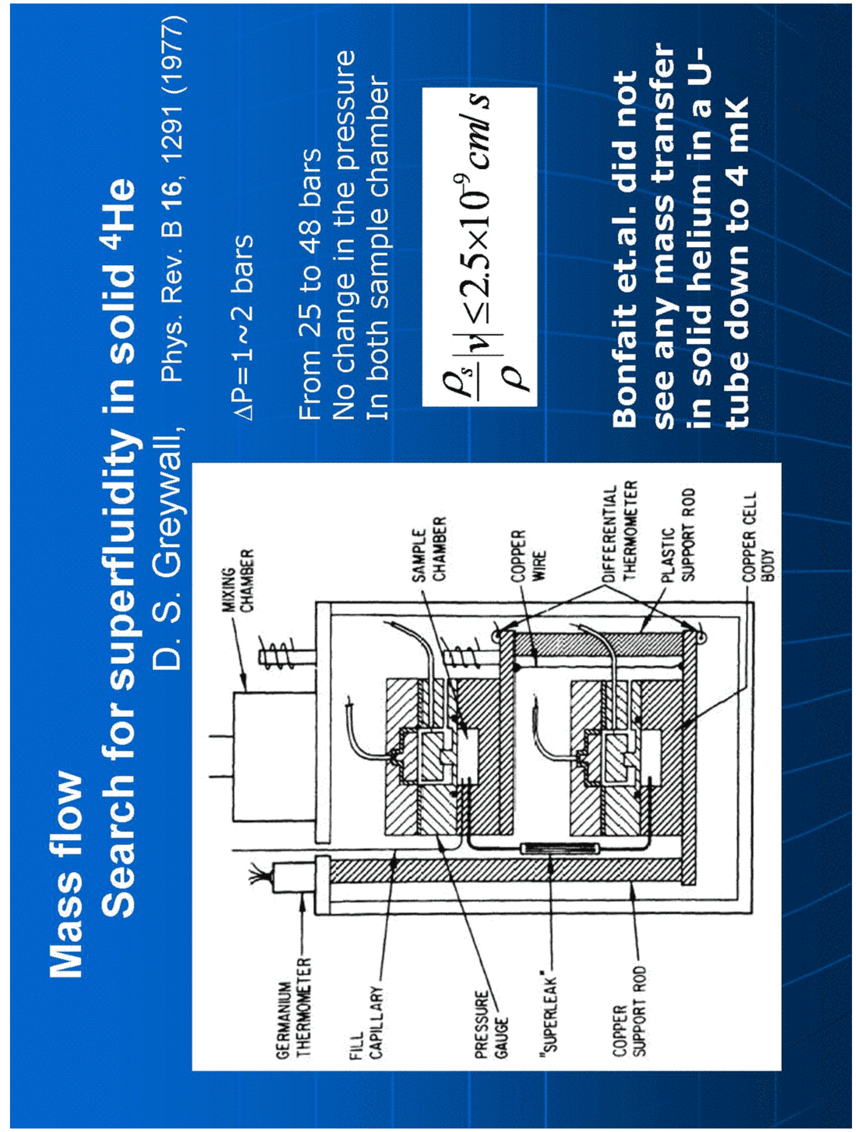
- Recently observed Xray measurement at ~0.7K and near melting curve shows 26%
  (Burns et al. *Phys. Rev. B* **55,** 5767(1997))

## 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)

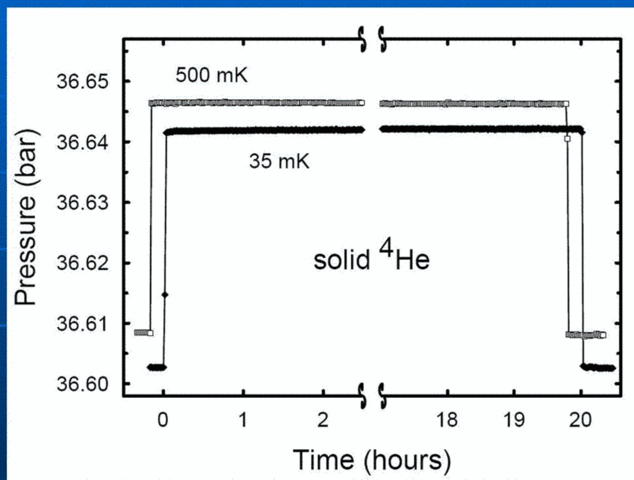
- However, interesting results are found in Ultrasound Measurements at UCSD.
  Goodkind Phys. Rev. Lett. **89**,095301(2002) and references therein


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)
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$_c$= 6.5x10$^5$ 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)
Solid helium


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
$\frac{\rho_s}{\rho}|v| \le 2.5\times10^{-9} cm/s$
Bonfait et.al. did not see any mass transfer in solid helium in a U-tube down to 4 mK
MIXING CHAMBER
SAMPLE CHAMBER
COPPER WIRE
DIFFERENTIAL THERMOMETER
PLASTIC SUPPORT ROD
COPPER CELL BODY
GERMANIUM THERMOMETER
FILL CAPILLARY
PRESSURE GAUGE
"SUPERLEAK"
COPPER SUPPORT ROD

## Pressure driven flow

1. J. Day et. al, Phys. Rev. Lett **95**, 035301 (2005)
2. J. Day and J. Beamish, condmat 0601149 (2006)



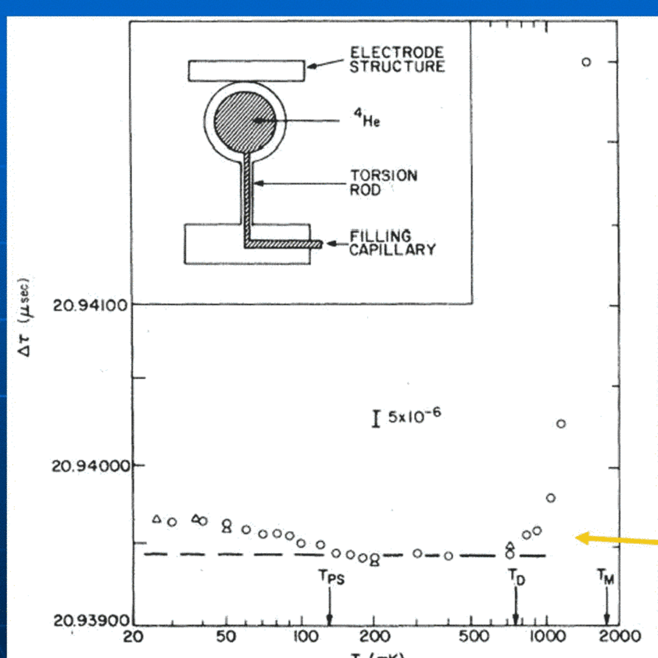

1. No evidence of mass flow from bulk Into vycor
2. Analogous to Greywall

$$\frac{\rho_s}{\rho}|v| \leq 1.5\times10^{-12} cm/s$$

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"

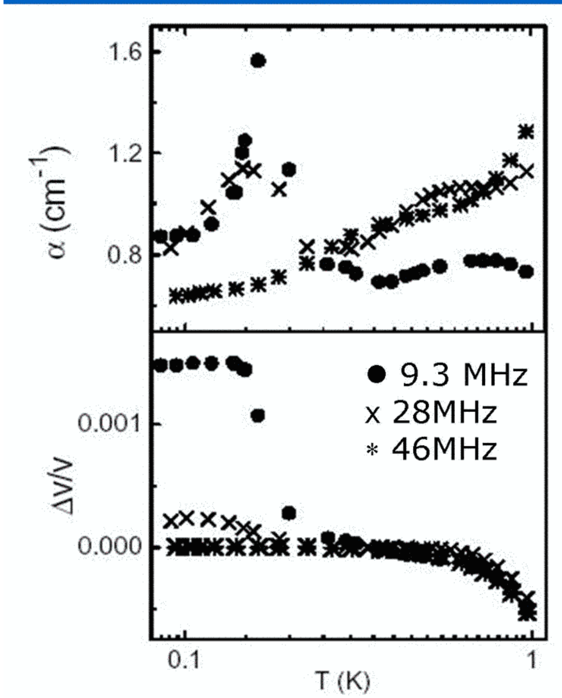
From 25-48bars

$\rho_s$ < 5 parts in $10^6$

$v_c$ < 5 μm/sec

$^3$He impurities 411ppm

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



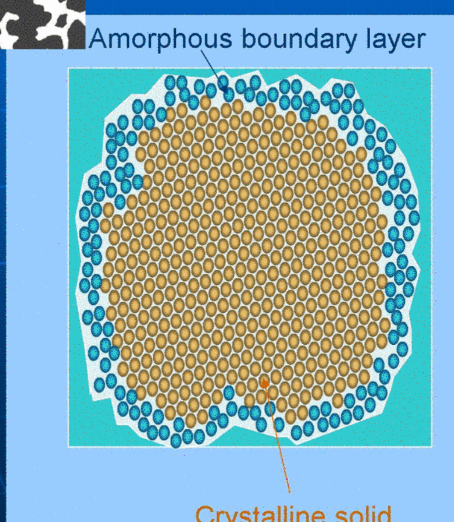

The results are interpreted by the authors as showing BEC of thermally activated vacancies above 200mK.

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?

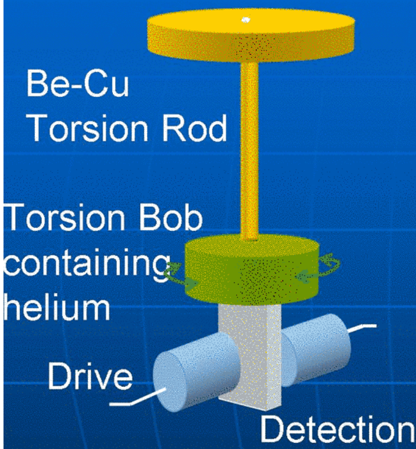



Solidification proceeds in two different directions:

1) In the center of the pore a solid cluster has crystalline order identical to bulk $^4$He
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




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

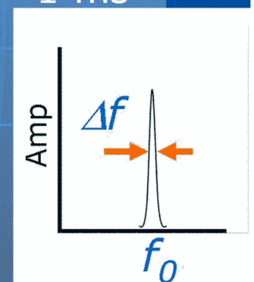
### Resolution

Resonant period ($\tau_o$) ~ 1 ms

stability in $\tau$ is 0.1ns

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

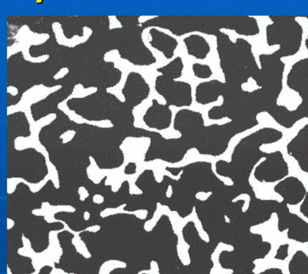
Mass sensitivity ~$10^{-7}$g



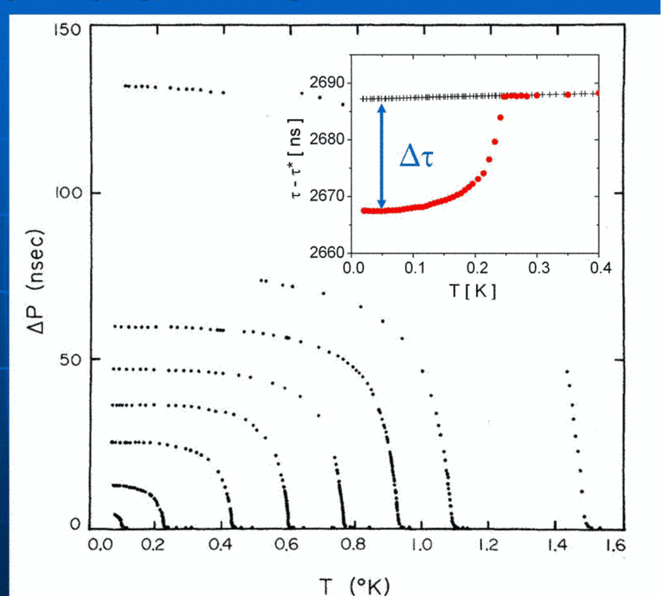

$Q = f_0/\Delta f \sim 2\times10^6$

## Torsional oscillator studies of superfluid films

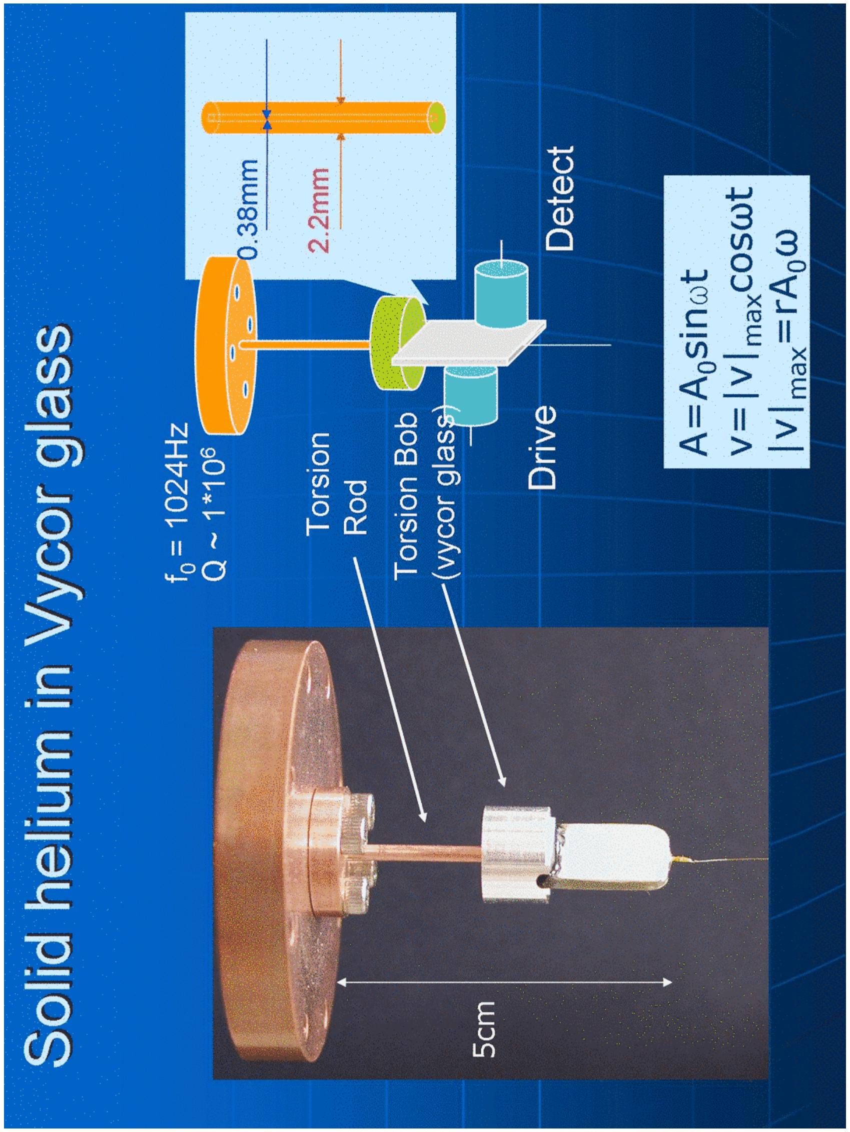
Vycor

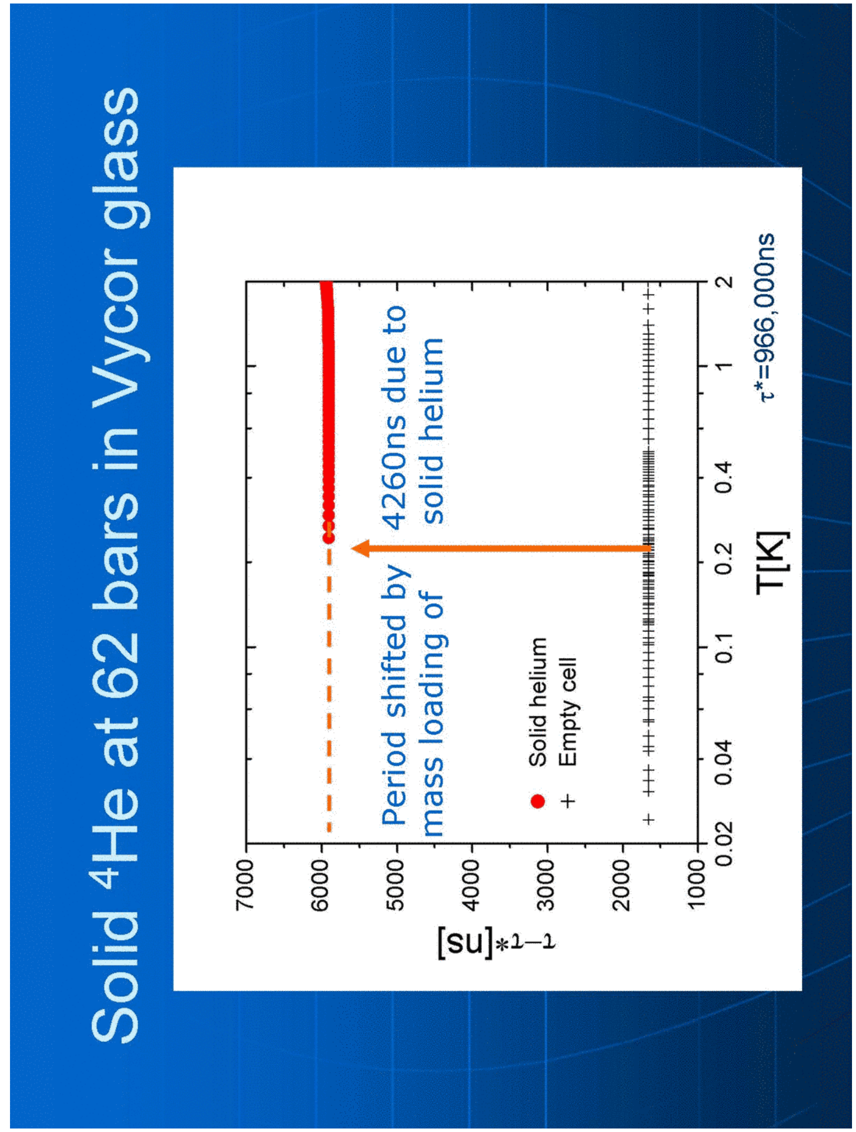


Above Tc the adsorbed normal liquid film behaves as solid and oscillates with the cell, since the viscous penetration depth at 1kHz is about 3 μm.

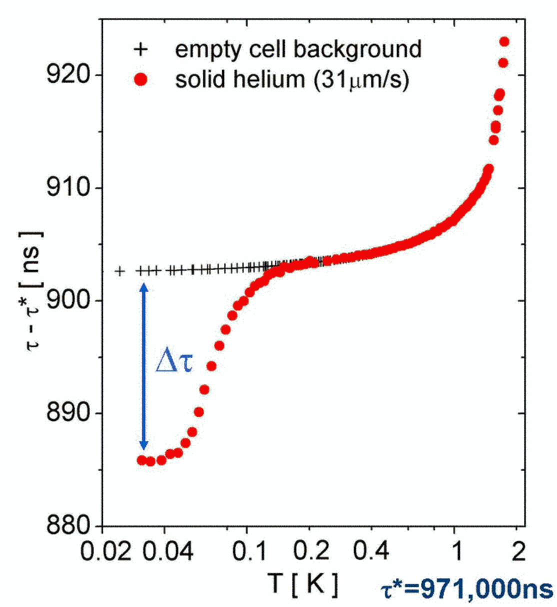



Berthold, Bishop, Reppy, *PRL* **39**, 348(1977)

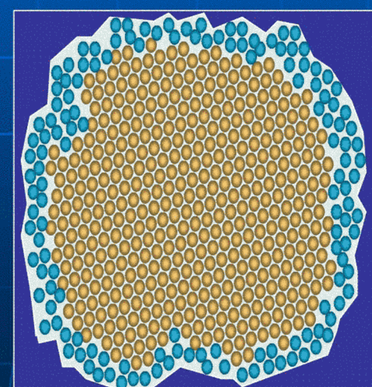

Solid helium in Vycor glass
f0 = 1024Hz
Q ~ 1*10^6
Torsion Rod
Torsion Bob
(vycor glass)
0.38mm
2.2mm
Detect
Drive
A=A0sinωt
v=|v|maxcosωt
|v|max=rA0ω
5cm


Solid 4He at 62 bars in Vycor glass
τ-τ*[ns]
7000
6000
5000
4000
3000
2000
1000
0.02
0.04
0.1
0.2
0.4
1
2
T[K]
Period shifted by
mass loading of
4260ns due to
solid helium
Solid helium
Empty cell
τ*=966,000ns

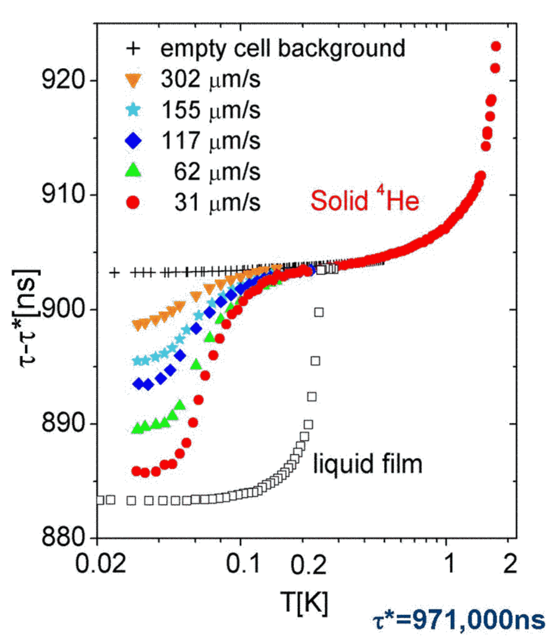
## Supersolid response of helium in vycor glass




- Period drops at 175mK → appearance of NCRI
- size of period drop $-\Delta\tau \sim 17$ns



## Superfluid response




Total mass loading =4260ns

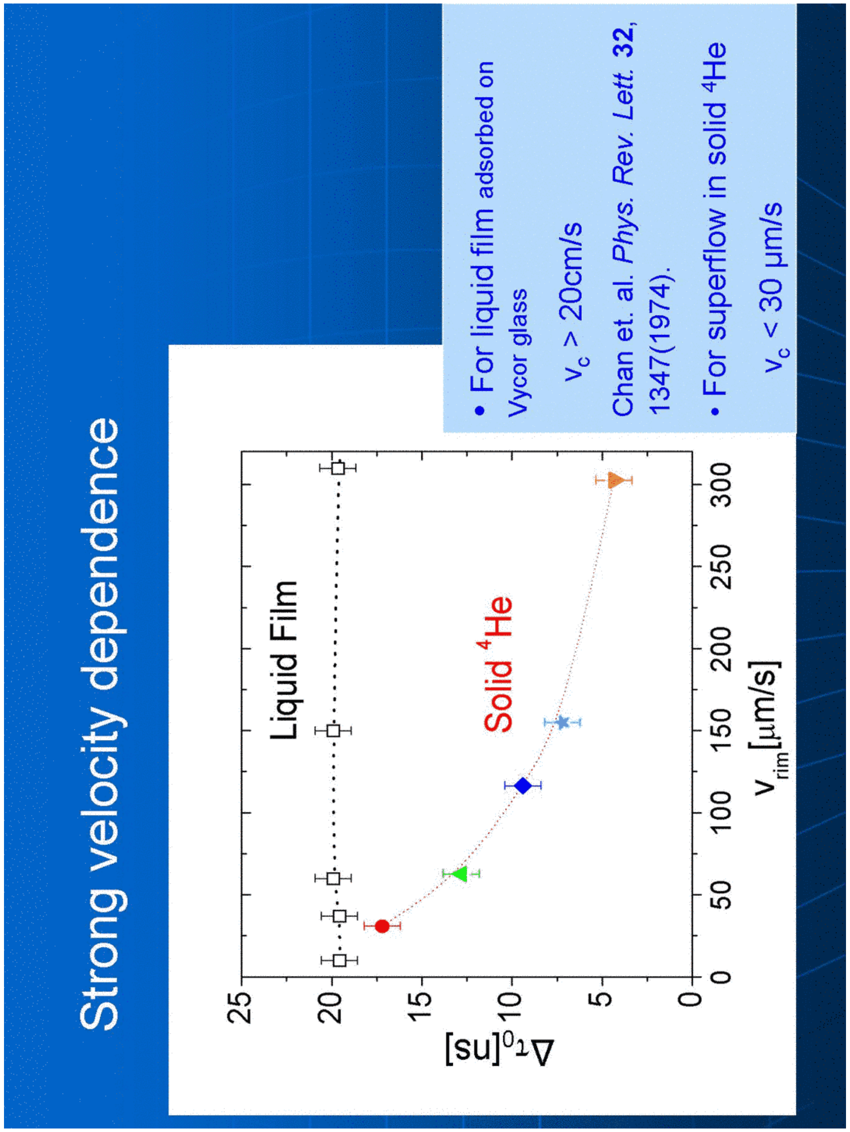
Measured decoupling

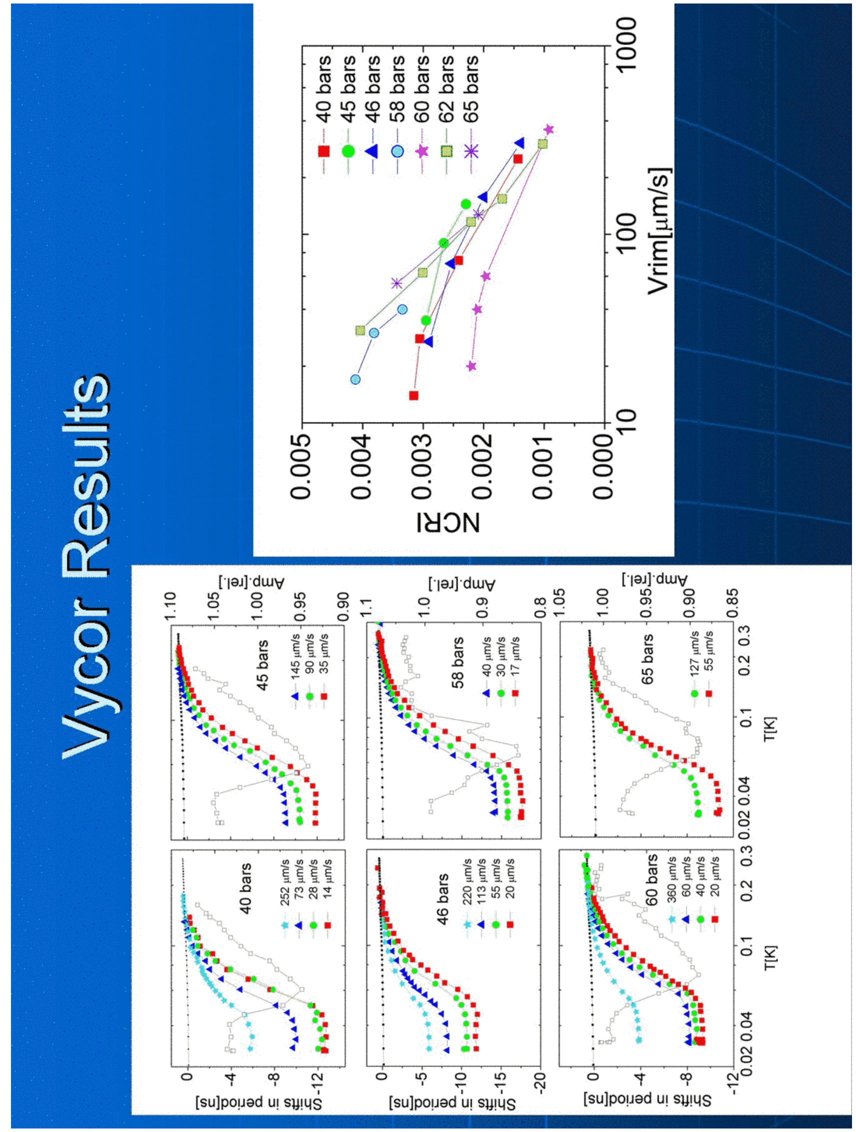
$-\Delta\tau_o$=17ns

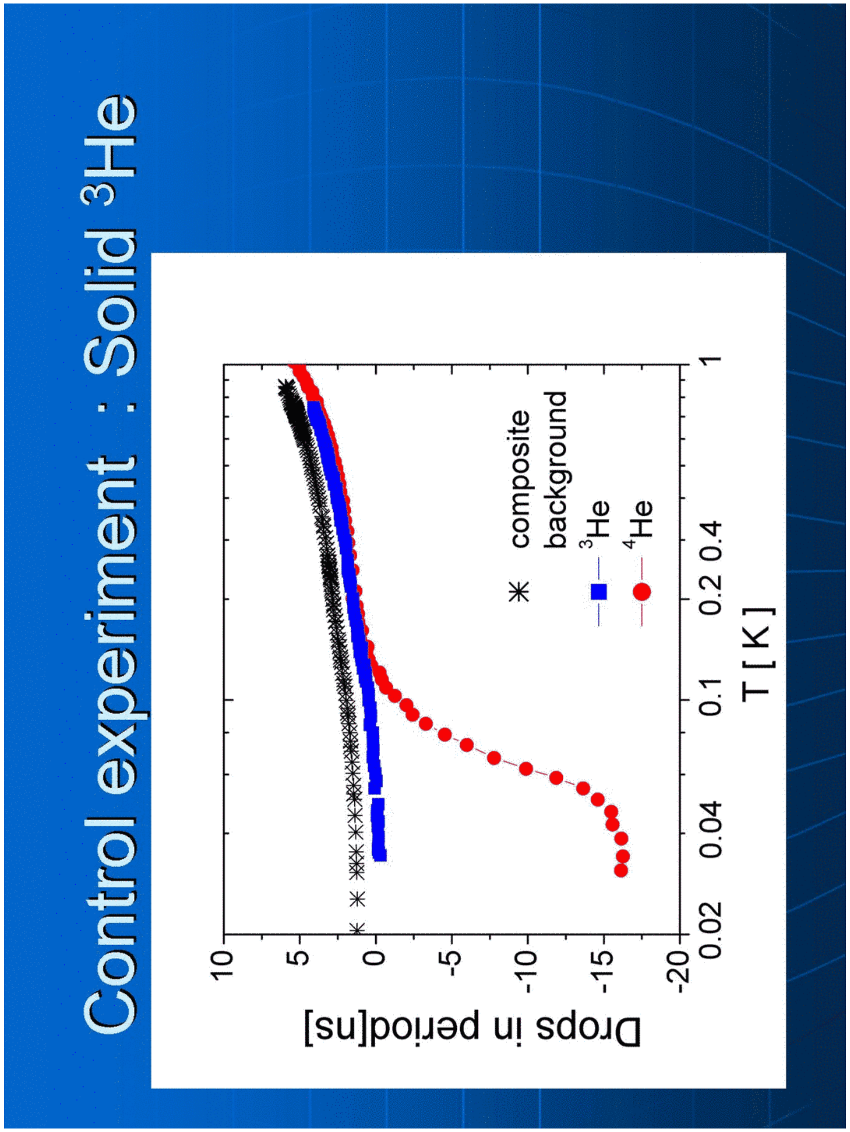
" Apparent supersolid fraction"= 0.4%

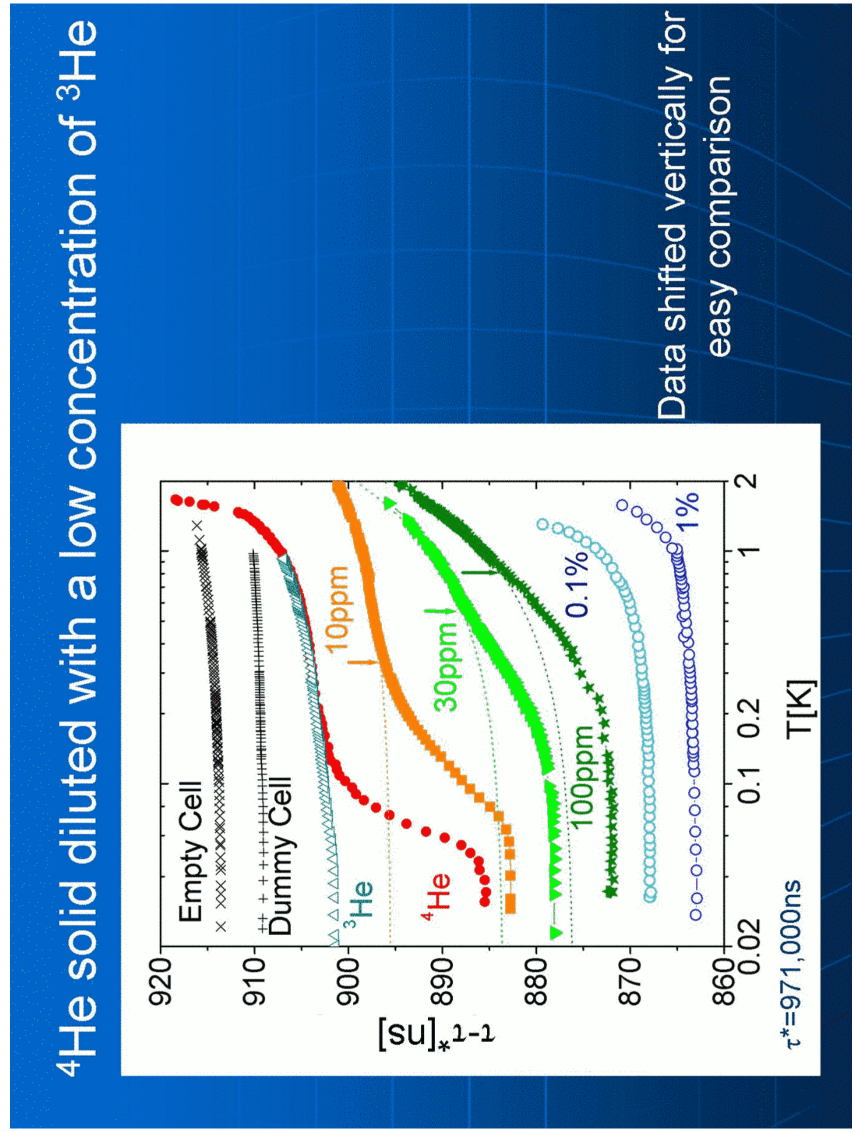
(with tortuosity correction $\rho_s/\rho$ =2%

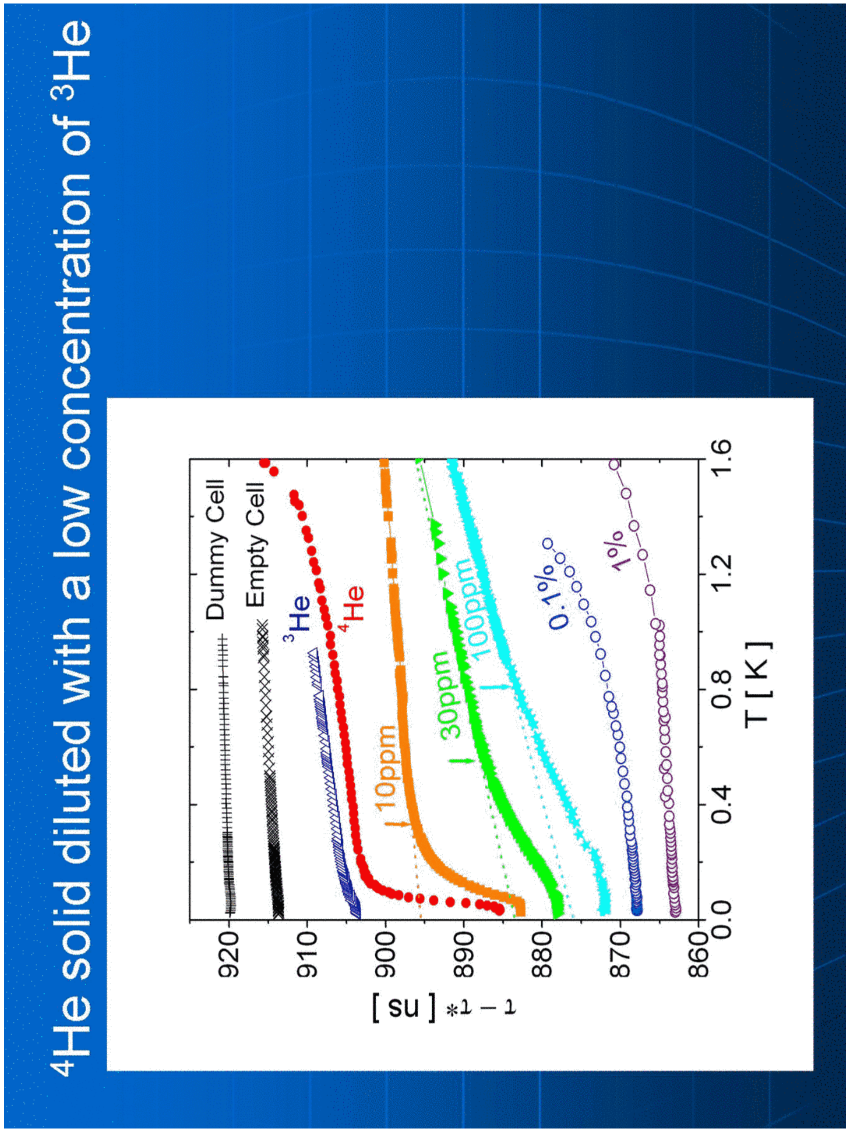
Weak pressure dependence

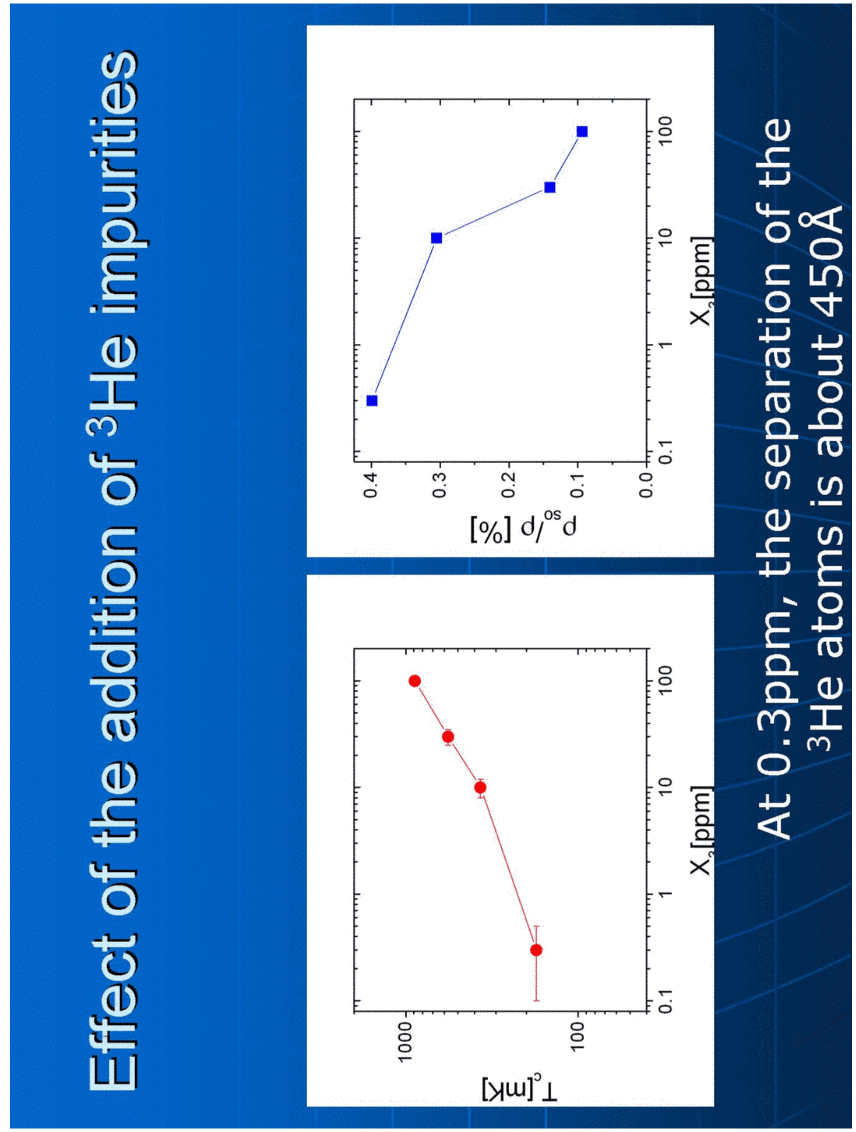

Strong velocity dependence
Liquid Film
Solid 4He
Δτ0[ns]
vrim[µm/s]
• For liquid film adsorbed on Vycor glass
vc > 20cm/s
Chan et. al. Phys. Rev. Lett. 32, 1347(1974).
• For superflow in solid 4He
vc < 30 µm/s


Vycor Results
NCRI
Vrim[µm/s]
40 bars
45 bars
46 bars
58 bars
60 bars
62 bars
65 bars
Shifts in period[ns]
Amp.[rel.]
T[K]

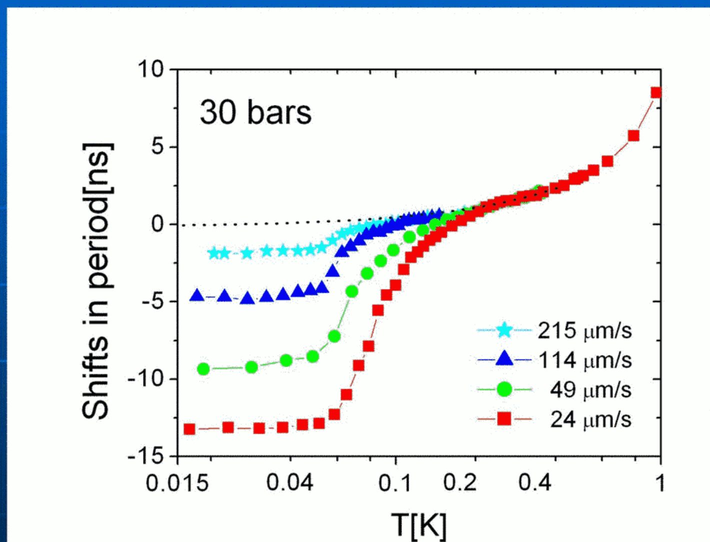

Control experiment : Solid 3He
Drops in period[ns]
T [ K ]
composite background
3He
4He
10
5
0
-5
-10
-15
-20
0.02
0.04
0.1
0.2 0.4
1

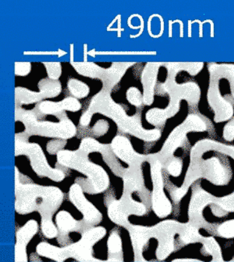

4He solid diluted with a low concentration of 3He
Data shifted vertically for easy comparison
τ-τ*[ns]
T[K]
Empty Cell
Dummy Cell
3He
4He
10ppm
30ppm
100ppm
0.1%
1%
τ*=971,000ns
920
910
900
890
880
870
860
0.02
0.1
0.2
1
2


4He solid diluted with a low concentration of 3He
τ − τ* [ ns ]
T [ K ]
Dummy Cell
Empty Cell
3He
4He
10ppm
30ppm
100ppm
0.1%
1%


Effect of the addition of 3He impurities
Tc[mK]
X3[ppm]
ρso/ρ [%]
At 0.3ppm, the separation of the
3He atoms is about 450Å

## Solid helium in porous gold



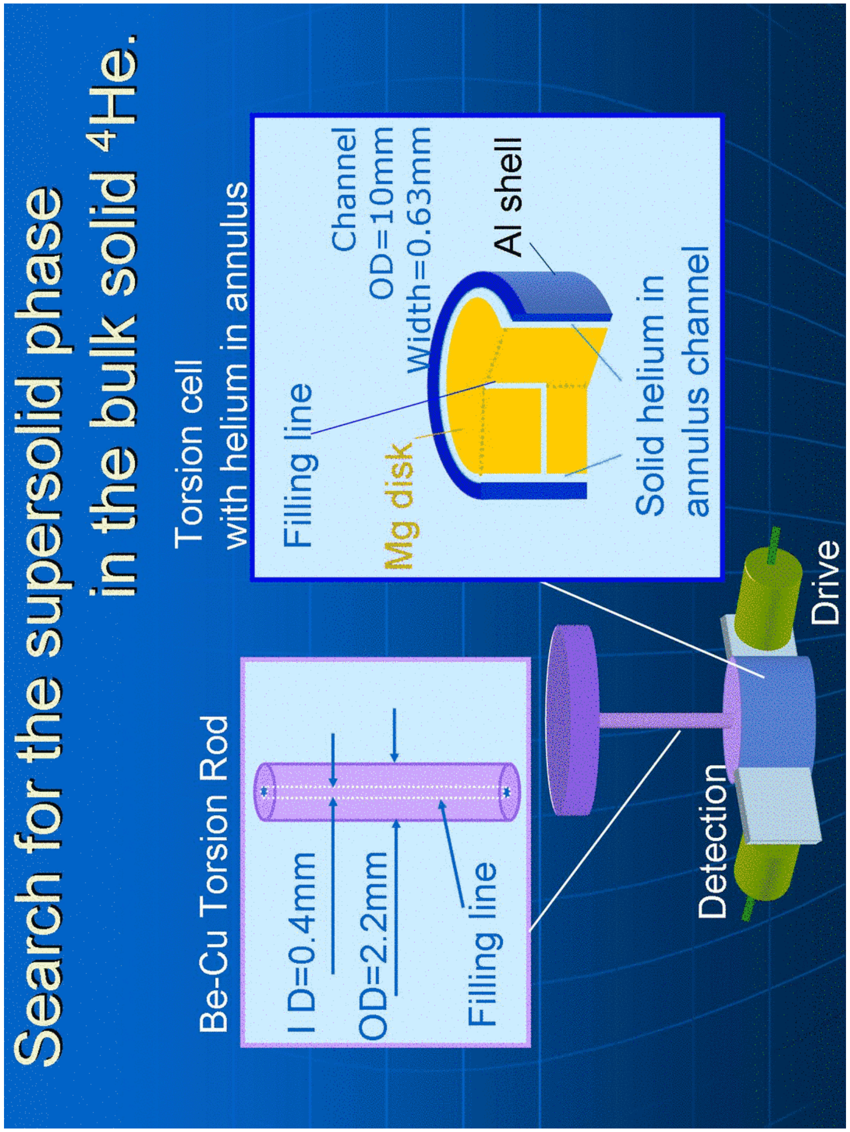

Porous Gold

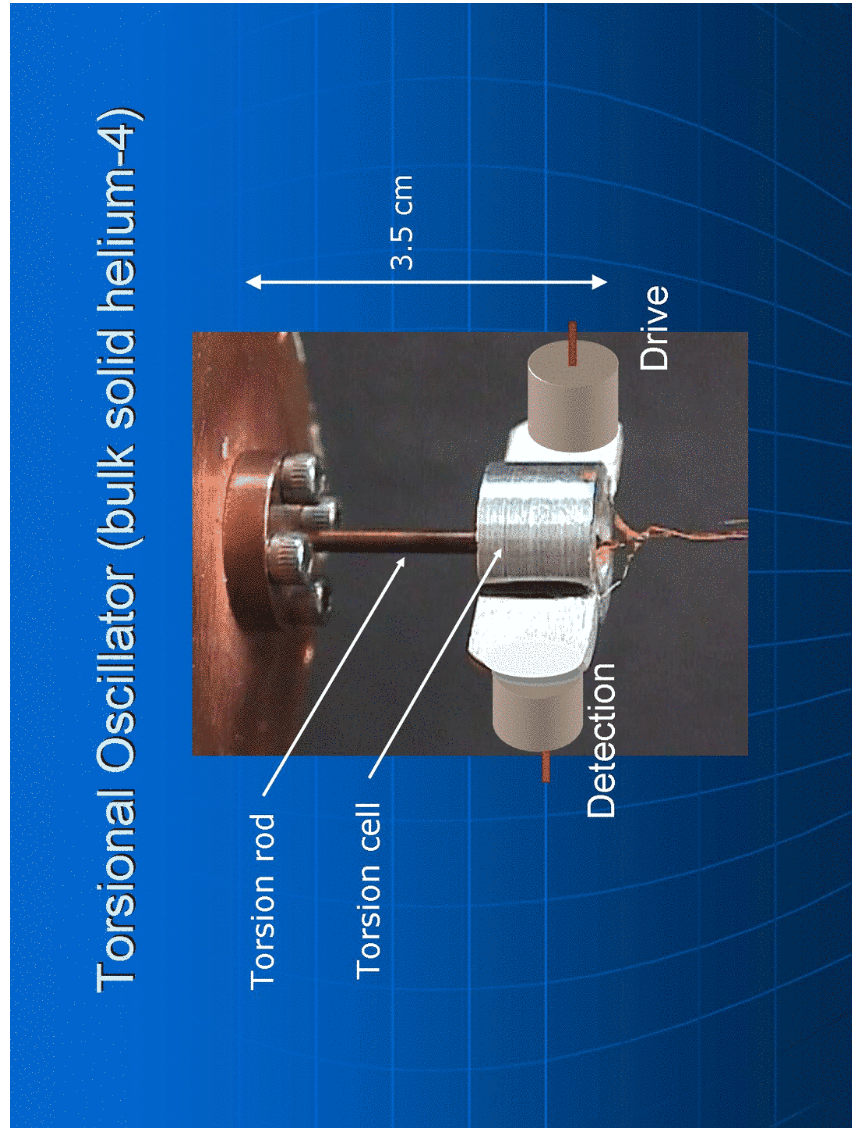
$f_0$=359Hz

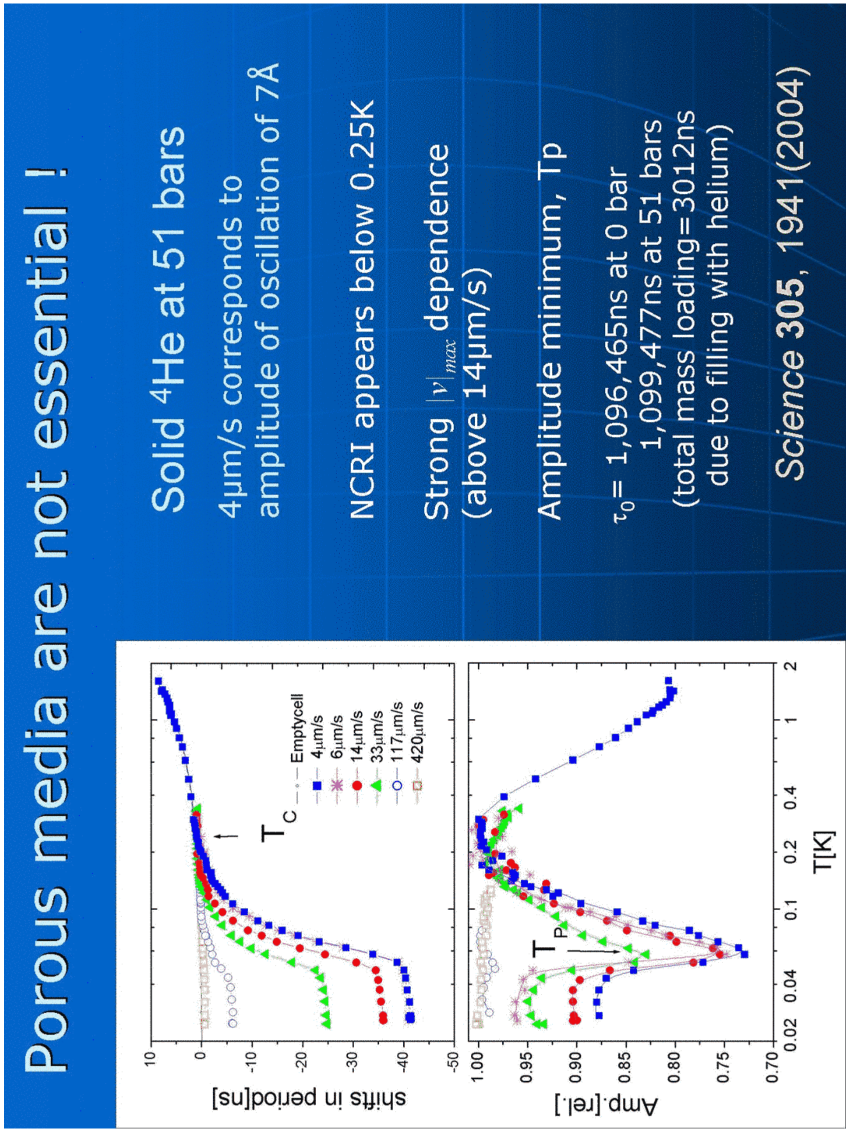
*J. Low Temp. Phys.* **138**, 859(2005)

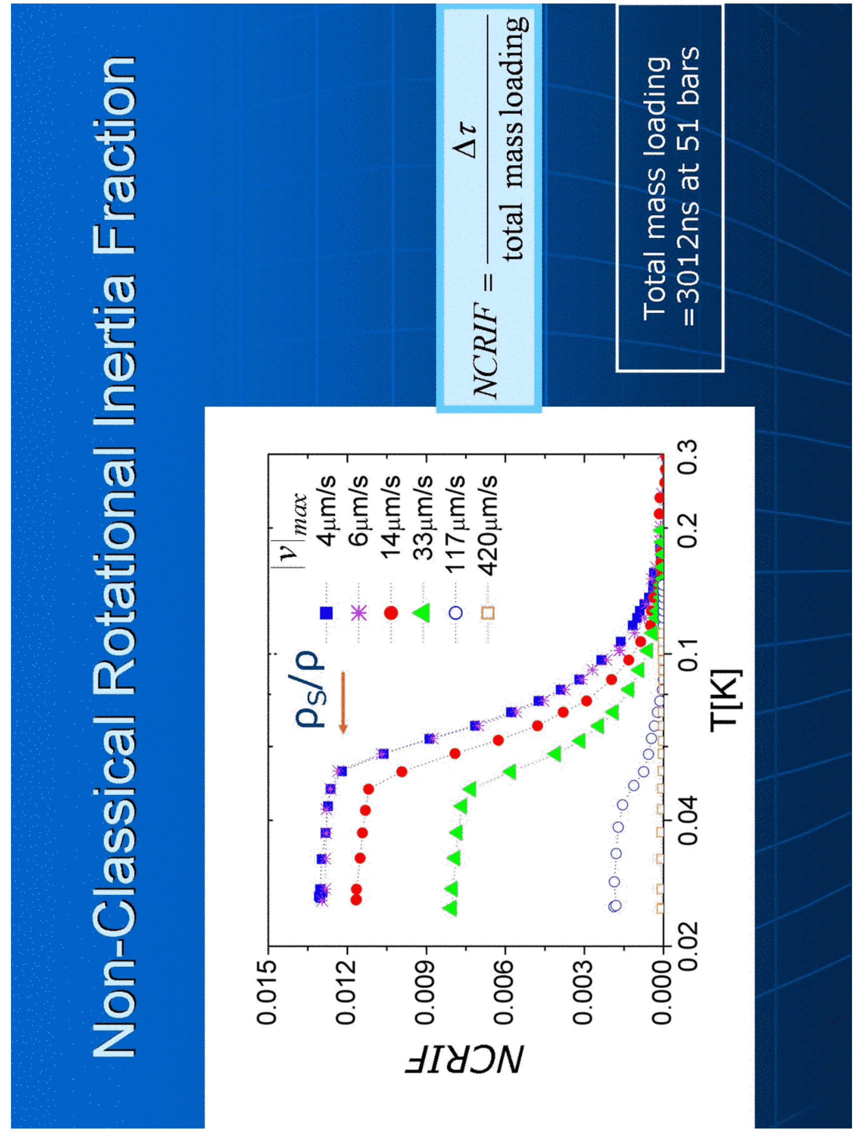
## Is a porous matrix crucial for the appearance of the supersolid phase?

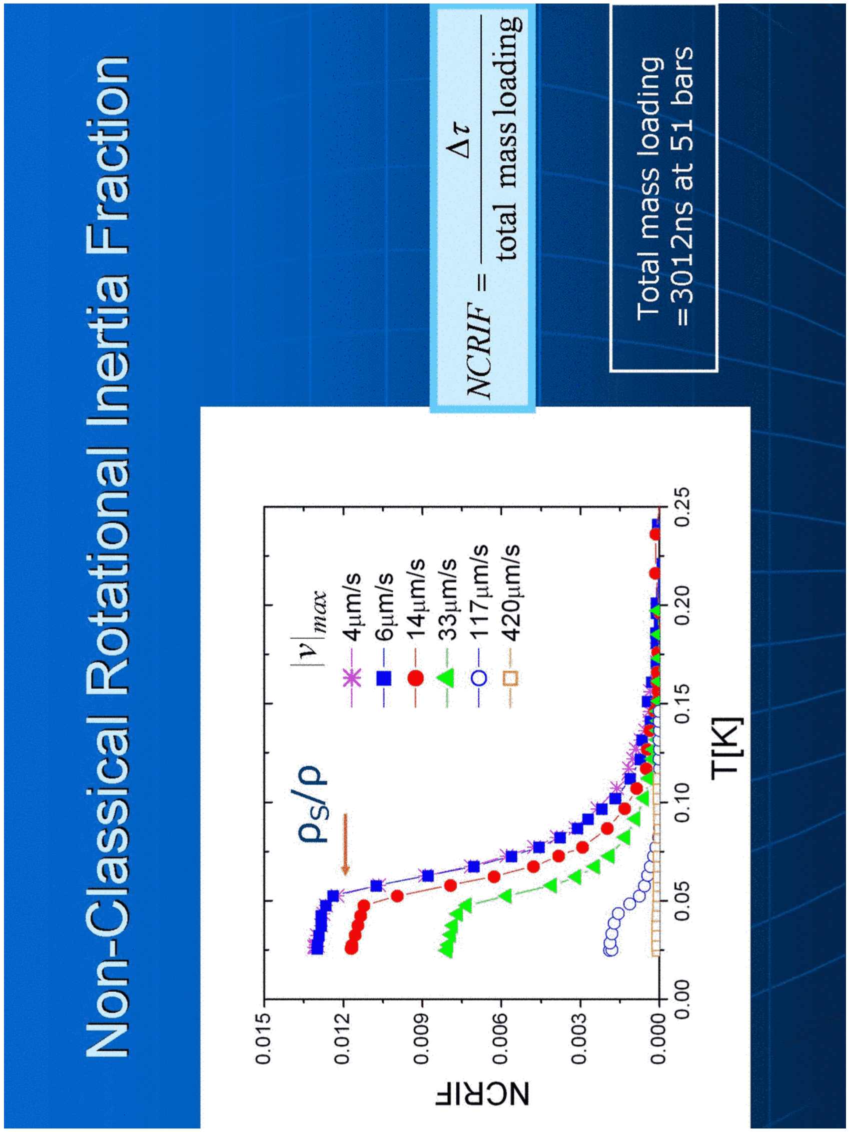
| | Porous gold | Vycor glass |
|---|---|---|
| Pore diameter | 490nm | 7nm |
| A/V | $9m^2/cc$ | $500m^2/cc$ |
| $T_C$ | ~0.2K | ~0.2K |
| $\rho_S/\rho$ (tortuosity) | 0.008 (0.012) | 0.002~0.005 (0.01~0.025) |

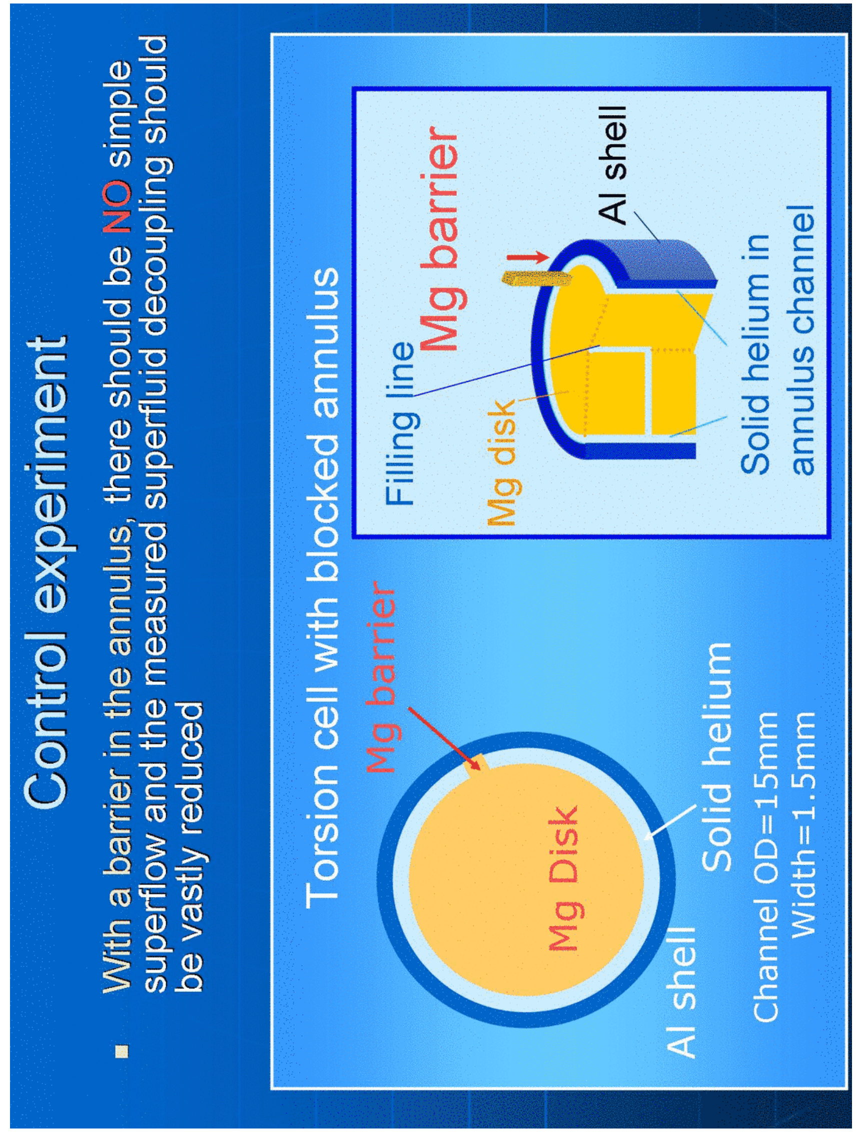

Search for the supersolid phase
in the bulk solid 4He.
Be-Cu Torsion Rod
I D=0.4mm
OD=2.2mm
Filling line
Torsion cell
with helium in annulus
Filling line
Mg disk
Channel
OD=10mm
Width=0.63mm
Al shell
Solid helium in
annulus channel
Detection
Drive

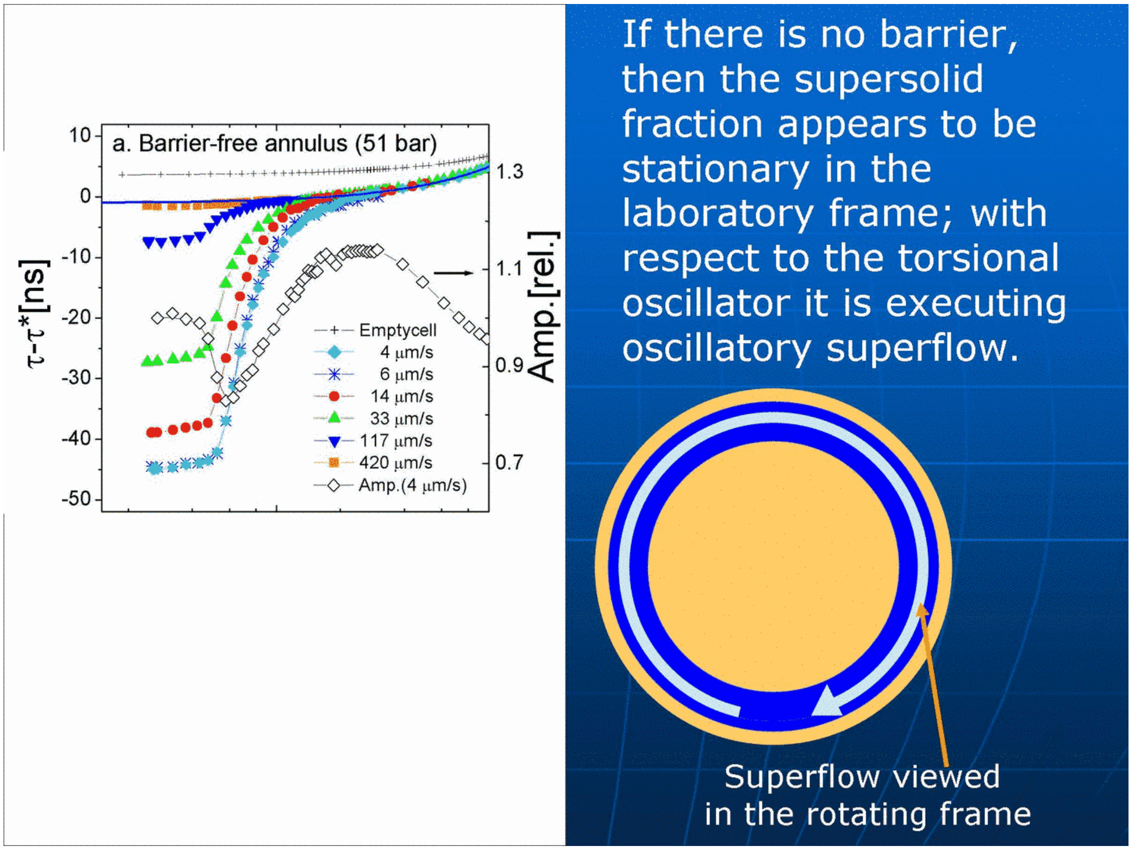

Torsional Oscillator (bulk solid helium-4)
3.5 cm
Drive
Detection
Torsion rod
Torsion cell

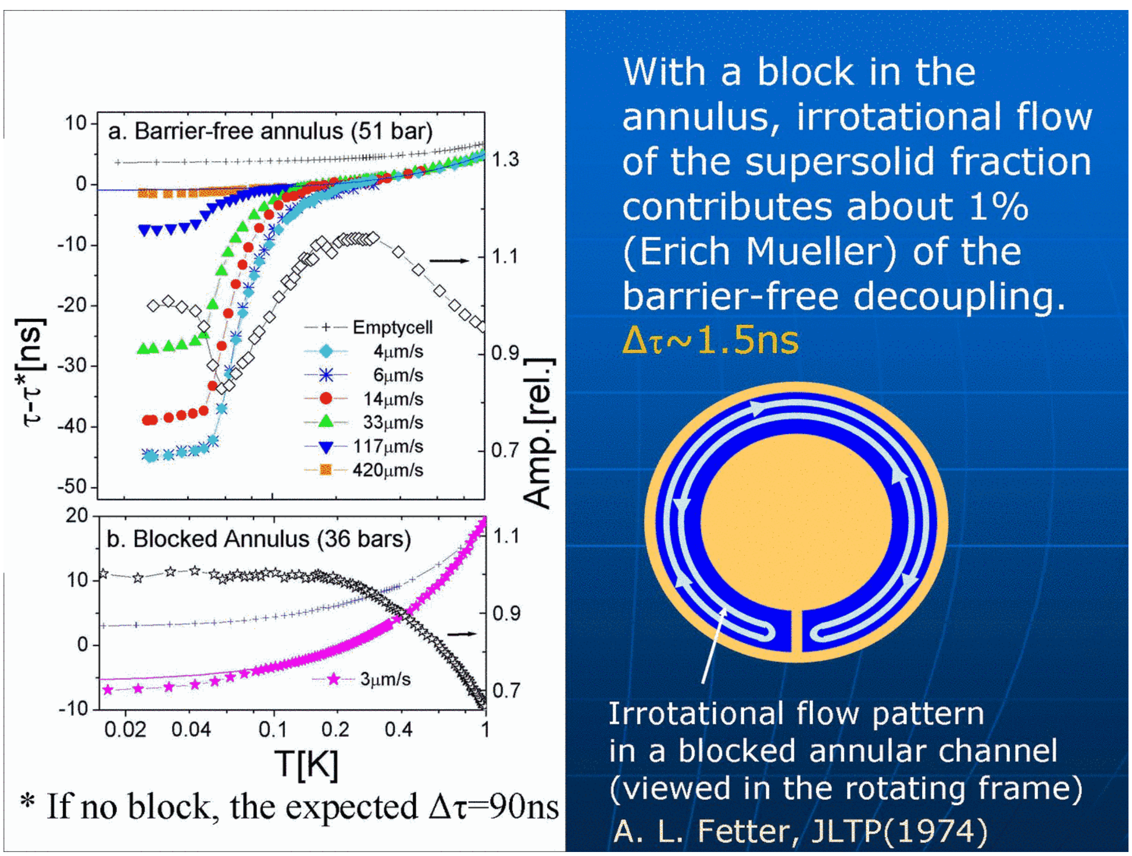

Porous media are not essential !
Solid 4He at 51 bars
4μm/s corresponds to amplitude of oscillation of 7Å
NCRI appears below 0.25K
Strong |v|max dependence (above 14μm/s)
Amplitude minimum, Tp
τ0= 1,096,465ns at 0 bar
1,099,477ns at 51 bars
(total mass loading=3012ns due to filling with helium)
Science 305, 1941(2004)
shifts in period[ns]
Amp.[rel.]
T[K]
TC
TP
Emptycell
4μm/s
6μm/s
14μm/s
33μm/s
117μm/s
420μm/s

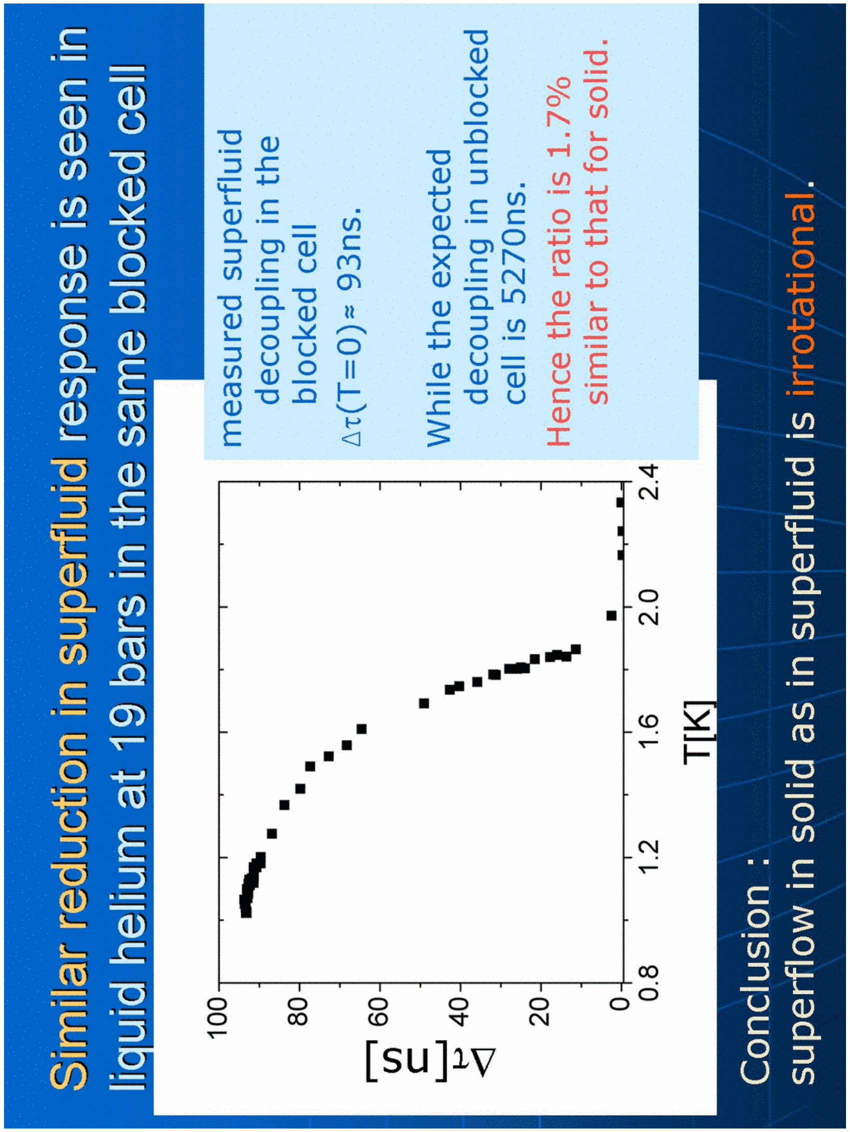

Non-Classical Rotational Inertia Fraction
NCRIF = Δτ / total mass loading
Total mass loading =3012ns at 51 bars
ρs/ρ
NCRIF
T[K]
|v|max
4μm/s
6μm/s
14μm/s
33μm/s
117μm/s
420μm/s

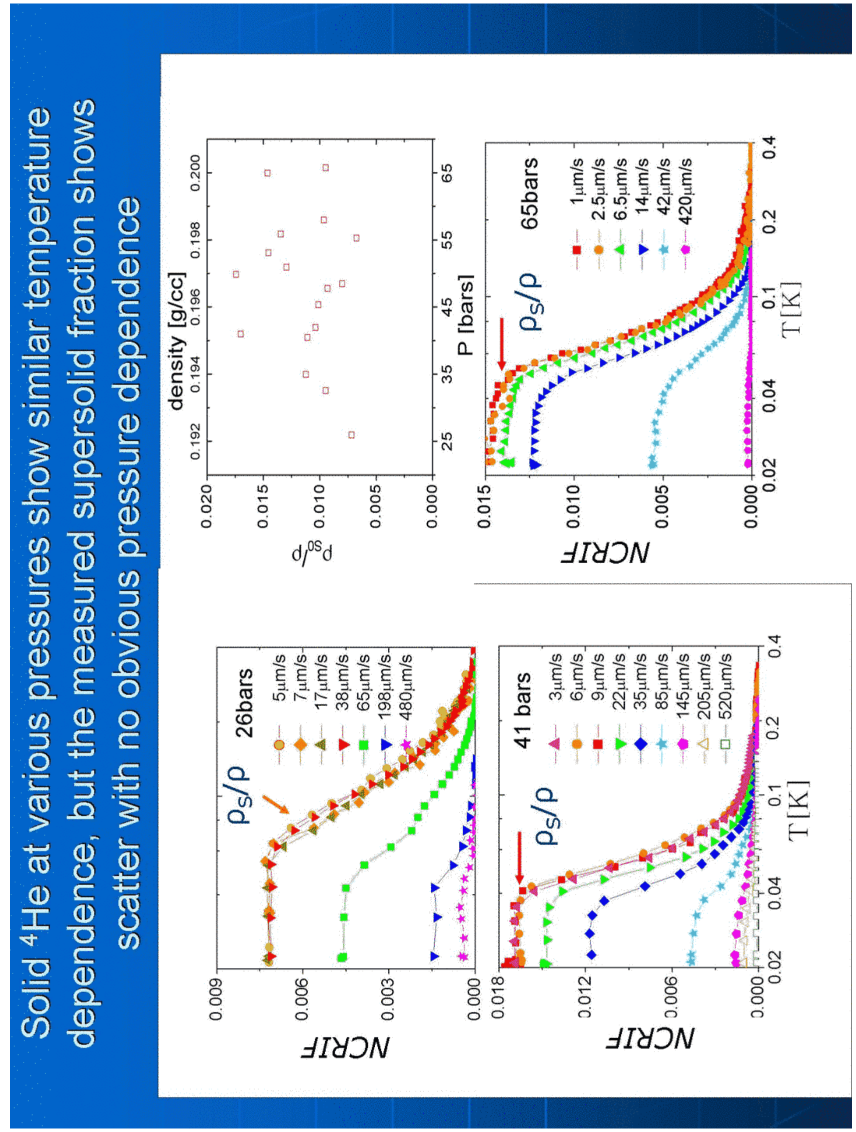

Non-Classical Rotational Inertia Fraction
$NCRIF = \frac{\Delta\tau}{\text{total mass loading}}$
Total mass loading
=3012ns at 51 bars
$\rho_S/\rho$
$|v|_{max}$
4μm/s
6μm/s
14μm/s
33μm/s
117μm/s
420μm/s
NCRIF
0.015
0.012
0.009
0.006
0.003
0.000
0.00
0.05
0.10
0.15
0.20
0.25
T[K]


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
Mg barrier
Mg Disk
Al shell
Solid helium
Channel OD=15mm
Width=1.5mm
Filling line
Mg barrier
Al shell
Mg disk
Solid helium in annulus channel


a. Barrier-free annulus (51 bar)
τ-τ*[ns]
Amp.[rel.]
Emptycell
4 μm/s
6 μm/s
14 μm/s
33 μm/s
117 μm/s
420 μm/s
Amp.(4 μm/s)
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.
Superflow viewed in the rotating frame


a. Barrier-free annulus (51 bar)
b. Blocked Annulus (36 bars)
τ-τ*[ns]
Amp.[rel.]
T[K]
Emptycell
4μm/s
6μm/s
14μm/s
33μm/s
117μm/s
420μm/s
3μm/s
* 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
Δτ(T=0) ≈ 93ns.
While the expected decoupling in unblocked cell is 5270ns.
Hence the ratio is 1.7% similar to that for solid.
Δτ[ns]
T[K]
100
80
60
40
20
0
0.8
1.2
1.6
2.0
2.4
Conclusion :
superflow in solid as in superfluid is irrotational.


Solid 4He at various pressures show similar temperature dependence, but the measured supersolid fraction shows scatter with no obvious pressure dependence
NCRIF
ρs/ρ
26bars
5µm/s
7µm/s
17µm/s
38µm/s
65µm/s
198µm/s
480µm/s
41 bars
3µm/s
6µm/s
9µm/s
22µm/s
35µm/s
85µm/s
145µm/s
205µm/s
520µm/s
65bars
1µm/s
2.5µm/s
6.5µm/s
14µm/s
42µm/s
420µm/s
density [g/cc]
P [bars]
ρs0/ρ
T[K]

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

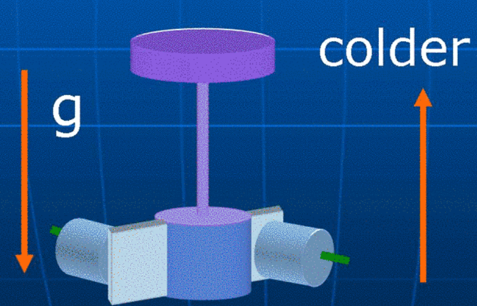
"…helium tends to solidify as a single crystal (or perhaps as a few single crystals) rather than in a polycrystalline form."

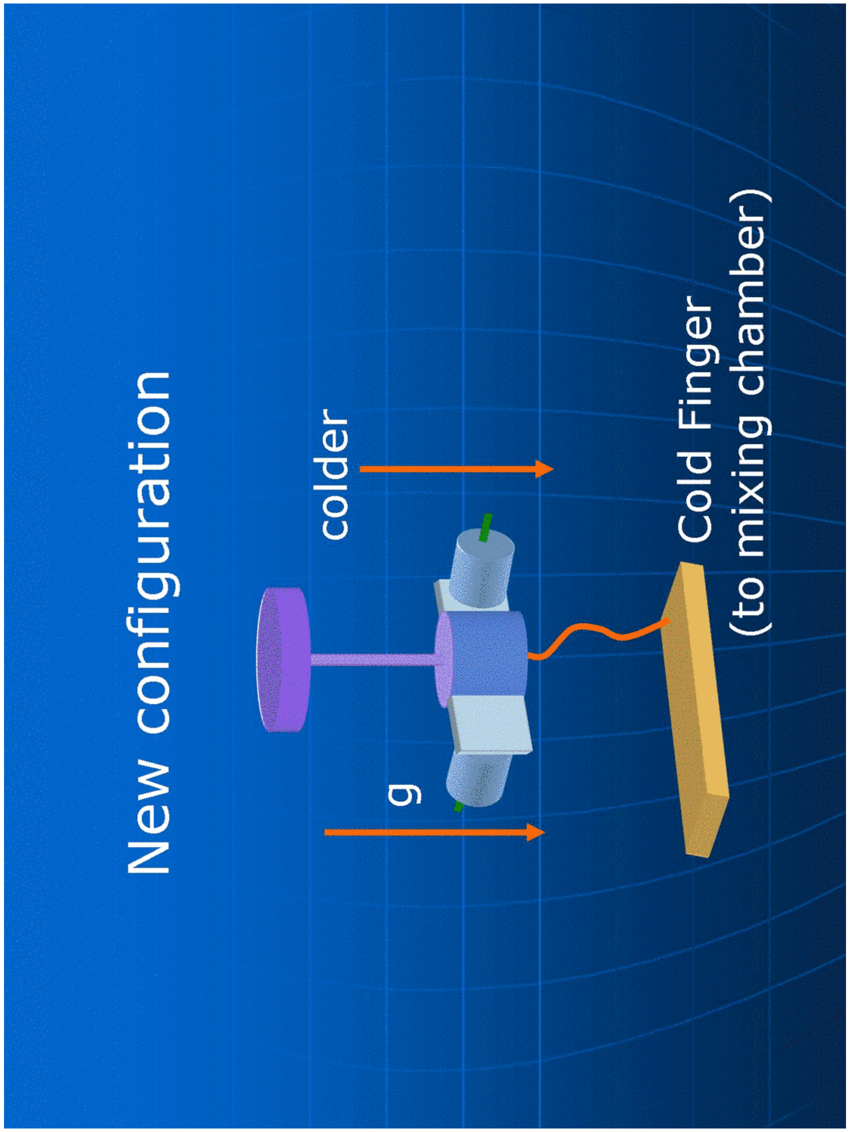
The properties of liquid and solid helium, J. Wilks p584 (Clarendon, London, 1967)

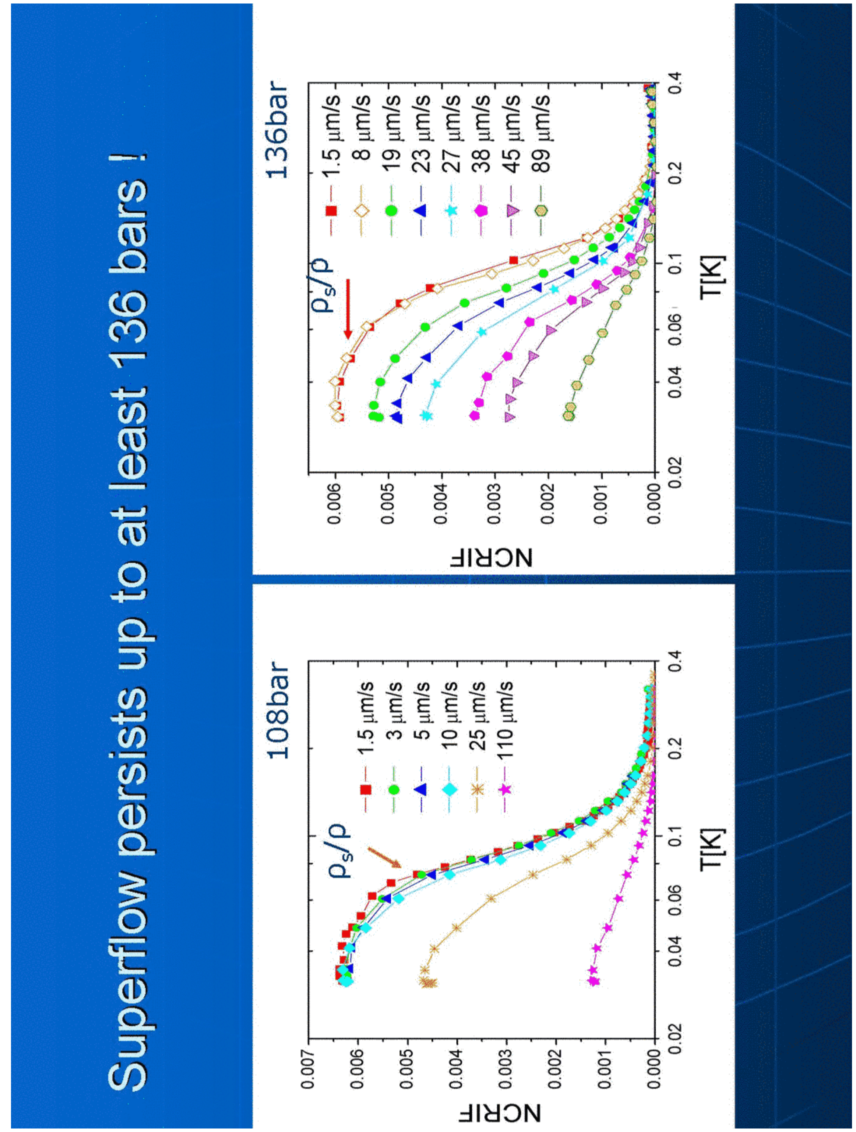
The $^4He$ crystallites inside the 'bulk' torsional cell probably have different orientations with dimensions limited by the channel width of the annulus ~0.63mm or i.d. of torsion rod at 0.4 mm.

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.

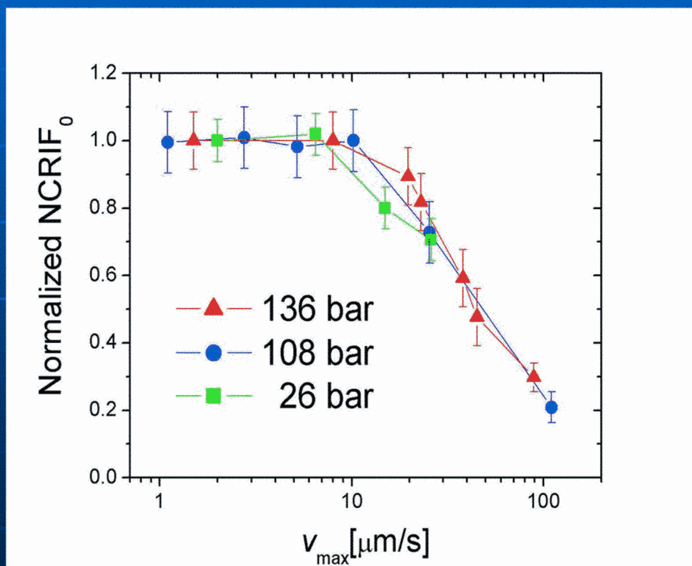
The crystallites were likely nucleated from the torsion rod with dimension of 0.4 mm.

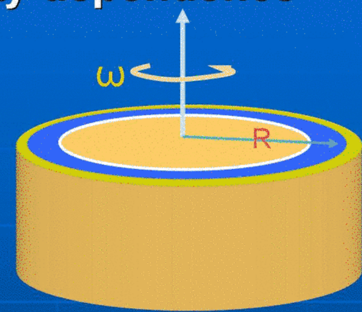



New configuration
colder
g
Cold Finger
(to mixing chamber)


Superflow persists up to at least 136 bars !
108bar
ρs/ρ
1.5 µm/s
3 µm/s
5 µm/s
10 µm/s
25 µm/s
110 µm/s
NCRIF
T[K]
136bar
ρs/ρ
1.5 µm/s
8 µm/s
19 µm/s
23 µm/s
27 µm/s
38 µm/s
45 µm/s
89 µm/s
NCRIF
T[K]

## Strong and 'universal' velocity dependence in all samples



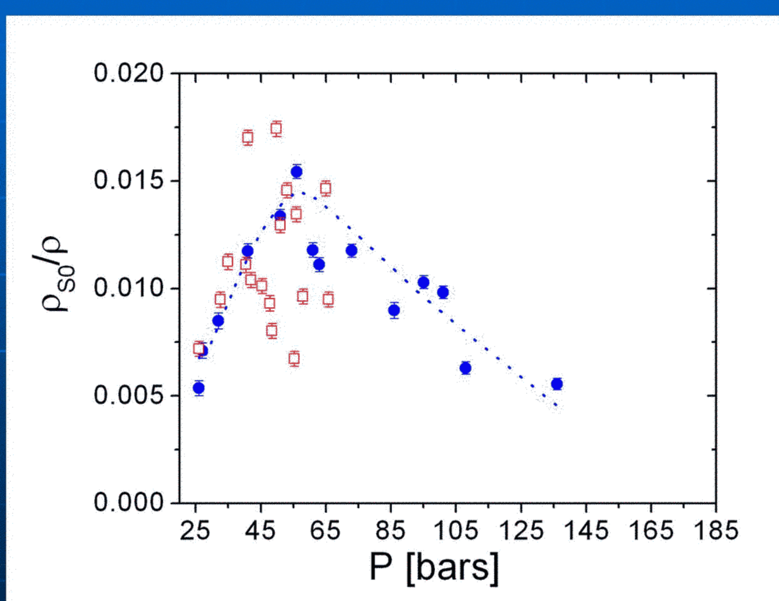

$v_C$~ 10μm/s

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

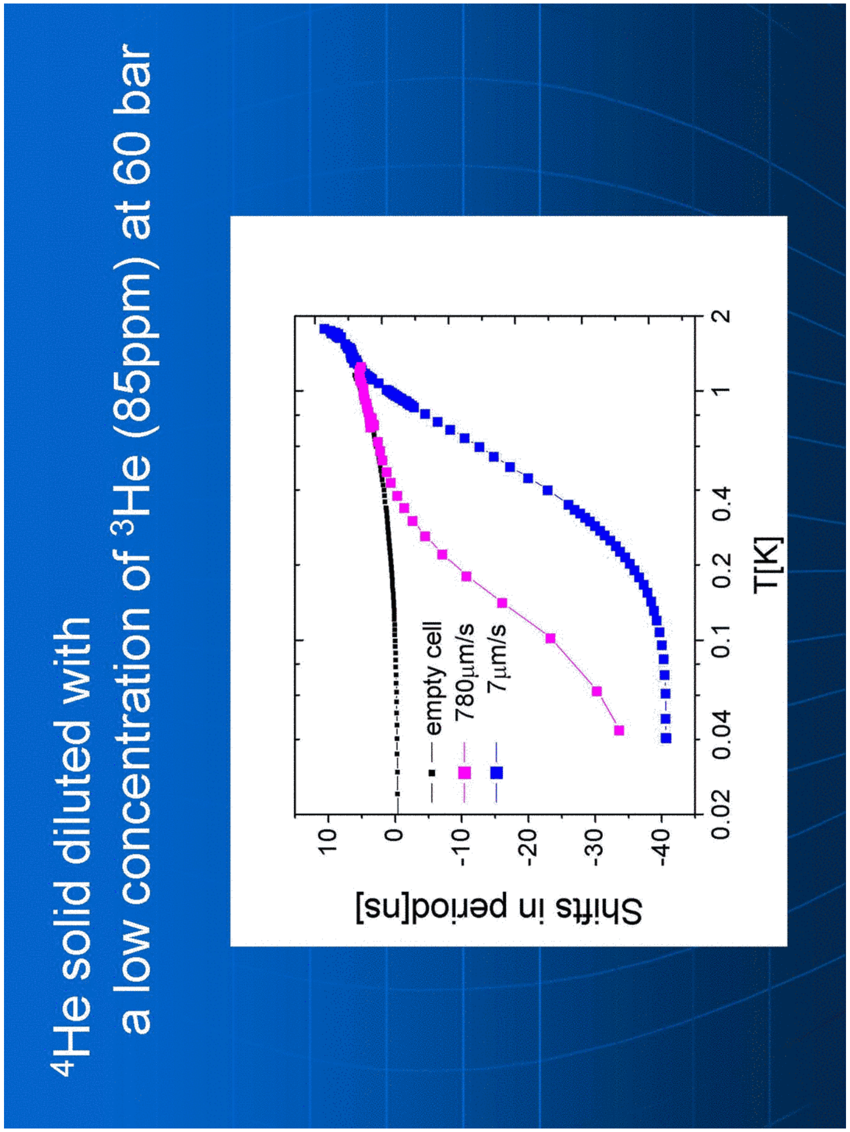
$$v_s = \frac{h}{2\pi R m} \cdot n$$

=3.16μm/s for $n=1$

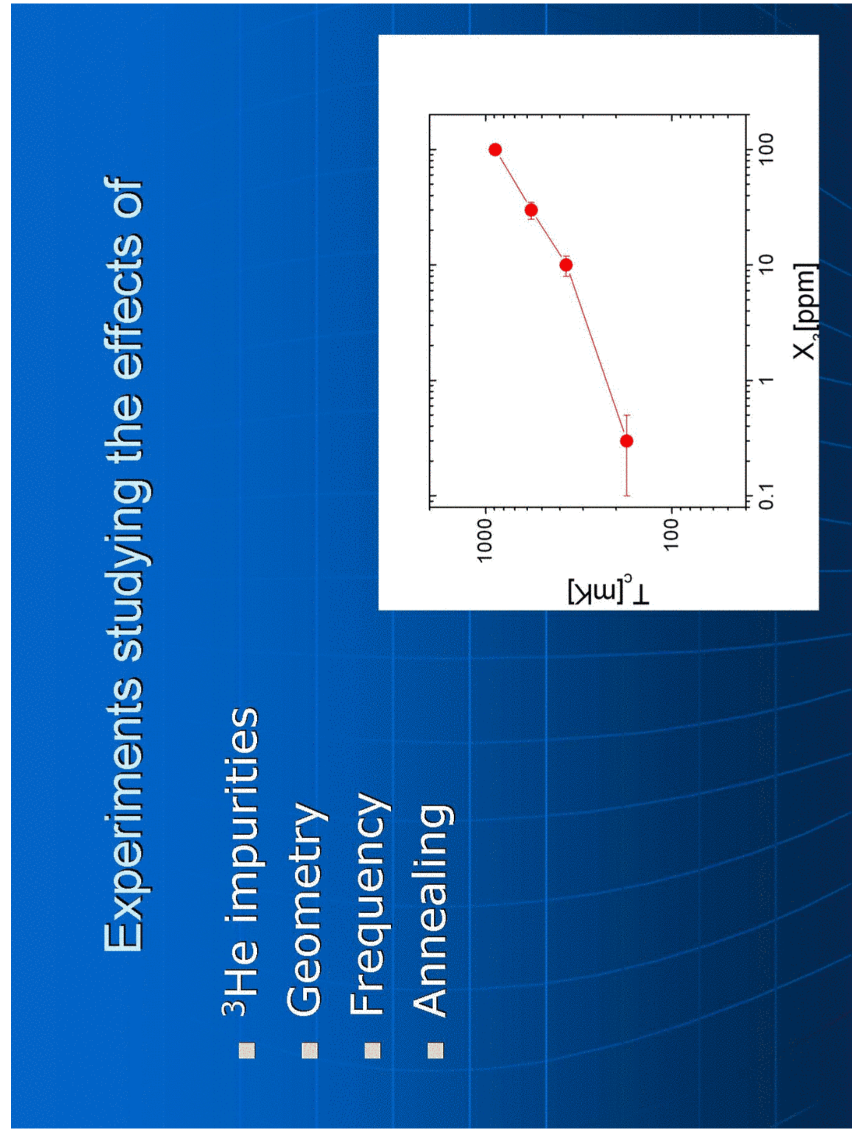
## Pressure dependence of supersolid fraction




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



4He solid diluted with
a low concentration of 3He (85ppm) at 60 bar
Shifts in period[ns]
T[K]
empty cell
780μm/s
7μm/s
10
0
-10
-20
-30
-40
0.02
0.04
0.1
0.2
0.4
1
2

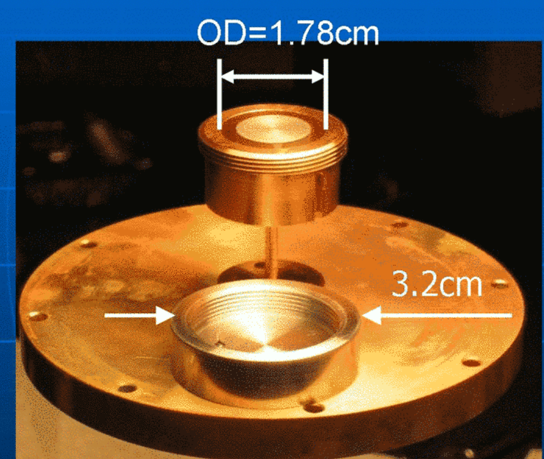



Experiments studying the effects of
3He impurities
Geometry
Frequency
Annealing
Tc[mK]
X3[ppm]
1000
100
0.1
1
10
100

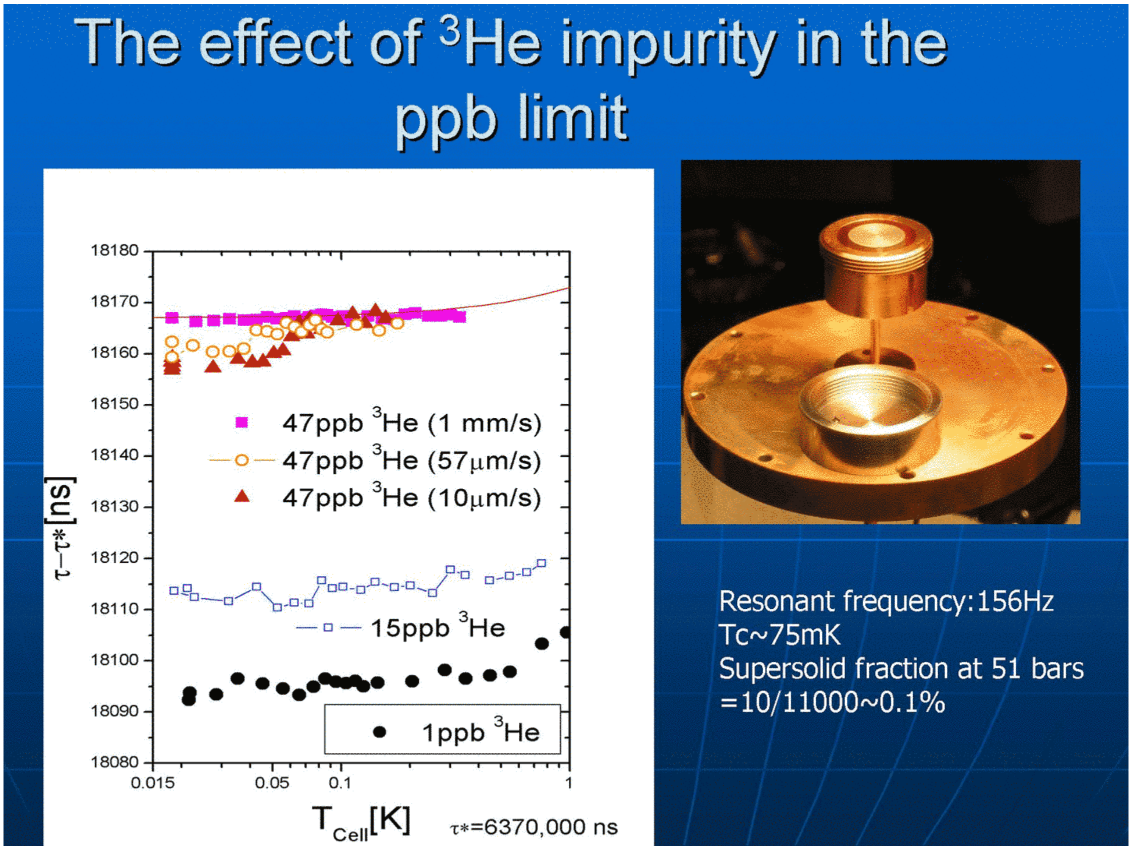
# Bulk TO

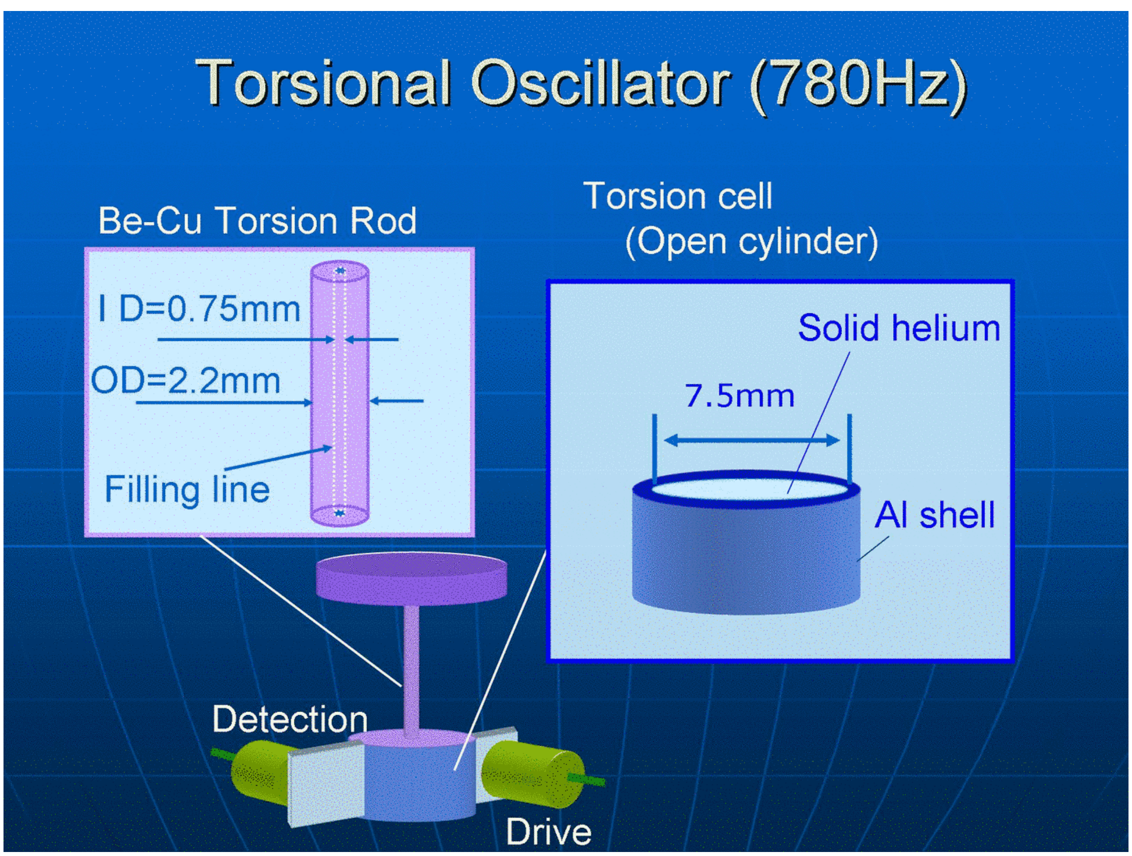
| $f_0$ | Cell Dimension | $h/2\pi rm$ | $\rho s/\rho$ | "$T_c$" |
|---|---|---|---|---|
| 912Hz Annular Channel, 0.3ppm | OD=1cm w=0.63mm | 3.16μm/s | 0.6%-1.5% | ~200mK |
| 156 Hz Annular Channel, 47ppb | OD=1.78cm w=0.5cm | 1.8μm/s | 0.1% | 75mK |
| 780 Hz Open Cylinder, 47ppb | OD=0.75cm | 4.2μm/s | 0.2% | 75mK |

# Low frequency (high pressure) Torsional Oscillator




Resonant frequency =156Hz
$Q\sim5*10^5$
OD=1.78cm
W = 0.5cm


The effect of ³He impurity in the ppb limit
47ppb ³He (1 mm/s)
47ppb ³He (57μm/s)
47ppb ³He (10μm/s)
15ppb ³He
1ppb ³He
τ−τ*[ns]
T_Cell[K]
τ*=6370,000 ns
Resonant frequency:156Hz
Tc~75mK
Supersolid fraction at 51 bars
=10/11000~0.1%

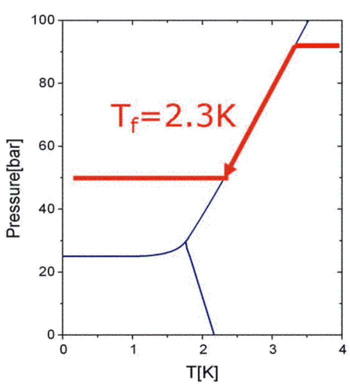

Torsional Oscillator (780Hz)
Be-Cu Torsion Rod
I D=0.75mm
OD=2.2mm
Filling line
Torsion cell
(Open cylinder)
Solid helium
7.5mm
Al shell
Detection
Drive

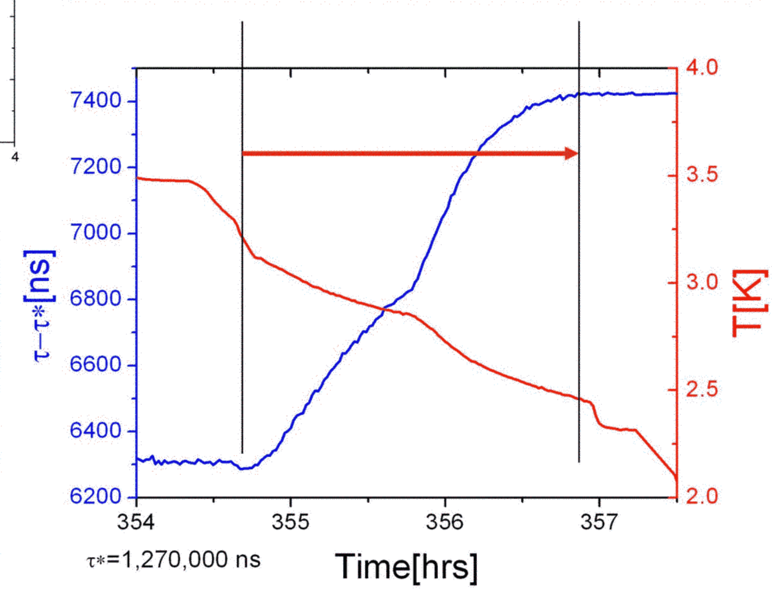
# Open Cylinder TO (780Hz); annealing effects?

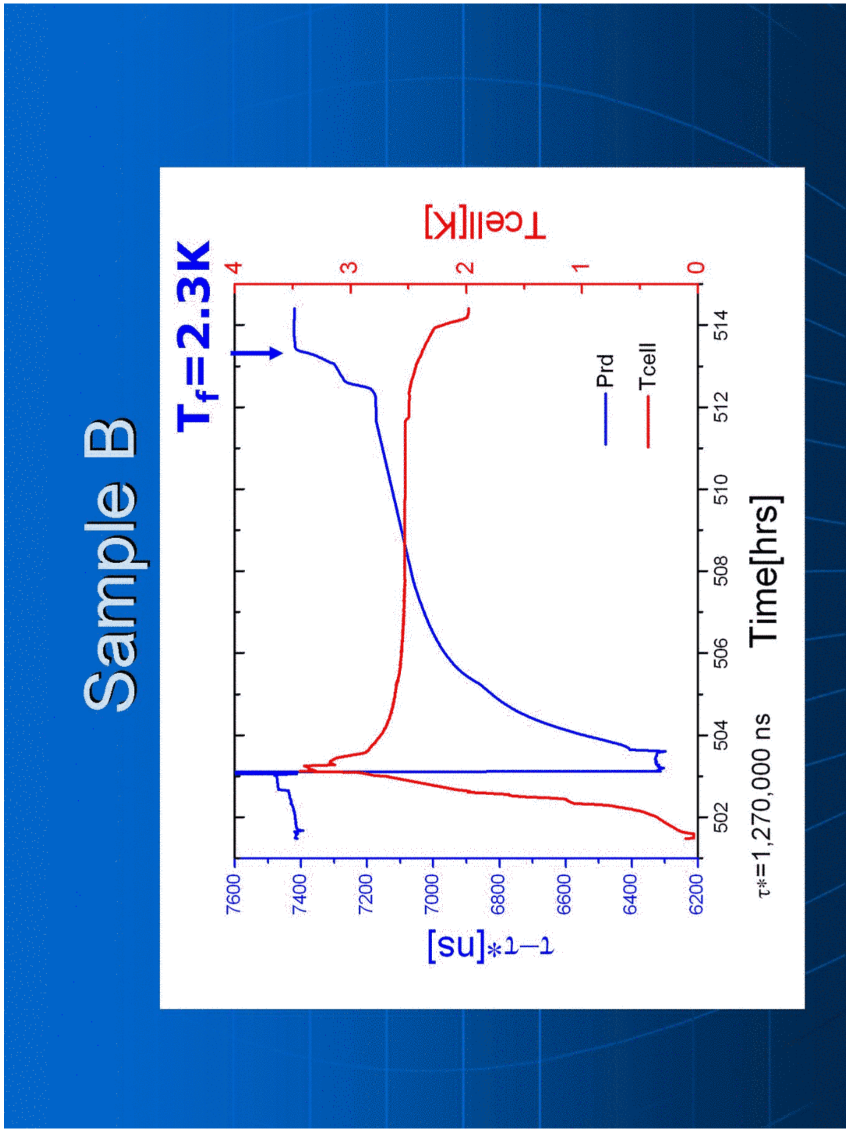
| | Time through melting line | $X_3$ | $\rho_s/\rho$ | $T_c$ |
|---|---|---|---|---|
| Sample A | 2.3hrs | 47ppb | 2ns/1130ns =0.18% | 75mK |
| Sample B | 9hrs | 47ppb | 2.9ns/1130ns =0.25% | 75mK |
| Sample C | 20 hrs at less than 40mK below Tm + cooling with 40mK/hr to 1.6K | 47ppb | 2.2ns/1130ns =0.19% | 100mK |

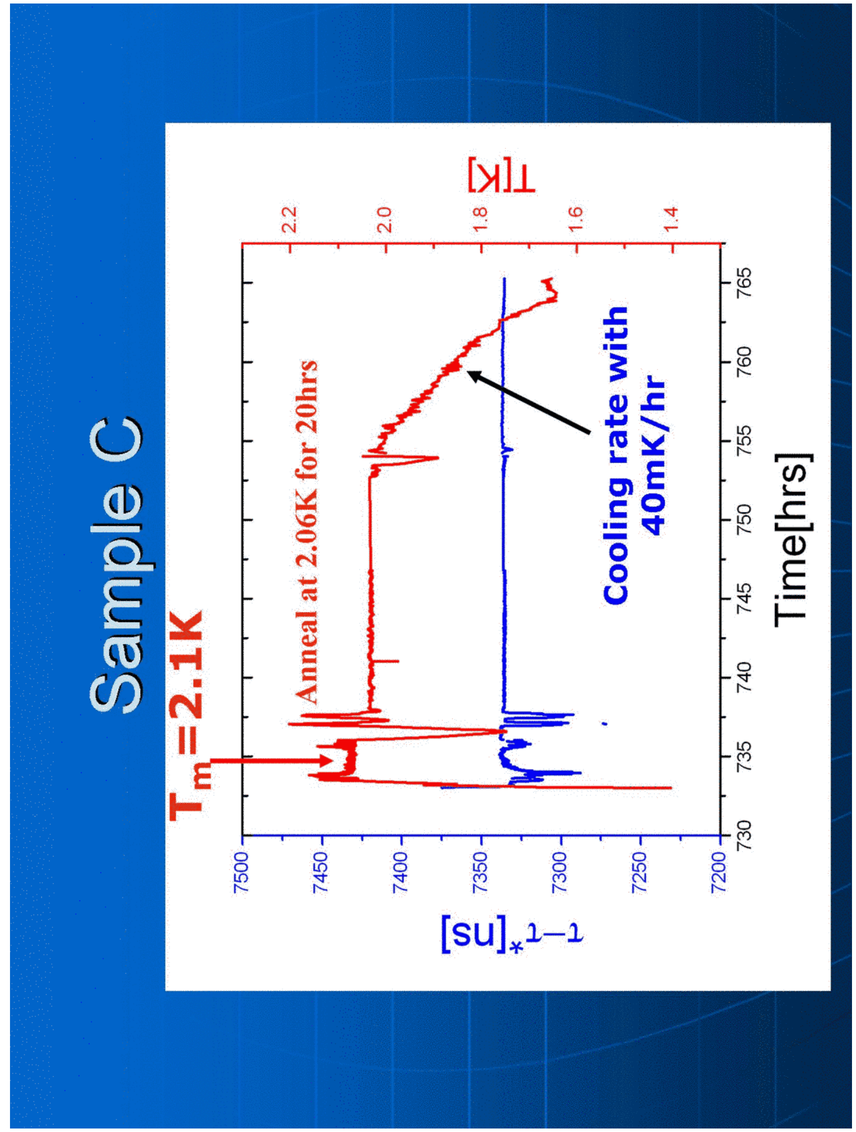
# Sample A

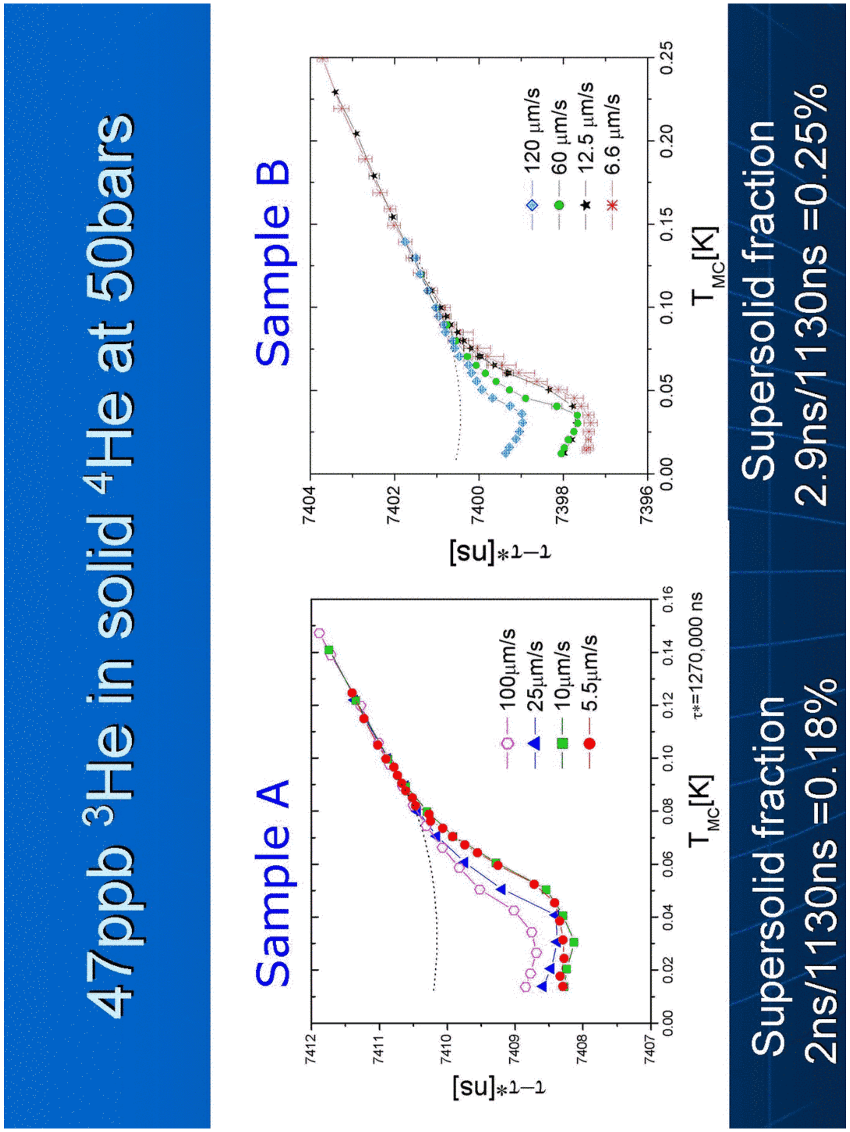
Growing solid helium for 2.3hrs

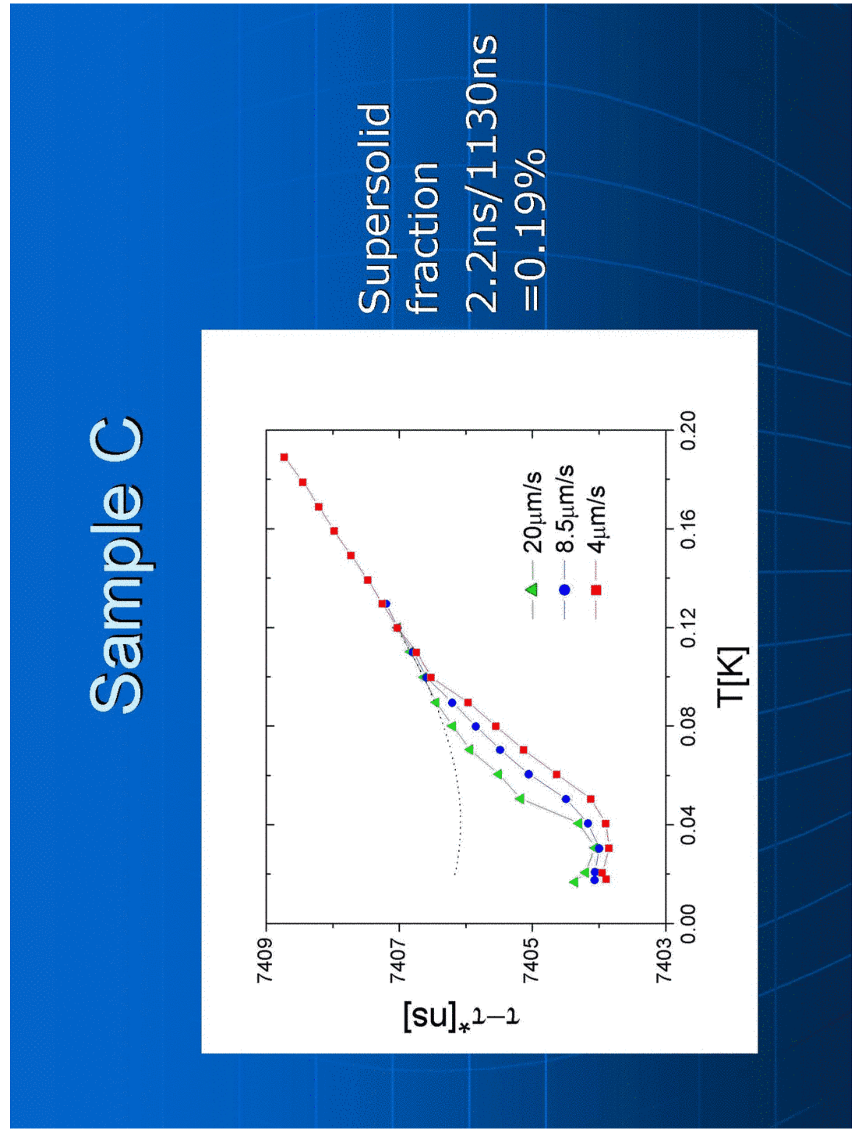


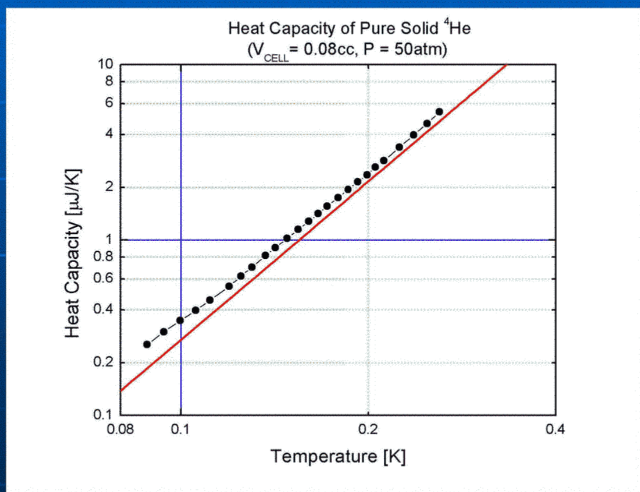

Sample B
Tf=2.3K
Tcell[K]
Prd
Tcell
Time[hrs]
τ*=1,270,000 ns
τ−τ*[ns]

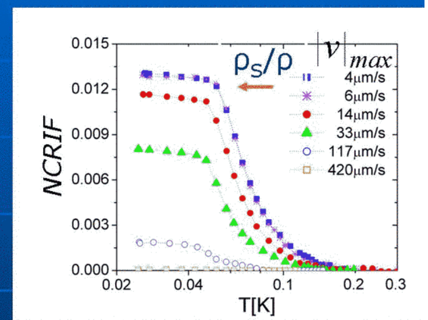

Sample C
Tm=2.1K
Anneal at 2.06K for 20hrs
Cooling rate with 40mK/hr
T[K]
Time[hrs]
τ−τ*[ns]


47ppb 3He in solid 4He at 50bars
Sample A
Sample B
100μm/s
25μm/s
10μm/s
5.5μm/s
120 μm/s
60 μm/s
12.5 μm/s
6.6 μm/s
T_MC[K]
τ*=1270,000 ns
Supersolid fraction
2ns/1130ns =0.18%
Supersolid fraction
2.9ns/1130ns =0.25%


Sample C
Supersolid
fraction
2.2ns/1130ns
=0.19%
20μm/s
8.5μm/s
4μm/s
T[K]

## Direct heat capacity measurements have not seen any peak or deviation from the Debye $T^3$ behavior




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

## Summary and questions:

- "Transition" to supersolid state is found near 200 mK for solid helium is found 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 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

- When the He-3 concentration is increased from 0.3ppm, 'Tc' appears to increase and the supersolid fraction decreases for both the Vycor and the bulk experiment.
- However, when the He-3 concentration is greatly reduced, both Tc and supersolid density drops. 'Tc' is 75 mK ( same shape!) for 47 ppb He-3.The supersolid phase for 1ppb and 10ppb sample either exists below 30 mK or does not exist at all. Experiments on very pure He-4 samples are in progress
- The supersolid fraction for the 47ppb sample is found to be 0.1 % in the cell oscillating at 158 Hz and near 0.2% in the open cell at 780 Hz.
- Why He-3 impurities play such important roles? and how?

## Summary and questions, III

- 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. Can we further reduce the scatter?
- If one can grow a perfect single crystal ( how?) , what will happen to the supersolid fraction?
- What is the origin of the pressure dependence of the supersolid fraction that first increase and then decrease with pressure?
- What is the origin of the small critical velocity that correspond to a few units of quantum circulation?

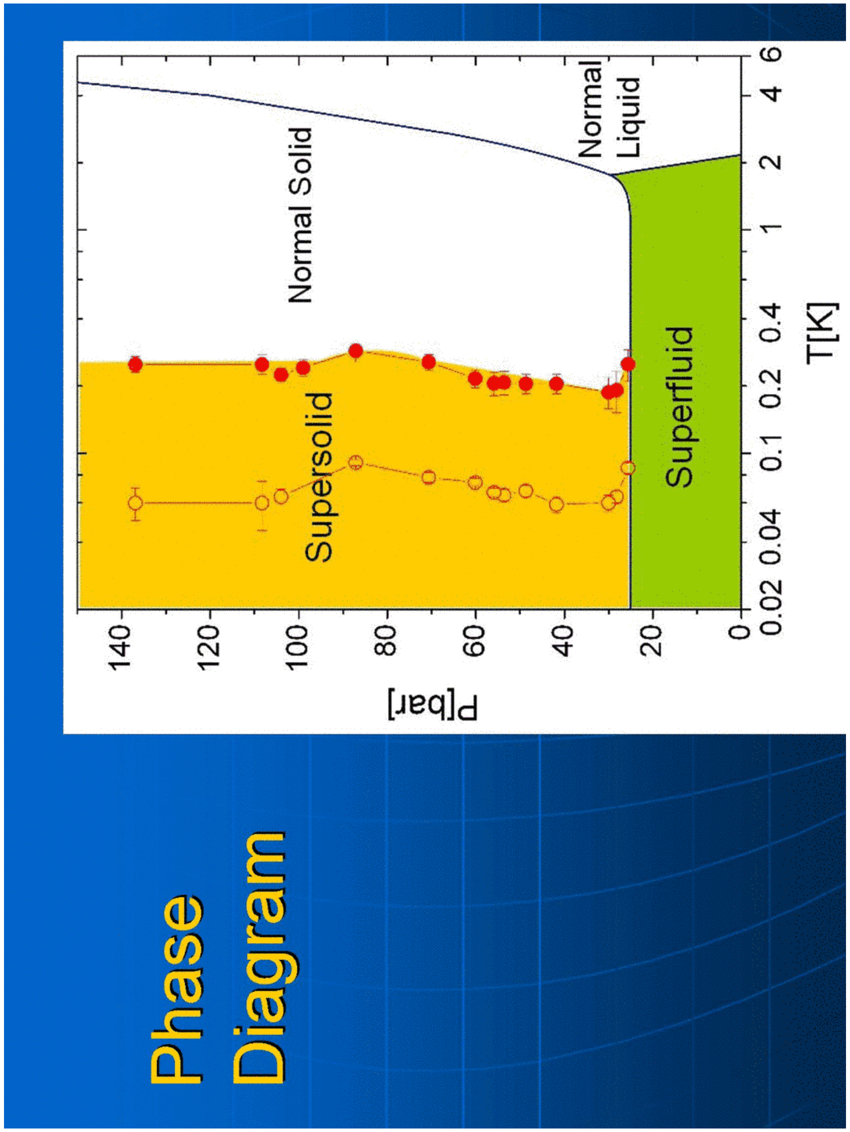
## Summary and questions, IV

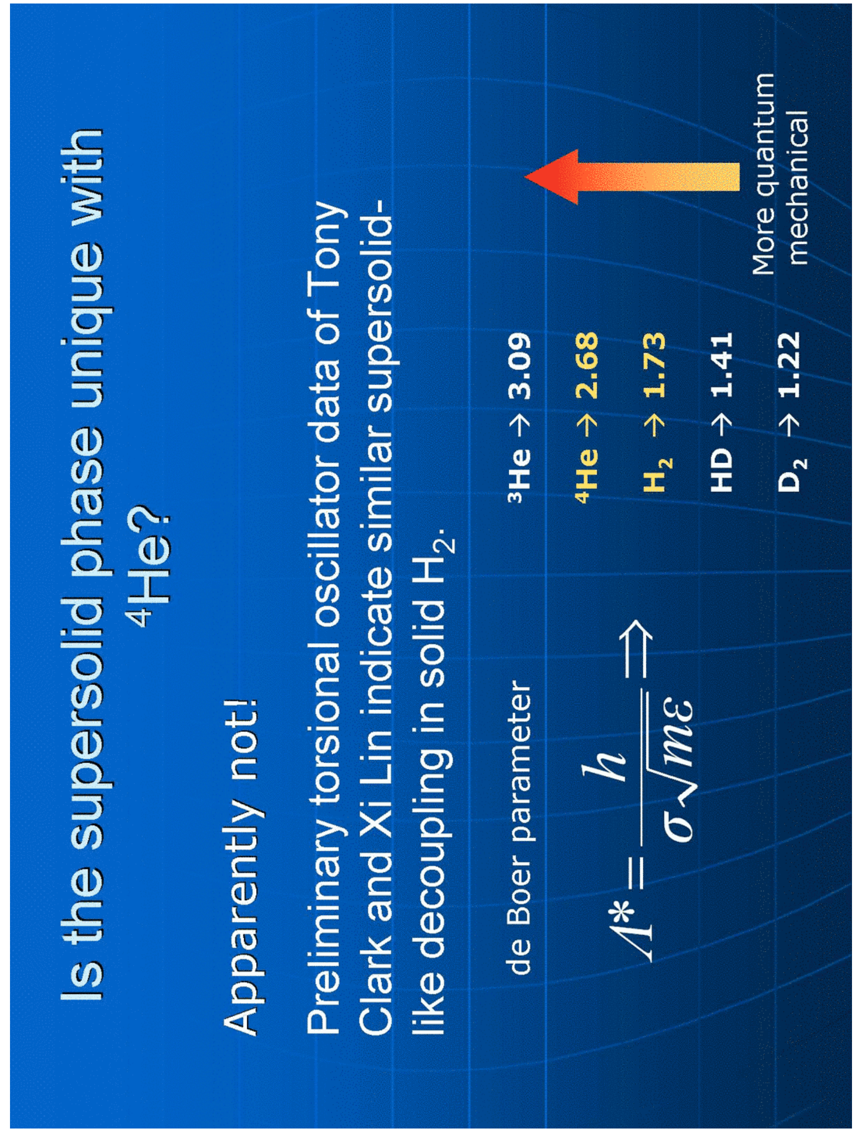
- Are there frequency and geometry( annulus vs. open cells) effects? With the help of Reppy and Shirahama, we will know soon!
- At 0.3ppm He-3, the samples in a disk of porous gold (360 Hz, 490 nm); and in a disk of Vycor(1K Hz, 7nm) and in an annulus of 0.6mm ( 1KHz), the supersolid fraction of solids between 30 and values are well within a factor of 2.
- At 47ppb He-3, the solid sample in an annulus of 5mm ( at 156 Hz) show a supersolid fraction of 0.1%, while in an open cylindrical cell of 7.5mm( 780Hz) it is 0.2%. Tc are the same.

## Summary and questions; V
## effect of annealing

The solid samples were grown from liquid through the liquid-solid coexistence region. The time it takes to cool down from liquid to around 1K is typically 4 to 5 hours.

When we took 20 hours, the supersolid fraction differs by 20 % for the 47ppb sample in a open cell.


Phase Diagram
P[bar]
140
120
100
80
60
40
20
0
T[K]
0.02
0.04
0.1
0.2
0.4
1
2
4
6
Normal Solid
Normal Liquid
Supersolid
Superfluid


Is the supersolid phase unique with $^4$He?
Apparently not!
Preliminary torsional oscillator data of Tony Clark and Xi Lin indicate similar supersolid-like decoupling in solid $H_2$.
de Boer parameter
$\Lambda^* = \frac{h}{\sigma\sqrt{m\varepsilon}} \Rightarrow$
$^3$He → 3.09
$^4$He → 2.68
$H_2$ → 1.73
HD → 1.41
$D_2$ → 1.22
More quantum mechanical

## Experimental Details for Hydrogen

- Triple point, $T_t$ = 13.8K
- $\rho_{solid}(T=0) = 0.85 * \rho_{liquid}(T=T_t)$
  - Pressure change of 100bar constitutes a 5% change in $\rho_{solid}$
- Ortho-para conversion
  - Equilibrium phase at low temperature is p-$H_2$
  - OP Conversion releases heat
  - Conversion rate in solid $H_2$ is slow:

$$\frac{dx_1}{dt} = -k\,x_1^2$$

Where $k$ = 1.9% of $x_1$ per hour

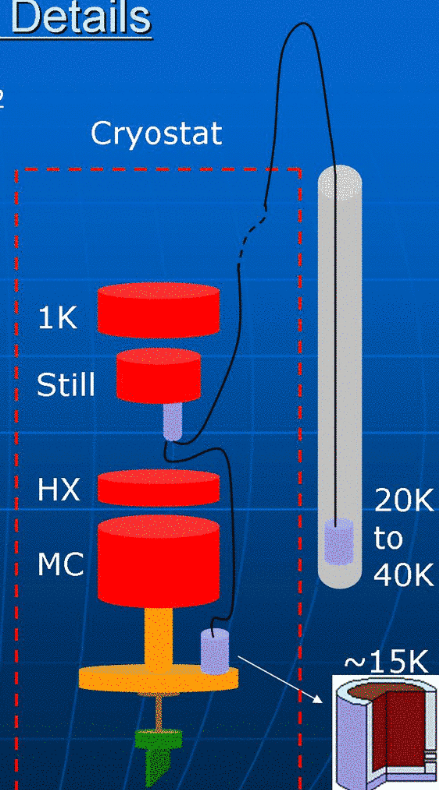
- Nominal impurity concentration
  - Natural abundance of HD is 310ppm in $H_2$

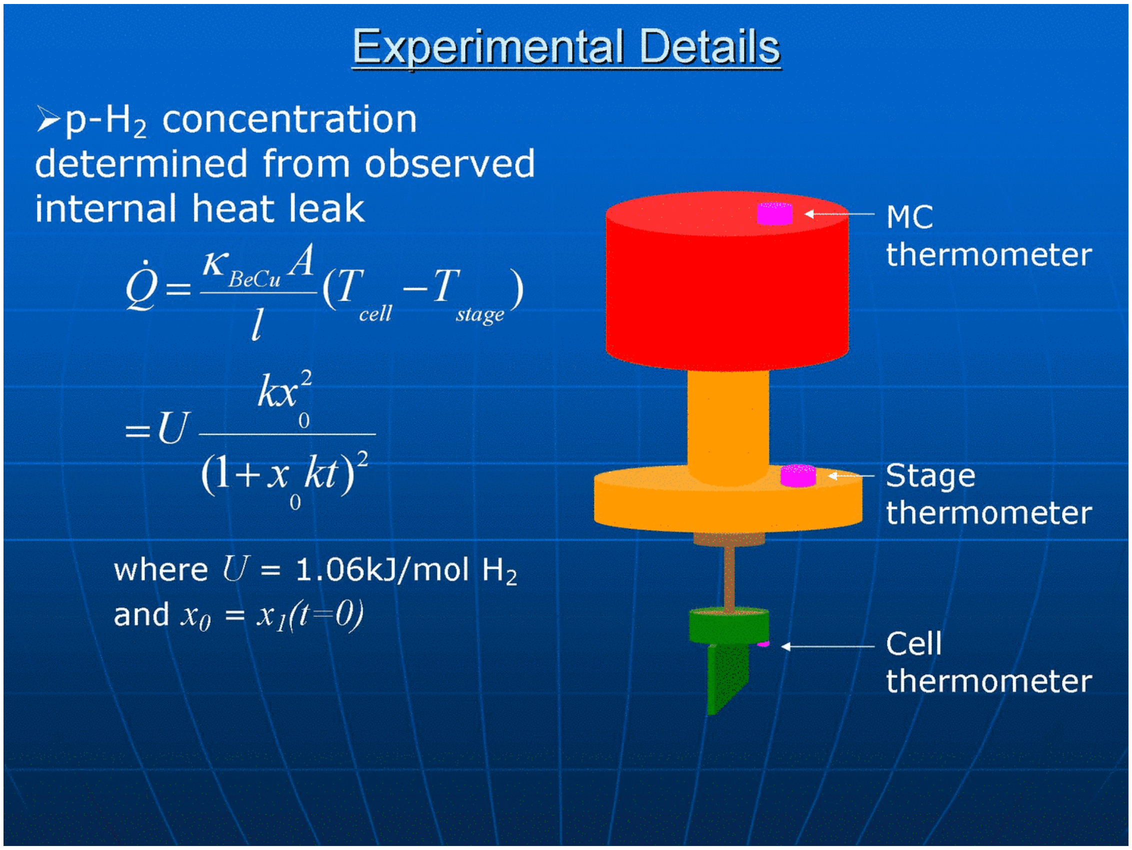
## Experimental Details

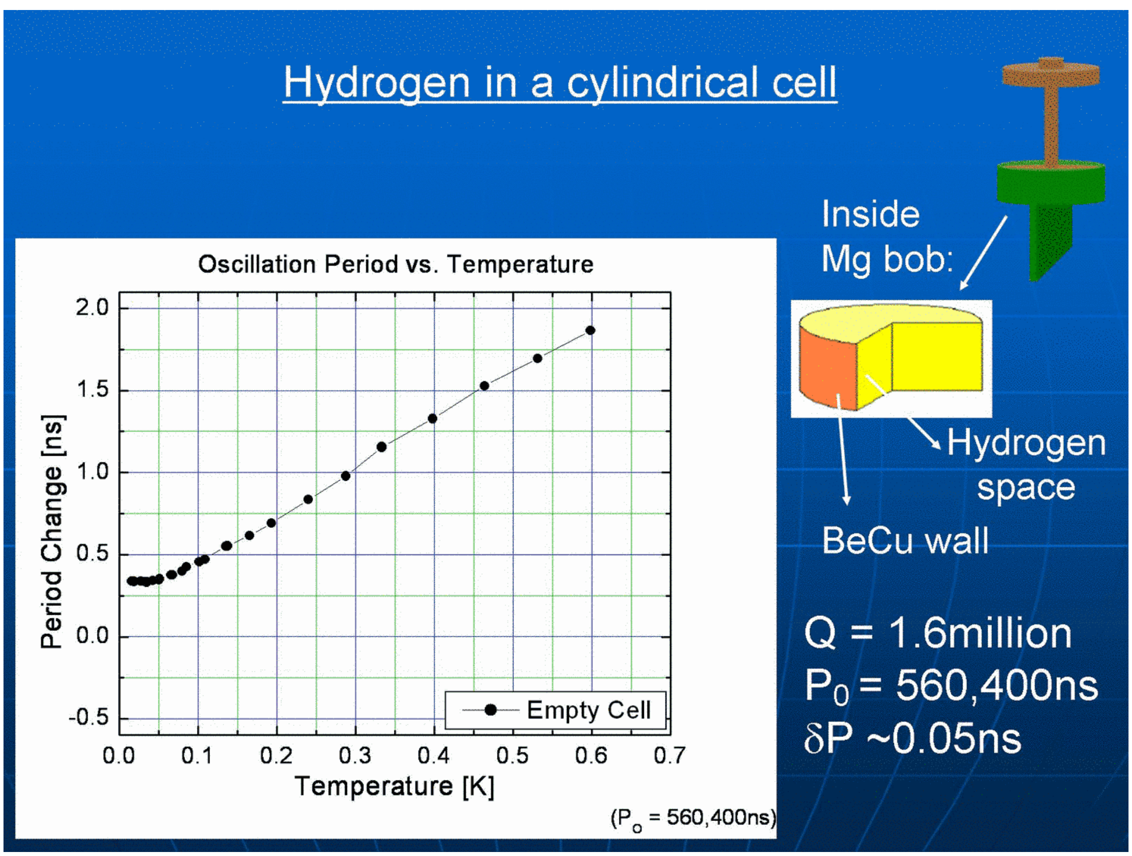
- Para- and ortho- species of $H_2$
  - Conversion rate in solid $H_2$

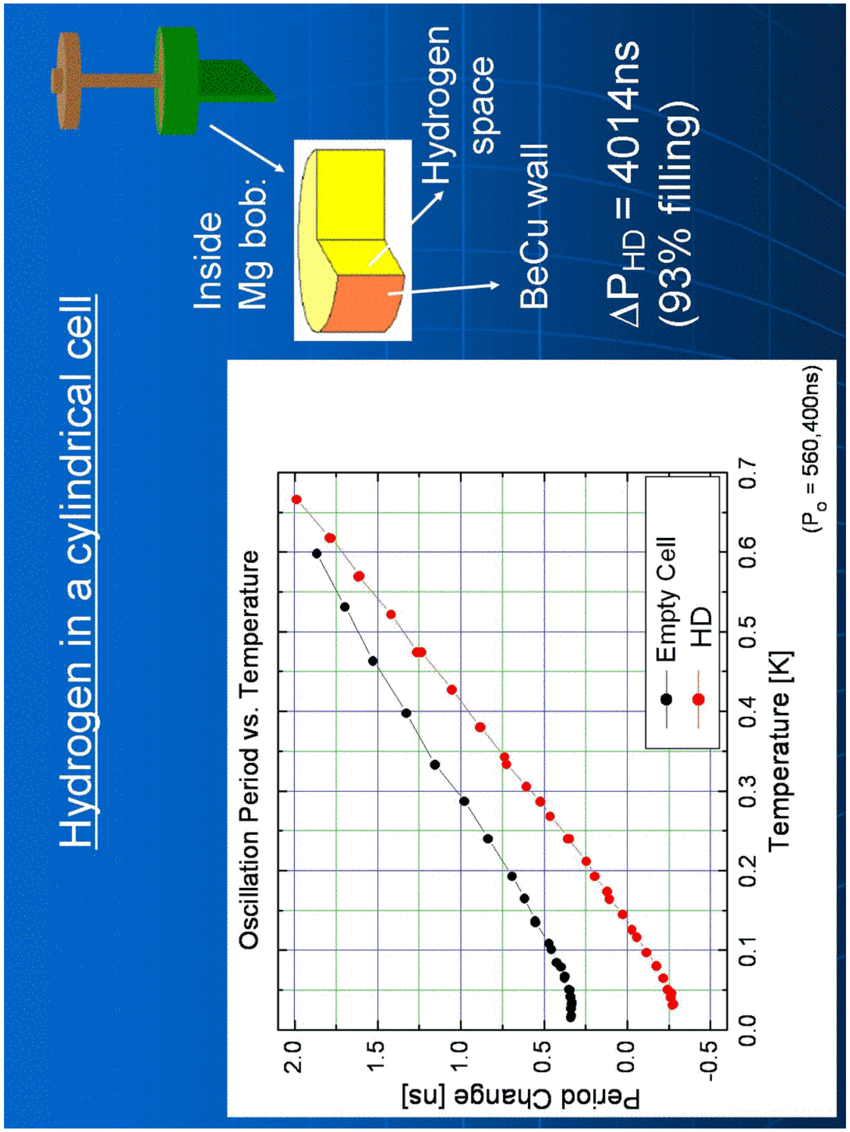
$$\frac{dx_1}{dt} = -k\,x_1^2$$

  - Catalyst: high surface area material containing magnetic impurities
- In most cases, samples were converted to the p-$H_2$ phase in a three step process
- Sample slowly cooled with exchange gas

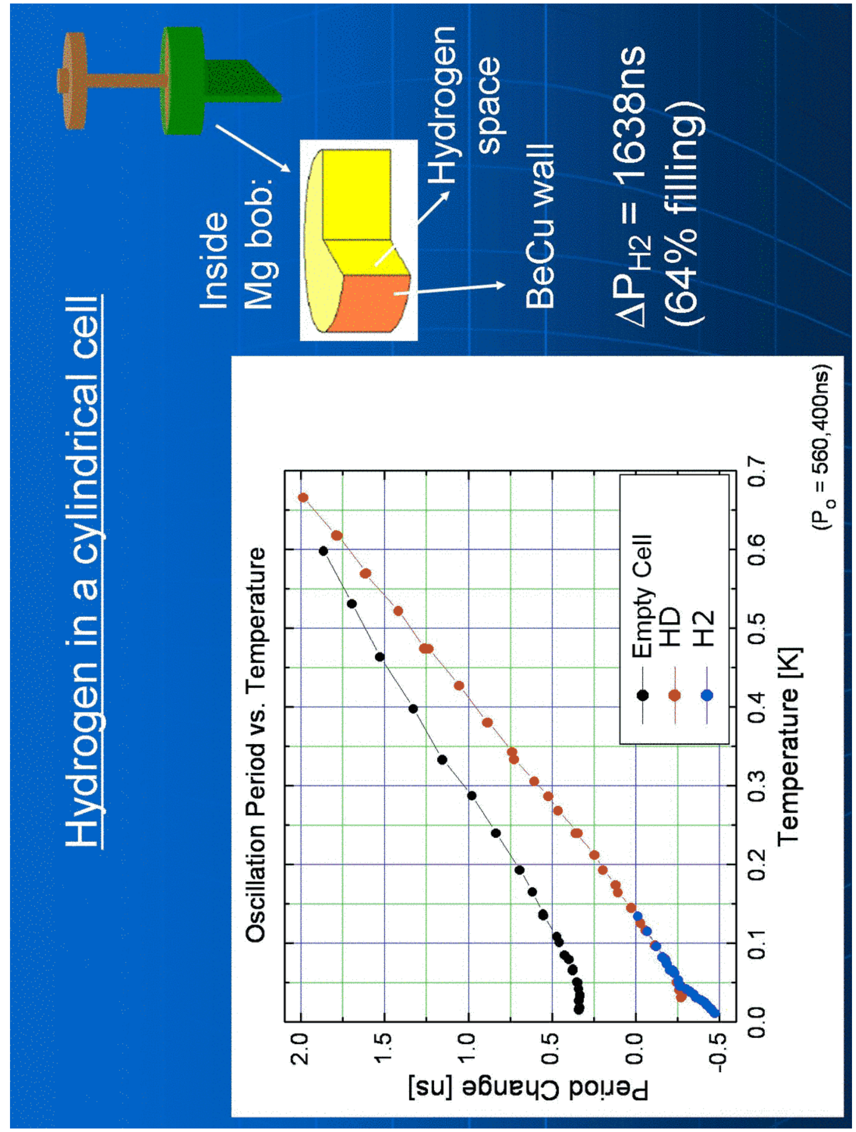



Experimental Details
➢p-$H_2$ concentration determined from observed internal heat leak
$\dot{Q} = \frac{\kappa_{BeCu} A}{l}(T_{cell} - T_{stage})$
$= U \frac{k x_0^2}{(1 + x_0 k t)^2}$
where $U$ = 1.06kJ/mol $H_2$
and $x_0 = x_1(t=0)$
MC thermometer
Stage thermometer
Cell thermometer

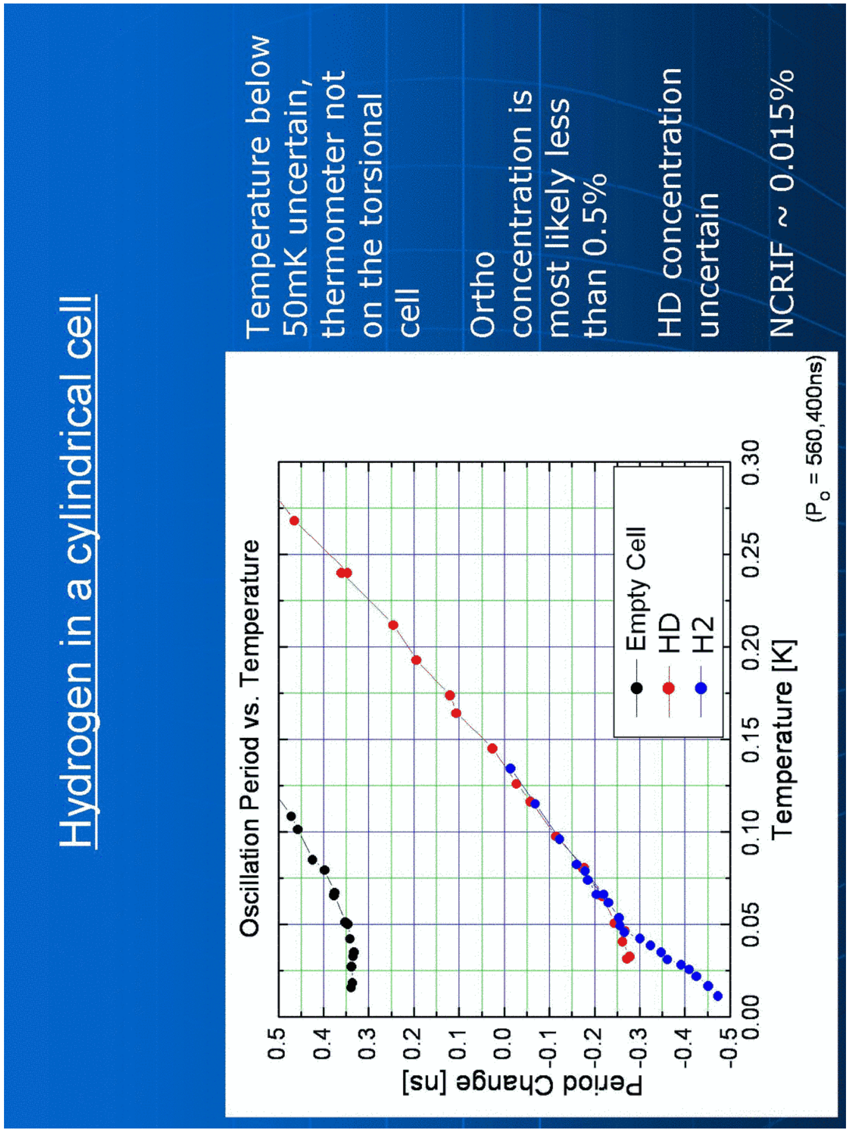

Hydrogen in a cylindrical cell
Oscillation Period vs. Temperature
Period Change [ns]
Temperature [K]
Empty Cell
($P_o$ = 560,400ns)
Inside Mg bob:
Hydrogen space
BeCu wall
Q = 1.6million
$P_0$ = 560,400ns
$\delta P$ ~0.05ns

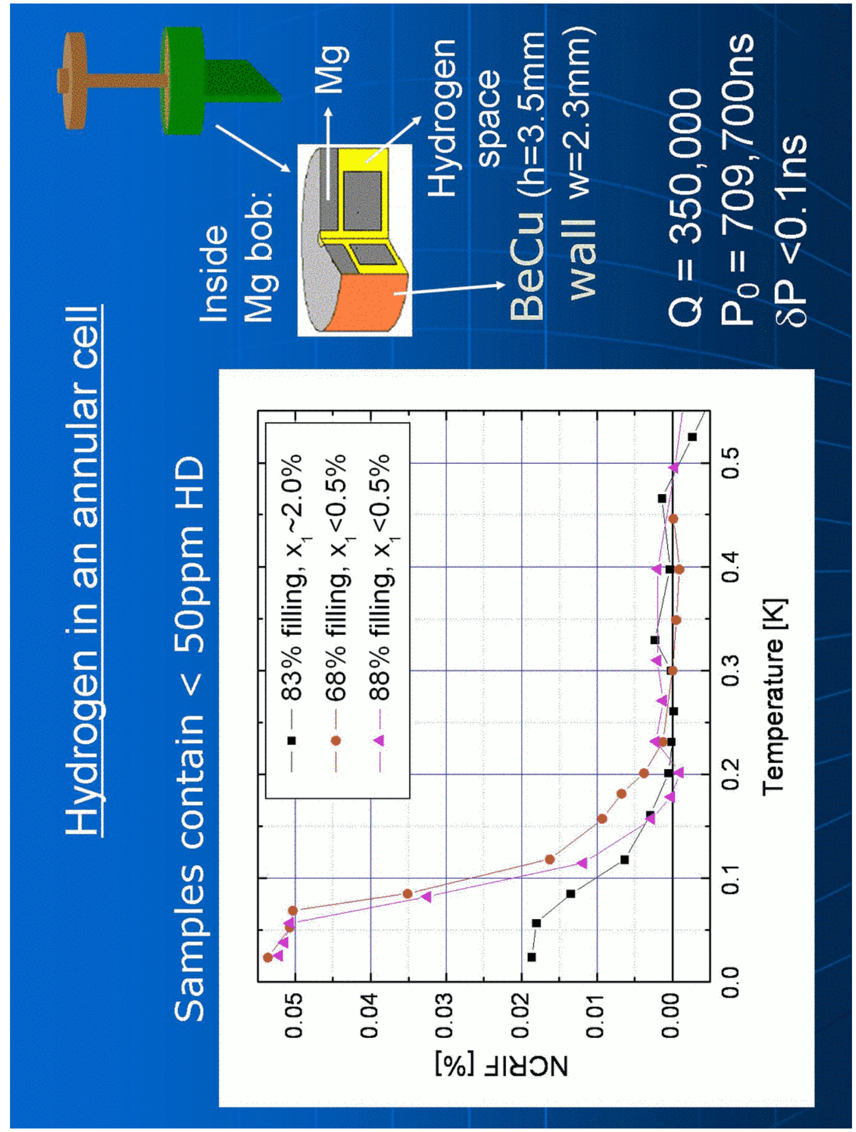


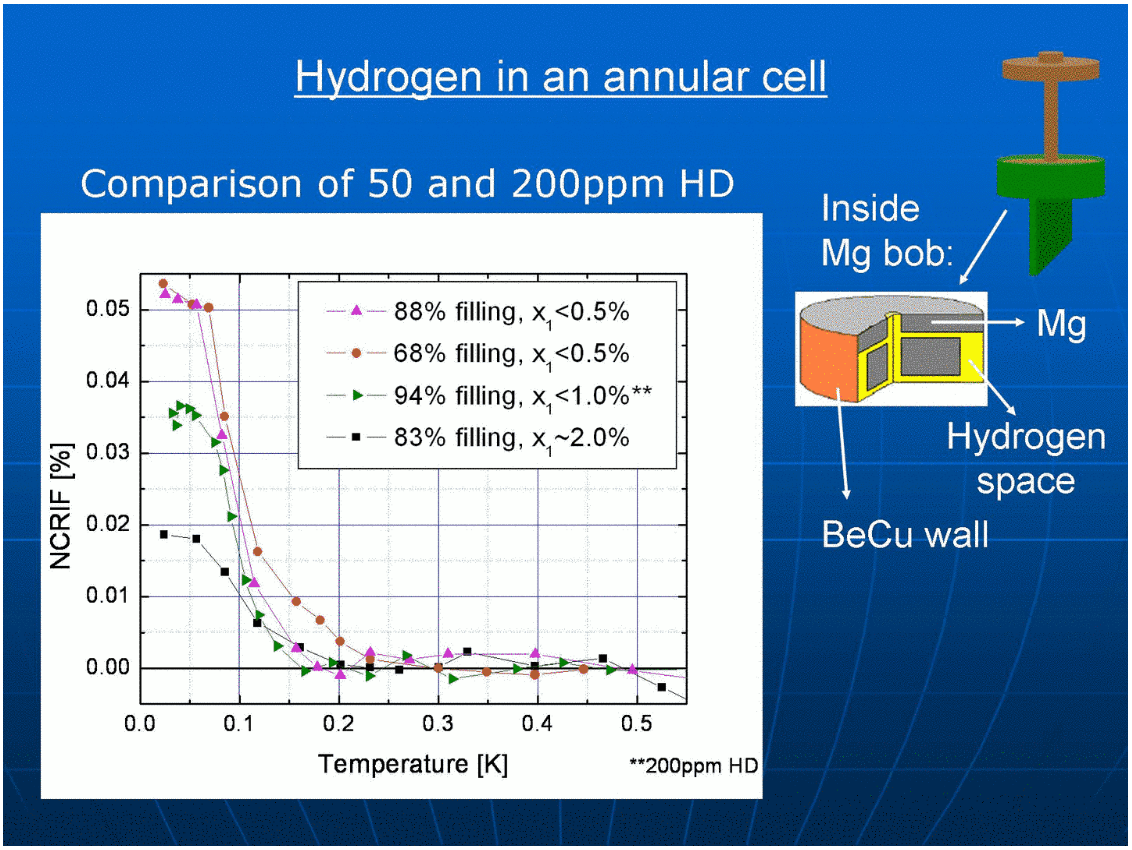
Hydrogen in a cylindrical cell
Inside Mg bob:
Hydrogen space
BeCu wall
ΔP_HD = 4014ns
(93% filling)
Oscillation Period vs. Temperature
Period Change [ns]
Temperature [K]
Empty Cell
HD
(P_o = 560,400ns)
2.0
1.5
1.0
0.5
0.0
-0.5
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7

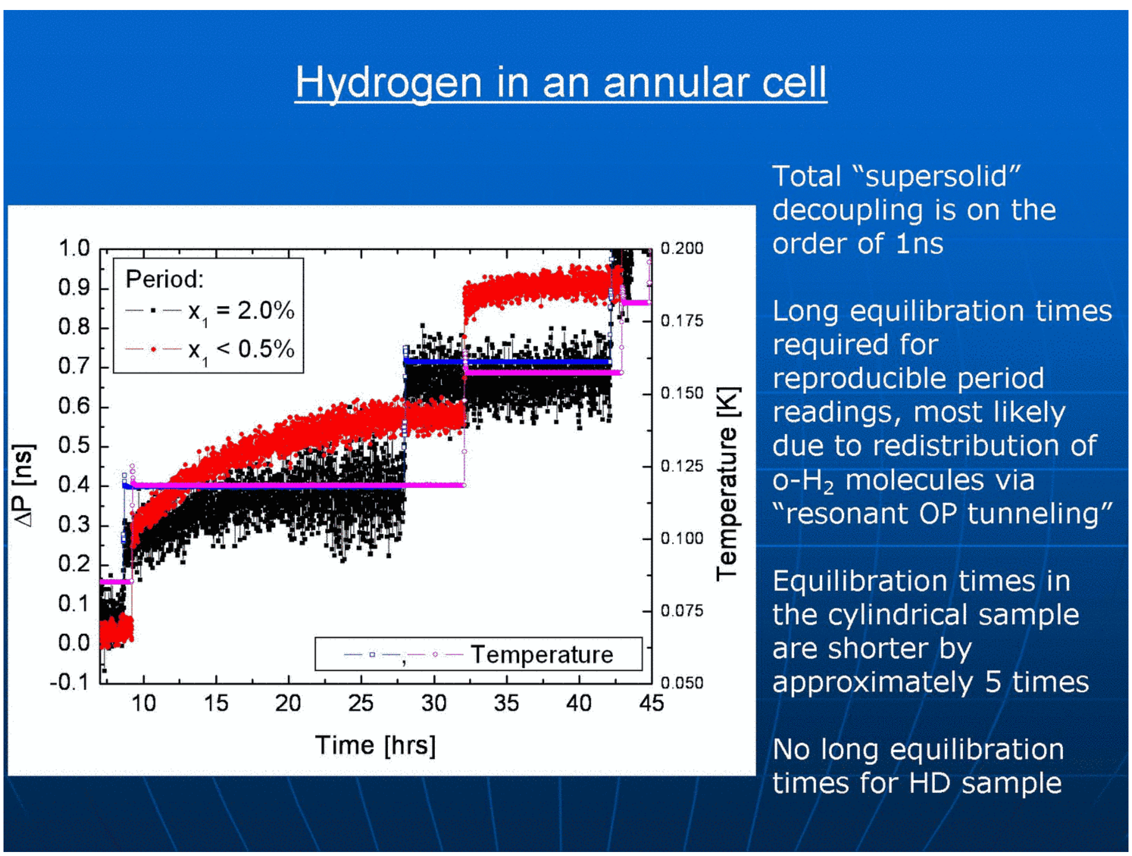



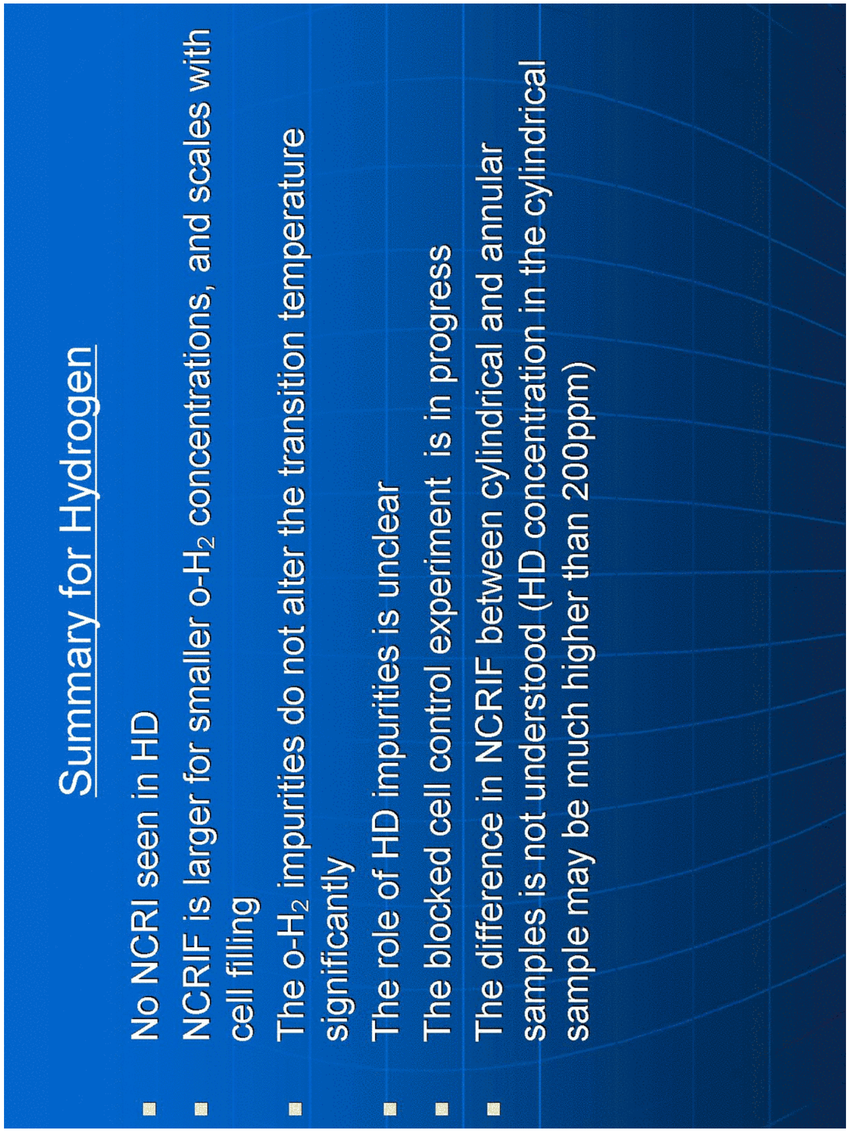
Hydrogen in a cylindrical cell
Inside Mg bob:
Hydrogen space
BeCu wall
ΔP_H2 = 1638ns
(64% filling)
Oscillation Period vs. Temperature
Period Change [ns]
Temperature [K]
Empty Cell
HD
H2
(P_o = 560,400ns)
2.0
1.5
1.0
0.5
0.0
-0.5
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7

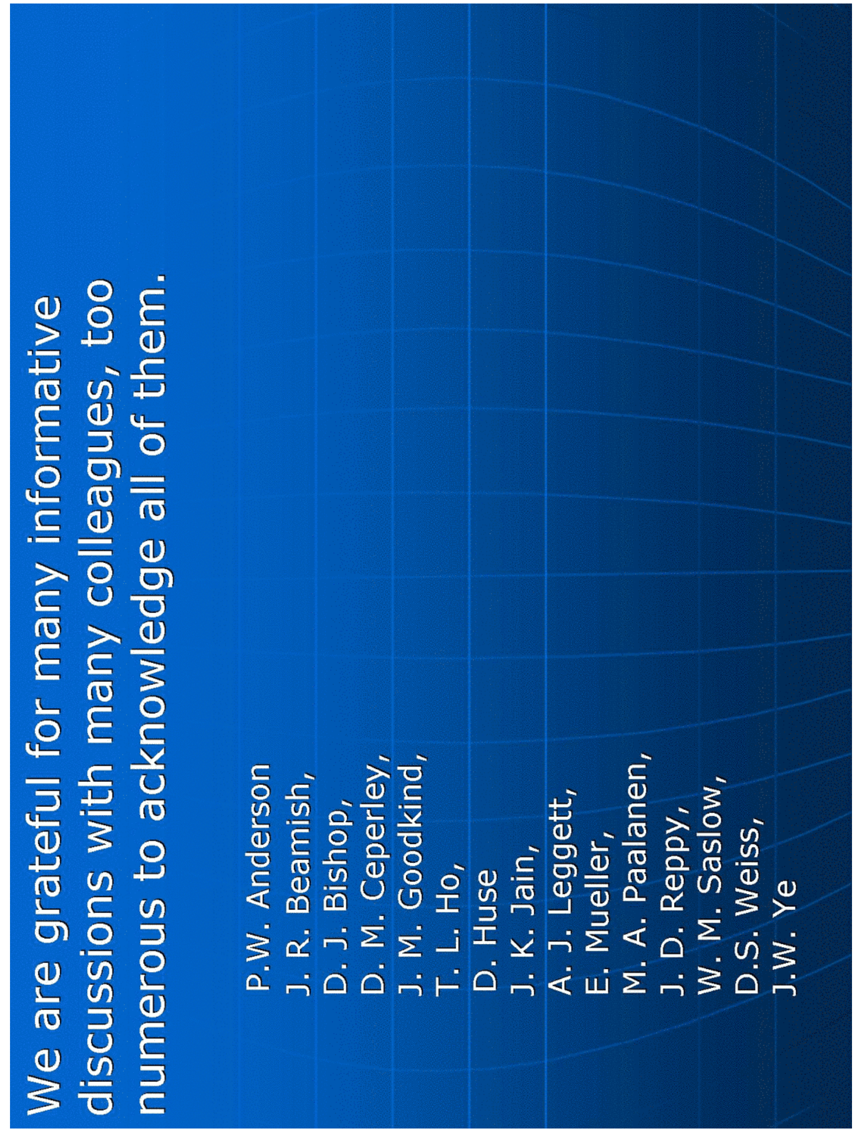

Hydrogen in a cylindrical cell
Oscillation Period vs. Temperature
Period Change [ns]
Temperature [K]
Empty Cell
HD
H2
($P_o$ = 560,400ns)
Temperature below 50mK uncertain, thermometer not on the torsional cell
Ortho concentration is most likely less than 0.5%
HD concentration uncertain
NCRIF ~ 0.015%


Hydrogen in an annular cell
Samples contain < 50ppm HD
NCRIF [%]
Temperature [K]
83% filling, $x_1$ ~2.0%
68% filling, $x_1$ <0.5%
88% filling, $x_1$ <0.5%
Inside Mg bob:
Mg
Hydrogen space
BeCu (h=3.5mm wall w=2.3mm)
Q = 350,000
$P_0$ = 709,700ns
$\delta P$ <0.1ns


Hydrogen in an annular cell
Comparison of 50 and 200ppm HD
NCRIF [%]
Temperature [K]
88% filling, $x_1$<0.5%
68% filling, $x_1$<0.5%
94% filling, $x_1$<1.0%**
83% filling, $x_1$~2.0%
**200ppm HD
Inside Mg bob:
Mg
Hydrogen space
BeCu wall


Hydrogen in an annular cell
Period:
$x_1$ = 2.0%
$x_1$ < 0.5%
Temperature
ΔP [ns]
Temperature [K]
Time [hrs]
Total "supersolid" decoupling is on the order of 1ns
Long equilibration times required for reproducible period readings, most likely due to redistribution of o-$H_2$ molecules via "resonant OP tunneling"
Equilibration times in the cylindrical sample are shorter by approximately 5 times
No long equilibration times for HD sample


Summary for Hydrogen
No NCRI seen in HD
NCRIF is larger for smaller o-$H_2$ concentrations, and scales with cell filling
The o-$H_2$ impurities do not alter the transition temperature significantly
The role of HD impurities is unclear
The blocked cell control experiment is in progress
The difference in NCRIF between cylindrical and annular samples is not understood (HD concentration in the cylindrical sample may be much higher than 200ppm)


We are grateful for many informative discussions with many colleagues, too numerous to acknowledge all of them.
P.W. Anderson
J. R. Beamish,
D. J. Bishop,
D. M. Ceperley,
J. M. Goodkind,
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D. Huse
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A. J. Leggett,
E. Mueller,
M. A. Paalanen,
J. D. Reppy,
W. M. Saslow,
D.S. Weiss,
J.W. Ye


Xi, Tony, Eunseong, Josh
STATE