How Super is solid He4?

M. Graf, I. Grigorenko, Z. Nussinov, S. Trugman,

AVB (Los Alamos), E. Abrahams (Rutgers)

1. Introduction: what to expect from superstate
2. Experiments that suggest Supersolidity
3. Experiments that raise questions.

Torsional oscillator considerations

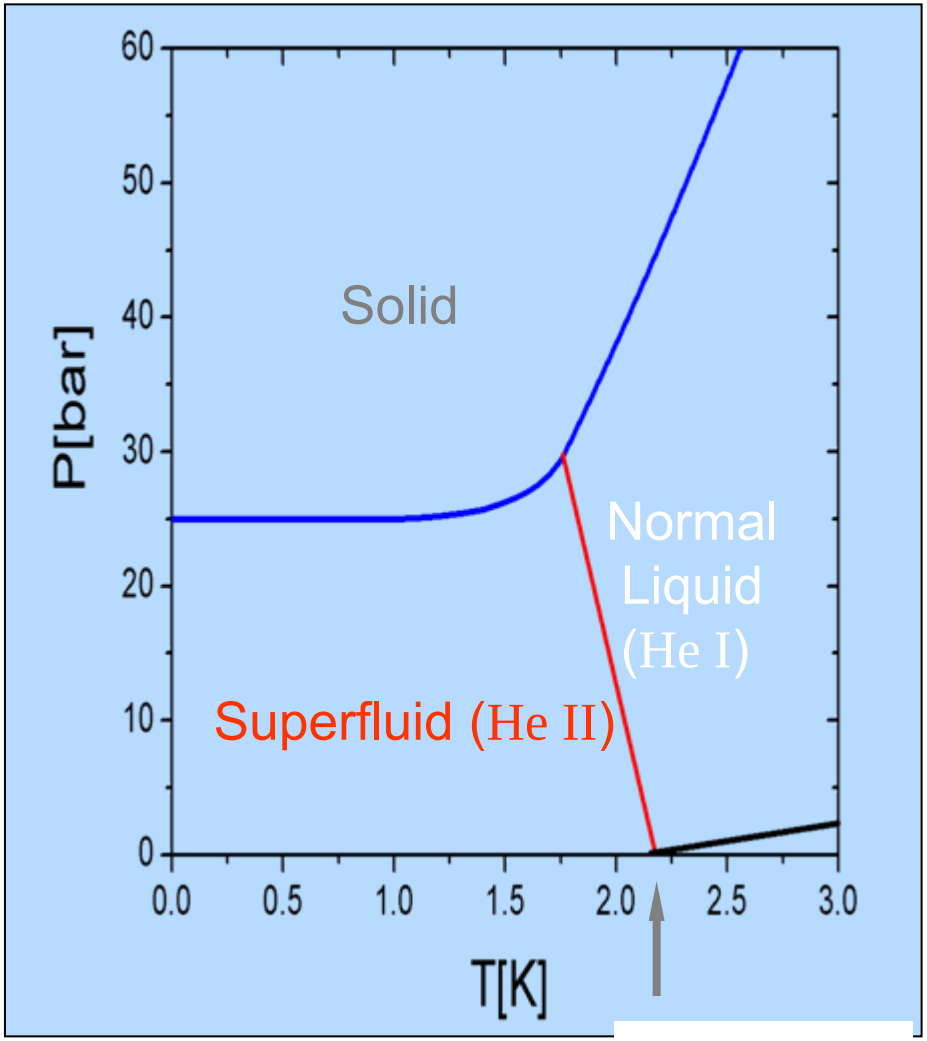
- Causality links dissipation and period.
- How to get a peak in dissipation and drop in period?

Thermodynamic considerations

- Counting frozen-in states of a glass.

3. Conclusion and future directions

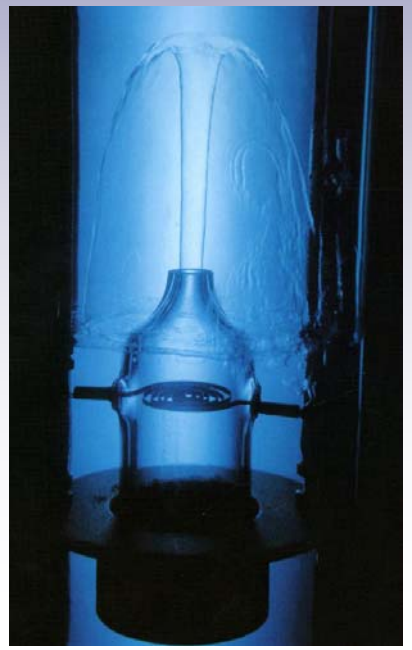
Superfluidity in liquid ^{4}He



$T_\lambda = 2.176K$

- Superfluid helium film can flow up a wall

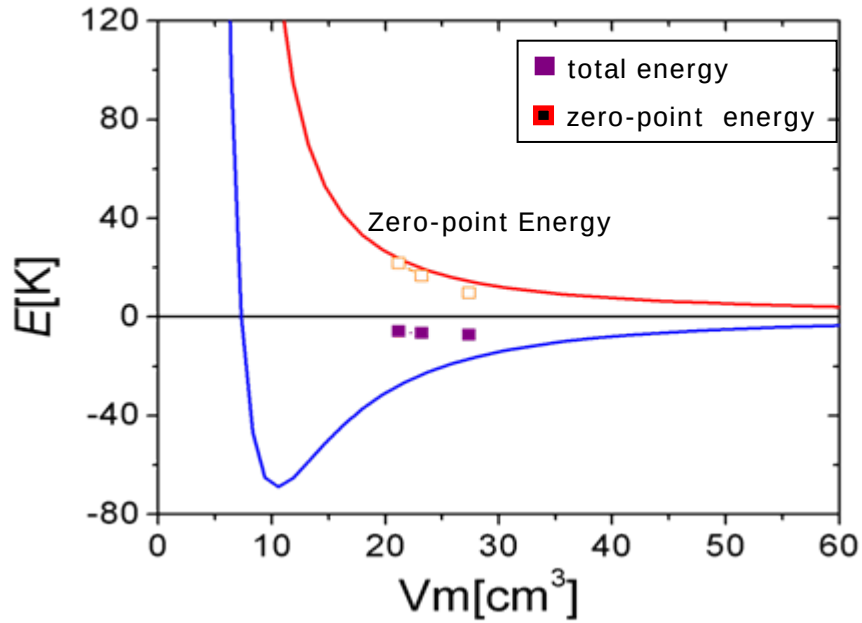
- Superfluid Fountain



- Lindemann Parameter

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

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

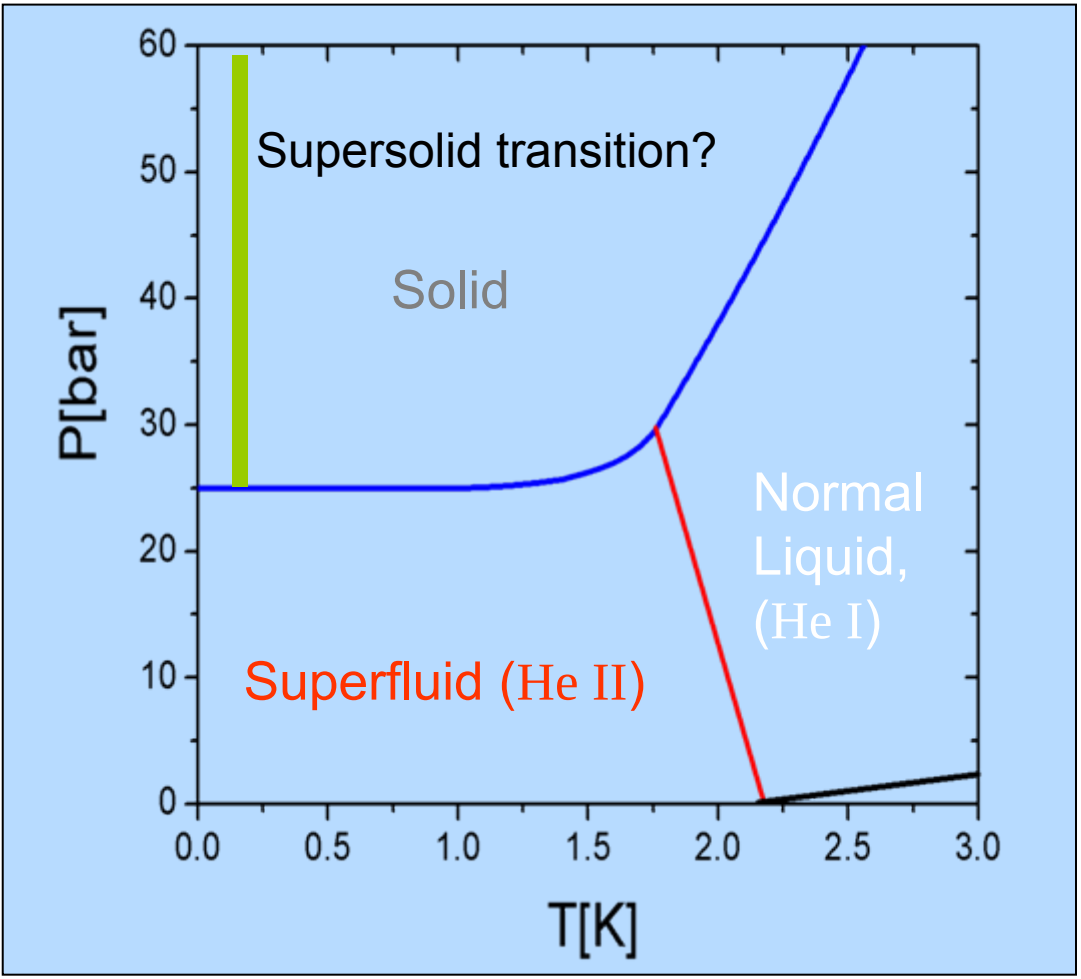


A classical solid will melt if the Lindemann's parameter exceeds the critical value of ~0.1 .

- X-ray measurement of the Debye-Waller factor of solid helium at ~0.7K and near melting curve shows this ratio to be 0.262.

(Burns and Issacs, *Phys. Rev. B* **55,** 5767(1997))

Phase diagram of ^{4}He



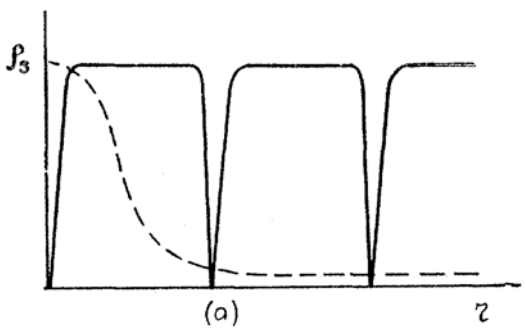
Fritz London is the first person to recognize that superfluidity in liquid ^{4}He is a BEC phenomenon.

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

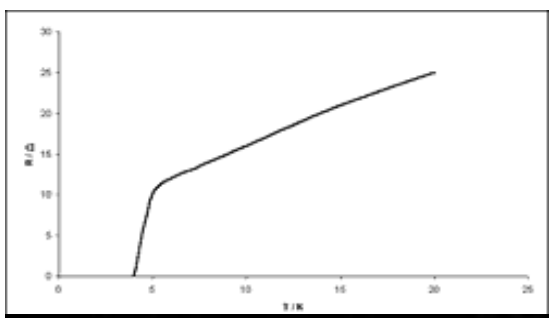
Possible kinds of superstate

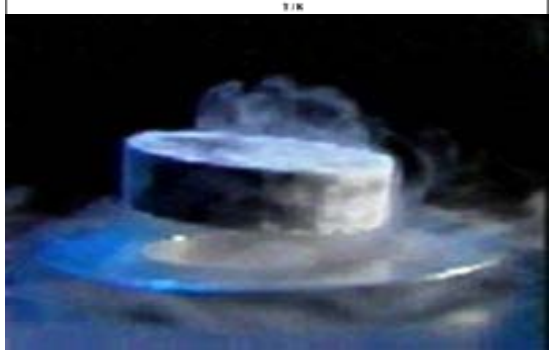
- Superfluid of bosonsHe4(Kapitza + ALLEN1939)
- ODLRO
- Superflow
- Vortices

$$\langle \Psi(r,t)\Psi(r',t)\rangle$$
$$\rightarrow \langle \Psi(r,t)\rangle\langle \Psi(r',t)\rangle_{r-r'\rightarrow\infty}$$



- Superconductor (KAMMERLING ONNES1911)
- ODLRO
- Superflow
- Vortices





- Supersolid (ANDREEV.LIFSHITZ, LEGGETT, REATTO,CHESTER, 69->now)
- ODLRO+ DLRO by same field
- Superflow
- Vortices

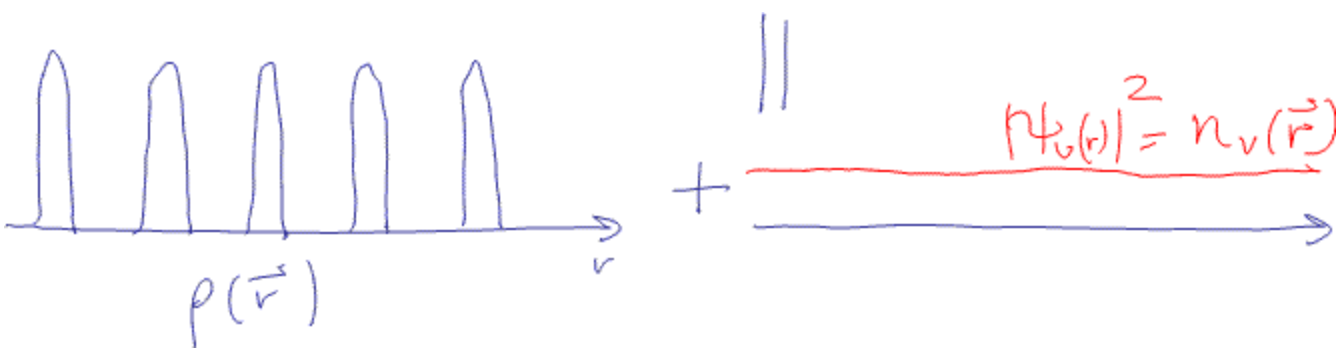
Detailed properties ?
Expected superresponse
Of a fluid yet is a solid

Two order parameters in supersolid state

Density $\rho(r) = \sum_{Q \in BZ} \rho_Q e^{iQr} + h.c.$

SS order parameter $\psi_v(r)$

4He wave function



Coarse graining to get to long length scale

Superconductor as a trivial supersolid

- Same field need to devlop both LRO for density and ODLRO.
- Case of metal SC as a trivial supersolid: electrons develop ODLRO and ions develop LRO for density

$$\left\langle c_{\uparrow}(k) c_{\downarrow}(-k) \right\rangle = ODLRO$$

- It is critical to have the same

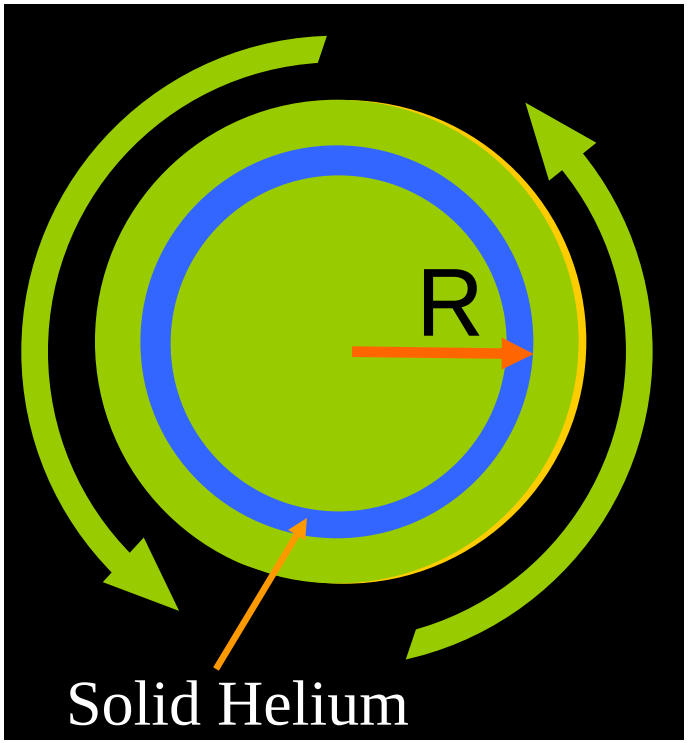
$$\left\langle \Psi_{ions}(r) \right\rangle = \sum_{k_i} A_i \cos(k_i r)$$

Field enter into both relations

The ideal method to detect superflow would be to subject solid helium to undergo dc or ac rotation to look for evidence of 'Non-Classical Rotational Inertia'.

Leggett, *Phys. Rev. Lett.* **25**, 1543 (1970)

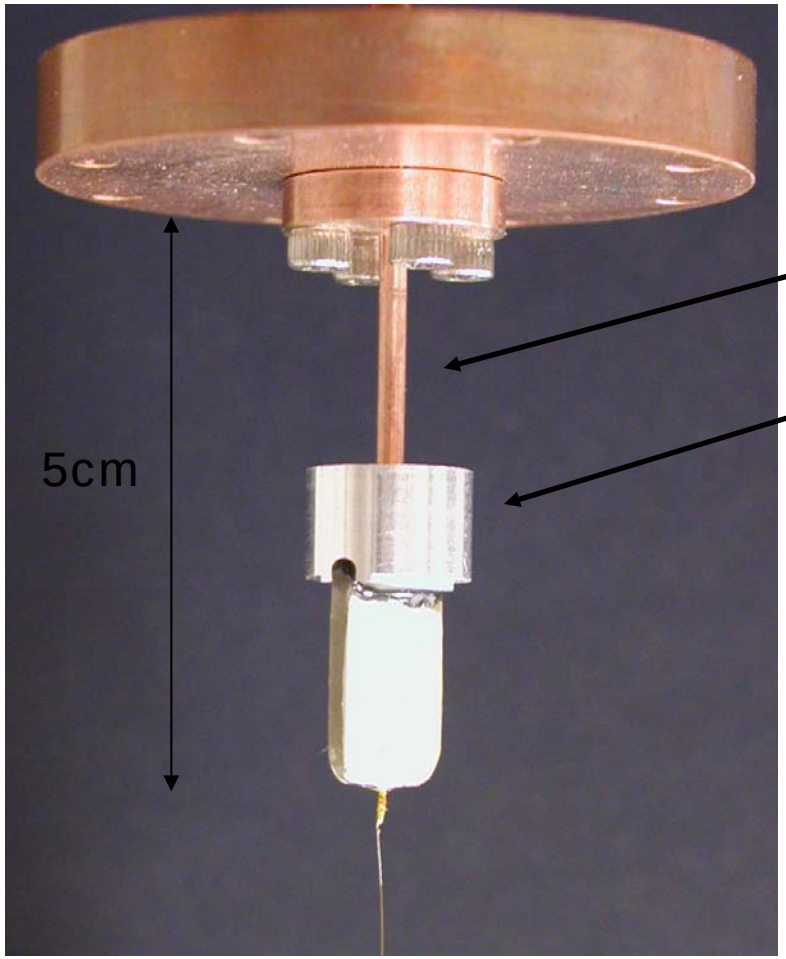
Quantum exchange of particles arranged in an annulus under rotation leads to a measured moment of inertia that is smaller than the classical value



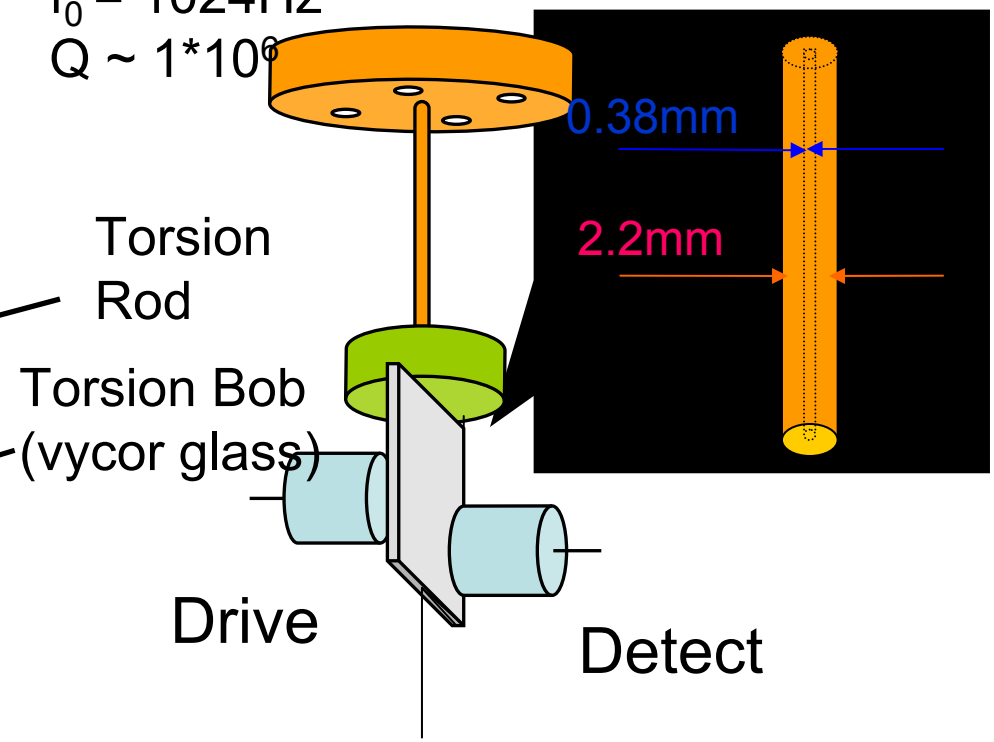
$$I(T)=I_{classical}[1-f_s(T)]$$

$f_s(T)$ is the supersolid fraction
Its upper limit is estimated by different theorists to range from 10^{-6} to 0.4; Leggett: 10^{-4}

Experimental set up Solid helium in TO

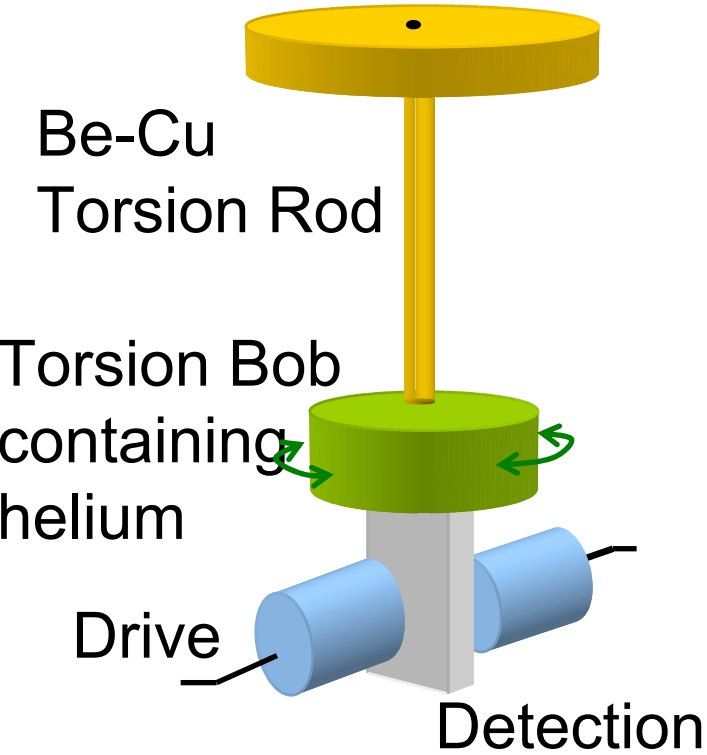


f_0 = 1024Hz
Q ~ $1*10^6$



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

Torsional oscillator is ideal for the detection of superfluidity



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

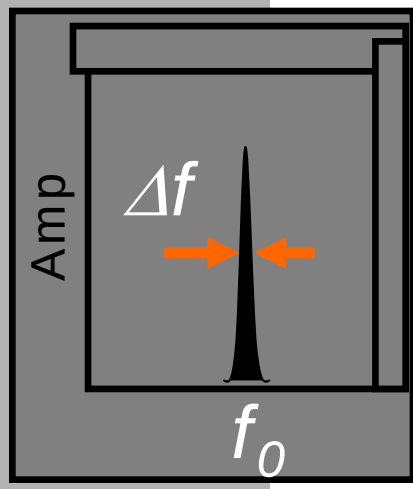
Resolution

Resonant period (τ_o) ~ 1 ms

stability in τ is 0.1ns

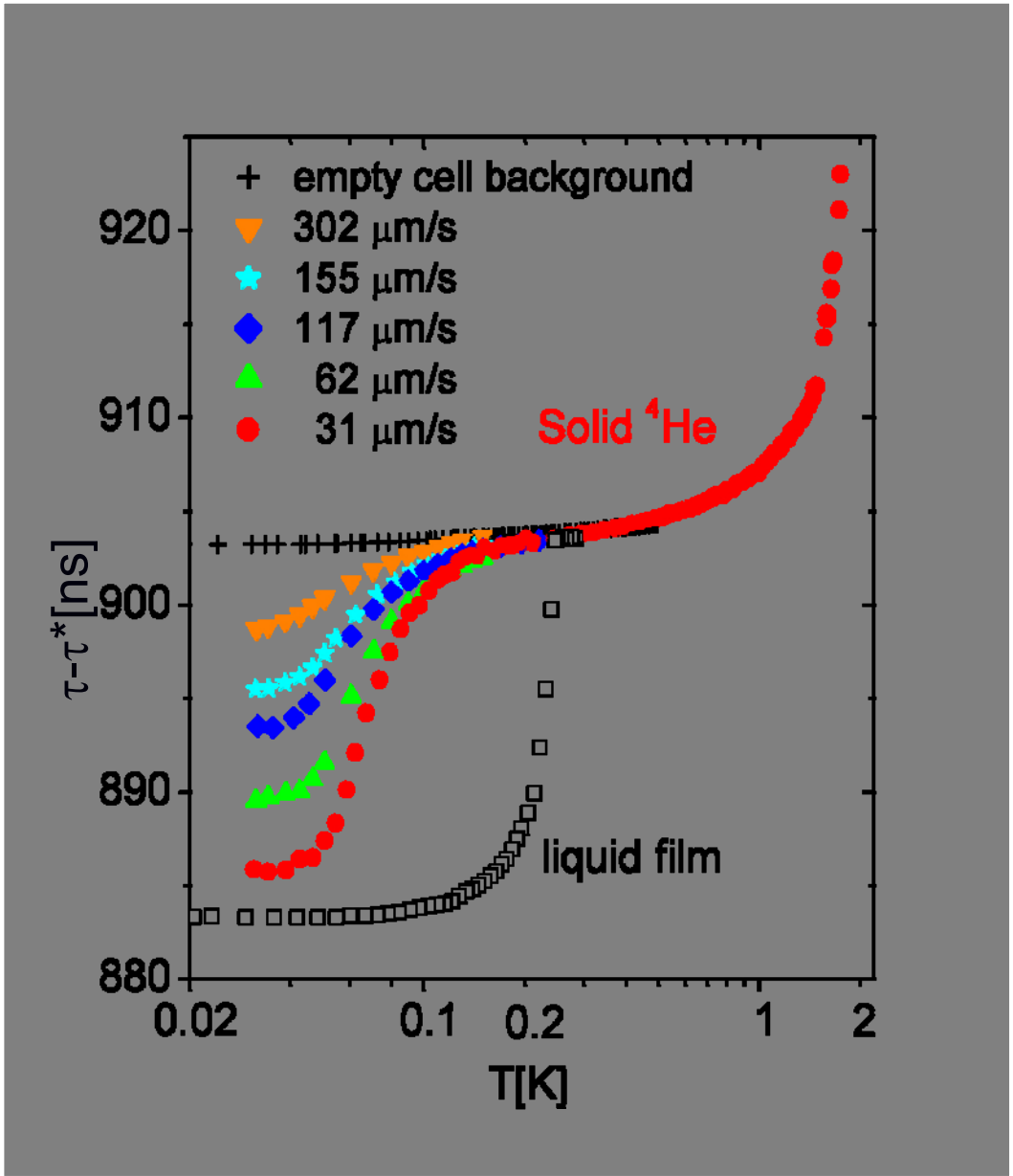
$\delta\tau/\tau_o = 5\times10^{-7}$

Mass sensitivity ~10^{-7}g



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

Superfluid response



Probable observation of a supersolid helium phase

E. Kim & M. H. W. Chan

Department of Physics, The Pennsylvania State University, University Park, Pennsylvania 16802, USA

Kim and Chan, Nature 2004

Total mass loading =4260ns

Measured decoupling

$-\Delta\tau_o$=17ns

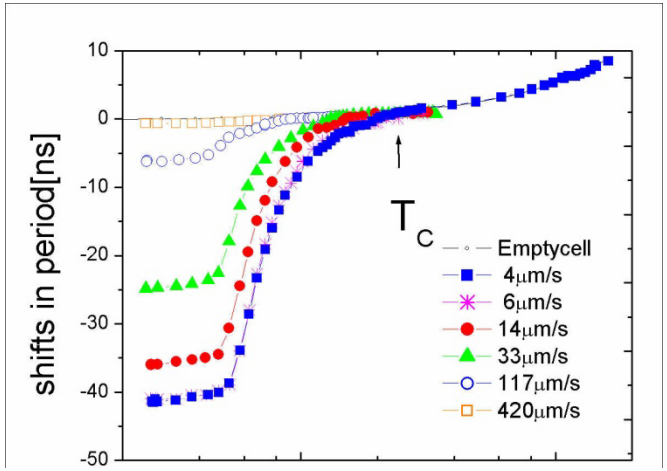
“ Apparent supersolid fraction”= 0.4%

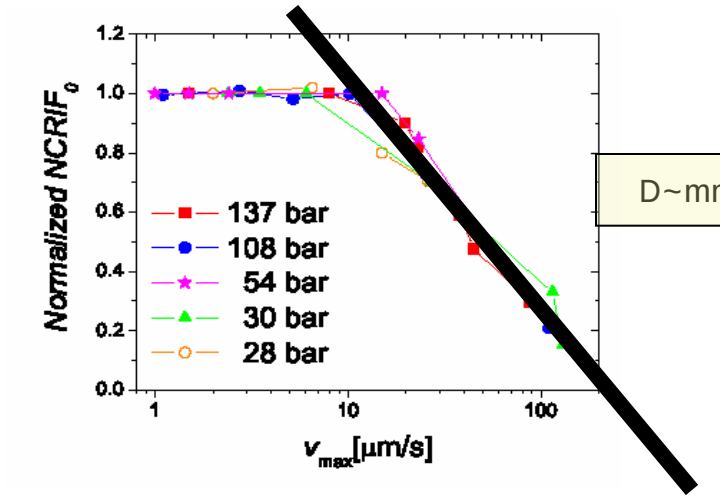
(with tortuosity correction ρ_s/ρ =2%

Weak pressure dependence

TO decoupling and critical velocity

Kim and Chan, Nature **427**,225(2004)





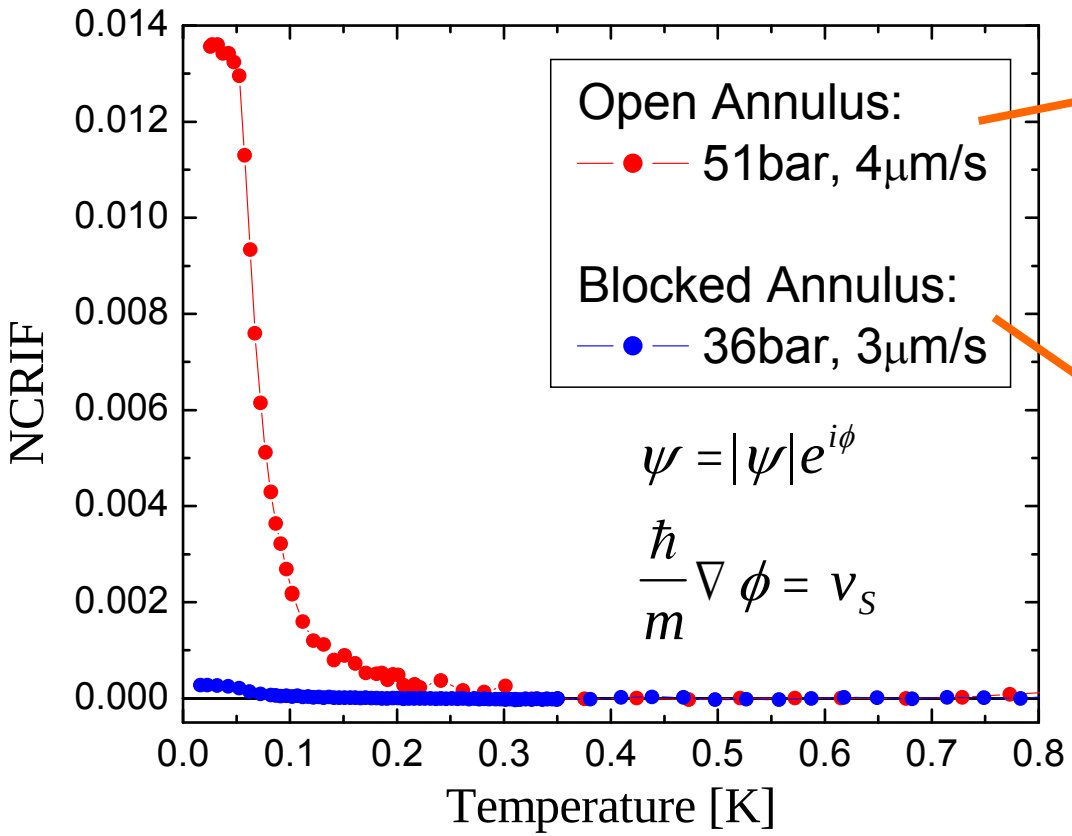
D~mm

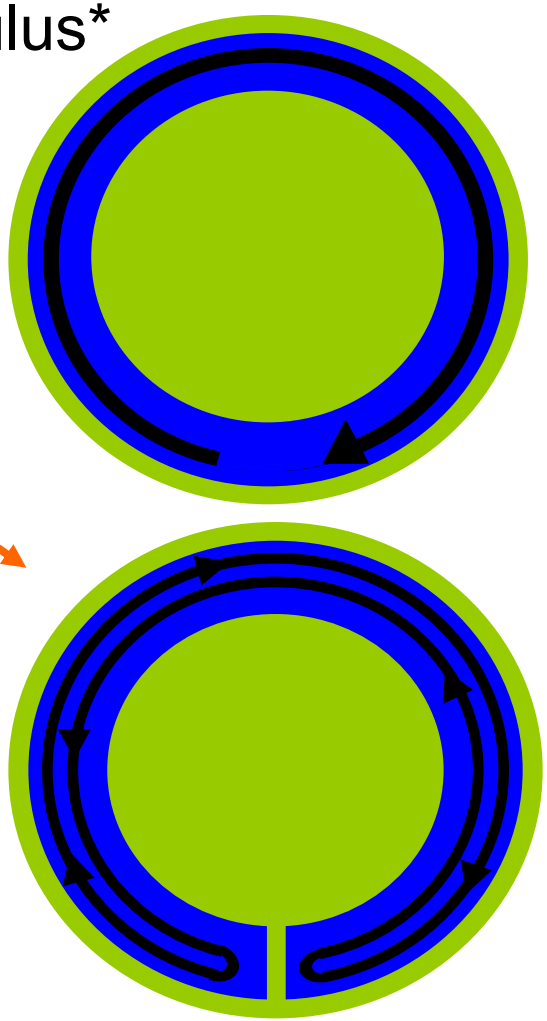
v_C ~ 10 μm/s for both

This log(v) line suggests the vortex liquid (PW Anderson)

Control I:Irrotational Flow

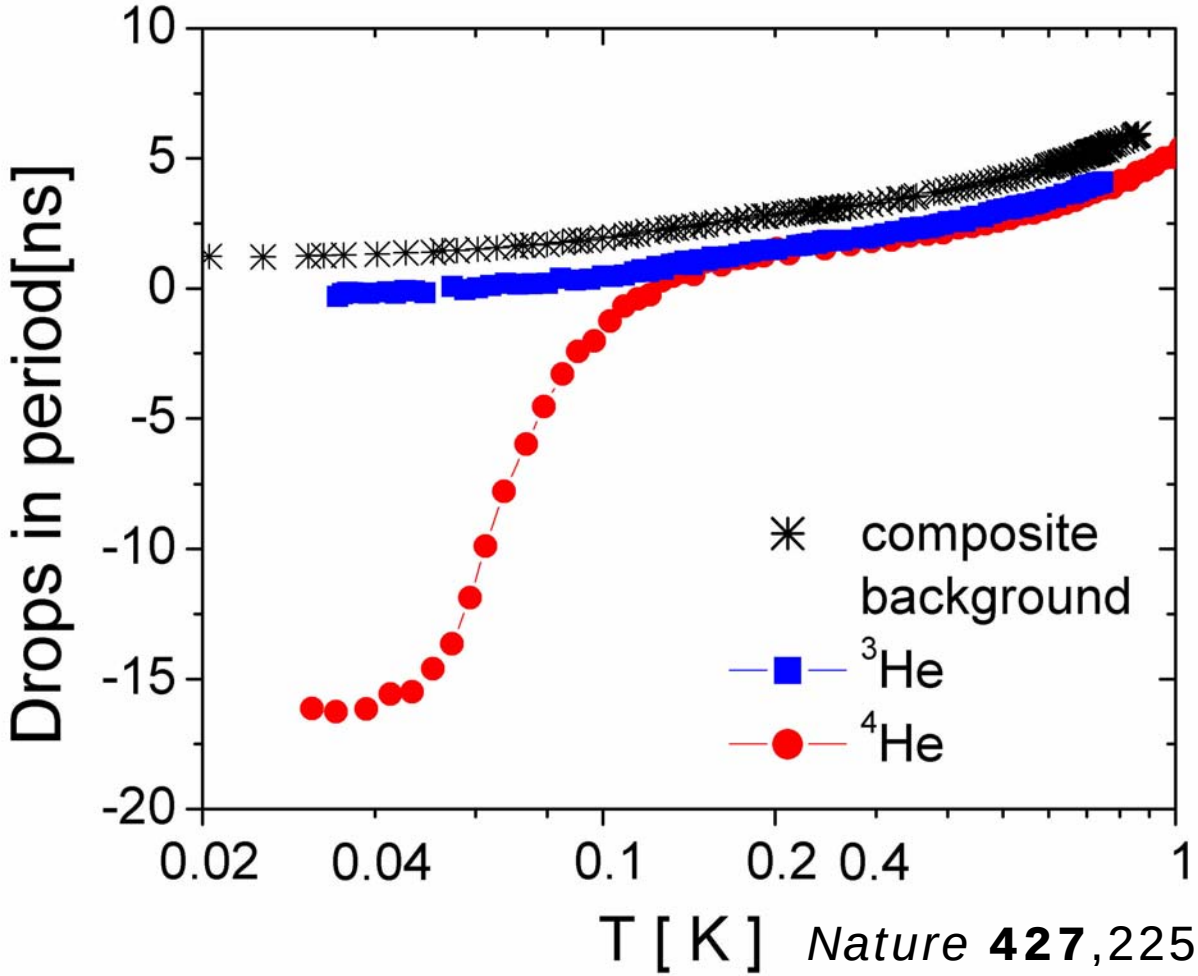
- Superfluids exhibit potential (irrotational) flow
  - For our exact dimensions, NCRIF in the blocked cell should be about 1% that of the annulus*





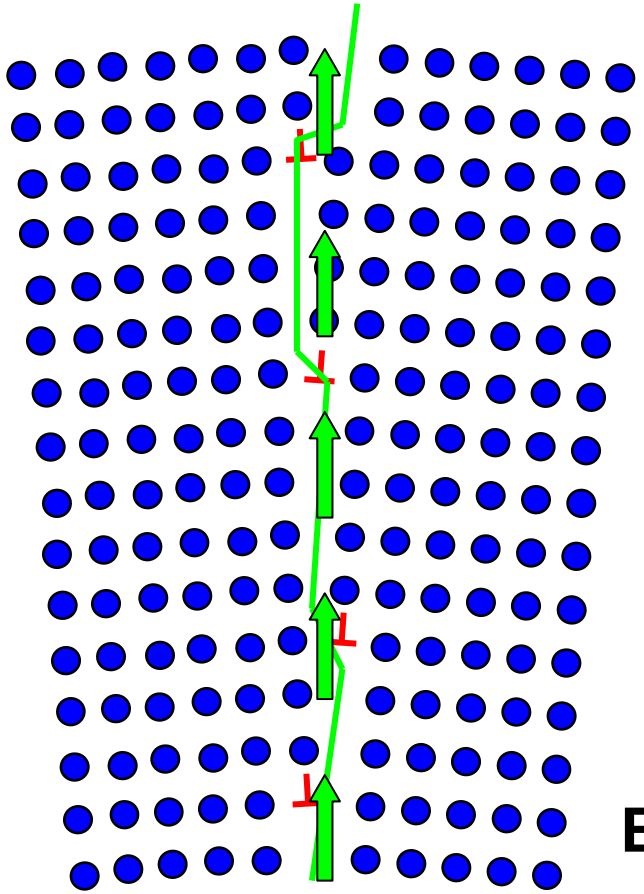
*E. Mueller, private communication.

Control experiment II : Solid ^{3}He?



Nature **427**,225(2004)

One explanation:Supersolidity and extended defects



superflow along grain boundaries (2D)?

or along dislocation lines (1D)?

or motion of dislocations?

Effect in TO has been seen in numerous labs (~4)
By now majority agrees that SS Can not occur in perfect crystal

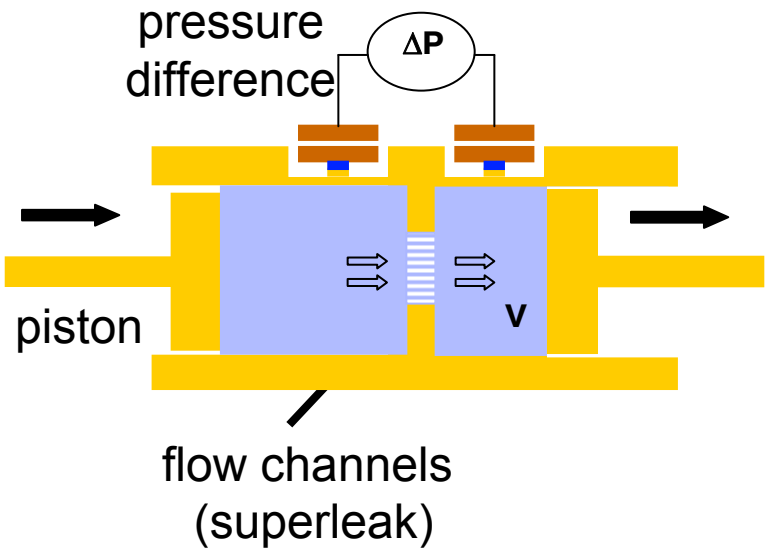
Evidence for glassy picture and/or against simplistic SS

- No evidence for a phase coherent flow. No evidence for superflow. (Beamish et al)
- Histeresis dependence, no rim velocity dependence.(Kojima et al)
- Evidence for linear term in specific heat. C~T indicating two level systems and possible glass. (LANL analysis, Chan data)
- Strong and unusual sensitivity to He3.(Chan et al)
- No evidence for a change in excitation spectrum from Inelastic Neutron Scattering.(Goodkind etal)
- Still we can not rule out the tiny SS component.
- Our point is that a large body of data needs glass to be explained. We propose a dislocation induced glass as a possible explanation.
- As an aside: it took less time to settle the superfliud 3He story then wat it takes to solve this puzzle.

Evidence against simplistic SS or evidence for glassy picture

- No evidence for a phase coherent flow. No evidence for superflow. (Beamish et al)

Critical velocity in liquid ^{4}He



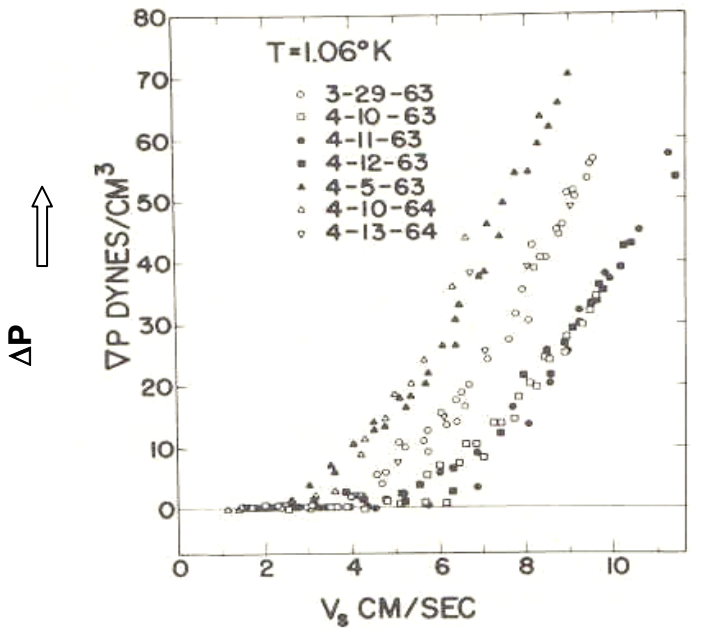
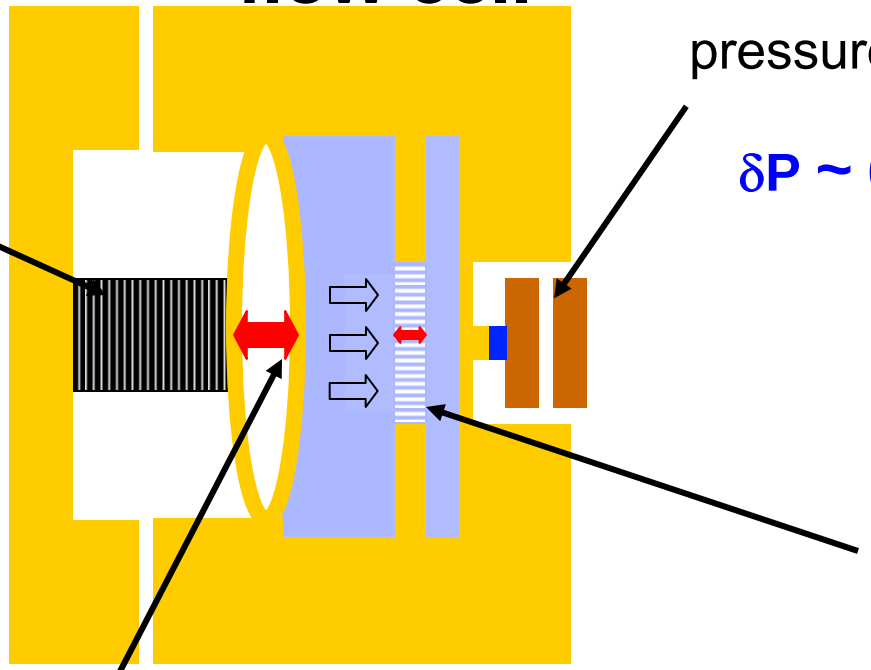


Fig. 8.11. Superfluid dissipation in forced flow.

v_S ⇨

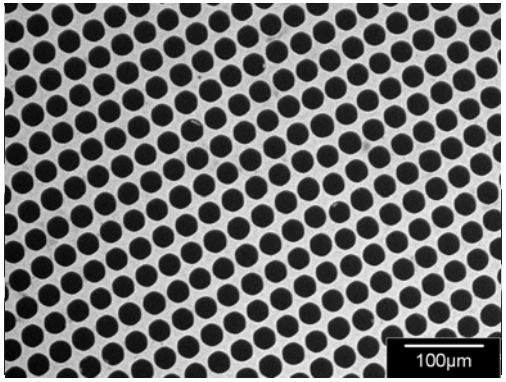
No flow of any kind: Solid helium flow cell



PZT stack

pressure capacitor

$\delta P \sim 0.2$ mbar $\Rightarrow$ $\delta x \sim 0.3$ nm



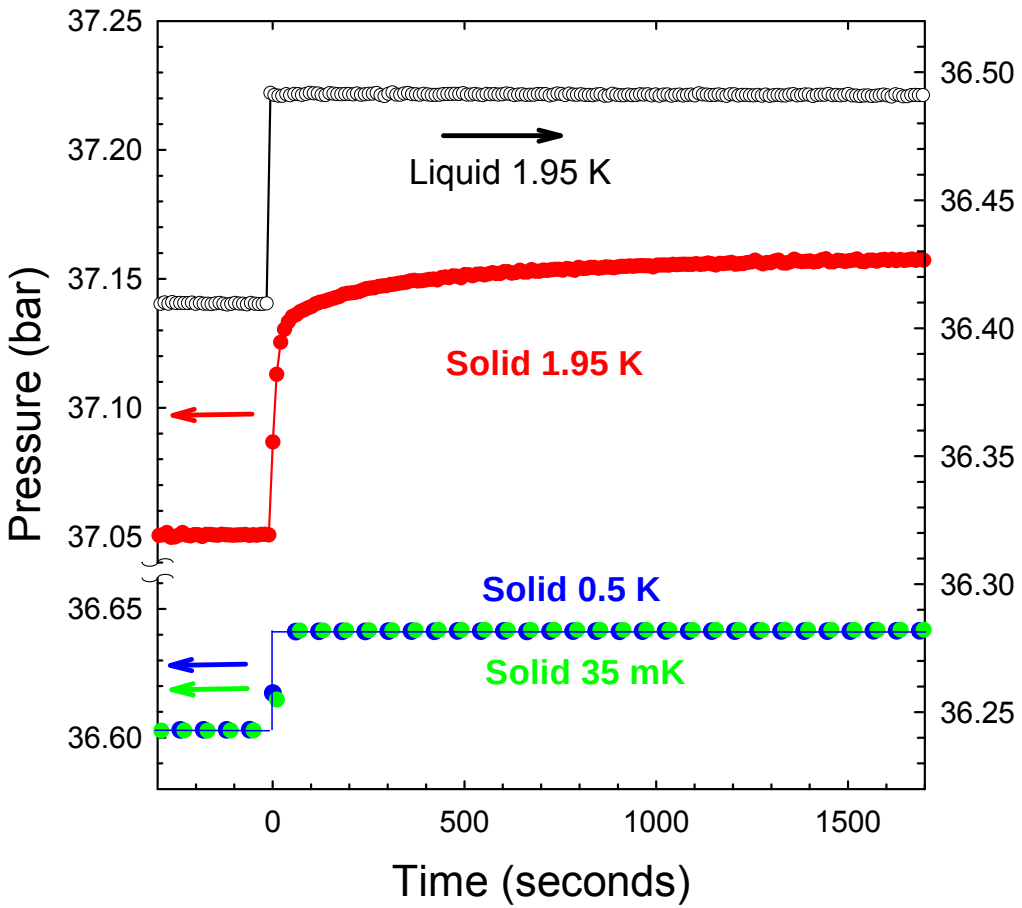
Diaphragm (squeeze):

$\Delta X \sim 1\ \mu m$ $\Rightarrow$ $\Delta P \sim 0.1$ bar

GCA: 36,000 holes
25 µm diameter
3 mm long

flex: $\Delta P \sim 0.1$ bar $\Rightarrow$ $\Delta x \sim 30$ nm

Does the solid flow below 200 mK?

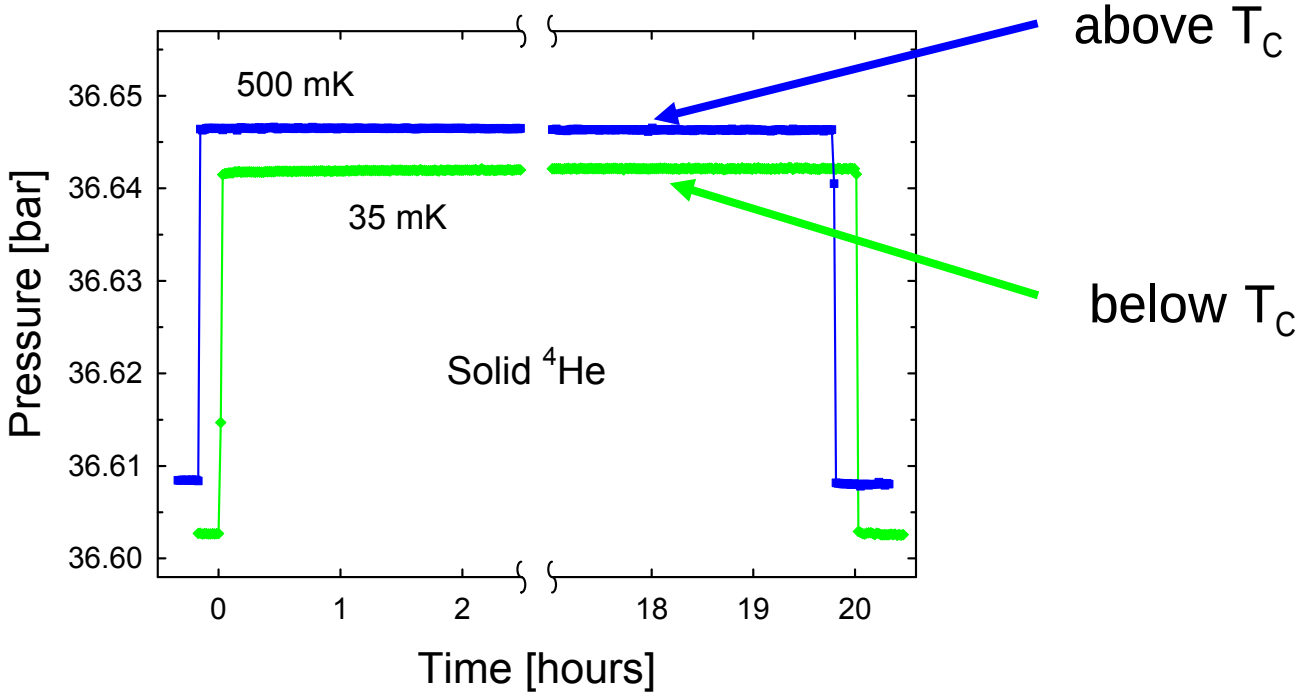


No difference between 500 and 35 mK

i.e. **no superflow**

Upper limit on possible DC superflow?

Isotopically pure ^{4}He (0.002 ppm ^{3}He)



δx < 0.7 nm over 20 hours ⇨ v < 1.2 x 10^{-5} nm/s

No superflow, no mass flow of any kind!

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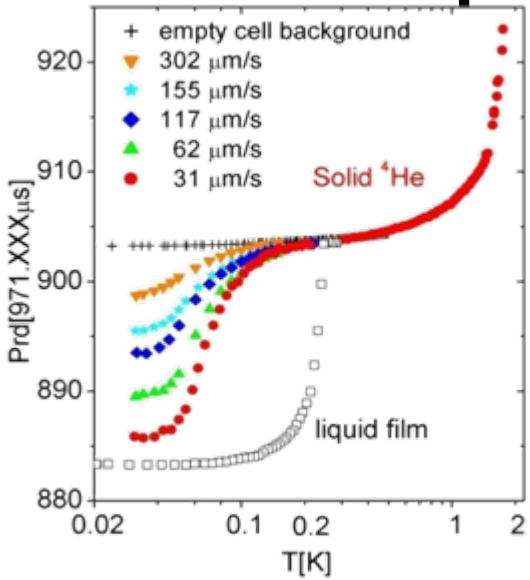
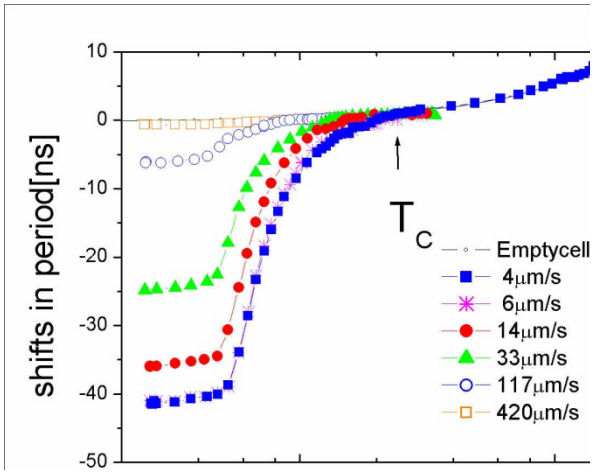
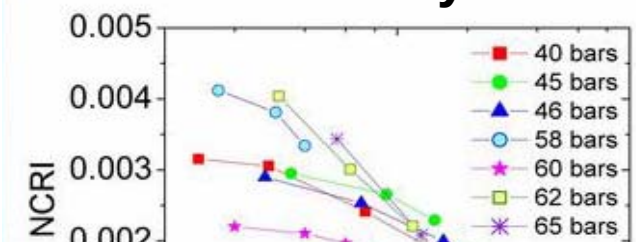
No rim velocity dependence

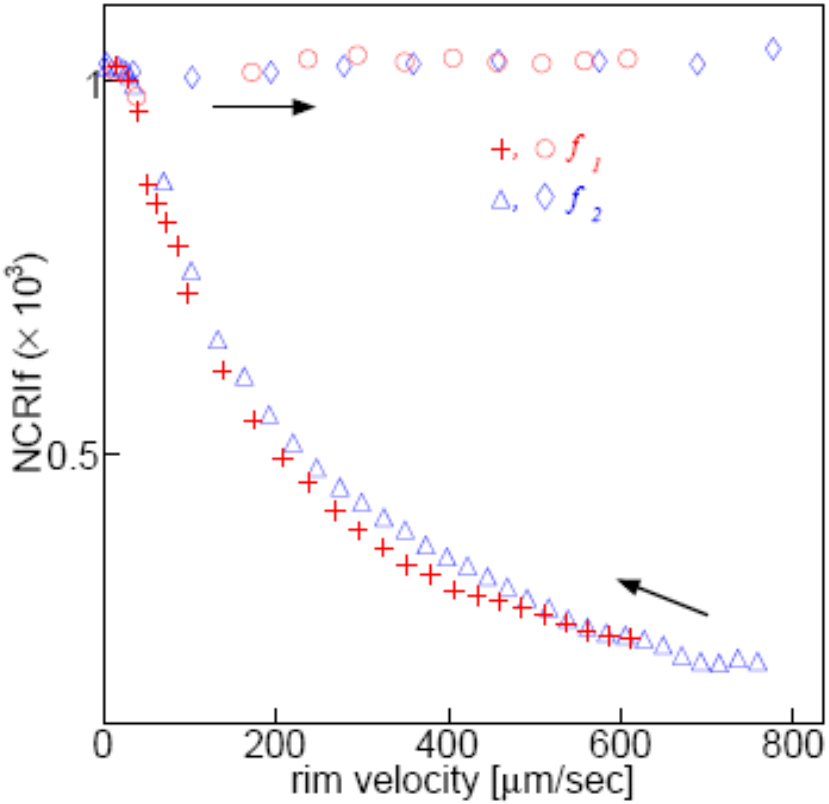
TO decoupling and critical velocity





Solid in Vycor





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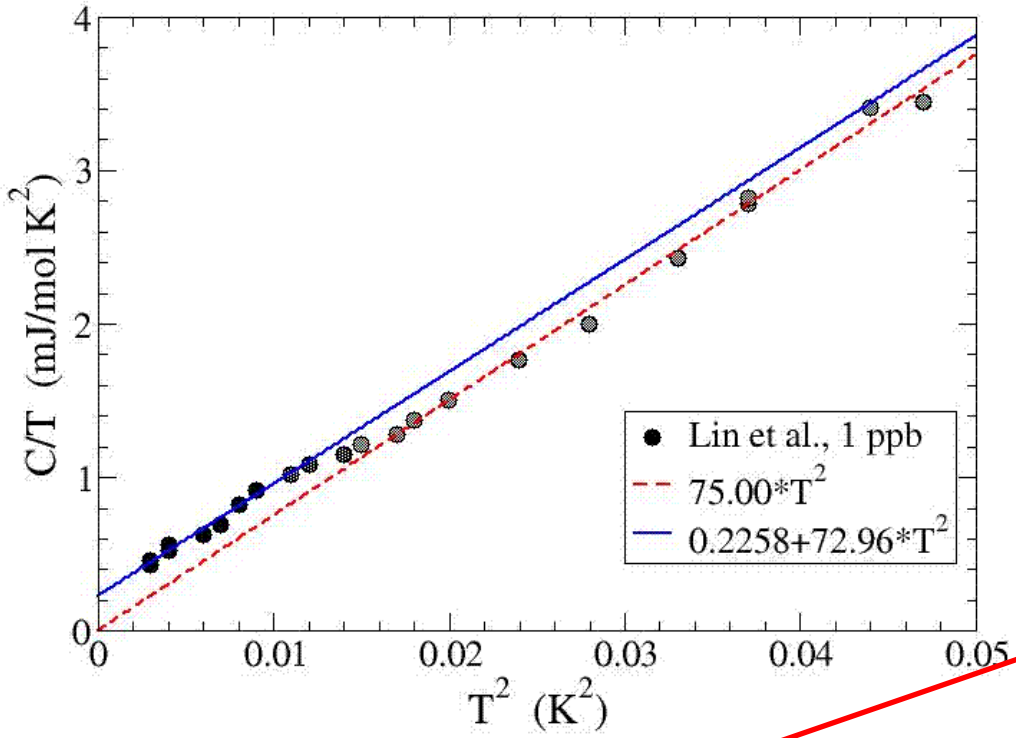
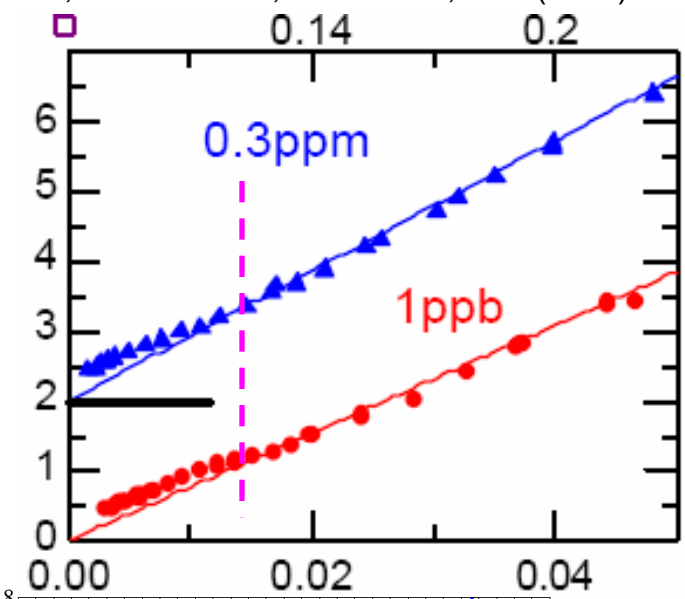
Excess specific heat (2) - Linear term in C

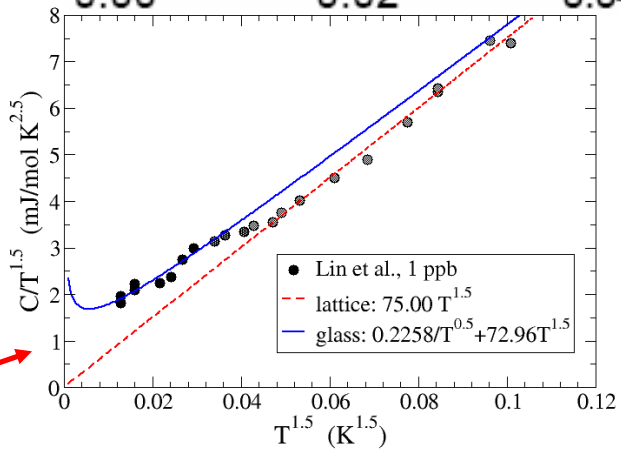
Lin, Clark & Chan, Nature **449**,1025 (2007)

Low temperature (quantum) glass or BEC?

Ultra-pure 1 ppb ^{3}He







1 mJ/(mol K$^{2.5}$)(0.08 K)$^{1.5}$ = 1.4 10^{-6} C_{BEC} $(T_c/T)^{1.5}$

1.4 ppm supersolid fraction?

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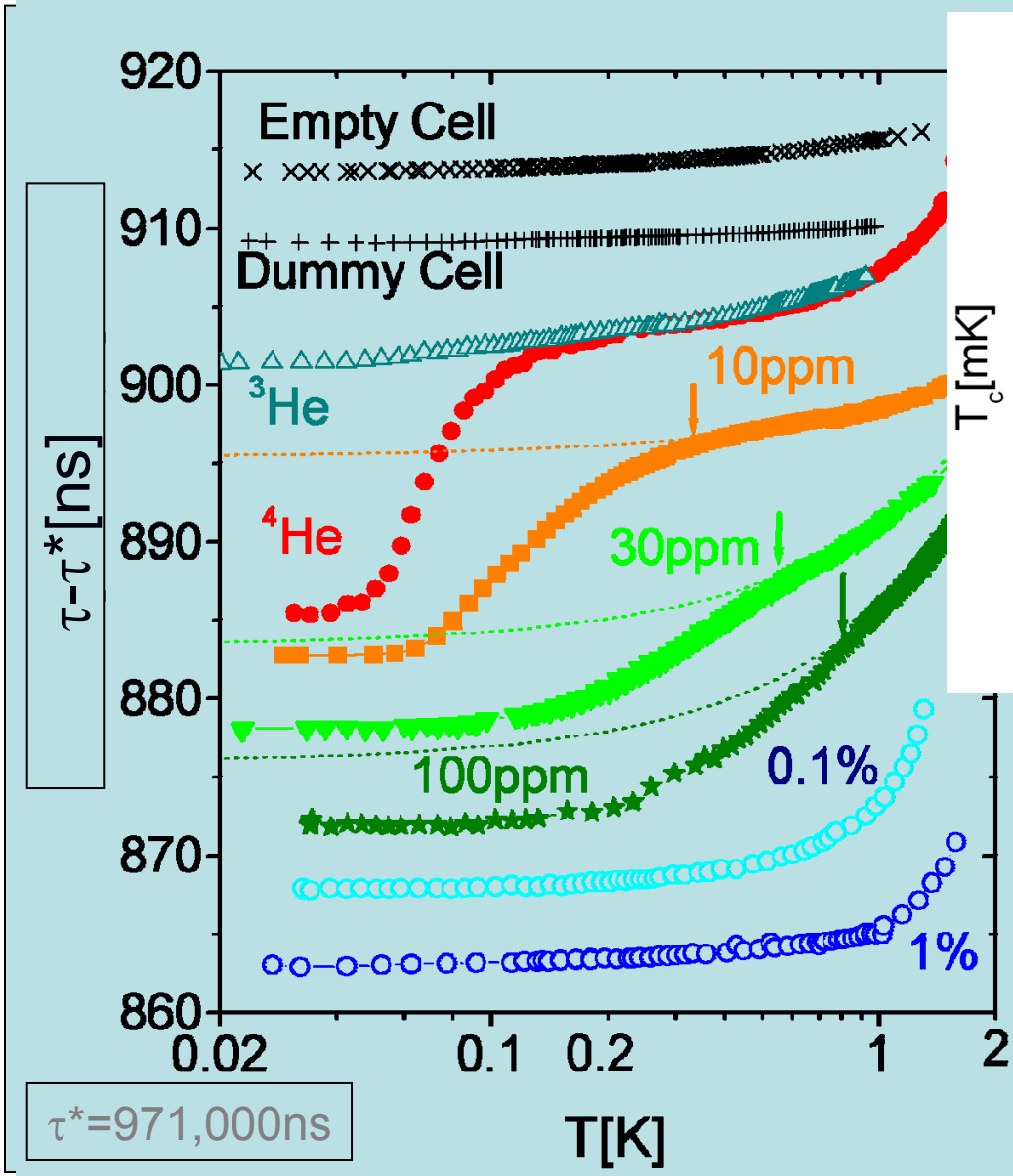
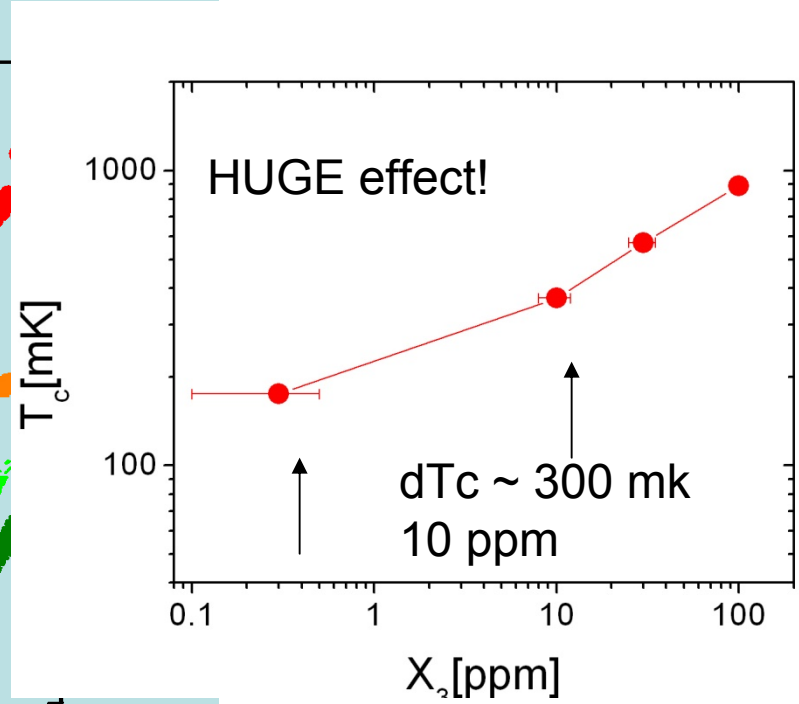
^{4}He solid diluted with a low concentration of ^{3}He



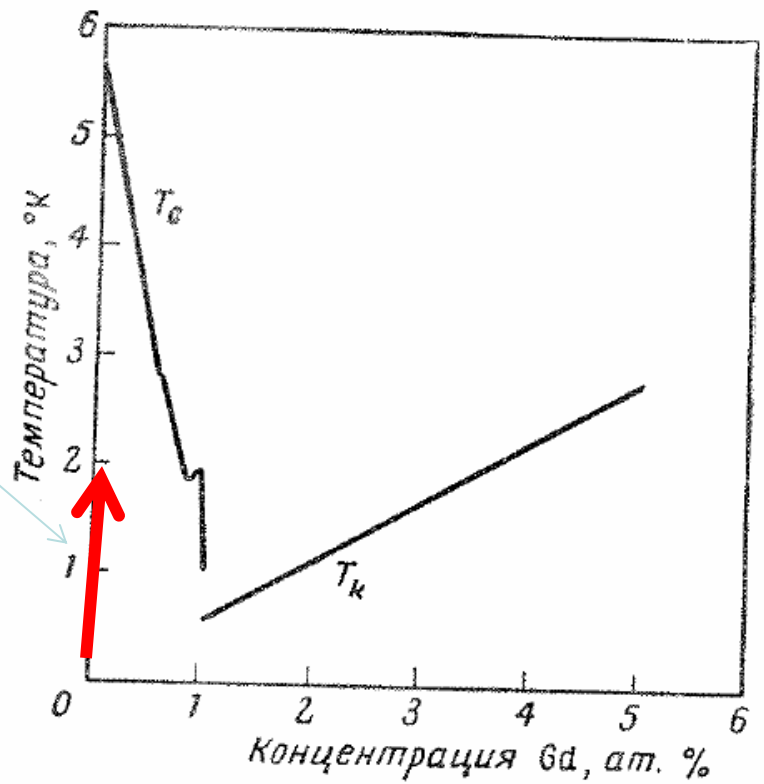


Data shifted vertically for easy comparison

Compare to effect of disorder in conventional SC

Huge slope
And opposite sign!

3He has highly
nontrivial effect
on SS state.
Not a simple add on!



Фиг. 65. Температура перехода сплава LaGd в сверхпроводящее (T_c) и ферромагнитное (T_K) состояния (Маттиас [123]).

Следует отметить сильное понижение сверхпроводящей температуры перехода при добавлении к La небольшого количества магнитных атомов Gd.

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- No evidence for a change in excitation spectrum from Inelastic Neutron Scattering.(Goodkind etal)

No change in Neutron scattering data in SS and solid phase

Roton-like mode in solid ^{4}He

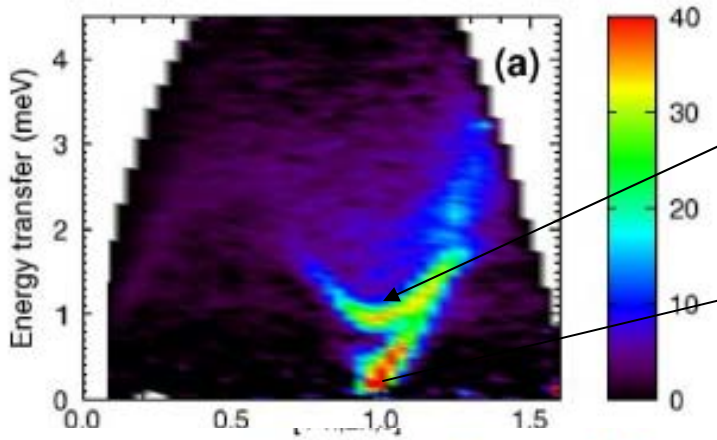
E. Blackburn,[1] S. K. Sinha,[1] C. Broholm,[2] J. R. D. Copley,[3] R. W. Erwin,[3] and J. M. Goodkind[1]

[1] *Physics Department, University of California, San Diego, La Jolla, California 92093, USA*

[2] *Department of Physics and Astronomy, The Johns Hopkins University, Baltimore, Maryland 21218, USA*

[3] *National Institute of Standards and Technology, Gaithersburg, Maryland 20899, USA*

(Dated: February 25, 2008)

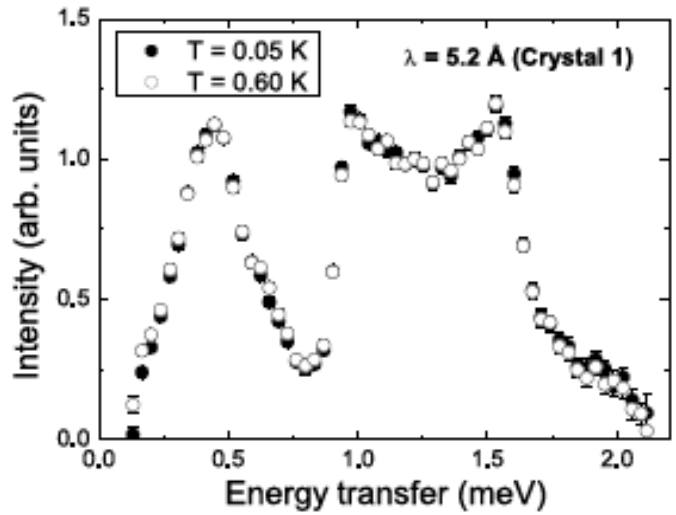


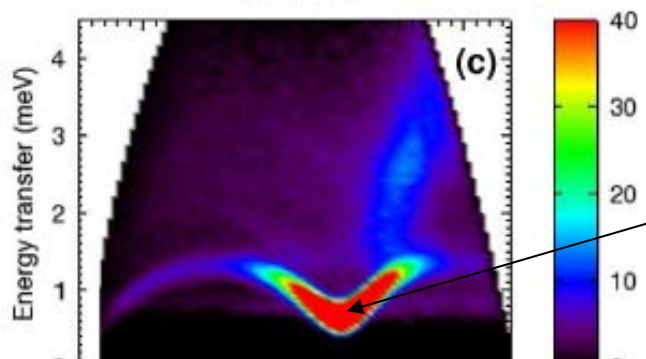
solid

Roton

Or vacancy

sound





liquid

roton

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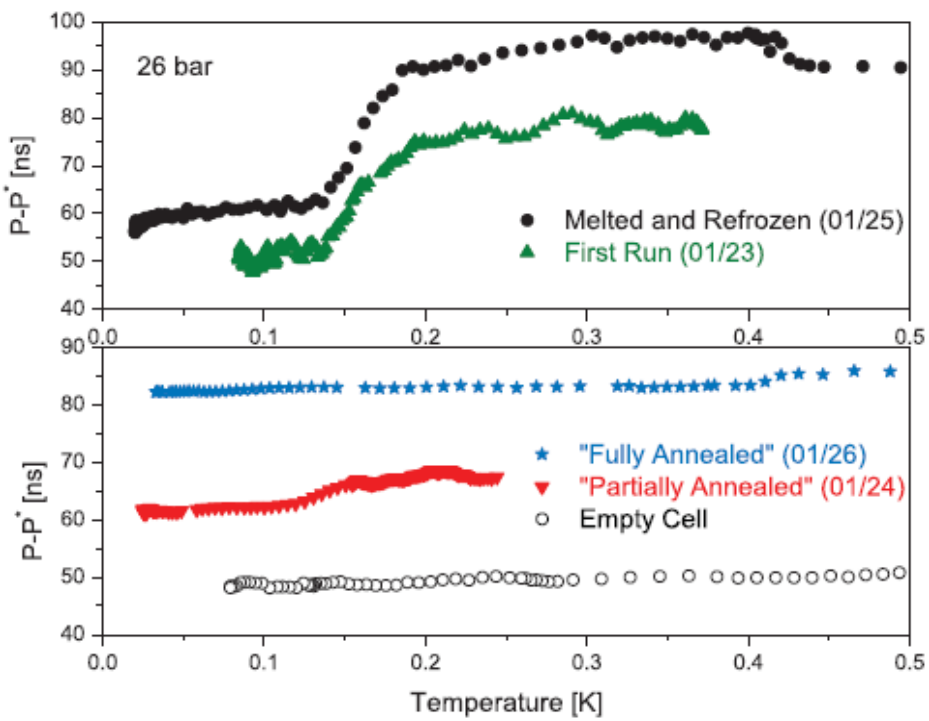
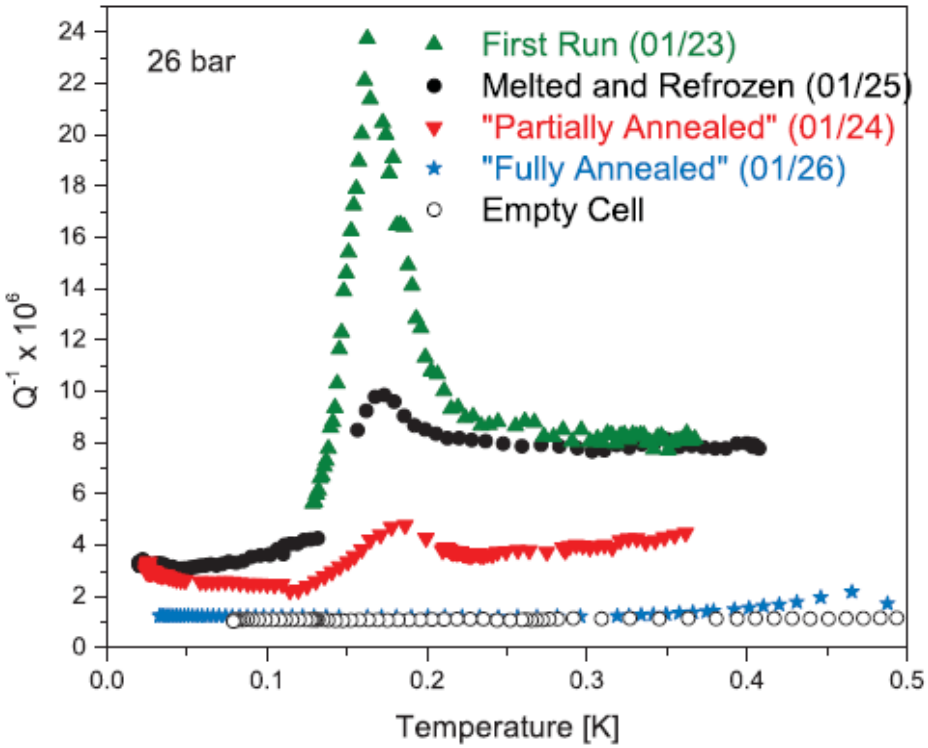
- Still we can not rule out the tiny SS component.
- Our point is that a large body of data needs glass to be explained. We propose a dislocation induced glass as a possible explanation.

Annealing effects

Quenched samples show large NCRI (~0.5%)
Annealed samples show NCRI < 0.05%
Velocities are between 9μm/s and 45μm/s

$f_0 = 185\text{Hz}$

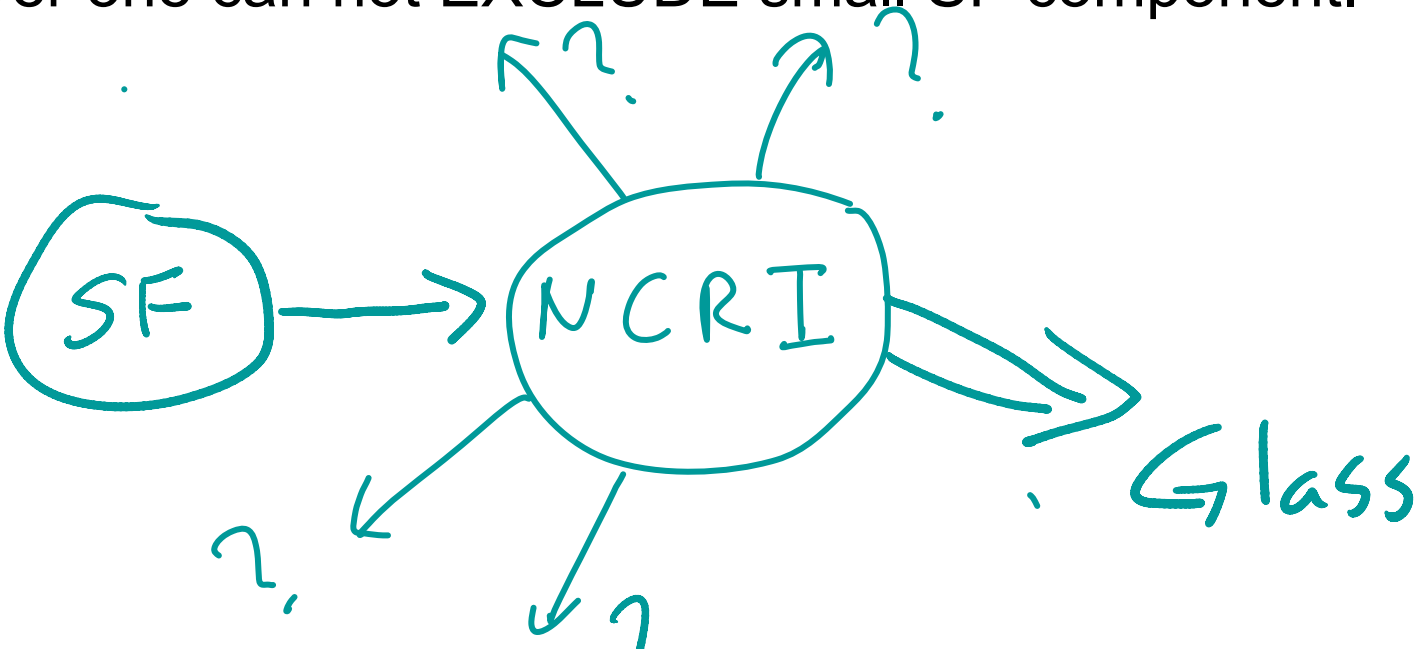




A.S. Rittner & J.D. Reppy, PRL 97, 165301 (2006).

Asymmetry in logic

- In case of SF He4 there were plenty of indications about persistent currents and phase coherent flow.
- Hence the Torsional oscillator experiments are naturally explained by SF.
- Logic does not work in reverse: TO anomaly does not imply Supercomponent. Occham's razor at work.
- To date no evidence of superflow of any kind.
- However one can not EXCLUDE small SF component.



Our point of view

- Definitely a feature seen in mechanical properties of He4.
- Mechanical anomaly and very likely not a Supersolid.
- Effect ranges from 0.1% to 30% and depends on S/V ratio
- Disorder and Glassiness (due to dislocations?) are the key to TO and solid He 4 anomalies seen.
- We developed a glass theory that
- A) allows to FIT the TO anomalies
- B) takes into account the thermodynamic features seen so far.
- Effect of 3He is not a benign add on. It is HUGE, organic and highly unexpected for a phase fluctuation driven superstate.
- Bulk characterization

Articles

1 **AVB and E. Abrahams**, *"Effect of impurities on supersolid condensate: a Ginzburg-Landau approach"*
cond-mat/0602530

Journal of Superconductivity and Novel Magnetism, Vol. 19, Nos. 3–5, July 2006 (© 2006)
DOI: 10.1007/s10948-006-0178-3

2. Thermodynamic considerations, **AVB, M. Graf, Z. Nussinov, and S. A. Trugman**, PRB 75, 094201 (2007); cond-mat/0606203
"Entropy of solid He4: the possible role of a dislocation glass"
Counting number of states across a phase transition.
Counting frozen-in states of a glass.

3. **Z. Nussinov, AVB, M. J. Graf, and S. A .Trugman**
"On the origin of the decrease in the torsional oscillator period of solid He4"
PhysRevB.76.014530, (2007)
Glass and possible non supersolid origin of torsional oscillator anomaly
Causality links dissipation and period.
How to get a peak in dissipation and drop in period?

4. Grigorenk et al, Two frequency TO fits with glass model, cond-mat07****

Thermodynamics and oscillator dynamics of glasses application to “supersolids”

1. Hypothesis: normal glass (due to dislocations?) responsible
- for most of the features
2. Torsional oscillator considerations
- Causality links dissipation and period.
- How to get a peak in dissipation and drop in period?

3. Counting number of states across a phase transition.
- Counting frozen-in states of a glass.
4. Enormous effect of 3He on glass state.

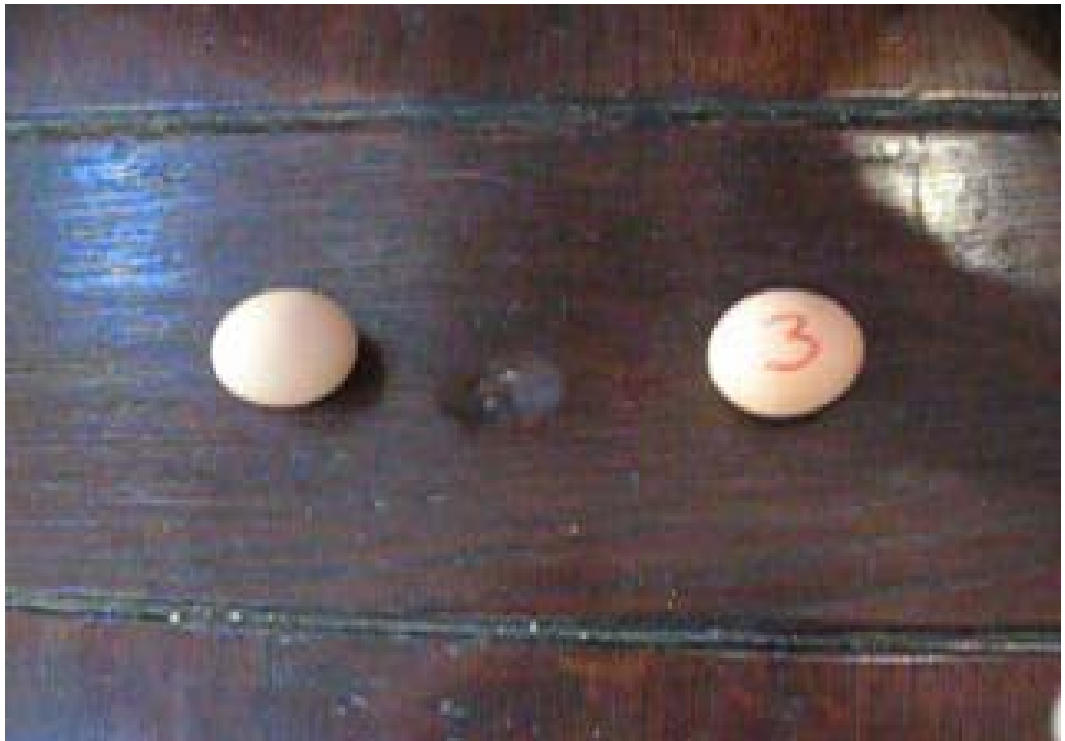
TO anomaly, not supersolid

Oscillation period
Is all that is observed

$$\tau(T) \sim \frac{I(T)}{\sqrt{4\alpha I(T) - \gamma^2(T)}}$$

Change in I(T) leads to NCRI

Change in damping γ(T) also causes change in period . Does not require NCRI to explain the effect.
4He Glass: freezout below 100mK



Simple table top analogy

Spinning an egg: apply external torque (spin) from time $t_{initial} \leq t \leq t_{final}$ and then let go

Hard boiled egg: fast rotation, low dissipation

Soft boiled egg: low rotational frequency, high dissipation

If the egg were an ideal rigid solid and no spurious effects were present: final angular rotation speed

$$\frac{d}{dt}\theta_{final} = \int_{t_{initial}}^{t_{final}} \frac{\tau_{ext}(t')}{I_{eff}} dt'$$

On its own, the change in rotational speed here can also be interpreted in terms of an effective missing moment of inertia in the hard boiled egg relative to that of the soft boiled egg.

General idea about dislocation glass

Balatsky et al., PRB **75**, 094201 (2007)

Nussinov et al., 2007, PhysRevB.76.014530

In any system, the real and imaginary parts of the poles of the angular response function $\chi(\omega, T)$ dictate the period and dissipation.

Any transition of a liquid-like component into a glass (whether classical or an exotic quantum “superglass”) will lead to such an angular response function. We argued it could be dislocation induced. $\chi(\omega, T)$

For sure:

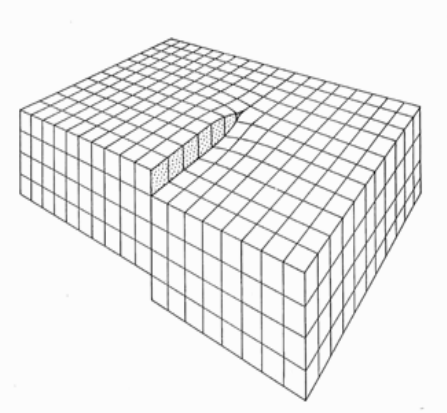
- solid helium has dislocations
- they move easily under stress
- they are pinned by impurities
- annealing removes some dislocations
- they are damped at high T, mobile at low T

Probably:

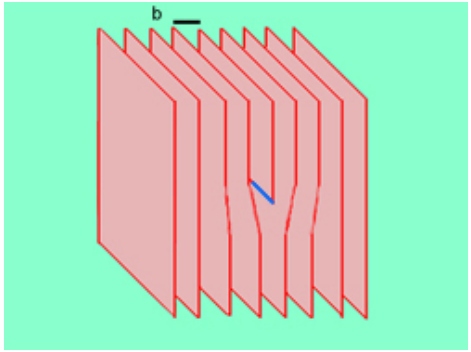
- slip involves edge dislocations in basal plane
- damping due to “fluttering” $B \sim gT^3$
- typical length ~ 5 μm
- ^{3}He binding ~ 0.3 – 0.7 K

Dislocations (non-equilibrium 1D defects)

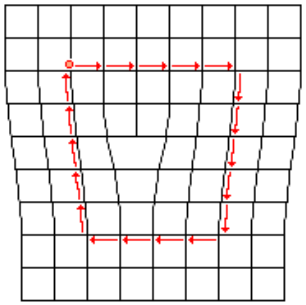
Screw dislocations (crystal growth):

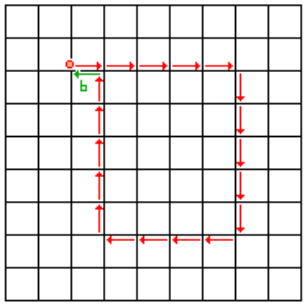


Edge dislocations (slip in hcp helium):



Burgers vector b (elastic strain field):

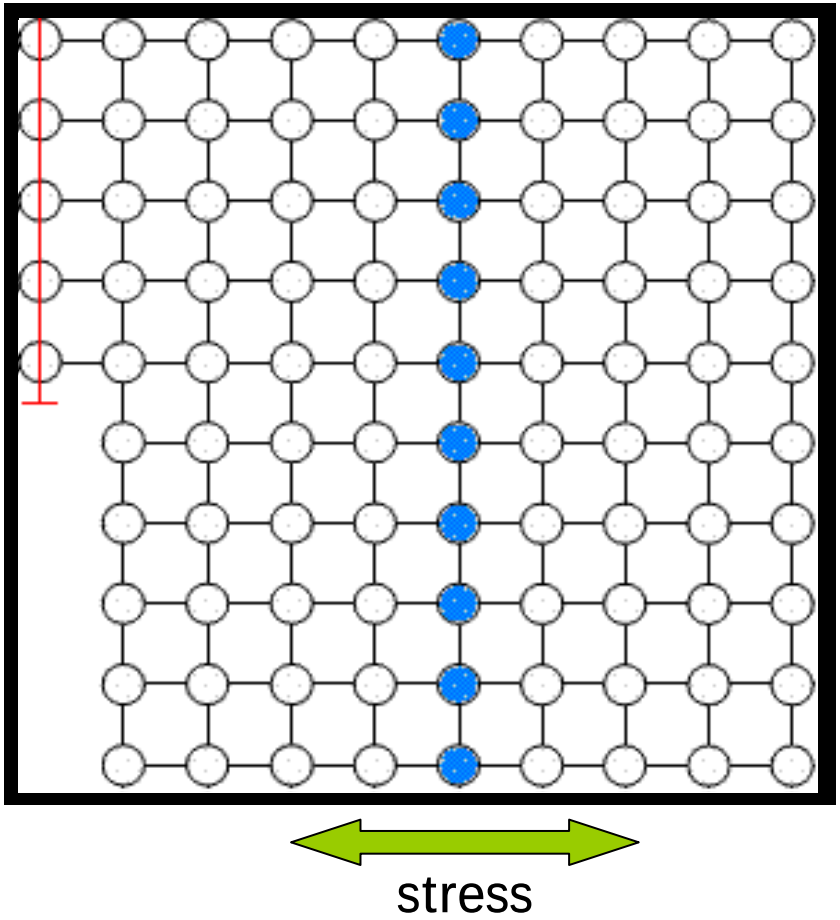




mass transport by motion of dislocations

- dislocations move under the influence of external forces (which cause internal stress in a crystal)

- **movement of a dislocation translates the whole crystal on one side of the glide plane by one lattice spacing relative to the other**
- **Thus it can mimic as a mass decoupling**



The torsional oscillator

Q: What is a torsional oscillator?
A: Oscillator = coupled system of pressure cell + something

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Q: What does torsional oscillator experiment report?
A: Linear response function of coupled system.

$$[I_{osc}\frac{d^2}{dt^2}+\gamma\frac{d}{dt}+\alpha]\theta=\tau_{ext}(t)+\int g(t,t';T)\theta(t')dt'$$

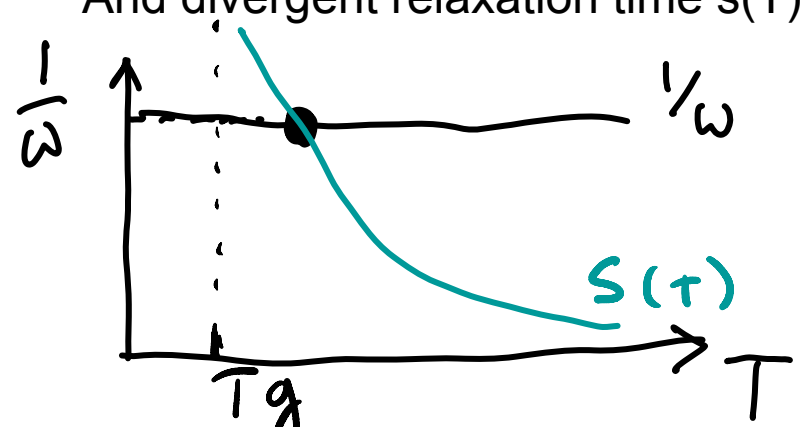
$$\theta(t)=\int dt'\chi(t,t')\tau_{ext}(t')\Rightarrow\theta(\omega)=\chi(\omega)\tau_{ext}(\omega)$$

$$\chi^{-1}=\chi_0^{-1}-g_{gl},\chi_0^{-1}=[\alpha-i\omega\gamma-I_{eff}\omega^2]$$

$$g_{gl}=g_0[1-i\omega s]^{-\beta},s(T)=s_0e^{DT_0/(T-T_0)}$$

Rittner and Reppy, PRL 2006.
Did you notice BeCu? See Todoshchenko's pressure gauge glitch, cond-mat/0703743!

Interplay between fixed frequency
And divergent relaxation time s(T)



Nussinov et al., PRB 2007.

T>>To, T <<To

$$-I\omega^2\varphi - C\varphi - g_{He}\varphi = 0$$

$$g = go(1 + i\omega s(T))$$

$$T >> T0$$

$$-I\omega^2 - (C - go) = 0$$

$$\tau^2 \sim \frac{I}{C - go}$$

$$-I\omega^2\varphi - C\varphi - g_{He}\varphi = 0$$

$$g = go(1 + i\omega s(T))^{\beta}$$

$$T << T0$$

$$-I\omega^2 - C = 0$$

$$\tau^2 \sim \frac{I}{C}$$

Period goes down on cooling
Effective model of backaction of glassy component

Simplifying limiting form (activated dynamics with no distribution of relaxation times)

To avoid the use of too many parameters in any fit, we focus on the simplest- and unphysical- limit of a real glass: that of vanishing transition temperature (activated dynamics) with no distribution of relaxation times.

$$s(T) = s_o \exp[\frac{\Delta}{k_B T}]$$

$$(T_0 \to 0)$$

$$g = \frac{g_0}{1 - i\omega s}$$

$$(\beta = 1)$$

Period and dissipation for simplistic model: activated dynamics

Period:

$$P = \frac{2\pi}{\omega_0 + y}$$

$$y = -\frac{g_0}{2 I_{eff} \omega_0} \frac{1}{1 + (\omega_0 s)^2}$$

Dissipation:

$$Q^{-1} = \frac{1}{\sqrt{\alpha I_{eff}}} \left(\frac{g_0 s}{1 + (\omega_0 s)^2} + \gamma \right)$$

ω_0 – Resonant oscillator frequency in low temperature limit

Cole Davison plot

$$\chi = 1/(1+i\omega s(T))^{\beta}$$

$$\tan\Theta = \omega s$$

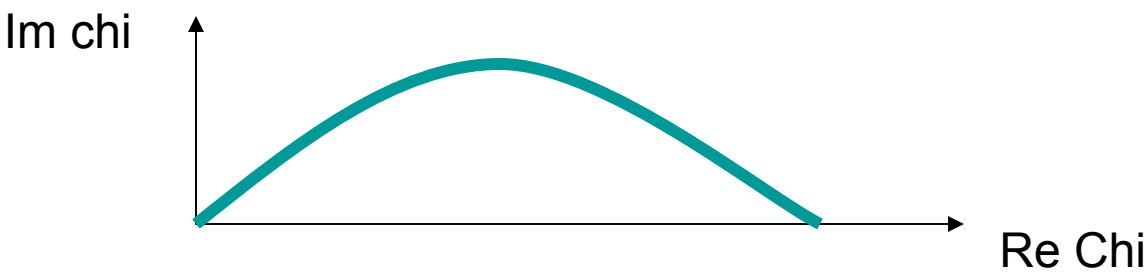
$$\chi'' \sim \sin(\beta\theta), \chi' \sim \cos(\beta\theta), \theta = \omega s$$

$$\chi \sim \exp(i\beta\Theta)$$

χ'' vs χ' an arc

semicircle only for $\beta = 1$

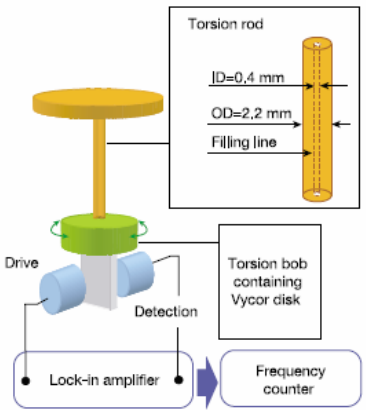
Otherwise it is an arc whose flattness is controlled by beta



Torsional oscillators

Nussinov et al., PRB **76**, 014530 (2007)

- *Q: What is a torsional oscillator?*
  - A: Oscillator = coupled system of pressure cell + something (^{4}He).
- *Q: What does torsional oscillator report?*
  - A: Linear response function of coupled system.



Kim & Chan, Nature (2004)

$$\left(I_{osc} \frac{d^2}{dt^2} + \gamma \frac{d}{dt} + \alpha \right) \theta(t) = \tau_{ext}(t) + \int \tilde{g}(t,t';T)\theta(t')dt'$$

$$\theta(t) = \int dt' \chi(t,t')\tau_{ext}(t') \Leftrightarrow \theta(\omega) = \chi(\omega)\tau_{ext}(\omega)$$

RPA-like response: $\chi^{-1} = \chi_0^{-1} - g$ and $\chi_0^{-1} = [\alpha - i\omega\gamma - I_{eff}\omega^2]$

<u>Supersolid:</u>

$$g_{ss}(\omega,T) \equiv -i\omega\gamma_{ss} - I_{ss}(T)\omega^2$$

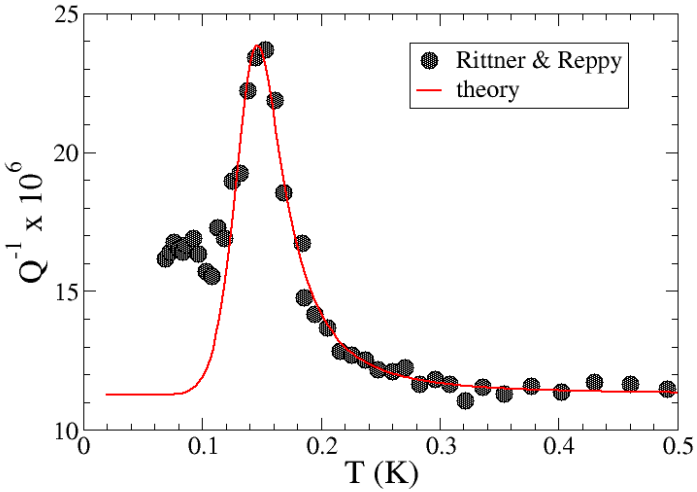
<u>Glass:</u>

$$g_{gl}(\omega,T) \equiv -g_0[1 - i\omega s]^{-\beta}$$

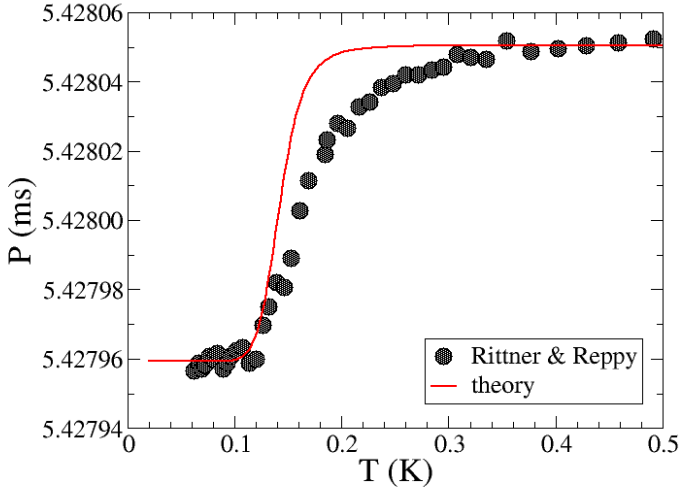
$$s(T) = s_0 e^{DT_0/(T-T_0)}$$

Torsional oscillators - Period and dissipation

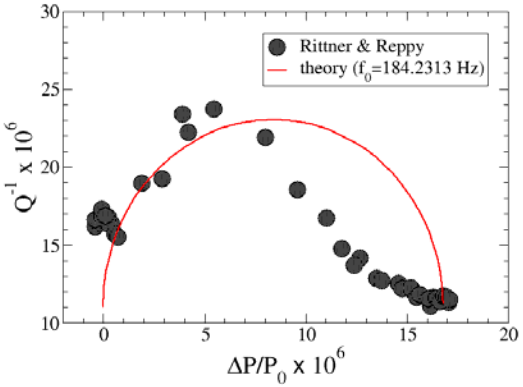
dissipation



period



Davidson-Cole-like plot



Great simplification:

Assumed glass parameter β=1!

Nussinov et al., PRB **76**, 014530 (2007)
Rittner and Reppy, PRL **97**, 165301 (2006)

Coupled torsional oscillators

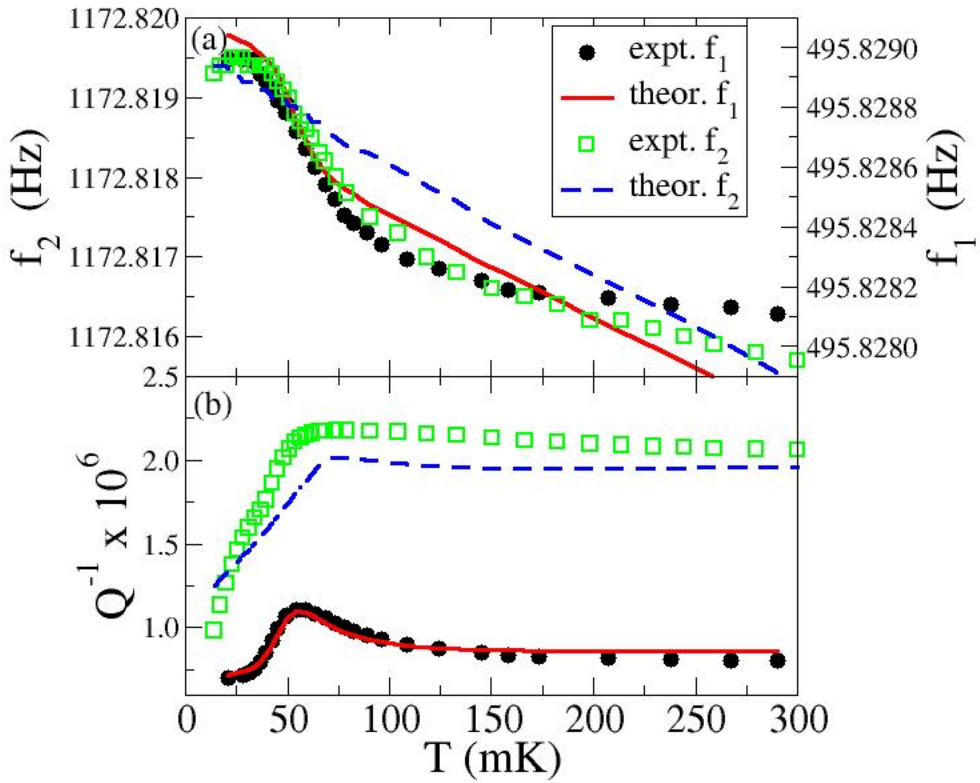
$$\boxed{\begin{aligned} -\omega^2 I_1\phi_1 - i\omega\gamma_1\phi_1 + \alpha_1\phi_1 + \alpha_2(\phi_1-\phi_2) &= 0\,, \\ -\omega^2(I_2+I_{He})\phi_2 - i\omega\gamma_2\phi_2 + g\phi_2 + \alpha_2(\phi_2-\phi_1) &= 0\,. \end{aligned}}$$

with glass term:

$$g(T) = g_0(1-i\omega s)^{-\beta}$$

$$s = s_0 e^{D/(T-T_0)}$$

Fitted glass parameter β=0.8



Data from Aoki, Graves, Kojima, PRL **99**, 015301 (2007)

Phase transition and entropy

•Entropy measures number of states.
•States are redistributed near 2nd order phase transition, even if there is no singularity in C.

BEC (Bose-Einstein Condensation) phase transition

$$C(T) = \frac{15}{4}\frac{\zeta(5/2)}{\zeta(3/2)} R \left(\frac{T}{T_c}\right)^{3/2}$$

$$S_{BEC}(T_c) = 5R$$

Balatsky et al., PRB **75**, 094201 (2007)

Low temperature normal glass

- Two-Level-System (TS) == glass model (tunneling)
  [Anderson, Halperin, Varma (1972), Phillips (1972)] .
- TS leads to linear specific heat at low temperatures!
- Perfect Debye crystal has cubic specific heat at low temperatures.

TS (e.g., dislocation glass):

$$P(E) = P_0 dE$$

$$C_{TS}(E,T) = k_B\left(\frac{E}{k_B T}\right)^2 \frac{e^{E/(k_B T)}}{(1+e^{E/(k_B T)})^2}$$

$$C = AT + BT^3$$

A is with 3He,
B is set by Debye temperature

A term is always present (dislocations) but grows with 3He

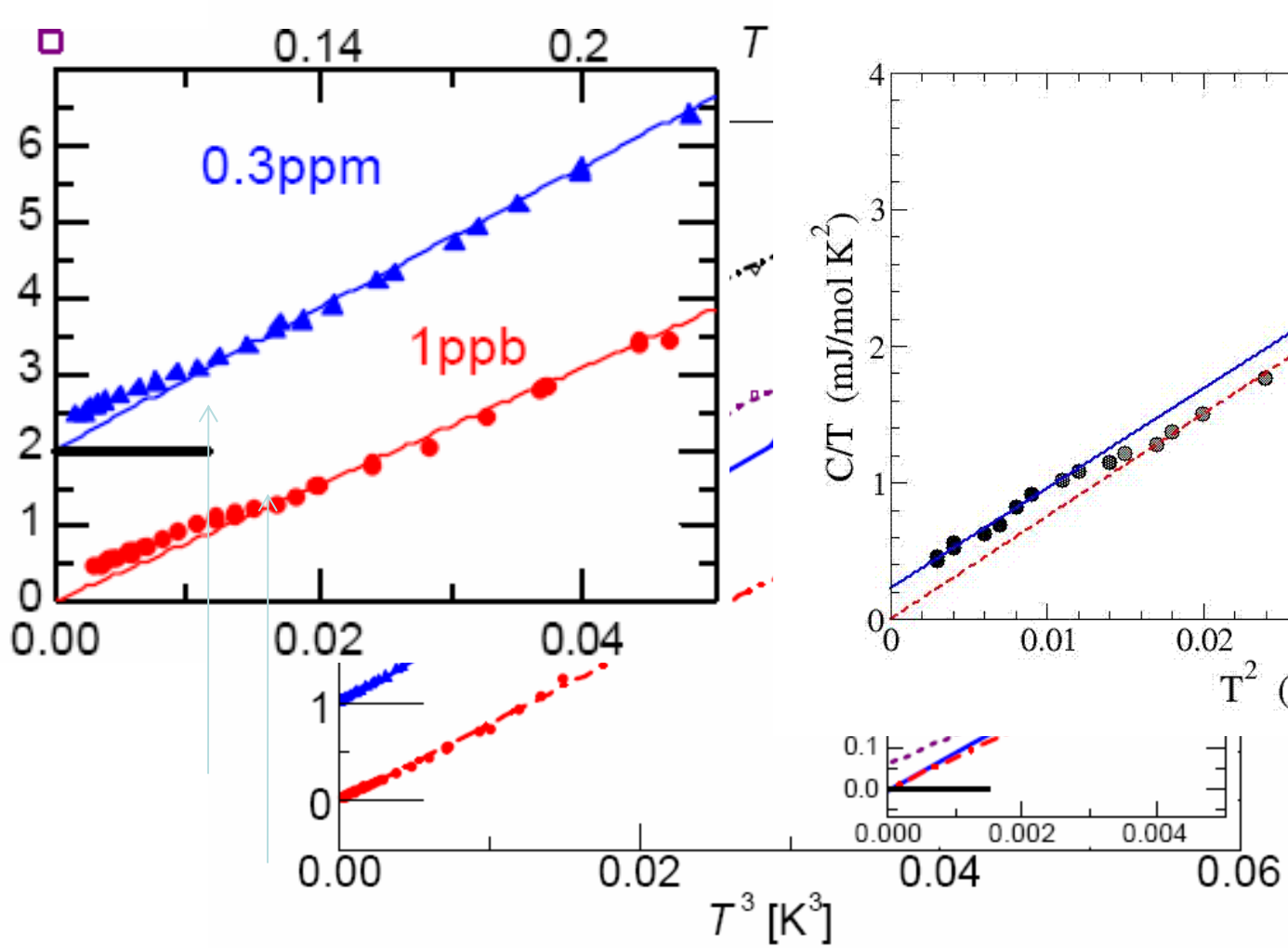
4He is a glass even without 3He.

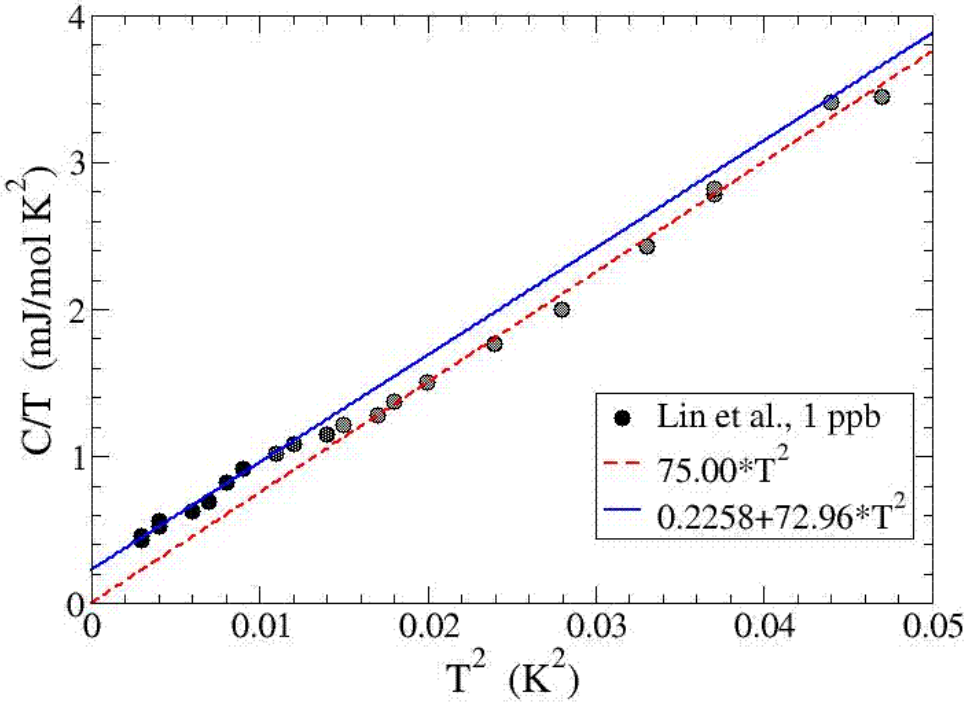
TABLE I. Summary of the linear and cubic coefficients of $C = AT + BT^3$ of solid ^{4}He with ^{3}He as solute, as well as its Debye temperatures Θ_D (Ref. 32). A is from the fits below ~120 mK, while B and Θ_D are from the fits between $200 < T \lesssim 500$ mK. Rough estimates of the uncertainties are in parentheses. For 30 ppm, A is close to zero as expected for this concentration.

^{3}He (ppm)	P (bar)	A [mJ/(K^2 mol)]	B [mJ/(K^4 mol)]	Θ_D (K)
30	39	0.09(4)	155(5)	23.2
760 (cooling)	38	1.4(2)	158(5)	23.1

Compare with recent data by Chan

Is there a linear term in specific heat due to glass?





What is working and where are problems for a normal glass?

• working:
•fits to specific heat
•Fits to torsional oscillator (the only ones so far)
•Annealing effect in some samples.
•No mass superflow in Beamish expts.
•Huge sensitivity to 3He effects.

•Not working(?)
•Blocking annulus: glass state in blocked and non blocked expts are different, need better characterization. Remains to be seen how reproducible it is and if blocking changes stiffness dramatically for the same sample quality.
•“NCRIF” as a function of rim velocity. Demonstrated to be not a general fact(new Chan data, Reppy data).

- **arXiv.org Search Results**
- Back to Search form | Next 25 resultsThe URL for this search is http://arxiv.org/find/cond-mat/1/ti:+supersolid/0/1/0/all/0/1
- **Showing results 1 through 25 (of 99 total) for ti:supersolid**
- 1. arXiv:0804.3364 [ps, pdf, other]
  - Title: A Unitary Fermi Supersolid: The Larkin-Ovchinnikov Phase
  - Authors: Aurel Bulgac, Michael McNeil Forbes
  - Comments: 4 pages, 3 figures, RevTeX4
  - Subjects: Superconductivity (cond-mat.supr-con); High Energy Physics - Phenomenology (hep-ph); Nuclear Theory (nucl-th)
- 2. arXiv:0804.1547 [ps, pdf, other]
  - Title: Supersolid state of ultracold fermions in an optical lattice
  - Authors: Akihisa Koga, Takuji Higashiyama, Kensuke Inaba, Seiichiro Suga, Norio Kawakami
  - Comments: 4 pages, 4 figures
  - Subjects: Superconductivity (cond-mat.supr-con)
- 3. arXiv:0804.0494 [ps, pdf, other]
  - Title: Stability of superfluid and supersolid phases of dipolar bosons in optical lattices
  - Authors: Ippei Danshita, Carlos A. R. Sá de Melo
  - Comments: 4 pages, 4 figures
  - Subjects: Other (cond-mat.other)
- 4. arXiv:0803.1116 [ps, pdf, other]
  - Title: Vacancy supersolid of hard-core bosons on the square lattice
  - Authors: Long Dang, Massimo Boninsegni, Lode Pollet
  - Comments: 4 pages, 8 figures
  - Subjects: Statistical Mechanics (cond-mat.stat-mech)
- 5. arXiv:0802.1991 [ps, pdf, other]
  - Title: Low-energy and relativistic dynamics of supersolids: variational principle
  - Authors: A.S. Peletminskii
  - Comments: 12 pages, submitted to PRB
  - Subjects: Statistical Mechanics (cond-mat.stat-mech)
- 6. arXiv:0802.0458 [ps, pdf, other]
  - Title: Ground state and thermal transitions in Field Induced spin-Supersolid Phase
  - Authors: P. Sengupta, C. D. Batista
  - Comments: To appear in the Journal of Applied Physics as proceedings of the 52nd. Magnetism and Magnetic Materials Conference, Tampa, Fl
  - Subjects: Strongly Correlated Electrons (cond-mat.str-el)
- 7. arXiv:0801.3984 [ps, pdf, other]
  - Title: Effects of fluctuations in the superfluid-supersolid phase transition on the lattice
  - Authors: Ralf Schützhold, Michael Uhlmann, Uwe R. Fischer
  - Comments: 4 pages of RevTex4

Conclusion

- Definitely a feature seen in mechanical properties of He4.
- Mechanical anomaly and not clear it is a Supersolid.
- Effect ranges from 0.1% to 30% and depends on S/V ratio
- Disorder and Glassiness (due to dislocations?) are the key to TO and solid He 4 anomalies seen.
- We developed a glass theory that
- A) allows to FIT the TO anomalies
- B) takes into account the thermodynamic features seen so far.
- Effect of 3He is not a benign add on. It is HUGE, organic and highly unexpected for a phase fluctuation driven superstate.
- Needed: blocked annulus experiment on 70% samples (Reppy)
- Bulk characterization to correlate structure to TO anomaly