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Workshop on Supersolid 2008

18 - 22 August 2008

Effects of crystal structure and statistics on defects and the elastic properties of solid helium

J. Beamish
University of Alberta, Canada

Effects of Crystal Structure and Statistics on the Elastic Properties of Solid Helium

John Beamish
James Day
Alex Syshchenko

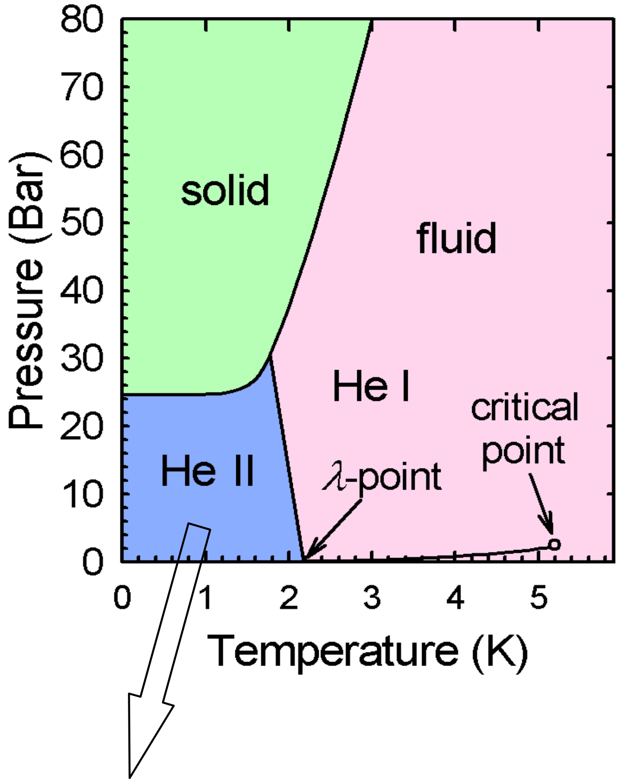
University of Alberta

Josh West
Tony Clark
Moses Chan …

Outline

- **supersolidity** in helium – TO experiments
- **shear modulus** anomaly in ^{4}He
- **dislocations** in helium and elastic behavior
- ^{3}**He** vs. ^{4}He (and bcc vs. hcp)

^{4}He phase diagram



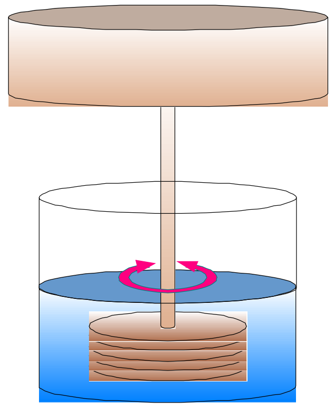
Superleaks

Persistent currents

Second sound

Hydrodynamic heat flow …

Torsional oscillator



Period

$$P \propto \sqrt{\frac{I_o + I_{He}}{k}}$$

Two fluid model

$$\rho_{He} = \rho_n + \rho_s$$

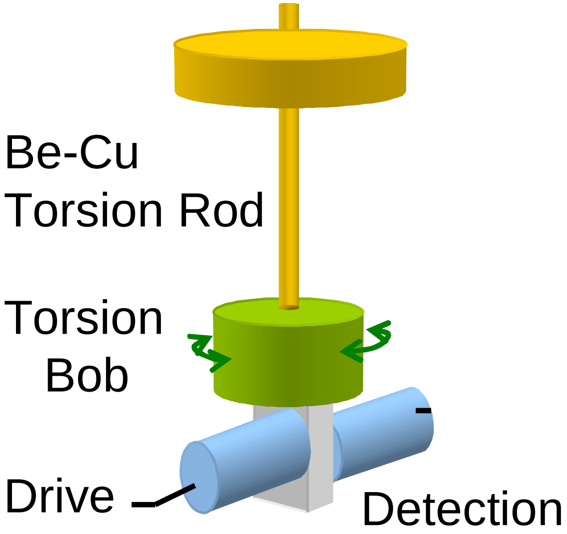
superfluid component decouples

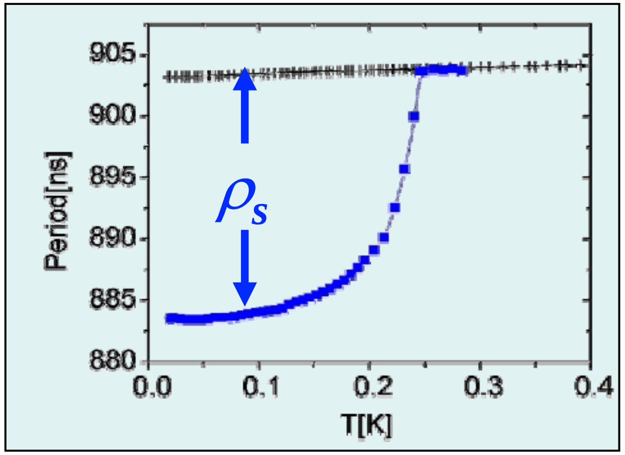
$\Rightarrow$ I_{He} decreases

$\Rightarrow$ **period decreases**

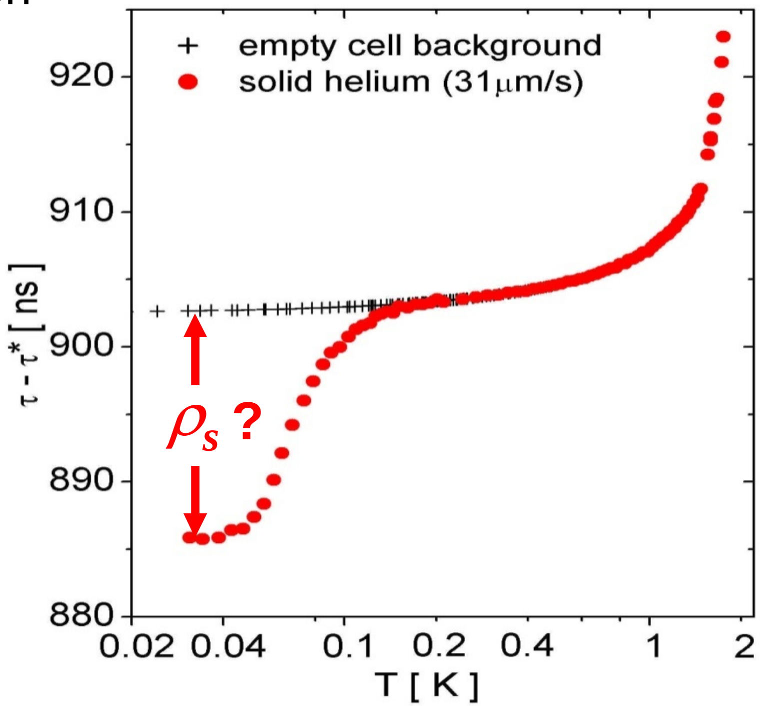
(frequency increases)

Kim and Chan (2004)



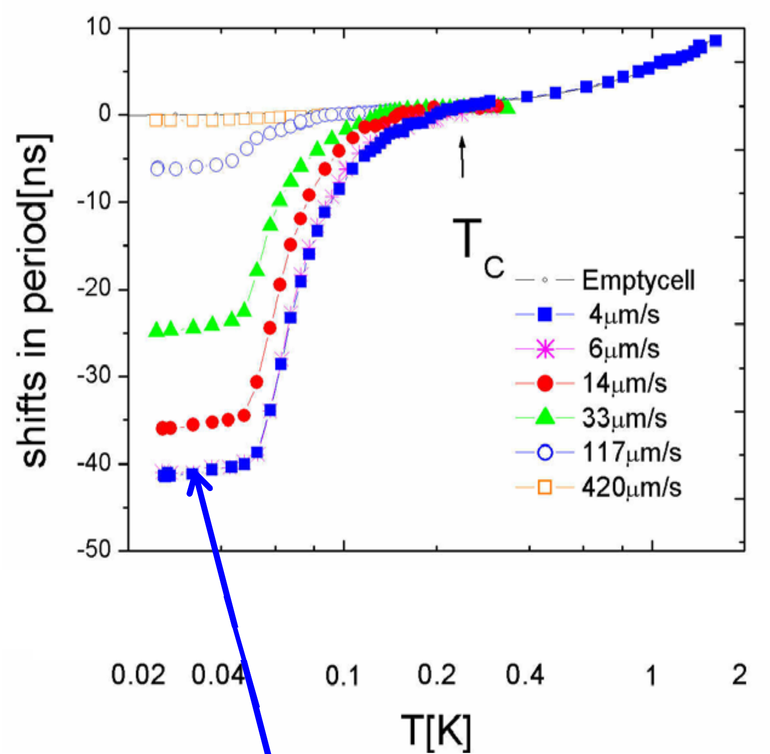


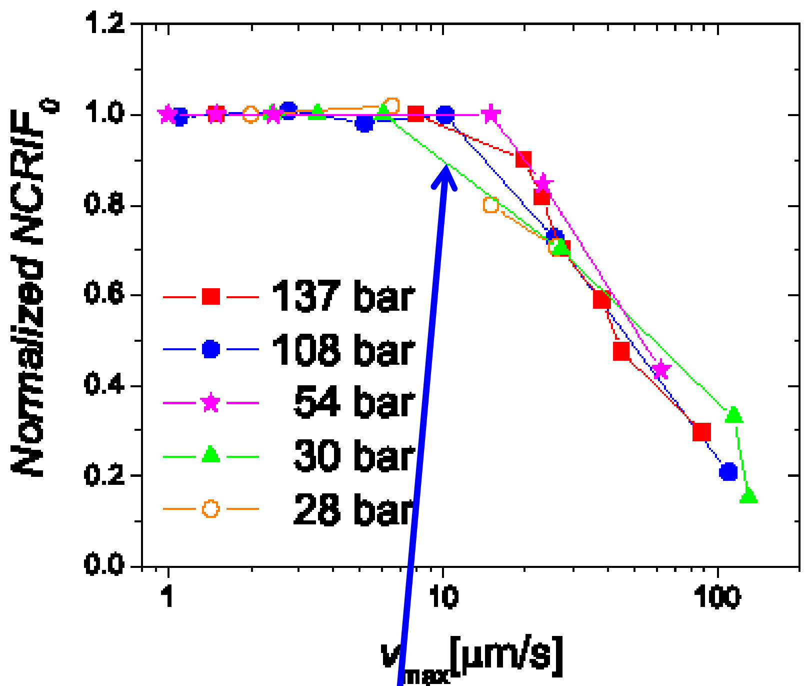
Superfluid film
on vycor



Solid ^{4}He
in vycor

Bulk ^{4}He: decoupling and amplitude dependence





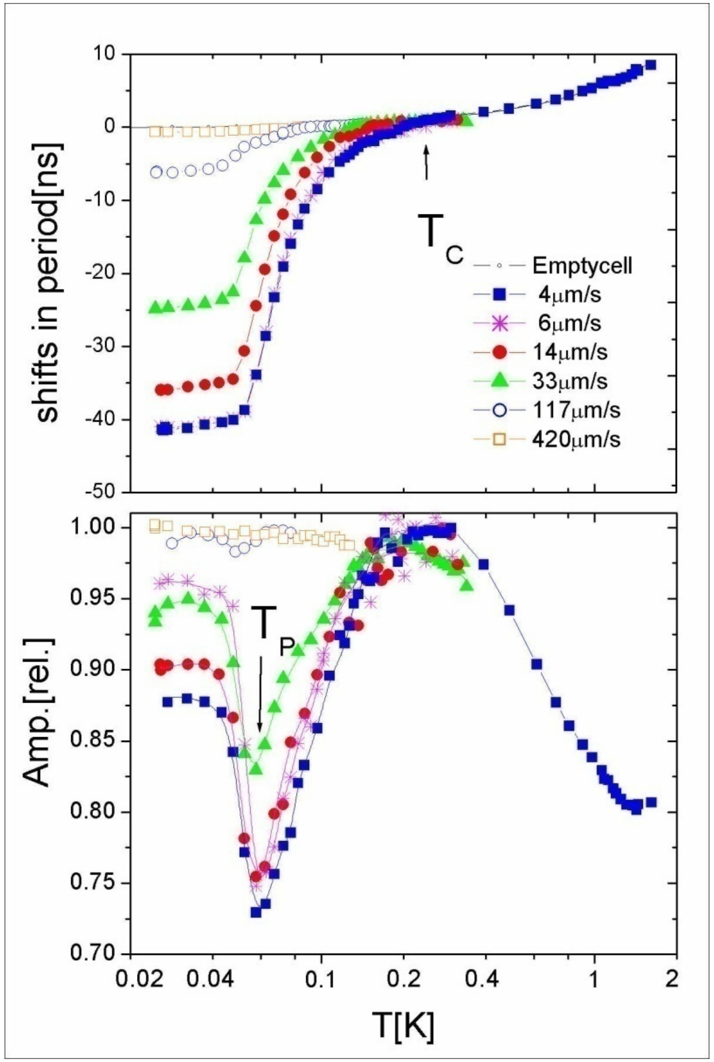
"non-classical rotational inertia"

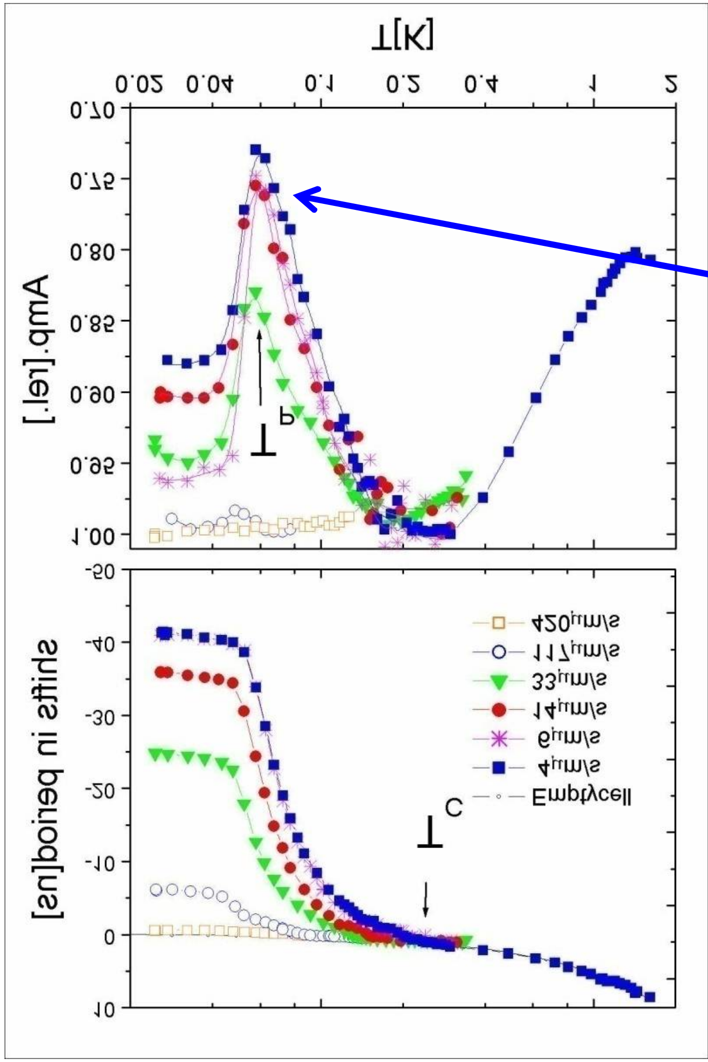
NCRI ~ 1%

critical velocity (at 910 Hz)

V_c ~ 10 μm/s

TO decoupling and dissipation





Dissipation peak
where NCRI
is changing

E. Kim & M.H.W. Chan, Science 305, 1941 (2004)

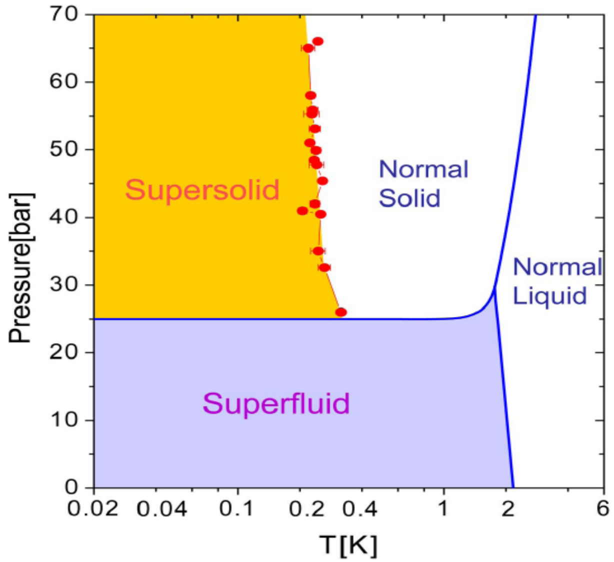
Torsional oscillator measurements
(confirmation of NCRI)

MHW Chan group (Penn State)

and 7 other groups:

Keio University (Shirahama)
ISSP (Kubota)
Cornell (Reppy, Davis)
Rutgers (Kojima)
KAIST (Kim)

“supersolid phase diagram”



NCRI: ~0.015% to ~16%
(in different cells)

T_C : ~ same in different cells
~ independent of pressure

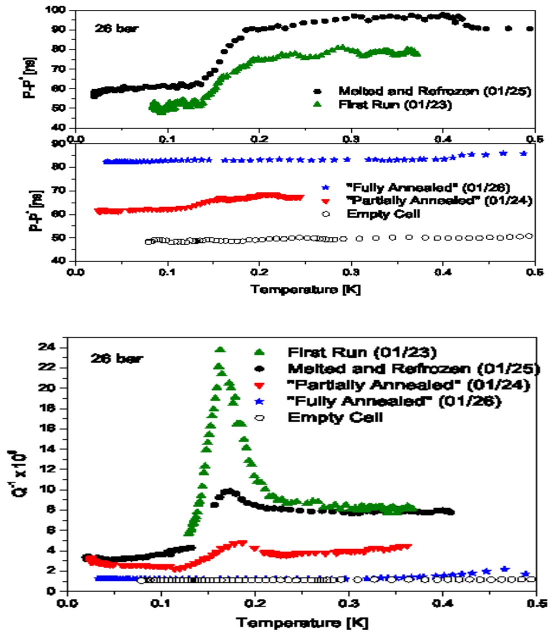
What about other properties, e.g. superflow, elasticity?

Role of defects in supersolid behavior?

Annealing effects

(but not all experiments
show large effects)

Rittner and Reppy (2006)



NCRI and dissipation
reduced/eliminated

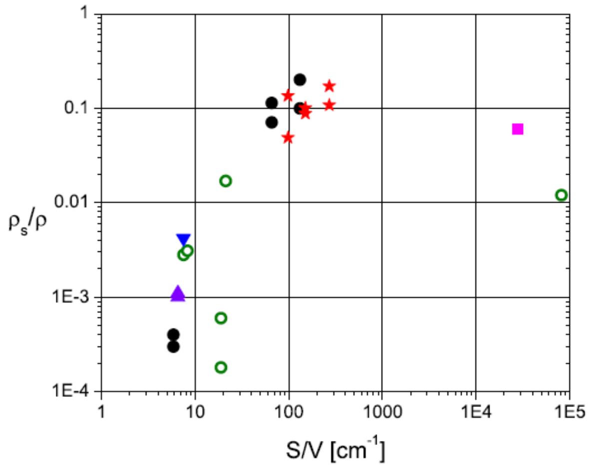
Role of defects in supersolid behavior?

Annealing effects

(but not all experiments
show large effects)

Wide variation in NCRI (0.015 % to 16%)

(seems to depend
on S/V ratio of cell)

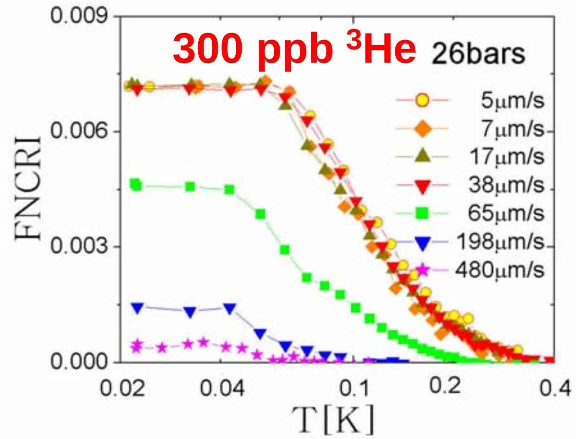


Role of defects in supersolid behavior?

MHW Chan et al.

Annealing effects

(but not all experiments show large effects)



Wide variation in NCRI (0.015 % to 16%)

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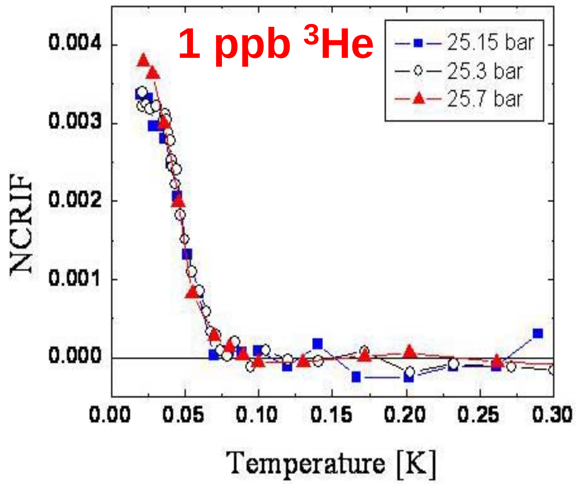


Sensitivity to ^{3}He impurities

(for x_3 below ppm)

Theory/PIMC: “no supersolidity in a commensurate perfect crystal” (either zero point vacancies or defects needed)

Why measure the elastic shear modulus?

• "a solid is something which hurts when you kick it" - PWA

i.e. a non-zero shear modulus μ at low frequency is a fundamental property distinguishing a solid from a liquid (and a supersolid from a superfluid?)

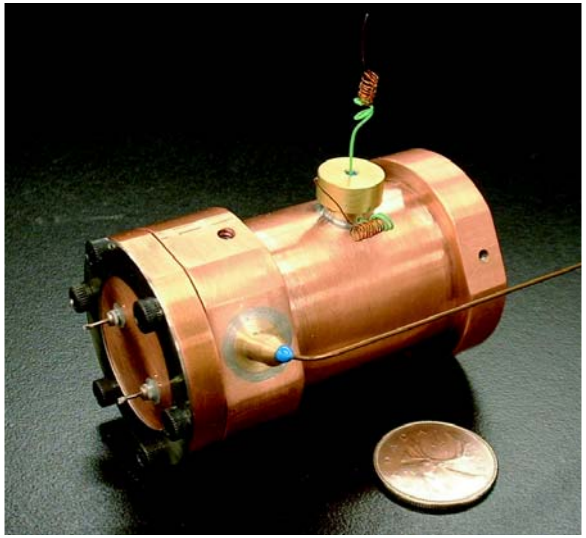
• it is a good probe of defect behavior (especially dislocations, which respond directly to shear stress)

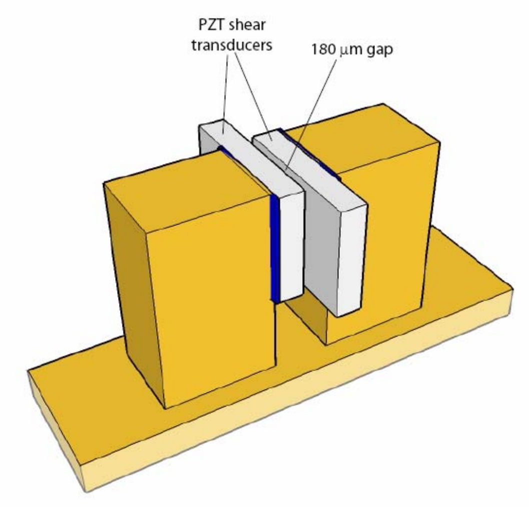
• sound modes depend on both μ and ρ

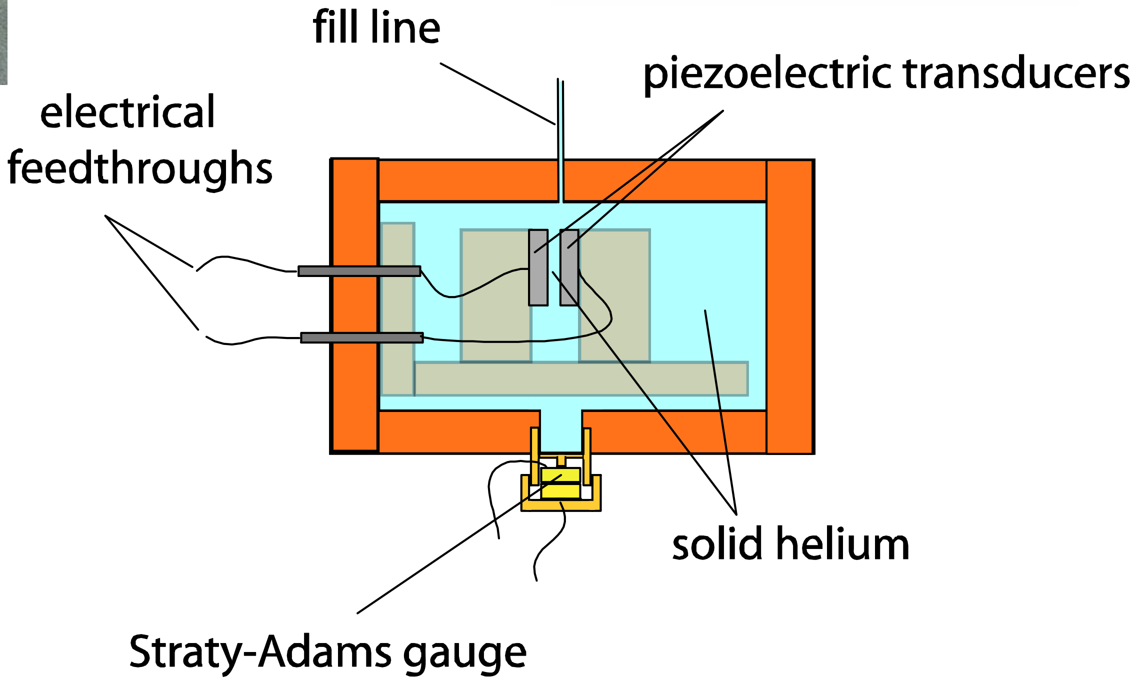
(measuring μ is complementary to TO's which measure ρ)

$\Rightarrow$ measure μ directly, at TO frequencies and low stress/strain

Shear modulus cell

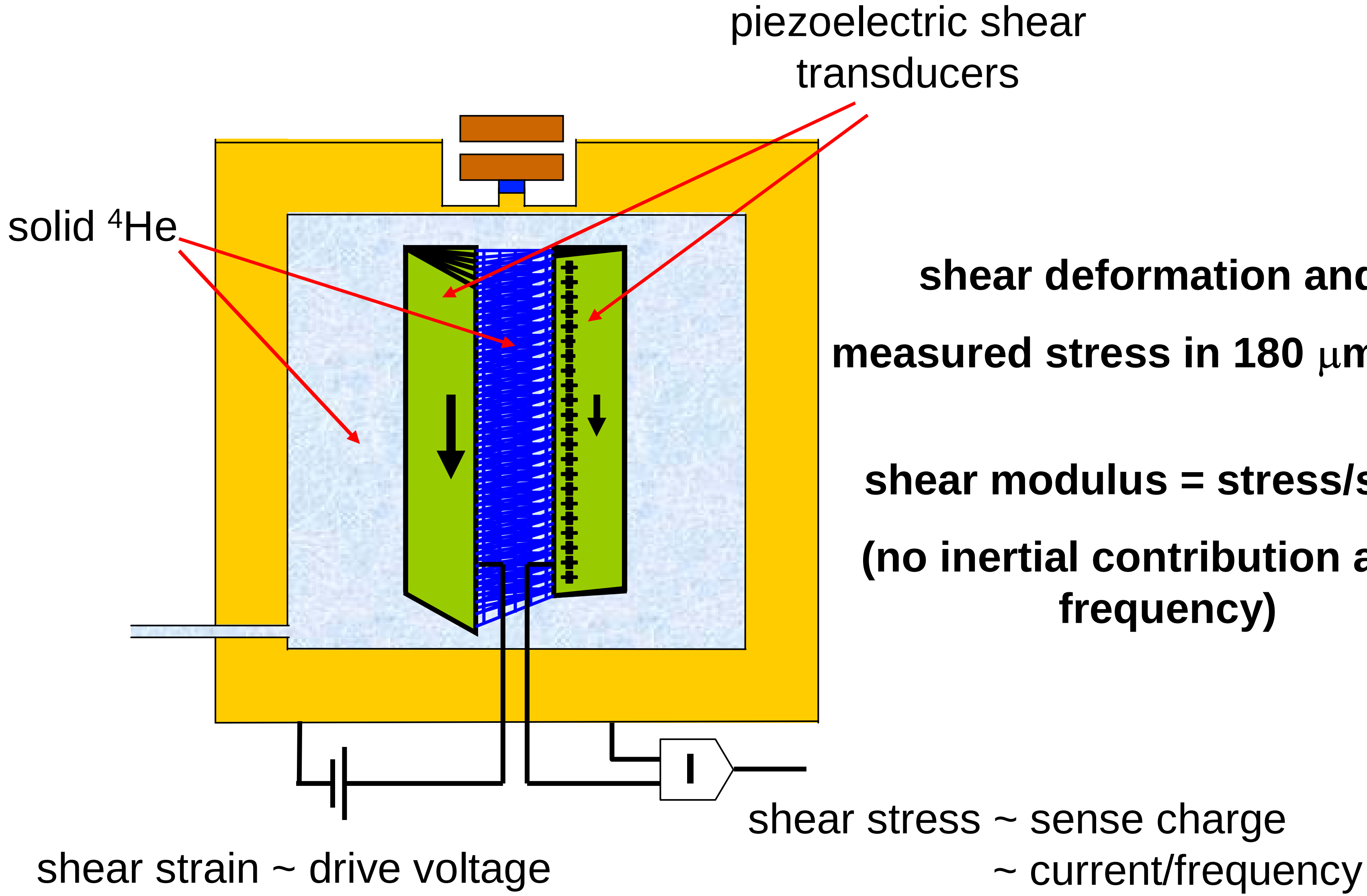






Direct shear modulus measurements

(variable frequency, amplitude)



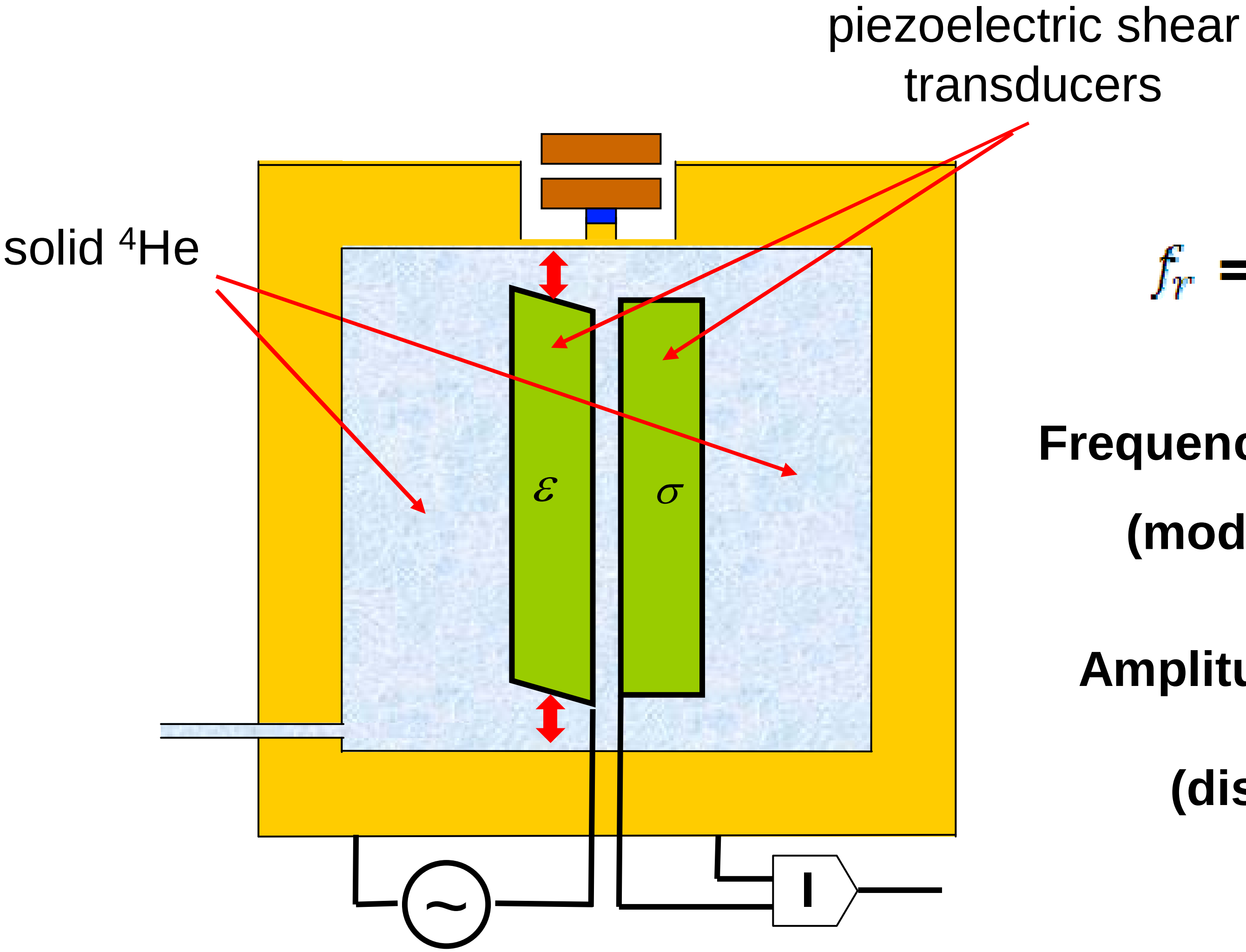
shear deformation and

measured stress in 180 μm gap

shear modulus = stress/strain

(no inertial contribution at low frequency)

Acoustic resonance in cell



$$f_r = \frac{v}{2L} \propto \sqrt{\frac{\mu}{\rho}}$$

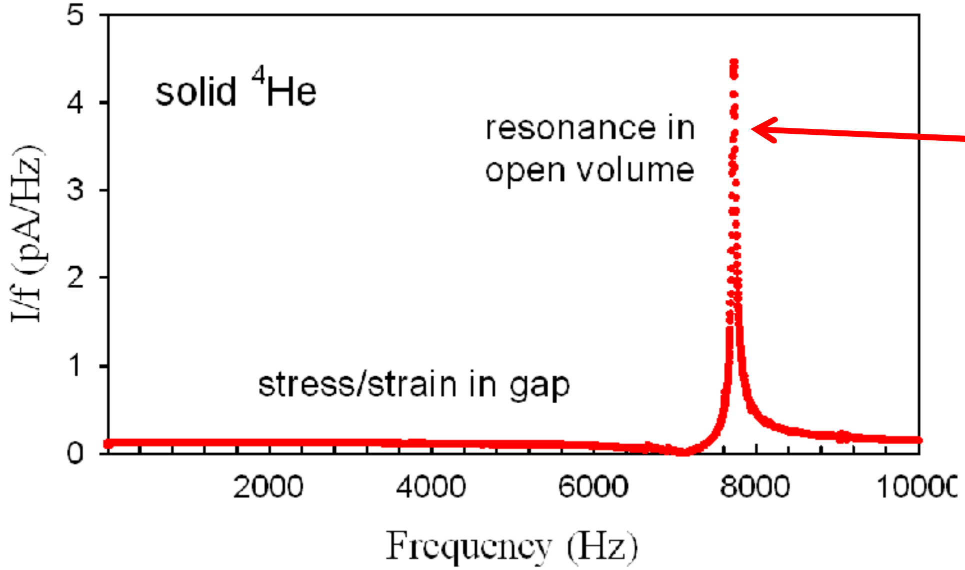
Frequency ⇨ sound speed

(modulus and inertia)

Amplitude/FWHM ⇨ Q

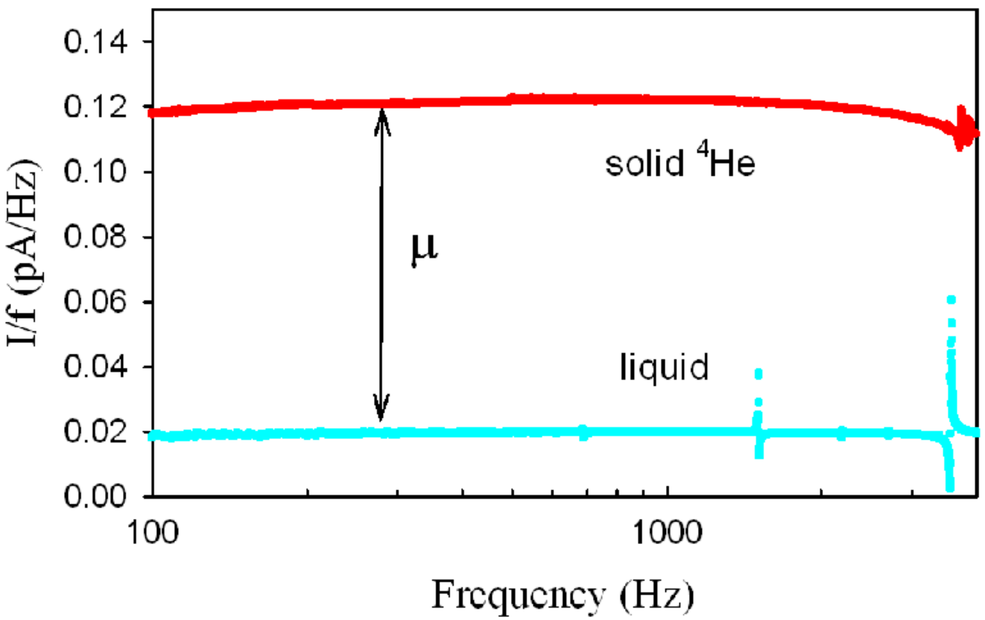
(dissipation 1/Q)

Modulus and resonance measurements



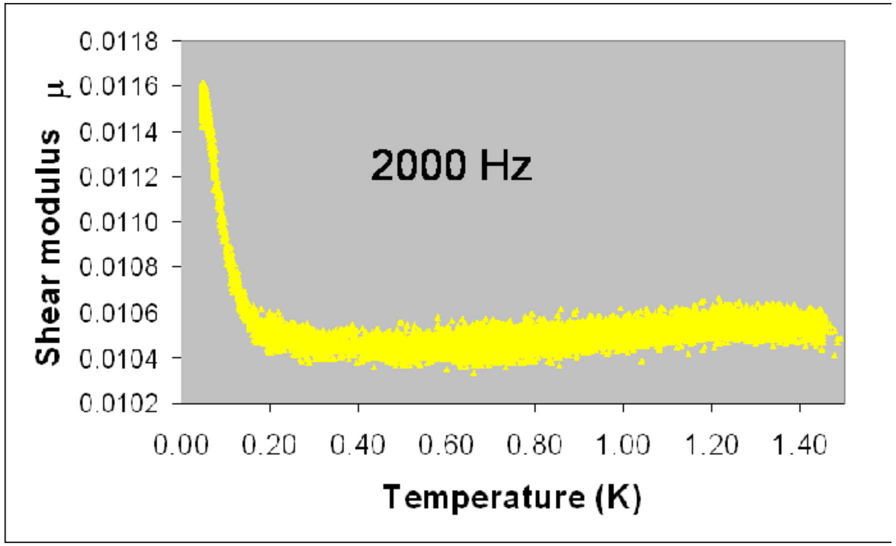
$$f_r = \frac{v}{2L} \propto \sqrt{\frac{\mu}{\rho}}$$

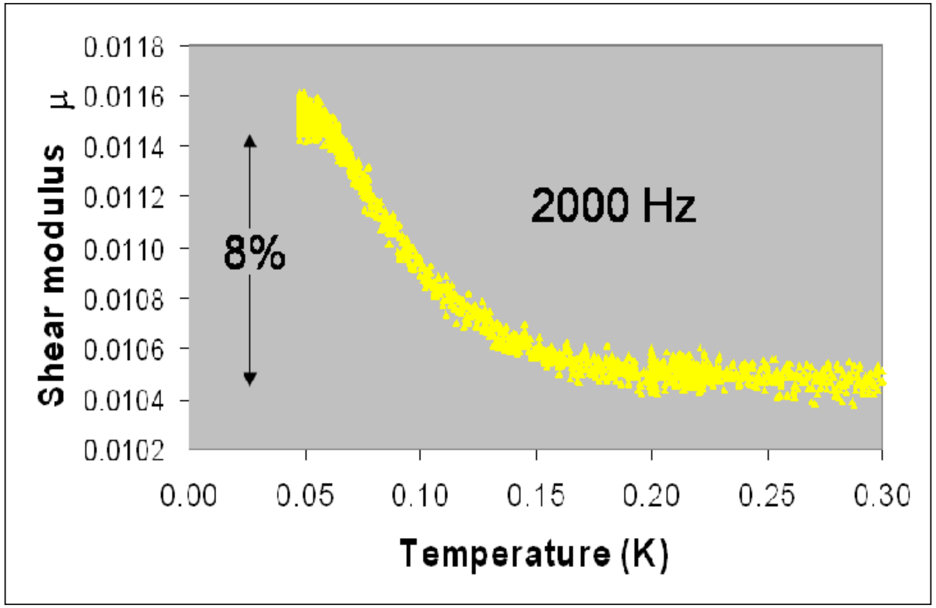
dissipation 1/Q from peak width



measure μ at any frequency
(~20 to 2000 Hz)

Temperature dependence of shear modulus of solid ^4He

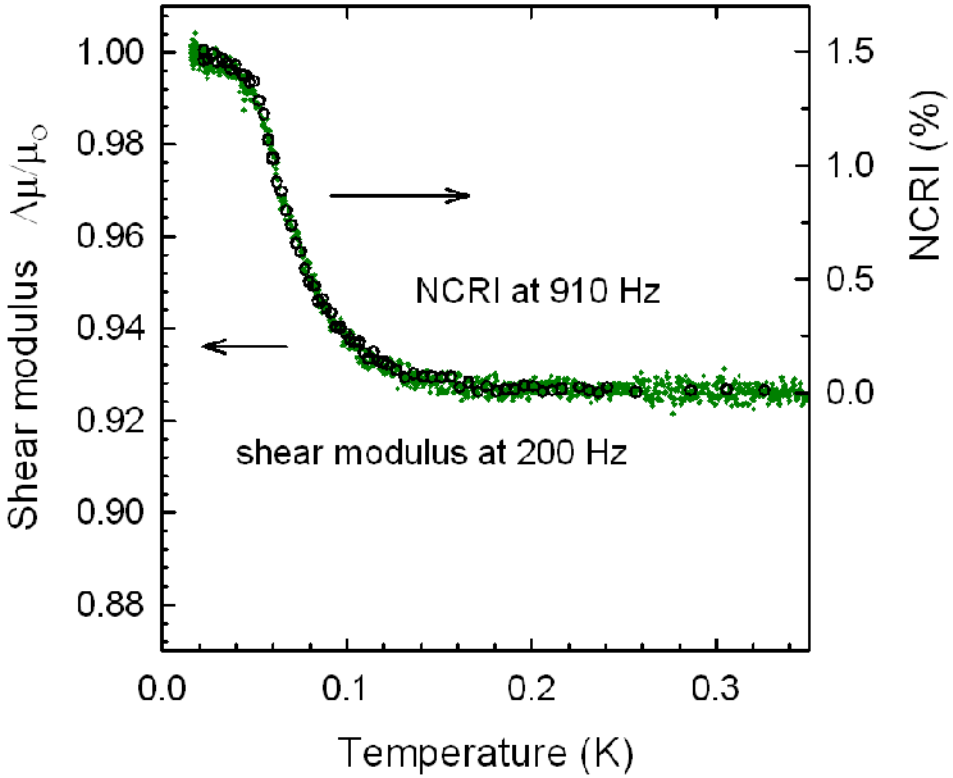




Modulus increases by ~8% below 200 mK (stiffening)

How does **$\Delta\mu$ compare to NCRI** in TO?

Modulus change vs. NCRI

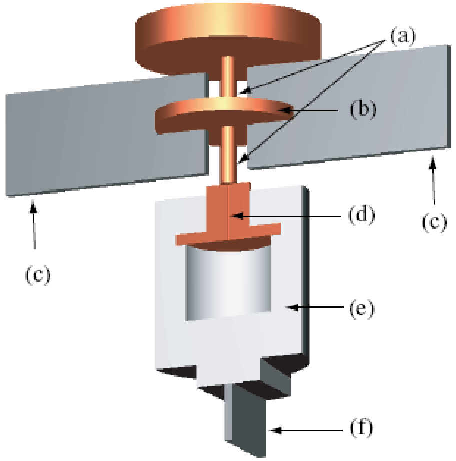


Very similar temperature dependences!

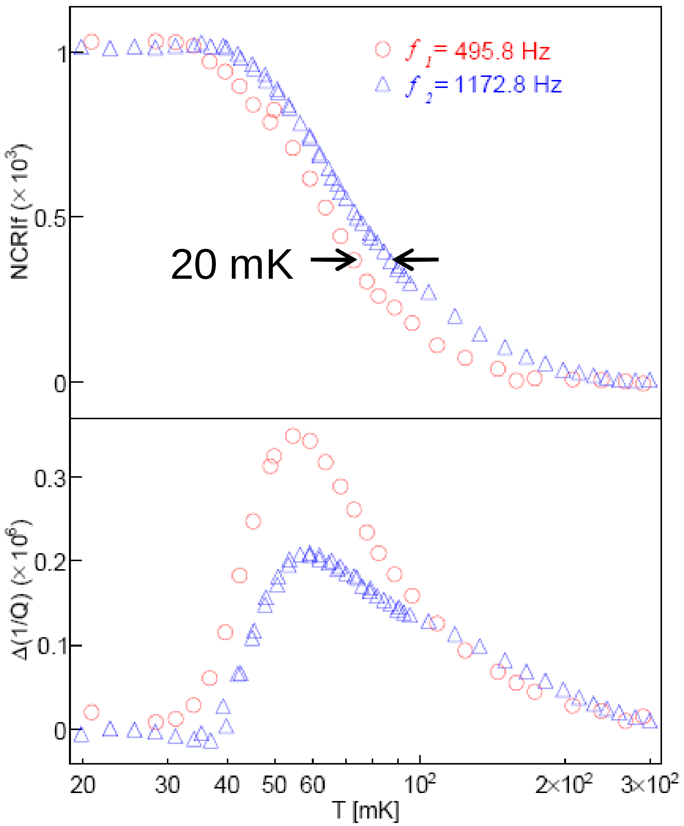
How similar?

How does $\Delta\mu$ **depend on frequency**?

Frequency dependence in TO



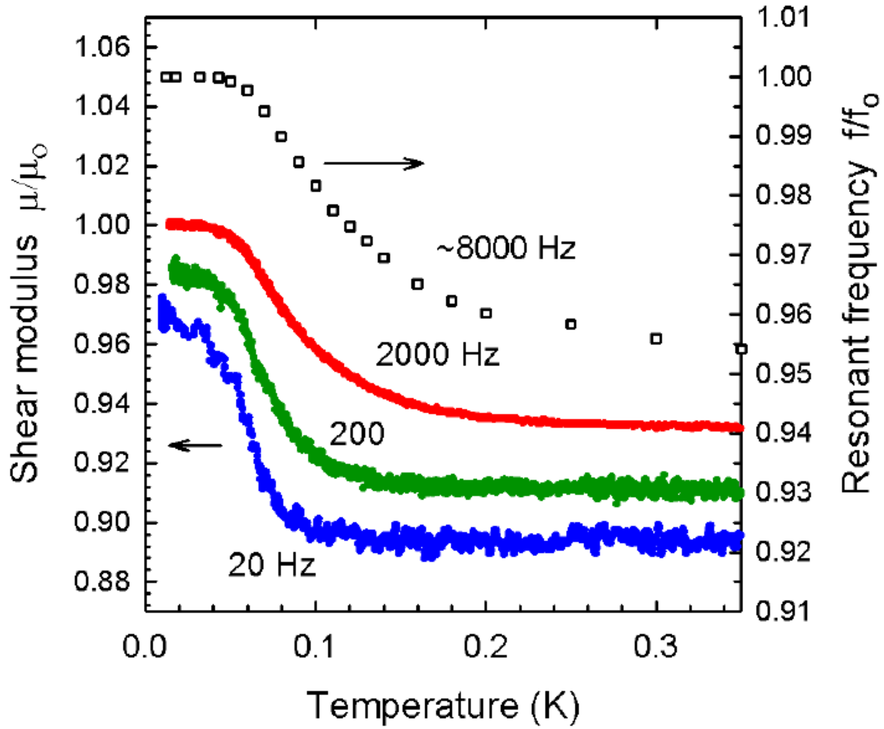
Rutgers double
torsional oscillator



decoupling
independent
of frequency
but onset shifts

dissipation peak

Frequency dependence of $\Delta\mu$

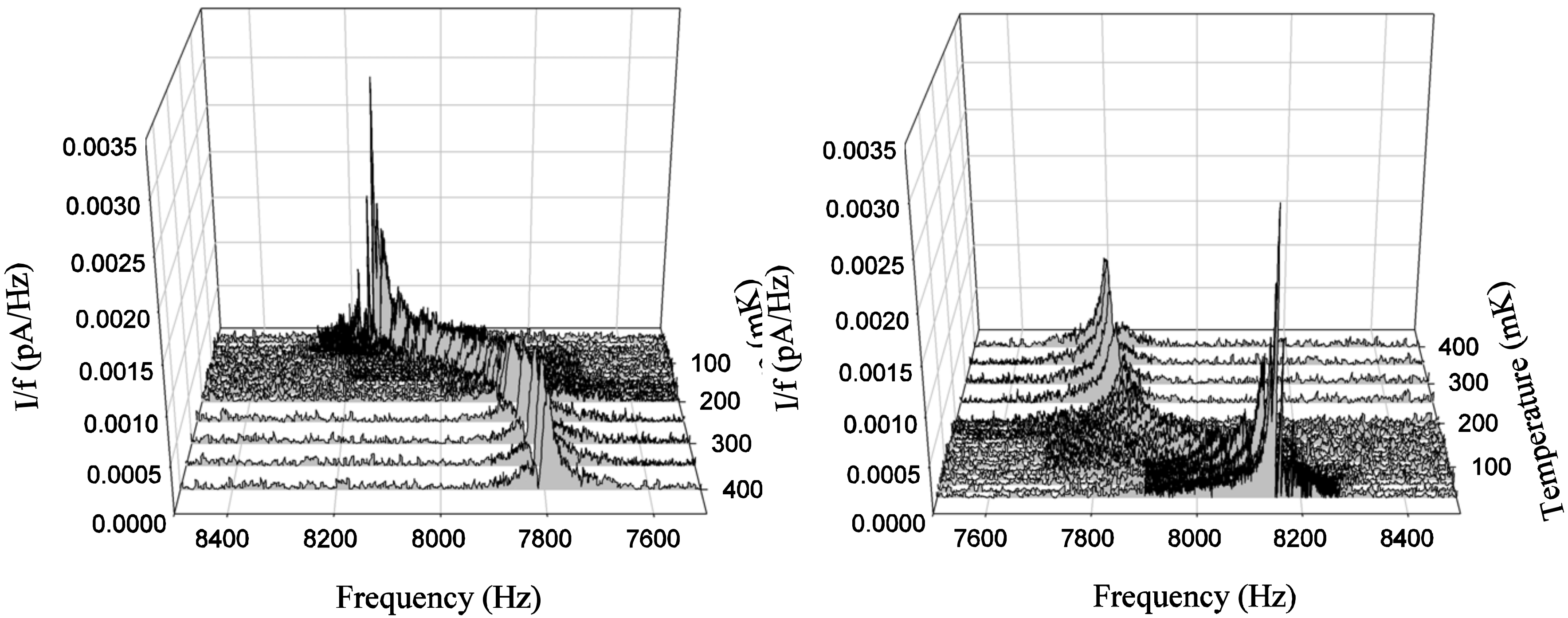


Magnitude of $\Delta\mu$ does not depend on frequency

Transition is sharper and moves to lower T at low frequencies

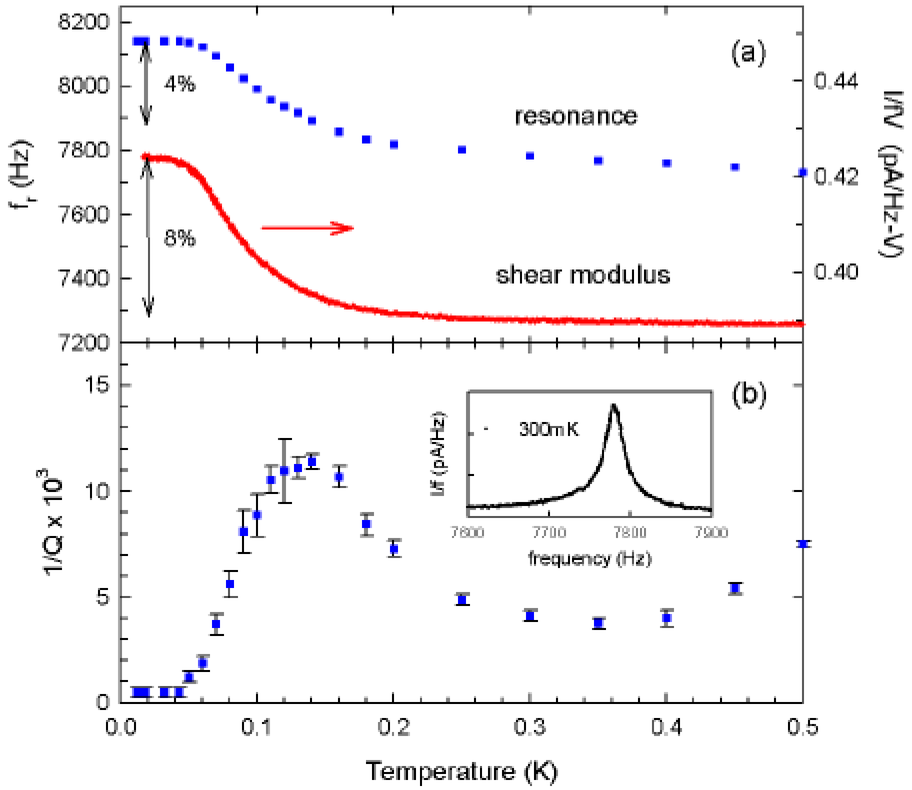
Acoustic resonance at ~8000 Hz shows similar behavior

Temperature dependence of acoustic peak



Peak position (sound speed) increases below 200 mK
Smallest peaks (highest dissipation) where peak shifts

Sound velocity and dissipation from acoustic peak

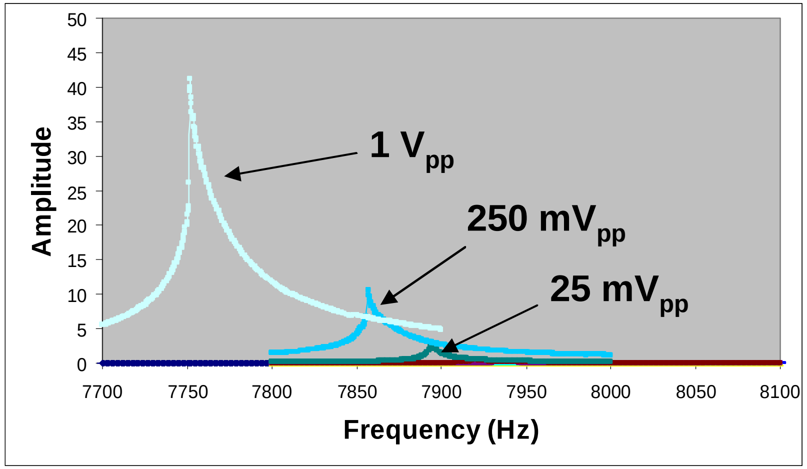


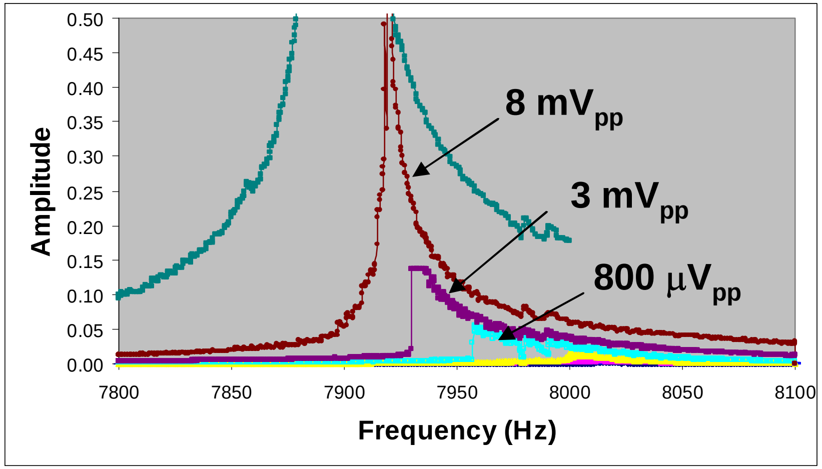
Sound speed reflects same changes in shear modulus $f_r \sim v \sim \mu^{1/2}$

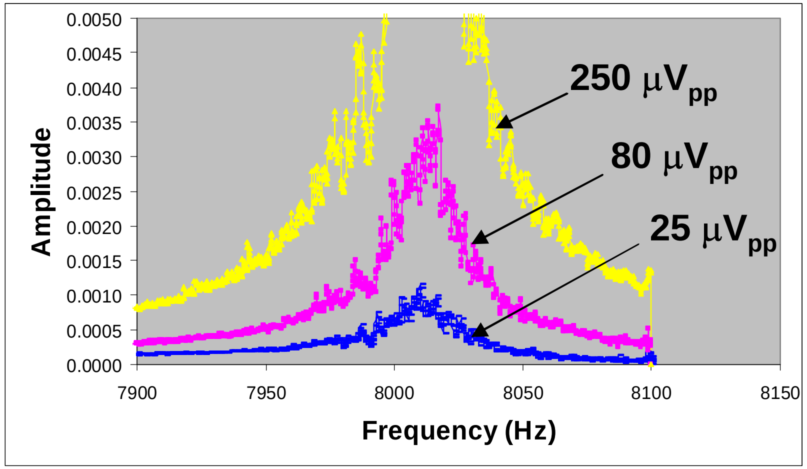
Dissipation peak near onset of stiffening

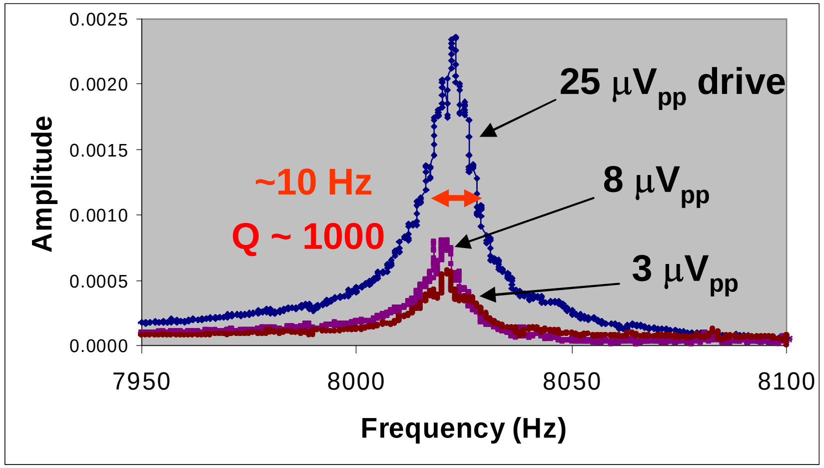
How do resonance and shear modulus depend on **amplitude**?

Amplitude dependence of acoustic resonance (18 mK)





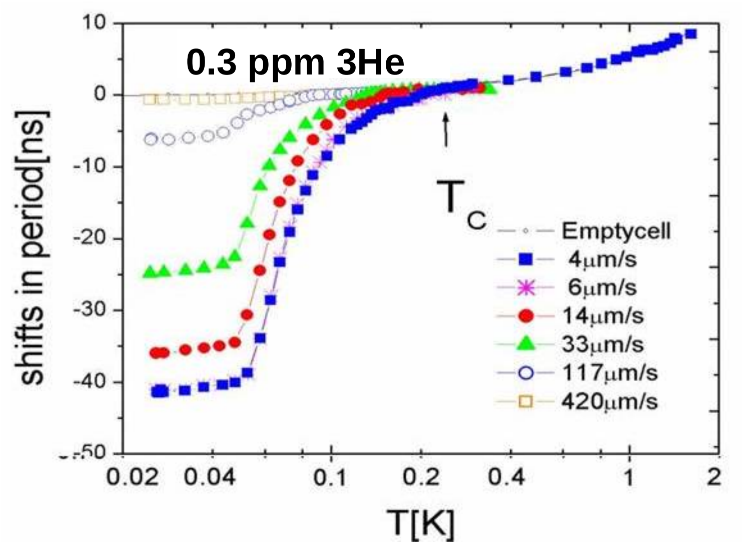


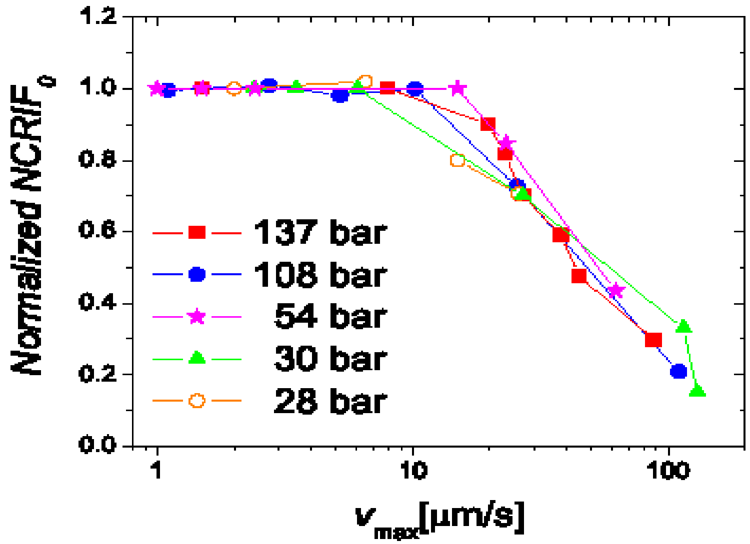


Peak position and shape constant at low amplitudes
Dissipation 1/Q small at low temperatures

Resonance strongly amplitude dependent - **what about μ?**

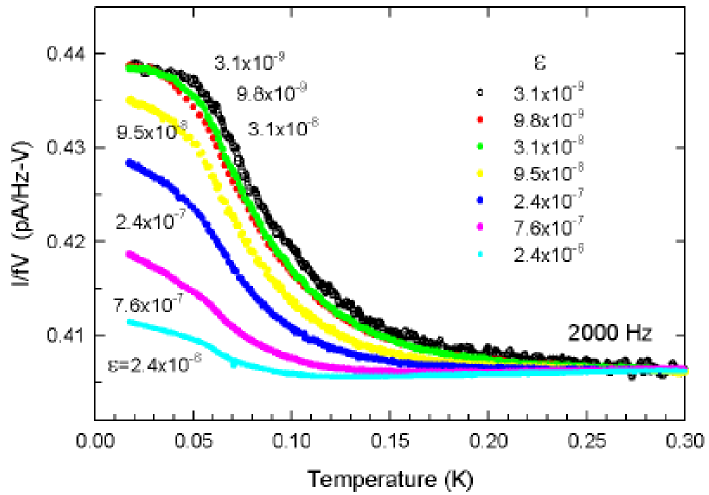
Amplitude dependence in TO

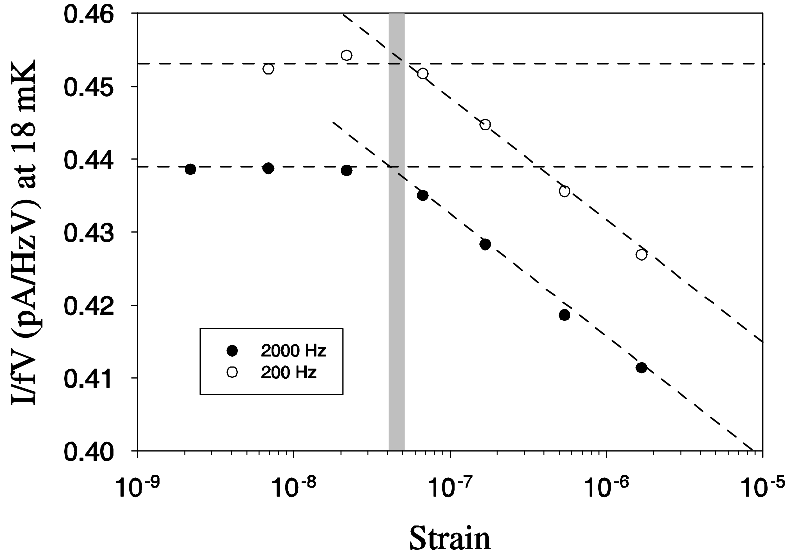




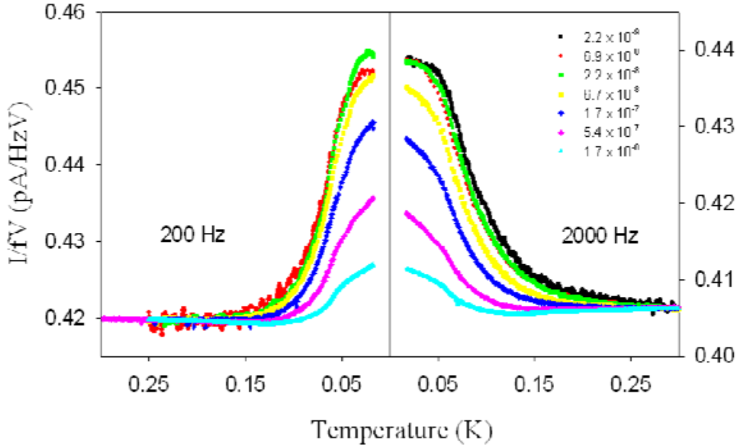
critical velocity $V_c \sim 10\ \mu m/s$

Amplitude dependence of $\Delta\mu$





Amplitude dependence sets in at very low strain $\varepsilon \sim 5\mathrm{x}10^{-8}$
(stress comparable to that in torsional oscillators)

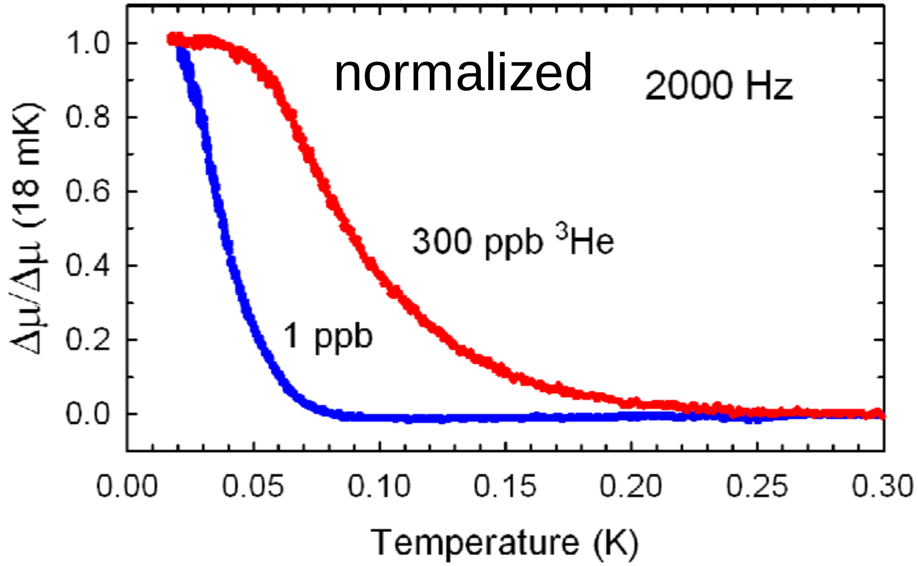


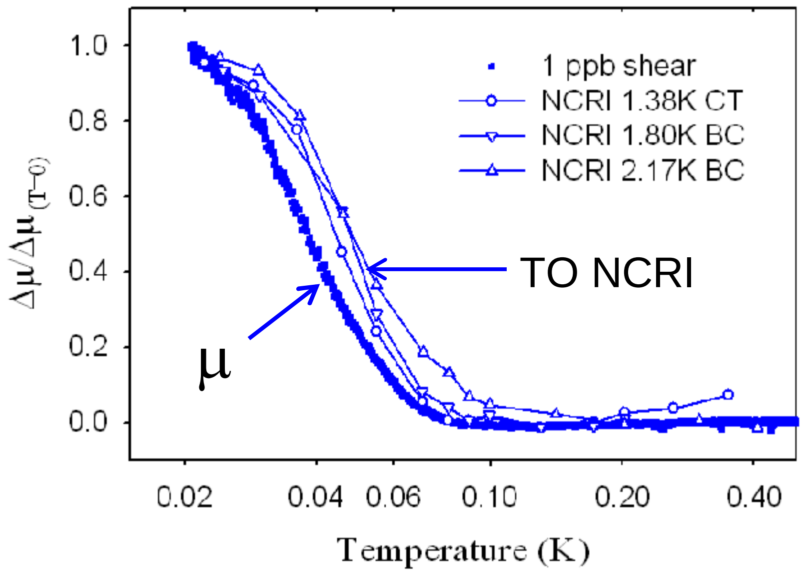
Independent of frequency ⟹ critical stress/strain, not velocity

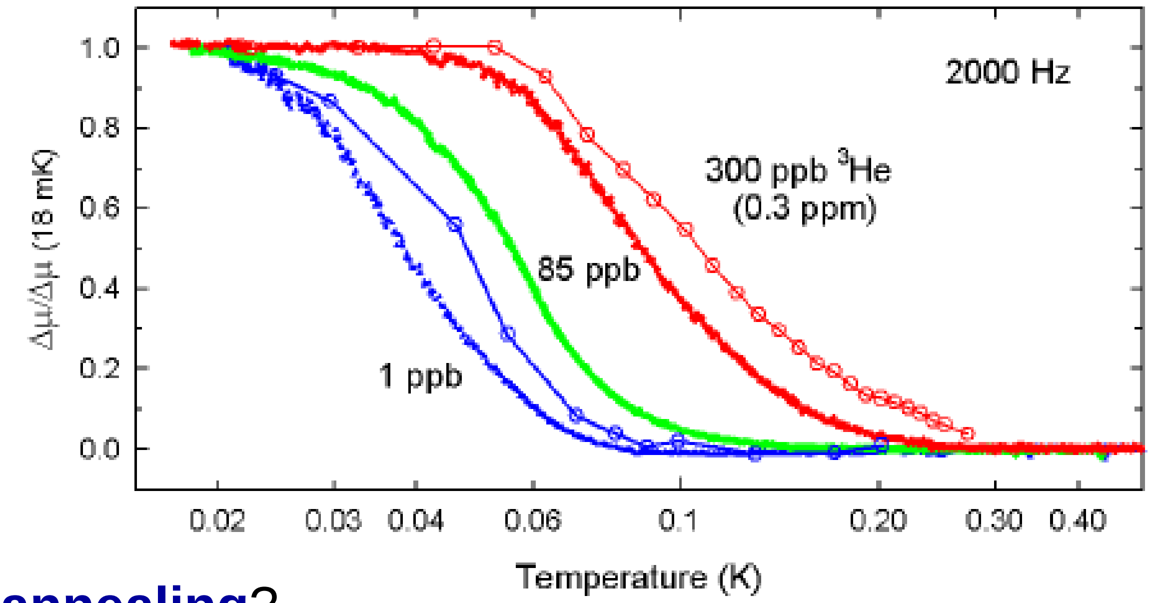
i.e. v_c ~ 0.1 μm/s at 2000 Hz but ~ 0.01 μm/s at 200 Hz

How does μ depend on **^{3}He impurity concentration**?

^{3}He dependence of μ

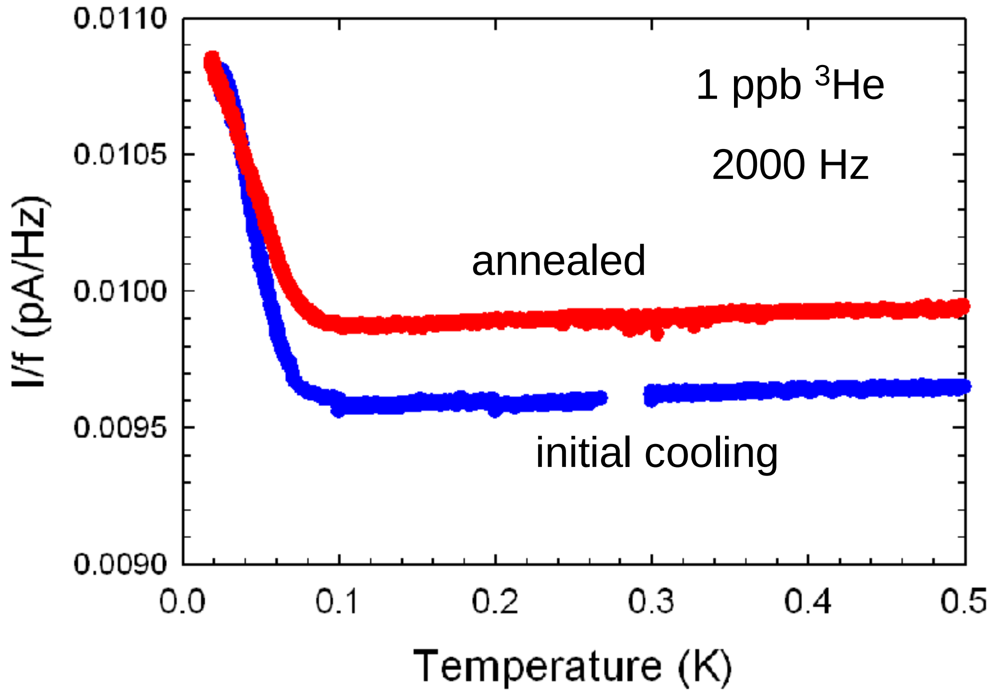






What about **annealing**?

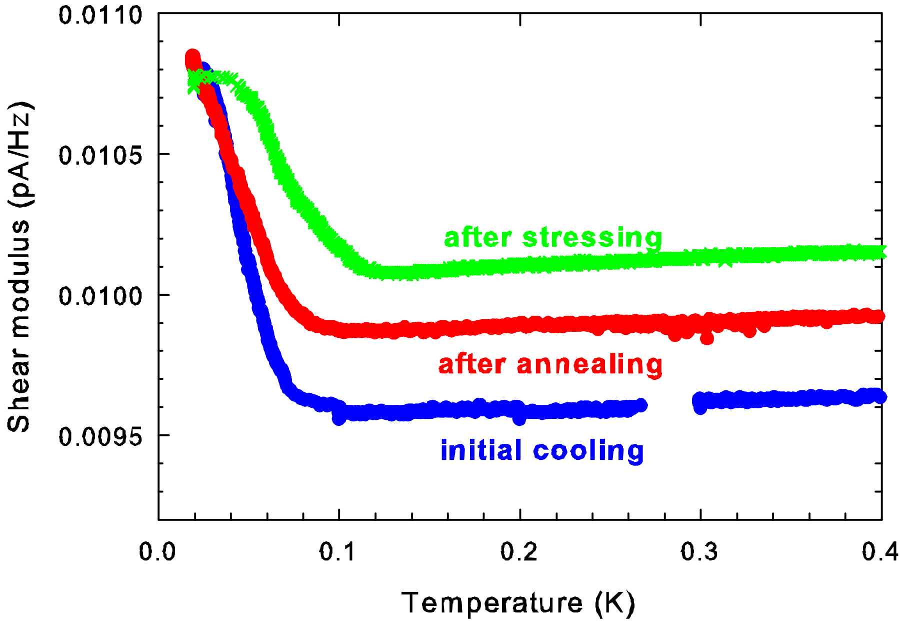
Annealing and stressing



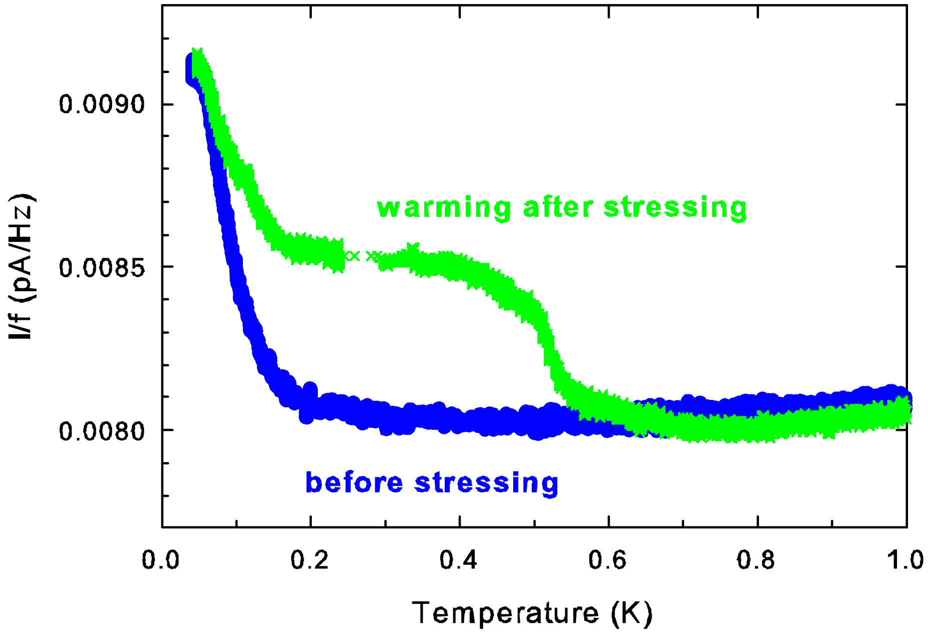
Low T values unchanged – annealing affects high T behavior

⇨ **low T** shear modulus is the **intrinsic** value!

Annealing and stressing



Annealing reduced $\Delta\mu$
Stressing reduced $\Delta\mu$
Low T values unchanged!



Stress-induced changes
anneal around 0.5 K

Torsional oscillator vs. shear modulus

Similarities:

- temperature dependence (onset T and shape)
- frequency dependence (magnitude constant, onset shifts)
- dissipation (peak where μ is changing rapidly)
- amplitude dependence (begins at comparable stresses)
- strong ^{3}He dependence (onset T and sharpness)
- annealing affects behavior

And: - amplitude/temperature hysteresis (“field cooled” vs ZFC)

- $\Delta\mu$ anomaly still present in single (CP) crystals

New features:

- the “anomaly” is in the high T behavior (low T is intrinsic μ)
- applying stress changes $\Delta\mu$

Possible Interpretations

1. **No connection** between NCRI and our observations
   (i.e. the many similarities are just a fluke)

2. Elastic stiffening at low T increases torsional oscillator frequency
   (i.e. apparent decoupling/NCRI is an **experimental artifact** or
   the low T transition is something else, e.g. to a **glassy state**)

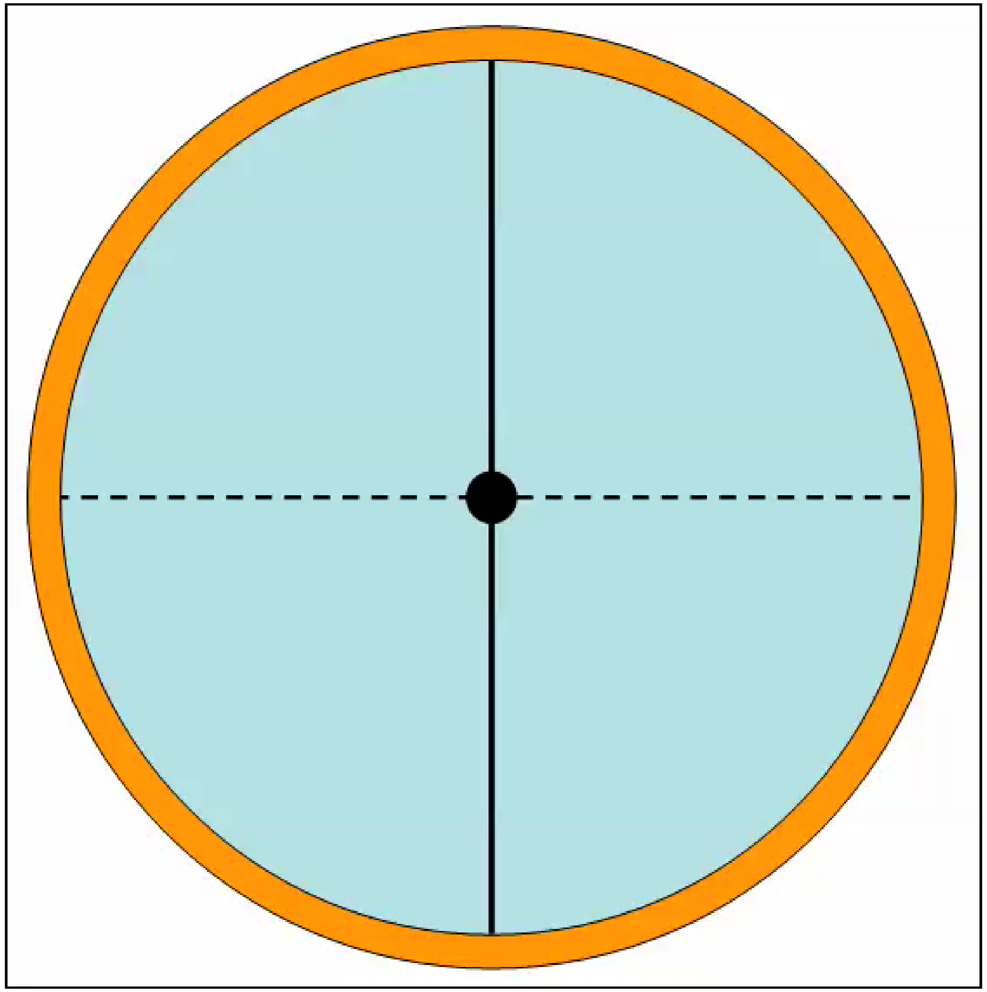
3. Stiffening and TO frequency changes **both related to new state**

   a) both are **intrinsic properties** of a supersolid

   b) both involve defects - **dislocations** weaken crystal and:

      - their presence allows supersolidity?
      or
      - their motion destroys supersolidity?

2. Effect of elastic stiffening on oscillator frequency



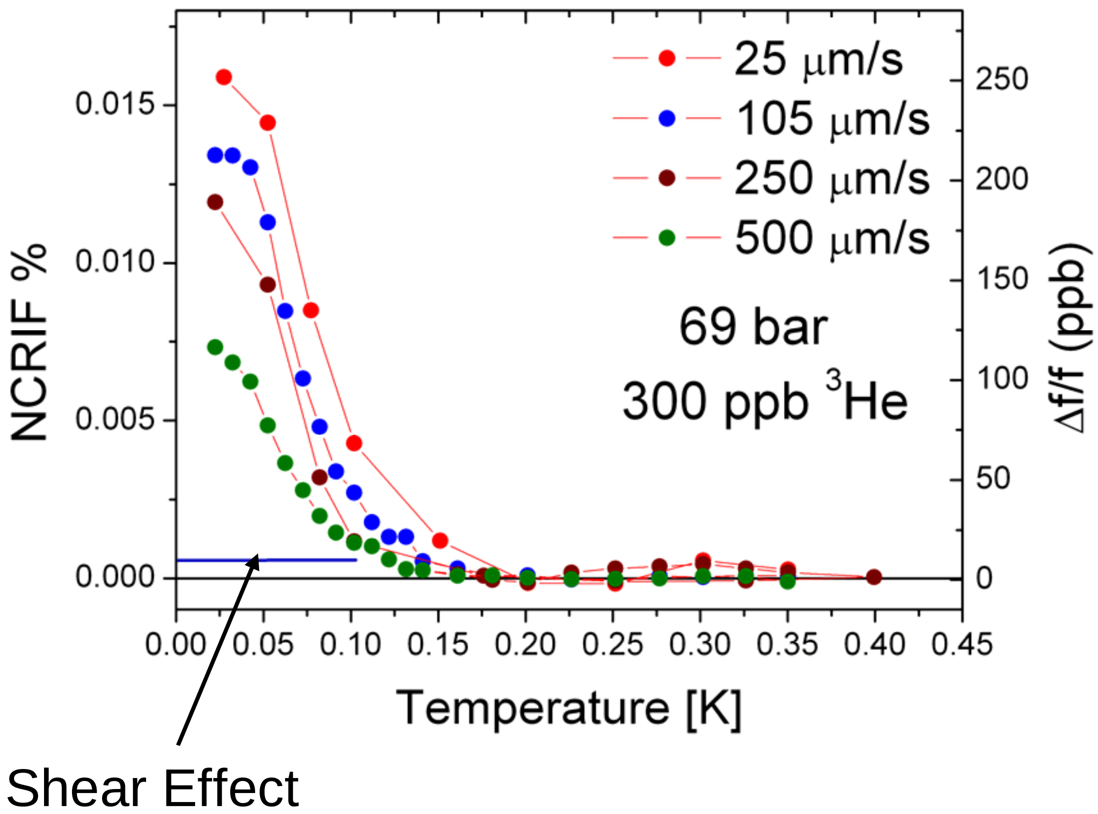
movie

Stiffening at low T will **increase** the frequency (i.e. mimic decoupling)

but wrong: magnitude
frequency dependence

doesn't explain: blocked annulus,
vycor/porous gold

Torsional oscillator results with solid ^{4}He



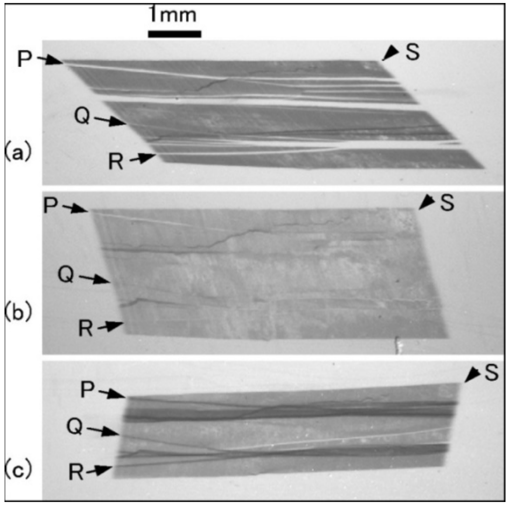
Small NCRI (0.016%) in this cell (but around 25X shear effect)

Dissipation peak associated with decoupling

3b. Dislocations in ^{4}He

"Known" facts:

- solid helium has dislocations ($\Lambda \sim 10^6$ cm^{-2} in fairly good crystals?)



Grain (sub)boundaries in hcp ^{4}He (Iwasa/Suzuki)

3b. Dislocations in ^{4}He

"Known" facts:

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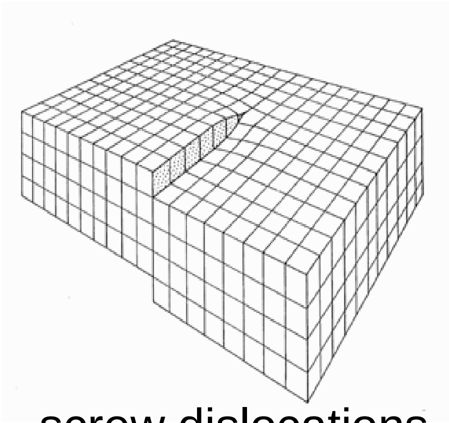
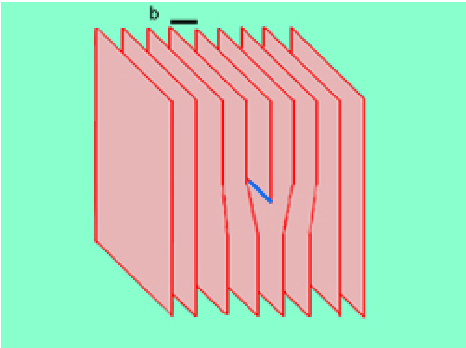
- edge dislocations glide easily in the basal plane (under shear stress)



screw dislocations
(crystal growth)



edge dislocations
glide in basal plane

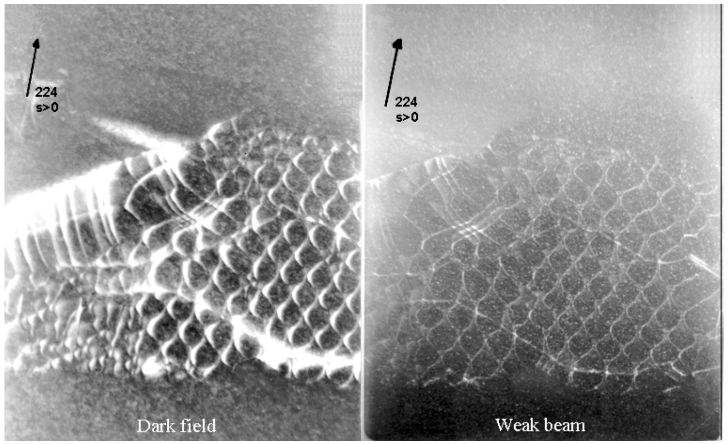
3b. Dislocations in ^{4}He

"Known" facts:

- solid helium has dislocations ($\Lambda \sim 10^6$ cm^{-2} in fairly good crystals?)

- edge dislocations glide easily in the basal plane (under shear stress)

- they are weakly pinned by impurities (^{3}He binding ~ 0.3 – 0.7 K) and more strongly where they intersect



Frank net in annealed metals

3b. Dislocations in ^{4}He

"Known" facts:

- solid helium has dislocations ($\Lambda \sim 10^6$ cm^{-2} in fairly good crystals?)

- edge dislocations glide easily in the basal plane (under shear stress)

- they are weakly pinned by impurities (^{3}He binding ~ 0.3 – 0.7 K)
  and more strongly where they intersect

- stress tears them away from impurities

- they are damped by phonons at high temperatures ($B \sim T^3$)

- annealing removes some dislocations

Dislocations in Helium (continued)

Things we **don't** know:

- how many dislocations are there in real helium crystals?
  (especially blocked capillary polycrystals)

-is there a Peierls barrier for basal plane edge dislocations?
  (or do they tunnel?)

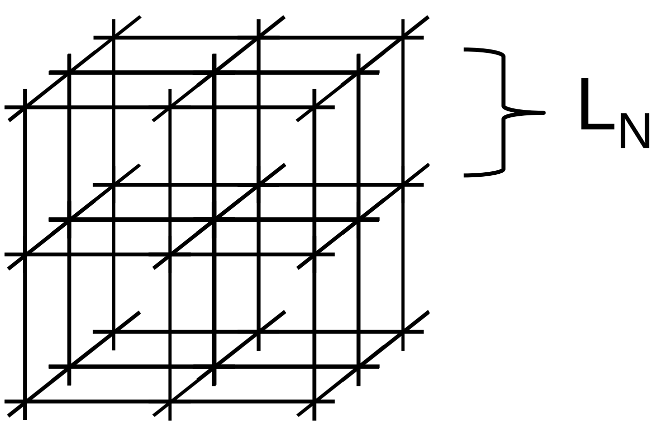
-are screw dislocations (and other edge dislocations) mobile?
  (important for flow, annealing and plastic deformation)

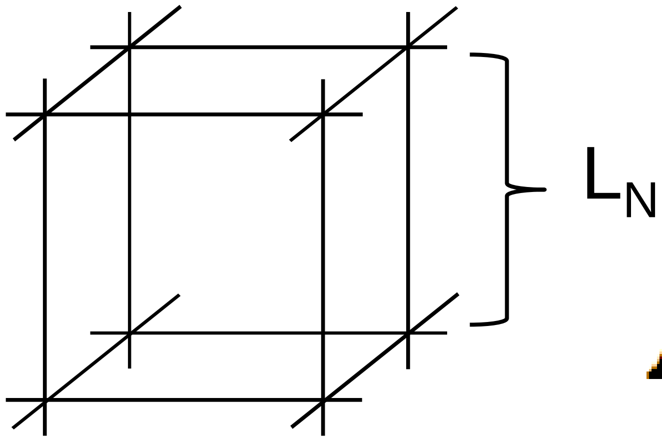
- what are kink energies in helium? are kinks delocalized??

- non-thermal plastic deformation (quantum metallurgy)??

- interaction of dislocations with vortices (pinning and phase jumps)???

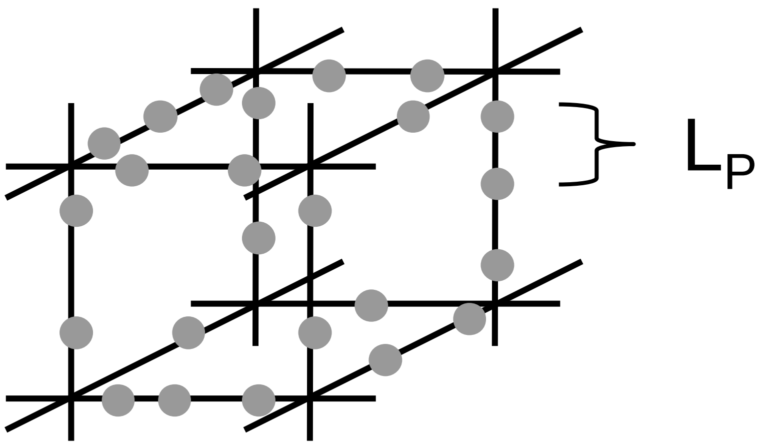
Network and impurity pinning





$$\Lambda L_N^2 = 3$$

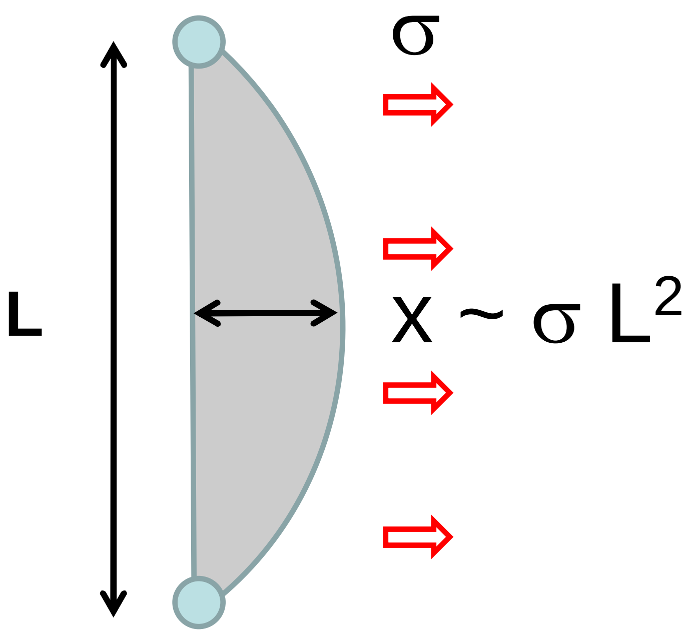
network pinning only



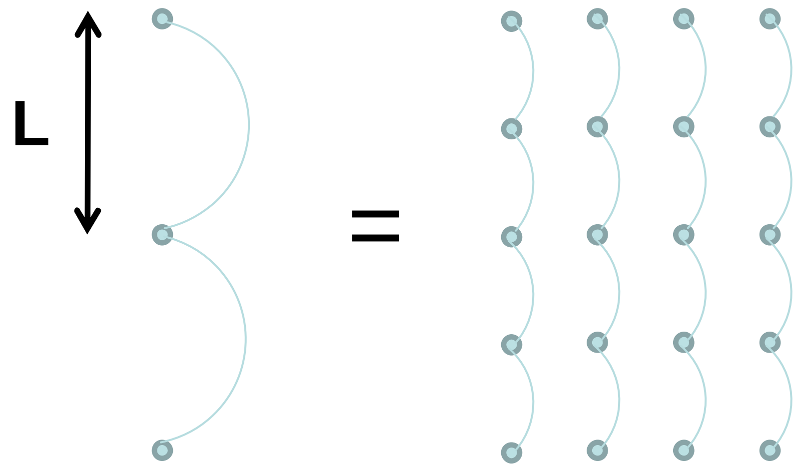
$$\Lambda L_P^2 \ll 3$$

impurity pinning

Effect of dislocations on shear modulus



displaced mass $\rho x L D$



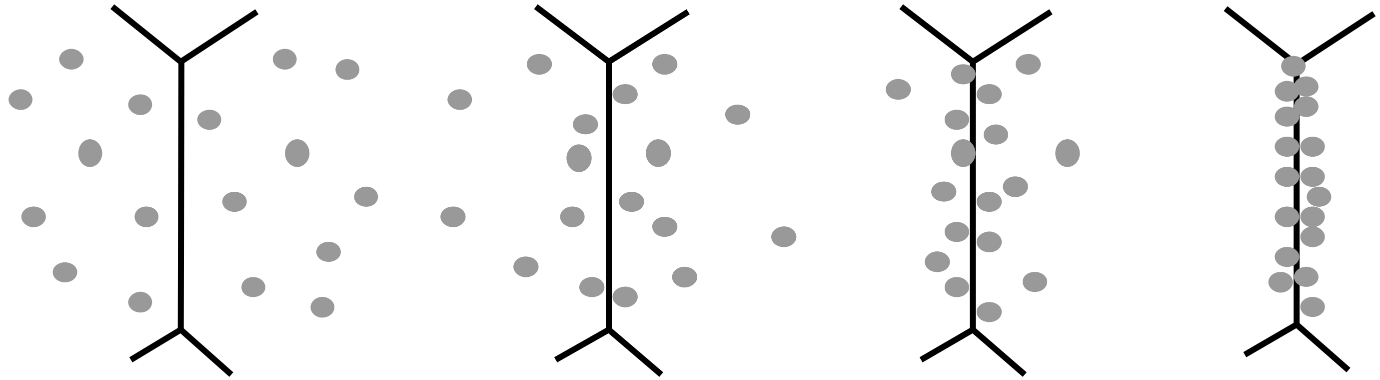
controlled by ΛL^2

may not vary as much as L

low frequency/low temperature: $\dfrac{\Delta\mu}{\mu} \approx 0.5 R \Lambda L^2$ **~ 30%**

Impurity pinning (e.g. ^{3}He)

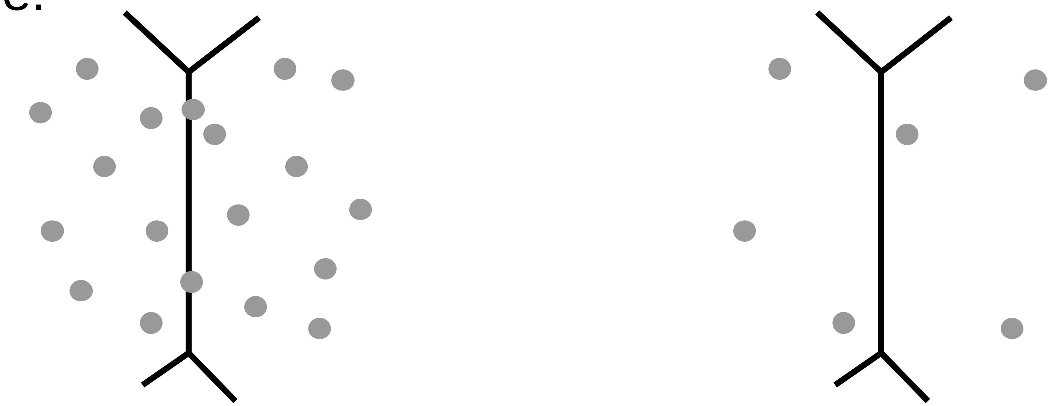
T dependence:



High T >> ε_B ~ 300 mK

Low T << ε_B (pinned)

X_3 dependence:

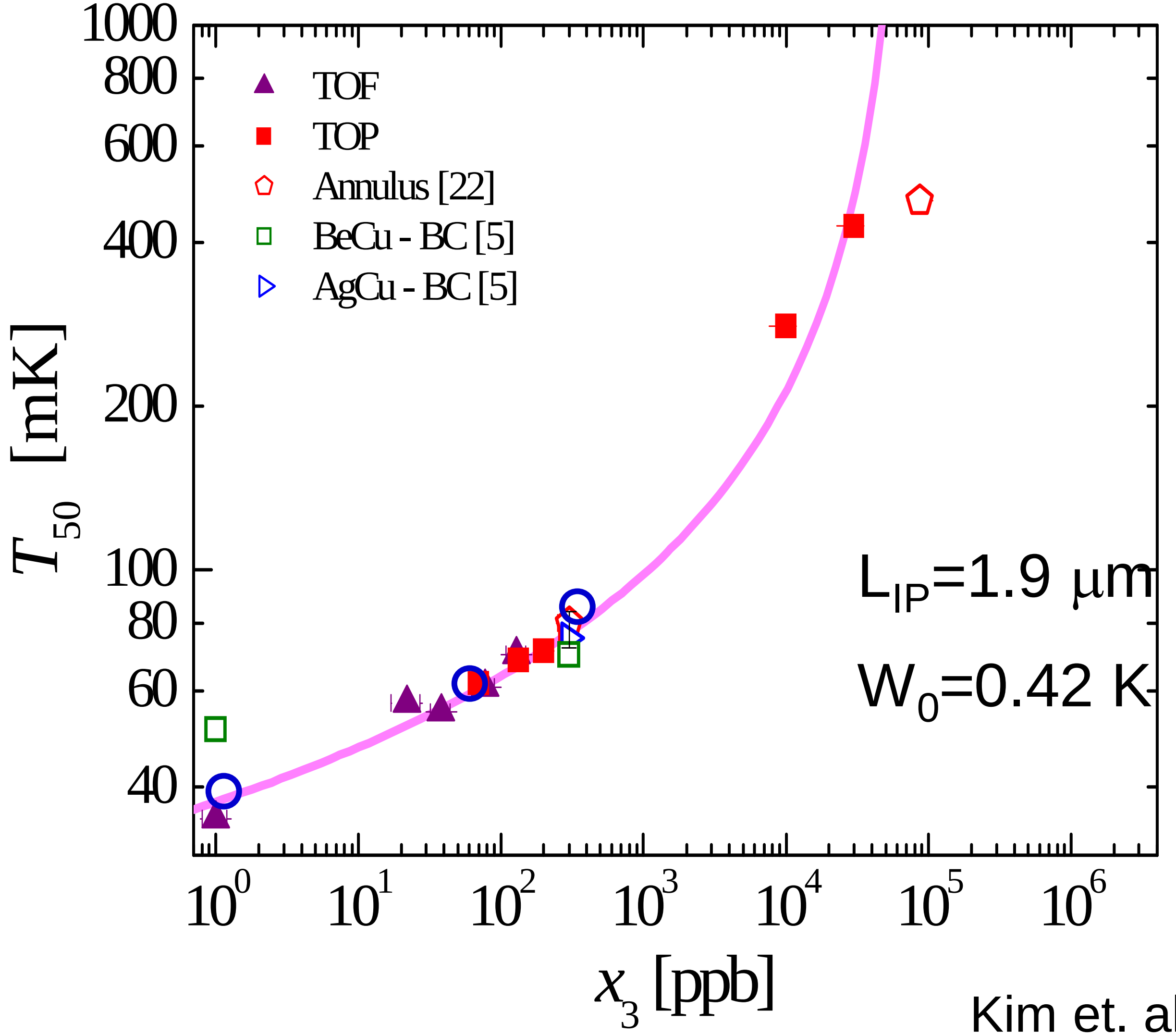


High ^{3}He concentration (pinned)

Low ^{3}He concentration

Onset T vs. ^{3}He impurities

$$T_{IP} = -2W_0 \left(\ln\left[\frac{x_3^2 L_{IP}^3 W_0}{4\mu b^6} \right] \right)^{-1}$$



L_{IP} ^{3}He pinning length

μ, shear modulus,

b, Burger's vector

Kim et. al, PRL 100,065301 (2008)

How can dislocations explain $\Delta\mu$?

^{3}He pins dislocations at low temperature ($\Rightarrow$ intrinsic μ)

Unpinned dislocation network weakens μ by up to 30% at high T
($\Delta\mu$ independent of frequency)

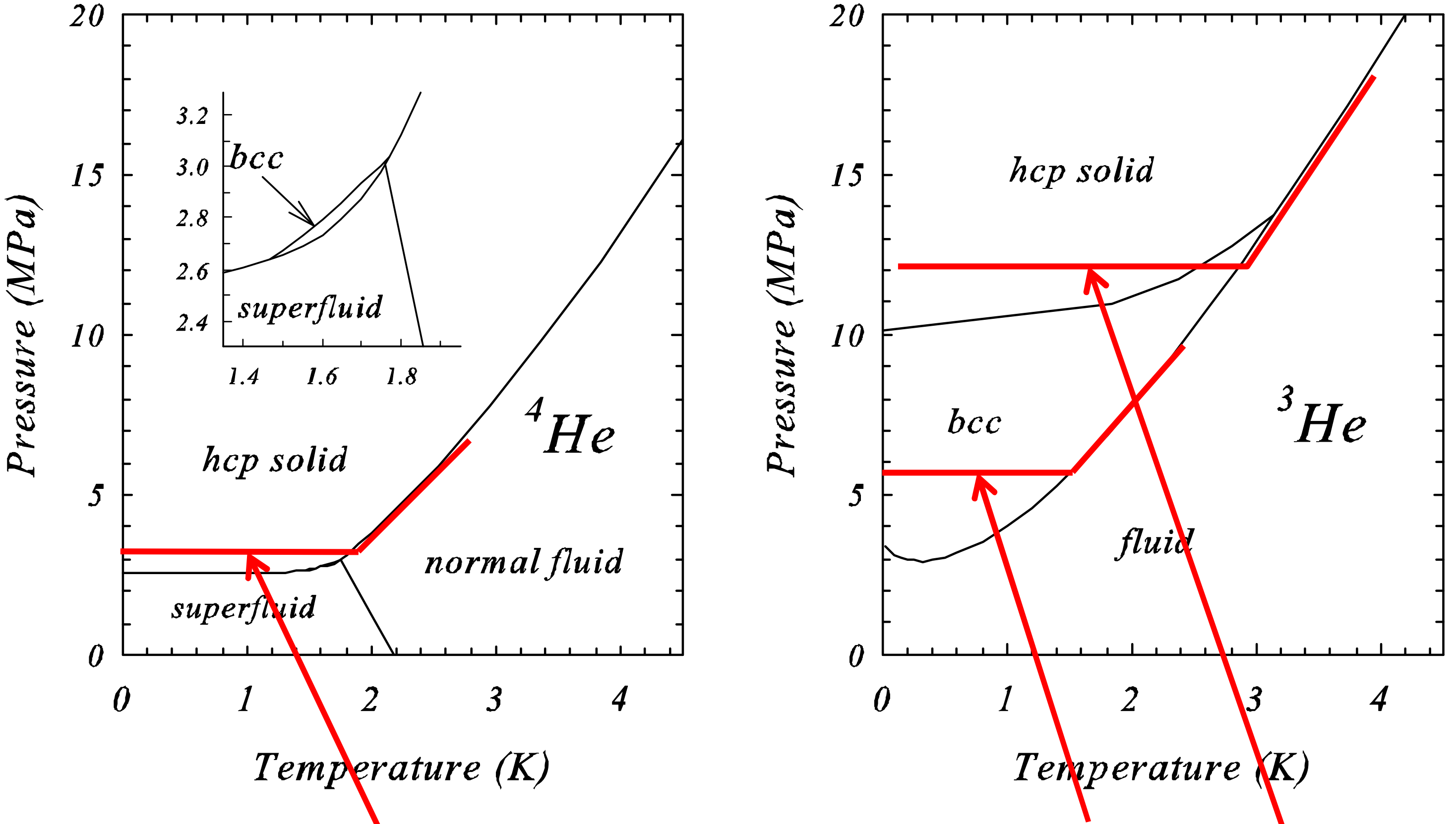
Large stresses unpin dislocations (amplitude dependence)

Annealing or stressing changes dislocation density/network and $\Delta\mu$

Even if you believe this, what is the connection to supersolidity?

What happens in **^{3}He**?

^{4}He and ^{3}He phase diagrams

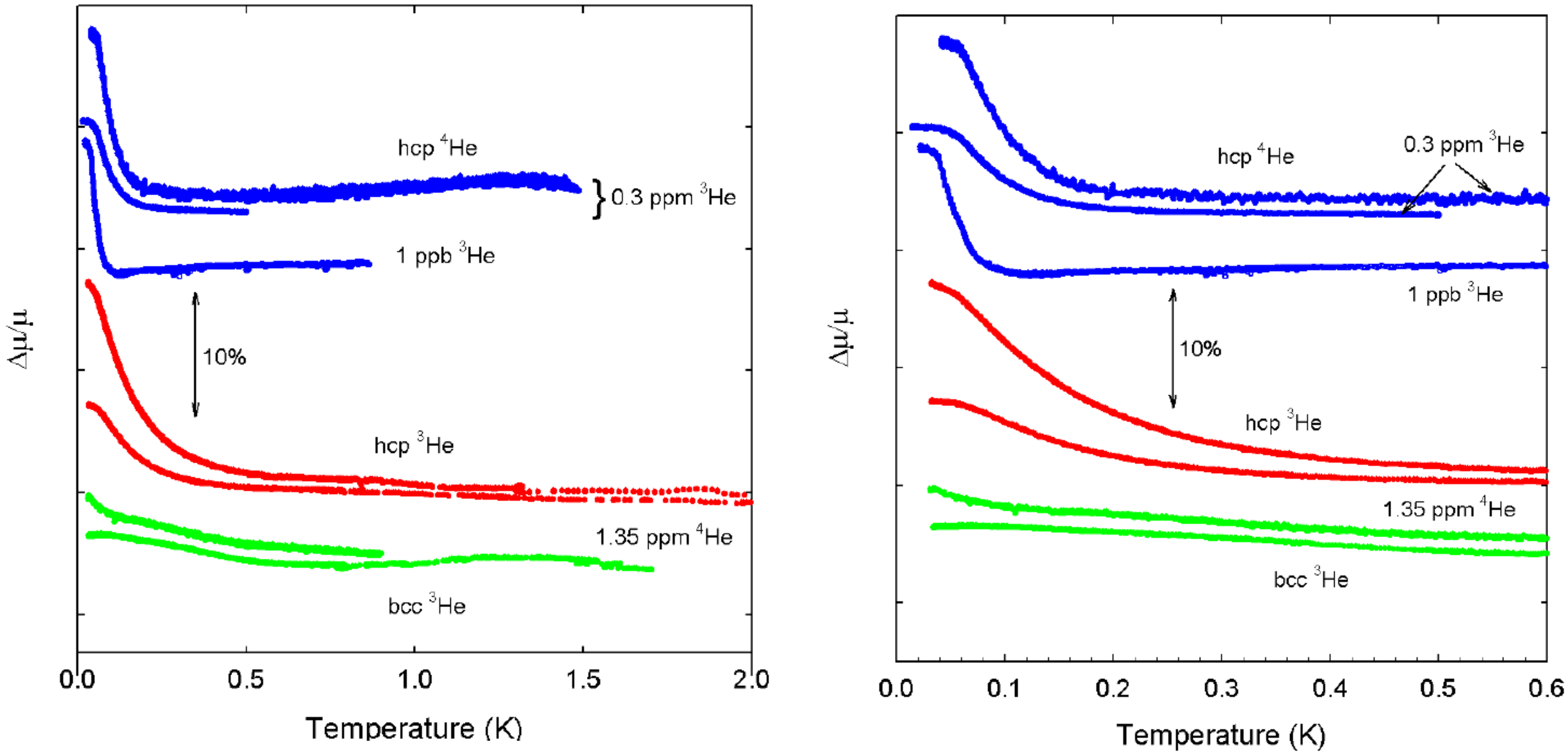


NCRI in ^{4}He
in the hcp phase

previous ^{3}He control
experiments in bcc phase
(and many ppm ^{4}He)

Look at modulus (Alberta) and NCRI (Penn State) in **pure hcp ^{3}He**

Shear modulus: ^4He vs. ^3He

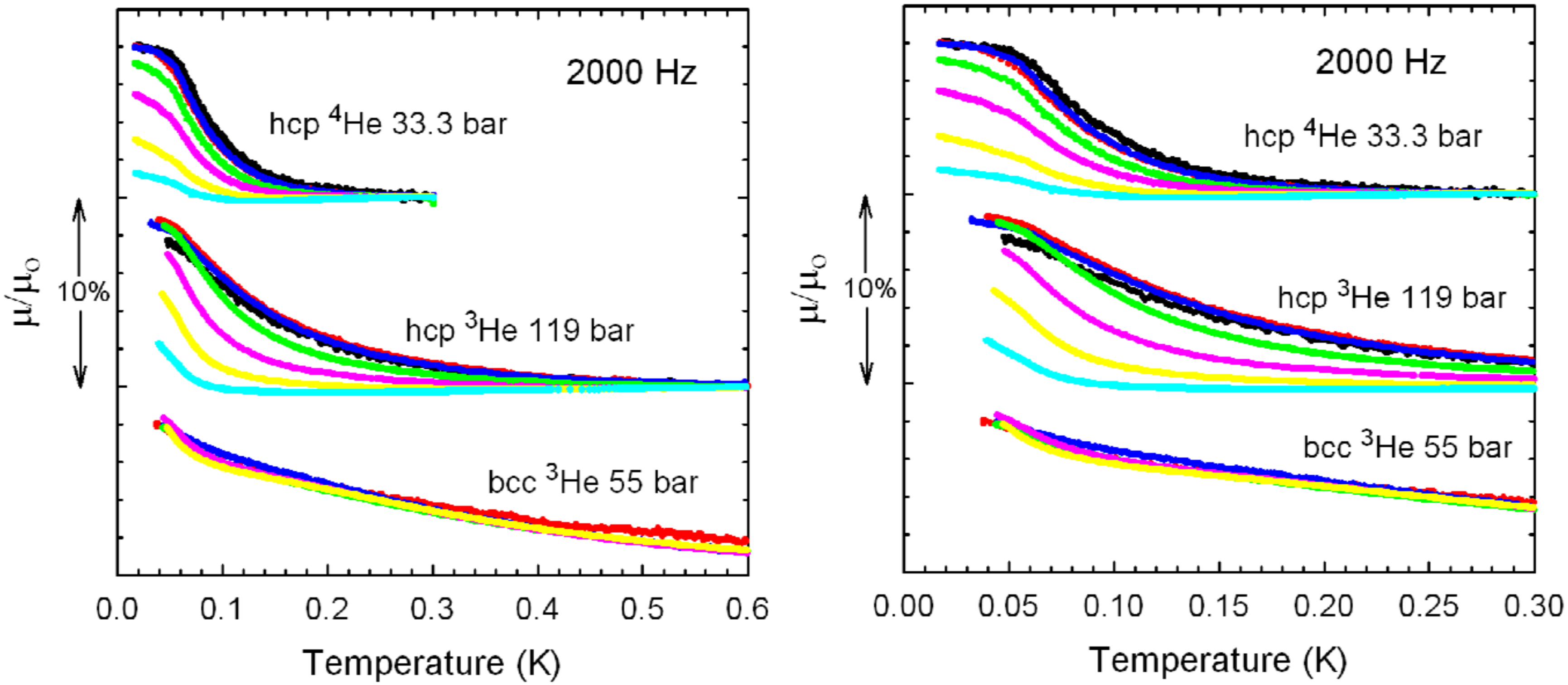


hcp (^4He **and** ^3He) shows low T stiffening (dislocation motion?)

bcc ^3He does not (dislocations not mobile??)

onset T higher in hcp ^3He (lower purity - 1.35 ppm ^4He??)

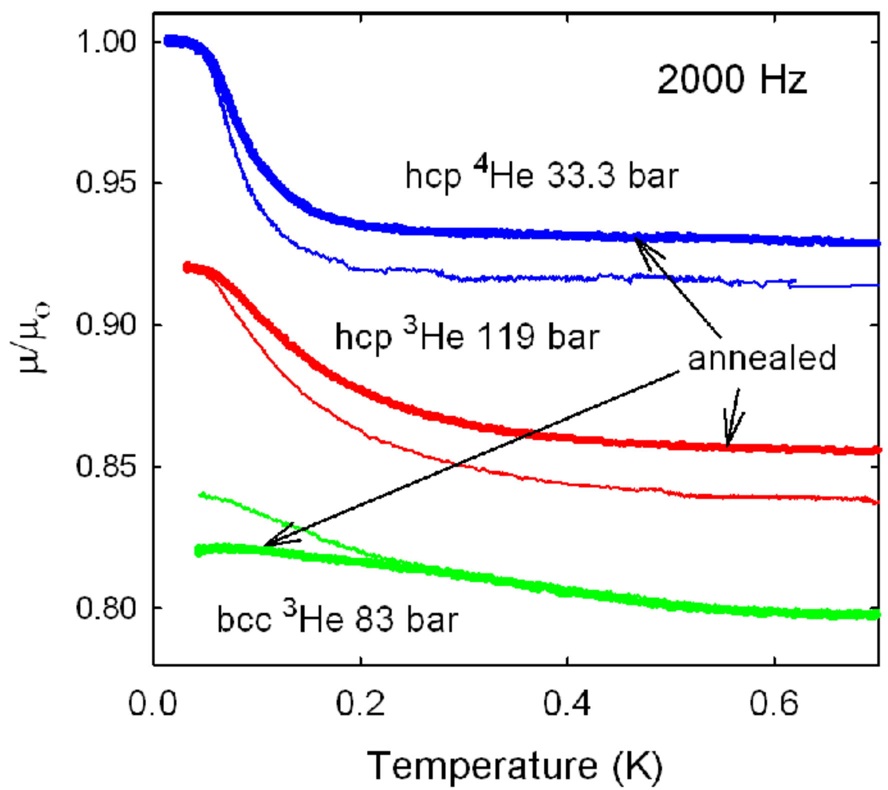
Amplitude dependence in ^4He and ^3He



Same amplitude dependence in hcp ^3He and ^4He

Not in bcc ^3He

Annealing effects in ^{3}He and ^{4}He



Same annealing in hcp ^{3}He and ^{4}He (modifying dislocation network?)

Annealing in bcc ^{3}He not systematic (and crystals not as stable)

Torsional oscillator response in ^{3}He?

hcp ^{4}He: boson; $\Delta\mu$ anomaly; TO decoupling observed

bcc ^{3}He: fermion; no $\Delta\mu$ $\Rightarrow$ no TO decoupling expected?

hcp ^{3}He: fermion; $\Delta\mu$ anomaly $\Rightarrow$???

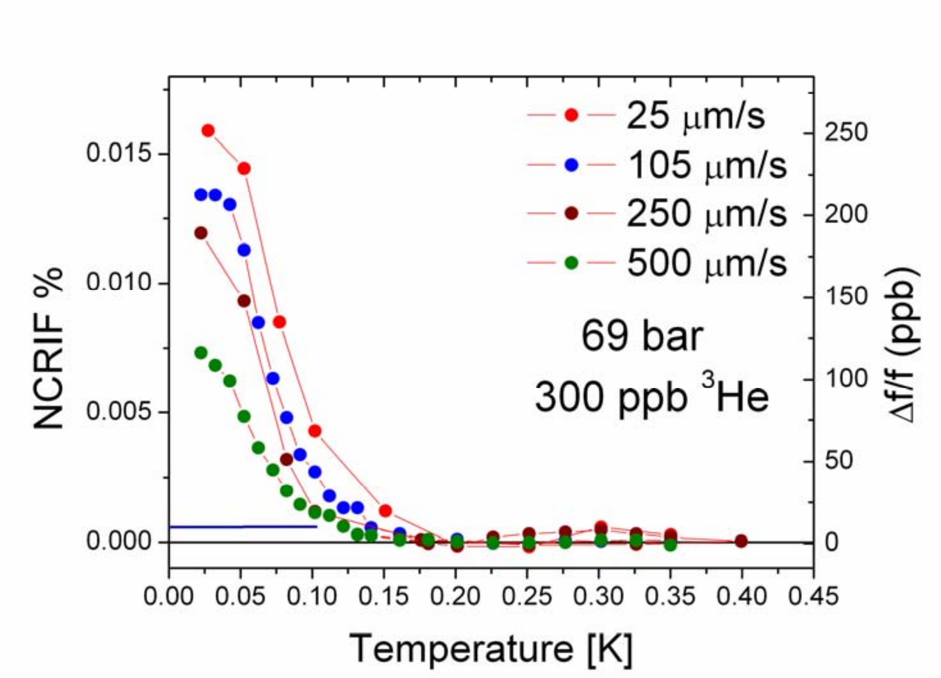
TO anomaly $\Rightarrow$ defects only – no quantum statistics

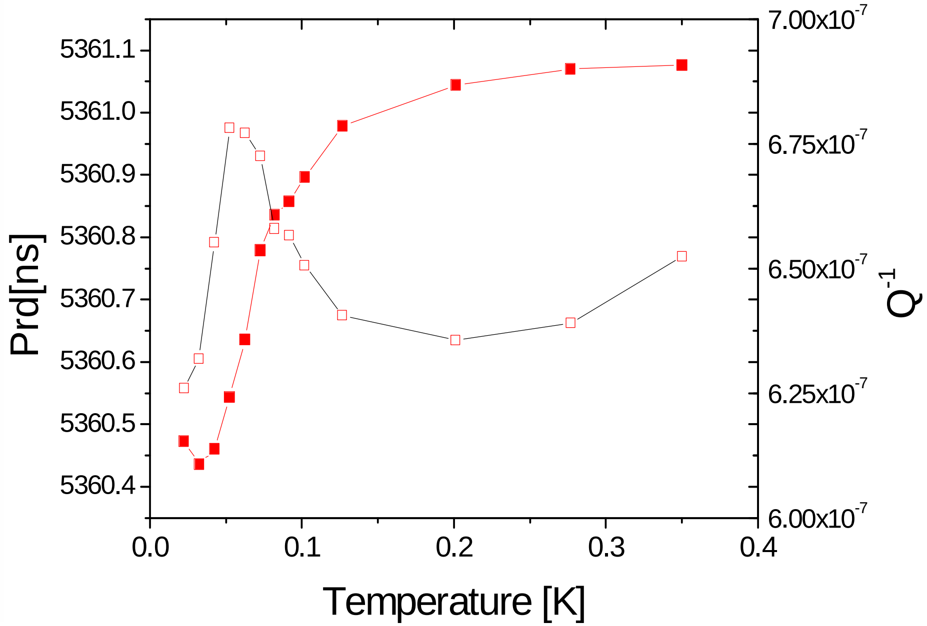
no TO anomaly $\Rightarrow$ NCRI depend on statistics

($\Delta\mu$ $\Rightarrow$ defects involved)

the most interesting possibility!

Torsional oscillator results with solid ^{4}He



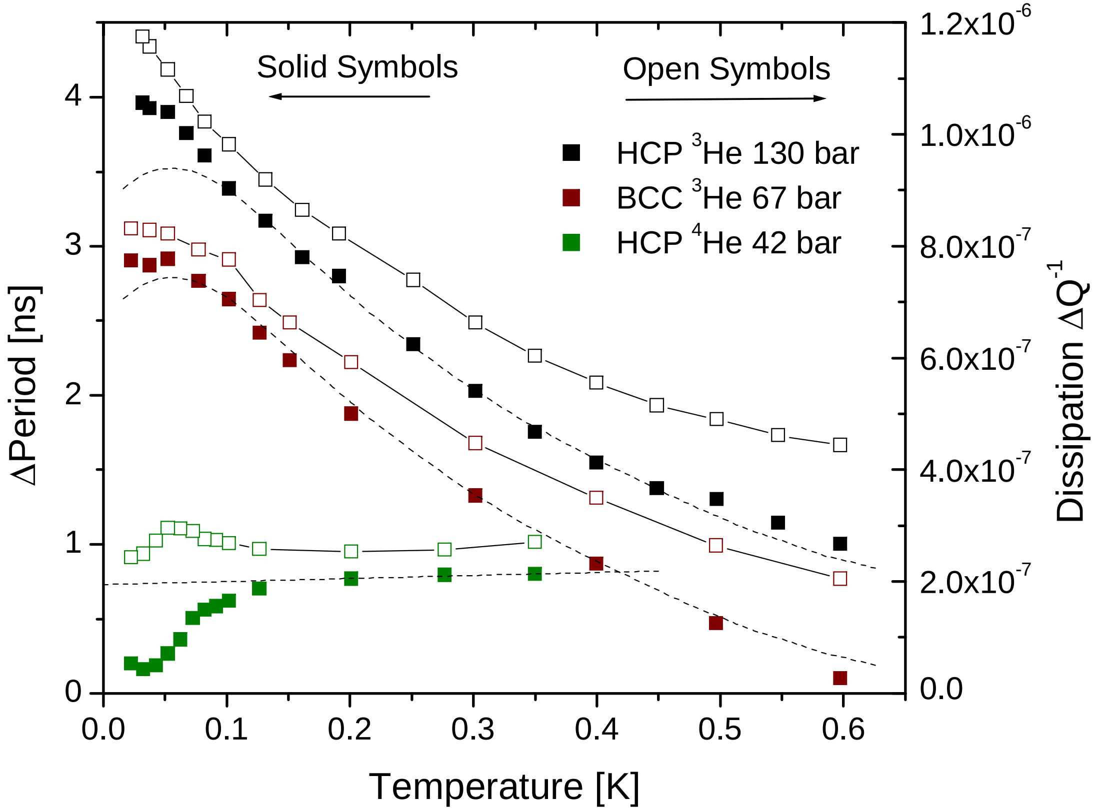


Small NCRI (0.016%) in this cell
Critical velocity/amplitude

Dissipation peak
with decoupling

Torsional oscillator results with solid ^{3}He and ^{4}He

Josh West and Moses Chan (Penn State)



Same ^{3}He gas used in Alberta for shear modulus

No NCRI signal from either HCP or BCC solid ^{3}He !

Summary/Conclusions

Shear modulus and NCRI are **clearly related**

Modulus effects can be explained by **dislocation mobility and pinning**
(intrinsic behavior at low T where dislocations are pinned)

Modulus changes do **not** trivially explain TO frequency changes
(but make a small contribution: ~ 1% to 10%)

Modulus/dislocation behavior is essentially the **same in hcp ^{3}He**
(but different in bcc ^{3}He)

Torsional oscillator decoupling only in ^{4}He, **not** in hcp (or bcc) ^{3}He