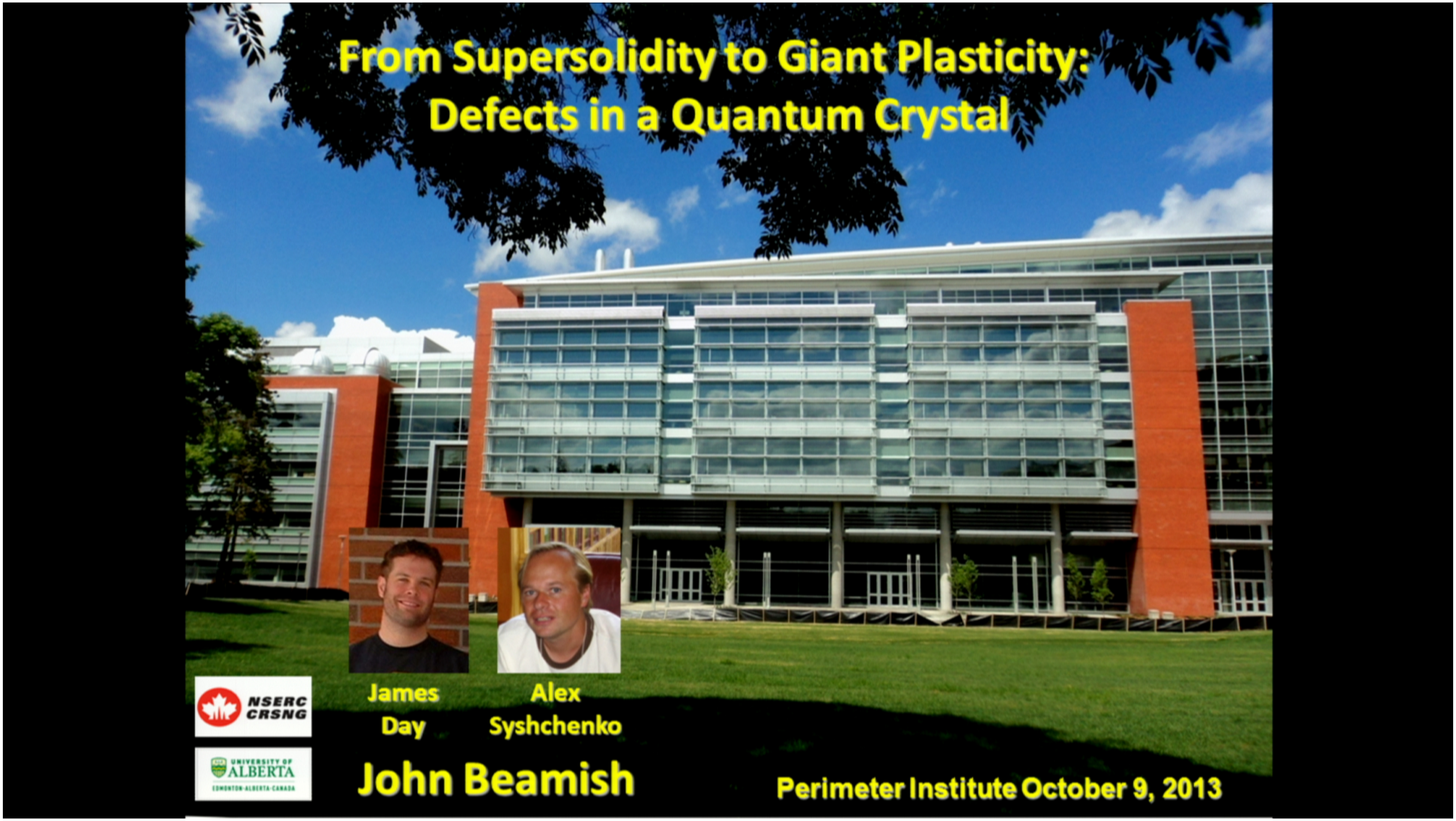
Title: From Supersolidity to Giant Plasticity: Defects in Quantum Crystals

Date: Oct 09, 2013 02:00 PM

URL: http://pirsa.org/13100065

Abstract: In 2004, Kim and Chan reported torsional
oscillator experiments on⁴He crystals which showed evidence of
â€œnon-classical rotational inertiaâ€•, the mass decoupling expected for a
long-sought â€œsupersolidâ€• state.   It soon
became clear that this behavior is not a property of perfect crystals â€“ defects
are involved. In 2007, we made elastic
measurements which showed, to our surprise, that the shear modulus of solid ⁴He
increases dramatically below 0.2 K, with the same dependence on temperature,
amplitude and ³He impurity concentration as the torsional oscillator
anomaly. These shear modulus changes are
due to dislocations and their interactions with impurities and vacancies. Our experiments raised an obvious question â€“ could
the torsional oscillator behavior be an artifact of the elastic changes, rather
than evidence of supersolidity? During
the past two years it has become clear that the answer is â€œyesâ€• and interest
has focused on the properties of dislocations in a quantum solid like ⁴He. By growing high quality single crystals in
optical cells, we have now been able to explore the behavior of dislocations in
⁴He in unprecedented detail. In some crystals the dislocations reduce the shear modulus by more than 80%, an extraordinary
effect we describe as â€œgiant plasticityâ€•. Solid helium has proved to be an ideal system in which to do materials
science, as well as to address fundamental questions about quantum solids.


From Supersolidity to Giant Plasticity:
Defects in a Quantum Crystal
NSERC CRSNG
UNIVERSITY OF ALBERTA
James Day
Alex Syshchenko
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Perimeter Institute October 9, 2013

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ECOLE
NORMALE
SUPERIEURE
A Haziot, A Fefferman, X Rojas
S Balibar (LPS ENS)
cnrs
erc

nature

January 2004

Probable observation of a supersolid helium phase

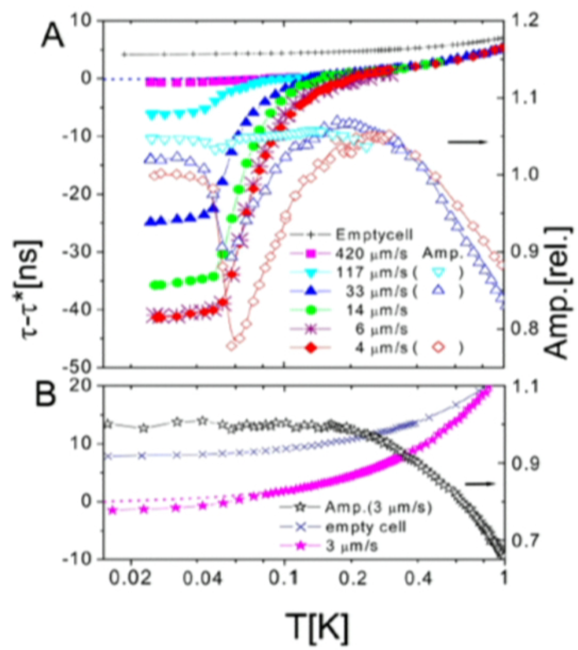
E. Kim & M. H. W. Chan

Science

September 2004

Observation of Superflow in Solid Helium

E. Kim and M. H. W. Chan*



"So, in conclusion, the data show that at temperatures approaching absolute zero, the moment of inertia changes, and the solid becomes a super-solid, which clearly appears to be a previously unknown state of matter."

Science AAAS

2005:

News Focus

Flowing Crystals Flummox Physicists

Signs of a Second Flowing Solid Deepen a Quantum Mystery

2006:

CONDENSED-MATTER PHYSICS

Free-Flowing Supersolid Confirmed, But Origins Remain Murky

CONDENSED-MATTER PHYSICS

Defects and perfect flows

Henry R. Glyde

2007:

PHYSICS

Cracking the Supersolid

Philip Phillips and Alexander V. Balatsky

Experimenters Agree: You Can Cross Off Flowing Crystals

2008:

Squeeze Play Makes Solid Helium Flow

2009:

PHYSICS

A Glassy State of Supersolid Helium

John Saunders

Helium is the most quantum liquid or solid

- small mass, weak forces ⇨ remains liquid to T=0
- low T, high density N/V ⇨ "quantum fluid"
- ^{4}He is a **boson** ⇨ "BEC" and **superfluidity**
- ^{3}He is a fermion ⇨ no superfluidity w/o pairing
- exchange, vacancies ⇨ helium is a "quantum solid"

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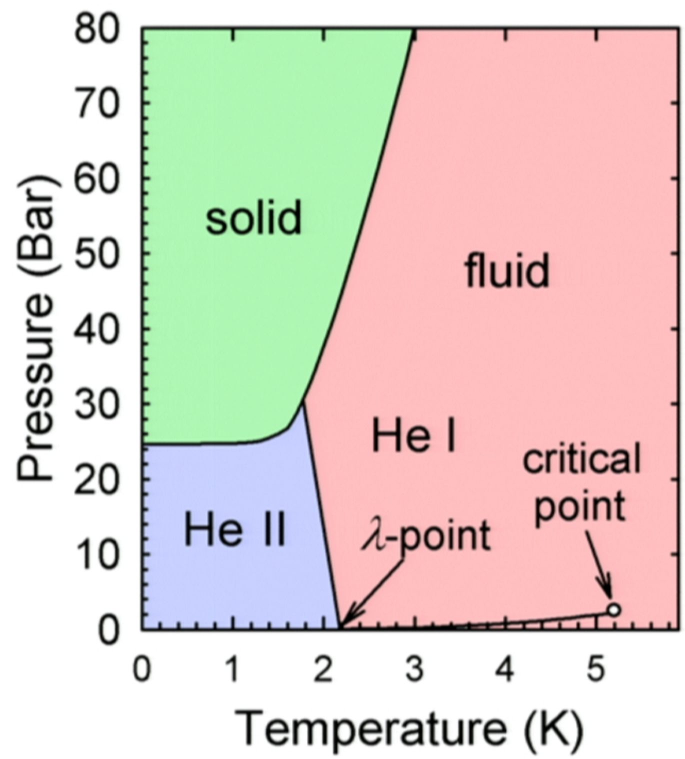
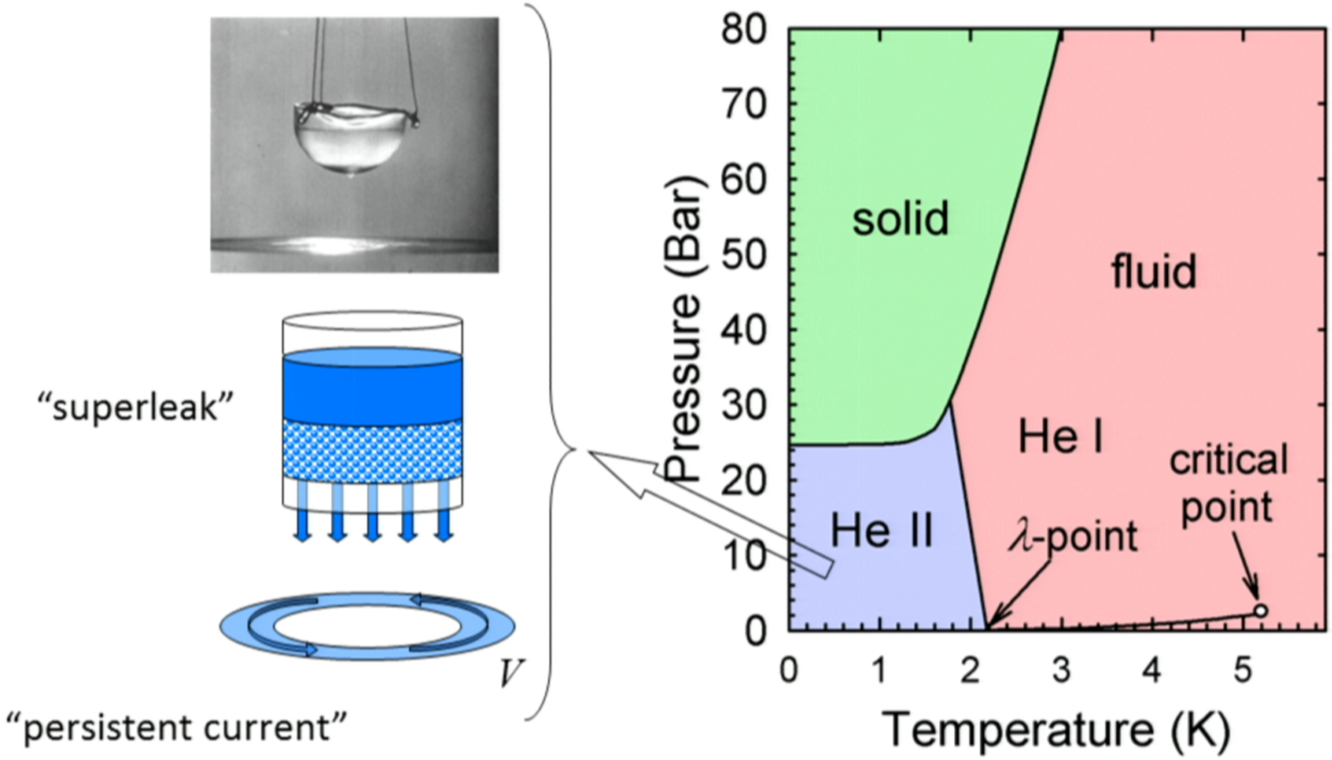
Superfluid phase below 2.17 K



Superfluid phase below 2.17 K



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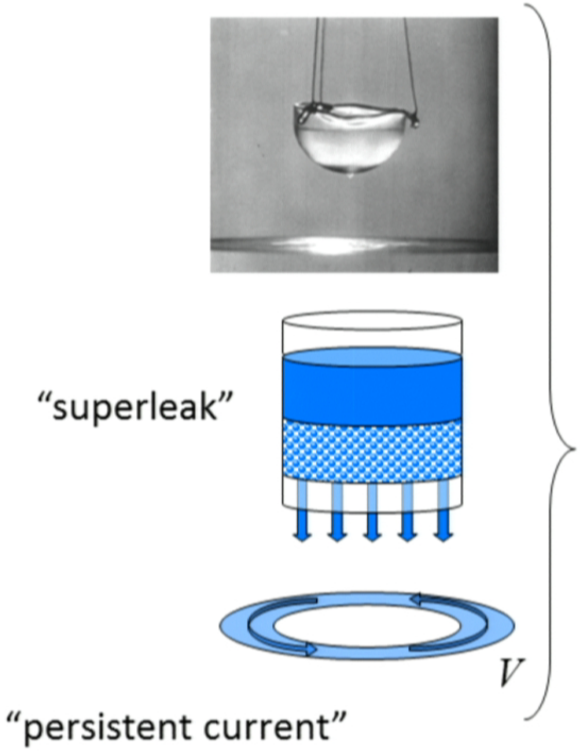

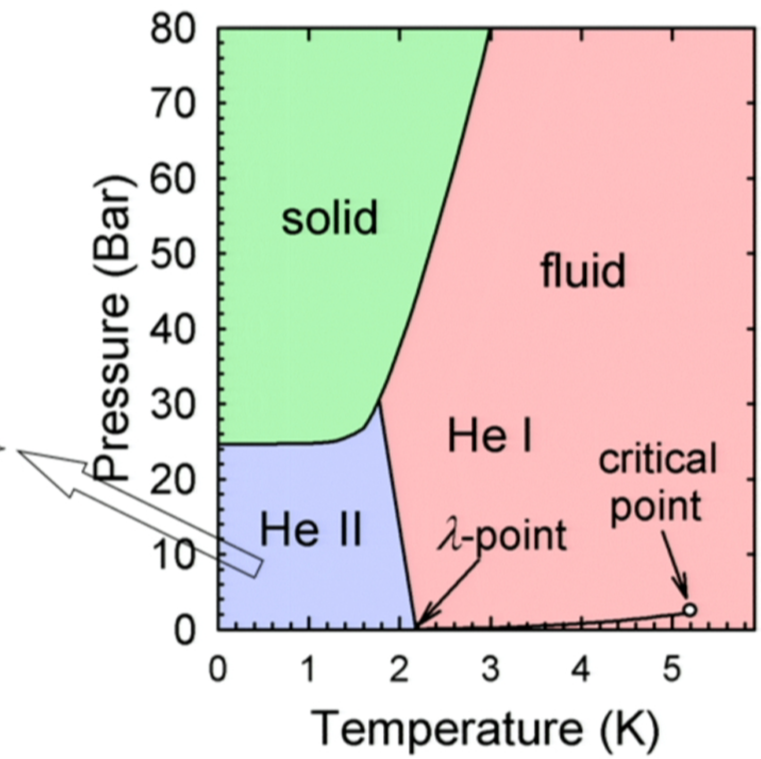

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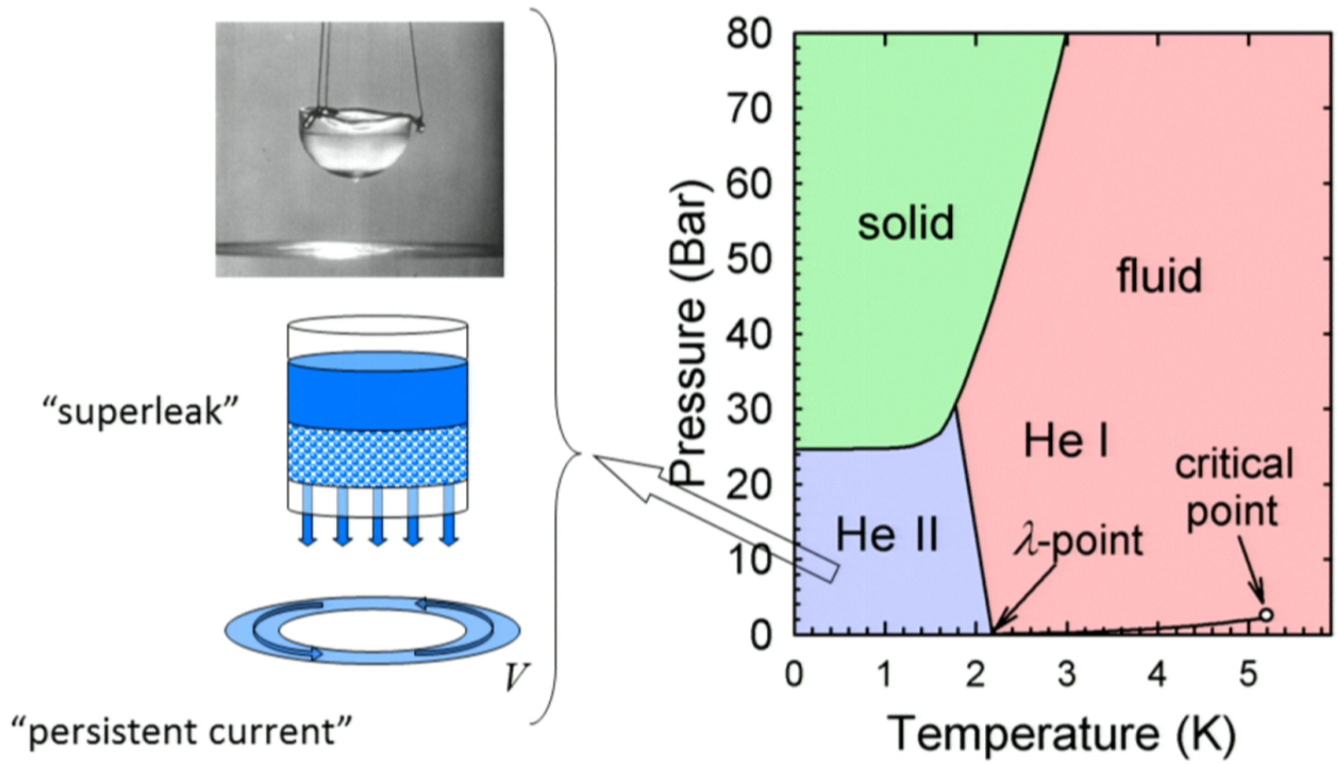
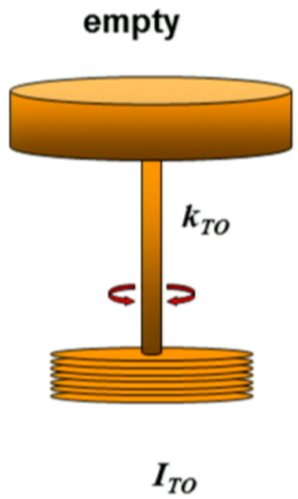


"**superflow**" below the λ point (2.17 K)
(at speeds below a "critical velocity")

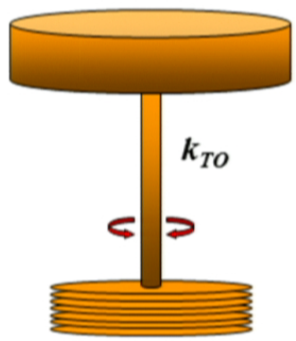
Torsional oscillator as a probe of superfluidity
(Andronikashvili experiment / 2 fluid model)



$$f = \frac{1}{2\pi}\sqrt{\frac{k_{TO}}{I_{TO}}}$$

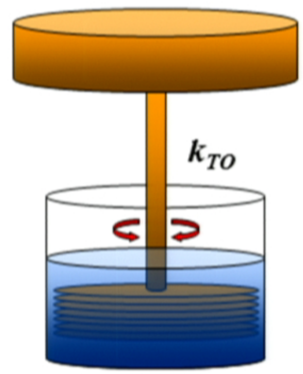
Torsional oscillator as a probe of superfluidity
(Andronikashvili experiment / 2 fluid model)

empty



I_{TO}

liquid ^{4}He



$I_{TO}+I_{He}$

$$f = \frac{1}{2\pi}\sqrt{\frac{k_{TO}}{I_{TO}}}$$

$$T > T_\lambda \;\Rightarrow\; f = \frac{1}{2\pi}\sqrt{\frac{k_{TO}}{I_{TO} + I_{He}}}$$

$$T < T_\lambda \;\Rightarrow\; f = \frac{1}{2\pi}\sqrt{\frac{k_{TO}}{I_{TO} + I_{He} - I_{SF}}}$$

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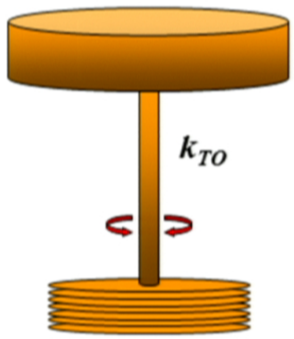

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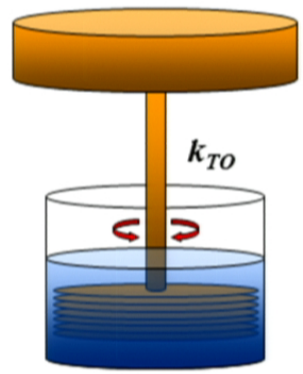

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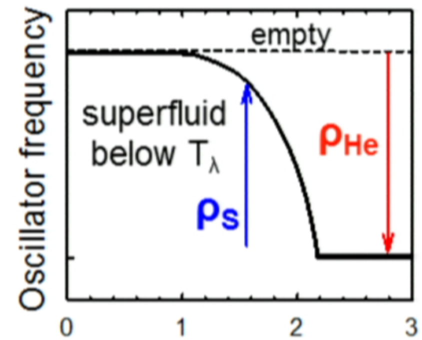

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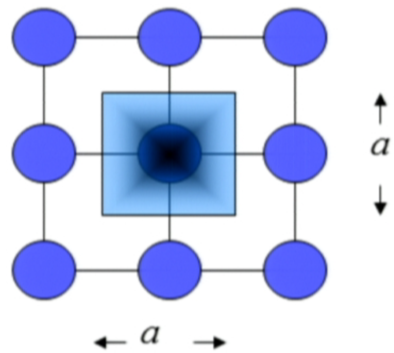
$$\rho_{He} = \rho_n + \rho_s$$

ρ_s decouples

"Quantum solids"
(zero point motion)



Uncertainty principle

$$\Delta x \Delta p_x \approx a \Delta p_x \approx \hbar$$

Zero point energy (ZPE)

$$\frac{(\Delta p_x)^2 + (\Delta p_y)^2 + (\Delta p_z)^2}{2m} \approx \frac{3\hbar^2}{2ma^2}$$

De Boer parameter

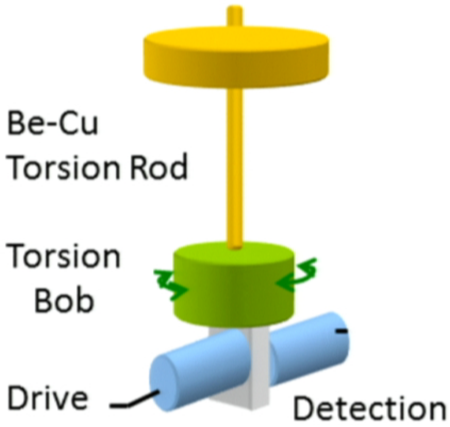
$$\Lambda^2 = \frac{h^2}{ma^2\varepsilon} \approx \left(\frac{ZPE}{PE}\right)$$

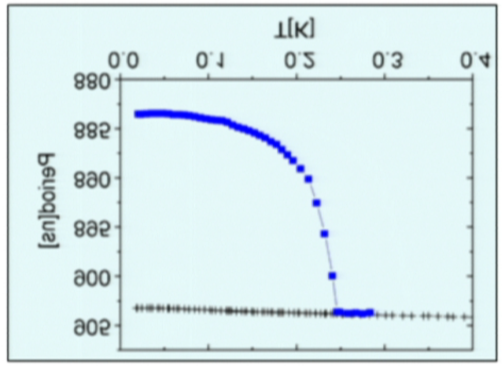
≈ 0.03 Ar

≈ 7 ^4He

Solid ^4He decoupling from a torsional oscillator

E. Kim & M.H.W. Chan, Nature 427, 225 (2004)





Superfluid film
on vycor

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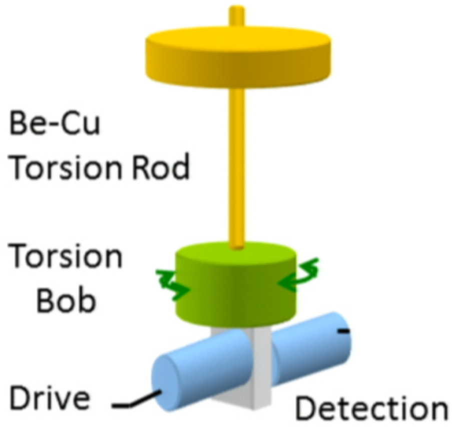

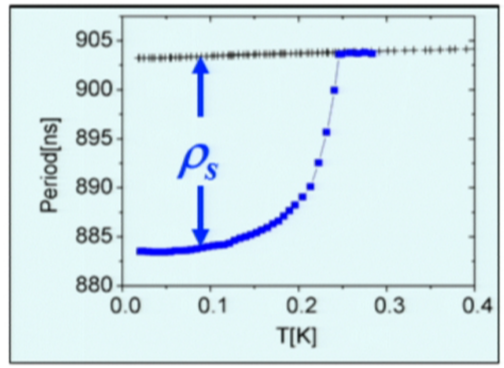

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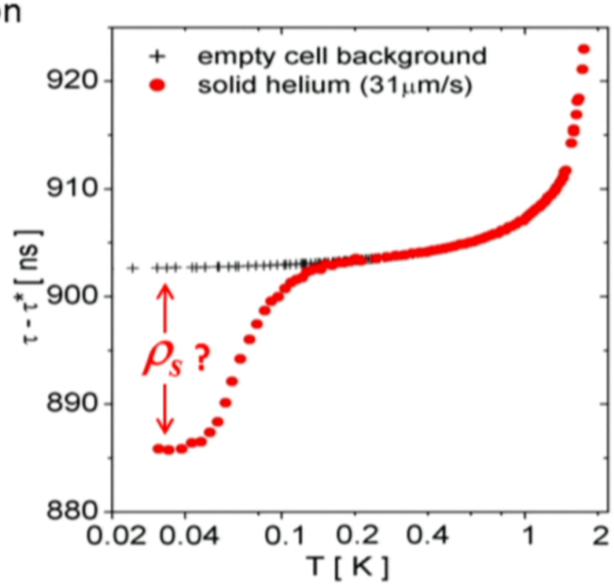

Solid ^{4}He
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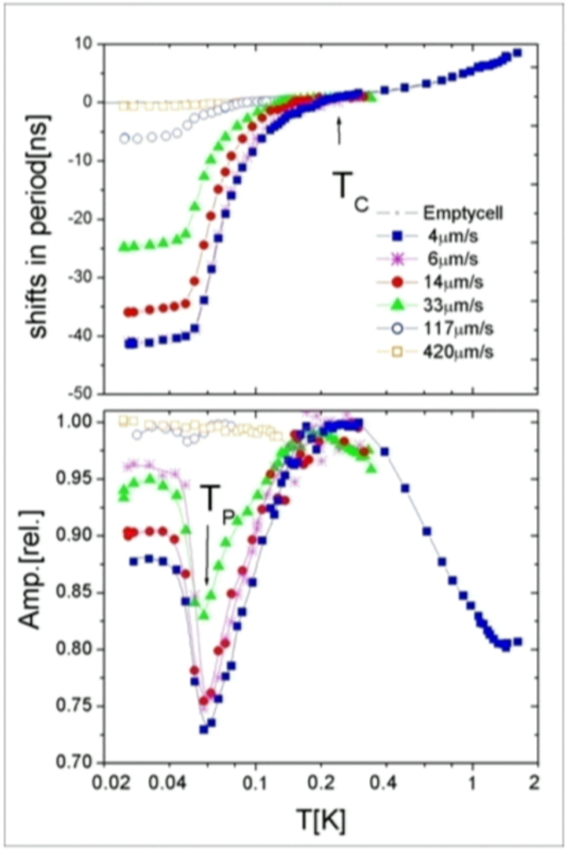
Bulk solid helium: decoupling and dissipation

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



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T[K]

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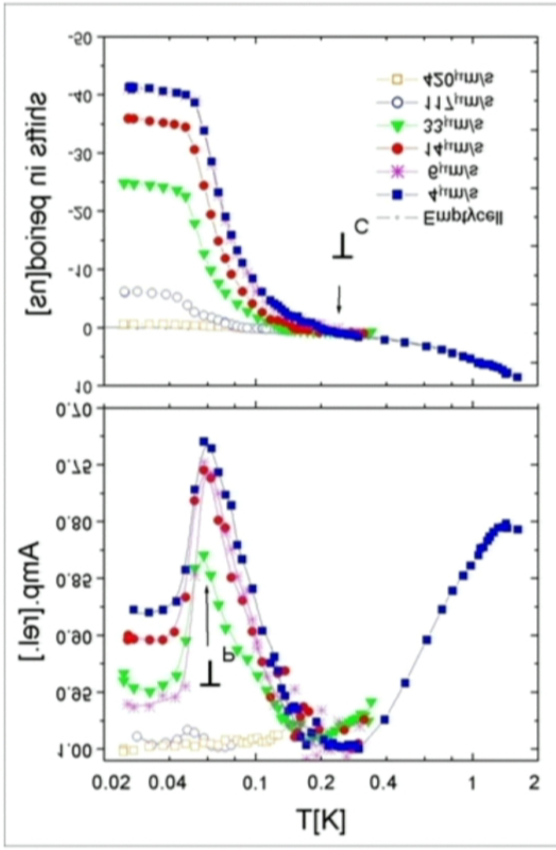
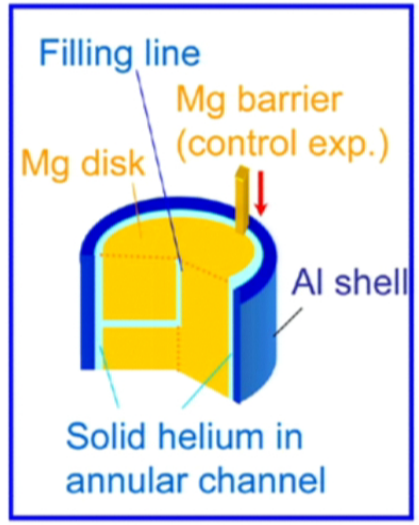




blocking path eliminates effect
i.e. long range coherent flow?

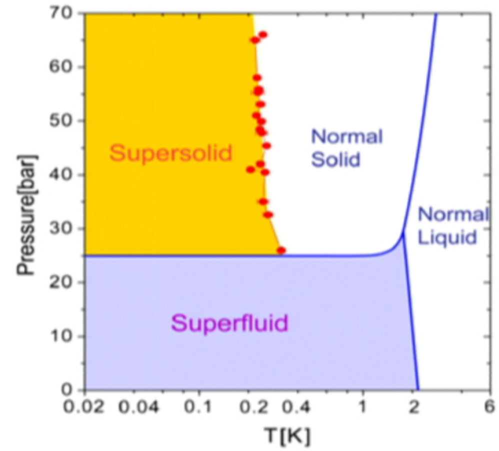
Torsional oscillator measurements

MHW Chan group (Penn State)

and at least 10 other places:

- Cornell (Reppy, Davis)
- Keio University (Shirahama)
- ISSP (Kubota)
- Rutgers (Kojima)
- KAIST & RIKEN (Kim/Kono)
- Royal Holloway (Cowan/Saunders)
- Manchester (Golov)
- ENS (Balibar/Chan)

“supersolid phase diagram”



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

T_c : ~ same in different cells
~ independent of pressure

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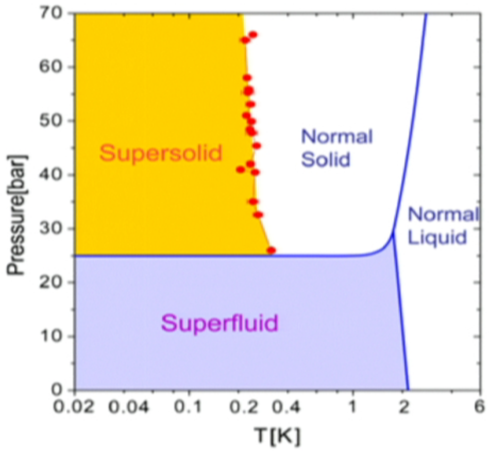

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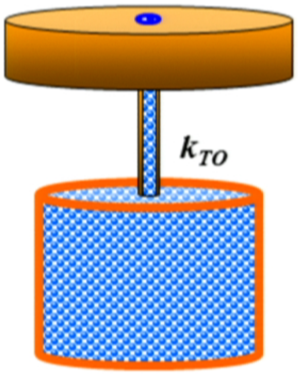
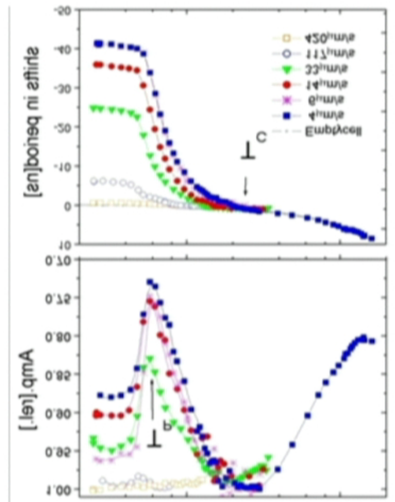
solid ^{4}He



k_{TO}

$I_{TO} + I_{He} (- I_{SS} ?)$

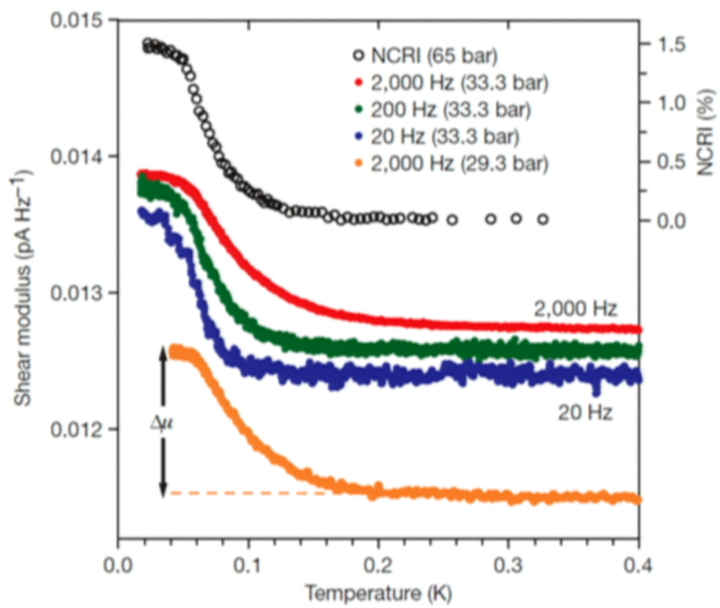


frequency increase
(decoupling - "NCRI" ~ 1% ?)

amplitude dependence
(critical velocity ~ 10 μm/s ?)

$$f = \frac{1}{2\pi}\sqrt{\frac{k_{TO}}{I_{TO} + I_{He} - I_{SS}}}$$

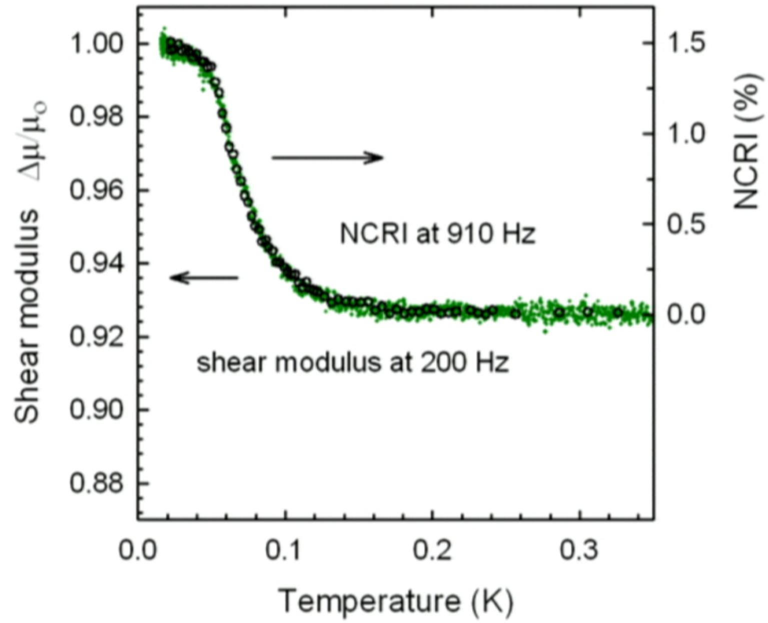
Modulus change vs. NCRI



Torsional oscillator
Kim and Chan (2004)

Shear modulus
Day and Beamish (2007)

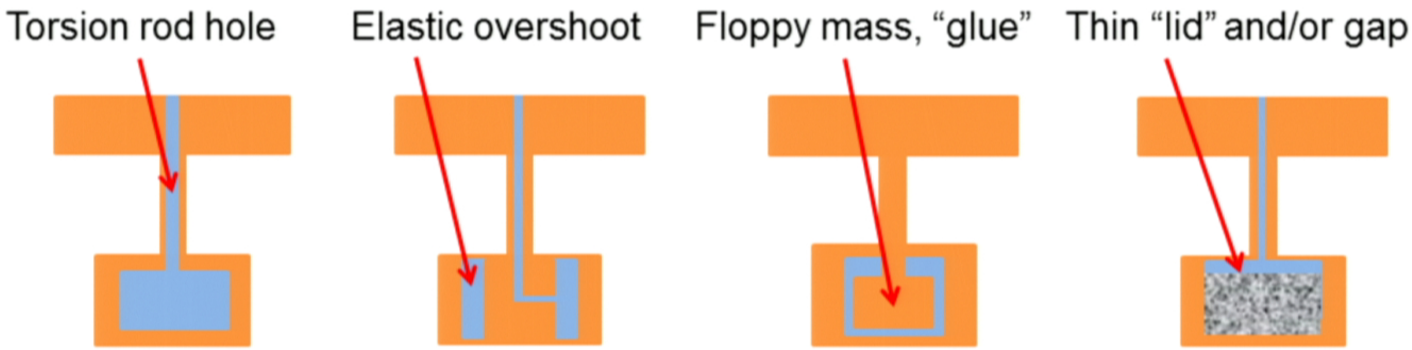
Modulus change vs. NCRI



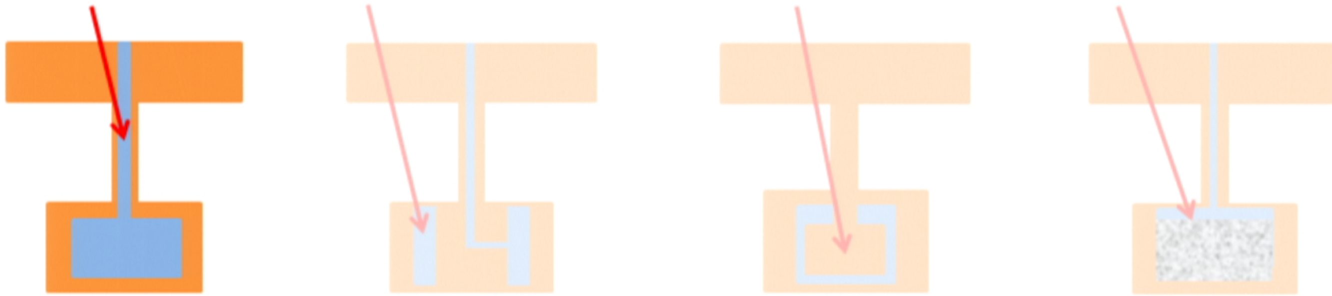
Torsional oscillator
Kim and Chan (2004)

Shear modulus
Day and Beamish (2007)

Elastic effects in torsional oscillators



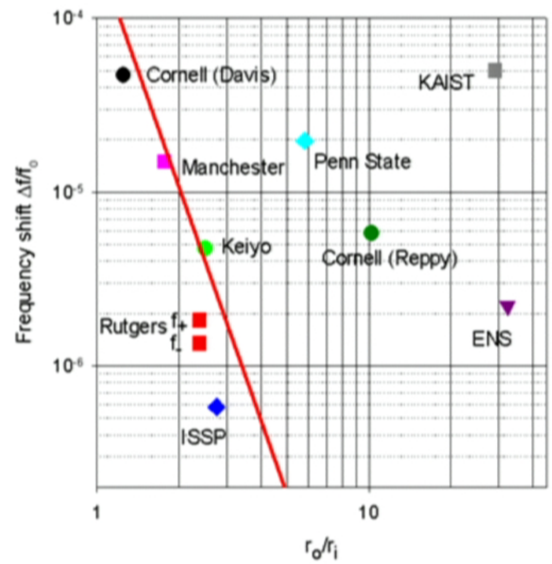
Torsion rod hole Elastic overshoot Floppy mass, “glue” Thin “lid” and/or gap



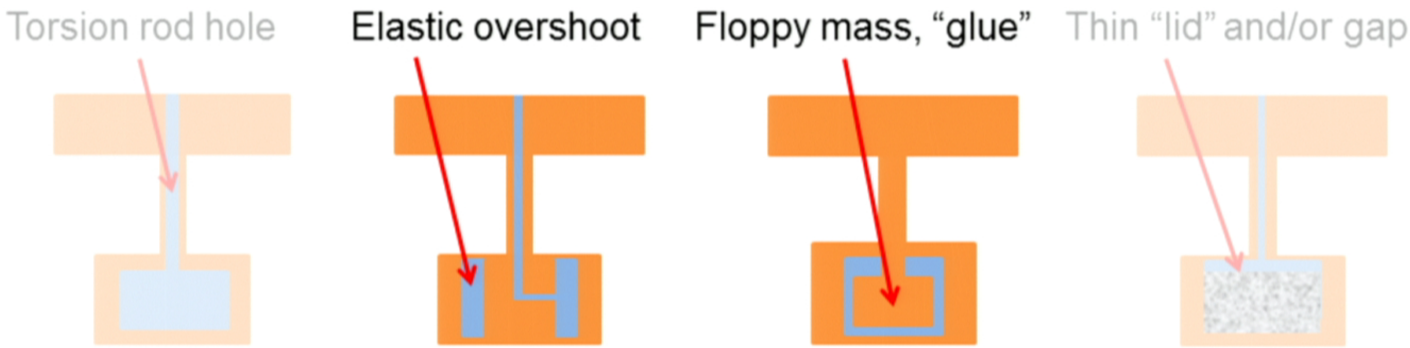
$$\frac{\Delta f_{\text{elastic}}}{f_0} = \frac{1}{2}\frac{\mu_{\text{He}}}{\mu_{\text{rod}}}\frac{1}{\left(\frac{r_o}{r_i}\right)^4 - 1}$$

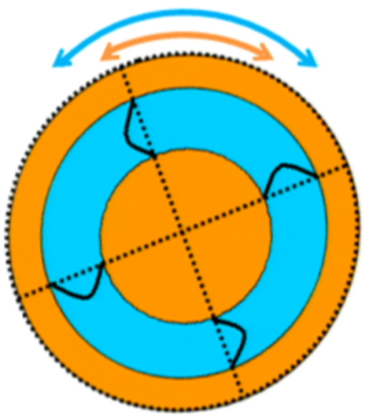
$$\frac{\mu_{He}}{\mu_{BeCu}} \approx 5\times 10^{-4} \Rightarrow \frac{\Delta f_{elastic}}{f_0} \approx 10^{-10} - 5\times 10^{-4}$$

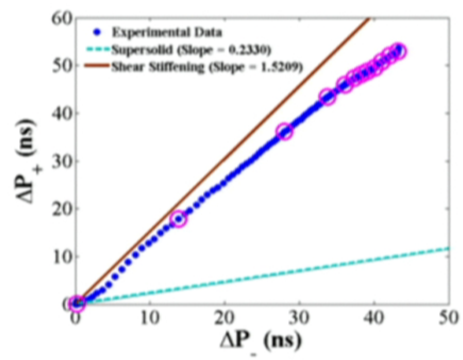
i.e. small (but so are the measured changes)

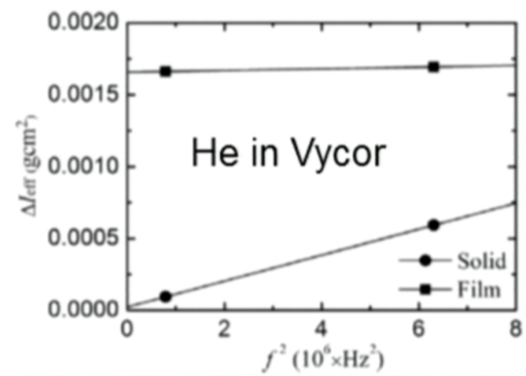


J. R. Beamish, A. D. Fefferman, A. Haziot, X. Rojas, and S. Balibar
PHYSICAL REVIEW B **85**, 180501(R) (2012)









proportional to ω^2

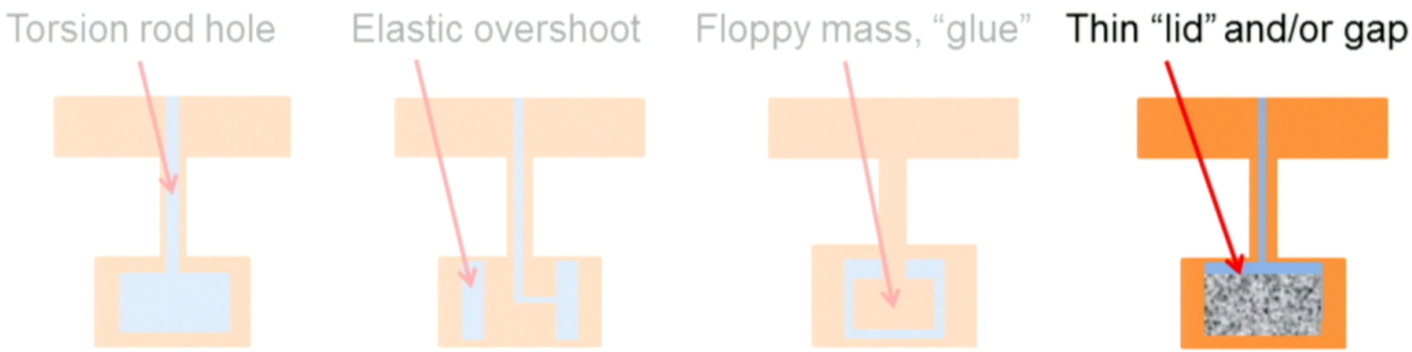
⇨ can distinguish from NCRI

Xiao Mi, Erich J. Mueller, and John D. Reppy

Journal of Physics: Conference Series **400** (2012) 012047

Xiao Mi and John D. Reppy

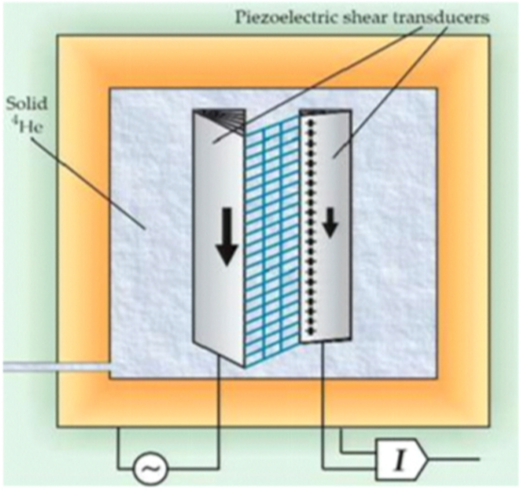
PRL **108,** 225305 (2012)



Humphrey J. Maris

PHYSICAL REVIEW B **86**, 020502(R) (2012)

Measuring shear modulus and dissipation



apply shear deformation ε

measure stress σ

in narrow gap D

strain ε ~ drive voltage V

stress σ ~ charge q ~ i/f

$$\mu = \sigma/\varepsilon \sim i/fV$$

stress lags strain by angle ϕ

$$1/Q = \phi$$

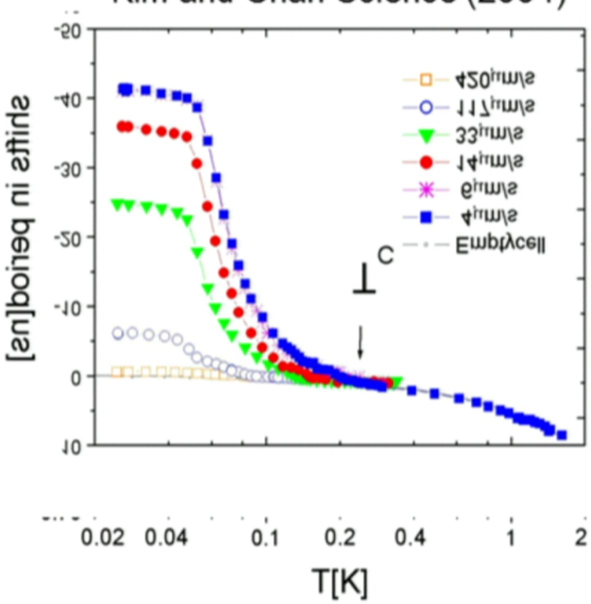
frequencies: 0.2 Hz to 20 kHz

strain: 10^{-10} - 10^{-3}

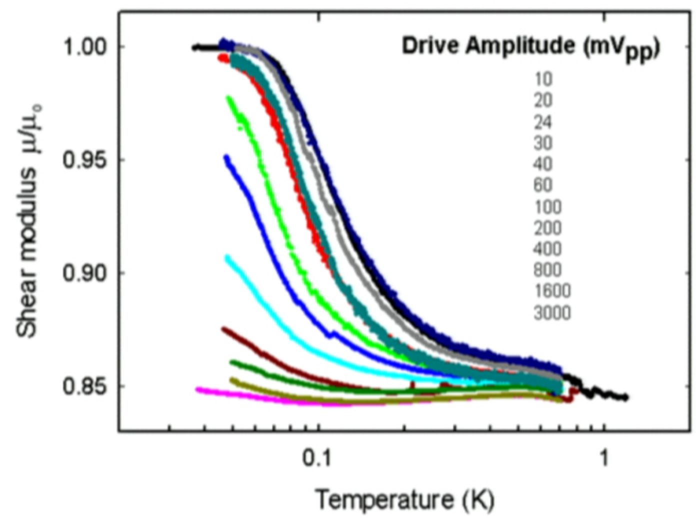
stress: 0.001 - 10^4 Pa

Amplitude dependence

Kim and Chan Science (2004)



Day and Beamish (2007)



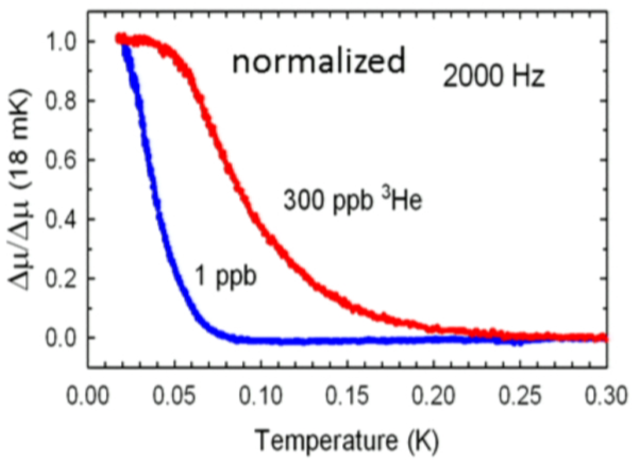
critical velocity

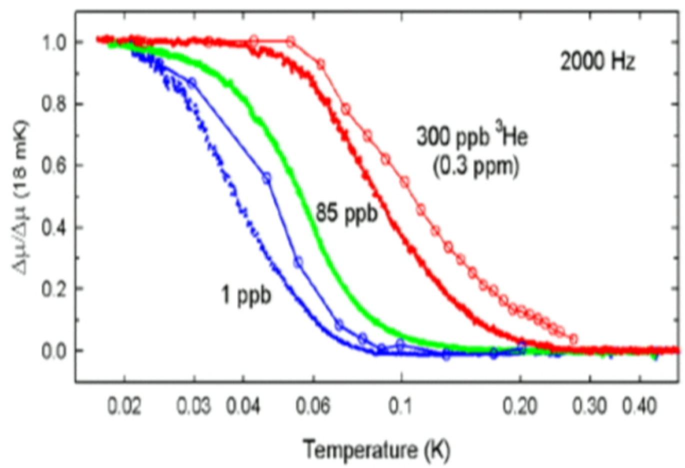
$v_c \sim 10\ \mu m/s$

critical strain/stress

$\varepsilon_c \sim 4 \times 10^{-8}$ $\sigma_c \sim 1$ Pa

Effect of ^{3}He impurities on μ

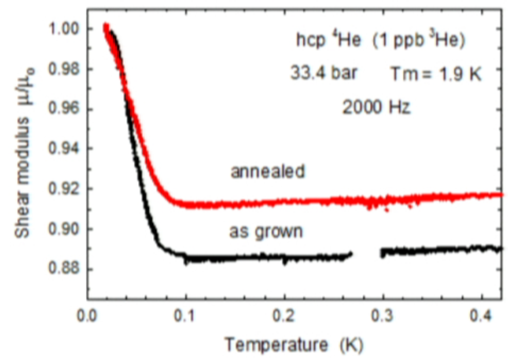




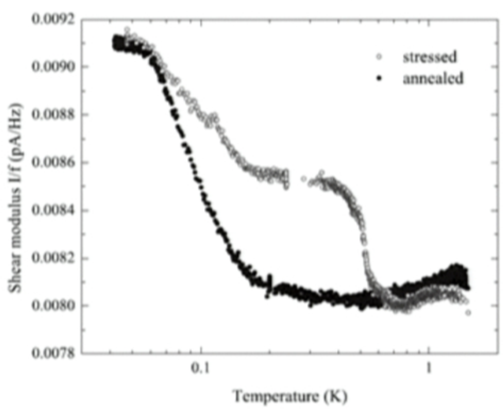
Extremely sensitive to minute amounts (ppb) of ^{3}He

Effects of annealing and stressing

annealing



stressing



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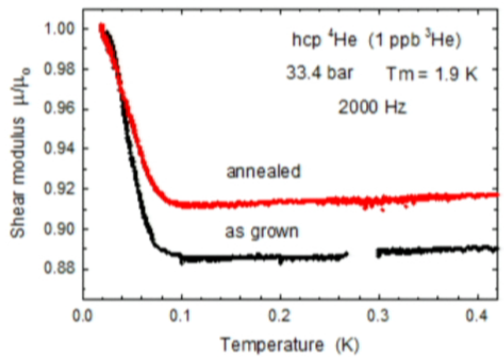
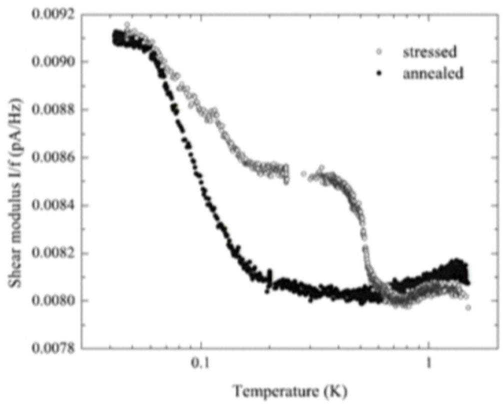


stressing



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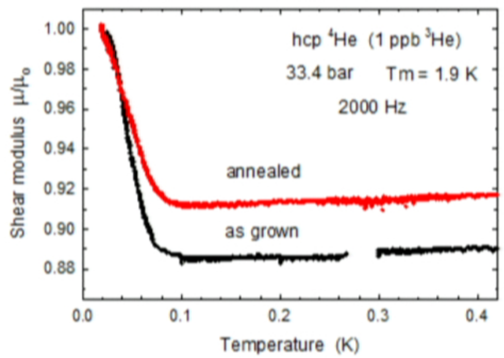

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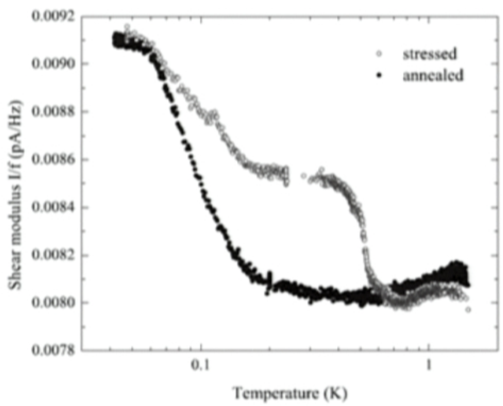
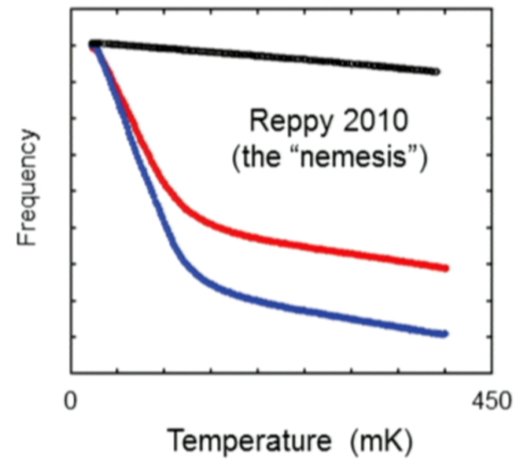


plastic deformation
in a torsional oscillator



intrinsic modulus
(and TO frequency) at **low T**

⇨ crystals **soften** at **high** temperature
(instead of stiffening or decoupling at low T)

Origin of modulus changes?

Large changes (softening) of shear modulus (up to 86%)

Variation in size of modulus changes (~ 5% to 86%)

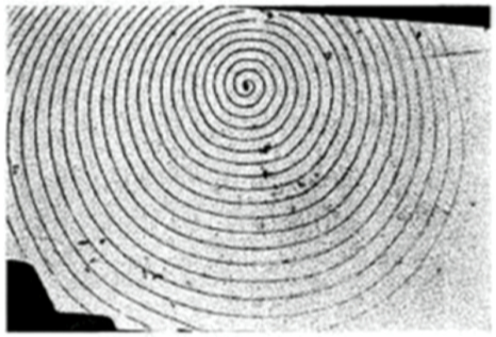
Extremely **sensitive to impurities** (^3He at < ppm level)

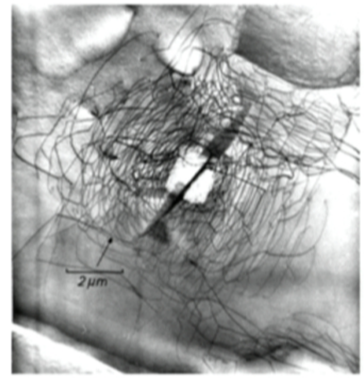
Shear modulus at high T depends on **annealing** and **plastic deformation**

⇨ **defects (dislocations) must be involved**

Dislocation basics

- almost all solids have dislocations (from growth or deformation)





Dislocation basics

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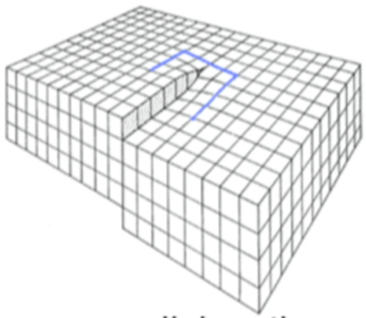
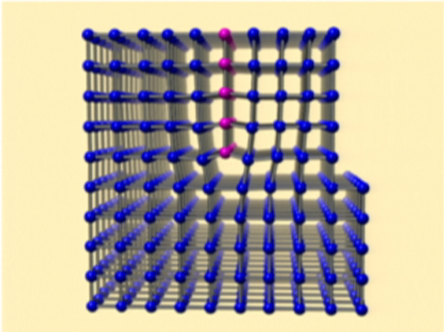
- dislocations “glide” under shear stress (larger than the “Peierls stress”)



screw dislocations
(crystal growth)



edge dislocations
glide in basal plane

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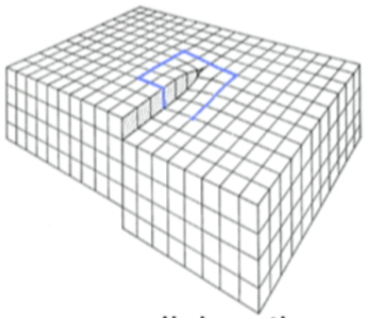

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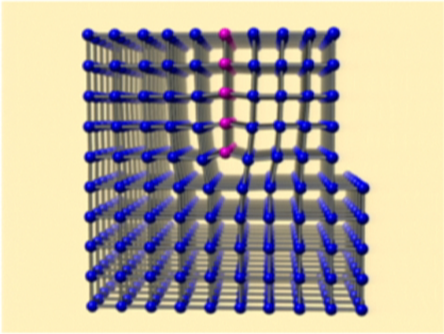

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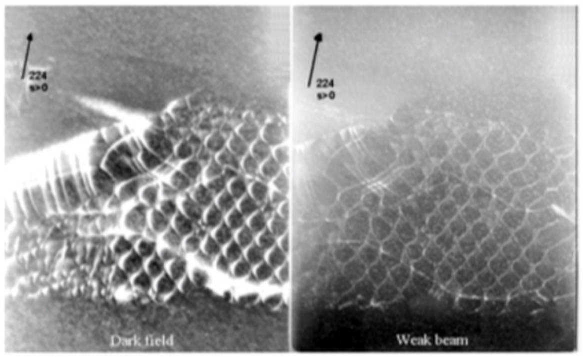

Frank network in annealed metals

^{3}He binding ~ 0.3 – 0.7 K

Dislocation basics

- almost all solids have dislocations (from growth or deformation)

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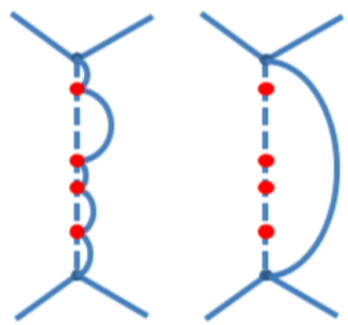
- they are strongly pinned where they intersect and weakly pinned by impurities

- stress tears them away from immobile impurities

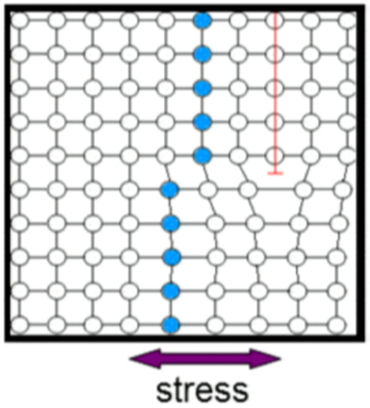


Effect of dislocations on shear modulus

dislocations move in
response to shear stress

moving a dislocation through
the crystal deforms it

the added strain reduces μ



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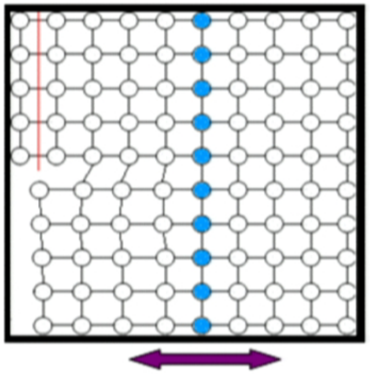

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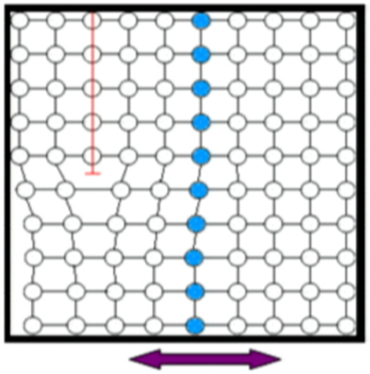

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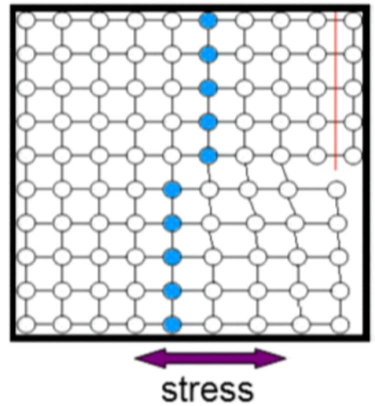
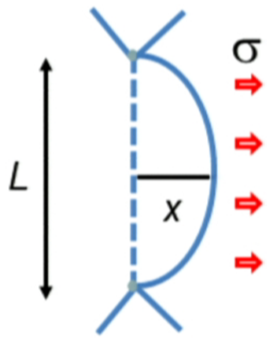
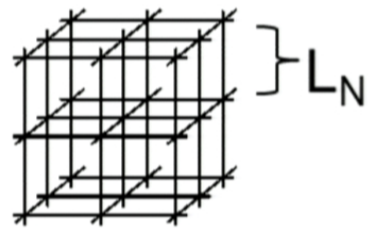




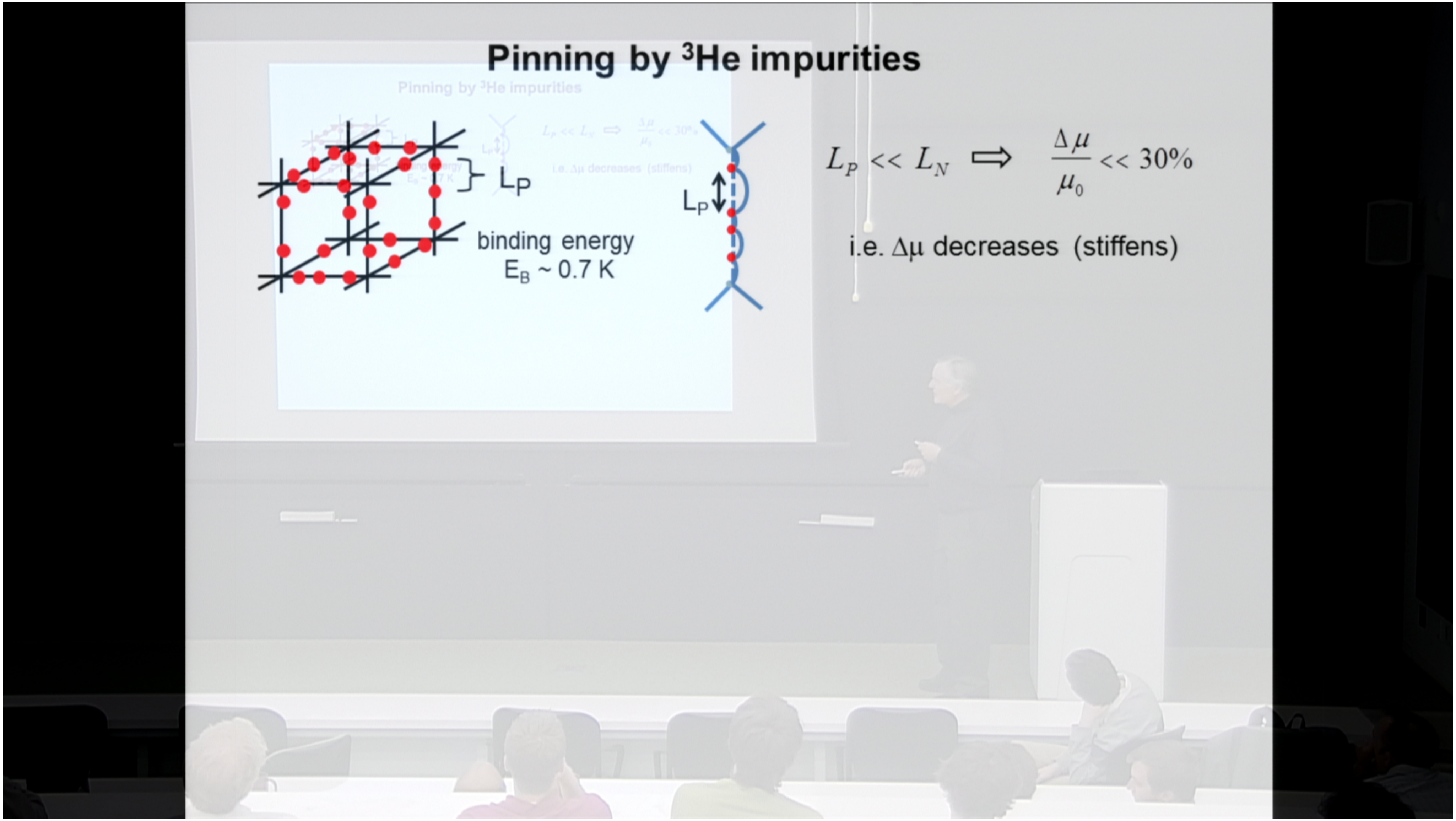


network
pinning

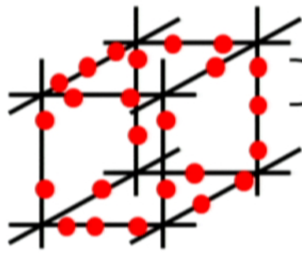
$$x \propto \sigma L^2 \Rightarrow \varepsilon_d \propto x\Lambda \propto \sigma\Lambda L^2$$

$$\Rightarrow \frac{\Delta\mu}{\mu_0} \approx 0.5R\Lambda L^2$$

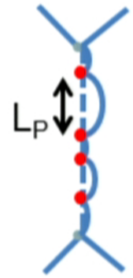
$$\Lambda L^2 = 3 \Rightarrow \frac{\Delta\mu}{\mu_0} \approx 30\%$$


Pinning by ³He impurities
L_P
binding energy
E_B ~ 0.7 K
L_P
L_P << L_N ⟹ Δμ/μ_0 << 30%
i.e. Δμ decreases (stiffens)

Pinning by ^{3}He impurities



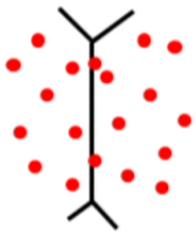
binding energy
$E_B \sim 0.7$ K



$$L_P << L_N \Rightarrow \frac{\Delta\mu}{\mu_0} << 30\%$$

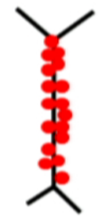
i.e. $\Delta\mu$ decreases (stiffens)

T dependence:



$\Rightarrow$

decreasing temperature



stiff at low T

Dislocations and the shear modulus of polycrystals

A mobile dislocation network reduces (softens) shear modulus μ
(by ~ 10% in polycrystals)

^{3}He impurities bind to dislocations (E_B ~ 0.3 – 0.7 K) and pin them
⇨ intrinsic μ: "stiff" at low temperature

Impurities thermally unbind from dislocations, letting them move
⇨ μ decreases: "soft" at high temperatures

Large stresses unpin dislocations ("breakaway")
⇨ μ decreases: "soft" at high amplitude

How to get precise information on dislocations in helium?

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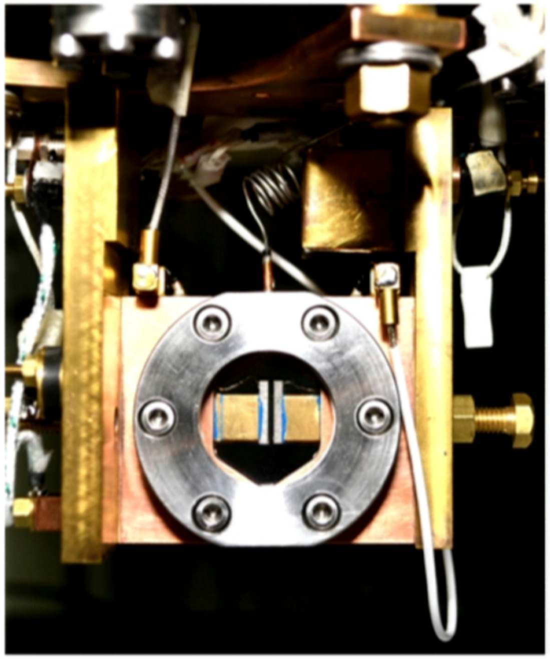
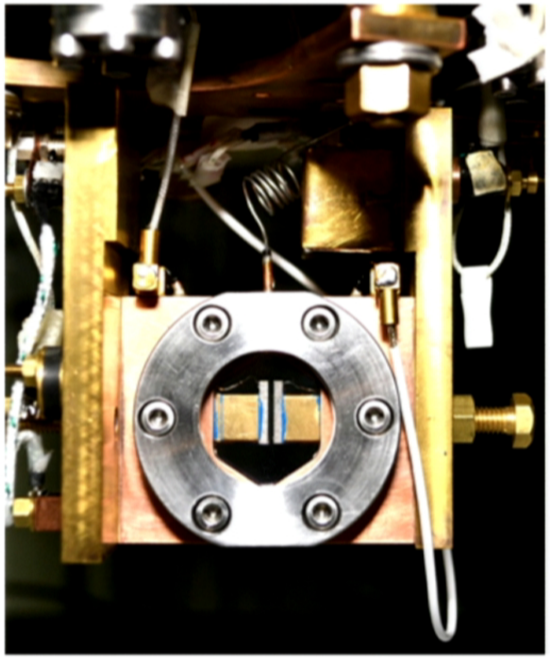
"Material science": control/measure sample quality

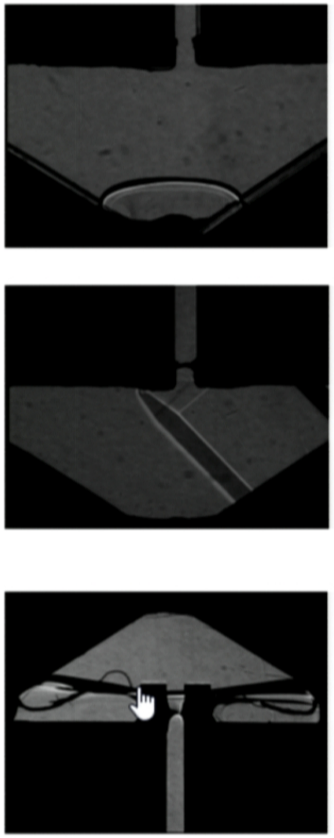
Growth of single crystals from superfluid



single crystal growth at 20 mK

Growth of single crystals from superfluid





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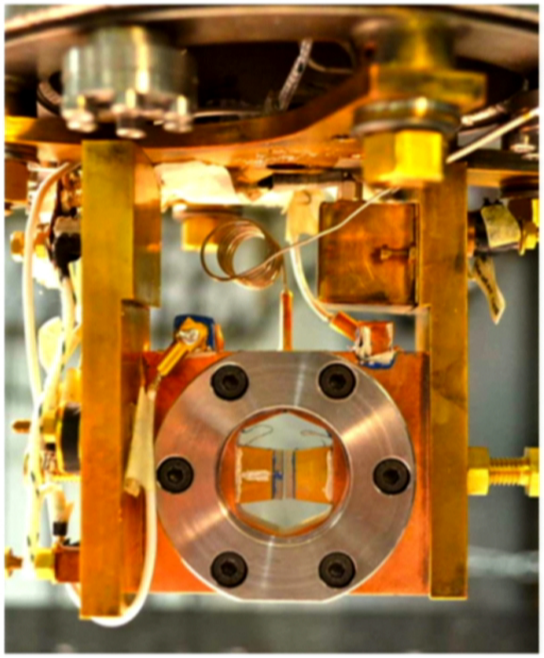
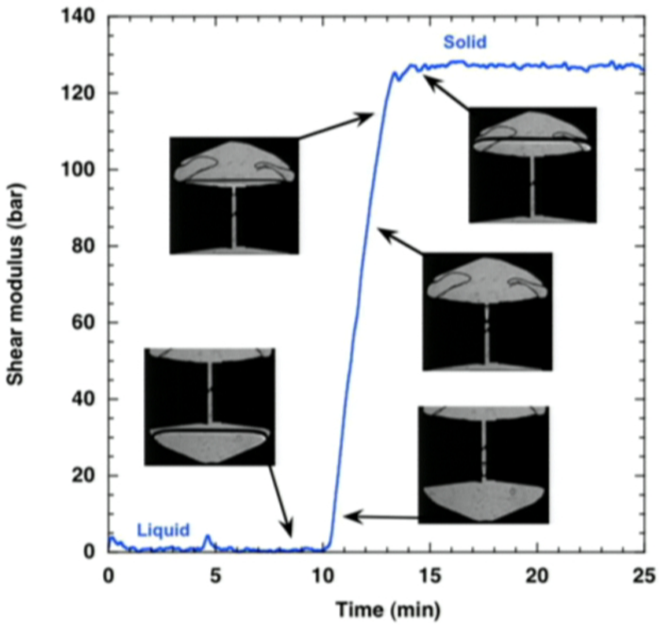
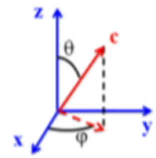




Anisotropy in single crystals: which C_{ij} changes?

$$\begin{pmatrix} c_{11} & c_{12} & c_{13} & 0 & 0 & 0 \\ c_{12} & c_{11} & c_{13} & 0 & 0 & 0 \\ c_{13} & c_{13} & c_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & c_{66} \end{pmatrix}$$



$$C' = M_z(-\phi)M_y(-\theta)CM_y^T(-\theta)M_z^T(-\phi)$$

$$\mu = c'_{44} = \frac{1}{4}(c_{11} - 2c_{13} + c_{33})sin^2 2\theta sin^2\phi + c_{44}(cos^2\theta cos^2\phi + cos^2 2\theta sin^2\phi) + c_{66}cos^2\phi sin^2\theta$$

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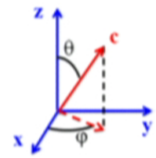

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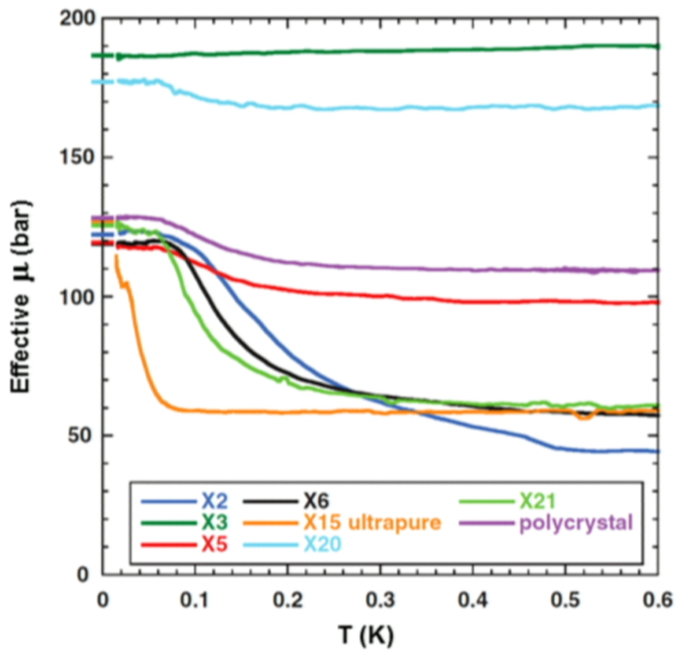

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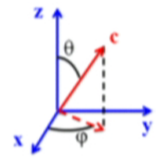

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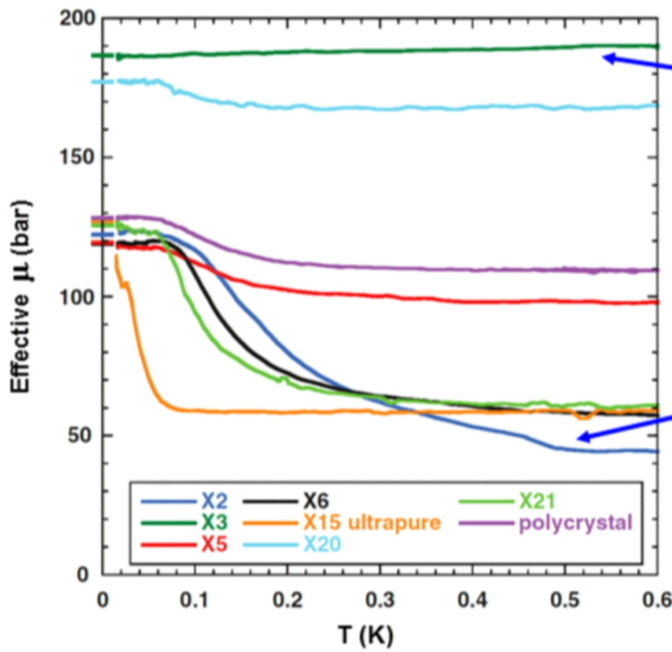
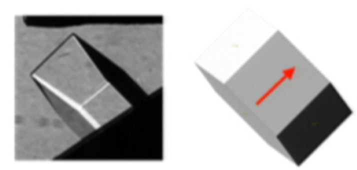
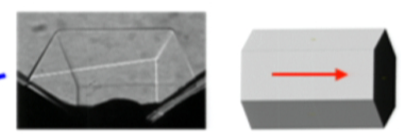




$\theta = 45°$ and $\phi = 85°$

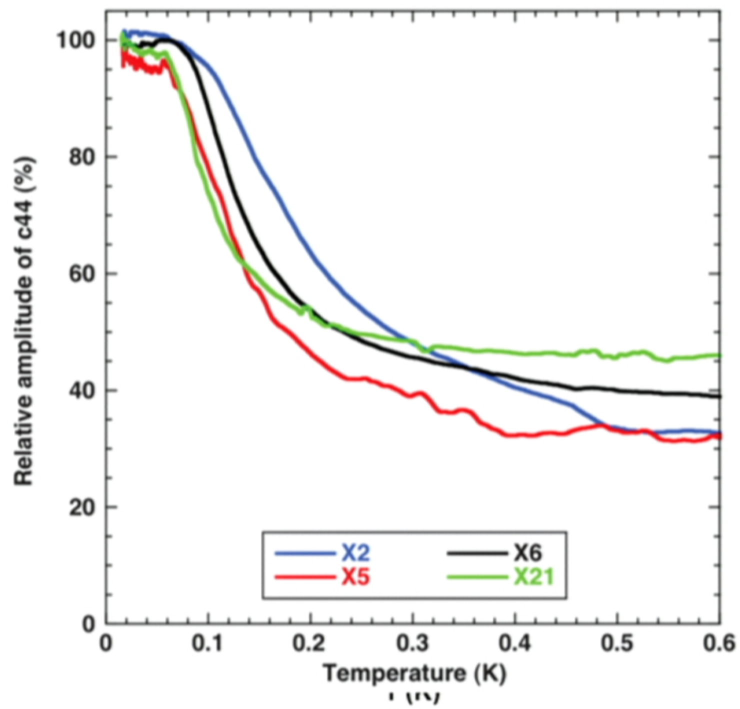
$0.25(c_{11} - 2c_{13} + c_{33}) + 0.004c_{44} + 0.004c_{66}$



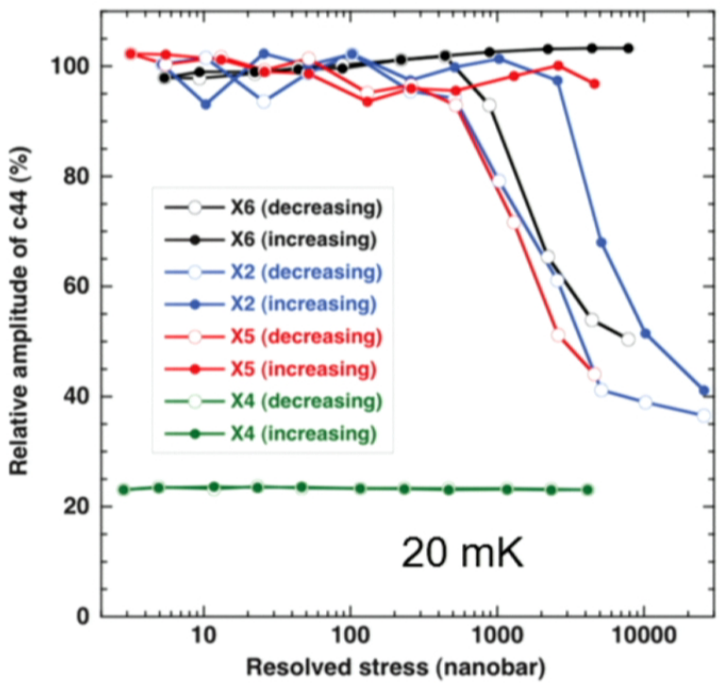
$\theta = 89.5°$ and $\phi = 85°$

$\mu = 0.0001(c_{11} - 2c_{13} + c_{33}) + 0.933c_{44} + 0.067c_{66}$

Variation of C_{44} in ^{4}He single crystals



What if there is no ^{3}He to pin the dislocations?



^{3}He breakaway stress ~ μbar

no ^{3}He ⇨ soft even at nanobar stresses

zero Peierls stress for dislocation (or kink) motion?

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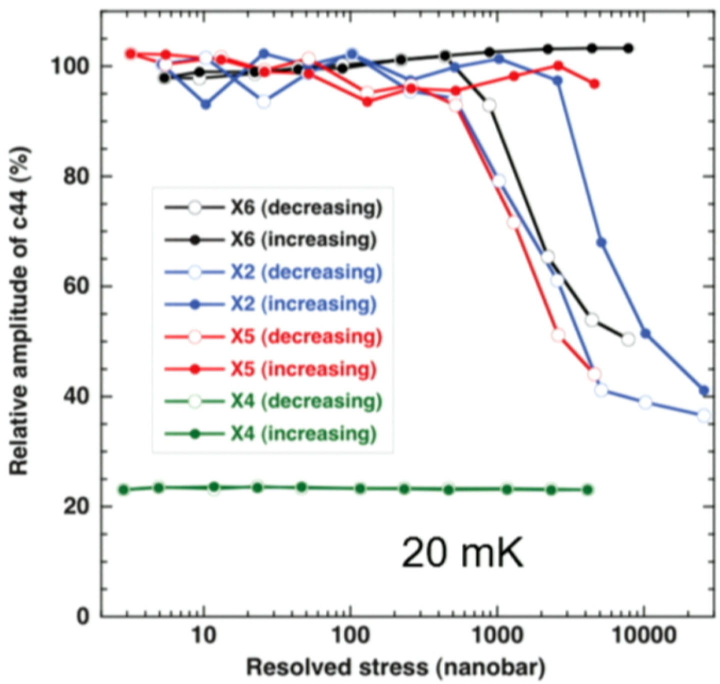

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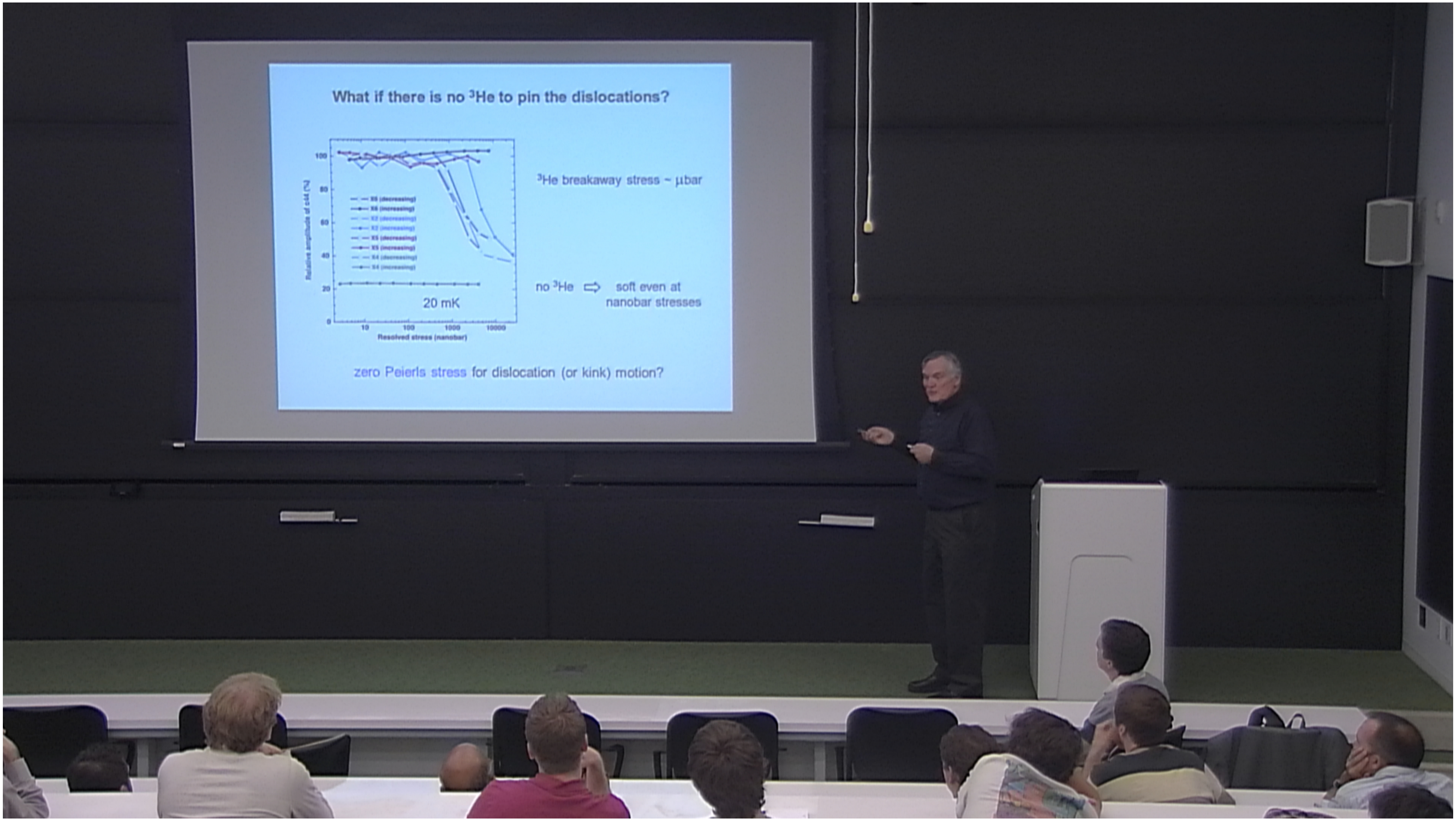
What if there is no ³He to pin the dislocations?
100
80
60
40
20
0
10
100
1000
10000
Resolved stress (nanobar)
20 mK
³He breakaway stress ~ µbar
no ³He ⇨ soft even at
nanobar stresses
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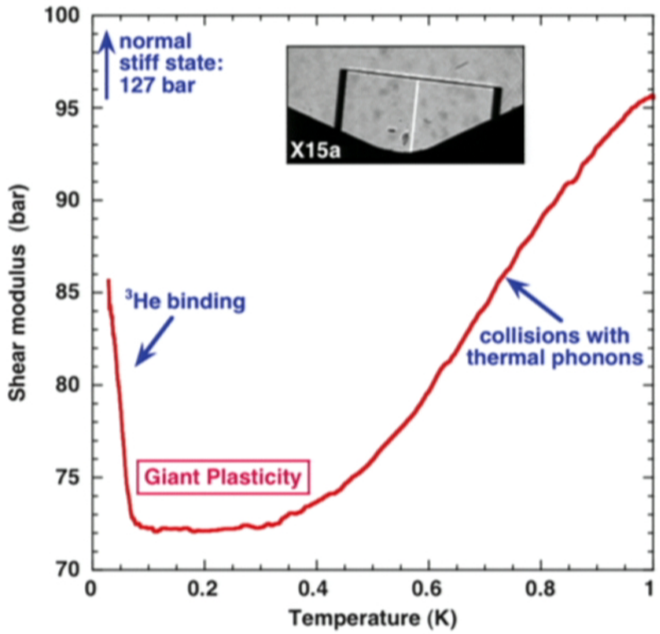
Giant Plasticity: the dislocation network in helium

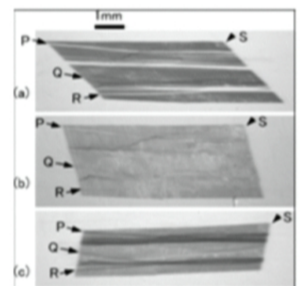


low frequency limit:

$$\frac{\Delta\mu}{\mu_{\mathrm{el}}} = \frac{\mu_{\mathrm{el}} - \mu}{\mu_{\mathrm{el}}} = \frac{R\Sigma\Lambda L^2}{1 + R\Sigma\Lambda L^2}$$

$$\frac{\Delta\mu}{\mu_0} \approx 70\% \quad \Rightarrow \quad \Lambda L^2 > 50$$

$\Rightarrow$ dislocations aligned in some way which avoids intersections (subboundaries?)

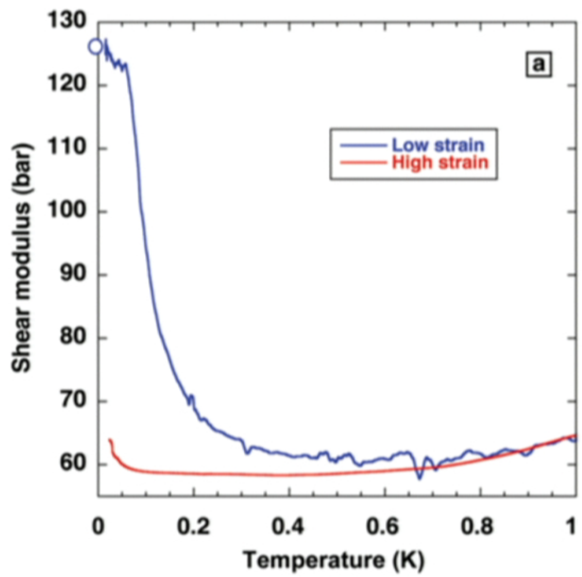


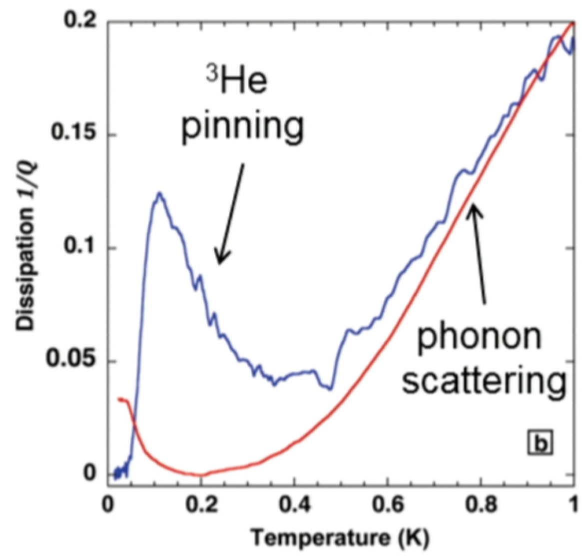
Can we measure dislocation density Λ and length L_N separately?

Dislocation damping, densities and lengths

$$\frac{\mu_{\rm el}}{\mu} = \frac{\epsilon_{\rm el} + \epsilon_{\rm dis}}{\epsilon_{\rm el}} = 1 + R\Sigma\Lambda L^2 \frac{1 - i\omega\tau}{1 + (\omega\tau)^2}$$

$$\frac{1}{Q} = \frac{\Delta\mu}{\mu_{\rm el}}\omega\tau = \frac{\Delta\mu}{\mu_{\rm el}}\omega\frac{BL^2}{\pi^2 C}$$

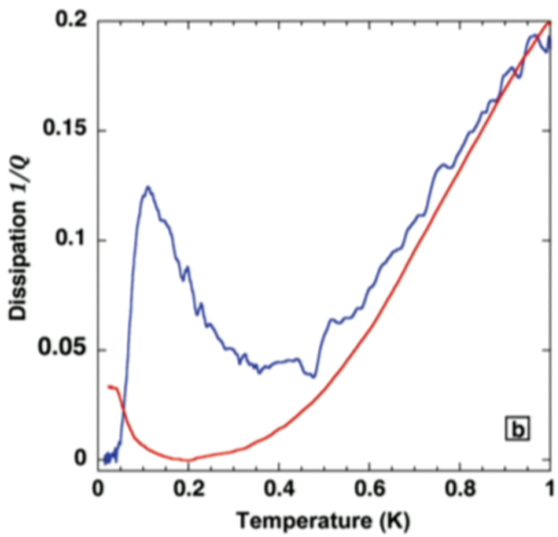


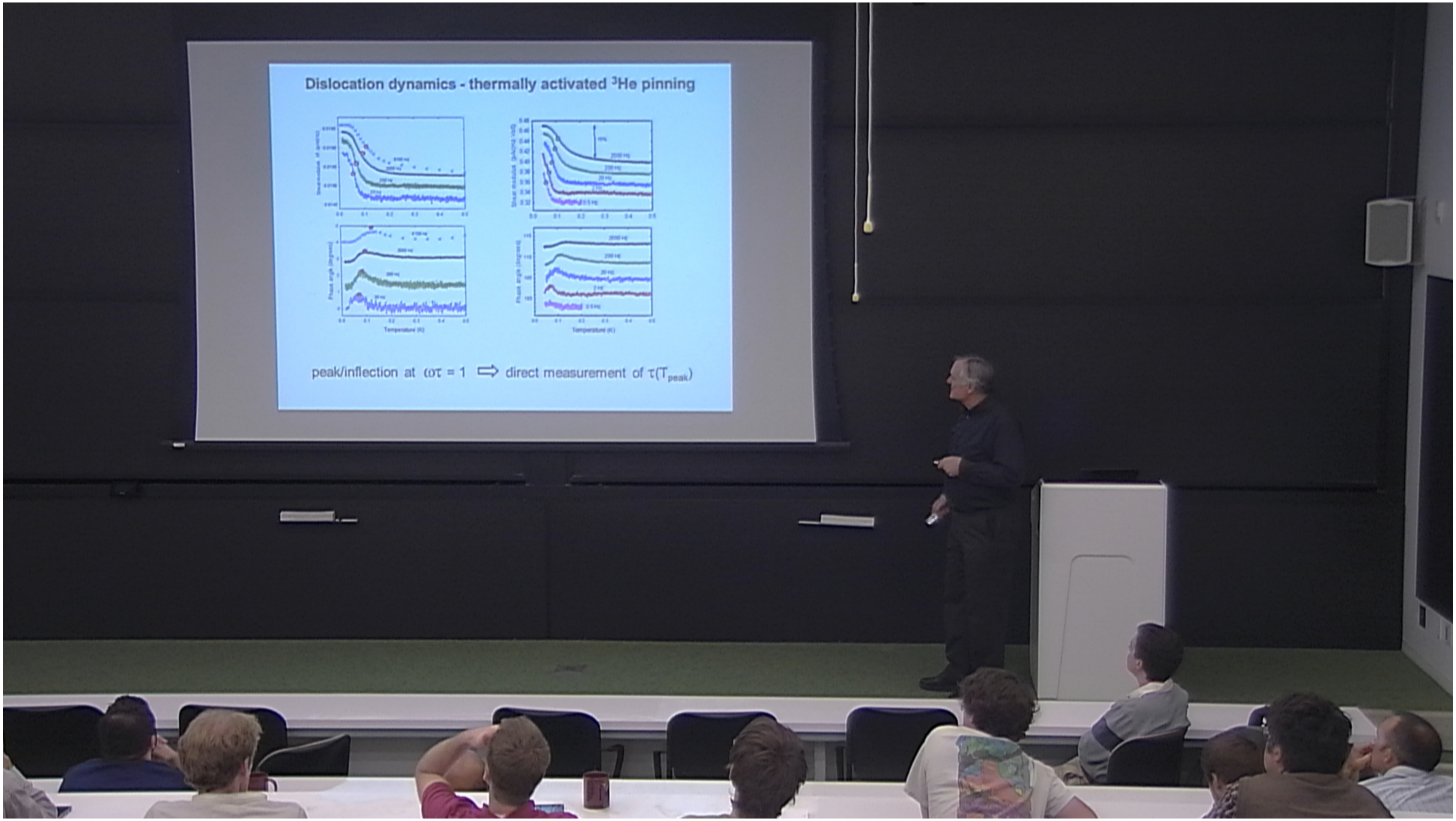


Phonon damping, dislocation densities and lengths

$$\frac{1}{Q} = \frac{\Delta\mu}{\mu_{\rm el}}\omega\tau = \frac{\Delta\mu}{\mu_{\rm el}}\omega\frac{BL^2}{\pi^2 C}$$

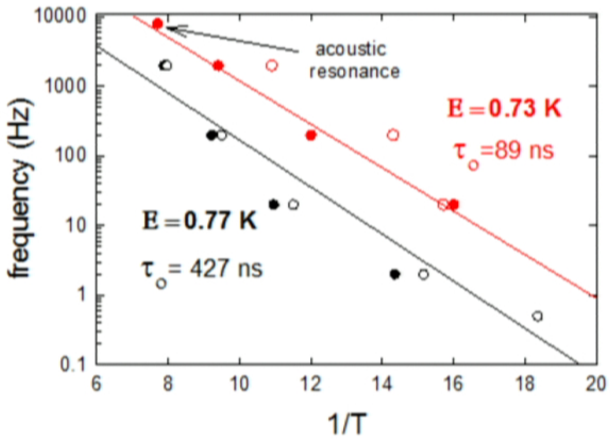
phonon "fluttering" $\Longrightarrow$ $B = \dfrac{14.4 k_B{}^3}{\pi^2\hbar^2 c^3}T^3$

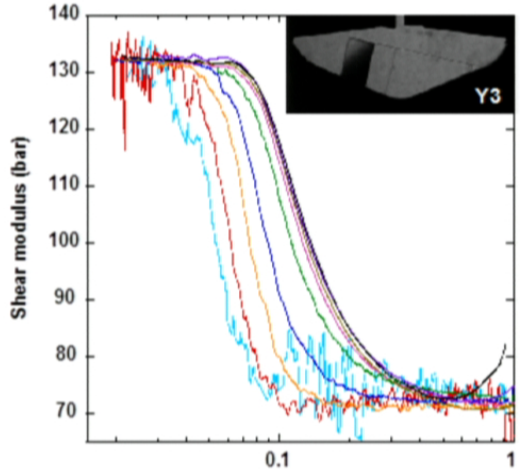




Dislocation dynamics - thermally activated ³He pinning
peak/inflection at ωτ = 1 ⇨ direct measurement of τ(T_peak)

Thermal activation energy for ^3He binding

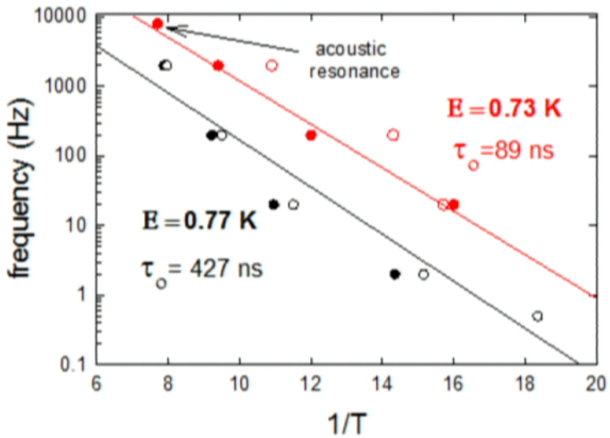


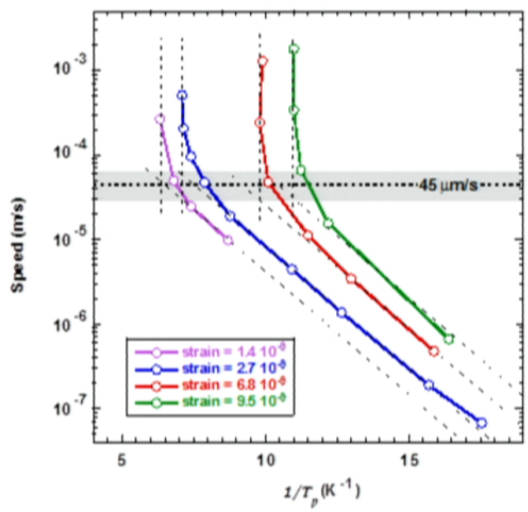


$$\omega\tau = (2\pi f)\left(\tau_o e^{\frac{E}{T}}\right) = 1$$

activation energy **E ~ 0.7 K**

Thermal activation energy for ^{3}He binding





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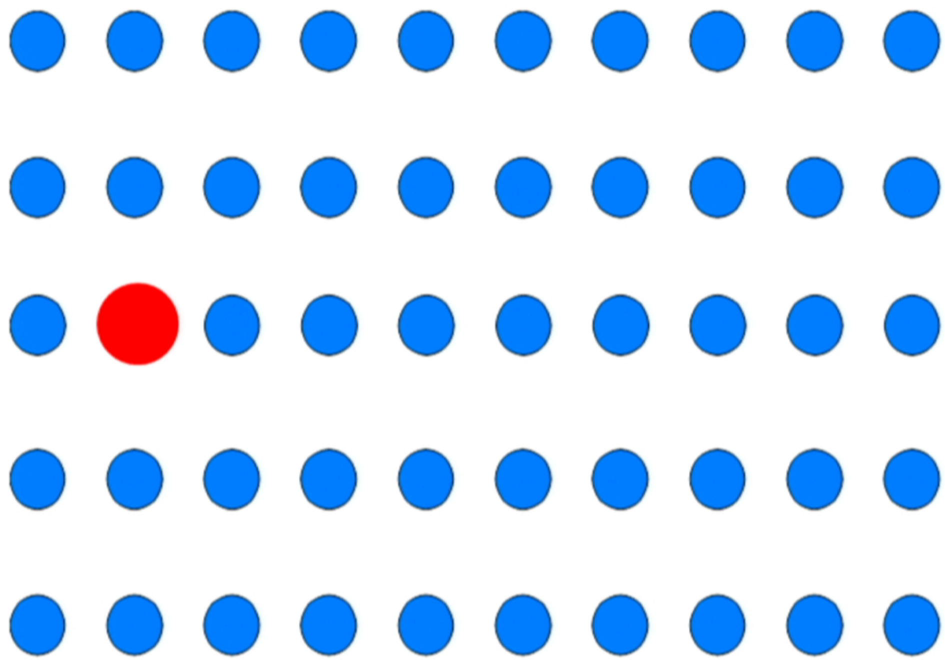
Tunneling of ^{3}He impurities in ^{4}He



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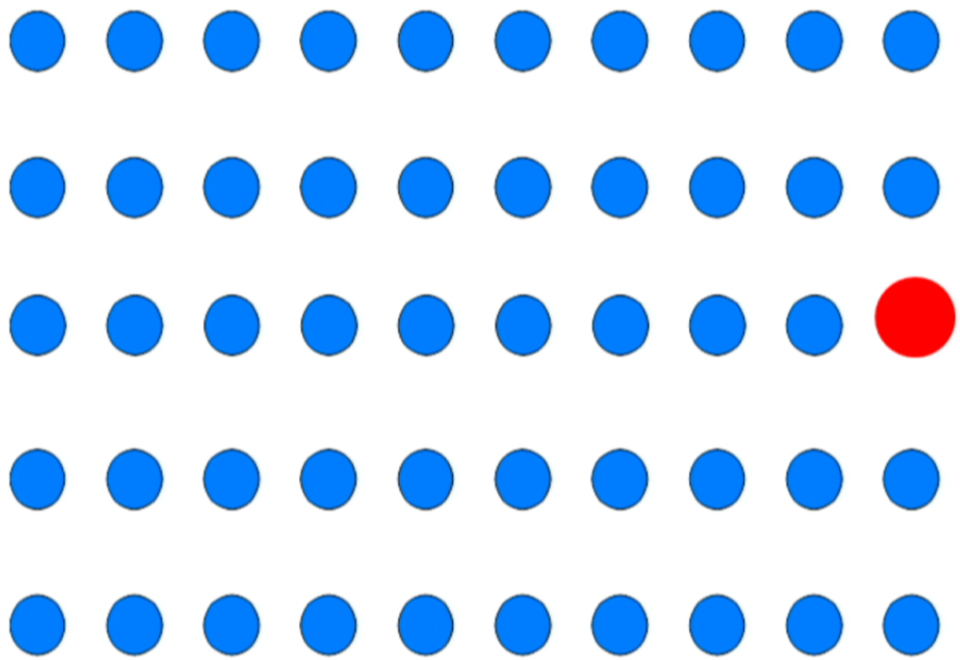

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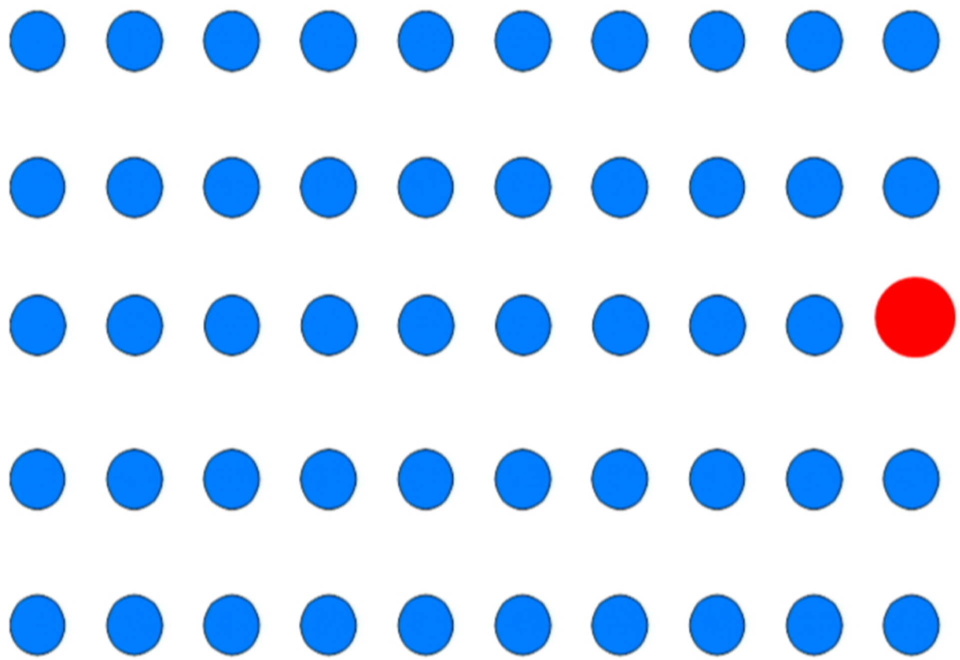

ballistic propagation of narrow band "**impuritons**"

$J_{34} \sim 10^{-4}$ K ~ MHz ⇨ V ~ mm/s

^3He-^3He scattering ⇨ $D_3 \sim 1/x_3$

Summary, current work, questions

The relevant dislocations glide in the basal plane of hcp ^{4}He (only C_{44} changes)

At low T they move without dissipation (if there is no ^{3}He to pin them)

They are mobile at extremely low stresses (10^{-4} Pa) and strains (10^{-10})

- zero Peierls barrier?

Summary, current work, questions

The relevant dislocations glide in the basal plane of hcp ^{4}He (only C_{44} changes)

At low T they move without dissipation (if there is no ^{3}He to pin them)

They are mobile at extremely low stresses (10^{-4} Pa) and strains (10^{-10})
- zero Peierls barrier?

Dislocations have a distribution of lengths, are aligned to minimize intersections

They can move over large distances (microns) at macroscopic speeds (cm/s)

^{3}He impurities damp the dislocations at low speeds, pin them at high speeds

Can we grow a perfect crystal (no impurities, no dislocations)?

Are dislocations mobile in solid ^{3}He?

Do quantum effects lead to unusual "quantum plasticity" in solid helium?
delocalized kinks? "superclimb"?? ductile at T=0?

Thank you