The Abdus Salam
International Centre for Theoretical Physics

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1959-14

Workshop on Supersolid 2008

18 - 22 August 2008

The effects of order and disorder on the supersolid phenomenon in He-4

J. West
Pennsylvania State University, USA

The effects of order and disorder on the supersolid phenomenon in ^{4}He

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Pennsylvania State University

In collaboration with:

Tony Clark and Xi Lin (Penn State)

Alex Syshchenko and John Beamish (Alberta)

Norbert Mulders (Delaware)

PENNSTATE 1855

"Supersolid 2008" Workshop

ICTP Trieste, Italy

August 20, 2008

NSF

DMR 0706339

I. Introduction

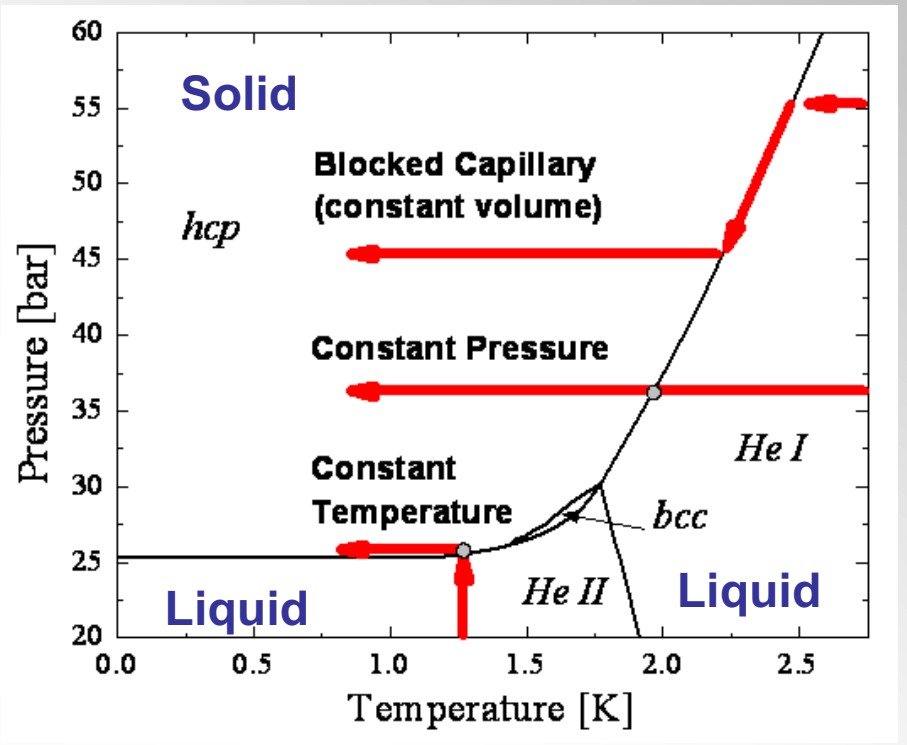
II. Heat capacity of solid ^{4}He (Lin and Clark)

III. Torsional Oscillator (TO) Results (Clark, West)

- Order
- Disorder
- Comparison with shear modulus results
- Current work

I. Helium Crystal Quality

- How do we know?
- Growth methods
- Strain in the crystal
- Types of defects
  - Grain boundaries, dislocations, vacanices/interstitials, impurities
- Determination of crystal quality
  - Ultrasound, x-ray or neutron scattering, optical, etc.



II. Heat capacity of solid ^{4}He (Lin and Clark)

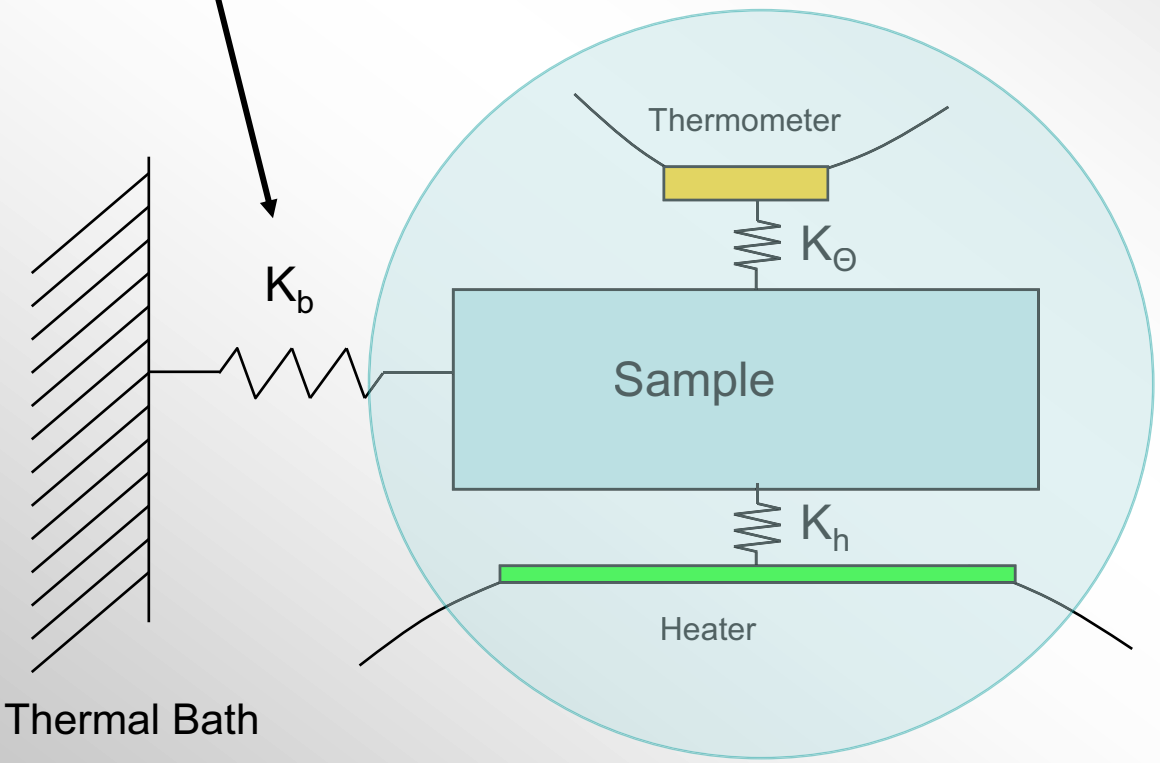
- Experimental Details
- Results for:
  - low ^{3}He impurity concentrations
  - different growth methods
  - ^{3}He-^{4}He mixtures

Experimental Details: AC Calorimetry

Cooling power during sample growth

$$\dot{Q} = \dot{Q}_0 (\cos \tfrac{1}{2} \omega t)^2 \longrightarrow T_{ac} = \frac{\dot{Q}}{2\omega C}$$

$$C = \frac{\dot{Q}}{2\omega T_{ac}}$$



Internal time constant << 1/ω

External time constant >> 1/ω

1. Paul F. Sullivan, G. Seidel, *Phys Rev*. **173**, 679 (1968).
2. Yaakov Kraftmakher, *Physics Reports*, **356** (2002) 1-117.

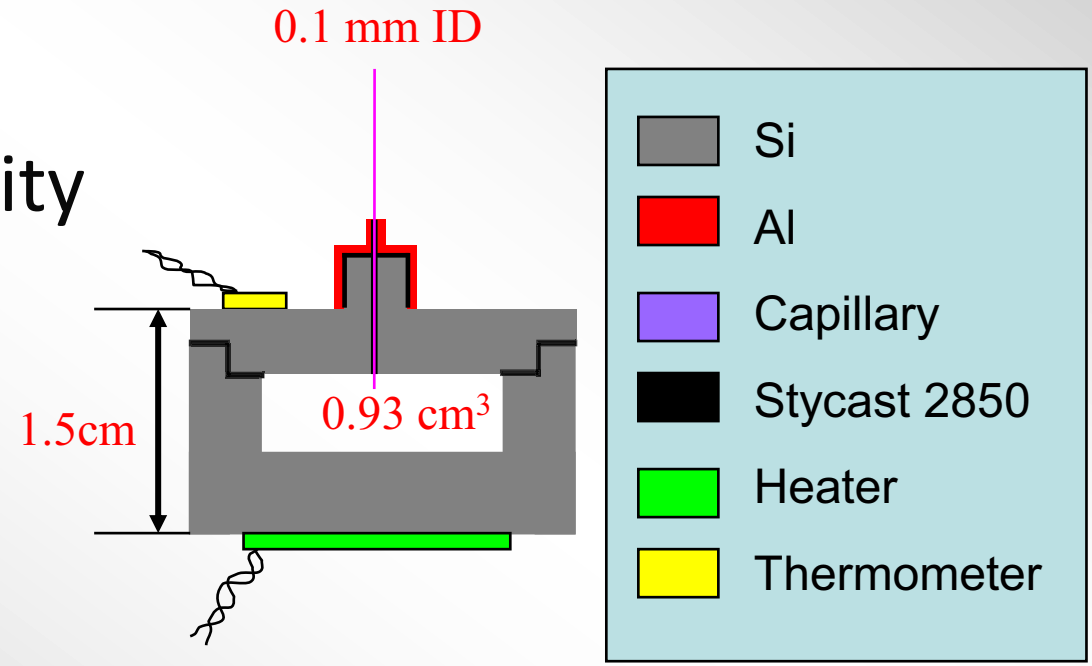
Experimental Details: Silicon cell

- Limited resolution below ~100mK in earlier studies due to metallic cells…

$$\frac{C_{He}}{C_{CELL}} < \frac{1}{10}$$

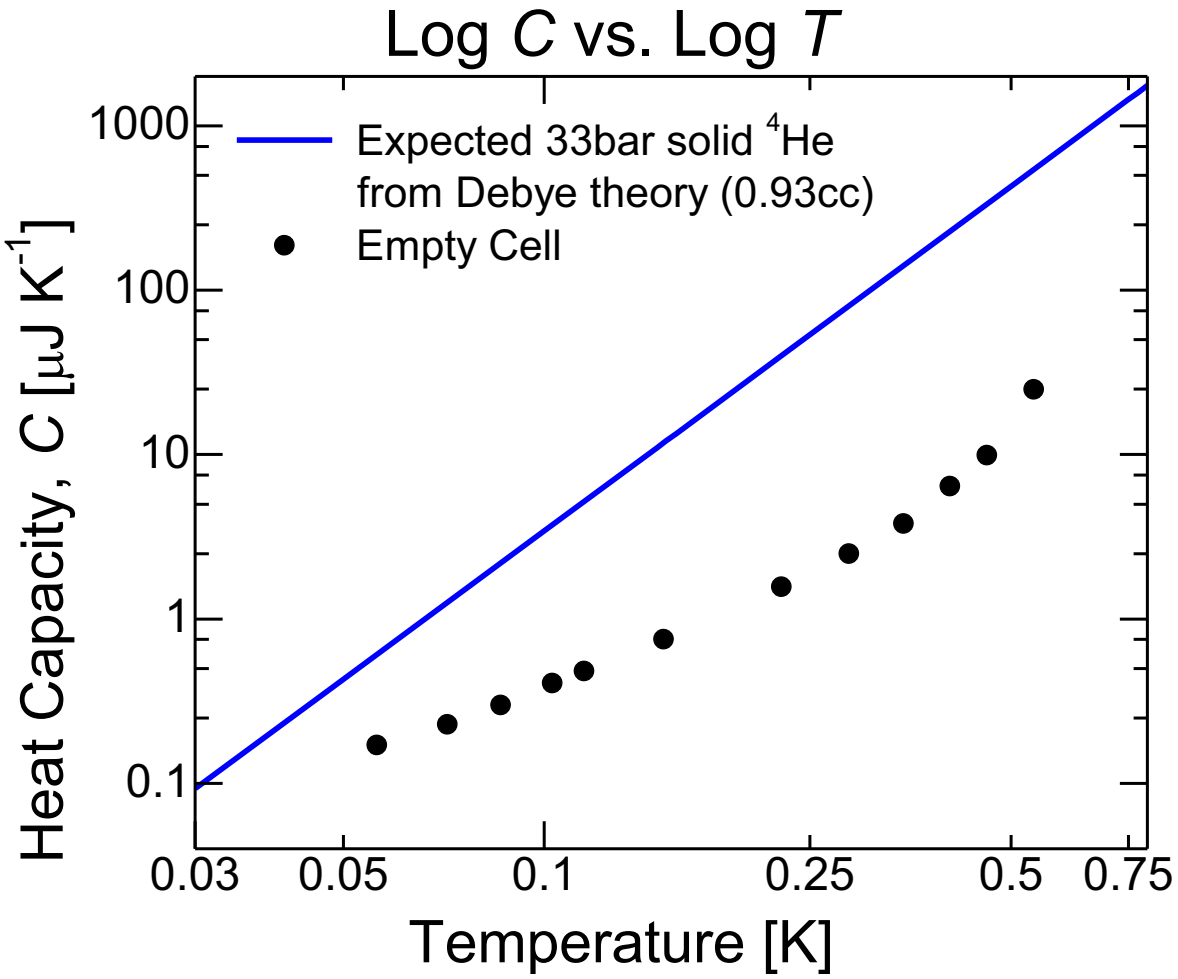
- Small heat capacity of silicon…

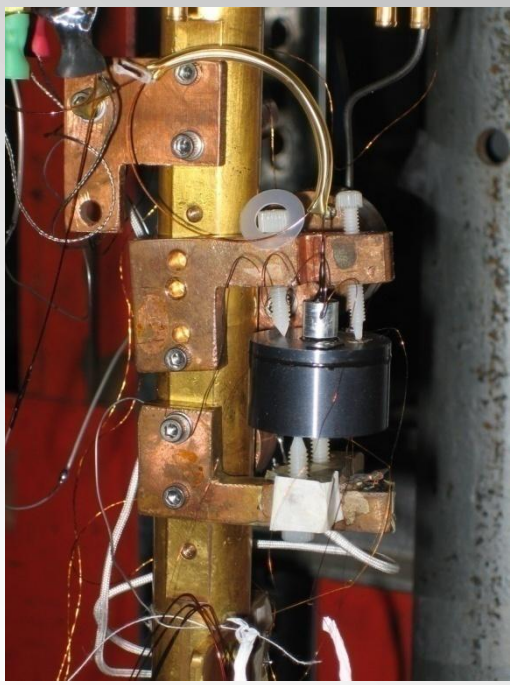
$$\frac{C_{He}}{C_{CELL}} > 10$$



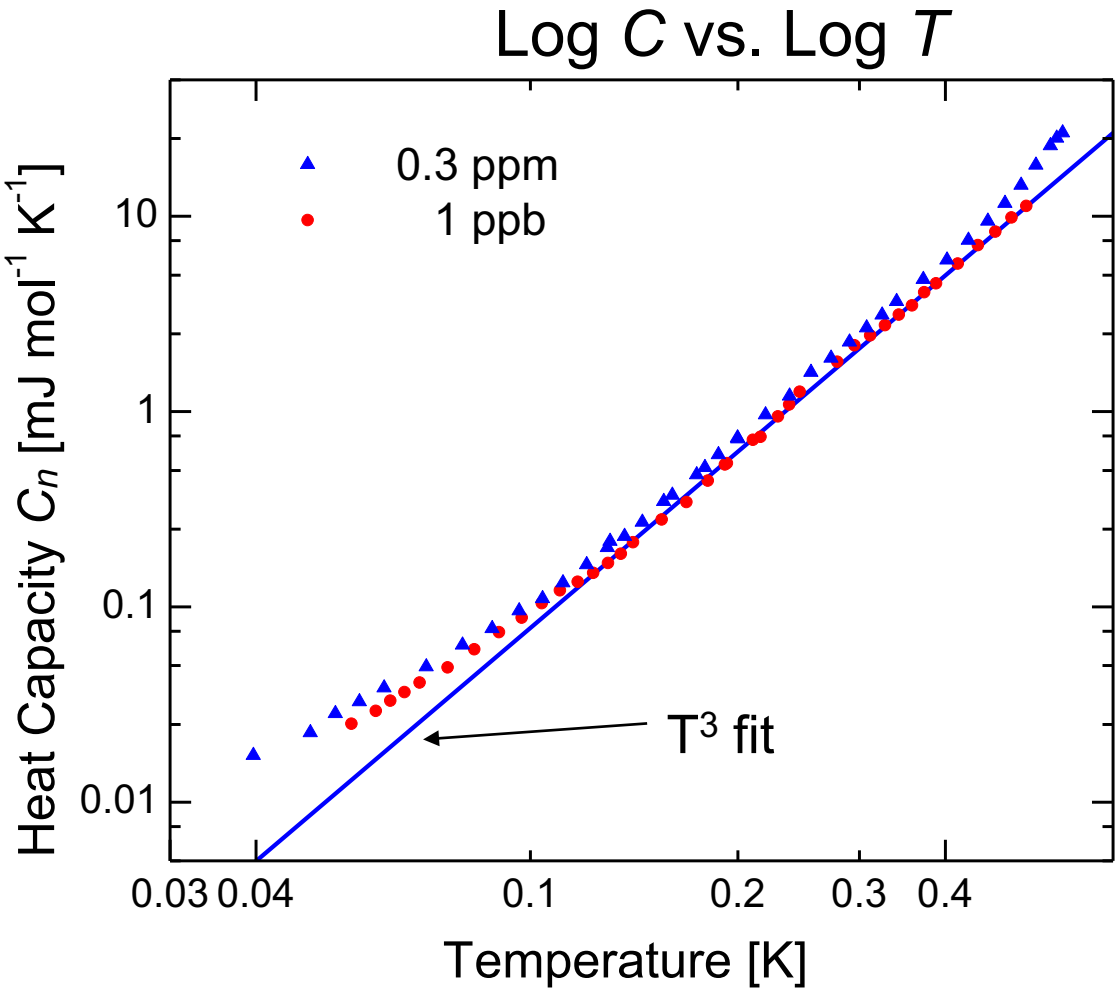
X. Lin, A. C. Clark and M. H. W. Chan, *Nature* **449**,1025 (2007).

Experimental Details: Silicon cell





Results: pure ^{4}He (0.3ppm & 1ppb)



Constant volume growth
20 hours to finish solidification.

No long time constant

No hysteresis

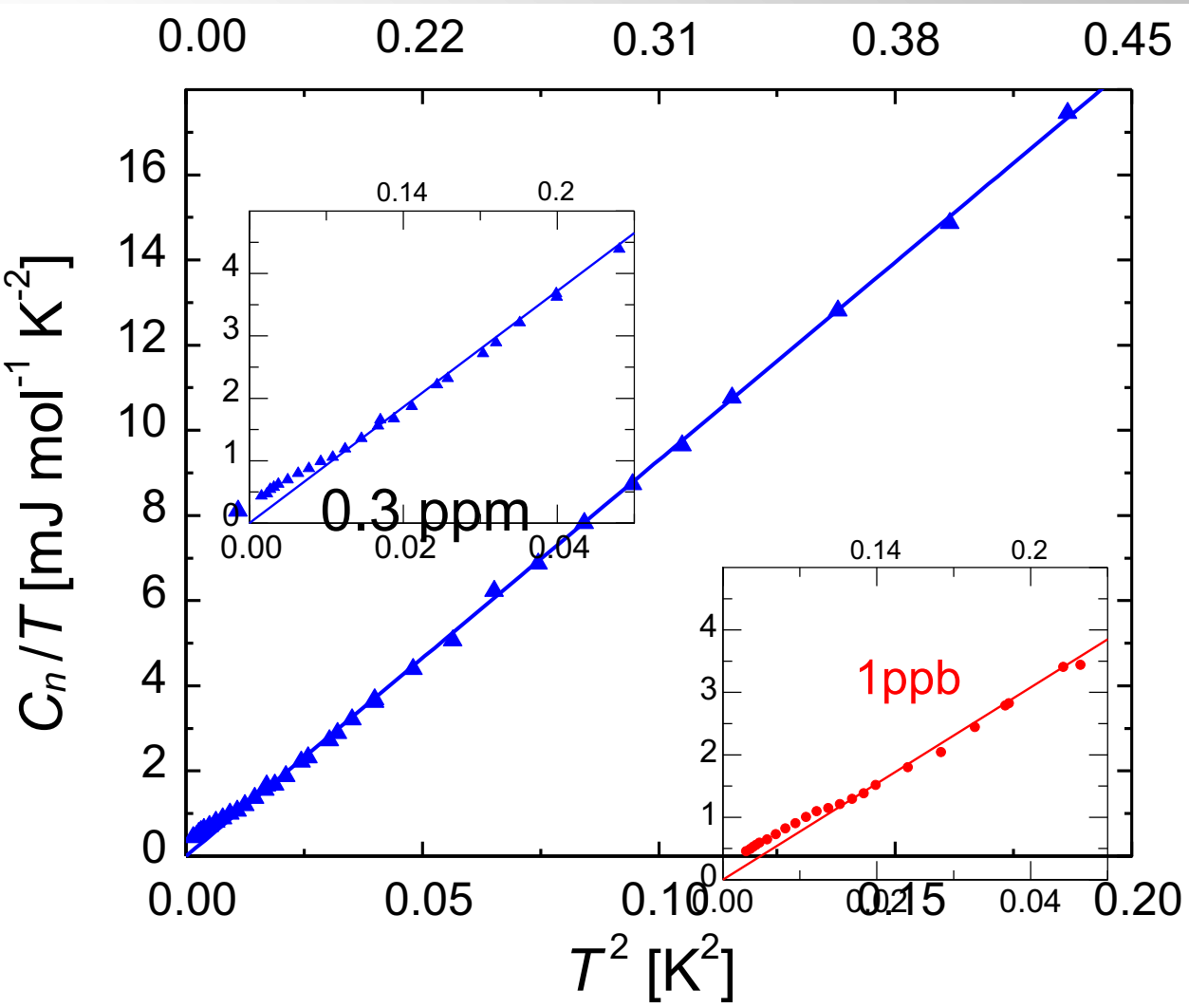
No annealing effect

No thermal cycling effect

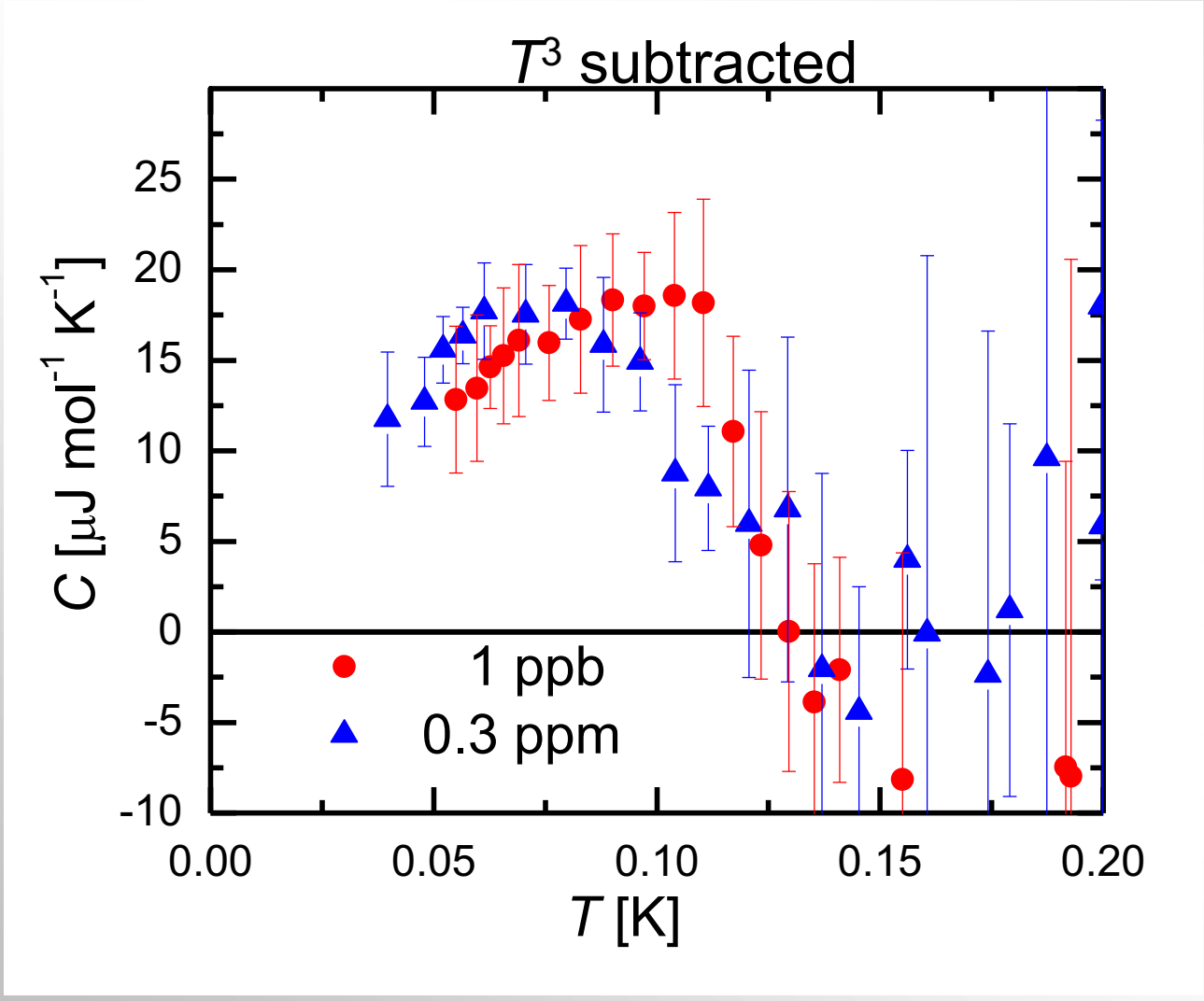
Results: Excess Linear Heat Capacity?

Shown as
C/T vs. T^2

No linear term



Results: After subtracting the Debye phonon term



~20 μJ mol^{-1} K^{-1}

~2.5×10^{-6} k_B per ^{4}He atom

Not phase separation:

1. No hysteresis observed
2. No long time constant
3. Independent of x_3 in position and size

Higher resolution with a new cell

Disadvantages of Si?

Si cells have a habit of exploding!

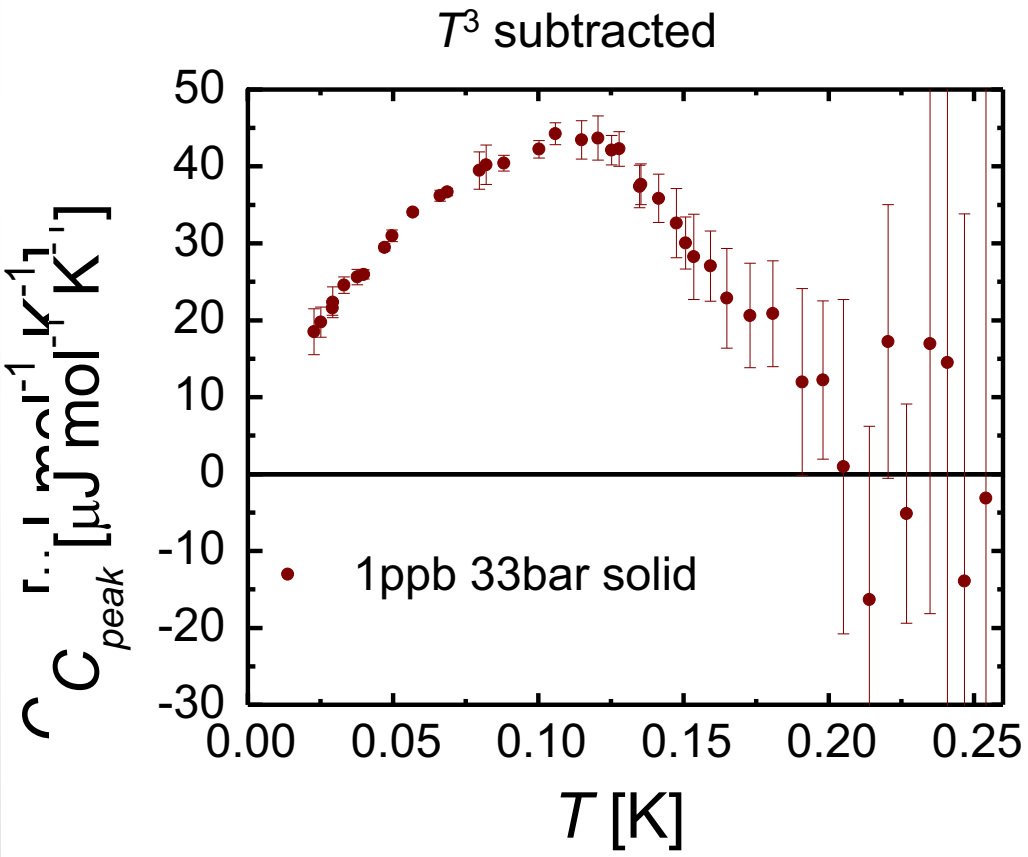
One year, ten cells, only one leak tight

New cell:

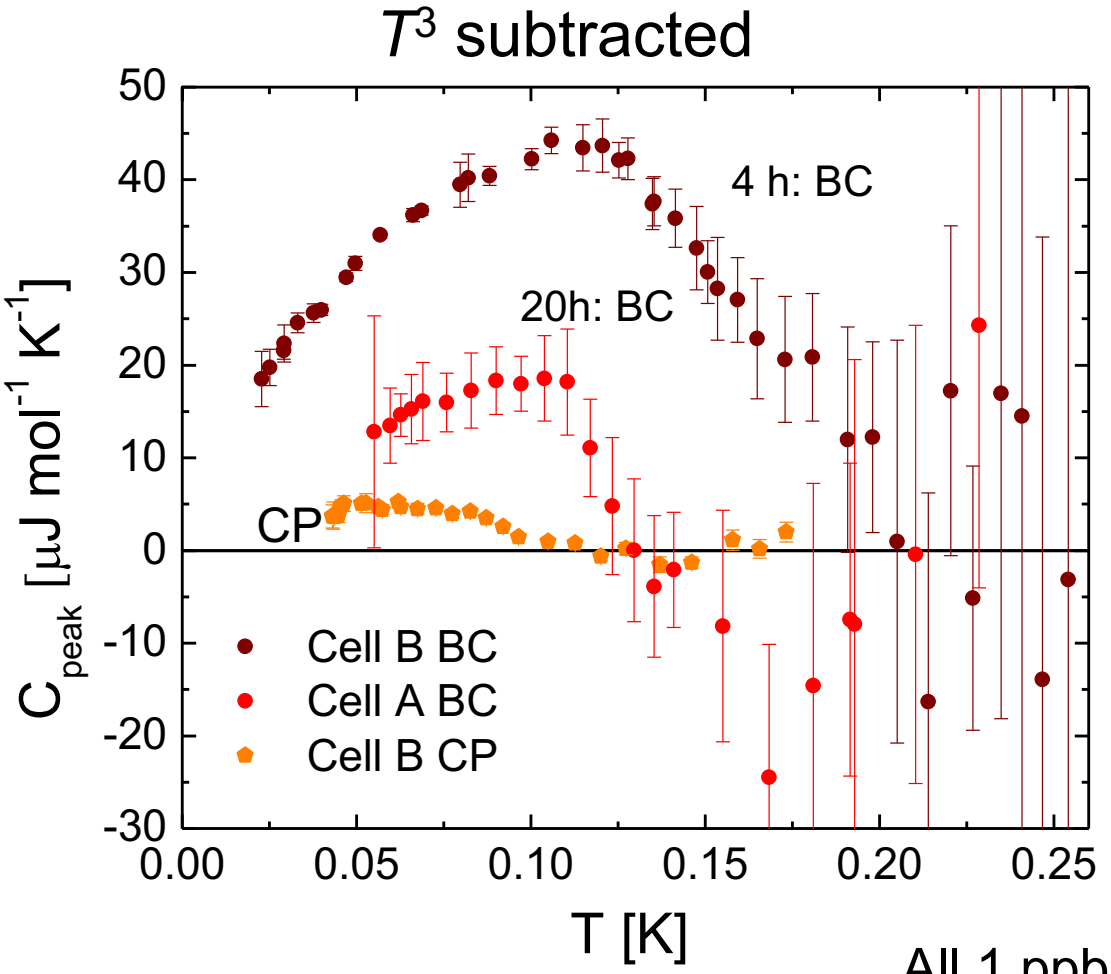
Improved resolution

4 hours to solidify a sample (instead of 20)

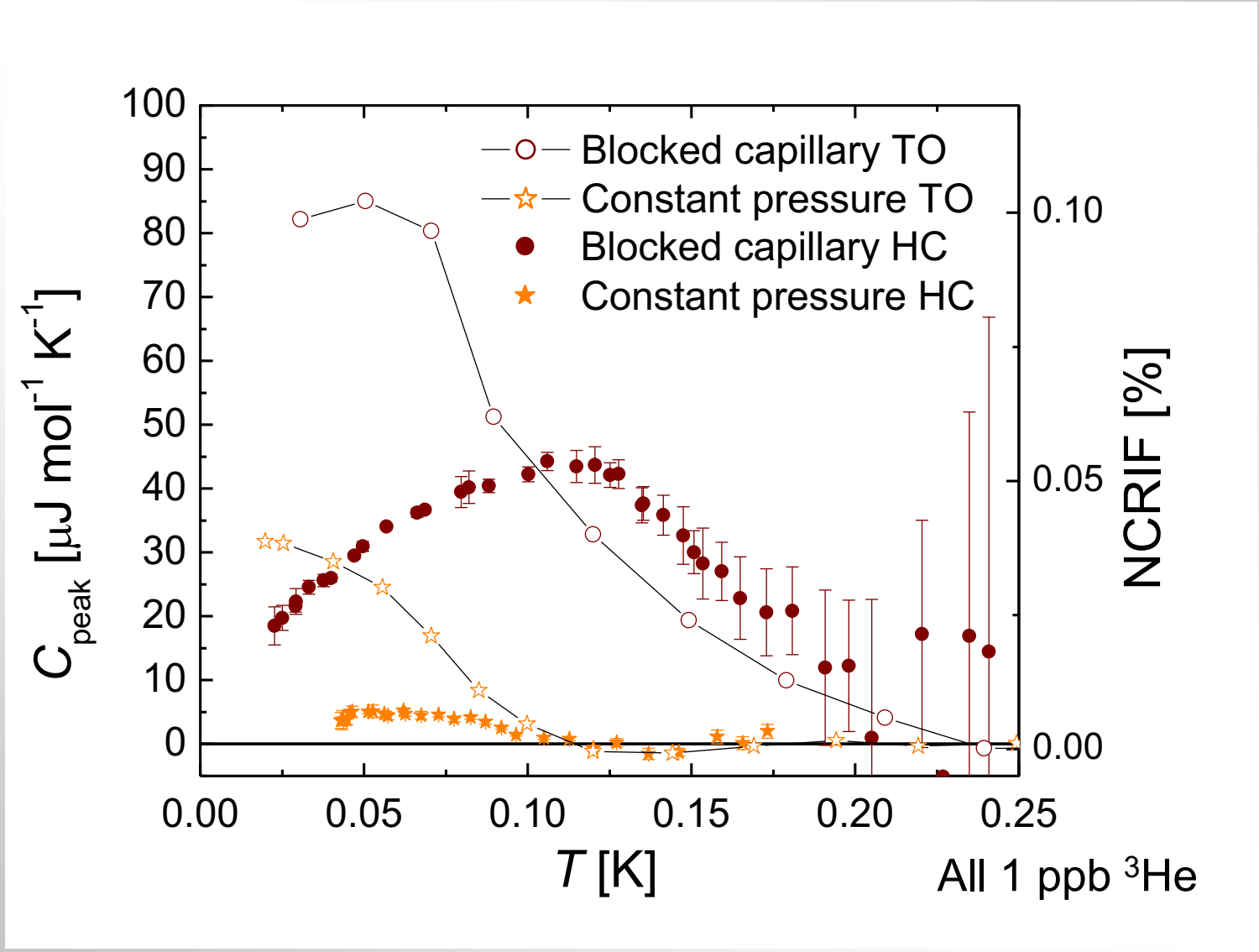
Improved base temperature 40mK → 25mK



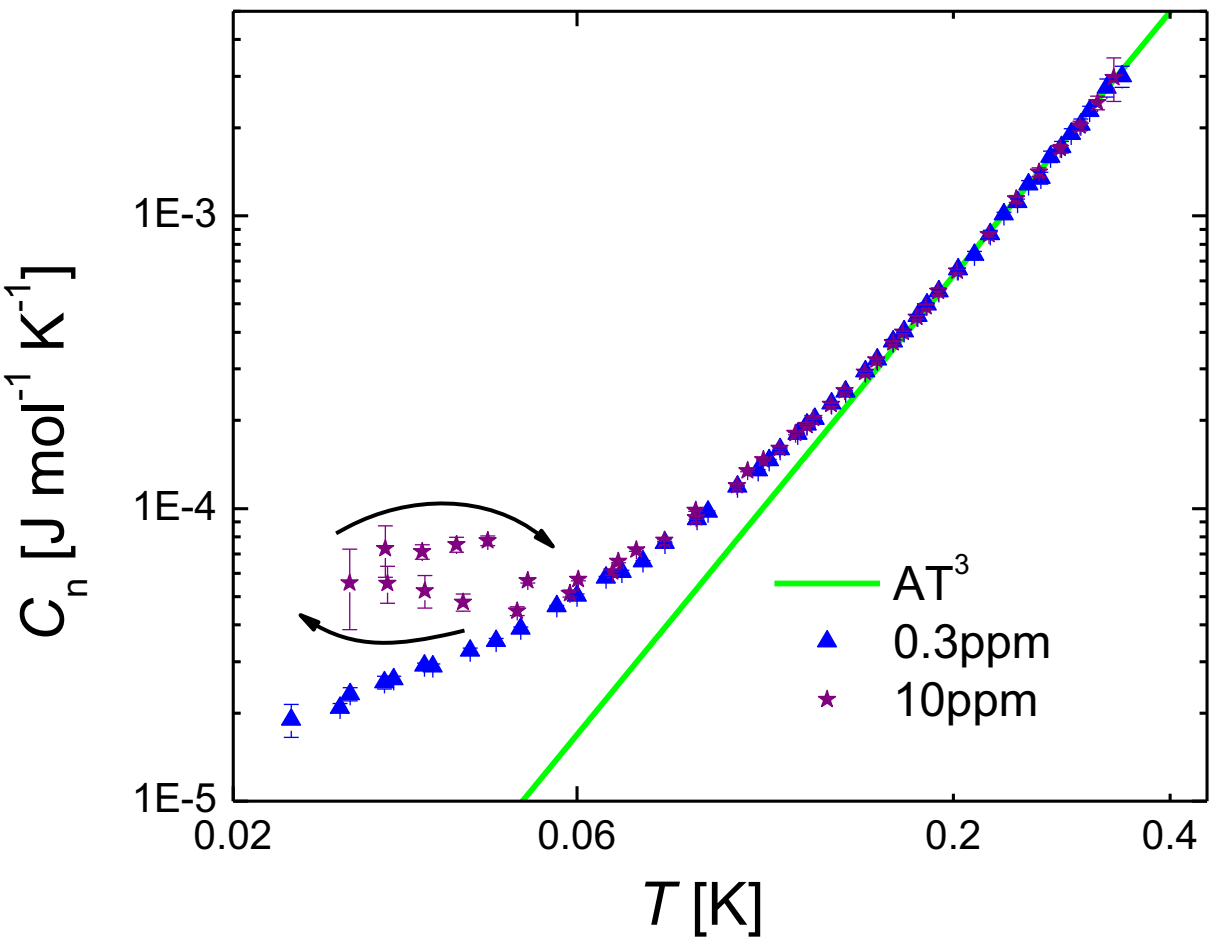
Constant Pressure Growth



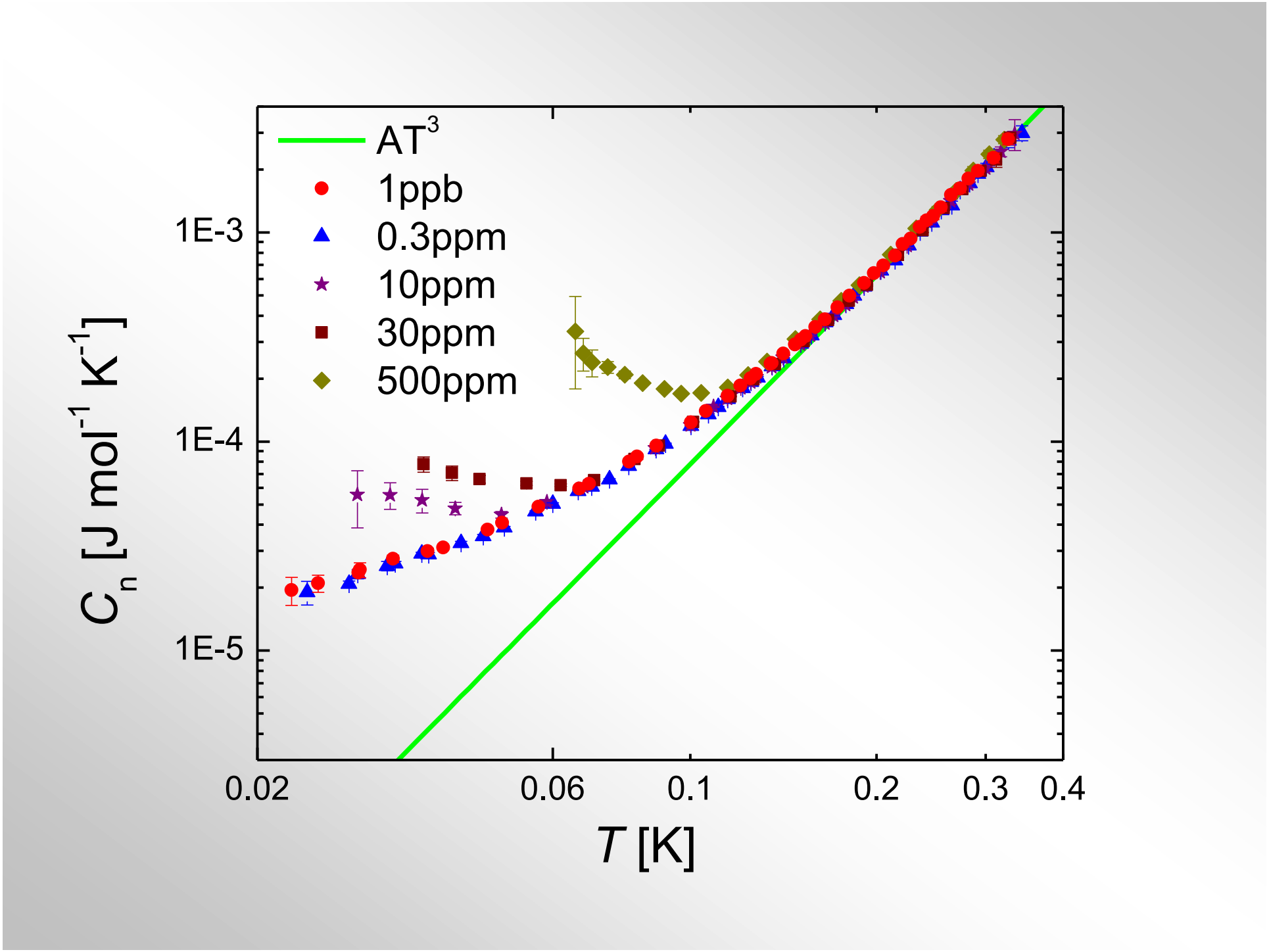
Comparison with TO results



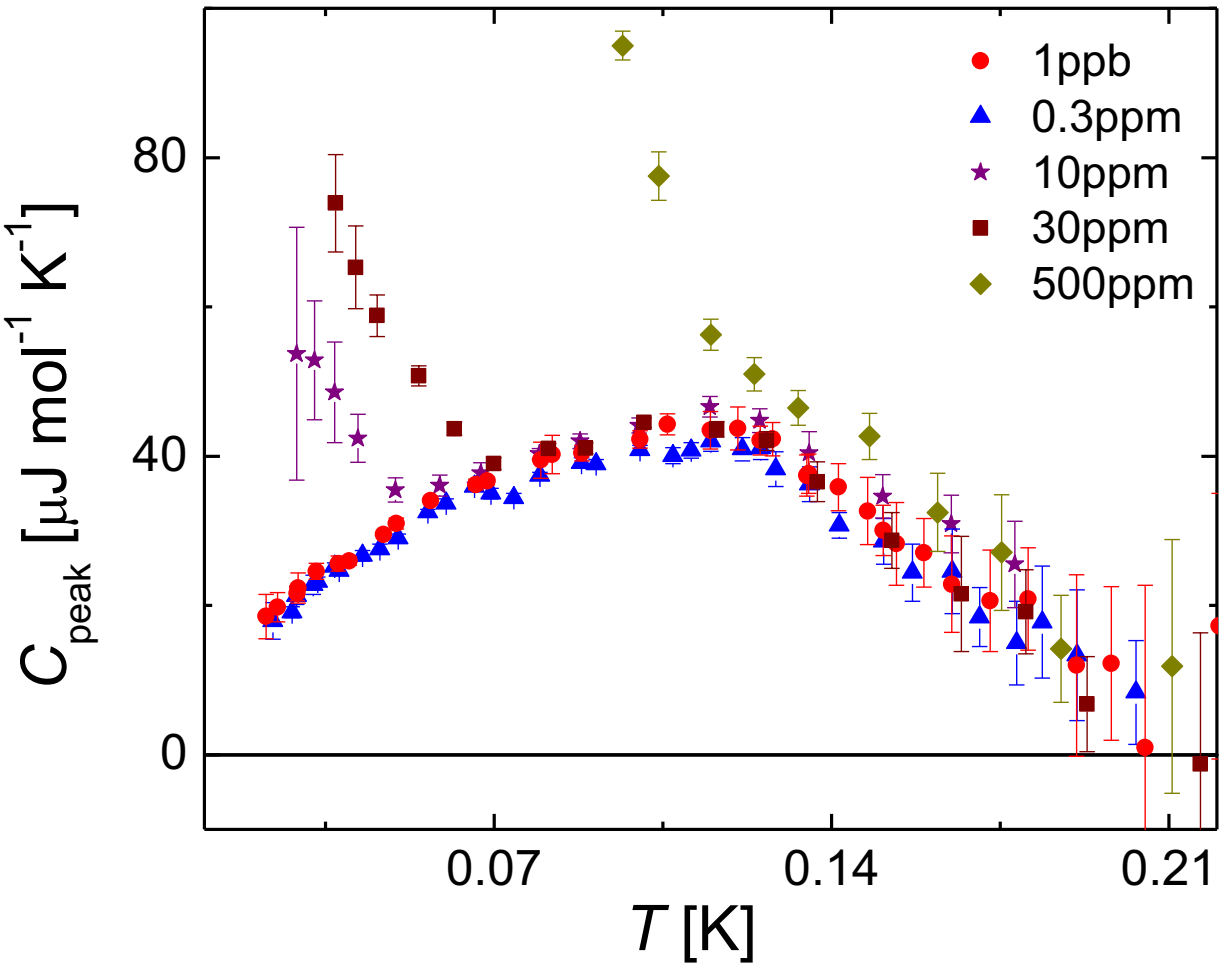
^{3}He-^{4}He mixtures



With improved resolution, hysteresis and long time constants are observed


AT3
1ppb
0.3ppm
10ppm
30ppm
500ppm
1E-3
1E-4
1E-5
Cn [J mol-1 K-1]
0.02
0.06
0.1
0.2
0.3
0.4
T [K]

^{3}He-^{4}He mixtures



Peak size and position is independent of x_3

Phase separation is observed in addition to the peak

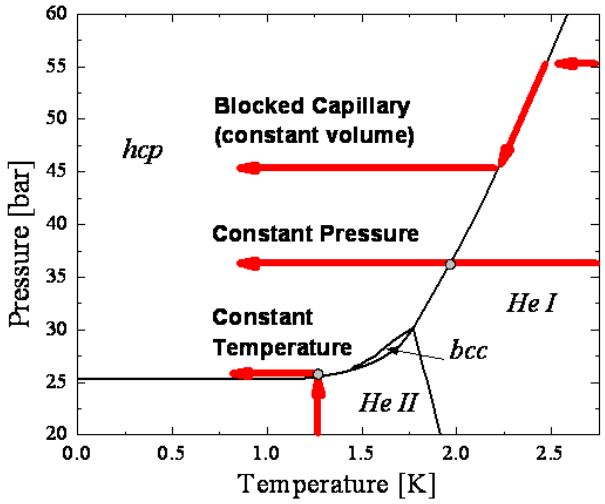
Summary of heat capacity results

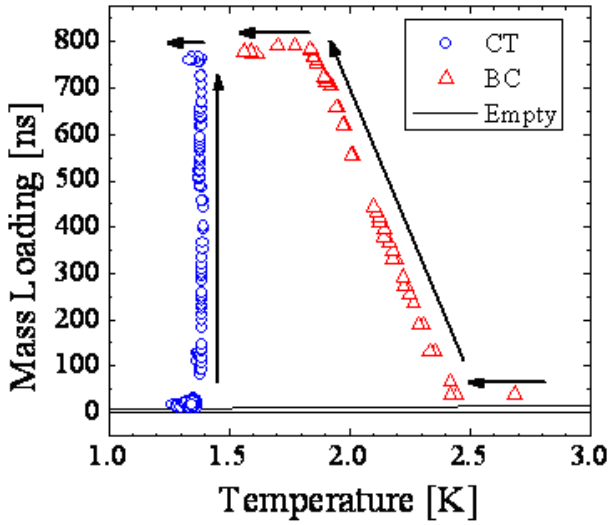
- We observe a broad heat capacity peak at low T
  Thermodynamic signature of the supersolid phase?
- No linear heat capacity term (also....no constant term)
- Heat capacity peak is independent of ^{3}He concentration
- Peak is sensitive to sample quality
- Phase separation is seen above 10 ppm

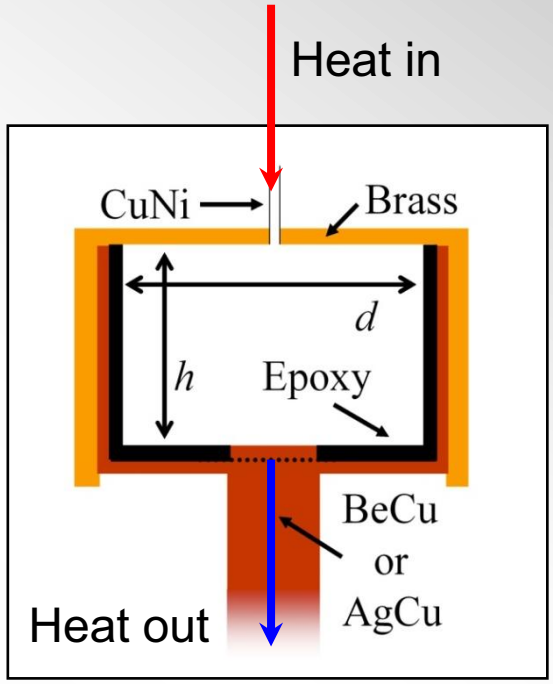
III. Torsional oscillator results

- High quality samples and annealing
- Extreme disorder
- Comparison with shear modulus results
- Current work

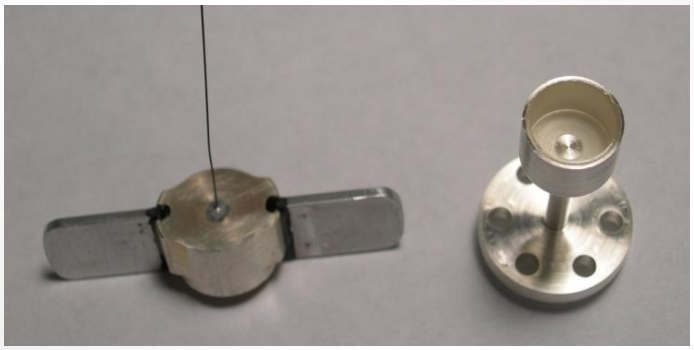
Experimental Details



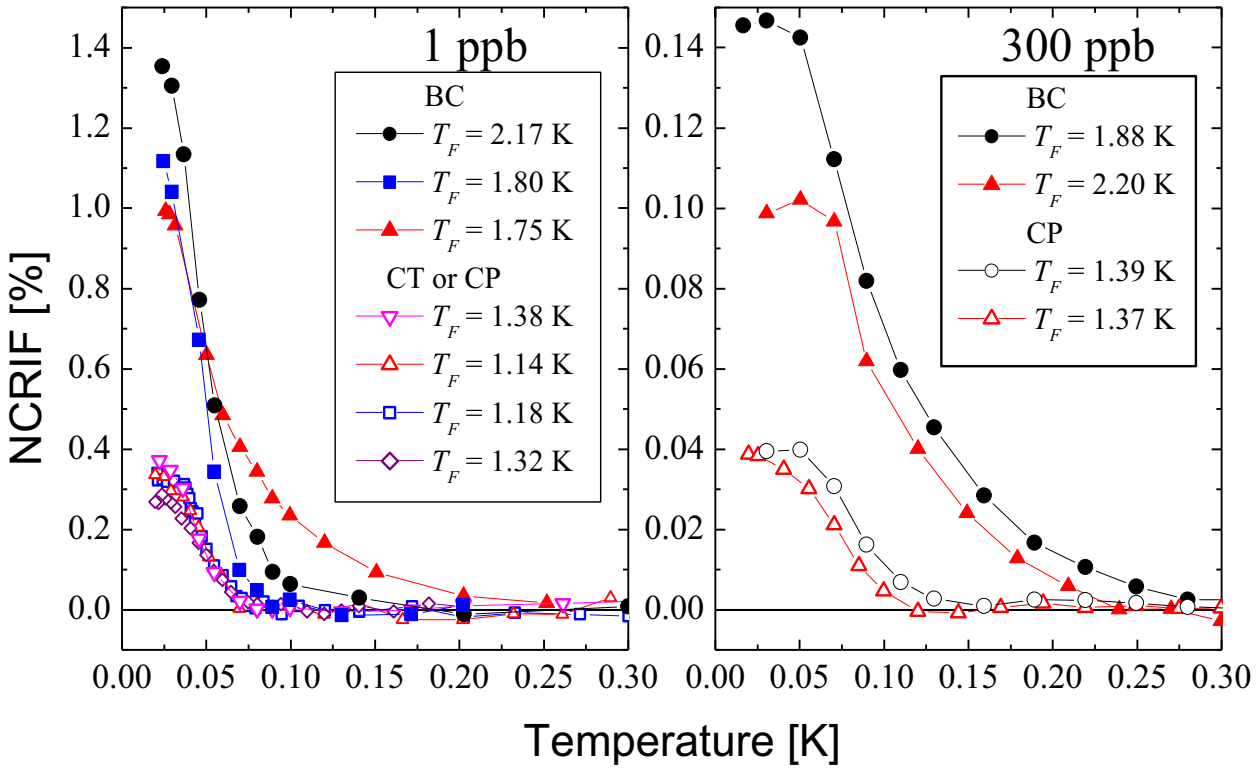




h ~ 5 mm
d ~ 10 mm
f_0 ~ 1 kHz



Results from different growth methods

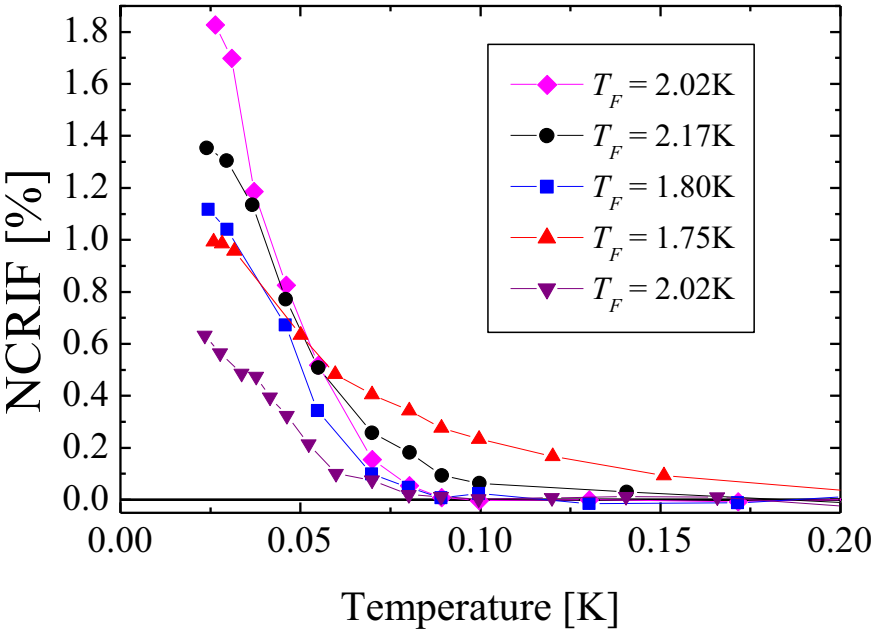


Comparing BC samples to CP/CT samples for two different sample cells. Note the factor of 10 difference in NCRIF.

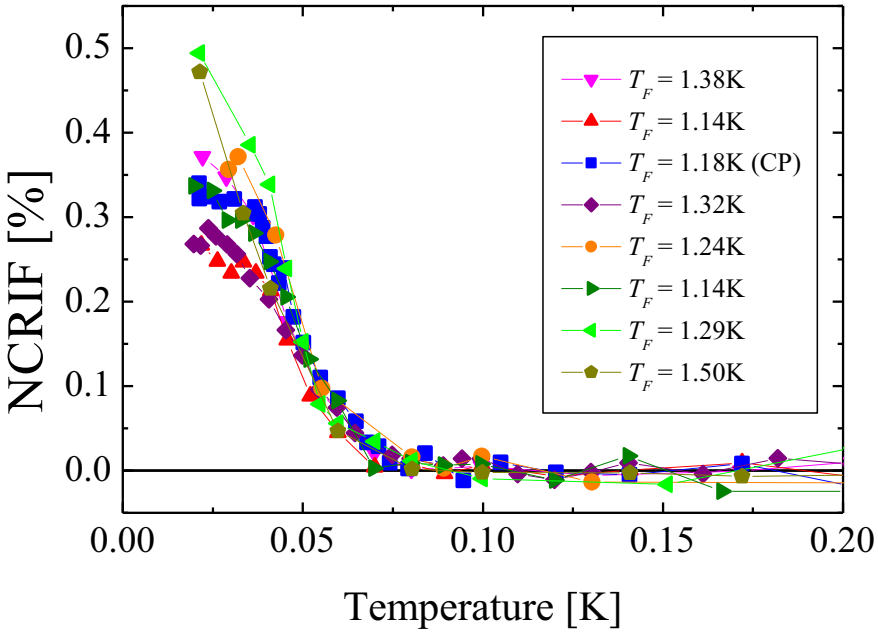
A.C. Clark, J.T. West & M.H.W. Chan, PRL **99**, 135302 (2007).

Reproducibility

Blocked Capillary Samples



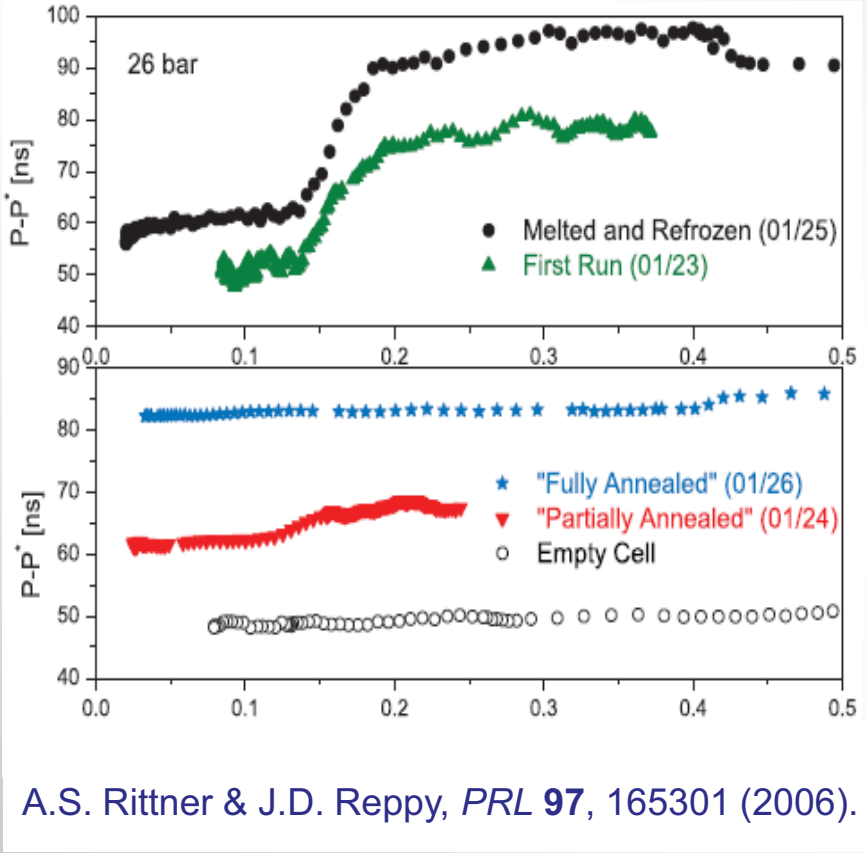
CP/CT Samples



Higher quality samples are more reproducible, particularly in the onset region.

A.C. Clark, J.T. West & M.H.W. Chan, PRL **99**, 135302 (2007).

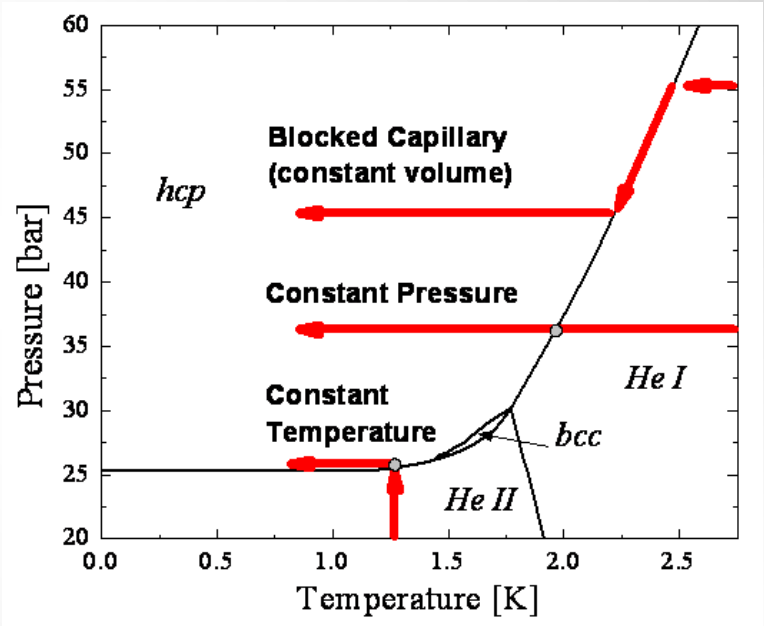
Annealing



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

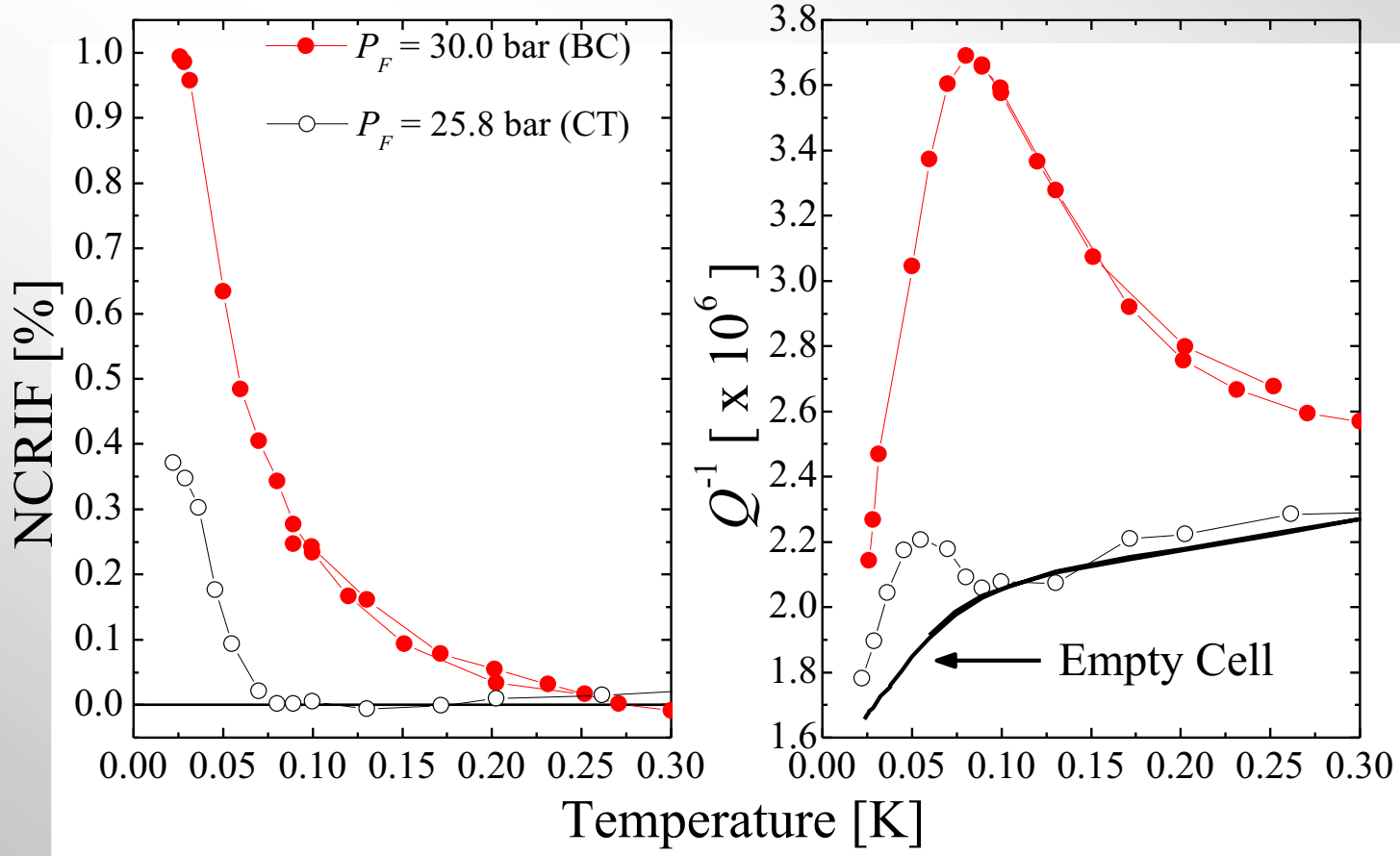
By annealing, Rittner and Reppy were able to reduce the NCRI signal to <0.05%.

The "worst" sample underwent a bcc-hcp transformation multiple times



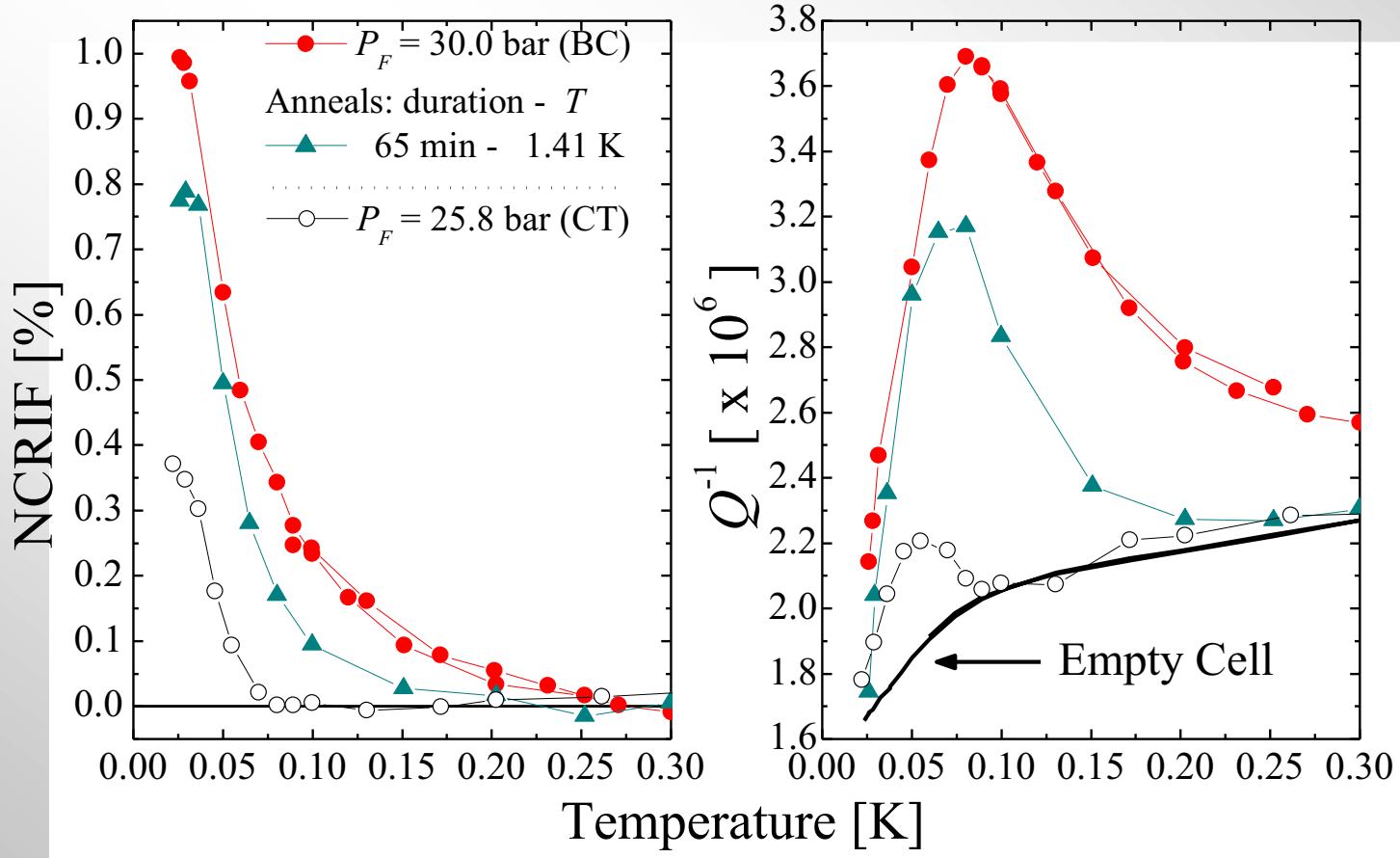
Annealing

- Annealing lowers NCRIF, T_O, and Q^{-1} peak



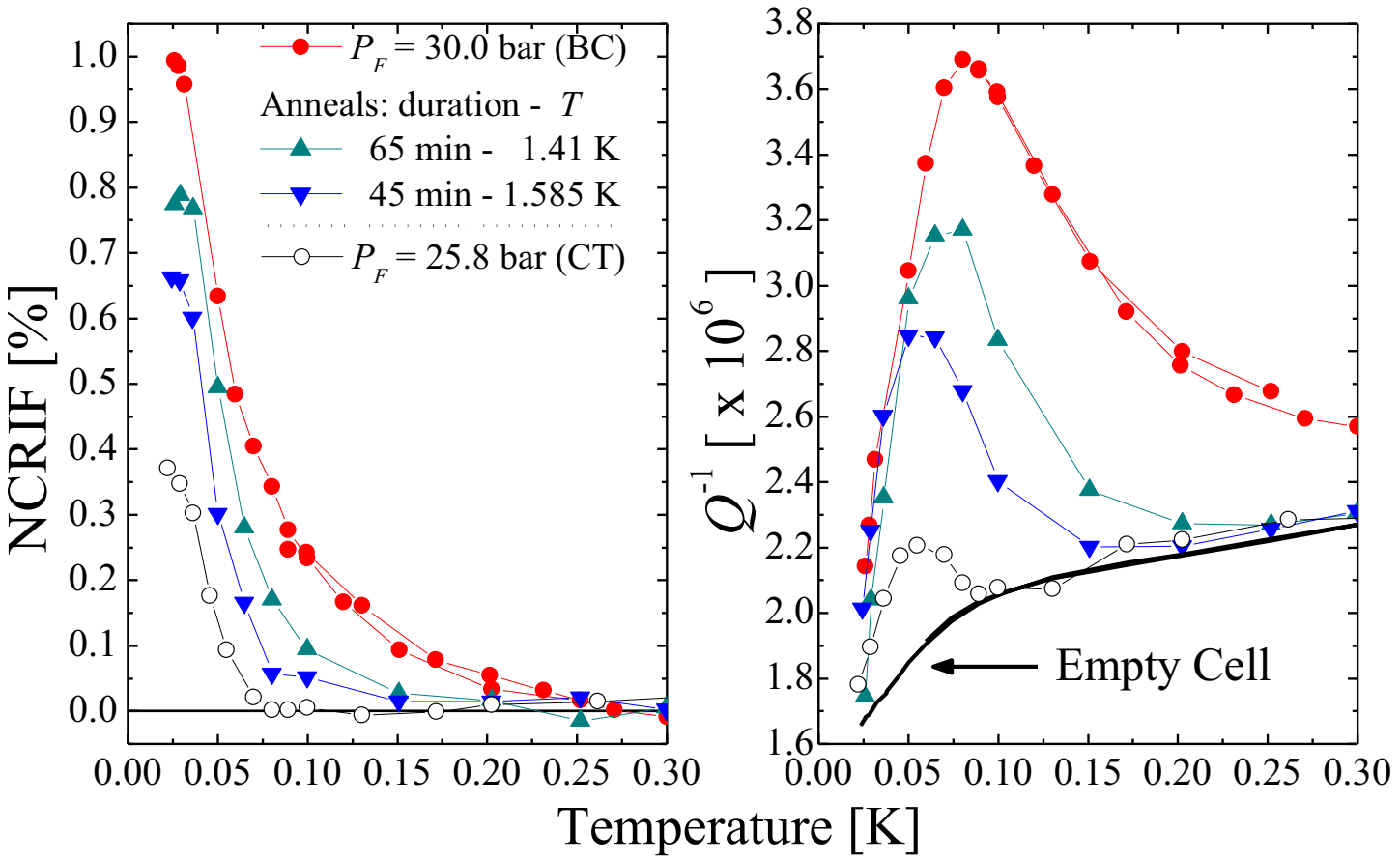
Annealing

- Annealing lowers NCRIF, T_O, and Q^{-1} peak



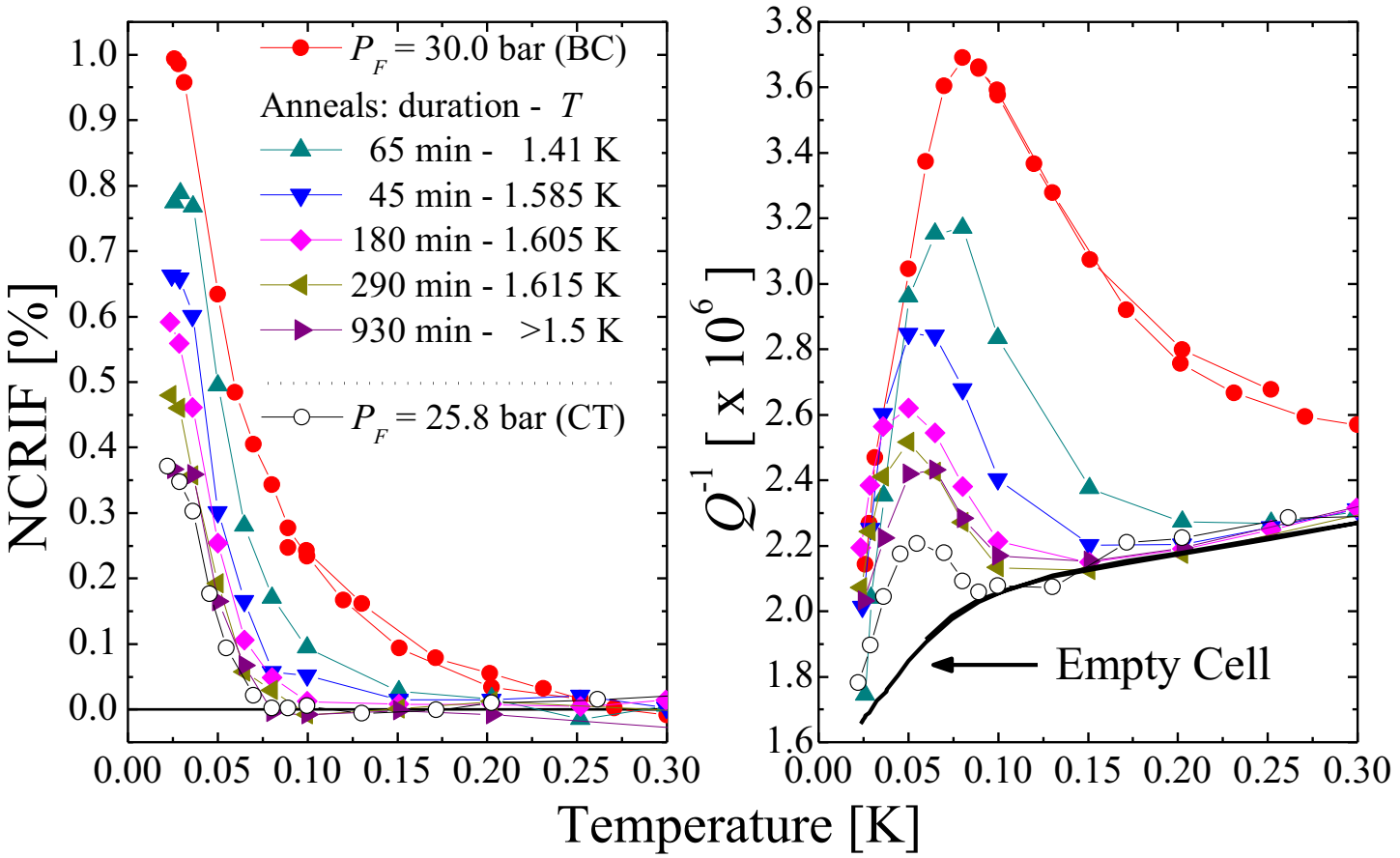
Annealing

- Again



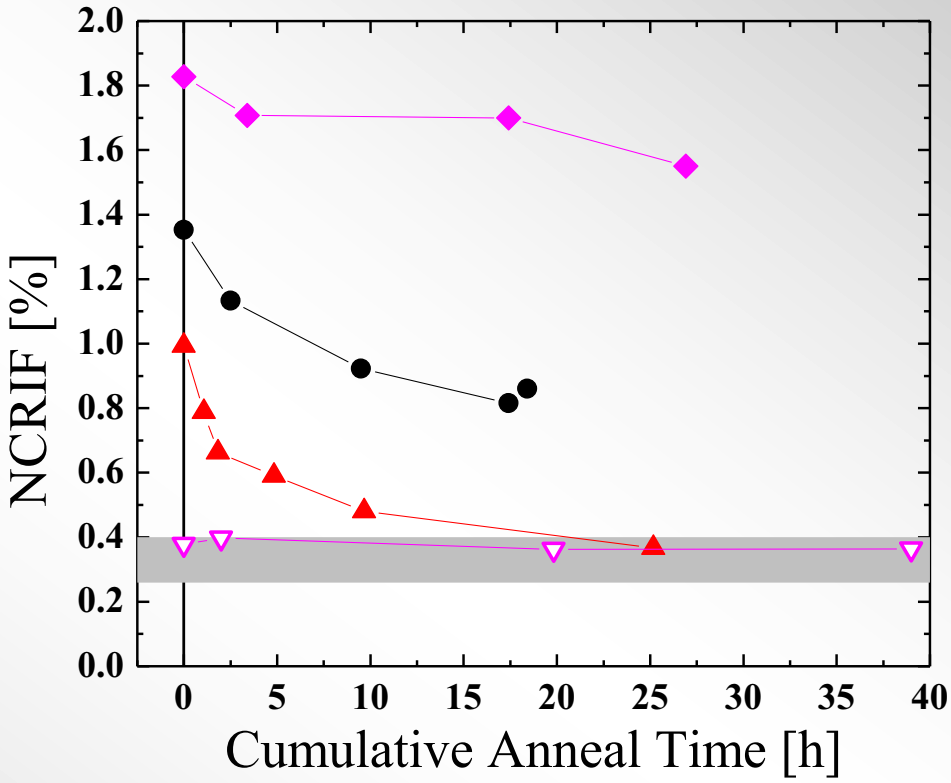
Annealing

- NCRIF, Q^{-1}, and T_O converge on that of the CT sample



Annealing…sometimes?

- Annealing effects more likely with large NCRI fractions
- Sometimes NCRIF increases
- CT sample unchanged
- Most dramatic change occurs in (likely polycrystalline) samples at low pressure
- Depends on the types of defects?



Annealing effect only for BeCu cell in Clark et. al. 2007 PRL.

Extreme disorder

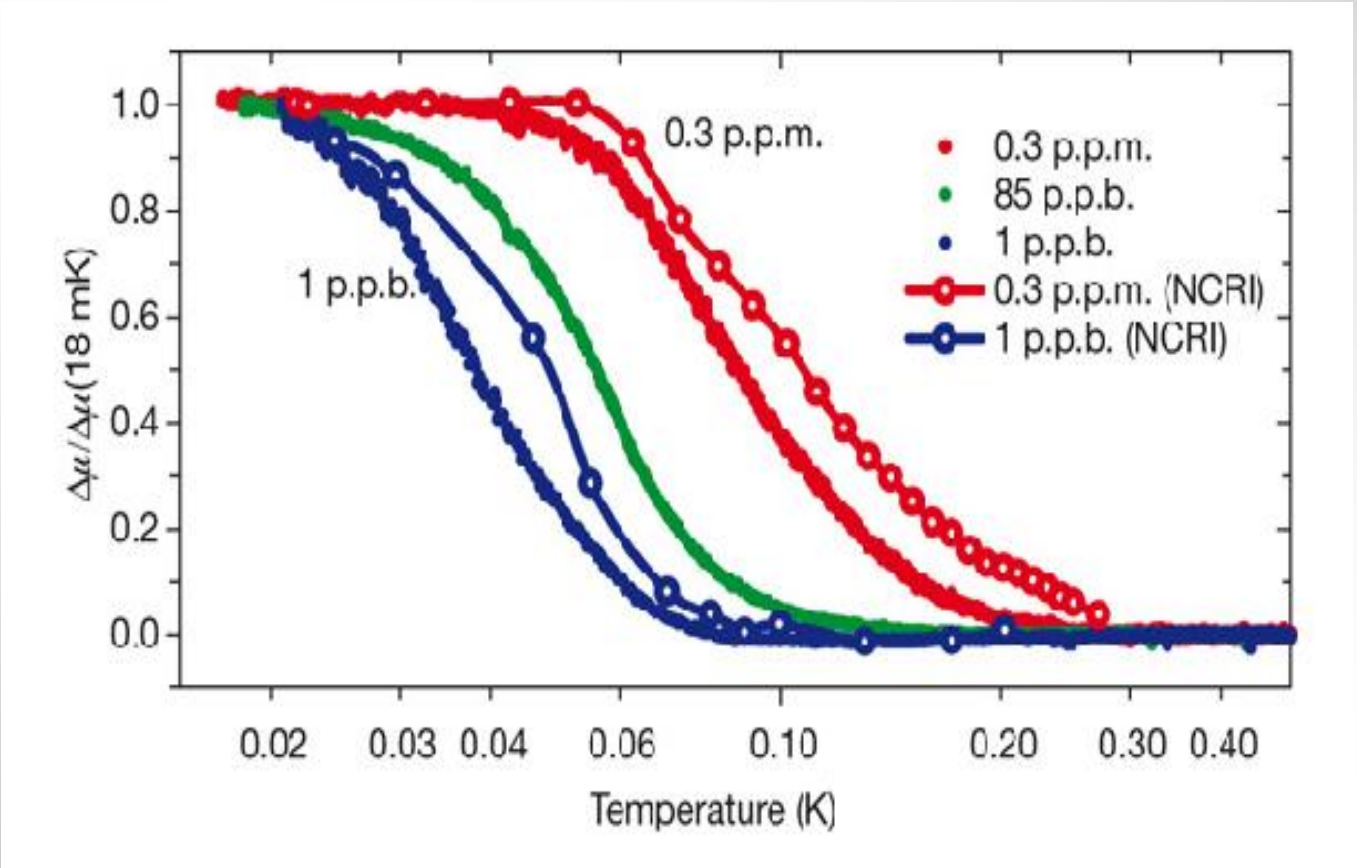
- We have intentionally grown highly disordered helium samples within aerogel
- From everything we have observed it seems reasonable to expect that this should have a very large NCRI

Drum roll ……..

Results will be shown by Norbert Mulders tomorrow at 11:30

Shear modulus and NCRI

Done in collaboration with Alex Syshchenko and John Beamish



James Day and John Beamish, Nature (London) **450**, 853 (2007).

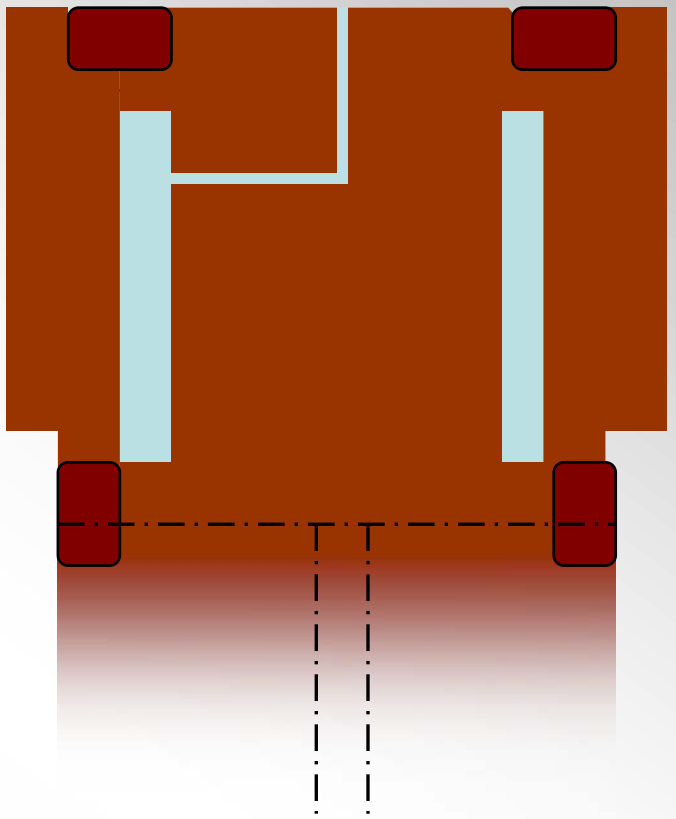
Extra-rigid cell

Helium Space:

OD = 10 mm

Annulus Width = 1.2 mm

Height = 6.4 mm



FEM Calculations

(for 20% c_{44} change)

Predicted Shifts:

$\Delta\tau < 0.02$ ns

$\Delta f/f < 10$ ppb

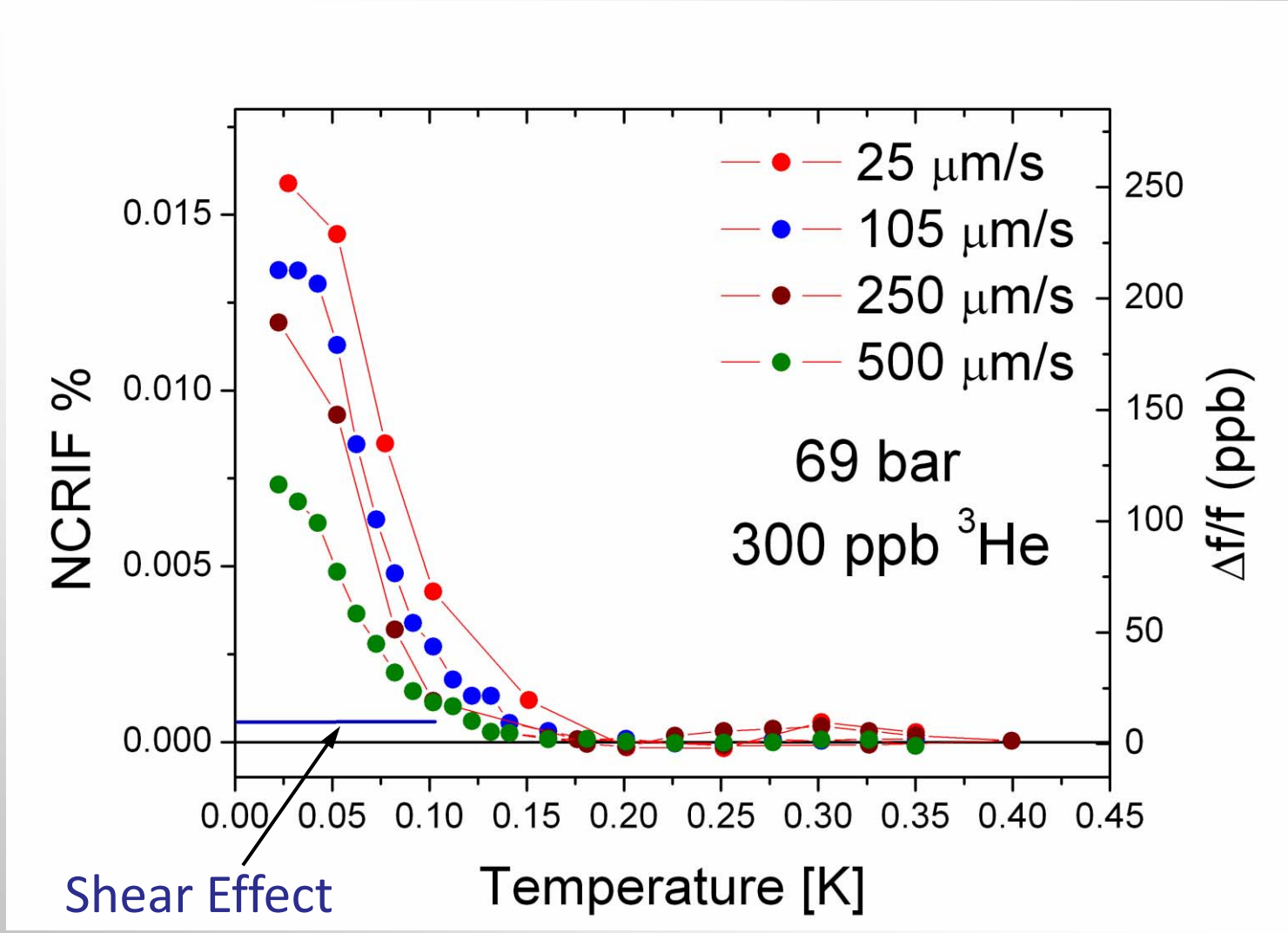
Frequency = 341 Hz

$Q \approx 1.6 \times 10^6$

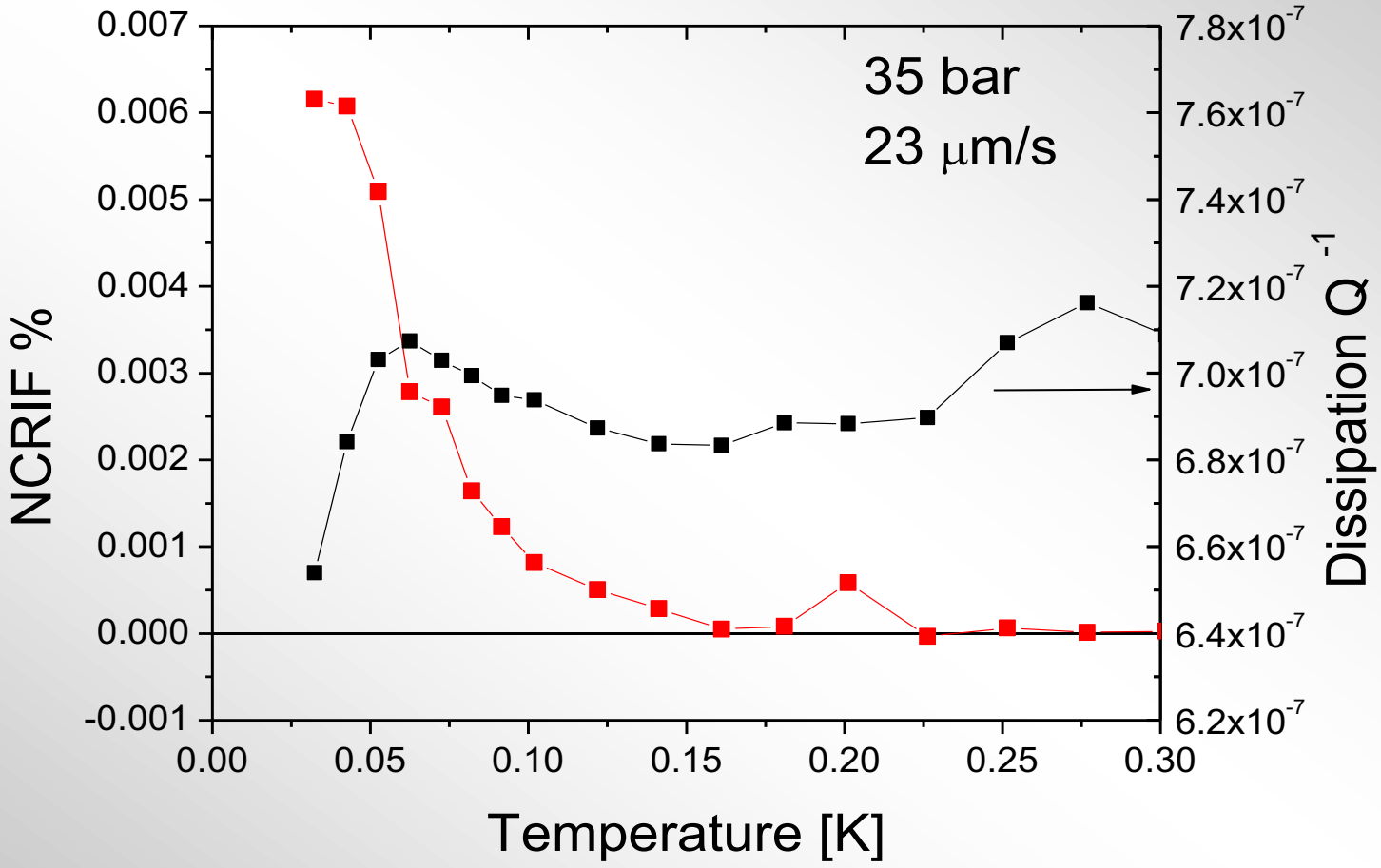
Mass Loading ≈ 4500 ns

(for 60 bar solid)

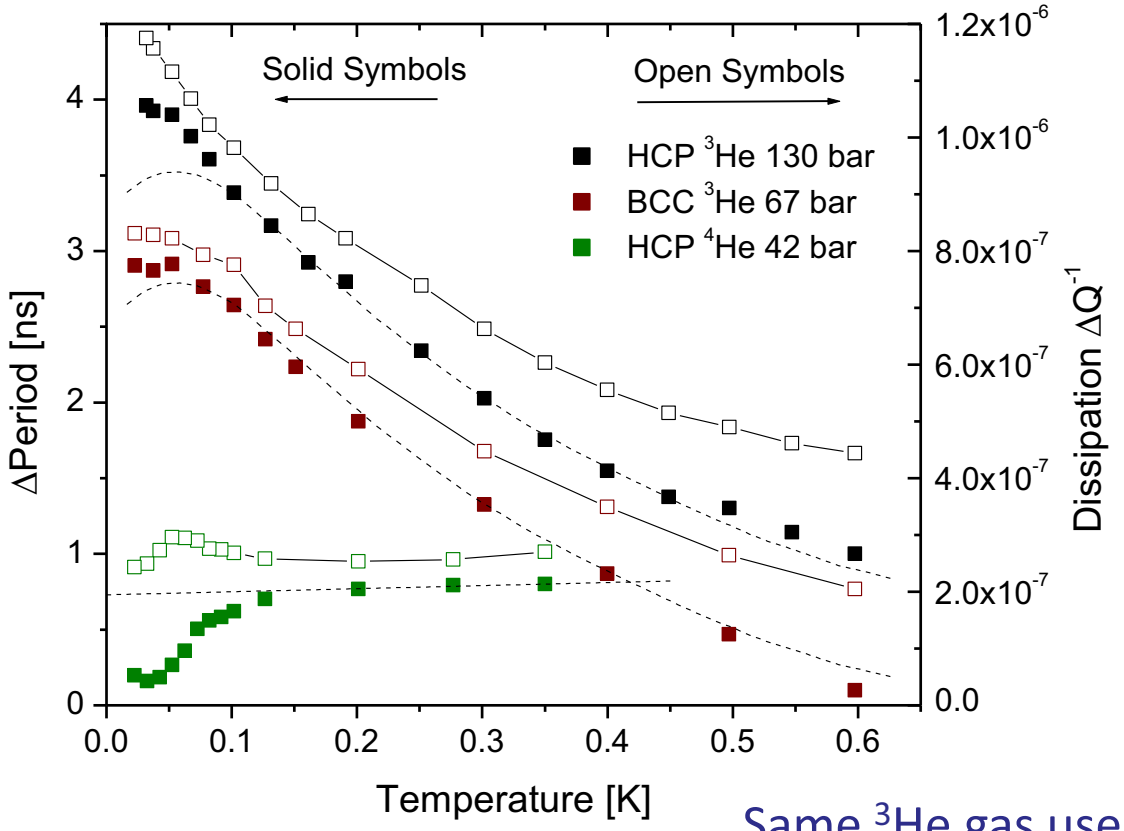
Rigid cell with solid ^{4}He



All the ‘usual’ features



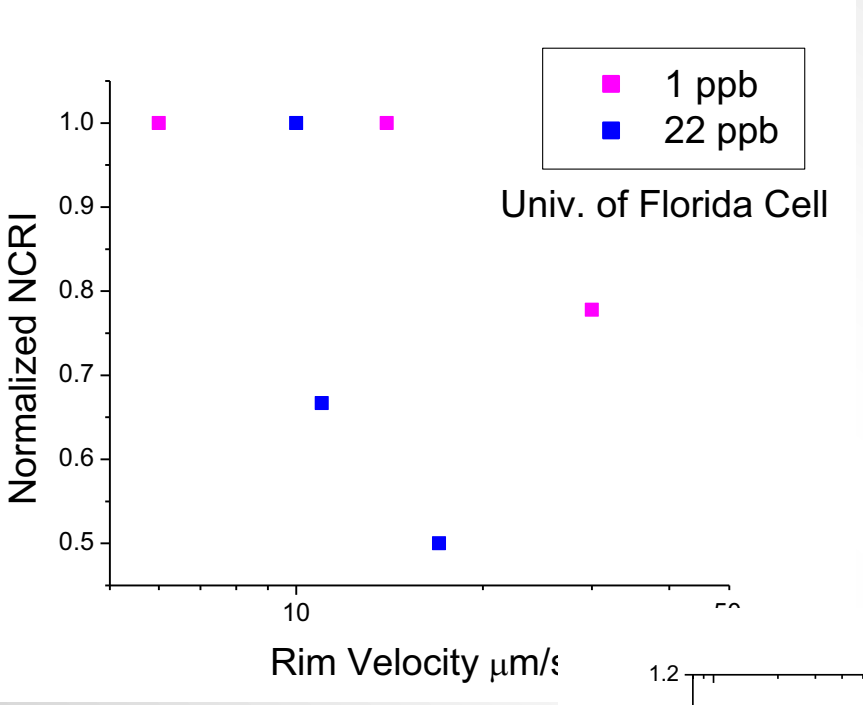
Rigid cell with solid ^{3}He

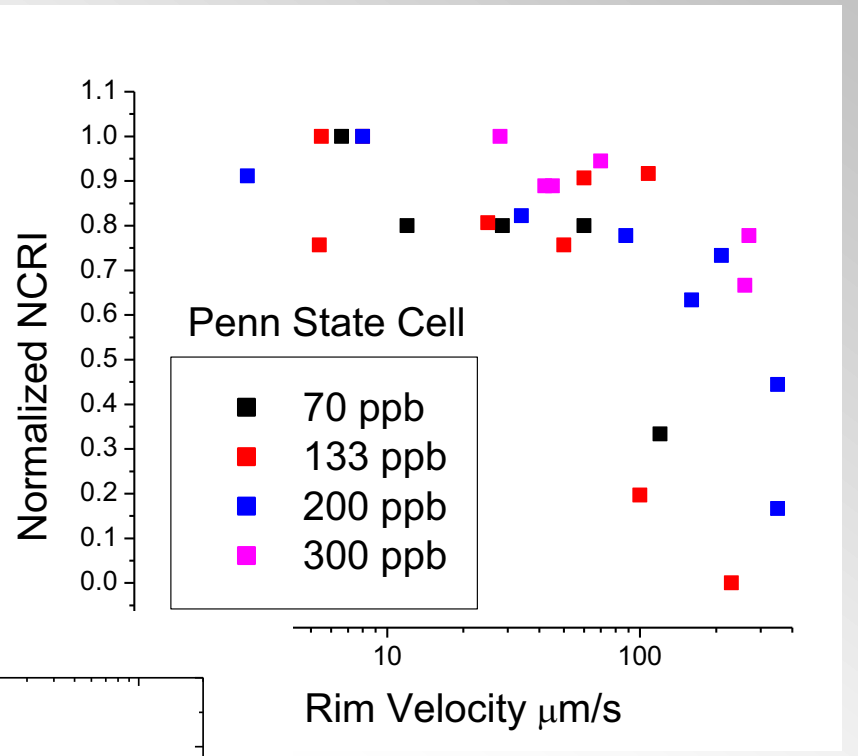


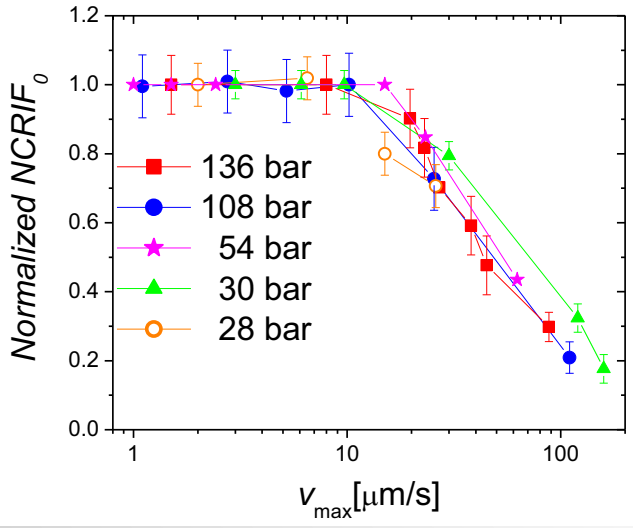
Same ^{3}He gas used in Alberta experiments

No NCRI signal from either HCP or BCC solid ^{3}He (<0.01%)

By special request



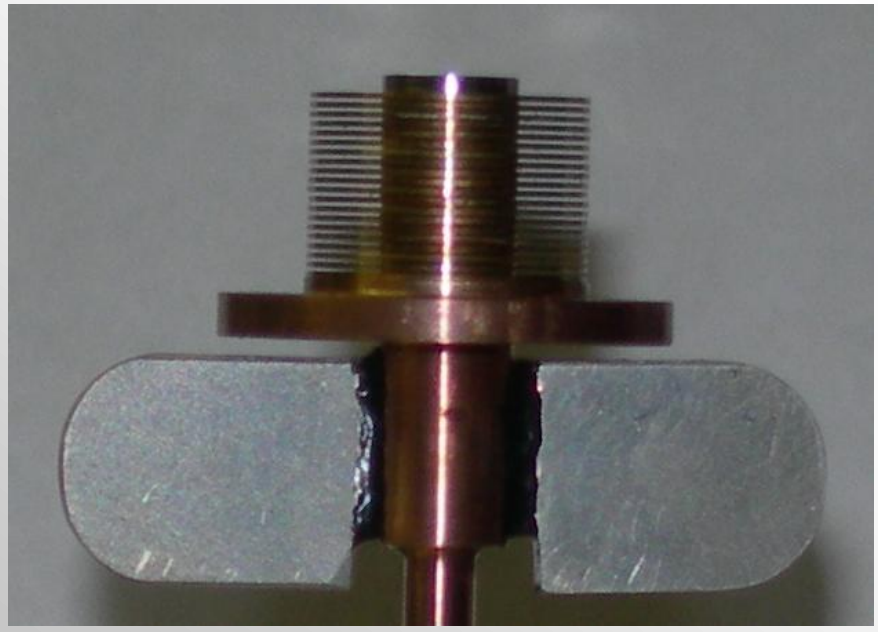


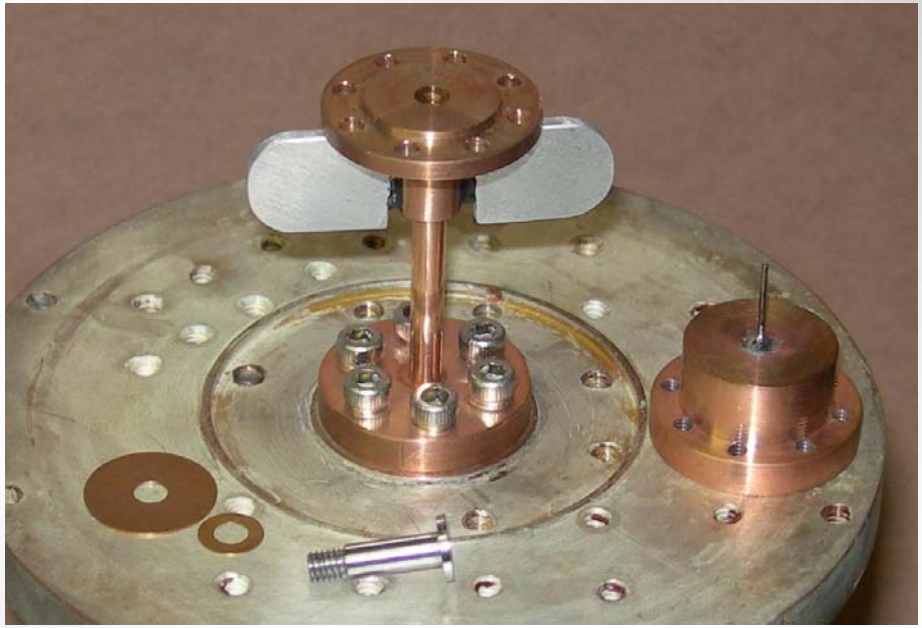


Kim and Chan
annulus data
300 ppb

Current Work

- Going in circles?
- Torsional oscillator with stacked discs
  - 0.15 mm spacing





Conclusions

- Sample quality does play a significant role in large crystals
  - High quality samples are more reproducible
  - Large NCRI fractions are more likely to anneal
- Many values are cell dependent (avg. NCRI, v_c)
  - However, all the trends are consistent
- Shear modulus effects can not account for the NCRI signal.