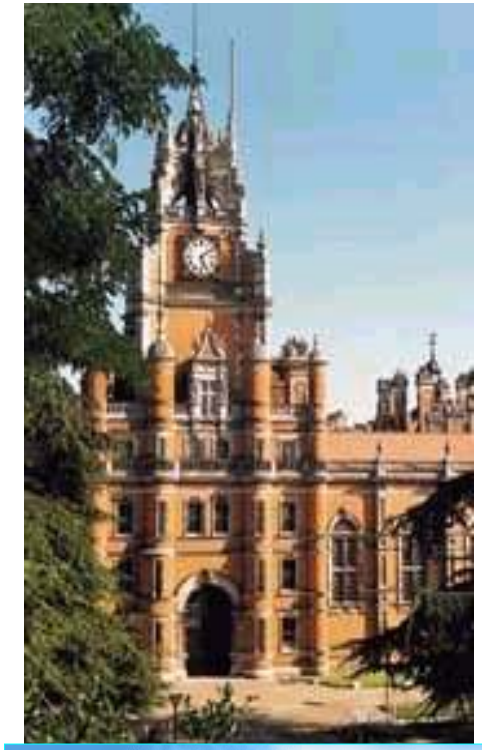
Torsional Oscillator Experiments on Helium Films on Graphite; The Search for a Two Dimensional Supersolid



Ján Nyéki, Anastasia Phillis,

Jeevak Parpia*, Brian Cowan

and John Saunders

Department of Physics, Royal Holloway University of London, Egham, UK

*LASSP, Department of Physics, Clark Hall, Cornell University, Ithaca, USA

Royal Holloway University of London

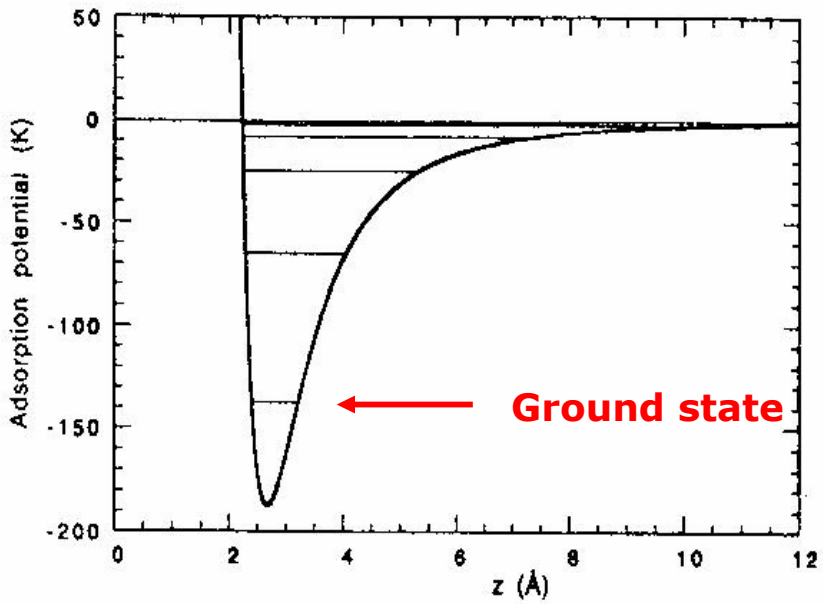
EPSRC Engineering and Physical Sciences Research Council

29/09/10, IPP Moscow

Dmitry Zimin Foundation Dynasty

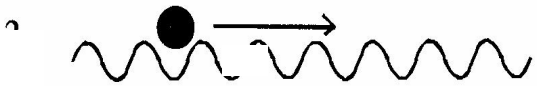
Why Graphite as Substrate ?

Adsorption potential

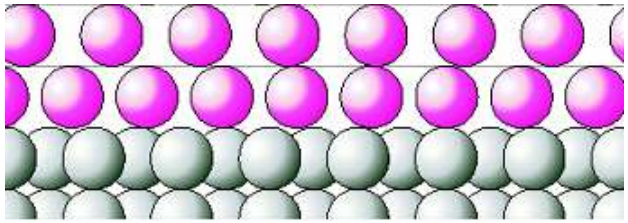


+ Periodic potential

arising from atomic structure of surface



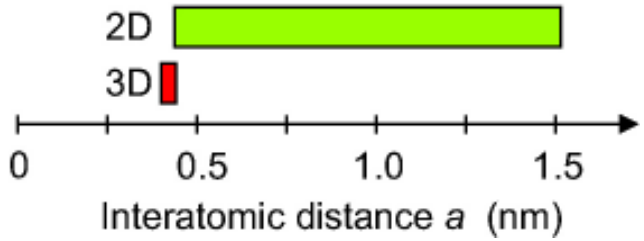
- Flat - minimalised disorder
- Helium film grows in layers.
- We can control the growth.
- Two solid He layers solidify
- Triangular lattice symmetry
- Cooling to submillikelvin range



Joly et al, Surf. Sci. 264 (1992) 419

2D Helium on Graphite

- Strongly correlated fermions or bosons
- Subject to an external triangular lattice potential
- Tuning parameters: interatomic distance
  binding potential
- No impurities

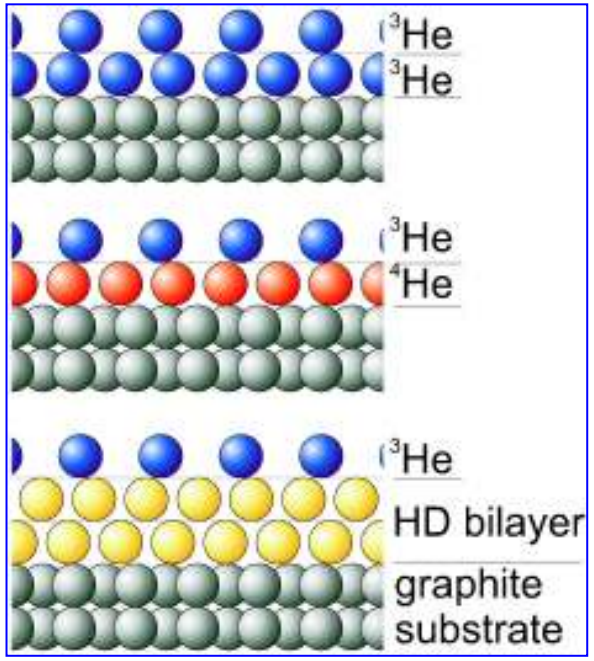


Experimental techniques

3He: NMR, heat capacity, neutron diffraction,
vapour pressure
4He: heat capacity, torsional oscillator,
neutron diffraction, third sound, vapour pressure

Temperature range ~ 15 μK to 15 K

Quests
Superfluidity of a ^{3}He monolayer
2D superfluid-insulator transition
2D supersolid

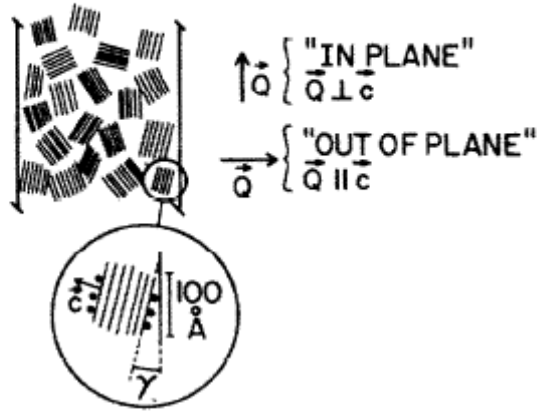


Exfoliated Graphite

Fukuyama, JPSJ 77 (2008) 111013

(a) (b)

Fig. 1. (Color online) Typical STM images of Grafoil surface at room temperature in the air. The scan area is 320 × 320 nm^2 (a) and 6 × 6 nm^2 (b).



(b)

Taub et al., PRB 16 (1977) 4551

Grafoil – atomically flat platelets 10-20 nm long, rolled, angle spread ±15°

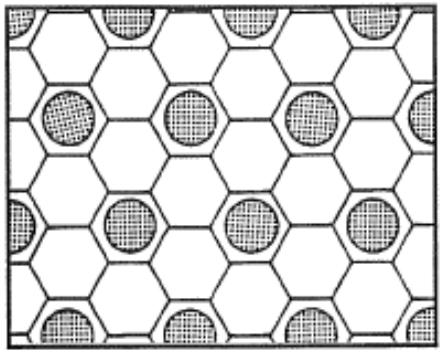
- surface area ~ 20 m^2/g
- density ~ 50% of bulk
- “deep sides”, edges 3-5%
- possible to cool below 1mK

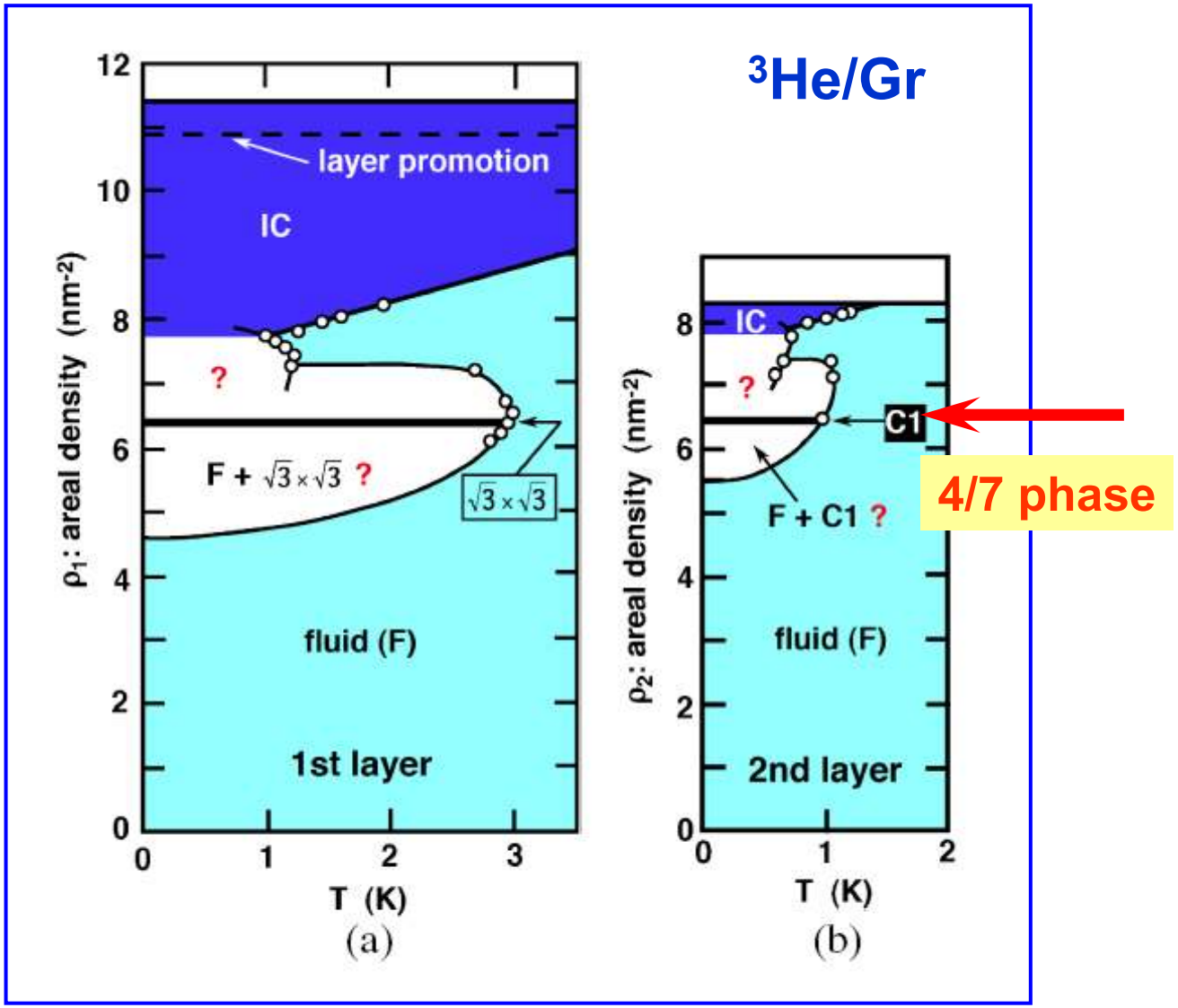
Layered Helium Films

Registered solid

(commensurate phase superlattice)

$\sqrt{3} \times \sqrt{3}$ 6.4 nm^{-2}





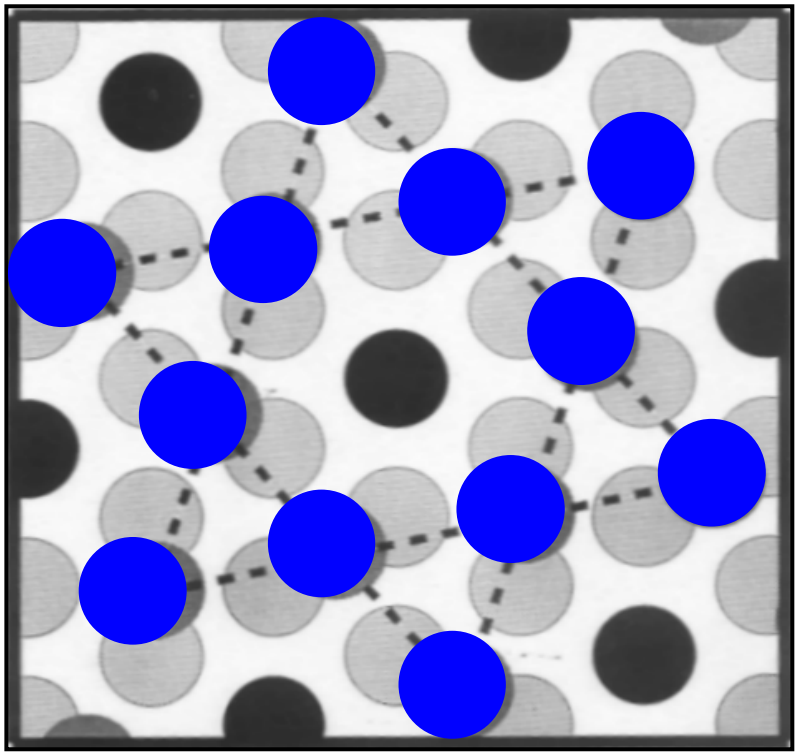
Fukuyama, JPSJ 77 (2008) 111013

Sibling system: 4/7 Phase in 3He films

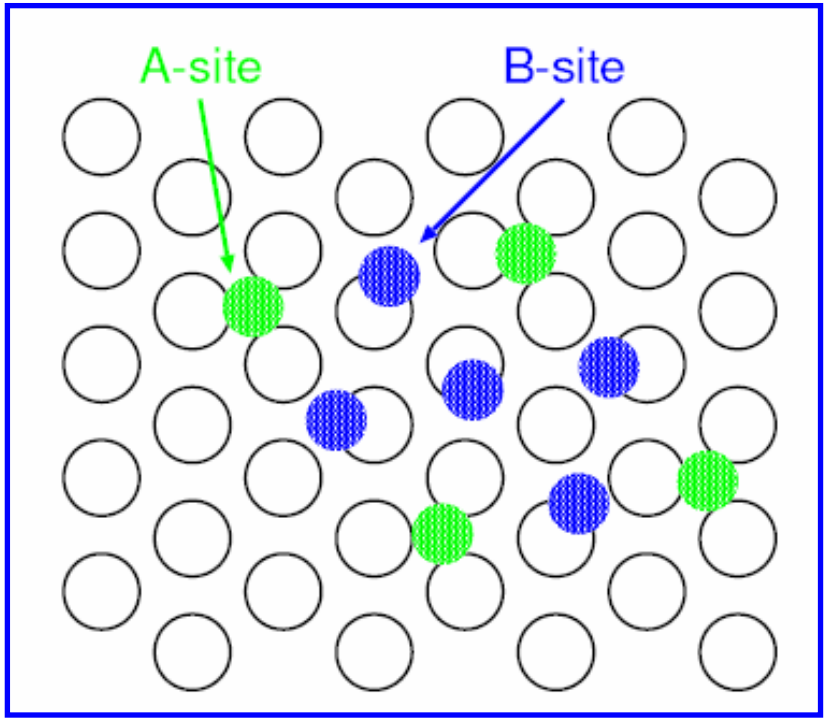
$$\frac{\text{2nd layer density}}{\text{1st layer density}} = \frac{\rho_2}{\rho_1} = \frac{4}{7}$$

Existence of 4/7 solid is clearly identified both experimentally and theoretically

- **Frustrated spin ½ magnet**
- **Mott insulator**
- **Gapless spin-liquid ground state**



Elser, PRL62 (1989) 2405



Takagi, J Phys Conf Ser 150 (2009) 032102

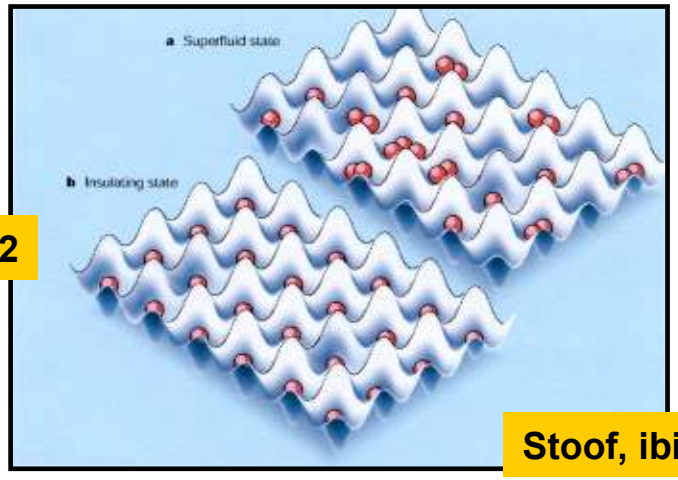
Motivation I

Quantum phase transition from a superfluid to a Mott insulator in a gas of ultracold atoms

Markus Greiner*, Olaf Mandel*, Tilman Esslinger†, Theodor W. Hänsch* & Immanuel Bloch*

* Sektion Physik, Ludwig-Maximilians-Universität, Schellingstrasse 4/III, D-80799 Munich, Germany
† Quantenelektronik, ETH Zürich, 8093 Zurich, Switzerland

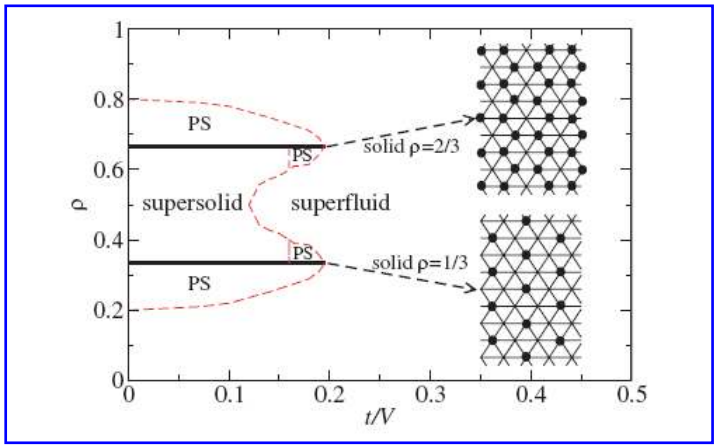
Greiner et al, Nature 415, Jan 2002



Stoof, ibid, N&V

Heidarian & Damle, PRL 95, 127206 (2005),
Melko et al, PRL 95, 127207 (2005),
Bonisegni & Prokof'ev, PRL 95, 237204 (2005) + ...

Revived theoretical interest



Wessel and Troyer, PRL 95, 127205 (2005)

Triangular lattice symmetry supports formation of supersolid

Can we study this phenomenon in 2D helium-4 ?
(alternative system of bosons in externally imposed lattice potential)

Searching for Supersolid

Superfluid response

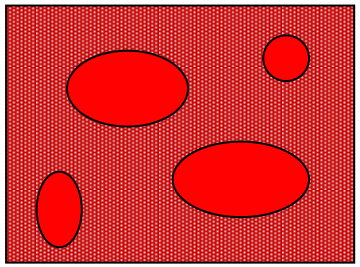
+

Broken translational symmetry

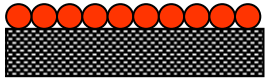
^{4}He/Gr 2nd Layer - Phase Diagram

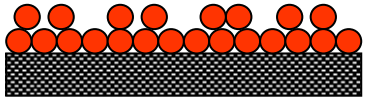
Pierce& Manusakis, PRL 81, 156 (1997) and PRB 59, 3802 (1999)

Puddling



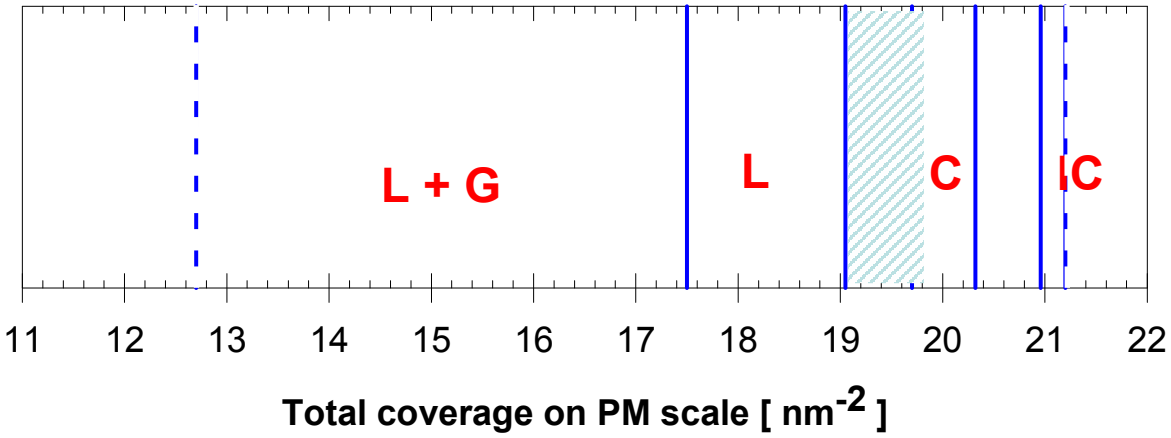
1st layer solid

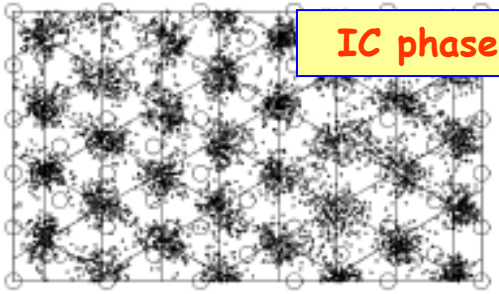




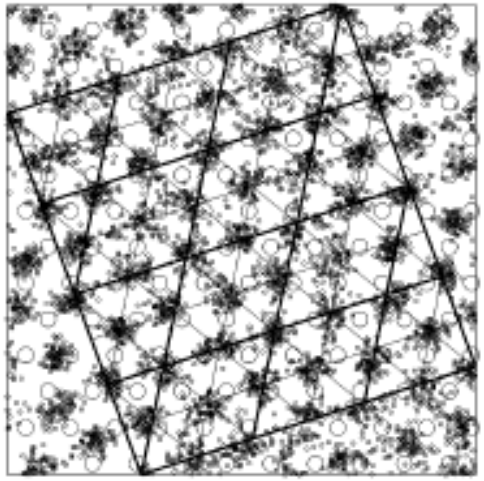
Commensurate 4/7 phase

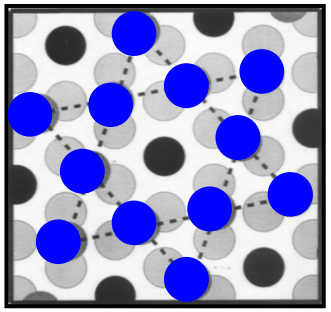
vacancies ?



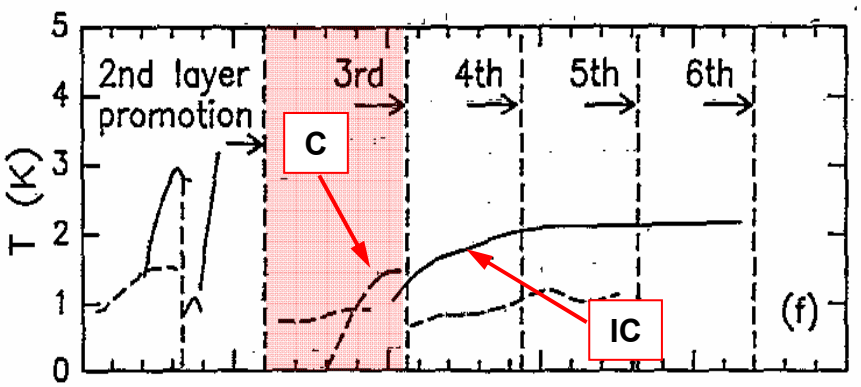


IC phase

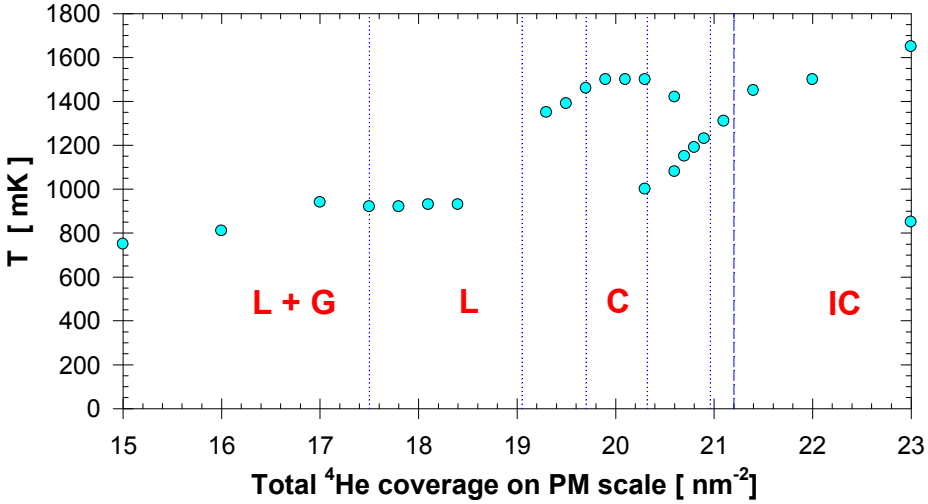


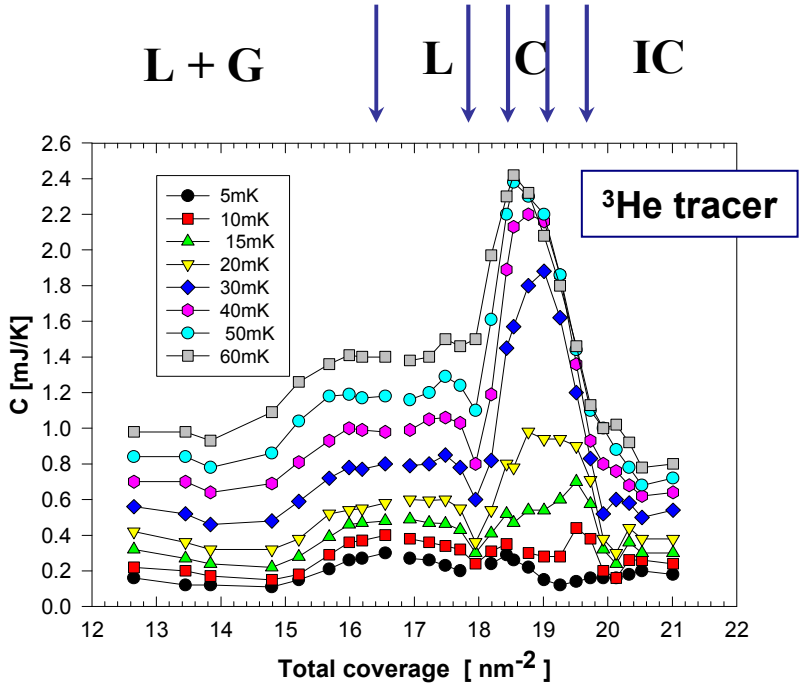


4/7 Phase in 4He films



Greywall, Busch: PRL 67 (1991) 3535





Ziouzia et al.: Physica B (2003) & PhD Thesis

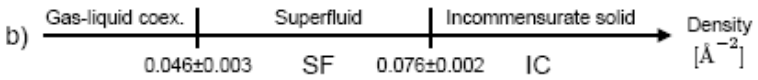
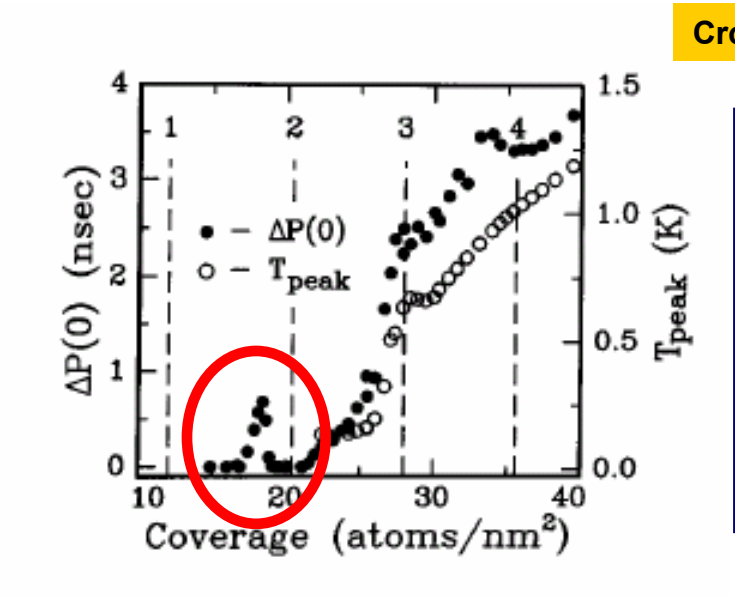


FIG. 1: Phase diagram of the first layer (a) and the second layer (b). There is *no* commensurate solid phase in the second layer.

Corboz et al., PRB78 (2008) 245414

Motivation II

Crowell & Reppy, PRB 53, 2701 (1993)

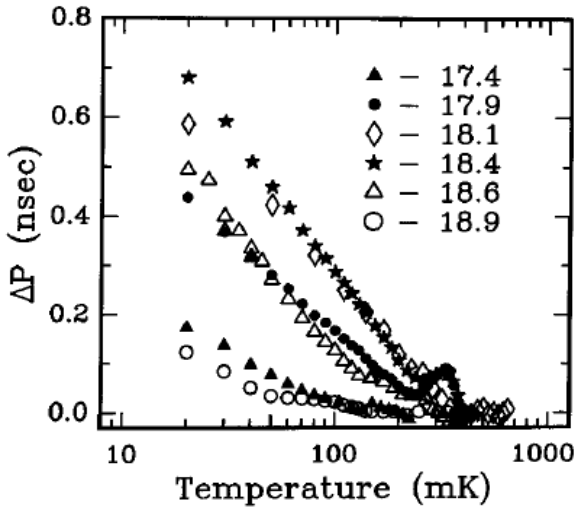


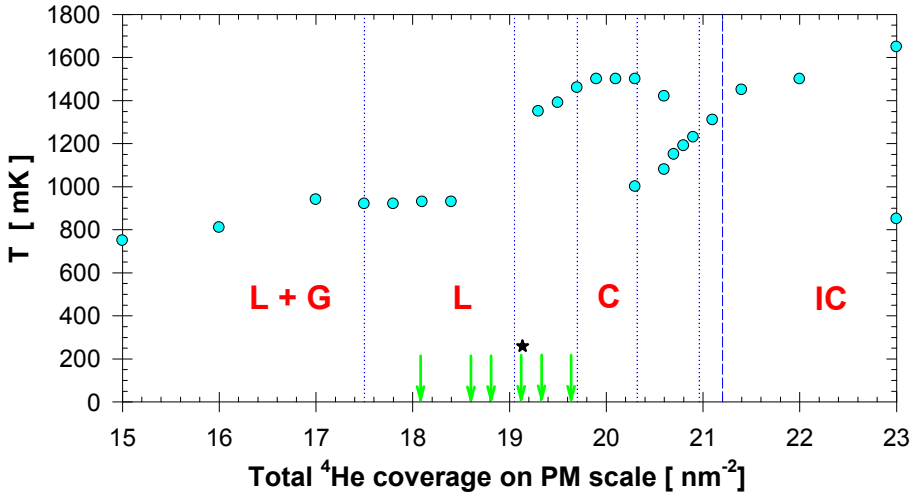
superfluid response in 2nd layer

20 mK – 600 mK

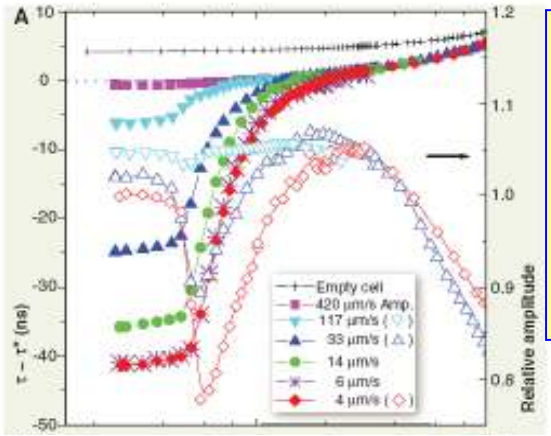
-lnT like dependence

no dissipation peaks reported





Chan, Science 319, 1207 (2008)

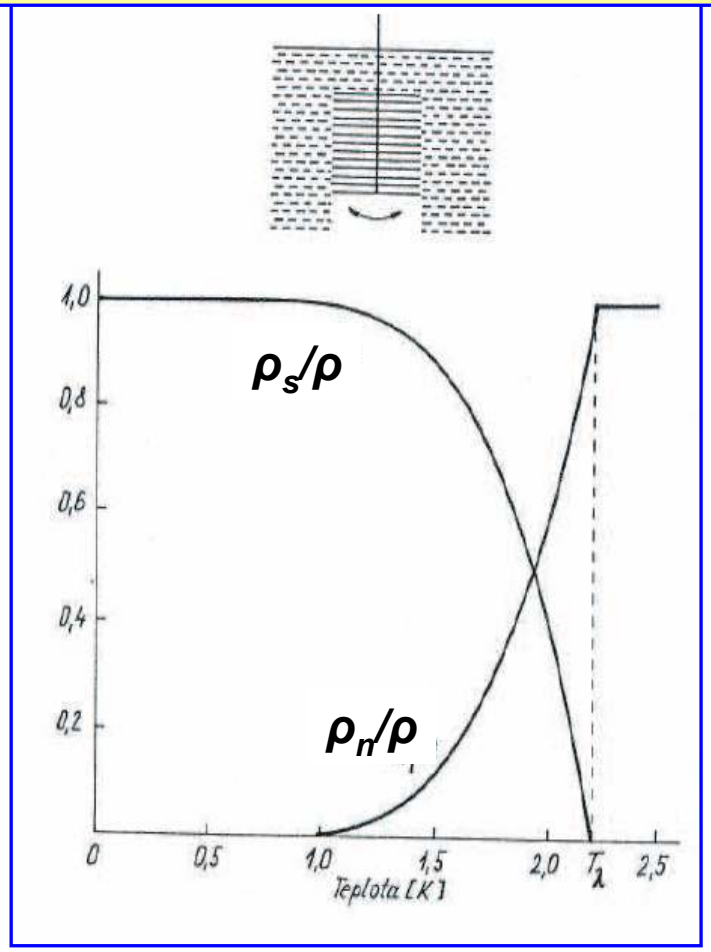


3D "Supersolidity"

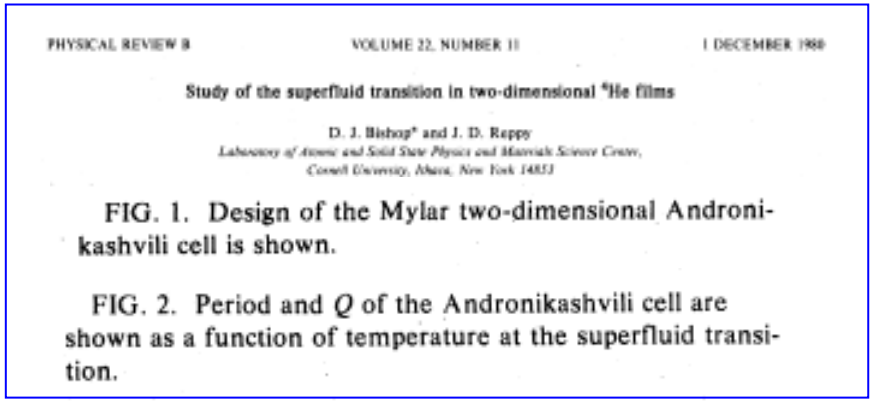
Sample annealing (disorder) and impurities play important role

Torsional Oscillator

Andronikashvili's experiment
Bulk liquid ^{4}He



E.L.Andronikashvili, Zh.Eksp.Teor.Fiz. 16 (1946) 780


PHYSICAL REVIEW B VOLUME 22, NUMBER 11 1 DECEMBER 1980

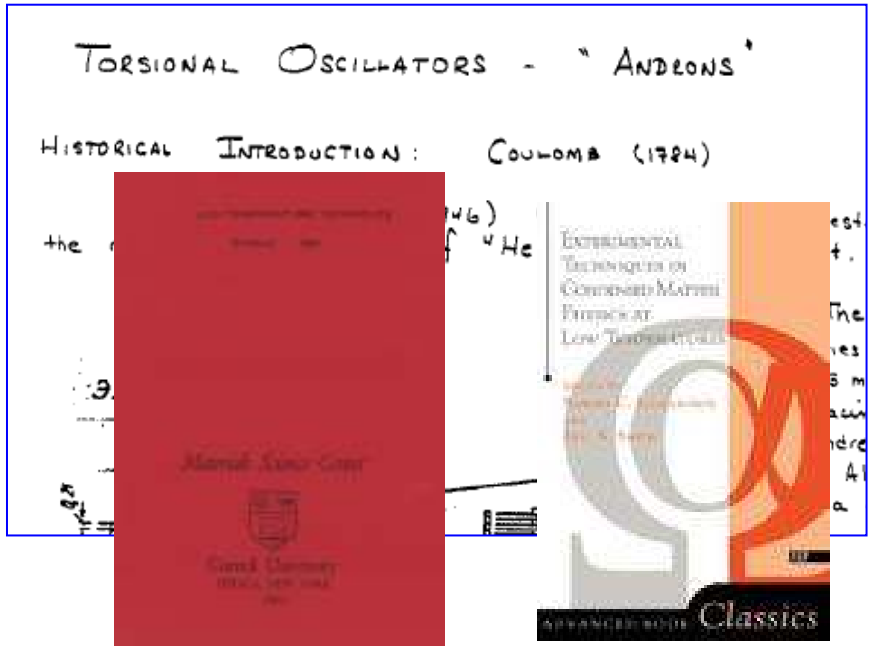
Study of the superfluid transition in two-dimensional ^{4}He films

D. J. Bishop* and J. D. Reppy
Laboratory of Atomic and Solid State Physics and Materials Science Center, Cornell University, Ithaca, New York 14853

FIG. 1. Design of the Mylar two-dimensional Andronikashvili cell is shown.

FIG. 2. Period and Q of the Andronikashvili cell are shown as a function of temperature at the superfluid transition.

Bishop & Reppy, PRB 22, 2701 (1980)



Torsional Oscillator Signal

Liquid ^{4}He films

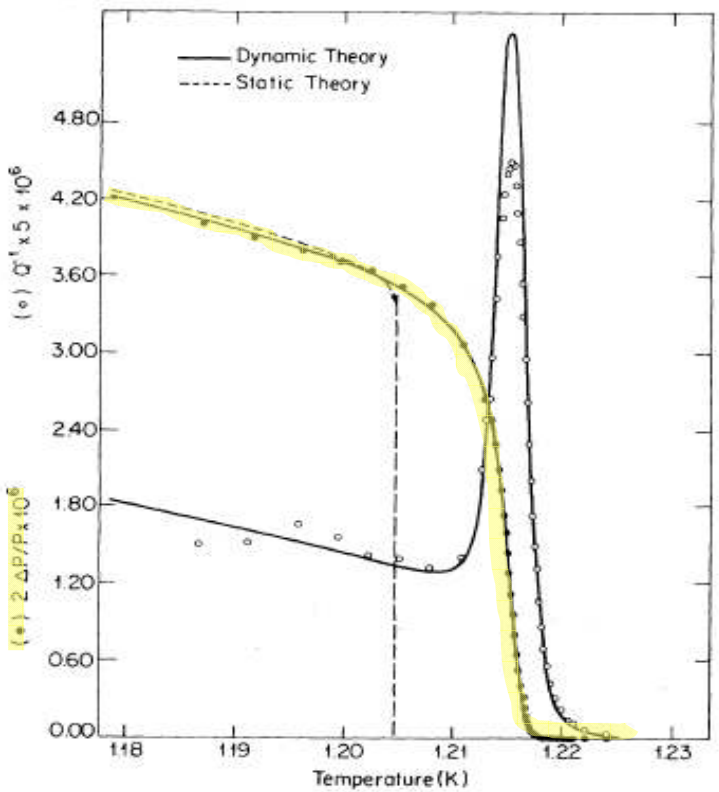


FIG. 2. The reduced period shift, $2\Delta P/P$, and dissipation Q^{-1} are shown for a superfluid transition temperature of 1.215 K. The solid lines are fits using the dynamic theory of AHNS (Ref. 6) and the dashed curve is the result of the static theory.

Bishop & Reppy, PRB 22, 2701 (1980)

Resonant frequency

$$\omega = \sqrt{\frac{k}{I}}$$

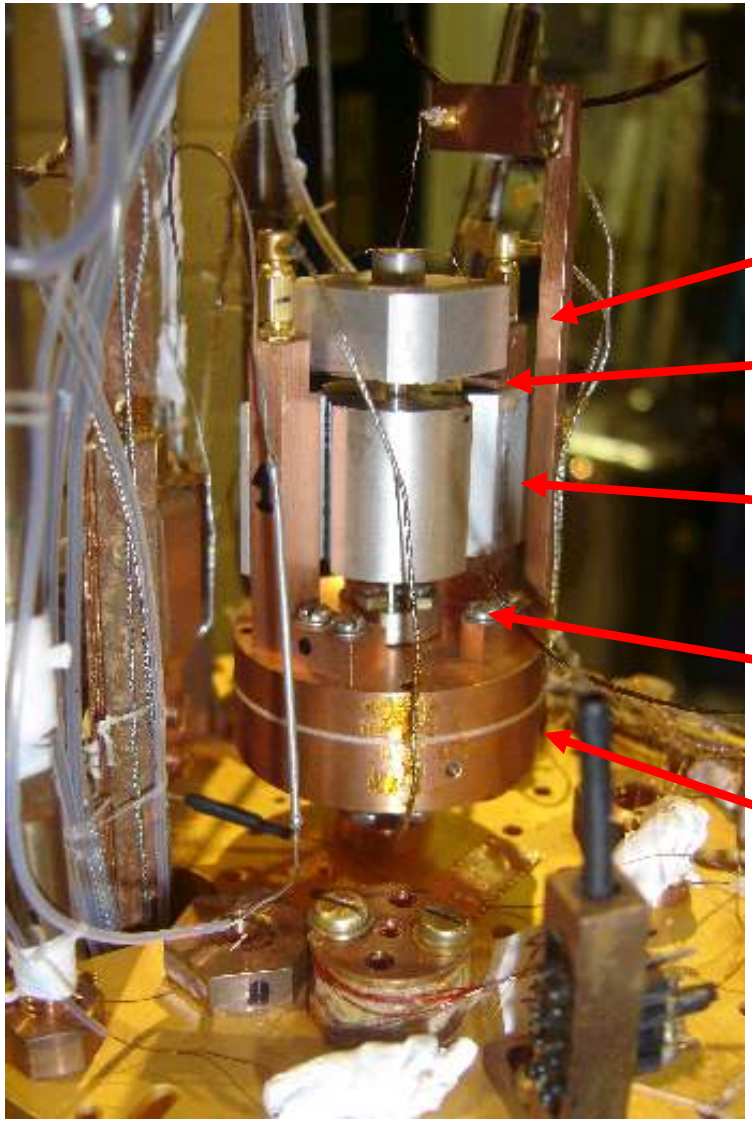
Amplitude$_{\text{Drive=const}}$ ~ Q

$$\Delta\left(\frac{1}{Q}\right) \approx \textit{Dissipated Energy}$$

Kosterlitz-Thouless theory

$$\frac{\rho_s(T_c^-)}{T_c} = \frac{2}{\pi} k_B \frac{m^2}{\hbar^2}$$

Experimental Cell: Torsional Oscillator



2 mK - 4000 mK (weak thermal link to the copper demagnetisation stage)

torsion element 1: contains exfoliated graphite sample ~ 35 m^2

torsion rod

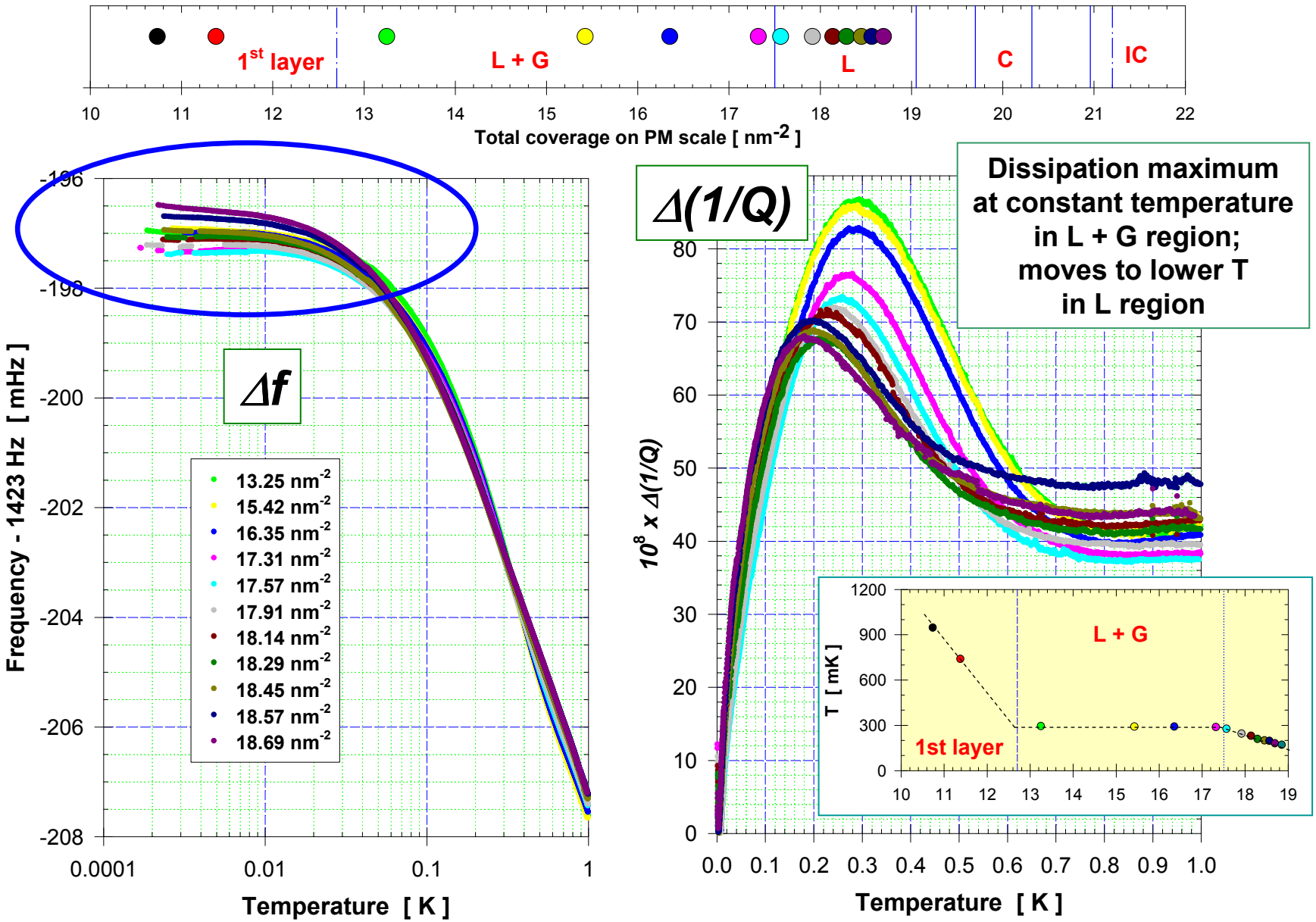
torsion element 2: coin silver cylinder, with two Mg electrodes biased at 100V

torsion rod

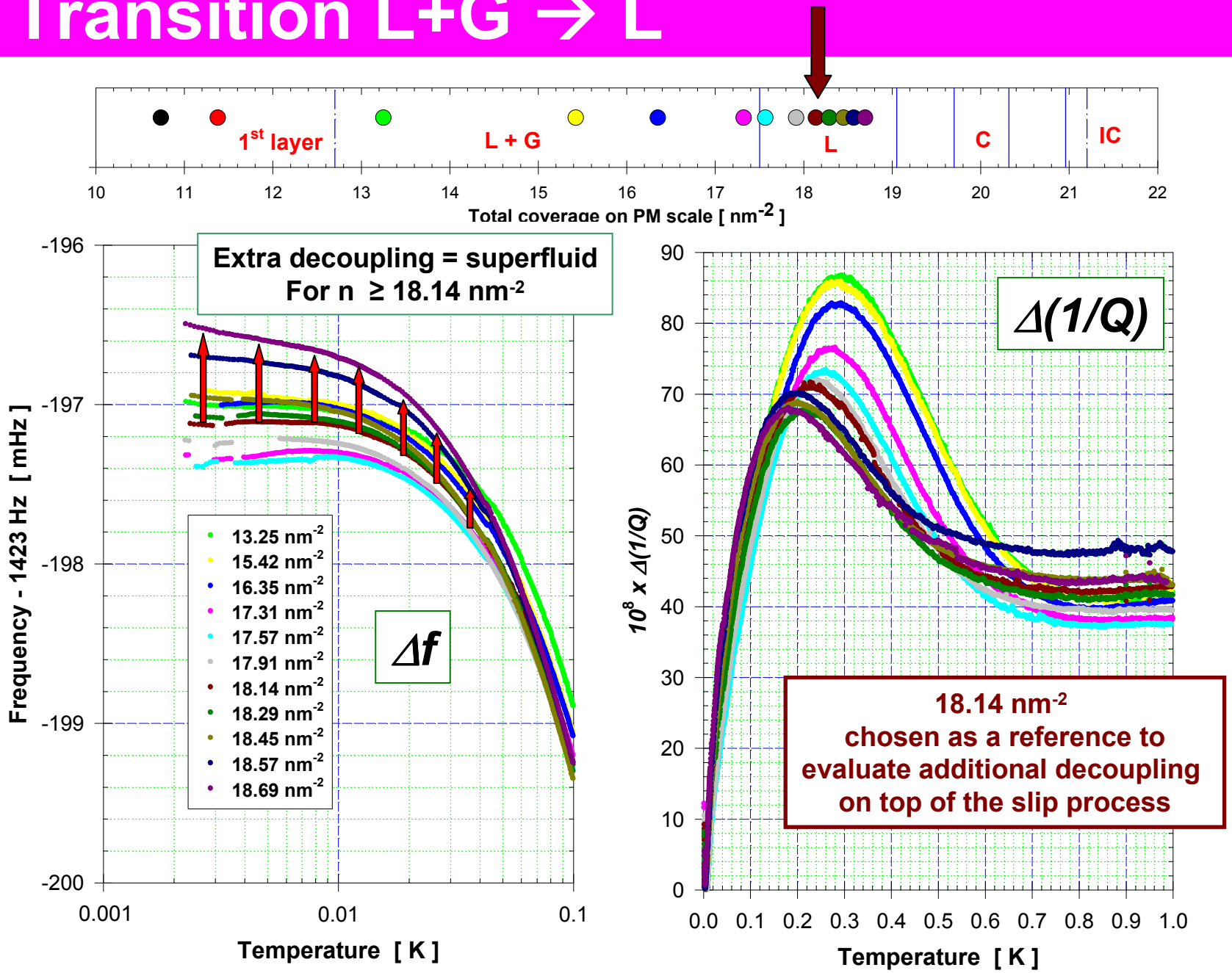
isolation mass + torsion rod (copper) mounted to cold-plate

Measure frequency shift and dissipation
quality factor Q ~ 250000 - 550000
working frequency ~ 1423 Hz;
detecting changes < 10 μHz ~ 2×10^{-7}g

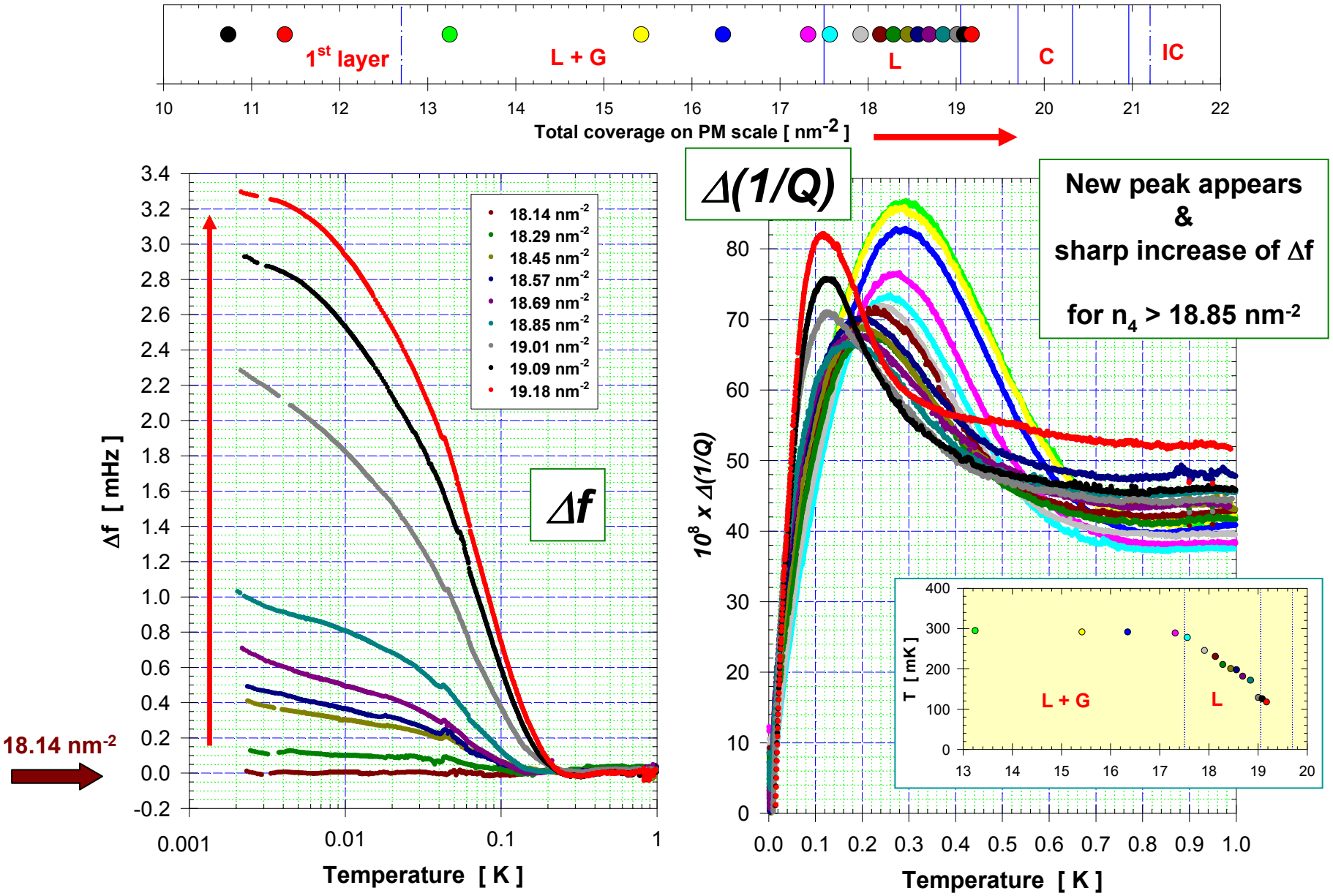
L+G Region


1st layer
L + G
L
C
IC
Total coverage on PM scale [nm-2]
Δf
Frequency - 1423 Hz [mHz]
Temperature [K]
13.25 nm-2
15.42 nm-2
16.35 nm-2
17.31 nm-2
17.57 nm-2
17.91 nm-2
18.14 nm-2
18.29 nm-2
18.45 nm-2
18.57 nm-2
18.69 nm-2
Δ(1/Q)
10^8 x Δ(1/Q)
Dissipation maximum at constant temperature in L + G region; moves to lower T in L region
T [mK]
L + G
1st layer

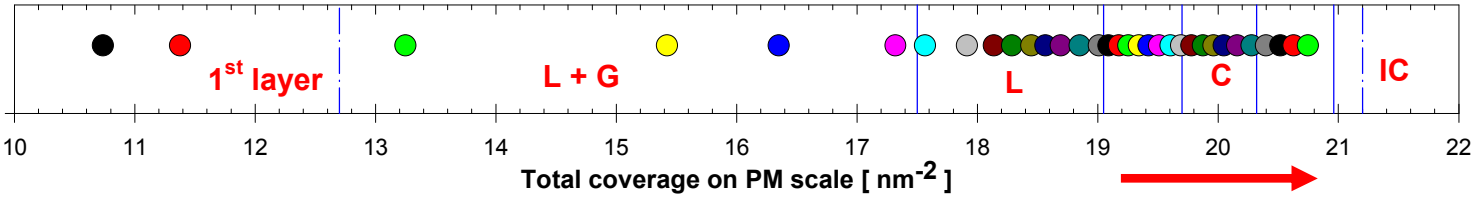
Transition L+G → L

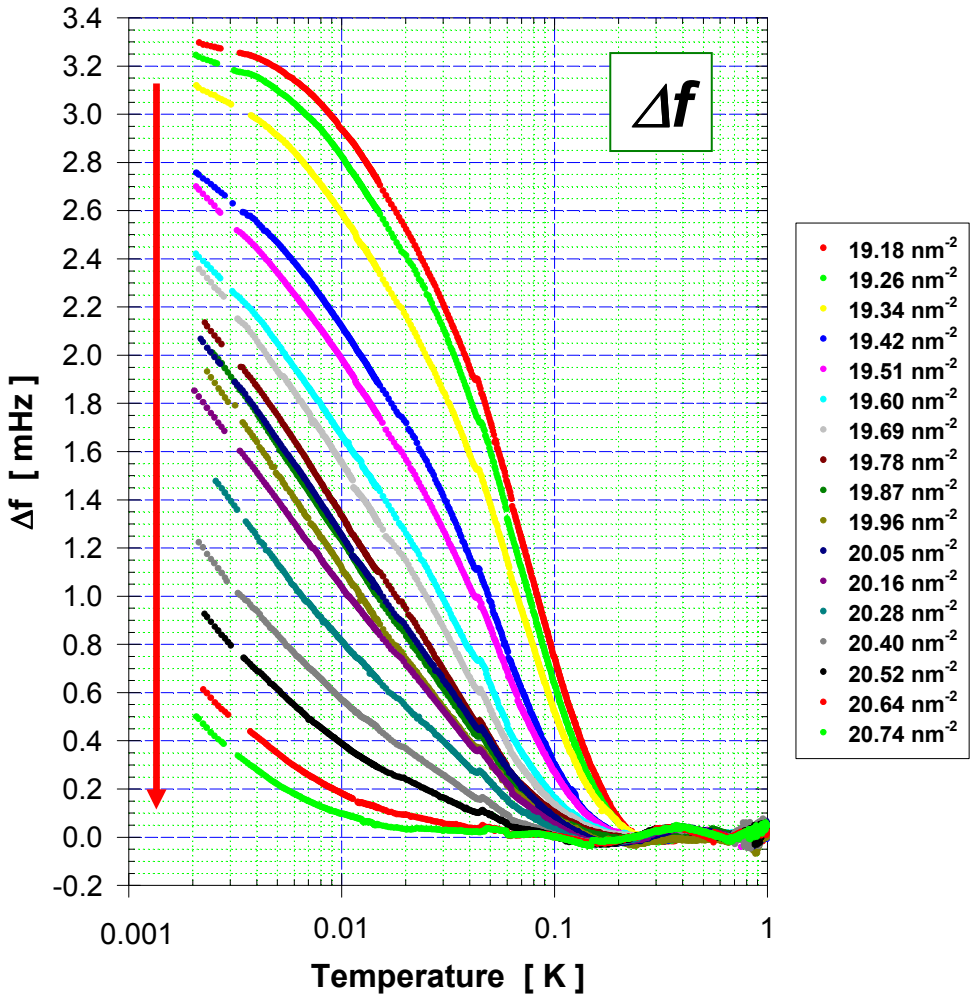


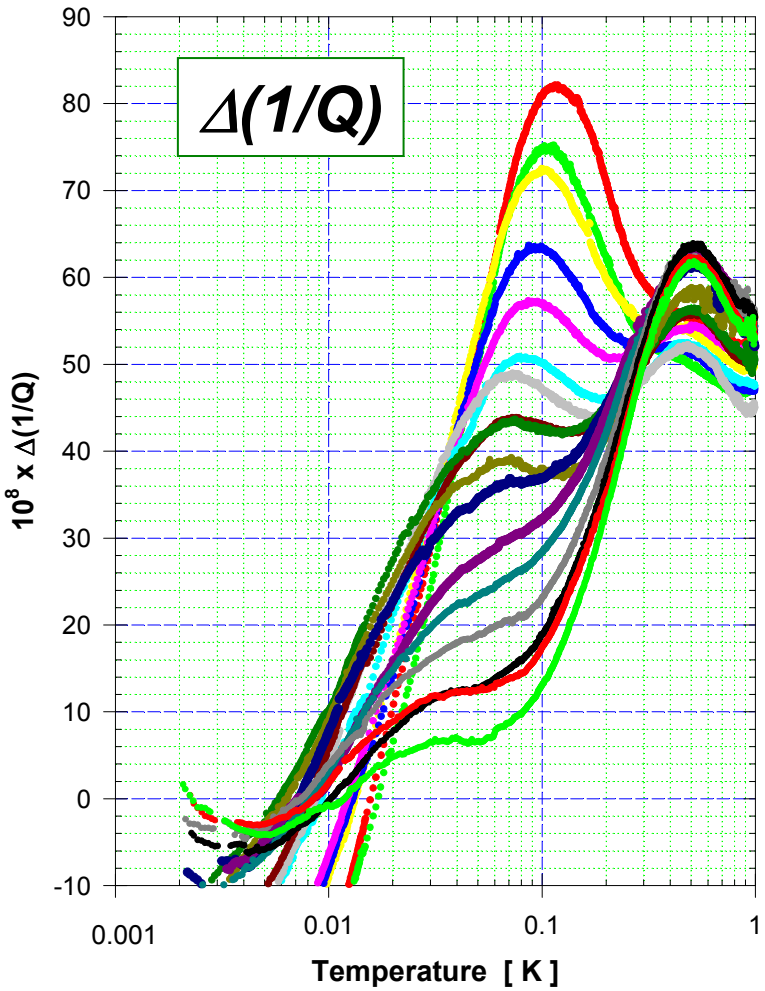
Homogeneous Fluid Region



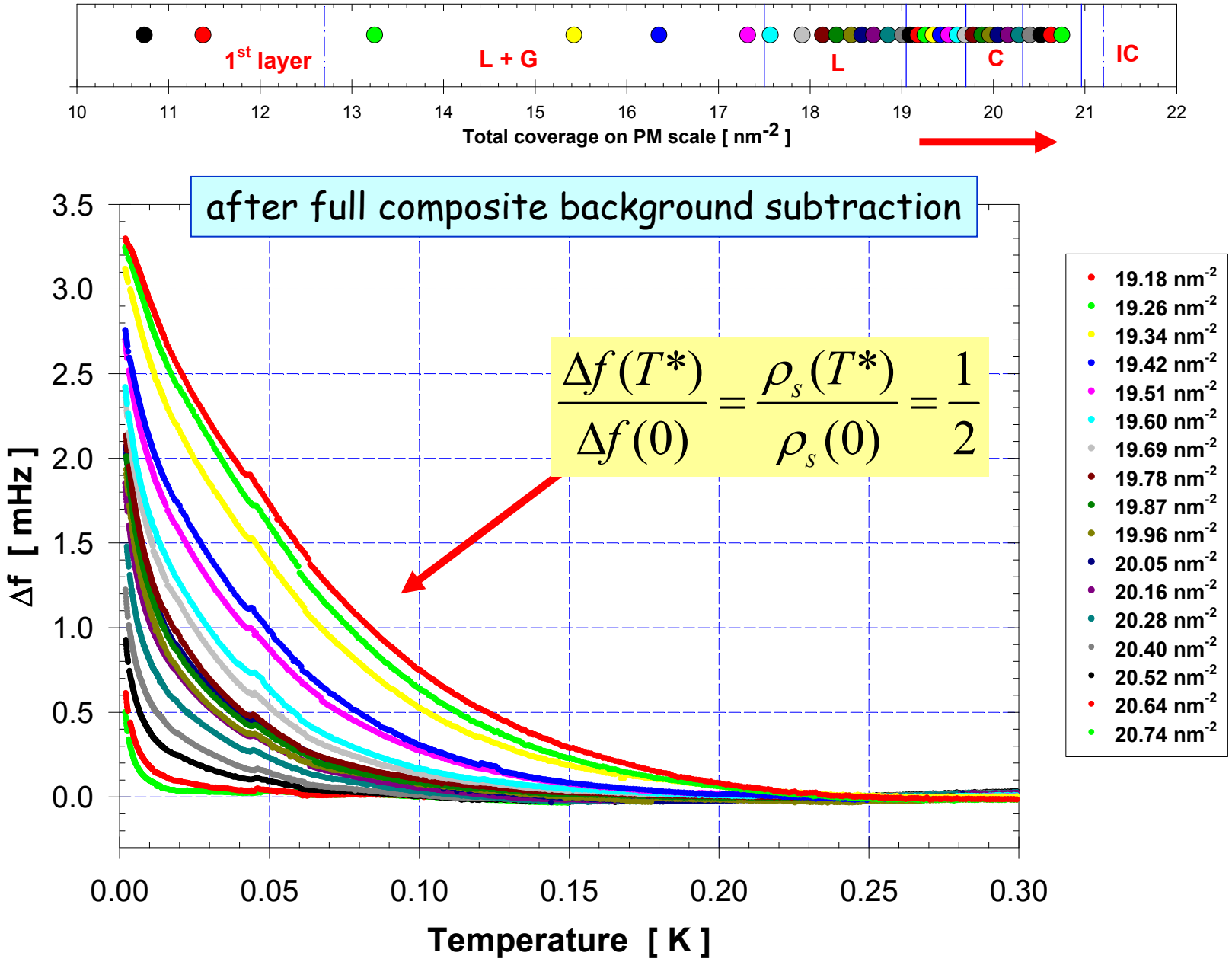
Super- response around C phase





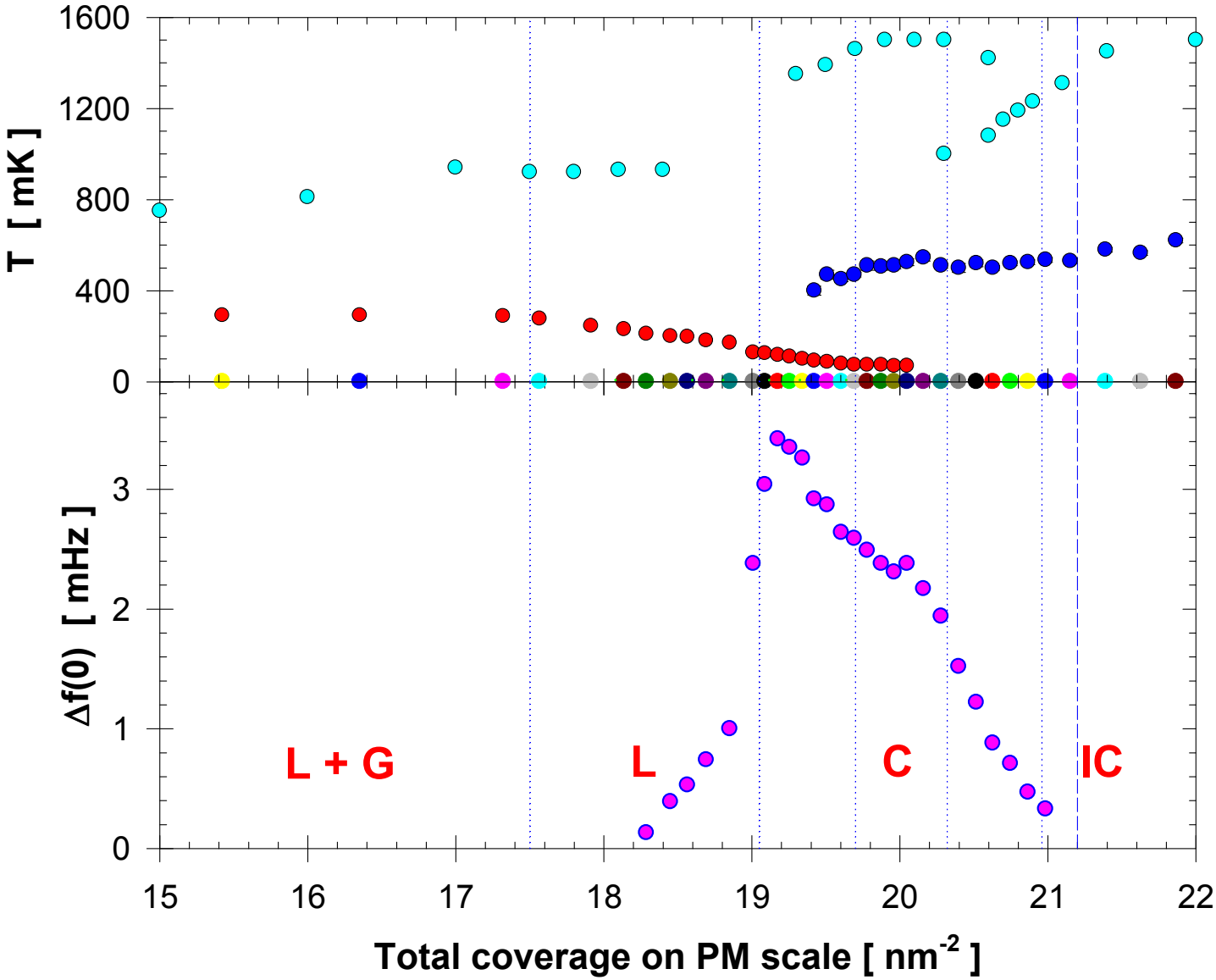


Super- response around C phase

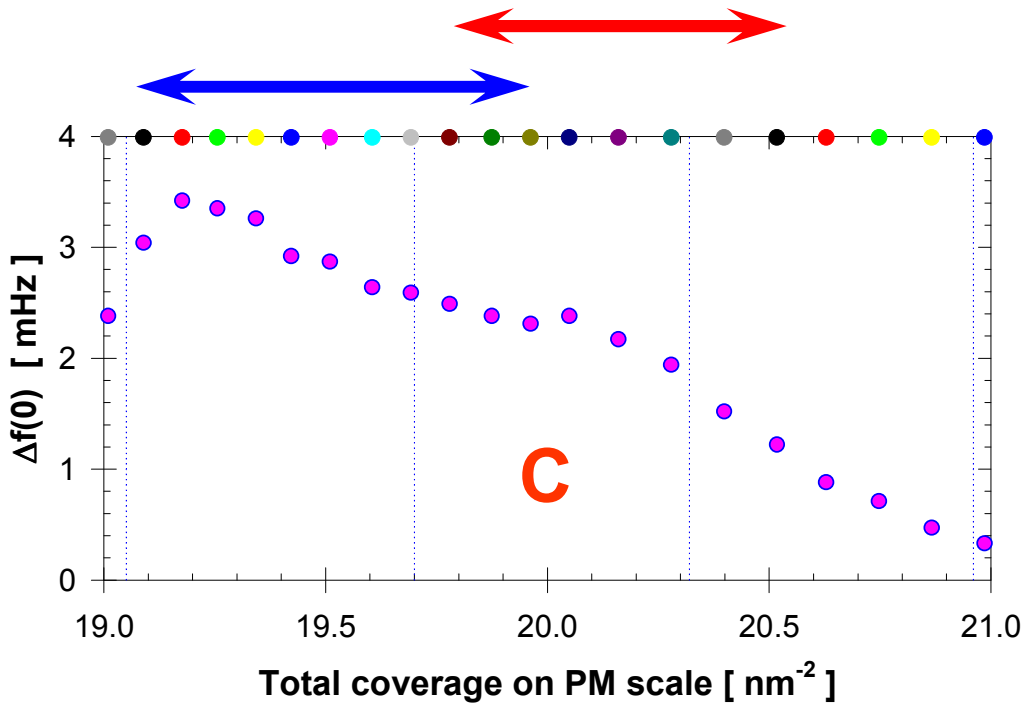


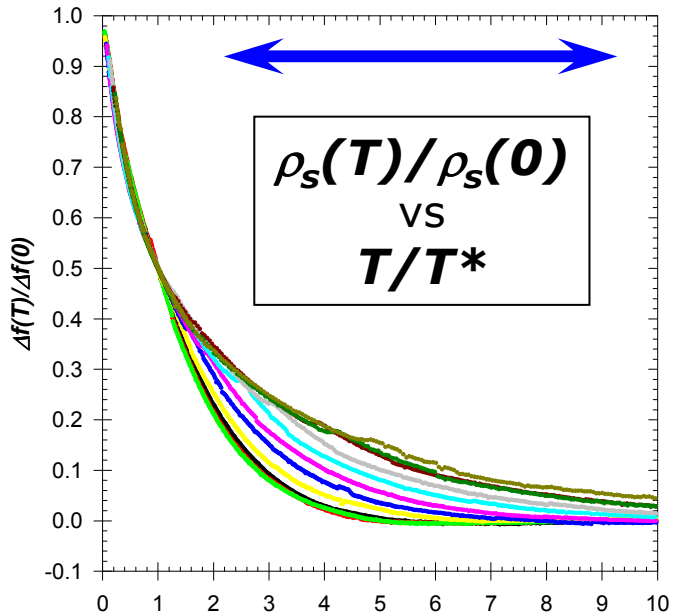
Super- Response Overwiev

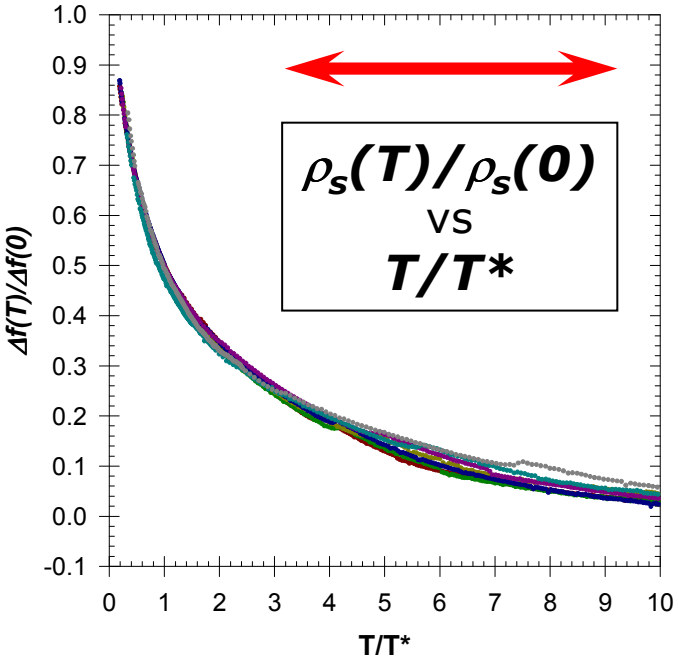
Not a simple structureless superfluid



Scaling



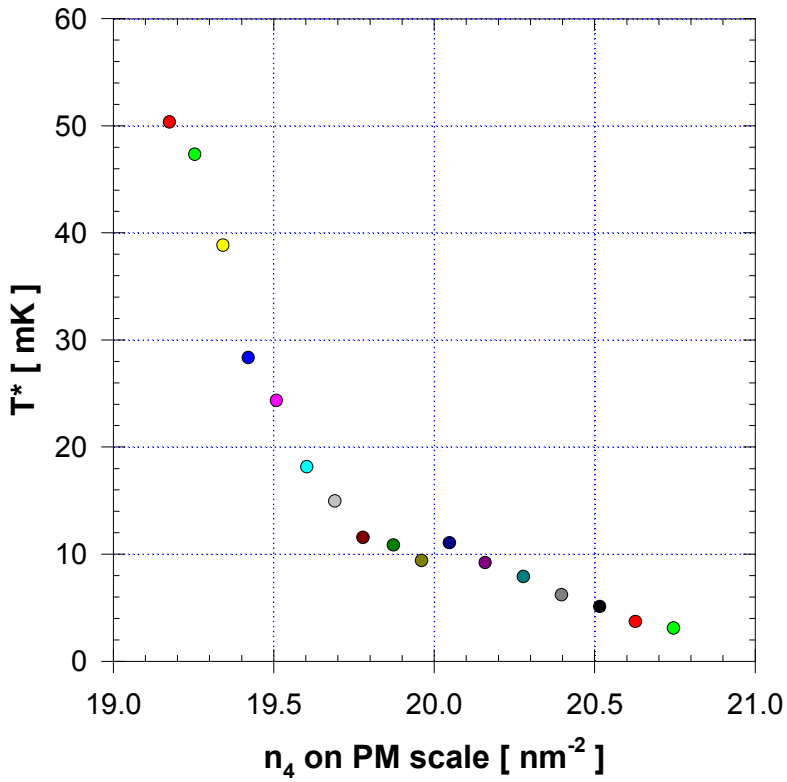


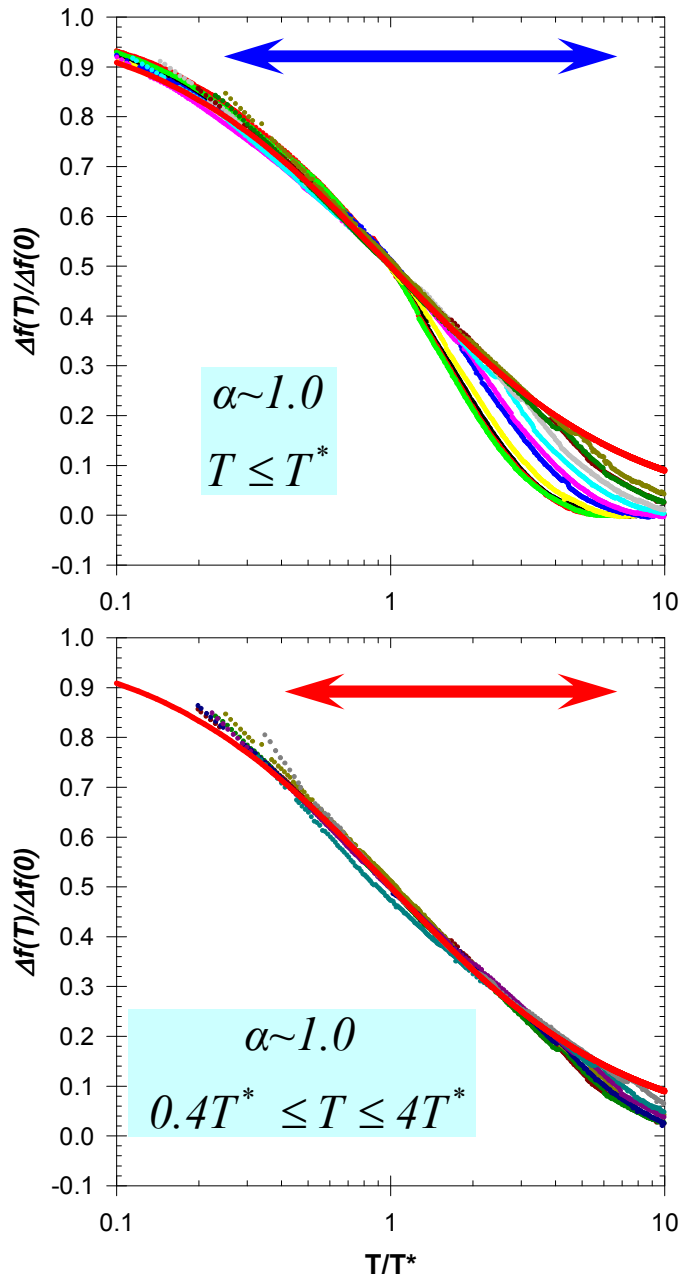


$$\frac{\Delta f(T^*)}{\Delta f(0)} = \frac{\rho_s(T^*)}{\rho_s(0)} = \frac{1}{2}$$

Superlattice density is a "pivotal" point in coverage dependence of super- response

Scaling

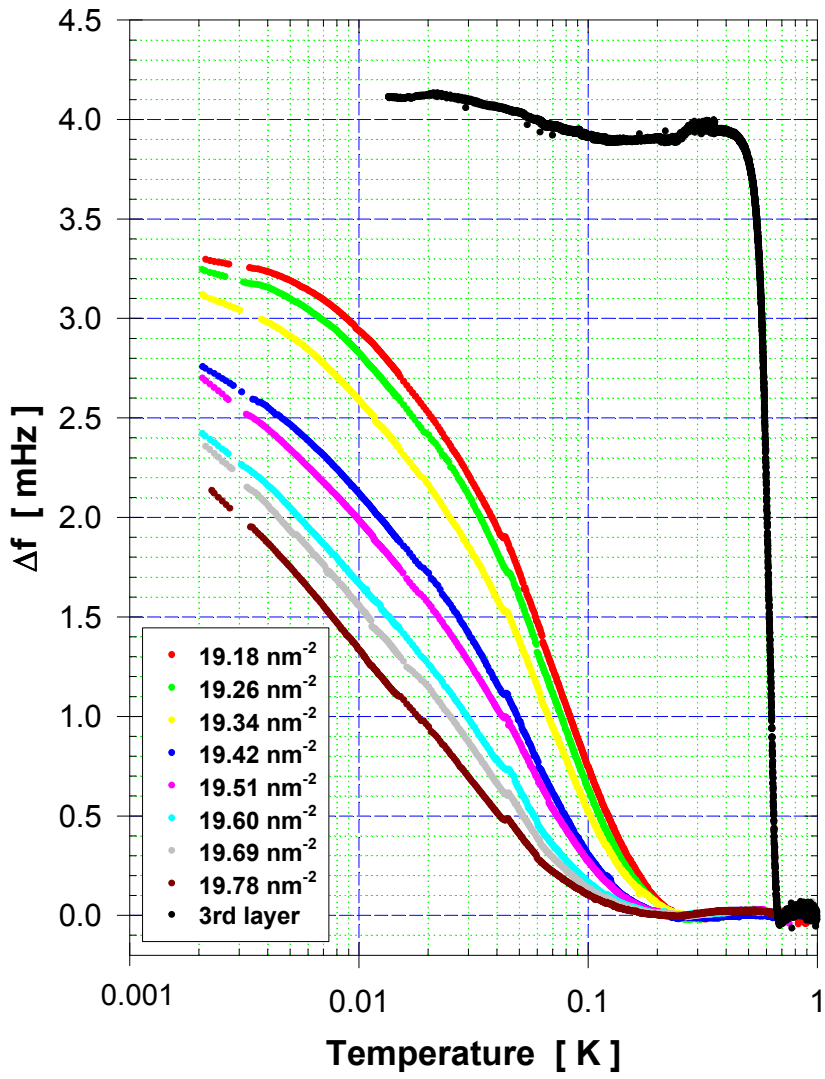




$$\rho_s(T) = \frac{\rho_s(0)}{1 + (T/T_0)^{\alpha}}$$

Jason Ho, private communication, 2010

Super- Fraction



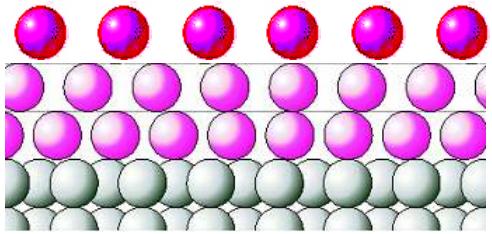
What is the value of super- fraction?

Compare with measurements of a KT superfluid monolayer in the same cell (3rd layer, $n_3 \sim 5.5\ nm^{-2}$)

Super- fraction at T→0:

~ 39% of 2nd layer for 19.18 nm^{-2} sample

~ 27% of 2nd layer for 19.78 nm^{-2} sample



X-factor for this cell = 0.942

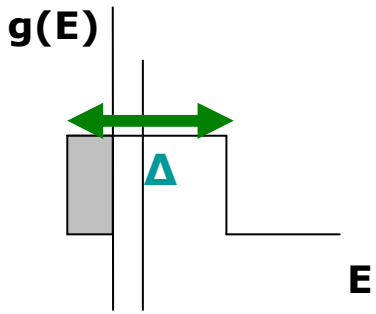
Measurements at perimeter velocity
25 ÷ 55 μm/s
checked up to ~ 500 **μm/s**

Super- response from superlattice?

Key: since $\Delta N \, \Delta\varphi \geq 1$, number fluctuations required to define phase.
[For this reason a commensurate solid cannot be a supersolid]

Zero-point vacancies **[Andreev & Lifshitz]** appear in the superlattice when $\Delta > 2U_V$.

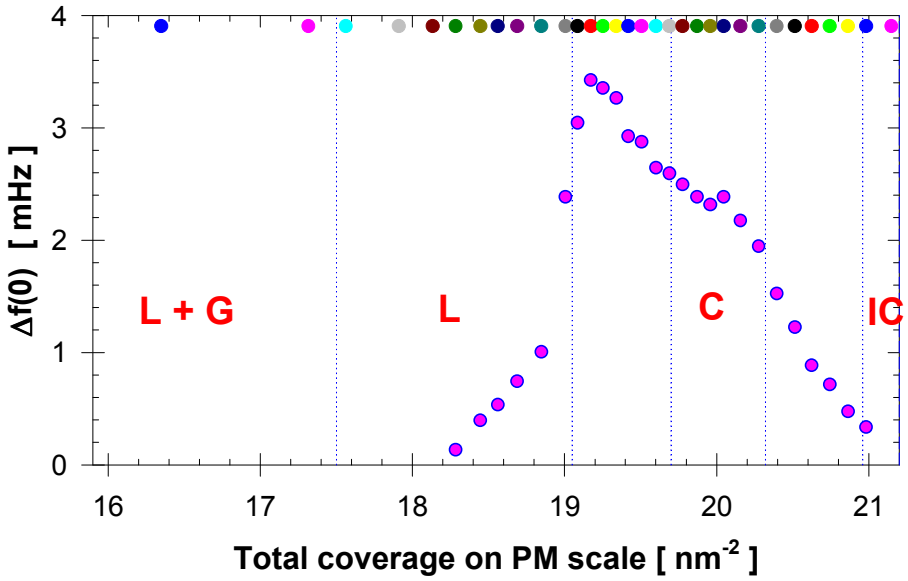
In 2D , Δ for 3He impuriton is much larger than in the bulk **[Ziouzia, PhD Thesis, London]**

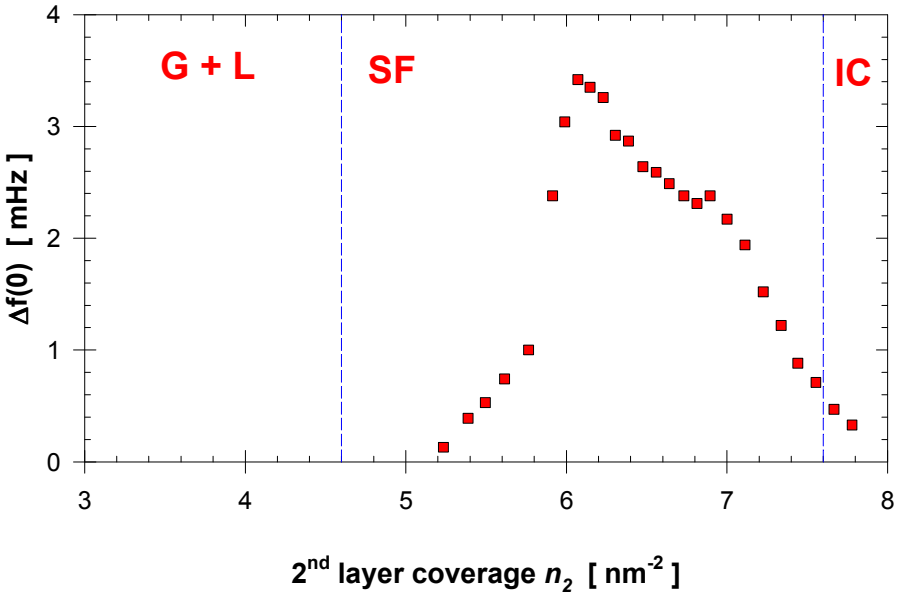


These number fluctuations are intrinsic to the 4/7 superlattice structure **[Watanabe, Imada, JPSJ 76 2007]**. Fluctuations into the 3rd layer.

The 2nd layer superlattice phase is unstable. **[Corboz et al., PRB 78 2008]**

Monte Carlo simulations

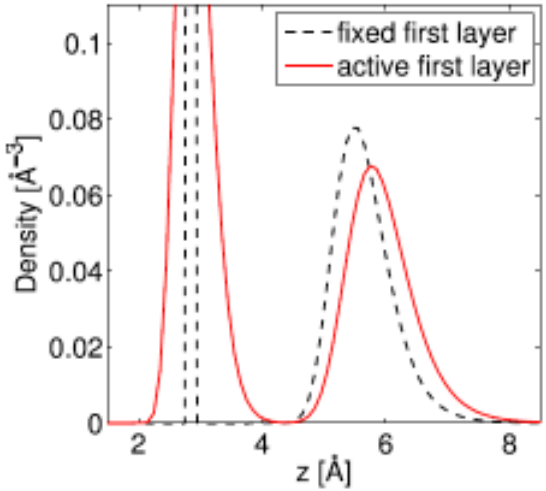




Pierce& Manousakis, PRL 81, 156 (1997) and PRB 59, 3802 (1999)

stable 4/7 phase

Two Monte Carlo simulations of the 2nd layer disagree about stability of the 4/7 superlattice solid phase



Corboz et al., PRB78 (2008) 245414

superfluid phase only

Momentum deficit in Quantum Glass

Reduced rotational inertia due to presence of tunelling two-level systems.

If "bulk" velocity ***v(t) ≠0*** the TLS has nonzero mean values of momenta $\langle p \rangle_{12}$ in both stationary states. In the ground state the projection of $\langle p \rangle_1$ onto ***v*** is negative.

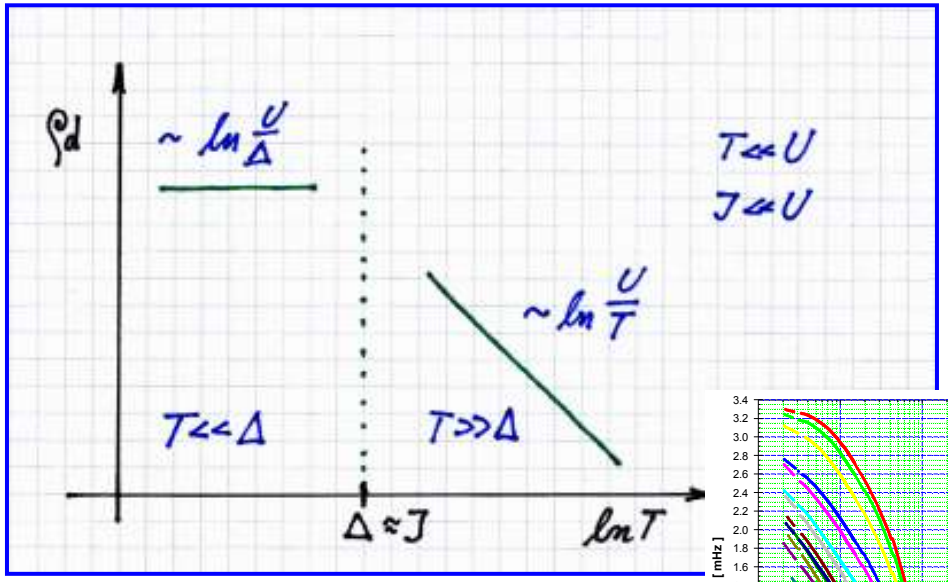
No superflow

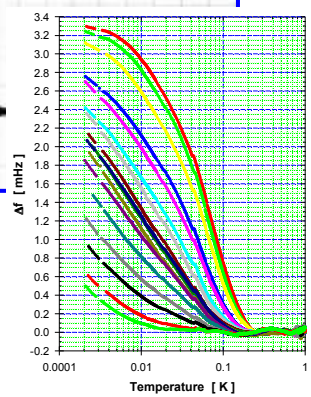
[Andreev, JETP Lett 85 2007, ZhETF 136 2009, Korshunov Pis'ma v ZhETF 90 2009]

$$\rho_d = \frac{N}{3\hbar^2} \langle m^2 J^2 a^2 \rangle \ln \frac{U}{\max(\Delta, T)}$$

$v_c \sim \hbar/(ma)$ In the 4/7 phase

a ~ 4.1 Å ➔ v_c~ 3.9 m/s





U - characteristic height of energy barrier

J - tunneling amplitude

Δ ≈ 1 mK ?

Summary

Motivation: Does vacancy doped commensurate phase $\sqrt{7} \times \sqrt{7}$ (4/7 phase) have a supersolid response?

- High precision TO measurements from 2mK to 4K. Second layer density is the tuning parameter.

- 1st layer interaction with the substrate present all time → careful measurements can distinguish that from 'super-' response; sensitive to 2nd layer structure

- Unusual temperature dependence of momentum deficit; no sharp onset: $\Delta f(T) \sim -\ln T$ near onset while $\Delta f(T) \sim T$ as $T \to 0$.

- $\Delta f(0)$ is tuned by n_2. Plateau-feature when $n \approx n_0$ (4/7) and vanishes near at incommensurate 2nd layer density n_I. Possible QCP at n_I.

- More than 25% of the 2nd layer contributes to super- signal when approaching n_0.

Summary II

Motivation: Does vacancy doped commensurate phase $\sqrt{7} \times \sqrt{7}$ (4/7 phase) have a supersolid response?

- After "pre-cursor" feature plot of $\Delta f(0)$ vs T^* shows two clear regimes. Boundary correlates with qualitative change in dependence of Δf on $\ln T$

- For a significant coverage range there is data collapse in $\Delta f(T)/\Delta f(0)$ vs T/T^* coordinates.

- Quantum glass model qualitatively agrees with observed $\Delta f(T) \sim -\ln T$ dependence. Energy scales involved need to be addressed.

- We need experimental evidence on the structure of putative 4/7 phase in the $T \rightarrow 0$ limit.