# Matti 80

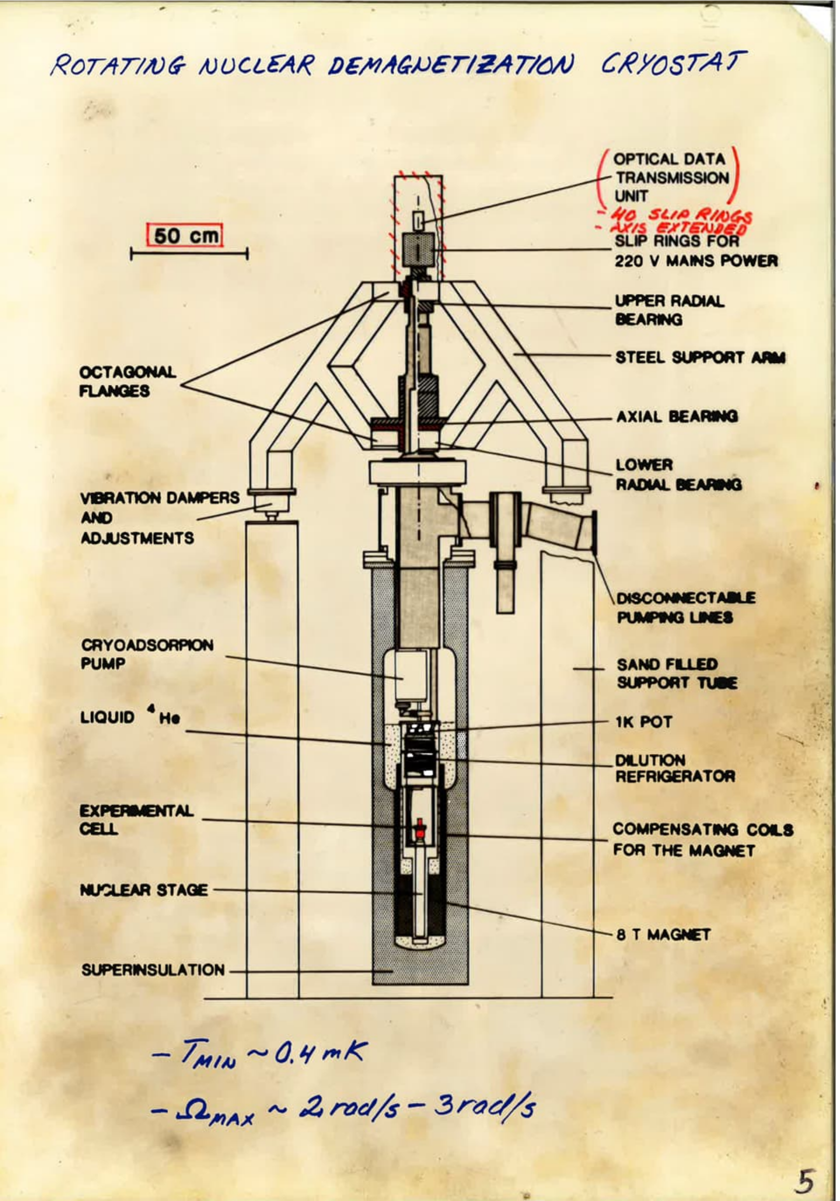
## TQM 50


2012


2015


1999

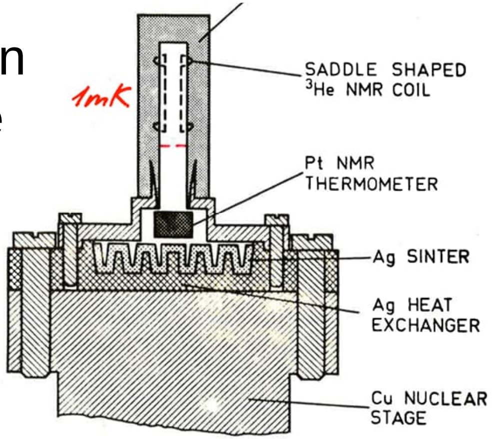
Many
happy
returns!

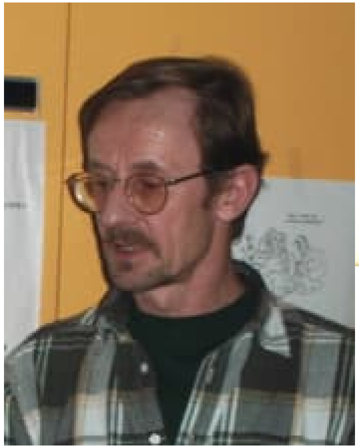


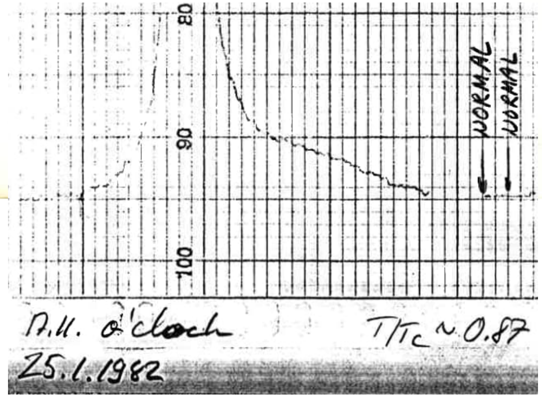
ROTATING NUCLEAR DEMAGNETIZATION CRYOSTAT

- $T_{MIN} \sim 0.4$ mK
- $\Omega_{MAX} \sim 2$ rad/s – 3 rad/s

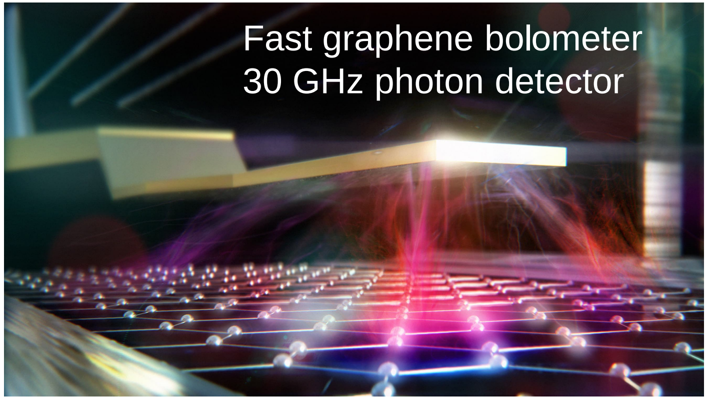
- ➢ Successful collaboration with Soviet Union
- ➢ Altogether ~30 PhD thesis works
- ➢ Perhaps the most successful project in the Finnish science over the years





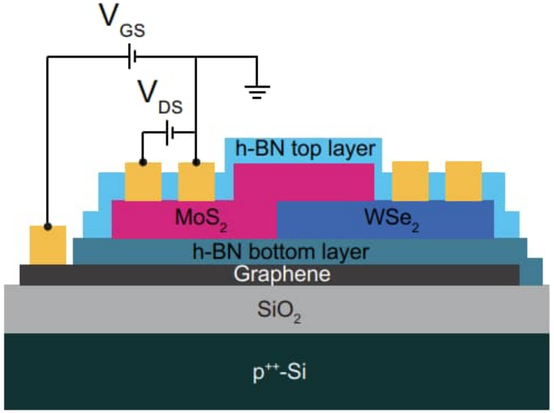


# Towards composite quantum matter

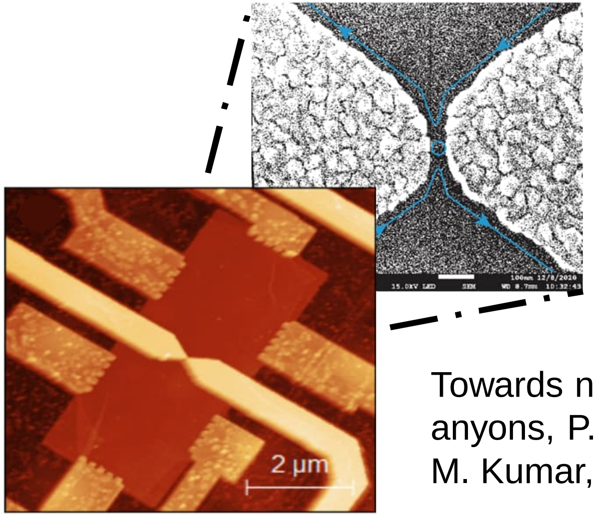


Fast graphene bolometer
30 GHz photon detector

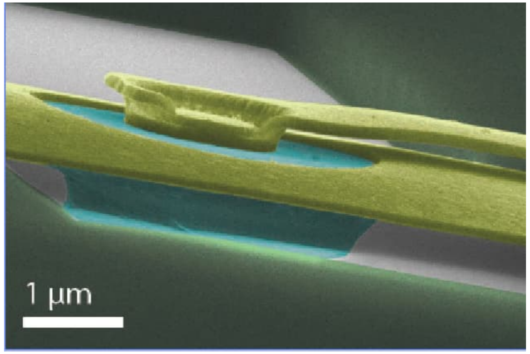
R. Kokkoniemi, …, PH,… , Nature **586**, 47 (2020).

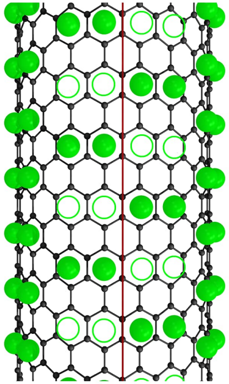


H. H. Yoon, …, PH, … , Science **378**, 296 (2022).



Towards non-Abelian anyons, P. Pandey, M. Kumar, PH





M. Kamada, …, PH, Nano Lett. **21**, 7637 (2021)

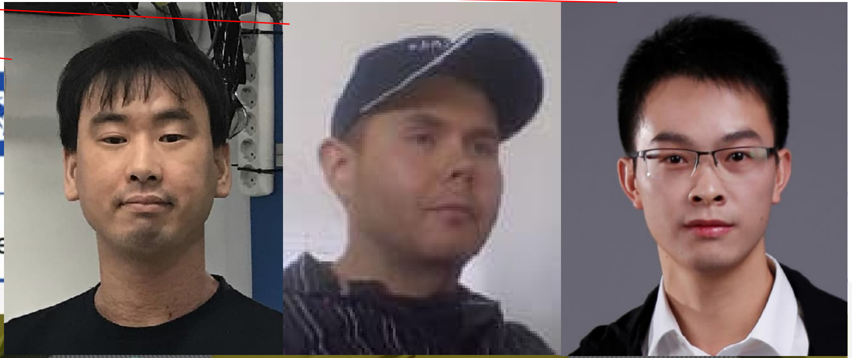
I. Todoshchenko, …. PH, Nature Comm. **13**, 5873 (2022)

pubs.acs.org/NanoLett

Letter

# Electrical Low-Frequency $1/f^{\gamma}$ Noise Due to Surface Diffusion of Scatterers on an Ultra-low-Noise Graphene Platform

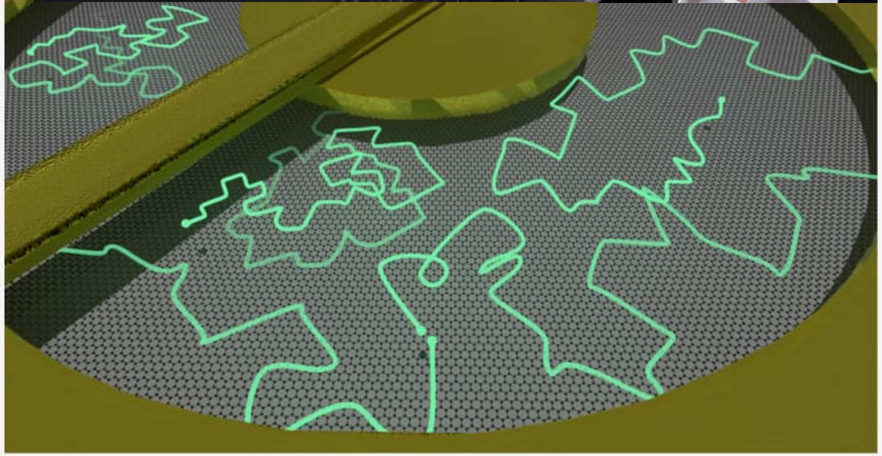
Masahiro Kamada, Antti Laitinen, Weijun Zeng, Marco Will, Jayanta Sarkar, Kirsi Tappura, Heikki Seppä, and Pertti Hakonen*



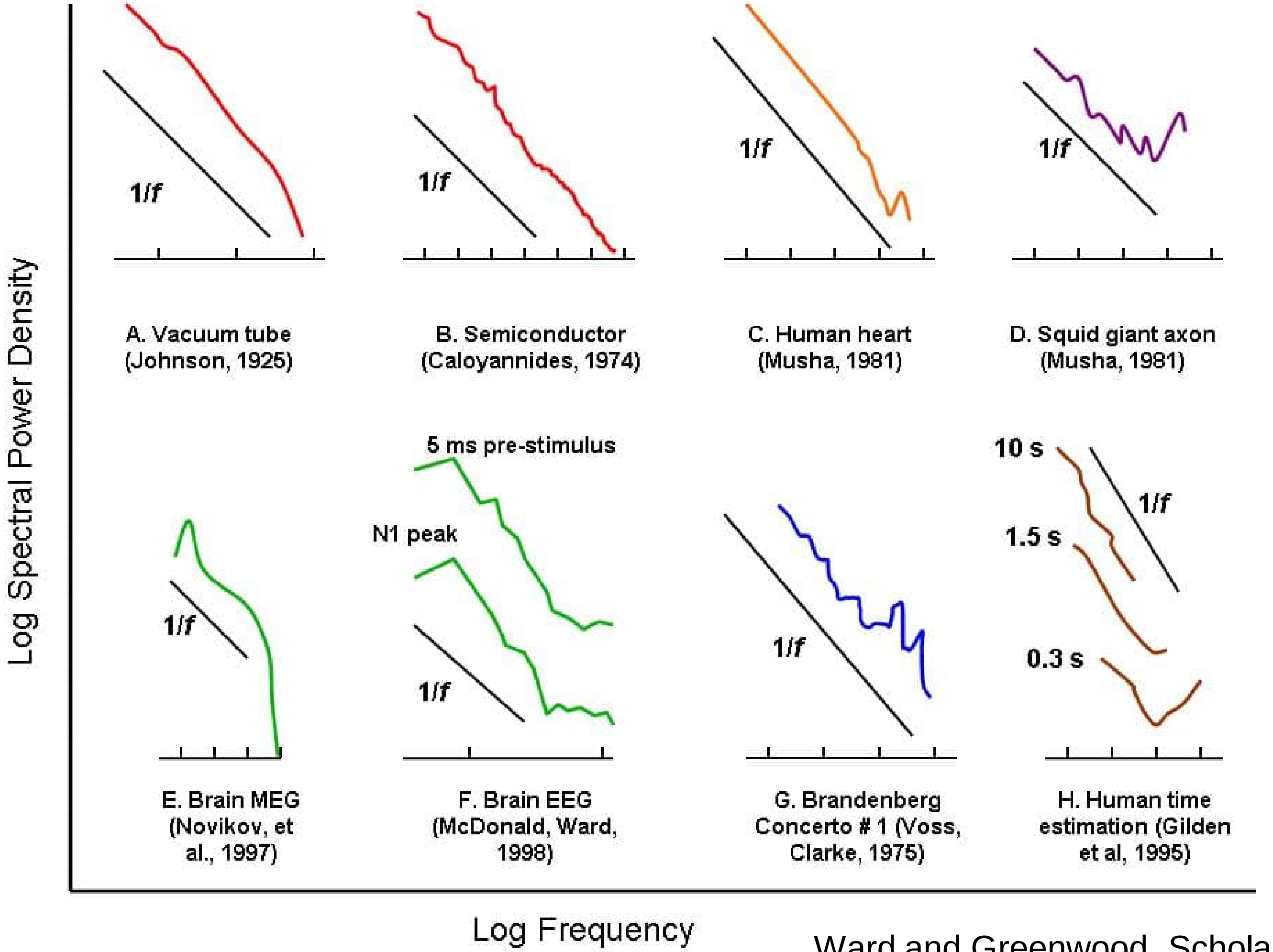
**Cite This:** *Nano Lett.* 2021, 21, 7637−7643

ACCESS | Metrics & More | Article Re

**ABSTRACT:** Low-frequency $1/f^{\gamma}$ noise is ubiquitous, even in high-end electronic devices. Recently, it was found that adsorbed $O_2$ molecules provide the dominant contribution to flux noise in superconducting quantum interference devices. To clarify the basic principles of such adsorbate noise, we have investigated low-frequency noise, while the mobility of surface adsorbates is varied by temperature. We measured low-frequency current noise in suspended monolayer graphene Corbino samples under the influence of adsorbed Ne atoms. Owing to the extremely small intrinsic noise of suspended graphene, we could resolve a combination of $1/f^{\gamma}$ and Lorentzian noise induced by the presence of Ne. We find that the $1/f^{\gamma}$ noise is caused by surface diffusion of Ne atoms and by temporary formation of few-Ne-atom clusters. Our results support the idea that clustering dynamics of defects is relevant for understanding of $1/f$ noise in metallic systems.



# Ubiquitous 1/f noise fluctuations in nature



A. Vacuum tube (Johnson, 1925)

B. Semiconductor (Caloyannides, 1974)

C. Human heart (Musha, 1981)

D. Squid giant axon (Musha, 1981)

E. Brain MEG (Novikov, et al., 1997)

F. Brain EEG (McDonald, Ward, 1998)

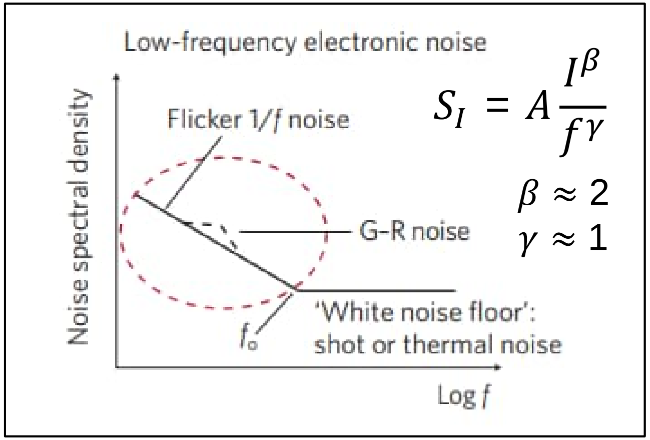
G. Brandenberg Concerto # 1 (Voss, Clarke, 1975)

H. Human time estimation (Gilden et al, 1995)

**Heart Rate Variability analysis**

Ward and Greenwood, Scholarpedia, 2007.

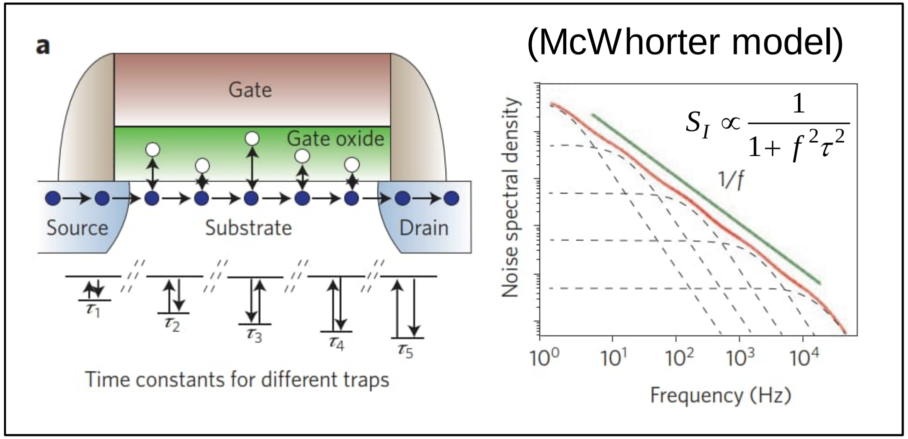
# Introduction to 1/f noise



$$S_I = A\frac{I^{\beta}}{f^{\gamma}}$$

$$\beta \approx 2$$

$$\gamma \approx 1$$



- ➢ Different time constant $\tau$ results 1/*f* behaviour

$$I = en\mu,$$

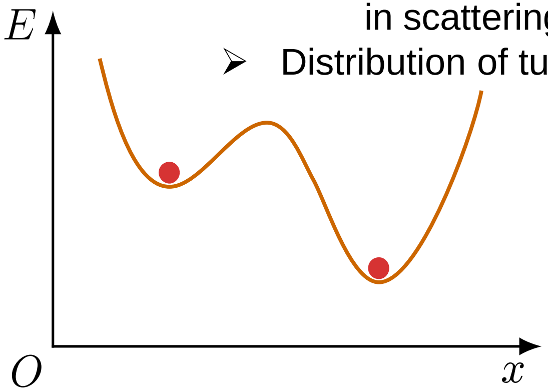
$$\delta I = e(\delta n)\mu + en(\delta\mu)$$

- ➢ Carrier number fluctuations $\delta n$
- ➢ Mobility fluctuations $\delta\mu$

**Suspended graphene has very small 1/f noise**

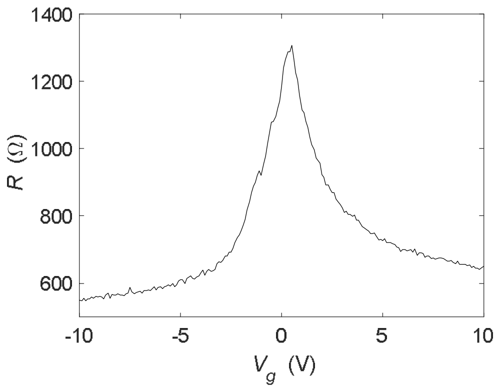
Kumar, Laitinen, and Hakonen
Appl. Phys. Lett. **106**, 263505 (2015)

- ➢ Tunneling two level systems: change in scattering potential
- ➢ Distribution of tunneling rates



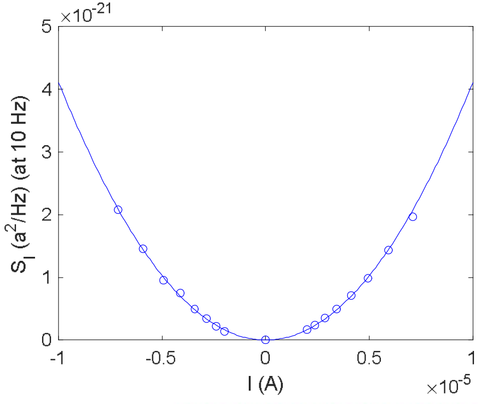
P. Dutta, and P. M. Horn, Rev. Mod. Phys. **53**, 497 (1981)

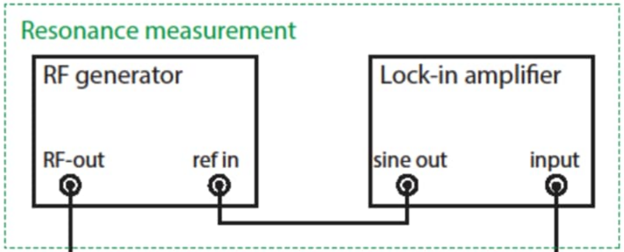
# Sample and schematic of measurement setup

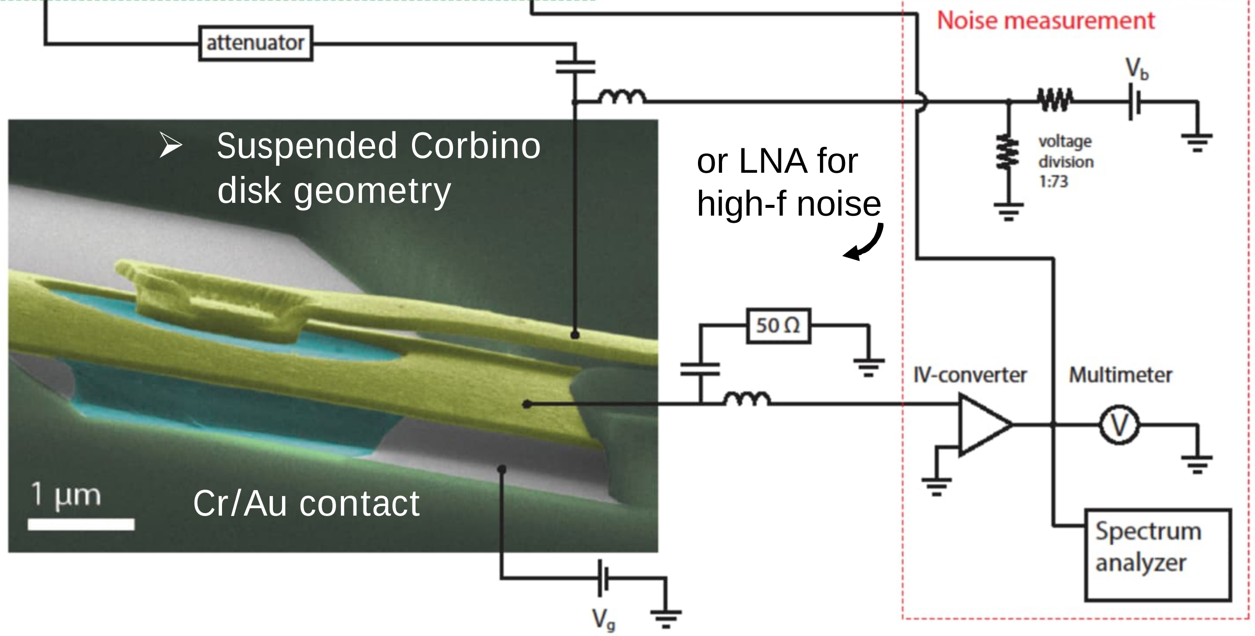


$$\mu \approx 10^5\,\mathrm{cm}^2/\mathrm{Vs}$$

- Mobility increased by neon: Strain induced
- Resonance frequency is increased by 2‰ in the presence of adsorbed neon

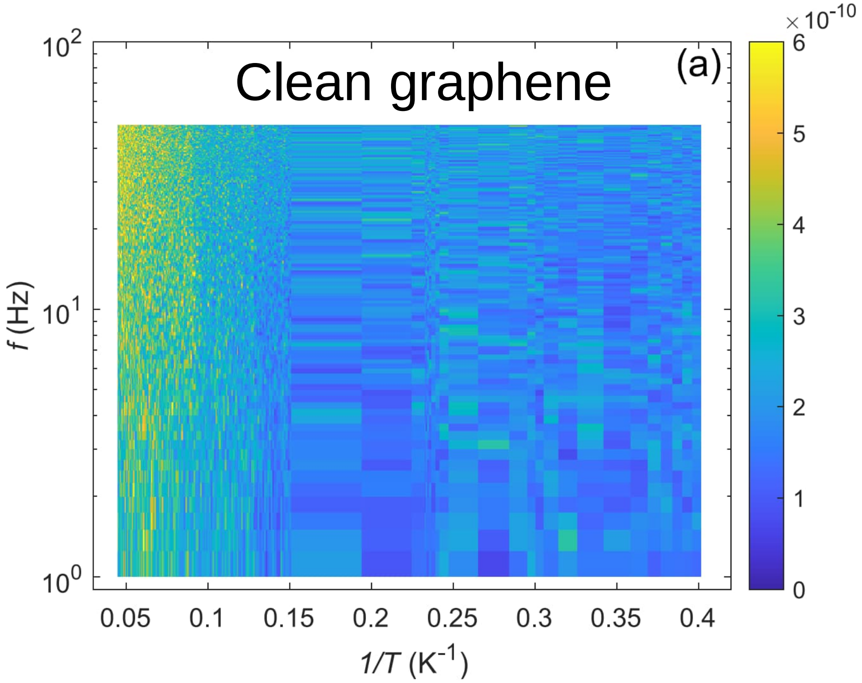


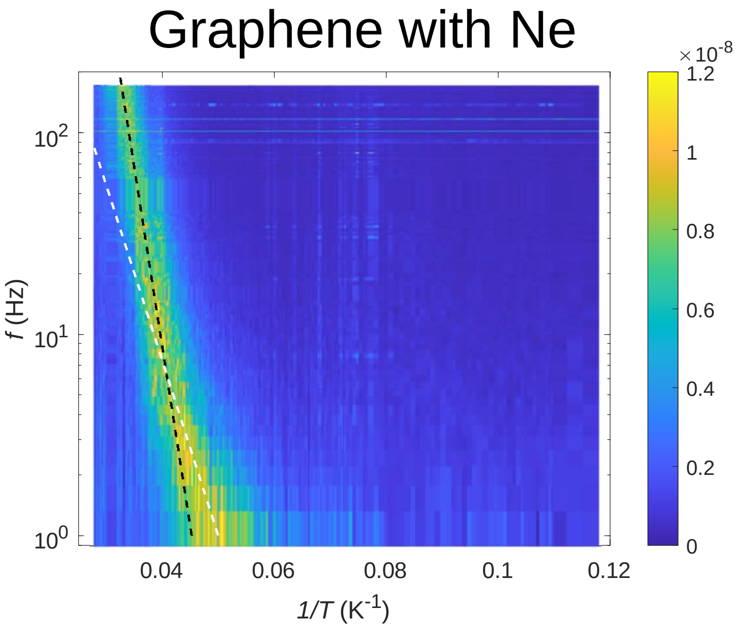




- Suspended Corbino disk geometry

# 1/f noise in graphene

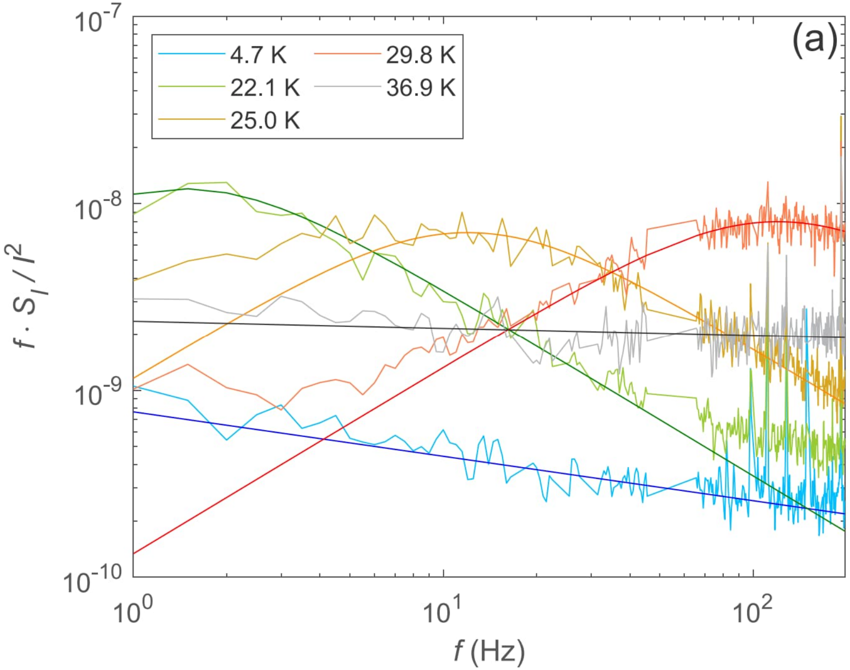




$$f\,S_I \propto \text{const.}$$

$$f\,S_I \propto \frac{f f_c}{f^2 + f_c^2}$$

# Adsorption/desorption processes

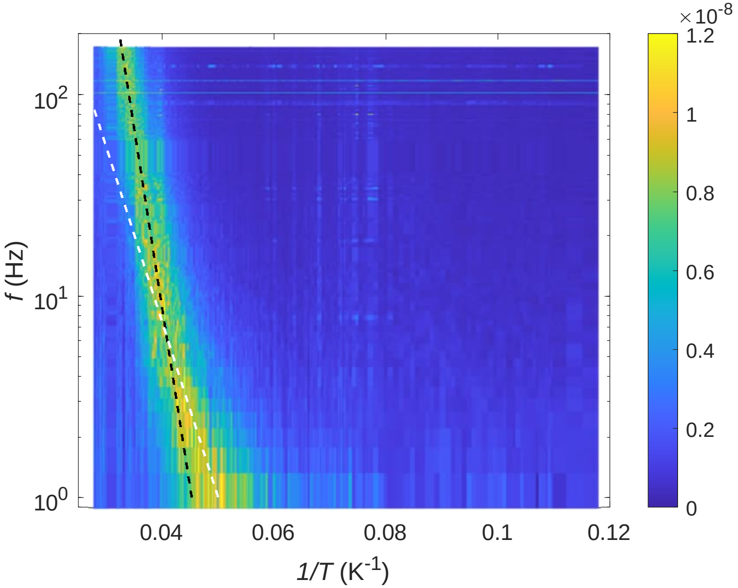


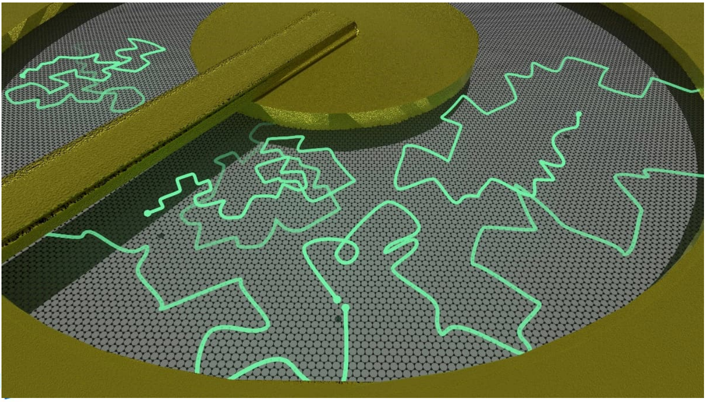
- Model: $$S_I = gN \frac{f_c}{f^2 + f_c^2}$$

$g$ — proportional to the strength of individual scatterers
$N$ — describes the number of particles involved
$f_c$ — frequency of desorption and adsorption processes

- Fitting: $f_c = 1.5$, 12, and 120 Hz
- $S_I^{max}$ is $T$-independent ⇨ $N \simeq$ const.

# Adsorption/desorption processes





- Model: $$f_c = f_0 \exp(-E_a / k_B T)$$

$f_0$ — attempt frequency

$E_a$ — activation energy

$$E_{a_1}/k_B = 410\text{ K}$$ Adsorption energy of neon onto graphene

$$E_a/k_B = 350\text{ K}$$ Measured adsorption energy on graphite

A. A. Antoniou1976

$$E_{a_2}/k_B = 200\text{ K}$$ Energy of trap states at the boundary

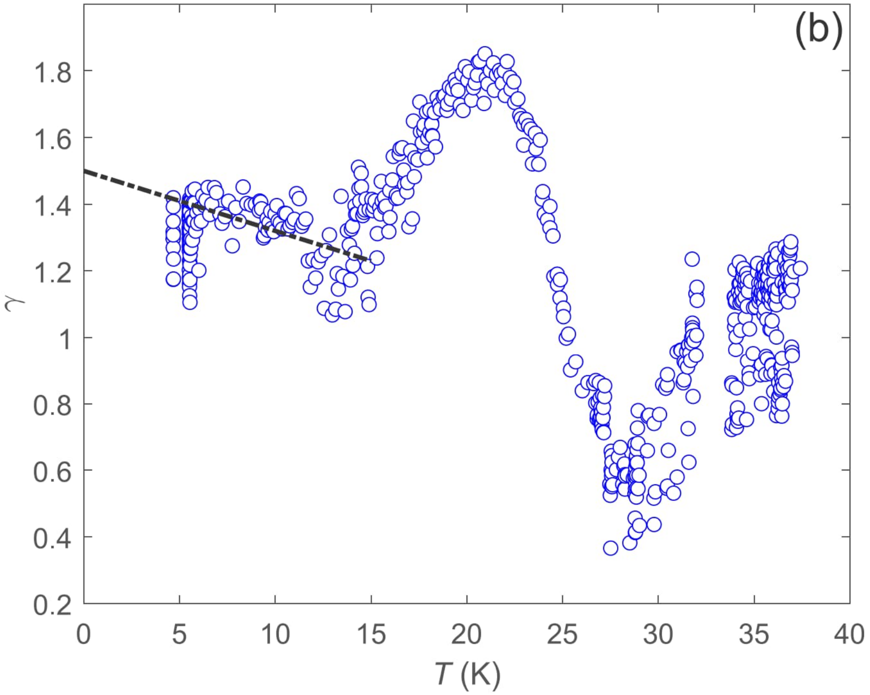
**At low T, detrapping from edge and random walk type of noise:**

$$\tau_d = \frac{L^2}{D} = \frac{L^2}{D_0}\exp\left(+\frac{E_d}{k_B T}\right)$$ **Diffusion time**

$$S_I = \frac{A}{f^{1.5}}$$

M. Kamada, …, PH, Nano Lett. **21**, 7637 (2021)

# Change of noise spectrum exponent



- Power law fitting model:

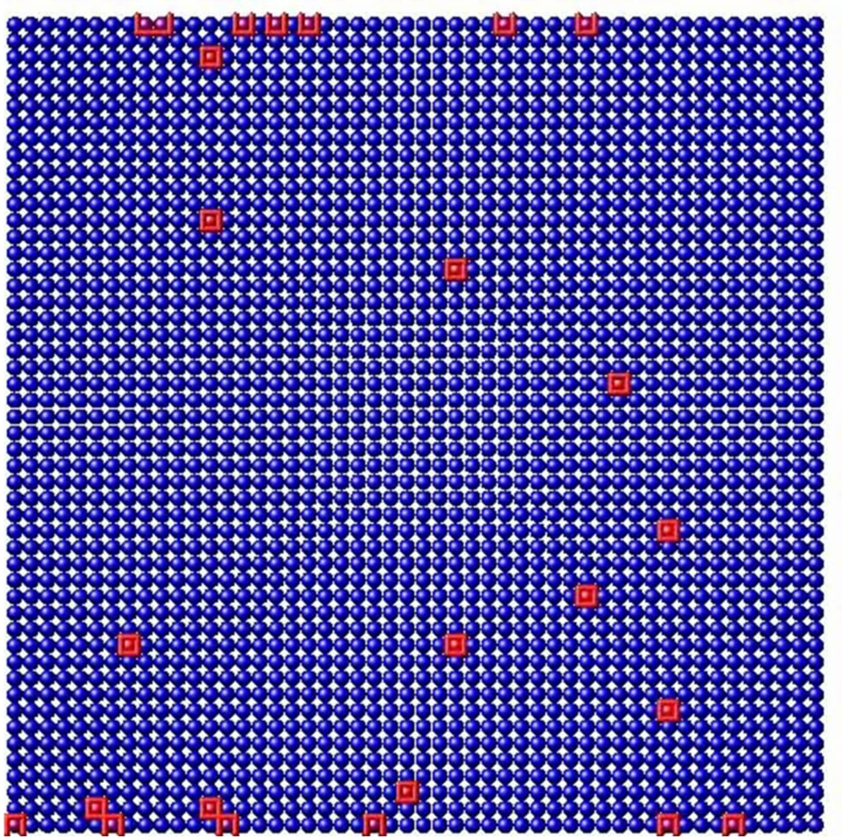
$$S_I \propto 1/f^{\gamma}$$

- 4 → 10 K

$$\gamma = 1.4 \rightarrow 1.2 \neq 1.5$$

- Diffusion model is insufficient
- Additional assumptions e.g., scattering changes via clustering/declustering

# Simulated noise due to clustering/declustering of Ne



$k_BT = 2$

- Hops to eight nearest neighbor sites possible

$$r = f_0 \exp\left(\frac{-E_d}{k_BT}\right), \text{ if } \Delta E \le 0,$$

$$r = f_0 \exp\left(-\frac{E_d + \Delta E}{k_BT}\right), \text{ if } \Delta E > 0,$$

$\Delta E = -2$, coordination increases by 1

$\Delta E = +2$, coordination decreases by 1

$f_0 = 1$

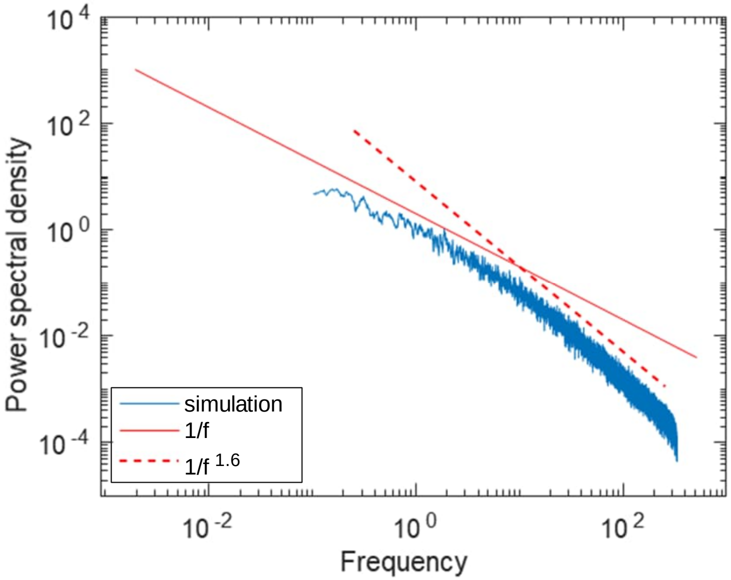
$E_d = 4$

- Adsorbant increases local resistance by $10^5$

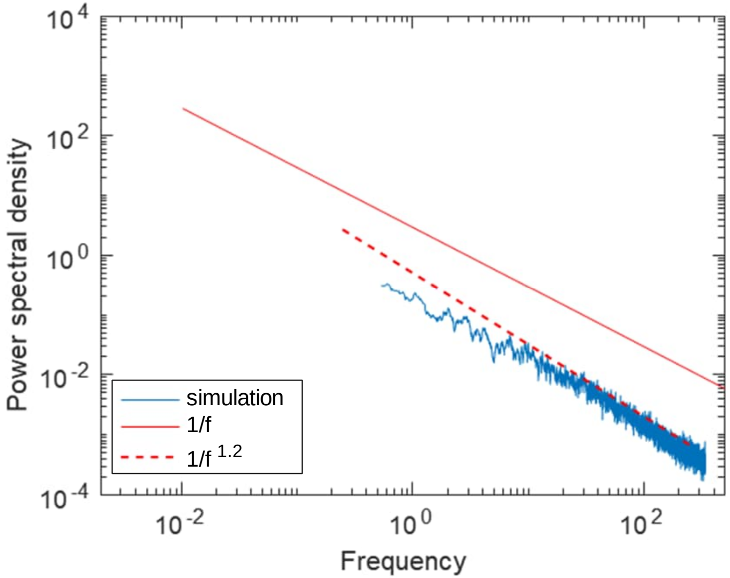
Kinetic Monte Carlo (kMC) simulation method
[Plimpton S. J., et al, SAND2009-6626 (2009)]

# Simulated noise due to clustering/declustering of Ne

- Resistance *R*(*t*) calculated from impurity distributions using FEM methods



$k_BT = 1.2$



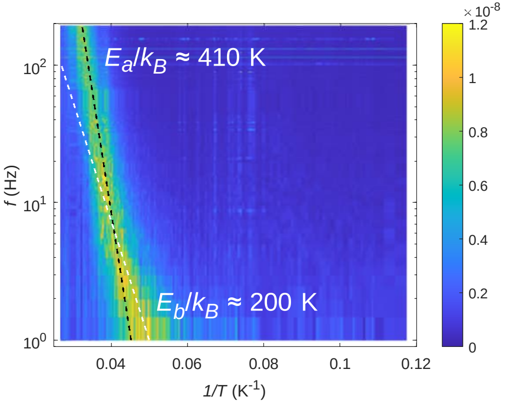
$k_BT = 2$

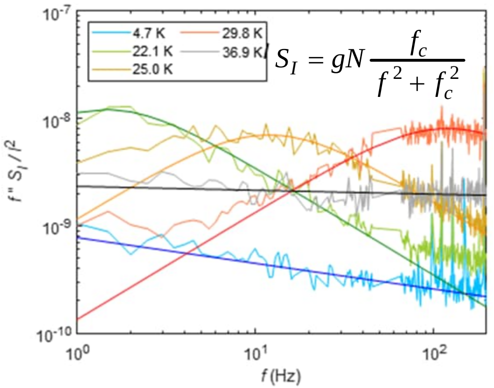
- Agree with experimental data $\gamma = 1.4 \rightarrow 1.2$ when $T = 4 \rightarrow 10$ K

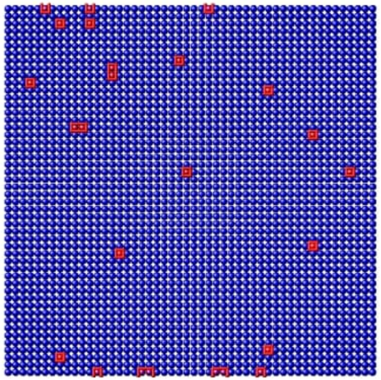
# Summary on 1/f noise induced by Ne diffusion

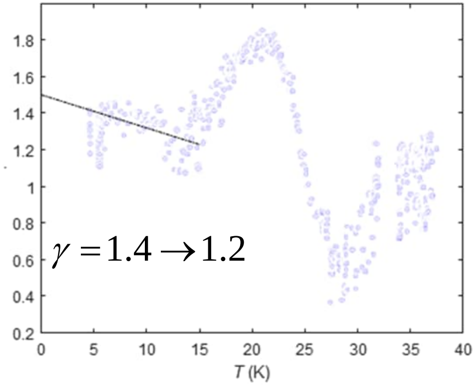
- **Neon enhances** 1/*f* **noise**
- **Ne induces strain in graphene**
- Adsorption/desorption
  → noise at higher *T*
- Diffusion & **clustering/declustering**
  → noise at lower *T*

- **Supports diffusing defects based theories** for explaining the origin of $1/f^{\gamma}$ noise in graphene/metals









# Topologically-imposed vacancies and mobile solid $^3$He on carbon nanotube

## Pertti Hakonen

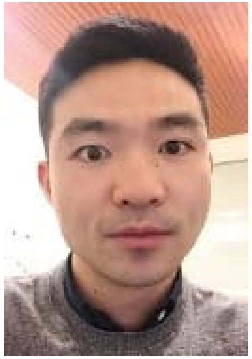
Aalto University


Igor Todoshchenko


J.-P. Kaikkonen


Marco Will


Elena Sergeicheva

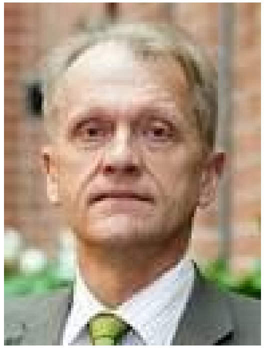

Yongping Liao

ACADEMY OF FINLAND


T. S. Abhilash


Masahiro Kamada

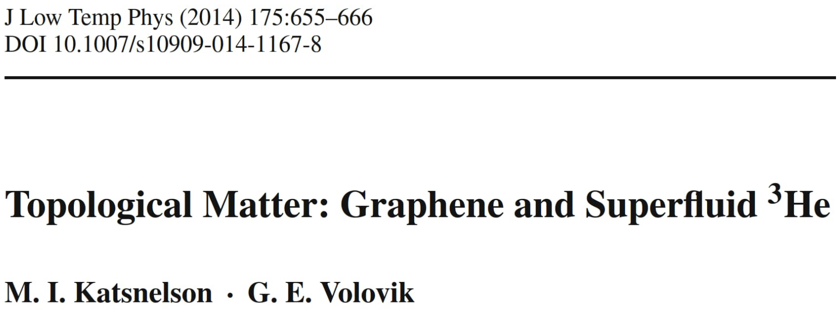

Alexander Savin


Esko Kauppinen

QuDeT

erc

# Excitonic condensates & exotic supercurrents?

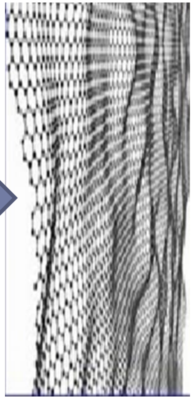


J Low Temp Phys (2014) 175:655–666
DOI 10.1007/s10909-014-1167-8

**Topological Matter: Graphene and Superfluid $^3$He**

**M. I. Katsnelson · G. E. Volovik**

$$\langle \Psi_1 \Psi_1 \rangle = A_1 e^{i\Phi_1}$$



$$\langle \Psi_2 \Psi_2 \rangle = A_2 e^{i\Phi_2}$$

Coherence across impenetrable graphene?

- Excitonic coupling
- Spin supercurrents

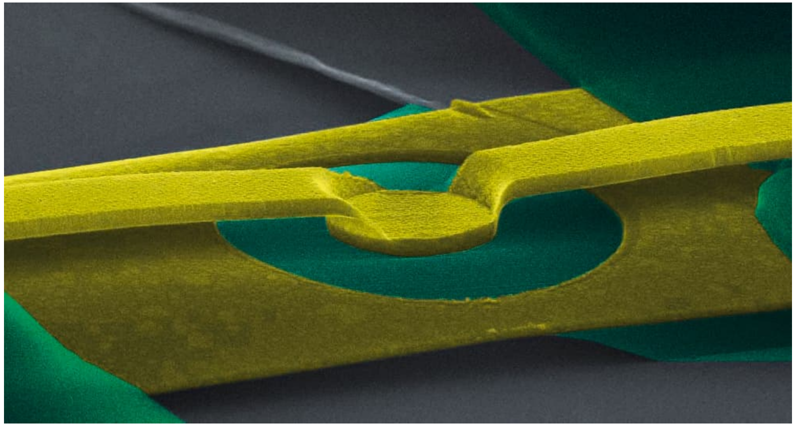
Cooper channel

$$\langle \Psi_1 \Psi_2 \rangle = B e^{i\phi}$$

Exciton channel

$$\langle \Psi_1 \Psi_2^\dagger \rangle = C e^{i\varphi}$$

**Coupling across graphene membrane**

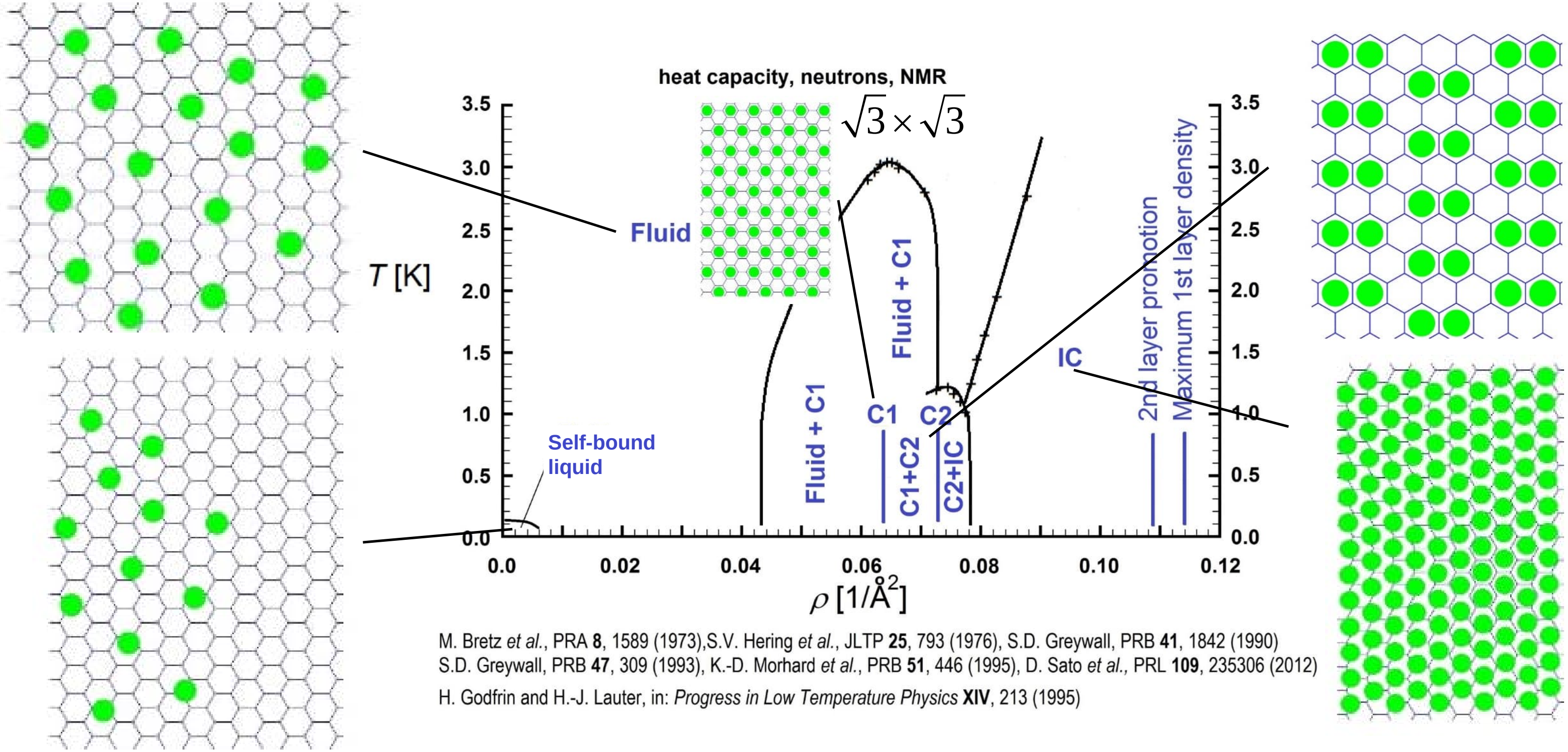


- Excitonic condensate in $^3$He/graphene/$^3$He?
- Double HPD/supercurrent through graphene

erc QuDeT

Quantum Devices in Topological matter: carbon nanotubes, graphene, and novel superfluids

# $^3$He on grafoil



M. Bretz *et al.*, PRA **8**, 1589 (1973),S.V. Hering *et al.*, JLTP **25**, 793 (1976), S.D. Greywall, PRB **41**, 1842 (1990)
S.D. Greywall, PRB **47**, 309 (1993), K.-D. Morhard *et al.*, PRB **51**, 446 (1995), D. Sato *et al.*, PRL **109**, 235306 (2012)

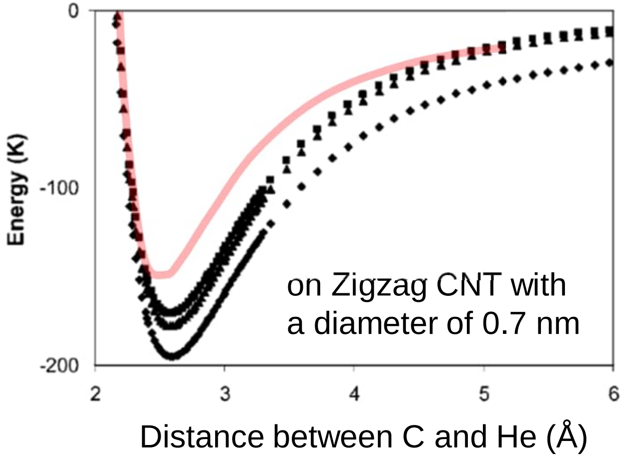
H. Godfrin and H.-J. Lauter, in: *Progress in Low Temperature Physics* **XIV**, 213 (1995)

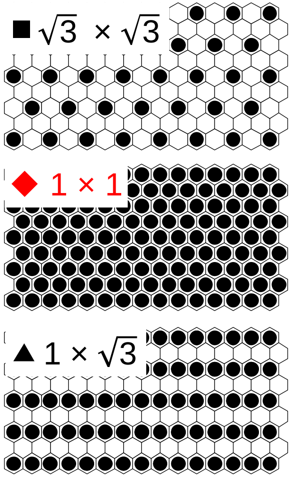
***What happens with chiral substrate – carbon nanotube***

# Curvature supported structures: dimerization?

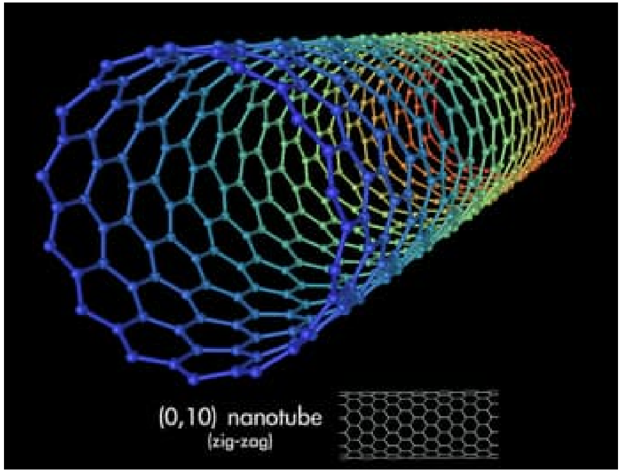
## New phases energetically favored on CNT

Lueking and Cole, PRB **75**, 195425 (2007)





Zig-zag nanotube



- $^4$He 1 × 1 phases on Fullerene ($C_{60}$ and $C_{70}$) are experimentally observed

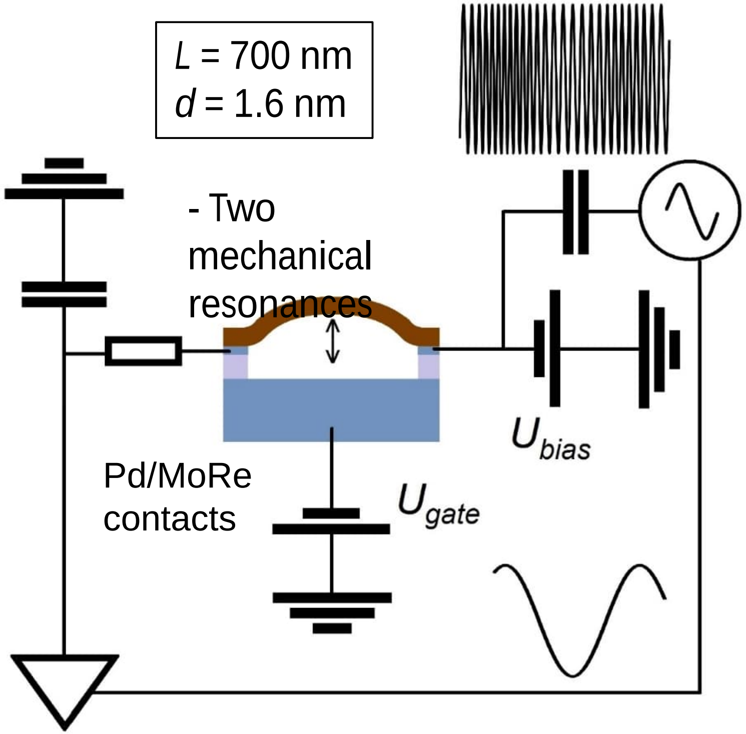
Leidlmair et al., PRL **108**, 076101 (2012)

Armchair carbon nanotubes: rings
M. C. Gordillo and J. Boronat, Phys. Rev. B 86, 165409 (2012)

**Chirality of CNT and frustration of superlattice:**
**⇨ Plenty of ordering possibilities**

# Experimental scheme

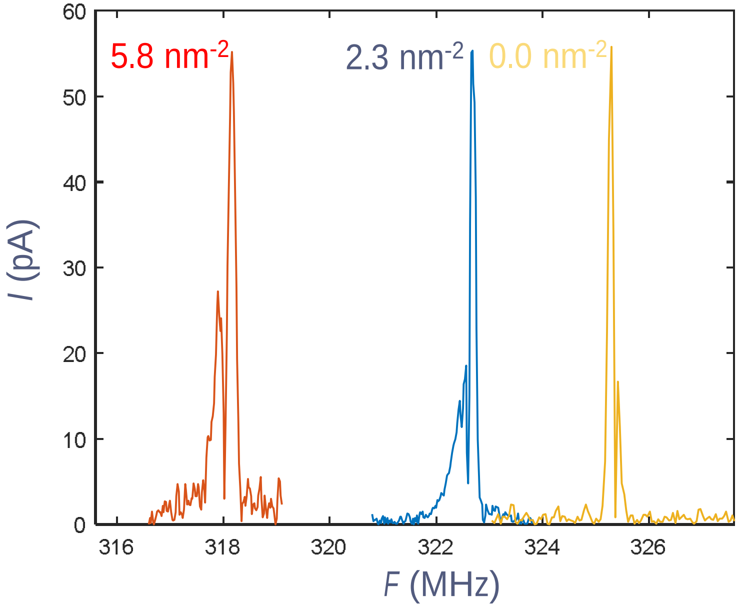
$L$ = 700 nm
$d$ = 1.6 nm



- Two mechanical resonances

$$F_0 \sim \sqrt{k/M}$$

$$< \Delta I > \propto \frac{d}{dF}\frac{1}{(F_0{}^2 - F^2) + iF\Gamma}$$



$$\frac{\delta F}{F_0} = -\frac{1}{2}\frac{\Delta M}{M_0} = -\frac{1}{8}\frac{\rho_{He}}{\rho_C}$$

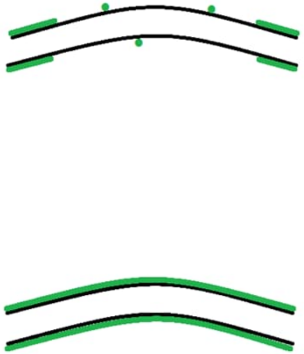
$$\rho_C = 0.382\ \text{Å}^{-2}$$

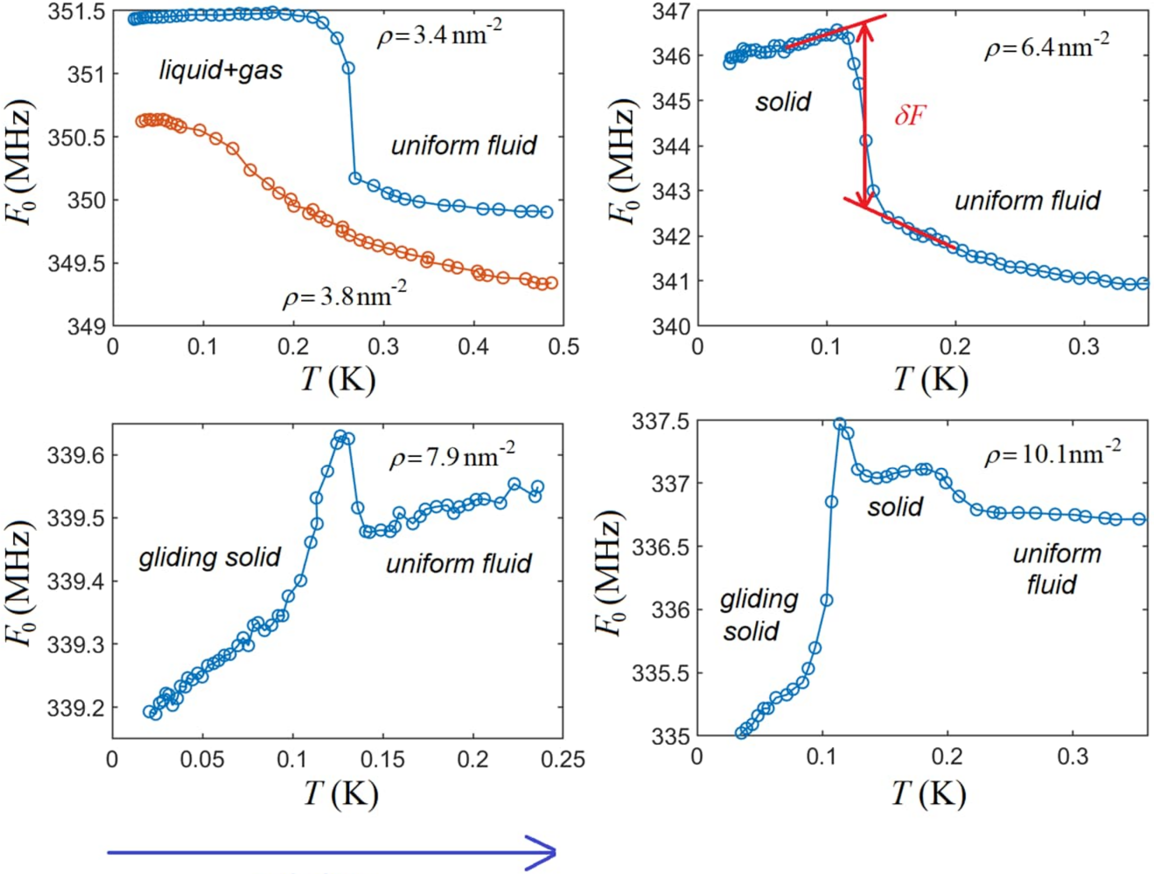
$$\rho_{He} = -8 \times \frac{\delta F}{F_0} \times 0.382\ \text{Å}^{-2}$$

# Frequency vs. temperature: Transitions

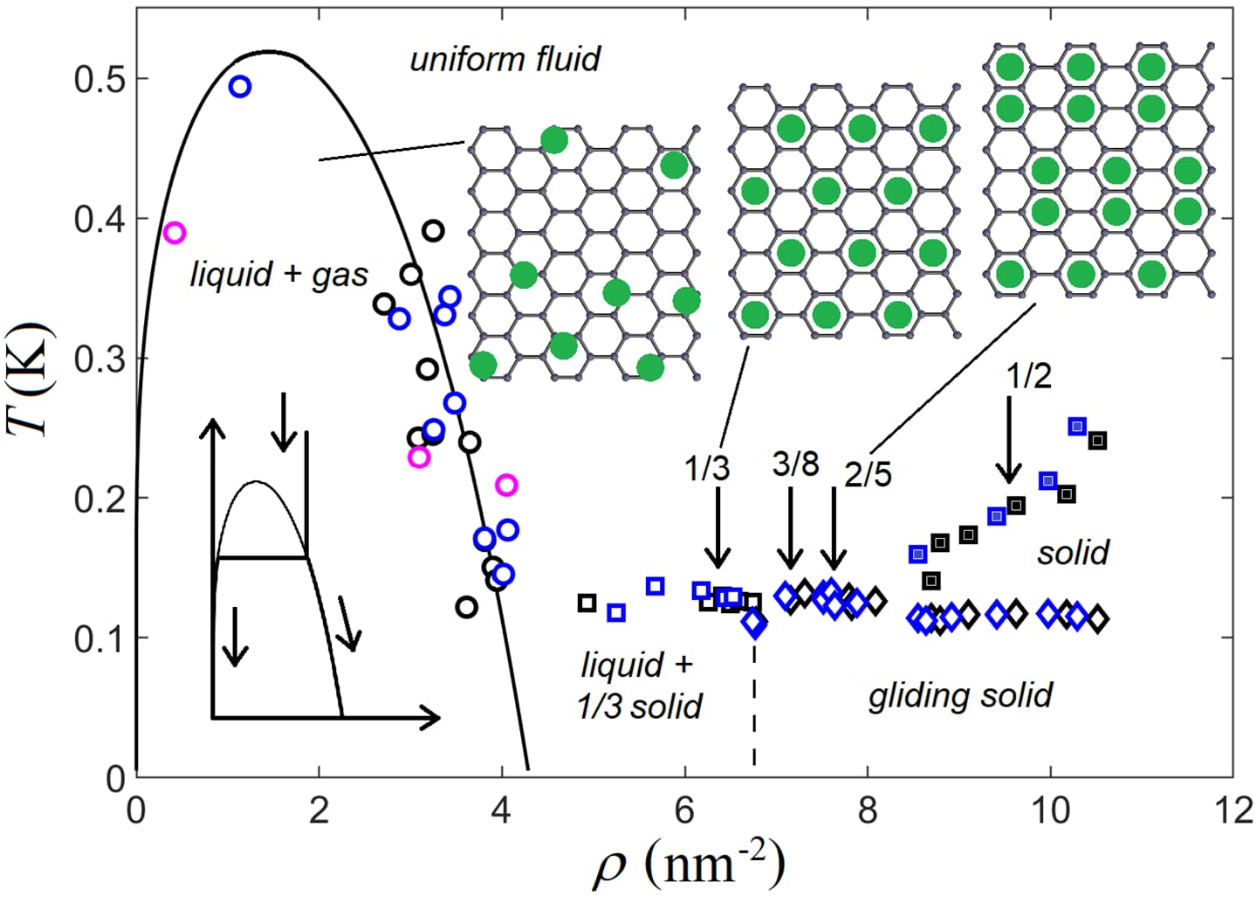
$$F_0 : \sqrt{\frac{k}{m}}$$

$$\frac{\Delta F_0}{F_0} = \frac{1}{2}\frac{\Delta k}{k} - \frac{1}{2}\frac{\Delta m}{m}$$

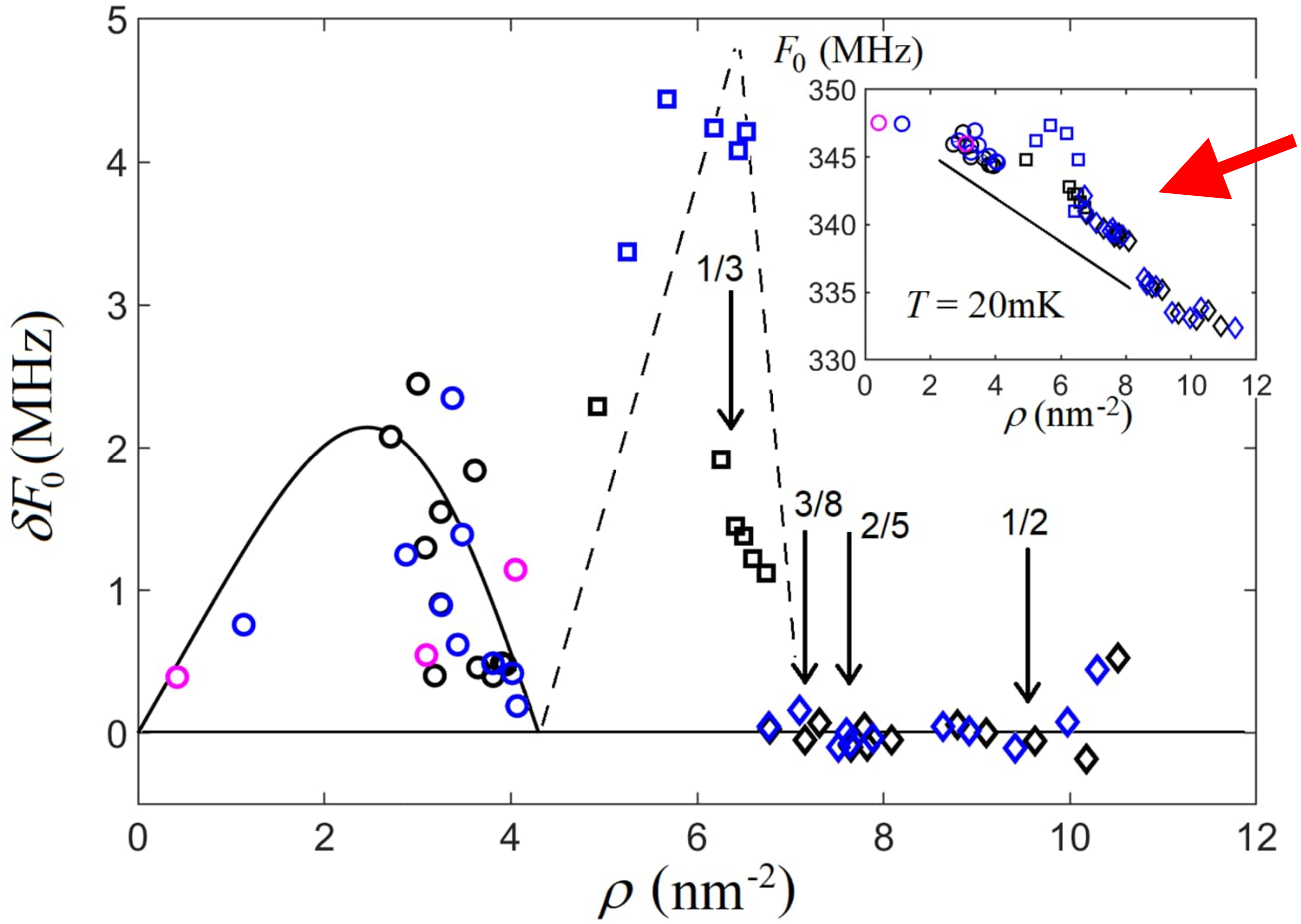




# Phase diagram



# Frequency jump at transition



Quantum phase transition

# Elementary excitations

- Frequency dominated by tension

$$F_0 = \frac{1}{2L}\sqrt{\frac{F}{\mu}}$$

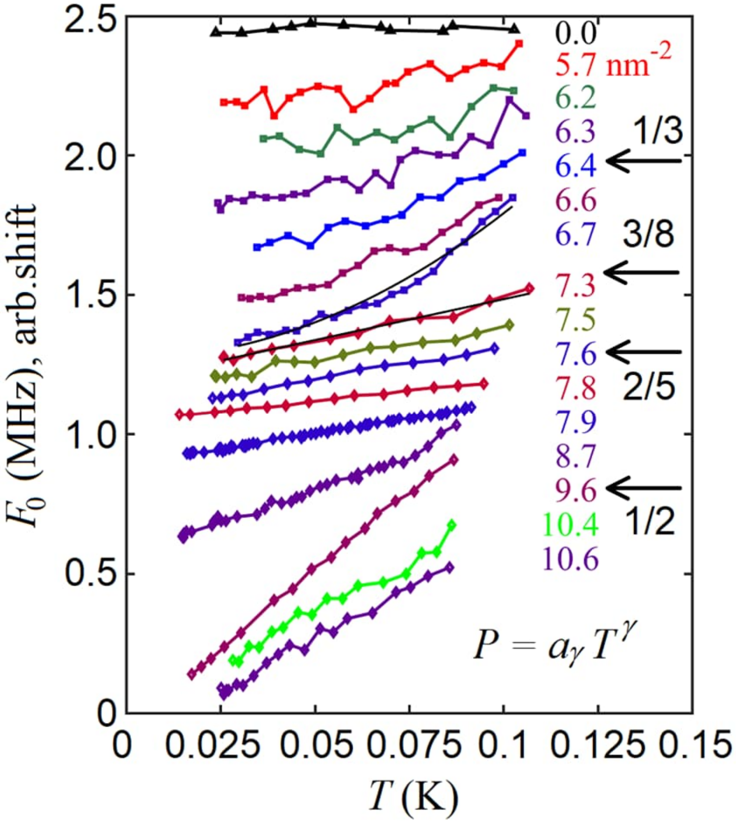
$$F = F_0 + P$$

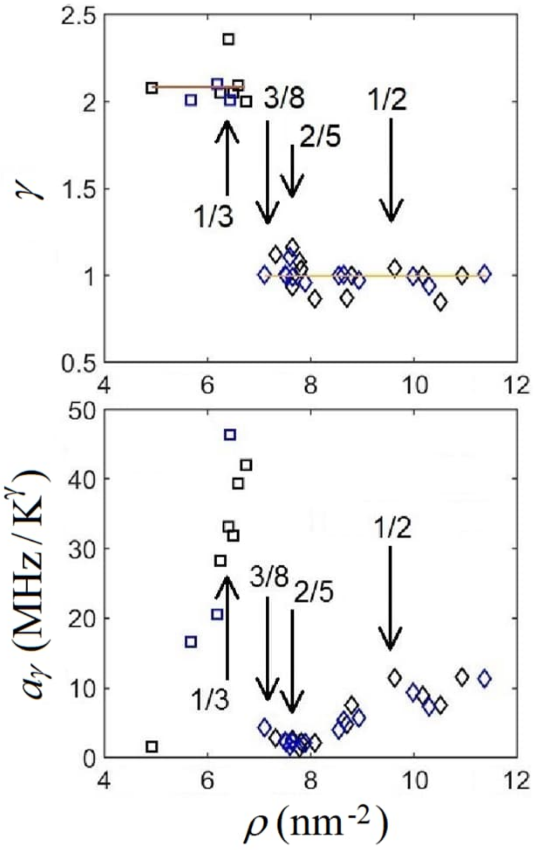
1D phonons

$$P \propto T^2$$

Ideal gas

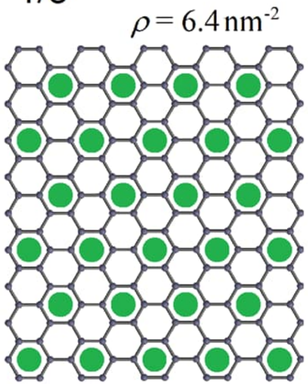
$$P \propto T$$



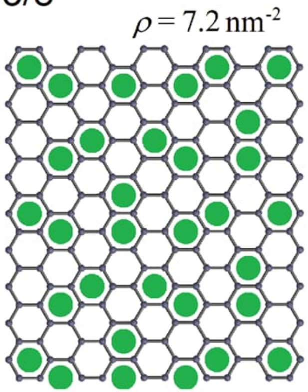


# Solid helium on top of nanotube carbon lattice

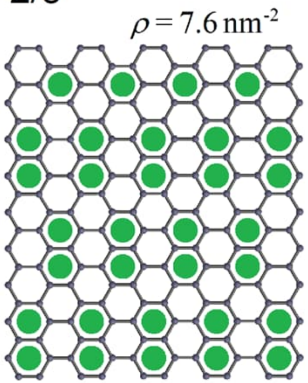
1/3



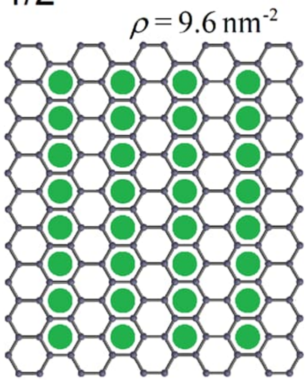
3/8



2/5



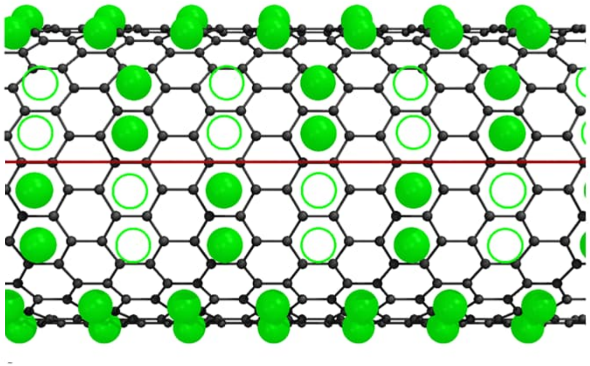
1/2



In 7/8 of CNTs carbon and helium lattices mismatch

*Topologically protected vacancies*

MISMATCH



Zero point vacancies like ideal gas – pressure linear in T

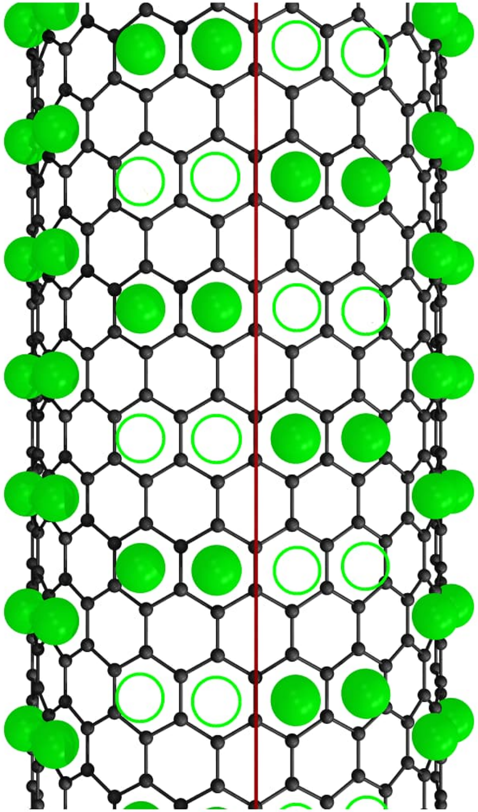
=> *F* (*T*) $\propto$ *T*

$$T^* ; \frac{4\pi^2 h^2 N_{vac}}{ML} \qquad T^* ; \; 5\text{ mK}$$

Possibility? Rings of helium atoms – mass density wave

# Conclusions on frustrated $^3$He on CNT

- Extraordinary, soft, *mobile solid state* has been observed
- The mobile solid phase has been identified as a bosonic dimer solid with *delocalized zero-point vacancies due to topological frustration*
- The topological vacancies *may enable Bose-Einstein condensation*, i.e. supersolidity, below 5 mK
- Quantum Monte Carlo simulations on the *stability of $^3$He dimer* on curved graphene surface are needed.



I. Todoshchenko, …. PH, Nature Comm. 13, 5873 (2022)

Happy Birthday Matti