Micro-machined Probes for the Study of Quantum Fluids

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Acknowledgments

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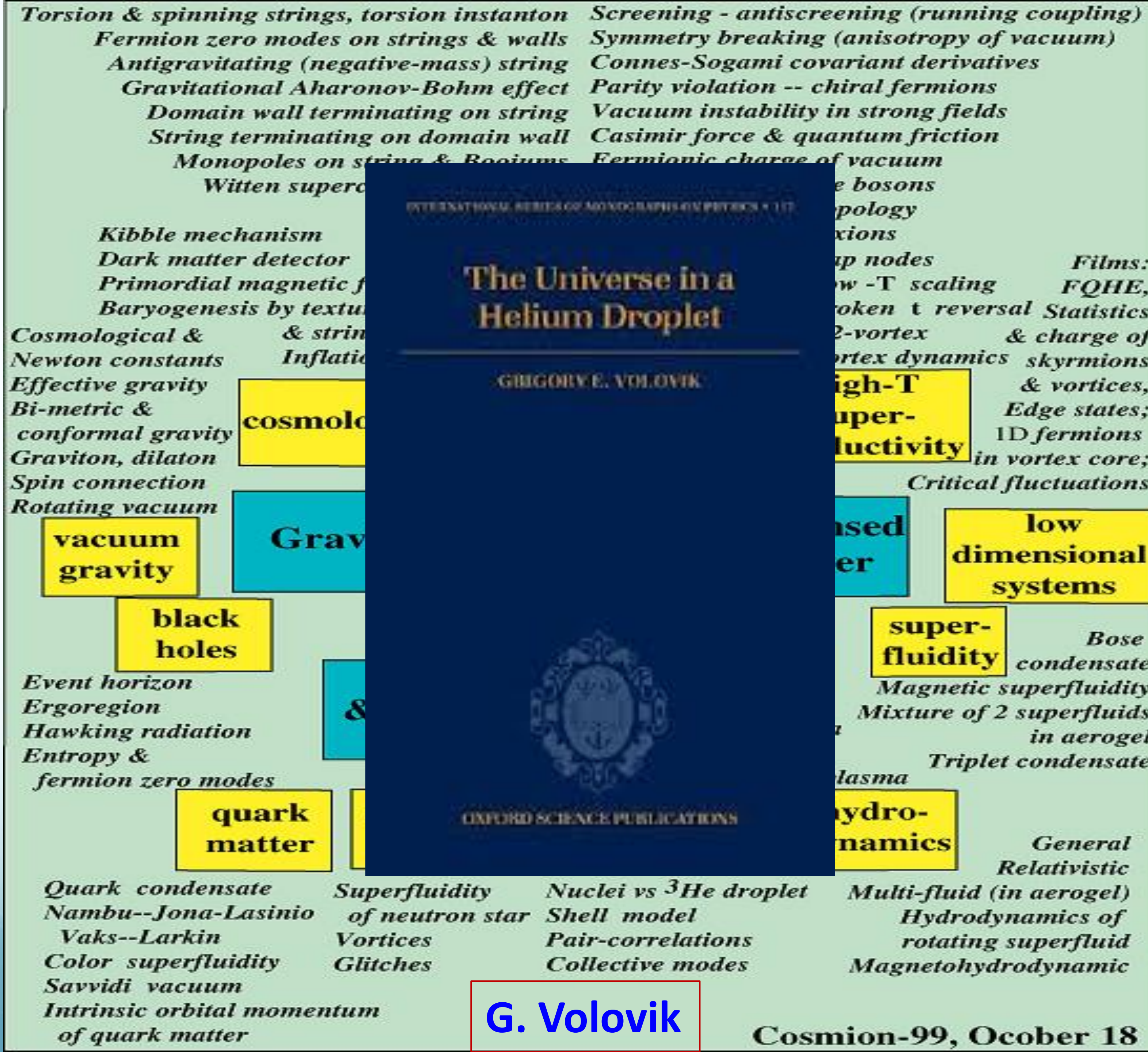
Quantum Fluids

	Species	n (cm^{-3})	T_C (T_o)
^3He	F	1.6×10^{22}	2 mK (3 K)
^4He	B	2.2×10^{22}	2.2 K (3 K)
e^- (Nb)	F	5.5×10^{22}	9 K (10^4 K)
n-star	F	4.0×10^{38}	10^{10} K (10^{12} K)

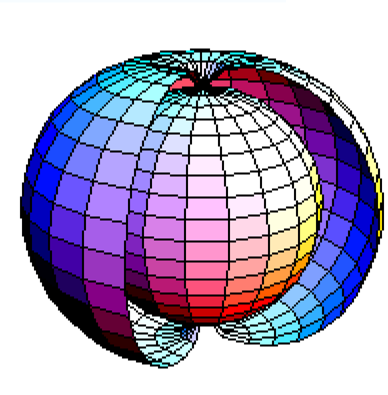
Emerging Complex Phenomena
from Simple Ingredients

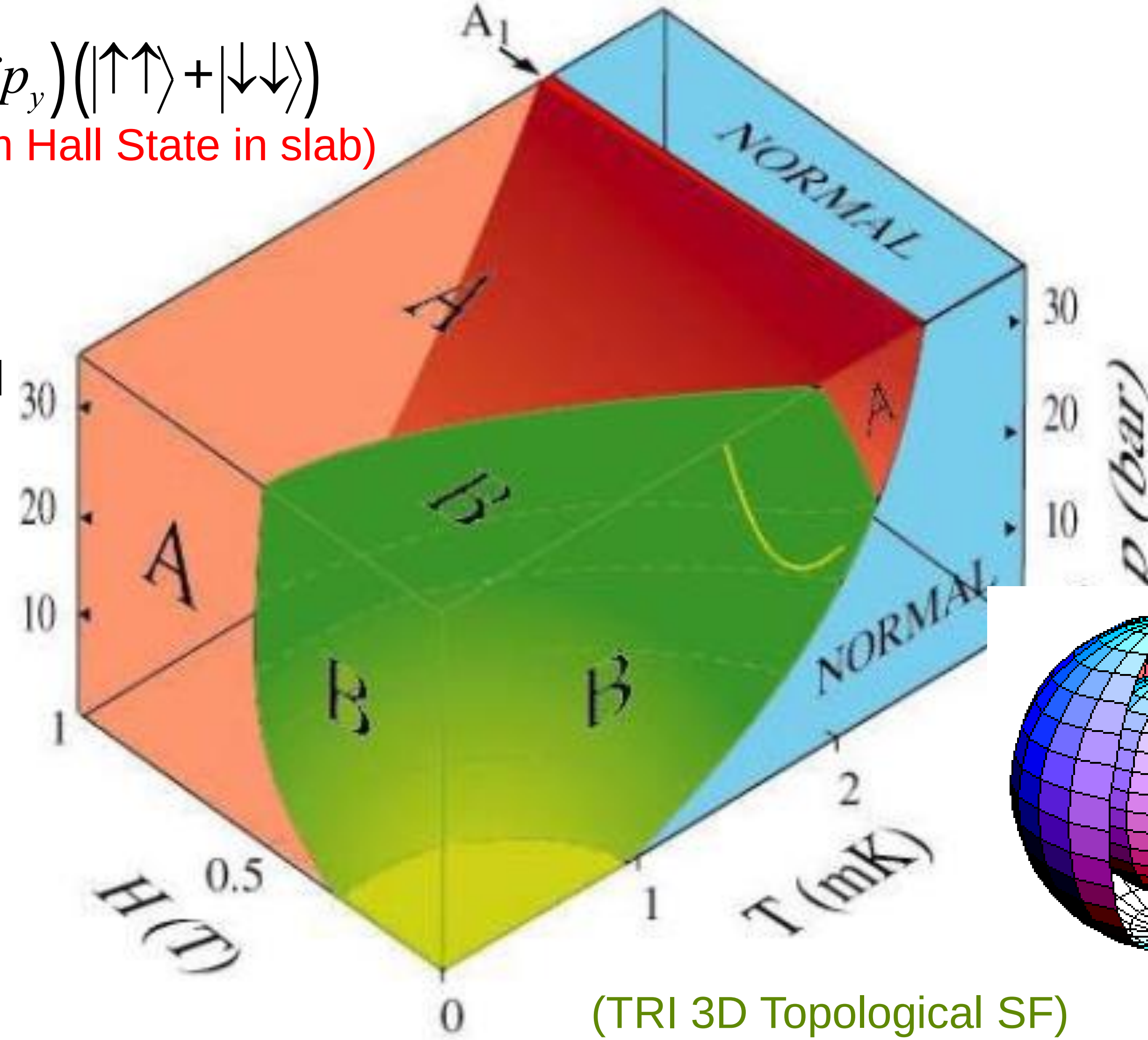

Torsion & spinning strings, torsion instanton
Fermion zero modes on strings & walls
Antigravitating (negative-mass) string
Gravitational Aharonov-Bohm effect
Domain wall terminating on string
String terminating on domain wall
Screening - antiscreening (running coupling)
Symmetry breaking (anisotropy of vacuum)
Connes-Sogami covariant derivatives
Parity violation -- chiral fermions
Vacuum instability in strong fields
Casimir force & quantum friction
Kibble mechanism
Dark matter detector
Cosmological &
Newton constants
Effective gravity
Bi-metric &
conformal gravity
Graviton, dilaton
Spin connection
Rotating vacuum
vacuum gravity
black holes
Event horizon
Ergoregion
Hawking radiation
Entropy &
fermion zero modes
quark matter
Films:
FQHE,
Statistics
& charge of
skyrmions
& vortices,
Edge states;
1D fermions
in vortex core;
Critical fluctuations
low dimensional systems
super-fluidity
Bose condensate
Magnetic superfluidity
Mixture of 2 superfluids in aerogel
Triplet condensate
General Relativistic
Multi-fluid (in aerogel)
Hydrodynamics of rotating superfluid
Magnetohydrodynamic
Quark condensate
Nambu--Jona-Lasinio
Vaks--Larkin
Color superfluidity
Savvidi vacuum
Intrinsic orbital momentum of quark matter
Superfluidity of neutron star
Vortices
Glitches
Nuclei vs 3He droplet
Shell model
Pair-correlations
Collective modes
The Universe in a Helium Droplet
GREGORY E. VOLOVIK
OXFORD SCIENCE PUBLICATIONS
G. Volovik
Cosmion-99, Ocober 18

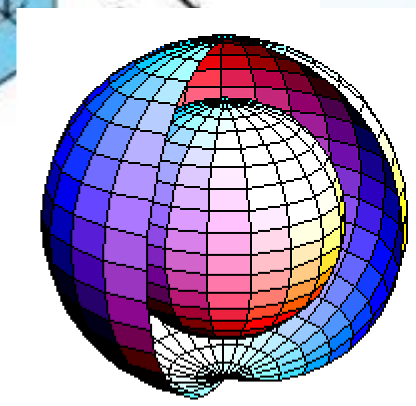
G = $SO_L(3)$ x $SO_S(3)$ x P x T x U(1) x t

$$|Y_A\rangle = D_A(p_x + ip_y)(|\uparrow\uparrow\rangle + |\downarrow\downarrow\rangle)$$

(Chiral SF, Quantum Hall State in slab)







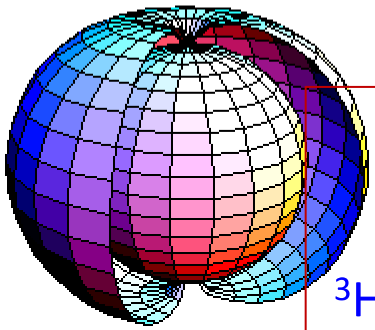
(TRI 3D Topological SF)

$$|Y_B\rangle = D_B\{(p_x + ip_y)|\downarrow\downarrow\rangle + (p_x - ip_y)|\uparrow\uparrow\rangle + p_z(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)\}$$

UVA

From Helsinki Univ. of Technology picture archive

Excitations of Superfluid ^{3}He



Femionic Excitations

^{3}He quasi-particles
^{3}He-A: Weyl chiral fermion out of Dirac cone (two nodes)
^{3}He-B: Massive Dirac fermion (isotropic gap)

Bosonic Excitations

18 Order parameter collective modes
→ Finger Print of Underlying Symmetry
Some are Goldstone modes (zero gap)
Some are massive modes with a finite gap

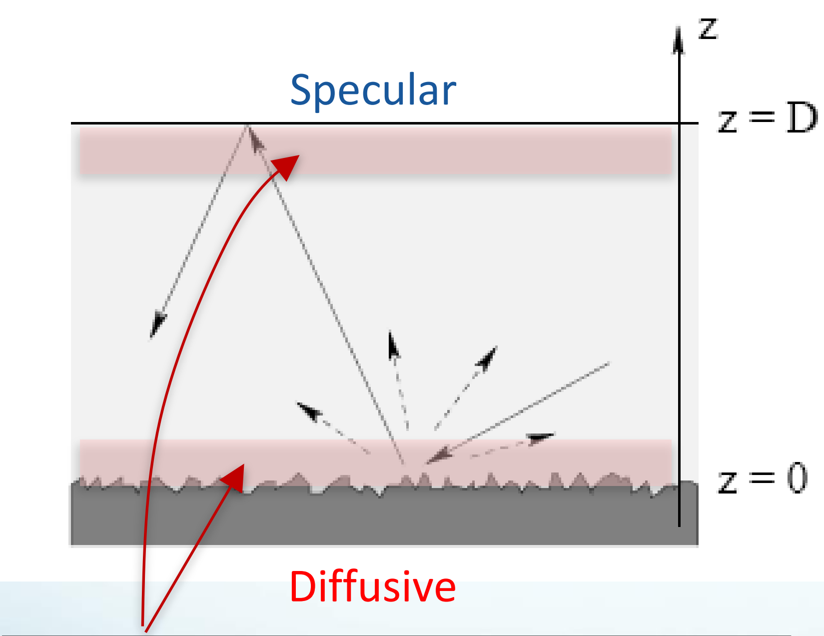
$$E^2 = c^2 q^2 + b^2 (\Delta)$$

Topological Excitations

Vortices (regular, ½, q-vortex, vortex sheet)
Particle-like topological excitations in superfluid films....

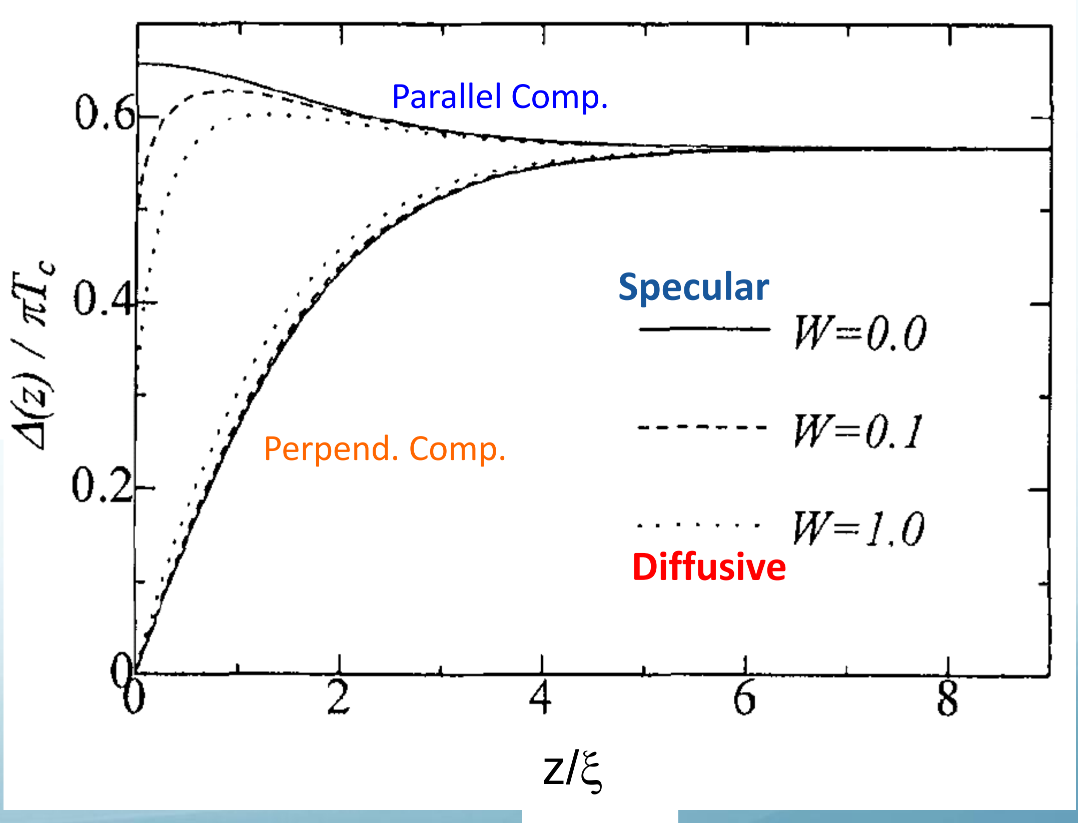
Suppression of Order Parameter near the Boundary

Pair-breaking Scattering



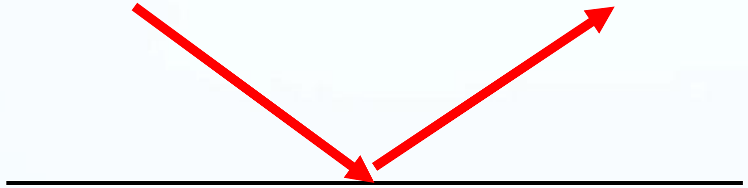
Aoki *et al.*, PRL (2005)

Okuda and Nomura, J. Phys.: Condens. Matter (2012)



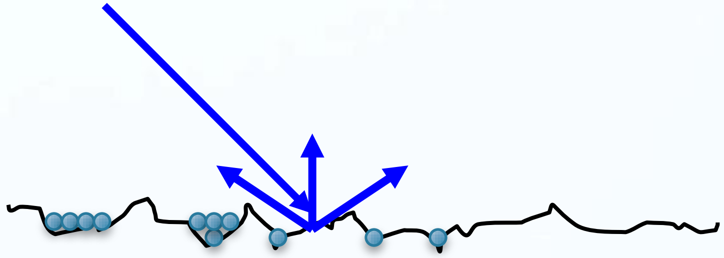
Surface Scattering in ^{3}He-B

Specular limit

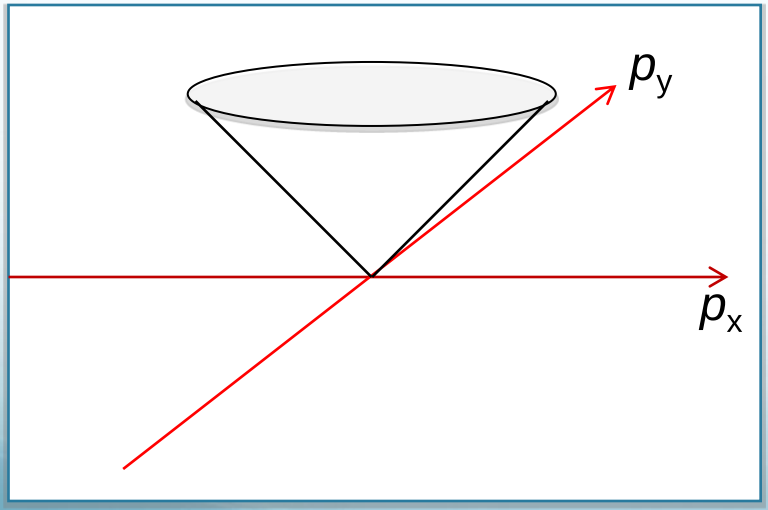


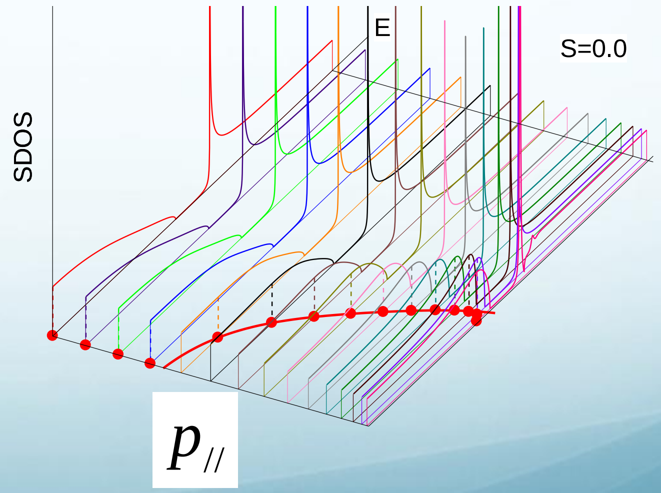
S = 1

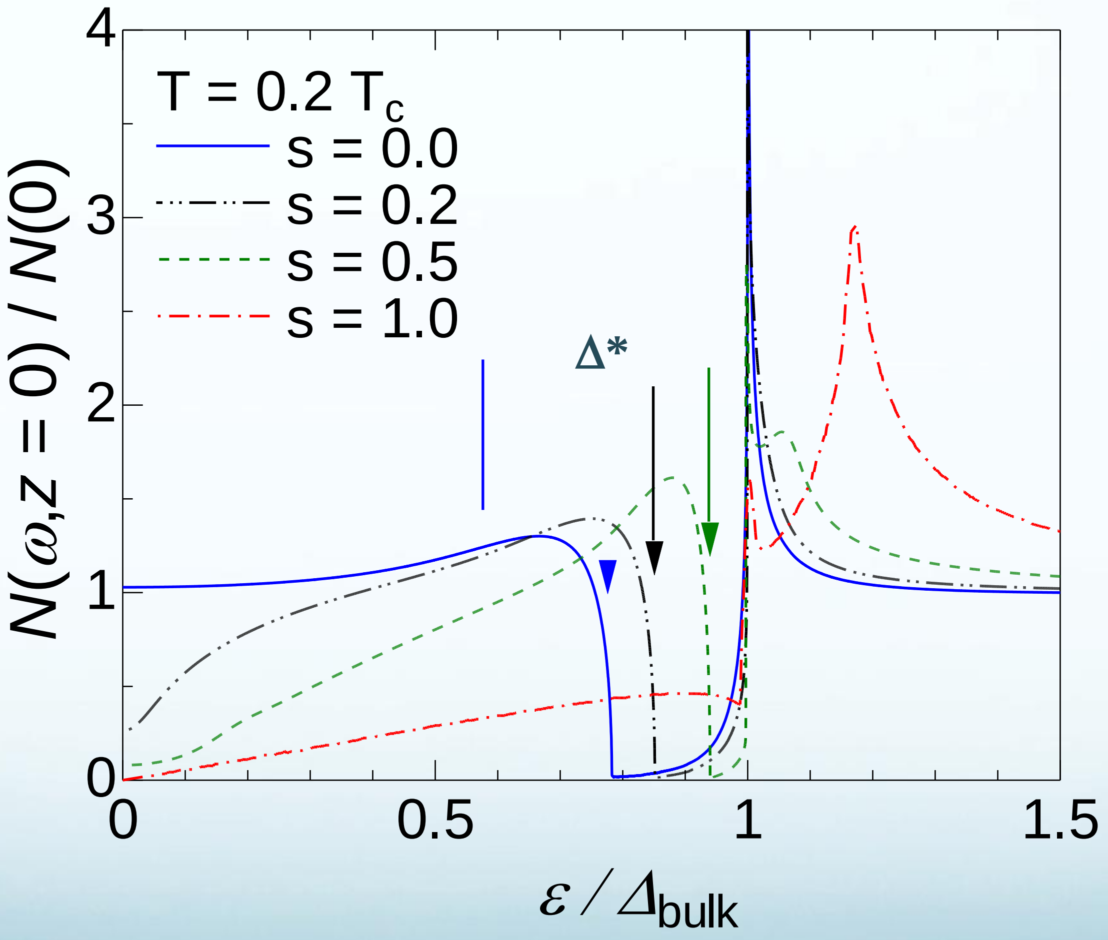
Diffusive limit



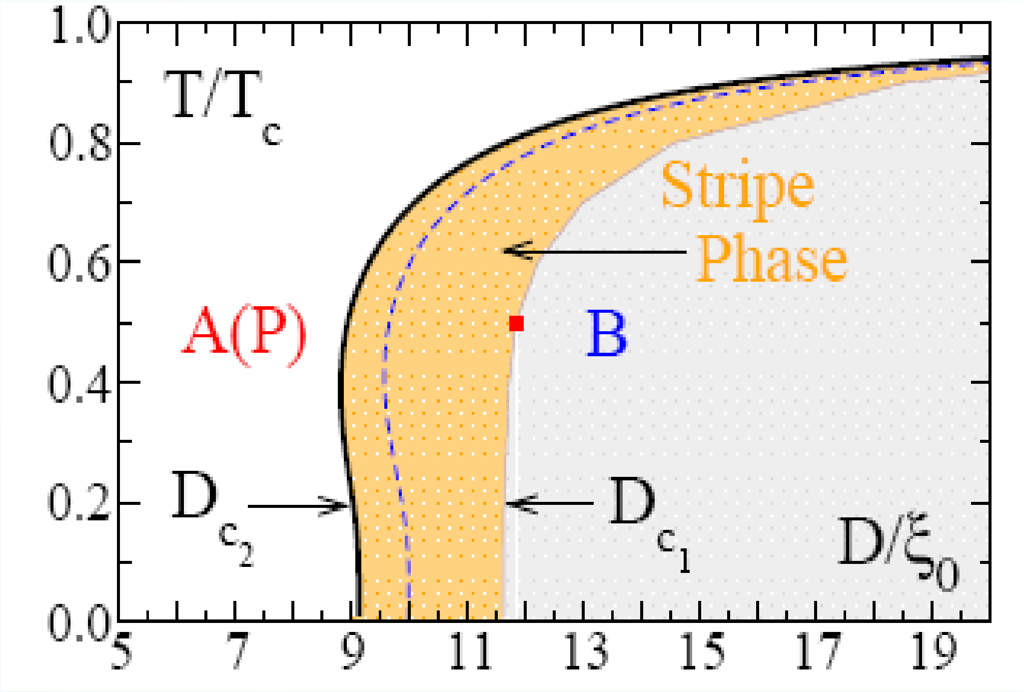
S = 0

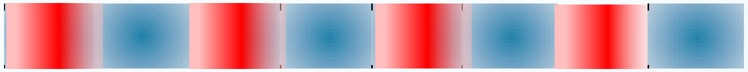





T = 0.2 T_c
s = 0.0
s = 0.2
s = 0.5
s = 1.0
Δ*
$N(\omega, z = 0) / N(0)$
$\varepsilon / \Delta_{bulk}$
0
1
2
3
4
0
0.5
1
1.5

Vorontsov and Sauls, PRL 98, 045301 (2007).





Superfluid + Spontaneously Broken Trans Symmetry

Last symmetry survived in Superfluid ^{3}He is broken.

Confinement effect (c.f. Zeeman splitting)

Inhomogeneous superfluid

~ Orbital version of FFLO

DIRECT MOTIVATION

- Interesting physics emerging from the localized surface excitations*** in superfluid ^3He: Inhomogeneous SF*, Topological excitations (Majorana)**, …
- Lack of spatial/momentum resolved probes in quantum fluids - crucial in understanding the nature of excitations. e.g. ARPES, Neutron scattering, STM ...
- Imbed detectors, quasi-particles generated internally in quantum fluids.

* Vorontsov, Sauls, *Phys. Rev. Lett.* (2007).
** Chung and Zhang, *Phys. Rev. Lett.* (2009).
** Murakawa *et al*., *Phys. Rev. Lett.* (2008); *J. Jpn. Phys. Soc.* (2011).

Tsutsumi, Ichioka, and Machida, *Phys. Rev. B* (2011).
Sauls, *Phys. Rev. B* (2011).
Mizushima, *Phys. Rev.* B (2012).
Wu and Sauls, accepted in *Phys. Rev. B* (2013).

DEVICE

DEVICE CRITERIA

- Form a well-defined slab or film

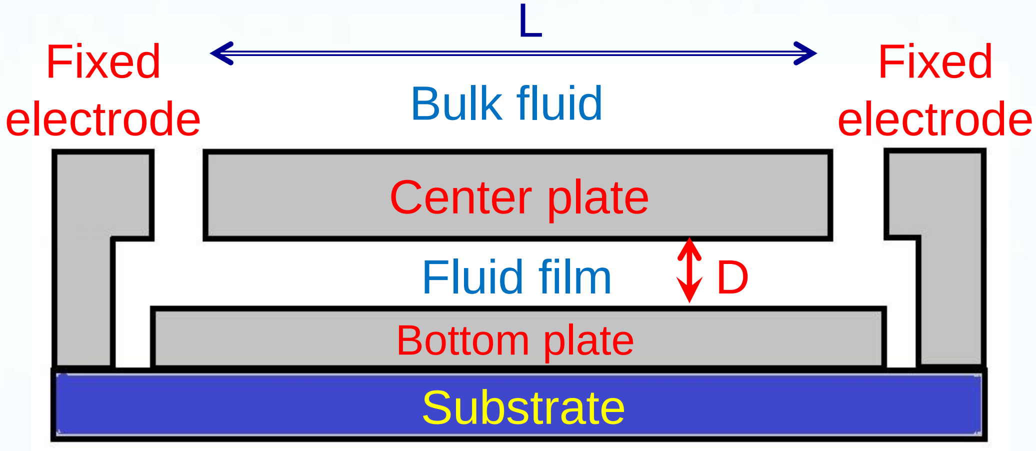
  of variable $d < 1\ \mu m$

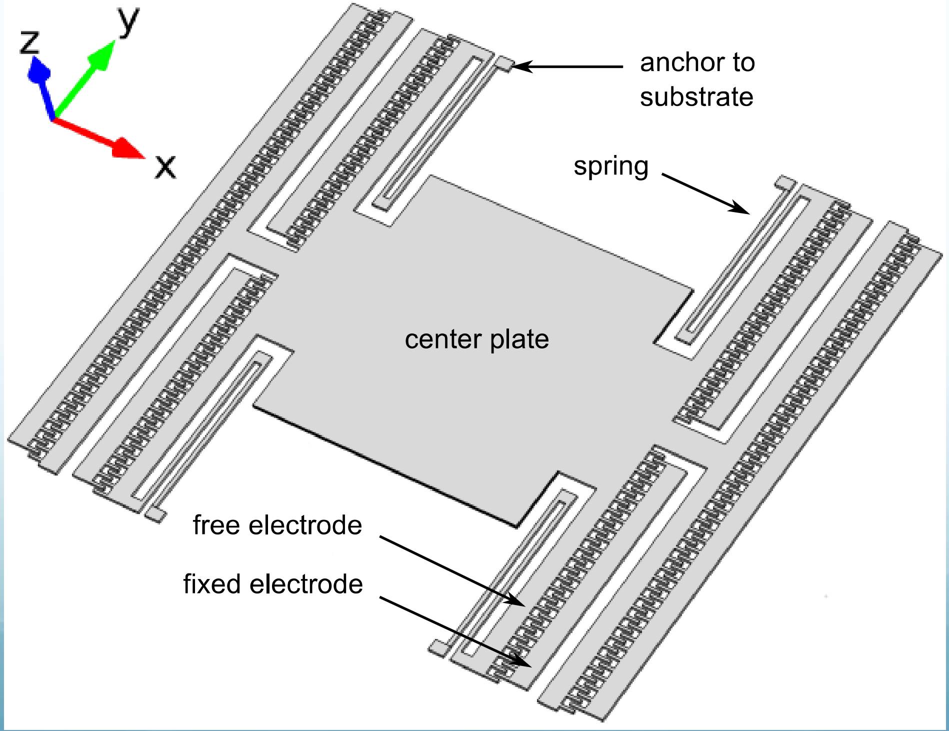
  at any sample pressure

- High resolution surface sensitive probe
- Controllable surface quality or structure
- Scalable

D = 0.75,1.25, 2.00 μm

L = 200 μm





Fabrication

PolyMUMPS

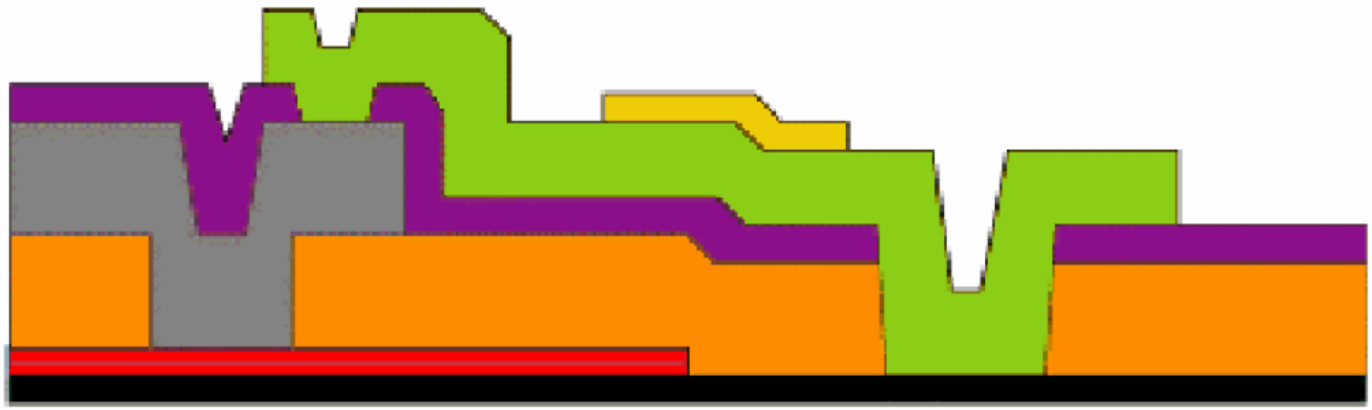
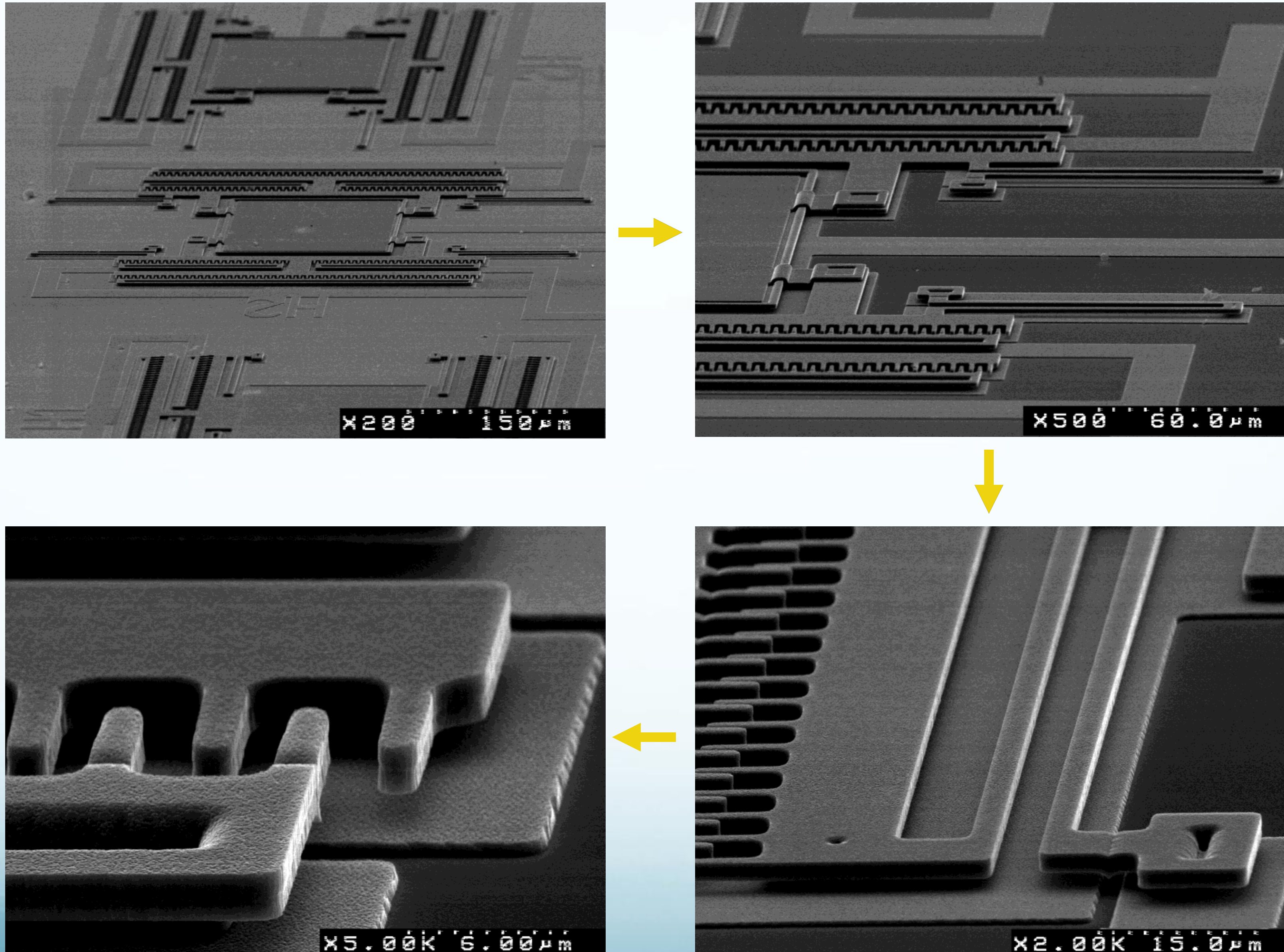
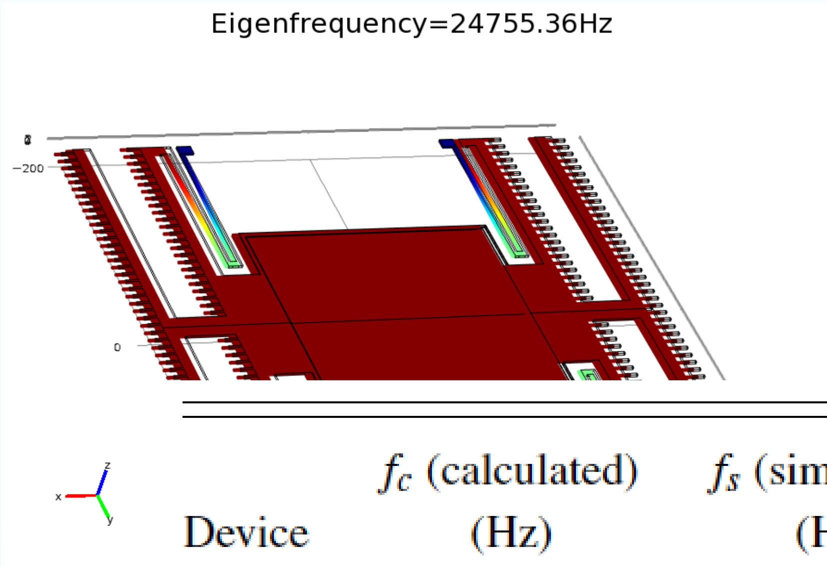


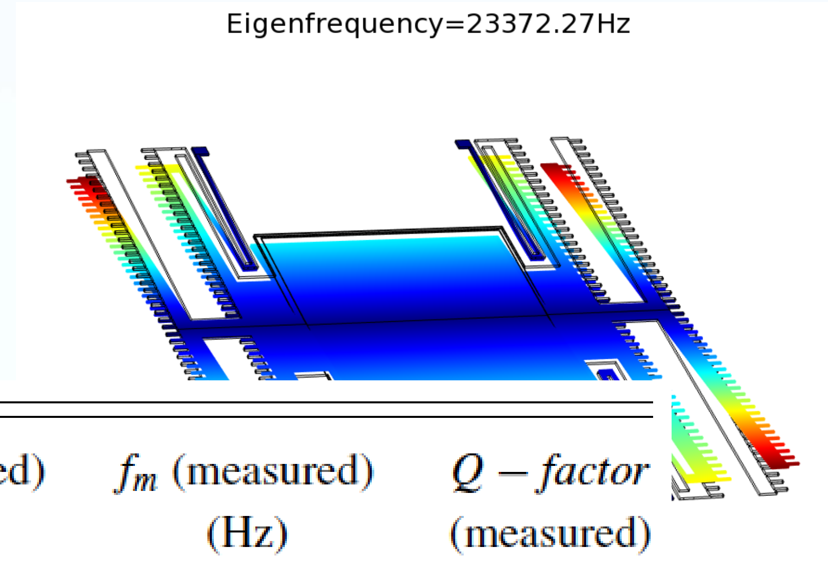
FIGURE 1.1. Cross sectional view showing all 7 layers of the PolyMUMPs process (not to scale).

Poly0	Poly1	Poly2	Metal
Nitride	1st Oxide	2nd Oxide	

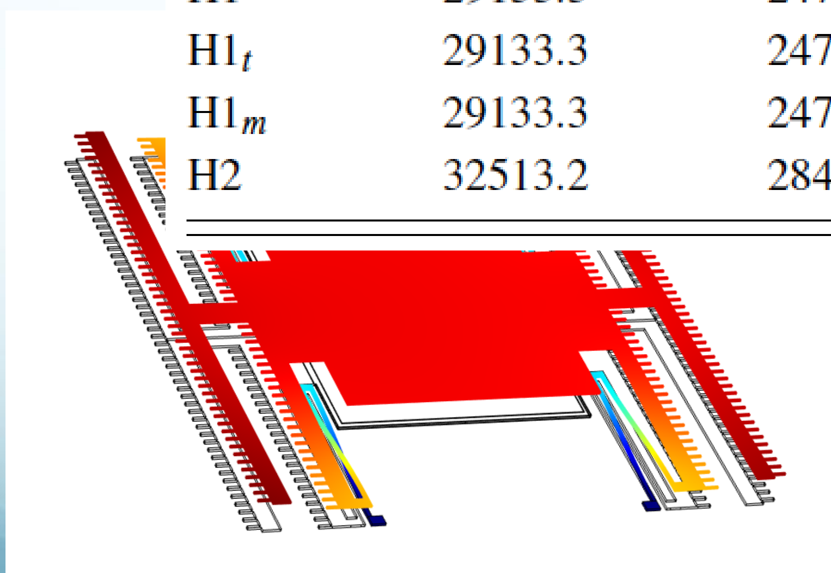
González *et al.* Rev. Sci. Instrum. **84**, 025003 (2013)

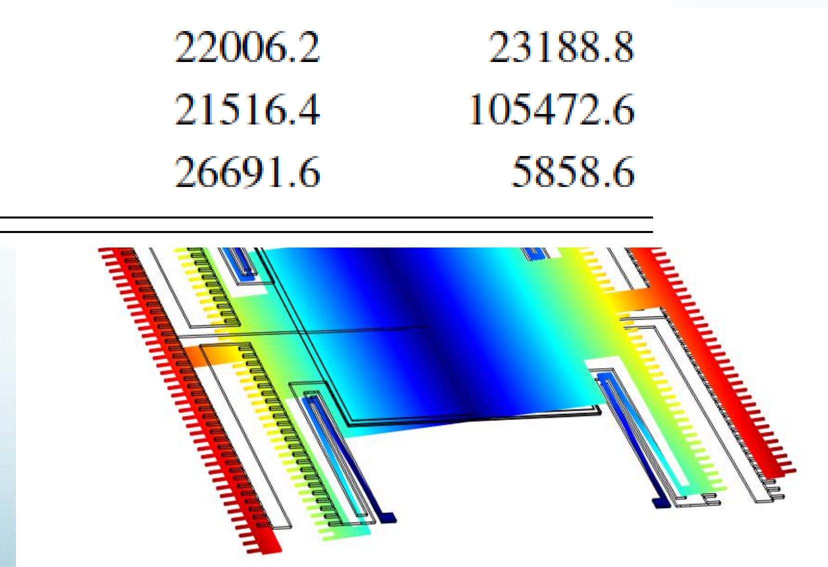






Device	f_c (calculated) (Hz)	f_s (simulated) (Hz)	f_m (measured) (Hz)	$Q - factor$ (measured)
H1	29133.3	24755.4	23063.1	6424.3
$H1_t$	29133.3	24755.4	22006.2	23188.8
$H1_m$	29133.3	24755.4	21516.4	105472.6
H2	32513.2	28438.3	26691.6	5858.6

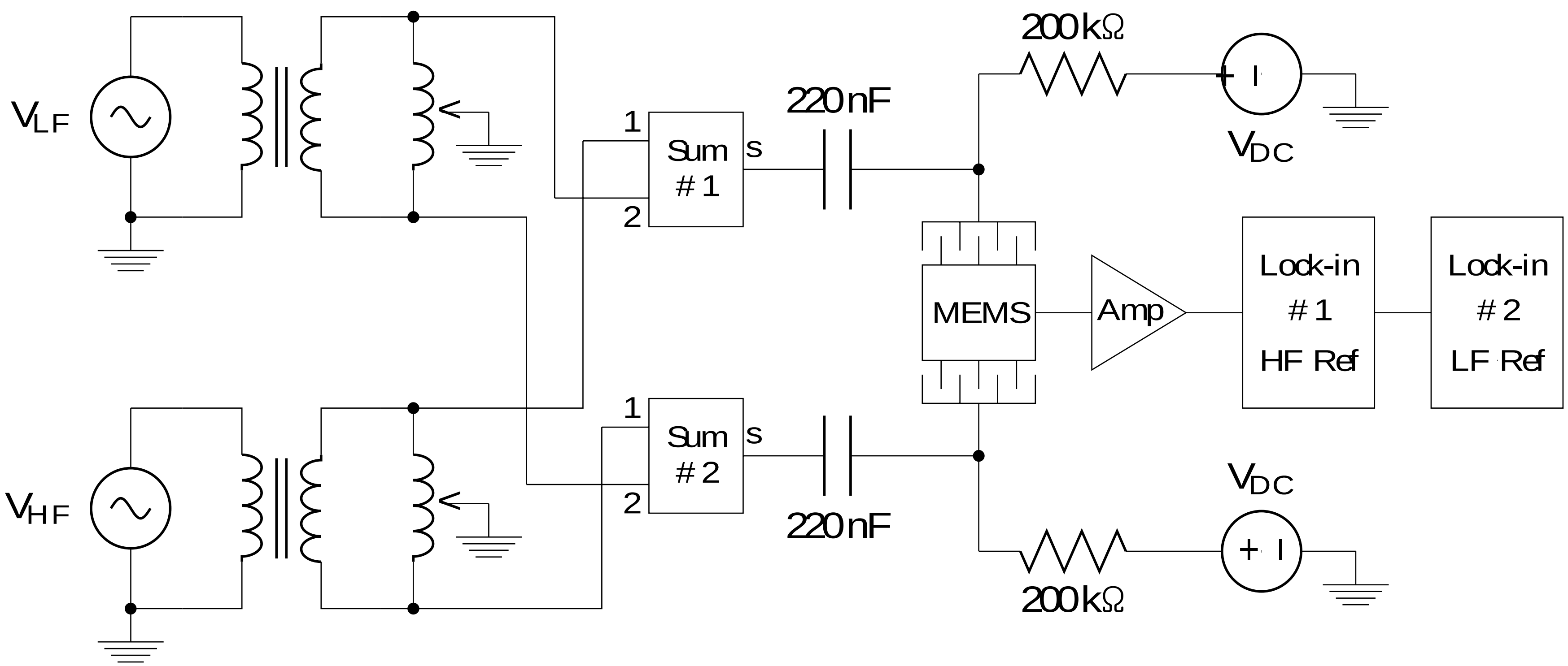


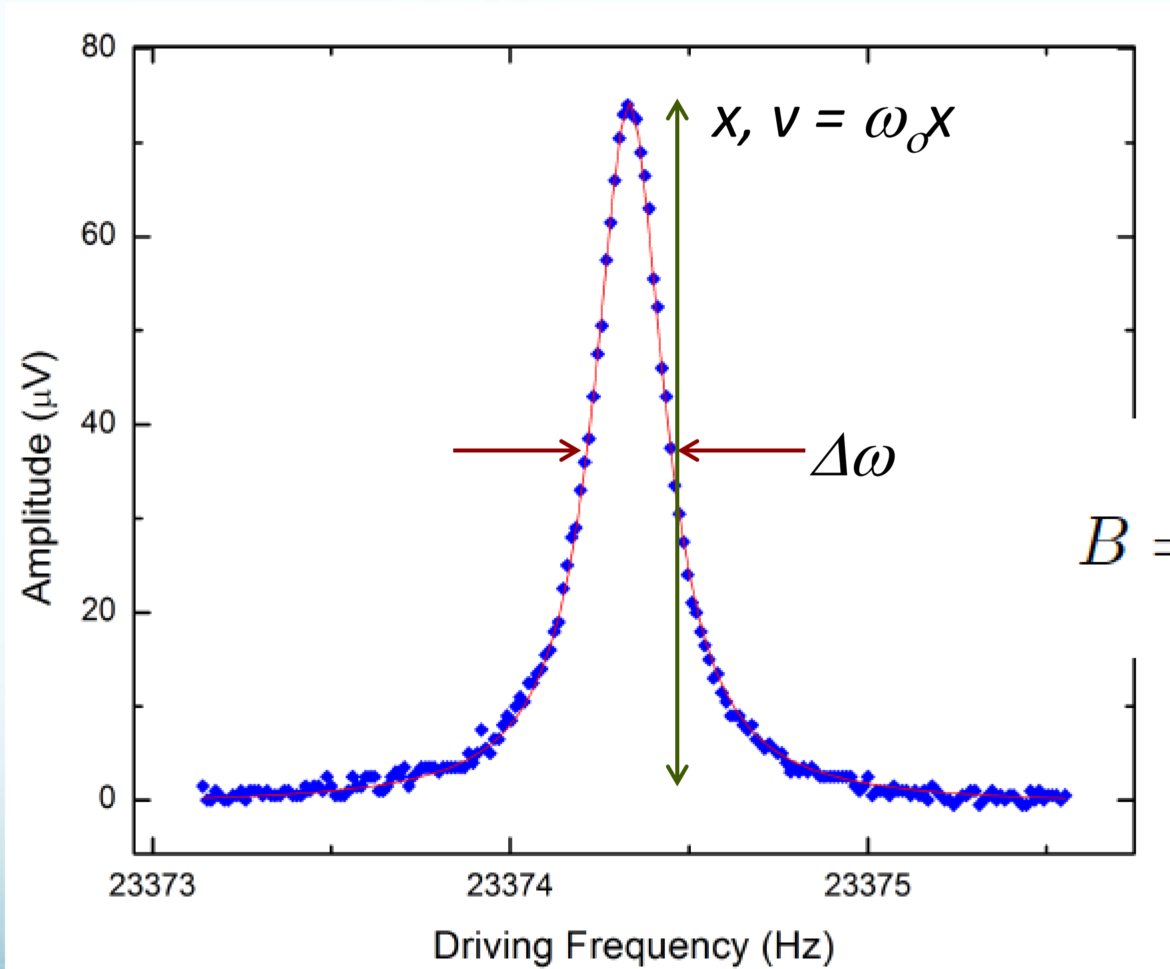


Z motion

Y-pivot

DETECTION SCHEME





$$\ddot{x} + \gamma \dot{x} + \omega_0^2 x = \frac{F}{m},$$

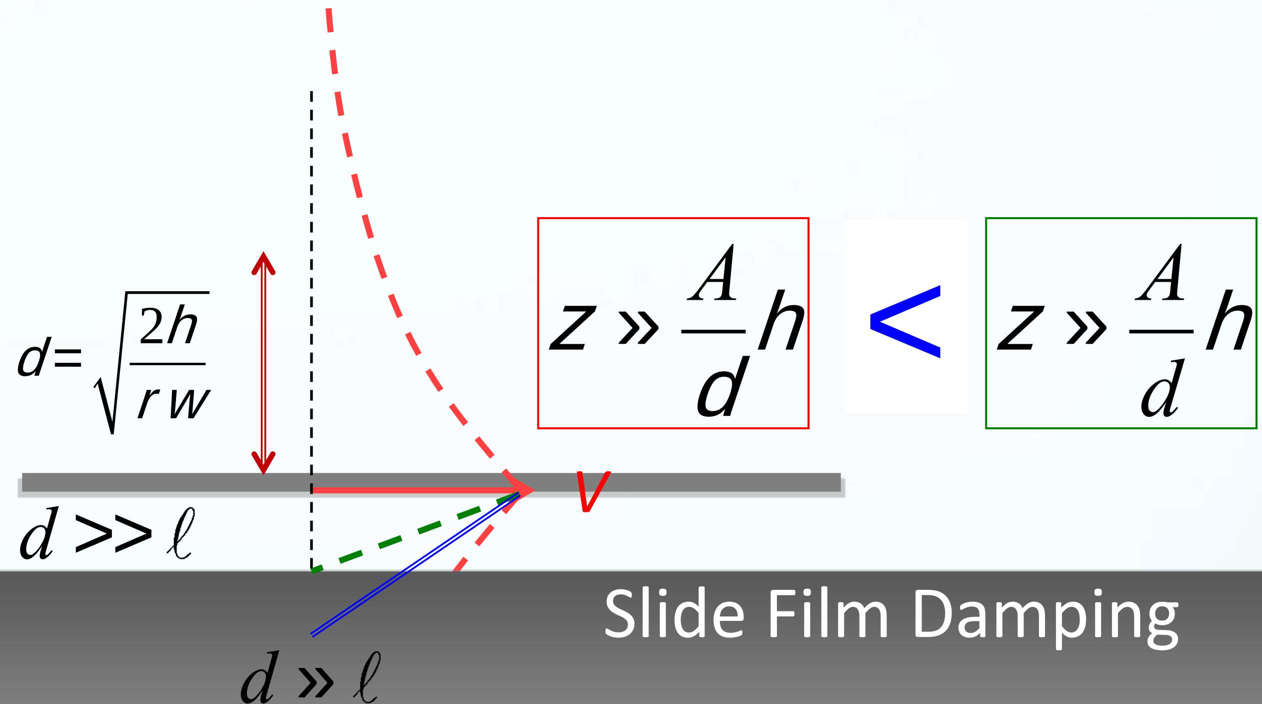
$$x = B e^{-i\omega t},$$

$$B = \frac{F}{m} \frac{(\omega_0^2 - \omega^2) + i(\gamma\omega)}{(\omega_0^2 - \omega^2)^2 + (\gamma\omega)^2}.$$

Q_{RT} » $10^3 - 10^4$

Q_{4K} » 10^5

LINEAR DAMPING



Slide Film Damping

Slip boundary condition

RT Air Damping

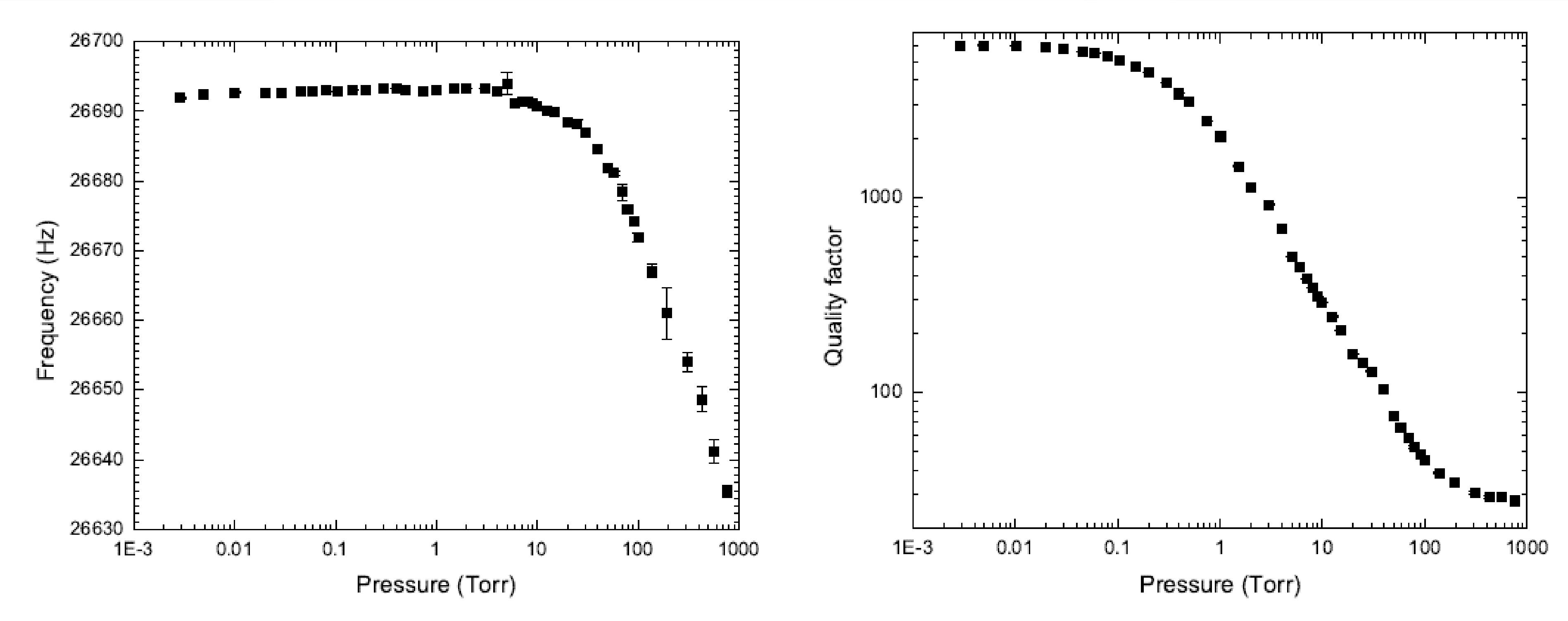
- Pressure dependent damping
- Slide film damping model

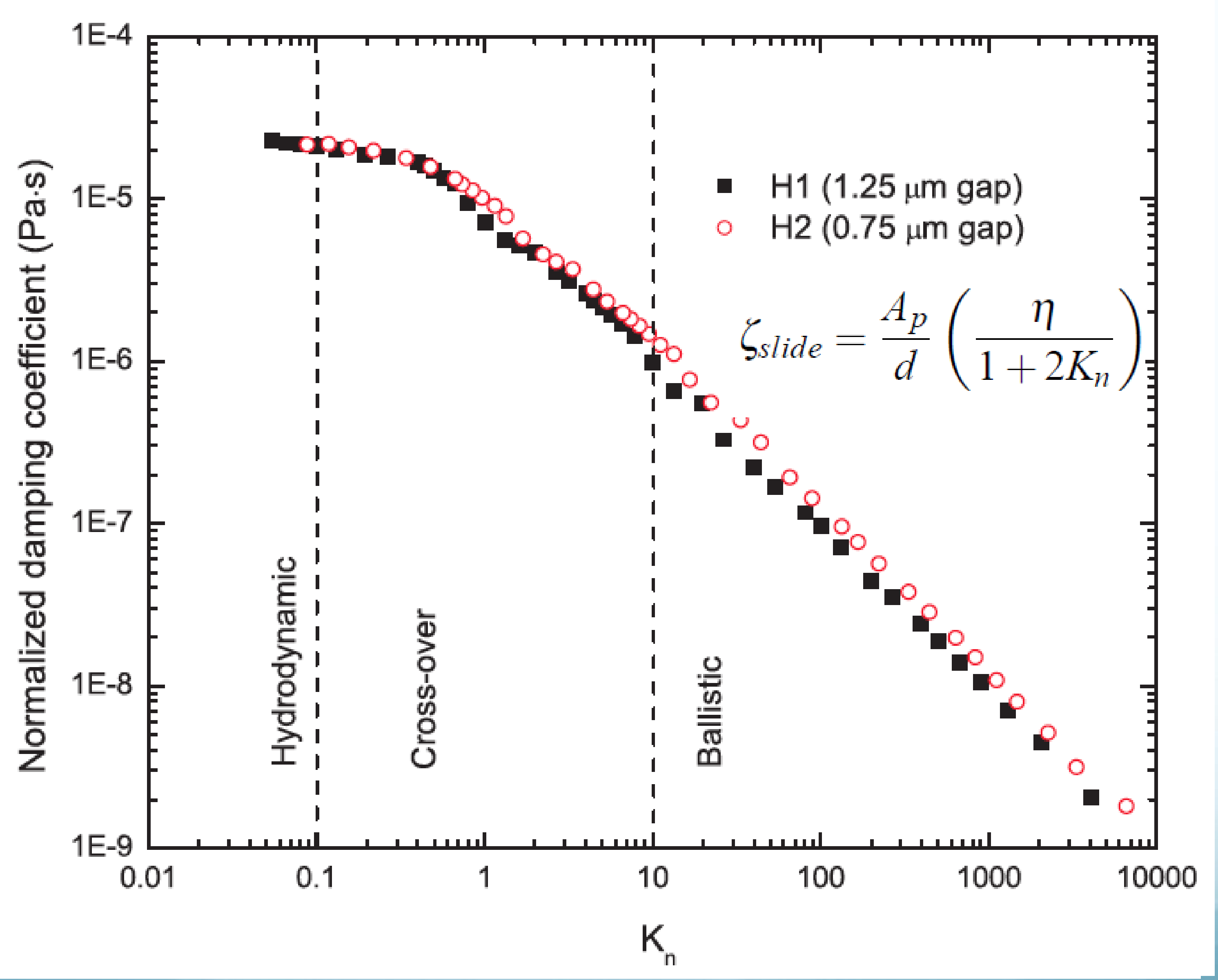
Bruschi *et al.*, Sensors and Actuators (2004)

$$\zeta_{slide} = \frac{A_p}{d}\left(\frac{\eta}{1+2K_n}\right) = m\Delta\omega$$

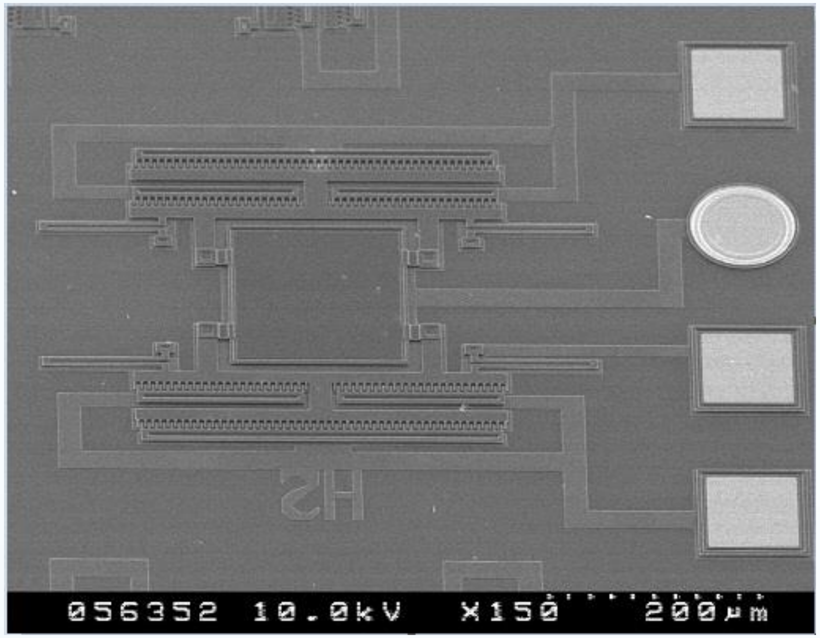
Effective viscosity

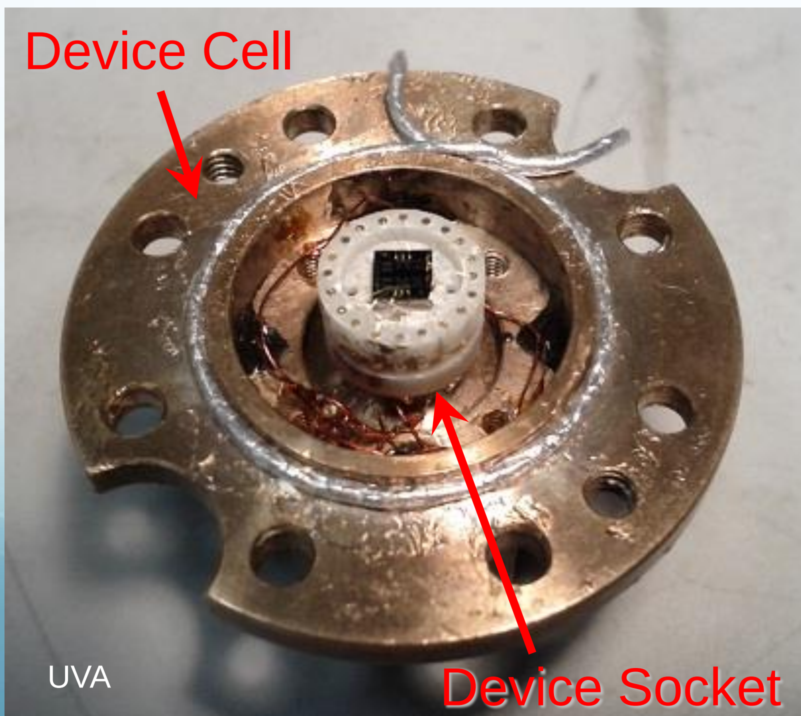
Pressure Dependence at RT

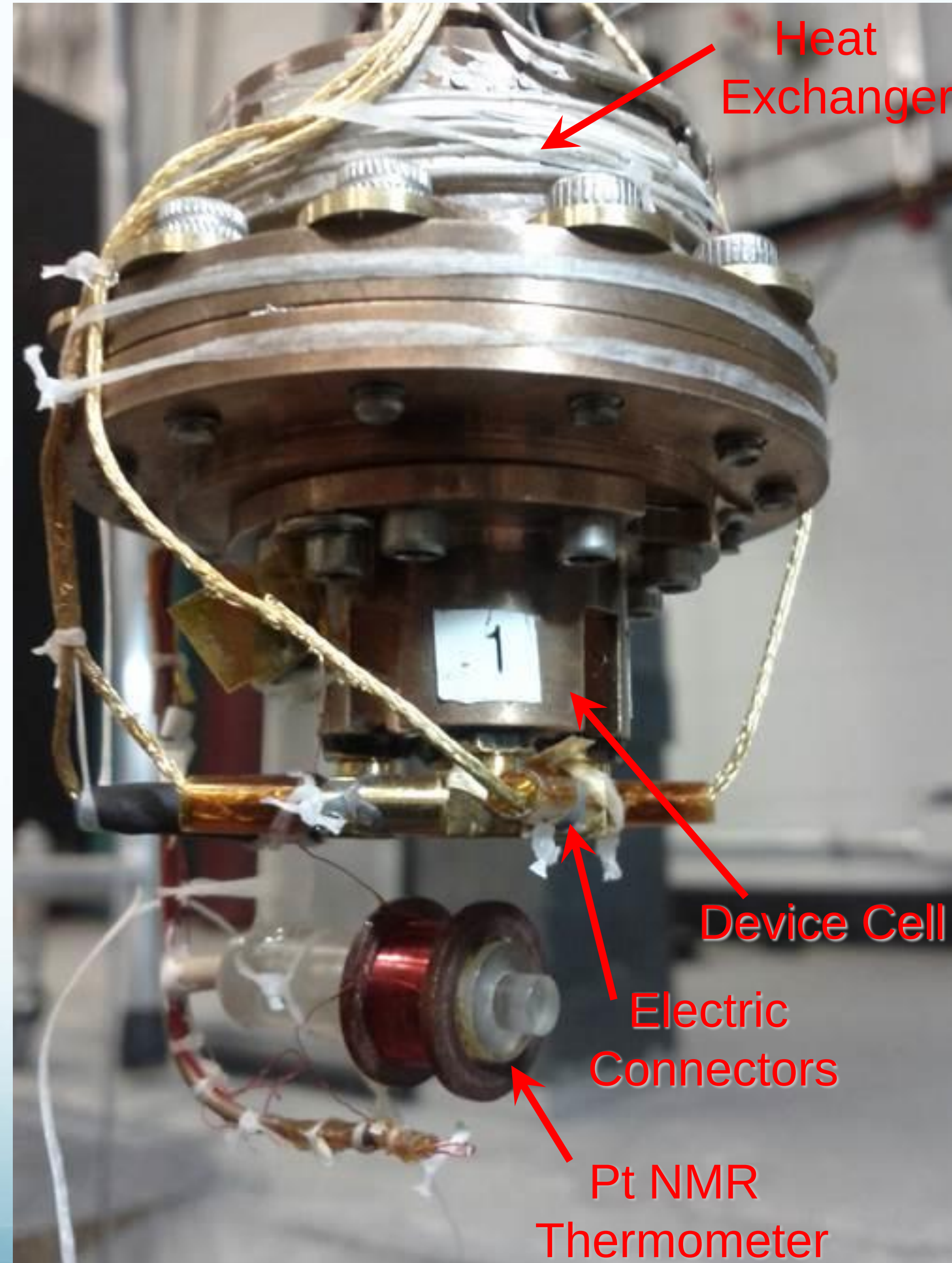




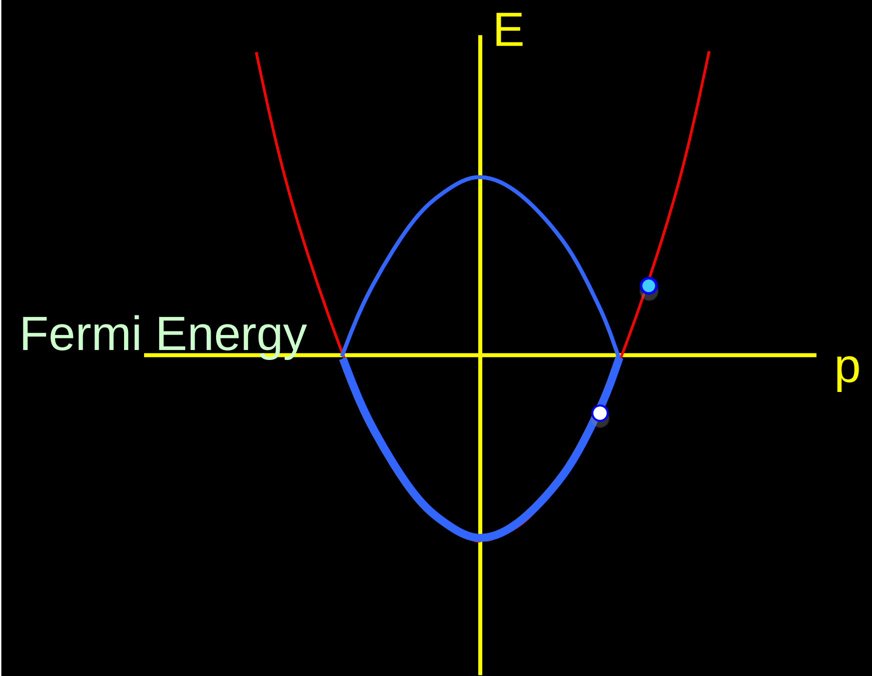
1E-4
1E-5
1E-6
1E-7
1E-8
1E-9
Normalized damping coefficient (Pa·s)
0.01
0.1
1
10
100
1000
10000
K_n
Hydrodynamic
Cross-over
Ballistic
H1 (1.25 μm gap)
H2 (0.75 μm gap)
$\zeta_{slide} = \frac{A_p}{d}\left(\frac{\eta}{1+2K_n}\right)$

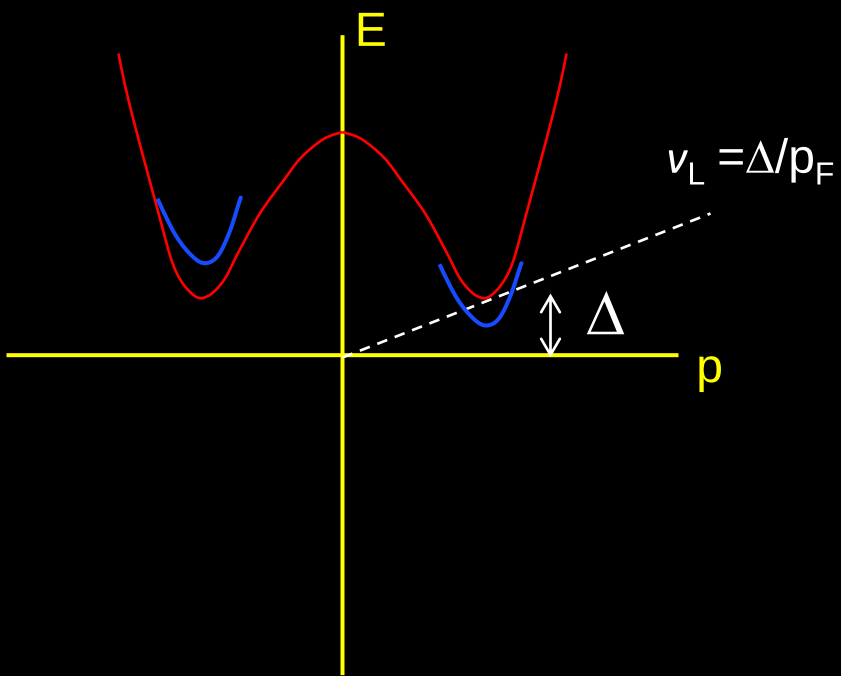

056352 10.0kV X150 200µm


Device Cell
Device Socket
UVA


Heat
Exchanger
Device Cell
Electric
Connectors
Pt NMR
Thermometer

Quasi-particle spectrum in fermion system





$$N_{qp}(T << T_C) \propto N(E_F) k_B T \exp\left(- \frac{D}{k_B T} \right) \approx \left(\frac{T}{T_F} \right) \exp\left(- \frac{D}{k_B T} \right)$$

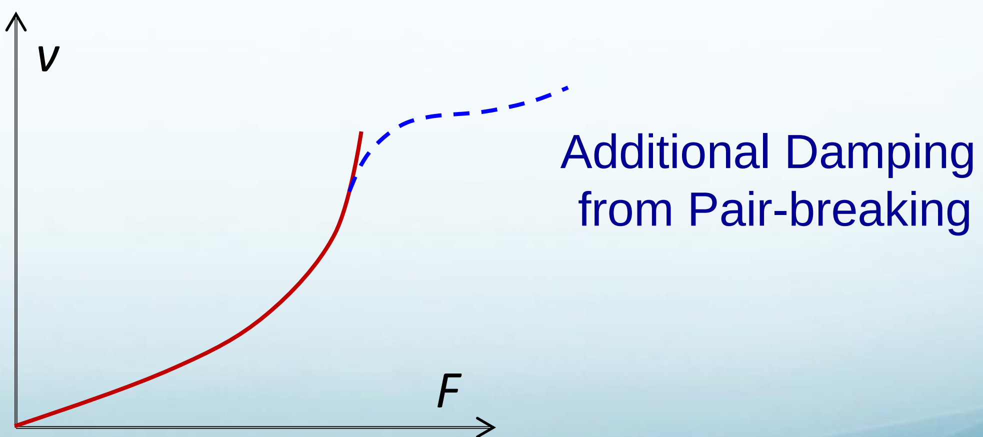
Quasi-particle Thermal Damping in ^{3}He-B at Low T

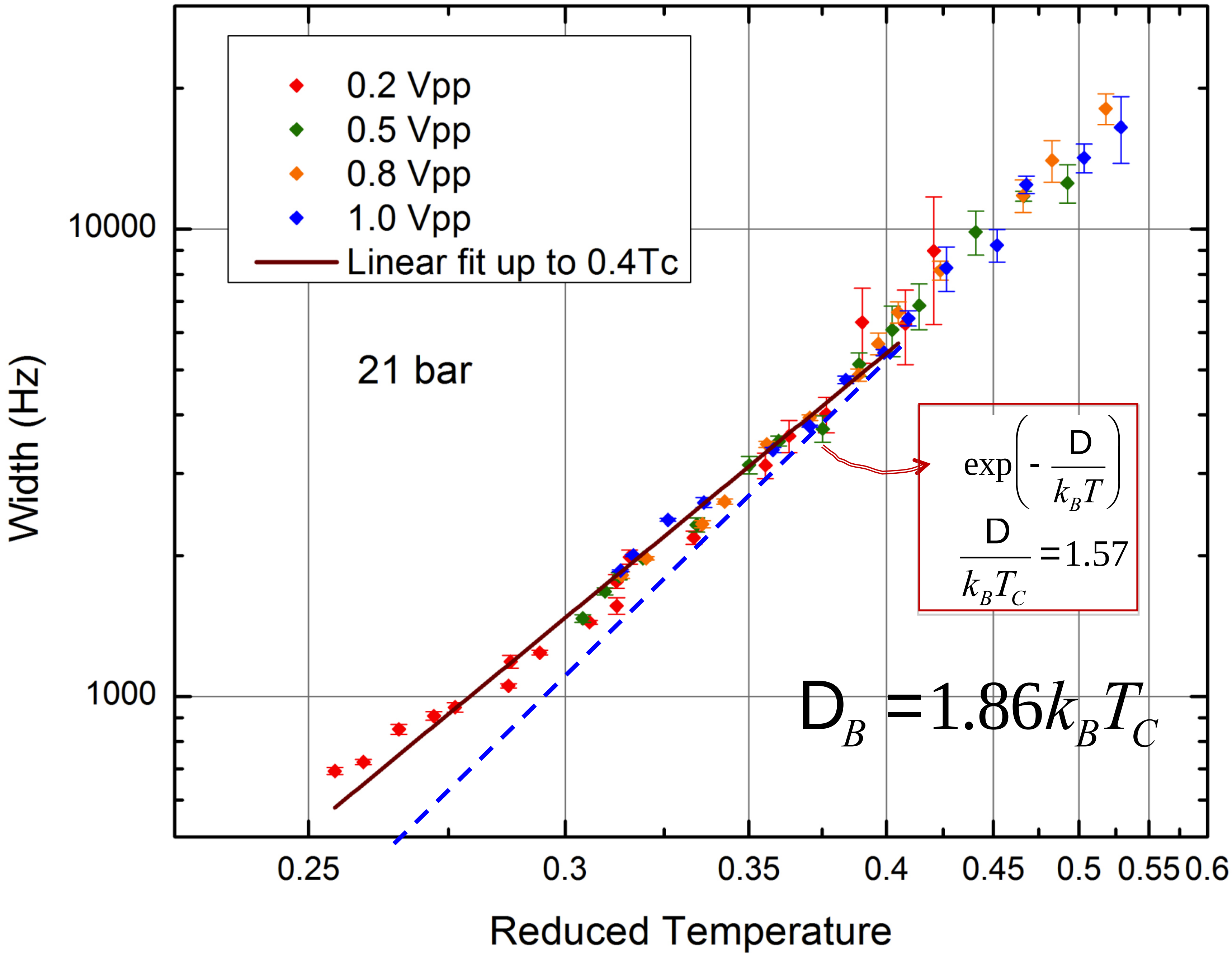
S.N. Fisher et al., PRL (1989)

$$N(p_F)k_BT\exp\left(-\frac{D}{k_BT}\right)$$

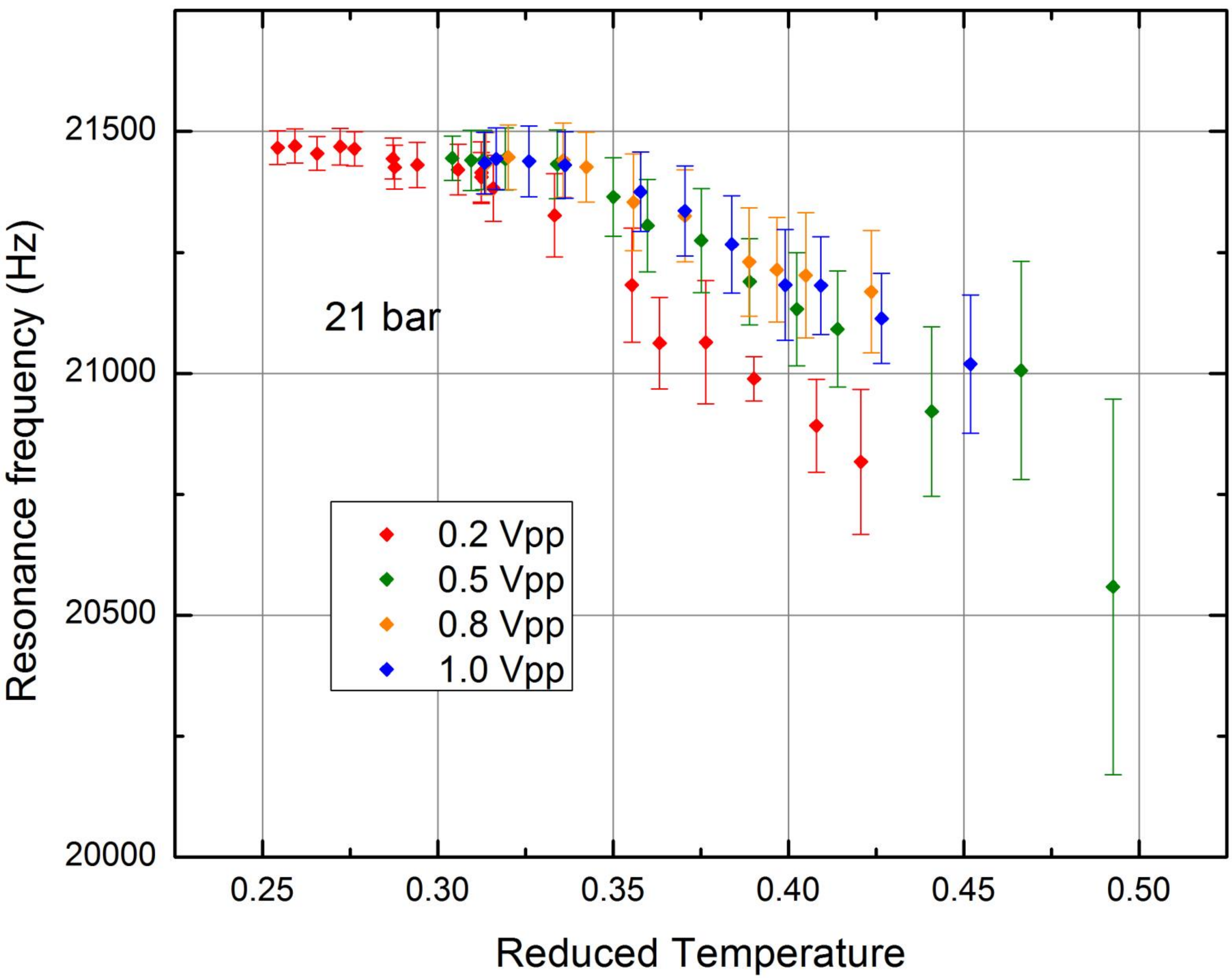
$$F^T_{damp} = 2A\sigma p_F \langle n v_g \rangle \frac{1}{\lambda}\left[1-\exp\left(-\frac{\lambda p_F v}{k_BT}\right)\right]$$

$$\propto \exp\left(-\frac{D}{k_BT}\right)\left\{A_1 u - A_2\frac{u^2}{k_BT}\right\}$$





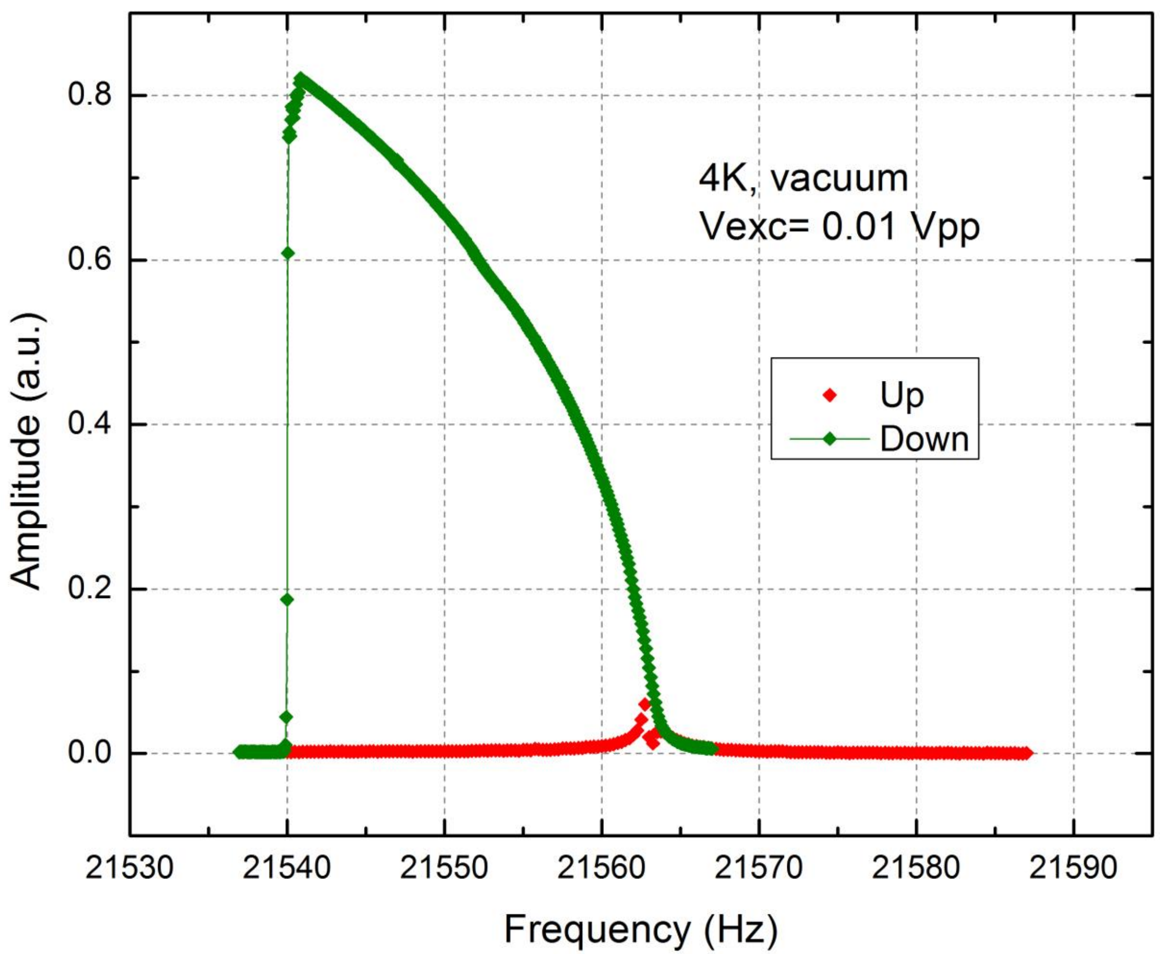
0.2 Vpp
0.5 Vpp
0.8 Vpp
1.0 Vpp
Linear fit up to 0.4Tc
21 bar
10000
1000
Width (Hz)
0.25
0.3
0.35
0.4
0.45
0.5
0.55
0.6
Reduced Temperature
$\exp\left(-\frac{D}{k_B T}\right)$
$\frac{D}{k_B T_C} = 1.57$
$D_B = 1.86 k_B T_C$



Resonance frequency (Hz)
21500
21000
20500
20000
0.25
0.30
0.35
0.40
0.45
0.50
Reduced Temperature
21 bar
0.2 Vpp
0.5 Vpp
0.8 Vpp
1.0 Vpp

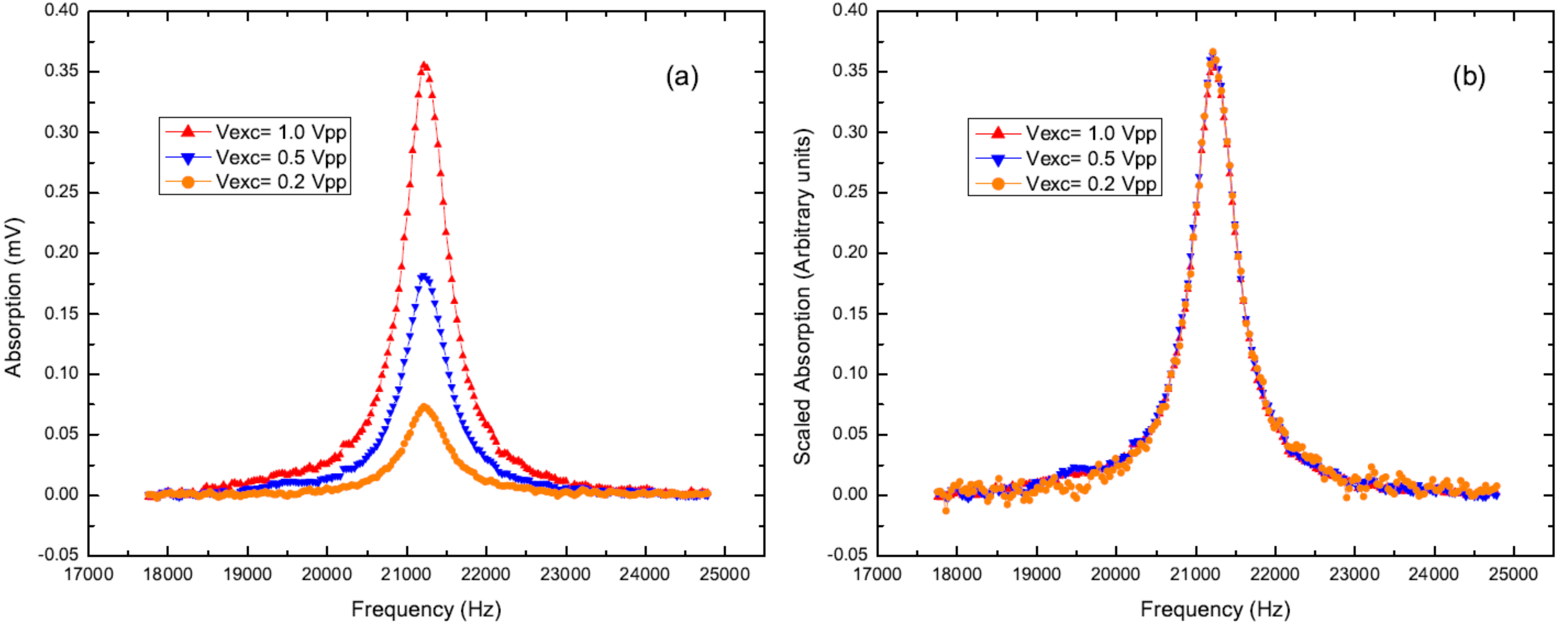
NON-LINEAR RESONANCES

Non-linear Behavior in Vacuum at 4 K
(Duffing Oscillation)

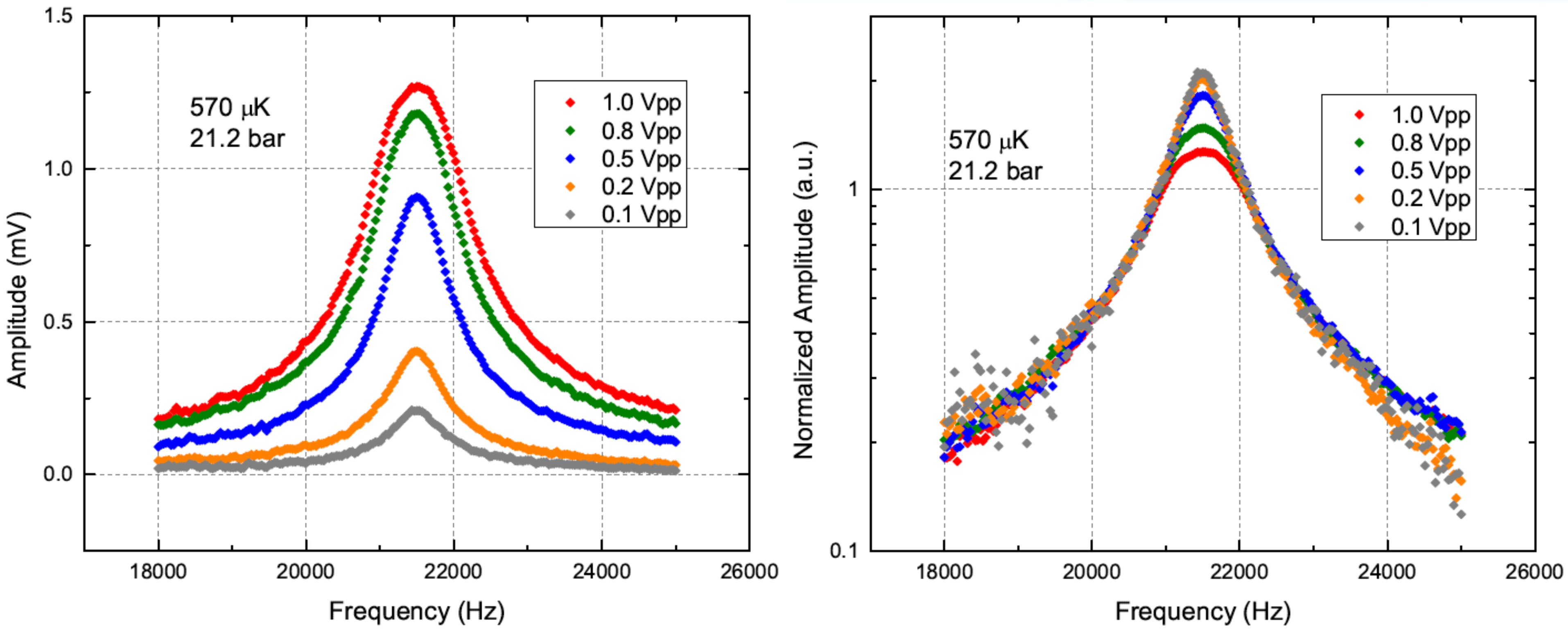


Non-linear Behavior in ^{3}He-B

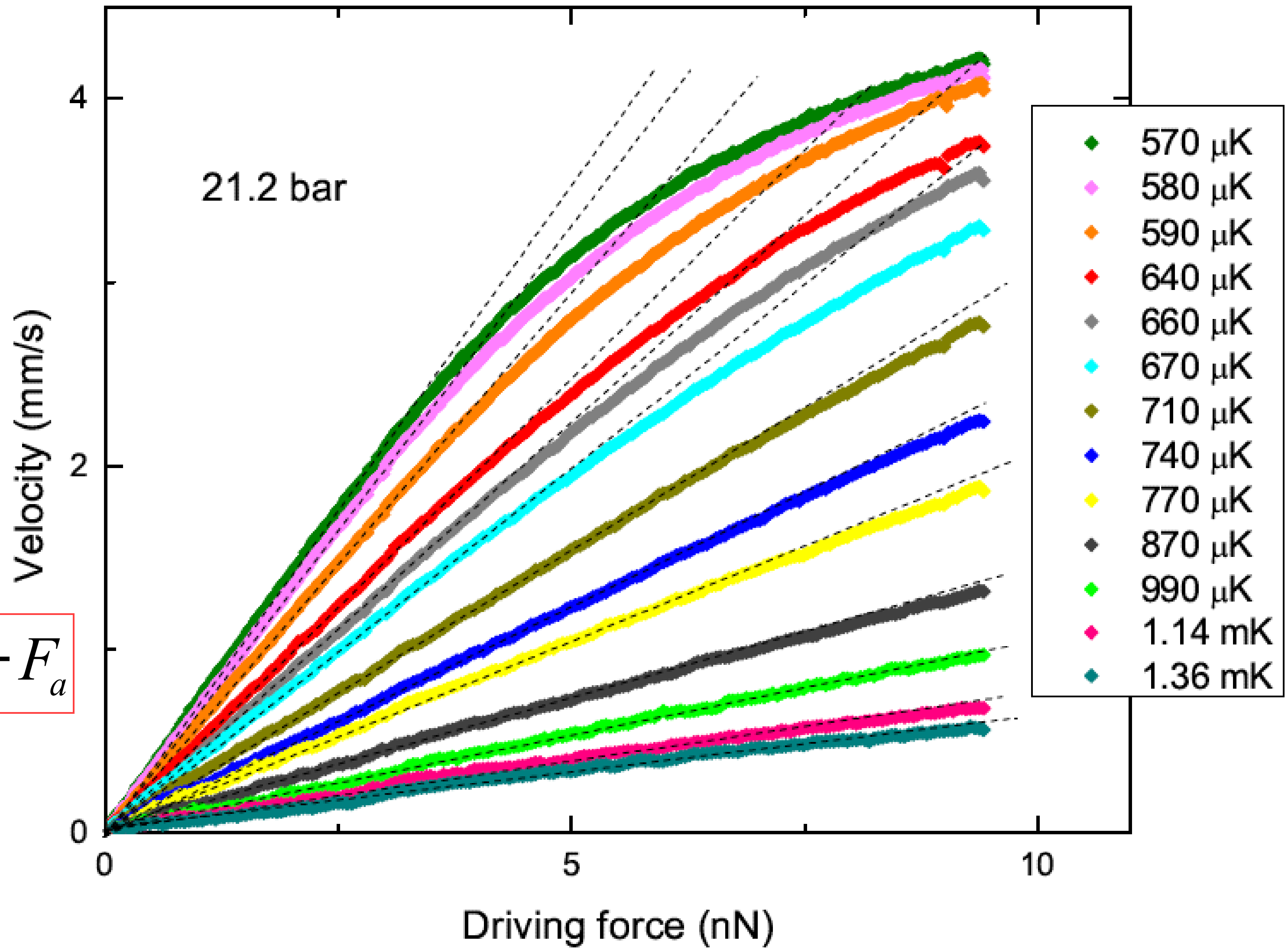
Normal Liquid ^{3}He



Superfluid ^{3}He
P = 21.2 bar and T = 0.57 mK

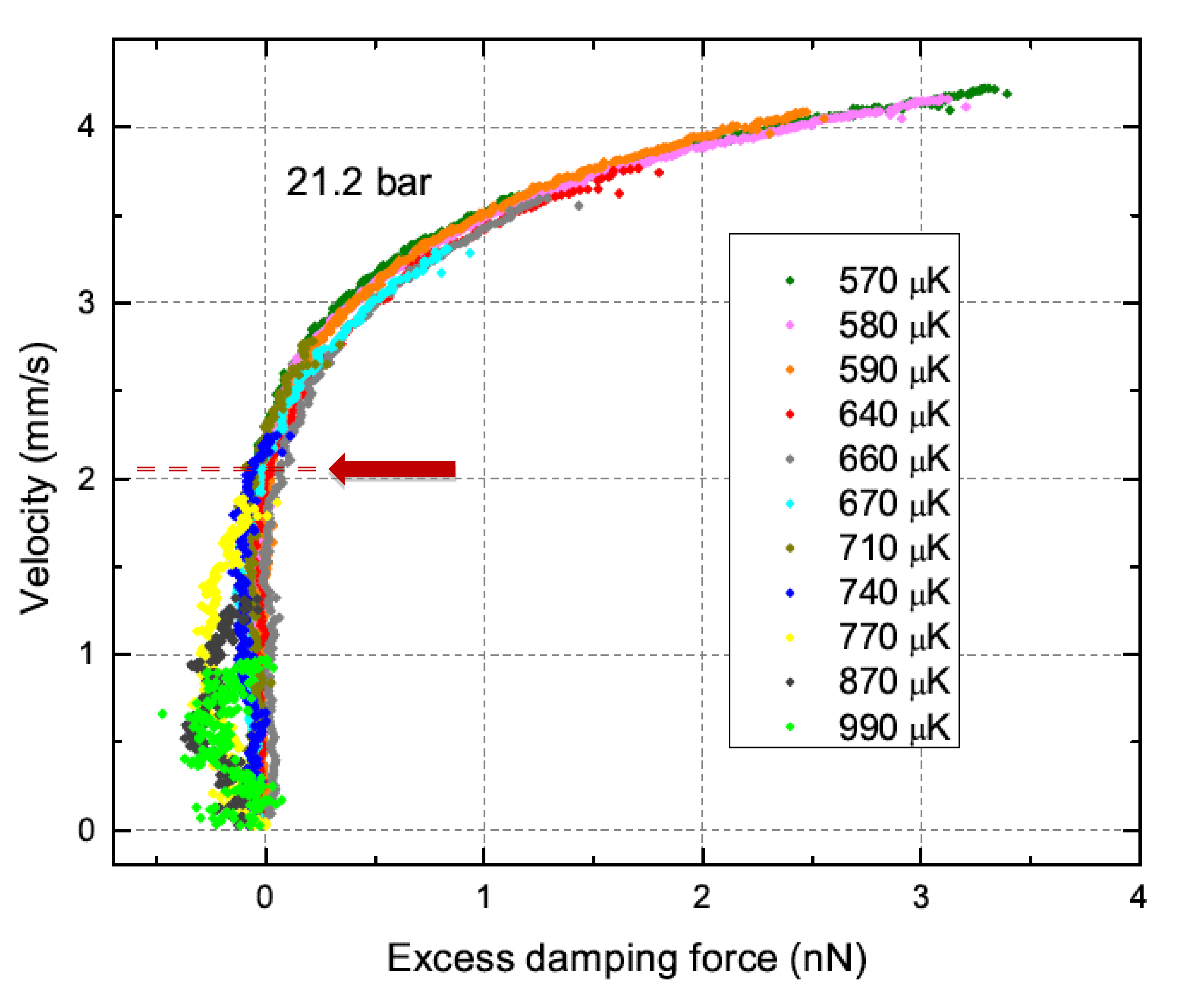


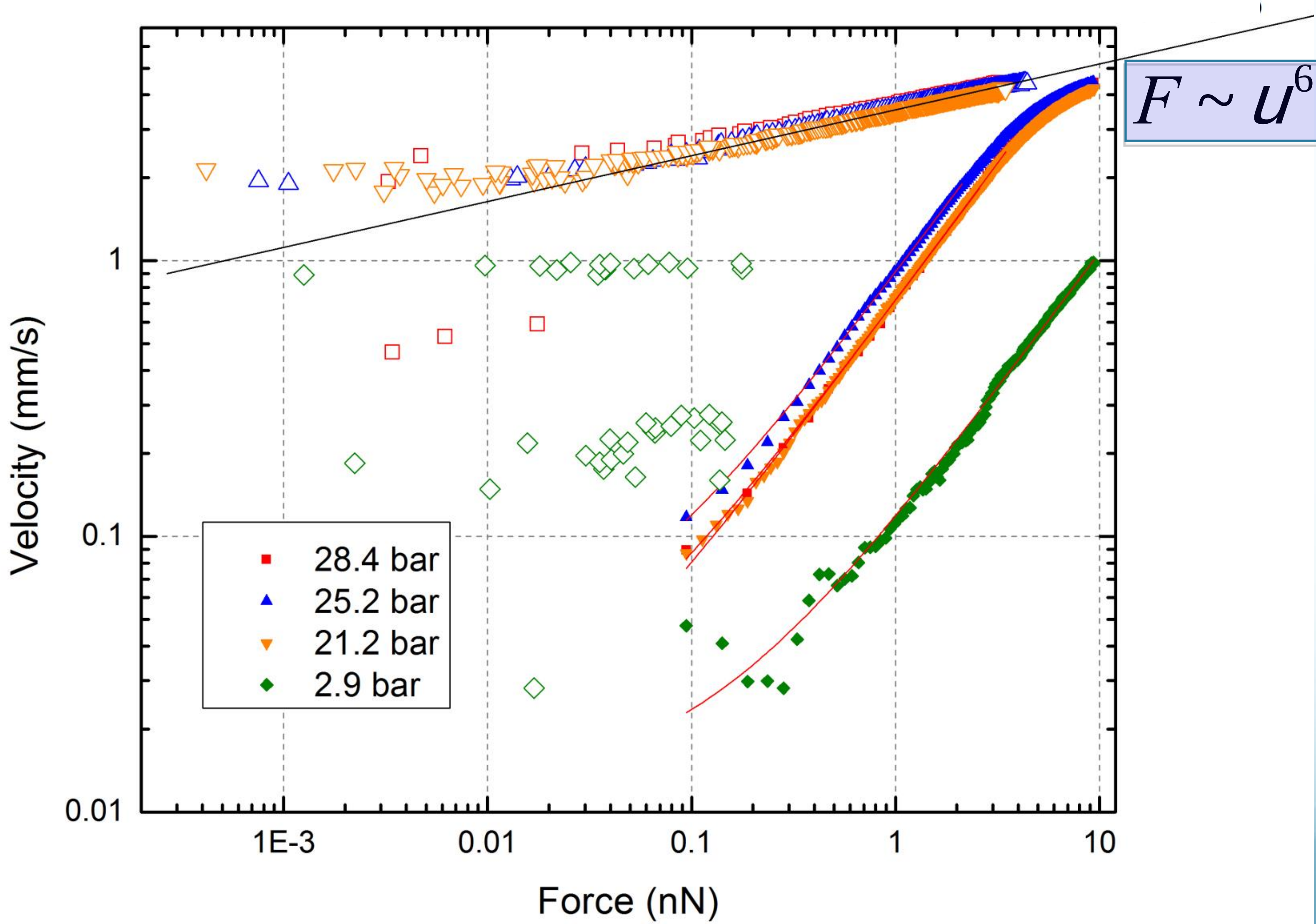
$$F^T_{damp} = 2A\sigma p_F \langle n v_g \rangle \frac{1}{\lambda}\left[1 - \exp\left(-\frac{\lambda p_F v}{k_B T}\right)\right]$$



$$F_d = F^T_{damp}(T) + F_a$$

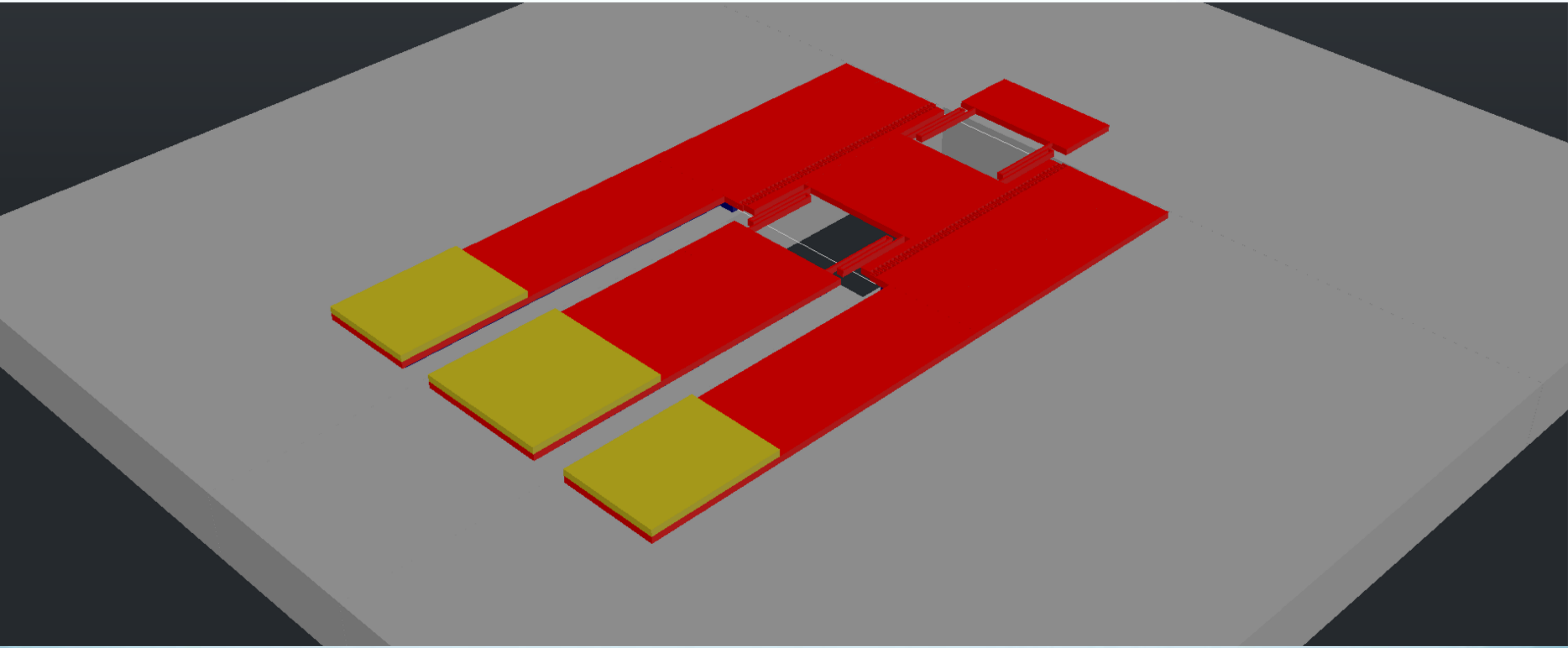
$$\lambda \frac{p_F u}{k_B T} < 0.1$$


21.2 bar
Velocity (mm/s)
Excess damping force (nN)
0
1
2
3
4
570 μK
580 μK
590 μK
640 μK
660 μK
670 μK
710 μK
740 μK
770 μK
870 μK
990 μK

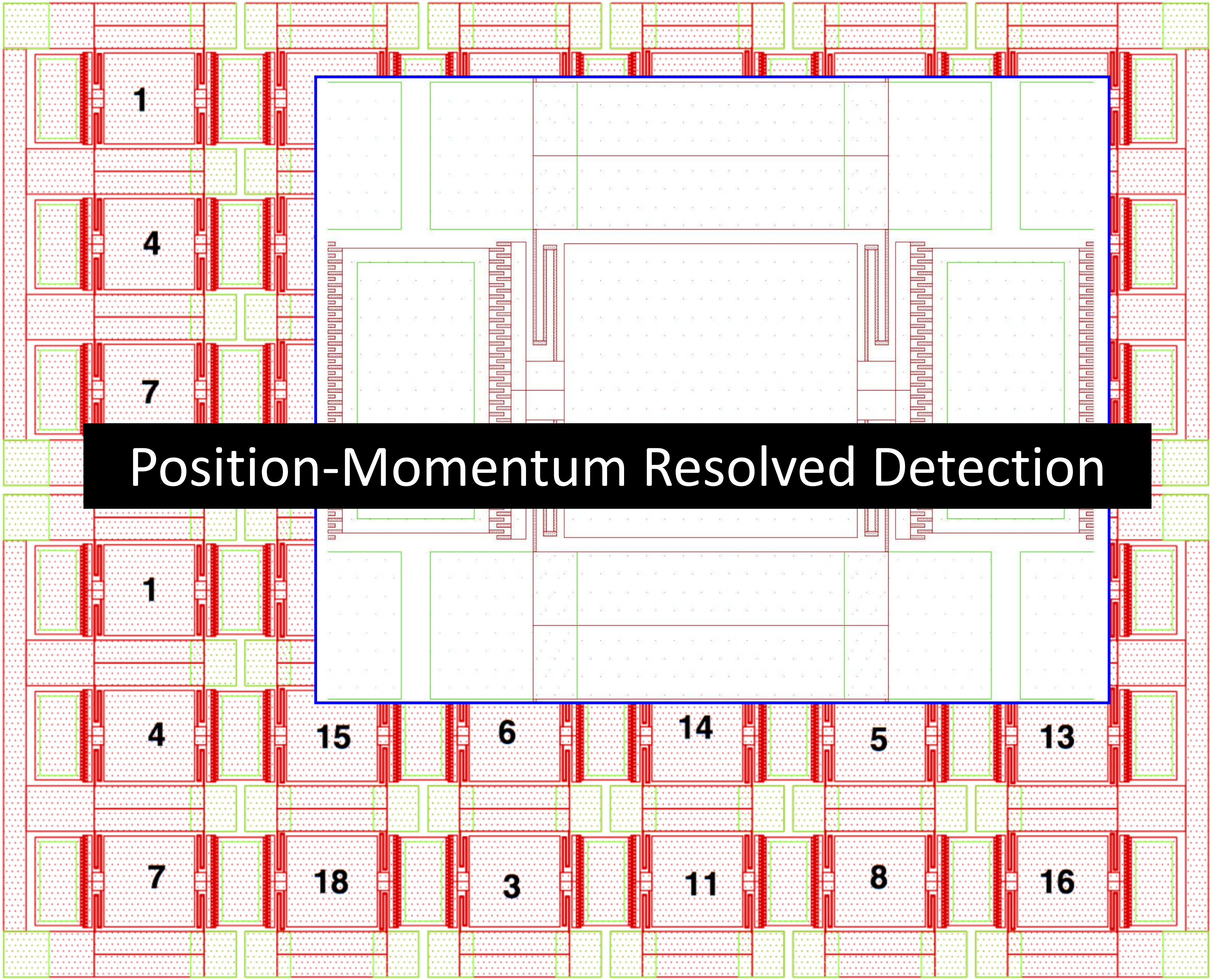

$F \sim u^6$
Velocity (mm/s)
Force (nN)
0.01
0.1
1
1E-3
0.01
0.1
1
10
28.4 bar
25.2 bar
21.2 bar
2.9 bar

FUTURE

Silicon-on-Oxide (SOI)



Position-Momentum Resolved Detection



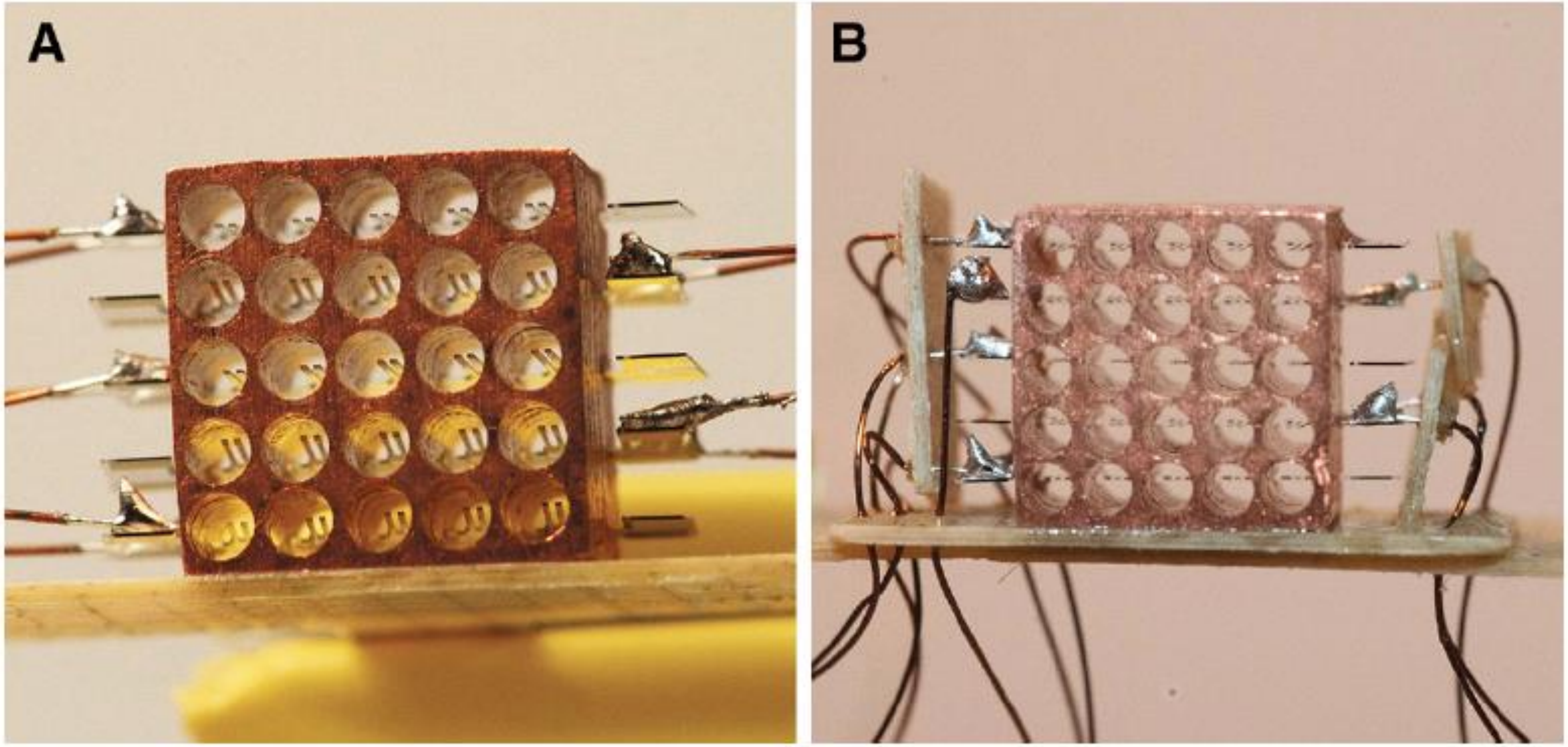


Fig. 4 **a** Photograph of the detector with the arrays installed. The external leads are attached on alternate sides. The tuning forks are seen to be approximately in the centres of each hole. Each hole with tuning fork forms a single pixel of the 25 pixel detector. **b** Photograph of the detector showing the supports for the leads which now pass through the Stycast-impregnated paper baseplate (Color figure online)

SUMMARY

- Using a commercial MEMS process we have developed robust oscillators with high quality factors suitable for ULT applications.

- Device measures fluid properties: damping in hydrodynamic and ballistic limit.

  Sensitive to quasi-particle collision in 3He-B

- Observed nonlinear temperature independent damping

  New tool for quantum turbulence study

  Effective surface sensitive tool in superfluid 3He.

- Future work/improvements:

  Simpler process (SOI MEMS) and simpler structure

Detector array → position-momentum resolved detection in ^{3}He