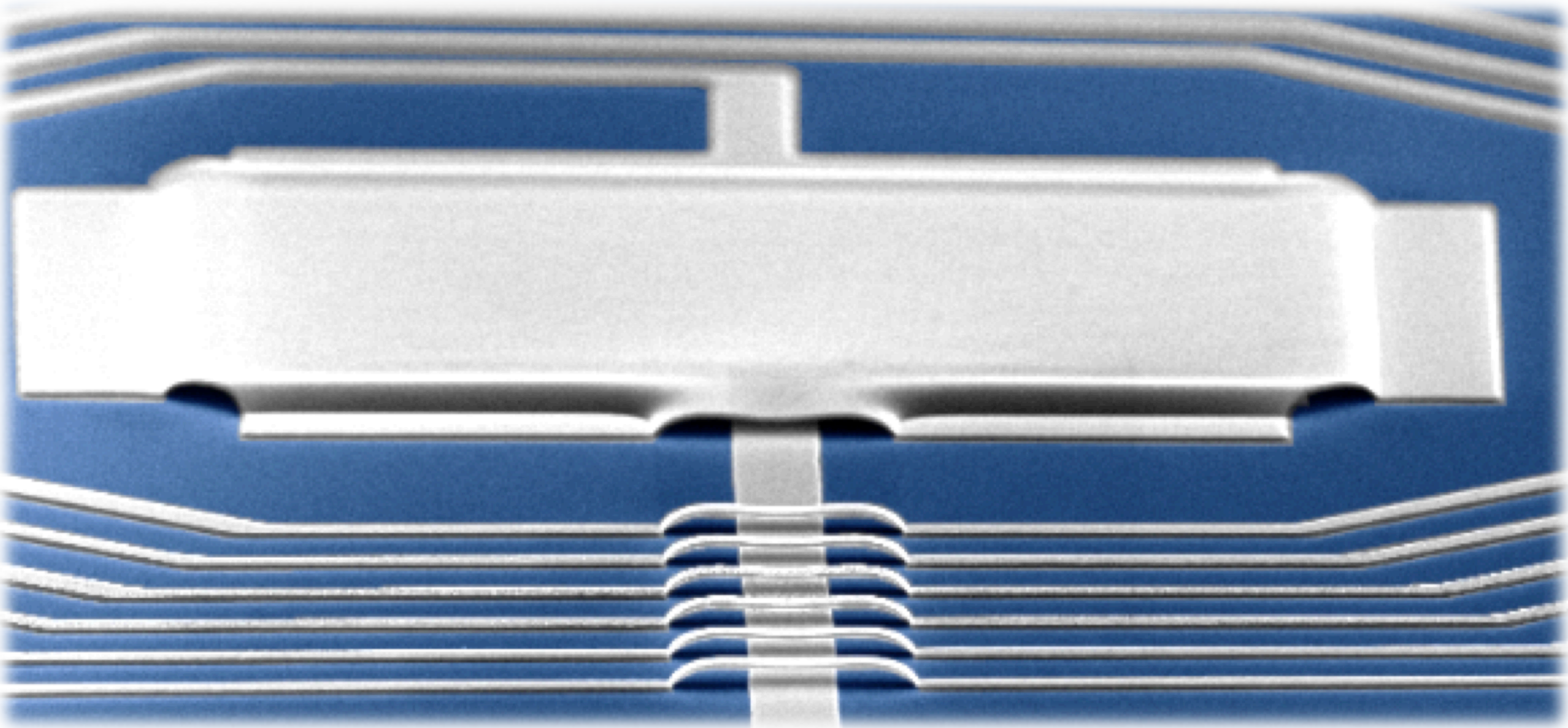
Quantum Sensors:

Superfluid Josephson Junctions



Keith Schwab, Caltech, Applied Physics

Remarkable Properties of Superfluid He-4

•Speed of first sound: c=240 m/s (x10 smaller than most metals)

•Speed of sound is tunable by 50% by adjusting pressure (0 to 25 atm)

•Density: ρ=145 Kg/m^3 (x10 less than most solids)

•Dielectric constant: 1.05, loss angle at microwave frequency is less than 10^{-10}

•Chemically pure (impurities freeze to container walls), <10^{-23} for our device (1mole)

•Isotopic impurities: He-3, concentration of n=10^{-7}. Concentration of n<10^{-14} has been achieved

•Transition temperature: T_λ= 2.17K, below this a complex macroscopic order parameter appears, Ψ

•Condensate available in liter quantities, no limit to lifetime

•Entropy resides in normal fluid density composed of rotons ($e^{-8K/kbT}$) and phonons (T^4) , can be cooled to millikelvin temperatures.

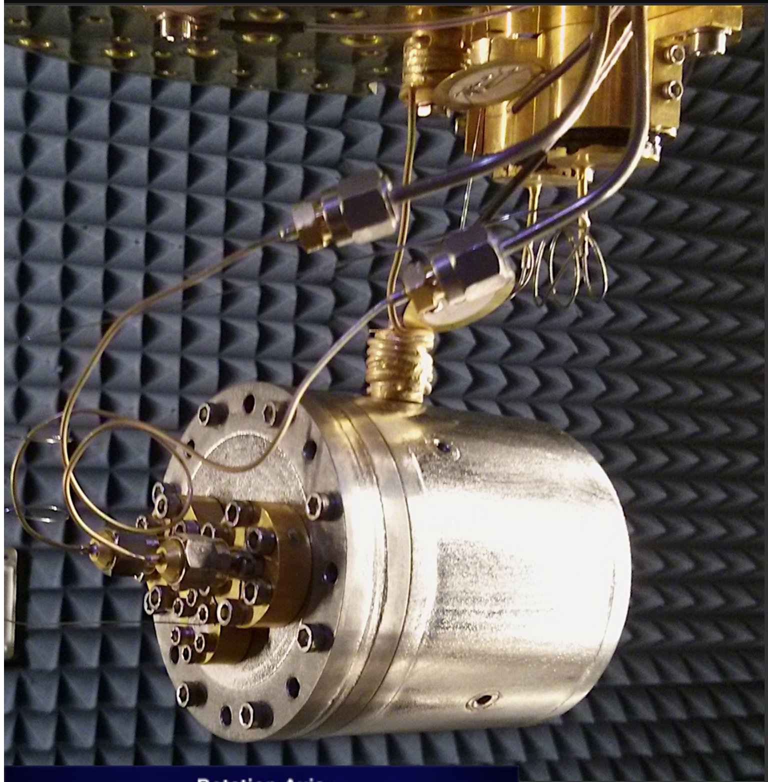
•Shows persistent mass currents (frictionless flow) below T_λ, quantized circulation around loops.

- Opportunities with Superfluid Helium

  - Superfluid Optomechanics
    - Quantum effects with gram/cm-scale mechanics
    - Continuous gravitational waves from pulsars
    - Search for limits to physical length scales

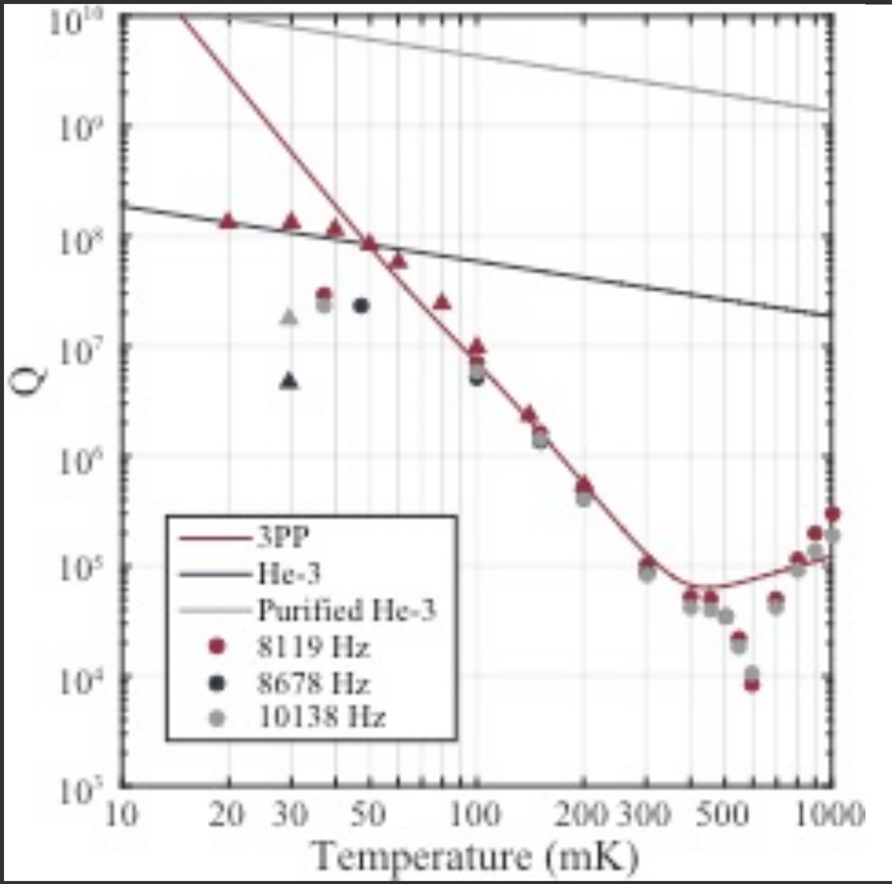
  - Superfluid Interferometers
    - New Josephson junction structures
    - Ultra-sensitive inertial sensor
    - Quantum circuits with helium

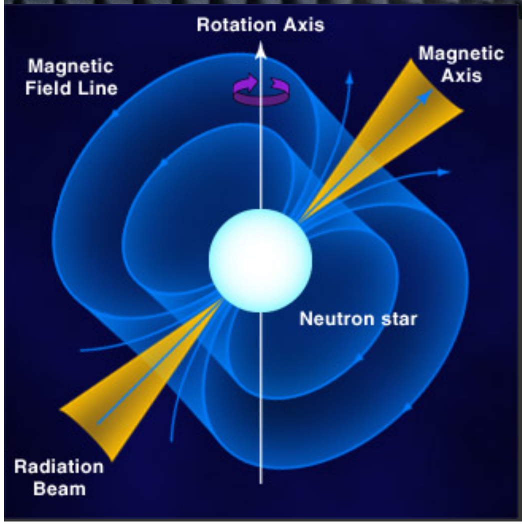
Ultra-high Q Superfluid Acoustic Resonators



F_{Nb} = 10GHz Q_{Nb} = 350M
F_{He} = 8KHz Q_{He} = 150M

Search for physics at length-scale below 1E-18m





Gravitational waves from nearby pulsars

Strain sensitivity h~1E-26 are possible

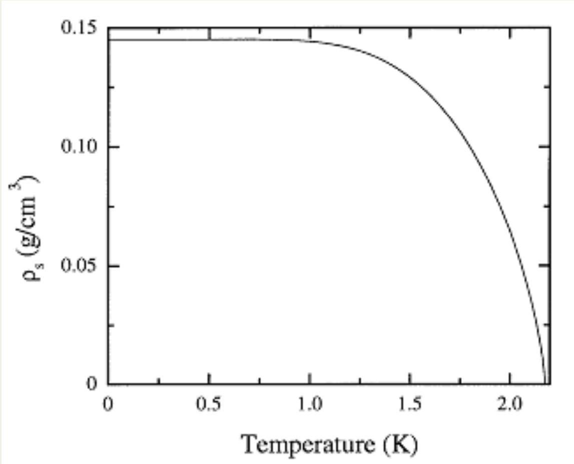
DeLorenzo and Schwab, JLPT *JLTP* **186**, 233 (2017)
Pikovski, et al. "Probing Planck-scale physics with quantum optics." *Nat. Phys*. 8.5 (2012): 393-397.
Detecting continuous gravitational waves with superfluid 4He, Singh, De Lorenzo, Pikovski, Schwab, New J. of Phys. 19 073023 (2017).

New Josephson Junction Structures for Helium-4

Superfluid ^{4}He: a quantum matter-wave

Below the transition temperature, a macroscopic complex order parameter appears:

$$\Psi\left(\vec{r},t\right)=\sqrt{\rho_s}e^{i\phi(\vec{r})}$$

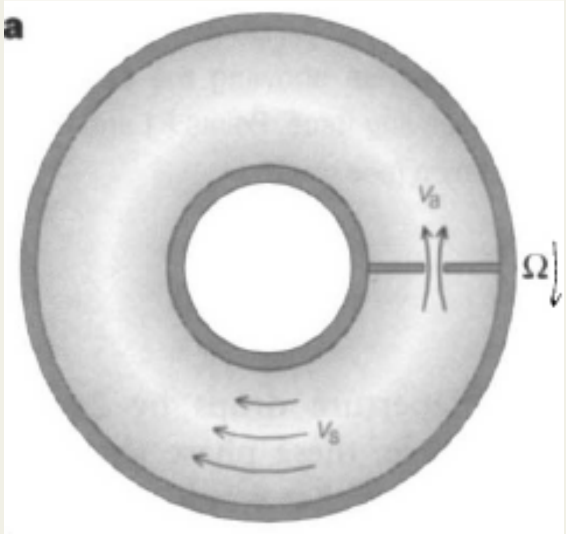


The wavelength of this matterwave is related to its velocity:

$$\vec{v}=\frac{\hbar}{m_4}\bigtriangledown\phi\left(\vec{r}\right)\rightarrow\lambda=\frac{h}{m_4}\frac{1}{v}=\frac{100nm}{v}$$

Rotation of a loop with a septum will induce a quantum phase difference:

$$\triangle\phi=4\pi\frac{h}{m_4}\vec{A}\cdot\vec{\Omega}$$



NB: Same relation between quantum phase and rotation rate for atom interferometers and optical Sagnac interferometers:

Past work with Helium – Superfluid gyroscope

letters to nature

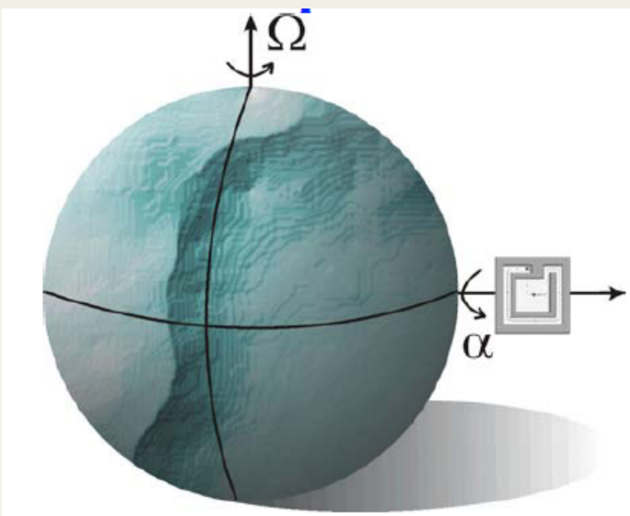
Detection of the Earth's rotation using superfluid phase coherence

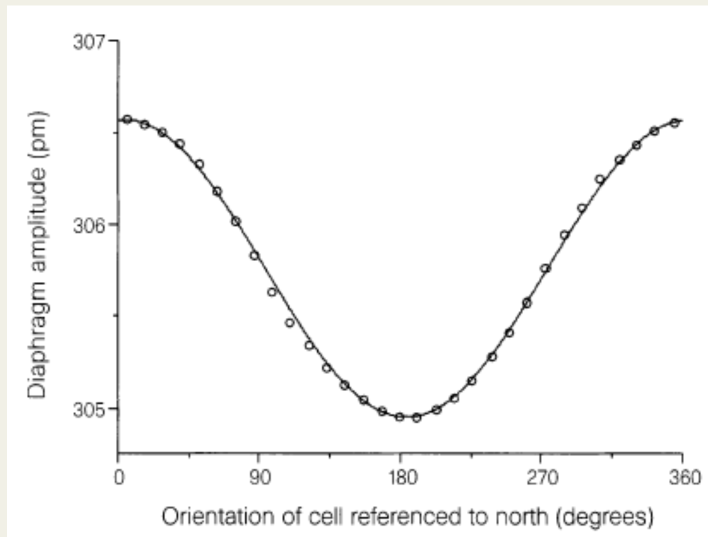
Keith Schwab, Niels Bruckner & Richard E. Packard

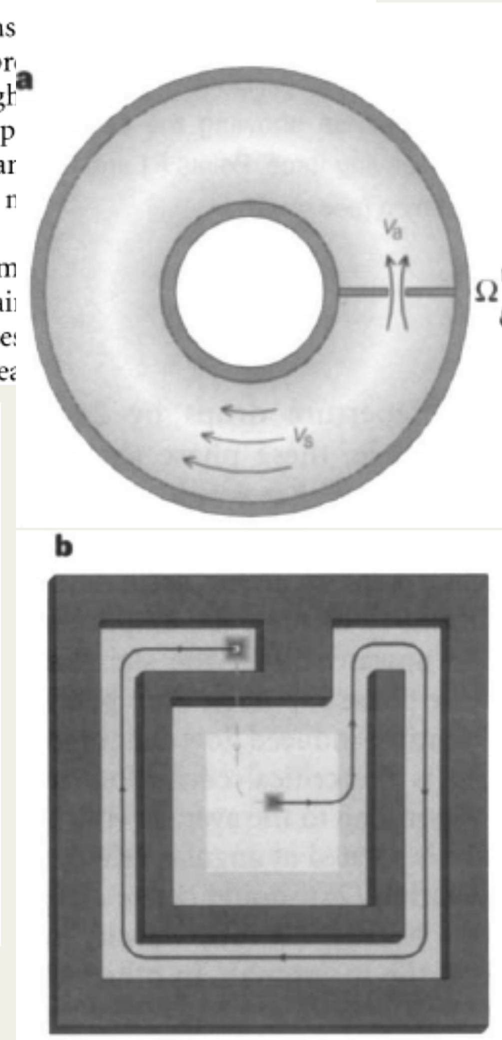
Physics Department, University of California, Berkeley, California 94707, USA

is given in the figure legend. The tens
seals the upper surface of the device pr
reservoir, and the fluid passing through
and around the peripheral channel p
reservoir. The oscillator has a resonar
exhibits a Q of 20,000 at $T = 280$ r
temperature.

Figure 2 is a plot of the oscillation am
applied electric drive. The observed stai
istic feature of these double-hole device
by the first step is due to the fluid rea





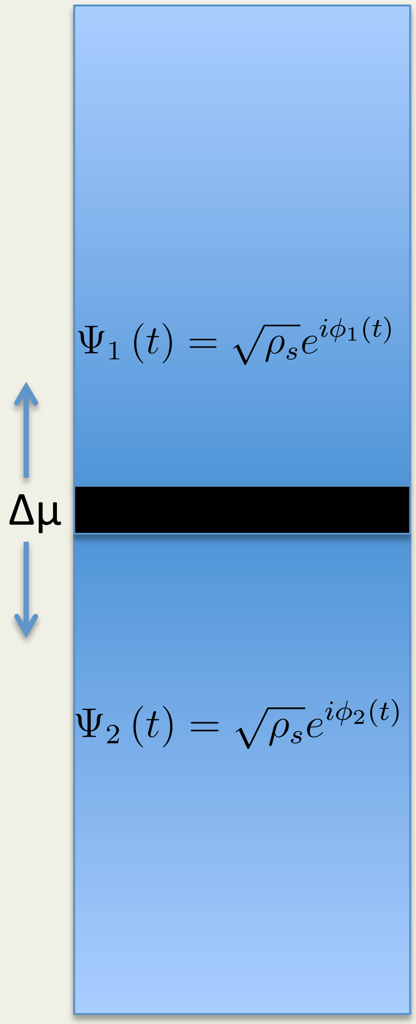


$0.3\,\Omega_{\oplus}\mathrm{Hz}^{-1/2}$ K.C. Schwab, et al, *Nature* **386**, 586 (1997)

$0.04\,\Omega_{\oplus}\mathrm{Hz}^{-1/2}$ N. Bruckner, et al, *J. Appl. Phys.* ***93**, 1798 (2003)*, no detectable drift to 10^{-5} Hz

What is the Josephson effect and why is it useful for interferometers?

Planar structure



condensate

tunnel junction

condensate

$$\triangle\phi(t) = \phi_1(t) - \phi_2(t)$$

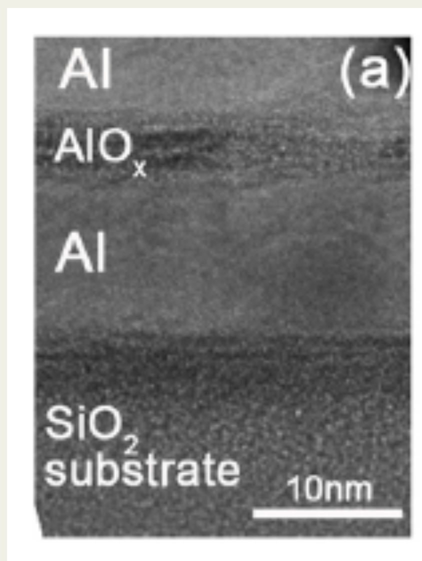
Consequences of Schrodinger dynamics:

DC Josephson effect:

$$I(\triangle\phi) = I_c \sin\triangle\phi$$

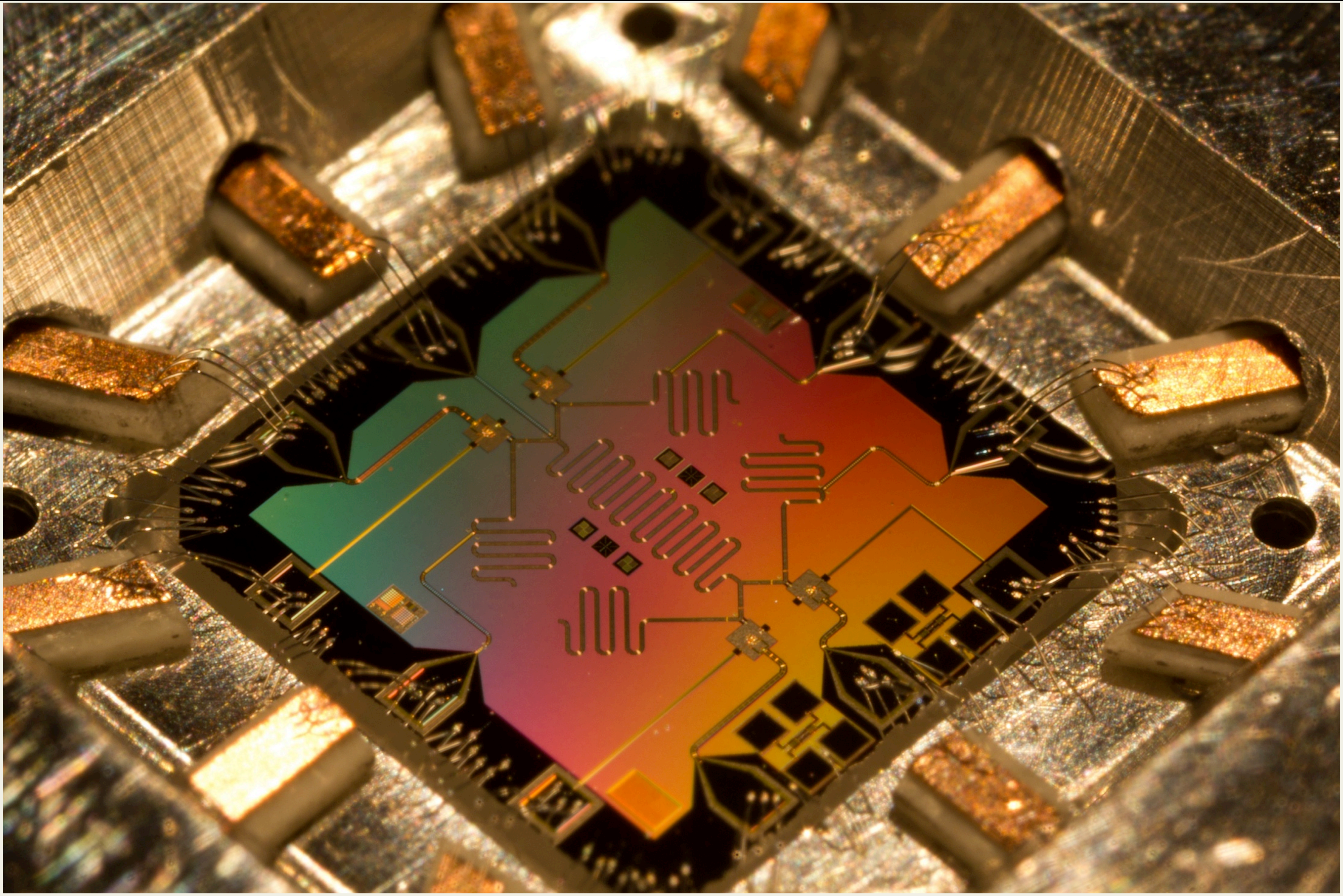
AC Josephson effect:

$$\frac{d}{dt}\Delta\phi(t) = -\frac{\Delta\mu}{\hbar}$$



Zeng, L. J., et al. "Nanoscale interaction layer at the interface between Al films and SiO2 substrates of Al/AlOx/Al Josephson tunnel junctions." *Journal of Applied Physics* 113.14 (2013): 143905.

Where does this lead? State of the art quantum computing devices



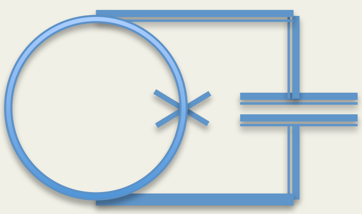
Martinis Group

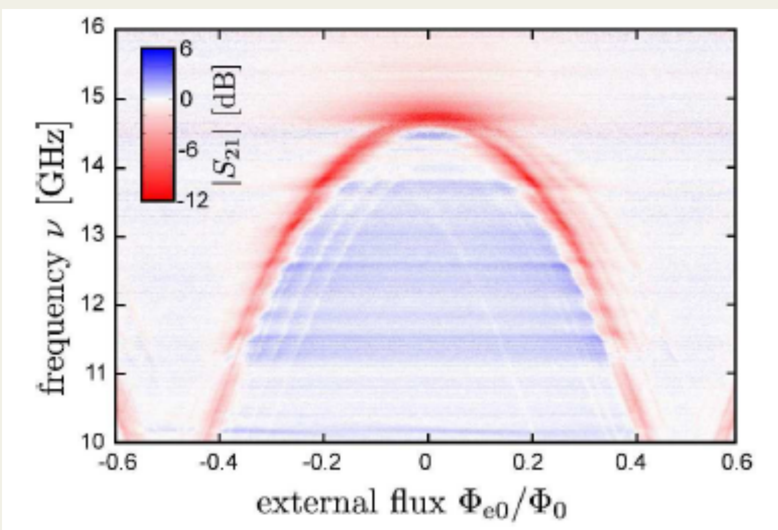
Non-linear response of junction provides signal for quantum phase

Single junction interferometer:

Frequency of resonance is modulated with quantum phase

$$L_J(\triangle\phi) = \frac{\hbar}{m_4}\frac{1}{I_c \cos\triangle\phi}$$

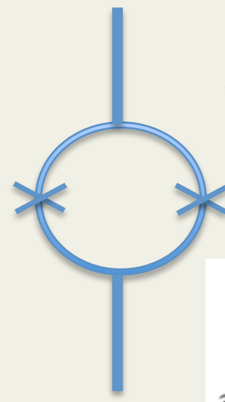


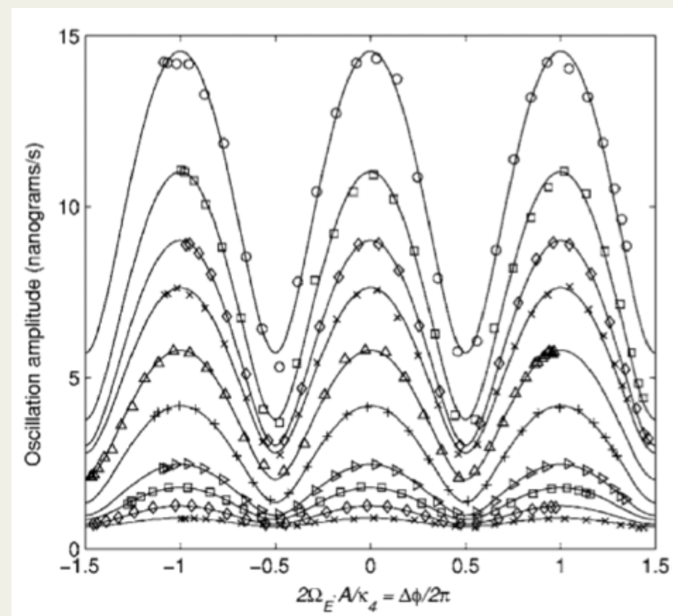


Two junction interferometer:

Critical current of parallel junctions is modulated by quantum phase

$$I_{c(total)}(\triangle\phi) = 2I_c\,|\sin(\triangle\phi/2)|$$





Past work with Helium – Josephson Effect in ^{4}He

First observed in 4He in 2001 at JPL: Sukhatme, Kalyani, et al. "Observation of the ideal Josephson effect in superfluid 4He." *Nature* 411.6835 (2001): 280-283.

Junction structure explored was an array of submicron apertures

Since coherence length is 0.3nm for $T << T_\lambda$ Josephson effect was observed in 4He working very close to T_λ:
$T_\lambda - T < (100\mu K – 1mK)$

$$\xi(T) = \frac{0.3nm}{(1 - T/T_\lambda)^{2/3}}$$

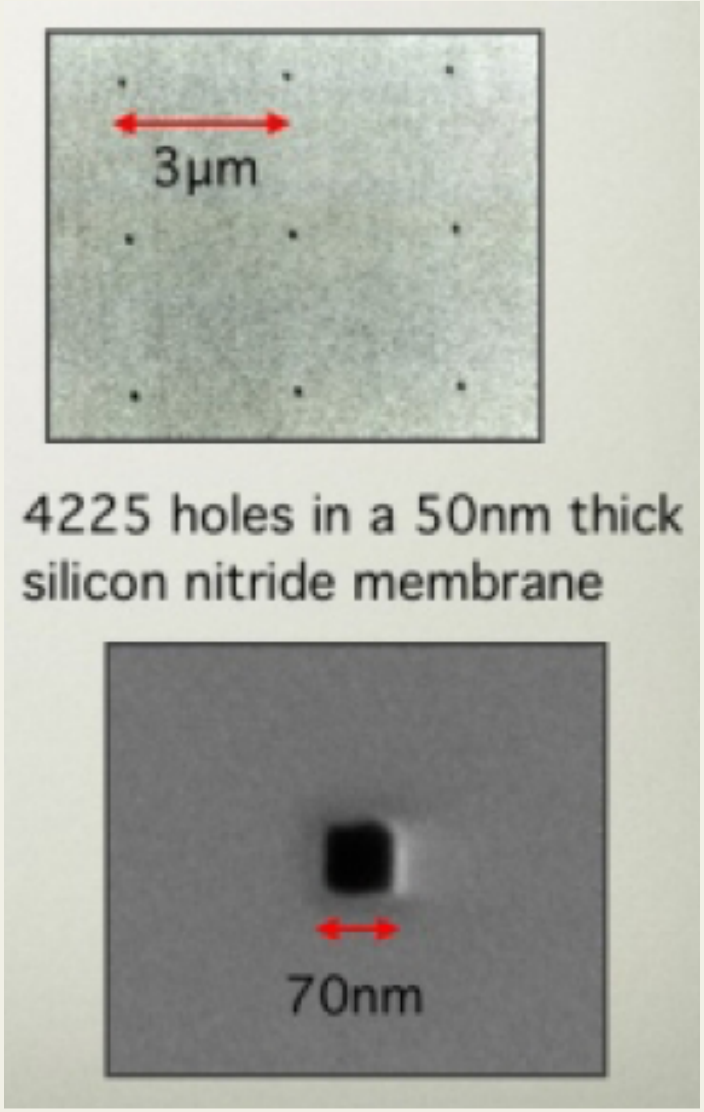
This has significant disadvantages for the ultimate sensitivity interferometry:

$\rho_s/\rho_o \sim 0.001 - 0.01$ which limits critical mass current I_C

T~2K which adds thermal noise

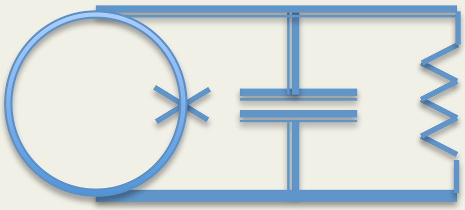
Furthermore, detection of the superfluid current was far from fundamental thermal limits.

Ω/rtHz ~1.0 $\Omega_\oplus$/rtHz



Sato, Y., and R. E. Packard. "Superfluid helium quantum interference devices: physics and applications." *Reports on Progress in Physics* 75.1 (2012): 016401.

Ultimate sensitivity of superfluid Interferometers



Dissipation and noise originate from thermal motion of normal component, this produces a pressure noise across the junction which give a current noise and resulting phase noise.

$$\Delta\phi = \frac{4\pi h}{m_4} A \cdot \Omega = \frac{4\pi}{\kappa_0} A \cdot \Omega$$

Ultimate resolution limited by thermal noise

$$\Delta\Omega/\sqrt{Hz} \sim \frac{\kappa_0}{4A}\sqrt{\frac{2k_b T m_4}{\pi^3 f Q \hbar I_c}} \sim 3 \cdot 10^{-7}\Omega_\oplus/\sqrt{\mathrm{Hz}}$$

F=100Hz
Q=100
I_c = 10^{-8} kg/s
T=1.2K
A=10^{-3} m^2

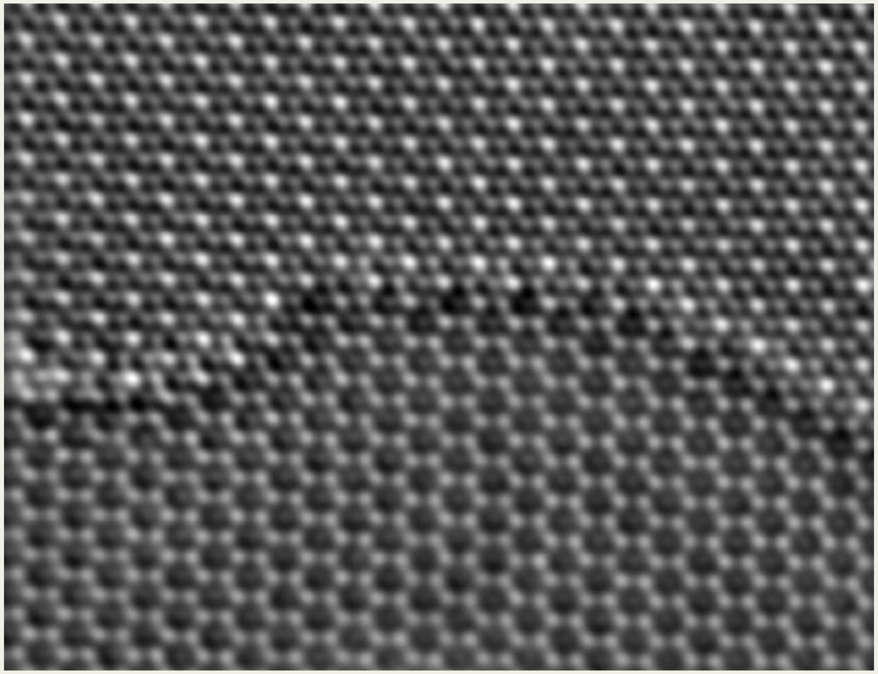
This is sufficient to observe fluctuations in length of day: $10^{-9} \cdot \Omega_\oplus$ (1 rev in 3M yrs)

Compare this to best realized sensitivity of $1 \cdot \Omega_\oplus/Hz^{1/2}$ with Josephson effect and $0.04 \cdot \Omega_\oplus/Hz^{1/2}$ with phase slips

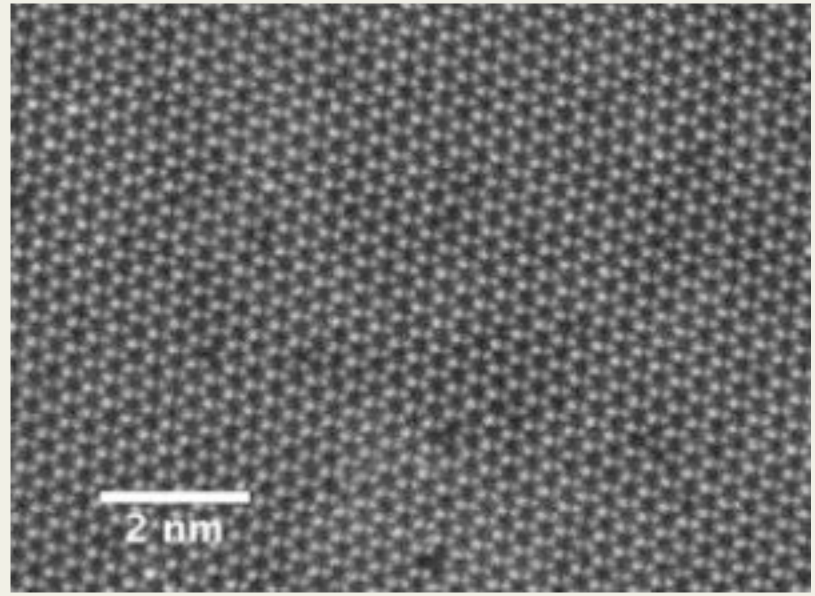
$0.3\,\Omega_\oplus Hz^{-1/2}$ K.C. Schwab, et al, *Nature* **386**, 586 (1997).

$0.04\,\Omega_\oplus Hz^{-1/2}$ N. Bruckner, et al, *J. Appl. Phys.* ***93***, *1798 (2003)*.

Planar junction structures for Helium-4 (graphene and transition metal dichalgagenides)----too opaque



High resolution TEM of single and double layer graphene
Urban, Knut W. "The challenges of graphene." *Nature materials* 10.3 (2011): 165-166.



High resolution TEM of single layer of $MoSe_2$
X. Wang, et al., *Chemical Vapor Deposition Growth of Crystalline Monolayer MoSe2*
ACS Nano, (2014), 8, 5125-5131

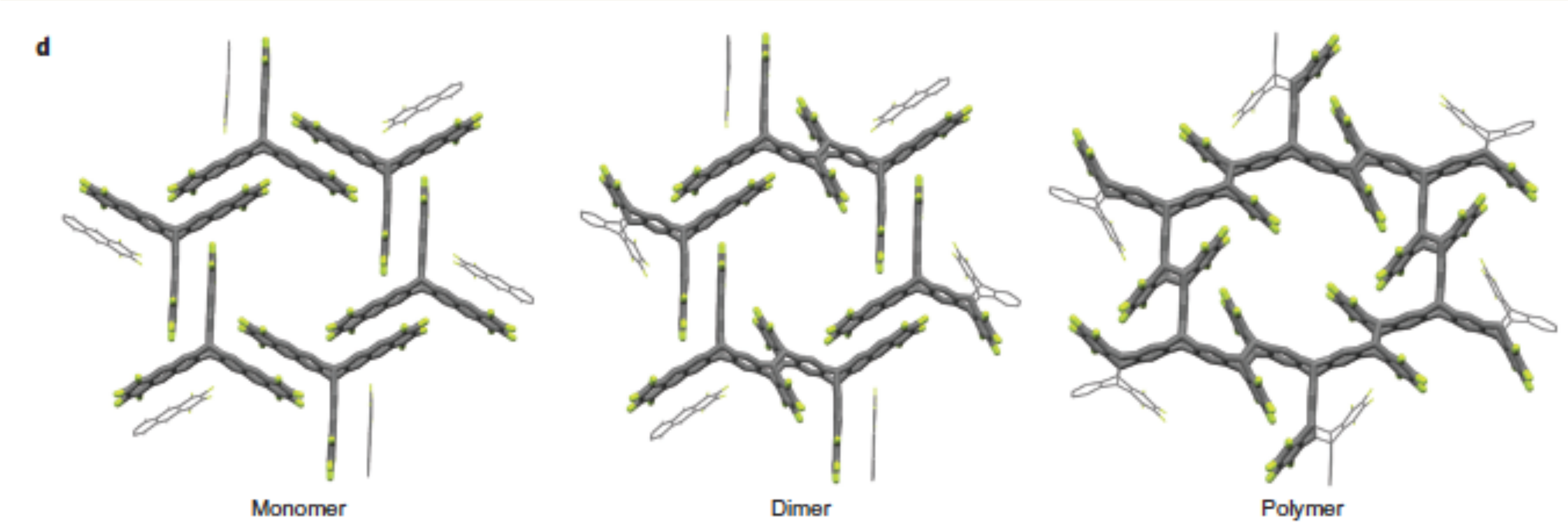
5eV barrier for He atom

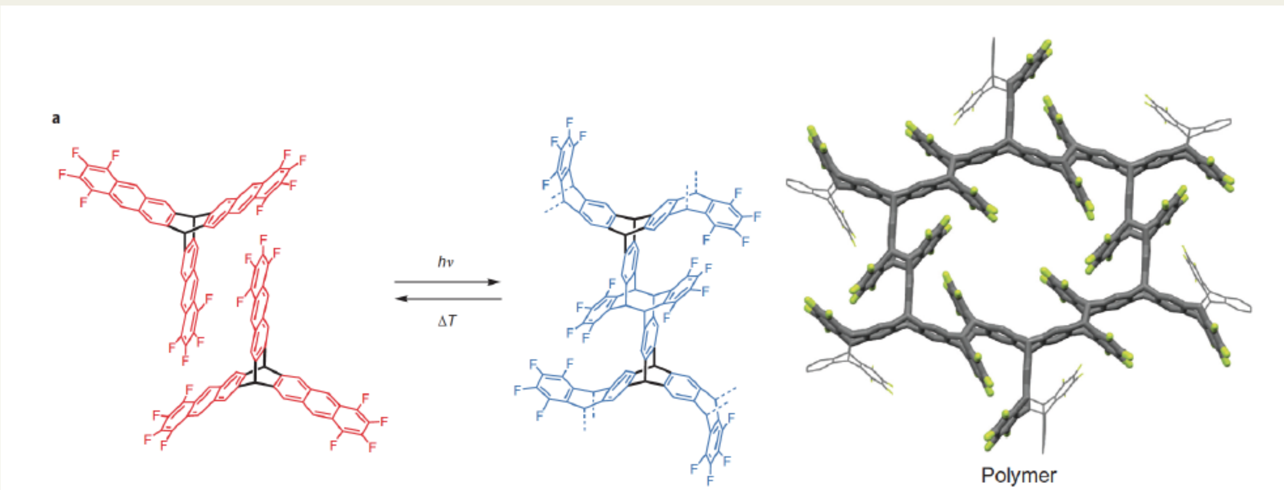
20eV barrier for He atom

$$\Gamma \sim \omega \exp\left(-l\sqrt{\frac{2m_{He}}{\hbar^2}\left(V-E\right)}\right) \sim e^{-300}$$

Quantum tunneling rate way too small

Molecular engineered 2D materials --- Prof. Ben King (Univ. of Nevada, Reno)

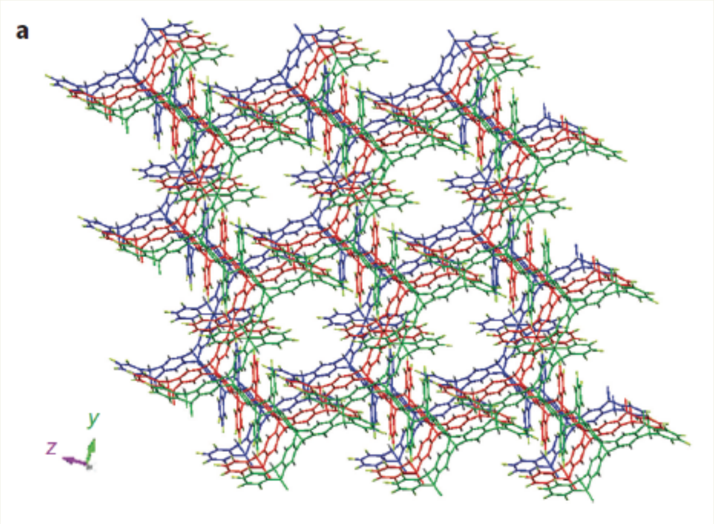


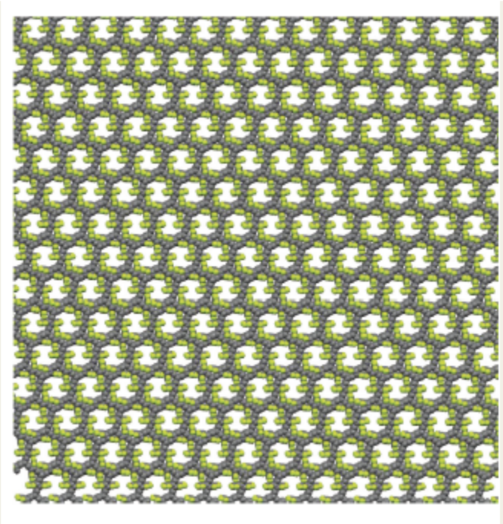


Other possibilities are BN with some of the nitrogen atoms knocked out with TEM, or defects in graphene sheets

Kissel, P.; Murray, D.J.; Wulftange, W.J.; Catalano, V.J.; King, B.T. A nanoporous two-dimensional polymer by single-crystal-to-single-crystal photopolymerization. *Nat. Chem.* **2014**, *6*, 774-778.

Molecular engineered 2D materials --- Prof. Ben King (Univ. of Nevada, Reno)





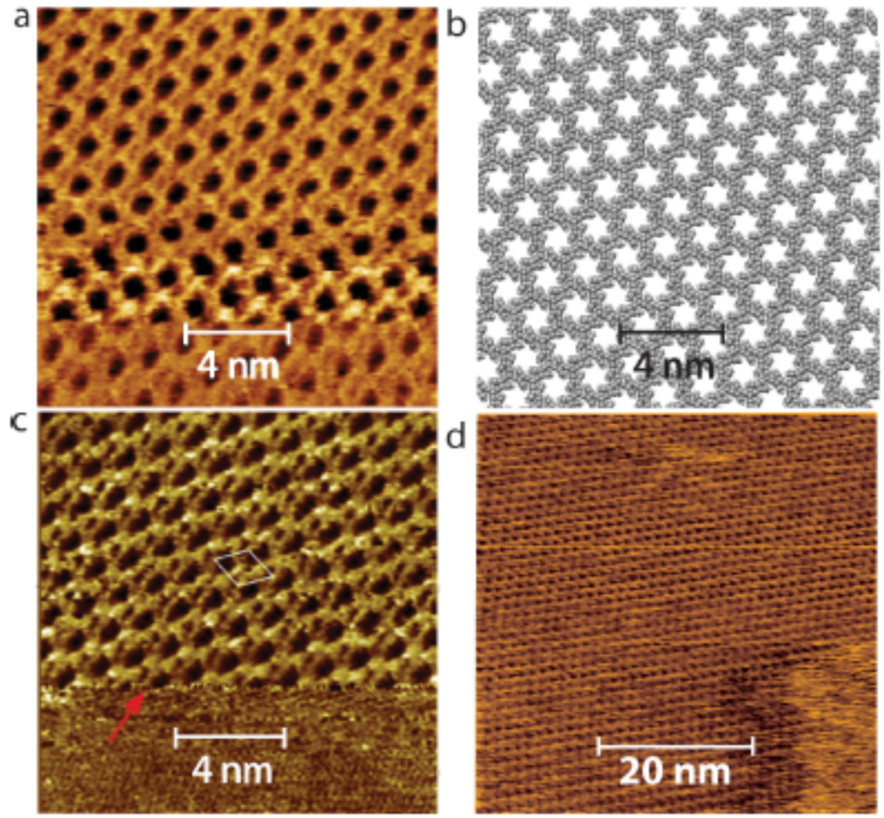
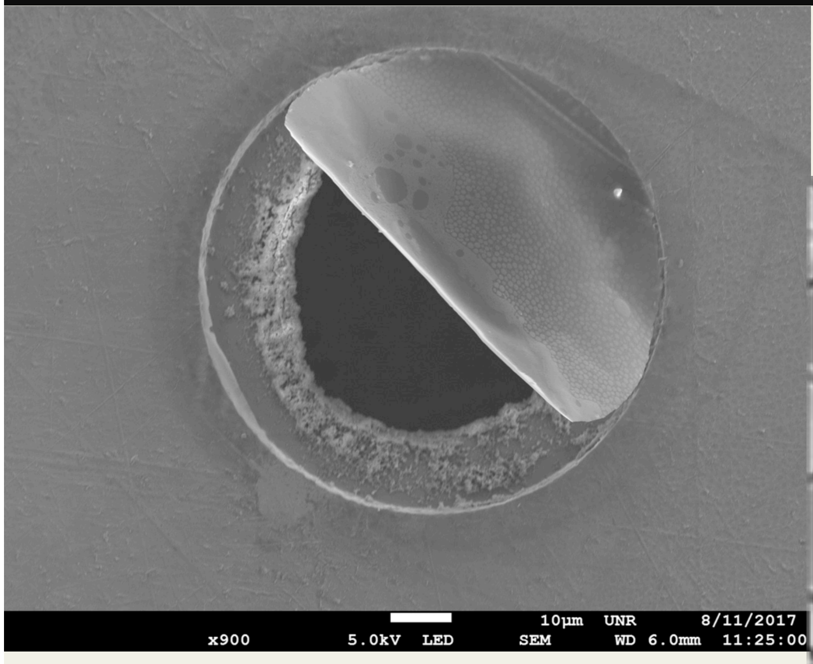
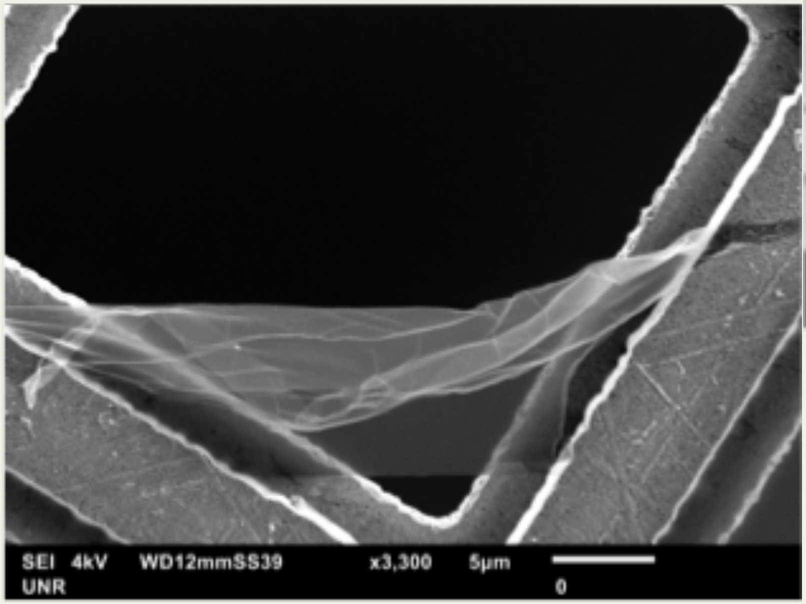


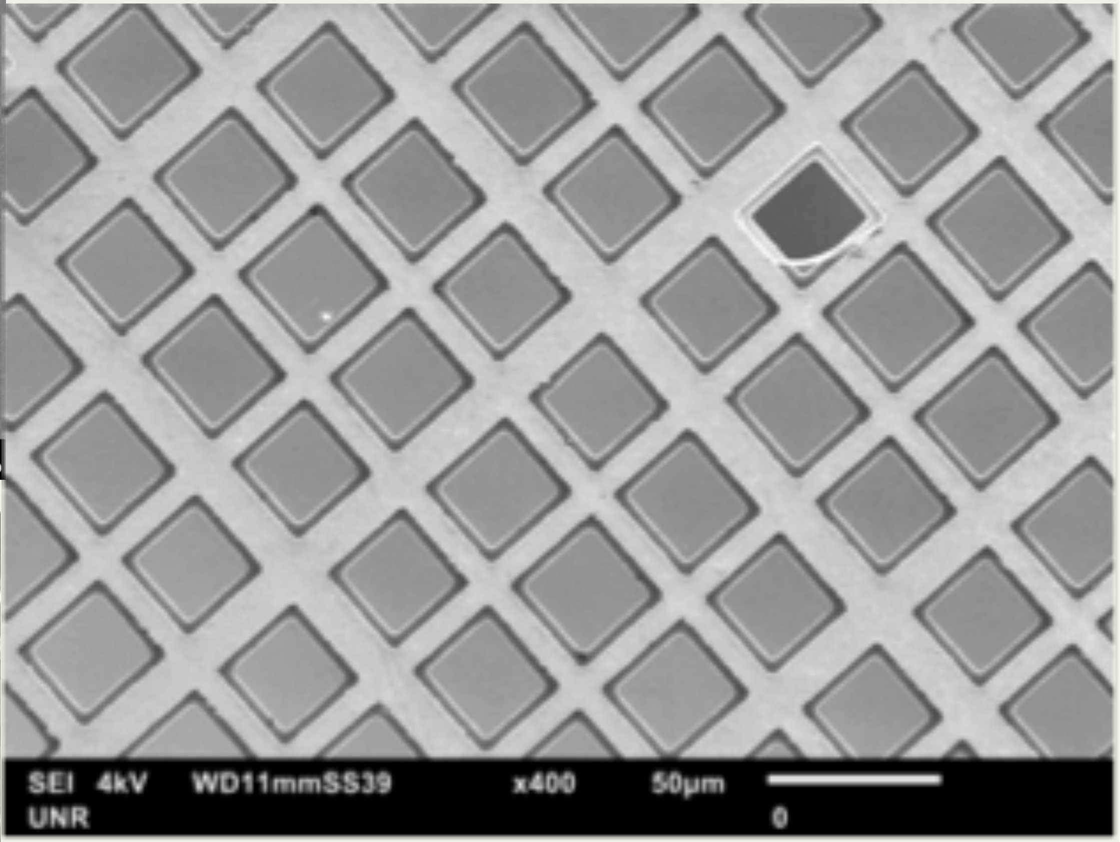
Figure 5. (a) STM image (+ 0.91 V, 28 pA) of poly(antrip-DEG) on HOPG. (b) Simulated poly(antrip-DEG) *p*6 lattice at the same scale as image a. (c) Split image of monolayer poly(antrip-DEG) on HOPG showing both the 2DP lattice and the underlying HOPG lattice; the arrow marks the scan-line where the imaging parameters were changed. (d) Wide view STM image (+1.0 V, 25 pA) of poly(antrip-DEG) on HOPG under 1-phenyloctane showing a domain edge at the lower right corner.

Large Area Synthesis of a Nanoporous Two-Dimensional Polymer at the Air/Water Interface, Murray, Patterson, Payamyar, Bhola, Song, Lackinger, Schluter, King, *J. Am. Chem. Soc.* **137**, 3450 (2015)

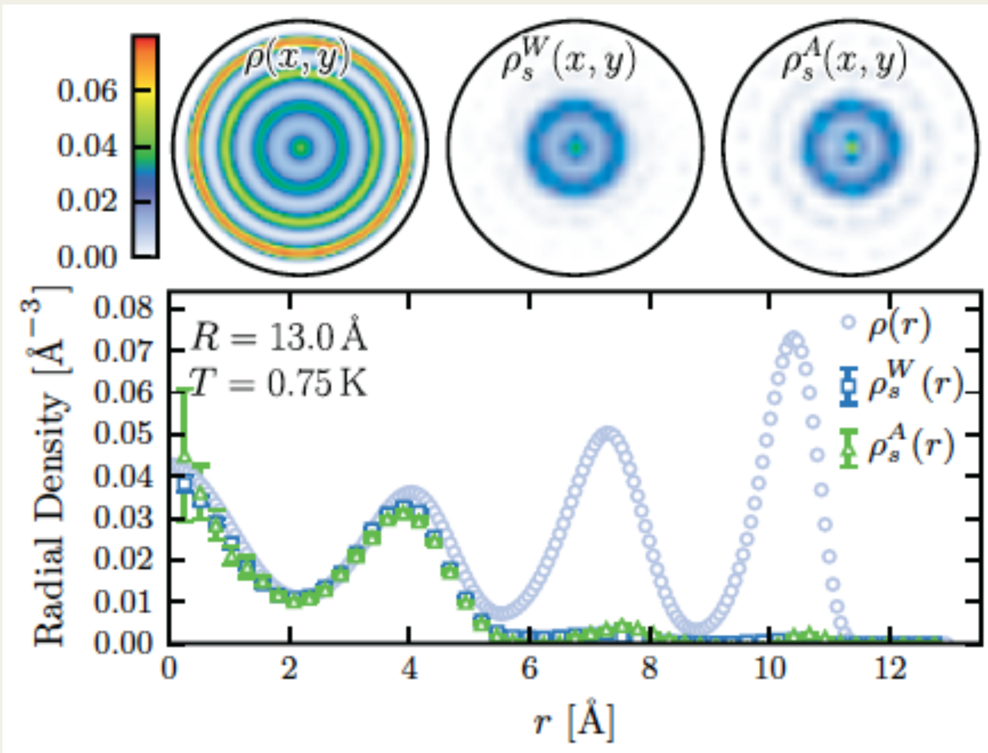
Molecular engineered 2D materials --- Prof. Ben King (Univ. of Nevada, Reno)

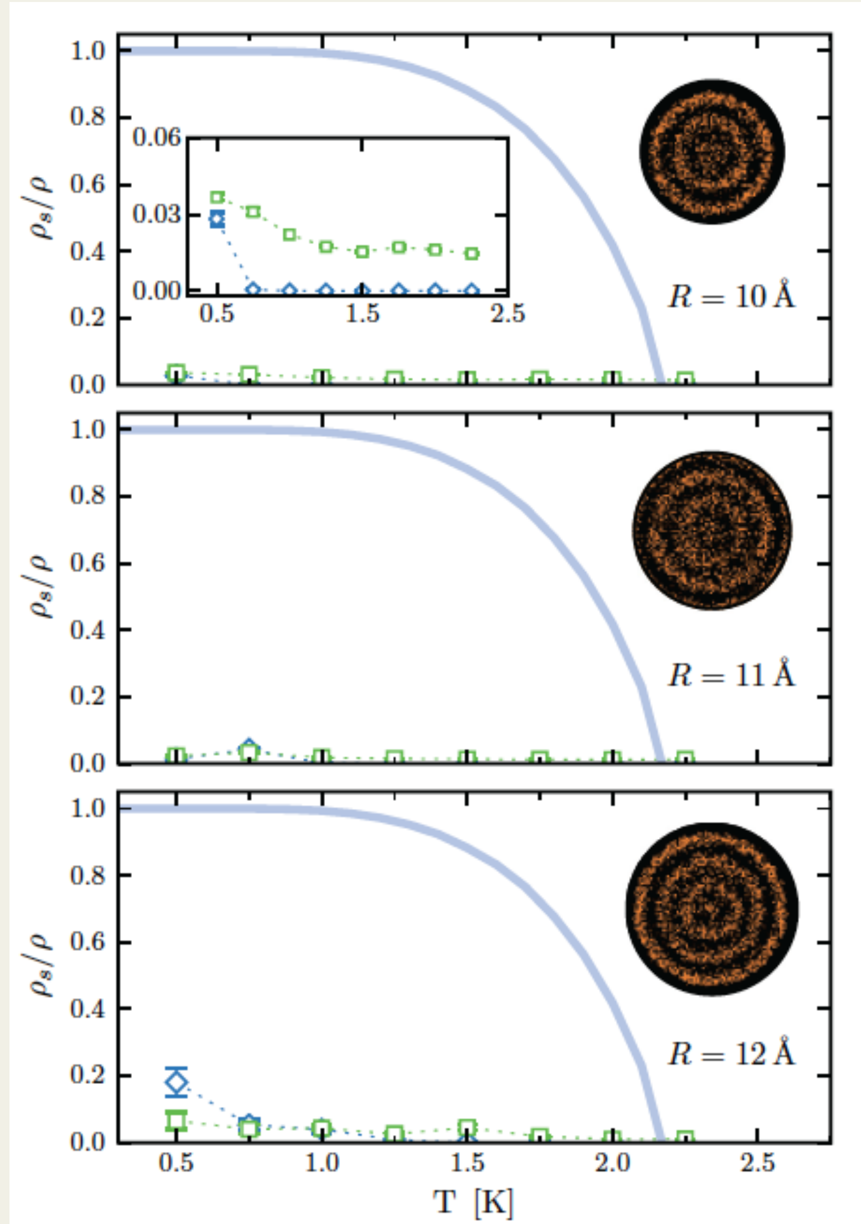






Computing the behavior of helium in junctions

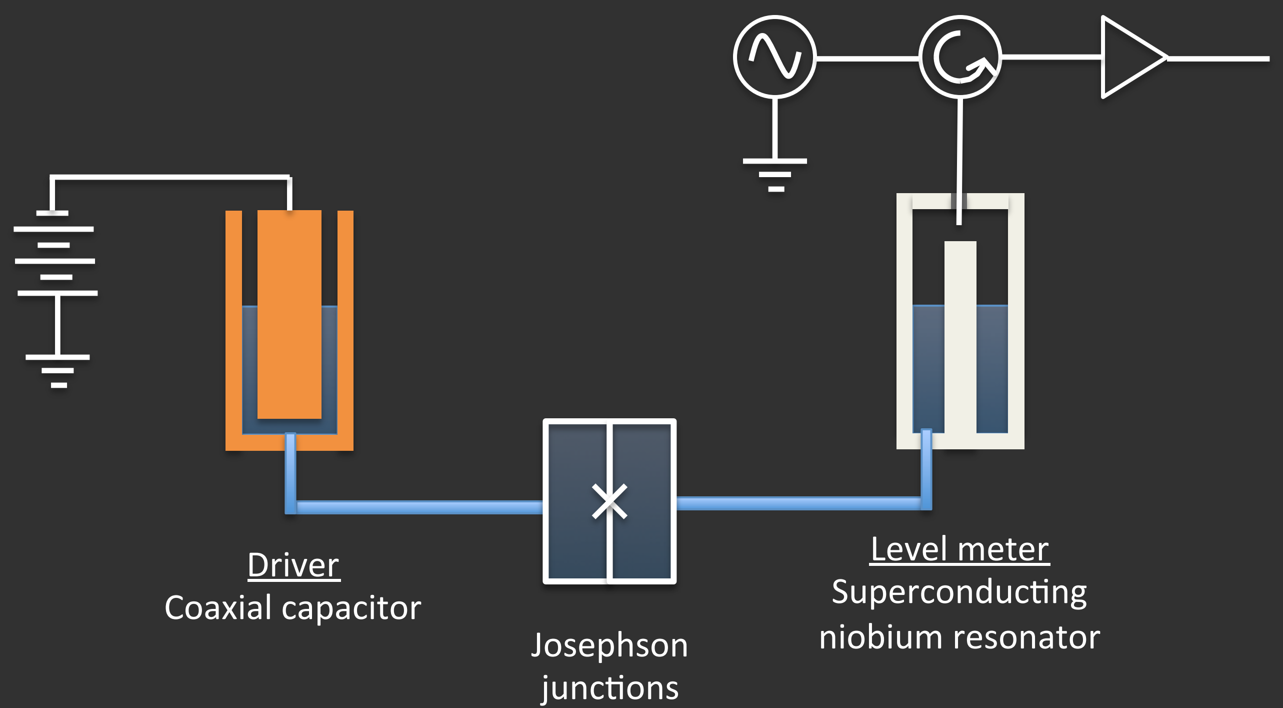




Local superfluidity at the nanoscale, Kulchytskyy, Gervais, Del Maestro, *Phys. Rev. B* **88** , 064512 (2013)

Path integral Monte Carlo simulation of global and local superfluidity in liquid 4He reservoirs separated by nanoscale apertures, Volkoff, Kwon, Whaley, *Phys. Rev. B* **94**, 144510 (2016).

Scheme to measure transport through 2D molecular material



$$\Delta m = \rho\pi\left(R_{out}^2 - R_{in}^2\right)\Delta x = \frac{\pi\left(\epsilon_{He}-1\right)\epsilon_0}{g\log\left(\frac{R_{out}}{R_{in}}\right)}V_{DC}^2$$

$$\Delta m = \rho_0 A_{\mu w}\Delta x = \frac{2\rho_0 A_{\mu w} l}{Q_{\mu w}}\cdot\frac{\Delta V}{V_p}$$

V_{DC} = 30V

Δm = 10^{-9} kg
Δx = 10^{-6} m

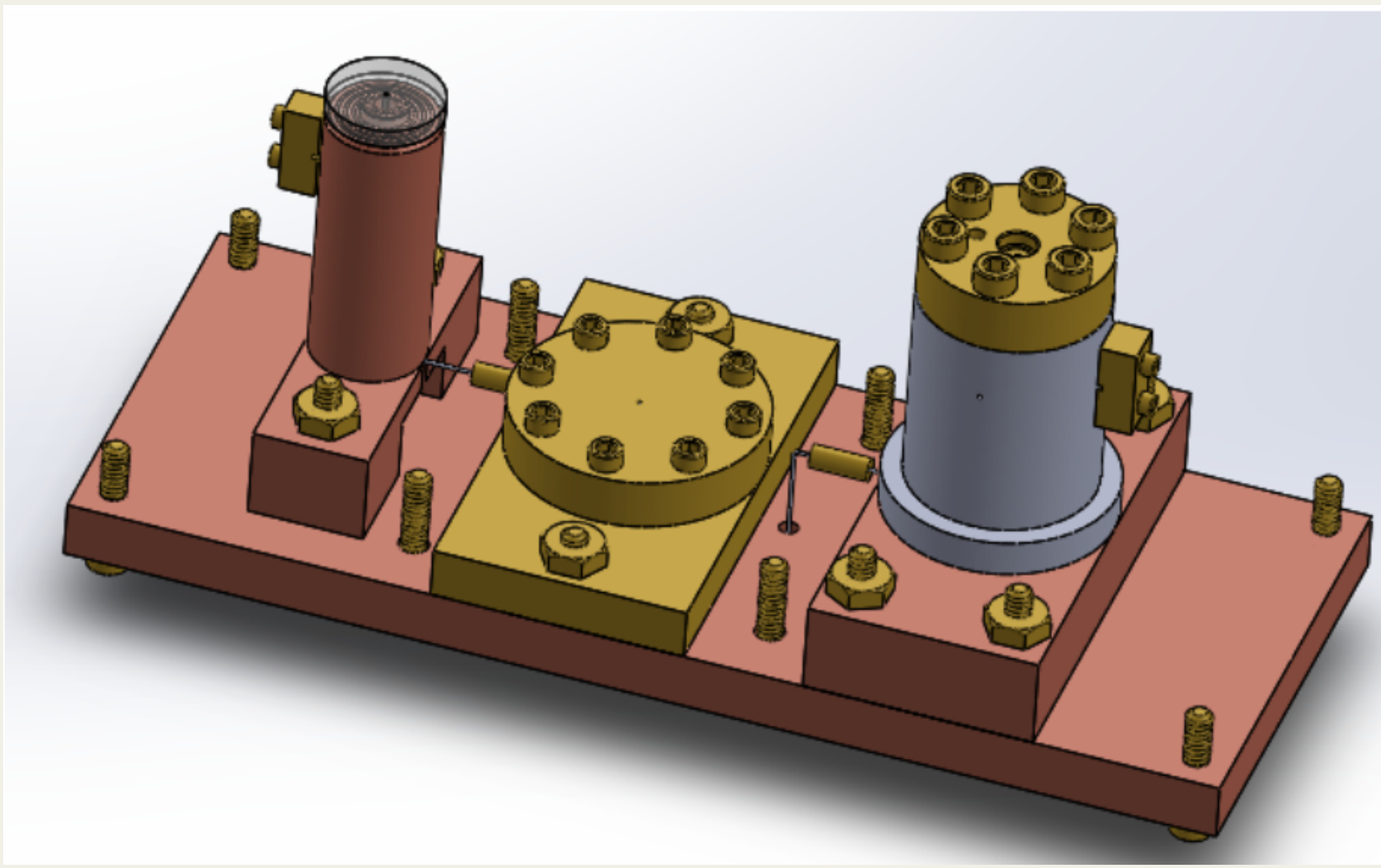
Q=10^6
Vp=10mV
Aμw=10^{-5}m^2
Δm = 10^{-17} kg in 1 sec of measurement
Δx = 10^{-14} m

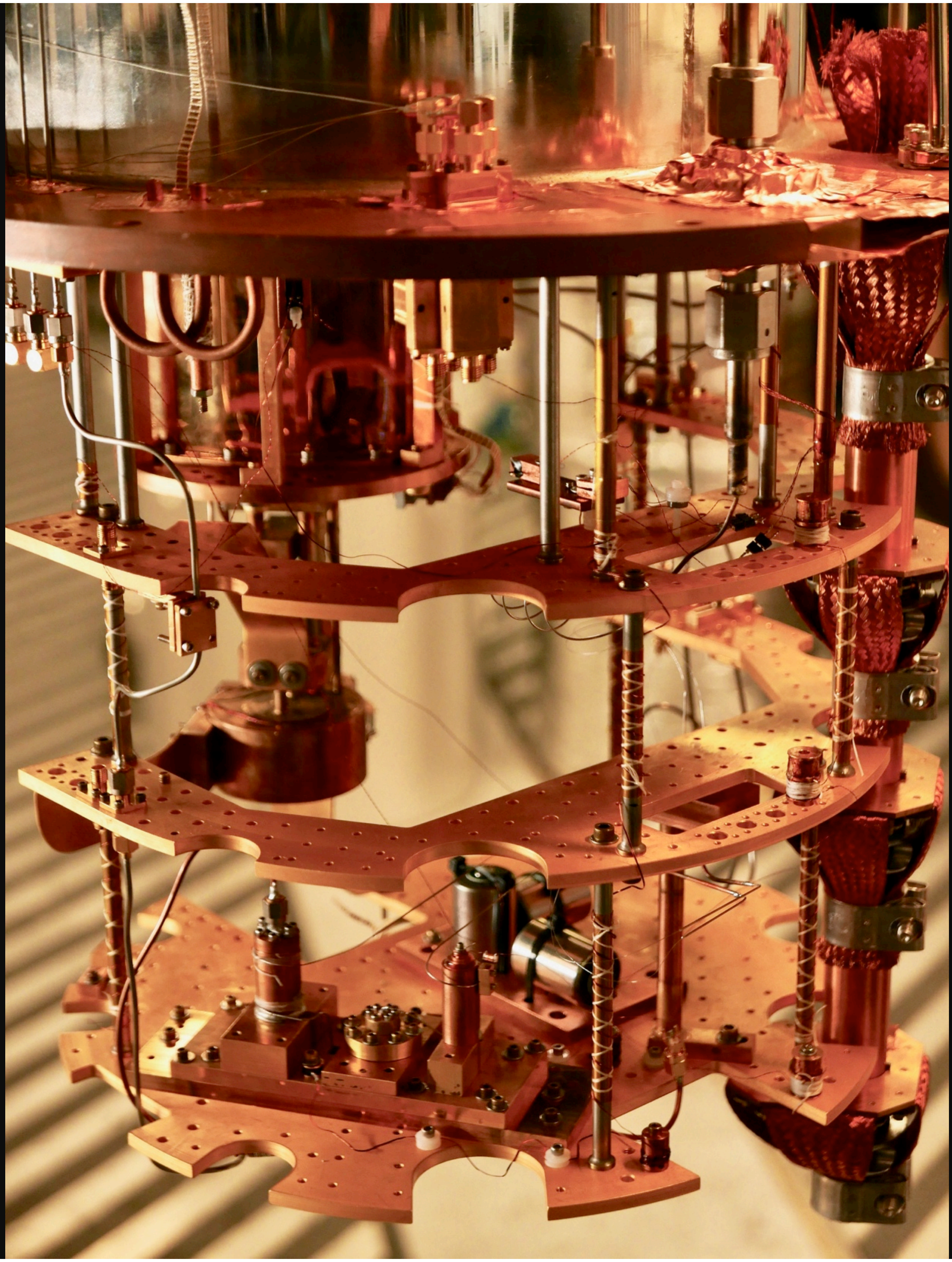
Superfluid Interferometers – advances in Josephson Junctions and detection

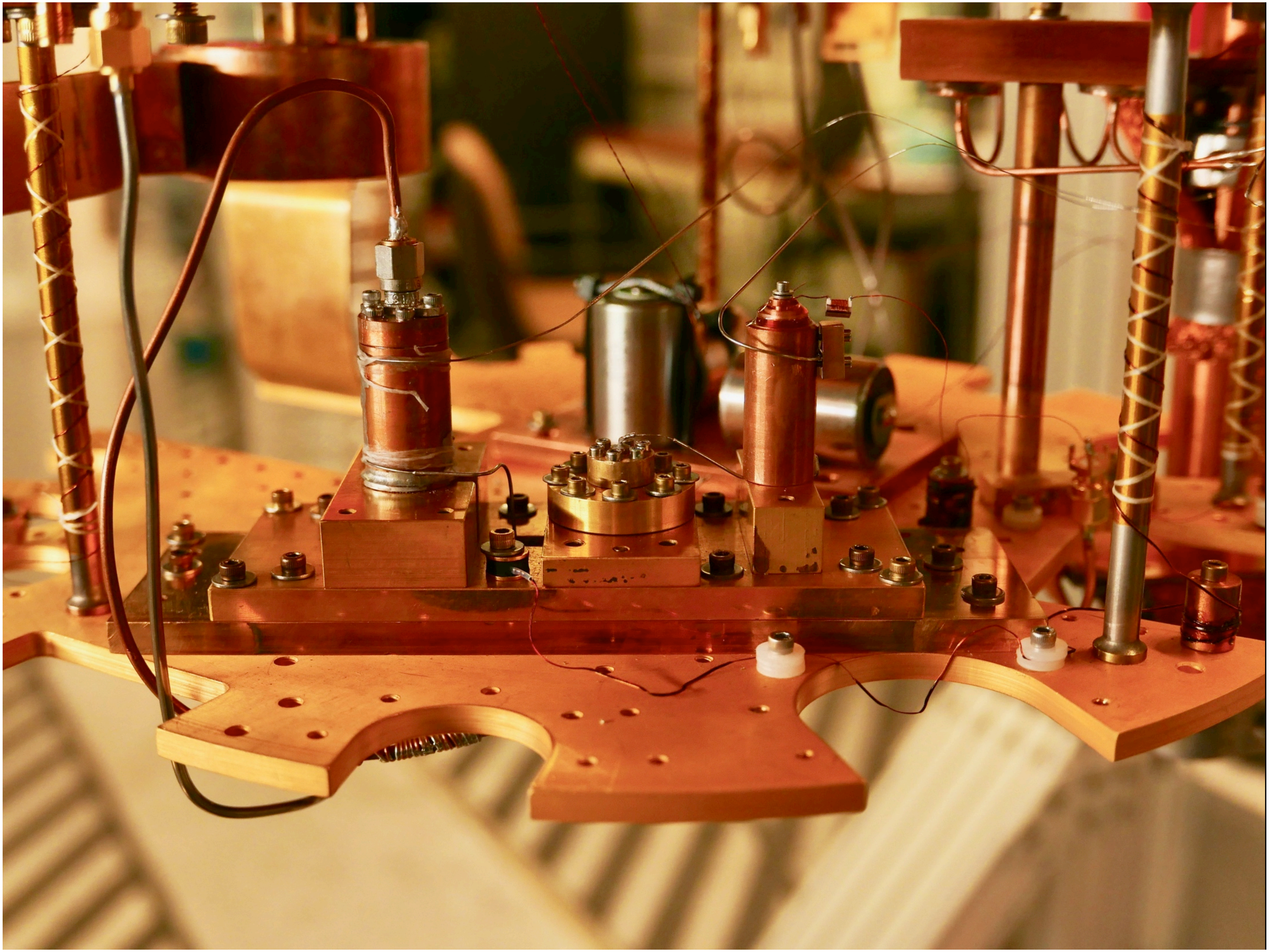
<u>Driver</u>
Coaxial capacitor

Josephson
junctions

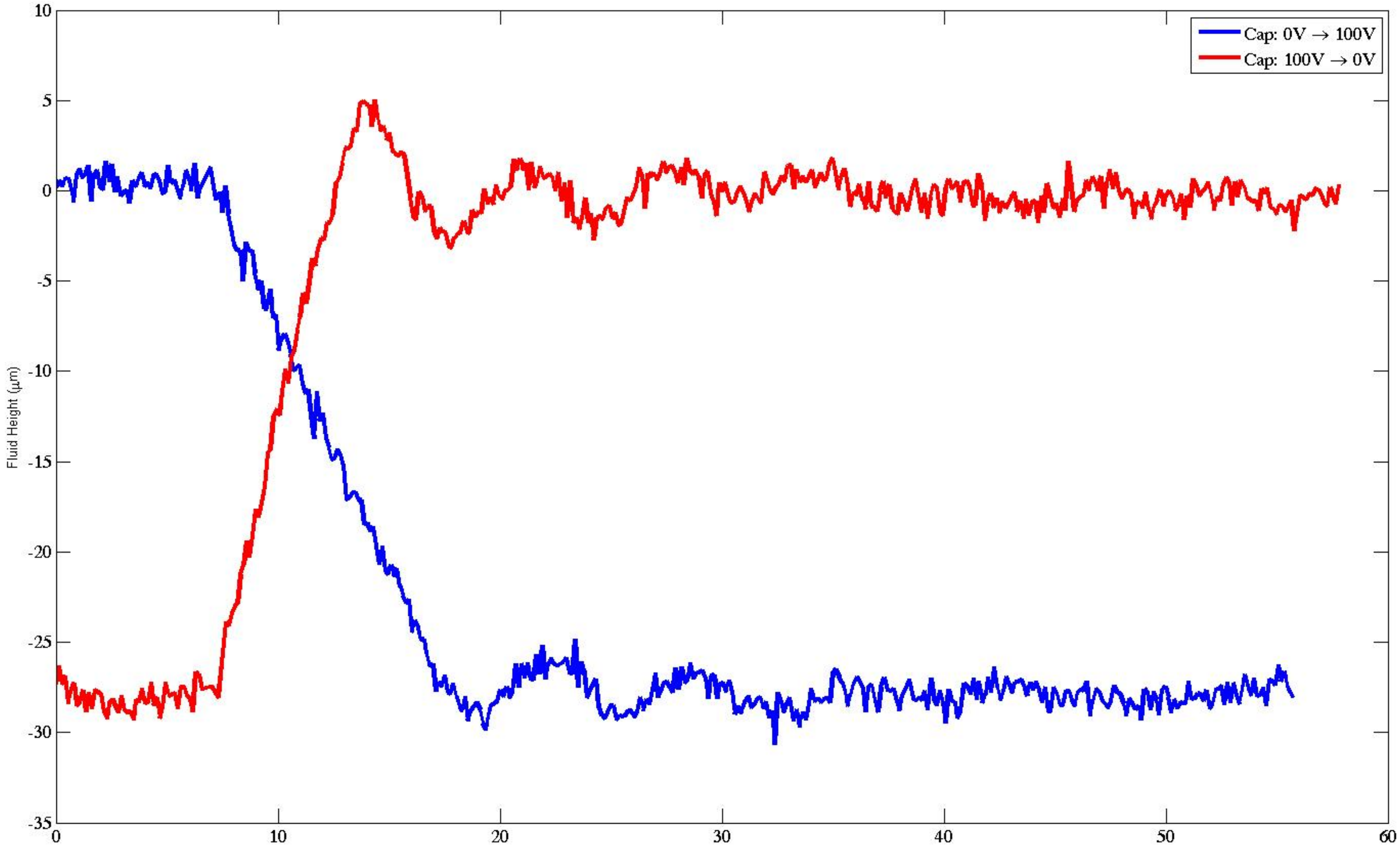
<u>Level meter</u>
Superconducting
niobium resonator



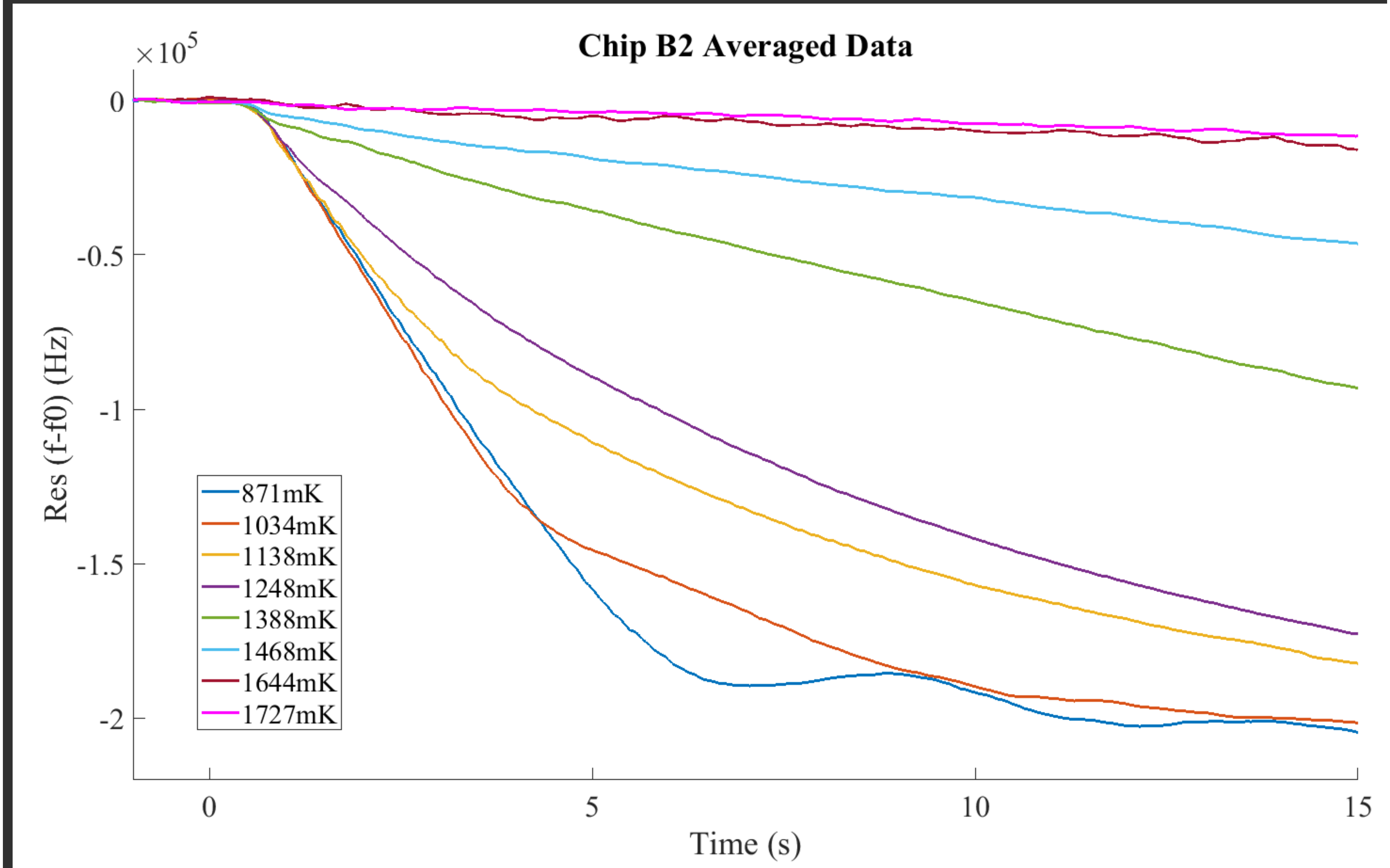




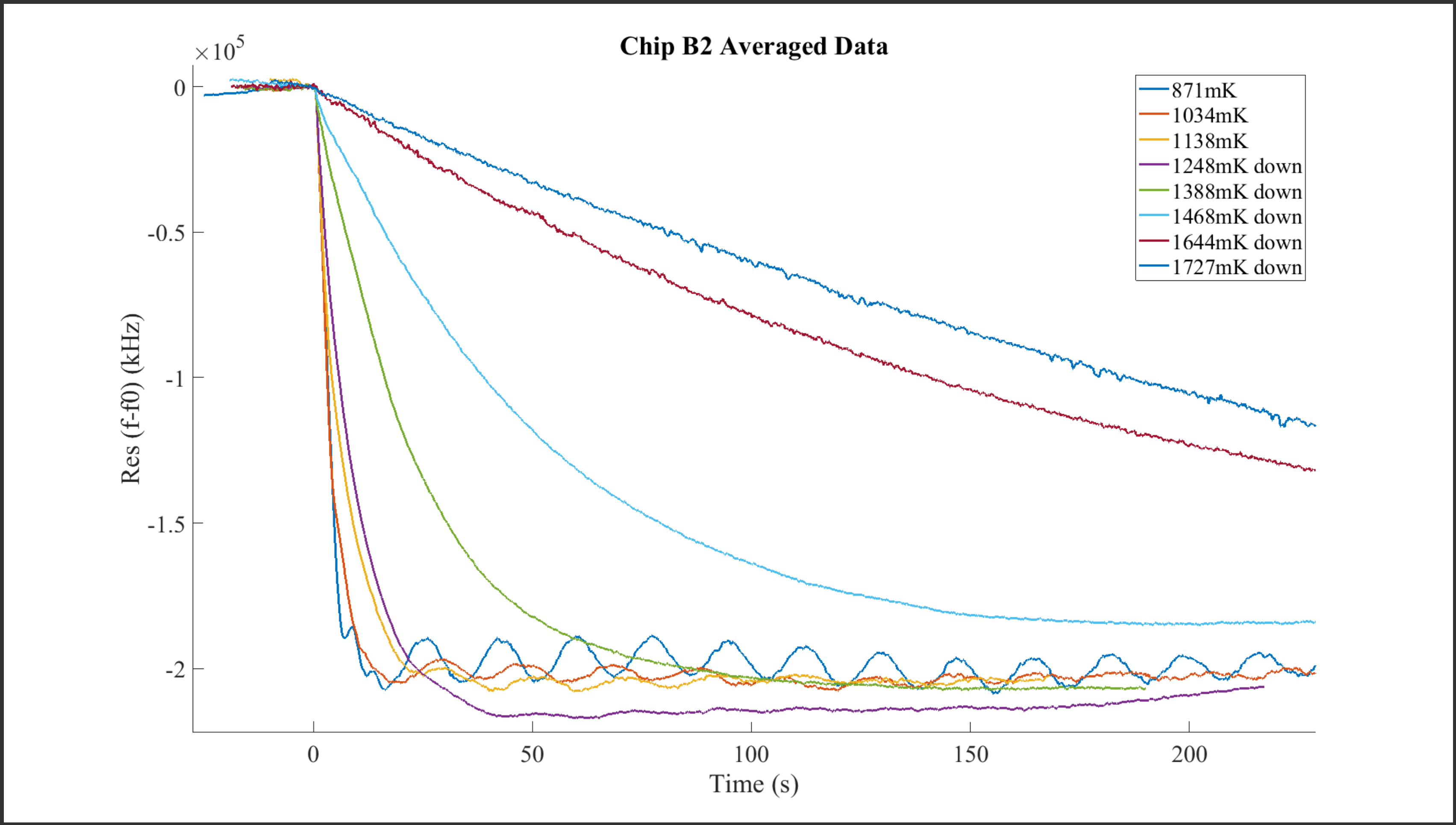
Moving and detecting the motion of the superfluid



Superflow through 2 μ m aperture in SiN



Superflow through 2μm aperture in SiN



Comparison to state of the art gryoscopes

Lasers Interferometers $10^{-7}\,\Omega_{\oplus}\mathrm{Hz}^{-1/2}$

KU Schreiber, T Klugel, J-PR Wells, RB Hurst, and A Gebauer. How to detect the chandler and the annual wobble of the earth with a large ring laser gyroscope. *Phys. Rev. Lett.*, **107**(17):173904, 2011.

Atom Interferometers $10^{-5}\,\Omega_{\oplus}\mathrm{Hz}^{-1/2}$

DS Durfee, YK Shaham, and MA Kasevich. Long-term stability of an area-reversible atominterferometer sagnac gyroscope. *Phys. Rev. Lett.*, **97**(24):240801, 2006.

Spinning Balls: $10^{-8}\,\Omega_{\oplus}\mathrm{Hz}^{-1/2}$

CWF Everitt, et al. Gravity probe b: Final results of a space experiment to test general relativity. *Phys. Rev. Lett.*, **106**(22):221101, 2011.

Superfluid ^{4}He: $4\cdot10^{-2}\,\Omega_{\oplus}\mathrm{Hz}^{-1/2}$

N. Bruckner, et al, *J. Appl. Phys.* ***93**, 1798 (2003)*, no detectable drift to 10^{-5} Hz

Superfluid ^{3}He: $5\cdot10^{-3}\,\Omega_{\oplus}\mathrm{Hz}^{-1/2}$

Avenel, Yu Mukharsky, and E Varoquaux. Superuid gyrometers. *J. Low Temp. Phys.*, **135(5-6)**:745-772, 2004.

$1\cdot10^{-4}\,\Omega_{\oplus}\mathrm{Hz}^{-1/2} \rightarrow 2\cdot10^{-6}\,\mathrm{deg/Hr}^{1/2}$

Potential impact

Navigation:
Ultra-precise GPS, keeping up with very small variations in Earth's rotation, ~cm over 24 hrs

Future navigation requirements?

Precision pointing:
telescopes, imaging, directed energy weapons, defense
Hubble 10^{-10} rad/s over a day

Scientific:
General relativistic effects (Lense-Thirring)

Quantum phase measurement tool

Quantum Information:
Flux qubit analog