Superfluid Gyroscopes

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LBNL
Instrumentation Colloquium

- **Why are sensitive gyroscopes useful?**
- **What superfluid properties are relevant?**
- **How does a superfluid gyro operate?**
- **Who are the Berkeley scientists involved?**

Why?

1. Rotational Seismology

To detect rotational seismic waves causes by anisotropies in the crust inner core boundary. To determine torques on buildings due to seismic events.

2. Geodesy

To monitor small changes in the Earth's rotation. Data used to investigate terrestrial processes and to update the GPS navigation system

Presently monitored with VLBI array of radio telescopes. Resolution is better than $10^{-9}\Omega_E$ with 24 hour averaging time. ($4x10^{-12}\ rad/\sec/\sqrt{Hz}$)

3. Inertial navigation

To guide ships and planes inertially with precision equal to GPS. ($5x10^{-10}\ rad/\sec/\sqrt{Hz}$)

4. Tests of general relativity: frame dragging-gravito-magnetic field of the Earth. (similar requirements to geodesy)

What?

- **Superfluid (Quantum fluid)**

- **Finite number of the particles in a single quantum state**

^4He $T_\lambda = 2.17K$

^3He $T_c = 10^{-3}K$

Simple wave function

$$\psi = |\psi| e^{i\phi}$$

Apply current operator and find: $j_s = |\psi|^2 \frac{\hbar}{m} \nabla \phi = \rho_s v_s$

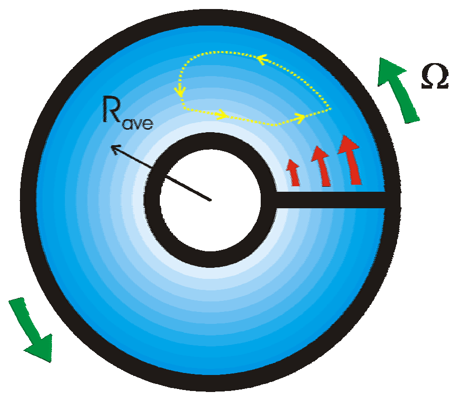
where

$$v_s = \frac{\hbar}{m} \nabla \phi$$

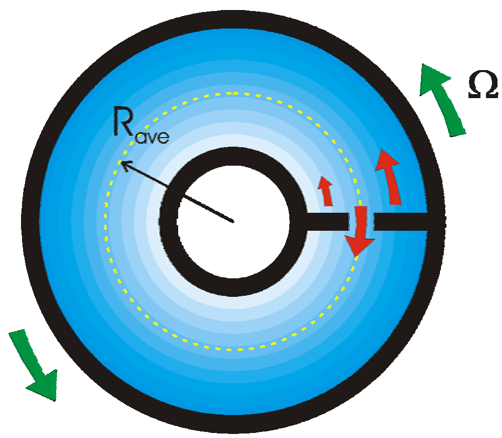
$\oint v_s \cdot dl = n\, h/m$ **Quantized vortex lines (Feynman, 1954)**

How?

1. **^{4}He phase slip gyroscope**



The rotation forces the fluid to move (almost) like a rigid body, thus creating a phase gradient.



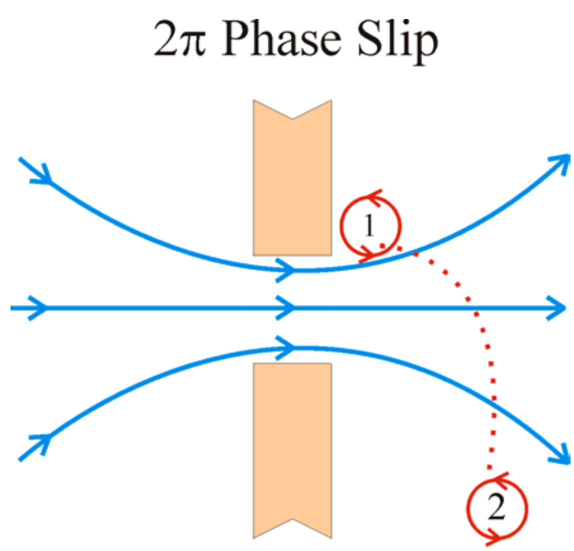
$$\oint v_s \cdot dl = 0; \qquad \Omega R 2\pi R - v_a l = 0$$

$$v_a = \Omega R\left(2\pi R / l\right) = 2\vec{\Omega} \cdot \vec{A} / l$$

if R~50cm and $l \sim 50nm$, velocity amplification is 10^7

How can we monitor flow through the small aperture?

Phase slip concept:
(Anderson 1964)

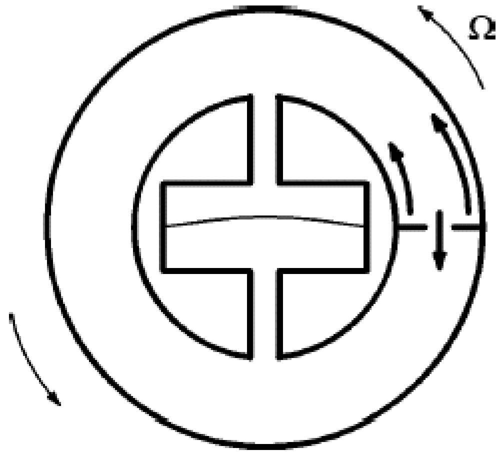


Superfluid accelerates until reaching a critical velocity at which a (thermally activated) phase slip occurs.

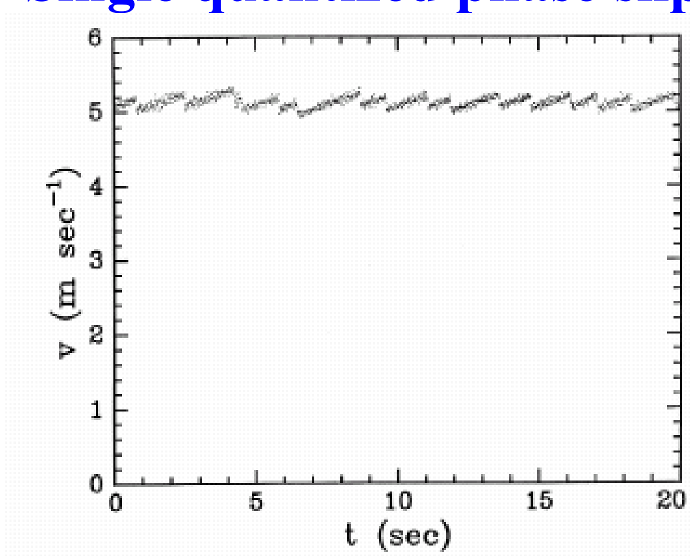
velocity decrement is:

$$\delta v_s = \frac{h}{ml}$$

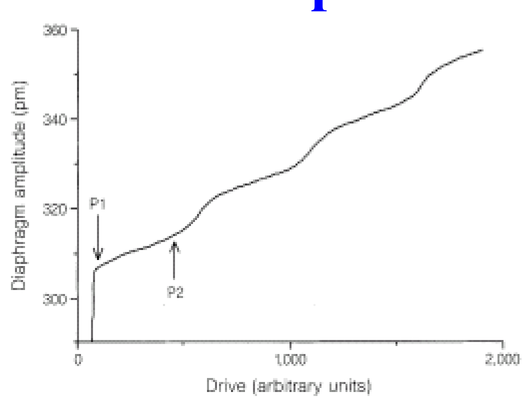
Phase slip gyroscope



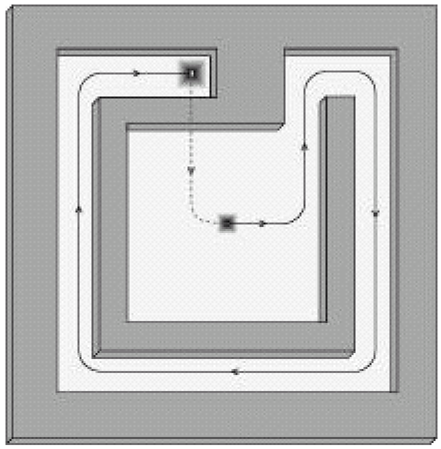
Single quantized phase slips



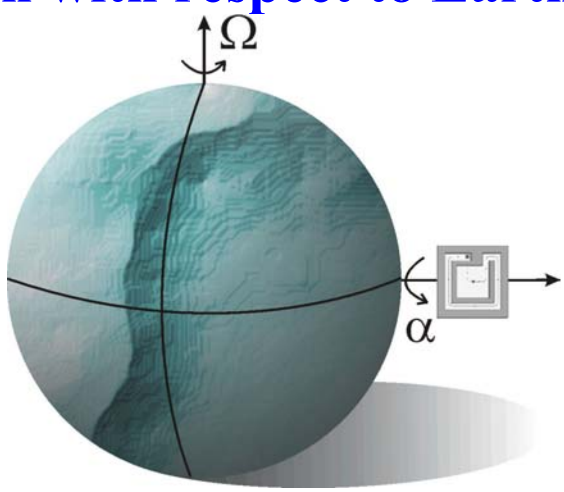
Staircase pattern



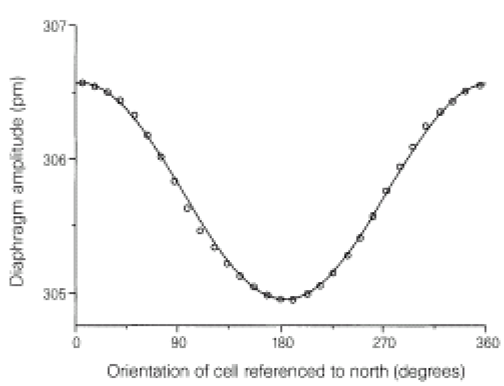
gyro on a chip



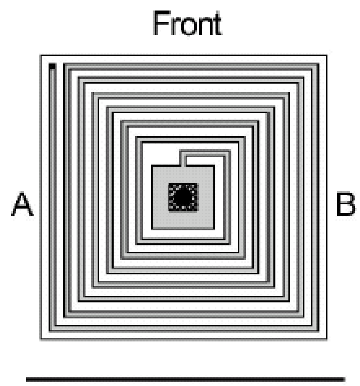
Reorientation with respect to Earth's axis

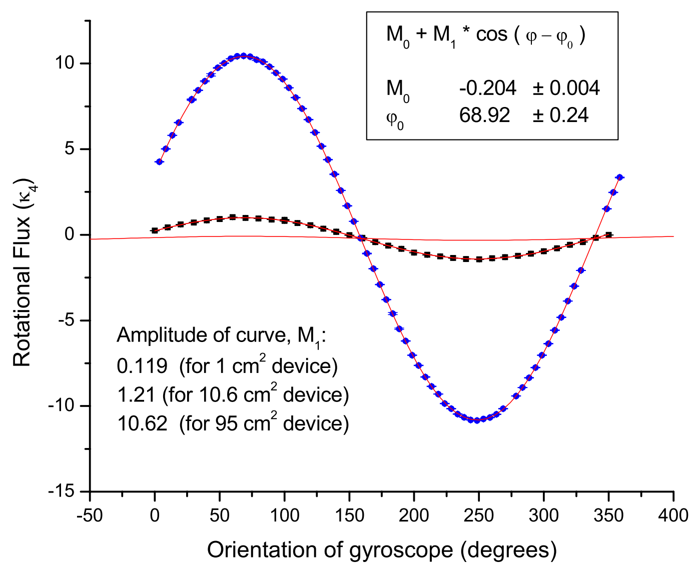


T~0.3K



Multiturn gyro

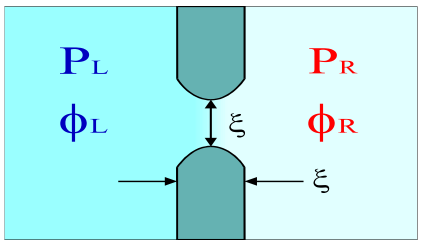


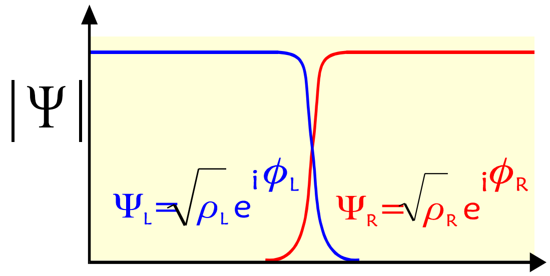


The ^{4}He phase slip gyro is ultimately limited by the k_BT fluctuations responsible for the phase slip nucleation process.

2. The ^{3}He Quantum Interference Gyroscope

Relies on the dc-Josephson effect





dc-Josephson equation

$$I = I_c \sin \Delta\phi$$

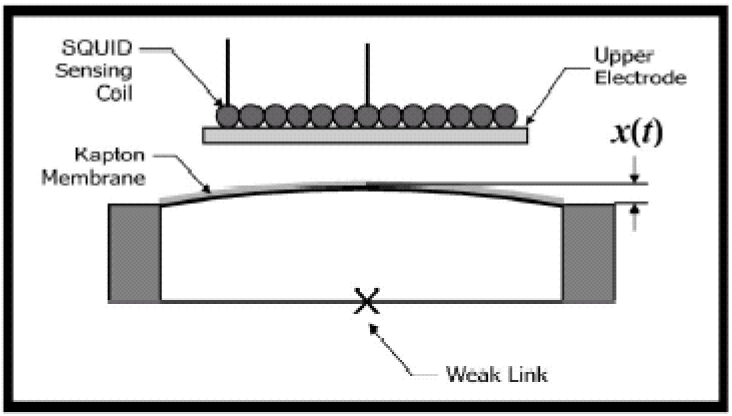
ac-Josephson equation (a disguised F=ma)

$$\frac{d\phi}{dt} = -\frac{\Delta\mu}{\hbar} = -\frac{2m_3\Delta P}{\hbar\rho}$$

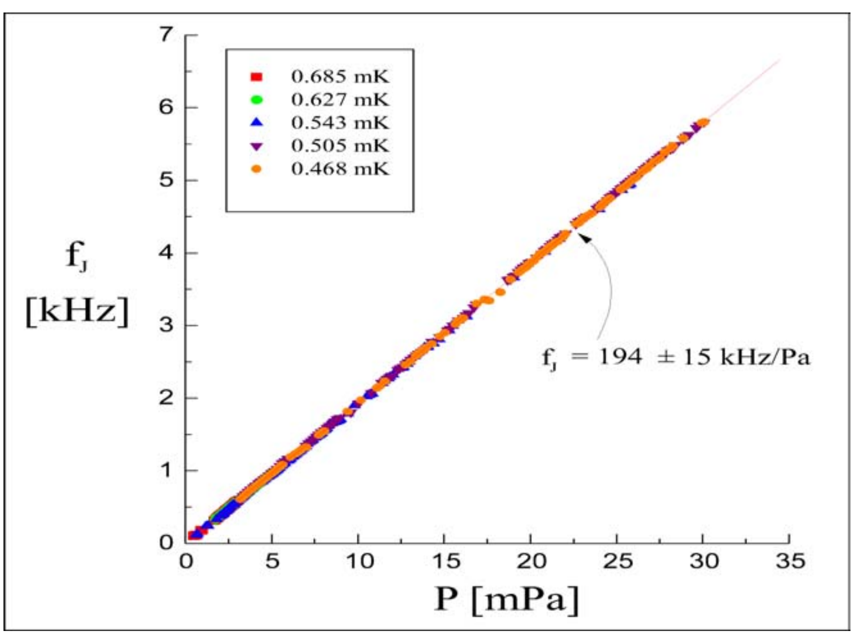
For fixed $\Delta P = P_L - P_R$ the current oscillates at frequency

$$f_j = \frac{2m_3\Delta P}{h\rho}$$

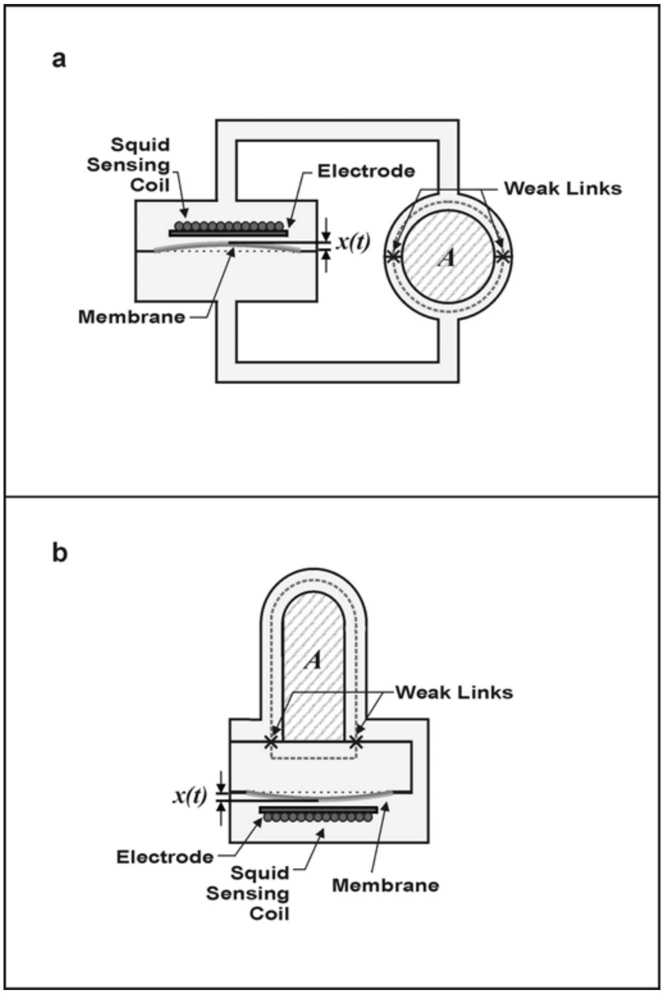
Arrays (65x65=4225) of small (~60nm) apertures behave as weak links for ^{3}He. T<1mK (10^{-3}K)



$$f_j = \frac{2m_3 \Delta P}{h\rho}$$

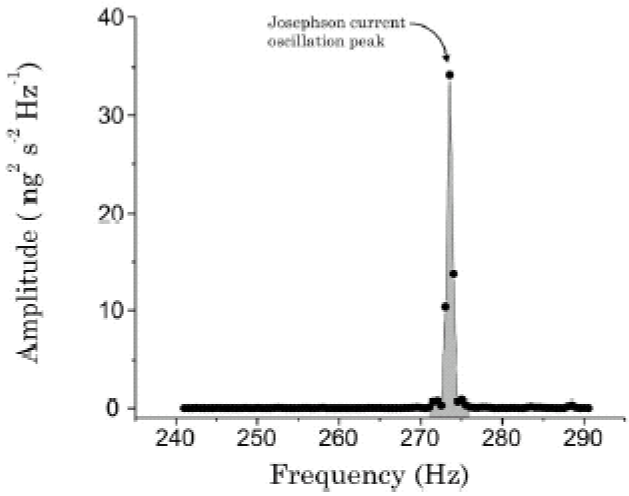


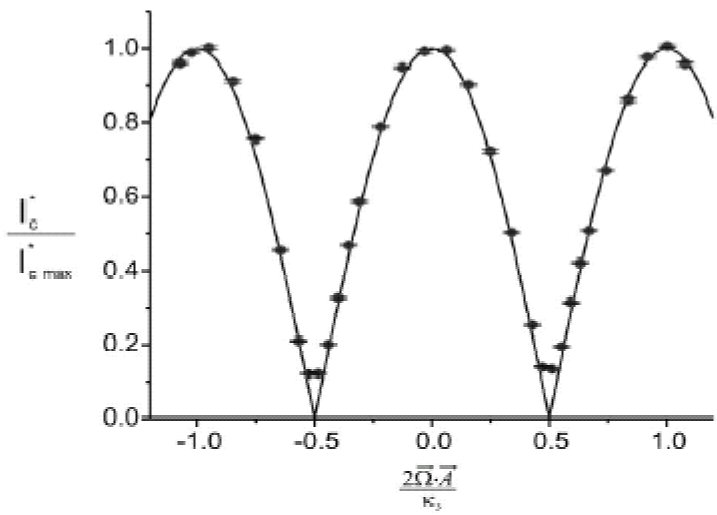
Interference gyroscope



The effective critical current of the entire device is modulated by the rotation flux threading the ring (see Feynman vol 3 chap 21)

$$I_c^* = 2I_c \left| \cos \frac{\pi 2\vec{\Omega} \cdot \vec{A}}{h / 2m_3} \right|$$





A prototype gyro based on this principle in Saclay finds

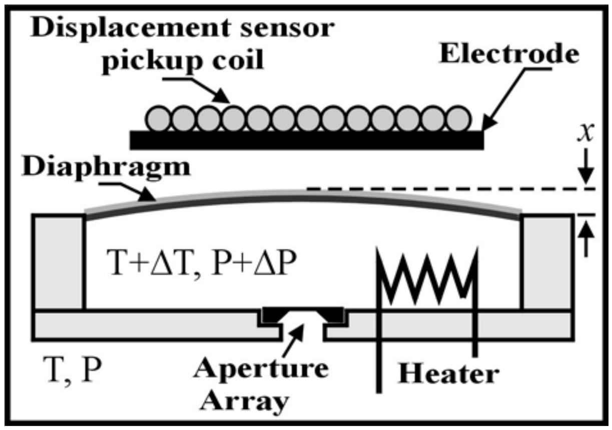
$$\delta\Omega \approx 5x10^{-3}\,\Omega_E / \sqrt{Hz}$$

for a 6cm^2 device.

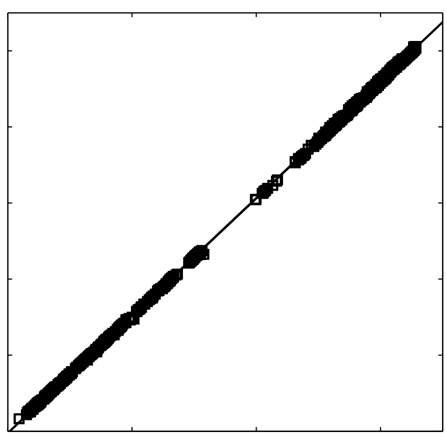
The ^{3}He interference gyroscope is not limited by thermal fluctuations and is potentially the most sensitive gyroscope: <u>BUT</u> it requires 1mK technology which is not user friendly to gyro users.

^{4}He quantum whistle gyroscope
(A work in progress)

Discovery 2004: Near T~2.1K

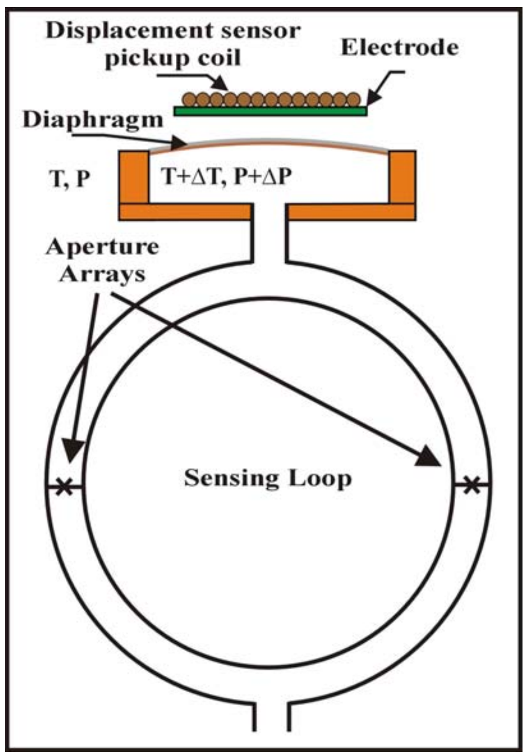


$$f_j = \frac{m_4 \Delta\mu}{h} = \frac{m_4}{h}\left[\frac{\Delta P}{\rho} + s\Delta T\right]$$



Amplitude fluctuation noise seems ~ 10^{-3}! Thermal fluctuations seem suppressed by 1/N where N=4225.

A proposed ^{4}He quantum whistle gyroscope



Rotation induces a phase shift between the two aperture arrays. This leads to interference at the microphone.

$$\Delta\phi = \int_1^2 \vec{\nabla}\phi \cdot d\vec{l} = \int_1^2 \frac{m_4}{\hbar}\vec{v}_s \cdot d\vec{l} = \frac{m_4}{\hbar}\Omega R \pi R = \frac{\vec{\Omega}\cdot\vec{A}}{\hbar / m_4}$$

Features:

- **Low noise of the ^3He interference gyroscope**
- **Cryocooler temperatures (T~2K)**
- **Possible "turn key" operation. No advanced cryogenic techniques required by the user.**

Summary

- **Quantum phase coherence in superfluids can detect absolute rotation**

- **In ^{4}He quantized phase slip phenomena can detect rotation. Operating temperature (T~0.3K) leads to simpler cryogenics but thermal noise limits rotation resolution**

- **In ^{3}He a sine-like current-phase relation leads to the superfluid analog of a dc SQUID. Potentially very low noise but high tech cryogenics. (T<1mK)**

- **Newly discovered quantum whistle in ^{4}He "should" lead to a gyroscope with excellent resolution and cryocooler operating temperatures (T~2K).**

- **Lots of R and D before prototypes surpass mechanical gyros, but definitely possible (Maybe even probable)**

Who?

Keith Schwab
Neils Bruckner

Ray Simmonds
Alosha Marchenkov

Seamus Davis
Stefano Vitale

Emile Hoskinson
Yuki Sato

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