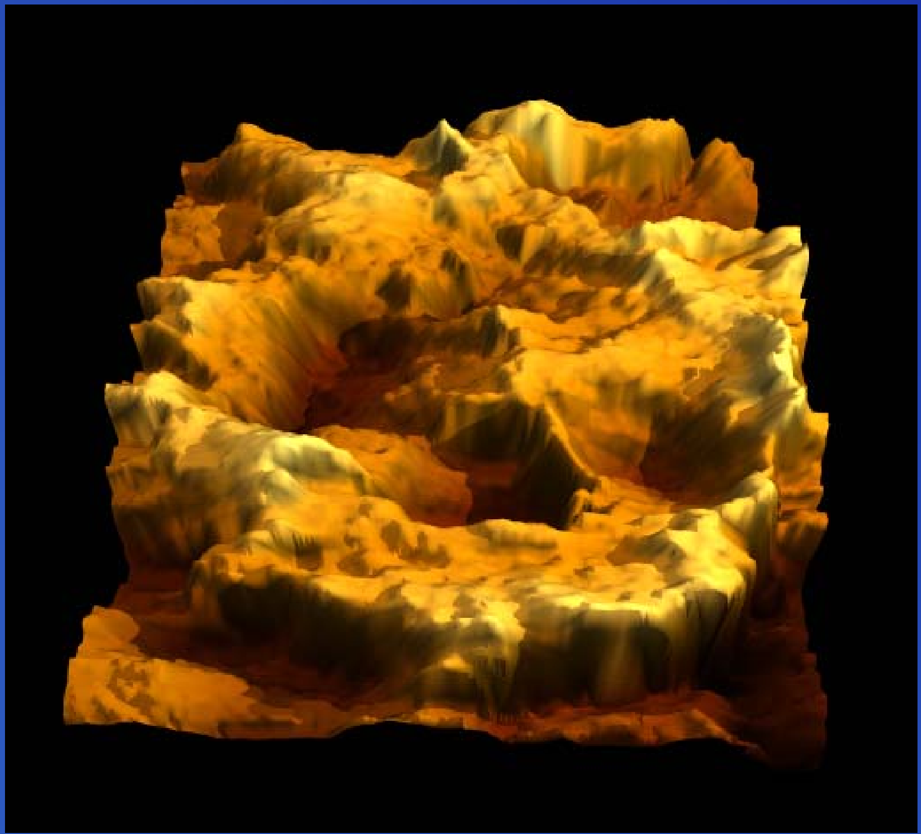
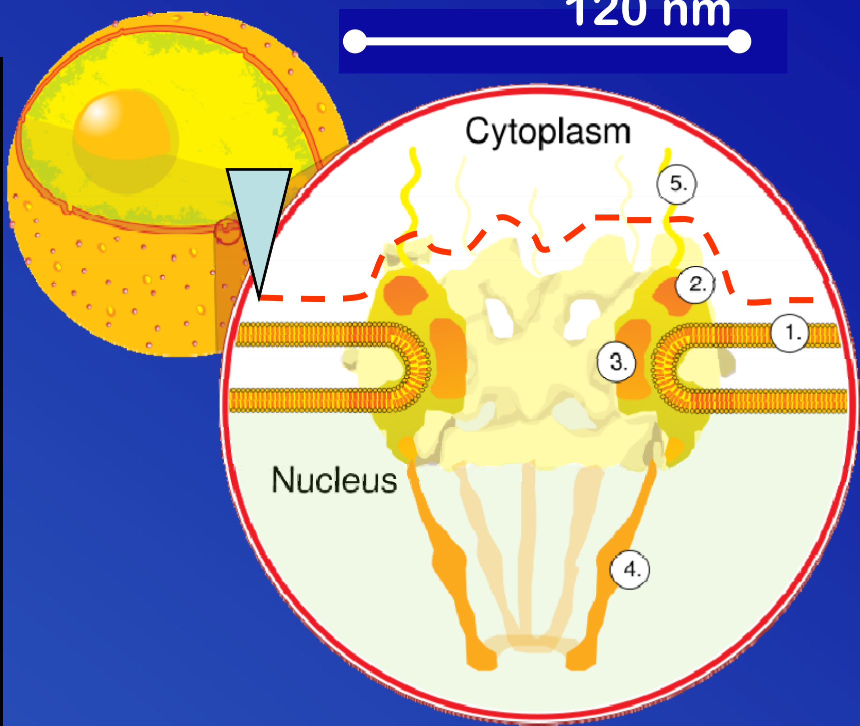
Taking Force Microscopy into the third dimension





Transport of large cargo aided by the fibers of the pore

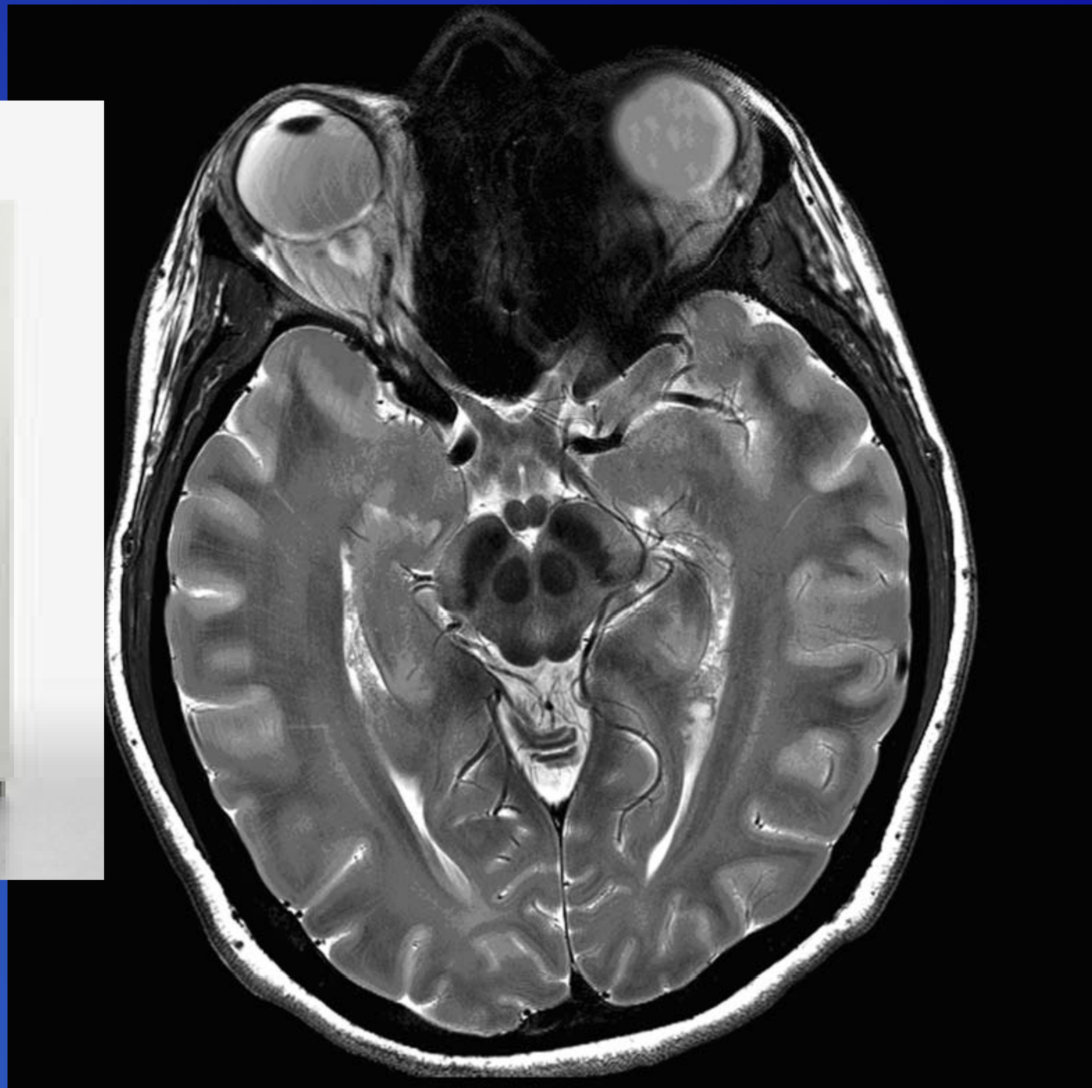
Sabbatical at IBM Almaden

MRI at the nanoscale …

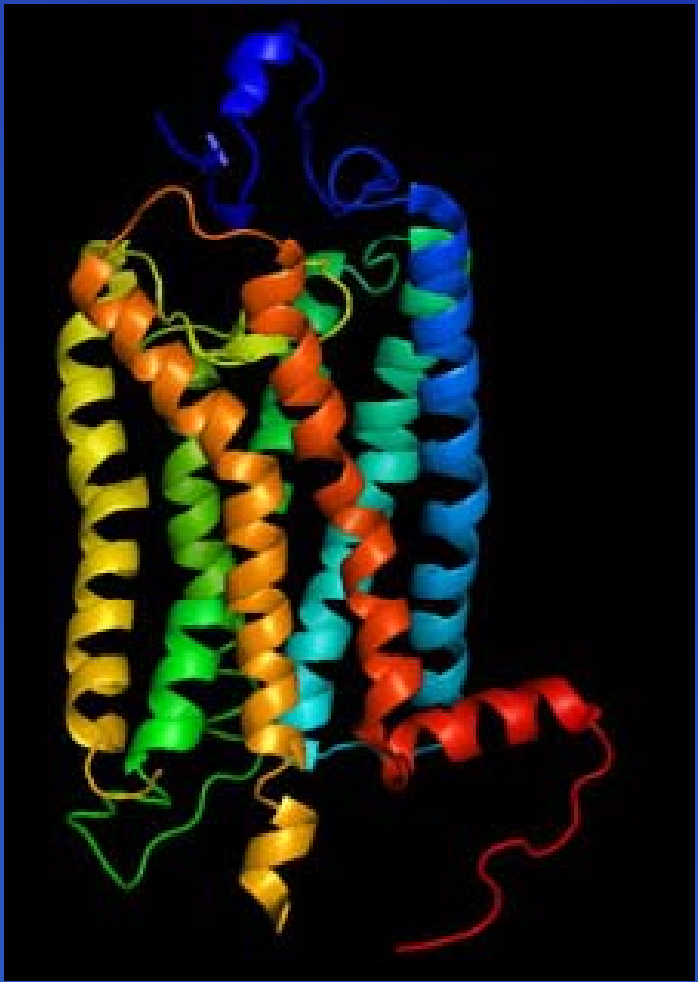
Dan Rugar, John Mamin Martino Poggio
Christian Degen

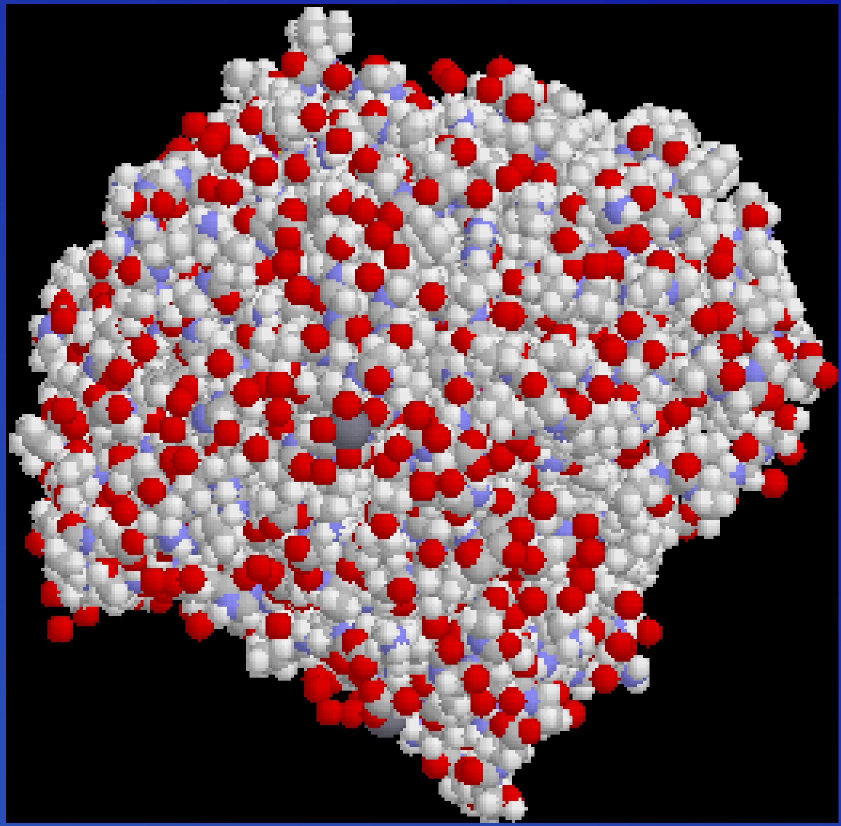
… through Force Microscopy at low temperature

MRI in the hospital needs a lot of protons for a radiosignal

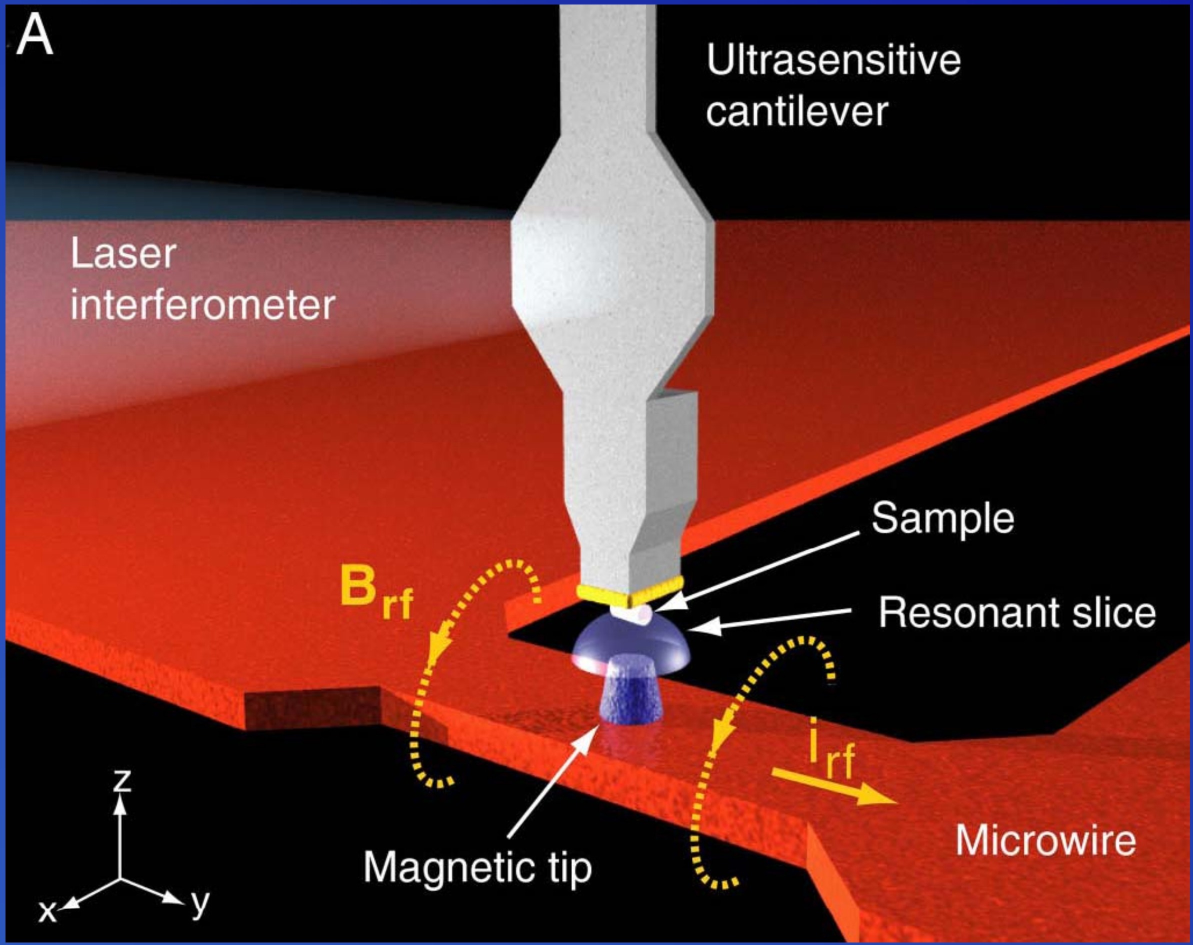


MRI ‘op de tast’
feel the force due to a single proton?



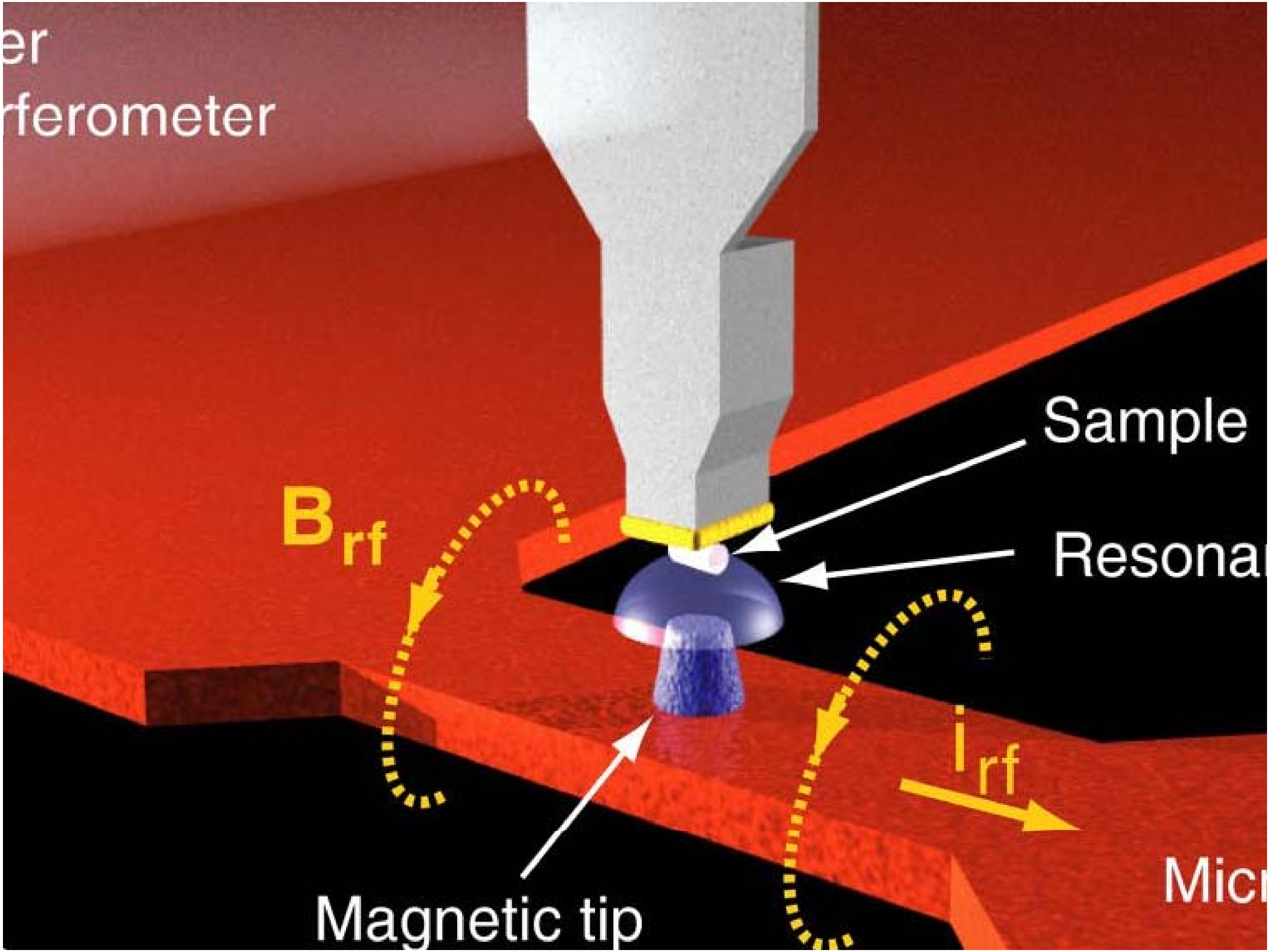


Magnetic Resonance Force Microscopy

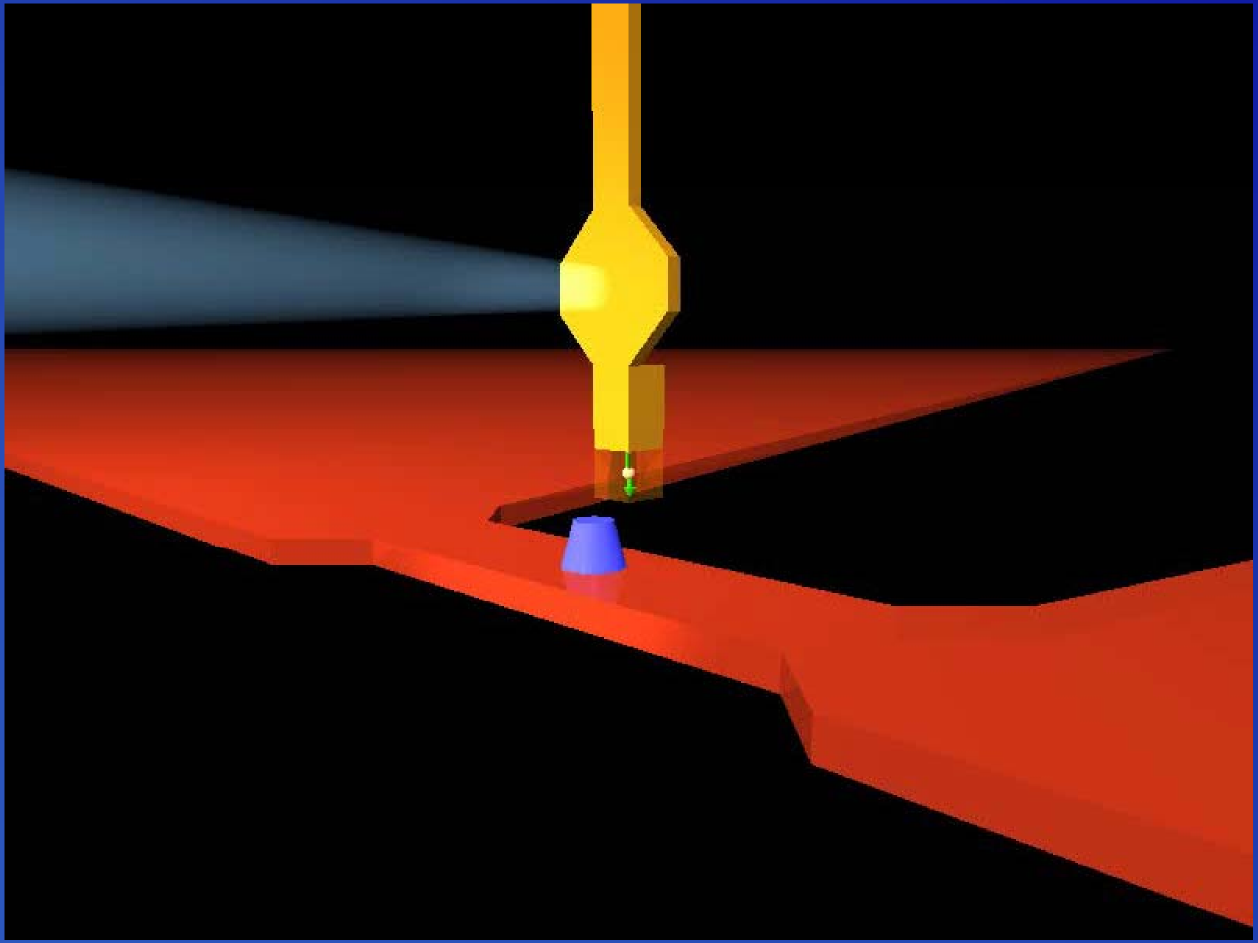


Sensing the force between a magnetic tip and nuclear-spins on the cantilever

Degen, Poggio, Mamin, Rettner, Rugar, IBM Research


er
rferometer
Sample
Resonar
B rf
Magnetic tip
i rf
Micr

Magnetic Resonance Force Microscopy

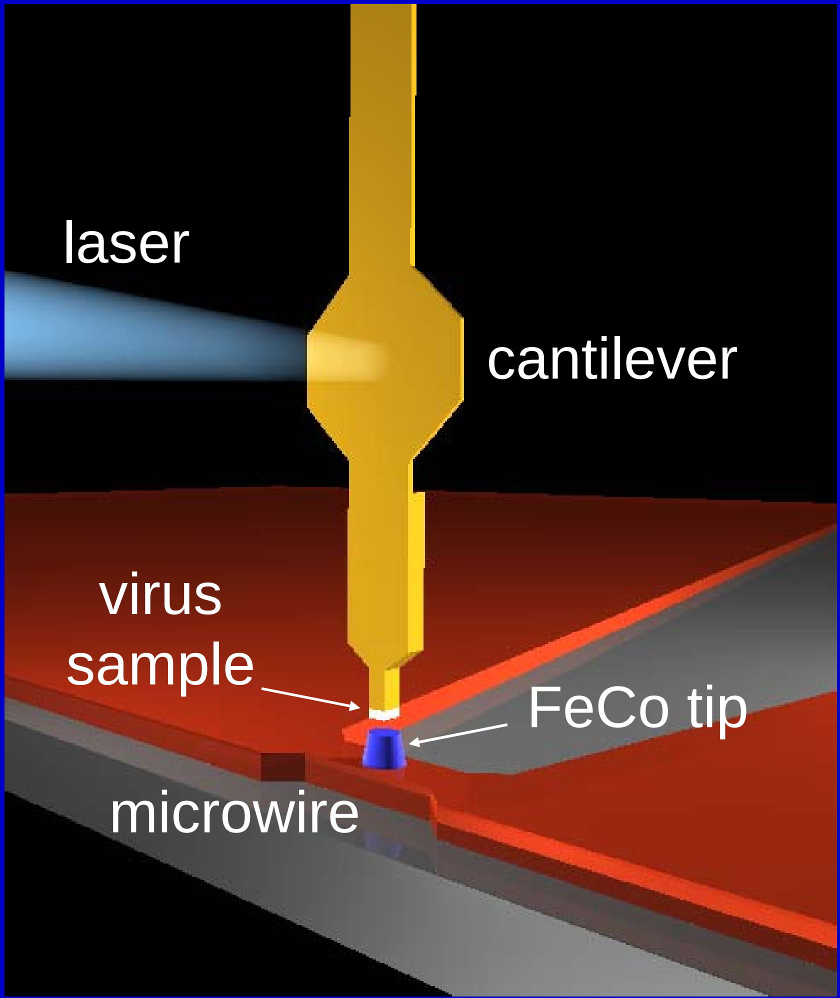


Sensing the force between a nuclear spin and a magnetic tip

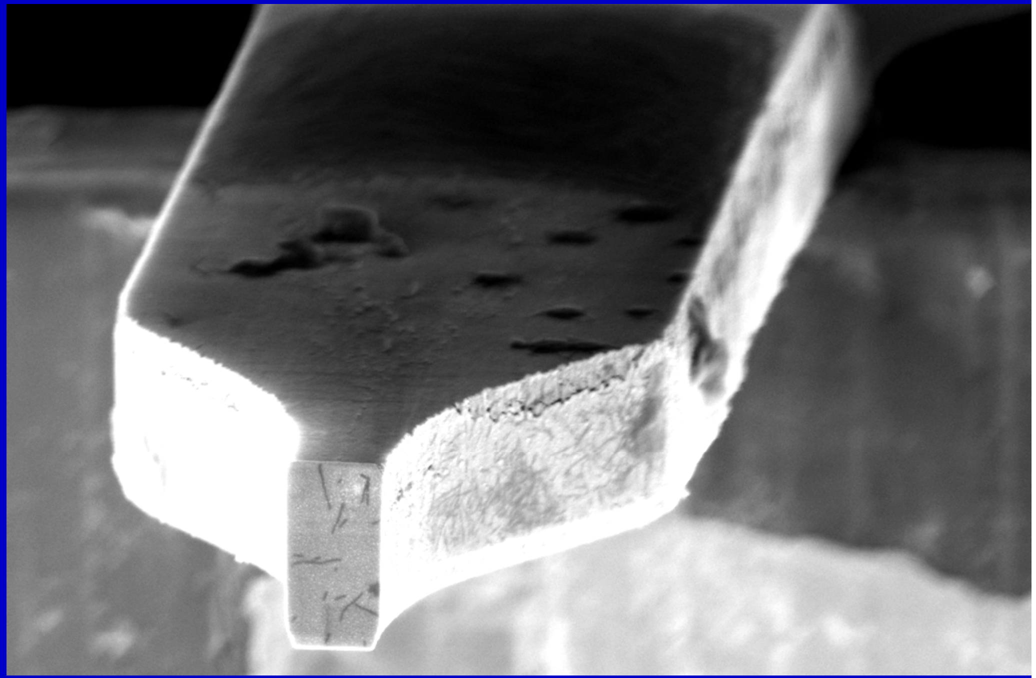
Degen, Poggio, Mamin, Rettner, Rugar

3D Virus Imaging Experiment

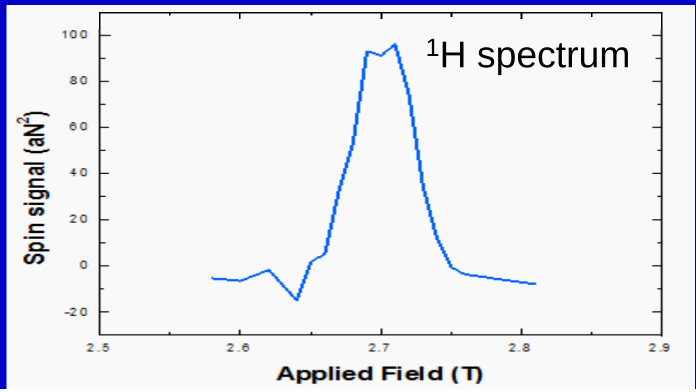
MRFM setup with microwire rf source and sample-on-cantilever geometry



Cantilever tip with tobacco mosaic virus



Strong MRFM proton signal from virus



Measuring Small forces is the key:

$$F = ma = -kx - \gamma v$$

$$F_n = \sqrt{4 k_B T \gamma}$$

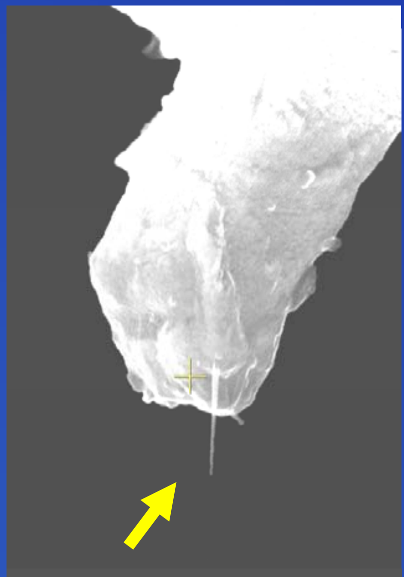
Thermal force noise is determined by damping and temperature only

Rugar cantilevers have γ = 4e-13 Ns/m

ERC starting grant:
Single proton spin resolution is achievable!

Large Field Gradient

Carbon Nanotubes



Bonus: lower noise

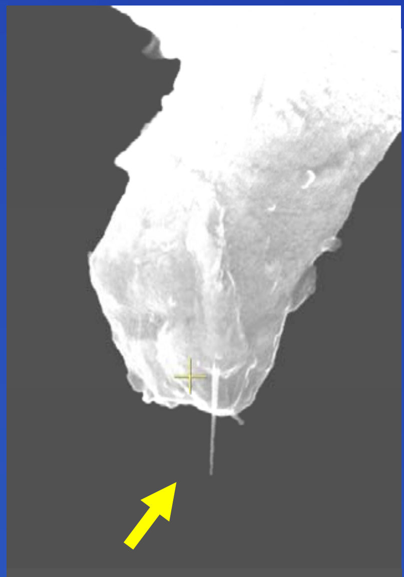
Ultralow temperatures

< 10 mK
Need new detection without interferometer

Single proton spin resolution is achievable! Where are the three orders of magnitude?

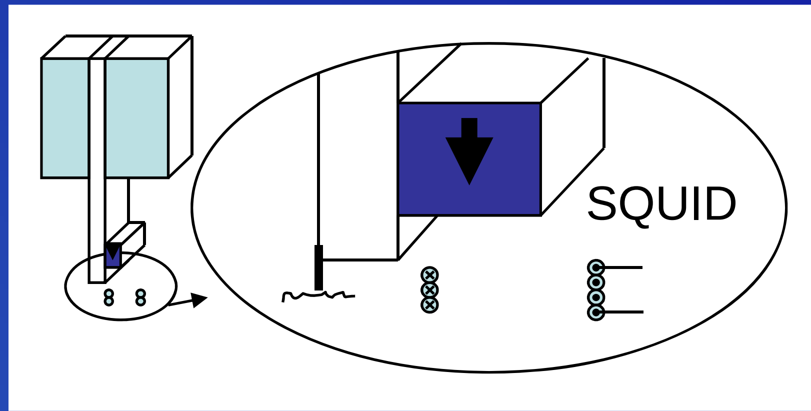
Large Field Gradient

Carbon Nanotubes



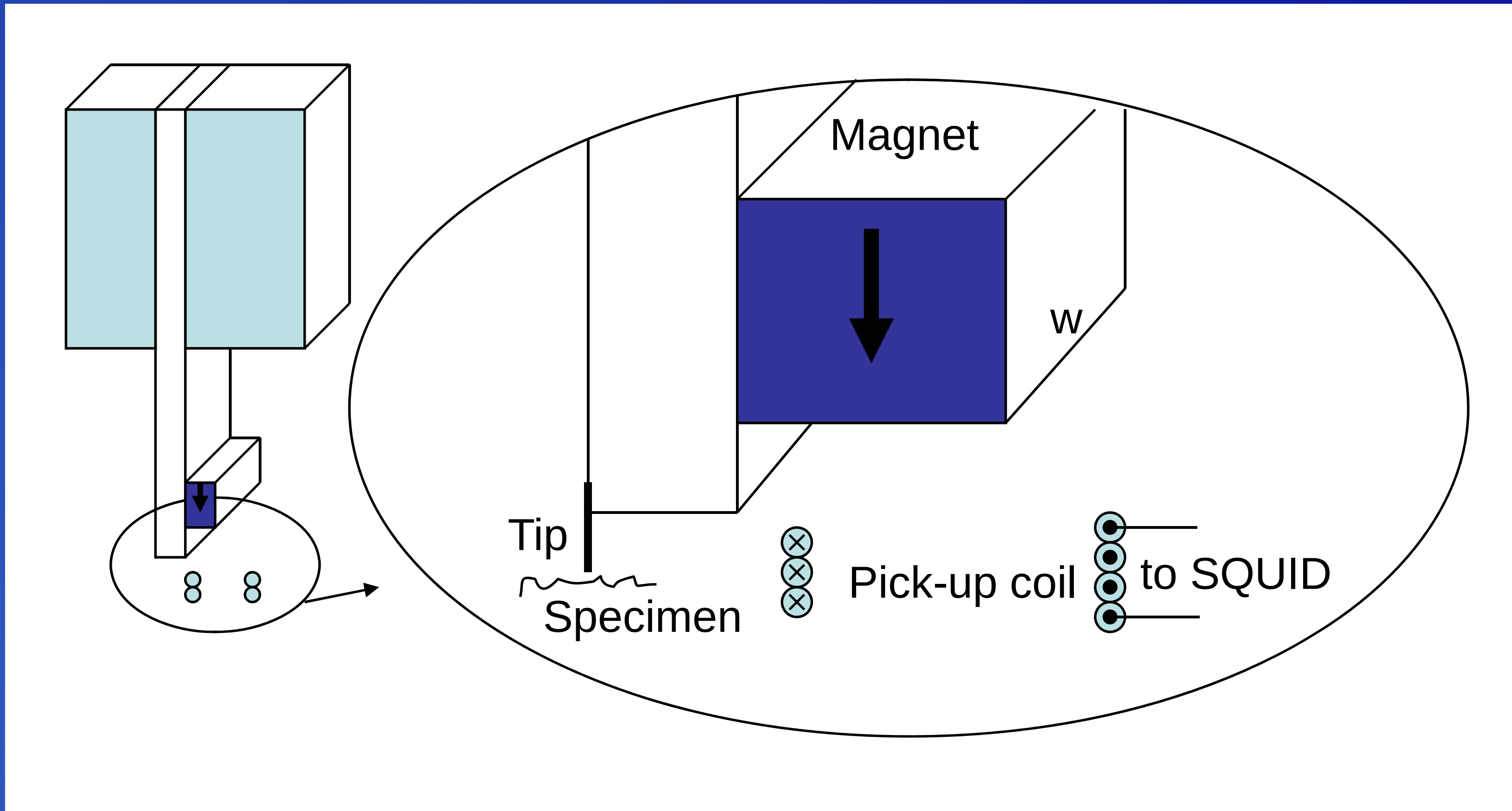
Bonus: lower noise

Ultralow temperatures



< 10 mK ?
Need new detection without interferometer

New detection scheme based on SQUID:



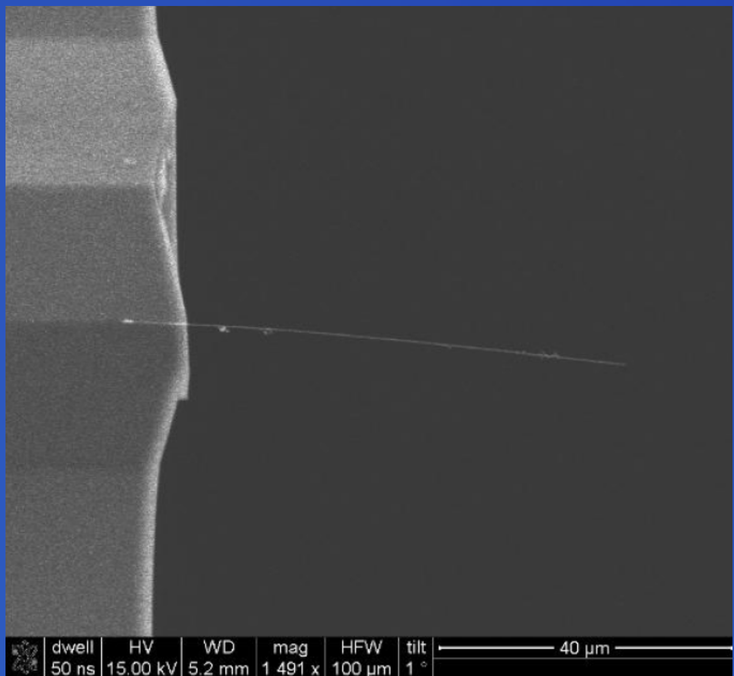
Superconducting Quantum Interference Device: Most sensitive magnetic detector

Alternative cantilever: SiC Nanowire

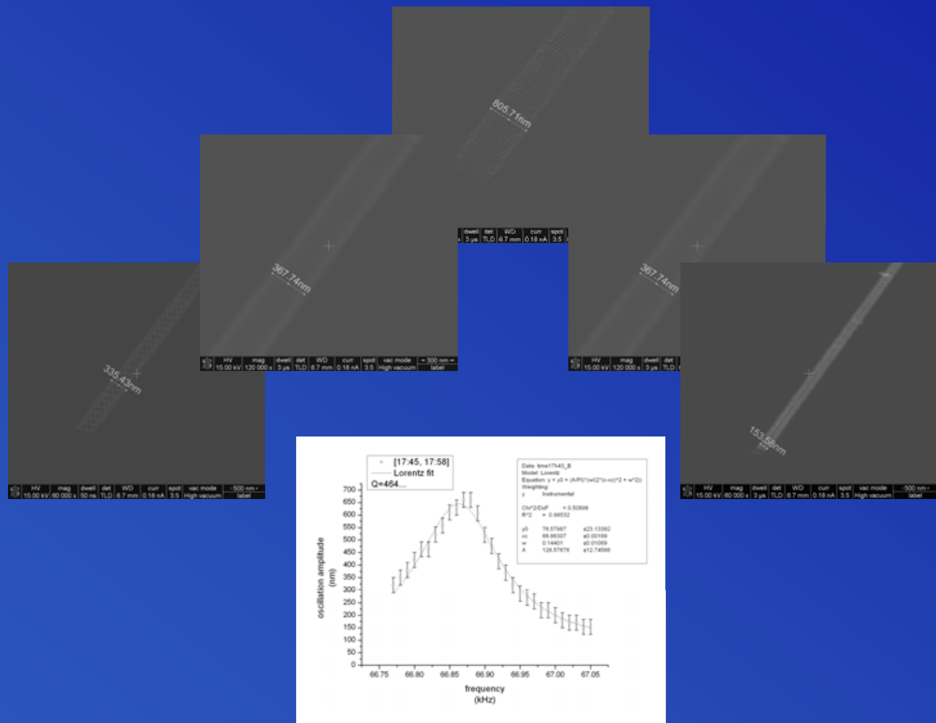
40 micron long

40 nm diameter γ = 1e-15 Ns/m

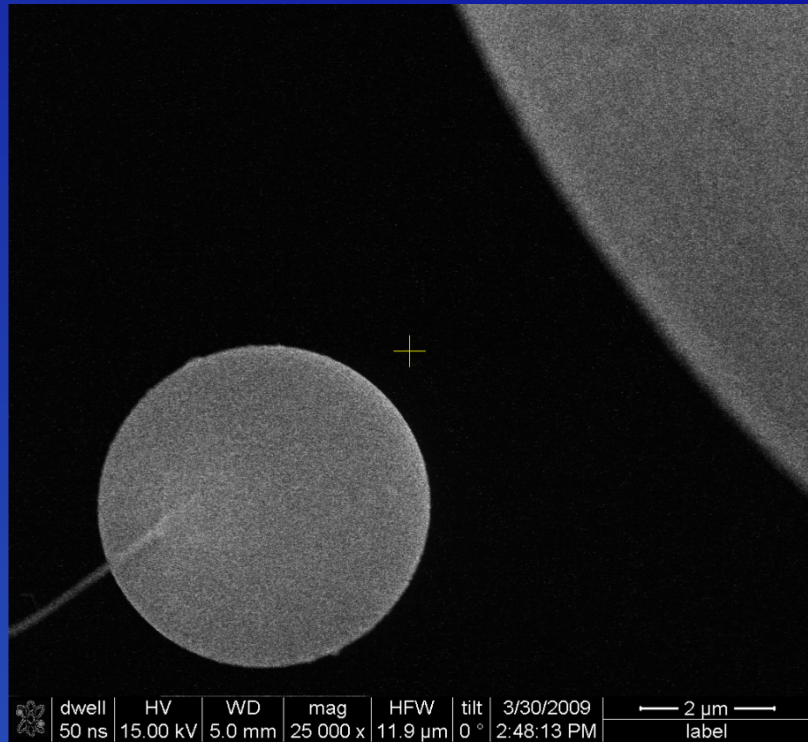
Very low damping even at room temperature



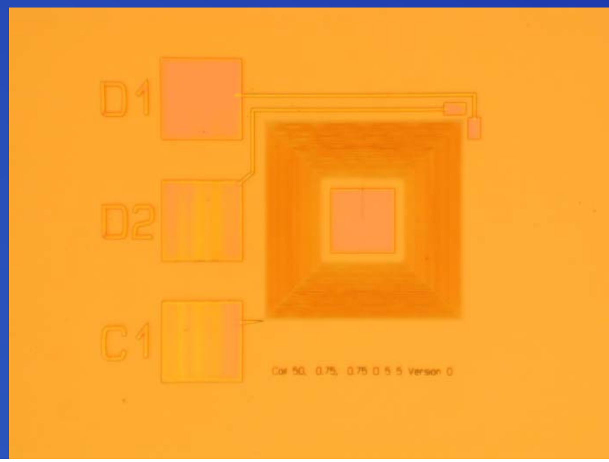
electrostatic actuation in SEM:



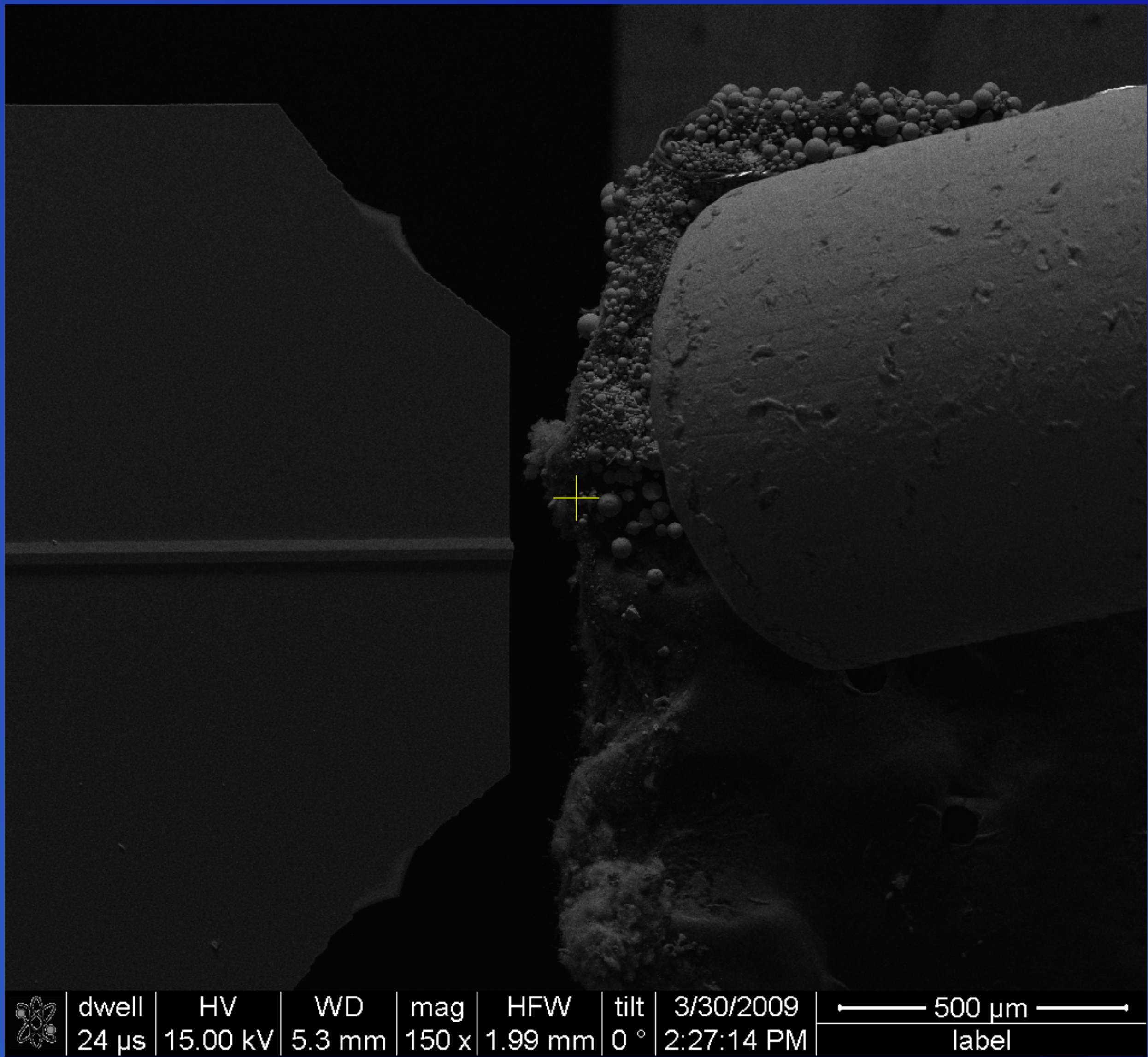
Nanowire with magnet:



Superconducting coil:



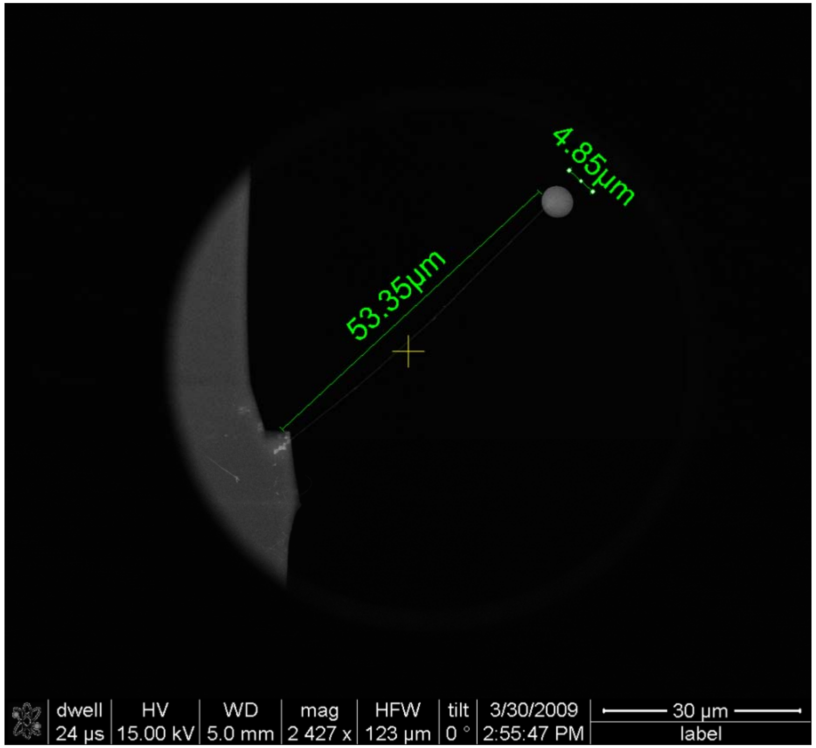
How do we make it?

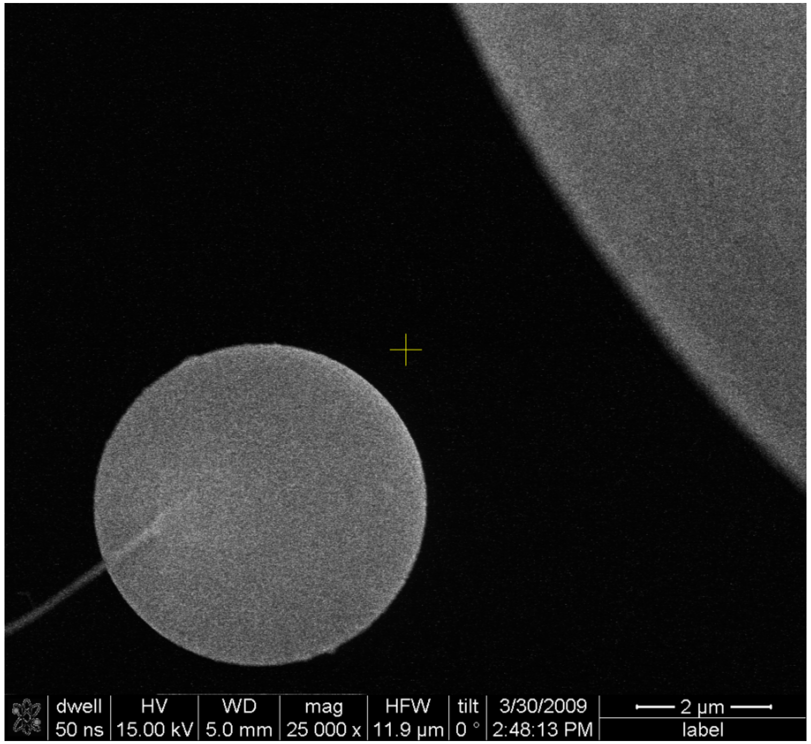


Cantilever II

A NdFeB (Neodymium-IJzer-Borium) spherical particle is attached to a 53.87 um long SiC nanowire, which is attached to a Si (previous AFM) chip.

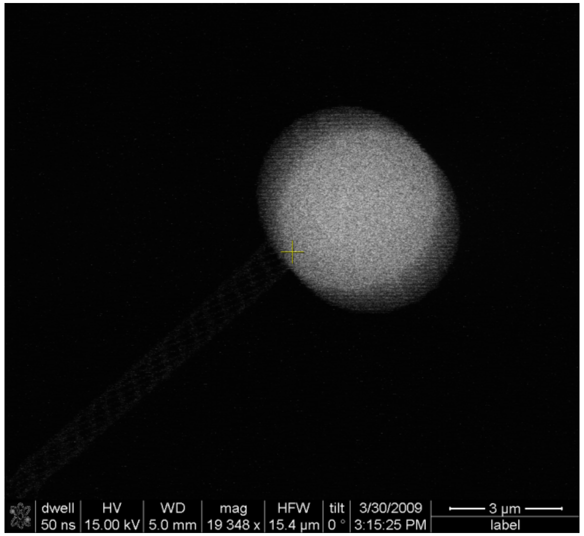
Characteristics:
Length = 53.35 um, Diameter = 100 nm
Resonance frequ. = 1.47 kHz (measured in SEM at RT)
Spring constant k = 4.5 E -5 (calculated from length and diameter)
Quality Factor Q = 1500 (measured in SEM at RT)
Damping coefficient R = 2.6 E-12 (calculated from Q)
Amplitude at resonance = 3,5 um (measured)
Expected noise amplitude at peak is 1 nm/sqrt(Hz) at resonance at 4K

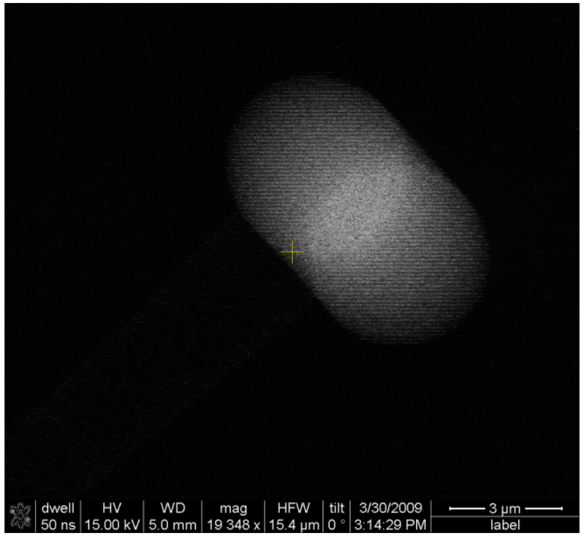


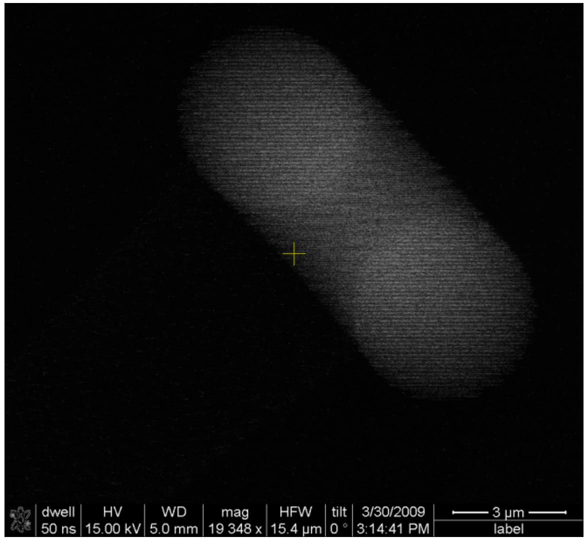


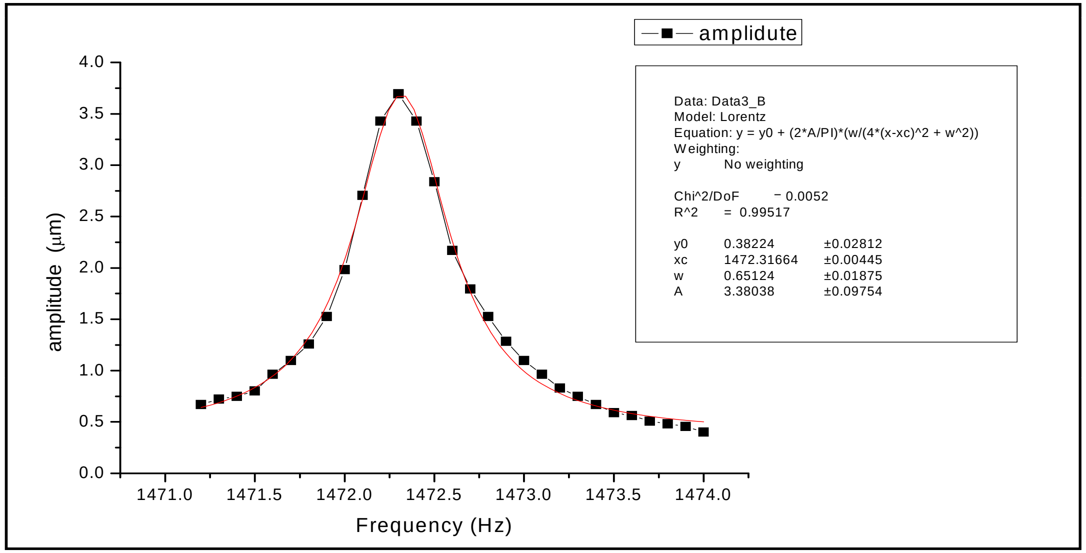
Resonance of Cantilever at RT

In the SEM a resonance is measured at 1472 Hz with Q of 2300 (by applying 1V DC and 10 mV ac)

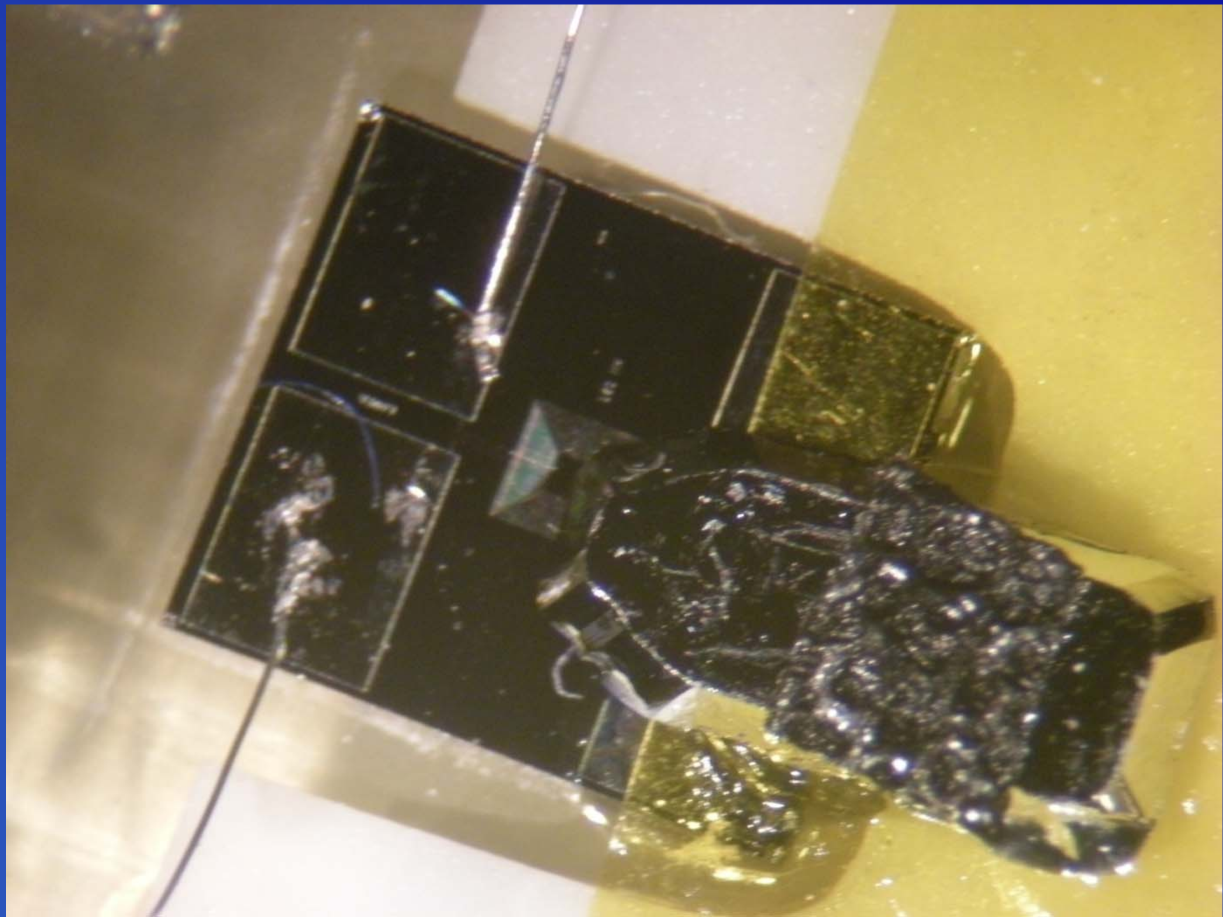






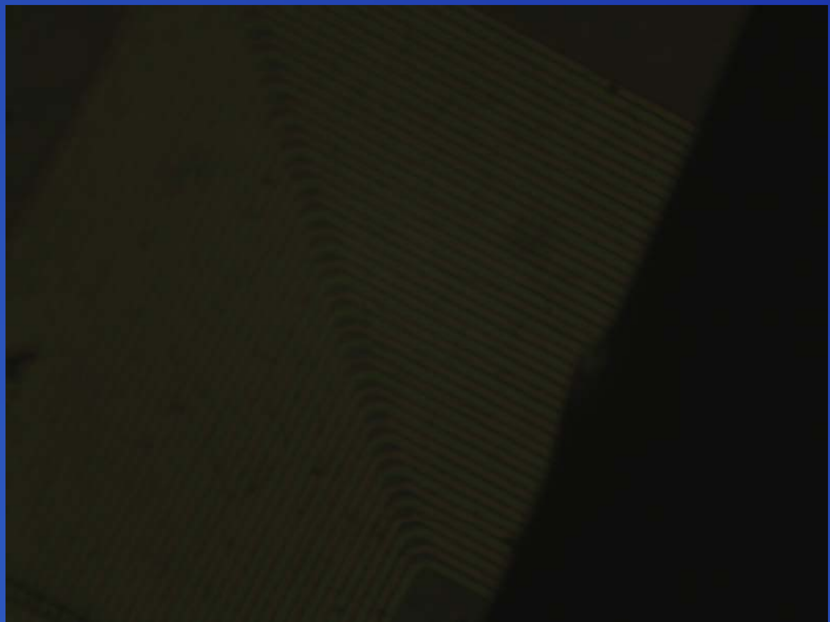


Nanowire with magnet in close proximity

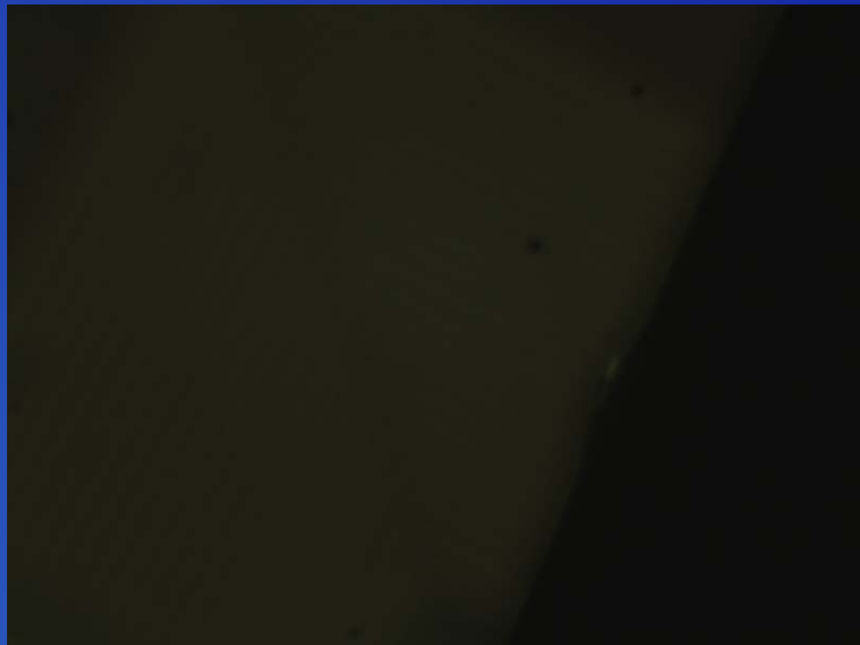


Of superconducting coil

Magnet is 60 micron above superconducting coil



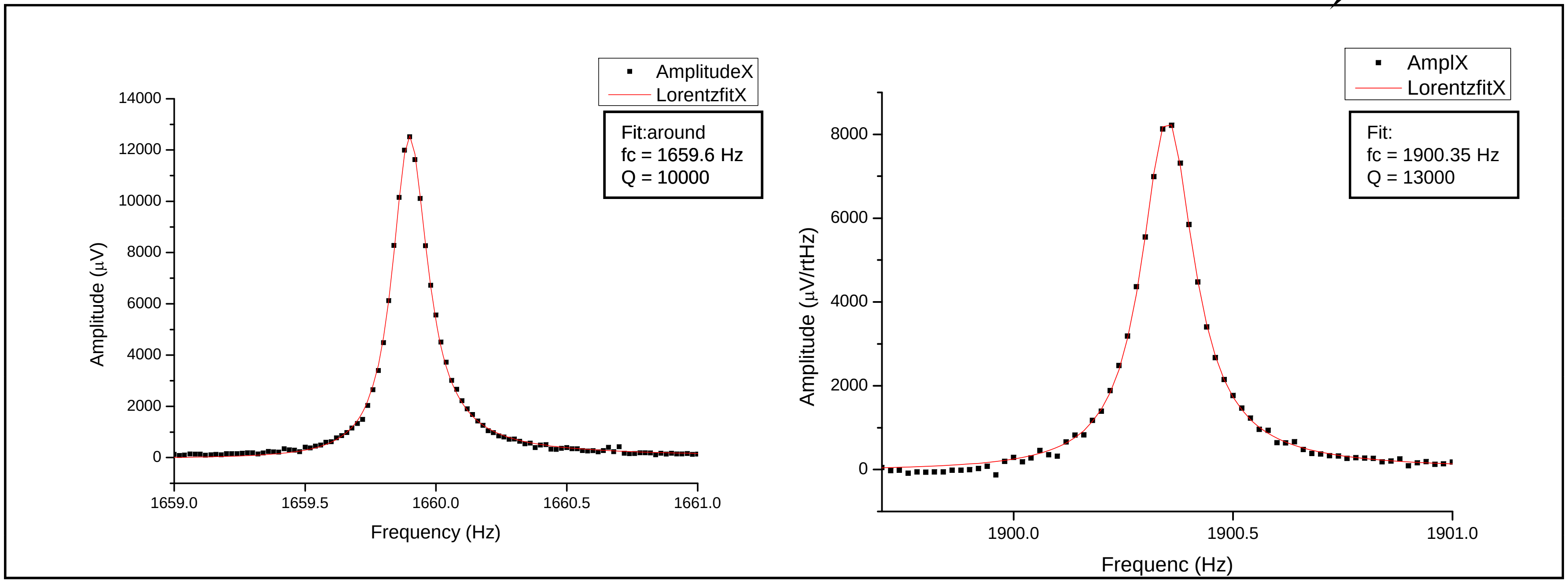
Can be actuated by a macroscopic magnet

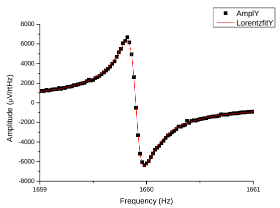


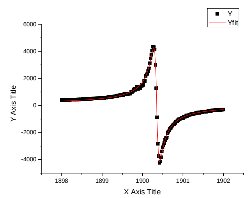
Cantilever driven resonances

Driven by a piezo element, we find resonances at 1660 and 1900 Hz.

x-signal



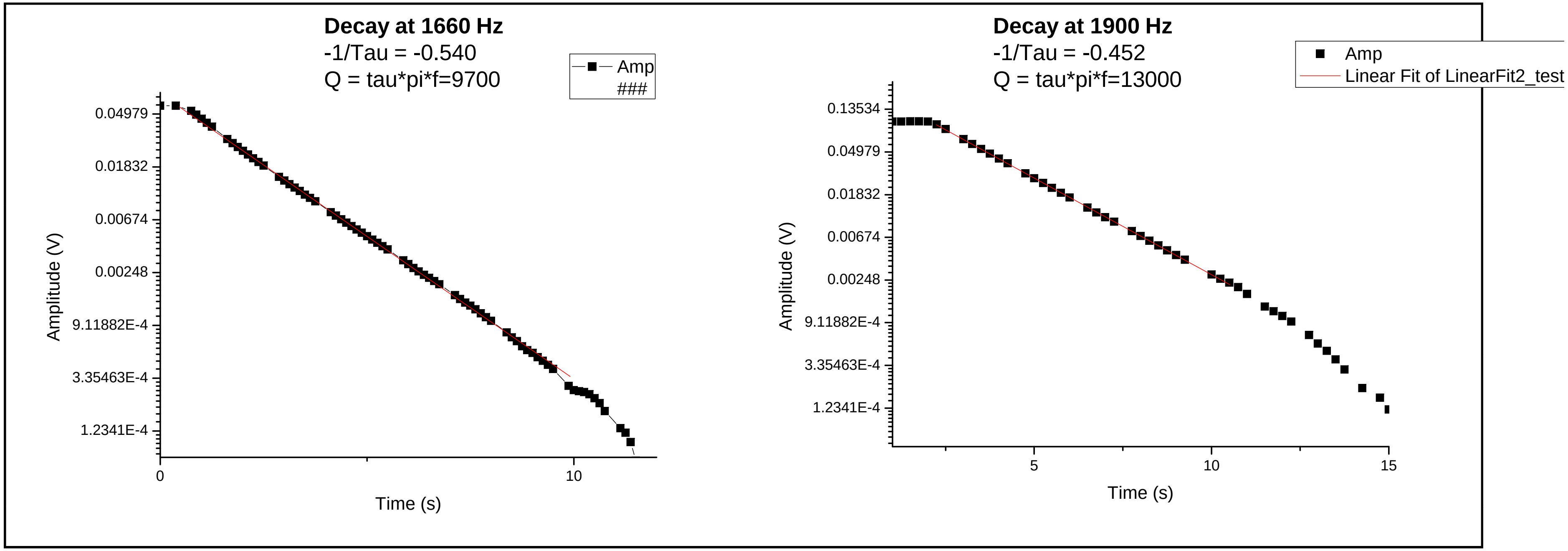




y-signal

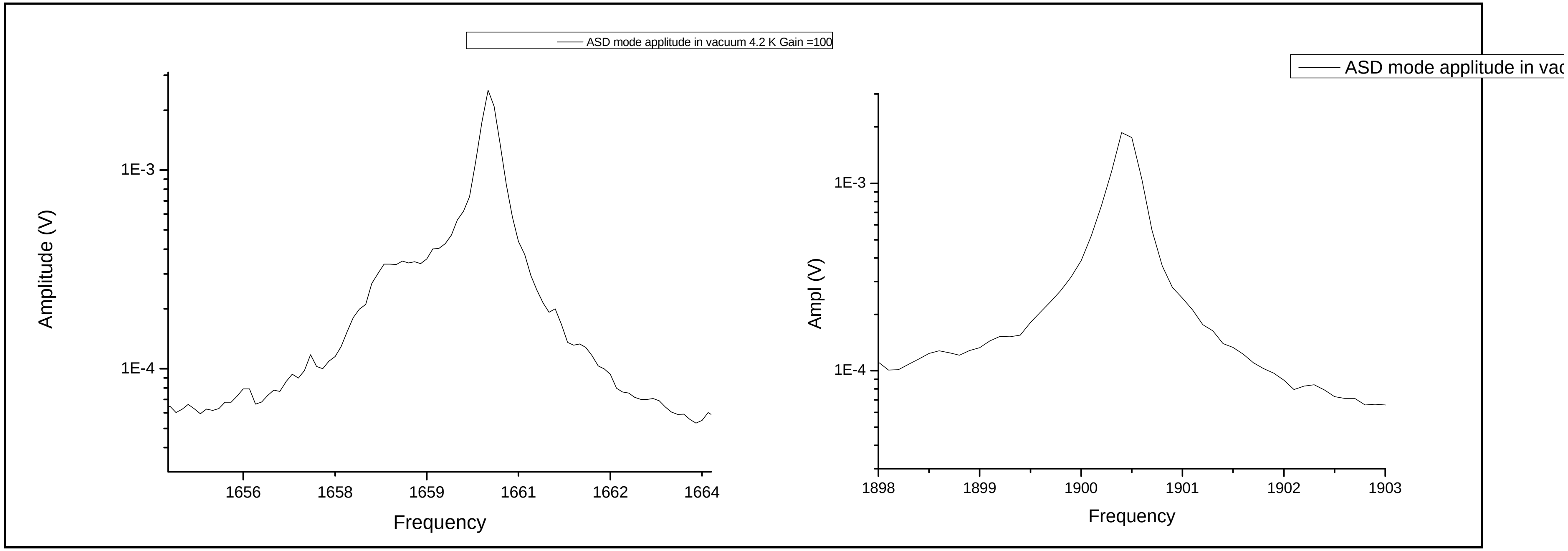
Cantilever decay of resonant motion

Switching of our driving pieze we find decay rates corresponding with the Q of the resonance peaks.



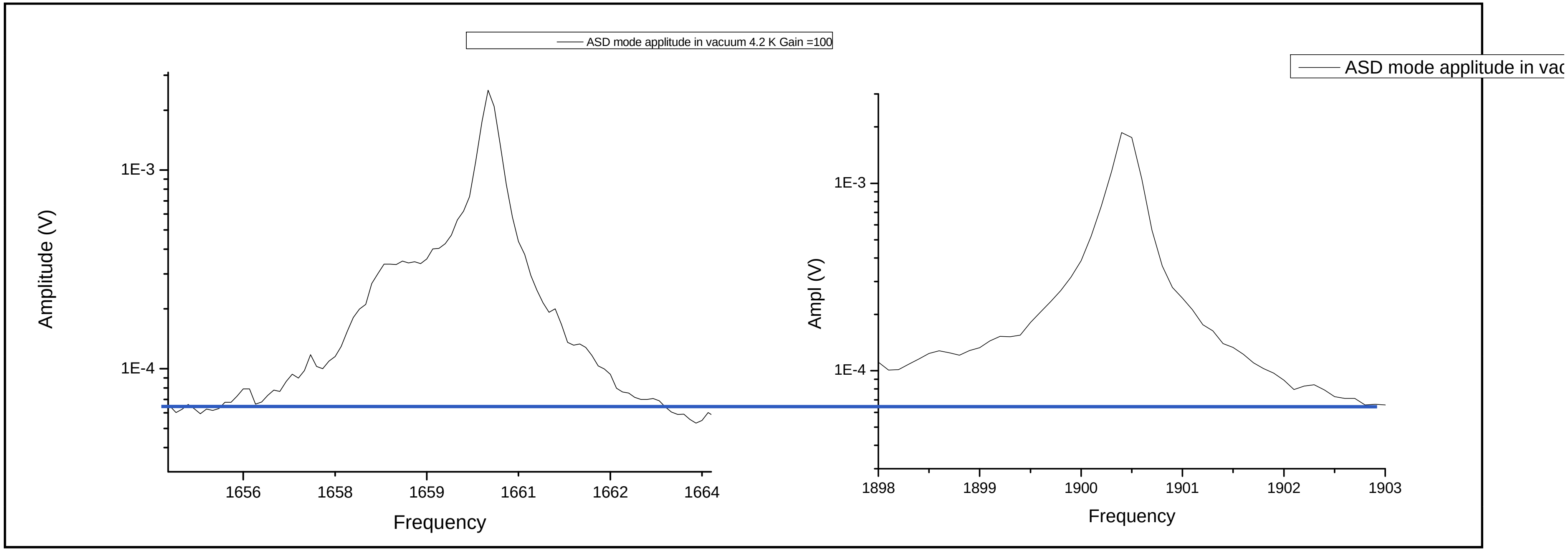
Cantilever thermal noise resonances

Without driving resonances are measured around 1660 Hz and 1900 Hz.



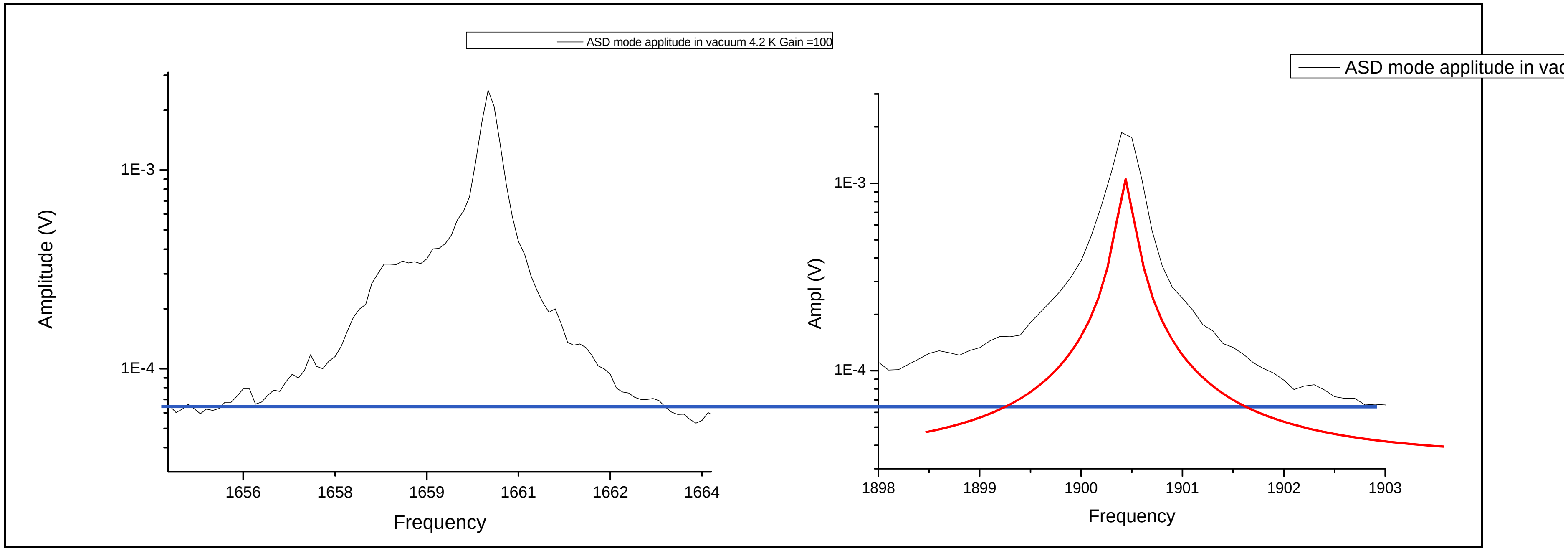
Cantilever thermal noise resonances

Without driving resonances are measured around 1660 Hz and 1900 Hz.
detection noise floor 40 pm/sqrt(Hz)



Cantilever thermal noise resonances

Without driving resonances are measured around 1660 Hz and 1900 Hz.
detection noise floor 40 pm/sqrt(Hz)



calculated thermal noise assuming a distance to the coil of 60 microns

Prospects with these cantilevers:

POSITION NOISE:

At 4K, 5 micron magnetic particle,
60 μm from coil » » » » 40 pm/√Hz

Optimize SQUID noise	÷ 2
Magnet at 30 μm	÷ 8
More coil windings	÷ 2
SQUID at 250 mK	÷ 4

Back action ?

» » » » 400 fm/√Hz ???

Measure a single electron or nuclear spin ?

Nuclear magnetic moment is small!

Gradient set by magnetic tip parameters and tip-sample spacing

$$\text{power SNR} = \frac{\left(\mu_{spin} G\right)^2}{S_F B}$$

Force noise spectral density set by cantilever friction,
Cantilever thermal motion
or
tip surface dissipation

Bandwidth set by spin relaxation rate

0.3 aN for proton
in $2*10^7$ T/m gradient

2 aN for electron
In $2*10^5$ T/m gradient

Prospects with these cantilevers:

FORCE NOISE:

At 4K thermal noise is 10 aN/√Hz

Rugar has 9 aN/√Hz at 4K

(1 aN/√Hz at 100 mK)

At room temperature Q can be made higher

- smaller cantilever diameter
- longer cantilever length

FUTURE PLANS

Cool down in dilution refrigerator in vacuum

what saturation temperature?

back action

environmental vibrations

poor heat conductivity

Cool down in 4He

thermal contact down to 100 mK

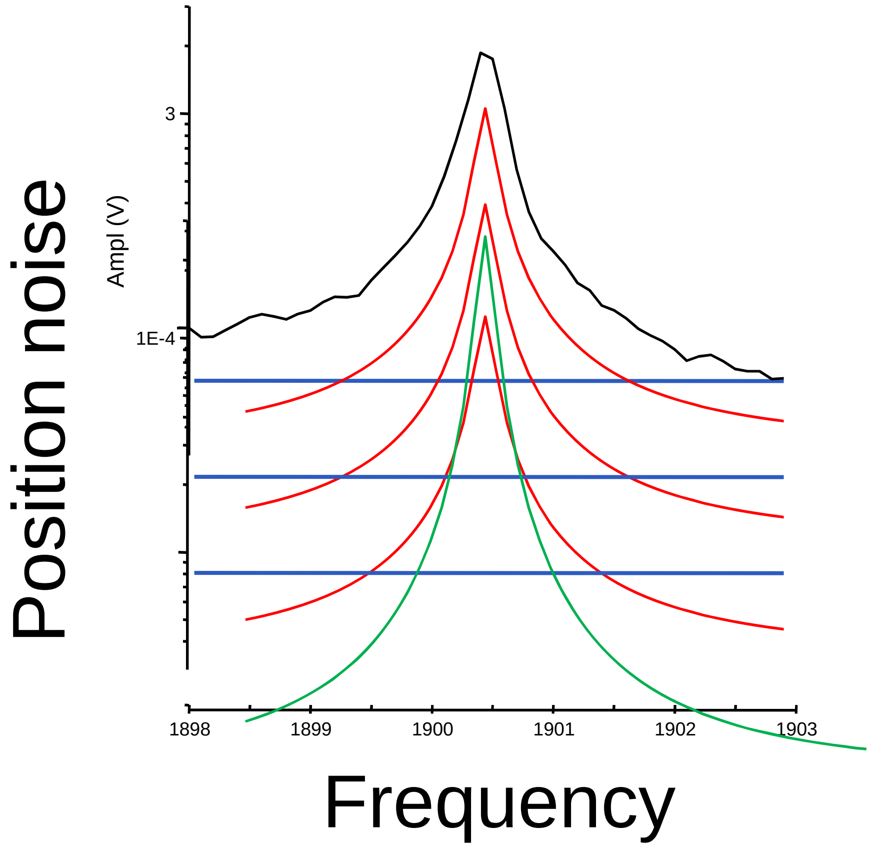
viscosity measurement

Visit Helsinki in August

Cantilever thermal noise resonances

SNR = 50 at 4K

Without vibrations
SNR =100 at 250 mK



FORCE NOISE:

Q can be a lot higher depending on

- cantilever diameter
- cantilever length
- surface treatment ??

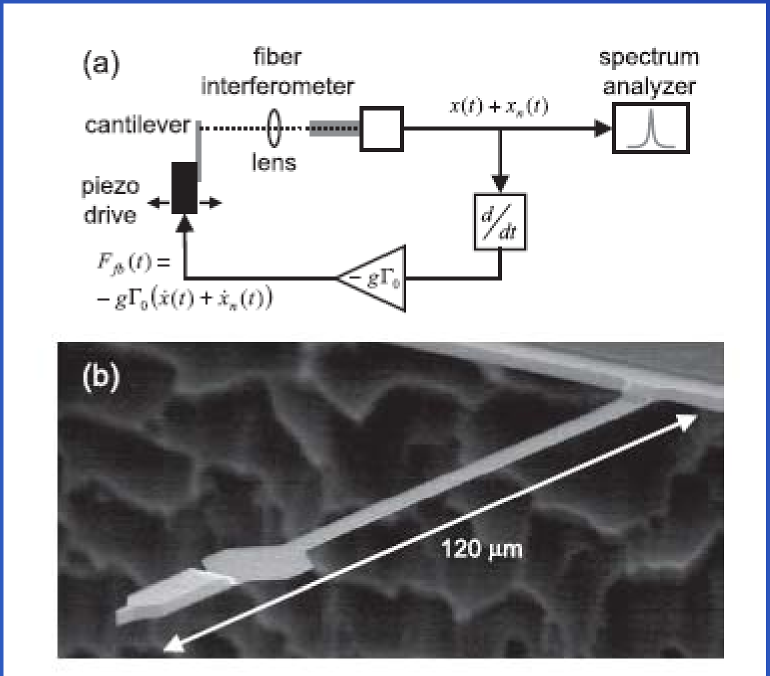
  SEM can be done more carefully, fire wire
- clamping losses
- ultra low temperatures ??

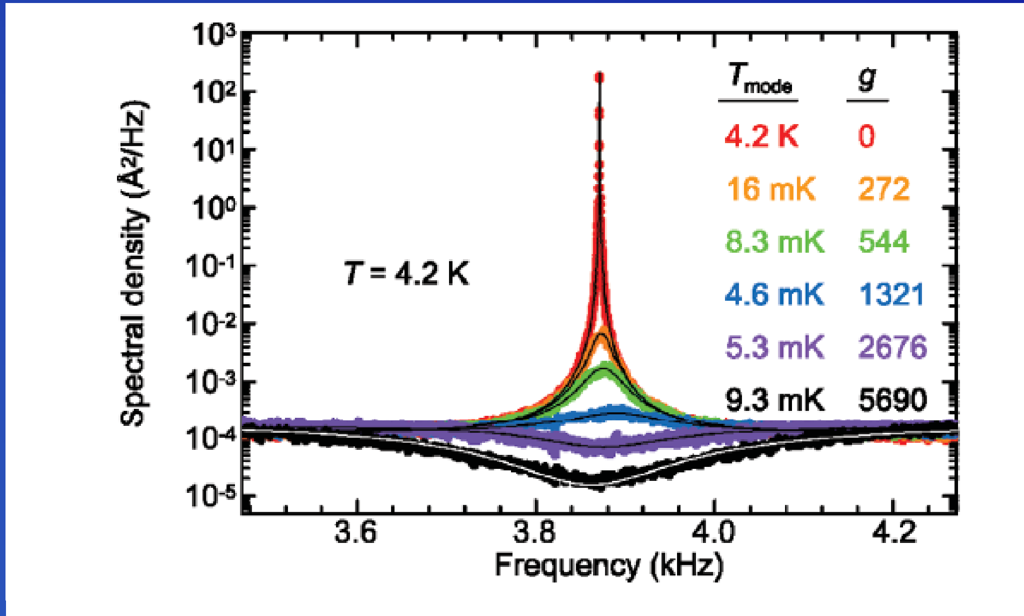
  transverse phonon energy ~ 1.5 K for 50 nm diameter wire

FEEDBACK COOLING:

At 4K and 40 pm/√Hz
 we could cool this cantilever to 150 mK

At 10 mK and 400 fm/√Hz
 we might cool this cantilever to 100 μK





Martino Poggio et al. PRL

Thermometer / VISCOSITY METER for $^3He/^4He$:

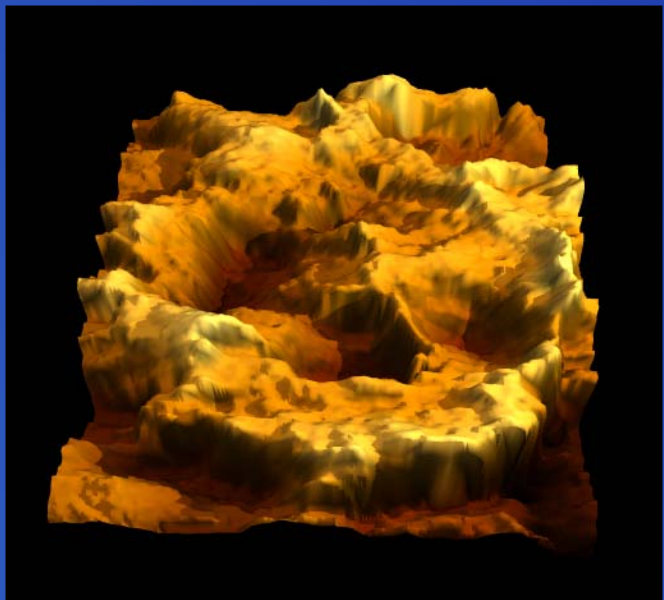
Pickett / et al. use a 1 micron diameter vibrating wire, ~ 5 mm long, in B-field

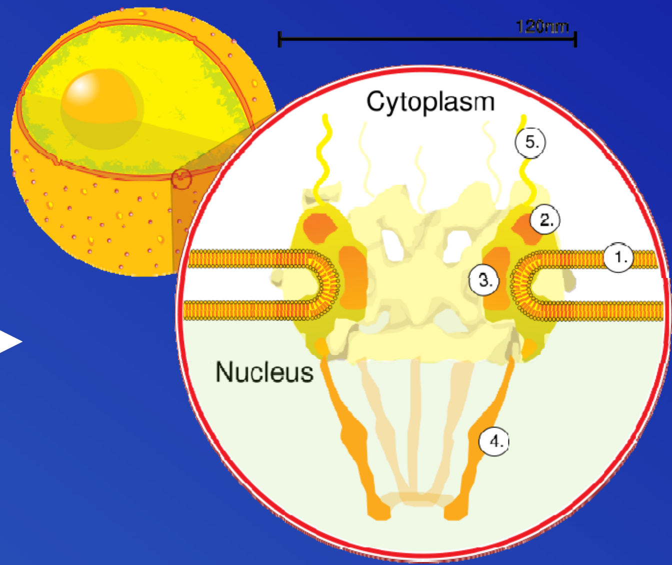
32 kHz tuning fork (k = 10 kN/m, Q=)
has intrinsic damping $\gamma = 4*10^{-8}$ Ns/m

SiC wire: (k < 0.1 mN/m, Q=10^6)
$\gamma = 4*10^{-13}$ Ns/m
hydrodynamic damping force scales with the radius of a sphere

… Ultimate Goal:

Single electron spin
Few nuclear spins





Structure determination of nuclear pore complexes

Acknowledgements:

Leiden

Peter Heemskerk
Sasha Usenko
Andrea Vinante
Allard Katan
Erwin Heeres
Anne France Beker

Marcel Hesselberth
Ruud van Egmond
Dian van der Zalm
FMD

IBM

Martino Poggio
Christian Degen
Mark Sherwood
John Mamin
Dan Rugar

STW
ERC starting grant