Carbon nanotube mechanical mass sensor with single molecule resolution at room temperature

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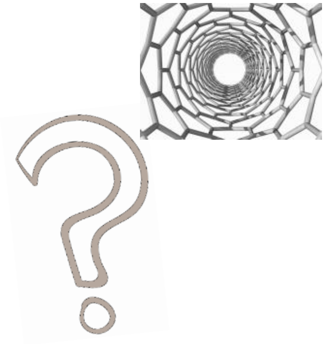
Outline

Introduction

Why do we use resonators and what type of resonators de we use?



Outline

Introduction → Experimental setup

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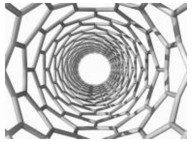
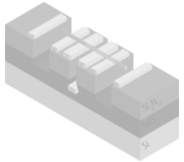


What is required to answer those questions?



Outline

Introduction → **Experimental setup** → **Results**

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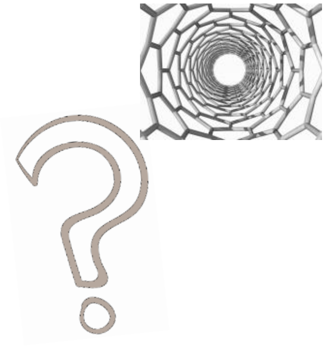

Experimental setup

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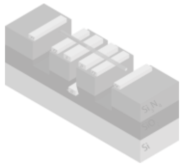
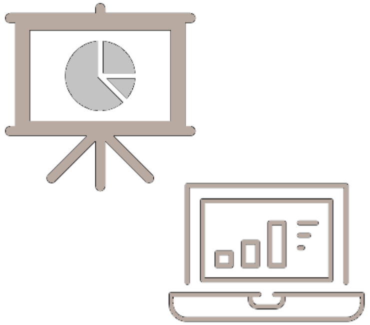


Results

How did we obtain our results and what do we unerstand from them?



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Introduction → **Experimental setup** → **Results** → **Conclusions**

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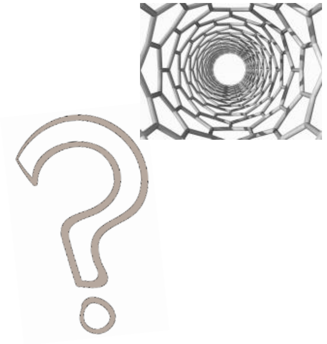

Experimental setup

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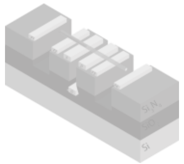

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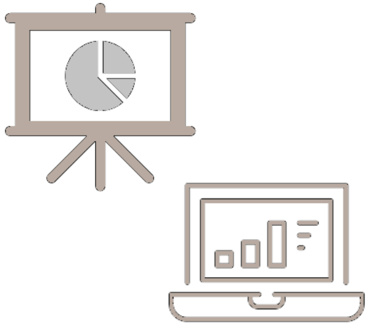
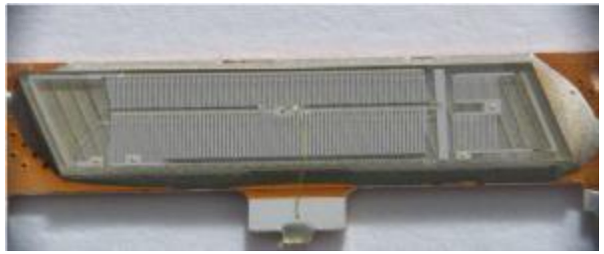


Conclusions

Motivation: why resonators?

- They are everywhere!

Surface acoustic wave detector (smartphone)



- Many applications, such as:
  - Sensing/metrology (including gravity waves)
  - Frequency conversion
  - Quantum test
  - Etc.

Interest of nanoscale resonators

- Shriking device dimensions reduces the mass: better sensitivity, higher zero-point fluctuations

$$Z_{zpf} = \sqrt{\frac{\hbar}{2 \cdot m_{eff} \cdot \omega_m}}$$

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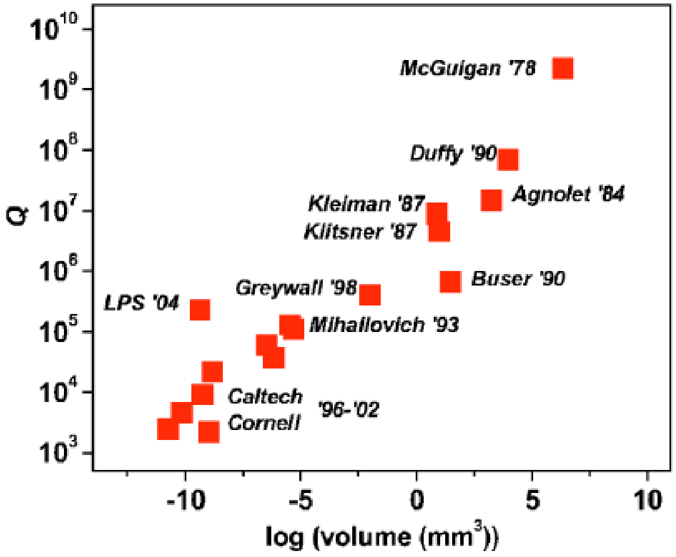
- Crystalline resonators suffers from surface defects

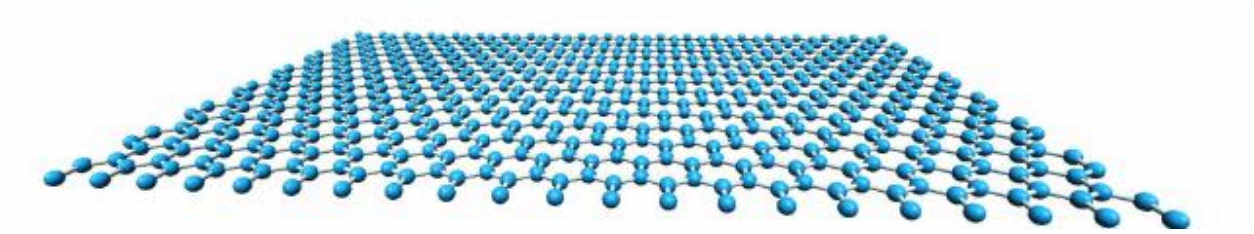
K. L. Ekinci & M. L. Roukes
Rev. Sci. Intrum. 2005



Solution: bottom-up materials

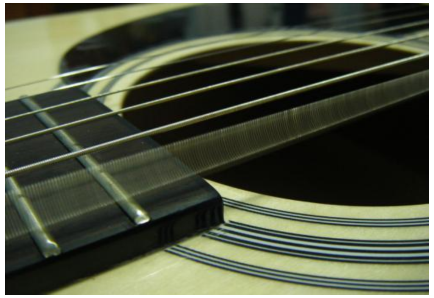
Carbon based resonators

- Graphene and nanotubes



- ➢ Nearly perfect structures, strong sp^2 bonds (high Young modulus)
- ➢ Recent progress in detection scheme has allowed to detect their motion ($\langle z \rangle$ ~ pm range), now technologically mature

Why SWCNTs as mechanical resonators?



- Eigen frequency defines frequency of a resonator:

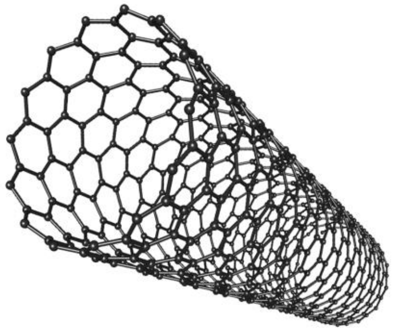
$$\omega_0 = 2\pi f_0 = \sqrt{\frac{k_0}{m_0}}$$

- Mass sensing and mass responsivity:

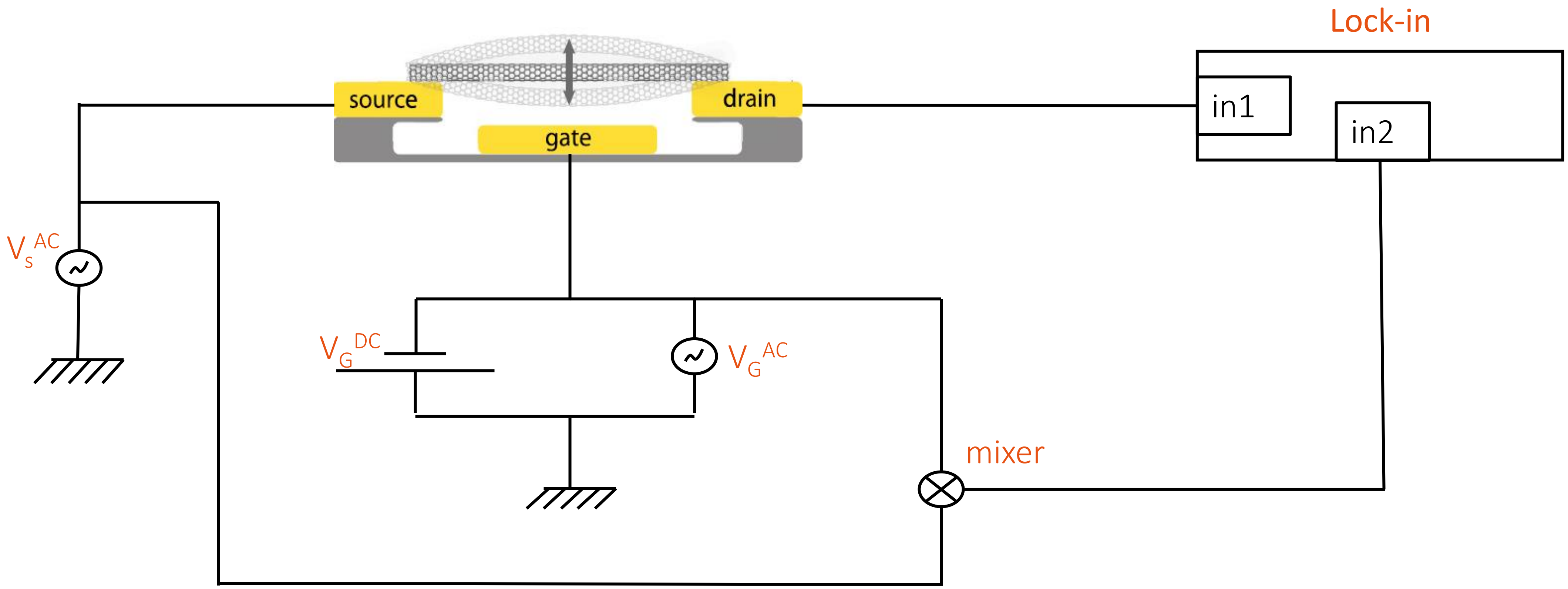
$$\delta m = \frac{2 \cdot meff}{f_0} \cdot \delta f$$

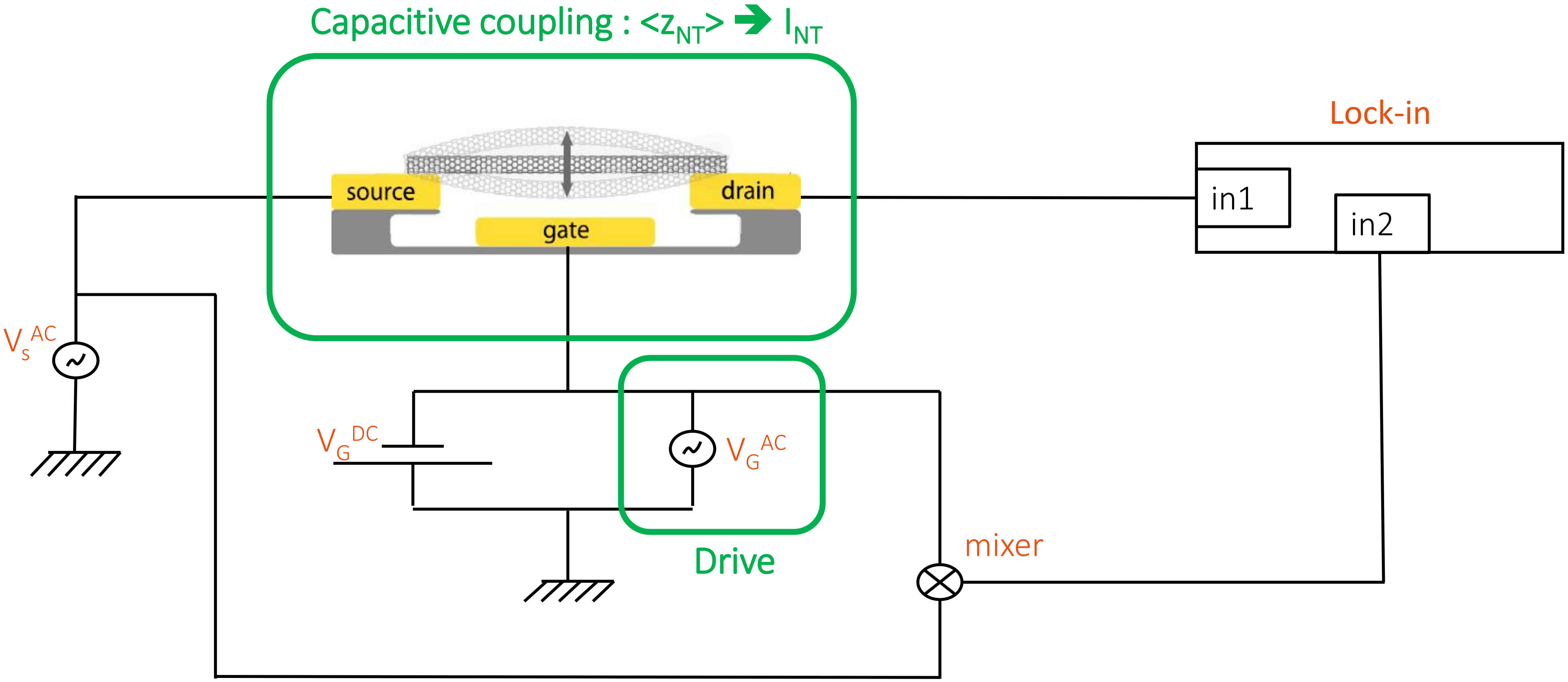
$$\delta f = \frac{f_0}{2 \cdot meff} \cdot \delta m$$

Mass responsivity (= GAIN)



- The interest of nanoresonators => low mass: $1.7 \times 10^{-24} g = 1.7\ yoctogram$


Lock-in
in1
in2
source
drain
gate
V_s^{AC}
V_G^{DC}
V_G^{AC}
mixer

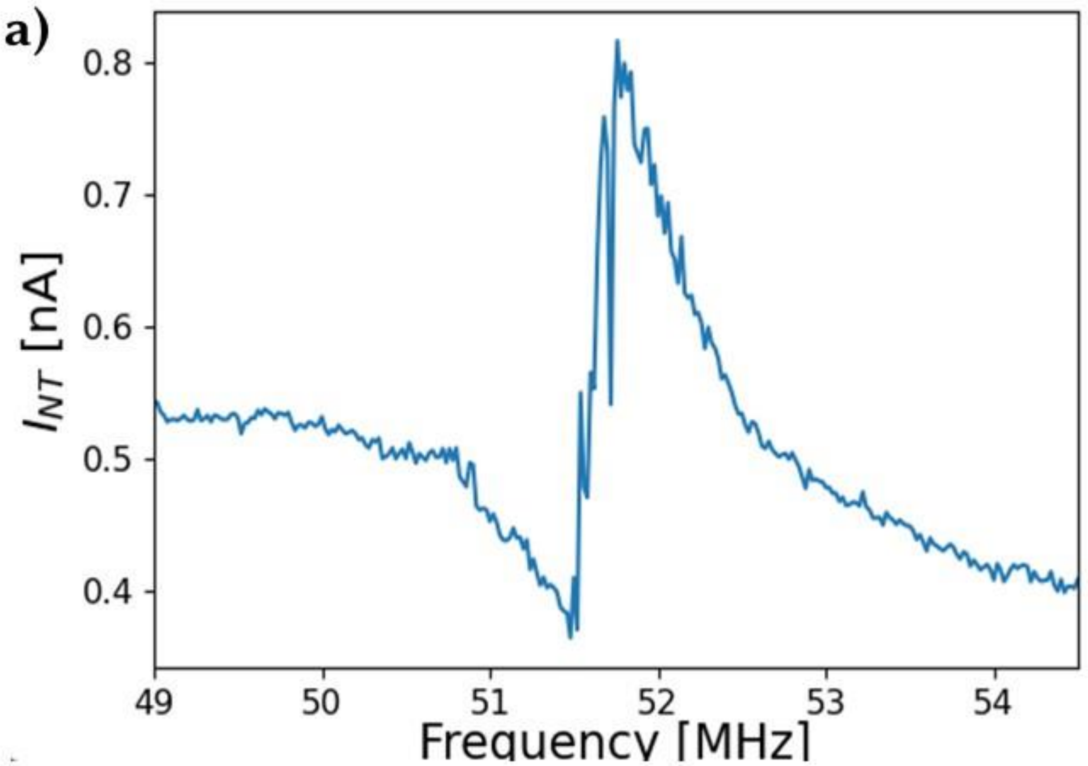


Capacitive coupling : <z_NT> ➔ I_NT
source
drain
gate
Lock-in
in1
in2
V_s^AC
V_G^DC
V_G^AC
Drive
mixer

Measured signals

Mechanical spectra

a)



Measured signals

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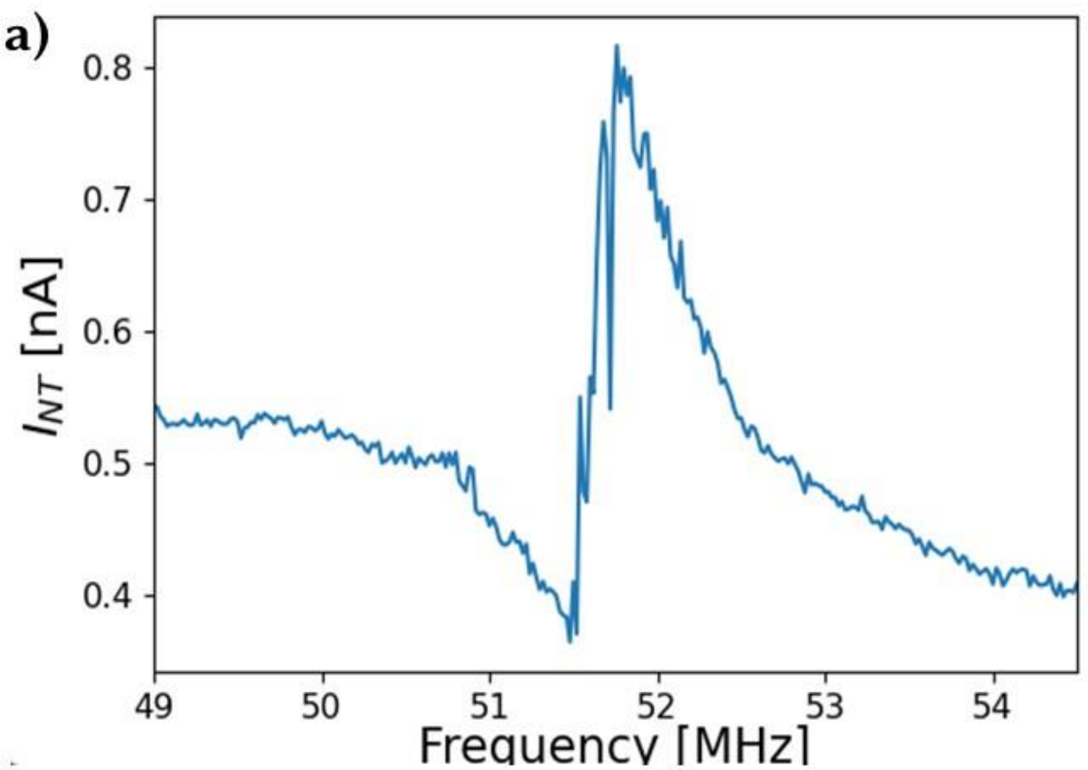
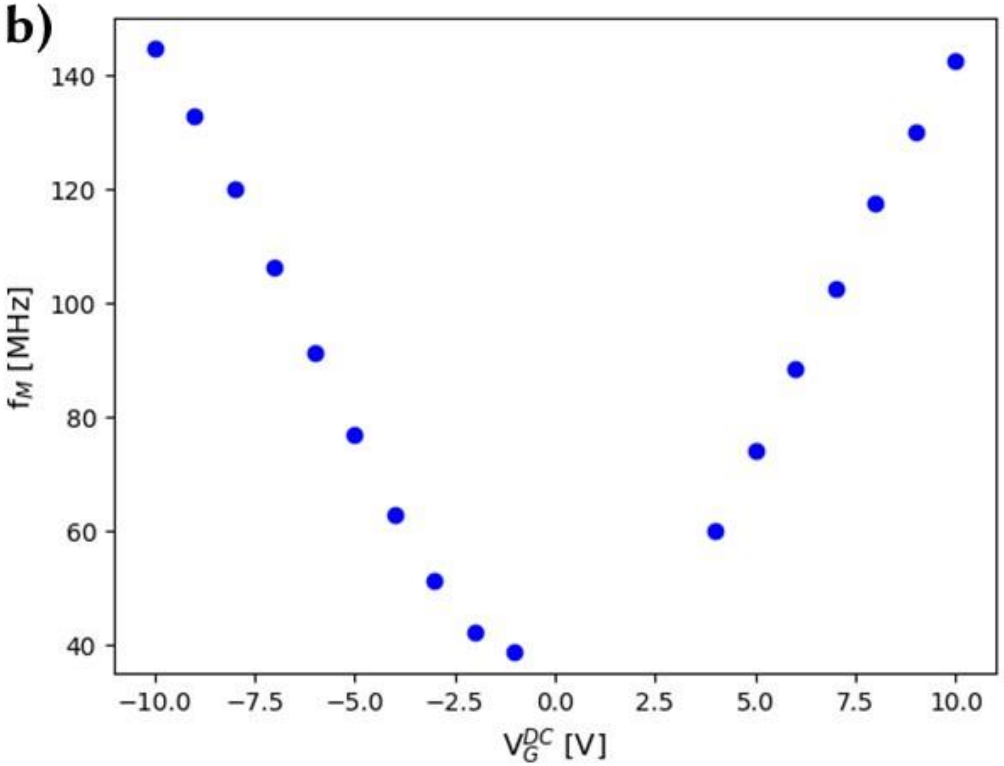


DC gate dependence of the resonance
(electrostatic hardening)



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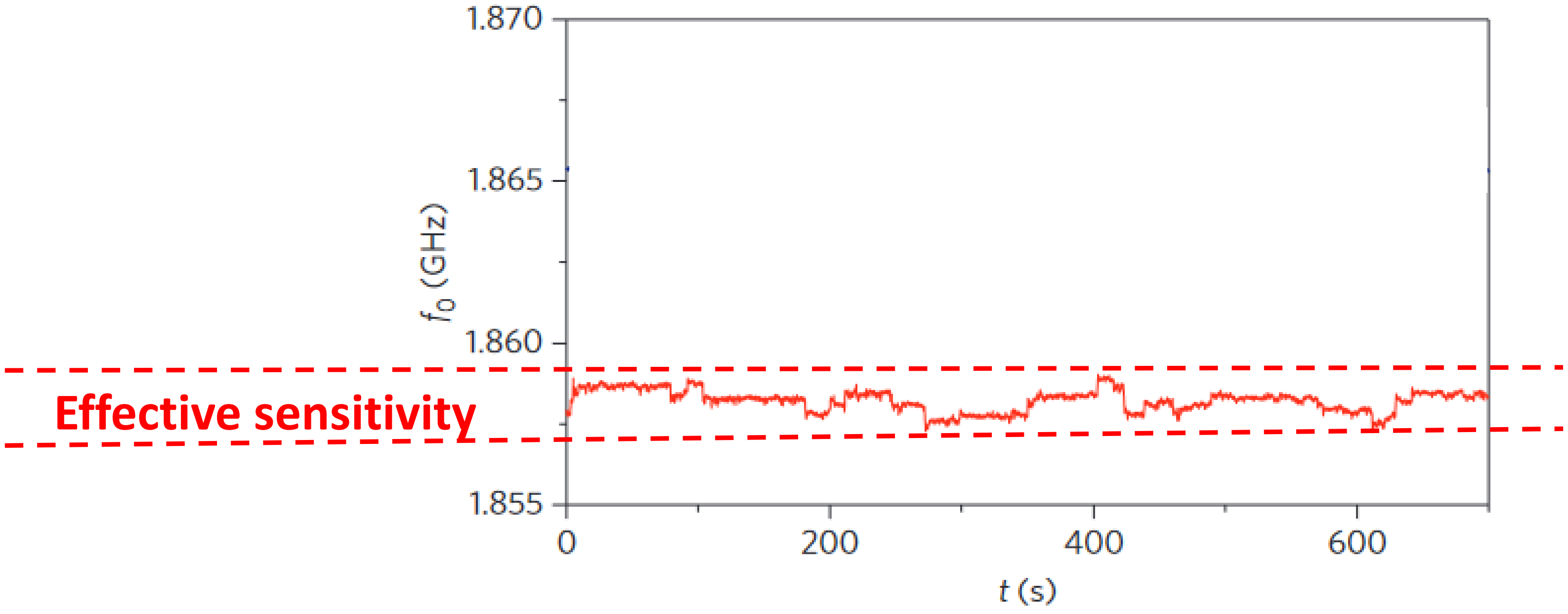
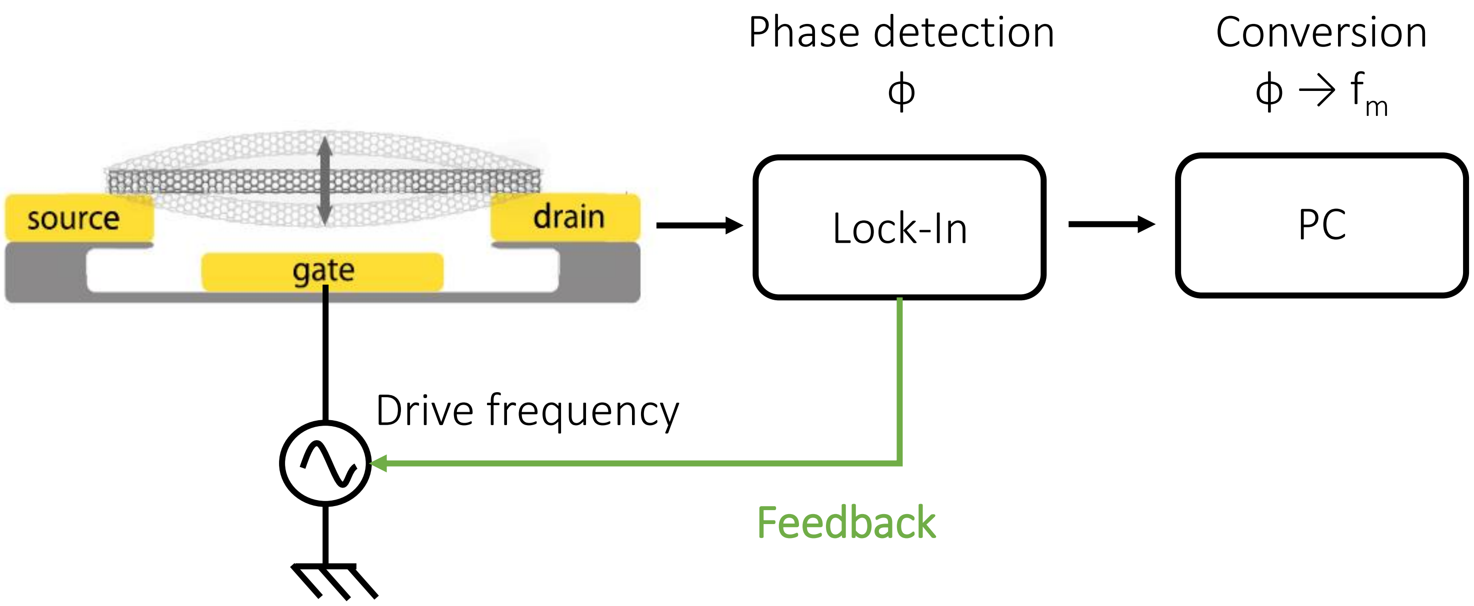
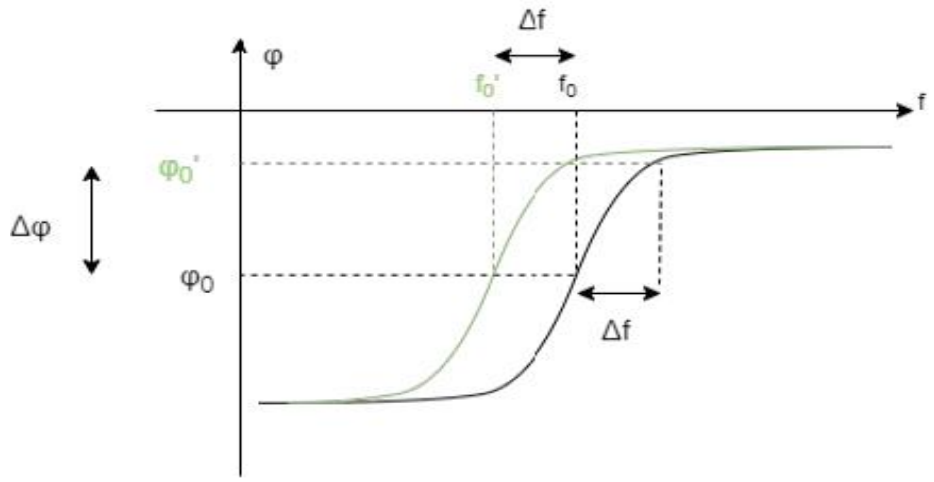


J. Chastes et al. (2012). A nanomechanical mass sensor with yoctogram resolution, Nat. Nano, 7, 5, 301-304.

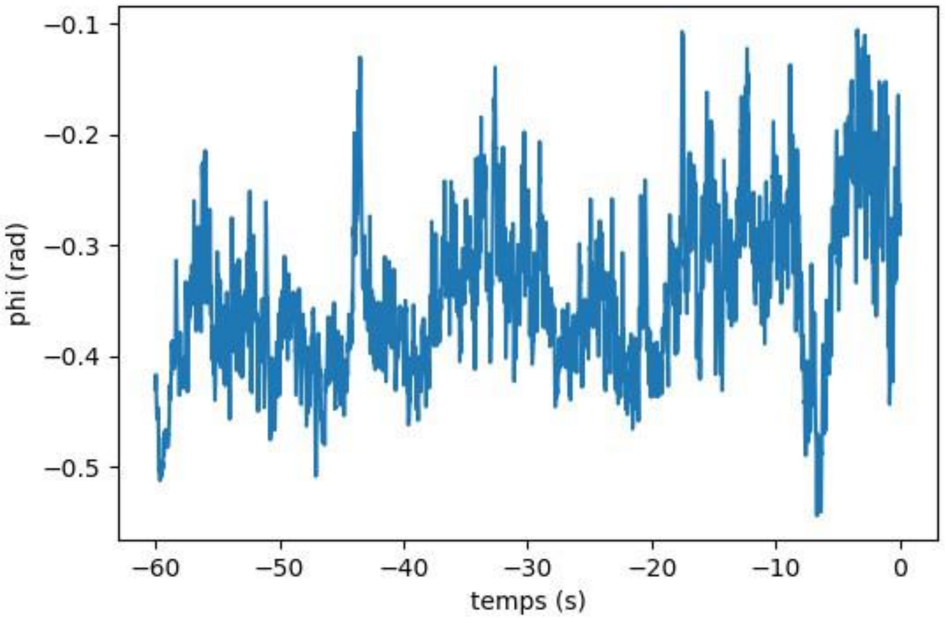
Open-loop vs Close-loop sensitivity





Open-loop

Recorded phase (free evolution)



Open-loop

Allan deviation $$\sigma_y(\tau) = \sqrt{\frac{1}{2(N-1)} \sum_{i=1}^{N} \left(\frac{\overline{f_{i+1}} - \overline{f_i}}{f_0}\right)^2}$$

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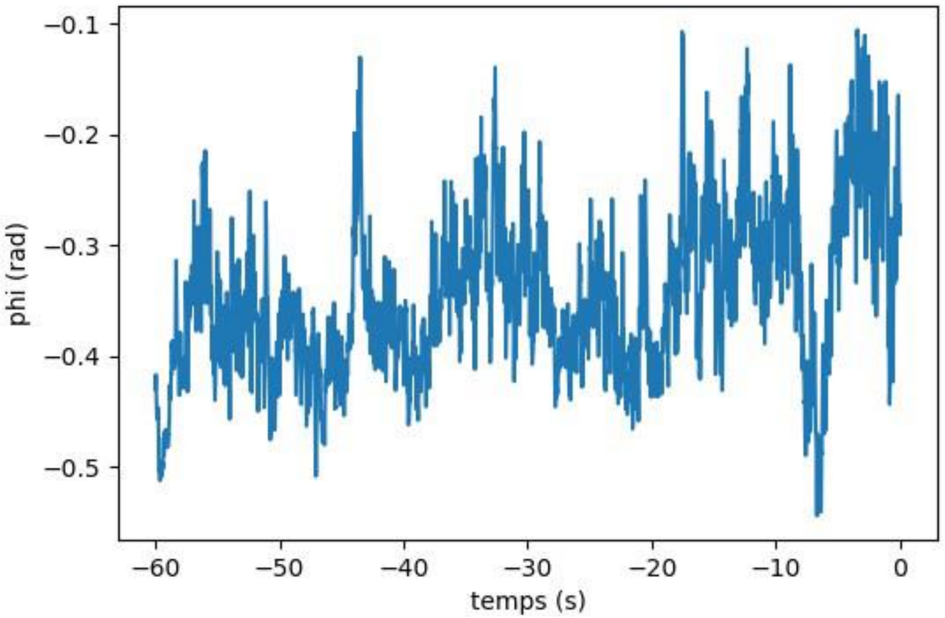

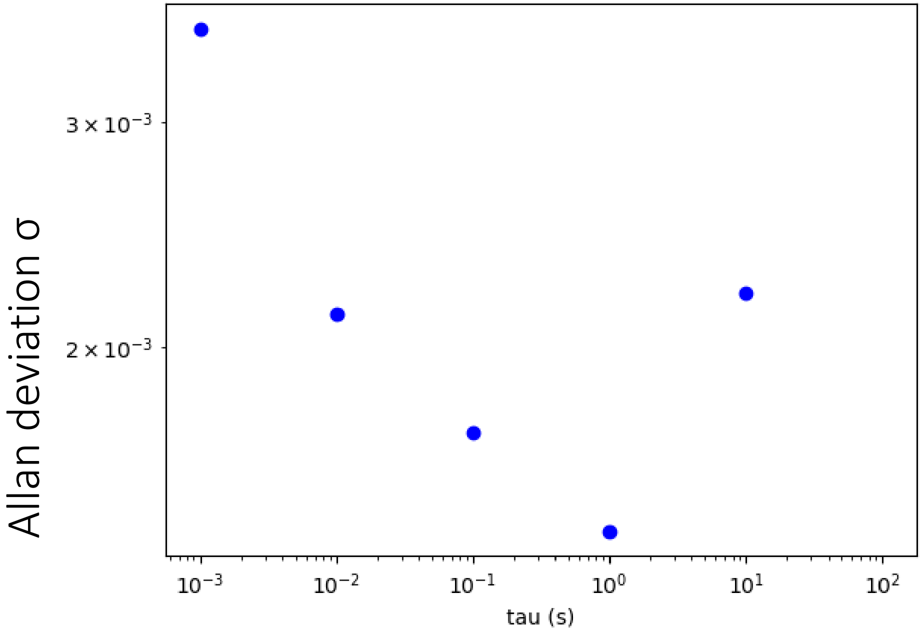

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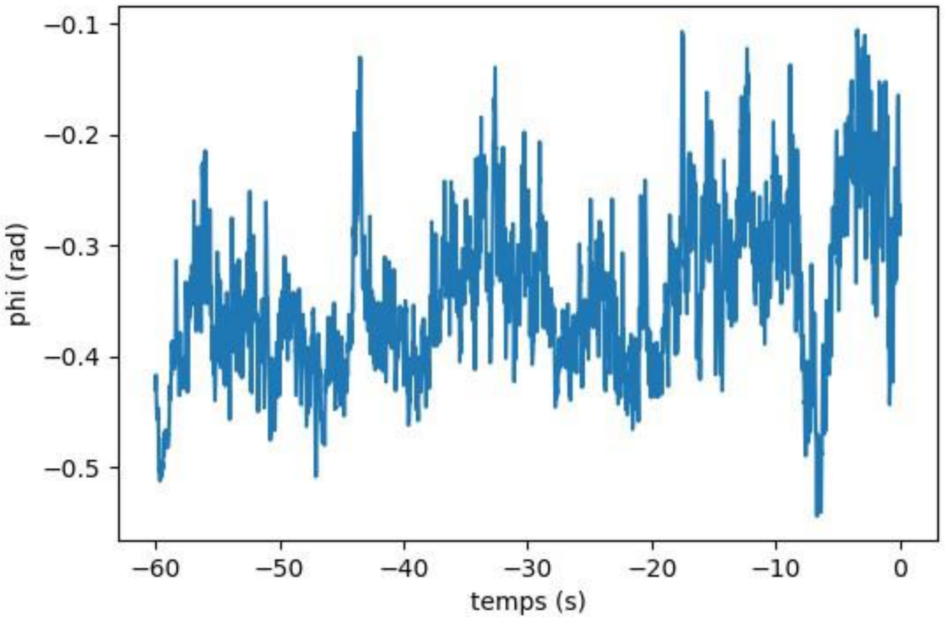

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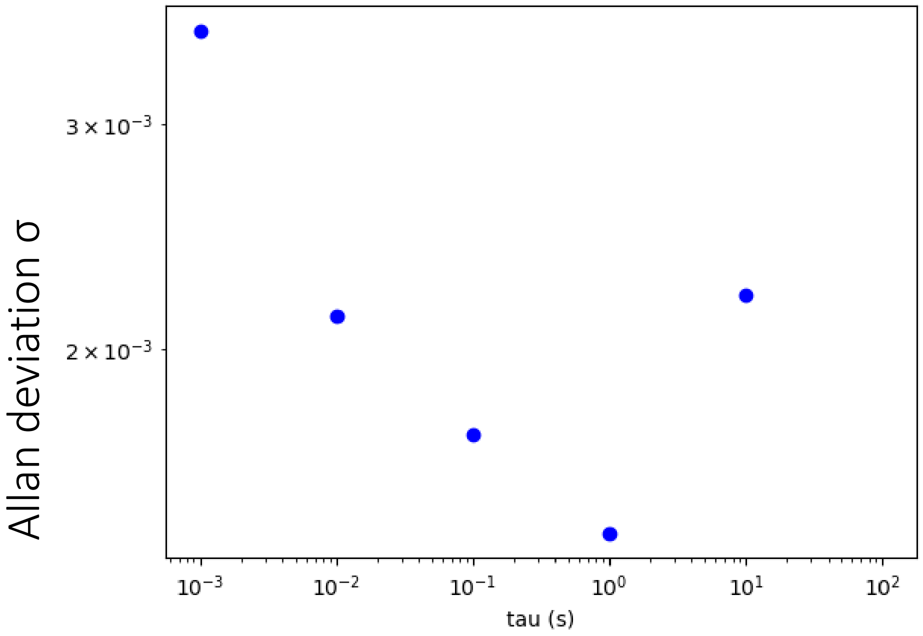
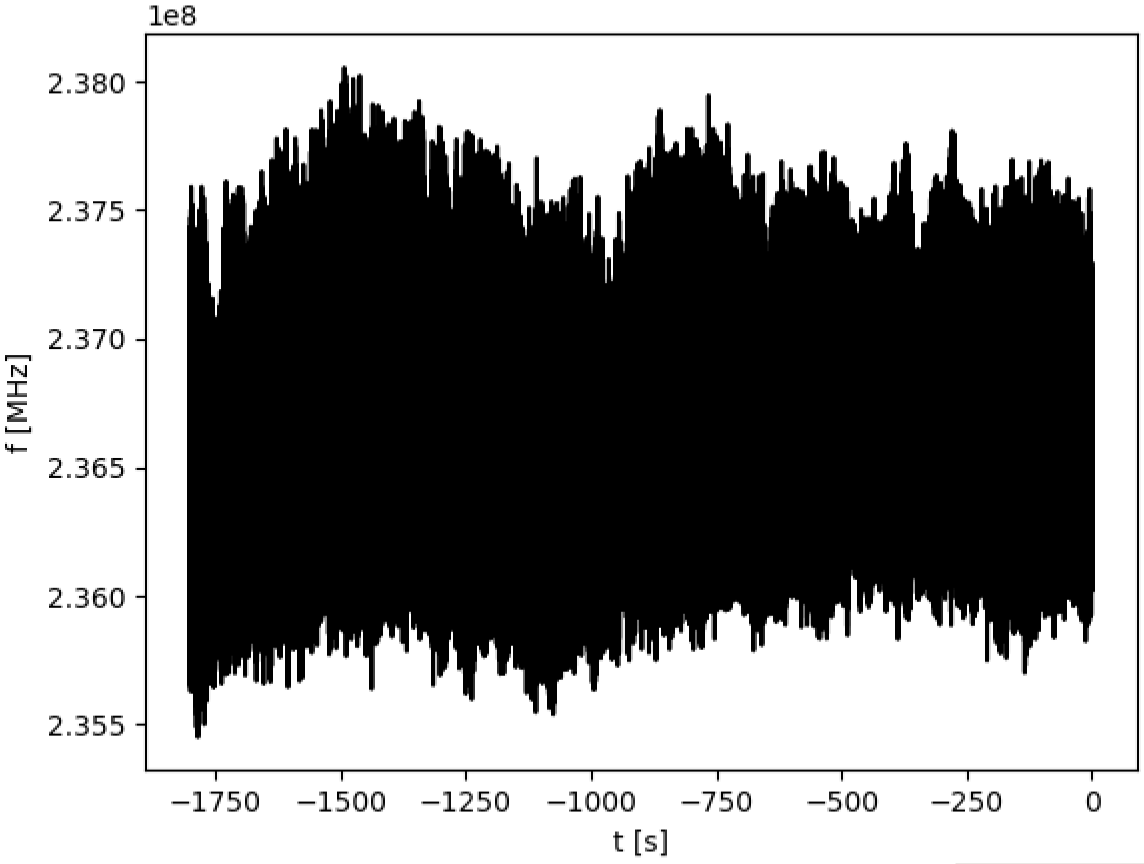
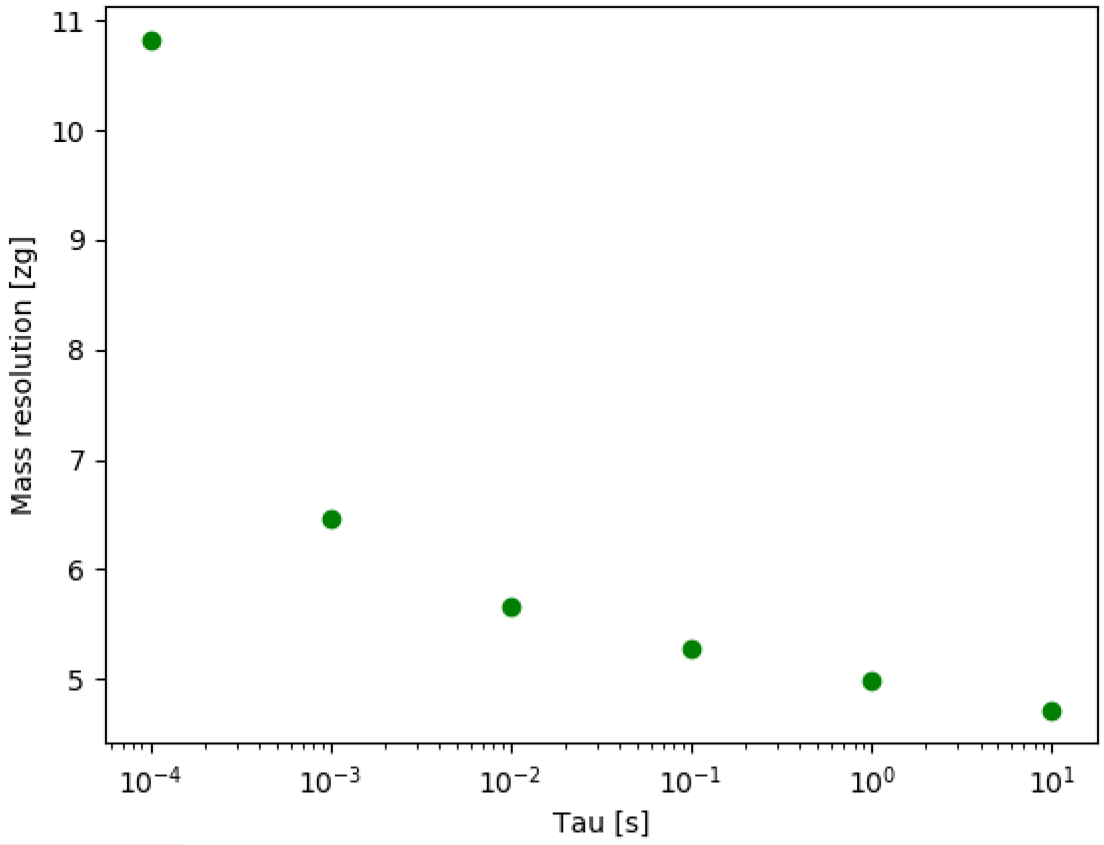


$\delta m_{lim} = 2 m_{eff} \sigma_y(\tau)$

Sensitivity ~ 10 zg

Close loop-sensitivity





Sensitivity ~ 5 zg

Reproducibility

Sample reference	Best sensitivity (RT, vacuum)
#1 open loop	10 zg = 10 000 yg
#1, close loop	5 zg = 5 000 yg
#2, run 1	270 yg
#2, run 2	**70 yg**

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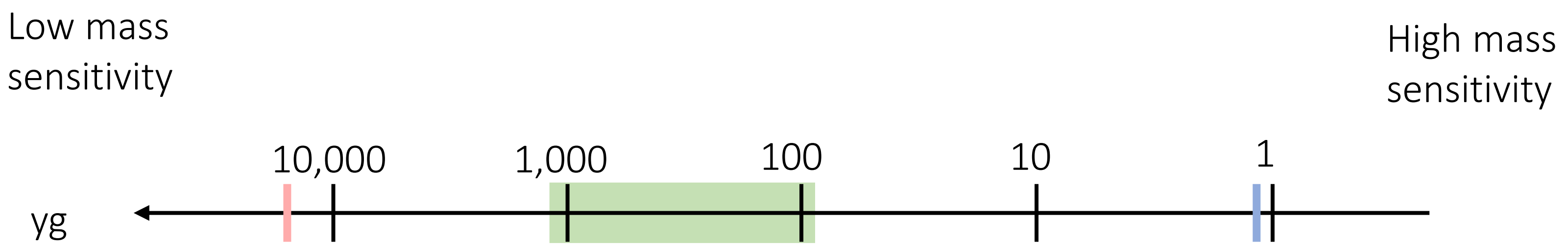


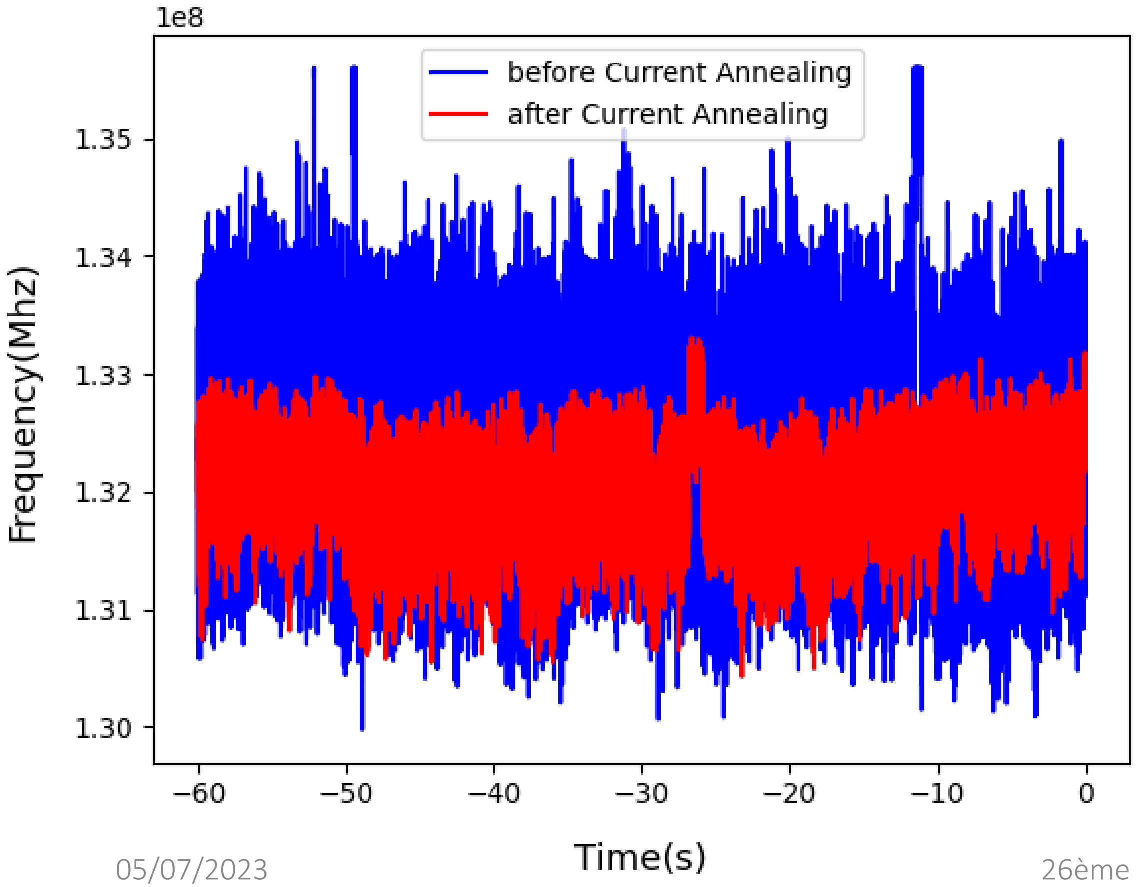
Lassagne et al.
Room temperature
25,000 yg

Our work
Room temperature
70 yg

Chaste et al.
Cryogenic environment
1.4 yg

What limits the sensitivity?

- Current annealing: cleaning the NT surface

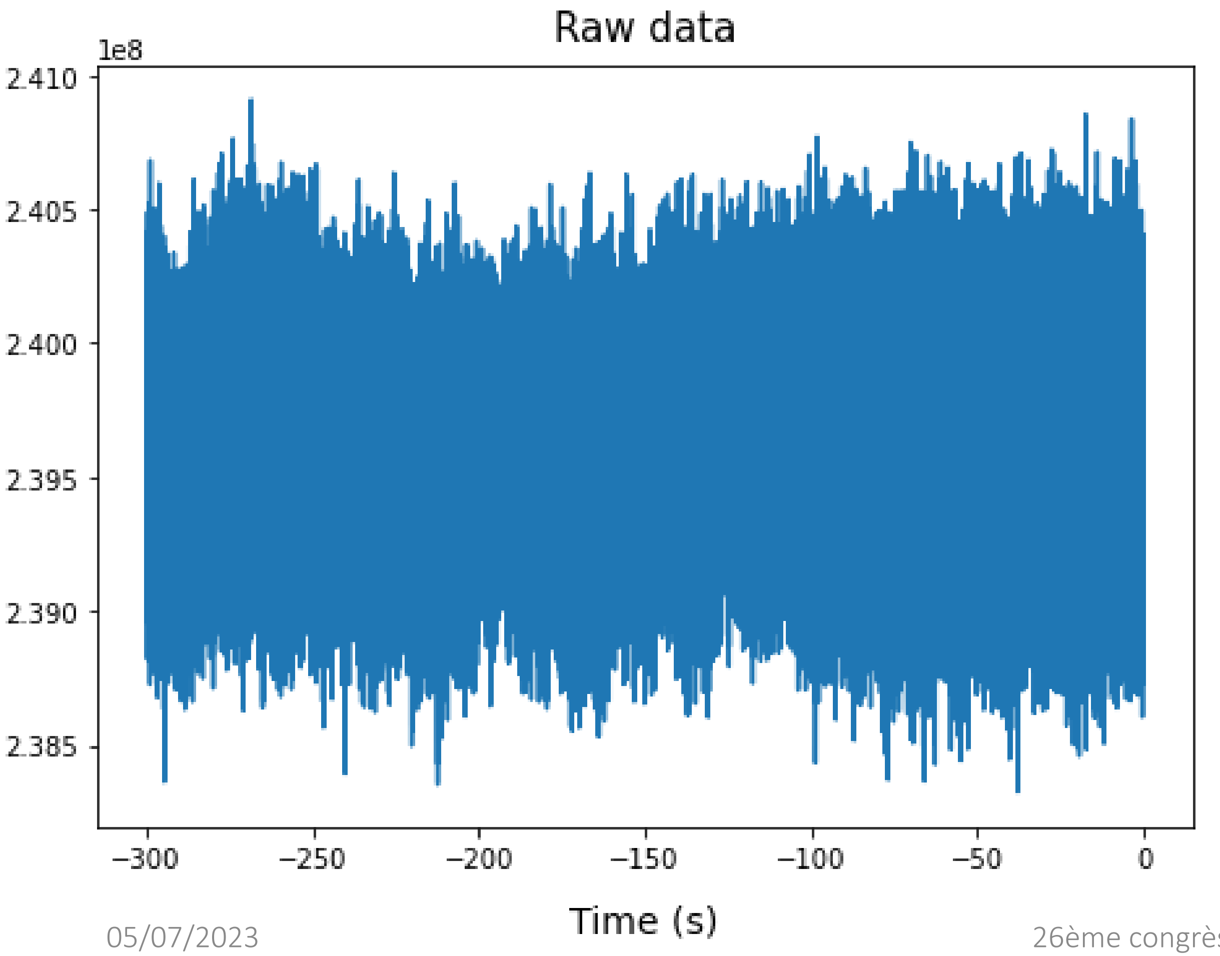


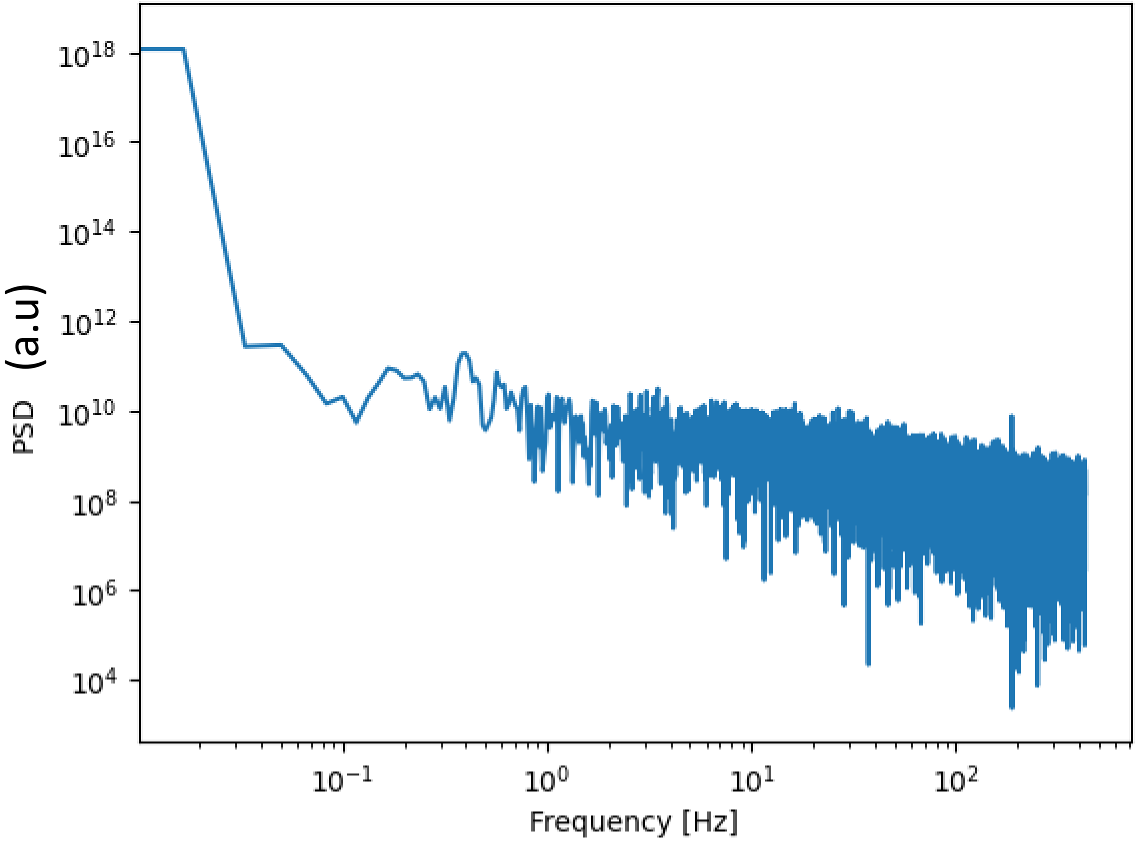
Before CA : 550 yg
After CA : 270 yg

Main mechanism: particle diffusion
Secondary mechanism: adsorption/desorption on random 'traps'

What limits the sensitivity?

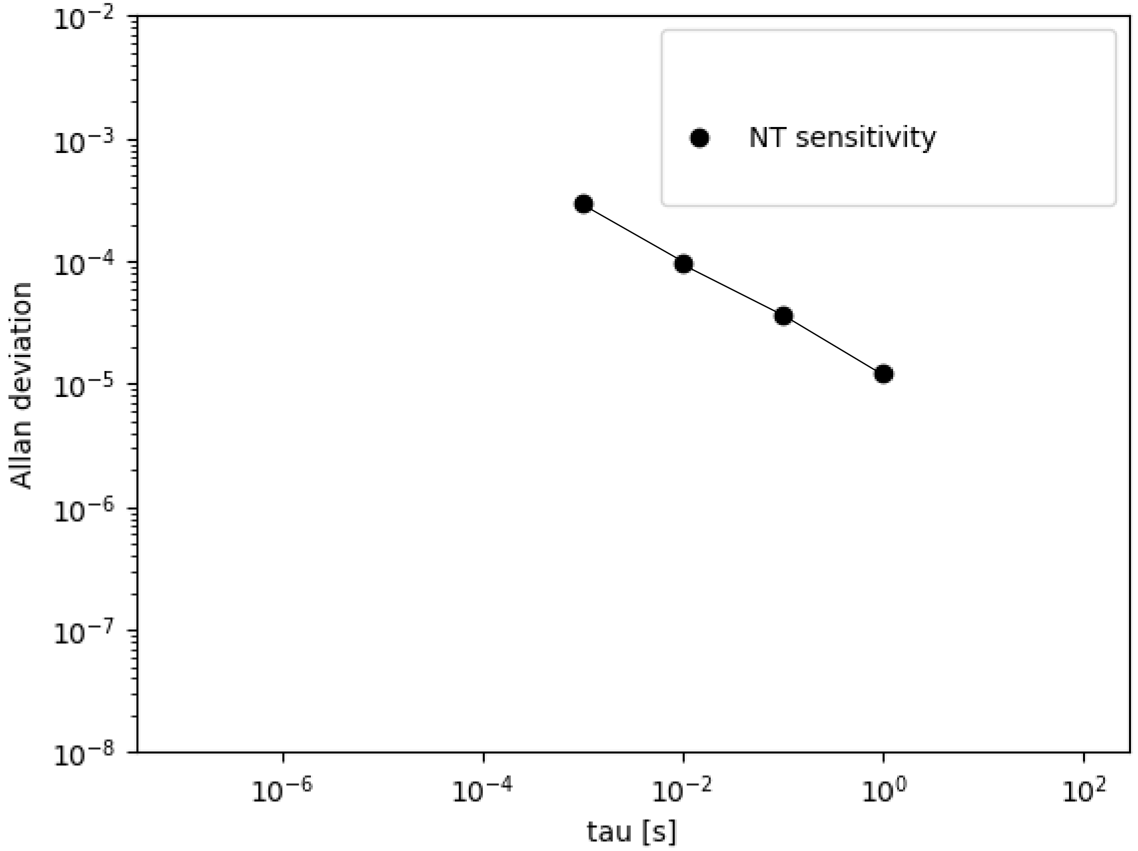
FFT: 1/f (pink) noise. Frequency fluctuations?





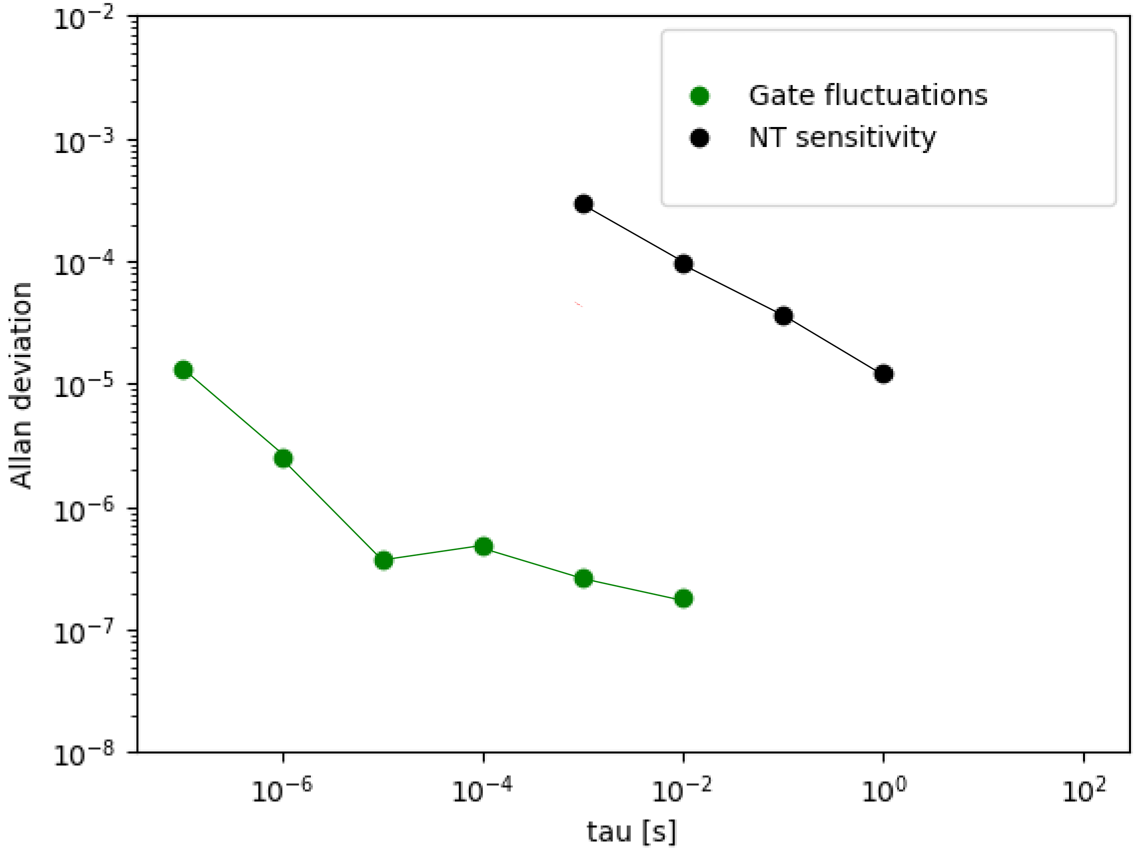
What limits the sensitivity?

Noise sources from the set-up:



What limits the sensitivity?

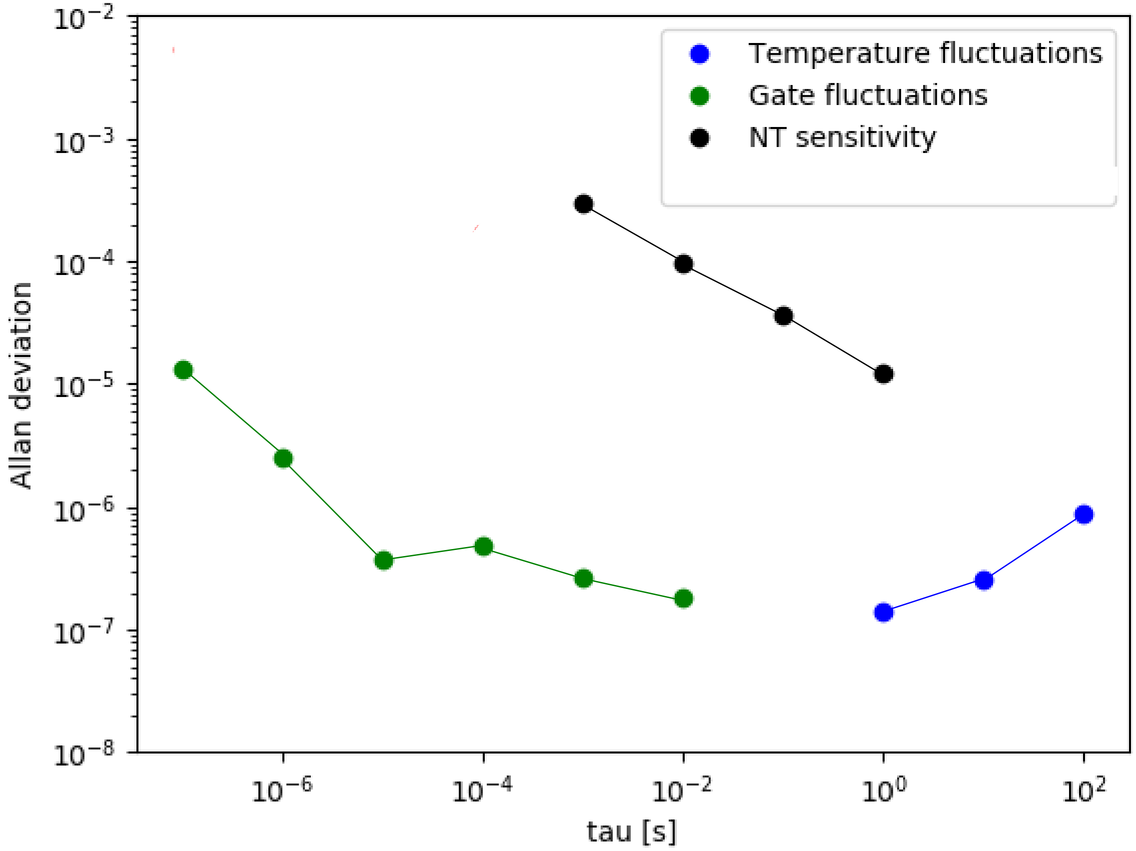
Noise sources from the set-up: DC sources,



Contribution of 1‰

What limits the sensitivity?

Noise sources from the set-up: DC sources, Temperature stability,



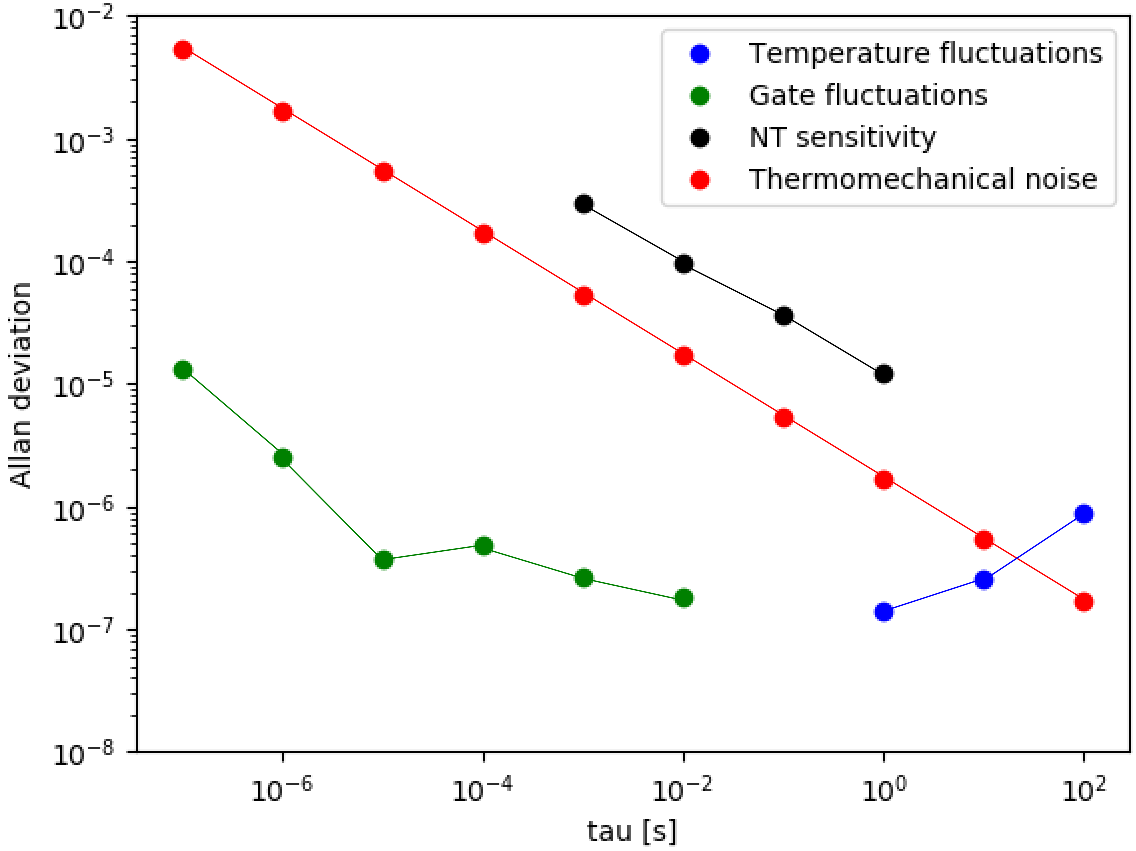
Contribution of 1‰

+

Contribution of 1%

What limits the sensitivity?

Noise sources from the set-up: DC sources, Temperature stability, Brownian noise



Contribution of 1‰

+

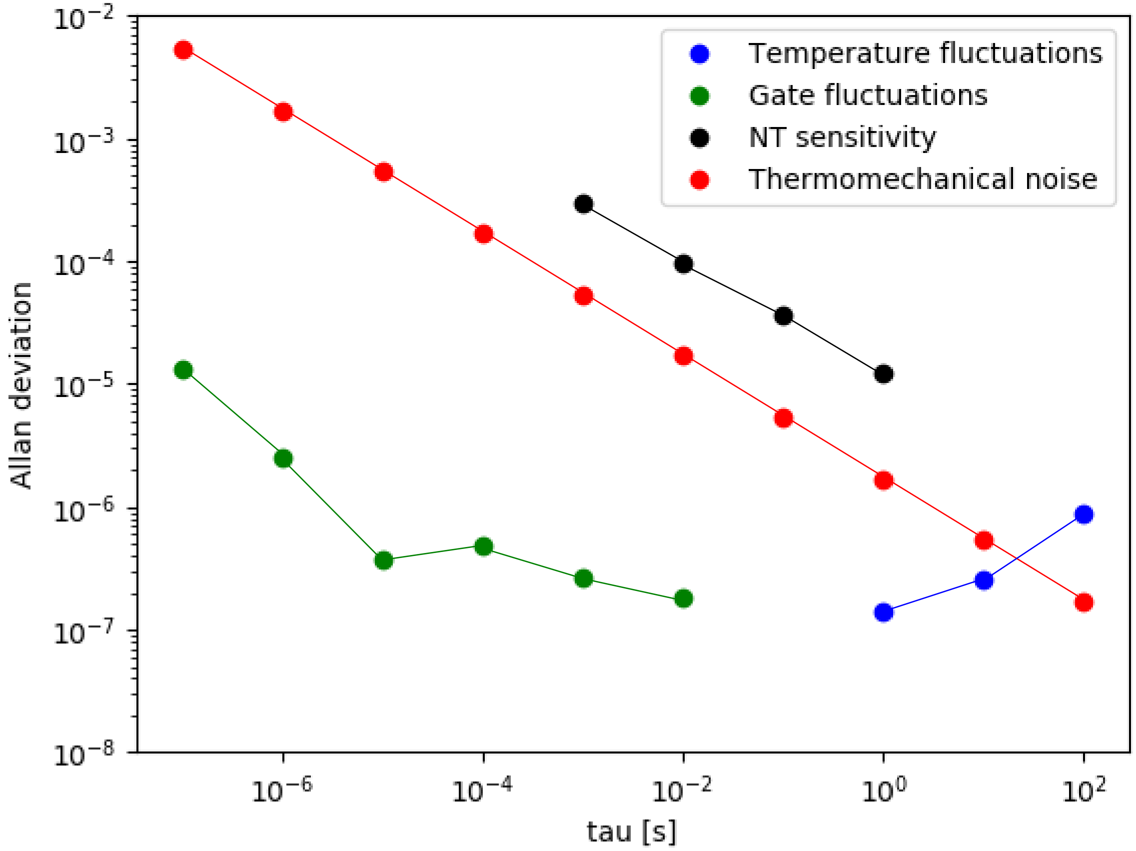
Contribution of 1%

+

Contribution of 10%

What limits the sensitivity?

Noise sources from the set-up: DC sources, Temperature stability, Brownian noise



Contribution of 1‰

+

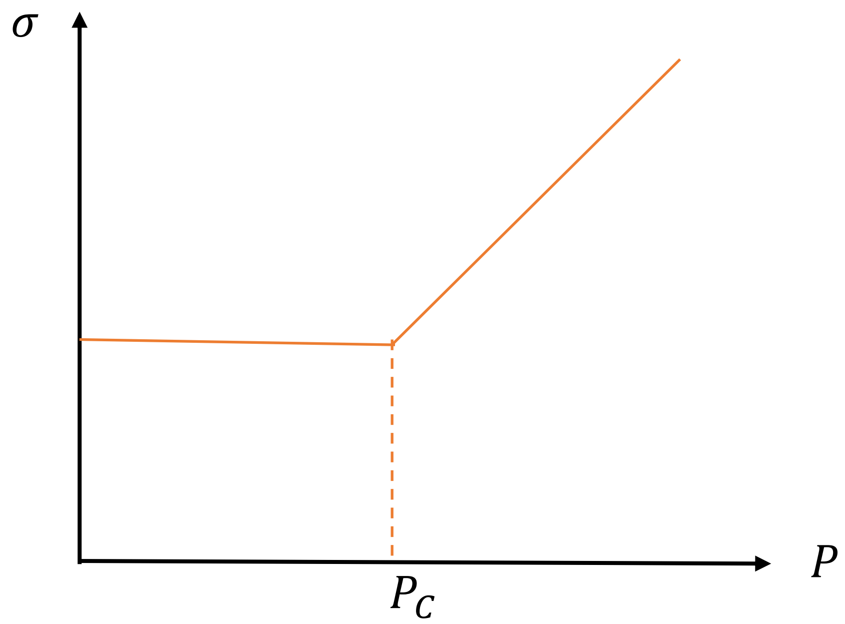
Contribution of 1%

+

Contribution of 10%

$\approx \mathbf{11\%}$

Progressively increasing pressure with dry N2



Expectation: Q degrades with P

⇒ sensitivity degrades (after a threshold P_c)

Expectations:
- Adsorption/desorption events more frequent

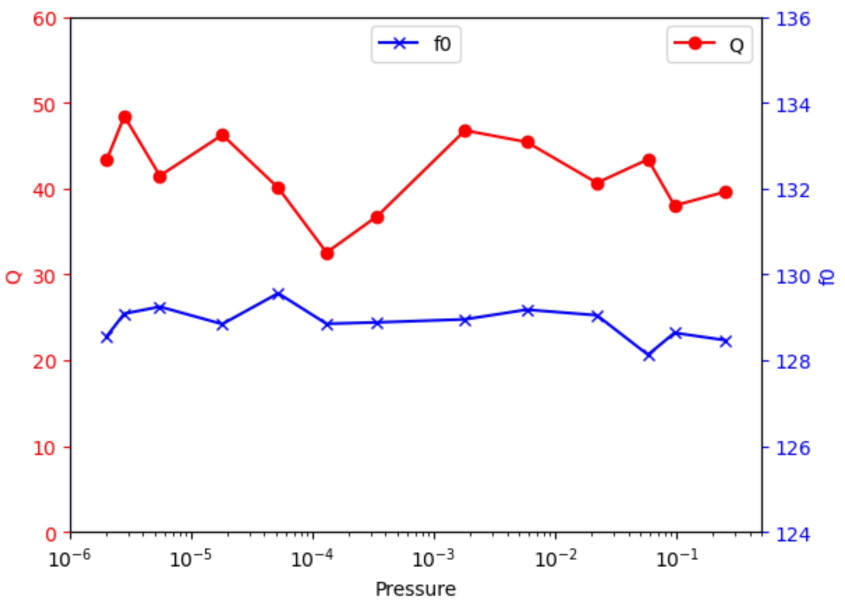
⇒ noise increases

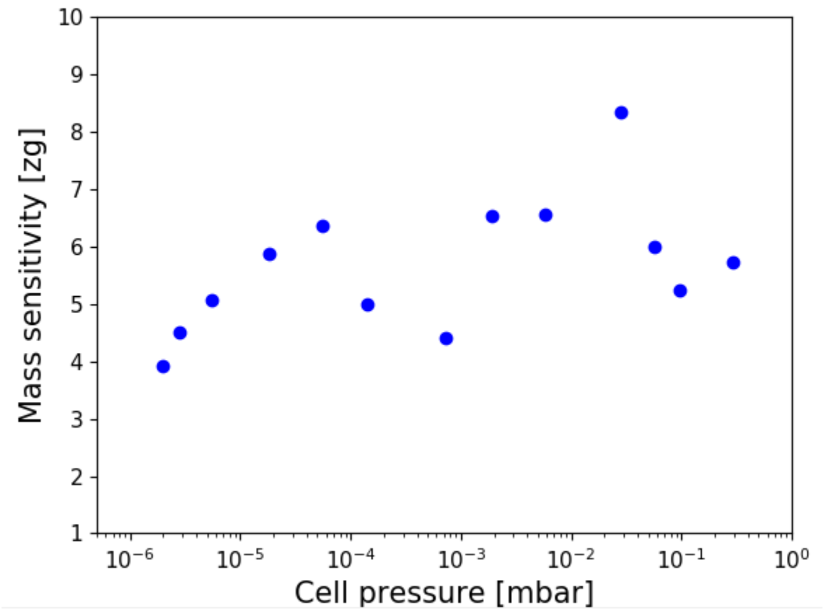
⇒ sensitivity degrades

- Momentum kick from gas increase

⇒ sensitivity decrease

Progressively increasing pressure with dry N2

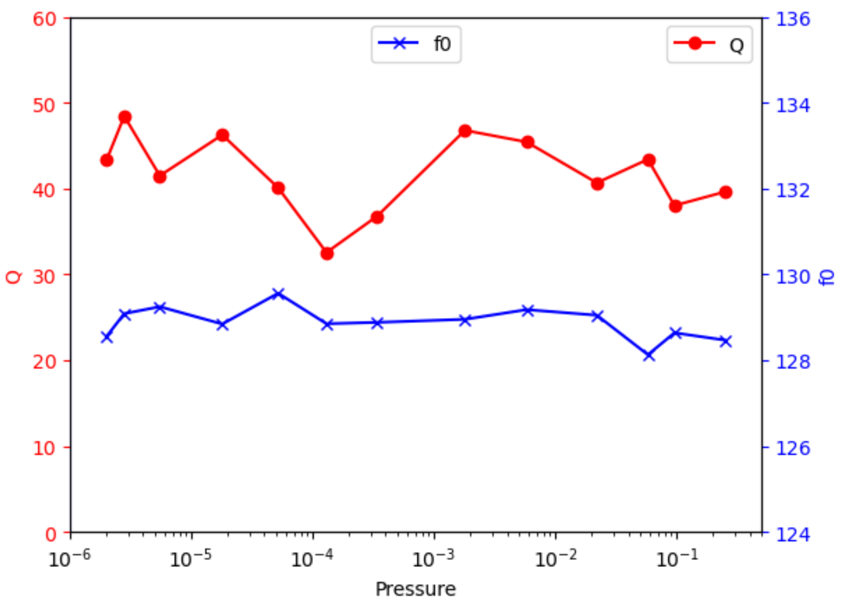


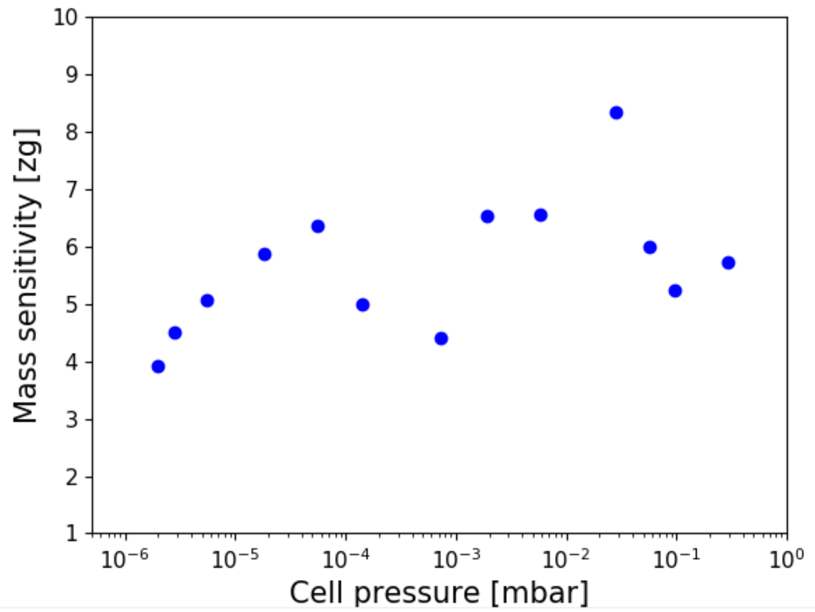


→ Sensitivity, Q anf f_0 all stay stable upon progressive increase of the pressure.

Exquisite sensitivity could be preserved up to ambient P?

Progressively increasing pressure with dry N2





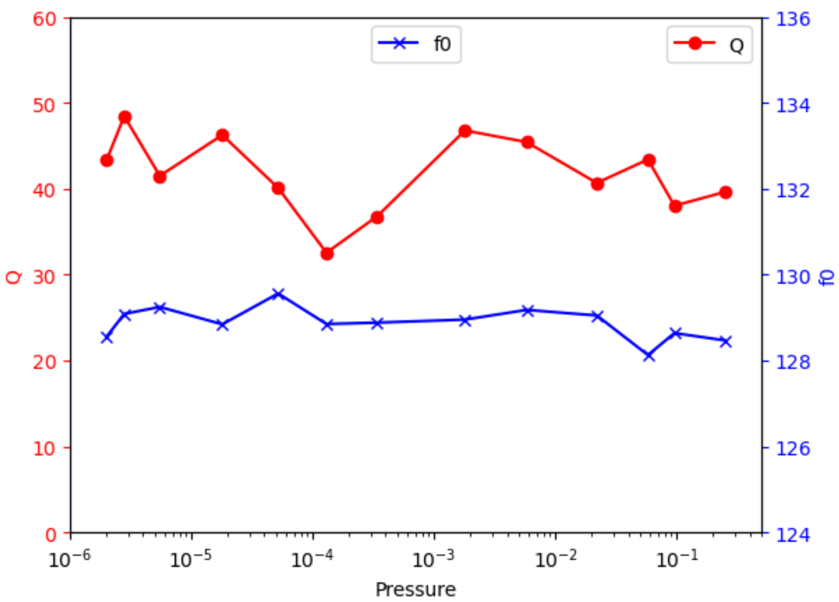
→ Sensitivity, Q anf f_0 all stay stable upon progressive increase of the pressure.

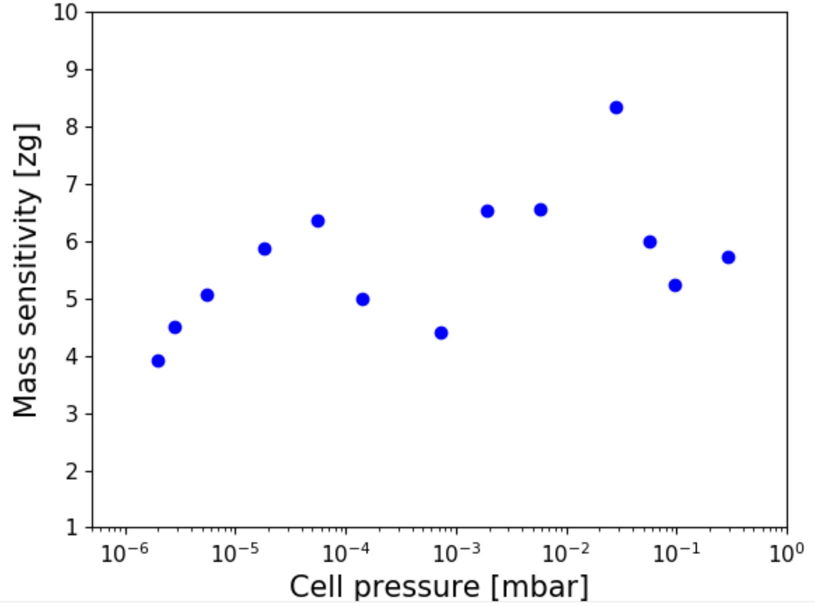
Exquisite sensitivity could be preserved up to ambient P?

Increasing T_{CNT}

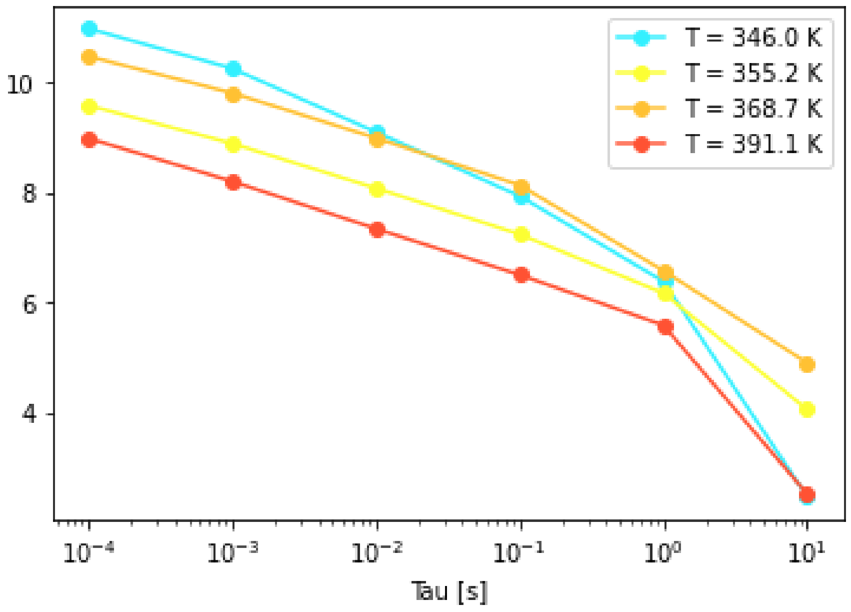
Expectations:
Particles should diffuse less by increasing the temperature

Progressively increasing pressure with dry N2





Increasing T_{CNT}



→ Sensitivity, Q anf f_0 all stay stable upon progressive increase of the pressure.

→ Not diffusion limited (vs T)

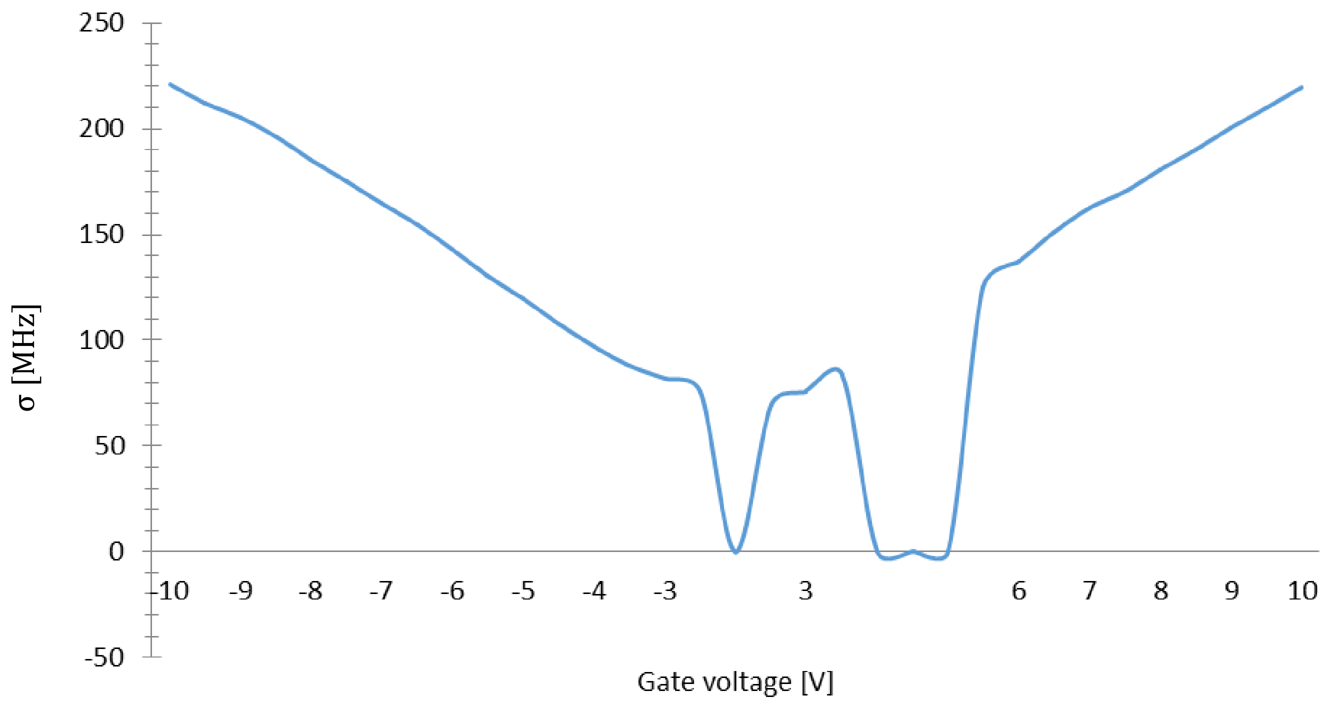
Exquisite sensitivity could be preserved up to ambient P?

Exquisite sensitivity is preserved up to ambient T!

By moving up and down very strongly, the bonds and contacts at the interface CNT-electrode get changed

= the quality factor Q should degrade

⇒ Q is linked to the sensitivity
⇒ If Q impacts σ : inverted parabola



By moving up and down very strongly, the bonds and contacts at the interface CNT-electrode get changed

= the quality factor Q should degrade

⇒ Q is linked to the sensitivity
⇒ If Q impacts σ : inverted parabola

⇒ σ is not impacted by Q
⇒ **Fastening point doesn't explain our limitations**

- Exquisite sensitivity of **70 yg at RT**.

2 orders of magnitude better than literature at RT (Lassagne et al., NL2008)

- **Reproducible**: on a device and on different devices

- Limitations? not thermomechanical, nor the setup.

- Sensitivity is preserved increasing P_{cell}. Might be the same at ambient pressure?