# Cooling the mechanical modes of an atomically-thin magnetic membrane

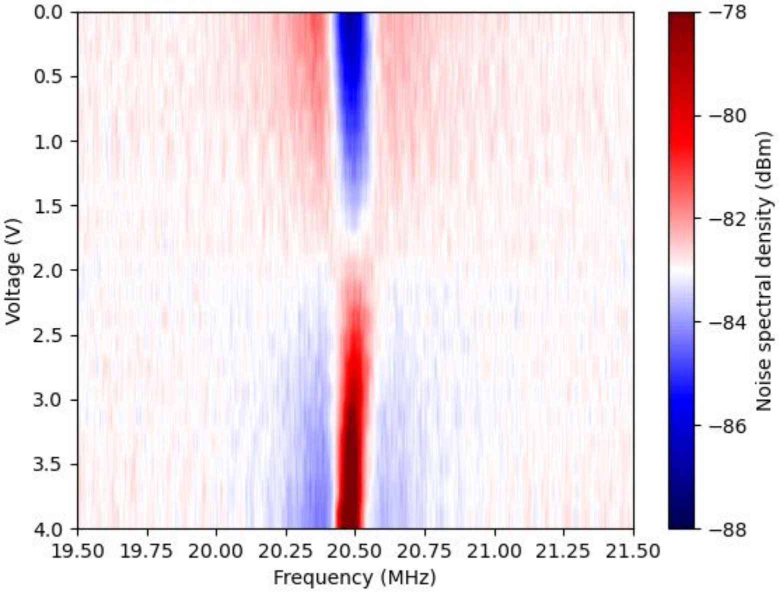
Davy Borowski, Quentin Fenoy
10/05/2022

Université de Strasbourg

At IPCMS
with A. Gloppe, J. Wolff and J. Thoraval

cnrs

# Table of contents

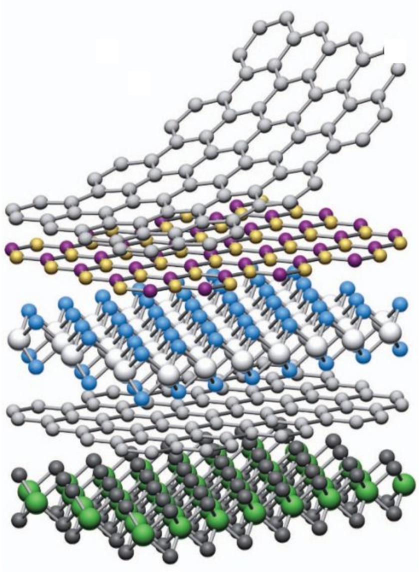


# Introduction

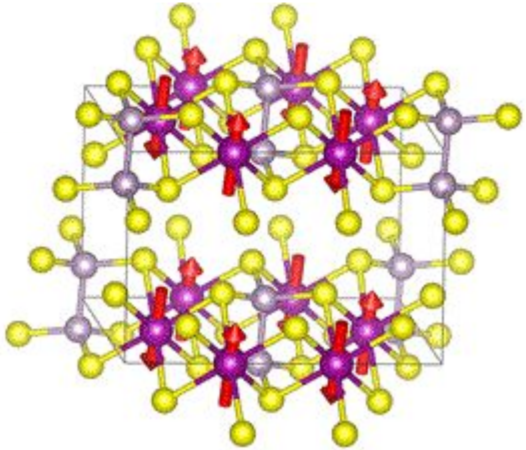
# General context

2016-2017 : Magnetic ordering in monolayer van der Waals materials

*Lee et al, Nano letters (2016), Huang et al, Nature (2017)*



*A.K. Geim et al, Nature (2013)*

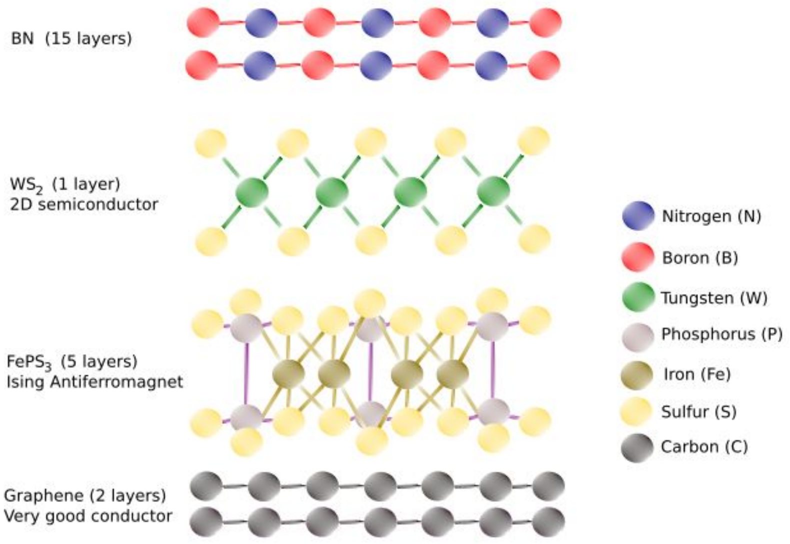


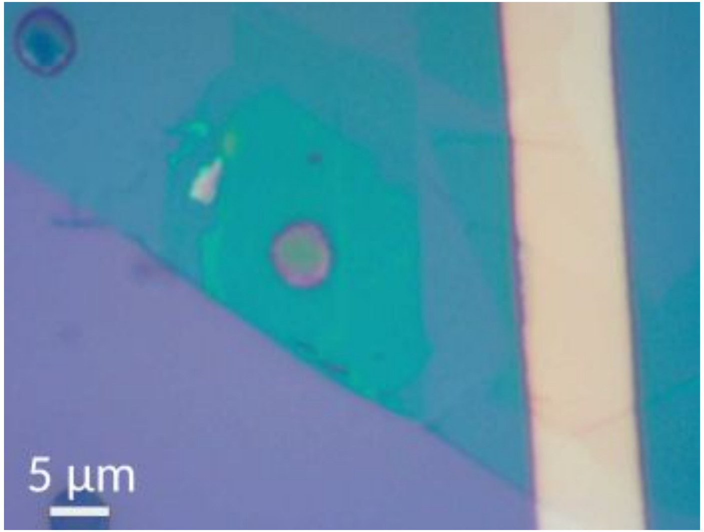
Antiferromagnetic ordering in $FePS_3$

*F. Kargar et al,  ACS Nano (2020)*

# Approach developed by the team

**PhD thesis of J. Wolff**: Probe and control magnetic order in atomically thin suspended membranes

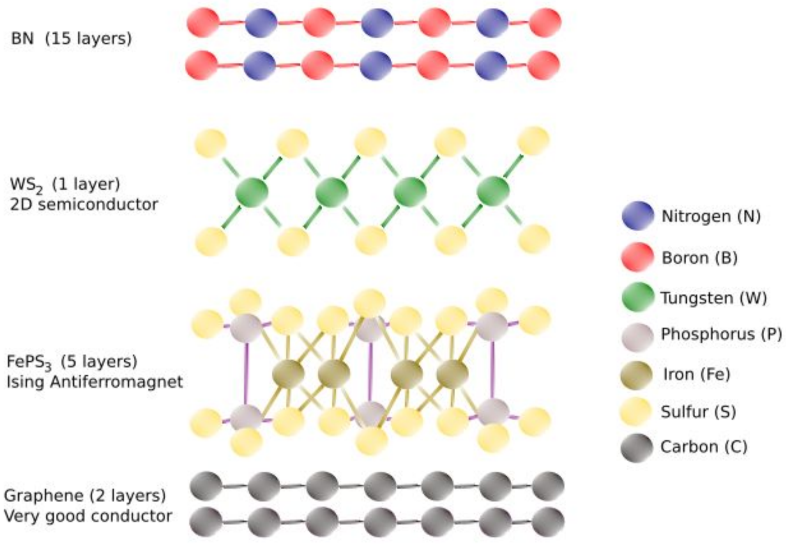


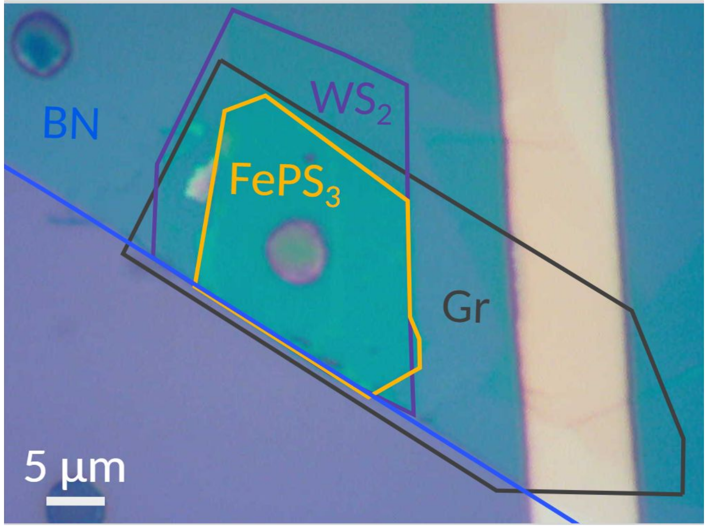


*Structure by J. Wolff (2022)*

# Approach developed by the team

**PhD thesis of J. Wolff**: Probe and control magnetic order in atomically thin suspended membranes





*Structure by J. Wolff (2022)*

# Experimental setup

Optomechanics: Mechanics with light

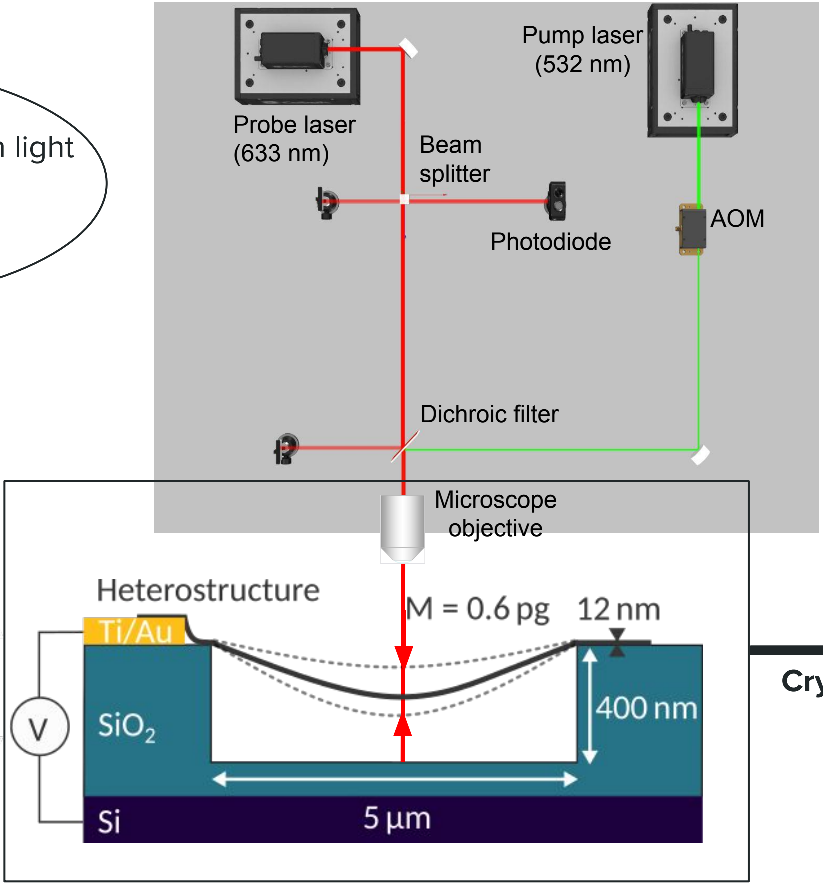
Detection of vibrations by **interferometry**

**Radiation pressure**:

$$F_{\mathrm{opt}} \propto P_{\mathrm{opt}}^{\mathrm{pump}}$$

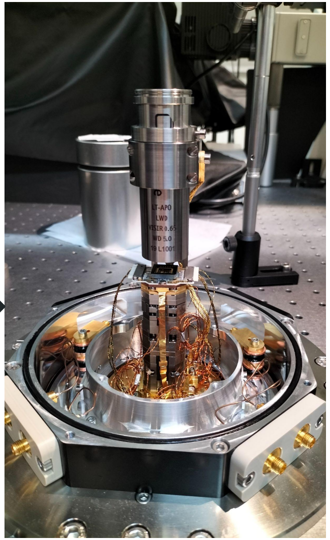
**Electrostatic force:**

$$F_{\mathrm{elec}} \propto V_{\mathrm{DC}} V_{\mathrm{AC}}(t)$$



**Cryostat**

Sample in a cryostat (4K-300K) to probe its phase transition



# Experimental setup

Optomechanics: Mechanics with light

Detection of vibrations by **interferometry**

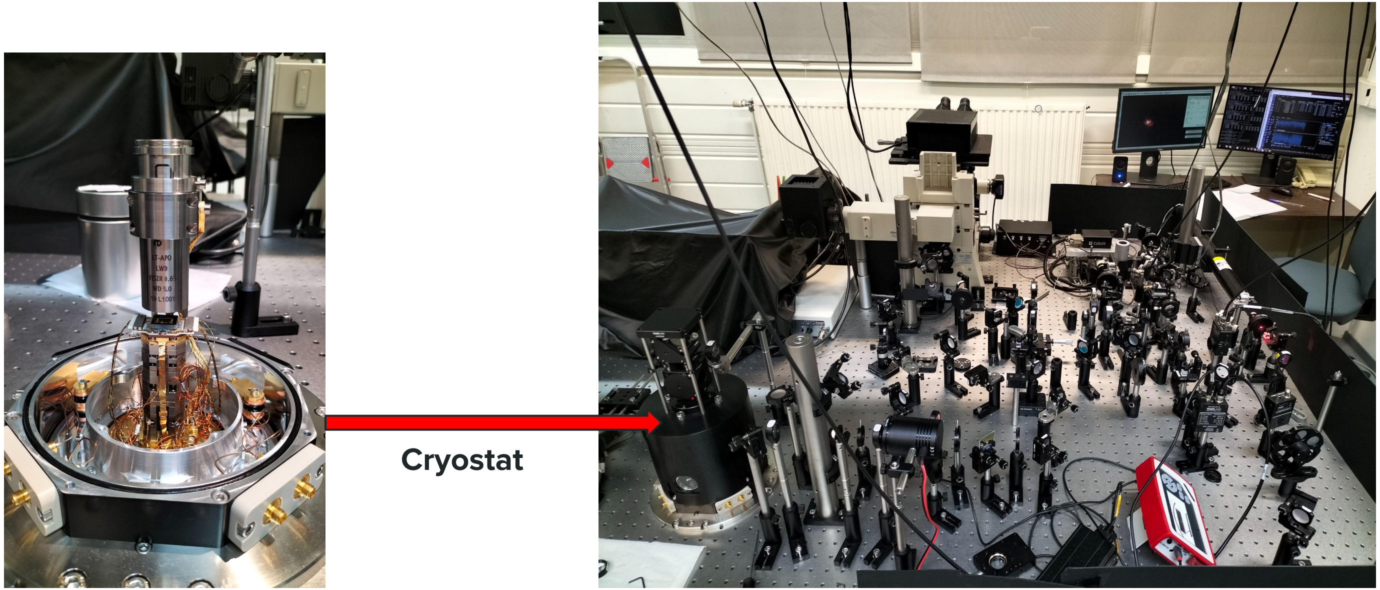
Sample in a cryostat (4K-300K)
to probe its phase transition

**Radiation pressure**:

$$F_{\mathrm{opt}} \propto P_{\mathrm{opt}}^{\mathrm{pump}}$$

**Electrostatic force:**

$$F_{\mathrm{elec}} \propto V_{\mathrm{DC}} V_{\mathrm{AC}}(t)$$



# Membrane dynamics

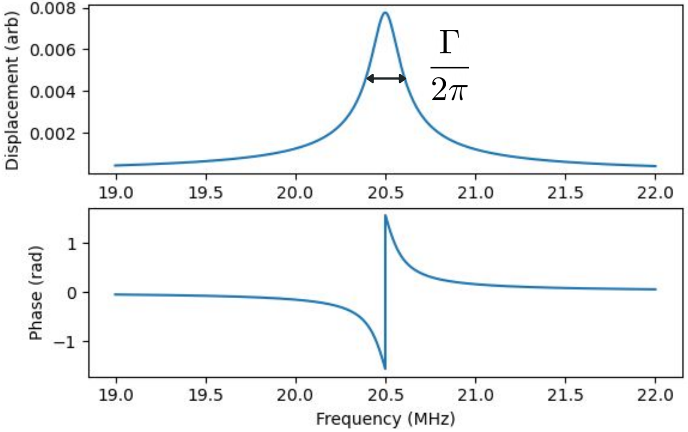
**Time domain** → **Fourier domain**

$$\ddot{z} - \Gamma \dot{z} + \omega_0^2 z = \frac{F_{\text{ext}}}{M}$$

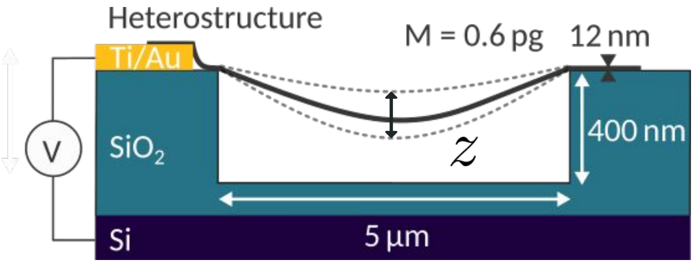
$$z(\omega) = \chi(\omega) F_{\text{ext}}(\omega)$$

**Mechanical susceptibility**

$$\chi(\omega) = \frac{1}{M(\omega_0^2 - \omega^2 - i\Gamma\omega)}$$



Mechanical response



# Displacement spectral density

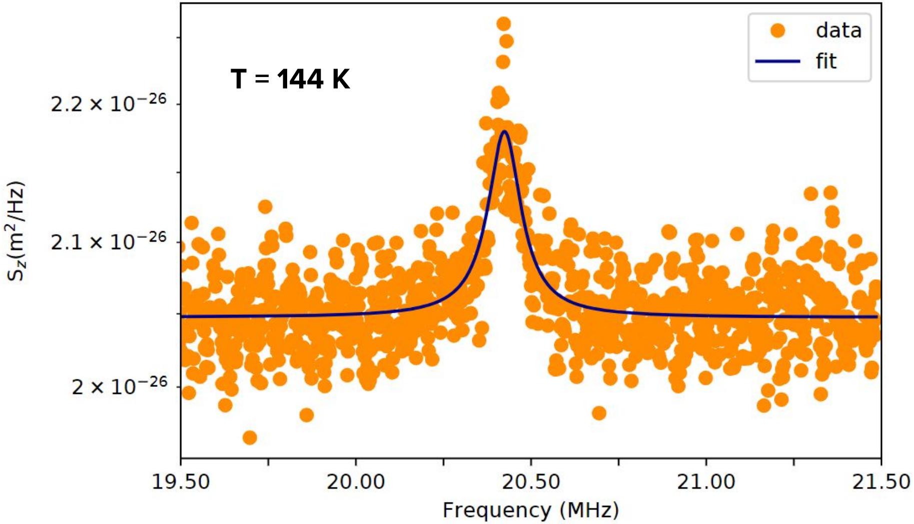
Fluctuation-dissipation theorem:

$$S_z(\omega) = \frac{2k_BT}{\omega}\mathrm{Im}(\chi(\omega))$$

In our case with only thermal fluctuations (Brownian motion) :

$$S_z(\omega) = \frac{2\Gamma k_BT}{M((\omega_0^2 - \omega^2)^2 + \Gamma^2\omega^2)}$$

Problem: low T…



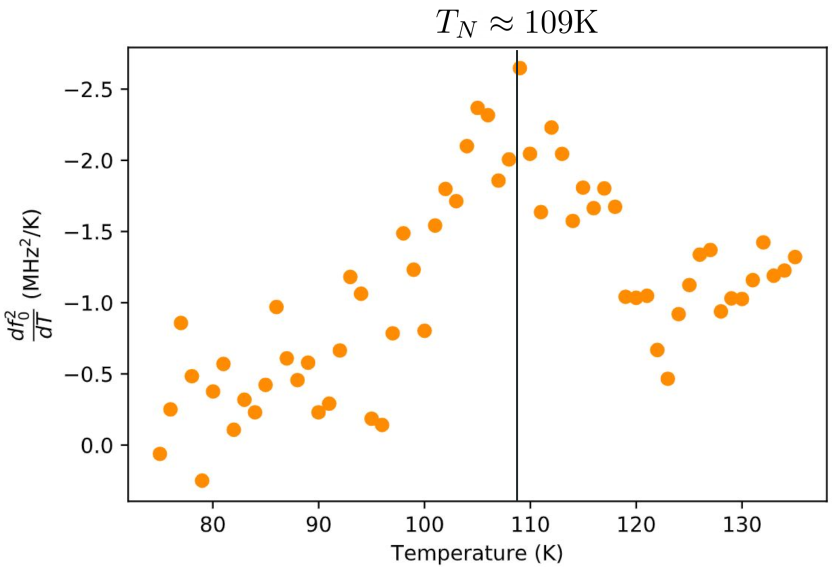
# Link between mechanical properties and magnetic order

Mechanical frequency

**Mechanical properties:** $f_0(T)$

Specific heat

**Thermodynamic properties:** $c_V(T) \propto \frac{df_0^2(T)}{dT}$



*J. Wolff (2022)*

⇒ Need a fine control on $\chi$ to increase the resolution on frequency shift induced by a change of the magnetic configuration

ie: decrease the mechanical damping

# Cold damping

# Recent examples

The international journal of science / 15 July 2021

nature

outlook
Autoimmune disease

QUANTUM MOTION

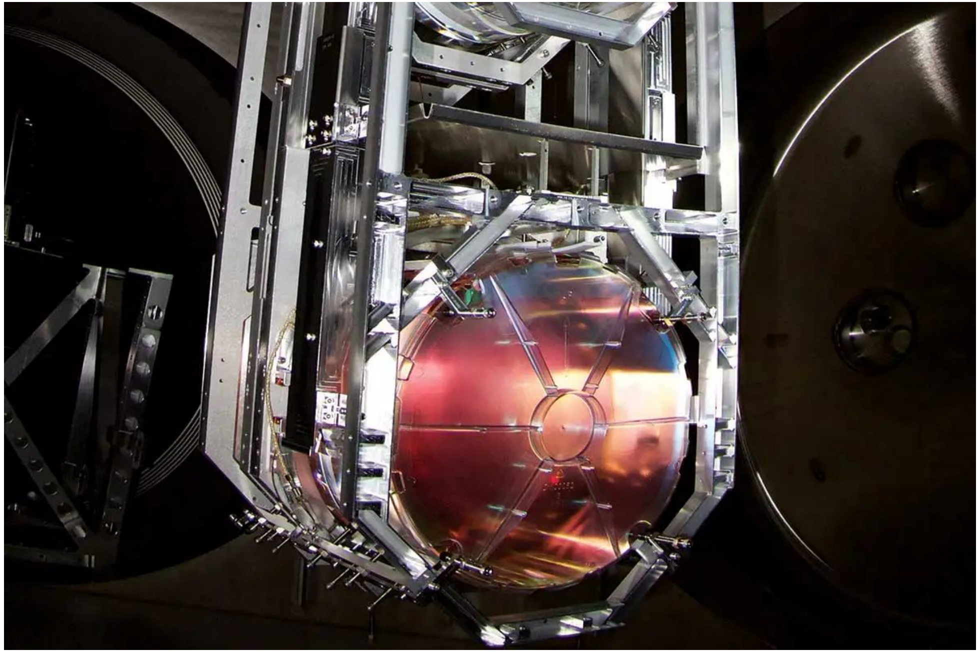
Precise measurement of trapped nanosphere enables cooling to ground state

**Coronavirus**
Genetic association studies reveal links to COVID risk

**Climate imbalance**
Deforestation turns part of Amazonia from carbon sink to source

**Internal exam**
Probing microbial metabolism in the microbiome of the gut

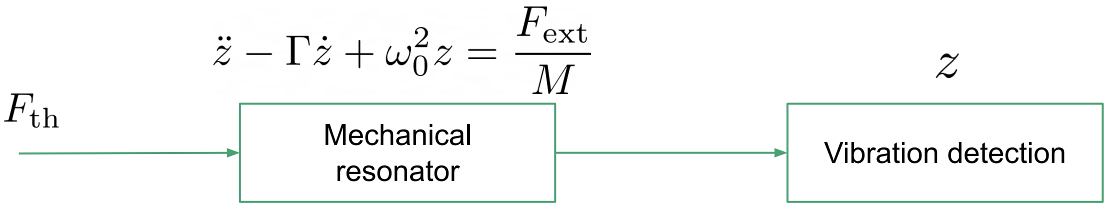
L. Magrini et al, Nature (2021)



L. Grossman, NewScientist (2016)

⇒ Often used to cool mechanical modes $\neq$ We want to decrease the damping : heat modes!

# Concept of cold damping



$$\ddot{z} - \Gamma\dot{z} + \omega_0^2 z = \frac{F_{\text{ext}}}{M}$$

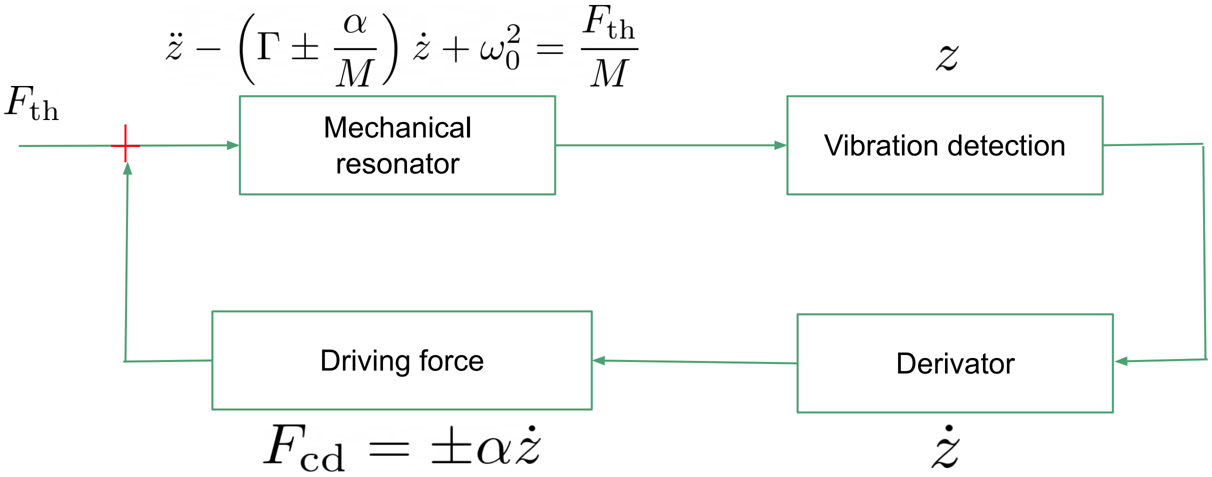
$F_{\text{th}}$

Mechanical resonator

$z$

Vibration detection

# Concept of cold damping



$$\ddot{z} - \left(\Gamma \pm \frac{\alpha}{M}\right)\dot{z} + \omega_0^2 = \frac{F_{\text{th}}}{M}$$

$$F_{\text{cd}} = \pm\alpha\dot{z}$$

**Changes effective damping:**

$$\Gamma_{\text{eff}} = \Gamma \pm \frac{\alpha}{M}$$

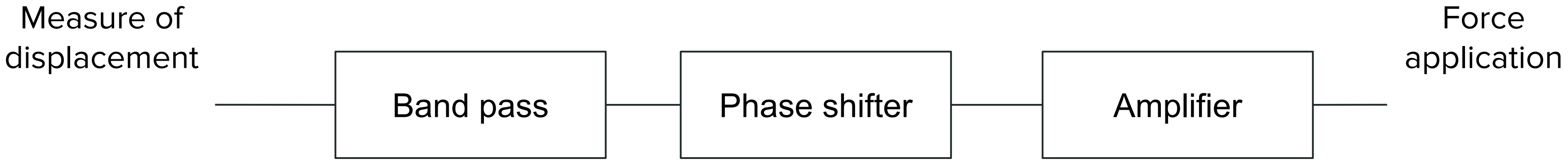
**We define:**

$$g = \pm\frac{\alpha}{M\Gamma} \qquad T_{\text{eff}} = \frac{T}{1+g}$$

# Implementation of cold damping

We add a **feedback electronic circuit**

$$\frac{d}{dt} = i\omega \approx \text{add } 90^\circ$$



Measure of displacement

Band pass

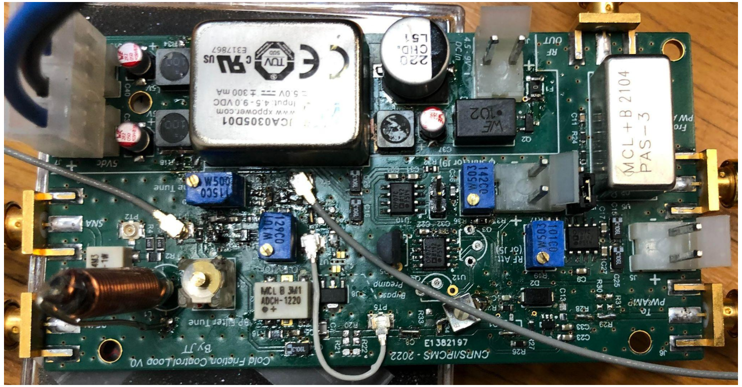
Phase shifter

Amplifier

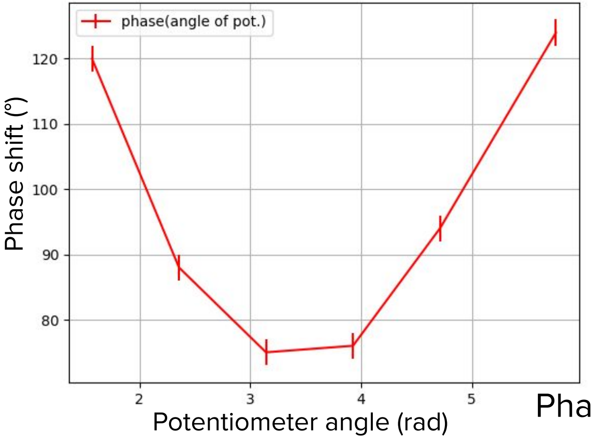
Force application

Simplified electronic circuit

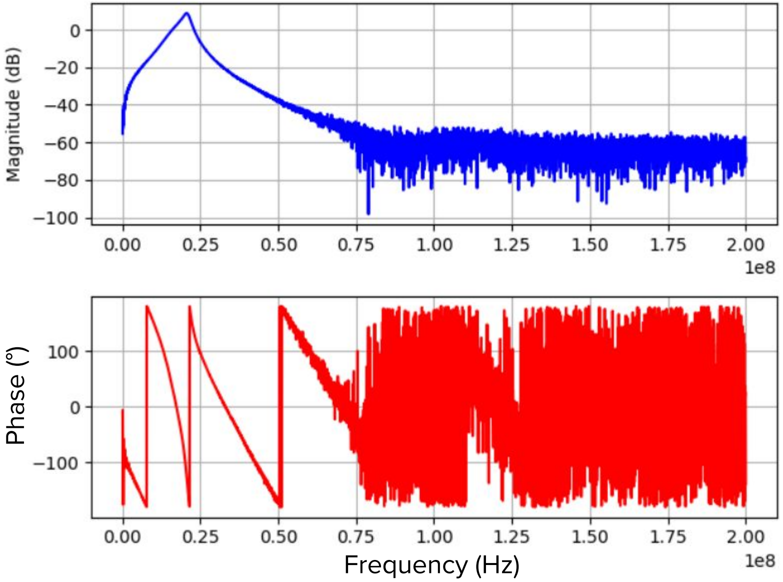
# The lab-made electronic circuit



Electronic circuit by J. Thoraval (IPCMS)

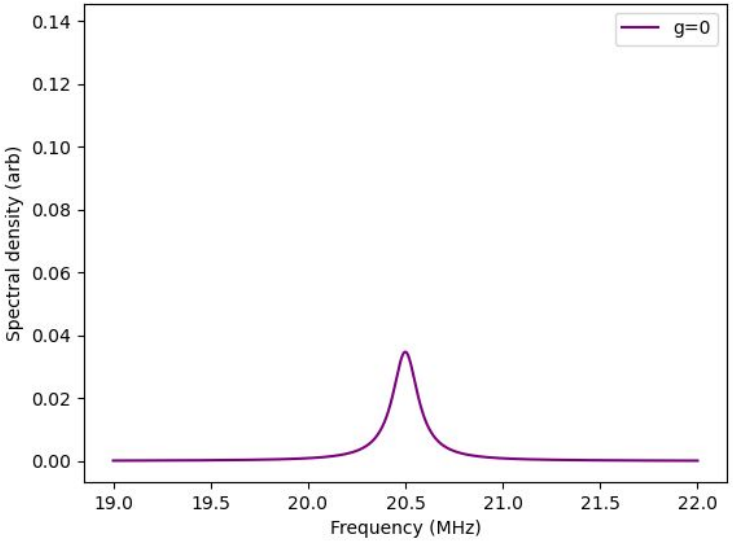


Phase shift control over 50°



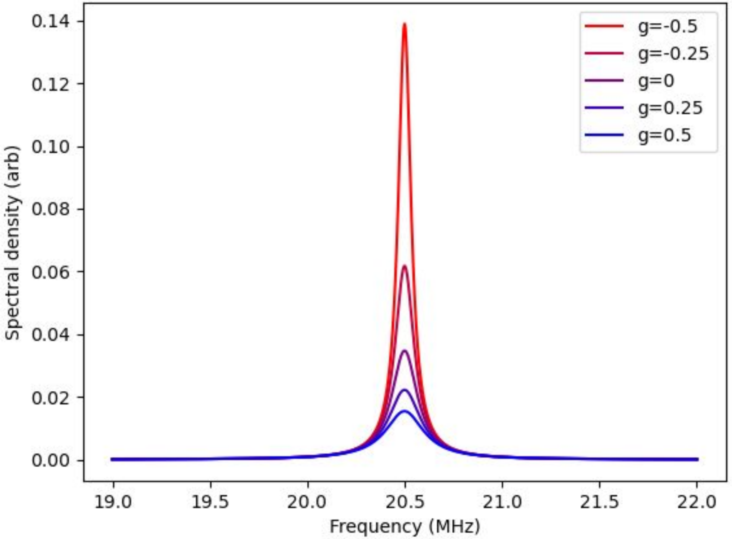
Transfer function of the circuit

# Expected results with cold damping



$$S_z(\omega) = \frac{2\Gamma k_B T}{M((\omega_0^2 - \omega^2)^2 + \Gamma^2\omega^2)}$$

# Expected results with cold damping



$$S_z(\omega) = \frac{2\Gamma k_B T}{M((\omega_0^2 - \omega^2)^2 + \Gamma^2\omega^2(1+g)^2)}$$

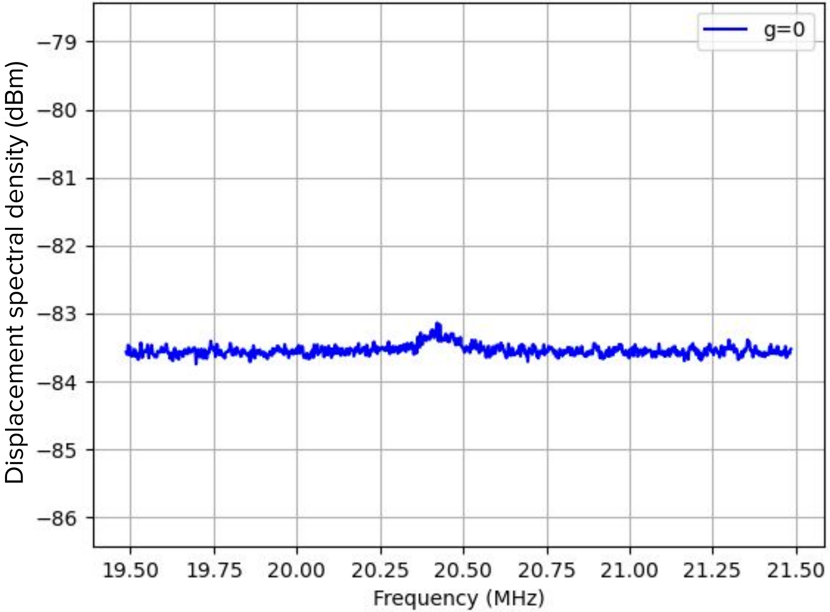
$$g = \pm \frac{\alpha}{M\Gamma}$$

# Results

# First measurements with cold damping

Probe laser: 633 nm, temperature: 144K, electrostatic force

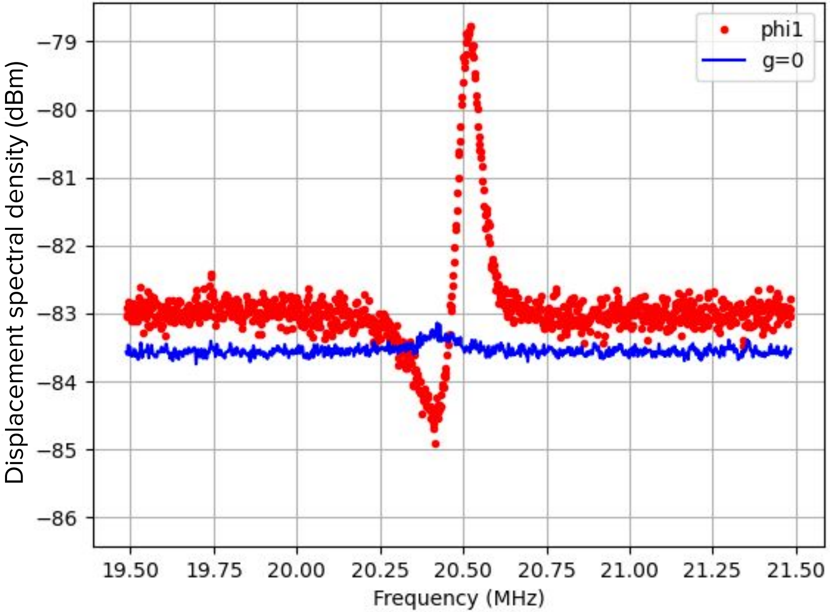
Brownian motion of the membrane (g=0)



# First measurements with cold damping

Probe laser: 633 nm, temperature: 144K, electrostatic force

There is an amplification effect !

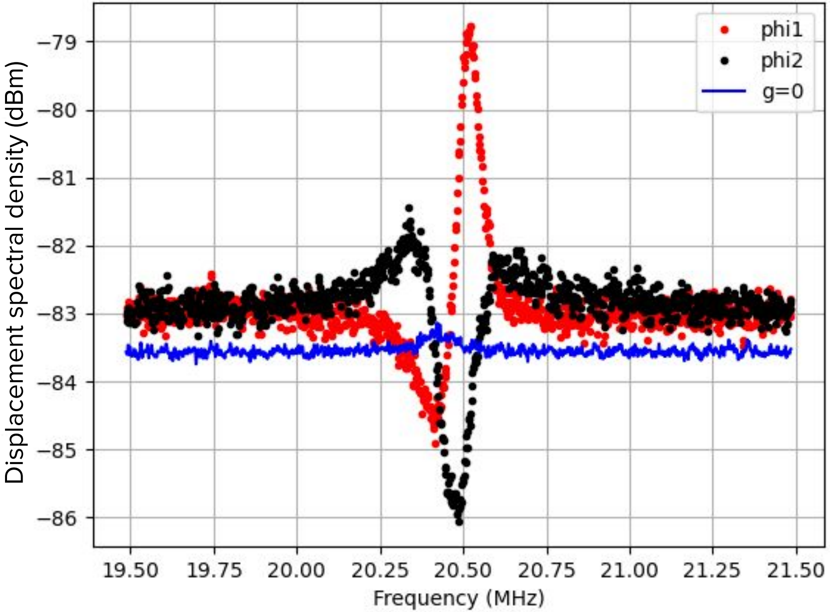


Let’s tune the phase!

# First measurements with cold damping

Probe laser: 633 nm, temperature: 144K, electrostatic force

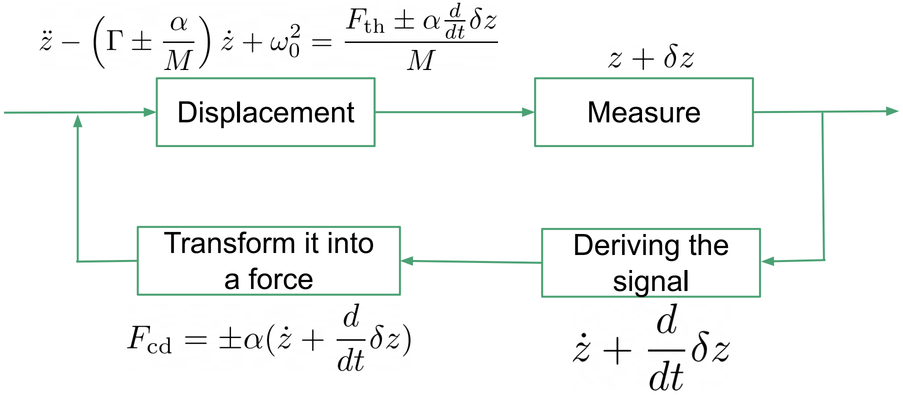
There is an amplification effect !



Curves cannot be explained by our current model...

# Model improvement

Measurement noise $\delta z$ reinjected in the feedback loop



$$\ddot{z} - \left(\Gamma \pm \frac{\alpha}{M}\right)\dot{z} + \omega_0^2 = \frac{F_{\mathrm{th}} \pm \alpha \frac{d}{dt}\delta z}{M}$$

$$z + \delta z$$

Displacement

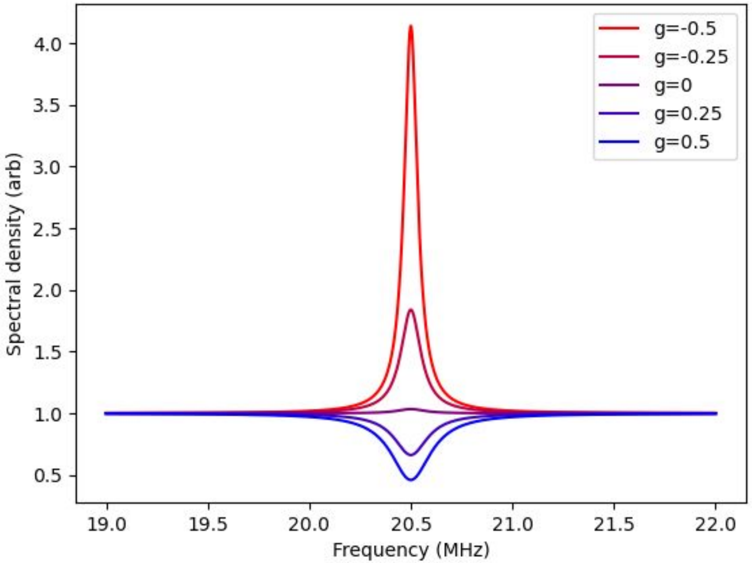
Measure

Transform it into a force

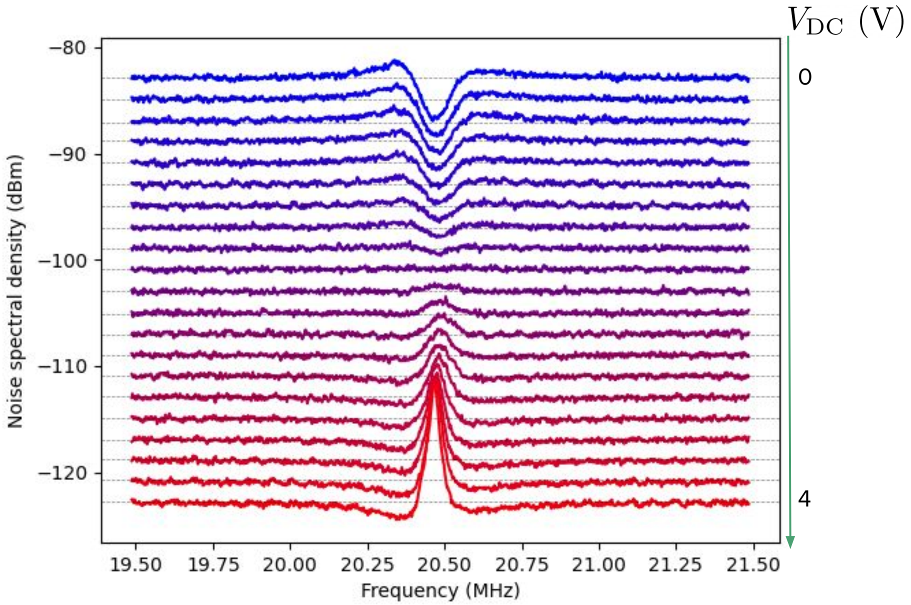
Deriving the signal

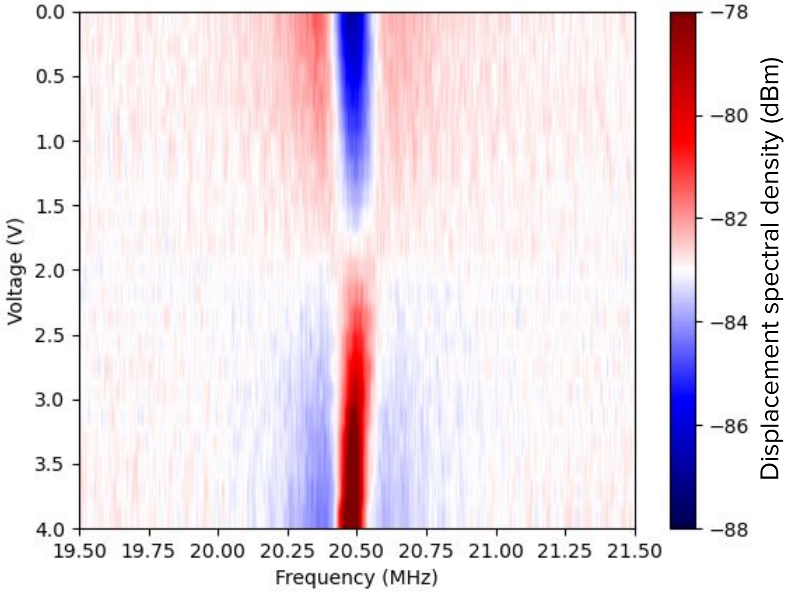
$$F_{\mathrm{cd}} = \pm\alpha(\dot{z} + \frac{d}{dt}\delta z)$$

$$\dot{z} + \frac{d}{dt}\delta z$$



# Effect of gain modification



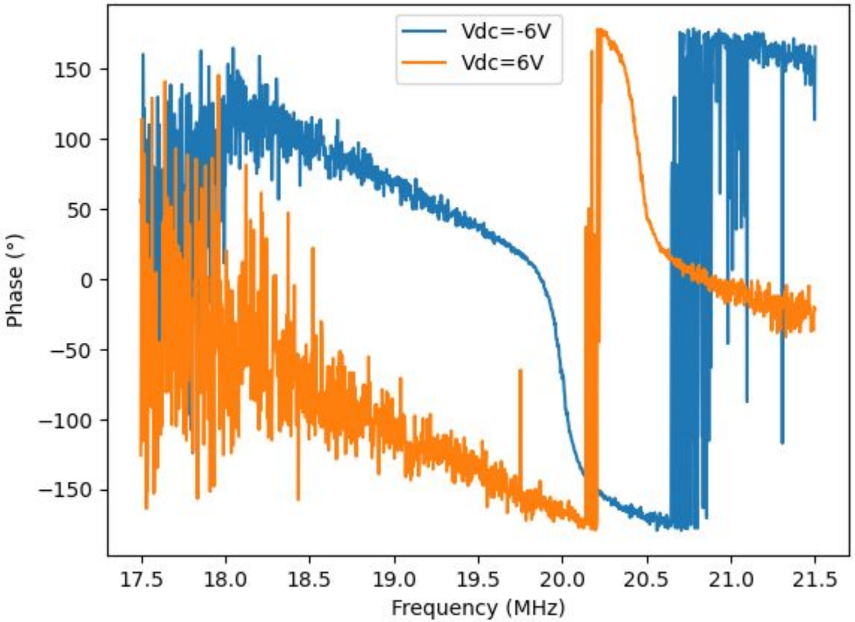


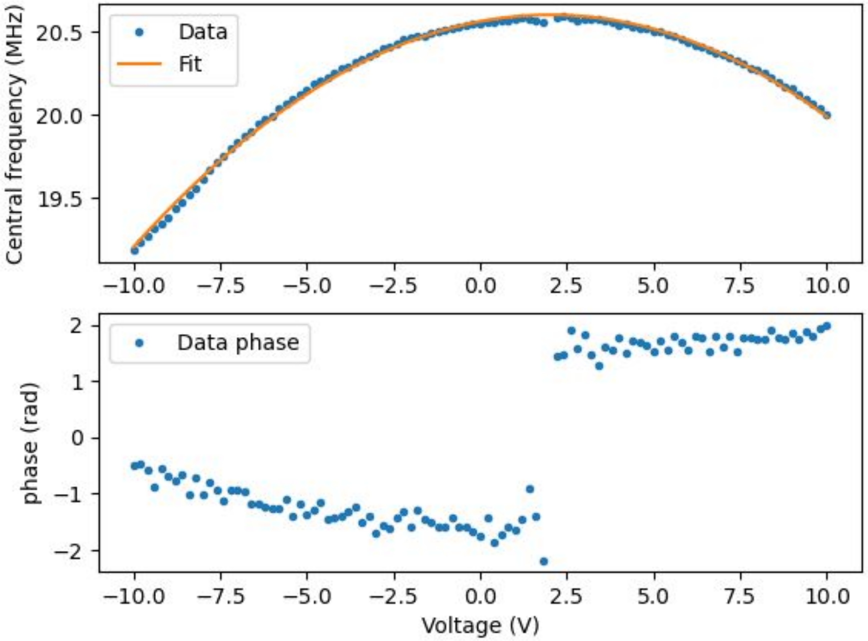
$$F_{\mathrm{elec}} \propto V_{\mathrm{DC}}$$

$$g \propto V_{\mathrm{DC}}$$

# Voltage ramp for the driven displacement

Not Brownian motion : we impose an external force

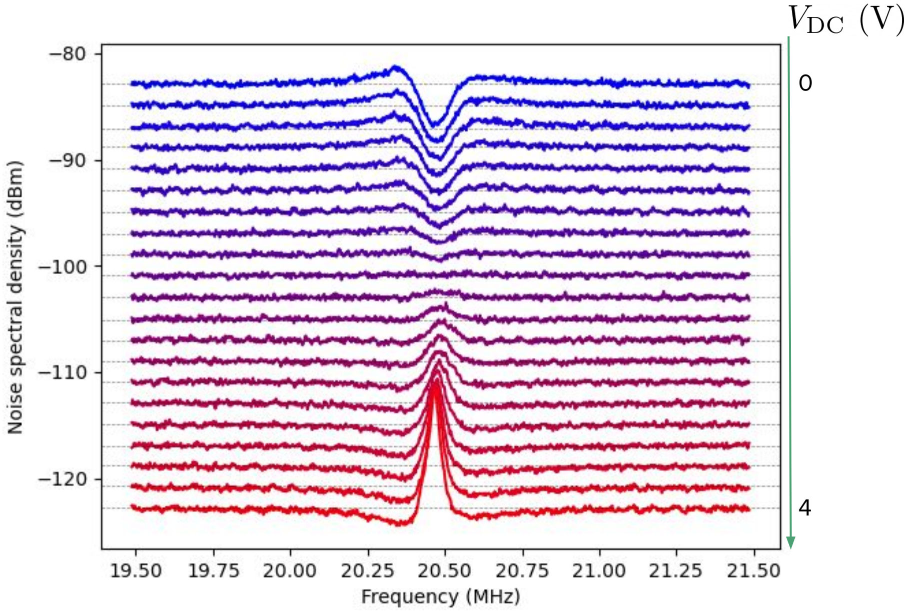


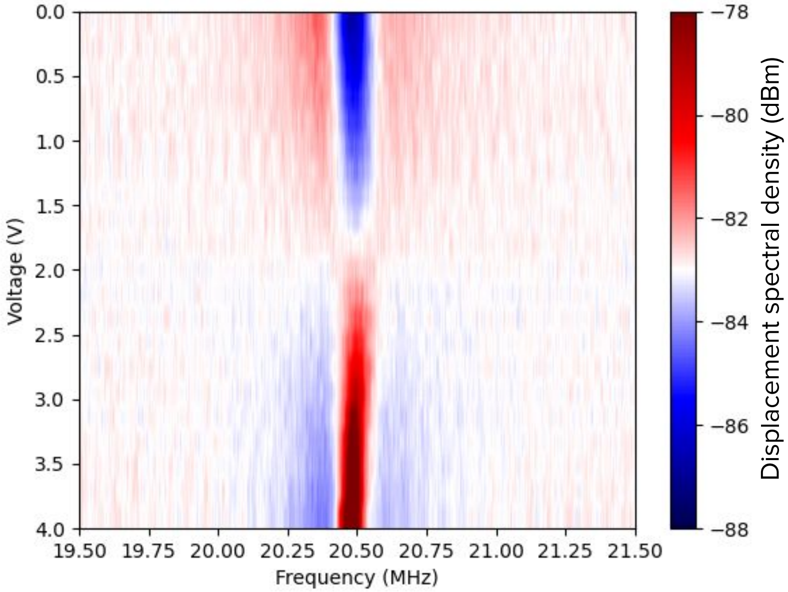


Membrane not electrically neutral

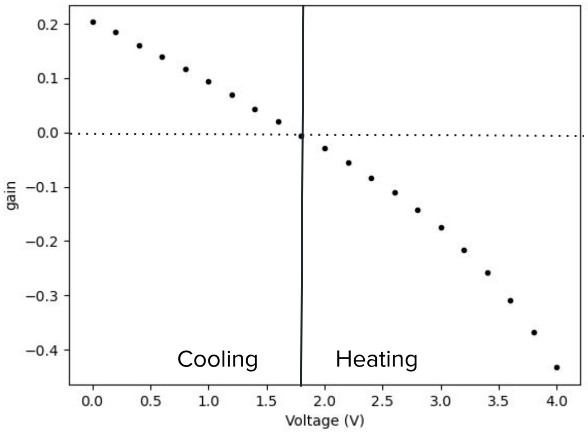
$$V_{\mathrm{DC}}^{\mathrm{eff}} \approx V_{\mathrm{DC}}^{\mathrm{app}} + 2\ \mathrm{V}$$

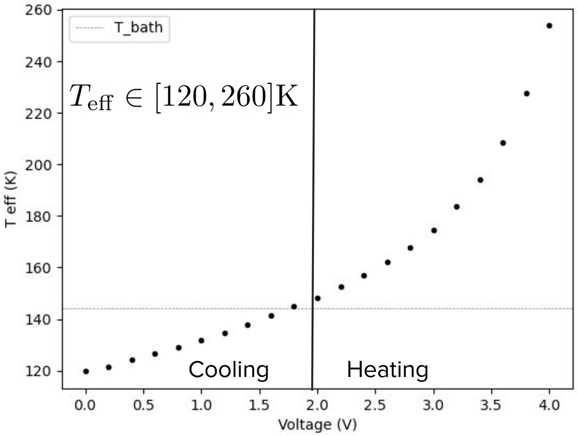
# Effect of gain modification



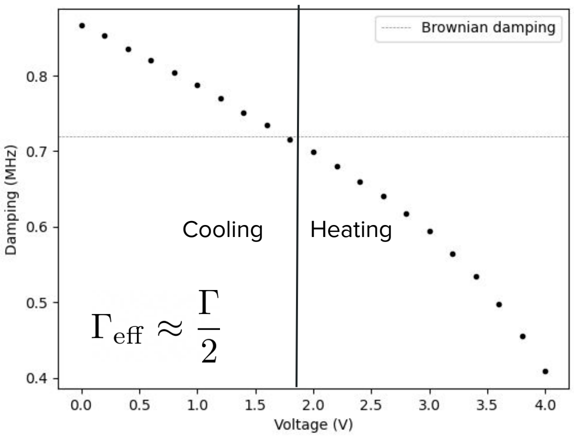


# Effect of gain modification





$T_{\text{eff}} \in [120, 260]\text{K}$

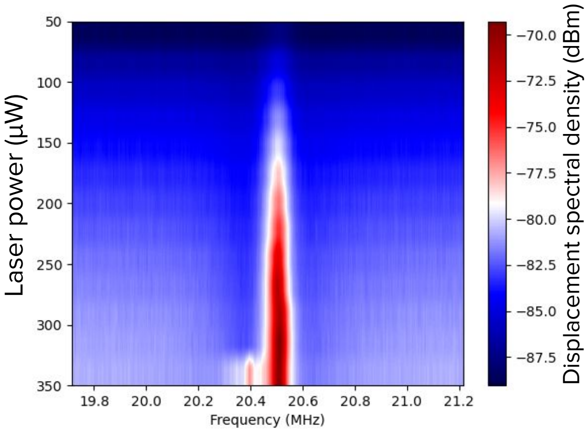


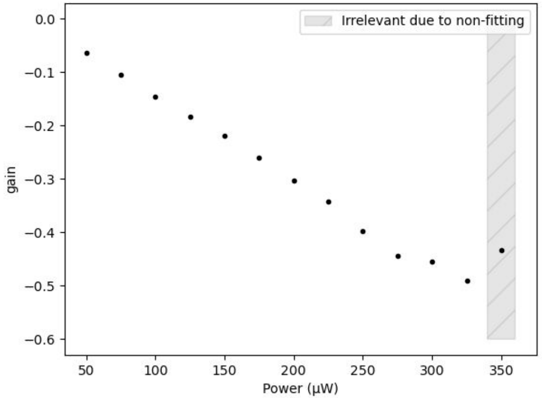
$\Gamma_{\text{eff}} \approx \frac{\Gamma}{2}$

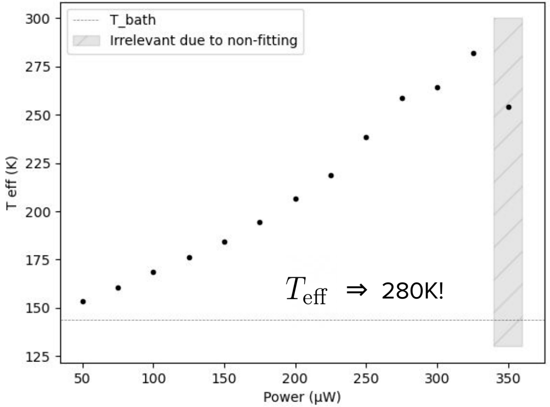
$$T_{\text{eff}} = \frac{T}{1+g}$$

$$\Gamma_{\text{eff}} = \Gamma(1+g)$$

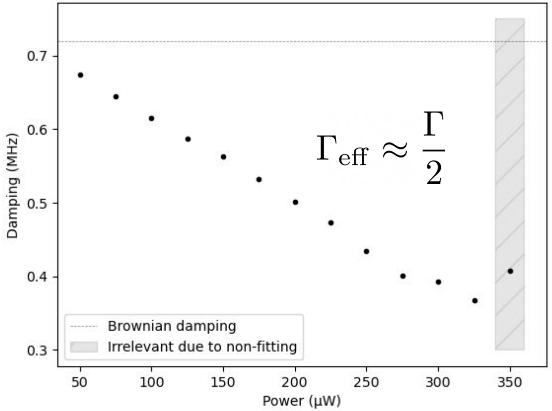
# Another method to modify the gain: optical power of the probe laser







$T_{\text{eff}}$ ⇒ 280K!

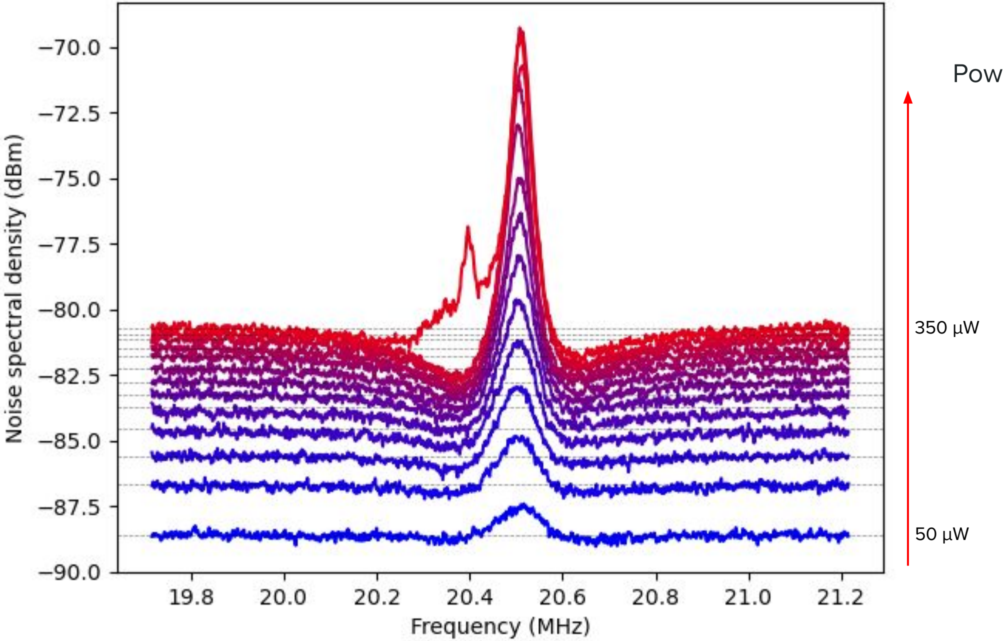


$$\Gamma_{\text{eff}} \approx \frac{\Gamma}{2}$$

# Limits of the method

If we apply a force too strong ⇒ Auto-oscillation: $\Gamma_{\text{eff}} \rightarrow 0$

Can not go higher



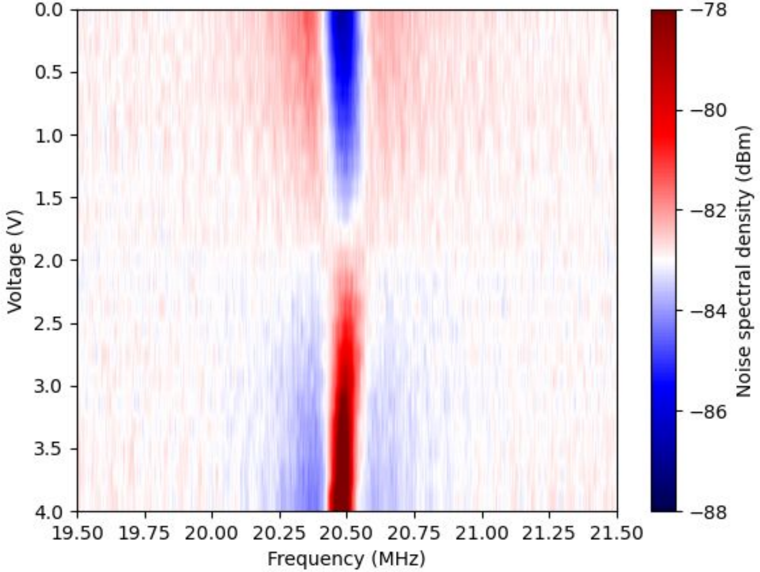
Power of the probing laser

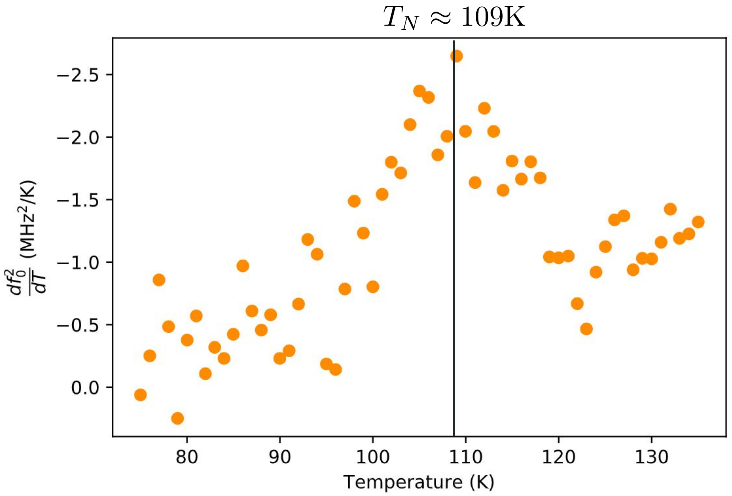
# Conclusion

# Conclusion and perspectives

$$\boxed{\Gamma_{\text{eff}} \approx \frac{\Gamma}{2}}$$

- First measurements and results very encouraging
- Will enable to work on a more sophisticated electronic circuit :
  - Electronic control of gain/phase
  - Band pass frequency following the temperature dependency of $f_0$
- Long term : enable to study phase transition of more exotic 2D magnetic materials!

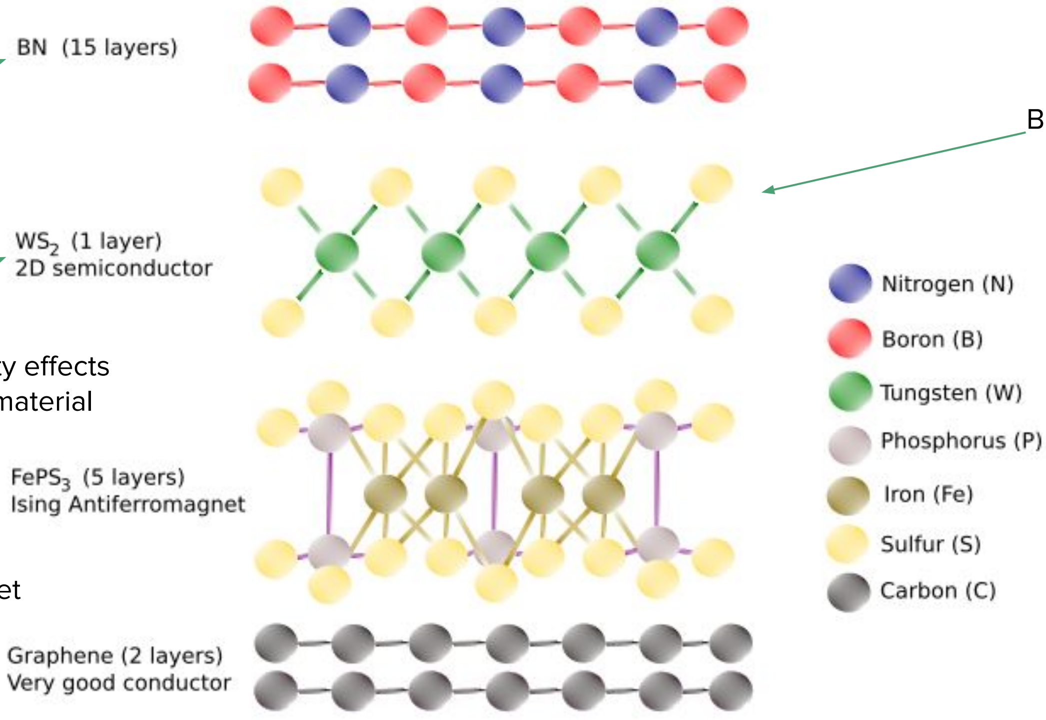




*J. Wolff (2022)*

# Appendices

# Membrane



Flatten the sample
surface, insulator

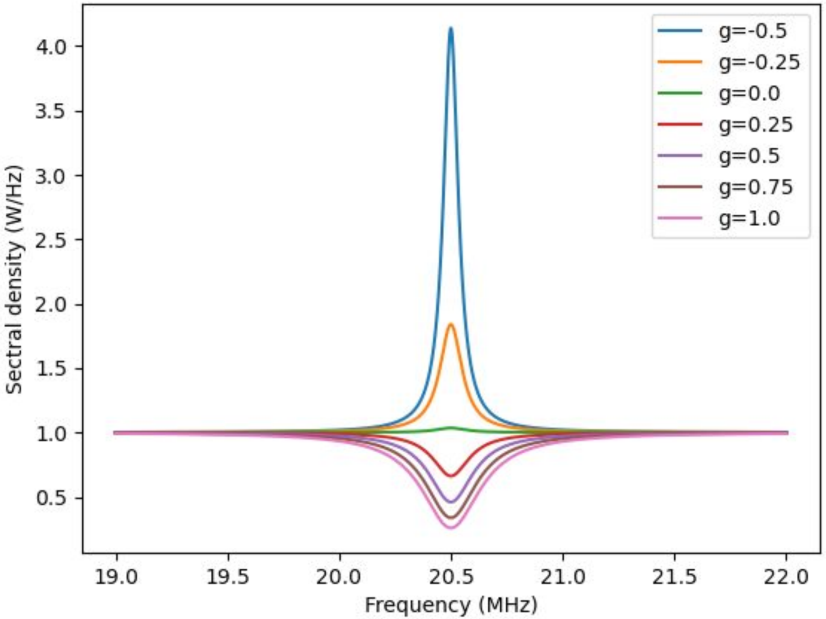
Be able to stick BN to
FePS3

Light emitter:
Study of proximity effects
with magnetic material

Antiferromagnet

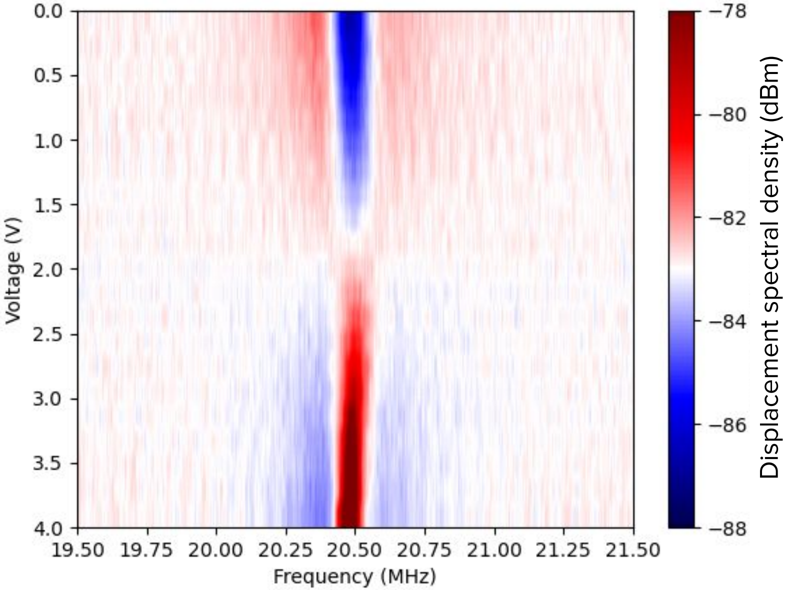
Gate: enables to apply
electrostatic force

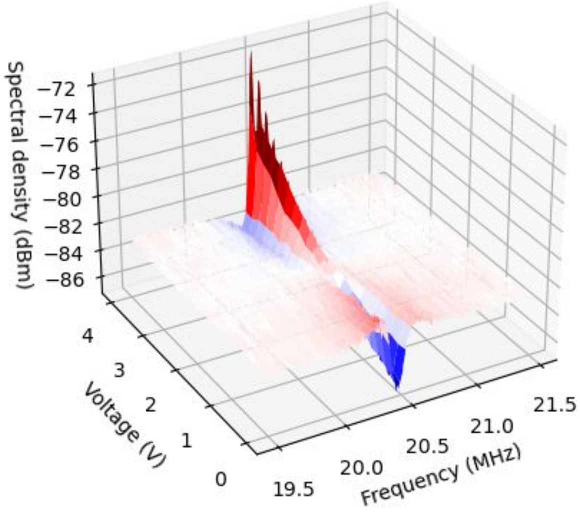
# Spectral density for the system



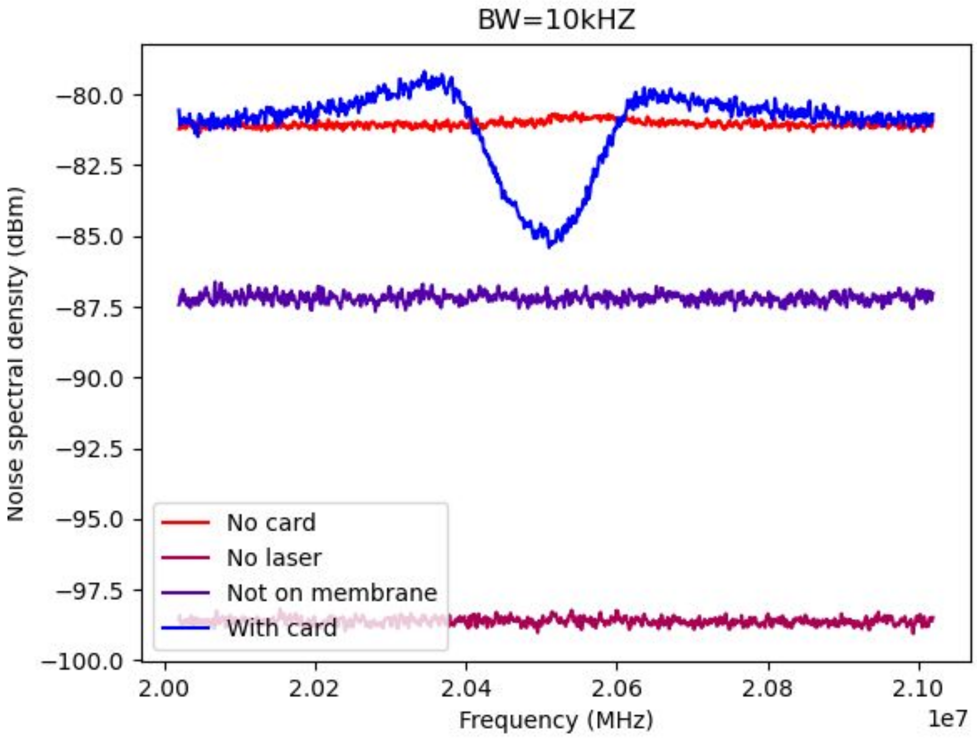
$$S_{\mathrm{x+sys}} = \frac{\frac{2k_B T\Gamma}{M} + [(\omega_0^2 - \omega^2)^2 + \Gamma^2\omega^2] S_{\mathrm{sys}}}{(\omega_0^2 - \omega^2)^2 + \Gamma^2\omega^2(1+g)^2}$$

# How to read an “imshow”?

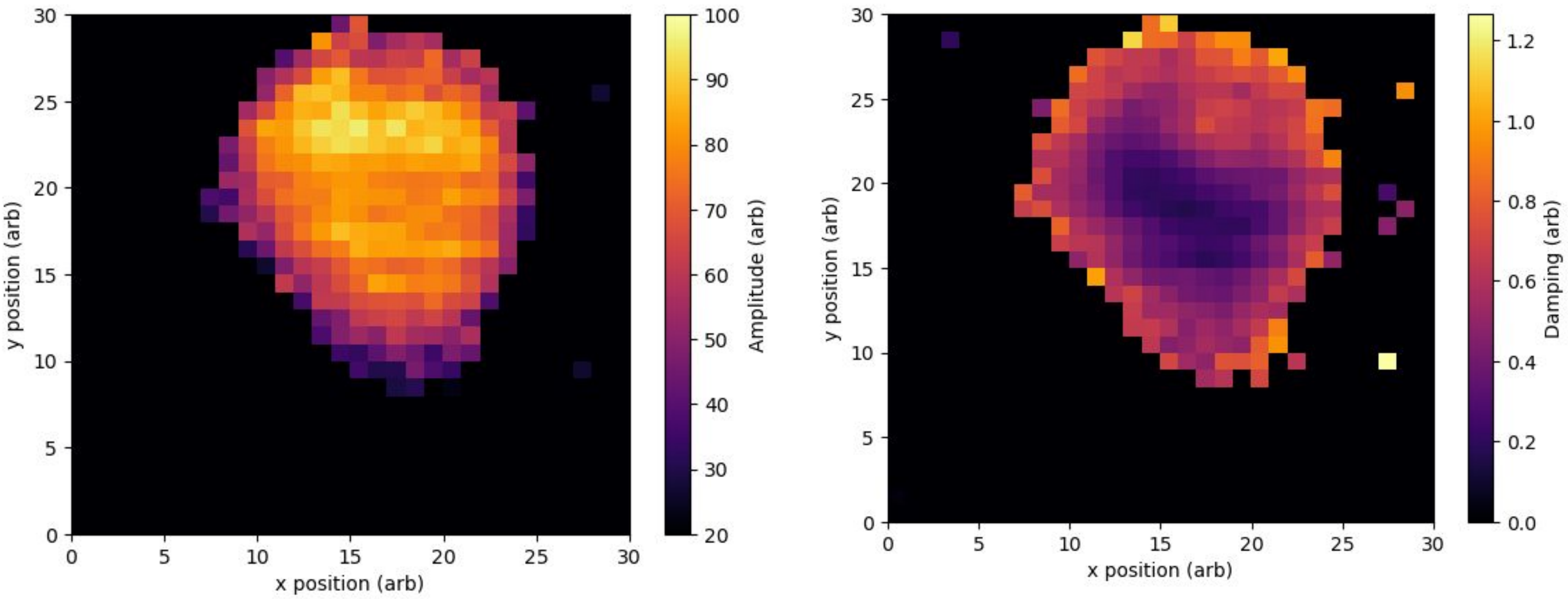




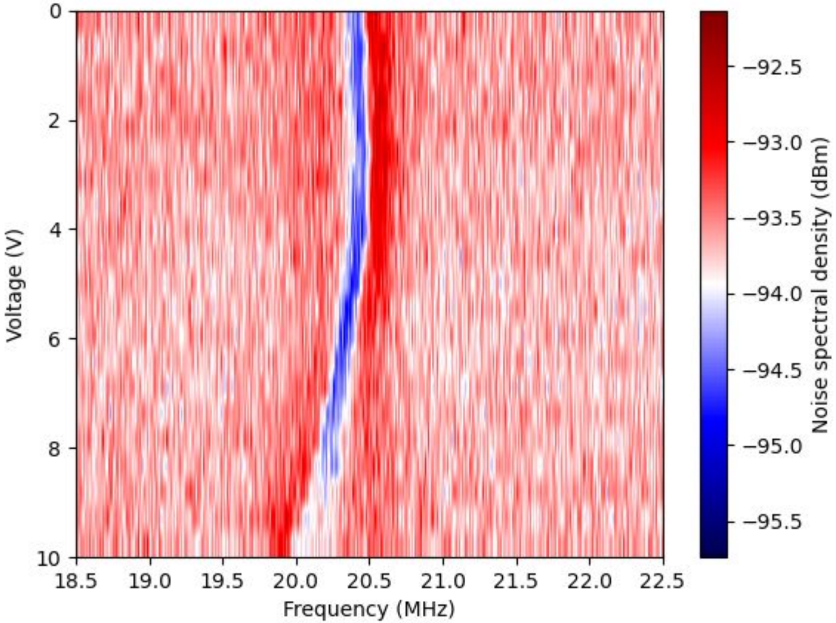
# Measurement backgrounds

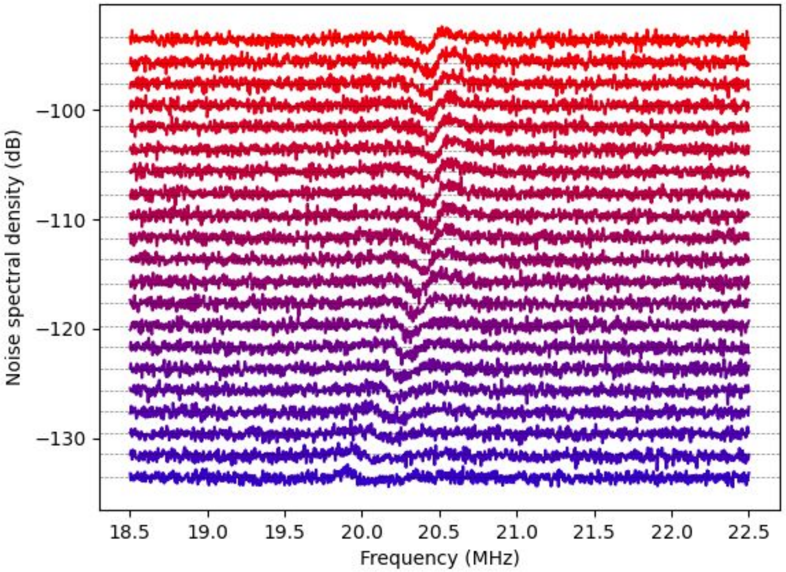


# Amplified brownian map of the first mode

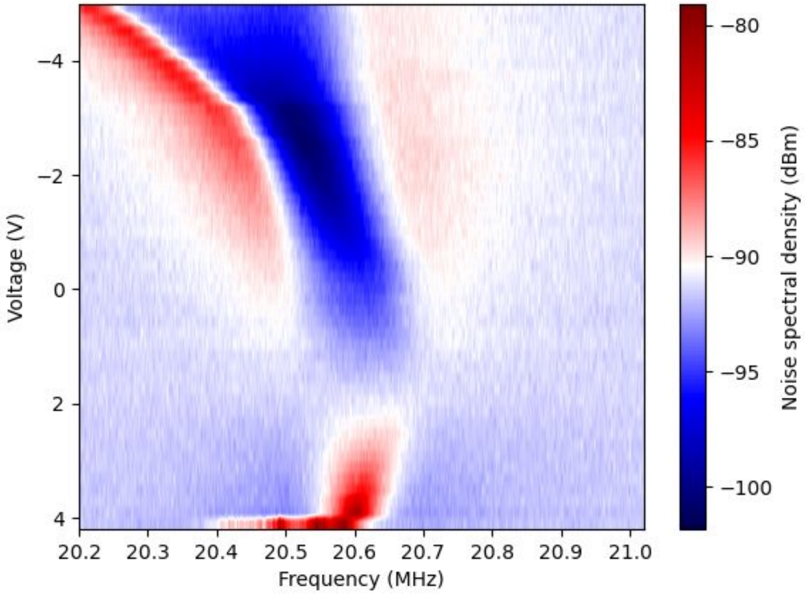


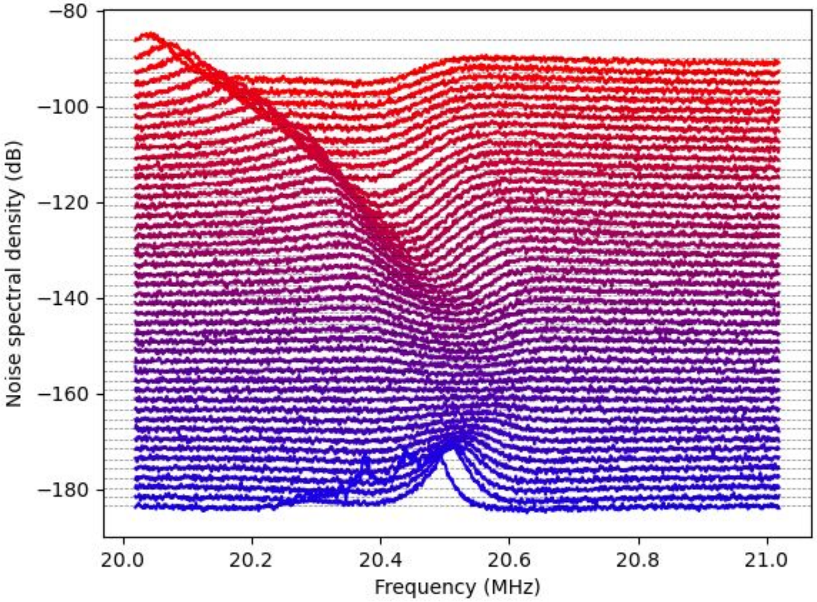
# Voltage ramp with radiation pressure



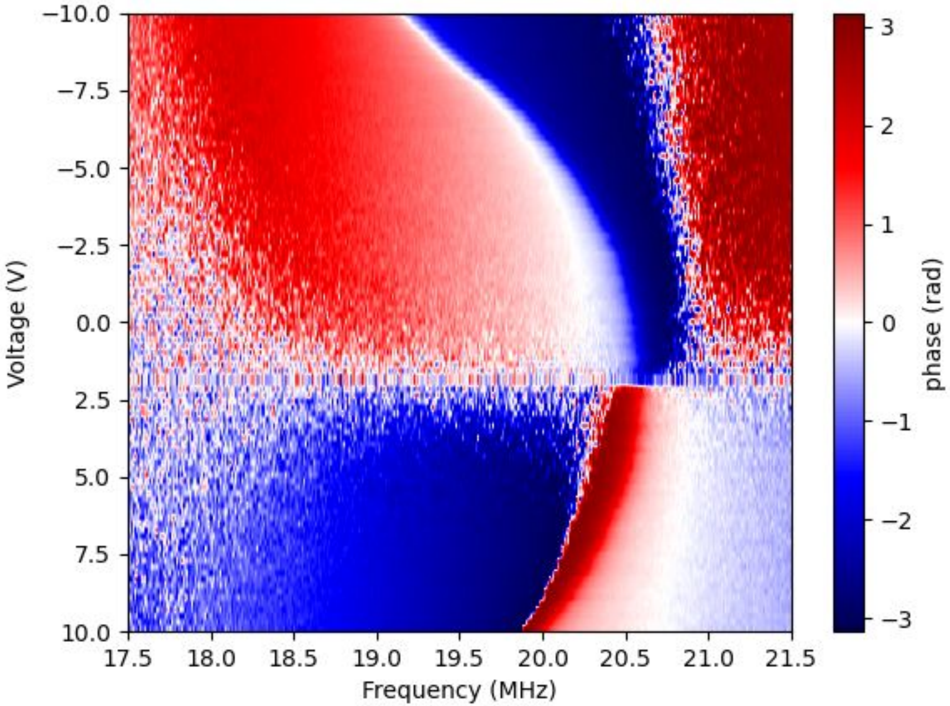


# Voltage ramp with electrostatic force (wider V range)





# Phase inversion



# Phase inversion