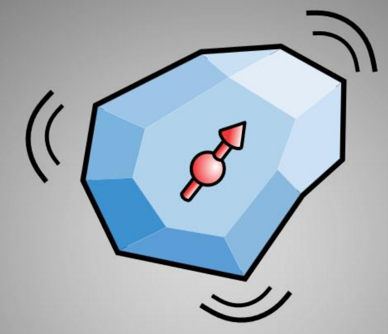
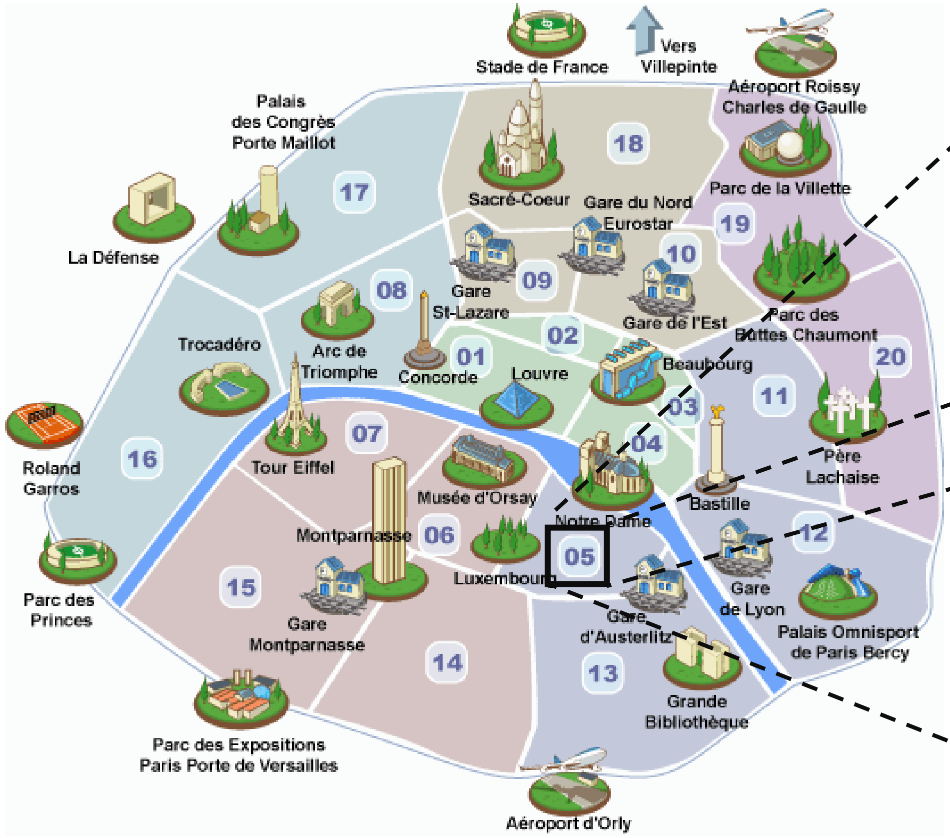


Maxime Perdriat, LPENS, Paris
ECT workshop, 2nd of August 2023*

Spin-mechanics with levitating diamonds

Location

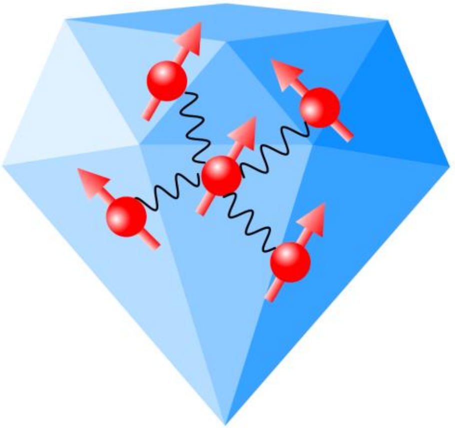


Paris

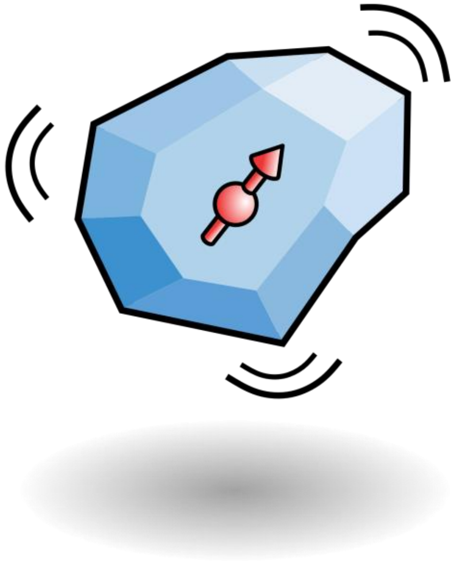
L'École Normale Supérieure

LPENS

Our research interests



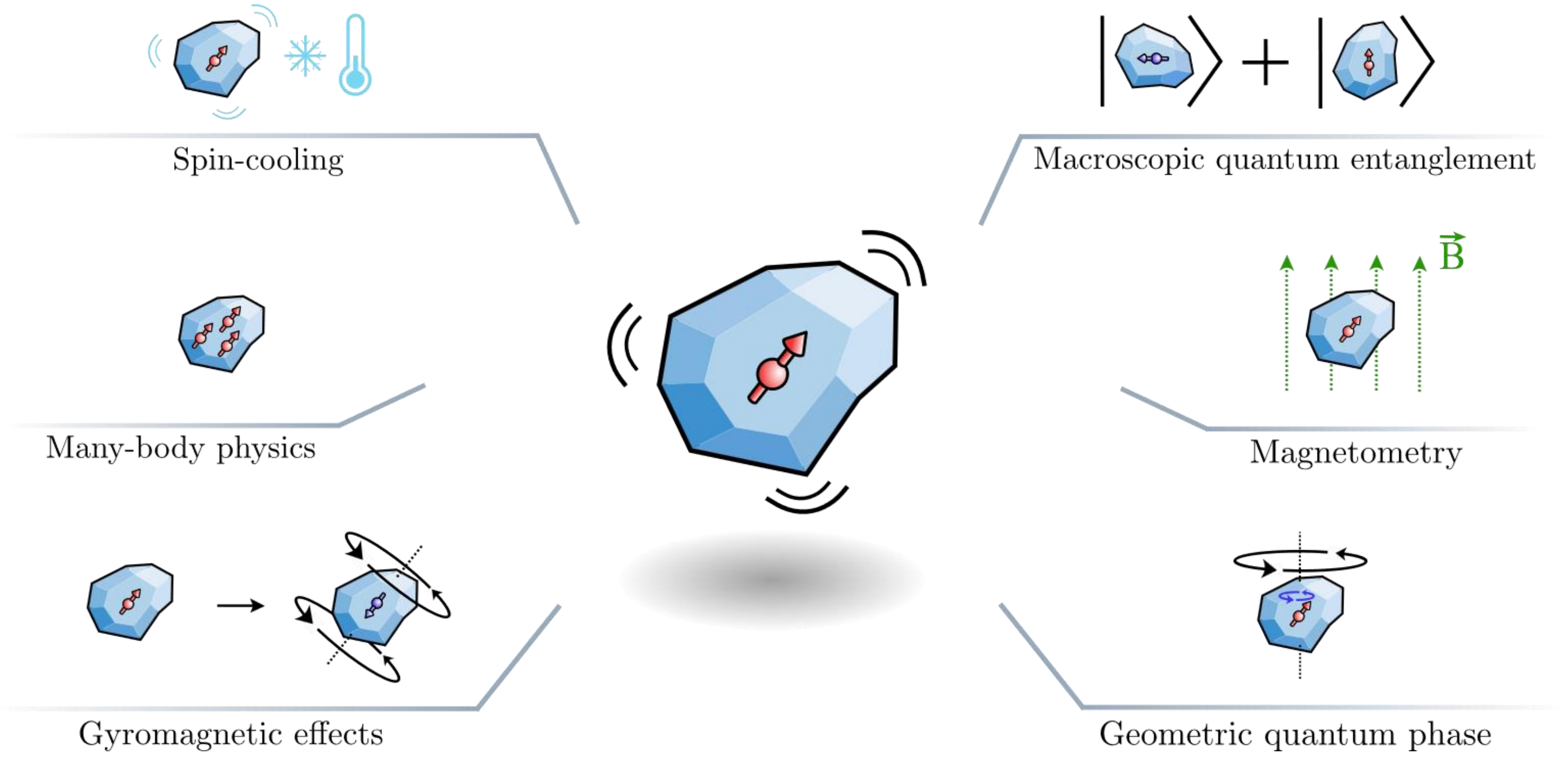
Magnetometry using dense NV ensembles [1]



Spin-mechanics with levitated magnetic particles [2]

[1] C. Pellet-Mary, et al., arXiv:2207.13899 (2022), [2] M. Perdriat, et al., MDPI 12, 651 (2021)

The interplay between spin and angular dynamics



Spin-cooling

Macroscopic quantum entanglement

Many-body physics

Magnetometry

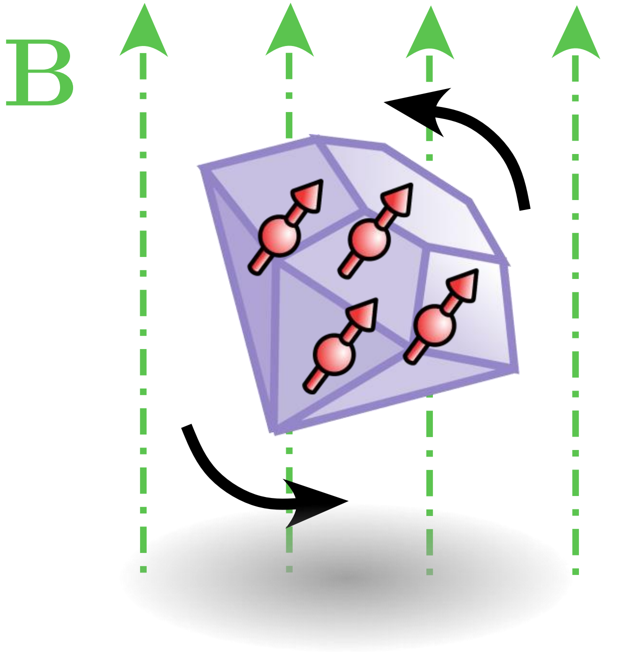
Gyromagnetic effects

Geometric quantum phase

Our approach: levitated diamonds embedded with NV centers

- **Angularly stable diamond**
  - 10-20 micron size diamond
  - Electrostatic levitation
  - Libration frequencies: ~100Hz-1kHz

- **Spin degree of freedom: the NV center**
  - Long coherence time: 1μs (300K)
  - Easily tunable
  - NV centers ensemble: $N=10^9$



- **Coupling: the magnetic torque**
  - Spin anisotropy
  - Magnetic field

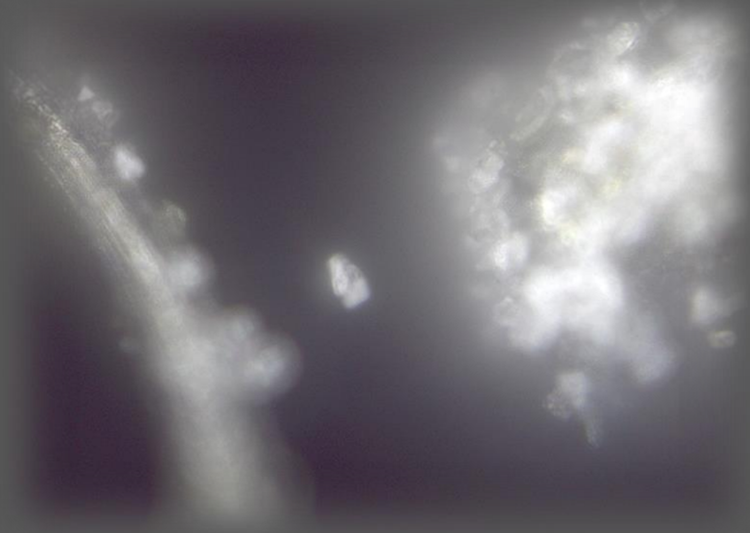
Outline

1 - Experimental set-up

2 - The NV^- center in diamond

3 - Spin-mechanics with levitating diamonds

4 - Rotation of diamonds in Paul traps



1

Experimental set-up

Micro Paul trap

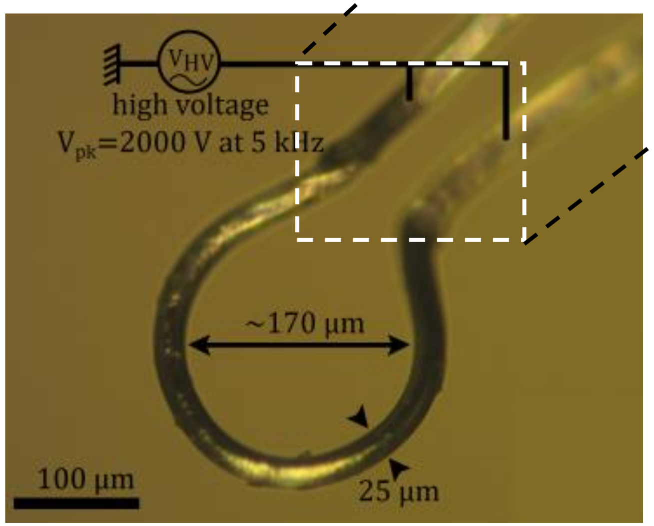
Trap parameters

$$V_{\mathrm{AC}} = 1000\ V.$$

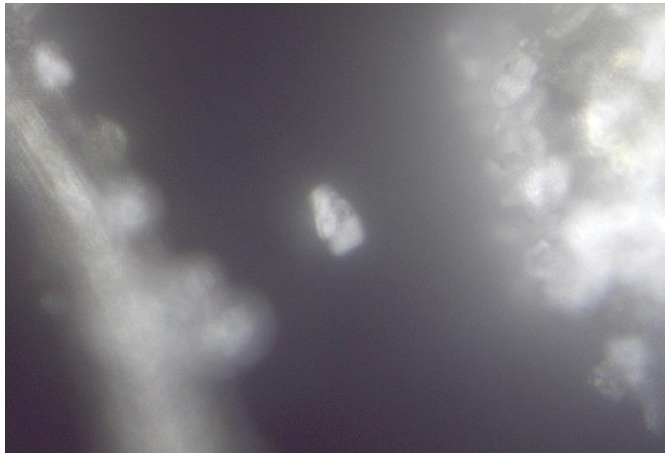
$$\Omega/2\pi = 1 - 10\ \mathrm{kHz}.$$

$$d = 100\ \mu m$$

Microwave current through the wire.



Micro Paul trap



Levitating 15 micron diamond

Levitating particles

Size: 10-20 microns

Electric charges: 1000-10000 charges

Types of particles: ferromagnets, YIG, hBN, diamonds.

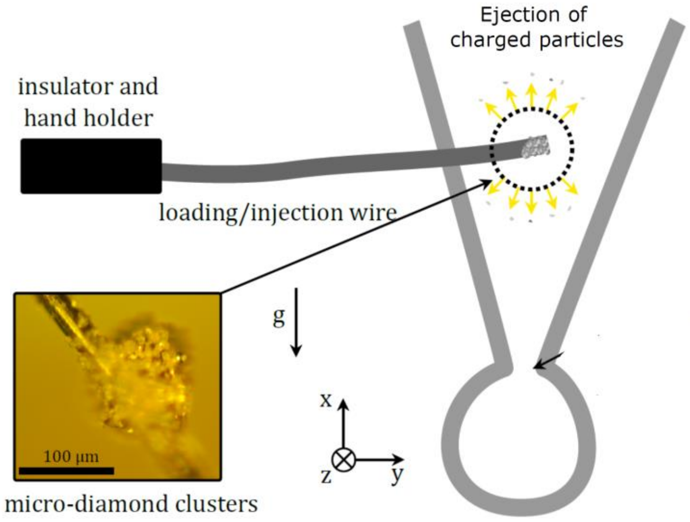
Angularly stable due to the particle and trap asymmetry.

Injection technique

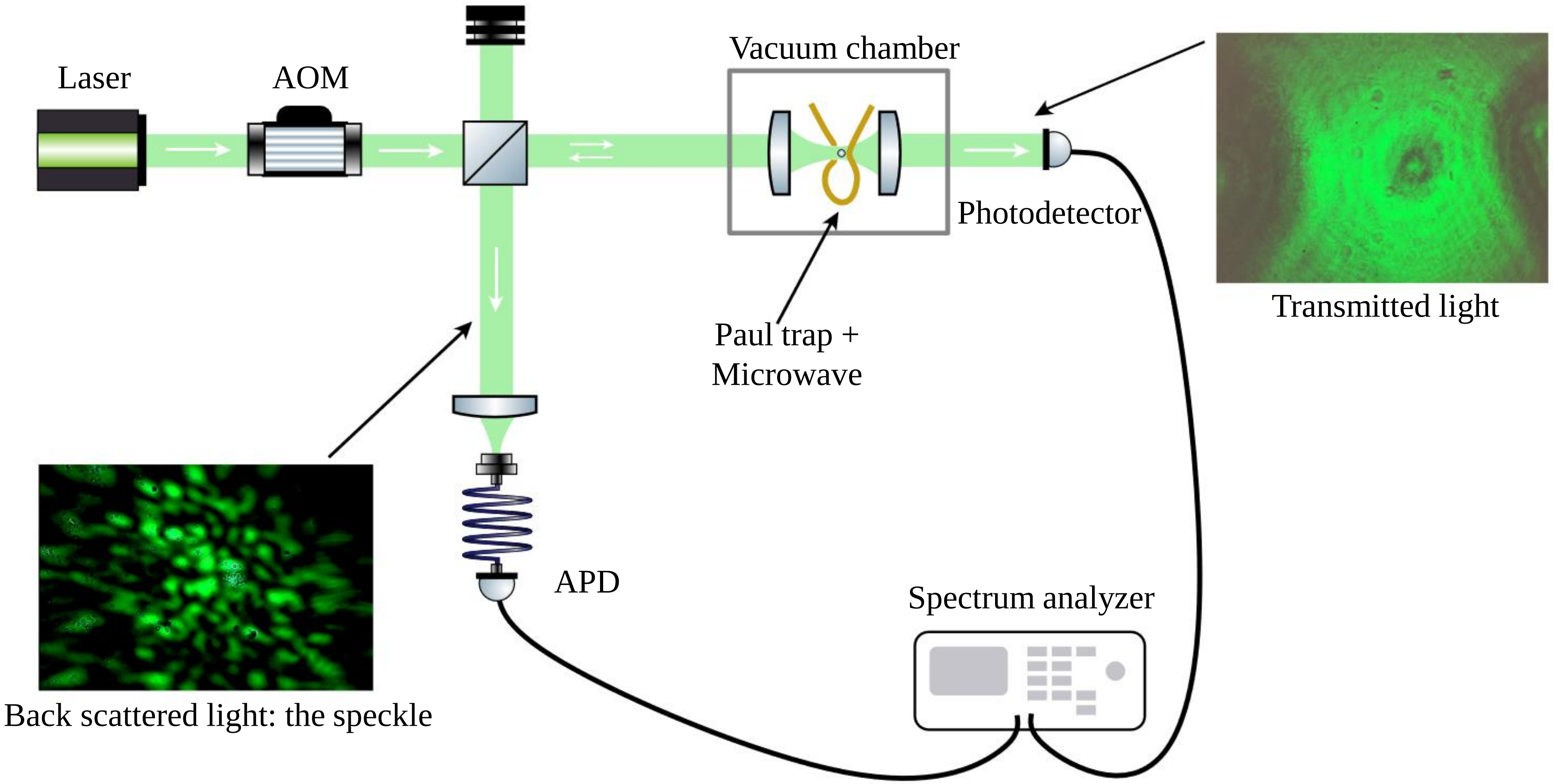
Efficient technique

Possibility to trap mutliple diamonds

Not clean loading technique…



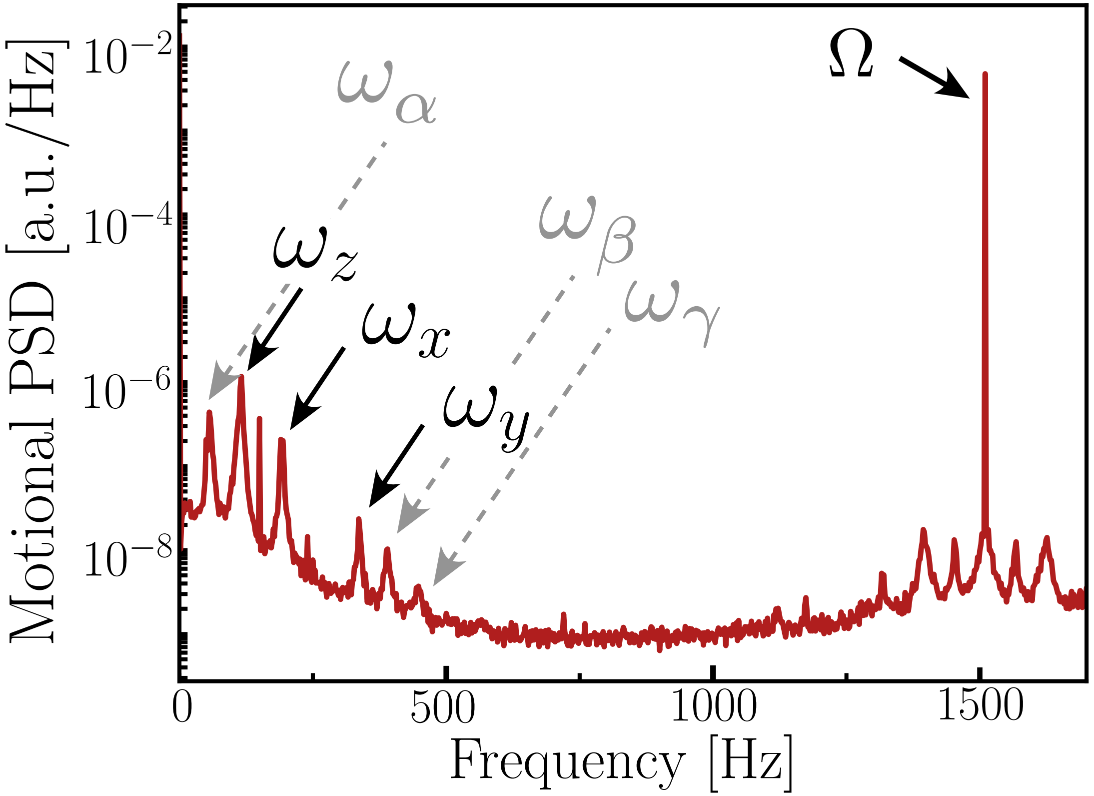
Optical set-up



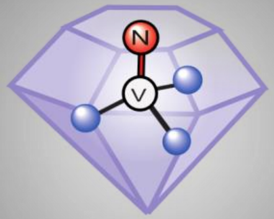
Both sensitive to the CoM and angular motion.

Mechanical modes at low pressure

- **PSD of an angularly stable diamond (1mbar)**



Diamonds quickly heat up at lower pressure due to laser absorption.

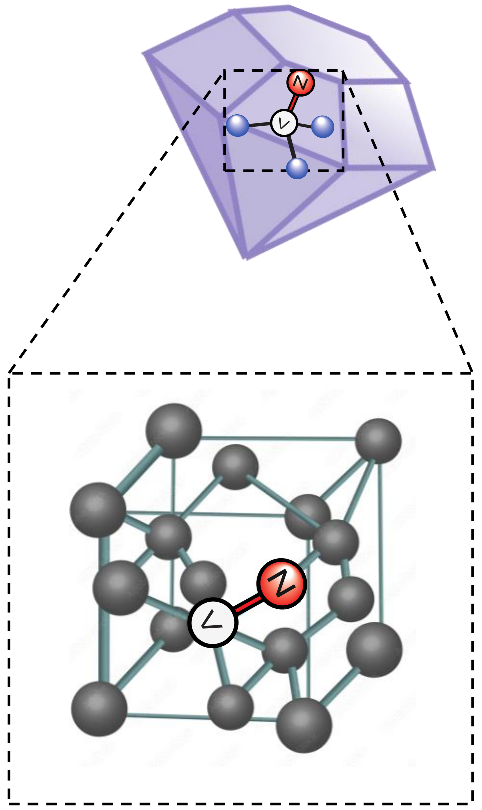


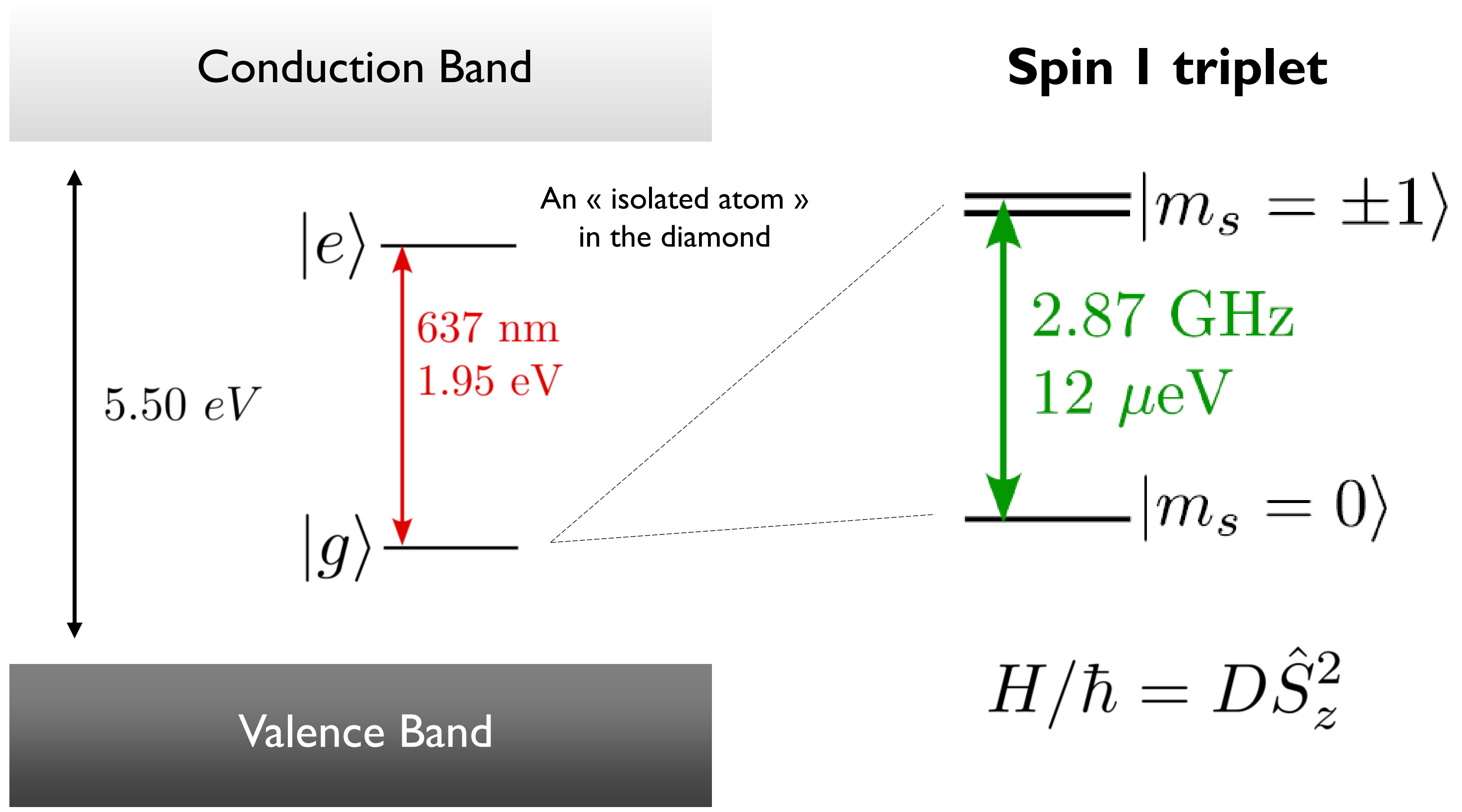
2

The NV$^-$ center in diamond

The NV$^-$ center in diamond: a tunable spin qubit

- **NV center electronic structure**





Conduction Band

$5.50\ eV$

$|e\rangle$

$|g\rangle$

637 nm
1.95 eV

An « isolated atom »
in the diamond

Valence Band

Spin 1 triplet

$|m_s = \pm 1\rangle$

2.87 GHz
12 μeV

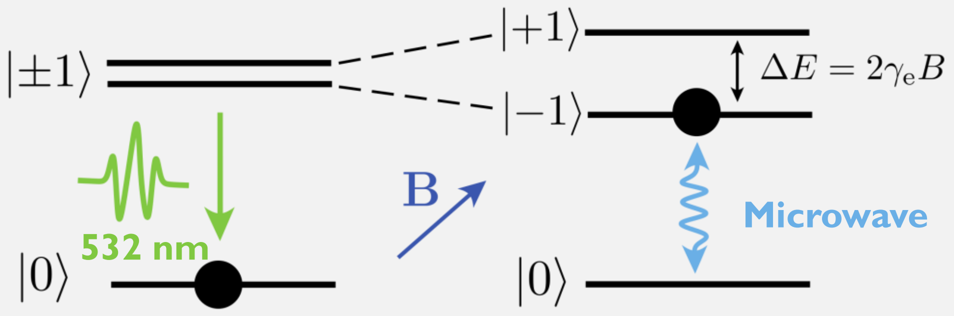
$|m_s = 0\rangle$

$$H/\hbar = D\hat{S}_z^2$$

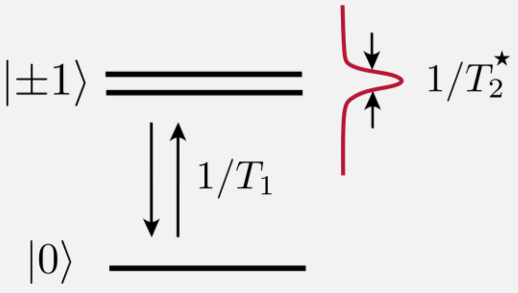
The NV$^-$ center in diamond: a tunable spin qubit

- **A highly controlable spin triplet at room temperature**

- **Optical pumping with a green laser in the |0> state**



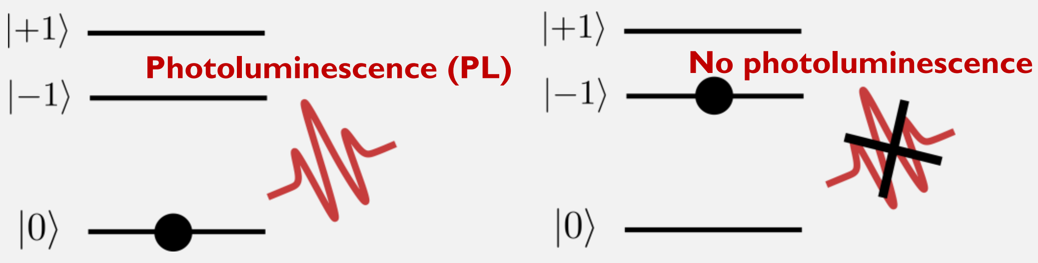
- **Exceptional life time and coherence time**



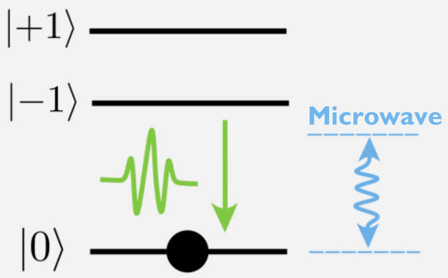
Spin lifetime: $T_1 \sim 1$ ms
limited by the phonon bath coupling

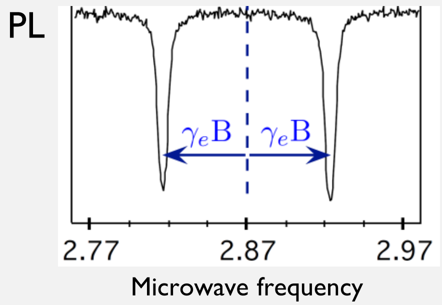
Spin coherence time: $T_2{}^{*} \sim 1\ \mu s$
limited by magnetic fluctuations

- **Optical read-out of the spin state**



- **Optically Detected Magnetic Resonance (ODMR)**



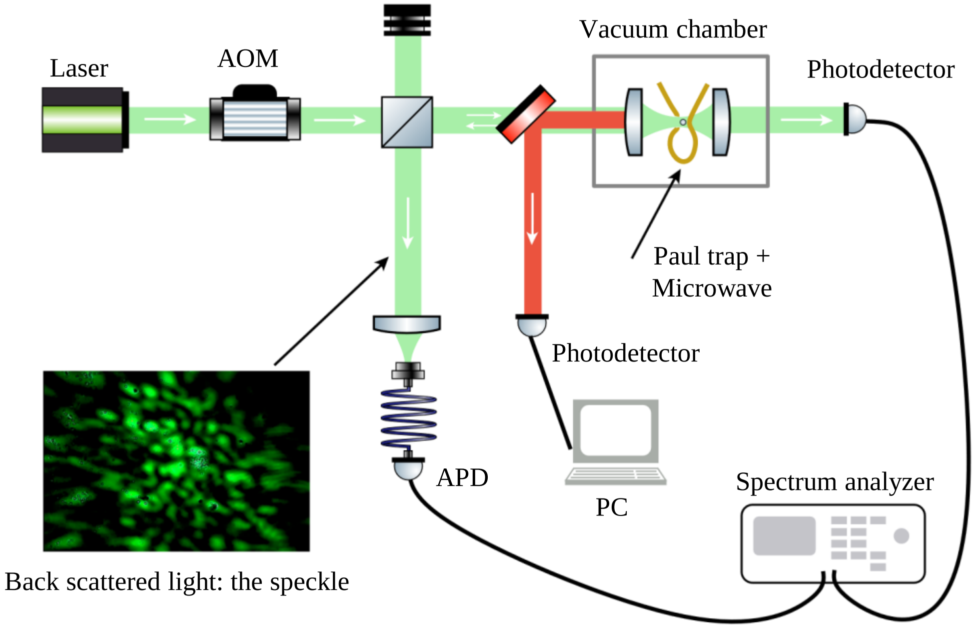


Extracted from [1]

[1] A. Dréau, PhD thesis (2013)

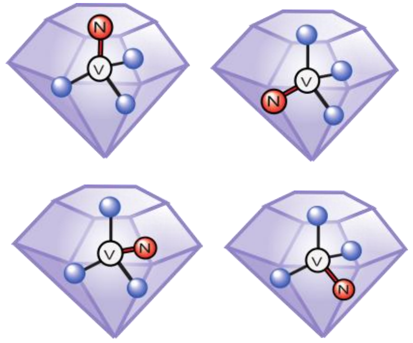
ODMR with angularly stable levitated diamonds

- **Optical set-up**

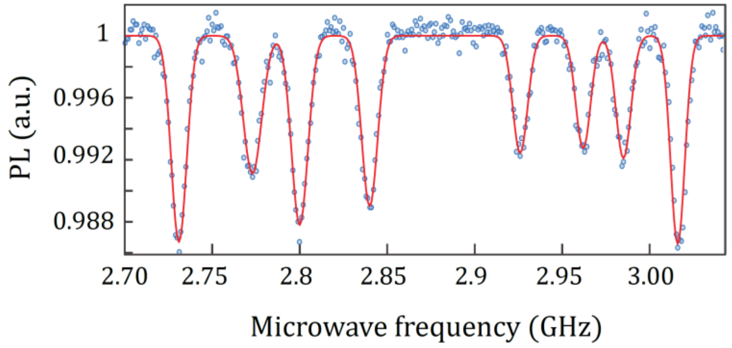


Back scattered light: the speckle

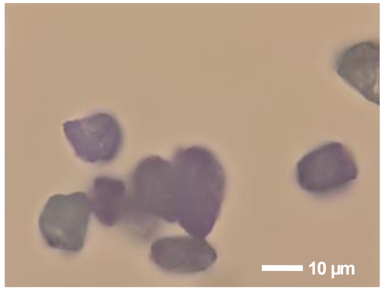
- **ODMR measurement [1]**



2 resonances X 4 classes = 8 resonances



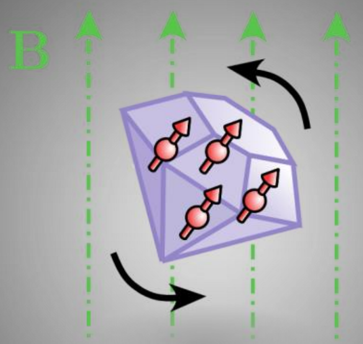
- **Highly doped diamonds**



Microscope image of diamonds
(from Adamas Nanotechnology company)

- **Fabrication technique**: High Pressure High Temperature
- **Size** : 15-20 microns
- **Highly doped in NV centers**: 3 parts per million => **N=10^9 NV centers**

[1] T. Delord, PRL 121, 053602 (2018)

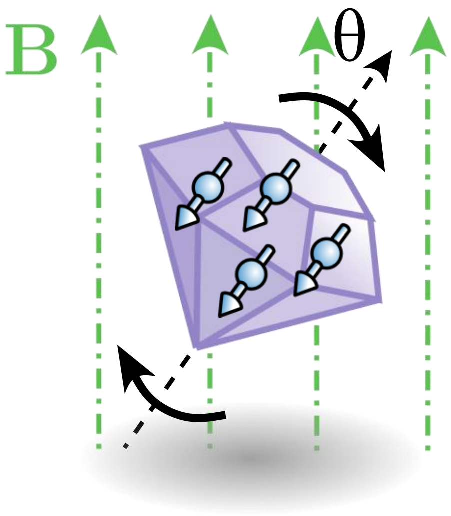


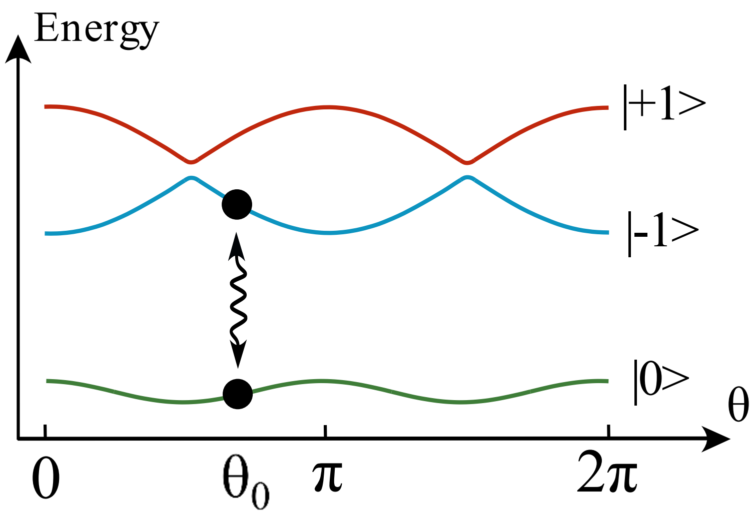
3

Spin-mechanics with levitating diamonds

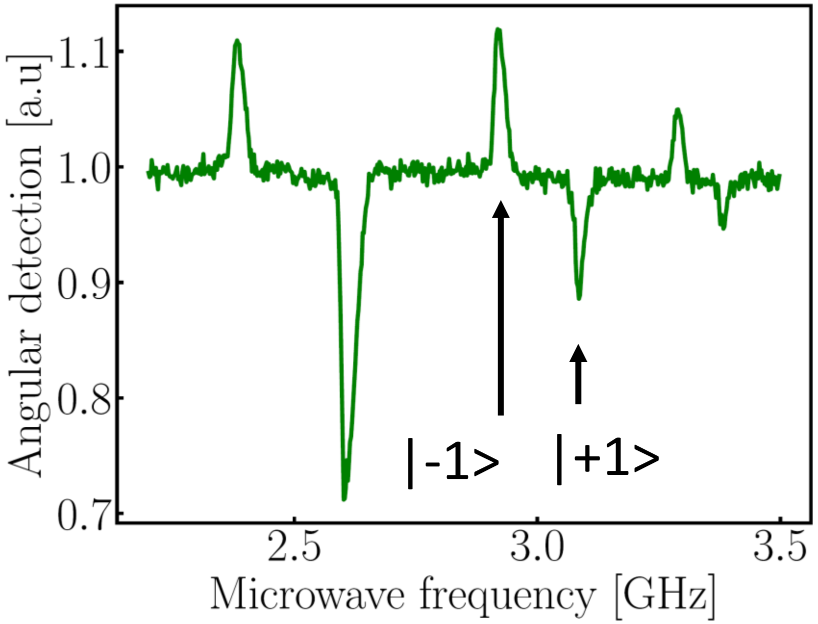
Spin-mechanical coupling: the magnetic torque

- **System**





- **Torque detected magnetic resonance [1]**



- **Magnetic torque estimation**
  - **Magnetic moment:** $\mathbf{m} = \pm\hbar|\gamma_e|N\mathbf{e}_z$
  - **Magnetic torque:** $\boldsymbol{\tau}_{\text{mag}} = \mathbf{m} \times \mathbf{B} \approx 10^{-17}$ N.m.
  - **Torque sensitivity (1 atm):** $\tau^{\text{min}}_{\text{meas}}\sqrt{t} = 10^{-19}\ \text{N.m}/\sqrt{\text{Hz}}$

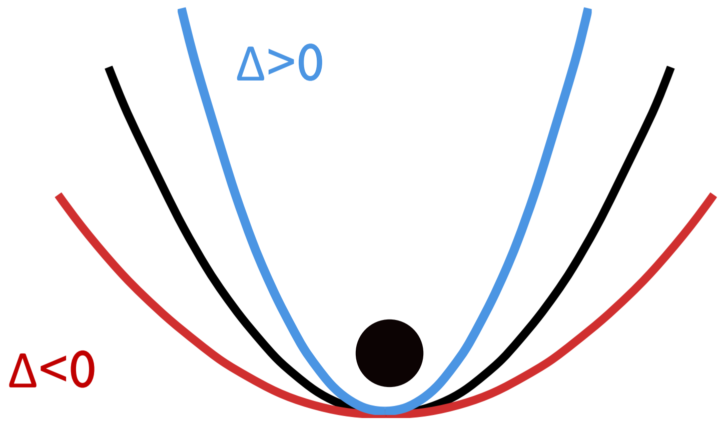
- ΔΘ ~ 10 mrad
- 4 NV classes

➡ The magnetic torque is measurable in less than 1 millisecond!

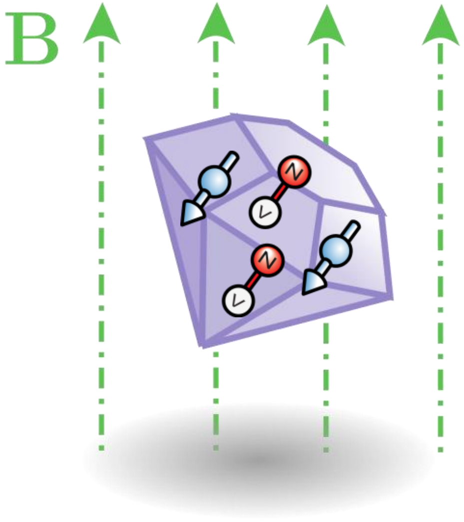
[1] T. Delord, P. Huillery et al., Nature 580, 56-59 (2020)

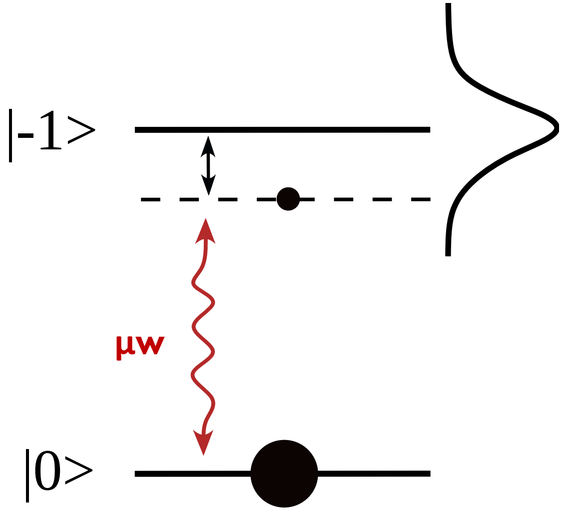
Dynamical back action: the spin-spring and spin-cooling

- **Principle**



Angular energy





Two-level system

- **Hamiltonian**

$$H/\hbar = \omega_\theta \hat{a}^\dagger \hat{a} + \frac{\Delta}{2}\hat{\sigma}_z^{\text{tot}} + \frac{\Omega}{2}\hat{\sigma}_x^{\text{tot}} + g_0 \hat{\sigma}_z^{\text{tot}}(\hat{a} + \hat{a}^\dagger)$$

$$\omega_\theta/2\pi \approx 100 \text{ Hz} \qquad g_0/2\pi \approx 100 \text{ Hz}$$

$$\Omega/2\pi < 10 \text{ MHz} \qquad g_N/2\pi \approx 1 \text{ MHz}$$

- **Magnetic torque**

$$\tau(\Delta,\theta,\ldots) = \underset{\substack{\nearrow \\ \text{Spin-torque}}}{\tau(\Delta,\theta=0,\ldots)} + \underset{\substack{\uparrow \\ \text{Spin-spring}}}{\frac{\partial\tau}{\partial\theta}\delta\theta}$$

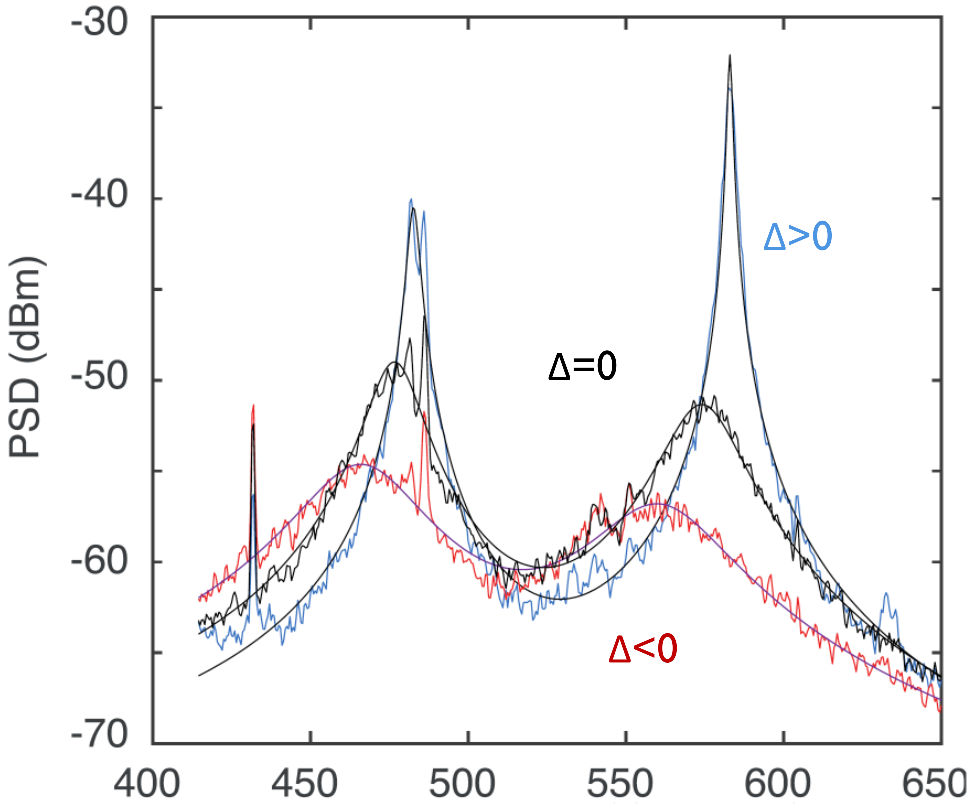
Red-detuned: Δ<0 spring-softening

Blue-detuned: Δ>0 spring-hardening

[1] T. Delord, P. Huillery et al., Nature 580, 56-59 (2020)

Dynamical back action: the spin-spring and spin-cooling

- **Experimental results**



PSD of two librational modes at 1 mbar [1].

- **Magnetization delay**

Spin population dynamical response: 100 µs

Angular dynamic: 1-10 ms

→ Spin response is only ten times faster than the mechanical dynamics.

- **Magnetic torque**

$$\tau(\Delta, \theta, ...) = \tau(\Delta, \theta = 0, ...) + \frac{\partial \tau}{\partial \theta}\delta\theta + \frac{\partial \tau}{\partial \dot{\theta}}\delta\dot{\theta}$$

Spin-torque

Spin-spring

Spin-cooling/heating

Red-detuned: Δ<0 : spin-cooling

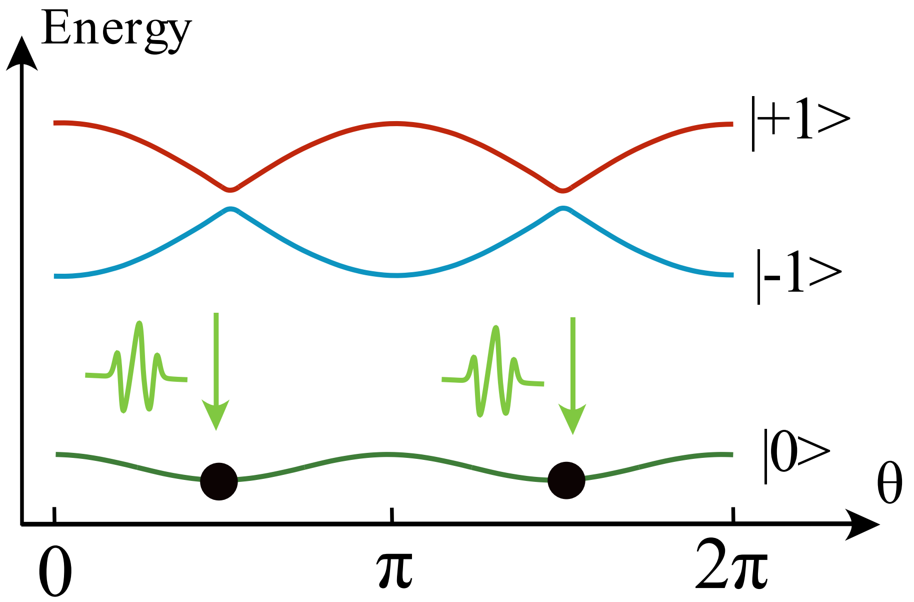
Blue-detuned: Δ>0 : spin-heating

→ Cooling to 80 K at 1 mbar.

[1] T. Delord, P. Huillery et al., Nature 580, 56-59 (2020)

Microwave free spin-mechanics

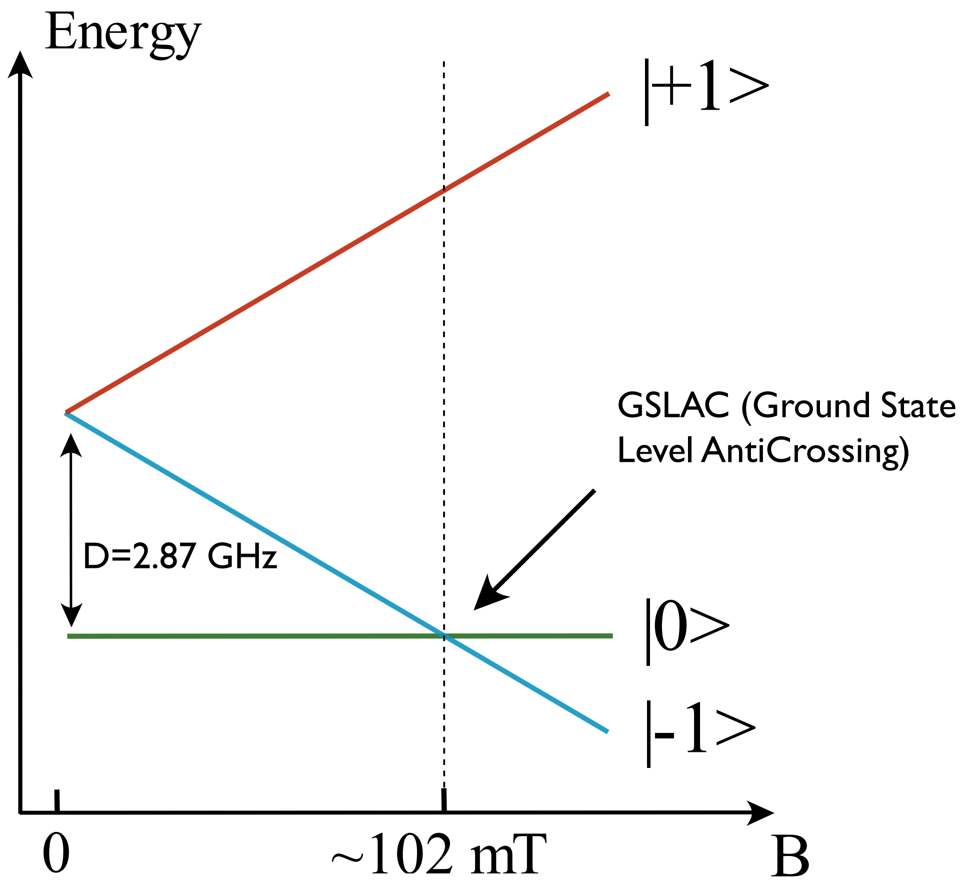
- **Constant amplitude, |B|=Cste**



The |0> state is magnetic due to the state mixing.

- Small magnetic torque.
- The four NV center classes torque compensate.

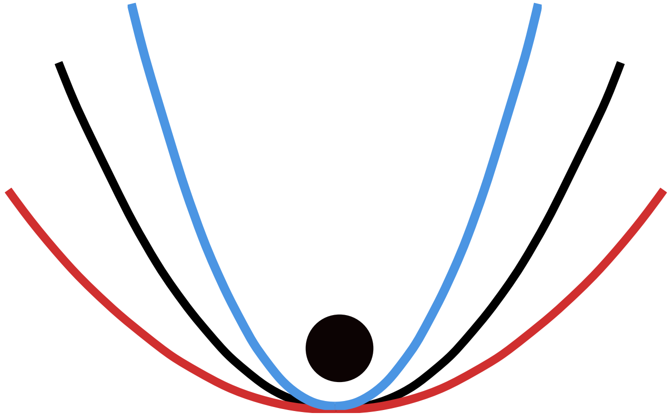
- **Longitudinal magnetic field, θ=0**



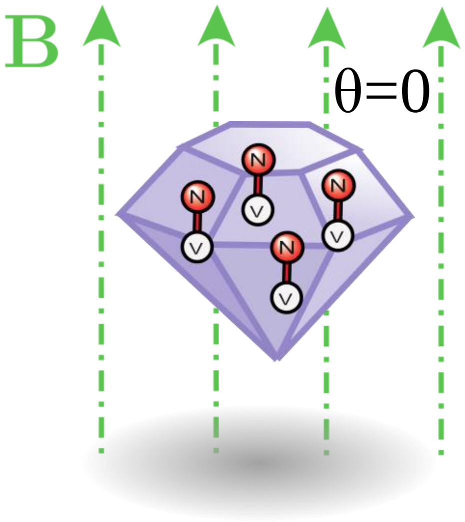
[1] M. Perdriat, et al., PRL (2022)

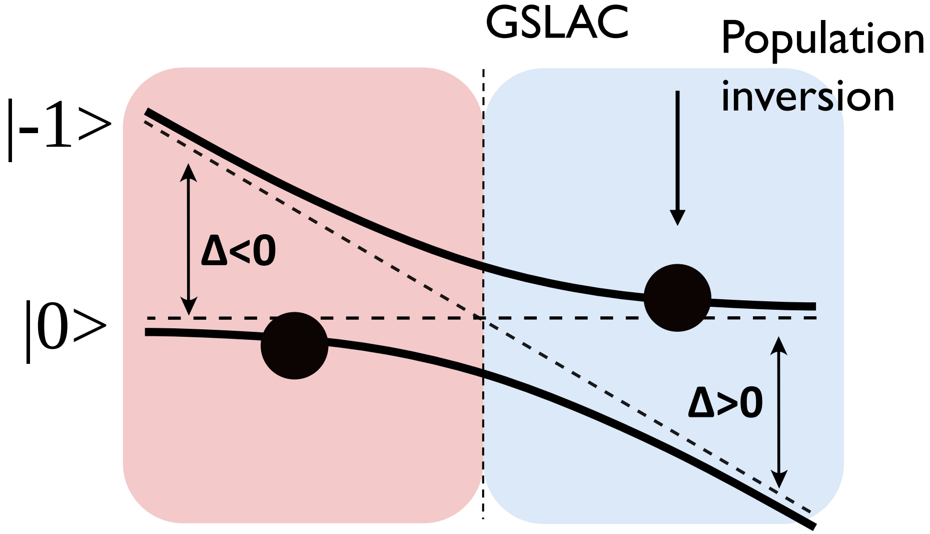
Microwave free spin-mechanics

- **System: longitudinal B field & B~102 mT**



Angular energy





Two-level system

- **Hamiltonian**

$$H/\hbar = \omega_\theta \hat{a}^\dagger \hat{a} + \frac{\Delta}{2}\hat{\sigma}_z^{\mathrm{tot}} + g_0 \hat{\sigma}_x^{\mathrm{tot}}(\hat{a} + \hat{a}^\dagger)$$

$$\omega_\theta/2\pi \approx 100 \text{ Hz}$$
$$g_0/2\pi \approx 1 \text{ kHz}$$

- **Magnetic torque**

$$\tau(\Delta, \theta, ...) = \underset{\substack{\uparrow \\ \text{Spin-spring}}}{\frac{\partial \tau}{\partial \theta}}\delta\theta$$

Red-detuned: Delta<0 spring-softening

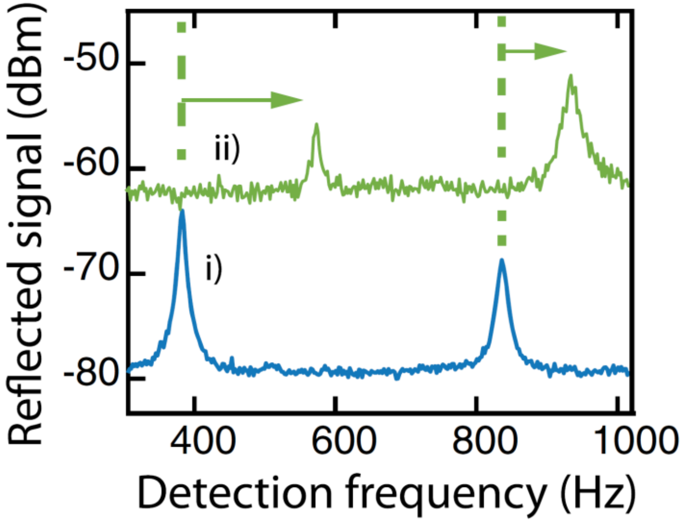
Blue-detuned: Delta>0 spring-hardening

[1] M. Perdriat, et al., PRL 128, 117203 (2022)

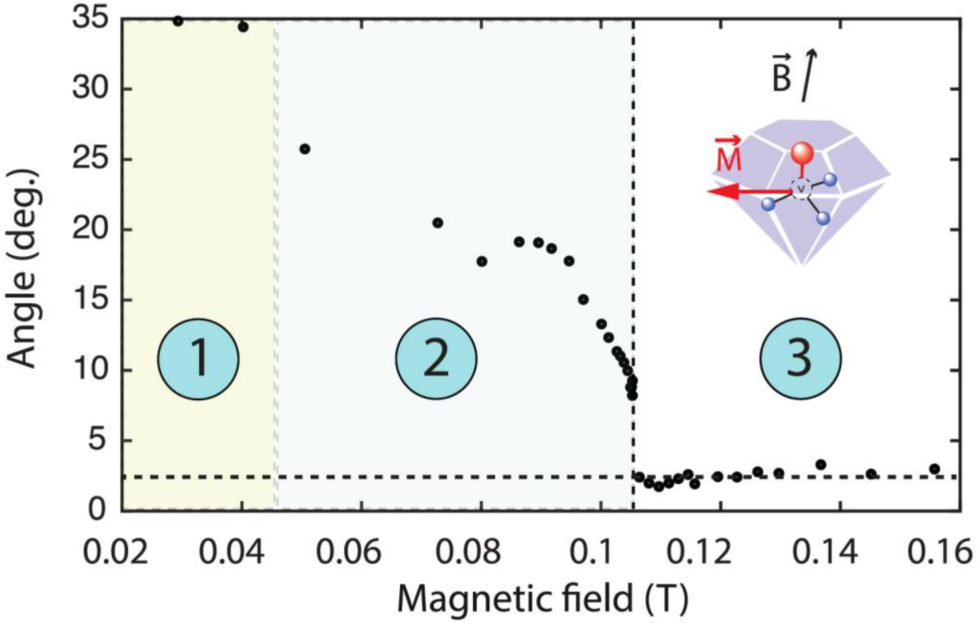
Microwave free spin-mechanics

- **Experimental results**

Librational modes of a diamond at 1 mbar after the GSLAC.



i) Without green laser optical pumping in the |0> state.
ii) With green laser optical pumping in the |0> state.

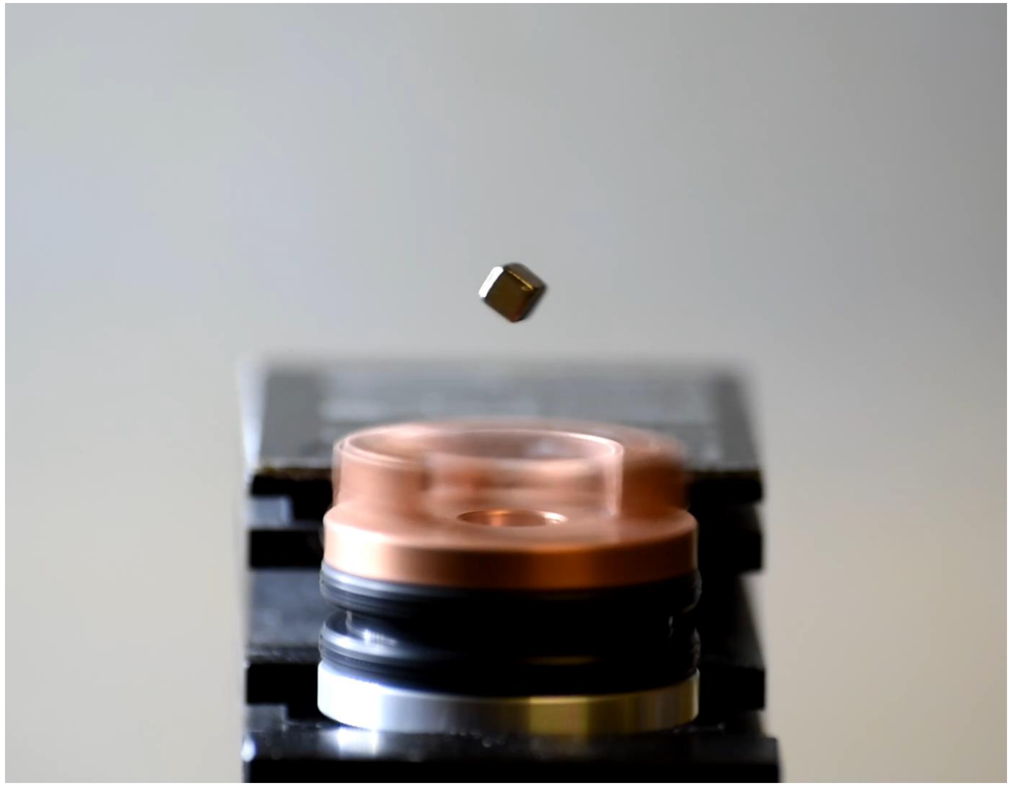


1: **Paul trap torque** >> spin torque
2: Paul trap torque ~ spin torque
3: **Spin torque** >> Paul trap torque

The spin-spring hardening is sufficient to fully align the diamond in the NV center direction.

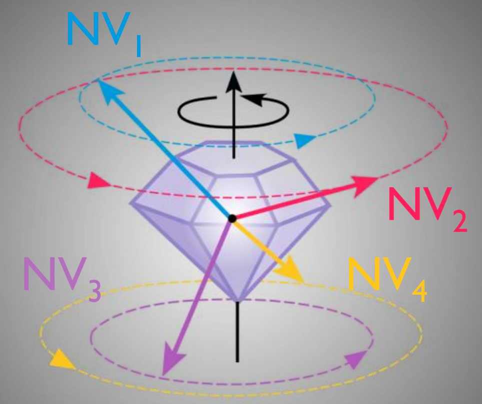
[1] M. Perdriat, et al., PRL 128, 117203 (2022)

For fun …: the magnetic Paul trap



Same principle than electric Paul trap using the magnetic dipole rather than the electric charge [1].

[1] M. Perdriat, et al., arXiv:2212.11622 (2022) soon in PRR

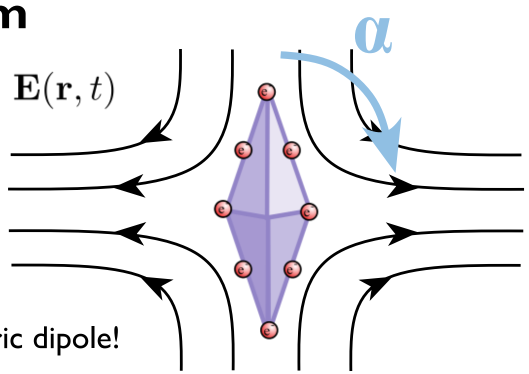


4

Rotation of diamonds in Paul trap

Reminders on the angular dynamics in Paul traps

- **System**



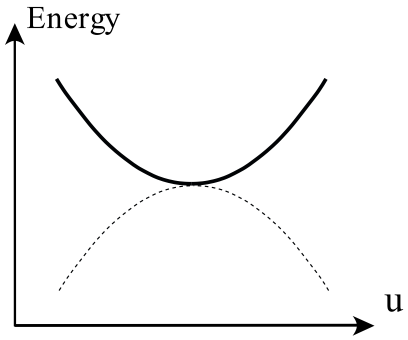
No electric dipole!

Asymmetric Paul trap & asymmetrically charged diamond.

- **CoM dynamics**

$$\ddot{u} + \omega_u^2 \cos(\Omega t) u = 0$$

$$\omega_u^2 = \frac{qU_{\mathrm{AC}}}{m z_0^2} \qquad q_u = 2\omega_u^2/\Omega^2$$



q_u<0.9 => CoM stability around u=0.

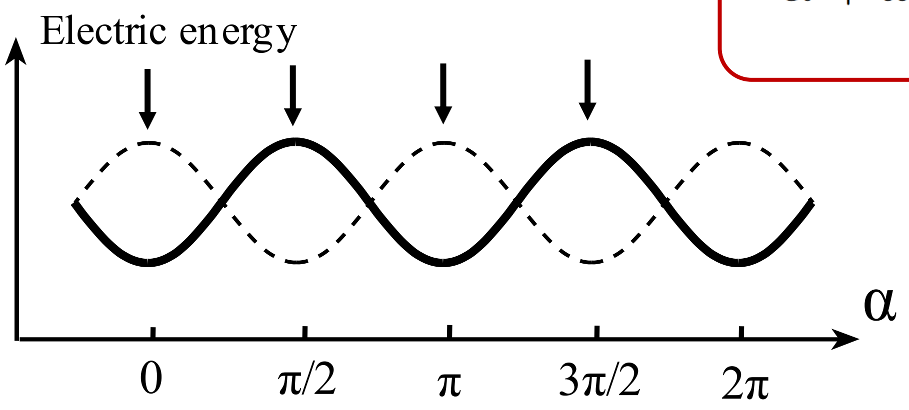
- **Angular dynamics (1D)**

$$\boxed{\ddot{\alpha} + \omega_\alpha^2 \cos(\Omega t) \frac{\sin(2\alpha)}{2} = 0.}$$

$$\omega_\alpha^2 \approx \frac{qU_{\mathrm{AC}}S}{I z_0^2} a_{\mathrm{trap}} a_{\mathrm{par.}}$$

a_{trap} : trap asymmetry

$a_{\mathrm{par.}}$: particle asymmetry



Linear regime : sin(2α)~2α,
Four stable positions q_α<0.9.

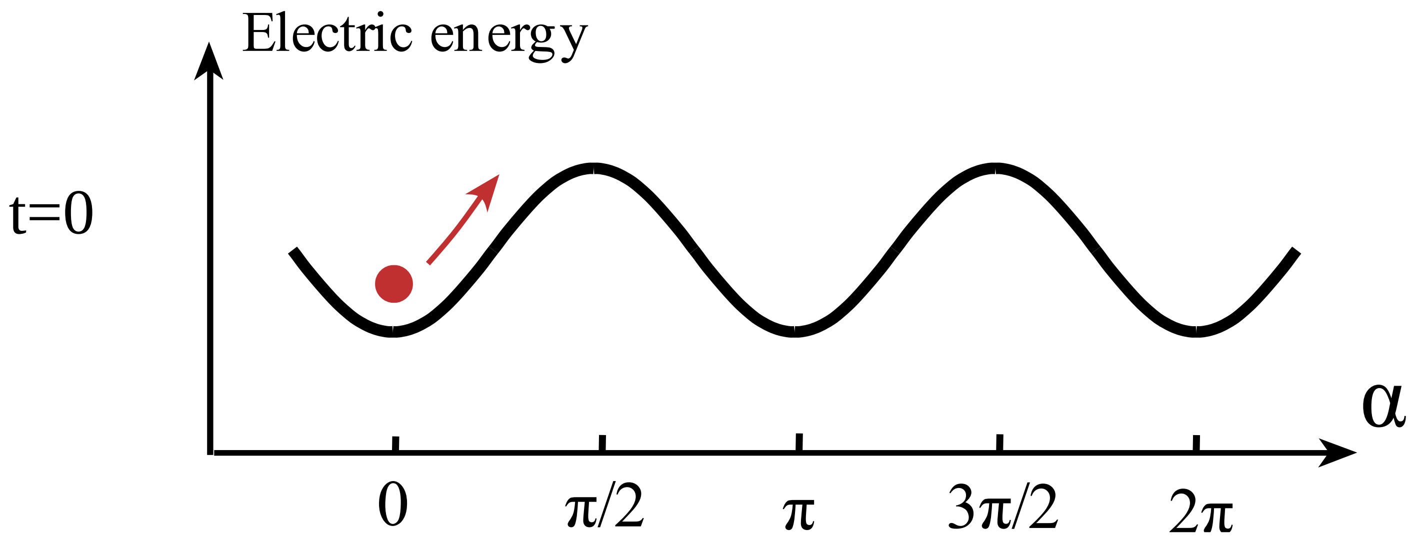
Libration

What happens when q_α > 0.9?

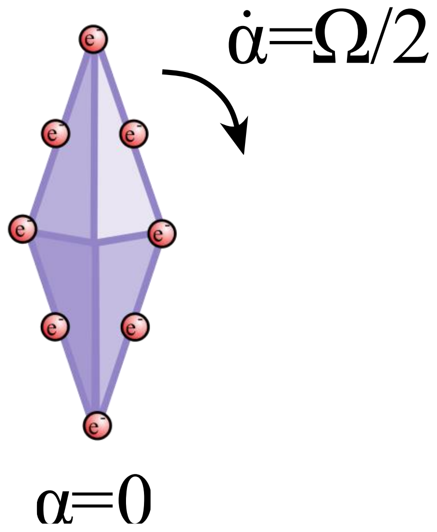
[1] M. Perdriat, et al., *in preparation* (2023) (Collaborators: Cosimo Rusconi & Ben Stickler)

Rotational-locking regime in Paul traps

- **Electric energy**



- **Initial conditions**



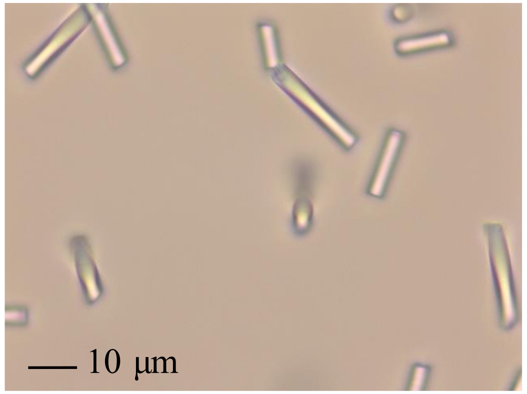
One full rotation for two Paul trap periods.

$$\boxed{\omega_{\rm rot} = \Omega/2 \propto \text{kHz.}}$$

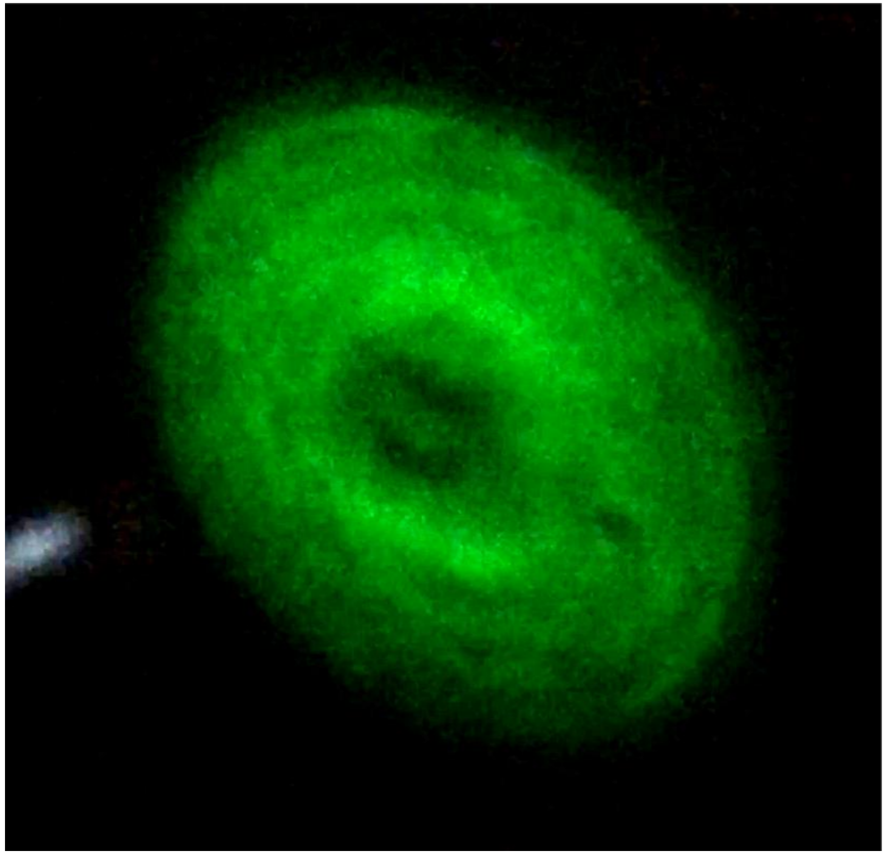
[1] M. Perdriat, et al., *in preparation* (2023) (Collaborators: Cosimo Rusconi & Ben Stickler)

Observation of the rotational-locking regime

- **Elongated particles**

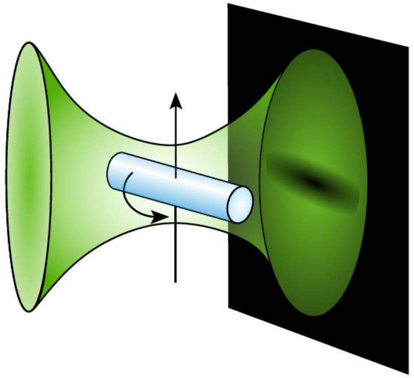


Cylindrical silica micro-rods
(from Nippon Electric Glass)



Stroboscopic view of a rotating silica micro-rod at half the Paul trap drive.

- **Rotation read out**



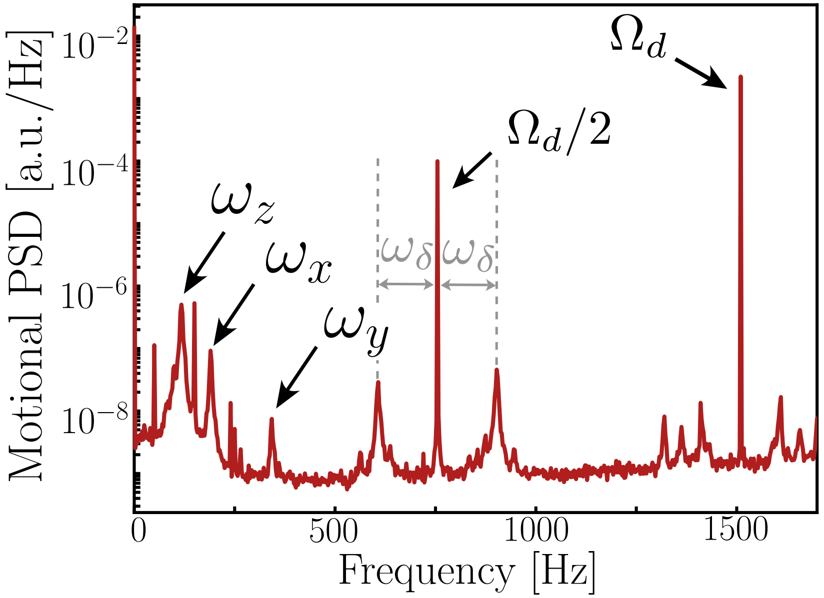
Transmitted light projected on a black board.

[1] M. Perdriat, et al., *in preparation* (2023) (Collaborators: Cosimo Rusconi & Ben Stickler)

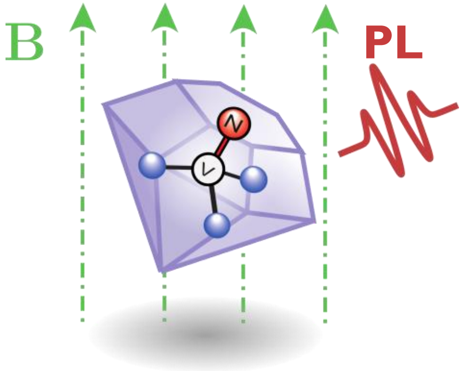
Rotating diamonds embedded with NV centers

- **Power Spectral Density (1 mbar)**

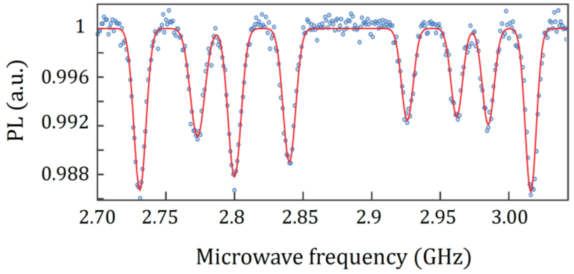
PSD of a 15 μm rotating diamond



- ***Reminder: the NV center can measure the angular position***



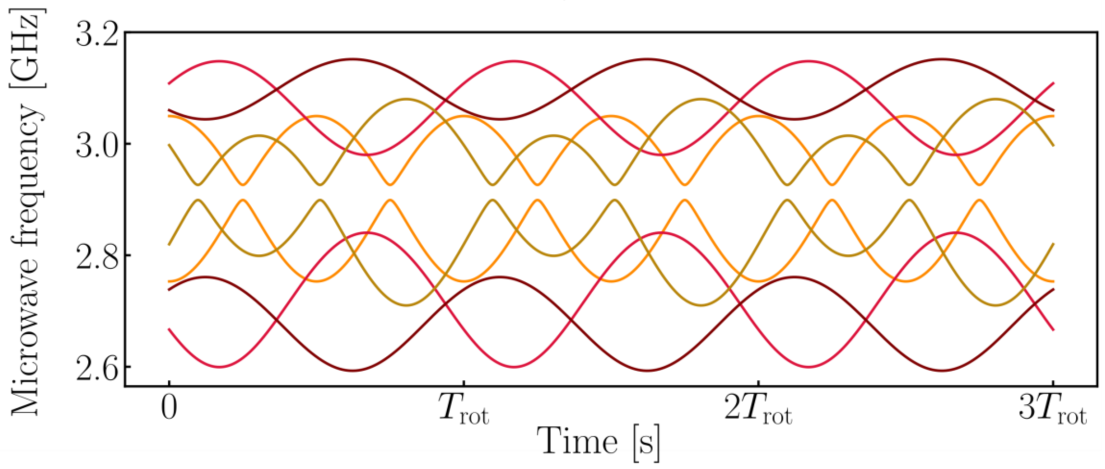
Continuous ODMR measurement

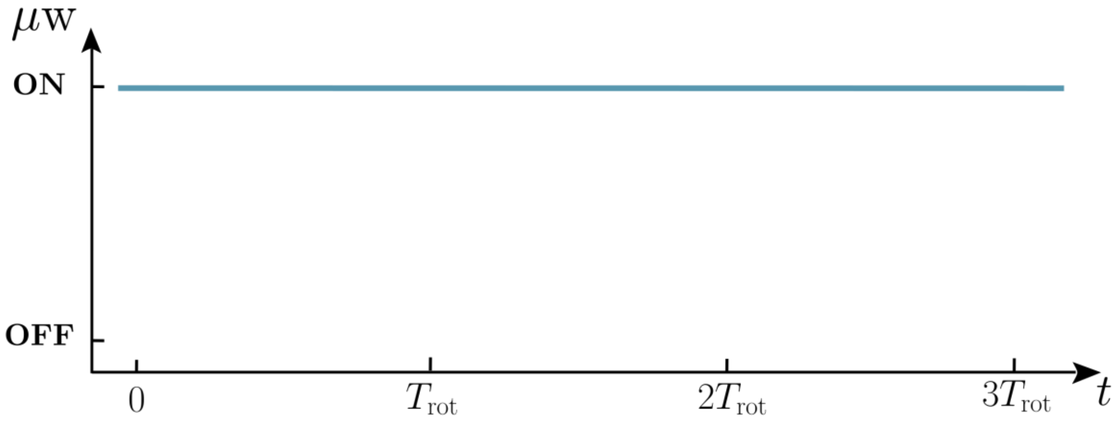


Idea: use NV centers to measure the angular motion.

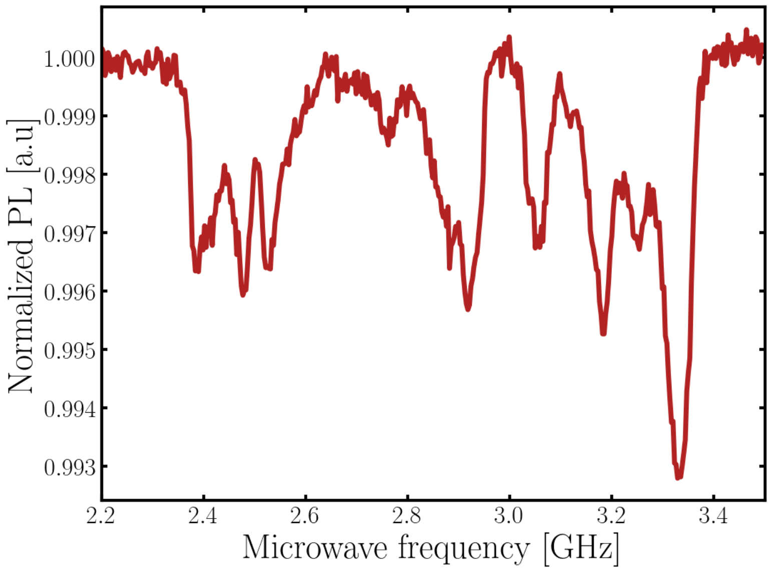
Continuous ODMR measurement

Evolution of the NV centers magnetic resonances as a function of time.





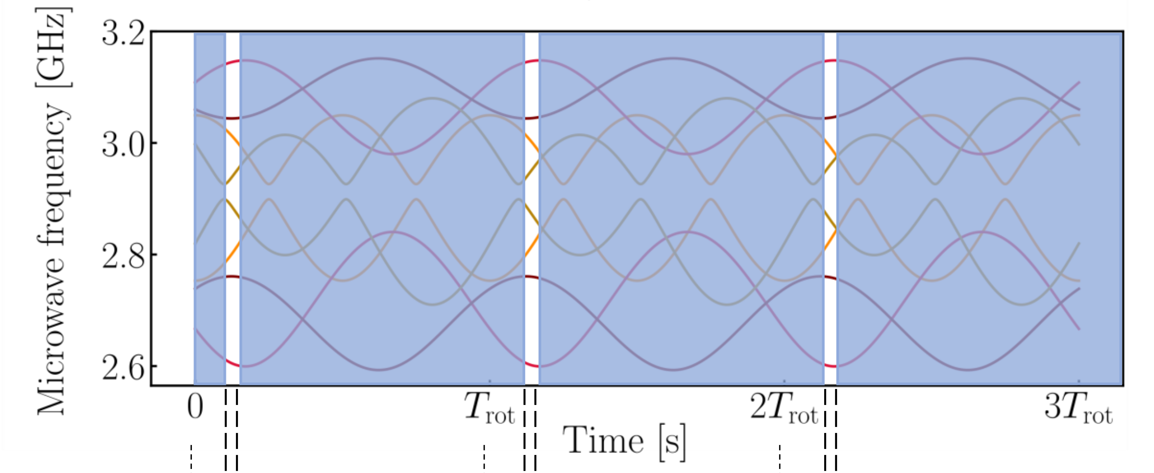
- **Experimental results**

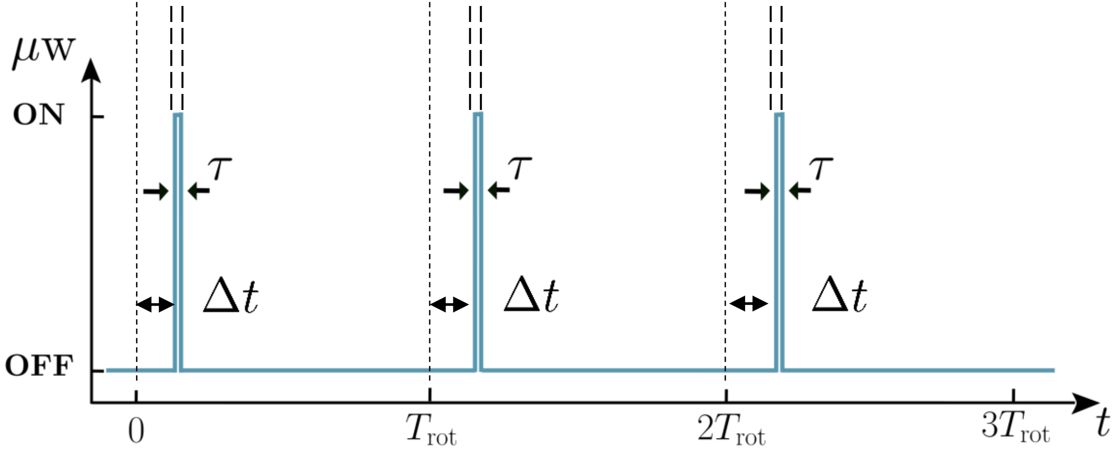


Continuous ODMR measurement with a rotating diamond.

Stroboscopic ODMR sequences

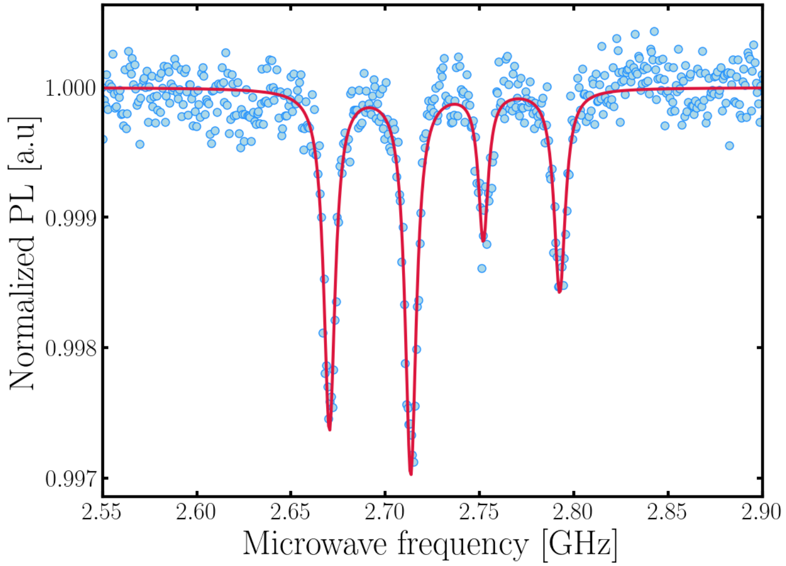
Evolution of the NV centers magnetic resonances as a function of time.





$$\tau = 0.1\%\ T_{\rm rot} \Longrightarrow \tau = 4\ \mu s$$

- **Experimental Results**



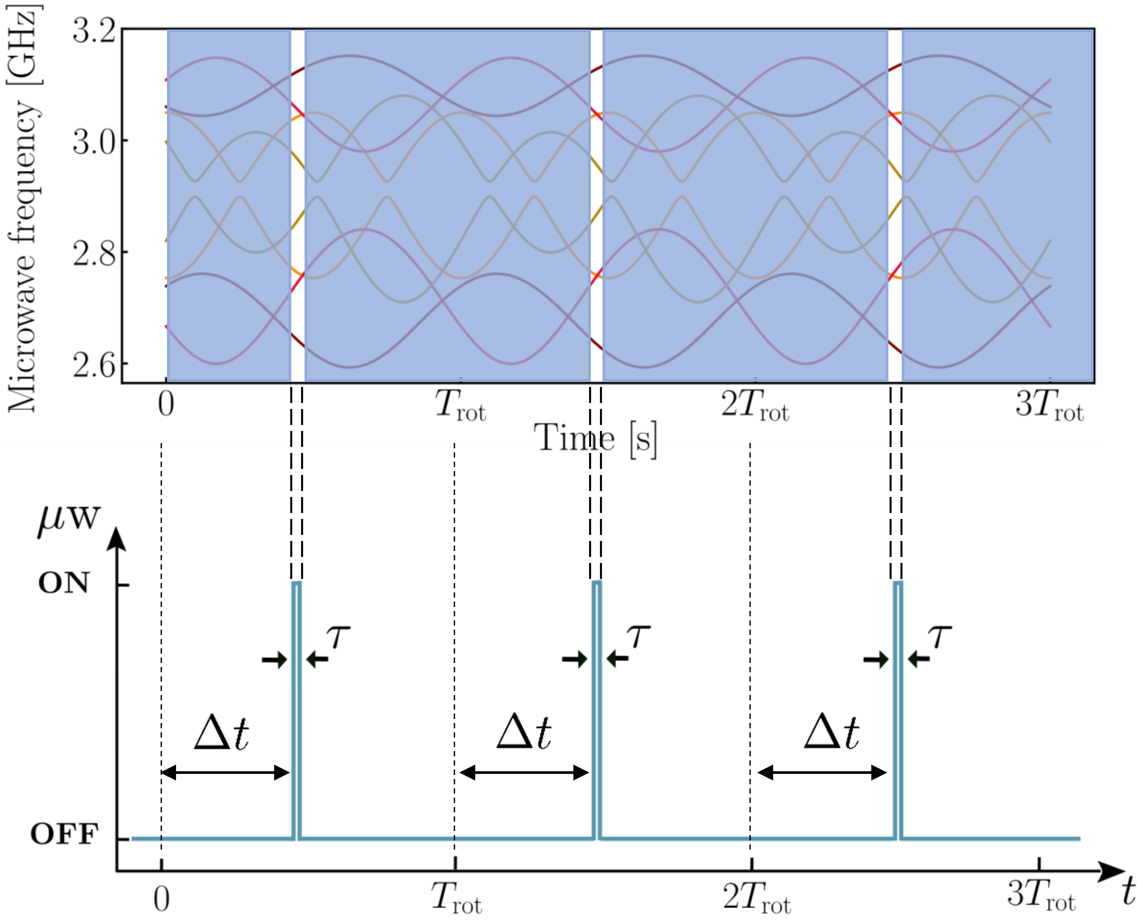
Stroboscopic ODMR measurement
with a rotating diamond.

Δt : stroboscopic delay

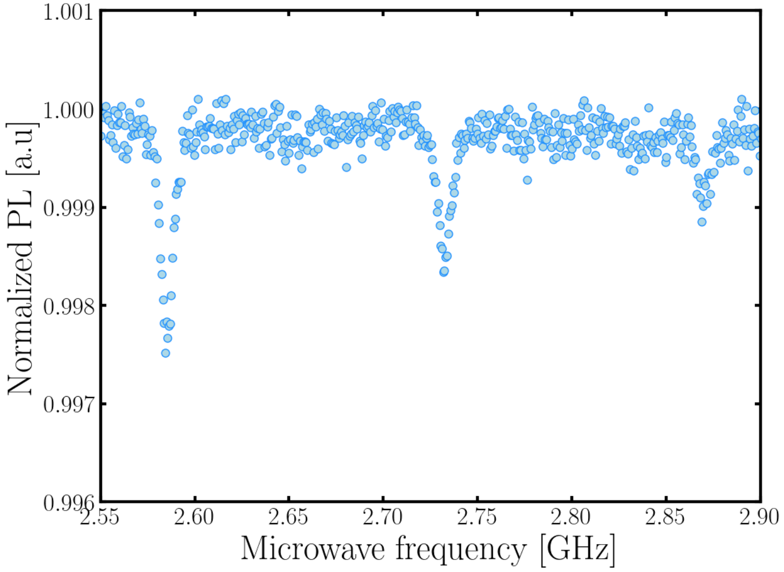
- Only the |0> -> |-1> transition
- No inhomogeneous broadening: the rotation is extremely stable even after 300 000 turns.
- No loss on the spin properties.
- 5 minutes of averaging.

Stroboscopic ODMR sequences

Evolution of the NV centers magnetic resonances as a function of time.



- **Experimental Results**



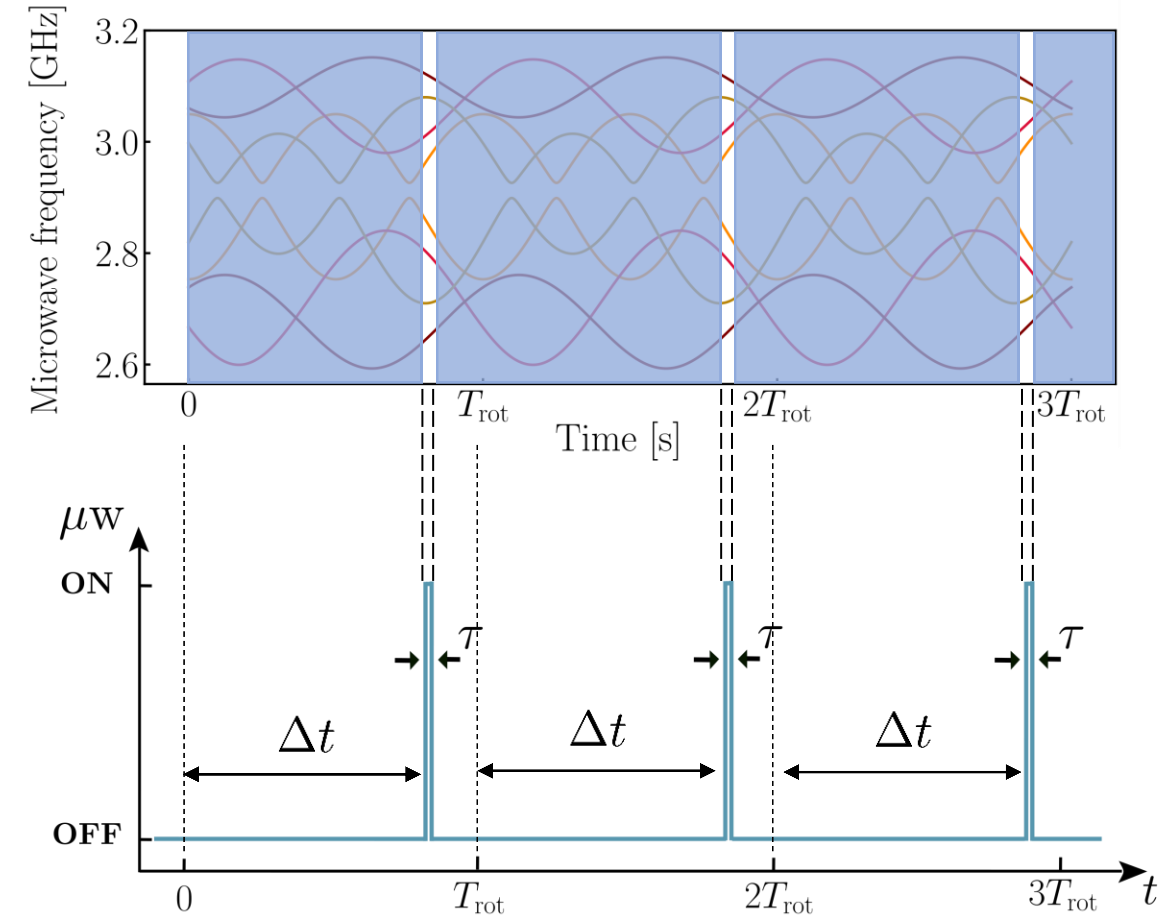
Stroboscopic ODMR measurement
with a rotating diamond.

Δt : stroboscopic delay

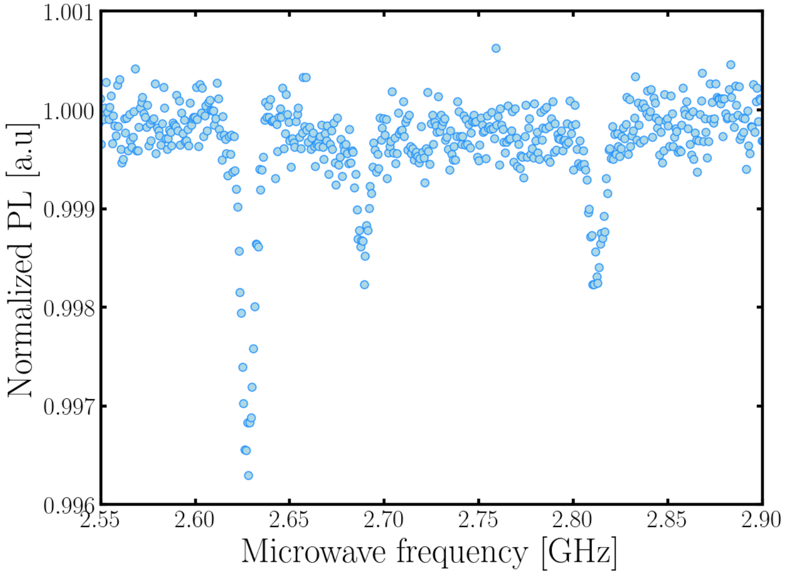
We can change the stroboscopic delay.

Stroboscopic ODMR sequences

Evolution of the NV centers magnetic resonances as a function of time.



- **Experimental Results**

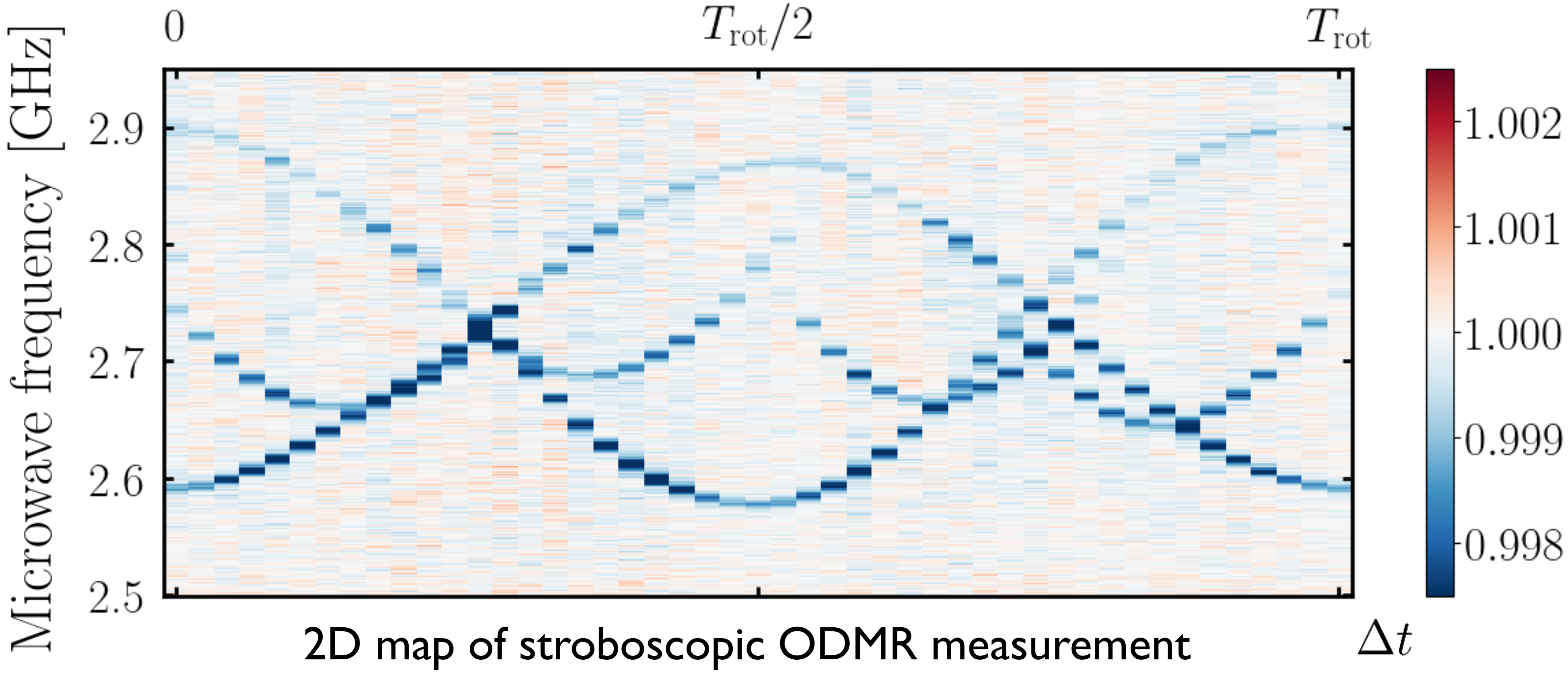


Stroboscopic ODMR measurement
with a rotating diamond.

Δt : stroboscopic delay

We can change the stroboscopic delay.

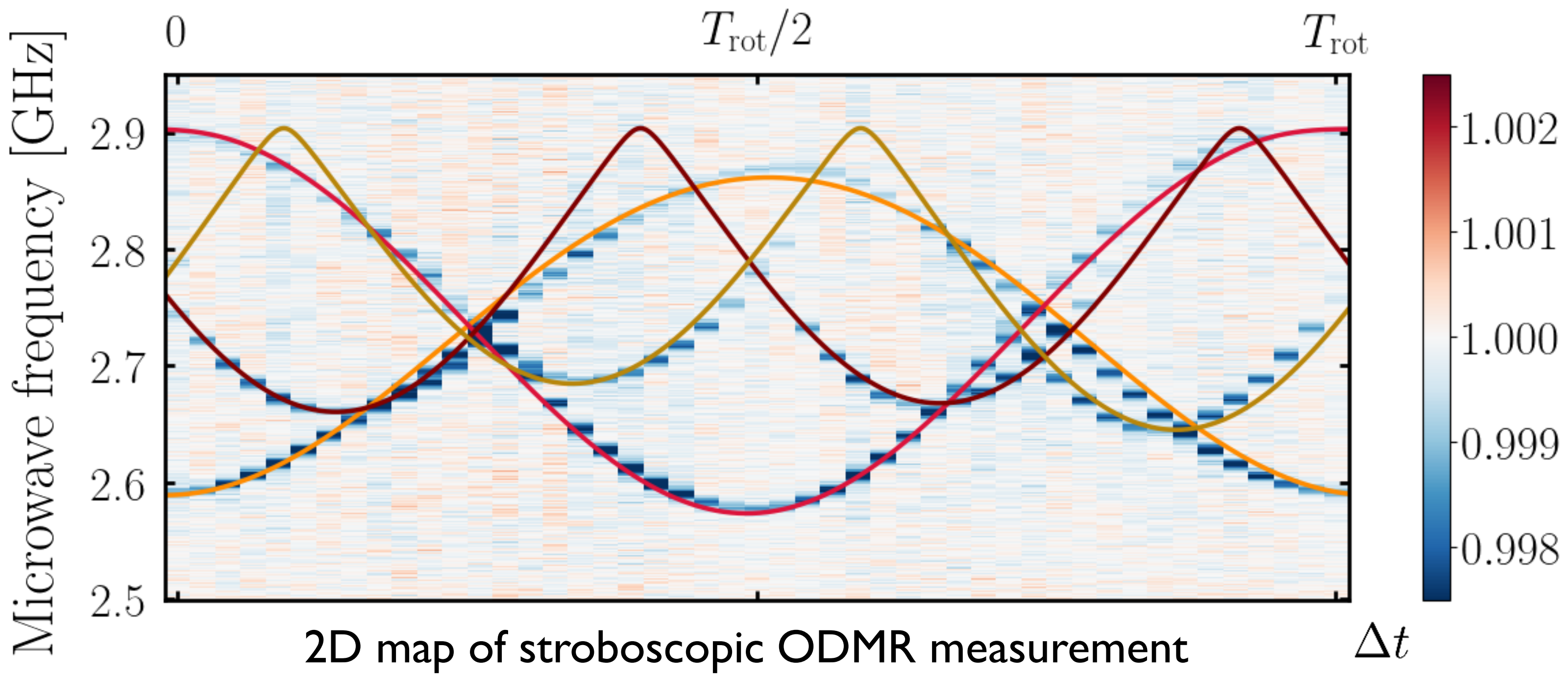
Angular trajectory reconstruction



2D map of stroboscopic ODMR measurement as a function of the delay.

- **Experimental Results**
  - Scan of the stroboscopic delay.
  - 50 different values of the delay.
  - Four hours of acquisition.

Angular trajectory reconstruction



2D map of stroboscopic ODMR measurement as a function of the delay.

- **Experimental Results**
  - Scan of the stroboscopic delay.
  - 50 different values of the delay.
  - Four hours of acquisition.

- **Fit with a rotation motion**
  - Almost perfect fit with a 1D rotation.
  - Only a shift of few angular degrees after 1 billion turns.

→ **Extremely stable 1D rotation.**

Perspectives with rotating magnetic particles in Paul traps

- **Advantages & drawbacks**

  - Slow rotation (~kHz)
  - No need for high power laser.
  - Demonstration of spin state control.
  - 3D angular confinement in the rotating frame.
  - Works for every charged particles with a quadrupol moment (diamonds, ferromagnets, silica microrods)
  - Extremely stable rotation.

- **Prospects**

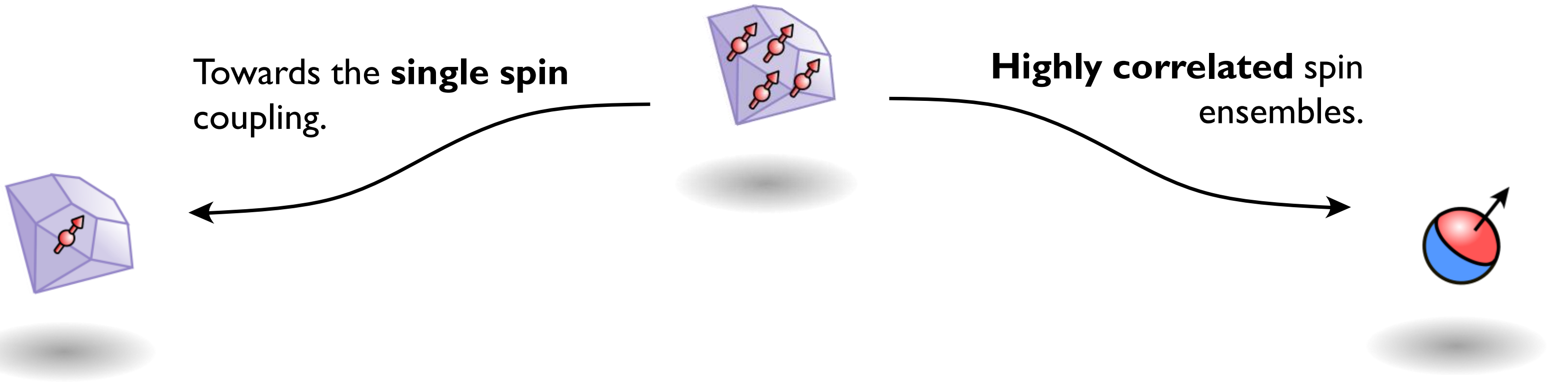
  - Spin-mechanics with gyroscopic modes in the rotating frame.
  - Observation of gyromagnetic effects.
  - Observation of the geometric quantum phase.

Conclusion

Key points

- NV centers in diamond are a powerful system to **read out** and **control** the angular motion.
- Paul traps give a stable and non invasive way to **fastly rotate levitated magnetic particles**.
- The interplay between magnetism and rotational degrees of freedom at the micro-scale offer a **rich playground**.

Perspectives



Towards the **single spin** coupling.

Highly correlated spin ensembles.

Macroscopic quantum superposition [1]

- Quantum precession [2]
- Quantum levitation [3]

[1] C.C. Rusconi et al. PRL (2022), T. Delord et al., PRA (2016), [2] D. F. J. Kimball et al., PRL (2016), [3] C.C. Rusconi et al. PRL (2017)

Team

Nano-optics group at LPENS

- **The diamond team:**

Team leader	**Postdocs**	**PhD student**
Gabriel Hétet	Alrik Durant Maxime Perdriat	Julien Voisin

Former students: Paul Huillery, Tom Delord, Clément Pellet-Mary, Louis Nicolas.

- **Collaborations:**

Experimental:

Diamond: Alexandre Tallaire, Vianney Mille, Jocelyn Achard (Paris XIII, Chimie Paris), **hBN**: Vincent Jacques, Guillaume Cassabois (L2C, Montpellier), **Rare earths**: Philippe Goldner, Alban Ferrier (IRCP), **YIG**: Jamal Ben Youssef (Univ. Brest), Grégoire de Loubens (CEA).

Theory:

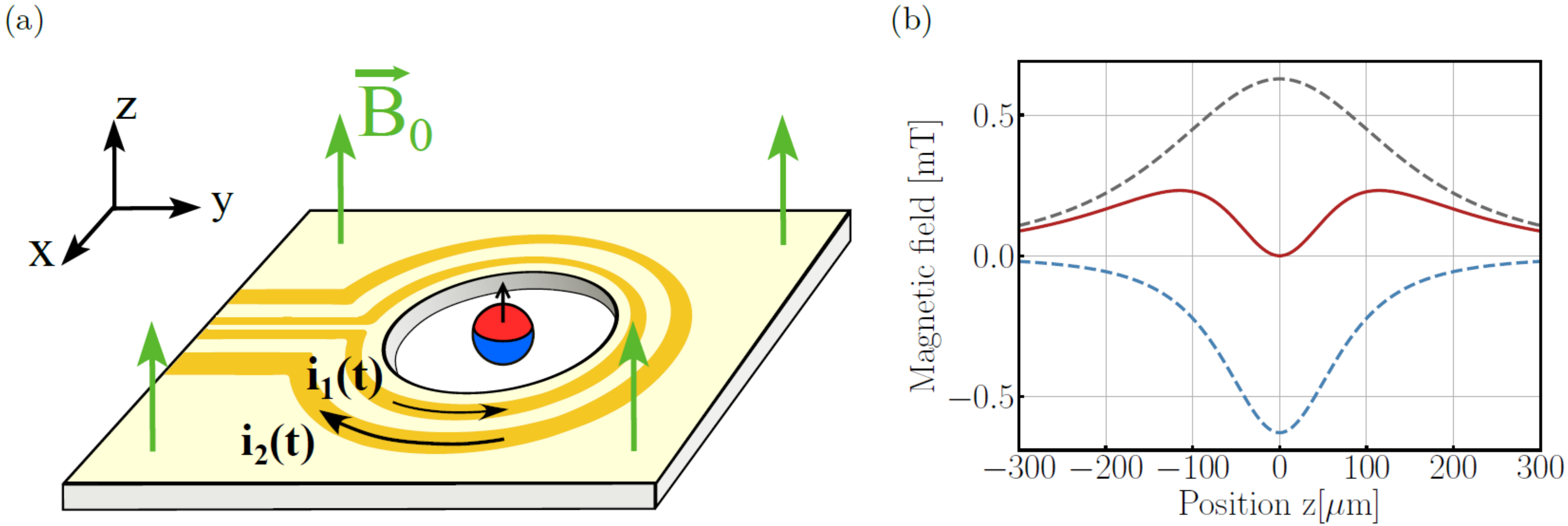
Cosimo Rusconi (Columbia University), Ben Stickler (Univ. Duisburg-Essen), Oriol Romero-Isart (IQOQI Innsbruck).

Lemaqume: ***Observe the precession of a trapped magnet***

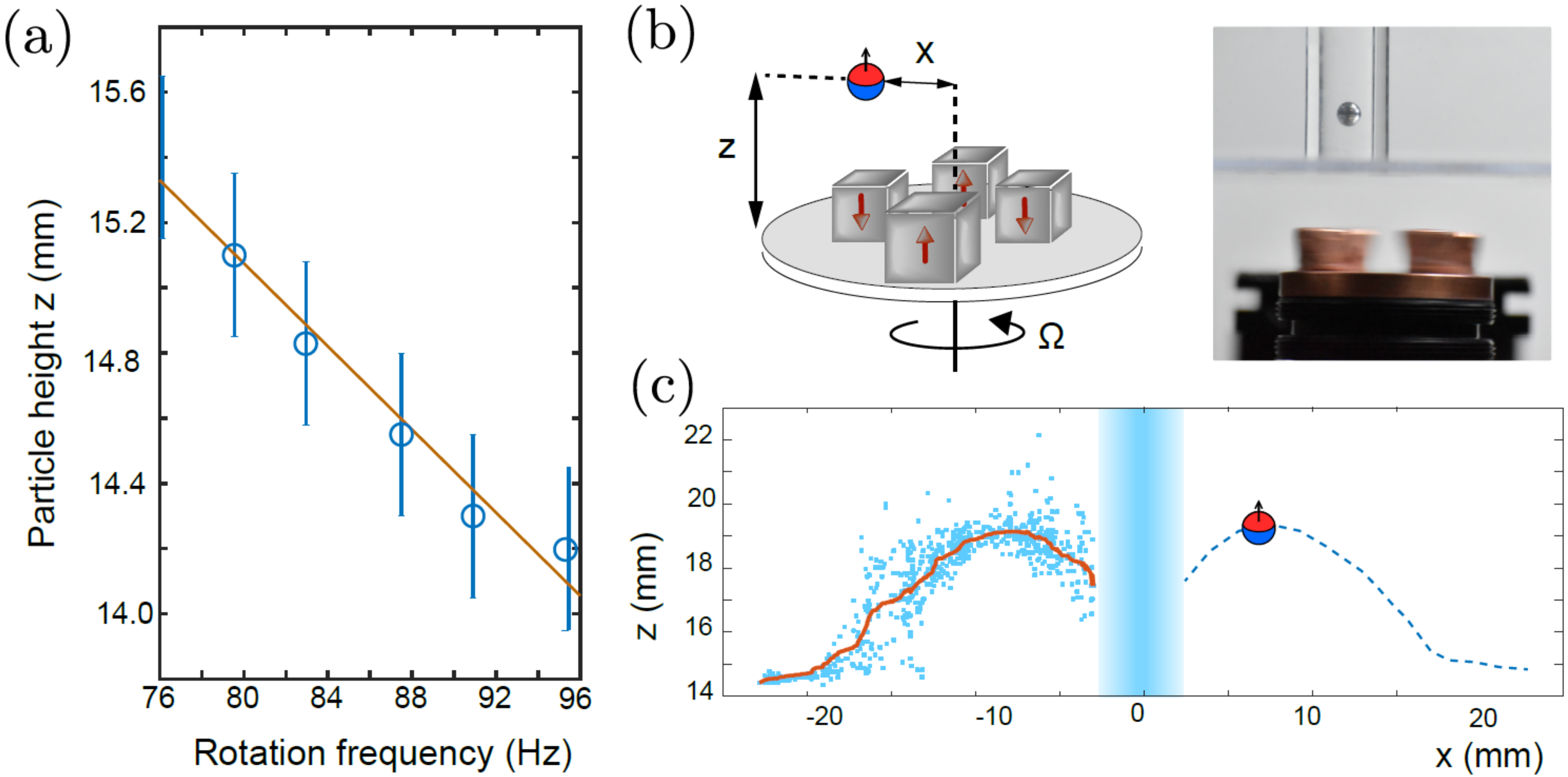
A. Vinante (Trento), M. Plenio (Ulm), D. Budker (Mainz), R. Folman (Ben-Gurion), H. Ulbricht (Southampton).

Thank you!

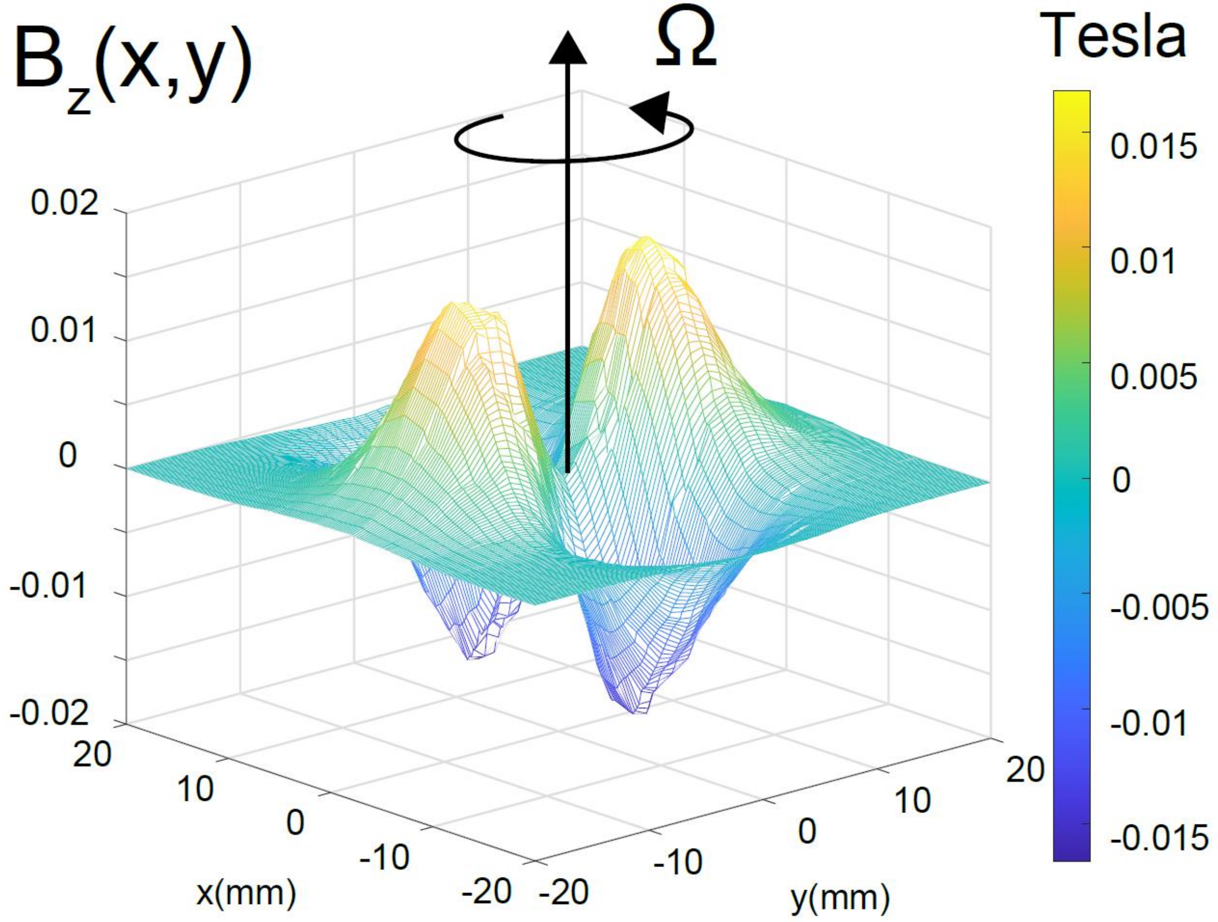
Magnetic Paul trap



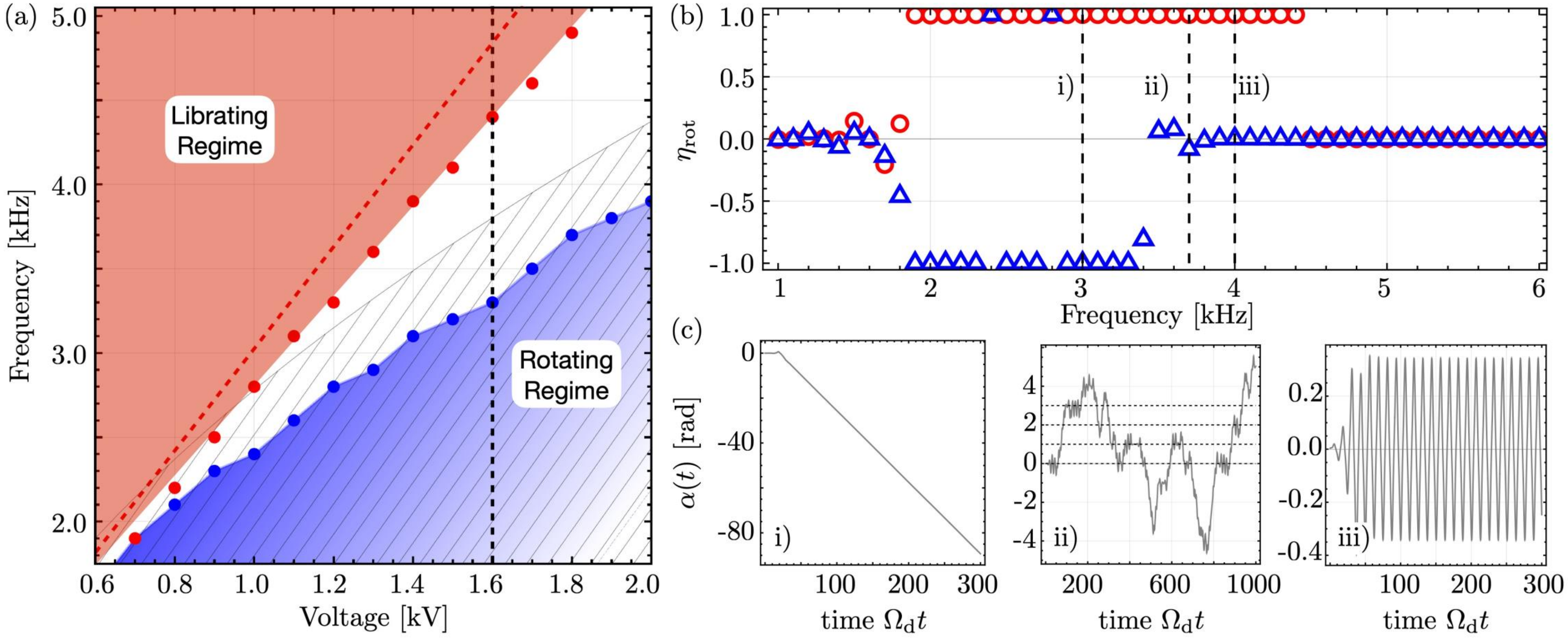
Magnetic Paul trap



Magnetic Paul trap



Stability diagram of the angular dynamics



[1] M. Perdriat, et al., *in preparation* (2023) (Collaborators: Cosimo Rusconi & Ben Stickler)

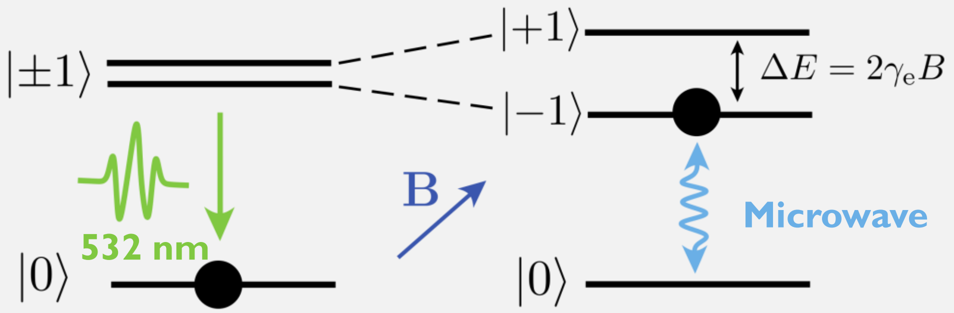
To do list

Spin nucléaire
Insister sur les théoriciens dans le travail du locking
Numérotation des pages
Slides en plus
Magnetic paul trap en bonus si le temps
Apres le microwave free, parler du papier de cosimo et dire que ben va en parler
Prospects à la fin des parties

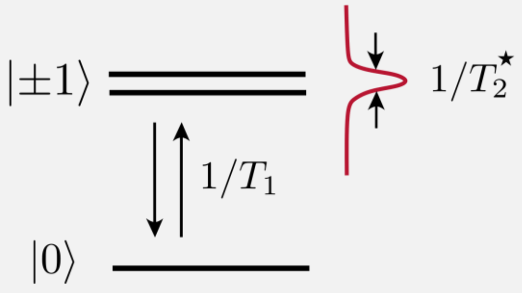
The NV$^-$ center in diamond: a tunable spin qubit

- **A highly controlable spin triplet at room temperature**

- **Optical pumping with a green laser in the |0> state**



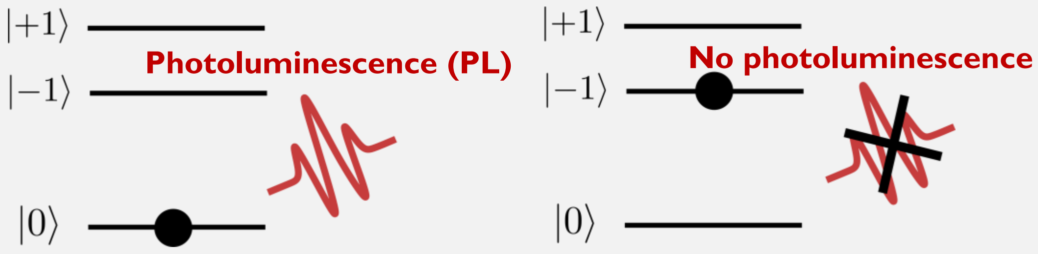
- **Exceptional life time and coherence time**



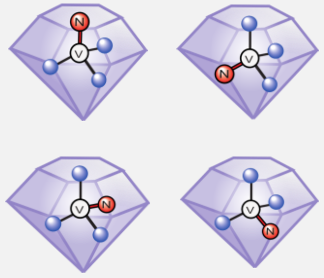
Spin lifetime: $T_1 \sim 1$ ms
limited by the phonon bath coupling

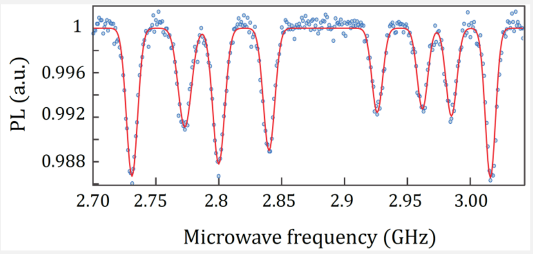
Spin coherence time: $T_2^* \sim 1\ \mu s$
limited by magnetic fluctuations

- **Optical read-out of the spin state**



- **ODMR with NV center ensemble**



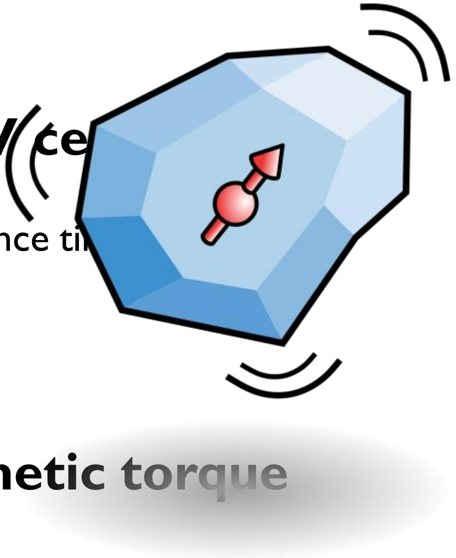


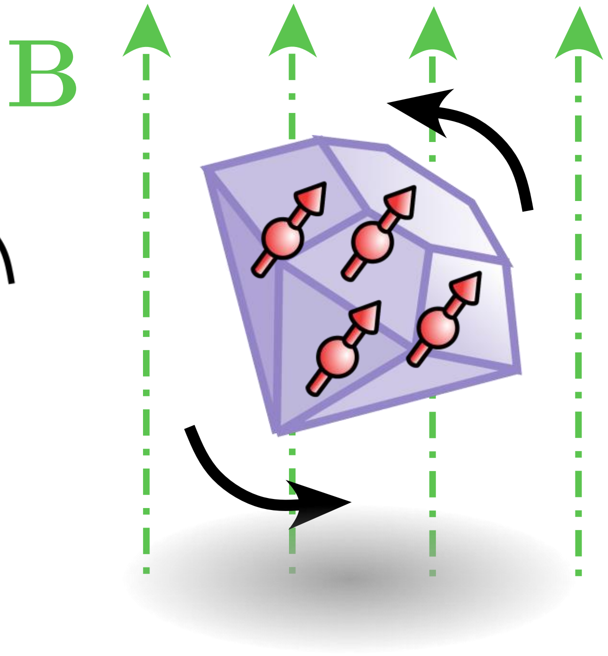
2 resonances X 4 classes = 8 resonances

[1] A. Dréau, PhD thesis (2013)

Our research interests

- **Angularly stable diamond**
  - 10-20 micron size diamond
  - Levitated in a Paul trap
  - Libration frequencies: ~100Hz-1kHz
- **Spin degree of freedom: the NV ce**
  - Long spin life time: 1 ms & long coherence ti
  - Easily tunable
  - NV centers ensemble: $N=10^9$
- **Coupling mechanism: the magnetic torque**
  - Spin anisotropy
  - Homogeneous magnetic field





Spin-mechanics with NV centers in levitating diamonds [2]

[1] C. Pellet-Mary, et al., arXiv (2022), [2] M. Perdriat, et al., MDPI (2021)