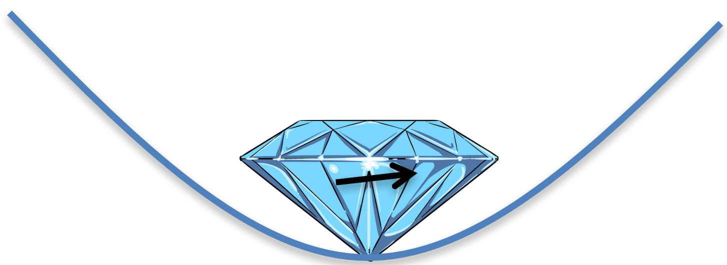
Quantum Optics with Levitating Diamonds

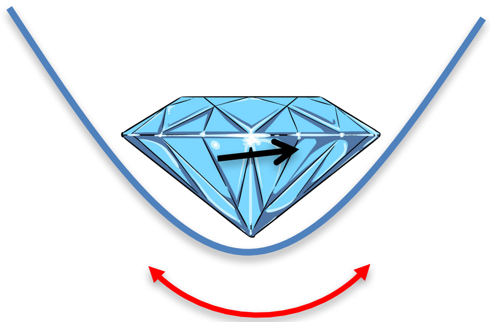
Gabriel Hétet



Laboratoire
Pierre Aigrain

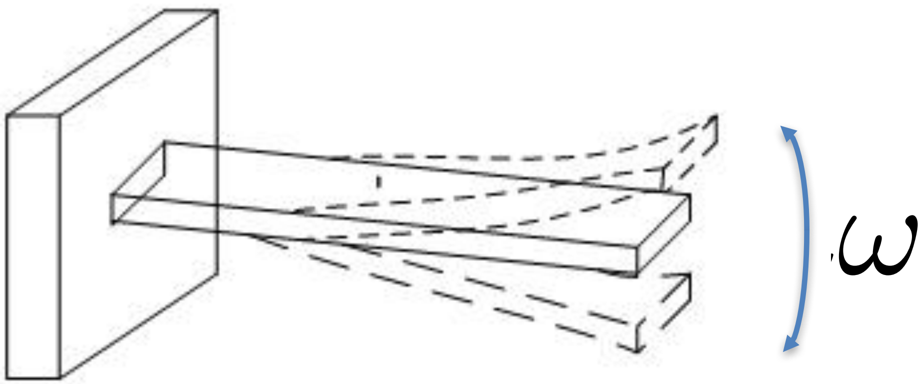
Outline

- Quantum optics with levitating macroscopic particles
- Coupling a single electron spin to the motion of levitating particle
- NV centers in Diamonds
- Towards quantum optical experiments with levitating diamonds



Quantum optics with macroscopic oscillators

Millions of atoms



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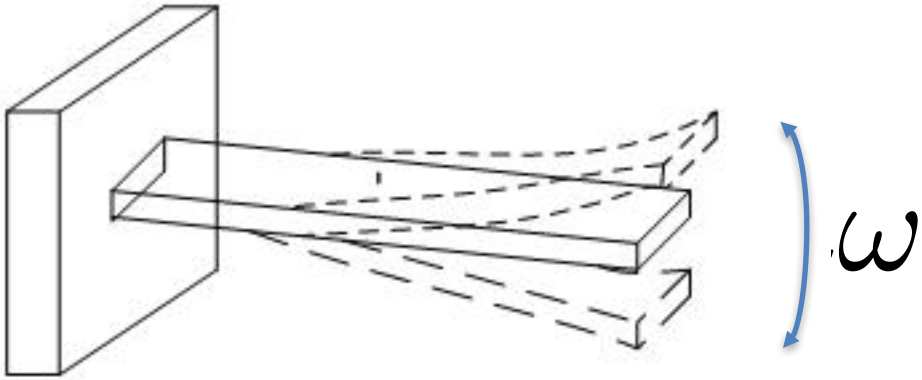

$$\hat{H} = \frac{\hat{p_x}^2}{2m} + \frac{1}{2} m\omega^2 \hat{x}^2$$

1D quantum harmonic oscillator

Quantum optics with macroscopic oscillators

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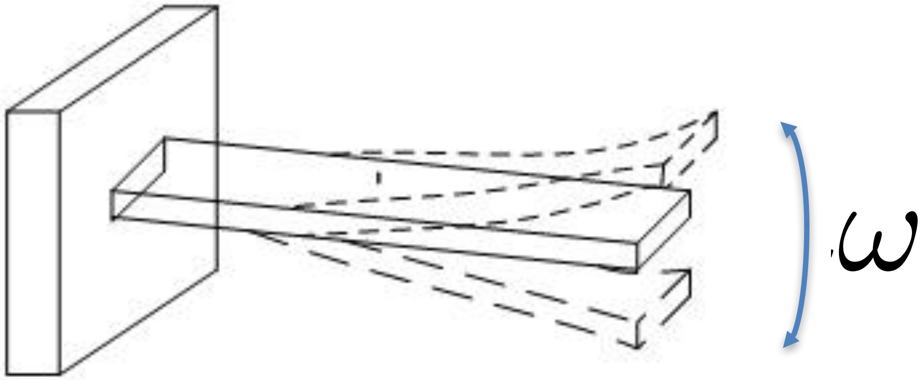

Number of phonons

$$\hat{H} = \frac{\hat{p_x}^2}{2m} + \frac{1}{2}m\omega^2\hat{x}^2 \longrightarrow \hat{H} = \hbar\omega(\hat{a}^\dagger\hat{a} + \frac{1}{2})$$

1D quantum harmonic oscillator

$$\begin{cases} \hat{x} = \sqrt{\frac{\hbar}{2m\omega}}(\hat{a} + \hat{a}^\dagger) \\ \hat{p_x} = -i\sqrt{\frac{\hbar}{2m\omega}}(\hat{a} - \hat{a}^\dagger) \end{cases}$$

$$[\hat{a}, \hat{a}^\dagger] = 1$$

Introducing ladder operators satisfying bosonic commutation relations

Quantum optics with macroscopic oscillators

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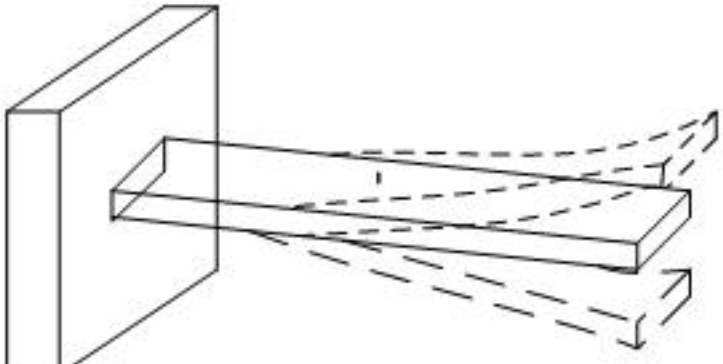
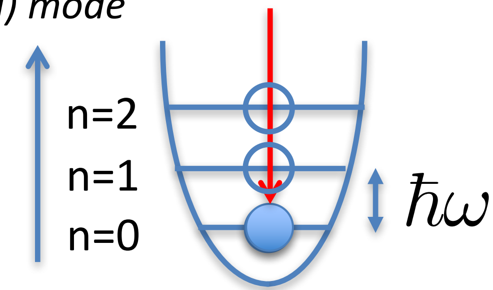


Energy in the centre of mass (COM) mode



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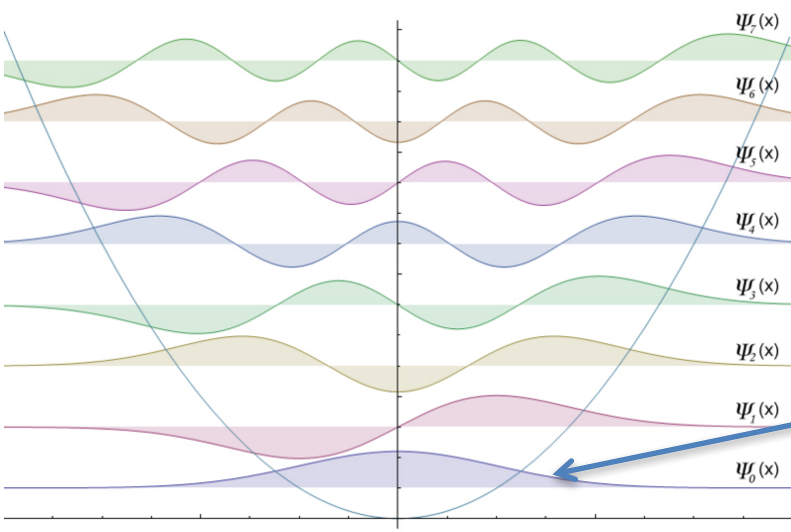

$$\sqrt{\langle\hat{x}^2\rangle} = \sqrt{\frac{\hbar}{2m\omega}}$$

Quantum optics with macroscopic oscillators

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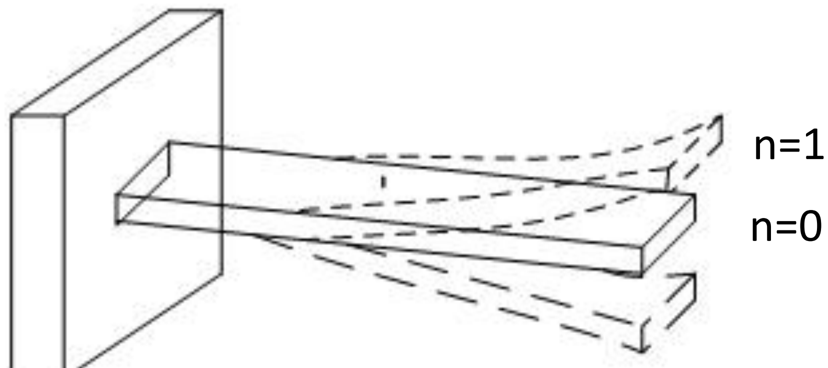

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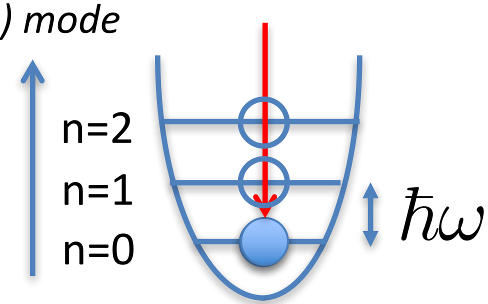

Ground state cooling of a mechanical oscillator

A. D. O'Connell et al. ***Nature*** ***464****, 697-703 (2010)…*

Quantum optics with macroscopic oscillators

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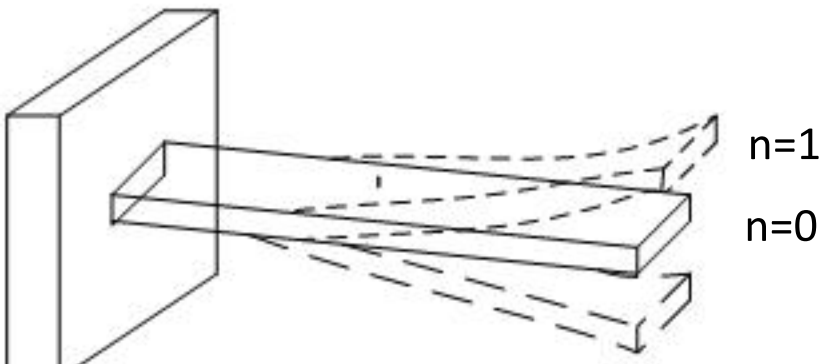

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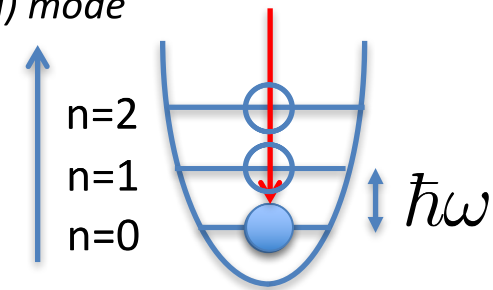

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Offers the prospect of creating
macroscopic quantum superpositions of the form :

$$|\psi\rangle = \frac{|n=0\rangle + |n=1\rangle}{\sqrt{2}}$$

if $kT_{c.m.} \ll \hbar\omega$

Quantum optics with macroscopic oscillators

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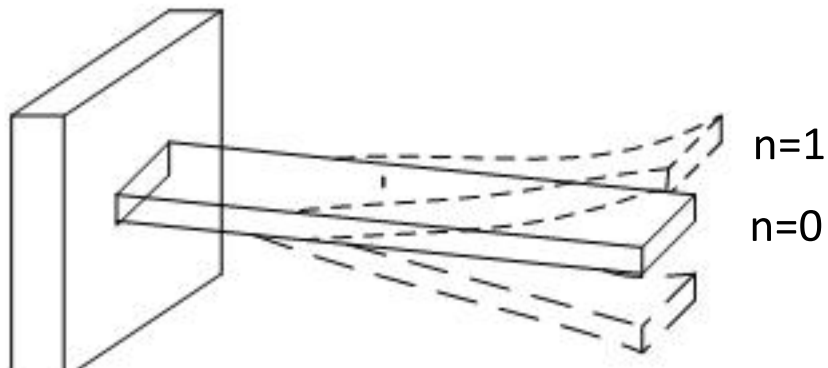

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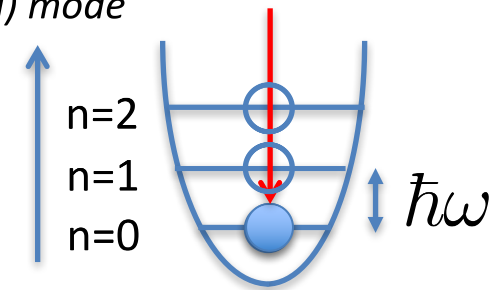

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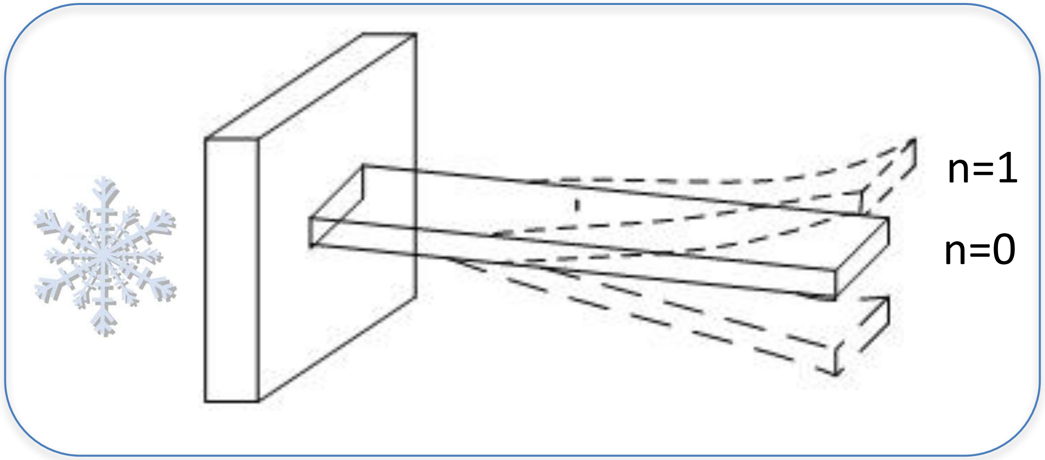
Motivation :

- New lights on the classical-quantum boundary
- Quantum sensing and information

Quantum optics with macroscopic oscillators



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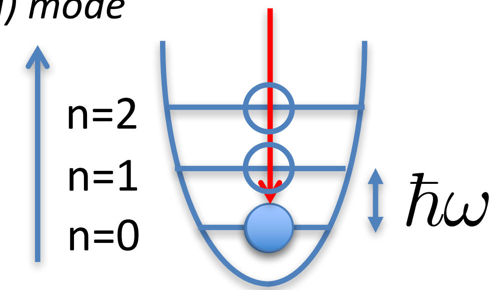

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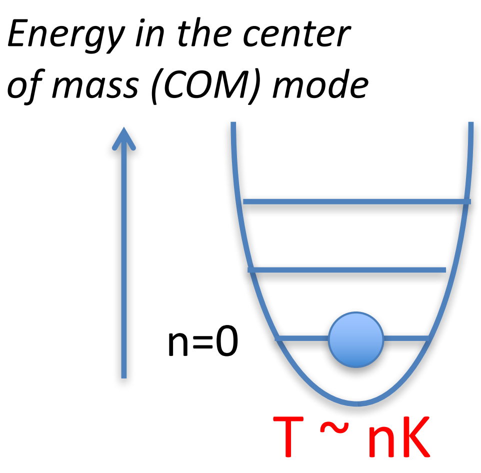
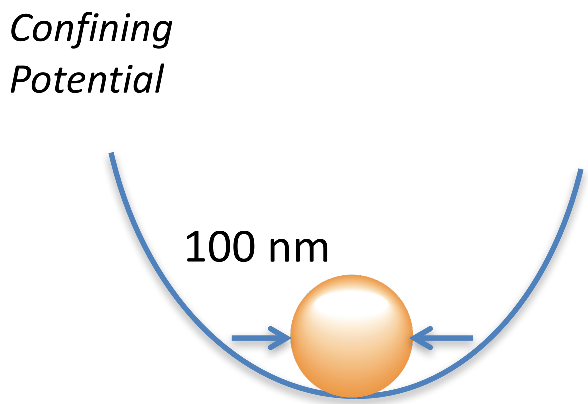
Ultra cold levitating macroscopic objects





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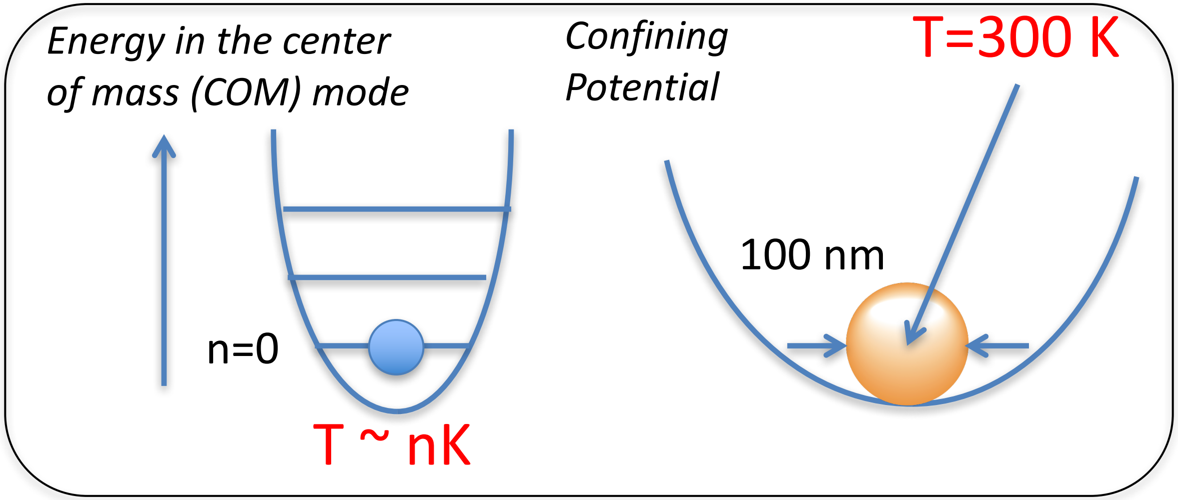

- No need to cool the particles themselves (mandatory with clamped oscillators).
- Ground state extension of the COM ~ picometer.

*Ashkin A, **APL** (1976)*
*Chang D. et al. **PNAS** (2010)*

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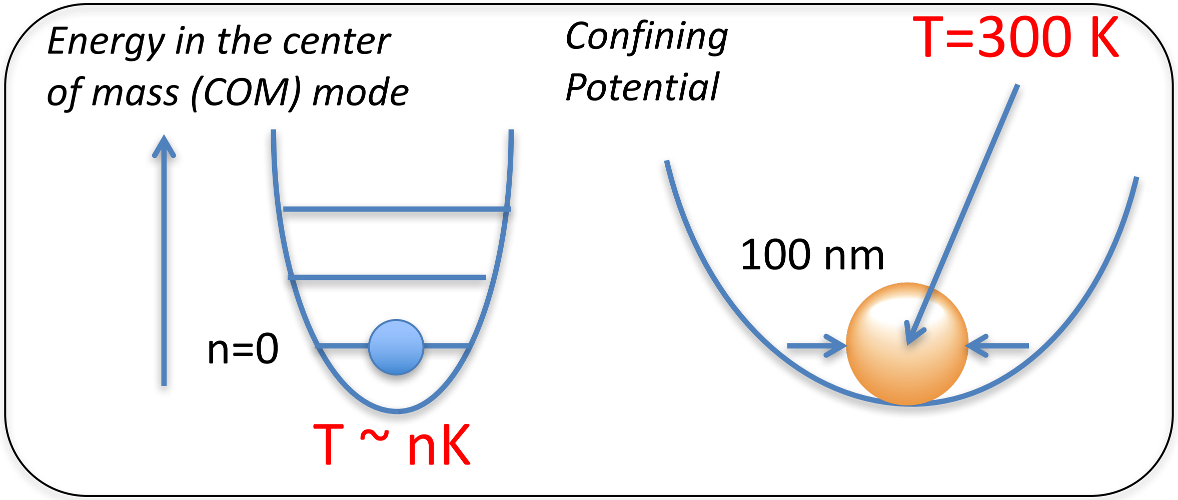

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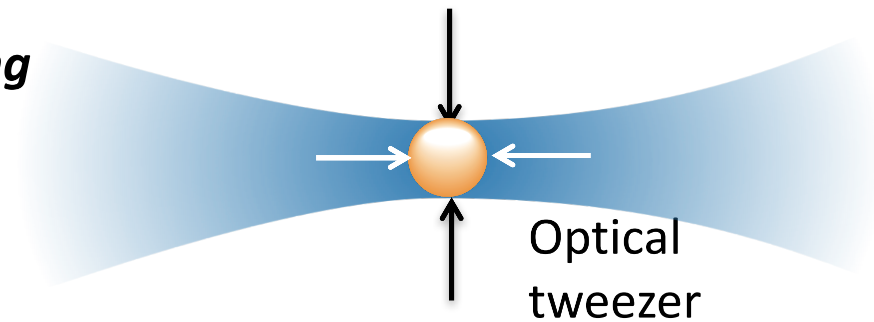
State of the art method : *Optical trapping*
The trapped object seeks high intensities (typically 300 mW of laser power with a 1 micron beam waist).



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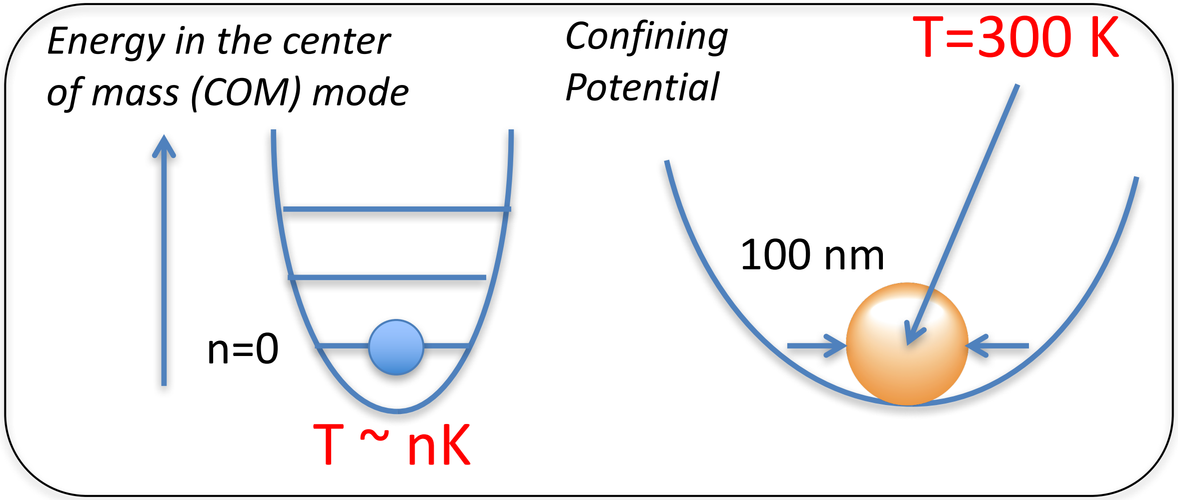

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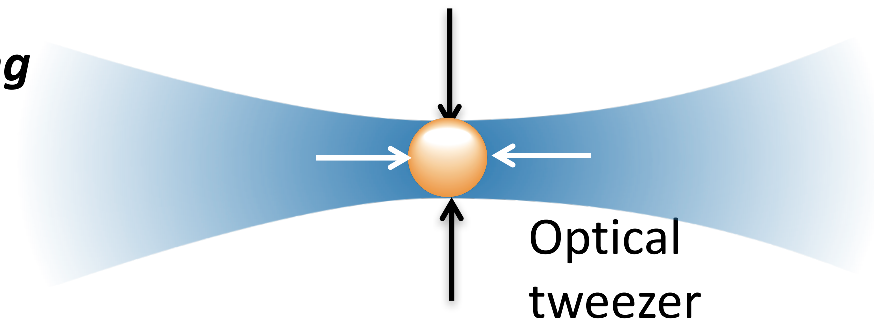
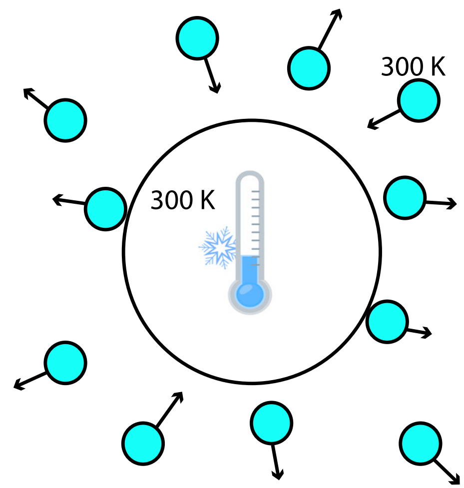


Problem: The laser light can hit up the particle and/or make it unstable

*L. P. Neukirch, **Nat. Phot**. (2016)*
*A. Rahman, **Scientific Reports** (2016)*

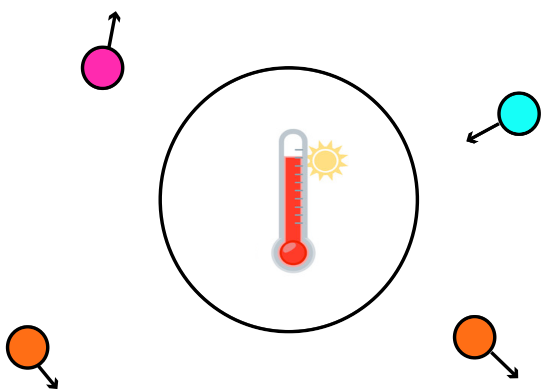
Ultra cold levitating macroscopic objects



Atmospheric pressure

Thermalisation :

$T_{gaz} = T_{particle}$



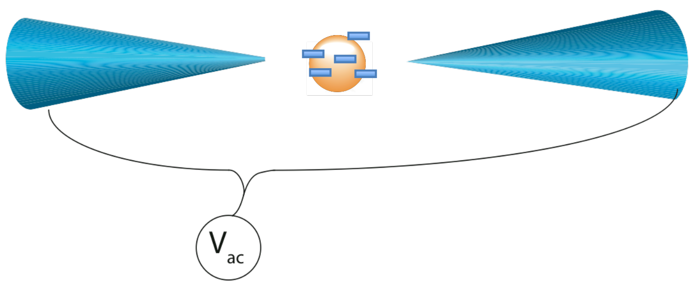
High vacuum

Out of equilibrium :

The particle
can warm up significantly

Scattering free trapping

The Paul trap



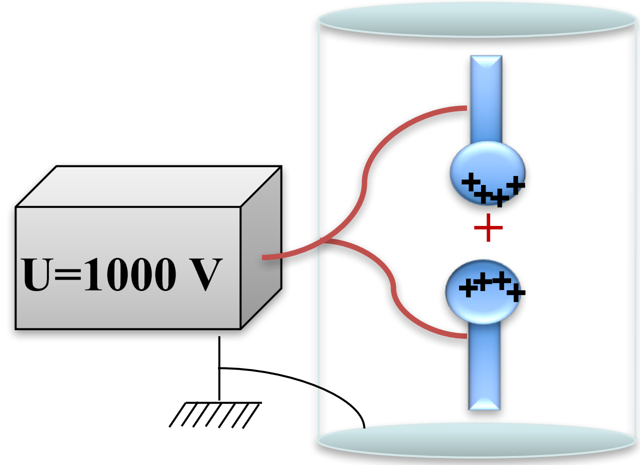
Charged trapped particle
in an electrodynamical potential

- No laser light
- Large potential depth
  → stays in the trap for days
- Single ion experiments showed
  control of the motion
  at the quantum level

A. Kulicke et al. ***APL*** *(2014)*
J. Millen, et al. ***PRL*** *(2015)*

How to trap a charged particle ?

Static Coulomb force :



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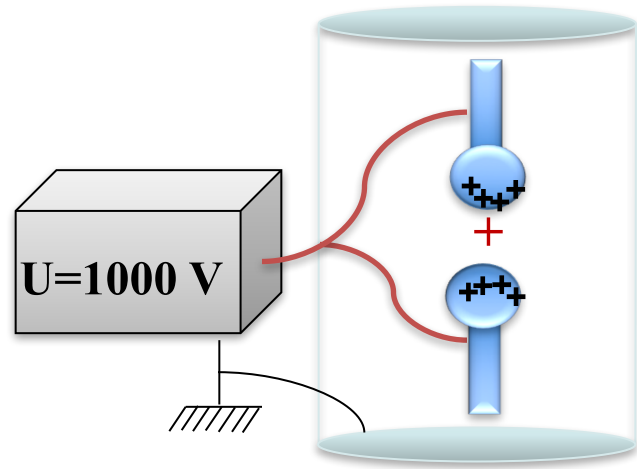
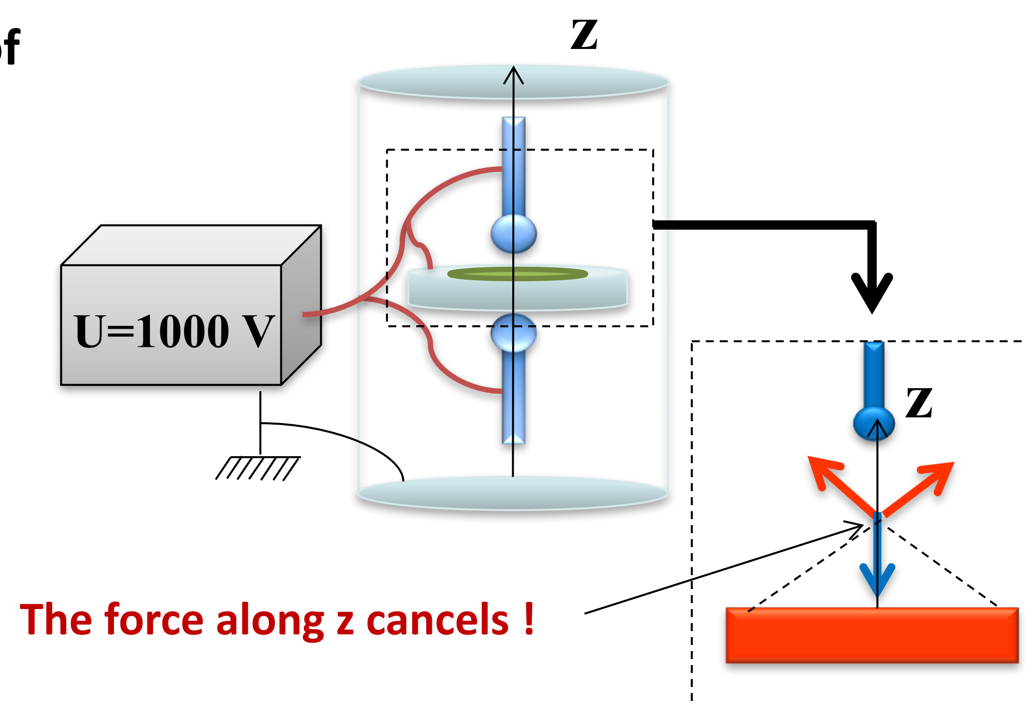


Restoring force in the 3 directions of space :

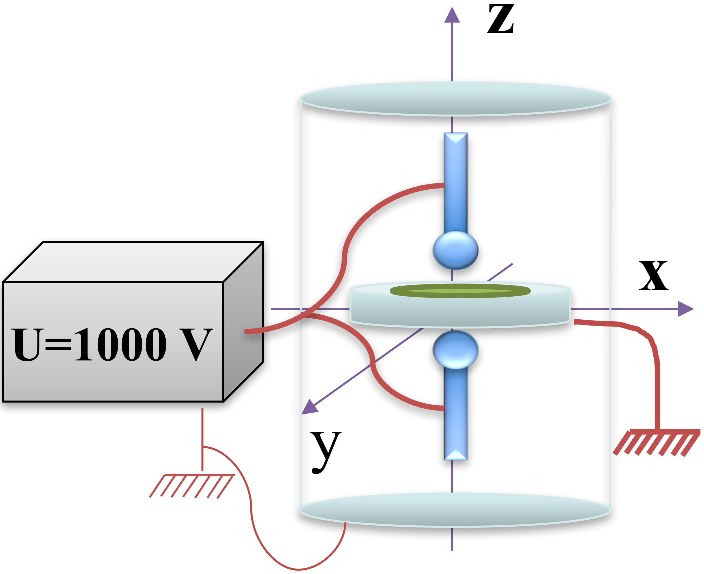
Confinement
along the ring plane.

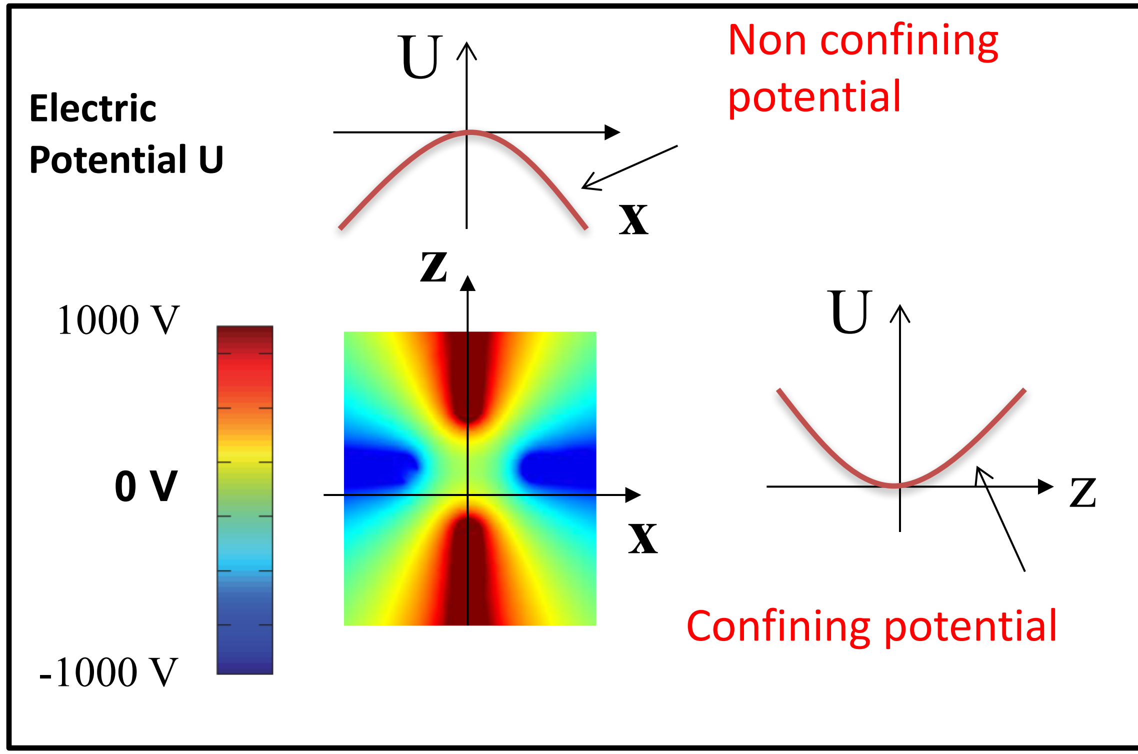
But no confinement
along the z direction
anymore :(



How to trap a charged particle ?

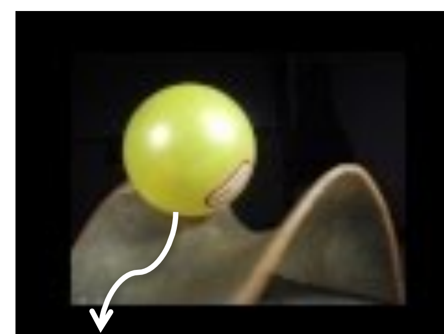
Other possibility :





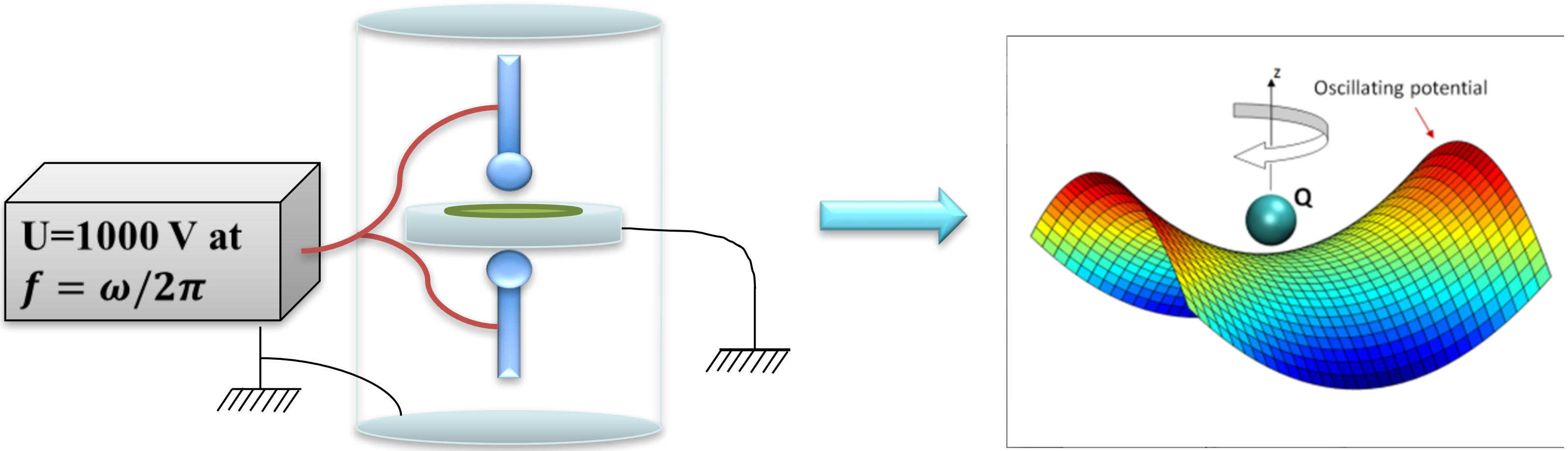
In electrostatics, whatever the geometry, at least one direction will not be confining!

Consequence of the conservation of the electric flux on a closed surface → $\oiint \vec{E} \cdot \vec{dS} = 0$



How to trap a charged particle ?

In electro-statics, one cannot confine a charged particle.
Idea : make the electric field oscillate.



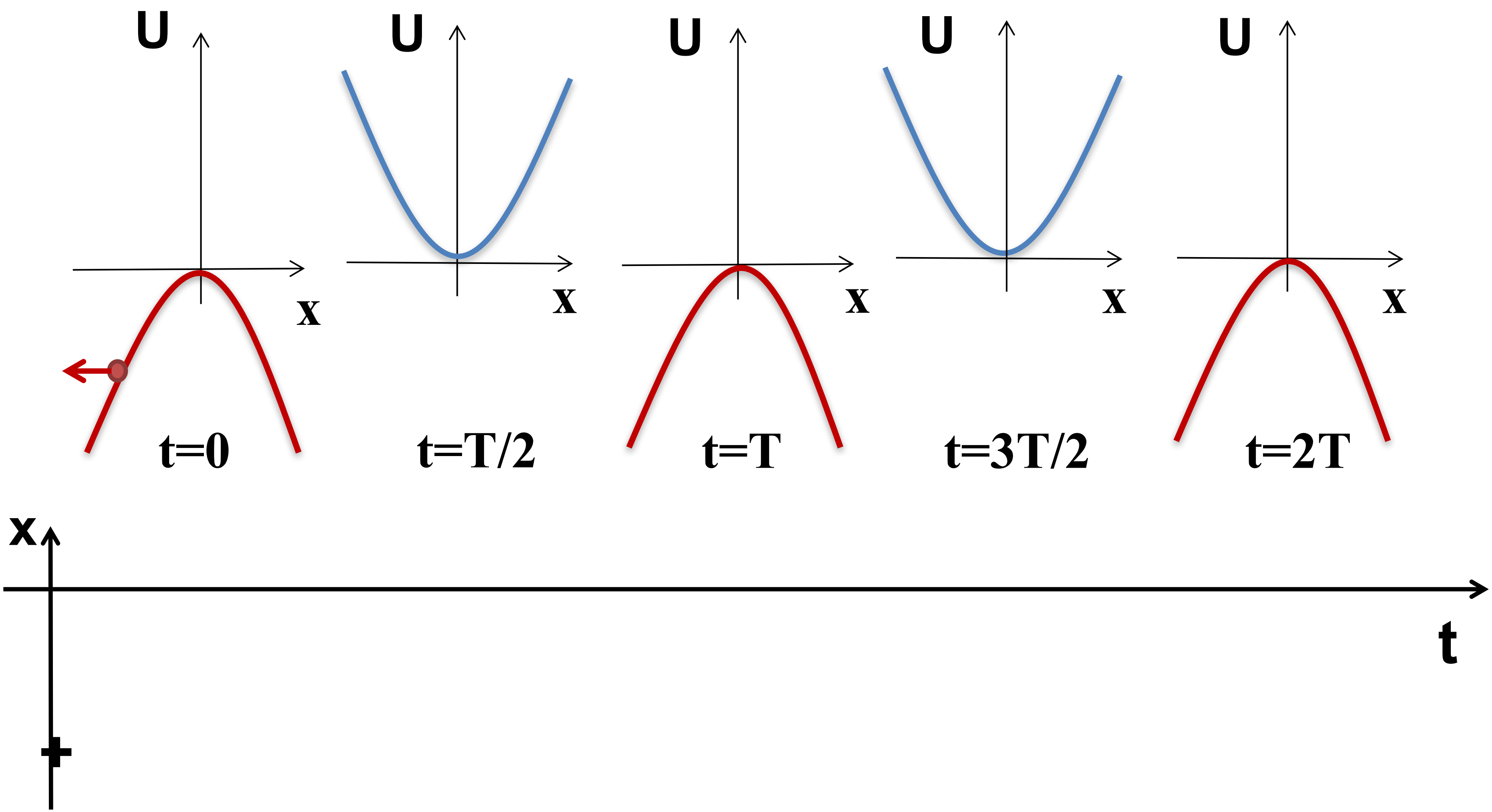
One can feel that the electric field has to oscillate more rapidly than the period $T_s = 2\pi/\omega_0$ in statics.

However, a priori, one cannot see why the force that brings the particle towards the center would compensate the force that pushes it away from it

How to trap a charged particle ?

$F = -kx\ \cos(\omega t)$ where k depends on the tension applied to the electrode.

During one cycle of oscillation with a period $T = \frac{2\pi}{\omega} \ll T_s = \sqrt{\frac{m}{k}}$



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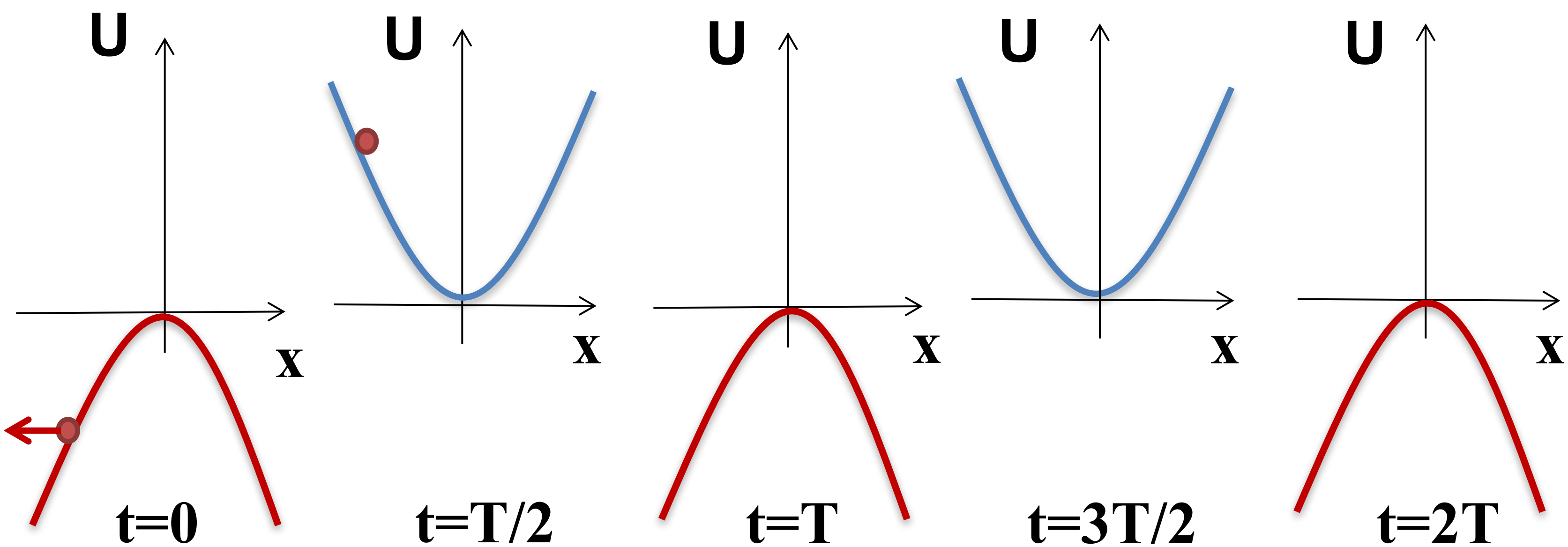

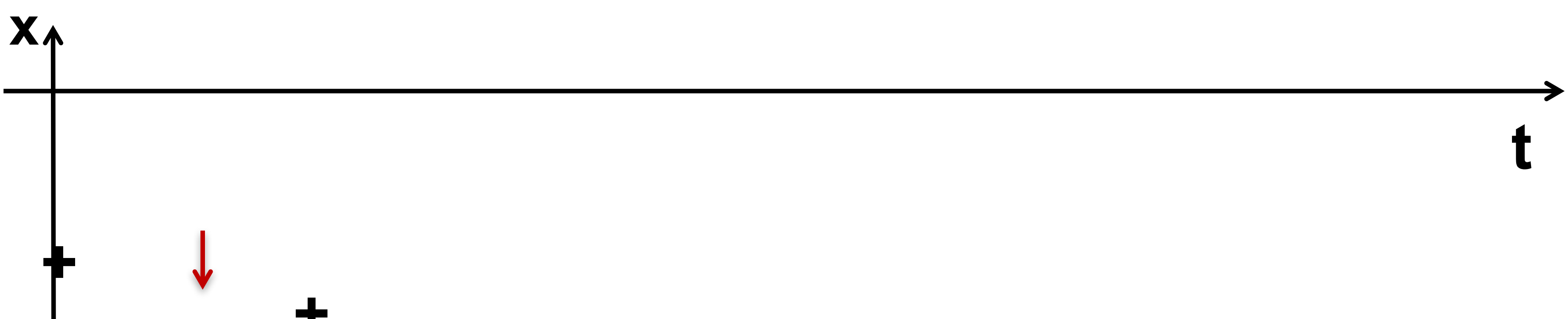

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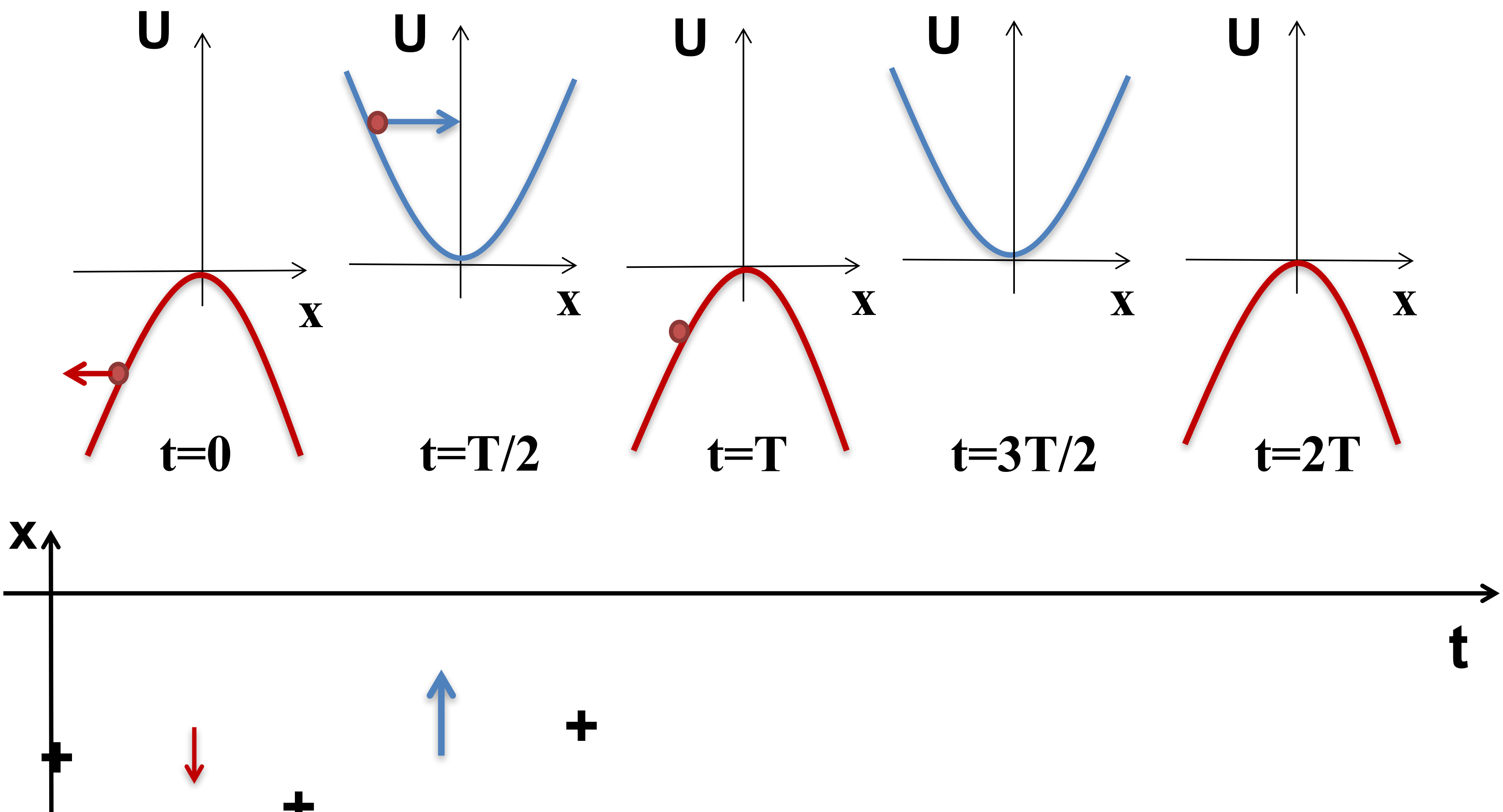

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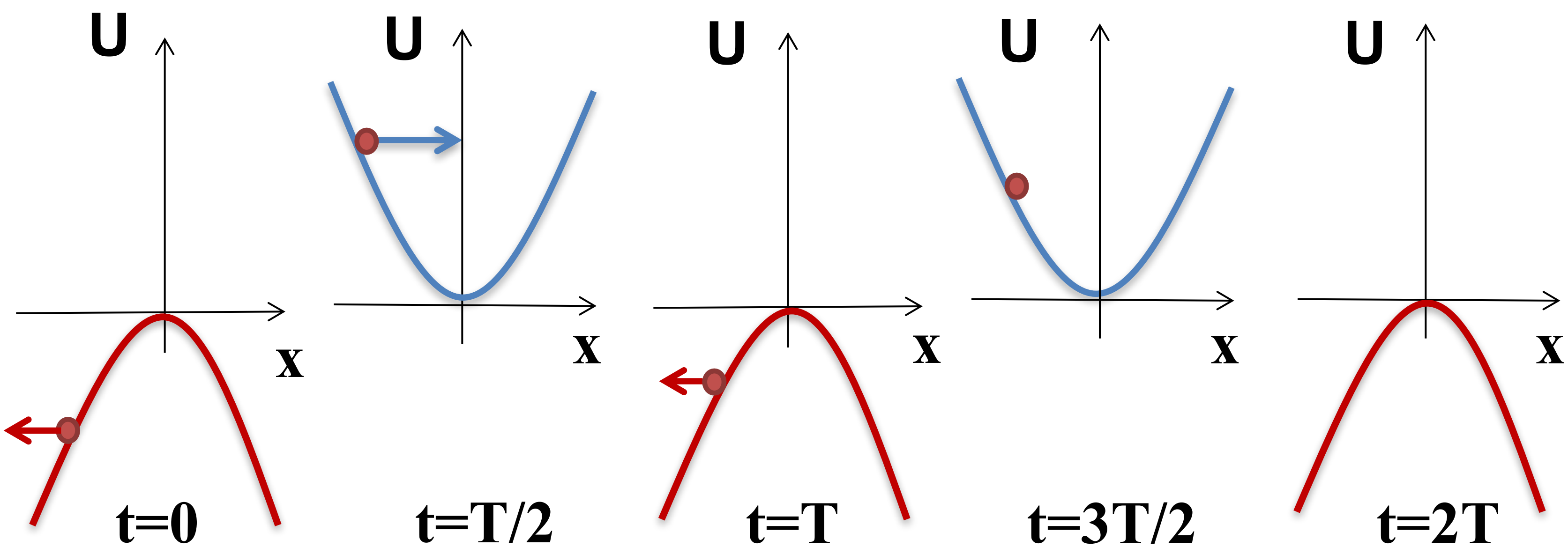

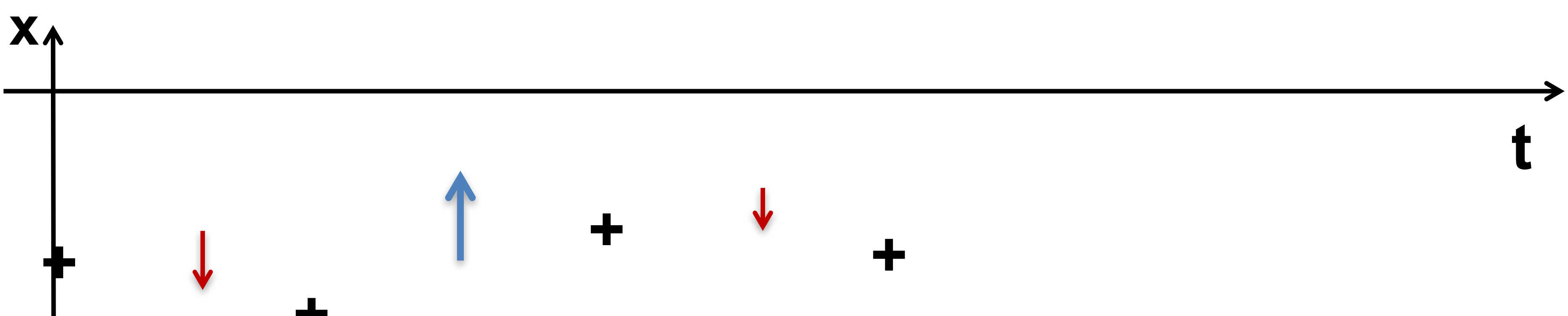

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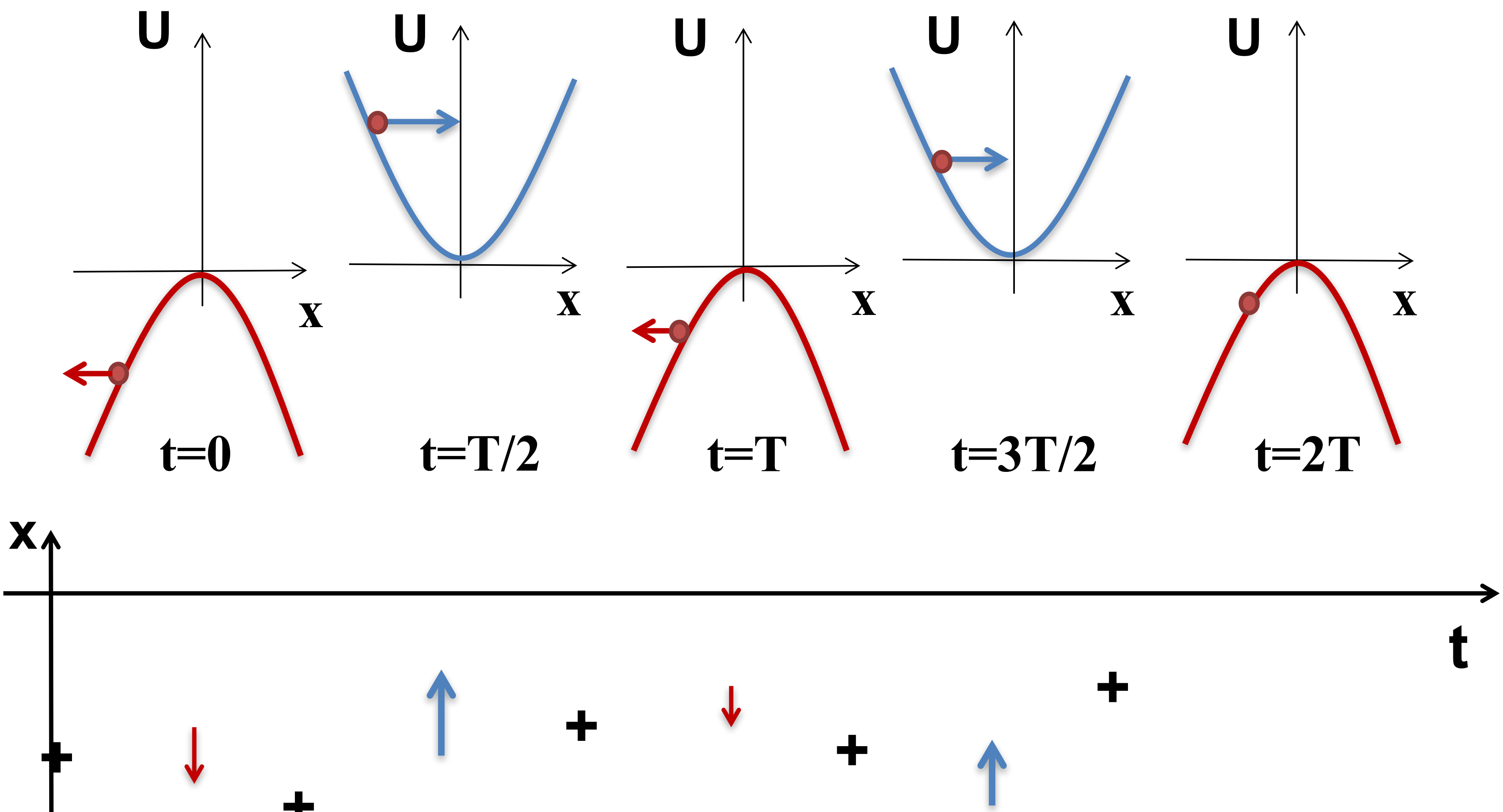

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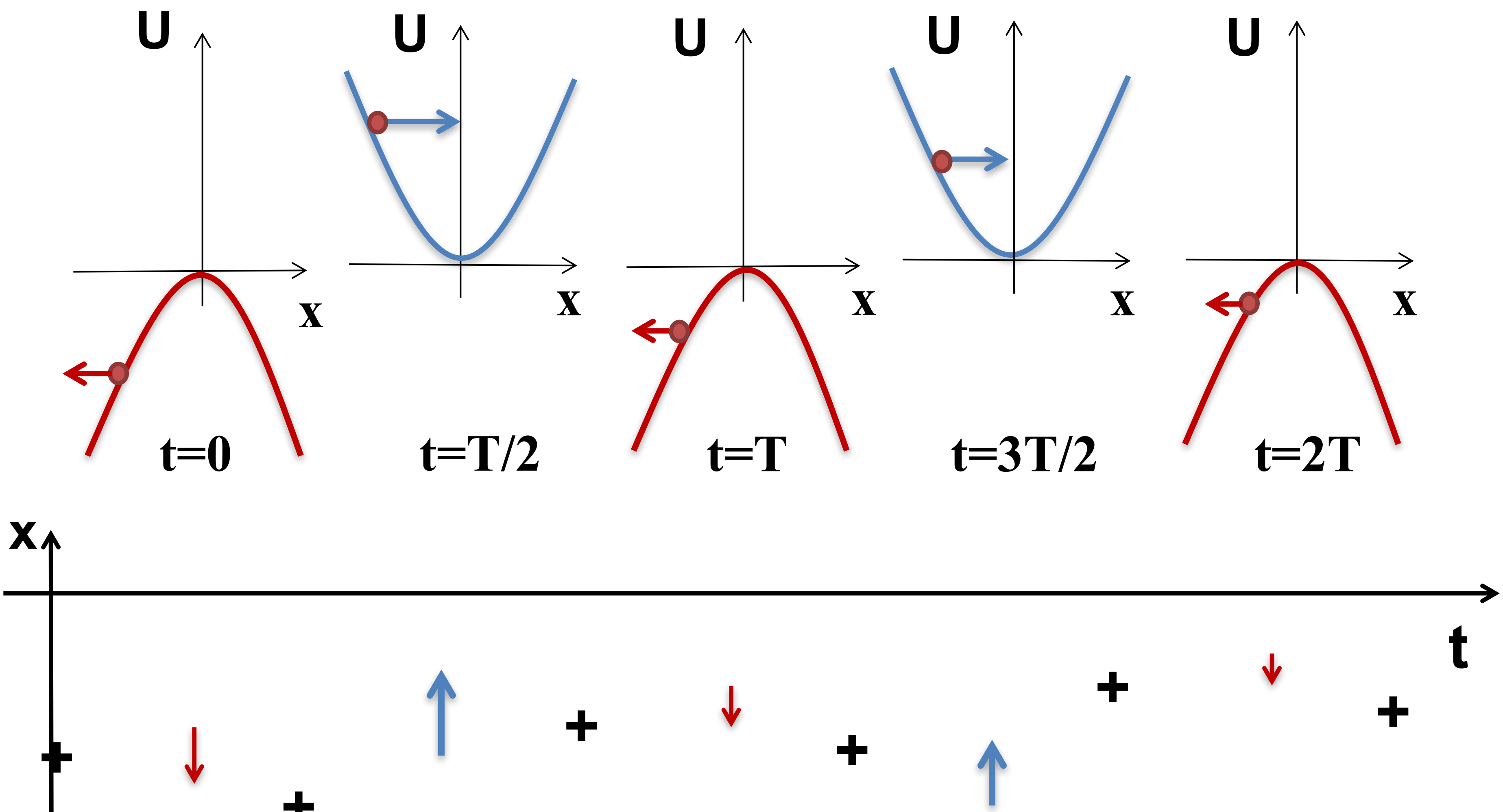

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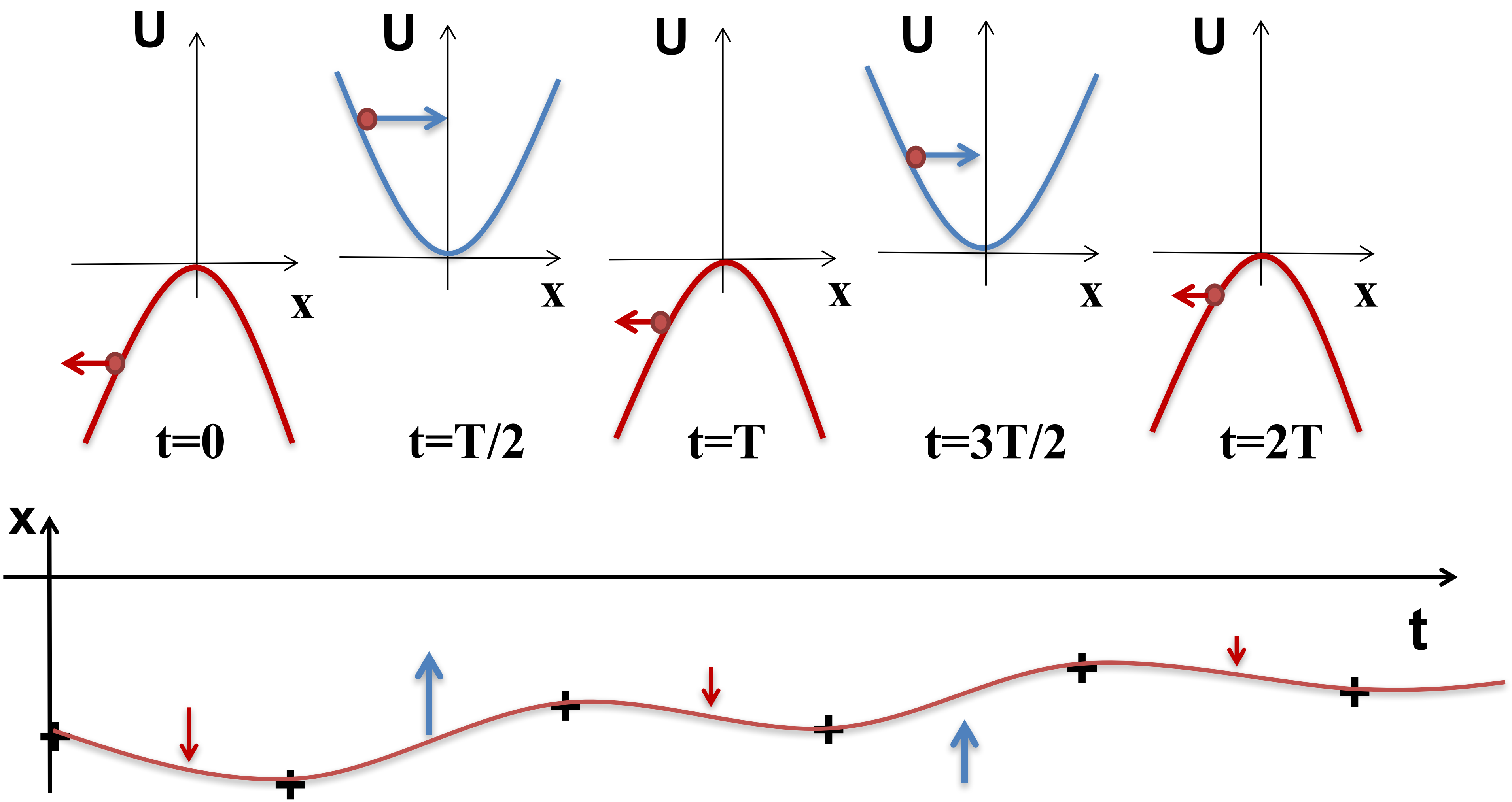
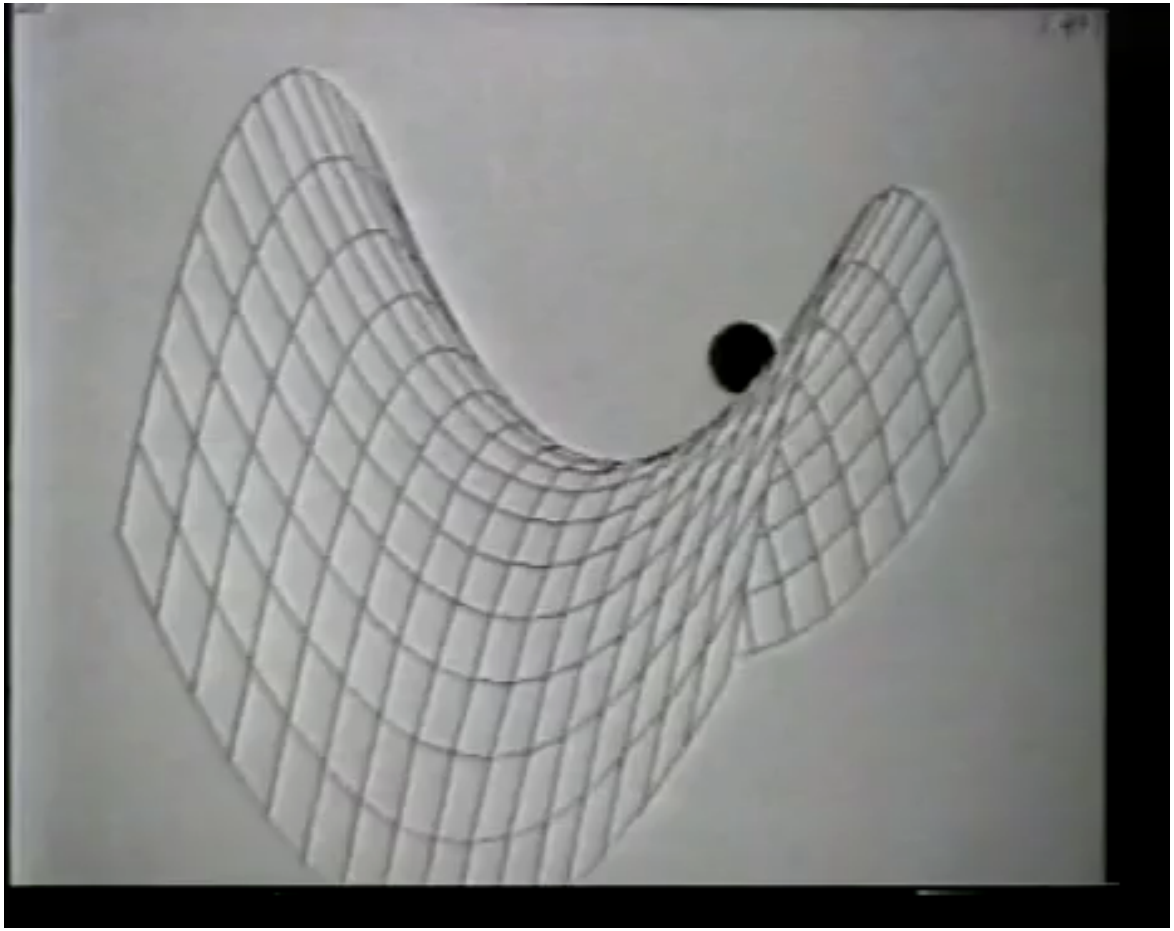


Little by little, the particle gets closer to the center…

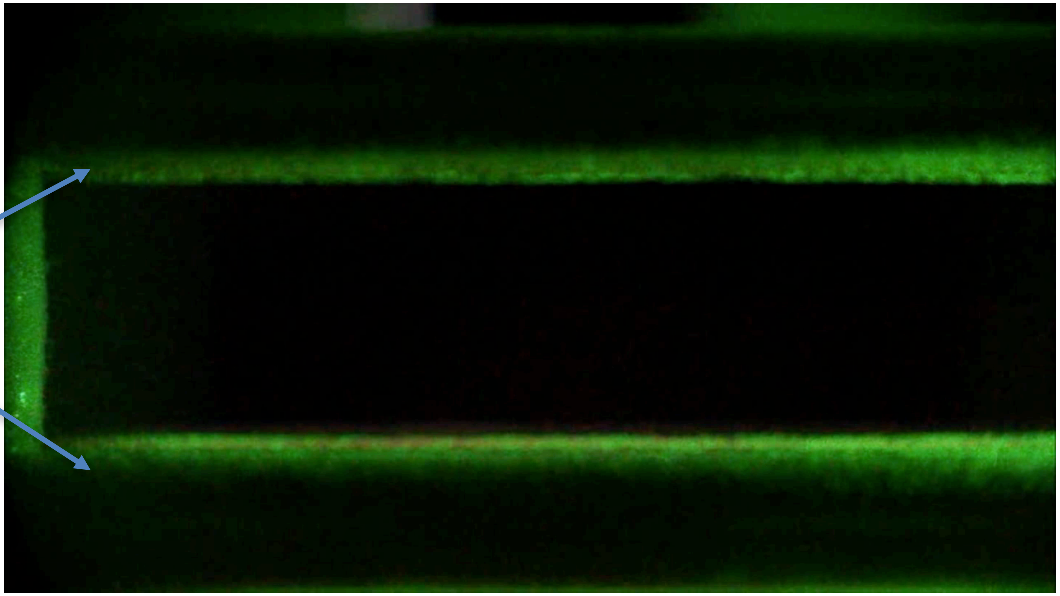
The Paul trap



Stable confinement if the trapping frequency
is larger than the static curvature

Linear Paul trap with Lycopodium particles

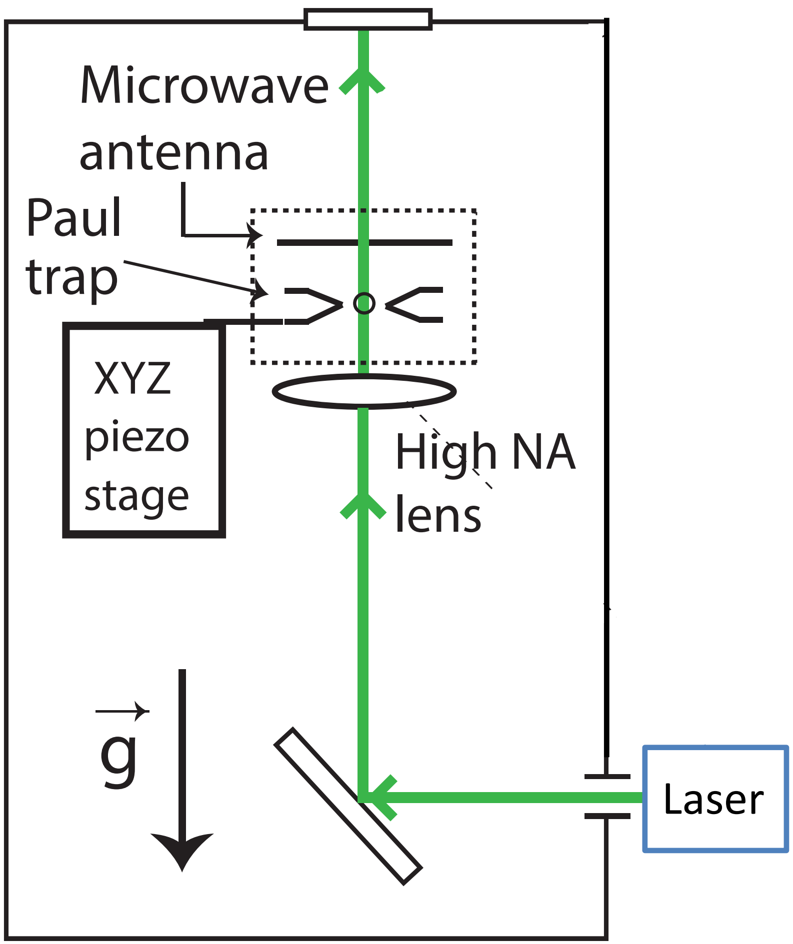
Electrodes



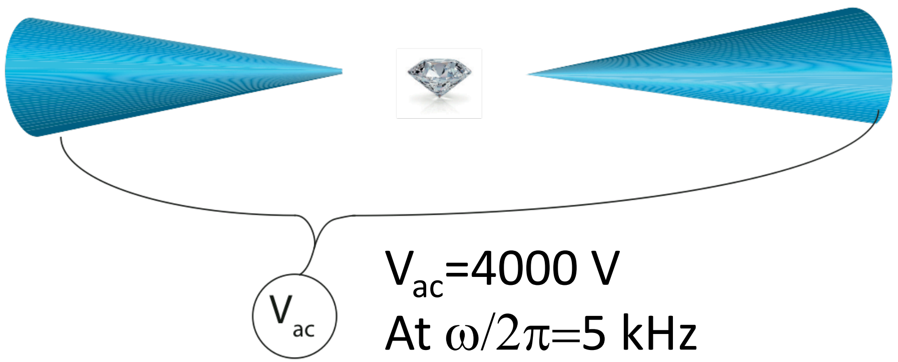
www.newtonianslabs.com

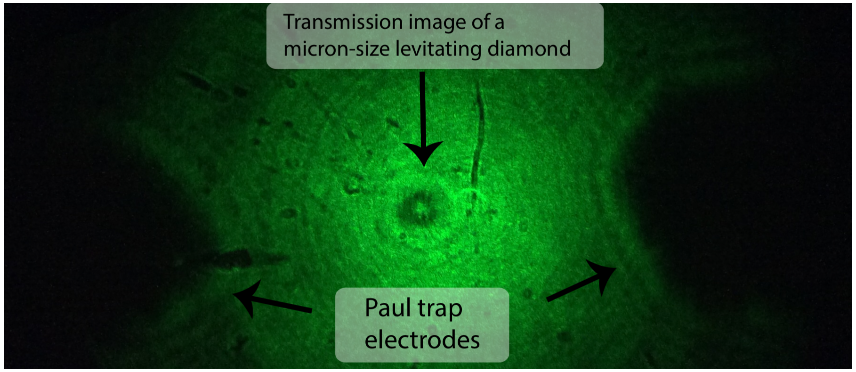
Loading Coulomb crystals with macroscopic particle

Experimental set-up



Injection : Approaching a diamond coated metallic tip to the trap center.



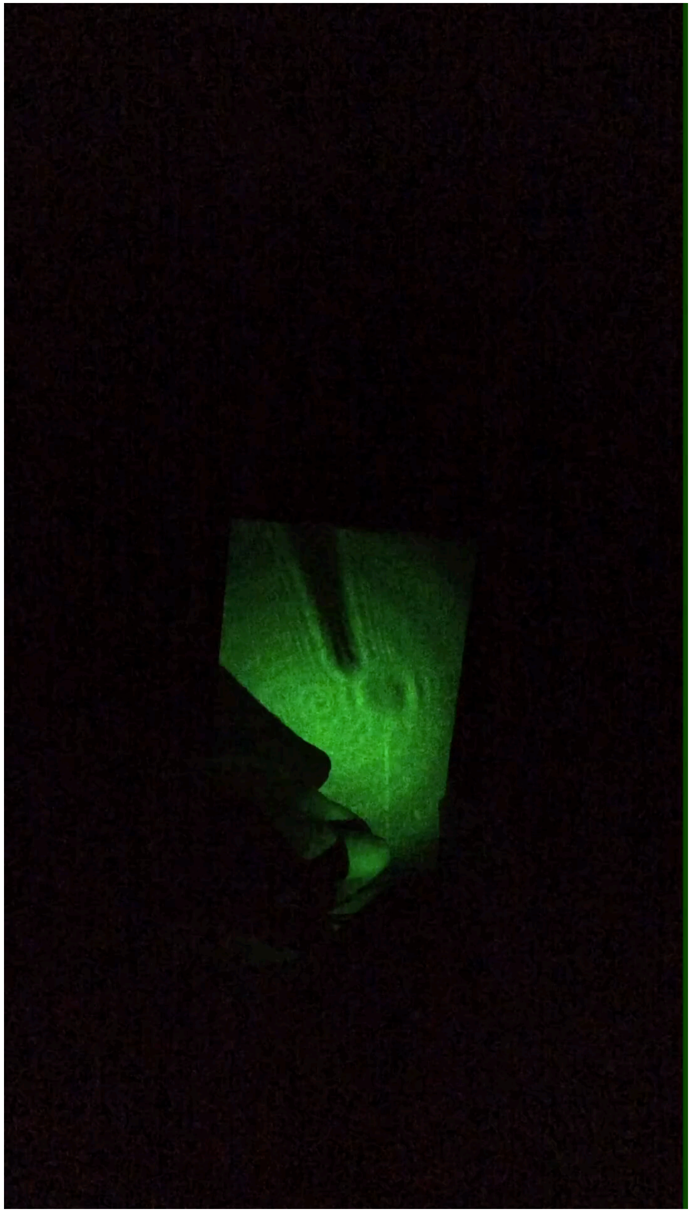


Trap frequency : $\omega_z/2\pi$=1 kHz

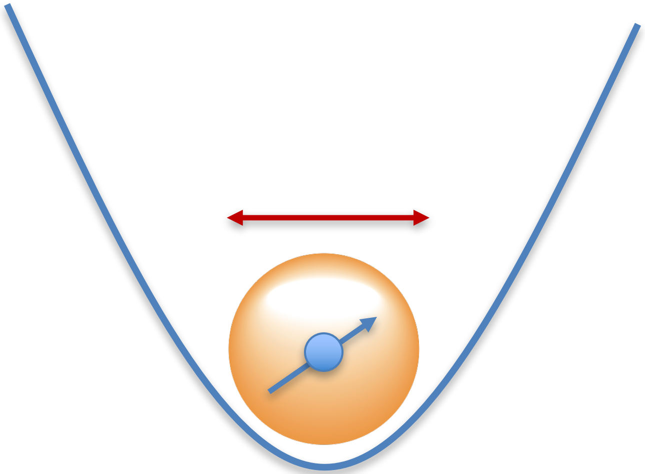
→ Charge surface : *5000 e^-*

Experimental set-up

Catching the levitating diamonds with a nano-fiber...



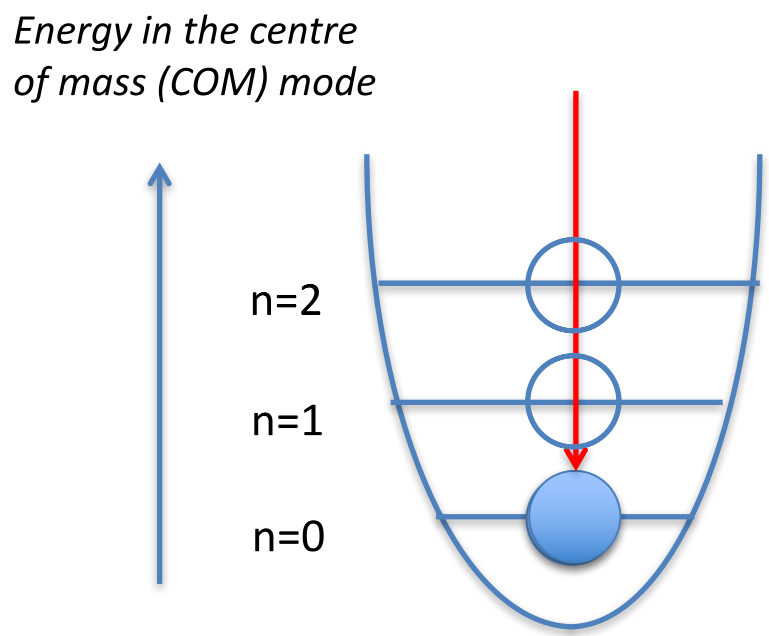
Quantum control of the motion using a single electron



Quantum optics with levitating systems

Cooling

$$\hat{H} = \hbar\omega_k(\hat{a}^\dagger\hat{a} + \frac{1}{2})$$



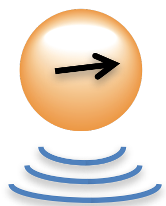
Schrödinger cat states

$$|\psi\rangle = \frac{|n=0\rangle + |n=1\rangle}{\sqrt{2}}$$

→ *Use a single embedded atom to cool the collective motion of billions of atoms and prepare Schrödinger cat states*

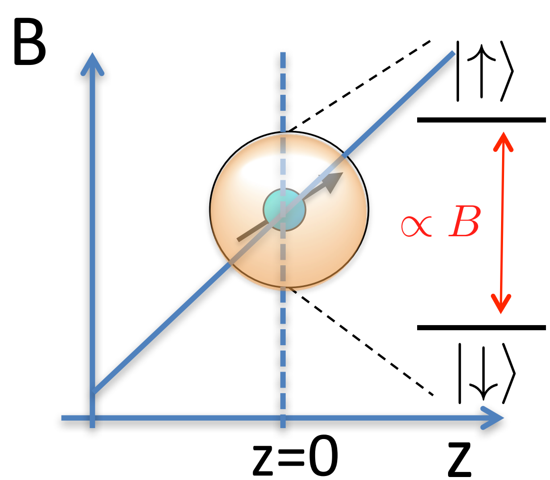
Single electron coupling to the motion

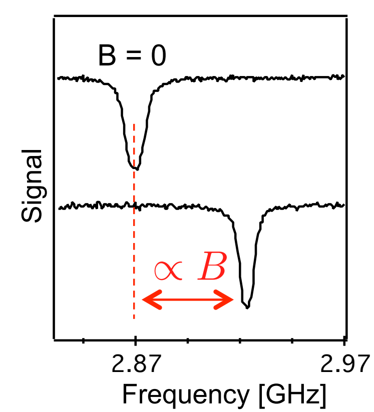
Read-out and coupling to the center of mass motion



A single embedded spin moving in a magnetic field gradient

→ Single atom resolution of the motion

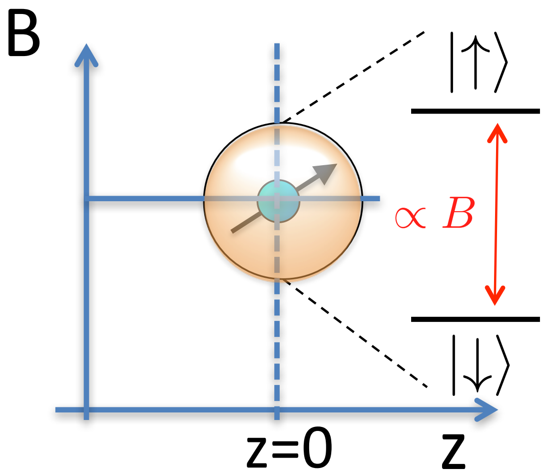


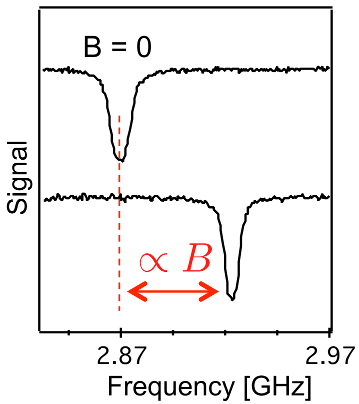


Frequency shift proportional to the displacement

Single electron coupling to the motion

Read-out and coupling to the rotational mode



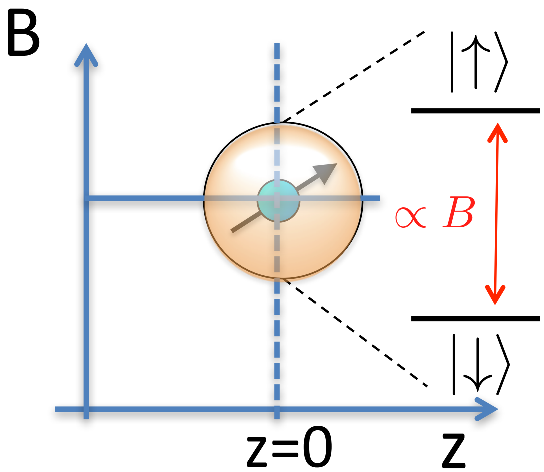


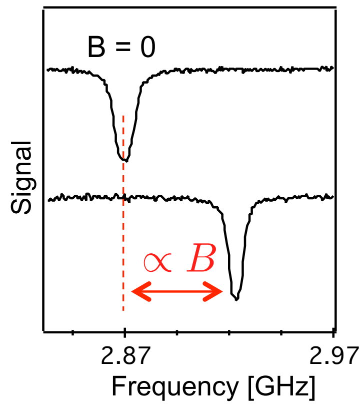
Frequency shift proportional to the displacement

Read-out *of the angular motion*

Single electron coupling to the motion

Read-out and coupling to the rotational mode





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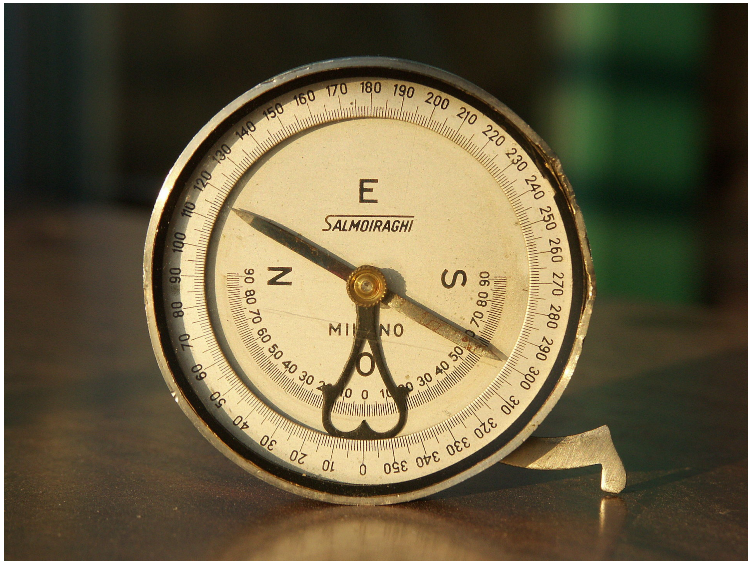


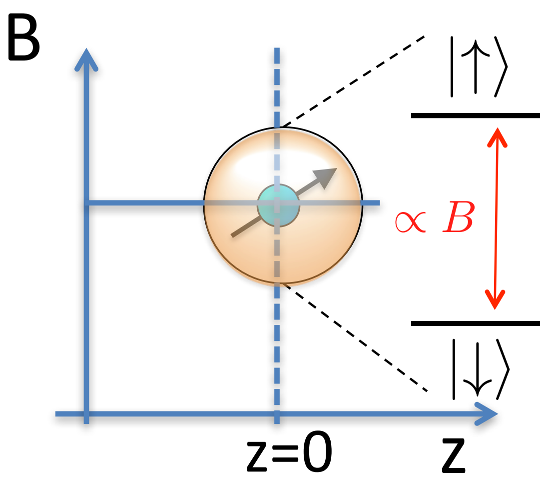
Magnetic compas

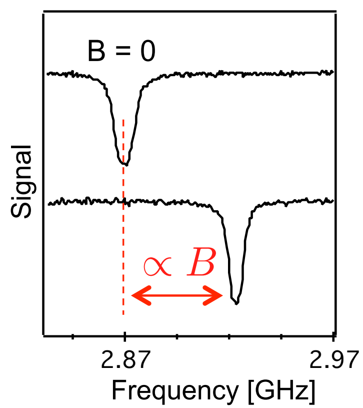
***Read-out** of the angular motion*

***Coupling to** the angular motion*

Single electron coupling to the motion

Read-out and coupling to the rotational mode





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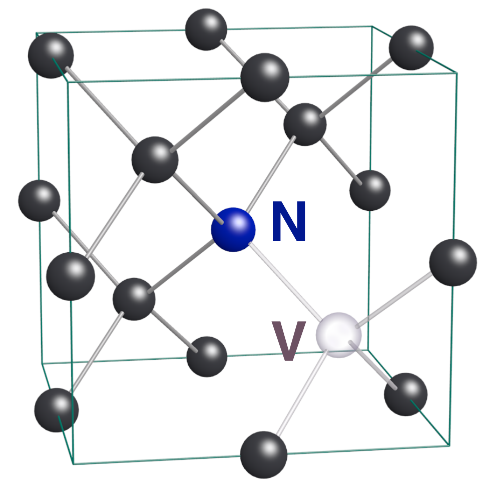


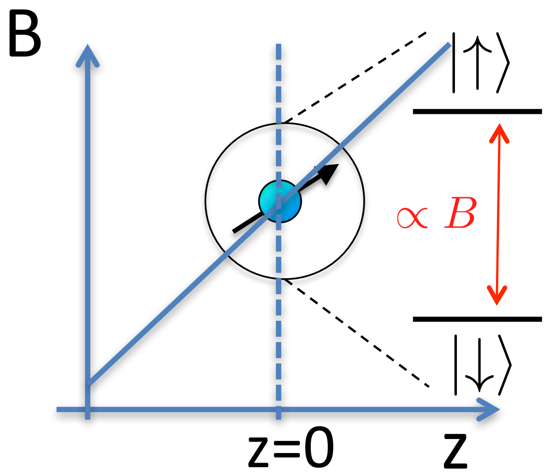
Single atom magnetic compas

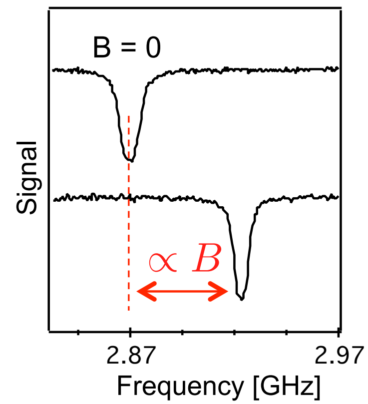
***Read-out** of the angular motion*

***Coupling to** the angular motion*

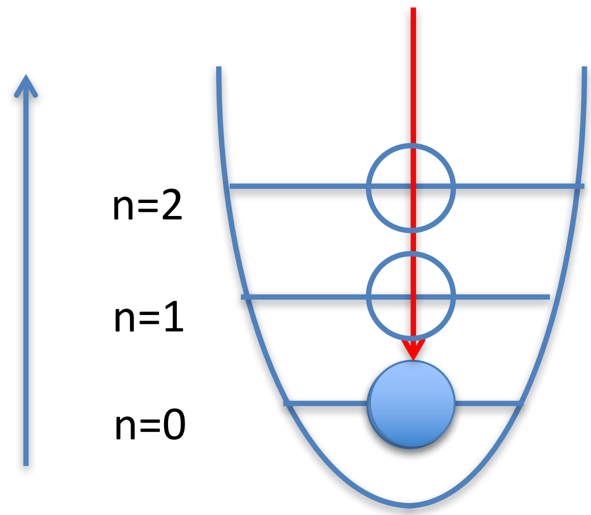
Coupling to the center of mass mode

COM mode





Energy in the centre of mass (COM) mode



$$H_{\rm int} = \vec{\mu} \cdot \vec{B} = \lambda_{\rm com} S_z (a + a^\dagger)$$

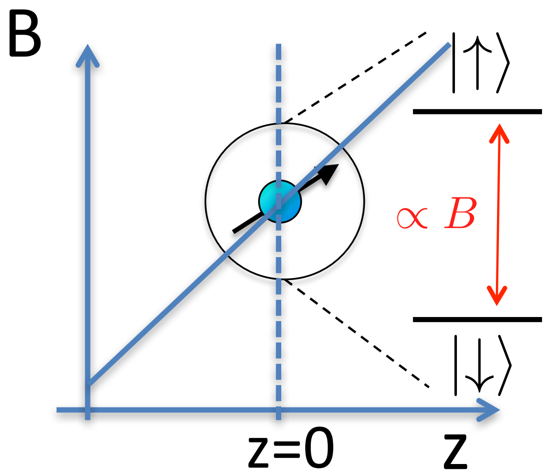
Coupling rate to the the COM mode :

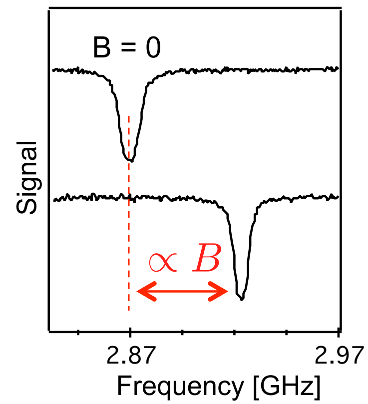
$$\lambda_{com} = g_s \mu_B G_m a_0 \rightarrow a_0 = \sqrt{\hbar / 2m\omega_{com}}$$

- **a=** Creation and annihilation operators of the center of mass mode.
- **Sz =** Pauli operator for the NV electronic spin

Coupling to the center of mass mode

COM mode





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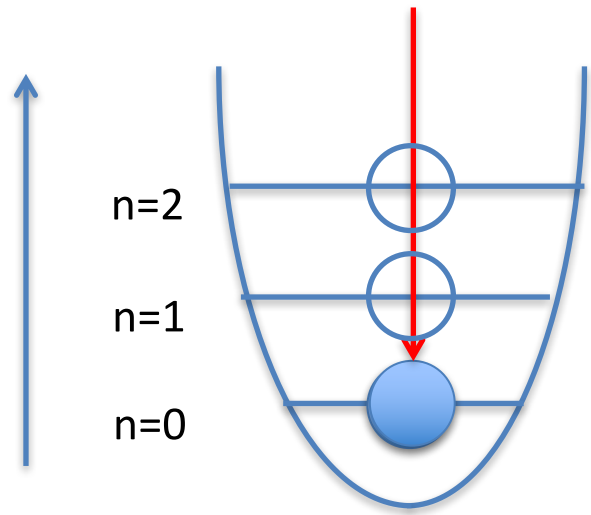

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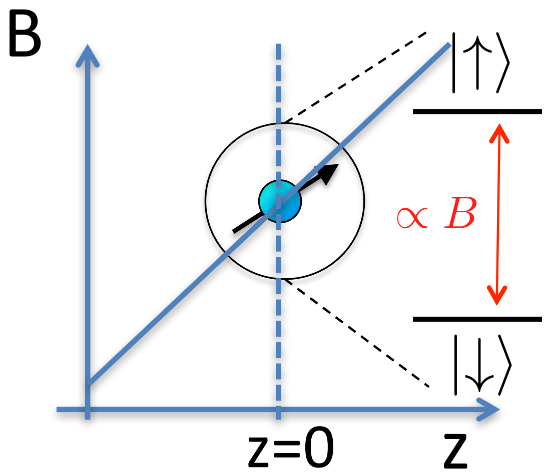
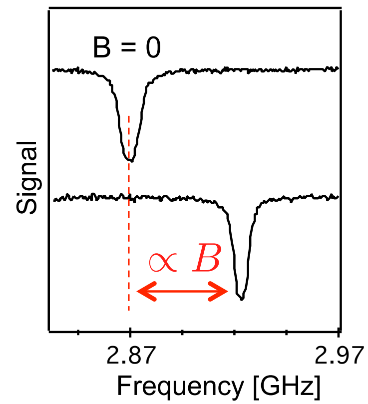
Strong coupling requires magnetic field gradients Gm in the **10^5 to 10^7 T/m range !**

P. Rabl et al. PRB (2009)

Coupling to the rotational mode

COM mode





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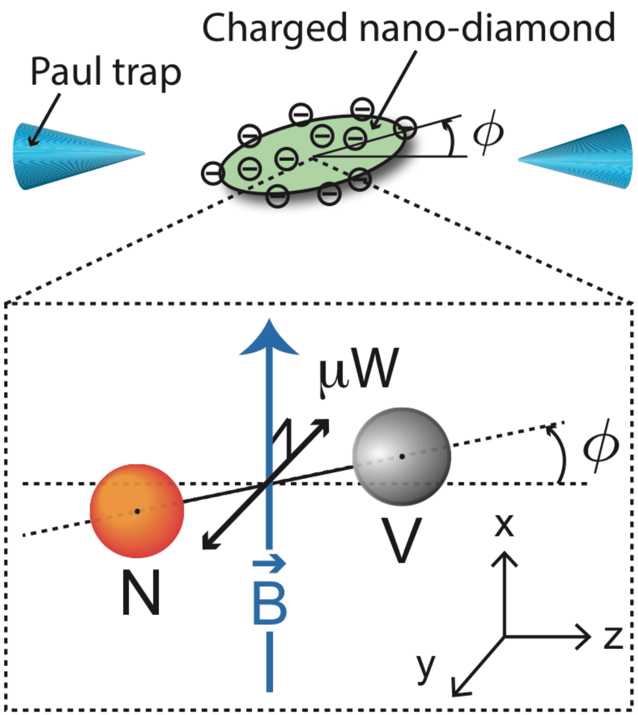
Rotational mode



$$\lambda_\phi = g_s \mu_B B \phi_0$$

where

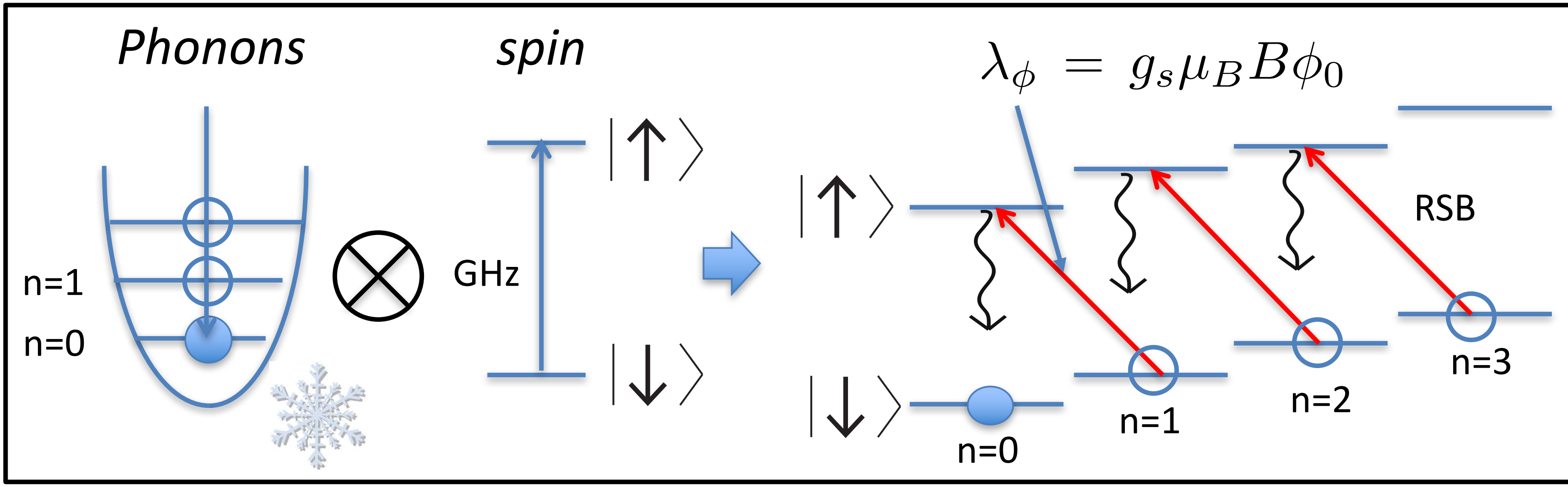
$$\phi_0 = \sqrt{\hbar / (2 I_y \omega_\phi)}$$

Requires homogeneous magnetic fields in the **mT range**

*T. Delord et al. **ArXiv** (2017)*

Towards quantum optical experiments

Ground state cooling



Use a single « atom » to cool the motion of thousands of atoms.

→ Picometer precision of a nanometer sized object.

Towards quantum optical experiments

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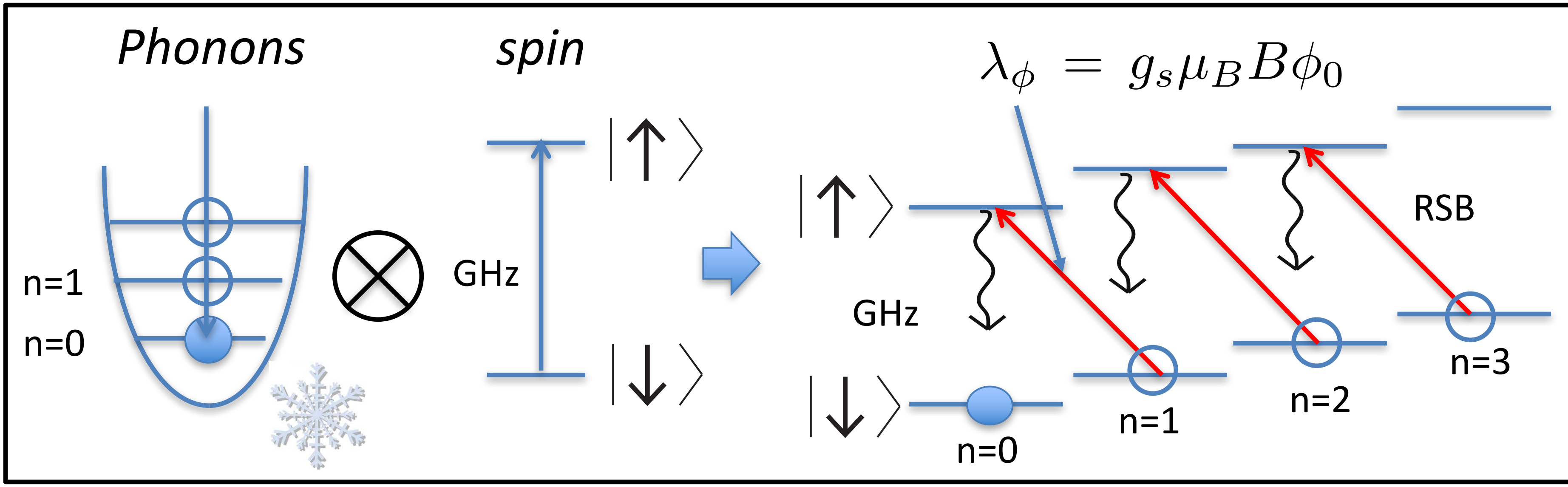


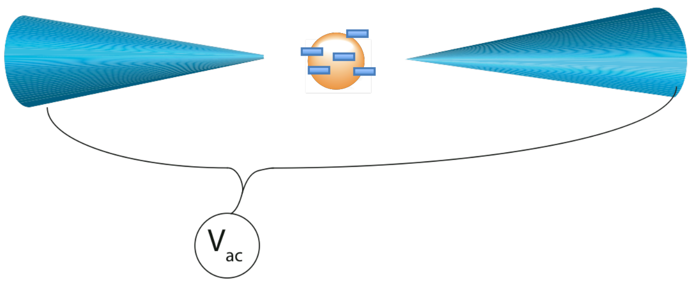
Use a single « atom » to cool the motion of thousands of atoms.
→ Picometer precision of a nanometer sized object.

Two requirements :

- **Angular stability of the diamond in the trap**
- **Low vacuum**

Summary

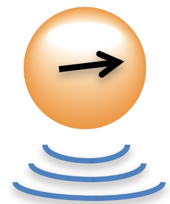
Trapping



Paul trap

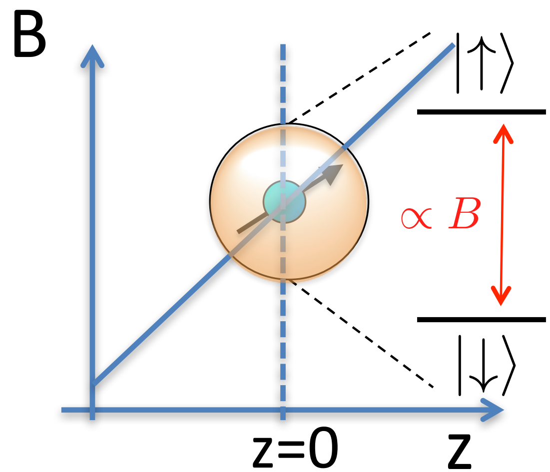
- No laser light
- Large potential depth
  → stays in the trap for days
- Single ion experiments showed control of the motion at the quantum level

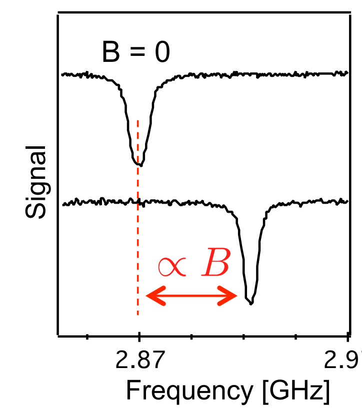
Read-out



A single embedded spin moving in a magnetic field gradient

→ Single atom resolution of the motion



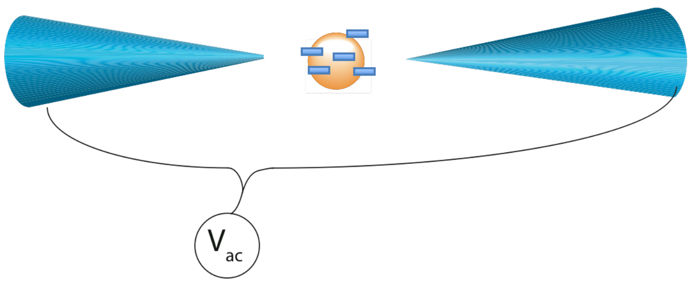


Frequency shift proportional to the displacement

A. Kulicke et al. ***APL*** *(2014)*
J. Millen, et al. ***PRL*** *(2015)*

Summary

Trapping



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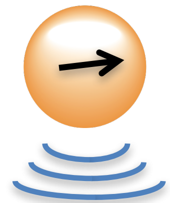

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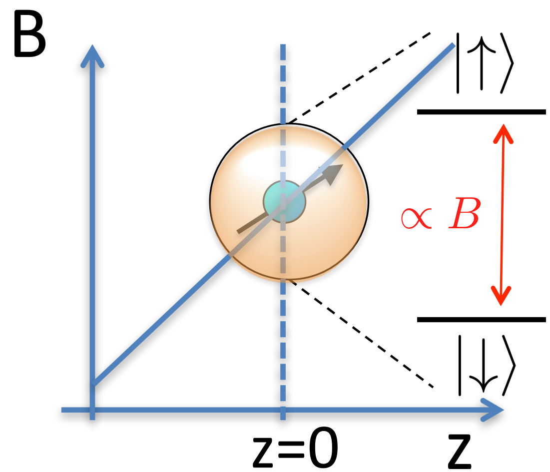
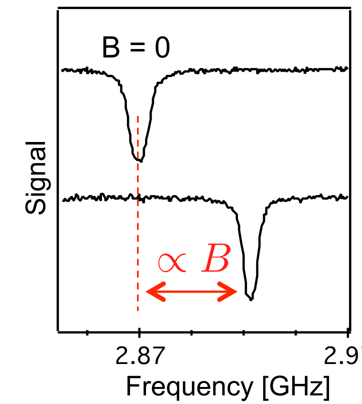
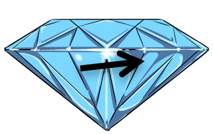




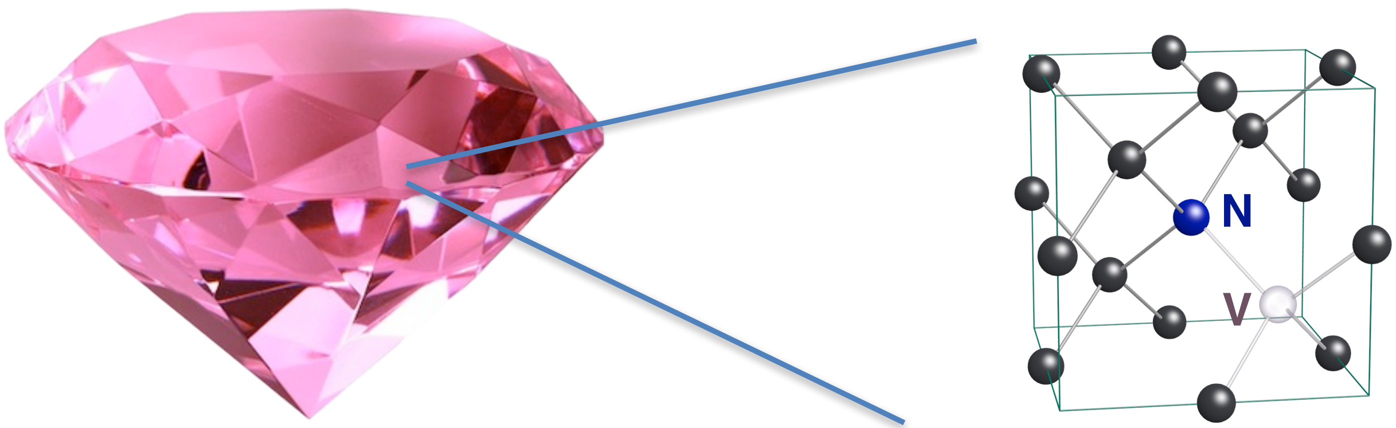
Frequency shift proportional to the displacement

→ NV centres in diamond



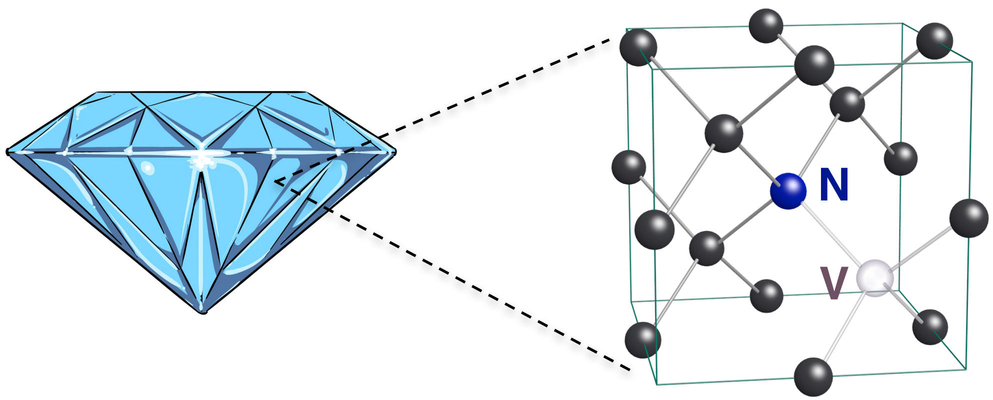
P. Rabl et al. PRB (2009)
O. Arcizet et al. Nat. Phys.(2011)

NV centers in diamond

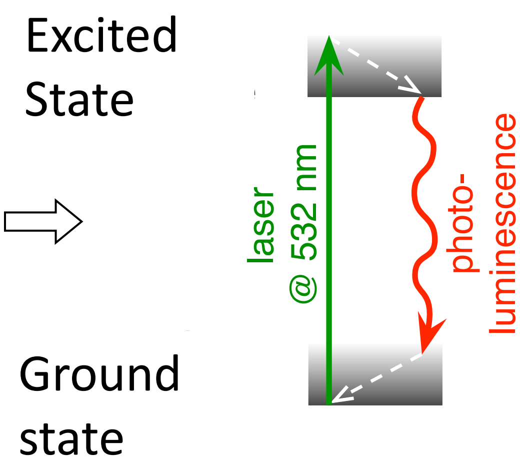


NV centers in diamond

Cristalline defect formed by one nitrogen atom (N) and one vacancy (V) on two adjacent sites of the diamond matrix



⇨

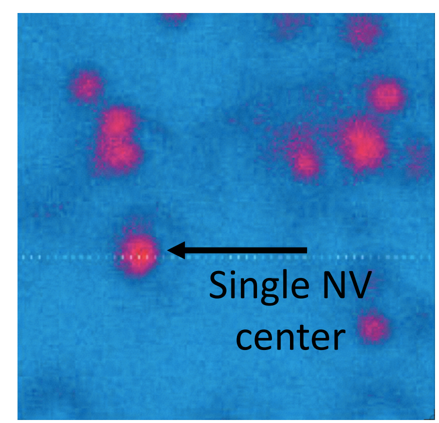


⟶ « artificial atom » in diamond

⟶ photoluminescence (PL) perfectly stable at room temperature

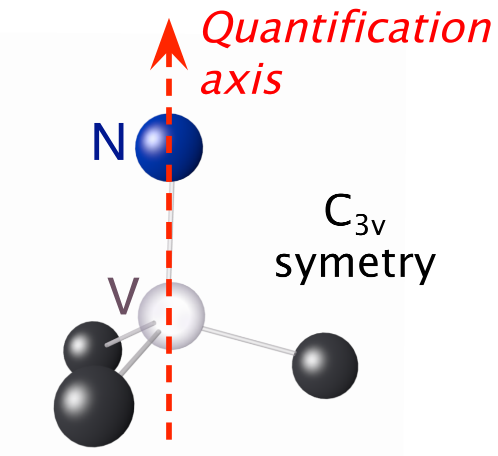
⇨ Single NV isolation   Gruber *et al.*, *Science* **276** (1997)

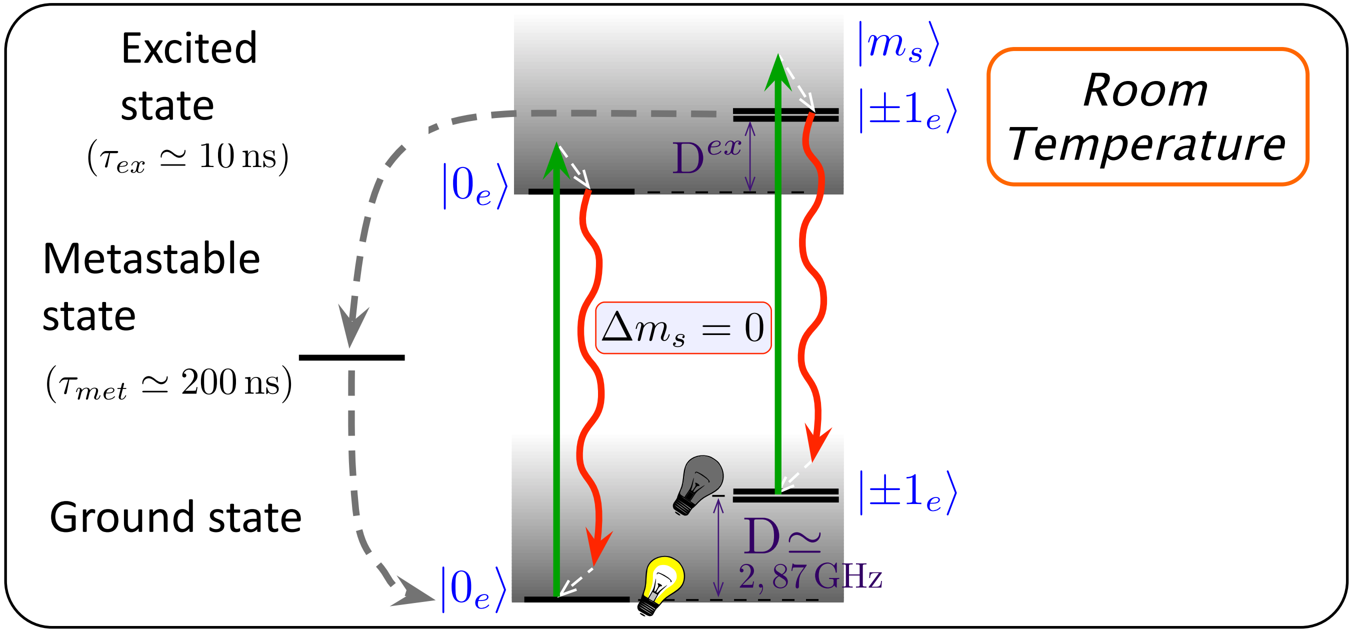
Detection via confocal microscopy



Spin properties of the NV center

- $S = 1$, the fondamental level is a spin triplet





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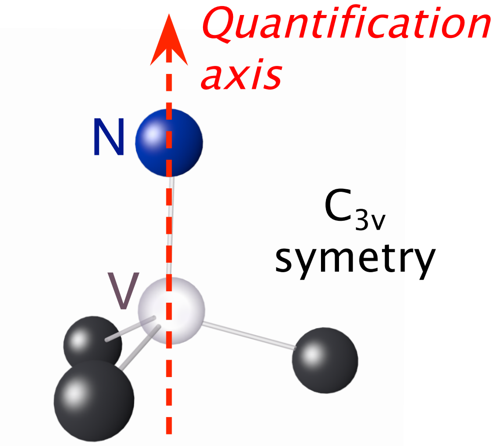

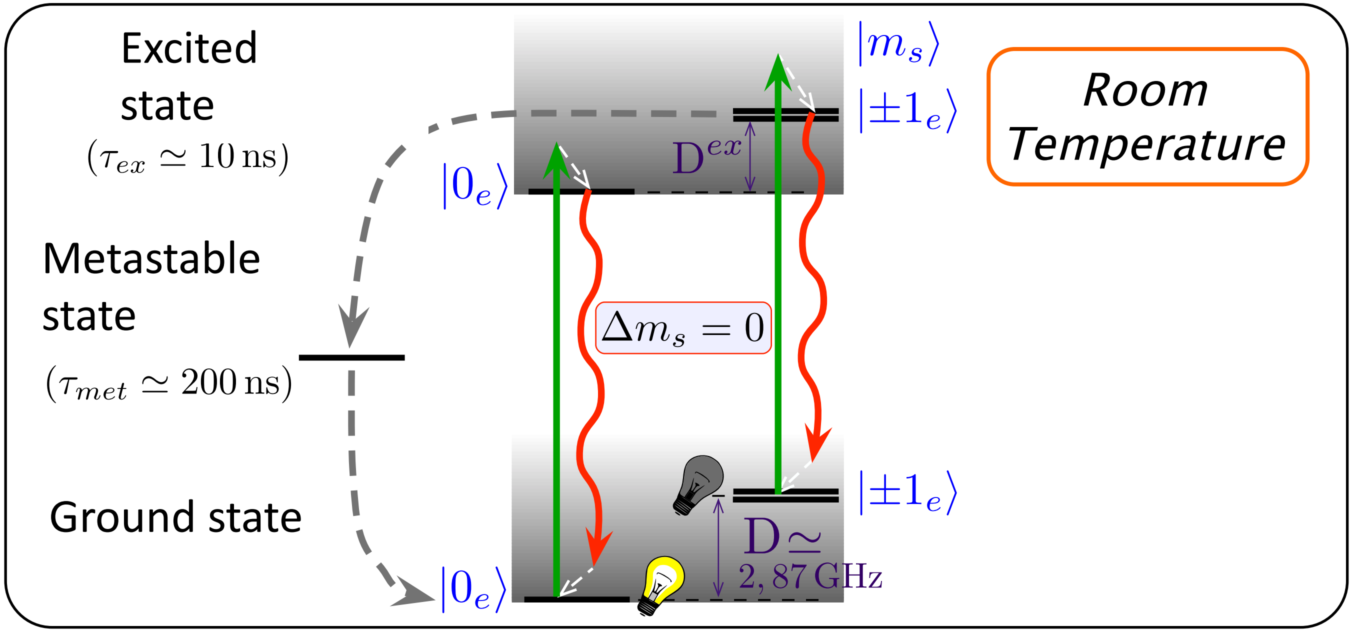

Optical pumping in the state $|0_e\rangle$

⟹ *Spin initialisation*

+

The PL level depends upon spin state

$|0_e\rangle \longrightarrow$ *«bright» state*

$|\pm1_e\rangle \longrightarrow$ *dark state*

⟹ *Optical read-out of spin state*

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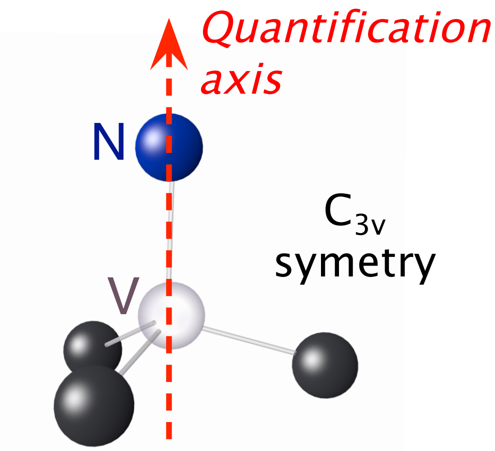

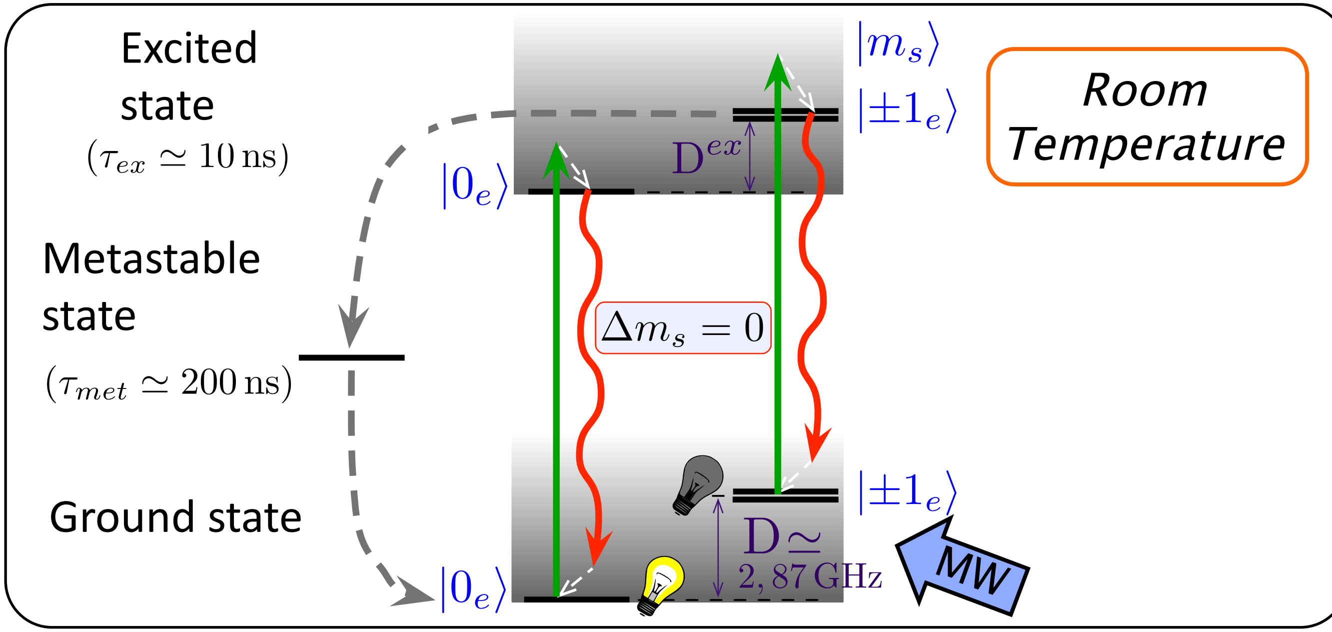

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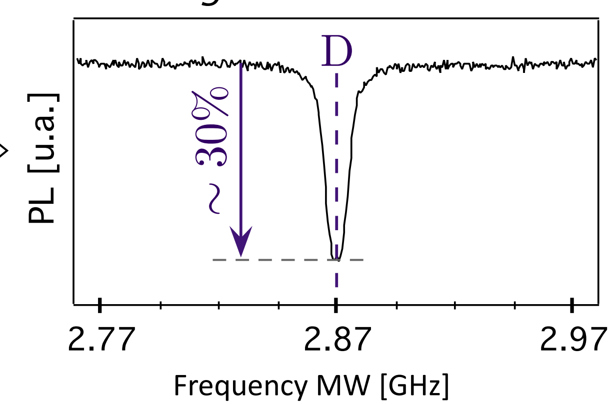
$\Rightarrow$

Optical detection of spin magnetic resonance



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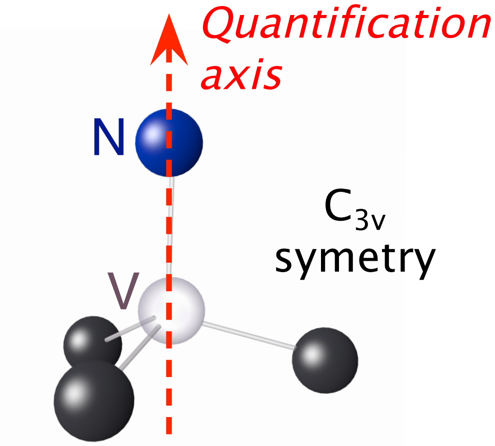

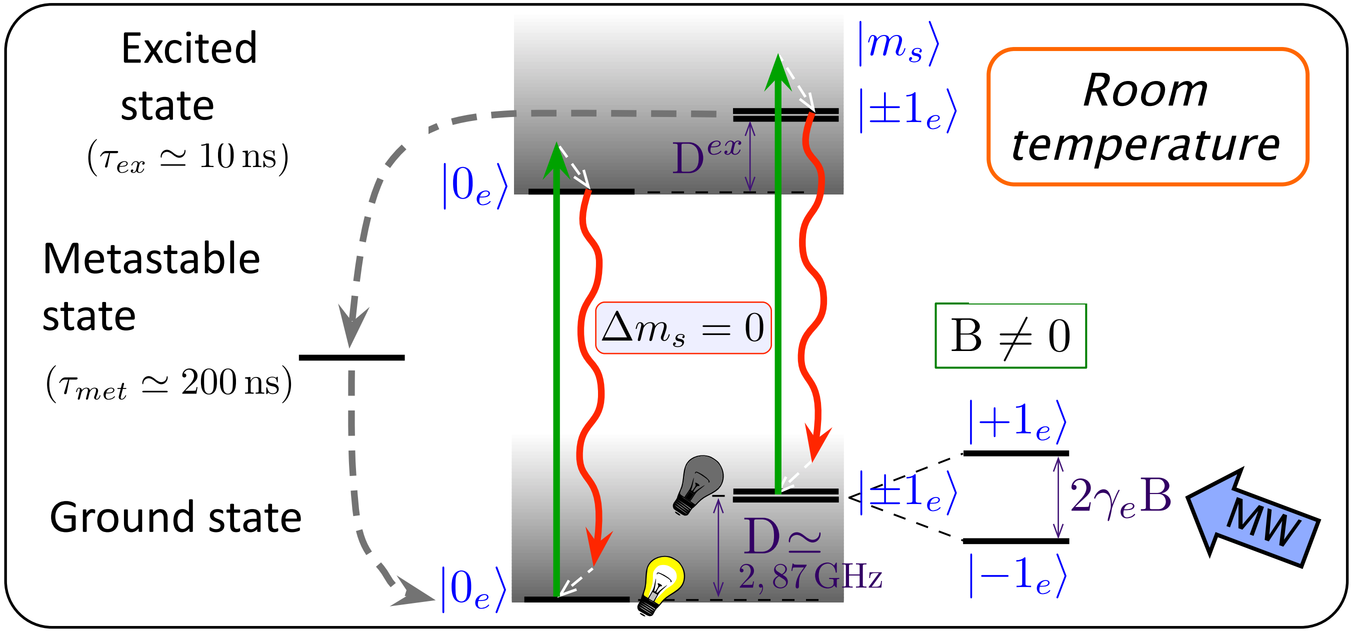

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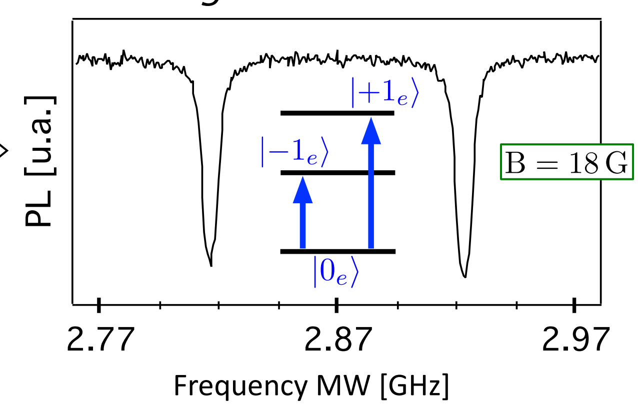
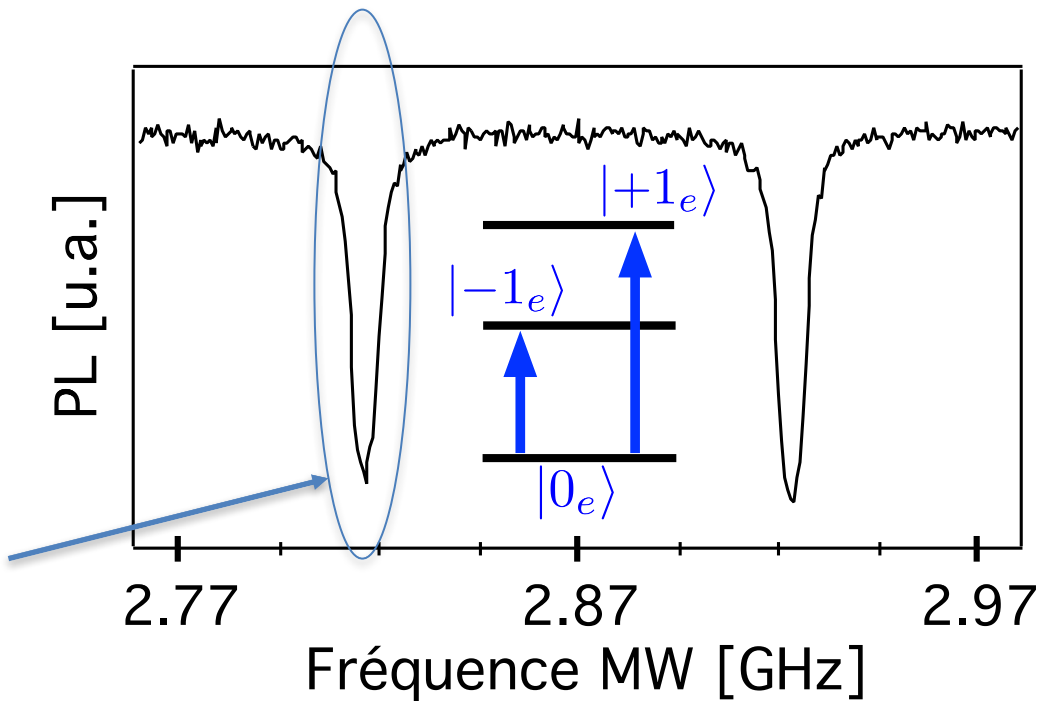


Applications of the NV center

Room temperature read out of a single electronic spin in diamond

ESR

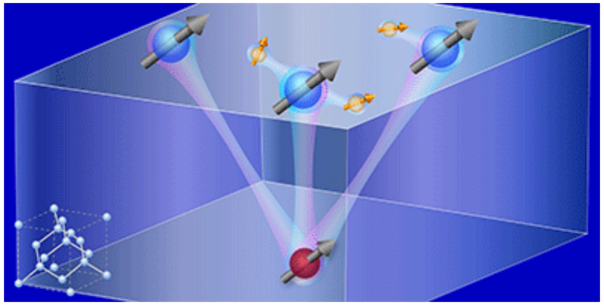


(Two level atom)

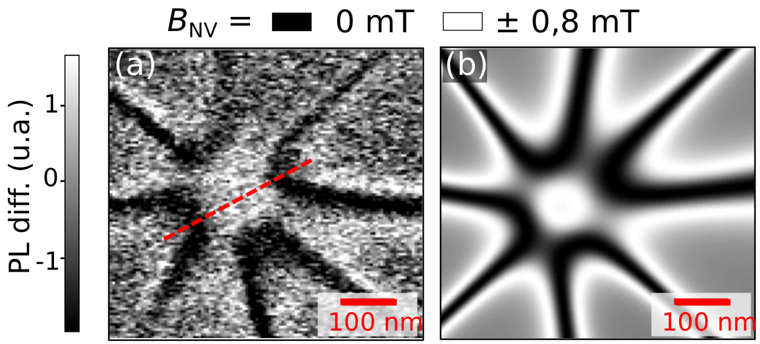
At the core of many applications in quantum physics

Applications of the NV center

Sensing magnetic fields with nm resolution



Single nuclear spins



Ferromagnetic vorteces

Applications of the NV center

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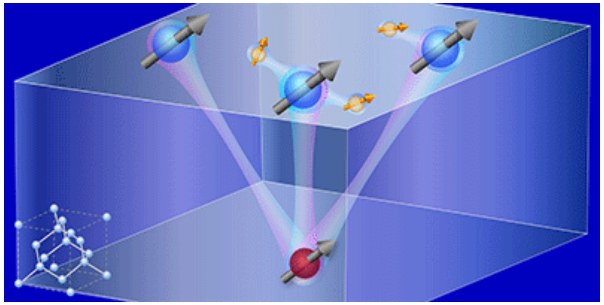

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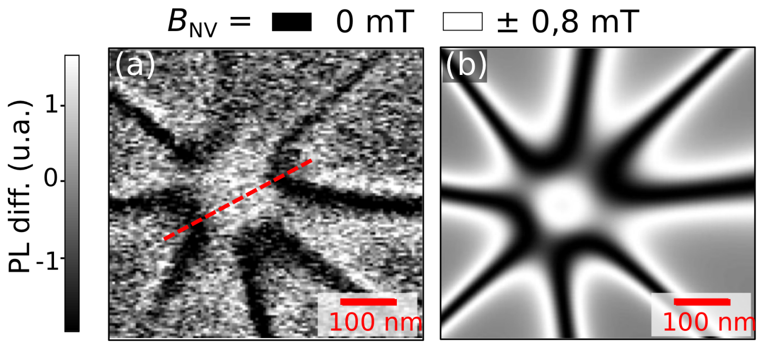
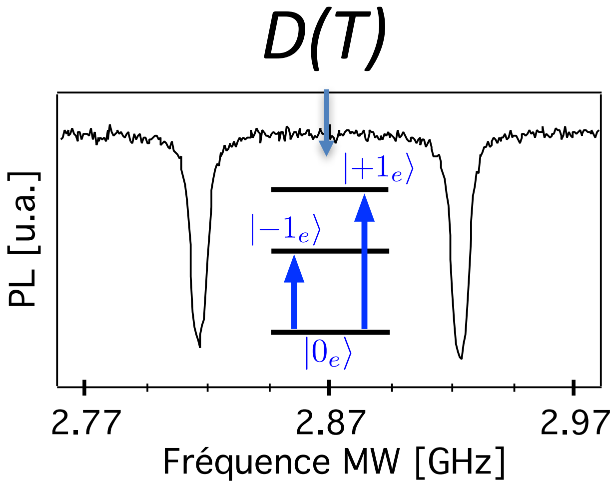
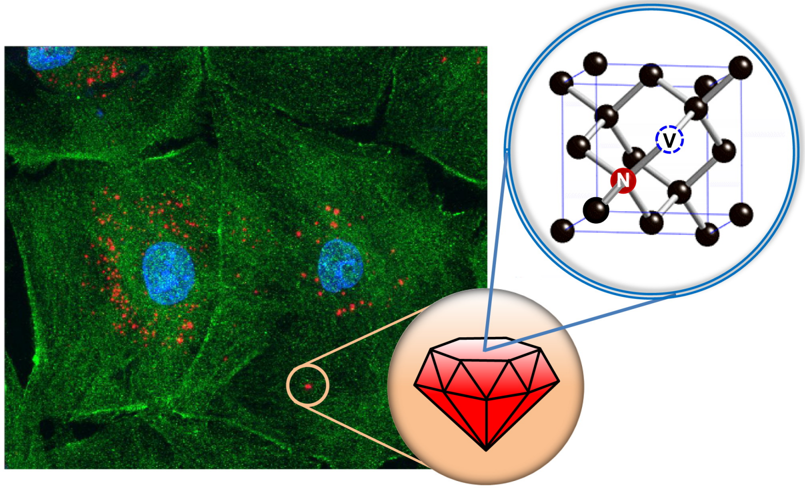


Ferromagnetic vorteces

Nanoscale thermometer





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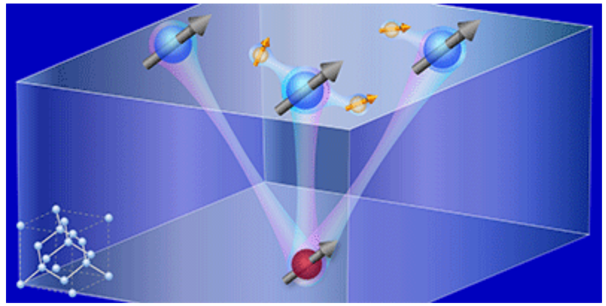

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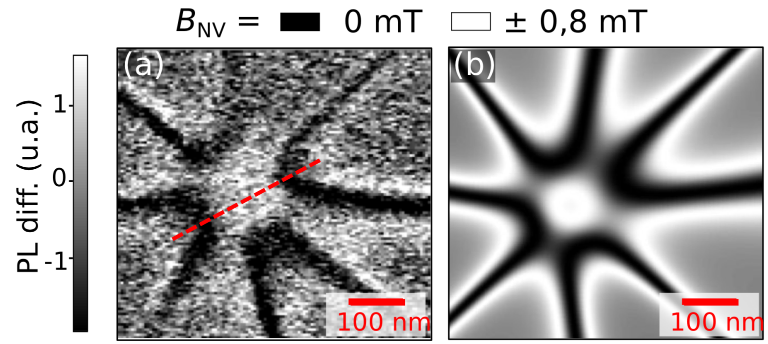
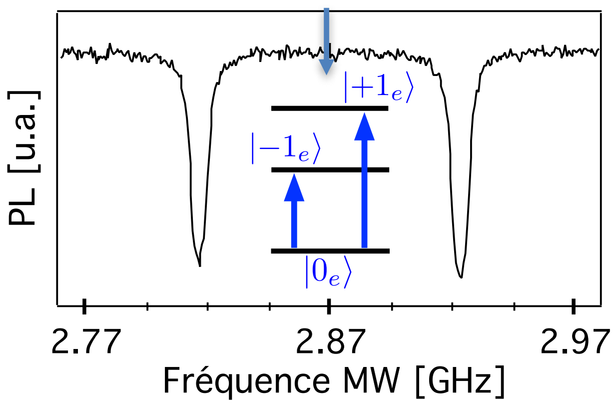
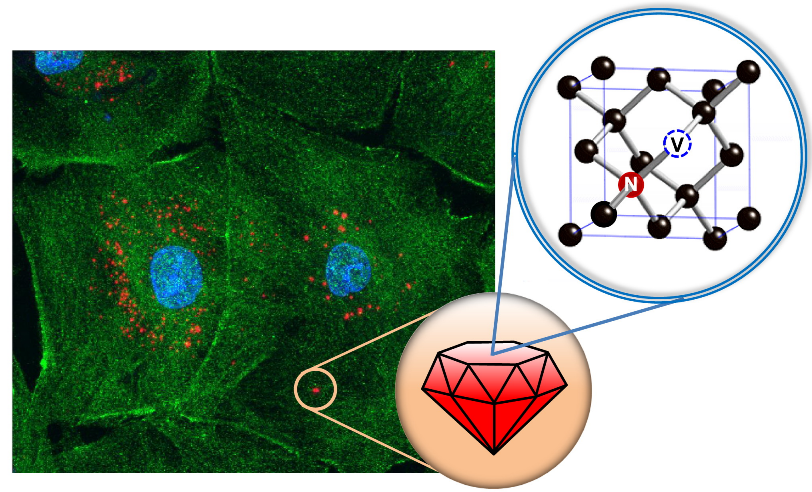


Ferromagnetic vorteces

Nanoscale thermometer

$D(T)$

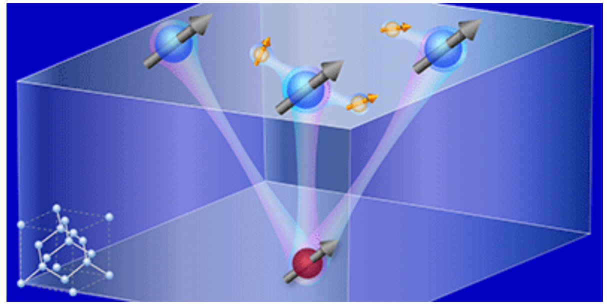




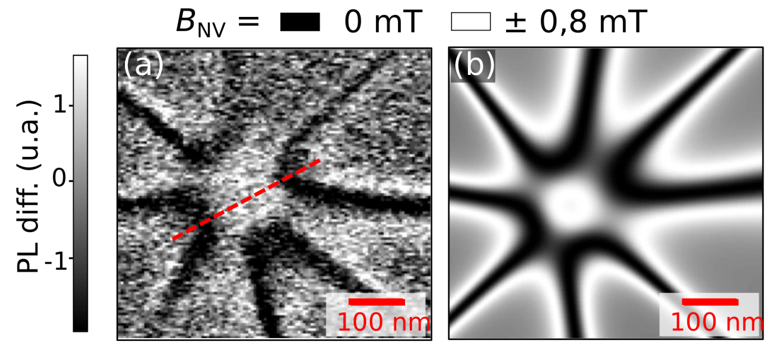
Quantum information

Applications of the NV center

Sensing magnetic fields with nm resolution

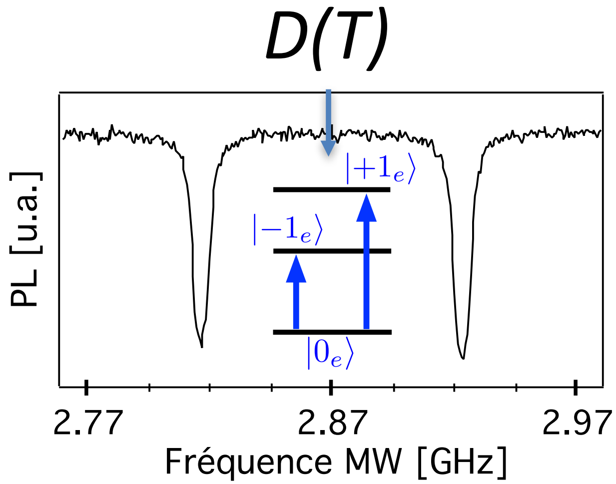


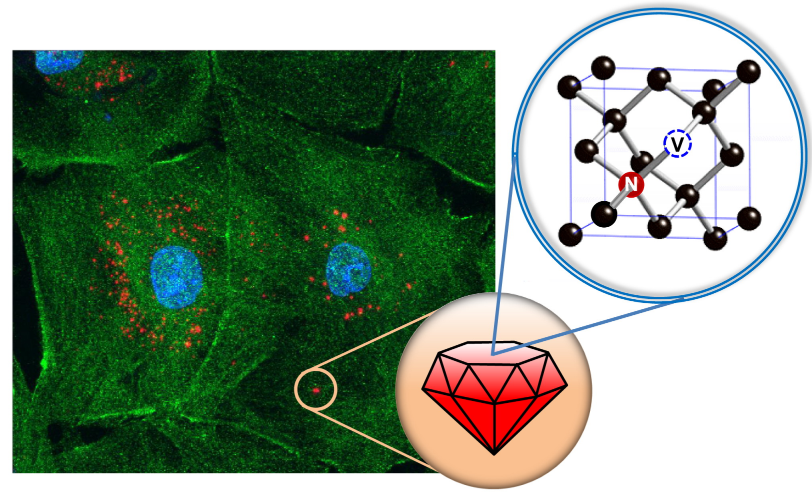
Single nuclear spins



Ferromagnetic vorteces

Nanoscale thermometer

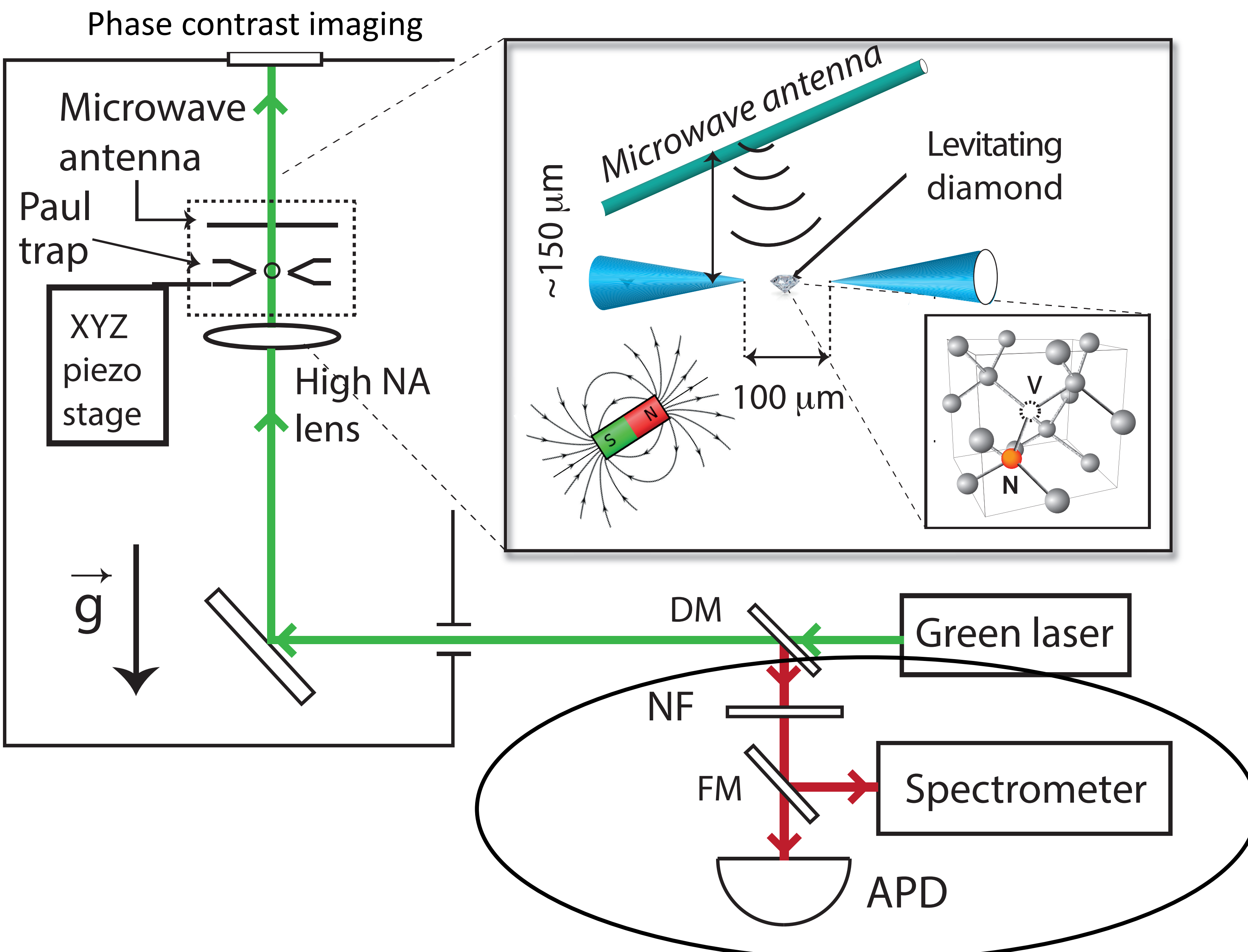




Quantum information

And for studying levitating quantum systems…

Experimental set-up

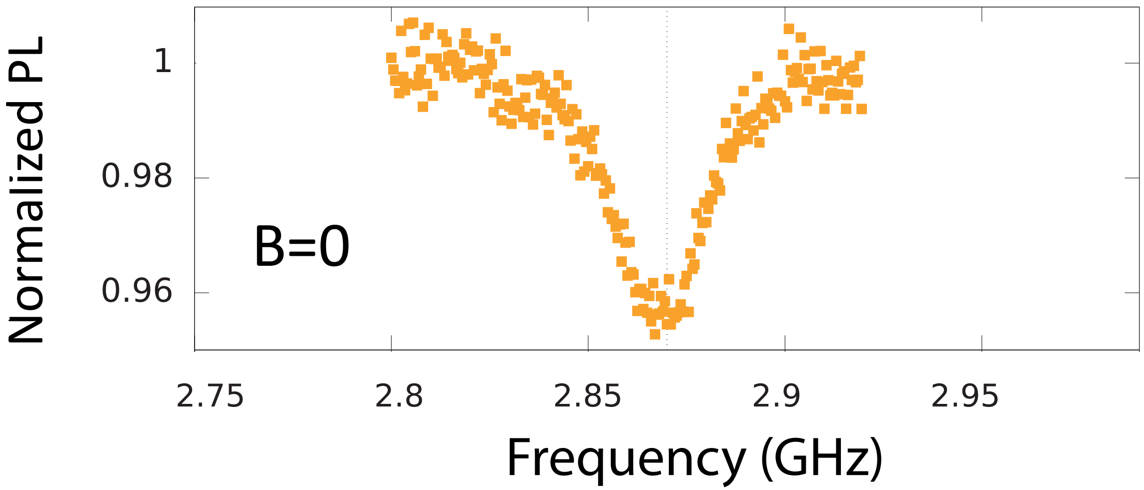


ESR with NVs in levitating diamonds

Electron Spin Resonance

No magnetic field

ESR contrast comparable to the ESR with deposited diamonds



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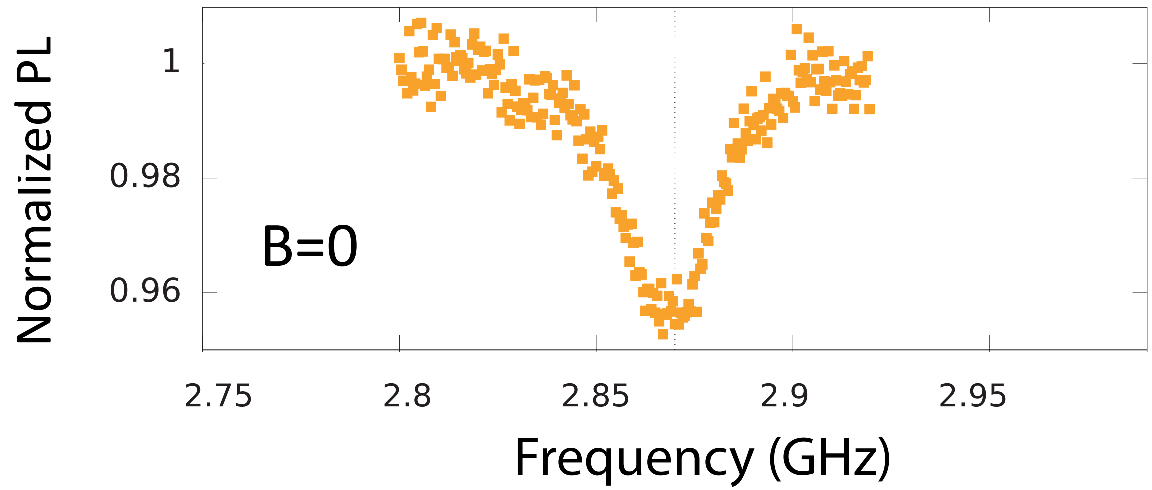
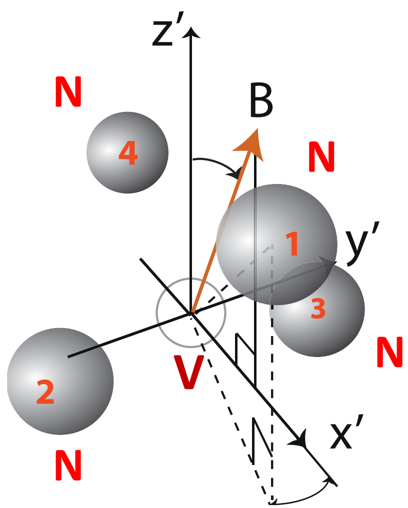


With a magnetic field

4 possible orientations

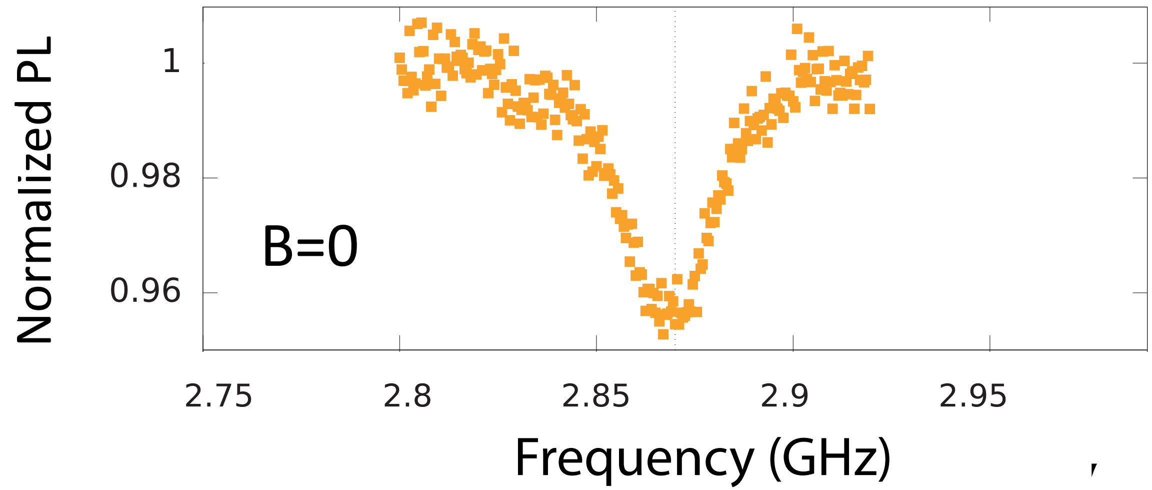


Electron Spin Resonance

ESR with NVs in levitating diamonds

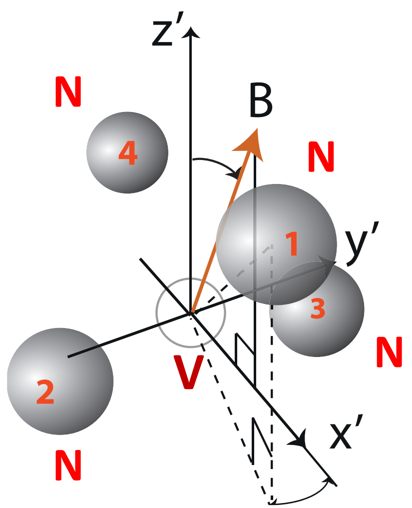
No magnetic field

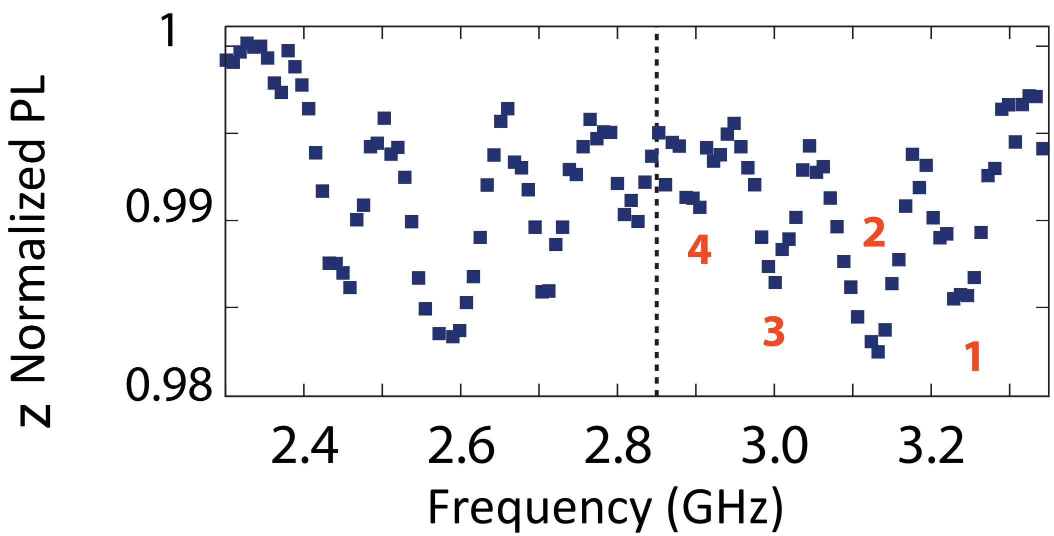
ESR contrast comparable to the ESR with deposited diamonds



With a magnetic field

4 possible orientations

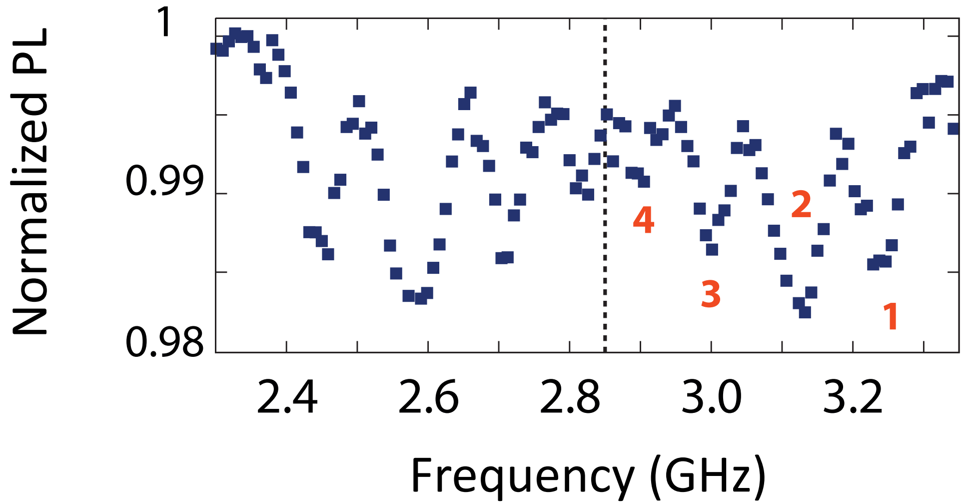


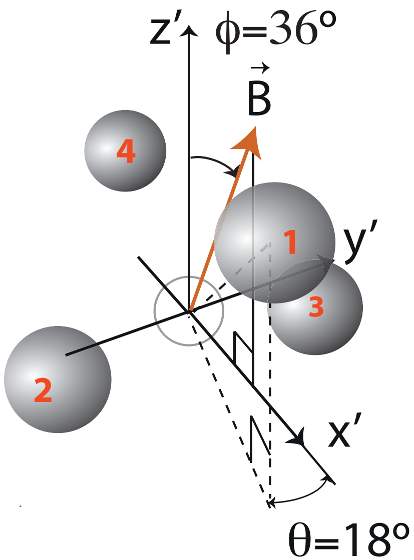


Angular stability !

Deterministic angle change

ESR with **10 microns** diameters diamonds





Deterministic angle change

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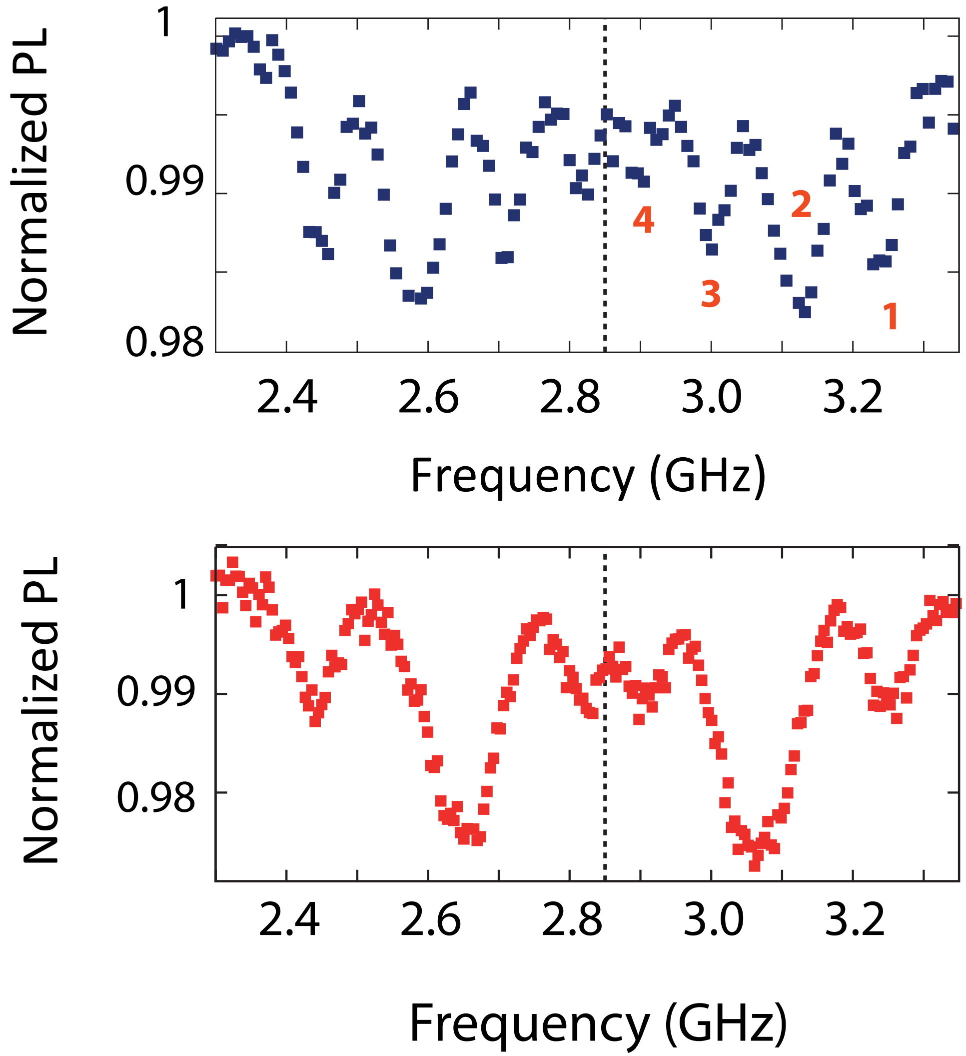
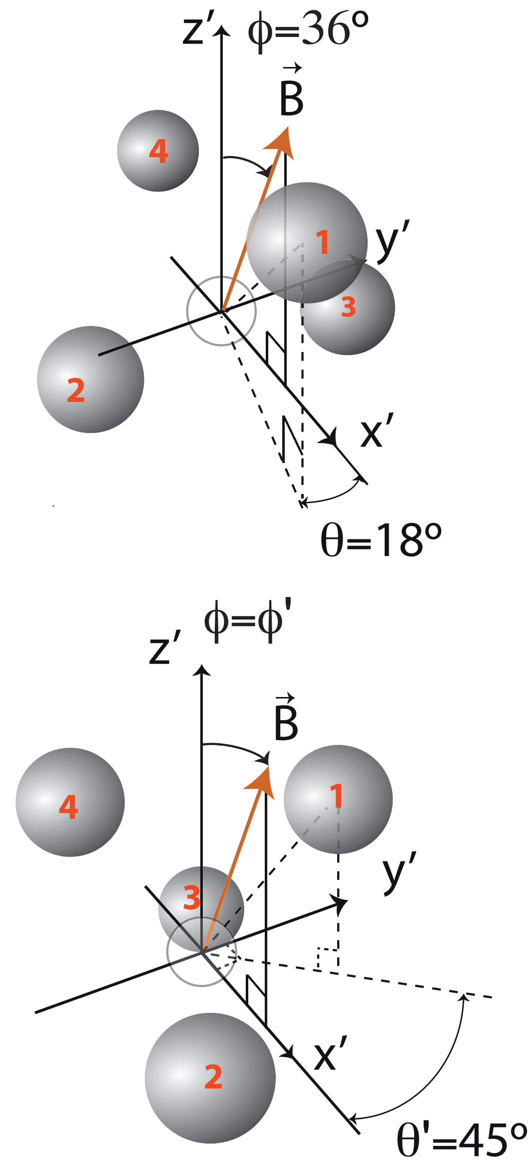
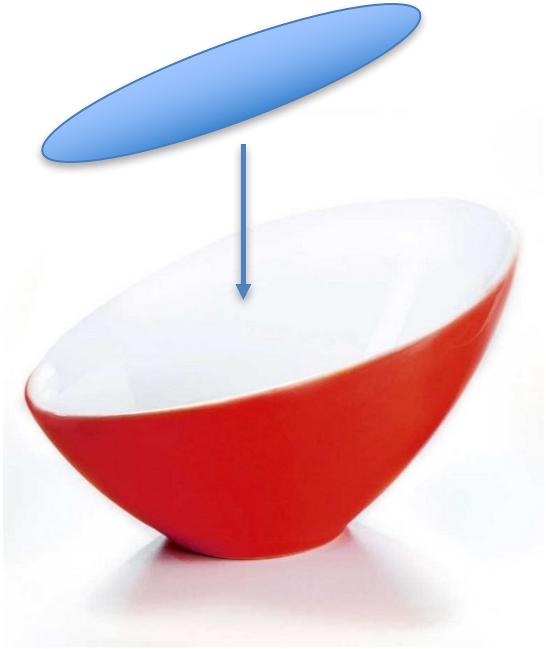




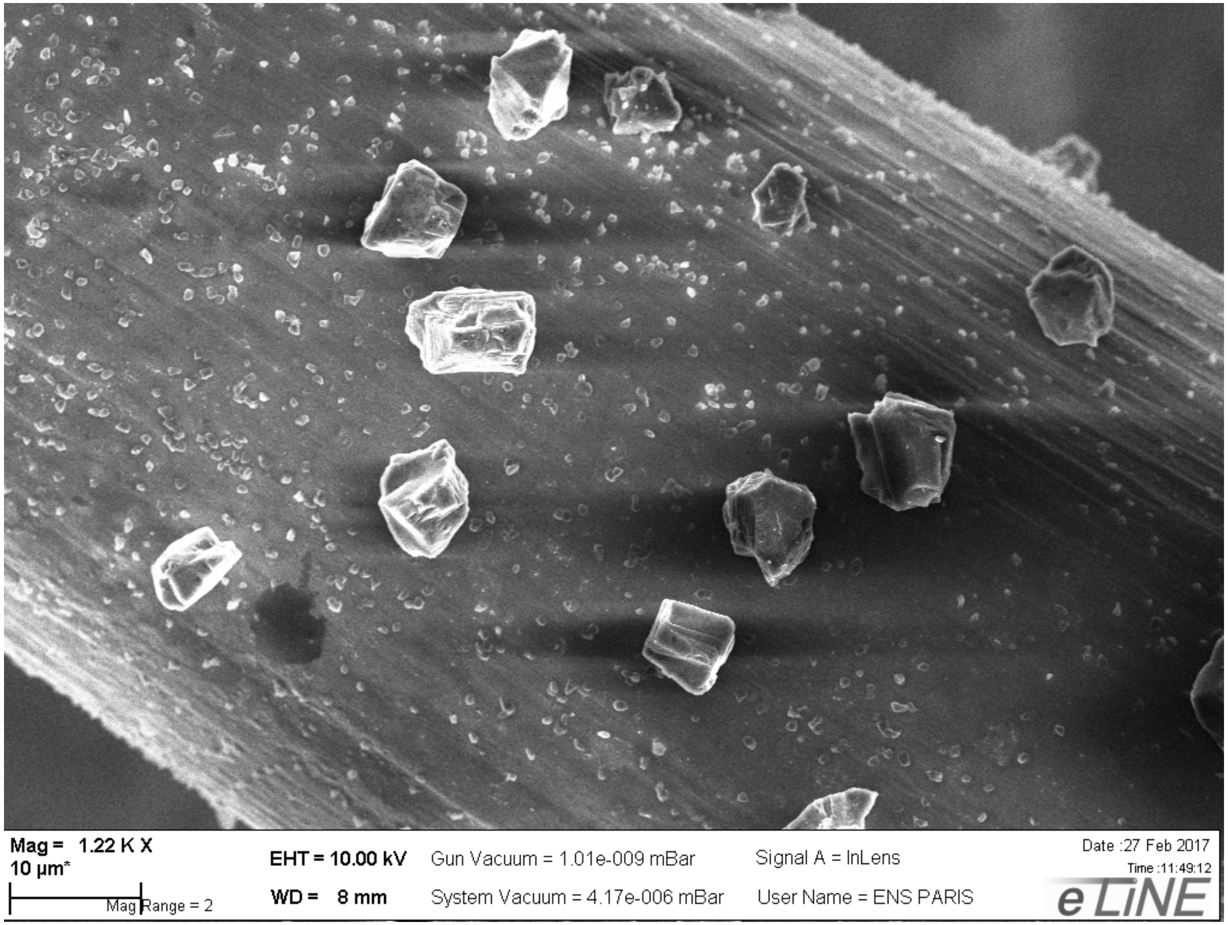
Deterministic angle change

An asymetrical particle enables locking the rotation along the most confining trap axis



Angular stability

MEB image of microdiamonds on the tungsten tip

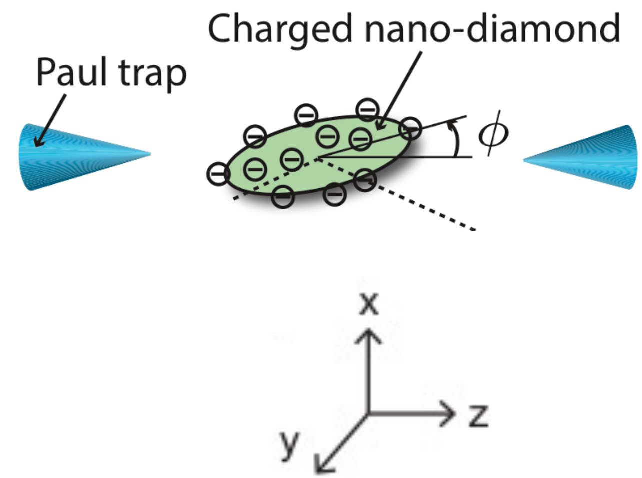


Highly asymmetric particles

Angular stability

Newton's law for an *ellipsoidal particule* :

$$\ddot{\phi} - \sqrt{2}\omega_\phi \Omega \cos(\Omega t)\frac{\sin(2\phi)}{2} = 0$$



In the small angle limit → **Matthieu equation.**

Angular stability with harmonic confinement at the frequency :

$$\omega_\phi = \omega_z m S_I / I_{yy}$$ ← *Inertia momentum Along y*

$$\mathrm{S_I} = \frac{3}{\mathrm{S}} \iint \left(\mathrm{z}^2 - \mathrm{x}^2\right) \mathrm{dS}$$

Angular stability

Newton's law for an *ellipsoidal particule* :

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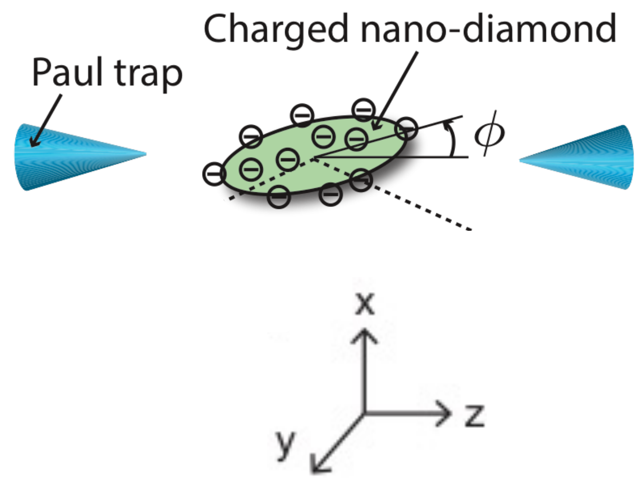

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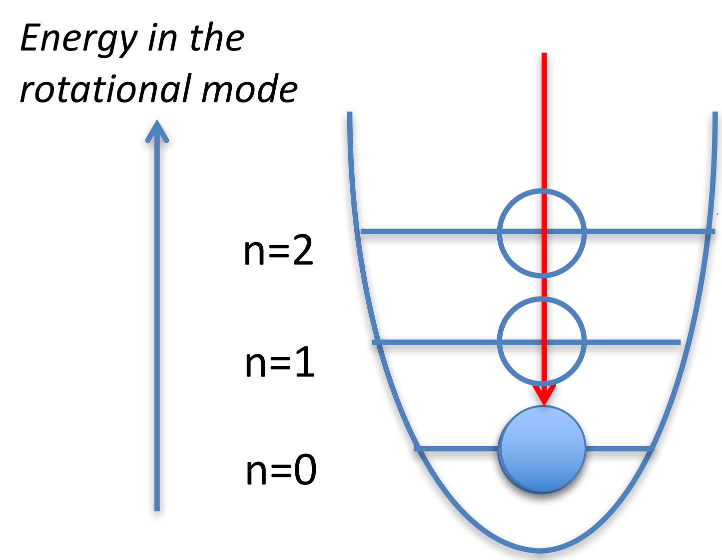
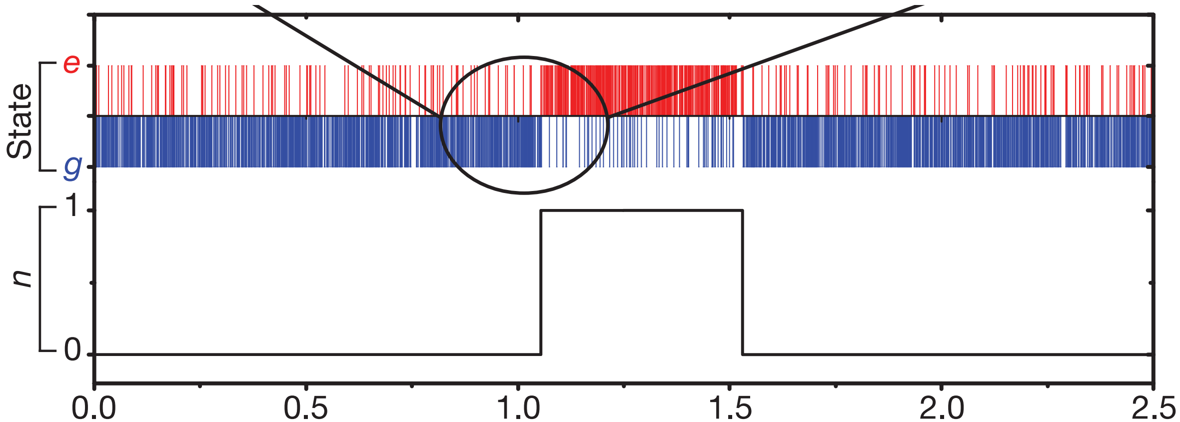


:-) Opens a path for *rotational quantum optics*

Towards quantum optical experiments with macroscopic oscillators

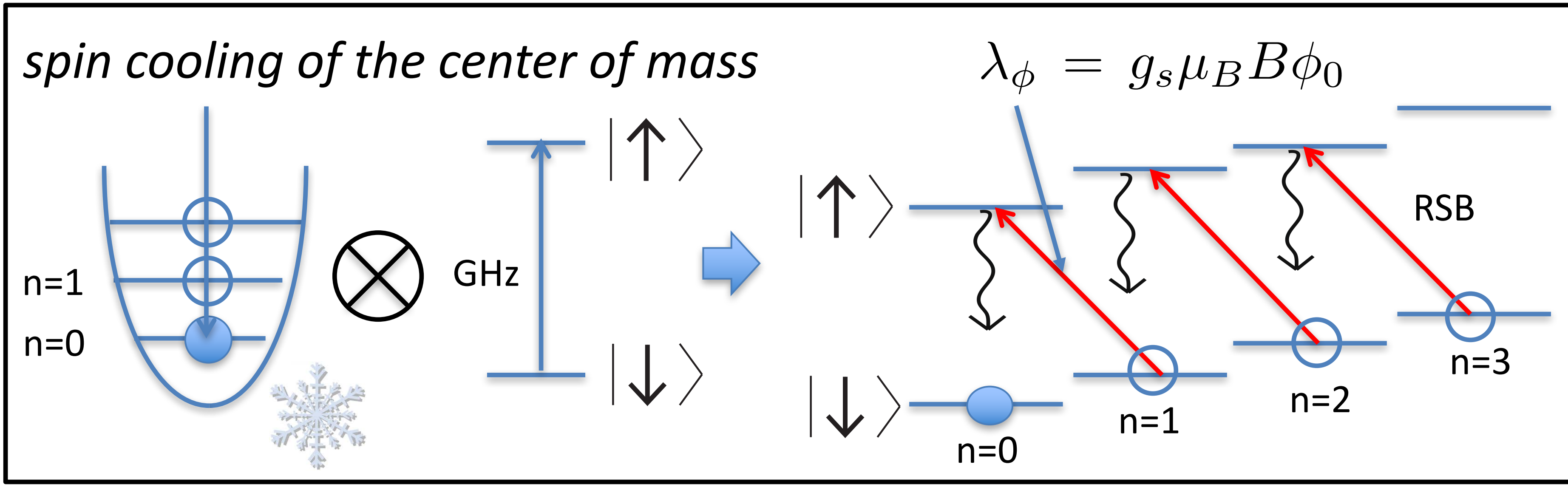
Quantum jump of a single photon !



Watching the life and death of a photon
Gleize et al. Nature *(2007) - S. Haroche's group*

Towards quantum optical experiments

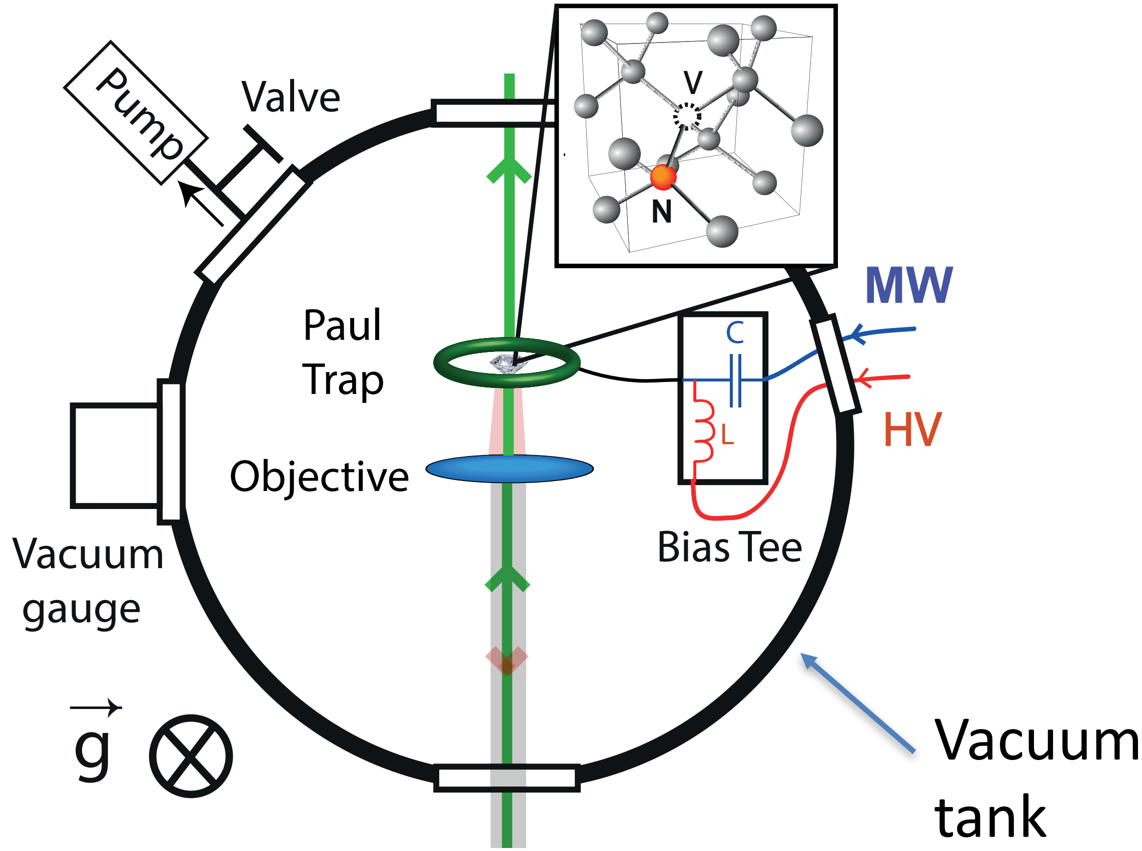
Ground state cooling



Use a single « atom » to cool the motion of thousands of atoms.
→ Picometer precision of a nanometer sized object.

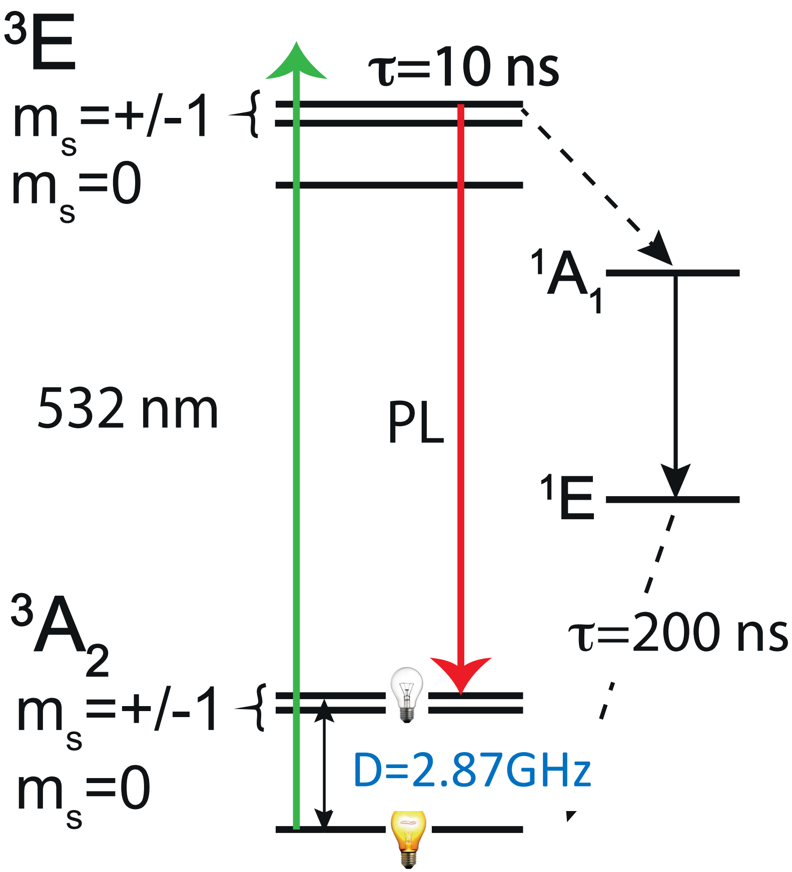
Final phonon number limited by the collision rate $1/\tau_{coll}$ with surrounding gaz particles. One needs $\lambda_\phi >> 1/\tau_{coll}$

Levitating diamonds under vacuum

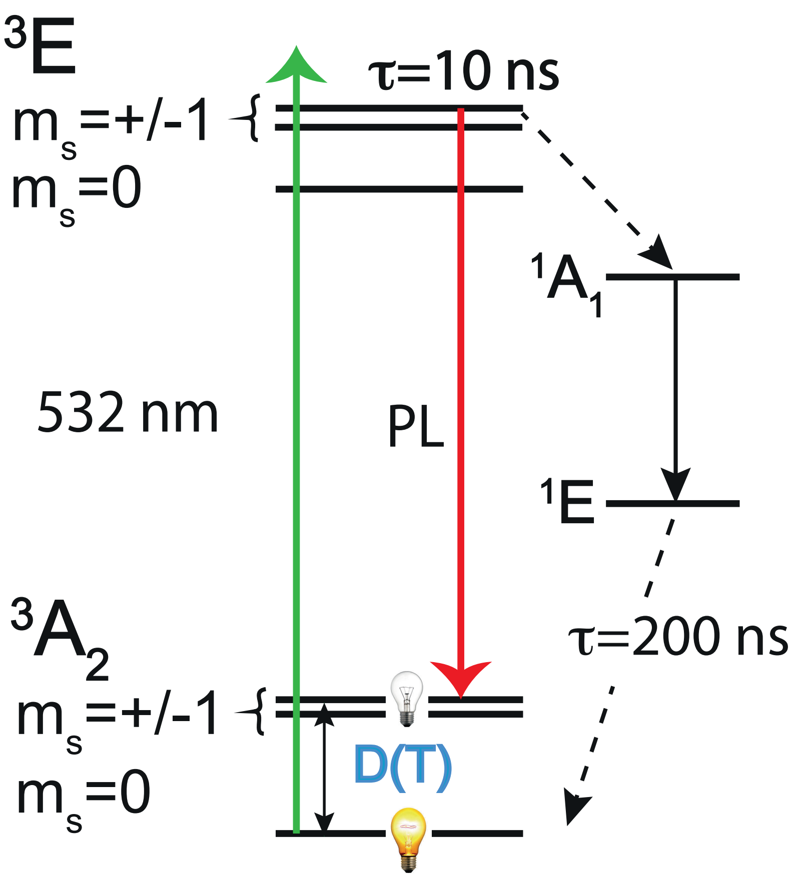


Diamonds levitating under vacuum

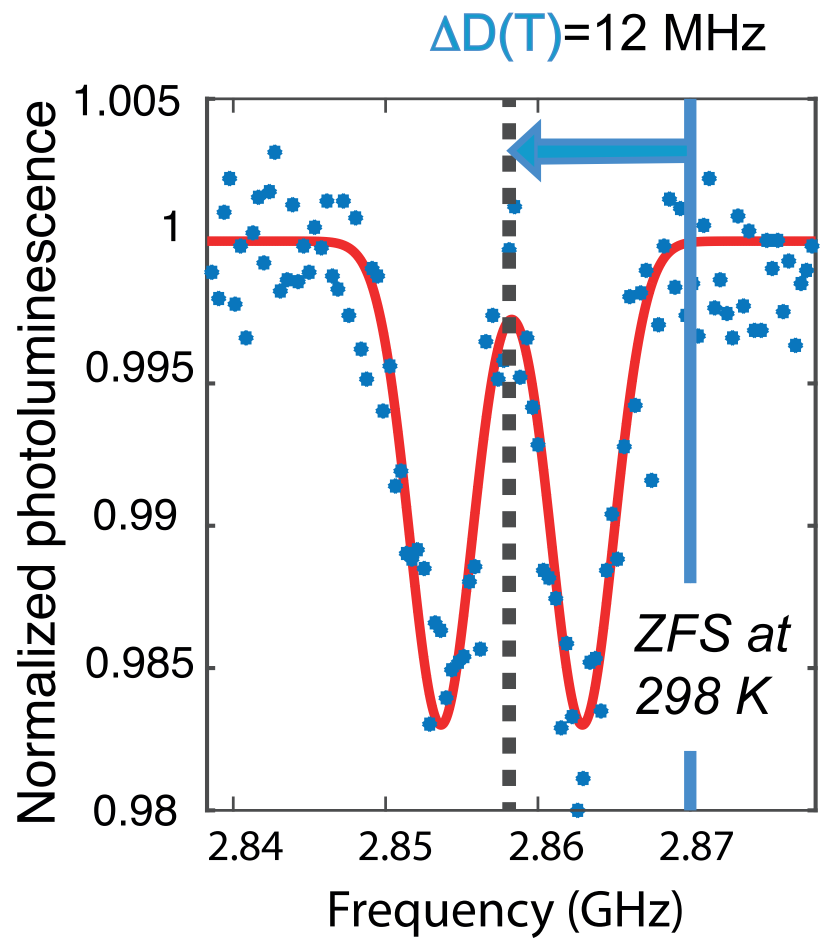
P= 1 bar



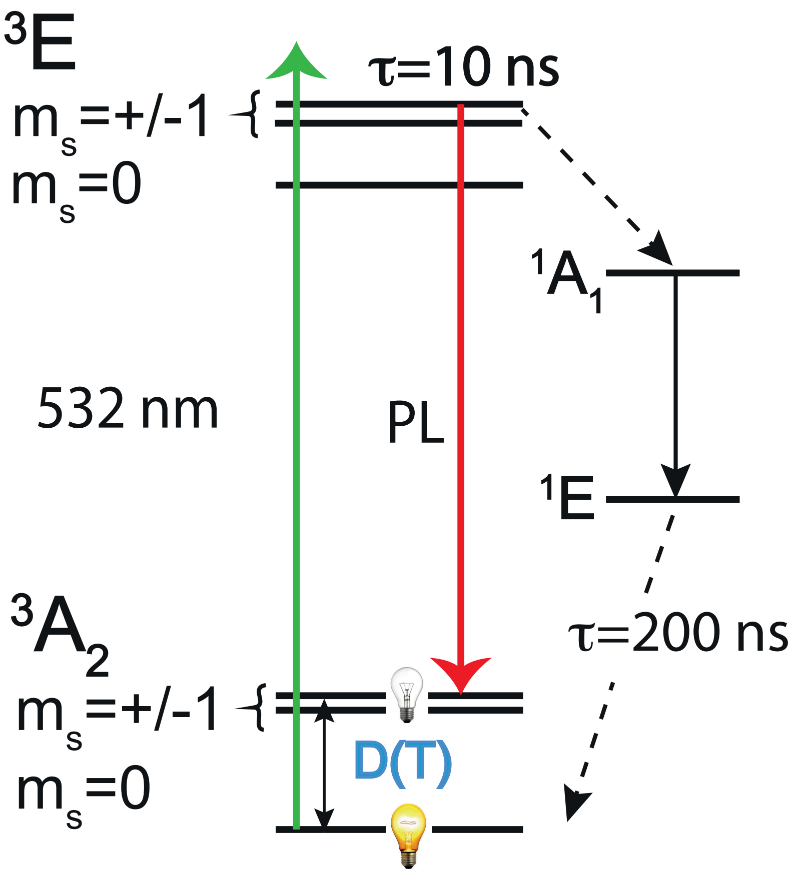
Diamonds levitating under vacuum



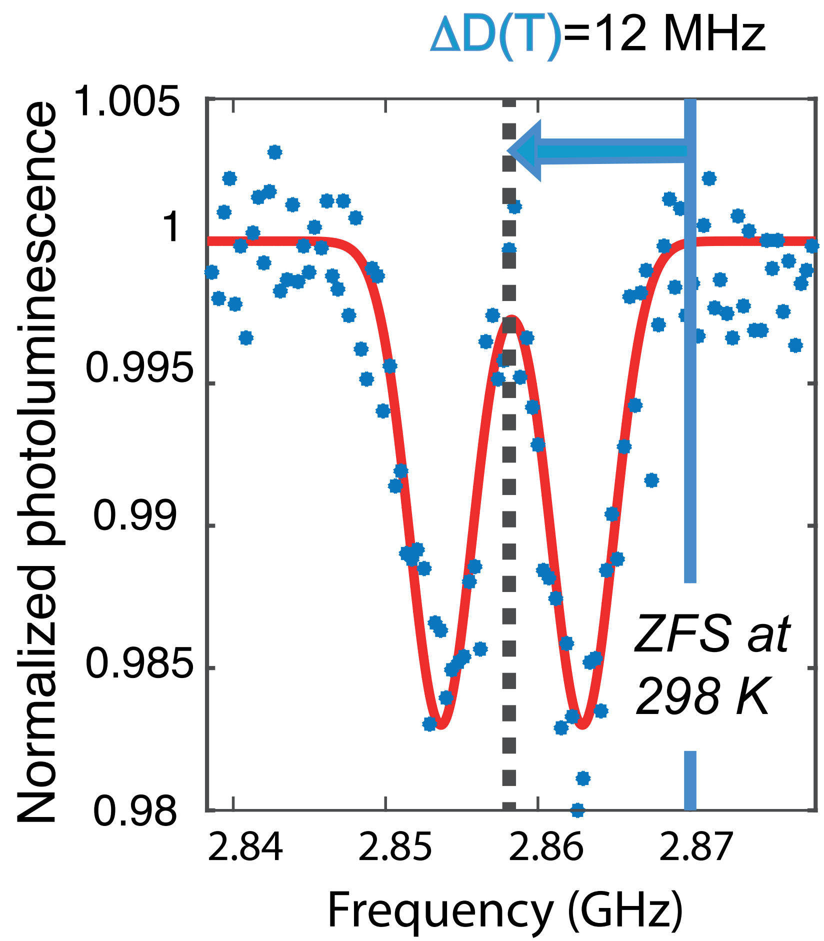
P= 0.1 mbar



Diamonds levitating under vacuum

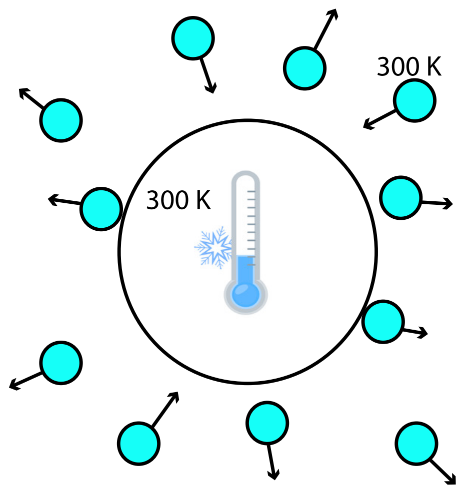


P= 0.1 mbar



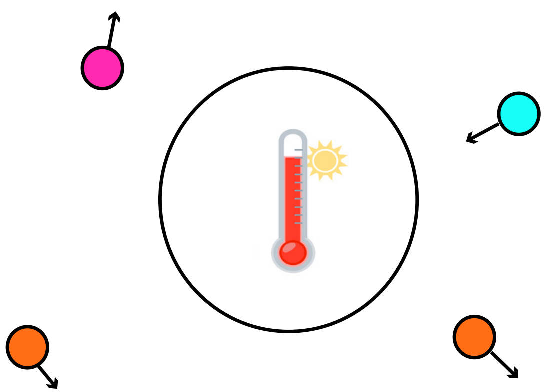
The diamond heats up !

NV thermometry



Thermalisation :

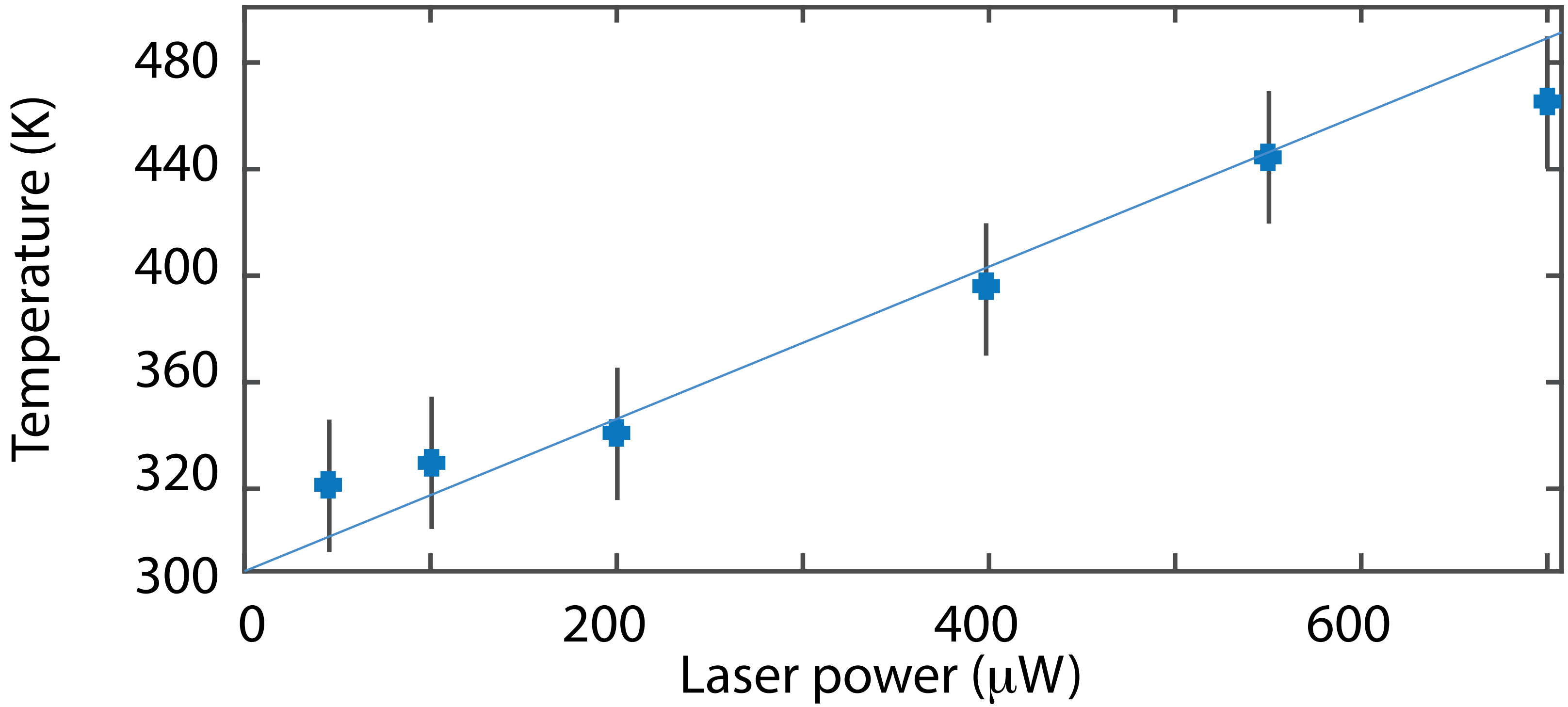
$T_{gaz} = T_{particle}$



Out of equilibrium :

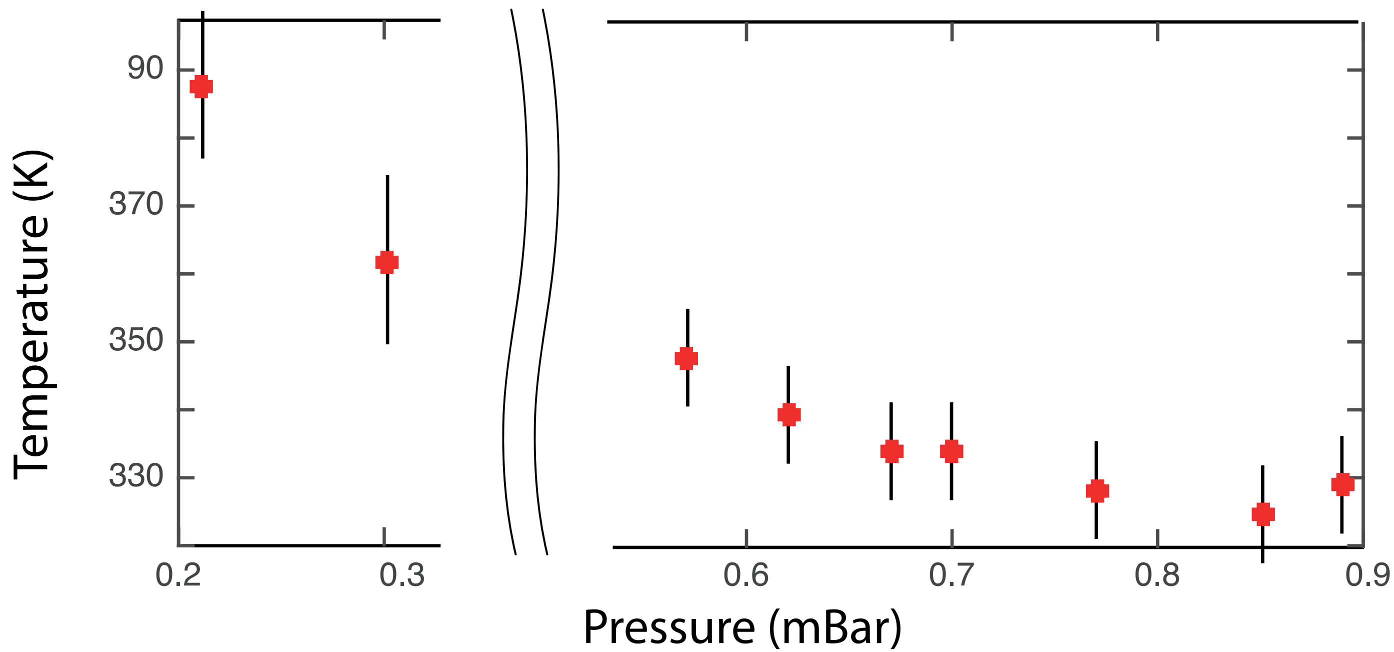
The particle can warm up significantly

NV thermometry



- Significant diamond heating at 0.1 mbar
- Depends linearly on the green laser power

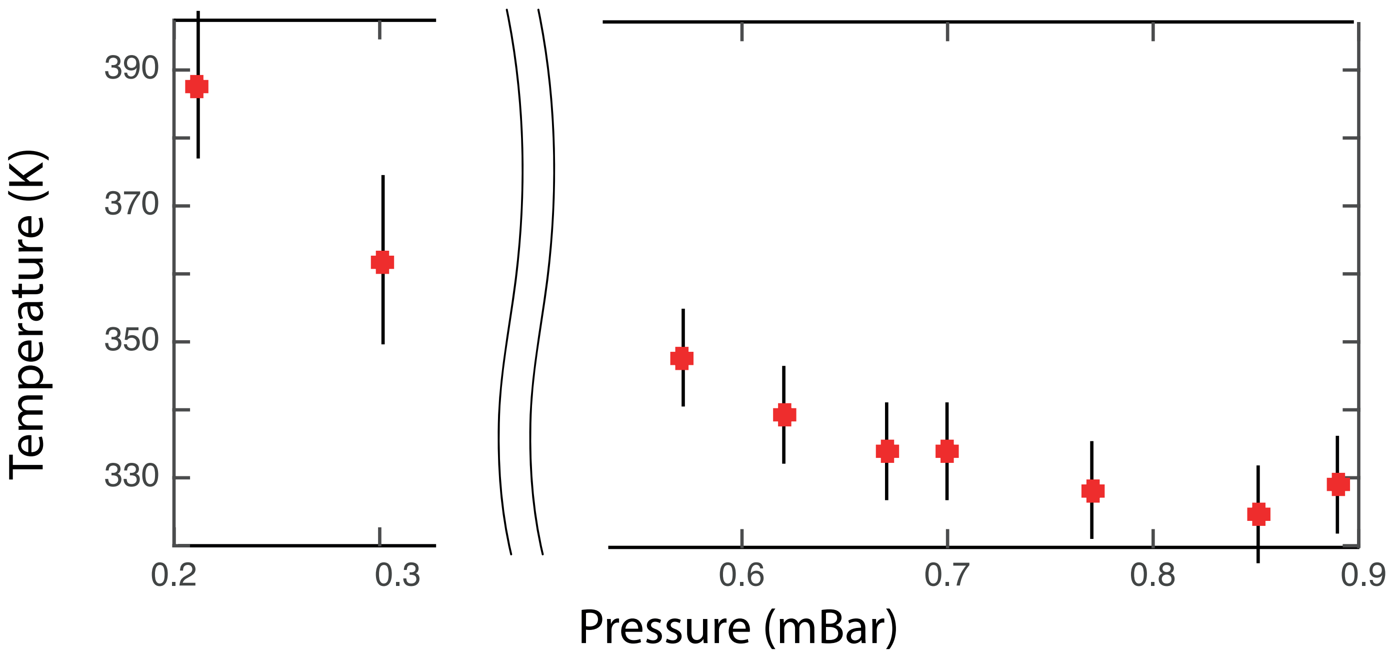
NV thermometry



- Heating depends on the gaz pressure

- At 0.01 mbars, the diamond escapes from the trap…

NV thermometry



→ **Solution :** use ultra-pur diamonds (CVD grown)

Conclusions / Perspectives

Conclusion :

- We observe efficient driving of NV centers in a diamond levitating in a Paul trap.
- The spin properties of deposited diamond particles are retained.
- We observed angle stability of single trapped monocrystals
  → *Necessary step towards spin-controlled levitating macroscopic objects.*
- NV spin enables reading locally the temperature of levitating objects

Perspectives :

- Increase the frequency → UV light, electron gun to increase the charge surface
- Ground state cooling of a massive object using a single electron
- Quantum non-demolition read-out of the collective modes

Conclusion

Collaborations :

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Loic Rondin (LAC, Paris)
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L. Guidoni
A. Tallaire (LSPM- Villetaneuse)
P. Maletinsky (Basel)
C. Becher(Saarbrücken)

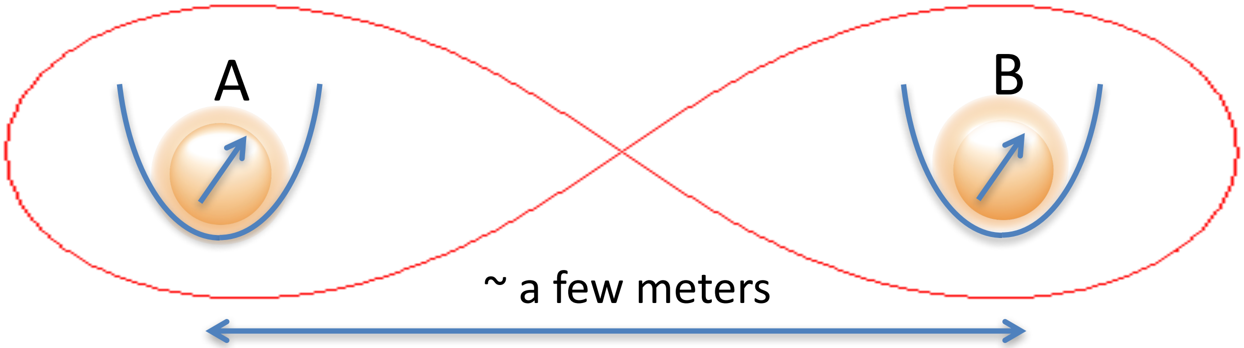
Team : Baptiste Vindolet, Tom Delord, Lucien Schwab, Martina Bodini, Louis Nicolas

Optics team at LPA :

Laboratoire Pierre Aigrain

ENS

Aim 3: Entangle the motion of distant macroscopic objects



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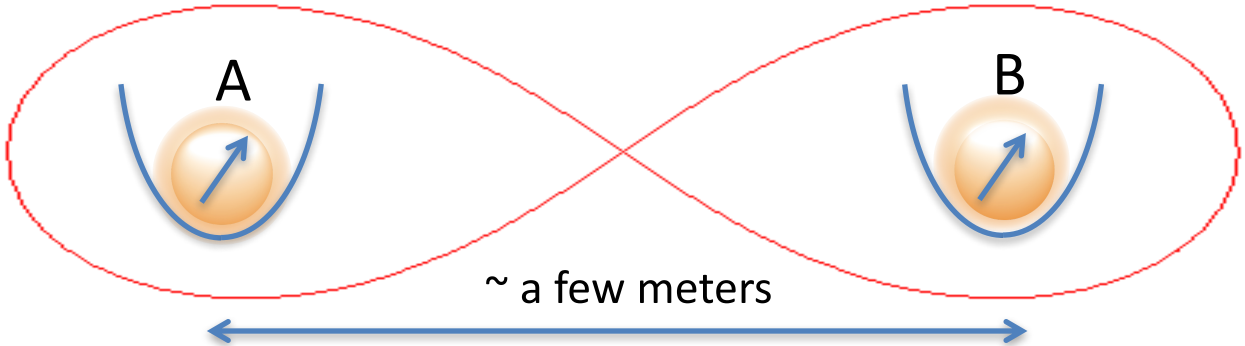
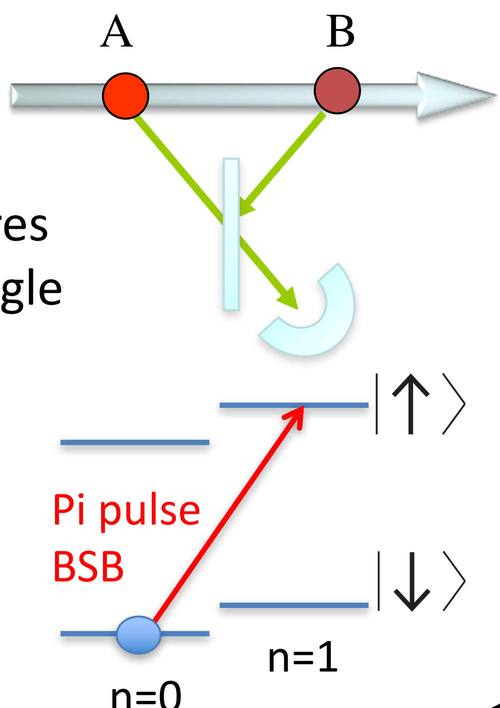


Methodology :

→ Entangle the spins from distant NV centres in diamonds using single photon scattering

→ Transfer spin entanglement to motional entanglement



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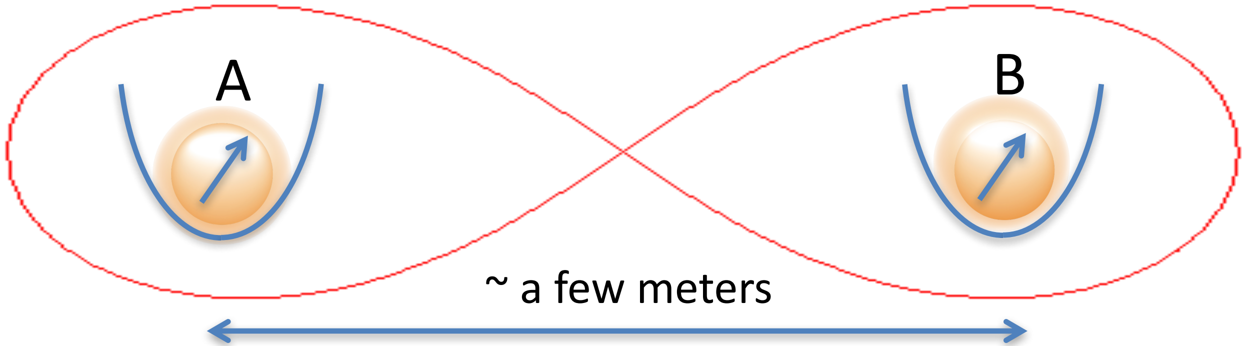
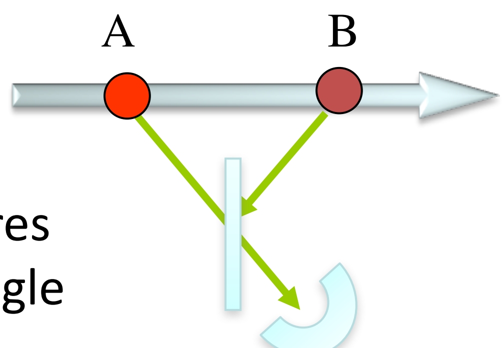


Methodology :



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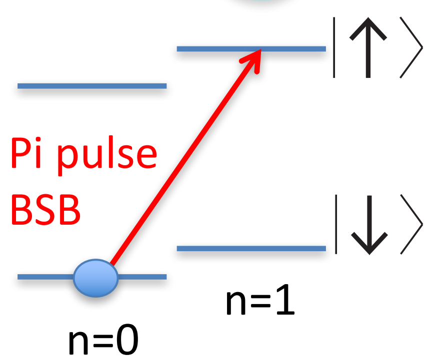
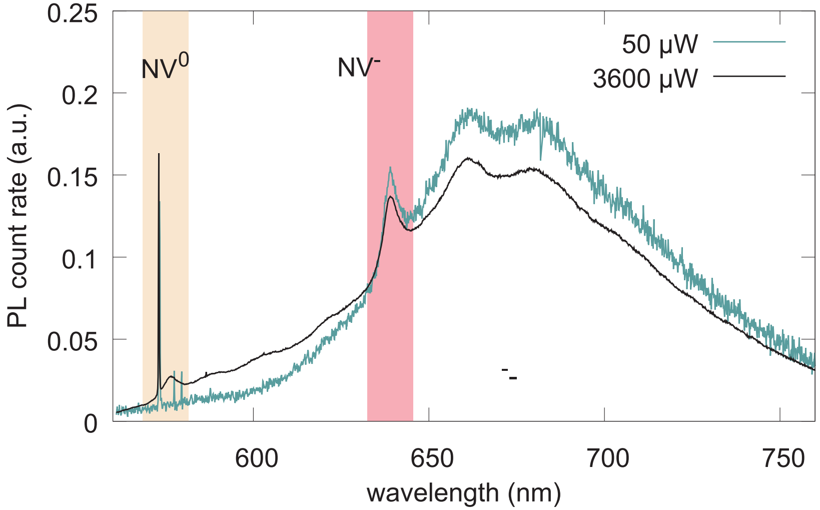


Implications :

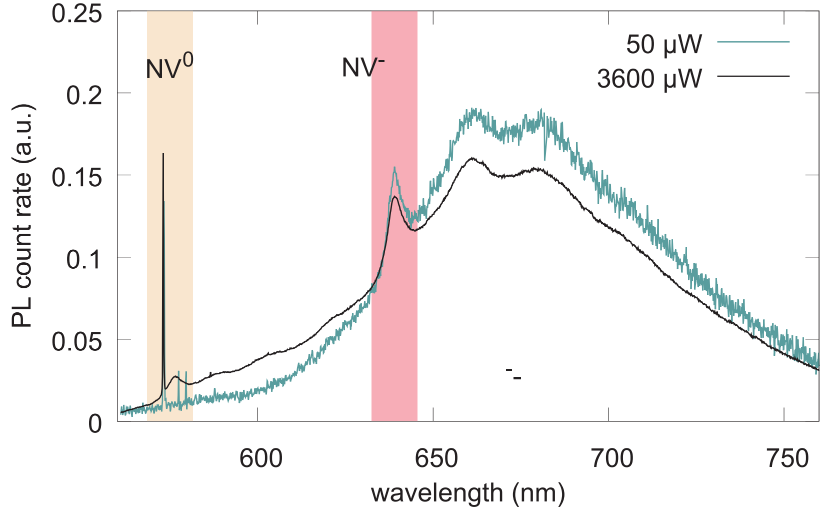
- Long lived entangled state → quantum memory
- Quantum information
- Sensitive detection of gravitational effects

Optical spectra

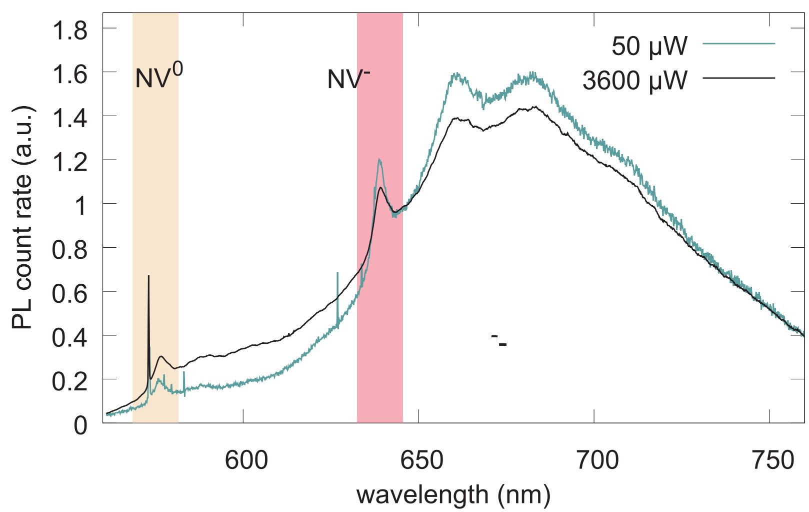


NV spectra from deposited nanodiamonds on
a quartz coverslip

Optical spectra



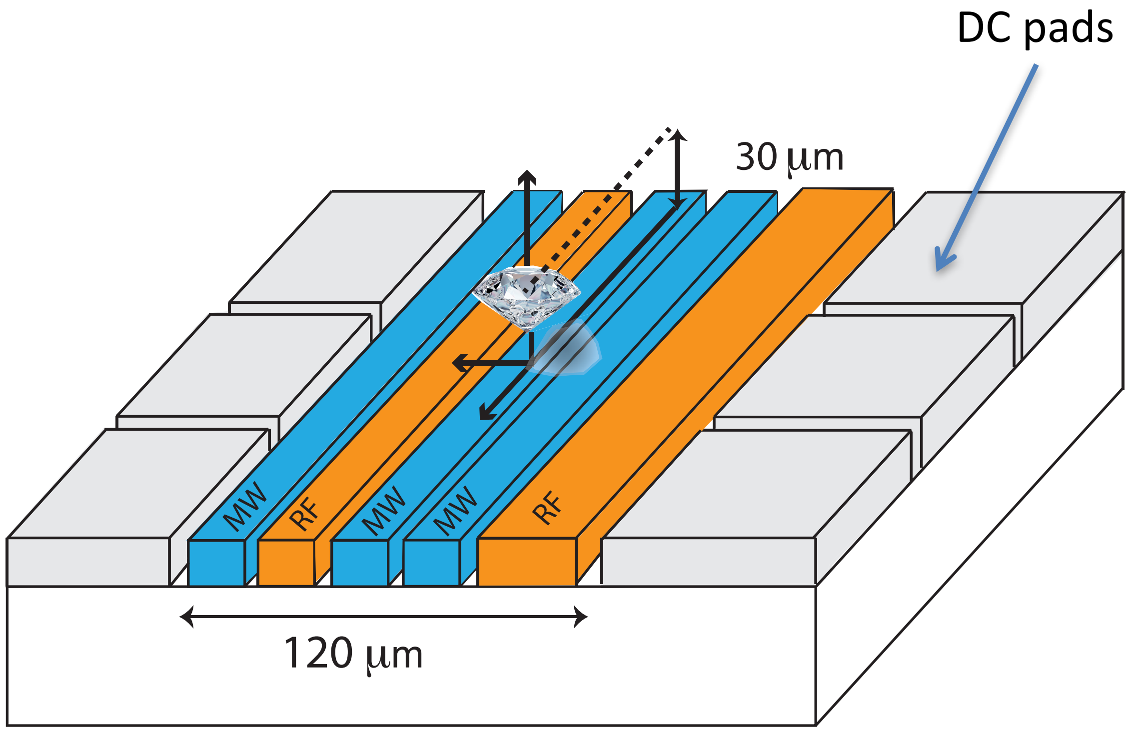
NV spectra from deposited nanodiamonds on a quartz coverslip



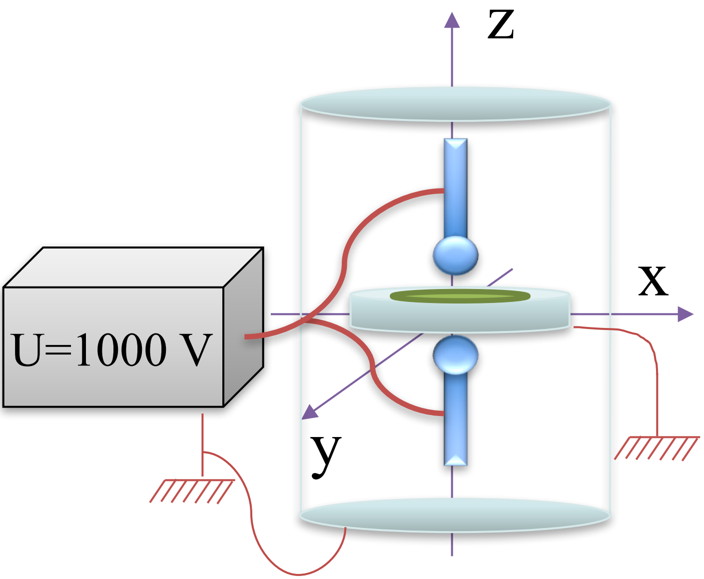
NV spectra from levitating nanodiamonds

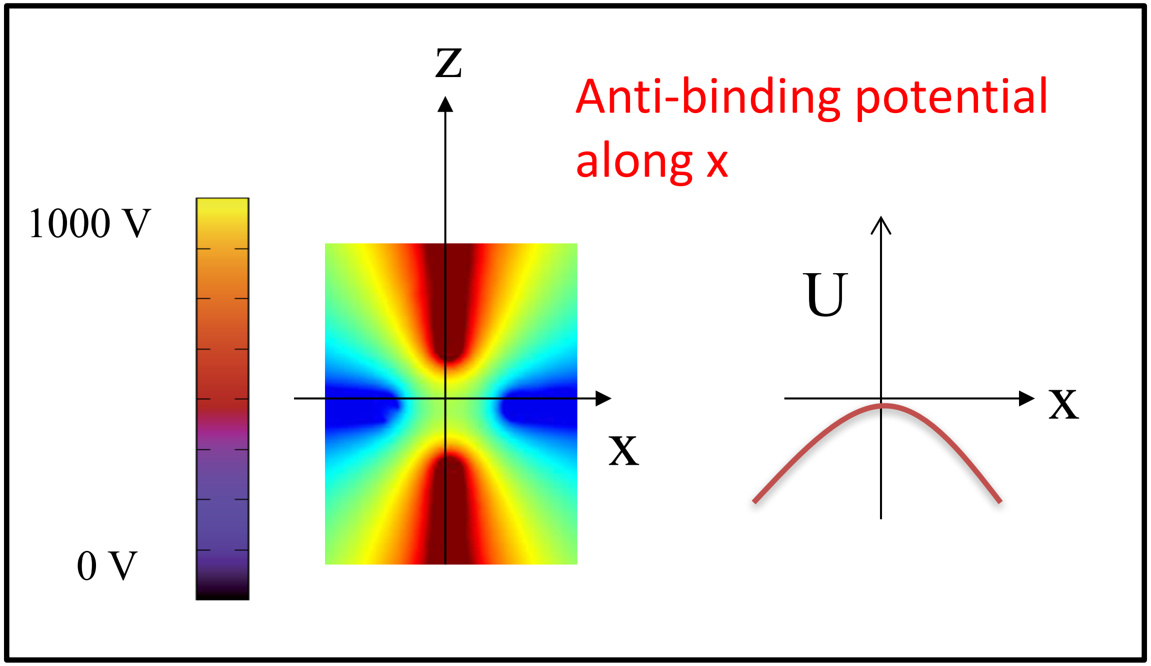
No apparent change in the photophysical properties

2D trap



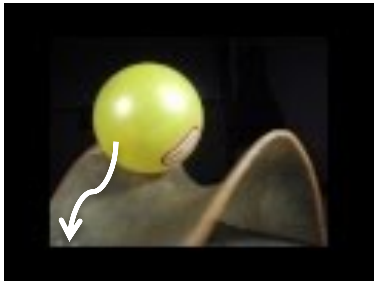
The electrodynamical trap





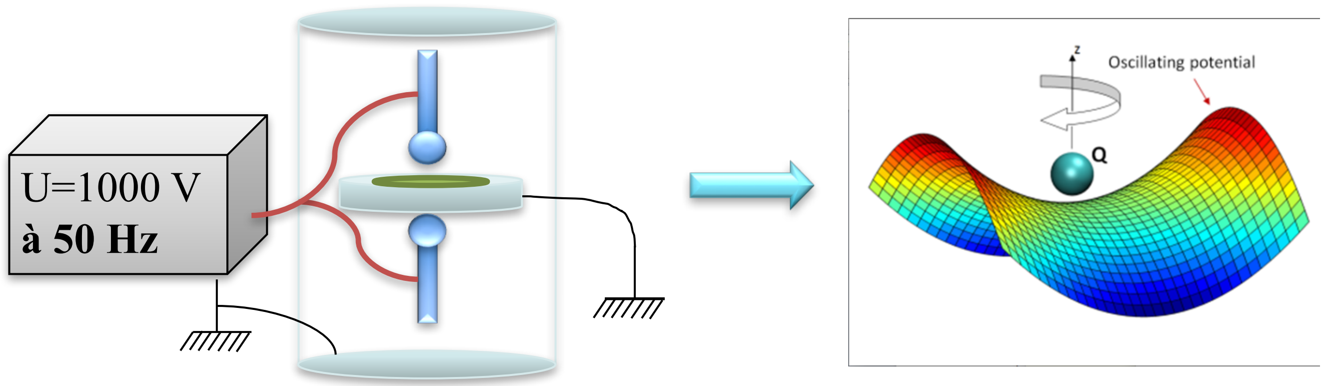
General law of electrostatics

Whatever the geometry, at least one direction will not be confining



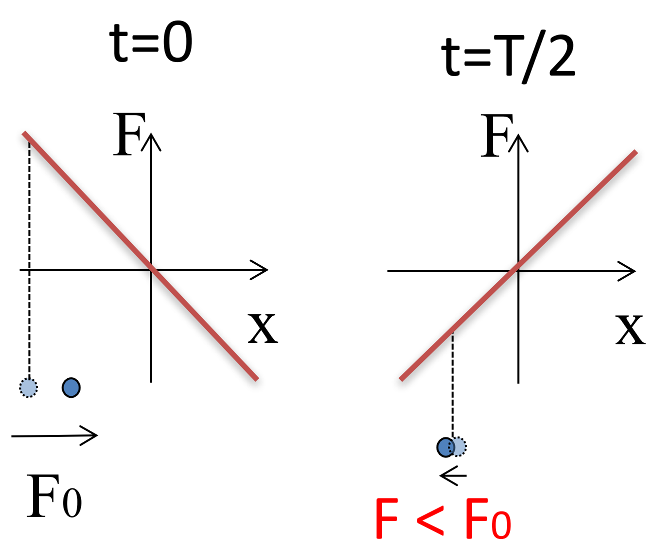
The electrodynamical trap

Idea (W. Paul 1967), use oscillating electric field

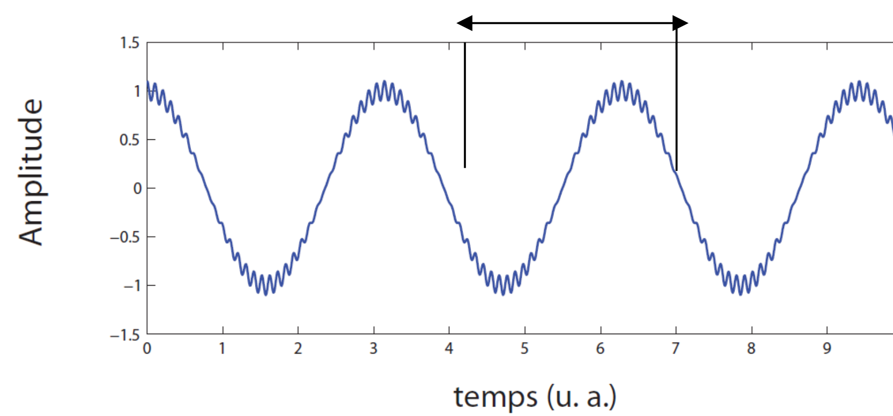


But why should the force that pushes the particule towards the center win over the one that pushes it away ?
One could expect no net force.

One dimensional case :



On average over one cycle, there is a restoring force due to the fast oscillating field.



Over one cycle, the force that brings the particle to the center is always greater

Dynamical stabilisation

The *micromotion induced by the* fast oscillatin

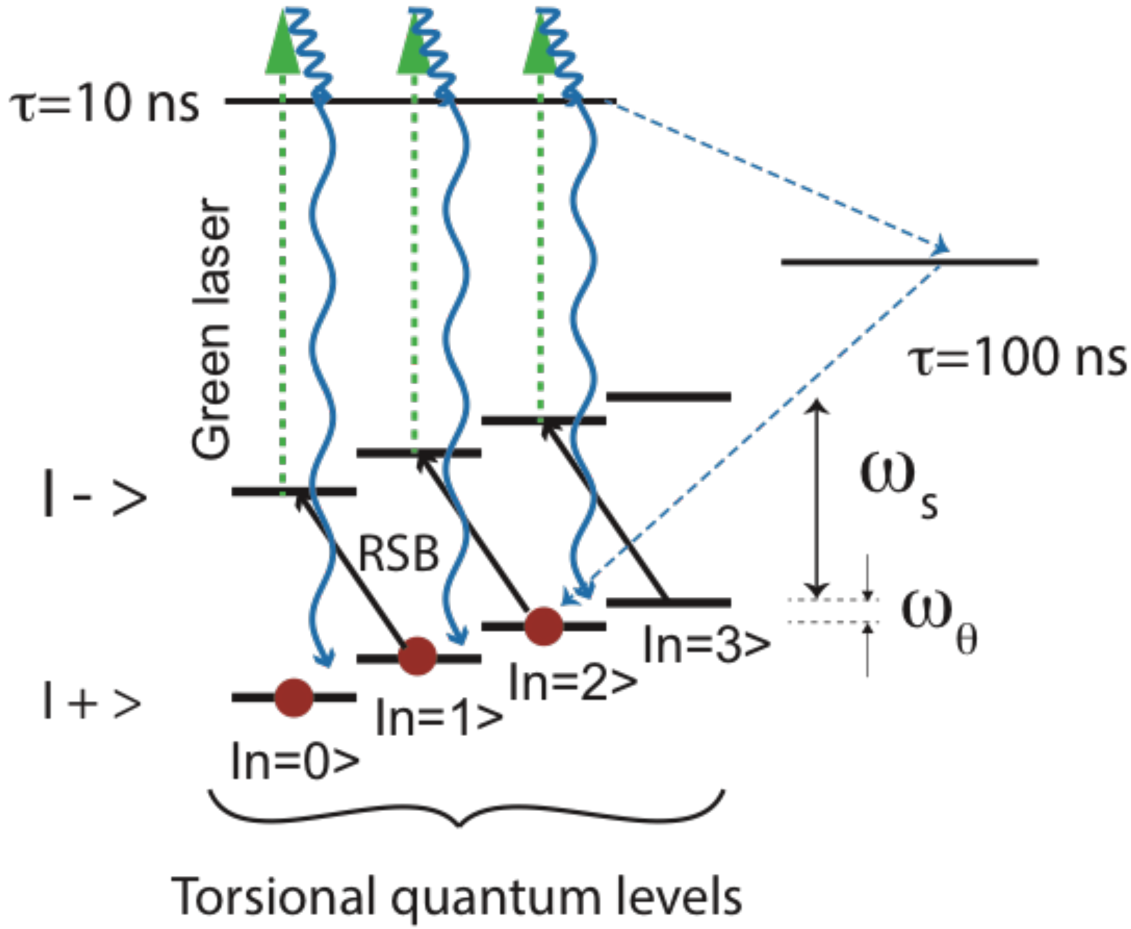
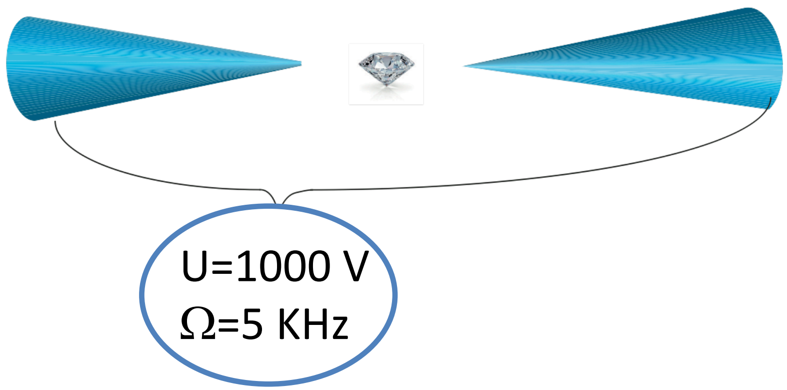
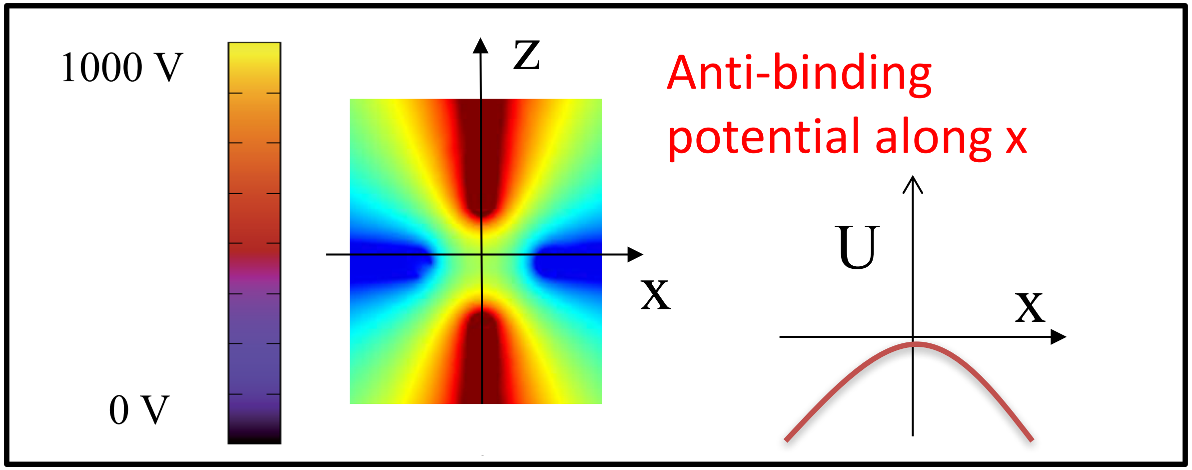


FIG. 2: Principle of hybrid torsional cooling.

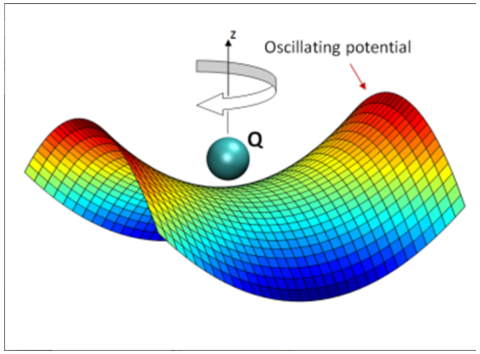
The Paul trap



- High optical access
- Tunable trap parameters after injection
- Ambient conditions



W. Paul (1967) proposed to use oscillating electric fields. :



Whatever the geometry, at least one direction will not be confining → General law of electrostatics

Radiation pressure force :

$$
\begin{aligned}
F_{rad} &= \int_{-\theta_m}^{\theta_m} \frac{h}{\lambda} 2R_n \cos\theta \frac{P\lambda}{hc} \frac{d\theta}{2\theta_m} \\
&= \frac{2R_n P}{c} \mathrm{sinc}(\theta_m).
\end{aligned}
$$

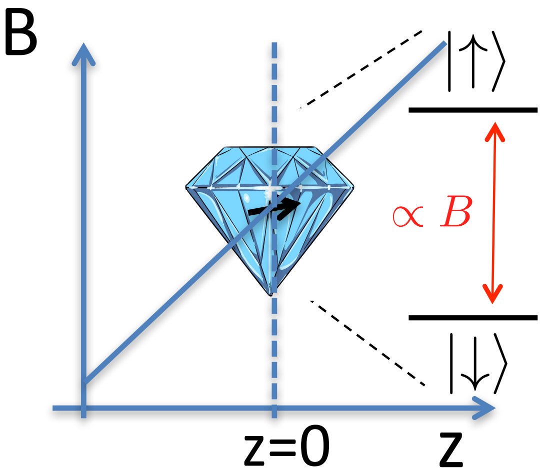
Displacement due to the laser

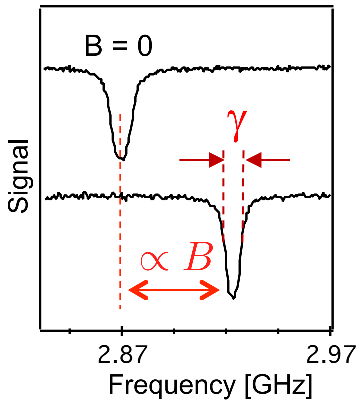
$$\Delta x = \frac{F_{rad}}{m\omega_x^2}$$

$\Delta x / P \sim 350\ \mathrm{nm/mW}$ For a micron size particule

$\Delta x / P \sim 11\ \mu\mathrm{m/mW}$ For a particule size of 100 nm

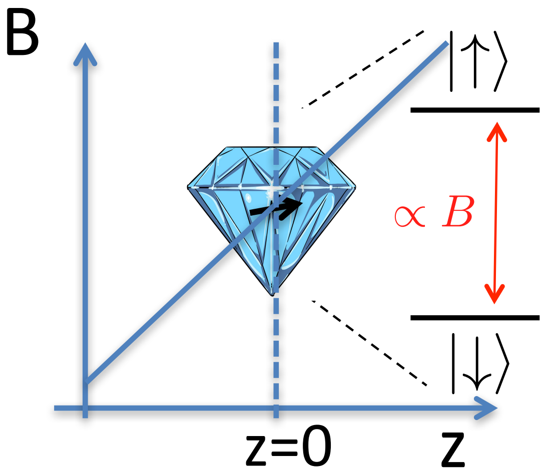
Coupling to the center of mass via the NV spin

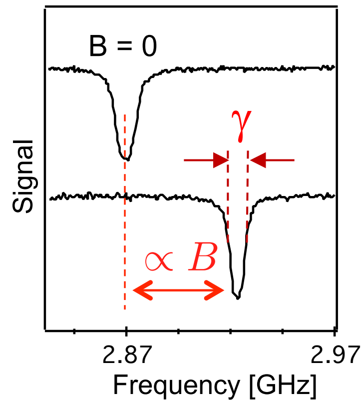




Frequency shift proportional to the displacement

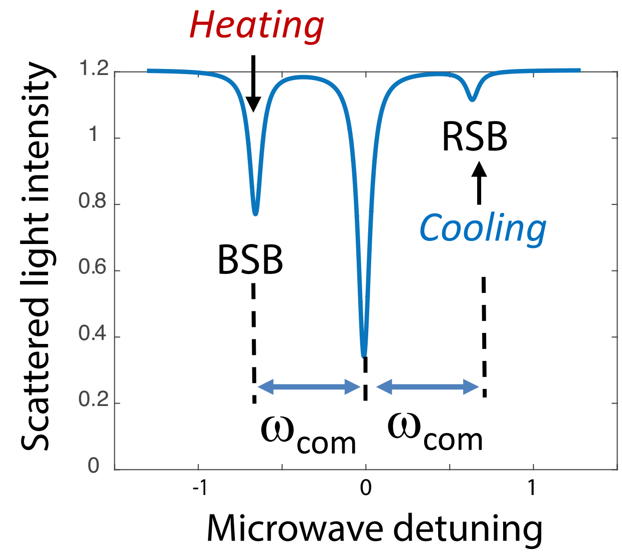
Coupling to the center of mass via the NV spin

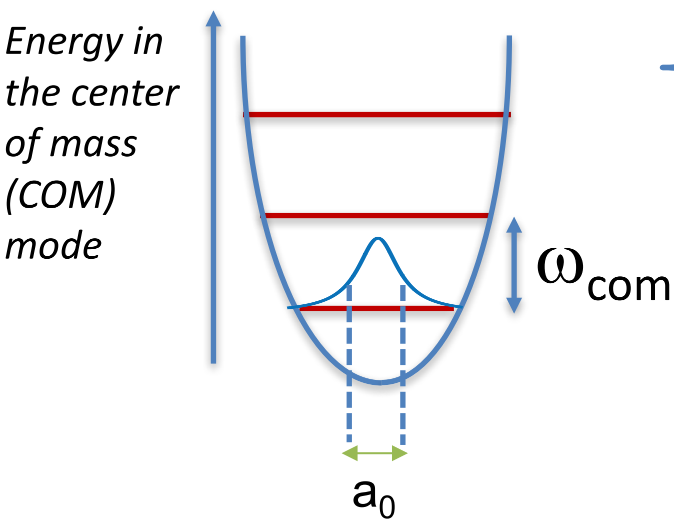




Frequency shift proportional to the displacement

Non-adiabatic regime : $\omega_{com} >> \gamma$





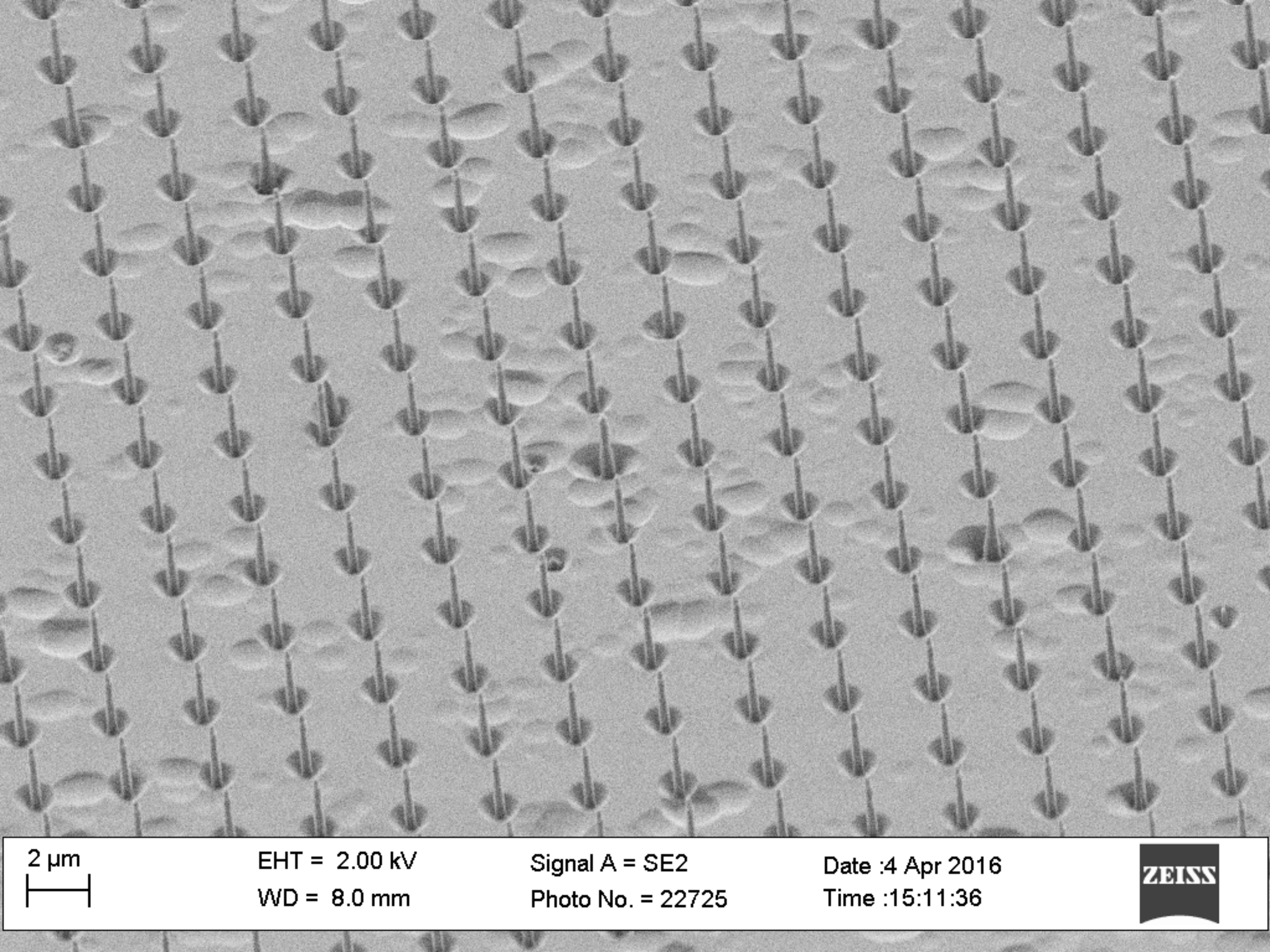
The Hamiltonian :

$$H_{\text{int}} = \vec{\mu} \cdot \vec{B} = \lambda_{\text{com}} S_z (a + a^\dagger)$$

Coupling rate to the the COM mode :

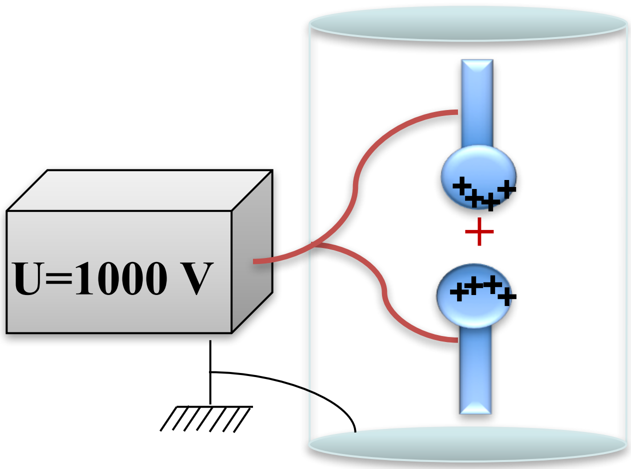
$$\lambda_{com} = g_s \mu_B G_m a_0 \longrightarrow \quad a_0 = \sqrt{\hbar / 2m\omega_{com}}$$

P. Rabl et al. ***PRB*** *(2009)*


2 µm
EHT = 2.00 kV
WD = 8.0 mm
Signal A = SE2
Photo No. = 22725
Date :4 Apr 2016
Time :15:11:36
ZEISS

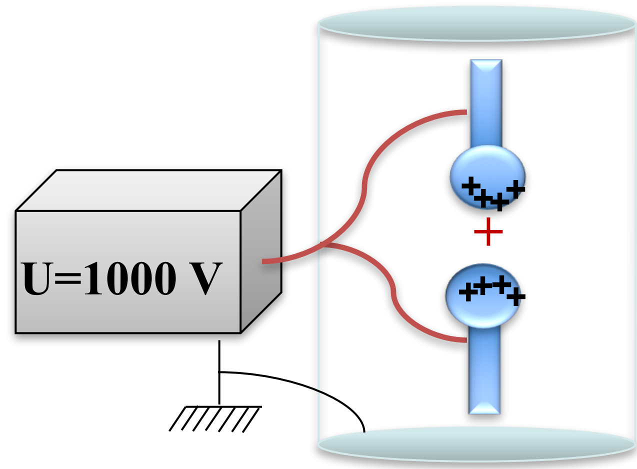
How to trap a charged particle ?

Static Coulomb force :



How to trap a charged particle ?

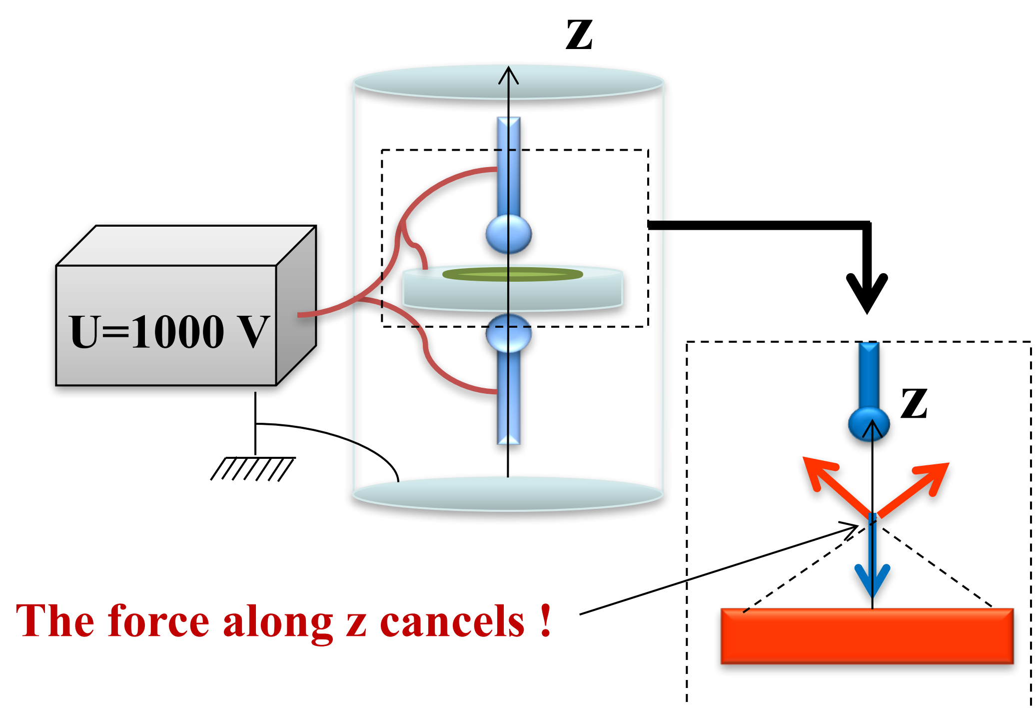
Static Coulomb force :



Restoring force in the 3 directions of space :

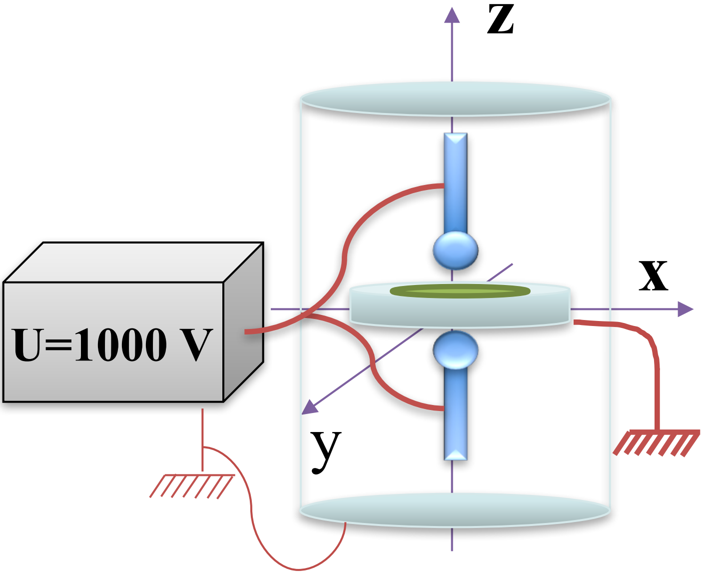
Confinement along the ring plane.

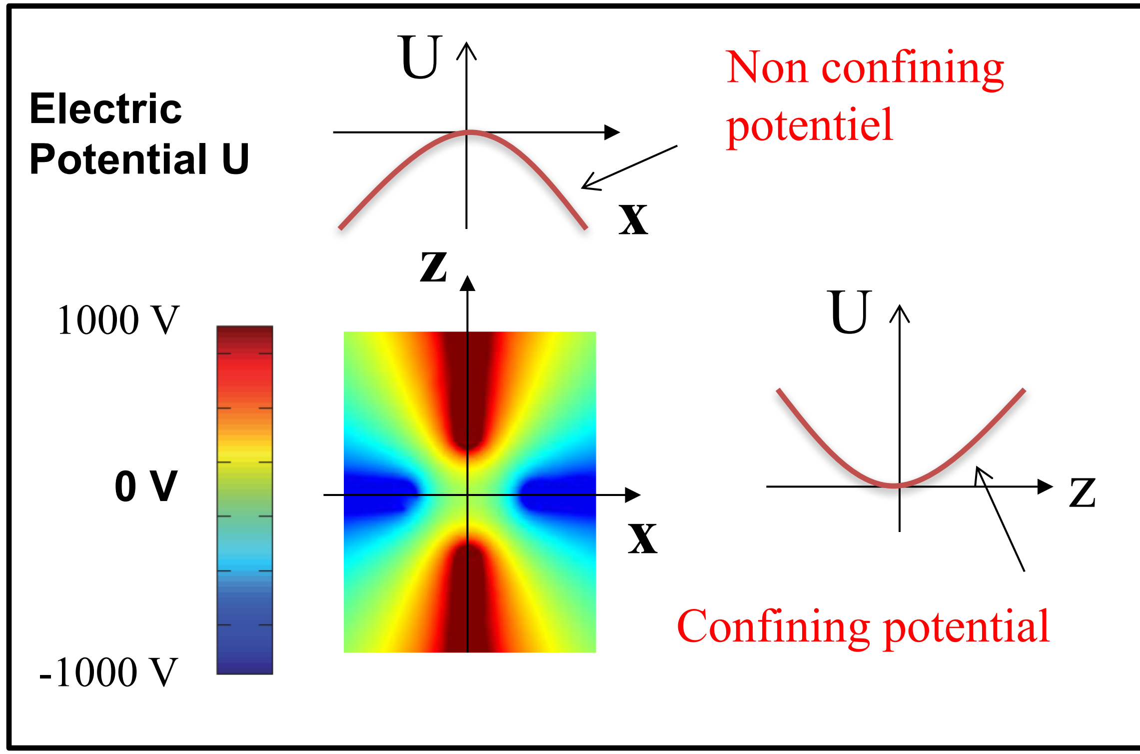
But no confinement along the z direction anymore :(



How to trap a charged particle ?

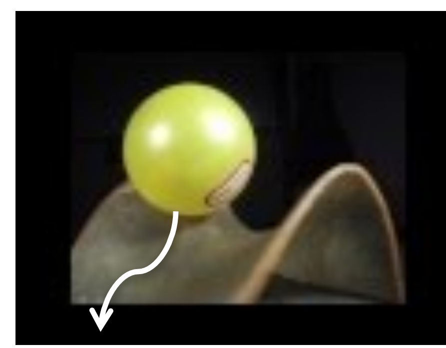
Other possibility :





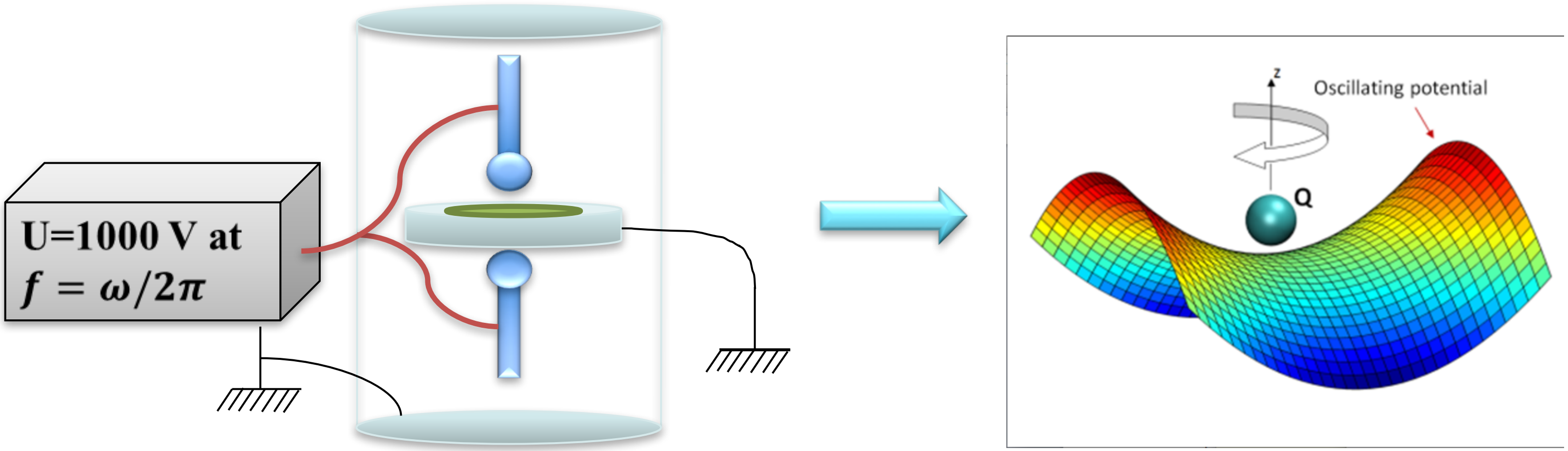
In electrostatics, whatever the geometry, at least one direction will not be confining!

Consequence of the conservation of the electric flux on a closed surface ⟶ $\oiint \vec{E} \cdot \vec{dS} = 0$



Solution ?

In statics, one cannot confine a charged particle.
Idea : **make the electric field oscillate.**



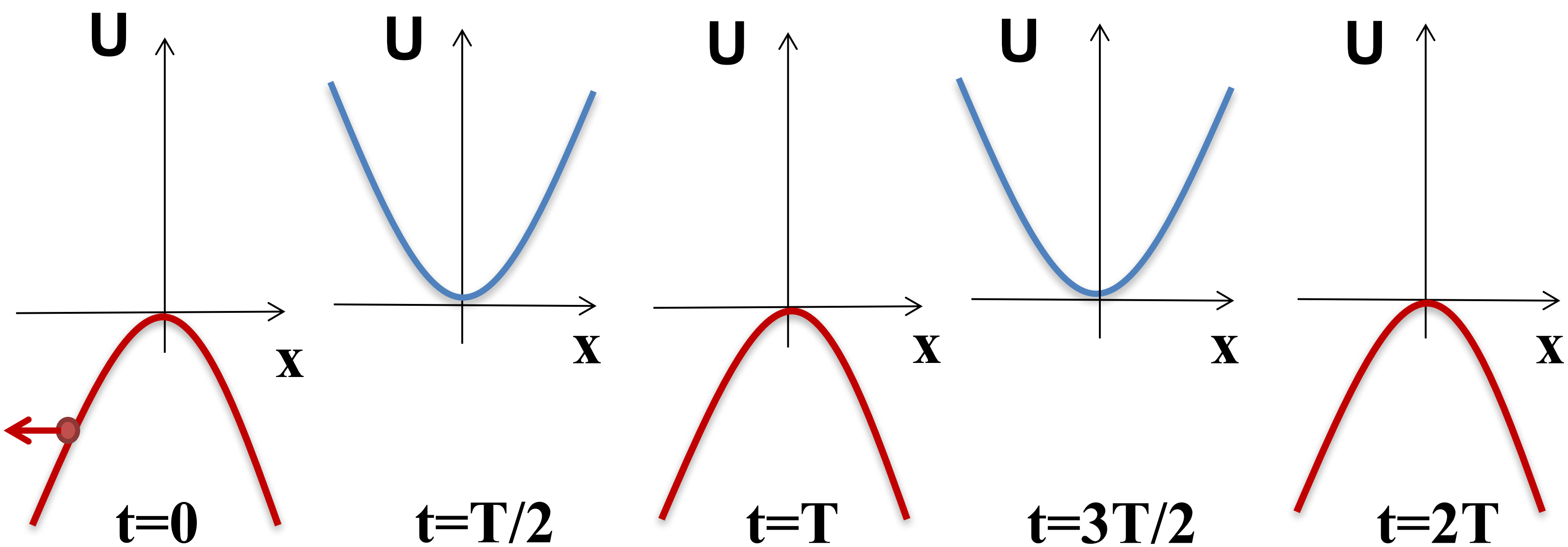
One can feel that the electric field has to oscillate more rapidly than the period $T_s = 2\pi/\omega_0$ in statics.

However, a priori, one cannot see why the force that brings the particle towards the center would compensate the force that pushes it away from it

One dimensional case

$F = -kx\ \cos(\omega t)$ **where k depends on the tension applied to the electrode.**

During one cycle of oscillation with a period $T = \frac{2\pi}{\omega} \ll T_s = \sqrt{\frac{m}{k}}$



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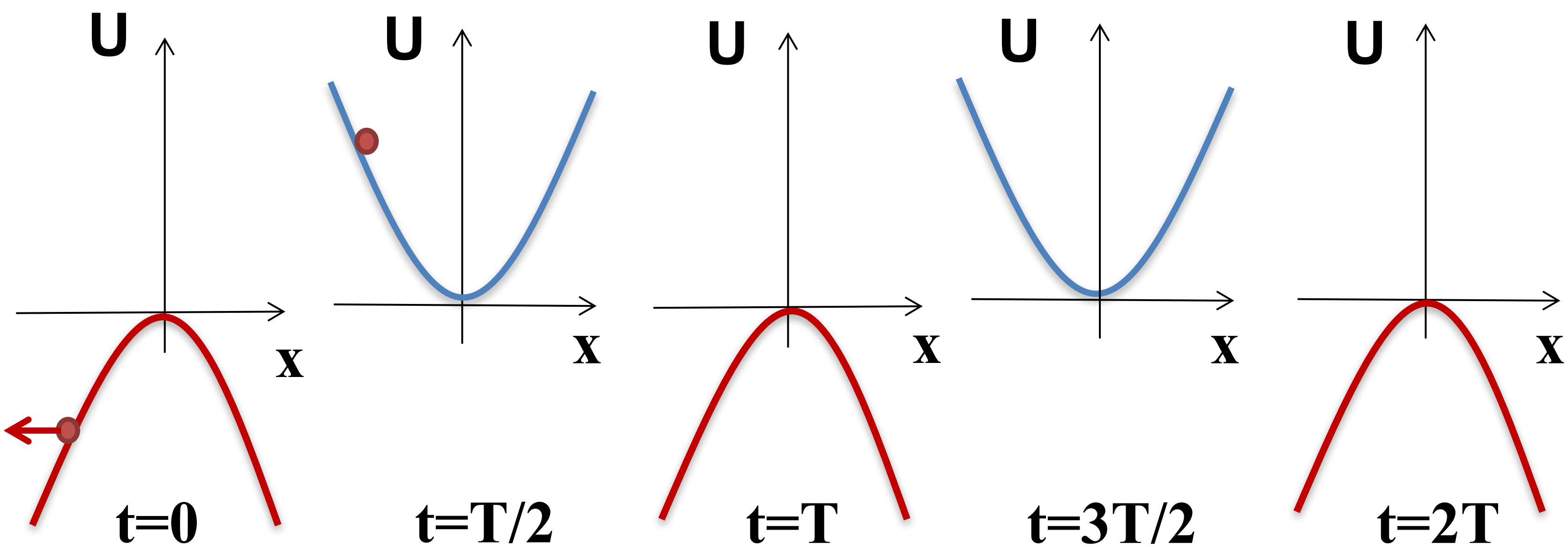

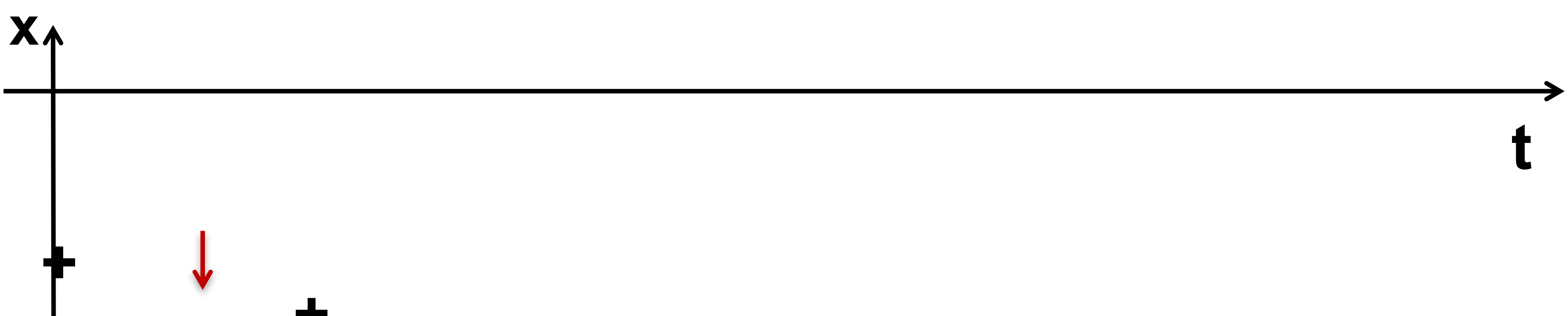

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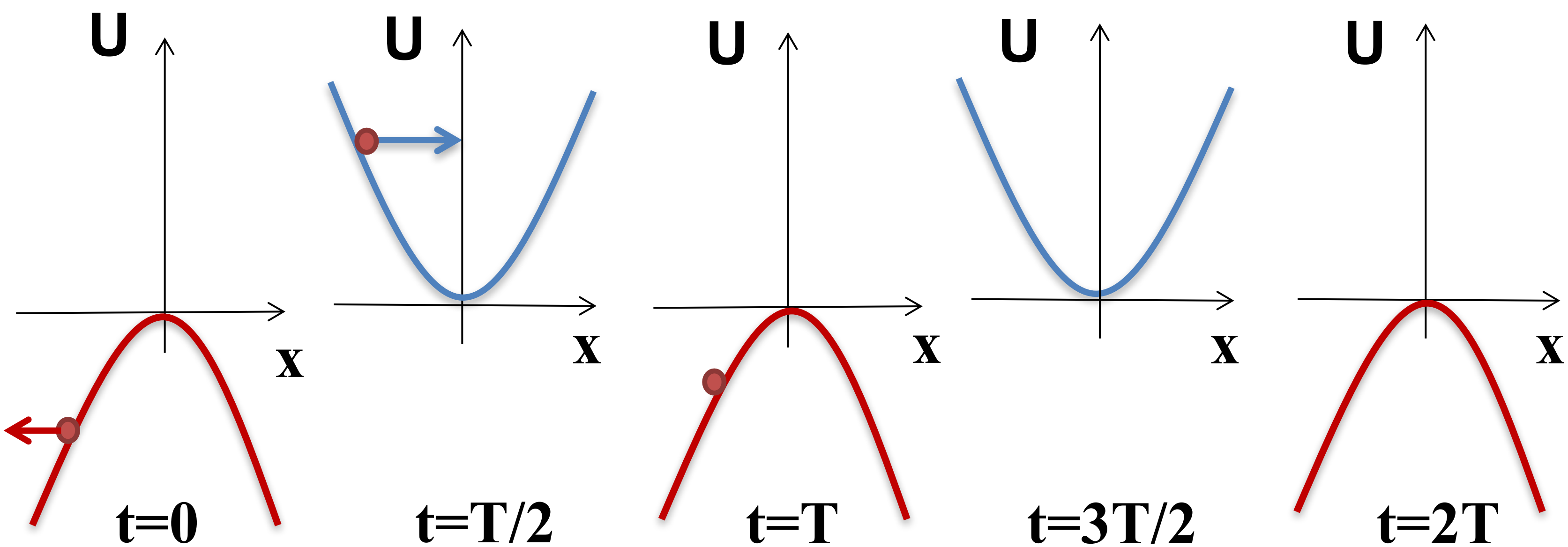

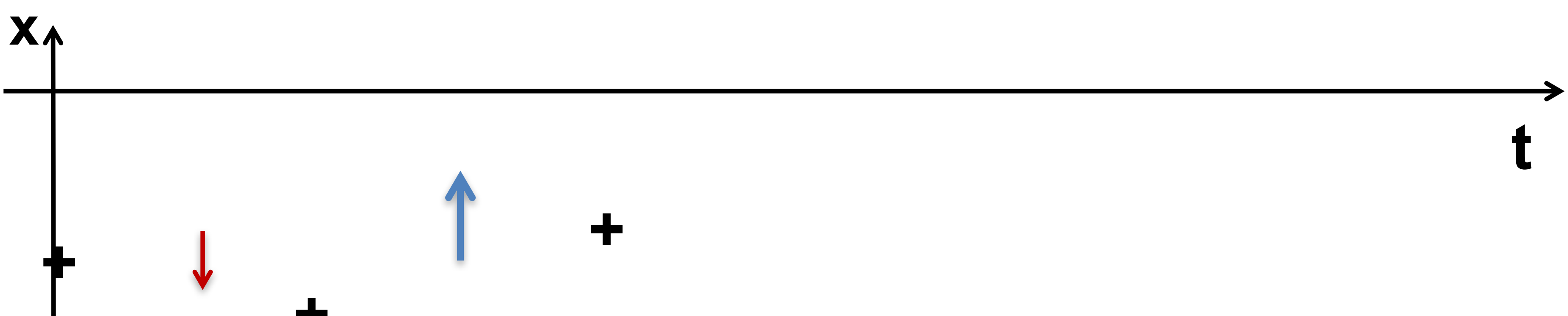

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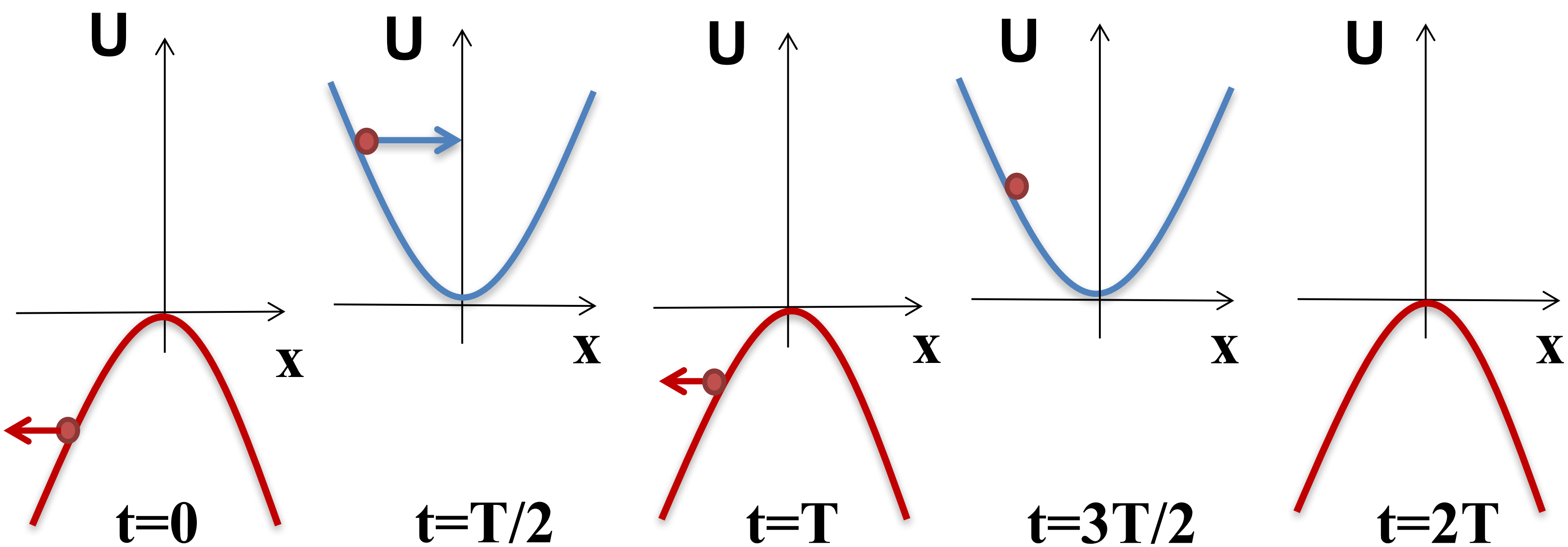

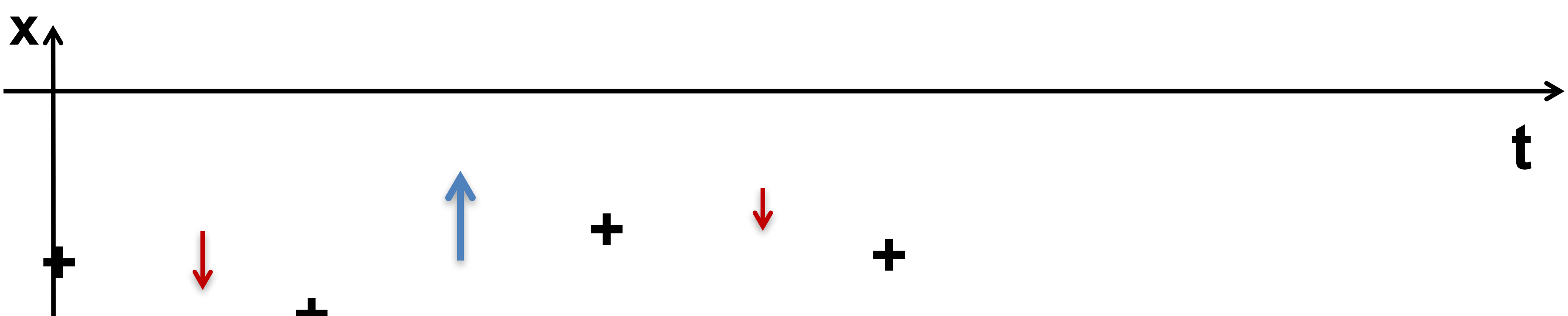

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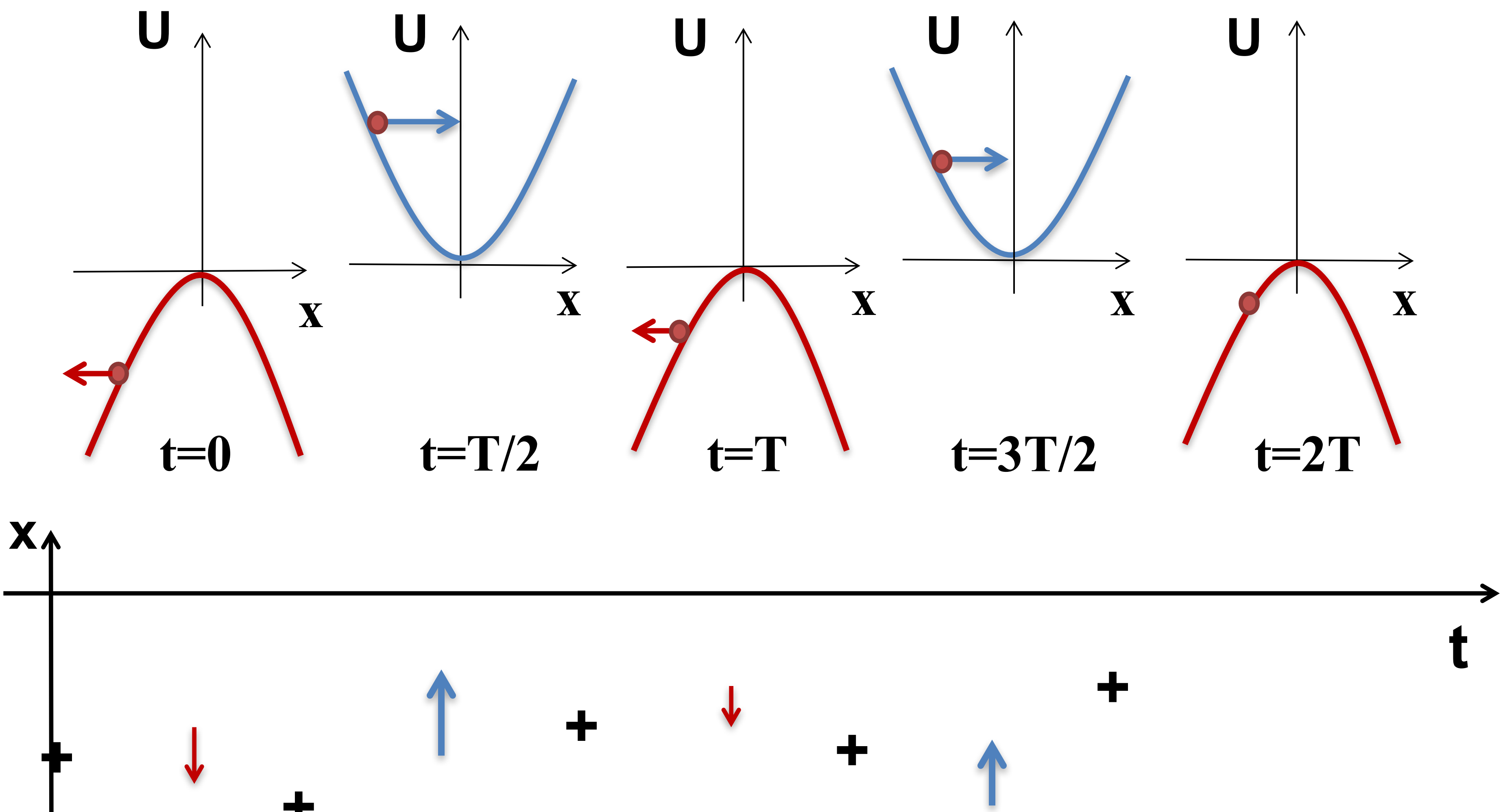

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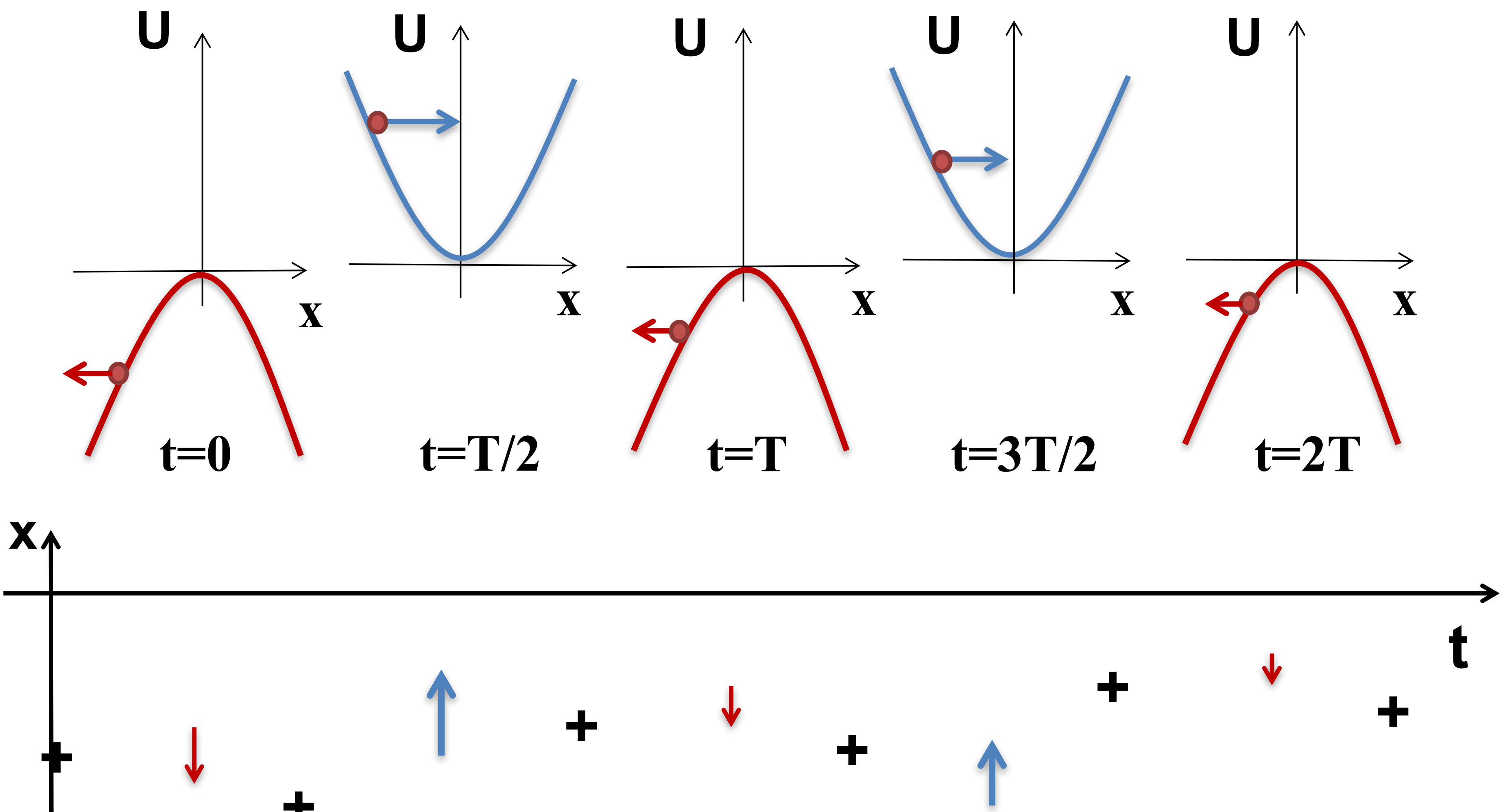

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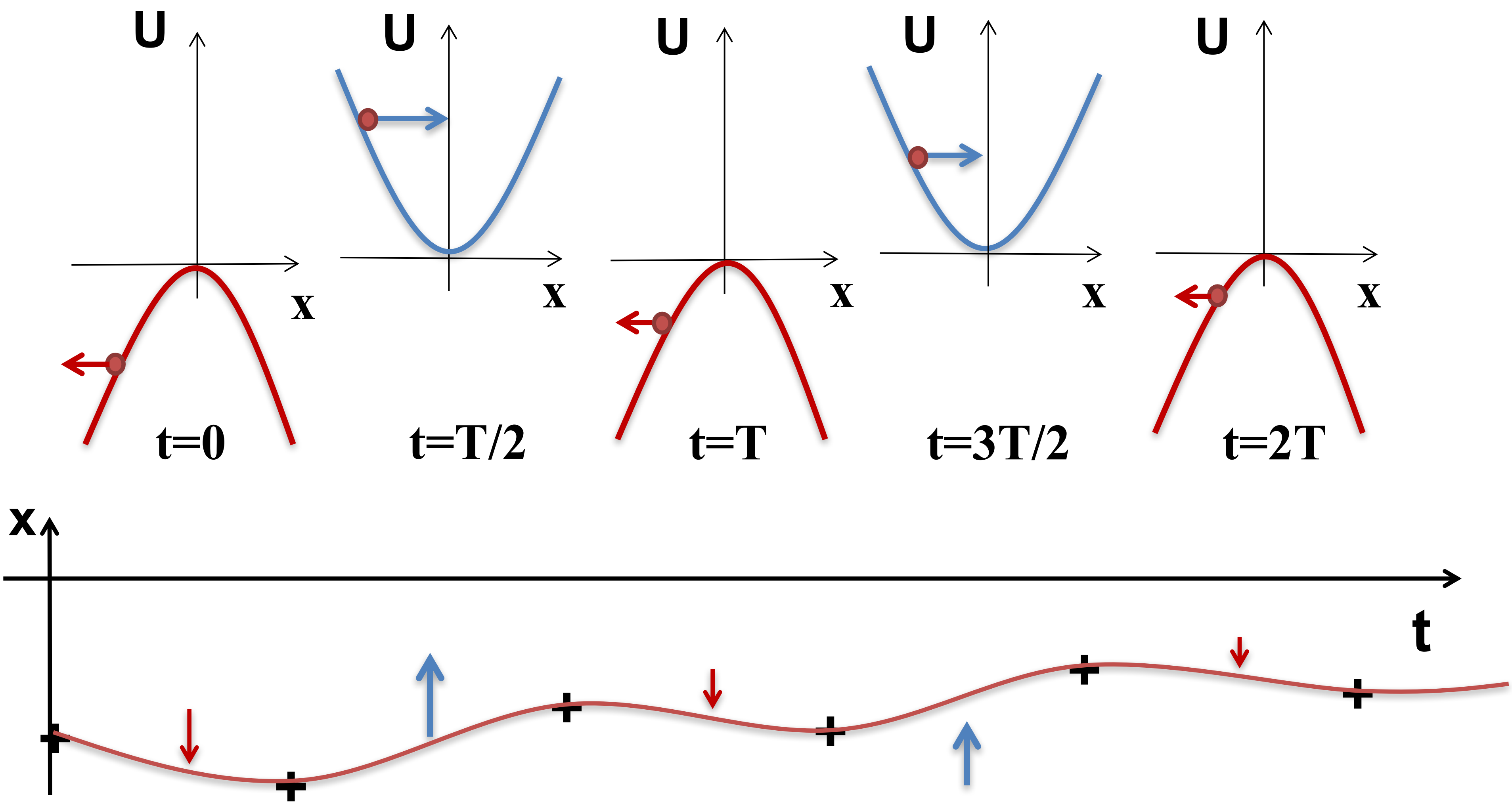

Little by little, the particle gets closer to the center…