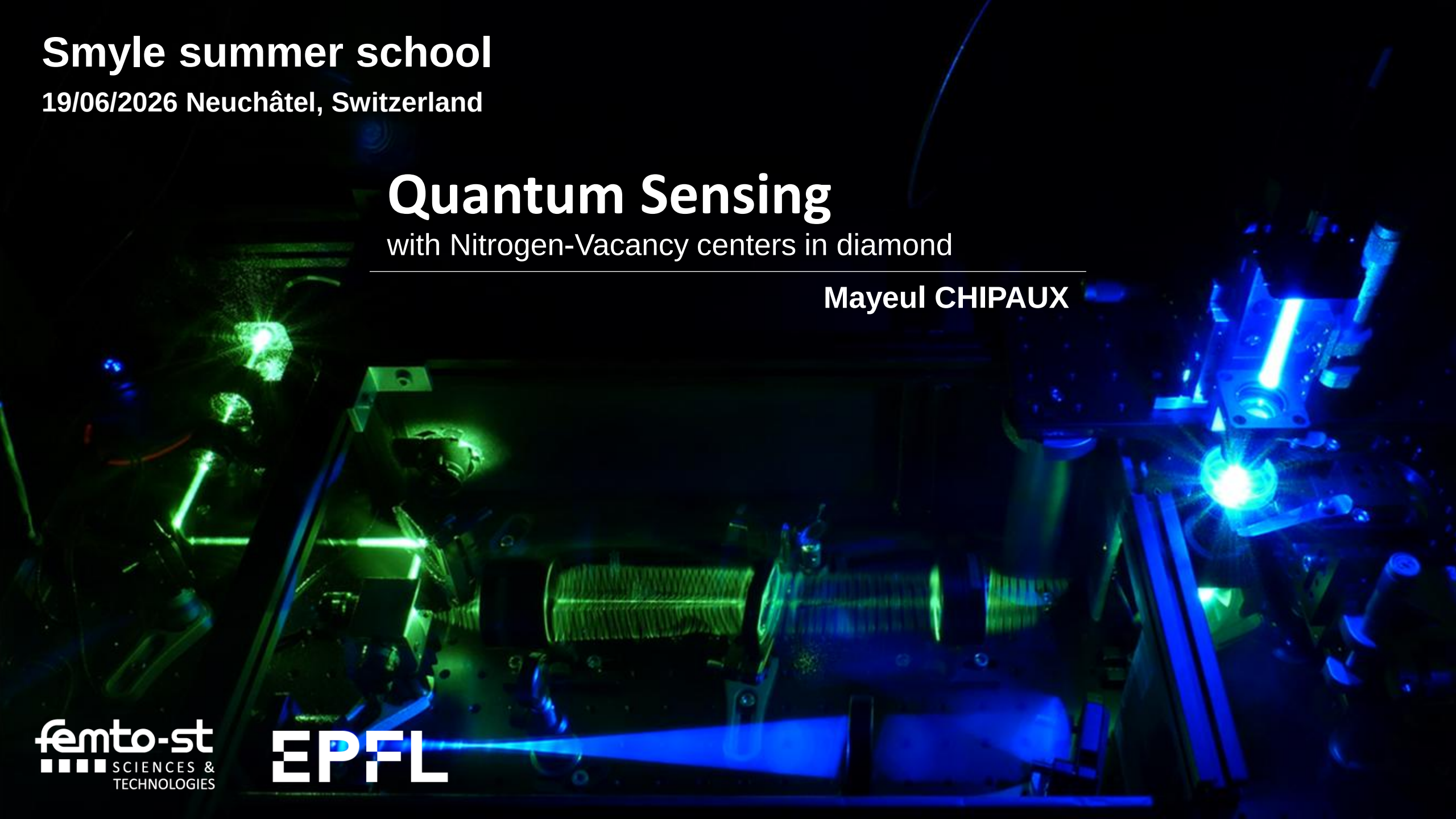
Smyle summer school

19/06/2026 Neuchâtel, Switzerland

Quantum Sensing

with Nitrogen-Vacancy centers in diamond

Mayeul CHIPAUX



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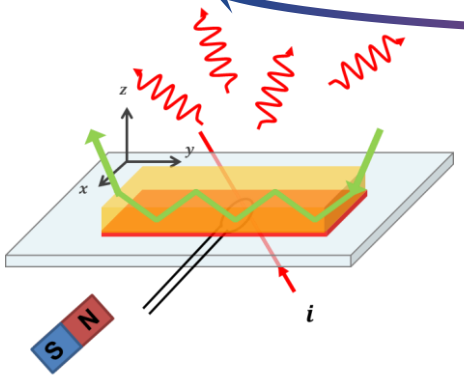
EPFL

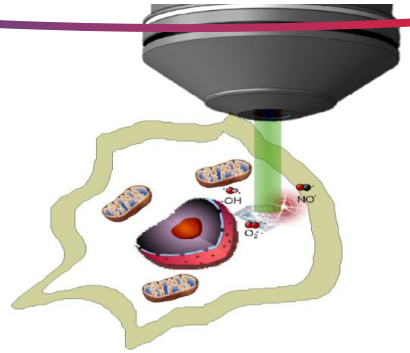
Who Am I?

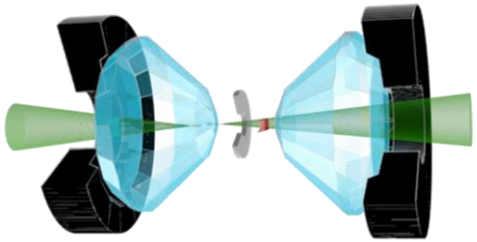
Research journey

2012 **Doctorate** → 2014 **Postdoc #1** → 2018 **Postdoc #2** → 2019

Doctorate	Postdoc #1	Postdoc #2
Ensembles in bulk Diamonds	**Nanodiamonds in living cells**	**Ensembles in Diamond anvils**
Wide field microscopy	**Confocal microscopy**	**High pressure study**







Doctorate	Postdoc #1	Postdoc #2
• Magnetic field sensing	• Sensing free radicals	• Magnetic field sensing
• Microwave spectroscopy	• EPR spectroscopy	• Study of other defects
THALES / école normale supérieure paris–saclay	university of groningen / EPFL	école normale supérieure paris–saclay / UNIVERSITÄT DES SAARLANDES
Dr. T. Debuisschert Prof. J.-F. Roch	Prof. R. Schirhagl	Prof. J.-F. Roch Prof. C. Becher

Who Am I?

EPFL

2020
At EPFL

Very large scale entangled states in diamond for 2.0 quantum technologies

Since 2024
Femto-ST

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Very large scale entangled states in diamond for 2.0 quantum technologies

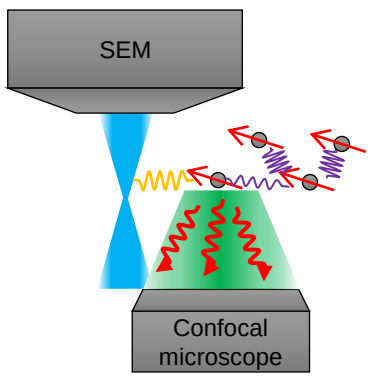
2024
Femto-ST

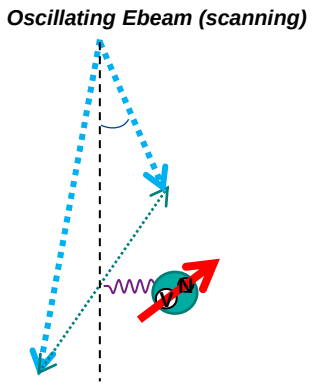
Selective quantum controls

Novel entanglement schemes

Twisting the use of a Scanning Electron Microscope to prepare any arbitrary entangled state

Spin coherent control





Quantum Sensing… with Nitrogen-Vacancy centers in diamond

- What is sensing?
- As opposed to metrology?
- What properties shall characterize a “good” sensor?

Sensitivity

Resolution

Accuracy

Range

Sensitivity

The sensitivity is defined as the minimum detectable signal* $v_{\min}$ that yields unit SNR for an integration time of 1 s ($T = 1$ s),

* C. L. Degen, F. Reinhard, P. Cappellaro, (2017). Quantum sensing. *Reviews of modern physics*, *89*(3), 035002.

0. Introduction

Quantum Sensing… with Nitrogen-Vacancy centers in diamond

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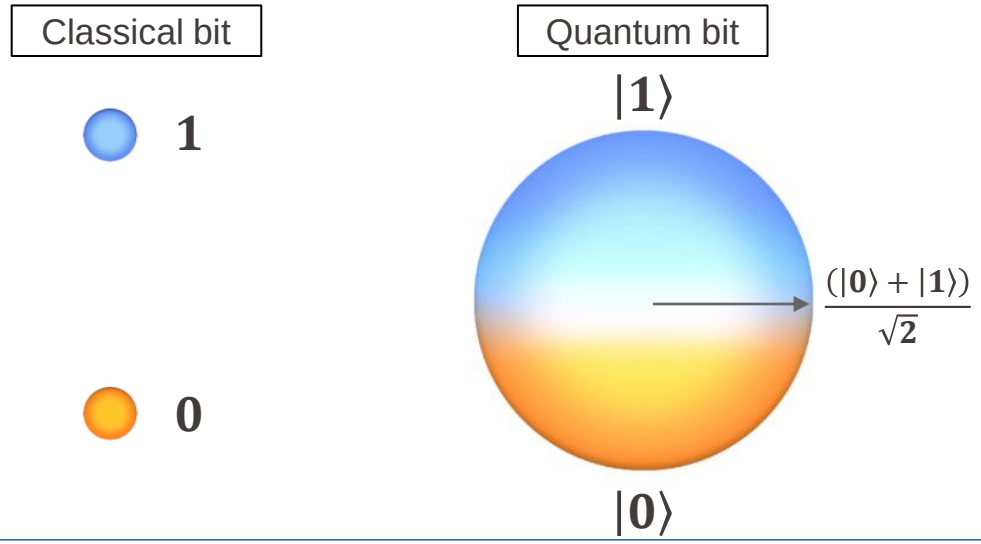
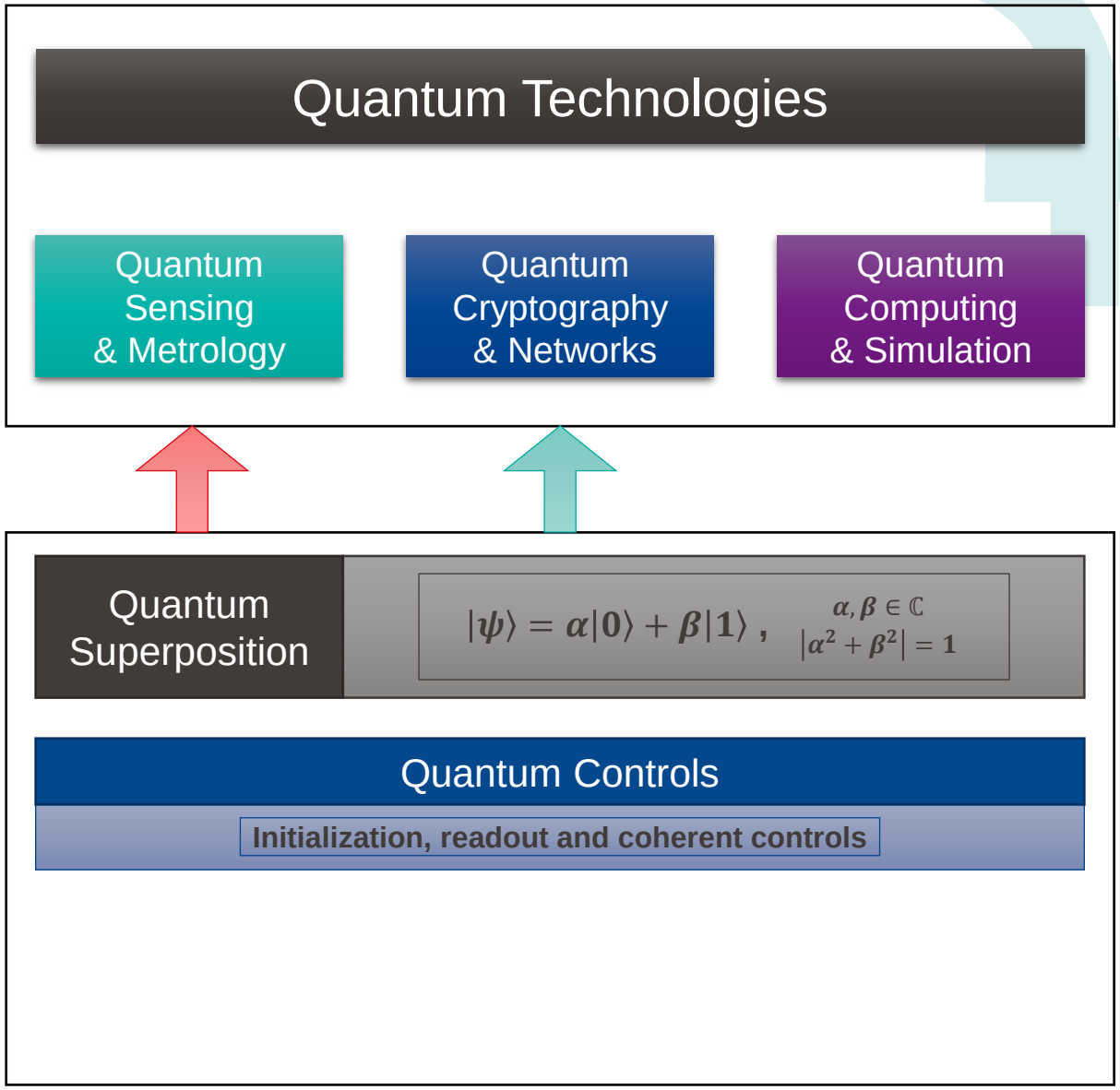
- What do they rely on?





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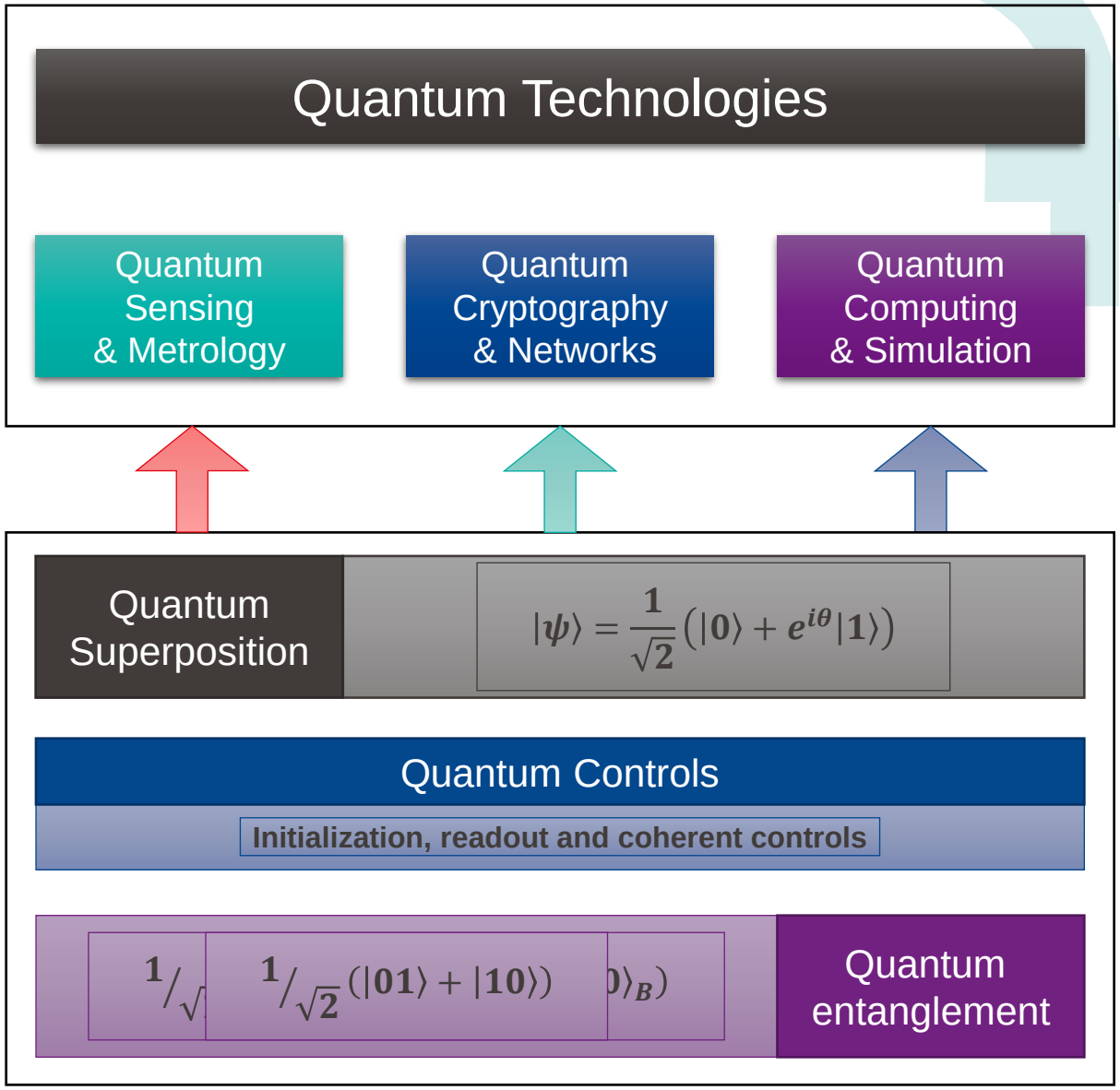

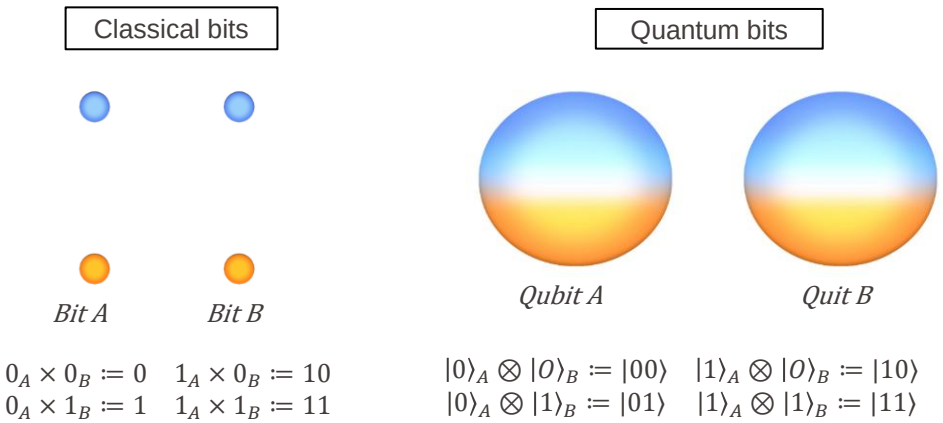

Quantum Sensing… with Nitrogen-Vacancy centers in diamond

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- As opposed to quantum metrology?
- What properties shall characterize a “good” quantum sens

Quantum Sensing & Metrology

Sensitivity

Resolution

Accuracy

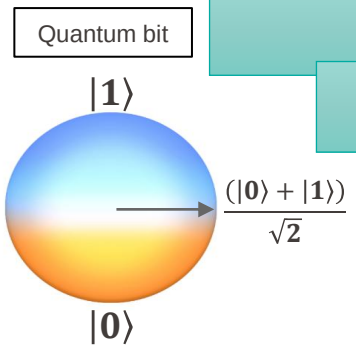
Range

Quantum Sensing*:

(I) Sensing by mean of a quantum object

(II) Use of quantum superposition

(III) Use of quantum entanglement



Quantum sensors*:

(1) Discrete energy levels

(2) Can be initialized and readout

(3) Can be coherently manipulated

(4) Interact with the desired quantity

* C. L. Degen, F. Reinhard, P. Cappellaro, (2017). Quantum sensing. *Reviews of modern physics*, *89*(3), 035002.

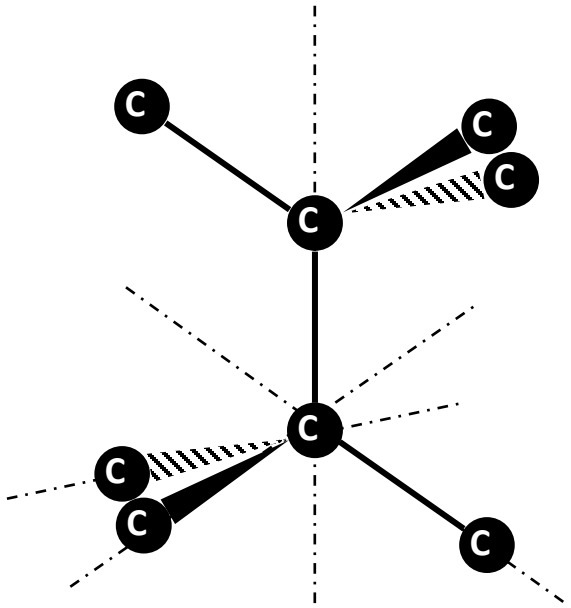
Quantum Sensing… with Nitrogen-Vacancy centers in diamond

Robuste, transparent

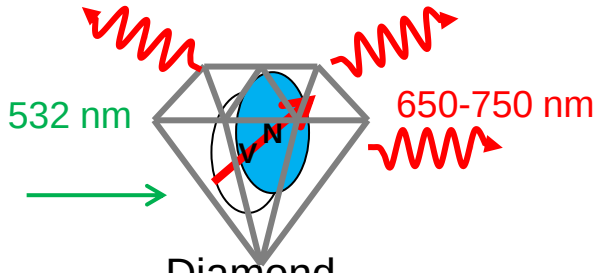
Very pure !

Can hold the defects that we like

Diamond



Quantum Sensing… with Nitrogen-Vacancy centers in diamond

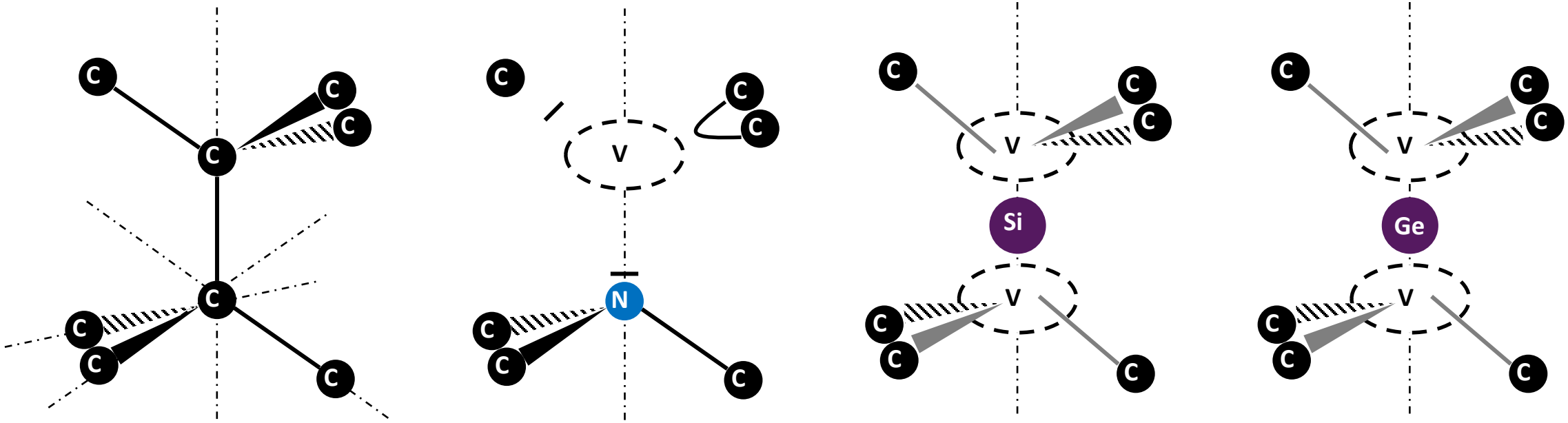


Diamond

NV center C_{3v}

SiV center D_{3d}

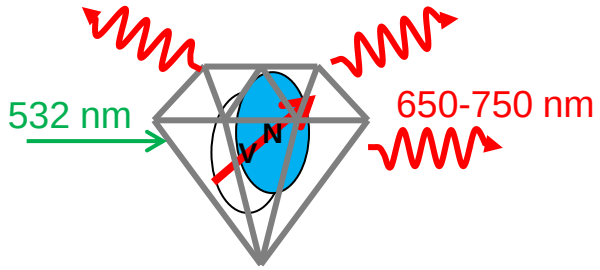
GeV center D_{3d}

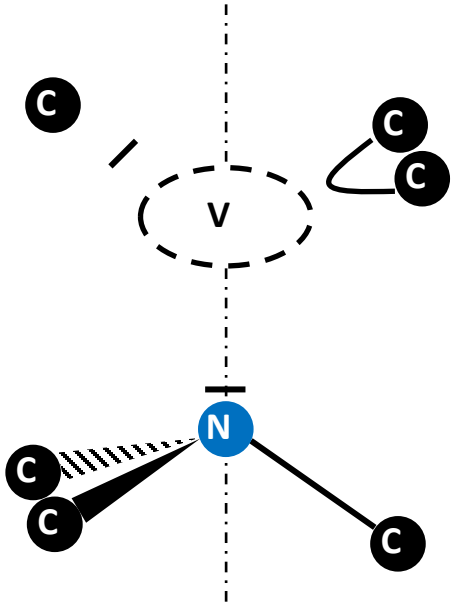


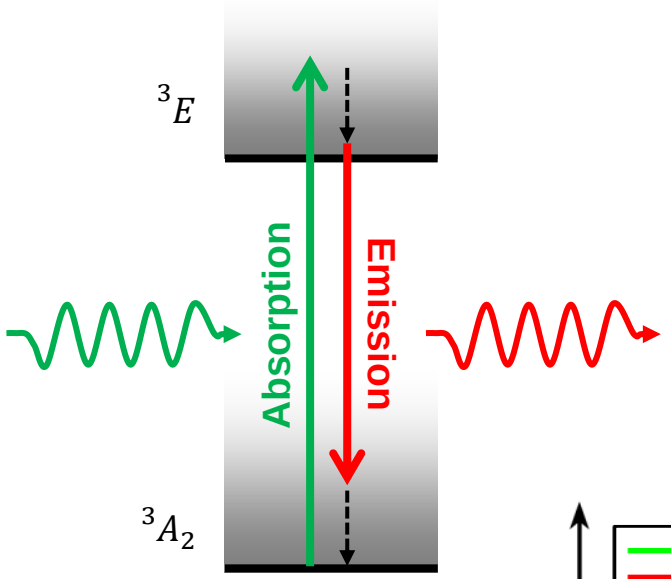
Zero Phonon Lines : 637 nm ↔ 1.95 eV | 738 nm ↔ 1.68 eV | 602 nm ↔ 2.06 eV

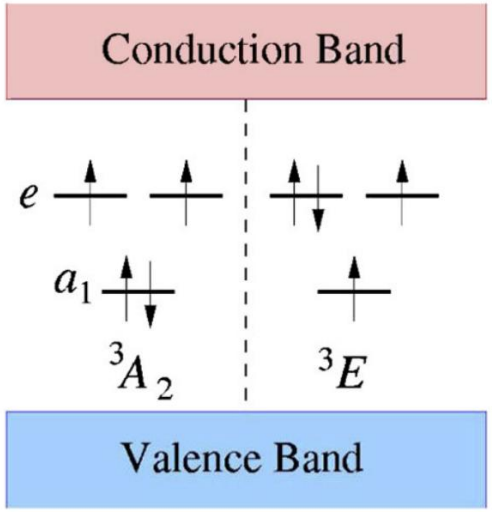
G. Wolfowicz, *et a.* (2021). *Nature Reviews Materials*, *6*(10), 906-925.

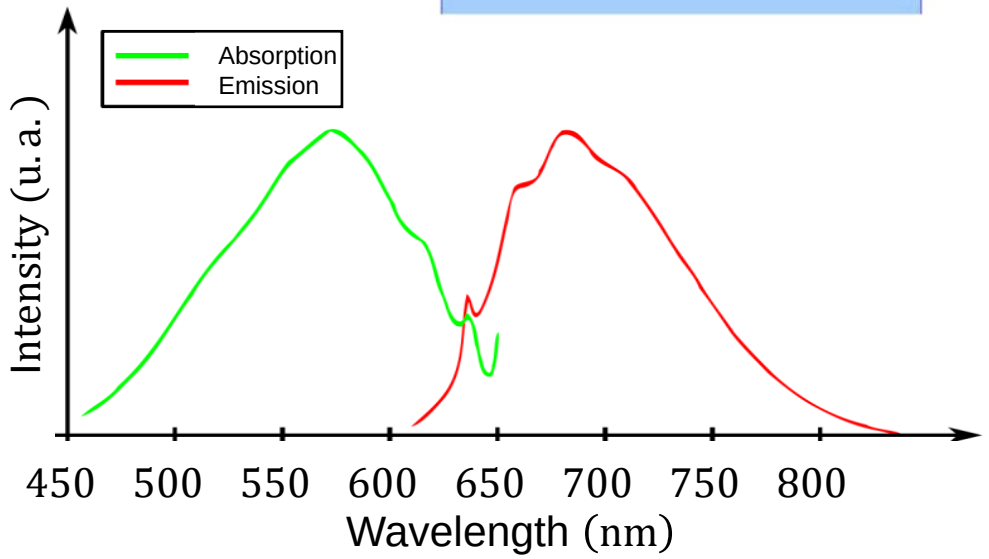
Quantum Sensing… with Nitrogen-Vacancy centers in diamond





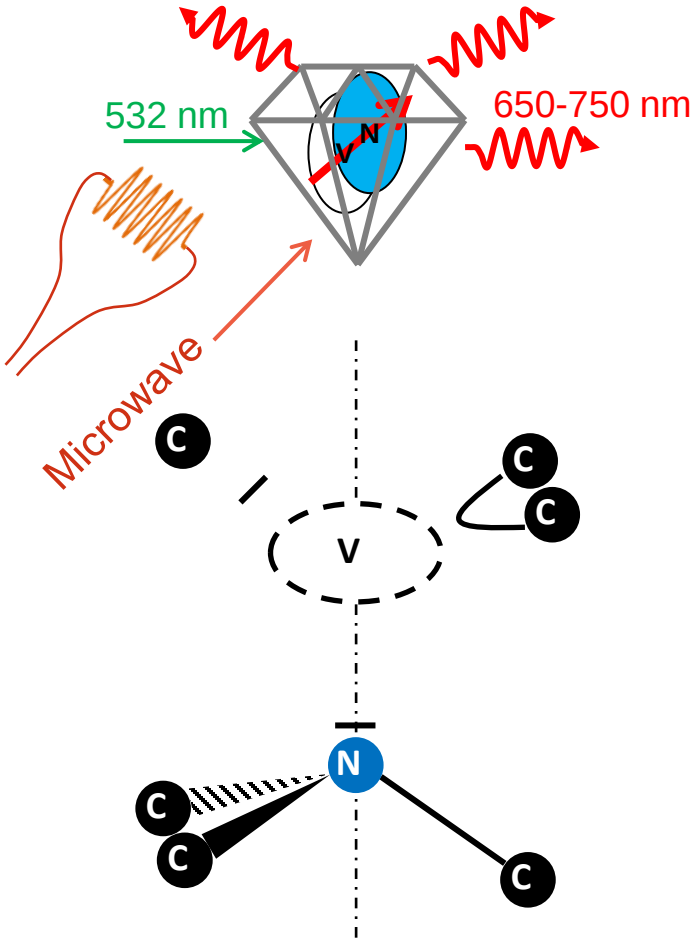


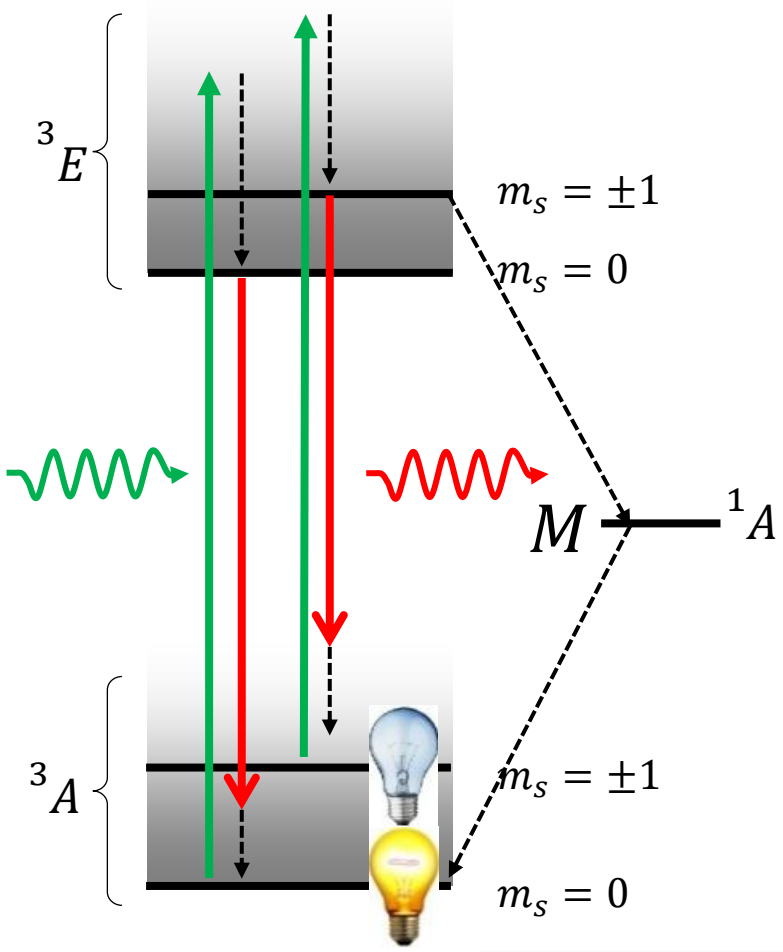




Zero Phonon Lines :

Quantum Sensing… with Nitrogen-Vacancy centers in diamond





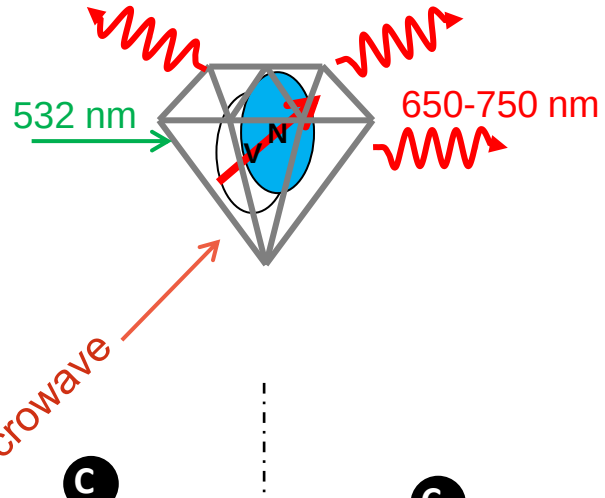
Optical readout of the spin state

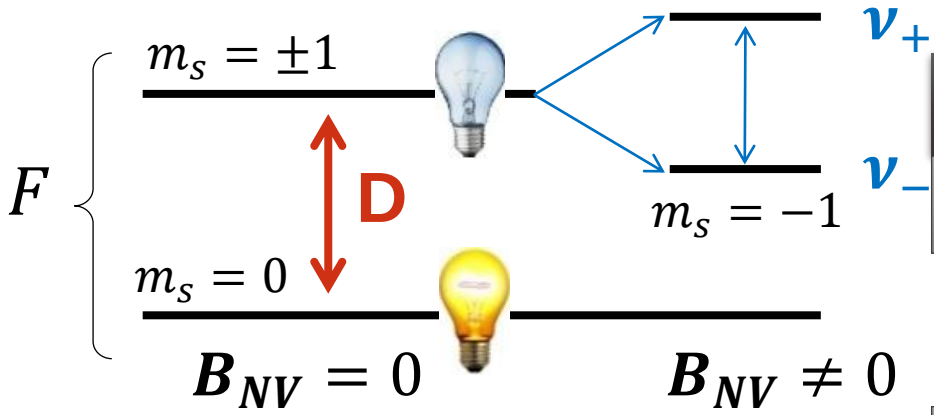
Optical initialization in spin zero

Optically Detected Magnetic Resonance

Transducer from microwave to optical signals

Quantum Sensing… with Nitrogen-Vacancy centers in diamond





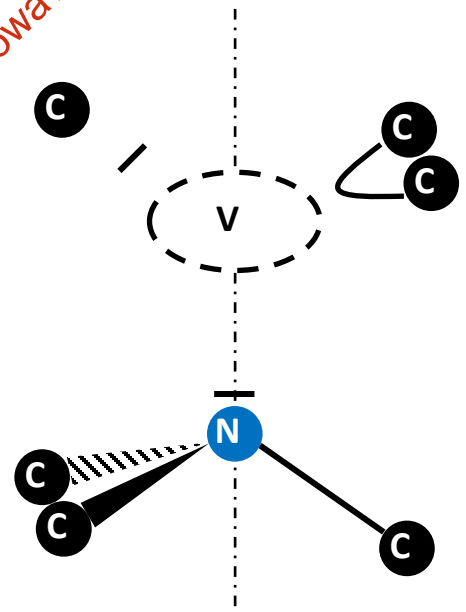
Zeeman Effect

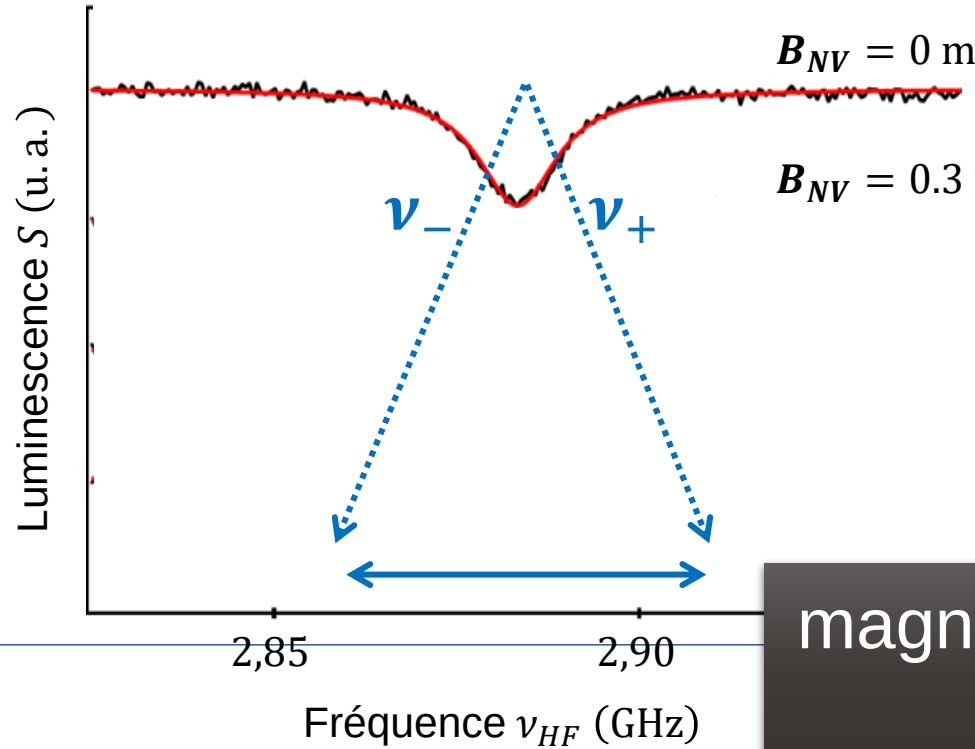
$$H_{GS} = DS^2 + \gamma_e B \cdot S$$

$D = 2{,}87$ GHz

$$\nu_- = D - \frac{g\mu_B}{h} \cdot B_{NV}$$

$$\nu_+ = D + \frac{g\mu_B}{h} \cdot B_{NV}$$

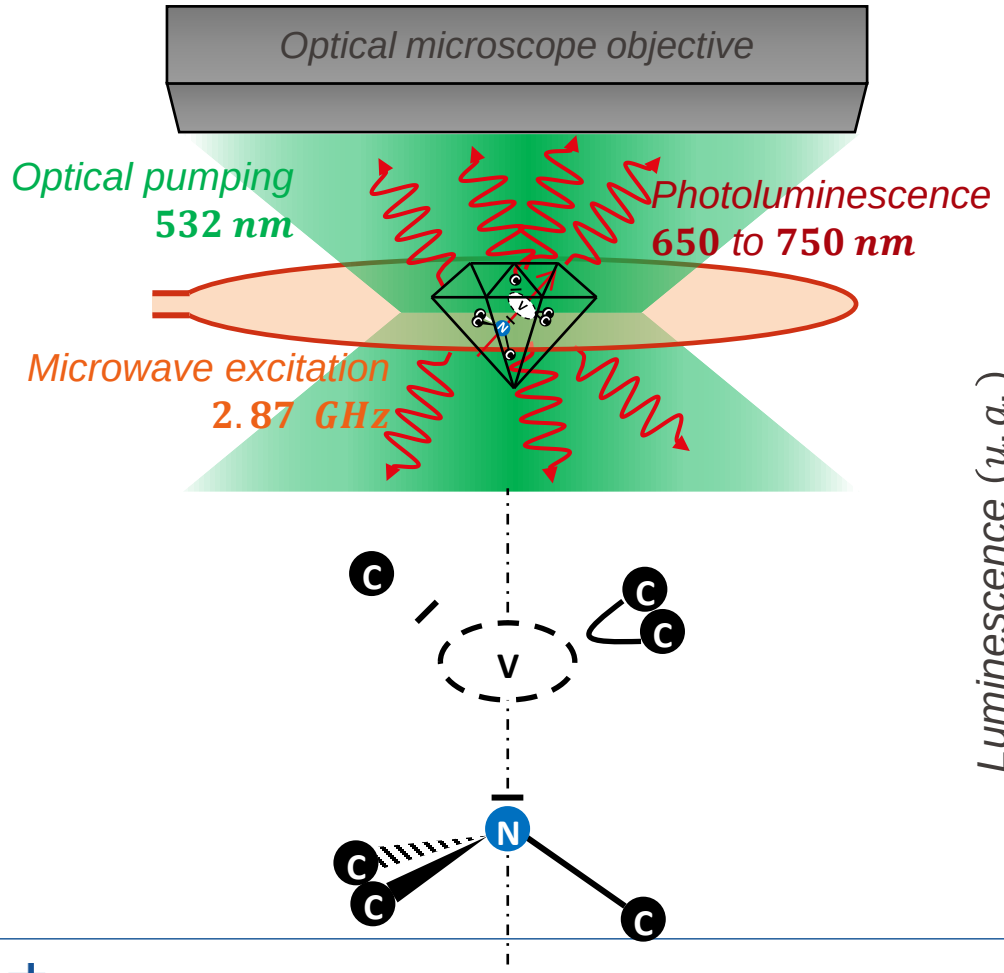




magnetic field / frequency Transducer

Quantum Sensing… with Nitrogen-Vacancy centers in diamond

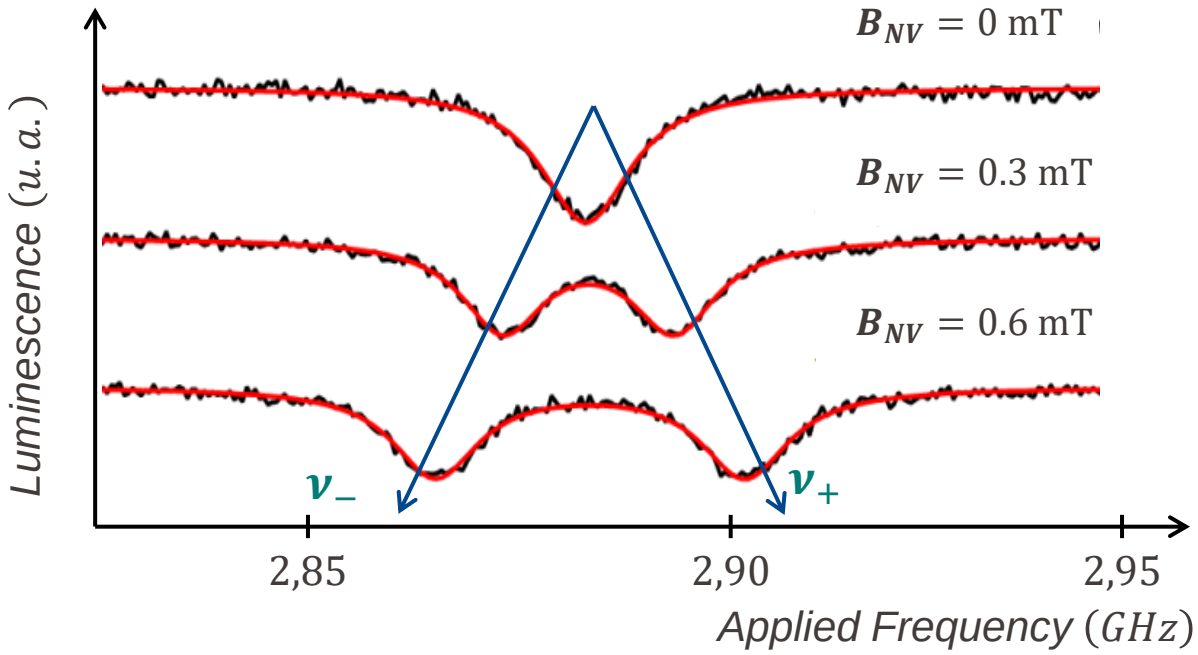
The Nitrogen-Vacancy center in Diamond



Quantum Sensing & Metrology

- *ODMR (Optically Detected Magnetic Resonance)*
- *Visible Light*
- *Solid state,*
- *Room temperature*

Even without entanglement



Quantum Sensing

with Nitrogen-Vacancy centers in diamond

Mayeul CHIPAUX

1. In the continuous wave mode
2. Pulse sequences
3. Case study, relaxometry
4. Quantum limits and entanglement

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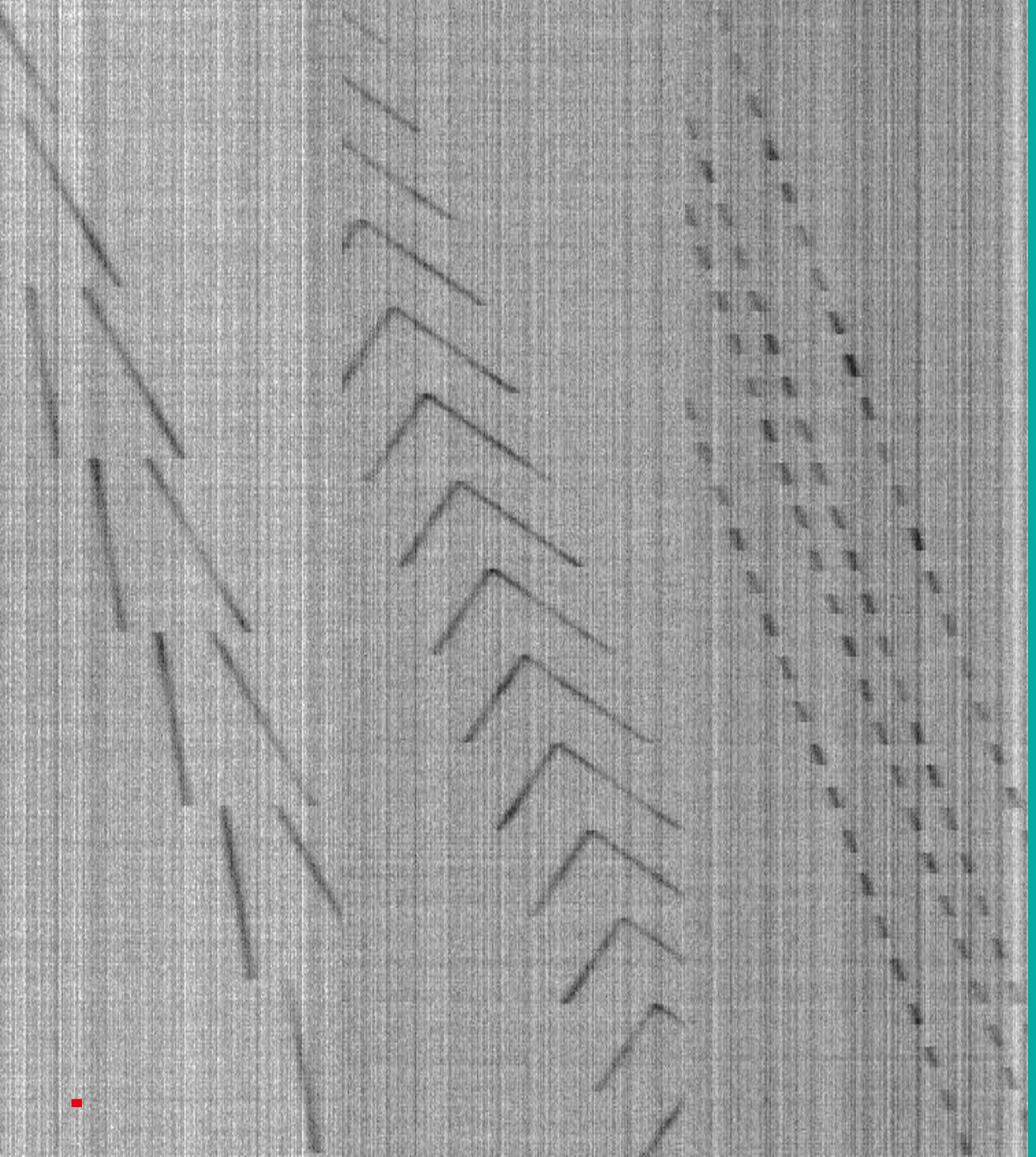


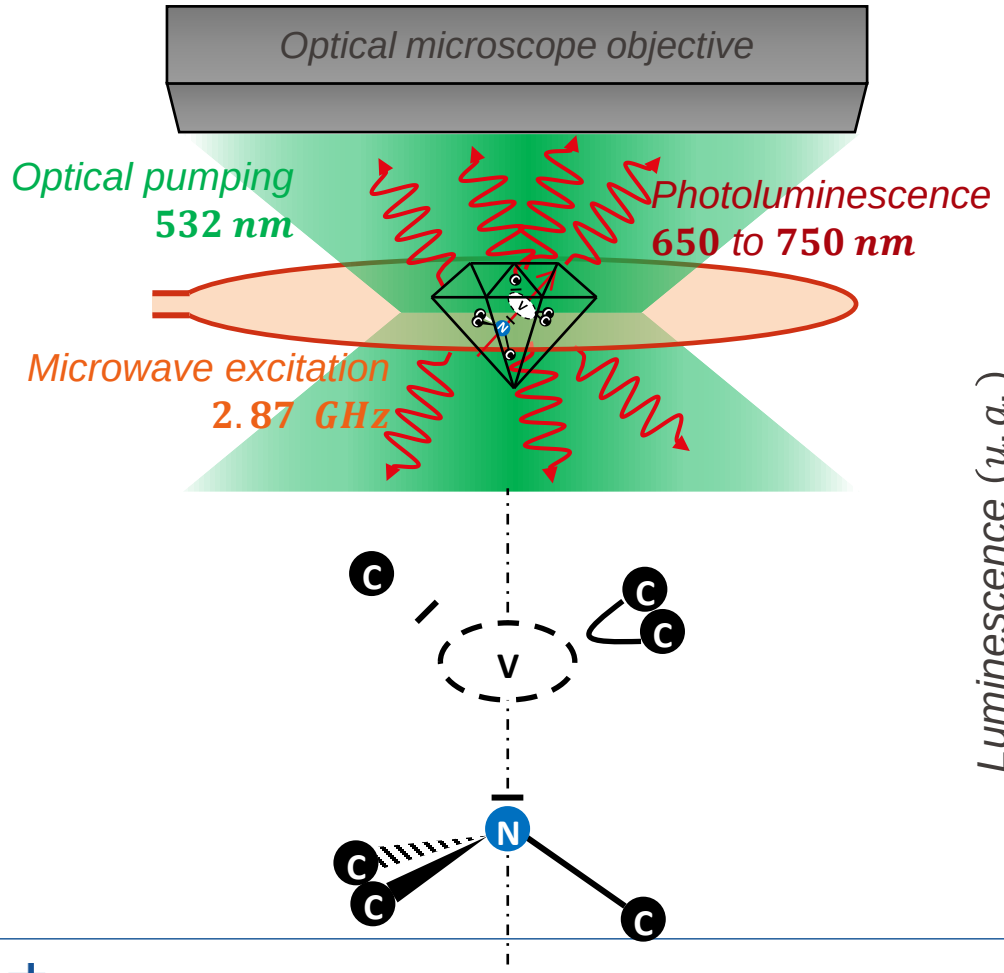
1. Sensing magnetic fields in the Continuous Wave mode

a. Scanning with single NV centers
b. Imaging with ensembles
c. Spectroscopy of microwave signals

1. In the CW mode

Scanning magnetic fields with a single NV center

The Nitrogen-Vacancy center in Diamond



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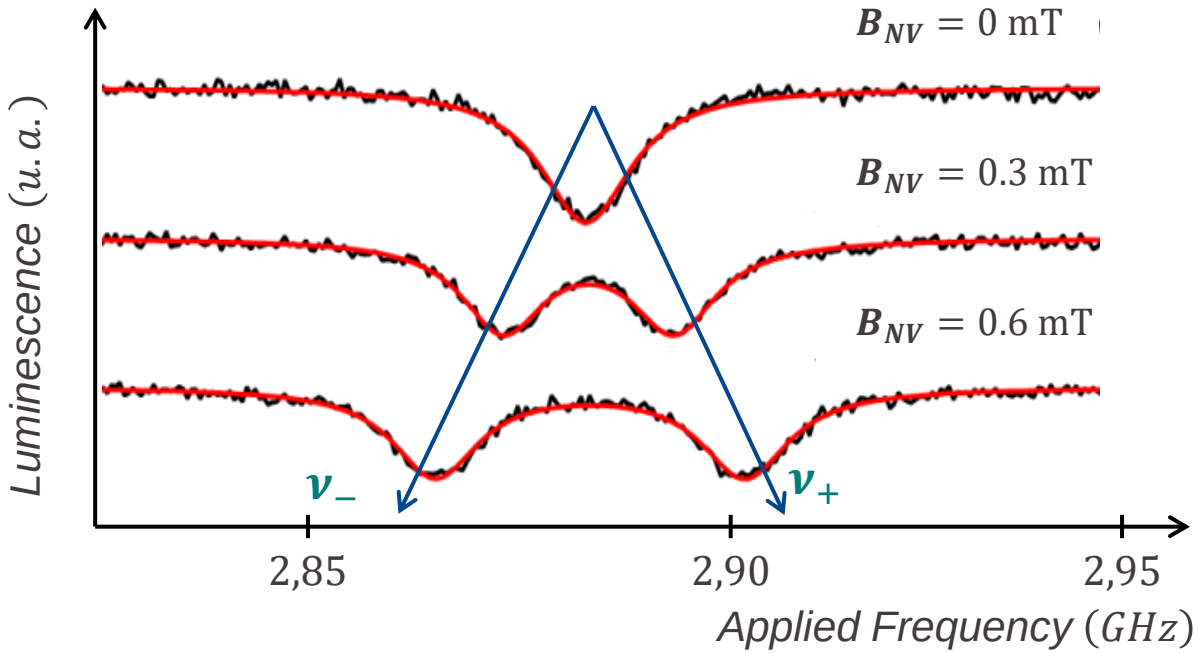


1. In the CW mode

Sensitivity ? Resolution?

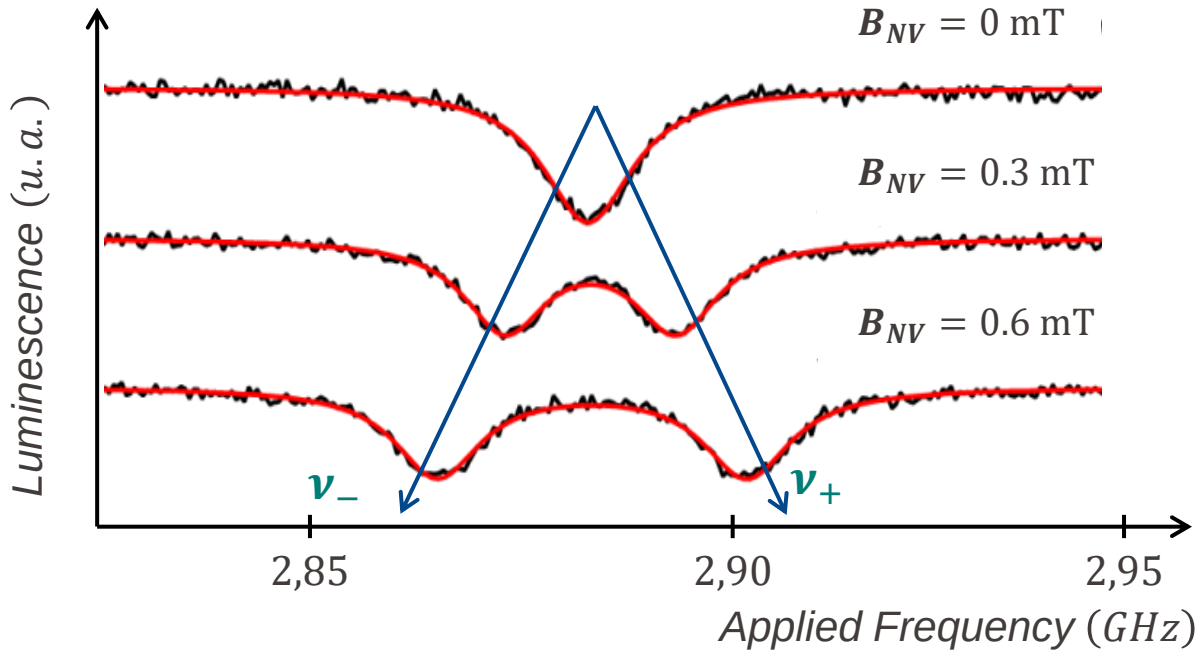
Quantum Sensing & Metrology

- *ODMR (Optically Detected Magnetic Resonance)*
- *Visible Light*
- *Solid state,*
- *Room temperature*

Even without entanglement

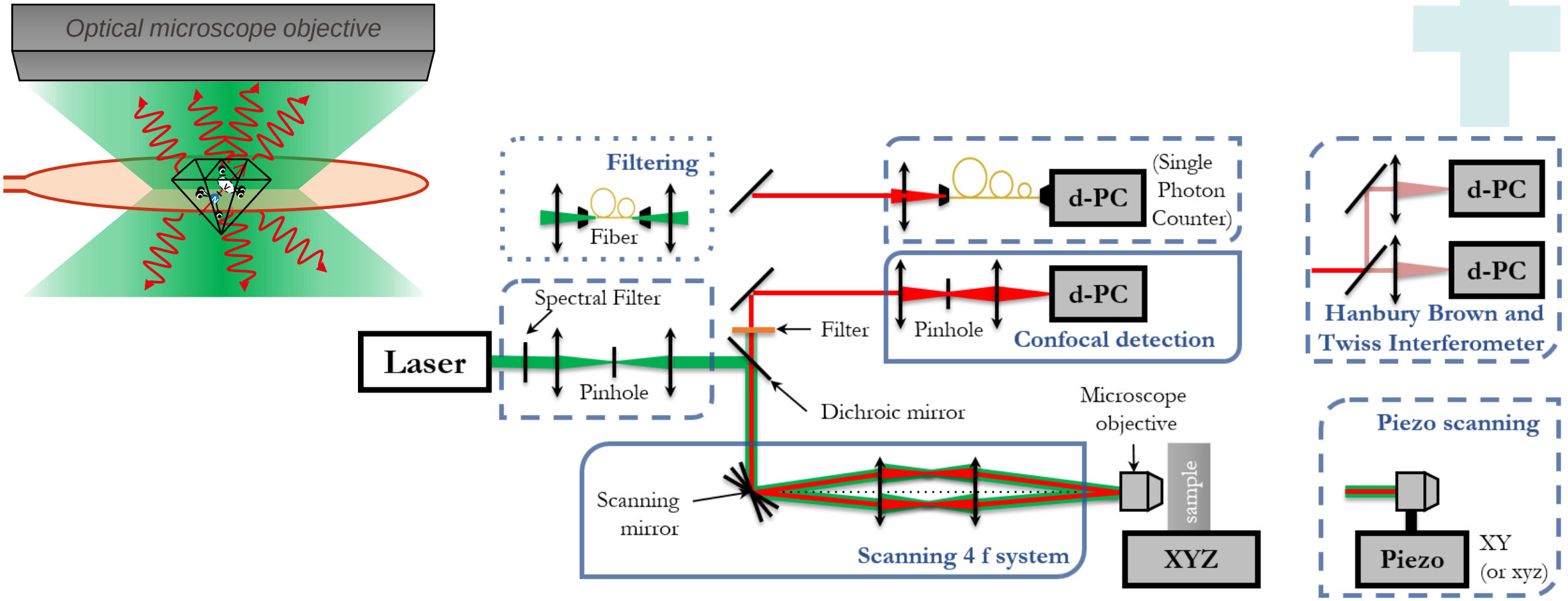
$$\eta_B = P_f \frac{\hbar}{g\mu_b} \cdot \frac{\Delta_\nu}{C\sqrt{R}} \qquad \text{en mT} \cdot Hz^{-1/2}$$

- R Rate of detected photons
- $\frac{g\mu_b}{\hbar}$ Electron-spin gyromagnetic ratio
- C Measurement contrast
- Δ_ν Linewidth $\Delta_\nu \approx \frac{1}{T_2^*}$
- $P_f \approx 0.77$



1. In the CW mode

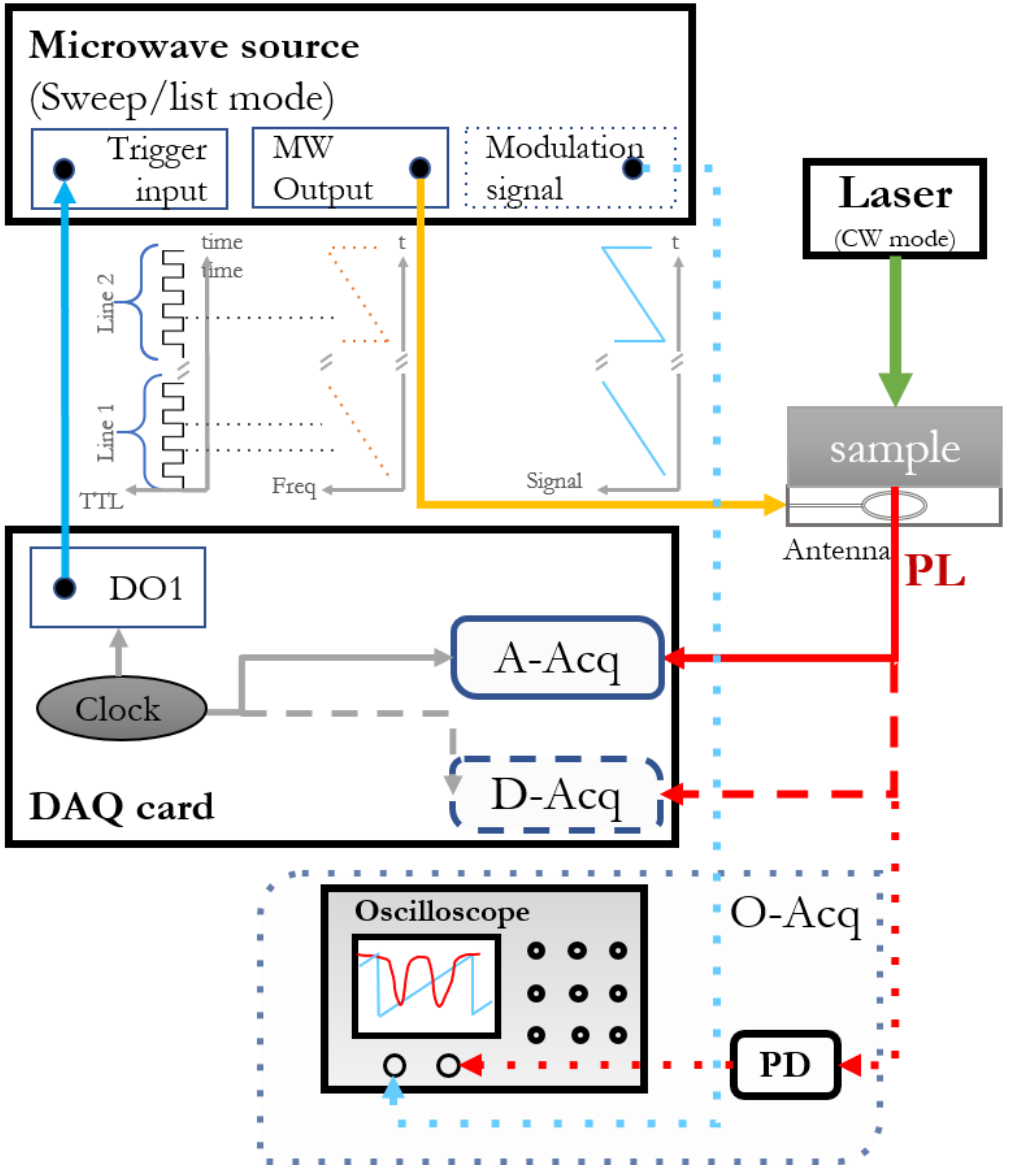
Confocal microscope

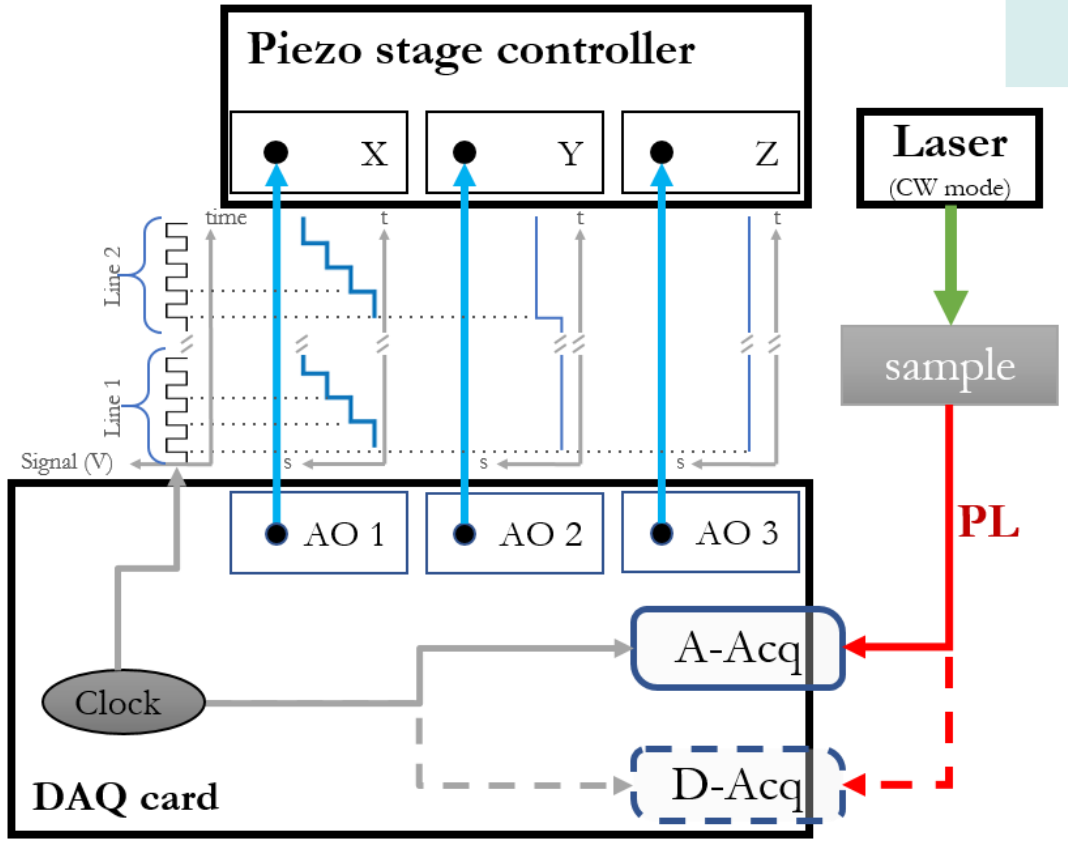


H. Babashah, H. Shirzad, et al. Optically detected magnetic resonance with an open source platform. *SciPost Physics Core*, *6*(4), 065. (2023)

1. In the CW mode

Scanning and microwave controls





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1. In the CW mode

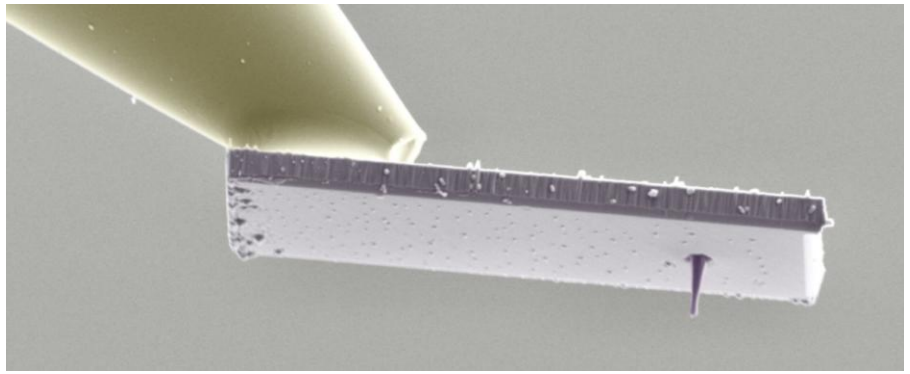
NV centers on AFM TIPs

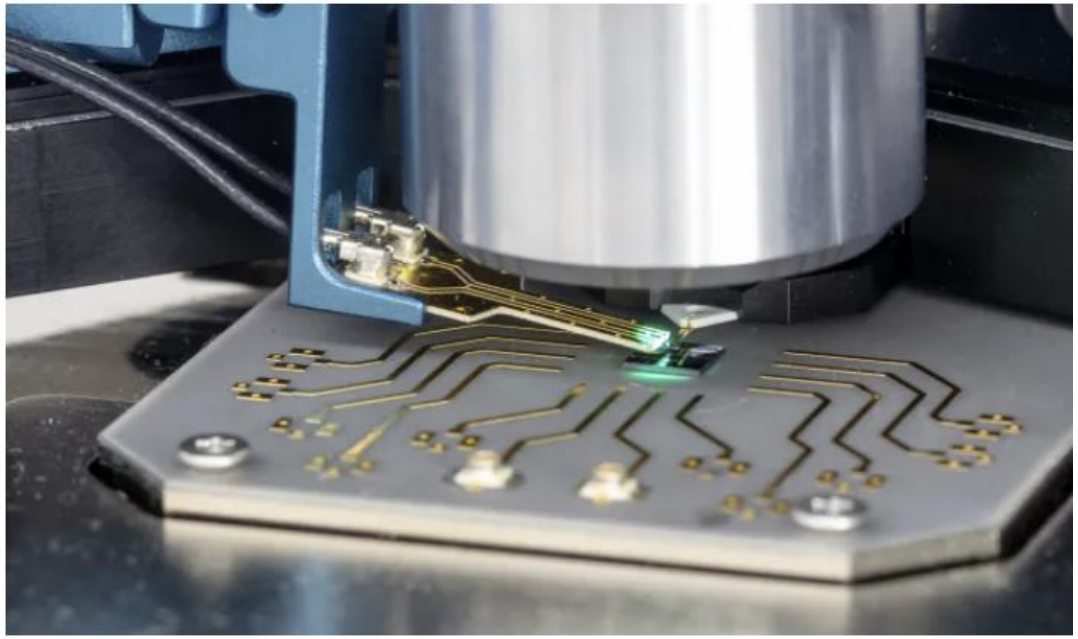
Resolution?

qnami

ZABRE

Nanometer magnetic fields made visible.





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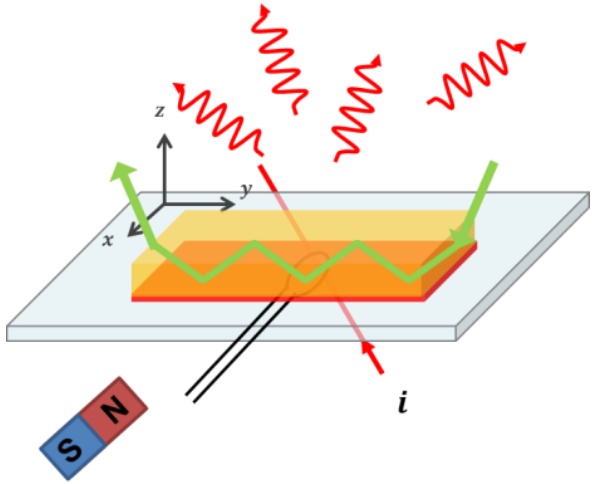
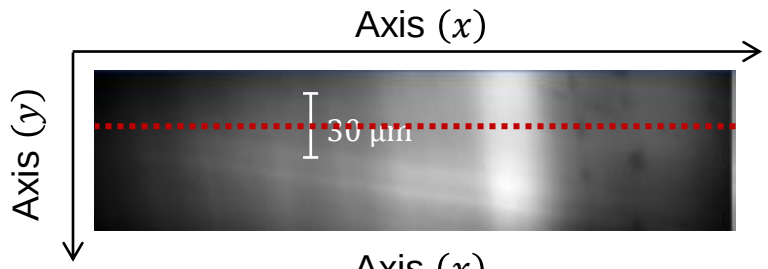
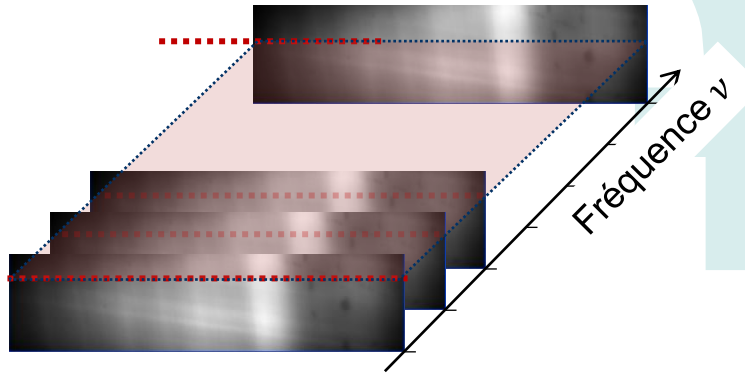
https://qnam1.ch/ https://qzabre.com

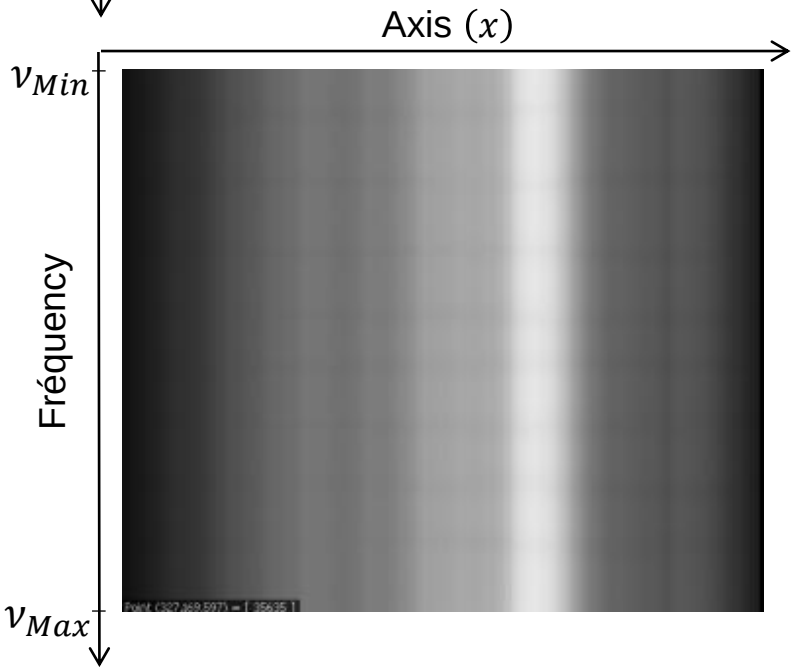
1. In the CW mode

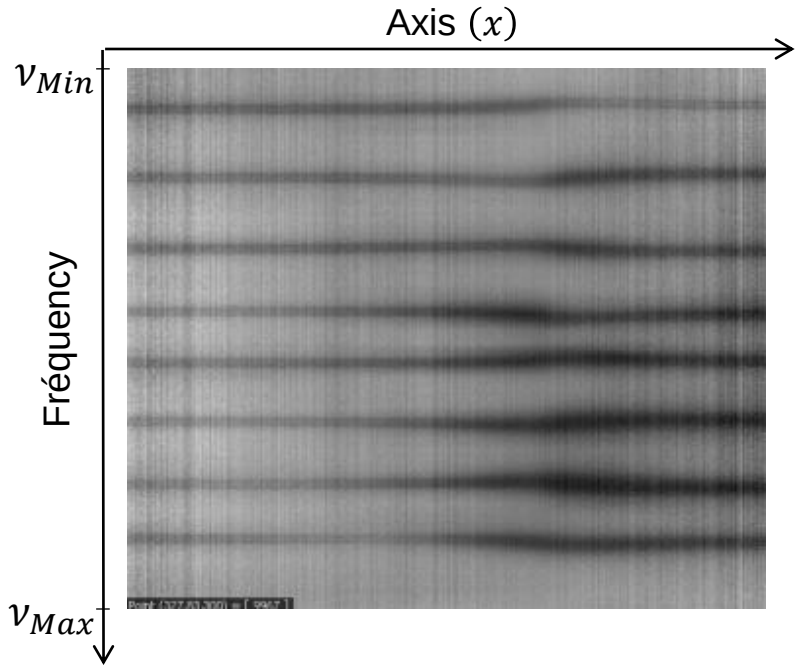
Imaging with an ensemble







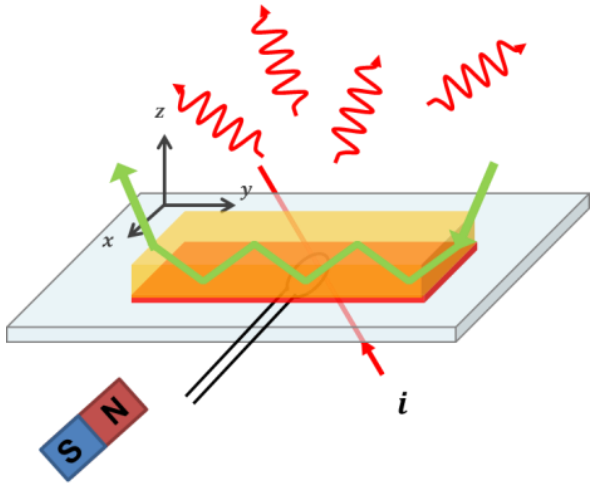


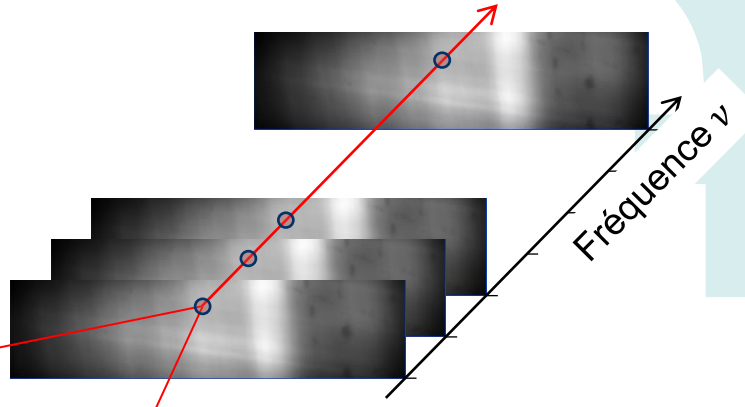


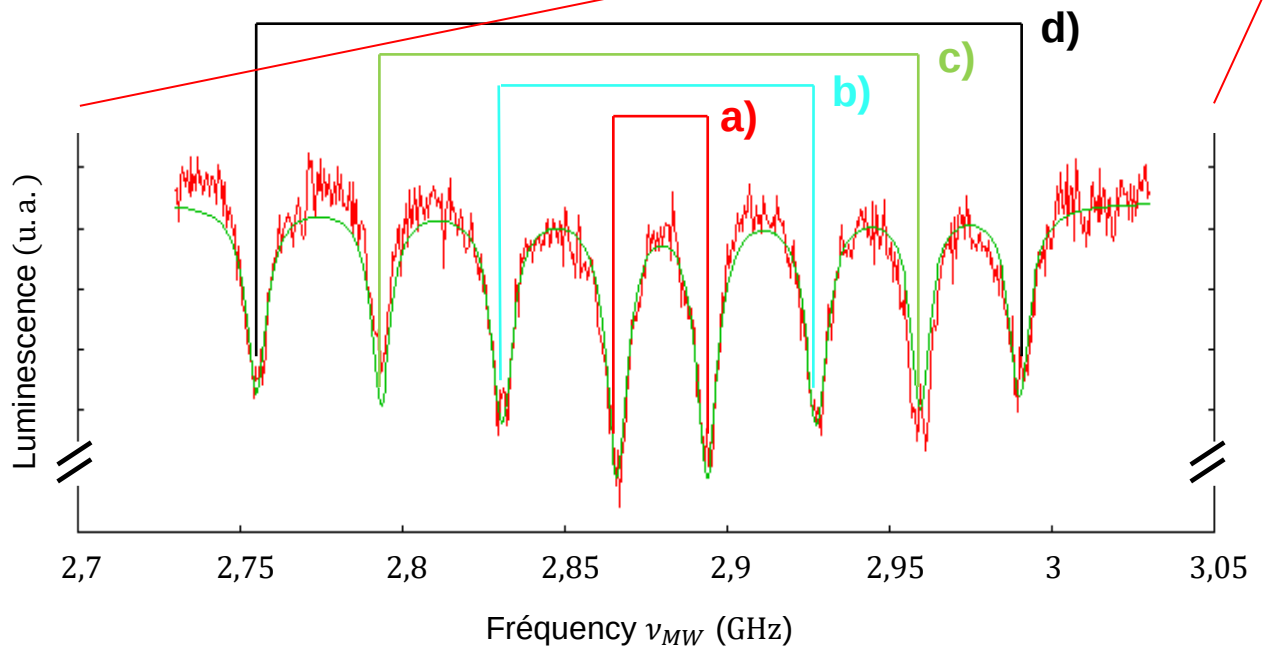
M. Chipaux, *et al.*, *Eur. Phys. J. D* **69:** 166 (2015)

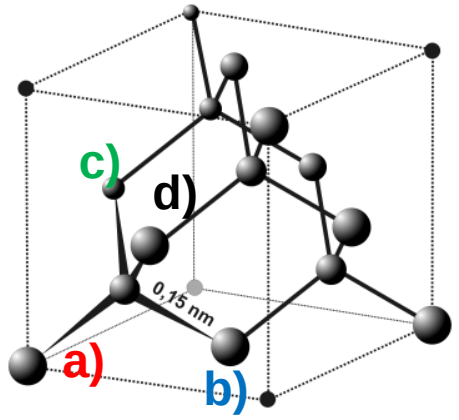
1. In the CW mode

Imaging with an ensemble









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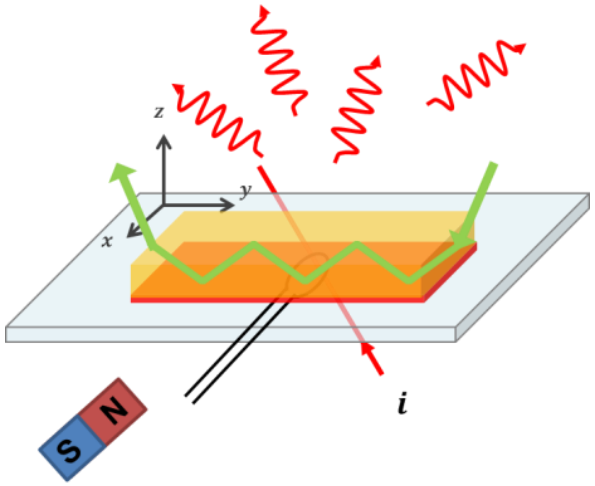
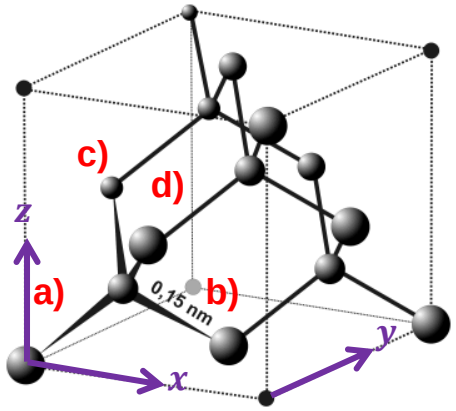
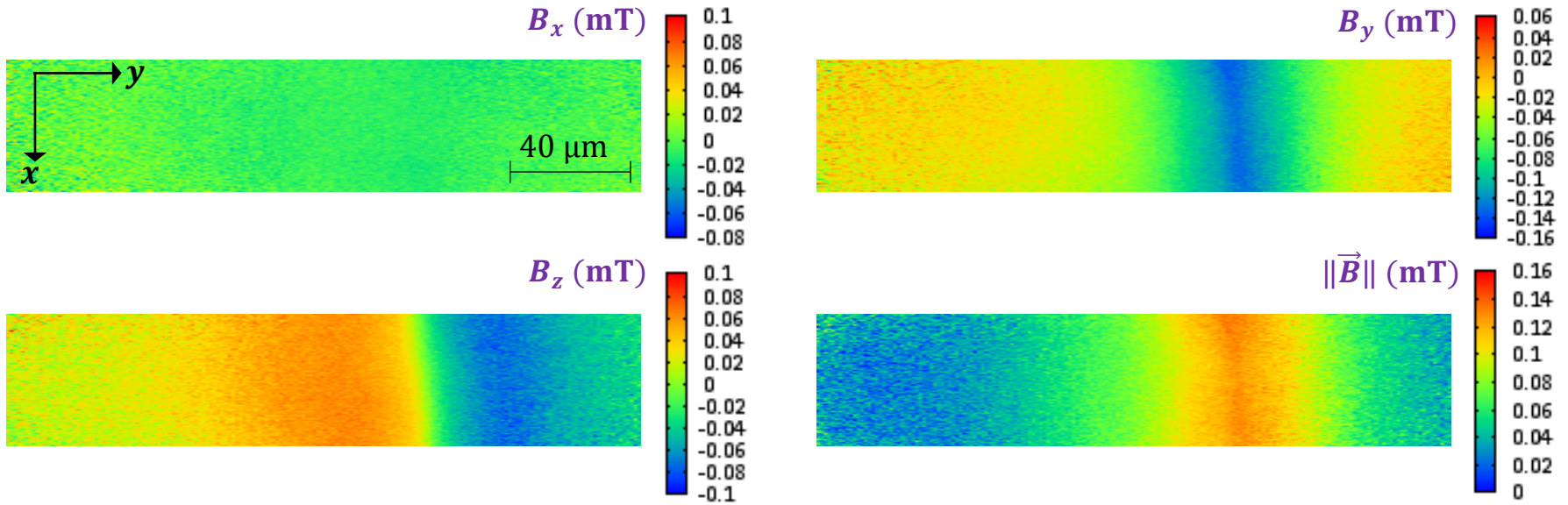
Imaging with an ensemble







M. Chipaux, *et al. Eur. Phys. J. D* **69:** 166 (2015)

1. In the CW mode

Sensitivity ? Resolution?

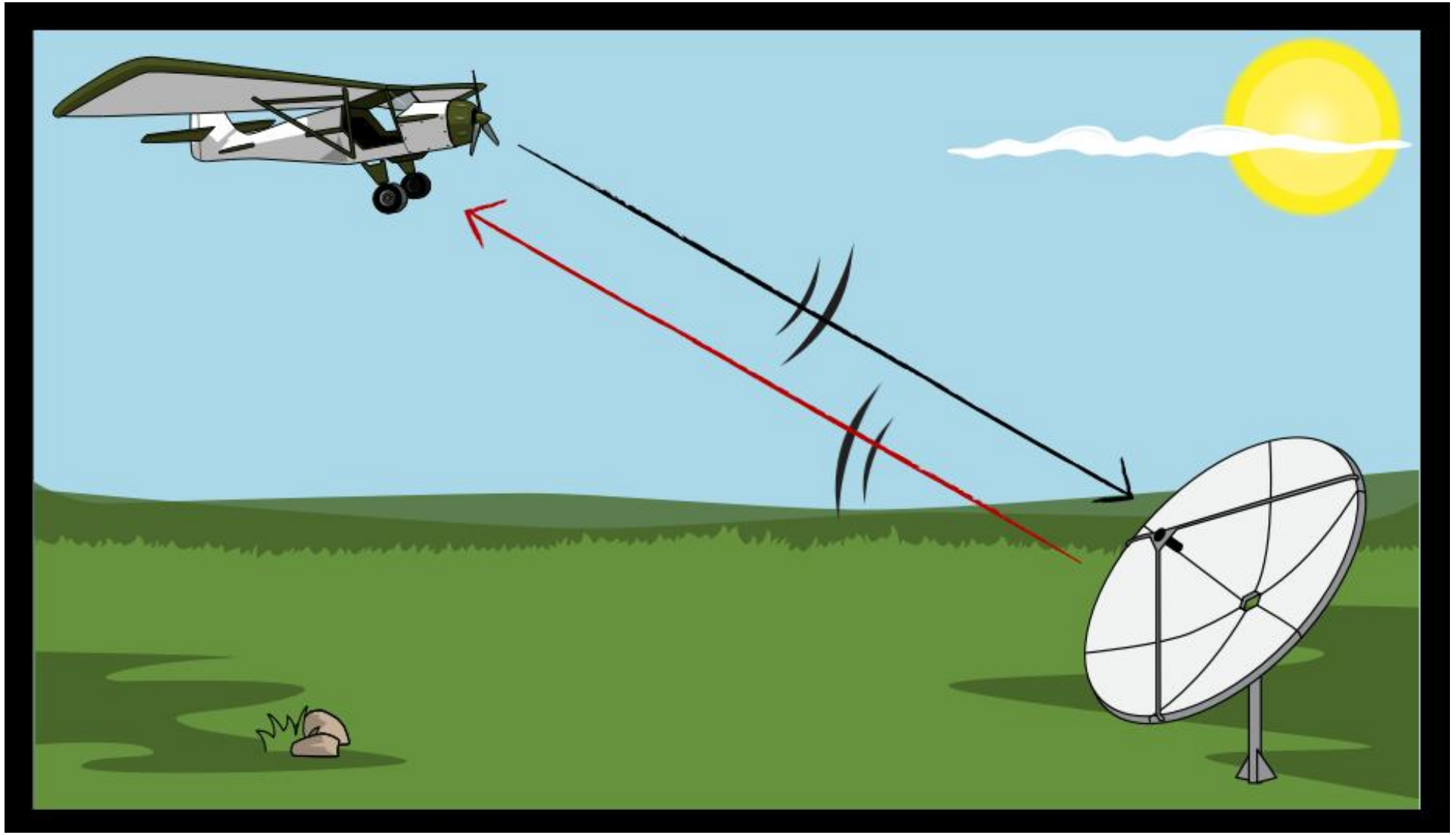
$$\eta_B = P_f \frac{\hbar}{g\mu_b} \cdot \frac{\Delta_\nu}{C\sqrt{R}} \qquad \text{en } \mu\text{T} \cdot \mu\text{m} \cdot \text{Hz}^{-1/2}$$

Applications ?

F. Casola, *et al.* (2018). *Nature Reviews Materials*, *3*(1), 17088.

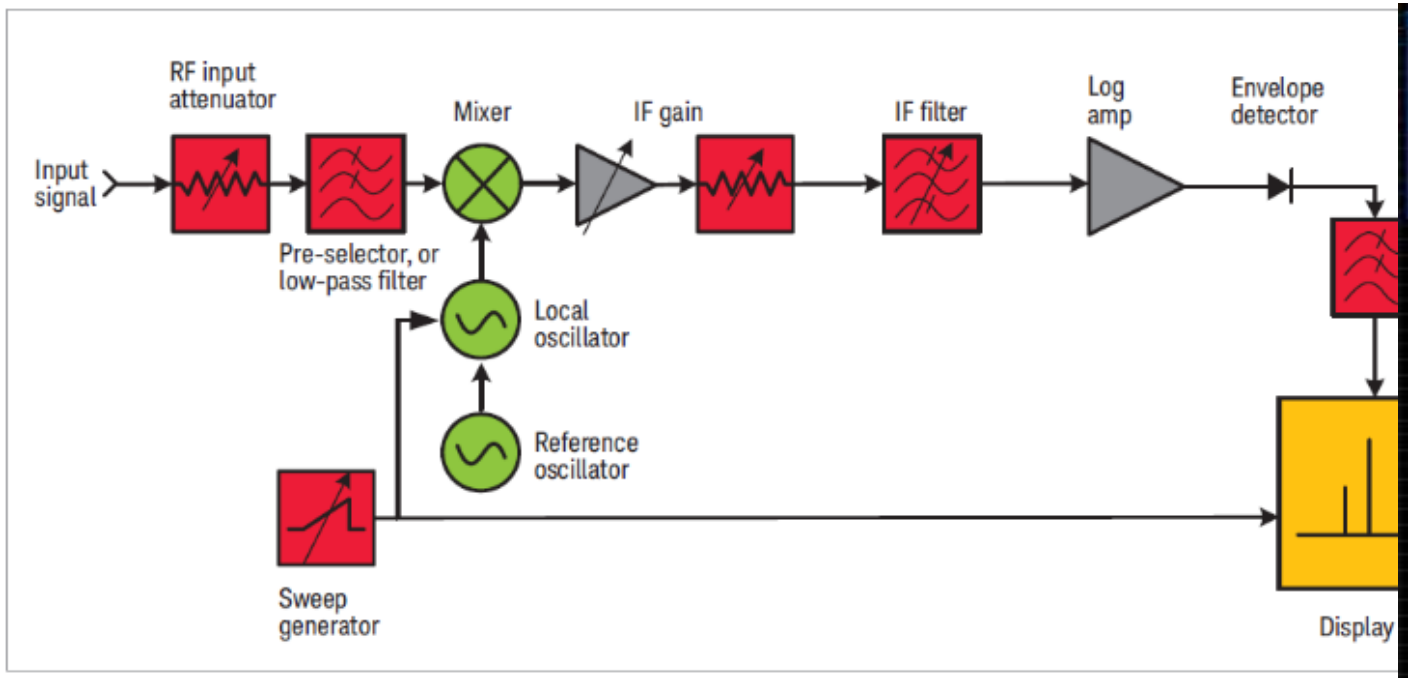
Toraille, *et al.* (2020). *New Journal of Physics*, 22(10), 103063

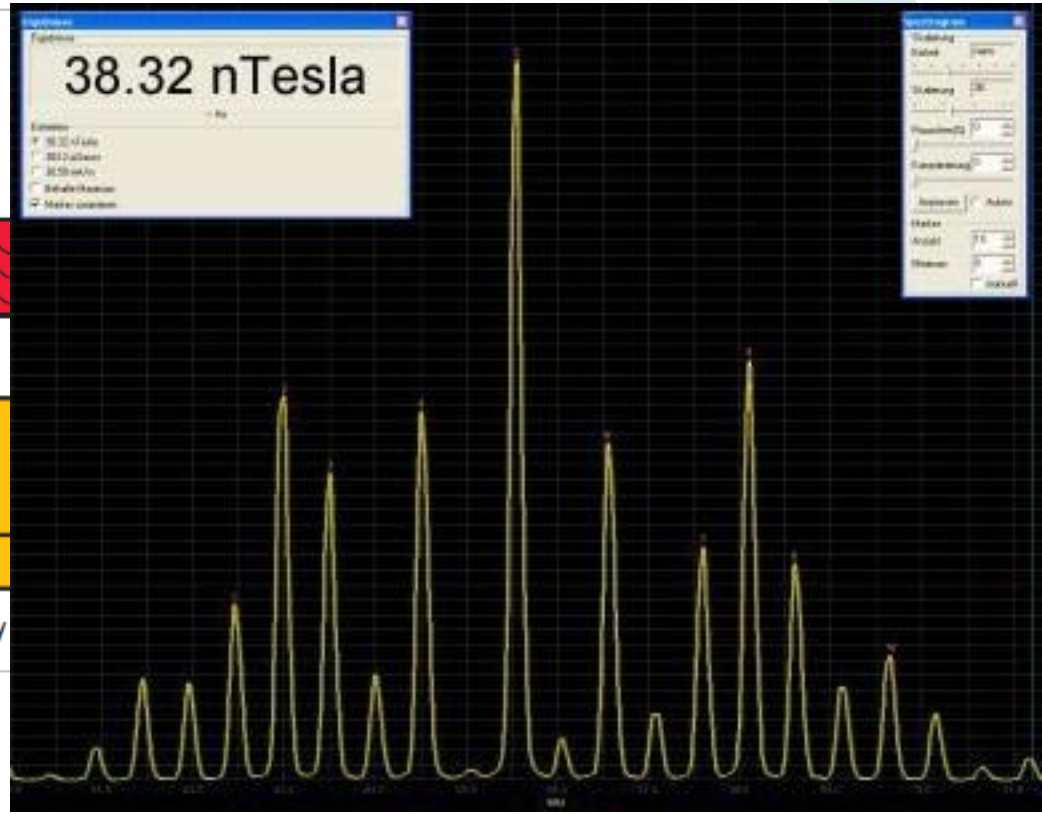
Applications ? Spectroscopy of microwave signals

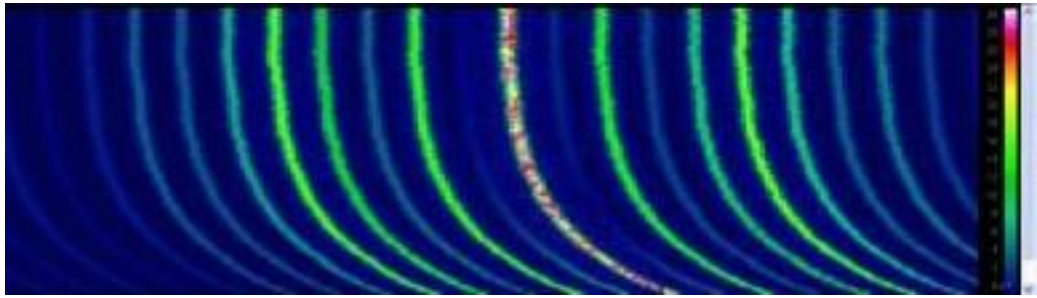


1. In the CW mode

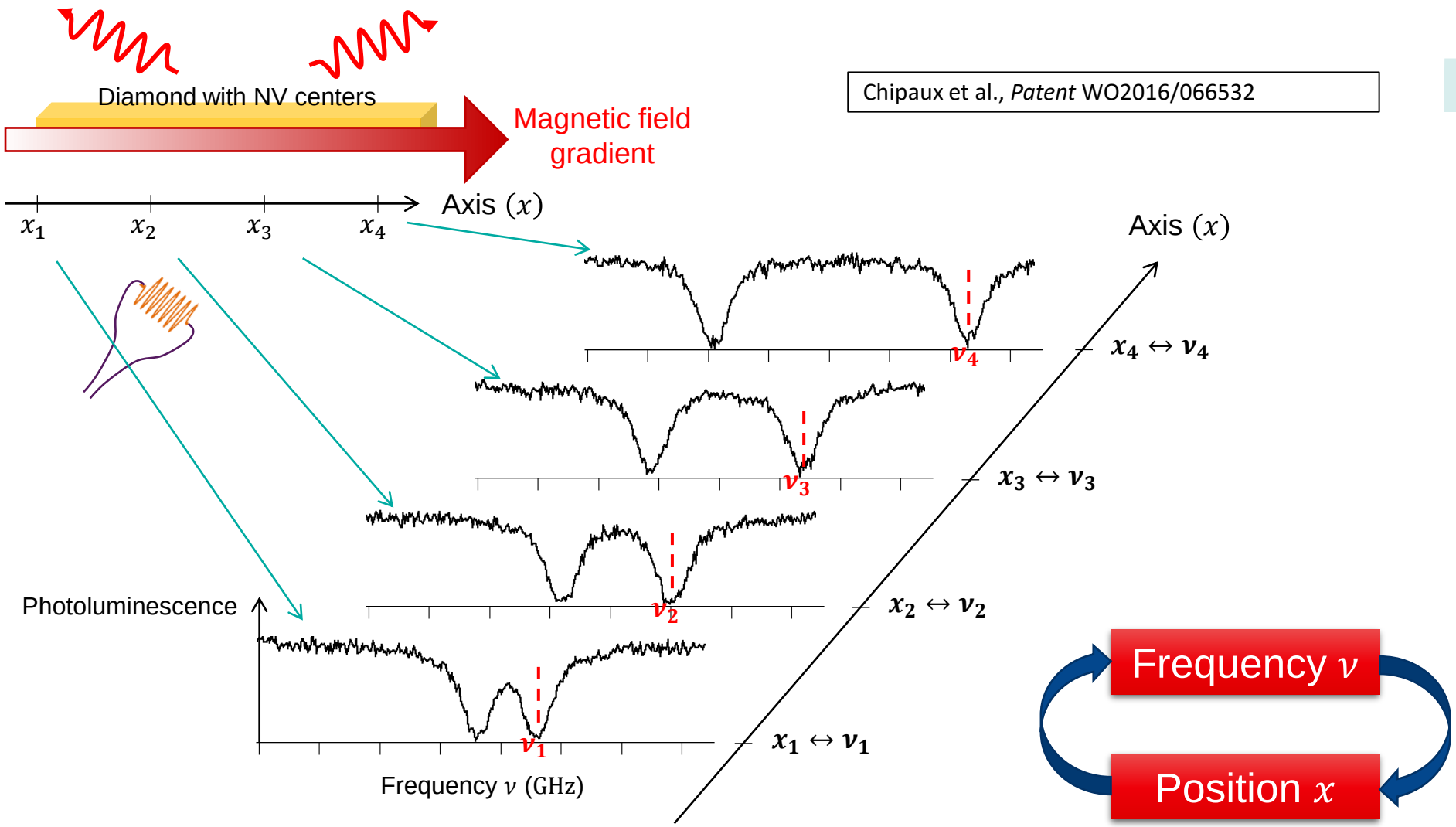
Applications ? Spectroscopy of microwave signals







Applications ? Spectroscopy of microwave signals



Chipaux et al., *Patent* WO2016/066532

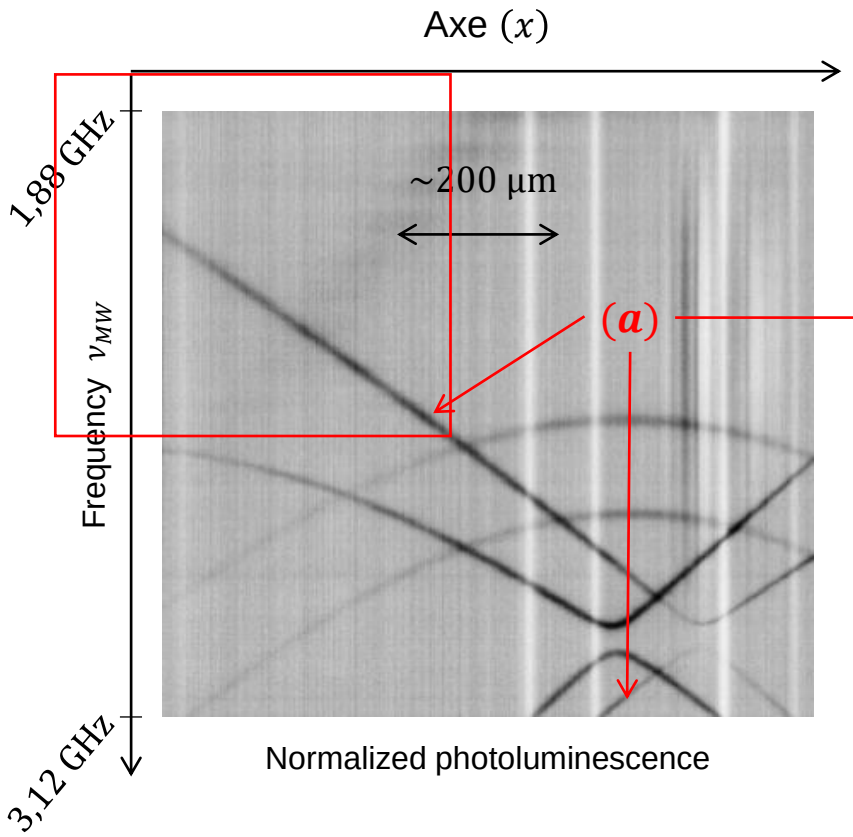
Frequency ν

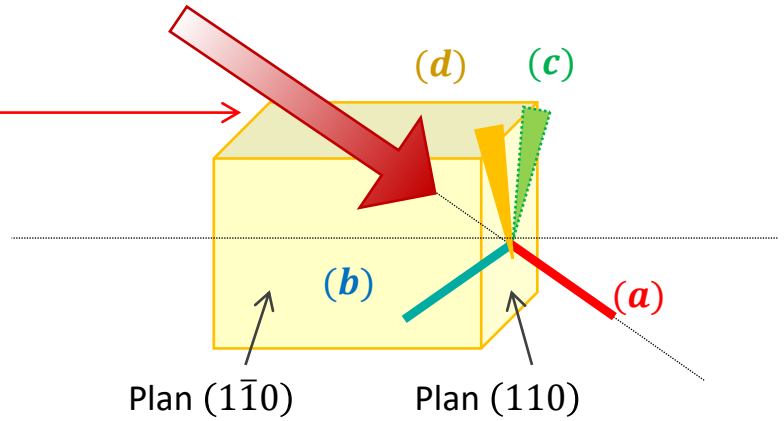
Position x

M. Chipaux, *et. al.*, *Appl. Phys. Lett.*107 (23), 233502 (2014)

M. Chipaux *et al.*, Patent WO2016/066532

Applications ? Spectroscopy of microwave signals



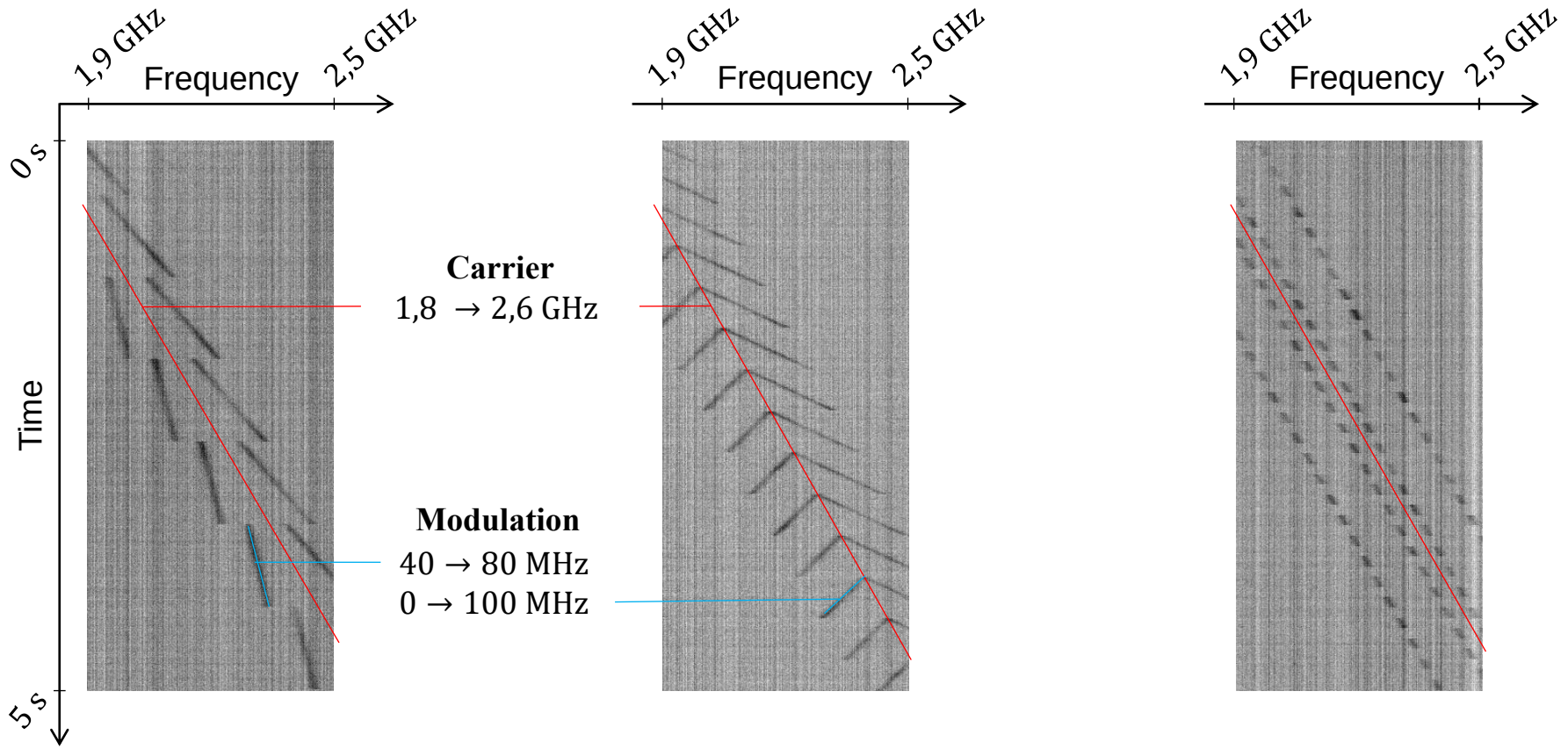


Bijection in a range of 700 MHz

M. Chipaux, *et. al.*, *Appl. Phys. Lett.*107 (23), 233502 (2014)
M. Chipaux *et al.*, Patent WO2016/066532

Applications ? Spectroscopy of microwave signals

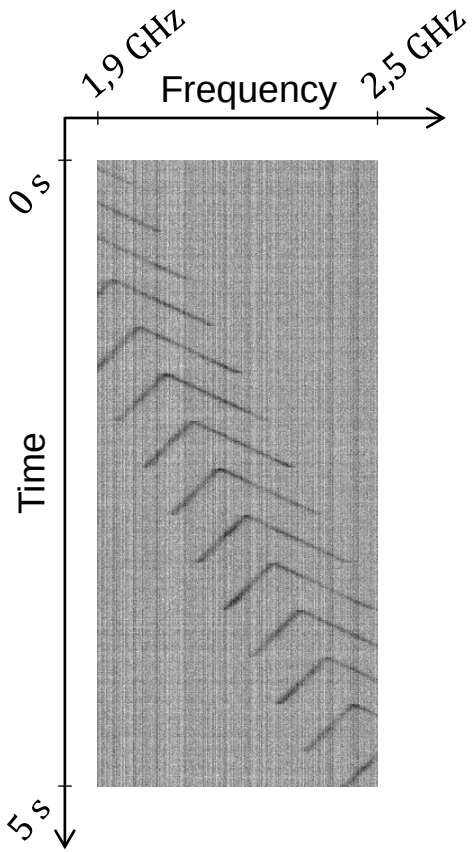
Real time analysis



M. Chipaux, *et. al.*, *Appl. Phys. Lett.*107 (23), 233502 (2014)
M. Chipaux *et al.*, Patent WO2016/066532

Applications ? Spectroscopy of microwave signals

What are the performances?



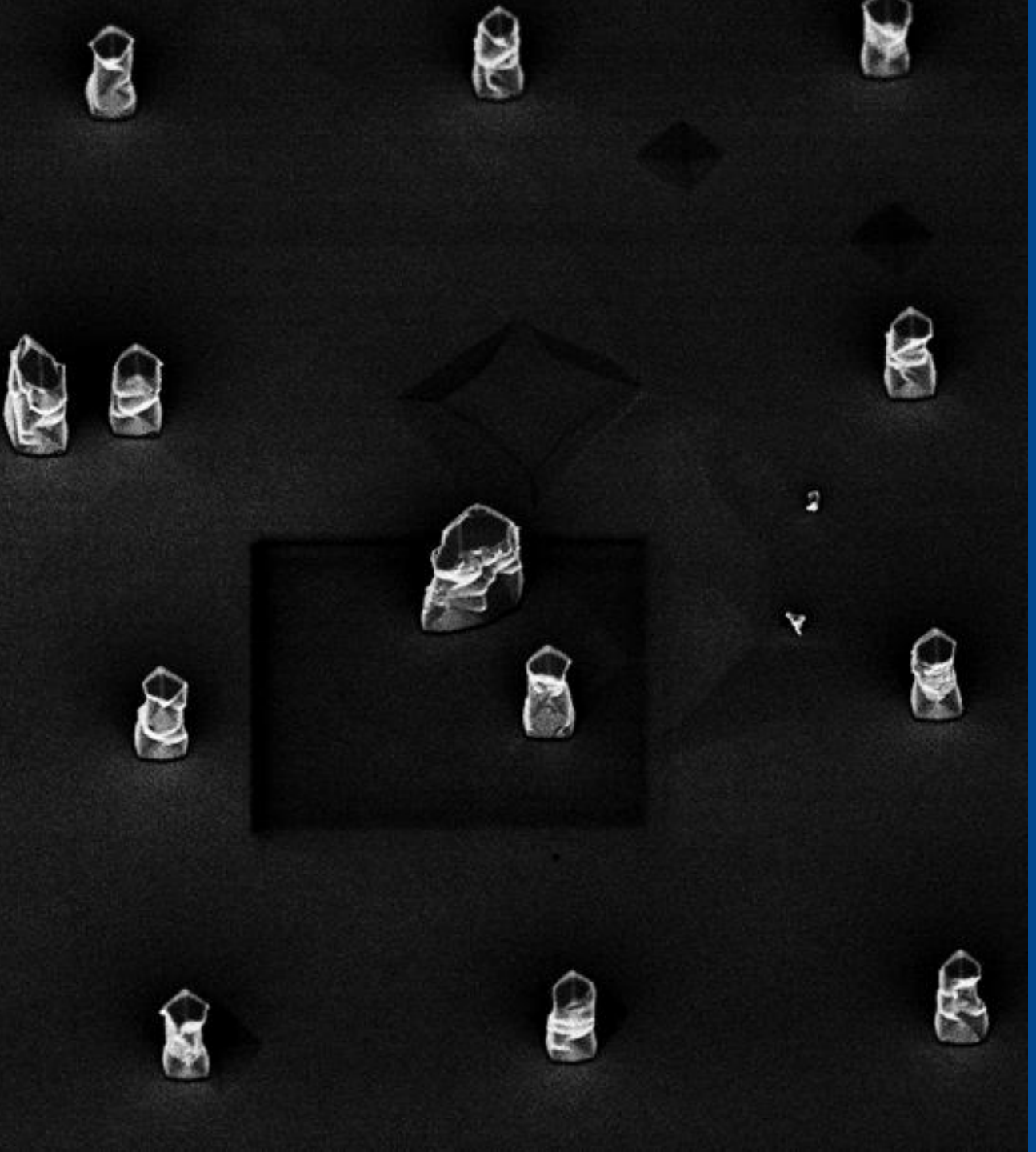
Refresh rate: 4 ms → (NV center photophysics) → Refresh rate: 1 µs

Frequency domain: 700 MHz → (Permanent magnets : 1 T) → 30 GHz

Resolution: 7 MHz → (Power broadening)

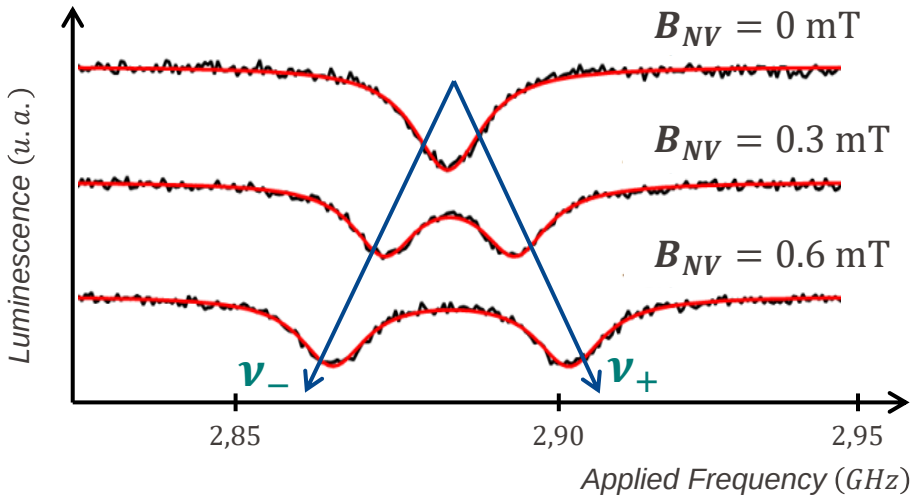
Number of channels: 4 000

M. Chipaux, *et. al.*, *Appl. Phys. Lett.*107 (23), 233502 (2014)
M. Chipaux *et al.*, Patent WO2016/066532



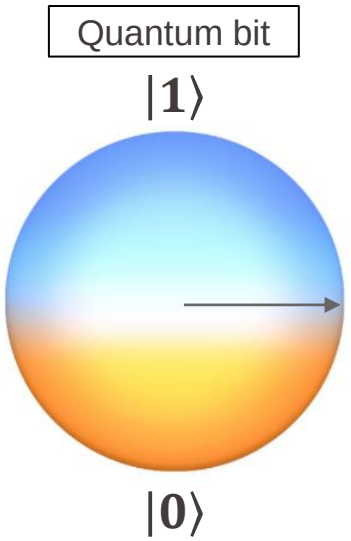
2. Pulse sequences

(o) Back to the CW case



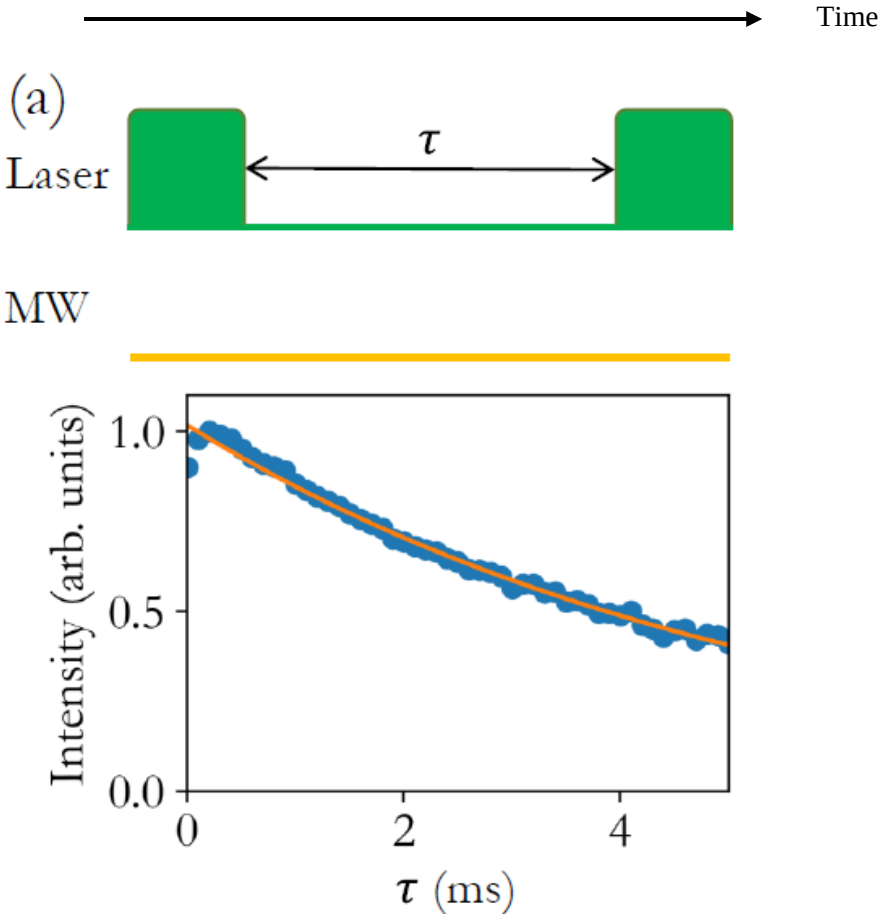
$$\eta_B = P_f \frac{\hbar}{g\mu_b} \cdot \frac{\Delta_\nu}{C\sqrt{R}} \qquad \text{en mT} \cdot Hz^{-1/2}$$

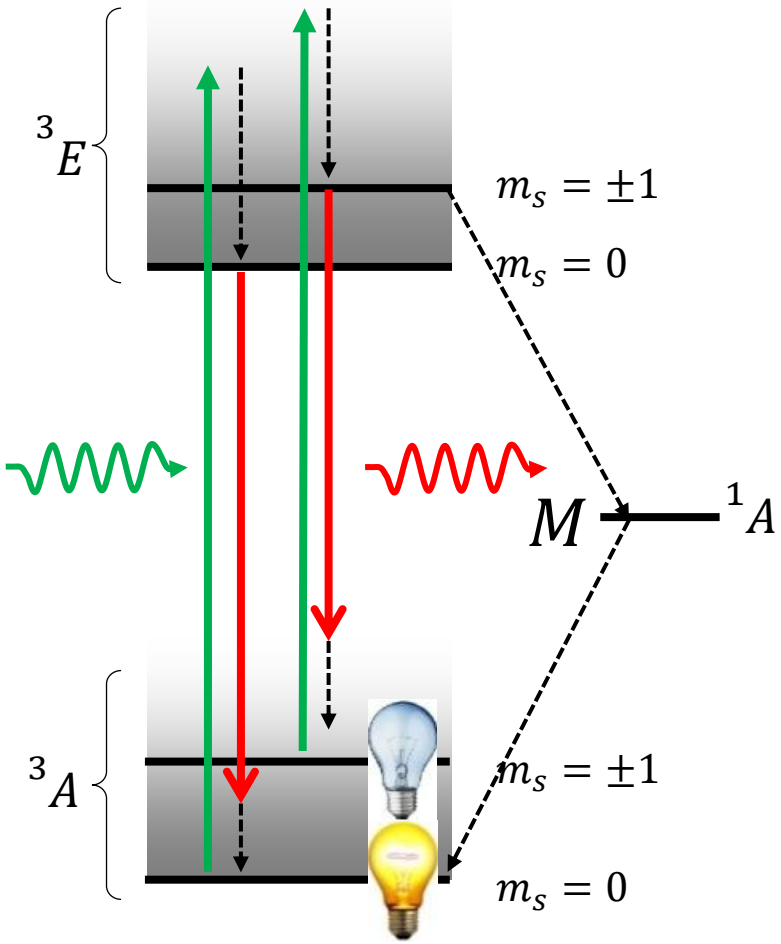
- R Rate of detected photons
- $\frac{g\mu_b}{\hbar}$ Electron-spin gyromagnetic ratio
- C Measurement contrast
- Δ_ν Linewidth $\Delta_\nu \approx \frac{1}{T_2^*}$
- $P_f \approx 0.77$

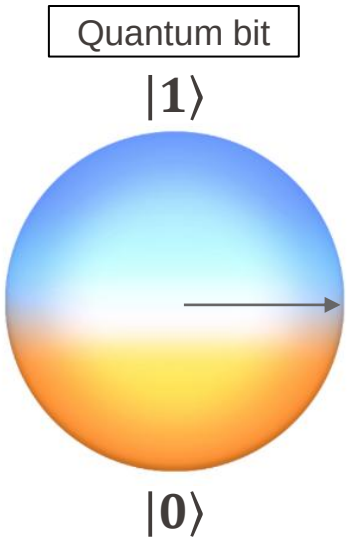


2. Pulse sequences

(a) Relaxometry (see chap. 3)

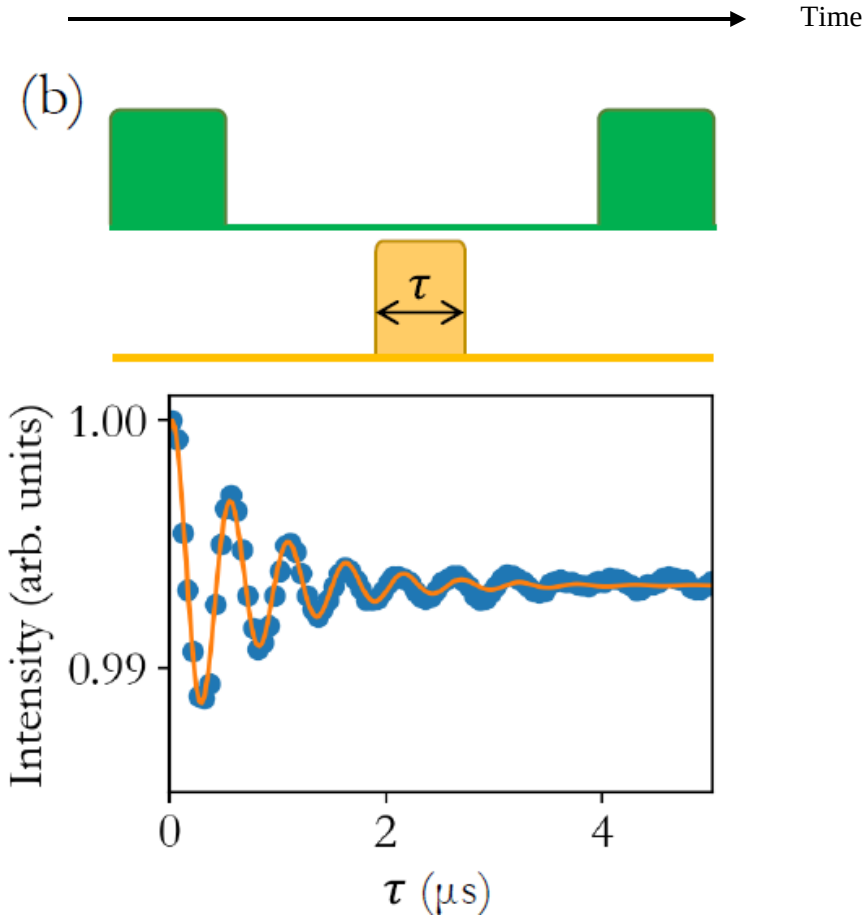


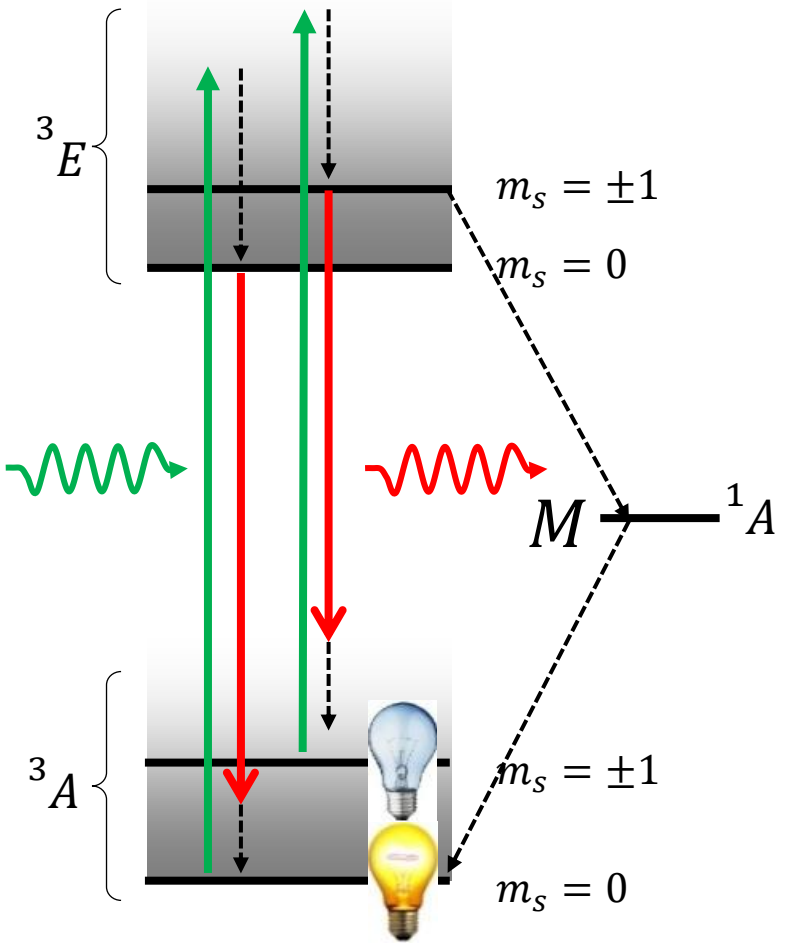


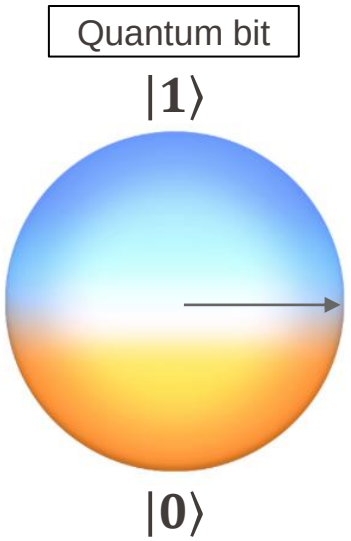


H. Babashah, H. Shirzad, et al. Optically detected magnetic resonance with an open source platform. *SciPost Physics Core*, *6*(4), 065 (2023)

(b) Rabi cycles



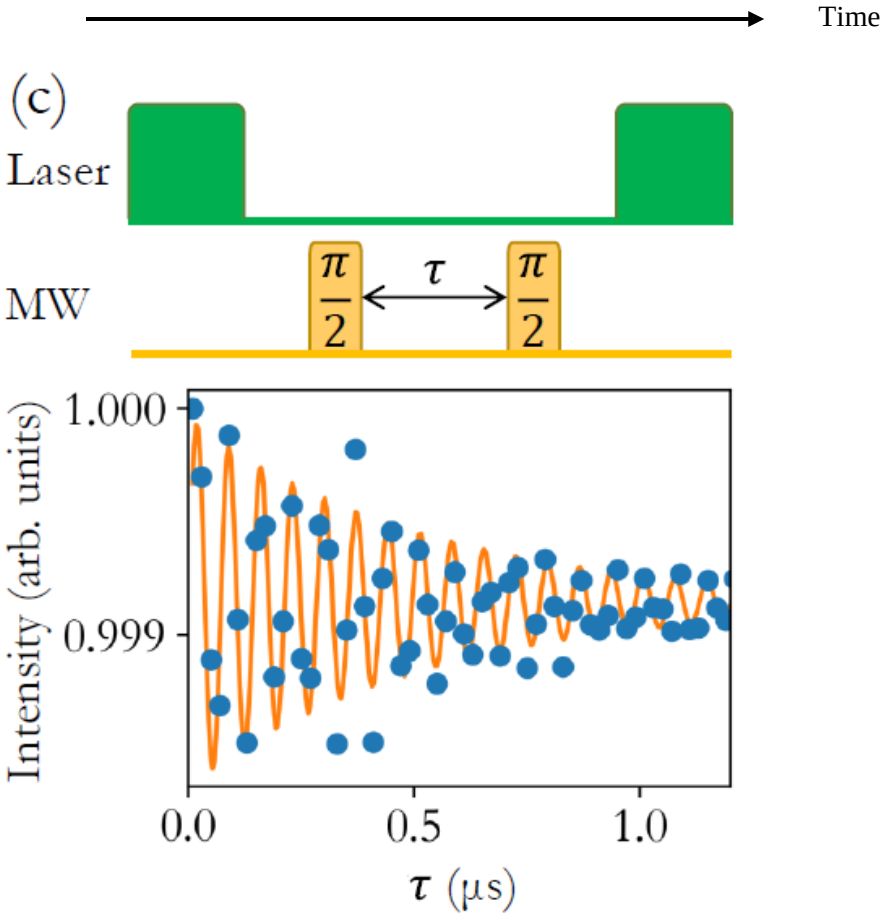


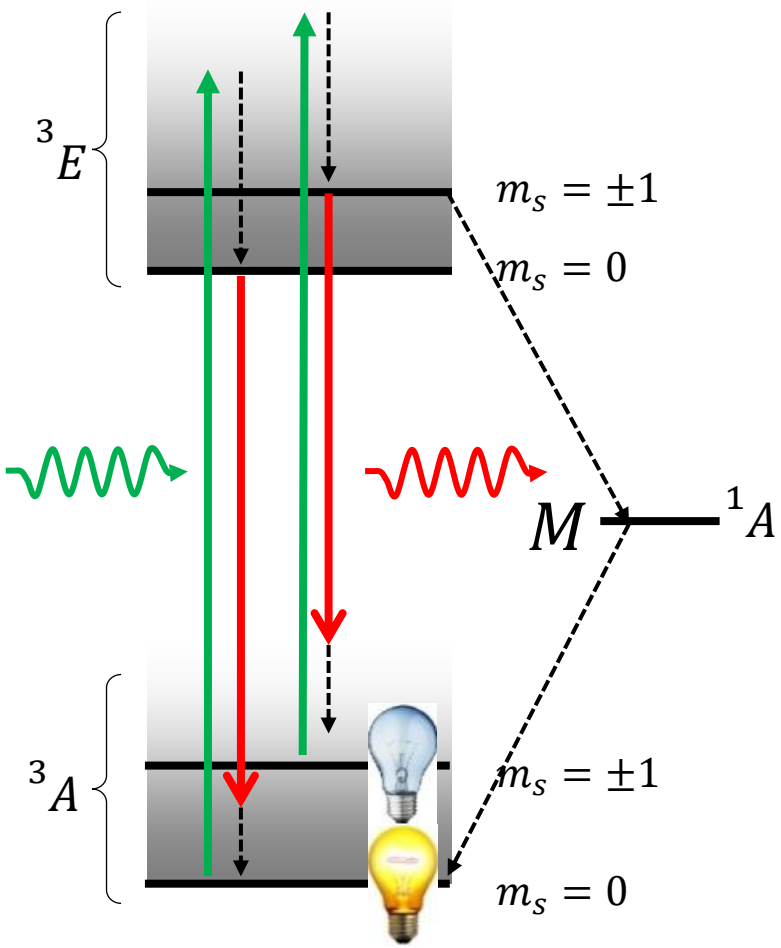


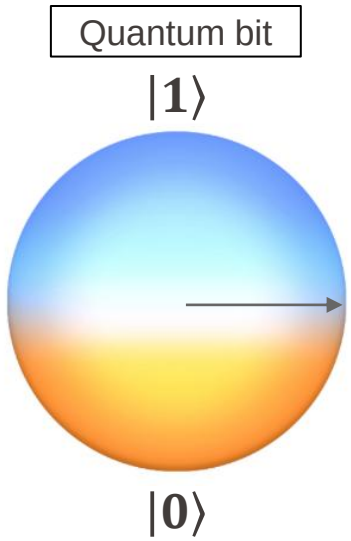
H. Babashah, H. Shirzad, et al. Optically detected magnetic resonance with an open source platform. SciPost Physics Core, 6(4), 065 (2023)

2. Pulse sequences

(c) Ramsey



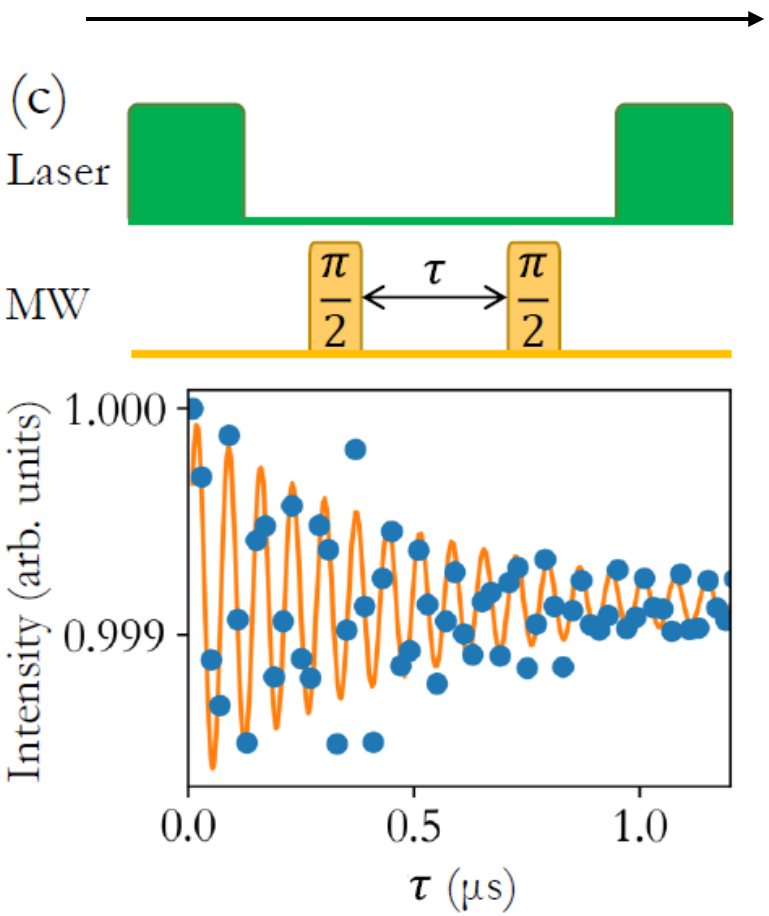




H. Babashah, H. Shirzad, et al. Optically detected magnetic resonance with an open source platform. SciPost Physics Core, 6(4), 065 (2023)

* J. M. Taylor, (2008). High-sensitivity diamond magnetometer with nanoscale resolution. *Nature Physics*, *4*(10), 810-816.

(c) Ramsey; sensitivity ?



$$\eta_{DC} \approx \frac{\hbar}{g\mu_b} \cdot \frac{1}{C\sqrt{\zeta \cdot T_2^*}} \quad \text{en mT} \cdot Hz^{-1/2}$$

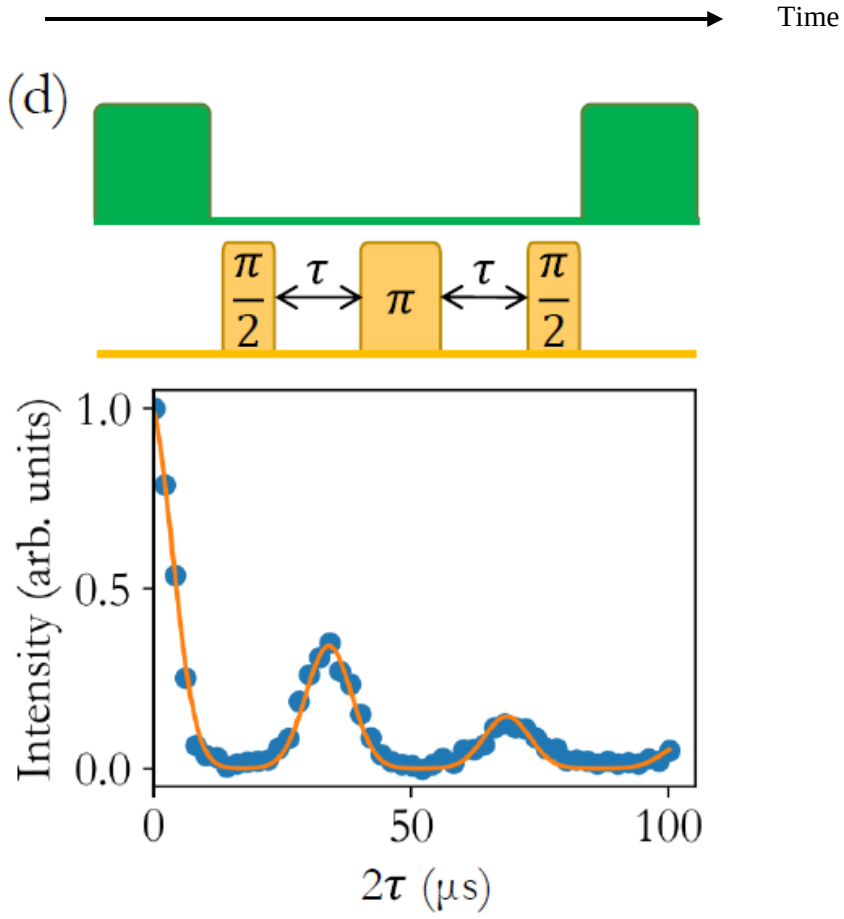
ζ Collection efficiency

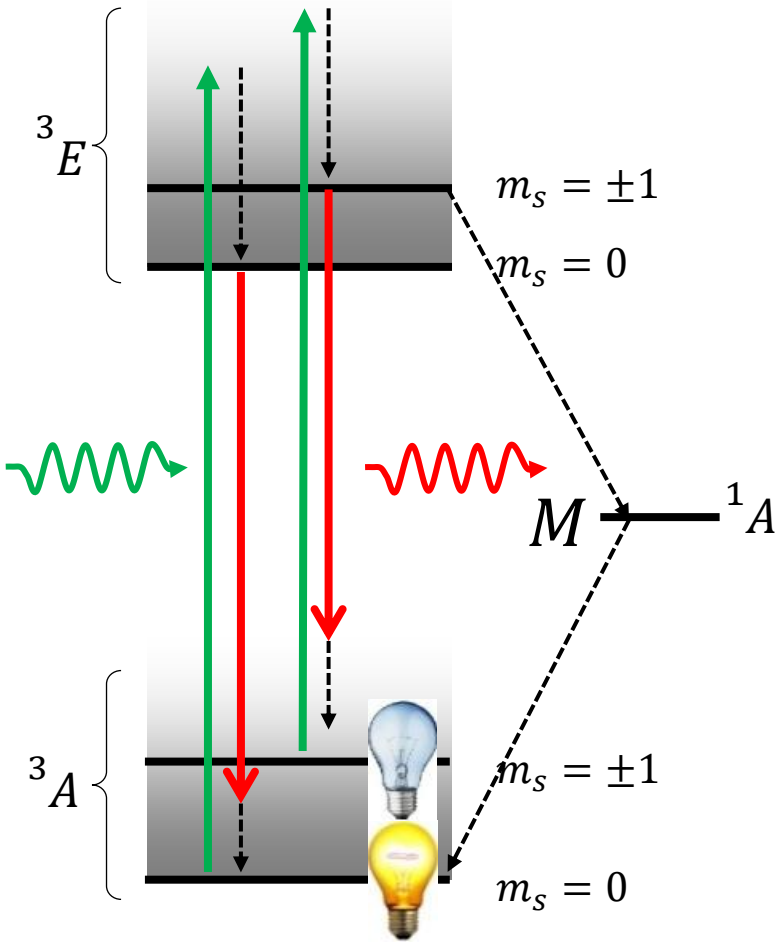
H. Babashah, H. Shirzad, et al. Optically detected magnetic resonance with an open source platform. SciPost Physics Core, 6(4), 065 (2023)

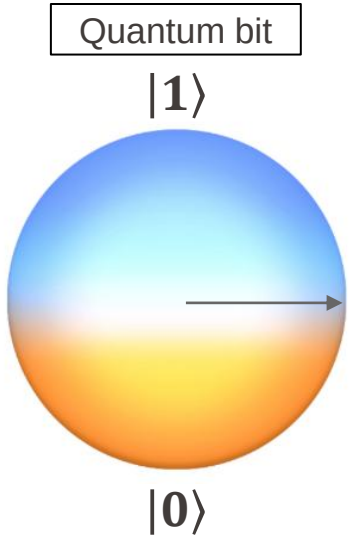
* J. M. Taylor, (2008). High-sensitivity diamond magnetometer with nanoscale resolution. *Nature Physics*, *4*(10), 810-816.

2. Pulse sequences

(d) Hahn echo



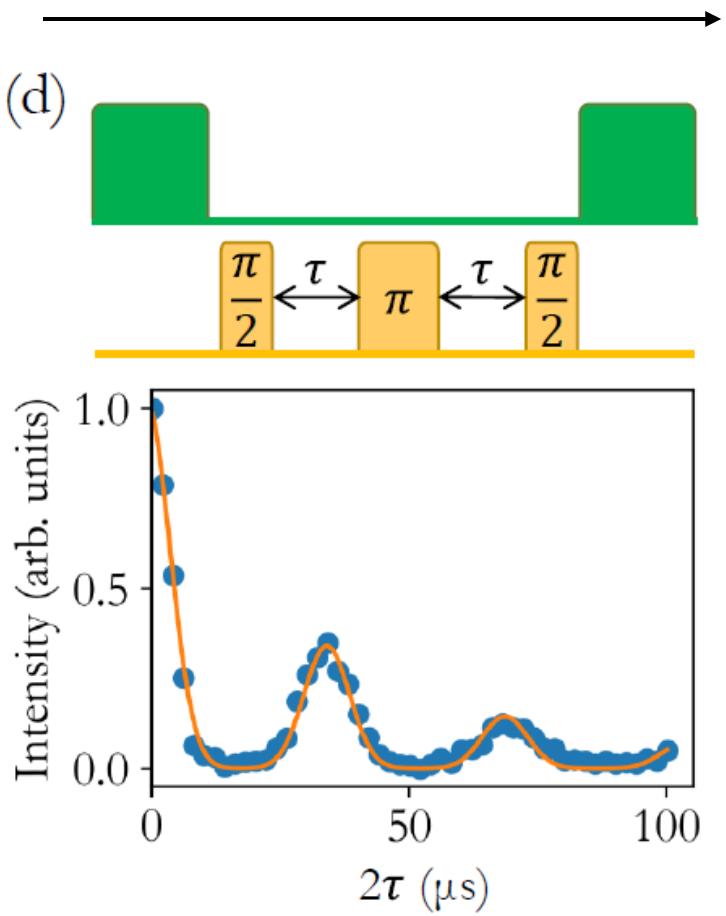




H. Babashah, H. Shirzad, et al. Optically detected magnetic resonance with an open source platform. SciPost Physics Core, 6(4), 065 (2023)

* J. M. Taylor, (2008). High-sensitivity diamond magnetometer with nanoscale resolution. *Nature Physics*, *4*(10), 810-816.

(d) Hahn echo; sensitivity?



$$\eta_{DC} \approx \frac{\hbar}{g\mu_b} \cdot \frac{1}{C\sqrt{\zeta \cdot T_2}}$$

en $\mathrm{mT} \cdot Hz^{-1/2}$

Improved by $\sqrt{\frac{T_2}{T_2^*}}$

H. Babashah, H. Shirzad, et al. Optically detected magnetic resonance with an open source platform. SciPost Physics Core, 6(4), 065 (2023)

* J. M. Taylor, (2008). High-sensitivity diamond magnetometer with nanoscale resolution. *Nature Physics*, *4*(10), 810-816.

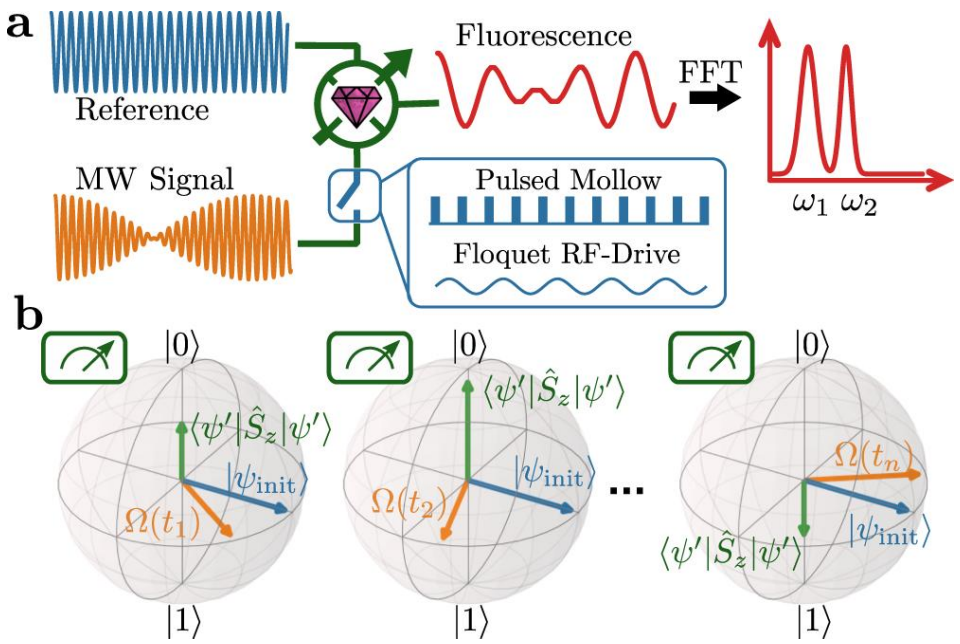
Quantum heterodyne sequence

Article | Open access | Published: 12 May 2021

Heterodyne sensing of microwaves with a quantum sensor

Jonas Meinel, Vadim Vorobyov, Boris Yavkin, Durga Dasari, Hitoshi Sumiya, Shinobu Onoda, Junichi Isoya & Jörg Wrachtrup

Nature Communications **12**, Article number: 2737 (2021) | Cite this article



EDITORS' SUGGESTION | LETTER

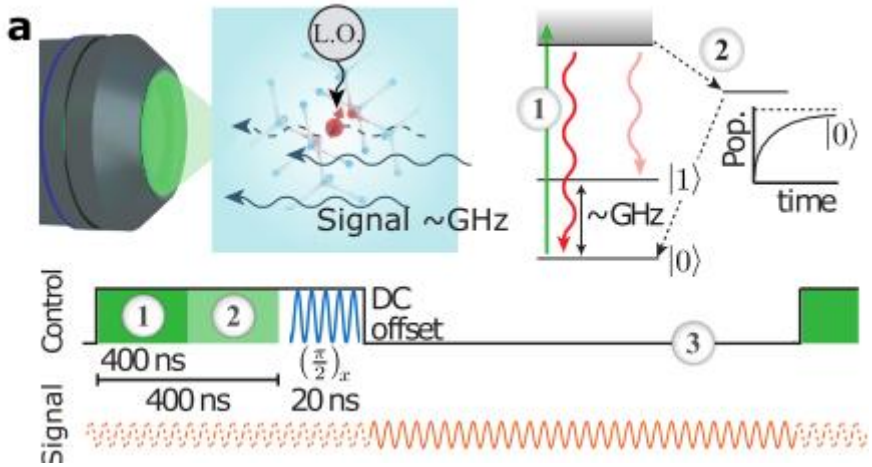
Phase-sensitive quantum spectroscopy with high-frequency resolution

Nicolas Staudenmaier[1], Simon Schmitt[1], Liam P. McGuinness[1,2,*], and Fedor Jelezko[1,3]

Show more

Phys. Rev. A **104**, L020602 – **Published 30 August, 2021**

DOI: https://doi.org/10.1103/PhysRevA.104.L020602



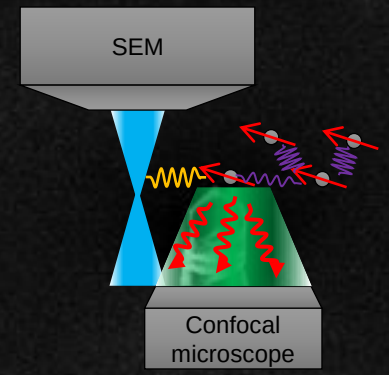
2. Pulse sequences

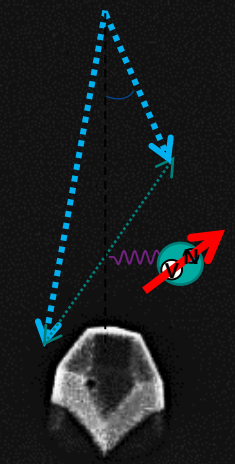
Link with my current research

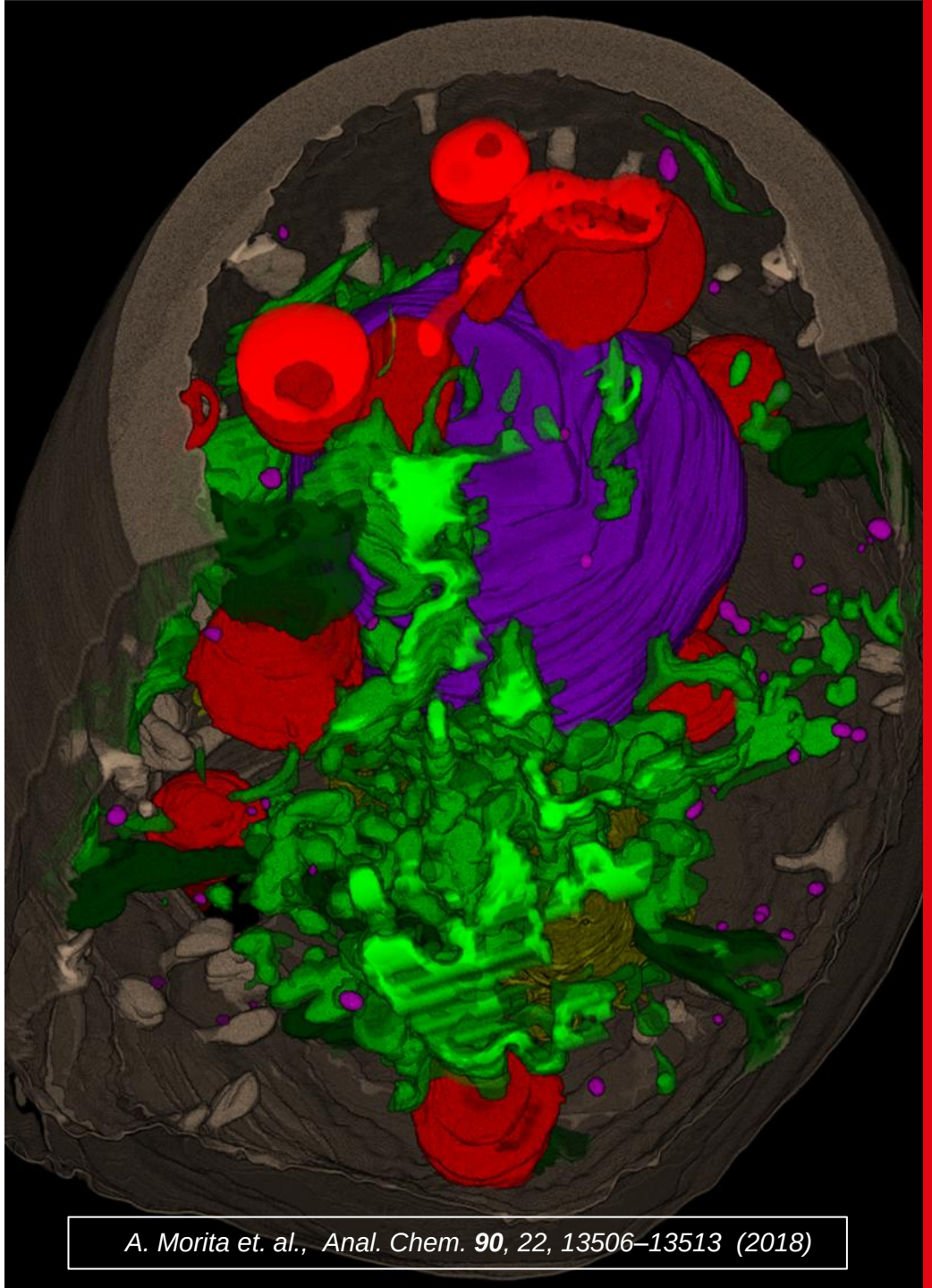
Selective quantum controls

Twisting the use of a Scanning Electron Microscope to prepare any arbitrary entangled state

Spin coherent control





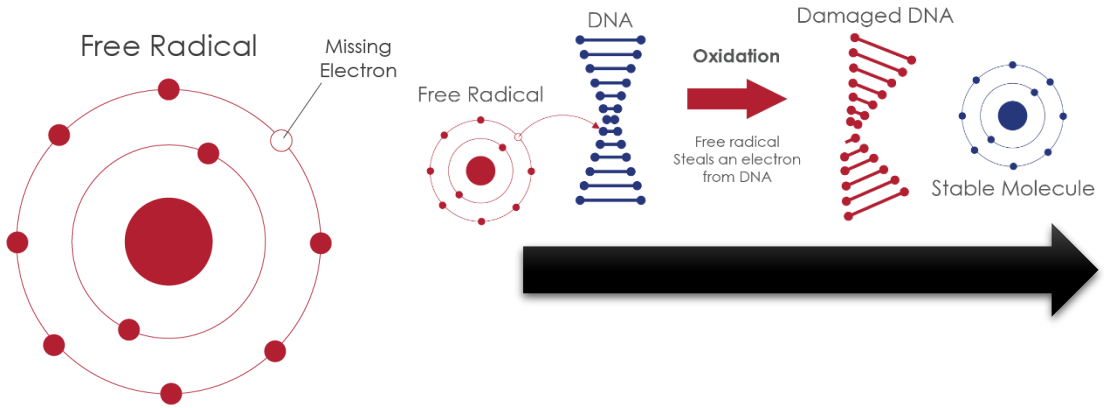


A. Morita et. al., Anal. Chem. ***90****, 22, 13506–13513 (2018)*

3. Sensing free radicals using relaxometry

Motivations

Free radicals



- Key roles in aging
- Maker for stress
- Signalling functions

Marker for metabolism, Illnesses, Ageing

M Chipaux *et al. Small* **14**, 1704263 (2018)

Challenges

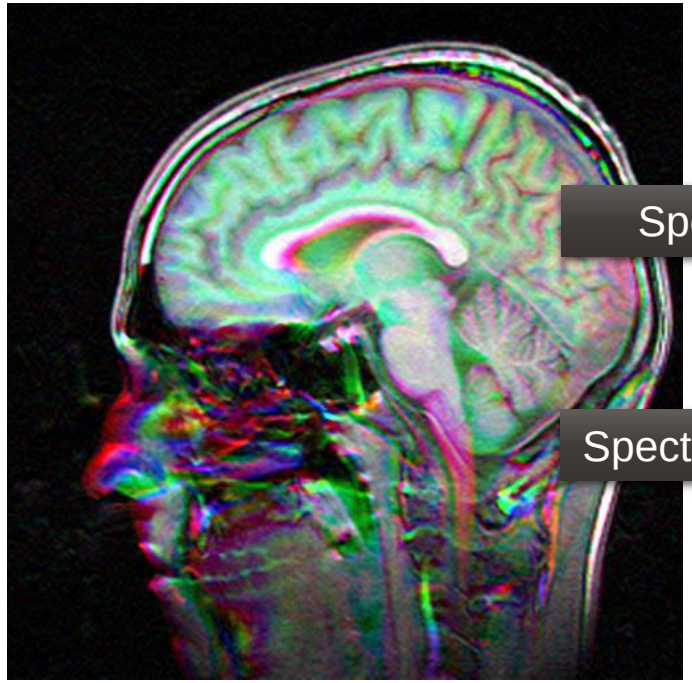
Interact with low energy photons

High reactivity Short life time

M Chipaux *et al. Small* **14**, 1704263 (2018)

Motivations

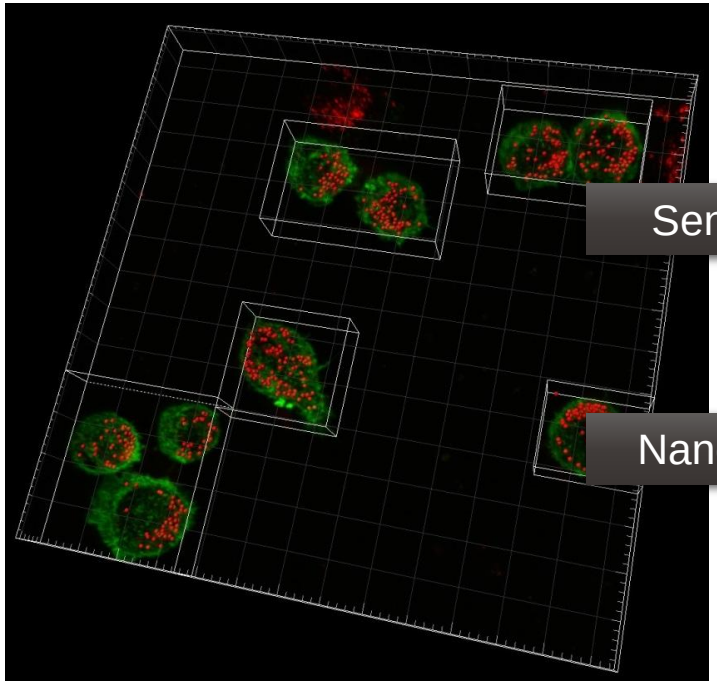
Magnetic resonance



Specific

Spectroscopy

Dye molecules



Sensitive

Nanoscale

Challenges

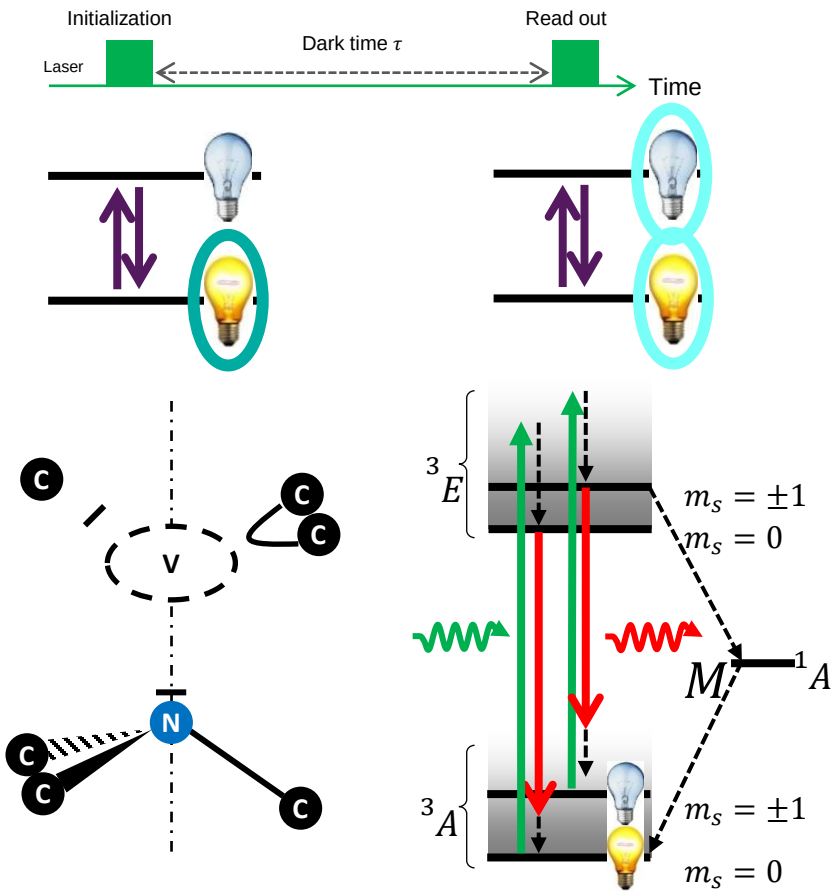
Interact with low energy photons

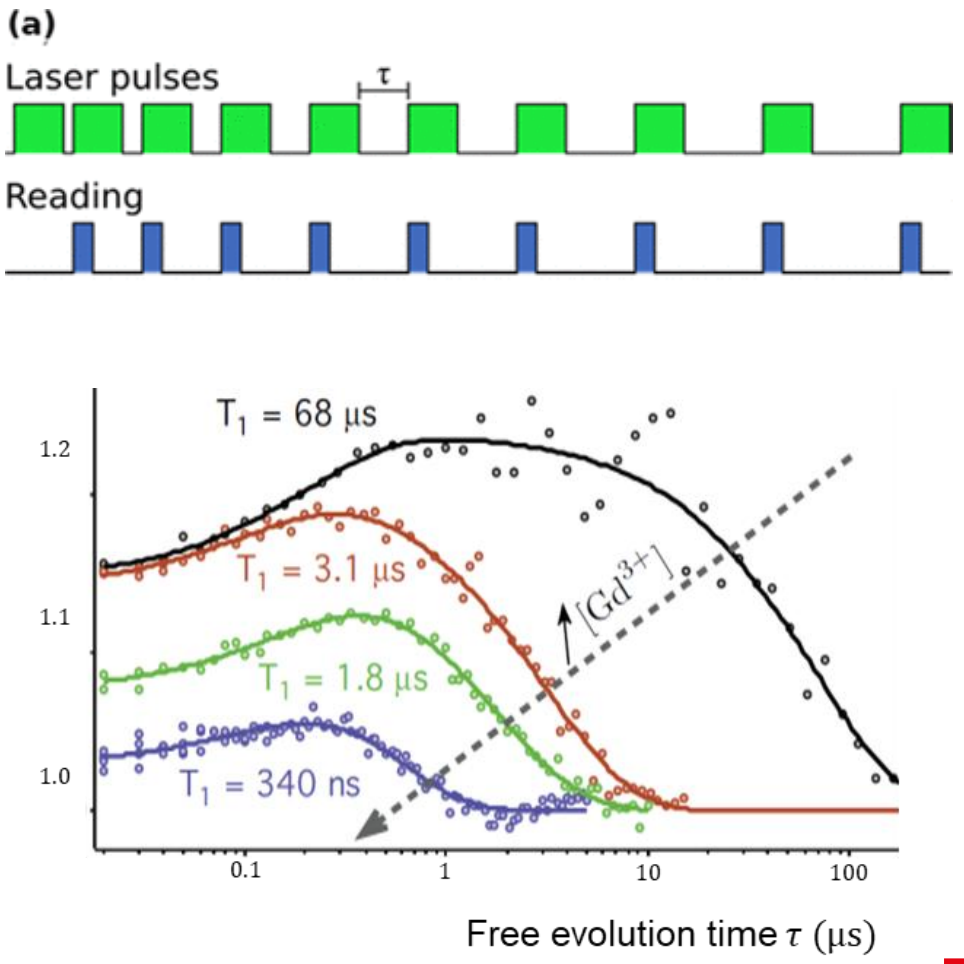
High reactivity
Short life time

M Chipaux *et al. Small* **14**, 1704263 (2018)

3. Relaxometry

Principles

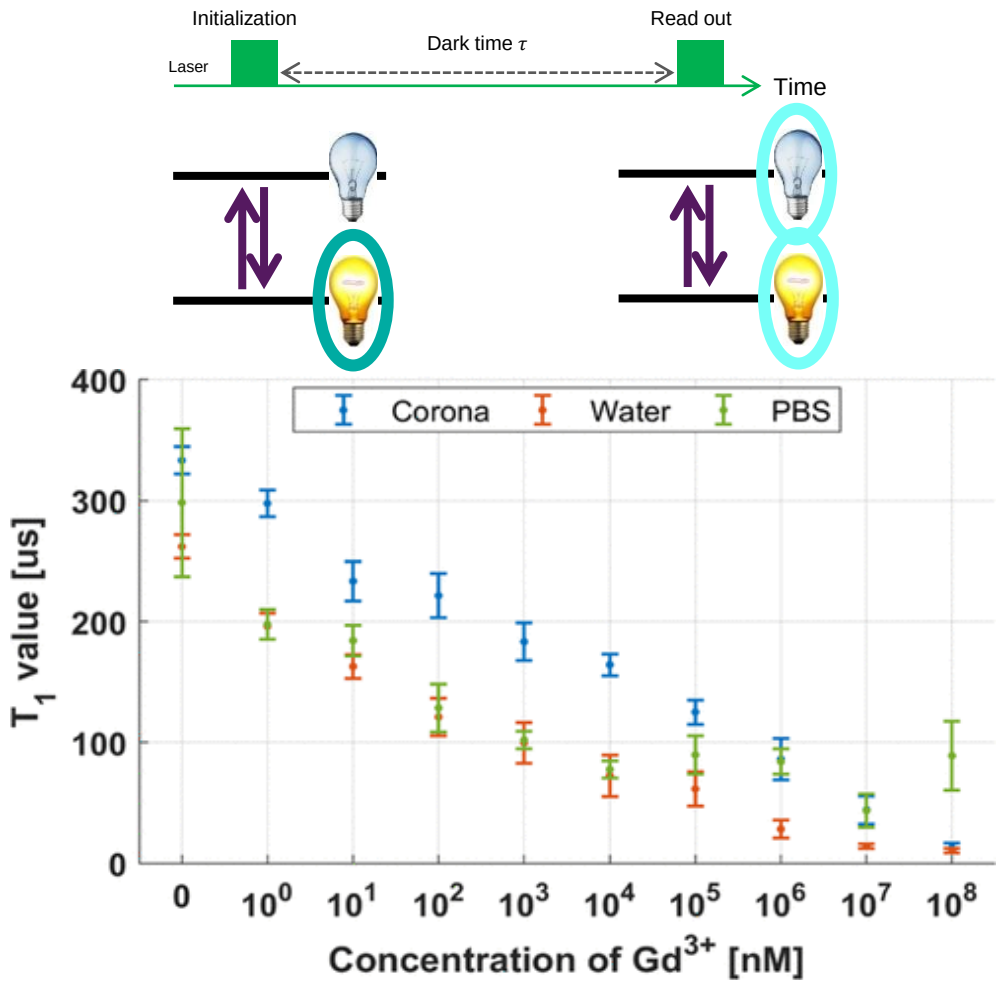


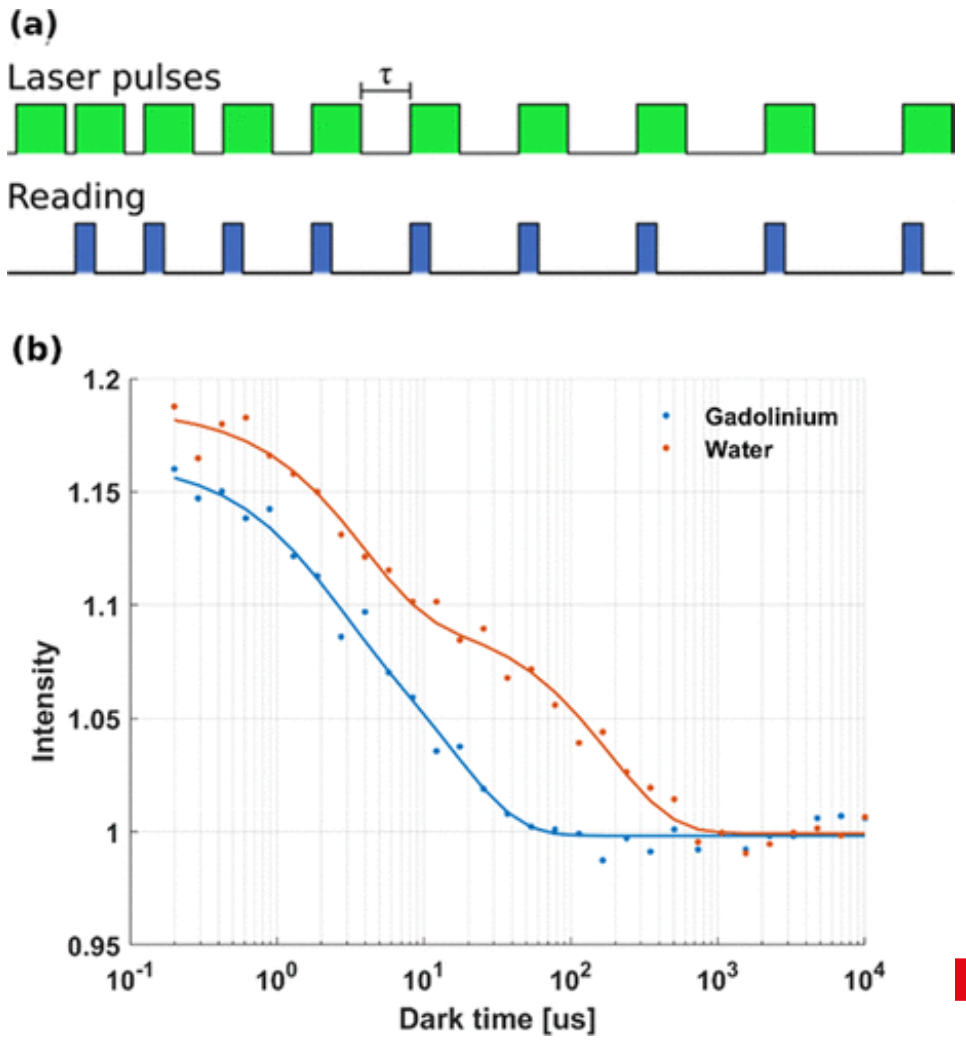


F. Perona Martinez *et. al.*, *ACS Sens.* **5**, 3862–3869 (2020)

3. Relaxometry

Principles

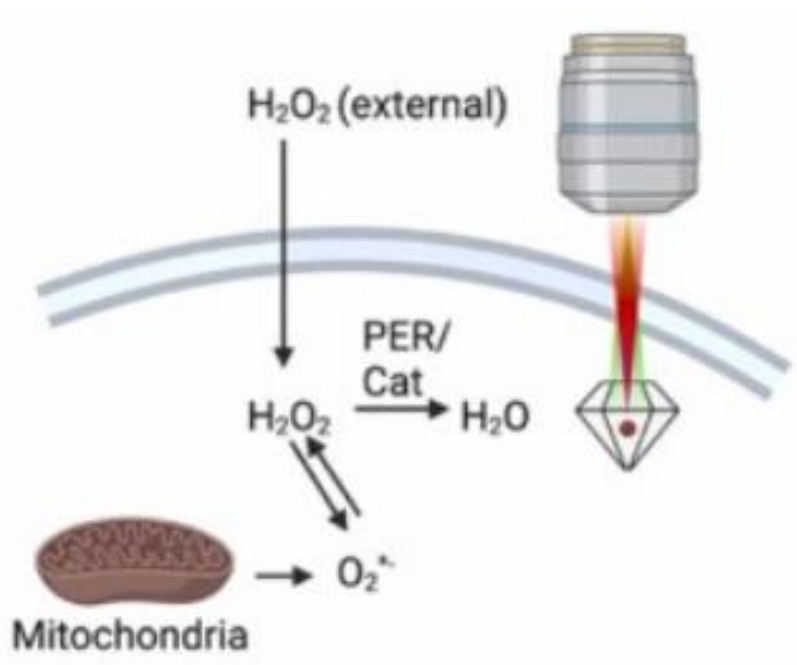


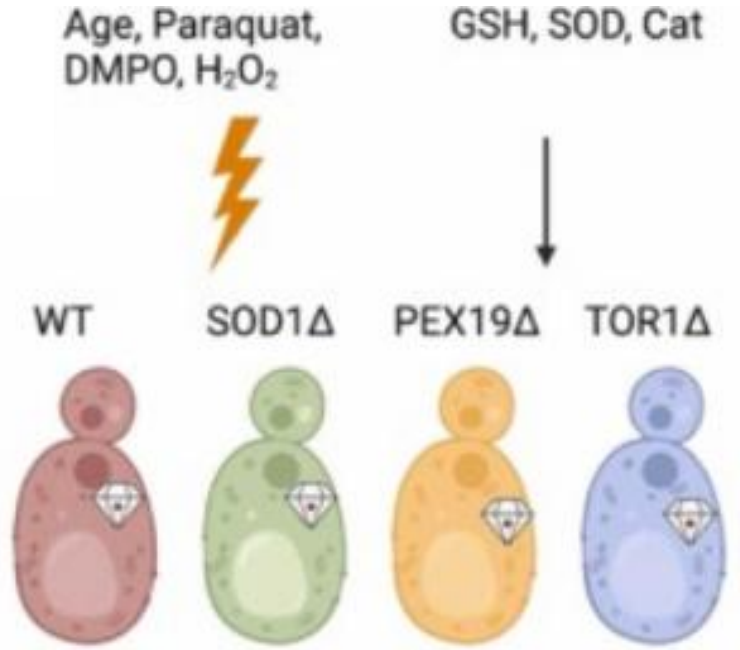


F. Perona Martinez *et. al., ACS Sens.* **5**, 3862–3869 (2020)

Application

T1 in Yeast cells mutant cells



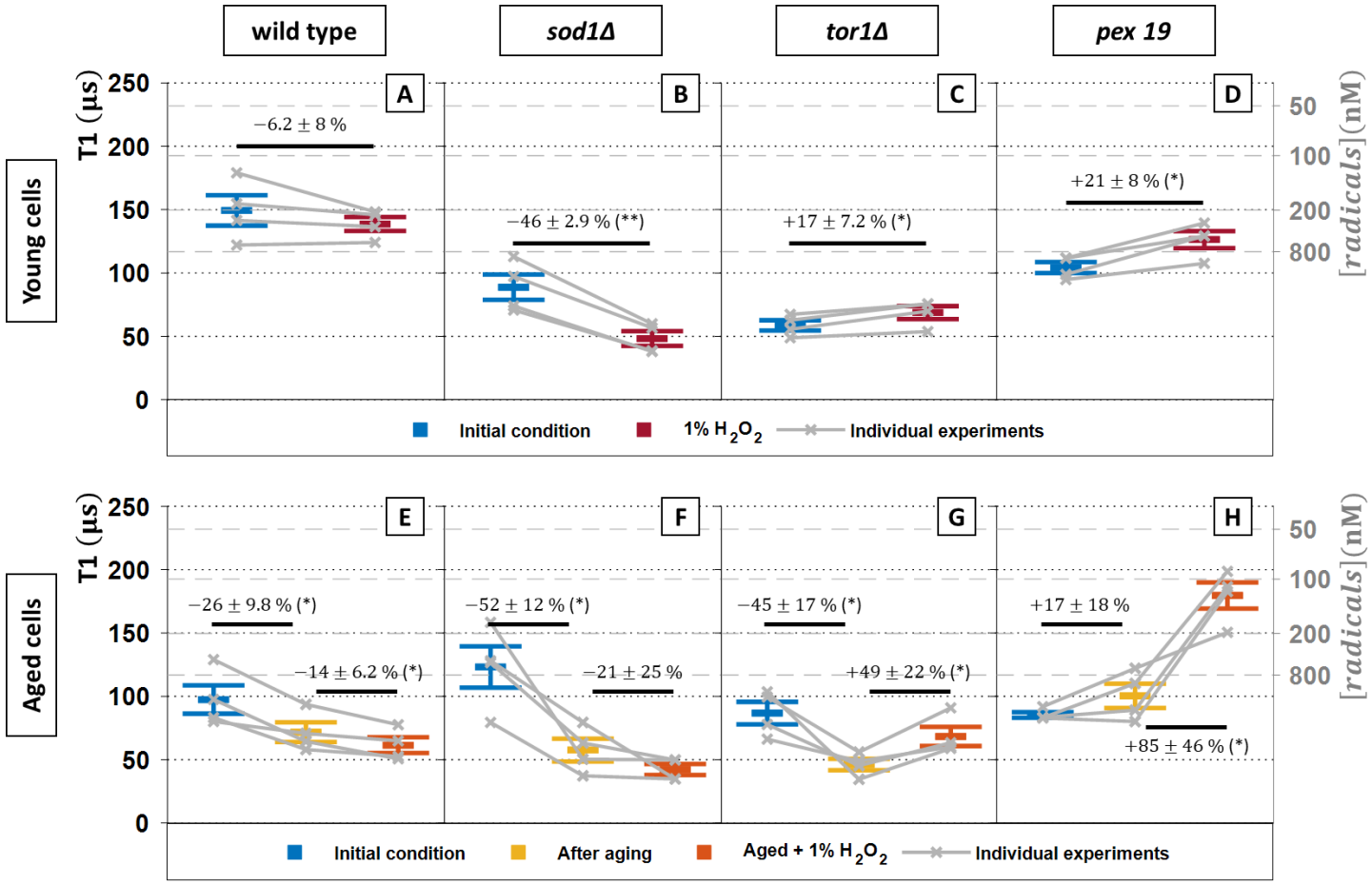


Yeast cells

A Morita *et al. Nano Today* **48**, 101704 (2023)

Application

T1 in Yeast cells mutant cells



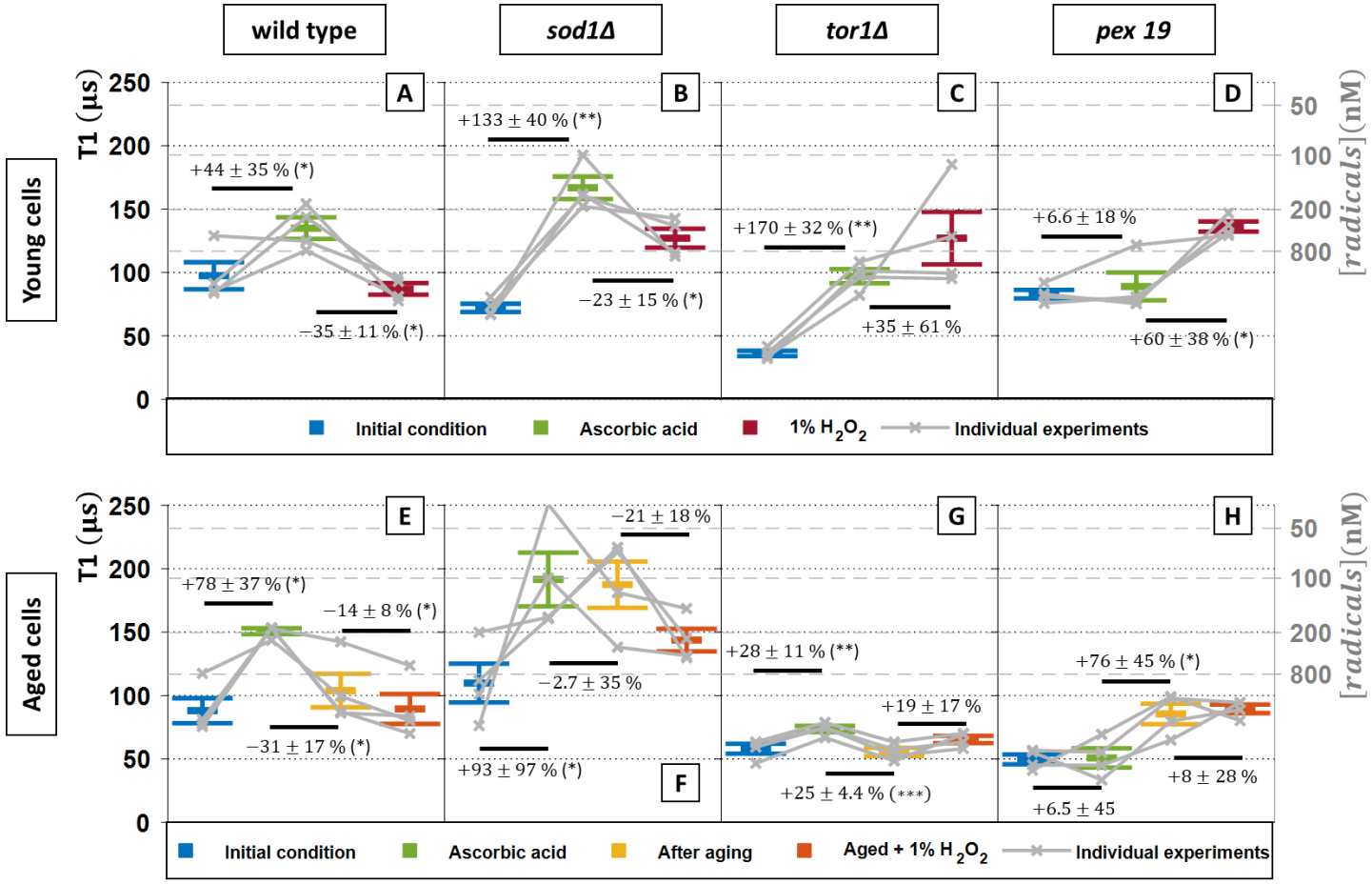
A Morita *et al. Nano Today* **48**, 101704 (2023)

Yeast cells

A Morita *et al. Nano Today* **48**, 101704 (2023)

Application

T1 in Yeast cells mutant cells



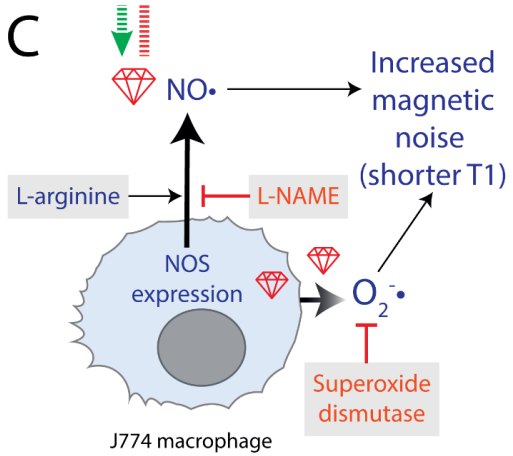
A Morita *et al. Nano Today* **48**, 101704 (2023)

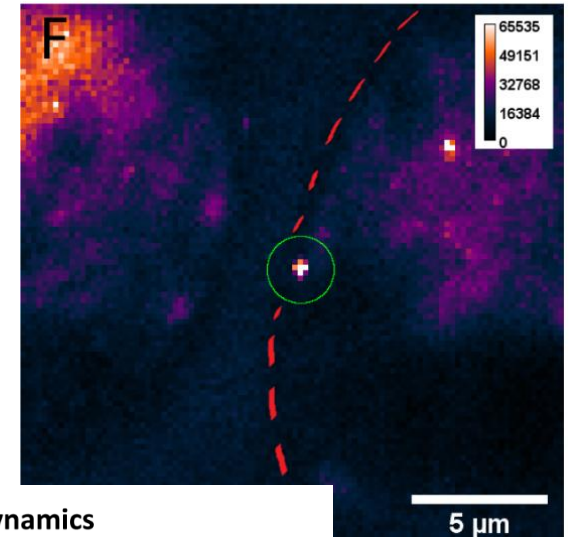
Yeast cells

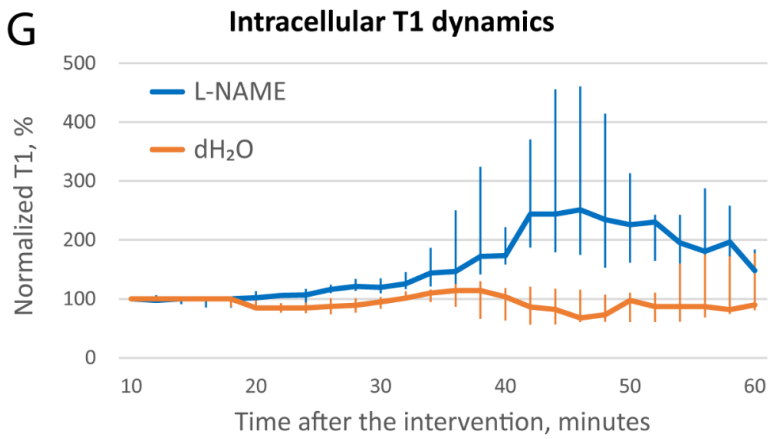
A Morita *et al. Nano Today* **48**, 101704 (2023)

Application

Nitric oxide radical



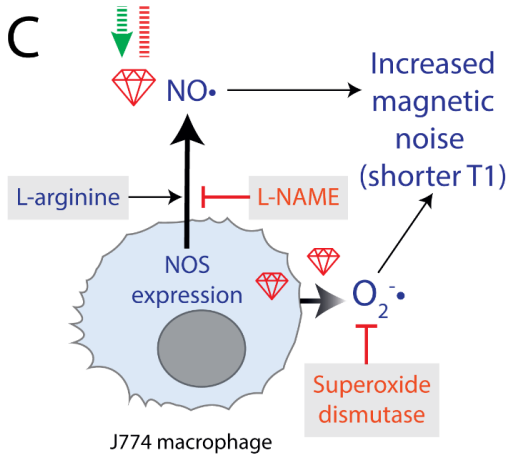


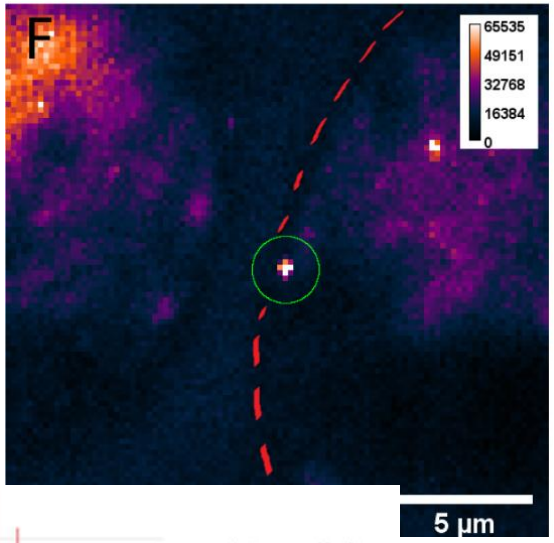


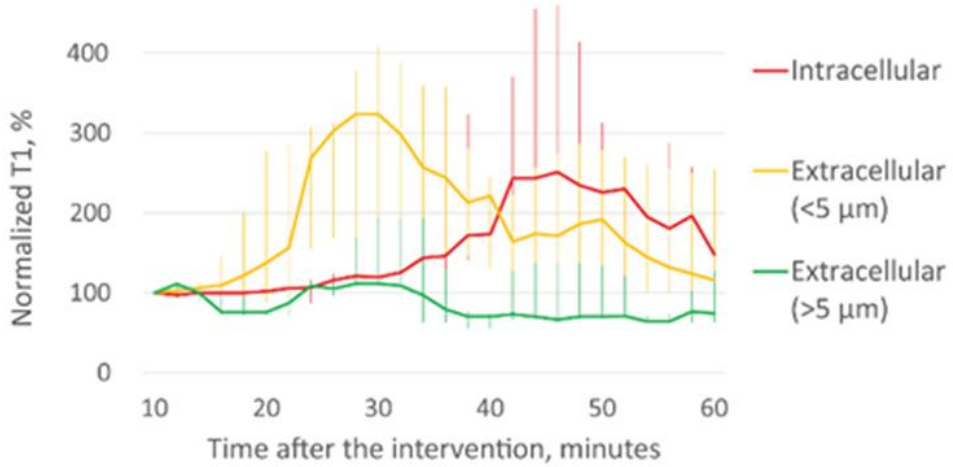
microphages (J774)

Application

Nitric oxide radical



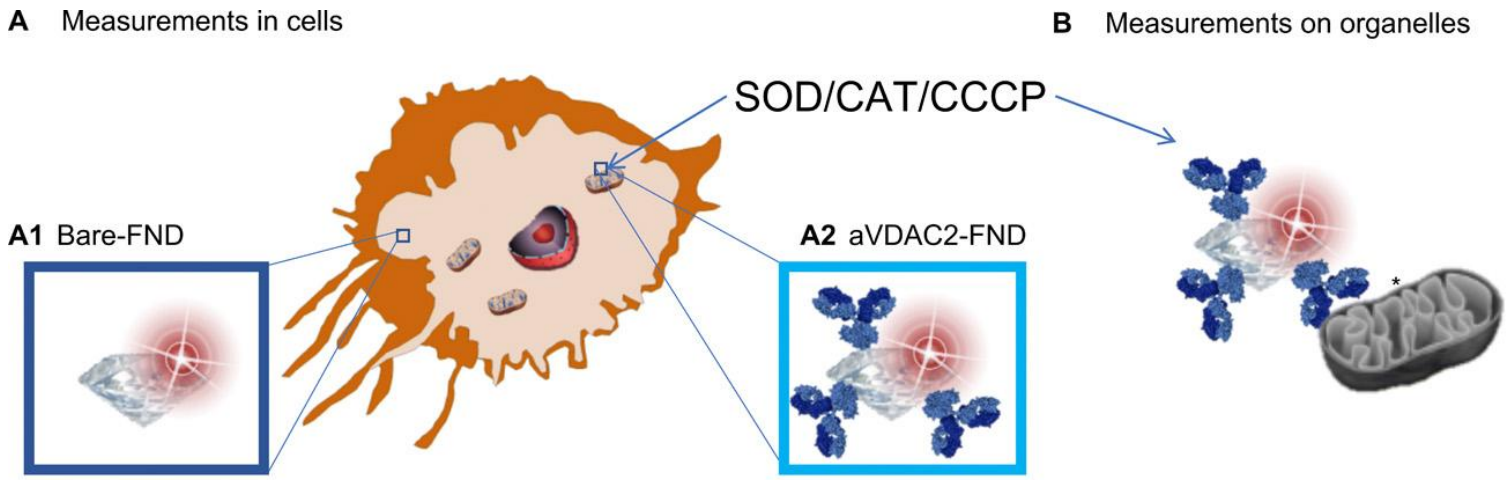




microphages (J774)

A. Sigaeva *et al. Small* **18**(39), 2105750 (2022)

Application

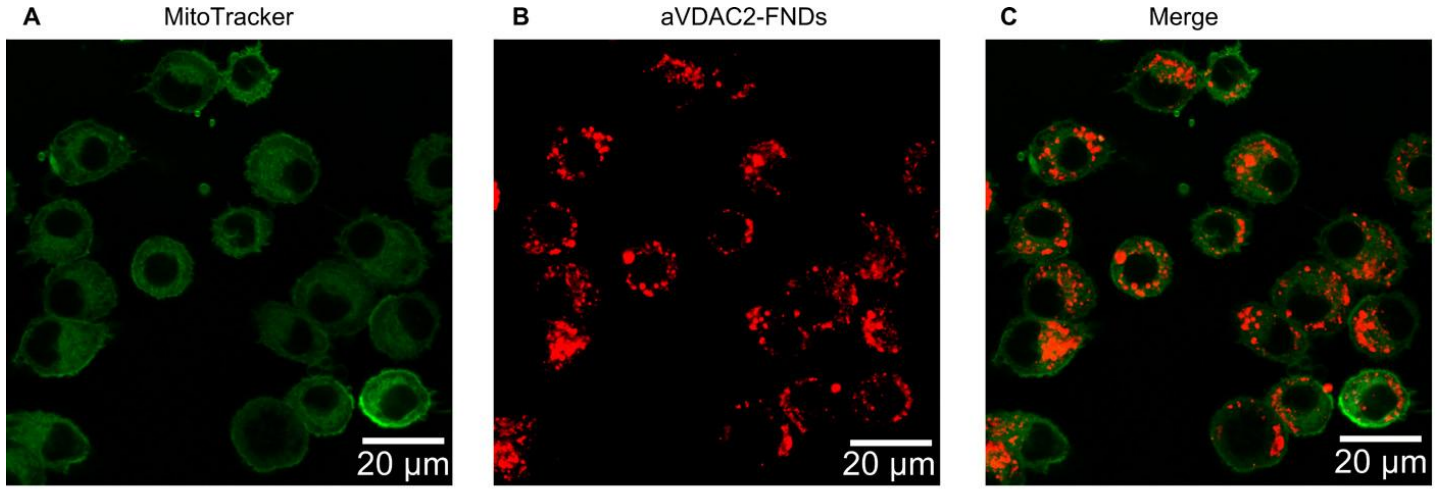


microphages (J774)

L. Nie *et al. Sci. Adv.* **7**, 21, eabf0573 (2021)

3. Relaxometry

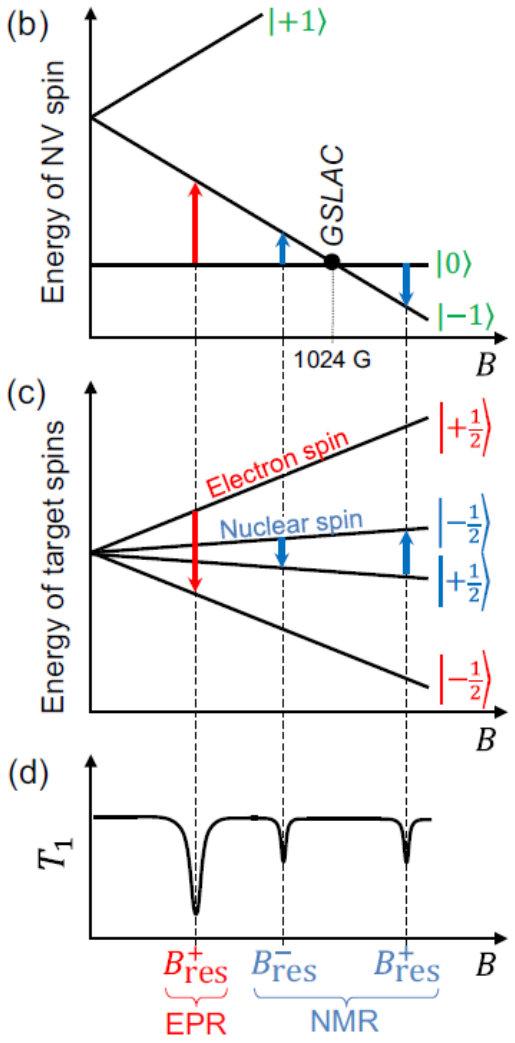
Application

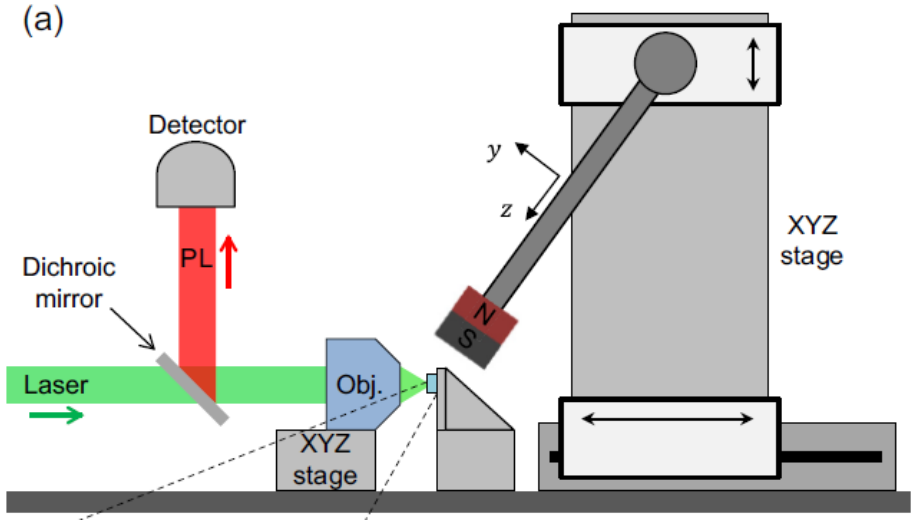


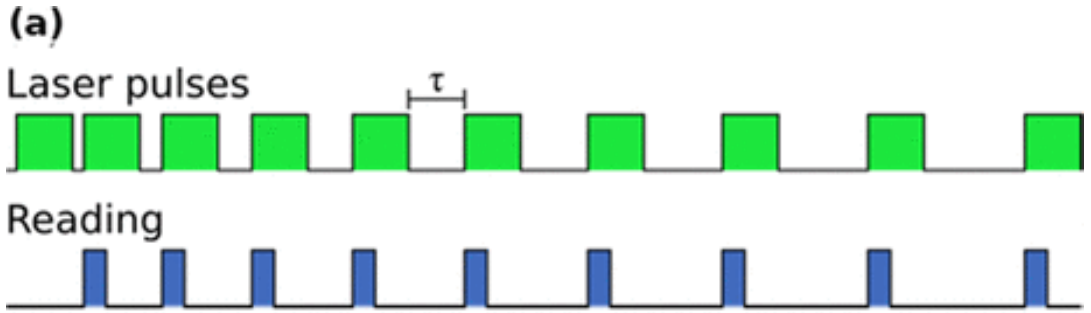
microphages (J774)

L. Nie *et al. Sci. Adv.* **7**, 21, eabf0573 (2021)

EPR Spectroscopy

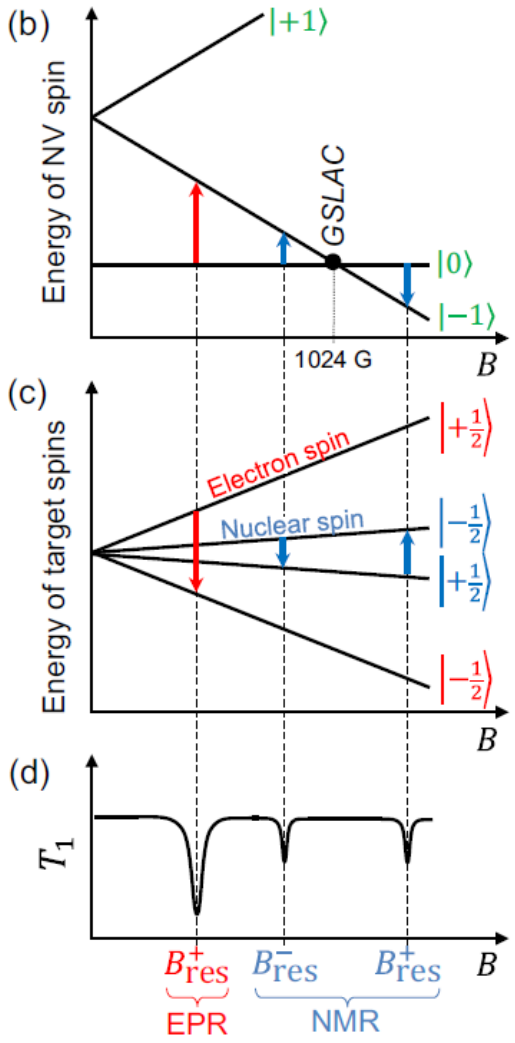


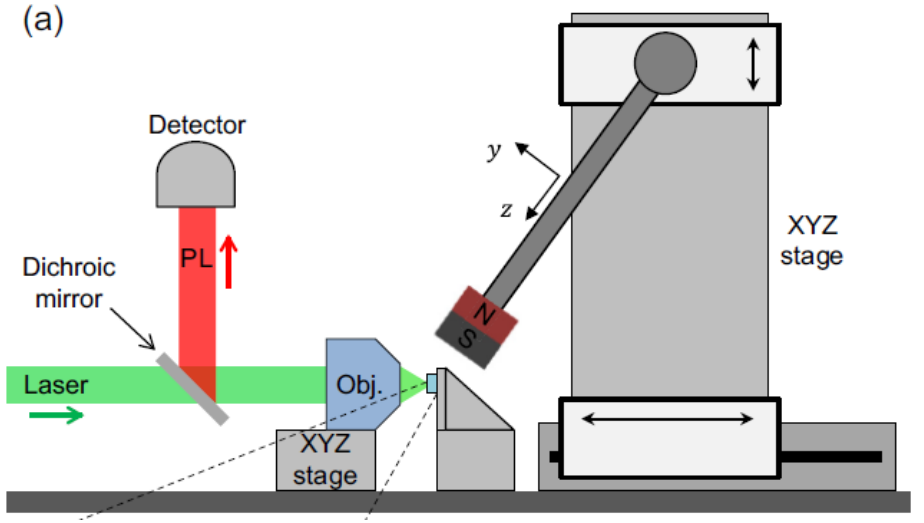


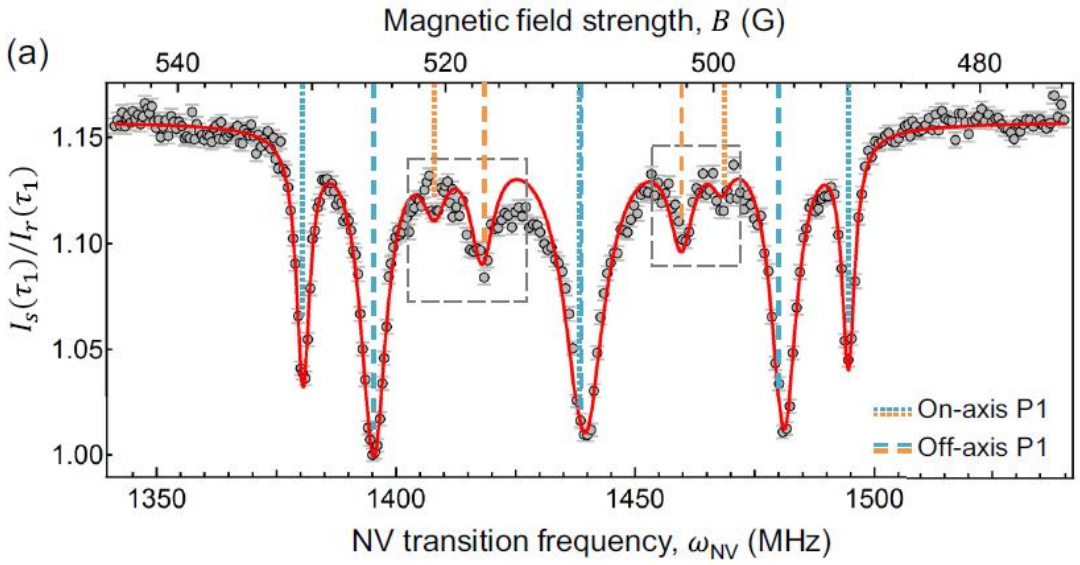


* Wood *et al.*, *PRB* **94**, 155402 (2016)

EPR Spectroscopy

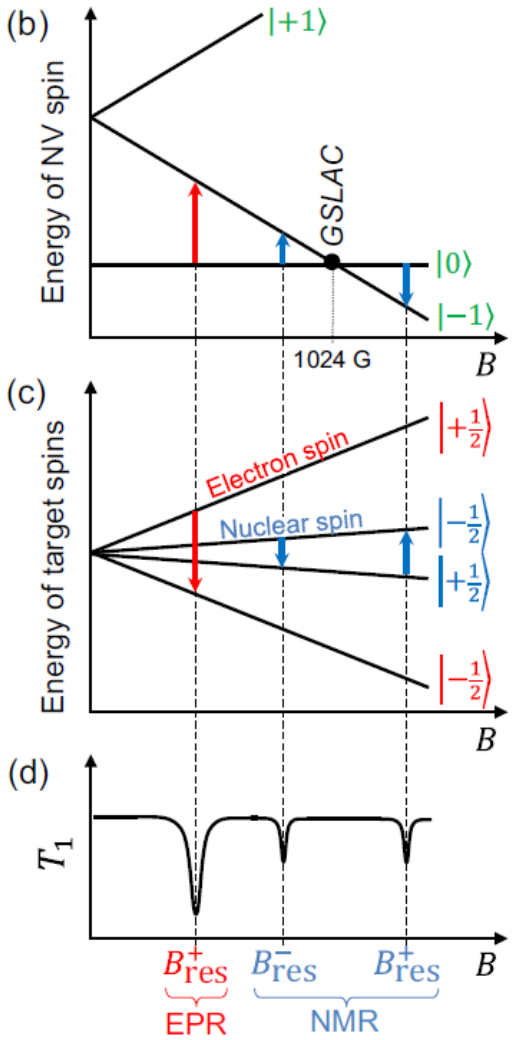


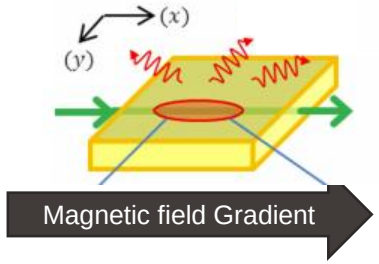


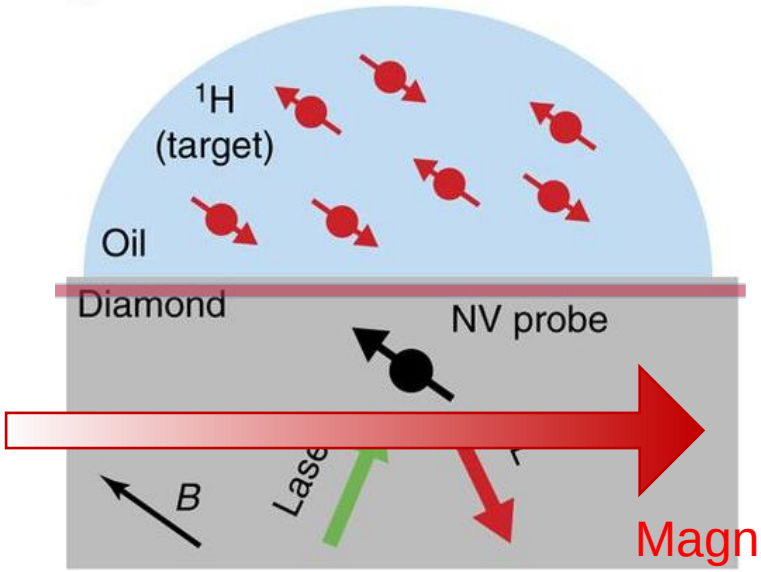


* Wood *et al.*, *PRB* **94**, 155402 (2016)

Fast EPR Spectroscopy

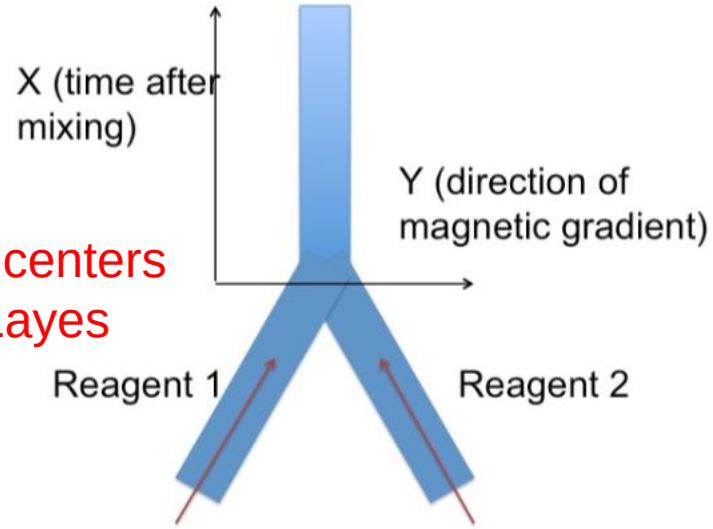






NV centers Layes

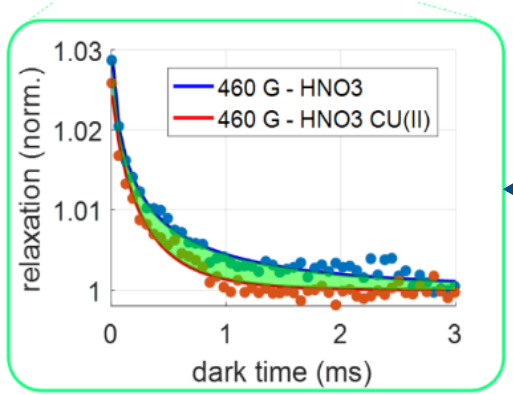
Magnetic field gradient

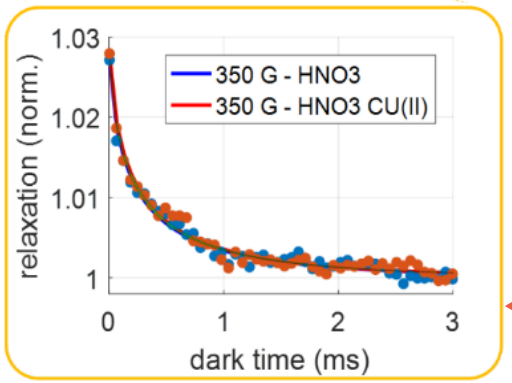


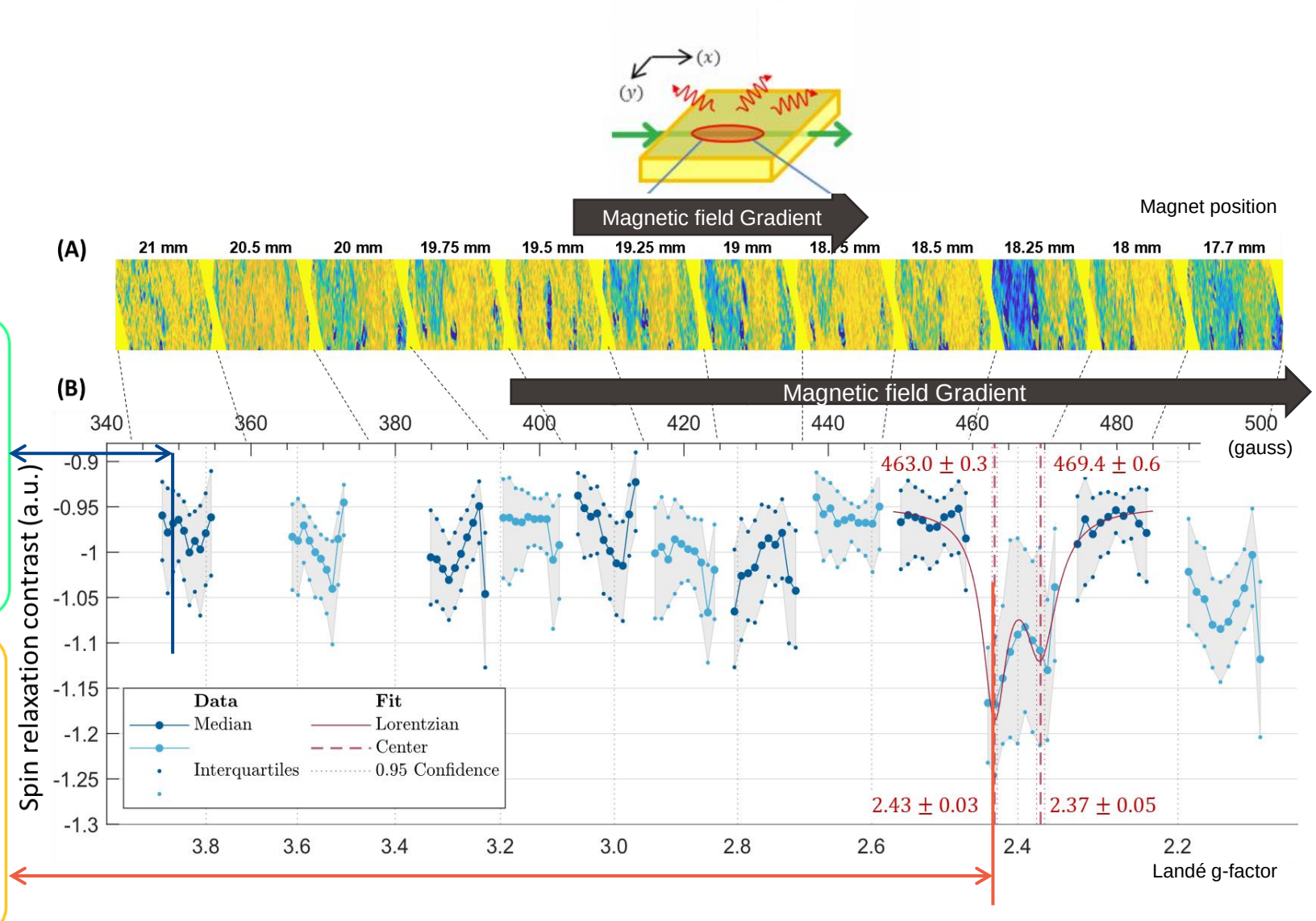
M. Chipaux, R. Schirhagl, Patent WO 2018/128543

C. Mignon, *et. al. ACS Sens.* **8**, 1667–1675 (2023)

Fast EPR Spectroscopy







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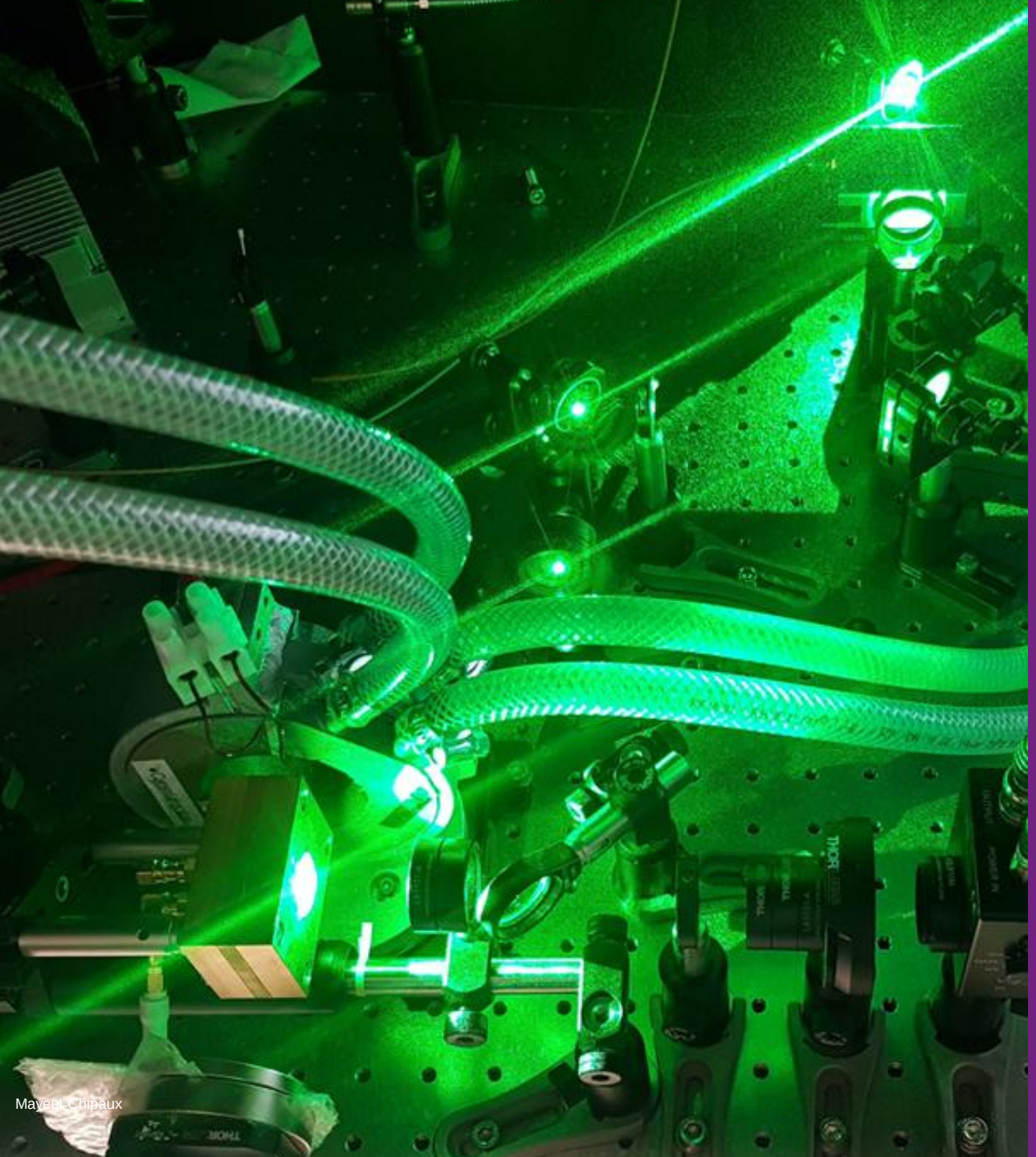


Mayeul Chipaux

4. Quantum limits and entanglement

4. Quantum limits and entanglement

- What does really limits our sensitivities?
- Ultimately what are the fundamental limits ?

1. Barry, John F., et al. "Sensitivity optimization for NV-diamond magnetometry." Reviews of modern physics 92.1 (2020): 015004.

4. Quantum limits and entanglement

Quantum projection noise (QPN)[1]

- Statistical spread caused by the projection onto a discrete observable.

Standard quantum limits (SQL)[2]

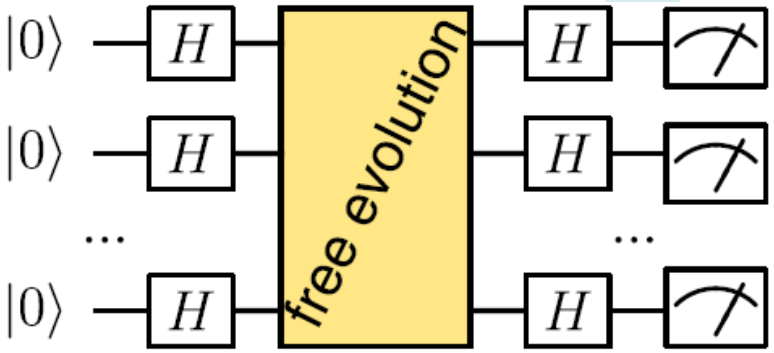
- Ultimate sensitivity set by N independent measurements

2. C. L. Degen, F. Reinhard, P. Cappellaro, (2017). Quantum sensing. *Reviews of modern physics*, *89*(3), 035002.

Heisenberg limit

- Ultimate sensitivity set by N entangled particles derived by the Heisenberg uncertainty relations
- Noon state

$$|NOON\rangle := \frac{1}{\sqrt{2}}(|N\rangle_a \otimes |0\rangle_b + |0\rangle_a \otimes |N\rangle_b)$$

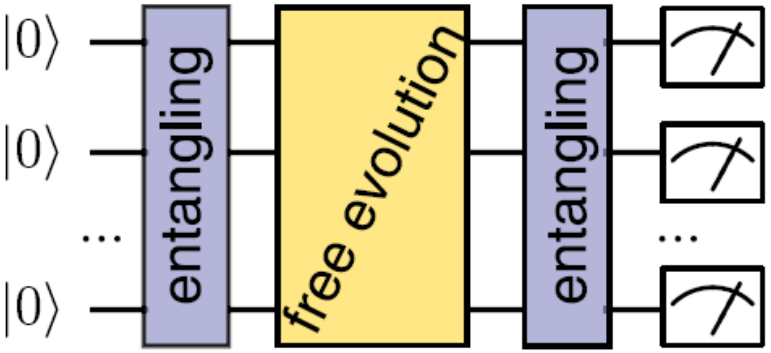


- Greenberger-Horne-Zeilinger (GHZ) State

$$|GHZ\rangle := \frac{1}{\sqrt{2}}(|0,0,\dots,0\rangle + |1,1,\dots,1\rangle)$$

- Dicke State

$$\left|D_n^N\right\rangle := \binom{N}{n}^{-\frac{1}{2}}(|1,0,0,\dots,0\rangle + |0,1,0,\dots,0\rangle \dots + |0,0,\dots 0,1\rangle)$$



- Squeezing

3. Giovannetti, V., Lloyd, S., & Maccone, L. (2011). Advances in quantum metrology. *Nature photonics*, *5*(4), 222-229.

4. A. L. Pezze et al. (2018). Quantum metrology with nonclassical states of atomic ensembles. *Reviews of Modern Physics*, 90(3), 035005.

5. Sinatra, A. (2022). Spin-squeezed states for metrology. *Applied Physics Letters*, *120*(12).

Smyle summer school

19/06/2026 Neuchâtel, Switzerland

Thank you !

Mayeul CHIPAUX*

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- * M Chipaux *et al.* Nanodiamonds and Their Applications in Cells, *Small* 14, 1704263 (2018)
- G. Wolfowicz *et al.* Quantum guidelines for solid-state spin defects. *Nature Reviews Materials,* 6(10), 906-925. (2021)
- F. Casola *et al.* Probing condensed matter physics with magnetometry based on nitrogen-vacancy centres in diamond. Nature Reviews Materials, 3(1), 17088. (2018)
- John F Barry *et al.* Sensitivity optimization for NV-diamond magnetometry, *Reviews of modern physics* 92.1 : 015004. (2020)

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- * Toraille, et al. *New Journal of Physics*, 22(10), 103063 (2020)

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- * A. Sigaeva *et al. Small* 18(39), 2105750 (2022)
- * C. Mignon et. al. ACS Sens. 8, 1667–1675 (2023)
- * M. Chipaux, R. Schirhagl, Patent WO 2018/128543

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