Quantum simulation of Time Crystal phase with nuclear spin layers in diamond

Javier Prior

Valencia, 22nd October 2025

Outline

1. Time Crystal
2. Introduction to NV-centers
3. Quantum simulations with nuclear spin layer
4. Experimental realization of time crystal phase
5. Conclusion

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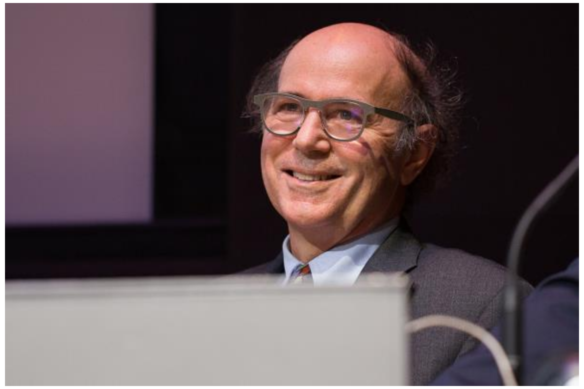
Time Crystal

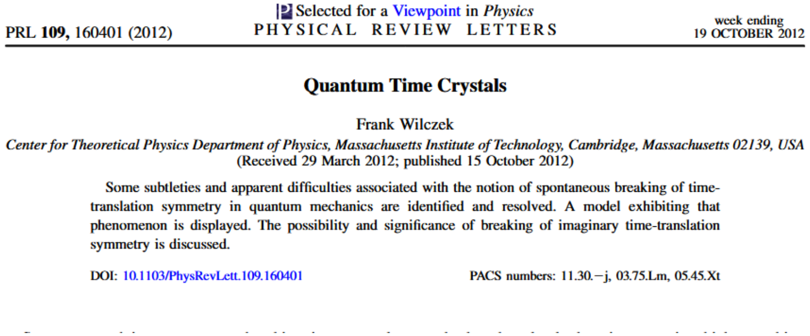
The existence of crystals in nature is a manifestation of spontaneous symmetry breaking, which occurs when the lowest-energy state of a system is less symmetrical than the equations governing the system.

Time Crystal

Wilczek (2012) thought if could make sense that a pattern that repeat in space could do something similar on time. He introduced in 2012 a new state of matter exhibiting periodic oscillations in the ground state. It was shown to be forbidden in thermal equilibrium but in 2017, states whose frequency deviates from the excitation frequency were detected in externally excited quantum systems.



Frank Wilczek, Nobel Prize (2004)



Selected for a Viewpoint in *Physics*
PRL **109,** 160401 (2012) PHYSICAL REVIEW LETTERS week ending 19 OCTOBER 2012

Quantum Time Crystals

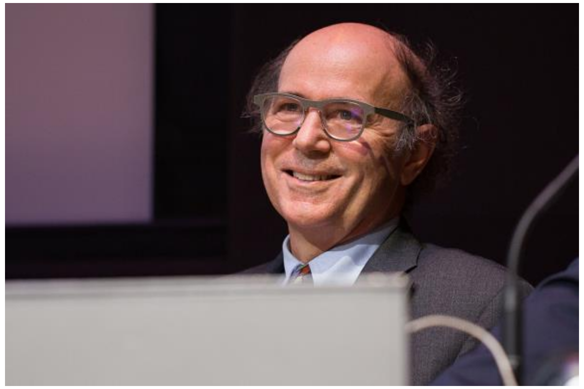
Frank Wilczek
Center for Theoretical Physics Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

(Received 29 March 2012; published 15 October 2012)

Some subtleties and apparent difficulties associated with the notion of spontaneous breaking of time-translation symmetry in quantum mechanics are identified and resolved. A model exhibiting that phenomenon is displayed. The possibility and significance of breaking of imaginary time-translation symmetry is discussed.

DOI: 10.1103/PhysRevLett.109.160401 PACS numbers: 11.30.−j, 03.75.Lm, 05.45.Xt

Time Crystal



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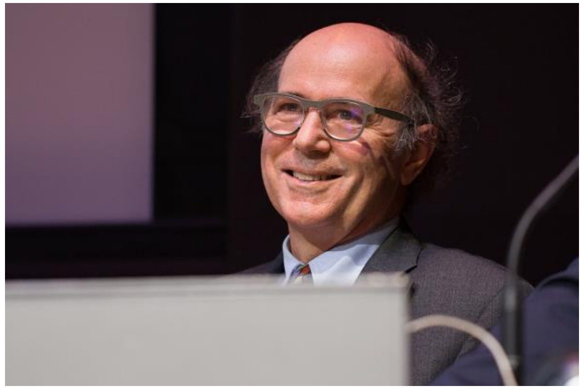
A time crystal is a non-equilibrium phase of matter, characterized by spontaneous breaking of time translation symmetry.



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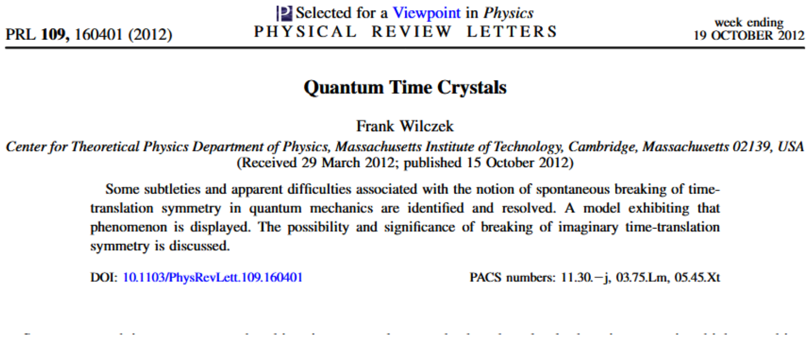

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Translational symmetry in time was shown to be forbidden in thermal equilibrium.

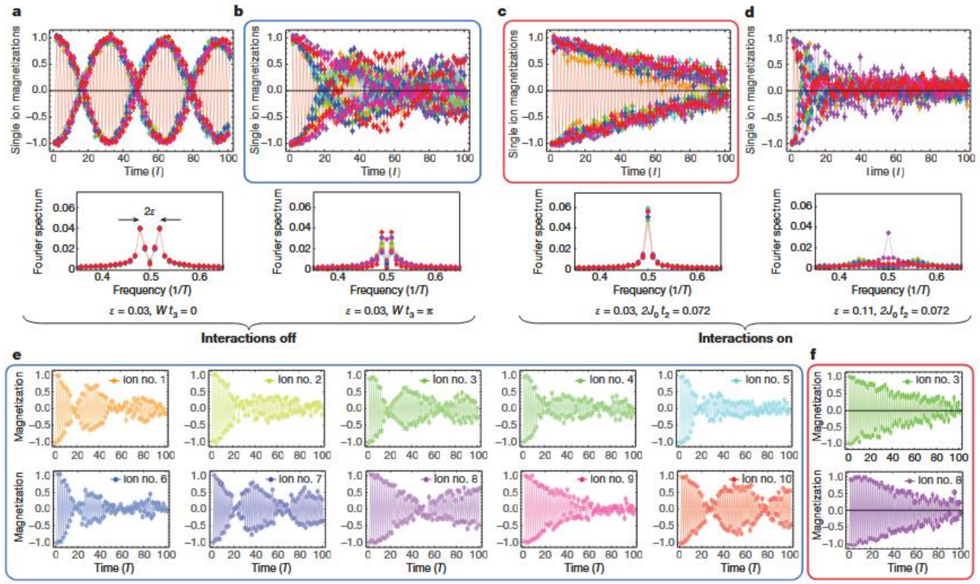
Time Crystal

LETTER

doi:10.1038/nature21413

Observation of a discrete time crystal

J. Zhang[1], P. W. Hess[1], A. Kyprianidis[1], P. Becker[1], A. Lee[1], J. Smith[1], G. Pagano[1], I.-D. Potirniche[2], A. C. Potter[3], A. Vishwanath[2,4], N. Y. Yao[2] & C. Monroe[1,5]



Experimental observation of a discrete time crystal, in an interacting spin chain of trapped atomic ions
Nature 218, Vol 543, (2017).

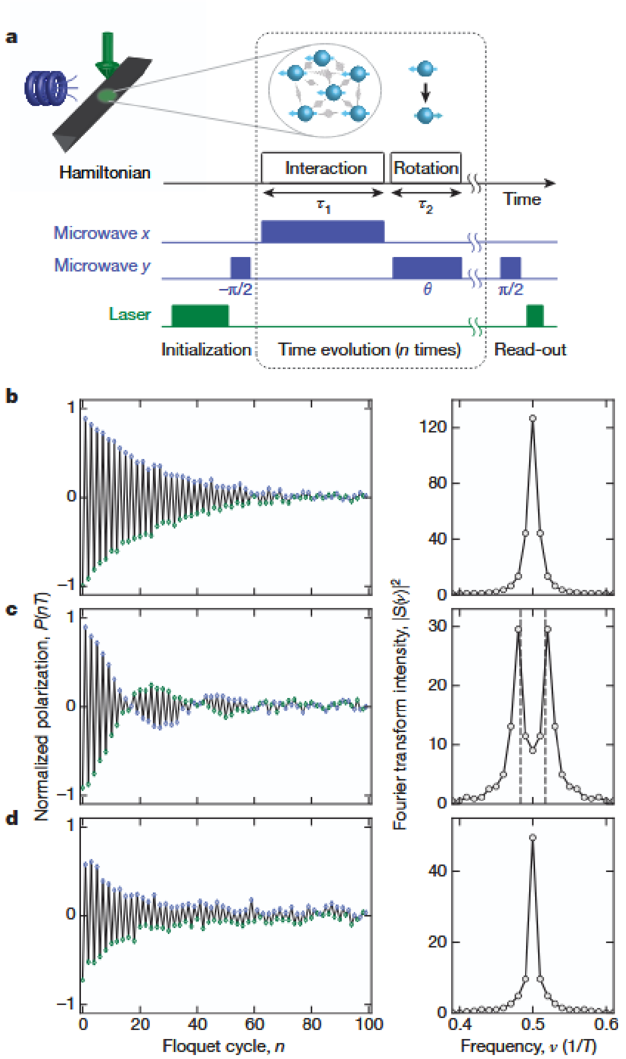
Time Crystal

LETTER

doi:10.1038/nature21426

Observation of discrete time-crystalline order in a disordered dipolar many-body system

Soonwon Choi[1]*, Joonhee Choi[1,2]*, Renate Landig[1]*, Georg Kucsko[1], Hengyun Zhou[1], Junichi Isoya[3], Fedor Jelezko[4], Shinobu Onoda[5], Hitoshi Sumiya[6], Vedika Khemani[1], Curt von Keyserlingk[7], Norman Y. Yao[8], Eugene Demler[1] & Mikhail D. Lukin[1]



They report the experimental observation of time-crystalline order in a driven, disordered ensemble of about one million dipolar spin impurities in diamond at room temperature. The temporal order is protected by strong interactions.
Nature 221, Vol 543 (2017).

Time Crystal

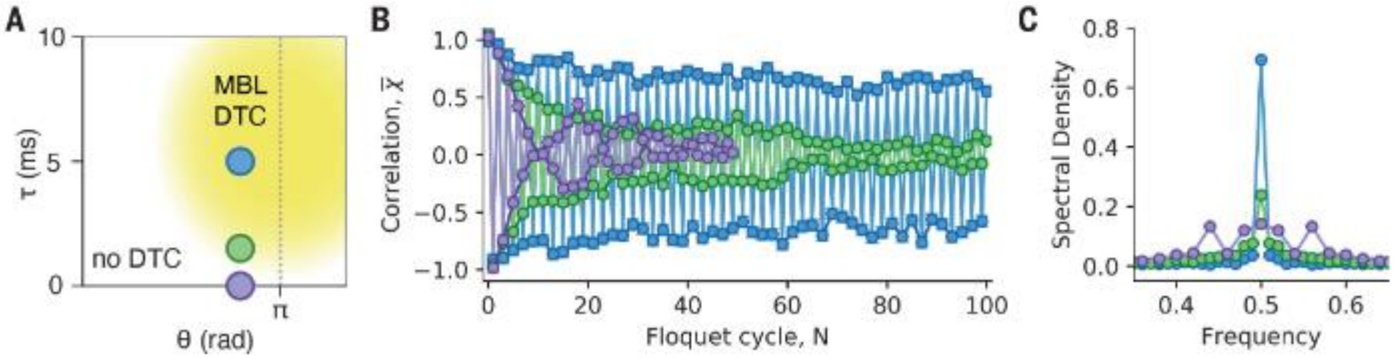
REPORT

QUANTUM SIMULATION

Many-body–localized discrete time crystal with a programmable spin-based quantum simulator

J. Randall[1,2]†, C. E. Bradley[1,2]†, F. V. van der Gronden[1,2], A. Galicia[1,2], M. H. Abobeih[1,2], M. Markham[3], D. J. Twitchen[3], F. Machado[4,5], N. Y. Yao[4,5], T. H. Taminiau[1,2]*

Science 374, 1474–1478 (2021)



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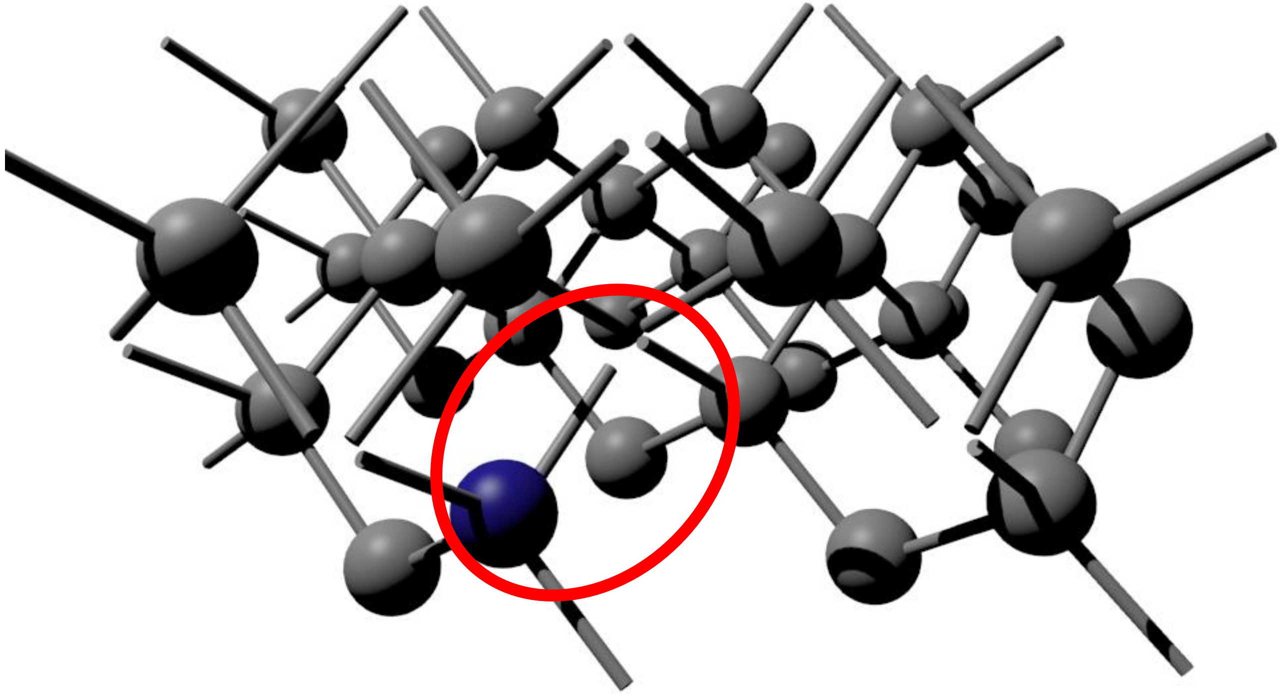
THE NV CENTER



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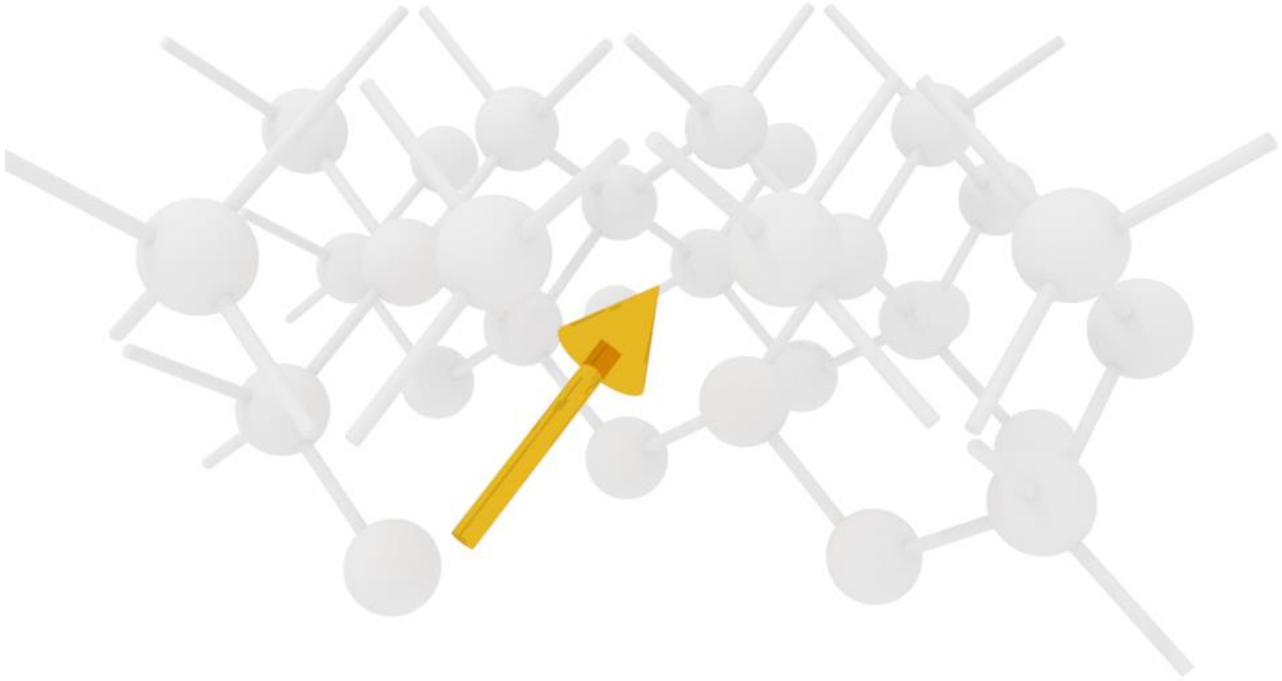

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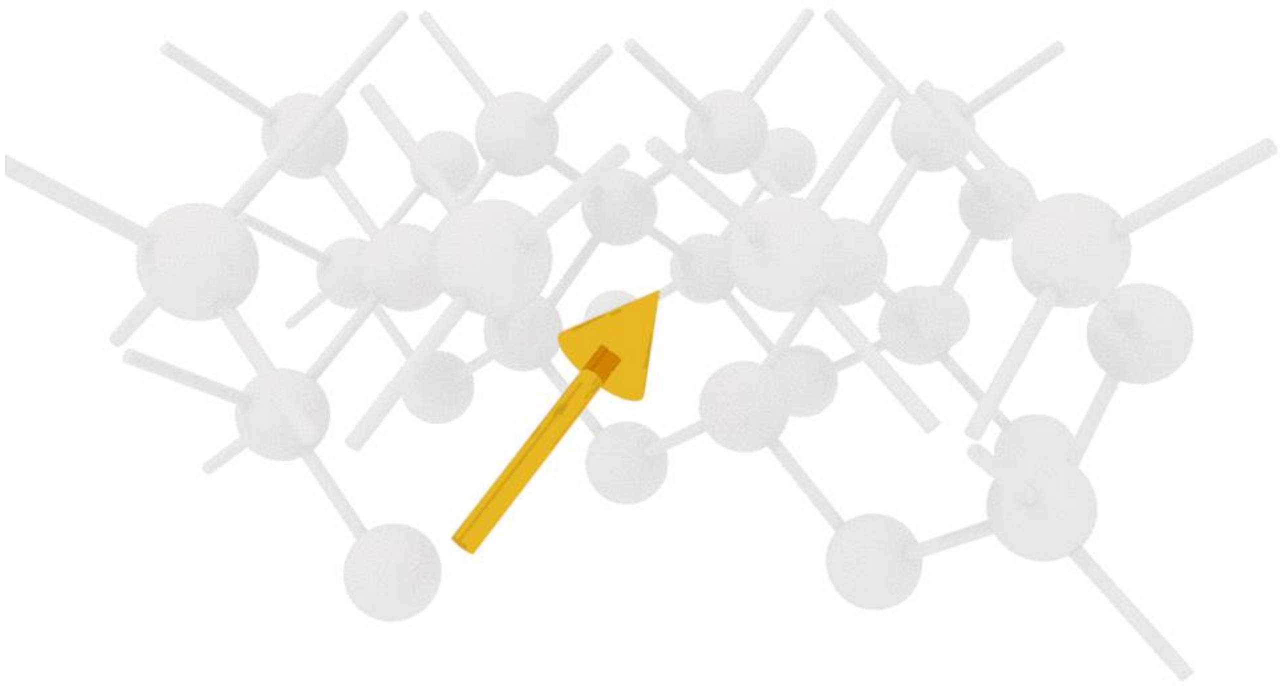

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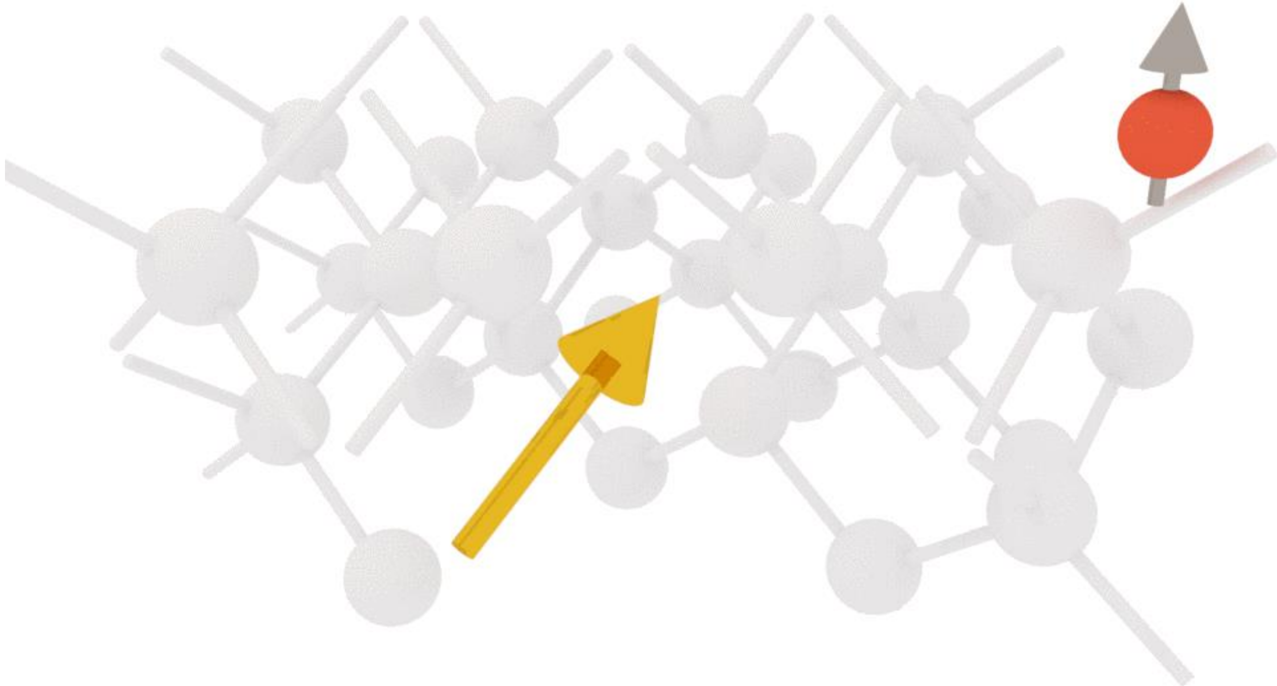

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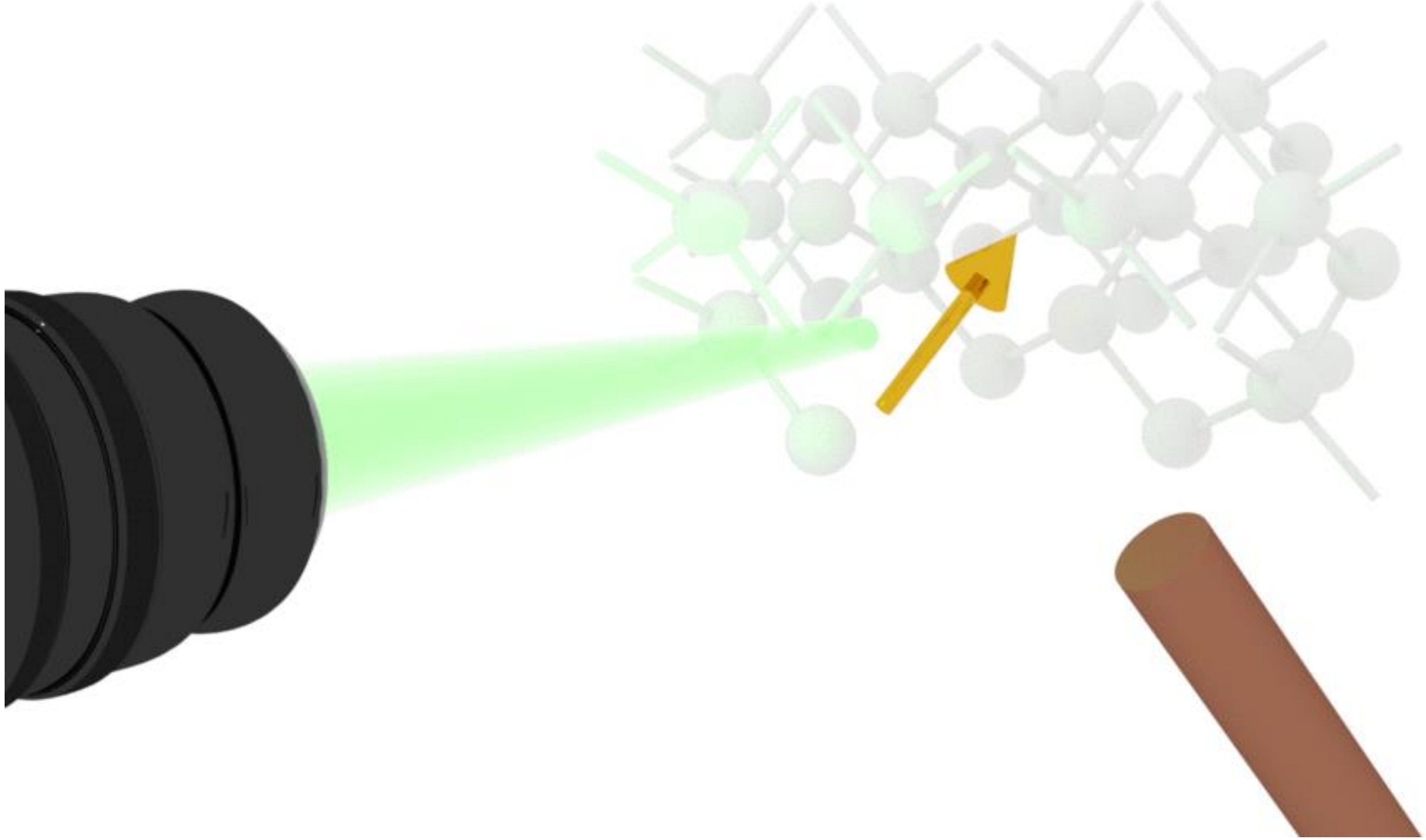

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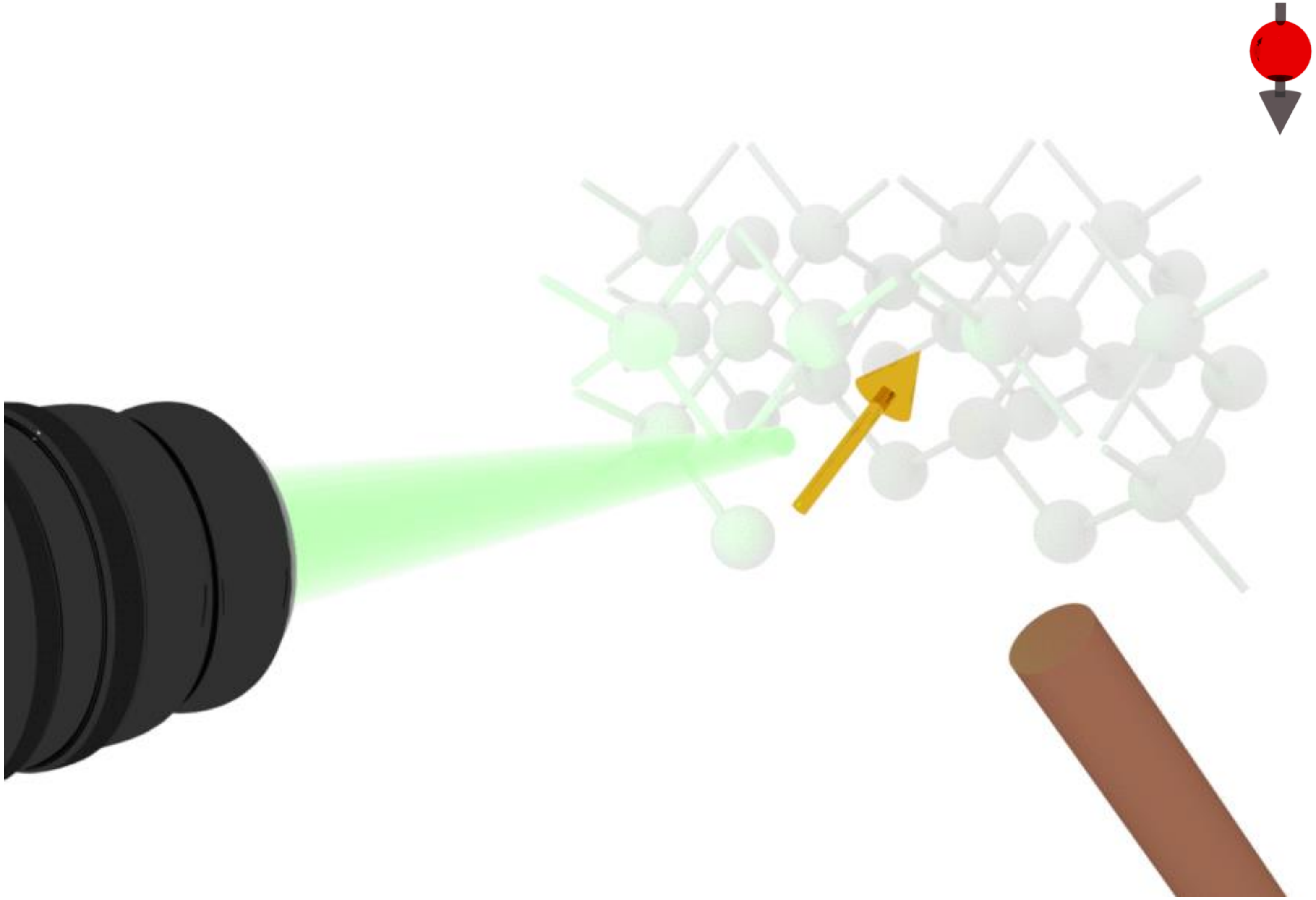

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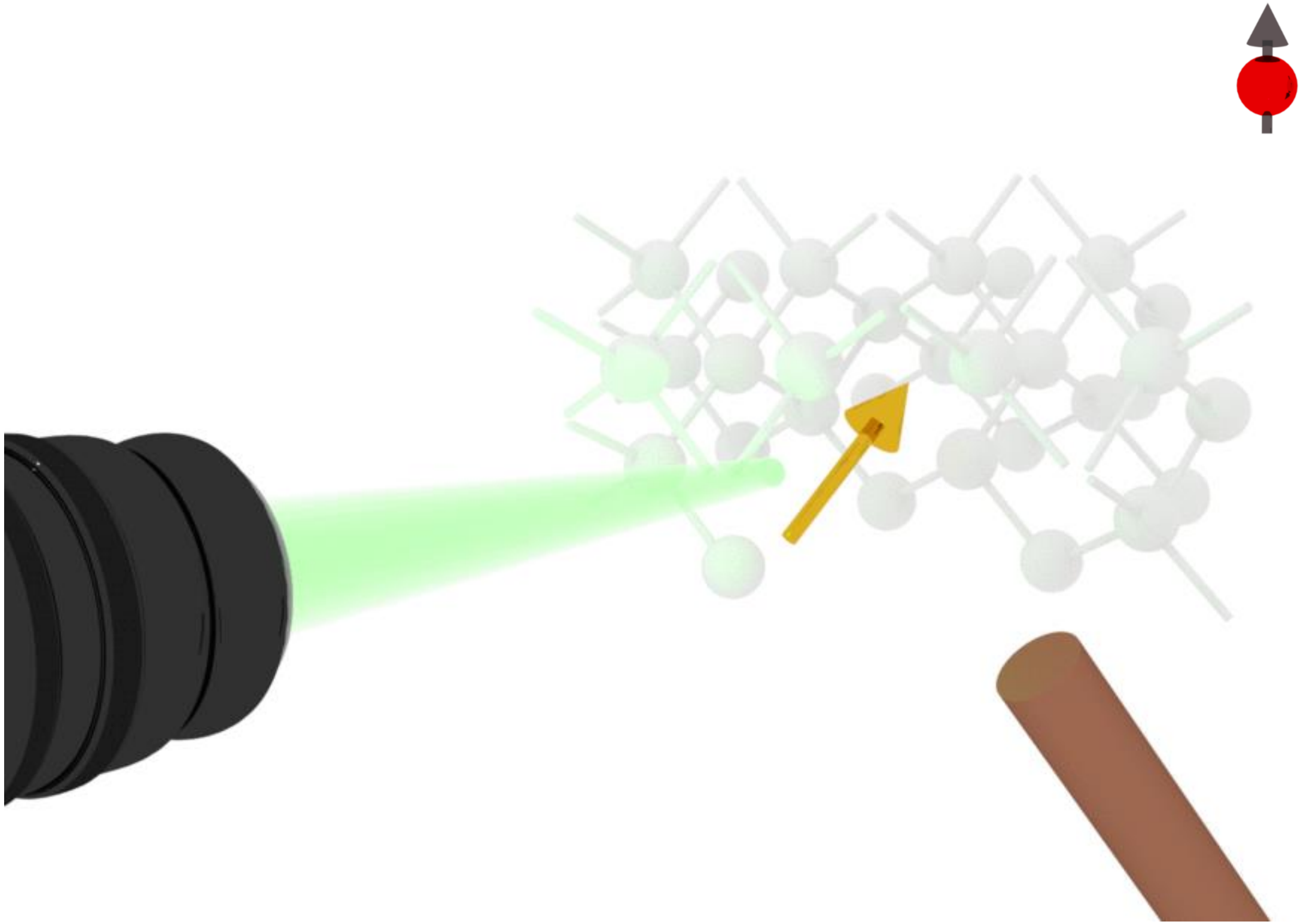
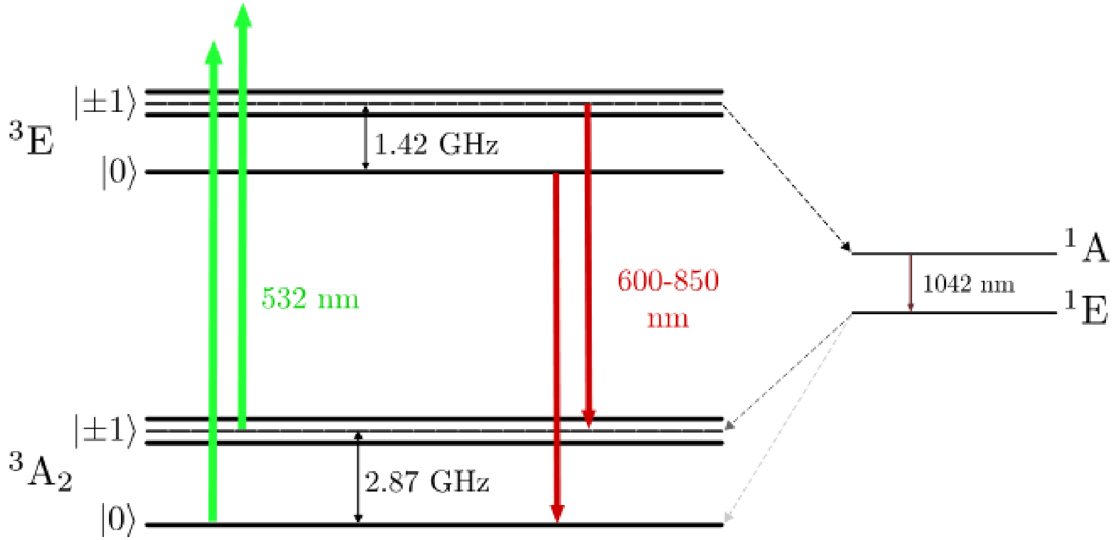


THE NV CENTER

- ✓ Electron spin
- ✓ Good properties conferred by the diamond lattice
  - In particular, long T_1, T_2
- ✓ Easy to polarize and read-out
- ✓ Easy to manipulate
- ✓ Room temperature platform operation
- ✓ Bio-compatibility

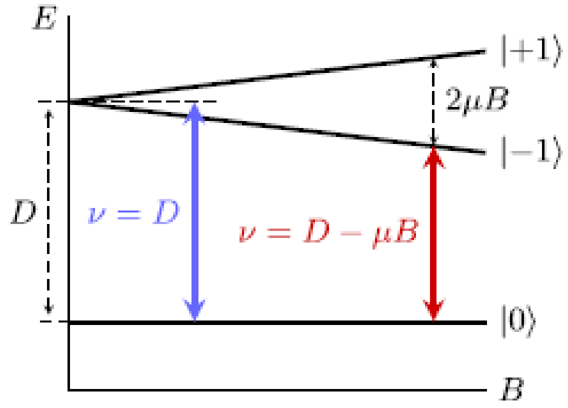
THE NV CENTER

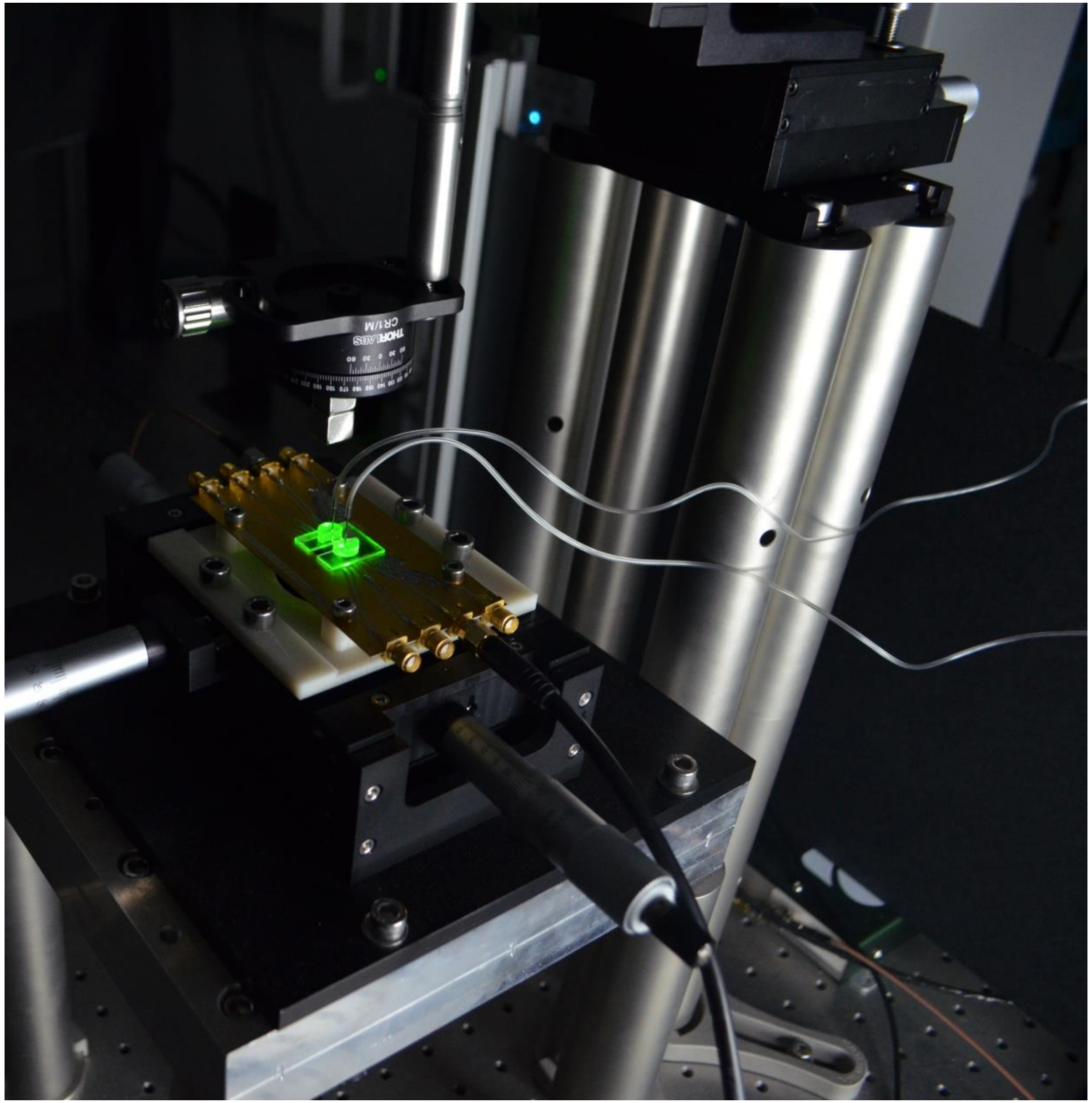
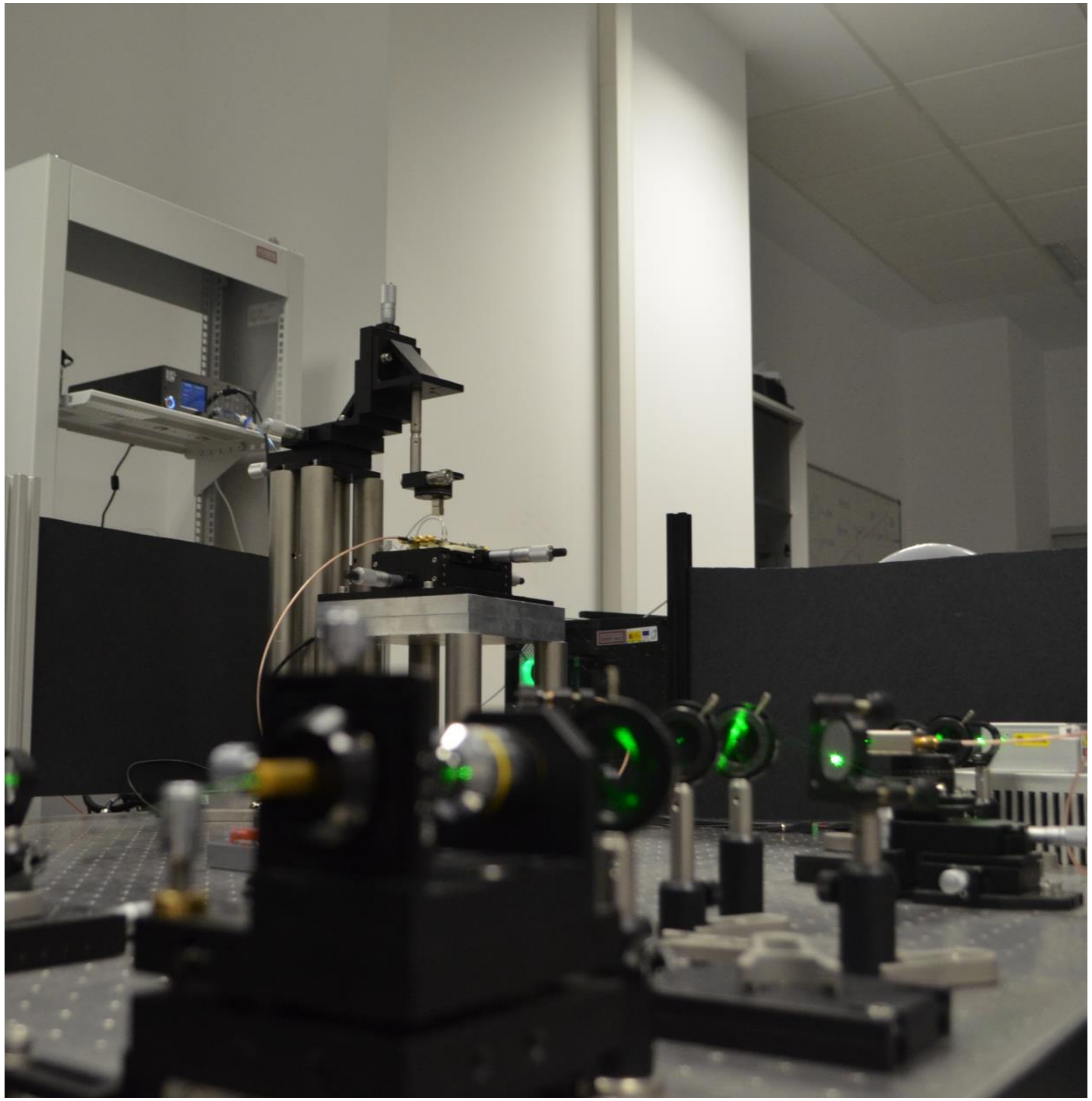
Electron spin + Characteristic level structure



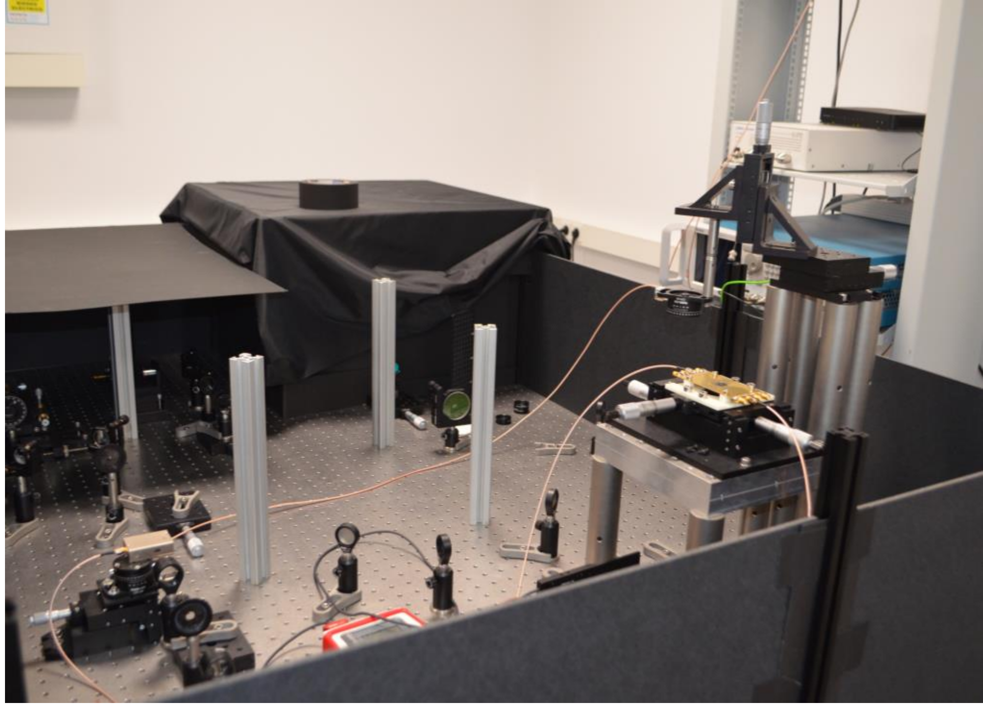
- When illuminated with green light:

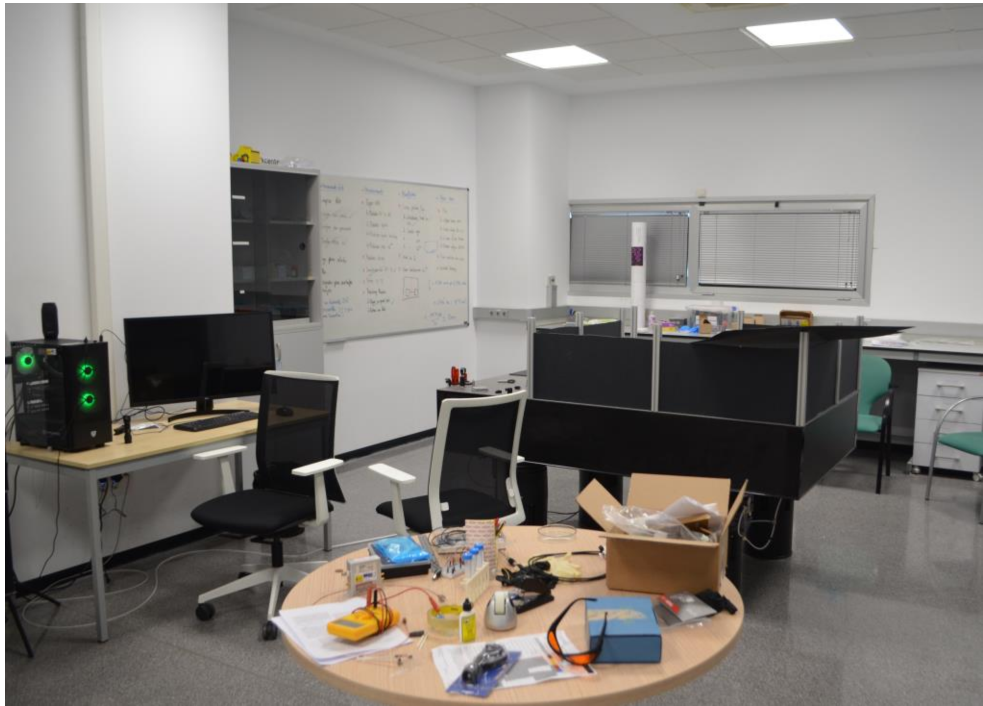
  - Polarization
  - Read-Out

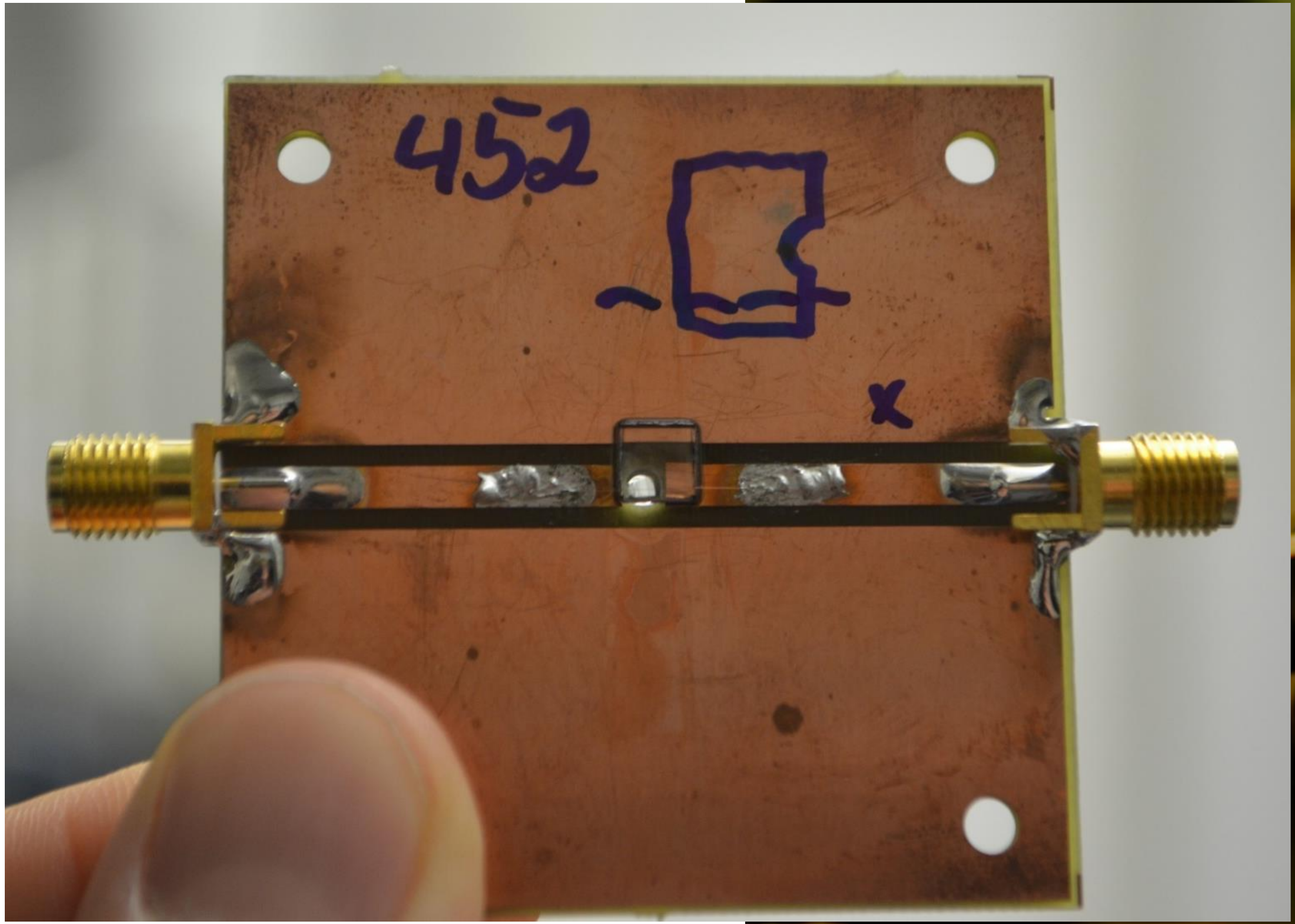



THORLABS
CR1/M



Newport
Stabilizer
High Performance



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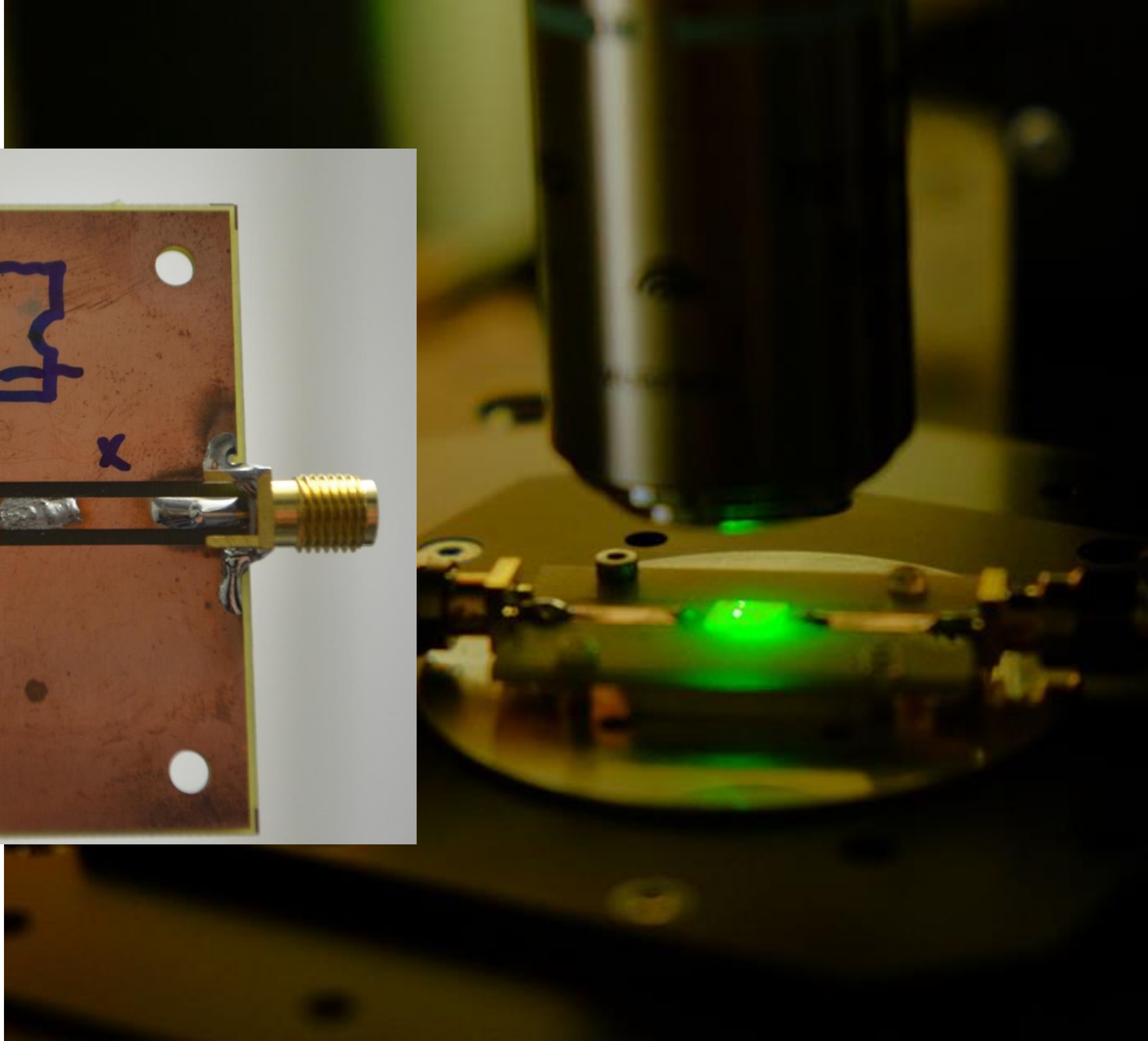
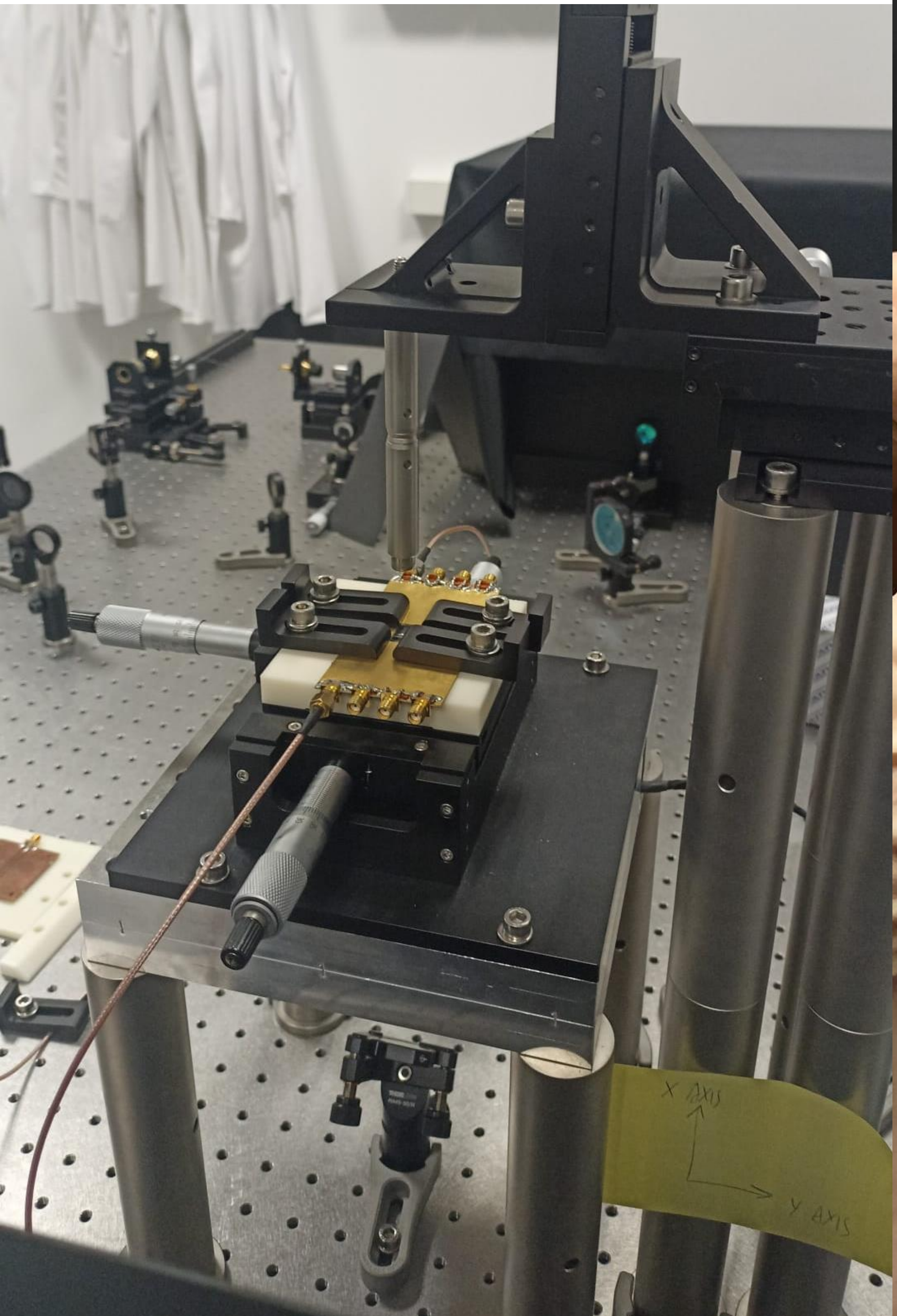
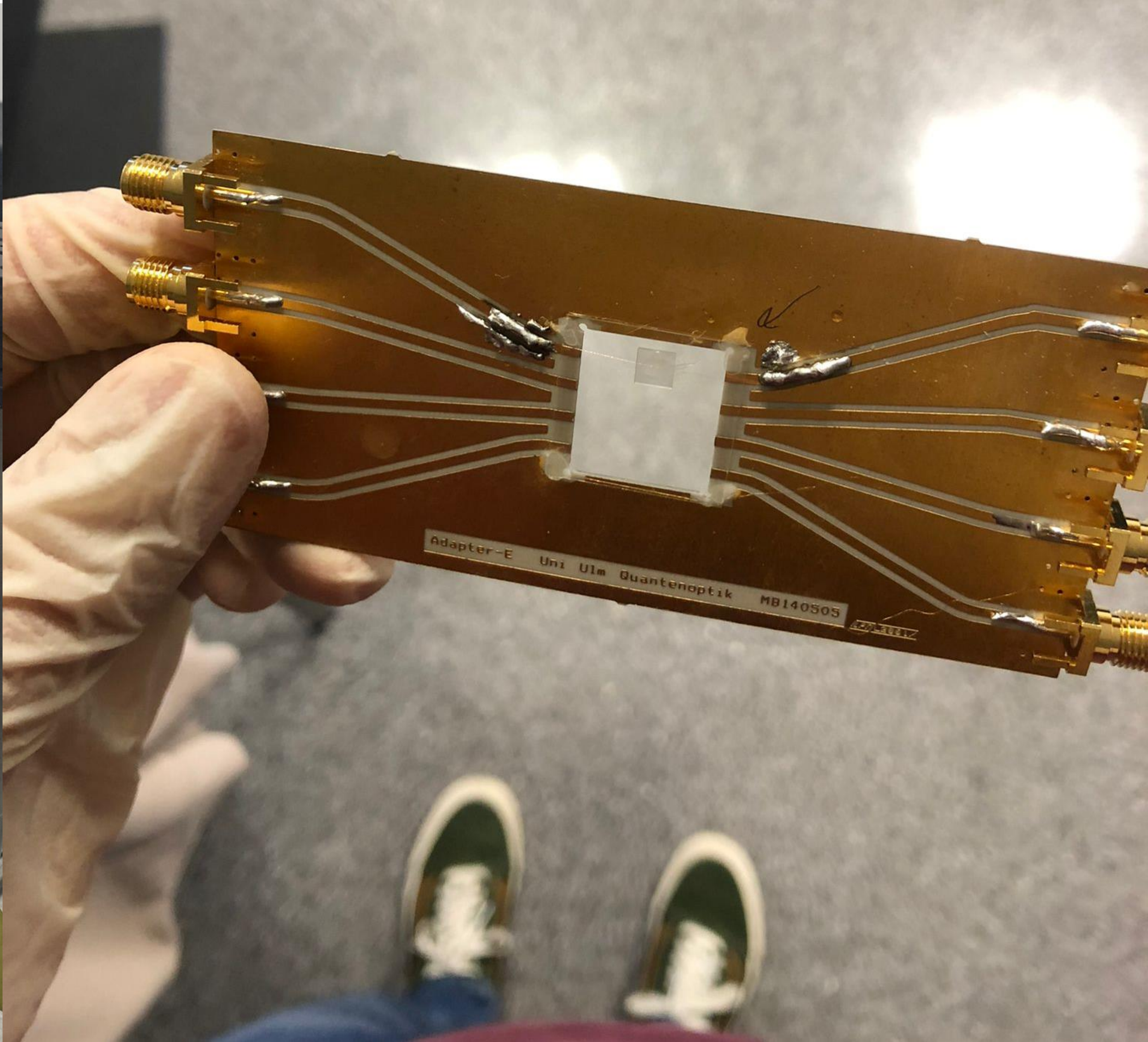
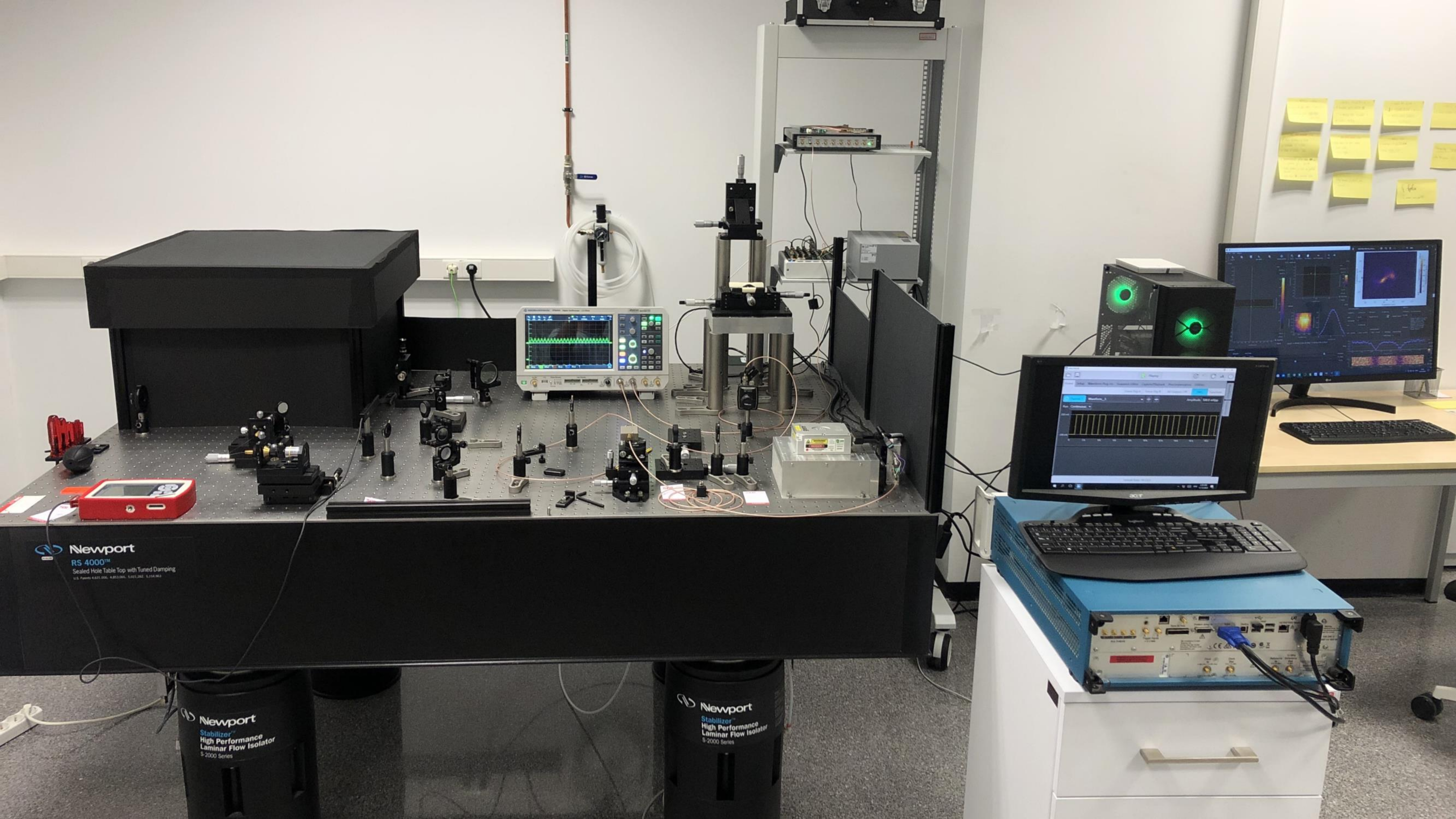



X AXIS
Y AXIS


Adapter-E Uni Ulm Quantenoptik MB140505


Newport
RS 4000™
Sealed Hole Table Top with Tuned Damping
Newport
Stabilizer™
High Performance
Laminar Flow Isolator
S-2000 Series
Newport
Stabilizer™
High Performance
Laminar Flow Isolator
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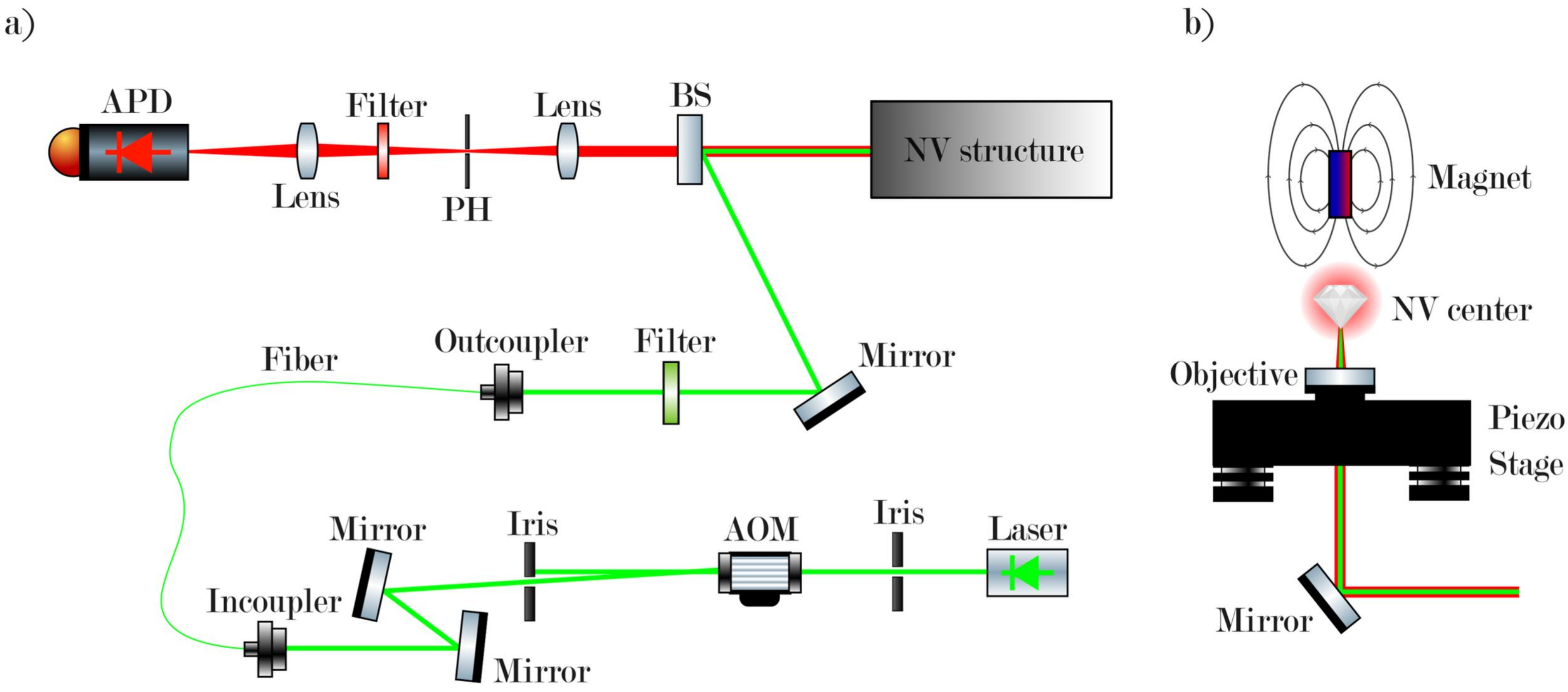
EXPERIMENTAL SET UP



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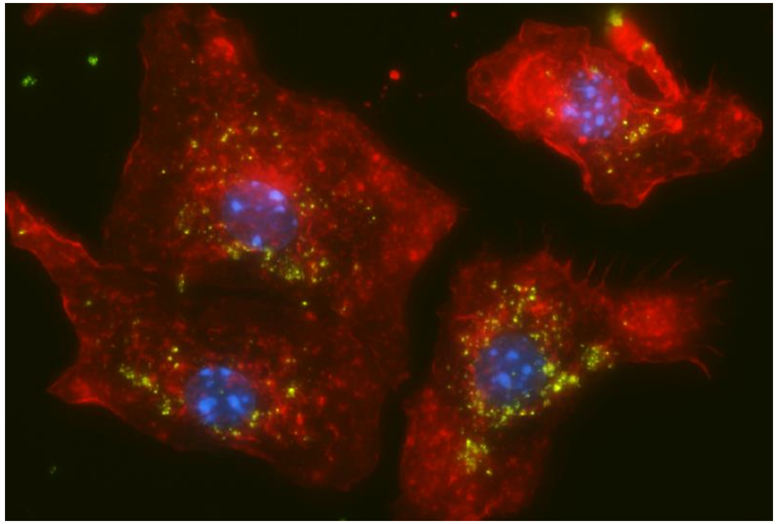
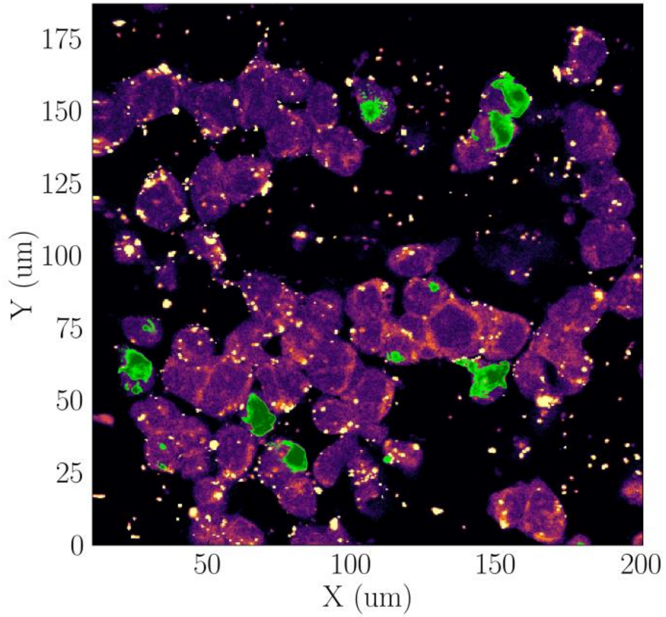
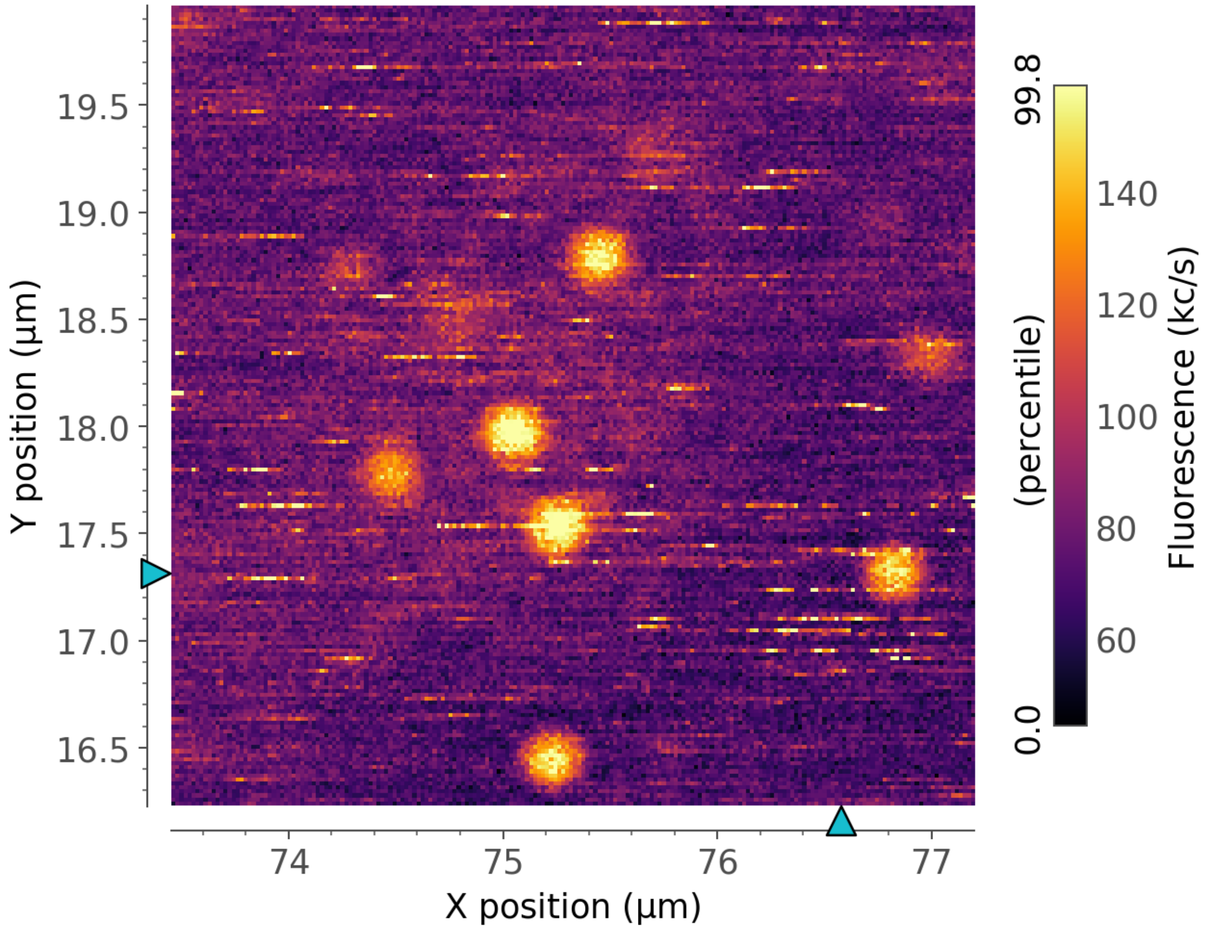
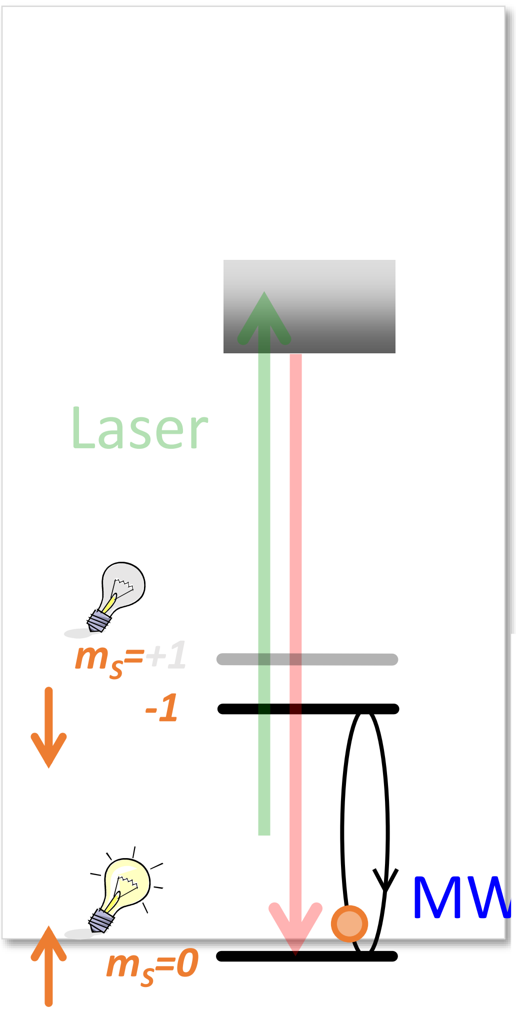


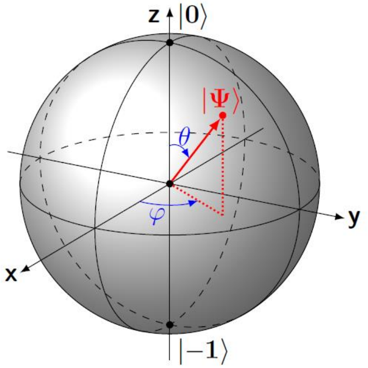


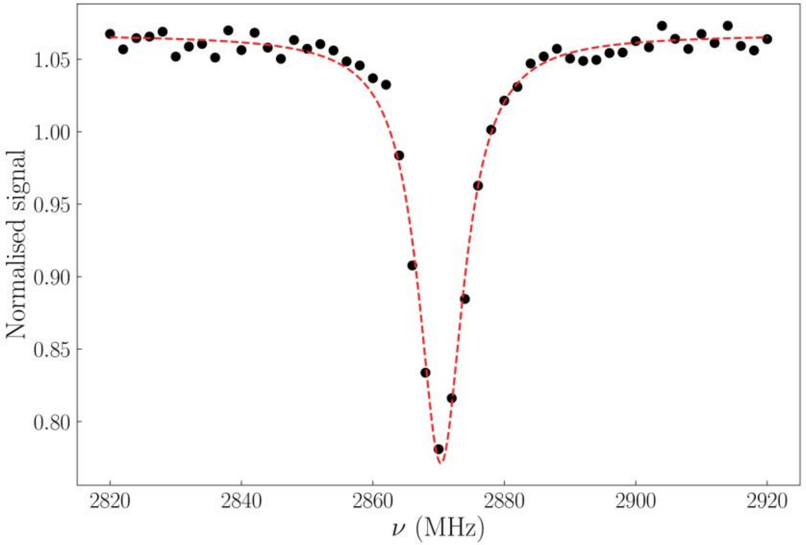


Optimization and characterization of laser excitation for quantum sensing with single nitrogen-vacancy centres. A. Martínez-Méndez, J. Moreno-Meseguer, M. Mrózek, R. González, A. Wojciechowski, P. Balasubramanian, F. Jelezko, J.Prior. arXiv:2507.10386. Journal of Applied Physics (2025).

CONTINUOUS ODMR







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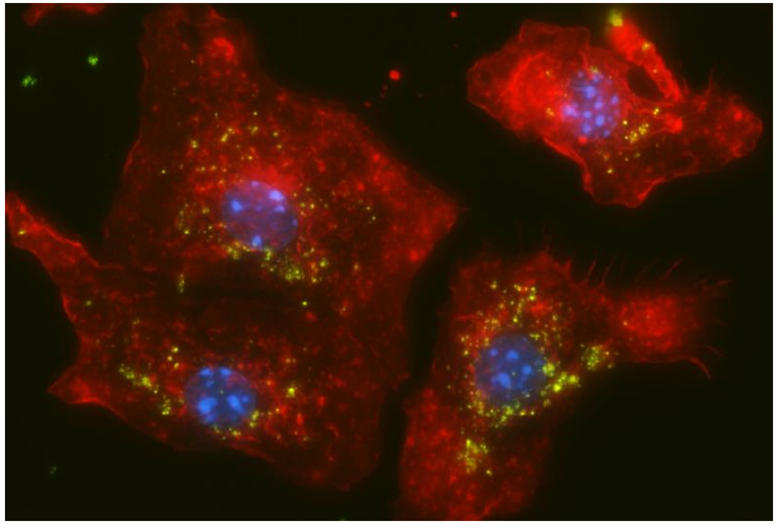

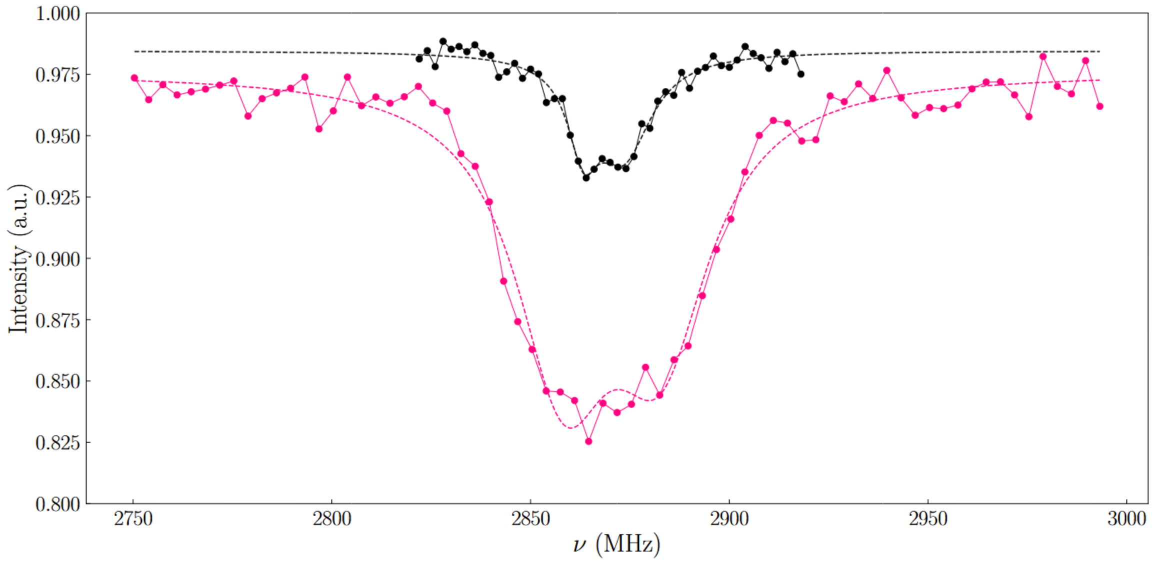

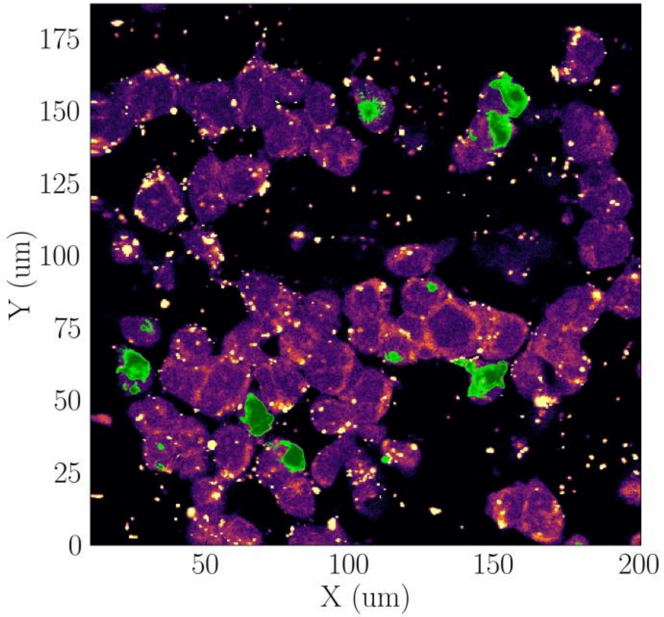

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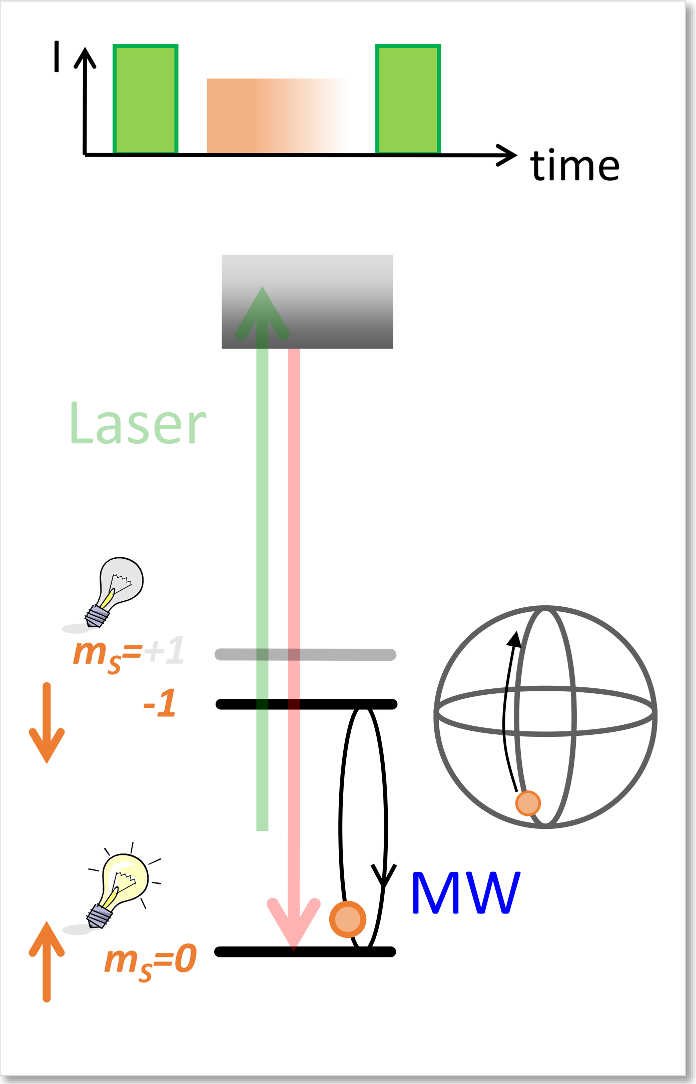
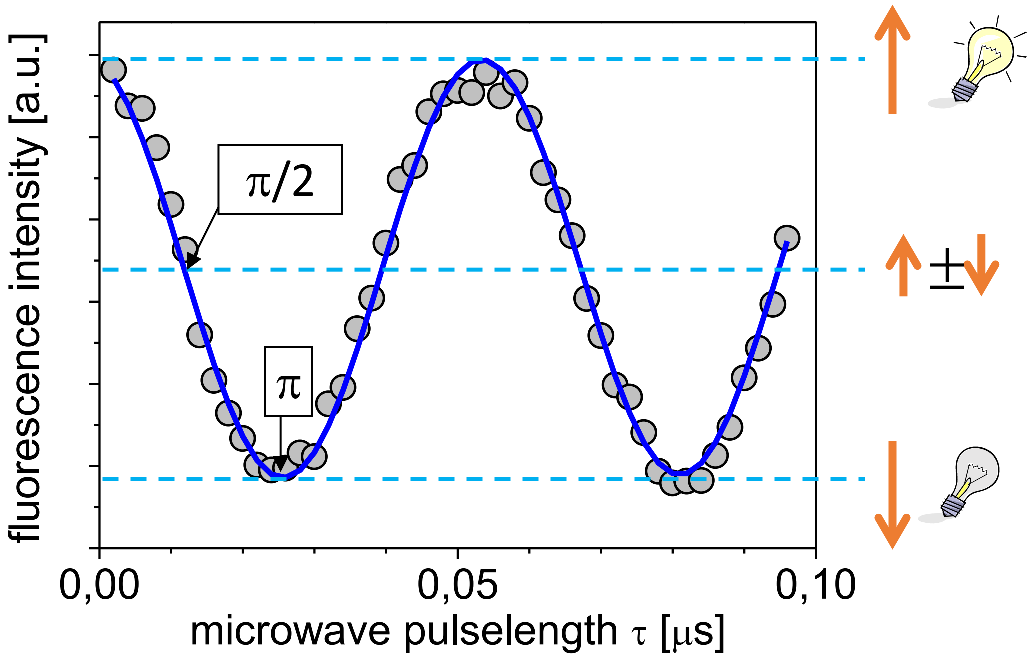
COHERENT CONTROL: RABI OSCILLATION





Jelezko et al., PRL 2004, Epstein Nat. Phys (2005), Childress Science (2006) Fuchs et al., *Science* **326**, 1520 (2009)

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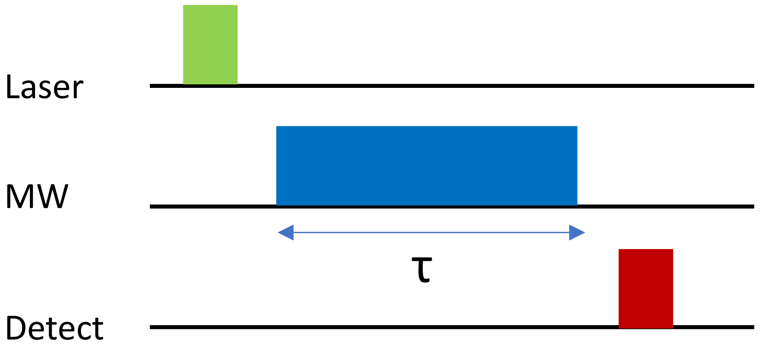

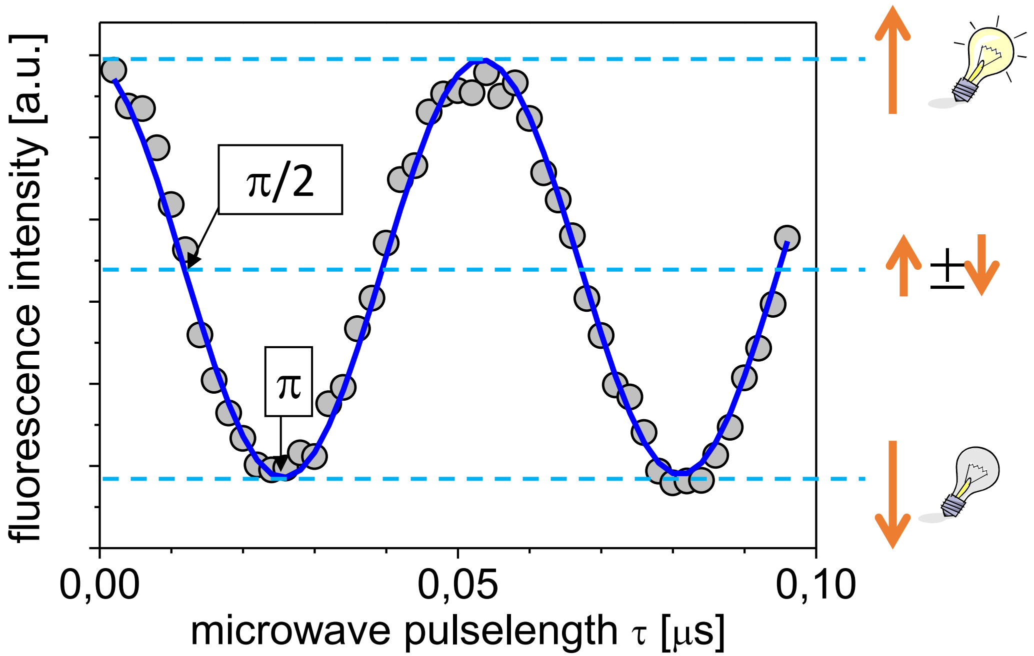

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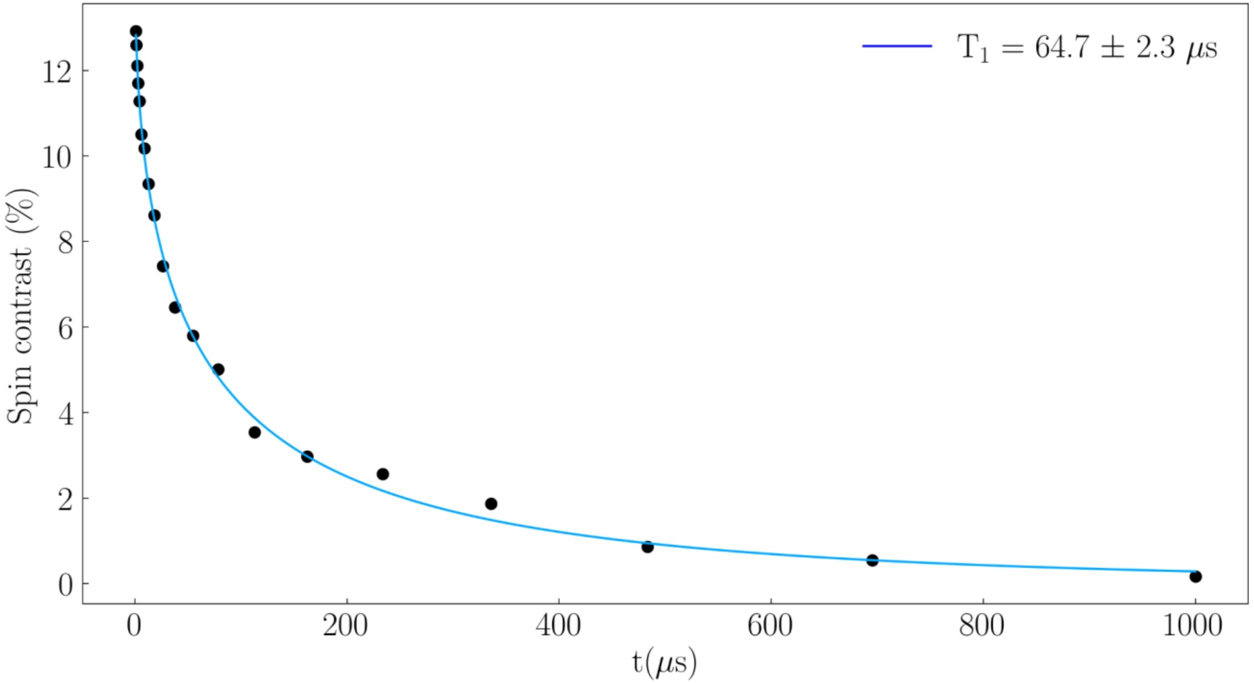
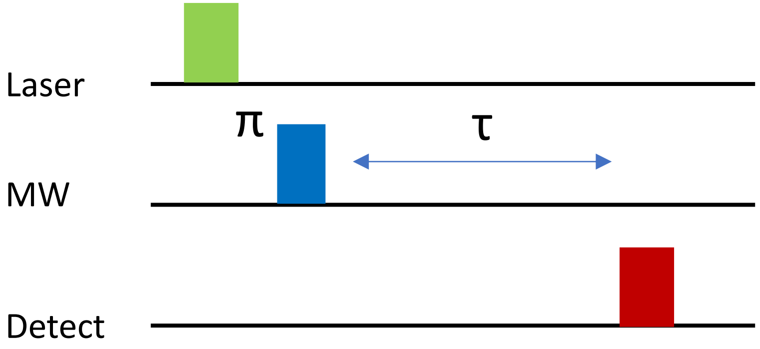
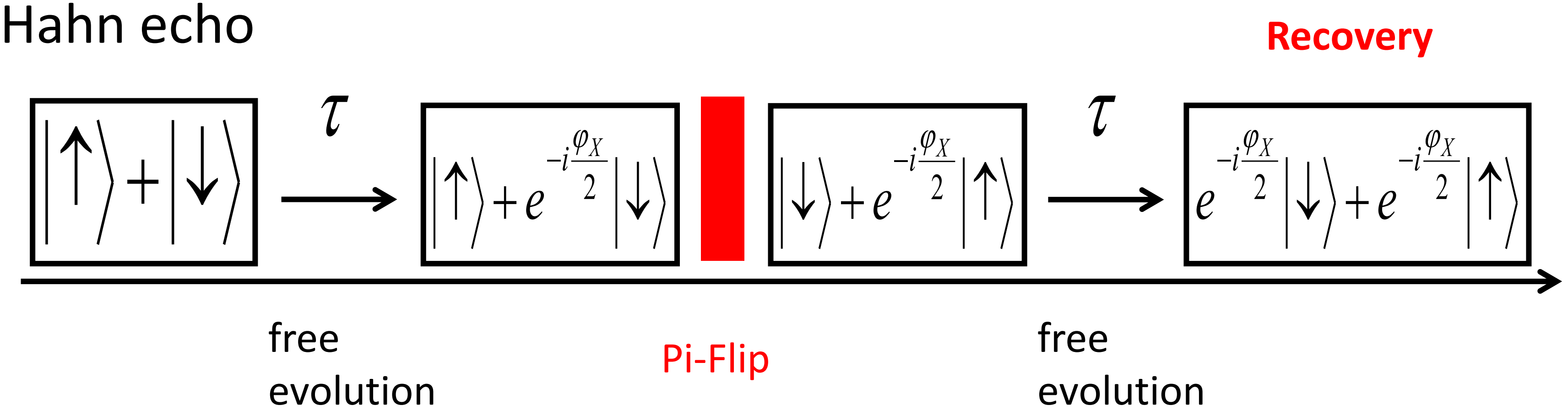
T_1 RELAXOMETRY



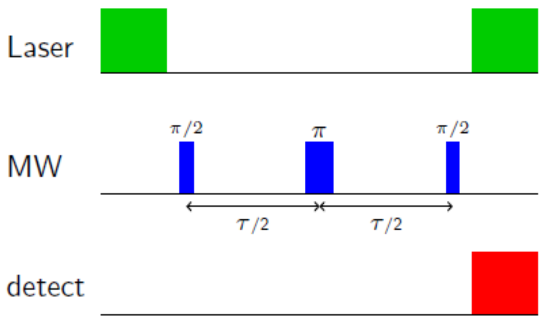


HAHN ECHO OSCILLATION

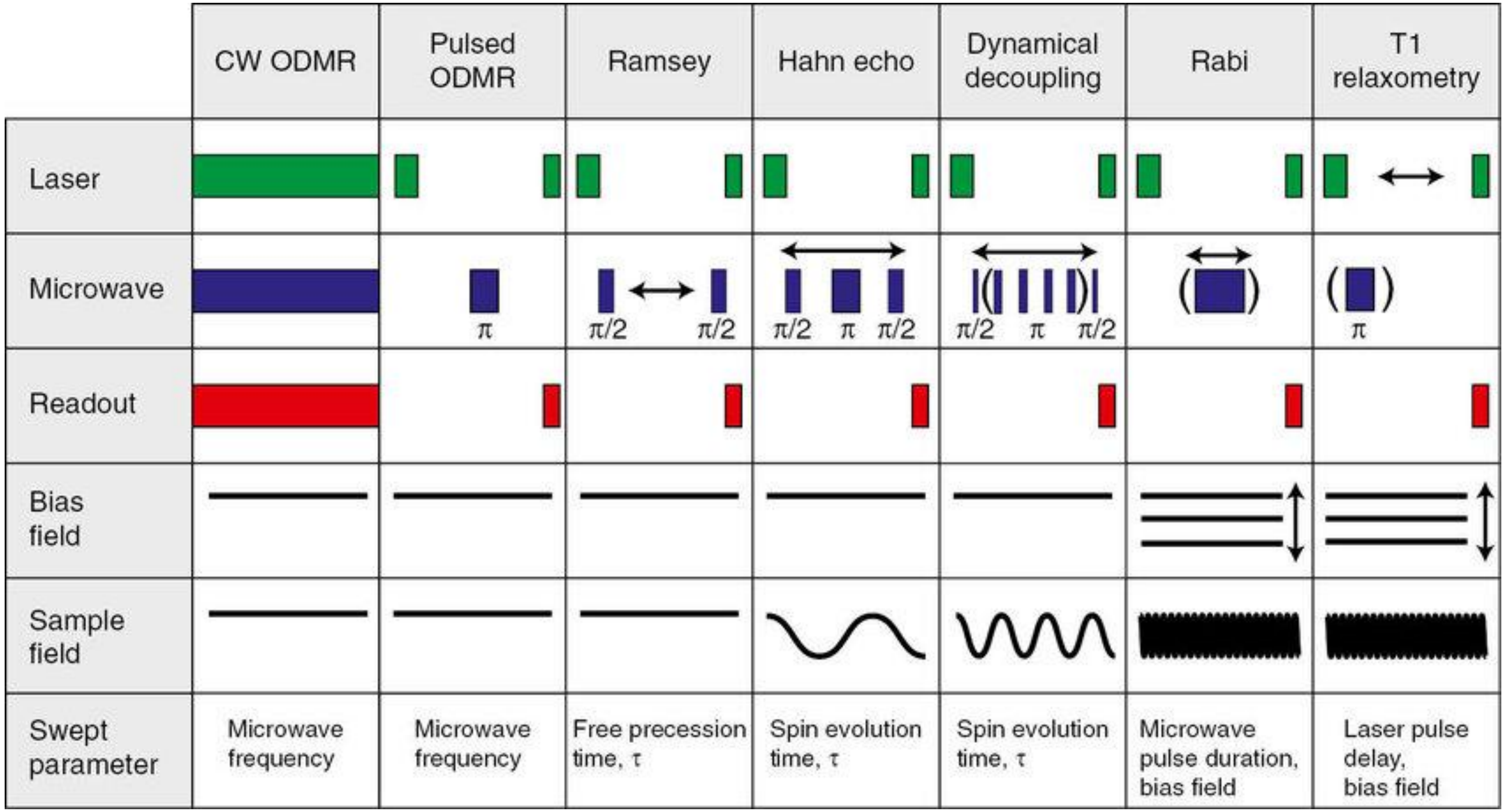
Hahn echo



- All phases of the different X-processes disappear
- Cancel static noise, sensing AC fields



MEASUREMENTS PROTOCOLS



Principles and techniques of the quantum diamond microscope E.V. Levine, M.J. Turner, P. Kehayias, C.A. Hart, N. Langellier. Nanophoton 8, 1945-1973, (2019).

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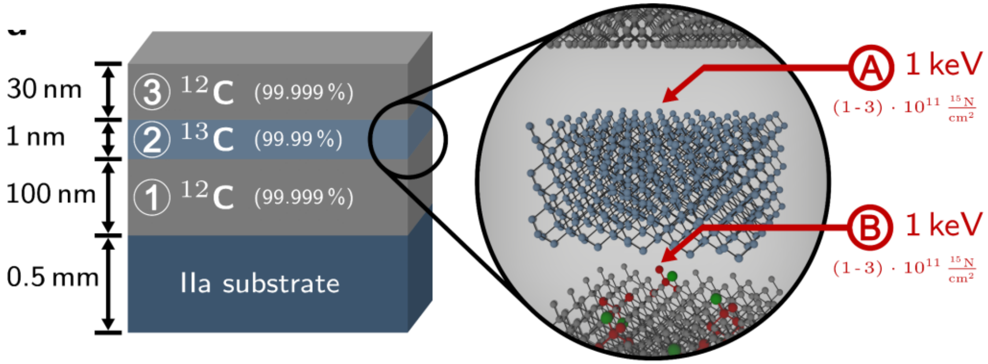

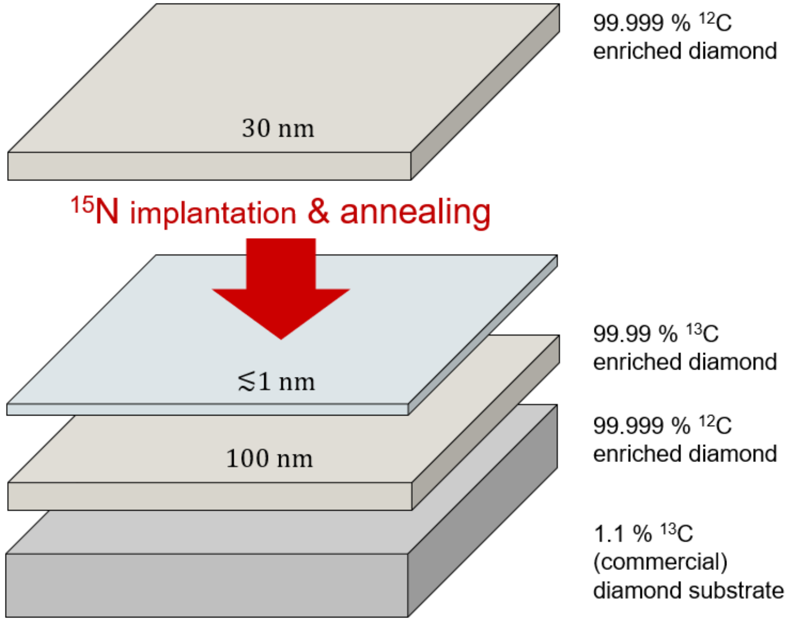

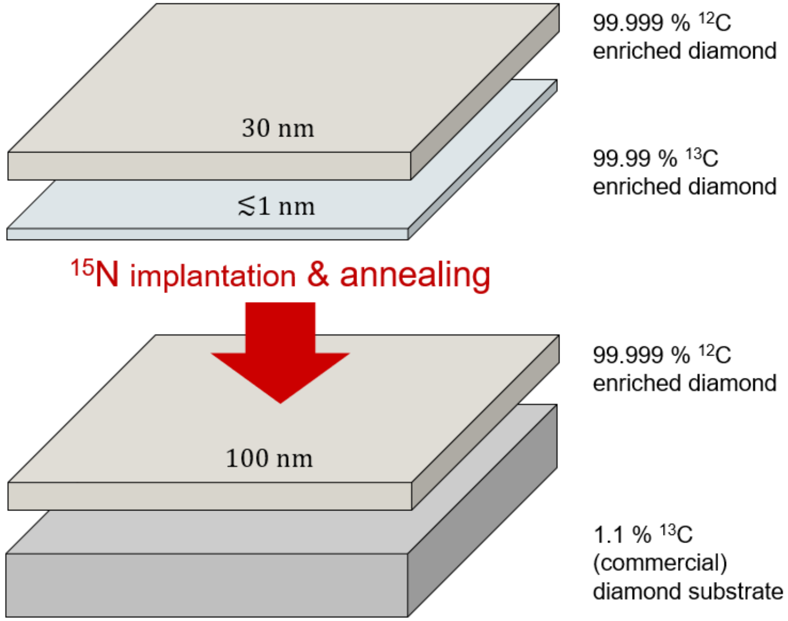

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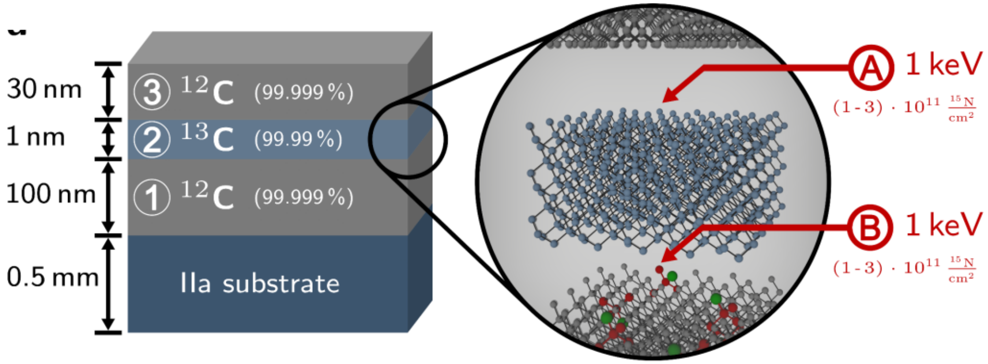
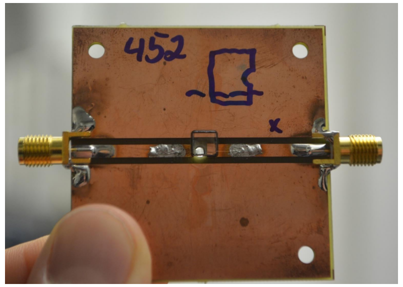
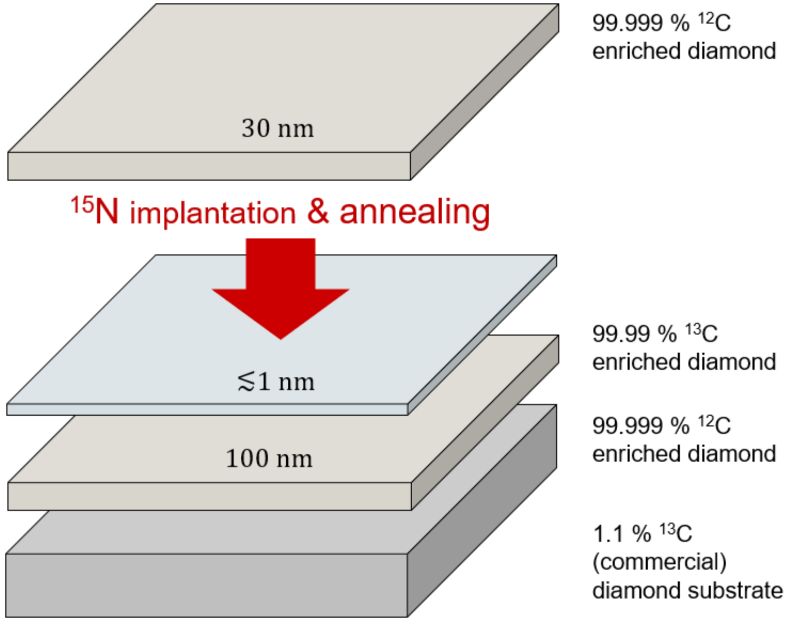
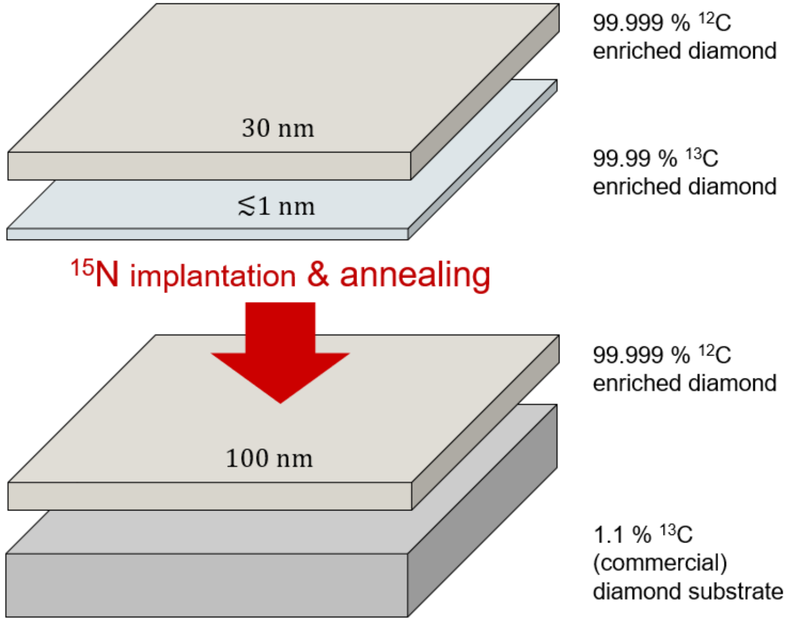
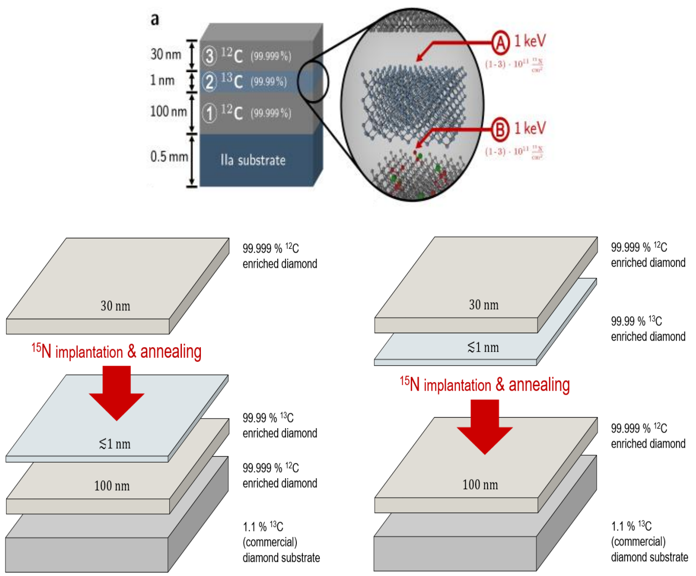


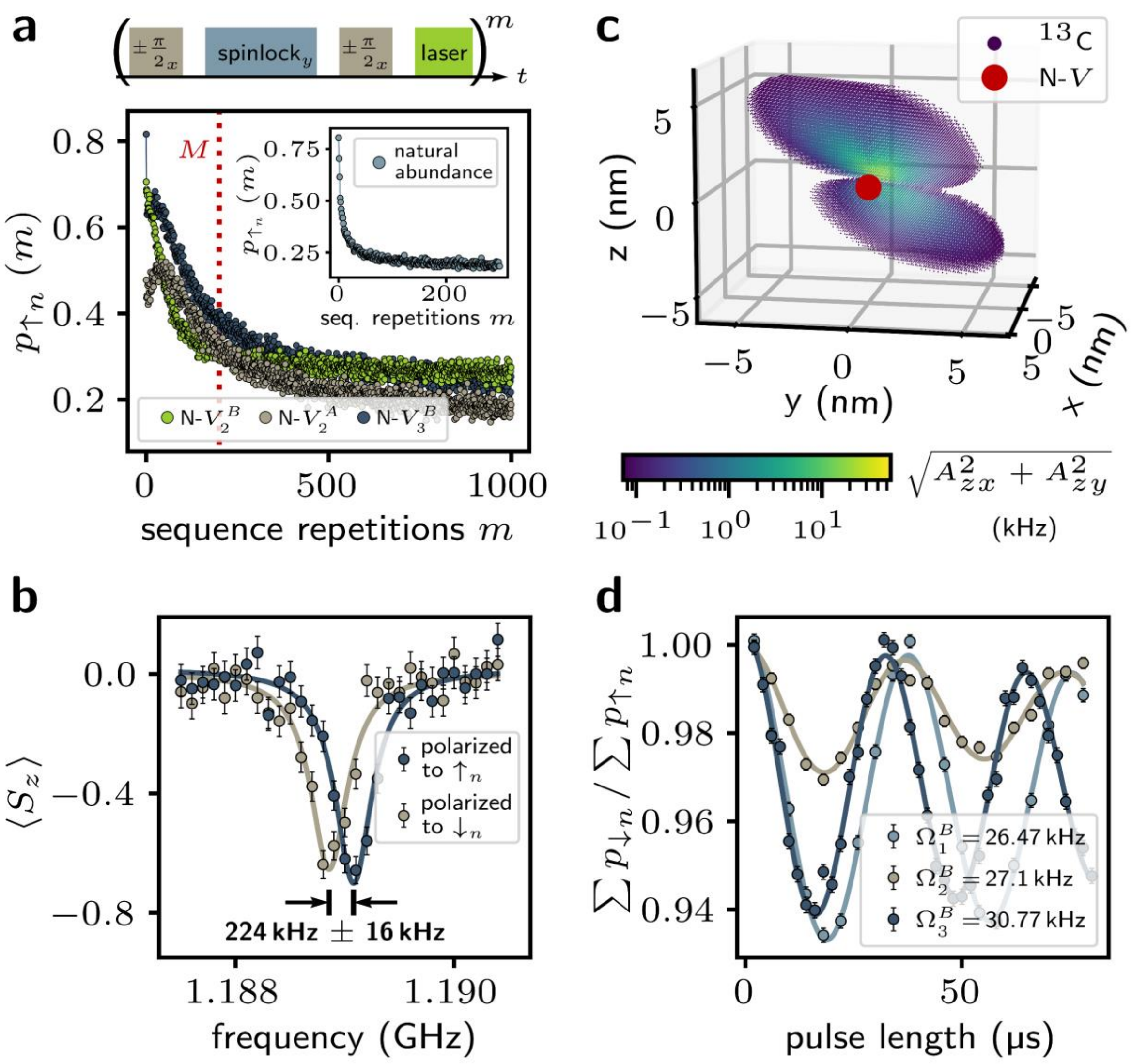






INITIALIZATION AND CONTROL OF ^{13}C LAYER





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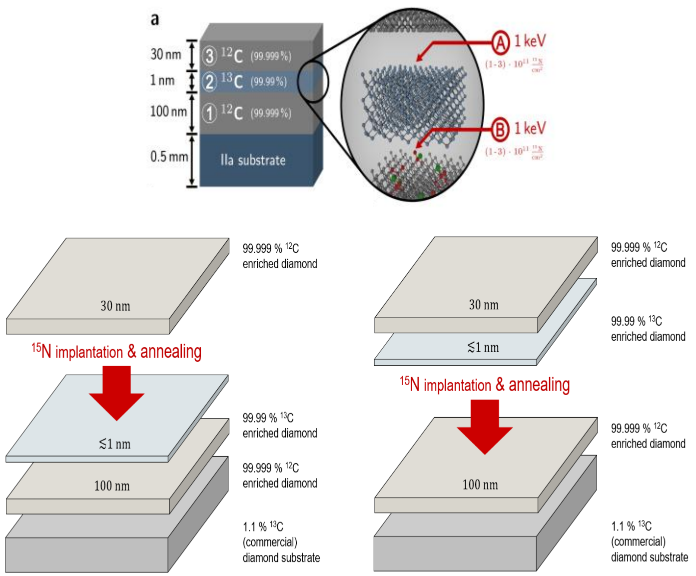

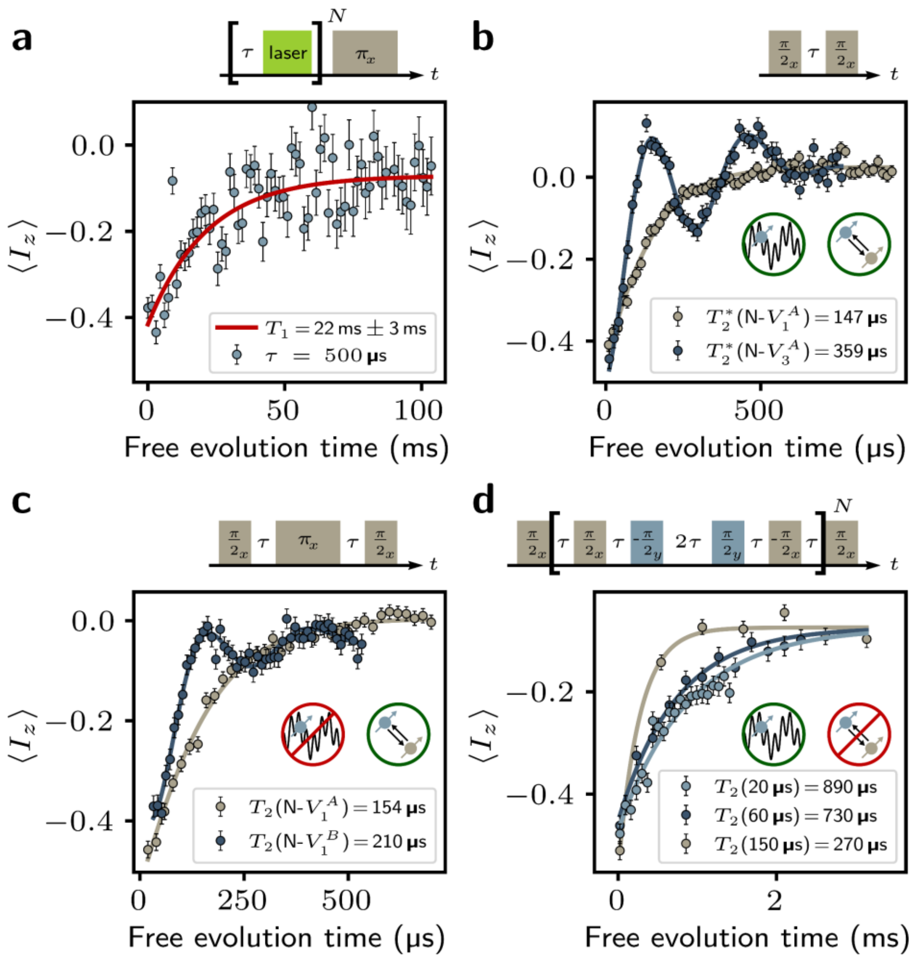

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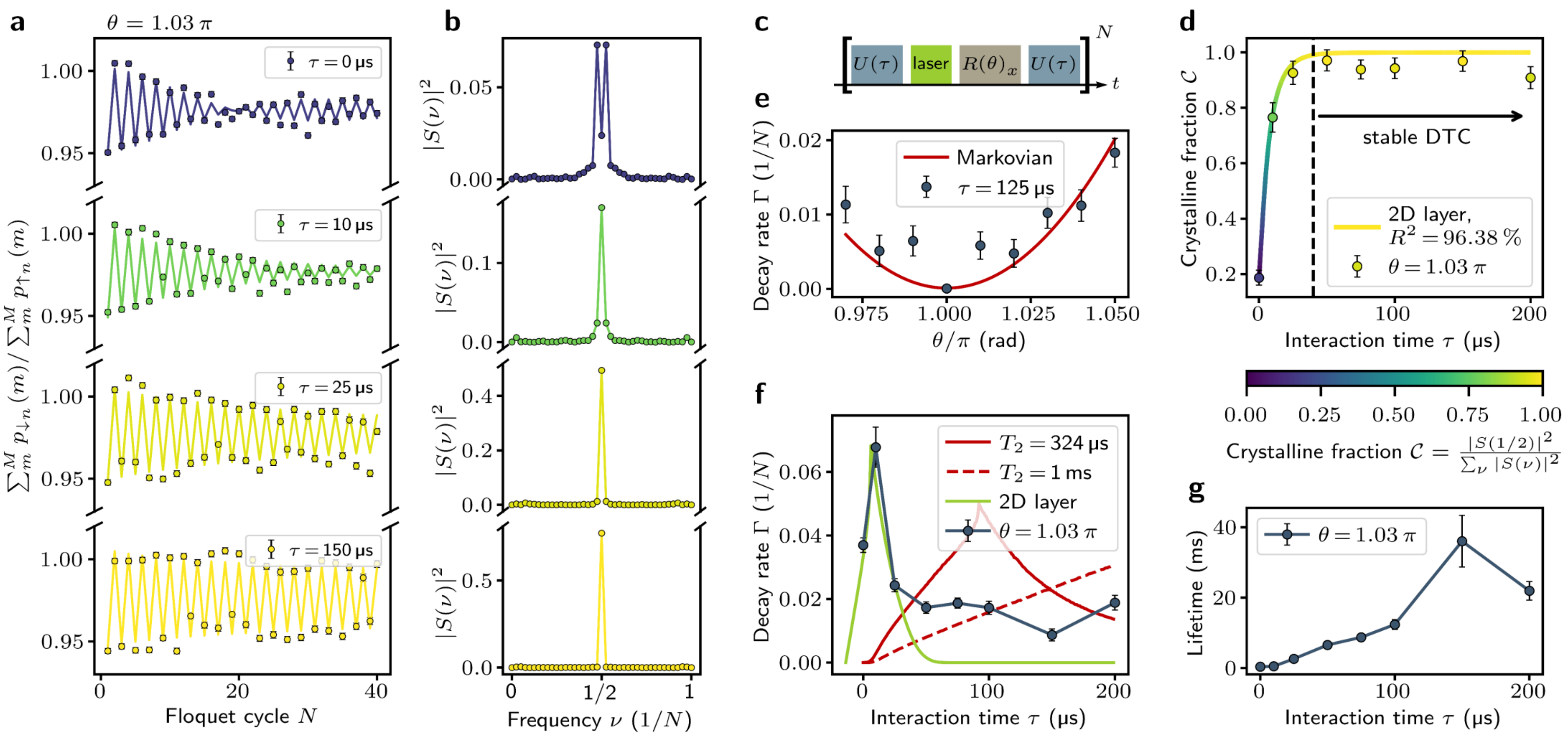
Time Crystal

A time crystal is a non-equilibrium phase of matter, characterized by spontaneous breaking of time translation symmetry.

Time-crystalline order manifests exhibiting oscillations at multiples of the driving period that persist in presence of perturbations.

Translational symmetry in time was shown to be forbidden in thermal equilibrium.

Time Crystal



Summary

1. Discrete time crystal order has been shown in a C_{13} layer.

2. C_{13} platform provides a scalable rout for exploring strongly correlated quantum phase.

In COLABORATION

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CA24109 - Many-body Open Quantum Systems (QOpen)

Description

QOpen aims to substantially boost understanding of complex many-body quantum systems that interact with their environment, leading to decoherence and dissipation. While these effects pose challenges for observing quantum coherent dynamics and have often impeded the development of quantum technologies, they can also be leveraged, e.g. for dissipative quantum error correction. Moreover, exploring non-equilibrium open quantum systems offers the opportunity to discover states of matter that are not achievable in thermal equilibrium.

The Action aims to address key challenges, such as understanding integrable and chaotic dissipative dynamics, thermalization, and the emergence of new, non-equilibrium quantum states of matter. It seeks to advance characterization and control methods for open quantum platforms and promote the development of novel numerical and analytical approaches for modeling these systems. A significant focus is placed on leveraging noisy intermediate-scale quantum (NISQ) devices, which are inherently dissipative many-body platforms, for these investigations.

QOpen establishes a collaborative European framework, bringing together experts from various disciplines and regions, with particular attention to inclusiveness target countries (ITCs). The Action highlights capacity-building through training and mentoring young researchers, engaging with the quantum industry, and promoting interdisciplinary and international collaborations. It aims to create a sustainable, inclusive research network to fuel future research and innovation in the field. While prioritizing fundamental research, the Action engages with the quantum industry sector

Action Details

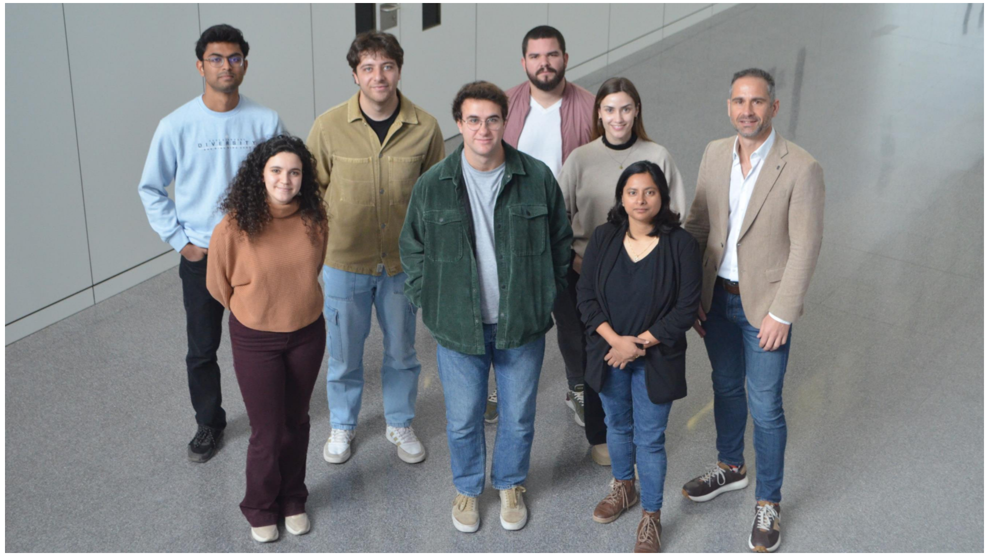
- **MoU** - 018/25
- **CSO Approval date** - 19/05/2025
- **Start date** - 30/09/2025
- **End date** - 29/09/2029

How can I participate?

- Read the Action Description MoU
- Inform the Main Proposer/Chair of your interest (email)
- Apply to join your Working Groups of interest

thanks

ASPECTS
aspects-quantum.com



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HORIZON EUROPE

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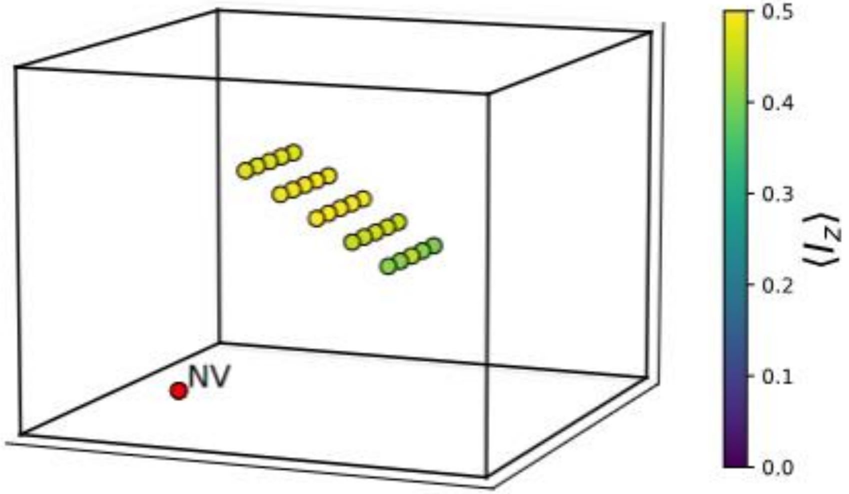
MODELIZATION

$$H = DS_z^2 + \gamma_e B S_z + \gamma_N B \sum_{i=1}^{N_p} I_z^{(i)} + S_z \sum_{i=1}^{N_p} \vec{A}^{(i)}\,\vec{I}^{(i)} + H_{MW}(t)$$

$$\vec{A} = \frac{\mu_0 \gamma_e \gamma_N (3\hat{x}\hat{z}, 3\hat{y}\hat{z}, 1 - 3\hat{z}^2)}{|\vec{r}|^3}$$

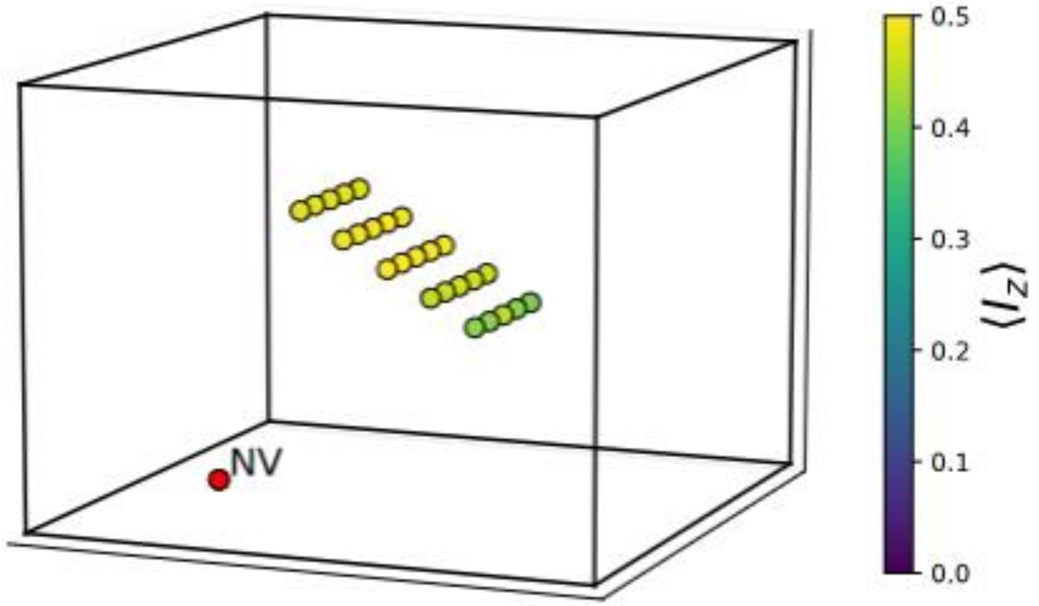
$$H_{MW}(t) = 2\Omega \cos(\omega t + \varphi) S_x$$

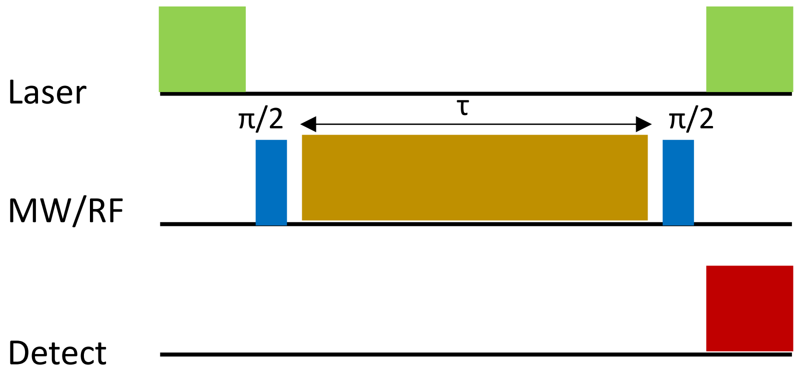


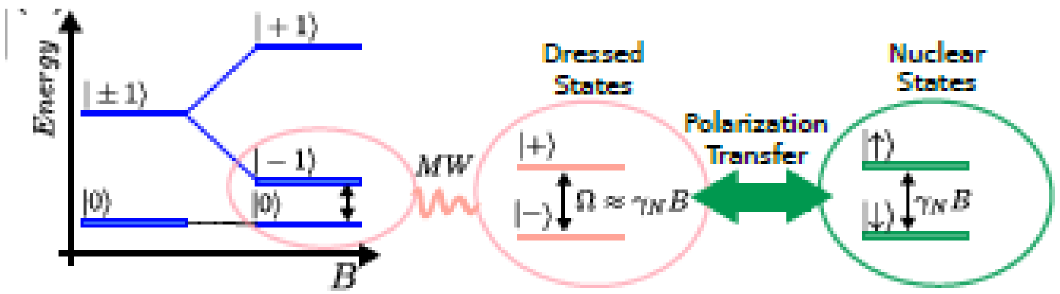
$$H_{RWA} = \frac{1}{2}\sigma_z \sum_{i=1}^{N_p} \vec{A}\,\vec{I}^{(i)} + \sum_{i=1}^{N_p} \vec{\omega}^{(i)}\,\vec{I}^{(i)} + \frac{\Omega}{2}\left(\sigma_x \cos\varphi + \sigma_y \sin\varphi\right)$$

$$\vec{\omega}^{(i)} = \gamma_N B \hat{z} - \frac{1}{2}\vec{A}^{(i)}$$

HARTMANN-HAHN DOUBLE RESONANCE





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ASPECTS
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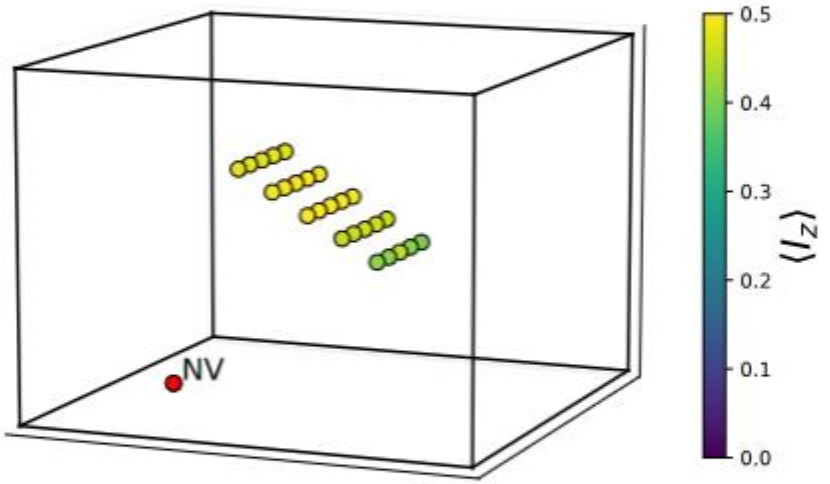
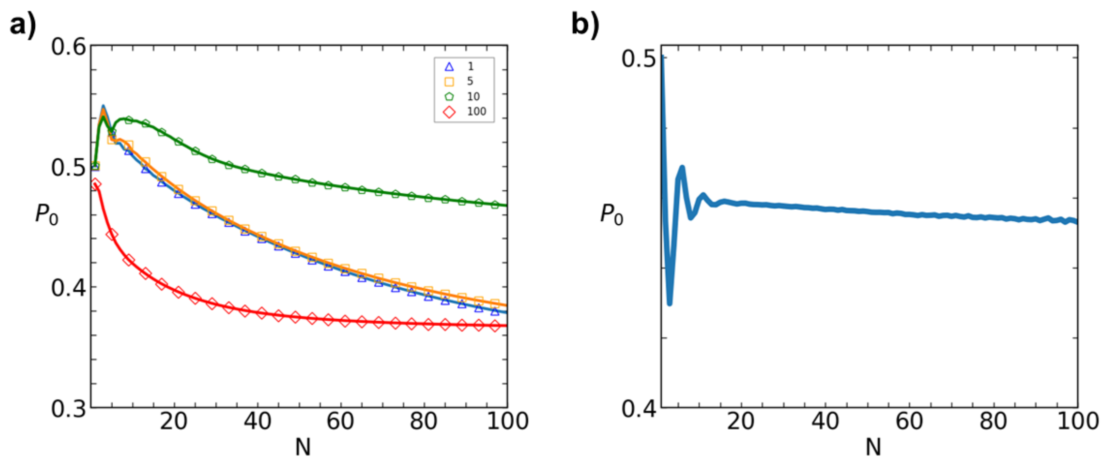
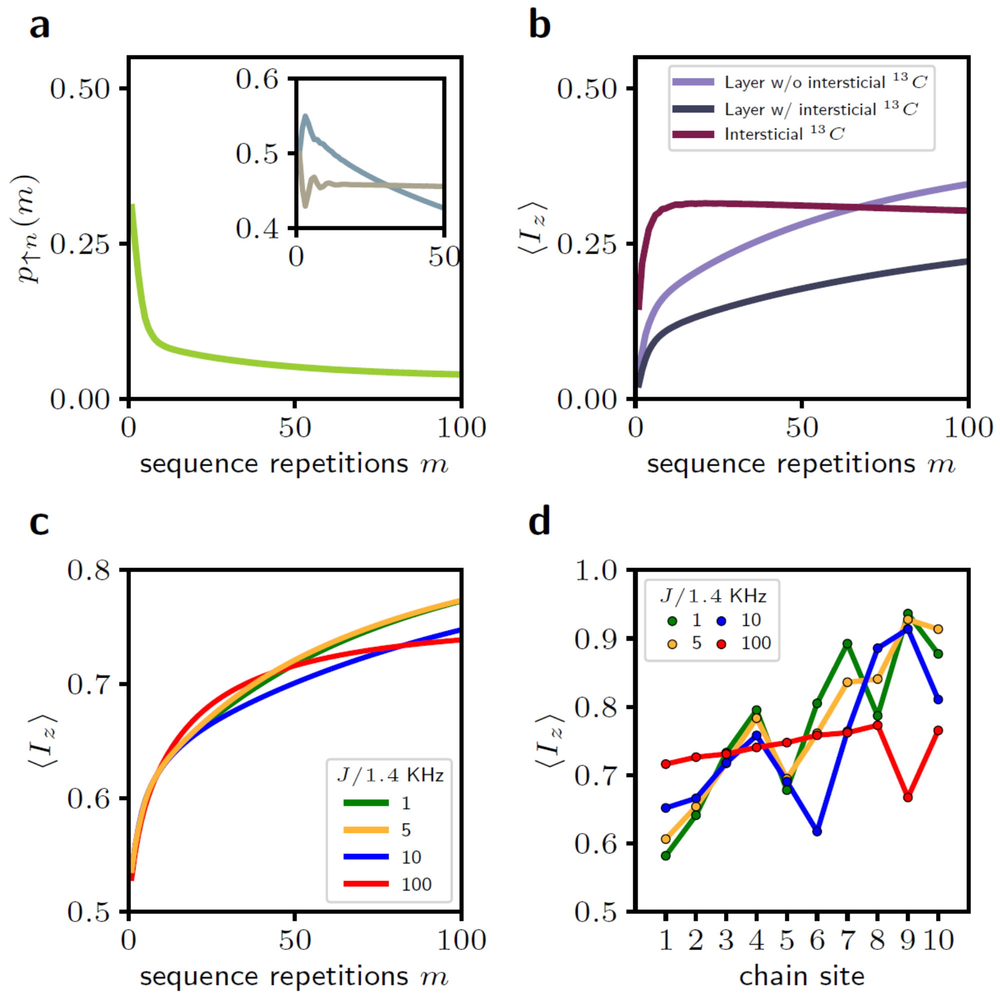
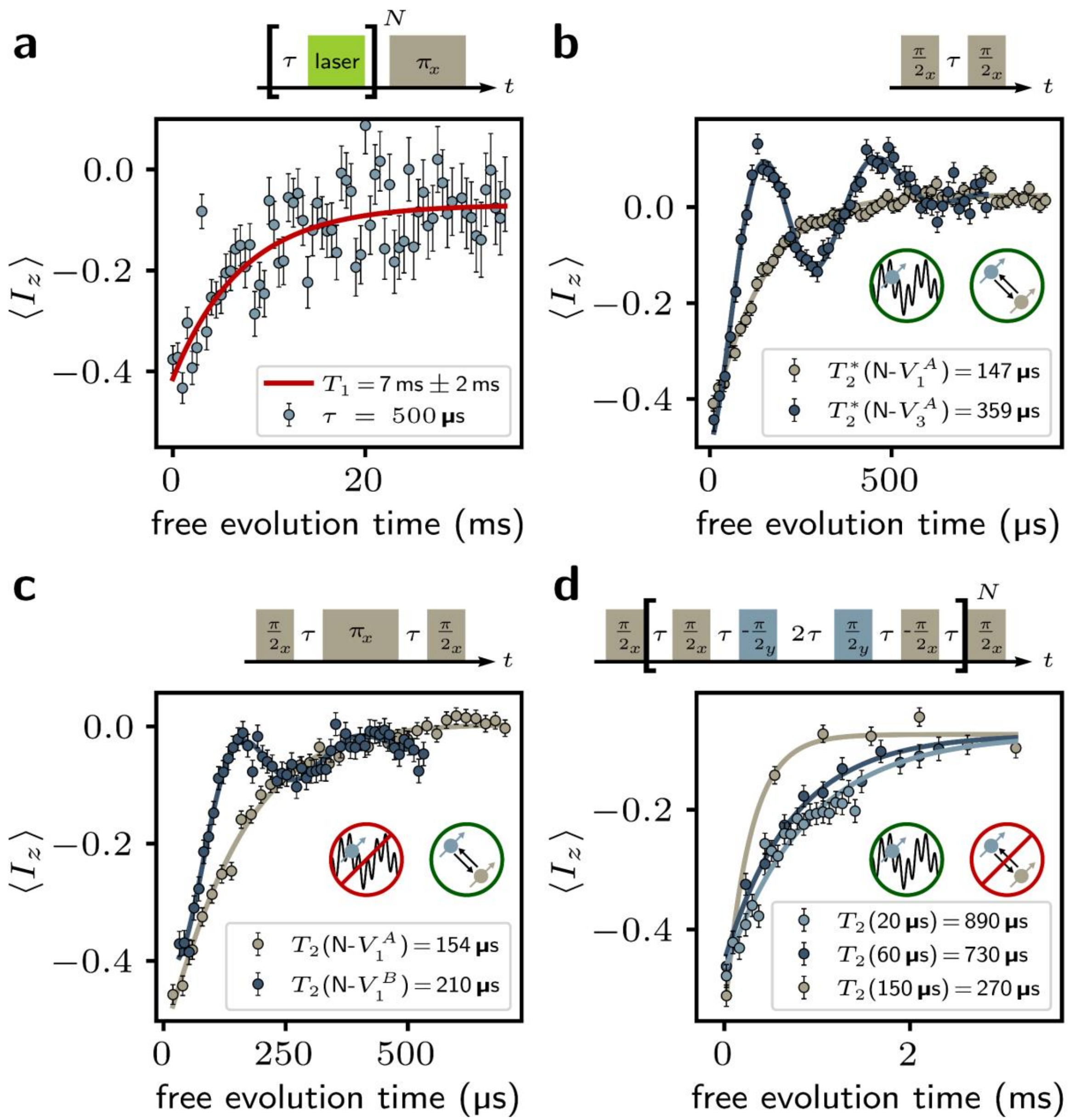
MODELIZATION

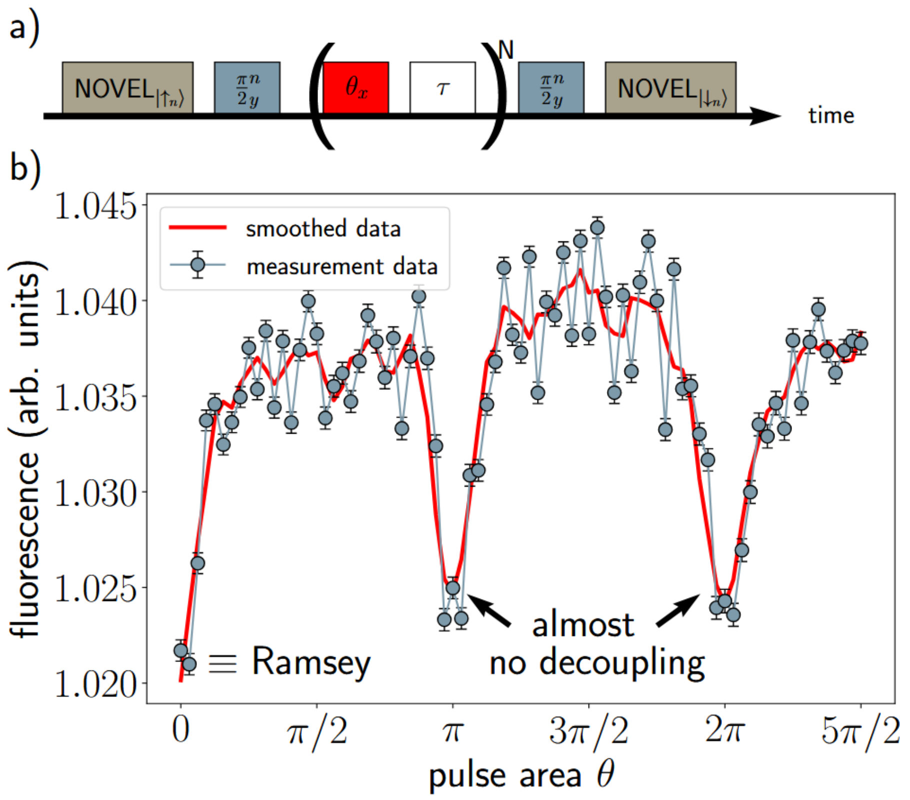




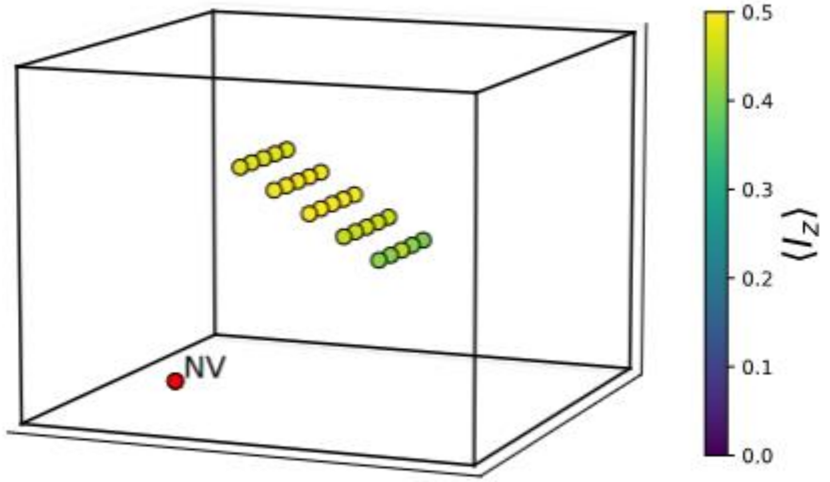




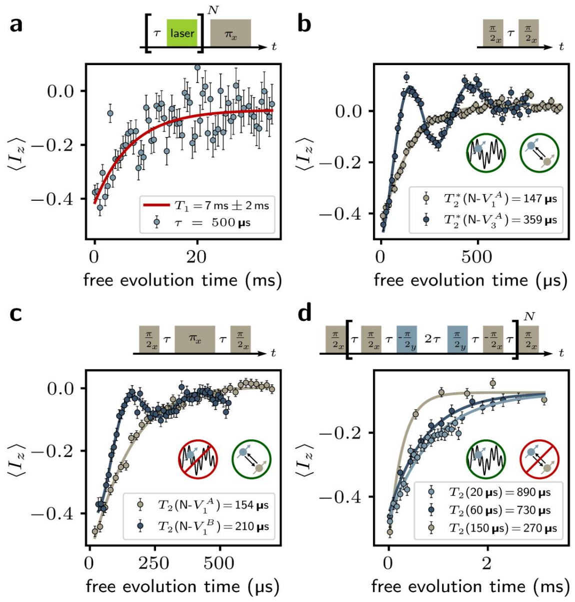
a
τ laser π_x t N
⟨I_z⟩
free evolution time (ms)
T_1 = 7 ms ± 2 ms
τ = 500 µs
b
π/2_x τ π/2_x t
T_2^*(N-V_1^A) = 147 µs
T_2^*(N-V_3^A) = 359 µs
free evolution time (µs)
c
π/2_x τ π_x τ π/2_x t
T_2(N-V_1^A) = 154 µs
T_2(N-V_1^B) = 210 µs
free evolution time (µs)
d
π/2_x τ π/2_x τ -π/2_y 2τ π/2_y τ -π/2_x τ π/2_x t N
T_2(20 µs) = 890 µs
T_2(60 µs) = 730 µs
T_2(150 µs) = 270 µs
free evolution time (ms)



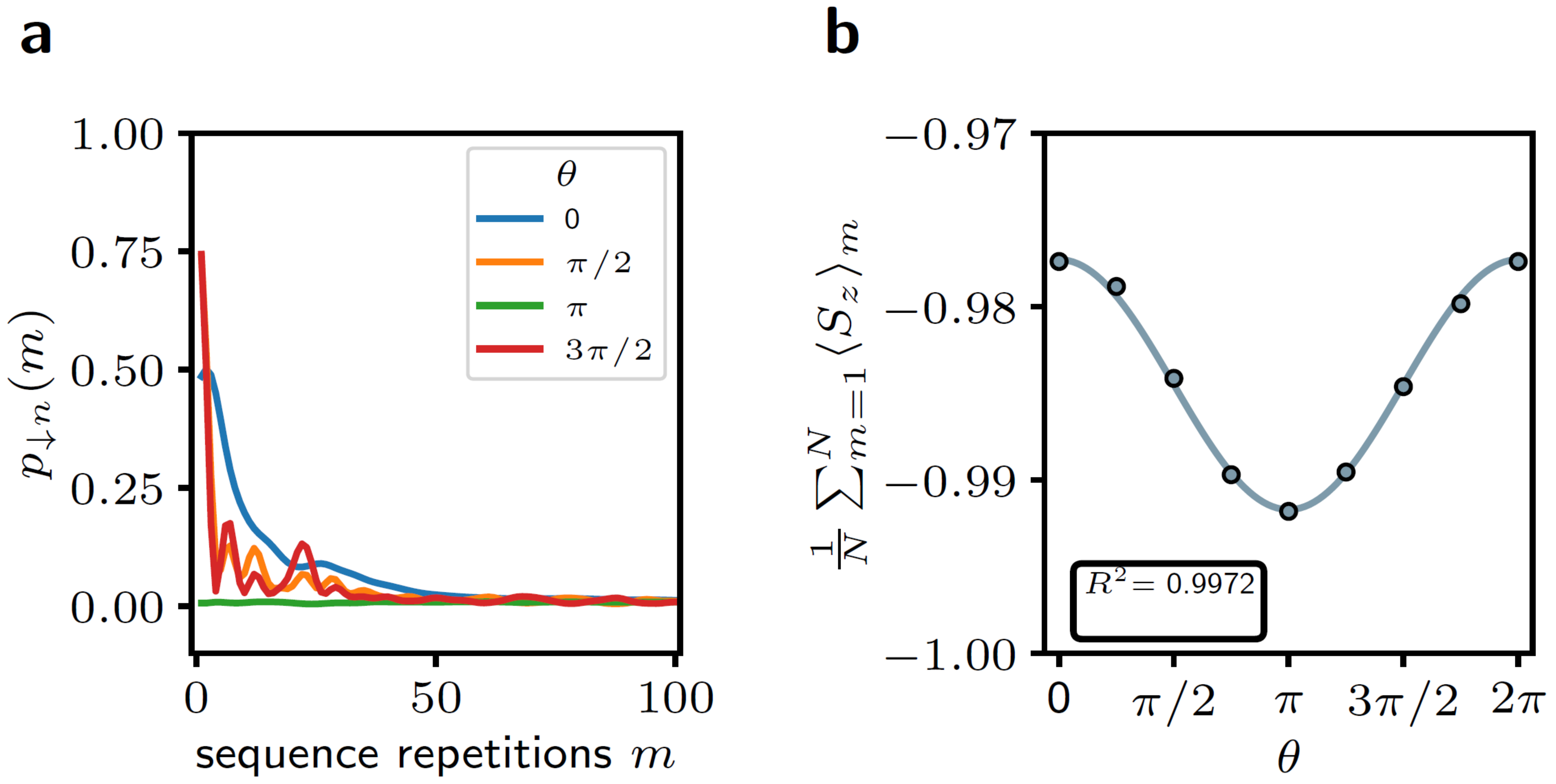
a)
NOVEL$_{|\uparrow_n\rangle}$
$\frac{\pi n}{2y}$
θ_x
τ
N
$\frac{\pi n}{2y}$
NOVEL$_{|\downarrow_n\rangle}$
time
b)
smoothed data
measurement data
fluorescence (arb. units)
1.045
1.040
1.035
1.030
1.025
1.020
$\equiv$ Ramsey
almost
no decoupling
0
$\pi/2$
π
$3\pi/2$
2π
$5\pi/2$
pulse area θ

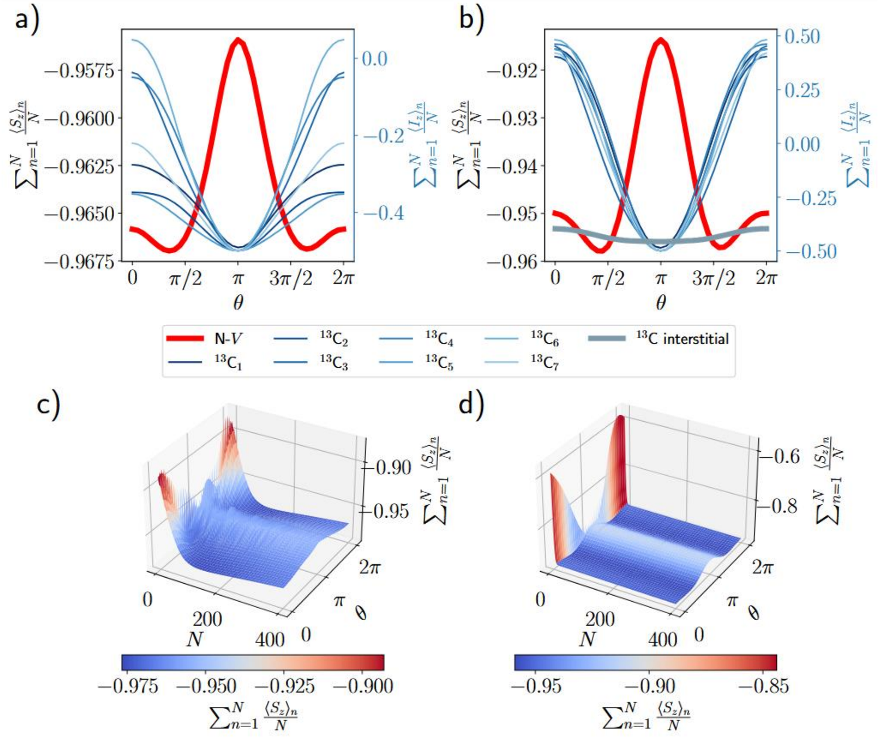


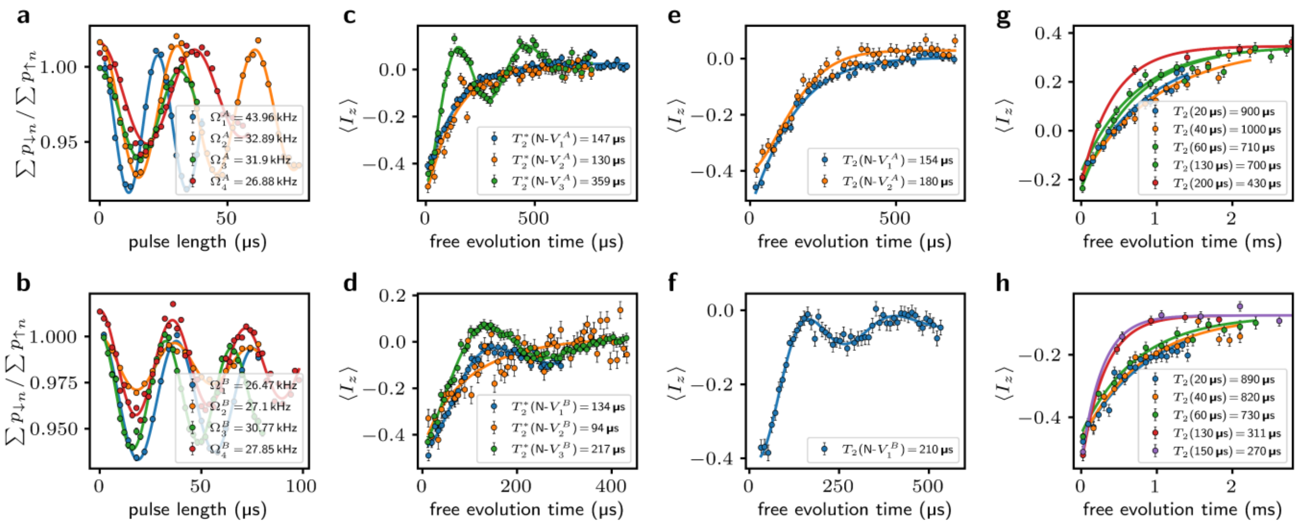
NV
$\langle I_z \rangle$
0.5
0.4
0.3
0.2
0.1
0.0



a
b
c
d
laser
$\langle I_z \rangle$
free evolution time (ms)
free evolution time (µs)
free evolution time (µs)
free evolution time (ms)
$T_1 = 7\,\mathrm{ms} \pm 2\,\mathrm{ms}$
$\tau = 500\,\mathrm{\mu s}$
$T_2^*(\text{N-}V_1^A) = 147\,\mathrm{\mu s}$
$T_2^*(\text{N-}V_3^A) = 359\,\mathrm{\mu s}$
$T_2(\text{N-}V_1^A) = 154\,\mathrm{\mu s}$
$T_2(\text{N-}V_1^B) = 210\,\mathrm{\mu s}$
$T_2(20\,\mathrm{\mu s}) = 890\,\mathrm{\mu s}$
$T_2(60\,\mathrm{\mu s}) = 730\,\mathrm{\mu s}$
$T_2(150\,\mathrm{\mu s}) = 270\,\mathrm{\mu s}$


a
b
1.00
0.75
0.50
0.25
0.00
$p_{\downarrow n}(m)$
0
50
100
sequence repetitions m
θ
0
$\pi/2$
π
$3\pi/2$
−0.97
−0.98
−0.99
−1.00
$\frac{1}{N}\sum_{m=1}^{N}\langle S_z\rangle_m$
$R^2 = 0.9972$
0
$\pi/2$
π
$3\pi/2$
2π
θ


a)
b)
θ
N-V
13C1
13C2
13C3
13C4
13C5
13C6
13C7
13C interstitial
c)
d)
N
θ


a
b
c
d
e
f
g
h
pulse length (μs)
free evolution time (μs)
free evolution time (ms)
Ω1A = 43.96 kHz
Ω2A = 32.89 kHz
Ω3A = 31.9 kHz
Ω4A = 26.88 kHz
Ω1B = 26.47 kHz
Ω2B = 27.1 kHz
Ω3B = 30.77 kHz
Ω4B = 27.85 kHz
T2*(N-V1A) = 147 μs
T2*(N-V2A) = 130 μs
T2*(N-V3A) = 359 μs
T2*(N-V1B) = 134 μs
T2*(N-V2B) = 94 μs
T2*(N-V3B) = 217 μs
T2(N-V1A) = 154 μs
T2(N-V2A) = 180 μs
T2(N-V1B) = 210 μs
T2(20 μs) = 900 μs
T2(40 μs) = 1000 μs
T2(60 μs) = 710 μs
T2(130 μs) = 700 μs
T2(200 μs) = 430 μs
T2(20 μs) = 890 μs
T2(40 μs) = 820 μs
T2(60 μs) = 730 μs
T2(130 μs) = 311 μs
T2(150 μs) = 270 μs

Summary

1. The spin conversion with MW π-pulses is really poor. This leads to inconclusive Rabi oscillations. AE-ODMR shows a big step ahead.

2. T_1 alternating measurements show high instability for measurement times of biological relevance (1-15 min).

3. An efficient protocol to measure at low or zero magnetic field has been introduced.

4. Utilising phase and amplitude noise it is possible to increase the resolution of nano-NMR experiments beyond the line-width paradigm.

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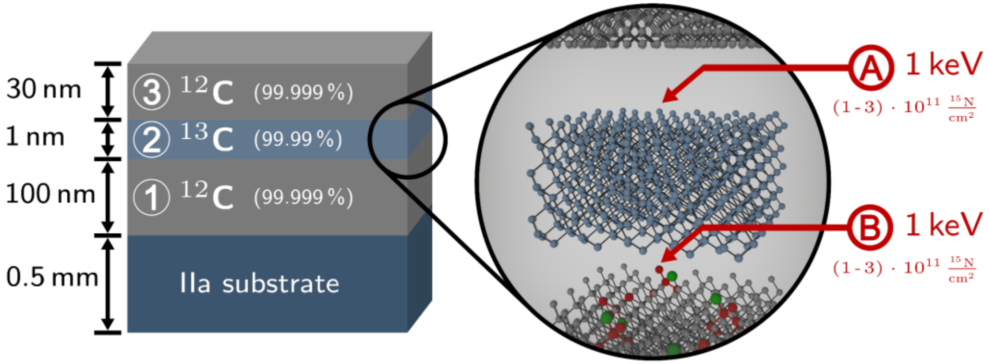
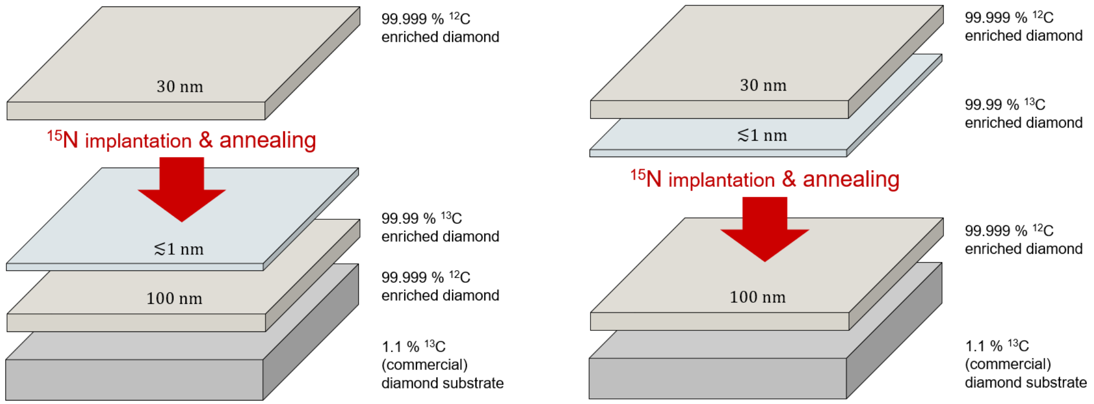
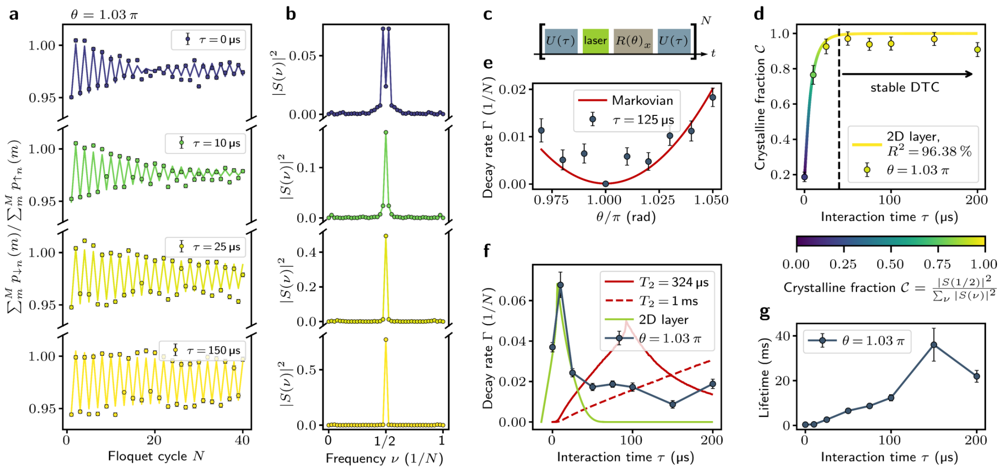
- ✓ Electron spin
- ✓ Good properties conferred by the diamond lattice
  - In particular, long T_1, T_2
- ✓ Easy to polarize and read-out
- ✓ Easy to manipulate
- ✓ Room temperature platform operation

NUCLEAR SPIN LAYERS IN DIAMONDS

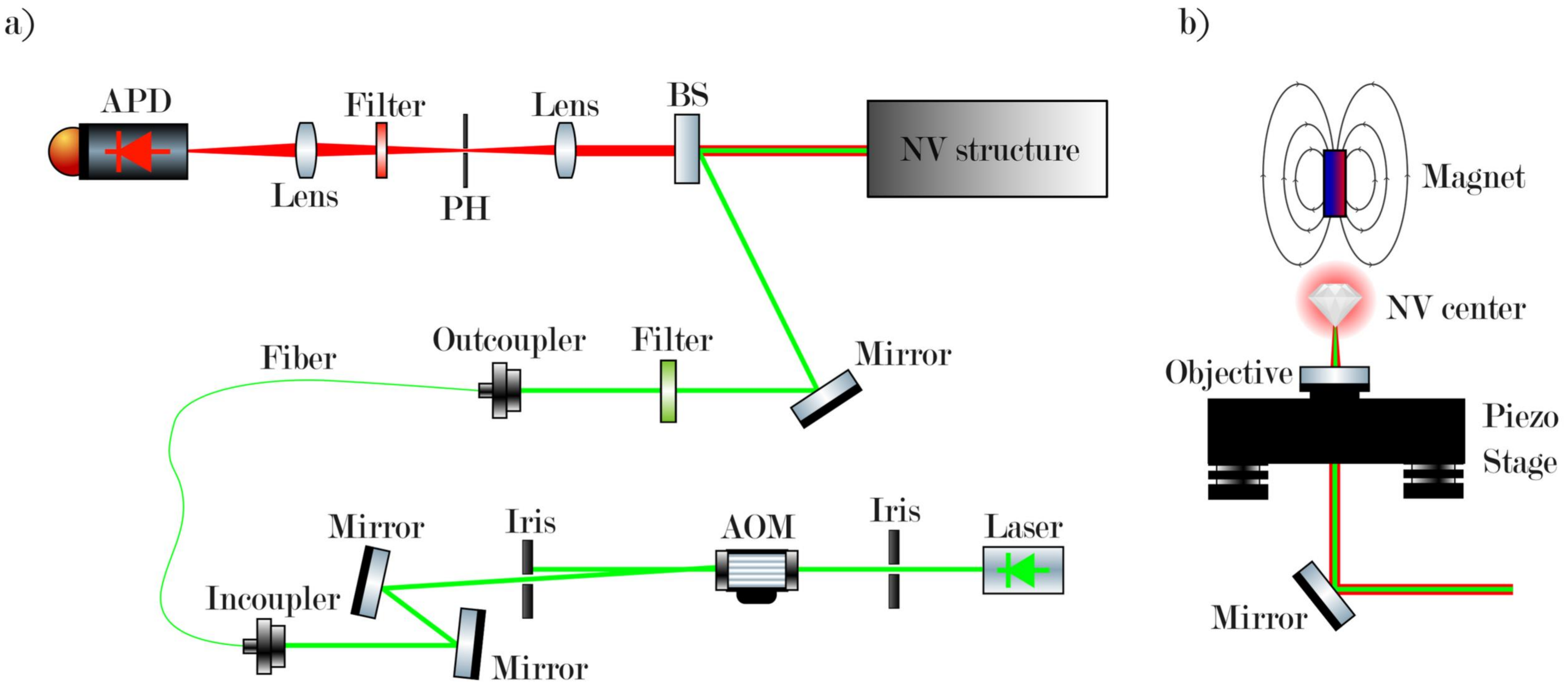




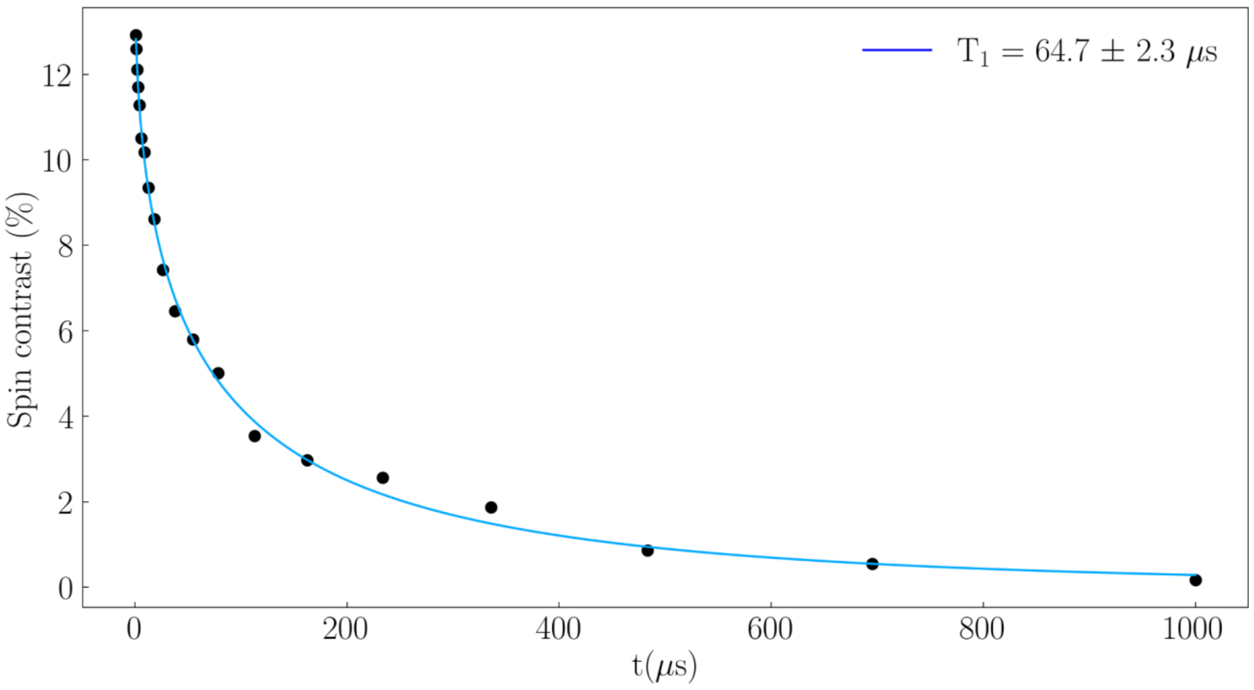
NUCLEAR SPIN LAYERS IN DIAMONDS

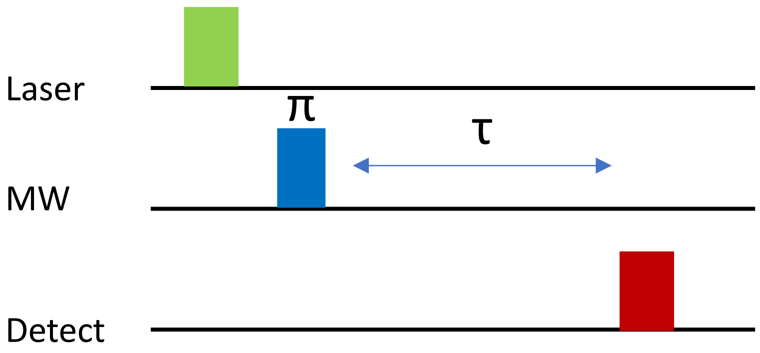


EXPERIMENTAL SET UP

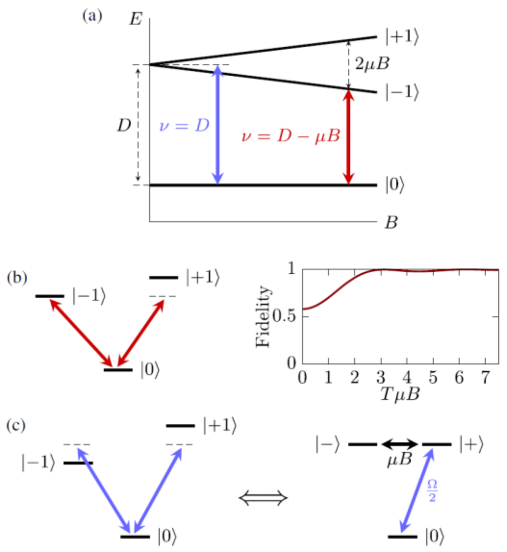


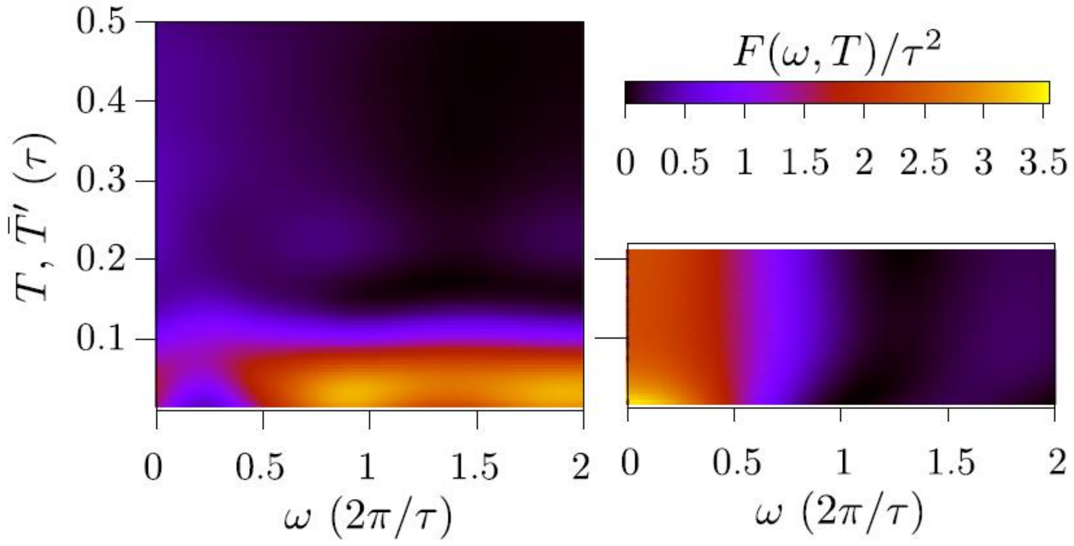
T1 (alternating) RELAXOMETRY

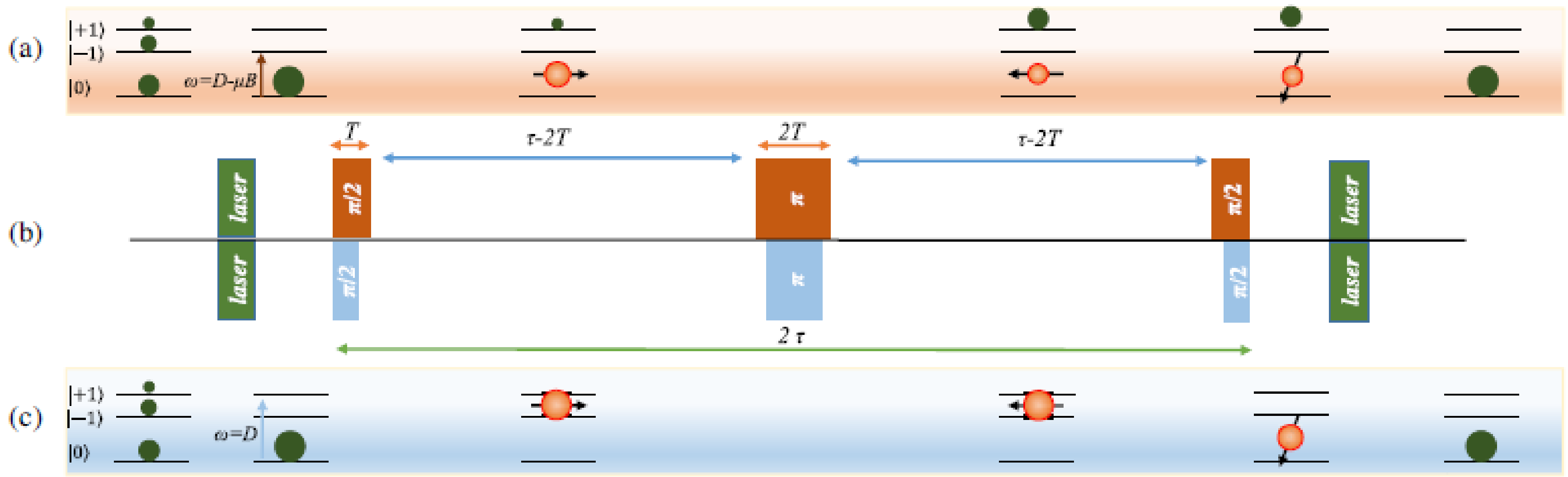




ALIGNMENT OF THE MAGNETIC FIELD







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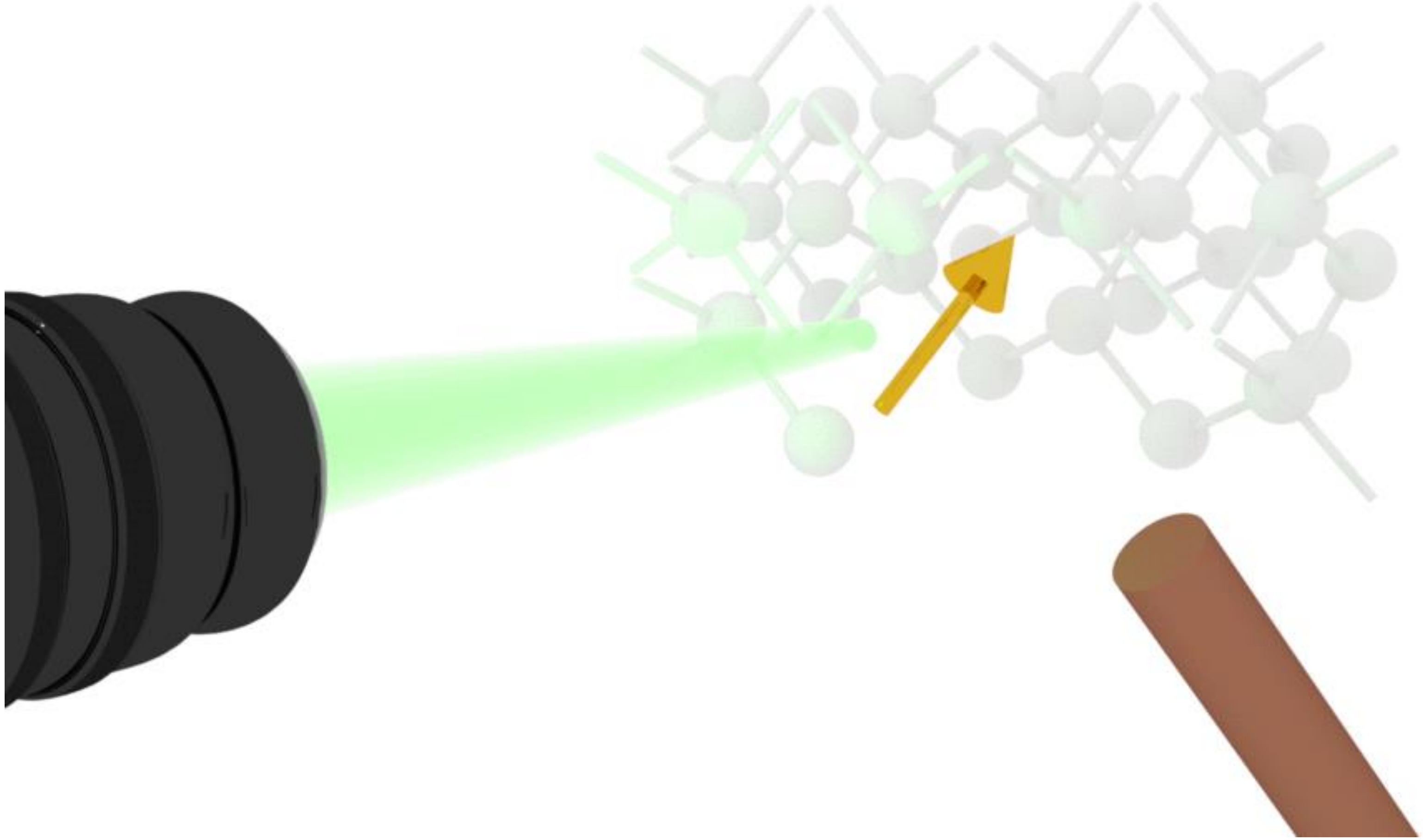
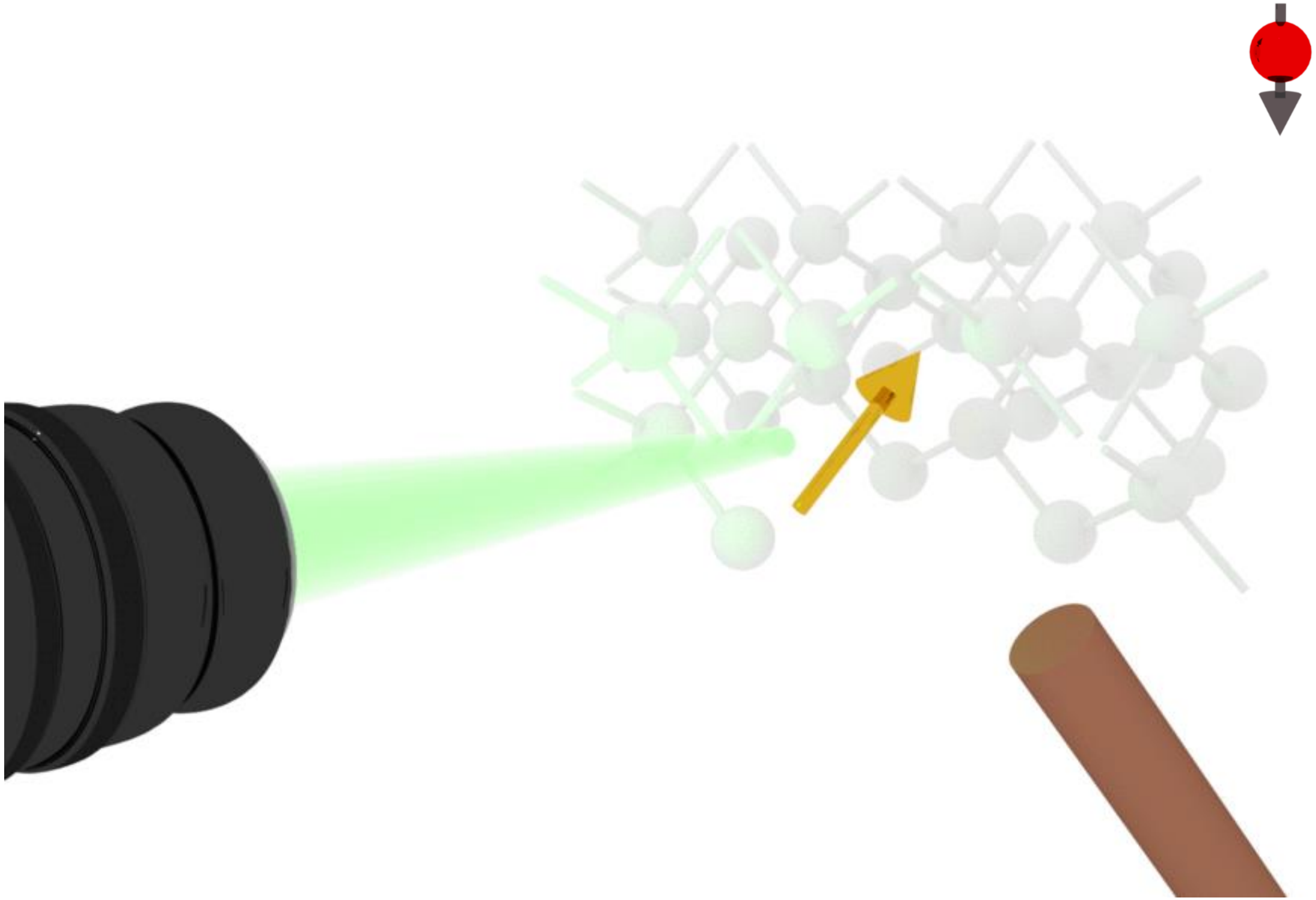


THE NV CENTER



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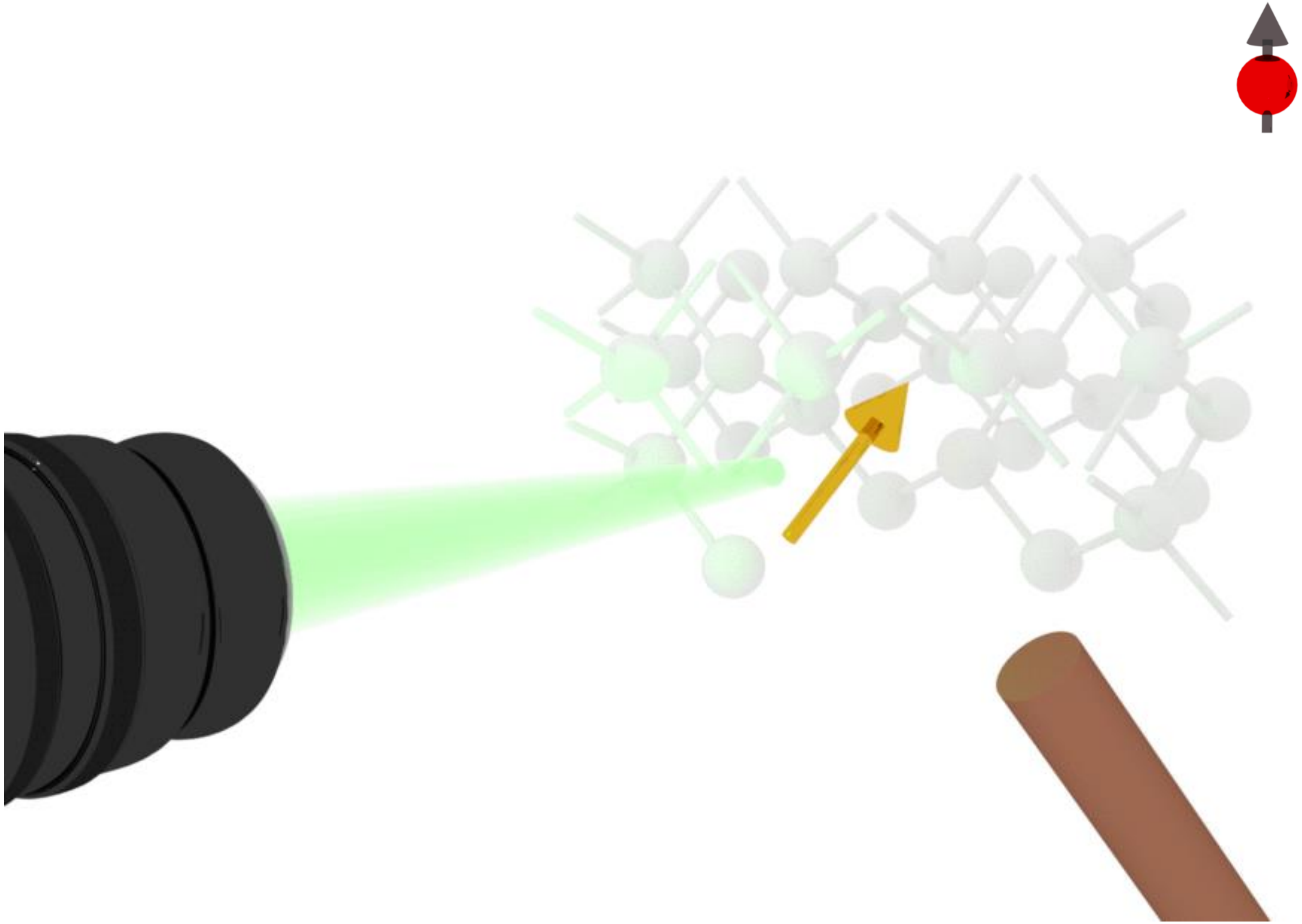
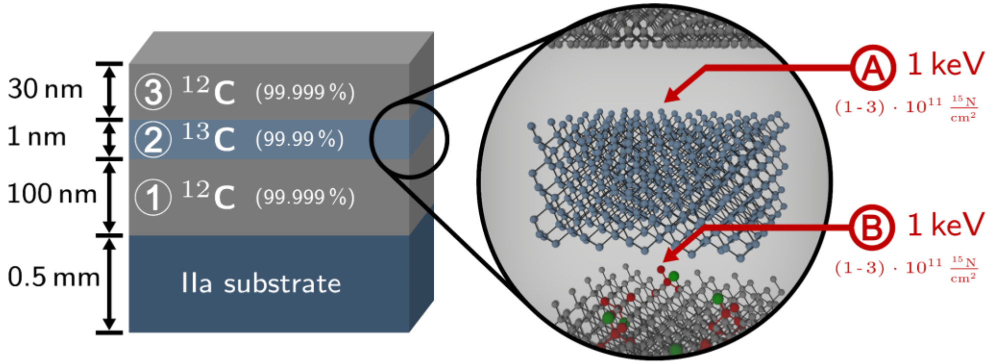
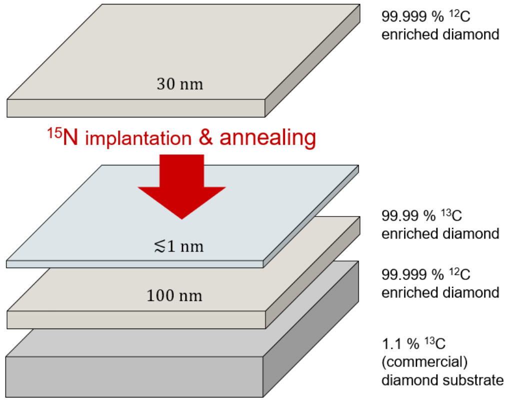
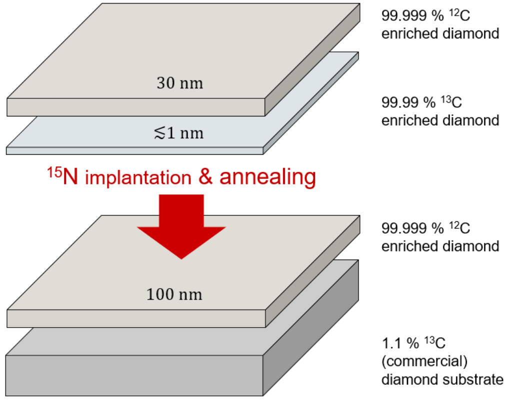
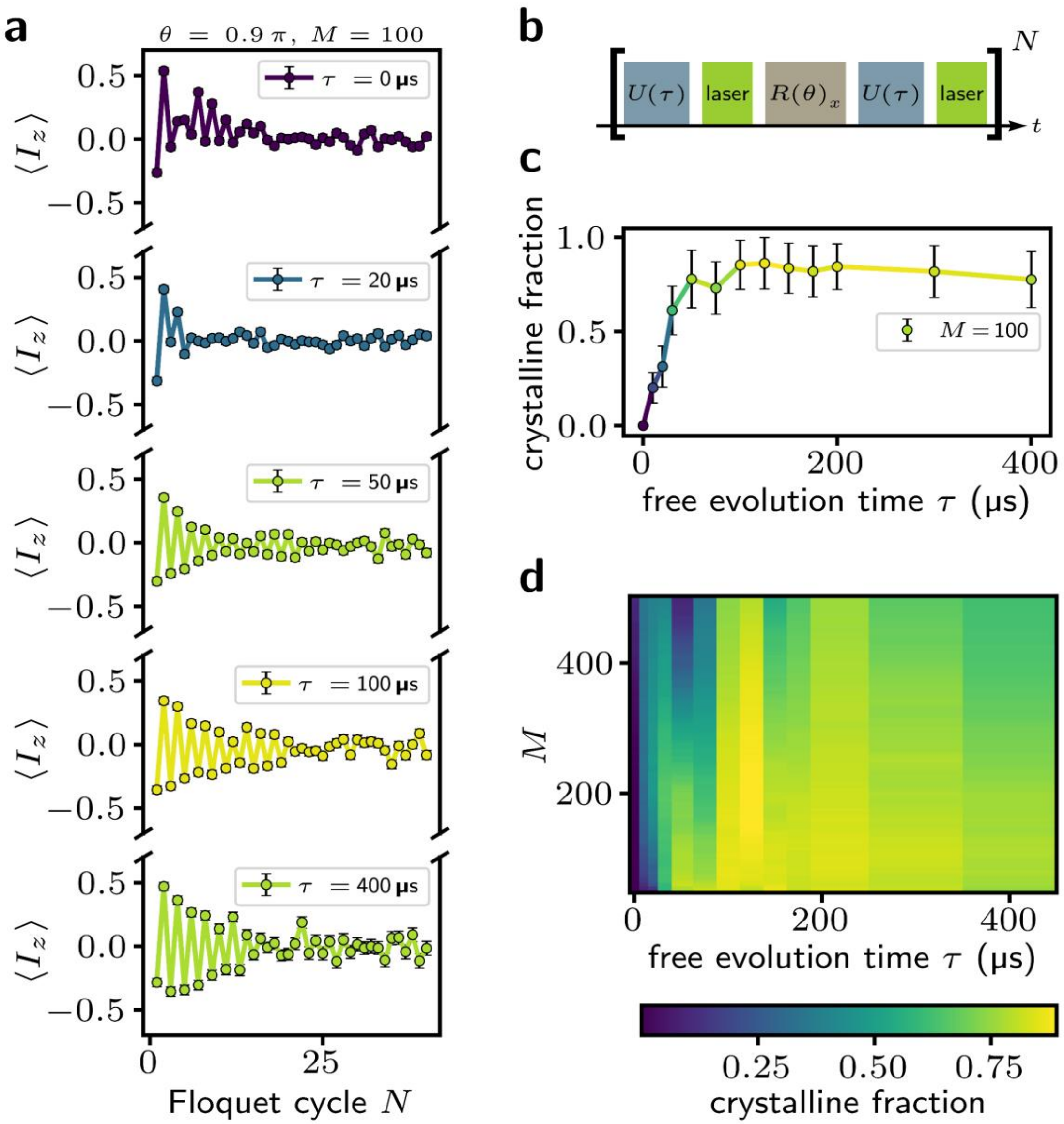


NUCLEAR SPIN LAYERS IN DIAMONDS









Time Crystal

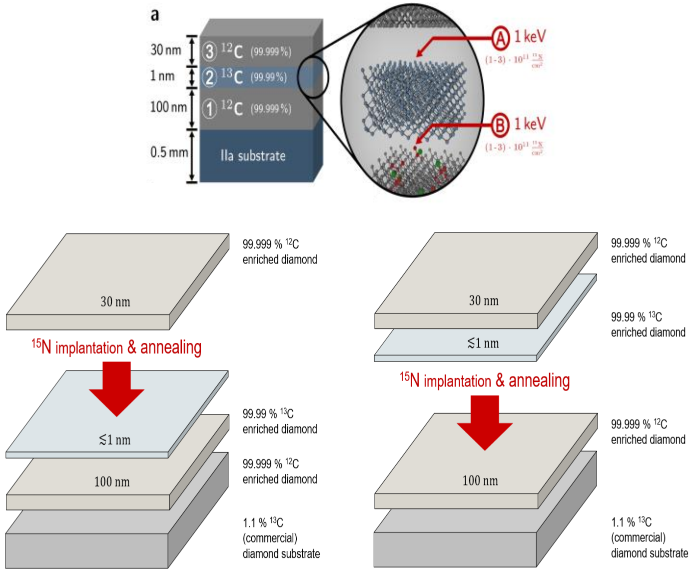
Spontaneous symmetry breaking is a fundamental concept . Breaking of spatial translational-formation of crystals and phase transition from liquid to solid.

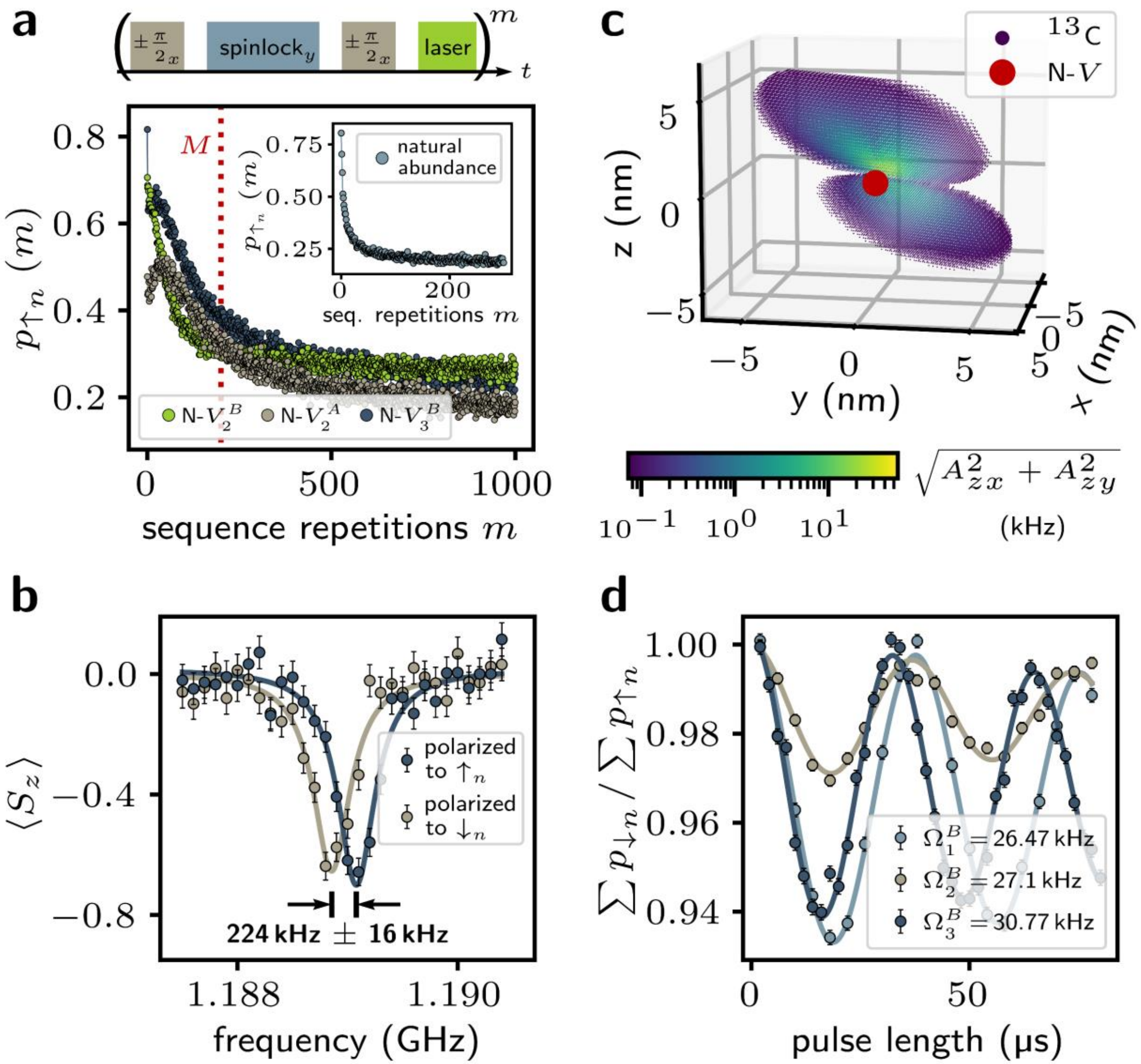
A time cristal is a non-equilibrium phase of matter, characterized by spontaneous breaking of time translation symmetry. It is forbidden in themal equilibrium.

The interplay between periodic driving, disorder and strong interactions in out of equilibrium systems has been predicted to result in exotic time crystalline phases.

In condensed matter physics, a **time crystal** is a quantum system of particles whose lowest-energy-state is one in which the particles are in repetitive motion. The system cannot lose energy to the environment and come to rest because it is already in its quantum ground state.

INITIALIZATION AND CONTROL OF C13 LAYER





Coherent control of solid state nuclear spin nano-ensembles. Unden, T., Tomek, *et al. npj Quantum Inf* **4**, 39 (2018). https://doi.org/10.1038/s41534-018-0089-8

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