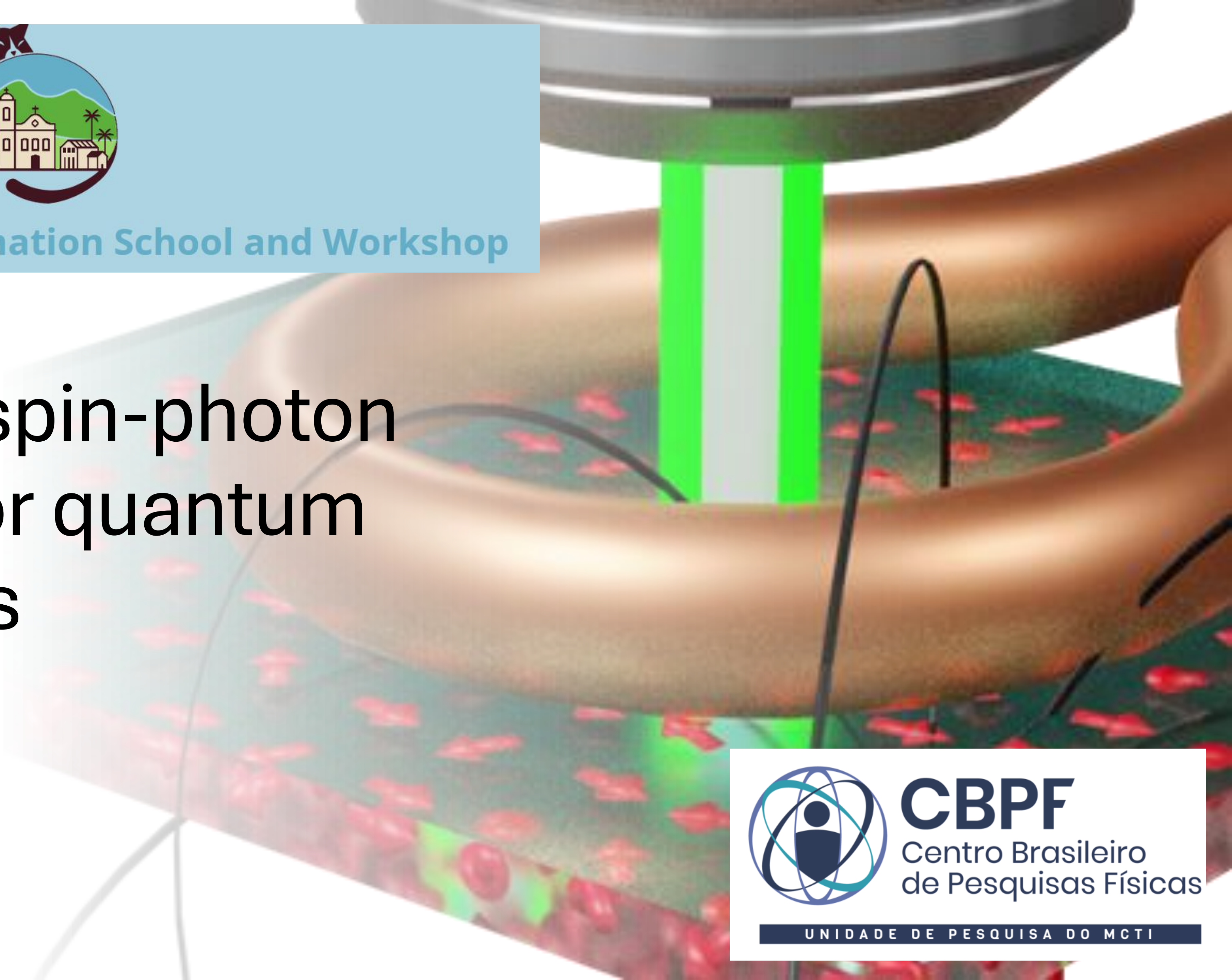
Paraty Quantum Information School and Workshop

Solid-state spin-photon interfaces for quantum technologies



Carmem M. Gilardoni
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Researcher, CBPF

06/08/2025

CBPF
Centro Brasileiro de Pesquisas Físicas
UNIDADE DE PESQUISA DO MCTI

Who am I?

Graduation

- 2011-2015
- Bachelor's Degree in Physics at the University of Brasilia

Masters

- 2015-2017
- Masters Degree in Nanosciences, University of Groningen (NL)

Doctorate

- 2017-2021
- PhD at the University of Groningen (NL)

Post-Doctorate

- 2022-2024
- University of Cambridge (UK)

Light-matter interaction

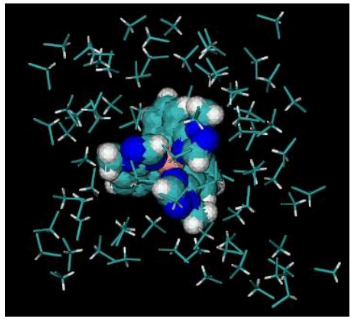
Masters

Nanoscience

Biophysics

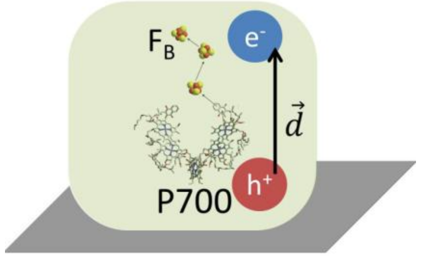
Iridescence in bird feathers and their nanoscopic structure

Chemistry



Spin-photon interactions of molecules dispersed in different solvents

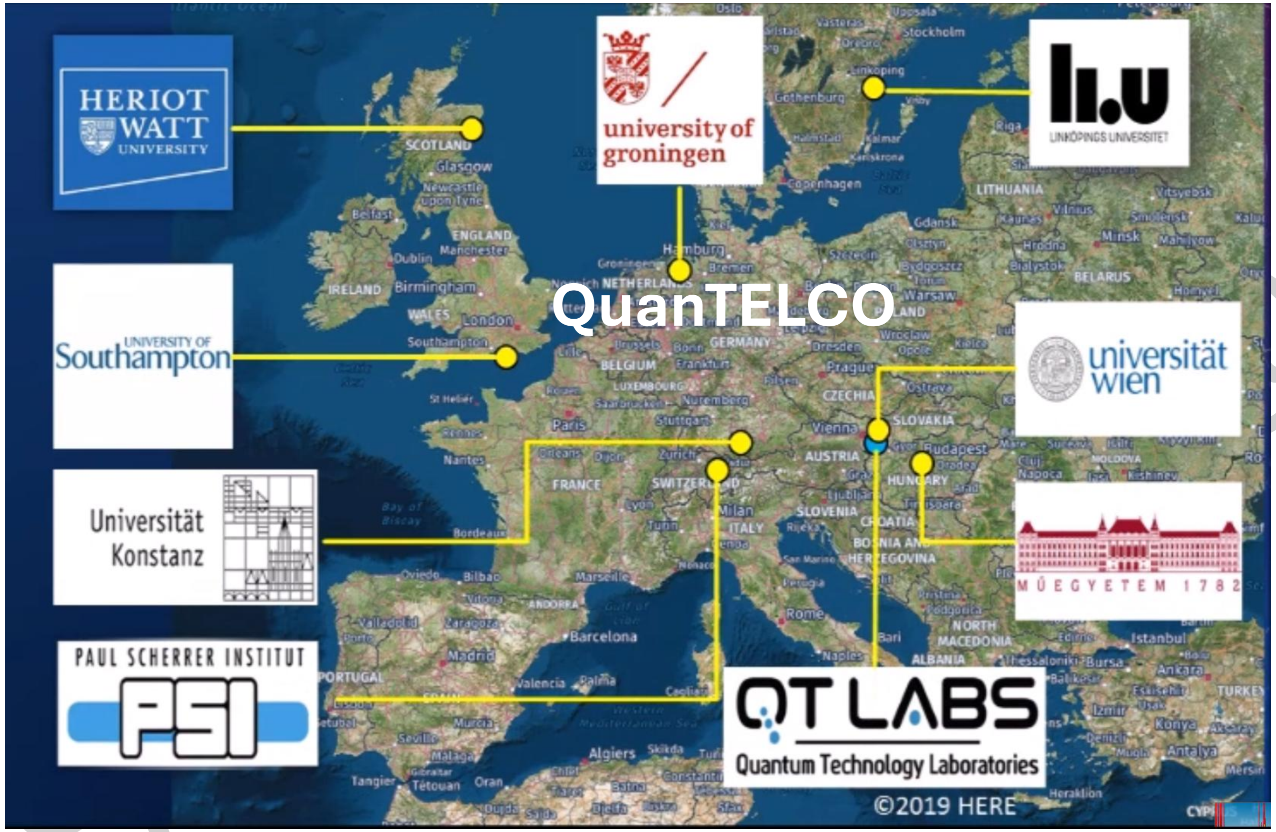
Physics

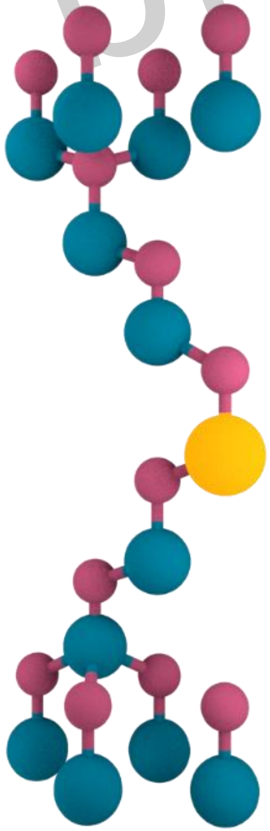


Graphene devices functionalized with Photosystem I

Doctorate

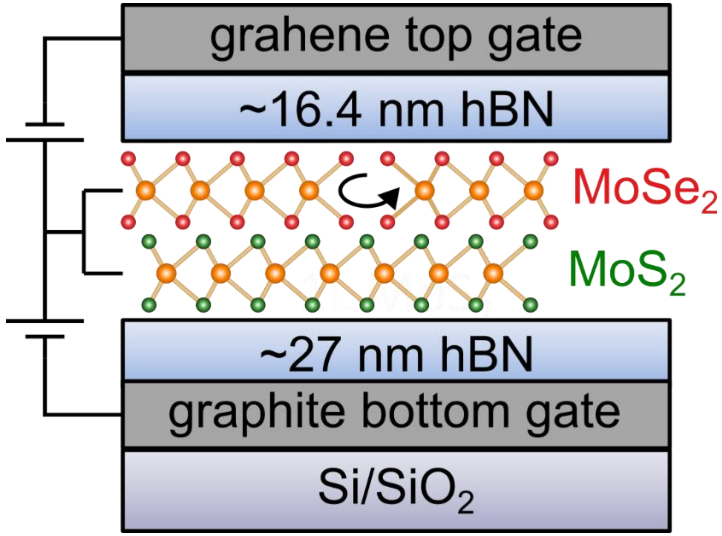
university of groningen

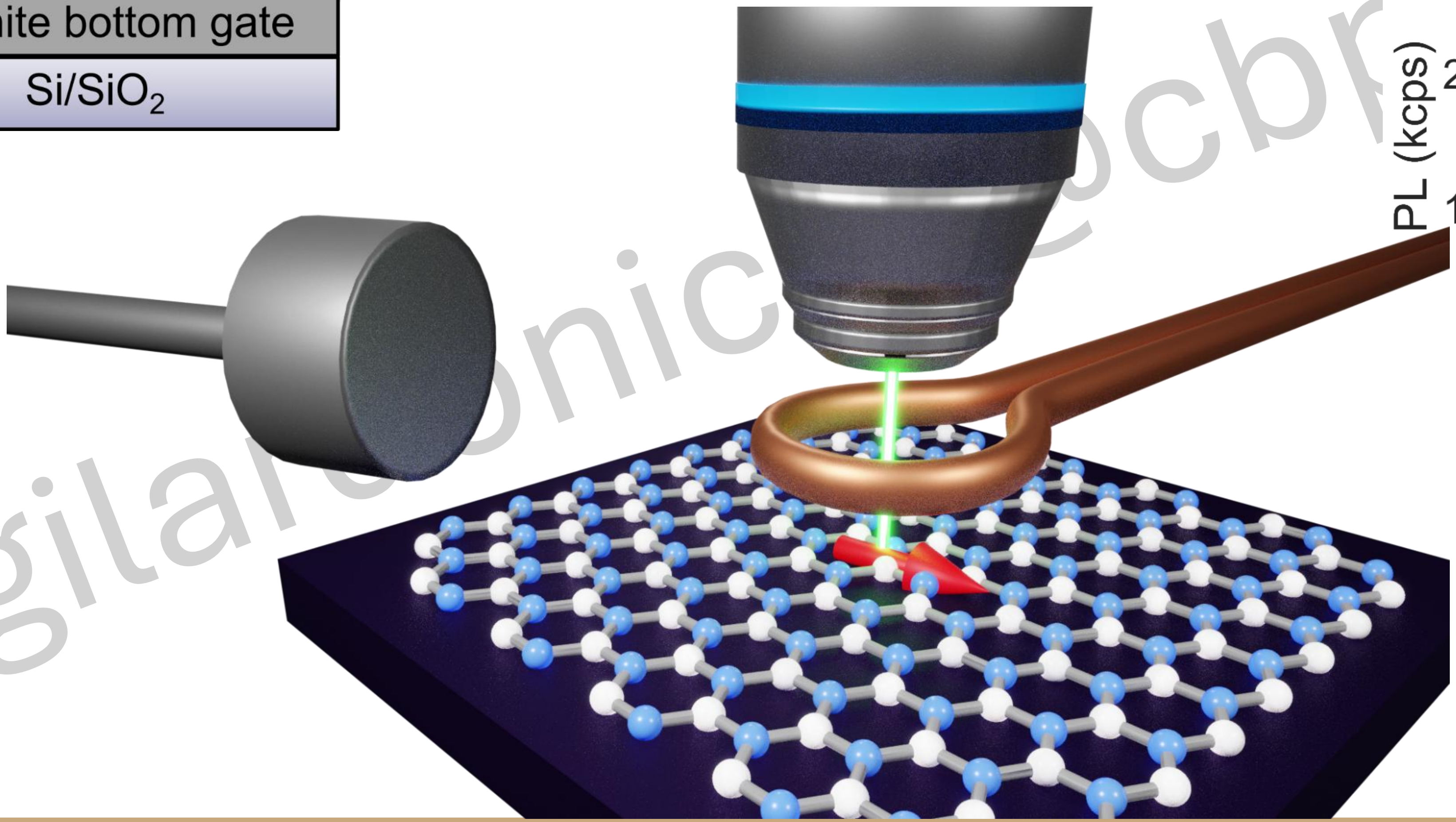


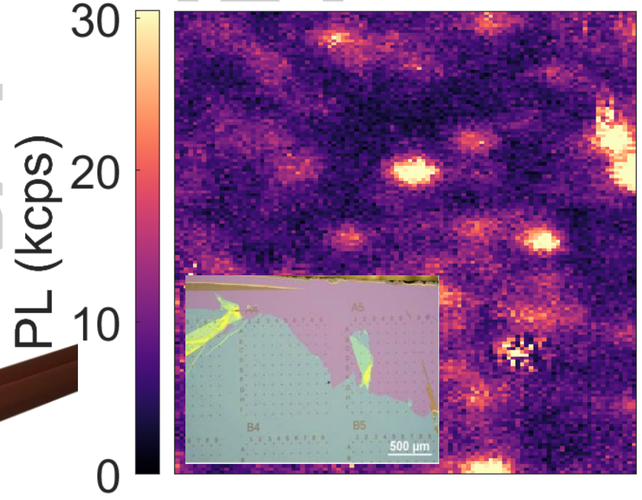


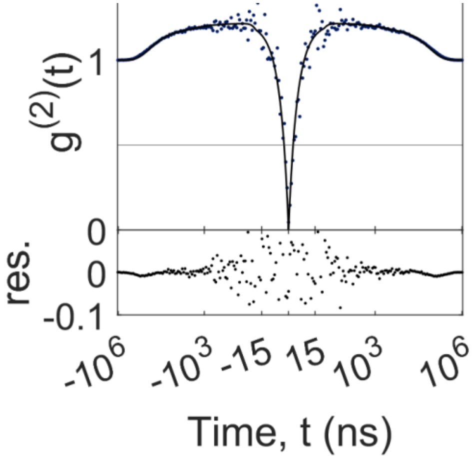
(Mo^{+1}/V^{0})

Post-Doctorate

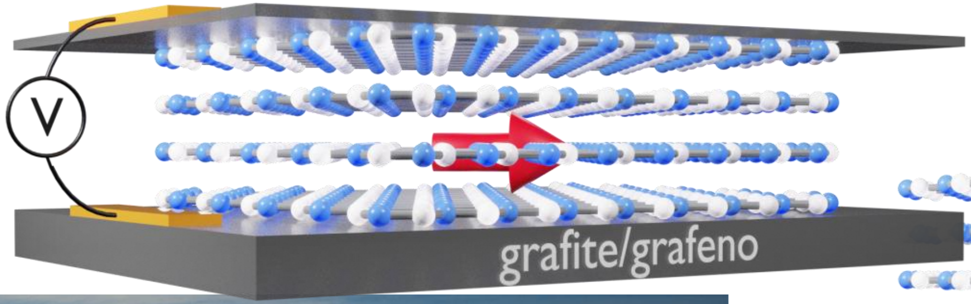


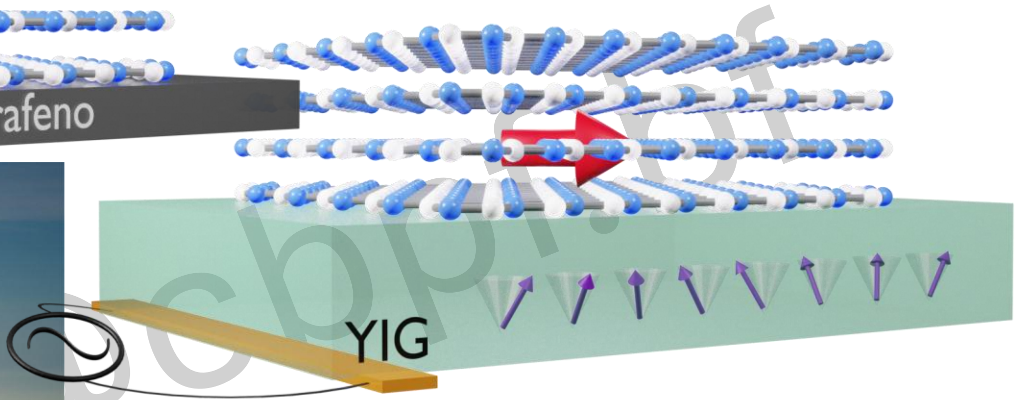


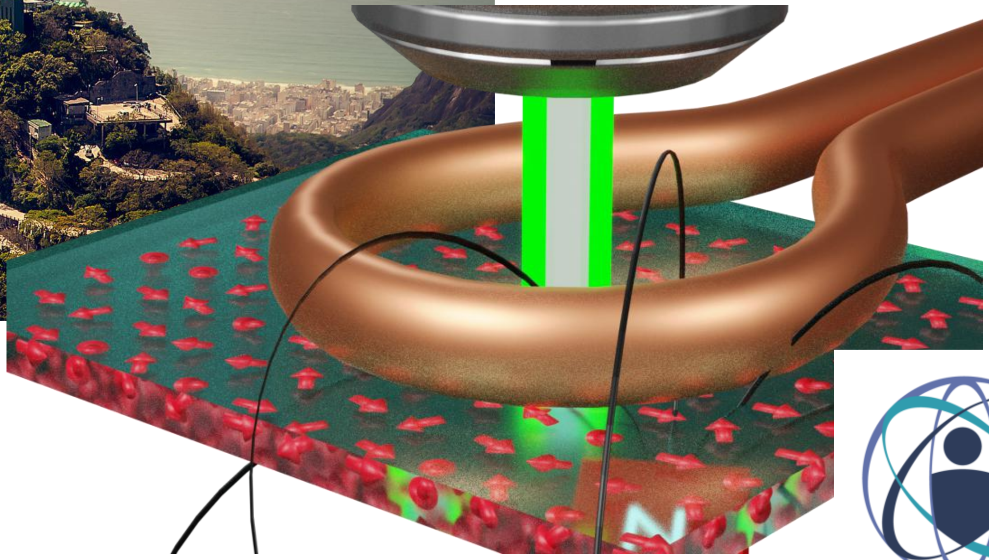




Now







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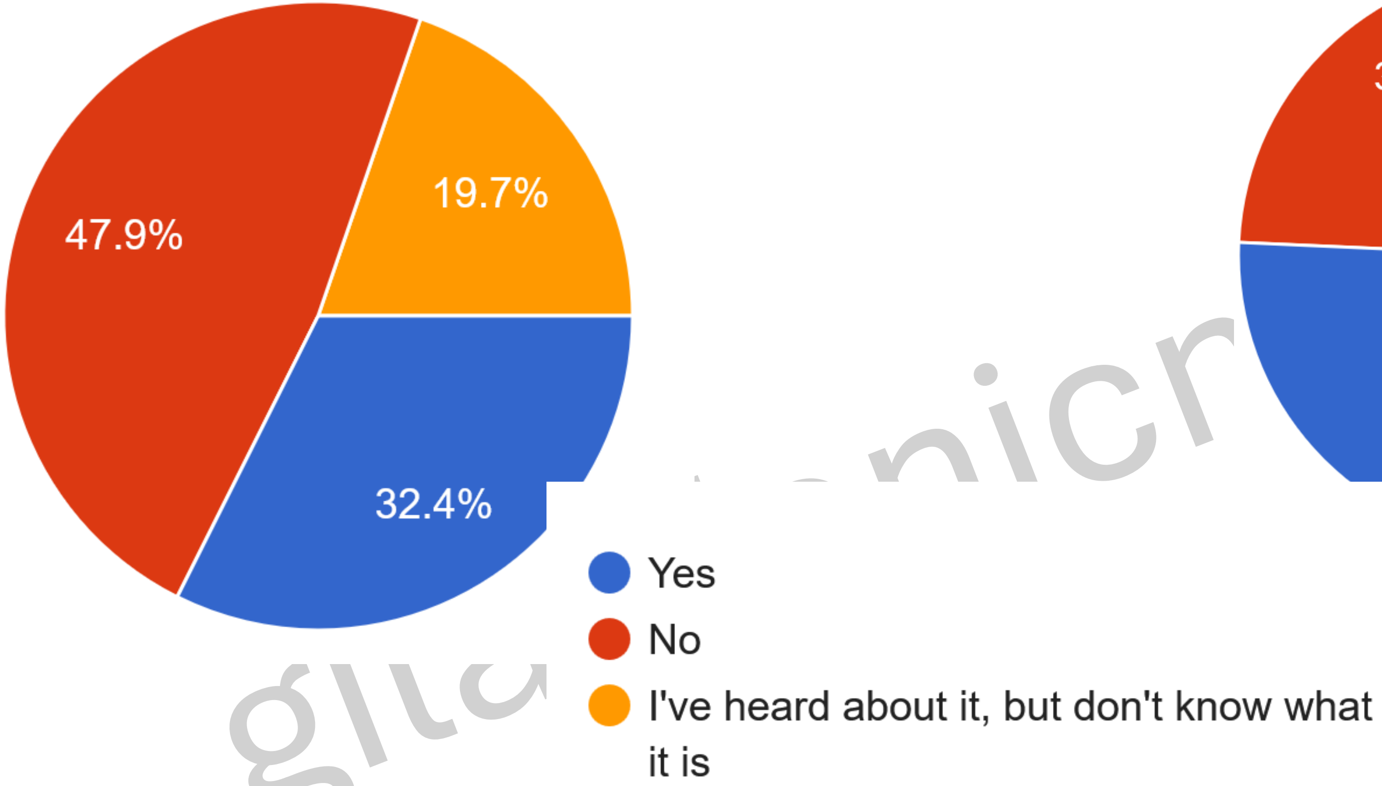
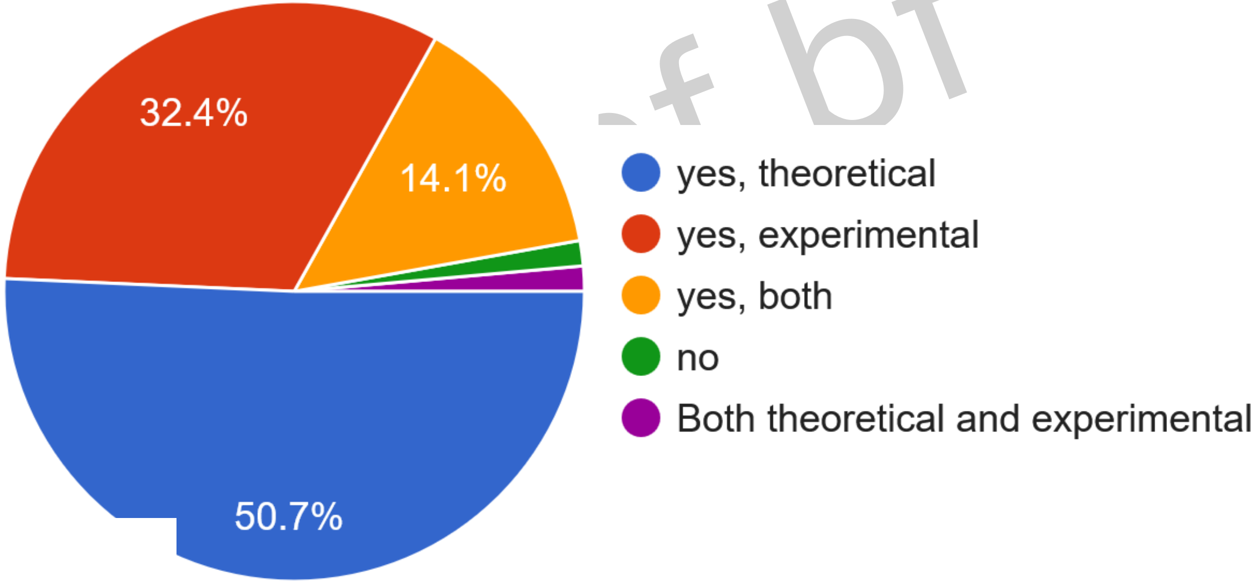
What about you?





Lab jargon, implementation strategies and challenges, etc.

The course

- Spin-photon interfaces, their applications and the current contenders
- Some demonstrations:
  - The NV center in diamond: a **prototypical system (not the best!)** with **demonstrations** in the three second-generation **quantum technologies**
  - Quantum communication protocols with solid state quantum memories
- What makes a good platform for implementation of each quantum technology?
- What are the main outstanding experimental challenges?

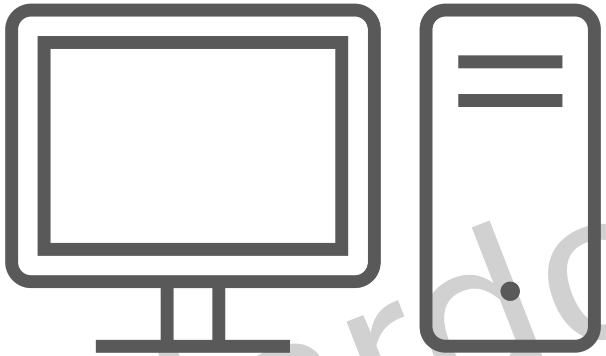
Agenda

- Wednesday (06/08/2025) – Introduction: the need for spin-photon interfaces, examples of solid state spin-photon interfaces, the NV system in diamond
- Thursday (07/08/2025) – The NV system in diamond: spin control protocols and implementation as quantum sensing and quantum computing platform.
- Saturday (09/08/2025) – Quantum communication demonstrations using the NV and alternative systems.

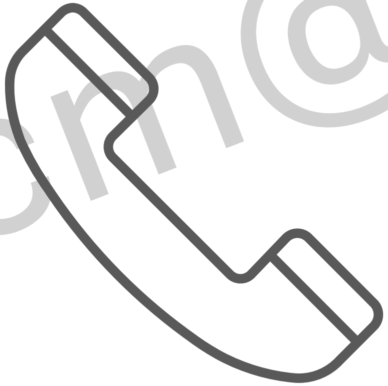
- Second generation quantum technologies

SUPERPOSITION: $|\psi\rangle = \cos\left(\frac{\theta}{2}\right)|0\rangle + e^{i\phi}\sin\left(\frac{\theta}{2}\right)|1\rangle$

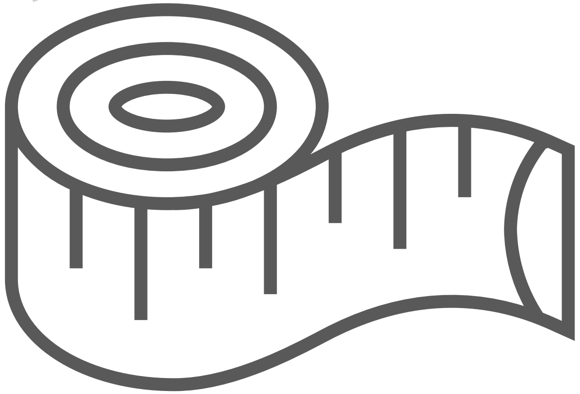
ENTANGLEMENT: $|\psi_{A,B}\rangle = |0_A 0_B\rangle + |1_A 1_B\rangle$



Quantum Computing

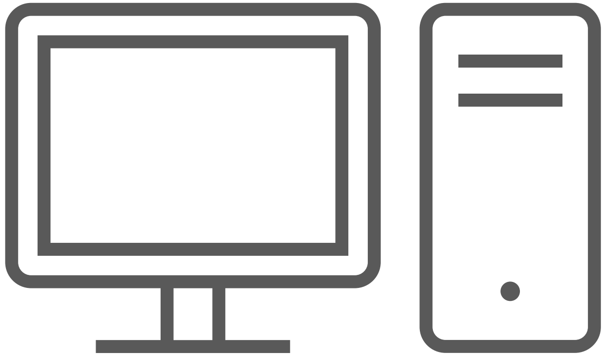


Quantum Communication

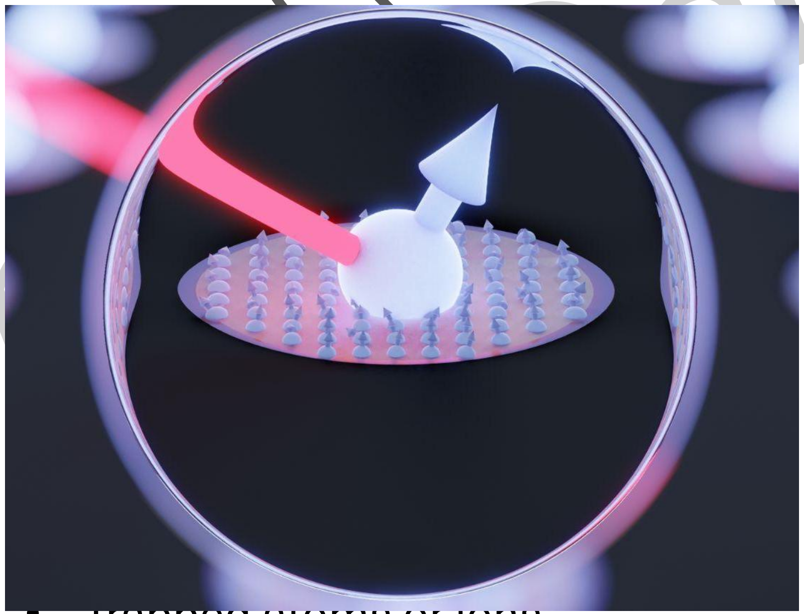


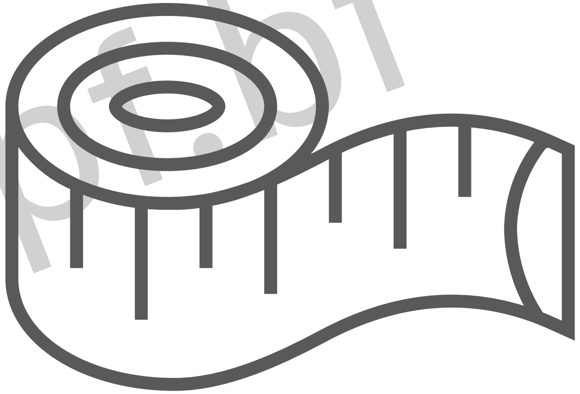
Quantum Sensing

What are the platforms being considered?



Quantum memories with optical access





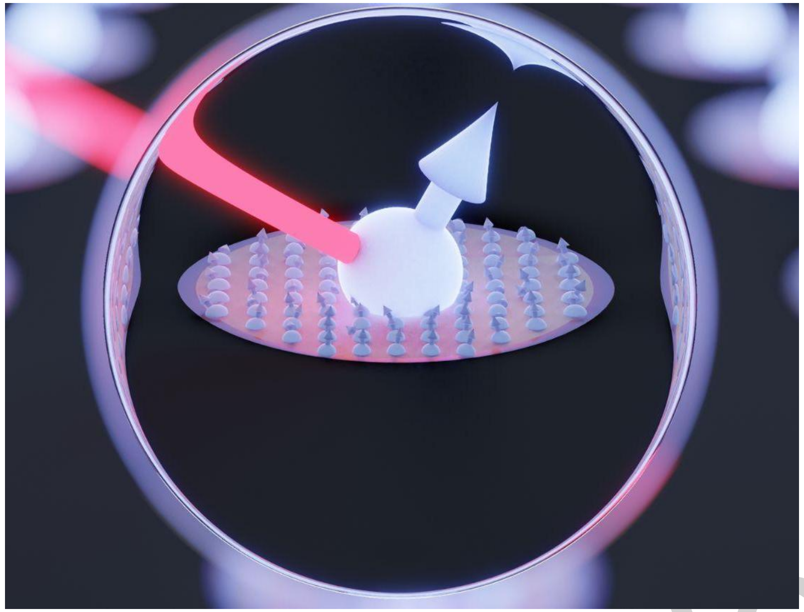
- Superconducting Devices
- Si Quantum Dots
- Trapped atoms or ions
- Nuclear Spins
- Photons
- ...

- Trapped atoms or ions

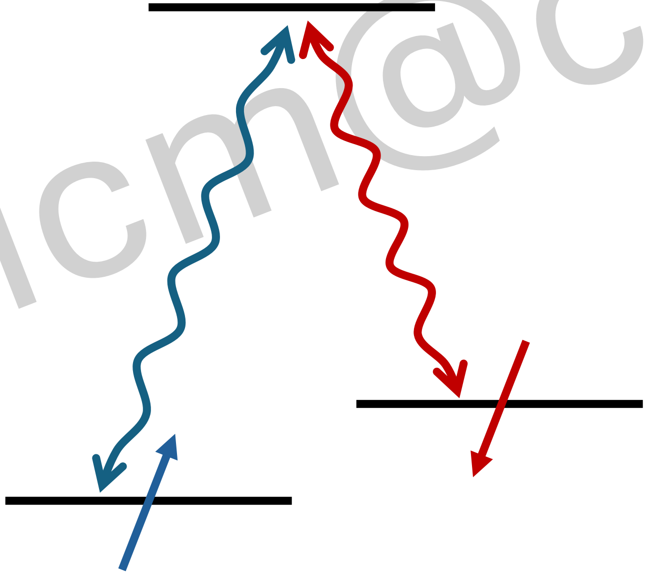
- Atomic vapor cells
- Trapped atoms or ions
- SQUIDs
- Defects in solids...

Systems with some quantized degree of freedom, relatively isolated from interactions with their environment, and amenable to quantum control

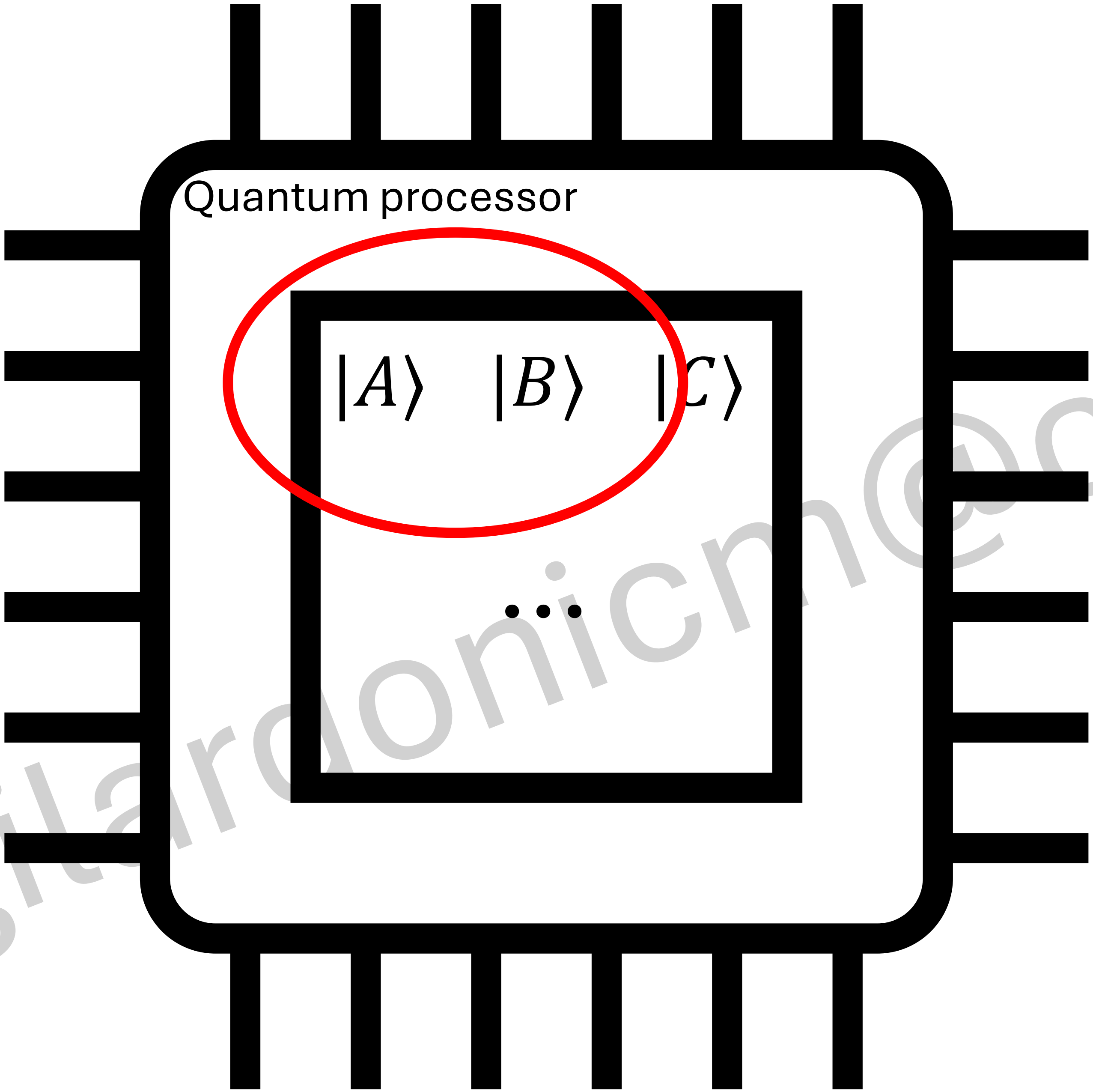
Quantum memories with optical access

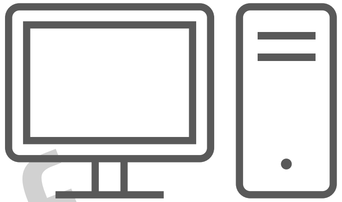


- Systems where I can **entangle** a local degree of freedom (spin, electronic state, etc.) to the degree of freedom of a single photon (time bin, polarization, etc)

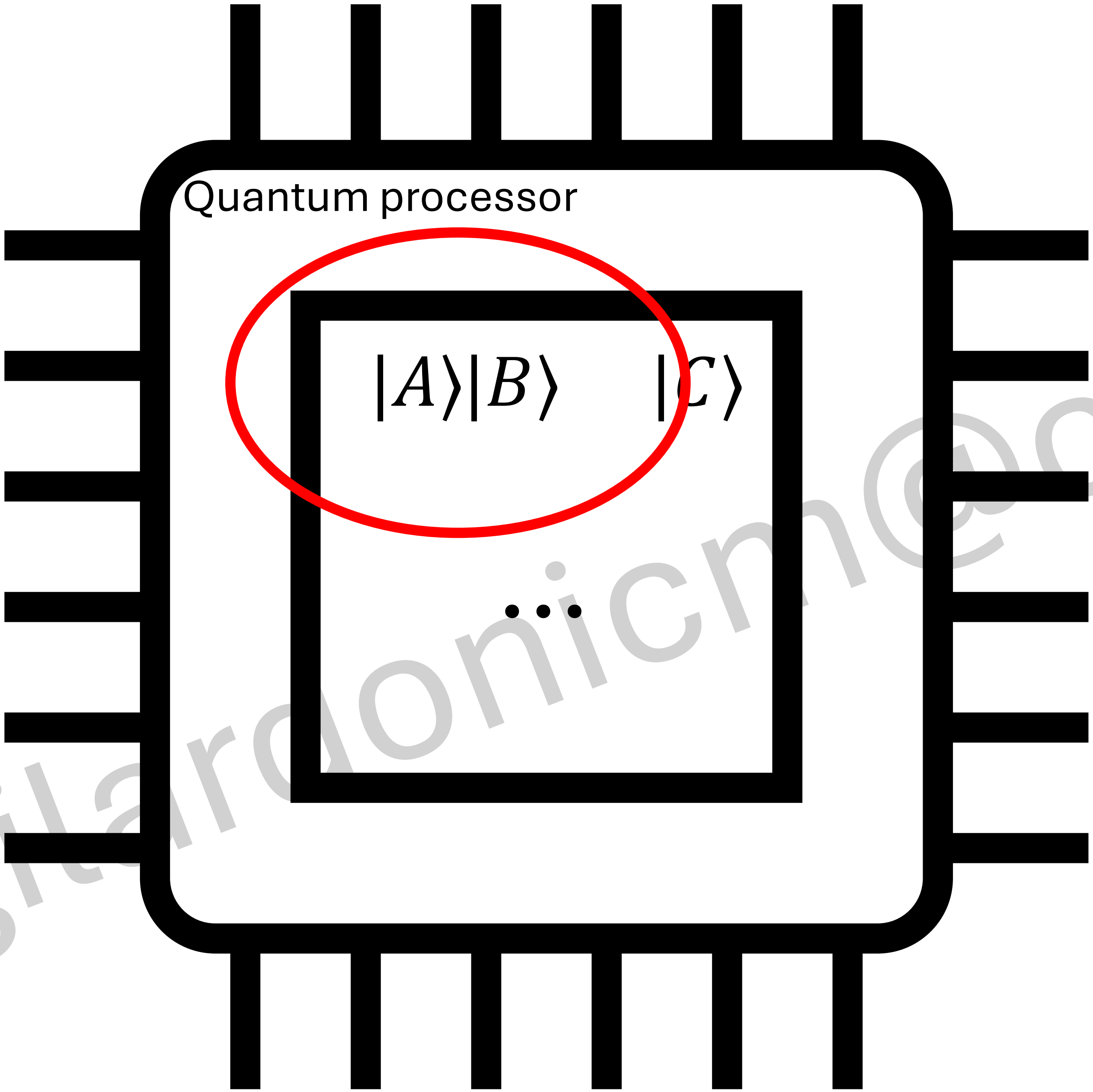


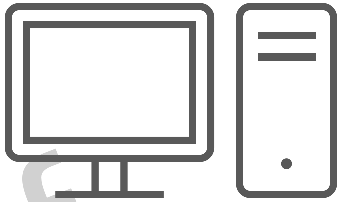
The emitted photon depends on the state of the local qubit (and the state of the qubit depends on the photon absorbed!)

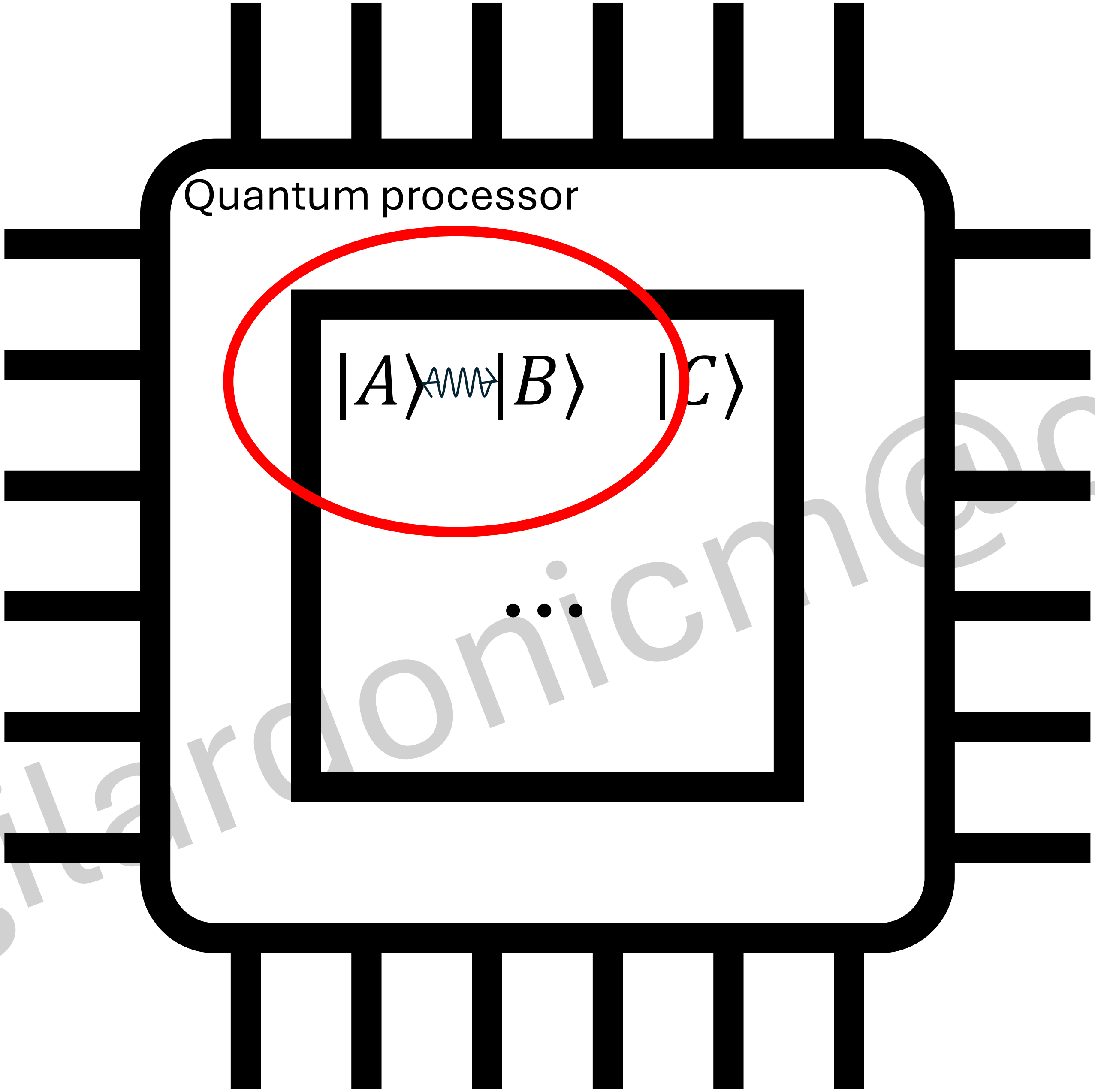


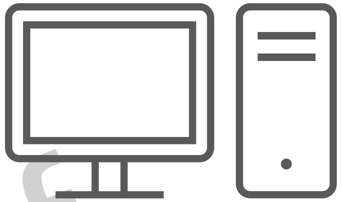


Quantum computing

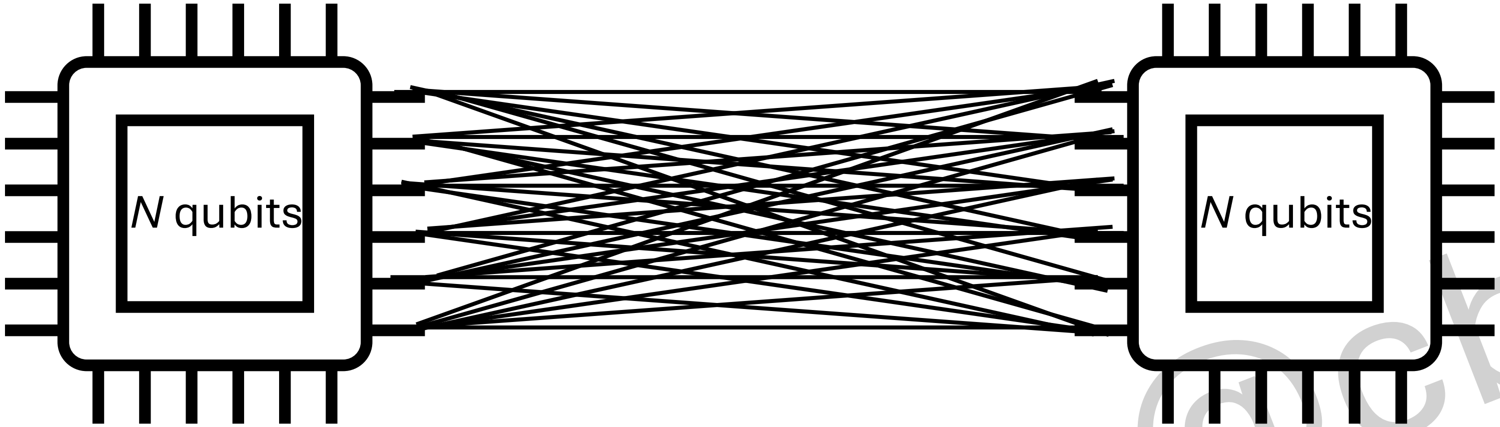

Quantum processor
$|A\rangle|B\rangle$
$|C\rangle$
$\dots$

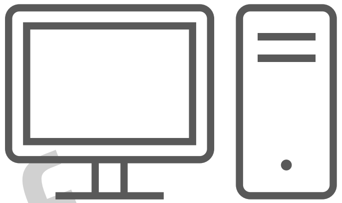

Quantum computing



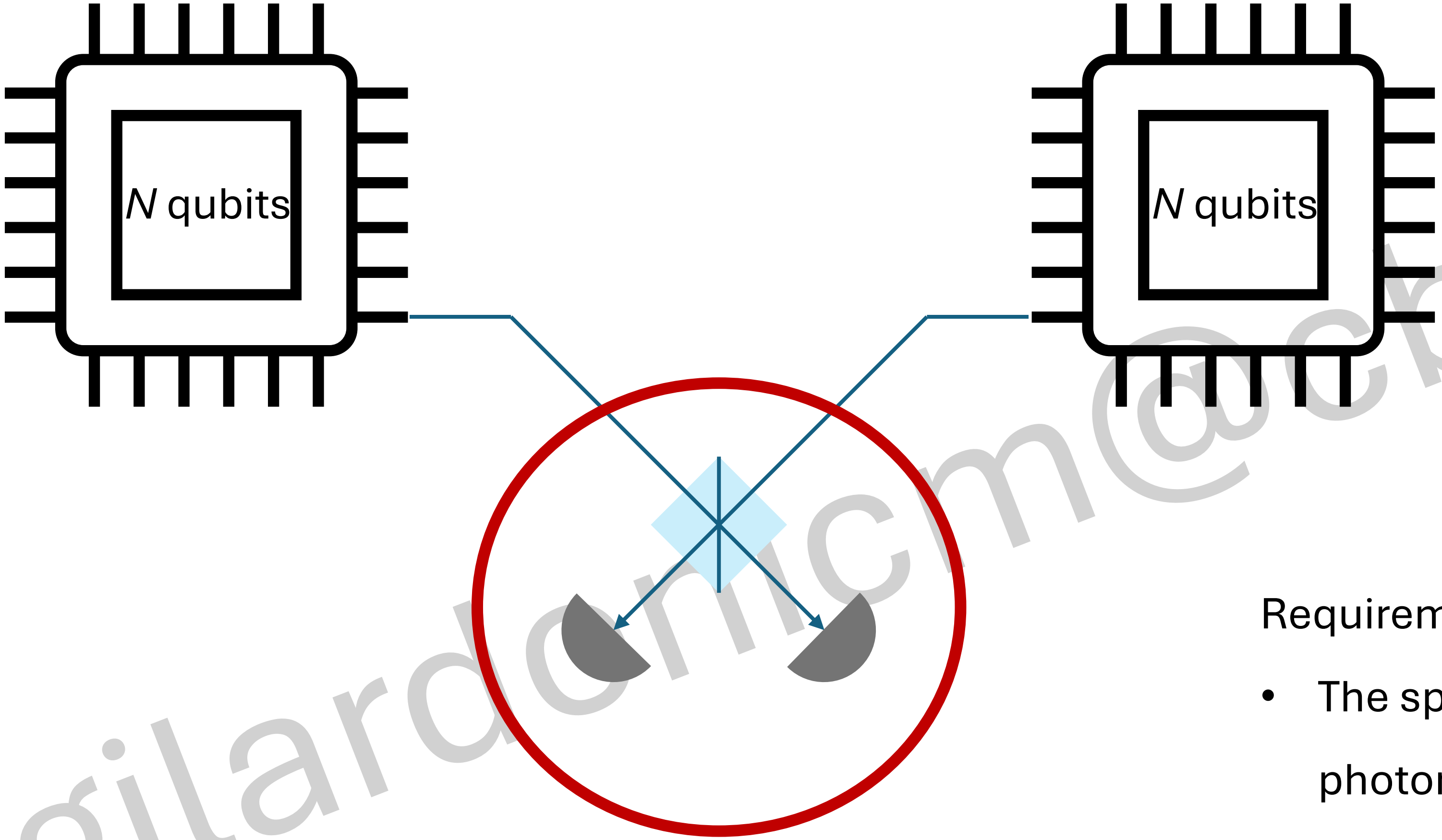


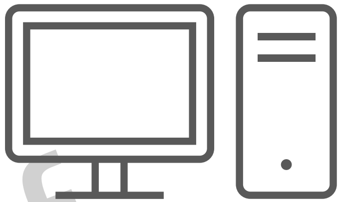
Quantum
computing





Quantum
computing





Quantum
computing

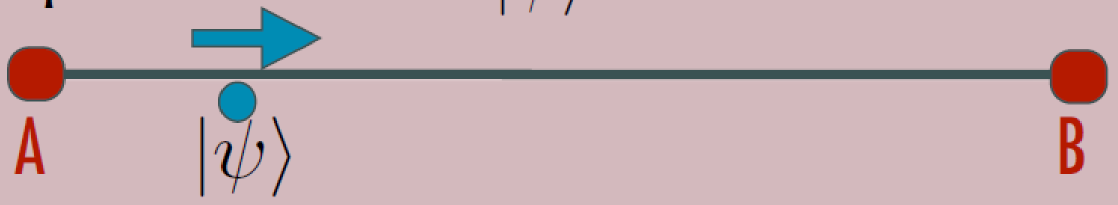
Requirements:

- The spin has an efficient interface – emits photons 'on demand'
- spin coherence time large enough to perform multiple gate operations

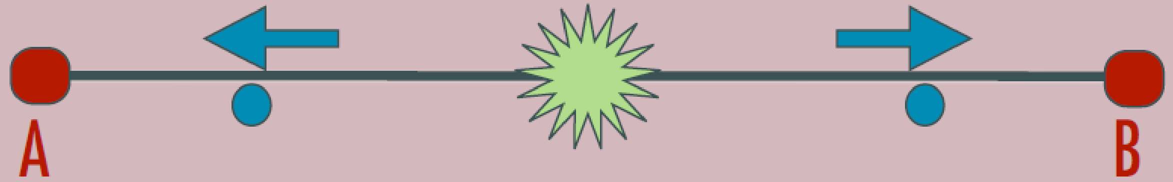
What is the role of the photons?

Quantum communication

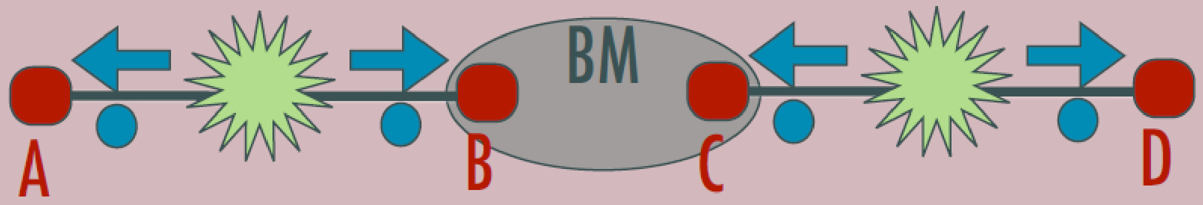
Protocol 1: Send photons in a state $|\psi\rangle$ from A to B



Protocol 2: Send one part of the state to A and the other to B



Protocol 3: Entanglement swapping:

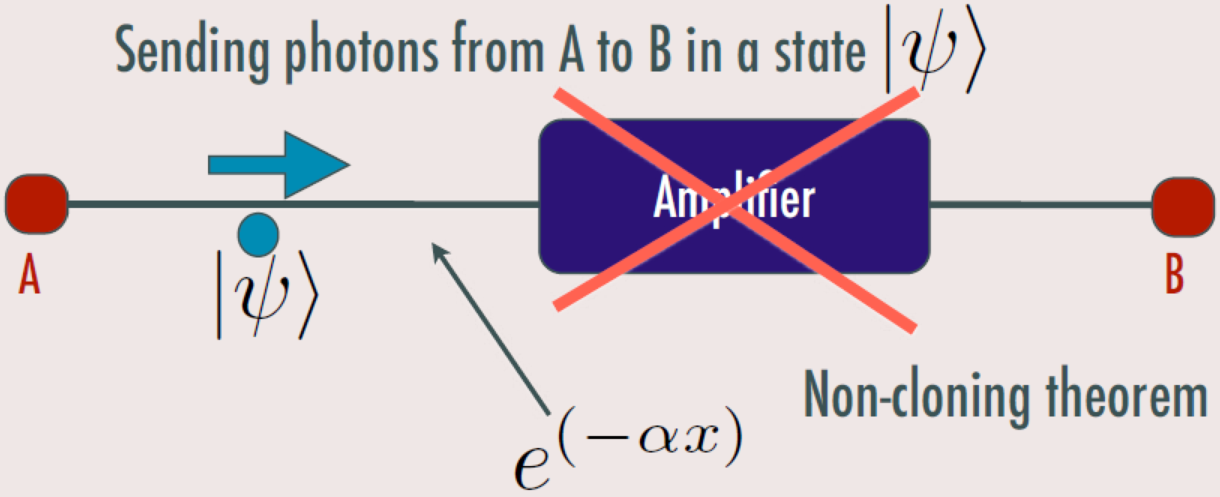


A. Ekert, Phys. Rev. Lett. **67**, 661 (1991).

Credit: Gabriel Horacio

Challenges in quantum communication

Quantum communication

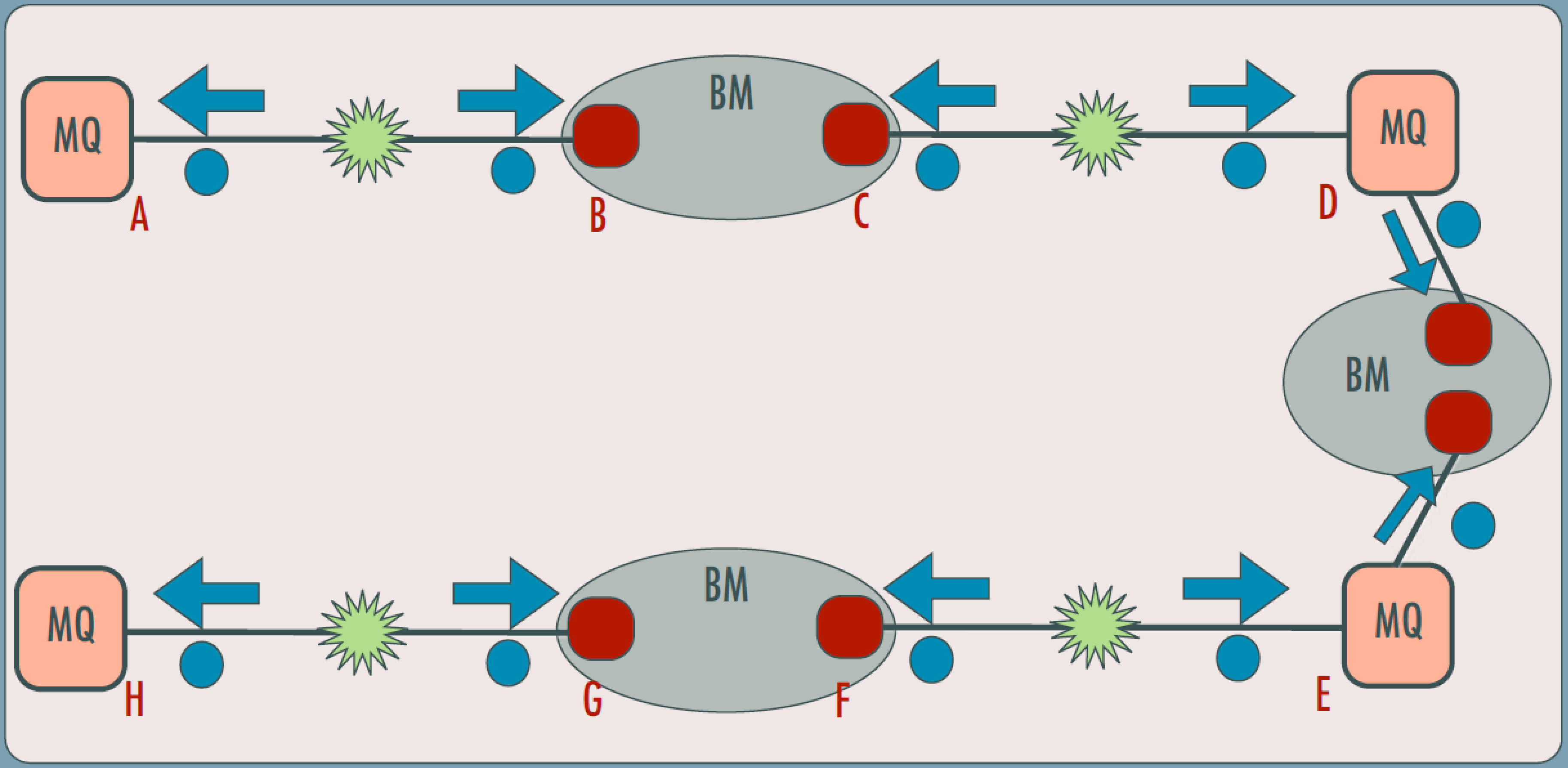


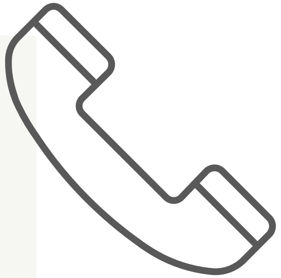
Fundamental limitation: loss in optical fibers or in free-space propagation

A piece of fiber that is 1 km long has a transmission of 95 percent.

Credit: Gabriel Horacio

Quantum Repeaters

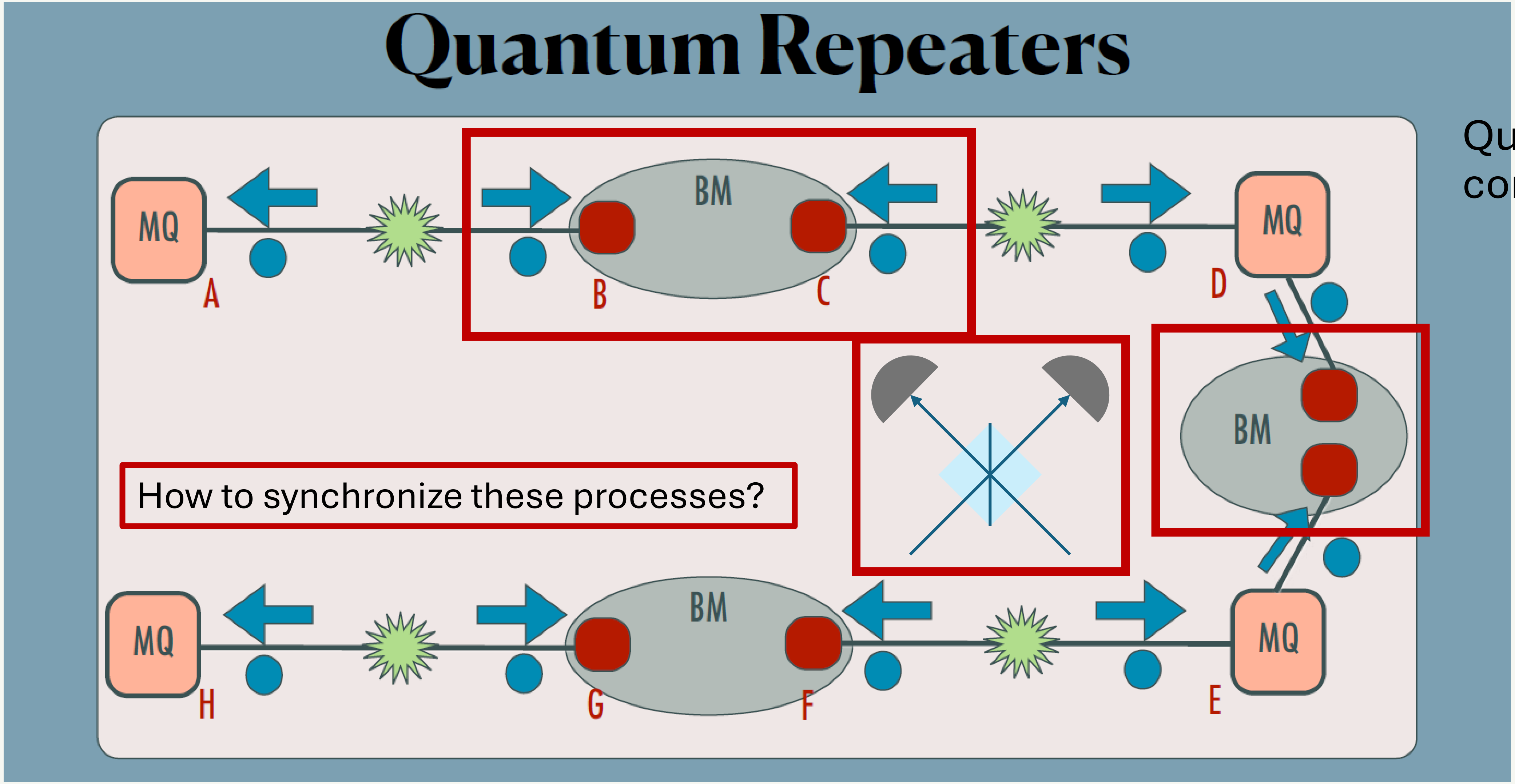


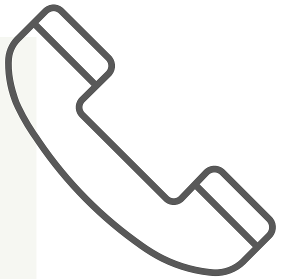


Quantum communication

N. Sangouard, C. Simon, H. De Riedmatten and N. Gisin, Rev. of Mod. Phys. **83**, 33 (2011).

Credit: Gabriel Horacio





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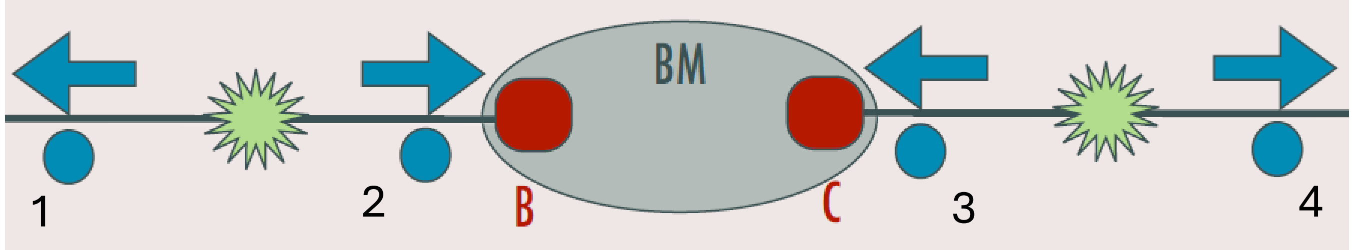
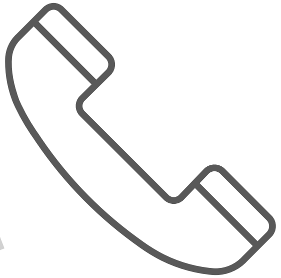
Credit: Gabriel Horacio





Quantum communication

Spin

Photon 2

Photon 3

The final state of the spin depends on the states of photons 2, 3

Bell measurement **on spin** projects photons 1 and 4 into an entangled state

Requirements:

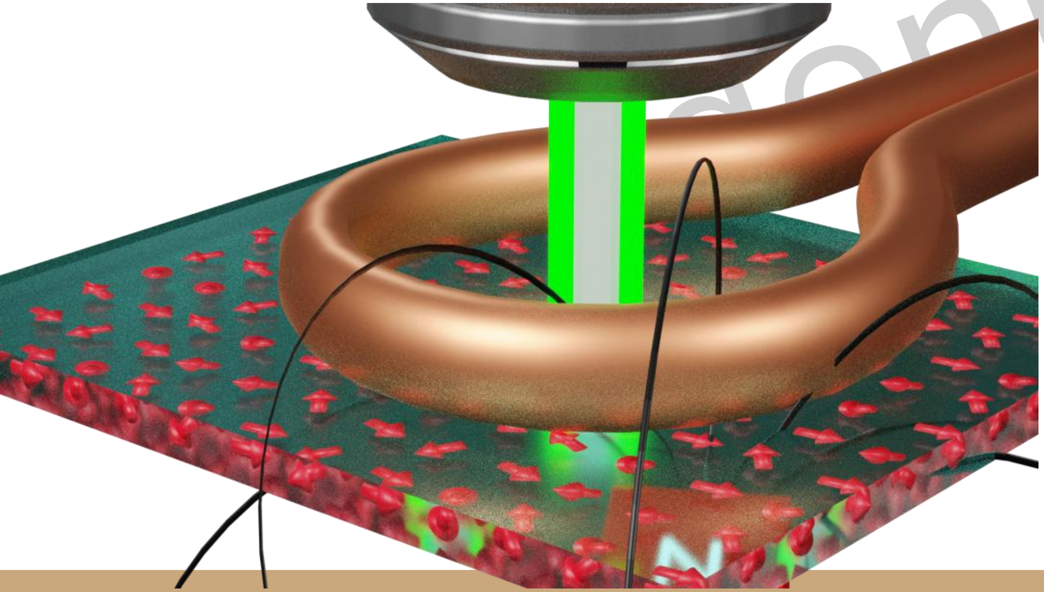
- The spin has an efficient interface (few attempts, the two photons must interact with probability close to 1)
- The coherence time of the spin must be large enough to sustain the coherent state until the arrival of the next photon:

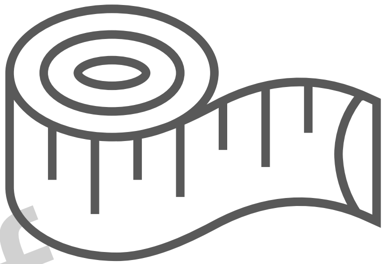
(for 10 km of fiber, $\tau \gg \frac{l_{fibra}}{c}, \tau \gg 30\ \mu s$

Quantum Sensors

$$i\hbar\frac{\partial}{\partial t}|\psi(t)\rangle = (H_0 + V(t))|\psi(t)\rangle$$

The evolution of coherent quantum states provides information about local fields (AC and DC)





Quantum sensing

Requirements:

- Non-invasive reading (via sensor illumination, for example)
- Versatility of operation: the sensor must be able to be initialized, function in different environments, etc
- The sensor is sensitive to external stimuli
- The coherence time of the sensor must be large enough to allow phase acquisition due to very small stimuli

Agenda

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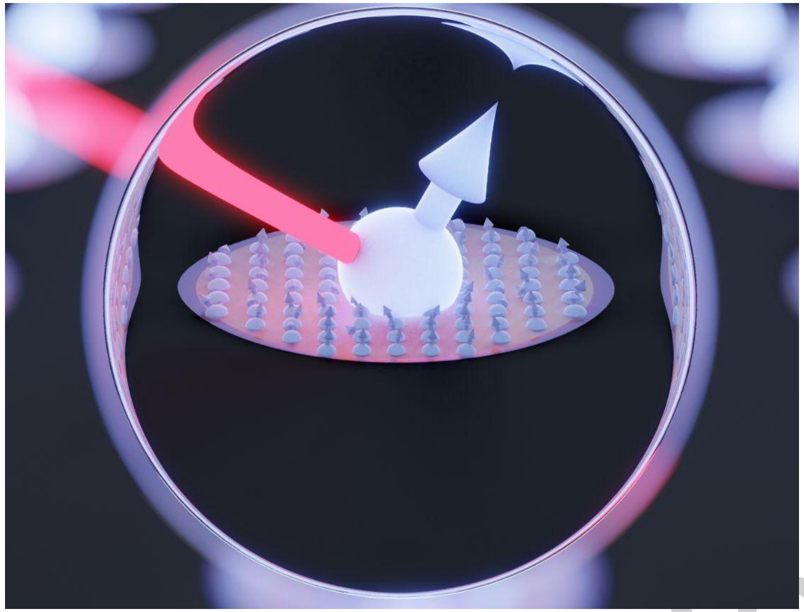
- Saturday (09/08/2025) – Quantum communication demonstrations using the NV and alternative systems.



- **(SA) Quantum dots in III-V semiconductors (GaAs, InGaAs, etc.)**
- Rydberg systems
- Trapped atoms or ions
- **Rare earth impurities**
- **Defects in solids**

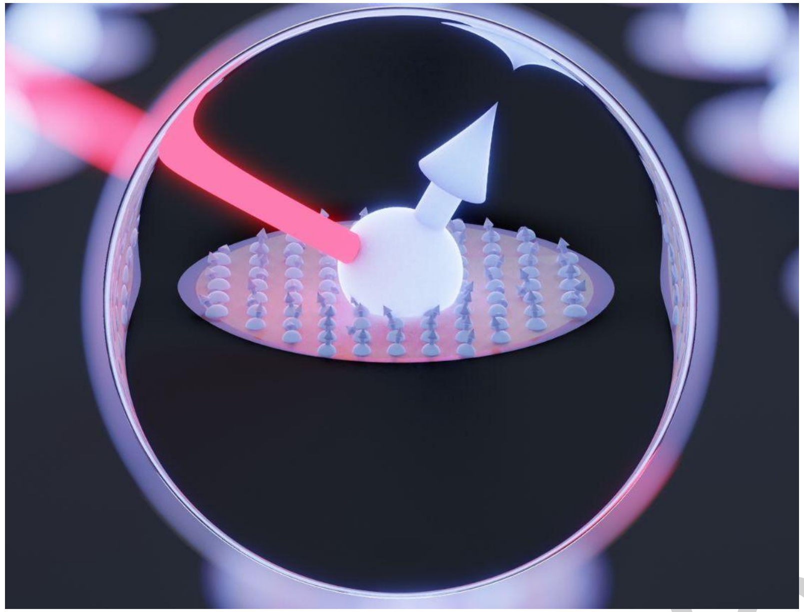
How to trap ions (for an *actual* quantum optician)

A trap
A vacuum chamber
Atoms
An ionization method
An observation method

How to trap ions (for a condensed matter scientist)

Put them inside a crystal

And then ensure that the Fermi level is correct, that you can couple light in and out, that it's isolated from crystalline degrees of freedom, etc etc.



- **(SA) Quantum dots in III-V semiconductors (GaAs, InGaAs, etc.)**
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- **Defects in solids**

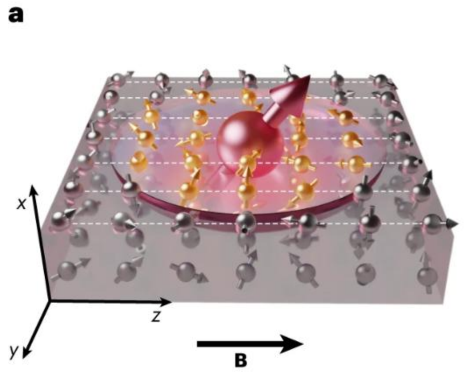
Spin requirements:

Long coherence times, (unique) addressability

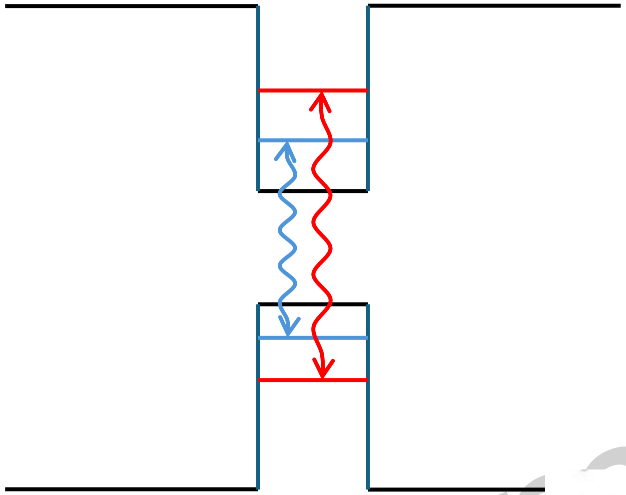
Optical requirements:

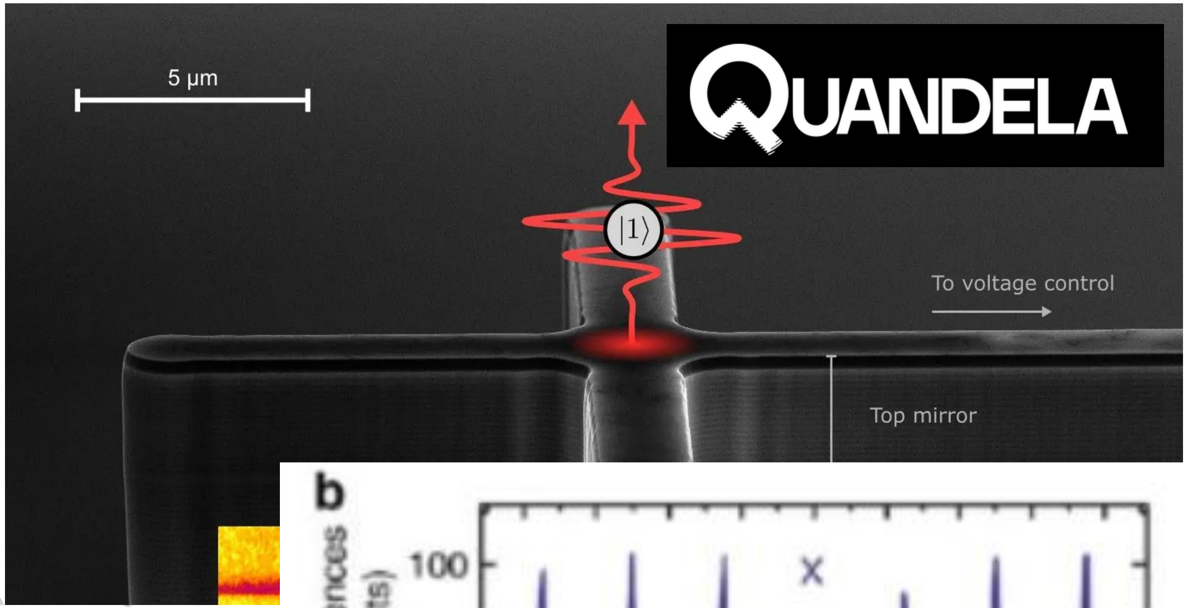
On-demand coherent photons (source functions as a generator of single, indistinguishable photons) that can be entangled with spin

Quantum dots in III-V materials



Nature Nanotechnology **18**, 257–263 (2023)



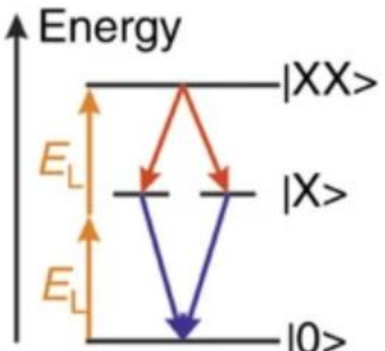


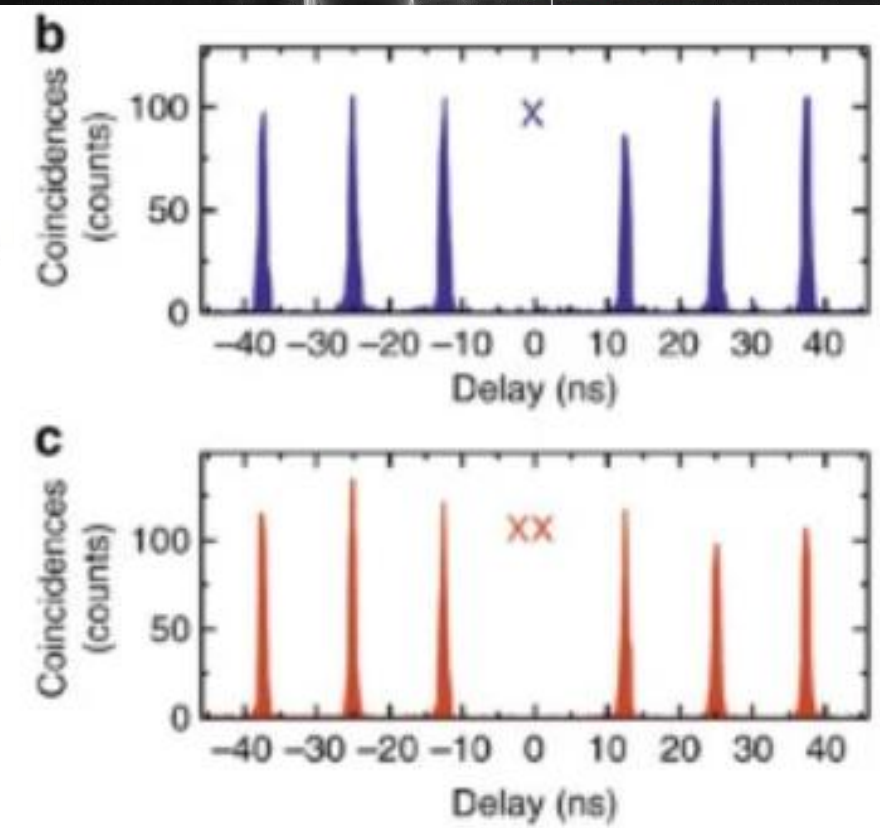
Article | Open access | Published: 26 May 2017

Highly indistinguishable and strongly entangled photons from symmetric GaAs quantum dots

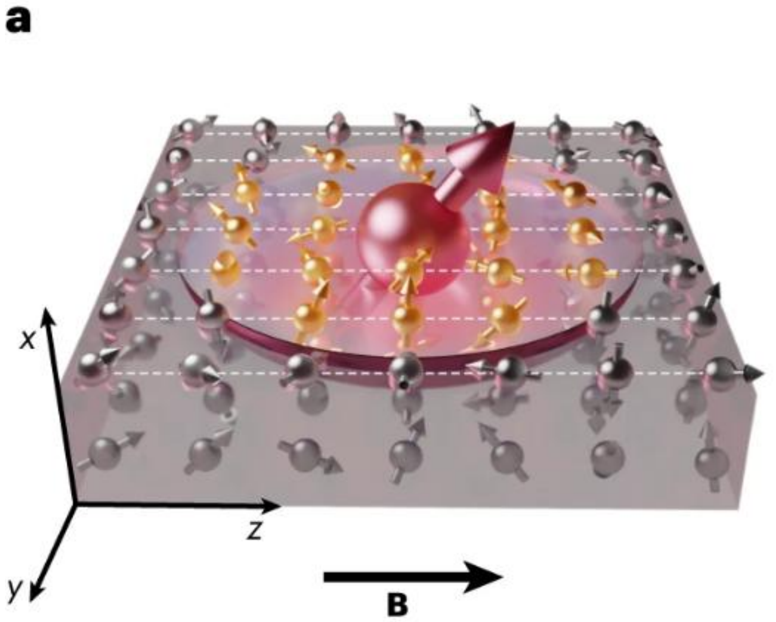
Daniel Huber, Marcus Reindl, Yongheng Huo, Huiying Huang, Johannes S. Wildmann, Oliver G. Schmidt, Armando Rastelli & Rinaldo Trotta

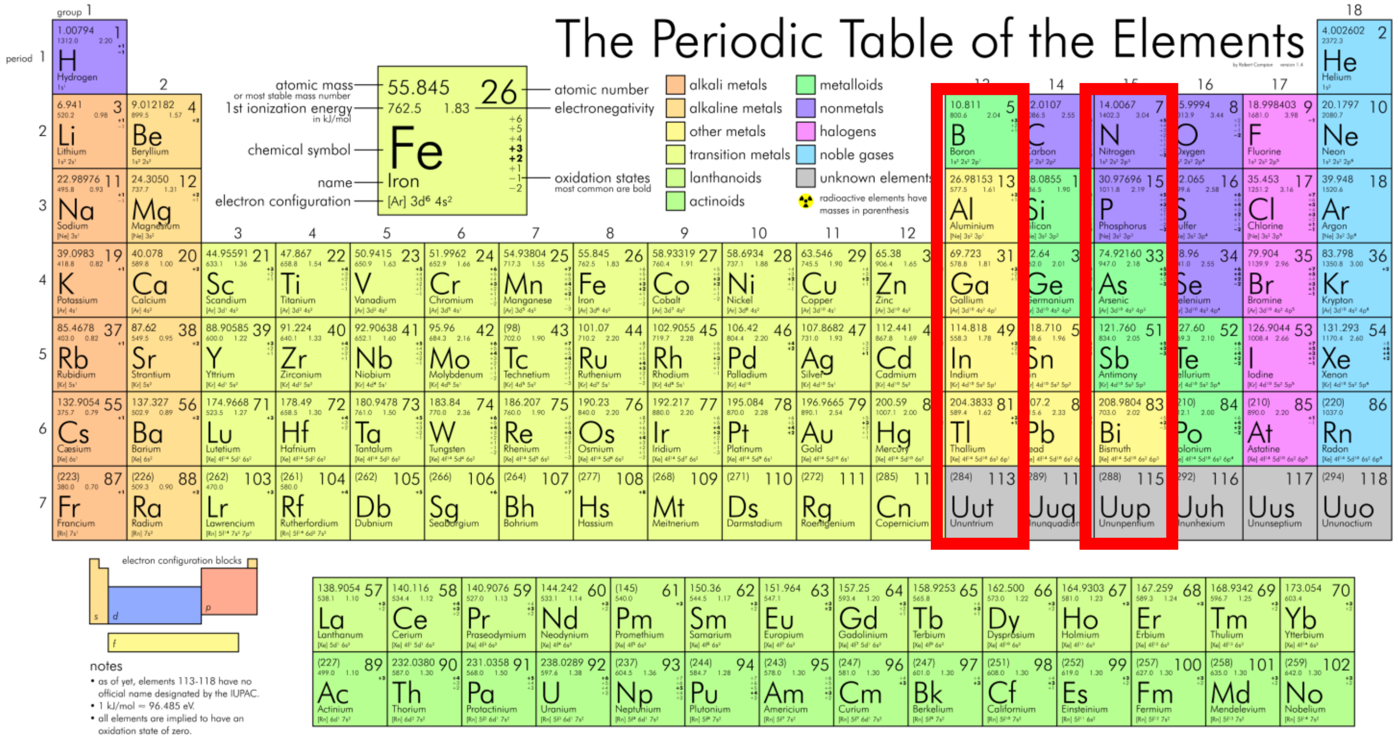
Nature Communications **8**, Article number: 15506 (2017) | Cite this article





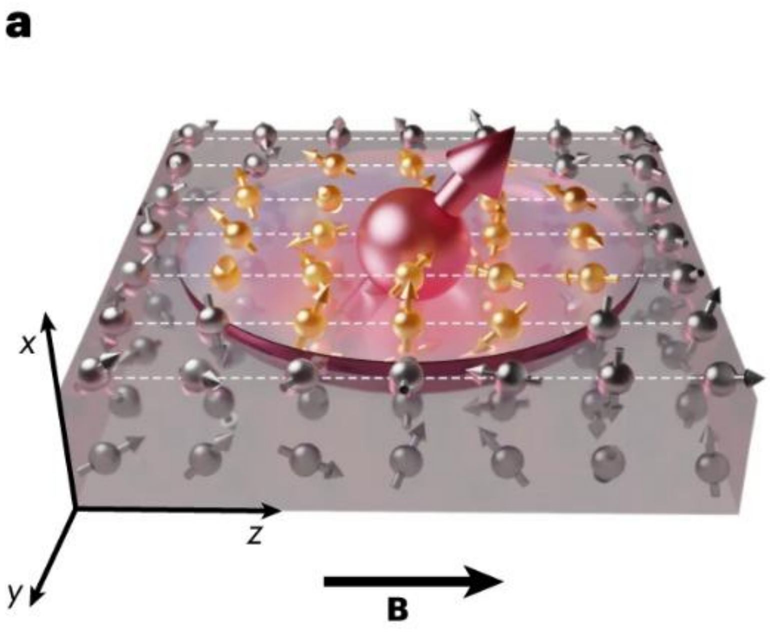
Quantum dots in III-V materials





Nature Nanotechnology **18**, 257–263 (2023)

Quantum dots in III-V materials

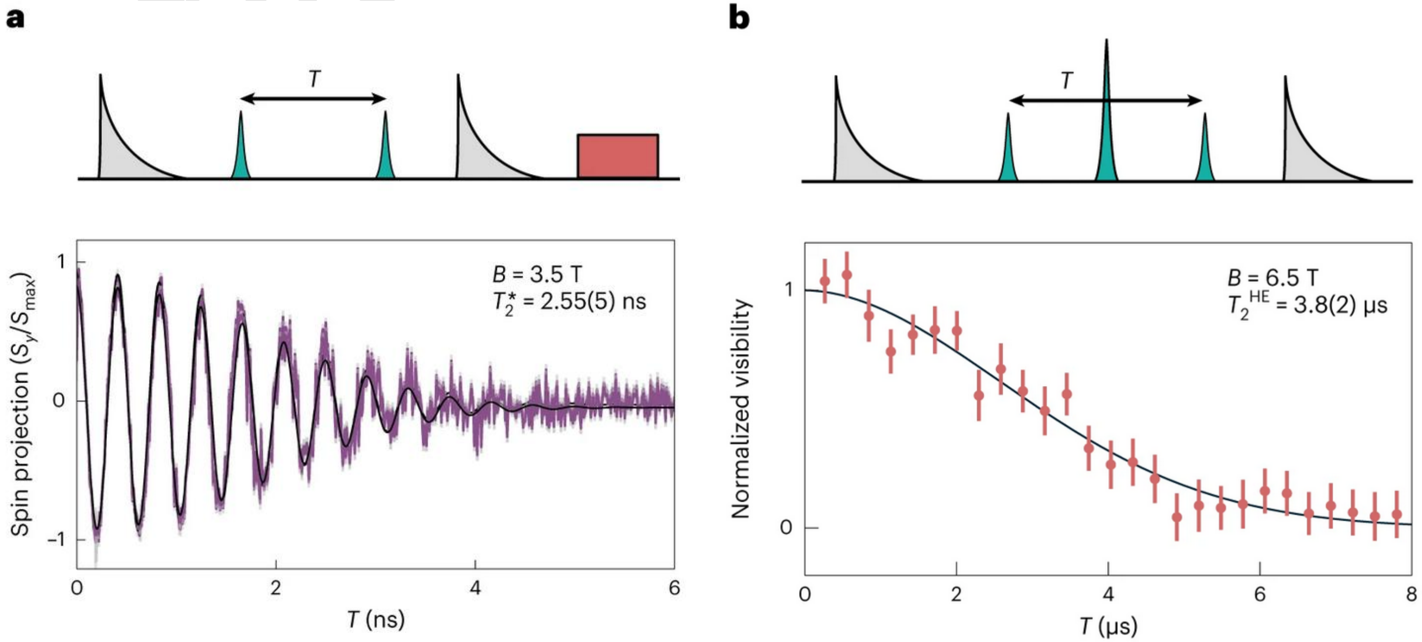


Article | Published: 26 January 2023

Ideal refocusing of an optically active spin qubit under strong hyperfine interactions

Leon Zaporski, Noah Shofer, Jonathan H. Bodey, Santanu Manna, George Gillard, Martin Hayhurst Appel, Christian Schimpf, Saimon Filipe Covre da Silva, John Jarman, Geoffroy Delamare, Gunhee Park, Urs Haeusler, Evgeny A. Chekhovich, Armando Rastelli, Dorian A. Gangloff, Mete Atatüre & Claire Le Gall

Nature Nanotechnology **18**, 257–263 (2023) | Cite this article



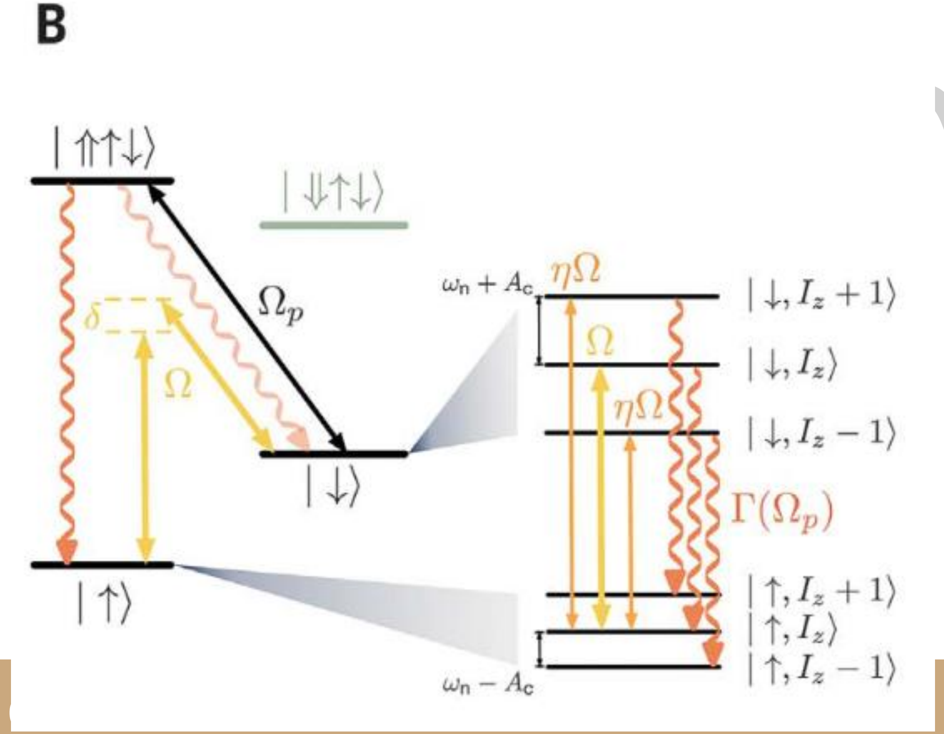
Quantum dots in III-V materials

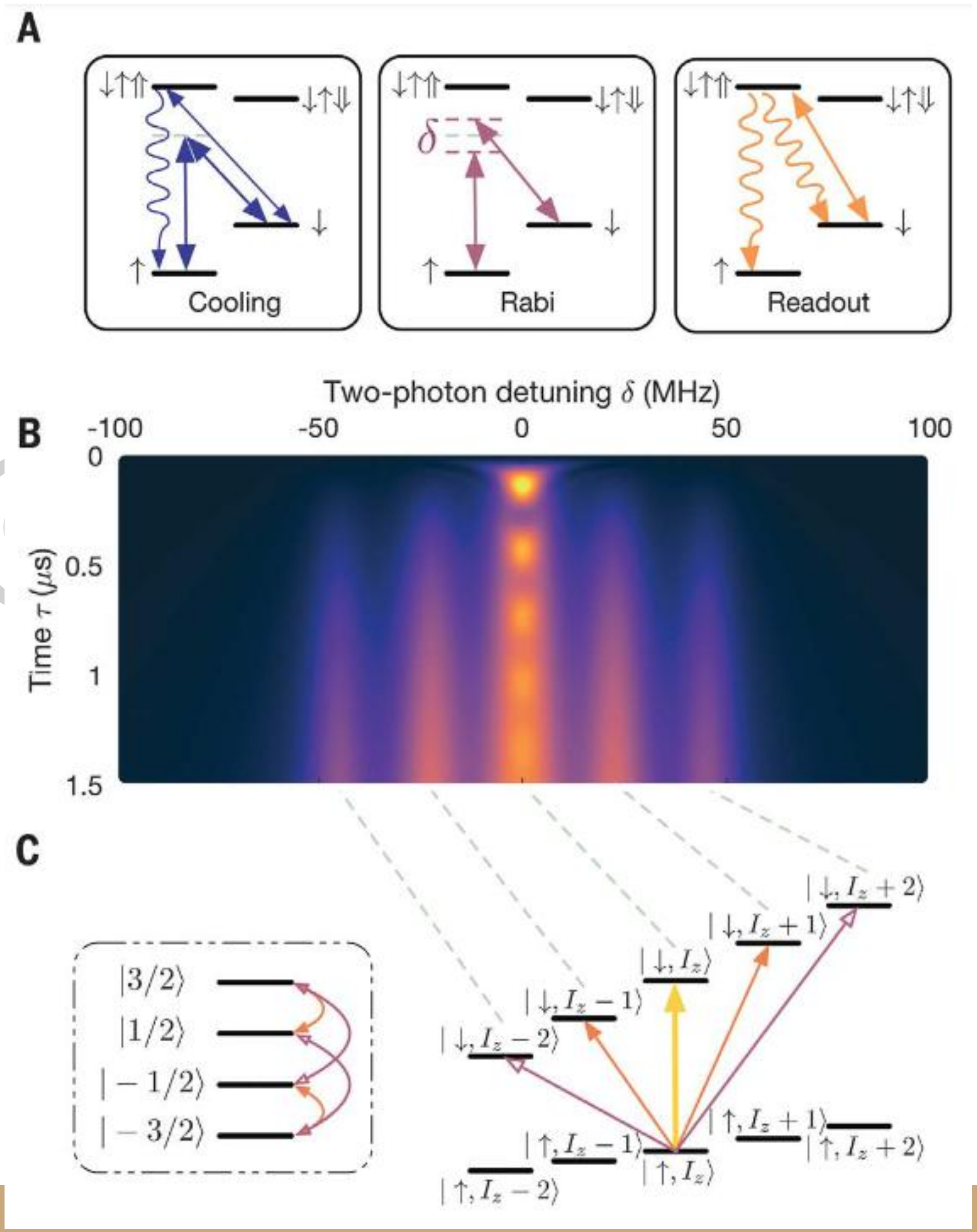
REPORT

QUANTUM OPTICS

Quantum interface of an electron and a nuclear ensemble

D. A. Gangloff[1]*†, G. Éthier-Majcher[1]*‡, C. Lang[1], E. V. Denning[1,2], J. H. Bodey[1], D. M. Jackson[1], E. Clarke[3], M. Hugues[4], C. Le Gall[1], M. Atatüre[1]†



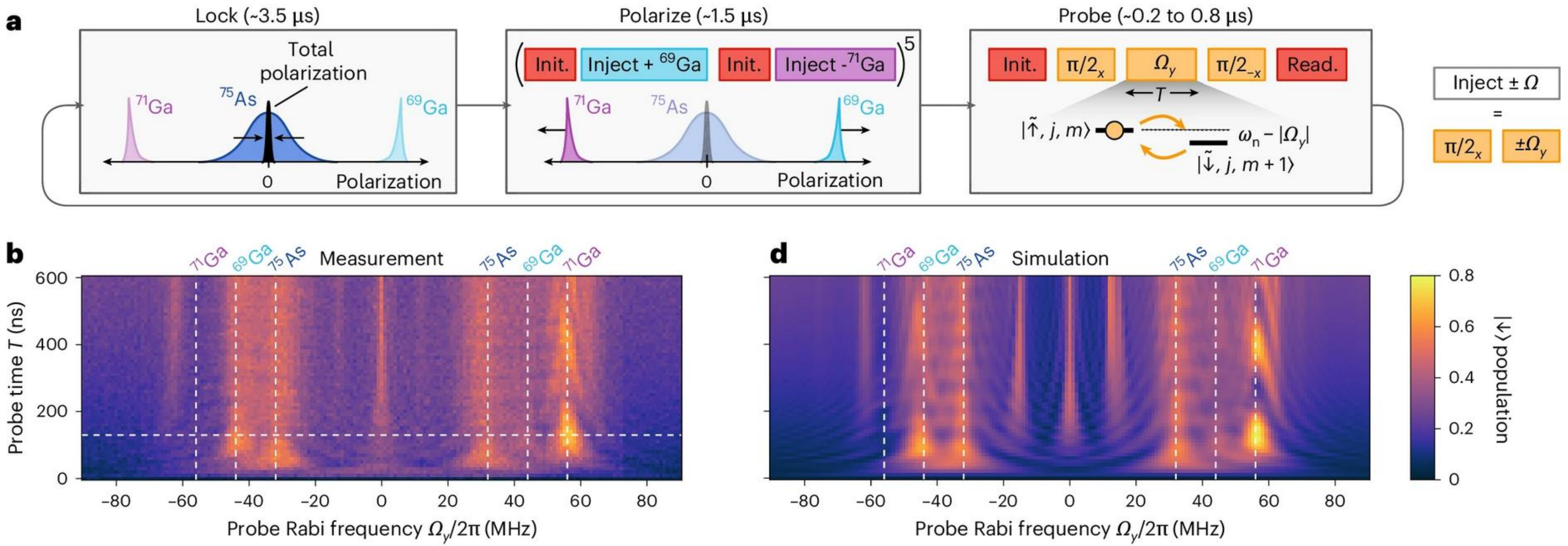


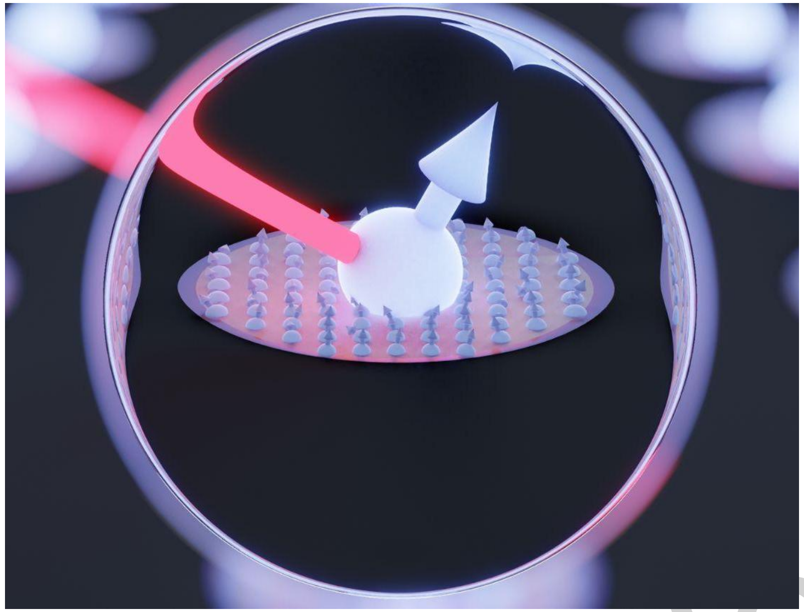
Article | Open access | Published: 24 January 2025

A many-body quantum register for a spin qubit

Martin Hayhurst Appel, Alexander Ghorbal, Noah Shofer, Leon Zaporski, Santanu Manna, Saimon Filipe Covre da Silva, Urs Haeusler, Claire Le Gall, Armando Rastelli, Dorian A. Gangloff & Mete Atatüre

Nature Physics 21, 368–373 (2025) | Cite this article





- **(SA) Quantum dots in III-V semiconductors (GaAs, InGaAs, etc.)**
- Rydberg systems
- Trapped atoms or ions
- **Rare earth impurities**
- **Defects in solids**

Spin requirements:

Long coherence times, (unique) addressability

Optical requirements:

On-demand coherent photons (source functions as a generator of single, indistinguishable photons) that can be entangled with spin

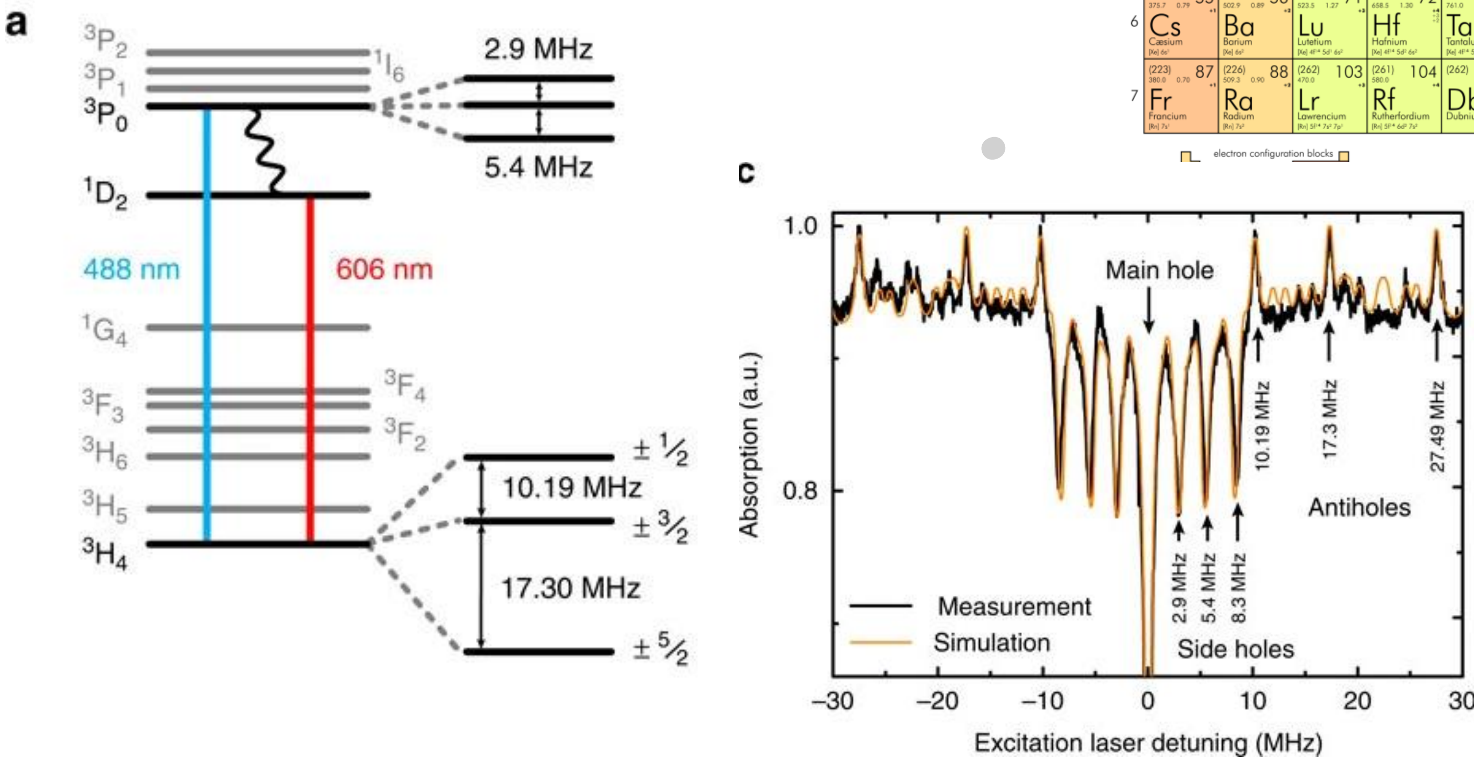
Rare earth atoms and ions in solids

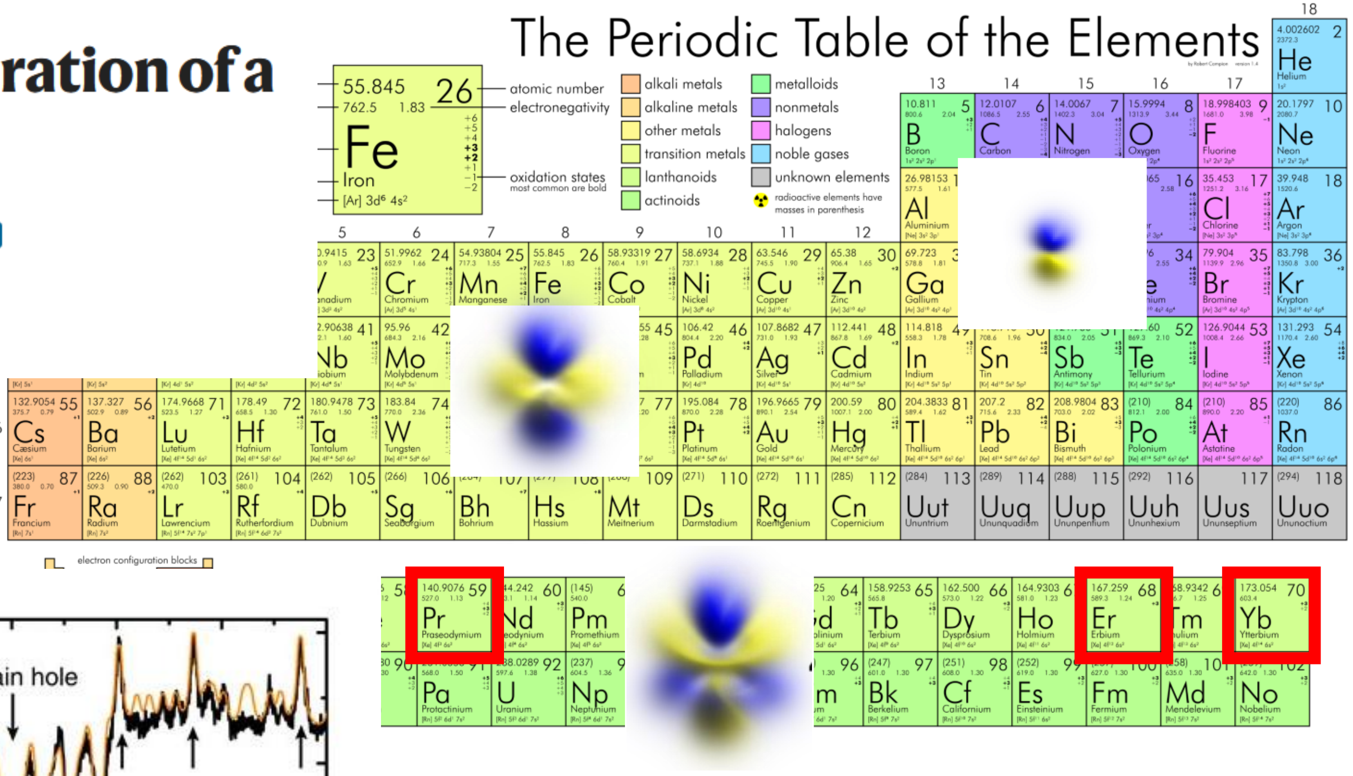
Article | Published: 11 April 2014

Spectroscopic detection and state preparation of a single praseodymium ion in a crystal

T. Utikal, E. Eichhammer, L. Petersen, A. Renn, S. Götzinger & V. Sandoghdar

Nature Communications 5, Article number: 3627 (2014) | Cite this article





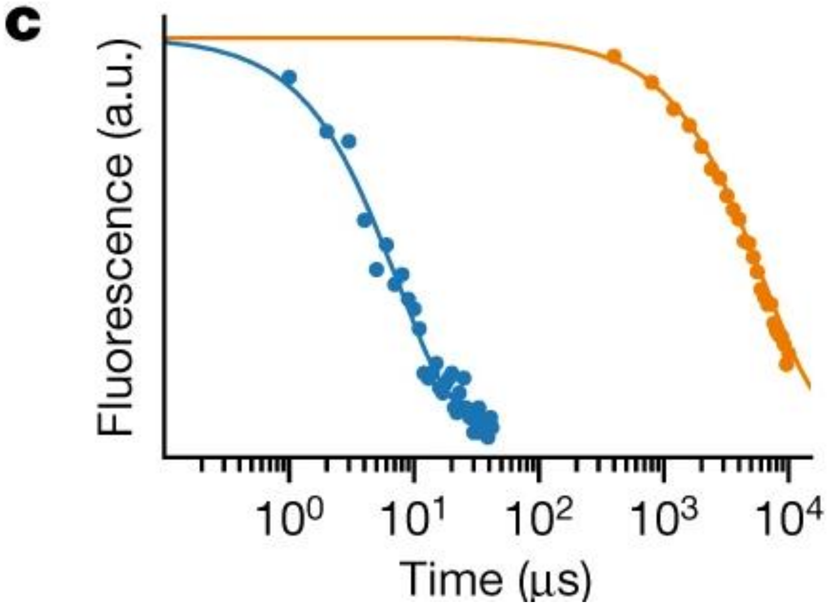
Rare earth atoms and ions in solids

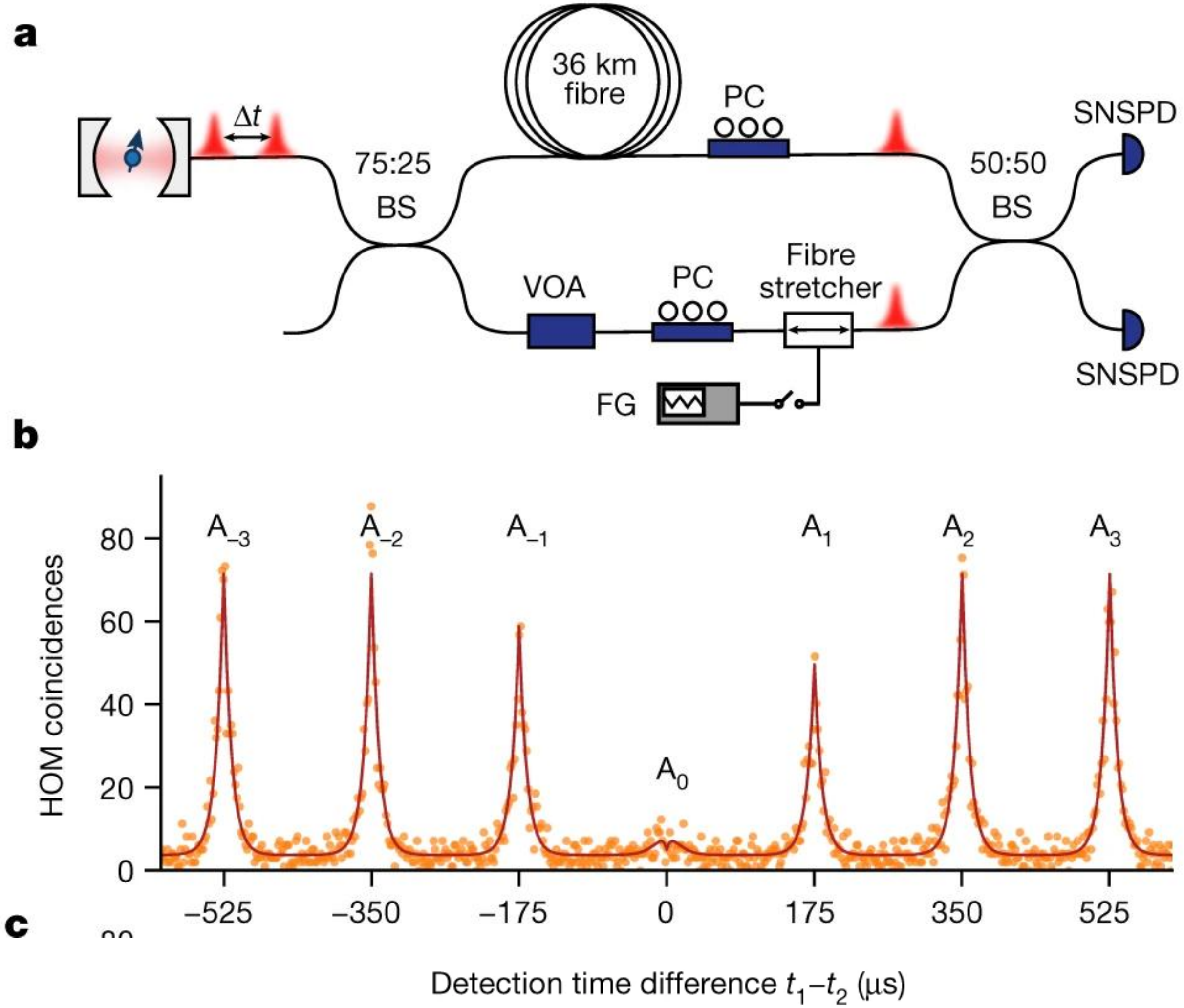
Article | Published: 30 August 2023

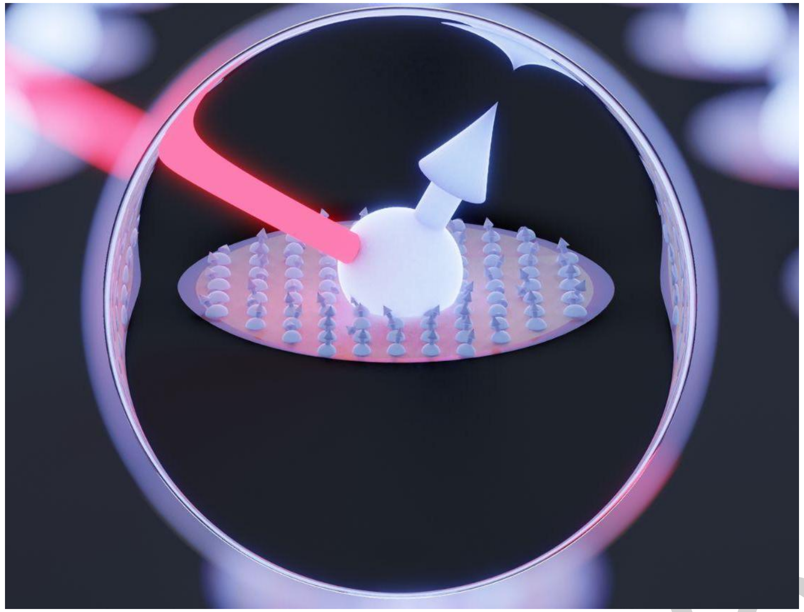
Indistinguishable telecom band photons from a single Er ion in the solid state

Salim Ourari, Łukasz Dusanowski, Sebastian P. Horvath, Mehmet T. Uysal, Christopher Stevenson, Mouktik Raha, Songtao Chen, Robert J. Cava, Nathalie P. de Leon & Jeff D.

Nature 620, 977–981 (2023) | Cite this article







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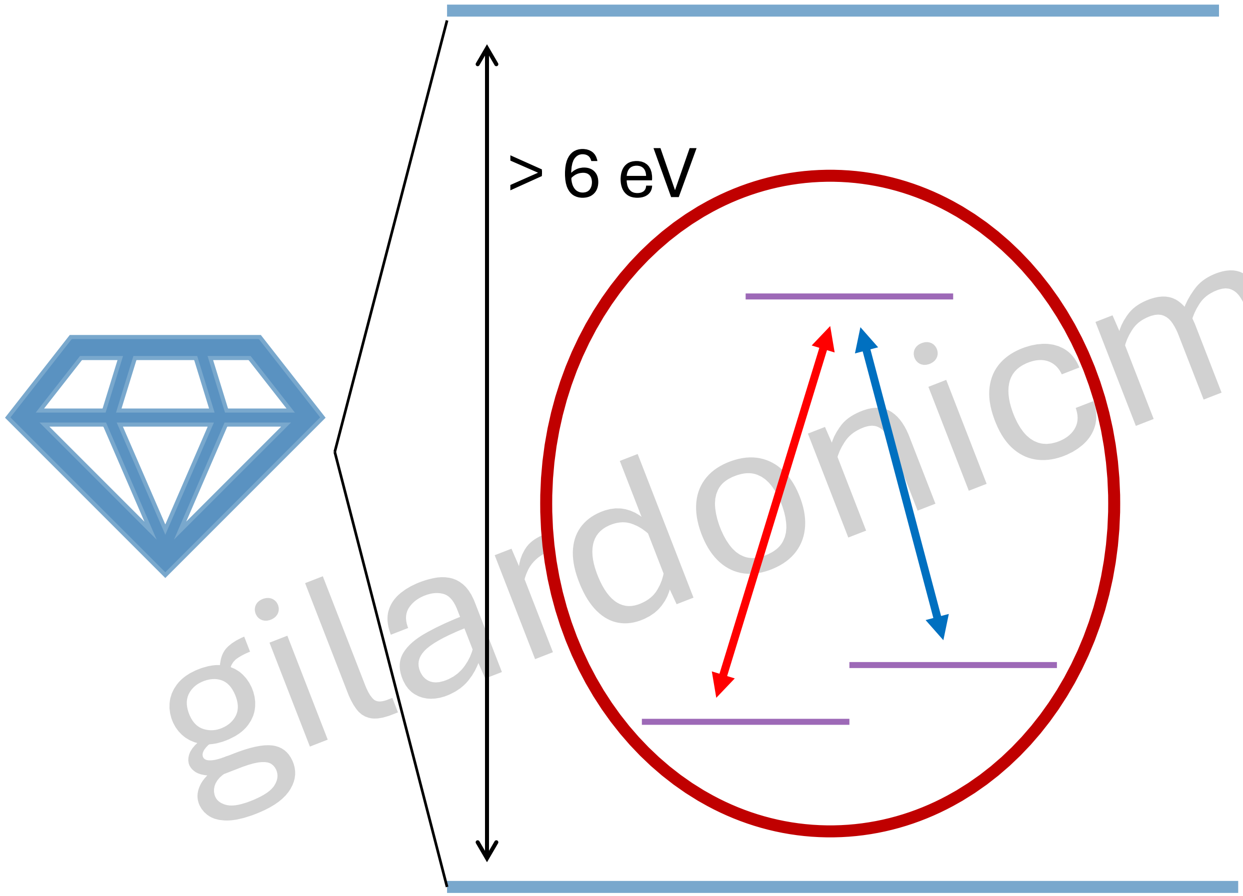
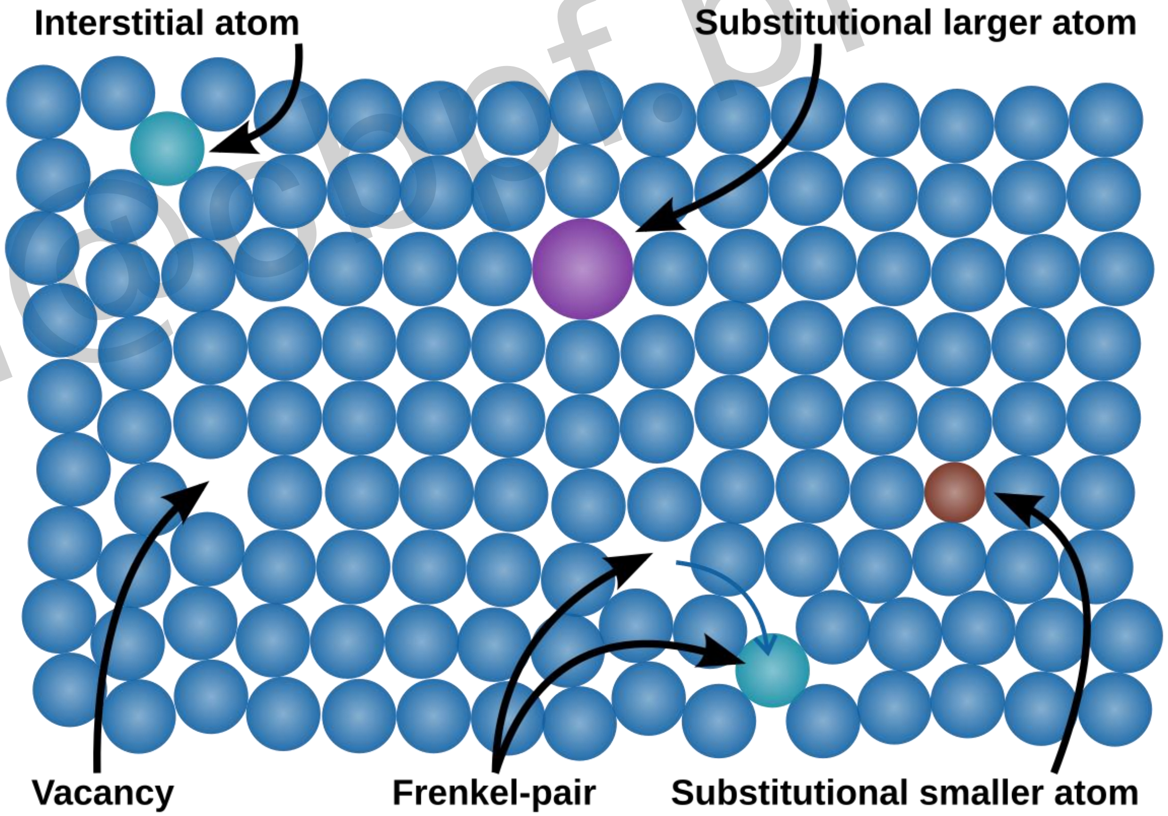
Color centers in insulators and semiconductors

'Artificial' molecular systems that are stabilized by the crystal





Agenda

- Wednesday (06/08/2025) – Introduction: the need for spin-photon interfaces, examples of solid-state spin-photon interfaces, **the NV system in diamond**
- Thursday (07/08/2025) – The NV system in diamond: electronic structure, spin control protocols and implementations as quantum sensors.
- Saturday (09/08/2025) – Quantum communication demonstrations using the NV and alternative systems.

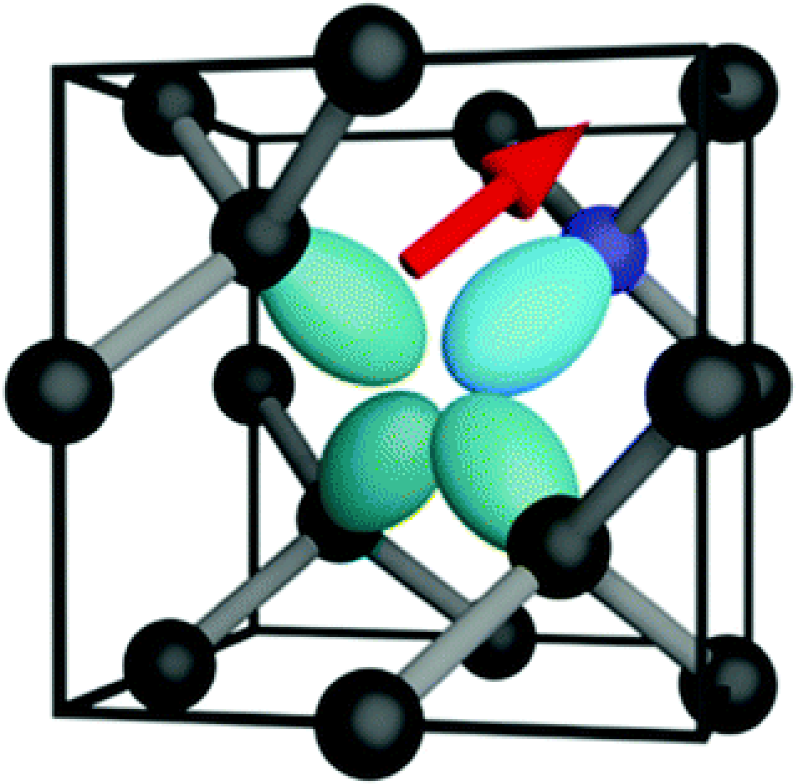
Photons

Electronic spin

Nuclear spin

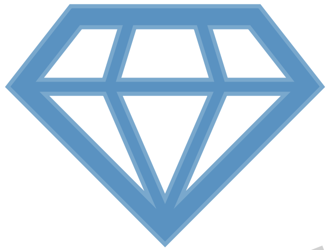
EM fields

Temperature, pressure, ...

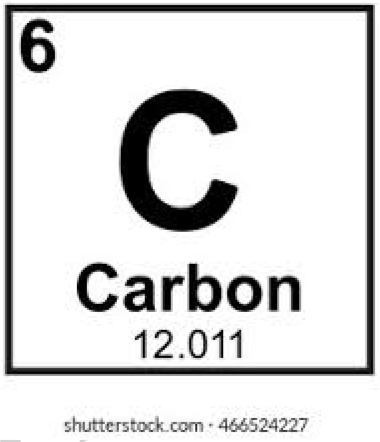


Diamond Electronic Structure

Arises from completely empty 3s orbitals



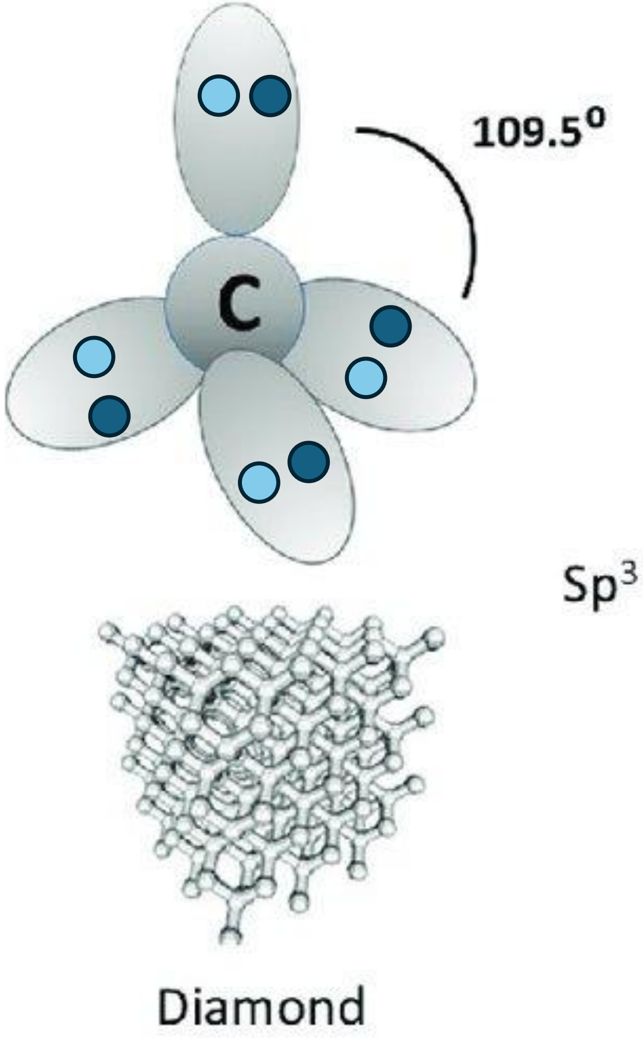
> 6 eV



1s2, 2s2, 2p2

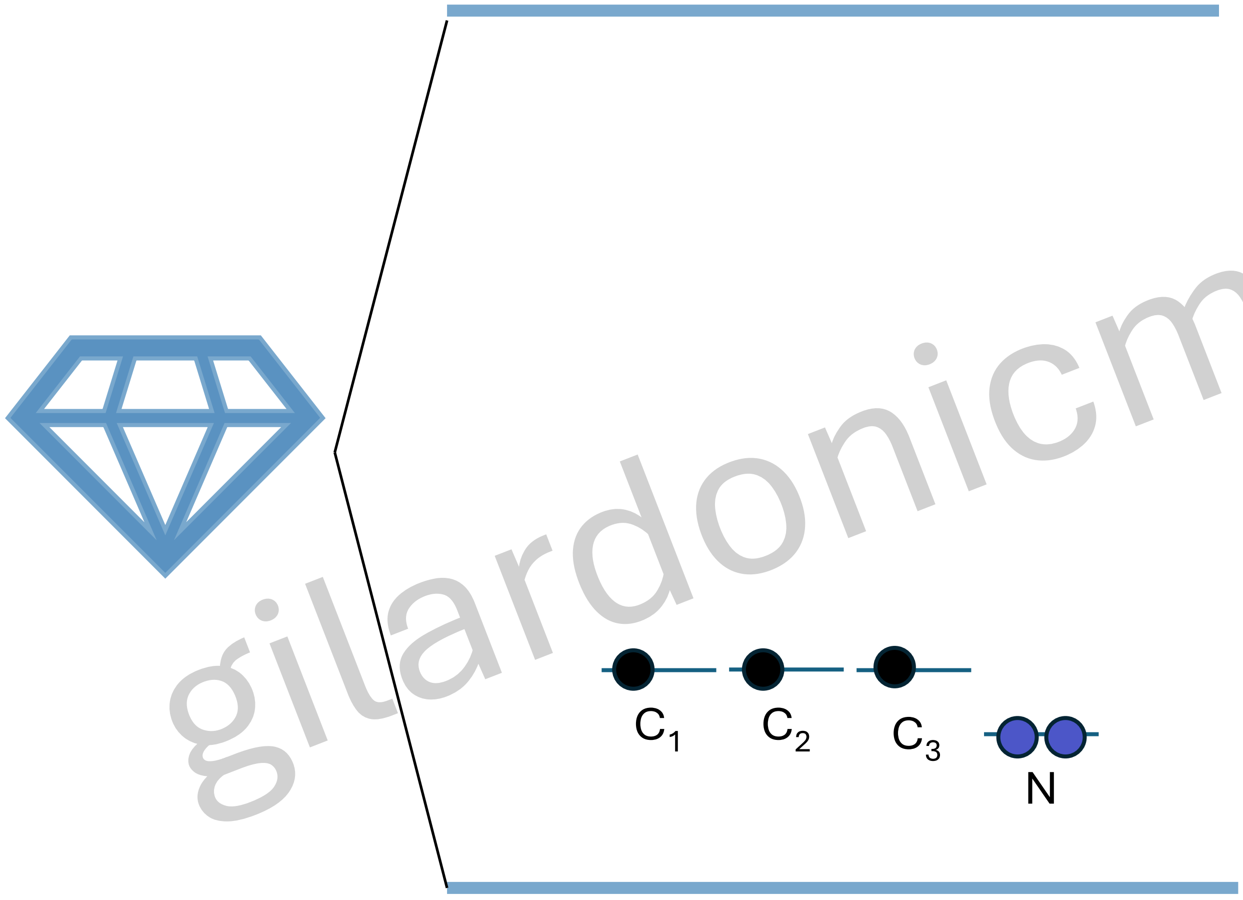
4 valence electrons

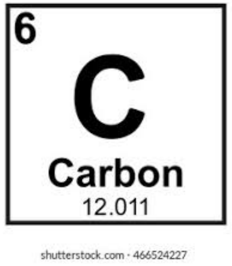
Arises from completely filled $2sp^3$ orbitals

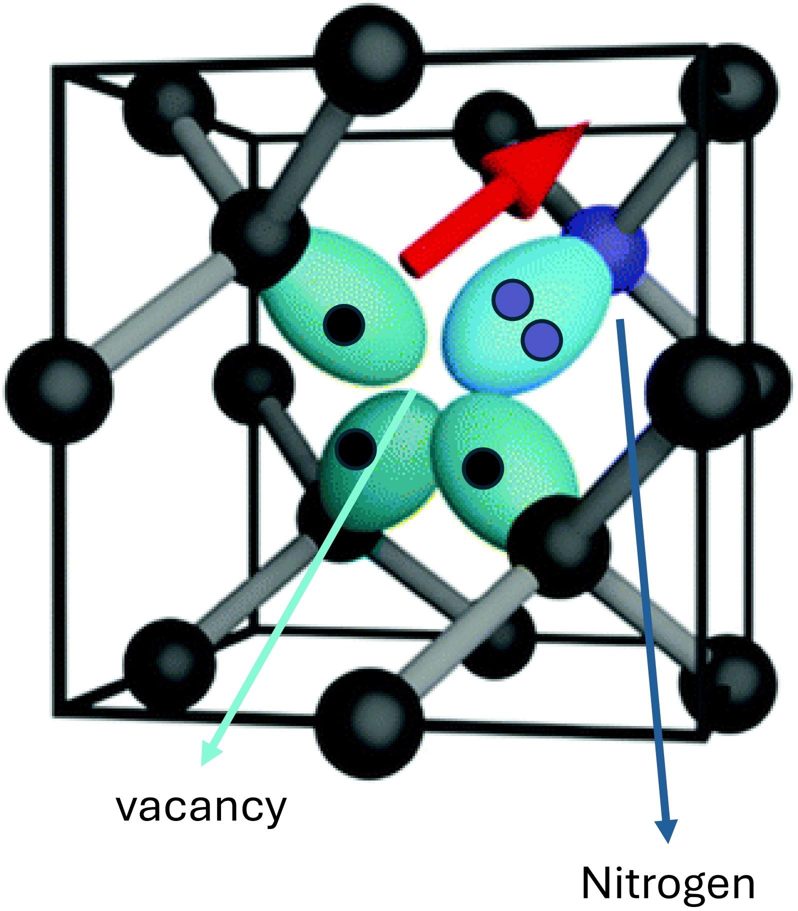


American Journal of Engineering and Applied Sciences
Volume 11 No. 2, 2018, 766-782

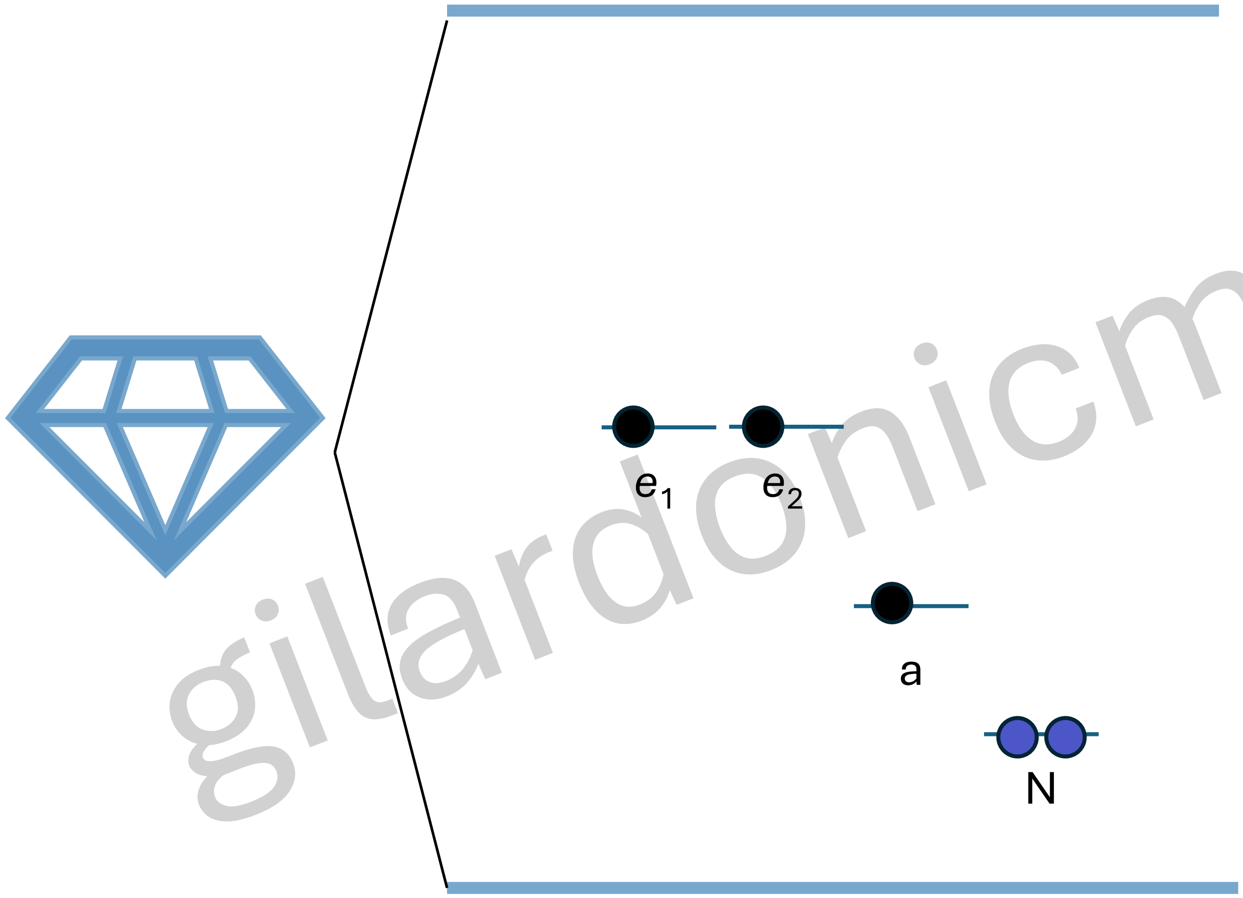
The NV system

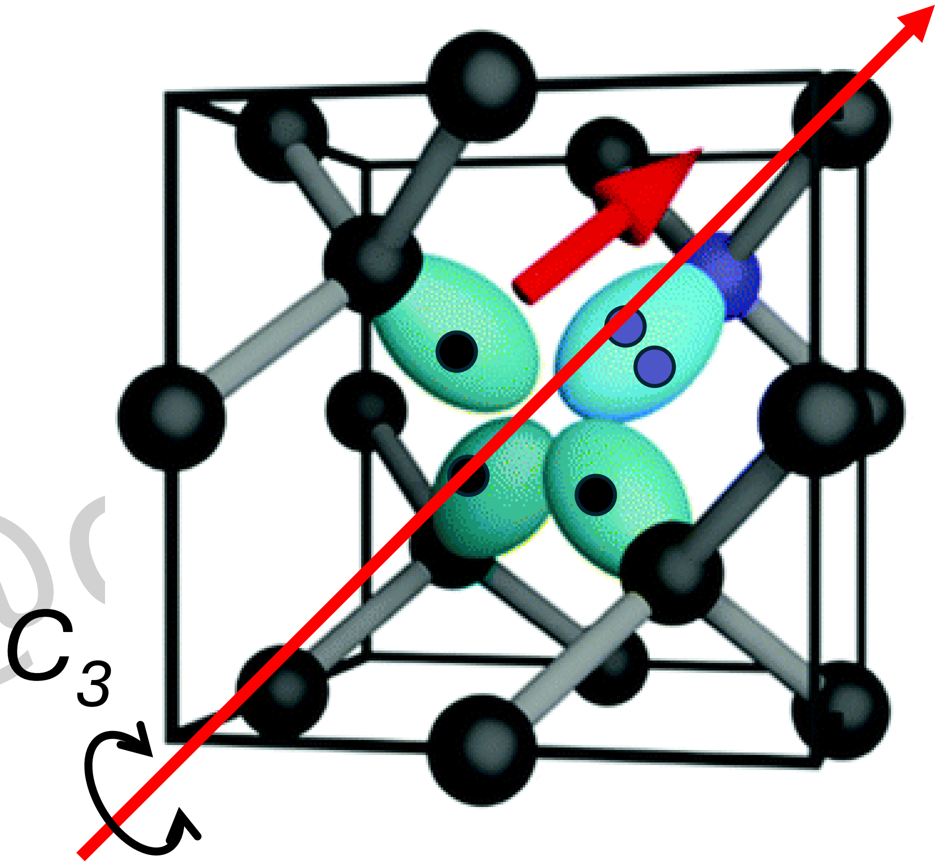






The NV system – the symmetries!

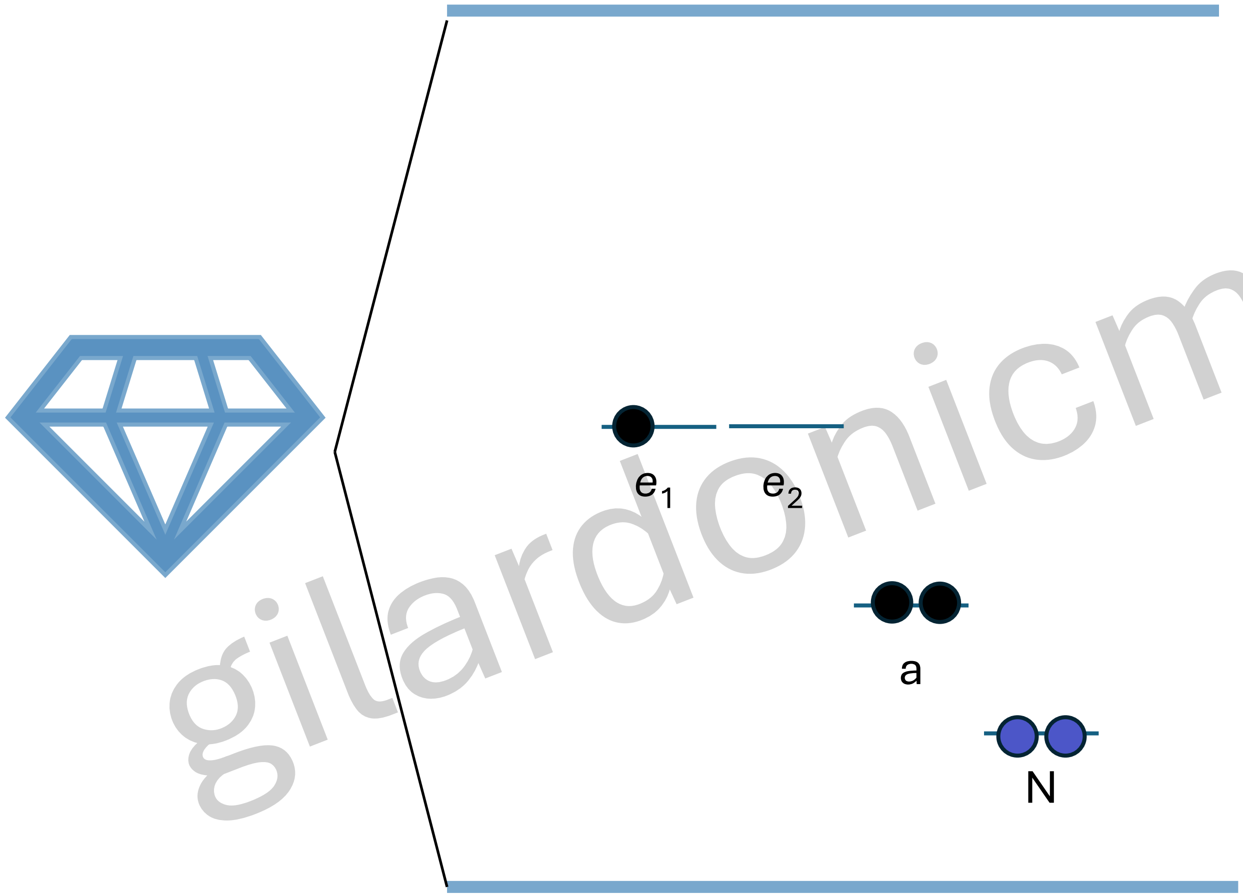


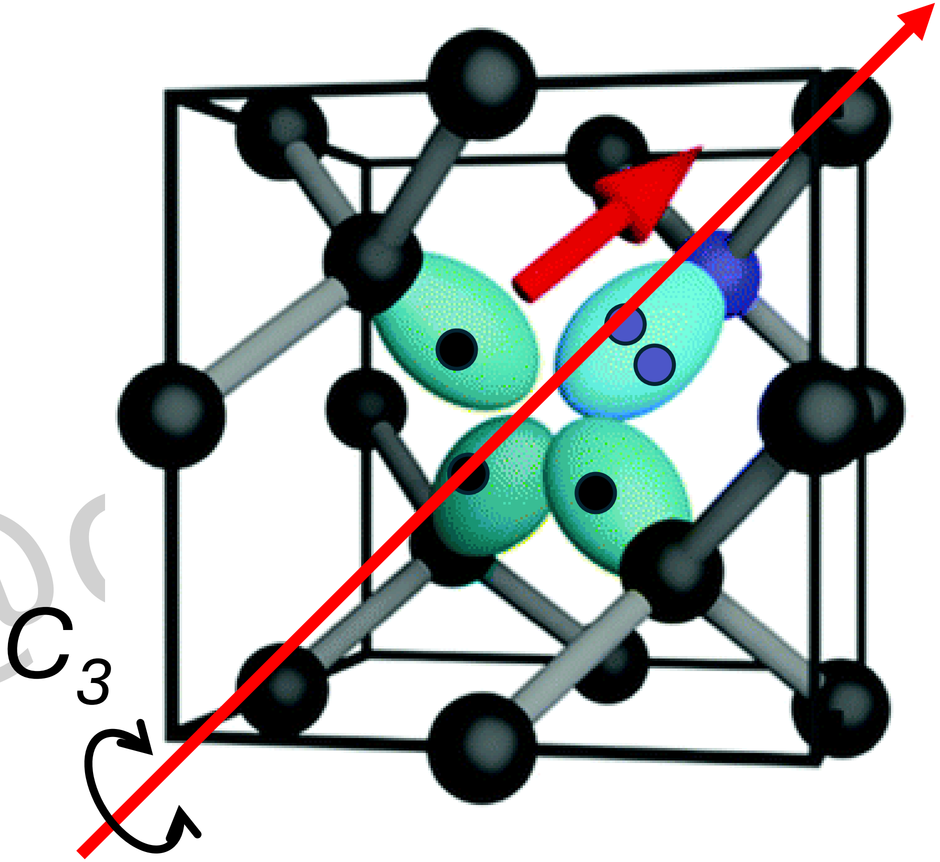


Orbital *a*: $C_1 + C_2 + C_3$

Orbitals *e*: 2C1 – C2 – C3
$2C_2 - C_3 - C_1$

The NV^0 – a defect with spin 1/2



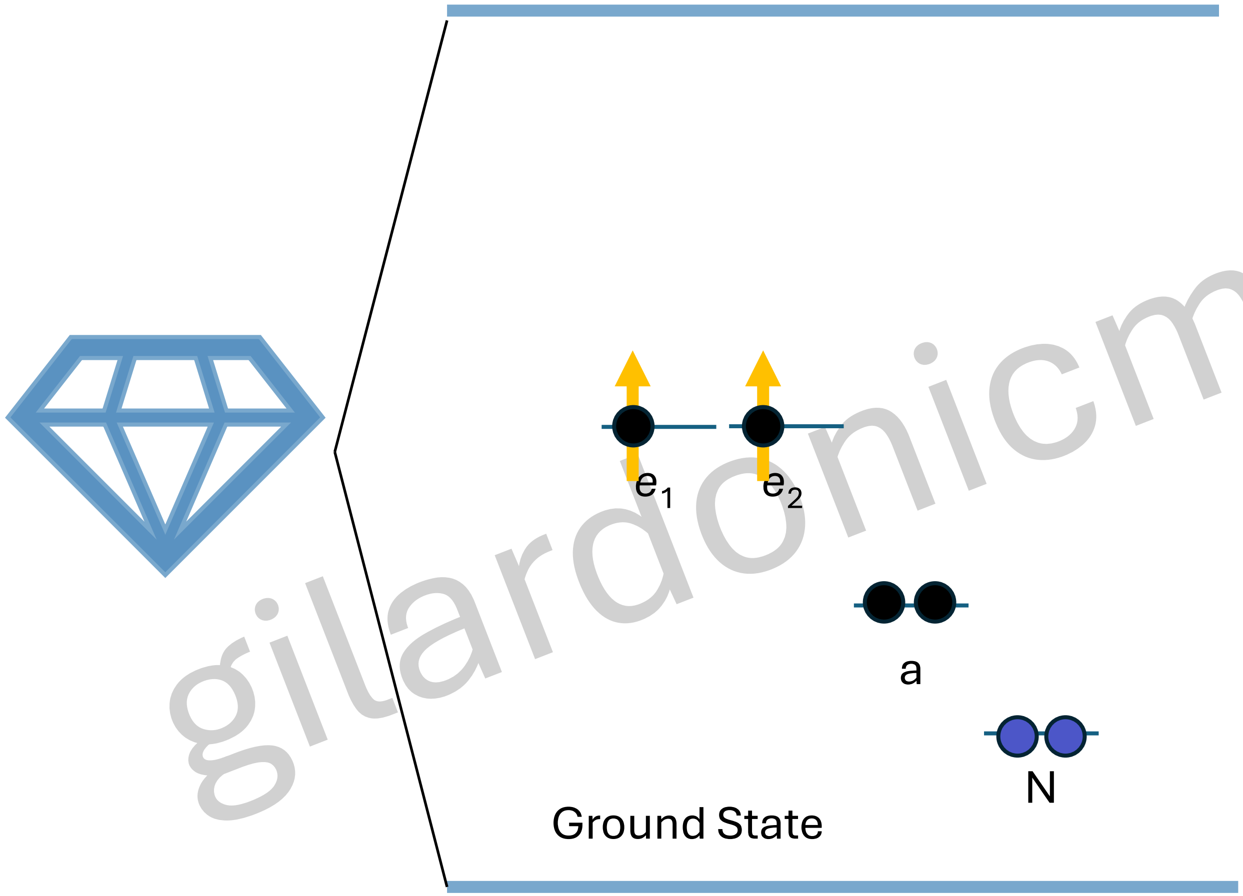


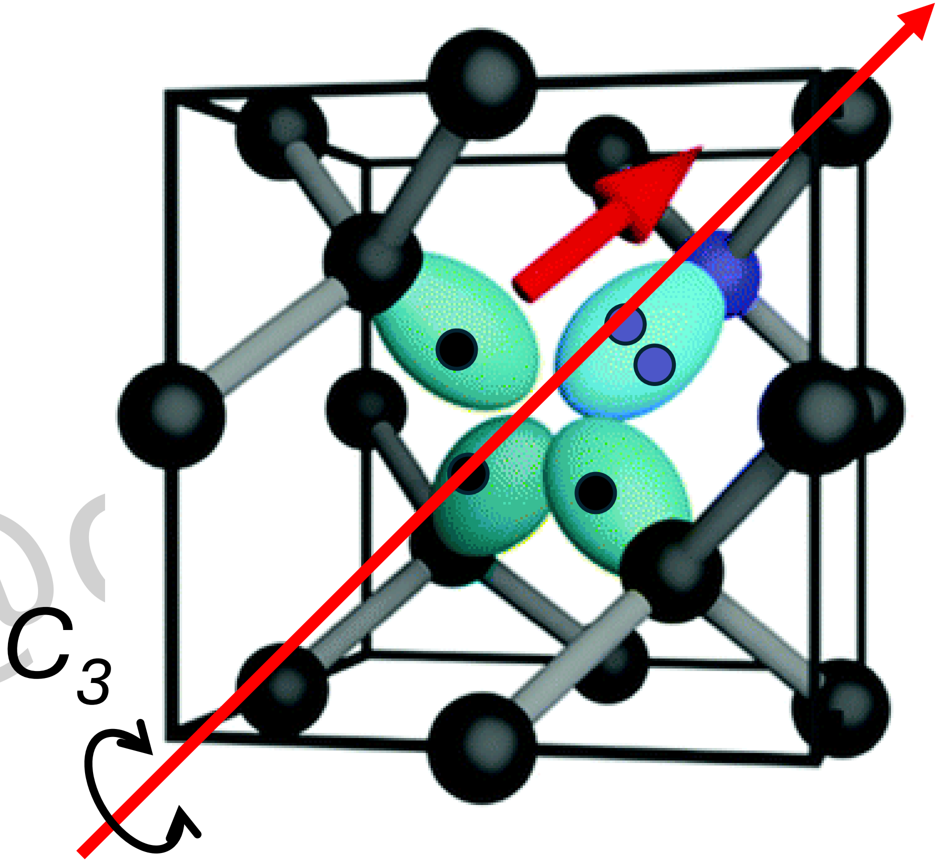
Orbital *a*: $C_1 + C_2 + C_3$

Orbitals *e*: $2C_1 - C_2 - C_3$

$2C_2 - C_3 - C_1$

The NV$^-$ – a defect with spin 1



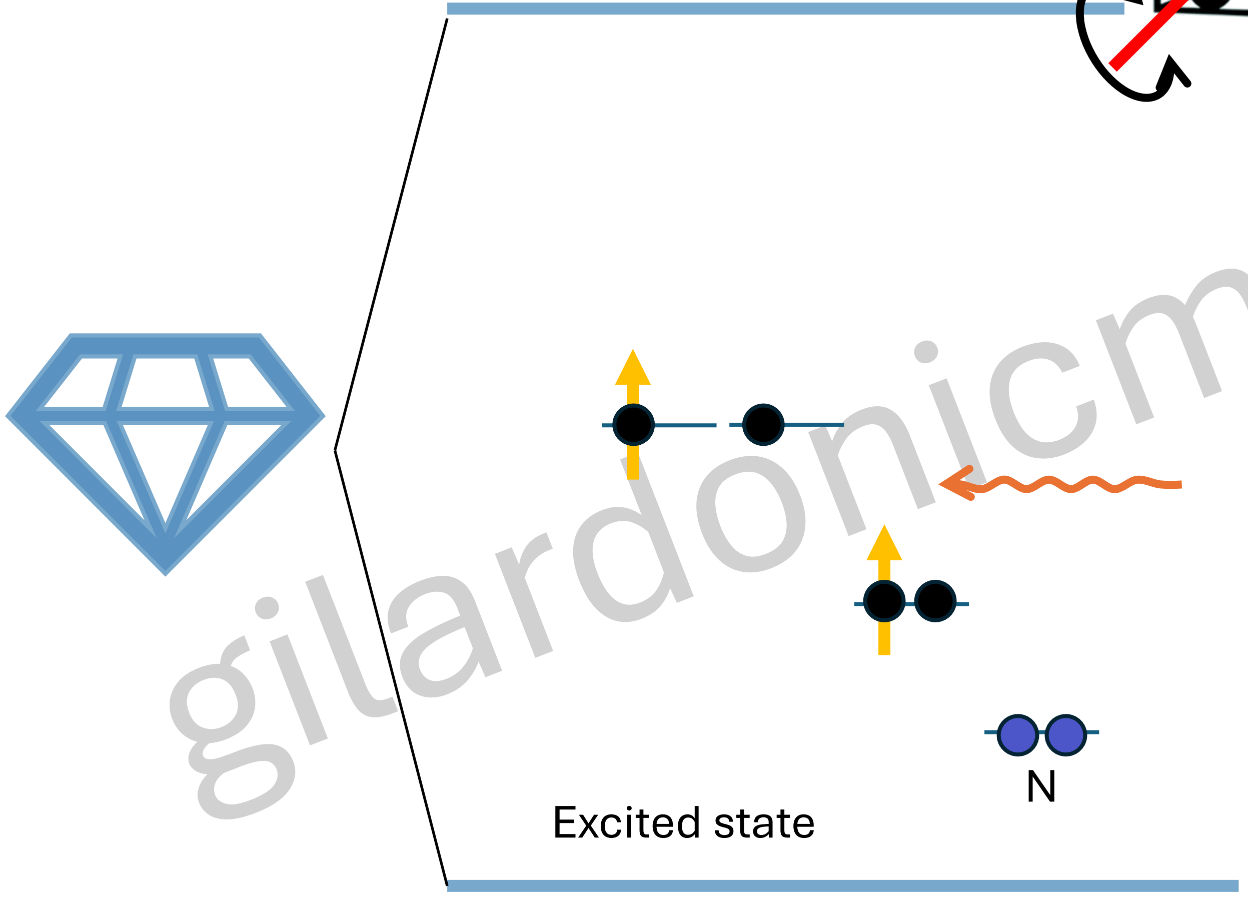


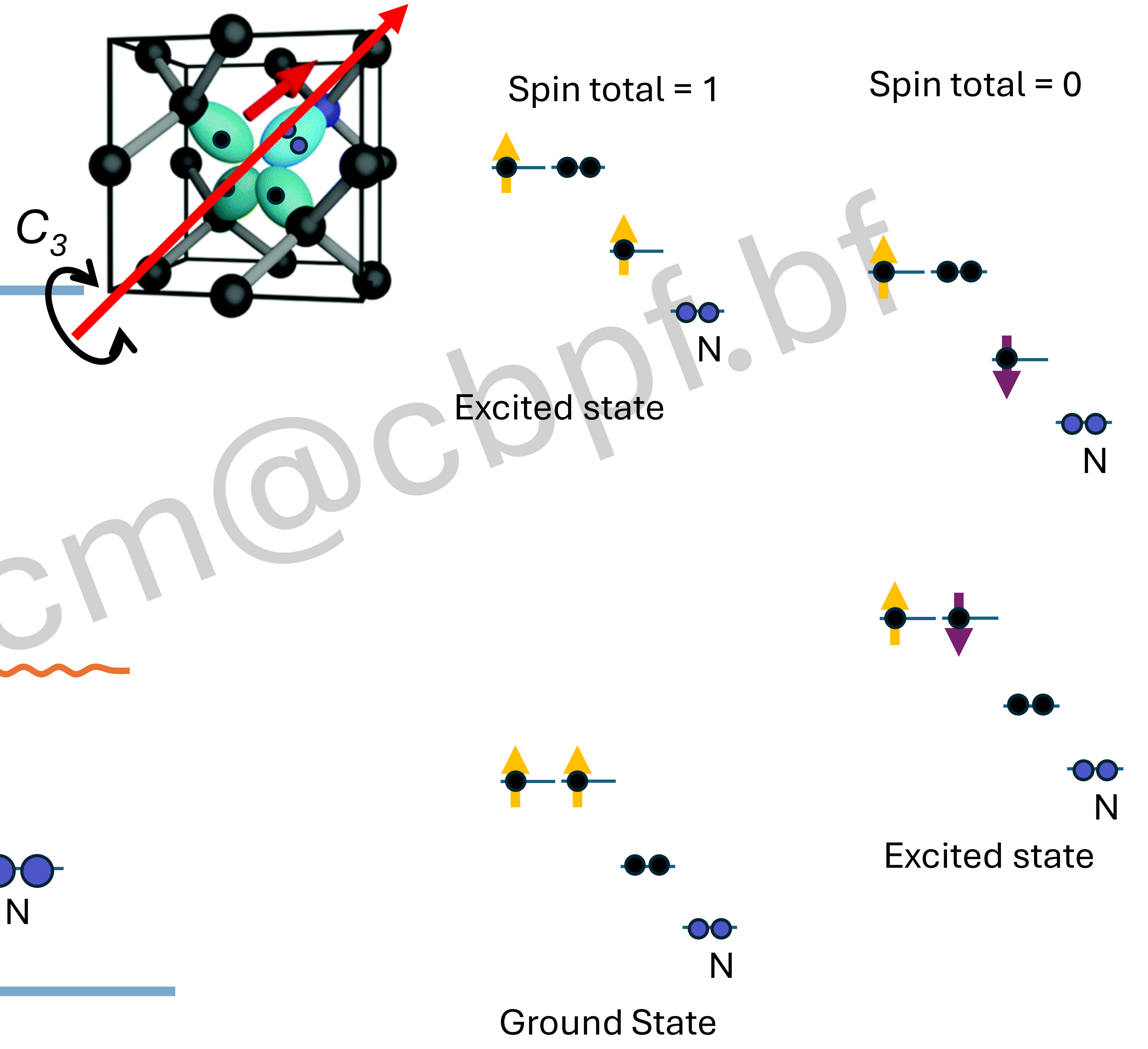
Orbital *a*: $C_1 + C_2 + C_3$

Orbitals *e*: 2C1 – C2 – C3

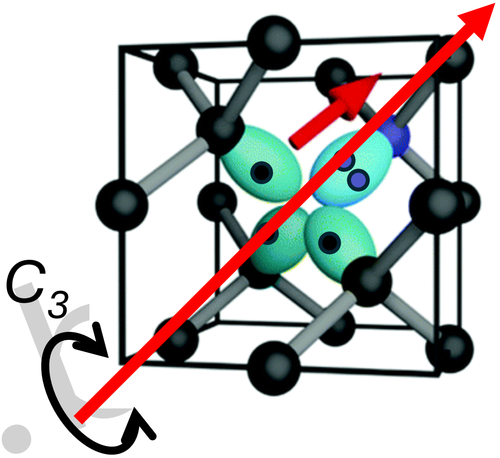
$2C_2 - C_3 - C_1$

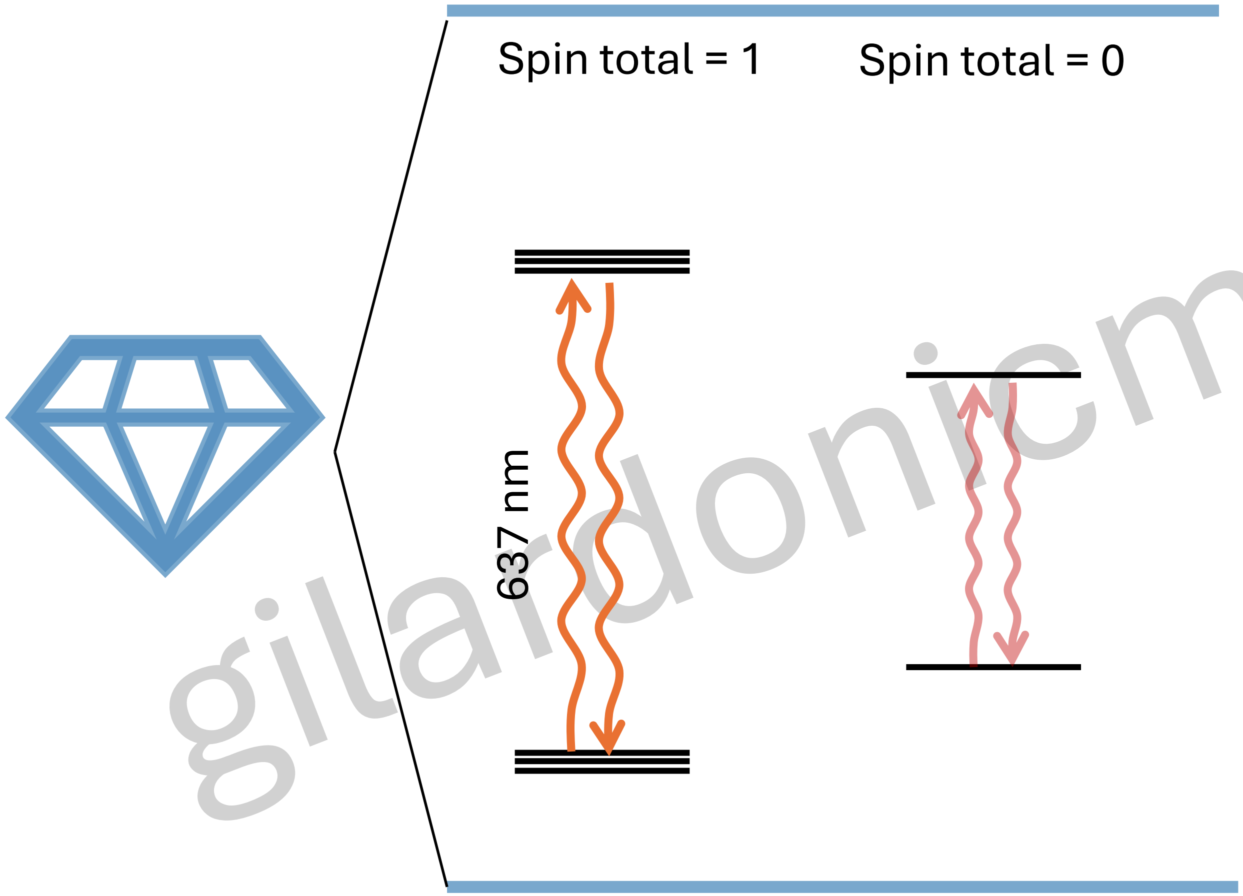
The NV⁻ – a defect with spin 1

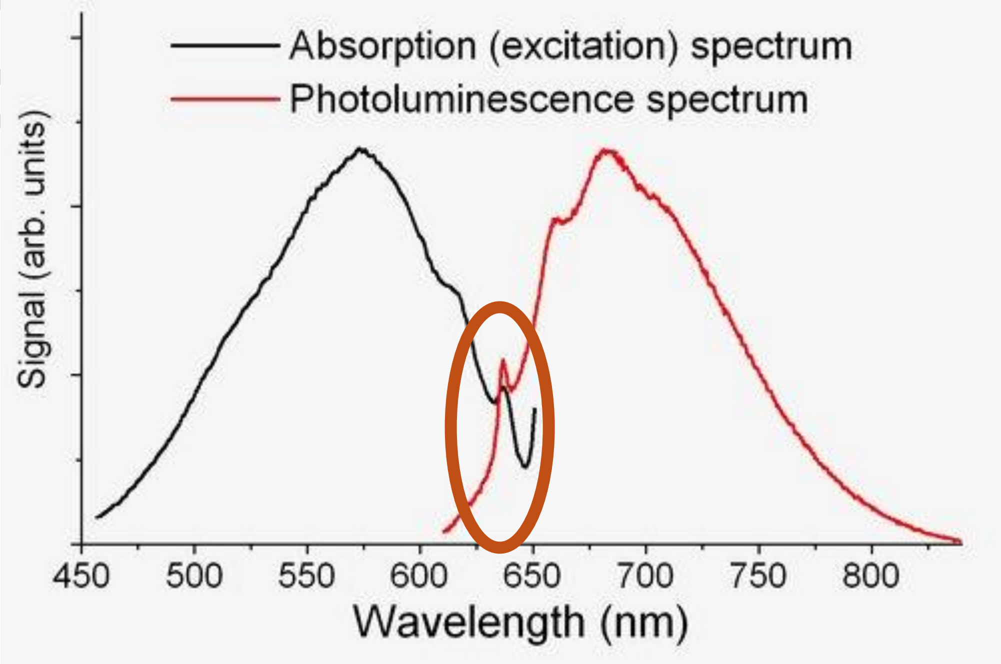




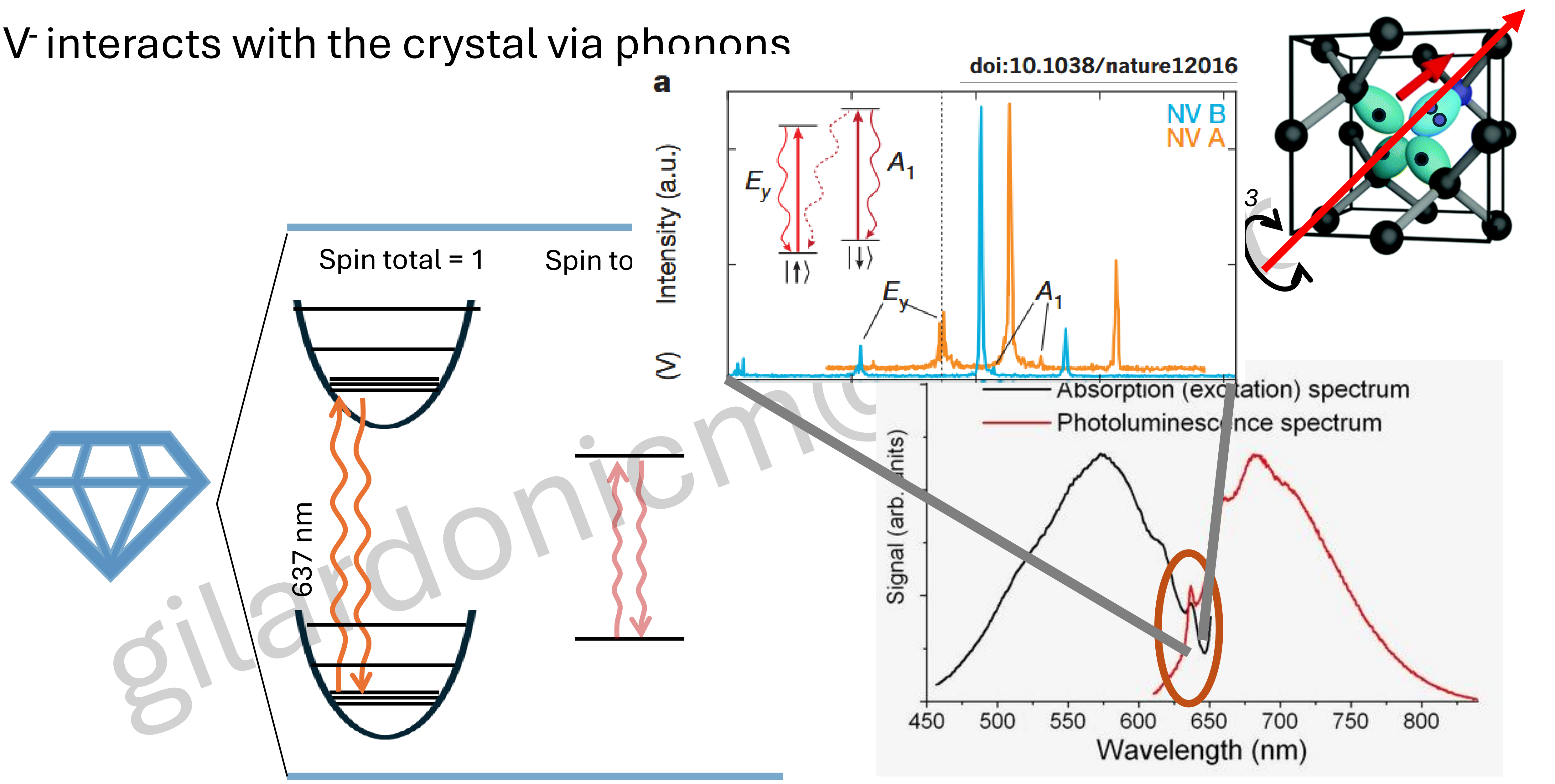
The NV⁻ – a defect with spin 1



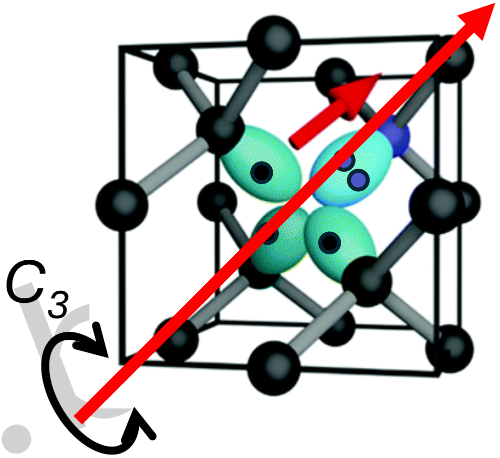


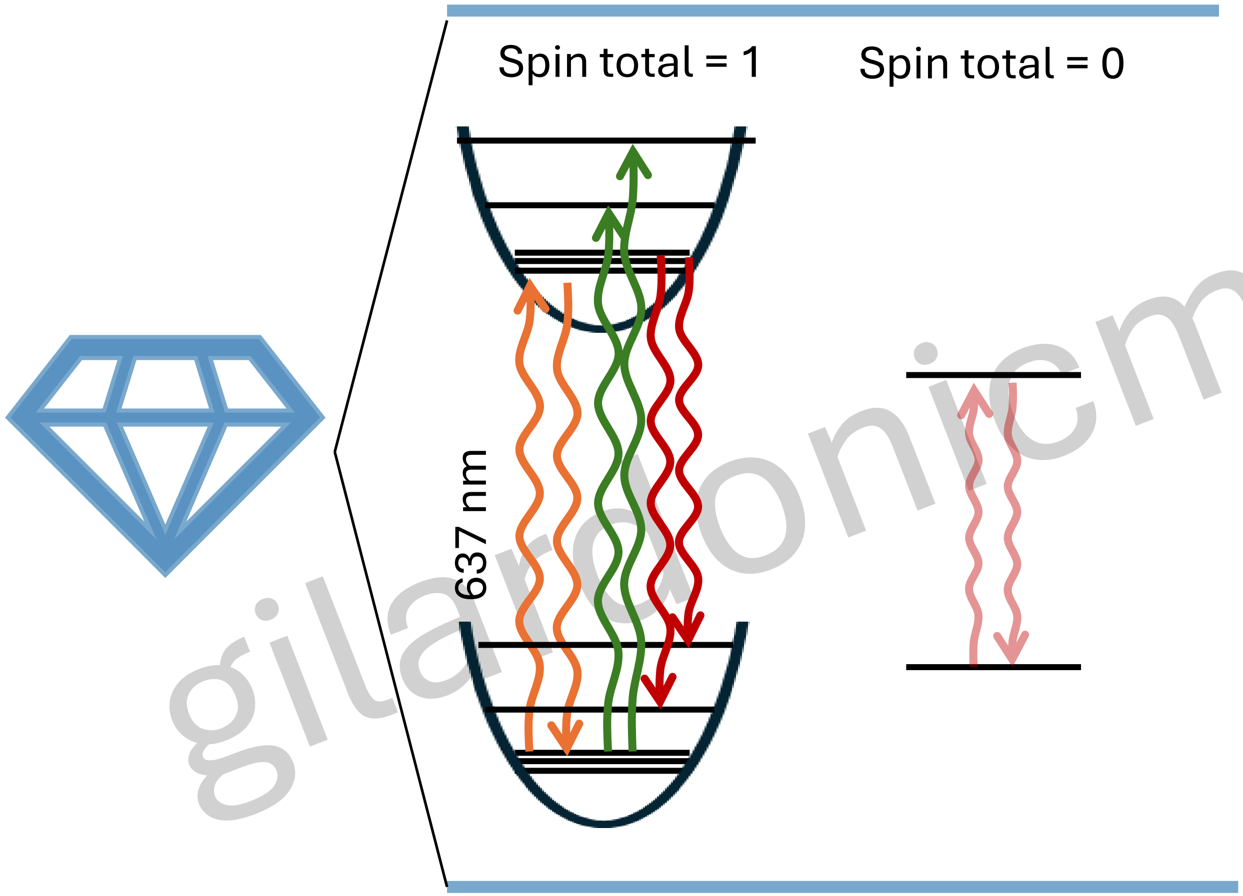


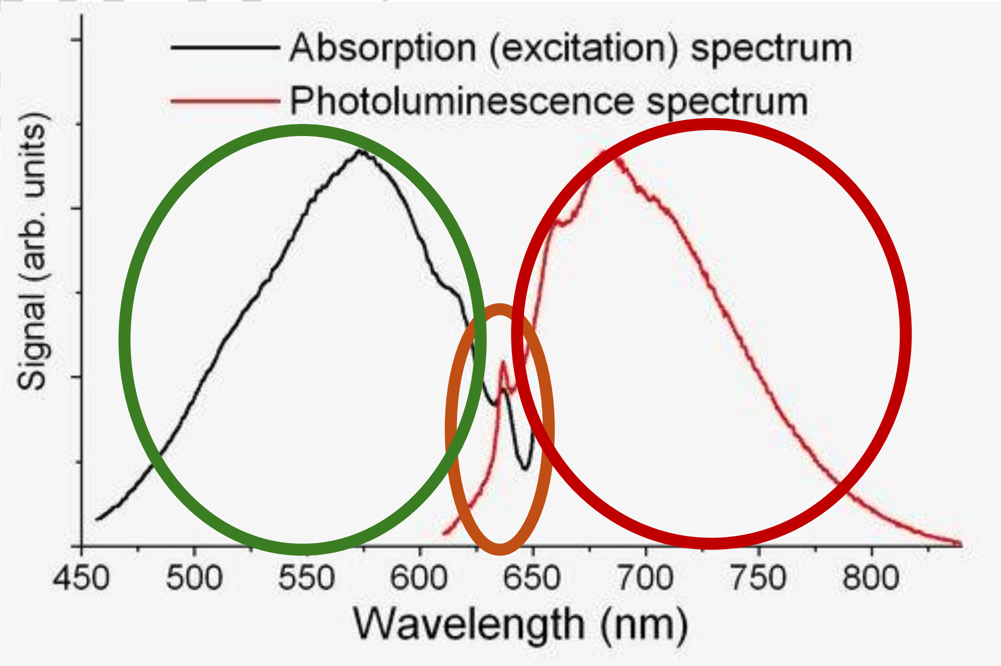
NV⁻ interacts with the crystal via phonons



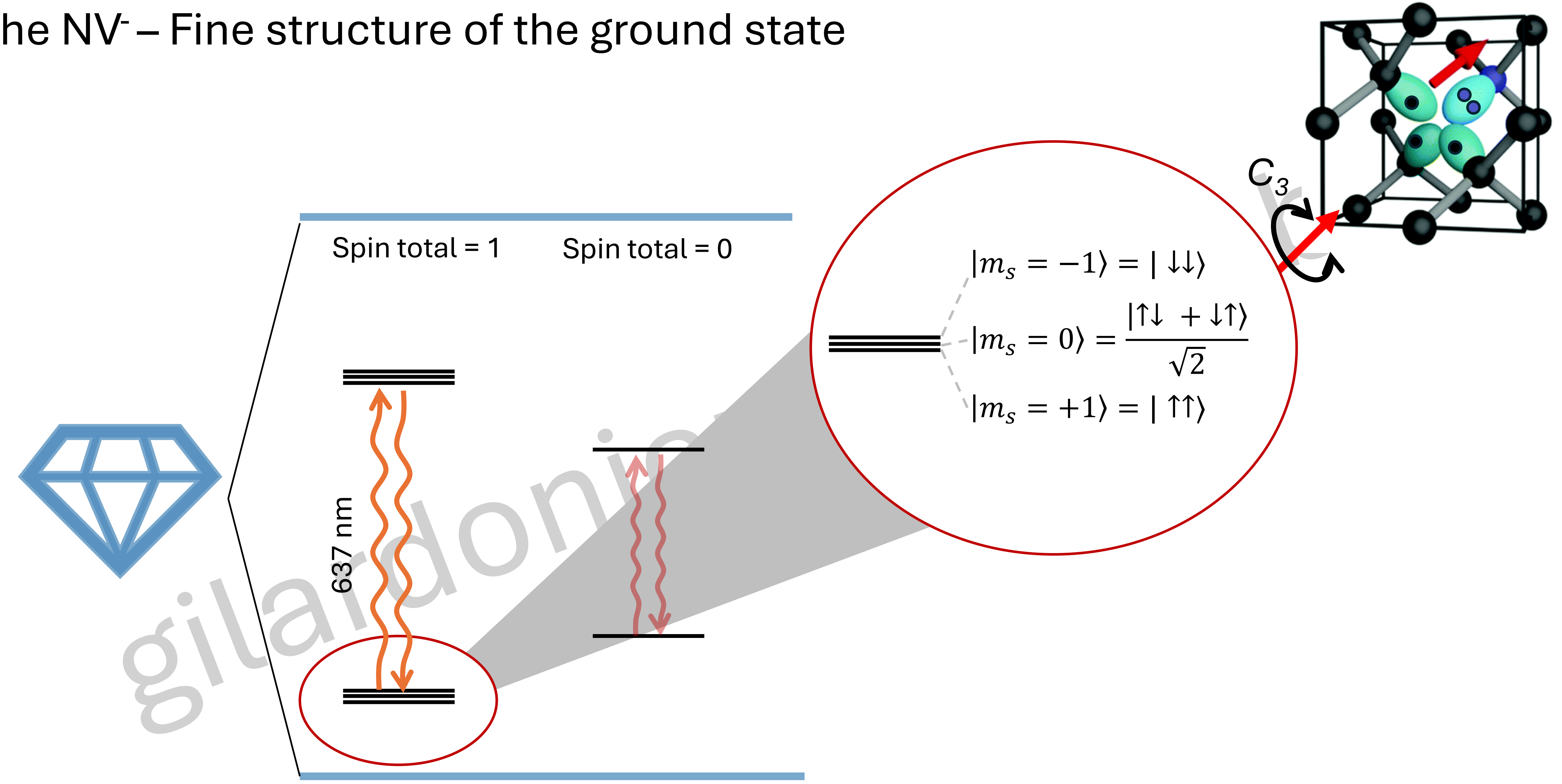
NV$^-$ interacts with the crystal via phonons



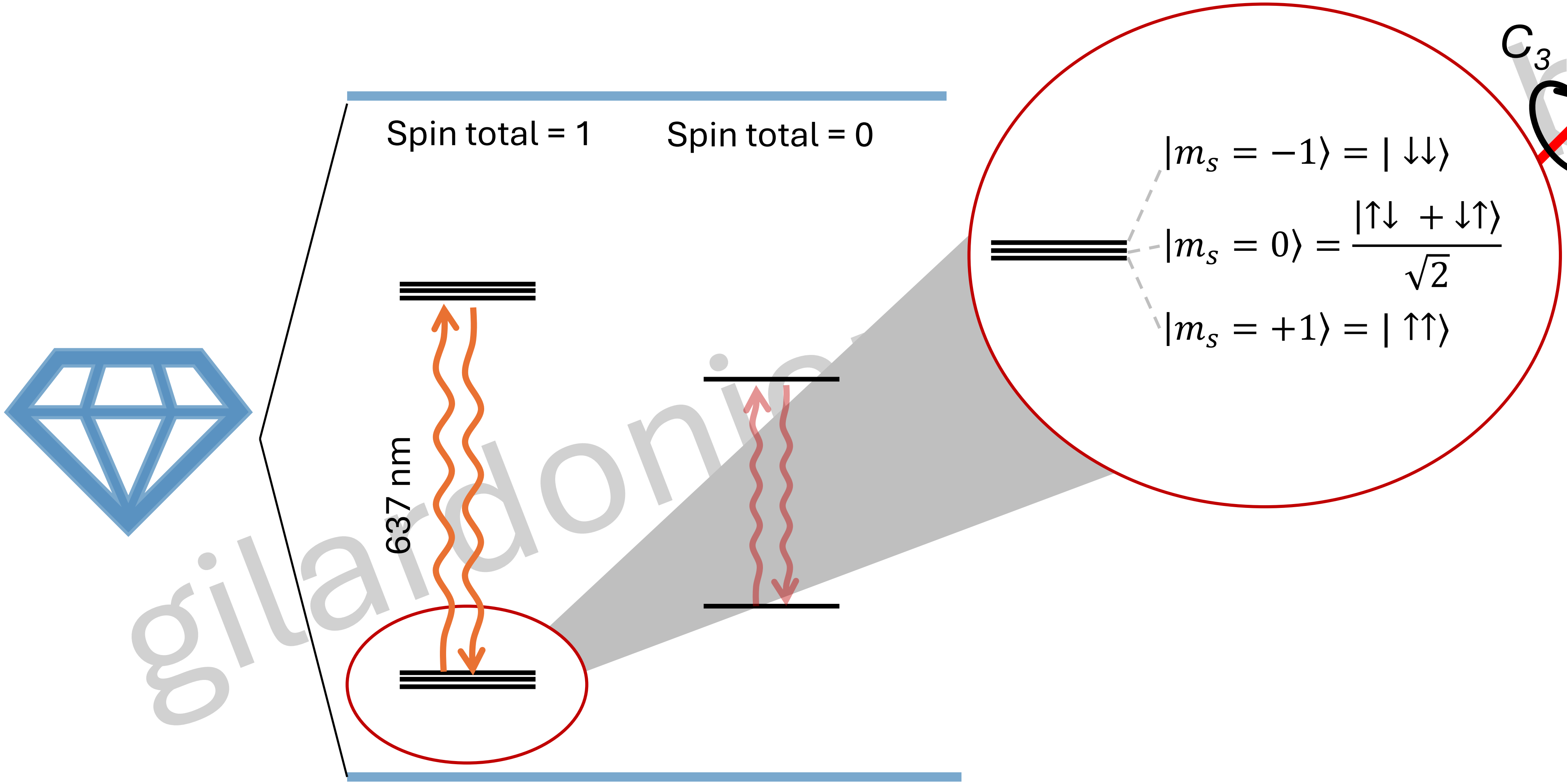


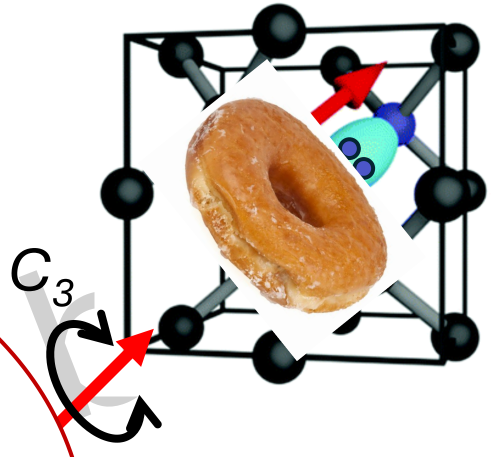


The NV⁻ – Fine structure of the ground state



The NV$^-$ – Fine structure of the ground state





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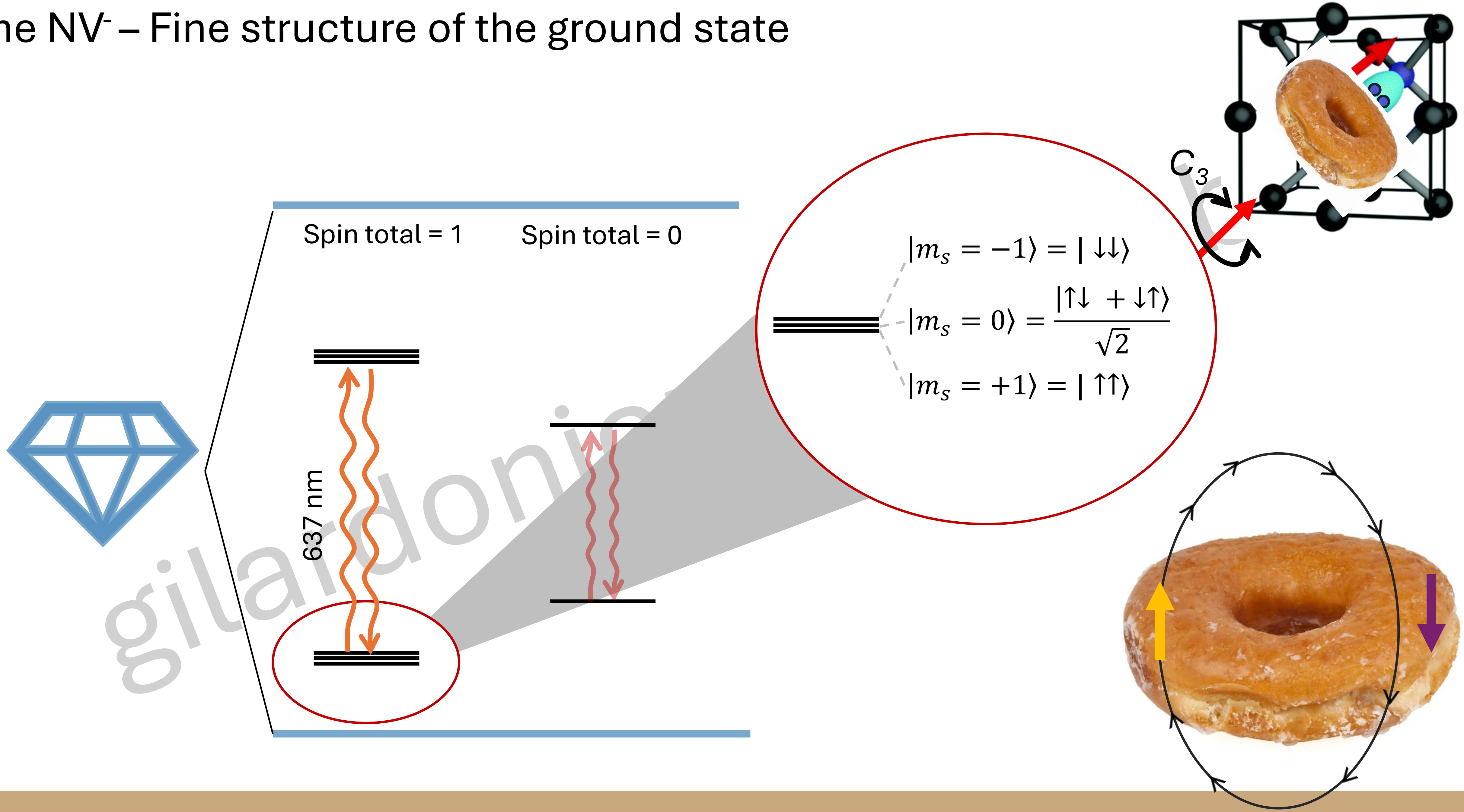

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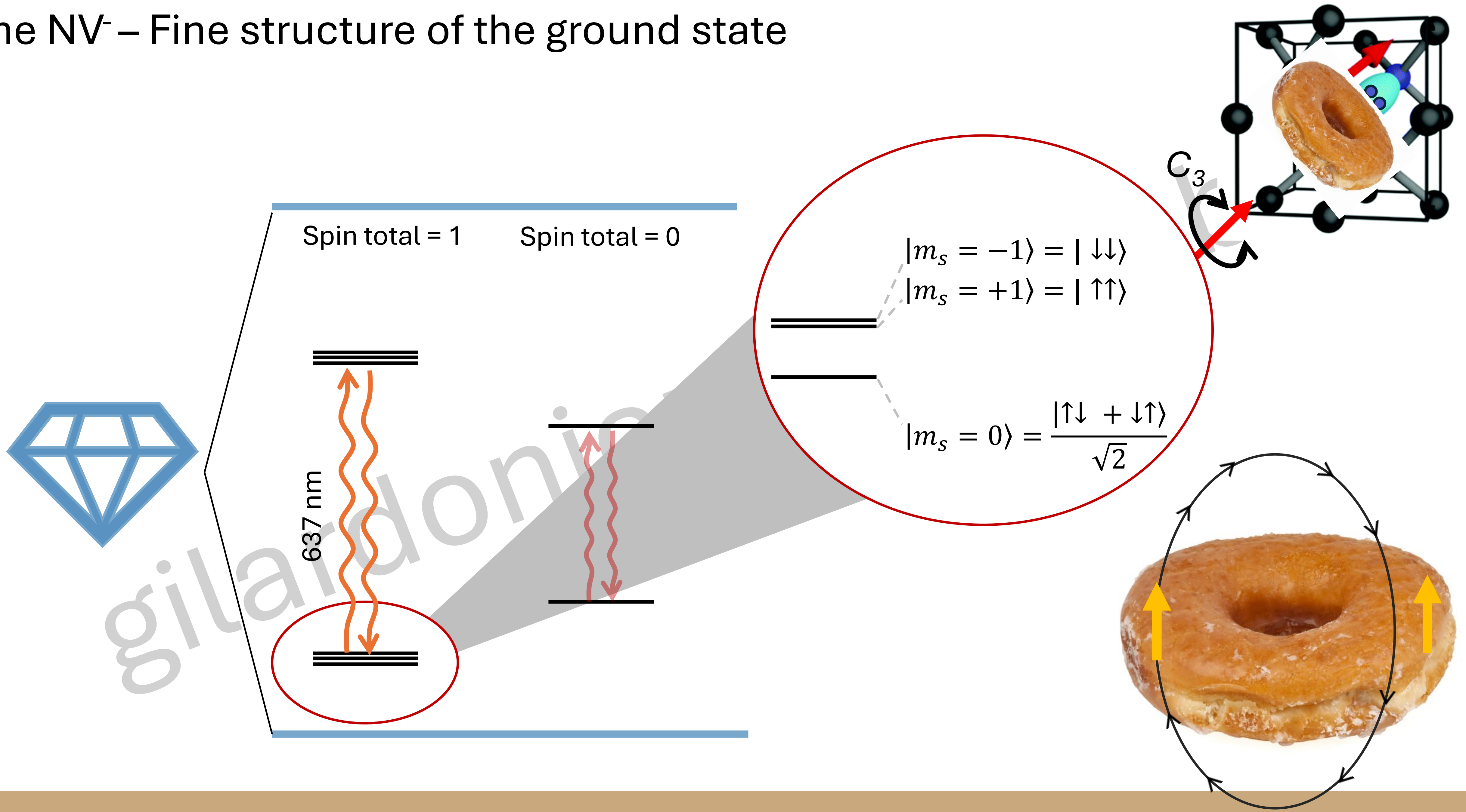

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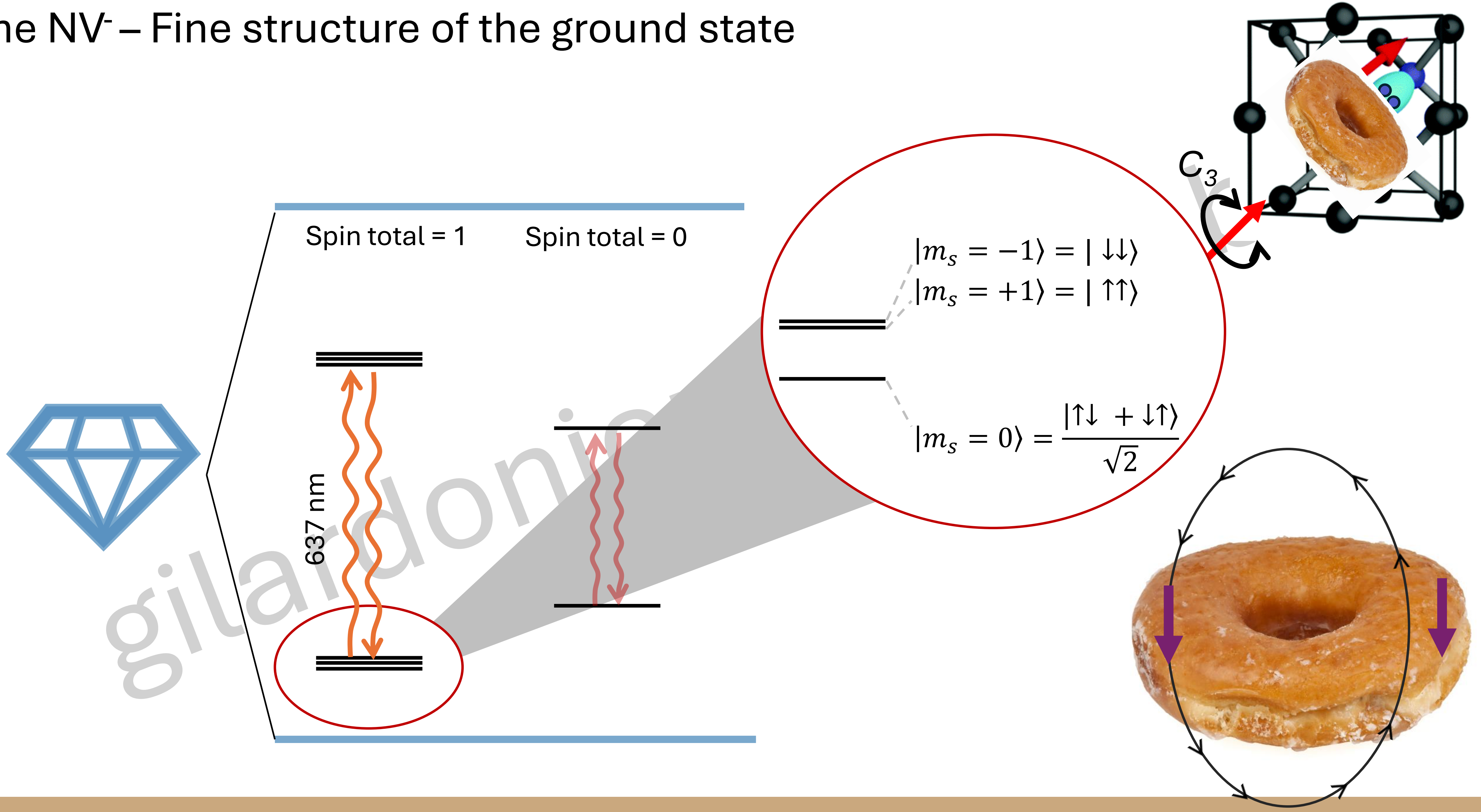

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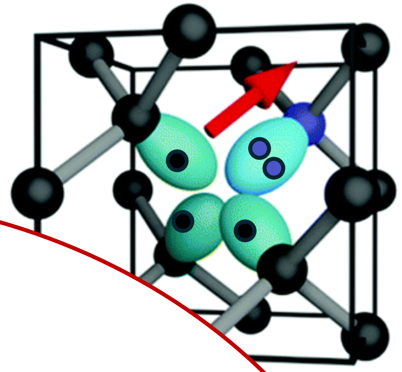

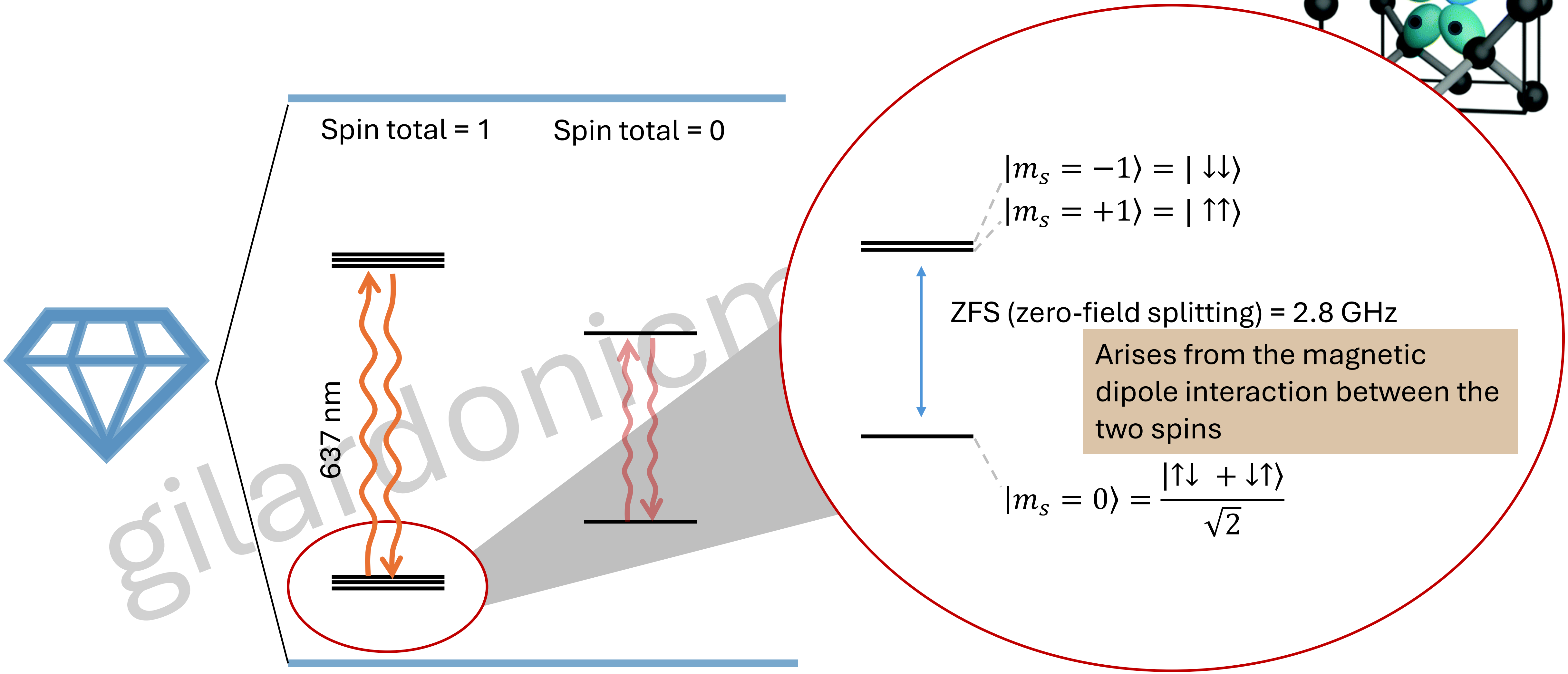

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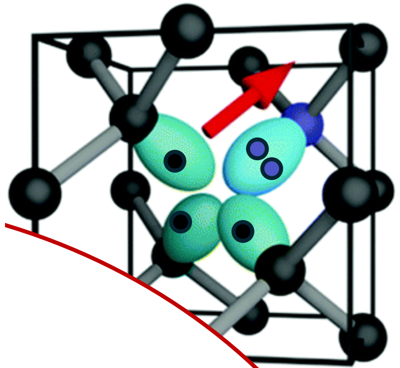
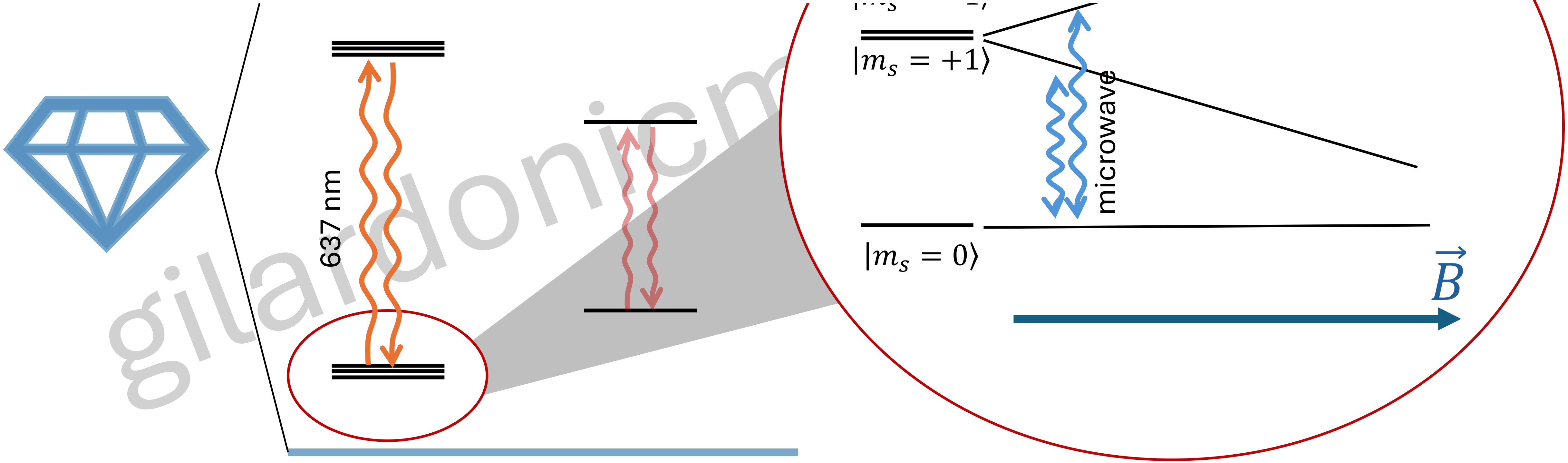
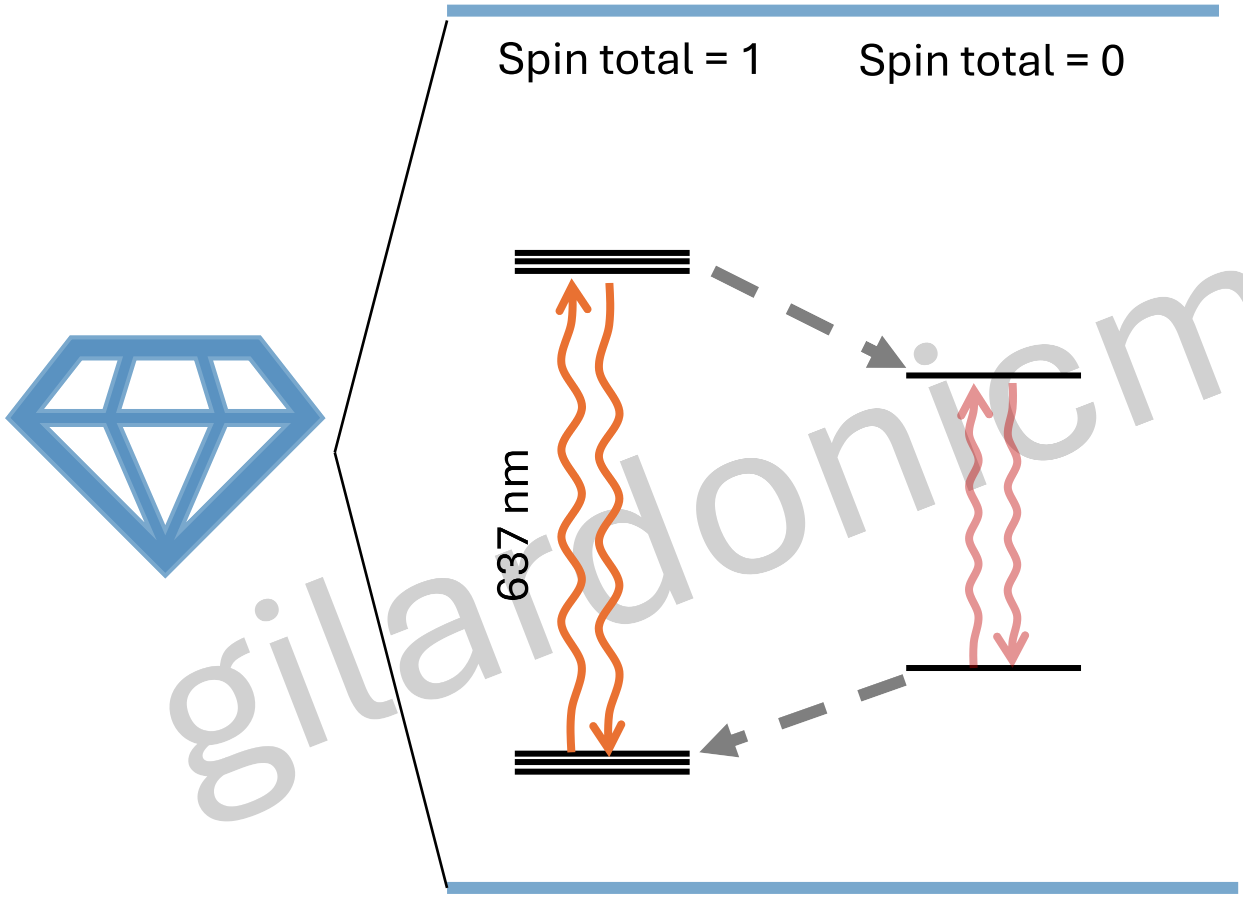


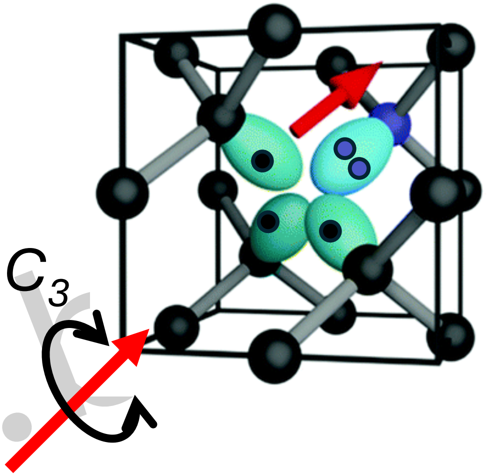
$$\hat{H} = \overbrace{\hbar D\left[\hat{S}_Z^2 - \frac{2}{3}\right] + \hbar E(\hat{S}_X^2 - \hat{S}_Y^2)}^{\text{zero-field term}} + \overbrace{\hbar\gamma_{nv}\vec{B}\cdot\hat{\vec{S}}}^{\text{magnetic interaction}} \overbrace{+\hbar\delta_{\parallel}\mathcal{E}_Z\left[\hat{S}_Z^2 - \frac{2}{3}\right] - \hbar\delta_{\perp}\left[\mathcal{E}_X(\hat{S}_X\hat{S}_Y + \hat{S}_Y\hat{S}_X) + \mathcal{E}_Y(\hat{S}_X^2 - \hat{S}_Y^2)\right]}^{\text{electric interaction}}$$

$$+\hbar\sum_{i=1}^{n}\left(\underbrace{\hat{\vec{S}}\mathcal{N}_i\hat{\vec{I}}_i}_{\text{hyperfine interaction}} + \underbrace{\gamma_i\vec{B}\cdot\hat{\vec{I}}_i}_{\text{nuclear Zeeman interaction}} + \underbrace{Q_i\hat{I}_{Z,i}^2}_{\text{nuclear quadrupole interaction}}\right)$$



The NV^- – photodynamics





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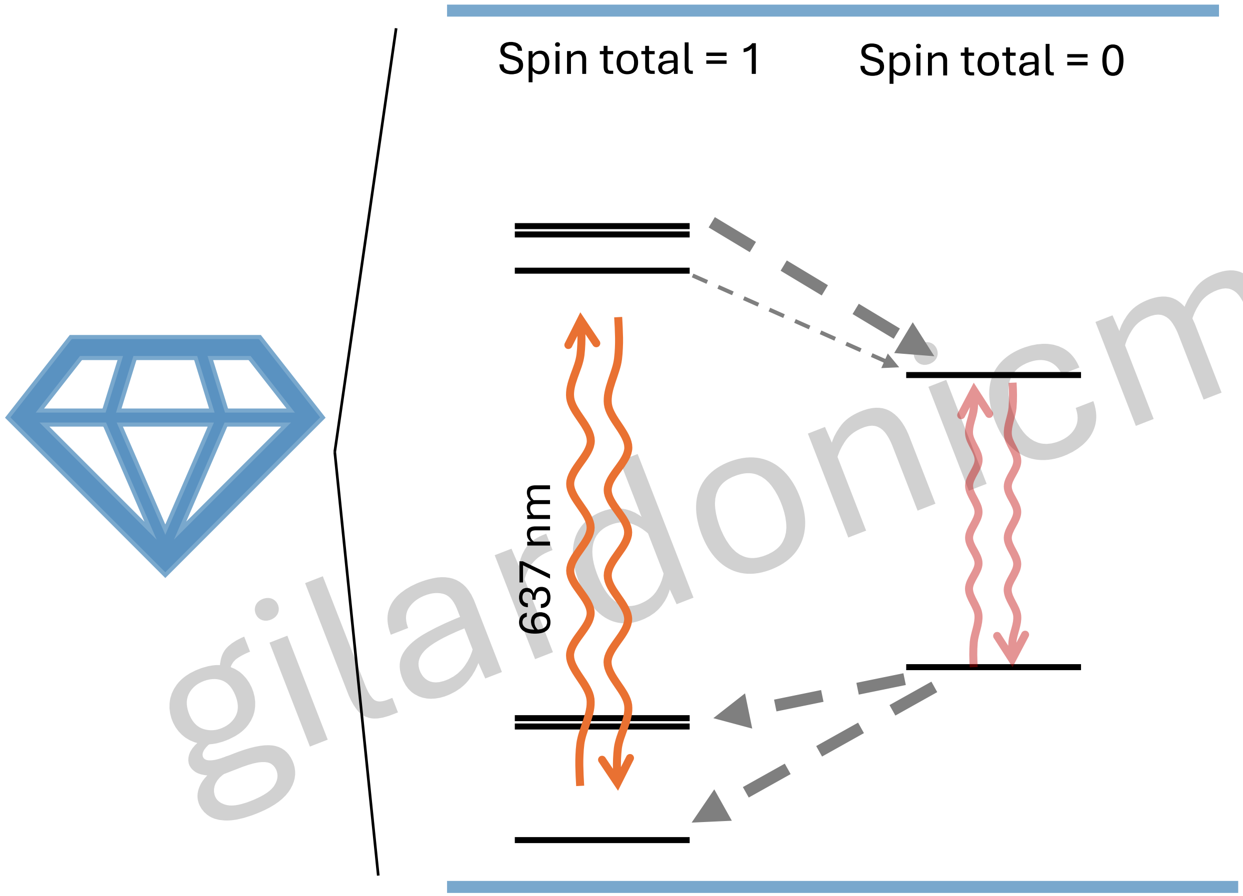

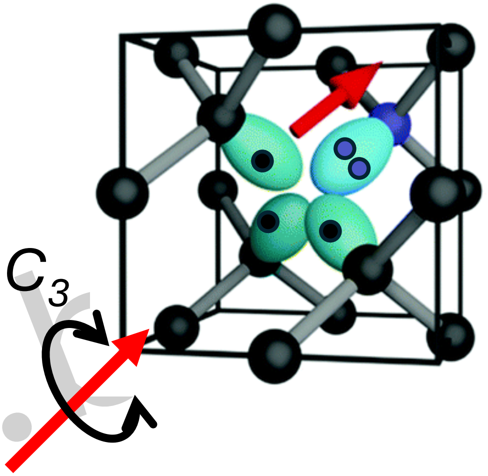

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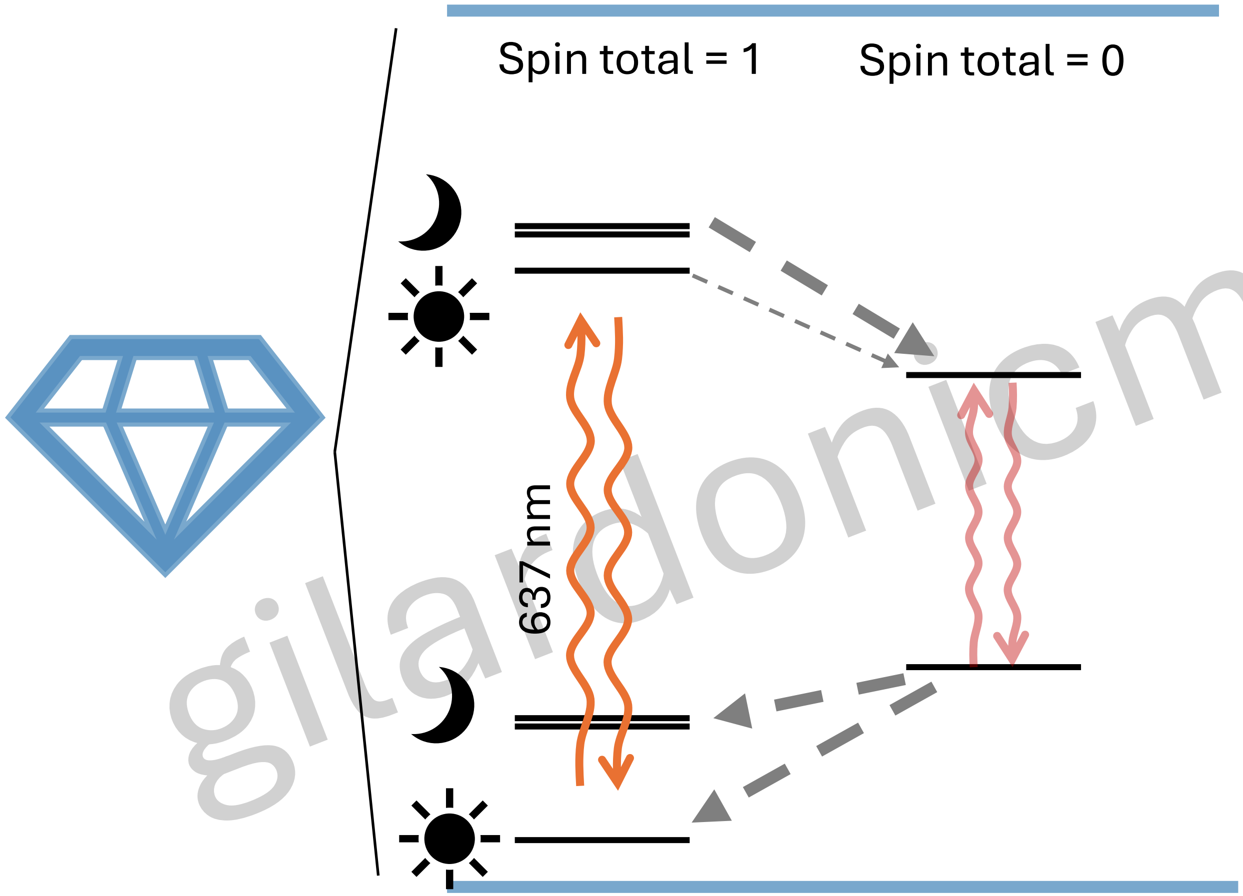
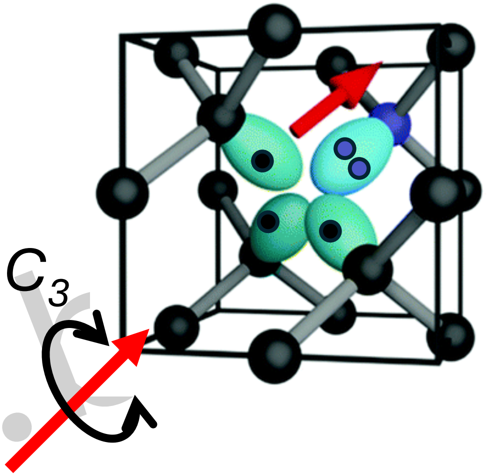
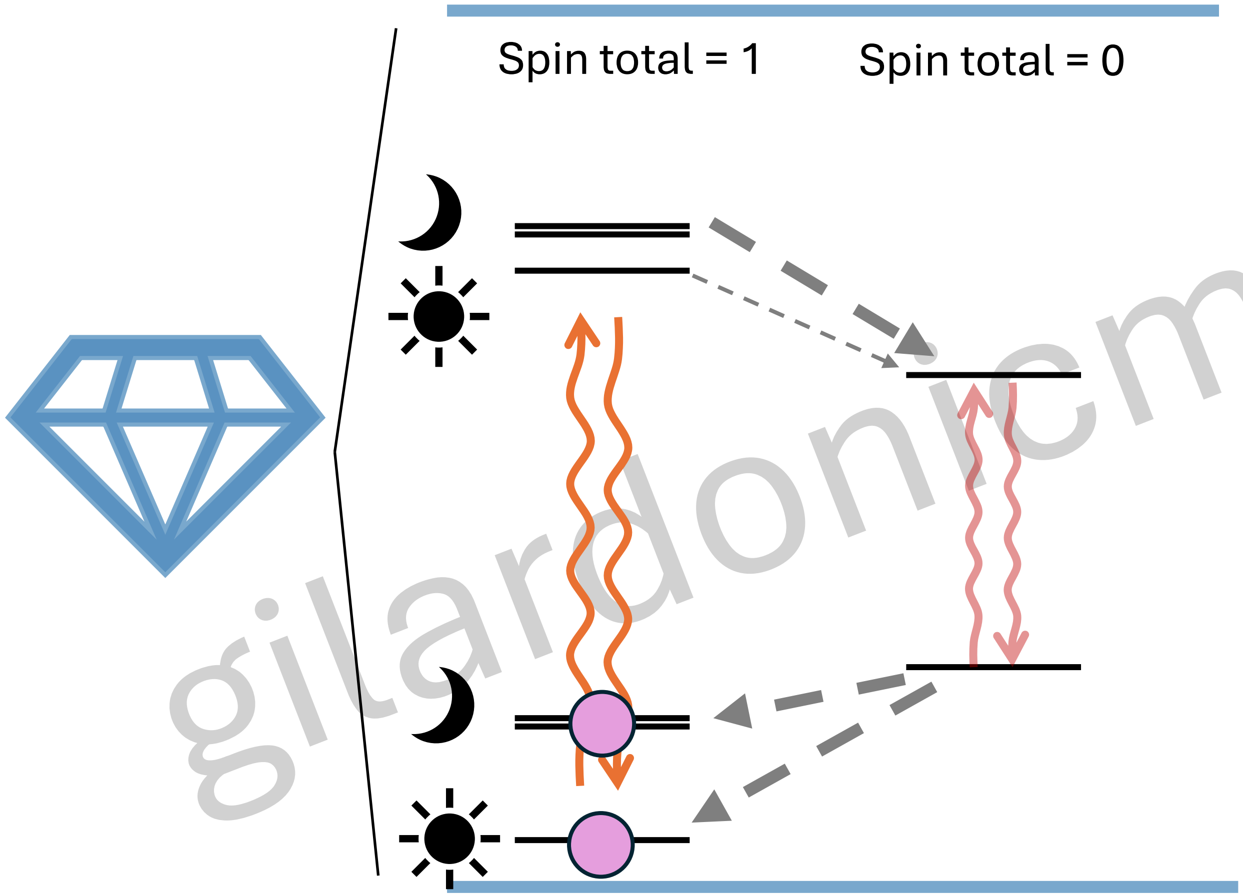
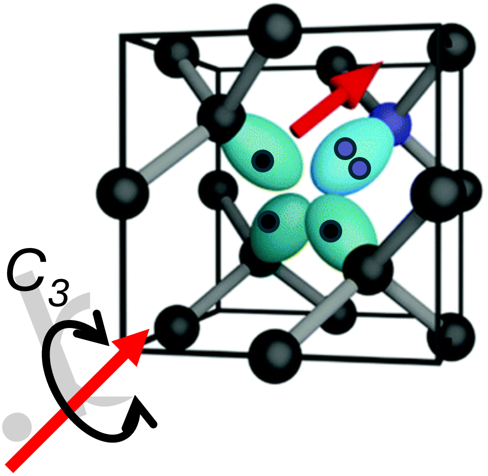




Consequence 1: The photon emission rate of NV depends on the spin state! I can *read* the spin state by detecting the emitted photons

The NV⁻ – photodynamics





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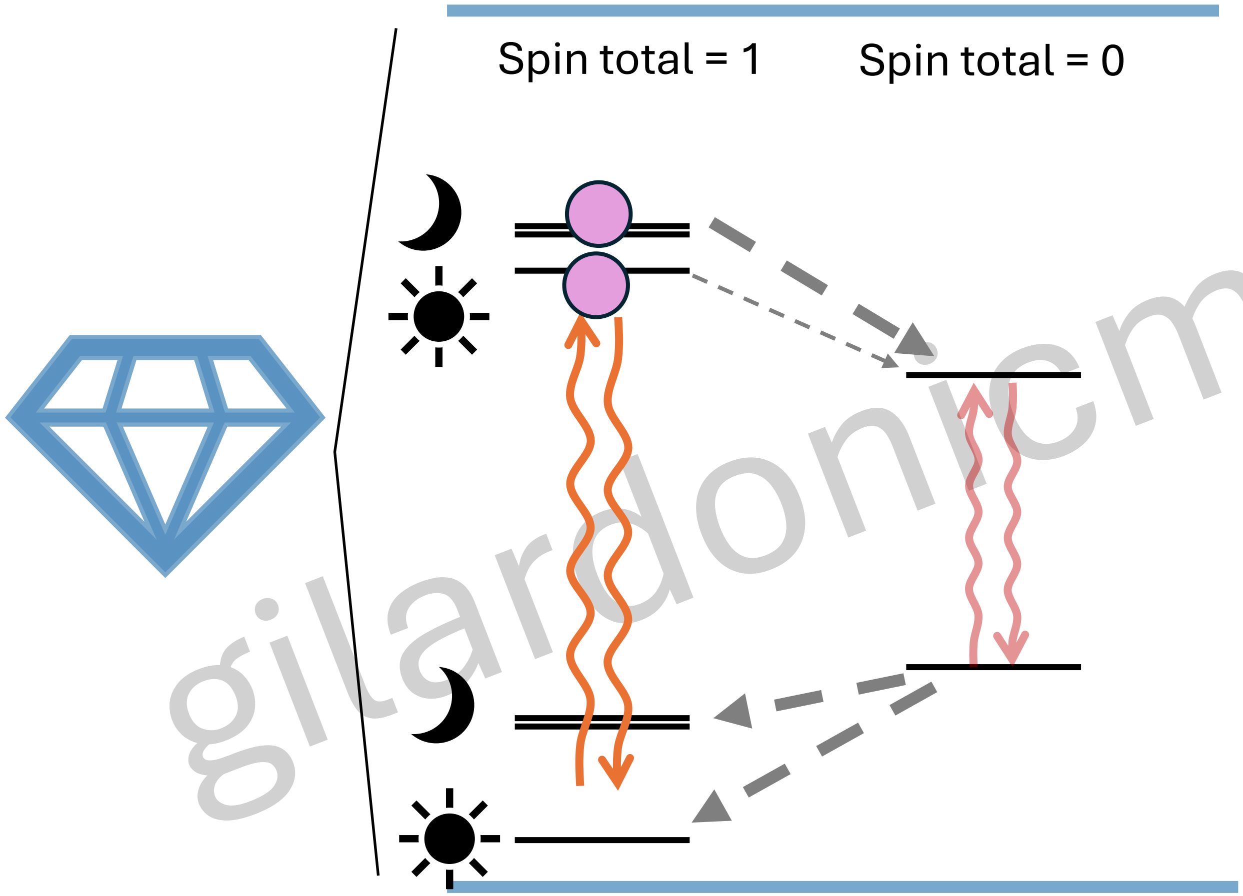

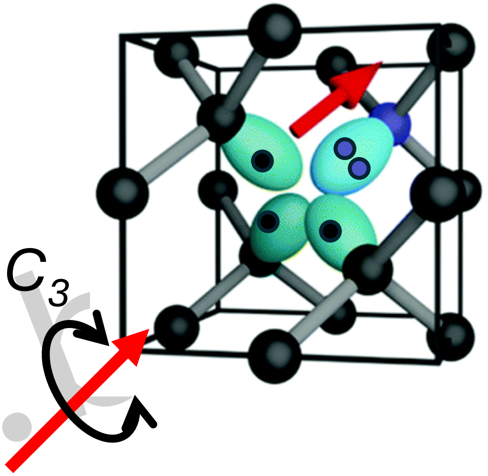

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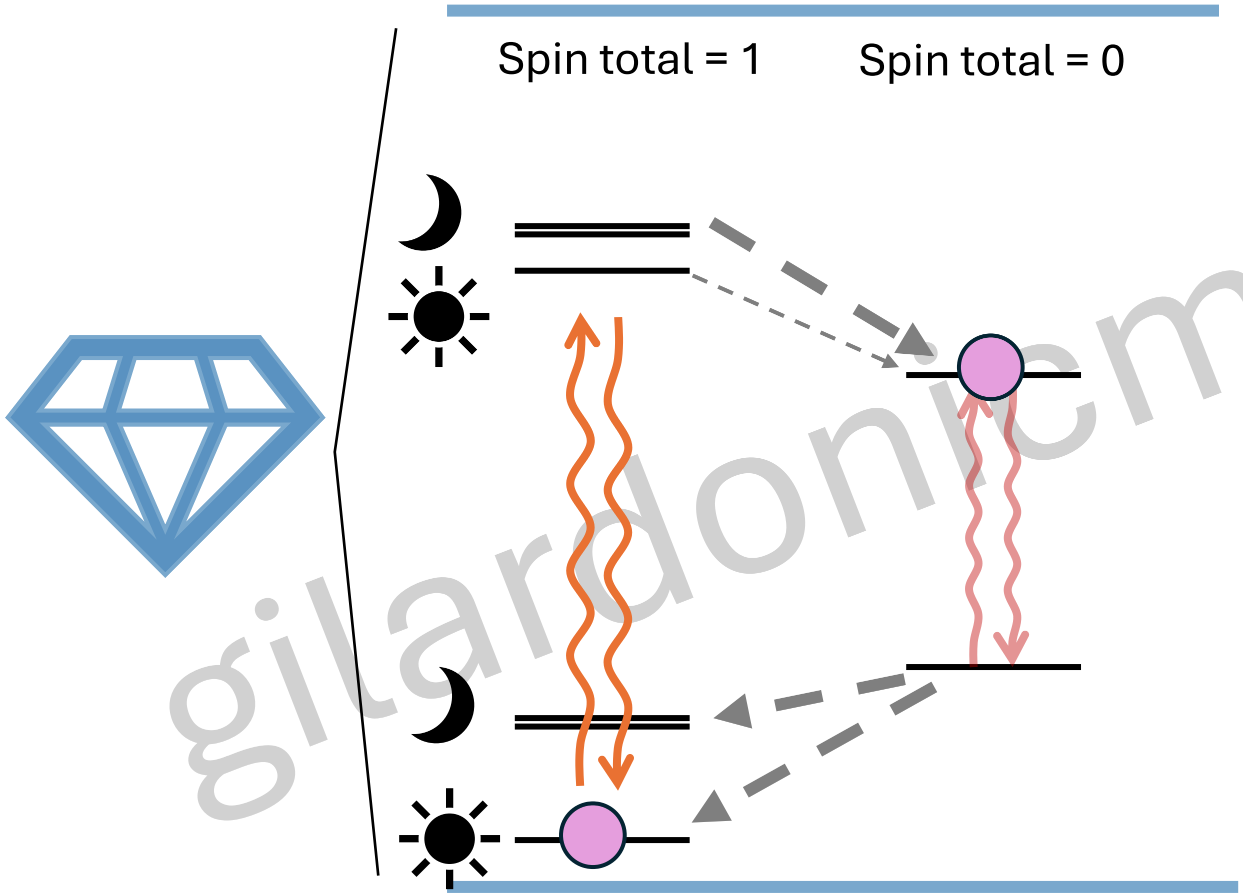
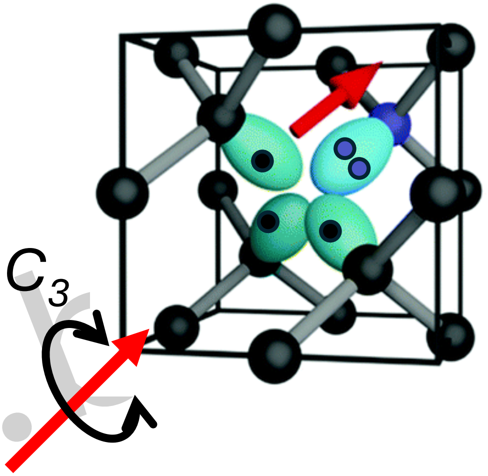
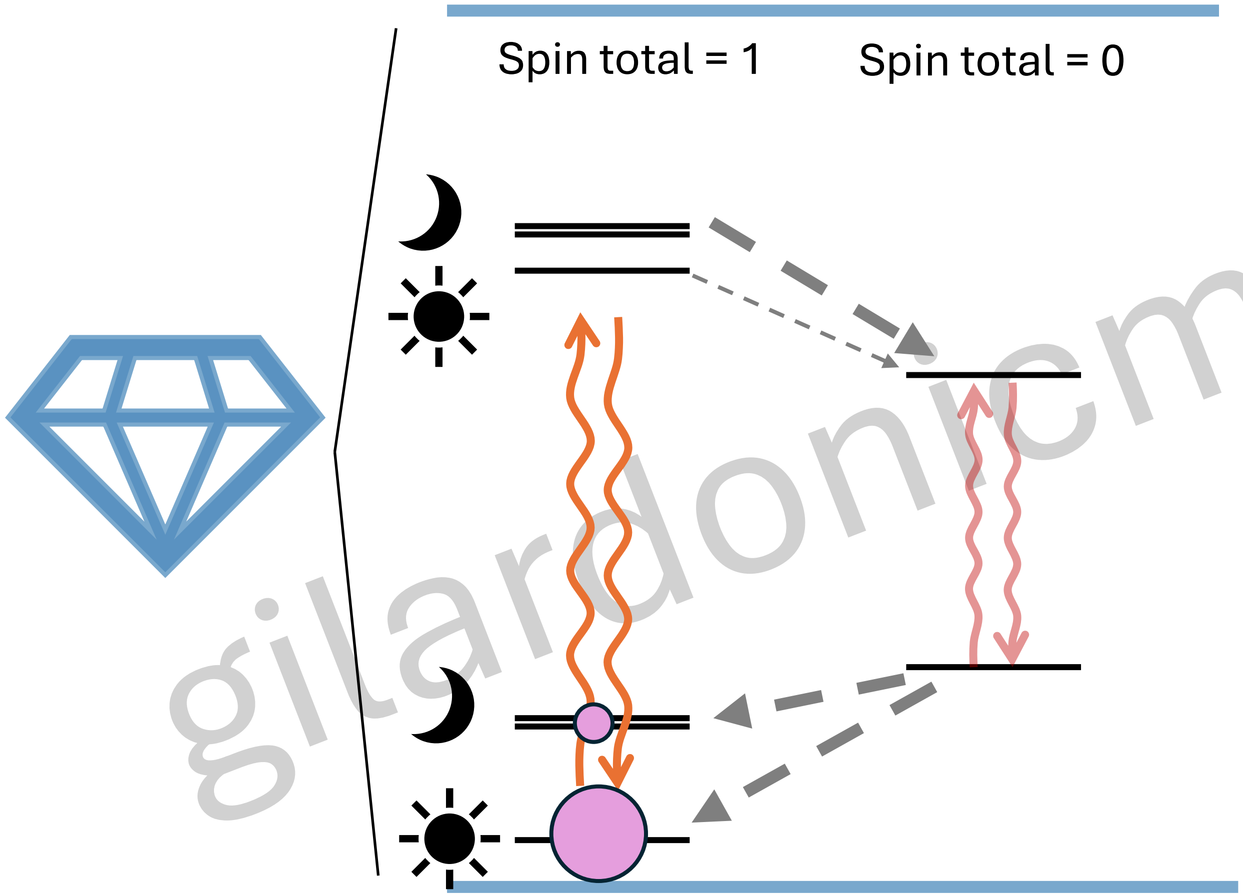
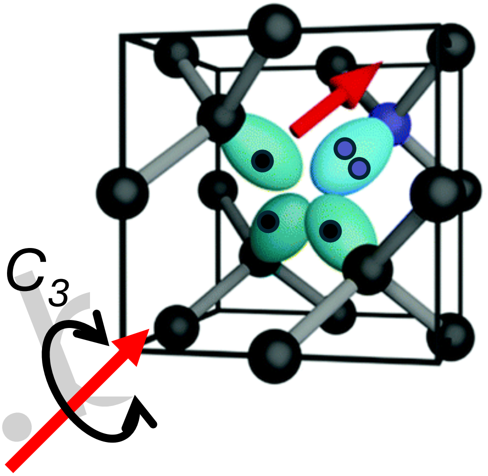




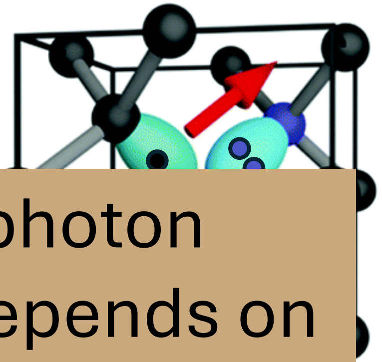
The NV$^-$ – photodynamics

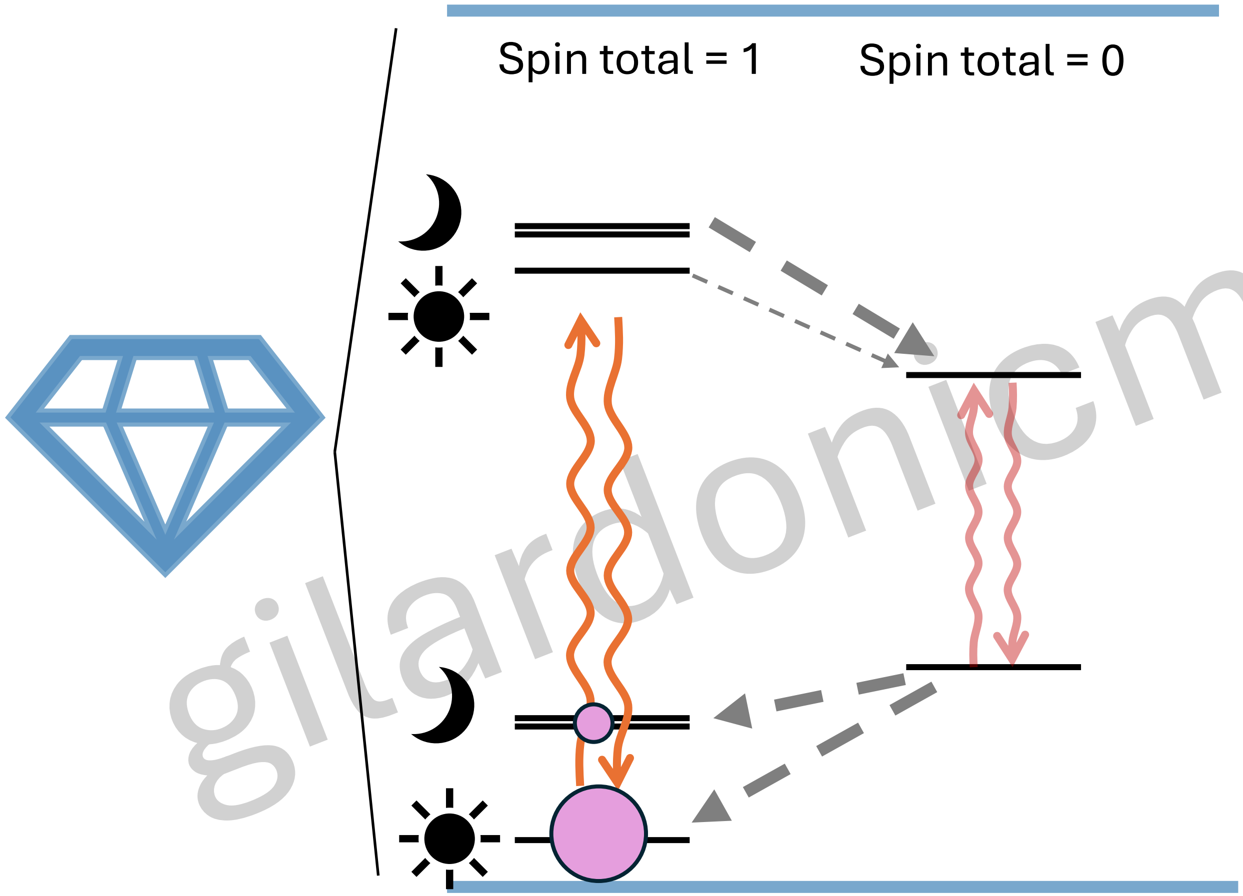




Consequence 2: Nv illumination allows you to *initialize* the spin through repeated optical transitions (even at room temperature, and non-resonantly!)

The NV$^-$ – photodynamics





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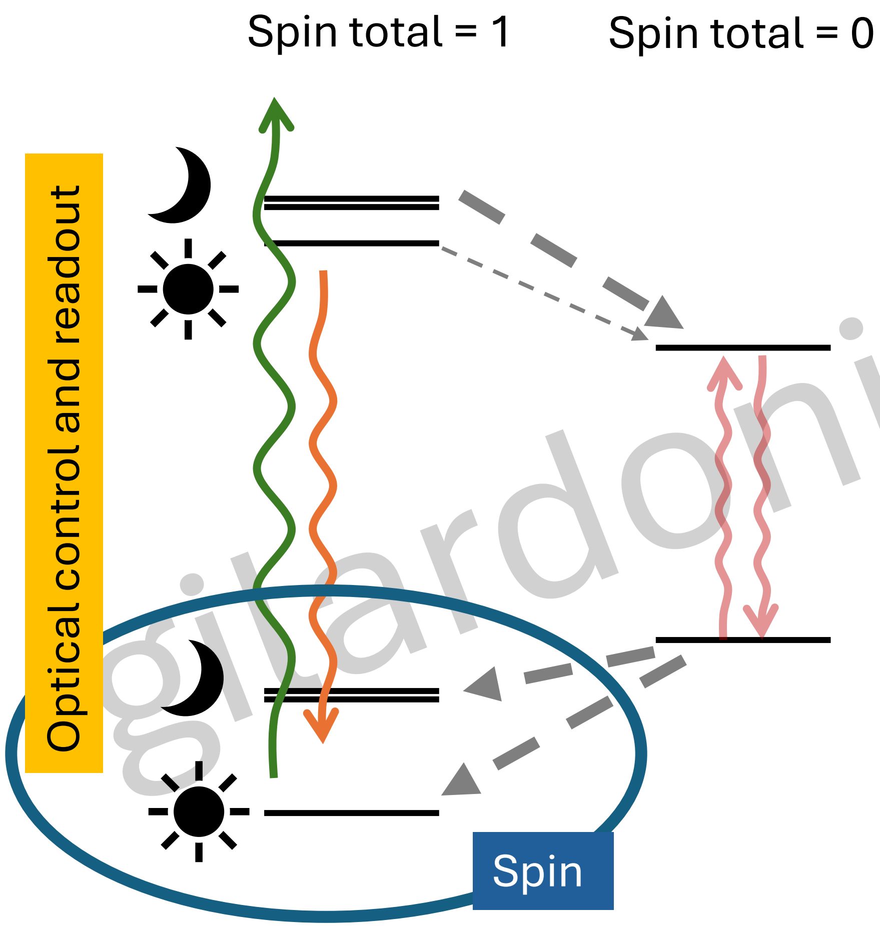
The NV^-



Qubit Operation Loop