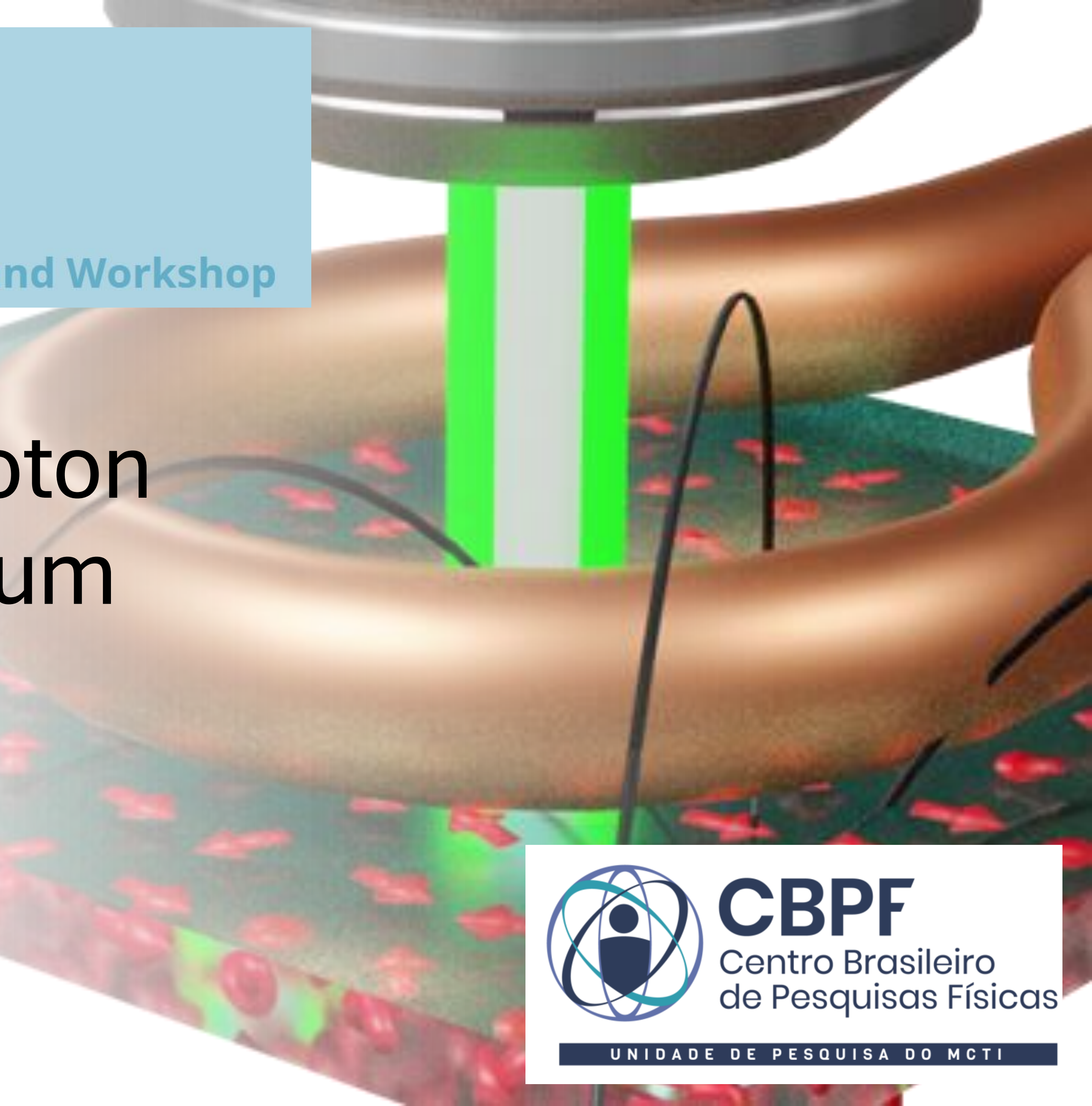
Paraty Quantum Information School and Workshop

Solid-state spin-photon interfaces for quantum technologies



Carmem M. Gilardoni
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Pesquisadora, CBPF

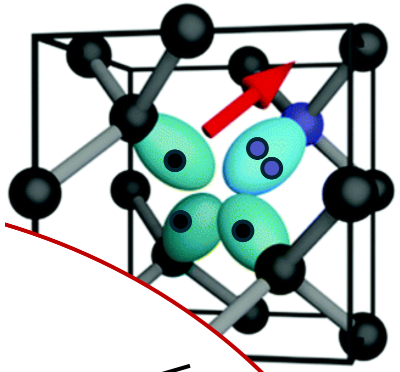
07/08/2025

CBPF
Centro Brasileiro de Pesquisas Físicas
UNIDADE DE PESQUISA DO MCTI

Agenda

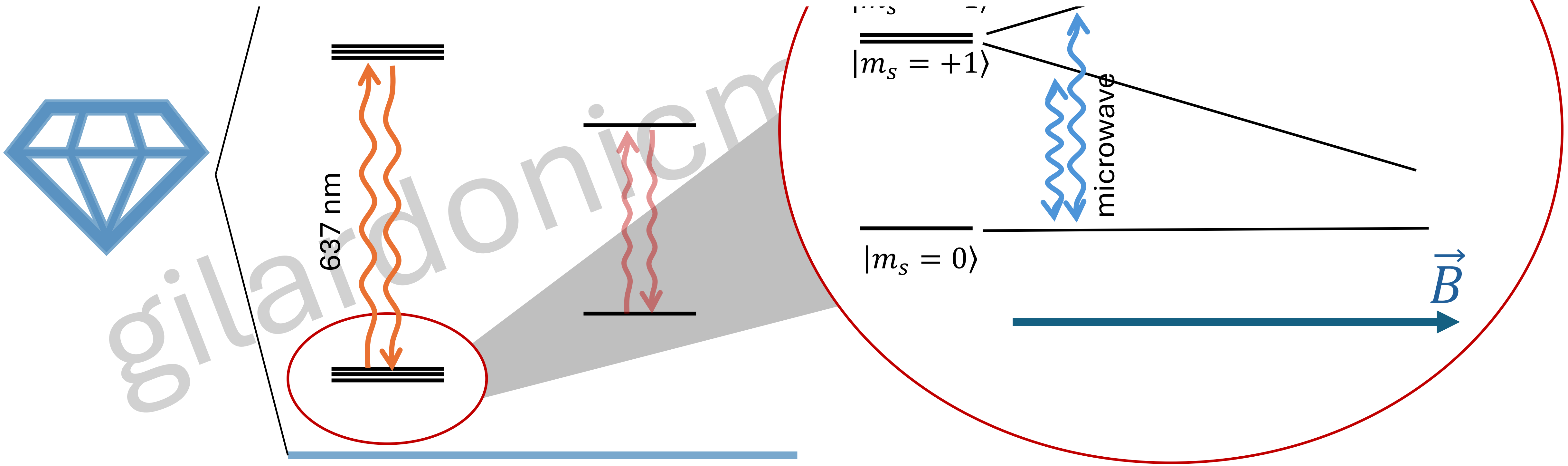
- Wednesday (06/08/2025) – Introduction: the need for spin-photon interfaces, examples of spin-photon interfaces, the NV system in diamond
- Thursday (07/08/2025) – The NV system in diamond: spin control protocols and implementation as quantum sensing and quantum computing platform.
- Saturday (09/08/2025)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

The NV⁻ – Fine structure of the ground state

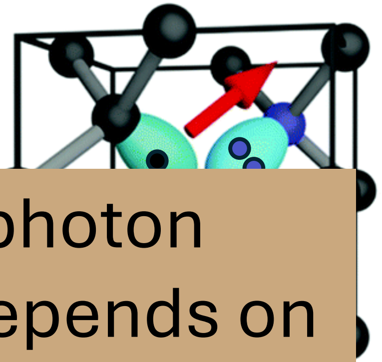


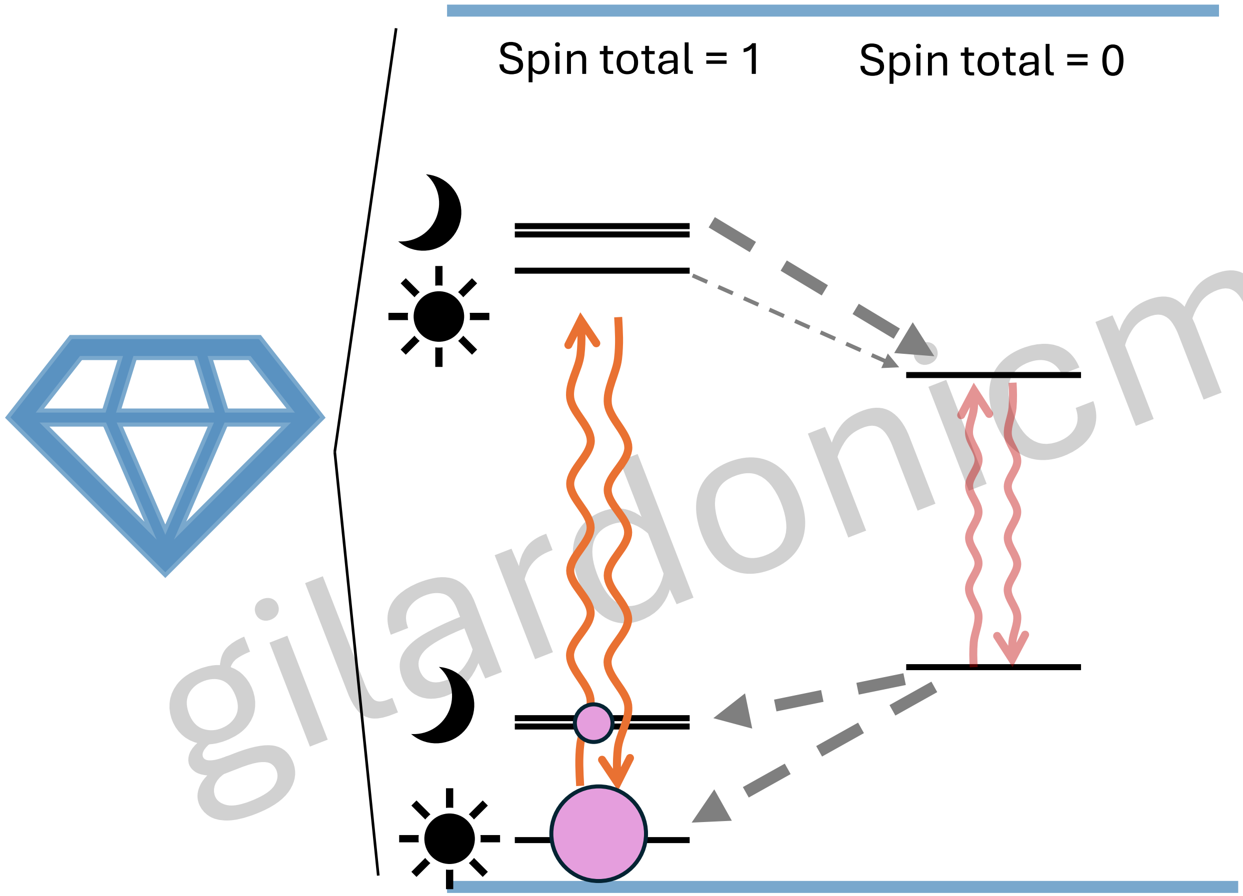
$$\hat{H} = \overbrace{\hbar D\left[\hat{S}_Z^2 - \frac{2}{3}\right] + \hbar E(\hat{S}_X^2 - \hat{S}_Y^2)}^{\text{zero-field term}} + \overbrace{\hbar\gamma_{nv}\vec{B}\cdot\hat{\vec{S}}}^{\text{magnetic interaction}} \overbrace{+\hbar\delta_{\parallel}\mathcal{E}_Z\left[\hat{S}_Z^2 - \frac{2}{3}\right]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

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



The NV⁻ – photodynamics

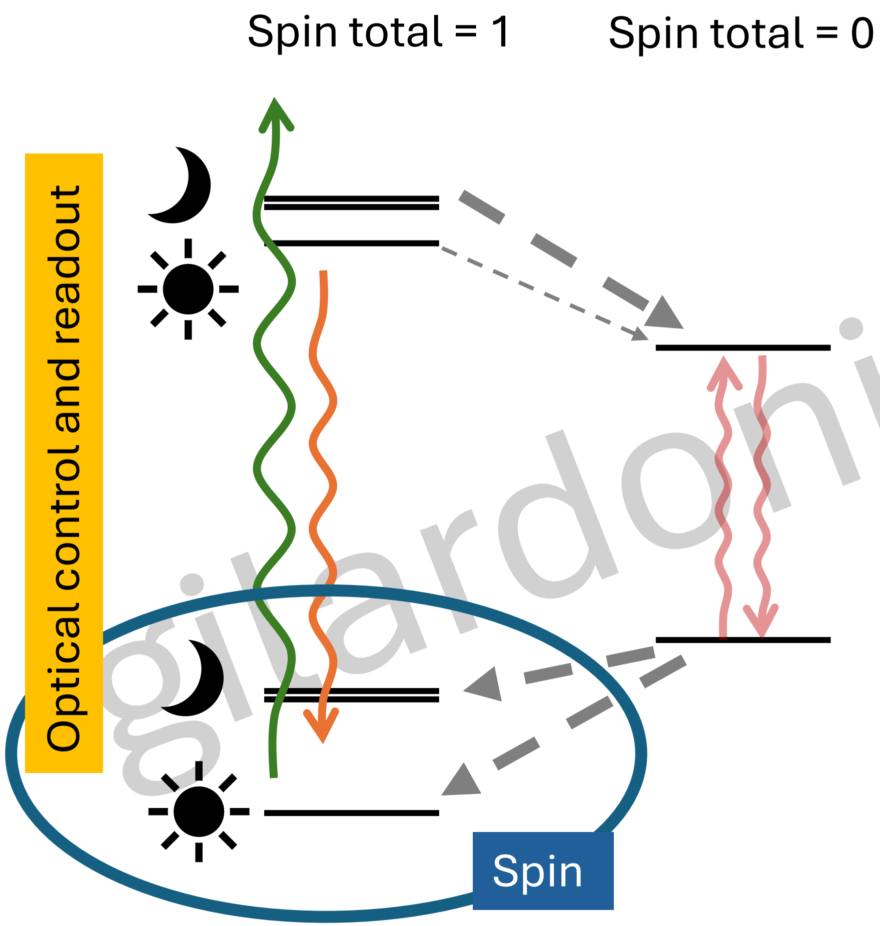




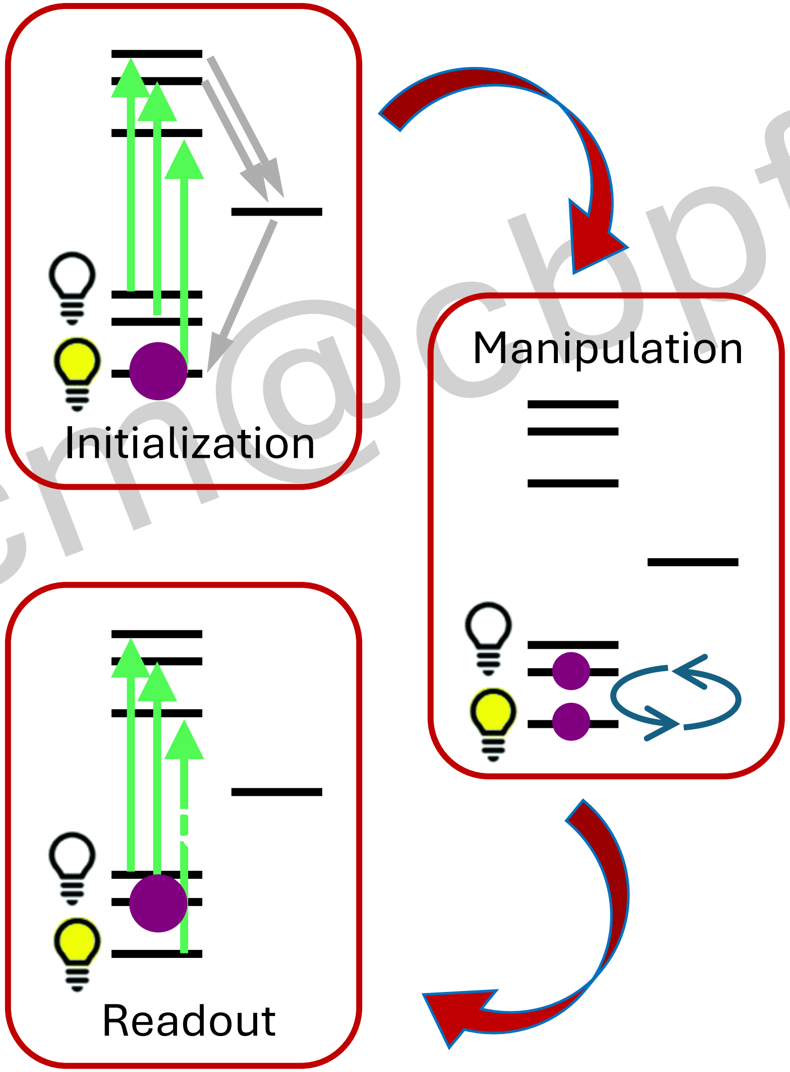
Consequence 1: The photon emission rate of NV depends on the spin state! I can *read* the spin state by detecting the emitted photons

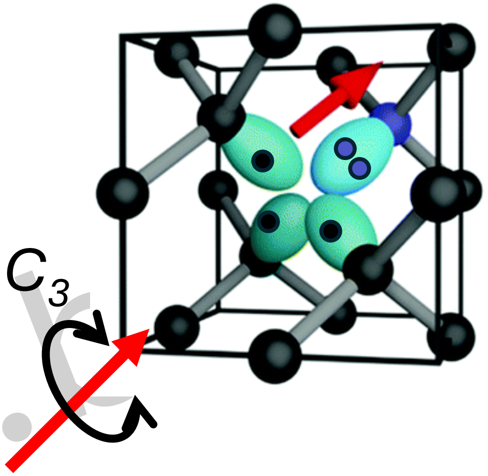
Consequence 2: NV illumination allows you to *initialize* the spin through repeated optical transitions (even at room temperature!)

The NV$^-$

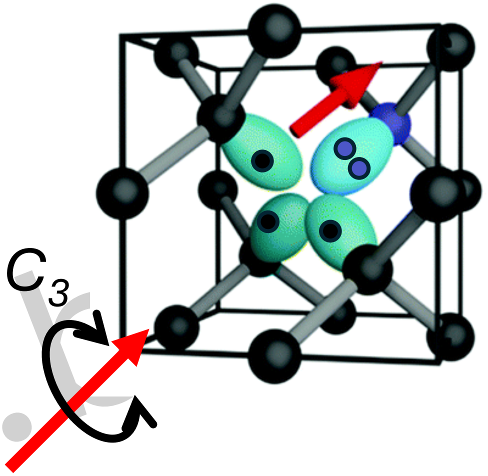


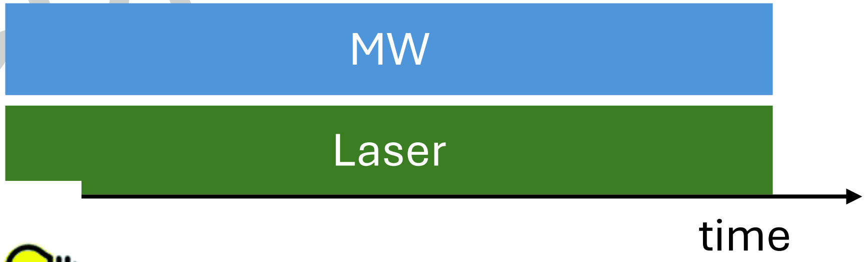
Qubit Operation Loop

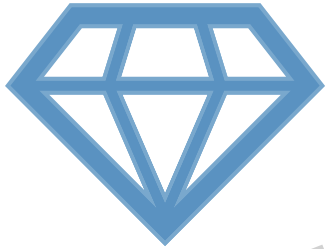


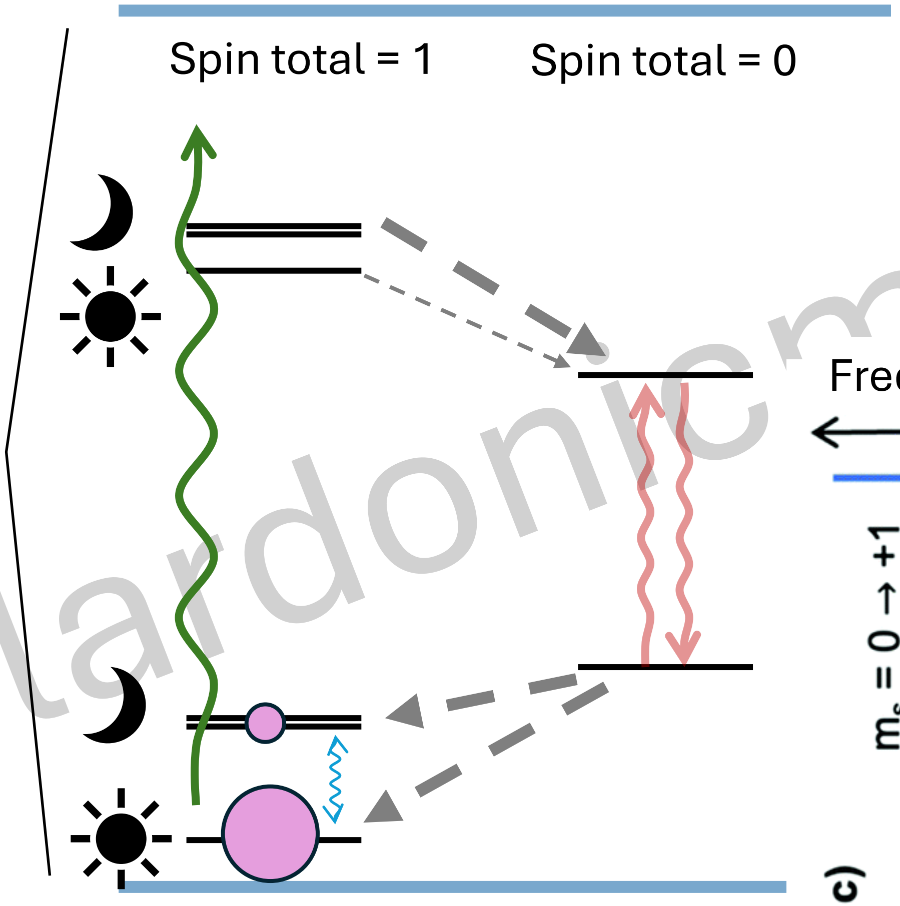


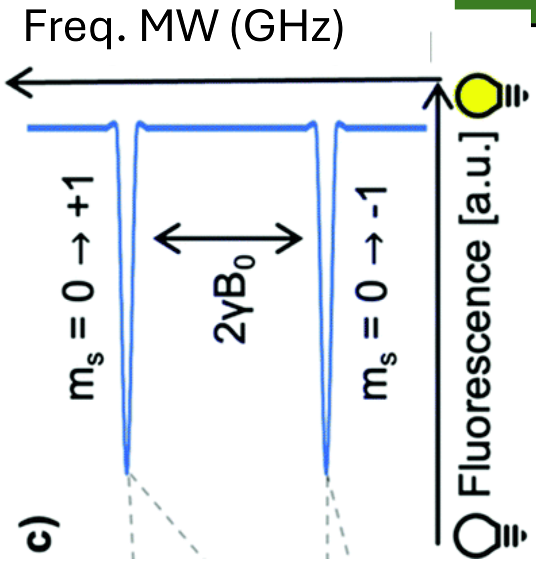
The NV^- – the continuous wave experiments





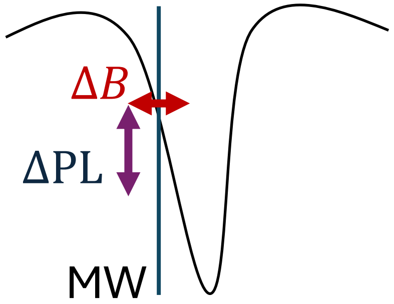






Chem. Commun., 2022, **58**, 8165

$$\eta_{DC} \propto \frac{1}{df/dB} \frac{\Delta\nu}{C\sqrt{PL}}$$



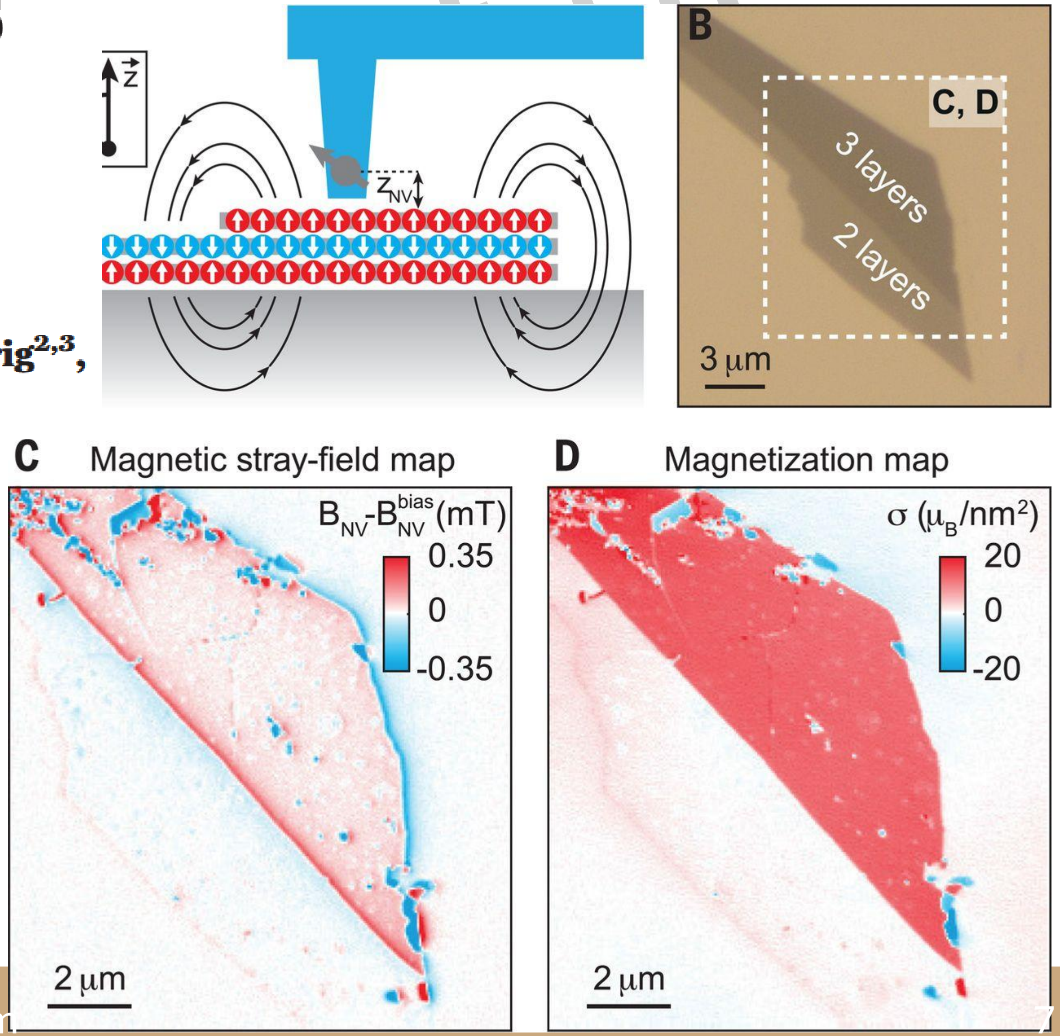
REPORT

MAGNETISM

Probing magnetism in 2D materials at the nanoscale with single-spin microscopy

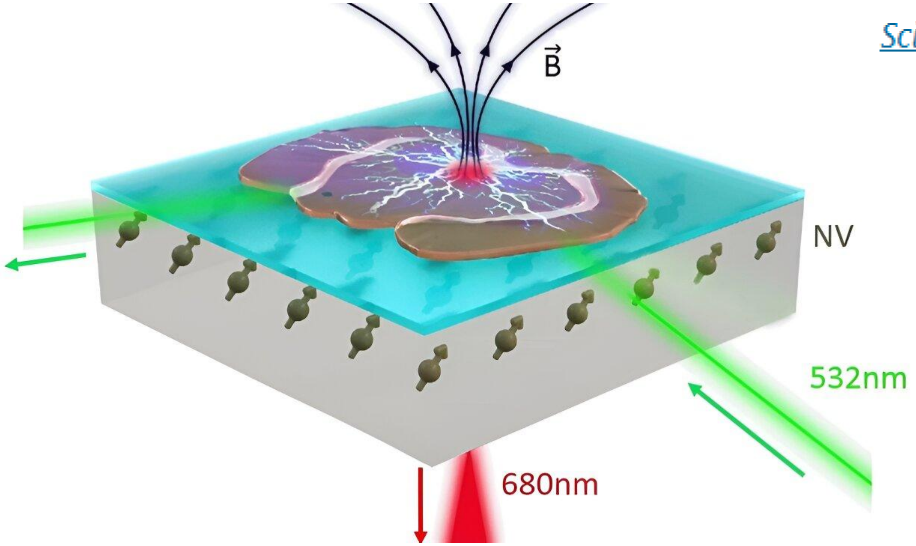
L. Thiel[1], Z. Wang[2,3], M. A. Tschudin[1], D. Rohner[1], I. Gutiérrez-Lezama[2,3], N. Ubrig[2,3], M. Gibertini[2,4], E. Giannini[2], A. F. Morpurgo[2,3], P. Maletinsky[1*]

Thiel *et al.*, *Science* **364**, 973–976 (2019)

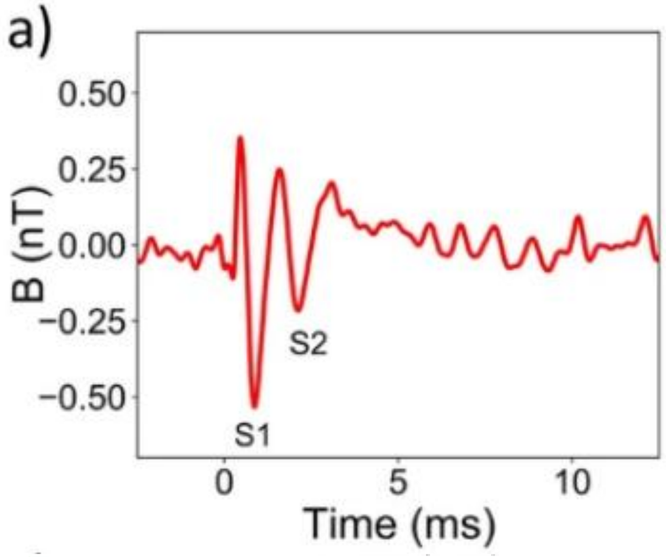


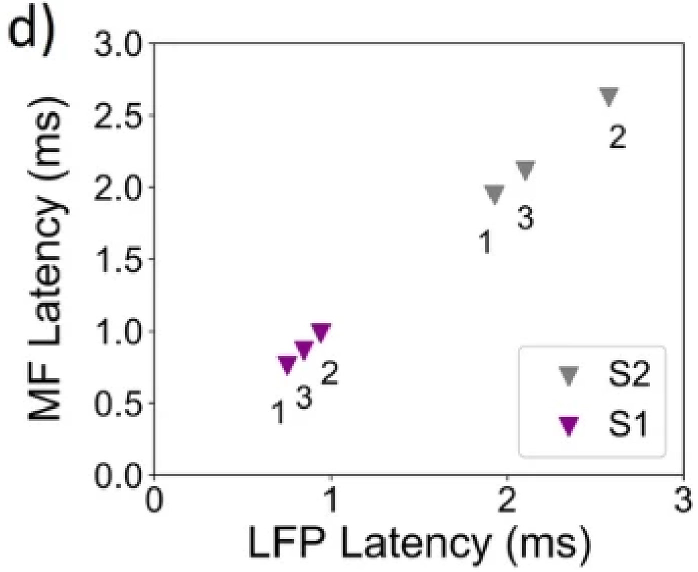
Microscopic-scale magnetic recording of brain neuronal electrical activity using a diamond quantum sensor

Nikolaj Winther Hansen[1,9], James Luke Webb[2,9]✉, Luca Troise[2,9], Christoffer Olsson[3], Leo Tomasevic[4], Ovidiu Brinza[5], Jocelyn Achard[5], Robert Staacke[6], Michael Kieschnick[6], Jan Meijer[6], Axel Thielscher[3,4], Hartwig Roman Siebner[4,7,8], Kirstine Berg-Sørensen[3], Jean-François Perrier[1], Alexander Huck[2] & Ulrik Lund Andersen[2]



Scientific Reports **13**, Article number: 12407 (2023)





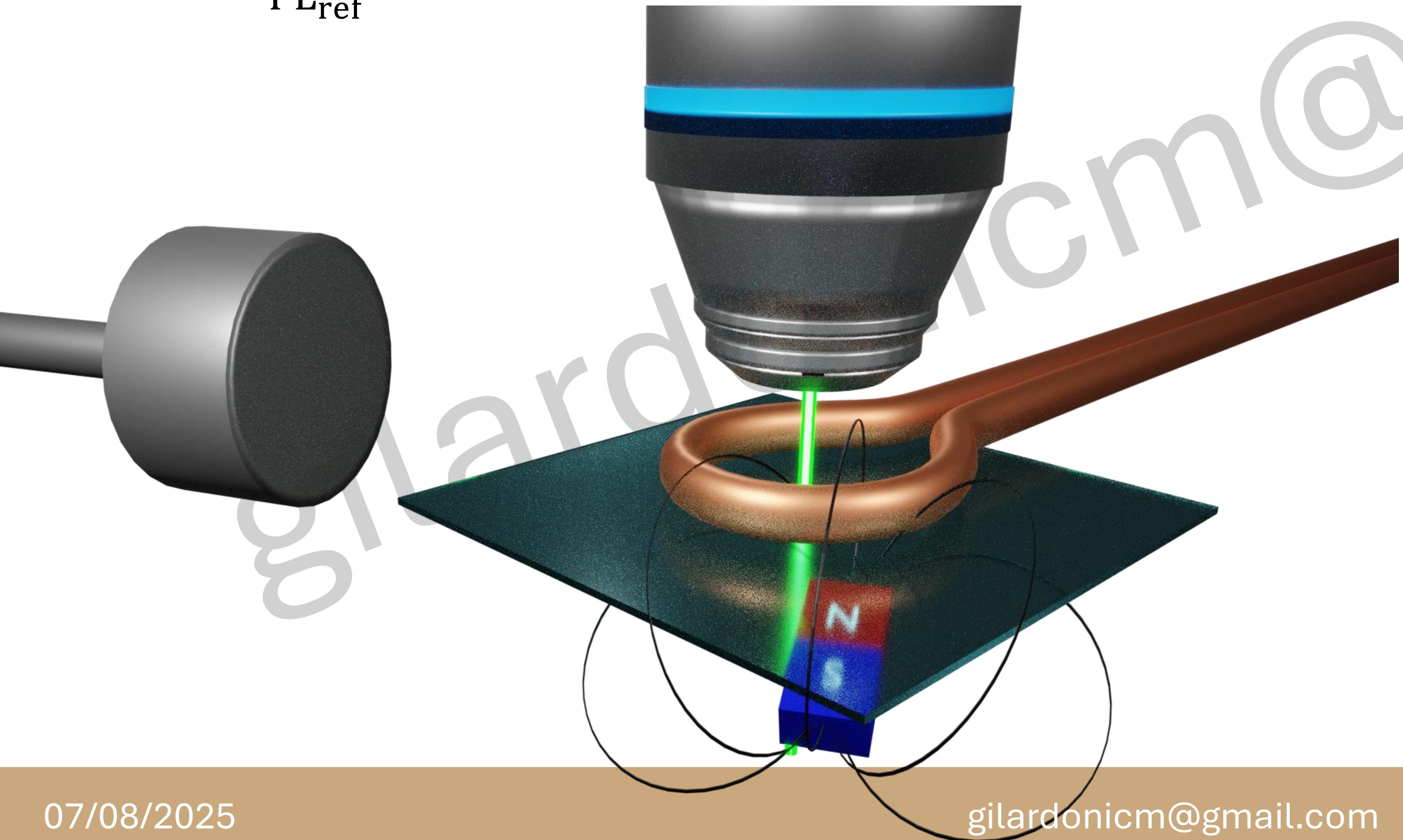
$$\eta_{DC} \propto \frac{1}{df/dB} \frac{\Delta\nu}{C\sqrt{PL}}$$

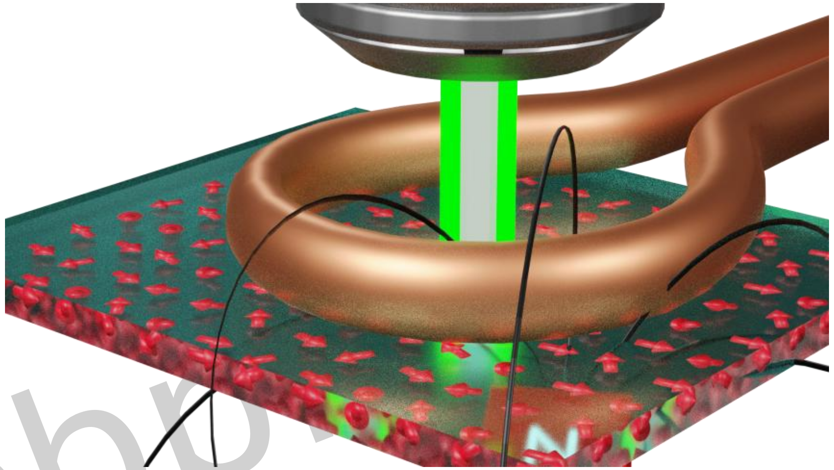
Laser

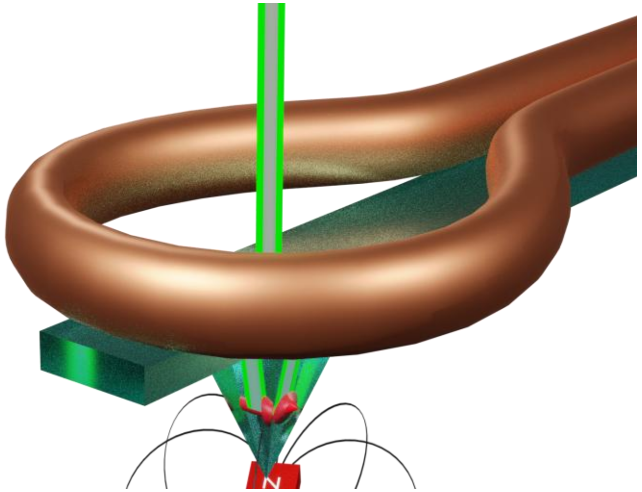
MW

signal Ref.

$$C = \frac{PL_{Sig} - PL_{ref}}{PL_{ref}}$$





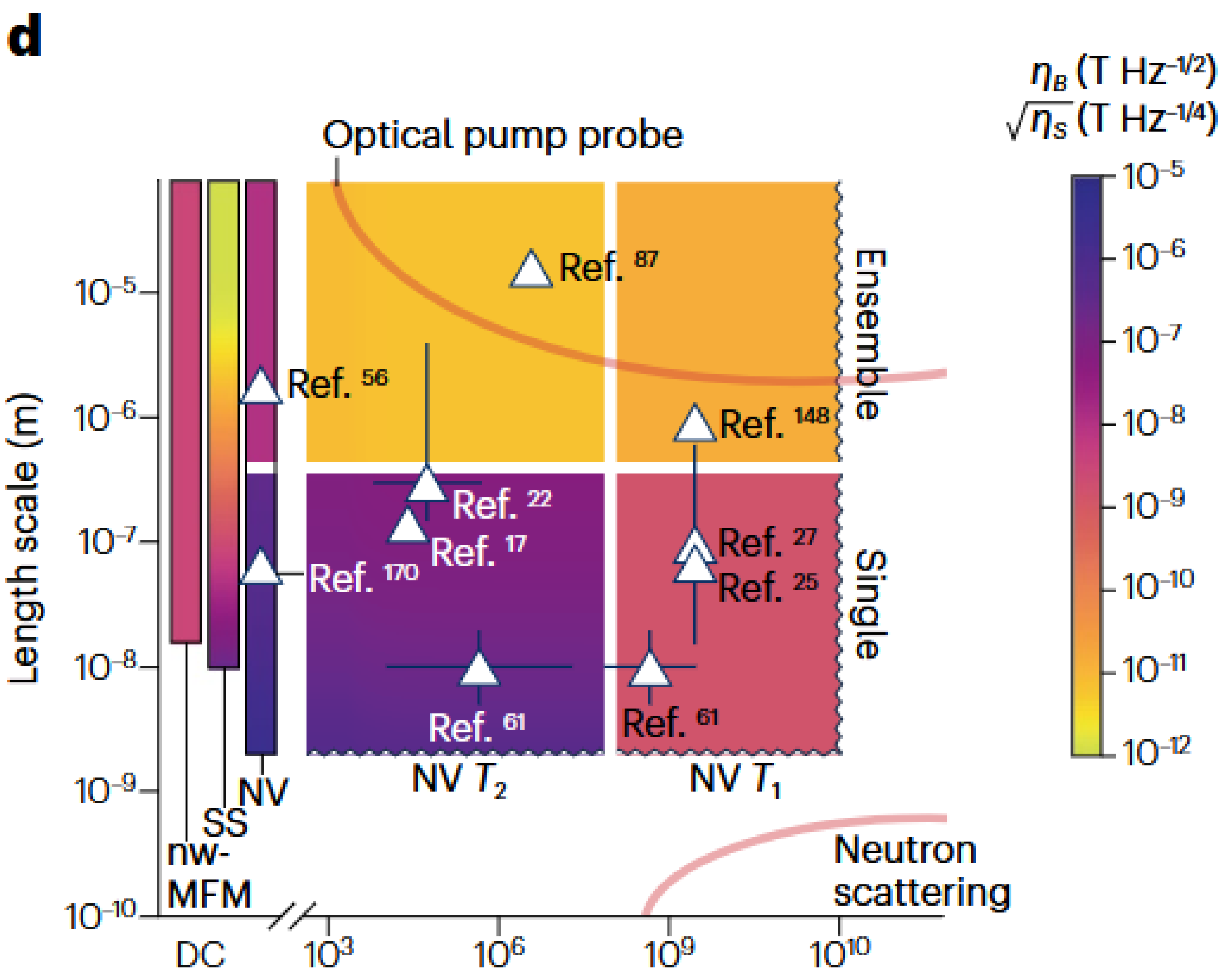


Laser

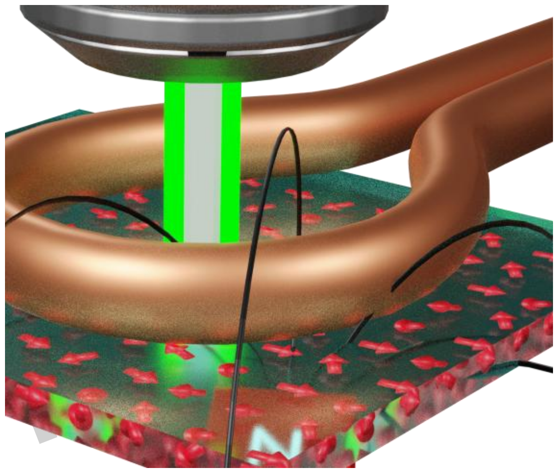
MW

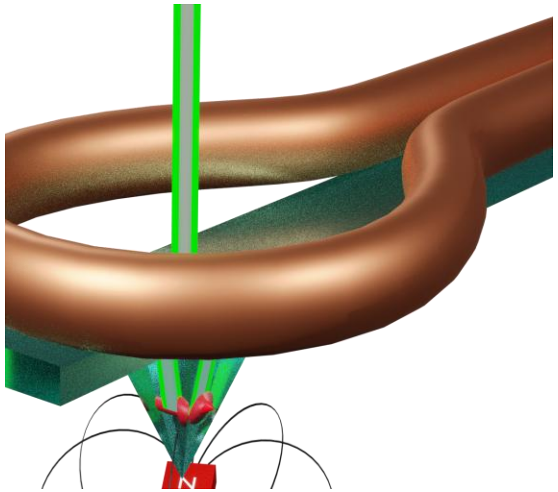
Itself | Ref

$$C = \frac{PL_{Sig} - PL_{ref}}{PL_{ref}}$$



Nature Reviews Physics
| Volume 6 | December 2024 | 753–768

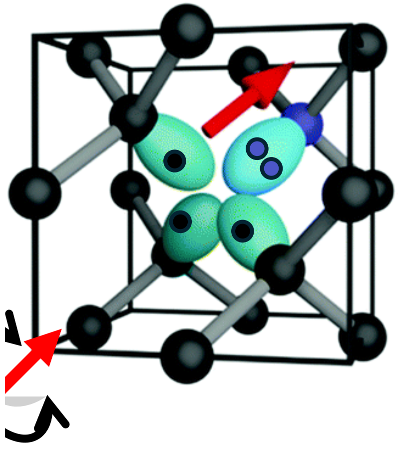


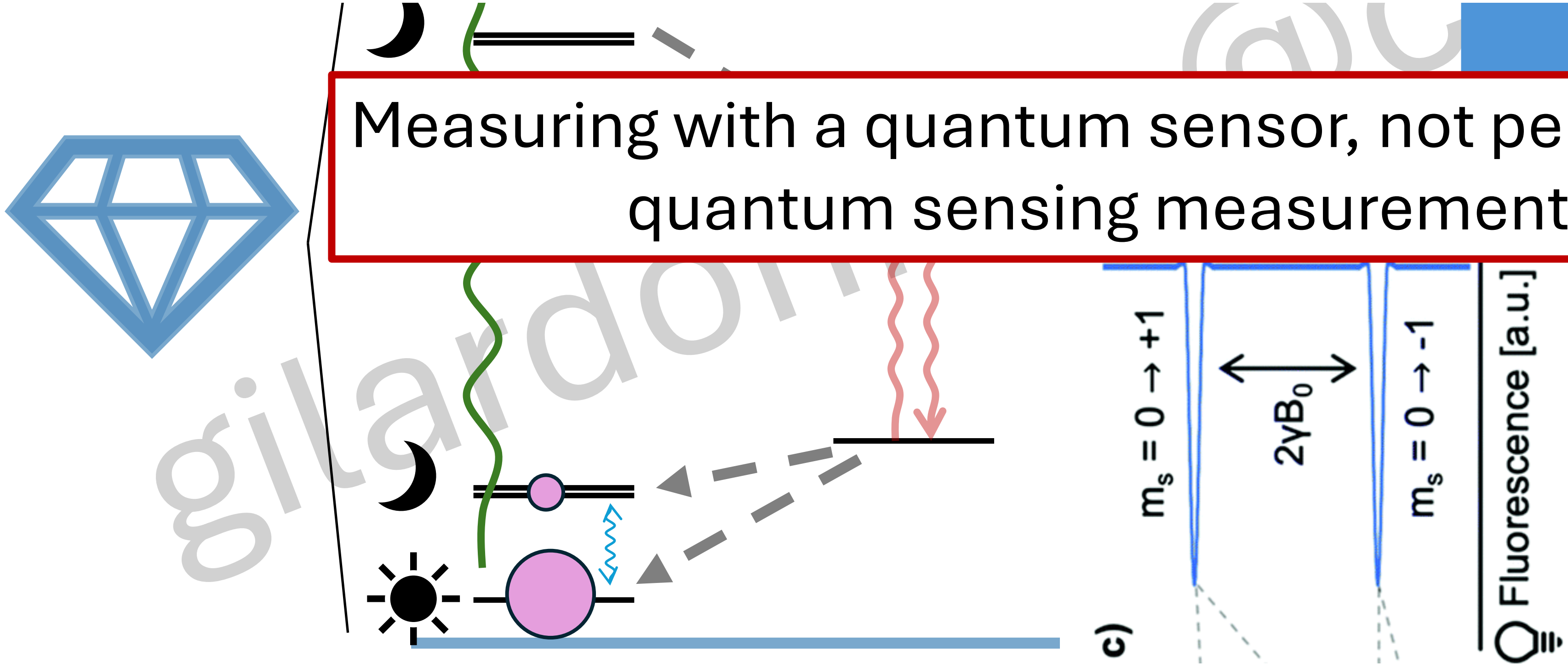


The NV⁻ – the CW experiments

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

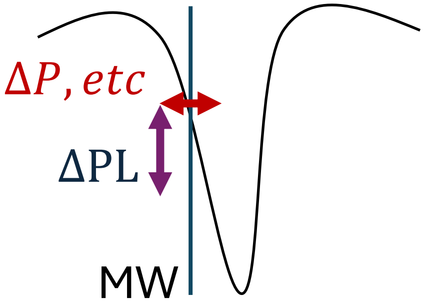
$$+\hbar\sum_{i=1}^{n}\left(\underbrace{\hat{\vec{S}}\,\mathcal{N}_i\hat{\vec{I}}_i}_{\text{hyperfine interaction}} + \underbrace{\gamma_i\vec{B}\cdot\hat{\vec{I}}_i}_{\text{nuclear Zeeman interaction}} + \underbrace{Q_i\hat{I}_{Z,i}^2}_{\text{nuclear quadrupole interaction}}\right)$$





Measuring with a quantum sensor, not performing a quantum sensing measurement!

$$\eta_{DC} \propto \frac{1}{df/dB}\frac{\Delta\nu}{C\sqrt{PL}}$$



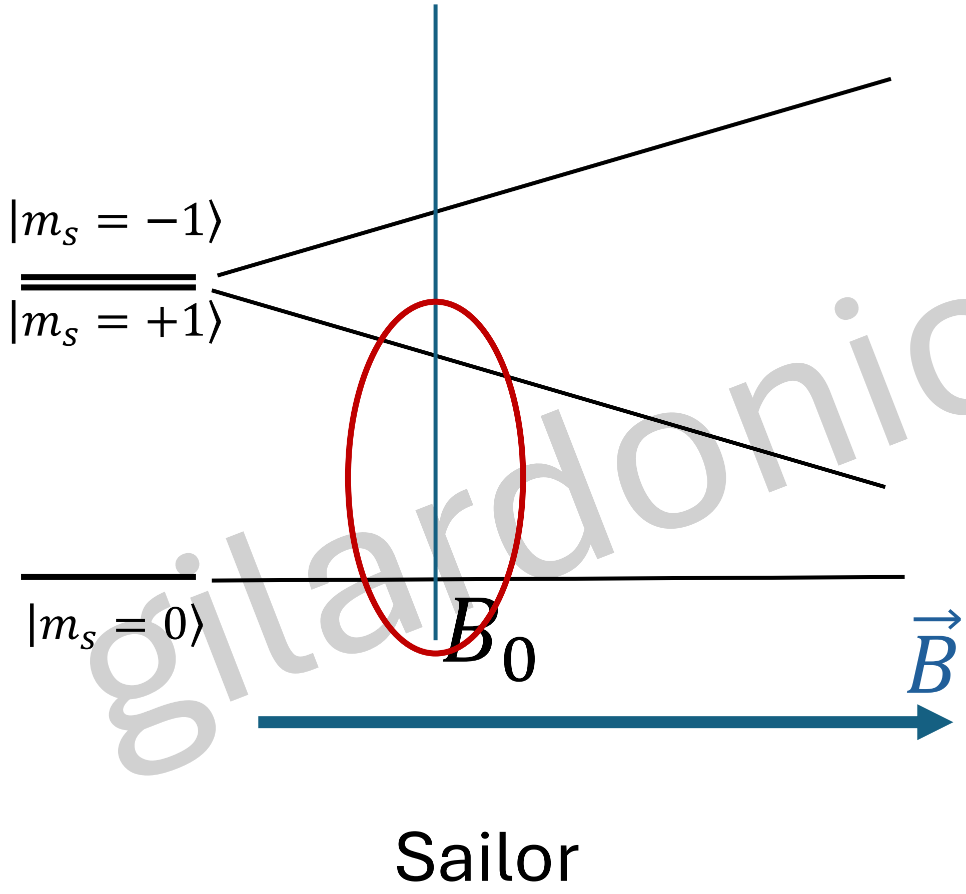
Chem. Commun., 2022, **58**, 8165

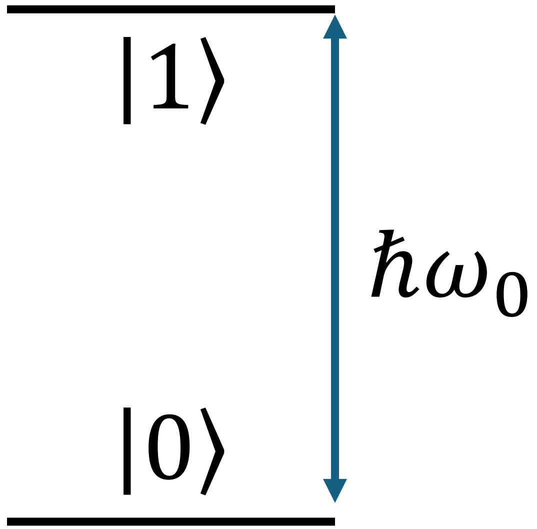
Ramsey, Echoes, Relaxometry

- The quantum state and its evolution in time

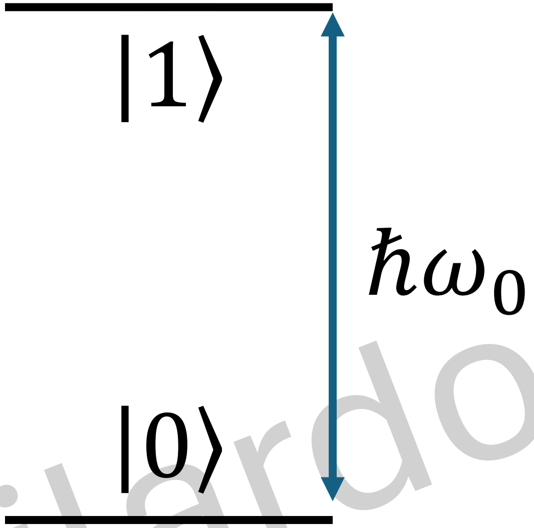
$$i\hbar \frac{\partial}{\partial t}|\psi(t)\rangle = H_0|\psi(t)\rangle$$

$$|\psi(t)\rangle = e^{-i\frac{H_0 t}{\hbar}}|\psi_0\rangle$$





Ramsey, Echoes, Relaxometry



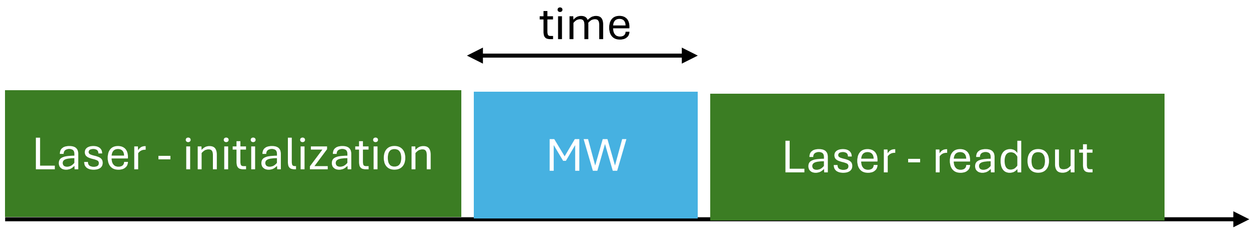
$$i\hbar\frac{\partial}{\partial t}|\psi(t)\rangle = H_0|\psi(t)\rangle$$

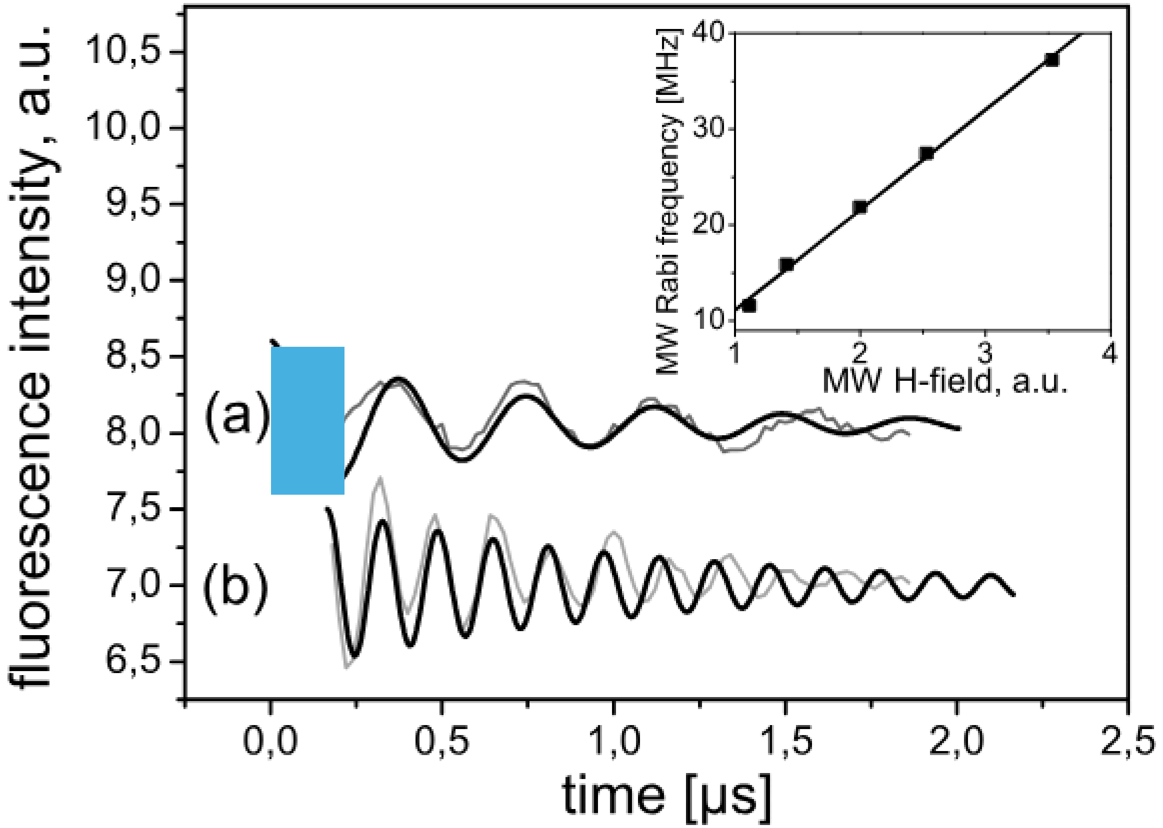
$$|\psi(t)\rangle = e^{-i\frac{H_0 t}{\hbar}}|\psi_0\rangle$$

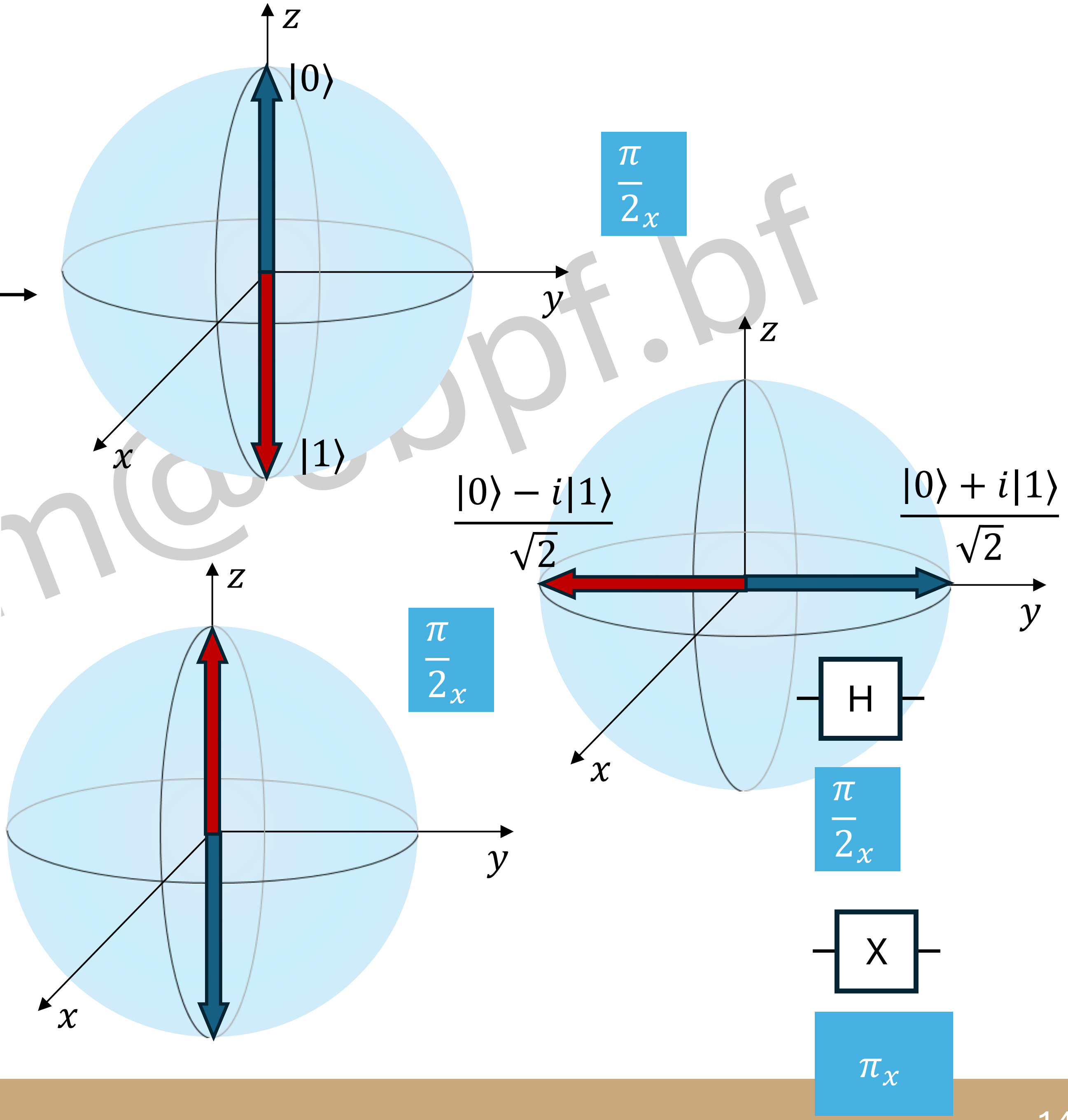
if $|\psi_0\rangle = c_0|0\rangle + c_1|1\rangle$,

$$|\psi(t)\rangle = c_0|0\rangle + c_1 e^{-i\omega_0 t}|1\rangle$$

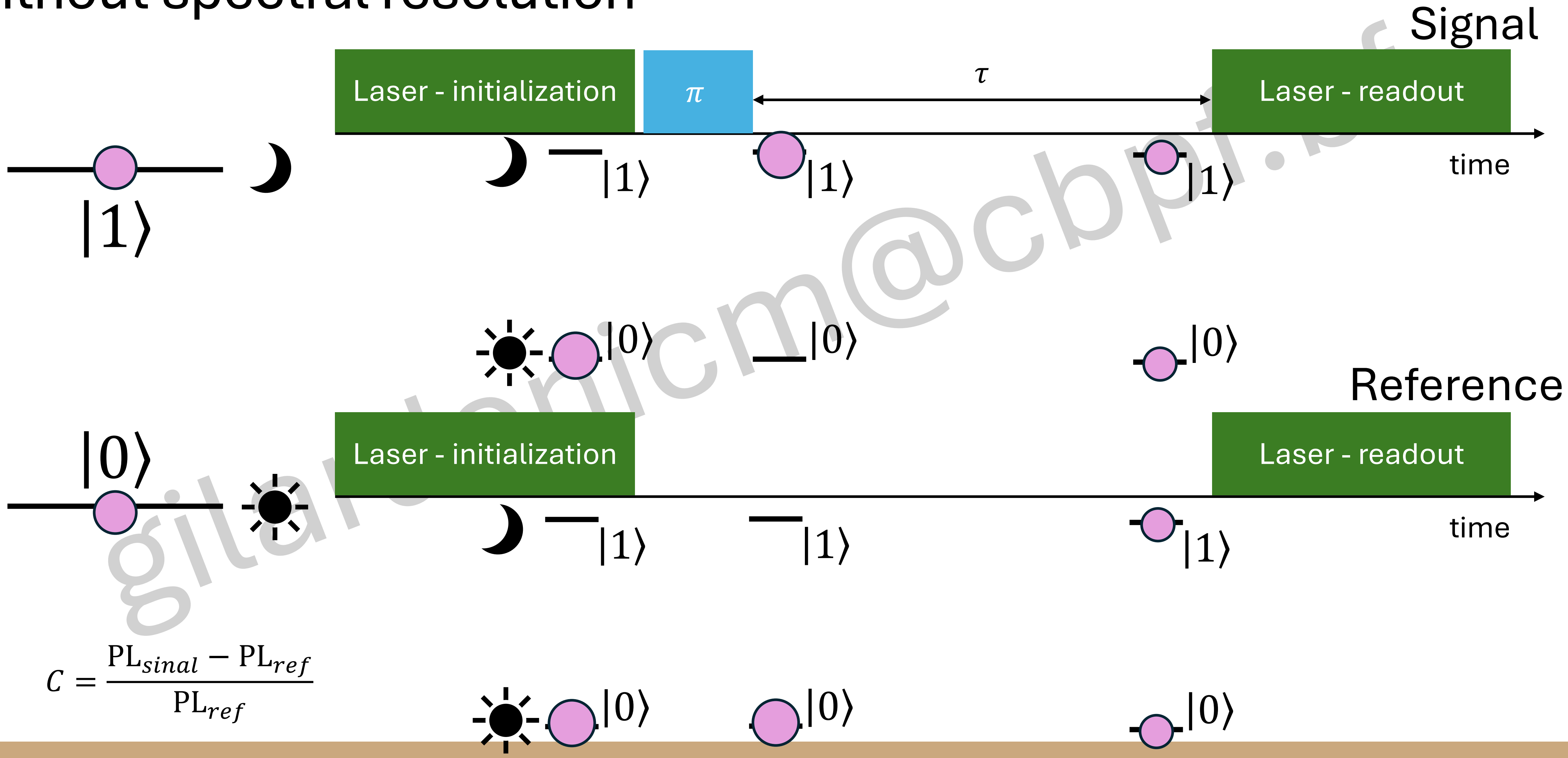
The effect of microwave pulses





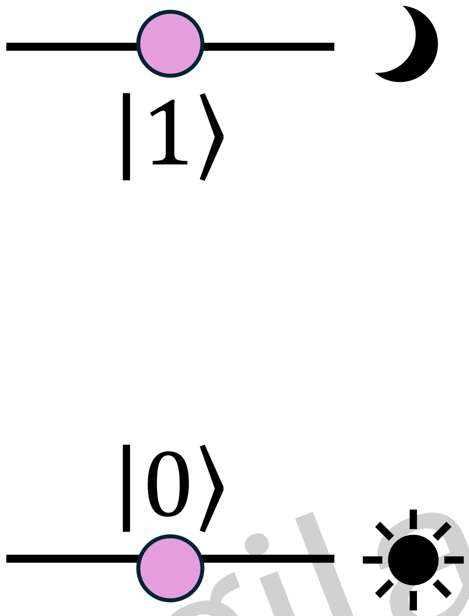


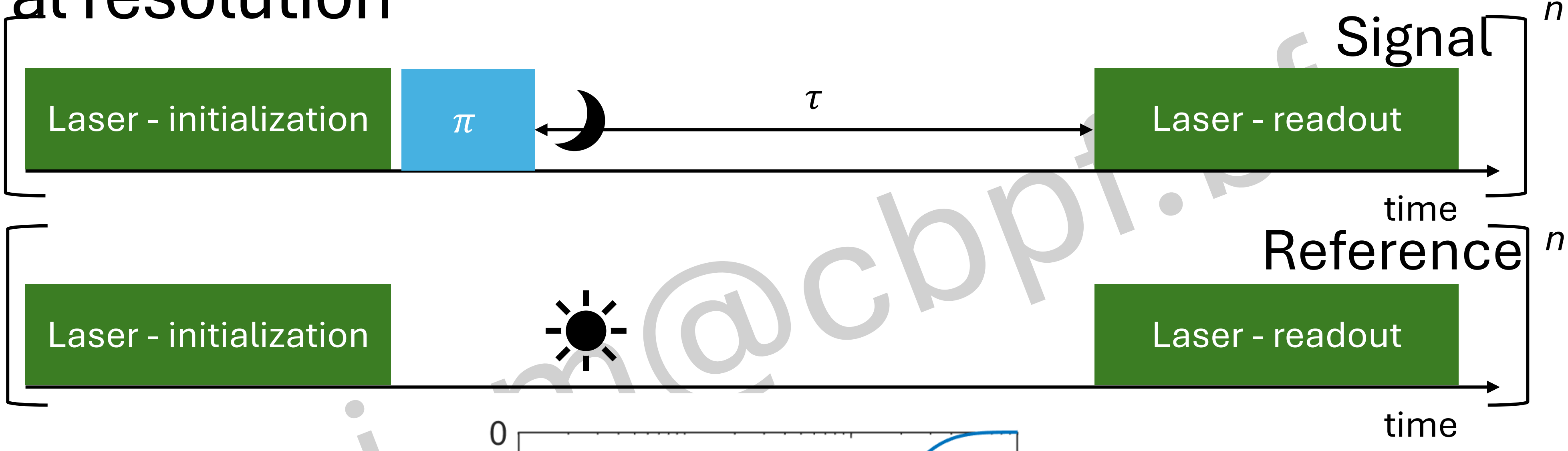
Relaxometry Measurement – quantum sensor of AC fields without spectral resolution

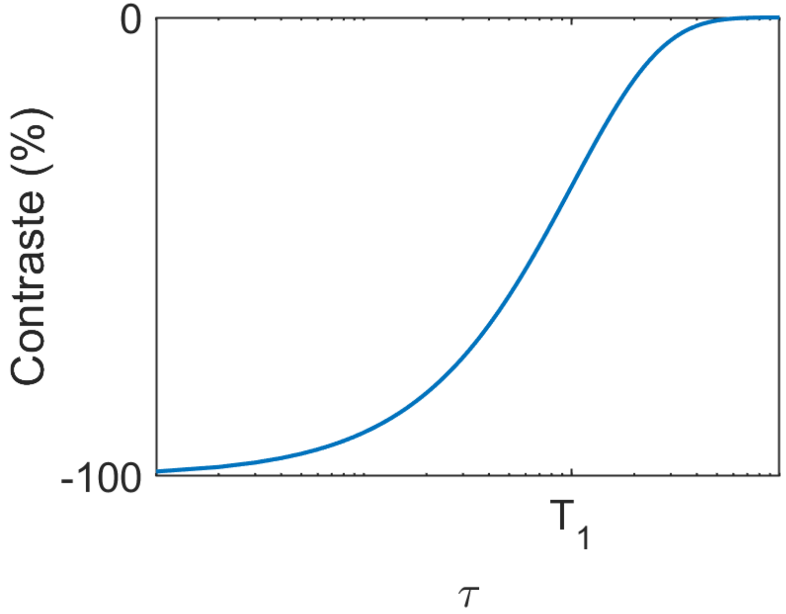


$$C = \frac{\mathrm{PL}_{sinal} - \mathrm{PL}_{ref}}{\mathrm{PL}_{ref}}$$

Relaxometry Measurement – quantum sensor of AC fields without spectral resolution





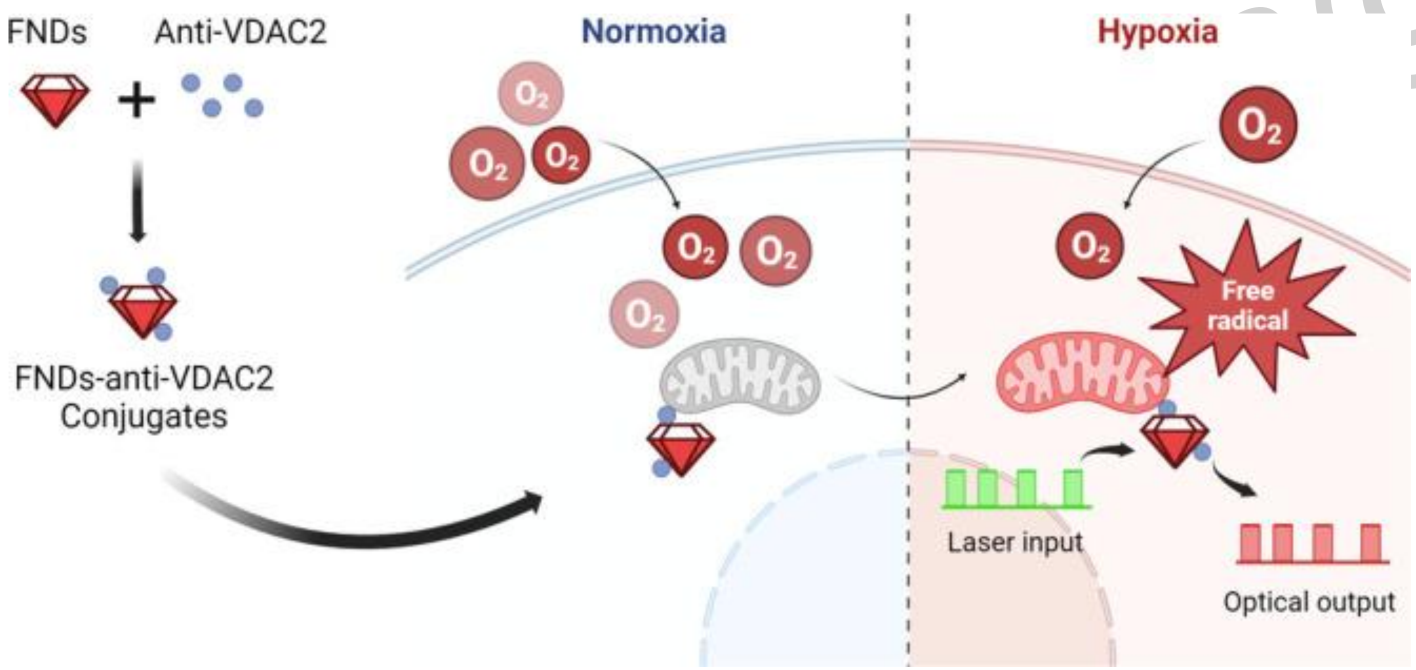


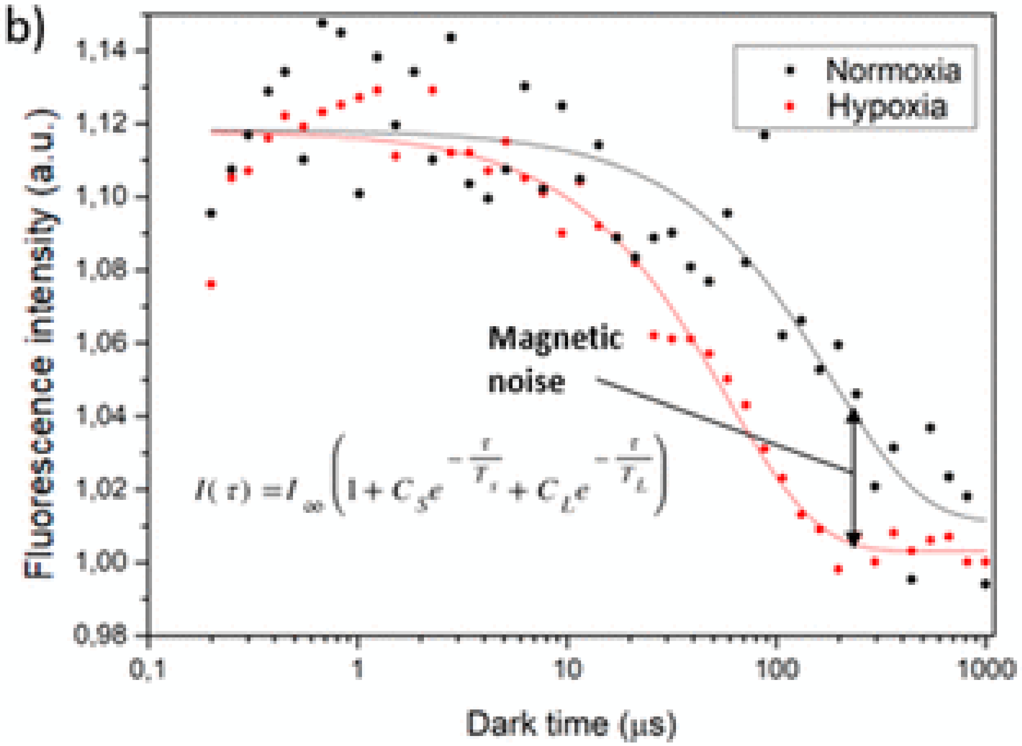
$$C = \frac{\mathrm{PL}_{sinal} - \mathrm{PL}_{ref}}{\mathrm{PL}_{ref}}$$

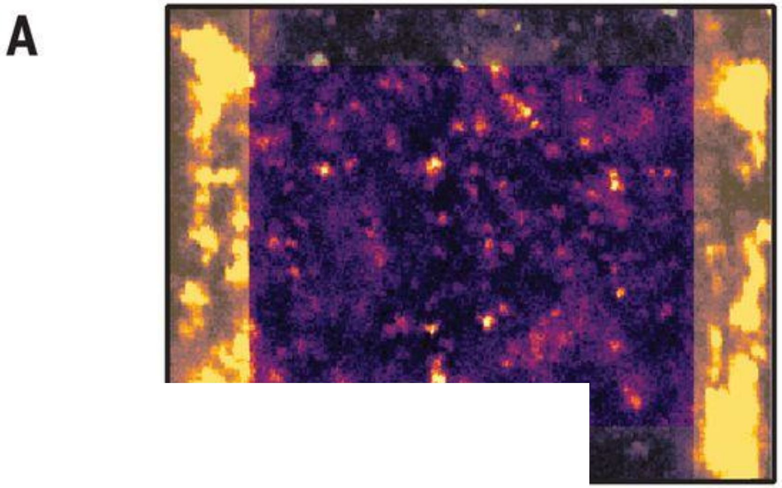
Quantum Sensing of Free Radical Generation in Mitochondria of Single Heart Muscle Cells during Hypoxia and Reoxygenation

Siyu Fan, Han Gao, Yue Zhang, Linyan Nie, Raquel Bártolo, Reinier Bron, Hélder A. Santos, and Romana Schirhagl*

Cite This: *ACS Nano* 2024, 18, 2982–2991 Read Online







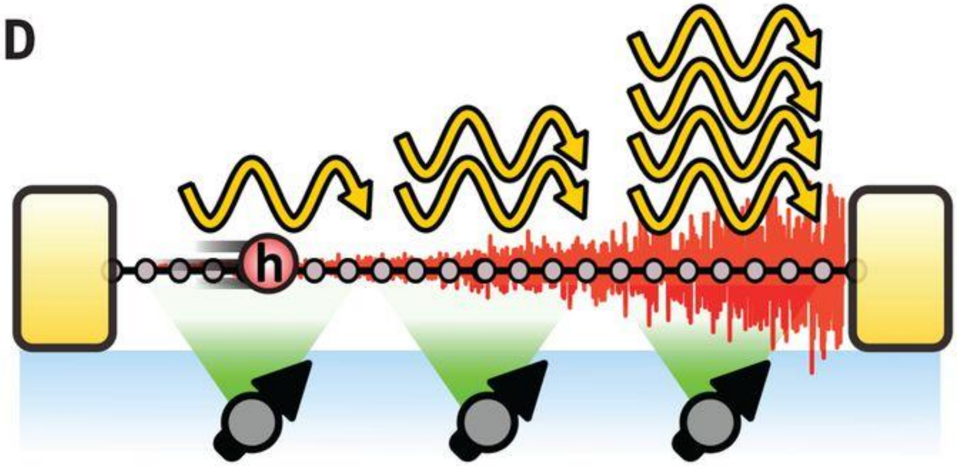
REPORT

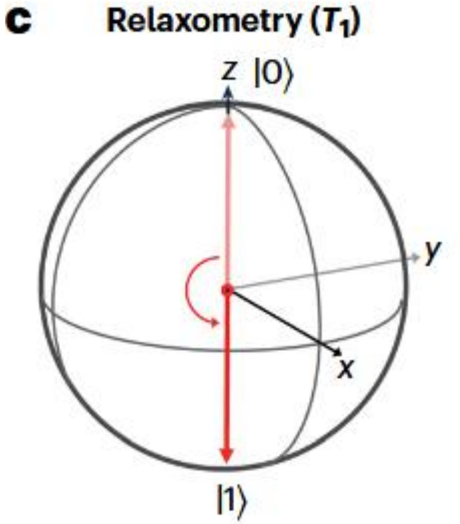
PHYSICS

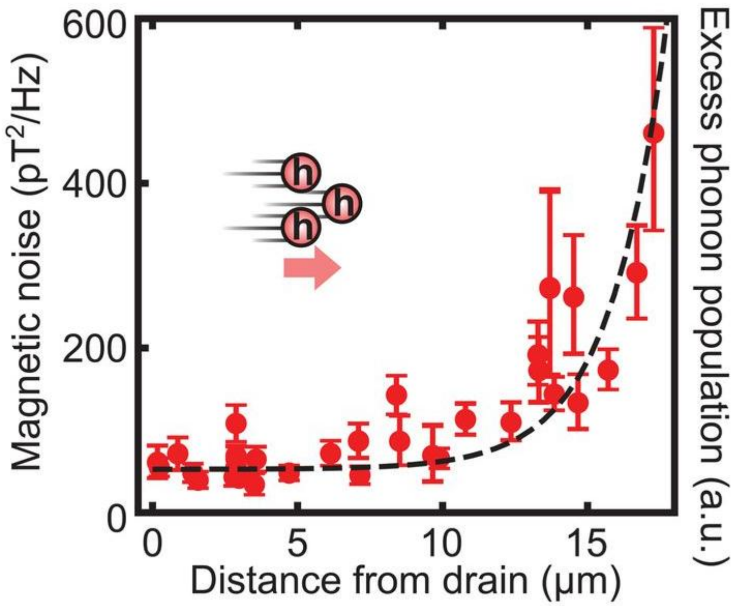
Electron-phonon instability in graphene revealed by global and local noise probes

Trond I. Andersen[1*], Bo L. Dwyer[1*], Javier D. Sanchez-Yamagishi[2*], Joaquin F. Rodriguez-Nieva[1], Kartiek Agarwal[3], Kenji Watanabe[4], Takashi Taniguchi[4], Eugene A. Demler[1], Philip Kim[1,5], Hongkun Park[1,6], Mikhail D. Lukin[1]†

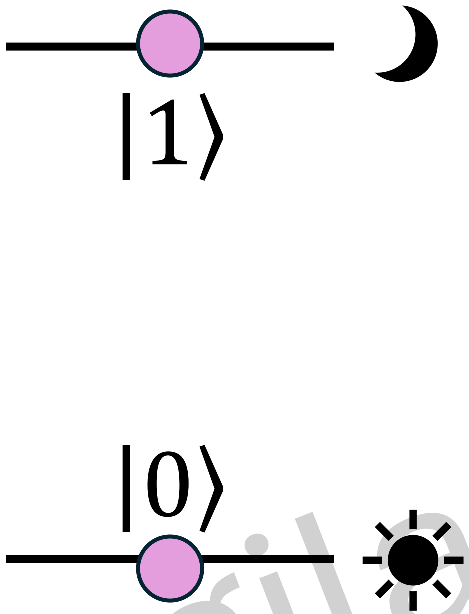
Andersen *et al.*, *Science* **364**, 154–157 (2019)

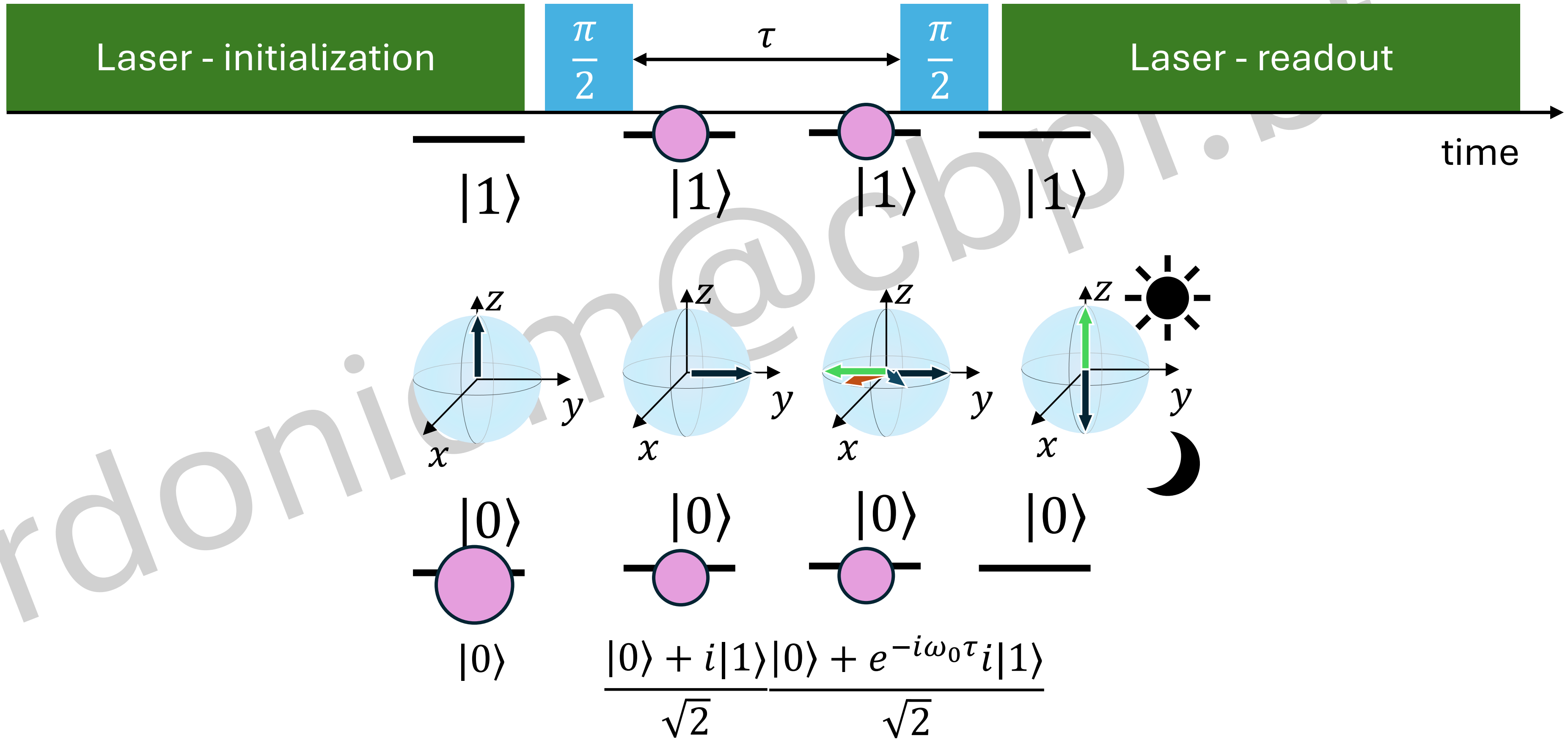






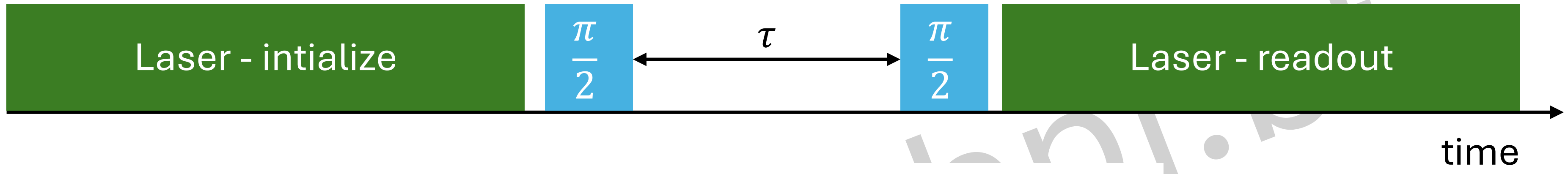
Ramsey measurement – quantum sensor of DC fields

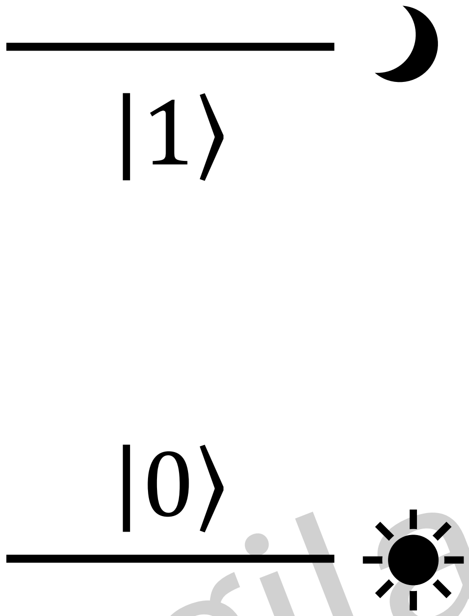


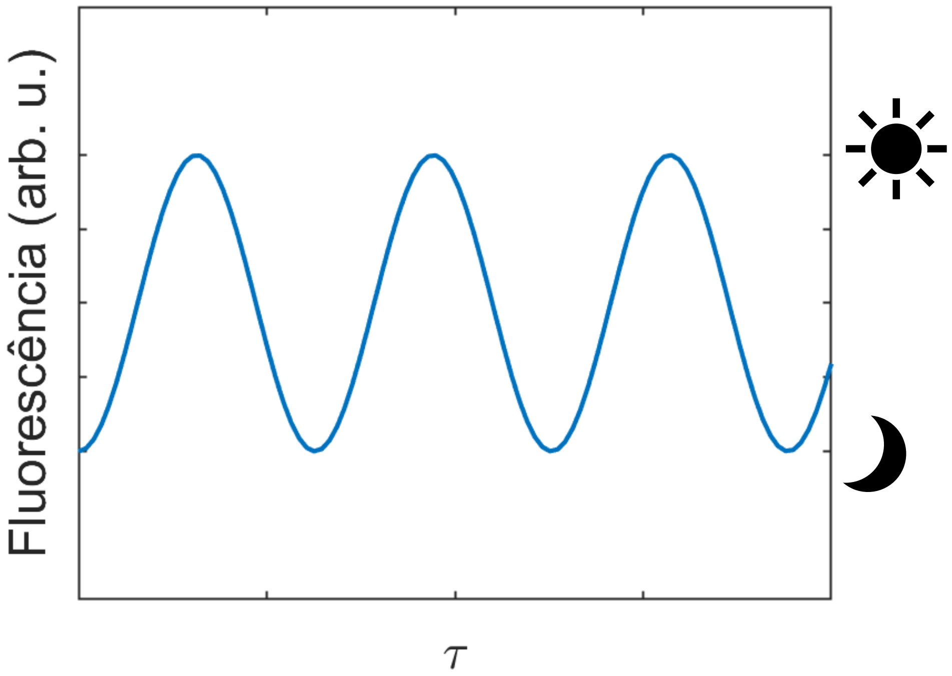


* The thermal state is not
a coherent state!

Ramsey measure – quantum sensor of DC fields

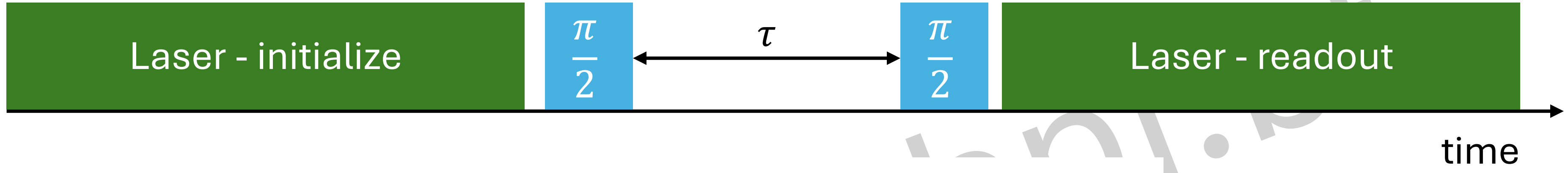


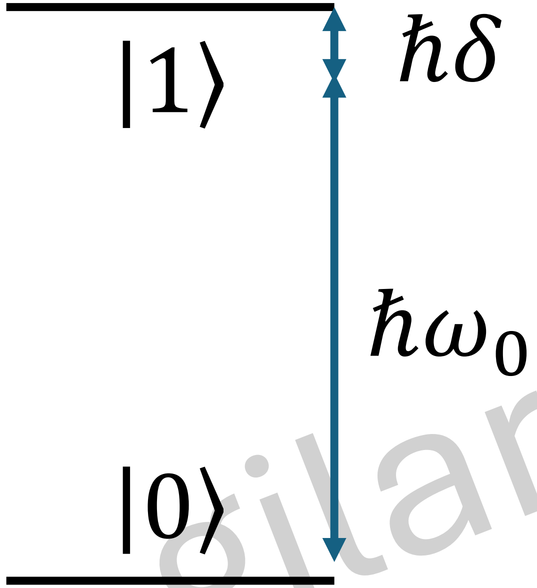


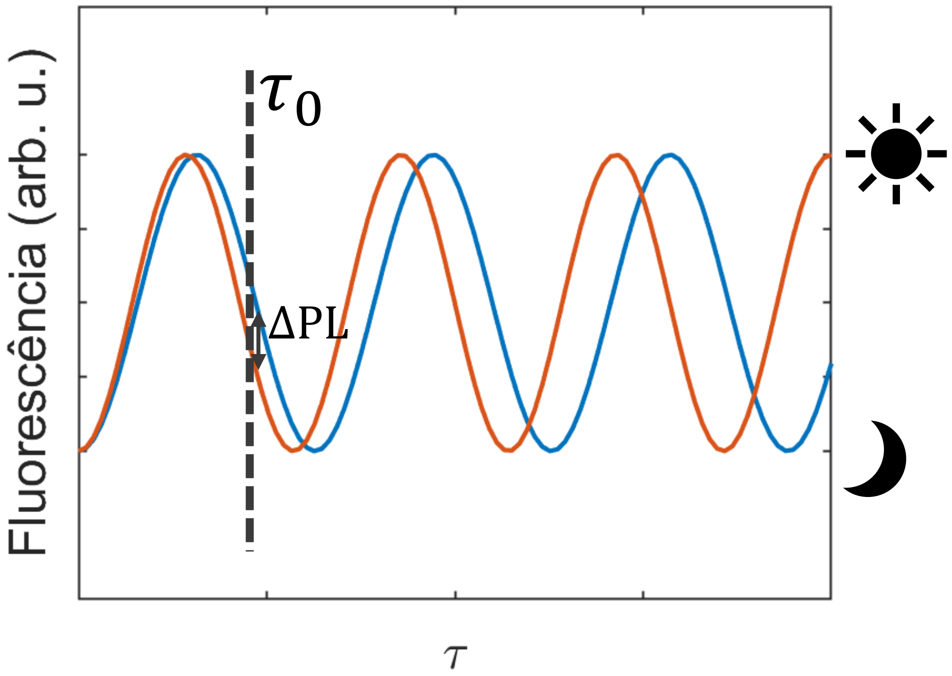


As it evolves, the quantum state acquires a phase that depends on the energy of the states

Ramsey measure – quantum sensor of DC fields



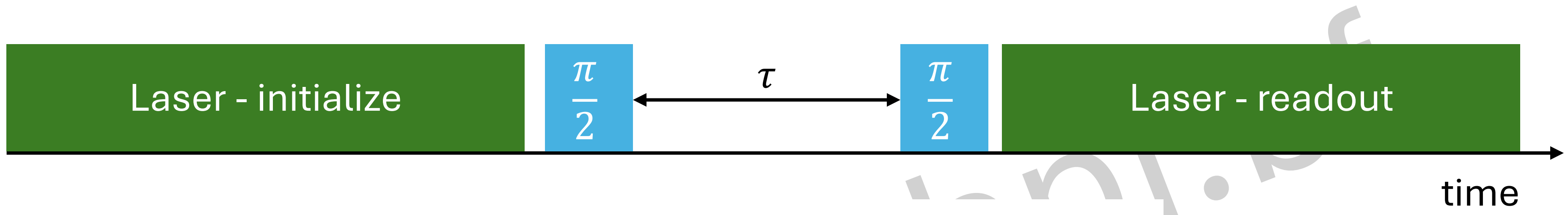


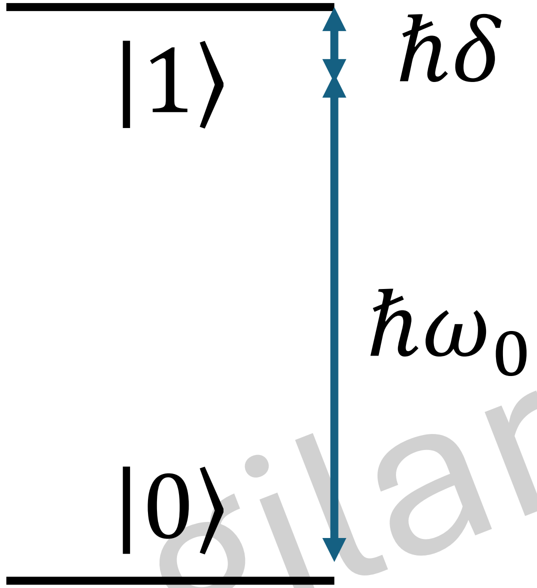


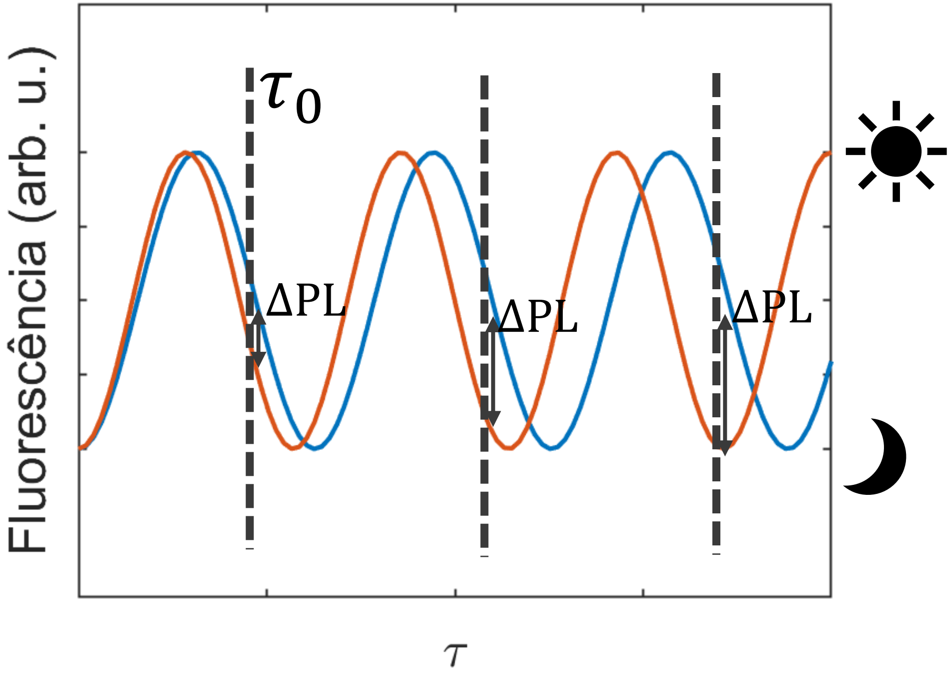
As it evolves, the quantum state acquires a phase that depends on the energy of the states

Ramsey's Measure

The longer the evolution time, the more information we can acquire about the system.





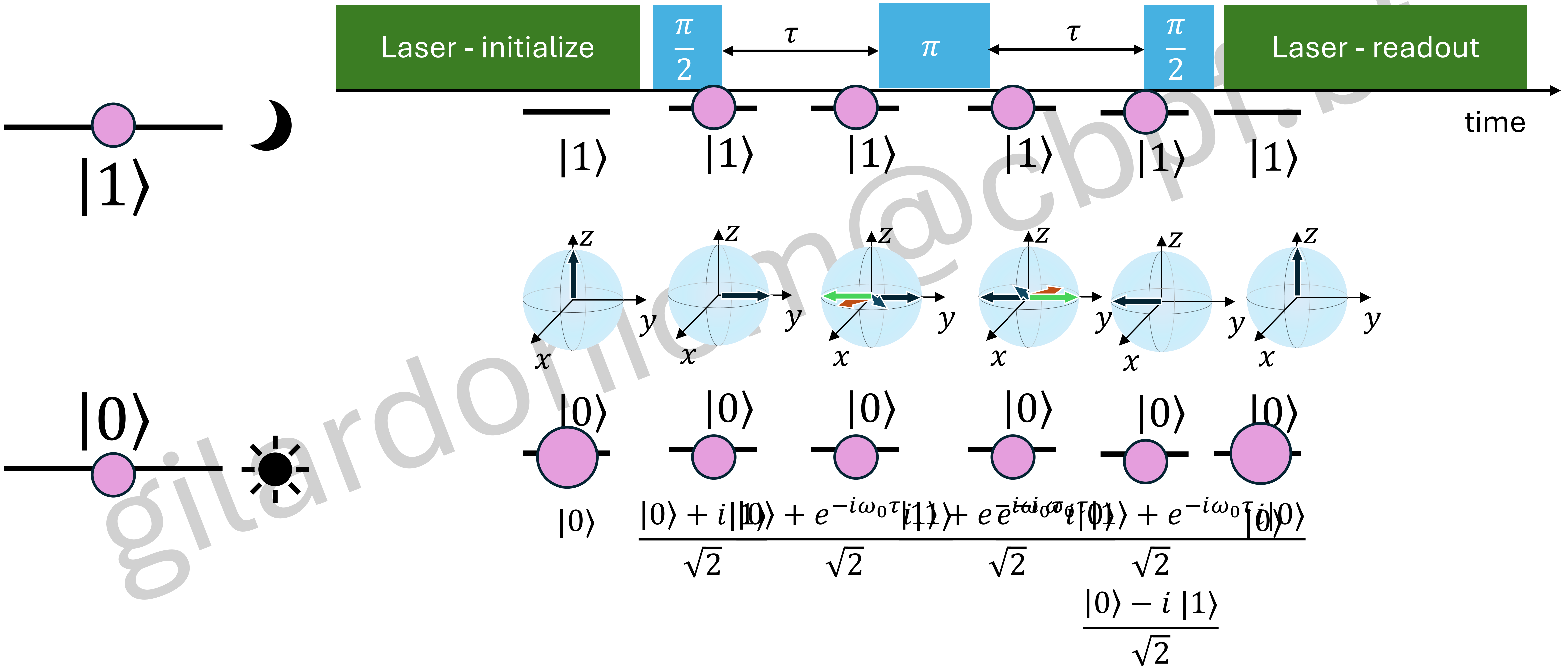


$$\eta_{DC} \propto \frac{\sqrt{2e}}{\gamma C \sqrt{T_2^*}}$$

As it evolves, the quantum state acquires a phase that depends on the energy of the states

Echo Measurement – decouple from the environment

This experiment is not sensitive to DC fields!!



Echo Measurement – decouple from the environment

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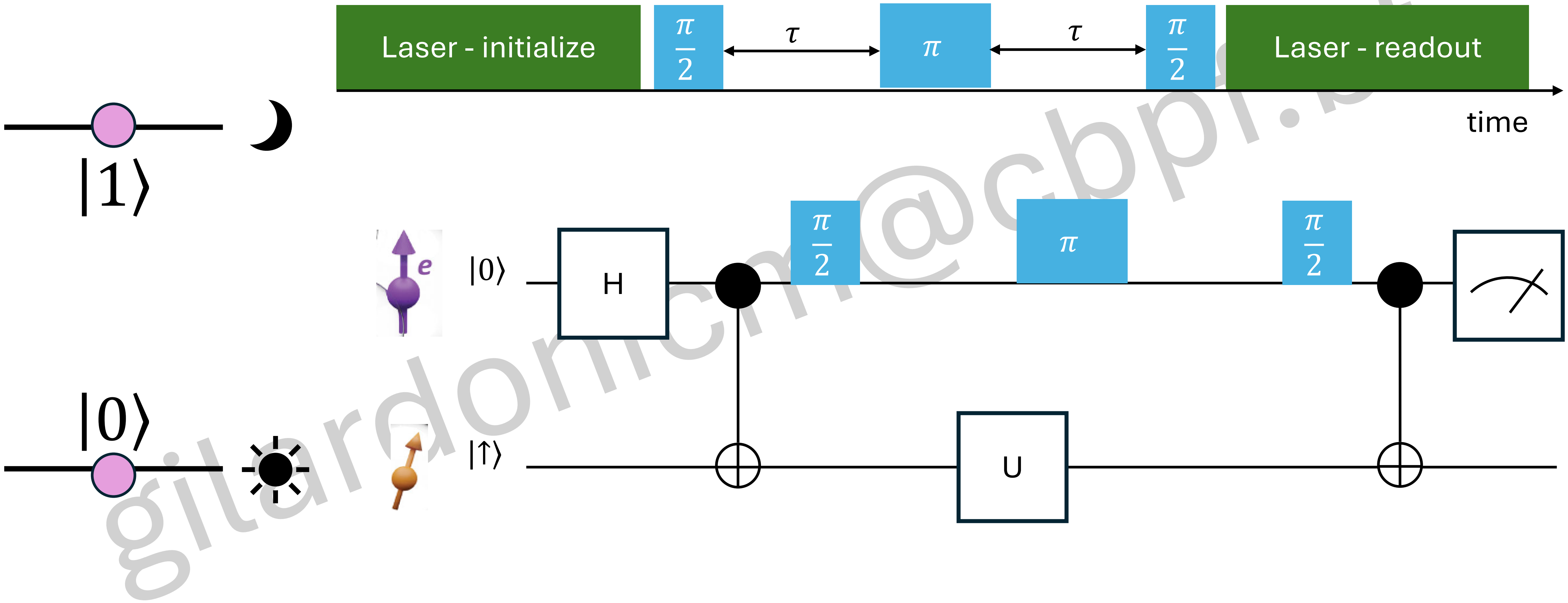
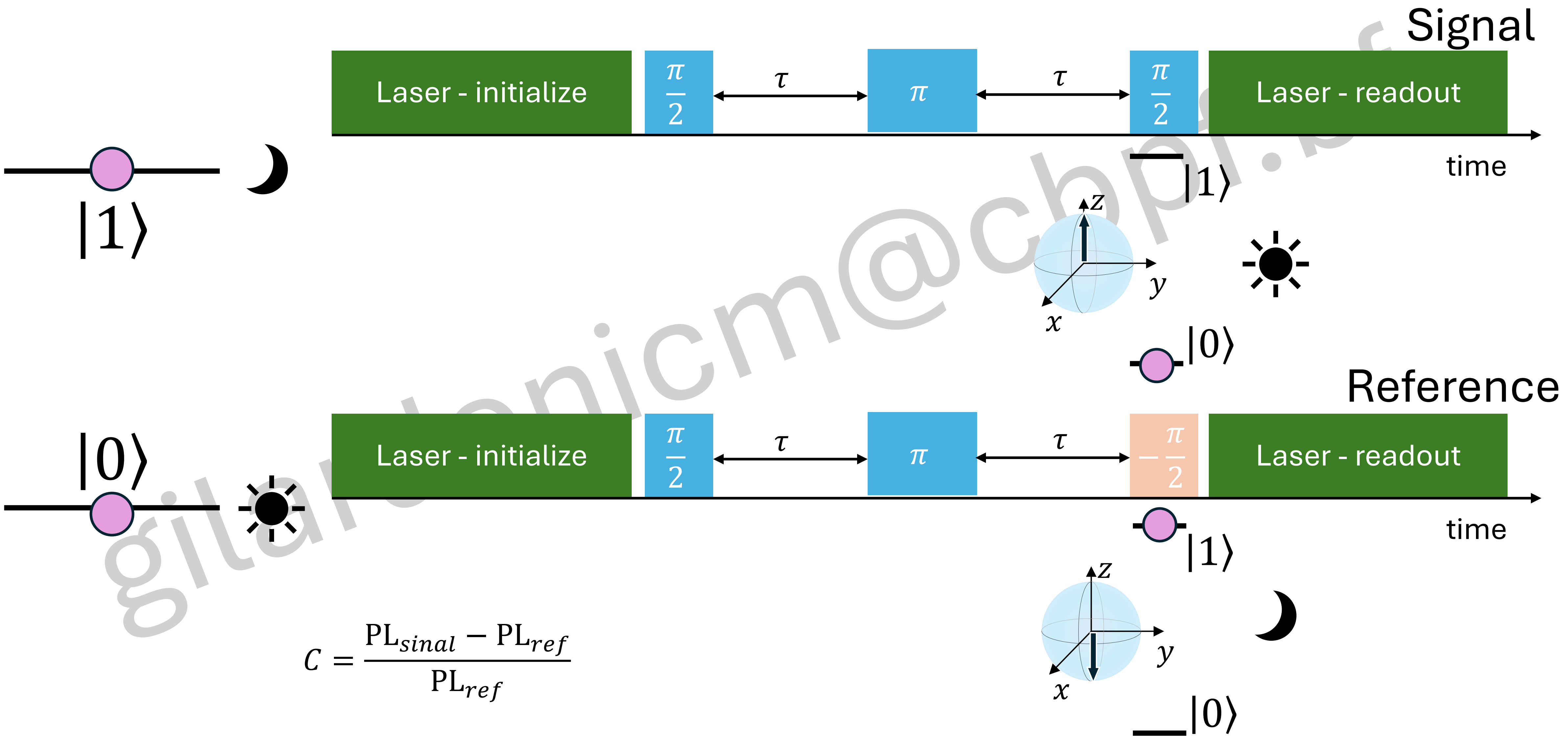


Echo Measurement – quantum sensor of AC fields

This experiment is not sensitive to DC fields!!



$$C = \frac{\mathrm{PL}_{sinal} - \mathrm{PL}_{ref}}{\mathrm{PL}_{ref}}$$

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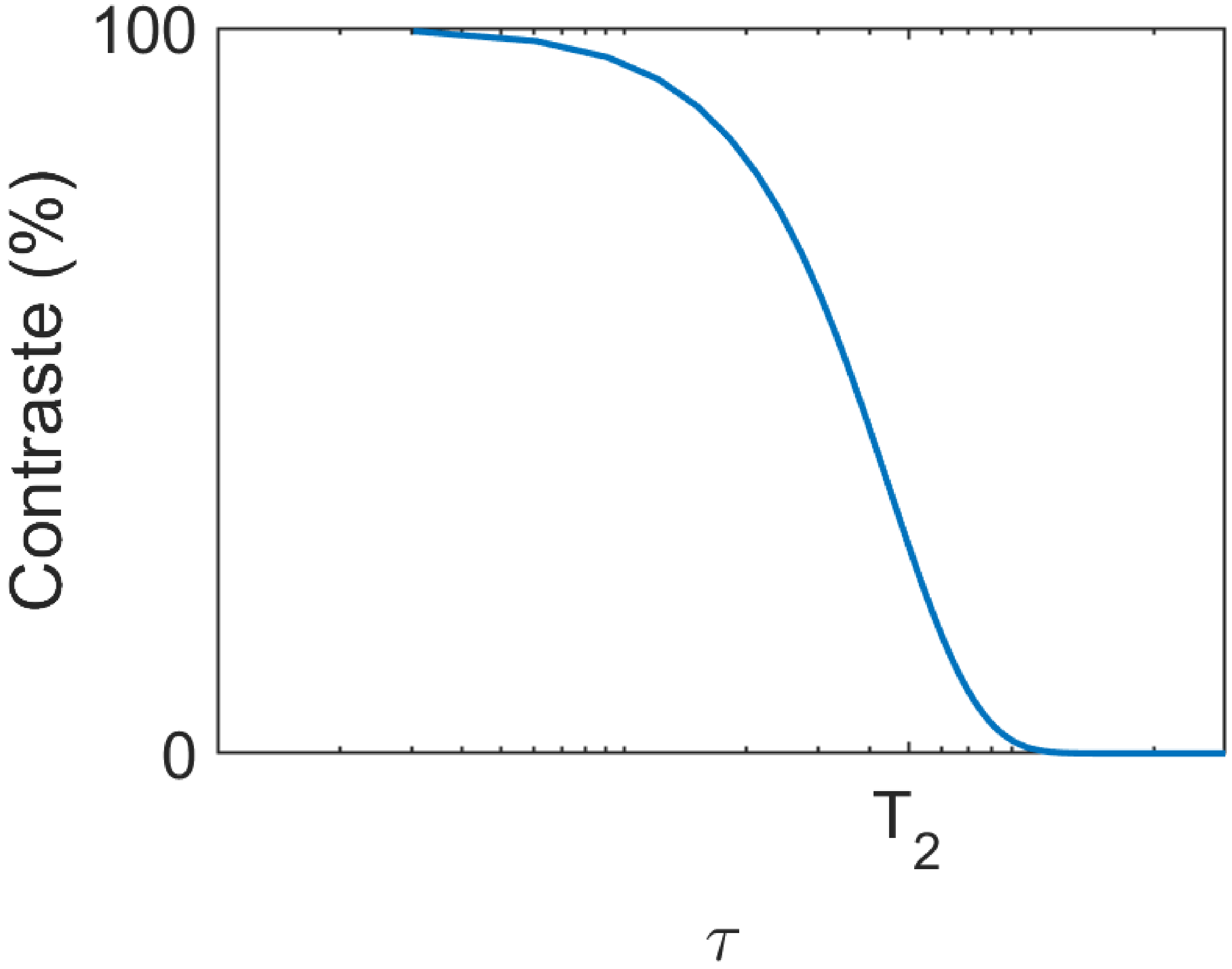

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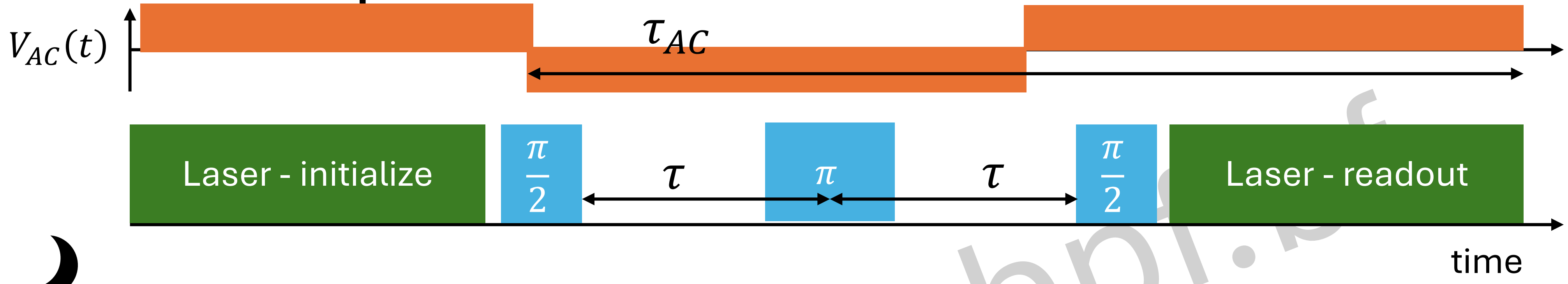
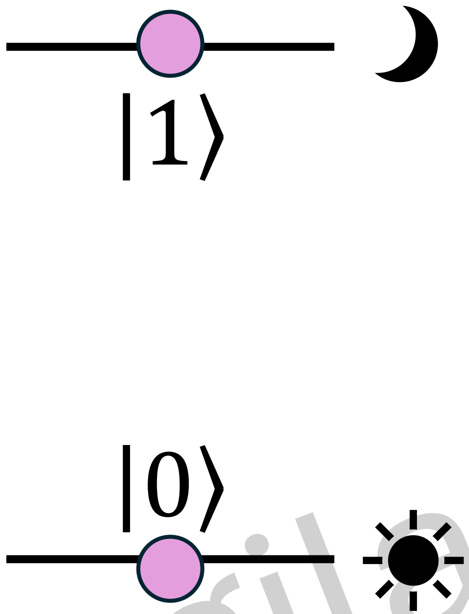
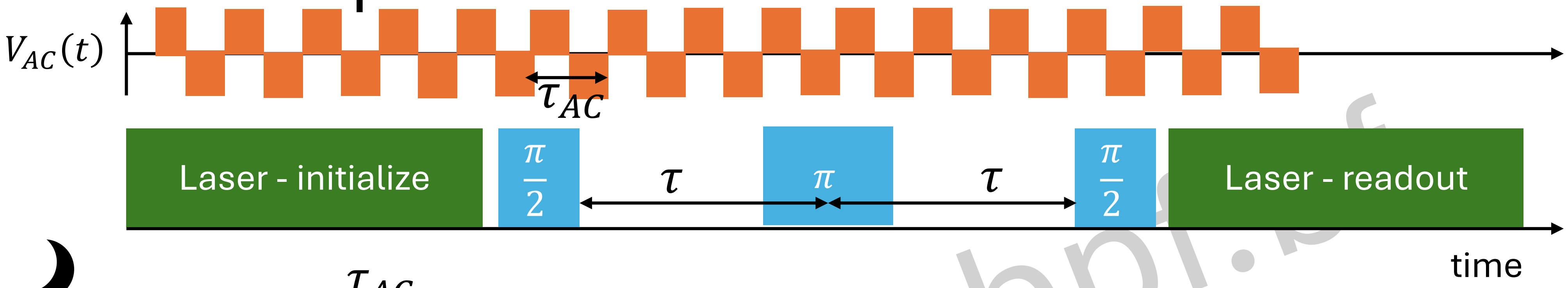


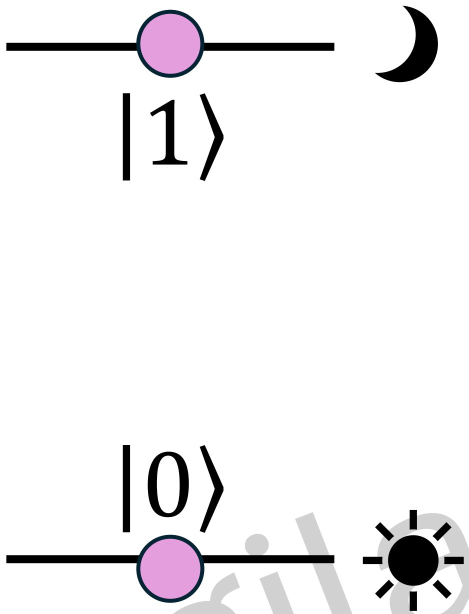


$$\tau \ll \frac{\tau_{AC}}{2}$$

The AC field is 'almost' a DC field, and does not affect my measurement

Echo Measurement – quantum sensor of AC fields

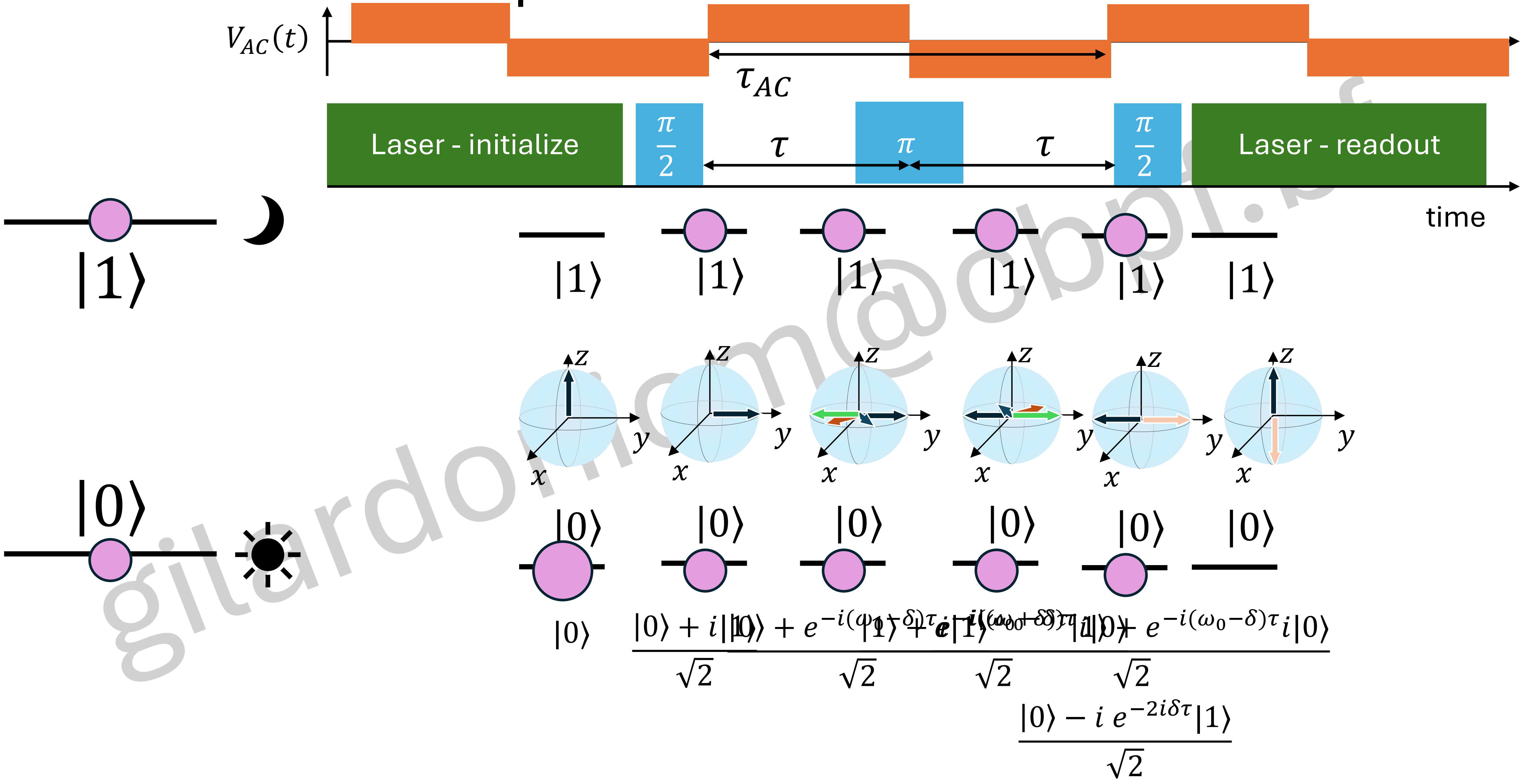




$$\tau \gg \frac{\tau_{AC}}{2}$$

The AC field oscillates several times during a cycle; averages out to zero.

Echo Measurement – quantum sensor of AC fields



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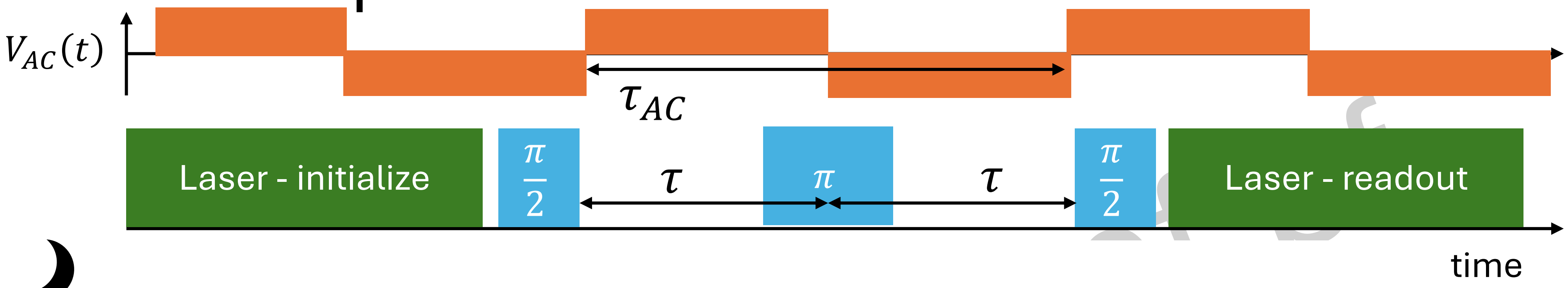

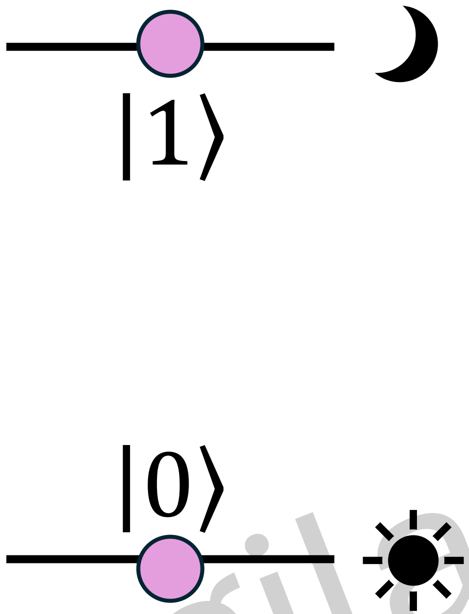

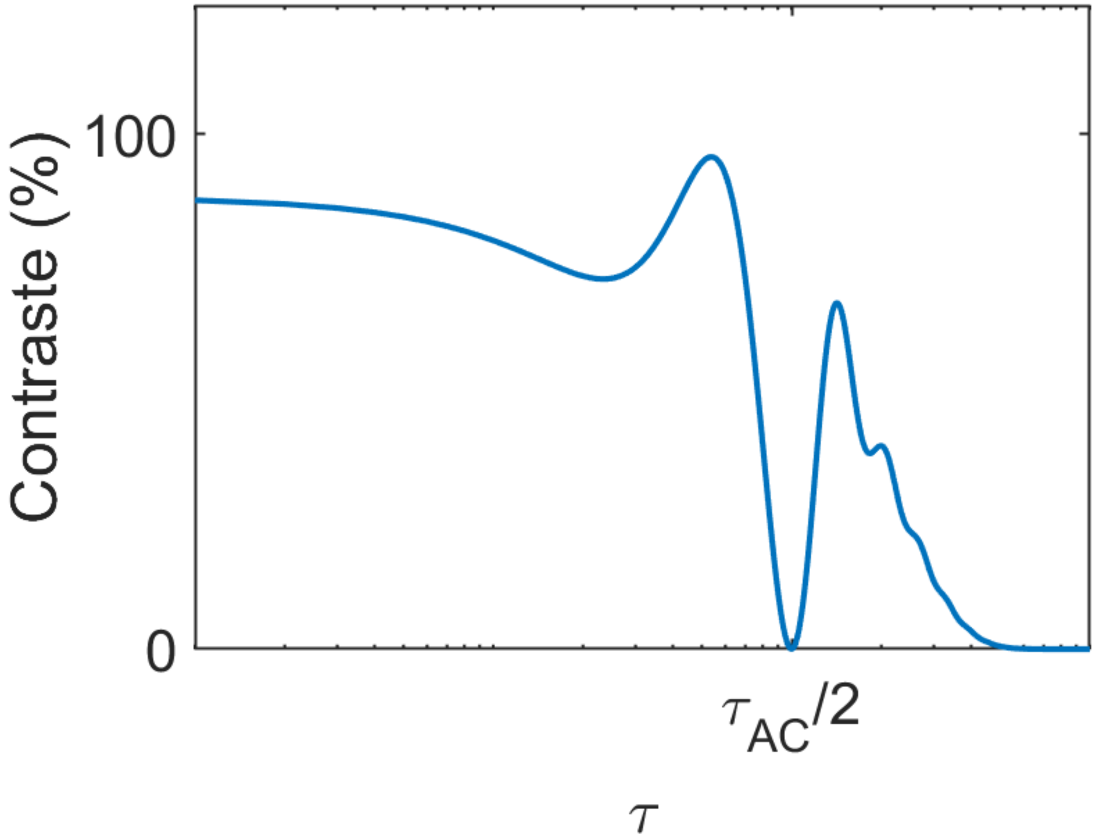

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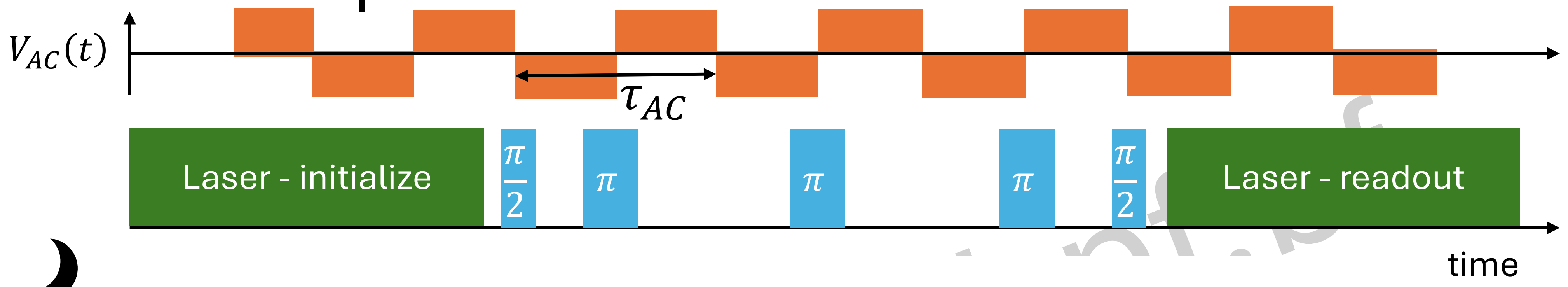
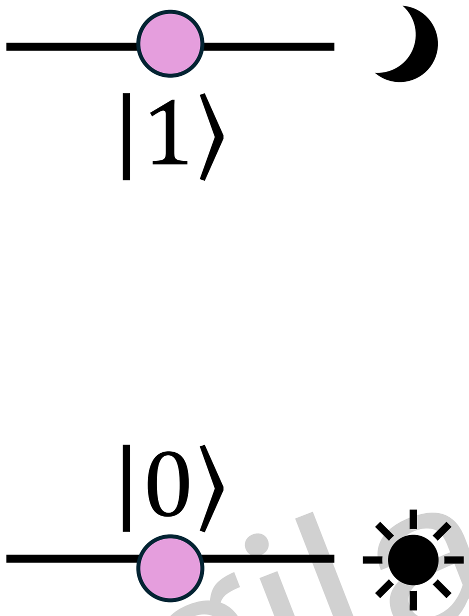
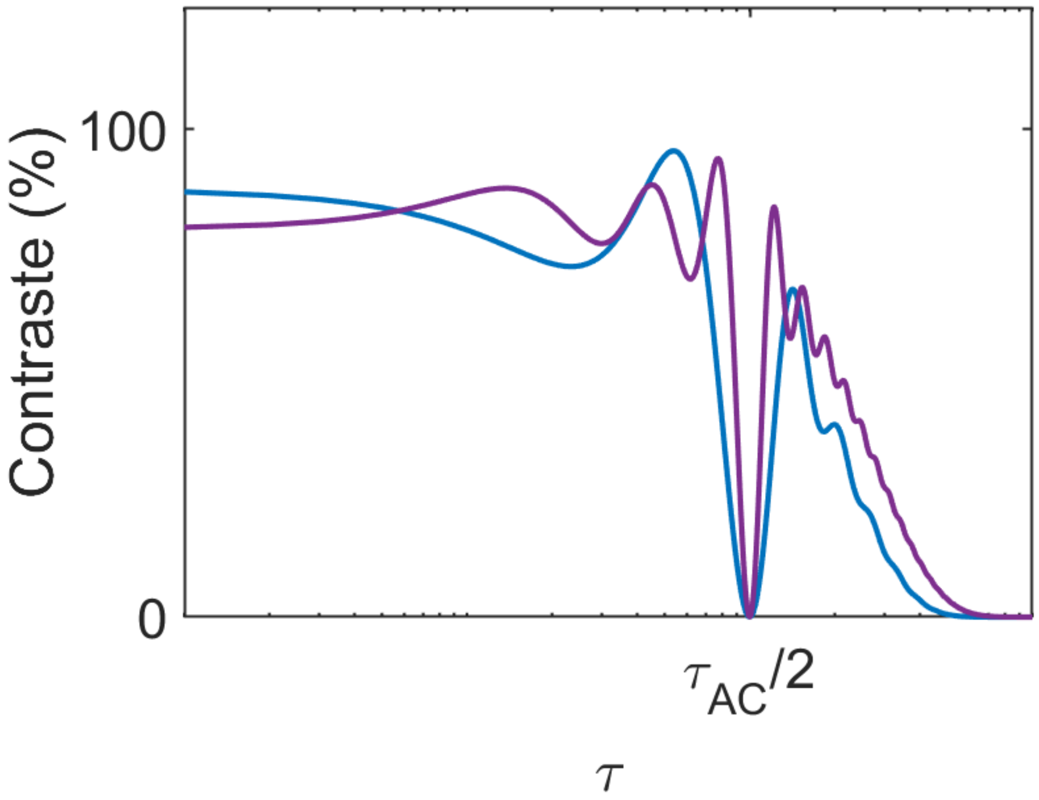






Some remarks:

- Parameter estimation is a statistical process!

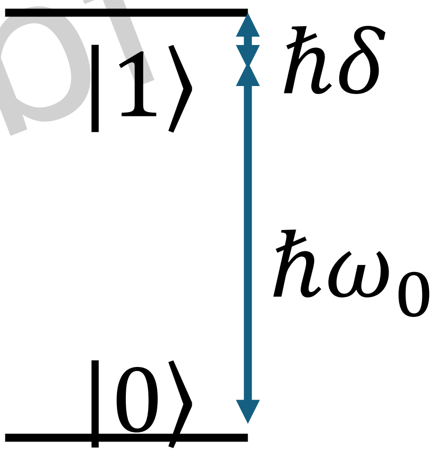
  The question is: how sure can we be that the inferred parameter θ coincides with the real physical parameter ΔB, given that we observe a change in the photon emission rate ΔPL?

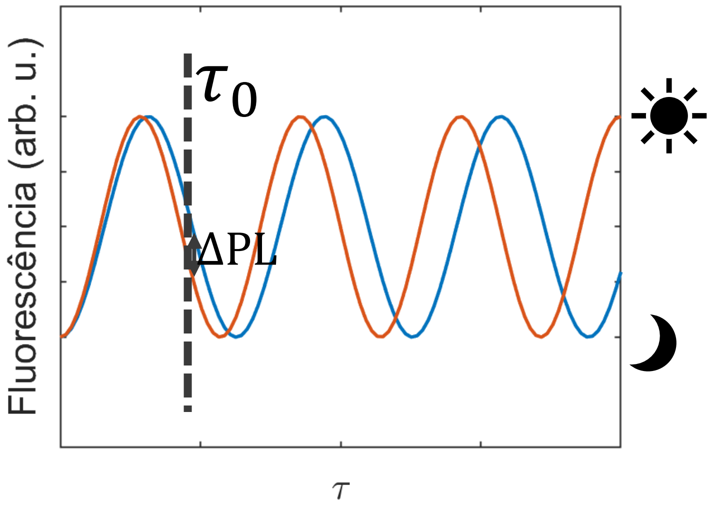
  The accuracy of my estimation is given by the Cramer-Rao bound,

$$(\Delta\theta)^2 \geq \frac{1}{M\,F_Q}$$

Number of measurements

Quantum Fisher information: how much does my observable change with respect to parameter θ





Some remarks:

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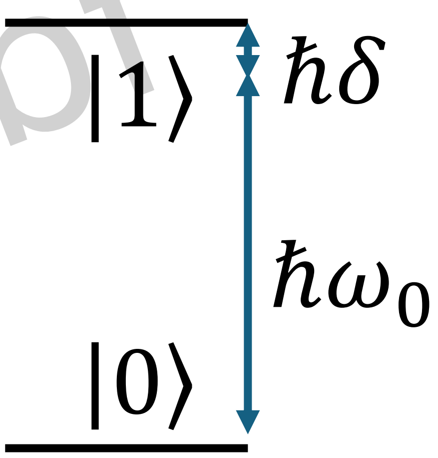
  The question is: how sure can we be that the inferred parameter θ coincides with the real physical parameter ΔB, given that we observe a change in the photon emission rate ΔPL?

$$P_N(\Delta\theta|\Delta B) := \sum p_{est}^{(N)}(\Delta\theta|\Delta PL)p_N(\Delta PL|\Delta B)$$



  The accuracy of my estimation is given by the Cramer-Rao bound,

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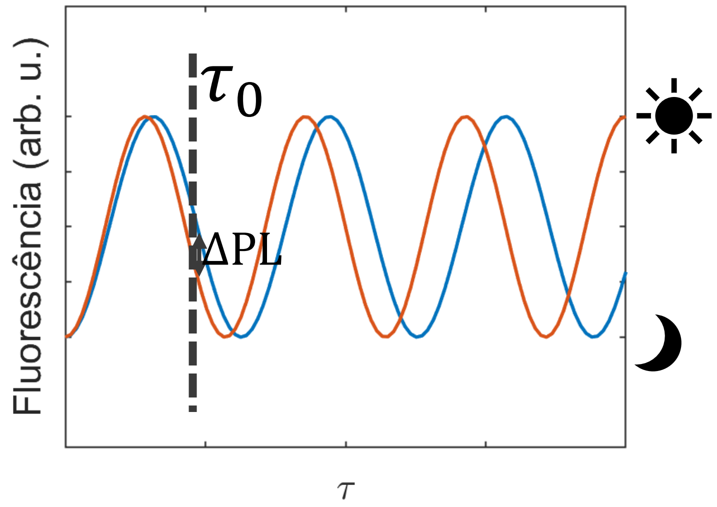
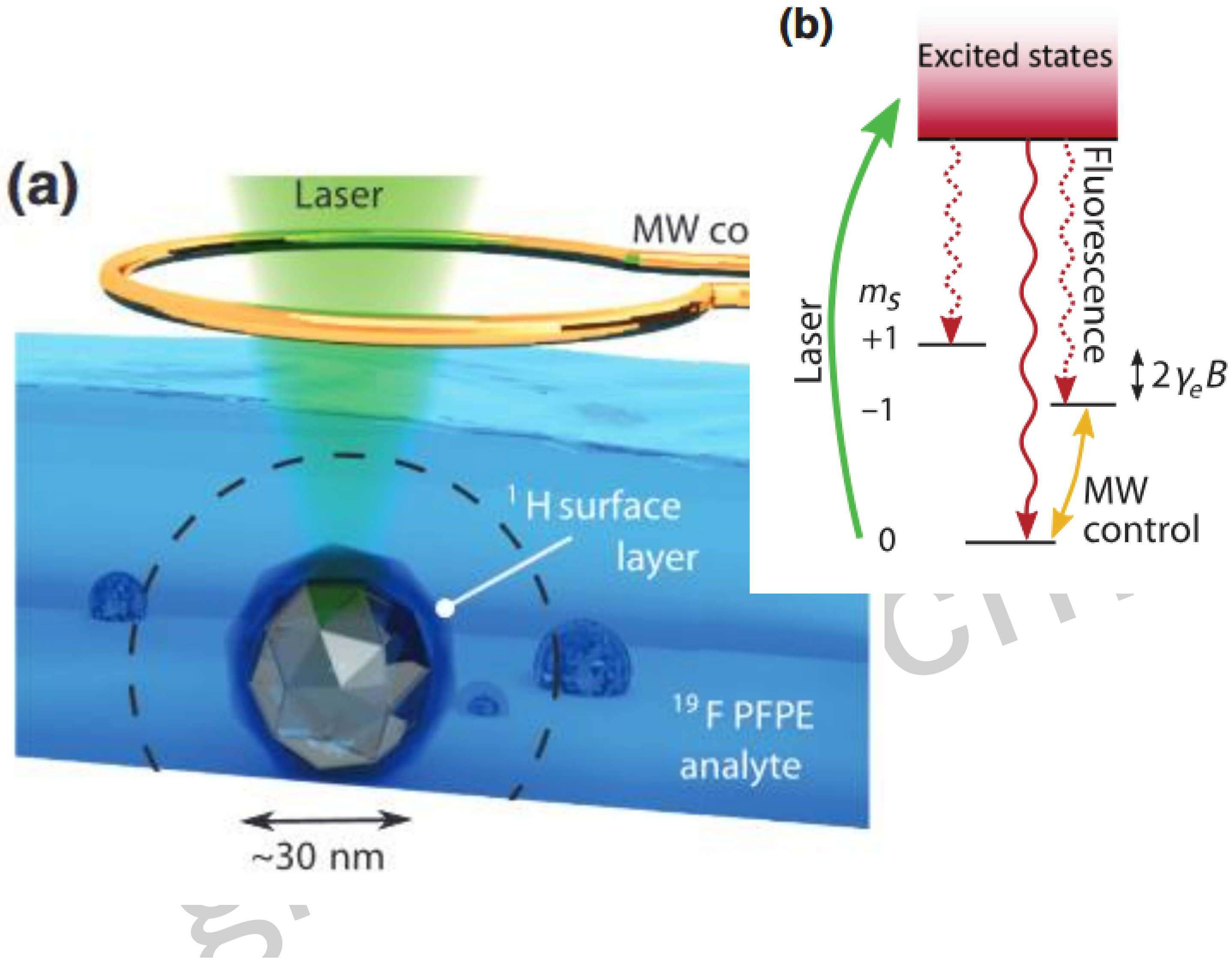
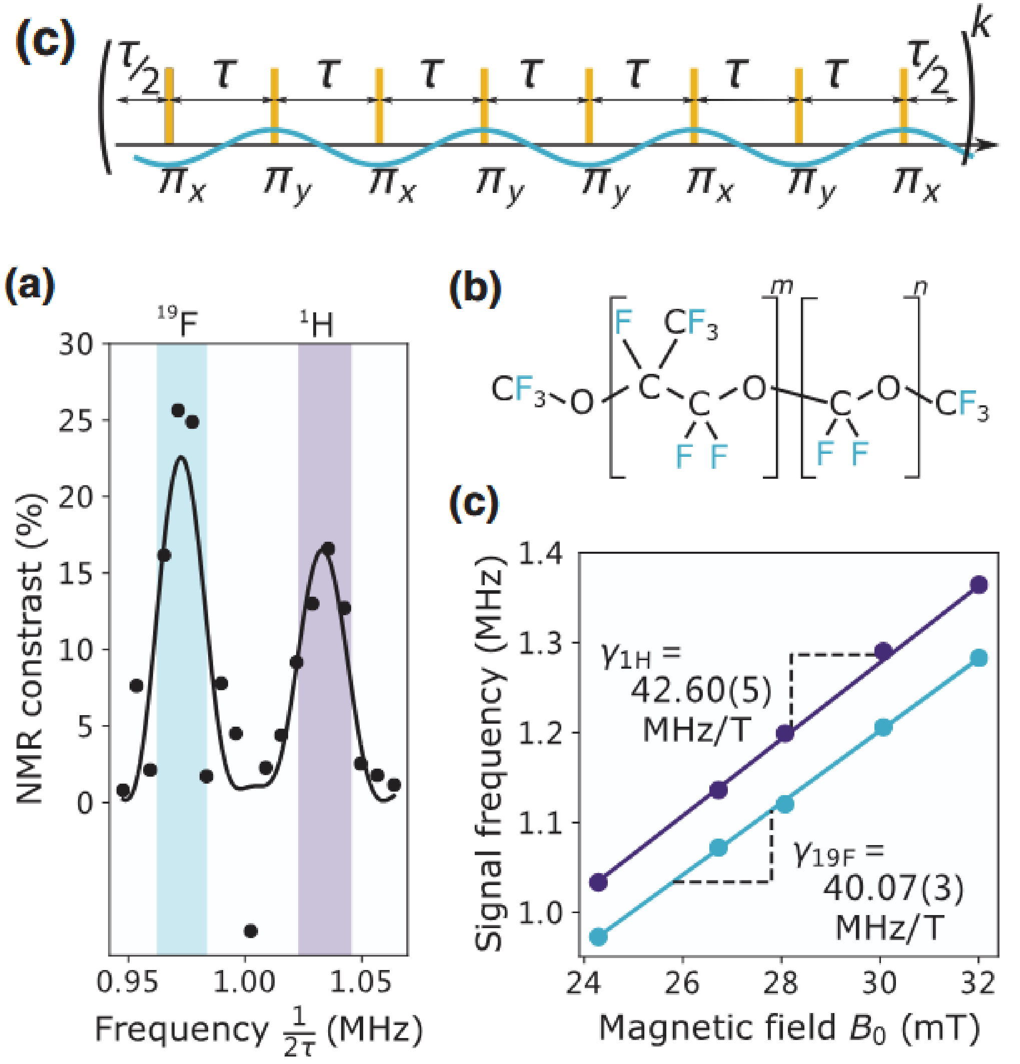
$$F_N(\Delta B) := \sum \frac{1}{p_N(\Delta PL|\Delta B)}\left(\frac{\partial p_N(\Delta PL|\Delta B)}{\partial(\Delta B)}\right)$$







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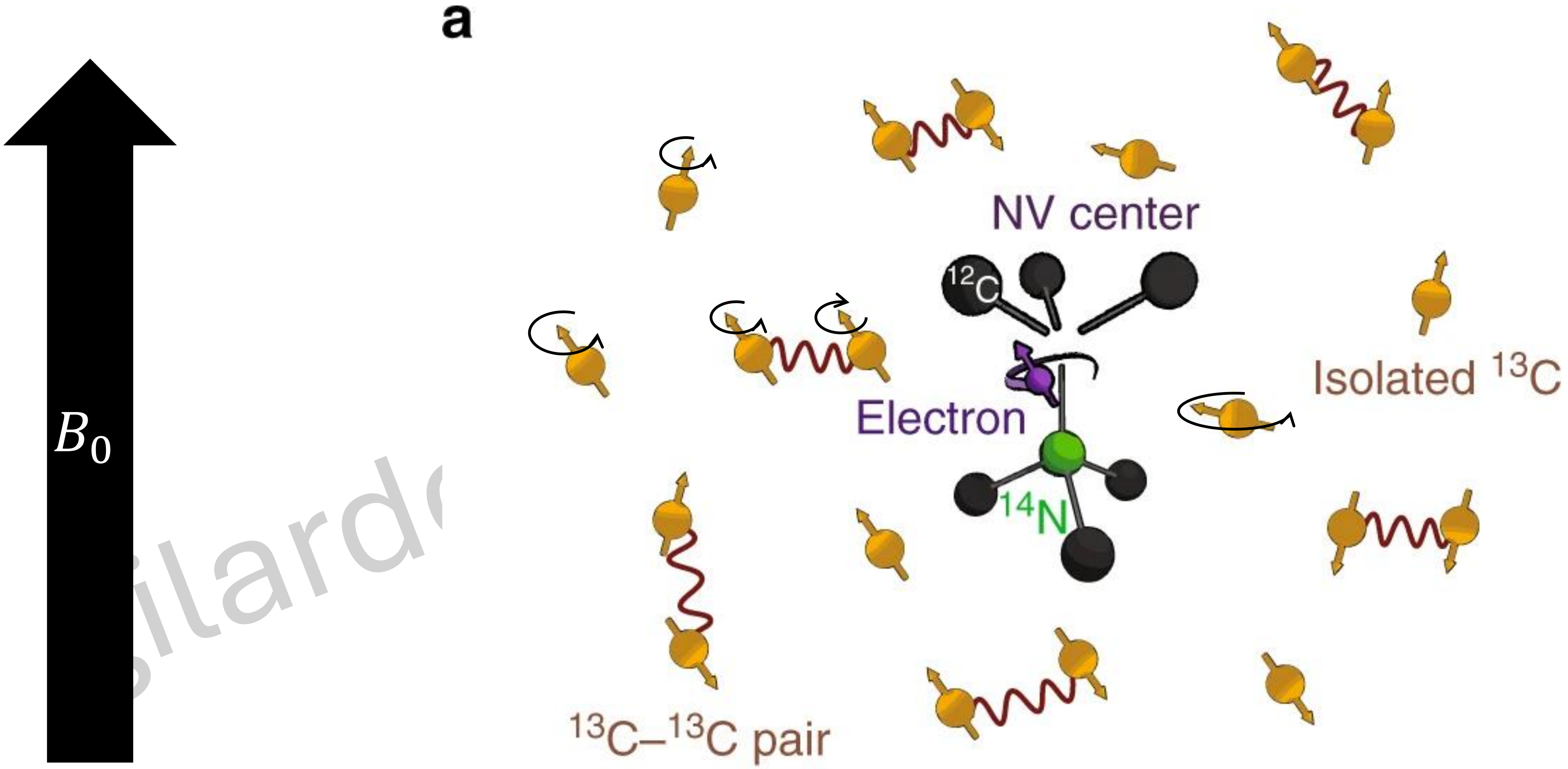
PHYS. REV. APPLIED **13,** 044004 (2020)

Nuclear spins generate AC fields (Larmor of the nucleus itself)

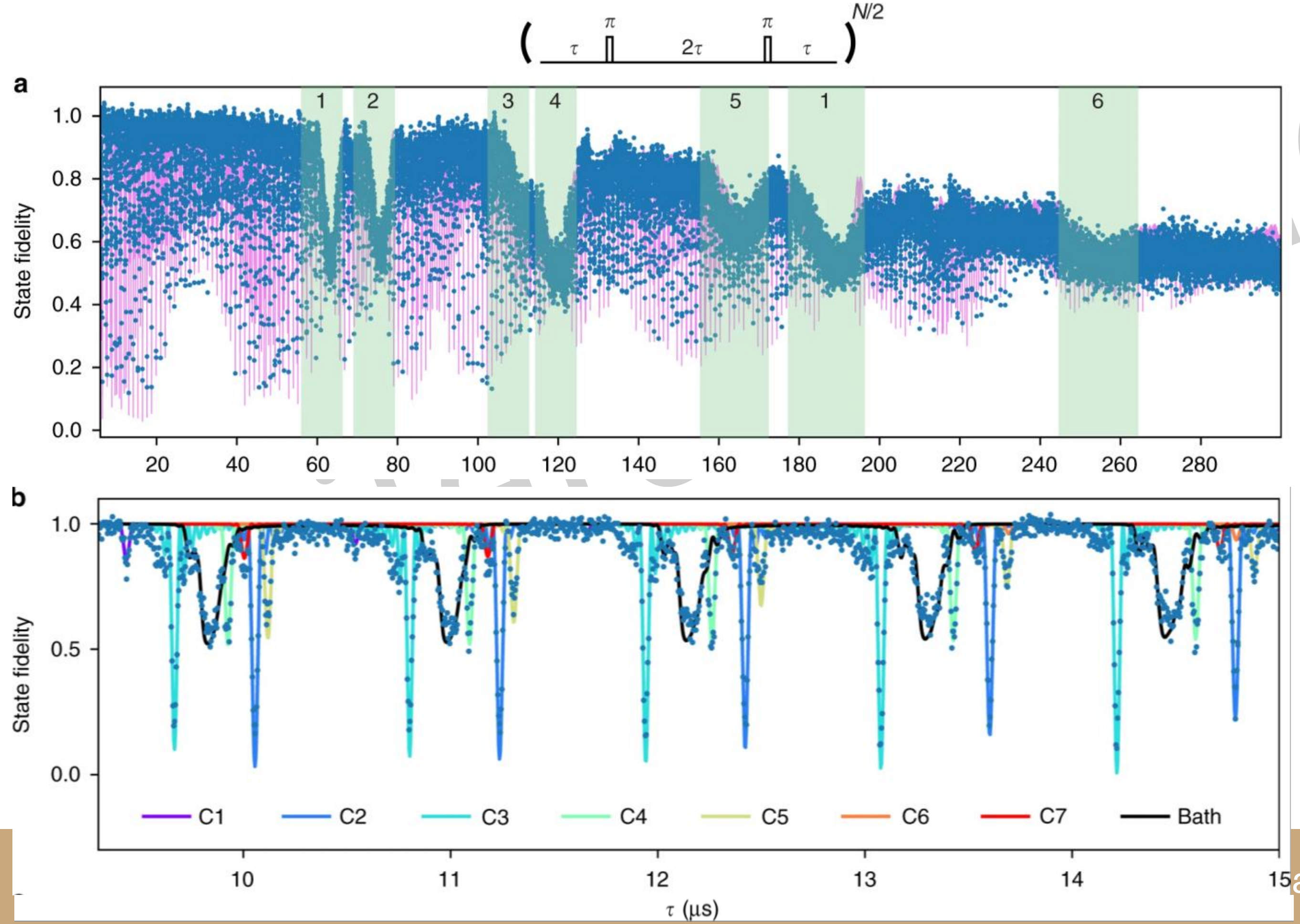


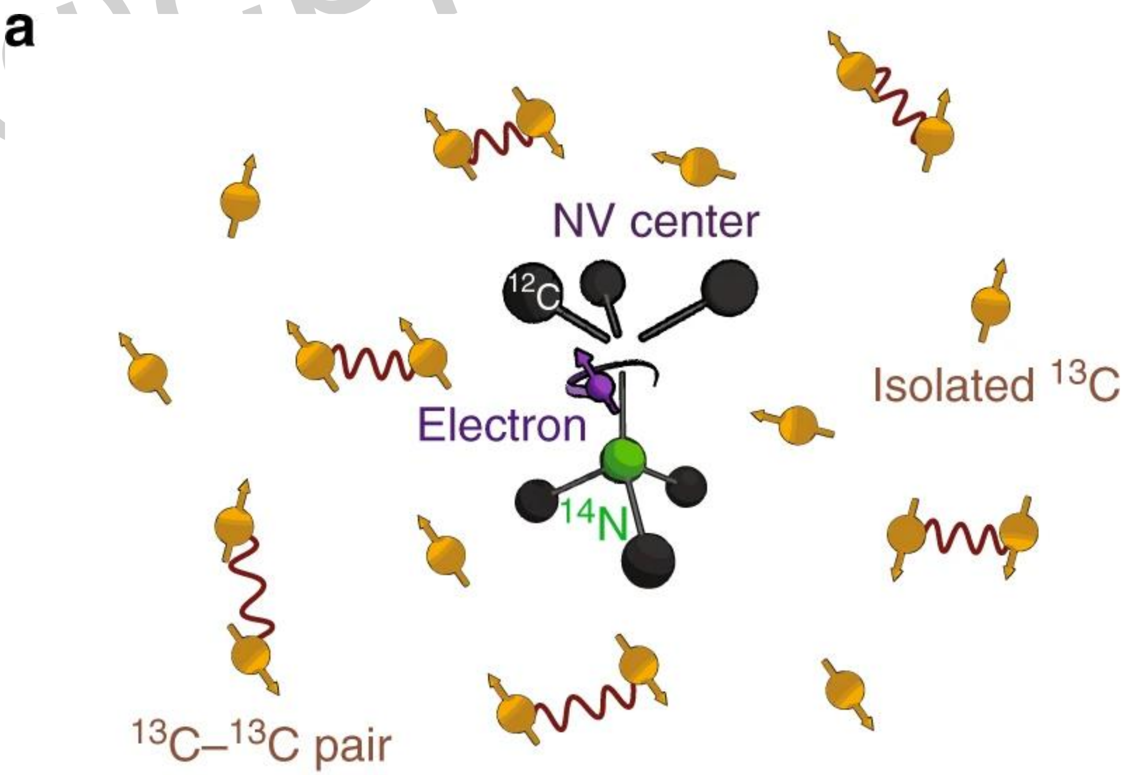
Article | Open access | Published: 29 June 2018

One-second coherence for a single electron spin coupled to a multi-qubit nuclear-spin environment

M. H. Abobeih, J. Cramer, M. A. Bakker, N. Kalb, M. Markham, D. J. Twitchen & T. H. Taminiau

Nature Communications **9**, Article number: 2552 (2018) | Cite this article





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Every sensor is an actuator!

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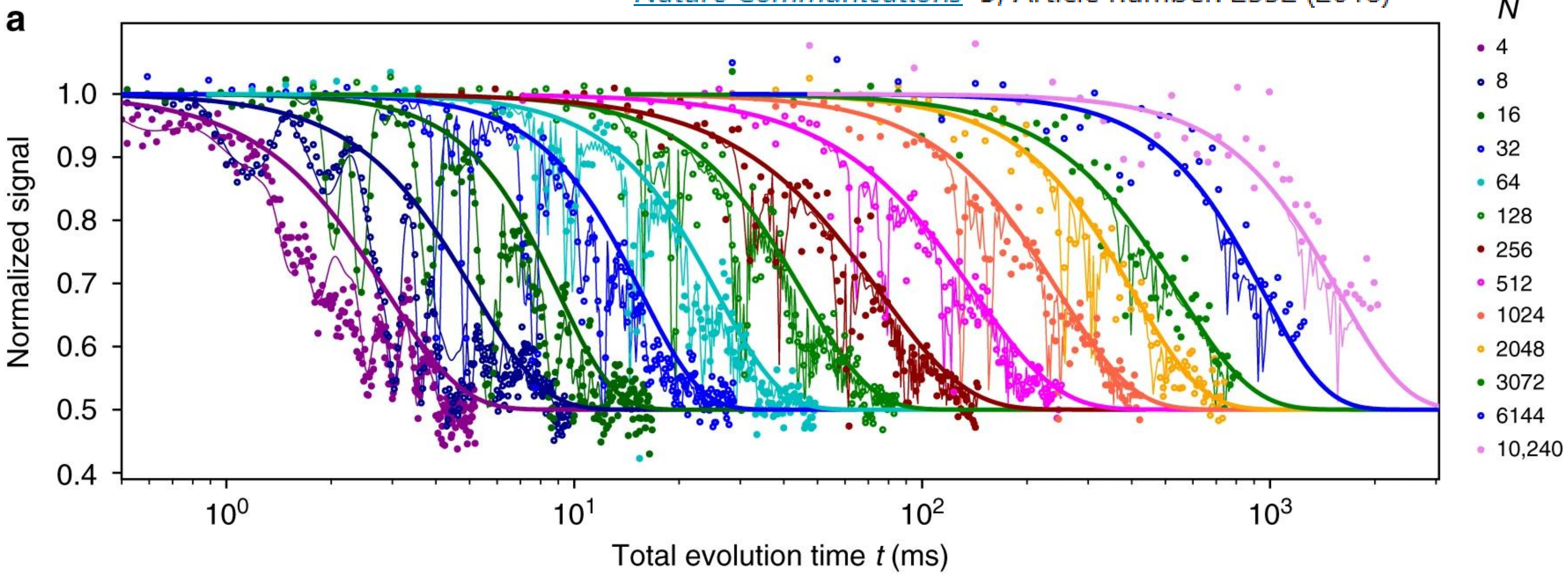

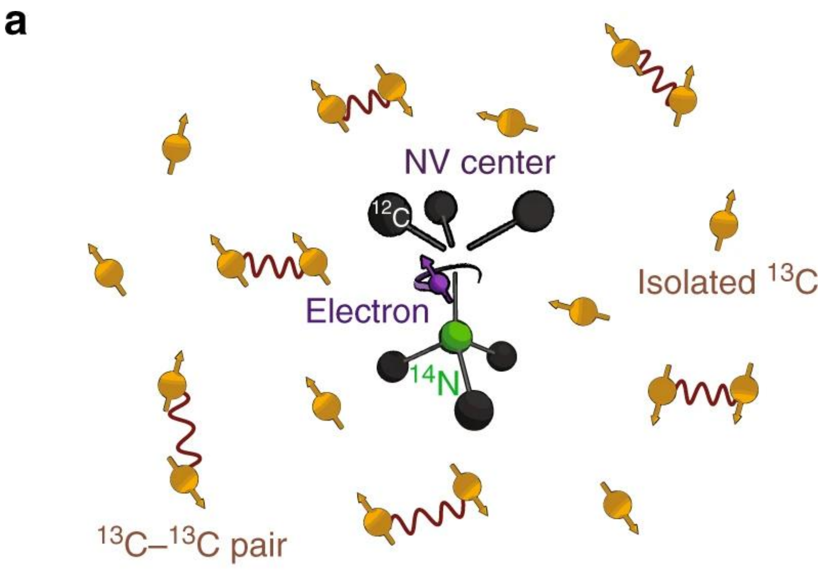

PHYSICAL REVIEW X 9, 031045 (2019)

Featured in Physics

A Ten-Qubit Solid-State Spin Register with Quantum Memory up to One Minute

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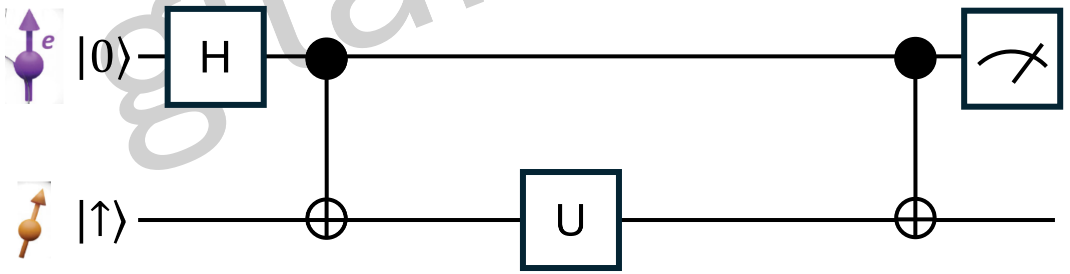
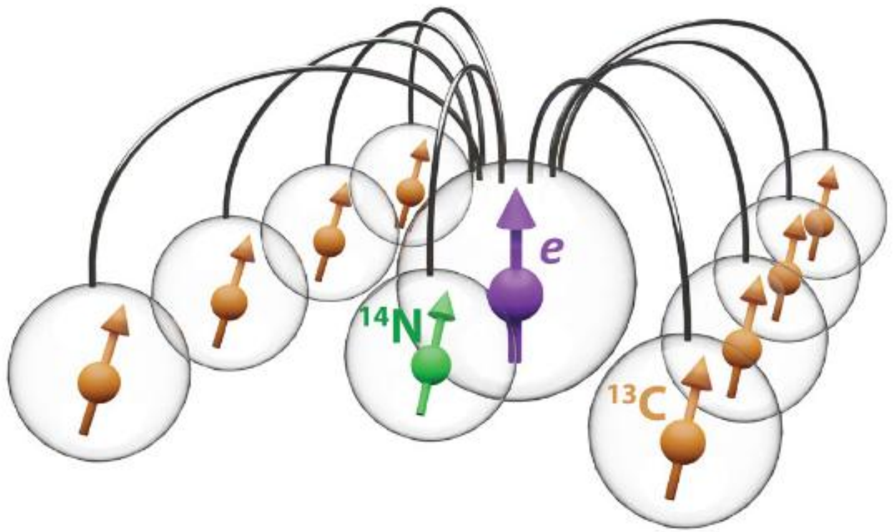
(Received 9 May 2019; published 11 September 2019)

- Challenge: nuclear spin control @ MHz, slow process!
  - The electron decoheres while we drive the nuclear spin
  - The interaction nuclear spin-rf field depends on electron-spin evolution





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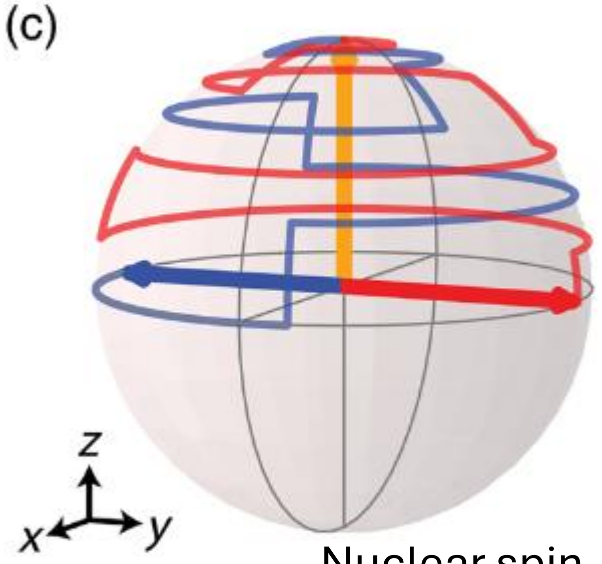
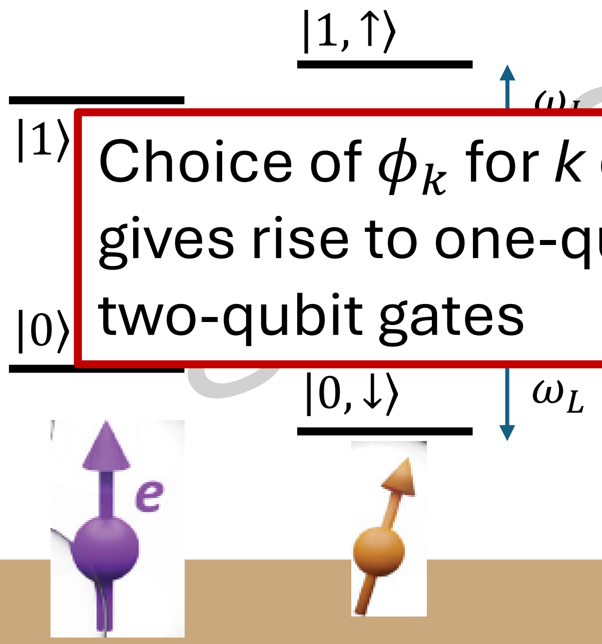


Nuclear spin

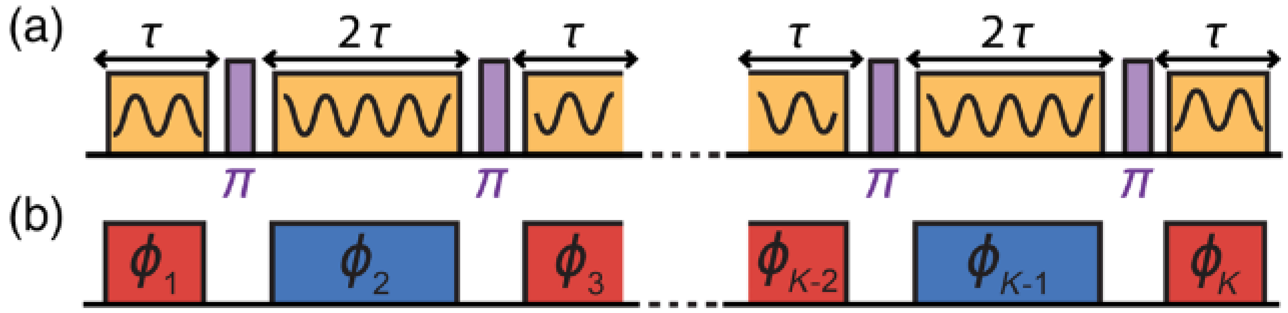
$$H = \omega_L I_z + A_{\parallel} S_z I_z + A_{\perp} S_z I_x,$$

In the rotating wave approximation:

$$H = |0\rangle\langle 0| \otimes (\omega_L - \omega_1) I_z + |1\rangle\langle 1| \otimes \Omega(\cos\phi\, I_x + \sin\phi\, I_y)$$



Choice of ϕ_k for k even, odd, gives rise to one-qubit and two-qubit gates



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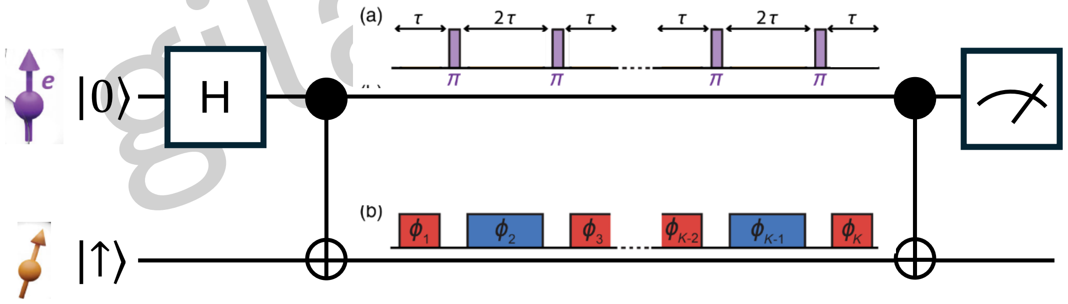

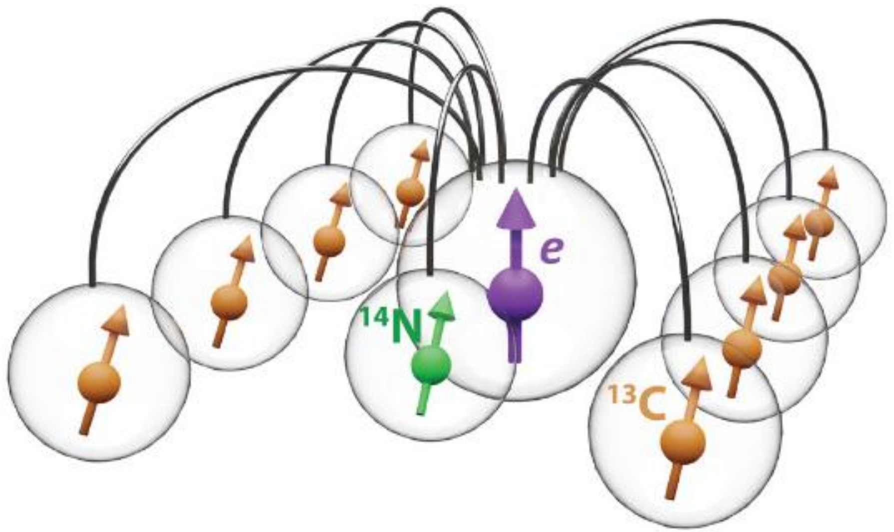

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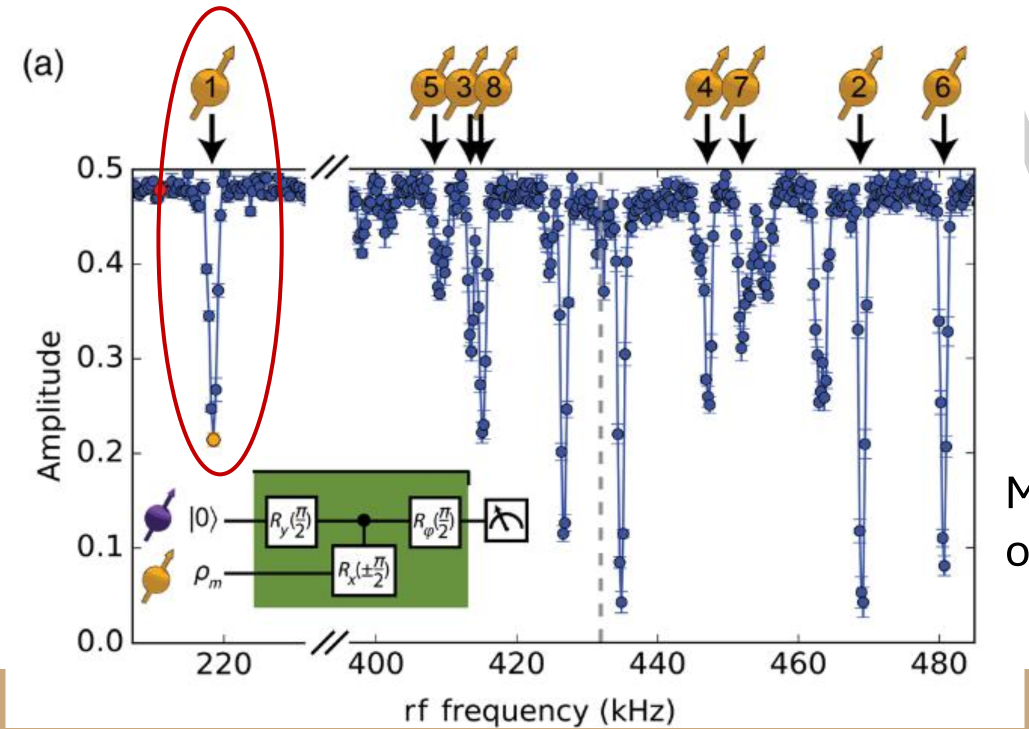
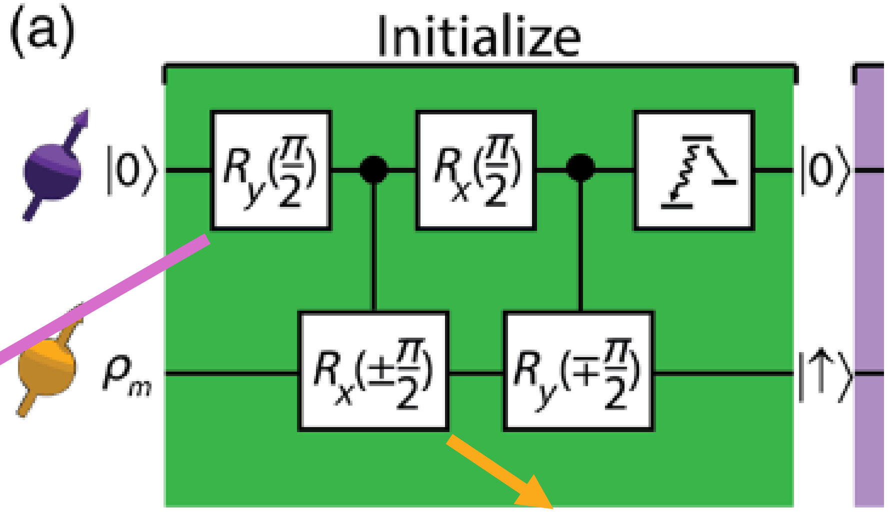
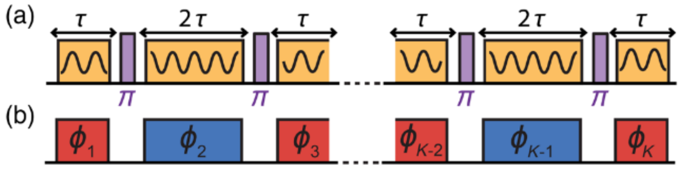




Microwave pulses on the electron spin



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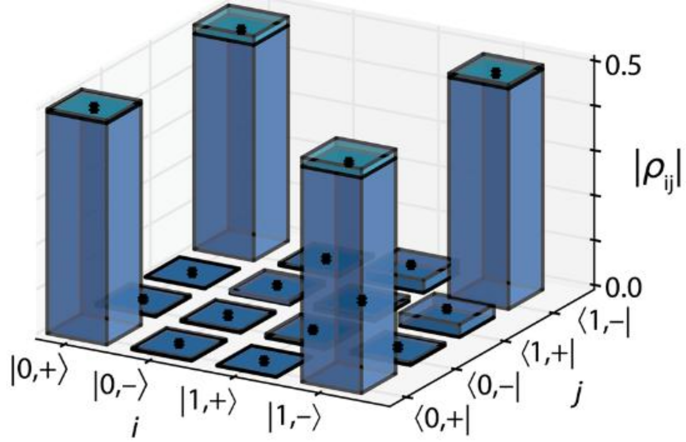

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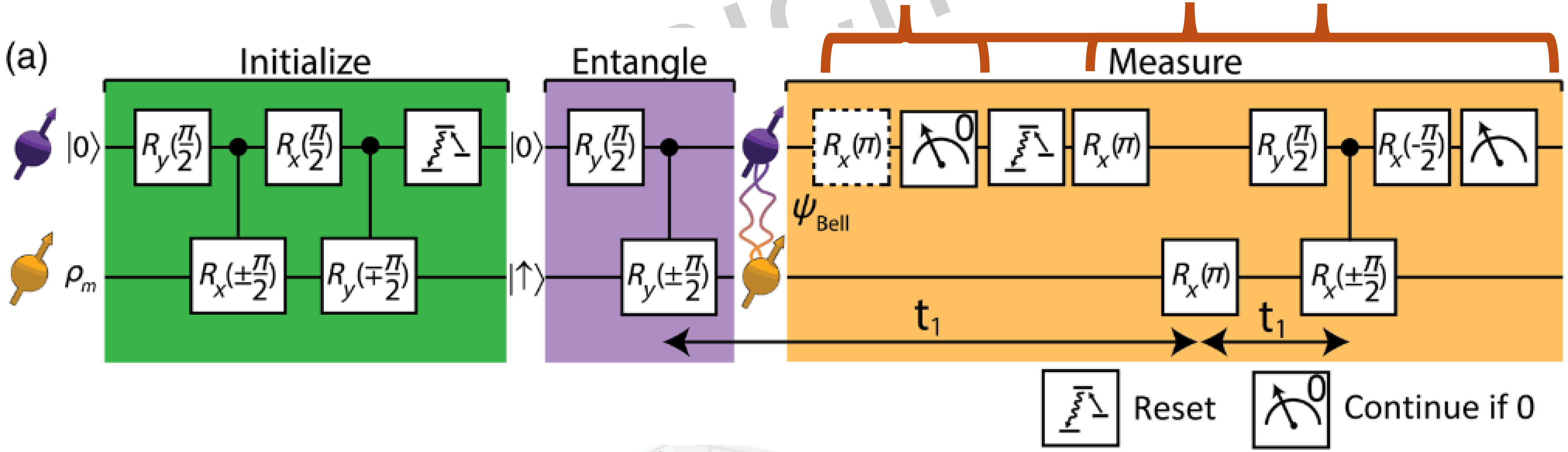

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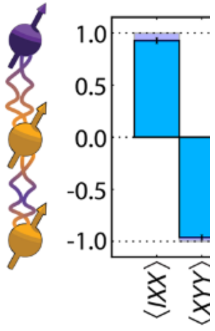

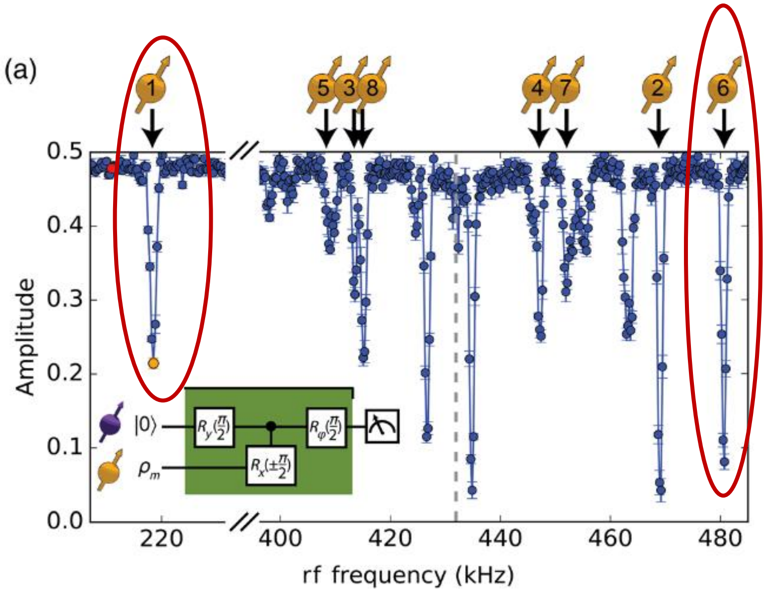

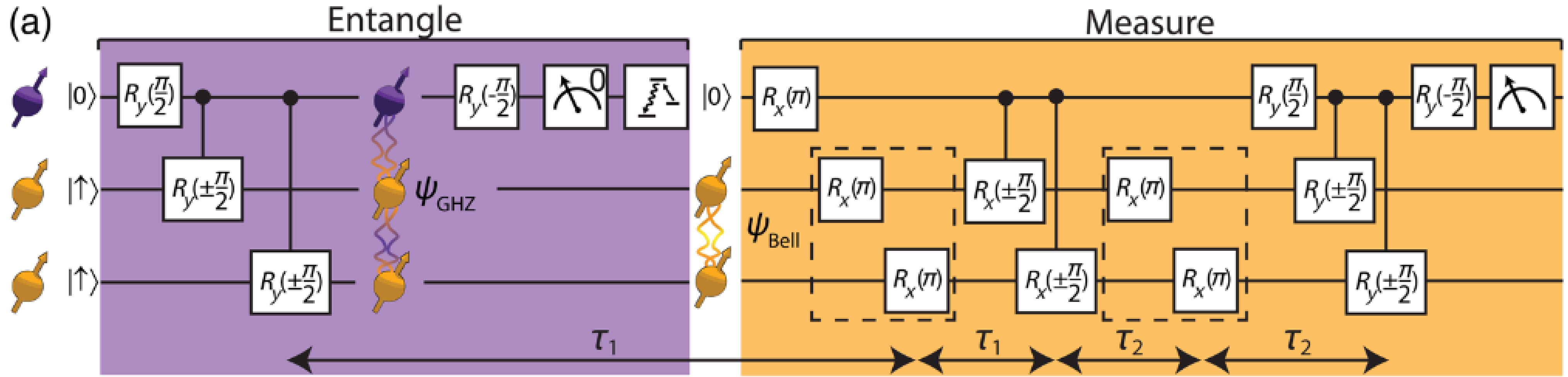

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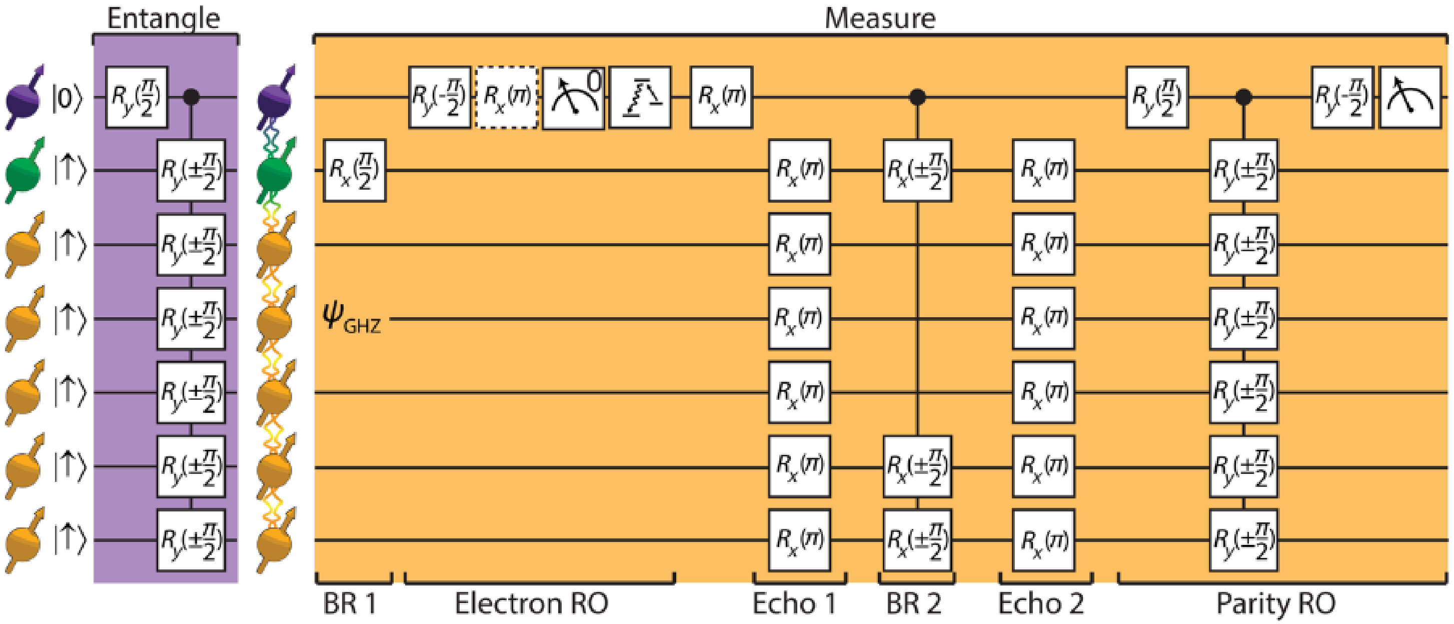
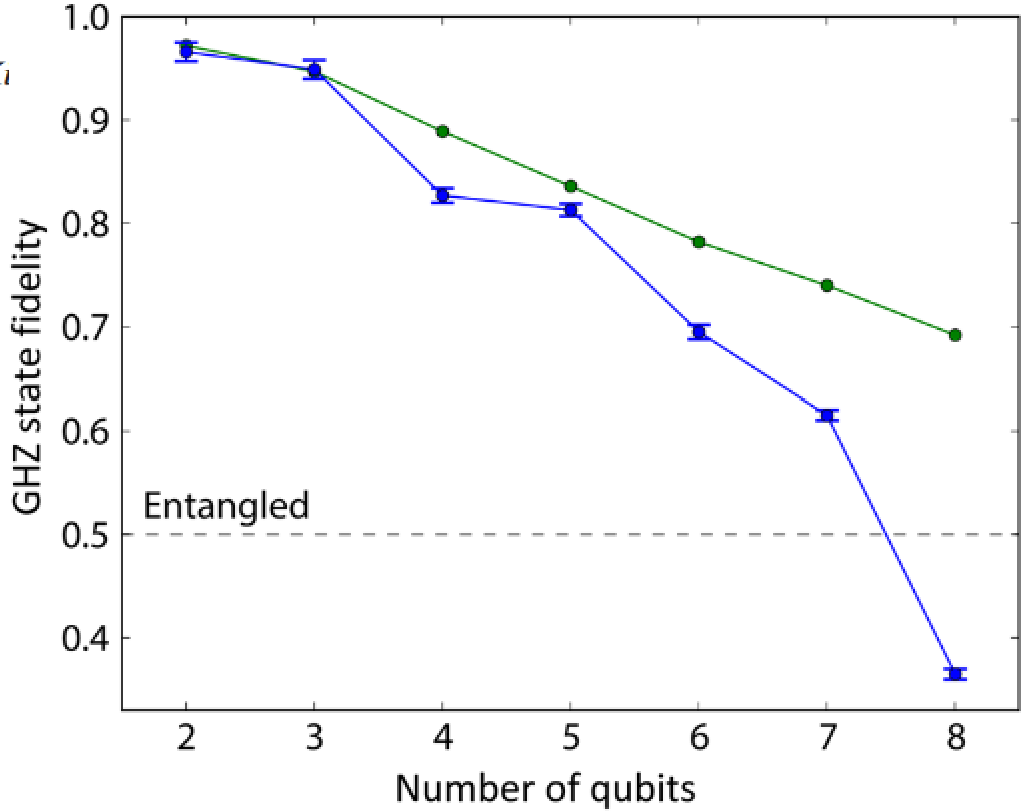




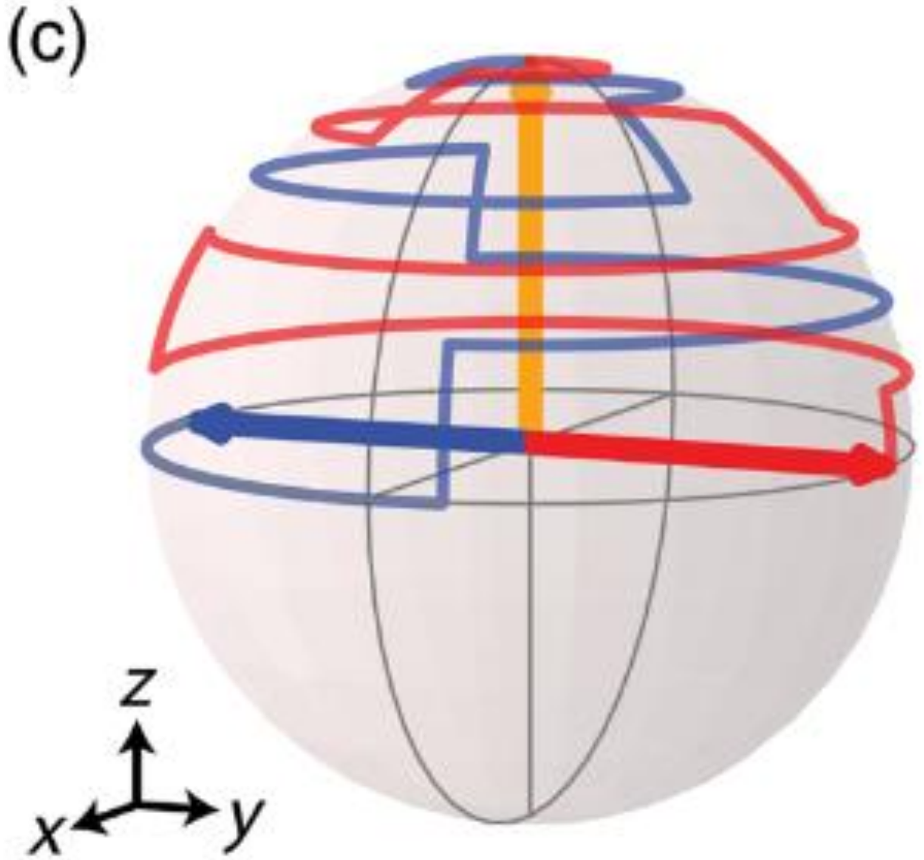
Agenda

- Wednesday (06/08/2025) – Introduction: the need for spin-photon interfaces, examples of 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.

Some remarks:

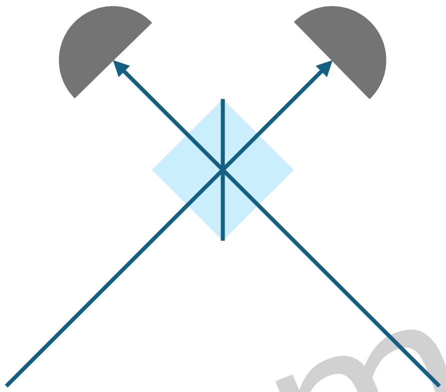
- This type of approach is very general! Useful for any system with multiple, strongly coupled degrees of freedom, where we need to 'select' our coupling times

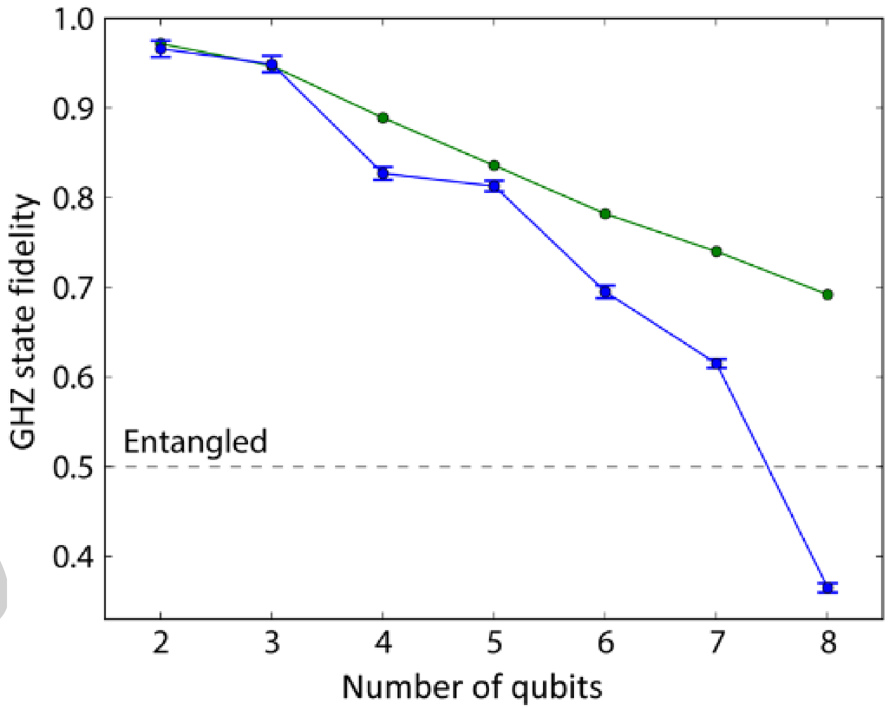
Quantum dots (both III-V, and Si)
Other defect systems

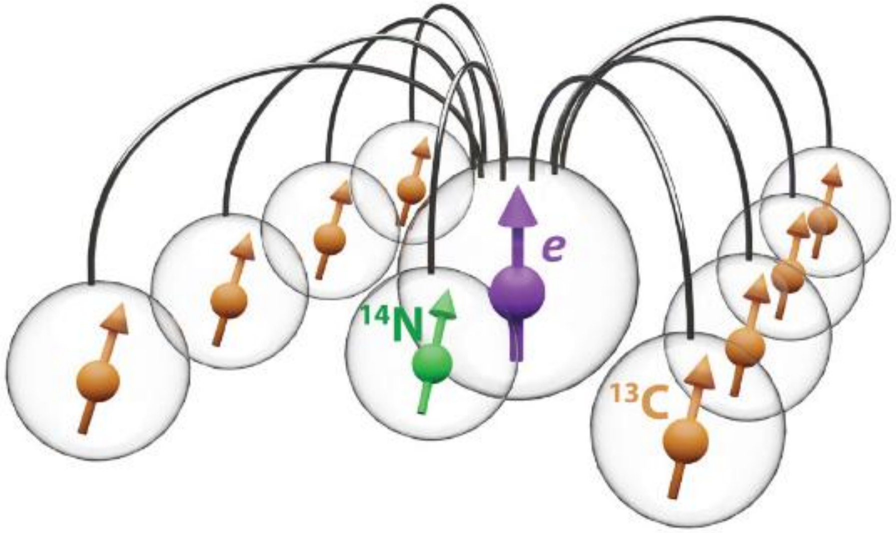


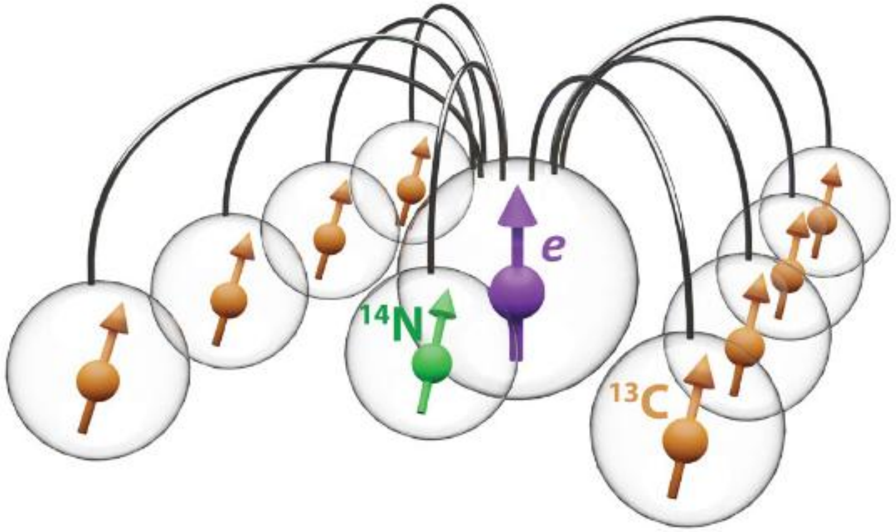
Some remarks:

- Is this the limit?





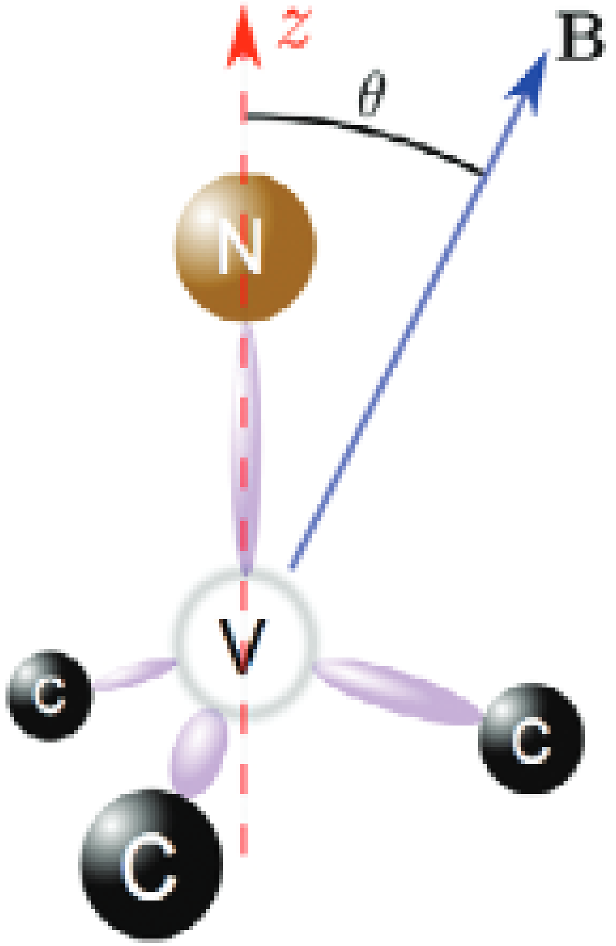


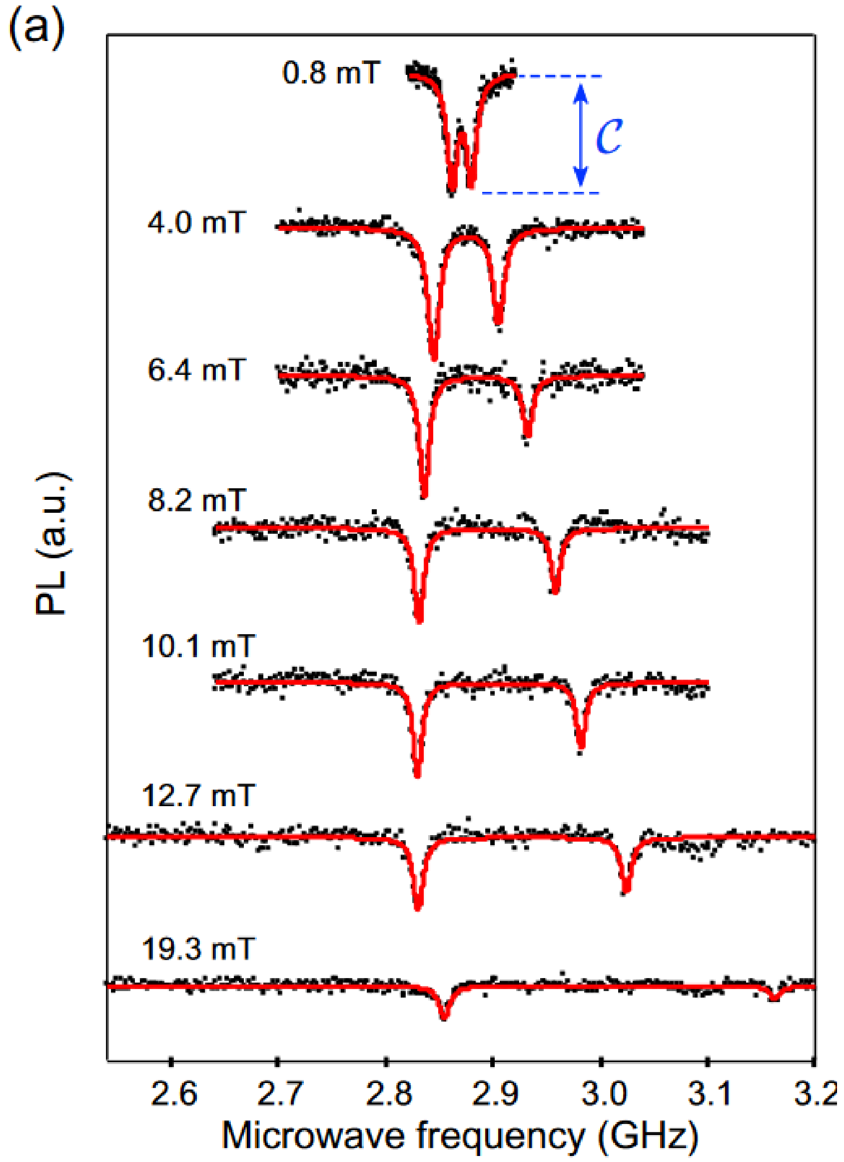


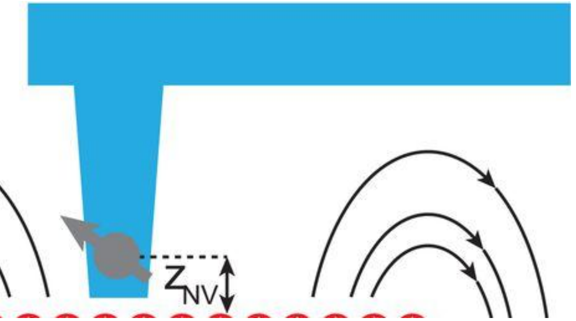
The NV has limited bandwidth

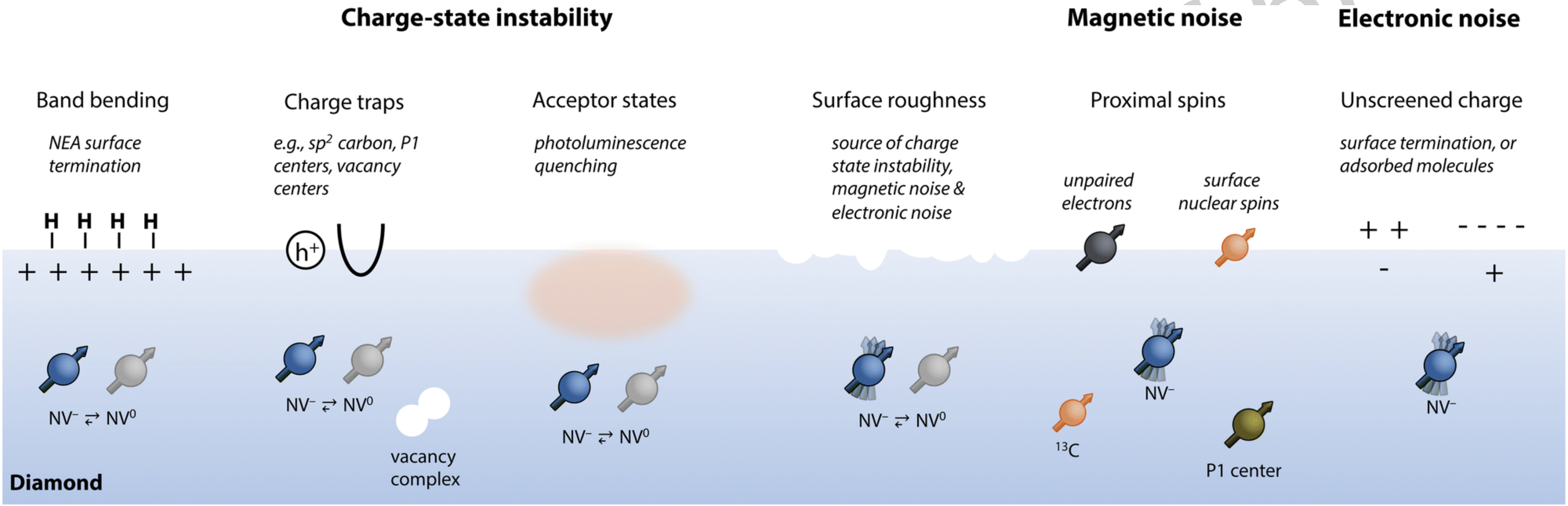
arXiv:2408.10348

J-P Tetienne *et al* 2012 *New J. Phys.* **14** 103033









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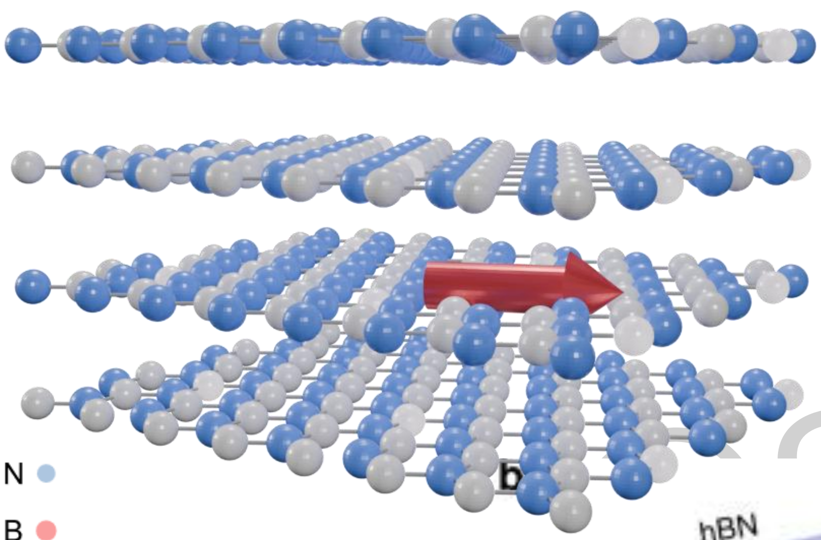
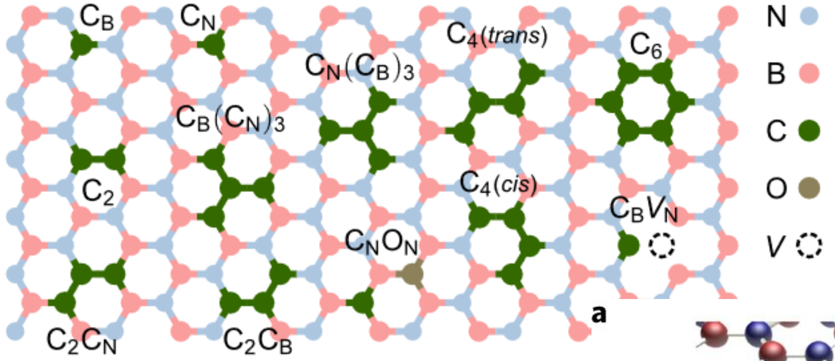
- > 6 eV bandgap
- Compatible with nanofabrication





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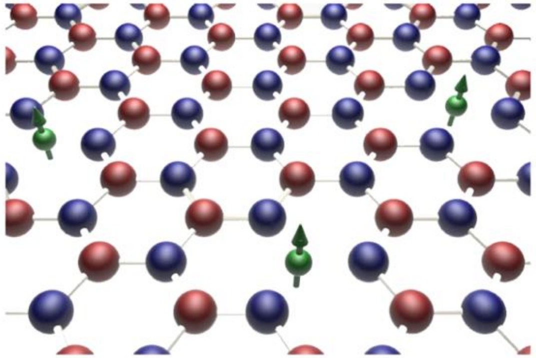

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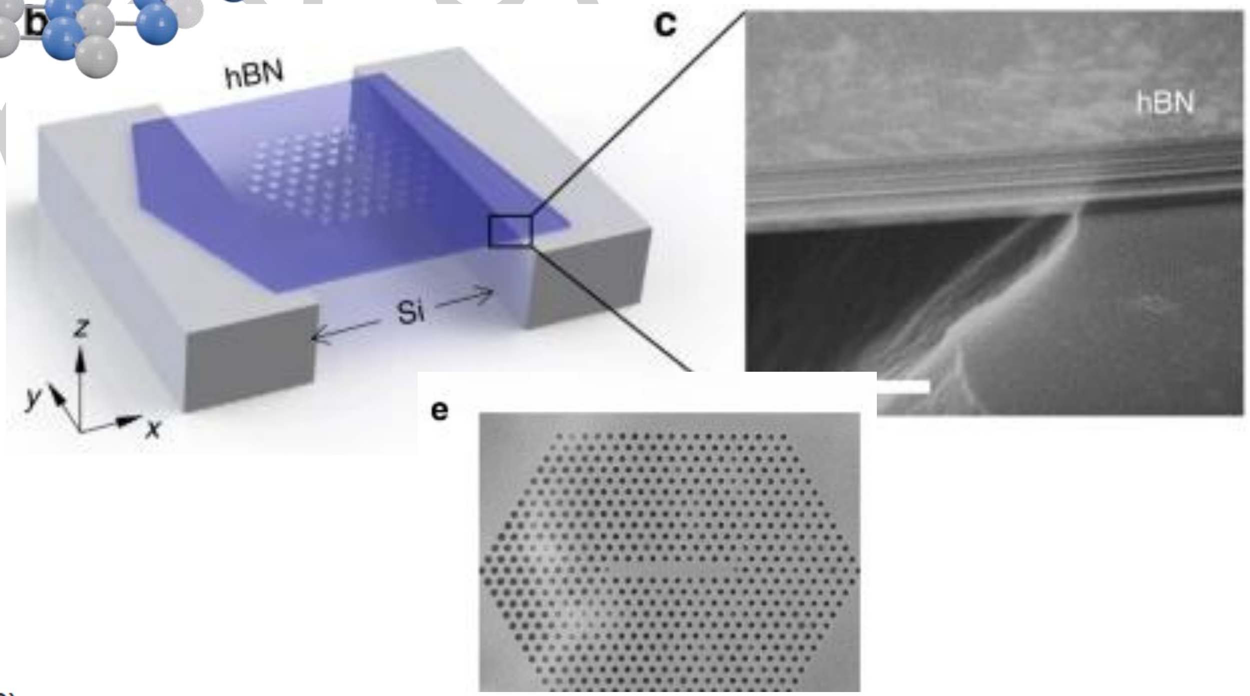

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