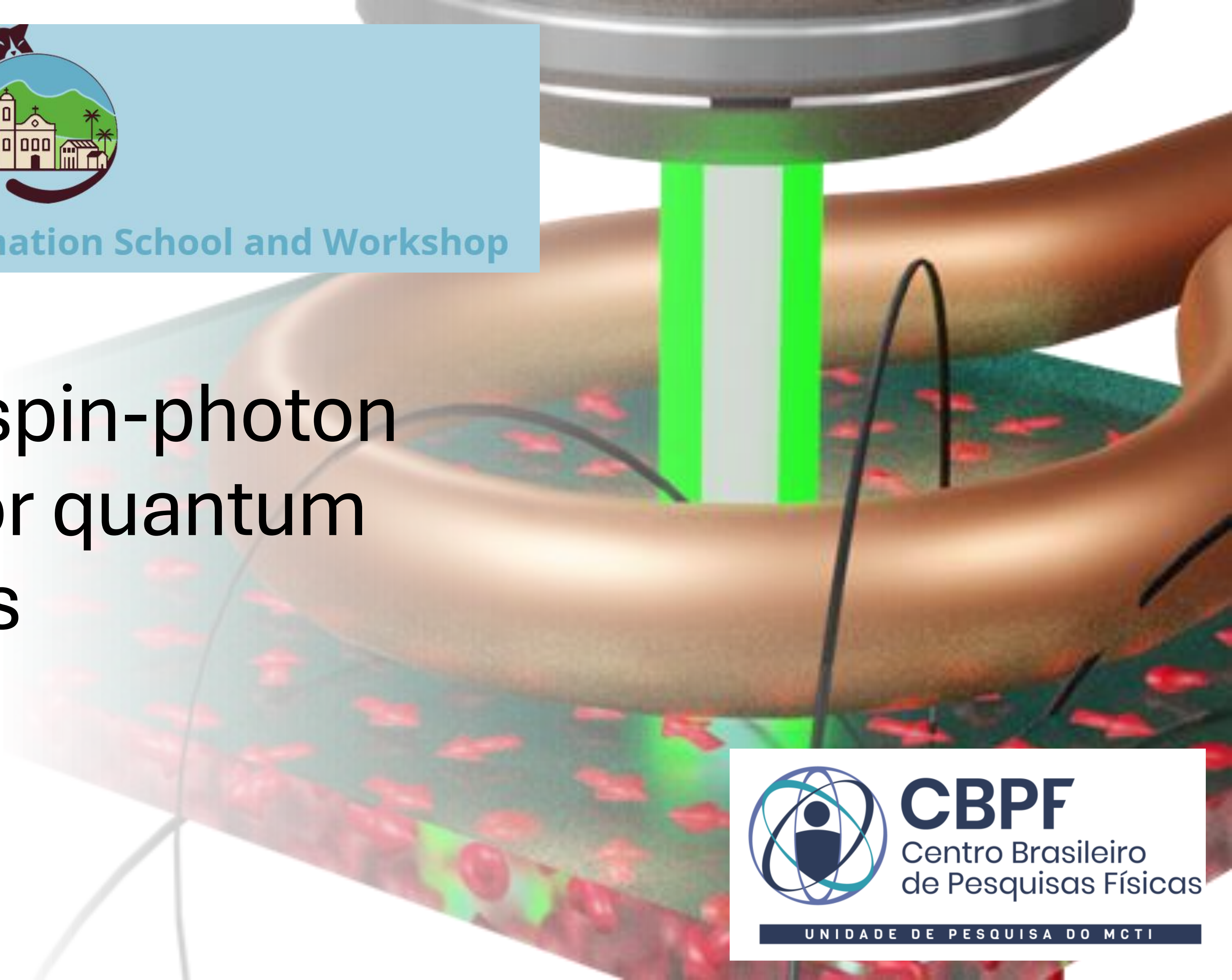
Paraty Quantum Information School and Workshop

Solid-state spin-photon interfaces for quantum technologies



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09/08/2025

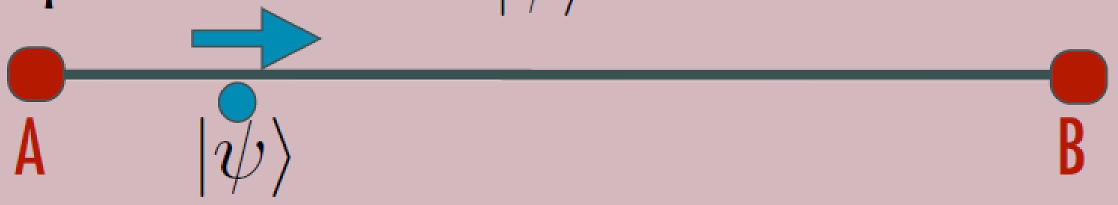
CBPF
Centro Brasileiro de Pesquisas Físicas
UNIDADE DE PESQUISA DO MCTI

Agenda

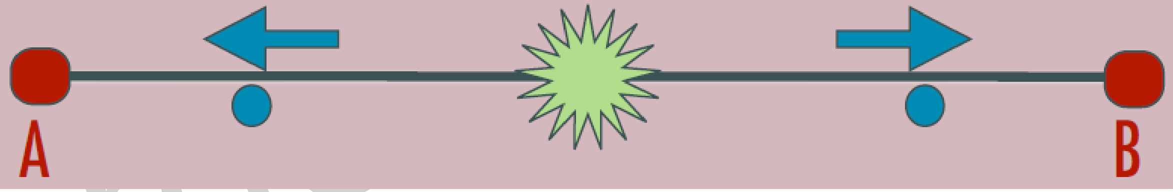
- Wednesday (06/08/2025) – Introduction: the need for spin-photon interfaces, examples of spin-photon interfaces, the NV system in diamond
- Thursday (07/08/2025) – The NV system in diamond: spin control protocols and implementation as quantum sensing and quantum computing platform.
- Saturday (09/08/2025)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

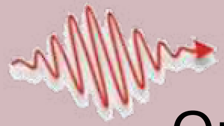
What is the role of the photons?

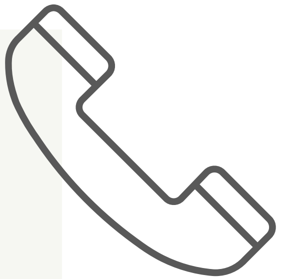
Protocol 1: Send photons in a state $|\psi\rangle$ from A to B



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





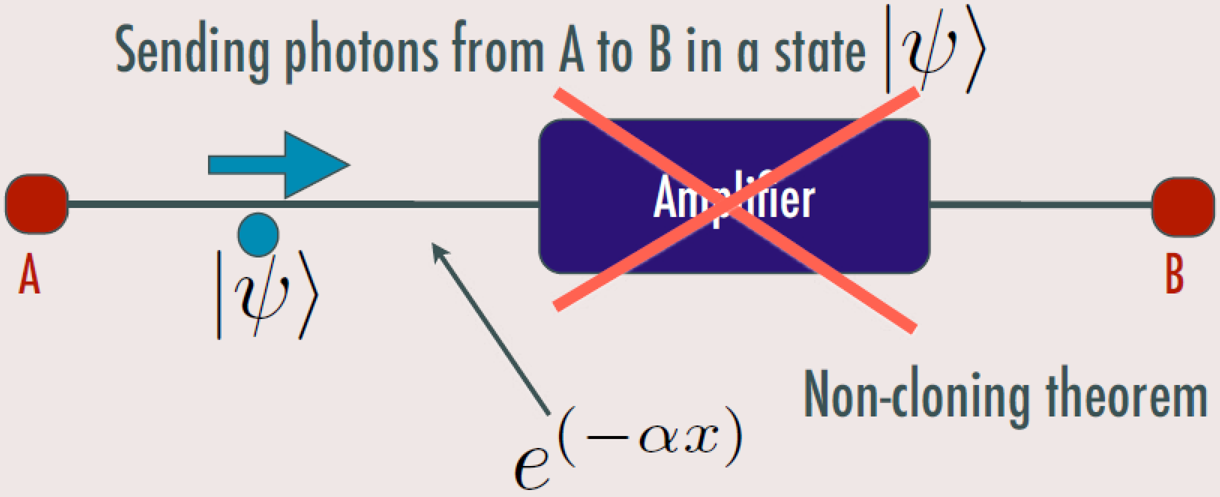


Quantum communication

Credit: Gabriel Horacio

Challenges in quantum communication

Quantum communication

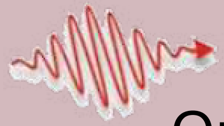


Fundamental limitation: loss in optical fibers or in free-space propagation

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

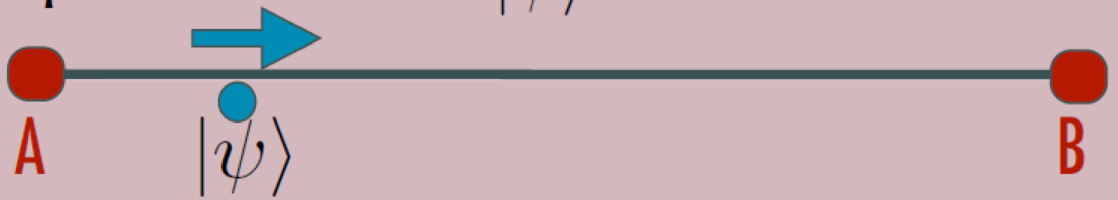
Credit: Gabriel Horacio

What is the role of the photons?

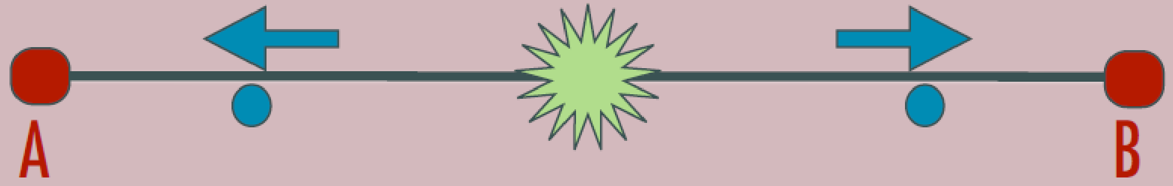


Quantum communication

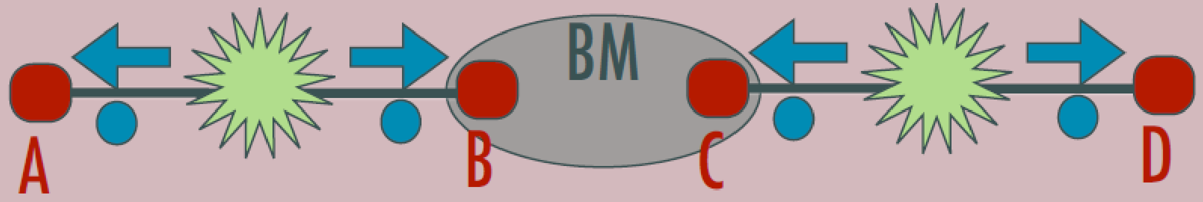
Protocol 1: Send photons in a state $|\psi\rangle$ from A to B

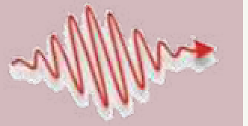


Protocol 2: Send one part of the state to A and the other to B



Protocol 3: Entanglement swapping:

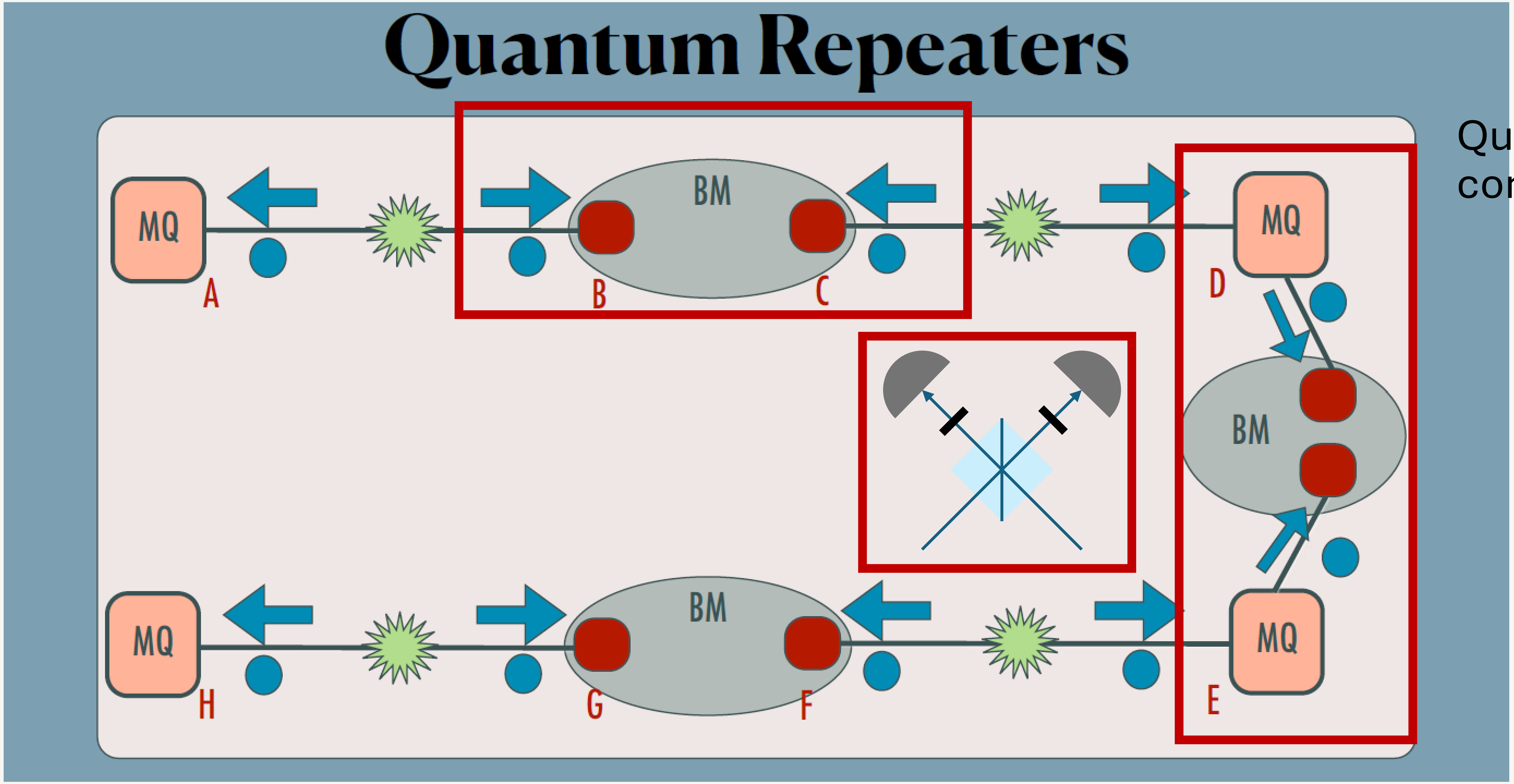


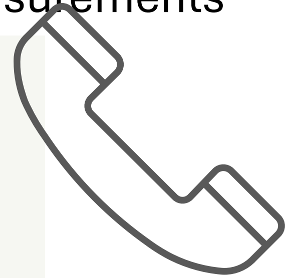


A. Ekert, Phys. Rev. Lett. **67**, 661 (1991).

Credit: Gabriel Horacio

Objective: Establish entanglement between two quantum memories using photons and projective measurements



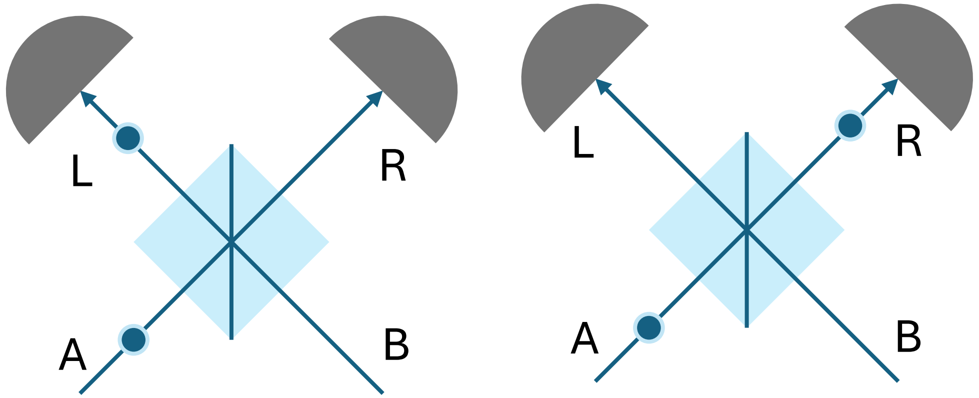


Quantum communication

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

Credit: Gabo

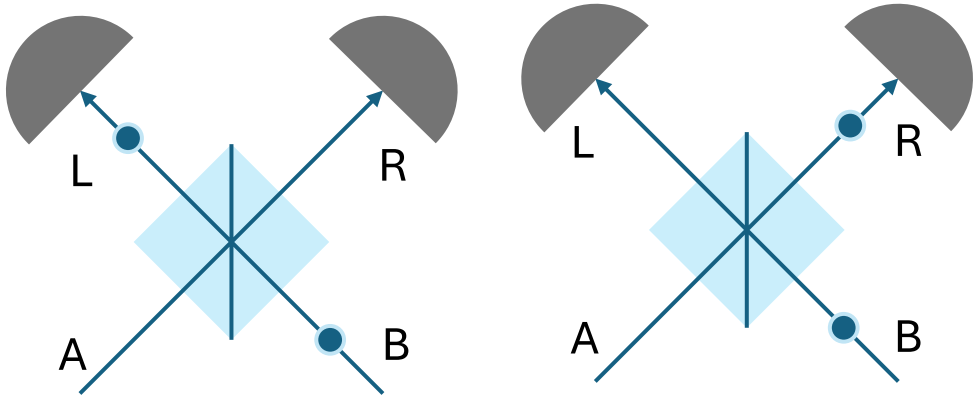
Hong-Ou-Mandel Interference



$$|\psi_{out}\rangle = \frac{|0_L, 1_R\rangle + |1_L, 0_R\rangle}{\sqrt{2}}$$

$$|\psi_{in}\rangle = |1_A\rangle$$

Hong-Ou-Mandel Interference

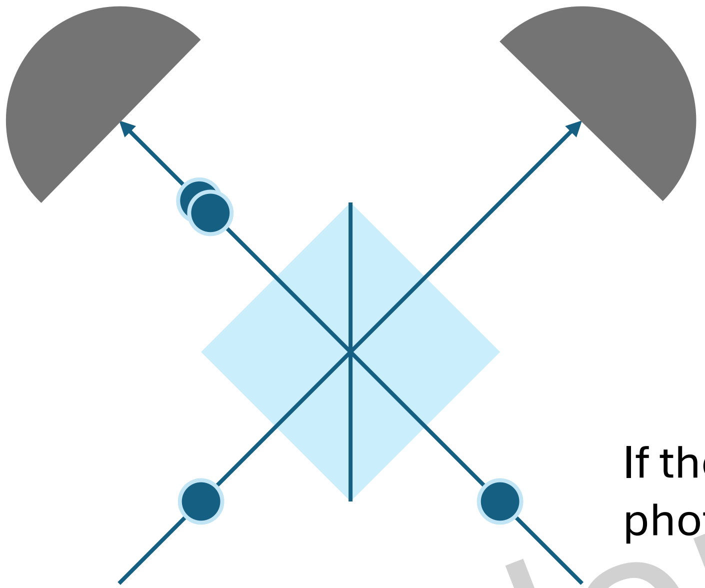


$$|\psi_{in}\rangle = |1_B\rangle$$

$$|\psi_{out}\rangle = \frac{|1_L, 0_R\rangle - |0_L, 1_R\rangle}{\sqrt{2}}$$

It arises because the two sides of the half-mirror are not the same! A phase of pi arises!

Hong-Ou-Mandel Interference



$$|\psi_{in}\rangle = |1_A, 1_B\rangle$$

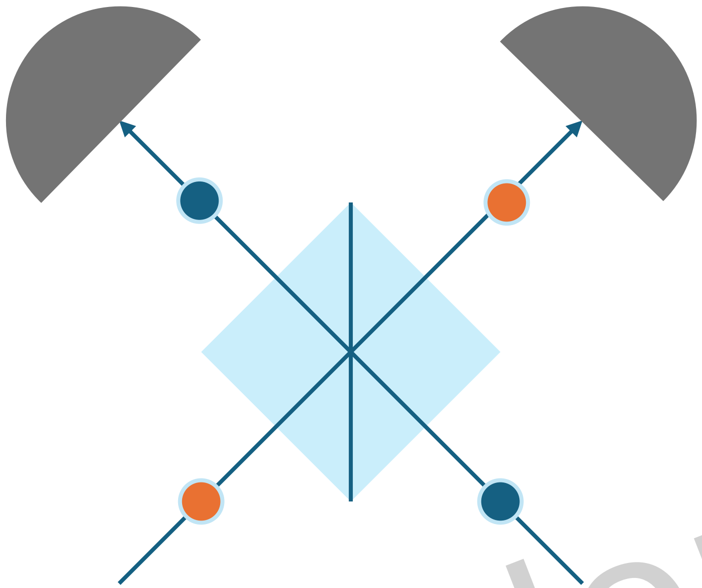
$$|\psi_{out}\rangle = \left(\frac{|0_{A,L}, 1_{A,R}\rangle + |1_{A,L}, 0_{A,R}\rangle}{\sqrt{2}}\right)\left(\frac{|1_{B,L}, 0_{B,R}\rangle - |0_{B,L}, 1_{B,R}\rangle}{\sqrt{2}}\right)$$

$$|\psi_{out}\rangle = \frac{|0_{A,L},1_{A,R}\rangle|1_{B,L},0_{B,R}\rangle + |1_{A,L},0_{A,R}\rangle|1_{B,L},0_{B,R}\rangle - |0_{A,L},1_{A,R}\rangle|0_{B,L},1_{B,R}\rangle - |1_{A,L},0_{A,R}\rangle|0_{B,L},1_{B,R}\rangle}{2}$$

If the photons are indistinguishable, I can't know who is photon A and who is photon B!

$$|\psi_{out}\rangle = \frac{|1_L,1_R\rangle + |2_L,0_R\rangle - |0_L,2_R\rangle - |1_L,1_R\rangle}{2} = \frac{|2_L,0_R\rangle - |0_L,2_R\rangle}{\sqrt{2}}$$

Hong-Ou-Mandel Interference



$|\psi_{in}\rangle = |1_A, 1_B\rangle$

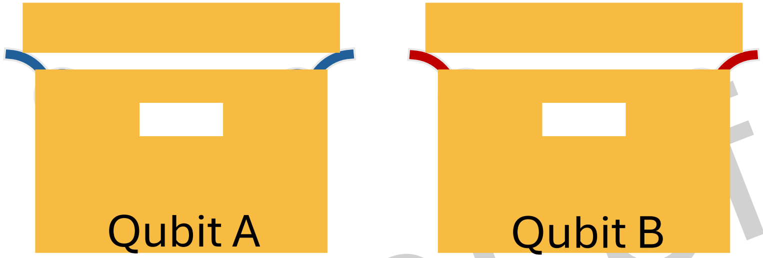
$$|\psi_{out}\rangle = \left(\frac{|0_{A,L}, 1_{A,R}\rangle + |1_{A,L}, 0_{A,R}\rangle}{\sqrt{2}}\right)\left(\frac{|1_{B,L}, 0_{B,R}\rangle - |0_{B,L}, 1_{B,R}\rangle}{\sqrt{2}}\right)$$

$$|\psi_{out}\rangle = \frac{|0_{A,L},1_{A,R}\rangle|1_{B,L},0_{B,R}\rangle + |1_{A,L},0_{A,R}\rangle|1_{B,L},0_{B,R}\rangle - |0_{A,L},1_{A,R}\rangle|0_{B,L},1_{B,R}\rangle - |1_{A,L},0_{A,R}\rangle|0_{B,L},1_{B,R}\rangle}{2}$$

$$|\psi_{out}\rangle = \frac{|1_{A,L},1_{B,R}\rangle + |1_{A,L},1_{B,L}\rangle - |1_{A,R},1_{B,R}\rangle - |1_{B,L},1_{A,R}\rangle}{2}$$

Projective measurement

$$|\psi_0\rangle = \frac{|\alpha_A, \gamma_B\rangle + |\beta_A, \theta_B\rangle}{\sqrt{2}}$$



Postulate of Quantum Mechanics: the collapse of the wave function

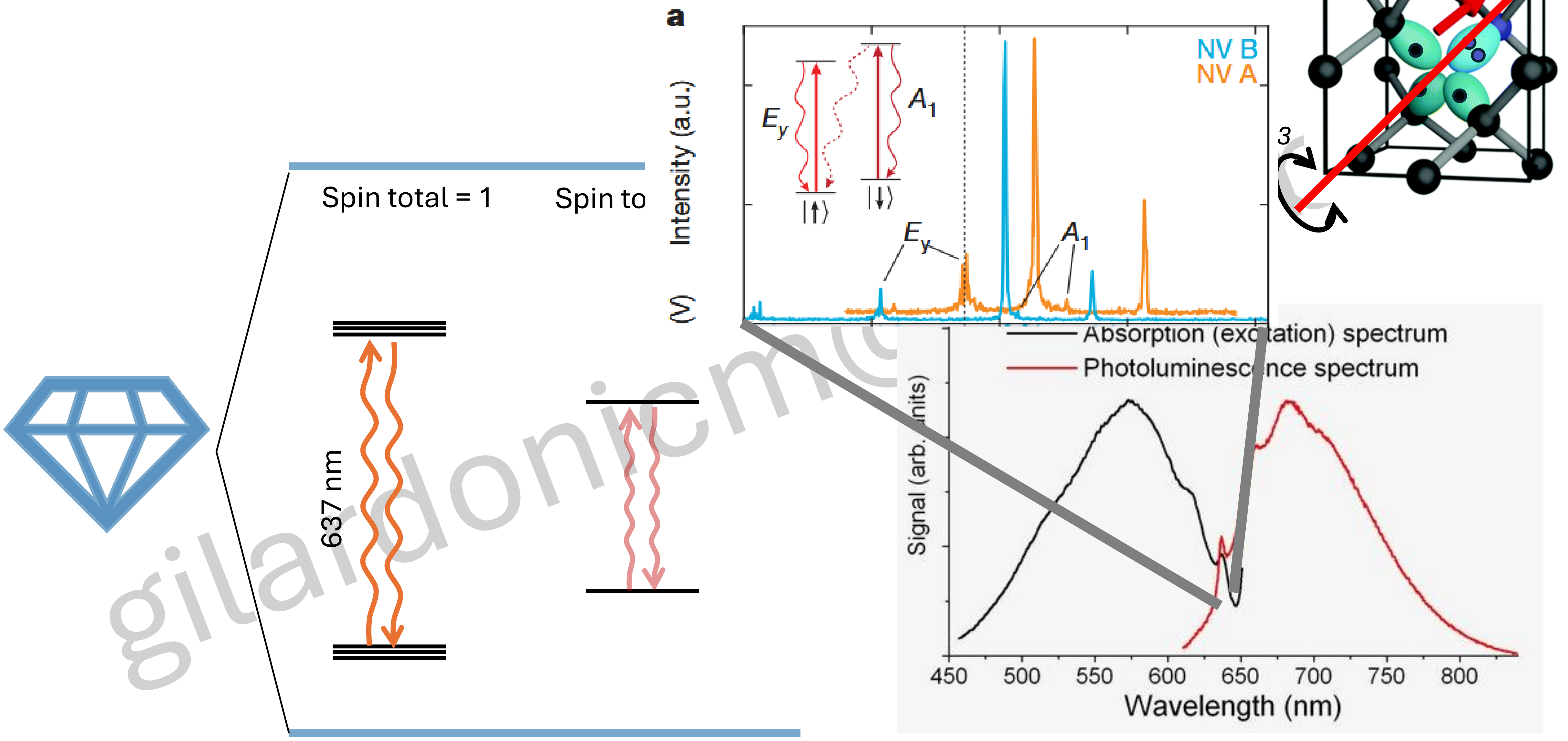
$$|\psi\rangle = \frac{P_a|\psi_0\rangle}{\sqrt{\langle\psi_0|P_a\psi_0\rangle}}, P_a = |a\rangle\langle a|$$

$$P_\gamma = |\gamma_B\rangle\langle\gamma_B|$$

$$|\psi\rangle = \frac{|\gamma_B\rangle\langle\gamma_B|\alpha_A, \gamma_B\rangle + |\gamma_B\rangle\langle\gamma_B|\beta_A, \theta_B\rangle}{N}$$

$$|\psi\rangle = |\alpha_A, \gamma_B\rangle$$

The NV⁻ – a defect with spin 1



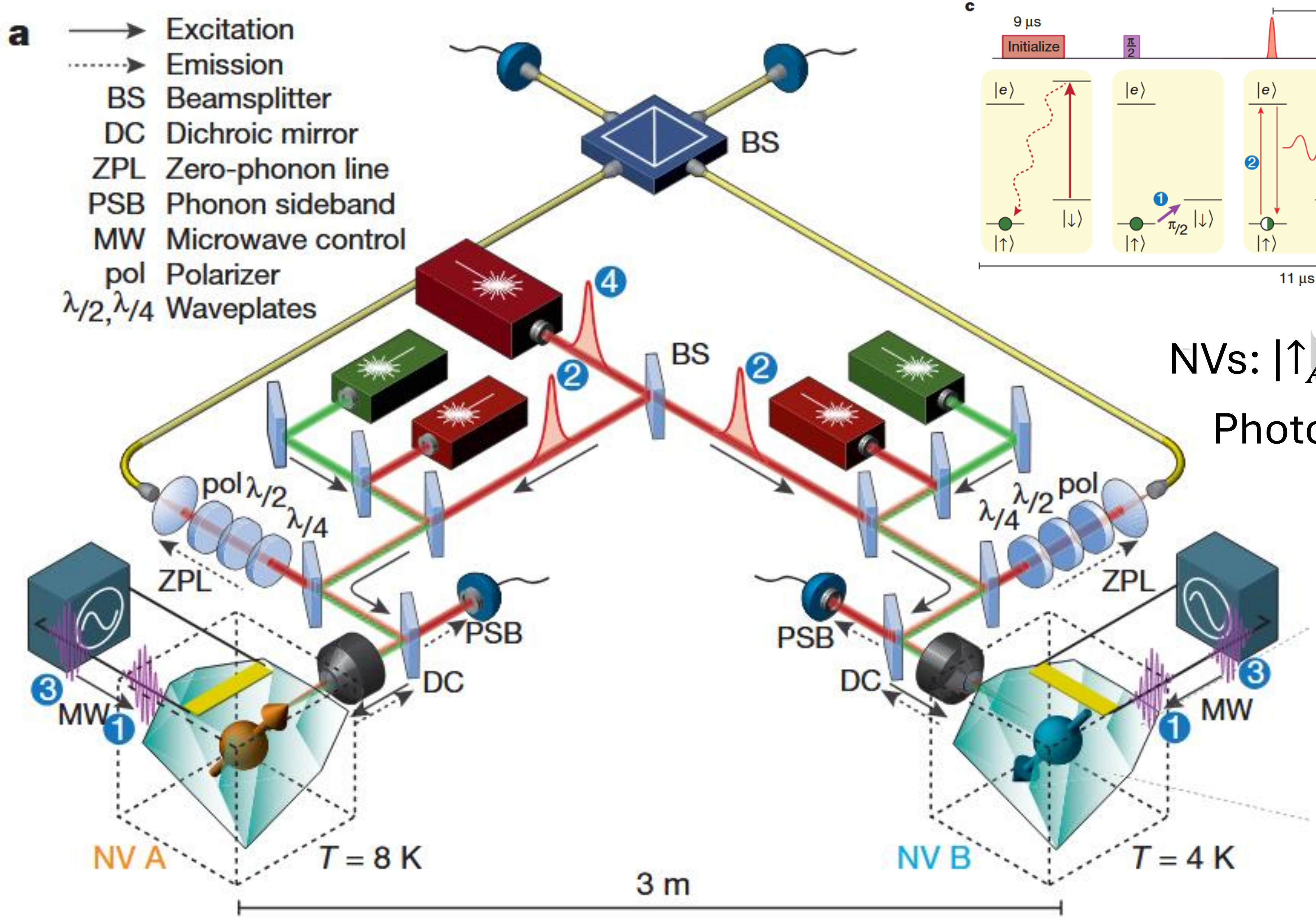
LETTER

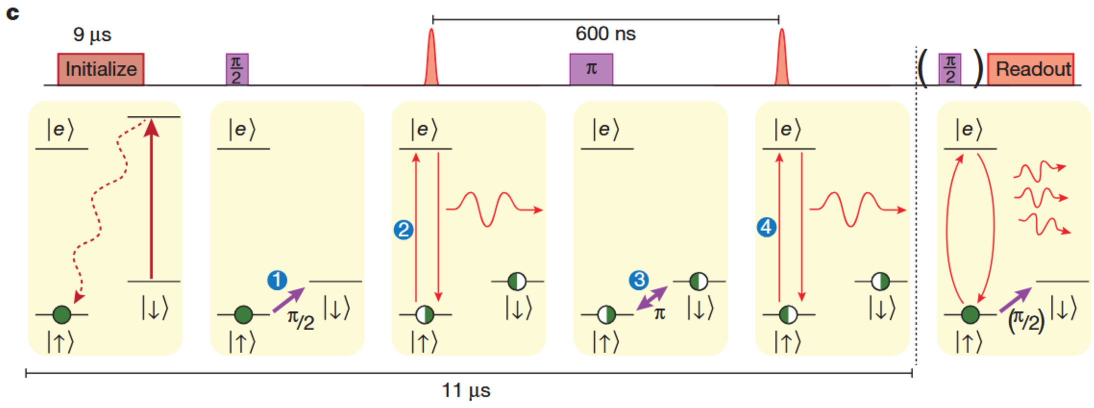
doi:10.1038/nature12016

Heralded entanglement between solid-state qubits separated by three metres

H. Bernien[1], B. Hensen[1], W. Pfaff[1], G. Koolstra[1], M. S. Blok[1], L. Robledo[1], T. H. Taminiau[1], M. Markham[2], D. J. Twitchen[2], L. Childress[3] & R. Hanson[1]

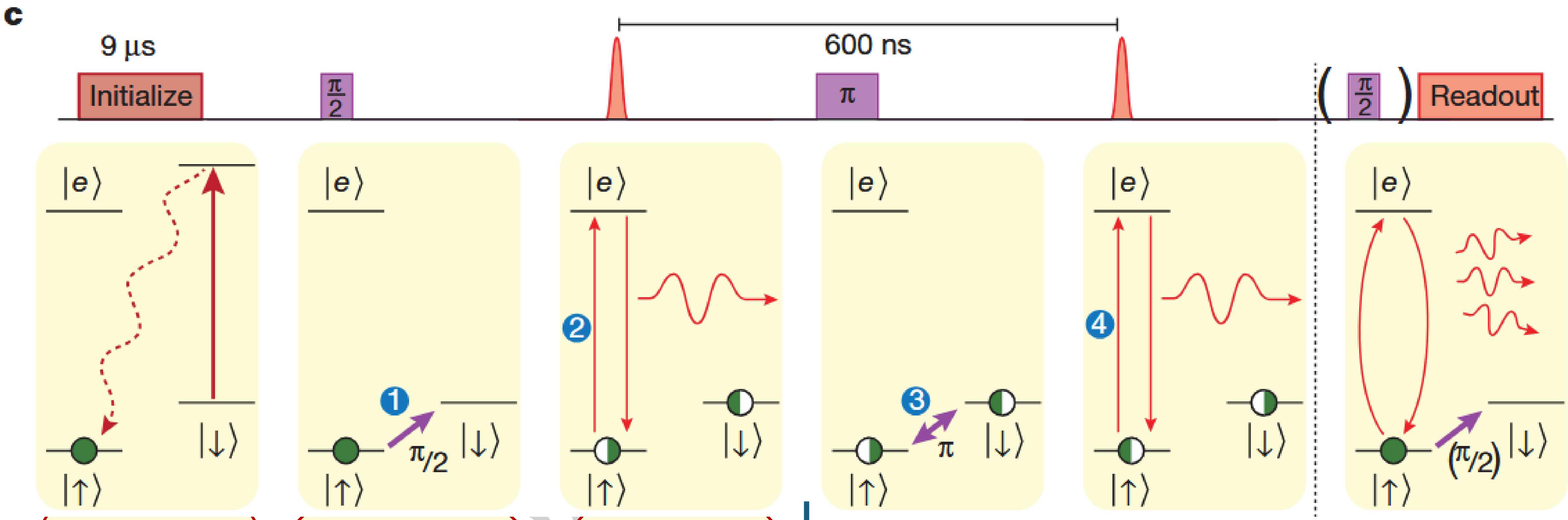
2013





NVs: $|\uparrow_A\rangle, |\downarrow_A\rangle, |\uparrow_B\rangle, |\downarrow_B\rangle$

Photons: $|1_A\rangle, |0_A\rangle, |1_B\rangle, |0_B\rangle$



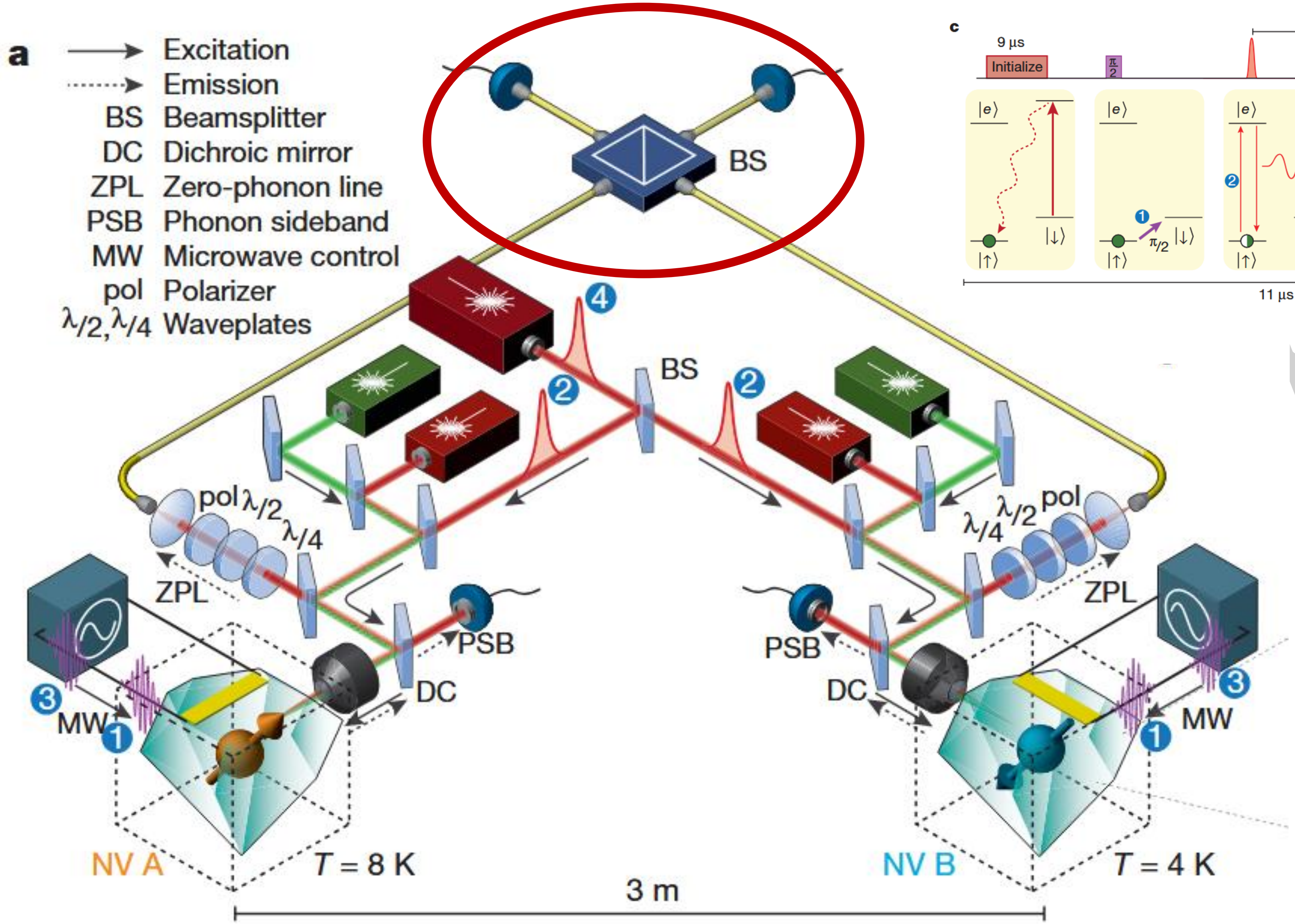
$$|\psi\rangle = |\uparrow_A\rangle|\uparrow_B\rangle$$

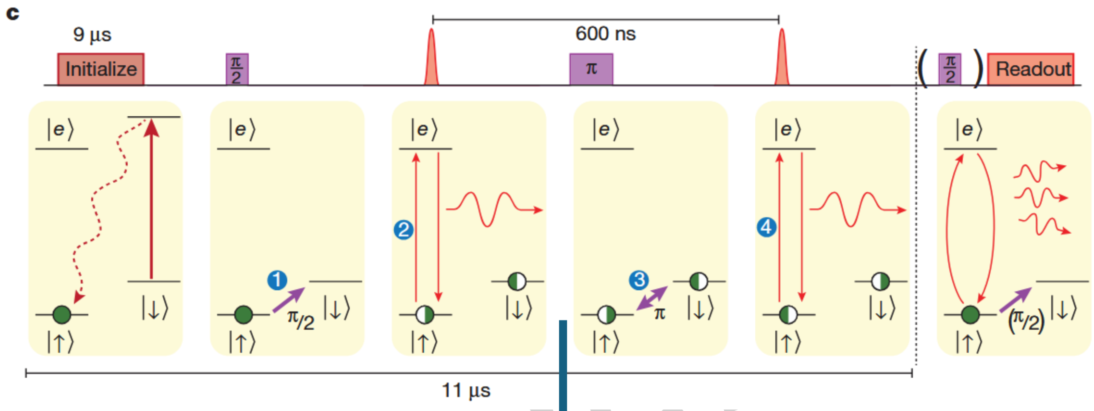
$$|\psi\rangle = \left(\frac{|\uparrow_A\rangle+|\downarrow_A\rangle}{\sqrt{2}}\right)\left(\frac{|\uparrow_B\rangle+|\downarrow_B\rangle}{\sqrt{2}}\right)$$

Projective measurement

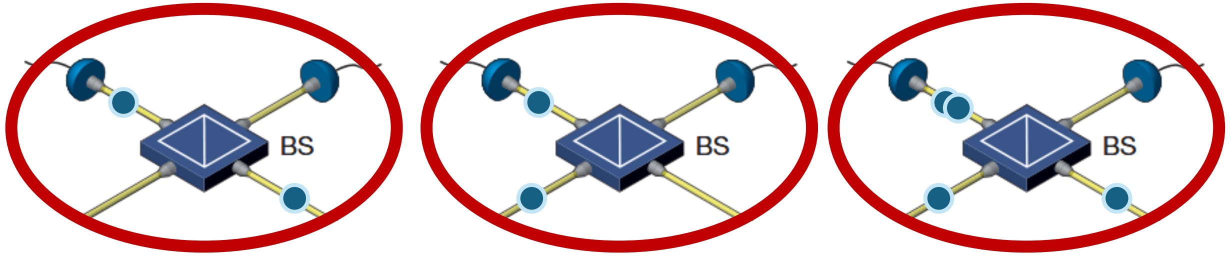
$$|\psi\rangle = \left(\frac{|\uparrow_A,1_A\rangle+|\downarrow_A,0_A\rangle}{\sqrt{2}}\right)\left(\frac{|\uparrow_B,1_B\rangle+|\downarrow_B,0_B\rangle}{\sqrt{2}}\right)$$

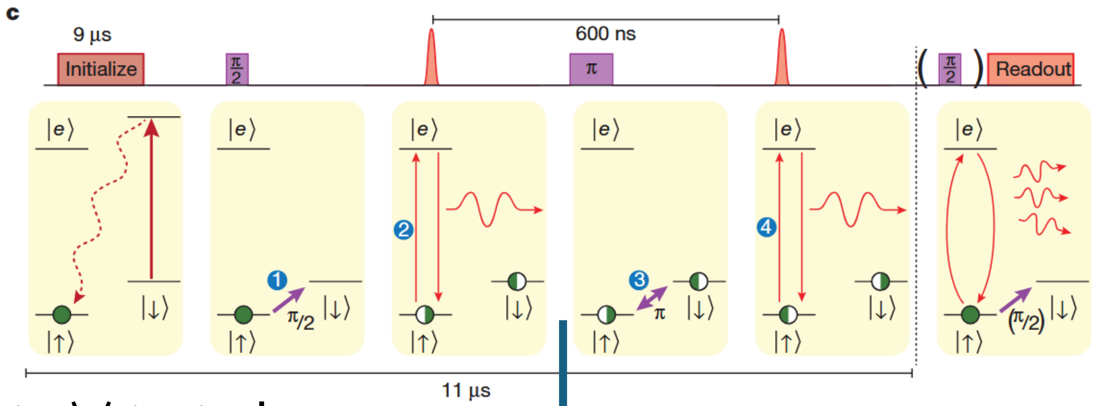
So far, no interaction between NVs A and B!
The spaces are completely separable.





Projective measurement: measuring a photon in one of the detectors





$$P_{click\ left} = |0_A 1_B\rangle\langle 0_A 1_B| + |1_A 0_B\rangle\langle 1_A 0_B| + |1_A 1_B\rangle\langle 1_A 1_B|$$

$$P_{click\ right} = -|0_A 1_B\rangle\langle 0_A 1_B| + |1_A 0_B\rangle\langle 1_A 0_B| - |1_A 1_B\rangle\langle 1_A 1_B|$$

Projective measurement: measuring a photon in one of the detectors

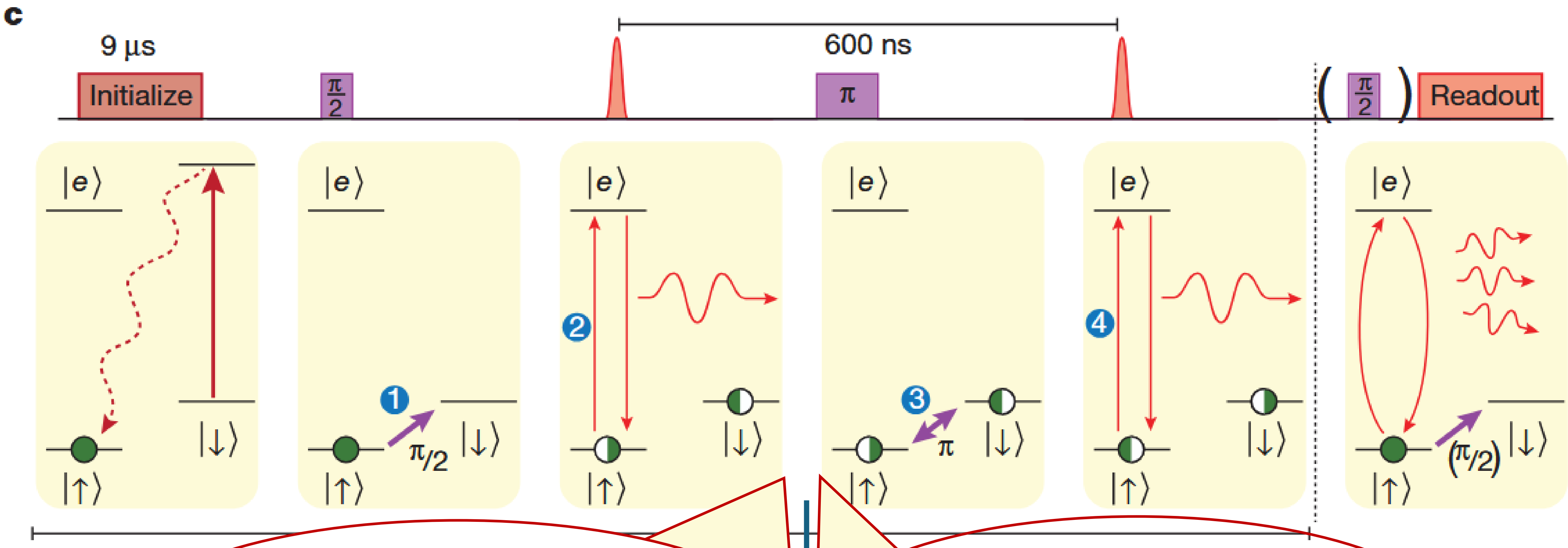
$$|\psi_0\rangle = \left(\frac{|\uparrow_A, 1_A\rangle + |\downarrow_A, 0_A\rangle}{\sqrt{2}}\right)\left(\frac{|\uparrow_B, 1_B\rangle + |\downarrow_B, 0_B\rangle}{\sqrt{2}}\right)$$

$$|\psi_0\rangle = \left(\frac{|\uparrow_A, \uparrow_B, 1_A, 1_B\rangle + |\downarrow_A, \uparrow_B, 0_A, 1_B\rangle + |\uparrow_A, \downarrow_B, 1_A, 0_B\rangle + |\downarrow_A, \downarrow_B, 0_A, 0_B\rangle}{2}\right)$$

$$|\psi\rangle = \left(\frac{\pm|\uparrow_A, \uparrow_B, 1_A, 1_B\rangle \pm |\downarrow_A, \uparrow_B, 0_A, 1_B\rangle + |\uparrow_A, \downarrow_B, 1_A, 0_B\rangle}{\sqrt{3}}\right)$$

$$|\psi_{spin}\rangle = \left(\frac{\pm|\uparrow_A, \uparrow_B\rangle \pm |\downarrow_A, \uparrow_B\rangle + |\uparrow_A, \downarrow_B\rangle}{\sqrt{3}}\right)$$

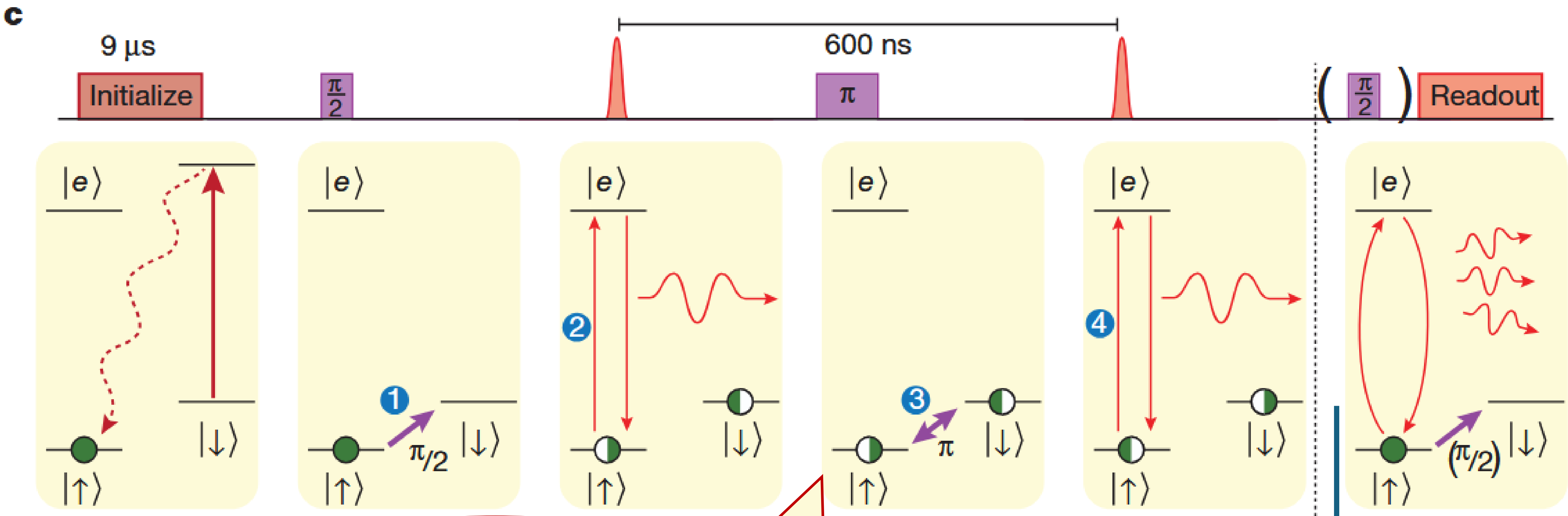
It's already an entangled state, but it's not a maximally entangled state



$$|\psi\rangle = \left(\frac{|\uparrow_A, 1_A\rangle + |\downarrow_A, 0_A\rangle}{\sqrt{2}}\right)\left(\frac{|\uparrow_B, 1_B\rangle + |\downarrow_B, 0_B\rangle}{\sqrt{2}}\right)$$

$$|\psi_{spin}\rangle = \left(\frac{\pm|\uparrow_A, \uparrow_B\rangle \pm |\downarrow_A, \uparrow_B\rangle + |\uparrow_A, \downarrow_B\rangle}{\sqrt{3}}\right)$$

Projective measurement: measuring a photon in one of the detectors

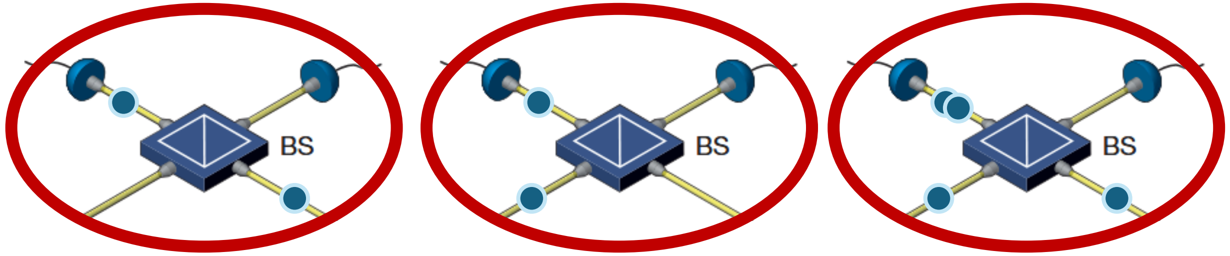


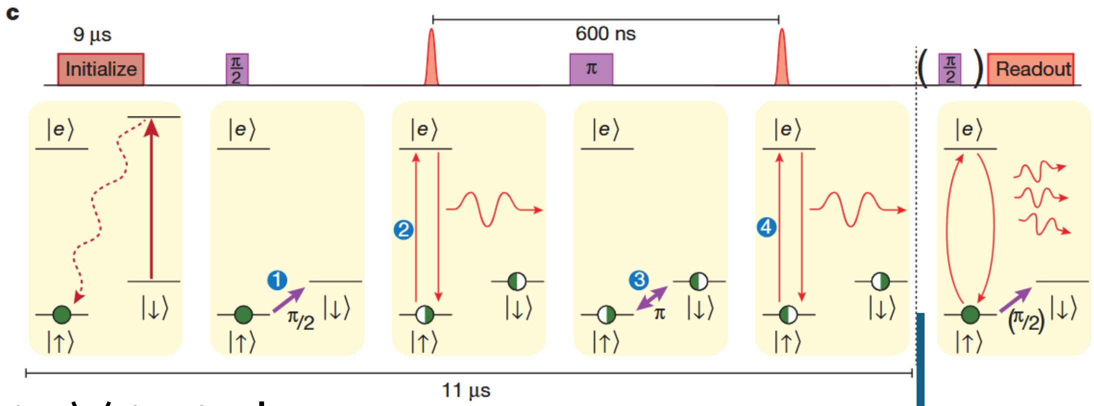
$$|\psi_{spin}\rangle = \left(\frac{\pm|\uparrow_A,\uparrow_B\rangle \pm |\downarrow_A,\uparrow_B\rangle + |\uparrow_A,\downarrow_B\rangle}{\sqrt{3}}\right)$$

$$|\psi\rangle = \left(\frac{\pm|\downarrow_A,\downarrow_B,0_A,0_B\rangle \pm |\uparrow_A,\downarrow_B,1_A,0_B\rangle + |\downarrow_A,\uparrow_B,0_A,1_B\rangle}{\sqrt{3}}\right)$$

$$|\psi\rangle = \left(\frac{\pm|\downarrow_A,\downarrow_B\rangle \pm |\uparrow_A,\downarrow_B\rangle + |\downarrow_A,\uparrow_B\rangle}{\sqrt{3}}\right)$$

Projective measurement





$$P_{click\ left} = |0_A 1_B\rangle\langle 0_A 1_B| + |1_A 0_B\rangle\langle 1_A 0_B| + |1_A 1_B\rangle\langle 1_A 1_B|$$

$$P_{click\ right} = -|0_A 1_B\rangle\langle 0_A 1_B| + |1_A 0_B\rangle\langle 1_A 0_B| - |1_A 1_B\rangle\langle 1_A 1_B|$$

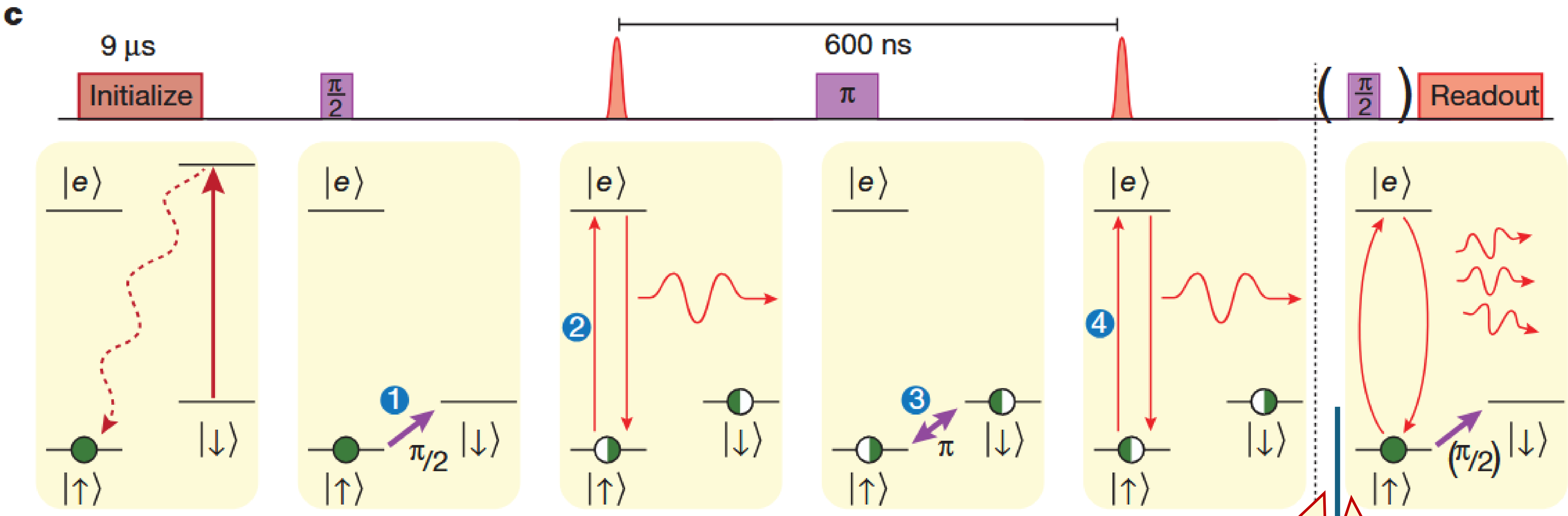
Projective measurement: measuring a photon in one of the detectors

$$|\psi_0\rangle = \left(\frac{\pm|\downarrow_A,\downarrow_B,0_A,0_B\rangle \pm |\uparrow_A,\downarrow_B,1_A,0_B\rangle + |\downarrow_A,\uparrow_B,0_A,1_B\rangle}{\sqrt{3}}\right)$$

$$|\psi\rangle = \left(\frac{|\downarrow_A,\uparrow_B,0_A,1_B\rangle \pm |\uparrow_A,\downarrow_B,1_A,0_B\rangle}{\sqrt{2}}\right)$$

$$|\psi_{spin}\rangle = \left(\frac{|\downarrow_A,\uparrow_B\rangle \pm |\uparrow_A,\downarrow_B\rangle}{\sqrt{2}}\right)$$

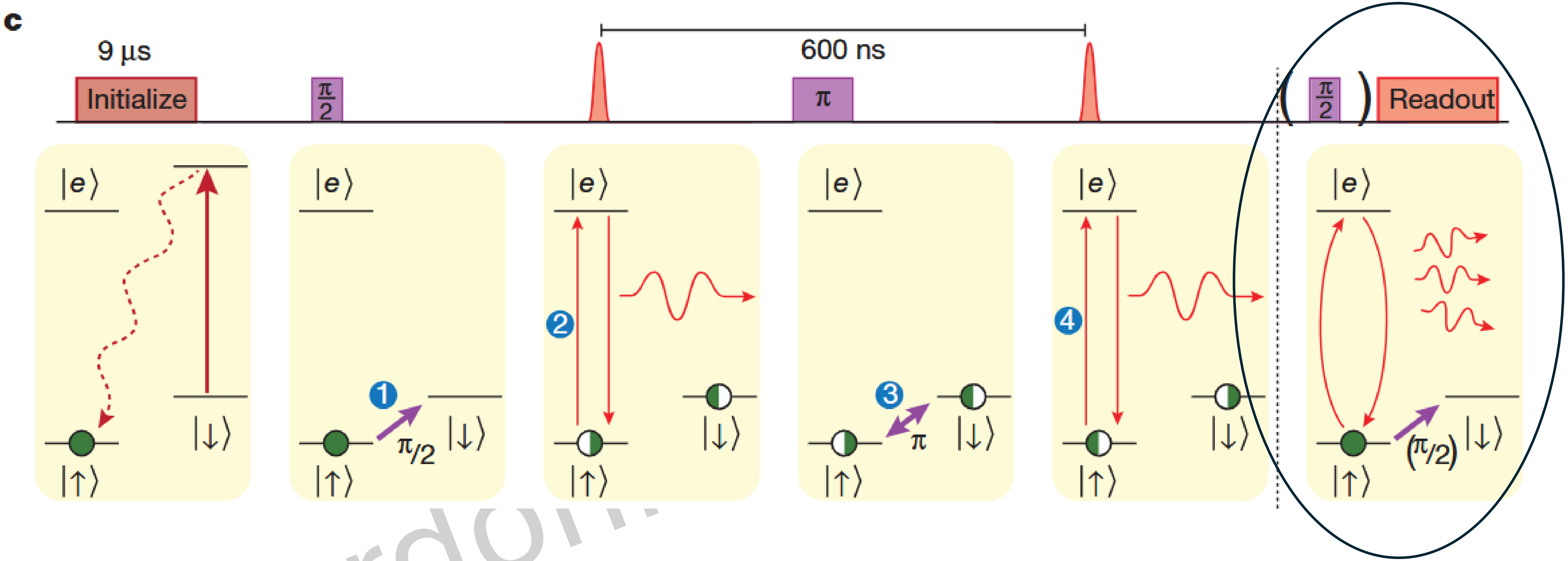
A Bell state!



$$|\psi\rangle = \left(\frac{\pm|\downarrow_A, \downarrow_B, 0_A, 0_B\rangle \pm |\uparrow_A, \downarrow_B, 1_A, 0_B\rangle + |\downarrow_A, \uparrow_B, 0_A, 1_B\rangle}{\sqrt{3}}\right)$$

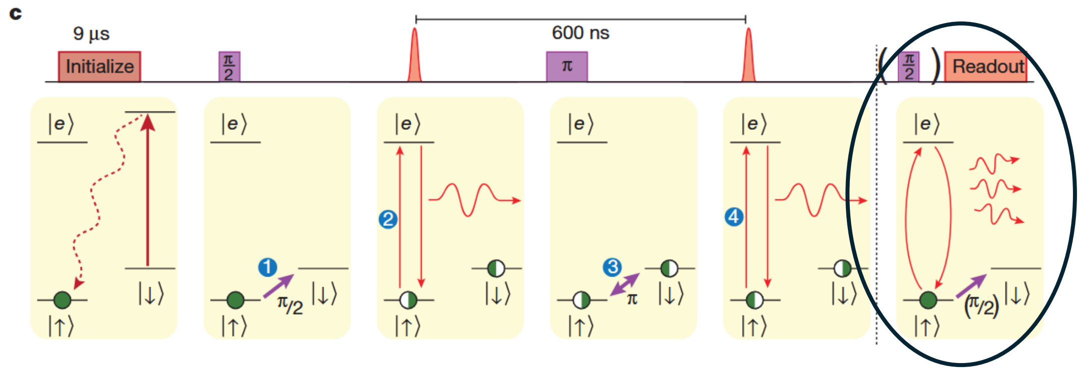
$$|\psi\rangle = \left(\frac{|\uparrow_A, \downarrow_B\rangle \pm |\downarrow_A, \uparrow_B\rangle}{\sqrt{2}}\right)$$

Projective measurement



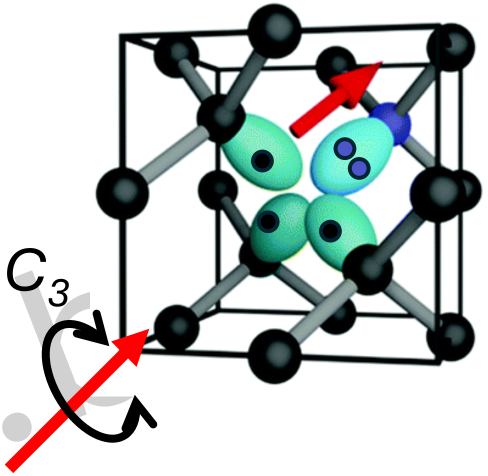
$$|\psi\rangle = \left(\frac{|\uparrow_A, \downarrow_B\rangle \pm |\downarrow_A, \uparrow_B\rangle}{\sqrt{2}}\right)$$

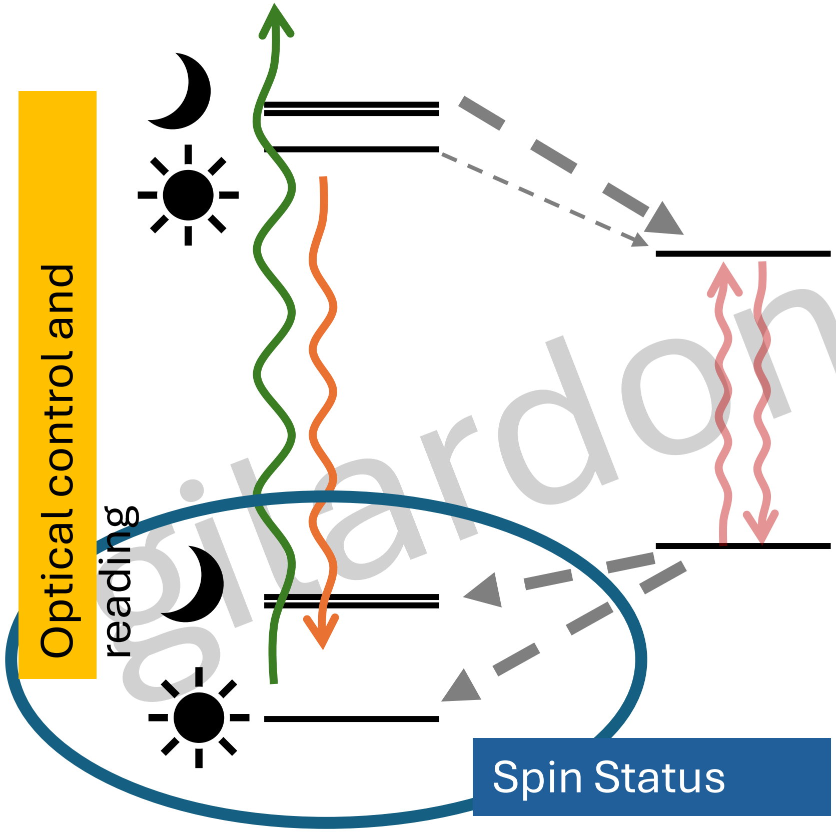
Qubit Operation Loop

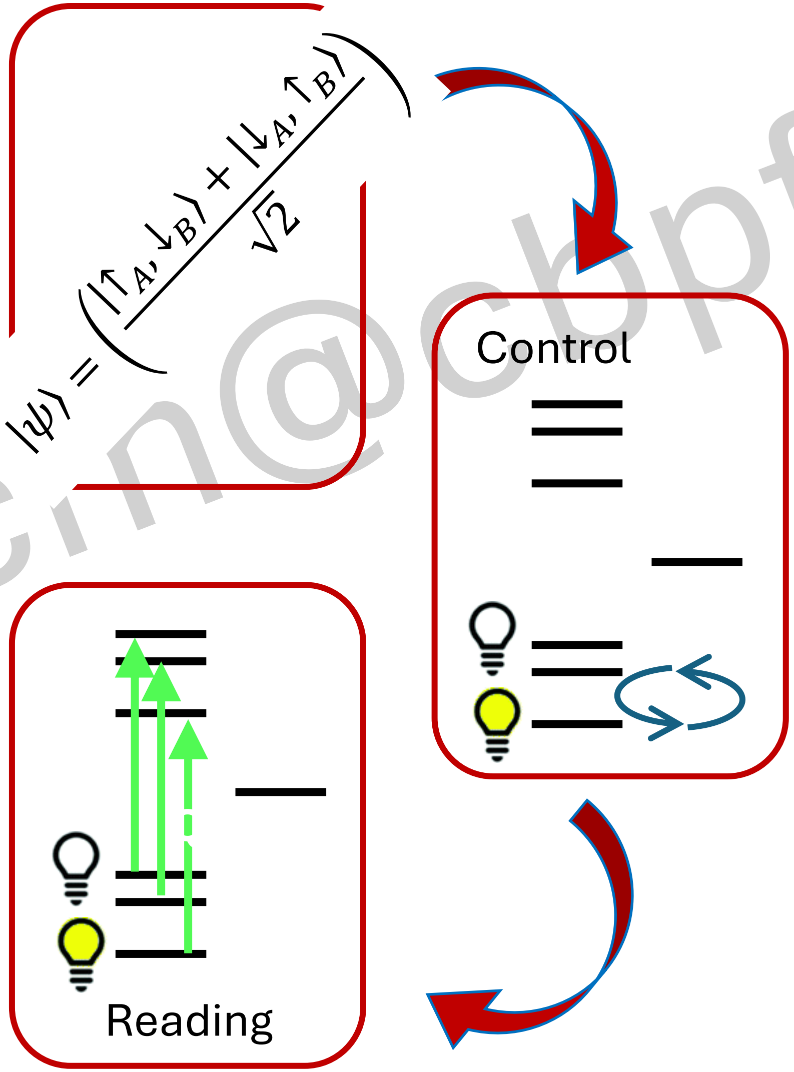


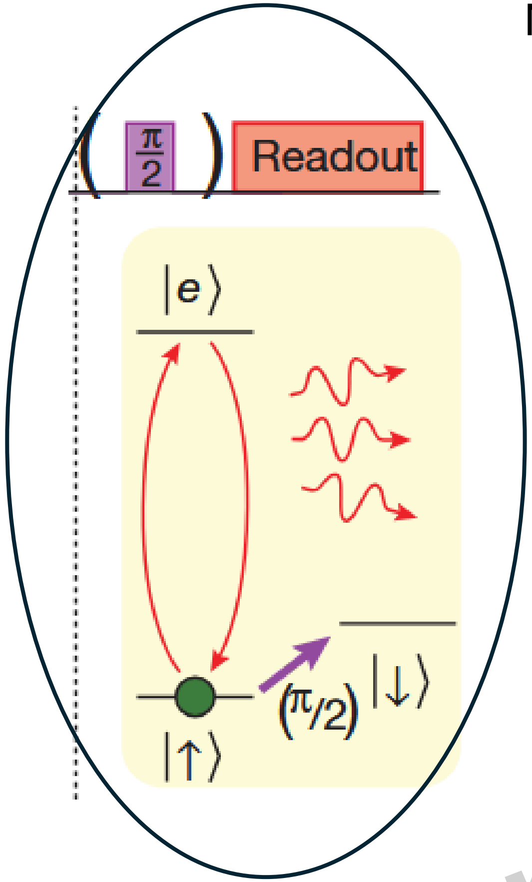
Spin total = 1

Spin total = 0



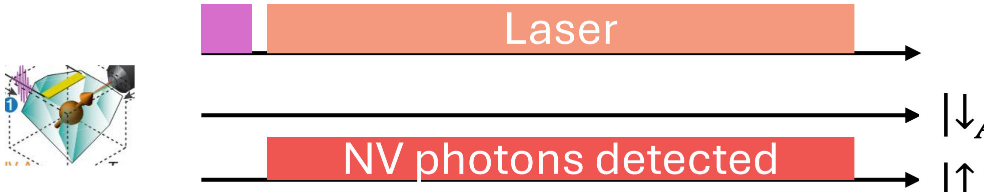


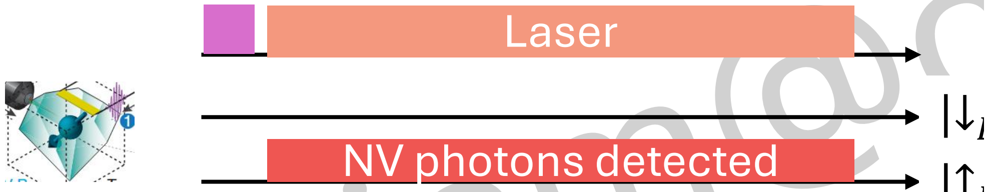




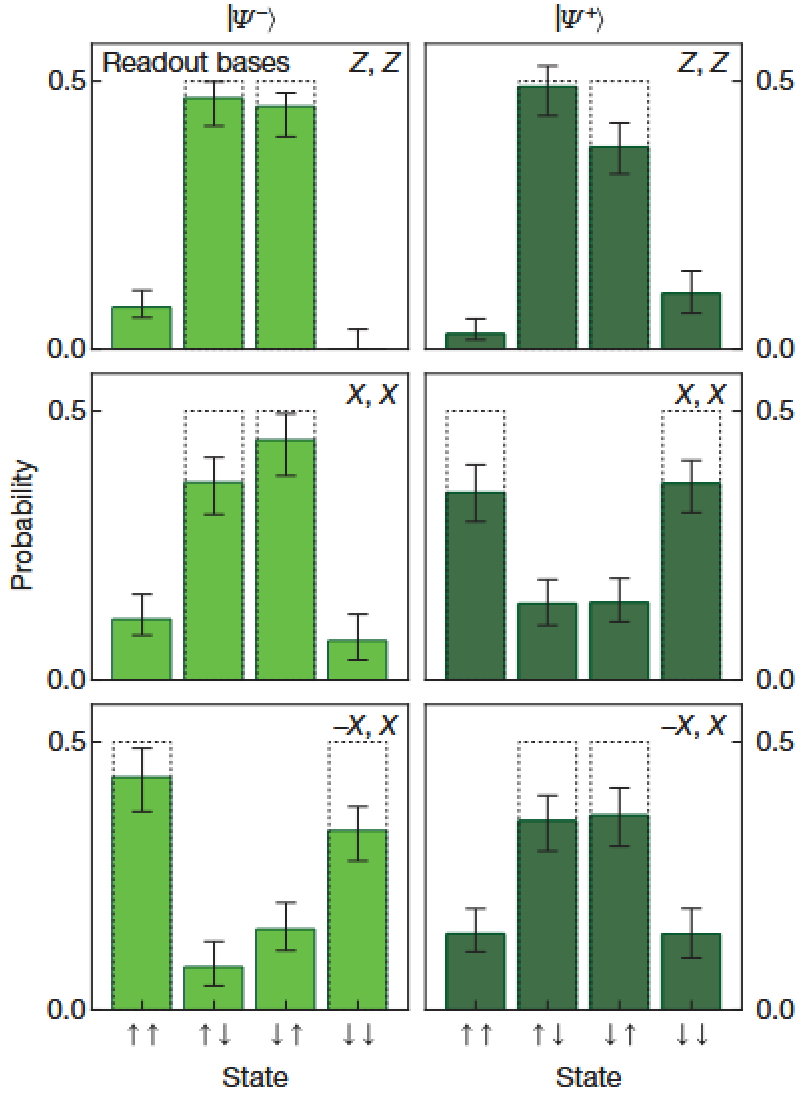
Measured in base Z (it is already the base on which we are operating)

Measured in base X (microwave pulse to rotate the spins)





Quantum state tomography



$$|\psi\rangle = \left(\frac{|\uparrow_A, \downarrow_B\rangle \pm |\downarrow_A, \uparrow_B\rangle}{\sqrt{2}}\right)$$

Can this be used to realize teleportation of a quantum state?

Qubits A and B are entangled, Alice has qubits A and C, Bob has qubit B

$|\psi\rangle_{AB} = |\Psi^+\rangle_{AB}$, or any other of the Bell states
$|\psi\rangle_C = \alpha|0\rangle_C + \beta|1\rangle_C$

$$|\psi\rangle_{ABC} = |\psi\rangle_C \otimes |\Psi^+\rangle_{AB}$$
$$|\psi\rangle_{ABC} = \frac{\alpha}{\sqrt{2}}(|100\rangle_{ABC} + |010\rangle_{ABC}) + \frac{\beta}{\sqrt{2}}(|101\rangle_{ABC} + |011\rangle_{ABC})$$

$$\begin{aligned}|\psi\rangle_{ABC} = 1/2[&|\Psi^+\rangle_{AC} \otimes (\alpha|0\rangle_B + \beta|1\rangle_B) + \\ &|\Psi^-\rangle_{AC} \otimes (-\alpha|0\rangle_B + \beta|1\rangle_B) + \\ &|\Phi^+\rangle_{AC} \otimes (\beta|0\rangle_B + \alpha|1\rangle_B) + \\ &|\Phi^-\rangle_{AC} \otimes (-\beta|0\rangle_B + \alpha|1\rangle_B)]\end{aligned}$$

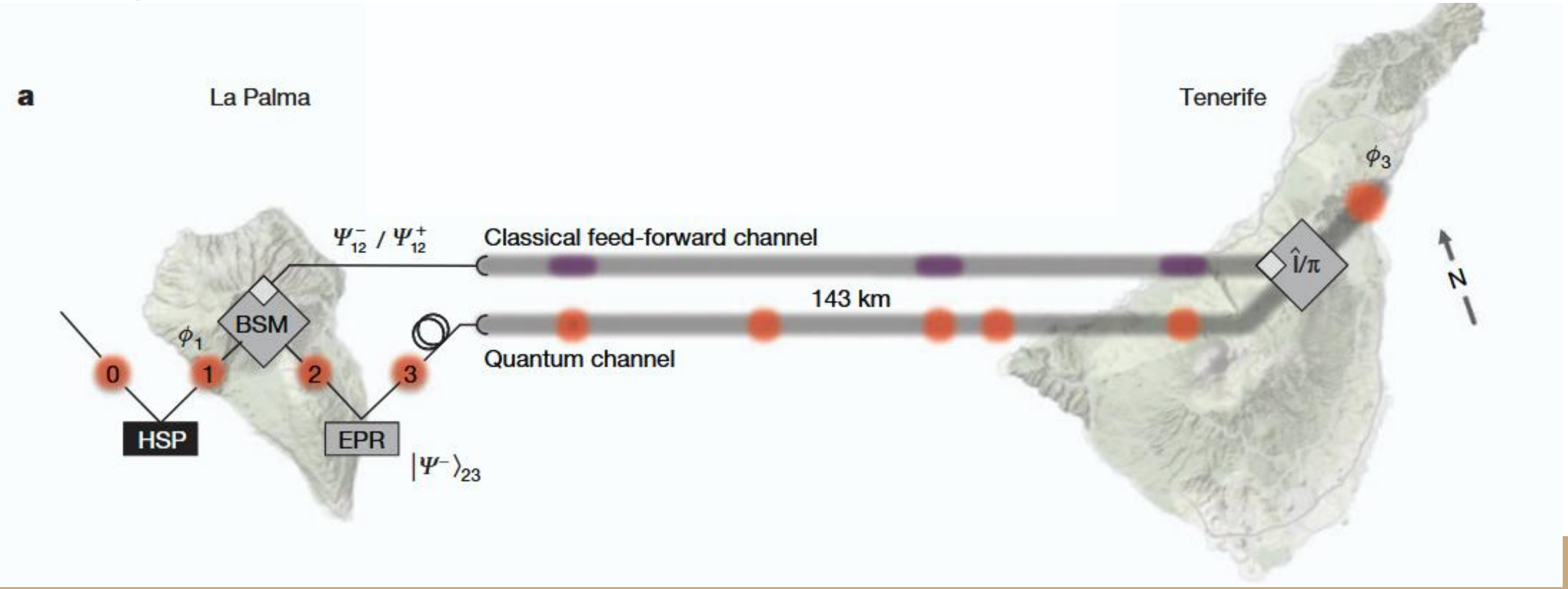
Alice measures her two qubits in the Bell basis and informs (feeds forward) what unitary transformation Bob needs to perform to recover Charlie's original state

LETTER

doi:10.1038/nature11472

Quantum teleportation over 143 kilometres using active feed-forward

Xiao-Song Ma[1,2]†, Thomas Herbst[1,2], Thomas Scheidl[1], Daqing Wang[1], Sebastian Kropatschek[1], William Naylor[1], Bernhard Wittmann[1,2], Alexandra Mech[1,2], Johannes Kofler[1,3], Elena Anisimova[4], Vadim Makarov[4], Thomas Jennewein[1,4], Rupert Ursin[1] & Anton Zeilinger[1,2]



RESEARCH ARTICLES

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QUANTUM INFORMATION

Unconditional quantum teleportation between distant solid-state quantum bits

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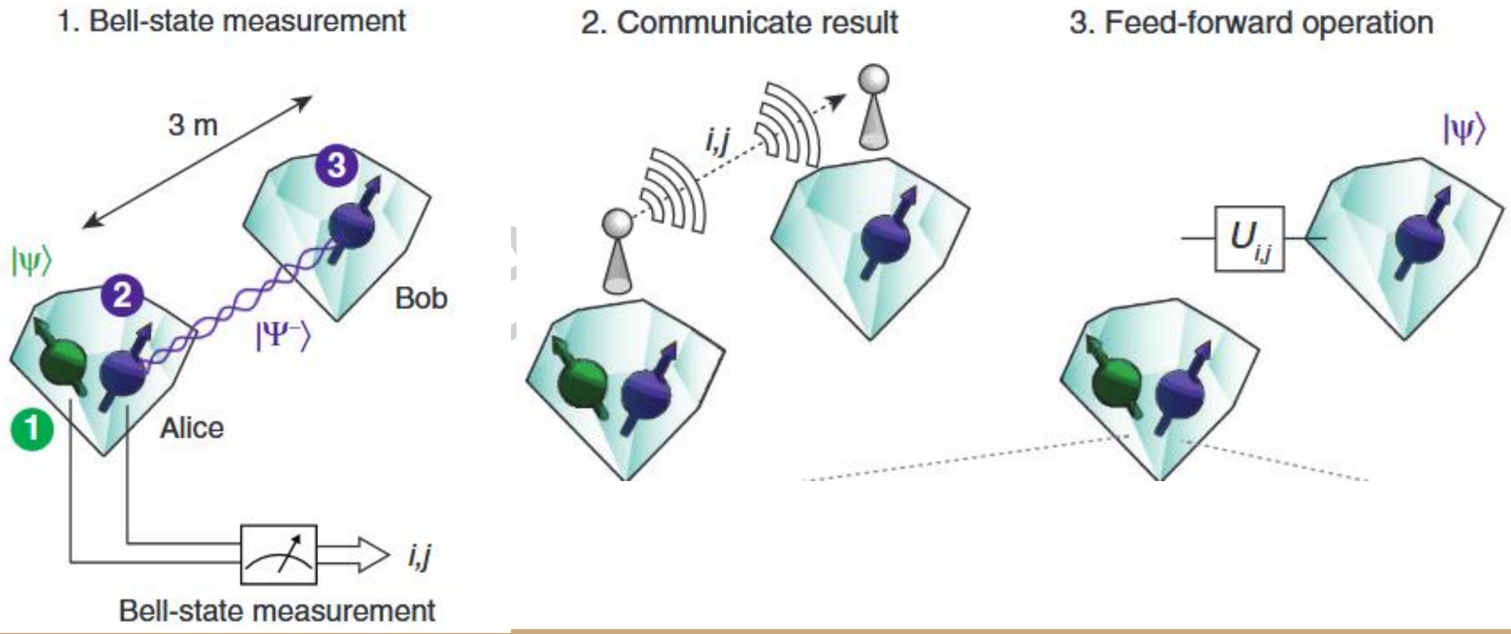

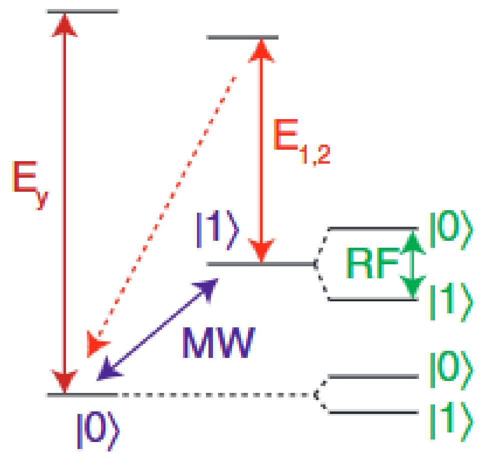

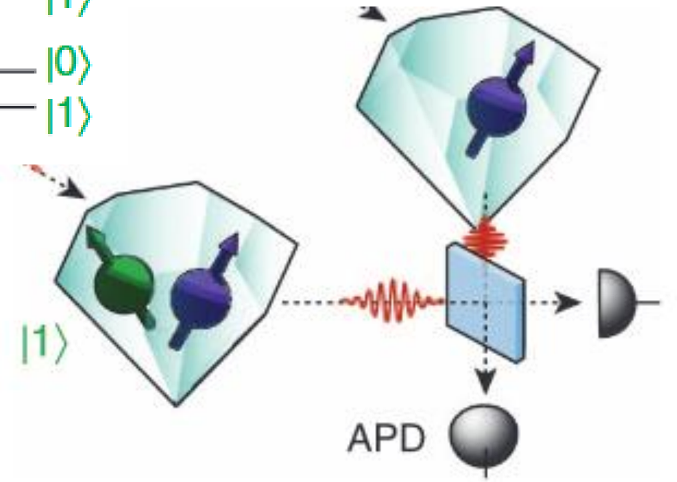

Arbitrary rotations on electron spin

Readout of electron spin

Conditional rotations on nuclear spin

RESEARCH ARTICLES

532 1 AUGUST 2014 • VOL 345 ISSUE 6196

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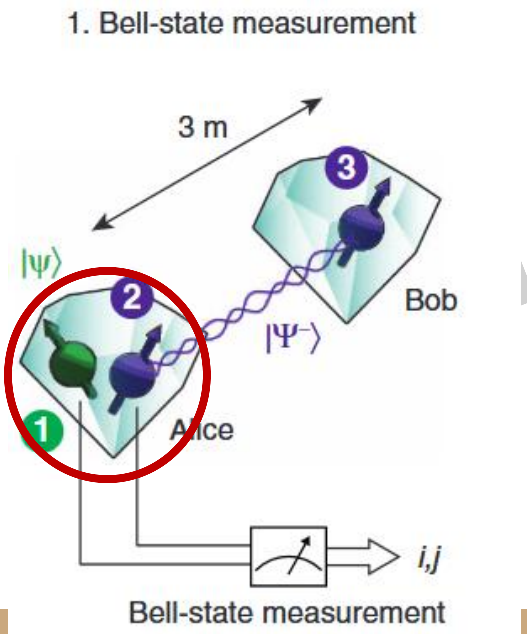

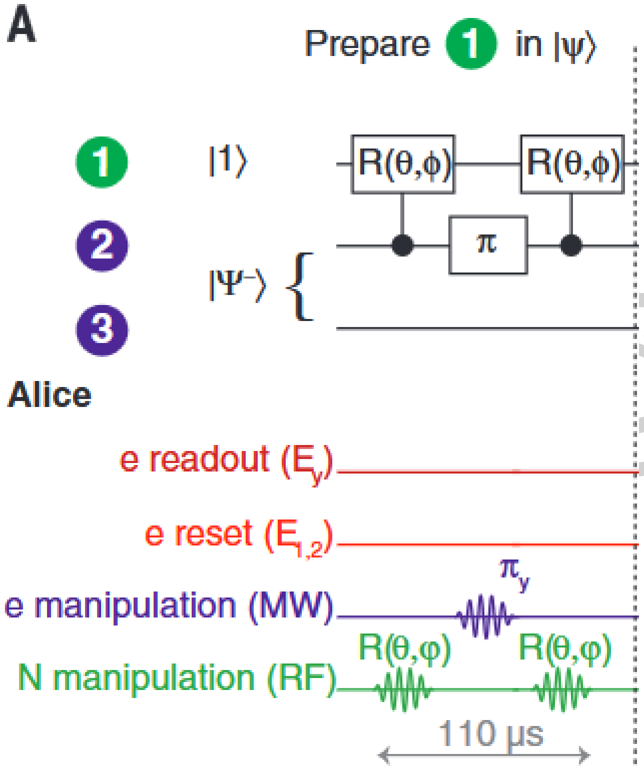

$$|\Phi^-\rangle_{A,B} \otimes (\alpha|0\rangle_C + \beta|1\rangle_C)$$

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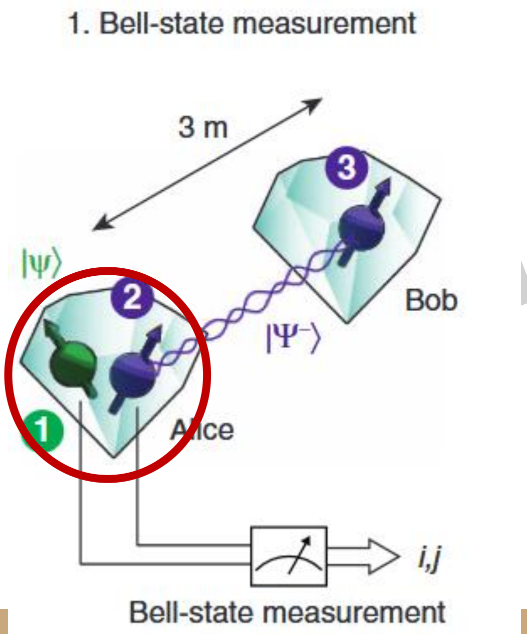

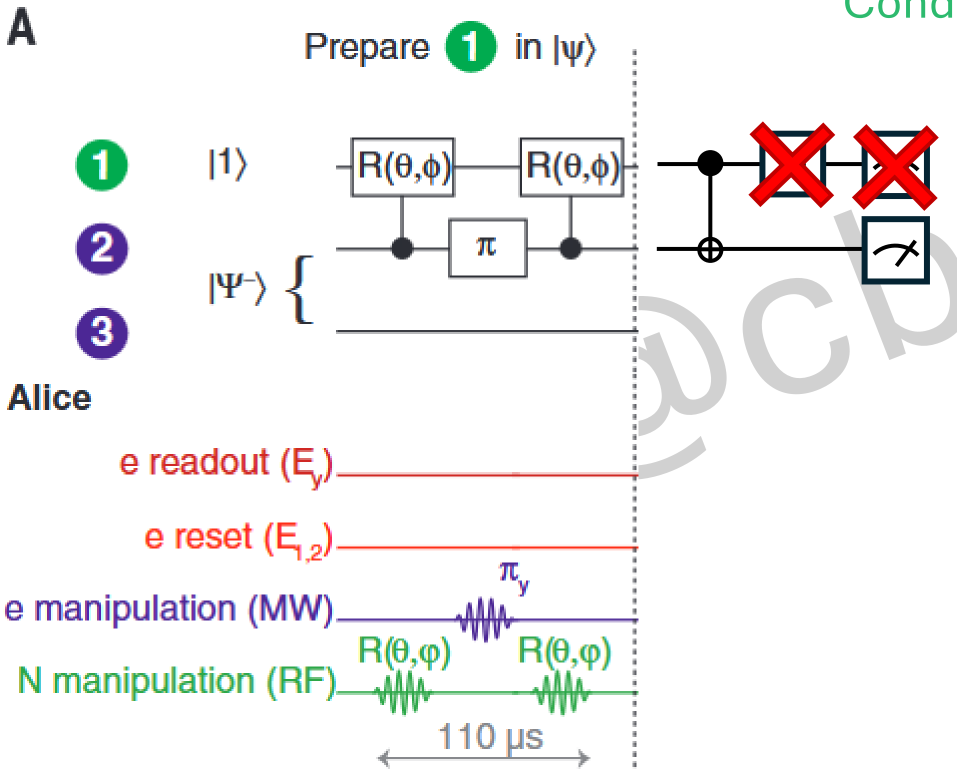

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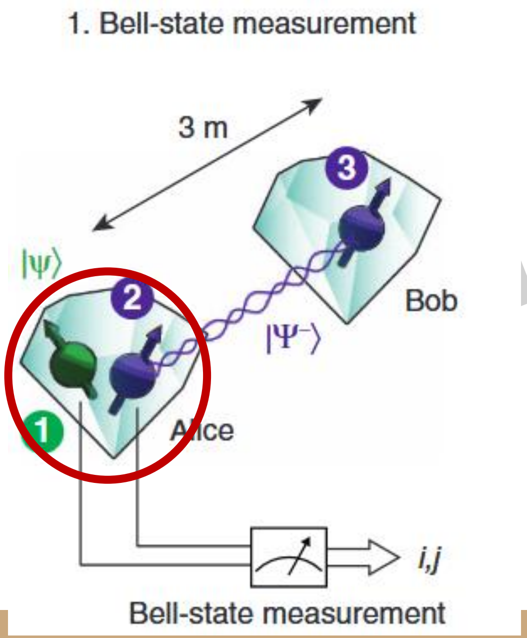

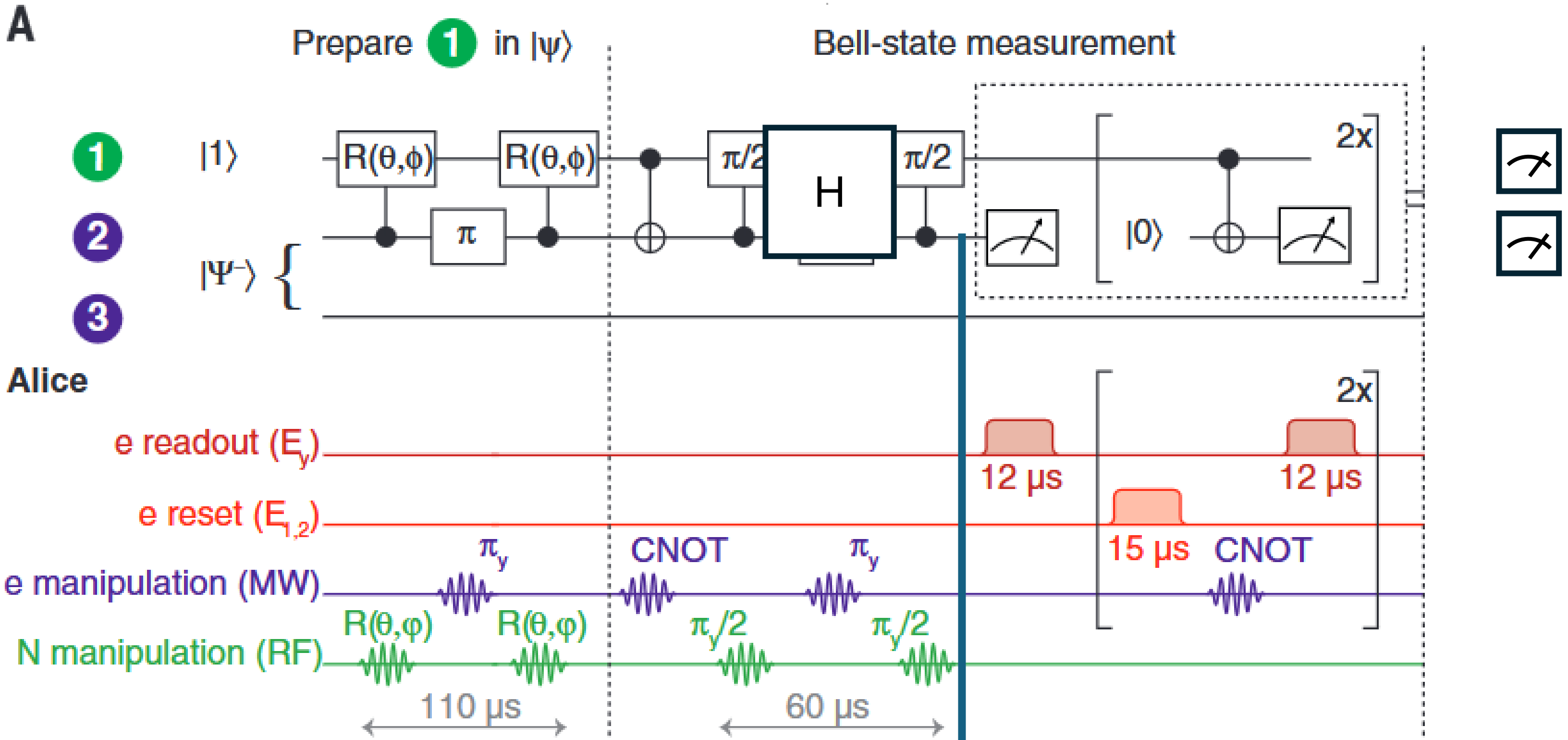

$$\alpha|0_x\rangle_C|\Psi^-\rangle_{A,B} + \beta|1_x\rangle_C|\Phi^-\rangle_{A,B}$$

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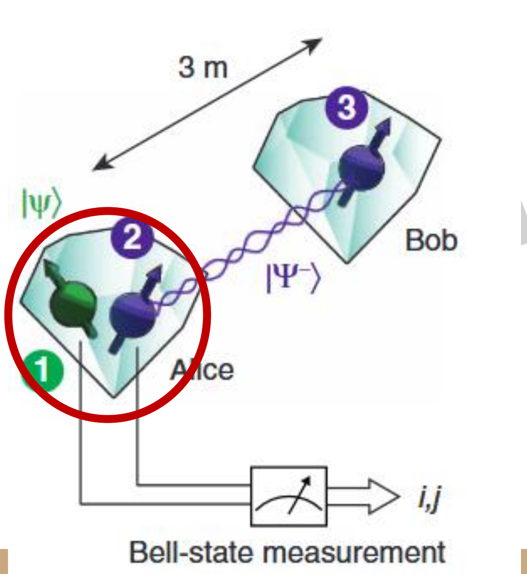
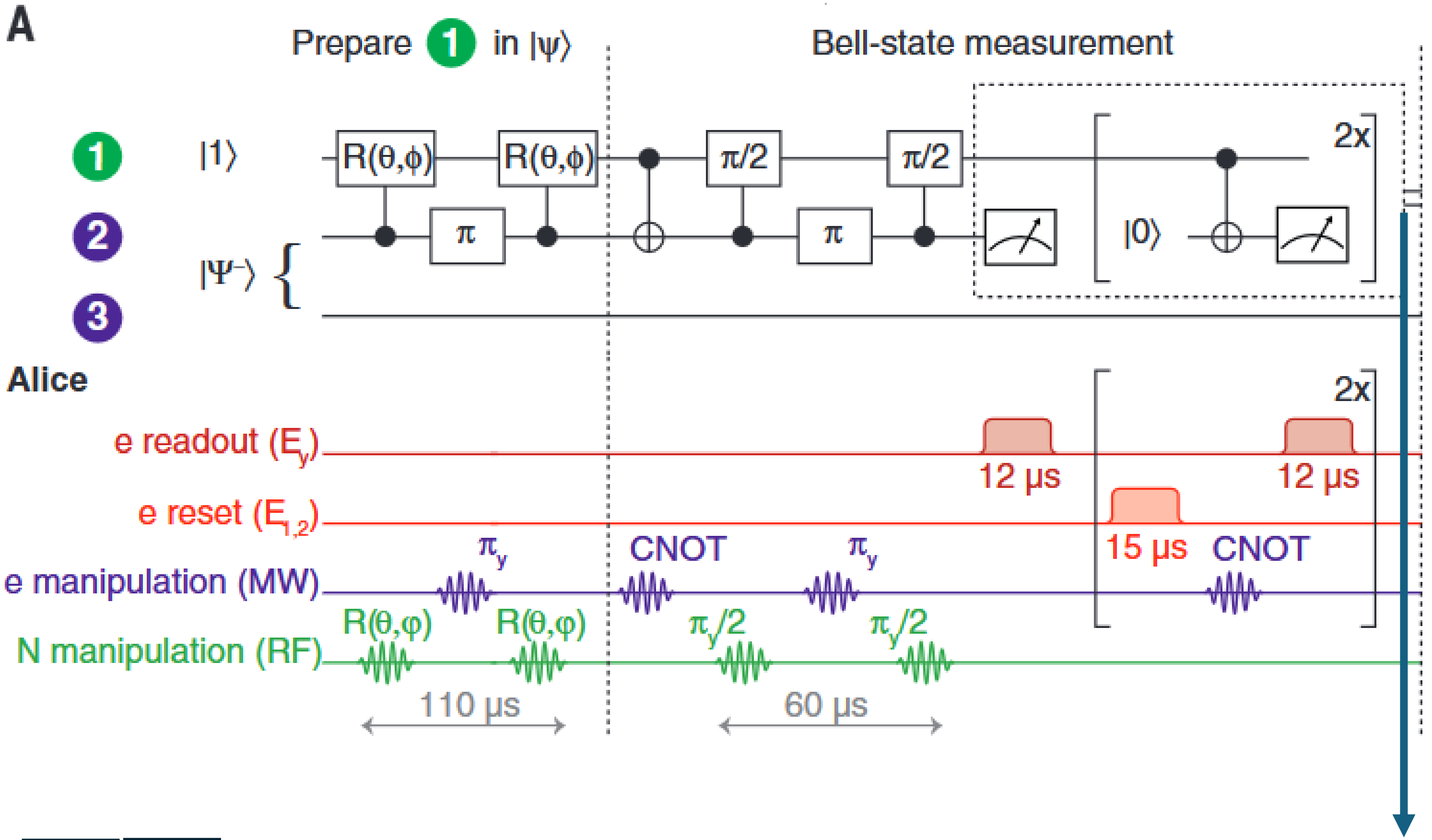
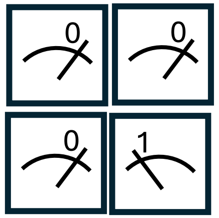
1. Bell-state measurement

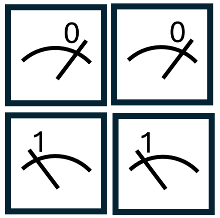






$|00\rangle_{AC} \otimes (\beta|0\rangle_B - \alpha|1\rangle_B)$

$|11\rangle_{AC} \otimes (\beta|0\rangle_B + \alpha|1\rangle_B)$



$|00\rangle_{AC} \otimes (\alpha|0\rangle_B - \beta|1\rangle_B)$

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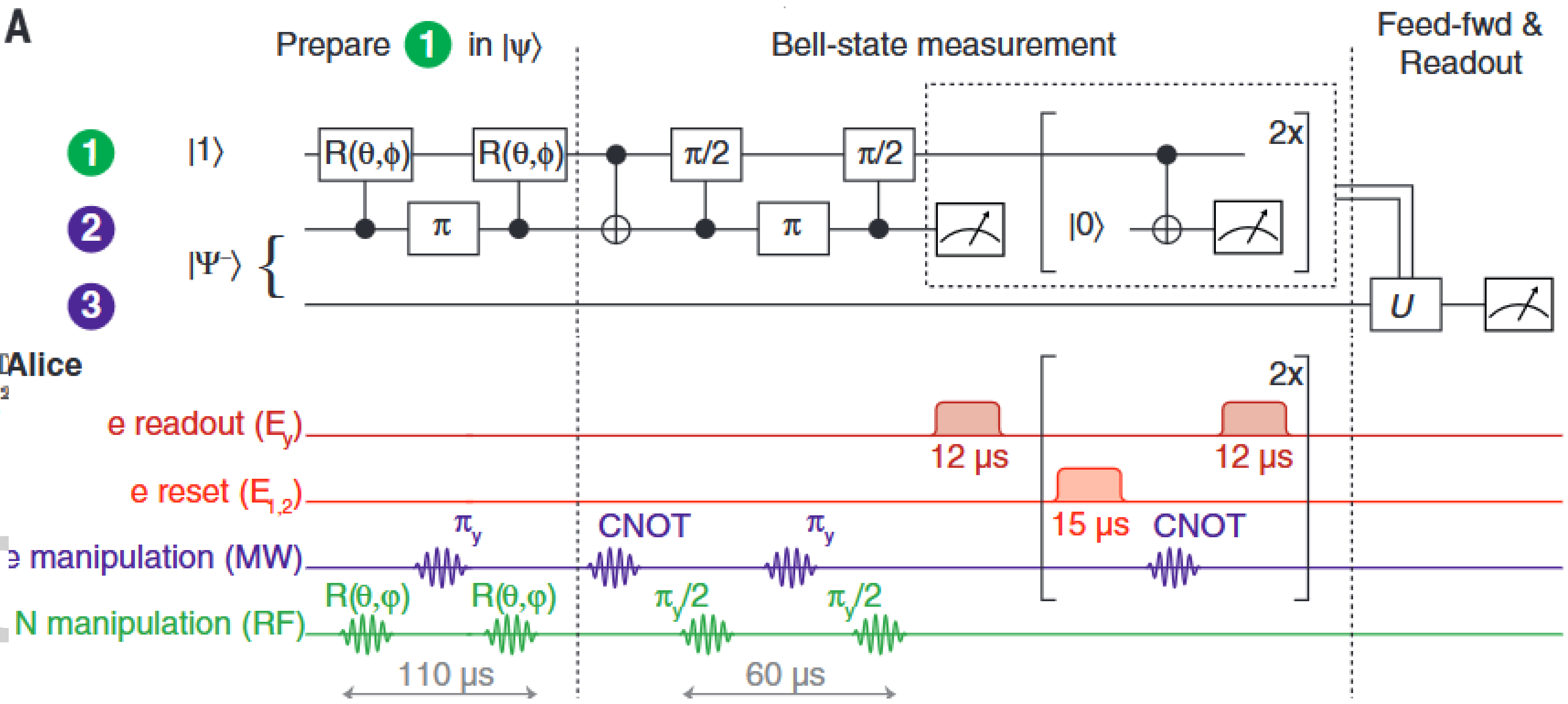

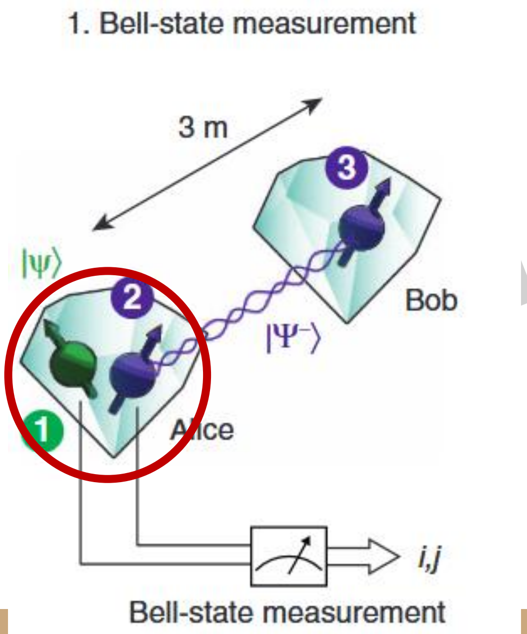

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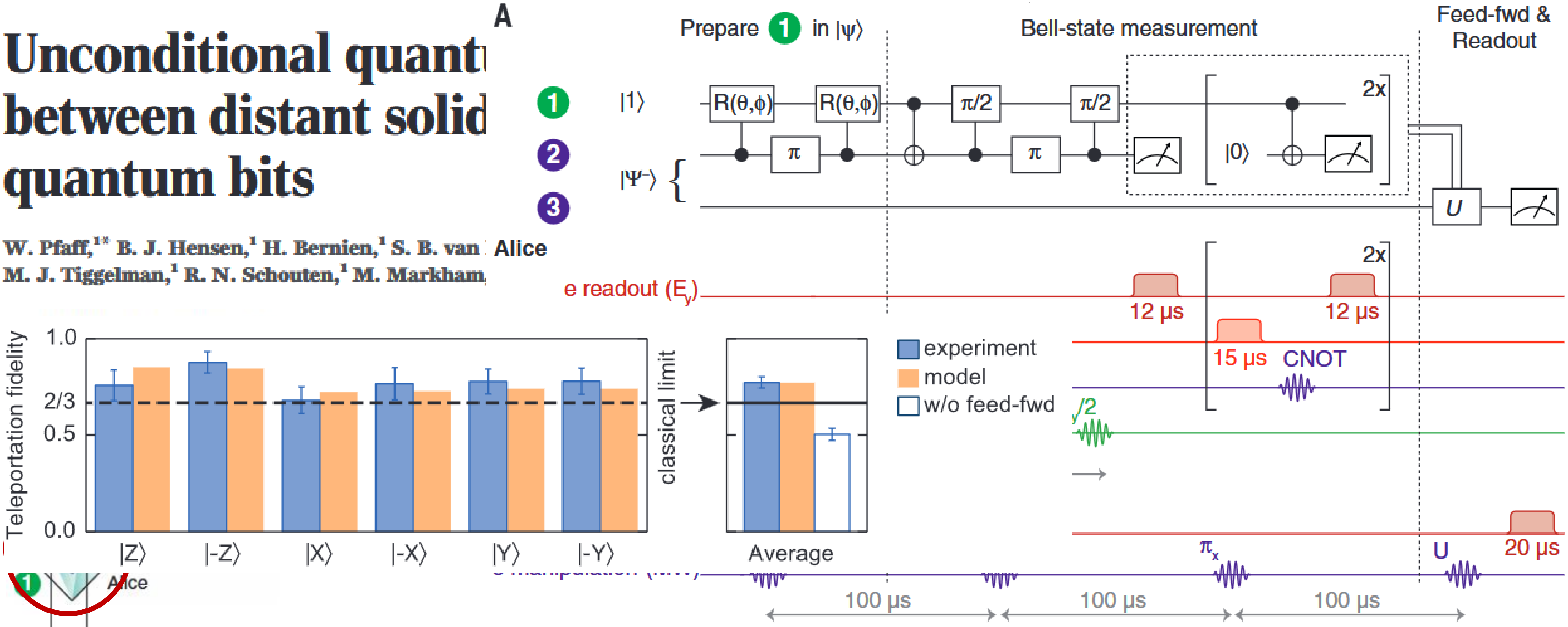

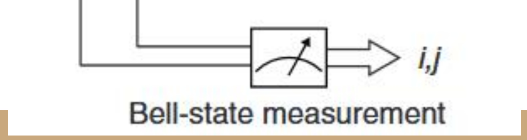

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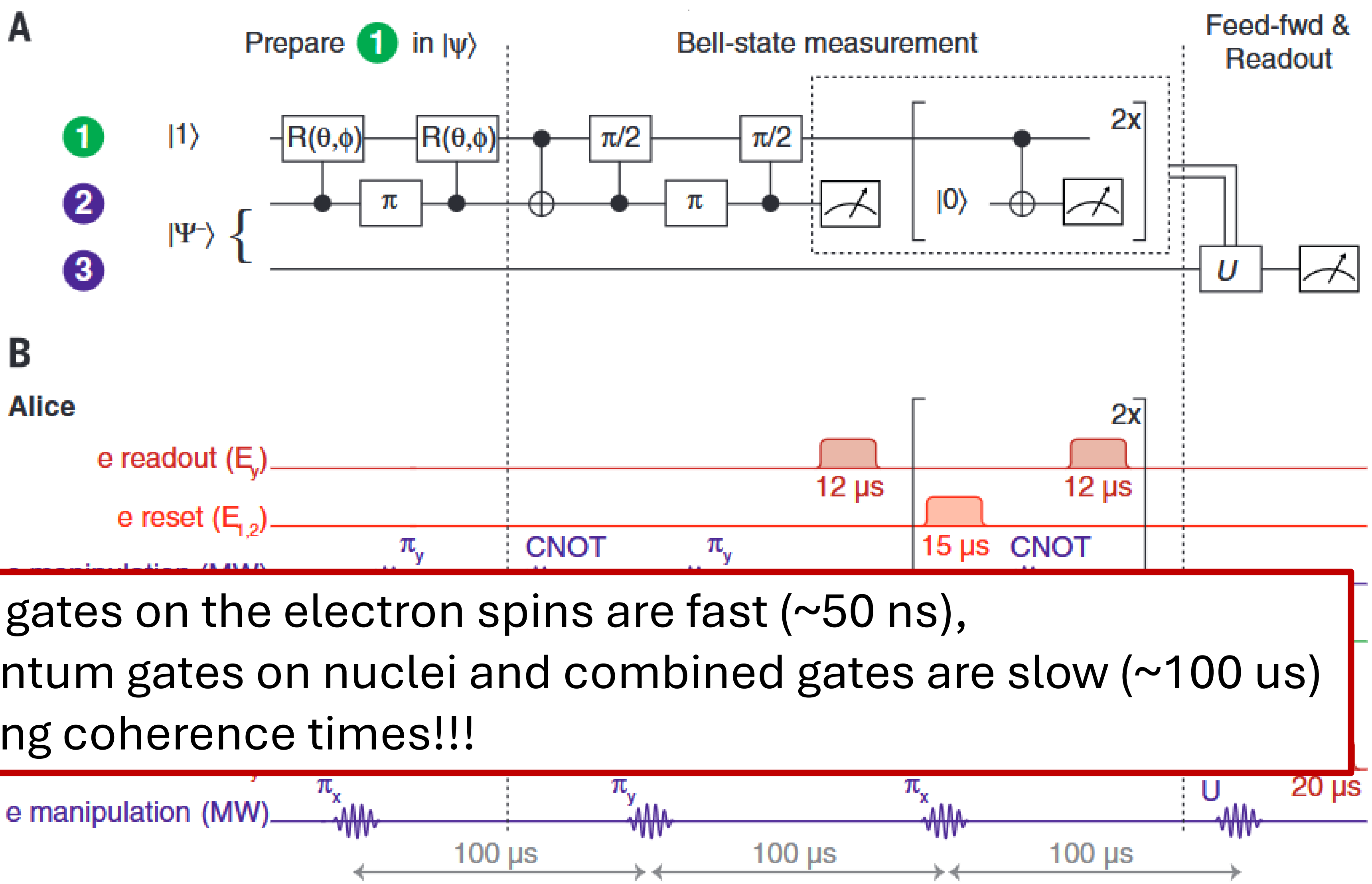

Even though individual gates on the electron spins are fast (~50 ns), implementation of quantum gates on nuclei and combined gates are slow (~100 us)
Electrons must have long coherence times!!!

Letter | Published: 21 October 2015

Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres

B. Hensen, H. Bernien, A. E. Dréau, A. Reiserer, N. Kalb, M. S. Blok, J. Ruitenberg, R. F. L. Vermeulen, R. N. Schouten, C. Abellán, W. Amaya, V. Pruneri, M. W. Mitchell, M. Markham, D. J. Twitchen, D. Elkouss, S.

Realization of a multinode quantum network of remote solid-state qubits

M. POMPILI, S. L. N. HERMANS, S. BAIER, H. K. C. BEUKERS, P. C. HUMPHREYS, R. N. SCHOUTEN, R. F. L. VERMEULEN, M. J. TIGGELMAN, L. DOS SANTOS MARTINS, [...], AND

SCIENCE • 16 Apr 2021 • Vol 372, Issu

Qubit teleportation between non-neighbouring nodes in a quantum network

S. L. N. Hermans, M. Pompili, H. K. C. Beukers, S. Baier, J. Borregaard & R. Hanson

Nature **605**, 663–668 (2022) | Cite this article

RESEARCH ARTICLES

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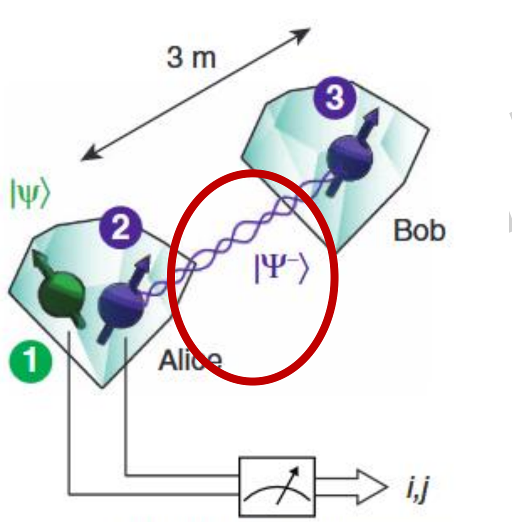
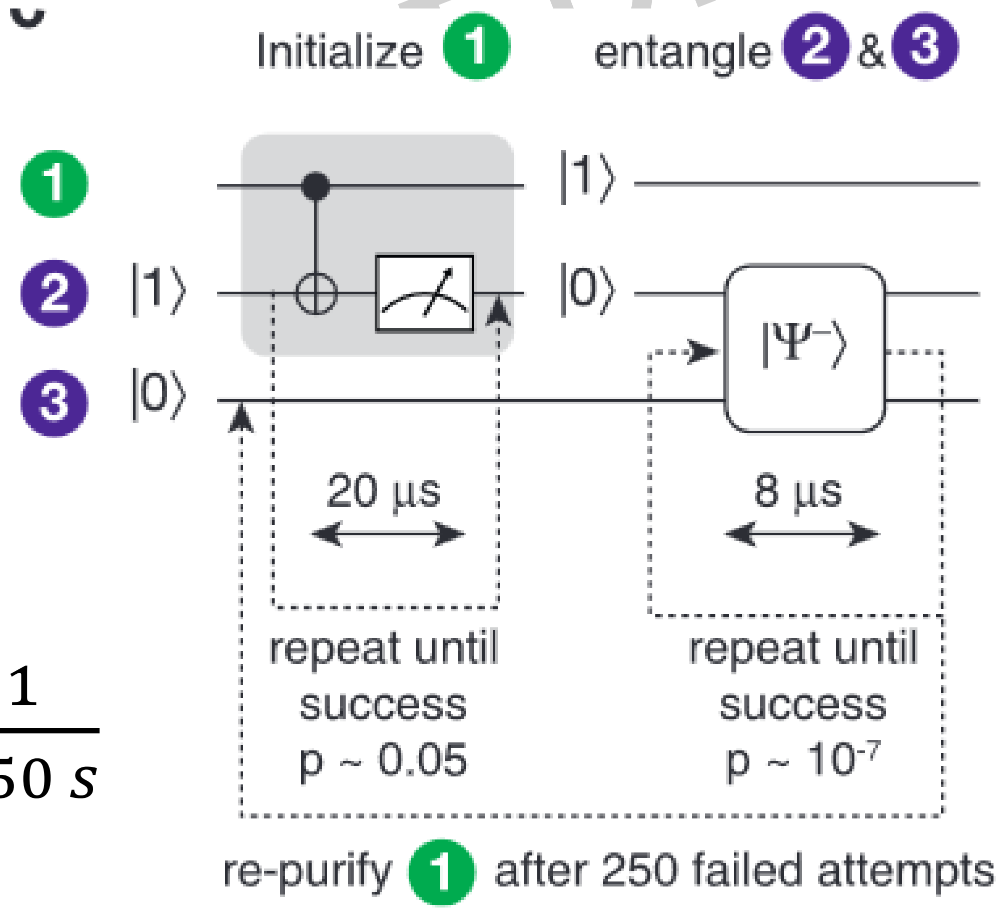


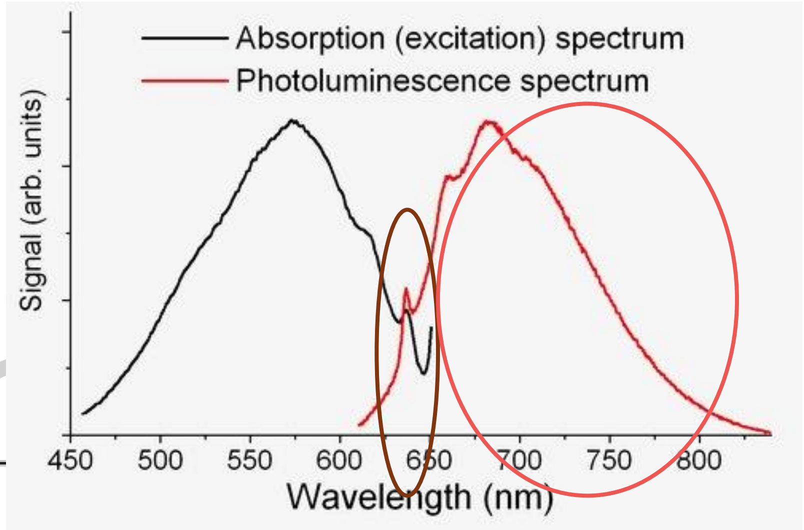
Bell-state measurement

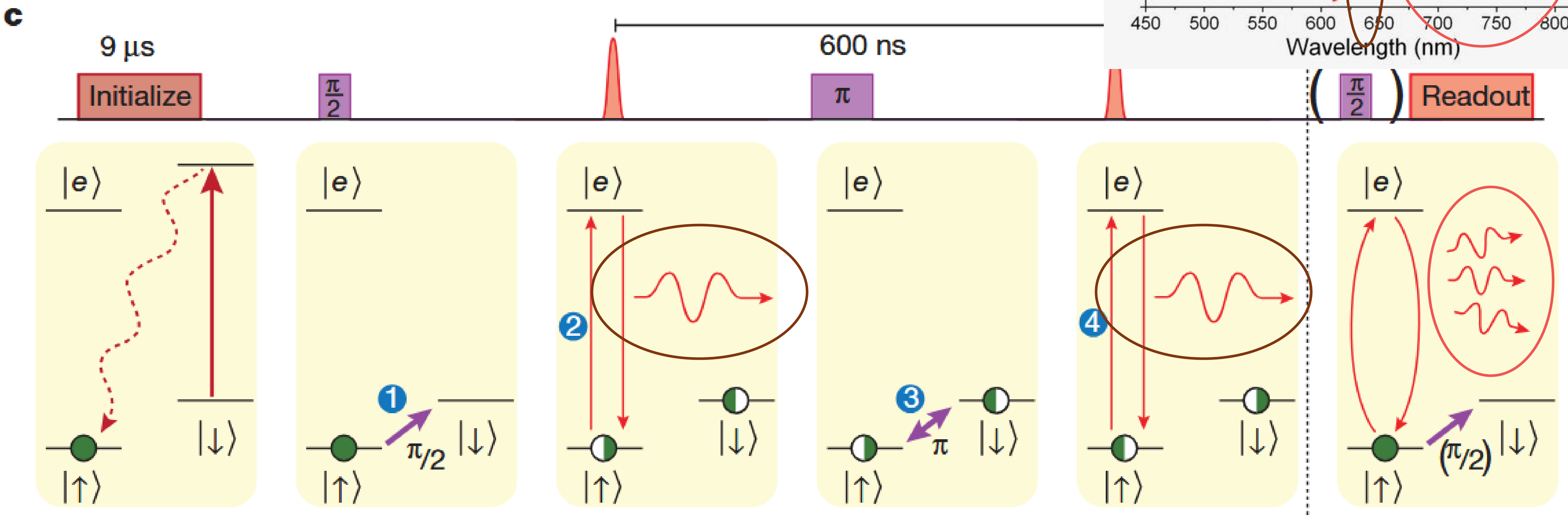
Success rate: $\frac{1}{250\ s}$



Challenge 1: Interfering photons must be indistinguishable!

Only <10% of the photons emitted by NV are useful!





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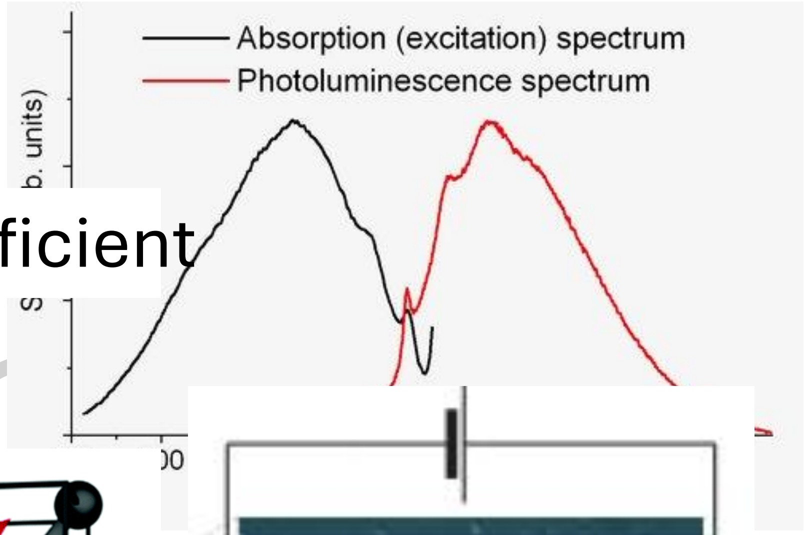
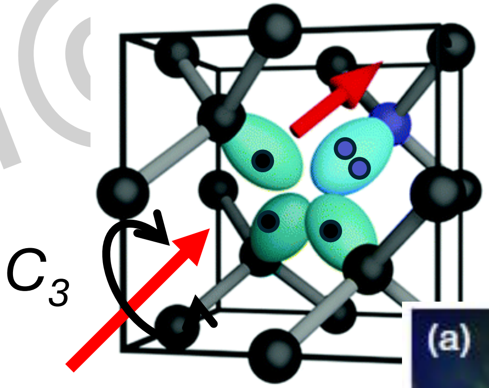
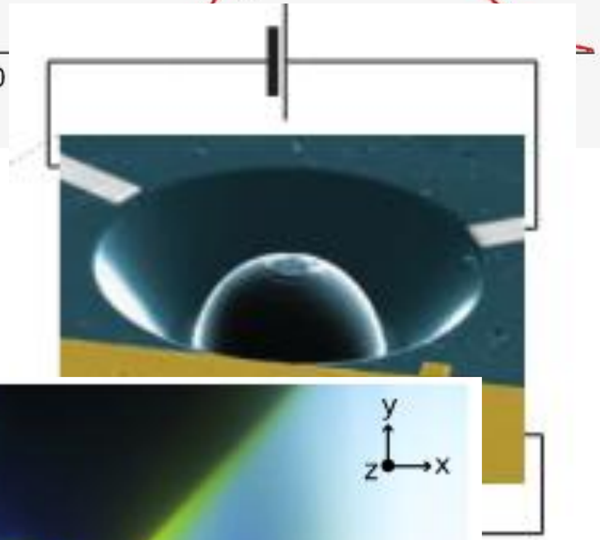


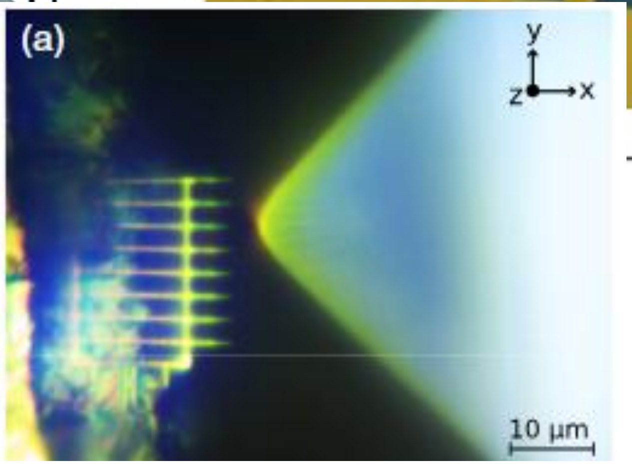
Challenge 2: Extracting photons from diamond is inefficient

The refractive index of diamond is very high, total internal reflection occurs

Cavities: enhancement of photon emission through Purcell effect, enhancement of photon collection through channeling into a directional mode, etc.





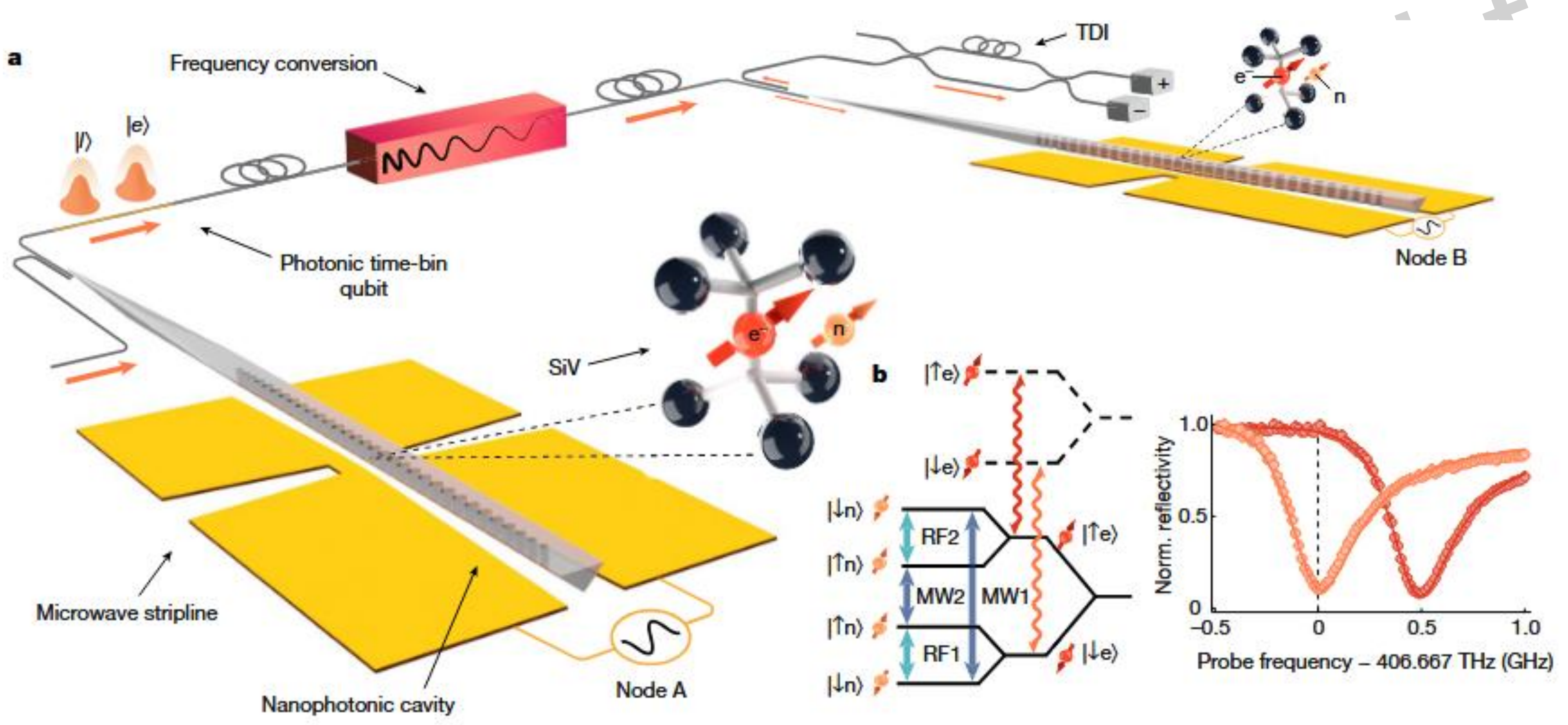


PHYSICAL REVIEW LETTERS **129**, 173603 (2022)

Challenge 3: Protocol relies on synchronization

Alternative platforms and protocols

Nature | Vol 629 | 16 May 2024 | 573

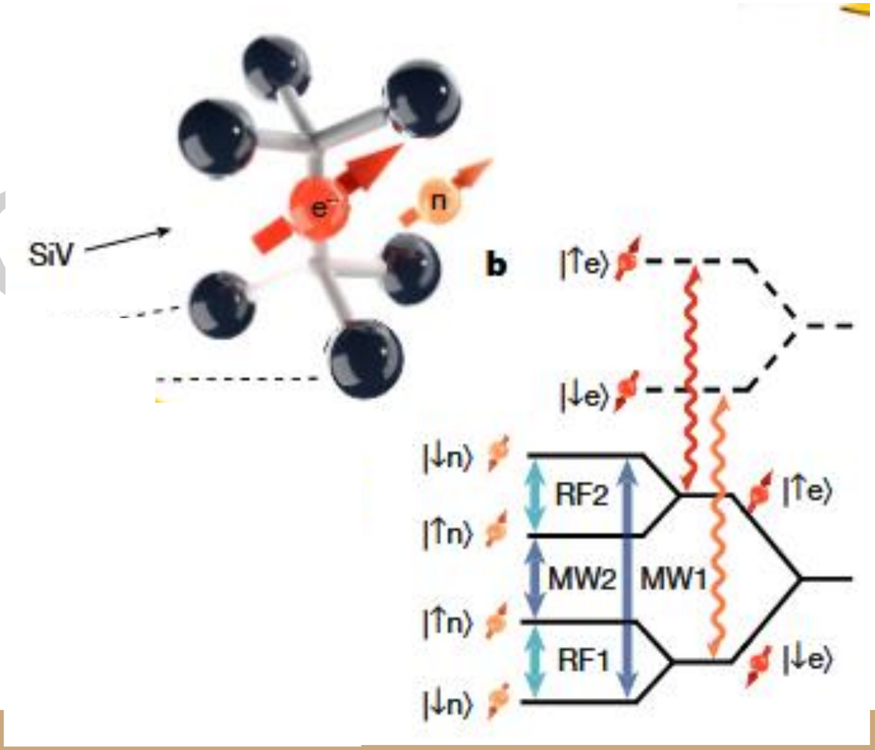


Article | Open access | Published: 15 May 2024

Entanglement of nanophotonic quantum memory nodes in a telecom network

C. M. Knaut, A. Suleymanzade, Y.-C. Wei, D. R. Assumpcao, P.-J. Stas, Y. Q. Huan, B. Machielse, E. N. Knall, M. Sutula, G. Baranes, N. Sinclair, C. De-Eknamkul, D. S. Levonian, M. K. Bhaskar, H. Park, M. Lončar & M. D. Lukin

Nature 629, 573–578 (2024) | Cite this article



- Available nuclear spin register
- High symmetry defect! Highly stable optical transition, low coupling to phonons, stable when integrated into cavities
- BUT: sub-K operation

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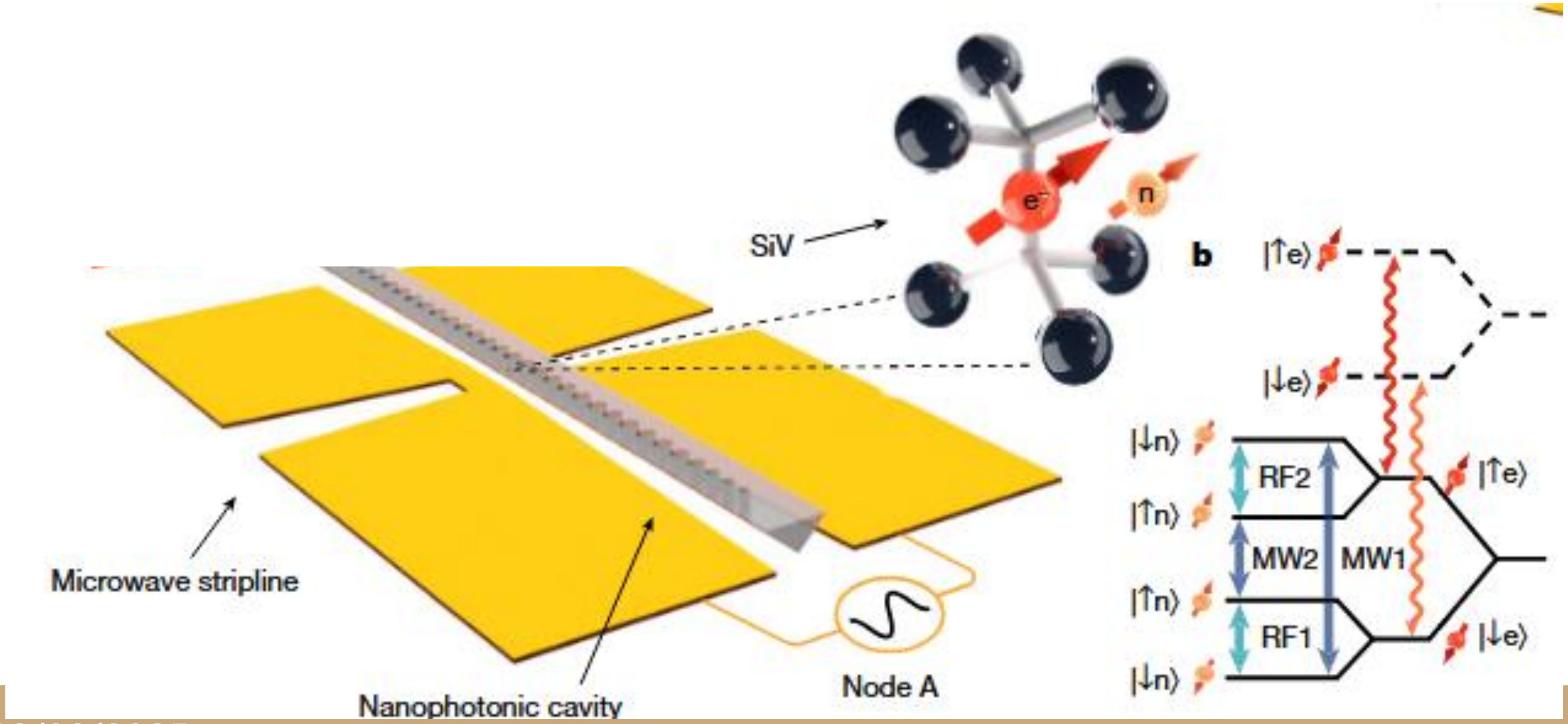

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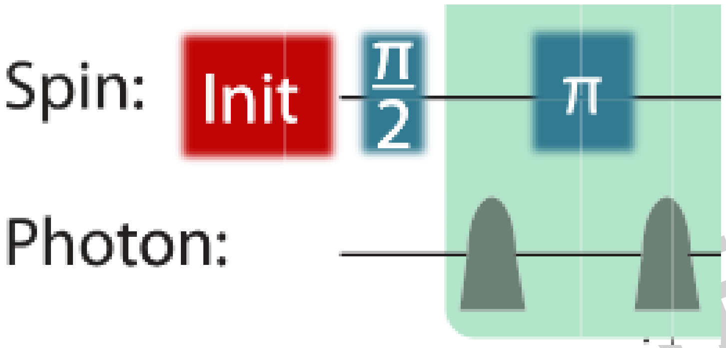
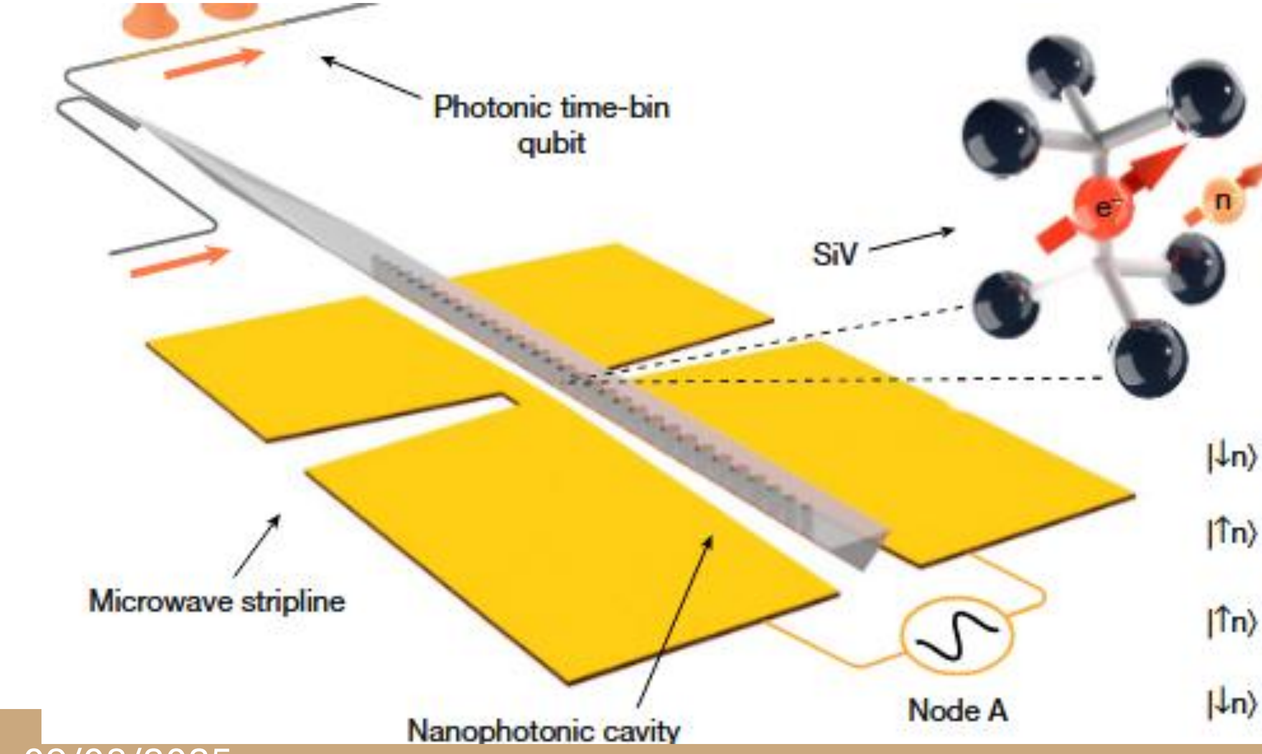
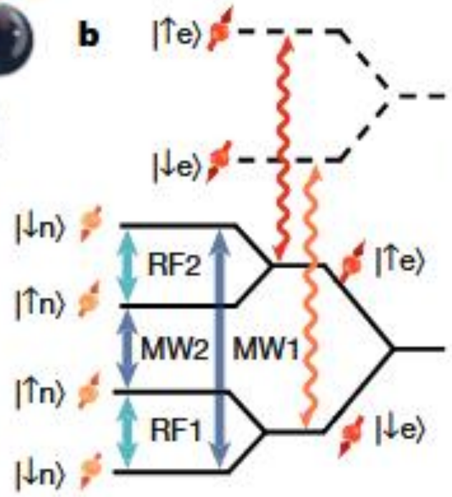
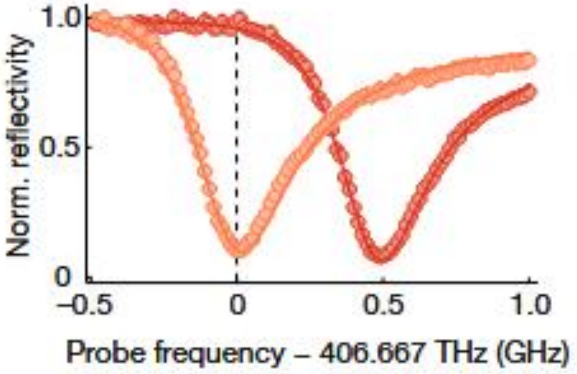
PHYSICAL REVIEW LETTERS 123, 183602 (2019)









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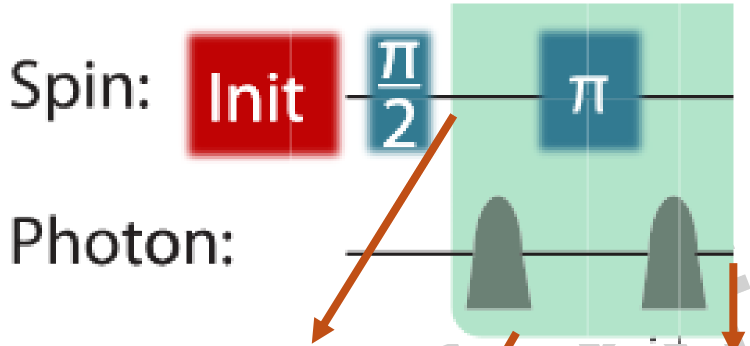
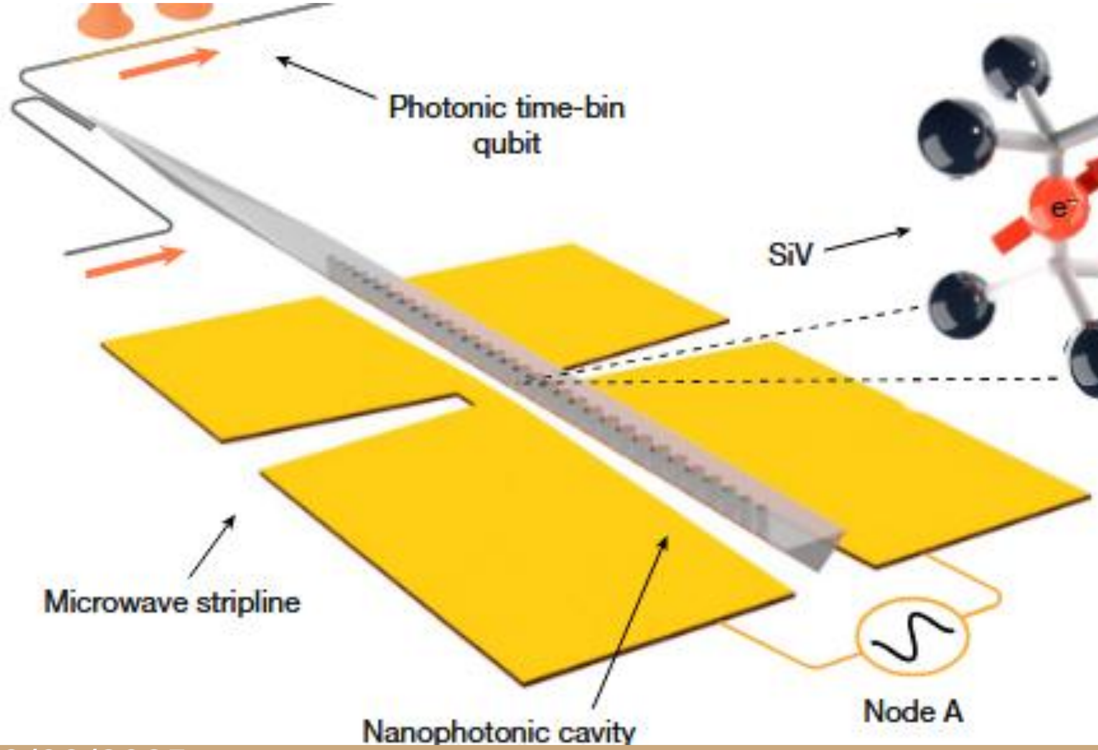
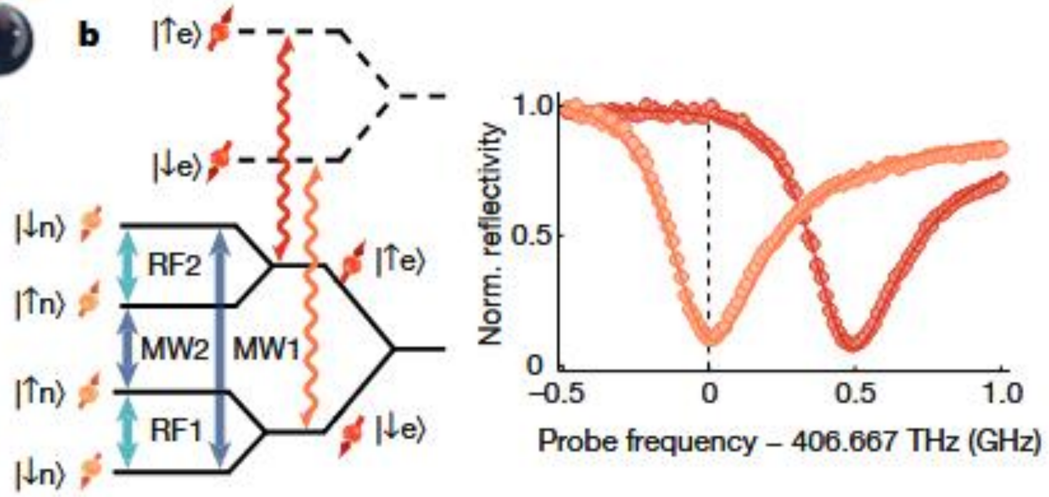


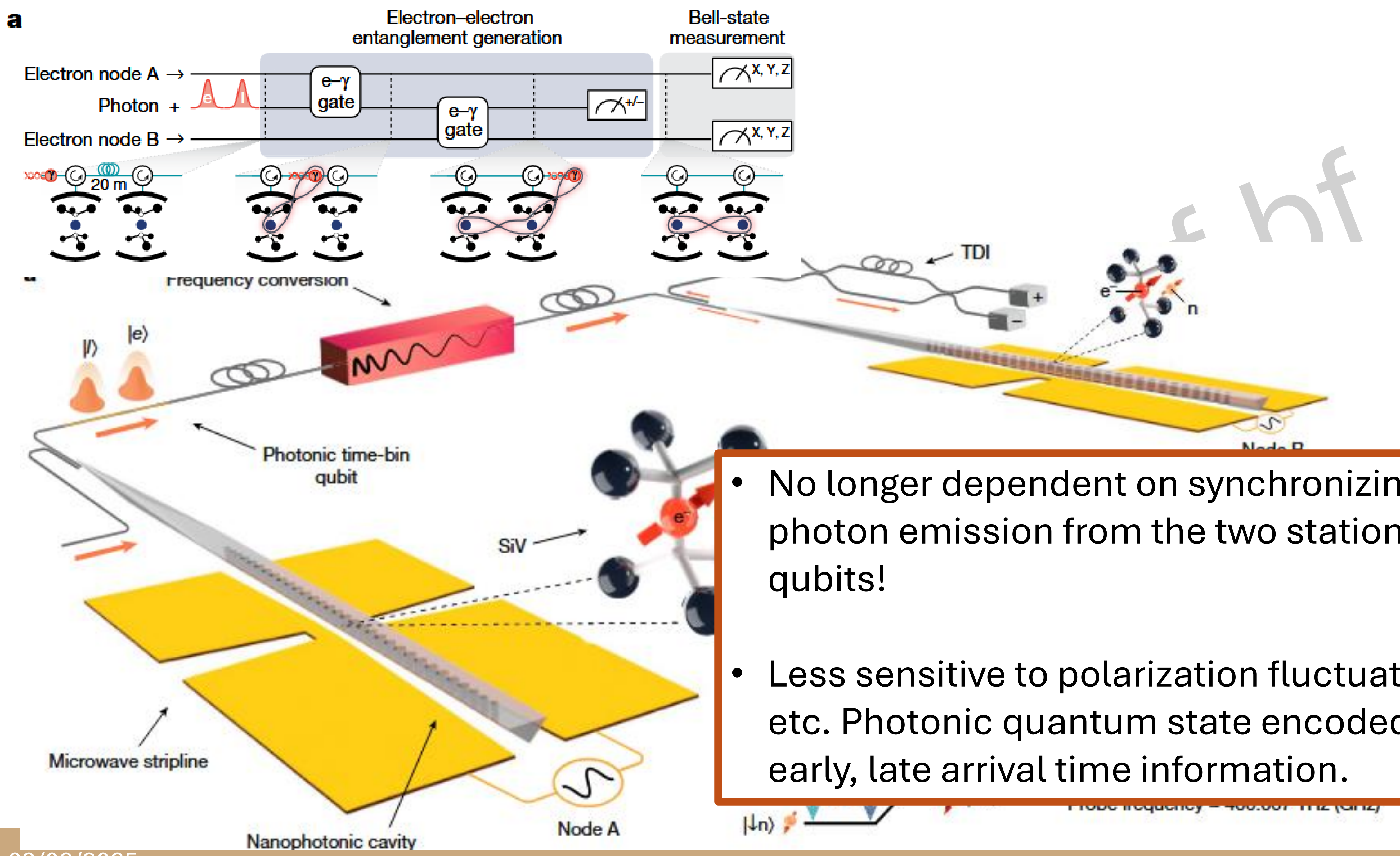
$|\psi_{spin}\rangle = (|\uparrow\rangle + |\downarrow\rangle)/\sqrt{2}$

$|\psi_{ent}\rangle = (\beta_l|\uparrow, l\rangle + \beta_e|\downarrow, e\rangle)/\sqrt{2}$

$|\psi_{phot}\rangle = (\beta_e|e\rangle + \beta_l|l\rangle)/\sqrt{2}$

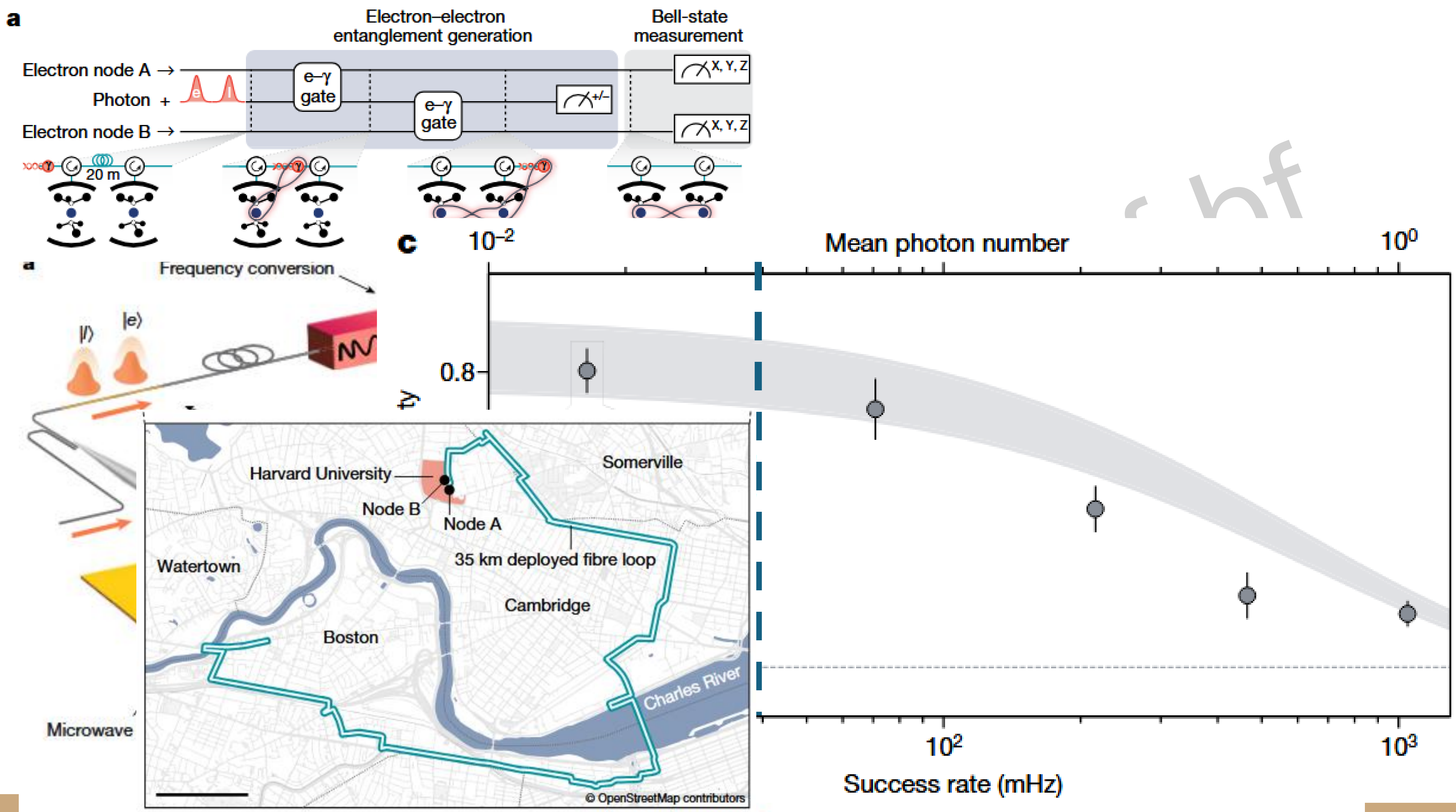




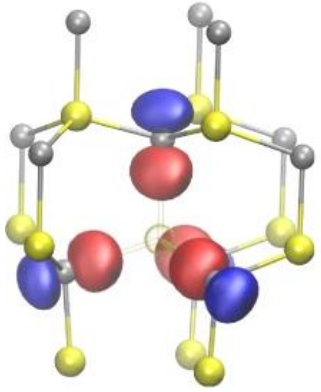


- No longer dependent on synchronizing the photon emission from the two stationary qubits!

- Less sensitive to polarization fluctuations, etc. Photonic quantum state encoded in early, late arrival time information.

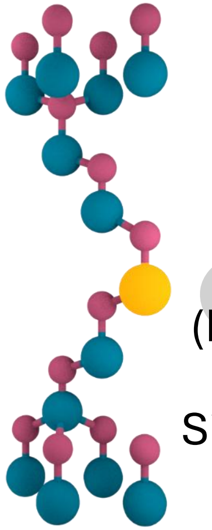

a
Electron–electron entanglement generation
Bell-state measurement
Electron node A →
Photon +
Electron node B →
e–γ gate
e–γ gate
X, Y, Z
X, Y, Z
+/–
20 m
Frequency conversion
|l⟩
|e⟩
Microwave
c
Mean photon number
10^{-2}
10^{0}
0.8
10^{2}
10^{3}
Success rate (mHz)
Harvard University
Somerville
Node B
Node A
35 km deployed fibre loop
Watertown
Cambridge
Boston
Charles River
© OpenStreetMap contributors

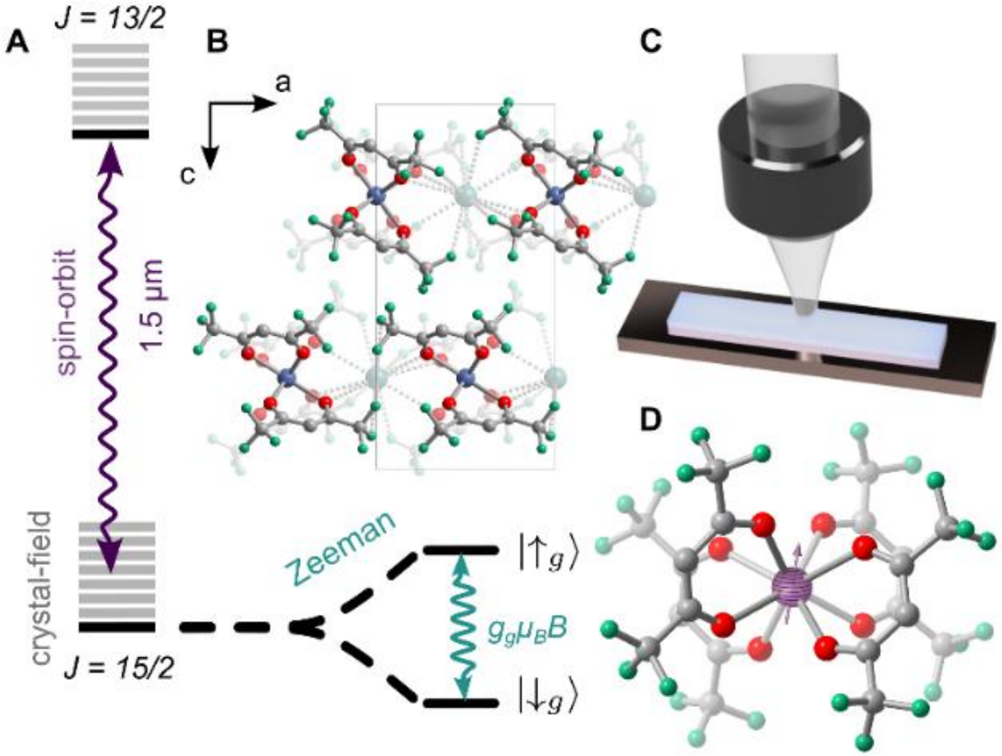
Systems analogous to NV, easier materials to process and optical transitions in the telecom



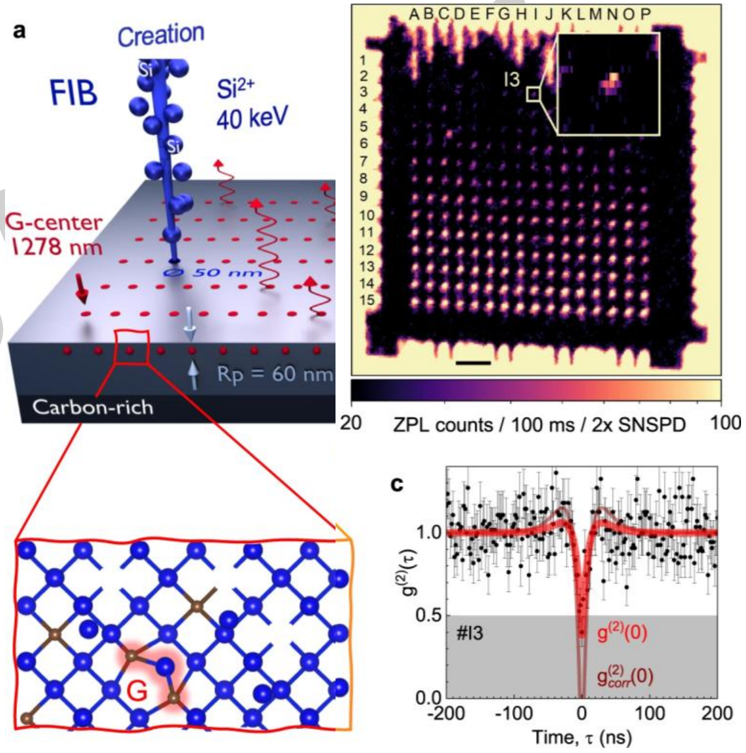
Ground state

Nature Communications **10**, Article number: 1954 (2019)

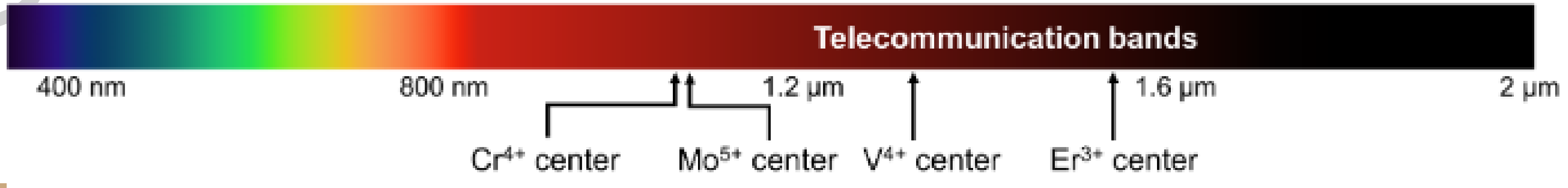




arXiv:2505.17195



Nature Communications **13**, Article number: 7683 (2022)



Some final remarks:

- Know your qubit! Mapping quantum circuits into actual physical operations on the qubit requires deep knowledge about the experimental platform, and creativity!

- Gate infidelity can add up quickly (even when we are doing nothing, we are doing something)

- There are still outstanding challenges on the material side of things, but this does not prevent us from testing platforms and learning from it.