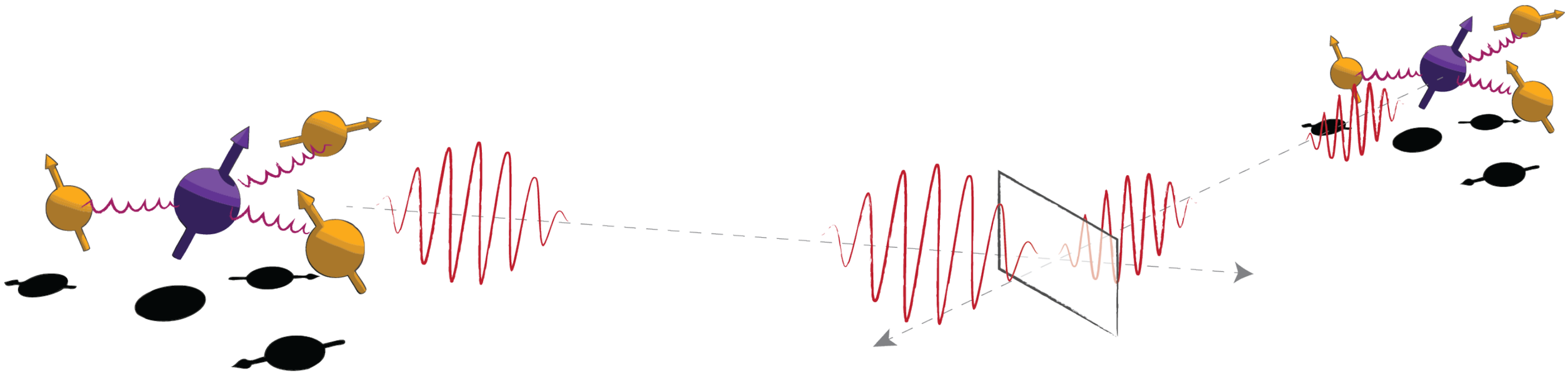
QUANTUM NETWORKS WITH SPINS IN DIAMOND

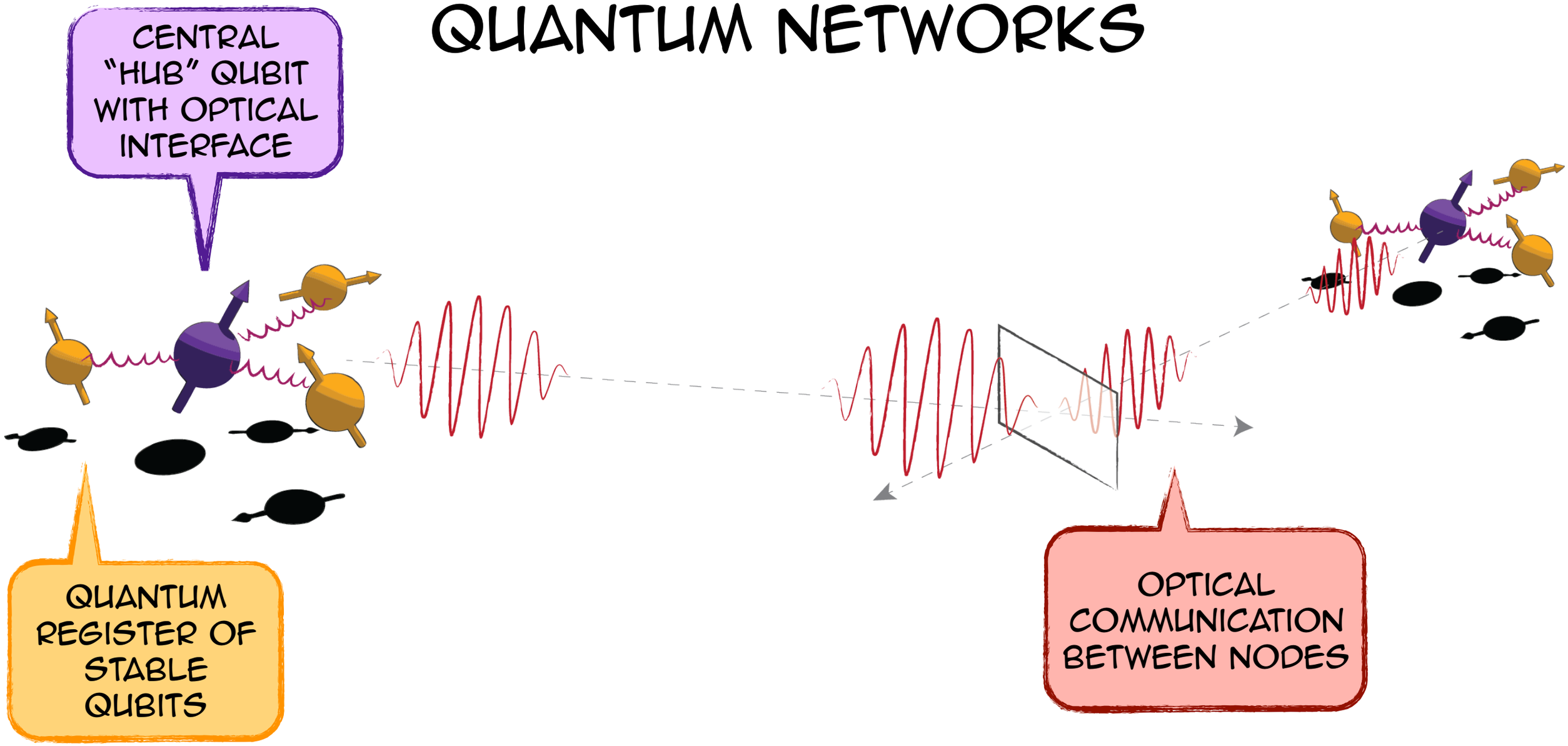


WOLFGANG PFAFF

HANSON GROUP
KAVLI INSTITUTE OF NANOSCIENCE DELFT, NETHERLANDS

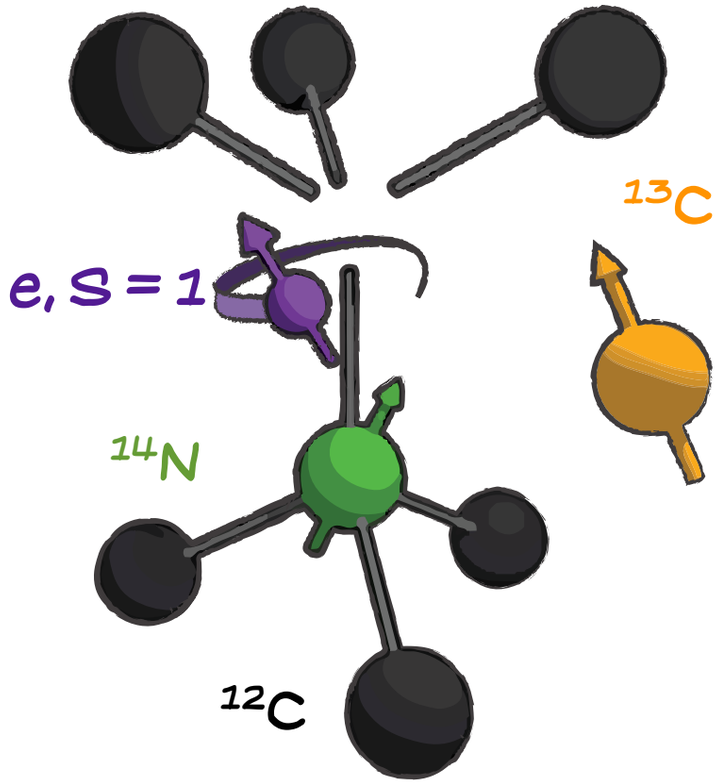
HANSONLAB.TUDELFT.NL

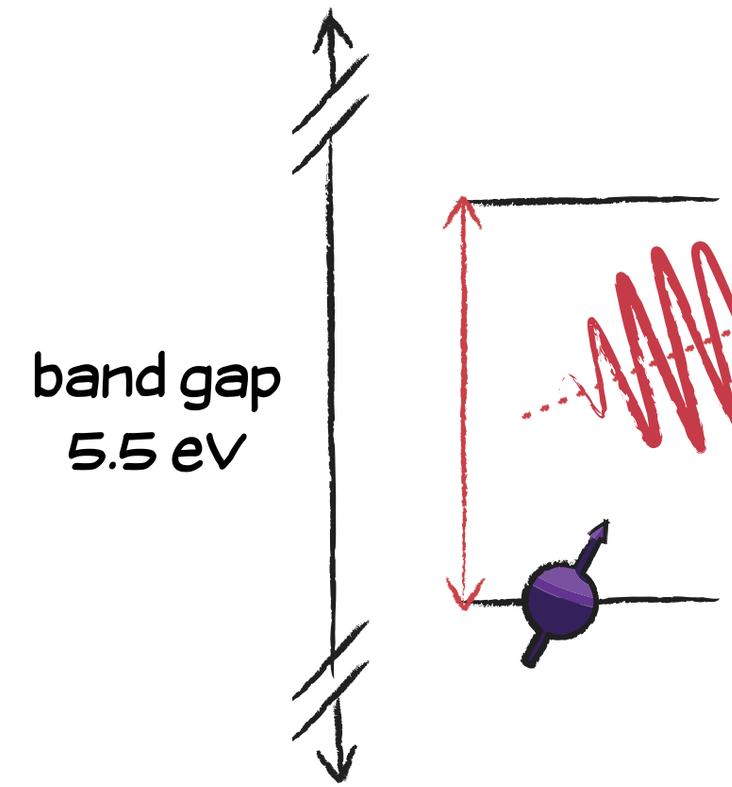
QUANTUM NETWORKS

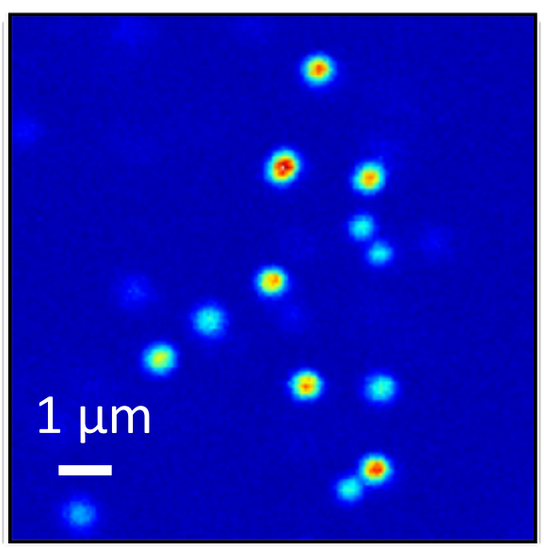


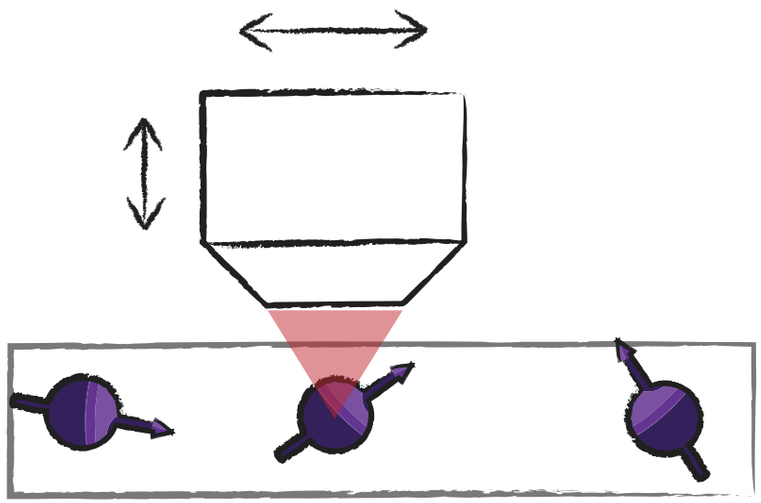
See, e.g., "The quantum internet", Kimble, Nature 453, 1023 (2008).

NV CENTER:
"ION TRAPPED IN A SOLID"



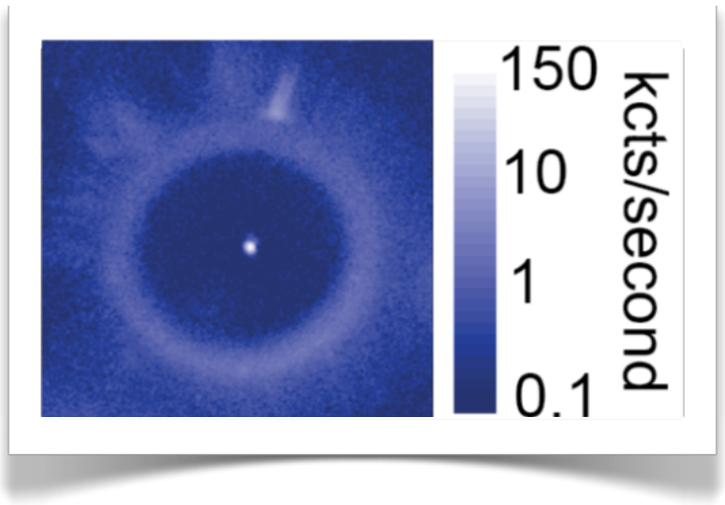


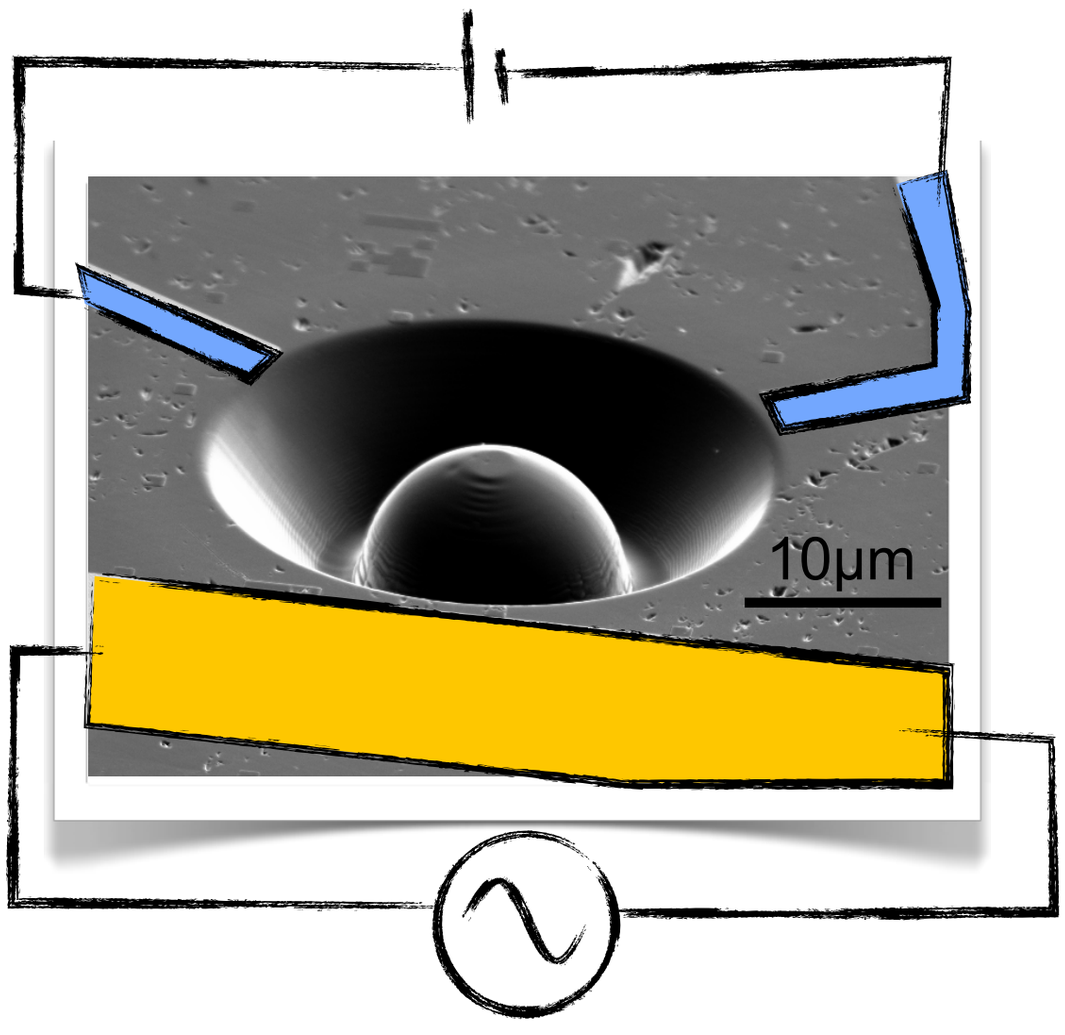


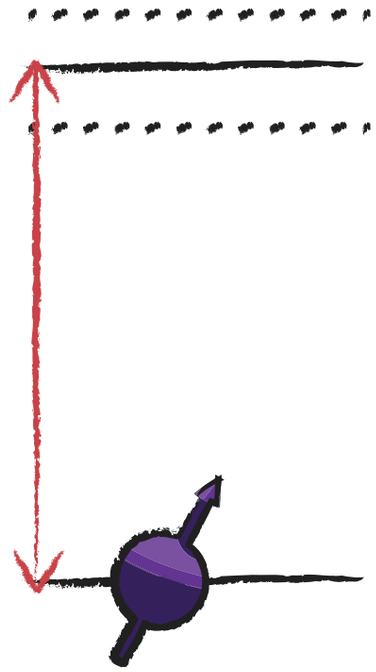


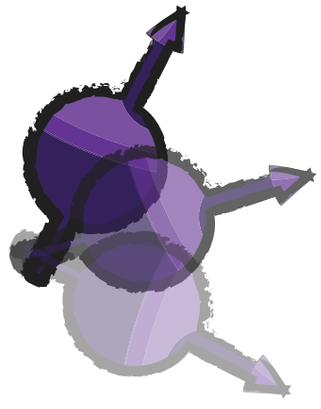
See, e.g., Awschalom, Epstein, Hanson, Scientific American 297, 84 (2007)

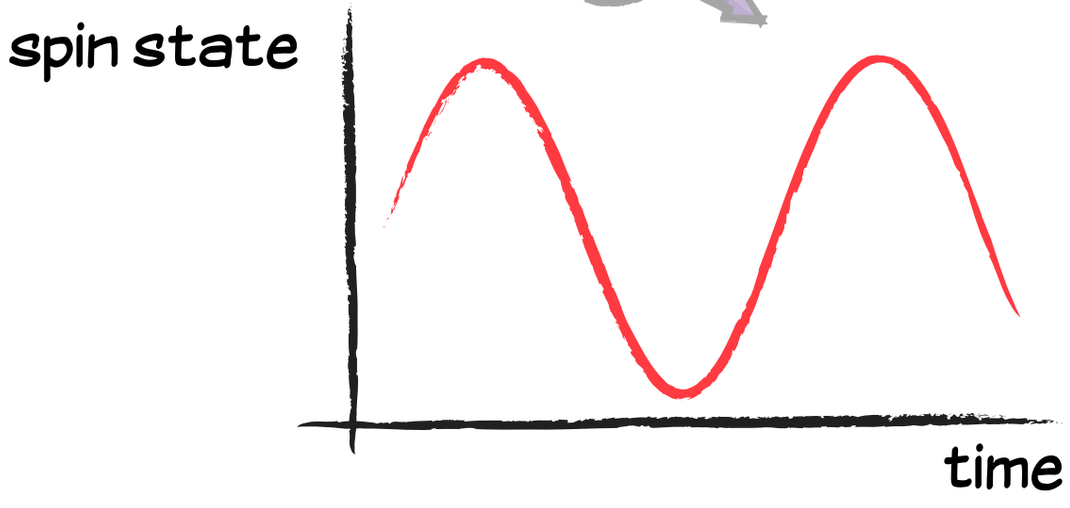
WIRING UP NV CENTERS



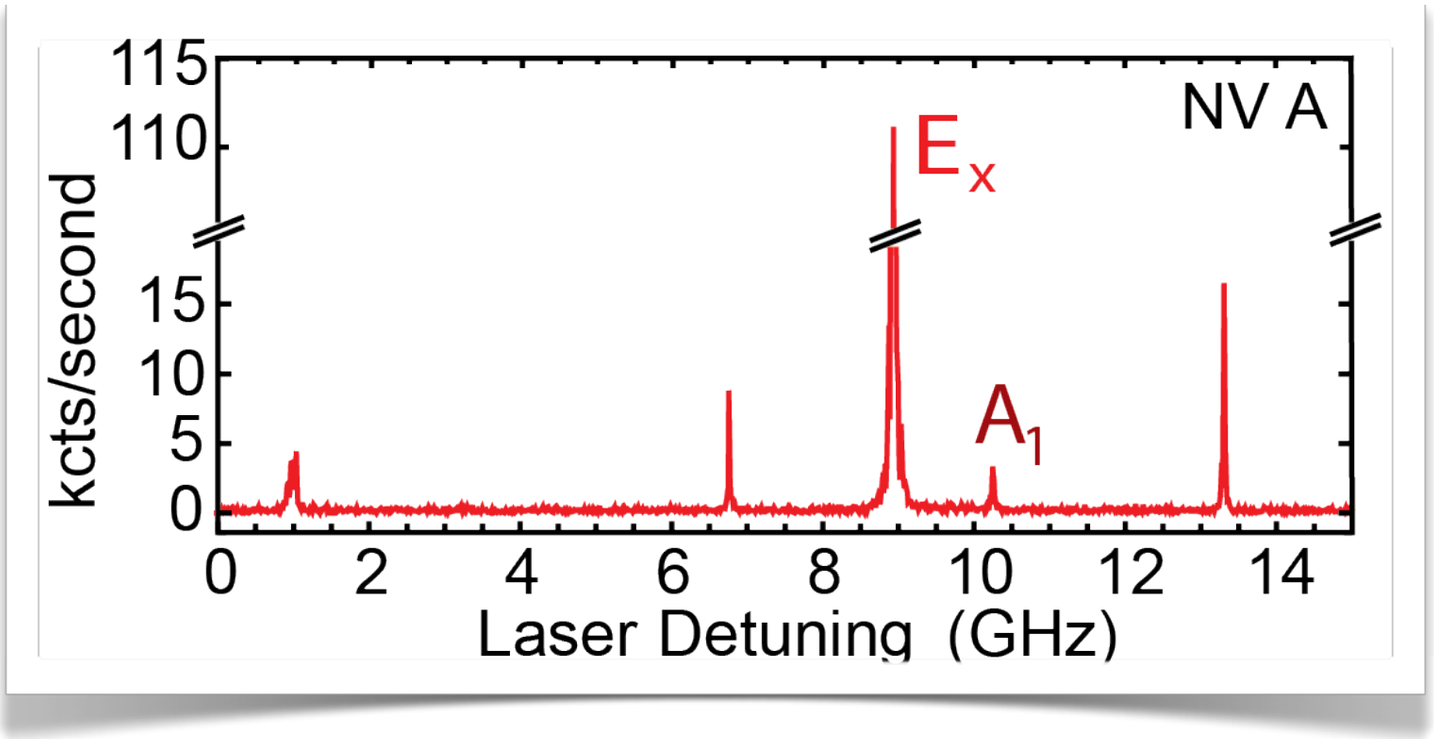


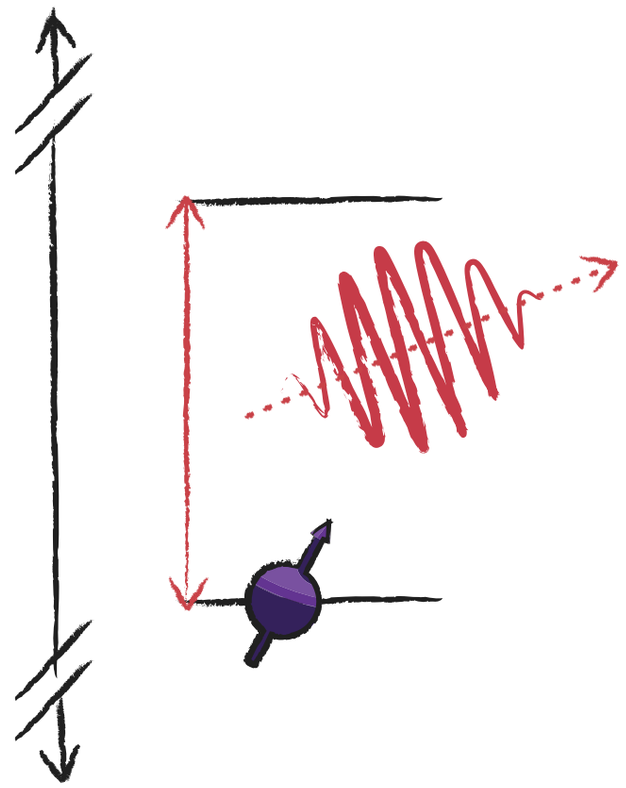






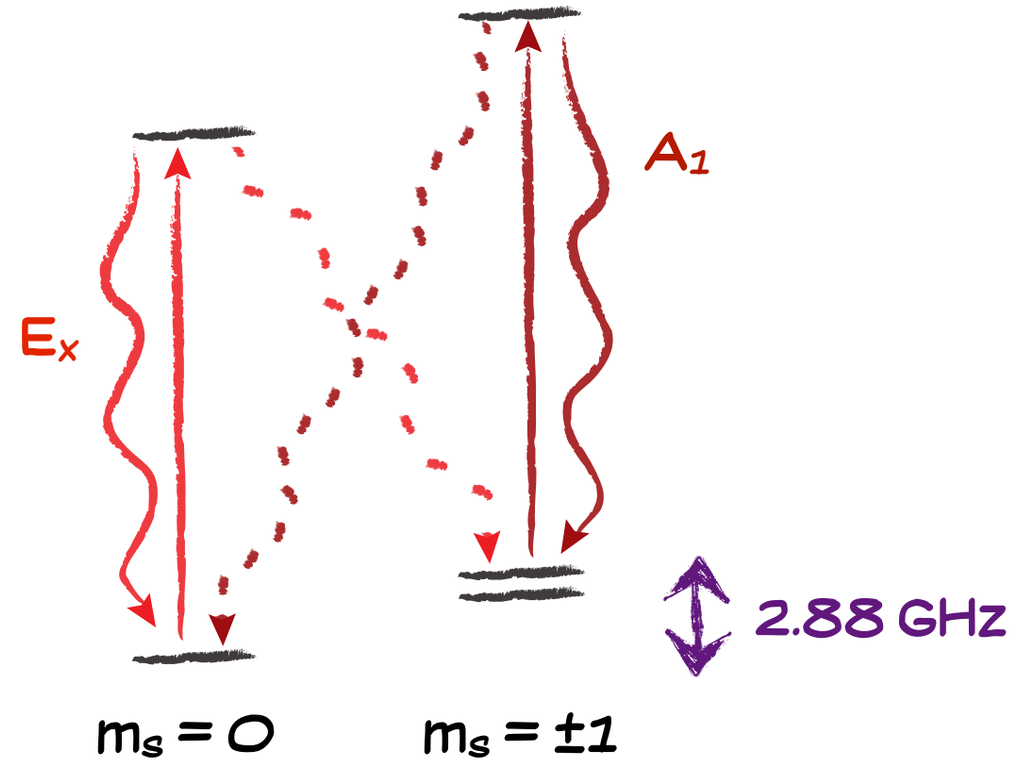
SPIN-RESOLVED OPTICAL EXCITATION ($T < 10$ K)

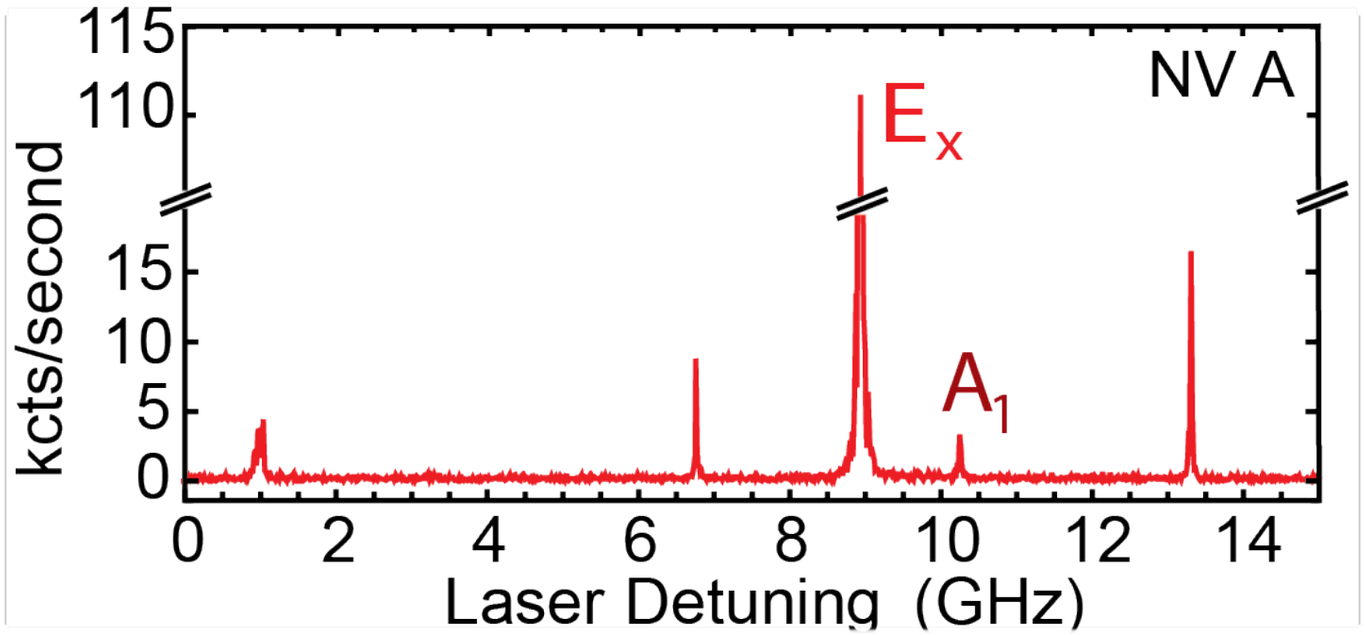




Early work in Stuttgart, Harvard, HP Labs

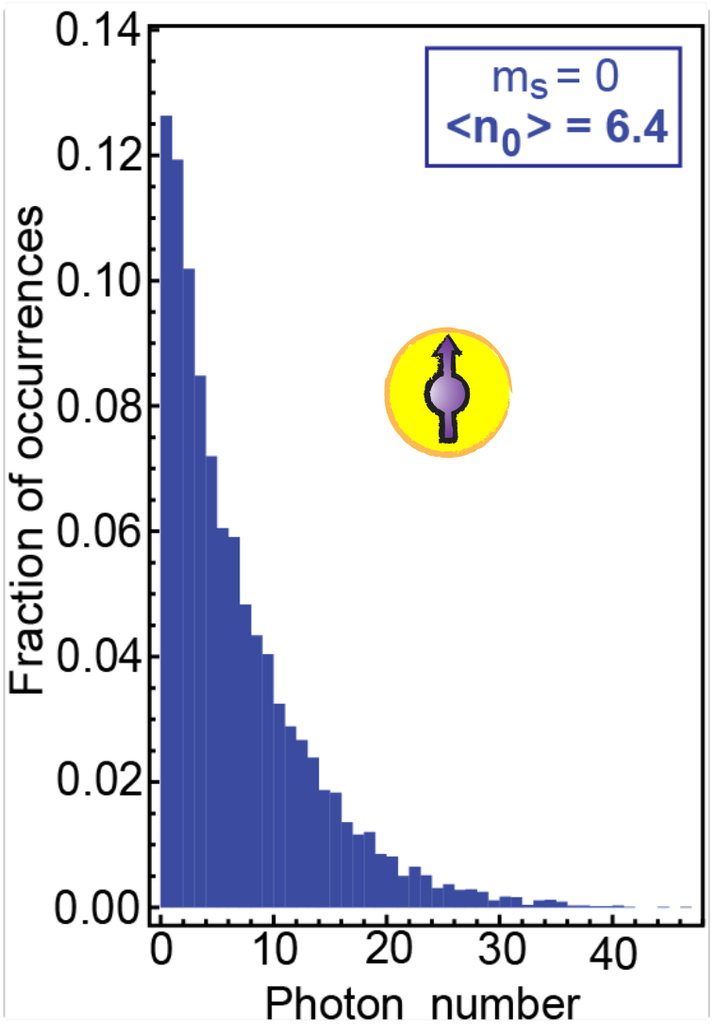
SPIN-RESOLVED OPTICAL EXCITATION ($T < 10$ K)

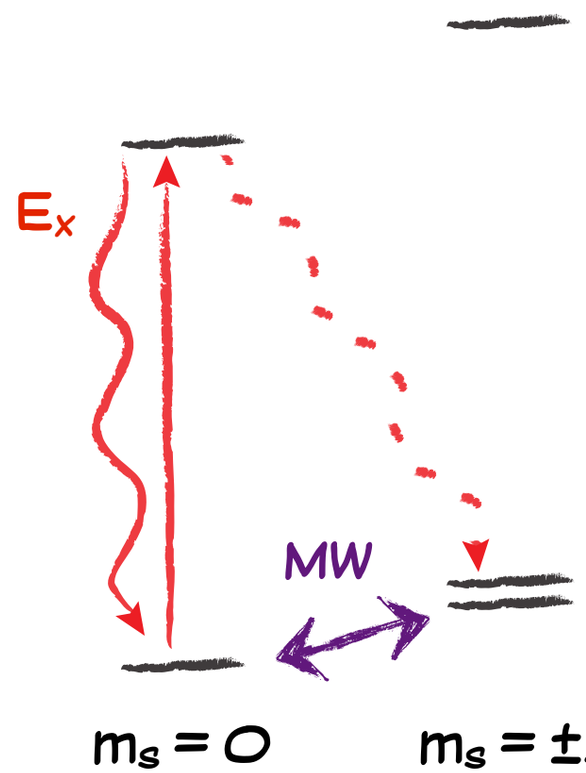




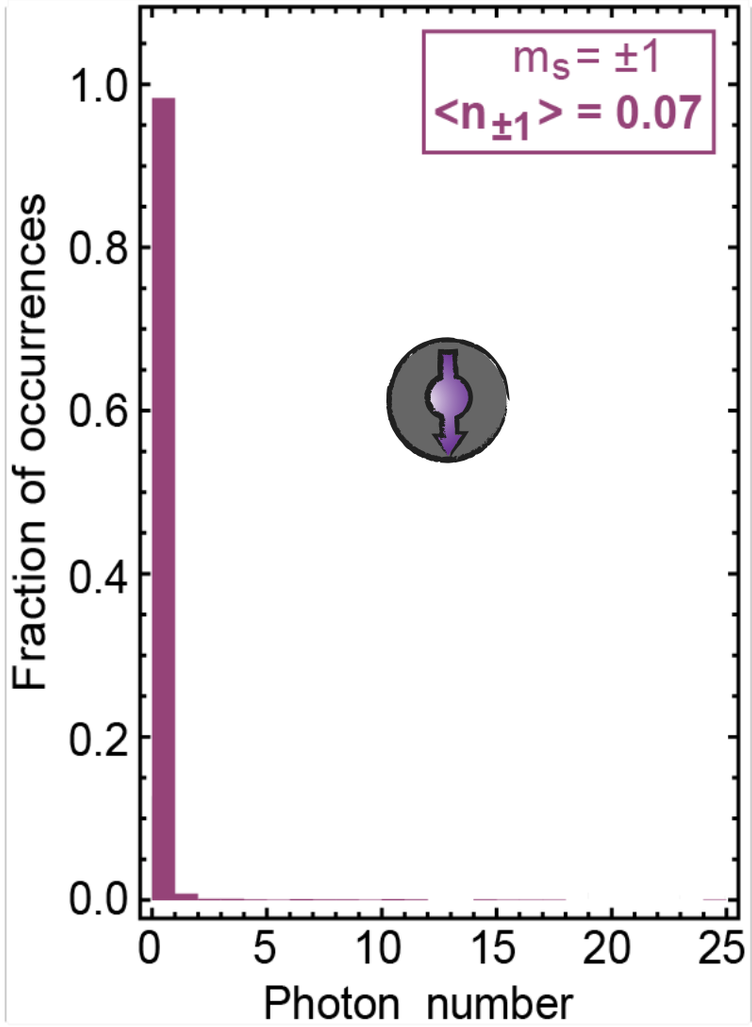
Early work in Stuttgart, Harvard, HP Labs

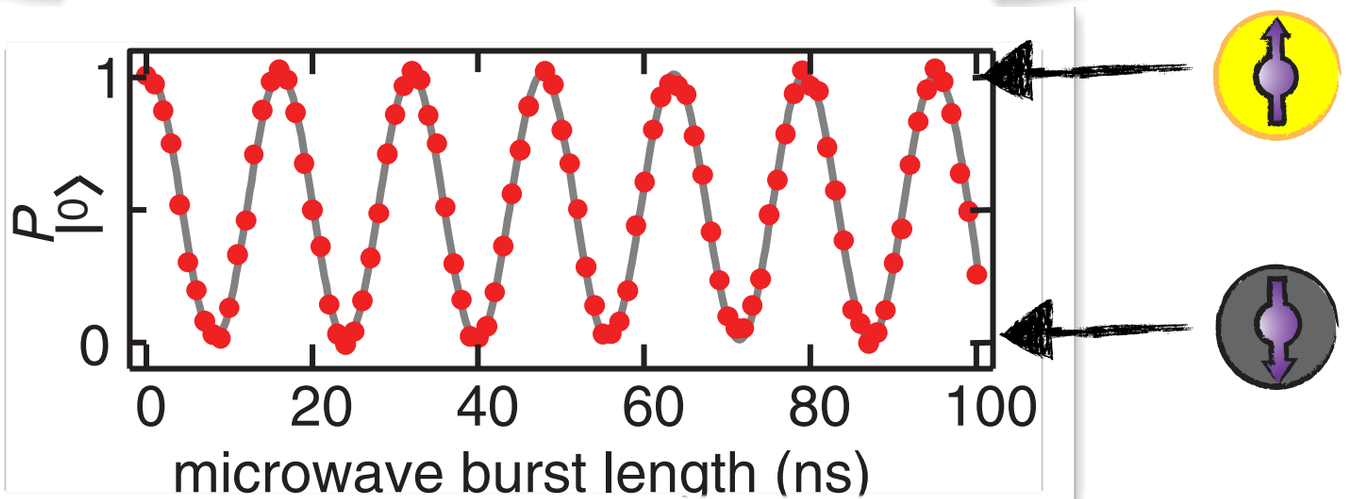
E-SPIN SINGLE-SHOT READOUT





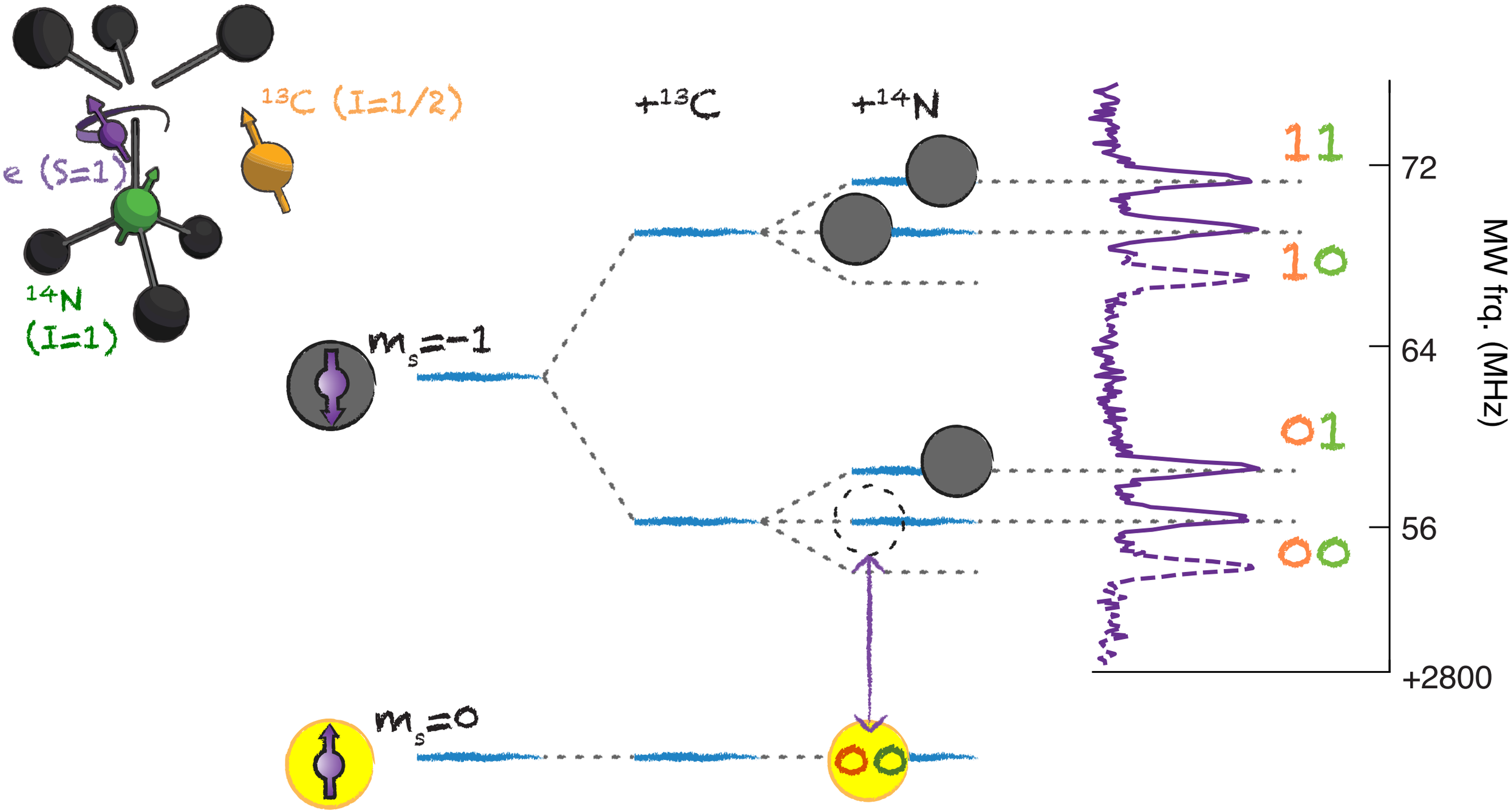
$\langle F_{readout} \rangle \sim 95\%$





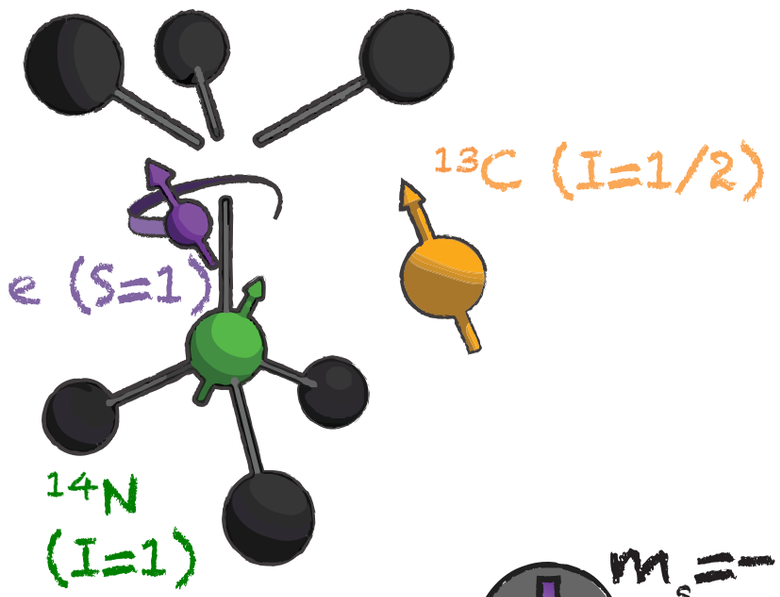
Robledo et al, Nature 477, 574 (2011)

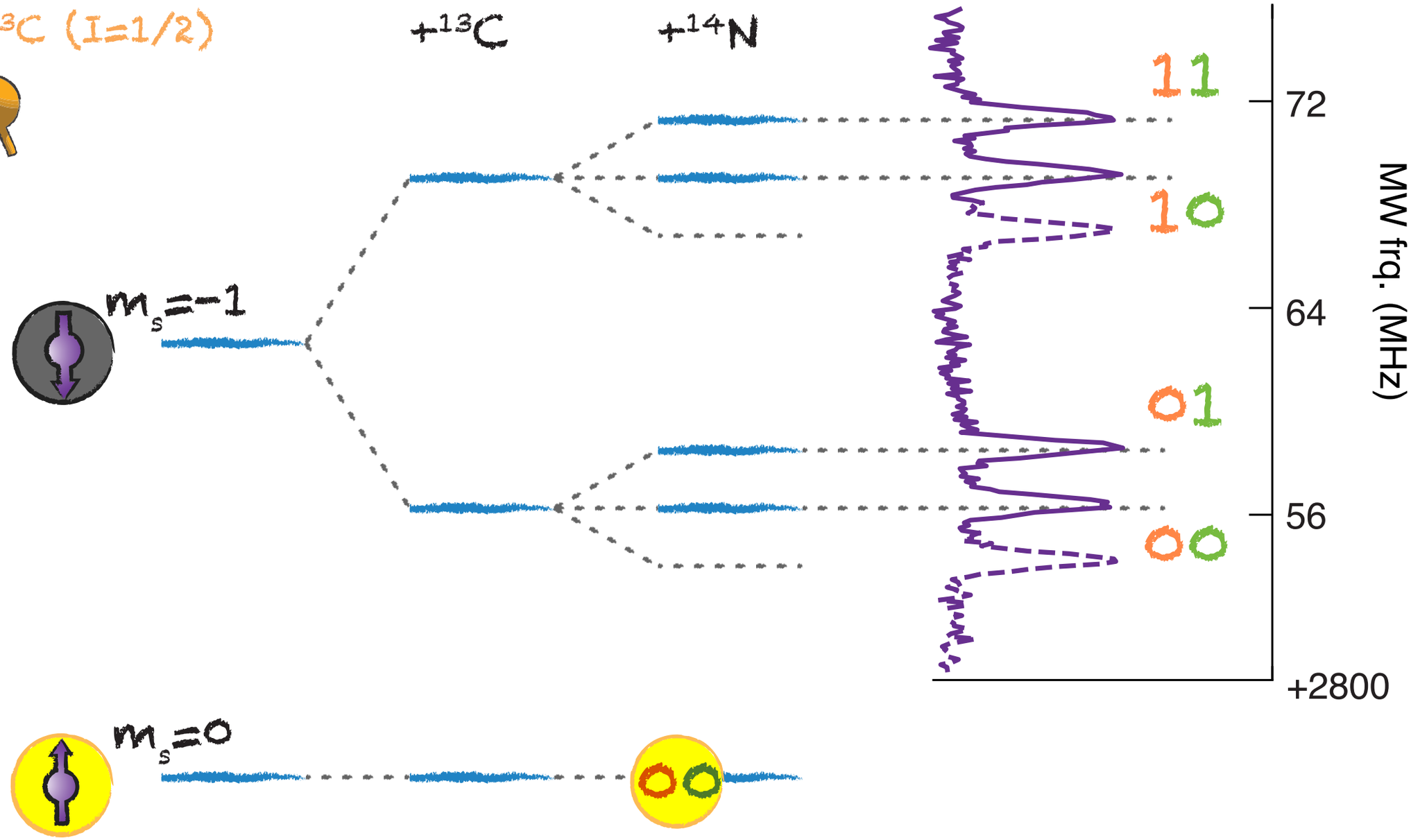
PROJECTIVE MEASUREMENT OF NUCLEAR SPINS



Robledo et al, Nature 477, 574 (2011)
Pfaff et al, Nature Physics 9, 29 (2013)
Inspired by earlier work: Jiang et al, Science (2009), Neumann et al, Science (2010)

PROJECTIVE MEASUREMENT OF NUCLEAR SPINS





Robledo et al, Nature 477, 574 (2011)
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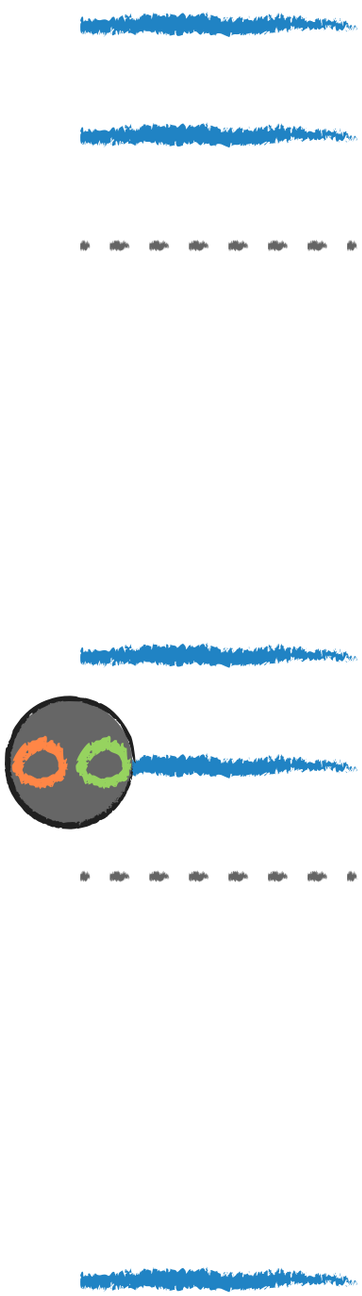
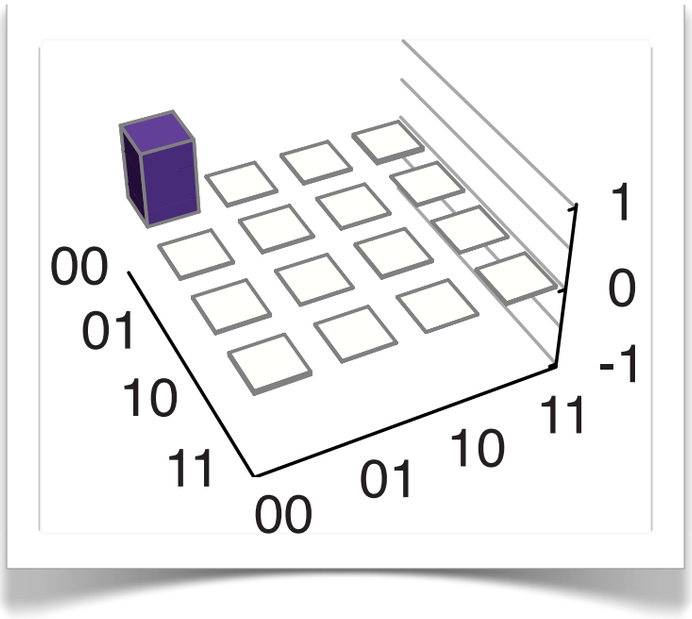
ENTANGLEMENT BY MEASUREMENT





Pfaff et al, Nature Physics 9, 29 (2013)

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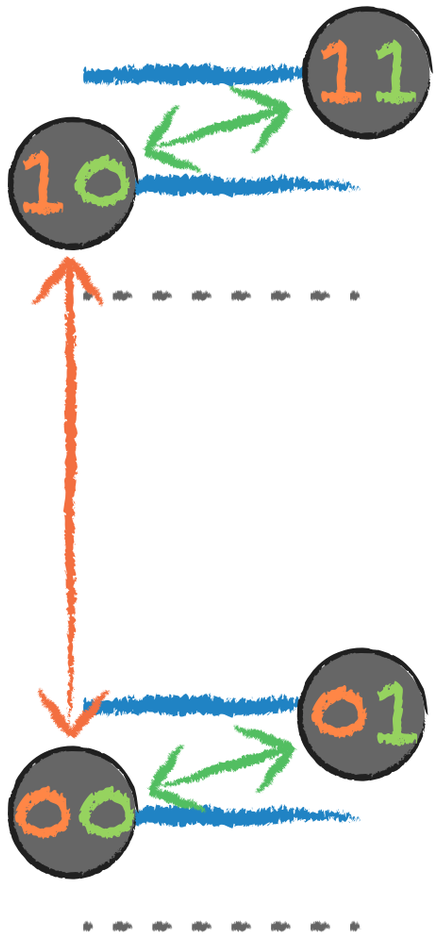

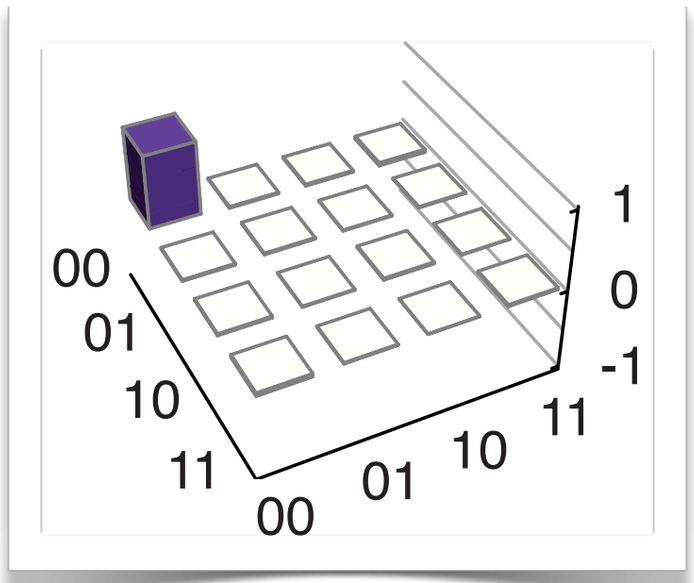

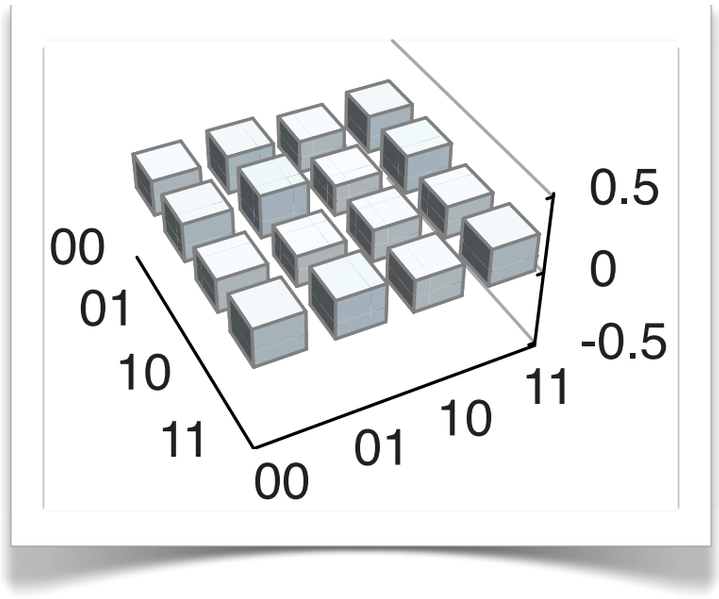

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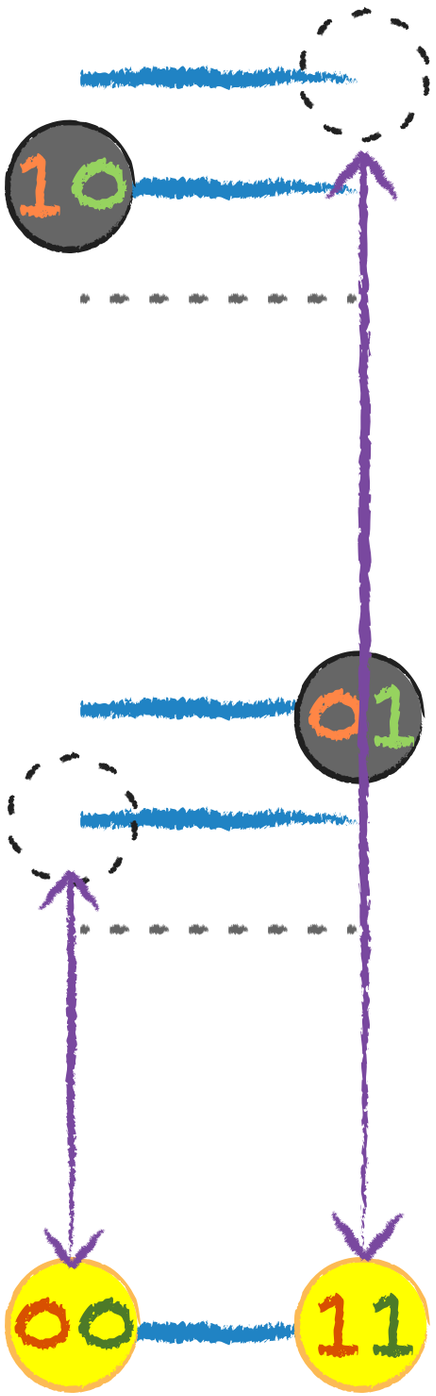

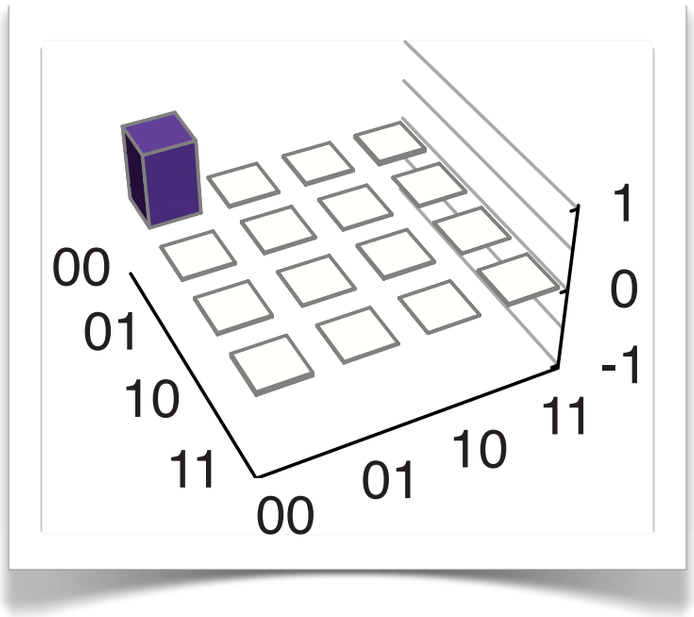

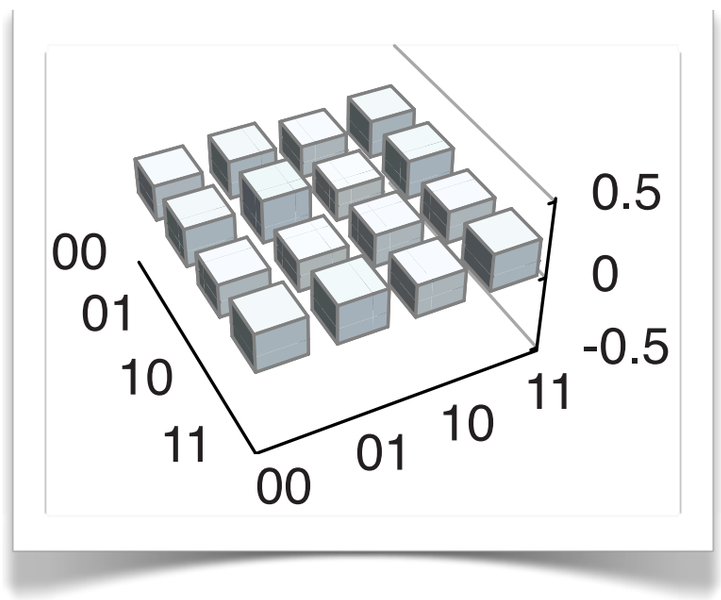

Pfaff et al, Nature Physics 9, 29 (2013)

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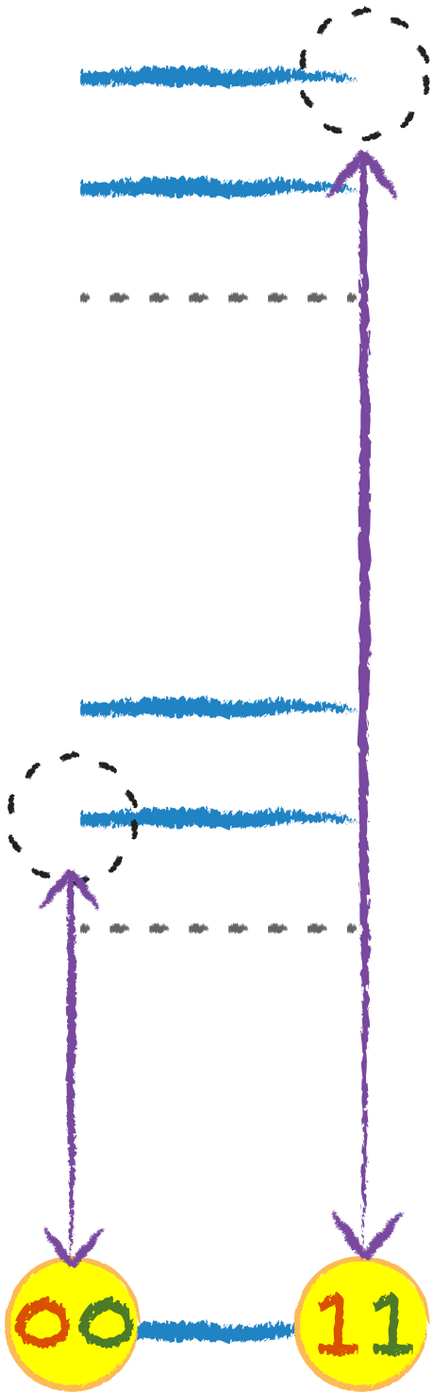
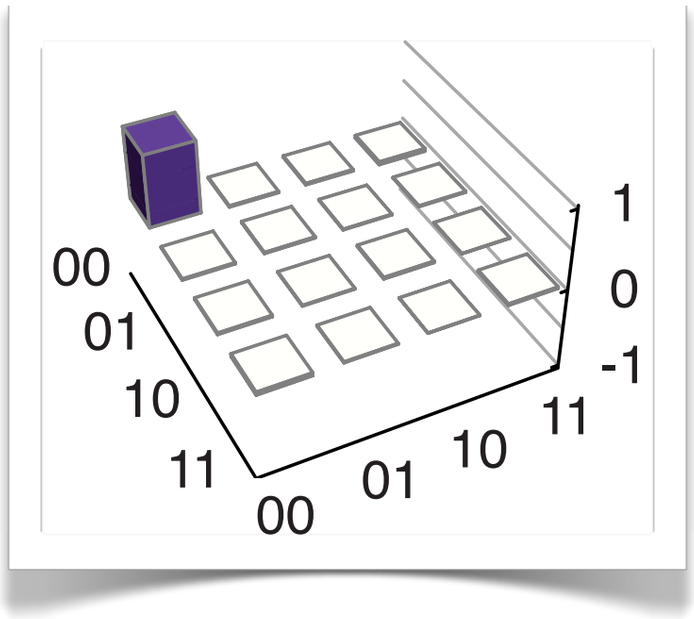
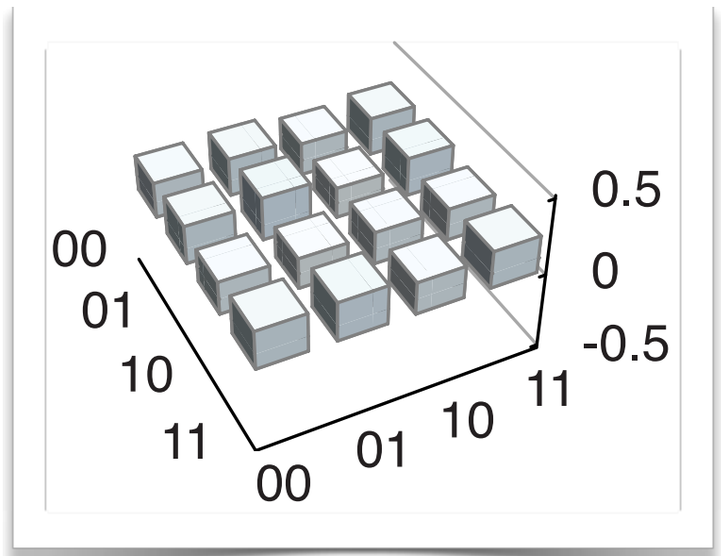
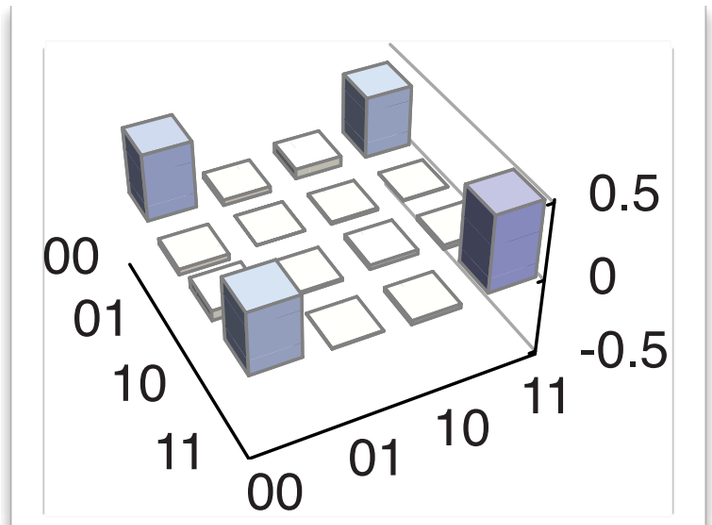






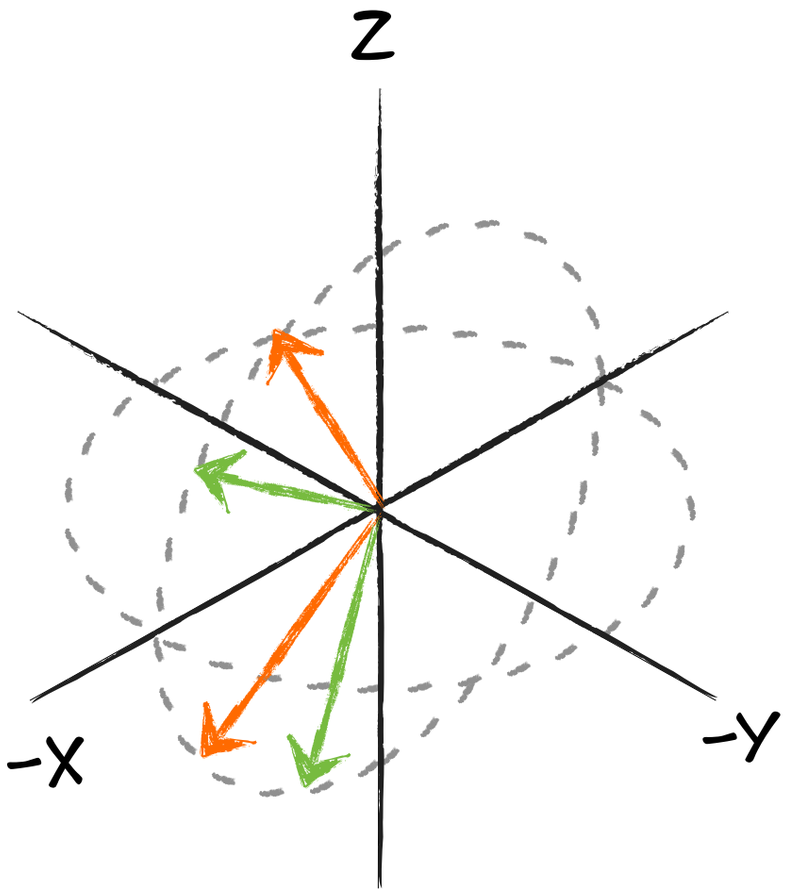


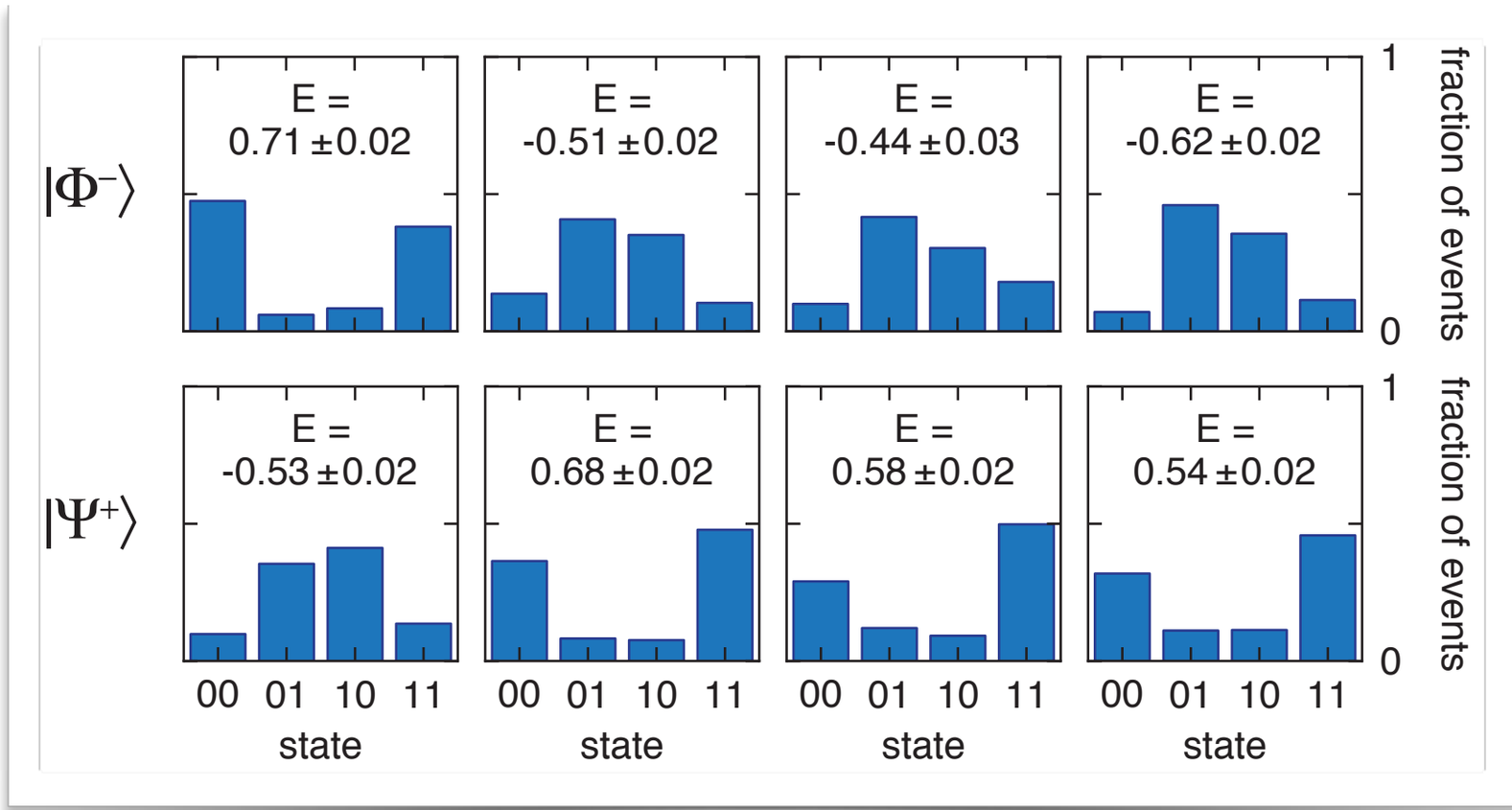
$|\Phi^+\rangle = 1/\sqrt{2}\,(|00\rangle + |11\rangle)$

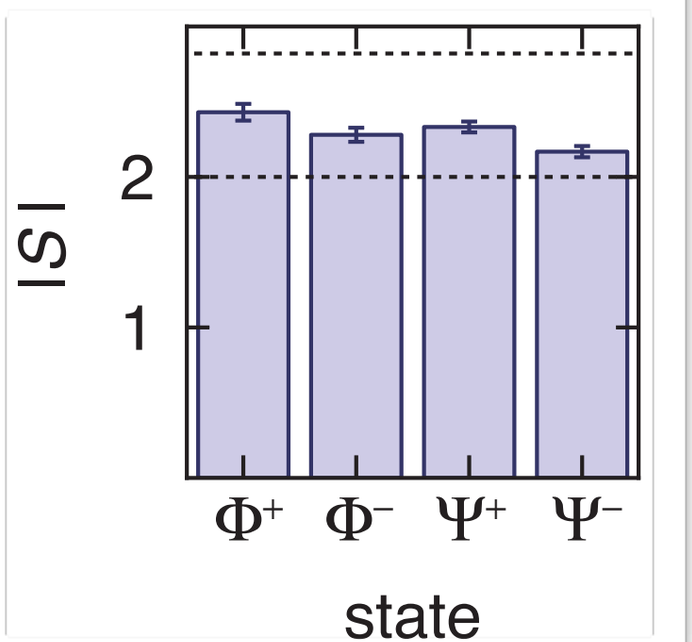
BELL STATE FIDELITY
F = (90±3)%

Pfaff et al, Nature Physics 9, 29 (2013)

BELL'S INEQUALITY





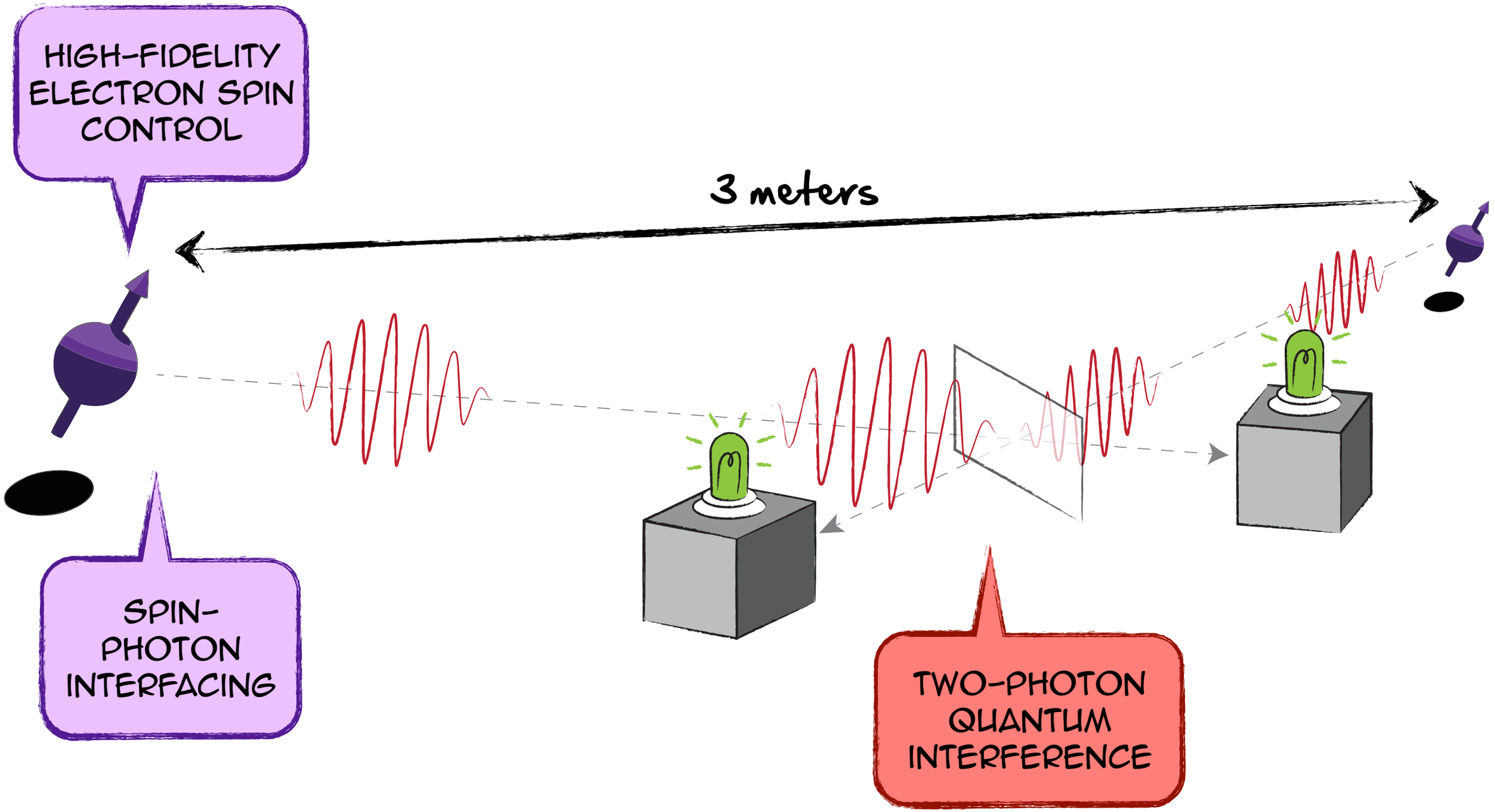


$$\langle |S| \rangle = 2.30 \pm 0.05$$

FIRST PROOF OF ENTANGLEMENT OF TWO NUCLEAR SPINS IN A SOLID

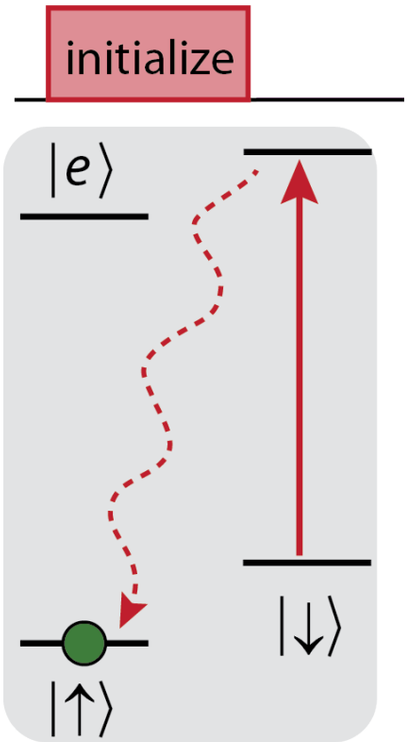
Pfaff et al, Nature Physics 9, 29 (2013)

ENTANGLEMENT OF DISTANT NV ELECTRON SPINS



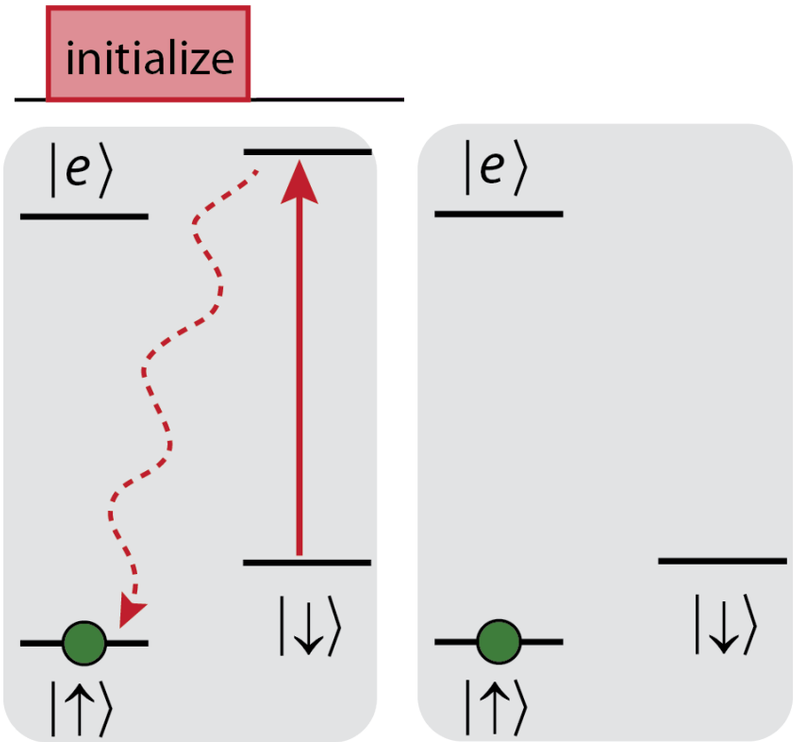
Pioneering work with ions:
Moehring et al., Nature 449, 68 (2007)

PROTOCOL



Barrett and Kok, PRA 71, 060310 (2005)

PROTOCOL



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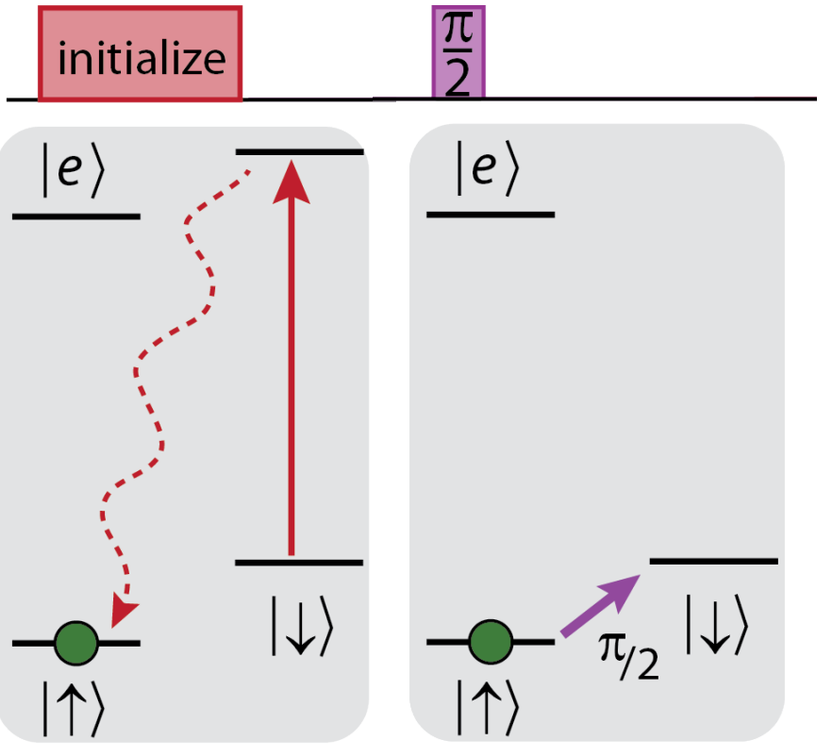

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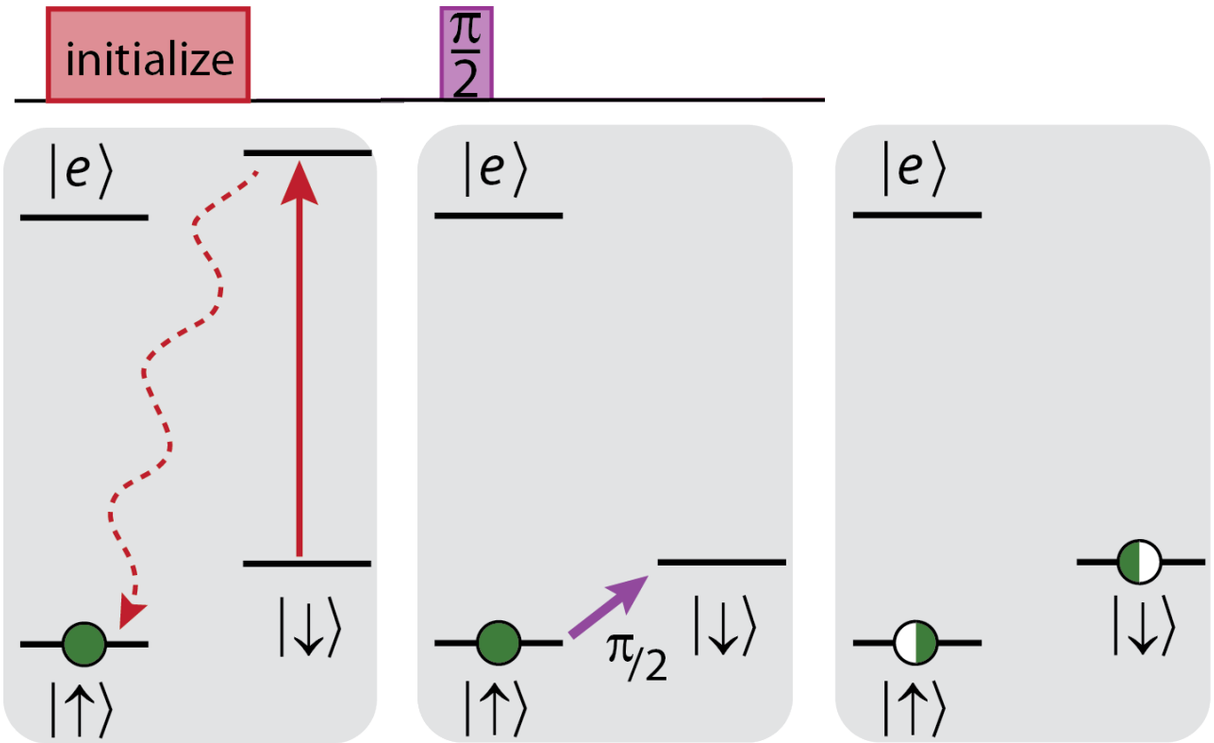
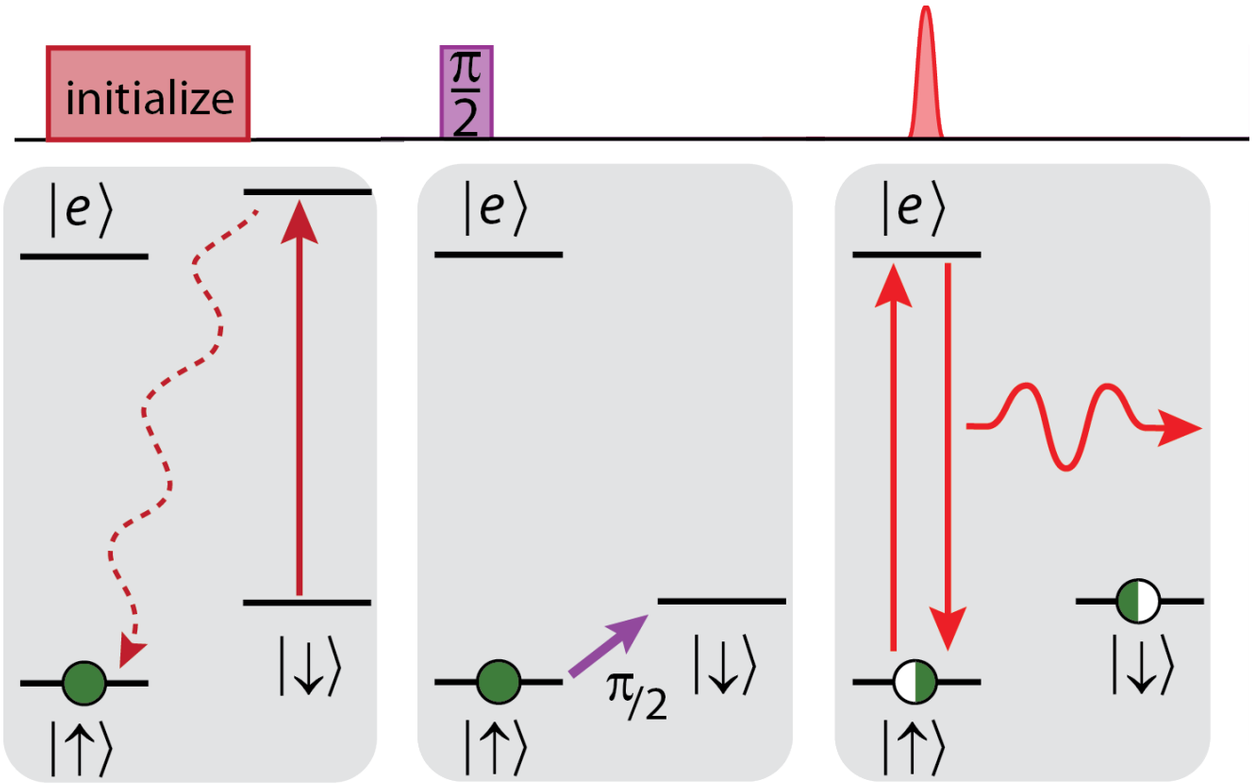


$\uparrow + \downarrow$

Barrett and Kok, PRA 71, 060310 (2005)

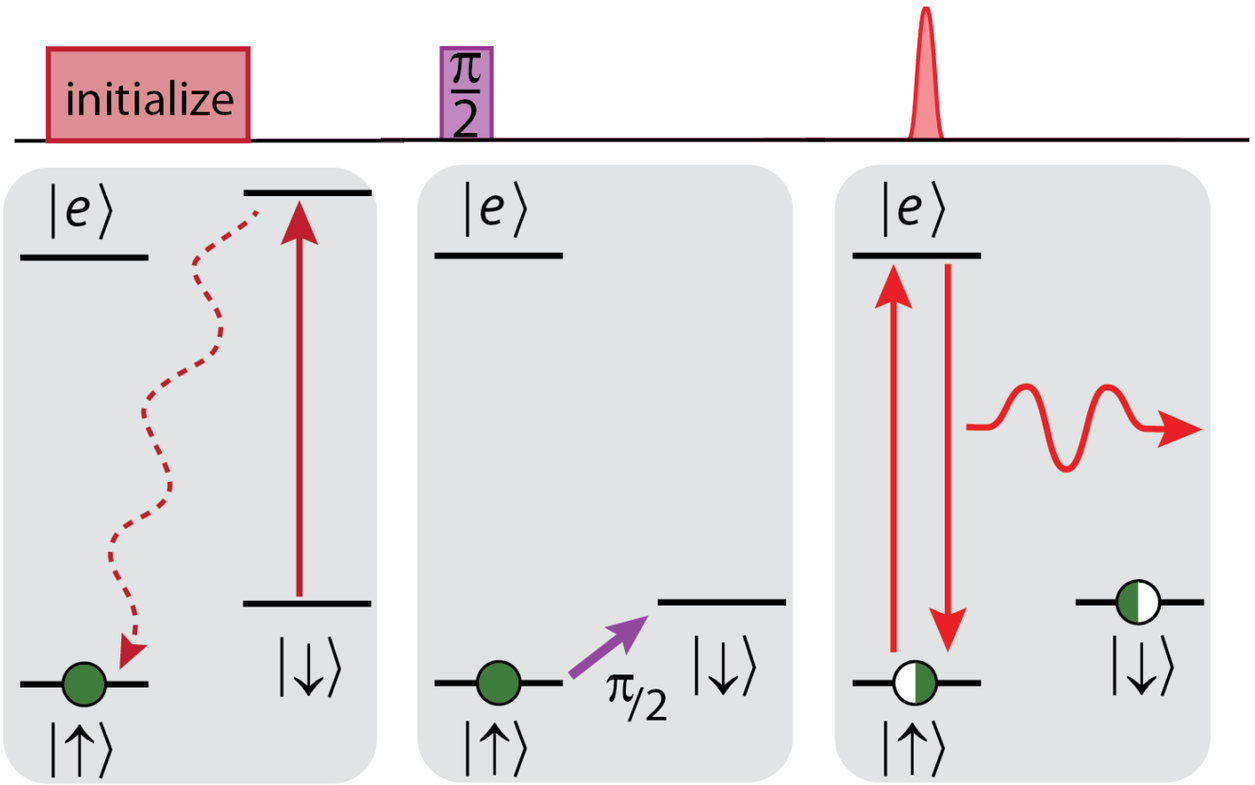
PROTOCOL



$\uparrow 1 + \downarrow 0$

Barrett and Kok, PRA 71, 060310 (2005)

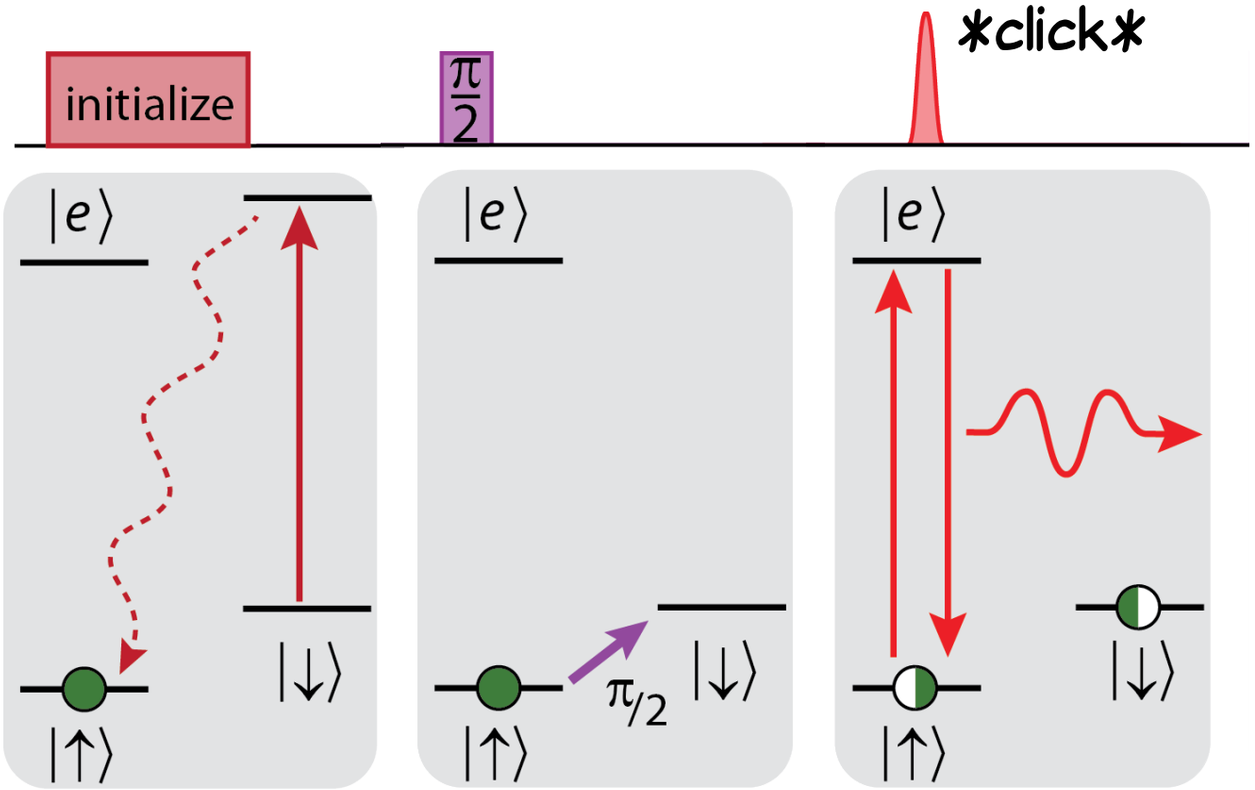
PROTOCOL



$$\uparrow_A\uparrow_B 1_A 1_B + \downarrow_A\downarrow_B 0_A 0_B + \uparrow_A\downarrow_B 1_A 0_B + \downarrow_A\uparrow_B 0_A 1_B$$

Barrett and Kok, PRA 71, 060310 (2005)

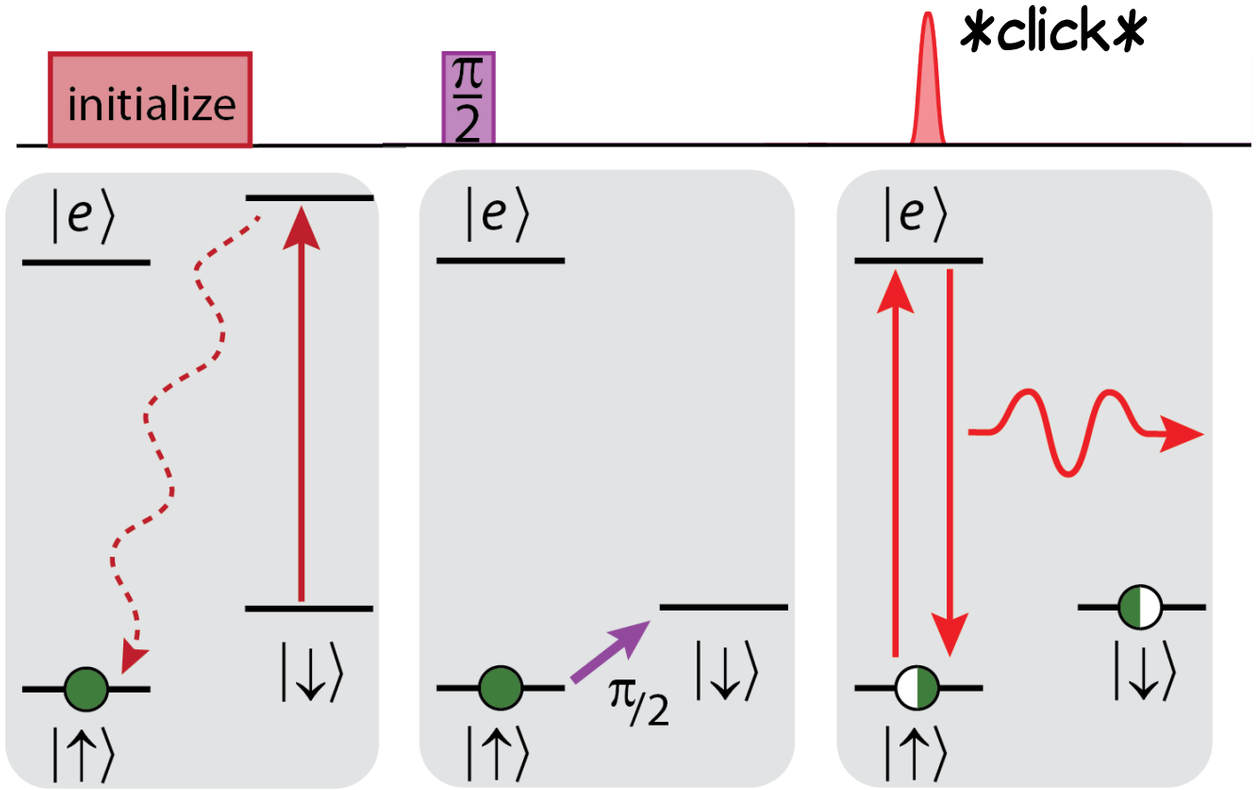
PROTOCOL



$$\uparrow_A\uparrow_B 1_A 1_B + \downarrow_A\downarrow_B 0_A 0_B + \uparrow_A\downarrow_B 1_A 0_B + \downarrow_A\uparrow_B 0_A 1_B$$

Barrett and Kok, PRA 71, 060310 (2005)

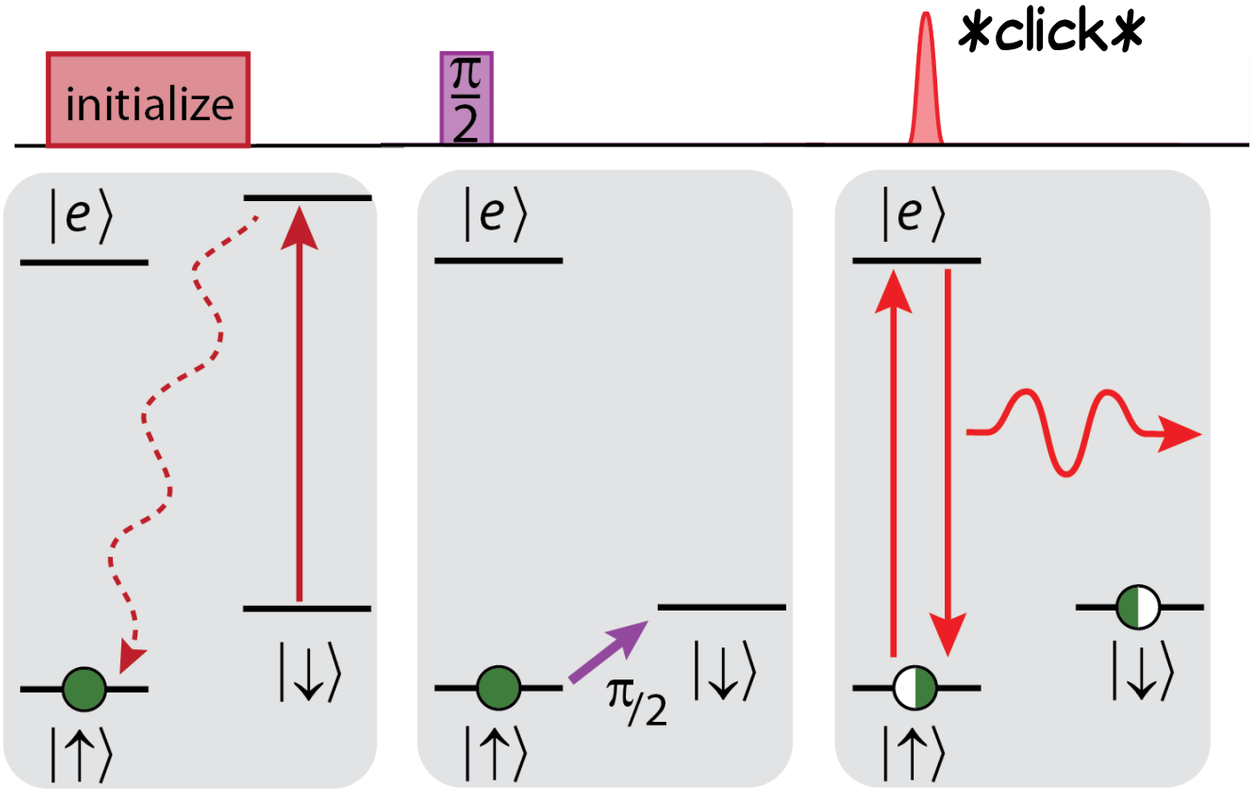
PROTOCOL



$$\uparrow_A\uparrow_B 1_A 1_B + \uparrow_A\downarrow_B 1_A 0_B + \downarrow_A\uparrow_B 0_A 1_B$$

Barrett and Kok, PRA 71, 060310 (2005)

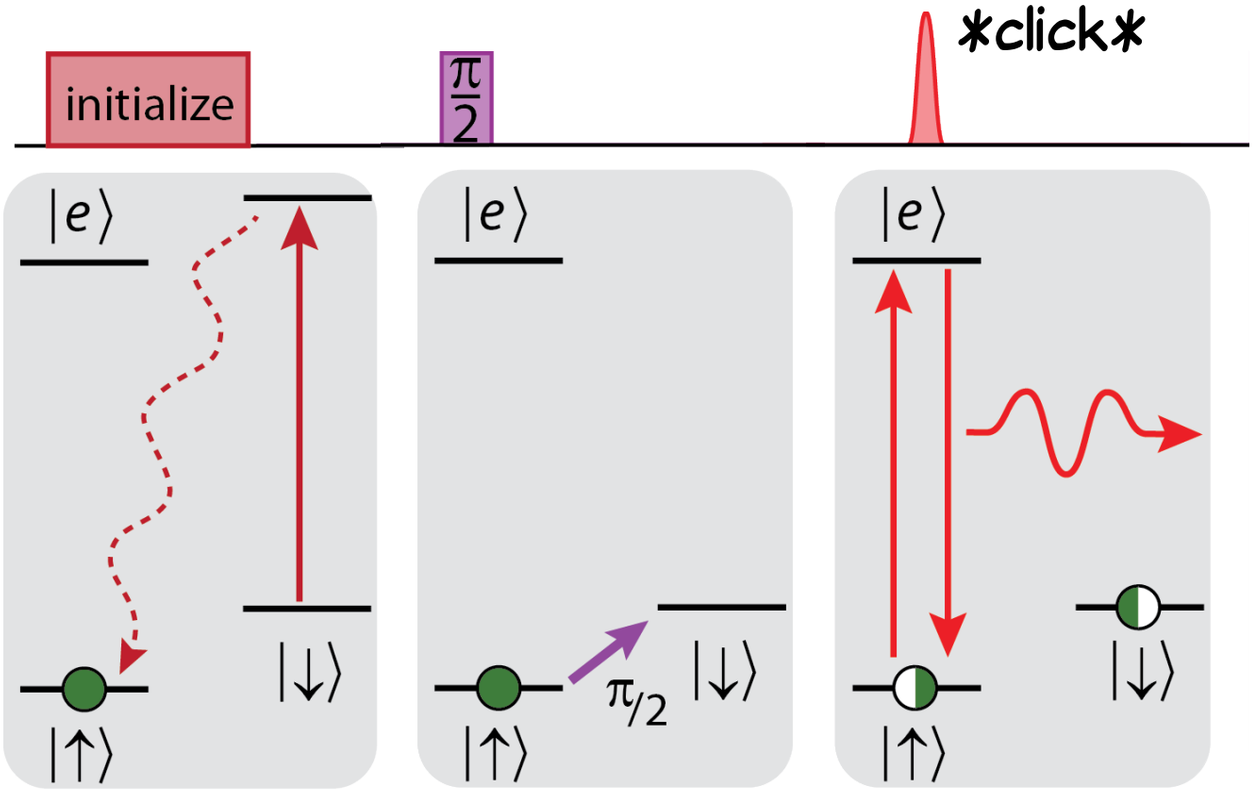
PROTOCOL



$$\uparrow_A\uparrow_B|_A|_B + \uparrow_A\downarrow_B \pm e^{-i\varphi}\downarrow_A\uparrow_B$$

Barrett and Kok, PRA 71, 060310 (2005)

PROTOCOL

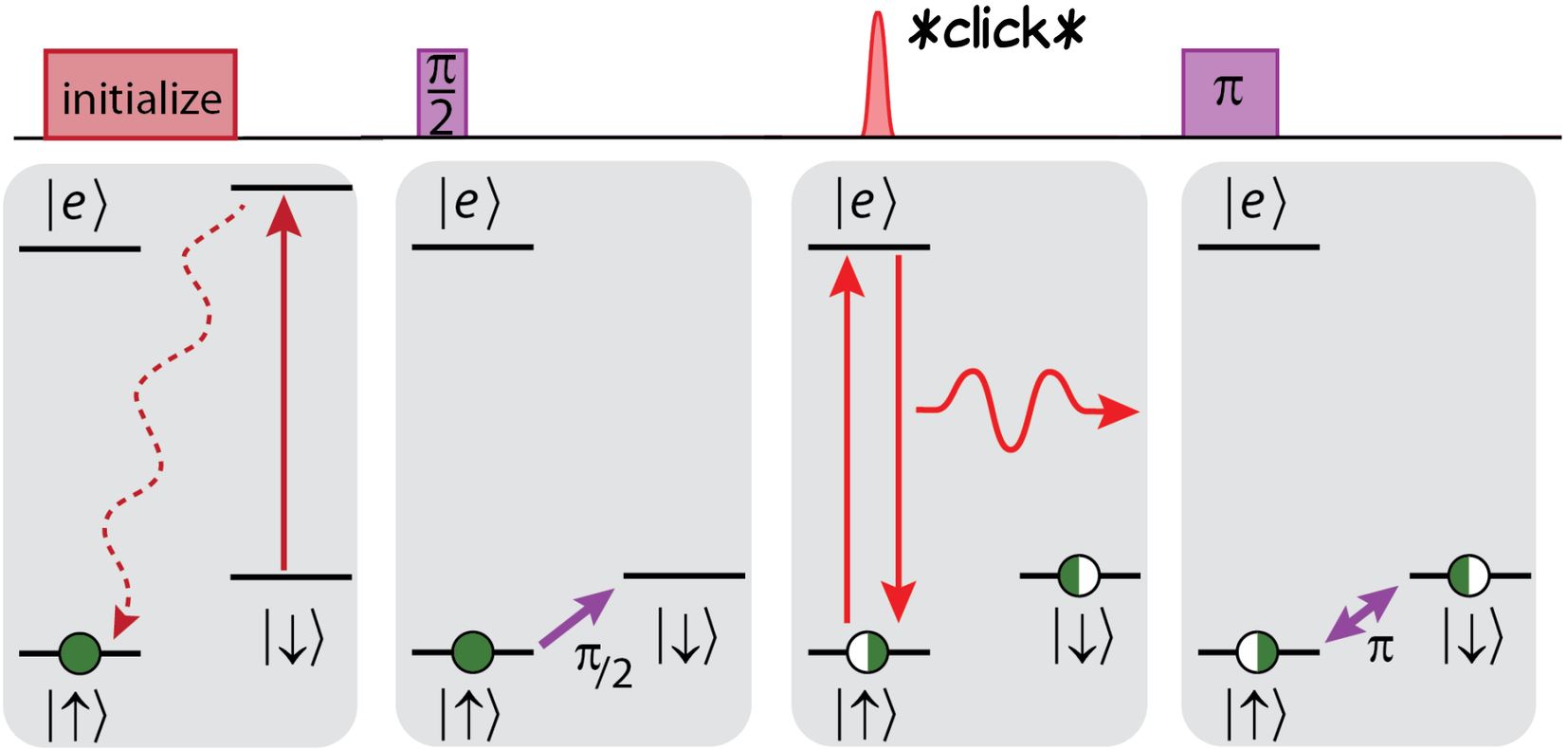


$\uparrow_A\uparrow_B$

$\uparrow_A\downarrow_B \pm e^{-i\varphi}\downarrow_A\uparrow_B$

Barrett and Kok, PRA 71, 060310 (2005)

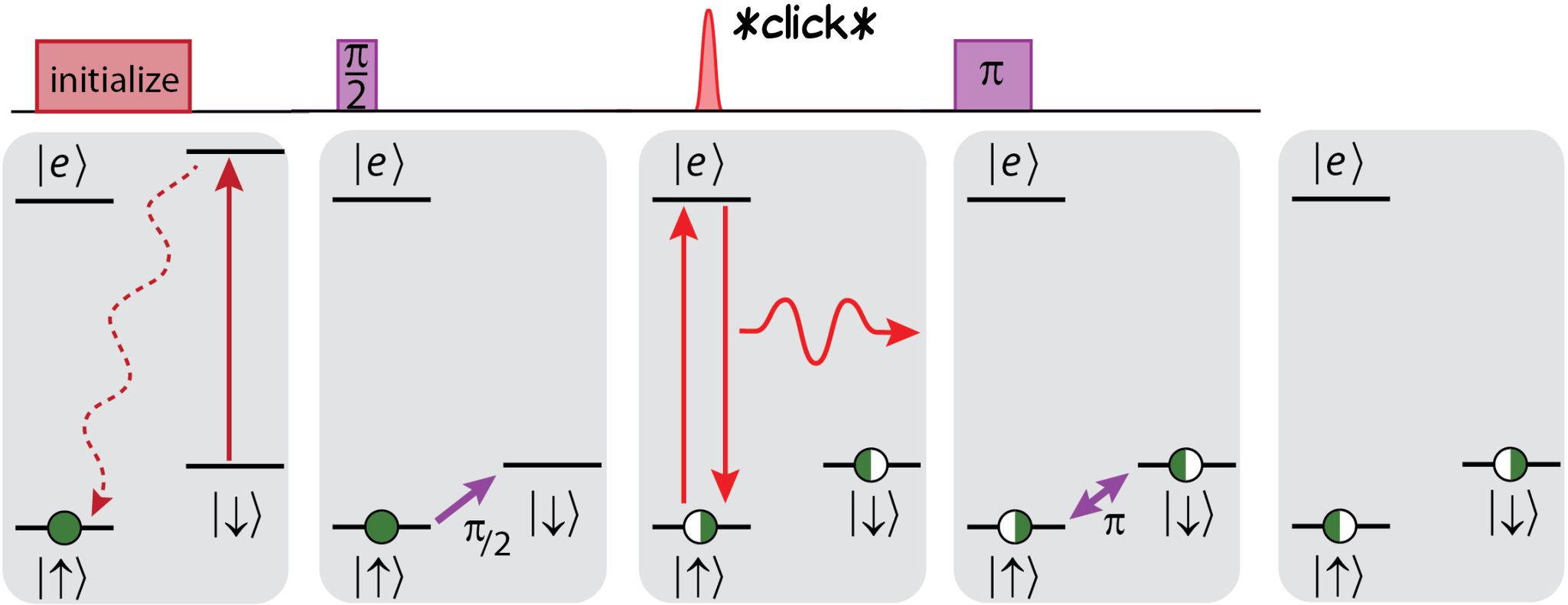
PROTOCOL



$$\downarrow_A\downarrow_B \qquad \downarrow_A\uparrow_B \pm e^{-i\varphi}\uparrow_A\downarrow_B$$

Barrett and Kok, PRA 71, 060310 (2005)

PROTOCOL

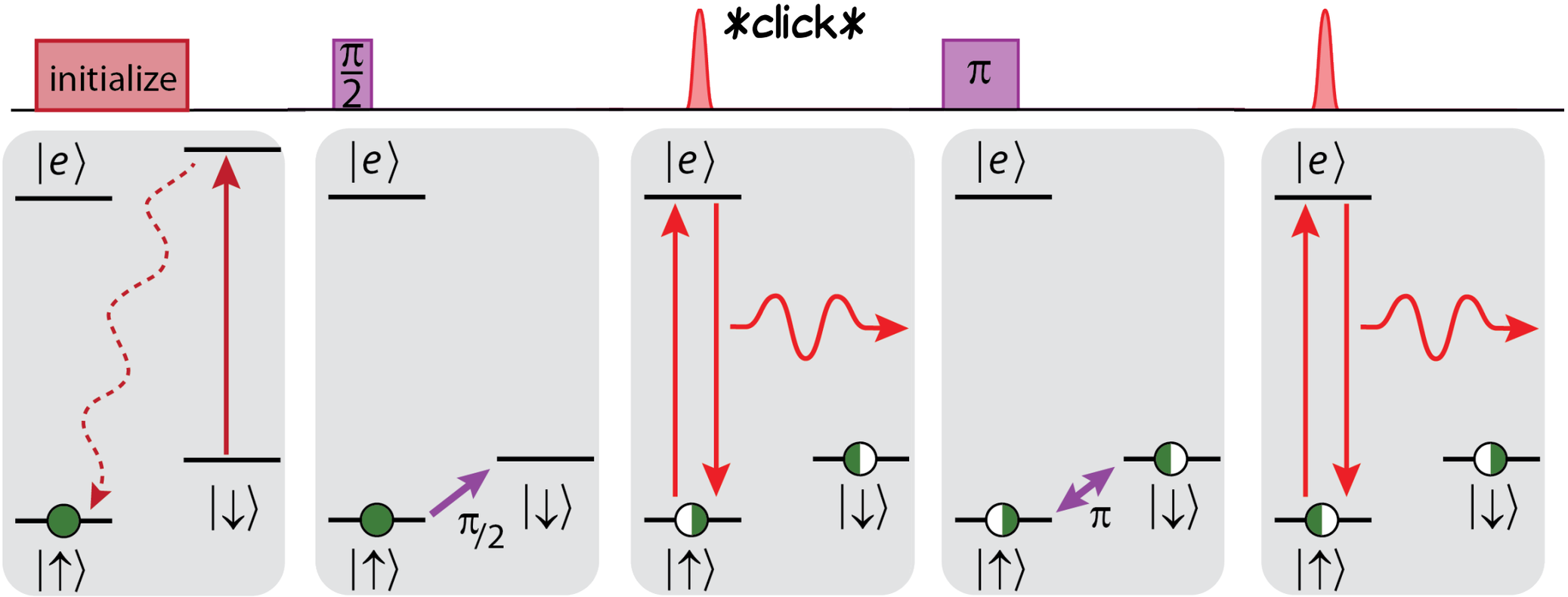


$\downarrow_A\downarrow_B$

$\downarrow_A\uparrow_B \pm e^{-i\varphi}\uparrow_A\downarrow_B$

Barrett and Kok, PRA 71, 060310 (2005)

PROTOCOL

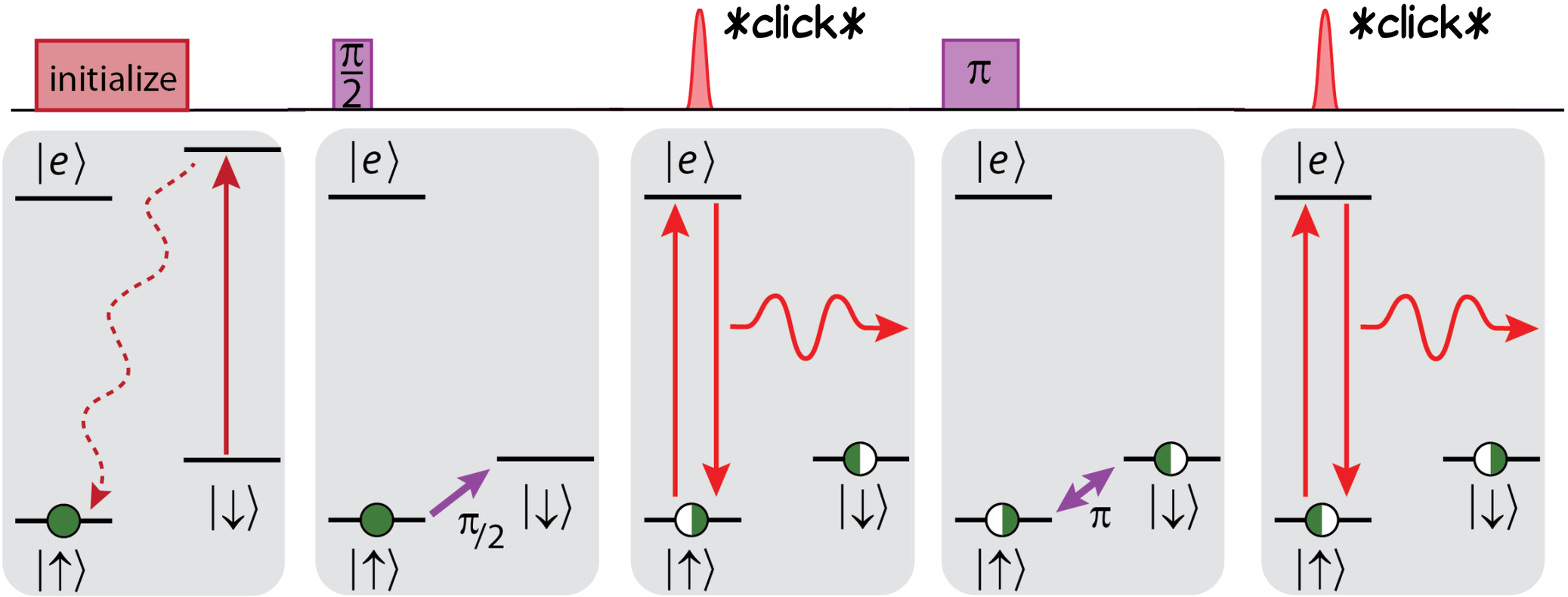


$\downarrow_A\downarrow_B$

$\downarrow_A\uparrow_B \pm e^{-i\varphi}\uparrow_A\downarrow_B$

Barrett and Kok, PRA 71, 060310 (2005)

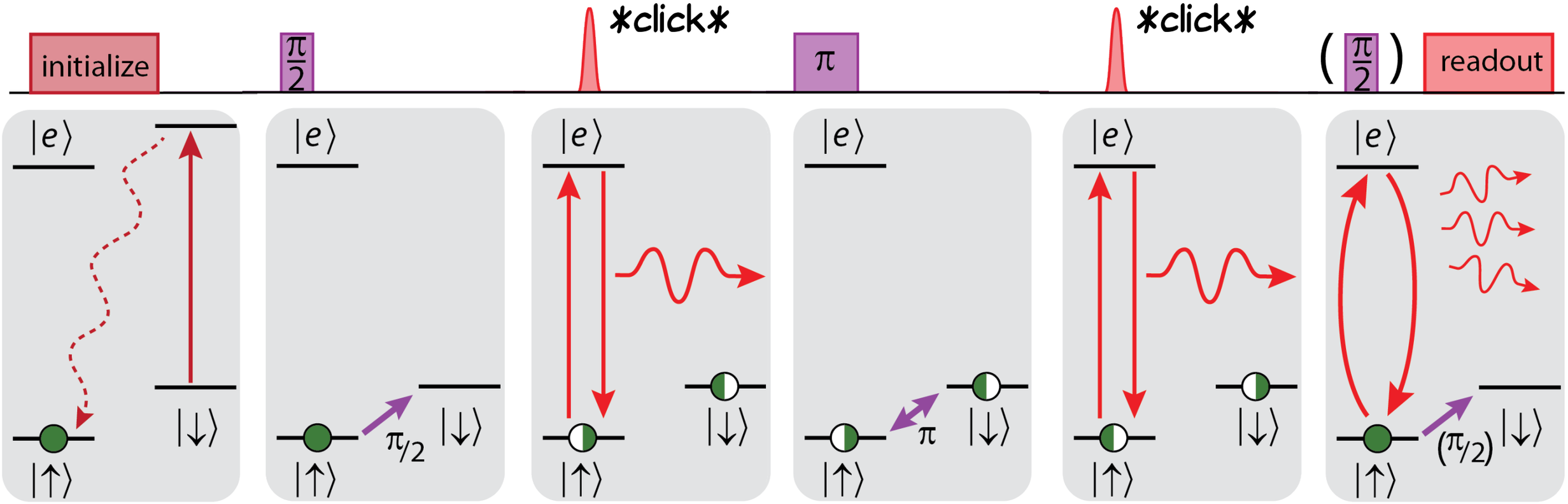
PROTOCOL



$$\downarrow_A\uparrow_B \pm \uparrow_A\downarrow_B$$

Barrett and Kok, PRA 71, 060310 (2005)

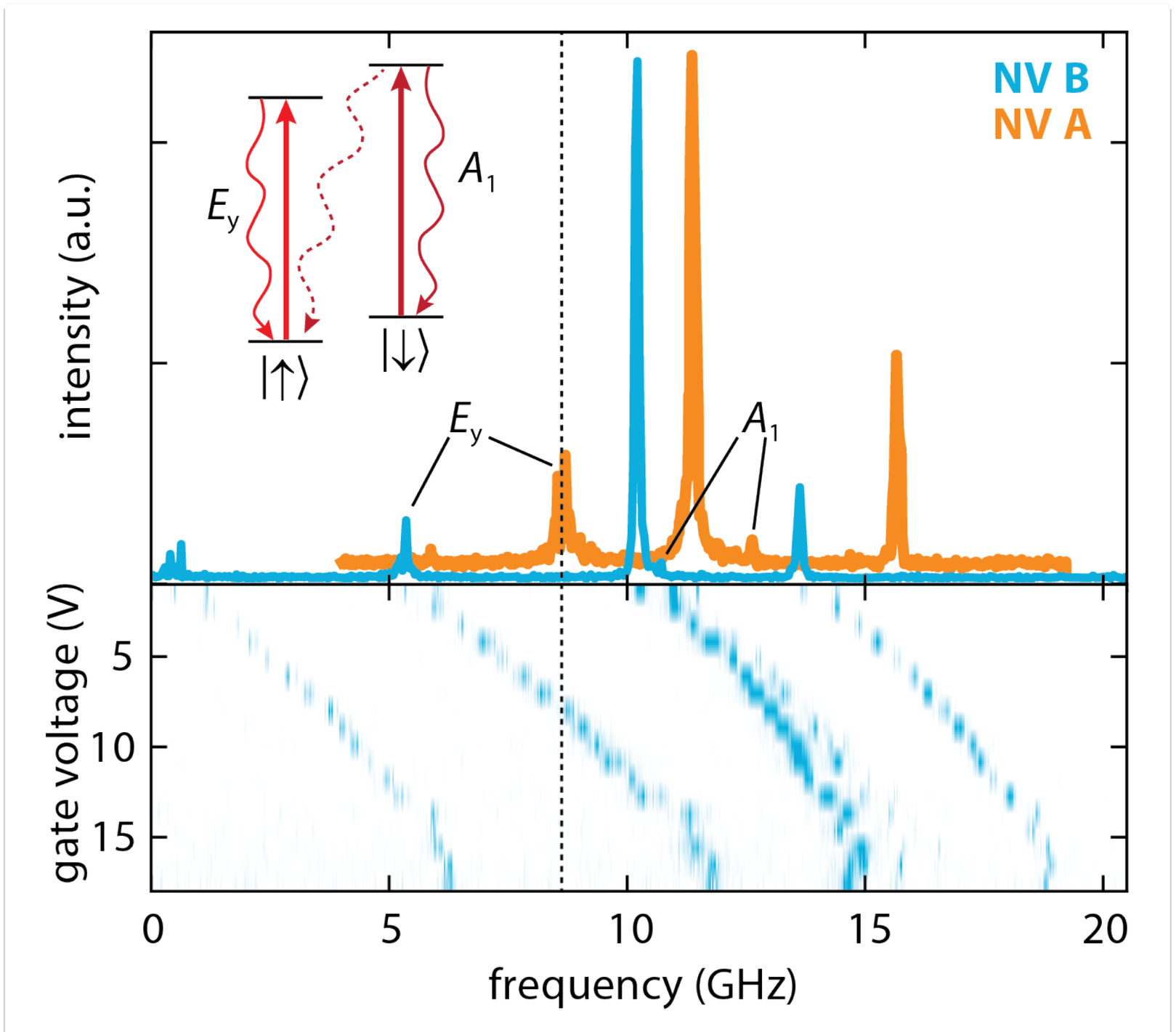
PROTOCOL

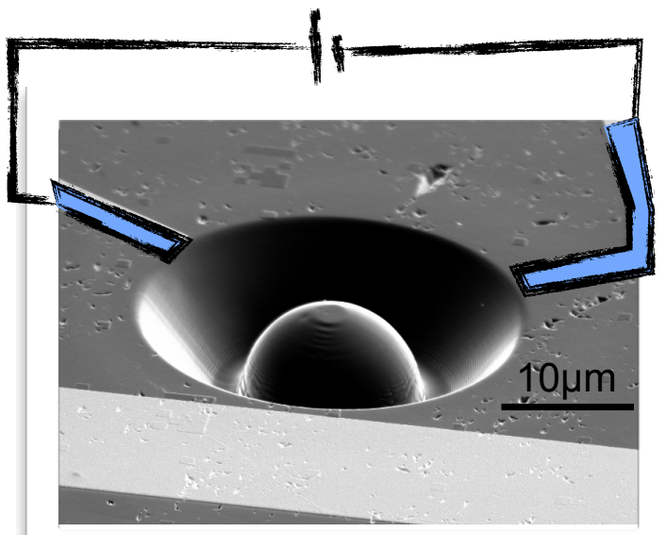


$$\downarrow_A\uparrow_B \pm \uparrow_A\downarrow_B$$

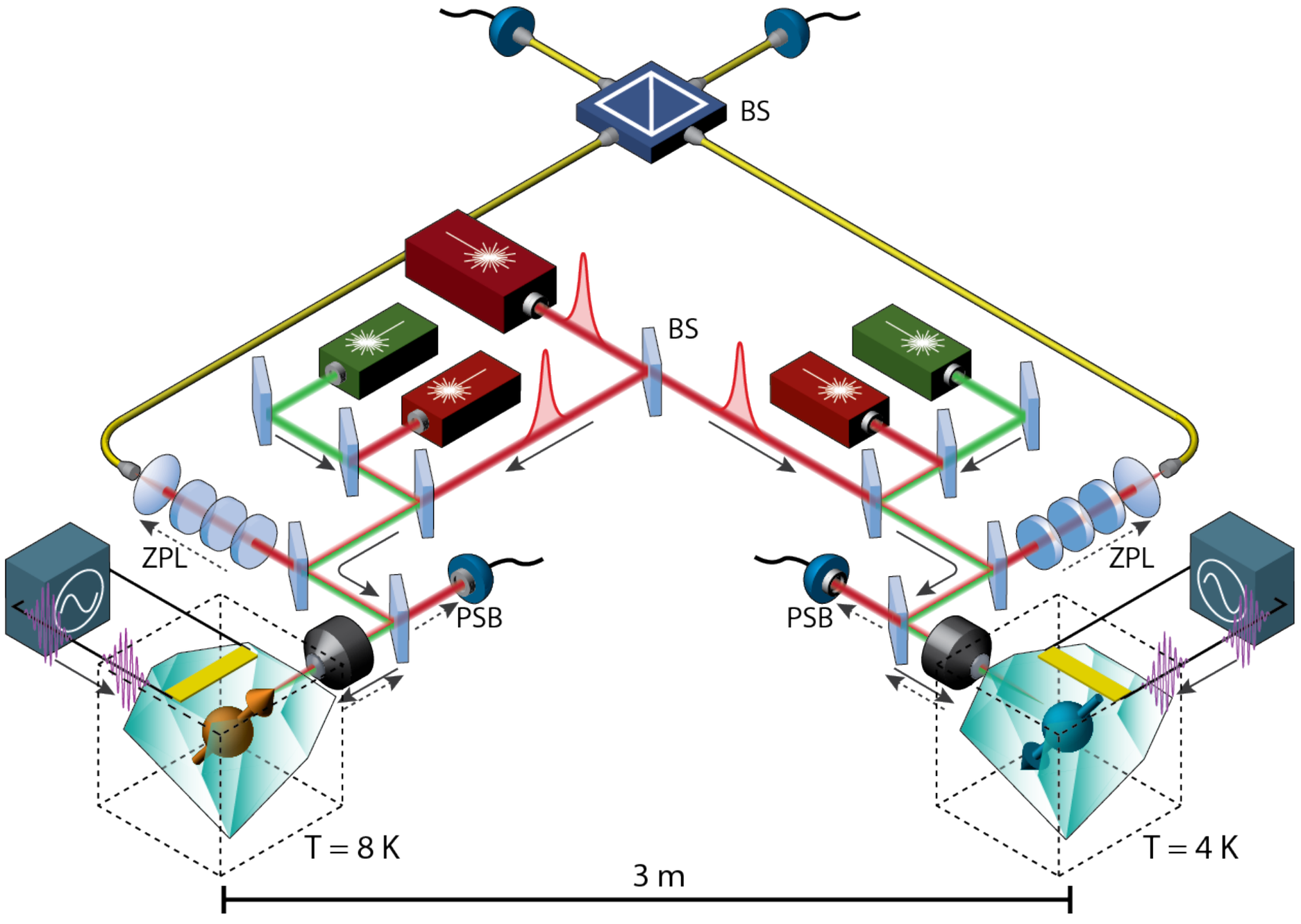
Barrett and Kok, PRA 71, 060310 (2005)

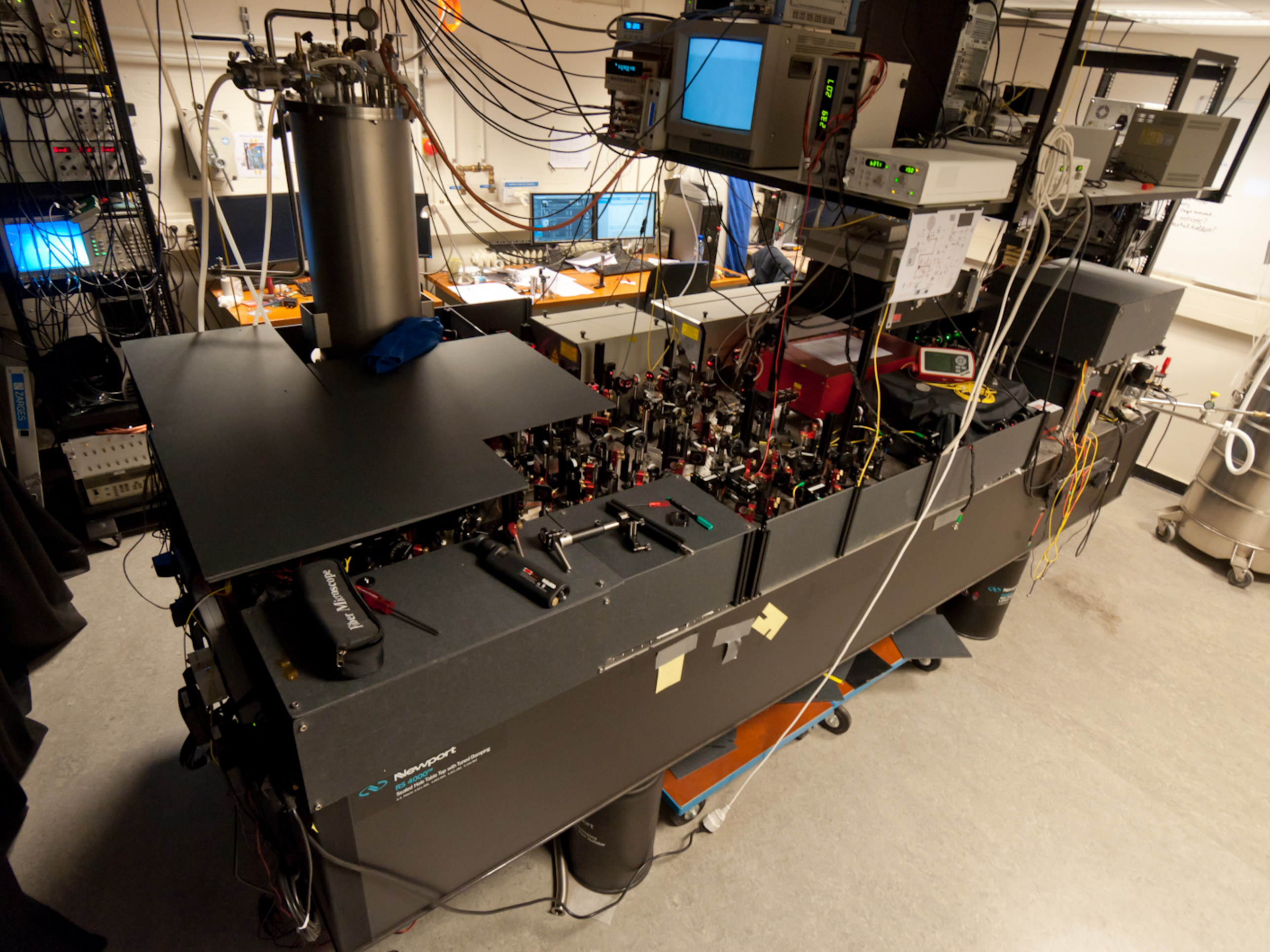
INDISTINGUISHABLE PHOTONS: STARK TUNING





SETUP



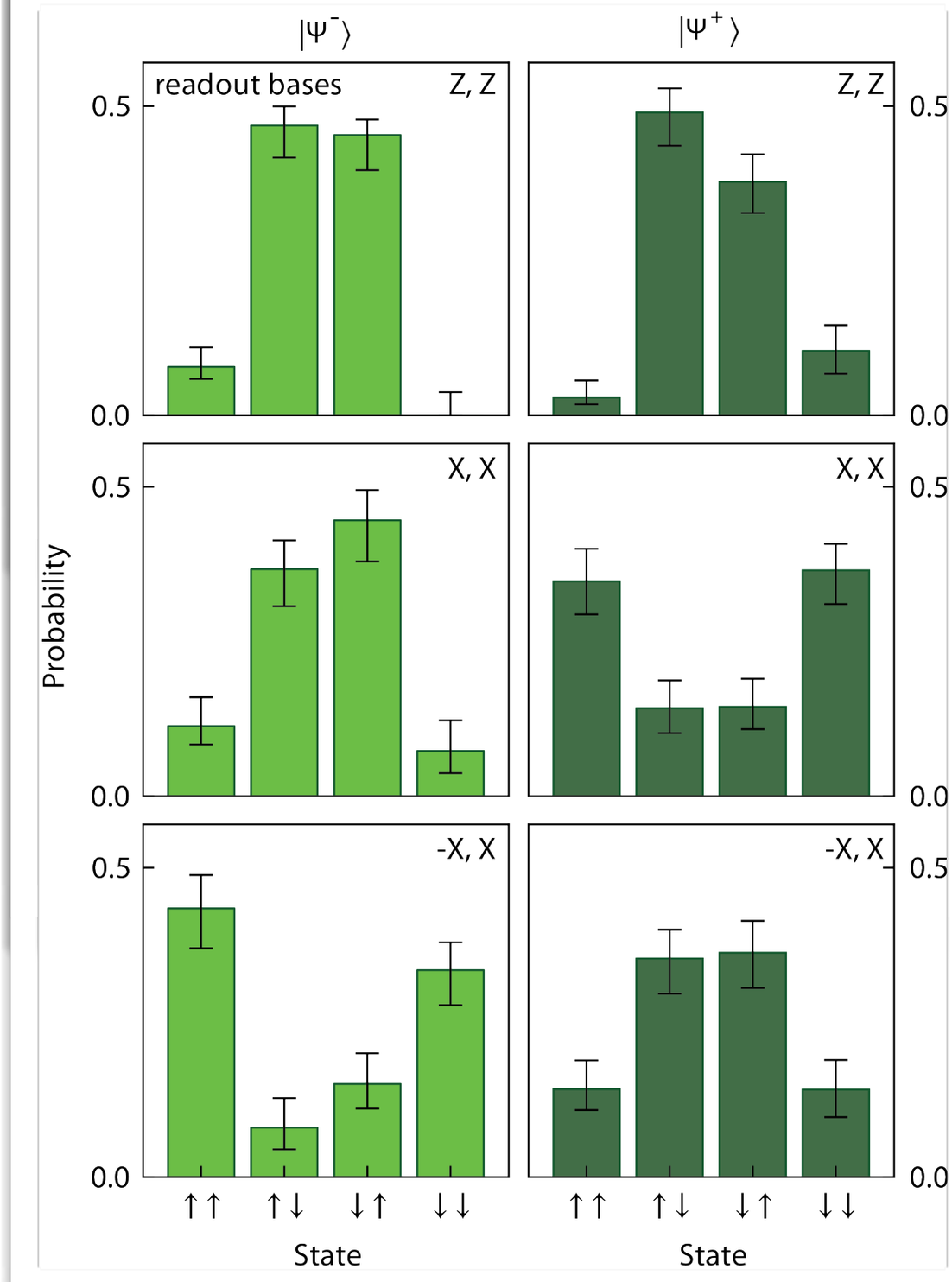

Fiber Microscope
Newport
RS 4000™

success-probability: ~ 1e-7
event rate: ~ 1/10 mins
for ~ 1000 events: 160 hrs

RESULT

$|\Psi^-\rangle = 1/\sqrt{2}\,(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$

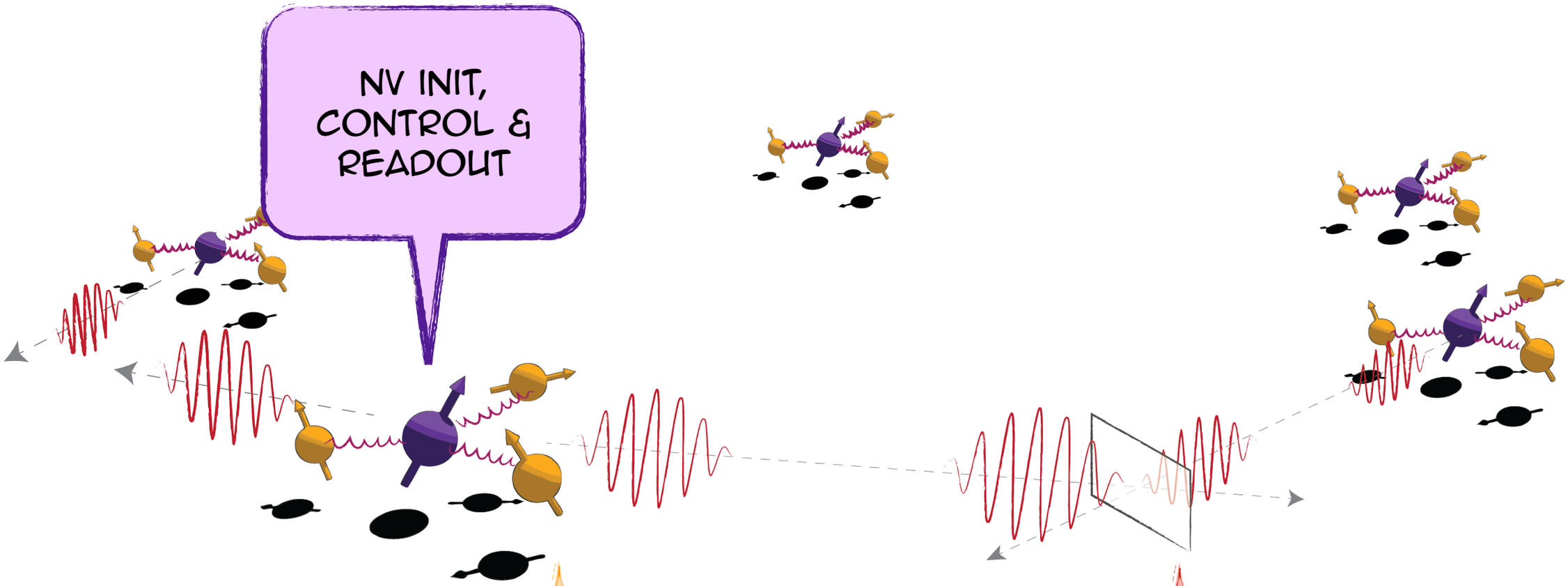
Bell state fidelity
F ~ (73±4)%
F > (69±5)%



$|\Psi^+\rangle = 1/\sqrt{2}\,(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)$

Bell state fidelity
F ~ (64±5)%
F > (58±6)%

Bernien et al, Nature 497, 89 (2013)



ENTANGLEMENT IN A NUCLEAR SPIN QUANTUM REGISTER

Pfaff et al,
Nature Physics 9, 29 (2013)

ENTANGLEMENT OF TWO SPINS AT A DISTANCE OF 3 M

Bernien et al,
Nature 497, 89 (2013)

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SAMPLES: ELEMENT 6

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