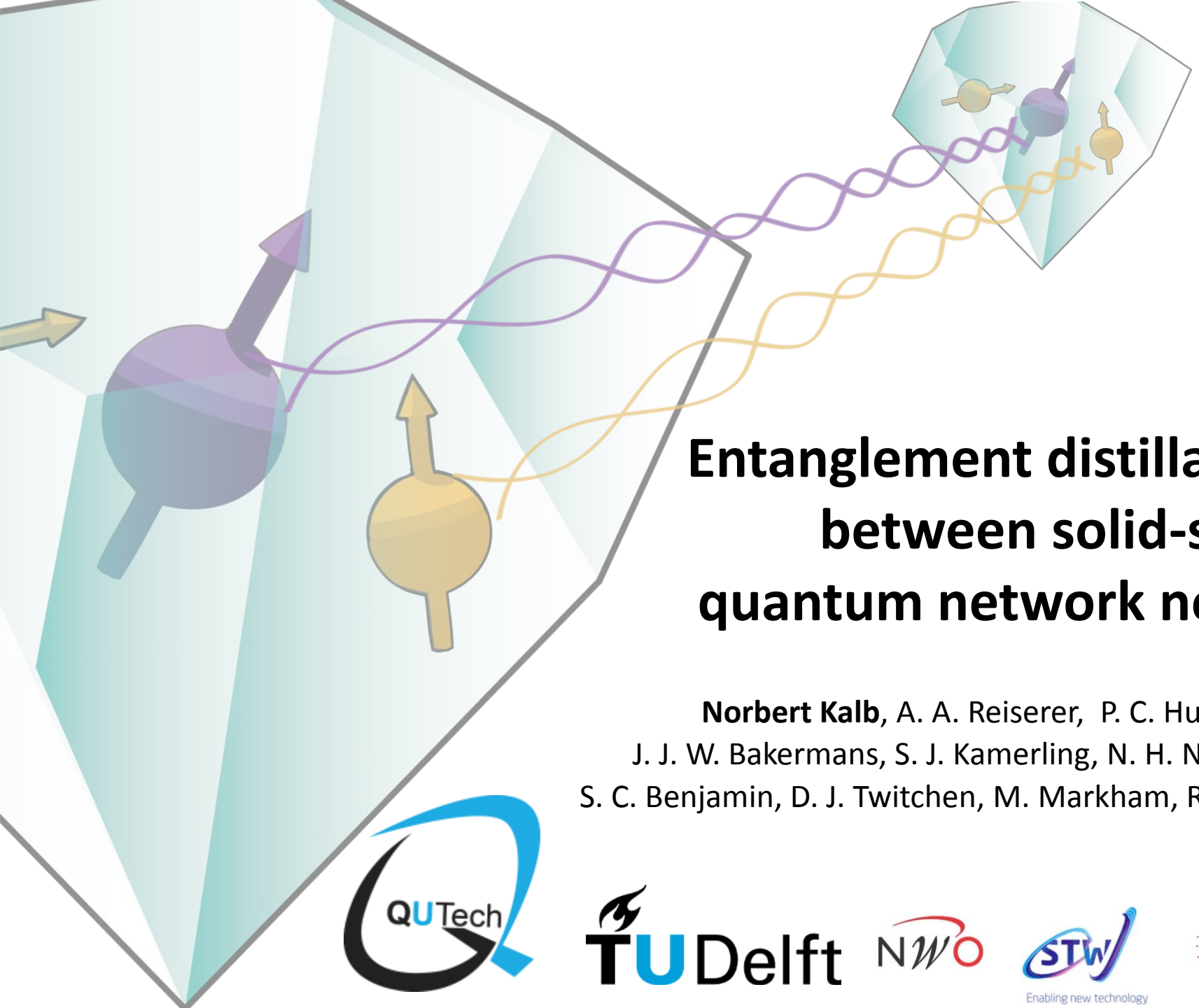


Entanglement distillation between solid-state quantum network nodes

Norbert Kalb, A. A. Reiserer, P. C. Humphreys, J. J. W. Bakermans, S. J. Kamerling, N. H. Nickerson, S. C. Benjamin, D. J. Twitchen, M. Markham, R. Hanson

QUTech

TU Delft

NWO

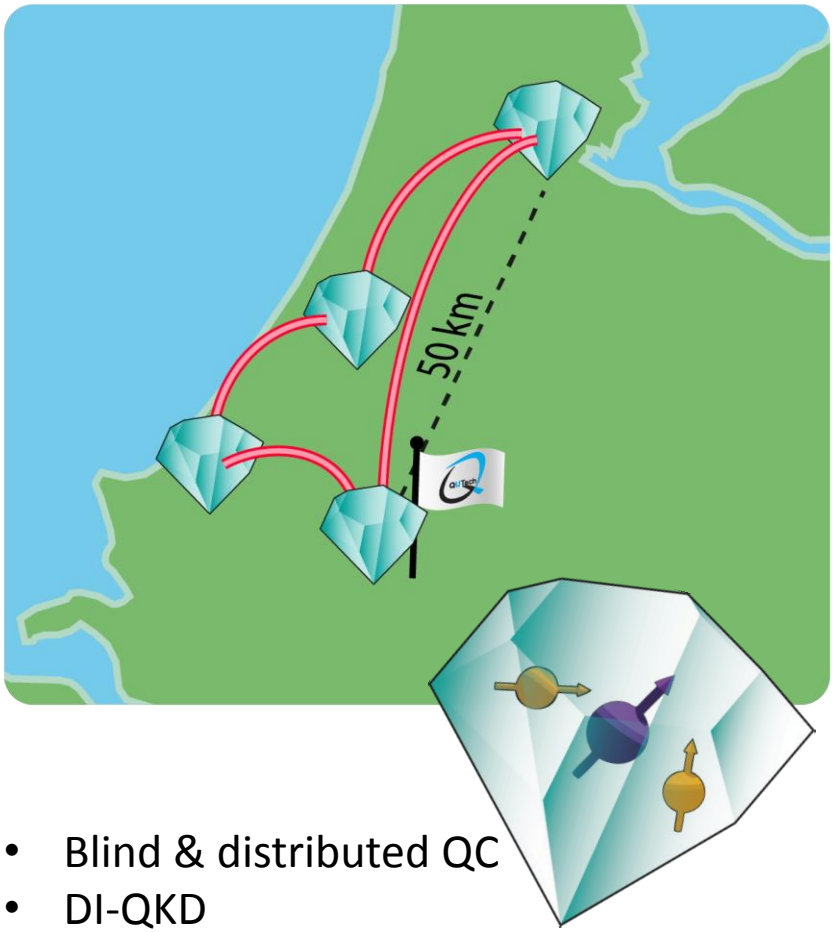
STW

Enabling new technology

erc

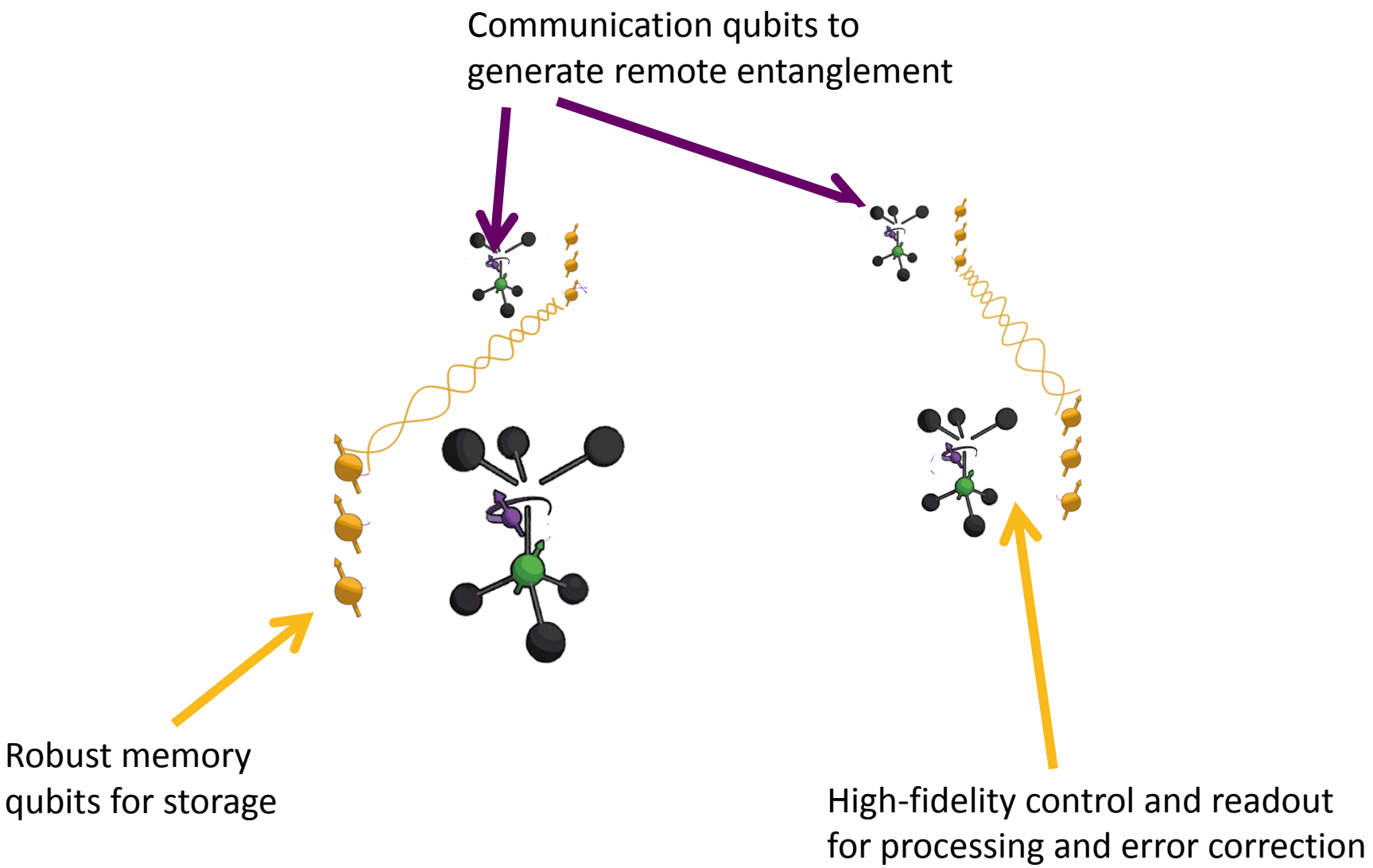
Our ambition: a first quantum internet

Collaboration between experimental physicists, theorists, material scientists, engineering support…



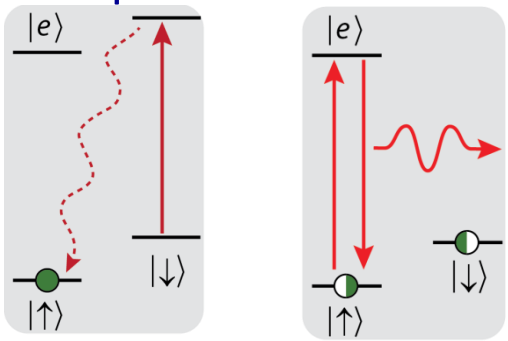
- Blind & distributed QC
- DI-QKD
- Metrology applications
- …

A diamond-based quantum network



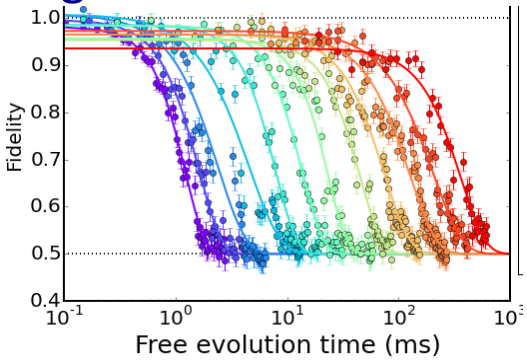
Why NV centres?

Optical interface



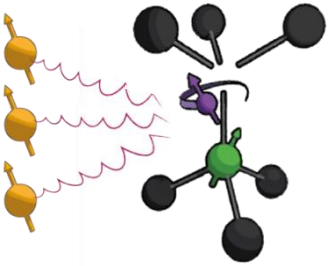
Nature 477 (2011)

Long coherence times ~1 *s*



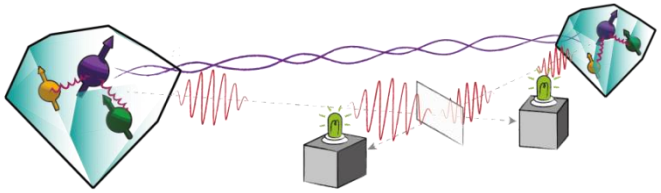
unpublished

Nuclear spin quantum register



Nat. Nano. 9 (2014); PRX (2016);
Nat. Commun. 7 (2016)

Remote entanglement

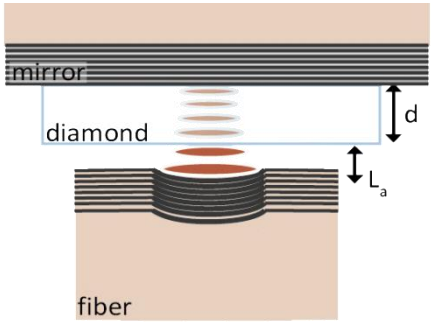


Nature 497 (2013); Science 345(2014);
Nature 526 (2015); Scient. Rep. 6, 30289 (2016)

Many related works by Stuttgart, Harvard, Chicago, Ulm,…

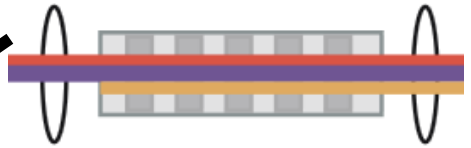
Diamond networks: A to-do list

Optical cavities:
expect rate x1000

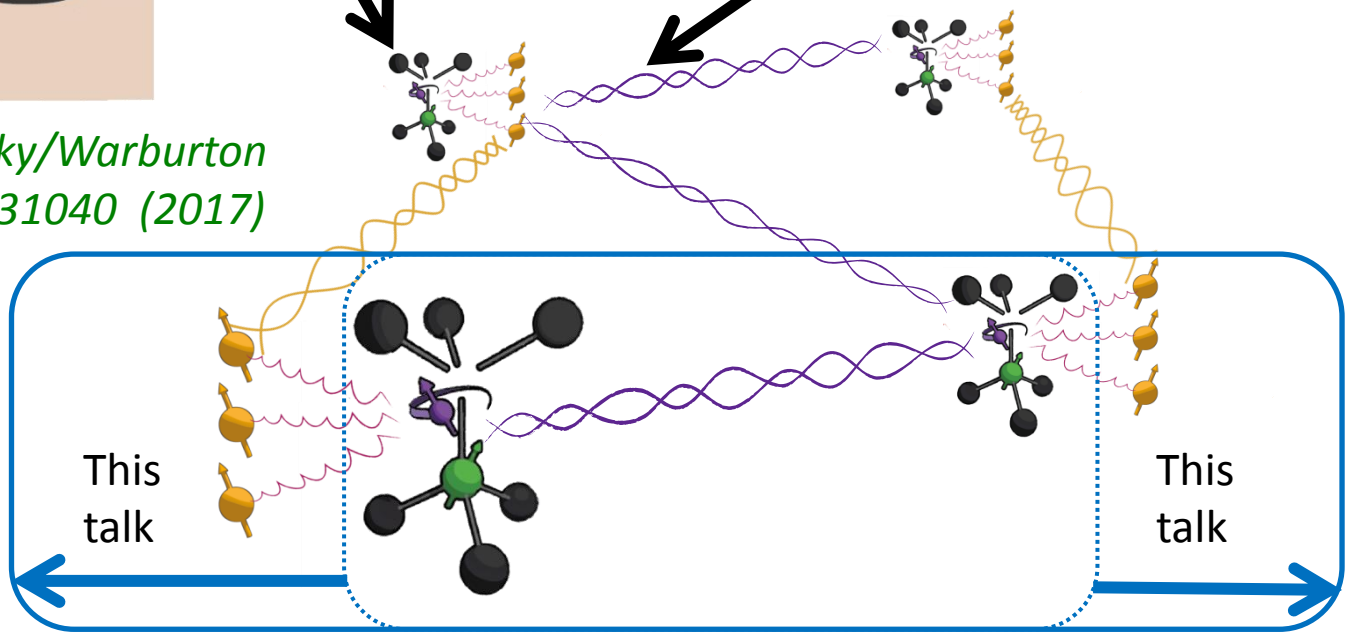


Maletinsky/Warburton
PRX 7, 031040 (2017)

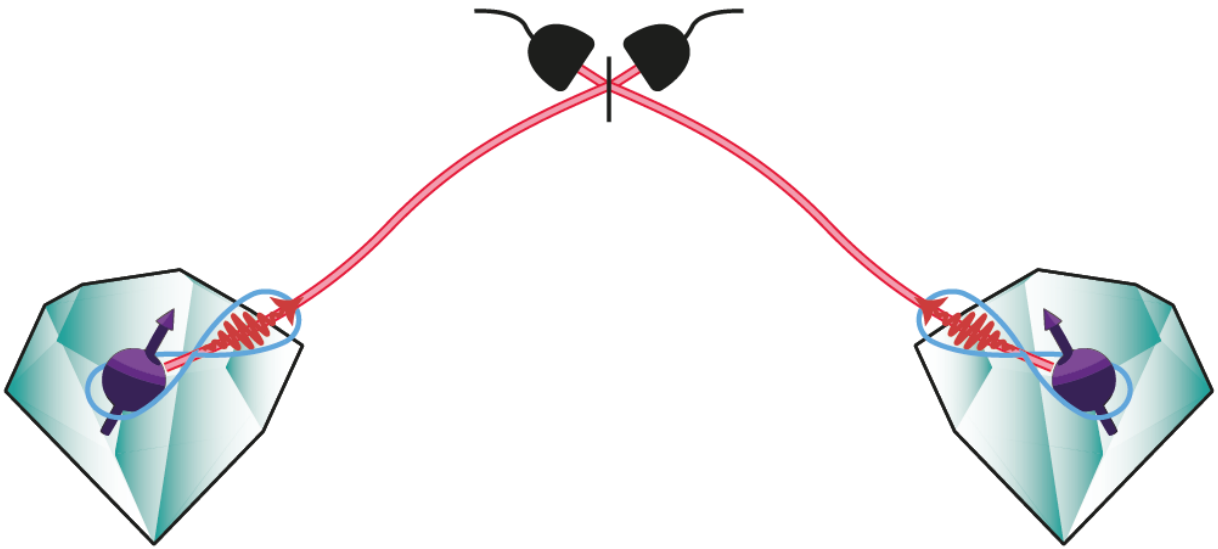
Telecom wavelength conversion

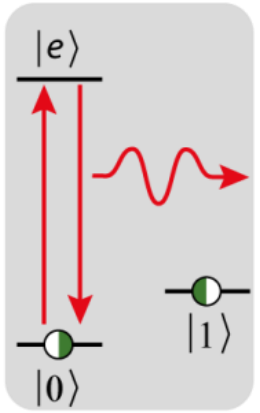


Zaske et al. PRL 109, 147404 (2012)

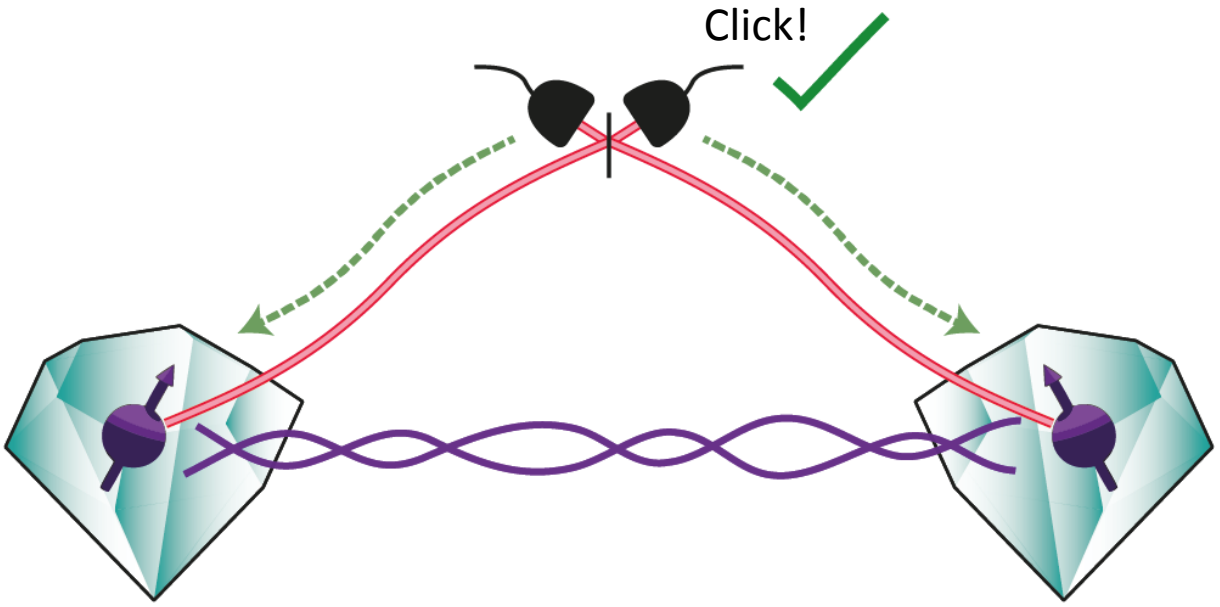


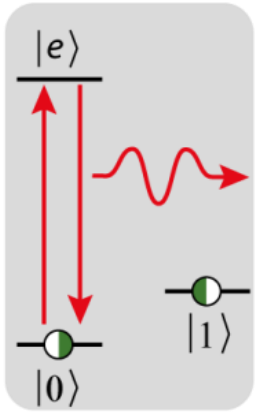
Wiring up the **ideal** quantum internet





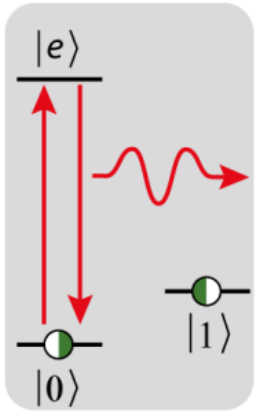
Wiring up the **ideal** quantum internet

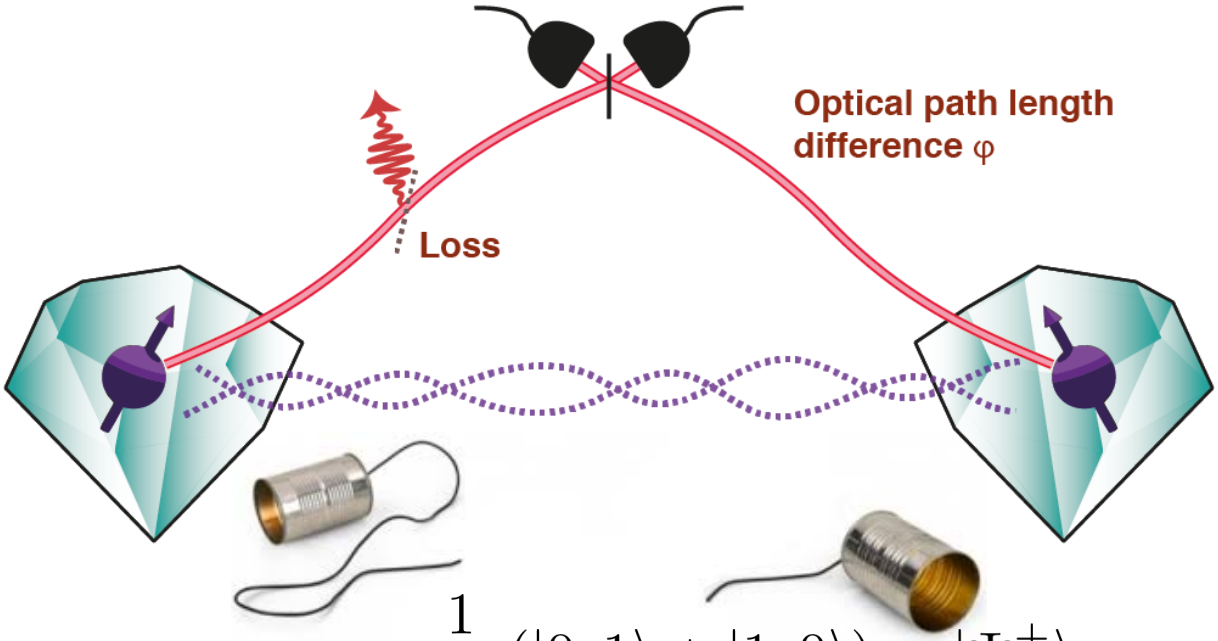




APD CLICK $\rightarrow \frac{1}{\sqrt{2}}(|0,1\rangle + |1,0\rangle) \equiv |\Psi^+\rangle$

Wiring up the **real** quantum internet





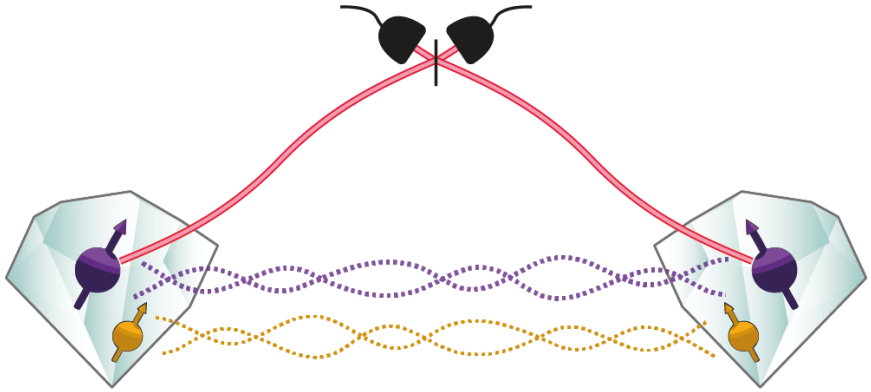
APD CLICK $\rightarrow \frac{1}{\sqrt{2}}(|0,1\rangle + |1,0\rangle) \equiv |\Psi^+\rangle$

APD CLICK $\rightarrow \frac{1}{2}|\Psi^+_\phi\rangle\langle\Psi^+_\phi| + \frac{1}{2}|0,0\rangle\langle 0,0|$

Phase dependent

Mixed state due to loss

Overcoming imperfections: The distillery



≡

Entanglement Distillation

$$2 \times \left(\frac{1}{2} |\Psi_\phi^+\rangle\langle\Psi_\phi^+| + \frac{1}{2} |0,0\rangle\langle 0,0| \right) \rightarrow |\Psi_0^+\rangle\langle\Psi_0^+|$$

Phase dependent Mixed state

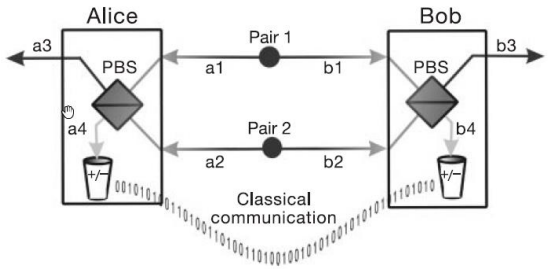
We use: Campbell & Benjamin, PRL **101**, *130502* (2008)

Initial protocols: Bennett et al., PRL (1996); Deutsch et al., PRL (1996)

Entanglement Distillation

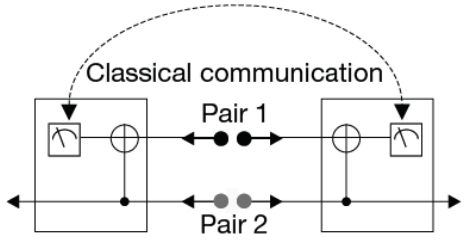
Photonic experiments –
only post-selected

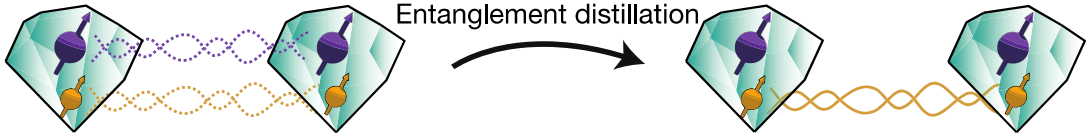
J.-W. Pan et al., *Nature* 423, 417 (2003)



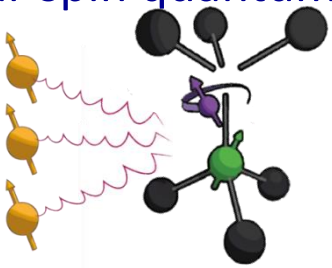
Trapped ions
local distillation within 1 trap

R. Reichle et al., *Nature* 443, 838 (2006)

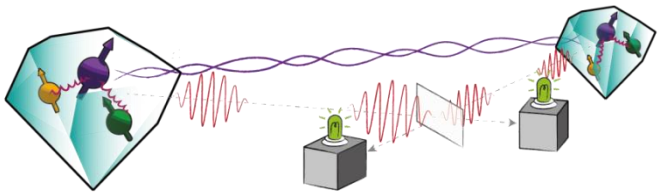




Nuclear spin quantum register

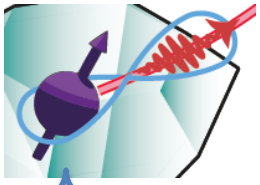


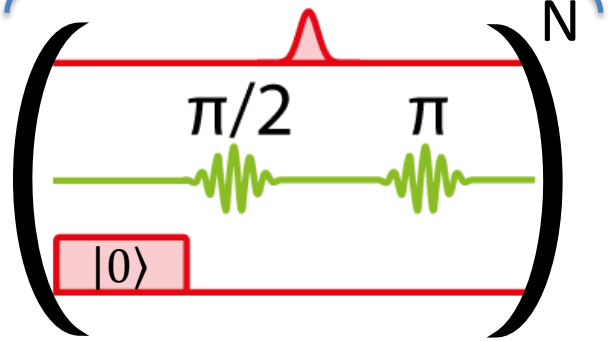
Remote entanglement



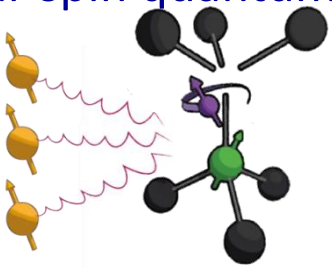
Always-on interactions

Entanglement generation sequence

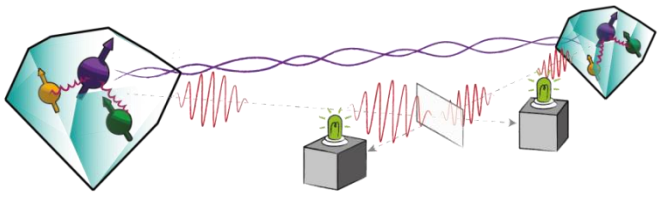




Nuclear spin quantum register

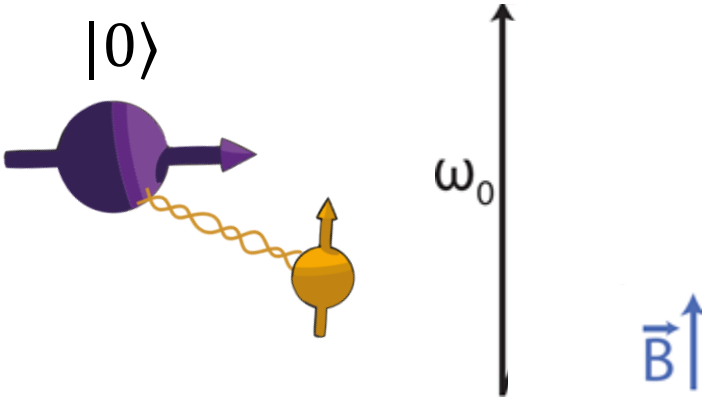


Remote entanglement

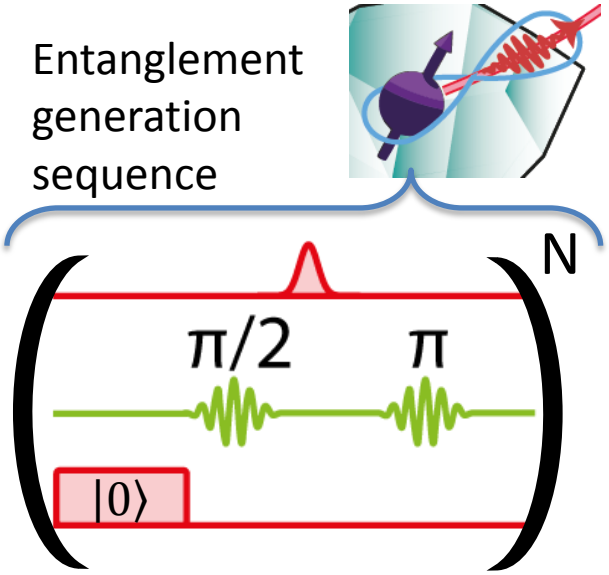


Always-on interactions

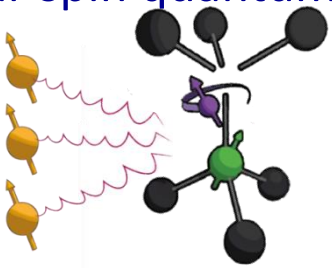
State dependent frequency
of the nuclear spin memory



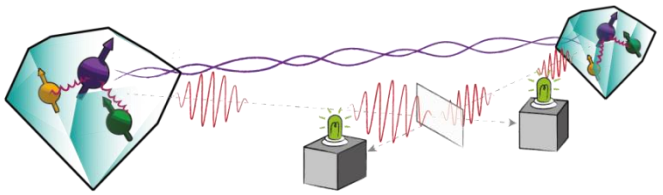
Entanglement
generation
sequence



Nuclear spin quantum register

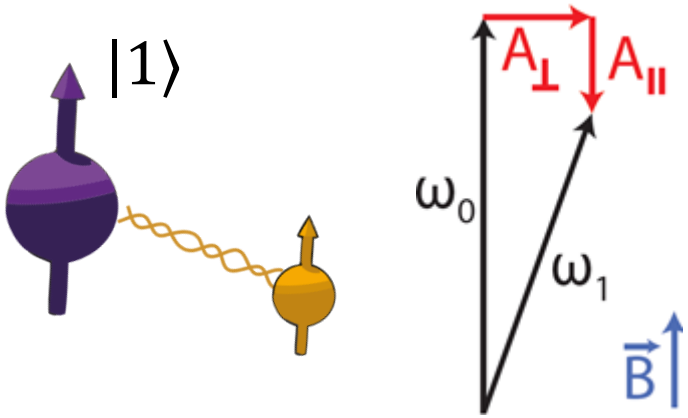


Remote entanglement

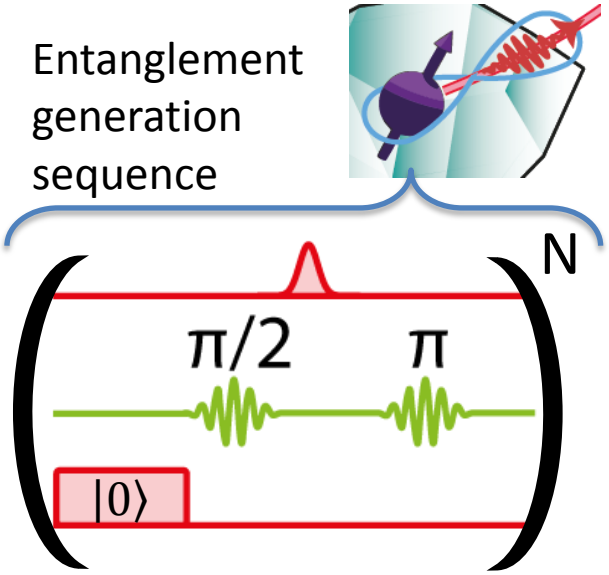


Always-on interactions

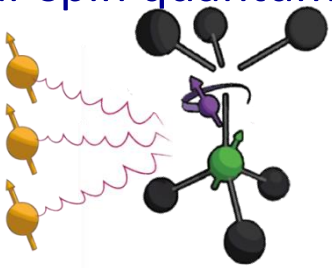
State dependent frequency
of the nuclear spin memory



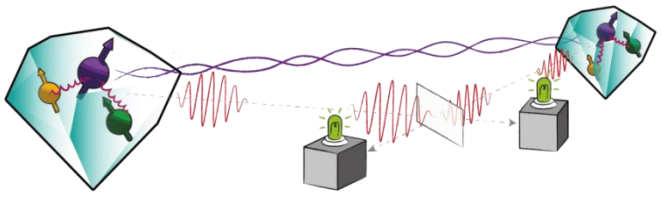
Entanglement
generation
sequence



Nuclear spin quantum register

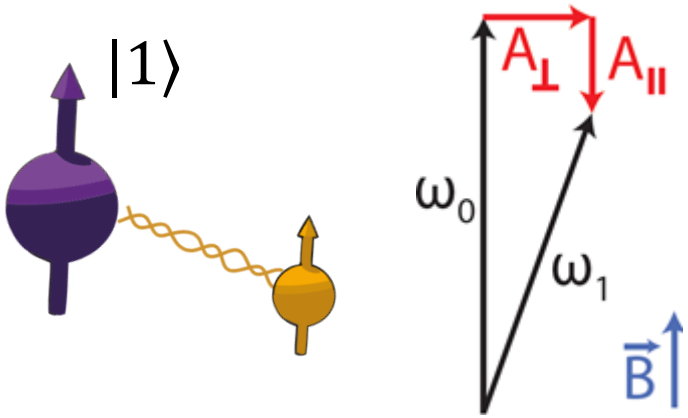


Remote entanglement

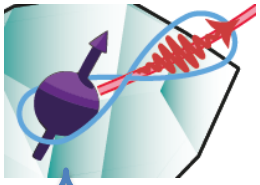


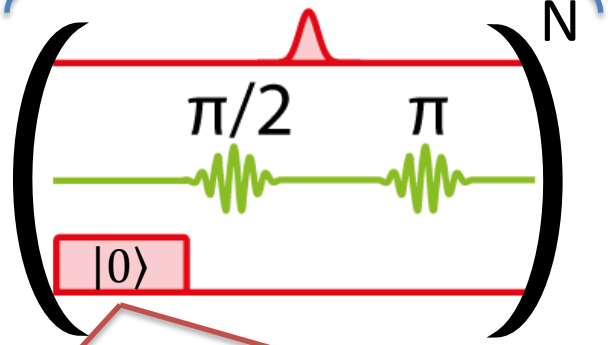
Always-on interactions

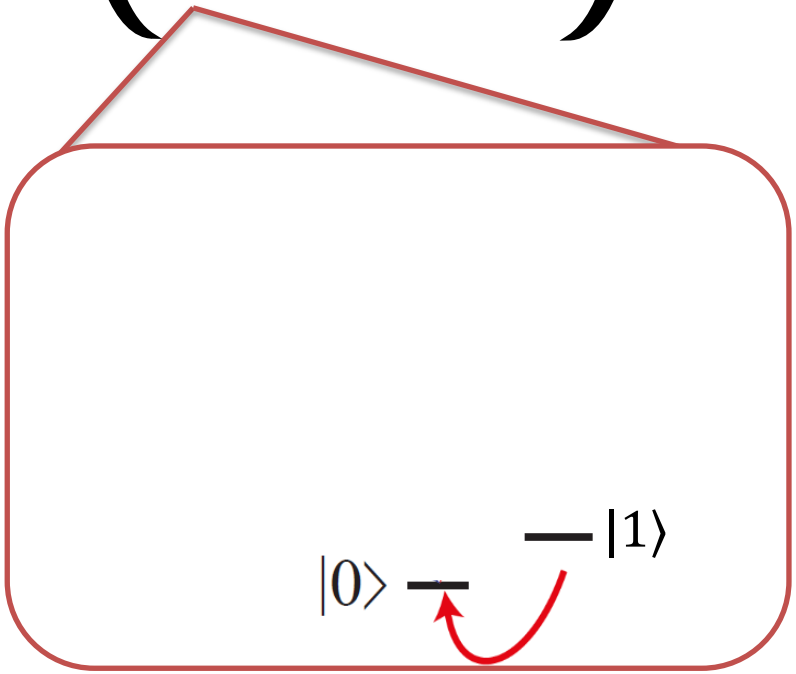
State dependent frequency
of the nuclear spin memory



Entanglement
generation
sequence



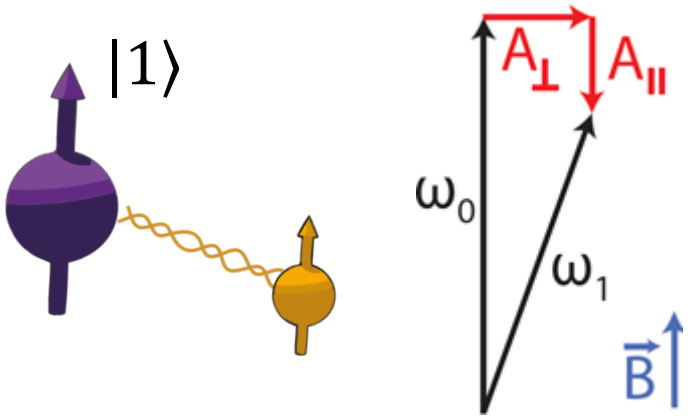




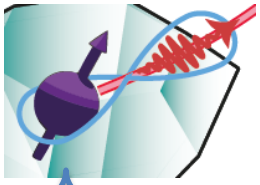
Reiserer*, NK*, et al., *PRX* **6**, 021040 (2016)

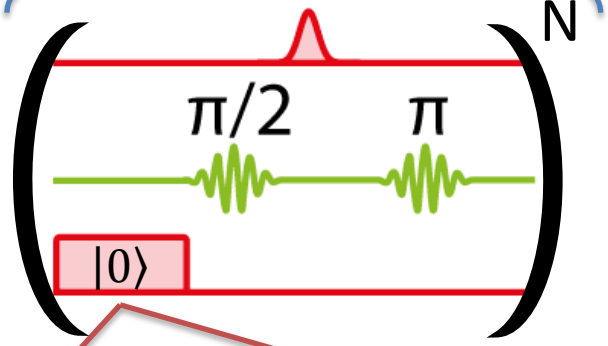
Always-on interactions

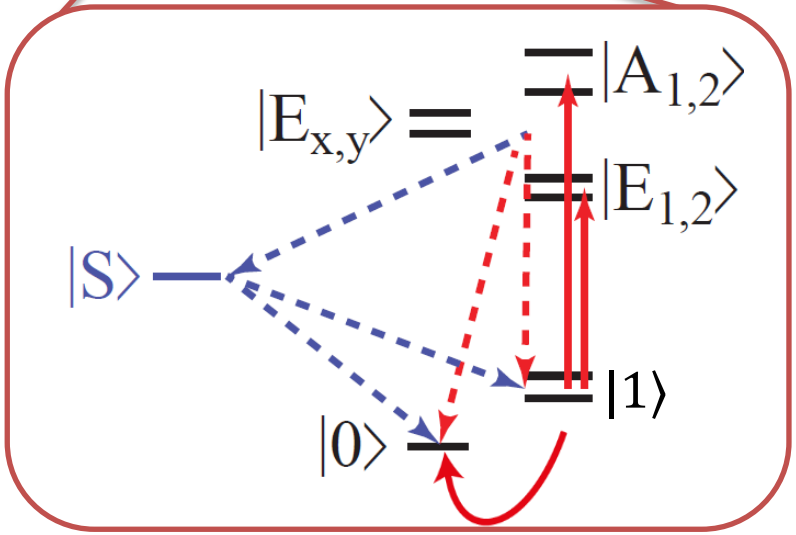
State dependent frequency
of the nuclear spin memory



Entanglement
generation
sequence







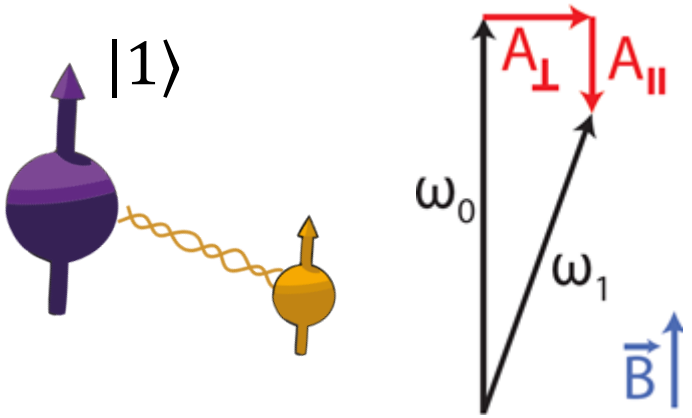
Reinitialization:
Complicated and probabilistic evolution
NV occupies spin states randomly

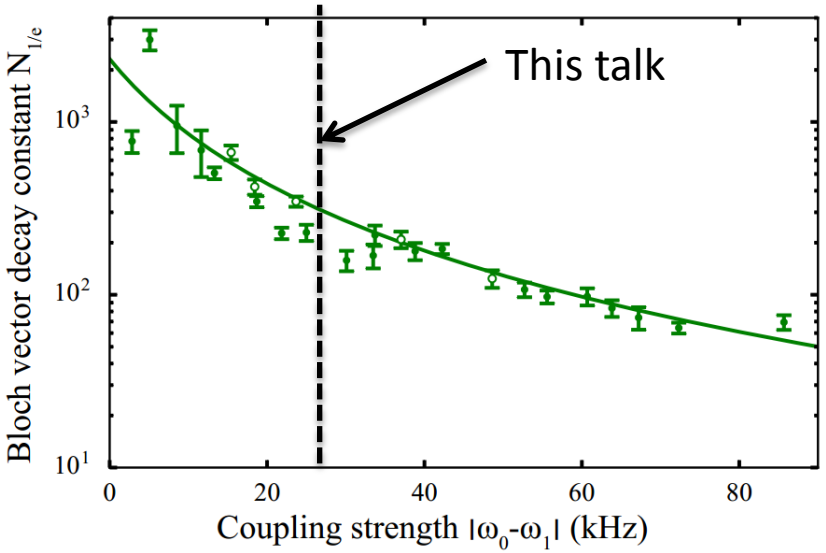
→ Causes nuclear dephasing

Reiserer*, NK*, et al., *PRX* **6**, 021040 (2016)

Always-on interactions

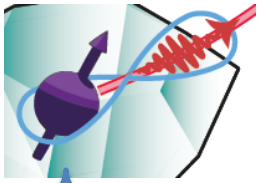
State dependent frequency
of the nuclear spin memory

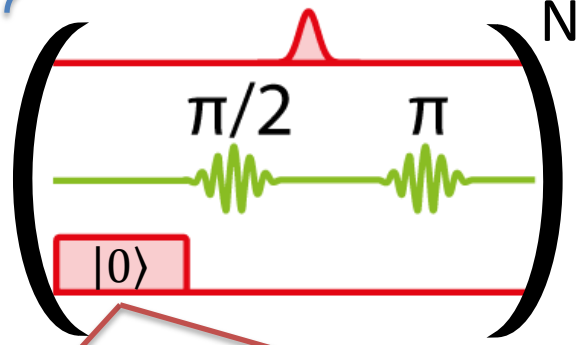


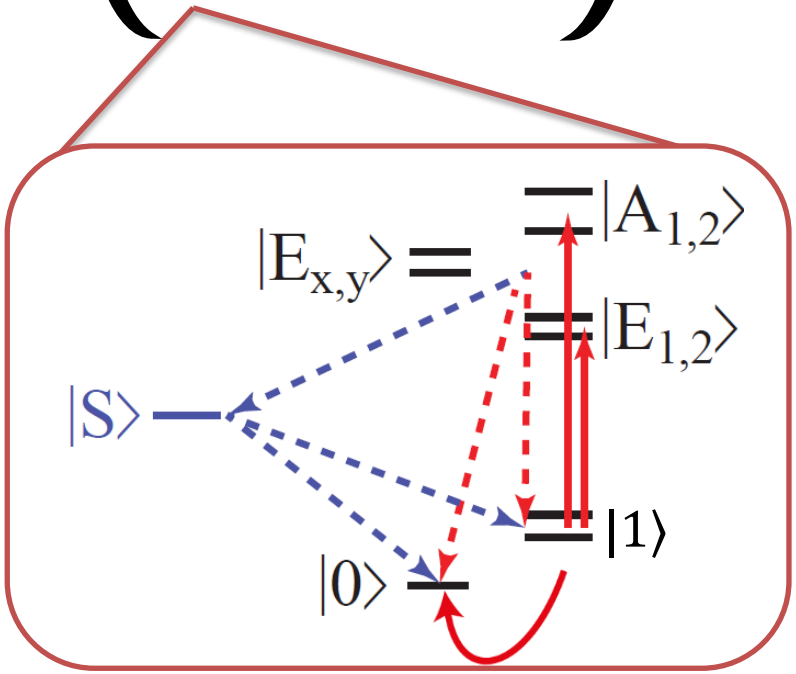


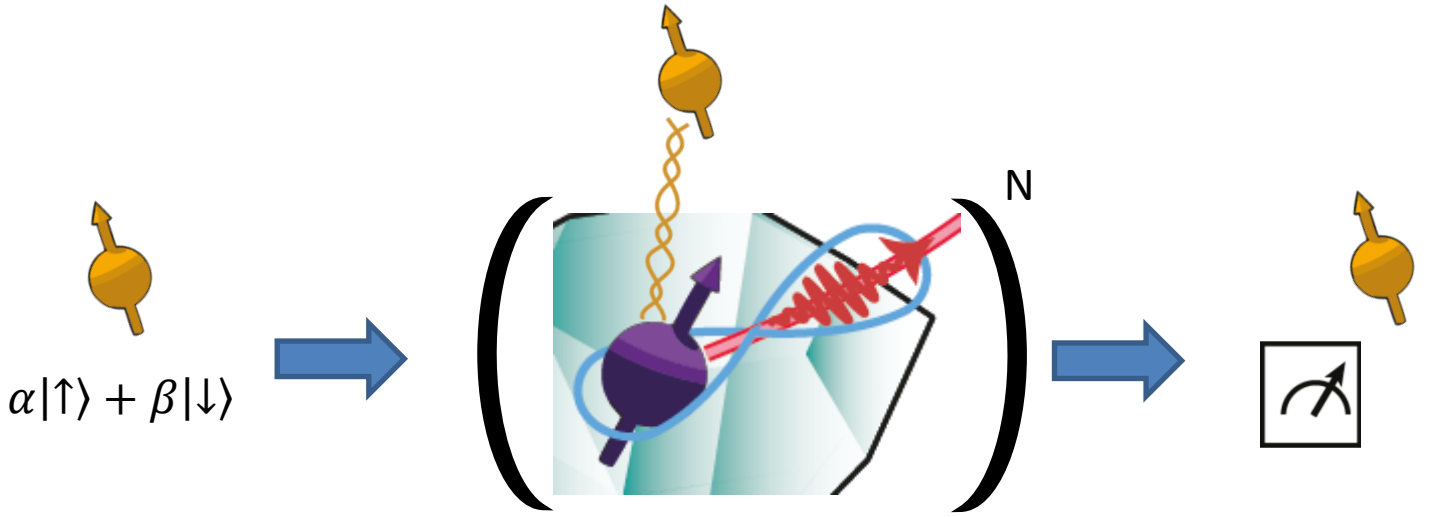
Reiserer*, NK*, et al., PRX **6**, 021040 (2016)

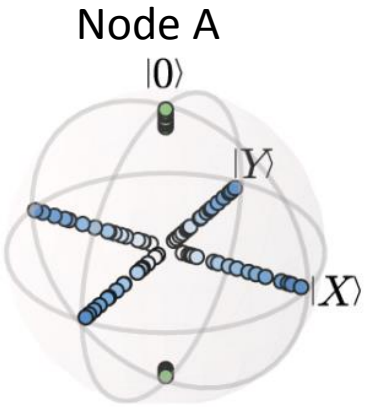
Entanglement
generation
sequence

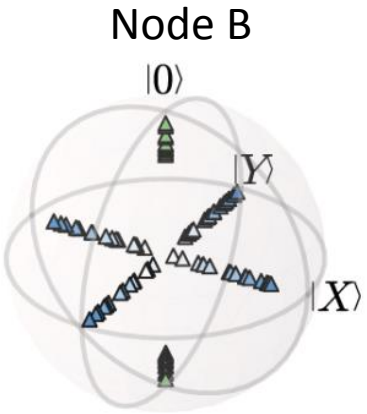


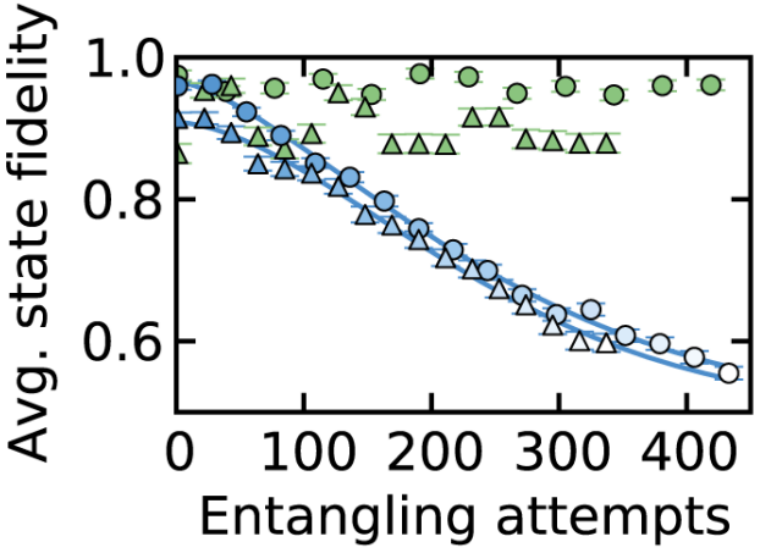





$\alpha|\uparrow\rangle + \beta|\downarrow\rangle$
N

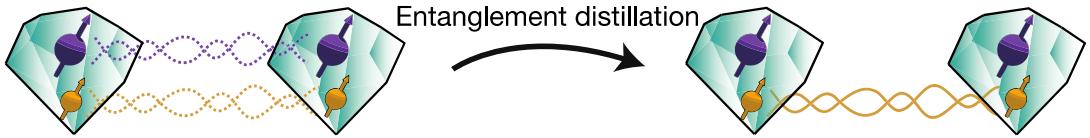

Node A
$|0\rangle$
$|Y\rangle$
$|X\rangle$

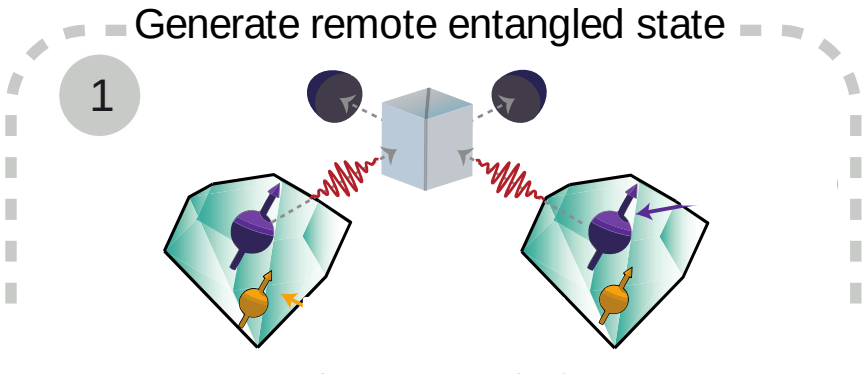

Node B
$|0\rangle$
$|Y\rangle$
$|X\rangle$


Avg. state fidelity
1.0
0.8
0.6
0
100
200
300
400
Entangling attempts

Distillation experiment

Science 356, 928 (2017)



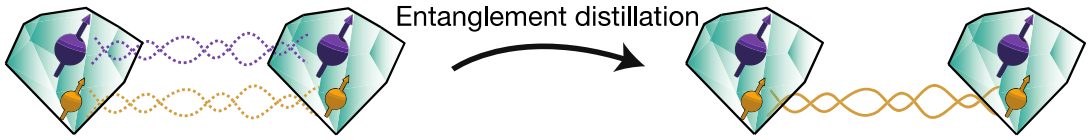


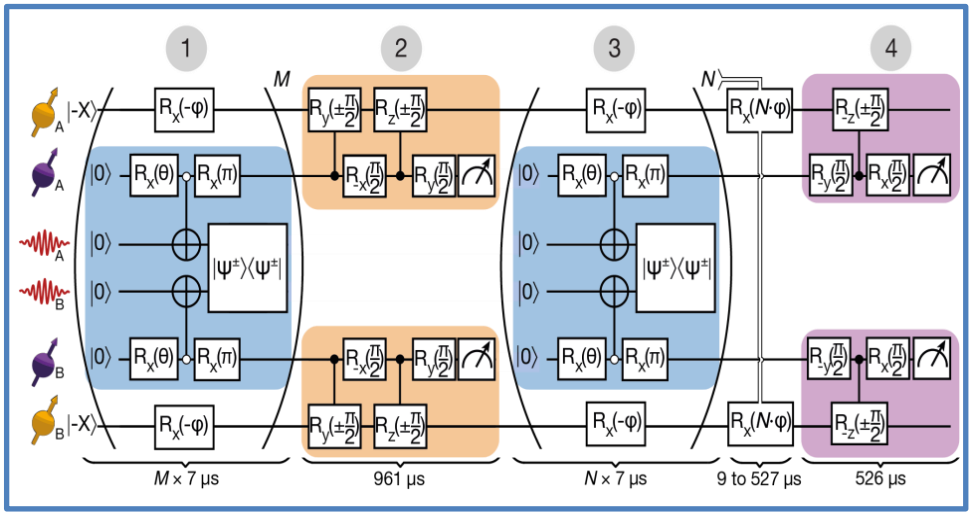
2m

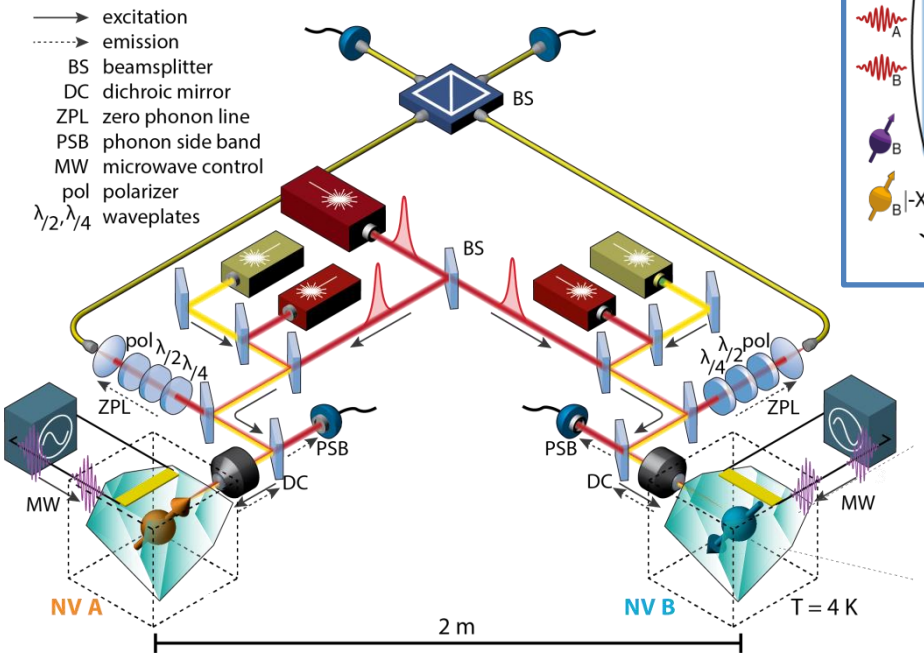
2m

Distillation experiment

Science 356, 928 (2017)

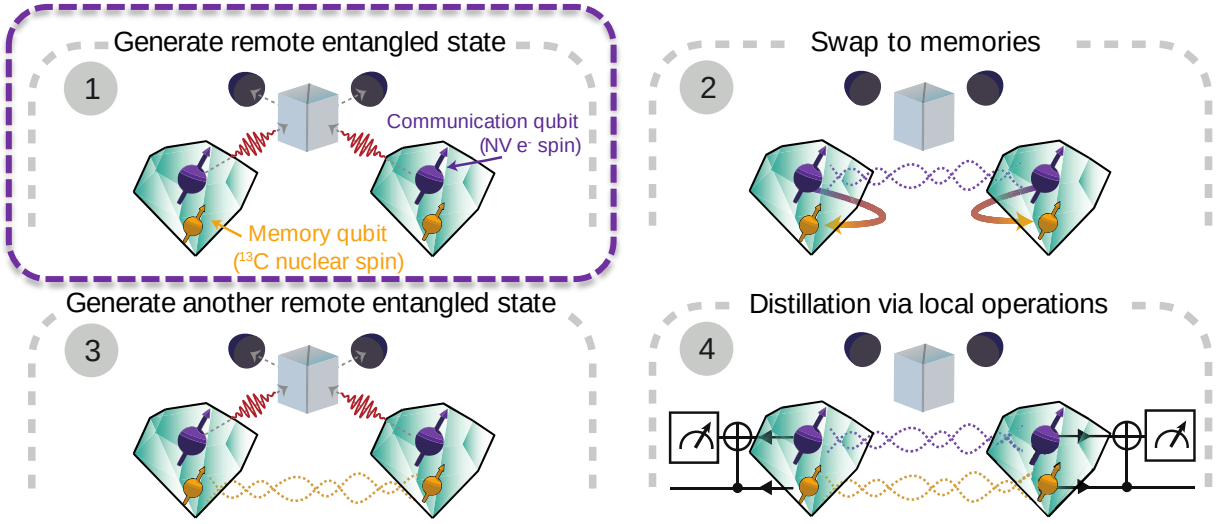


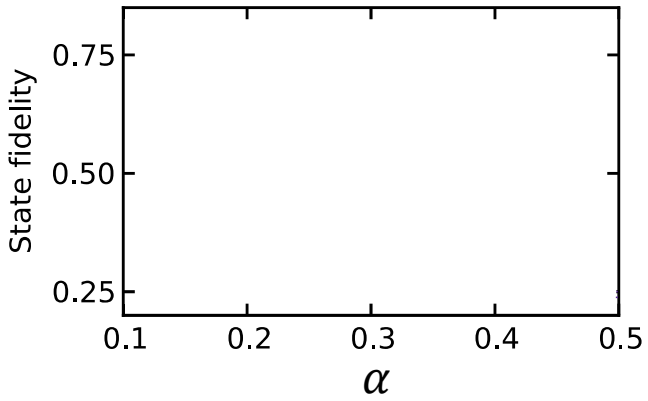




Distillation experiment

Science 356, 928 (2017)



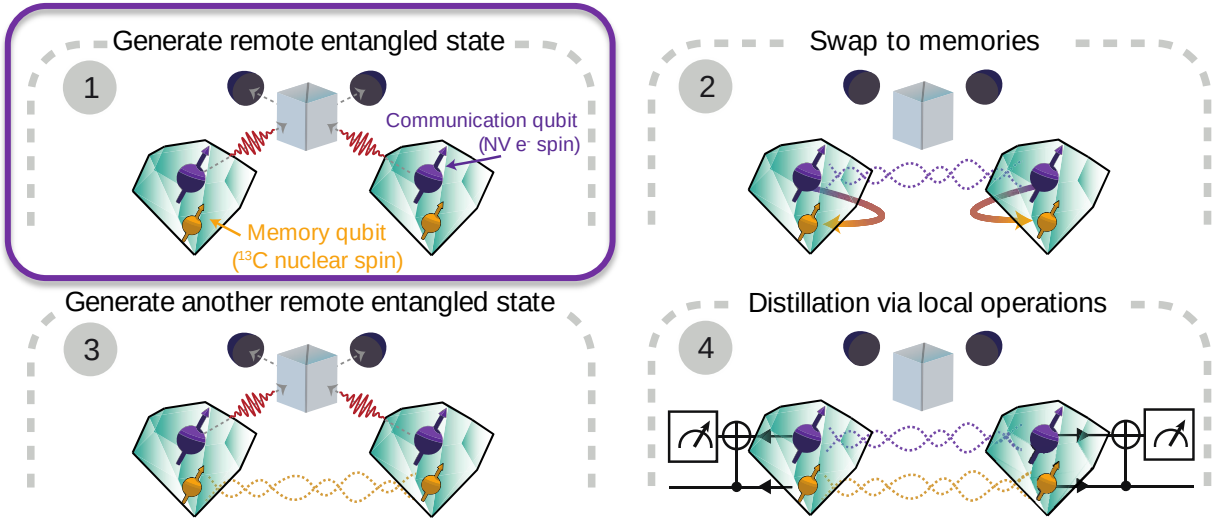


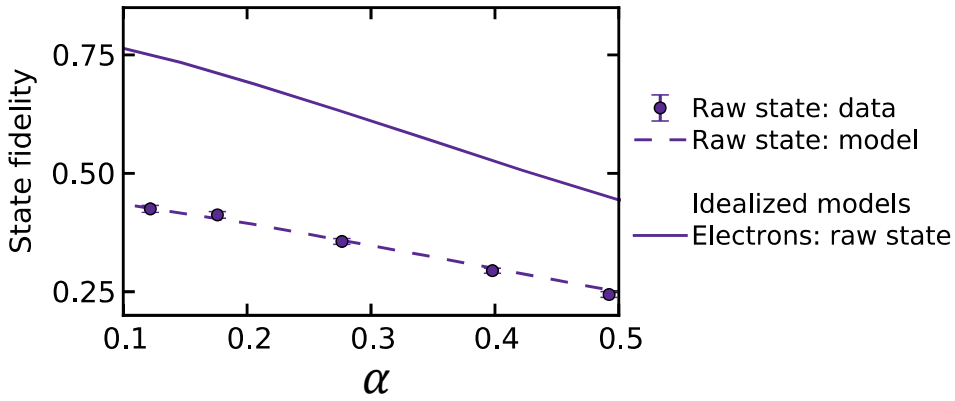
Raw state is of the form:

$$(1-\alpha)|\Psi_{\phi}^{\pm}\rangle\langle\Psi_{\phi}^{\pm}|+\alpha|0,0\rangle\langle 0,0|$$

Distillation experiment

Science 356, 928 (2017)



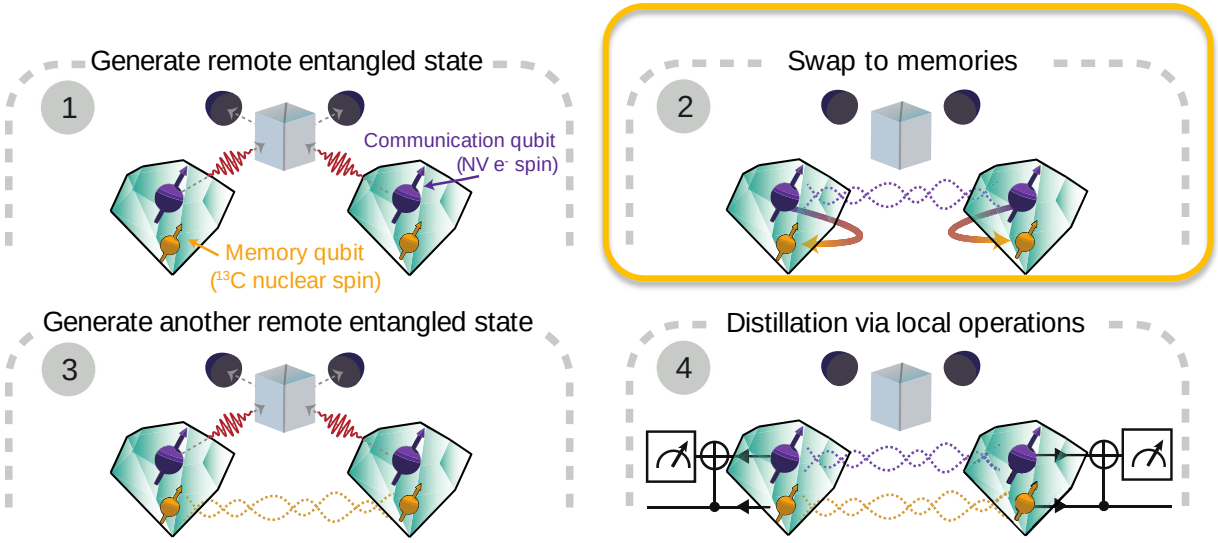


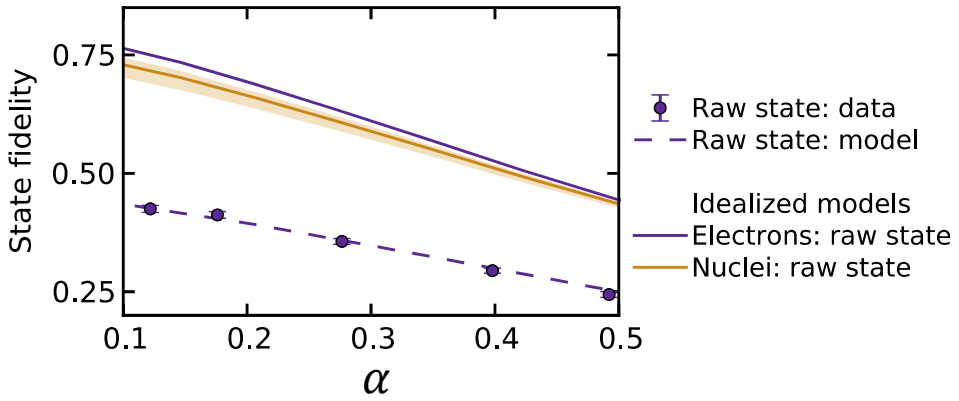
Raw state is of the form:

$$(1-\alpha)|\Psi_{\phi}^{\pm}\rangle\langle\Psi_{\phi}^{\pm}|+\alpha|0,0\rangle\langle 0,0|$$

Distillation experiment

Science 356, 928 (2017)



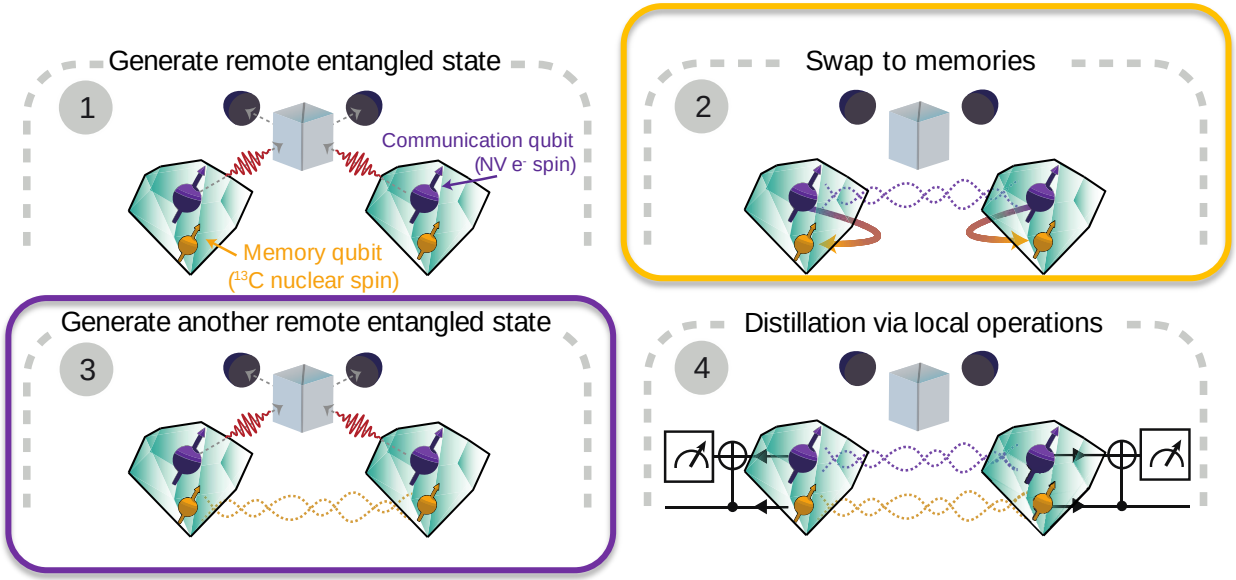


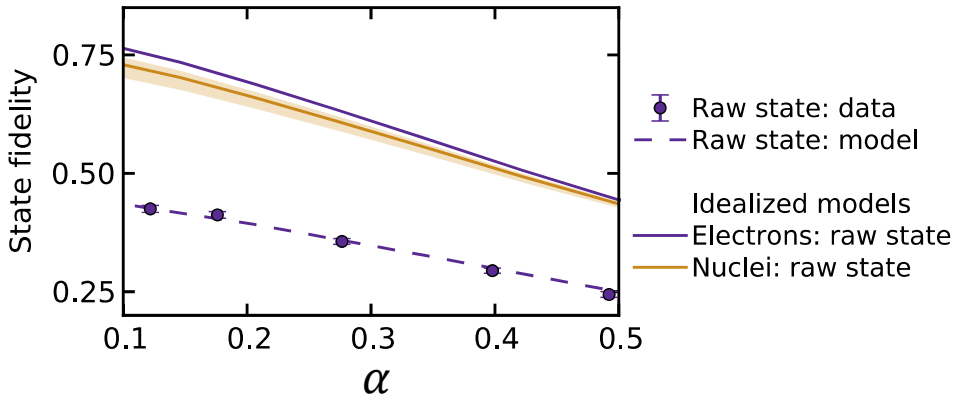
Raw state is of the form:

$$(1-\alpha)|\Psi_{\phi}^{\pm}\rangle\langle\Psi_{\phi}^{\pm}|+\alpha|0,0\rangle\langle 0,0|$$

Distillation experiment

Science 356, 928 (2017)



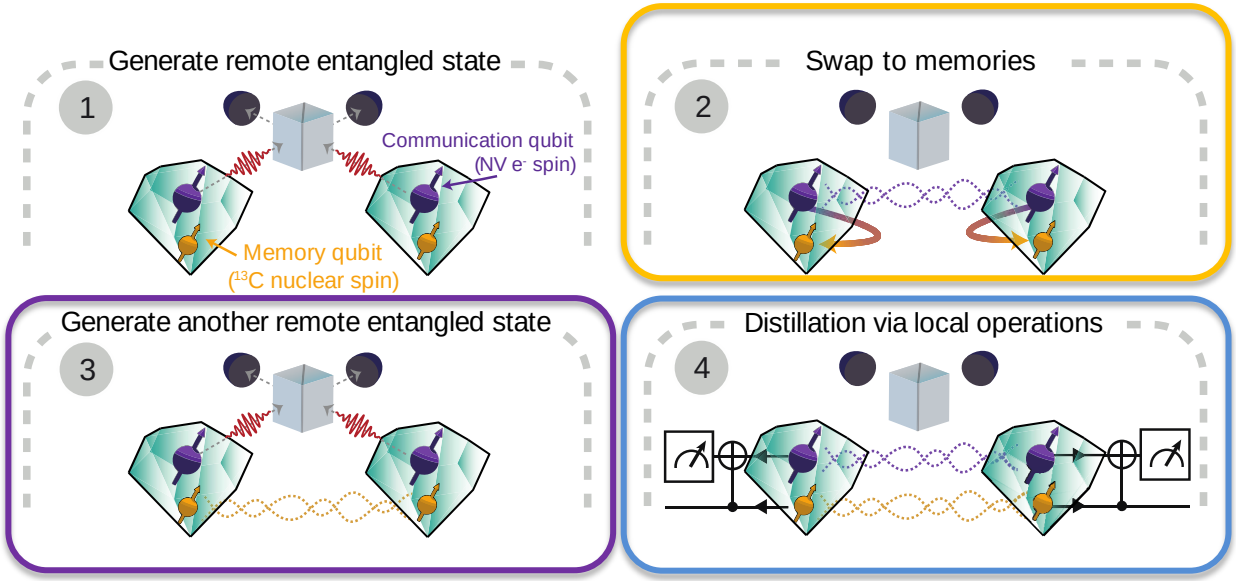


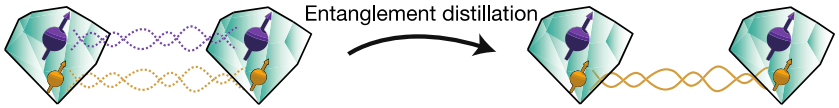
Raw state is of the form:

$$(1-\alpha)|\Psi_{\phi}^{\pm}\rangle\langle\Psi_{\phi}^{\pm}|+\alpha|0,0\rangle\langle 0,0|$$

Distillation experiment

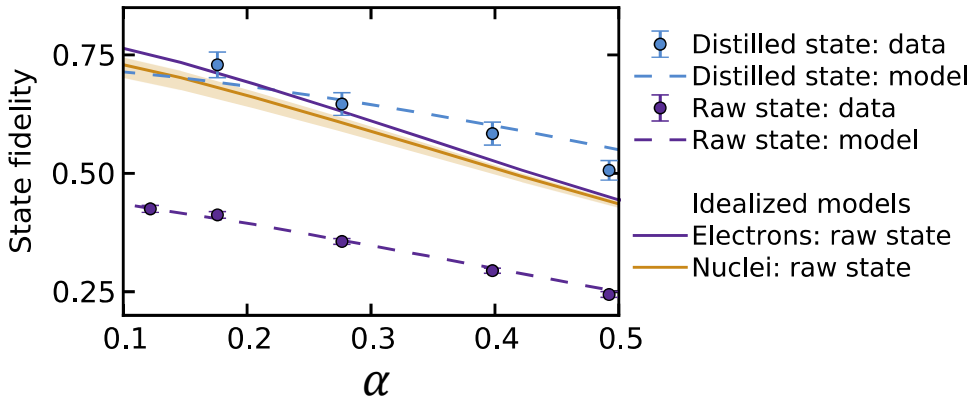
Science 356, 928 (2017)



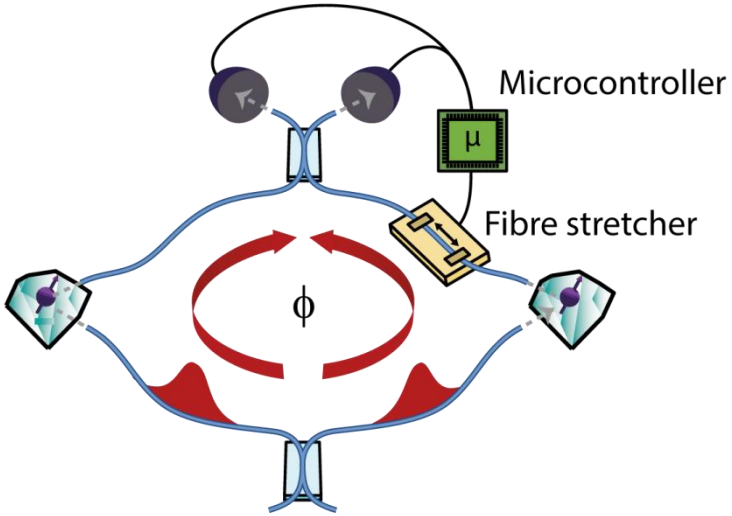


Raw state is of the form:

$$(1-\alpha)|\Psi_{\phi}^{\pm}\rangle\langle\Psi_{\phi}^{\pm}|+\alpha|0,0\rangle\langle 0,0|$$

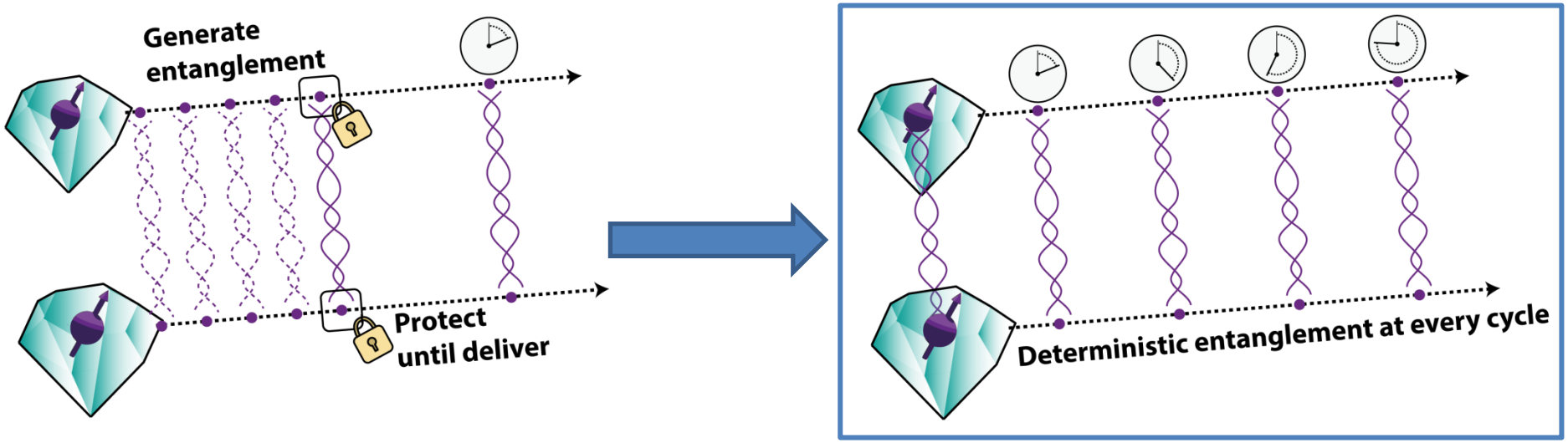


Deterministic entanglement generation

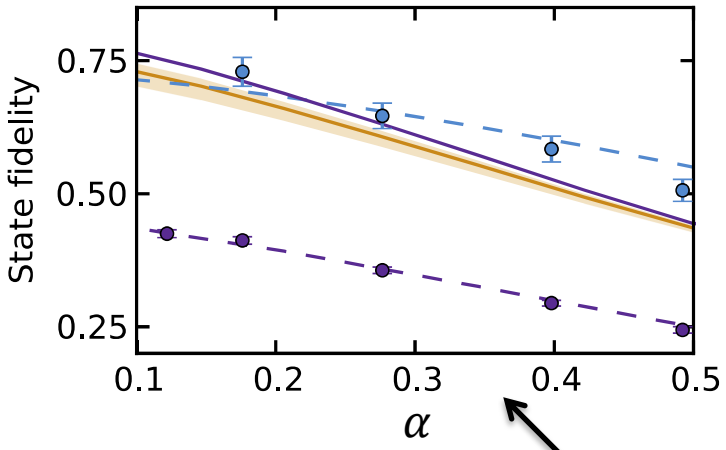


Measure and correct internal phase
Vastly increased entangling rate (40 Hz)!

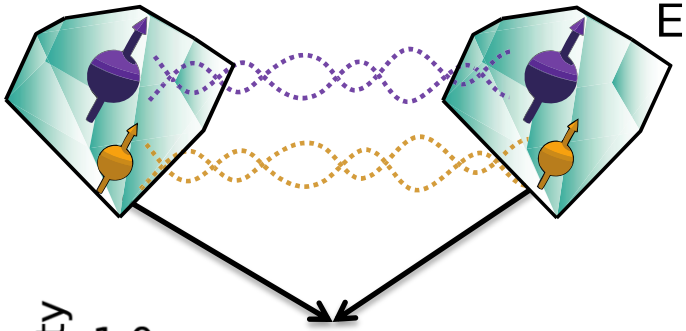
$$(1-\alpha)|\Psi_0^{\pm}\rangle\langle\Psi_0^{\pm}|+\alpha|0,0\rangle\langle 0,0|$$

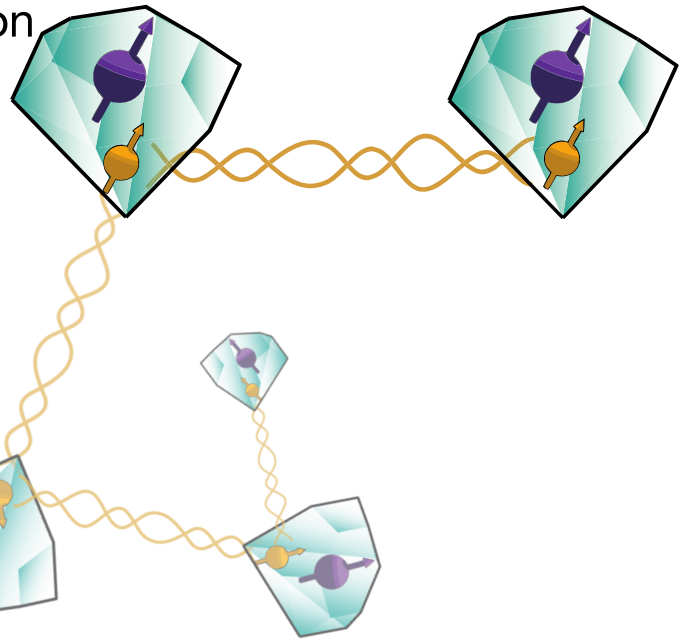


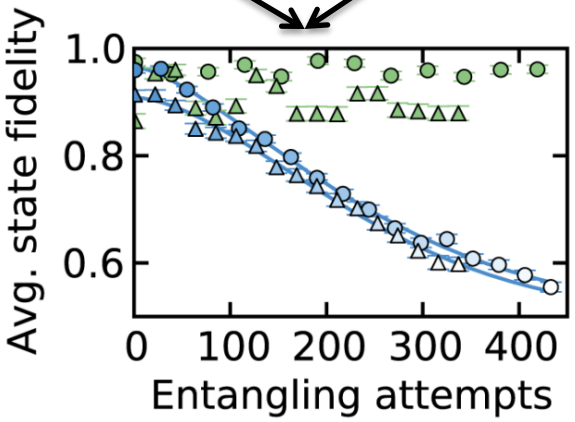
P. Humphreys, NK et al., in preparation



Entanglement distillation







NK et al., Science 356, 928 (2017)