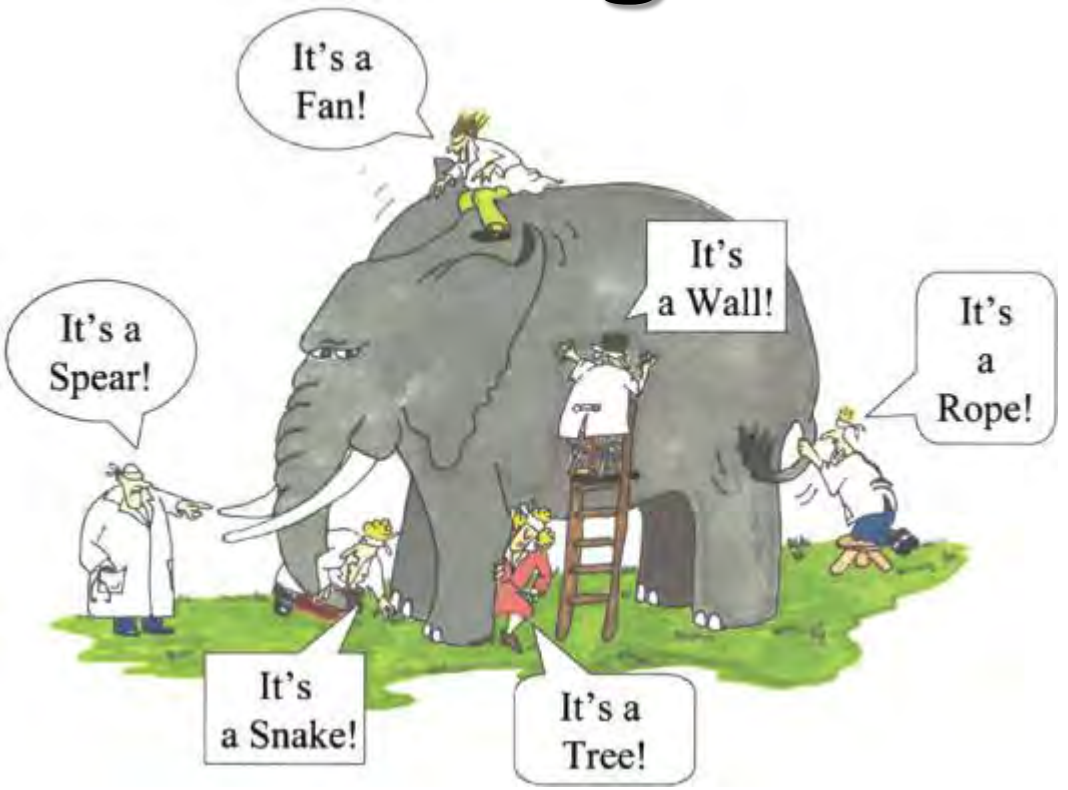
Quantum Networking for Youngsters



G. Rempe, MPQ, Germany

The whole can do …

… what parts can’t do.

10.1098/rsta.2003.1227

THE ROYAL SOCIETY

Quantum technology: the second quantum revolution

By Jonathan P. Dowling[1] and Gerard J. Milburn[2]

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[2] *Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Wilberforce Road, Cambridge CB3 0WA, UK and Centre for Quantum Computer Technology, The University of Queensland, St Lucia, QLD 4072, Australia*

Published online 20 June 2003

We are currently in the midst of a *second quantum revolution.* The first quantum revolution gave us new rules that govern physical reality. The second quantum revolution will take these rules and use them to develop new technologies. In this review we discuss the principles upon which quantum technology is based and the tools required to develop it. We discuss a number of examples of research programs that could deliver quantum technologies in coming decades including: quantum information technology, quantum electromechanical systems, coherent quantum electronics, quantum optics and coherent matter technology.

First quantum revolution

Superposition
Quantization
Uncertainty
Tunneling

Classical wave concepts

Second quantum revolution

Decoherence

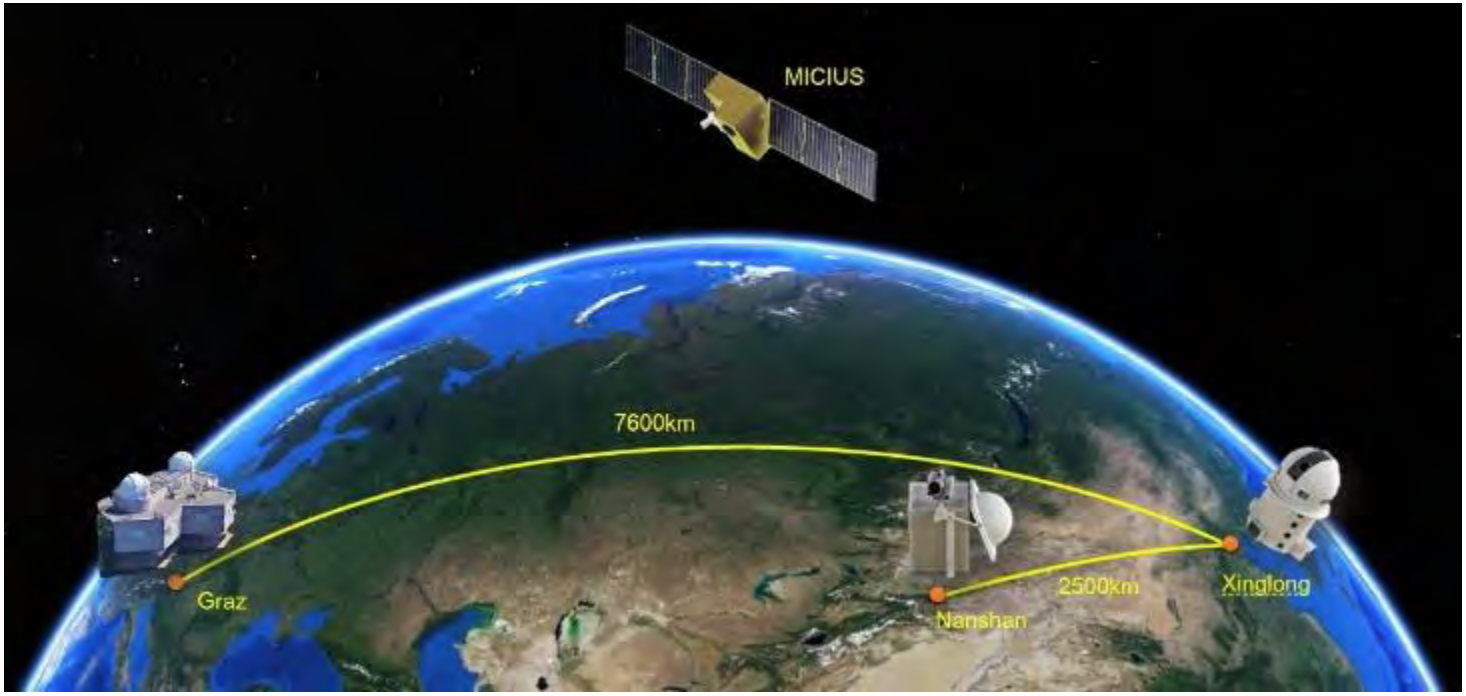
Collapse of superpositions

Entanglement

Superposition of correlations

Quantum information concepts

Quantum satellite for …



… quantum key distribution between classical observers.

Quantum internet for …

… quantum state distribution between quantum memories.

Quantum internet for …

… a global quantum cloud:
full quantum architecture.

$$\left(|g\rangle + |e\rangle\right)_{\text{Local memory}}$$

$$\left(|g\rangle + |e\rangle\right)_{\text{Local memory}}$$

map ↓ qubit

$$\left(|0\rangle + |1\rangle\right)_{\text{Messenger photon}}$$

$$\left(|g\rangle + |e\rangle\right)_{\text{Local memory}}$$

map ↓ qubit

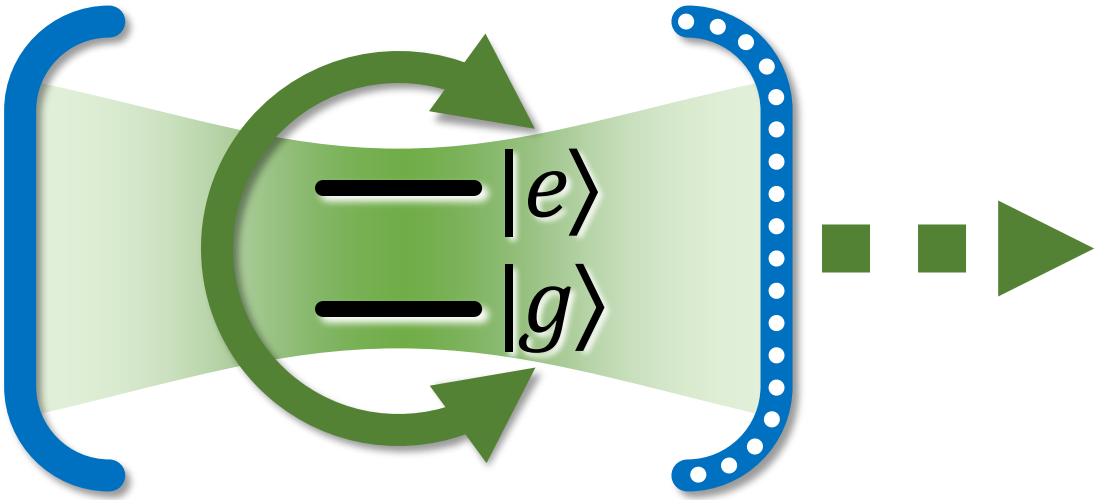
$$\left(|0\rangle + |1\rangle\right)_{\text{Messenger photon}}$$

map ↓ qubit

$$\left(|g\rangle + |e\rangle\right)_{\text{Remote memory}}$$

Cavity QED:

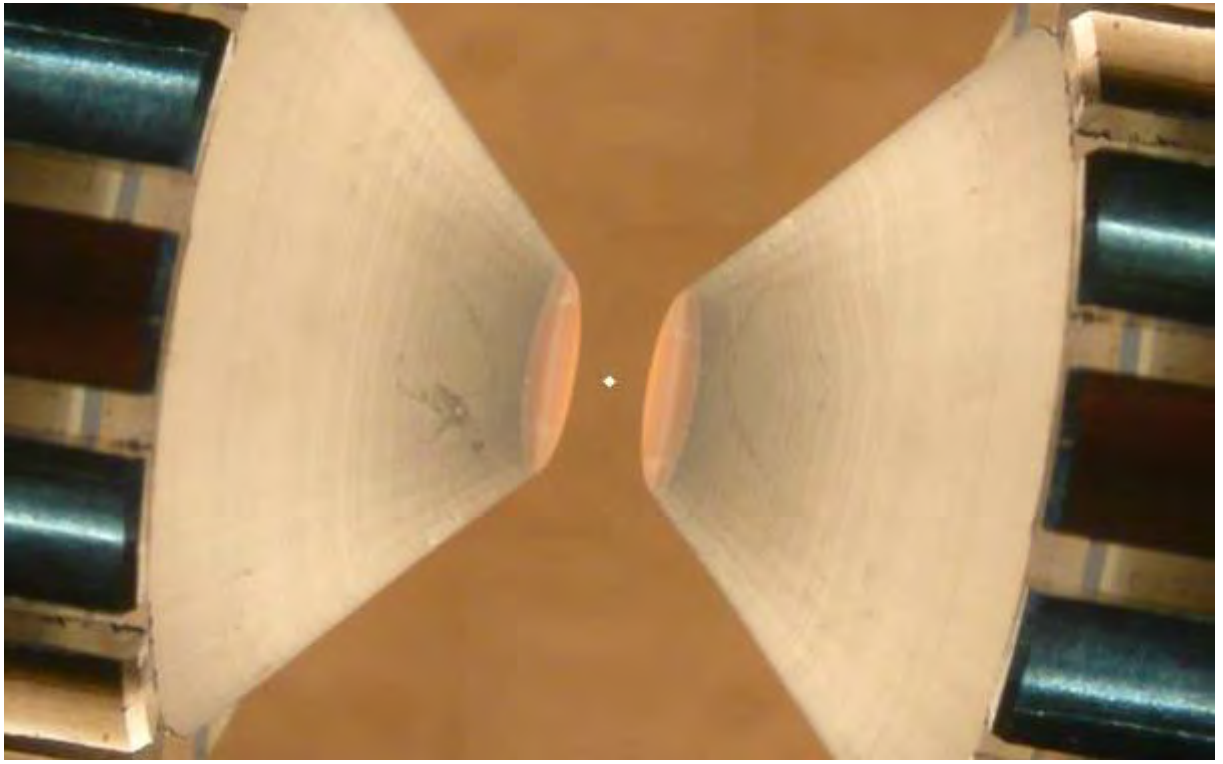
Strong light-matter coupling



Atom = Quantum memory

Cavity = Quantum interface

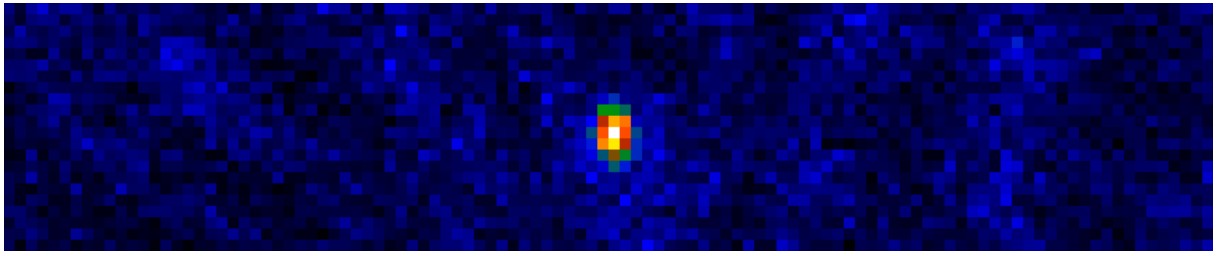
Fabry-Pérot resonator:



Optical finesse $\leq 2\times10^{6}$

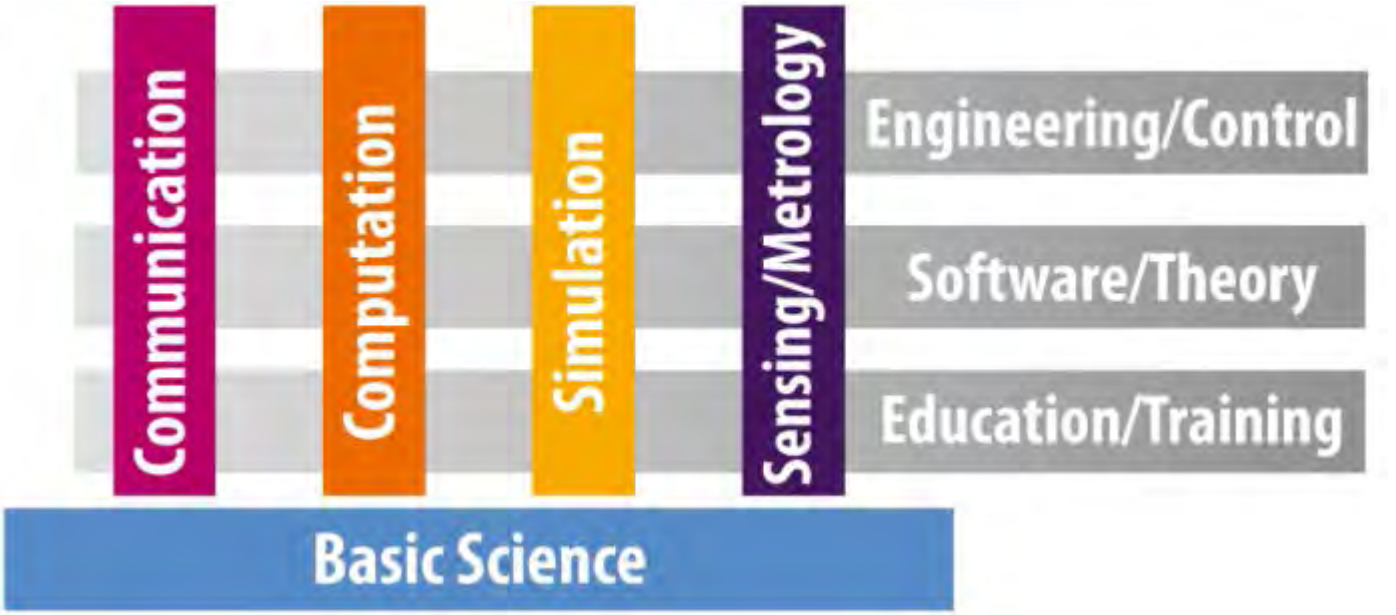
Localized atom:

cavity/feedback/lattice/Raman cooling



Stationary qubit, fully controlled – internal, external, and optical.

The cavity QED advantage:



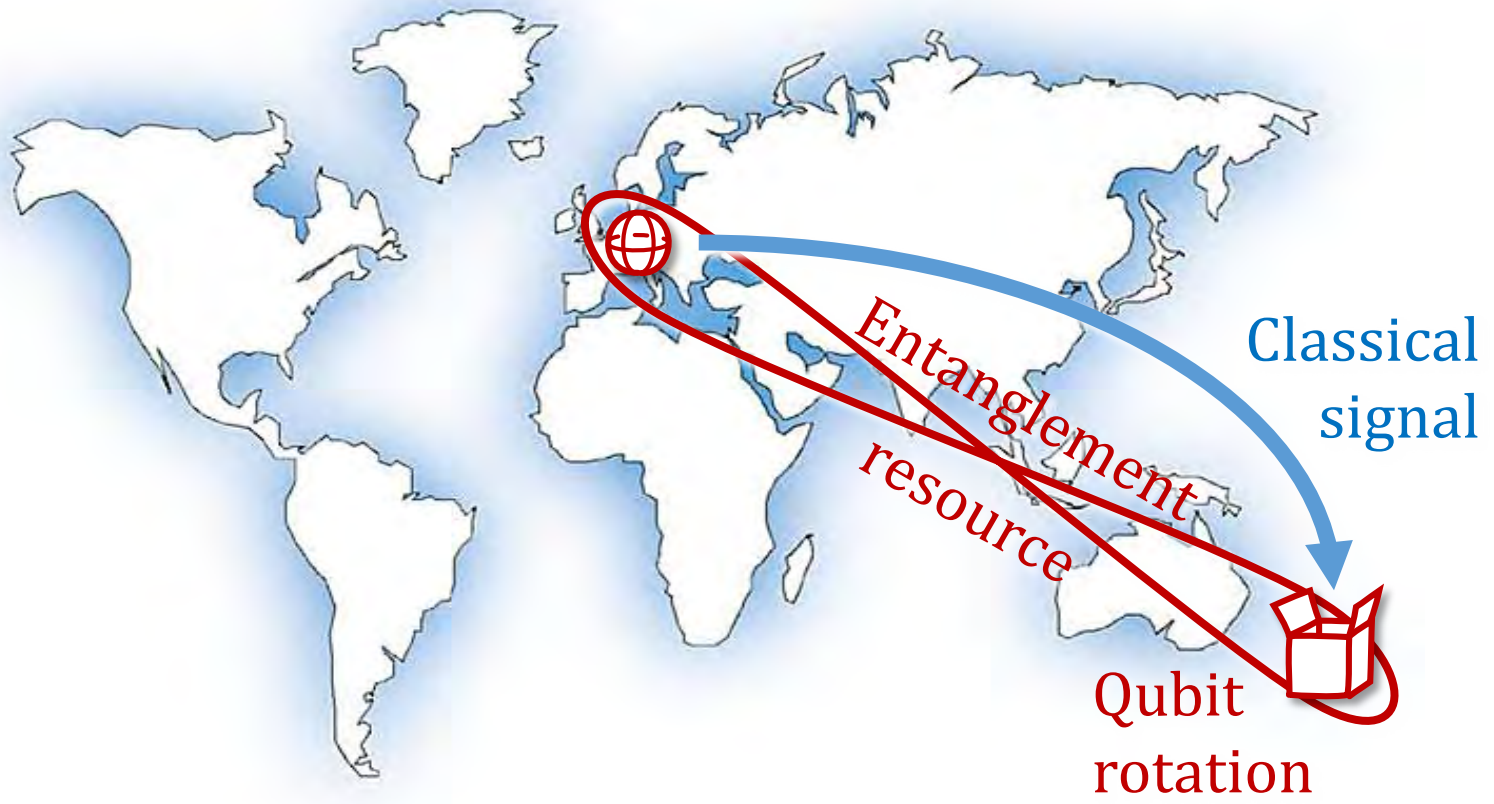
Can communicate,
compute, simulate & sense

Quantum communication:

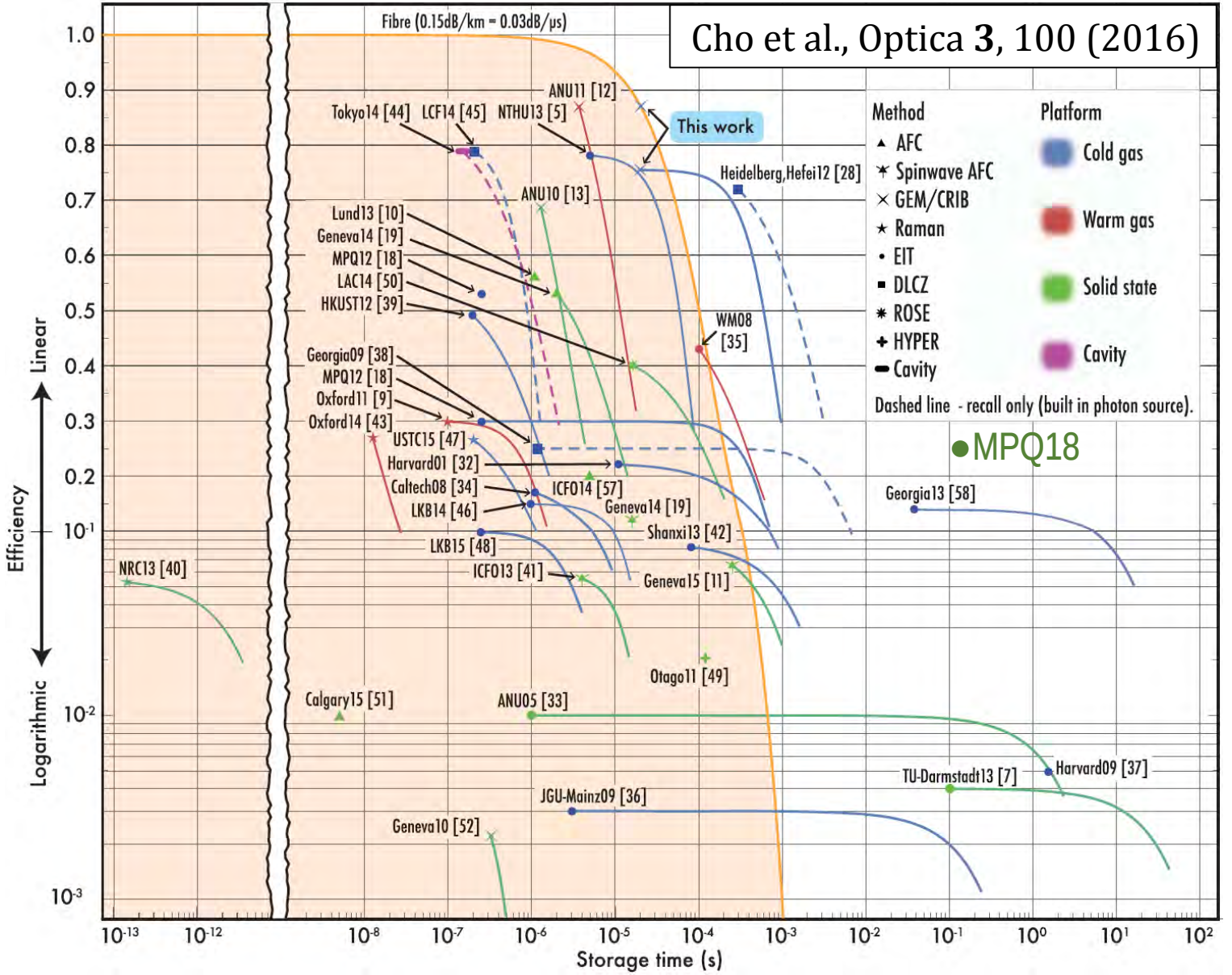
M. Körber
S. Langenfeld
O. Morin
A. Neuzner

Worldwide teleportation needs long-lived memories.

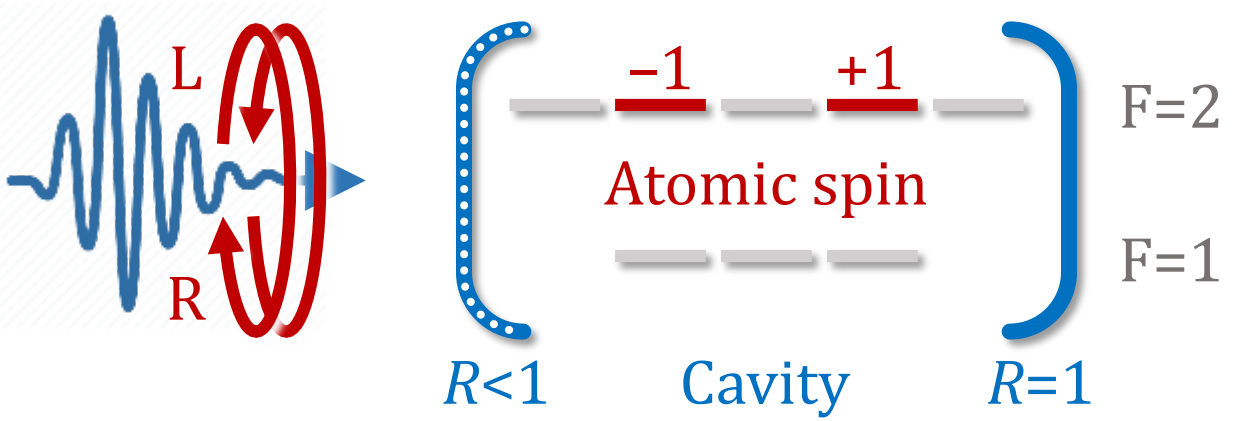
Worldwide teleportation:



66ms transmission time.

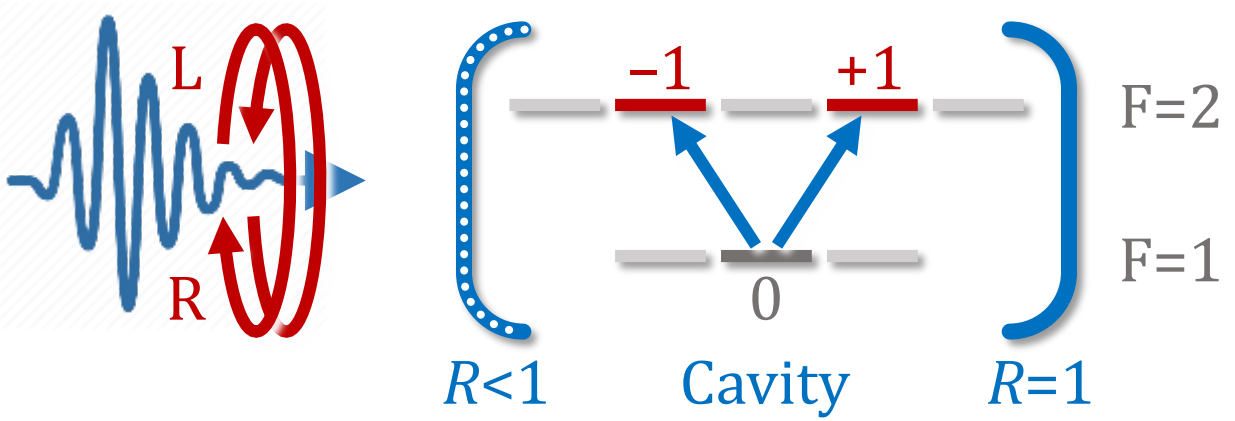

Cho et al., Optica 3, 100 (2016)
Fibre (0.15dB/km = 0.03dB/μs)
This work
Tokyo14 [44]
LCF14 [45]
NTHU13 [5]
ANU11 [12]
Heidelberg,Hefei12 [28]
ANU10 [13]
Lund13 [10]
Geneva14 [19]
MPQ12 [18]
LAC14 [50]
HKUST12 [39]
WM08 [35]
Georgia09 [38]
MPQ12 [18]
Oxford11 [9]
Oxford14 [43]
USTC15 [47]
Harvard01 [32]
Caltech08 [34]
LKB14 [46]
LKB15 [48]
ICFO14 [57]
Geneva14 [19]
Shanxi13 [42]
ICFO13 [41]
Geneva15 [11]
NRC13 [40]
Otago11 [49]
Calgary15 [51]
ANU05 [33]
Georgia13 [58]
TU-Darmstadt13 [7]
Harvard09 [37]
JGU-Mainz09 [36]
Geneva10 [52]
Method
AFC
Spinwave AFC
GEM/CRIB
Raman
EIT
DLCZ
ROSE
HYPER
Cavity
Platform
Cold gas
Warm gas
Solid state
Cavity
Dashed line - recall only (built in photon source).
MPQ18
Efficiency
Linear
Logarithmic
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
10-1
10-2
10-3
10-13
10-12
10-8
10-7
10-6
10-5
10-4
10-3
10-2
10-1
100
101
102
Storage time (s)

Quantum memory: Interface basis



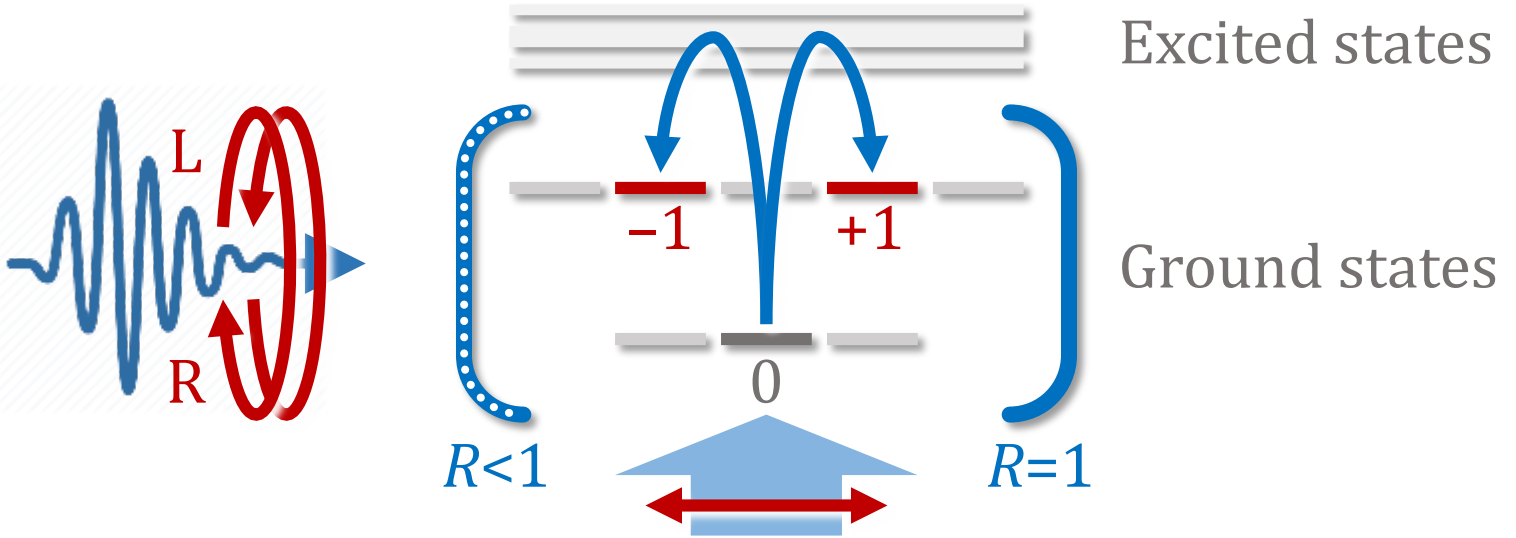
Conservation of angular momentum.

Quantum memory: Interface basis



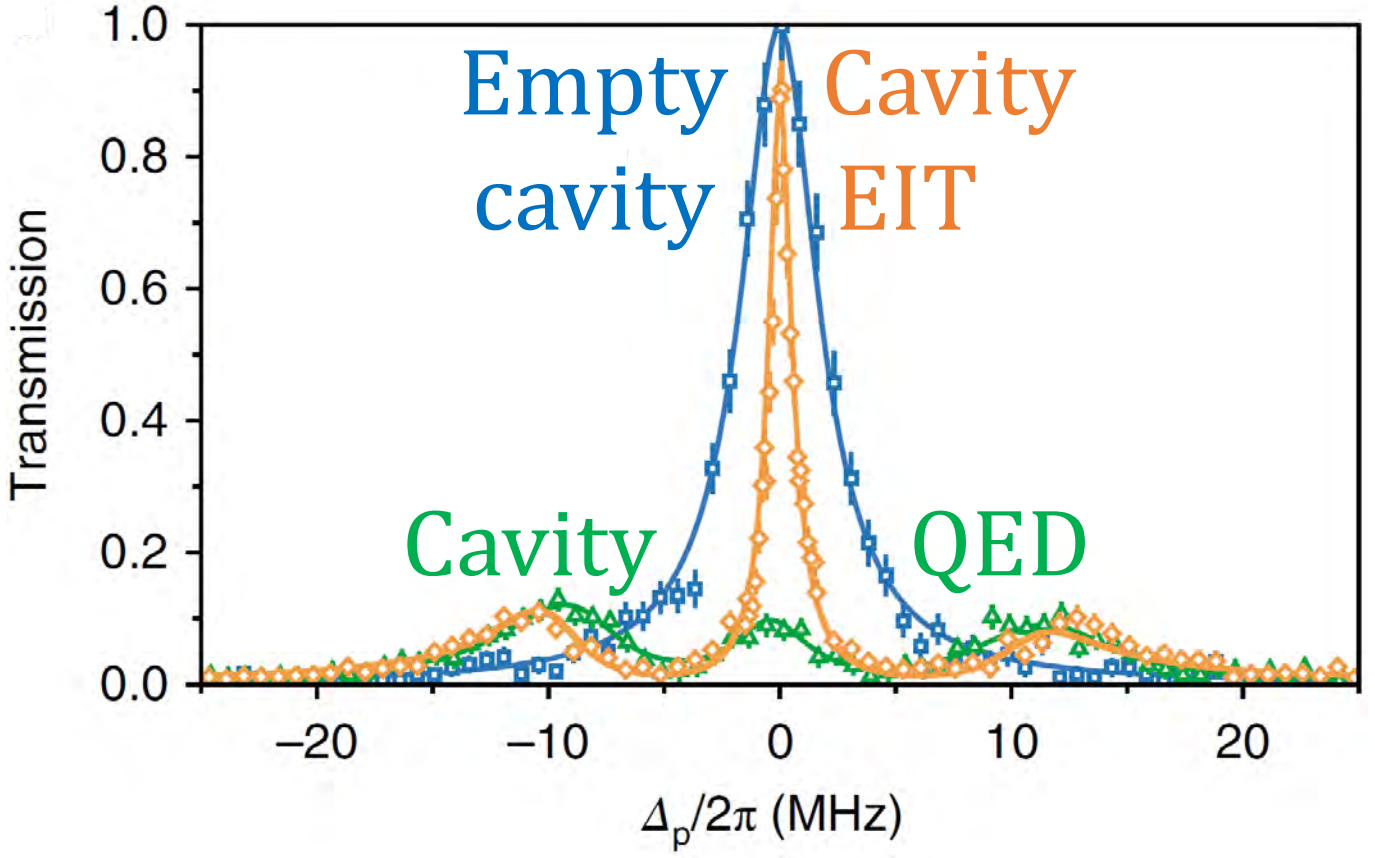
Absorbing atom reflects photon.

Quantum memory: Interface basis



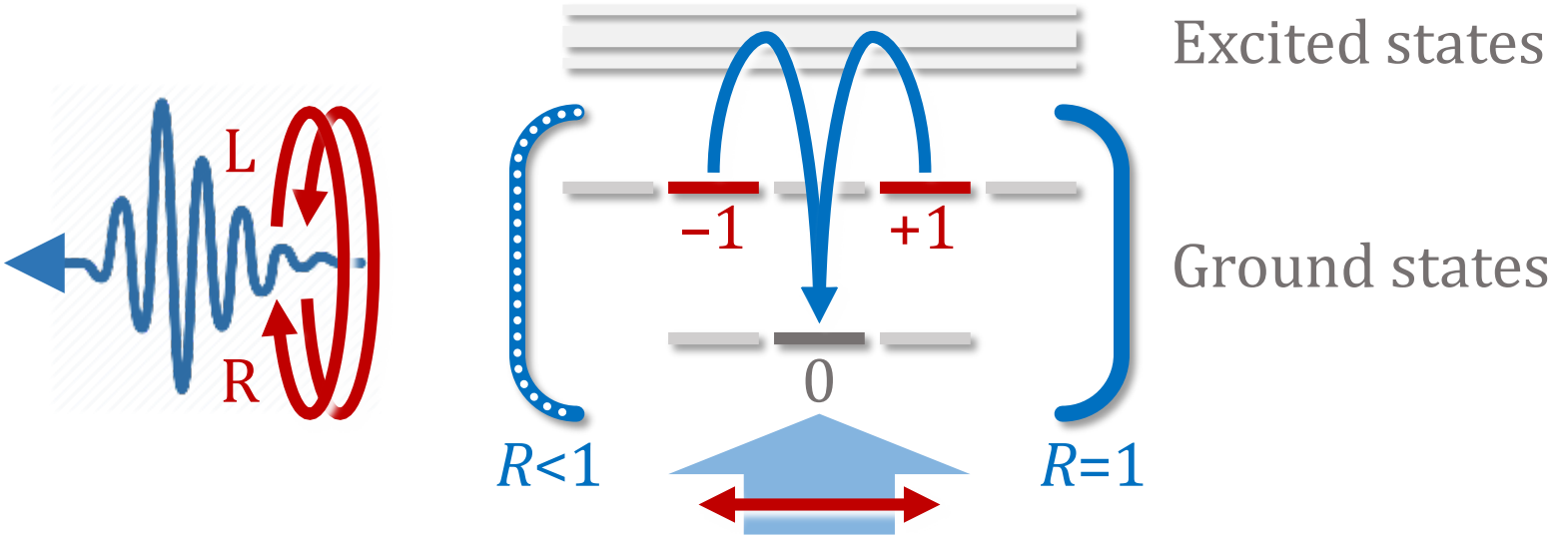
Write process: Cavity EIT

Cavity EIT



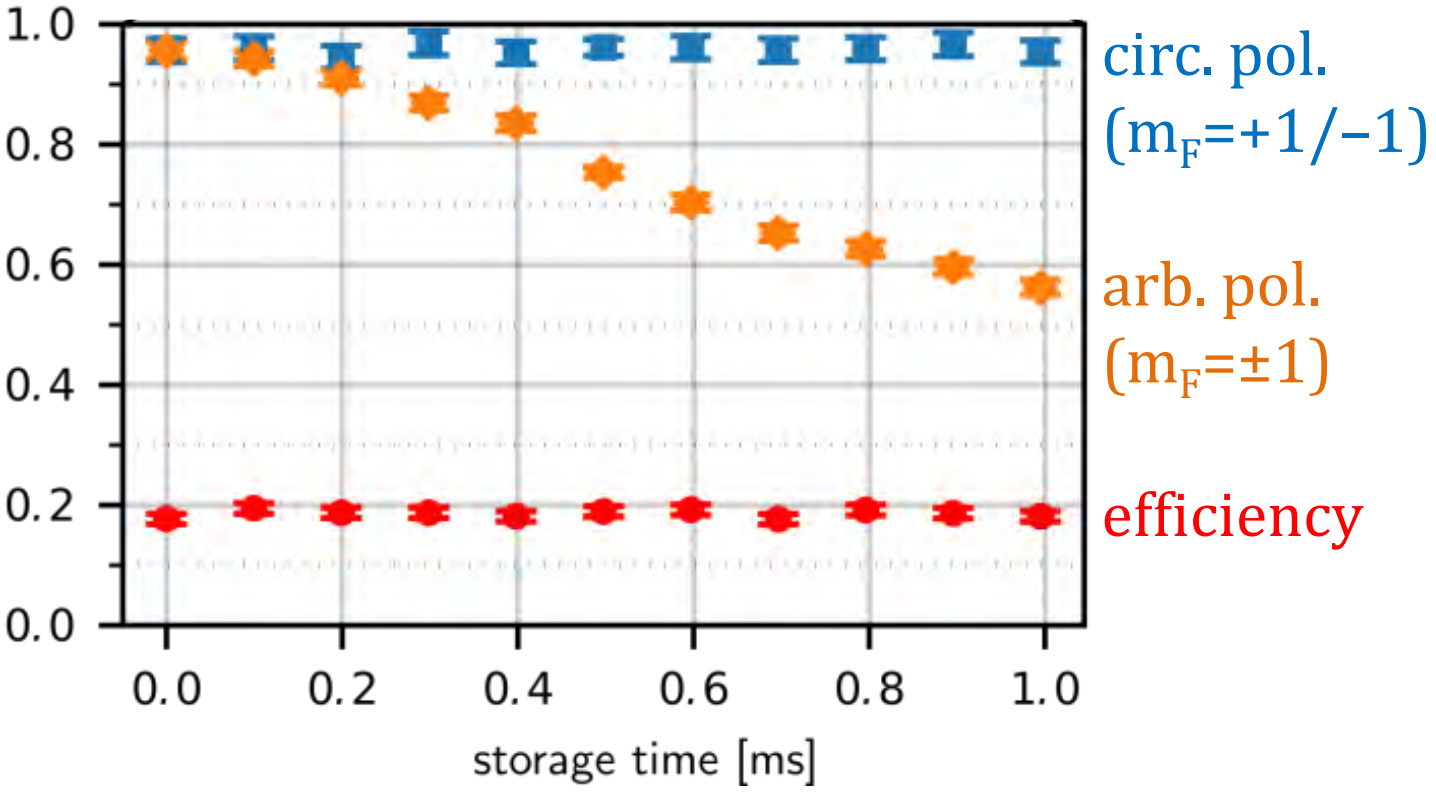
Slow/stopped light.

Quantum memory: Interface basis



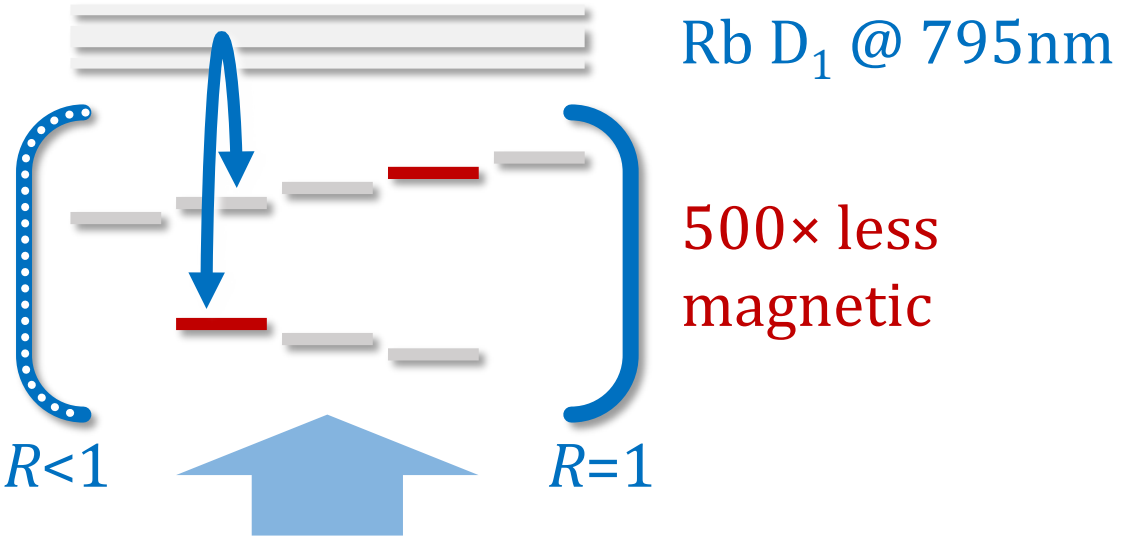
Read process: Vacuum STIRAP

Efficiency & fidelity (2011):



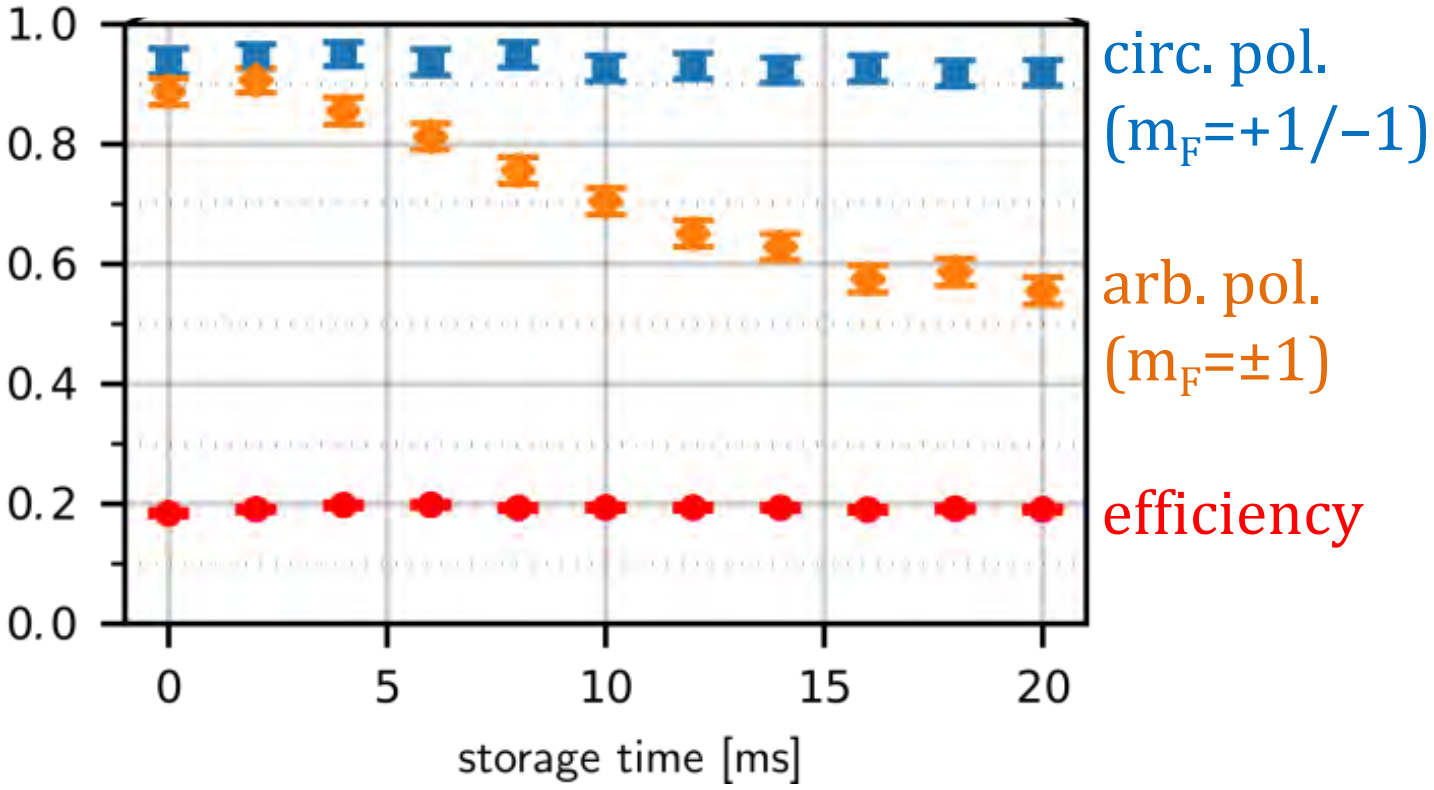
Longer than ~500µs?

Quantum memory: Memory basis



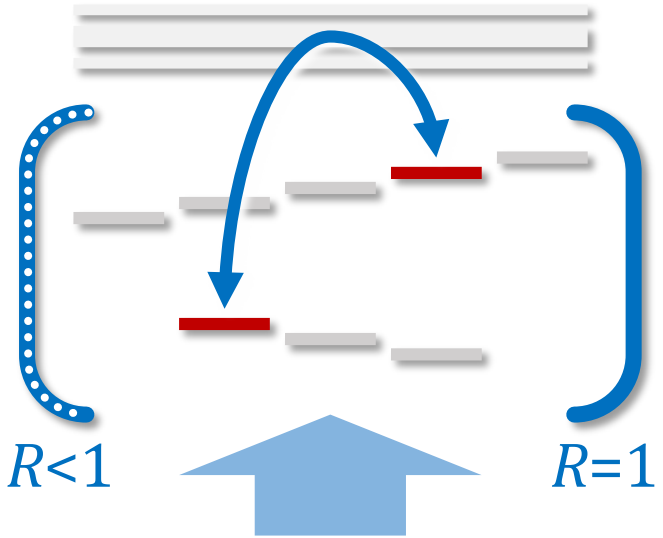
Raman transfer into pseudo-clock states.

Efficiency & fidelity (2018):



~20× longer lifetime.

Quantum memory: Memory basis

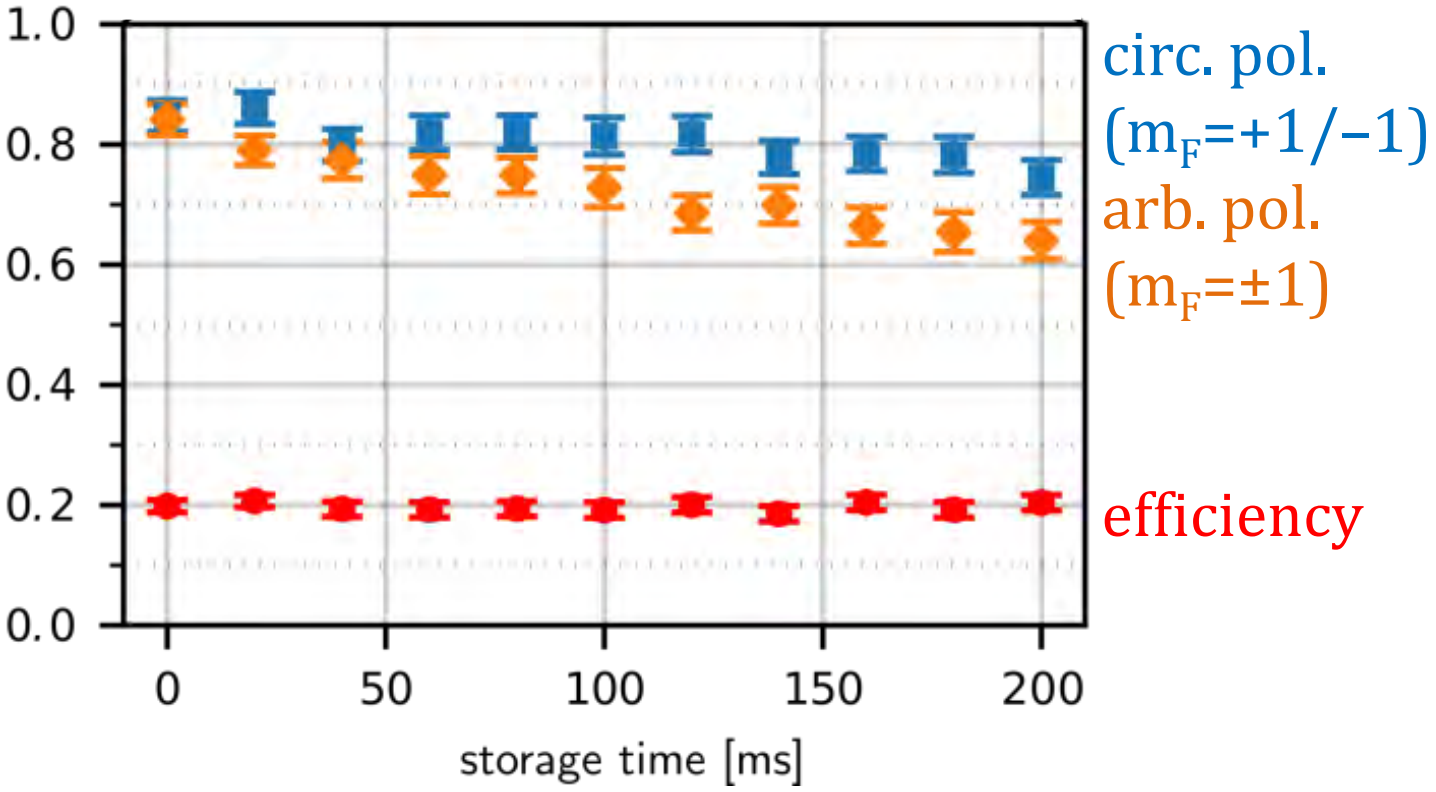


Rb D_1 @ 795nm

Inhomogeneous dephasing from distribution of trapping sites

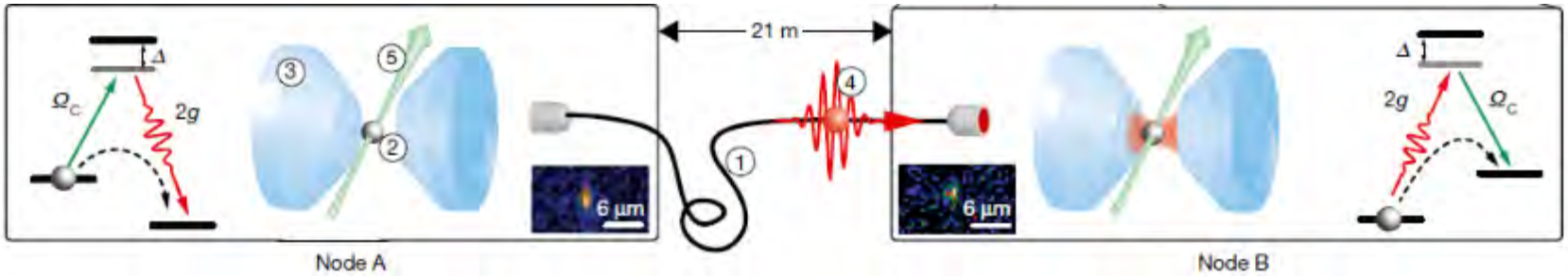
Rephase qubit with spin echo.

Efficiency & fidelity (2018):



~200× longer (>66ms).

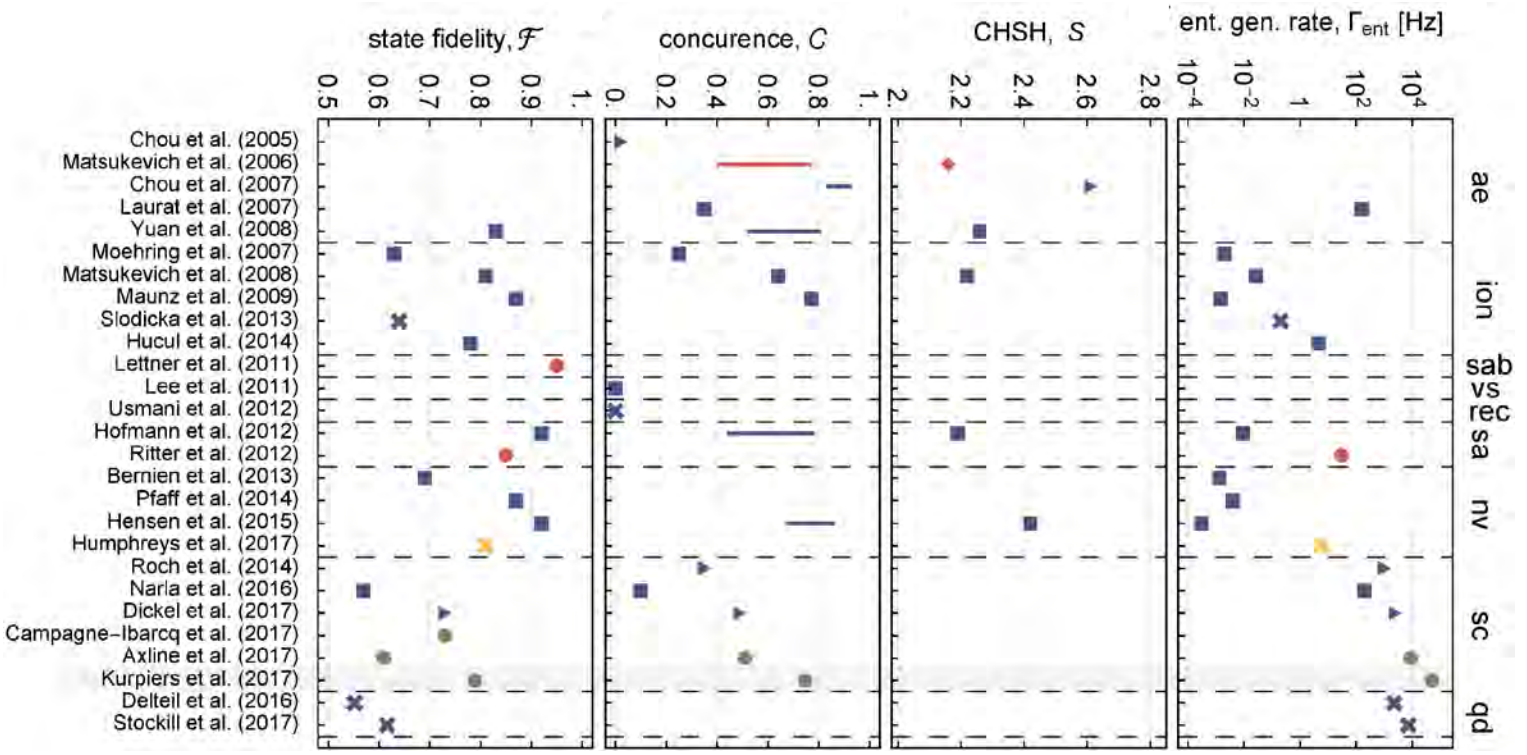
Mk I network (– 2012)



Emission & absorption:

1) State transfer
2) Entanglement
3) Teleportation

Remote entanglement ...

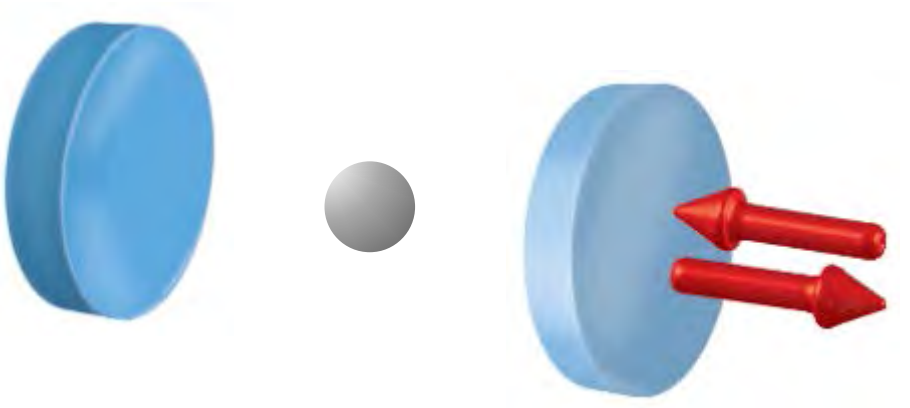


Kurpiers et al., Nature **558**, 264 (2018)

... across hardware platforms

Mk II network (2013 –)

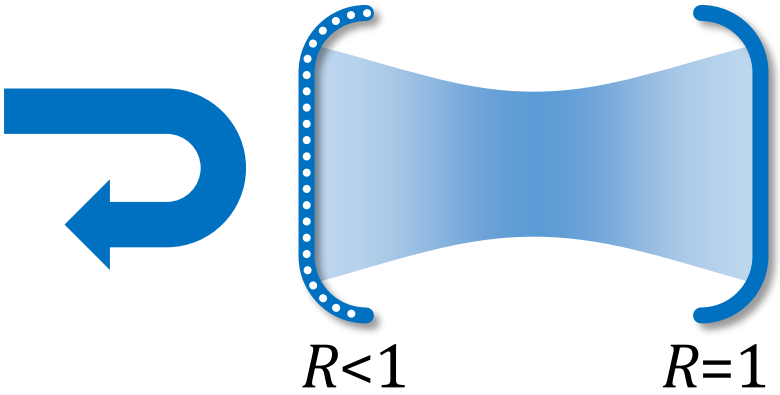
N. Kalb
A. Reiserer
S. Ritter



Reflection & detection:

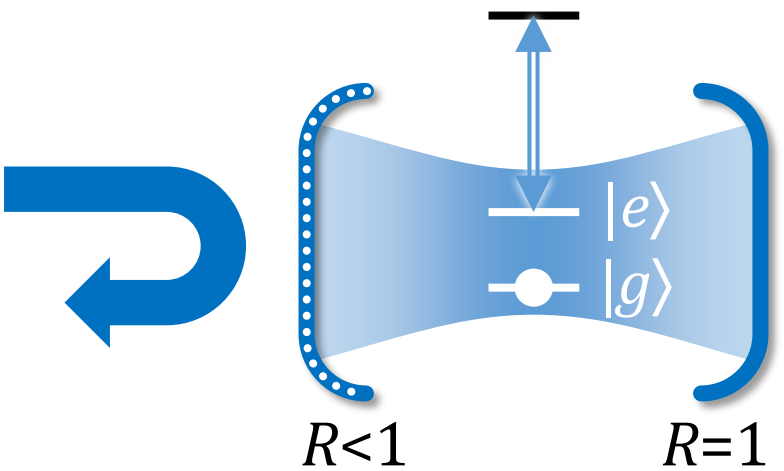
1) Success herald.
2) Modular design.

Photon reflection (from back mirror):



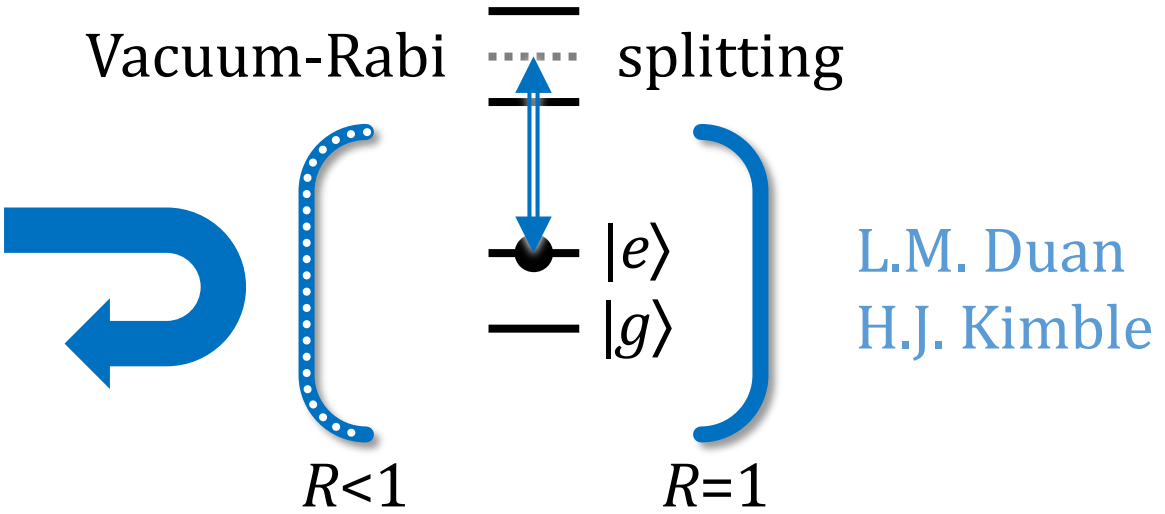
π phase shift.

Photon reflection (from back mirror):



π phase shift.

Photon reflection (from front mirror):



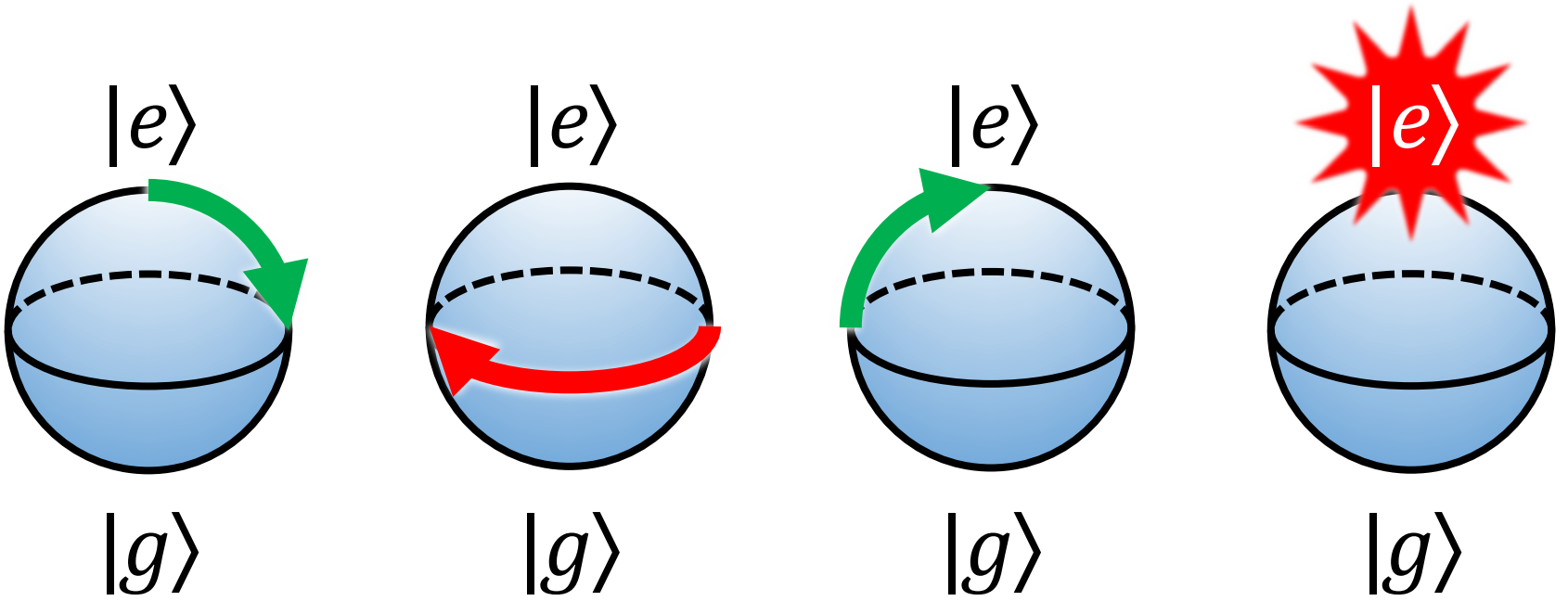
0 phase shift.

Quantum non-demolition photon-number detection:

$$|1\rangle(|e\rangle+|g\rangle)\rightarrow|1\rangle(|e\rangle-|g\rangle)$$

1) Tracks a photon.
2) Heralds success.

Experimental protocol:



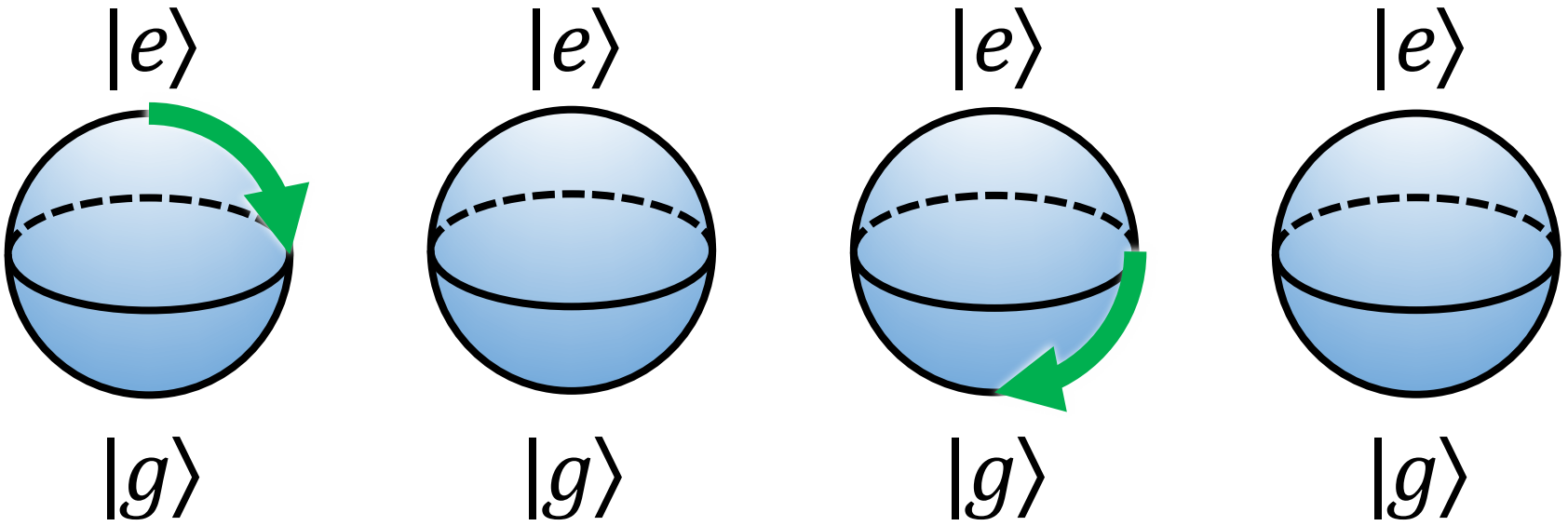
Qubit rotation

One photon

Qubit rotation

Qubit detection

Experimental protocol:

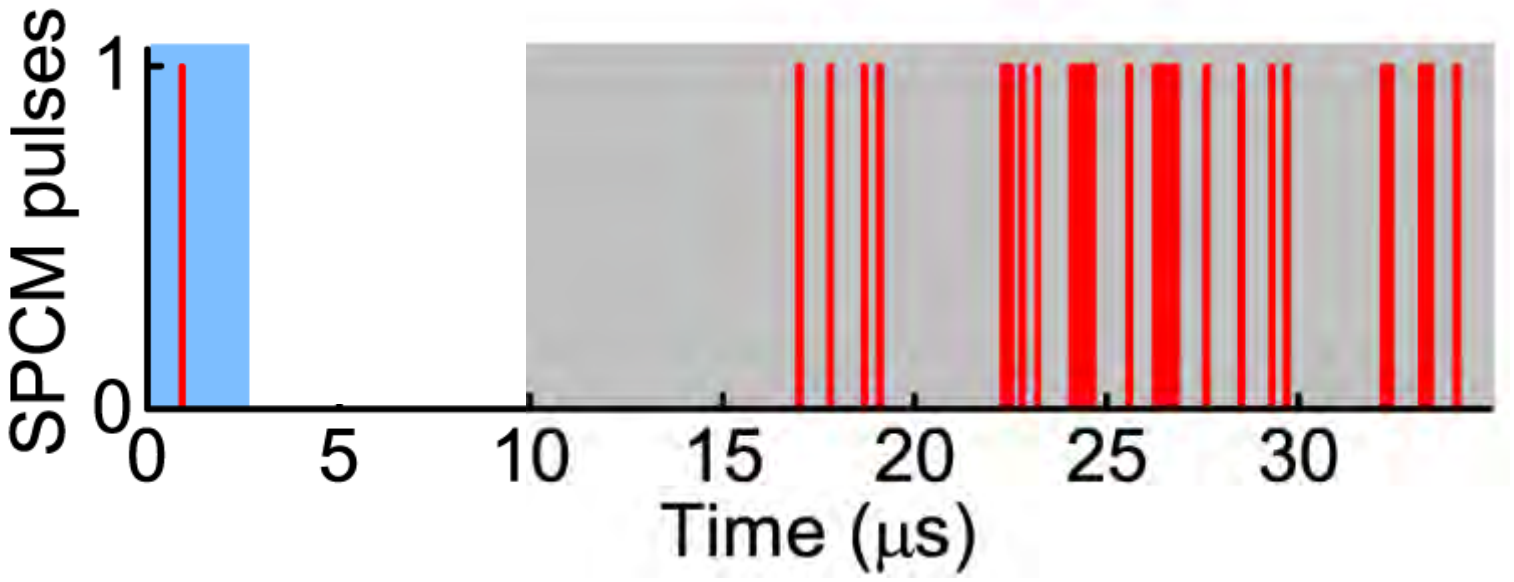


Qubit rotation

Zero photon

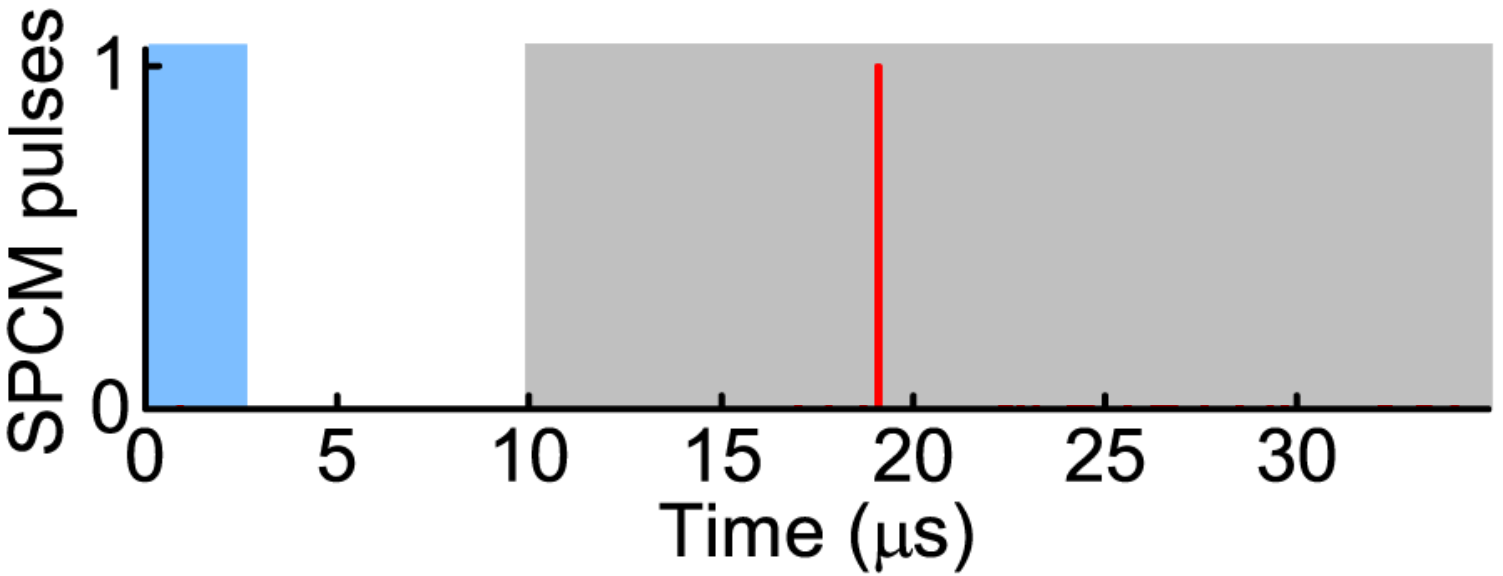
Qubit rotation

Qubit detection



Send photon and detect it with a photon counter.

Second detection via laser-induced atom fluorescence.

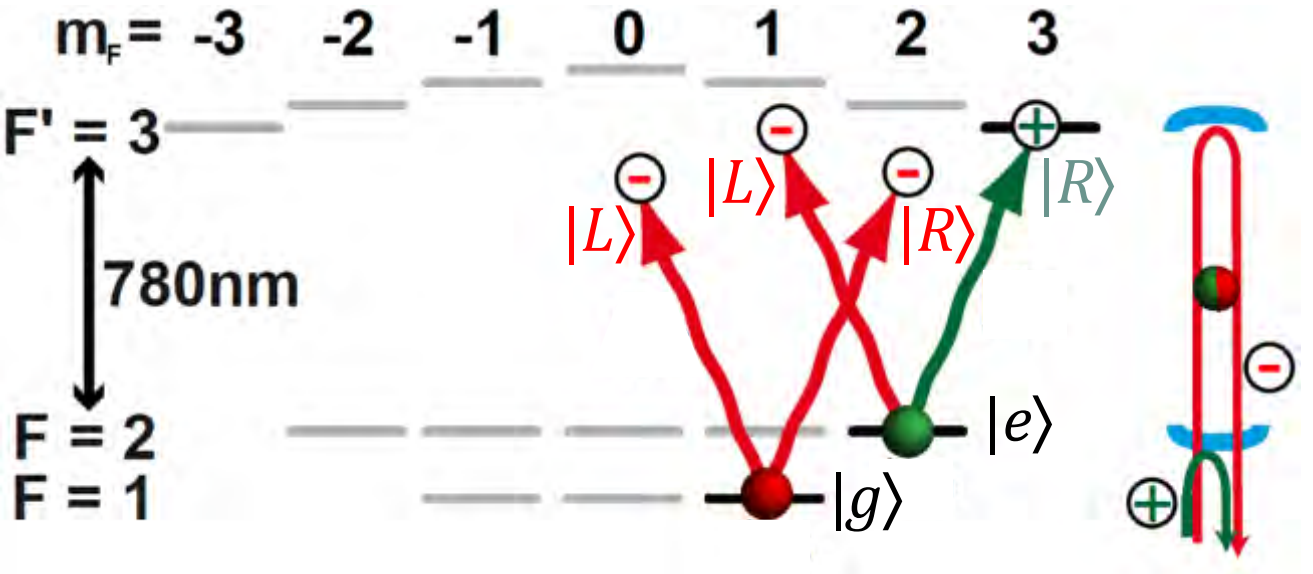


No incoming photon.

Only dark clicks from the atom.

We see a given photon with 87% probability, and it survives with a probability of ~66%.

Qubit-qubit interaction:



1) Hybrid quantum gate.
2) Optical quantum gate.

$$\overbrace{\left(|L\rangle + |R\rangle\right)}^{|H\rangle} \otimes \left(|g\rangle + |e\rangle\right)$$

$$\overbrace{\left(|L\rangle + |R\rangle\right)}^{|H\rangle} \otimes \left(|g\rangle + |e\rangle\right)$$

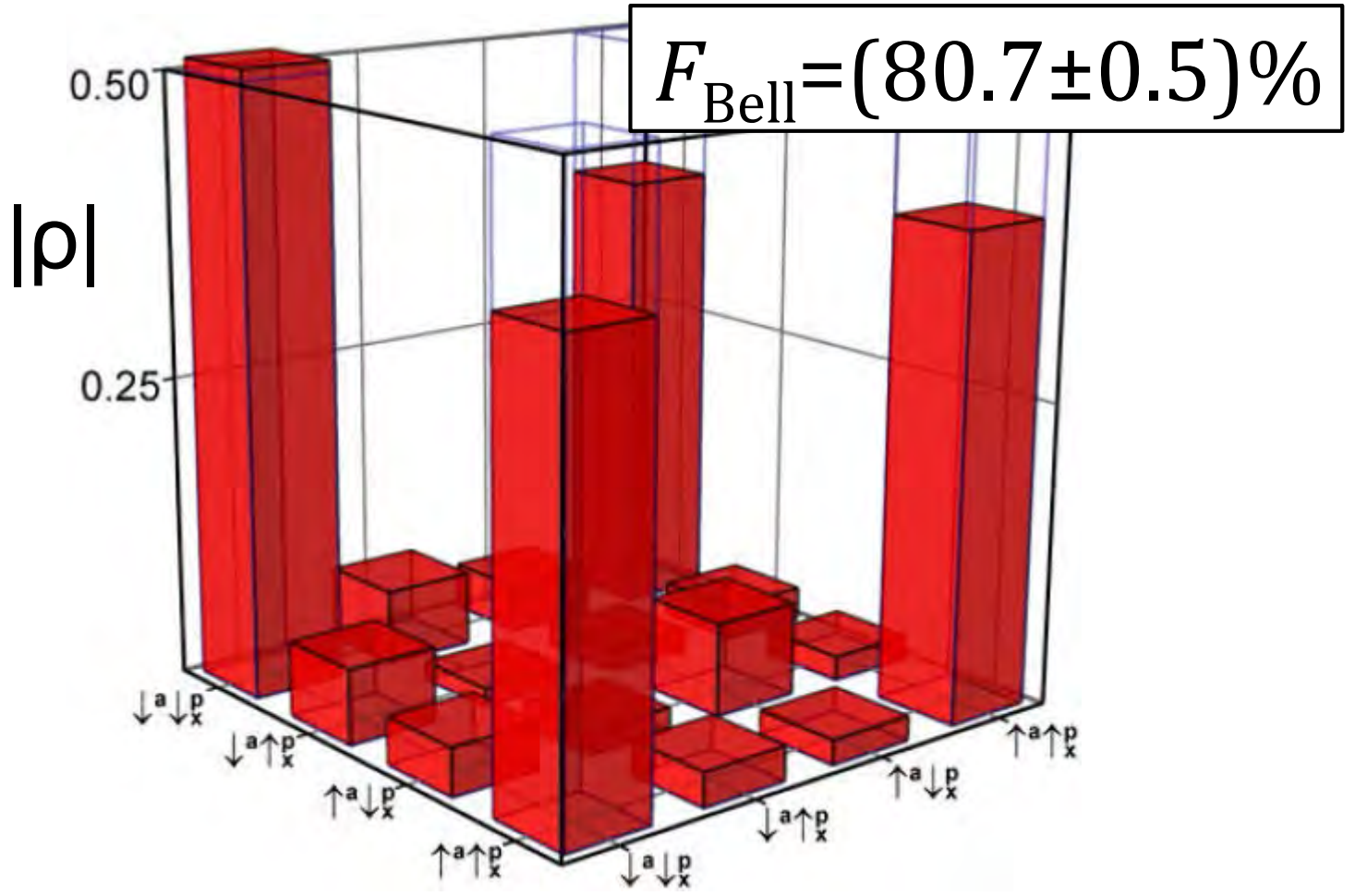
$$\rightarrow |L,g\rangle + |L,e\rangle + |R,g\rangle - |R,e\rangle$$

$$\overbrace{\left(|L\rangle + |R\rangle\right)}^{|H\rangle} \otimes \left(|g\rangle + |e\rangle\right)$$

$$\rightarrow |L,g\rangle + |L,e\rangle + |R,g\rangle - |R,e\rangle$$

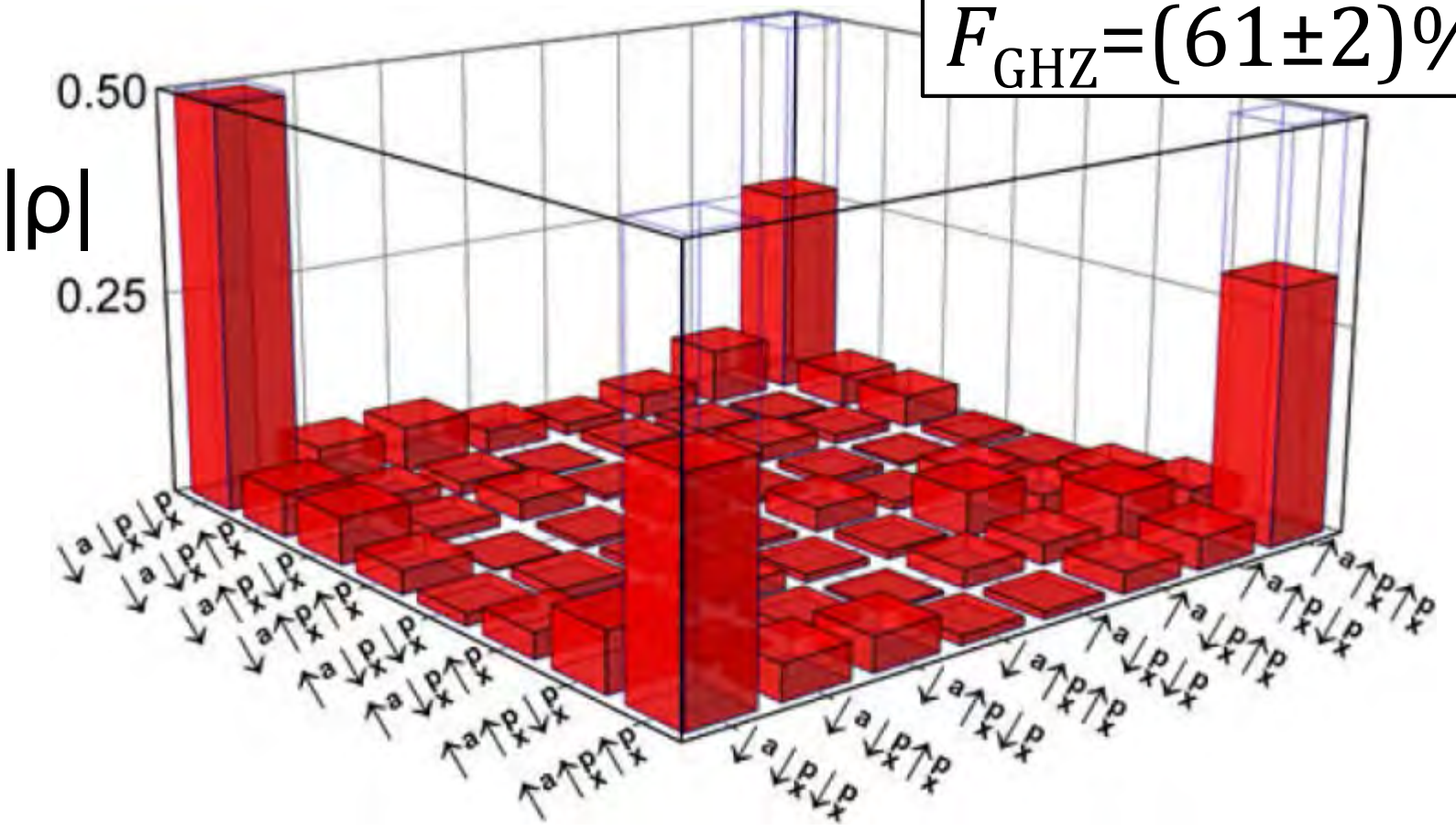
$$= \underbrace{\left(|L\rangle + |R\rangle\right)}_{|H\rangle}|g\rangle + \underbrace{\left(|L\rangle - |R\rangle\right)}_{|V\rangle}|e\rangle$$

$$|H\rangle(|g\rangle+|e\rangle)\rightarrow|Hg\rangle+|Ve\rangle$$



$$|HH\rangle(|g\rangle+|e\rangle)\rightarrow|HHg\rangle+|VVe\rangle$$

$F_{\mathrm{GHZ}}=(61\pm2)\%$



$$\underbrace{\left(\alpha|H\rangle+\beta|V\rangle\right)}_{\text{light}}\left(|g\rangle+|e\rangle\right)$$

$$\underbrace{\left(\alpha\left|H\right\rangle+\beta\left|V\right\rangle\right)}_{\text{light}}\left(\left|g\right\rangle+\left|e\right\rangle\right)$$

$$\xrightarrow[\text{reflection}]{\text{qubit}}\left|H\right\rangle\left(\alpha\left|g\right\rangle+\beta\left|e\right\rangle\right)$$

$$+\underbrace{\left|V\right\rangle}_{\text{herald}}\left(\alpha\left|e\right\rangle+\beta\left|g\right\rangle\right)$$

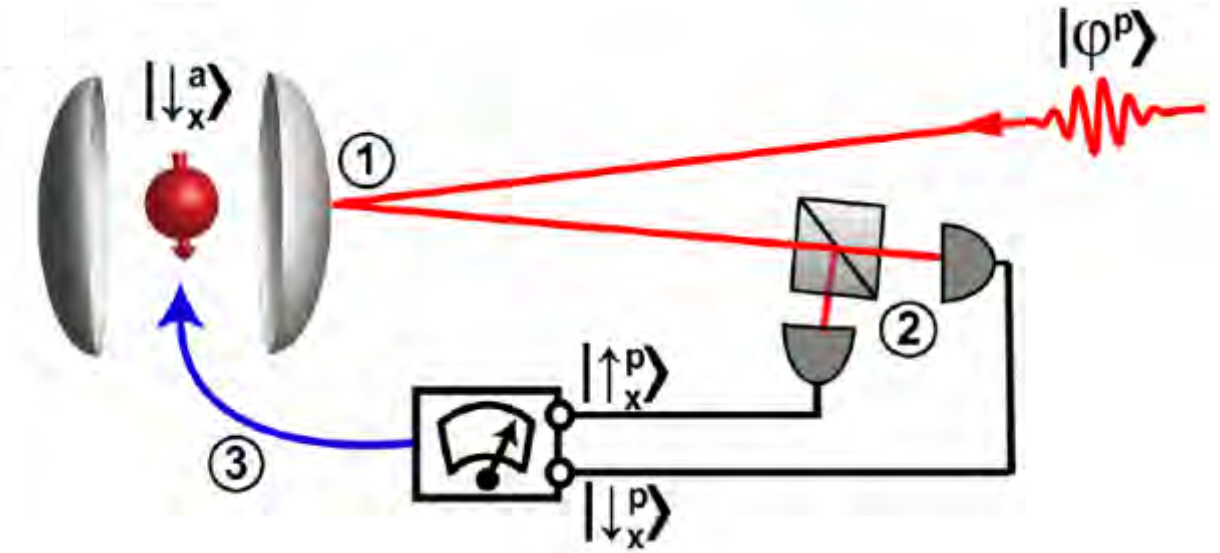
$$\underbrace{\left(\alpha|H\rangle+\beta|V\rangle\right)}_{\text{light}}\left(|g\rangle+|e\rangle\right)$$

$$\xrightarrow[\text{reflection}]{\text{qubit}} |H\rangle\left(\alpha|g\rangle+\beta|e\rangle\right)$$

$$+\underbrace{|V\rangle}_{\text{herald}}\left(\alpha|e\rangle+\beta|g\rangle\right)$$

$$\xrightarrow[\text{on atom}]{\text{feedback}} \underbrace{\alpha|g\rangle+\beta|e\rangle}_{\text{matter}}$$

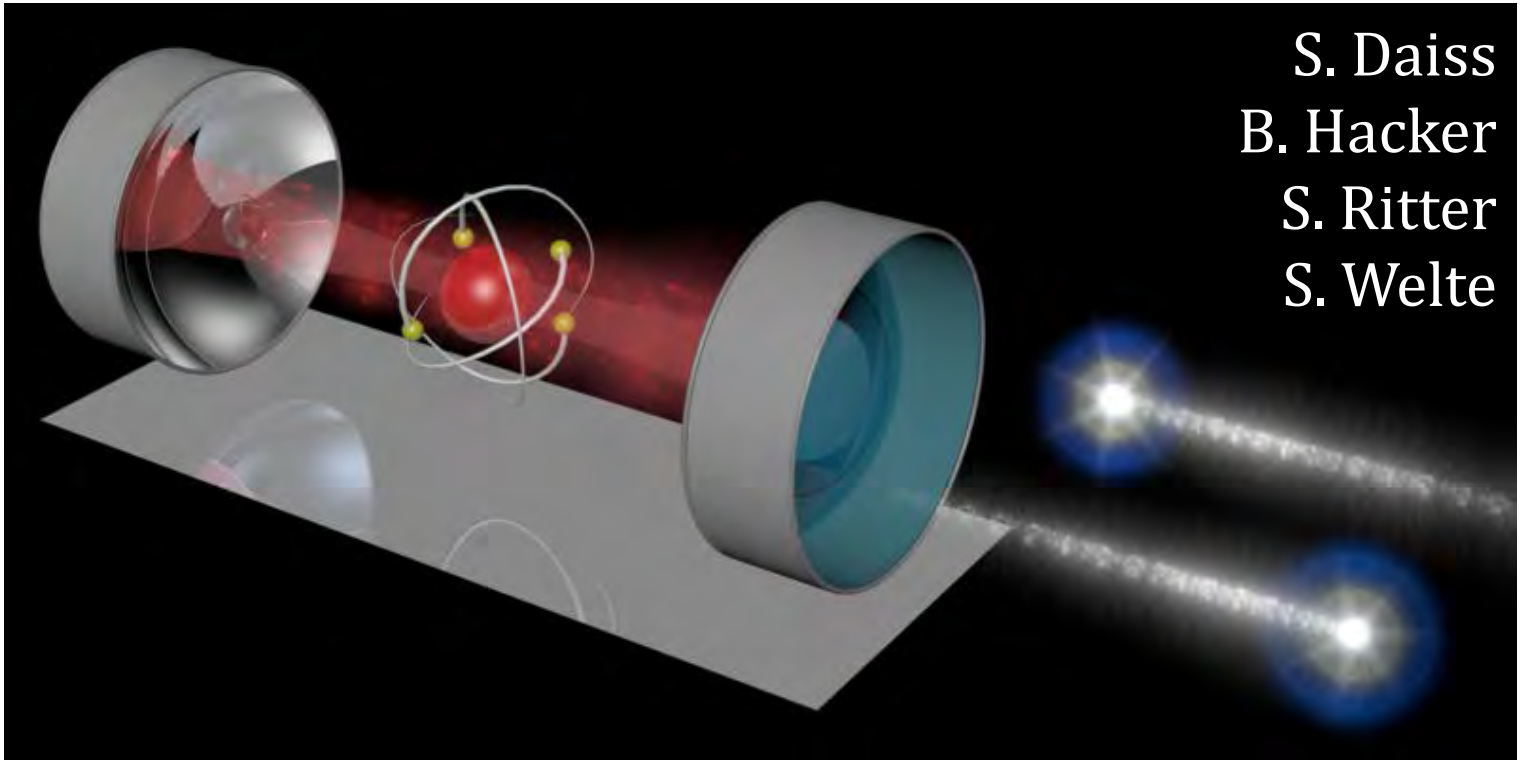
Heralded memory:



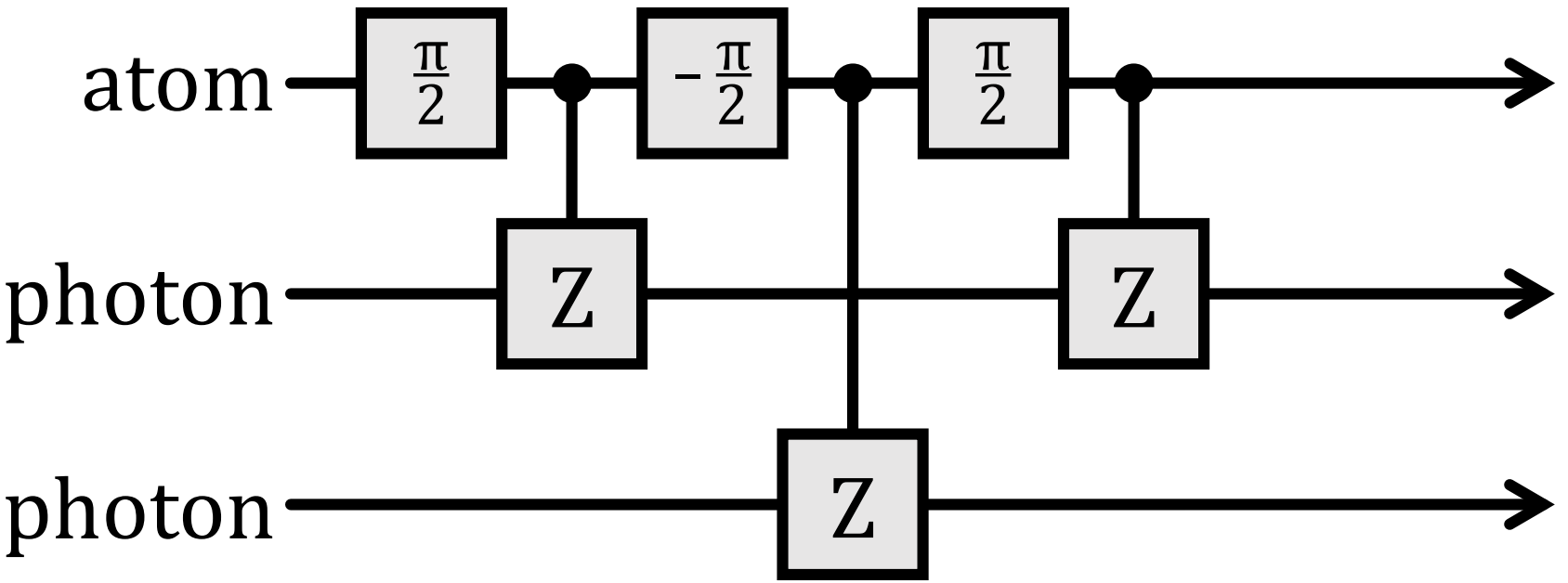
Write-read combined:

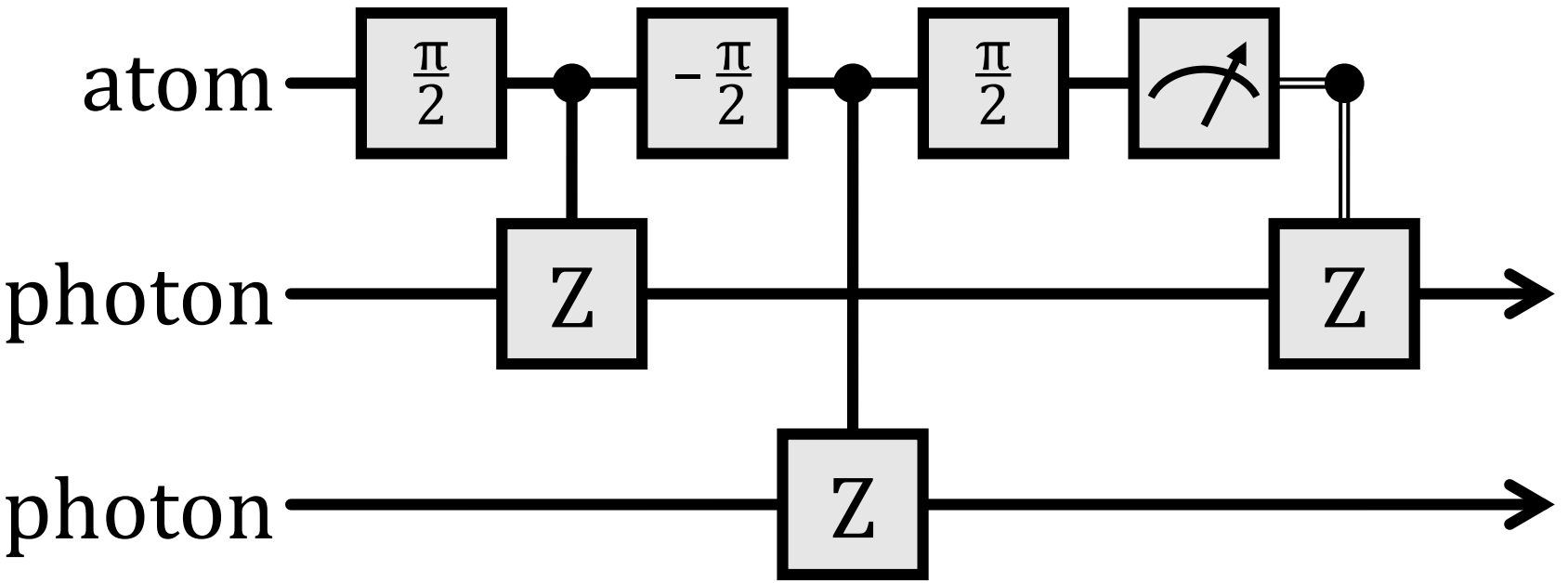
η=39%, F=86%

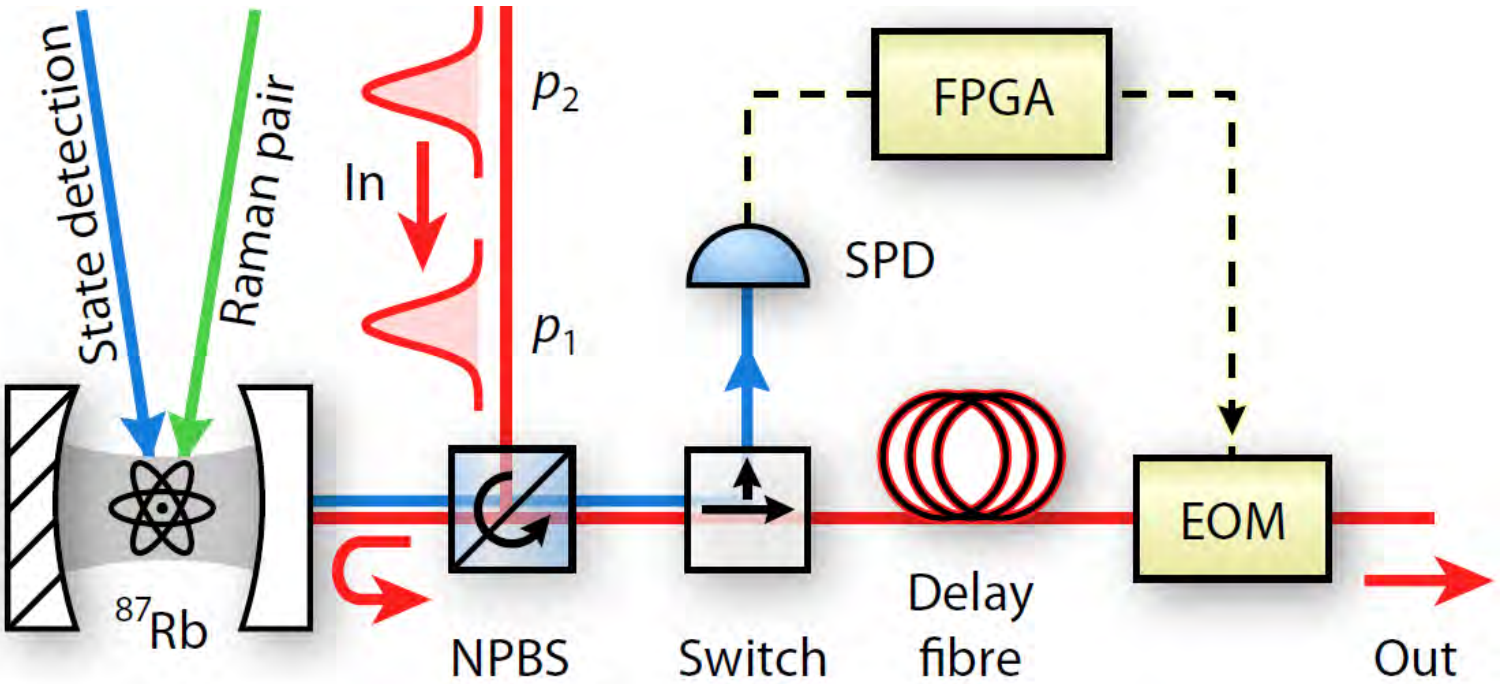
Quantum computation:

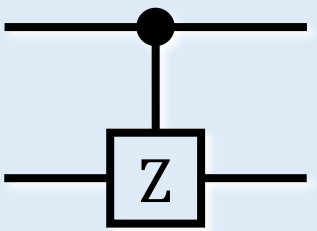
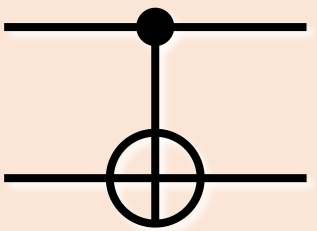
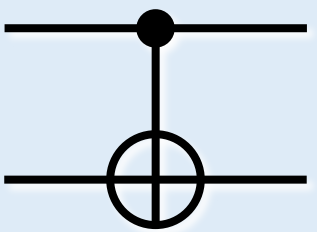
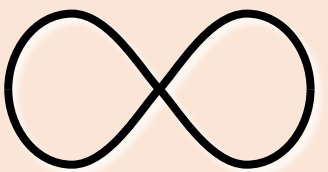


Photons can be ideal qubits.

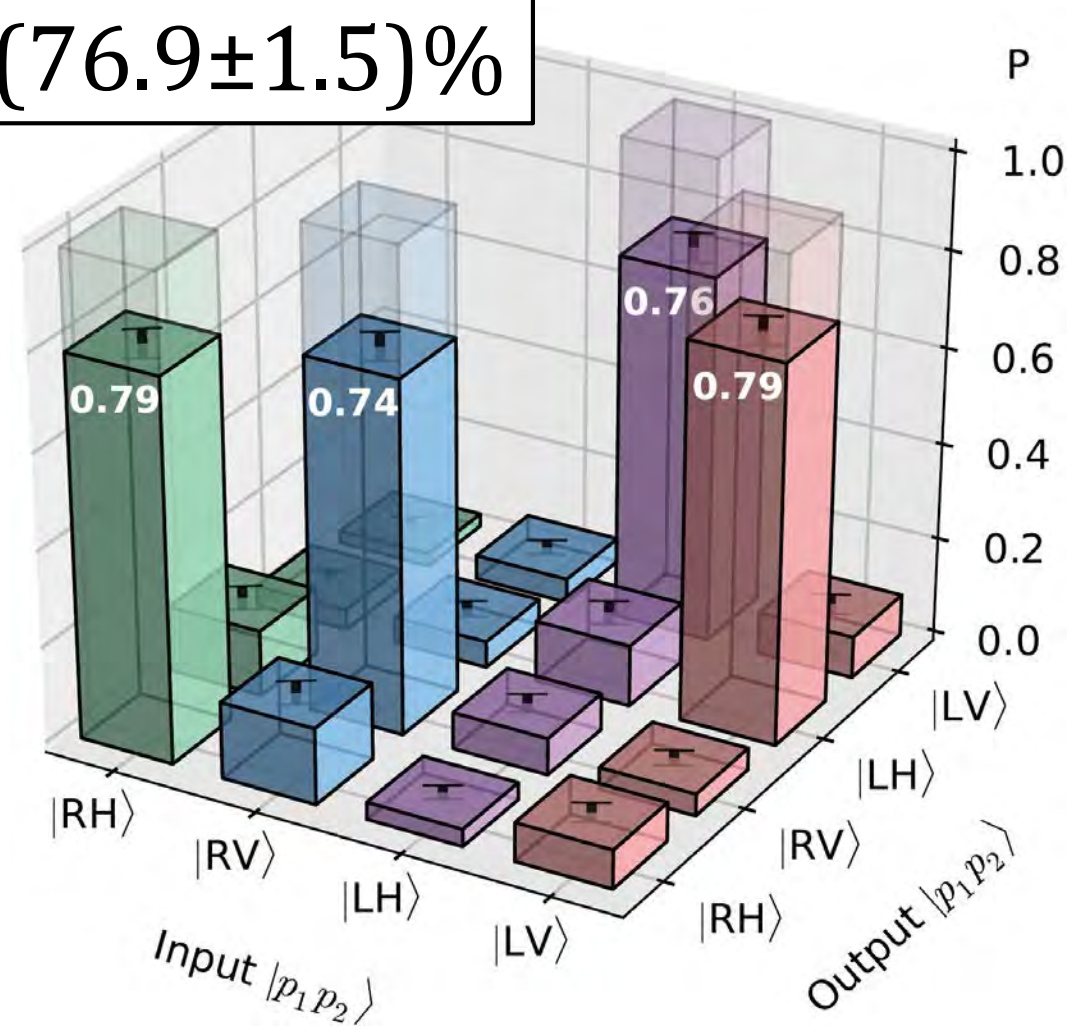

atom
photon
photon
π/2
−π/2
π/2
Z
Z
Z


atom
photon
photon
π/2
−π/2
π/2
Z
Z
Z


State detection
Raman pair
In
p_2
p_1
FPGA
SPD
^{87}Rb
NPBS
Switch
Delay fibre
EOM
Out

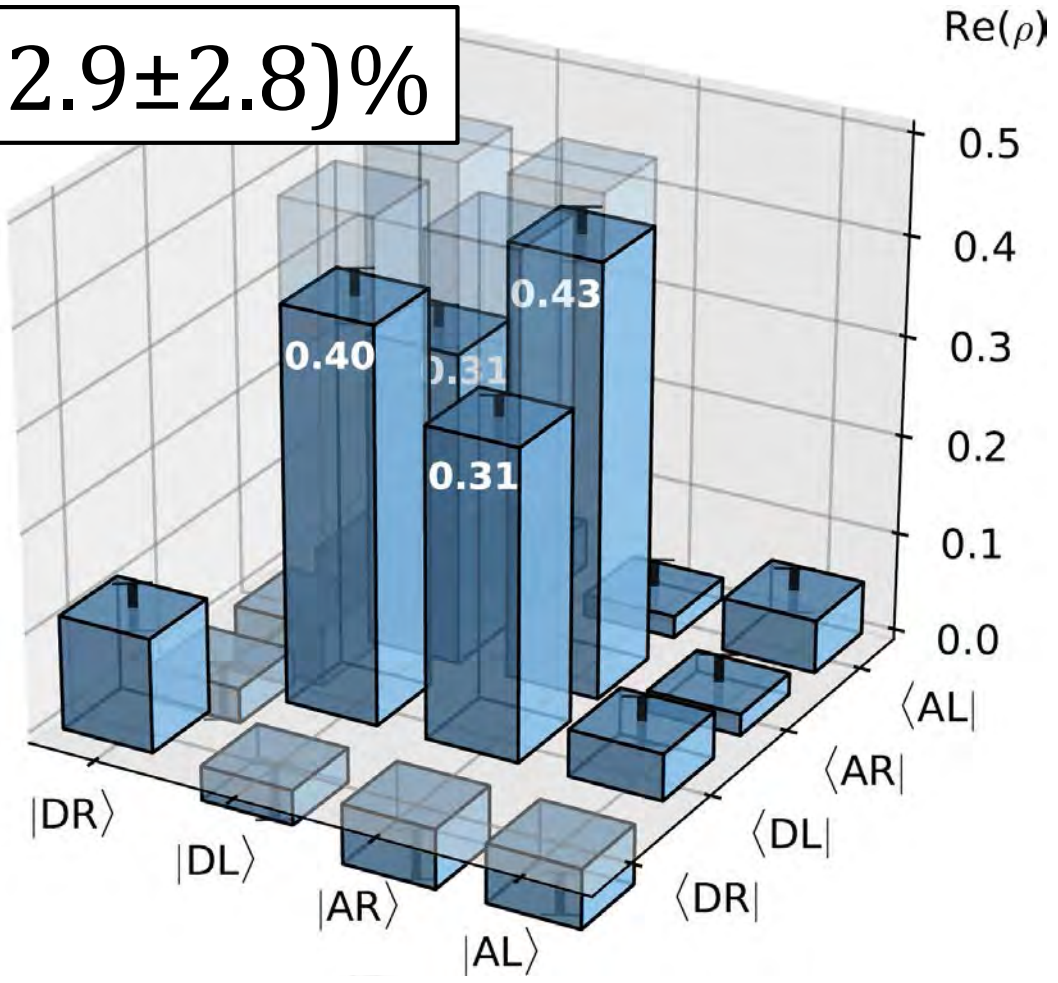
photon	target: circular	target: linear
control: circular		
control: linear		

$F_{\mathrm{CNOT}}=(76.9\pm1.5)\%$



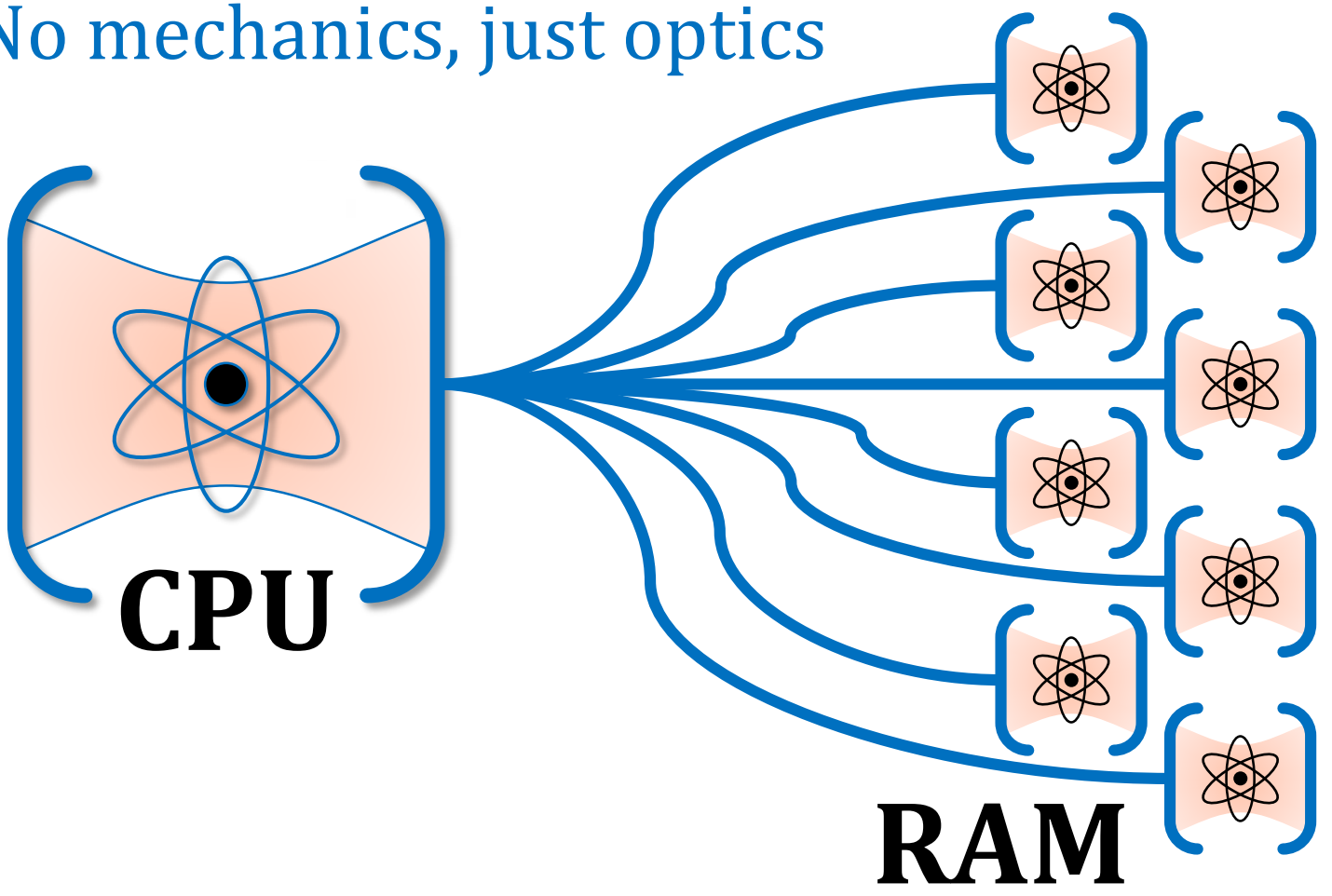
$$|D\rangle|D\rangle \rightarrow |DL\rangle + |AR\rangle$$

$F_{\text{Bell}}=(72.9\pm2.8)\%$



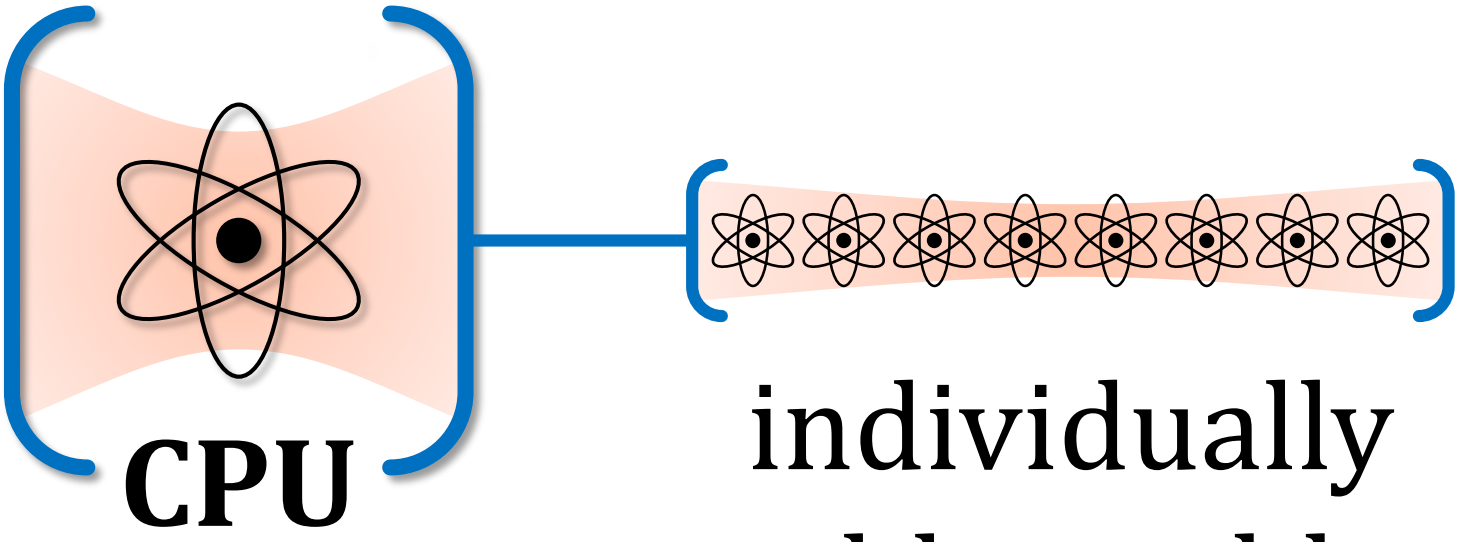
Scalable quantum computer

No mechanics, just optics

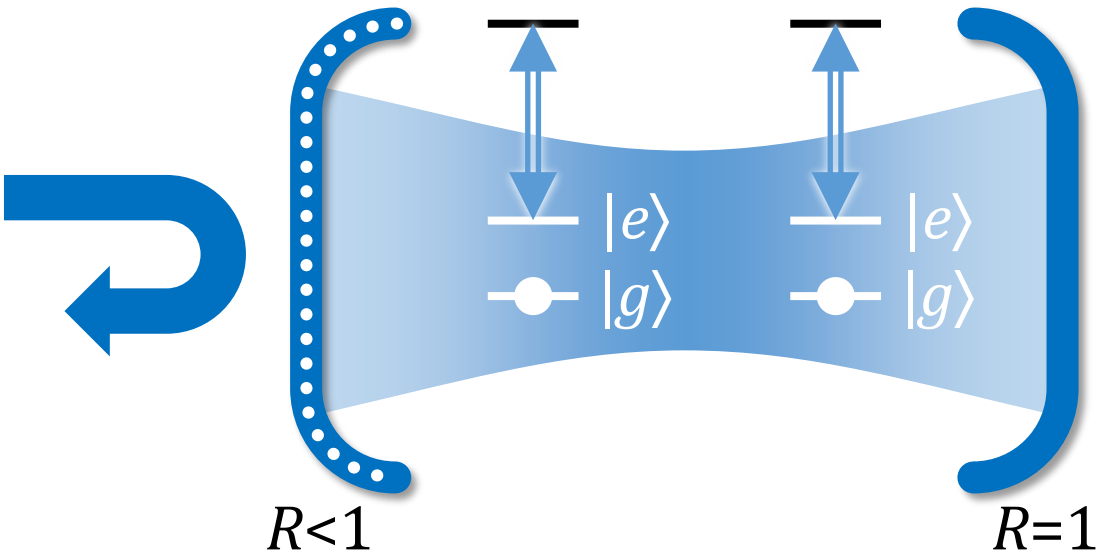


Scalable quantum computer

No mechanics, just optics

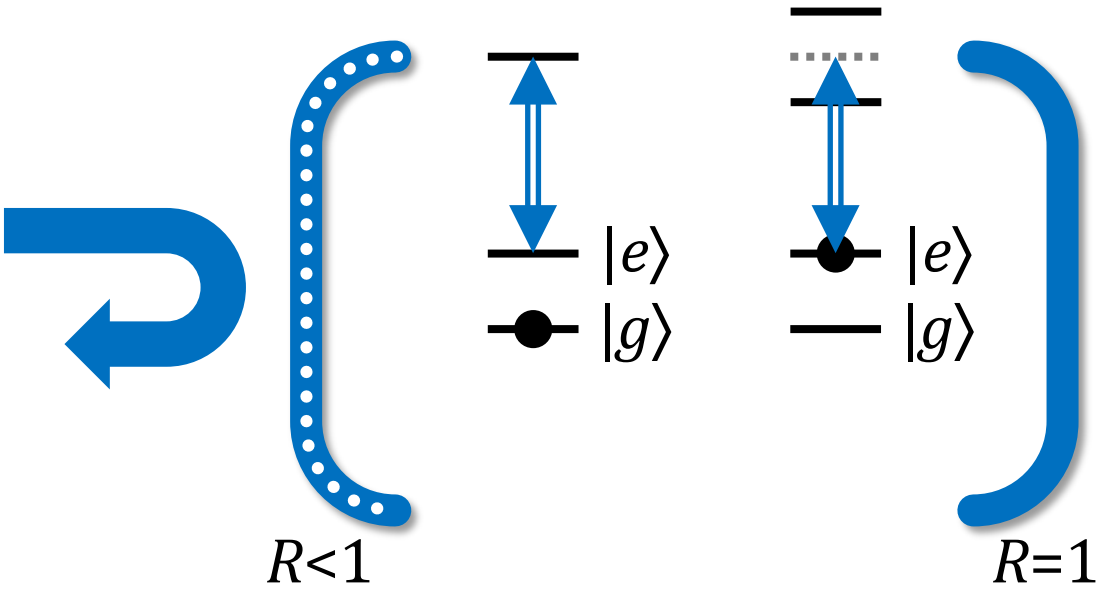


Atom-atom gate:



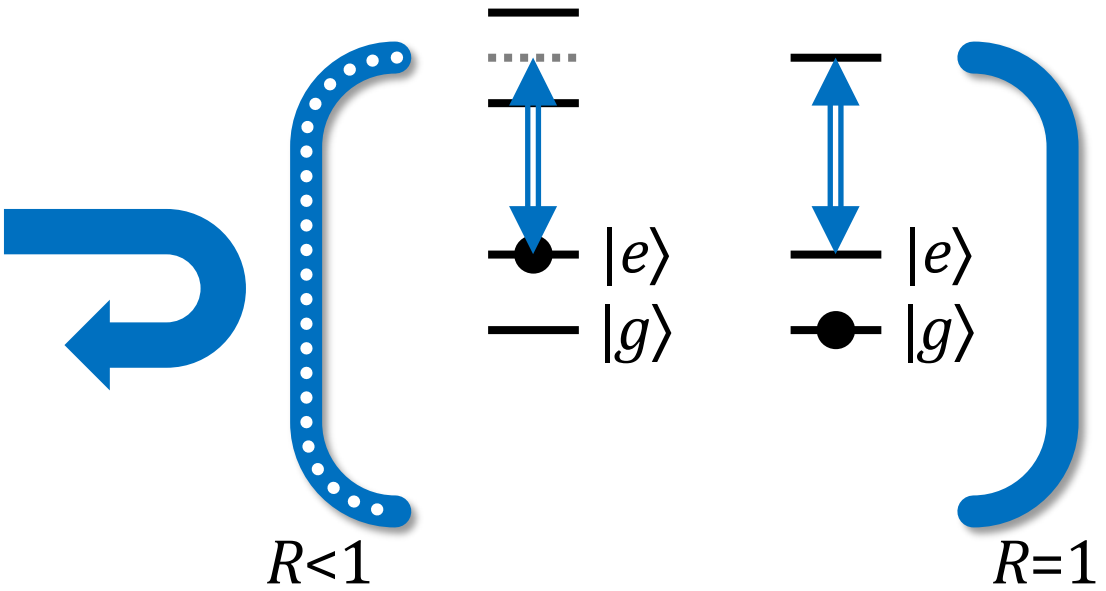
π phase shift.

Atom-atom gate:



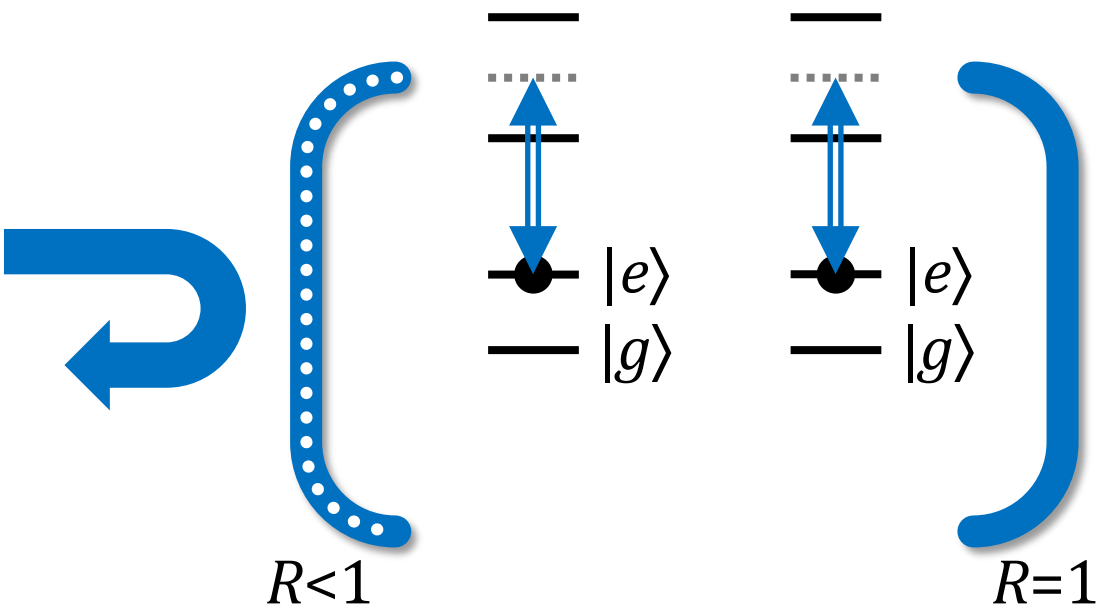
0 phase shift.

Atom-atom gate:



0 phase shift.

Atom-atom gate:



0 phase shift.

$$|eg\rangle - |ge\rangle \rightarrow |eg\rangle - |ge\rangle$$

$$|eg\rangle + |ge\rangle \rightarrow |eg\rangle + |ge\rangle$$

$$|ee\rangle - |gg\rangle \rightarrow |ee\rangle + |gg\rangle$$

$$|ee\rangle + |gg\rangle \rightarrow |ee\rangle - |gg\rangle$$

$$\left(|e\rangle + |g\rangle\right) \otimes \left(|e\rangle + |g\rangle\right)$$

$$=$$

$$|ee\rangle + |eg\rangle + |ge\rangle + |gg\rangle$$

$$(|e\rangle + |g\rangle) \otimes (|e\rangle + |g\rangle)$$

$$=$$

$$|ee\rangle + |eg\rangle + |ge\rangle + |gg\rangle$$

cavity ↓ carving

$$\cancel{|ee\rangle} + |eg\rangle + |ge\rangle + \cancel{|gg\rangle}$$

$$|ee\rangle\overbrace{\left(|L\rangle - i|R\rangle\right)}^{|A\rangle}$$

$$\xrightarrow[\text{reflection}]{\text{qubit}}$$

$$|ee\rangle\underbrace{\left(|L\rangle + i|R\rangle\right)}_{|D\rangle}$$

$$|ee\rangle|A\rangle \rightarrow |ee\rangle|D\rangle$$

$$|eg\rangle|A\rangle \rightarrow |eg\rangle|D\rangle$$

$$|ge\rangle|A\rangle \rightarrow |ge\rangle|D\rangle$$

$$|gg\rangle|A\rangle \rightarrow |gg\rangle|A\rangle$$

* up to an overall minus sign

$$|ee\rangle|A\rangle \rightarrow |ee\rangle|D\rangle$$

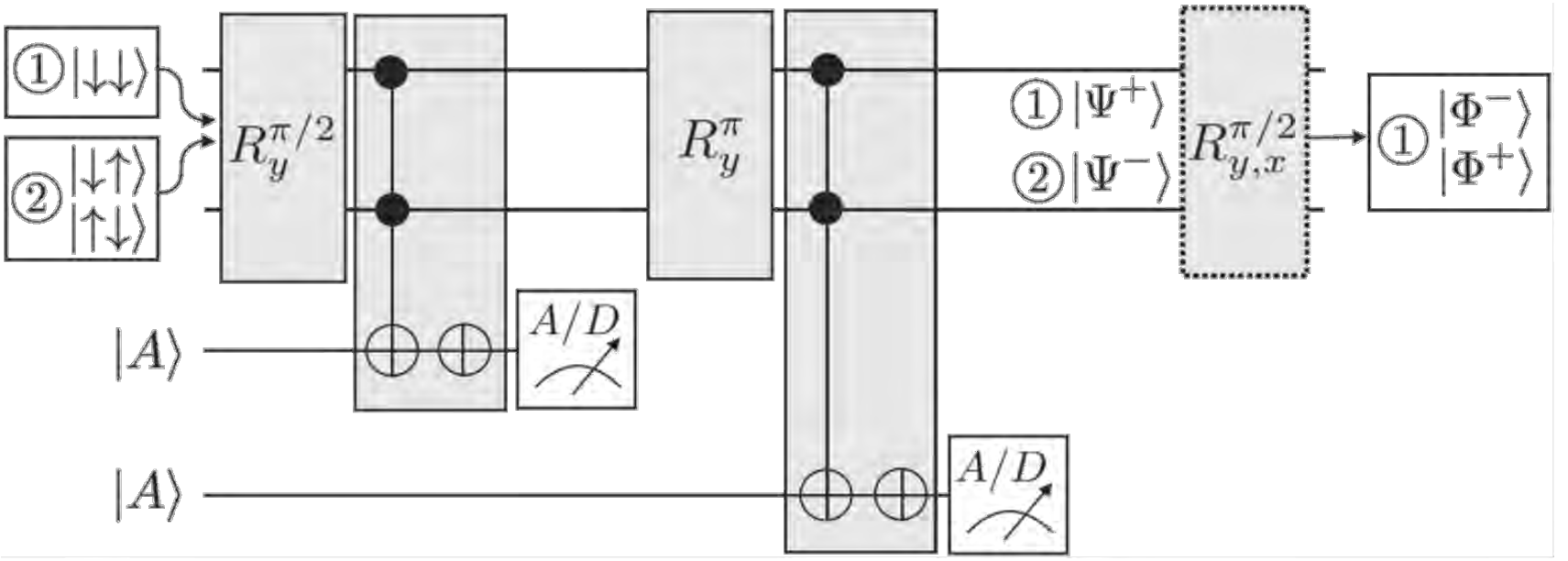
$$|eg\rangle|A\rangle \rightarrow |eg\rangle|D\rangle$$

$$|ge\rangle|A\rangle \rightarrow |ge\rangle|D\rangle$$

$$|gg\rangle|A\rangle \not\rightarrow |gg\rangle|A\rangle$$

* up to an overall minus sign

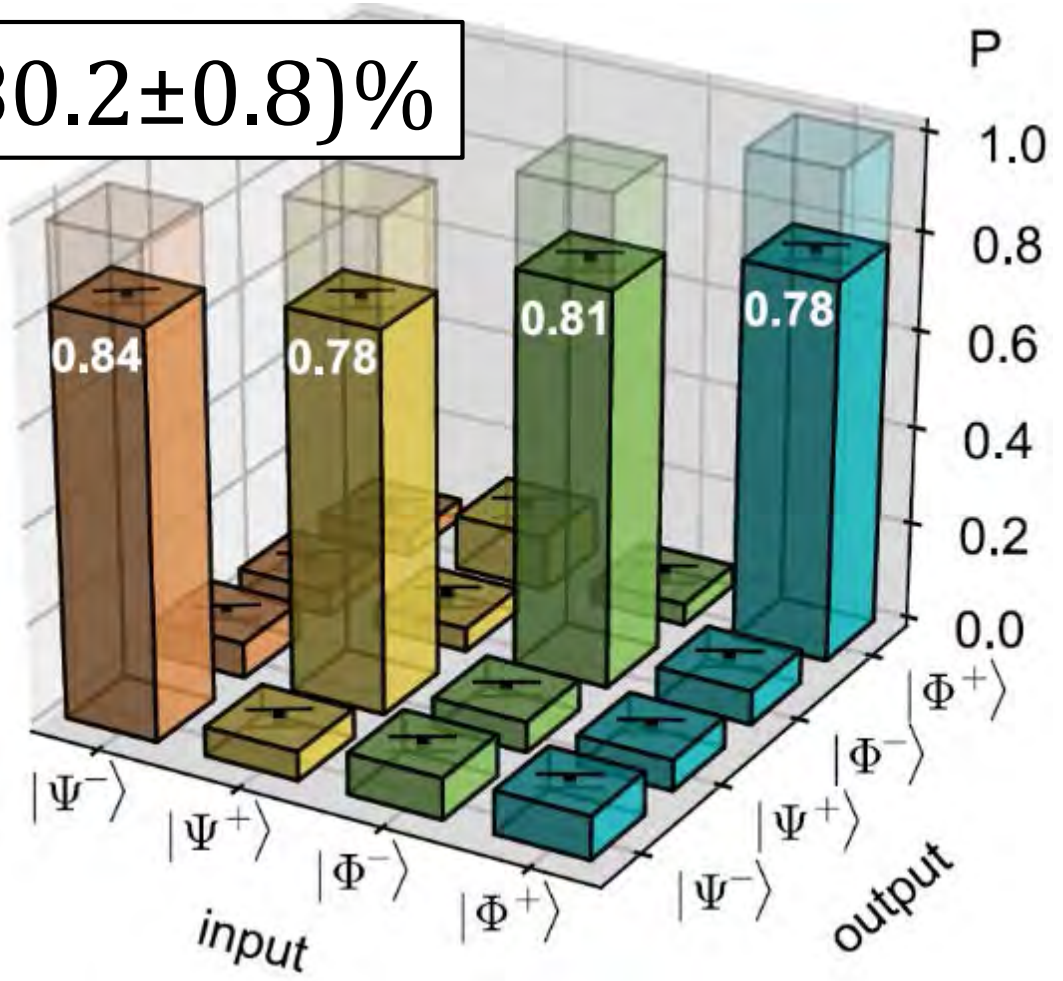
Double cavity carving:



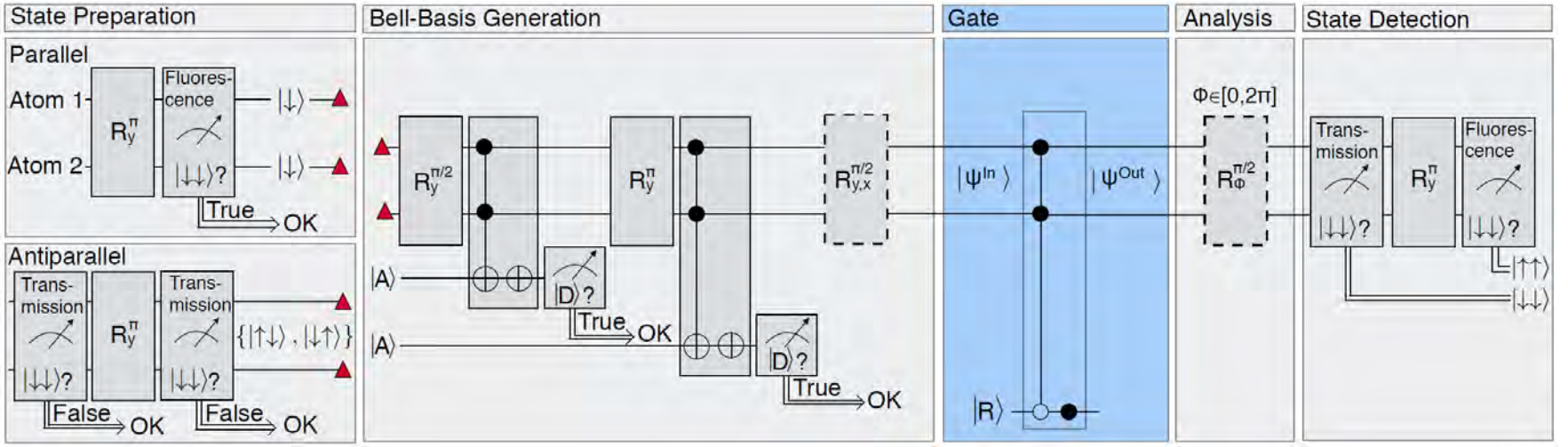
Polarization rotation heralds entanglement.

Gate input:

$F_{\mathrm{Bell}}=(80.2\pm0.8)\%$



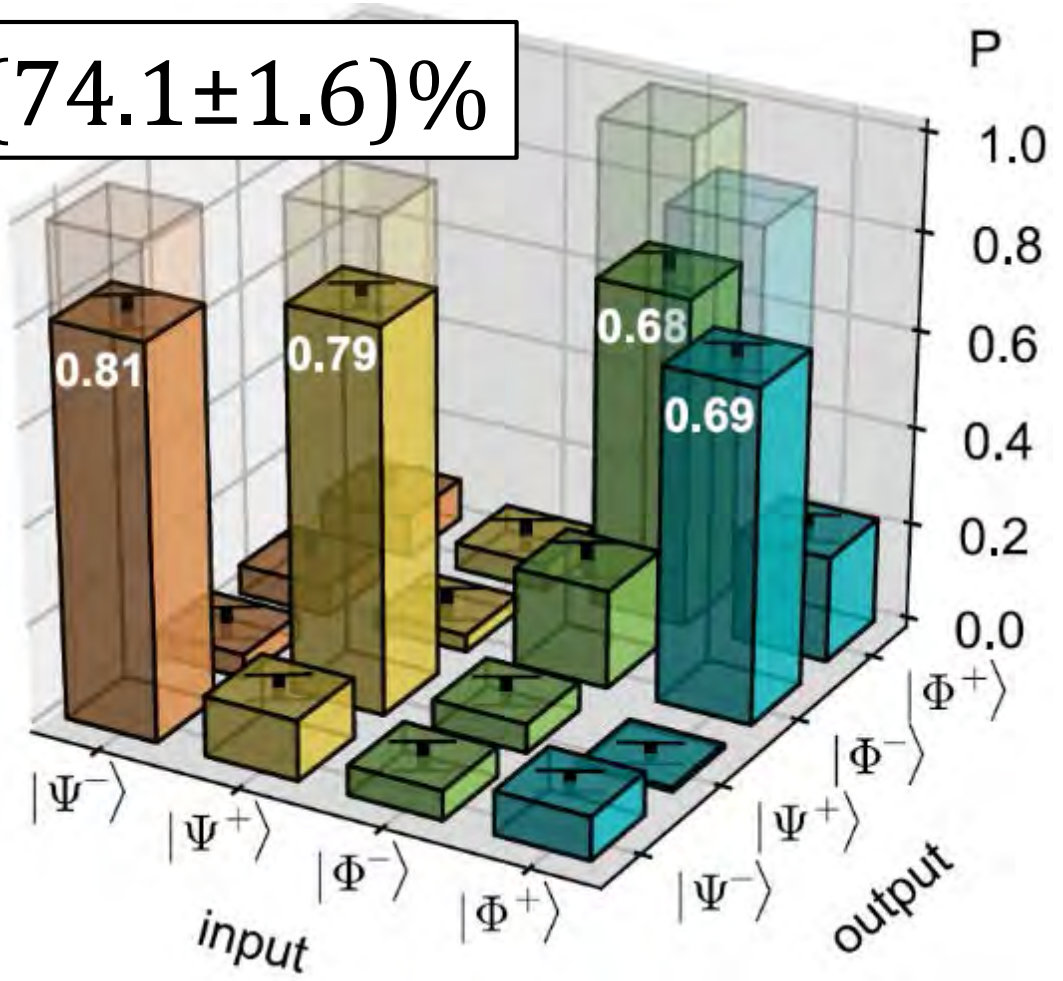
Quantum gate:



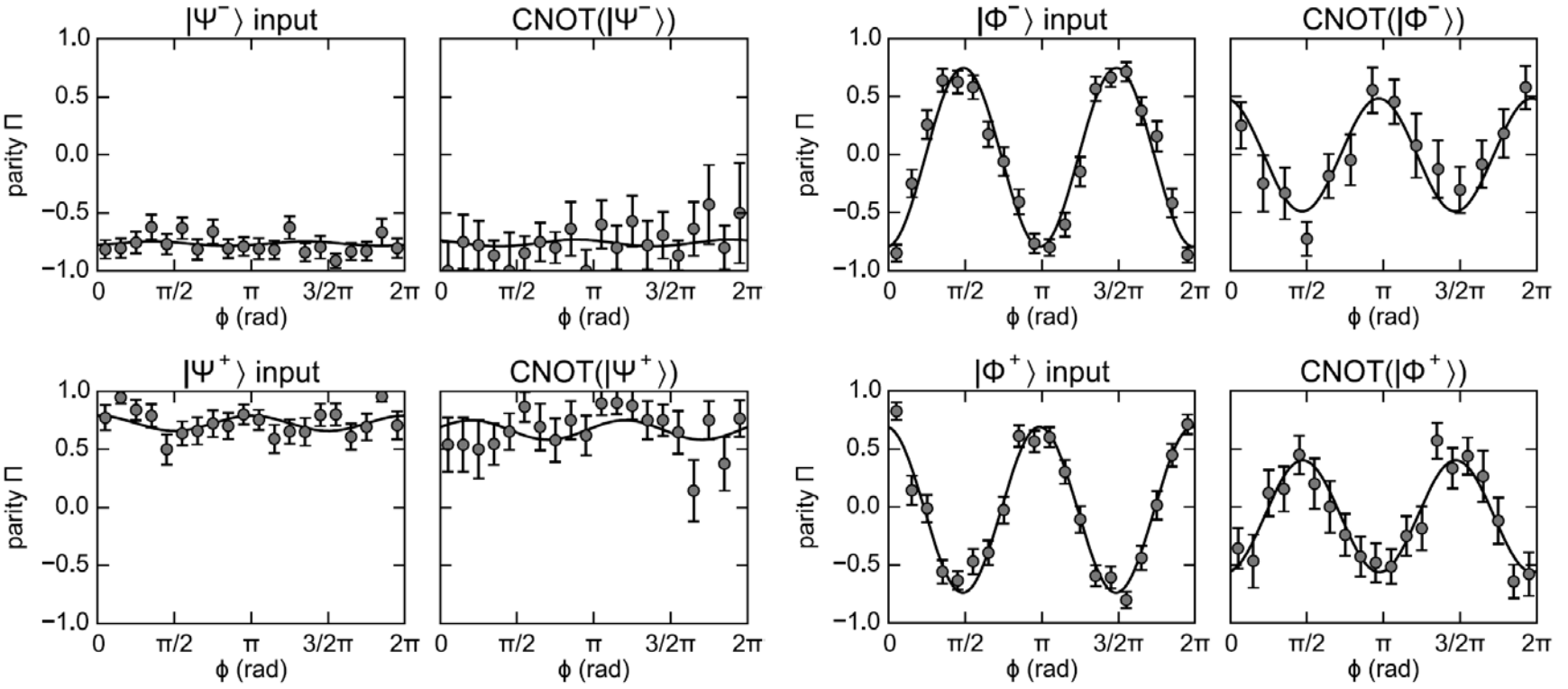
Just one more reflection of a “classical” photon!

Gate output:

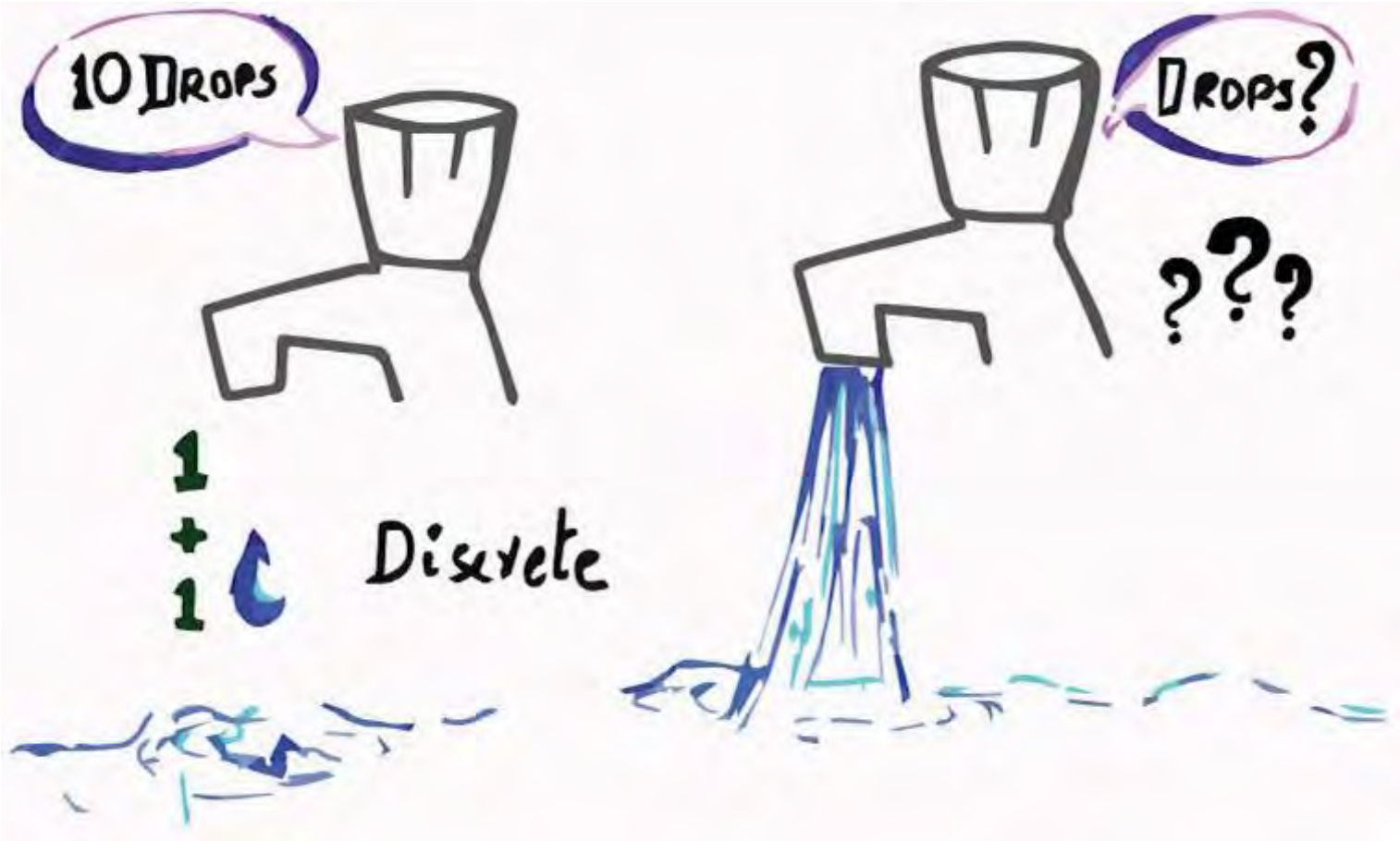
$F_{\mathrm{CNOT}}=(74.1\pm1.6)\%$



Parity oscillations …

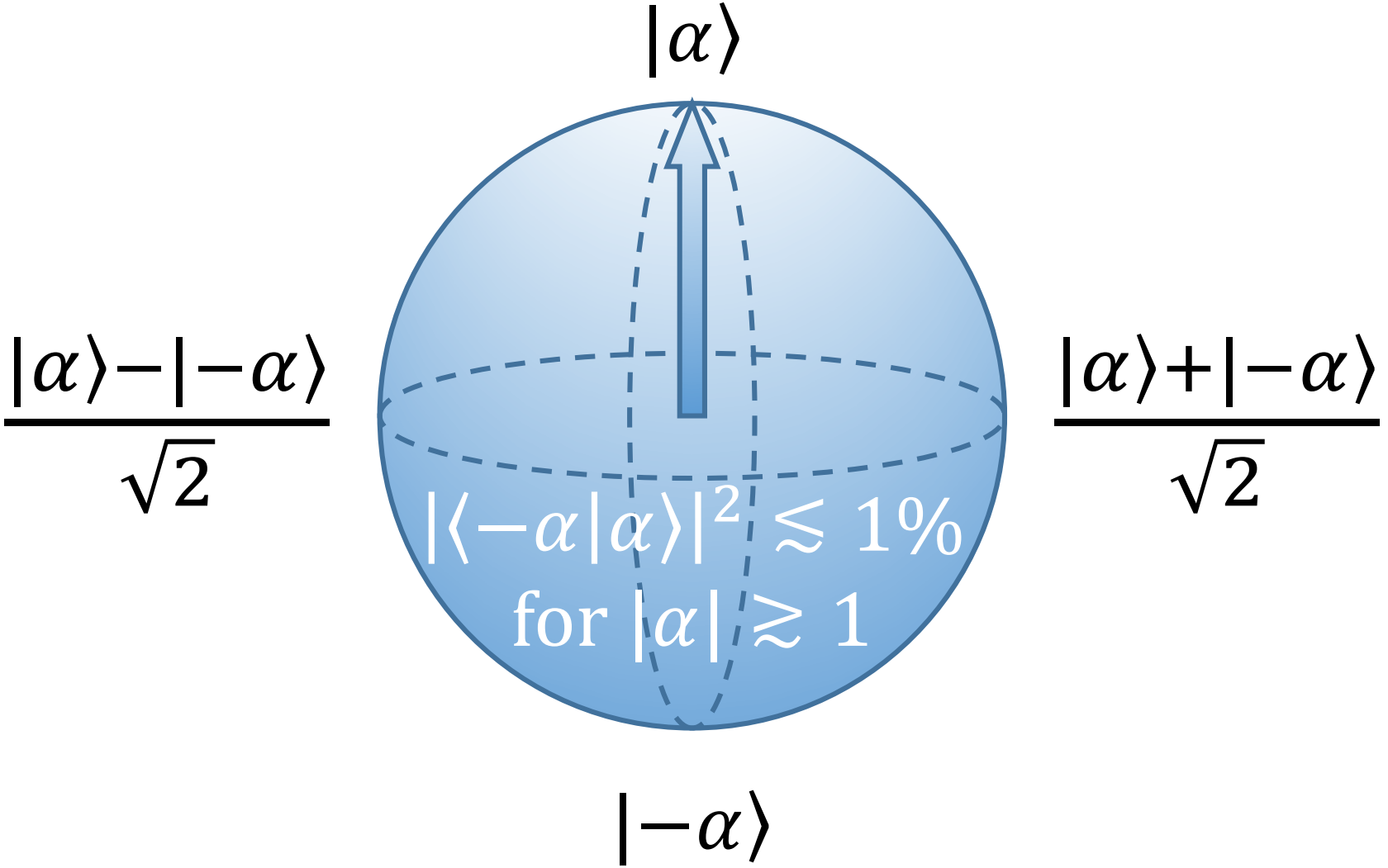


… before/after gate execution

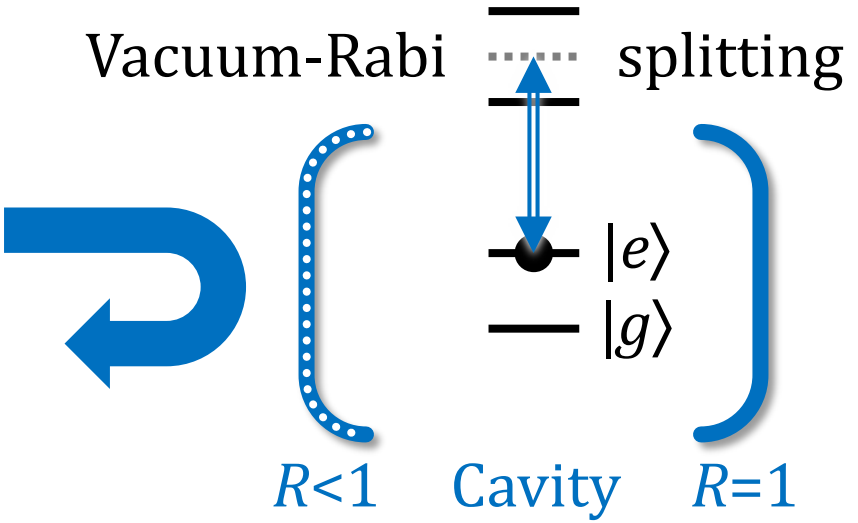


S. Daiss, B. Hacker, L. Li, S. Welte

Continuous variables

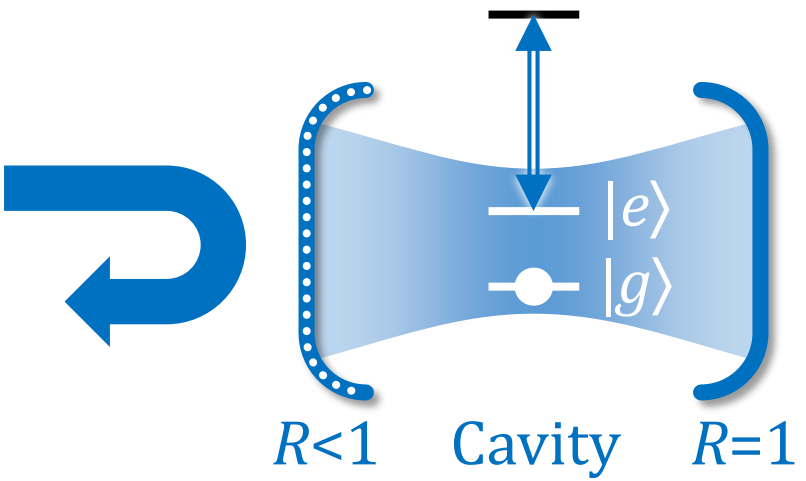


Photon reflection (from front mirror):



$$|\alpha\rangle \rightarrow |\alpha\rangle$$

Photon reflection (from back mirror):



$$|\alpha\rangle \rightarrow |-\alpha\rangle$$

$$\left(|e\rangle + |g\rangle\right) \otimes |\alpha\rangle$$

$$\xrightarrow[\text{reflection}]{\text{light}} \quad |e,\alpha\rangle + |g,-\alpha\rangle$$

Flying cat state with size ~1km

(Duan et al.)

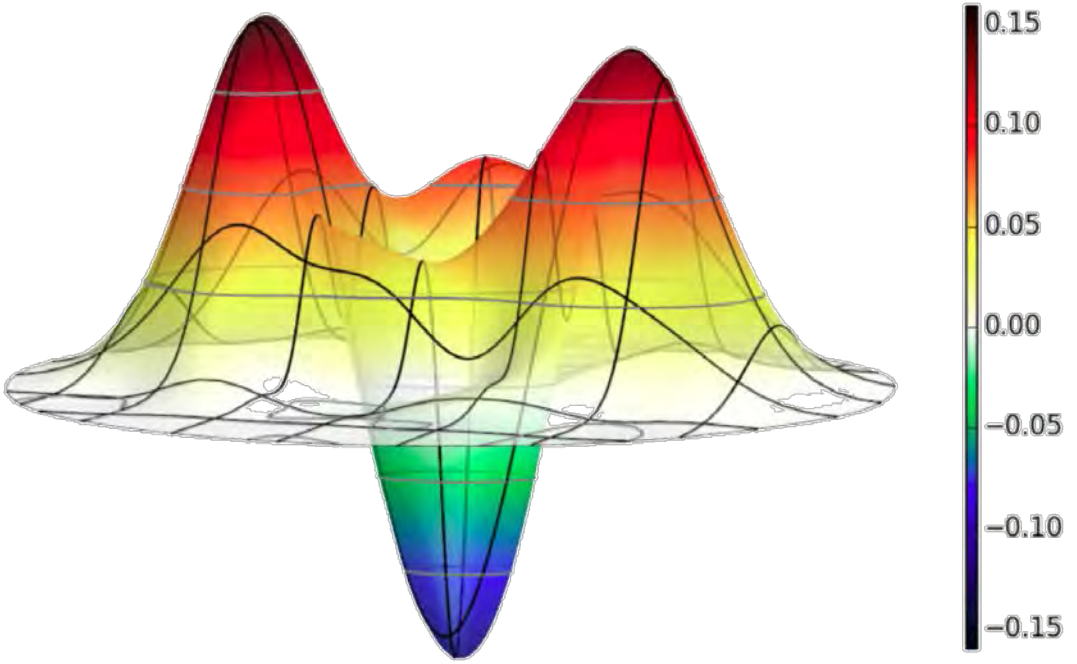
$$\left(|e\rangle + |g\rangle\right) \otimes |\alpha\rangle$$

$$\xrightarrow[\text{reflection}]{\text{light}} \quad |e,\alpha\rangle + |g,-\alpha\rangle$$

$$\xrightarrow[\text{rotation}]{\text{atom}} \quad |e\rangle \overbrace{\left(|\alpha\rangle - |-\alpha\rangle\right)}^{\text{odd cat}}$$

$$+ |g\rangle \underbrace{\left(|\alpha\rangle + |-\alpha\rangle\right)}_{\text{even cat}}$$

Optical cat



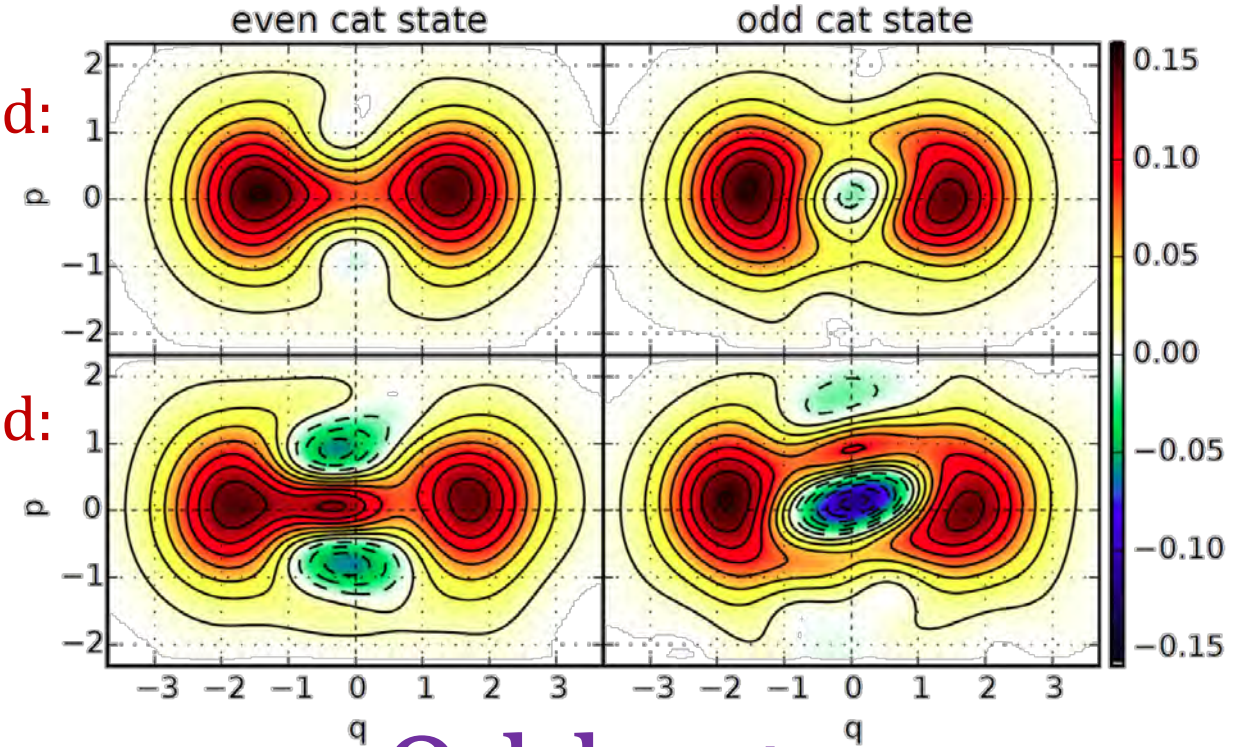
Odd cat:

$W(0,0) = -0.117(14)$

Optical cats

Detected:

Emitted:



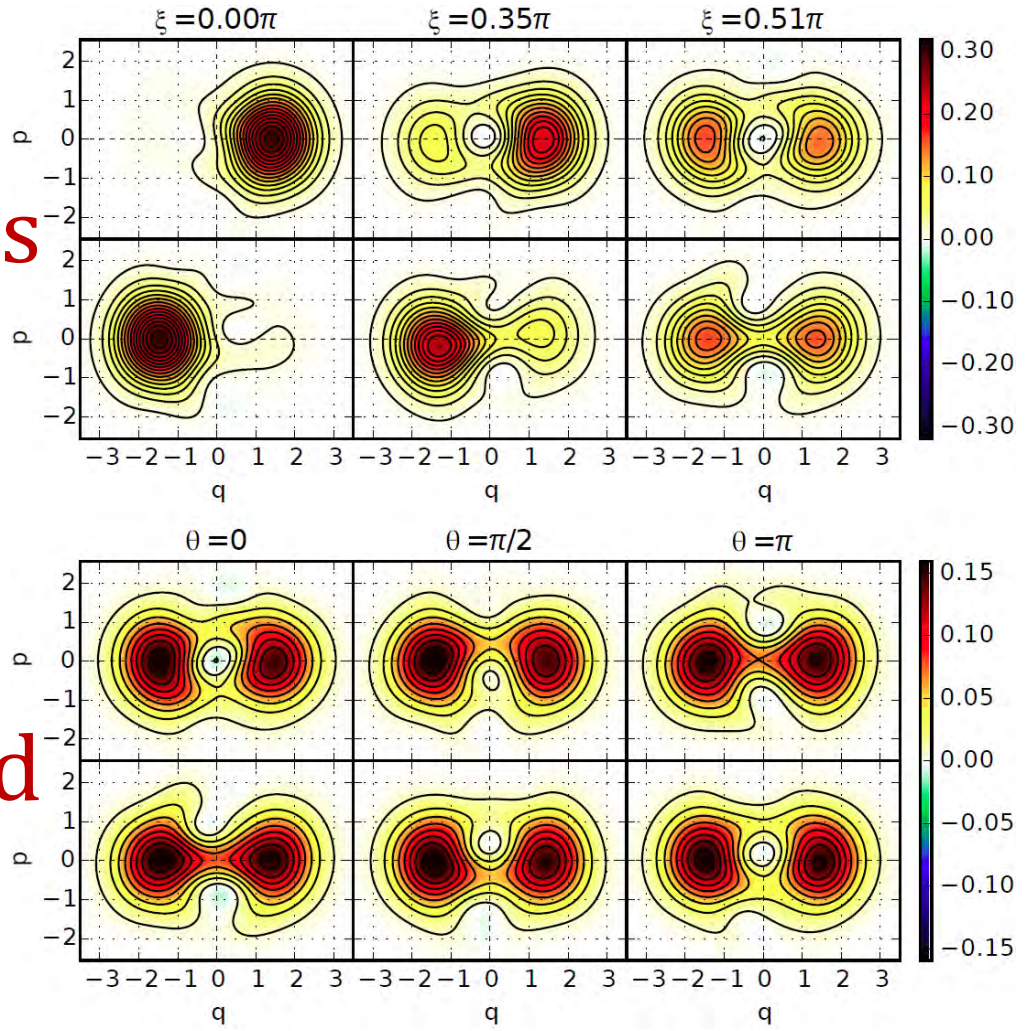
Odd cat:

$$W(0,0) = -0.117(14)$$

Tuned cats

Cattiness

Even/odd



Take-home message:

Light-matter entanglement is a resource now, available on demand.

A.Reiserer & GR, Rev. Mod. Phys. **87**, 1379 (2015)