

Me



Durham



The rise and rise of Rydberg atoms!

2000

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Highlights Recent Accepted Collections Authors Referees

Fast Quantum Gates for Neutral Atoms

D. Jaksch, J. I. Cirac, P. Zoller, S. L. Rolston, R. Côté, and M. D. Lukin
Phys. Rev. Lett. **85**, 2208 – Published 4 September 2000

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2016



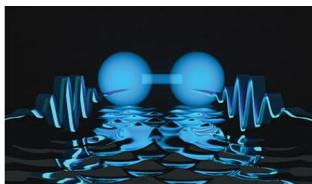
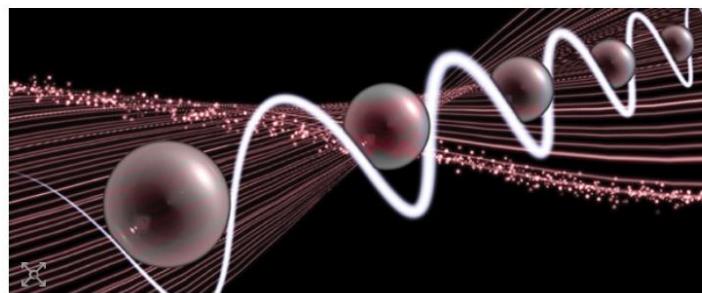
QUANTUM COMPUTING | FEATURE

The rise of Rydberg physics

07 Apr 2016

Taken from the April 2016 issue of Physics World

Quantum computers of the future could operate via the energy transitions of excited atoms, or even from pure light, if a rapidly growing area of atomic physics continues to meet with success, writes Keith Cooper



The rise and rise of Rydberg atoms!

2020

2000

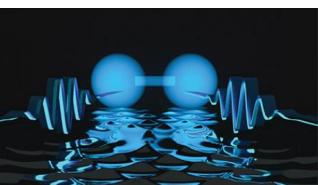
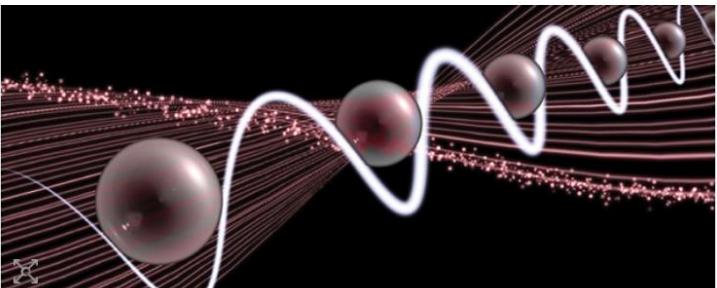
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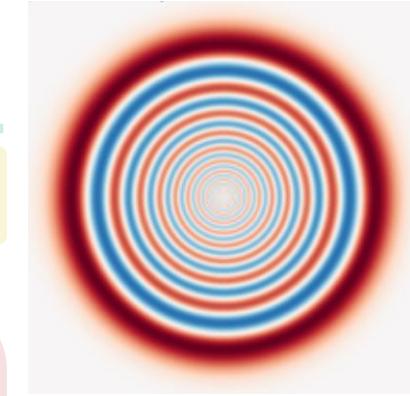
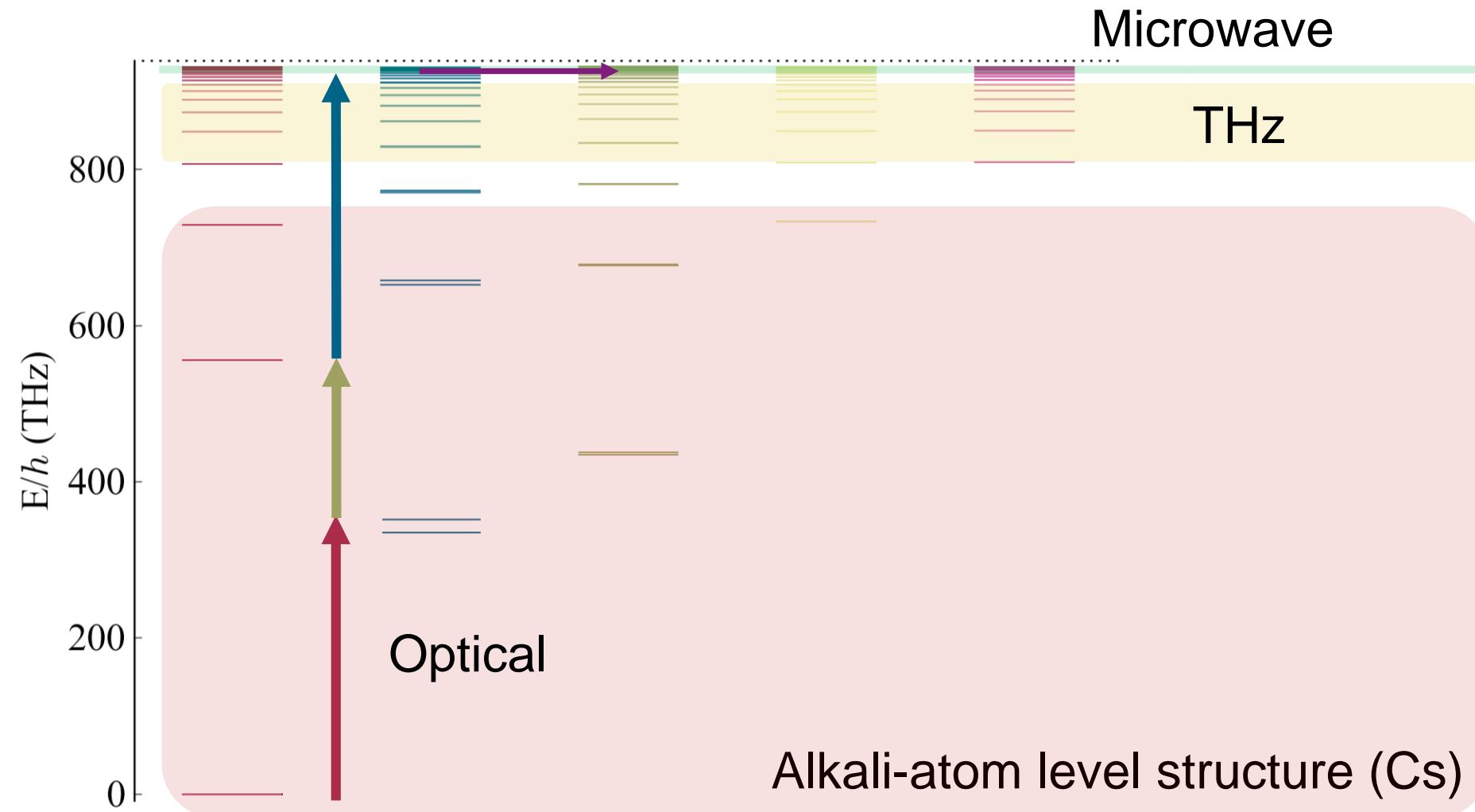
<https://pasqal.io/2020/10/26/1329/>



<http://photonics.phys.strath.ac.uk/square/>



The magic of Rydberg atoms!



Microwave dressing of Rydberg dark states

M Tanasittikosol, J D Pritchard, D Maxwell, A Gauguet, K J Weatherill,
R M Potvliege and C S Adams

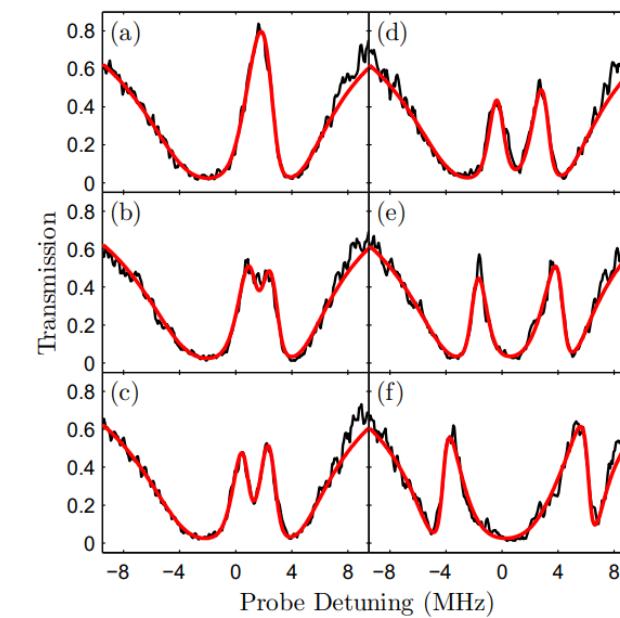
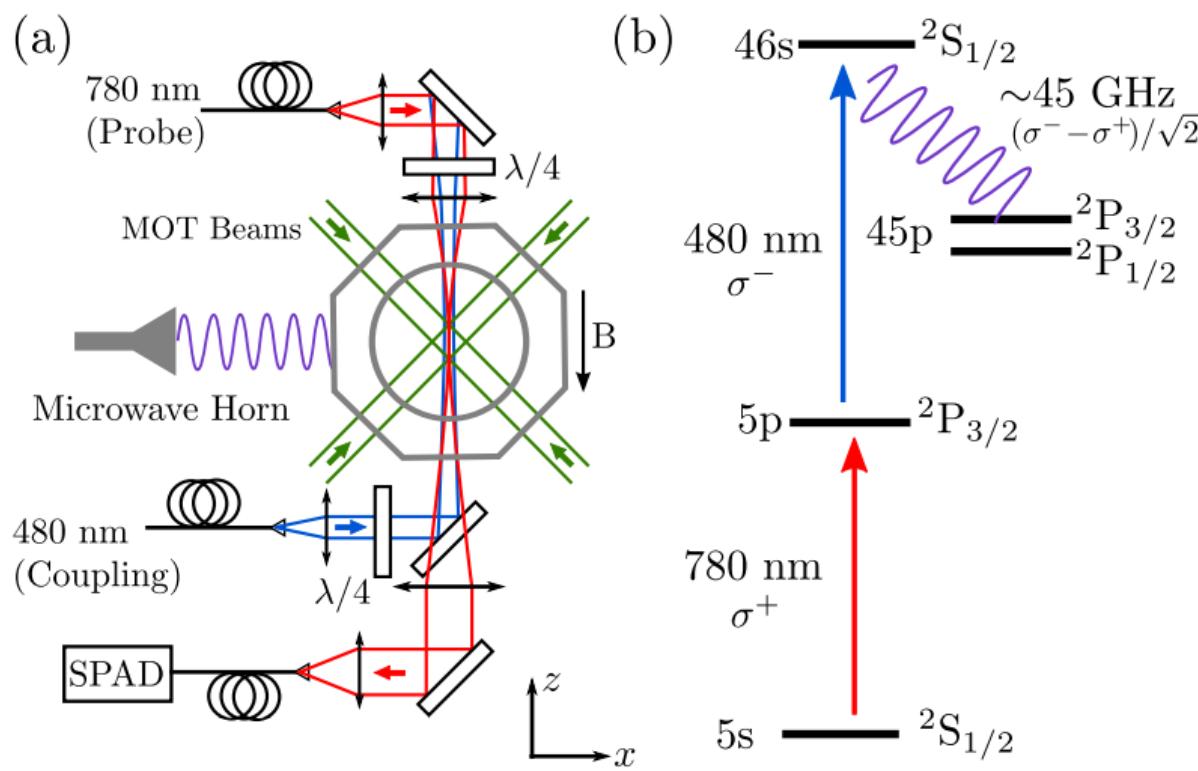
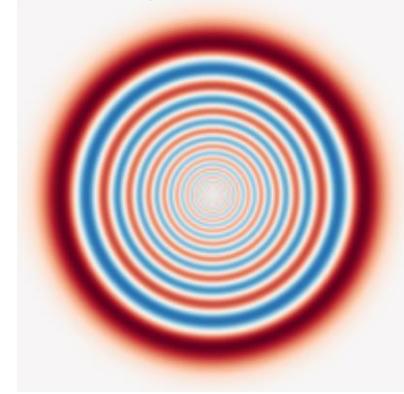
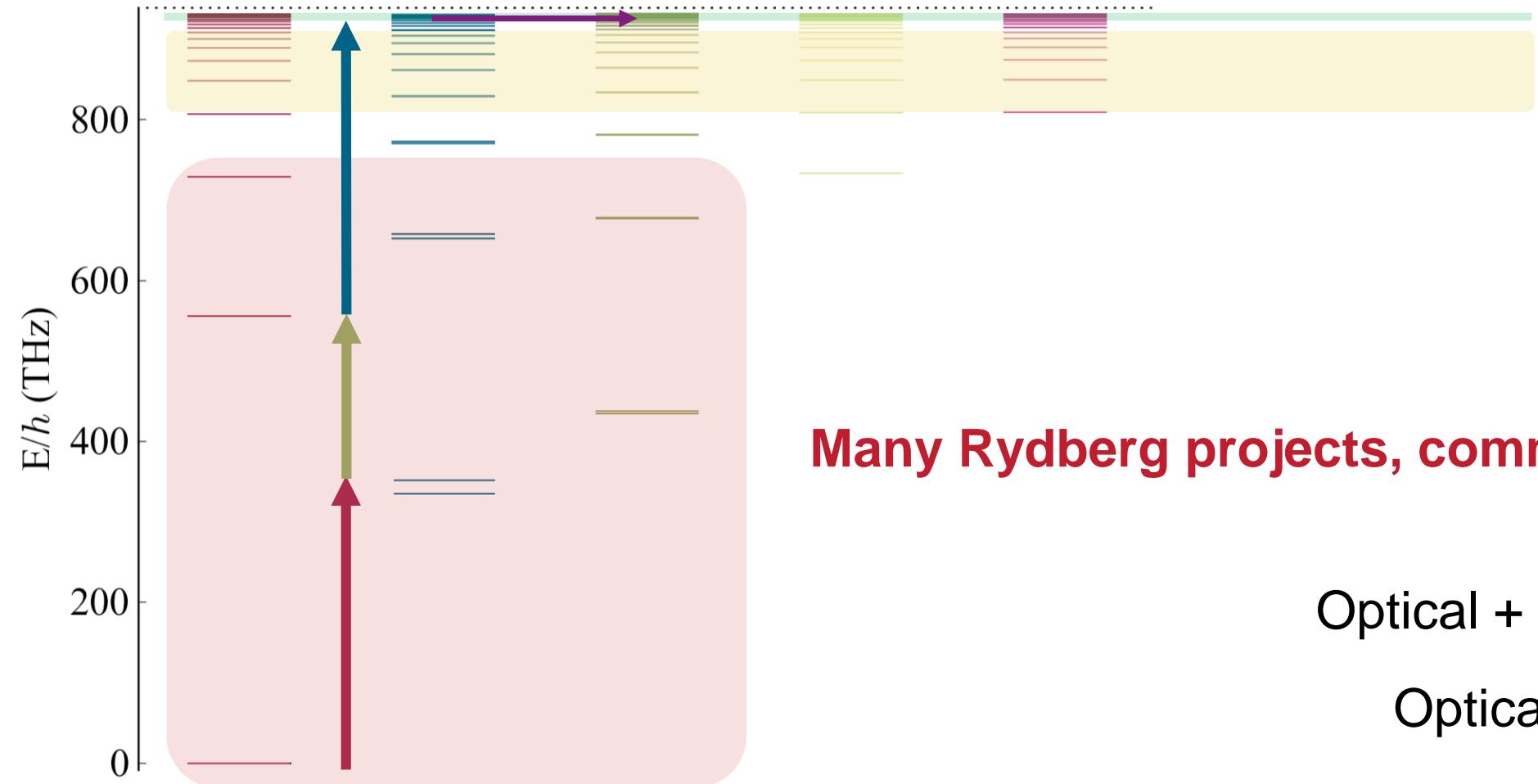


Figure 2. EIT spectra with increasing microwave coupling. The microwave Rabi frequencies, Ω_μ^r from the fit parameters, are (a) 0, (b) 2.2, (c) 3.6, (d) 6.8 (e) 12.2, and (f) $21.0 \times 2\pi$ MHz; these values match the scaling of microwave power in the experiment, although the microwave electric field cannot be measured.

The magic of Rydberg atoms!



Many Rydberg projects, common theme.

Optical + Microwave

Optical + THz



Team Cuprite

Durham



Matt Jones

Charles Adams



Liam Gallagher



Josh Rogers



Dani Pizzey



Jon Pritchett

DAAD

RISE
Research Internships
in Science and Engineering

EPSRC

Cardiff



Stephen Lynch



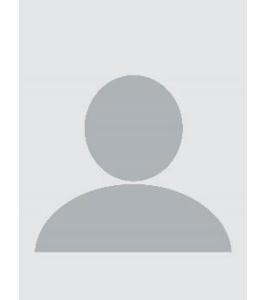
Wolfgang Langbein



Sam Gavin-Pitt



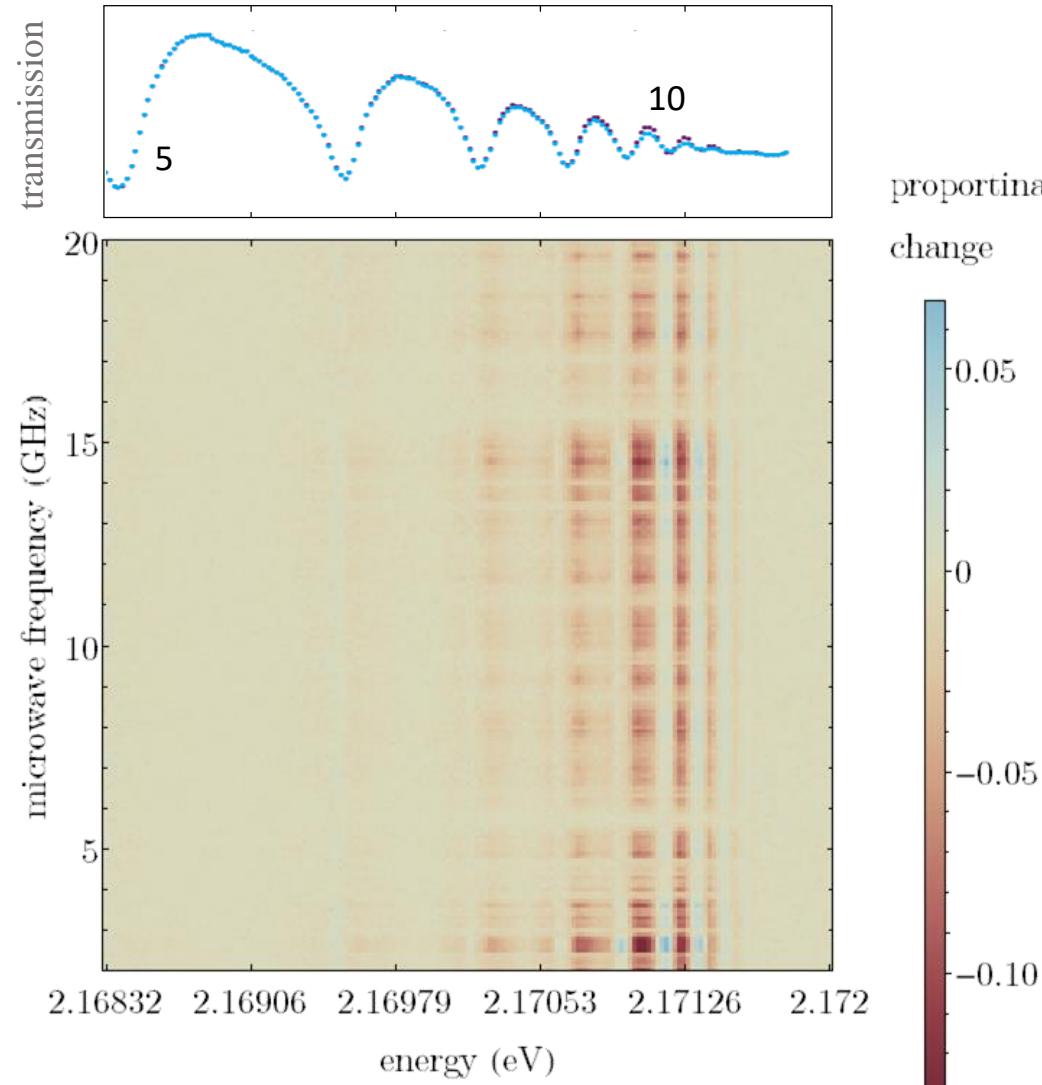
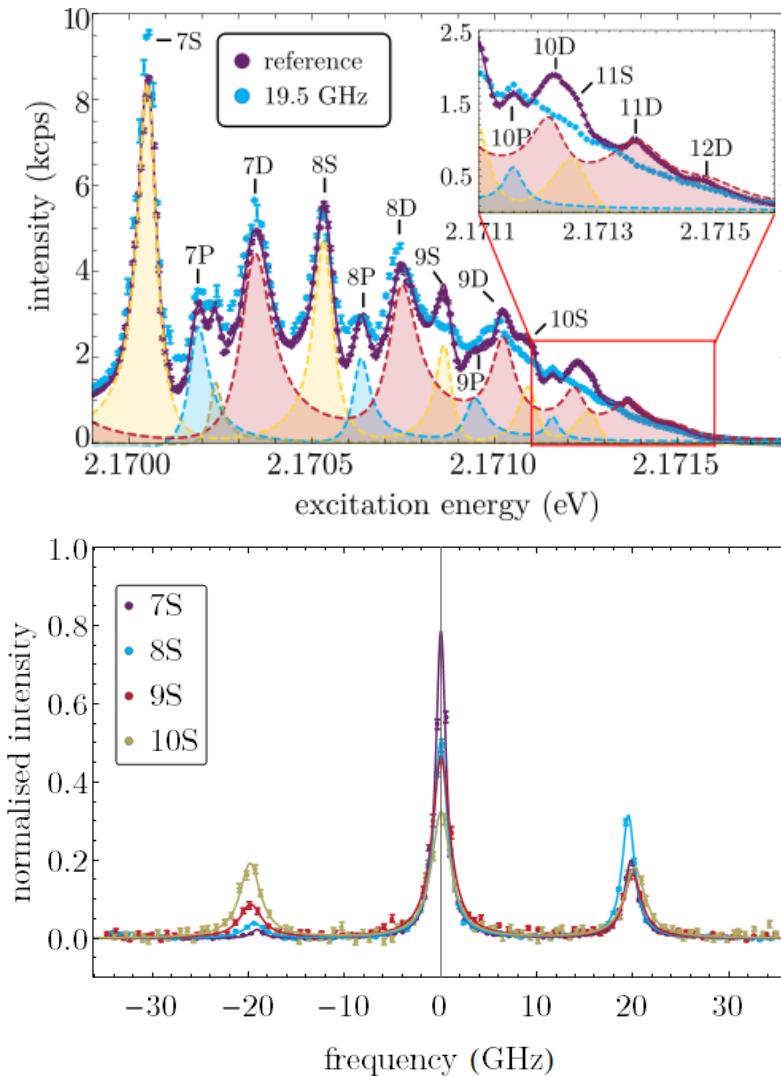
Chris Hodges



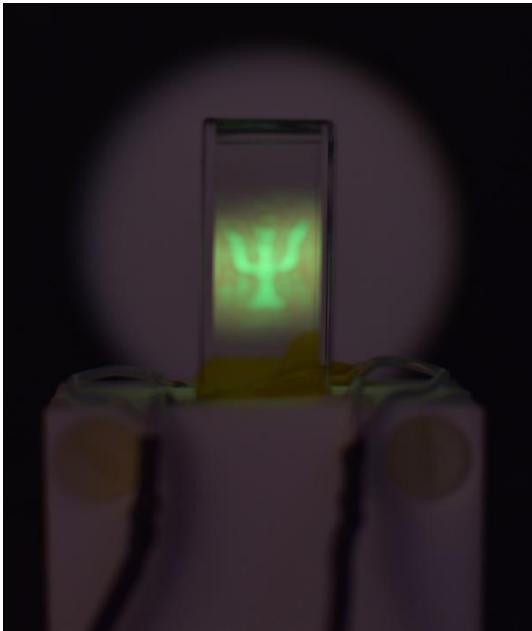
Aisha Albeladi



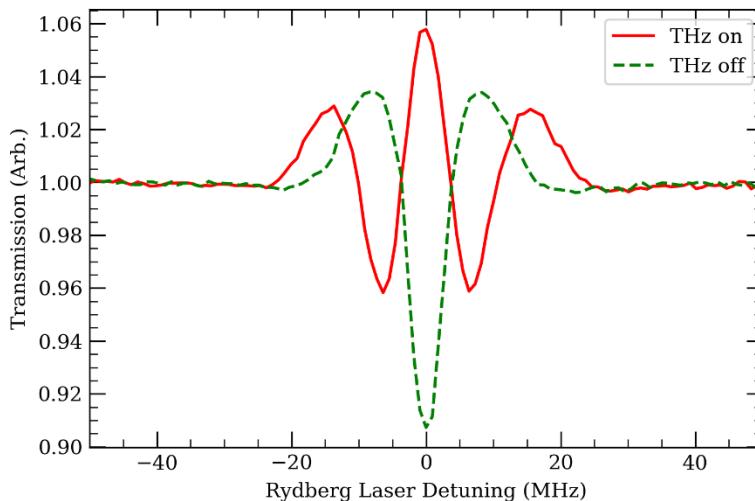
Microwave-driven excitonic state mixing



Team THz



- Interactions of thermal Rydberg vapours (Rb & Cs) with THz fields
- High-speed 2D THz imaging
- THz sensing using Rydberg EIT



Prof. Kevin Weatherill
(he/him)



Prof. Charles Adams
(he/him)



Dr Shuying Chen
(she/her)



Dr Lucy Downes
(she/her)

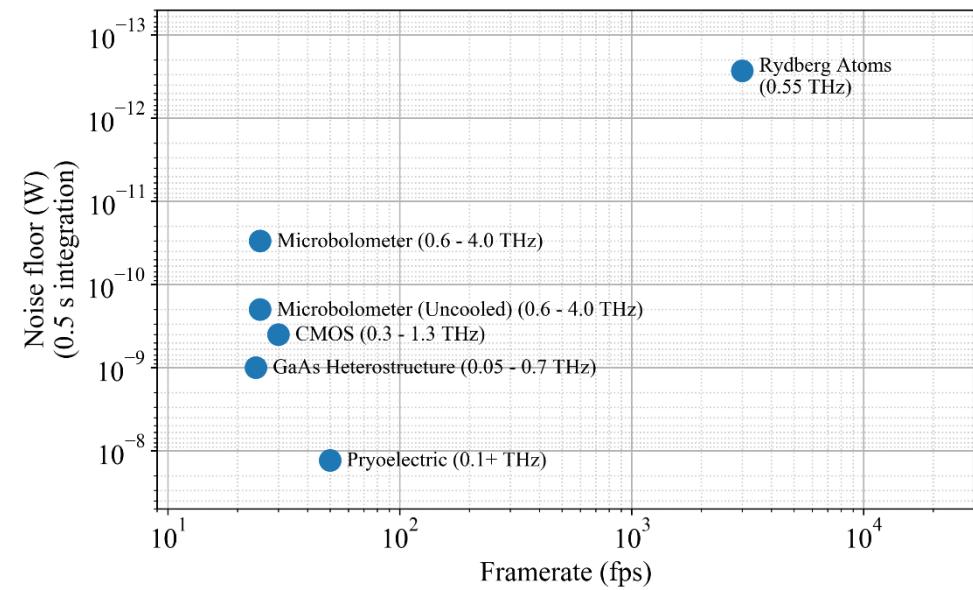


Dr Andrew MacKellar
(he/him)



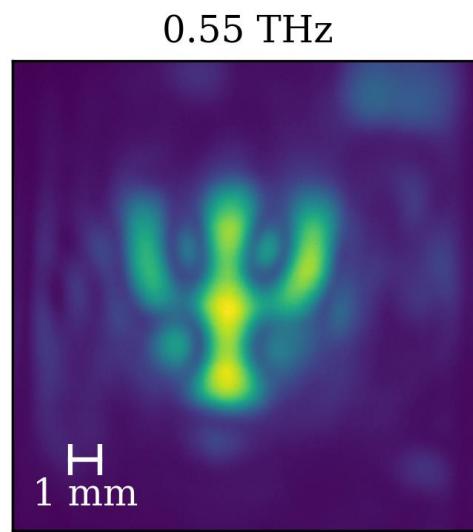
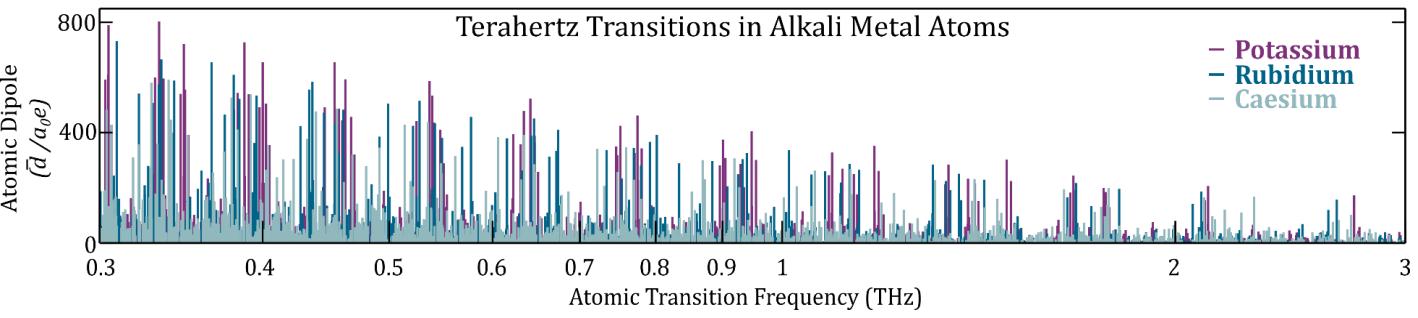
Mr Matt Jamieson
(he/him)

> 1 THz?

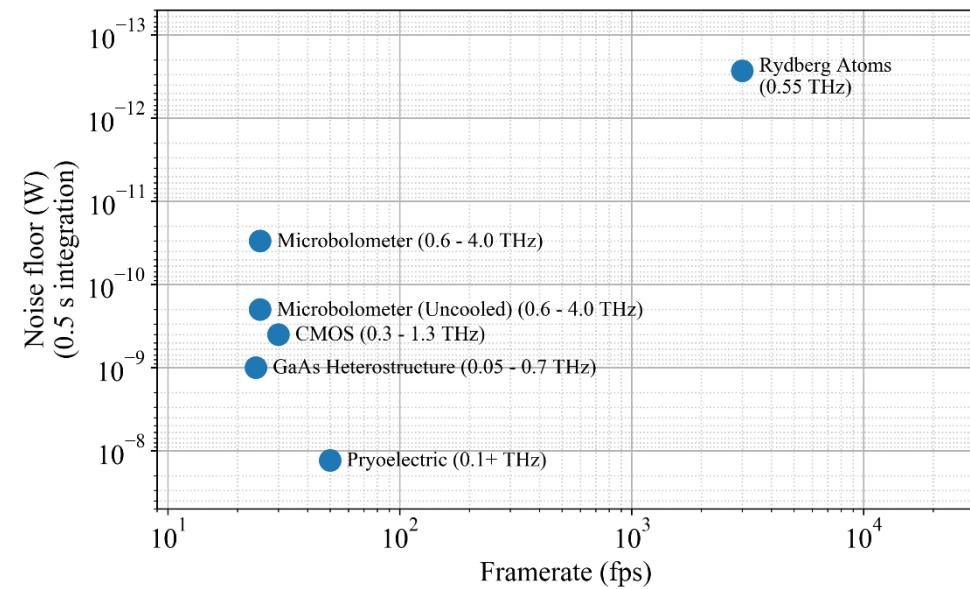


L. A. Downes *et al.*, Phys. Rev. X **10**, 011027 (2020)

D. M. Mittleman,
"Twenty years of terahertz imaging [Invited],"
Opt. Express **26**, 9417-9431 (2018)

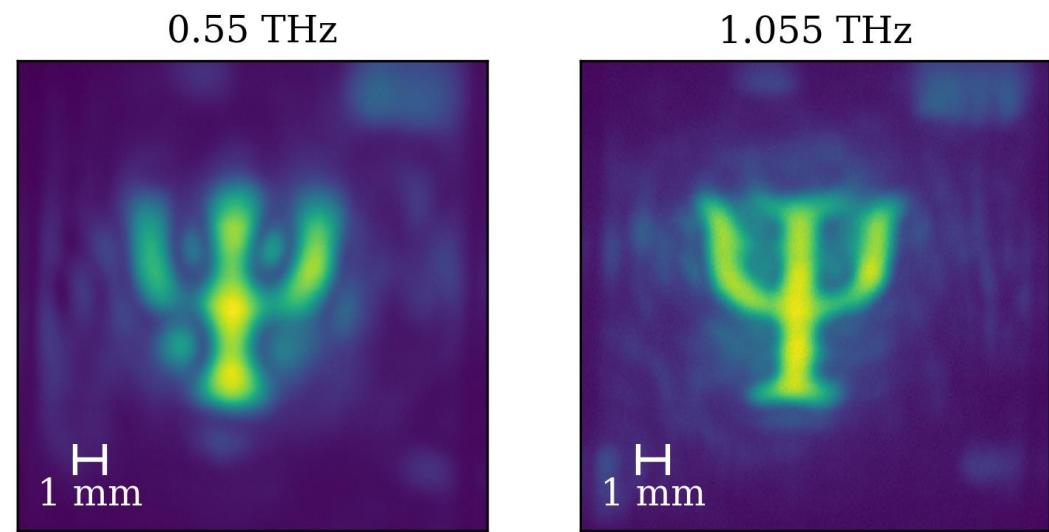
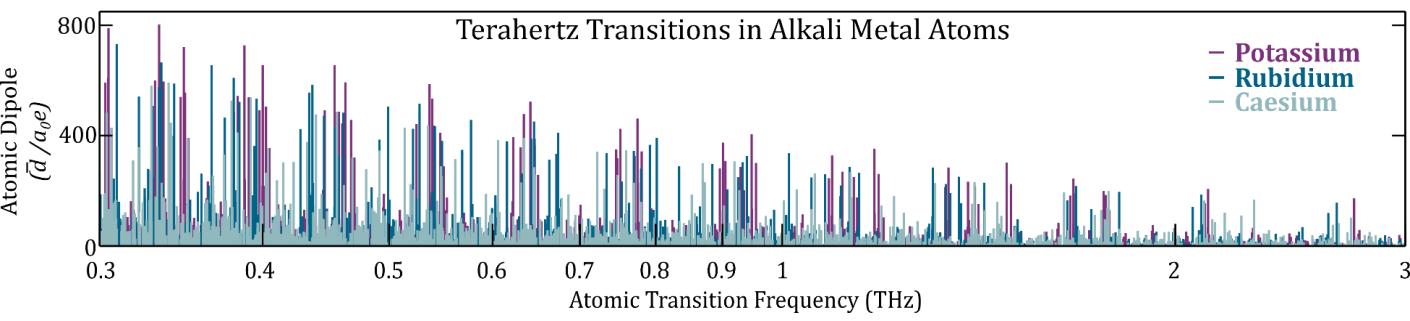


> 1 THz!



L. A. Downes *et al.*, Phys. Rev. X **10**, 011027 (2020)

D. M. Mittleman,
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Opt. Express **26**, 9417-9431 (2018)



Rydberg EIT/quantum optics

Motivation

Quantum non-linear optics

ICFO, Weizmann, Odense, Tsinghua, Hefei, Stuttgart, Heidelberg, Michigan, JQI, Toronto, Okinawa



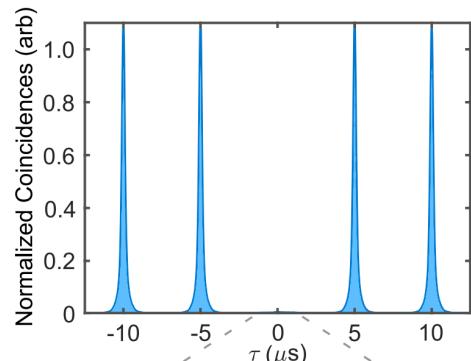
On-demand indistinguishable single photons from an efficient and pure source based on a Rydberg ensemble

D. P. ORNELAS-HUERTA,¹ A. N. CRADOCK,¹ E. A. GOLDSCHMIDT,^{2,3} A. J. HACHTEL,¹ Y. WANG,¹ P. BIENIAS,^{1,4} A. V. GORSHKOV,^{1,4} S. L. ROLSTON,¹ AND J. V. PORTO^{1,*}

<https://www.osapublishing.org/optica/fulltext.cfm?uri=optica-7-7-813&id=433459>

Photons are cheap, robust, ideal for quantum communications and networks

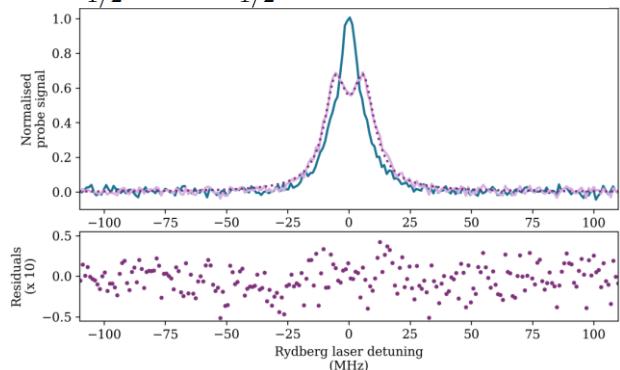
but strong photon-photon interactions remain challenging.



Rydberg EIT (rf sensing, phase transitions)

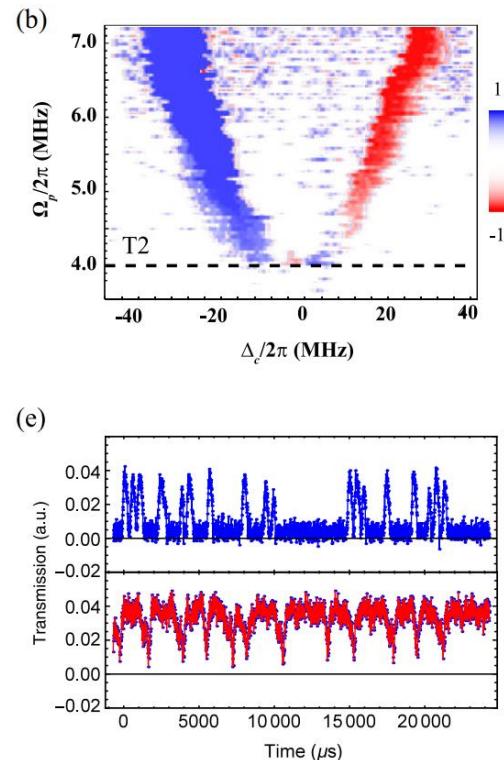
Shanxi, NIST, Quantum Valley, Hefei, Otago, Sandia, Tübingen, Guangzhou

$29P_{1/2} \rightarrow 28S_{1/2}$ transition at 639 GHz



<http://etheses.dur.ac.uk/13797/>

<https://journals.aps.org/prx/abstract/10.1103/PhysRevX.10.021023>



Team photon



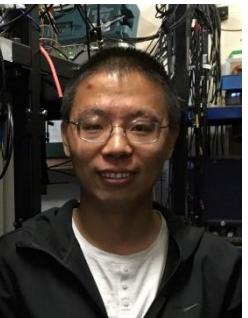
Charles Adams



Kevin Weatherill



Nick Spong



Yuechun Jiao



Max
Festenstein

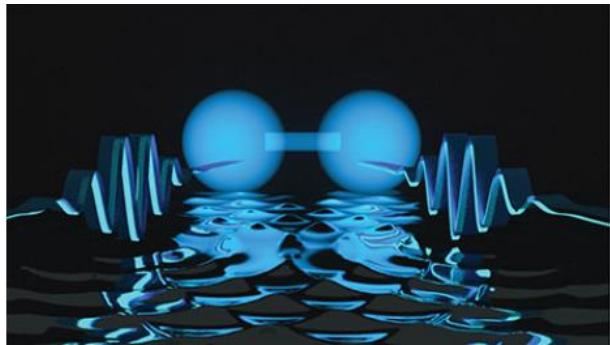


Oliver Hughes



Anton Charman

Rydberg quantum optics



Funding

EPSRC



[dstl]

Rydberg polaritons

VOLUME 84, NUMBER 22

PHYSICAL REVIEW LETTERS

29 MAY 2000

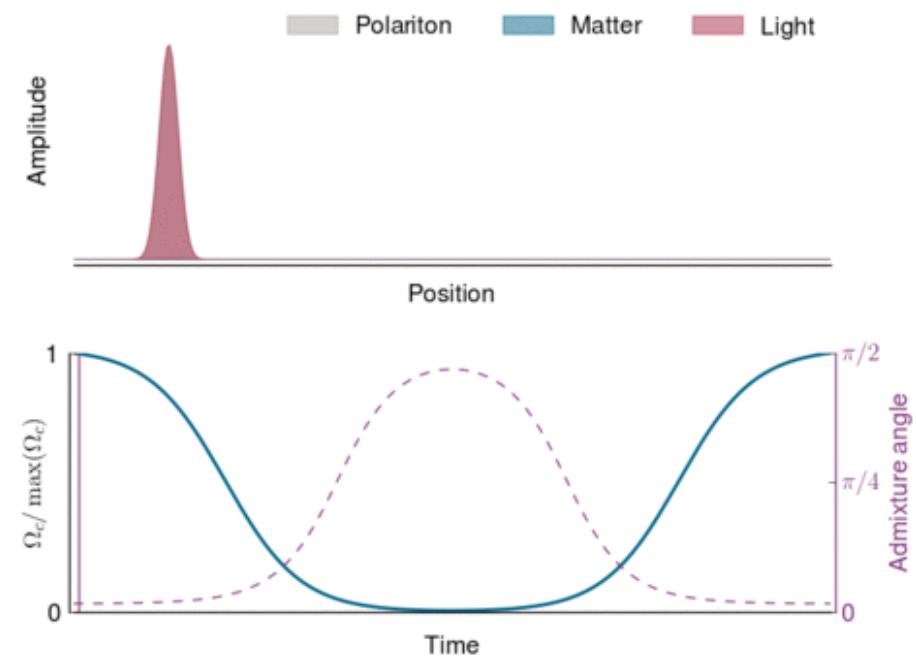
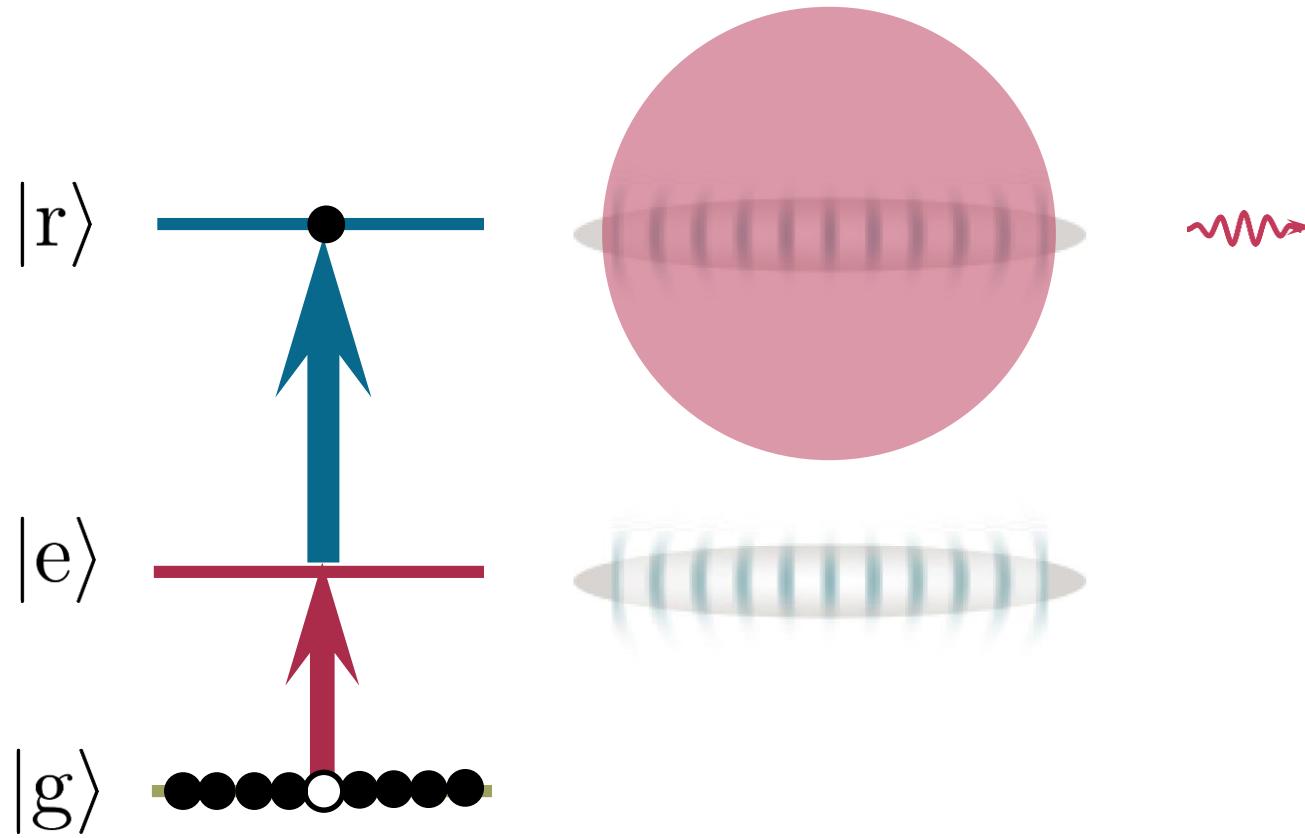
Dark-State Polaritons in Electromagnetically Induced Transparency

M. Fleischhauer¹ and M. D. Lukin²

¹Sektion Physik, Ludwig-Maximilians-Universität München, Theresienstrasse 37, D-80333 München, Germany

²ITAMP, Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138

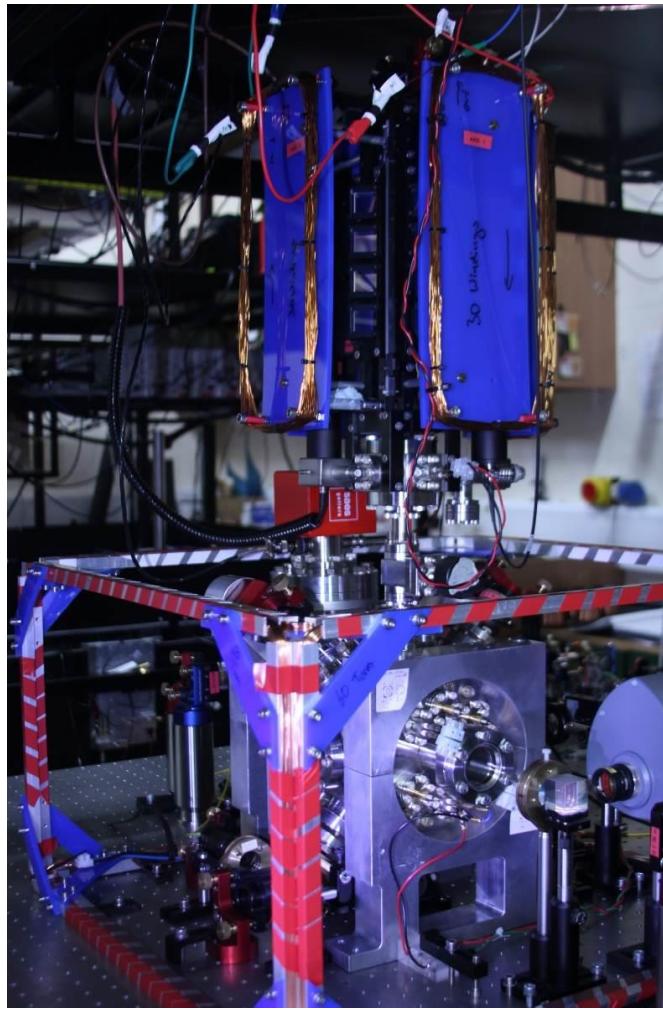
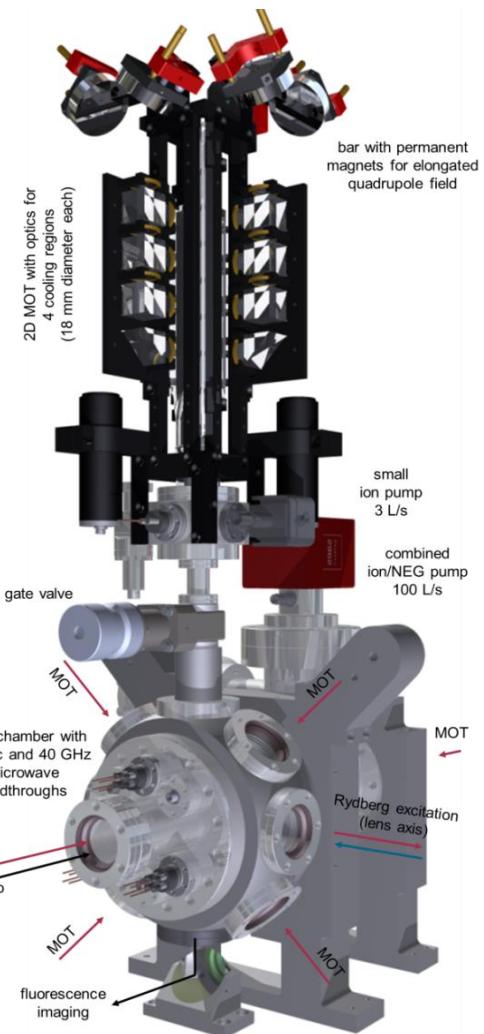
(Received 26 January 2000)



Spin wave

$$|\psi\rangle = \frac{1}{\sqrt{N}} \sum_{\nu} e^{i\mathbf{k}\cdot\mathbf{r}} |b_{\nu}\rangle$$

Experimental set up

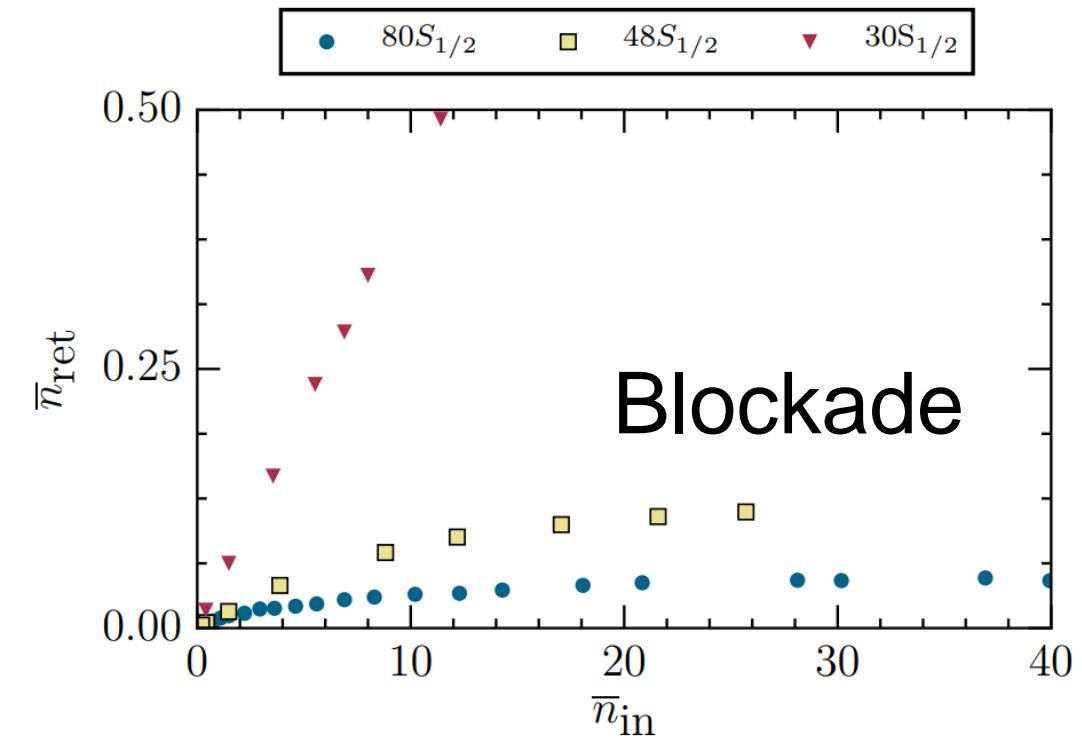
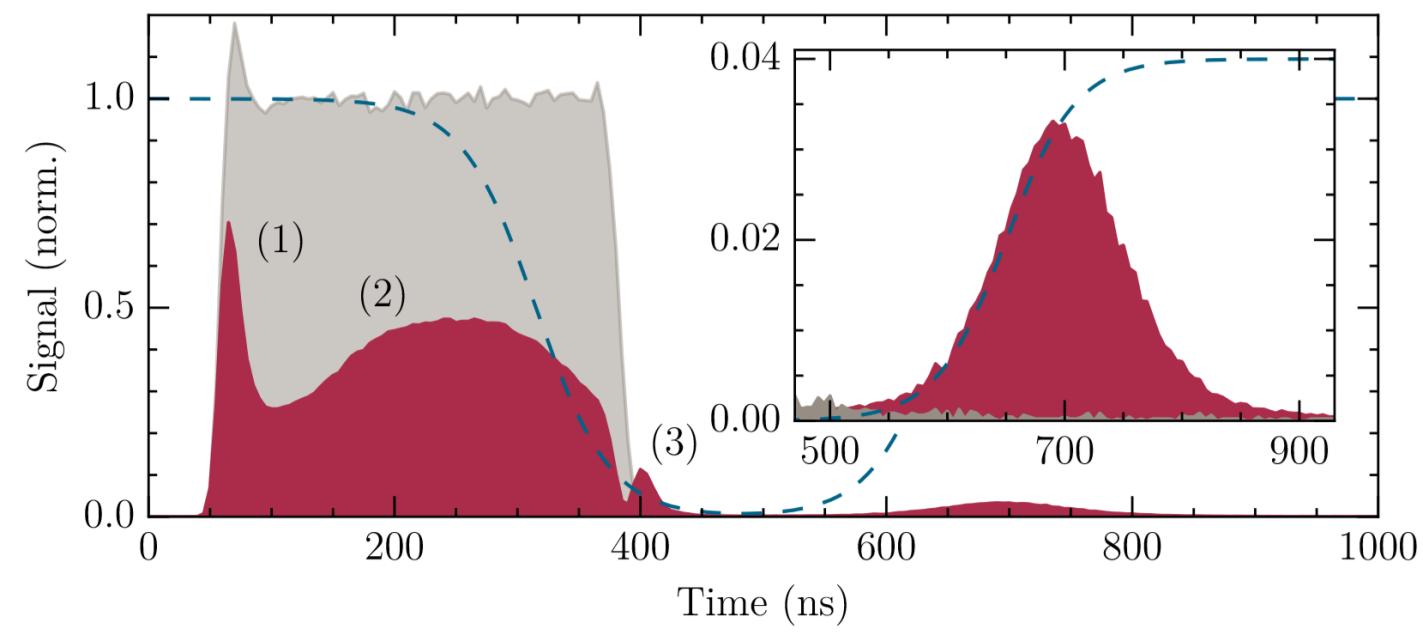


Hannes Busche



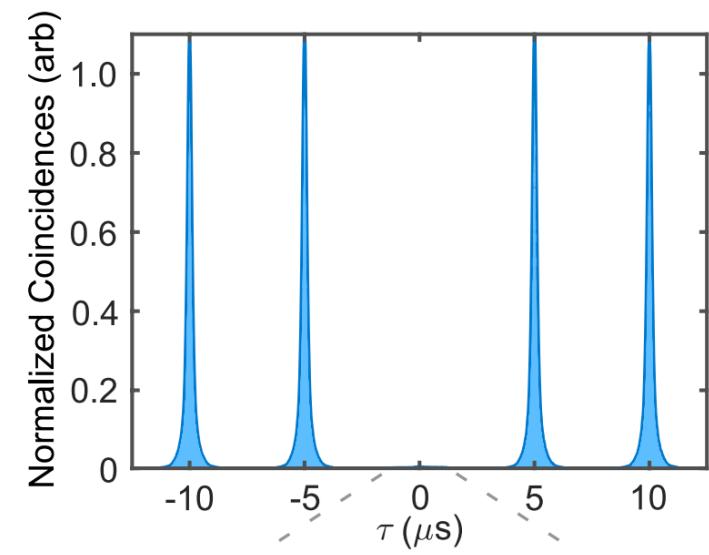
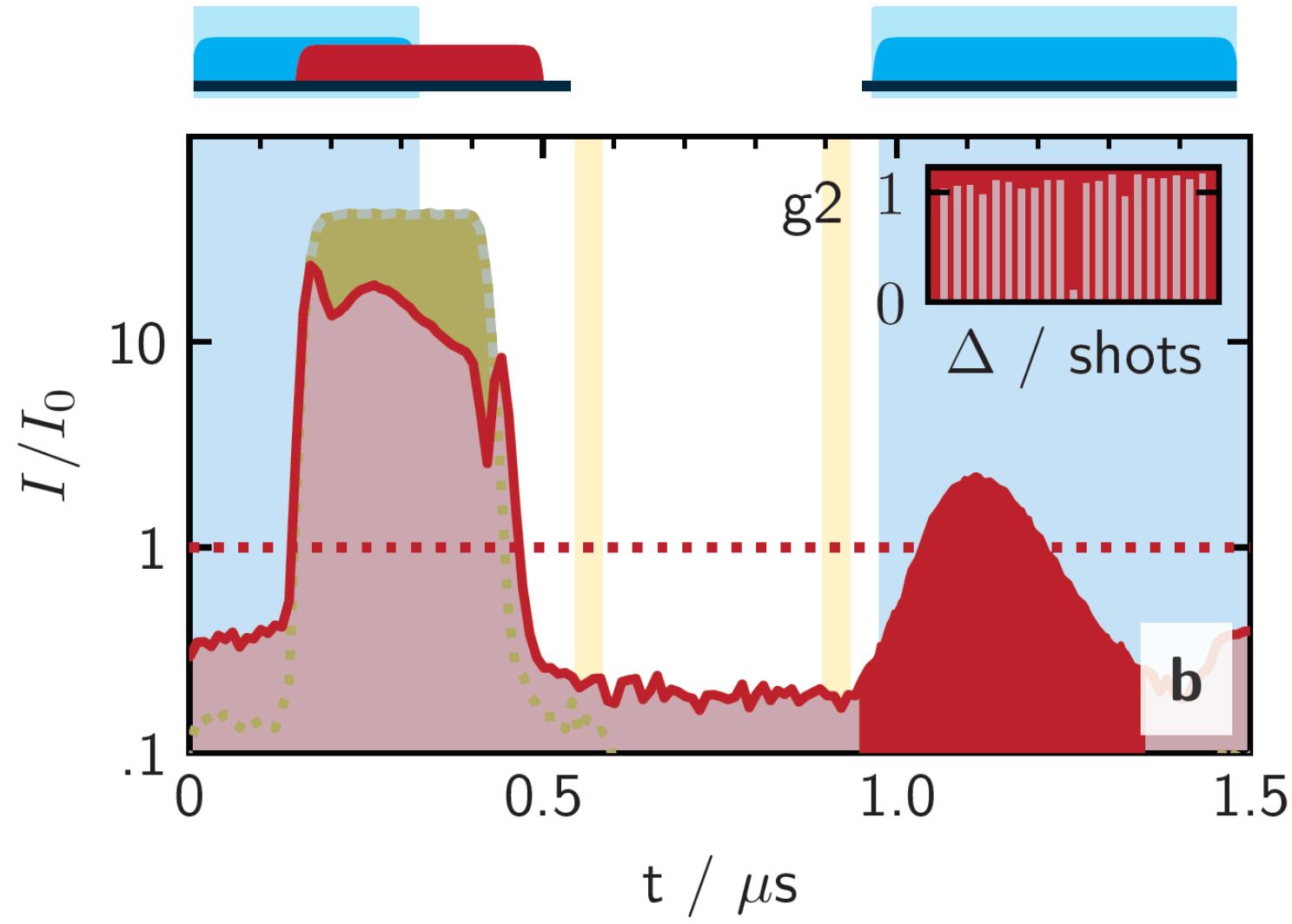
Effect of Rydberg blockade on photon storage

Simon Ball

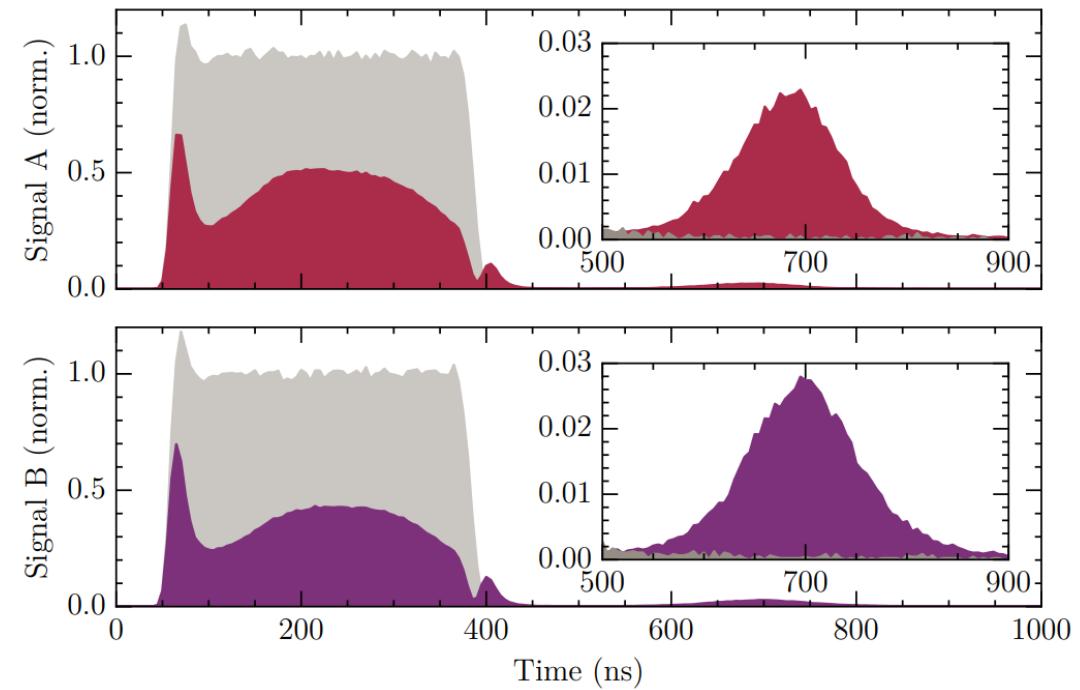
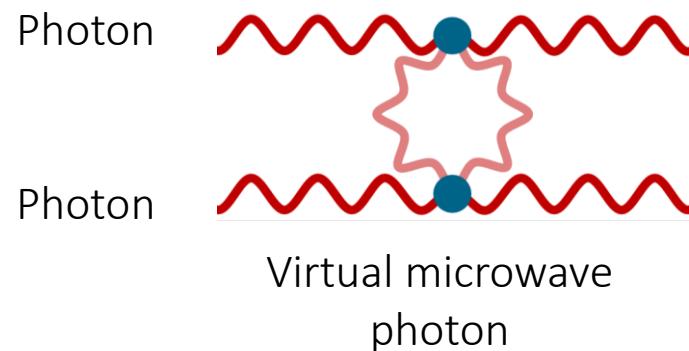
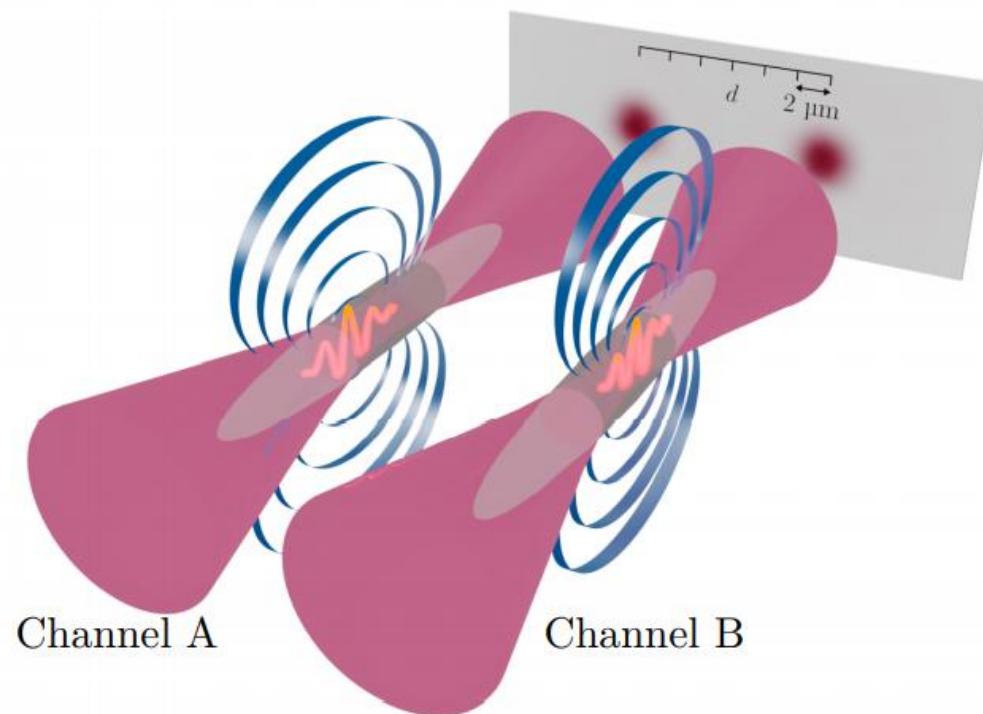


Write

Read-out



Two channel, two photon experiments

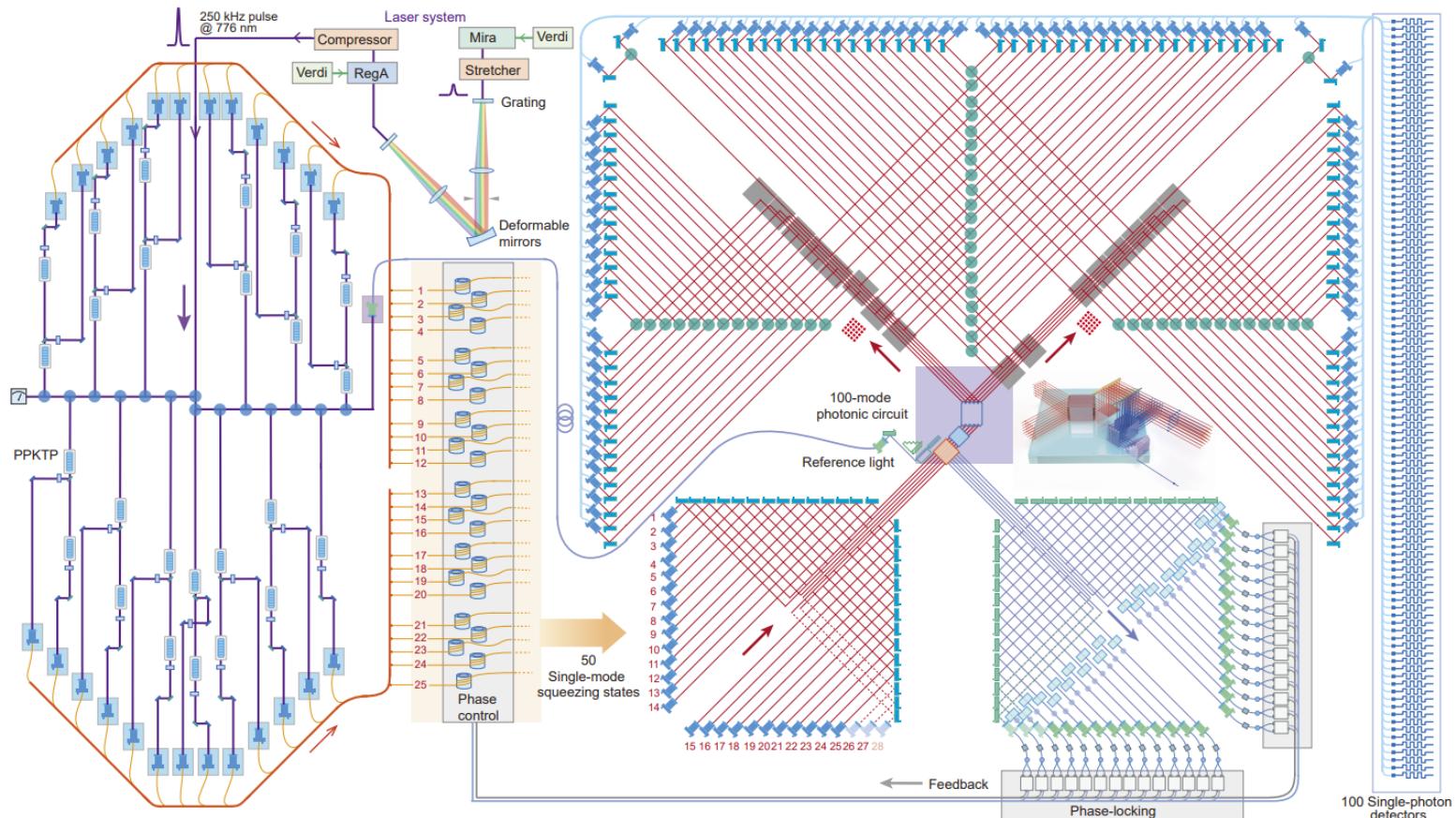


See H Busche et al Nature Phys. 13, 655 (2017)

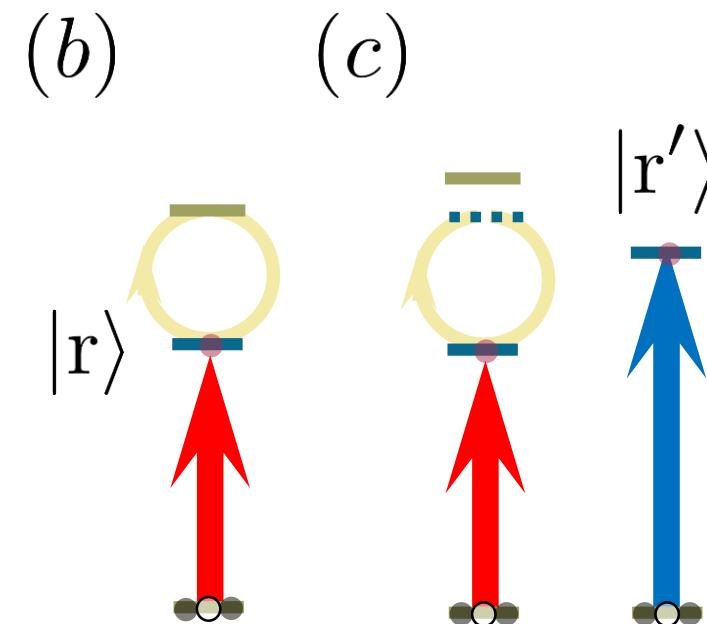
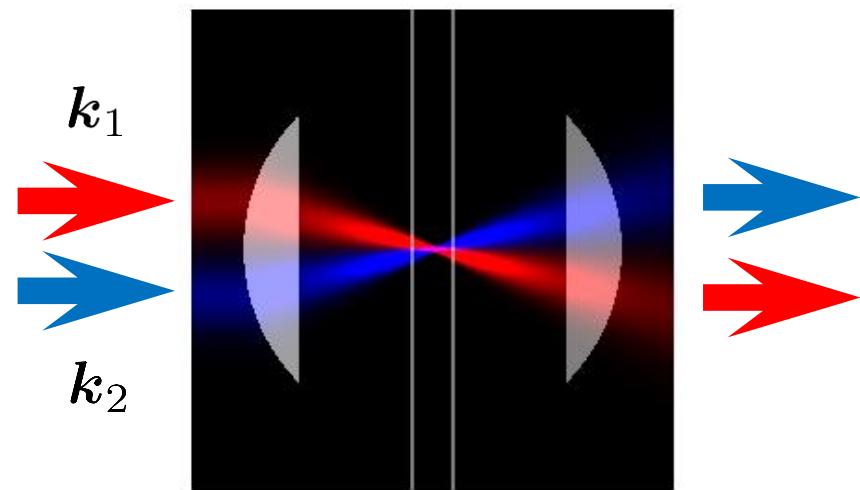
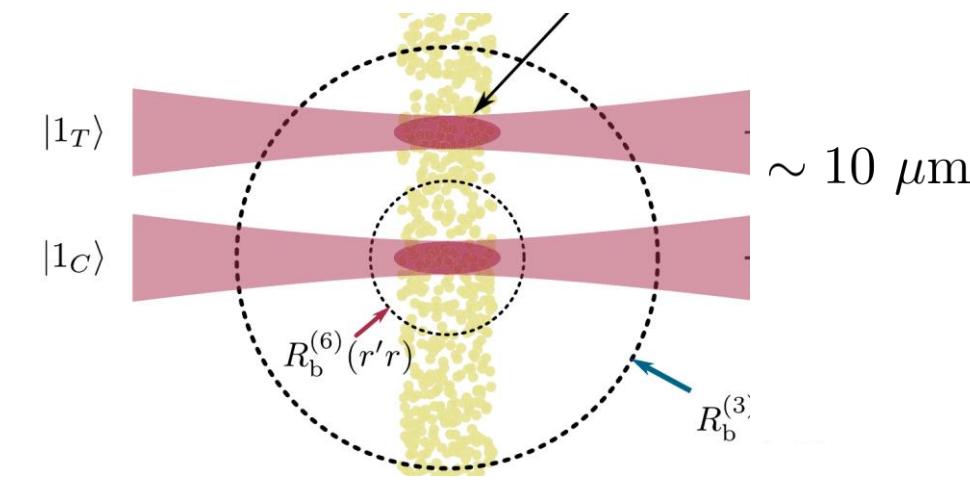
Cite as: H.-S. Zhong *et al.*, *Science* 10.1126/science.abe8770 (2020).

Quantum computational advantage using photons

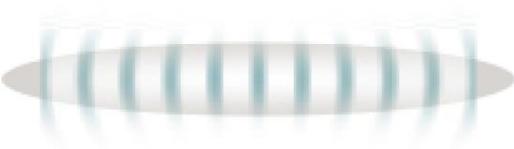
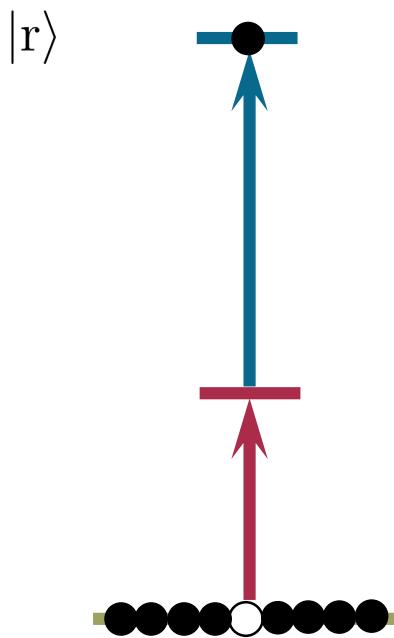
Han-Sen Zhong^{1,2*}, Hui Wang^{1,2*}, Yu-Hao Deng^{1,2*}, Ming-Cheng Chen^{1,2*}, Li-Chao Peng^{1,2},
Yi-Han Luo^{1,2}, Jian Qin^{1,2}, Dian Wu^{1,2}, Xing Ding^{1,2}, Yi Hu^{1,2}, Peng Hu³, Xiao-Yan Yang³,
Wei-Jun Zhang³, Hao Li³, Yuxuan Li⁴, Xiao Jiang^{1,2}, Lin Gan⁴, Guangwen Yang⁴, Lixing You³,
Zhen Wang³, Li Li^{1,2}, Nai-Le Liu^{1,2}, Chao-Yang Lu^{1,2}, Jian-Wei Pan^{1,2†}



Can we use microwaves to control the interactions?

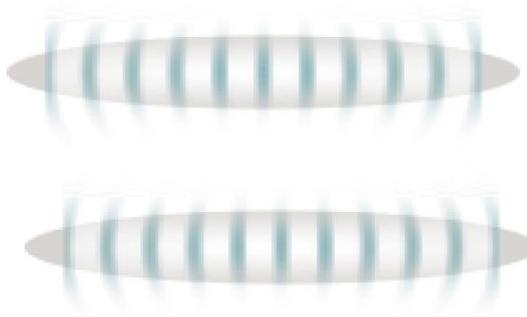
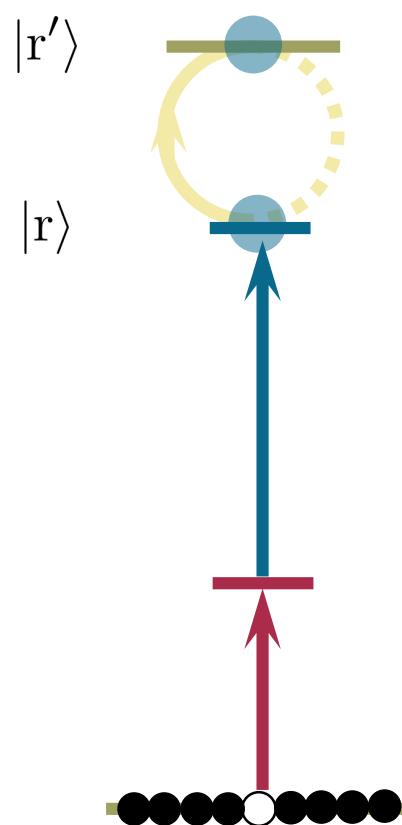


Collective encoding



$$|0\rangle = \frac{1}{\sqrt{N}} \sum_{j=1}^N e^{ik \cdot R_j} |g_0 g_1 \dots r_j \dots g_N\rangle$$

Collective encoding

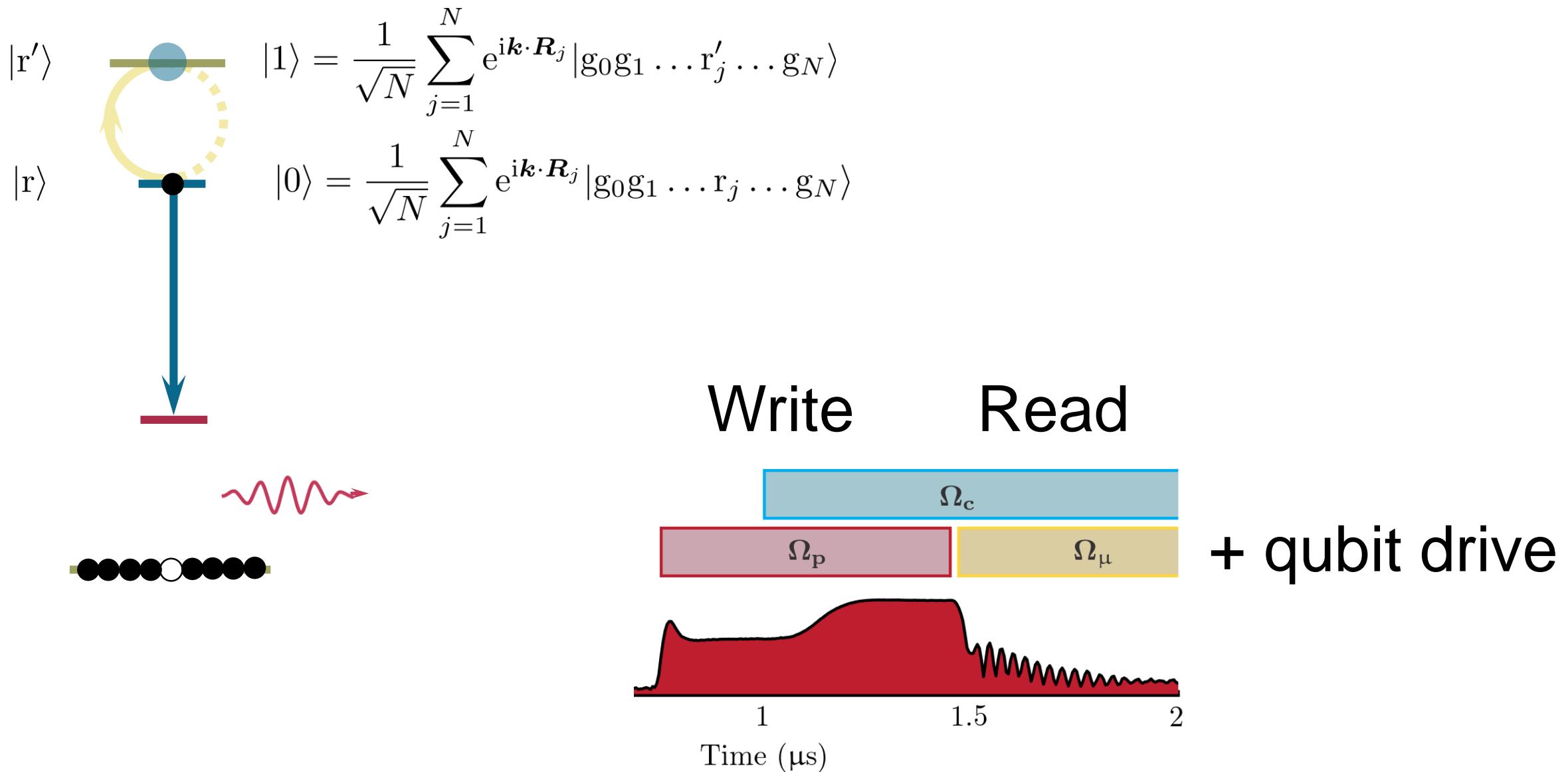


$$|1\rangle = \frac{1}{\sqrt{N}} \sum_{j=1}^N e^{ik \cdot R_j} |g_0 g_1 \dots r'_j \dots g_N\rangle$$
$$|0\rangle = \frac{1}{\sqrt{N}} \sum_{j=1}^N e^{ik \cdot R_j} |g_0 g_1 \dots r_j \dots g_N\rangle$$

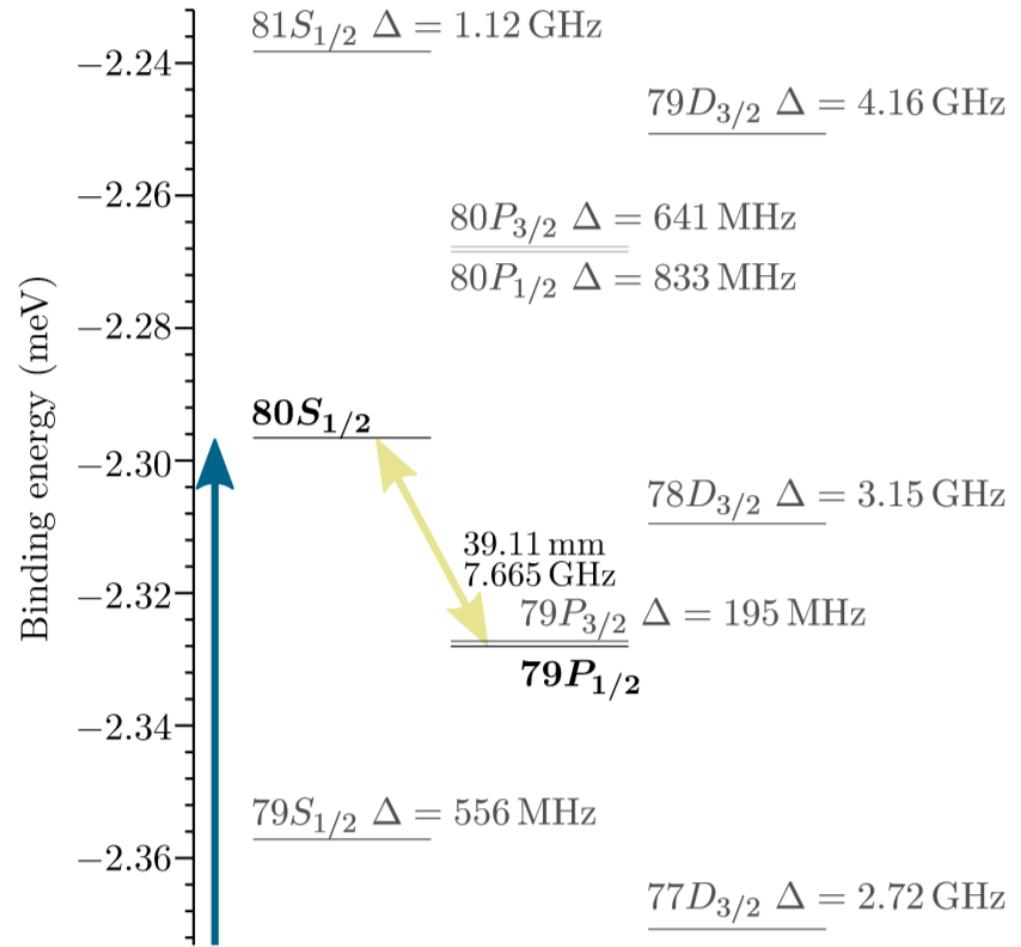
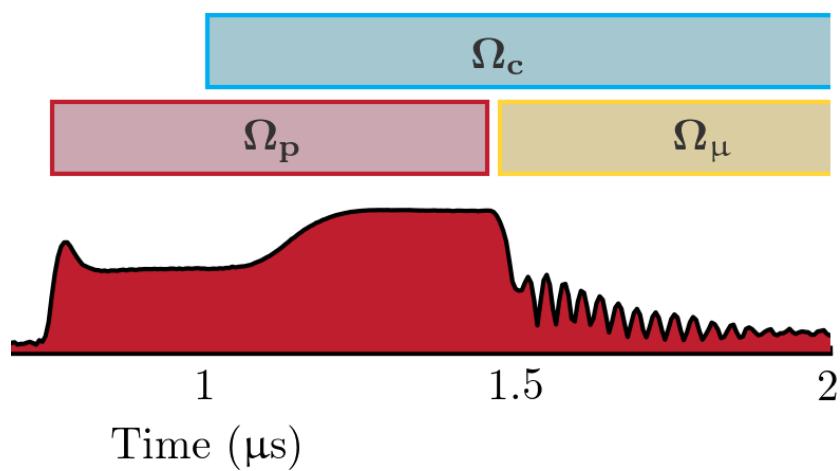
Collectively-encoded qubit:

1. Rabi frequency independent of N .
2. Fast Rabi oscillation on nanosecond time scale
3. Direct read-out as a single photon.
4. Quantum information shared amongst N atoms.

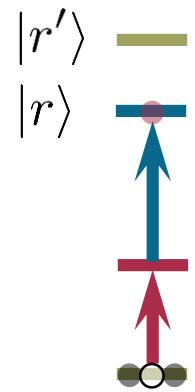
Collectively-encoded qubit (continuous read-out)



Not a two-level system!



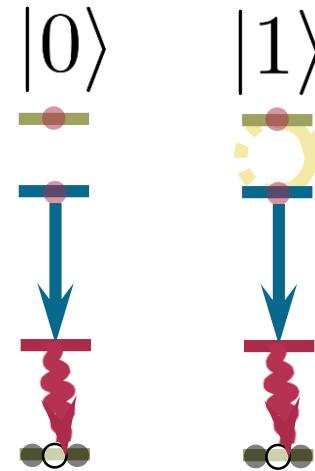
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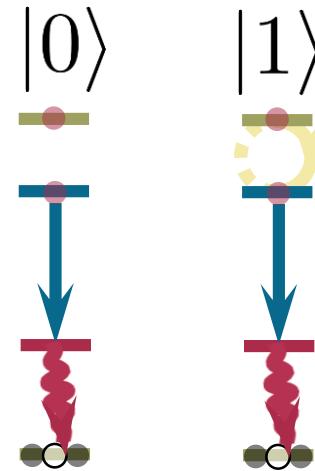
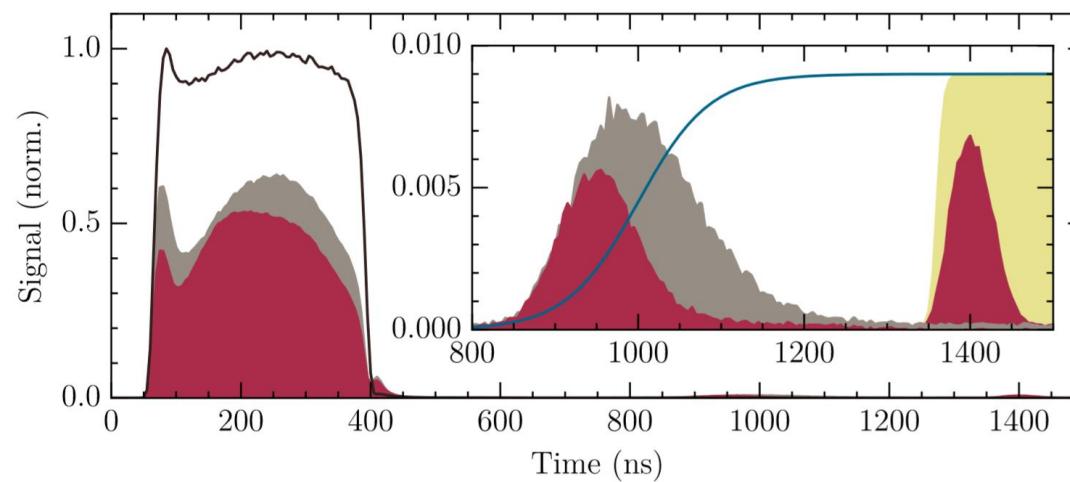
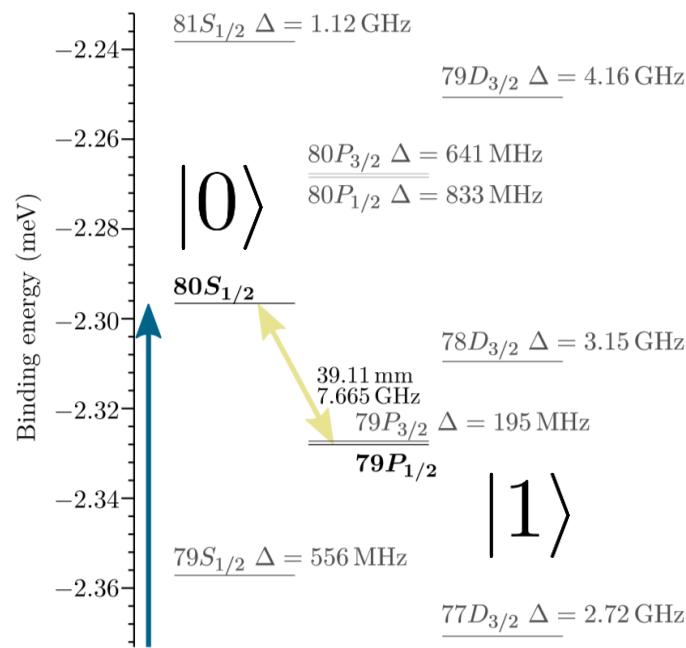
MICROWAVE



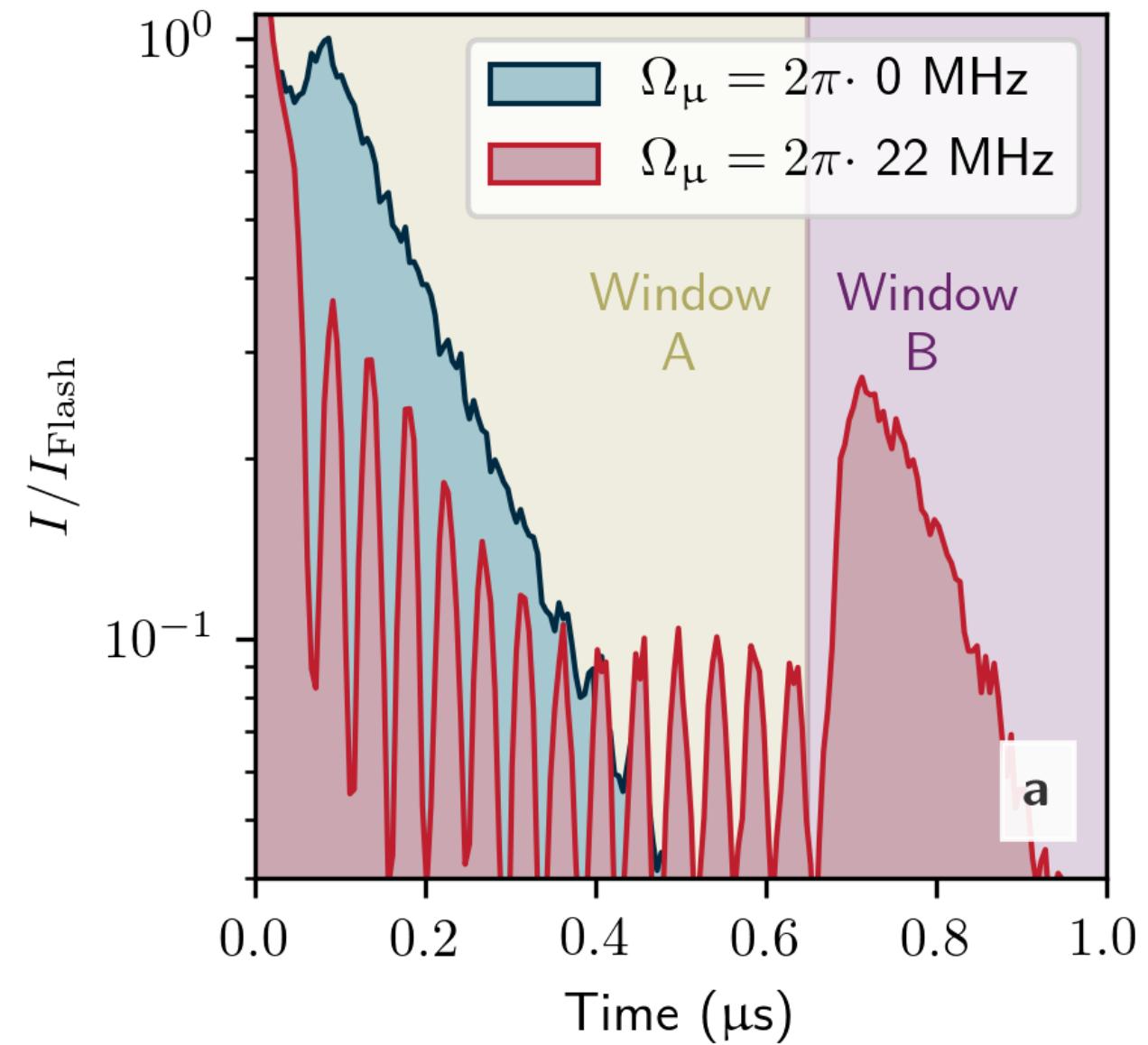
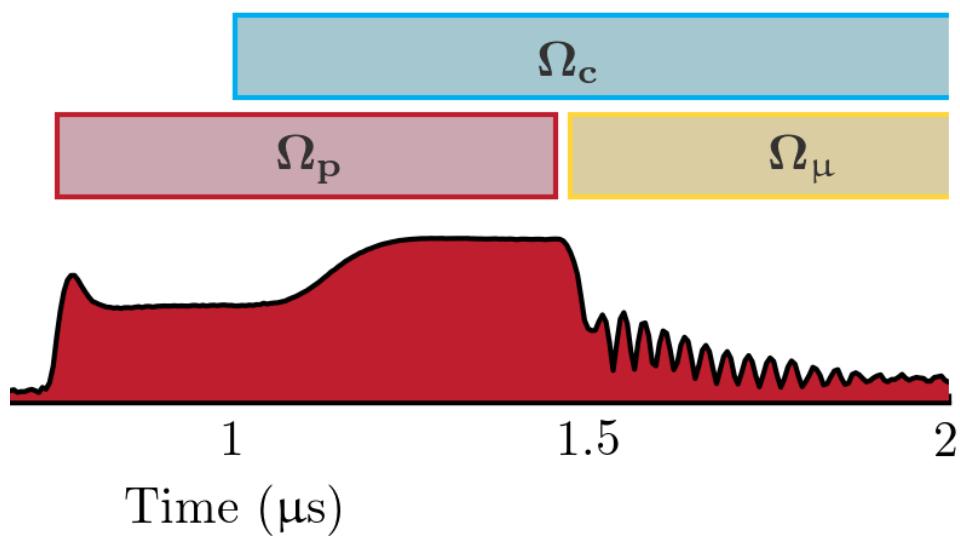
READ



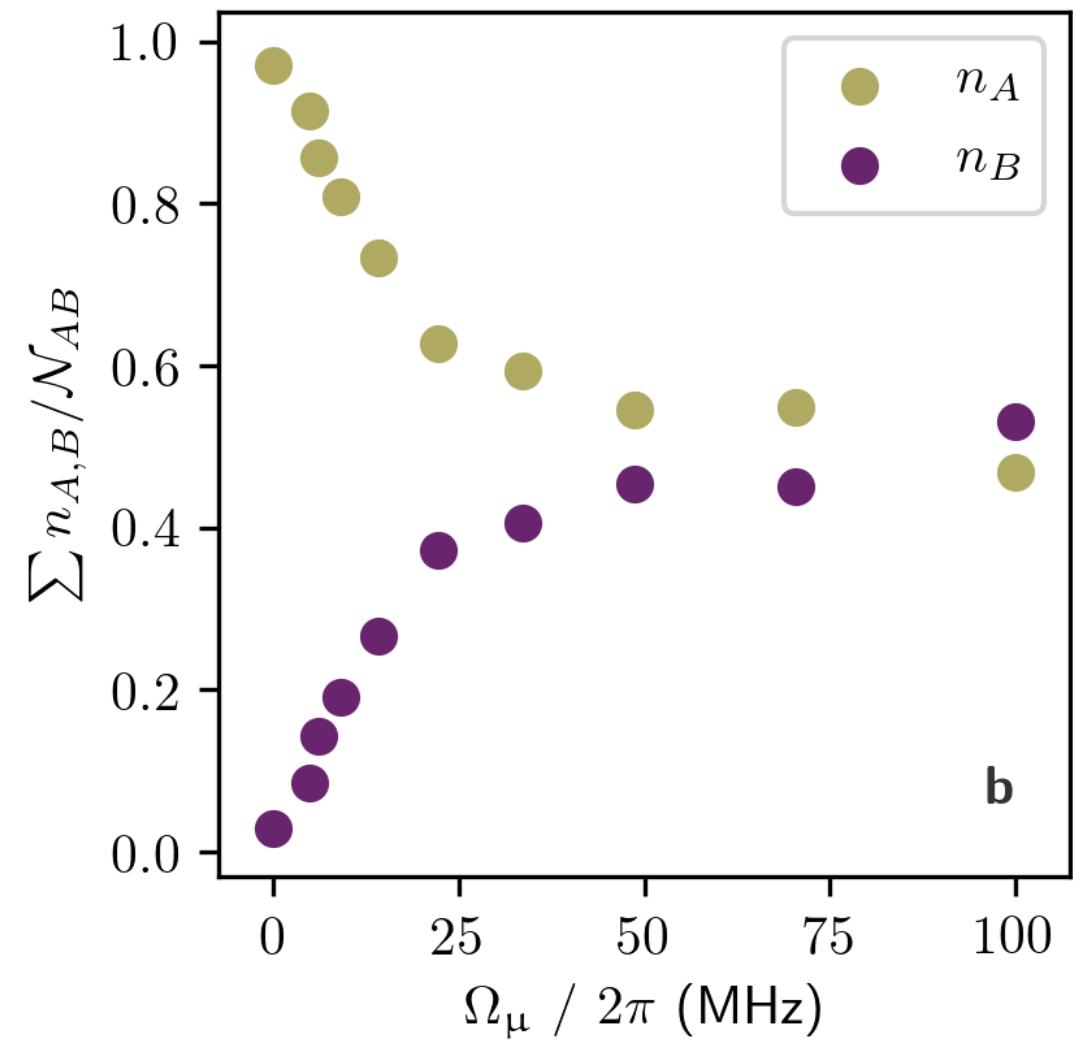
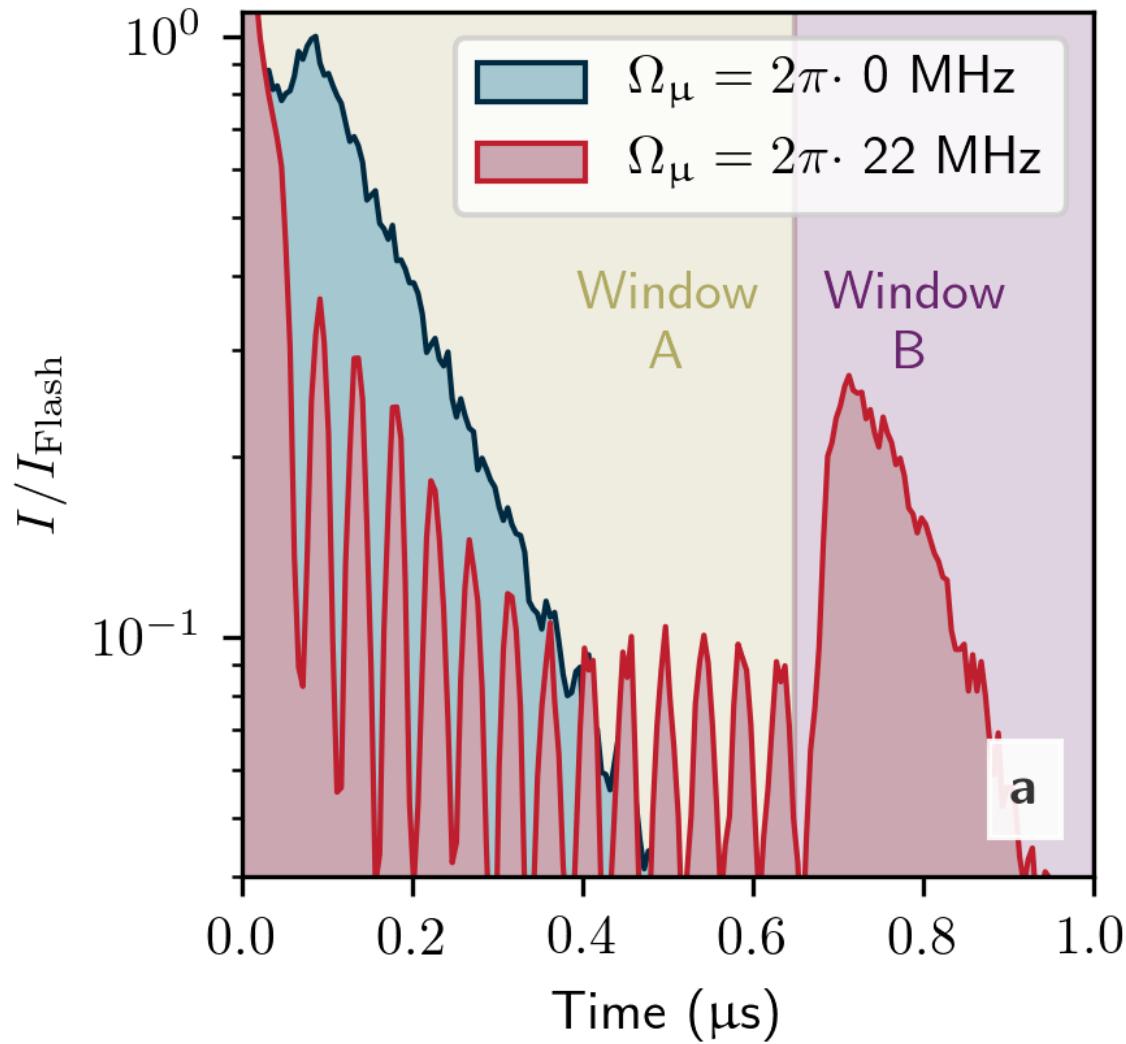
READ

 $|0\rangle$ $|1\rangle$ *ns**np*

Coherent population trapping

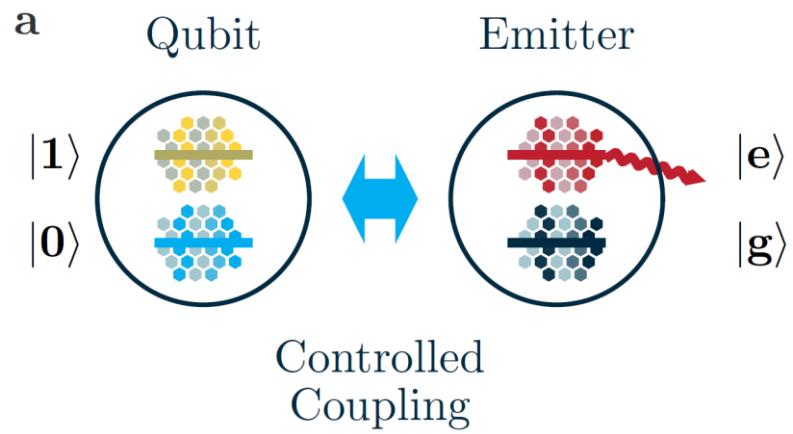


Coherent population trapping

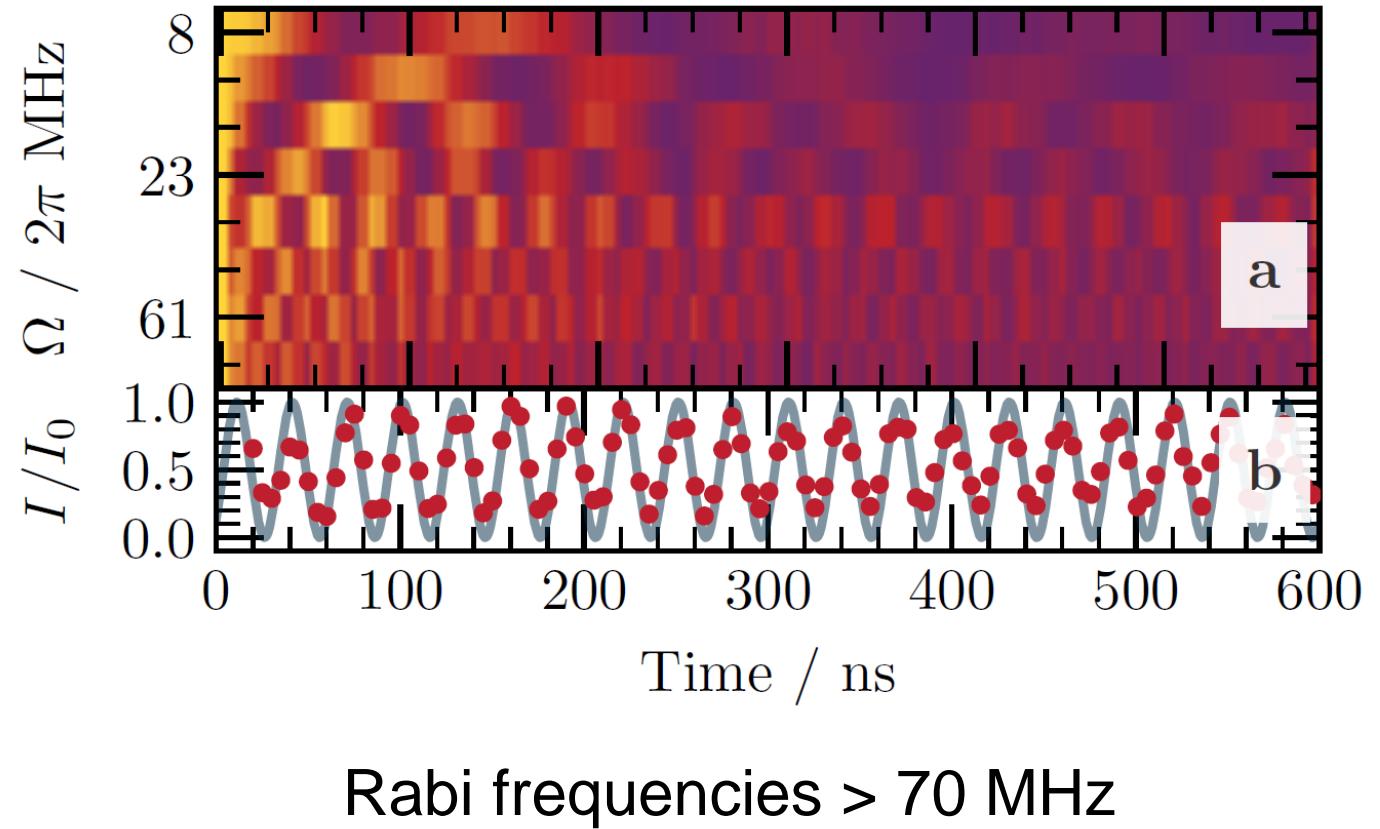


Fast Rabi oscillations

Strong driving

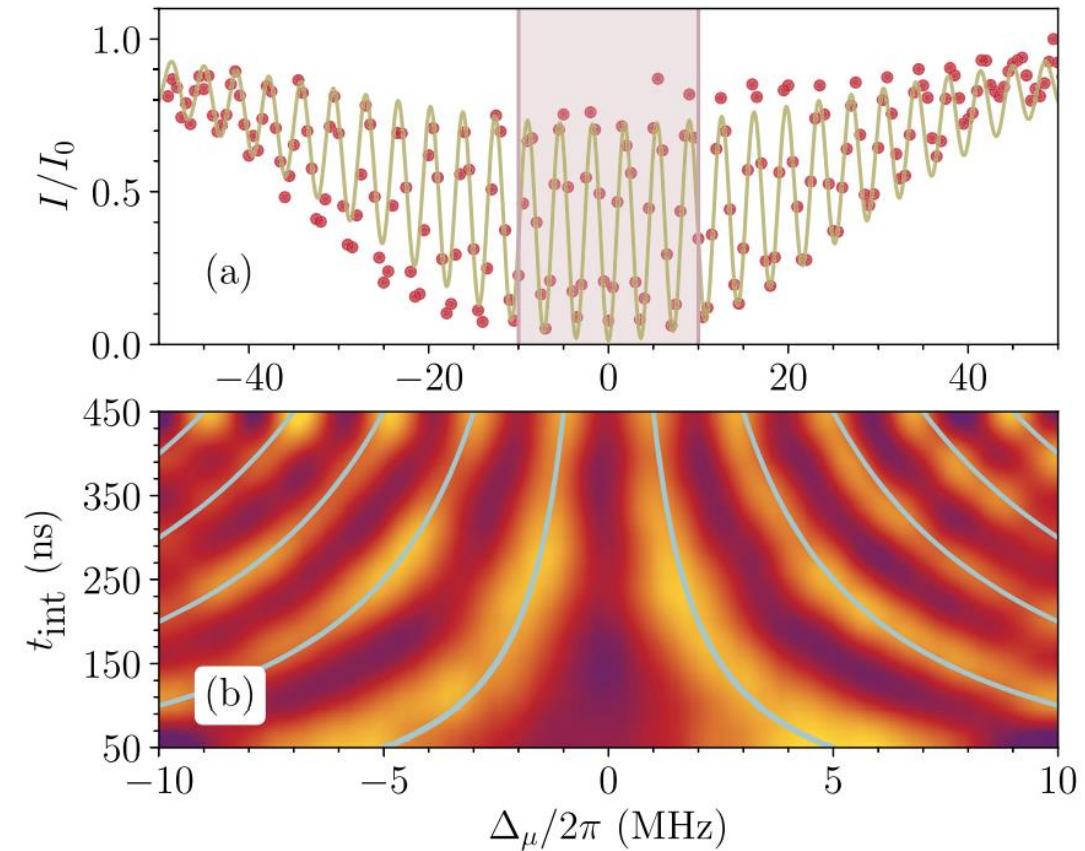
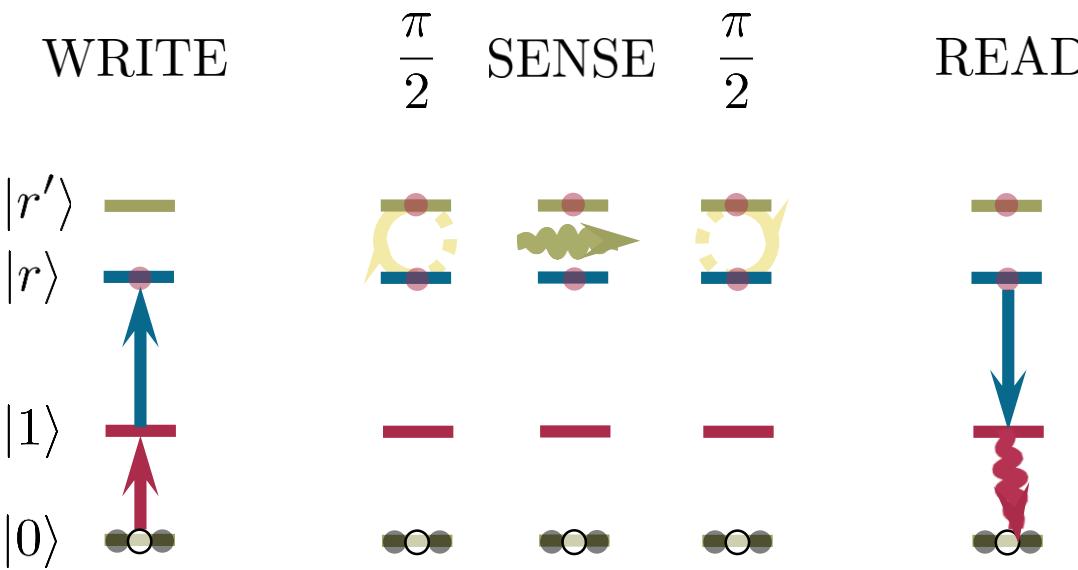


Weak coupling

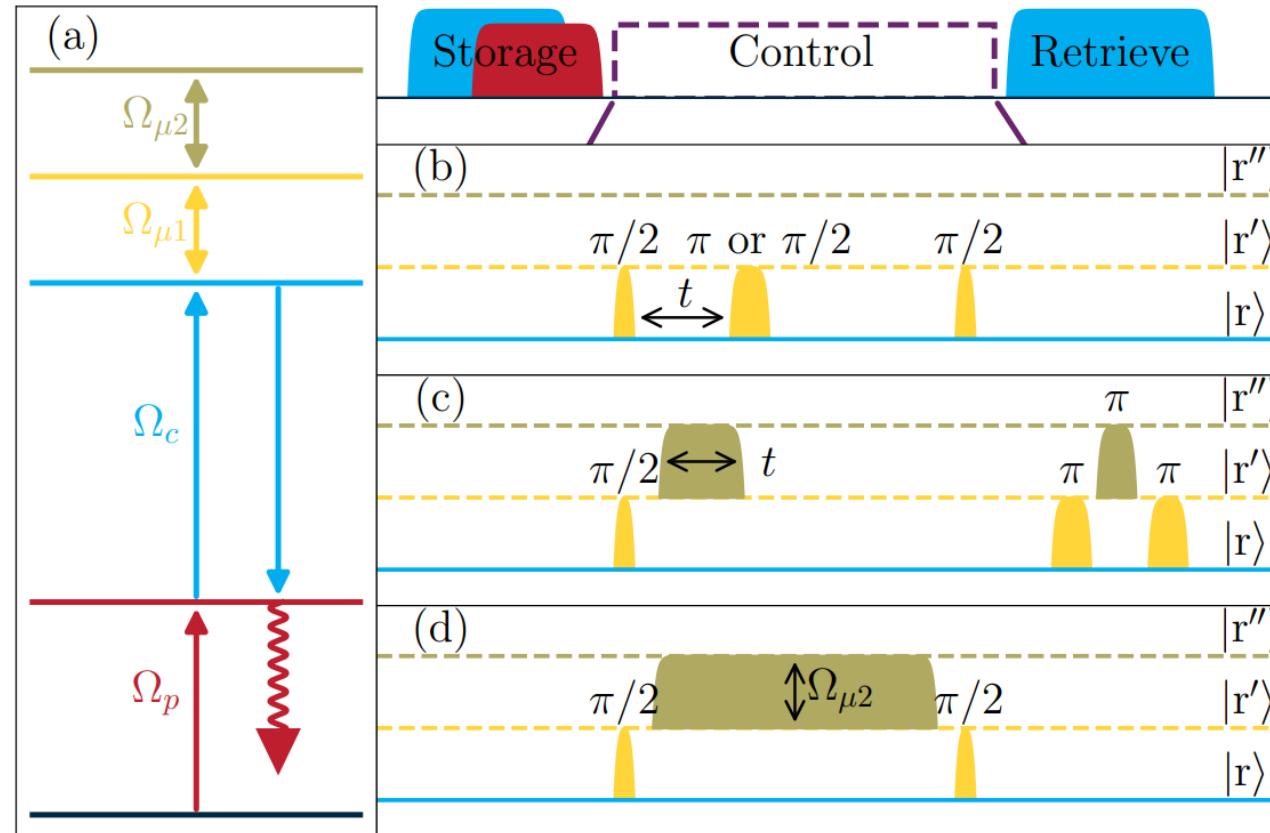


Single-photon stored-light Ramsey interferometry using Rydberg polaritons

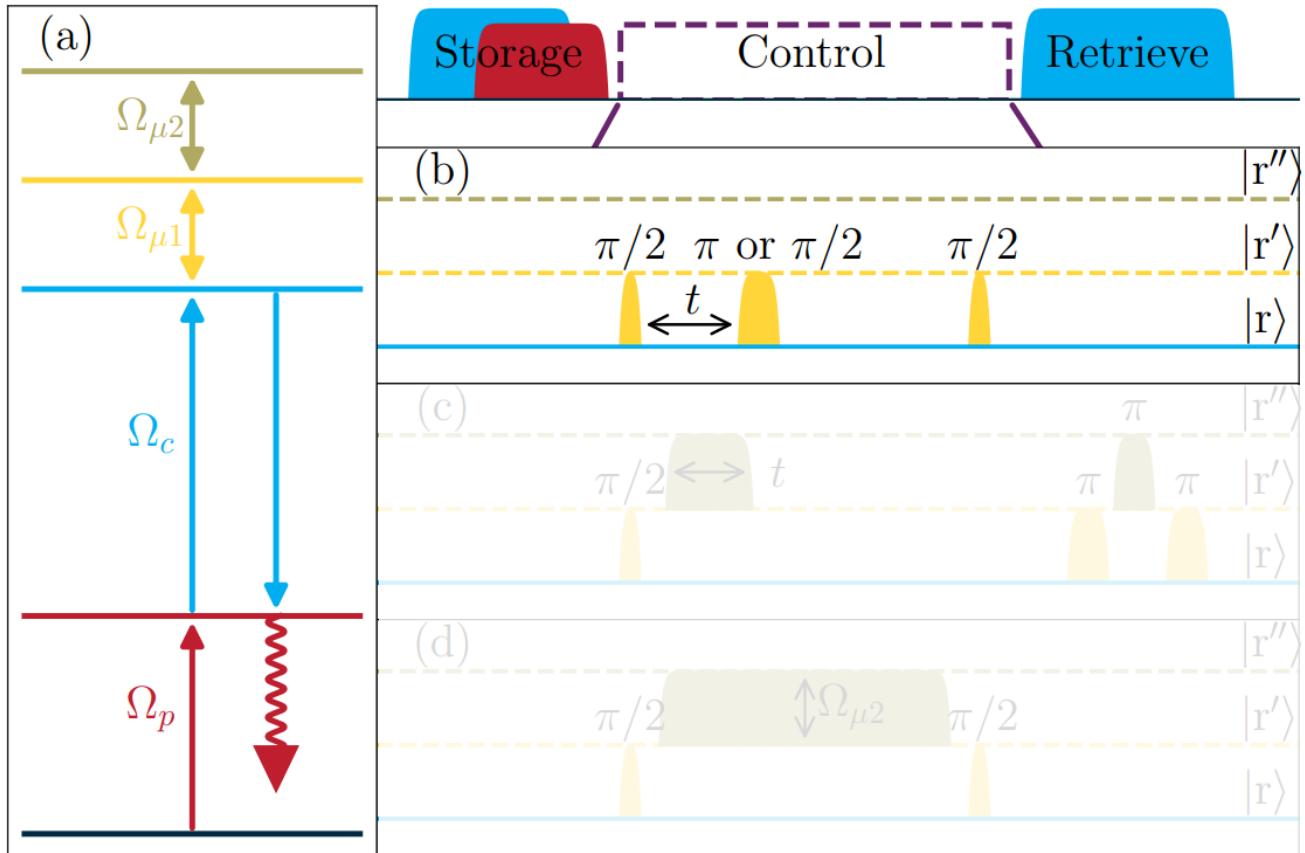
YUECHUN JIAO,^{1,2} NICHOLAS L. R. SPONG,¹ OLIVER D. W. HUGHES,¹ CHLOE SO,¹
TEODORA ILIEVA,¹ KEVIN J. WEATHERILL,¹ AND CHARLES S. ADAMS^{1,*}



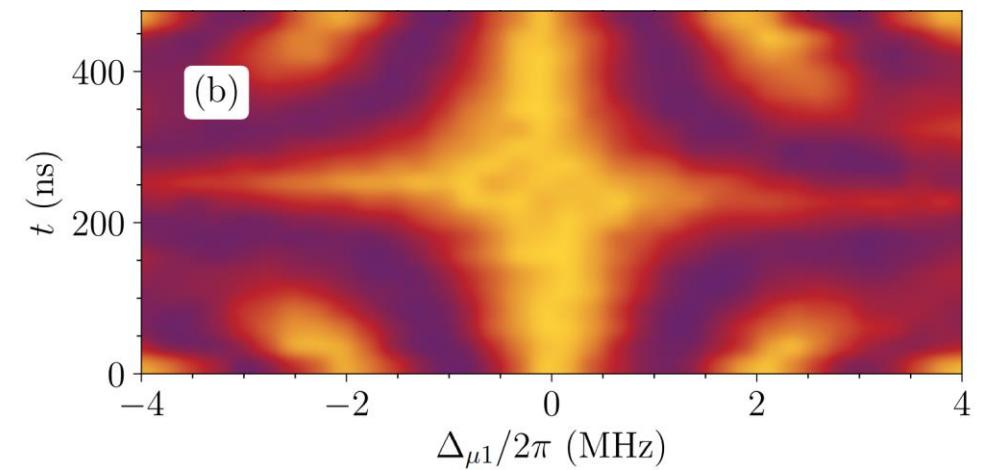
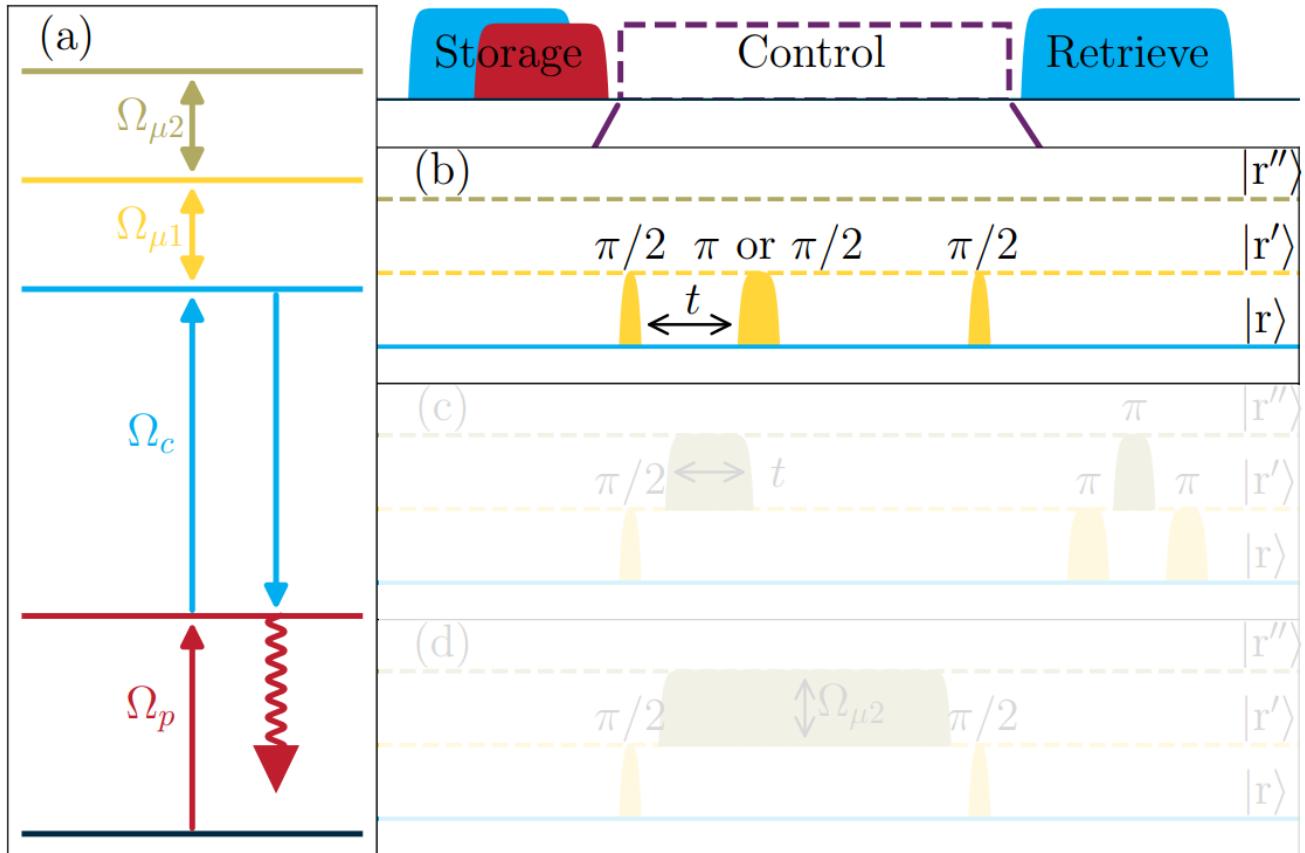
More microwaves



Spin echo

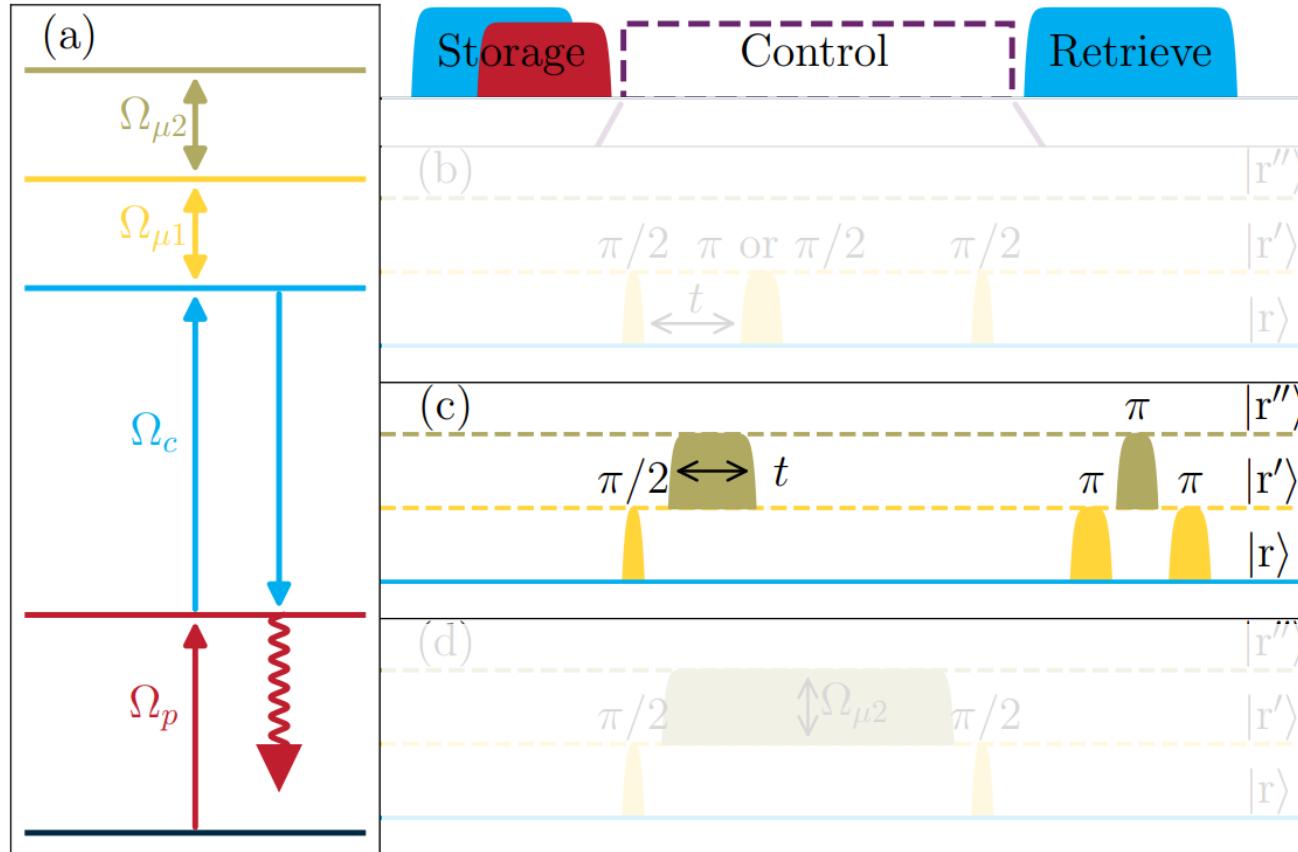


Spin echo



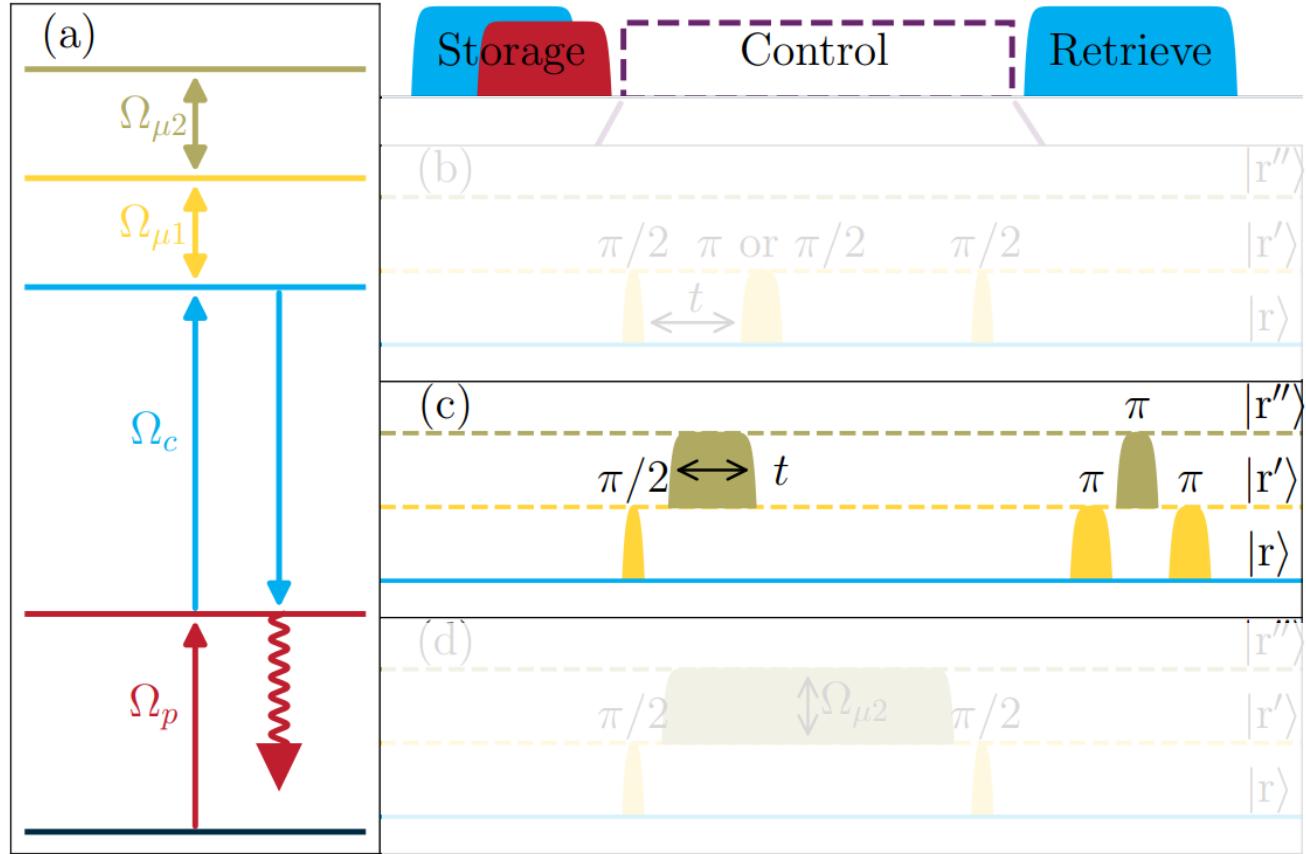
Single photon qutrits

$$|\psi\rangle = a|0\rangle + b|1\rangle + c|2\rangle$$



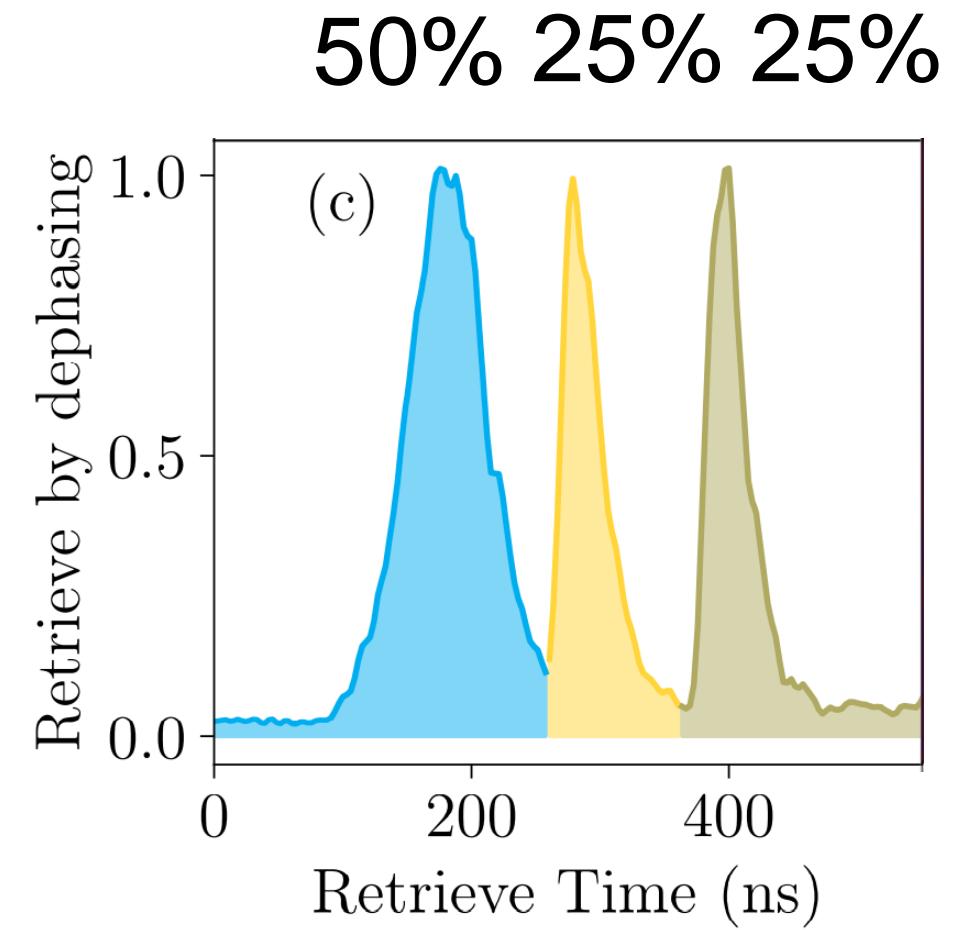
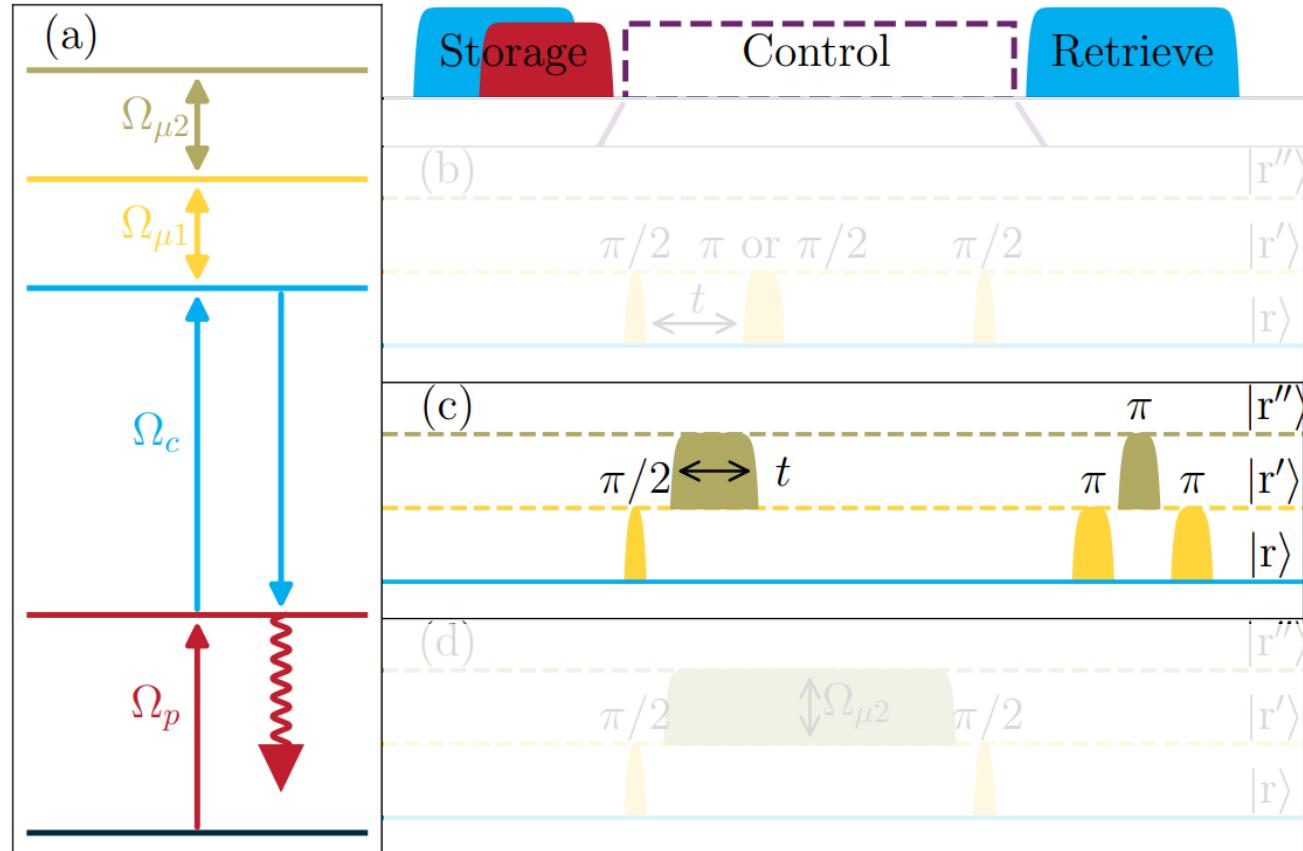
Single photon qutrits

$$|\psi\rangle = \frac{1}{\sqrt{2}} \left[|0\rangle + \frac{1}{\sqrt{2}}(|1\rangle + |2\rangle) \right]$$

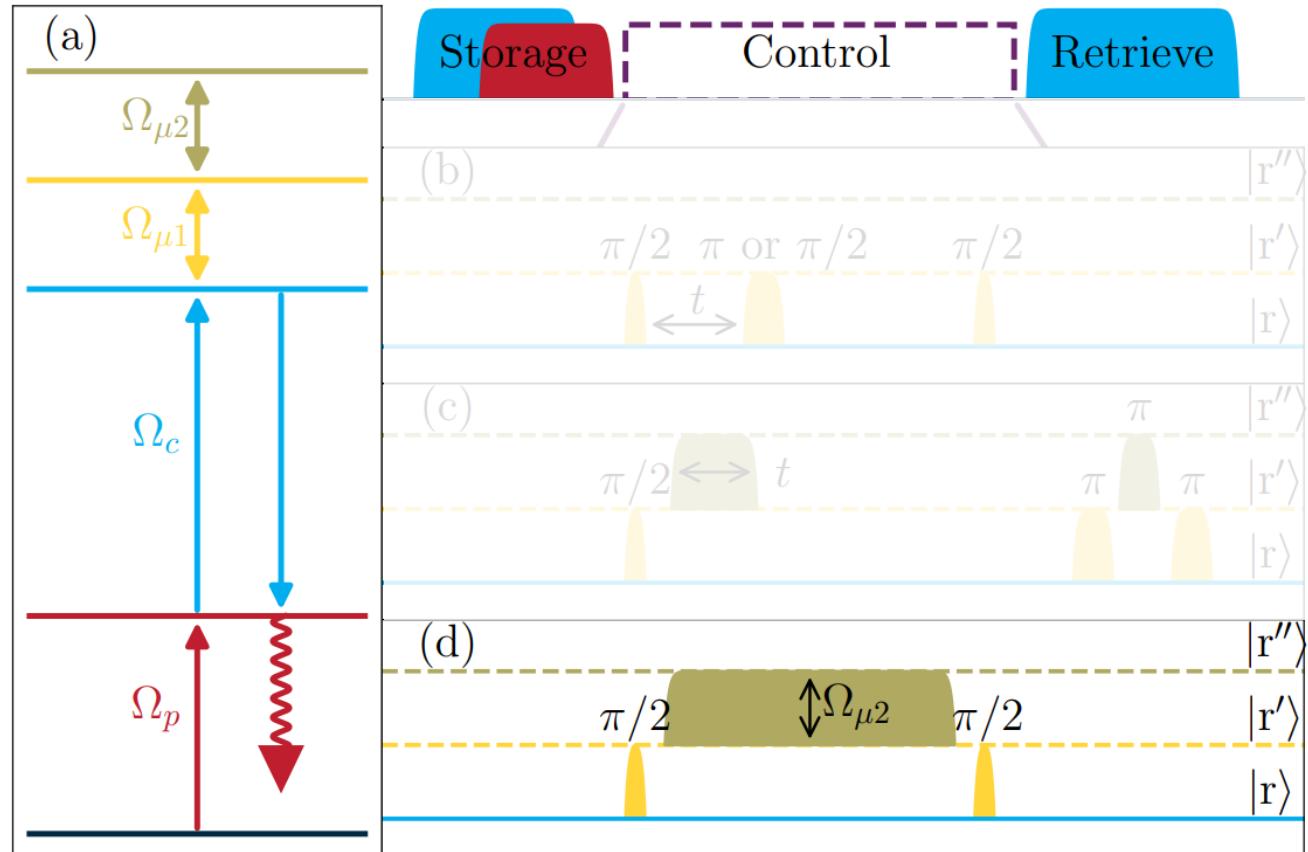


Single photon qutrits

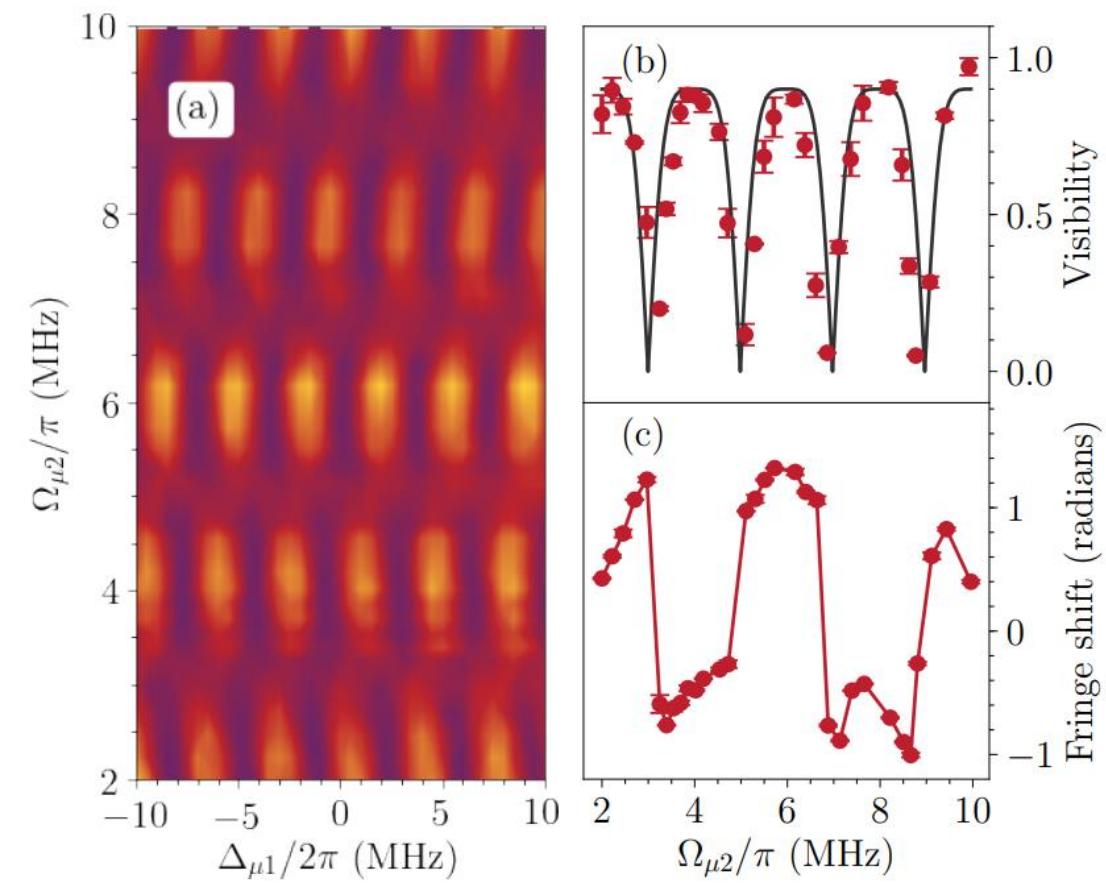
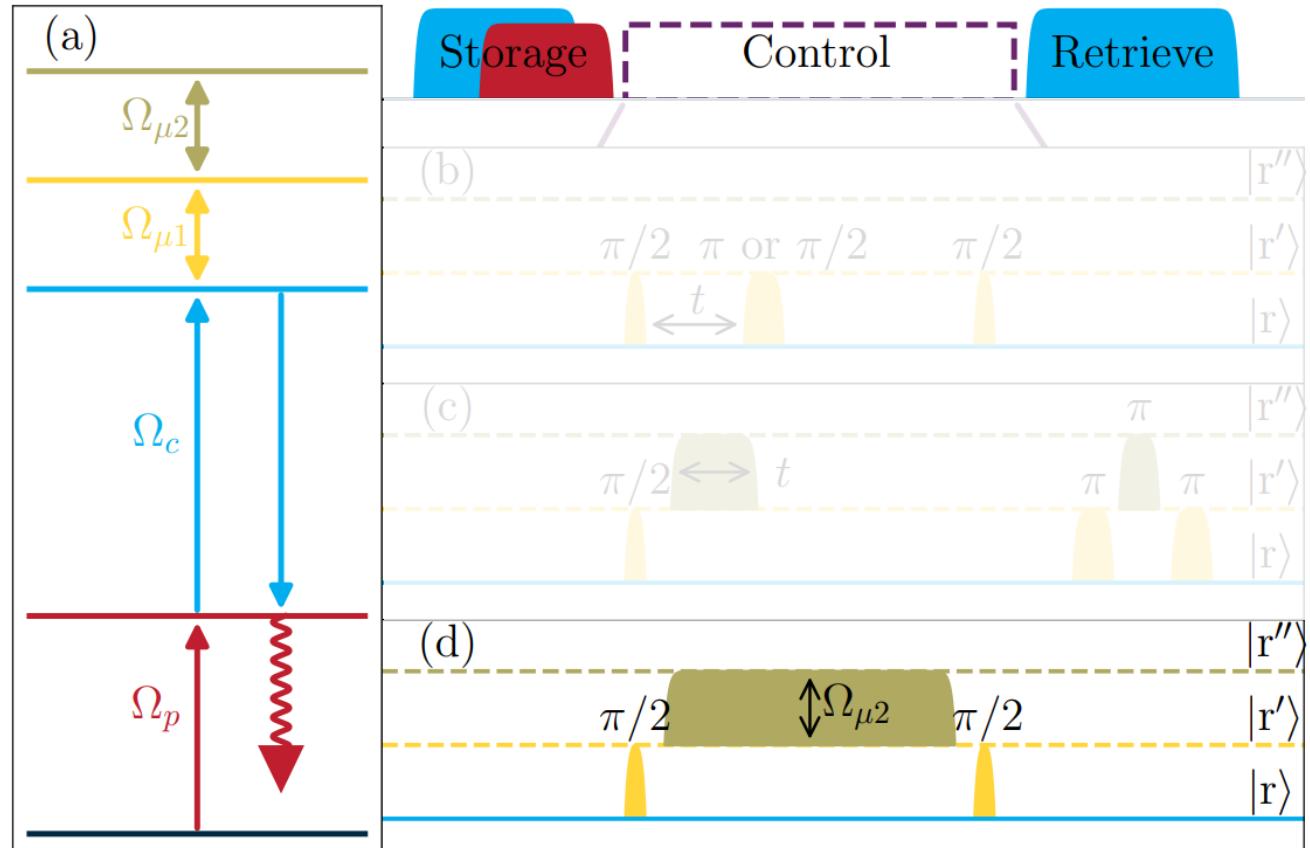
$$|\psi\rangle = \frac{1}{\sqrt{2}} \left[|0\rangle + \frac{1}{\sqrt{2}}(|1\rangle + |2\rangle) \right]$$



Single photon qutrits



Single photon qutrits

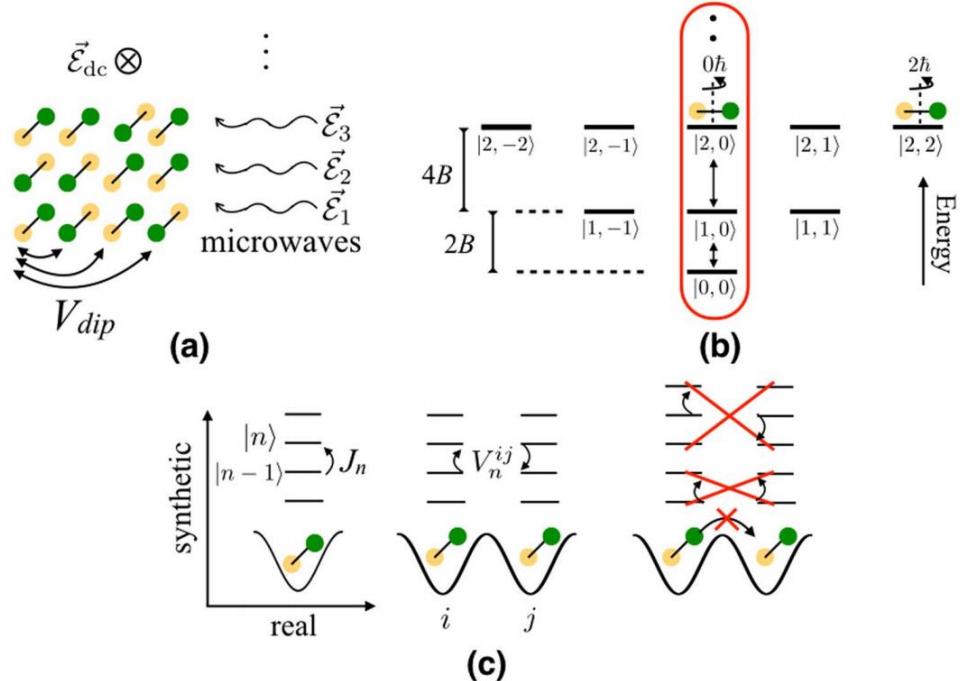


Outlook

Synthetic dimensions

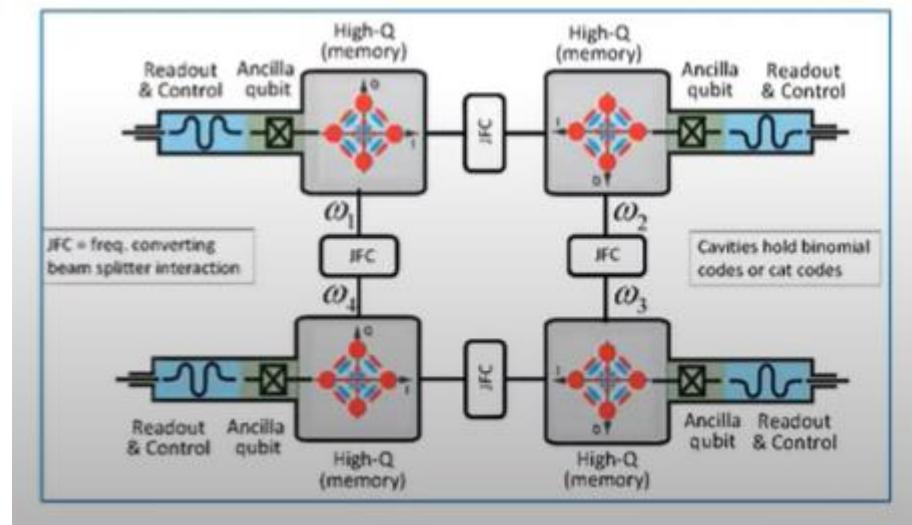
Synthetic dimensions in ultracold polar molecules

Bhuvanesh Sundar^{1,2}, Bryce Gadway¹ & Kaden R. A. Hazzard^{1,2}



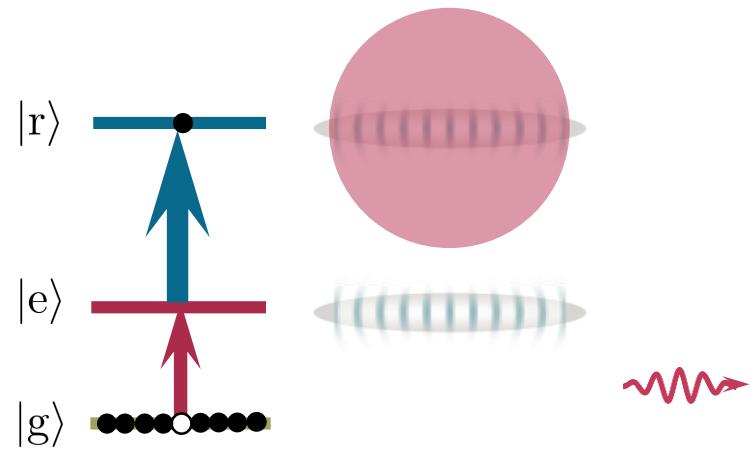
Bosonic encoding

Steven Girvin
Bosonic quantum error correction and quantum simulation

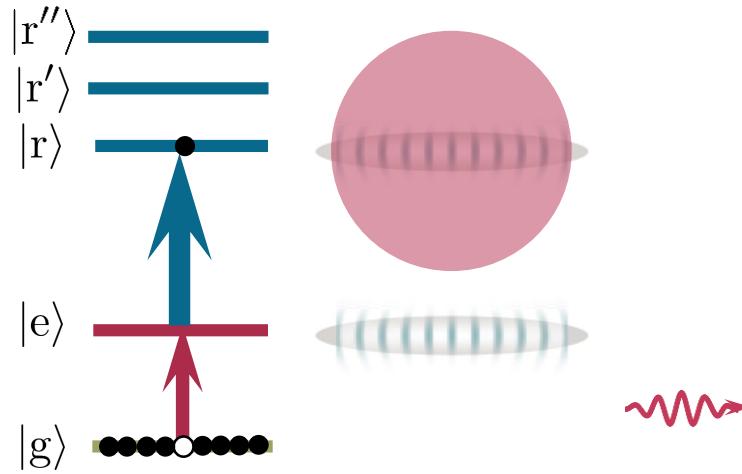


The quantum information lives not in the matter qubits but instead in 'photonic' modes of cavities

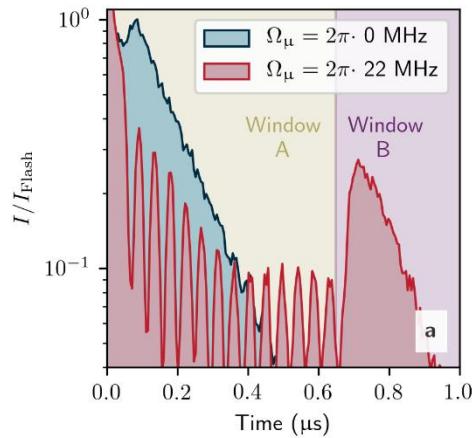
Summary: Rydberg quantum optics



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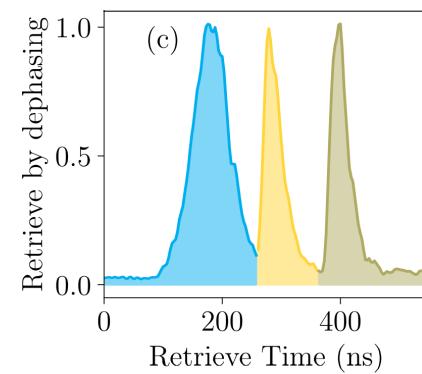


Collectively encoded qubits:
continuous measurement

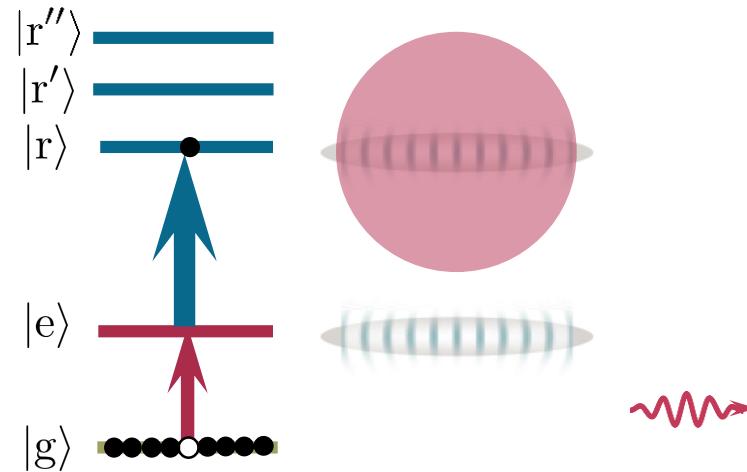


Photonic qutrits

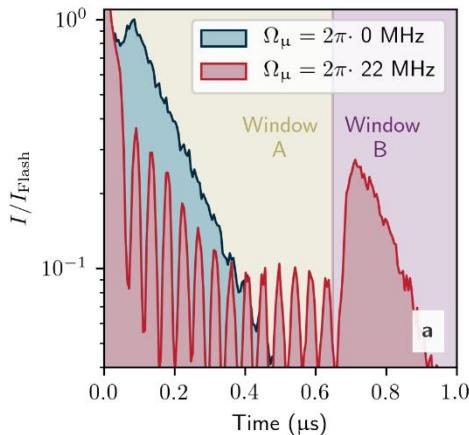
$$|\psi\rangle = \frac{1}{\sqrt{2}} \left[|0\rangle + \frac{1}{\sqrt{2}}(|1\rangle + |2\rangle) \right]$$



Summary: Rydberg quantum optics

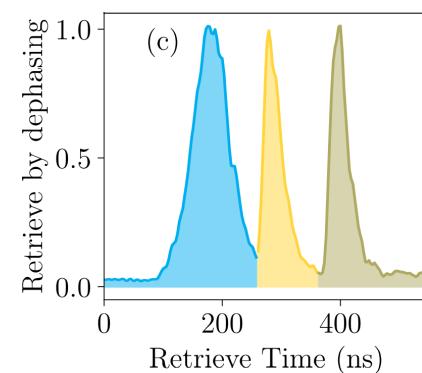


Collectively encoded qubits:
continuous measurement



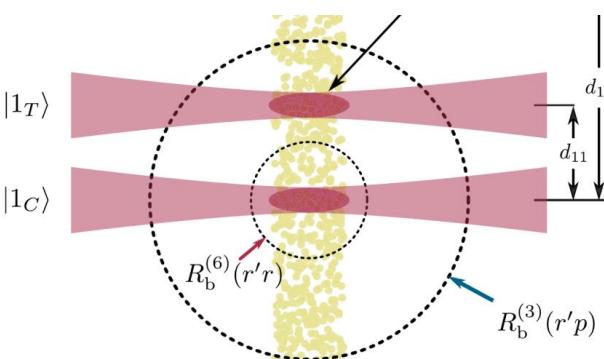
Photonic qutrits

$$|\psi\rangle = \frac{1}{\sqrt{2}} \left[|0\rangle + \frac{1}{\sqrt{2}}(|1\rangle + |2\rangle) \right]$$

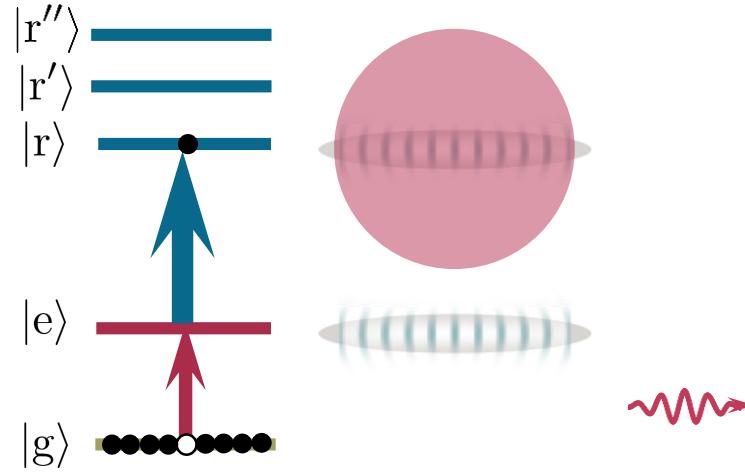


Outlook

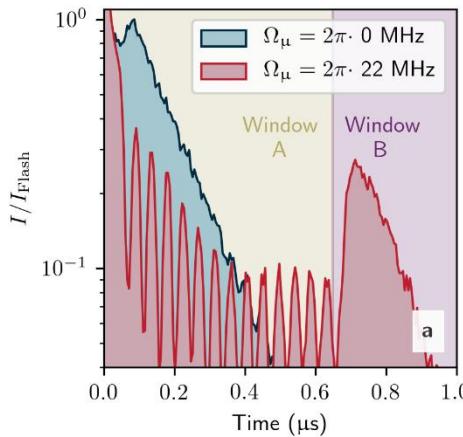
Photonic qutrit interactions



Summary: Rydberg quantum optics

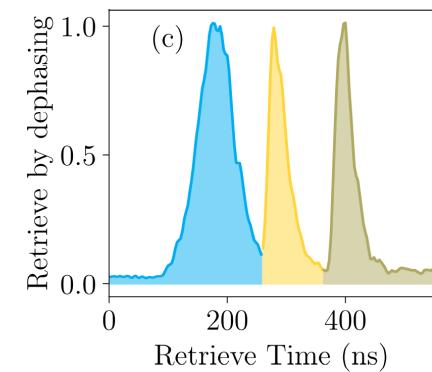


Collectively encoded qubits:
continuous measurement



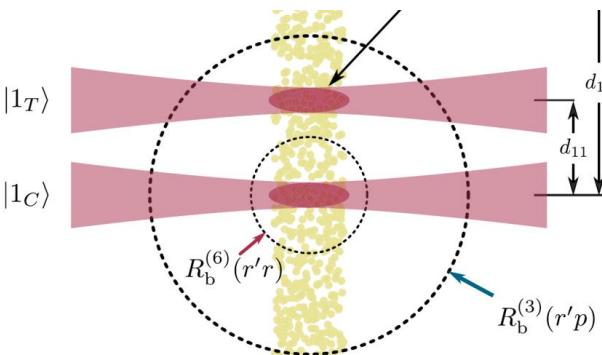
Photonic qutrits

$$|\psi\rangle = \frac{1}{\sqrt{2}} \left[|0\rangle + \frac{1}{\sqrt{2}}(|1\rangle + |2\rangle) \right]$$



Outlook

Photonic qutrit interactions



Thank you!