



Coherent control & characterization of entanglement with atomic ensembles

Kyung Soo Choi

S. B. Papp, H. Deng, P. Lougovski, S. J. van Enk,
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and Quantum Control
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« Quantum networks »

Fundamental scientific questions and diverse experimental challenges

Quantum node

generate, process, store quantum information locally

Why quantum networks?

Huge Hilbert space
(e.g. distributed quantum computing and...)



Theoretical

- Does it “work” – capabilities
 - Quantum computation,

Experimental implementation

- Physical processes for reliable generation, processing, & transport of quantum states
 - A quantum interface between matter and light

Quantum channel
transport / distribute quantum entanglement over the entire network

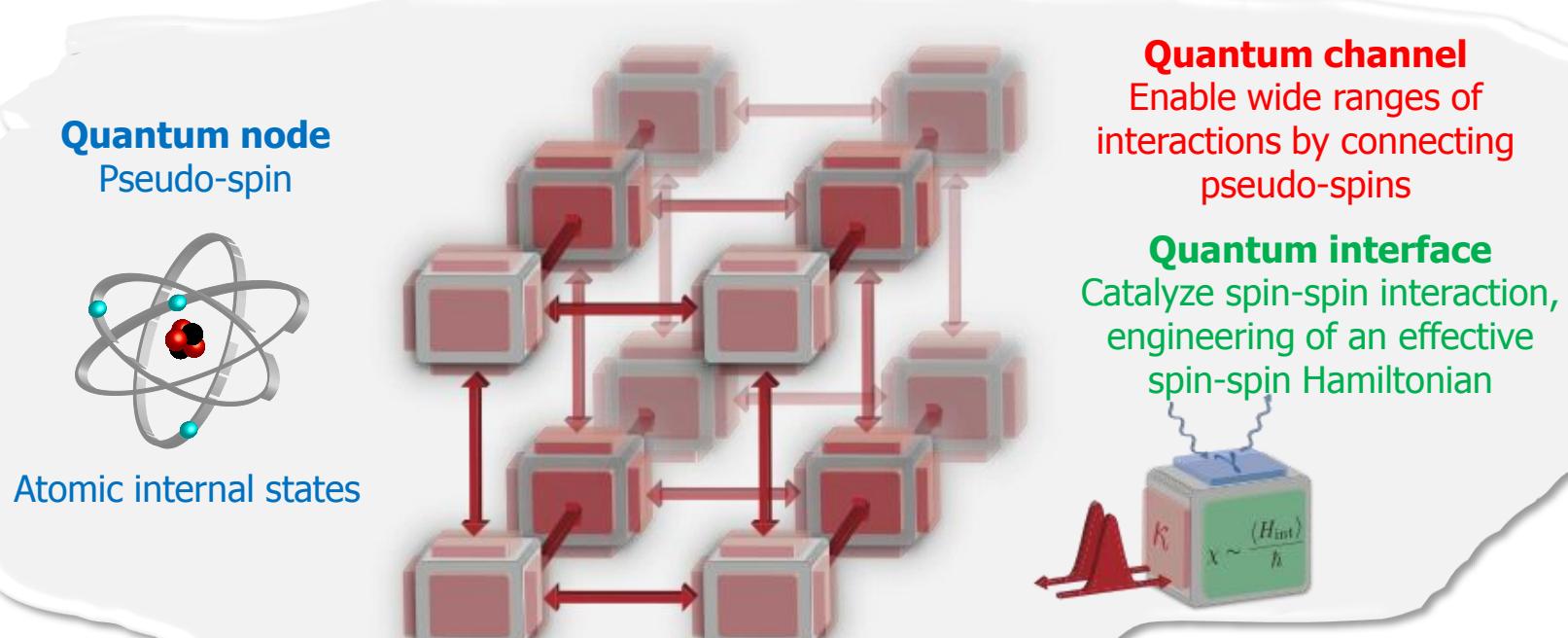
Quantum interface
map quantum resources into and out of photonic channels



Goal : develop physical resources that enable **quantum repeaters**, thereby allowing networks on distance scales larger than set by the attenuation length of fibers

« Quantum networks »

Quantum many-body system

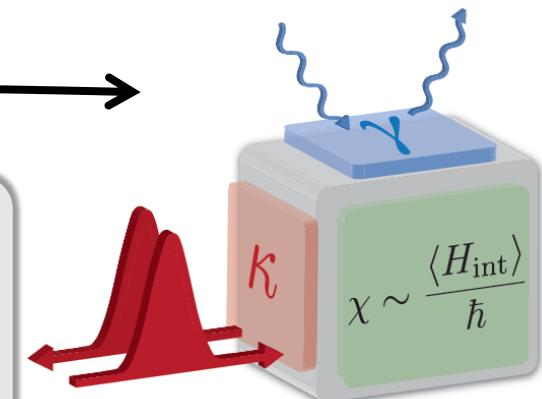


- **Quantum simulation**
 - Richard Feynman, 1982; Lloyd, *Science* (1994)
 - Trapped-ion quantum simulator
 - Leibfried *et. al.* *Phys. Rev. Lett.* 2002 ; Porras, Cirac, *Phys. Rev. Lett.* 2004; Friedenauer *et al.* *Nature Phys.* 2008.
 - Quantum phase transitions – Scaling of multipartite entanglement in 1-D spin chains (Vidal, Latorre, Rico, Kitaev. *Phys. Rev. Lett.* 2003)
- **Optimizing a quantum network**
 - “Entanglement” percolation (Acin, A., Cirac, J. I., Lewenstein, M. *Nature Phys.* 2007.)

Matter-light quantum interface

What's inside here?

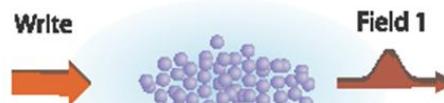
- Ensemble of $\sim 10^6$ Cs atoms
- Utilize strong interaction $\chi \sim g\sqrt{N}$ of single-photons and collective spin excitations (in the *single-excitation regime*)
- Input-output coupling $\kappa(t)$ user controlled coherently by lasers



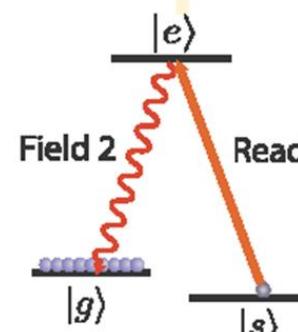
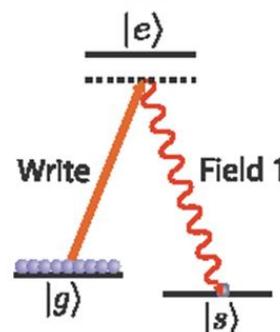
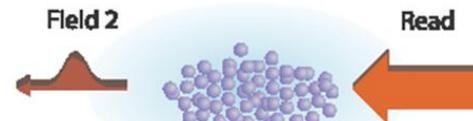
e.g. Writing and reading collective spin waves

Non-collinear geometry:
Harris group (2005)

1. Probabilistic Generation



2. Efficient readout⁴



Read-out processes:
EIT, off-resonant Raman,
photon echo (CRIB/AFC..)

Long-distance quantum communication with atomic ensembles and linear optics

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^{*} Institut für Theoretische Physik, Universität Innsbruck, A-6020 Innsbruck, Austria

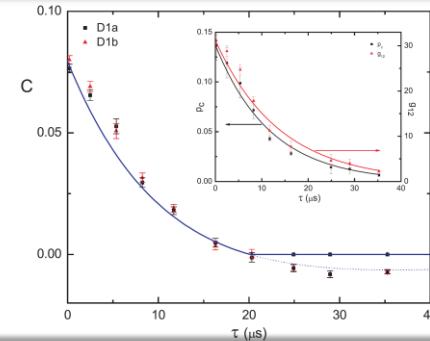
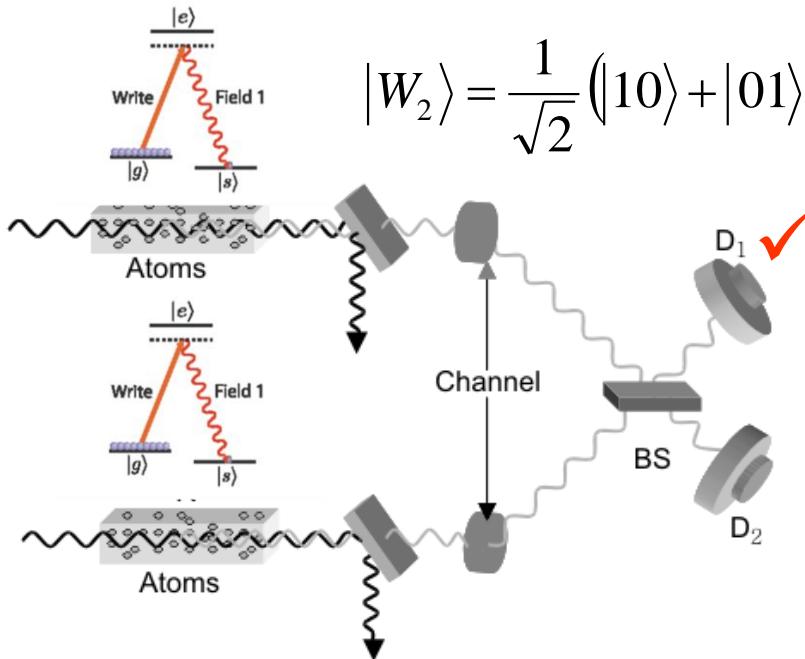
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[‡] Physics Department and ITAMP, Harvard University, Cambridge, Massachusetts 02138, USA

Quantum communication holds promise for absolutely secure transmission of secret messages and the faithful transfer of unknown quantum states. Photonic channels appear to be very attractive for the physical implementation of quantum communication. However, owing to losses and decoherence in the channel, the communication fidelity decreases exponentially with the channel length. Here we describe a scheme that allows the implementation of robust quantum communication over long lossy channels. The scheme involves laser manipulation of atomic ensembles, beam splitters, and single-photon detectors with moderate efficiencies, and is therefore compatible with current experimental technology. We show that the communication efficiency scales polynomially with the channel length, and hence the scheme should be operable over very long distances.

Measurement-induced entanglement

Entanglement generation

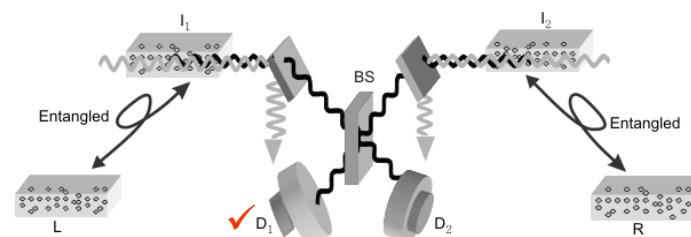


- Entanglement generated by quantum interference in the measurement process
- Heralded entanglement stored in the collective excitations of atomic ensembles
- Degree of entanglement stored in the ensemble ¹

$$C = 0.9 +/- 0.3$$

Entanglement connection

- Asynchronous preparation – sub-exponential scaling
- Functionality achieved by parallel operations



Measurement-induced entanglement : C. W. Chou, H. de Riedmatten, D. Felinto, S. V. Polyakov, S. J. van Enk, H. Jeff Kimble. *Nature* **438**, 828 (2005).

¹ J. Laurat, K. S. Choi, H. Deng, C-W. Chou and H. Jeff Kimble. *Phys. Rev. Lett.* **99**, 180504 (2007).

Reversible mapping of photonic entanglement

Vol 452 | 6 March 2008 | doi:10.1038/nature06670

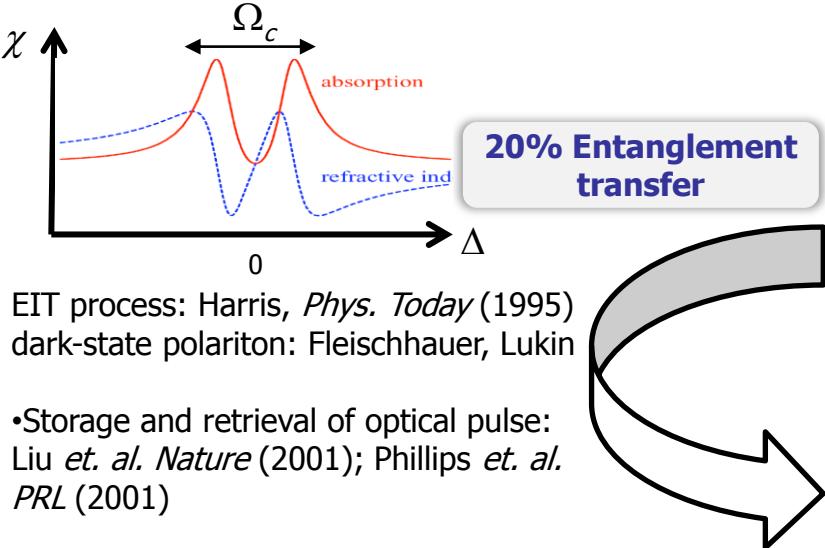
nature

Mapping photonic entanglement into and out of a quantum memory

K. S. Choi¹, H. Deng¹, J. Laurat^{1†} & H. J. Kimble¹

Nature, 452, 67 (2008)

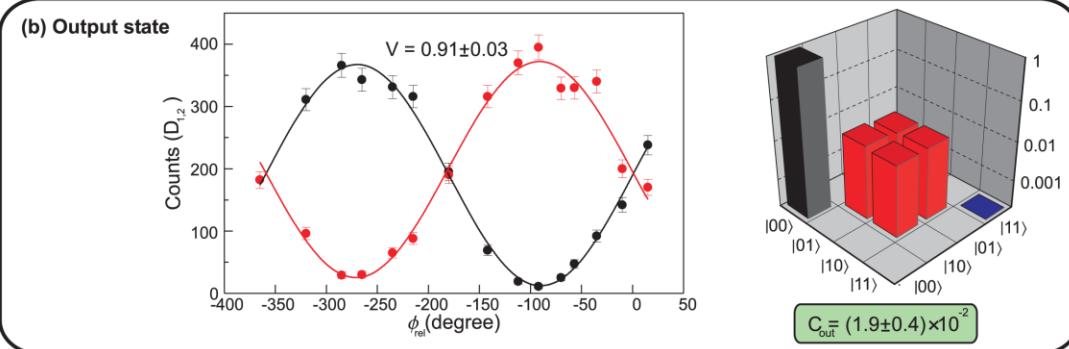
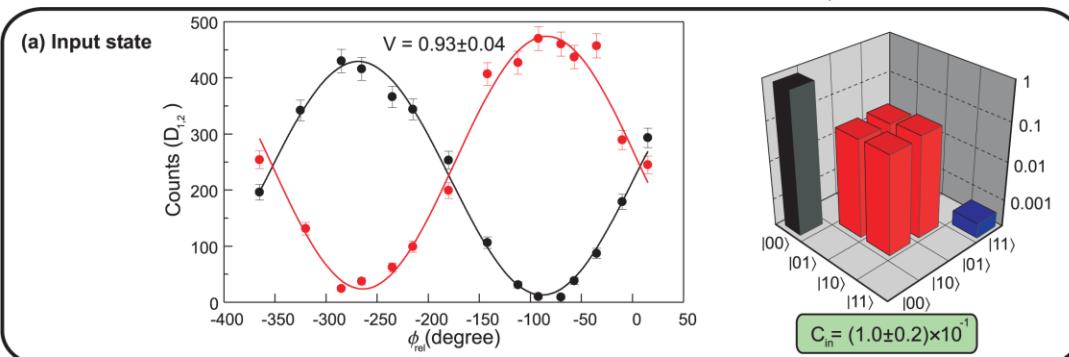
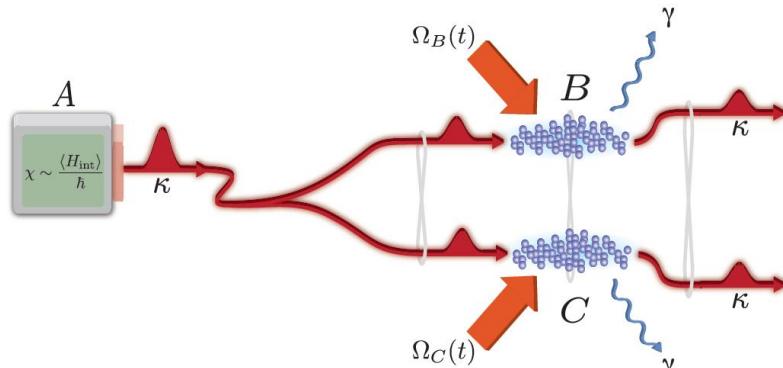
Dynamic electromagnetically induced transparency



EIT process: Harris, *Phys. Today* (1995)
dark-state polariton: Fleischhauer, Lukin

• Storage and retrieval of optical pulse:
Liu *et. al.* *Nature* (2001); Phillips *et. al.*
PRL (2001)

• Single-photon storage and retrieval:
Chaneliere *et al.* *Nature* 438, 833-836
(2005);
Eisaman *et al.* *Nature* 438, 837-841
(2005).

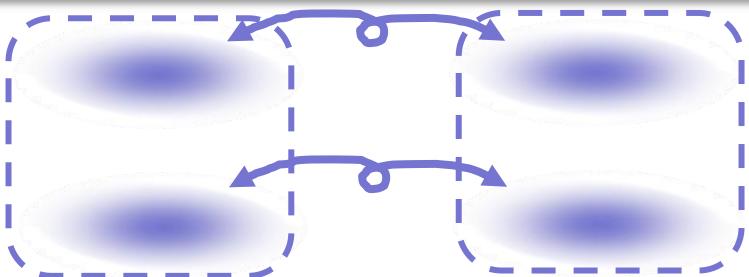


Tour de force DLCZ-based experiments



Functional Quantum Nodes for Entanglement Distribution over Scalable Quantum Networks

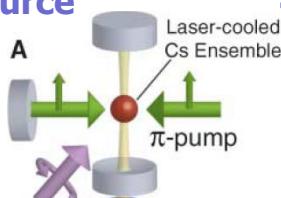
Chin-Wen Chou, Julien Laurat, Hui Deng, Kyung Soo Choi, Hugues de Riedmatten,*
Daniel Felinto,† H. Jeff Kimble‡



1) High efficiency single-photon source A High-Brightness Source of Narrowband, Identical-Photon Pairs

James K. Thompson,^{1*} Jonathan Simon,² Huanqian Loh,¹ Vladan Vuletić¹

SCIENCE VOL 313 7 JULY 2006



2) Long-lived quantum memories

LETTERS

PUBLISHED ONLINE: 7 DECEMBER 2008 | DOI: 10.1038/NPHYS152

nature physics

Long-lived quantum memory

R. Zhao¹, Y. O. Dudin¹, S. D. Jenkins^{1,2*}, C. J. Campbell¹, D. N. Matsukevich³, T. A. B. Kennedy¹ and A. Kuzmich¹

nature physics

LETTERS
PUBLISHED ONLINE: 7 DECEMBER 2008 | DOI:10.1038/NPHYS1153

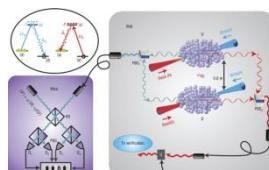
A millisecond quantum memory for scalable quantum networks

Bo Zhao^{1*}, Yu-Ao Chen^{1,2*}, Xiao-Hui Bao^{1,2}, Thorsten Strassel¹, Chih-Sung Chuu¹, Xian-Min Jin², Jörg Schmiedmayer³, Zhen-Sheng Yuan^{1,2}, Shuai Chen¹ and Jian-Wei Pan^{1,2†}

3) Applications

Memory-built-in quantum teleportation with photonic and atomic qubits

YU-AO CHEN^{1,2*}, SHUAI CHEN¹, ZHEN-SHENG YUAN^{1,2}, BO ZHAO¹, CHIH-SUNG CHUU¹, JÖRG SCHMIEDMAYER³ AND JIAN-WEI PAN^{1,2*}



4) Efficient generation of quantum states Single-photon bus connecting spin-wave quantum memories

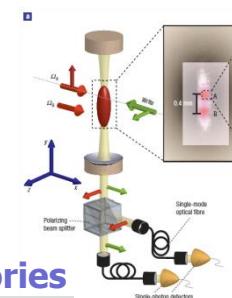
nature physics | VOL 3 | NOVEMBER 2007

JONATHAN SIMON^{1,2*}, HARUKA TANJI^{1,2}, SAIKAT GHOSH² AND VLADAN VULETIĆ²

¹Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA

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*e-mail: simonj@mit.edu



5) Multiplexed / multimode quantum memories

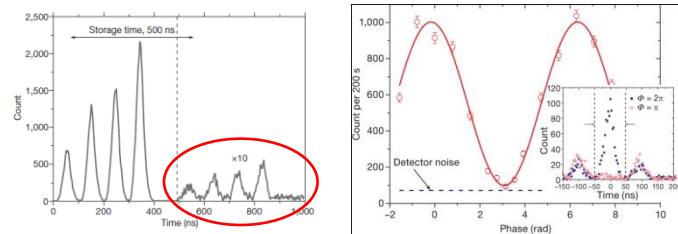
Vol 456 | 11 December 2008 | doi:10.1038/nature07607

nature

LETTERS

A solid-state light-matter interface at the single-photon level

Hugues de Riedmatten^{1*}, Mikael Afzelius^{1*}, Matthias U. Staudt¹, Christoph Simon¹ & Nicolas Gisin¹



6) Solid state ensembles / atom-chip integration

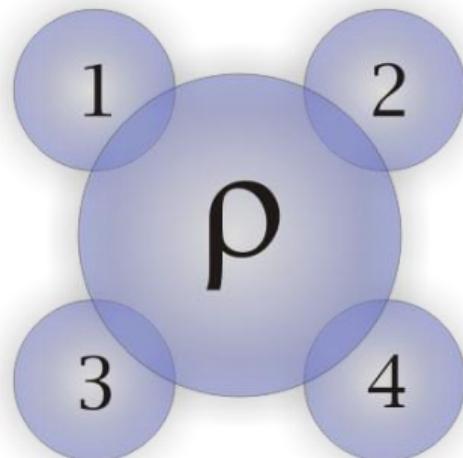
For a review: H. J. Kimble Quantum internet Nature (2008)
Sangouard, Simon, de Riedmatten, Gisin Arxiv 0906.2699

Generation and characterization of N-partite state

$$|\Psi_N\rangle \sim \sum_i^{i_{\max}} \lambda_i |\psi_i^{(1)}, \psi_i^{(2)}, \dots, \psi_i^{(N-1)}, \psi_i^{(N)}\rangle$$

- For example, a quadripartite W state –

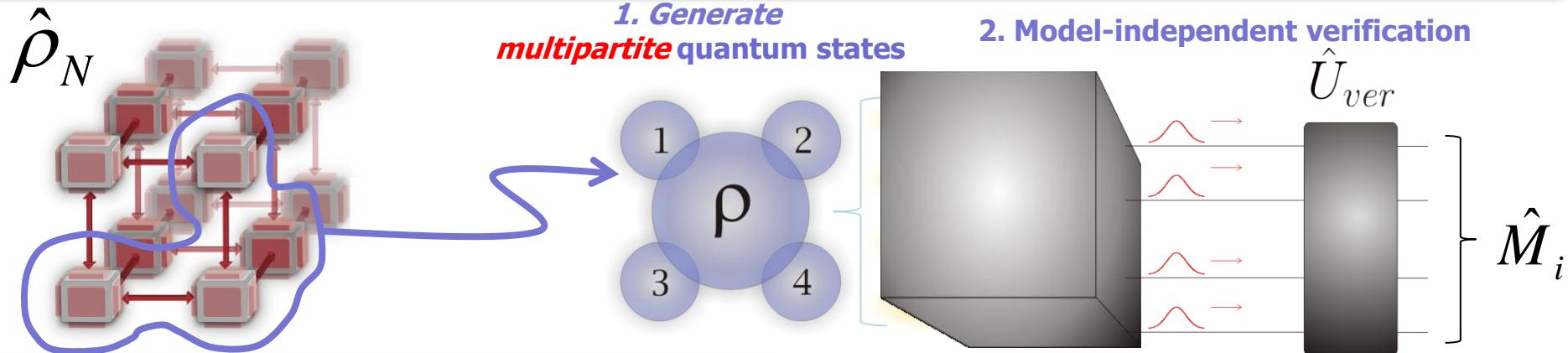
$$|W\rangle = \frac{1}{2} [(|1000\rangle + e^{i\phi_1}|0100\rangle) + e^{i\phi} (|0010\rangle + e^{i\phi_2}|0001\rangle)]$$



An excluded territory –
(with ensembles)



Quantum network: multipartite entanglement



Generation (*ensemble* landscape)

among other works...

- *a posteriori* entanglement
 - Kuzmich group - Matsukevich *et al.* PRL (2005); Pan group – Chen *et al.* Nat. Phys. (2008).
- ✓ *heralded* entanglement
 - Chou *et al.* Nature (2005); Laurat *et al.* PRL (2008); Pan group – Yuan *et al.* Nature (2008); Vučetić group – Tanji *et al.* PRL (2009)
- ✓ *deterministic* entanglement
 - direct mapping of photonic entanglement
 - Choi *et al.* Nature (2008); Vučetić groups - Simon *et al.* Nat. Phys (2007)
 - quantum gates
 - EIT stationary light - Andre *et al.* PRL (2005); Rydberg blockade - Jaksch *et al.* PRL (2000)

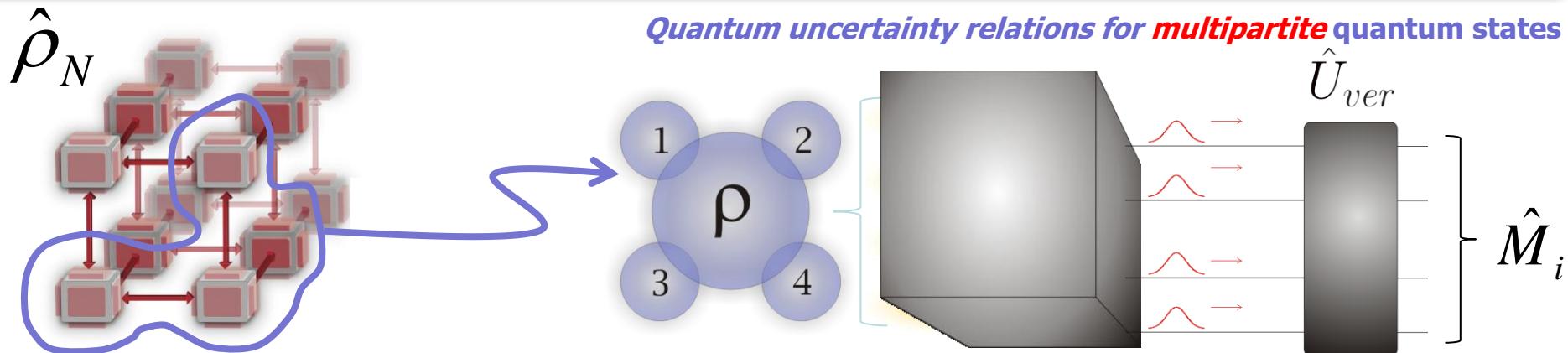
Characterization: an even harder problem

- ✓ *bipartite* entanglement ? well-developed
 - Among many others, tomography-based-entanglement monotones (NPT), CHSH inequality, teleportation, witness, etc ...
 - van Enk, Lutkenhaus, Kimble, PRA, (2005)
- ✓ *multipartite* entanglement ? not so much..
 - Generally, linear witness W^1
 - Exponentially larger state space dimension to search, numbers of measurements.
 - Overlap between less entangled states increases.
 - Classes of entanglement (for *qubits*, $N=3$, 2 classes; $N=4$, 9 classes)²

¹ Hahn-Banach theorem, Horodecki *et al.* Phys. Lett. (1996)

² Dur *et. al.* PRA (2000); Verstraete *et. al.* PRA (2002)

Quantum network: multipartite entanglement



- **Quantum resources**

- Quantum computing: Linear optics – KLM, *Nature* (2001); Cluster state – Raussendorf, Briegel (2001), Walther *et. al.* (2005) for atomic ensembles (Barrett *et. al.* arxiv 0804.0962)
- Quantum secret sharing – Hillery *et. al.* *PRA* (1999)
- Quantum simulation – Lloyd, *Science* (1996)
- Quantum metrology – Boto *et. al.* *PRL* (2000); Giovannetti, Lloyd, Maccone, *Science* (2004)
- Q... Q... Q...

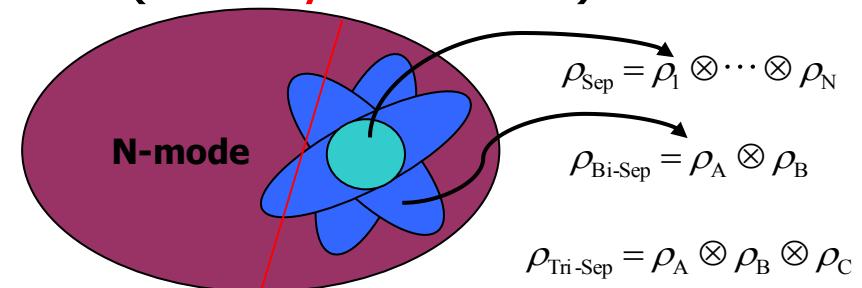
- **Implementations** → Witness

- Trapped ion – up to 8 ions (Leibfried *et. al.* *Nature* (2005); Haffner *et. al.* *Nature* (2005))
- PDC – Pan *et. al.* *Nature* (2000); 5 hyper-entangled photons (Gao *et. al.* arxiv 0809.4277)

N-partite generalization for *DLCZ*

$$|W_2\rangle = \frac{1}{\sqrt{2}}(|10\rangle + |01\rangle) \rightarrow |W_N\rangle$$

Only one genuine entanglement class (for any N modes)



Construct a *nonlinear/nonlocal* witness (extend to N, # of M, N & N-1)

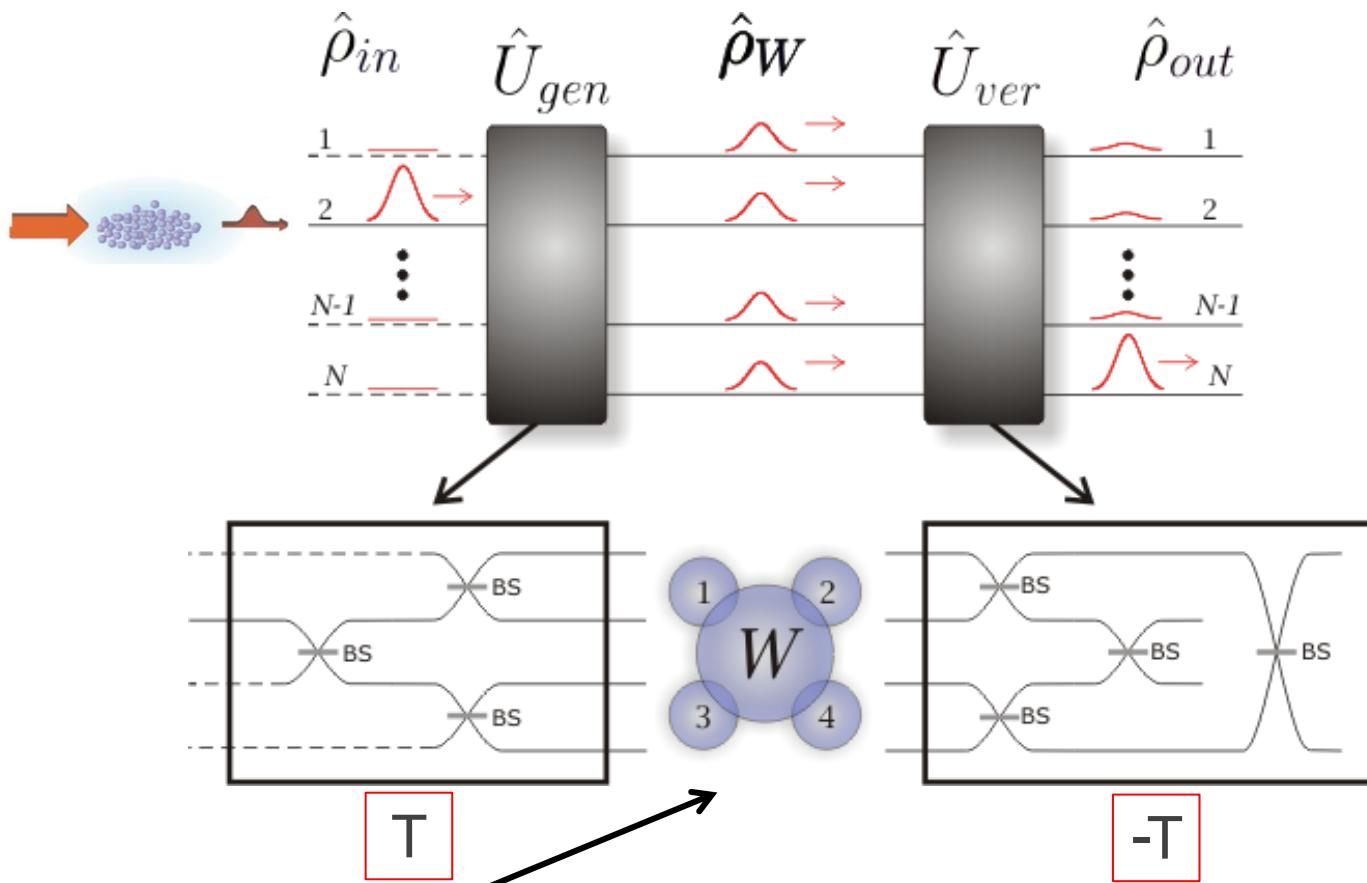
Photonic W -state generation and verification

Science

AAAS

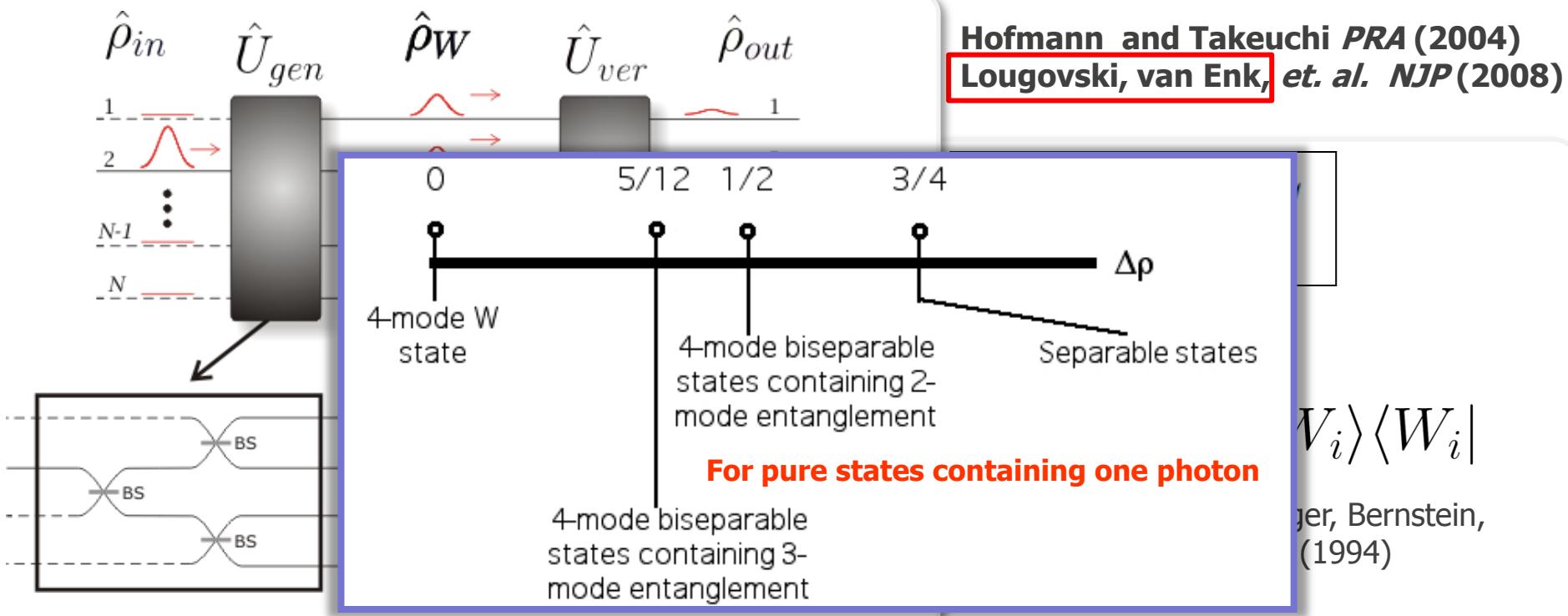
Characterization of Multipartite Entanglement for One Photon Shared Among Four Optical Modes

S. B. Papp*, K. S. Choi*, H. Deng, P. Lougovski, S. J. van Enk, H. J. Kimble



$$|W\rangle = \frac{1}{2} [(|1000\rangle + e^{i\phi_1}|0100\rangle) + e^{i\phi} (|0010\rangle + e^{i\phi_2}|0001\rangle)]$$

Uncertainty relations



$|V_i\rangle\langle W_i|$
Jen, Bernstein,
(1994)

Statistical measure Δ :

$$\Delta = \sum_i \langle \delta \hat{M}_i^2 \rangle = 1 - \sum_i \langle \hat{M}_i \rangle^2$$

$$|W_1\rangle = \frac{1}{2}(|1000\rangle + |0100\rangle + |0010\rangle + |0001\rangle)$$

(and 3 other possibilities ...)

Threshold for four-mode entanglement, calculate Δ for a state with at most 3 mode entanglement

$$\Psi_3 \approx |0\rangle \otimes (|100\rangle + |010\rangle + |001\rangle)$$

$$\Delta_b(\Psi_3) = 0.41$$

Caveat: multiple excitations

- Most experiments using entangled “photons” use only data where photons were detected (local filter)
- But this does not work for detecting *mode*-entanglement in

$$|01\rangle + |10\rangle$$

- Take the unentangled (product) state: [Wikipedia](#)

$$(|0\rangle + \varepsilon|1\rangle)|0\rangle|0\rangle +$$

- Data where

... but this still
component a
(non-local filter) → contamination analysis y_c

PHYSICAL REVIEW A 75, 052318 (2007)

Experimental procedures for entanglement verification

S. J. van Enk,^{1,2} N. Lütkenhaus,³ and H. J. Kimble^{2,4}

¹*Department of Physics, Oregon Center for Optics and Institute for Theoretical Science, University of Oregon, Eugene, Oregon 97403, USA*

²*Institute for Quantum Information, California Institute of Technology, Pasadena, California 91125, USA*

³*Institute of Quantum Computing and Department of Physics and Astronomy, University of Waterloo, Waterloo, Ontario, Canada N2L 3G1*

⁴*Norman Bridge Laboratory of Physics 12-33, California Institute of Technology, Pasadena, California 91125, USA*

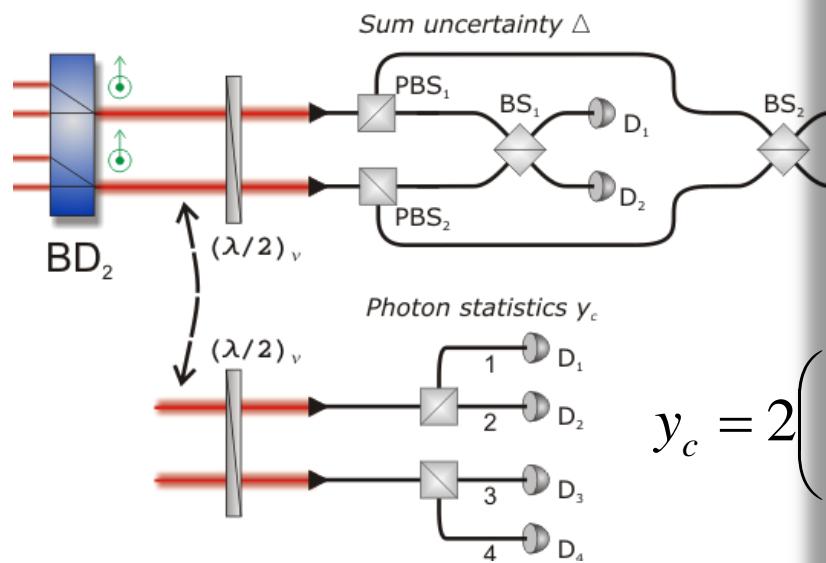
(Received 4 December 2006; published 15 May 2007)

We give an overview of different types of entanglement that can be generated in experiments, as well as of various protocols that can be used to verify or quantify entanglement. We propose several criteria that, we argue, should be applied to experimental entanglement verification procedures. Explicit examples demonstrate that not following these criteria will tend to result in overestimating the amount of entanglement generated in an experiment or in inferring entanglement when there is none. We distinguish protocols meant to refute or eliminate hidden-variable models from those meant to verify entanglement.

Operational procedures for verification

For verification, **two** measurements --

- 1.“Sum uncertainty” of the interfered optical modes
- 2.Characterize single photon source, “photon statistics”

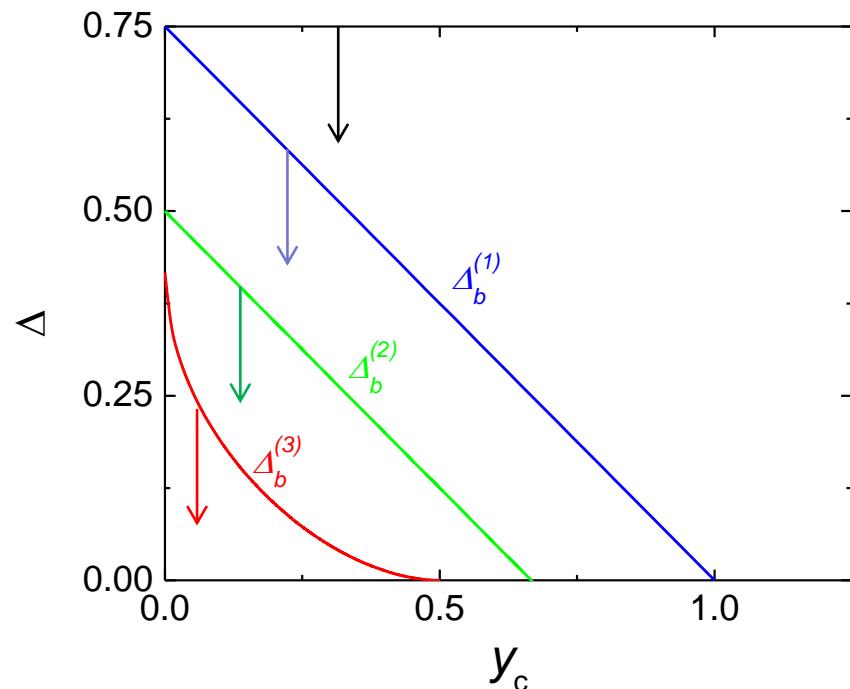


$$y_c = 2 \left(\dots \right)$$

Similar to $g^{(2)}$, y_c quantifies state
normalized s.t. $y_c=1$ for independent coherent states

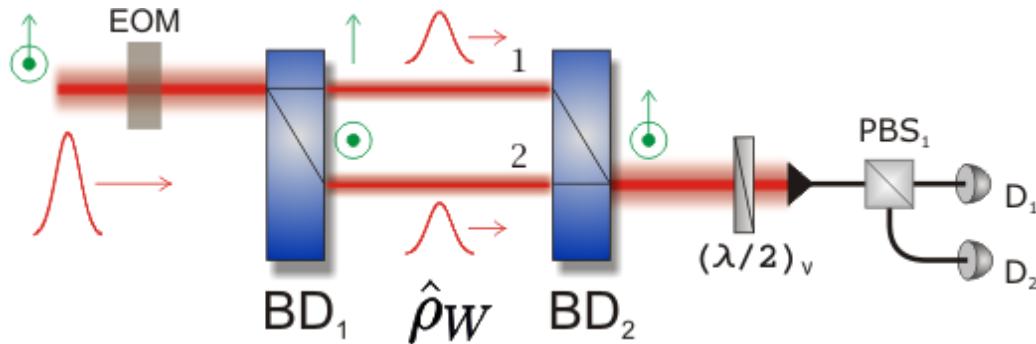
•Contamination analysis for *all possible less* entangled, and separable
 $\hat{\rho}(p_0, p_1, p_{\geq 2}) = \underbrace{p_0 \hat{\rho}_0 + p_1 \hat{\rho}_1 + p_{\geq 2} \hat{\rho}_{\geq 2}}_{\text{pure \& mixed states}}$

including higher order statistics
truncated by *LOCC*

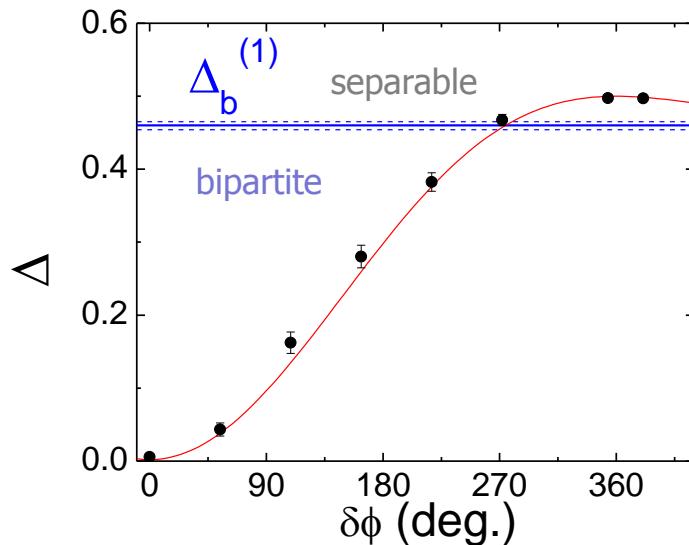


Bipartite entanglement

$$\Delta = \frac{1}{2}(1 - V^2)$$
 where V = fringe visibility

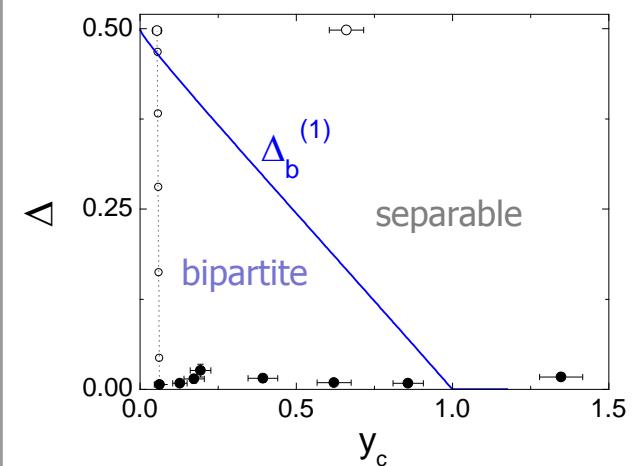
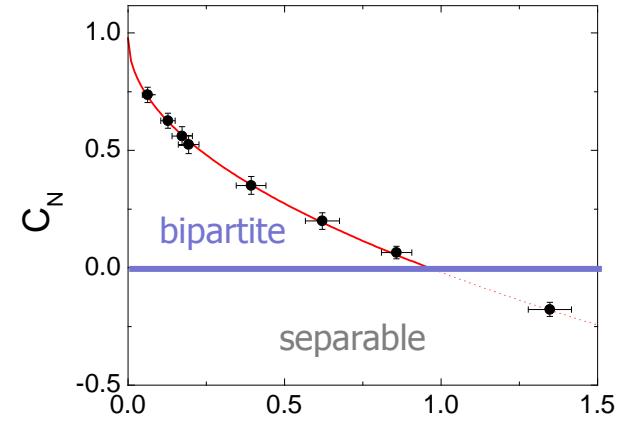


Δ vs. phase noise



$$C_N = \sqrt{1 - 2\Delta} - \sqrt{1 - 2\Delta_b}$$

Concurrence vs. Δ



Observation of quadripartite entanglement

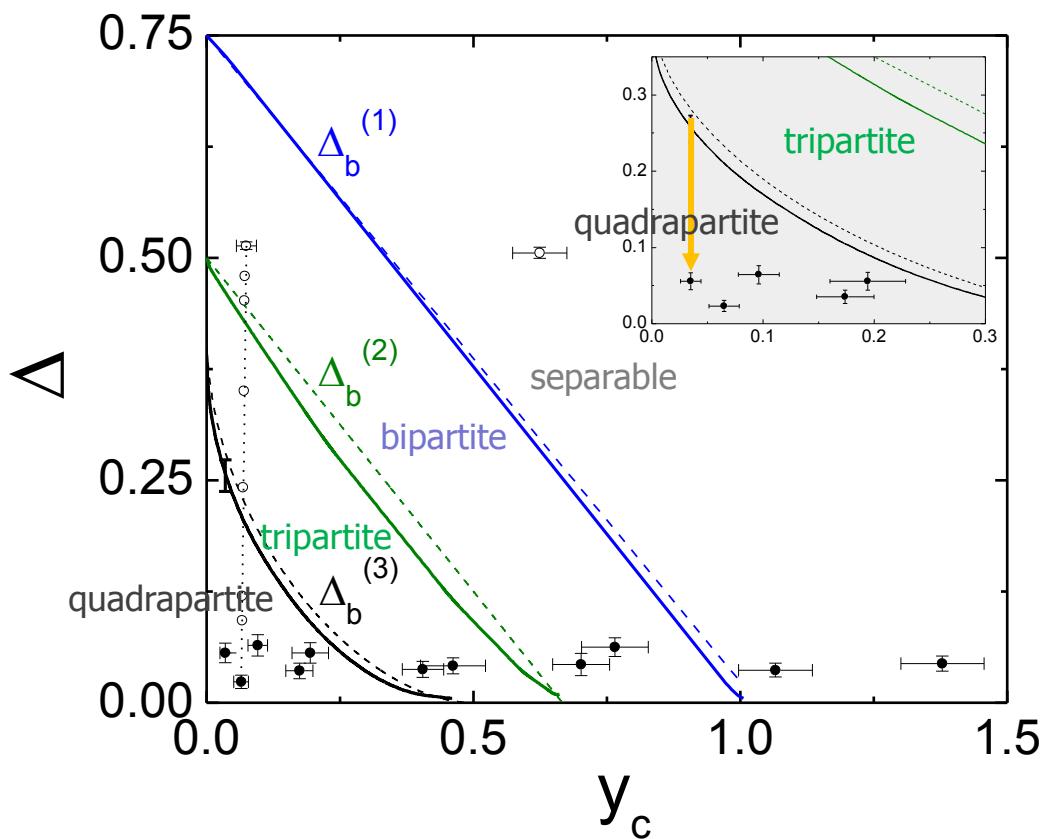


Δ

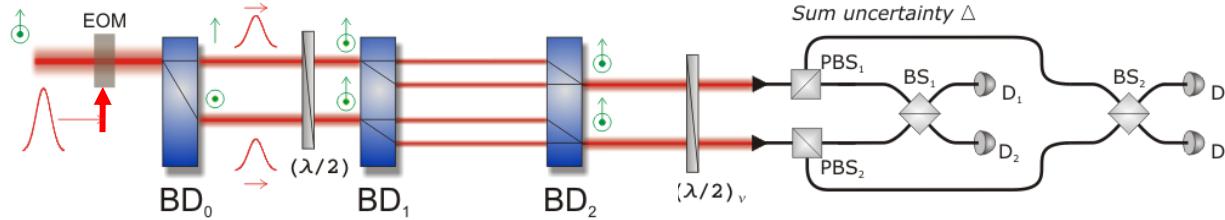
from fringe
visibilities V_{ijkl}

$$y_c = \frac{3}{2} \frac{p_{\geq 2} p_0}{p_1^2}$$

from photon statistics



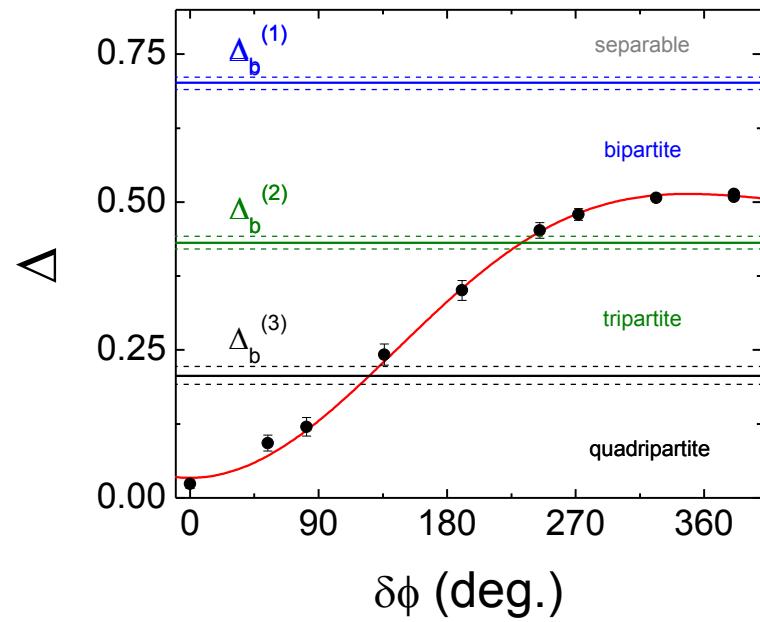
Robustness of photonic W-state



$$|W\rangle = \frac{1}{2} \left[(|1000\rangle + e^{i\phi_1}|0100\rangle) + e^{i\phi} (|0010\rangle + e^{i\phi_2}|0001\rangle) \right]$$

$$\rho = \frac{1}{2\phi_0} \int_{-\phi_0}^{\phi_0} |W(\phi)\rangle\langle W(\phi)| d\phi$$

Transitions from quadripartite to bipartite entanglement



- For a completely unknown phase ($2\phi_0=2\pi$),

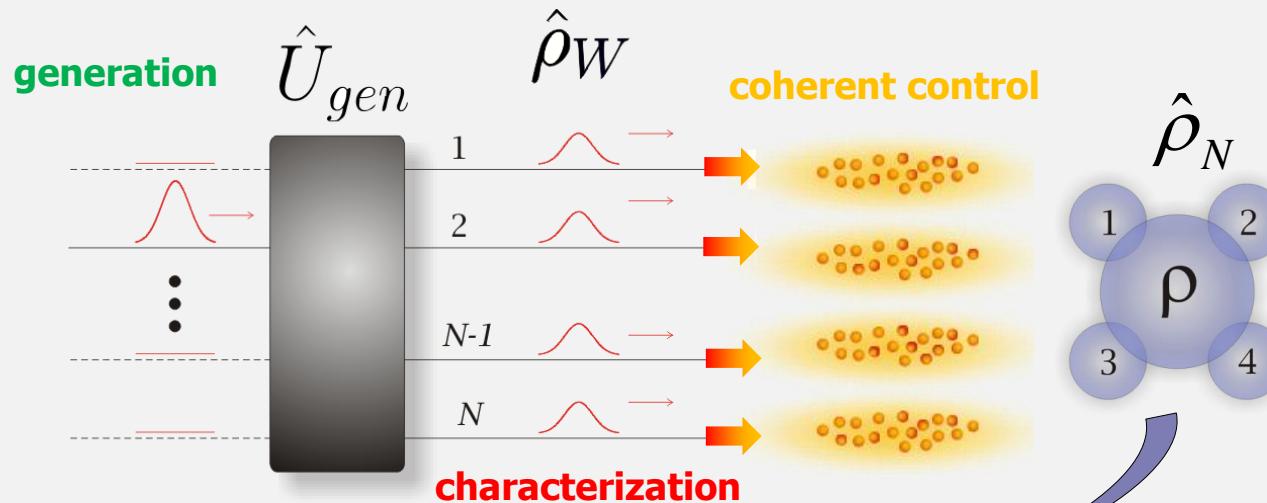
$$\rho = \frac{1}{2} \rho_{ent}^{(1,2)} \otimes \rho_{vac}^{(3,4)} + \frac{1}{2} \rho_{vac}^{(1,2)} \otimes \rho_{ent}^{(3,4)}$$

dephases from 4-mode ent. to 2-mode ent.

* Respective bipartite components still retain their entanglements (modes 1,2 & 3,4)

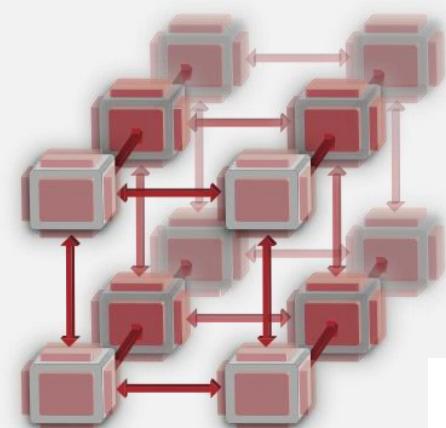
Atomic ensembles desiderata

Multipartite entanglement of atomic ensembles



Directions

- Quantum metrology
 - Verification protocol extendible to multipartite NOON state
- Multiple *functional* quantum nodes ($N > 2$)
 - Entangled “*qudits*” for quantum cryptography / quantum secret sharing / qubit encoding for quantum error correction
 - Parallelization of d^W states / scaling behavior
- Collective nature of *W* states in *superradiant* processes for DLCZ and BEC



Thank you !

Caltech quantum optics

Kyung Soo Choi

Scott Papp

Chin-Wen Chou, now at NIST Boulder

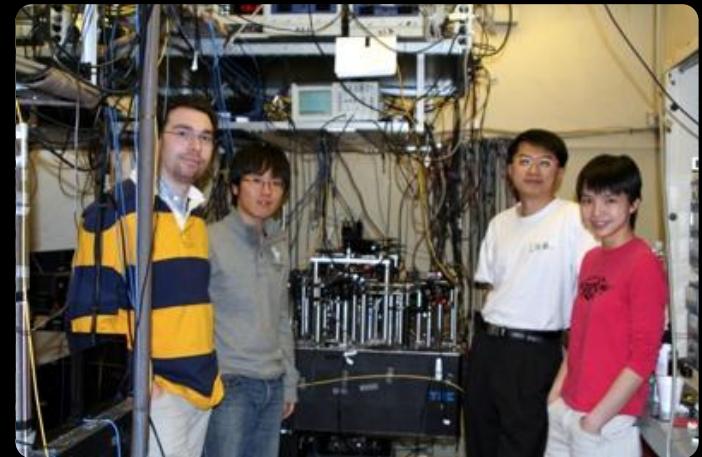
Daniel Felinto, now at Recife

Hui Deng, now at Michigan

Hugues de Riedmatten, now at Geneva

Julien Laurat, now at LKB Paris

Prof. H. Jeff Kimble

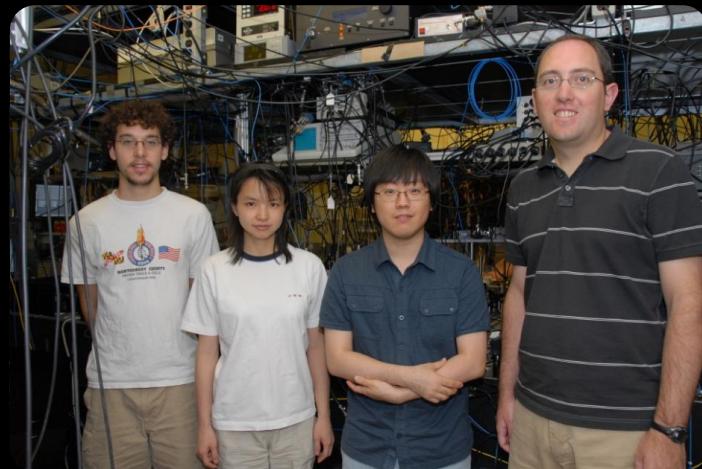


Theory

University of Oregon

Pavel Logovski, now at Stanford

Prof. Steven J. van Enk



Atomic ensembles desiderata

Multipartite entanglement of atomic ensembles

