Quantum Sensing with Atoms and Photons

Alexey V. Gorshkov

Joint Quantum Institute (JQI)
Joint Center for Quantum Information and Computer Science (QuICS)
NIST and University of Maryland

JOINT CENTER FOR QUANTUM INFORMATION AND COMPUTER SCIENCE

Intersections between Nuclear Physics and Quantum Information
Physics Division, Argonne National Laboratory
March 28, 2018

Outline

- quantum sensing with atoms
- quantum sensing with photons

(introductory/overview - no technical details)

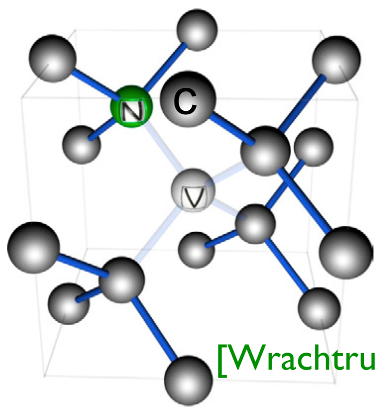
Quantum sensing with atoms

(all qubits, including honorary atoms)

Quantum sensors

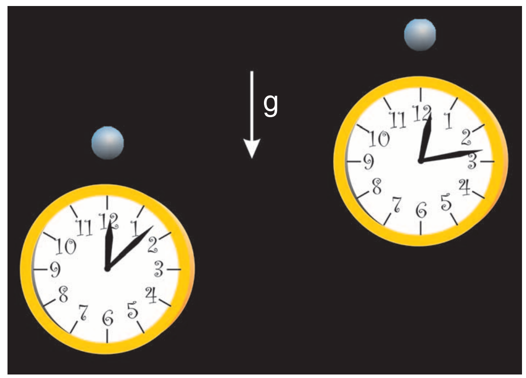
- combine high spatial resolution and high precision

NV-center magnetometer & thermometer



[Wrachtrup et al.]

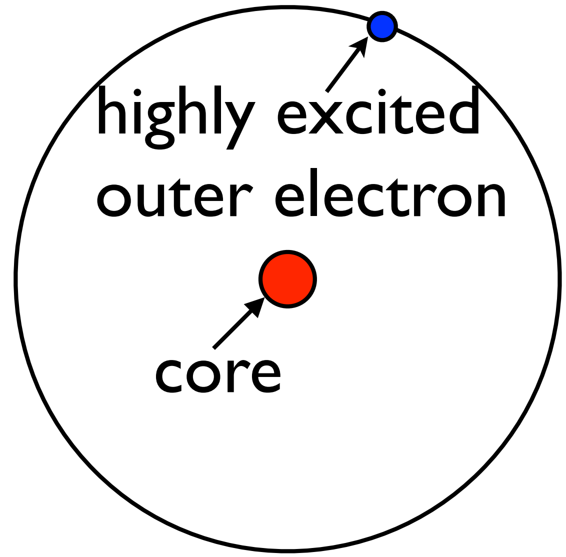
ion-clock gravimeter



[Chou, Wineland et al, 2010]

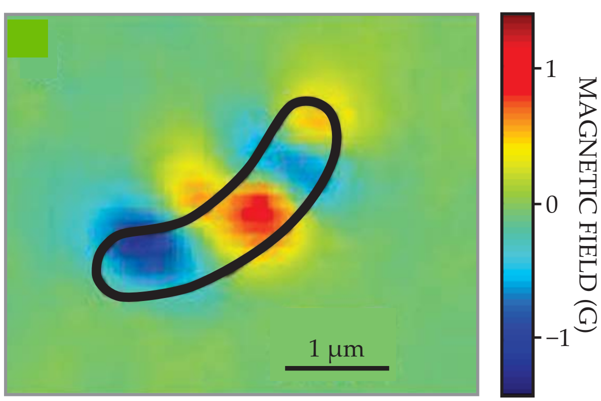
Rydberg-atom electrometer

[Facon, Haroche et al, 2016]



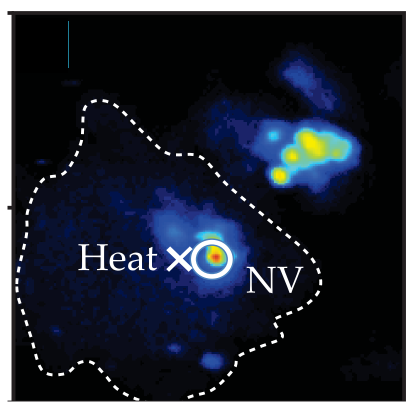
talk by Georg Raithel

magnetic imaging of live bacteria



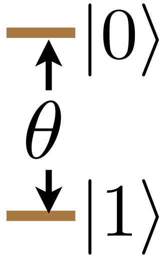
[Le Sage, Walsworth et al, 2013]

nanoscale thermometry of live human cells



[Kucsko, Lukin et al, 2013]

Quantum sensors



$$\hat{H} = \frac{1}{2}\theta \hat{Z}$$

parameter of interest

$$\hat{Z} = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \quad \hat{X} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

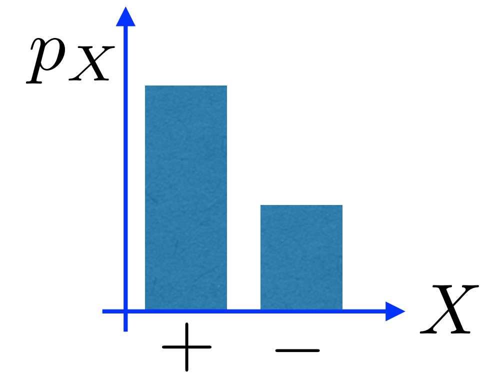
$$|\psi(t=0)\rangle = (|0\rangle + |1\rangle)/\sqrt{2}$$

$$|\psi(t)\rangle = e^{-i\hat{H}t}|\psi(0)\rangle = (e^{-i\theta t/2}|0\rangle + e^{i\theta t/2}|1\rangle)/\sqrt{2}$$

- measure $\hat{X}$. Eigenstates $|\pm\rangle = (|0\rangle \pm |1\rangle)/\sqrt{2}$

$$p_+ = |\langle + | \psi(t)\rangle|^2 = \cos^2(\theta t/2)$$

$$p_- = |\langle - | \psi(t)\rangle|^2 = \sin^2(\theta t/2)$$

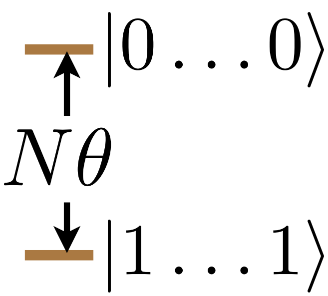


- sample random variable X whose distribution depends on θ
- Fisher info = info about θ in X: $F = \sum_{X=\pm} p_X \left(\frac{\partial \ln p_X}{\partial \theta}\right)^2 = t^2$
- Cramér-Rao bound: $\Delta\theta \geq \frac{1}{\sqrt{F}} = \frac{1}{t}$

[need many runs M to saturate $\Delta\theta \geq 1/\sqrt{FM}$]

N sensors

$$\hat{H} = \frac{1}{2}\theta \sum_{i=1}^{N} \hat{Z}_i$$



Used independently: $|\psi(0)\rangle \propto (|0\rangle + |1\rangle) \otimes \cdots \otimes (|0\rangle + |1\rangle)$

$$\Delta\theta = \frac{1}{t\sqrt{N}}$$ standard quantum limit

Using entanglement: $|\psi(0)\rangle \propto |0\ldots0\rangle + |1\ldots1\rangle \neq |\psi_1\rangle \otimes |\psi_2\rangle$

$$|\psi(t)\rangle \propto |0\ldots0\rangle + e^{iN\theta t}|1\ldots1\rangle$$

- measure $\hat{X}_1 \otimes \cdots \otimes \hat{X}_N$

$$\Delta\theta = \frac{1}{tN}$$

Heisenberg limit - best possible measurement

[Caves, Wineland, Holland, etc… ’90s]

- contributions to quantum noise from each sensor conspire to cancel
- not all entangled states useful; other useful states: spin-squeezed…

21st century quantum sensors

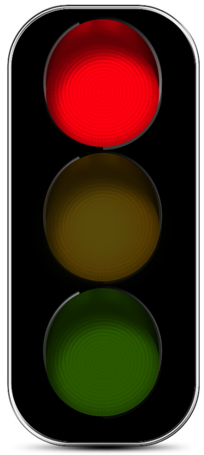
- challenge: entanglement hard to create and protect

  ⇒ entanglement has never resolved a real sensing bottleneck

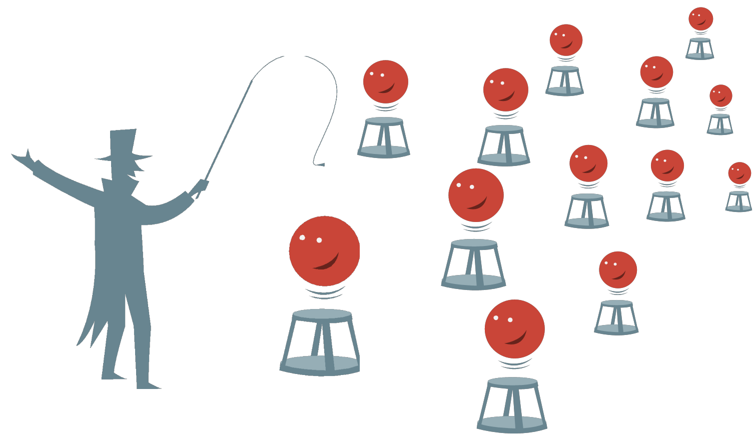
  ⇒ time is ripe to harness entanglement for quantum sensing

20th century

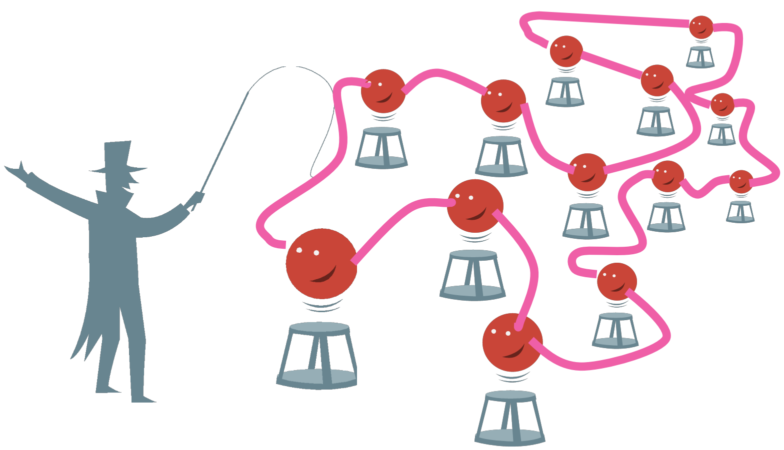
Precision measurement with *independent quantum systems*

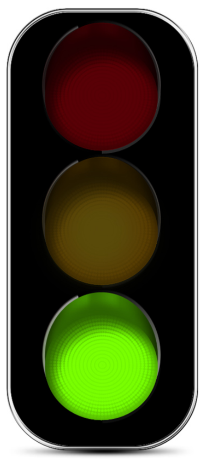


Independent atoms



Entanglemed atoms



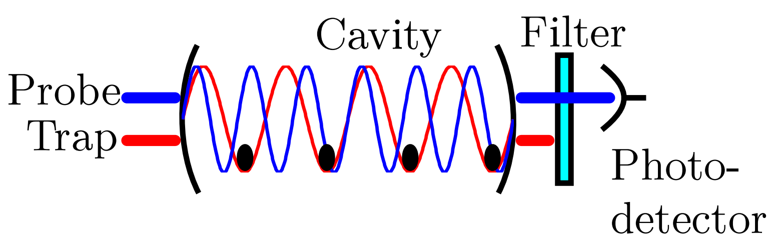


21st century

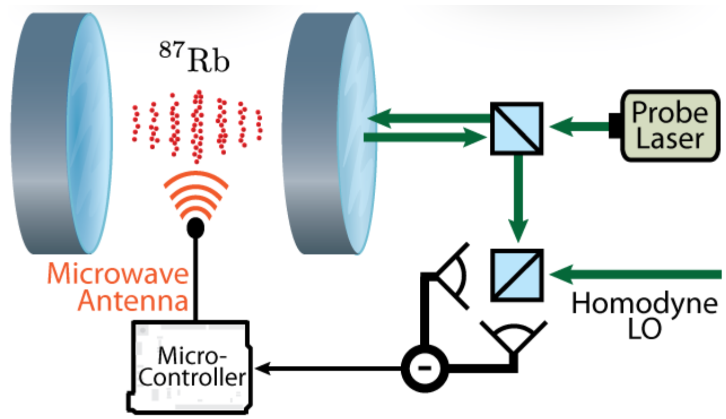
Enhanced performance with *entangled atoms*

Towards entangled sensors

- metrologically useful entanglement of neutral atoms



Leroux, Schleier-Smith, Vuletić,
PRL 104, 073602 (2010)



Cox, Greve, Weiner, Thompson
PRL 116, 093602 (2016)

- metrologically useful entanglement of trapped ions

same trap

$$|000000\rangle + |111111\rangle$$

Leibfried, …, Wineland,
Nature 438, 639 (2005)

two ions 1 meter apart

$$|00\rangle + |11\rangle$$

Moehring, …, Monroe,
Nature 449, 68 (2007)

Towards entangled sensors

• metrologically useful entanglement of NV centers in diamond

same diamond sample

$$|00\rangle + |11\rangle$$

Dolde, …, Jelezko, Wrachtrup,
Nature Phys. 9, 139 (2013)

two NV centers 3 meters apart

$$|00\rangle + |11\rangle$$

Bernien, …, Hanson,
Nature 497, 86 (2013)

…and lots of other experiments and proposals…

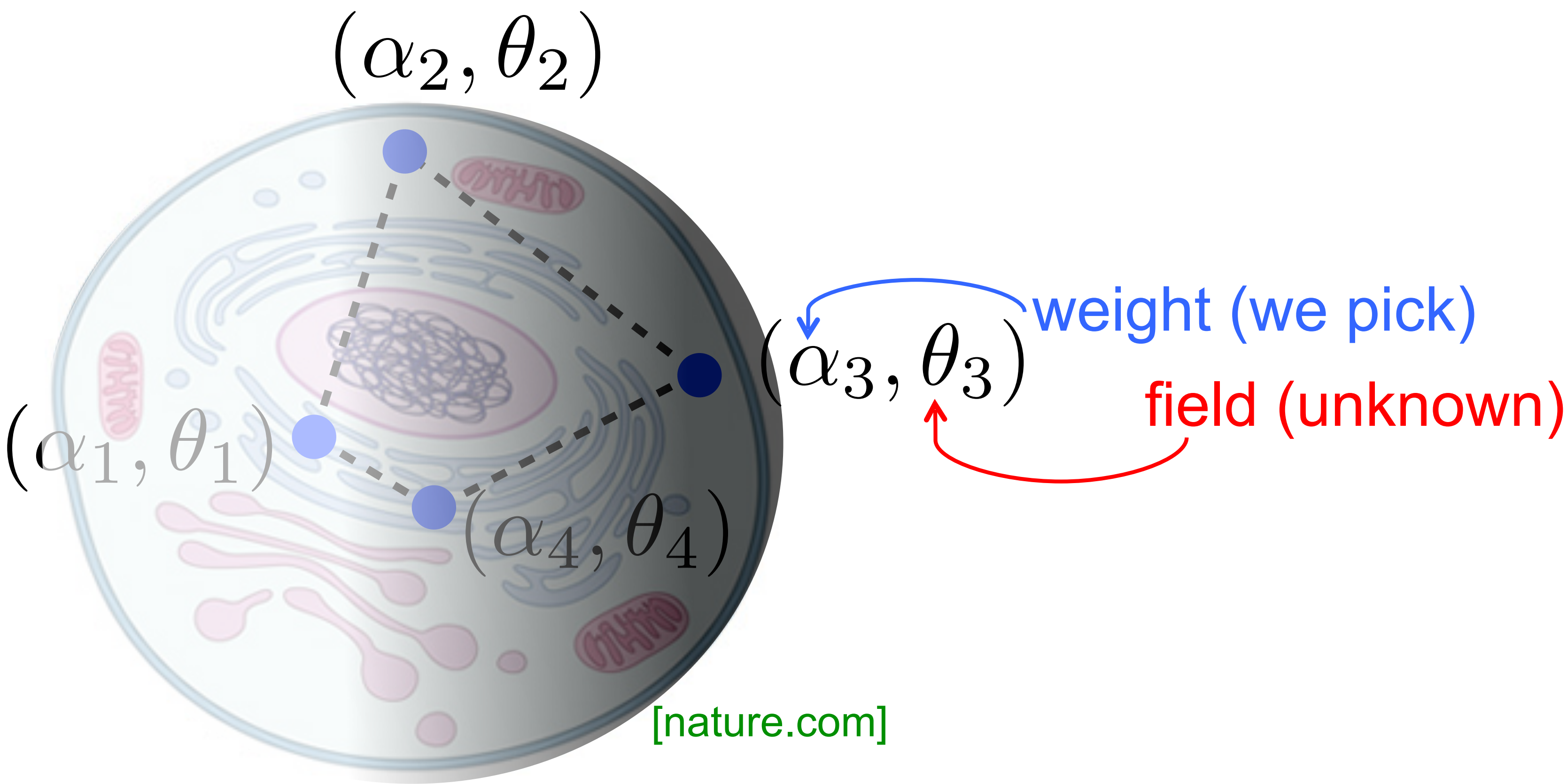
• potential applications to particle physics (and nuclear physics?):
[Preskill et al, DOE study group report on QI + particle physics]

- measure atomic and molecular dipole moments to test physics beyond the standard model
- detection of axion dark matter
- detect time variations of fundamental constants
- nuclear physics applications?

Quantum sensor network

$$\hat{H} = \frac{1}{2}\sum_{i=1}^{N} \theta_i \hat{Z}_i \qquad Q = \sum_{i=1}^{N} \alpha_i \theta_i$$

- measure a desired linear combination of fields at the sensors



- target spatial profile of desired signal (e.g. Fourier mode or spherical harmonic)

Eldredge, Foss-Feig, Gross, Rolston, AVG, arXiv:1607.04646; patent pending

Quantum sensor network

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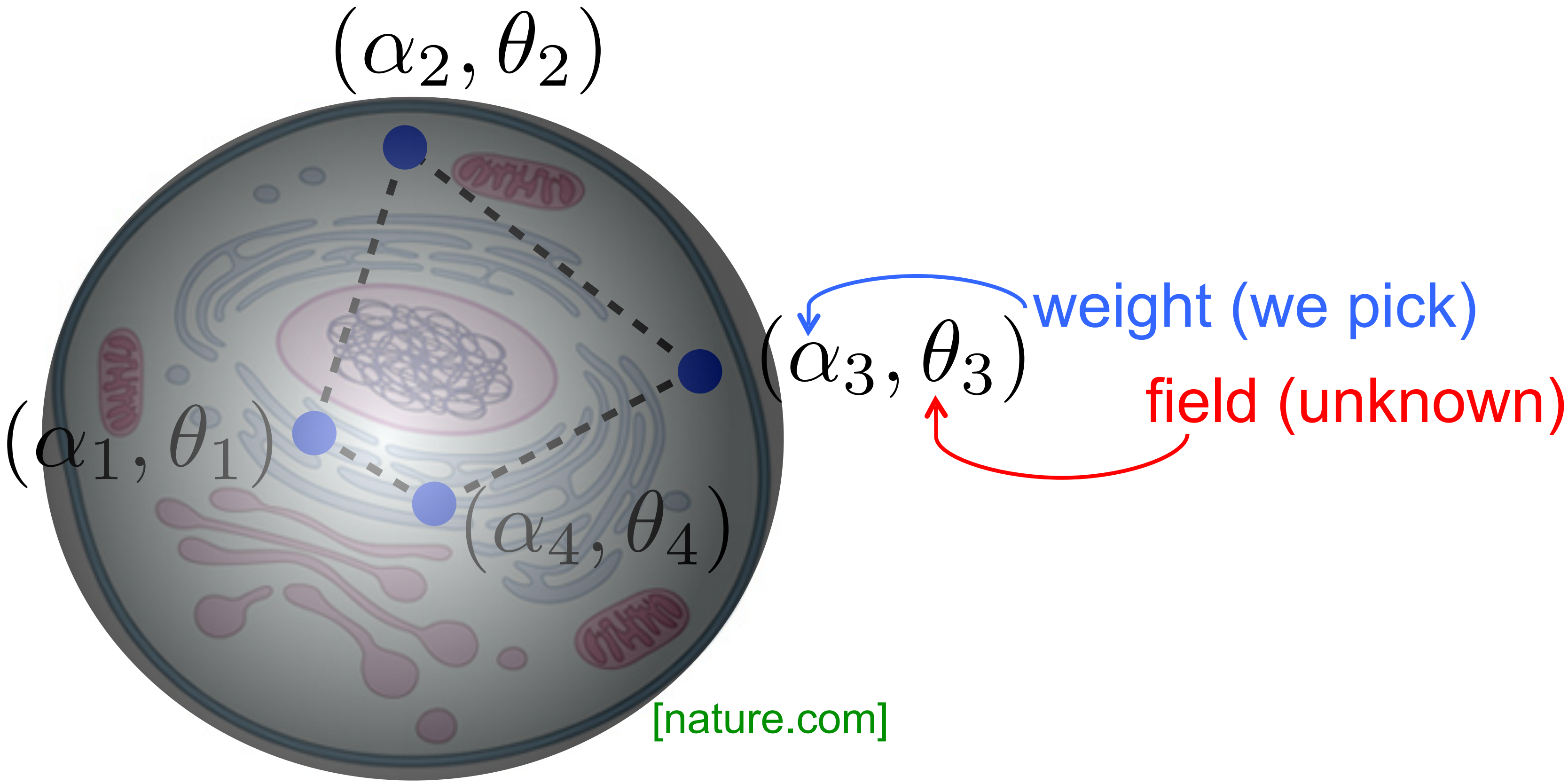

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Quantum sensor network

$$\hat{H} = \frac{1}{2}\sum_{i=1}^{N} \theta_i \hat{Z}_i \qquad\qquad Q = \sum_{i=1}^{N} \alpha_i \theta_i$$

- measure a desired linear combination of fields at the sensors

- found optimal protocol:

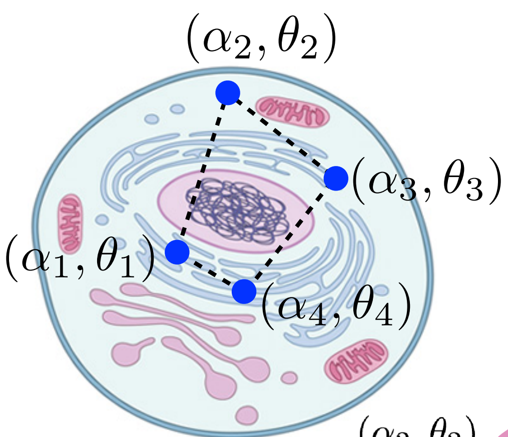
  $|\psi(0)\rangle \propto |0\ldots0\rangle + |1\ldots1\rangle$ & pulses during evolution

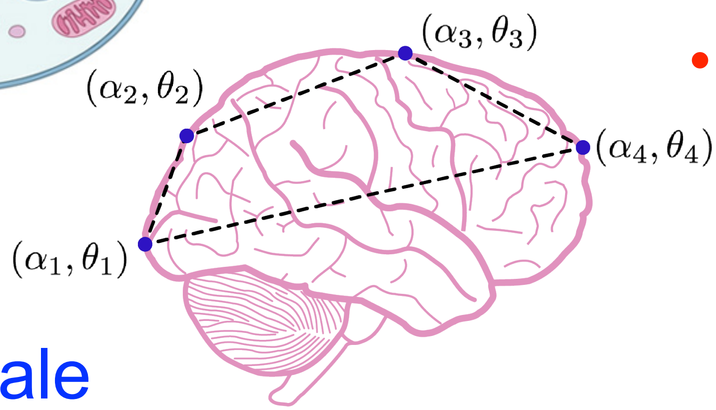
- tools: Fisher info matrix, Cramér-Rao bound

Eldredge, Foss-Feig, Gross, Rolston, AVG, arXiv:1607.04646; patent pending

Applications

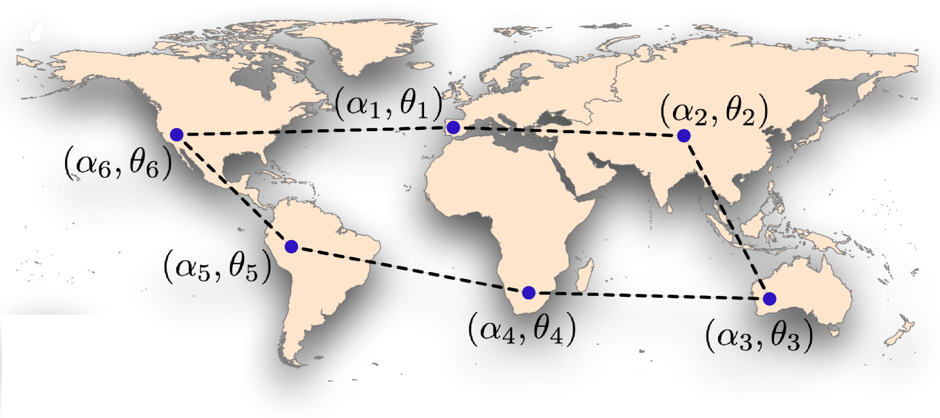
Small & intermediate scale





- biology & medicine (magnetic fields, electric fields, temperature, etc, inside human body/cell)
- nuclear physics?

Large scale



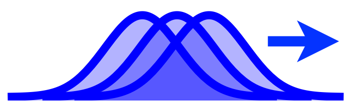
- geodesy & geophysics (earthquake/volcano prediction)
- e.g. magnetometry, electrometry, thermometry, gravimetry, etc…

Quantum sensing with photons

Sensing with photons

- optical photons: imaging, spectroscopy, radiometry, interferometry
- key resource: non-classical (including entangled) states of light

most classical: coherent states

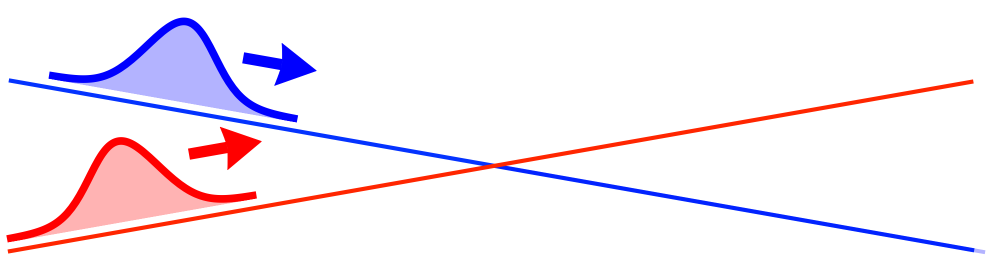


$$\hat{a}|\alpha\rangle = \alpha|\alpha\rangle$$

$$|\alpha\rangle = \sum_{n=0}^{\infty} c_n |n\rangle \qquad P(n) = |c_n|^2 = e^{-|\alpha|^2} \frac{|\alpha|^{2n}}{n!}$$

Poissonian

- need strong interactions between individual photons

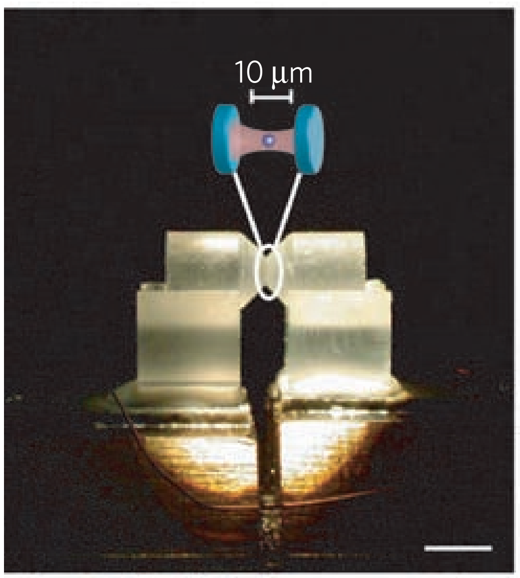


- nonlinearities in nonlinear crystals tiny at single-photon level

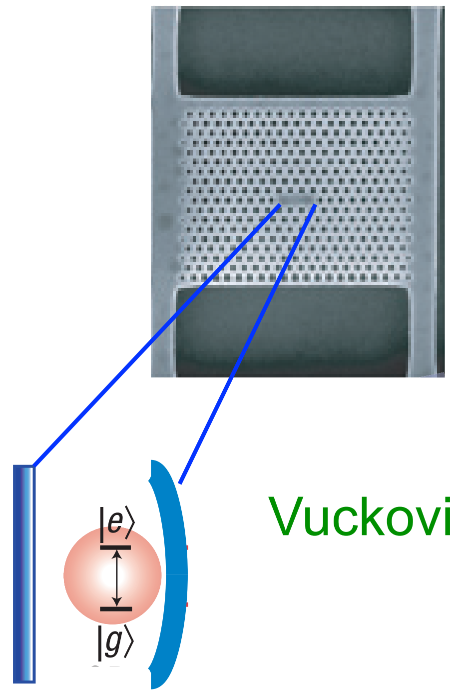
Photon-photon interactions

Typical approach to achieving interactions between optical photons:

- nonlinearity induced by individual atoms (or artificial atoms)



Kimble @ Caltech



Vuckovic @ Stanford

Hard!

Photon-photon interactions

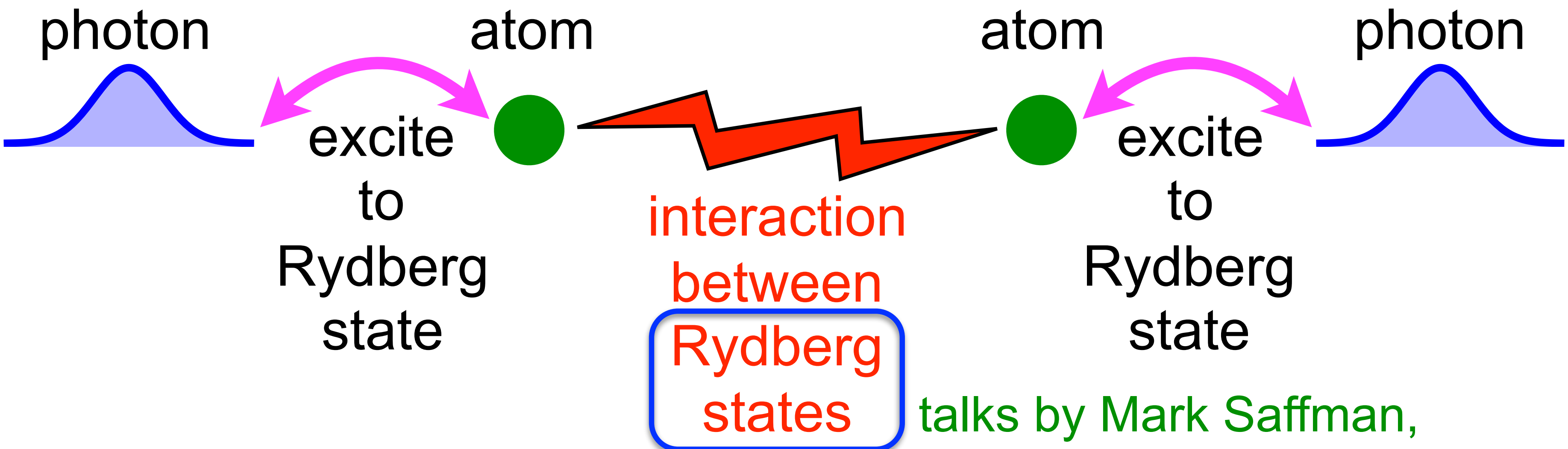
Typical approach to achieving interactions between optical photons:

- nonlinearity induced by individual atoms (or artificial atoms)

Our approach: Map strong atom-atom interactions onto strong photon-photon interactions

Photon-photon interactions

Map strong atom-atom interactions onto
strong photon-photon interactions



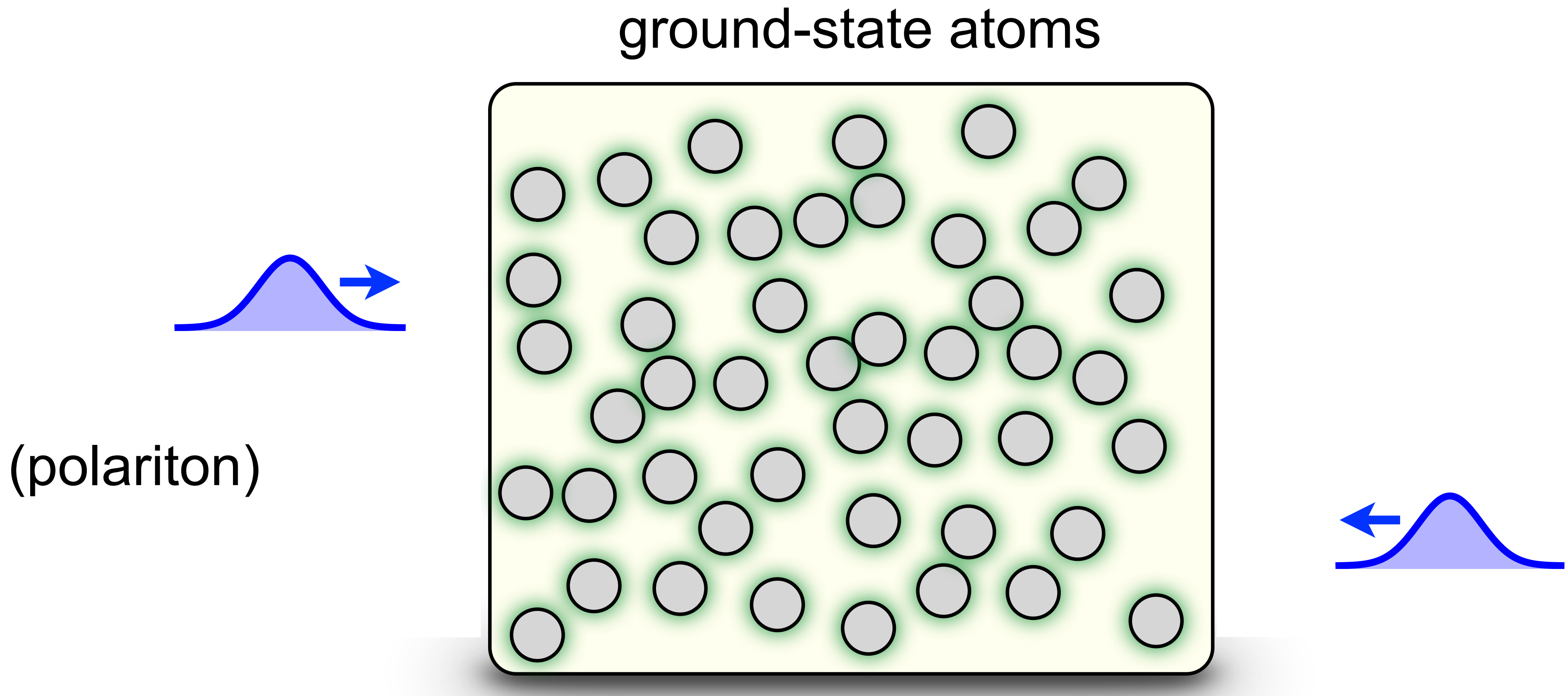
talks by Mark Saffman,
Georg Raithel

AVG et al, PRL 107, 133602 (2011)

Experiments: Adams, Kuzmich, Lukin & Vuletic, Pfau & Löw, Grangier, Weidemüller, Hofferberth, Dürr & Rempe, Simon, Firstenberg, Ourjoumtsev, etc…

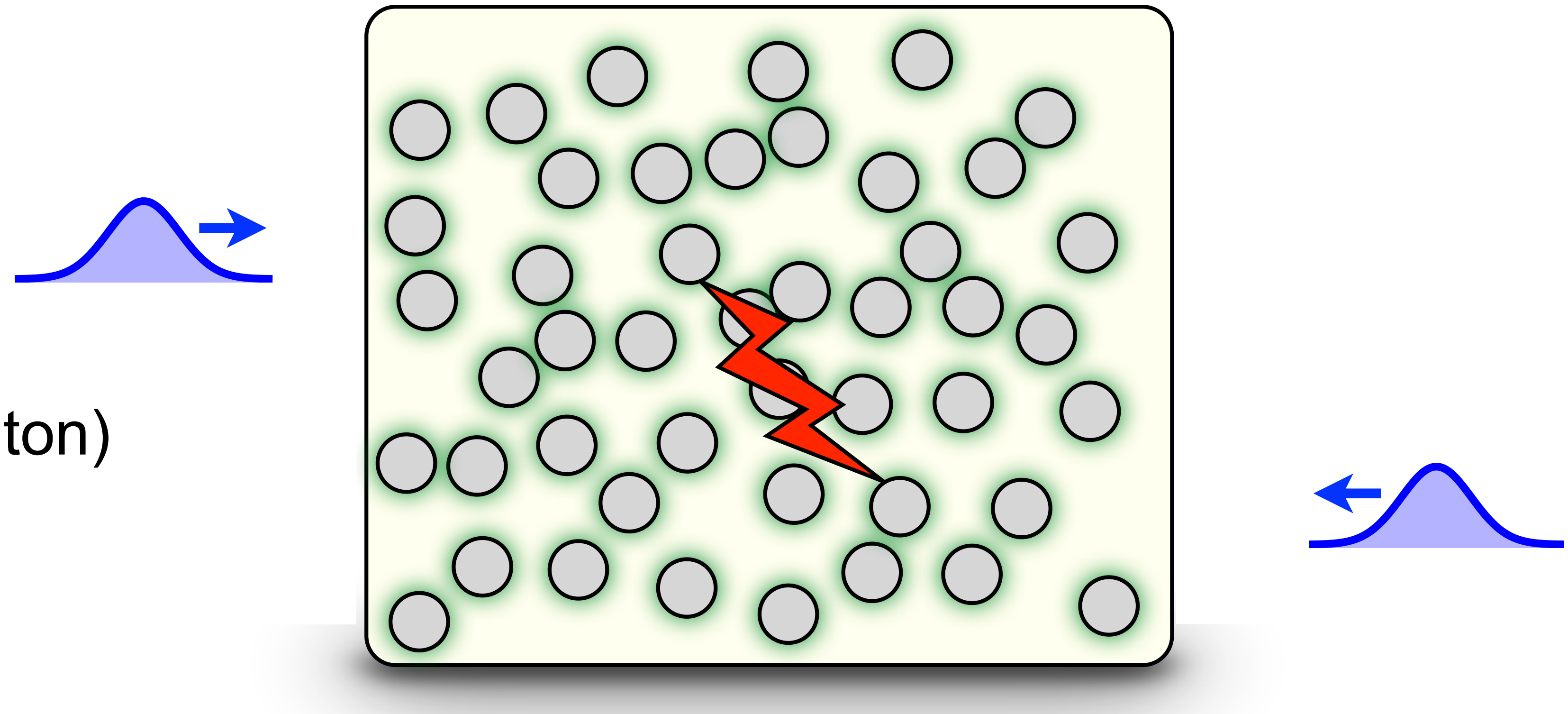
Theory: Kurizki, Fleischhauer, Petrosyan, Mølmer, Pohl, Lesanovsky, Kennedy, Brion, Büchler, Sørensen, most experimental groups above, etc...

Photon-photon interactions



• one photon drags along a Rydberg excitation

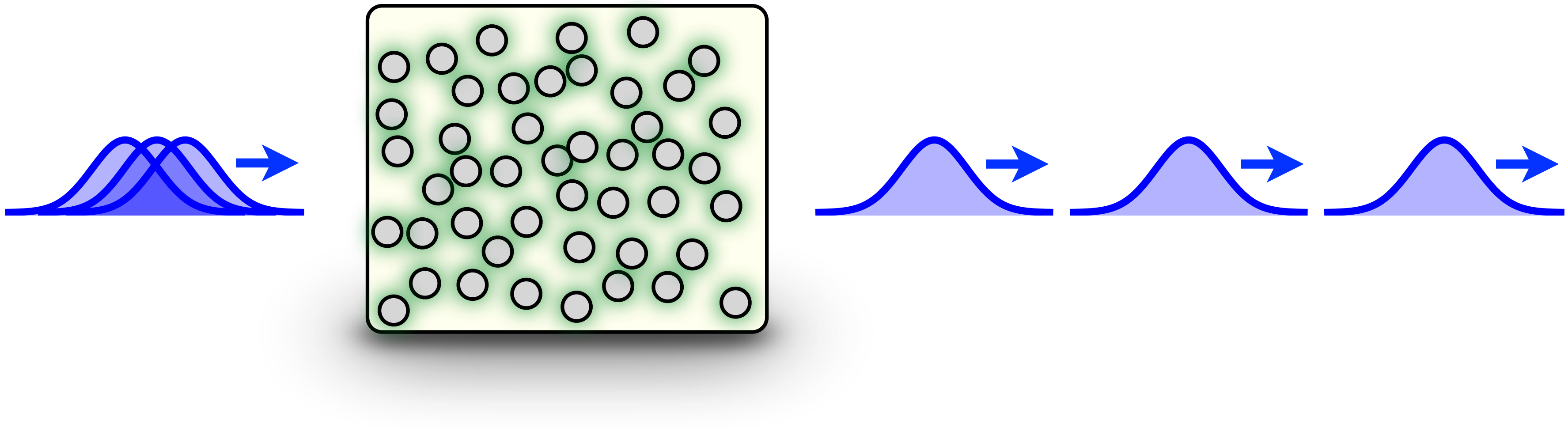
Photon-photon interactions



- one photon drags along a Rydberg excitation
- another photon drags along a Rydberg excitation
- Rydberg excitations feel strong, distant interactions

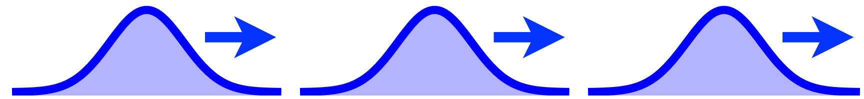
$\Rightarrow$ strong, distant photon-photon interactions

Regular trains of single photons

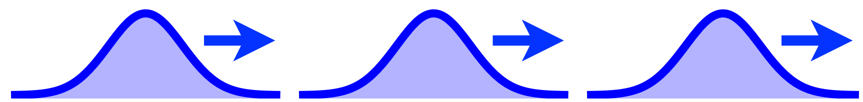


• high-rate, identical photons

theory [Zeuthen, Gullans, Maghrebi, AVG, PRL 119, 043602 (2017)
+ ongoing collaboration with Chang group]
experiment [collaboration with Hofferberth group]
[related experiment: Dudin, Kuzmich, Science 336, 887 (2012)]



Sensing application: radiometry

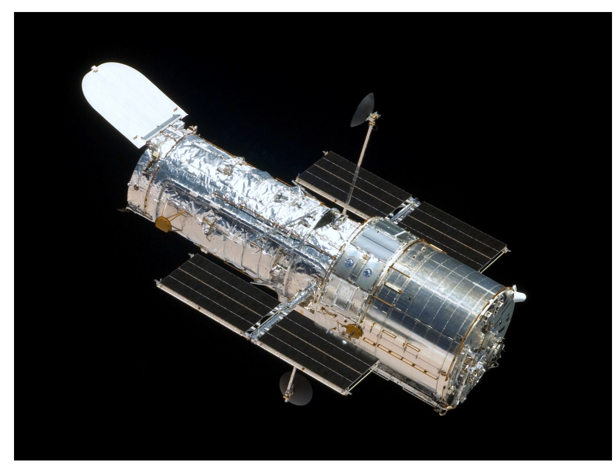


||

standard candle

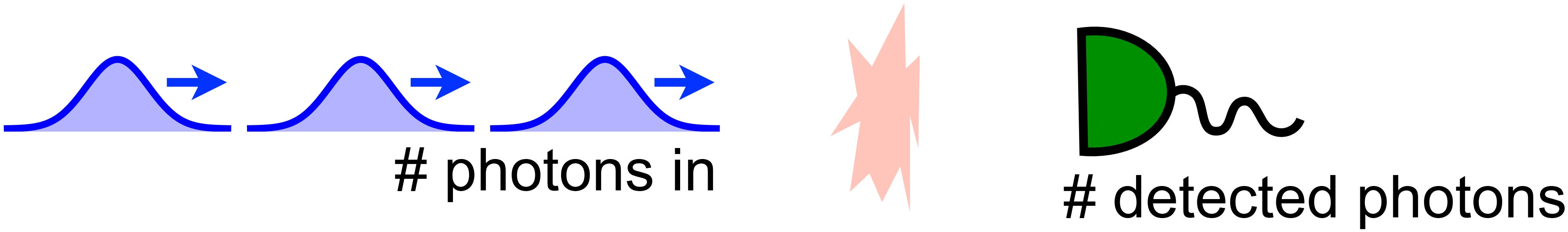
• calibration of photon and analog detectors

Hubble



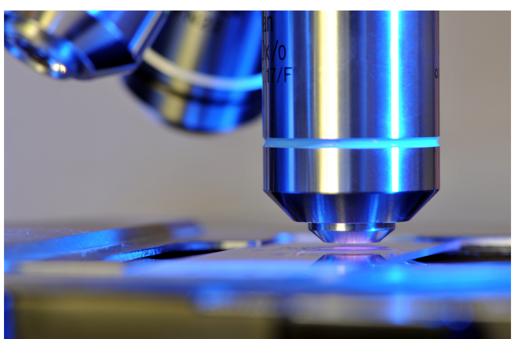
⇒ metrology, sensing, chemistry, physics, astronomy, … nuclear physics?

Sensing applications: imaging, spectroscopy, trace detection



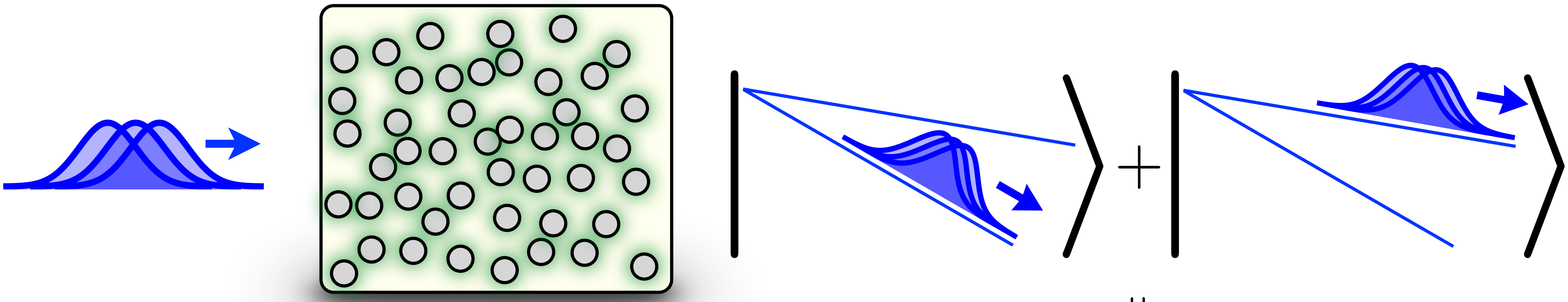
• no shot noise (no Poisson!)

• dramatically reduced measurement uncertainty in imaging & spectroscopy of low-absorption & quantity-limited samples



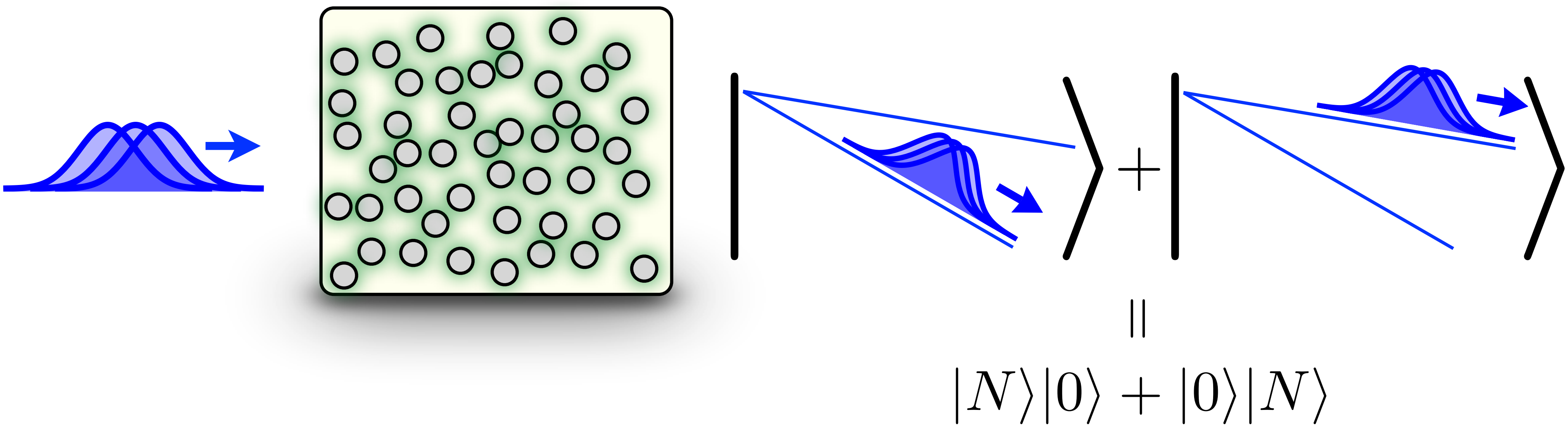
⇒ chemistry, biology, forensics, security, … nuclear physics?

Schrödinger-cat state of light



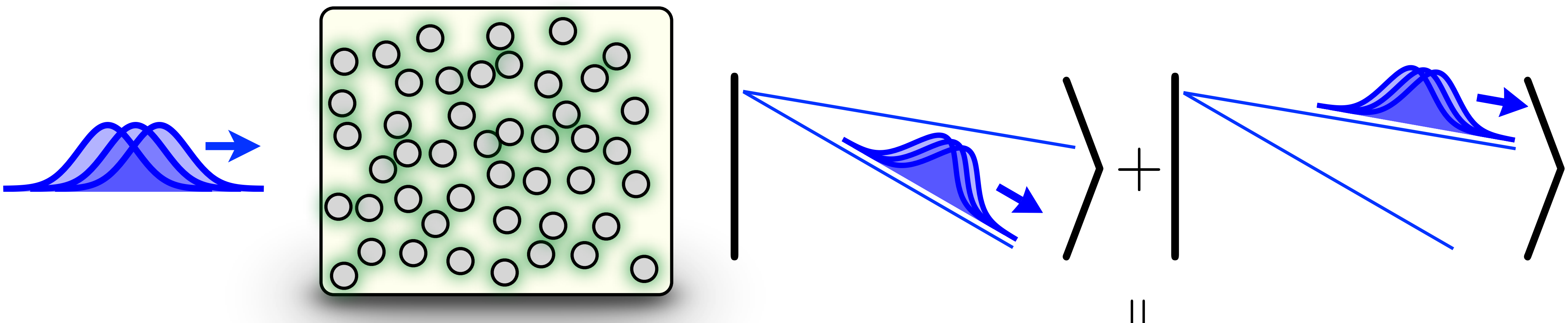
$$= $$

$$|N\rangle|0\rangle + |0\rangle|N\rangle$$



+
=
$|N\rangle|0\rangle + |0\rangle|N\rangle$

Sensing applications: interferometry, imaging



$$= \quad |N\rangle|0\rangle + |0\rangle|N\rangle$$

- interferometry with maximum per-photon sensitivity

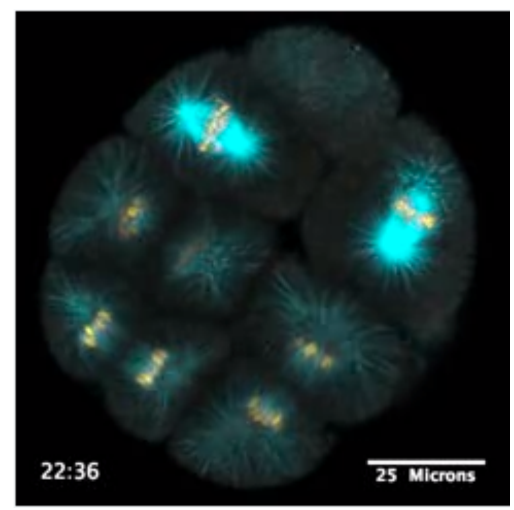
$$\frac{1}{N} \text{ (Heisenberg)} \quad \text{vs} \quad \frac{1}{\sqrt{N}}$$

[• other states: e.g. squeezed]

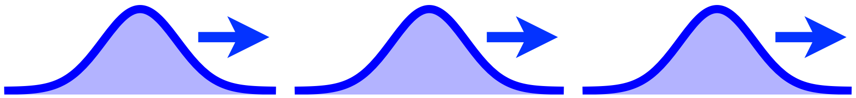
- imaging, sensing, and spectroscopy of fragile photosensitive samples

⇒ chemistry, biology, materials science, forensics, … nuclear physics?

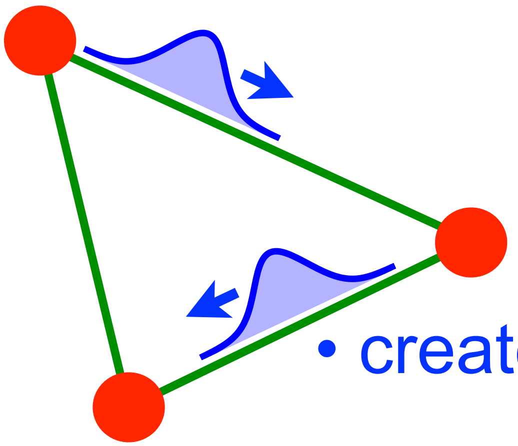
live cells



Quantum networks & internet

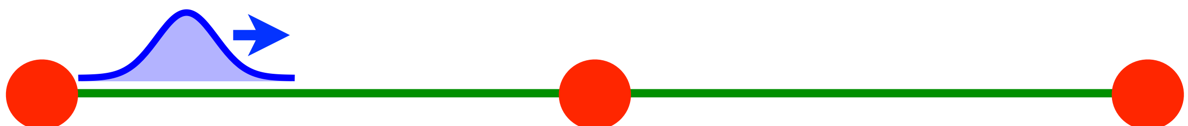


+ photon-photon gates



route & process single photons

• create remote entanglement



quantum repeater

~~amplifier~~

• use for distributed sensing with atoms (first part of talk)

Non-sensing applications of interacting photons

- quantum networks & remote entanglement: secure long-distance communication, long-base-line interferometry, commerce and e-commerce (e.g. unforgeable virtual money),…
- quantum computing
- exotic few-body and many-body physics:

- tunable mass, interactions, dimensionality
- in contrast to electrons: bosons, no tunable chemical potential, preparation, probing, …
- 2-photon bound states

  Expt: Firstenberg, Peyronel, Liang, AVG, Lukin, Vuletić, Nature 502, 71 (2013)
  Theory: Maghrebi, Gullans, …, Martin,…, AVG, PRL 115, 123601 (2015)
- 3-photon bound states (and perhaps 3-body force)

  Expt: Liang, …, Gullans, AVG, Thompson, Chin, Lukin, Vuletić, Science 359, 783 (2018)
  Theory: Gullans, …, AVG, PRL 117, 113601 (2016) [effective field theory (EFT)]
  Gullans, …, AVG, Taylor, PRL 119, 233601 (2017) [Efimov states]
- simulate nuclear physics?

Thank you

Graduate Students

Jeremy Young
Yidan Wang
Zachary Eldredge
Abhinav Deshpande
Fangli Liu
Su-Kuan Chu
Minh Tran
Andrew Guo
Ani Bapat

Postdocs

Mohammad Maghrebi → Asst. Prof. @ Michigan State
Zhe-Xuan Gong → Asst. Prof. @ Colorado School of Mines
Sergey Syzranov → Asst. Prof. @ UC Santa Cruz
James Garrison
Paraj Titum
Rex Lundgren
Przemek Bienias

$$$: NSF QIS, ARO MURI, ARO, AFOSR, NSF PFC@JQI, ARL CDQI

Thank you

Quantum sensor network

Zach Eldredge

Michael Foss-Feig (ARL)

Jonathan Gross (U of New Mexico)

Steve Rolston (JQI)

arXiv:1607.04646; patent pending

$$$: NSF QIS, ARO MURI, ARO, AFOSR, NSF PFC@JQI, ARL CDQI

Thank you
Interacting photons

Harvard/MIT experiment:

Qiyu Liang, Aditya Venkatramani, Sergio Cantu, Travis Nicholson,
Jeff Thompson (→Princeton), Cheng Chin (on leave from Chicago),
Misha Lukin, Vladan Vuletić, …

Stuttgart (→ SDU, Denmark) experiment:

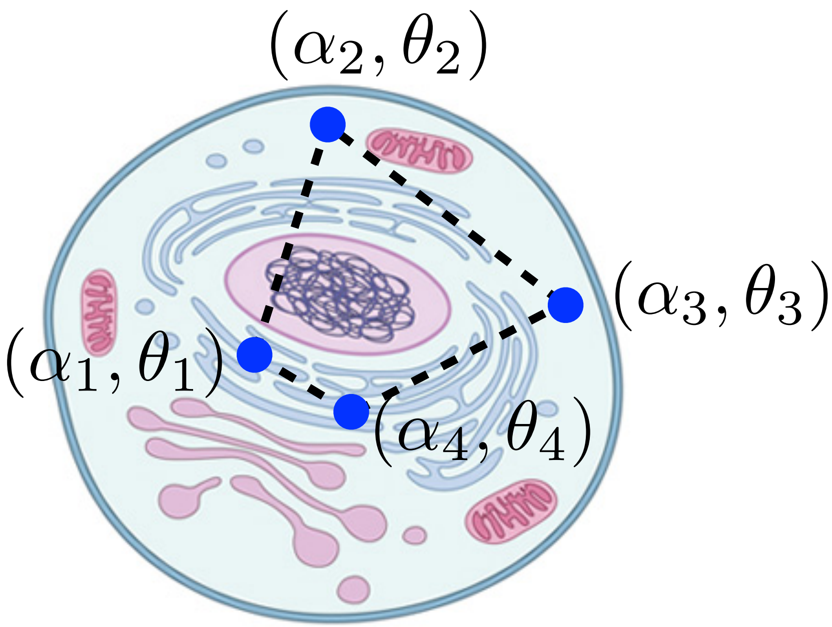
Ivan Mirgorodskiy, Christoph Braun, Christoph Tresp,
Asaf Paris-Mandoki, Sebastian Hofferberth, …

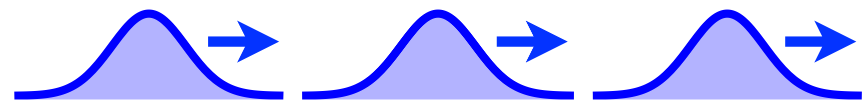
Theory collaborators:

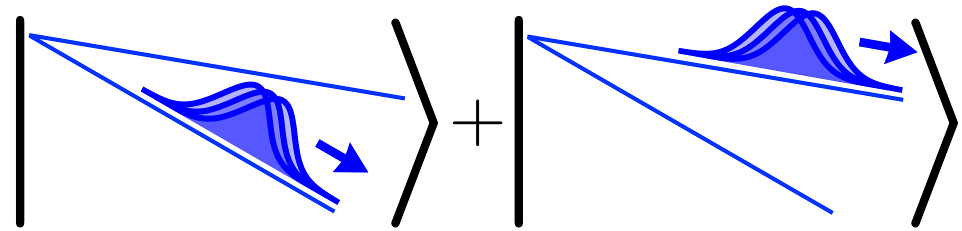
the experimental teams above, Michael Gullans (JQI→Princeton),
Yidan Wang (JQI), Mohammad Maghrebi (JQI→Michigan State),
Ivar Martin (Argonne), Emil Zeuthen (Copenhagen), Rejish Nath (Pune),
Przemek Bienias (JQI), Paraj Titum (JQI), Darrick Chang (ICFO),
James Douglas (ICFO), Marco Manzoni (ICFO),
Thomas Pohl (Aarhus), Callum Murray (Aarhus), …

$$$: NSF QIS, ARO MURI, ARO,
AFOSR, NSF PFC@JQI, ARL CDQI

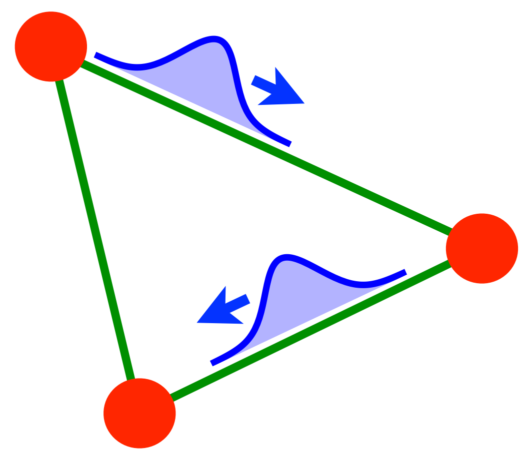
Conclusions







$$Q = \sum_{i=1}^{N} \alpha_i \theta_i$$



Eldredge, Foss-Feig, Gross,
Rolston, AVG, arXiv:1607.04646

Thank You