Strongly interacting photons

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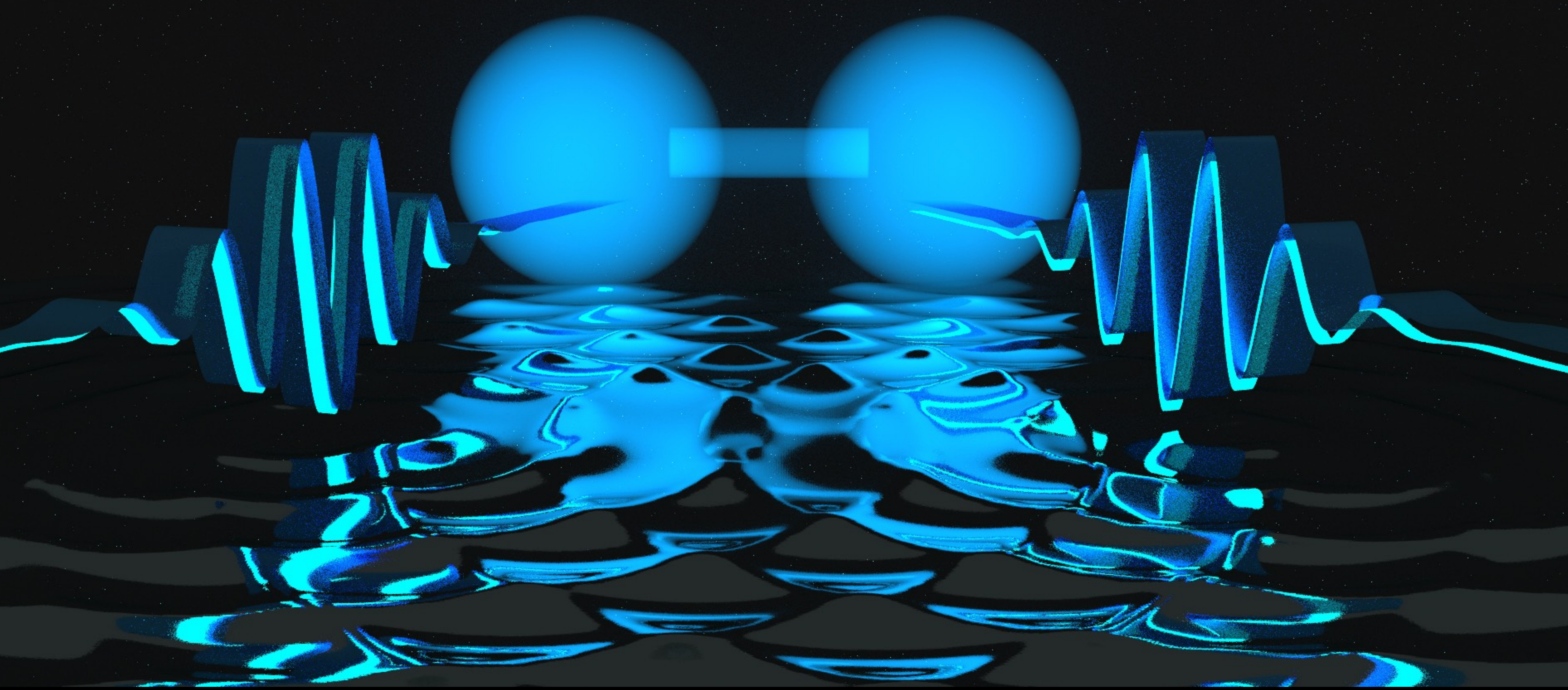
Joint Quantum Institute (JQI), University of Maryland



"Photon Molecule"
Courtesy of E. Edwards/JQI

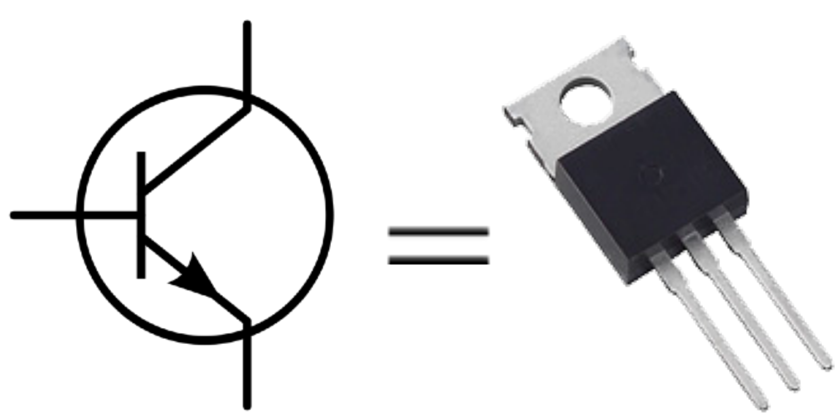
Workshop on Quantum Sensing
Argonne, Illinois
December 13, 2017

Electrons vs. Photons

electrons interact strongly

$$F = \frac{1}{4\pi\epsilon_0}\frac{e^2}{r^2}$$

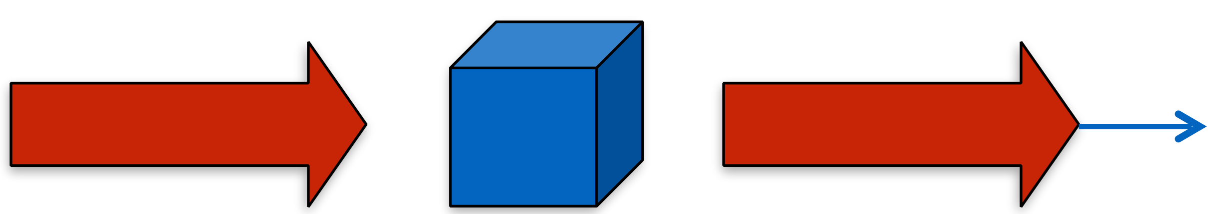
transistor



small electrical signals
control huge currents

photons interact extremely weakly

nonlinear crystal

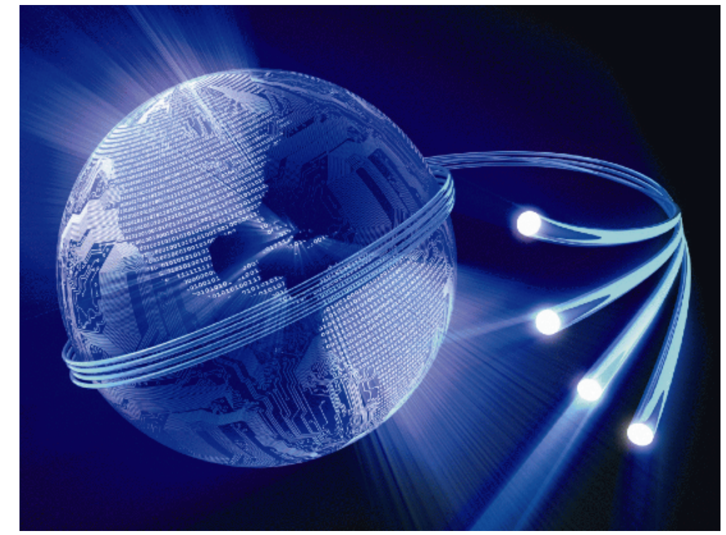


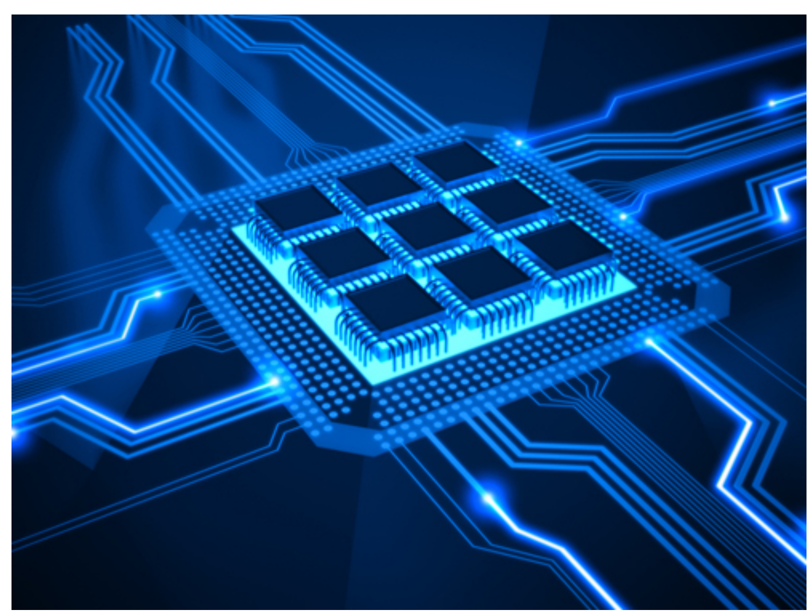
even huge optical intensities
only control tiny optical signals

Electronics vs. Photonics

electrons
process information

photons
transmit information



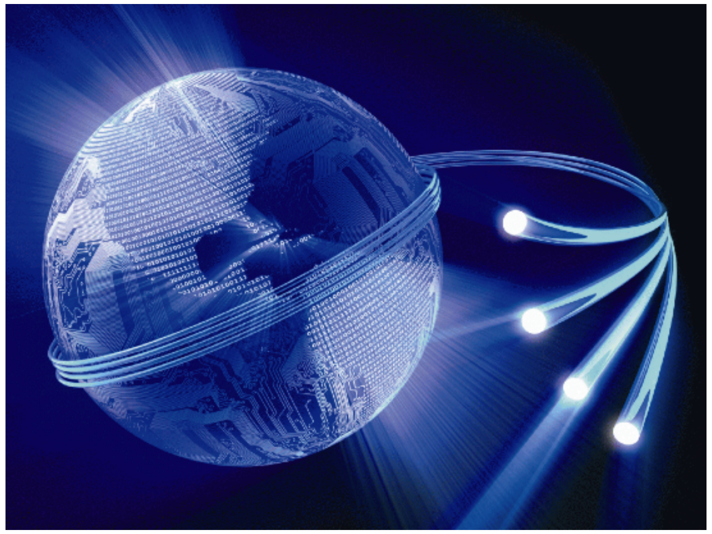


converting photons to electrical signals is “expensive”

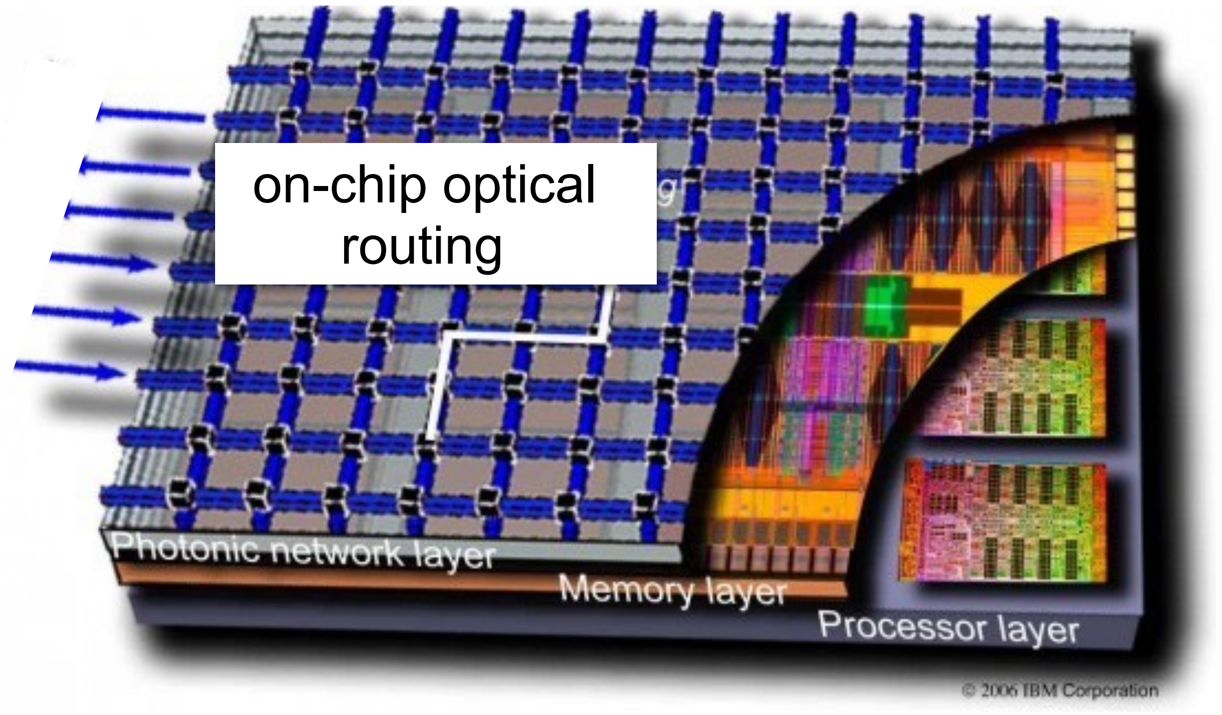
Electronics vs. Photonics

electrons
process information

photons
transmit information

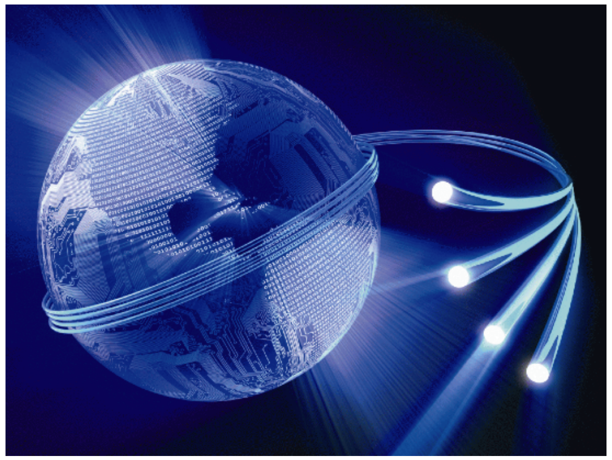


On-chip optical routing
motivates direct on-chip
optical processing

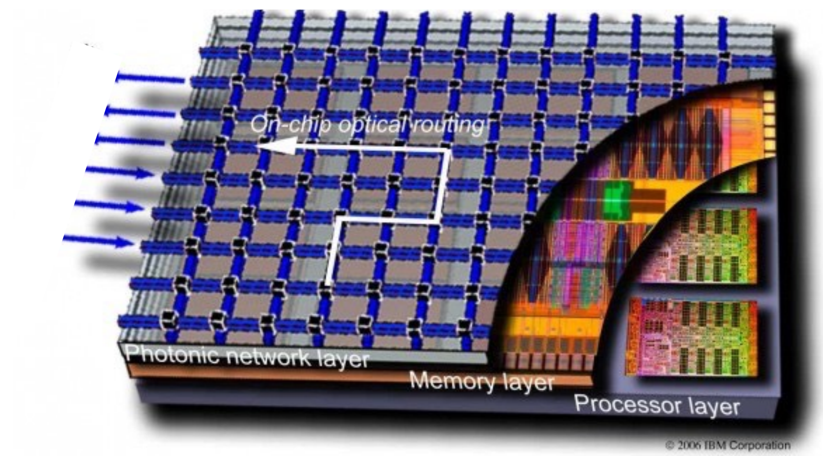


What are interacting photons good for?

Quantum & classical information processing



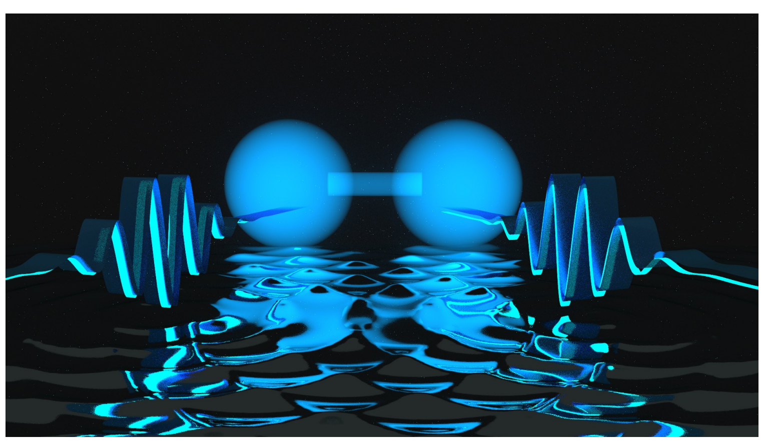
Low-power computation



Secure communication and e-commerce

unforgeable virtual money

New states of matter



Quantum sensing and metrology

radiometry

Standard candle
(a fixed no. of photons)

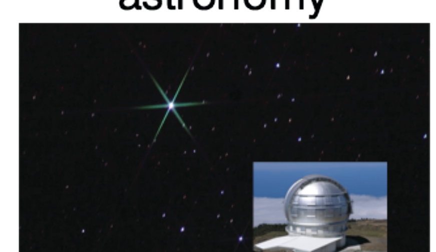
spectroscopy

sensitive analysis

imaging

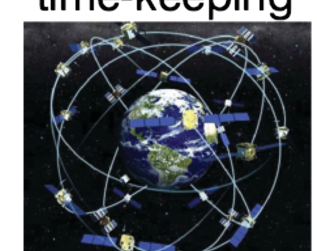
detection below noise

astronomy



long-baseline interferometry

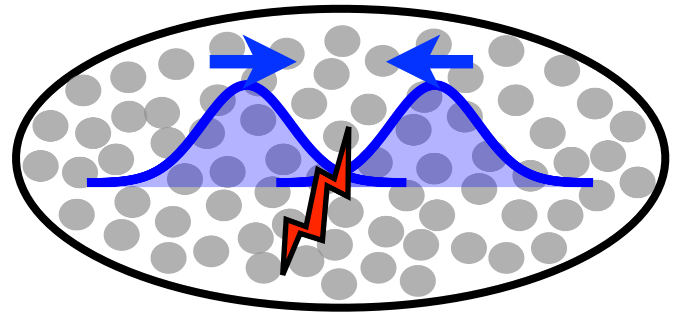
time-keeping

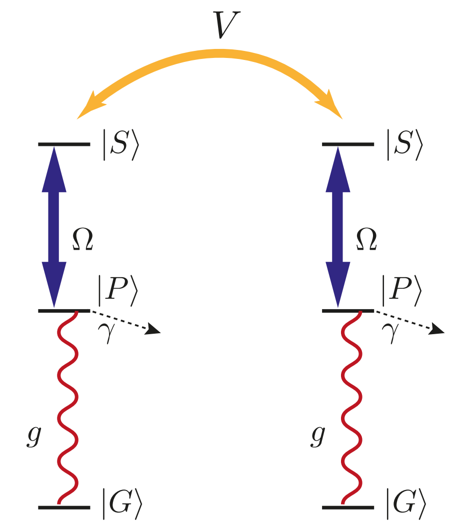


quantumly linked clocks

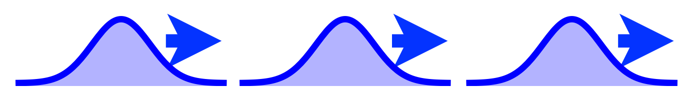
Outline

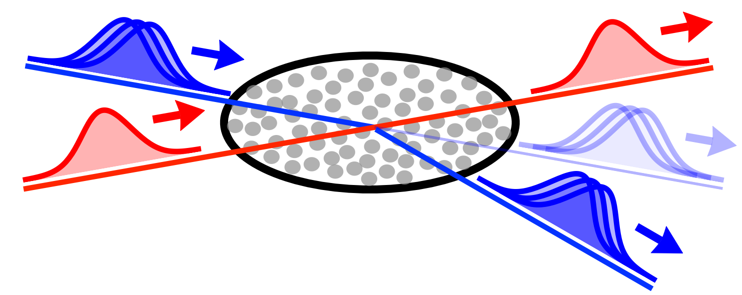
I. Basics
- interacting photons
- Rydberg-EIT



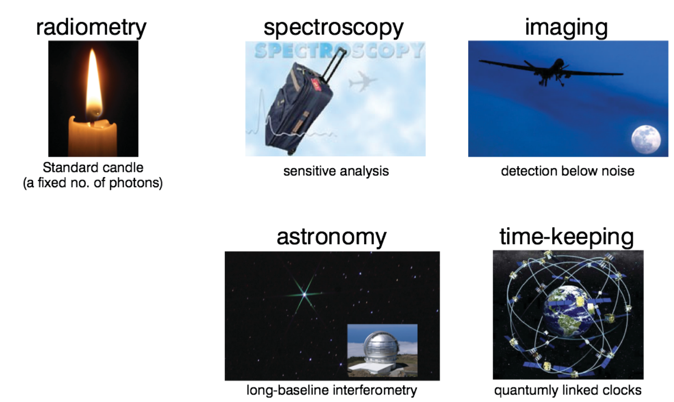


II. Rydberg-EIT toolbox for sensing

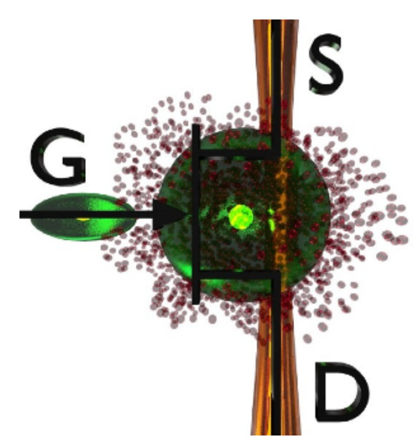


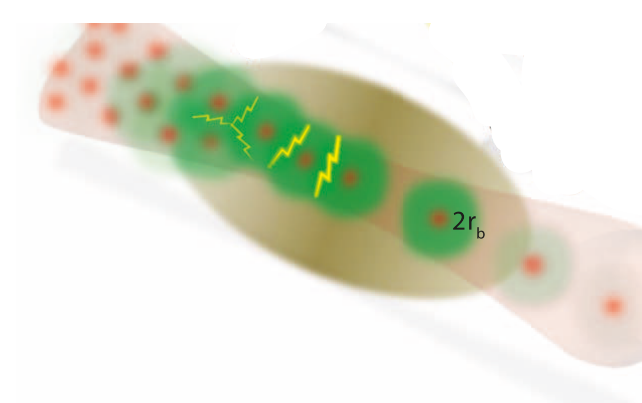


III. Sensing with interacting photons
- examples



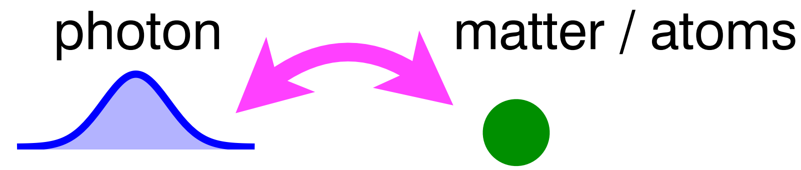
II. Rydberg-EIT
- experimental progress
- challenges and limitations



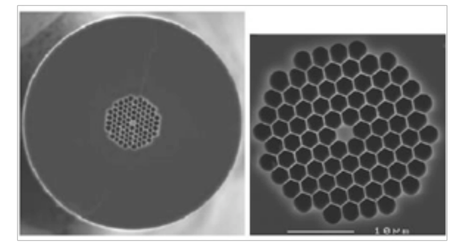


How to make photons interact?

- General idea

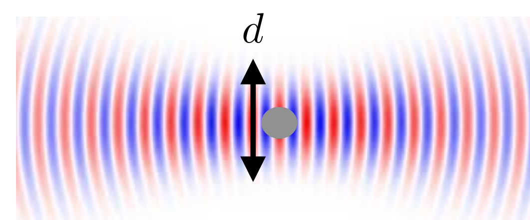


- Kerr nonlinearity of conventional materials
  - extremely weak effects for single photons, even for highly nonlinear fibres



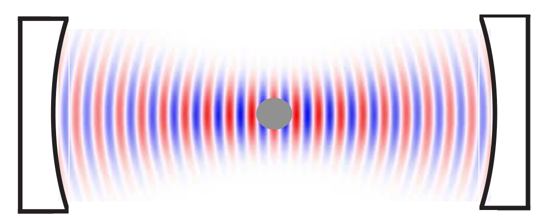
$$n = n_0 + \frac{3\chi^{(3)}}{8n_0}|\mathbf{E}_\omega|^2$$

- Single scatterer
  - mode matching between the input field and the dipolar emission pattern ∼10%



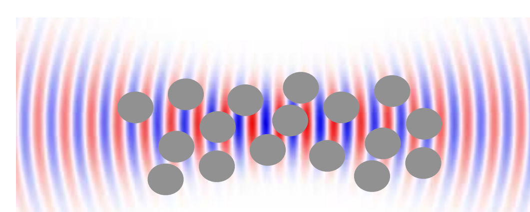
$$p \approx d^2/\lambda^2$$

- Cavity or waveguide
  - additional complexity of a hybrid system
  - coupling efficiency and bandwidth reduced with increasing finesse



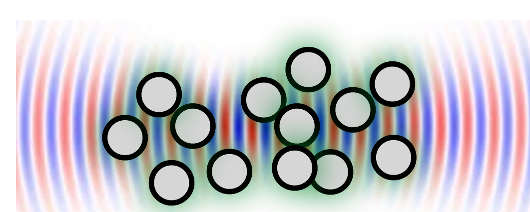
$$p \approx F d^2/\lambda^2$$

- Ensemble of atoms
  - weak nonlinearities



$$p \approx N d^2/\lambda^2$$

- Ensemble of Rydberg atoms [this talk]
  - strong interaction (Rydberg)
  - photon localisation (EIT)

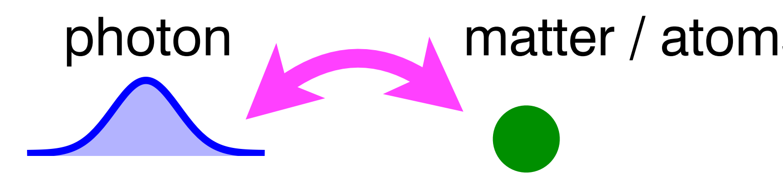


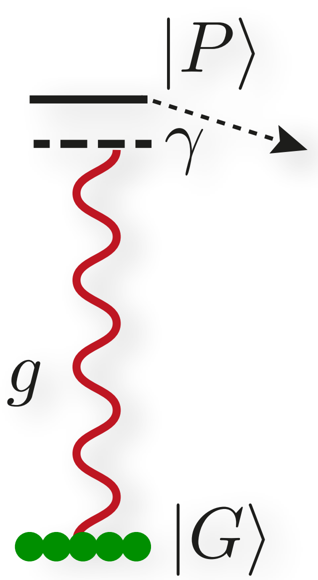
optical domain: nano-photonics, opto-mechanics, graphene, quantum dots
microwave domain: cavity QED, superconducting circuits

review: Chang et al., Nat. Photonics (2014)

Electromagnetically Induced Transparency

Dielectric response



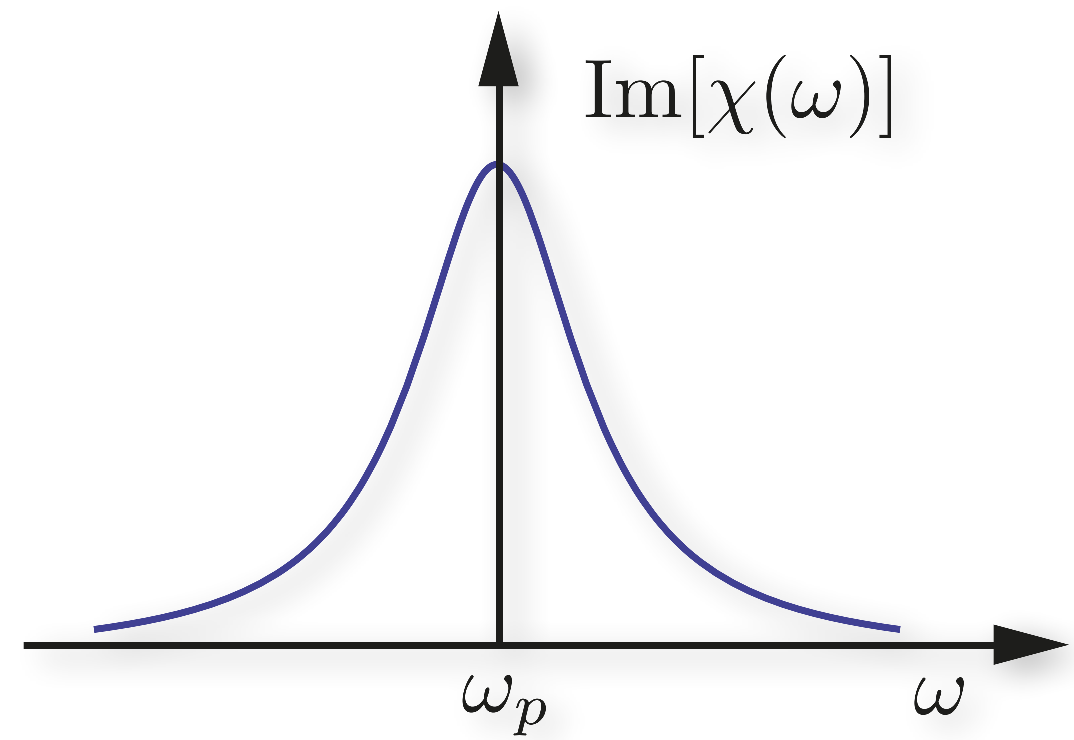


two-level atom

- absorption from p-level

three-level atom

- interference in response
- transmission at two photon resonance



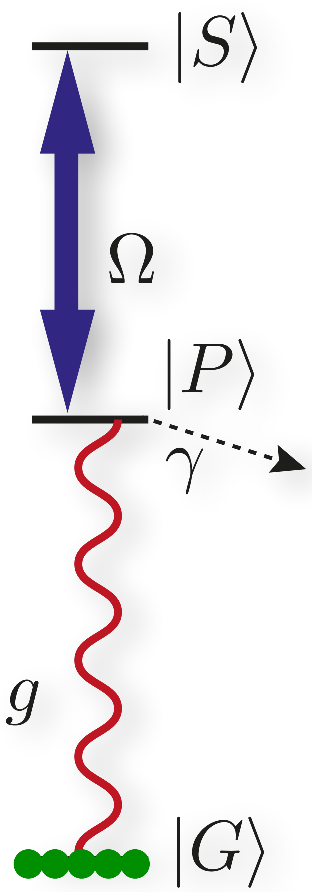
Dark state

- dissipation free state
- polariton: superposition of photon and excited state
- group velocity << speed of light

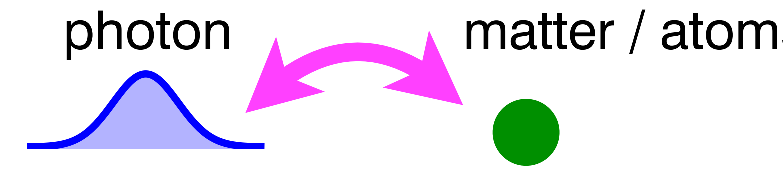
$$\frac{\Omega|G,1\rangle - g|S,0\rangle}{\sqrt{\Omega^2 + g^2}}$$

M. Fleischhauer, M. D. Lukin, 2001

Electromagnetically Induced Transparency



Dielectric response



two-level atom

- absorption from p-level

three-level atom

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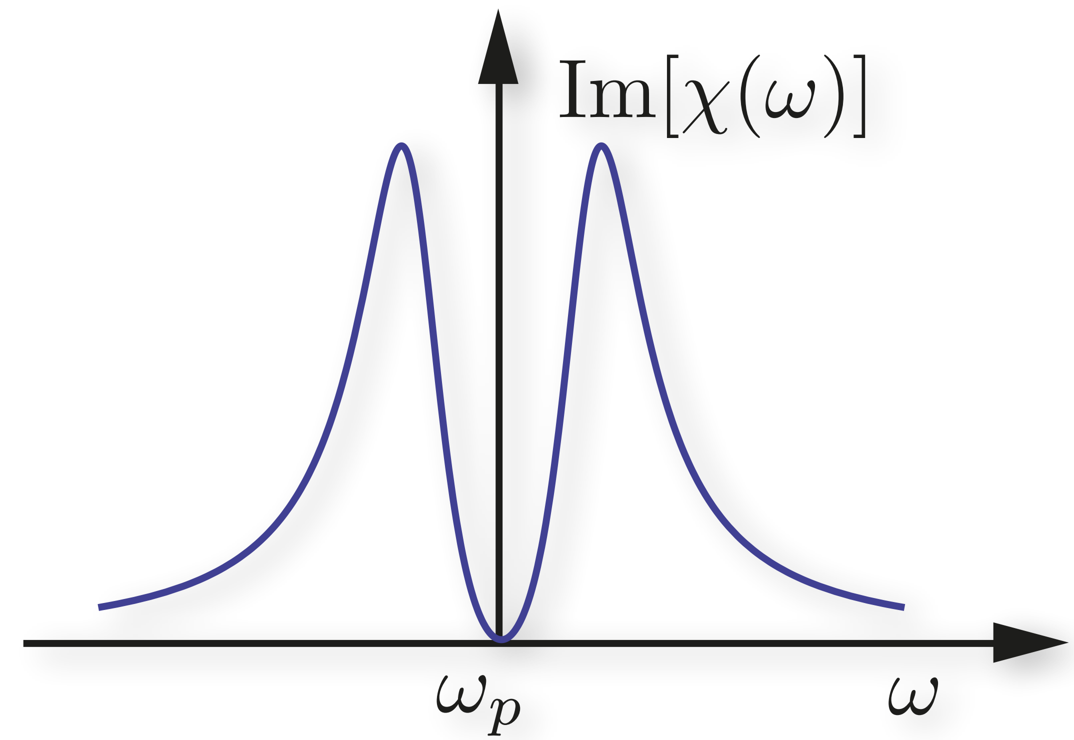

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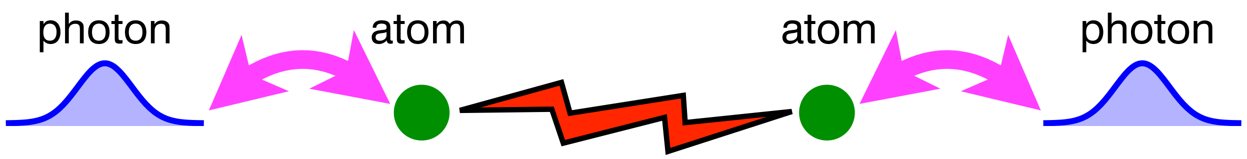
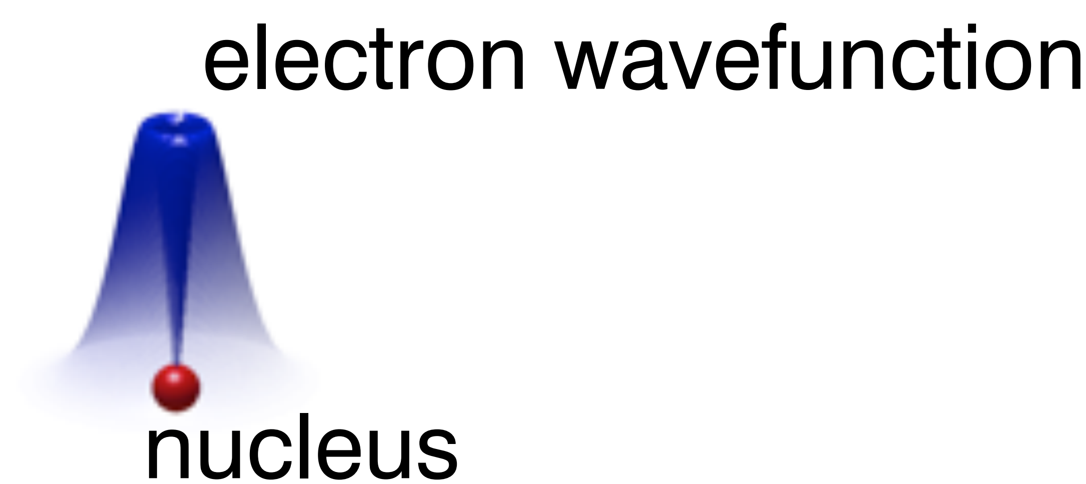
M. Fleischhauer, M. D. Lukin, 2001

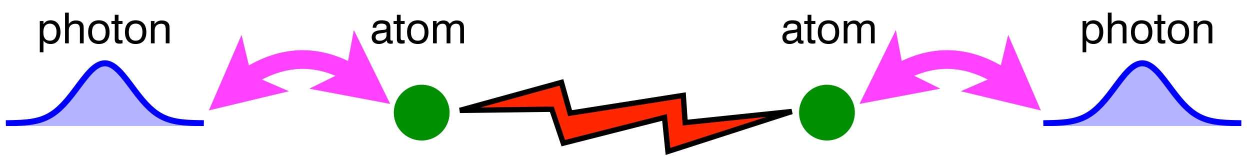
Rydberg excitations



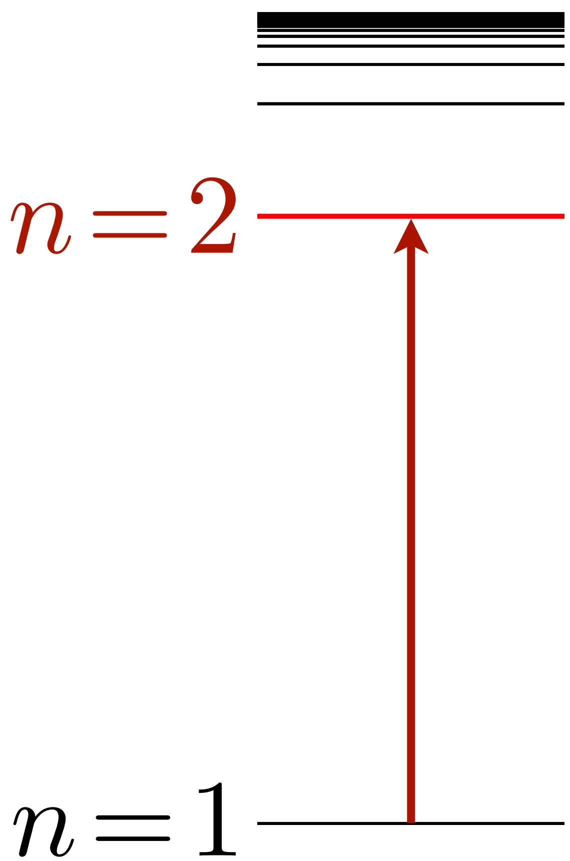
atomic levels:

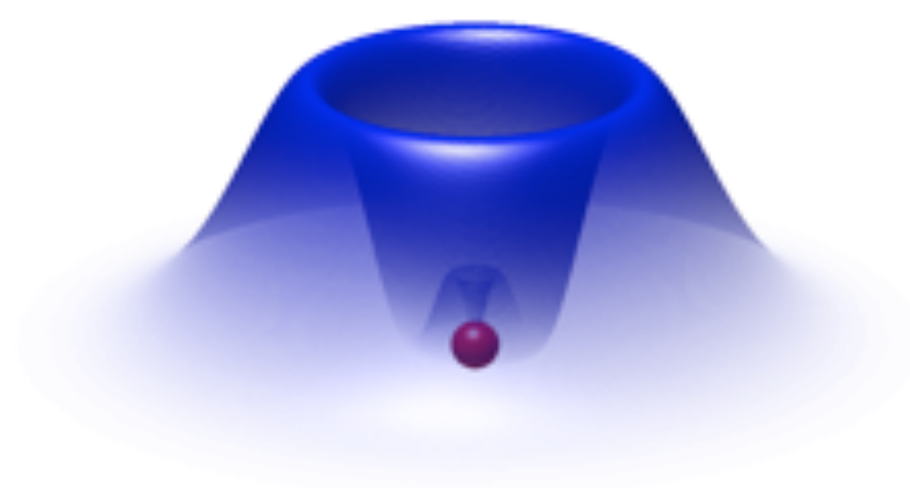


Rydberg excitations

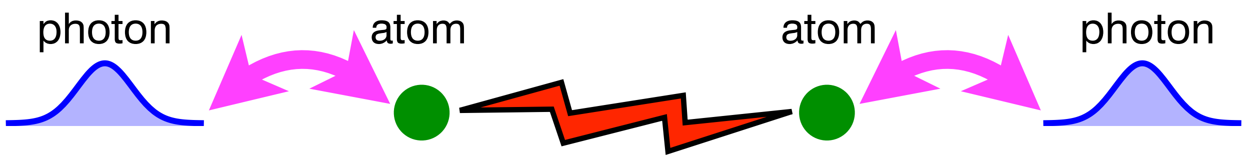


atomic levels:

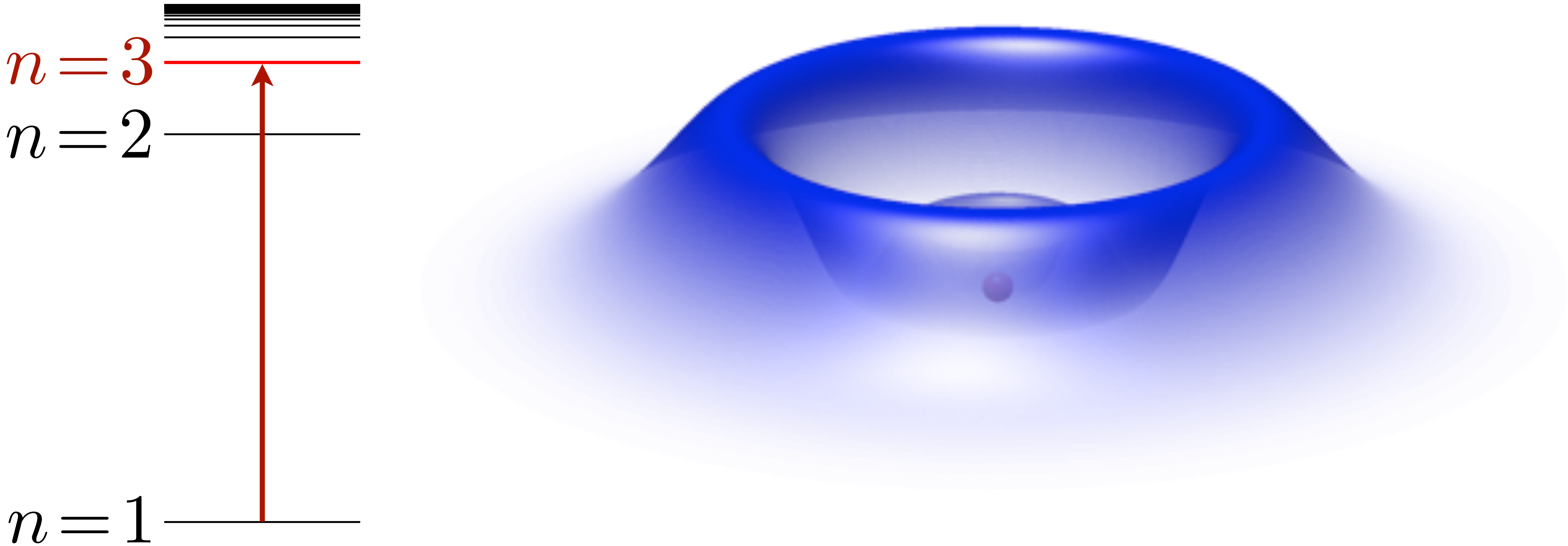




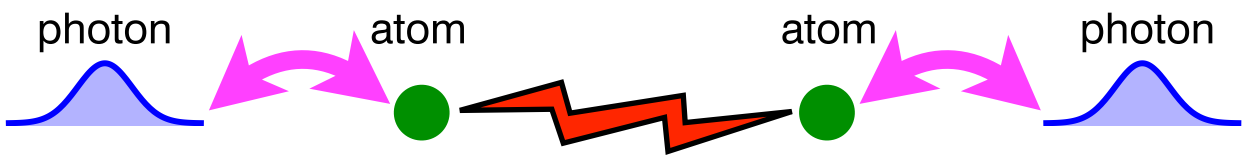
Rydberg excitations



atomic levels:



Rydberg excitations



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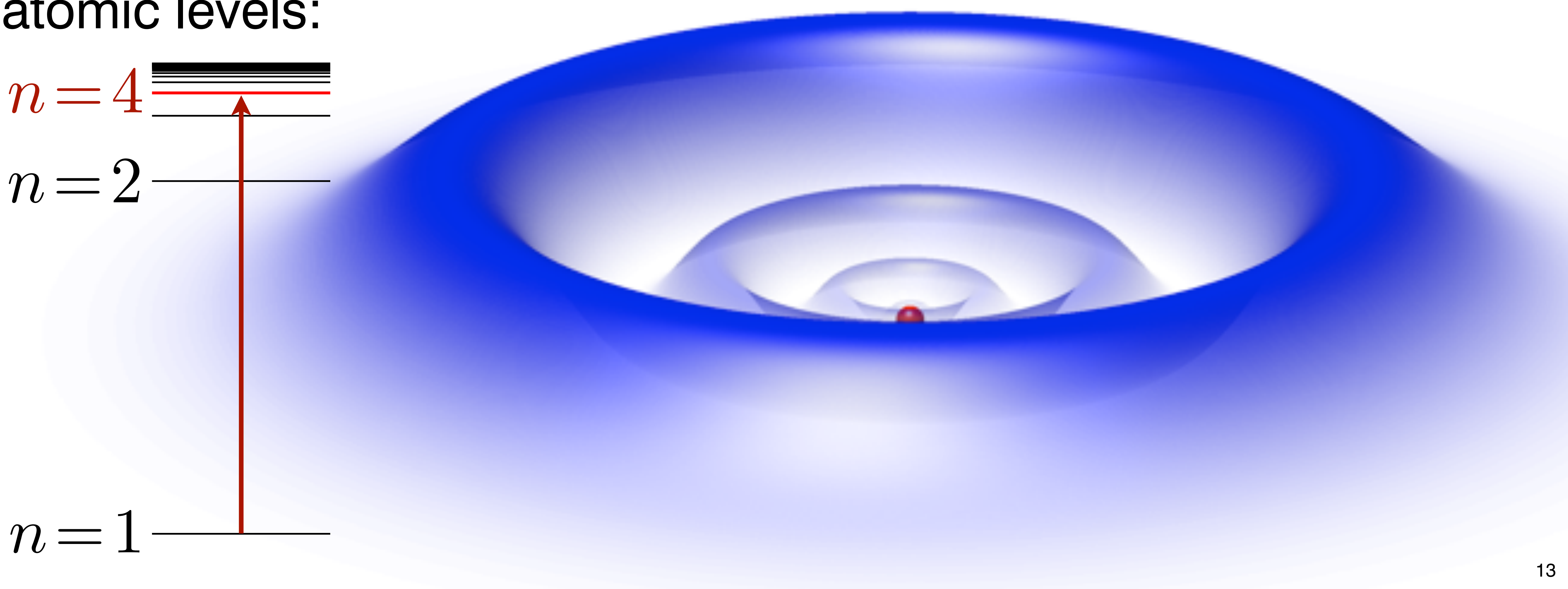
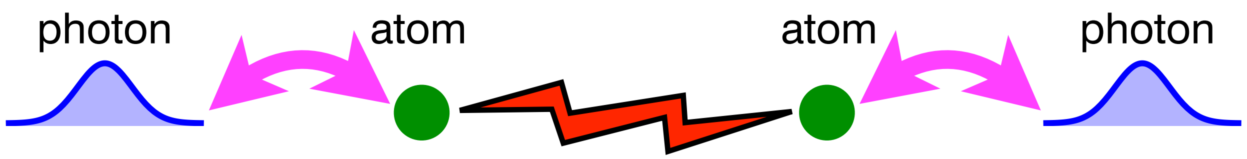
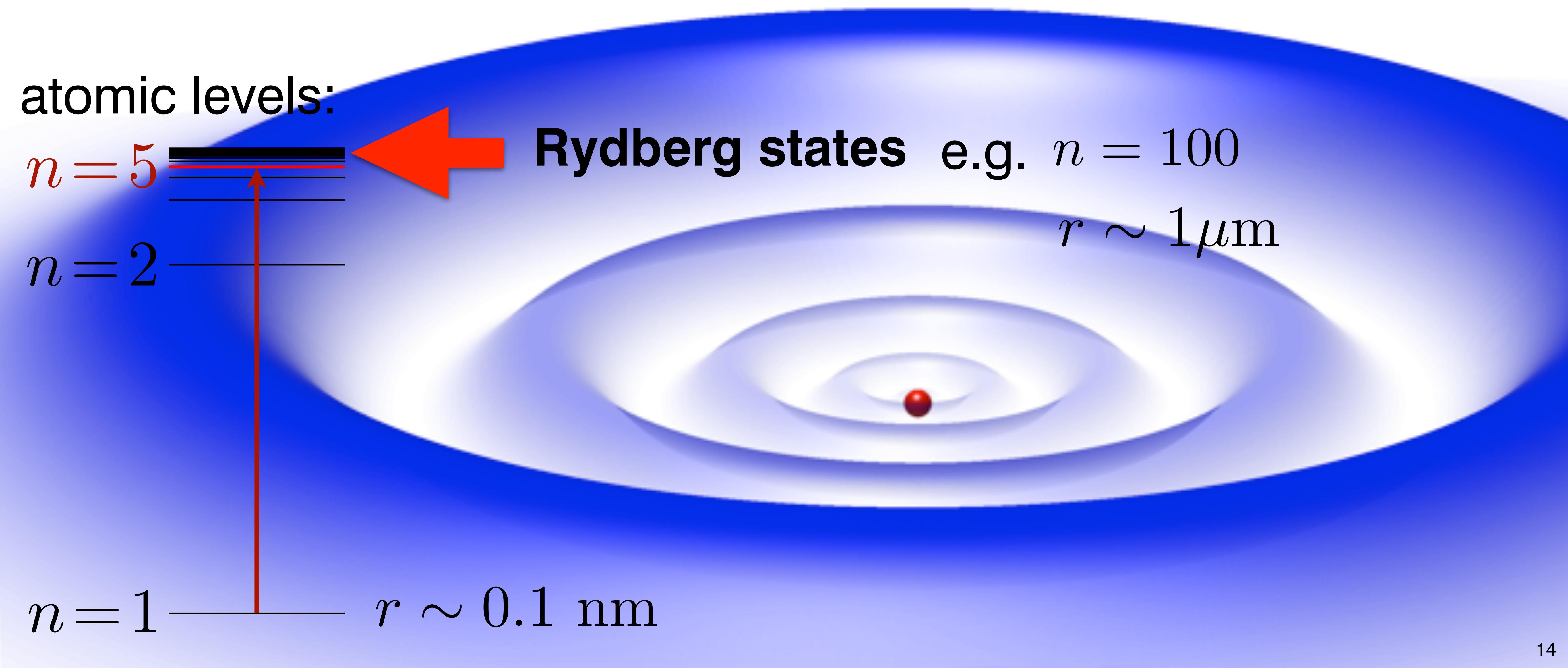


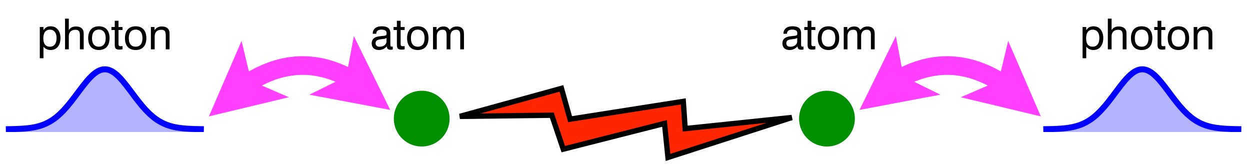
Rydberg excitations



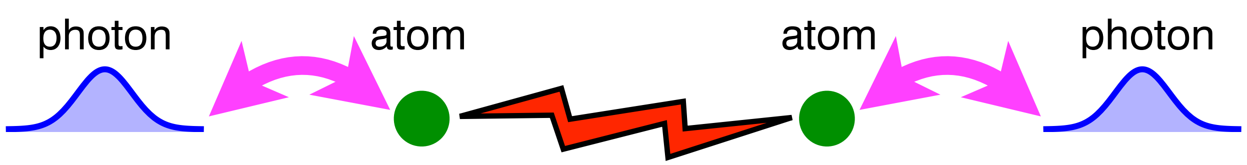
- large size: $r \sim n^2$

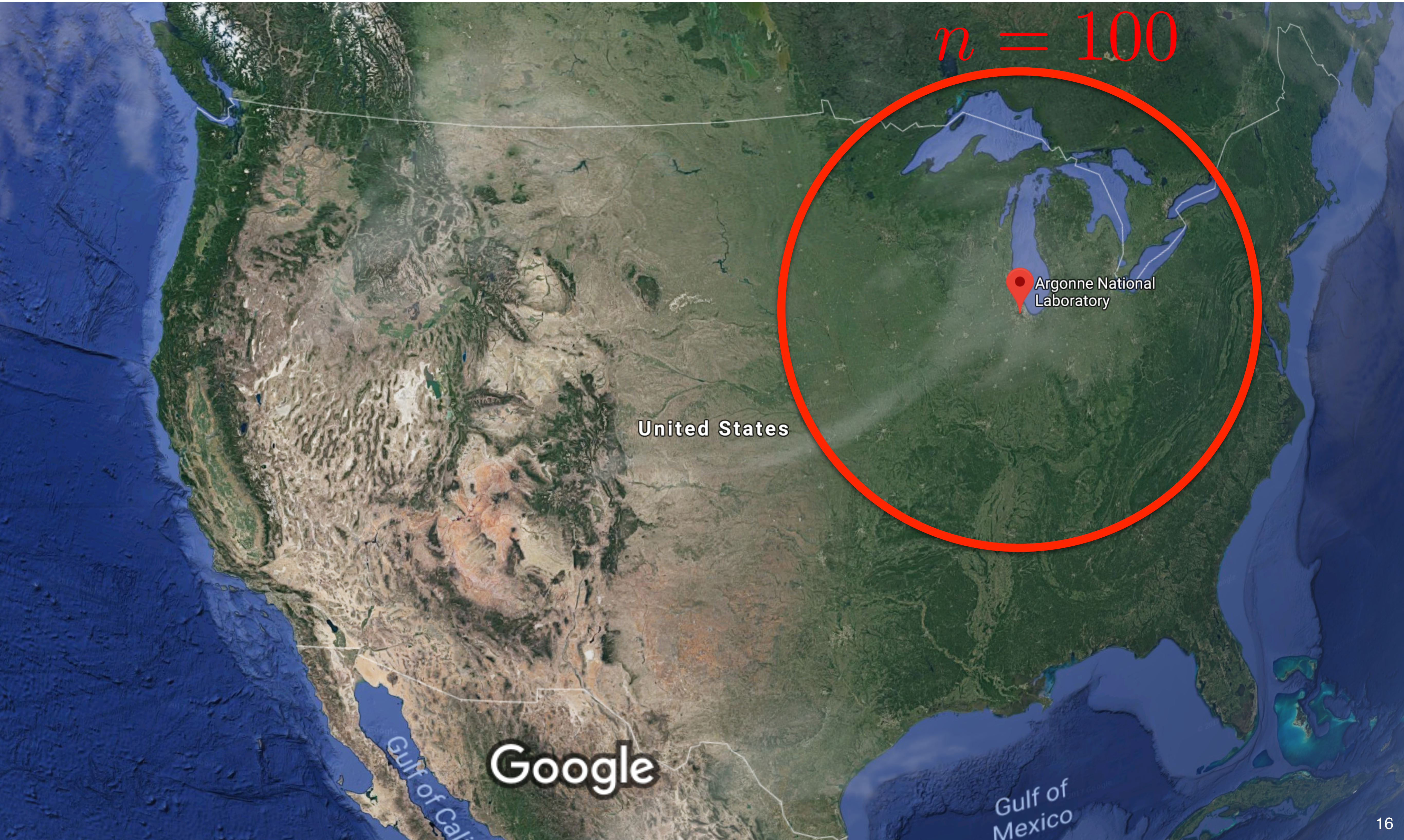


Rydberg excitations

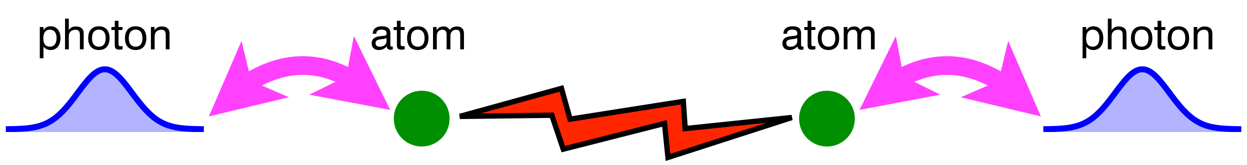


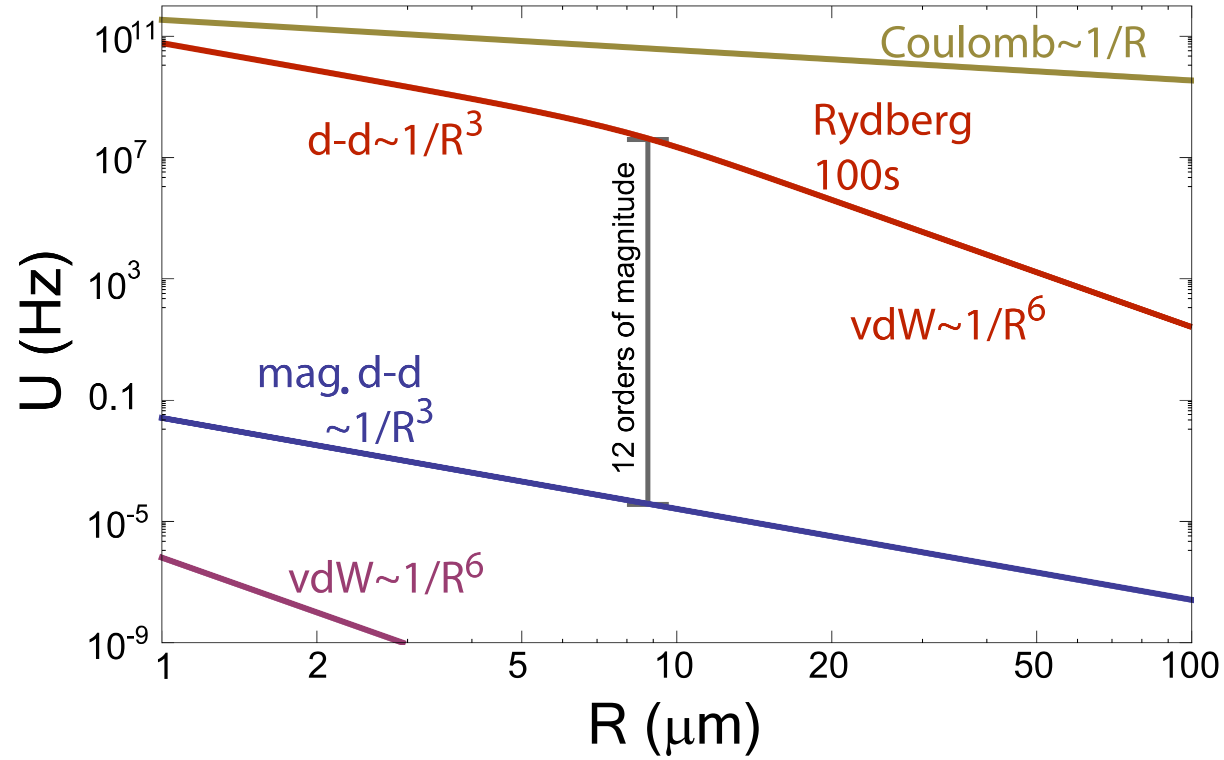
Rydberg excitations





Rydberg excitations





Rydberg-Rydberg interaction

- strong van der Waals interactions

$$C_6 \sim n^{11}$$

- long lifetime

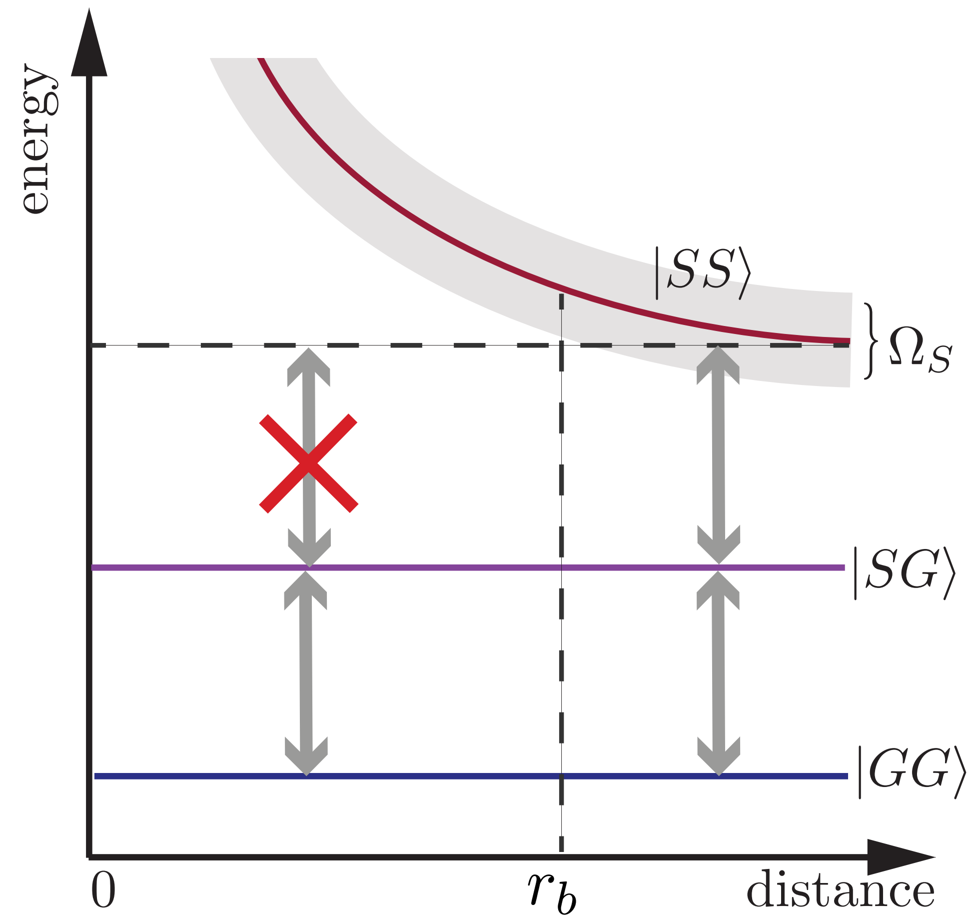
$$\tau \sim n^2$$

Blockade phenomena

- once a Rydberg atom is excited, further excitatons are shifted out of resonance

- Blockade radius

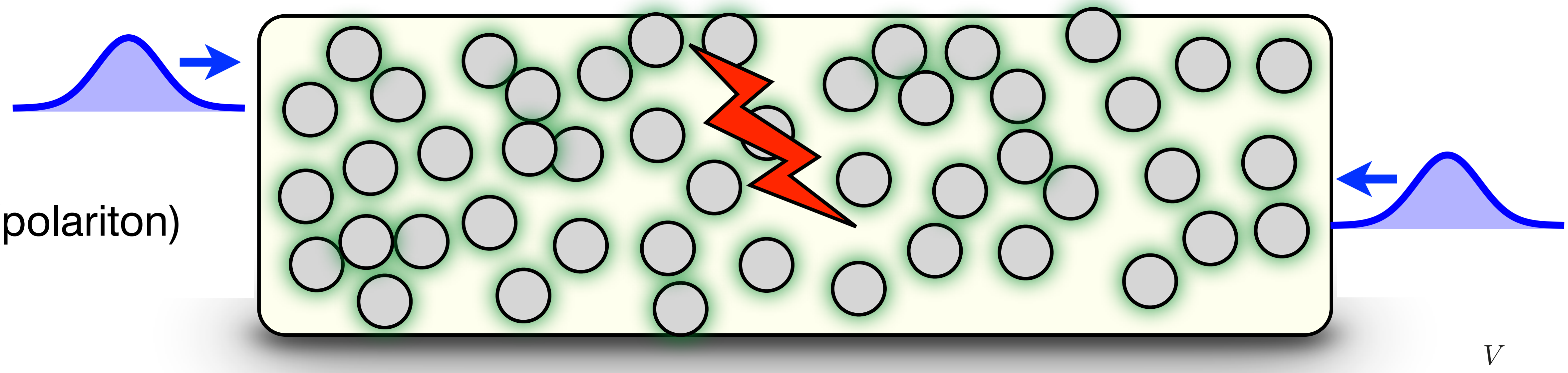
$$r_b = (C_6/\hbar\Omega_S)^{1/6} \sim 10\mu\mathrm{m}$$



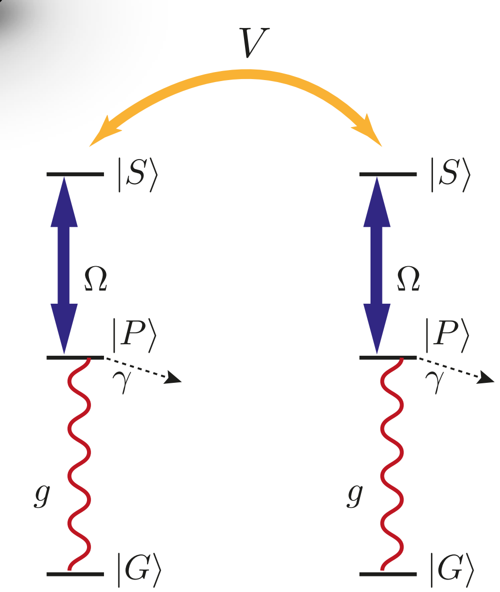
Experiment: Gallagher, Weidemüller, Pillet, Rolston, van den Heuvell, Gould, Pfau, Browaeys, Grangier, Saffman, Kuzmich, Lukin, Vuletic, Hofferberth, Adams, …
Theory: Robicheaux and Hernández, Ates, Pohl, Pattard, Rost, Stanojevic, Côté, Lukin, Fleischhauer, Cirac, Zoller, Lesanovsky, Chang, Buechler …

review: Saffman & Walker, RMP

The medium where photons interact strongly



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



⇒ strong, distant photon-photon interactions

Advantages of the Rydberg-EIT

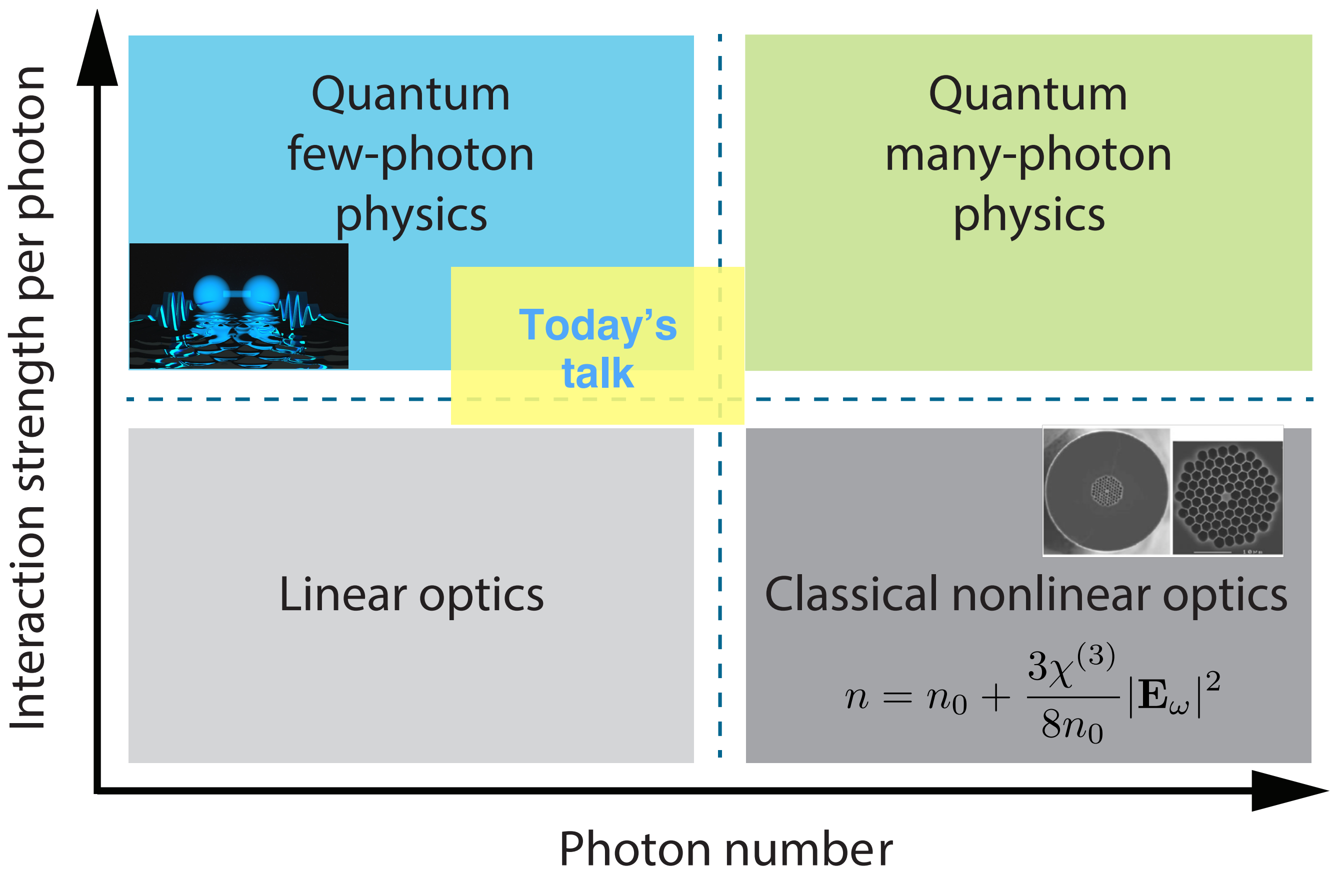
Strong interactions

Nonlocal interactions

Conventional nonlinearities:

1) interactions remain too weak for metrology applications

2) interactions are local: $v_{\text{eff}}\delta(r)$



review: Nat. Photonics, **8**, 685–694 (2014)

⇒ a “No Go” theorem:

High-fidelity operation for single photons **impossible** with conventional (local) nonlinearity.

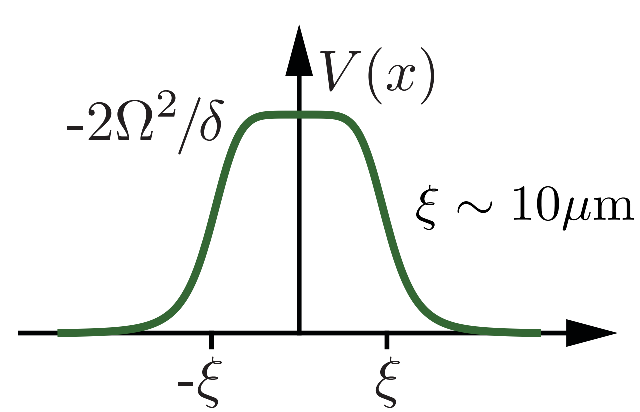
Jeffrey Shapiro, Phys. Rev. A, 2006

solution

Rydberg-EIT

Nonlocal interaction

$$v_{\text{eff}}\delta(r) \rightarrow \frac{V(0)}{1+(r/\xi)^6}$$

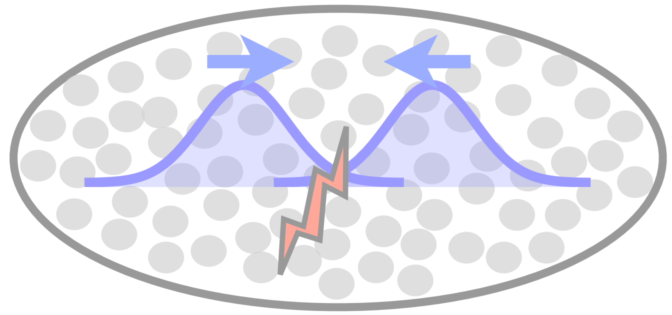


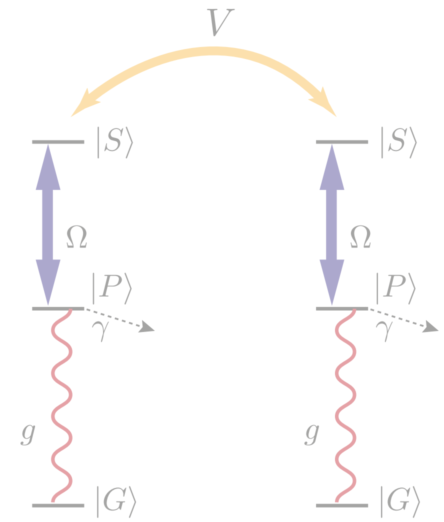
High-fidelity operation for single photons **possible** with **Rydberg-EIT** nonlinearity.

Outline

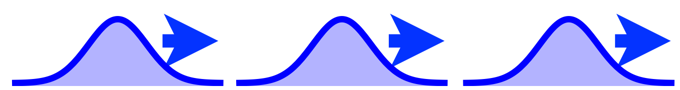
I. Basics

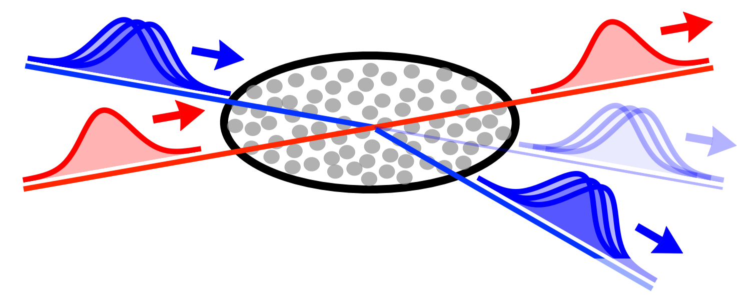
- interacting photons
- Rydberg-EIT





II. Rydberg-EIT toolbox for sensing



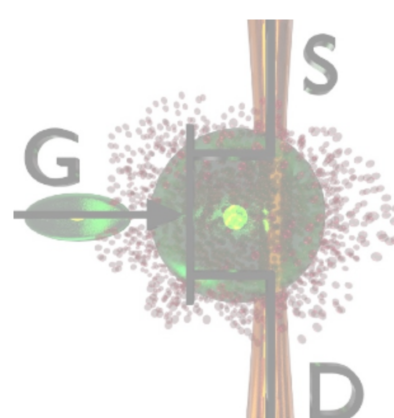


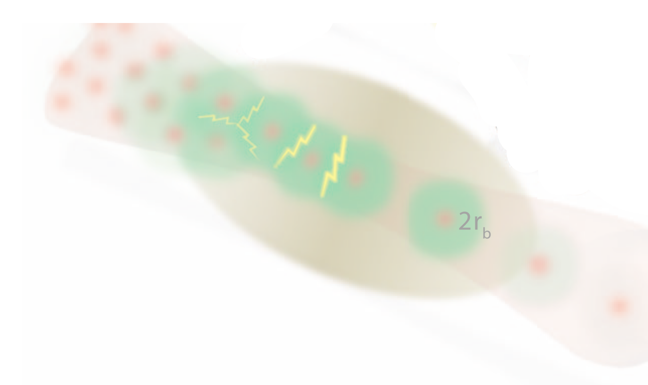
III. Sensing with interacting photons

- examples

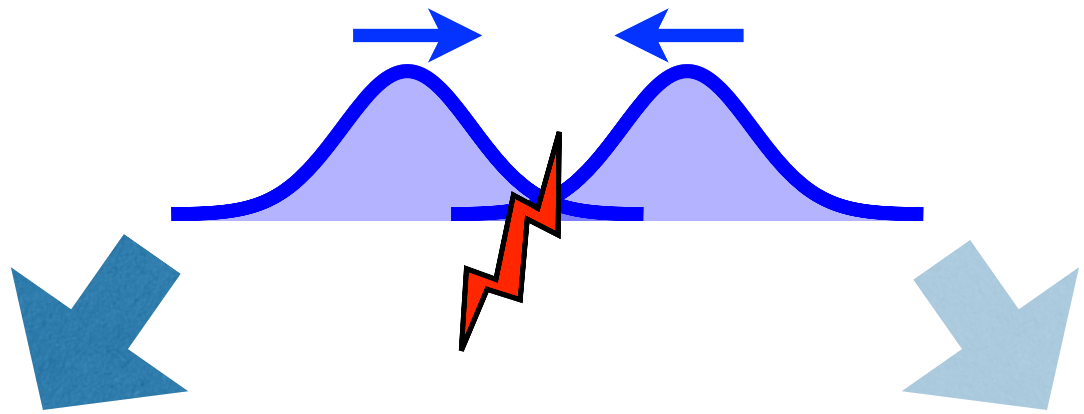
II. Rydberg-EIT

- experimental progress
- challenges and limitations



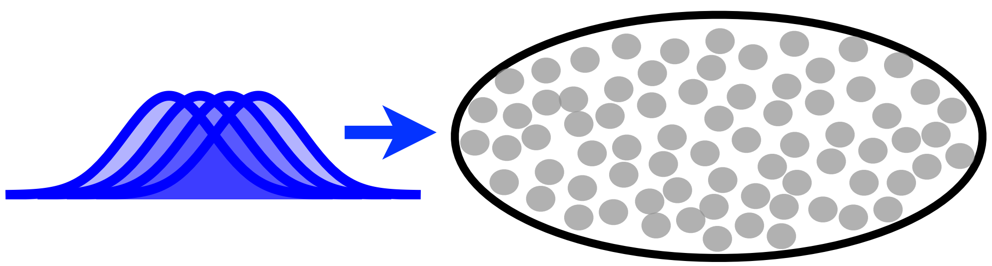


Rydberg-EIT toolbox for sensing



standard photon source

single-photon transistor



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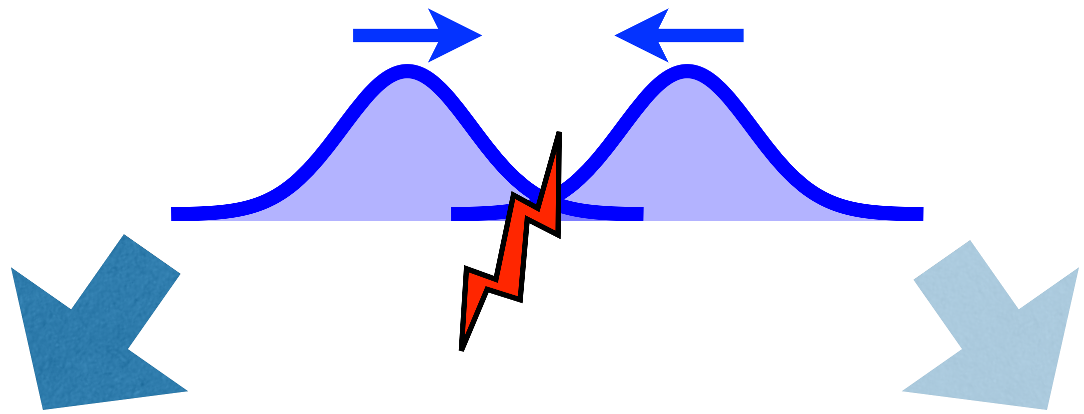

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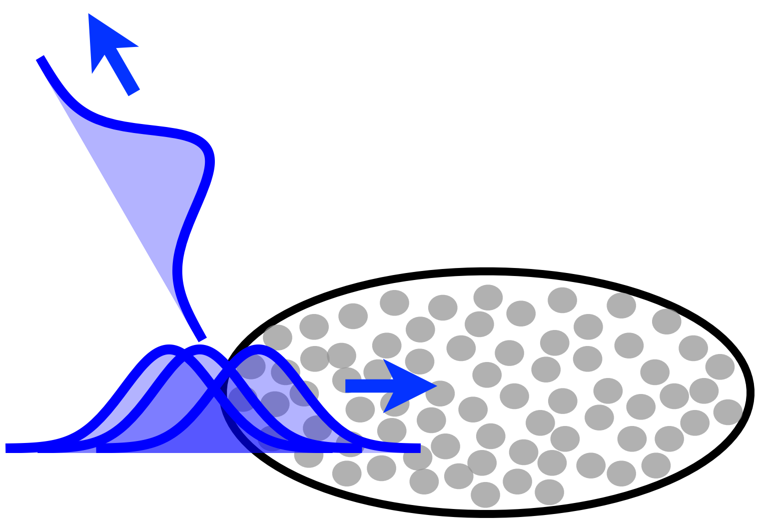
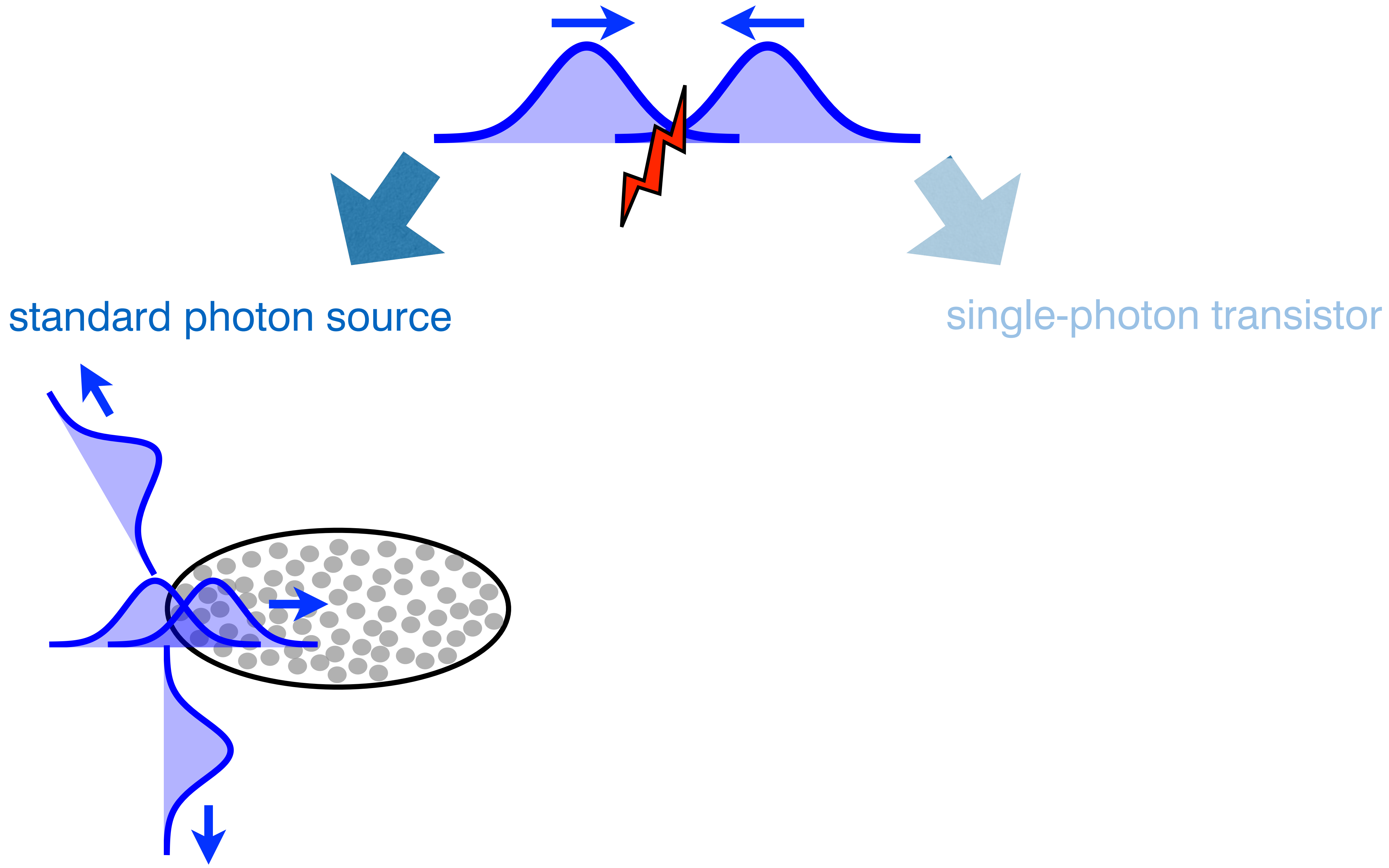
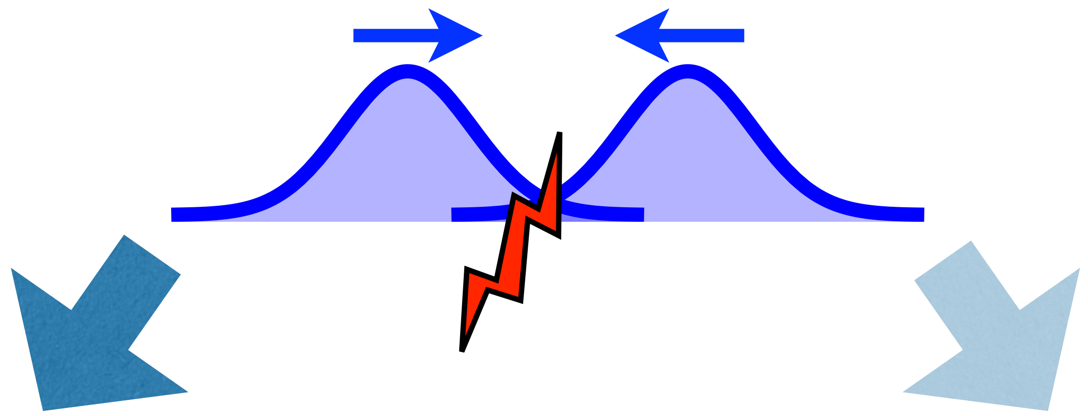


Rydberg-EIT toolbox for sensing

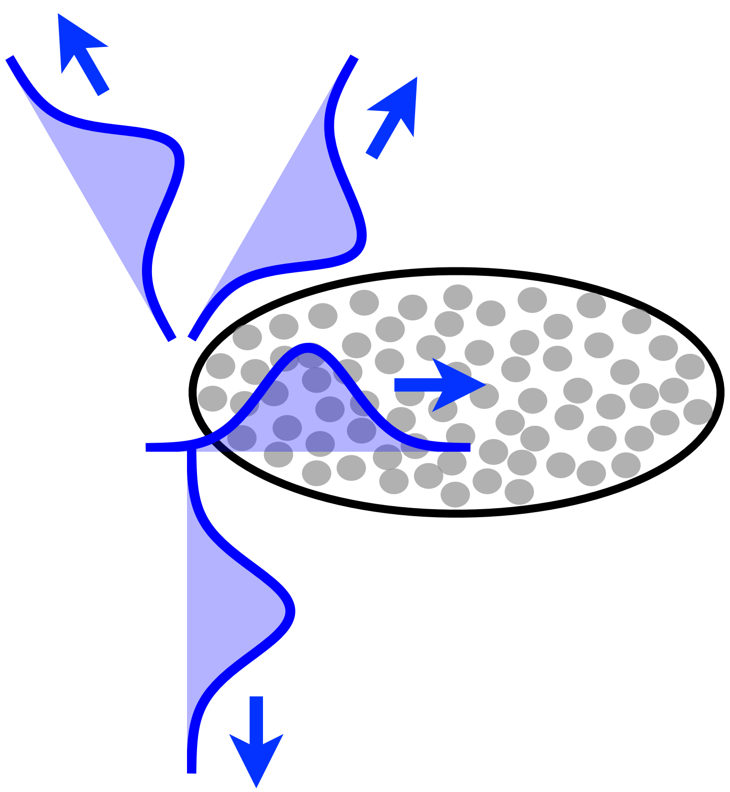


Rydberg-EIT toolbox for sensing

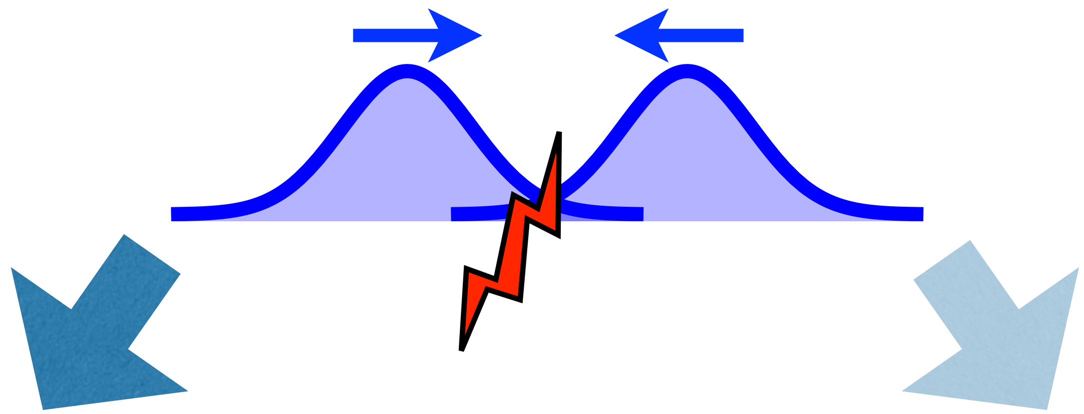


standard photon source

single-photon transistor

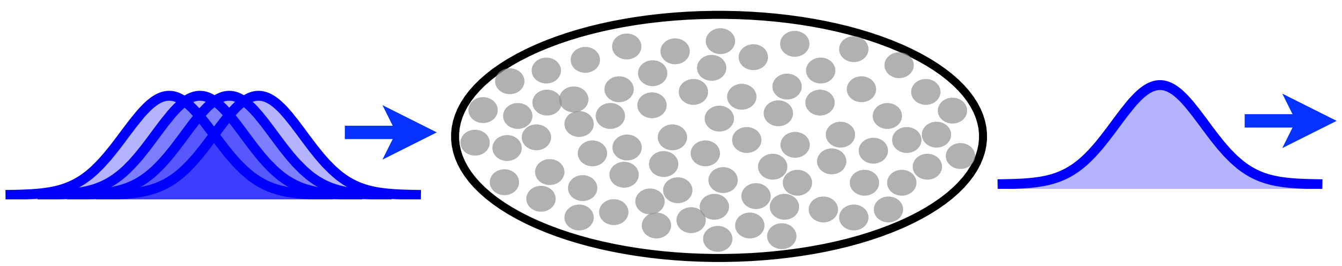


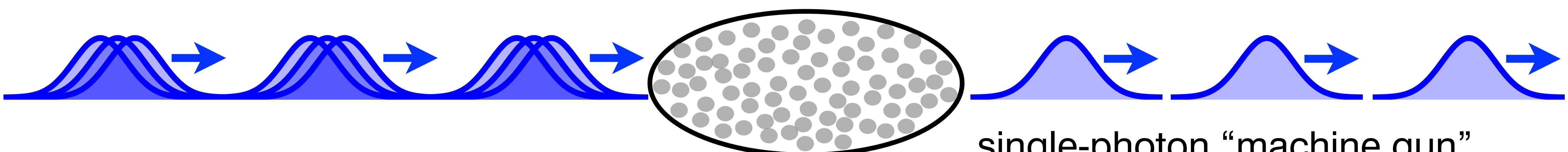
Rydberg-EIT toolbox for sensing



standard photon source

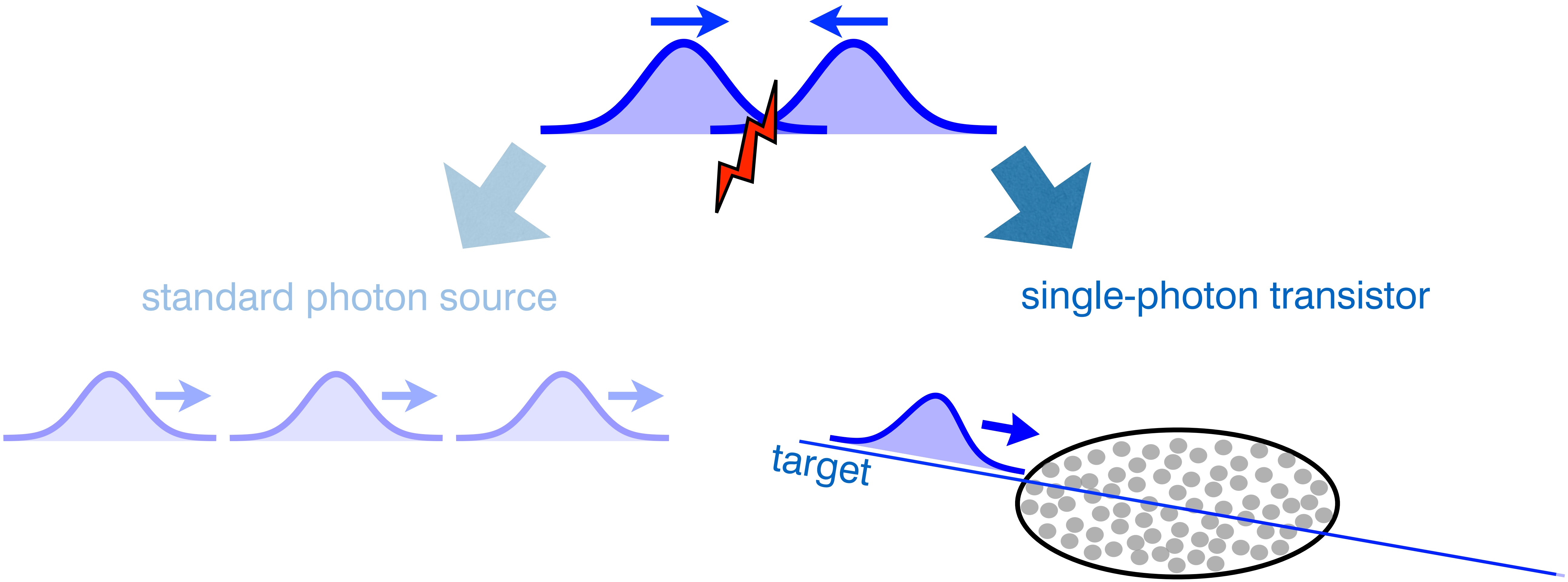
single-photon transistor



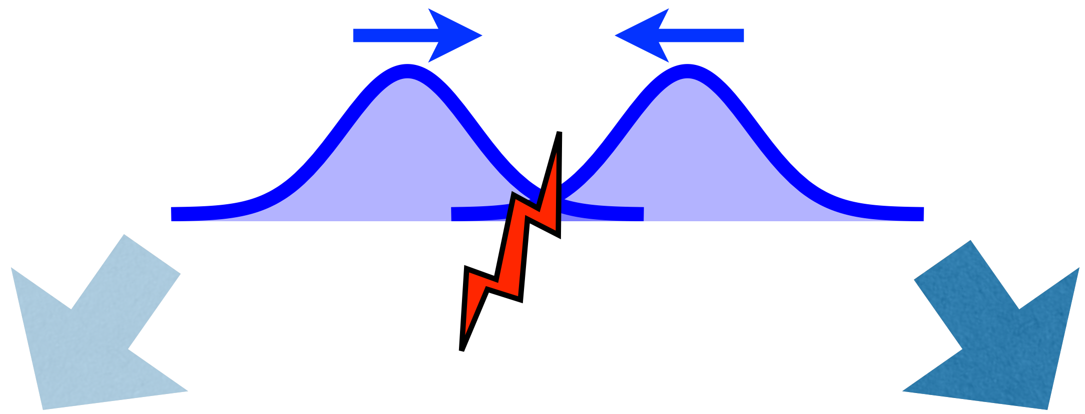


single-photon “machine gun”

Rydberg-EIT toolbox for sensing

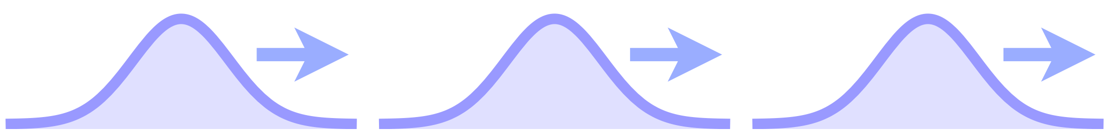


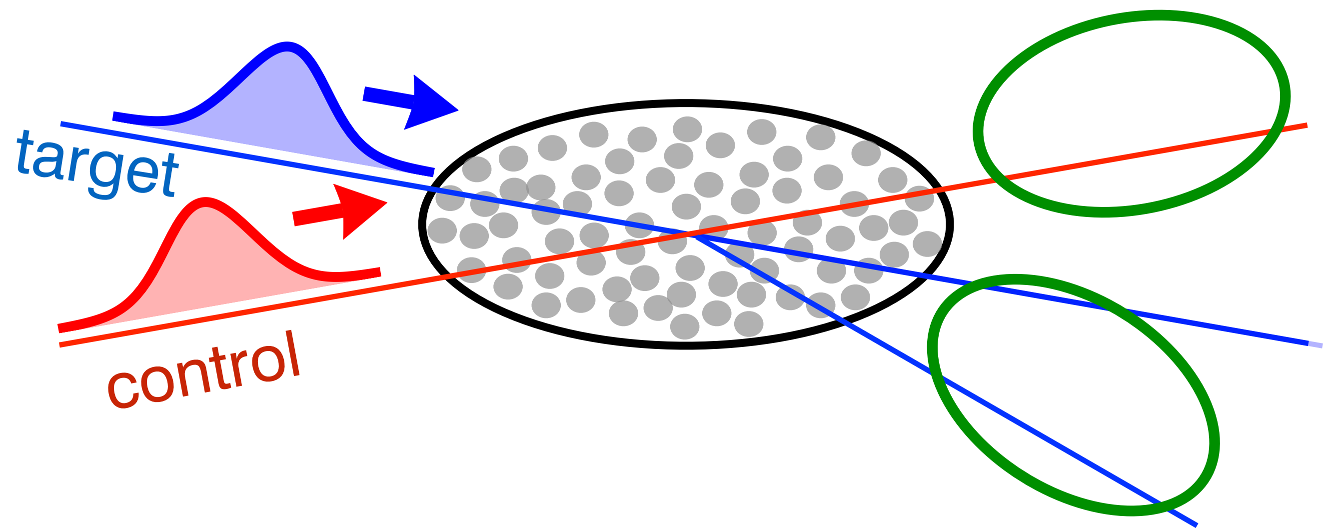
Rydberg-EIT toolbox for sensing



standard photon source

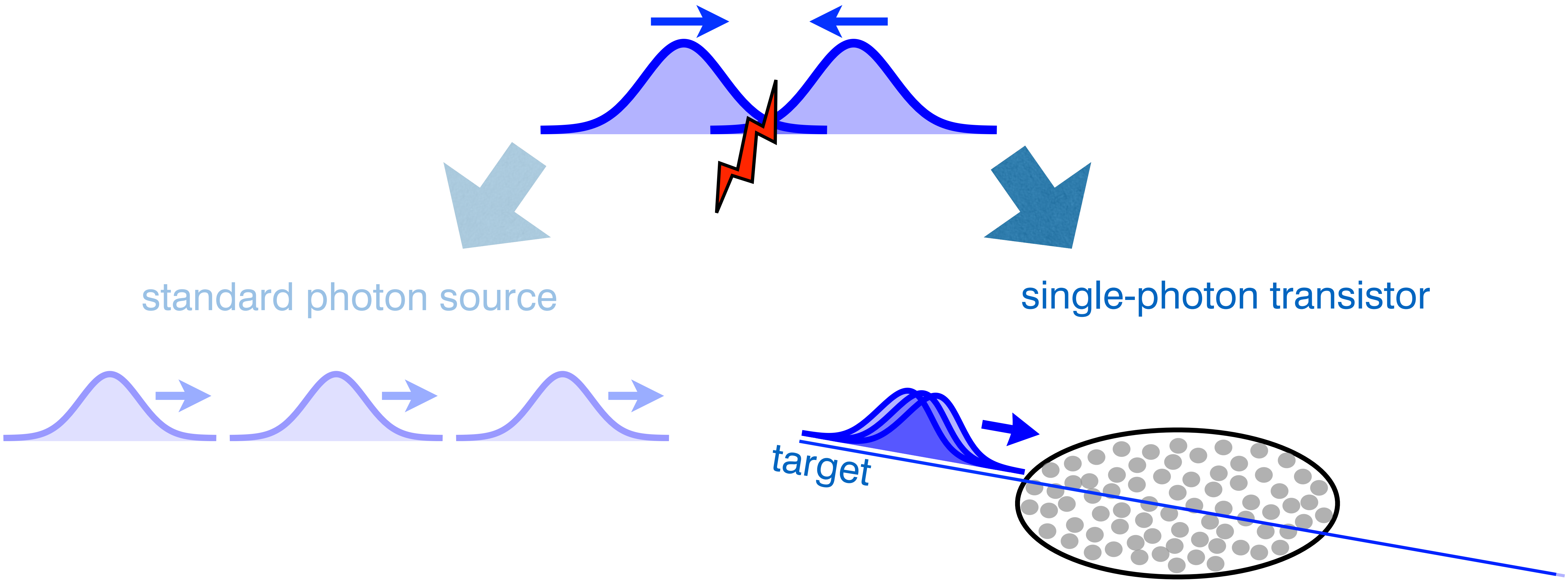
single-photon transistor



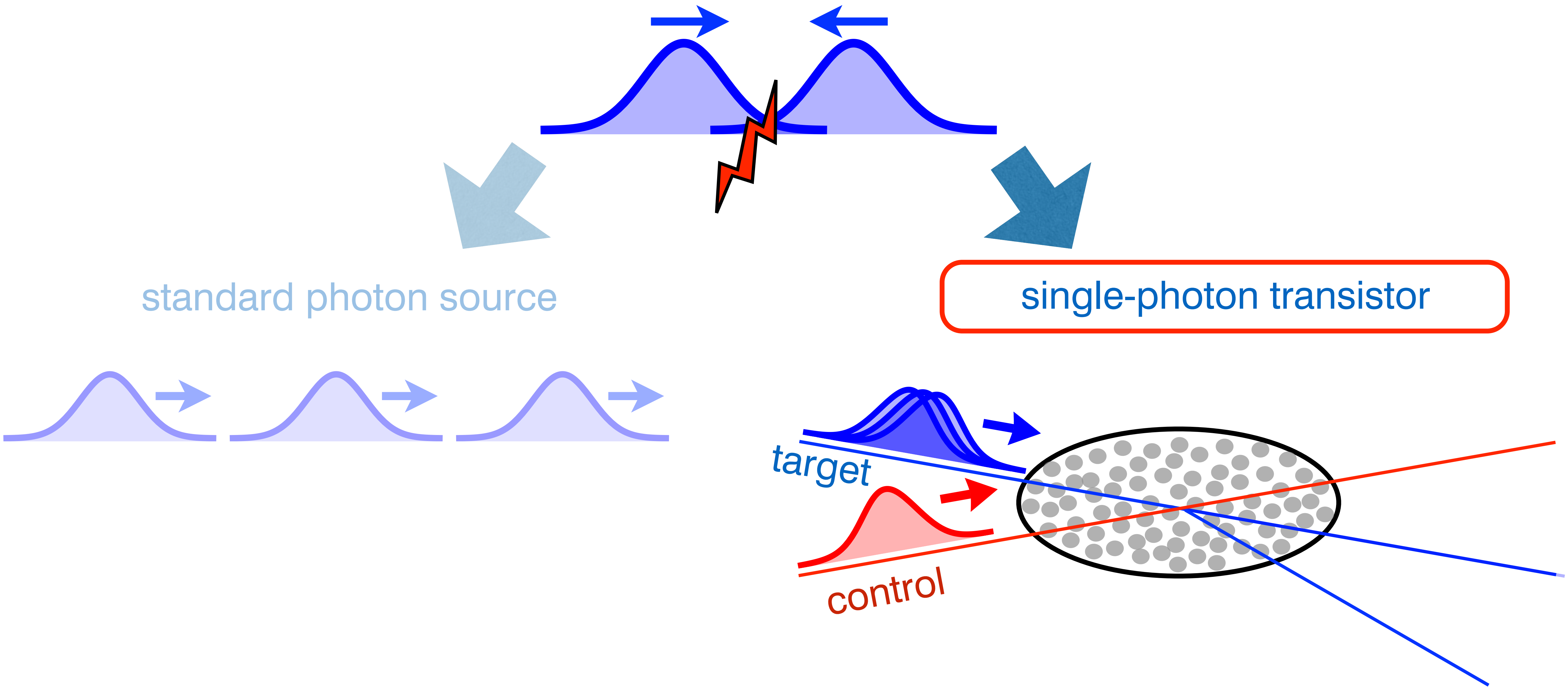


photon-photon gate

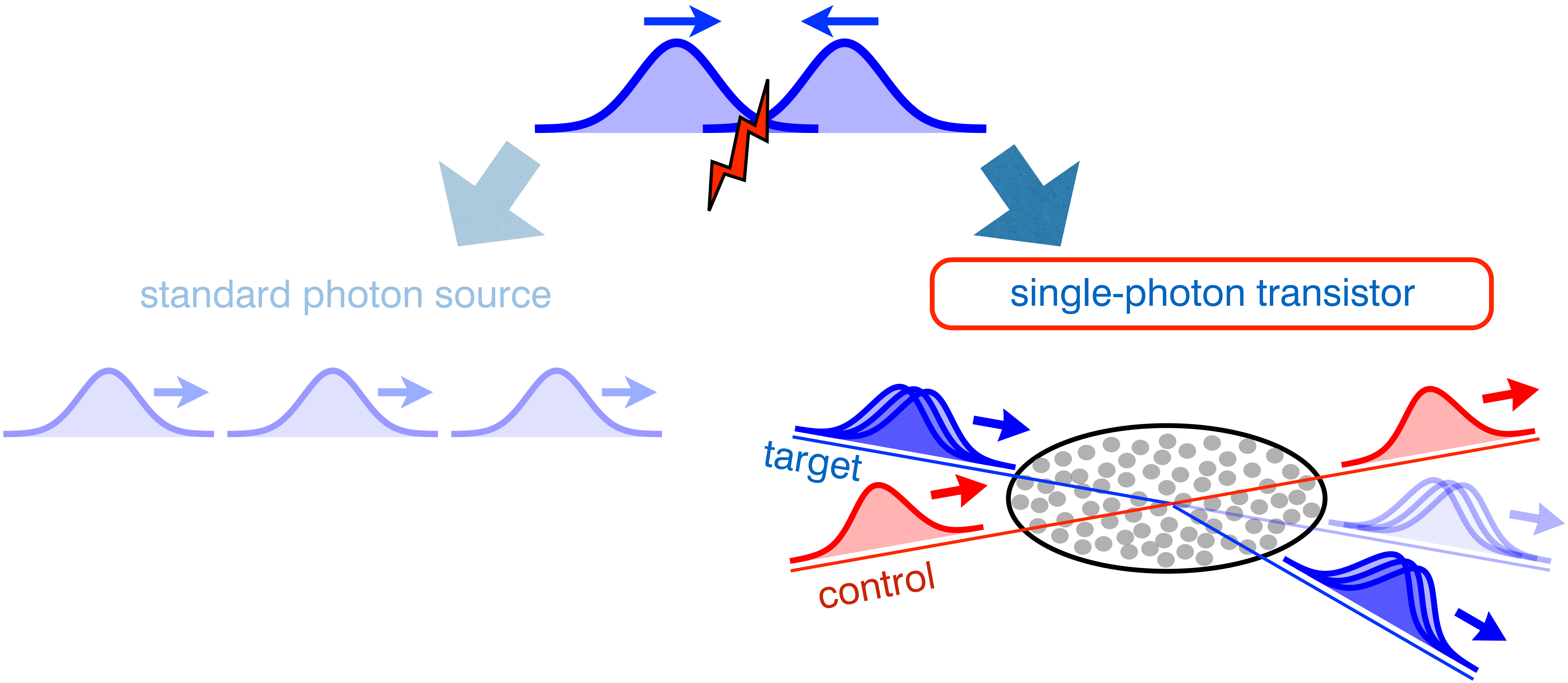
Rydberg-EIT toolbox for sensing



Rydberg-EIT toolbox for sensing

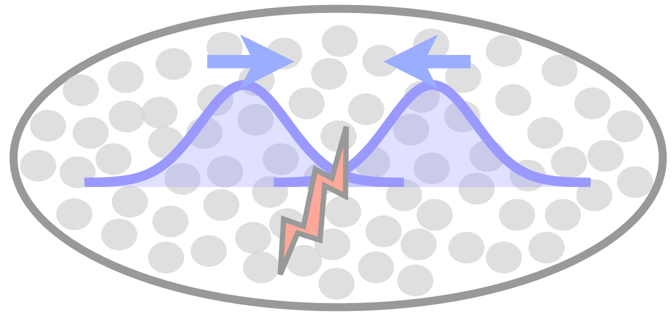


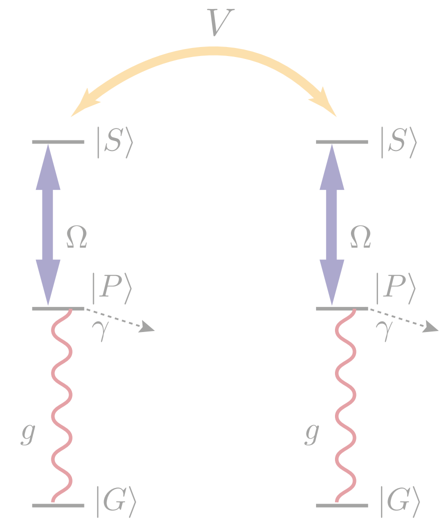
Rydberg-EIT toolbox for sensing



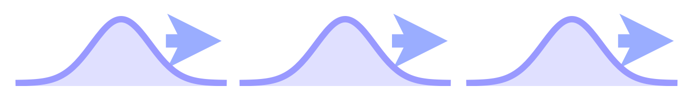
Outline

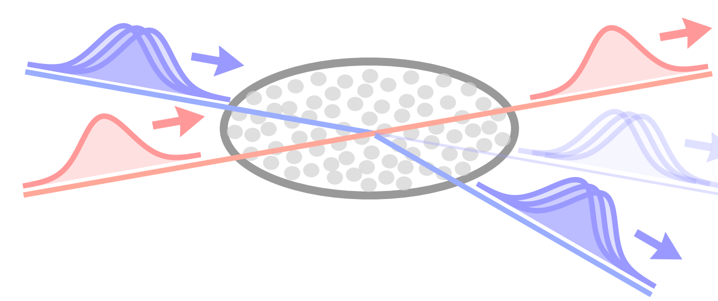
I. Basics
- interacting photons
- Rydberg-EIT





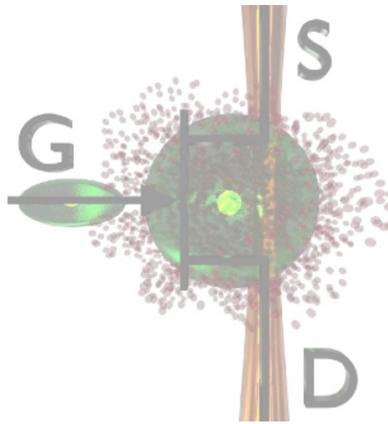
II. Rydberg-EIT toolbox for sensing

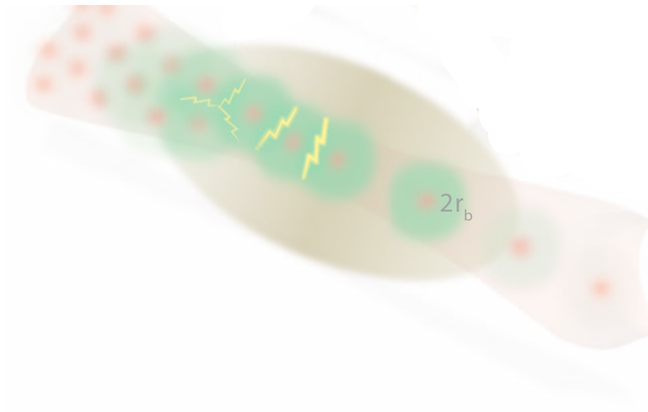




III. Sensing with interacting photons
- examples

II. Rydberg-EIT
- experimental progress
- challenges and limitations





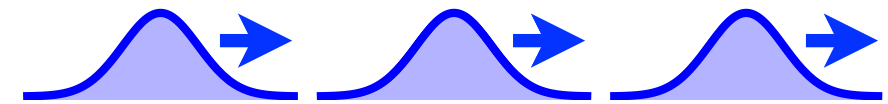
What are interacting photons good for?

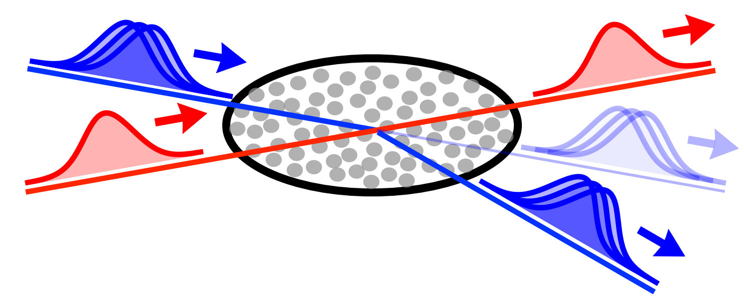
radiometry

Standard candle
(a fixed no. of photons)

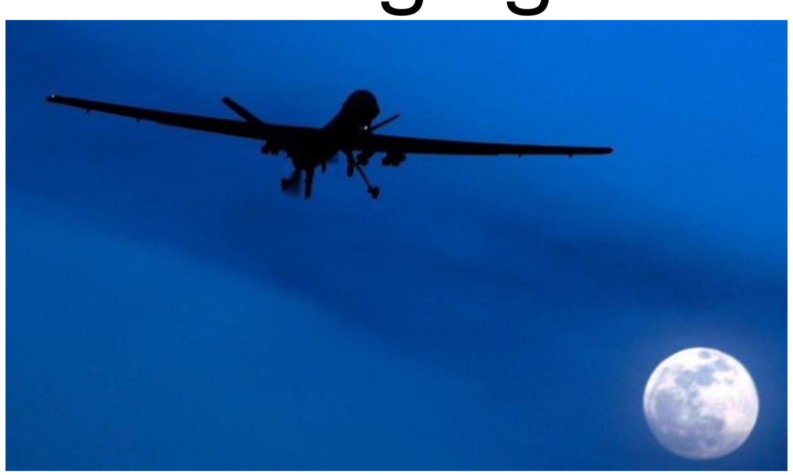
spectroscopy

sensitive analysis



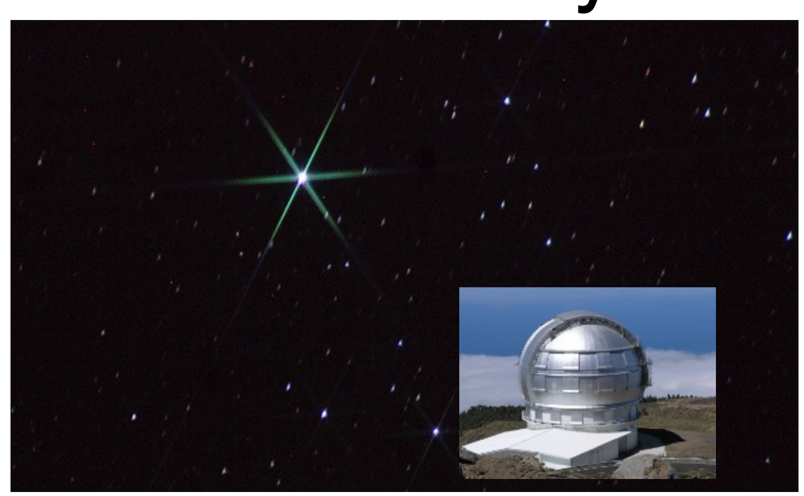


imaging



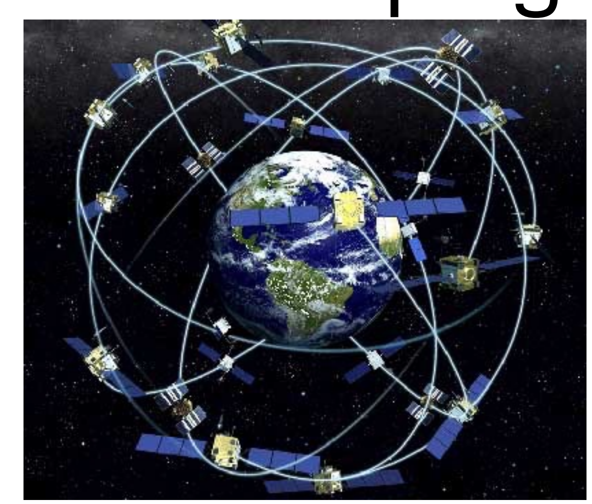
detection below noise

astronomy



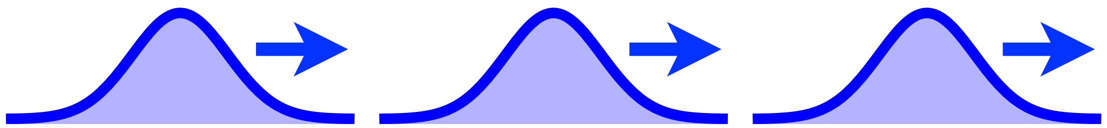
long-baseline interferometry

time-keeping



quantumly linked clocks

Impact: radiometry

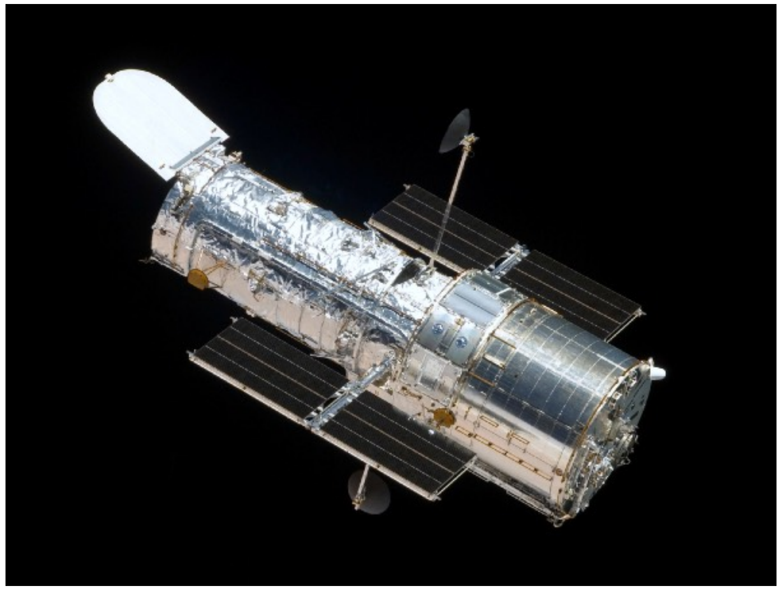


= standard candle

- unlike heralded sources: deterministic & higher-rate
- identical photons

- calibration of photon detectors

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

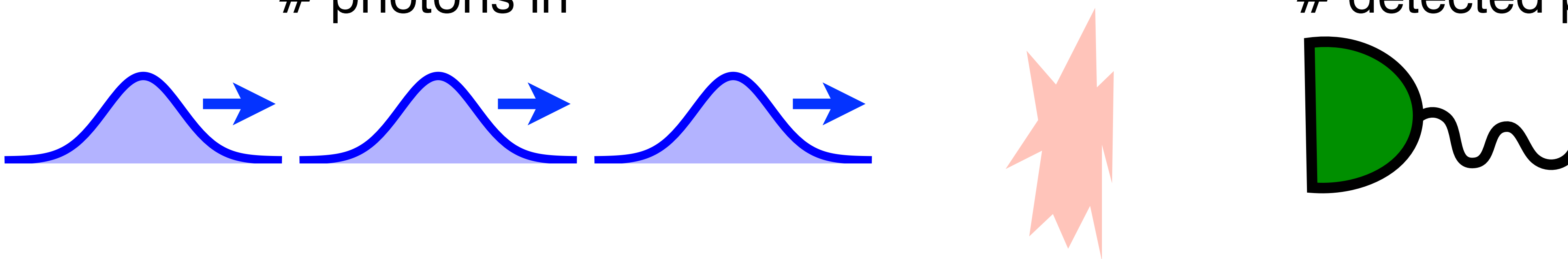


- nonlinear crystals: Barz et al., Science (2012)
- quantum-dots: Michler et al., Science (2000)

Impact: imaging, spectroscopy, trace detection

\# photons in

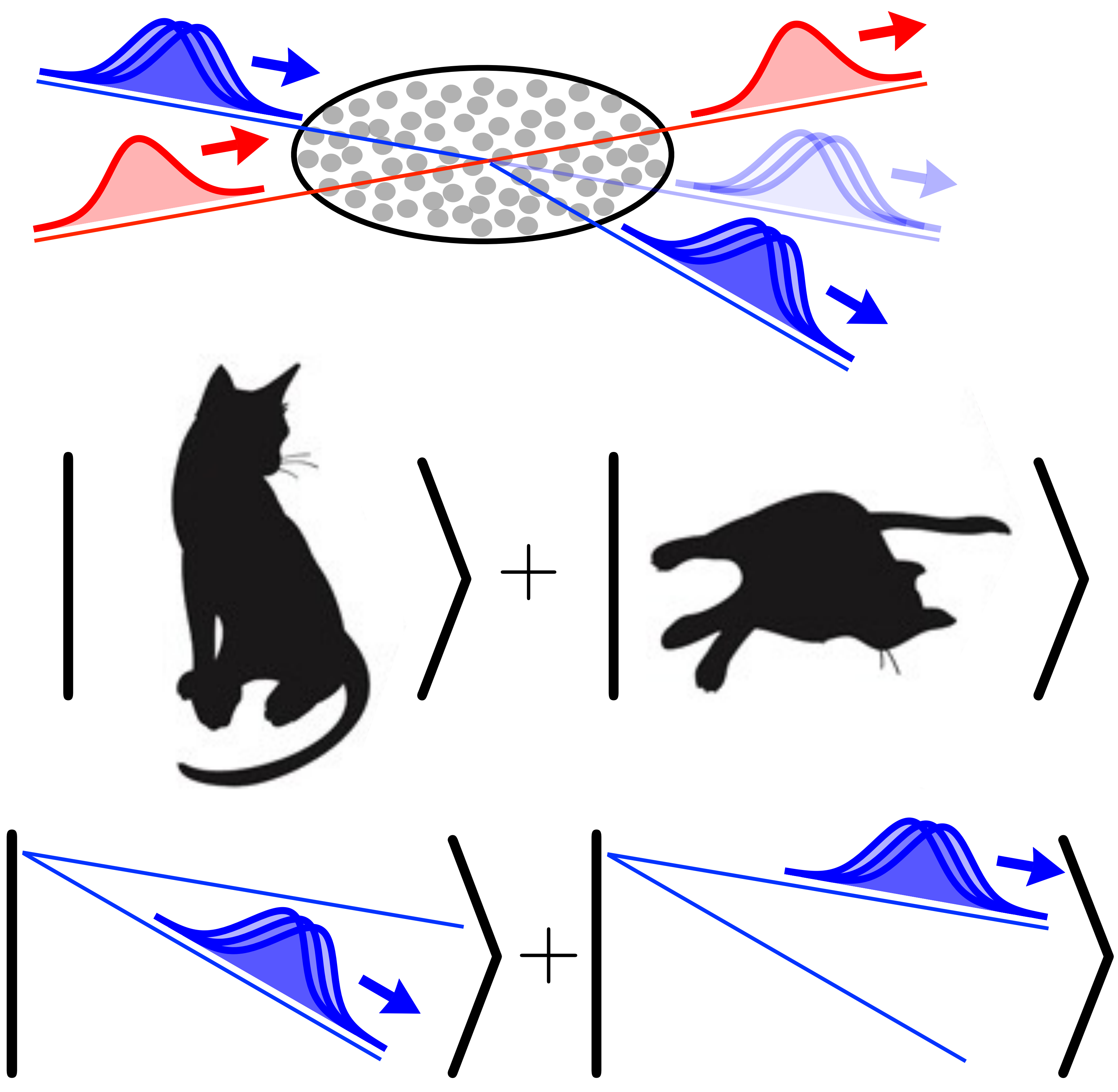
\# detected photons



- no shot noise
- dramatically reduced measurement uncertainty in imaging & spectroscopy of low-absorption & quantity-limited samples

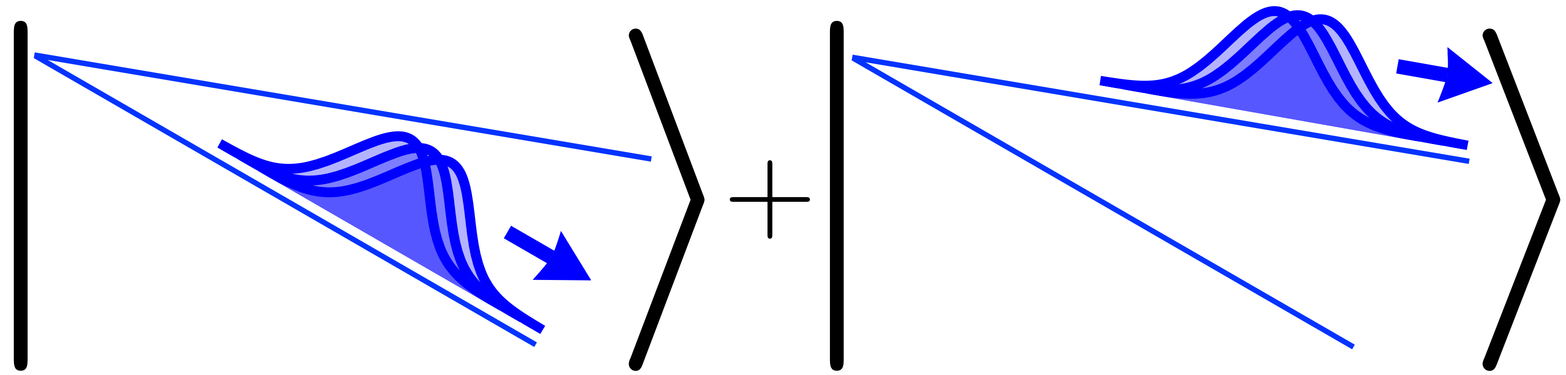
⇒ chemistry, biology, medicine, forensics, security, …

Schrödinger-cat state of light



Glancy, et al, JOSA B (2008)

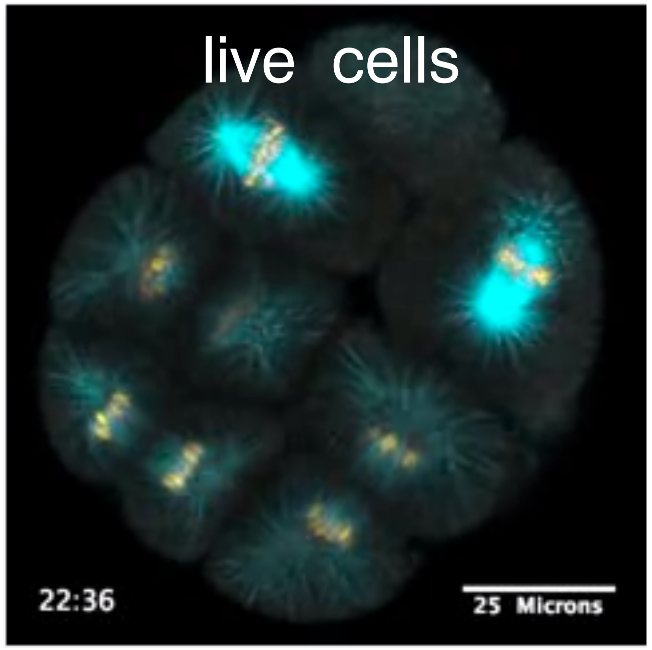
Impact: quantum-enhanced sensing & imaging



Schrödinger-cat state of light

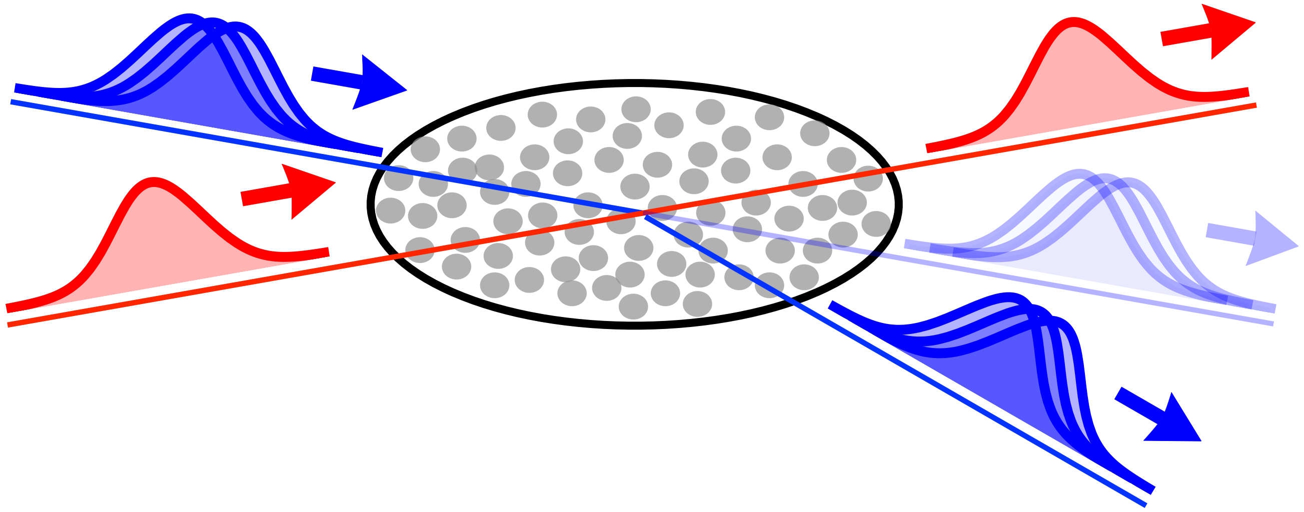
- interferometry with maximum per-photon sensitivity
- imaging, sensing, and spectroscopy of fragile photosensitive samples

⇒ chemistry, biology, medicine, materials science, forensics, …



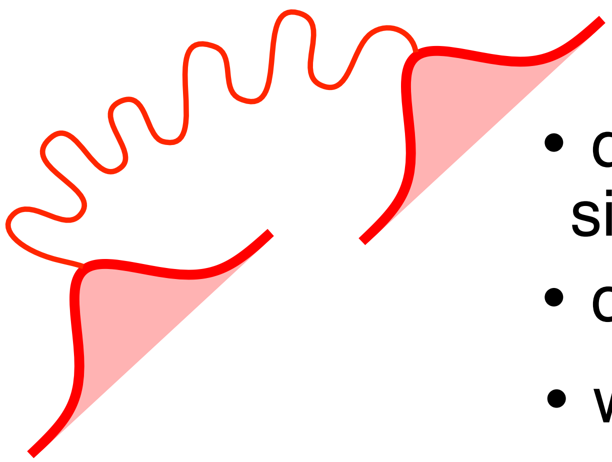
Israel et al., PRL (2014)

Impact: quantum-enhanced sensing & imaging



- quantumly connect (entangle) two photons

“quantum illumination”

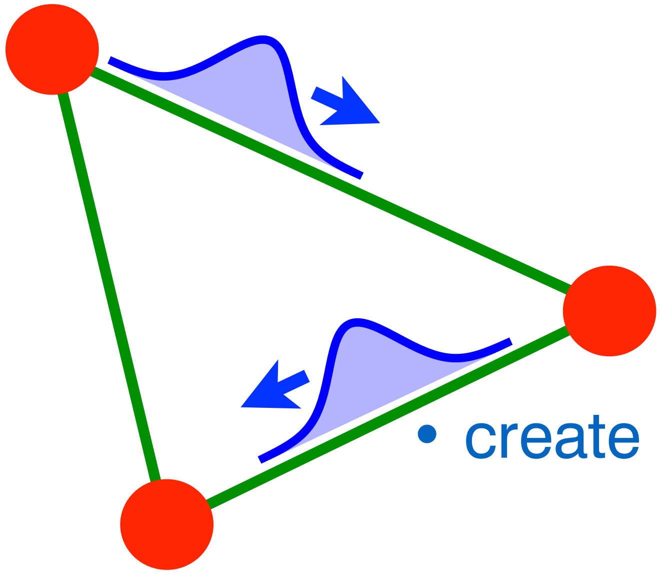


- detect reflected signal with an improved signal-to-noise ratio
- can also use for communication
- when signal weak & noise high

⇒ military, biological contexts…

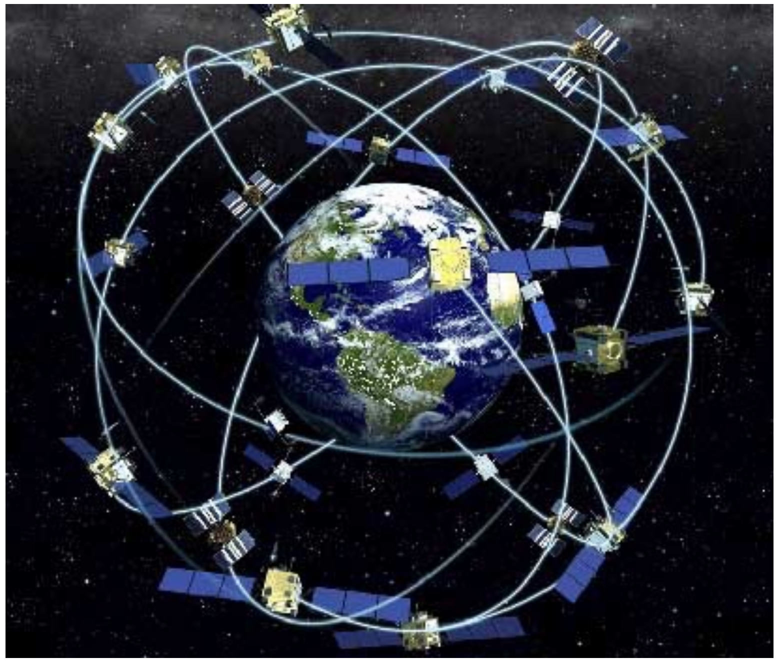
Tan et al., PRL (2008), Lloyd et al., Science (2008), Lopaeva et al., PRL (2013)

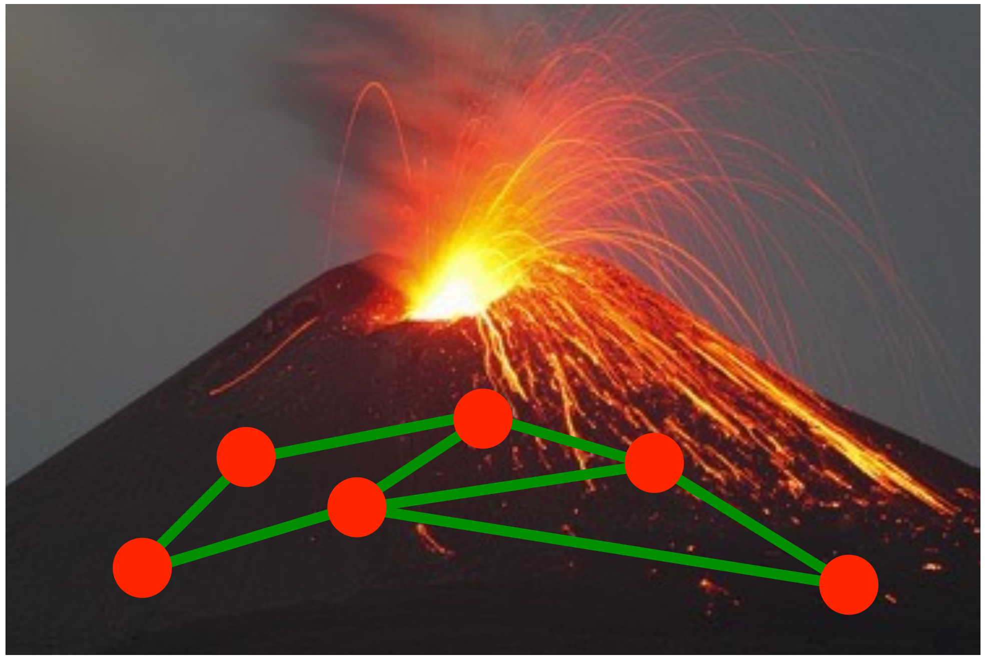
Impact: time-keeping and earth science



- create remote entanglement (quantum connection)

- quantumly connect (entangle) remote clocks or sensors

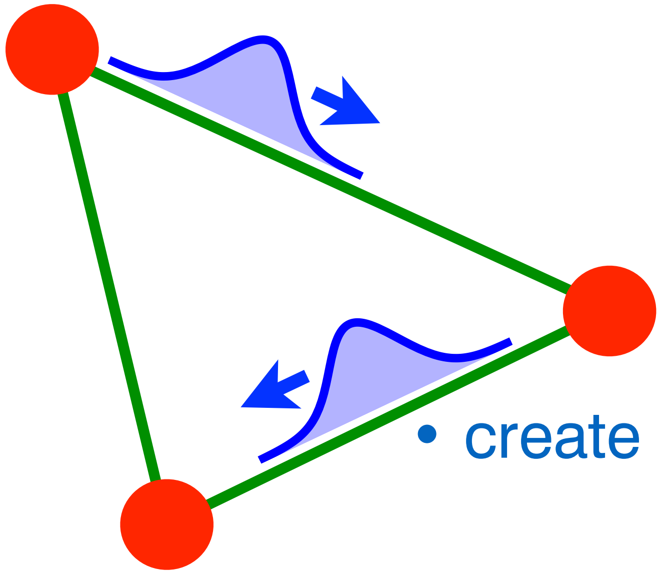




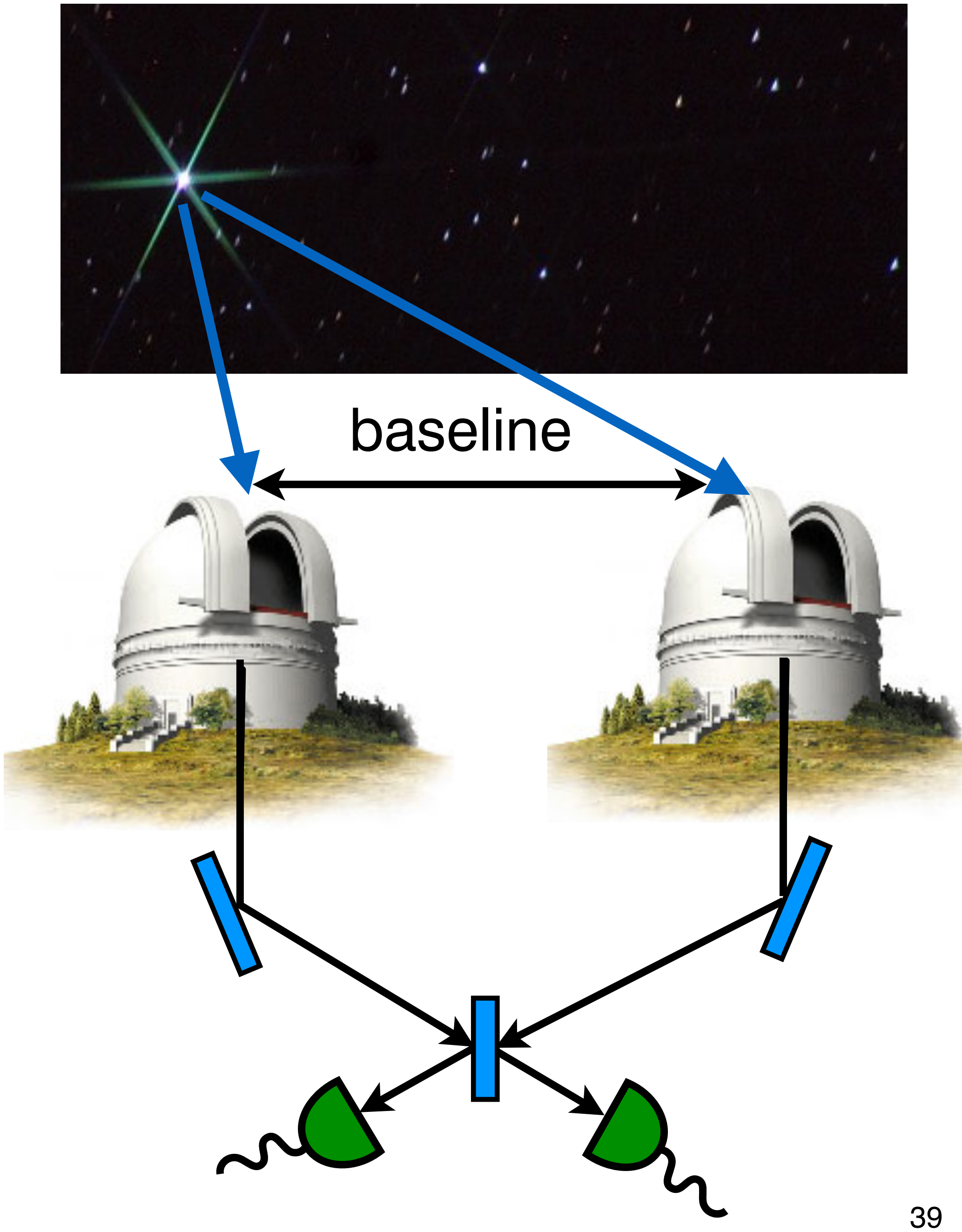
⇒ time-transfer, navigation, search for oil/gas/minerals, monitoring volcanos/earthquakes, …

Kómár et al., Nature Physics (2014)

Impact: long-baseline interferometry

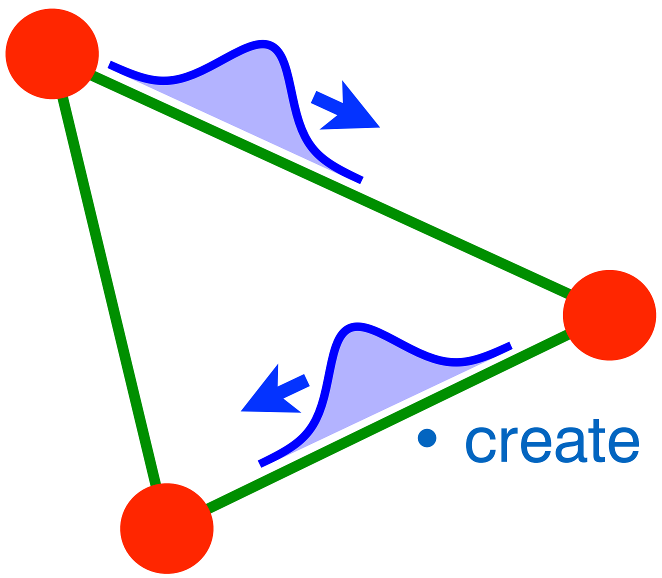


- create remote entanglement (quantum connection)

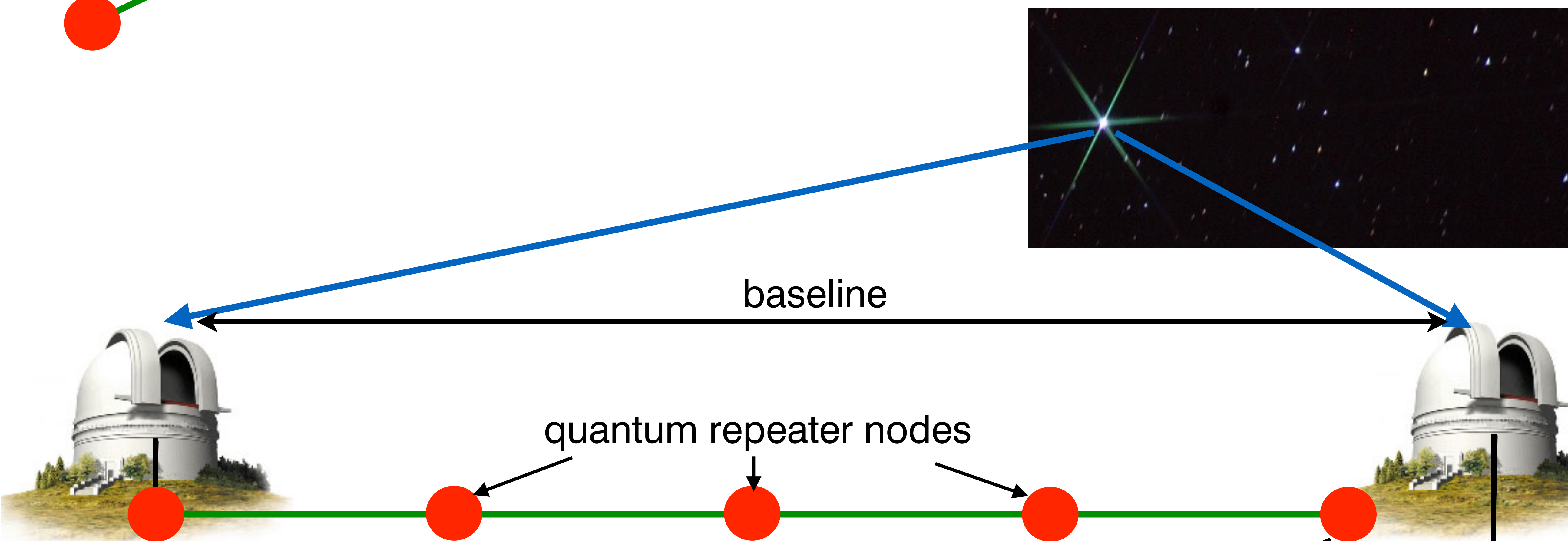


- determine position of light source when photons scarce and propagation lossy

Impact: long-baseline interferometry



- create remote entanglement (quantum connection)



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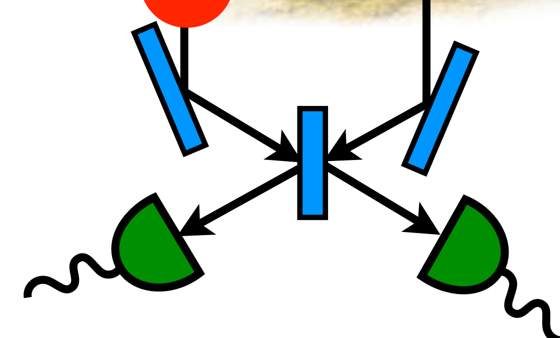
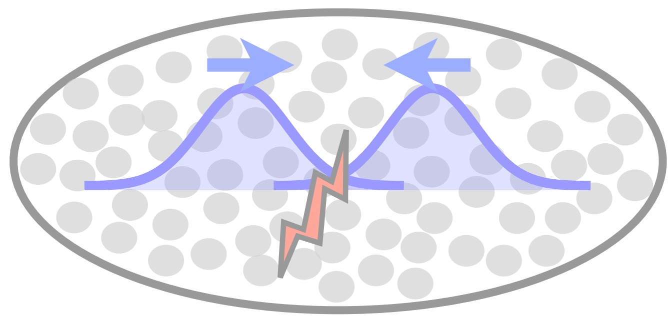


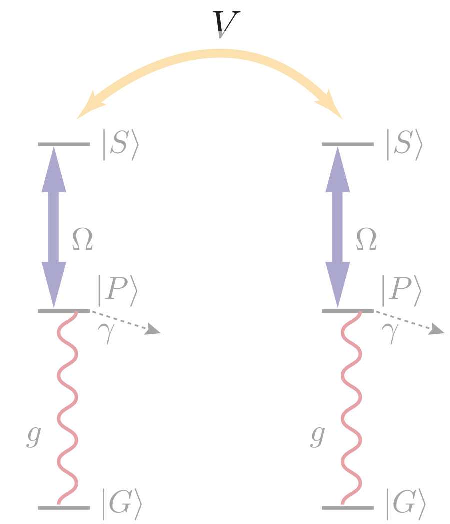
⇒ astronomy, reconnaissance, …

Briegel PRL (1998) ; Duan et al., Nature (2001); Gottesman et al., PRL (2012)

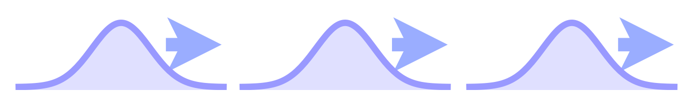
Outline

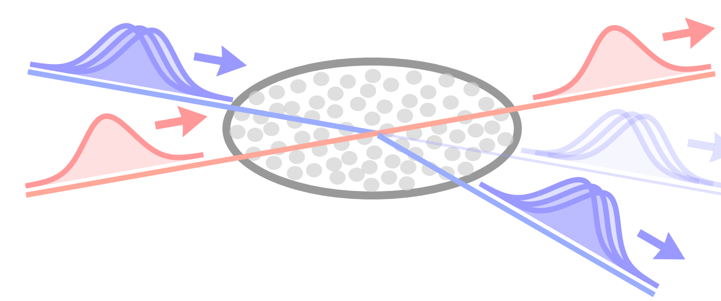
I. Basics
- interacting photons
- Rydberg-EIT





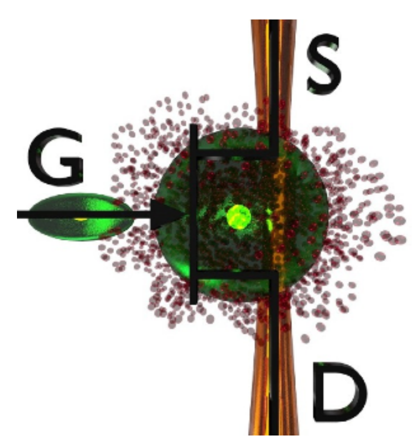
II. Rydberg-EIT toolbox for sensing

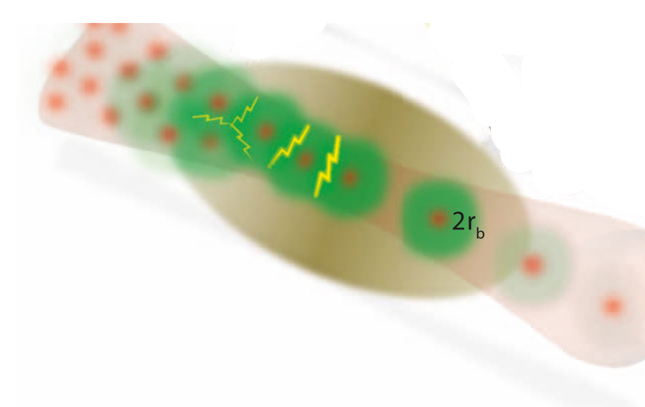




III. Sensing with interacting photons
- examples

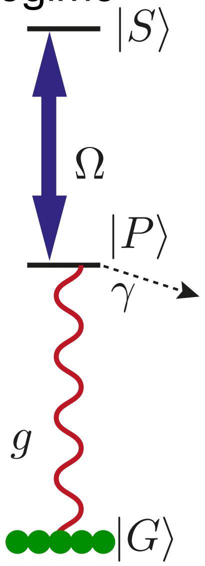
II. Rydberg-EIT
- experimental progress
- challenges and limitations



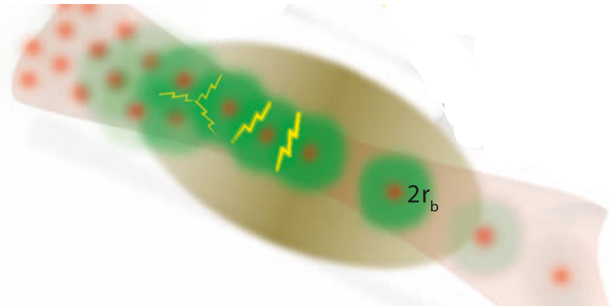


Progress in control of light using Rydberg EIT

Dissipative regime

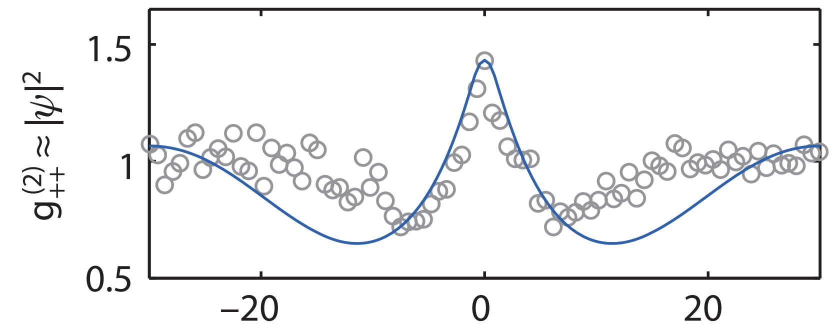


Dissipative anti-bunching
M. Lukin, V. Vuletic (Harvard/MIT)



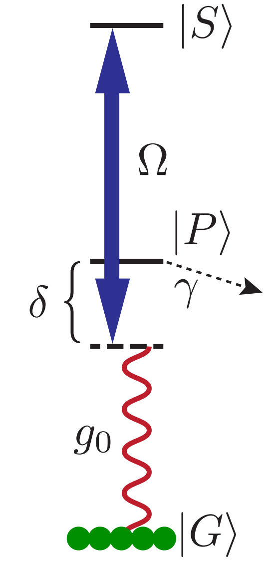
Nature **488**, 58-60 (2012)

- Formation of Bound states
M. Lukin, V. Vuletic (Harvard/MIT)

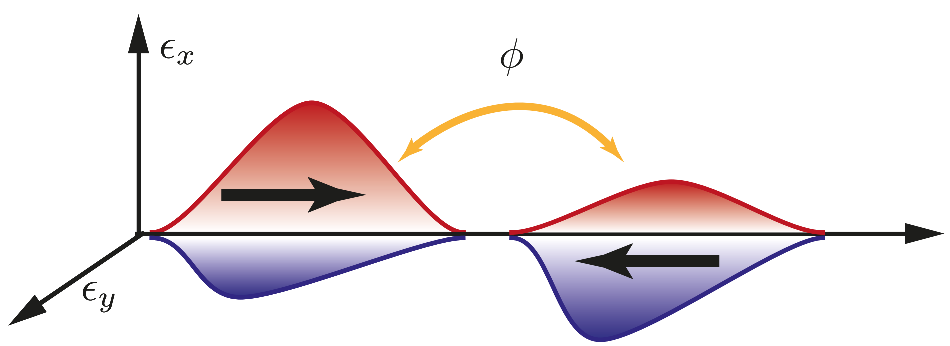


Nature **502**, 71 (2013)

Dispersive regime

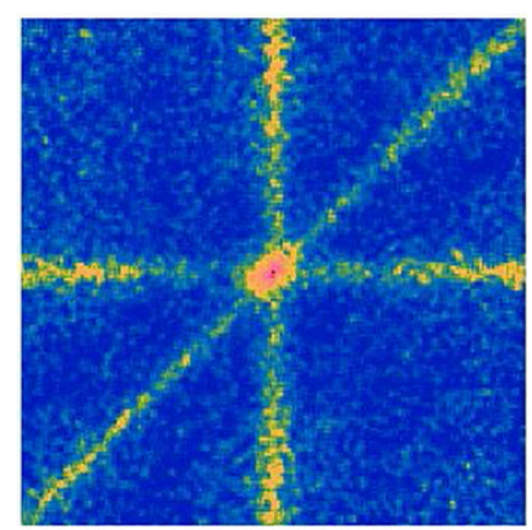


- Steps towards all-optical quantum phase gate
G. Rempe, S. Dürr (Garching)
Ch. Adams (Durham)
M. Lukin, V. Vuletic (symmetry protected)



Thompson et al., Nature (2017)
Tiarks et al., Science Advances (2016)
Busch et al., Nature Physics (2017)

- Three body interactions and bound states
M. Lukin, M. Vuletic (Harvard/MIT)



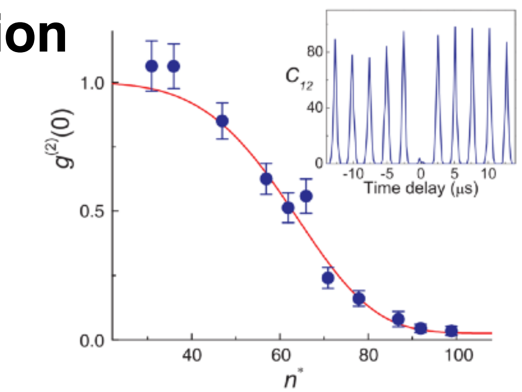
arXiv:1709.01478 (2017)

See also work of:
S. Whitlock, M. Weidemuller, A. Ourjoumtsev, P. Grangier, O. Firstenberg, J. Simon, T. Porto, S. Rolston, A. Kuzmich, S. Hofferberth, and others.

Progress towards single photon source & transistor

- Single-photon generation
A. Kuzmich (Michigan)

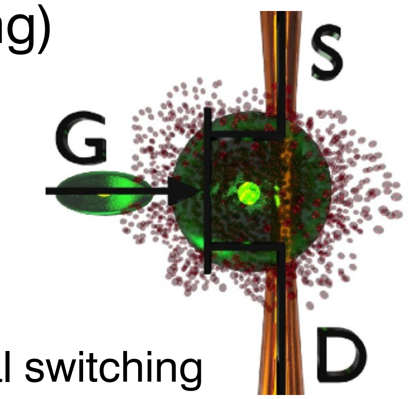
Dudin and Kuzmich, Science (2012)



Switchable medium (transistor)

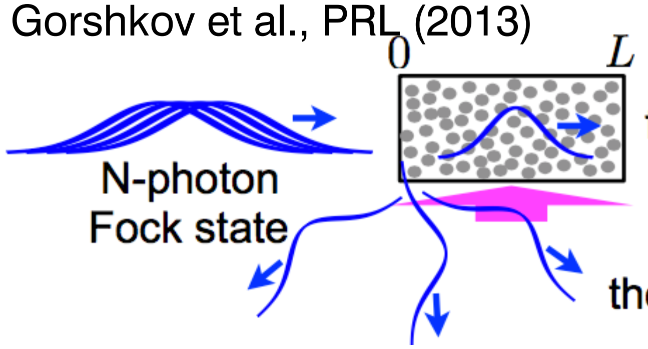
G. Rempe, S. Dürr (Garching)
S. Hofferberth (Stuttgart)

Phys Rev Lett **112**, 073901 (2014)
Phys Rev Lett **113**, 053601 (2014)
Phys Rev Lett **113**, 053602 (2014)



dissipative switching $\Rightarrow$ classical switching

Gorshkov et al., PRL (2013)



first photon goes through

the rest scattered

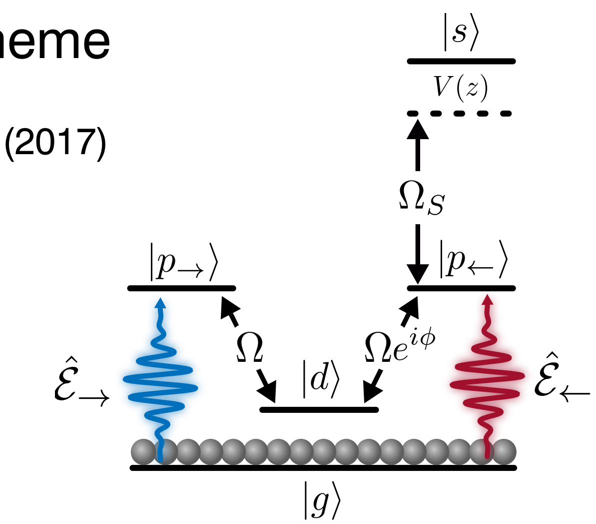
Disadvantages
- Impure (scattered photons carry information and degrade coherence)

Advantages:
+ high repetition
+ deterministic
+ identical photons

Compare with:
- atomic ensembles: Duan et al. Nature (2001)
- nonlinear crystals: Barz et al., Science (2012)
- quantum-dots: Michler et al., Science (2000)

Extensions: Multilevel scheme
C. Murray & T. Pohl (Aarhus)
Phys. Rev. X 7, 031007 (2017)

quantum switch with
~95% is possible!



Coherent (quantum) switching using other systems:

- cavity-QED: target photons back-reflected from the cavity (Chen et al., 2013; Reiserer et al., 2013)
- nanophotonic devices: scattered photons are returned to the well-defined fiber modes (O'Shea et al., 2013; Shomroni et al., 2014; Tiecke et al., 2014)

Challenges

Current state of the art: a few % fidelity

Goal: 99% fidelity

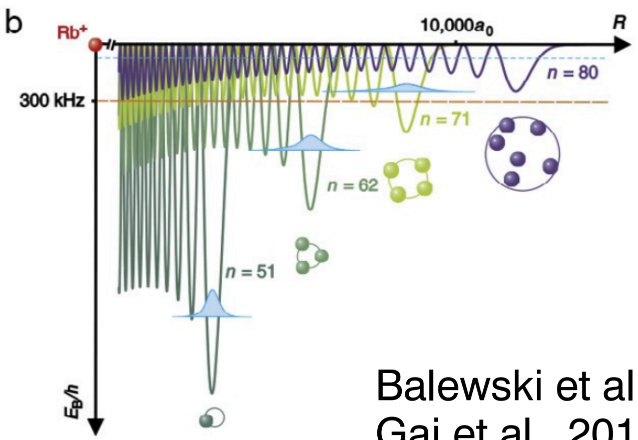
Technical challenges:

- cold dense cloud of atoms
- homogeneous density
- low three-body atomic loss
- low stray electric fields
- laser frequency & polarization stability
- optical mode-matching

Physical limitations:

Most of applications need higher OD_b

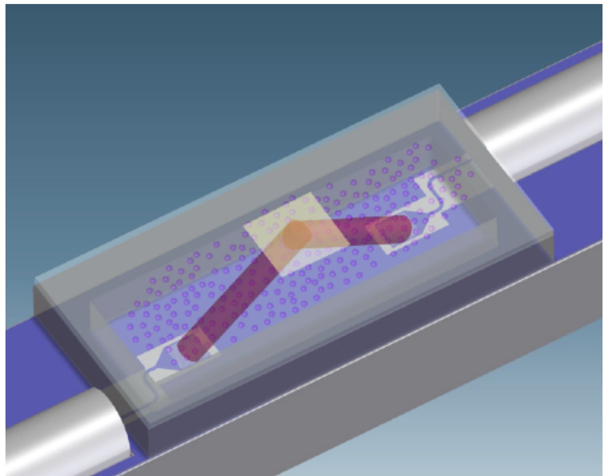
- challenging: formation of exotic long-range molecules ⇒ inhomogeneous broadening of the excitation line



Balewski et al., 2013;
Gaj et al., 2014

Future:

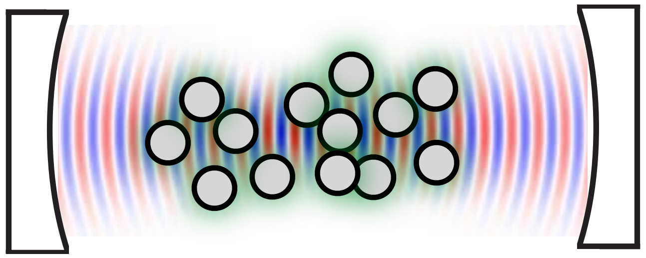
- chip-scale integration



Kartik Srinivasan (NIST)

Solution:

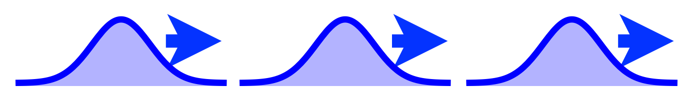
- Rydberg-medium inside an optical cavity ⇒ increase the effective OD_b

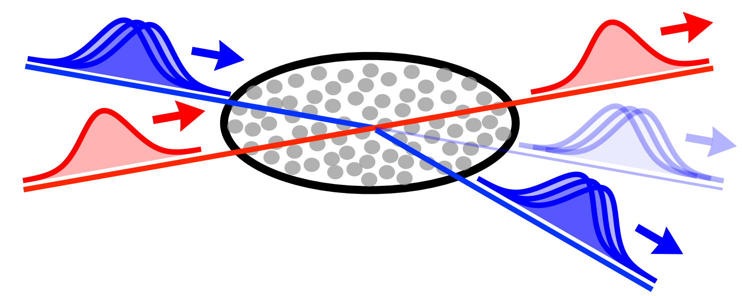


Parigi et al. (2012),
Das et al., (2015),
Borregaard et al., (2015)

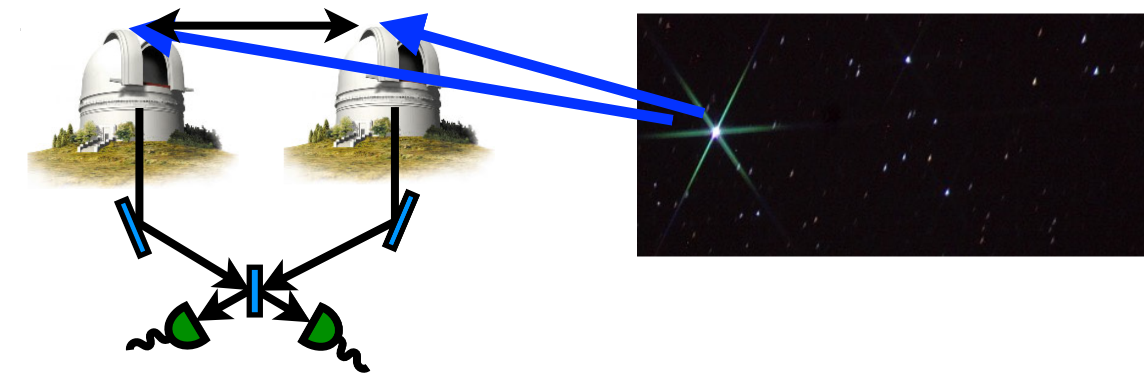
Summary

Rydberg-EIT toolbox for sensing
- single photon source
- quantum transistor

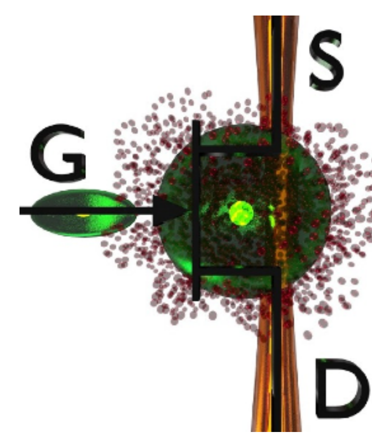


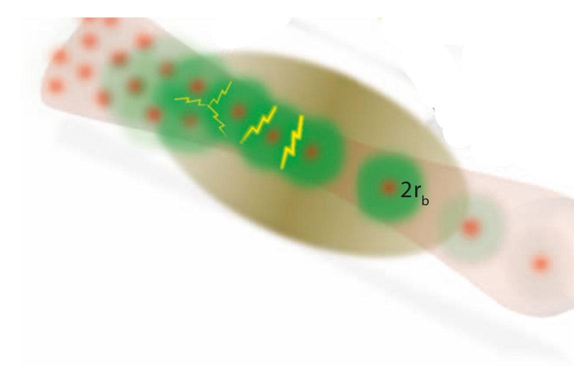


Sensing with interacting photons
- quantum-enhanced: radiometry, interferometry, spectroscopy, time-transfer, imaging



Rydberg-EIT
- many proof-of-principle demonstrations





Future
- address challenges
- explore extensions
- demonstrate sensing applications

Thank you!

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