Quantum Optics

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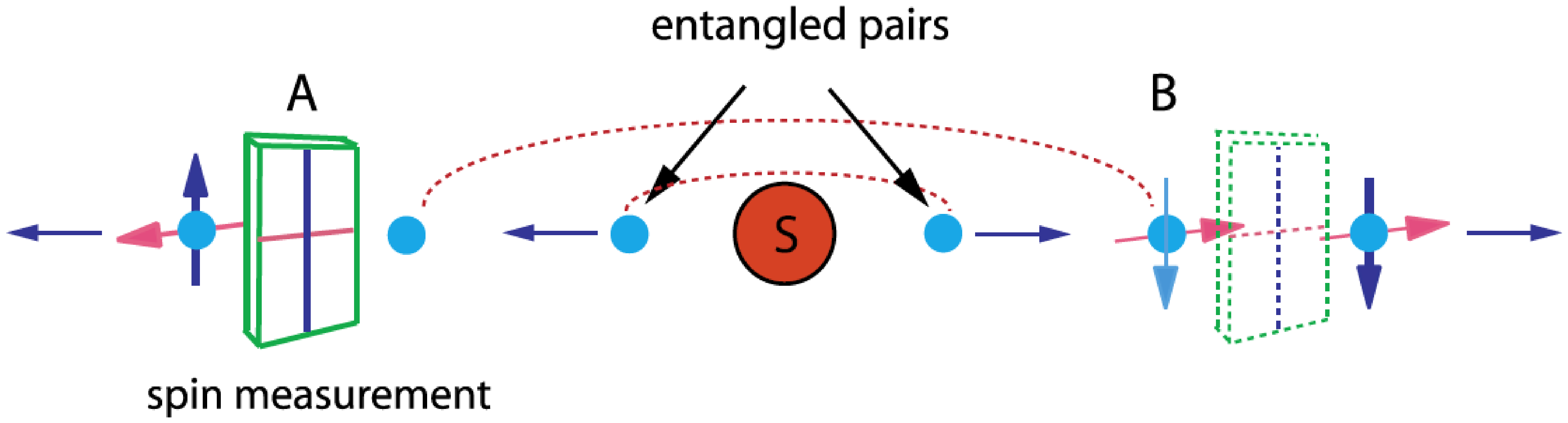
Nobel Prize 2022: Bell inequality experiments

Alain Aspect, John F. Clauser and Anton Zeilinger
“for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science”

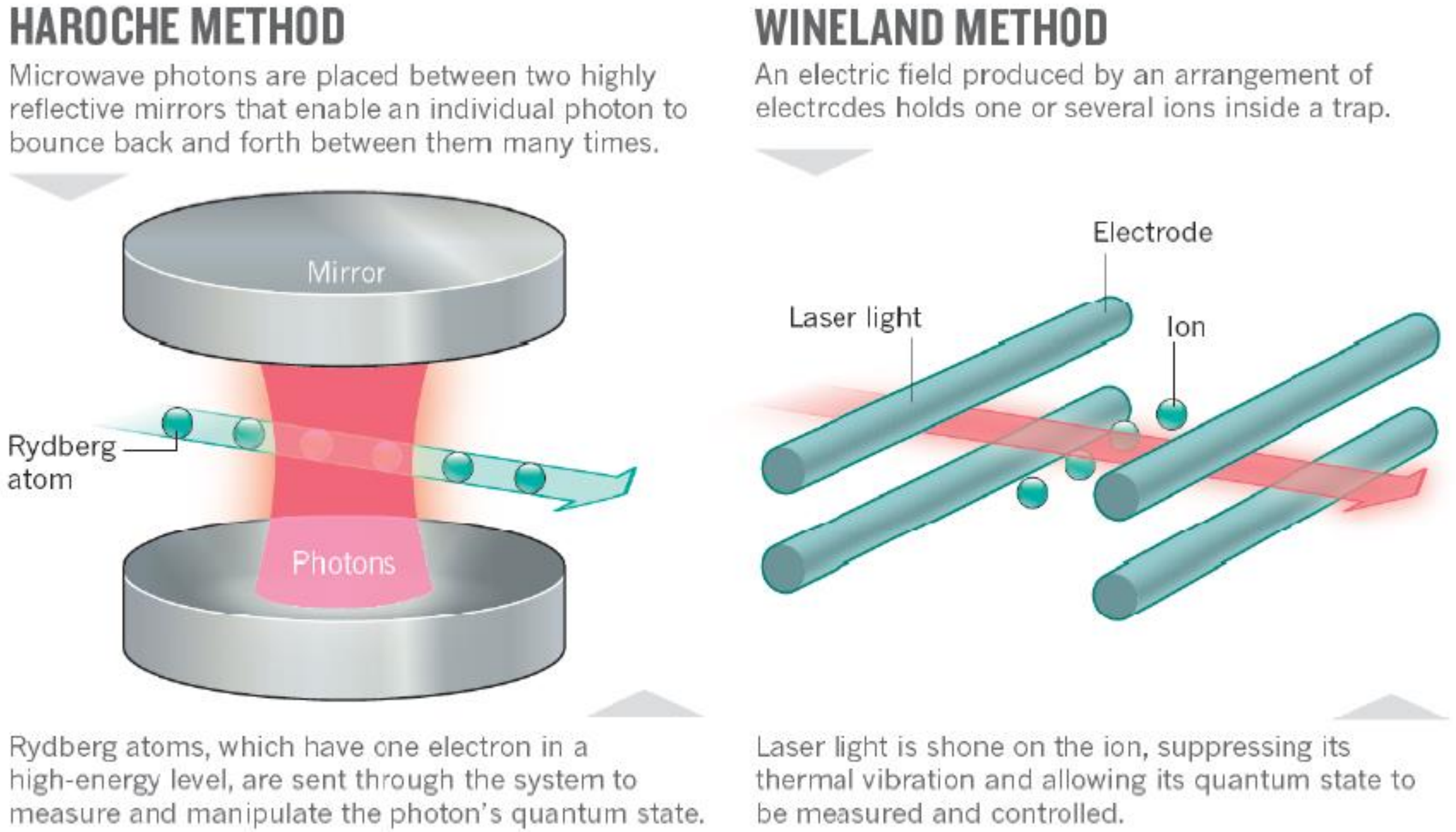


A number for experimental progress since the 70’s:
Fixed measurement axis
Detection efficiency loophole
Light-cone loophole….

Nobel Prize 2012

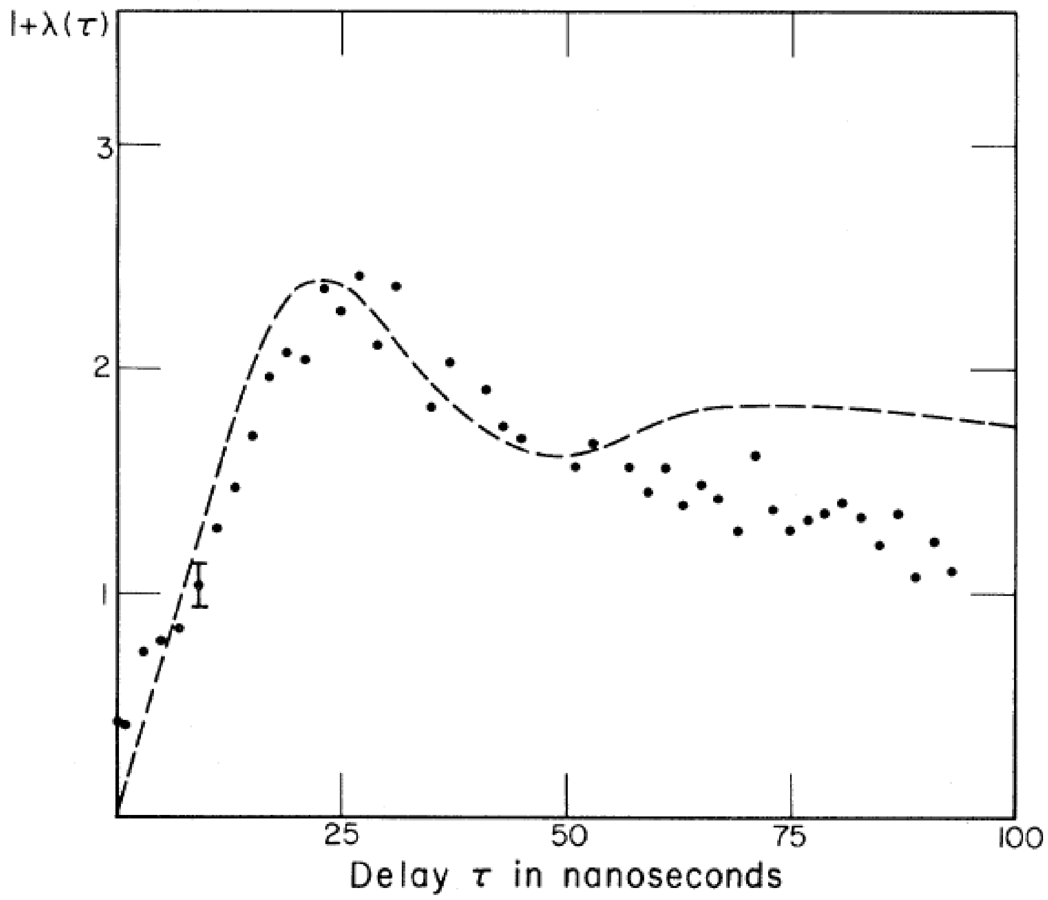
Serge Haroche and David Wineland

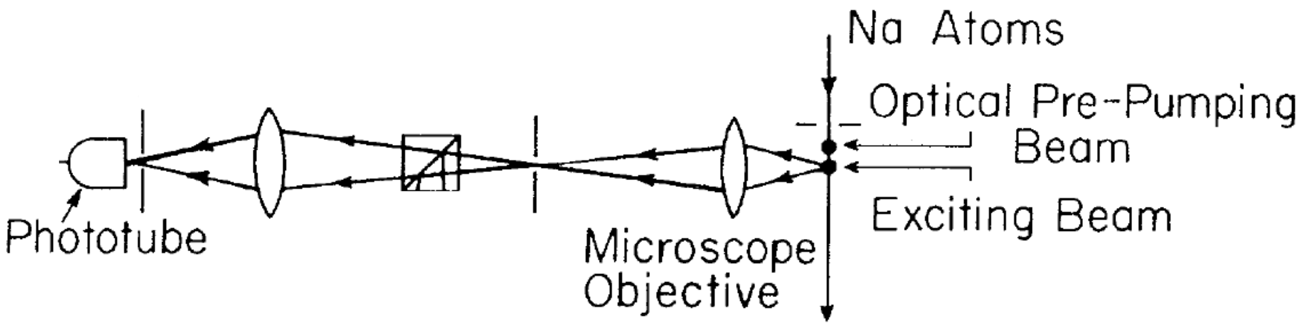
"for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems"



Kimble, Dagenais & Mandel experiment (1977)

Photon Antibunching in Resonance Fluorescence



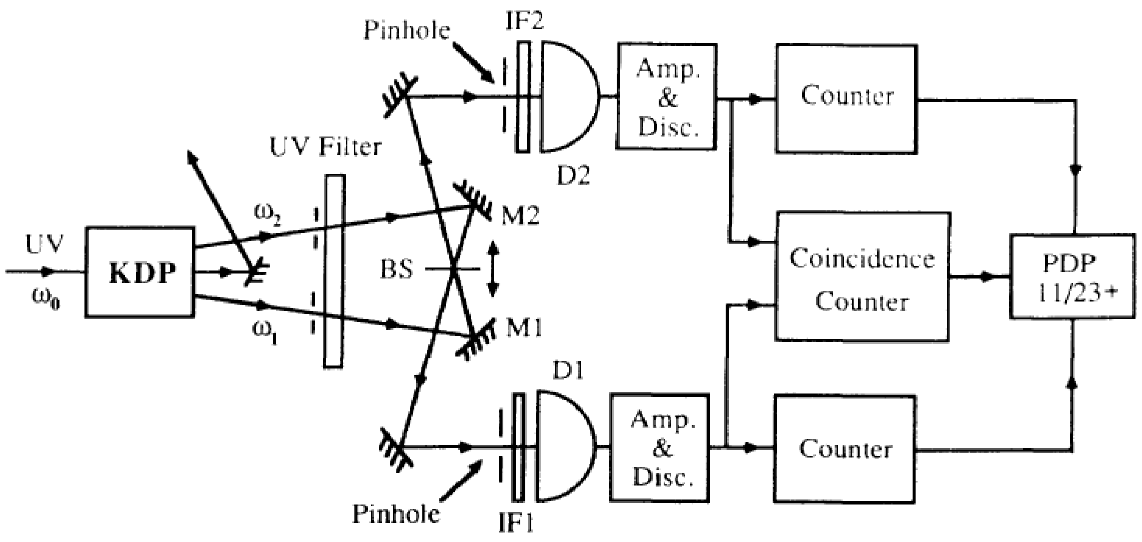


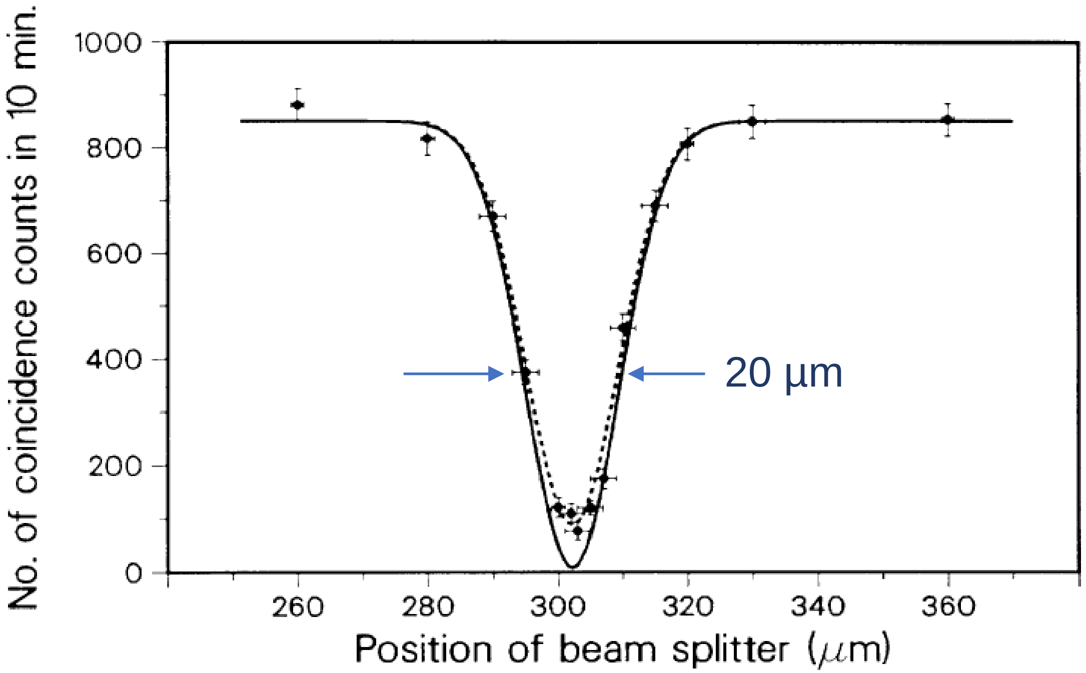
Correlations between successive photon detections
Goes to 0 for t→0 because atom needs first
to absorb a photon to emit one
Typical timescale: atomic lifetime (10s of ns)
Requirement: detection area must be limited to a single atom

Phys. Rev. Lett. ***39****, 691 (1977)*

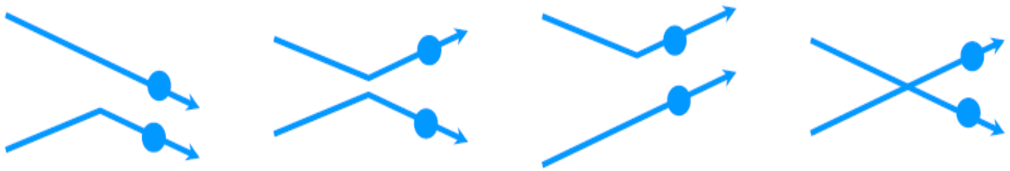
Hong, Ou & Mandel experiment (1987)

Measurement of subpicosecond time intervals between two photons by interference





Interference between the two amplitudes

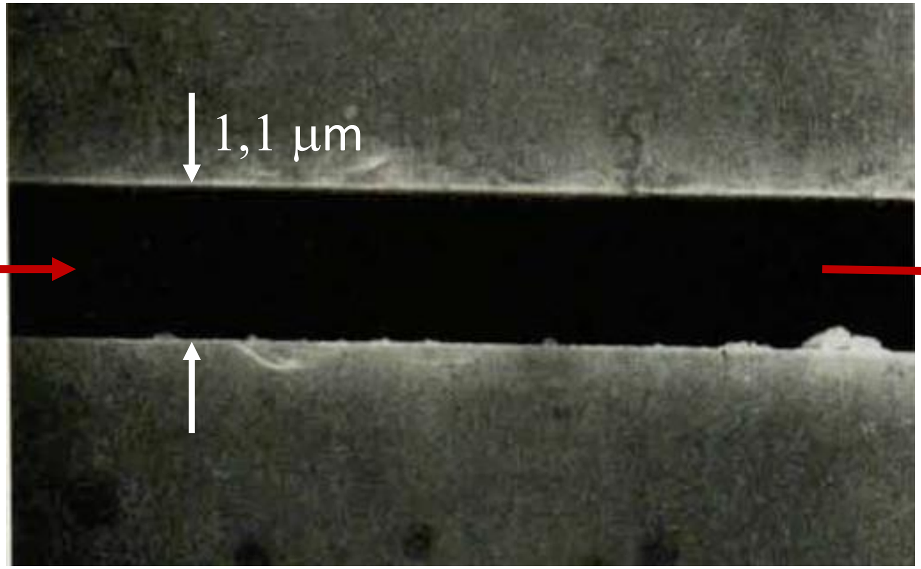


The 20-µm interval
correspond to the typical 100-fs duration
of the photon wavepacket
(limited by the IF filters)

Phys. Rev. Lett. ***59****, 2044 (1987)*

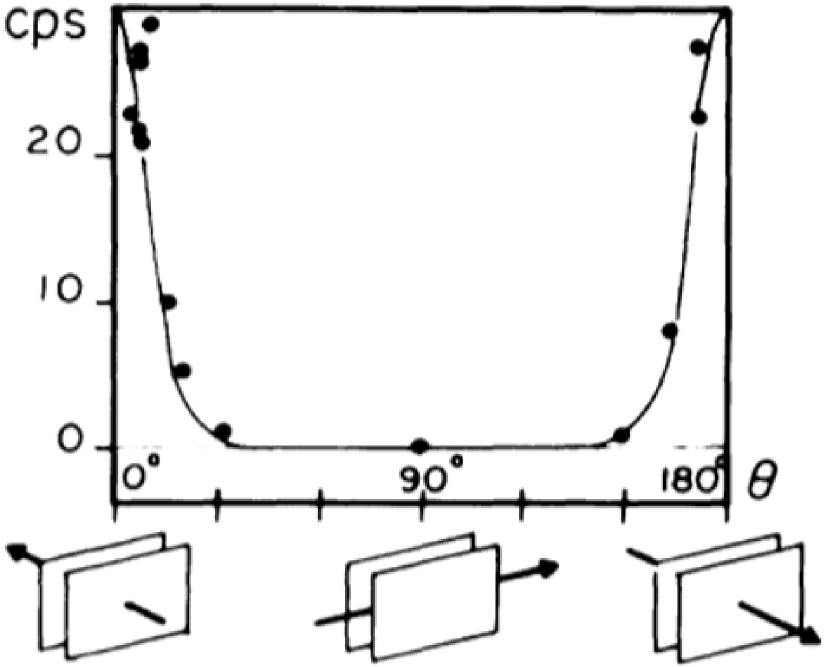
Inhibited spontaneous emission experiment

atoms



detection

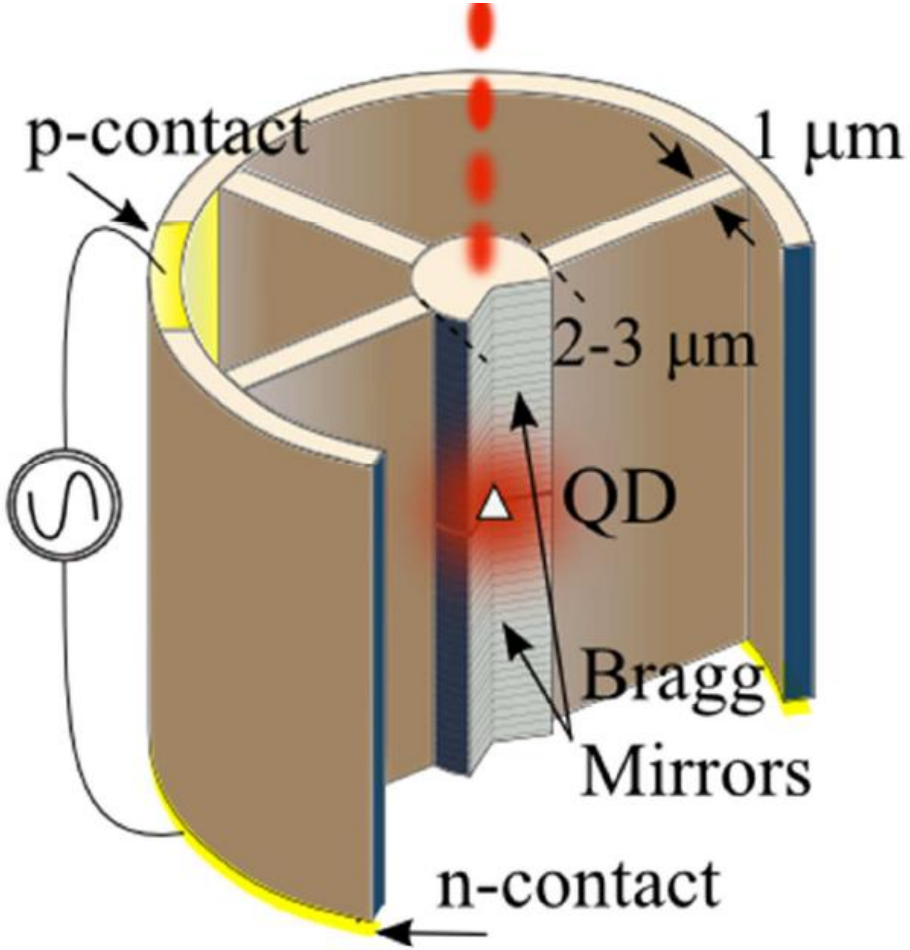
By orienting the atomic dipole, spontaneous emission is inhibited: atoms leave the cavity still excited

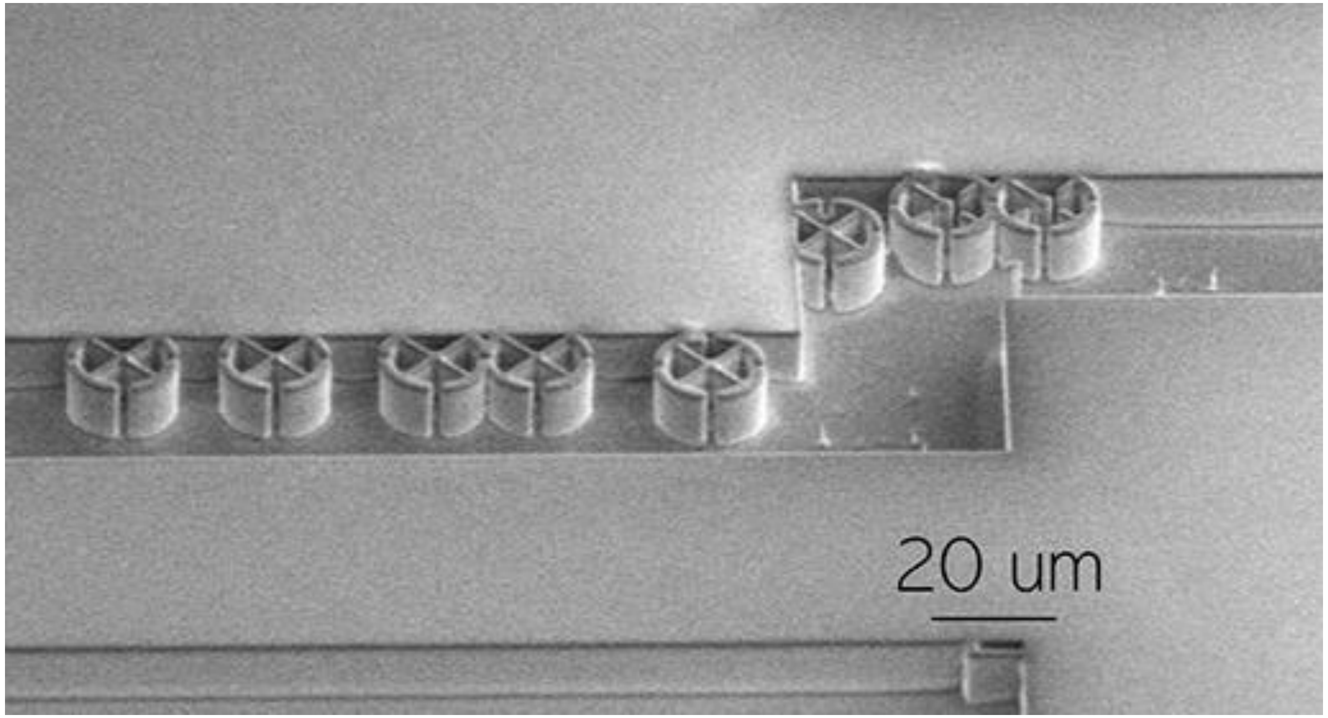


Experience by Serge Haroche (Yale, 1987):
Excited atoms go through a cavity smaller than λ/2

Phys. Rev. Lett. ***58****, 666 (1987)*

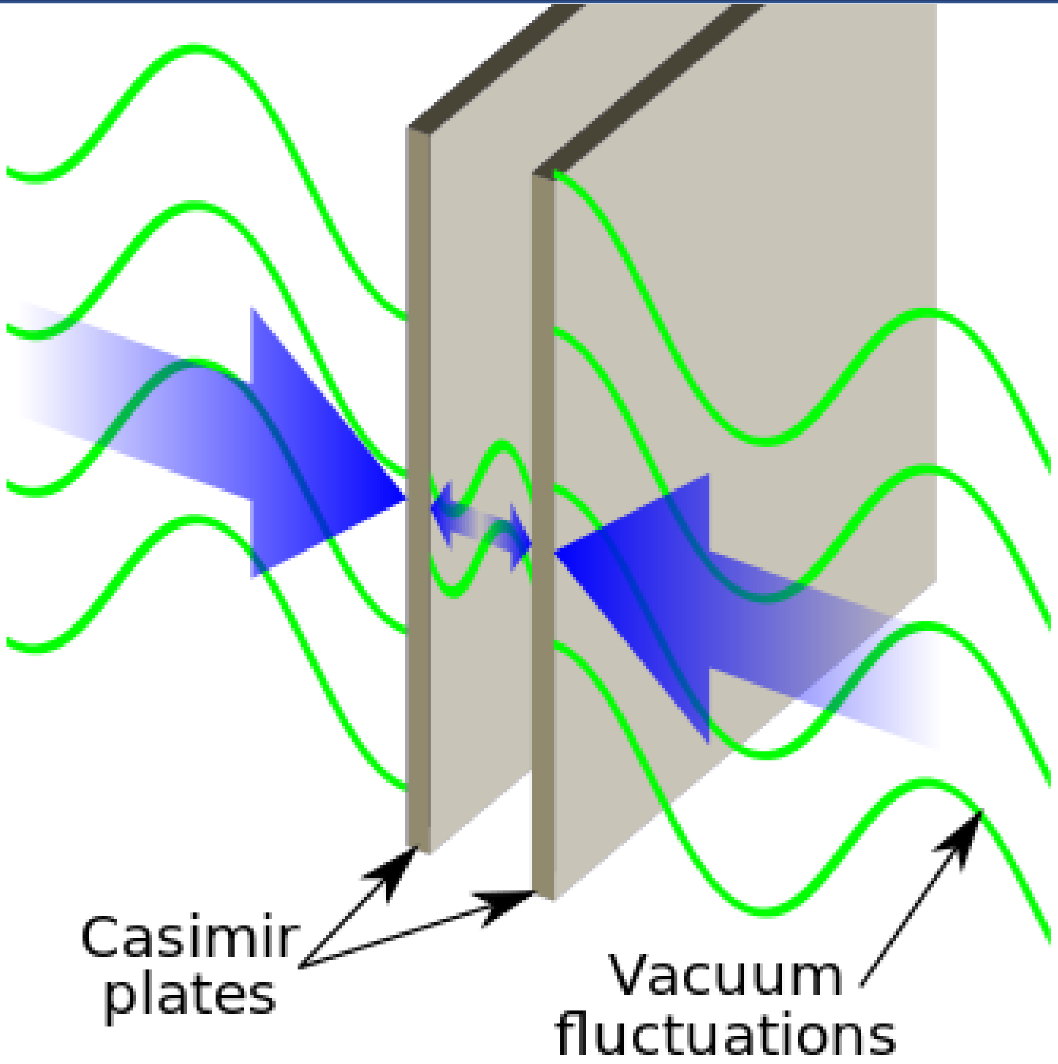
QUANDELA: a quantum start-up company





Quantum Communication and Information
Techniques commercially available

Casimir force



Casimir force (1948)
Two parallel metallic (non-charged) plates apply an attractive force upon each other because of the quantum fluctuations of the electromagnetic field

Imbalance between the modes inside/outside the cavity

$$\frac{F_{\mathrm{Cas}}}{L^2} = \frac{\pi^2}{240}\frac{\hbar c}{d^4}$$

Advanced Virgo: a gravitational-wave interferometer

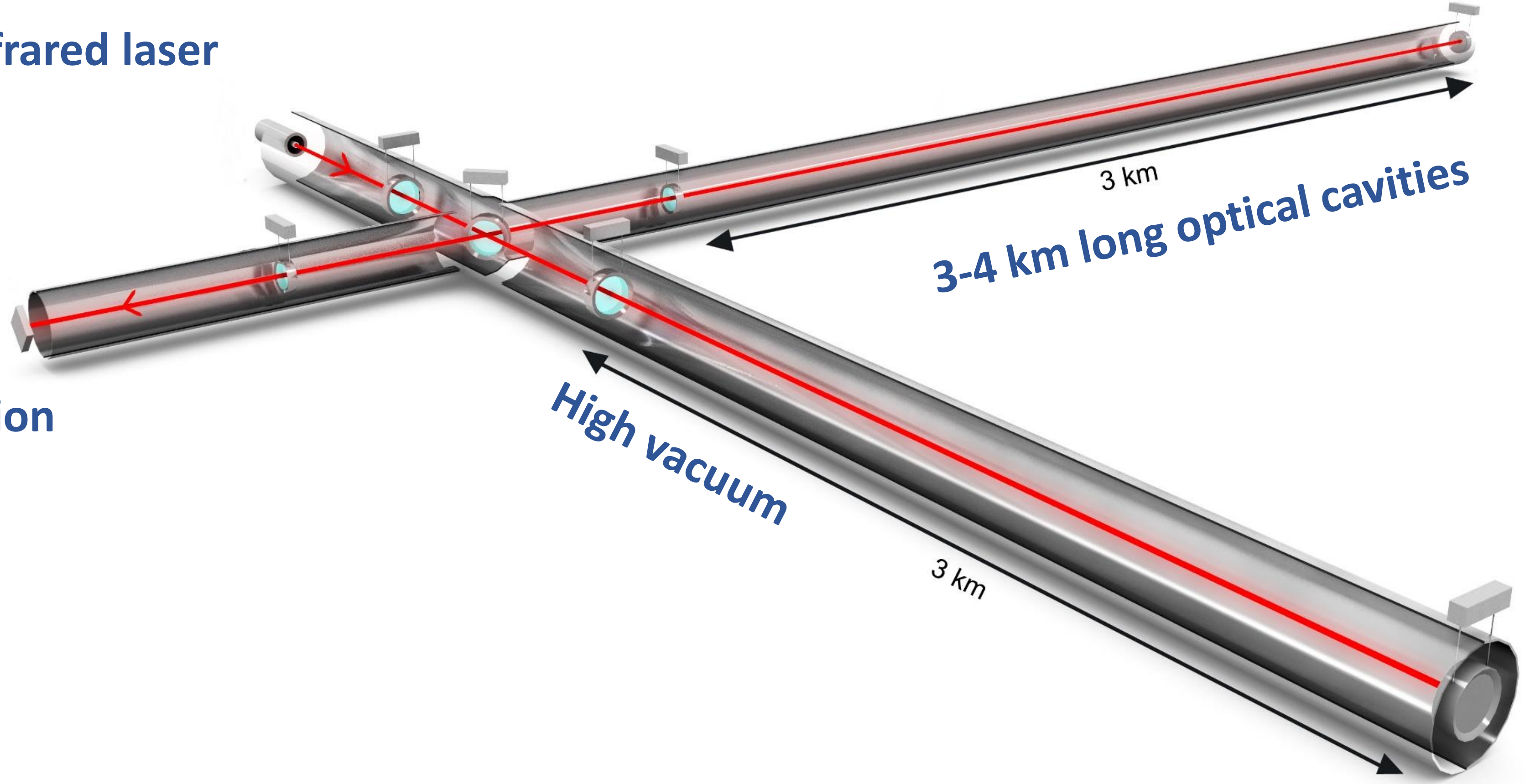
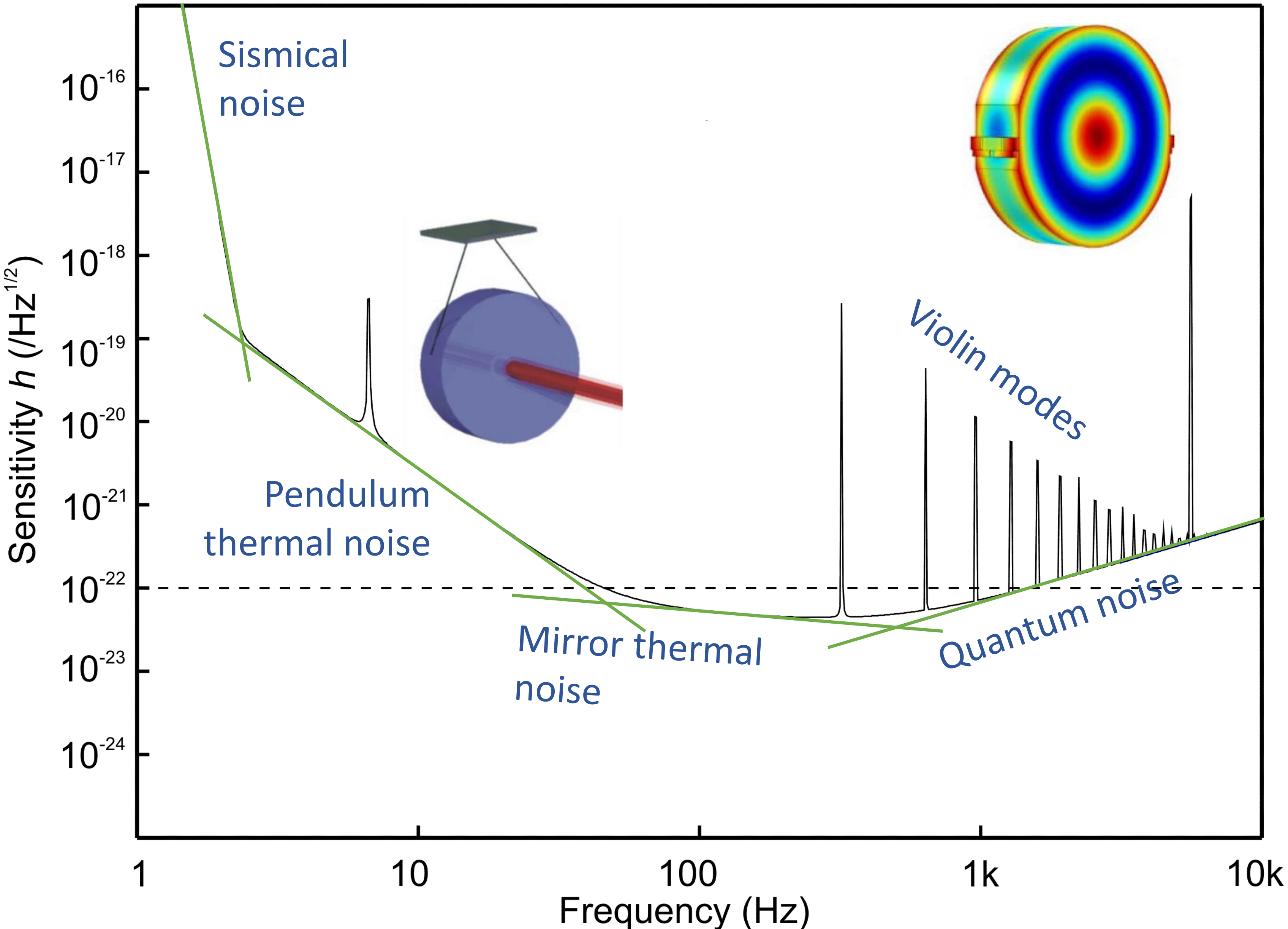
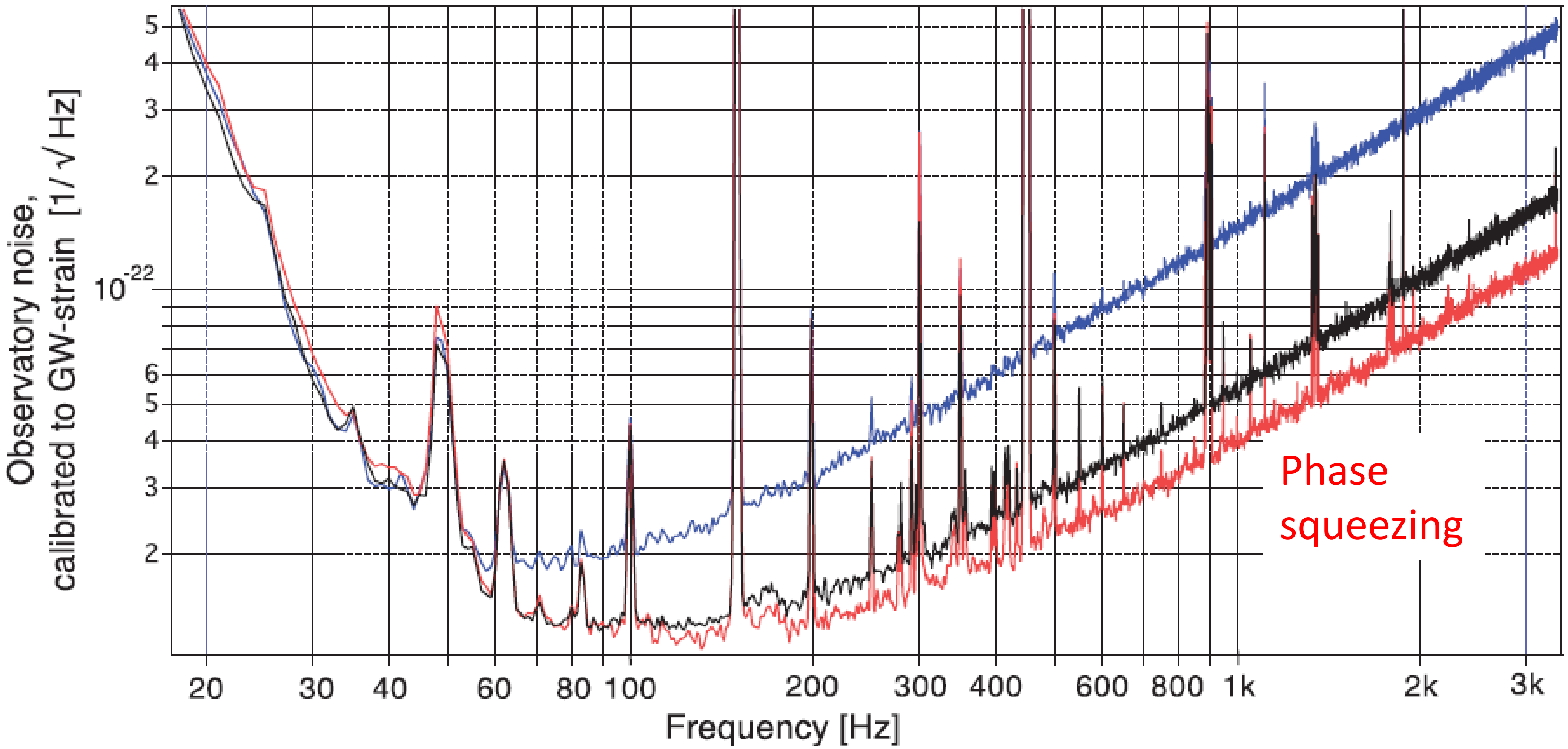


Image credit: CNRS – LAPP Annecy

Typical Virgo sensitivity curve (1st generation, 2007 - 2010)



Quantum noise reduction for Advanced Virgo



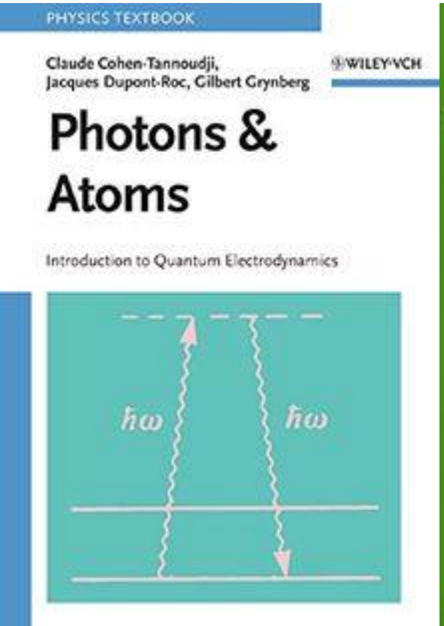
Squeezing quantum noise allows to reduce the noise by a factor 2 at high frequency
No excess noise at lower frequency (classical noise)

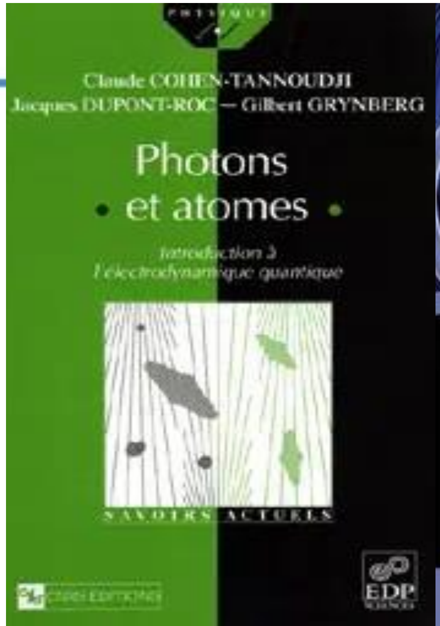
Phys. Rev. Lett. **123**, 231108 (2019)

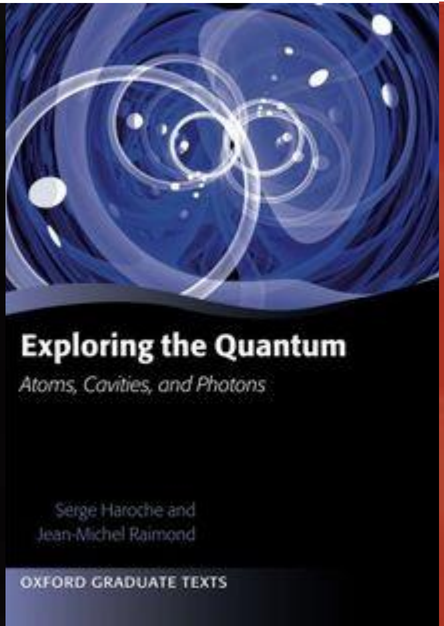
References

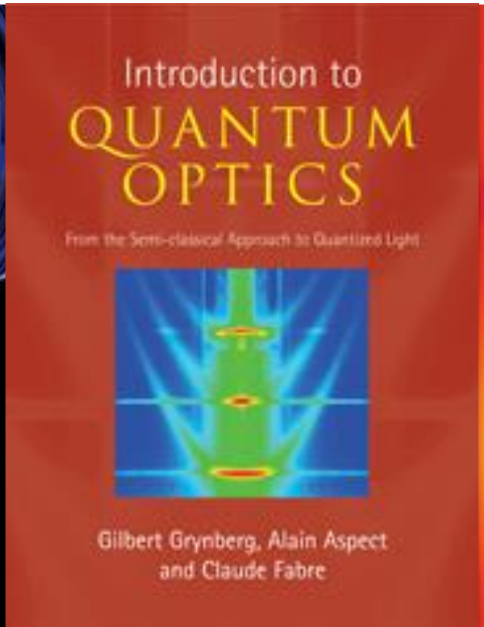
Jean-Michel Raimond, *Atoms and photons*
Lecture notes of the M2 ICFP course (now by Clément Sayrin)
http://www-lpl.univ-paris13.fr/bec/bec/Teaching/m2icfpatomsphotons.pdf

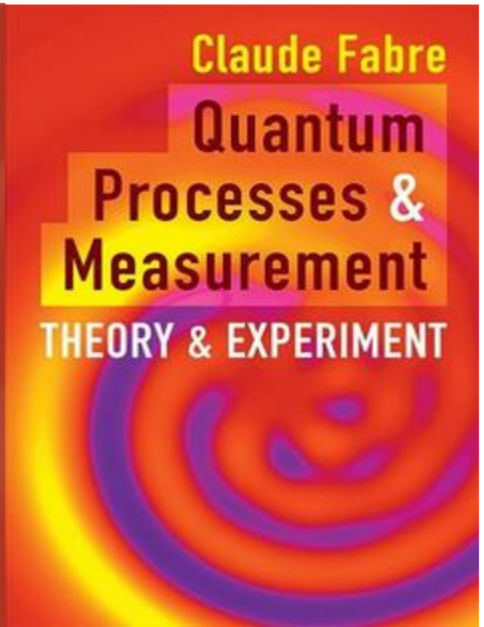
Claude Fabre, *Atomes et lumière – Interaction matière rayonnement*
(similar, but in french)
https://hal-sfo.ccsd.cnrs.fr/sfo-01581964v1
Evolution and Measurement of Quantum States, M1-ICFP course
available on www.phys.ens.fr
(+ a book just published at Cambridge UP)











Online course by Alain Aspect & Michel Brune

Cours | École Polytechnique

Quantum Optics 1 : Single Photons

Excellent online course (also with Quantum Optics 2 : Two photons and more)
Videos, quizzes and homeworks
www.coursera.org

Topics

Introduction:	
Examples of harmonic oscillators and TLS	
Chap 1: Field Quantization	Canonical quantization
Chap 2: Quantum states of the field	Different characterizations:
Vacuum, Fock states, squeezed states…	Wavefunction, density matrix, Wigner function…
Chap 3: Coupling of a quantum mode to a TLS	Quasi-classical and quantum regimes
Rabi oscillations, QND measurement	State estimation
Chap 4: Coupling of two Q modes	Heisenberg picture
Hong-Ou-Mandel experiment	
Chap 5: The mode continuum	
Spontaneous emission, Casimir force…	
Chap 6: Q description of a laser beam	Combining Q concepts with real experiments
Chap 7: Quantum Sensing	Open systems and Quantum Langevin equations
Radiation-pressure Noise and the SQL,	Squeezing with Nonlinear optics
application to GW interferometers	

Organization

	8h30 - 10h30	10h45 - 12h45
Sep 4th	Introduction: Examples of harmonic oscillators and two-level systems	Exercise 1: Introduction and properties of Wigner functions
	Chapter 1: Field Quantization	
Sep 11th	Chapter 2: Quantum states of the field	Exercise 2: Quantum LC-circuits; Transmon and Fluxonium qubits
	Vacuum, Fock states, coherent states, squeezed states, non-gaussian states	
Sep 18th	Chapter 3: Coupling of a Quantum mode to a TLS	Ex 3: Q squeezed states of trapped cold Cs atoms
	Generic Hamiltonian, dressed atom formalism	
	Resonant interaction: Rabi oscillations, generation of cat states	
Sep 25th	Detuned (dispersive) Interaction	Chapter 4: Coupling of two Quantum modes
	QND measurement of a cavity field	Beamsplitter interaction
Oct 2nd	Chapter 5: The Q continuum	Ex 4: Coupling of a TLS to a mechanical resonator
	Spontaneous emission, The Casimir force, Q mechanical effects in chemistry	
Oct 9th	Chapter 6: Q description of a laser beam	Ex 5: Introduction to decoherence
Oct 16th	Chapter 7: Quantum Sensing	Ex 6: Measurement of a Wigner function
	Quantum Radiation Pressure Noise and the Standard Quantum Limit	
	Squeezed light applications	
Oct 23rd	Ex 7: The Standard Q Limit	Ex 8: Vacuum squeezing generation

Exercise sessions with Alexandre
are an essential part of the course
Texts will be given with a 1-week delay
for you to work on it
Most (possibly all) texts will be associated
with (at least) on research article

(Handwritten) lecture notes
Slides used during the lectures
Exercise notes
Related articles
Documents…
will be available on the course moodle

https://moodle.psl.eu/course/view.php?id=27664

Organization (and validation)

	8h30 - 10h30	10h45 - 12h45	Homework
Sep 4th	Introduction: Examples of harmonic oscillators and two-level systems	Exercise 1: Introduction and properties of Wigner functions	python notebook to be emailed
	Chapter 1: Field Quantization		to alexandre.journeaux@lkb.ens.fr
Sep 11th	Chapter 2: Quantum states of the field	Exercise 2: Quantum LC-circuits; Transmon and Fluxonium qubits	
	Vacuum, Fock states, coherent states, squeezed states, non-gaussian states		
Sep 18th	Chapter 3: Coupling of a Quantum mode to a TLS	Ex 3: Q squeezed states of trapped cold Cs atoms	(Ex 2) Phys Rev X 2024 : Heavy fluxonium Qubit
	Generic Hamiltonian, dressed atom formalism		
	Resonant interaction: Rabi oscillations, generation of cat states		
Sep 25th	Detuned (dispersive) Interaction	Chapter 4: Coupling of two Quantum modes	(Ex 3) PRL 1999 : Squeezed states of Cs atoms
	QND measurement of a cavity field	Beamsplitter interaction	
Oct 2nd	Chapter 5: The Q continuum	Ex 4: Coupling of a TLS to a mechanical resonator	
	Spontaneous emission, The Casimir force, Q mechanical effects in chemistry		
Oct 9th	Chapter 6: Q description of a laser beam	Ex 5: Introduction to decoherence	(Ex 4) Nature 2010 : Quantum Ground State
			of a mechanical resonator
Oct 16th	Chapter 7: Quantum Sensing	Ex 6: Measurement of a Wigner function	(Ex 5) To be announced
	Quantum Radiation Pressure Noise and the Standard Quantum Limit		
	Squeezed light applications		
Oct 23rd	Ex 7: The Standard Q Limit	Ex 8: Vacuum squeezing generation	(Ex 6) Nature 2023 : cat-state of a mechanical resonator
Nov 4th			(Ex 7) Nature 2018 :
			SQL of a nanomechanical membrane

You are expected to work
(fits of experimental data, python codes…)
on the results discussed in the articles
and email a notebook to Alexandre 2 weeks
later (at most)

Your best 3 notebooks
will be used to validate
the course
(details to be discussed later)