Photonics
Q-Ex-2

Randolf Pohl
SoSe 2023

Tue 12:15-13:45 HS KPH
Thu 12:15-13:45 HS KPH
Thu Apr. 27: Sem 1 KPH

pohl@uni-mainz.de

Organization

- Language: German or English?
- Dates/Times for Lectures: 12:15 ok?
- 3 Lectures + 1 Exercises, on average
  - plan: 90 minutes exercise / lab / seminar every 2 weeks
  - problem sheets, papers
  - work in my lab
- Dropbox / Seafile
  - email into list
  - send me an email:
- Oral exams

Who am I?

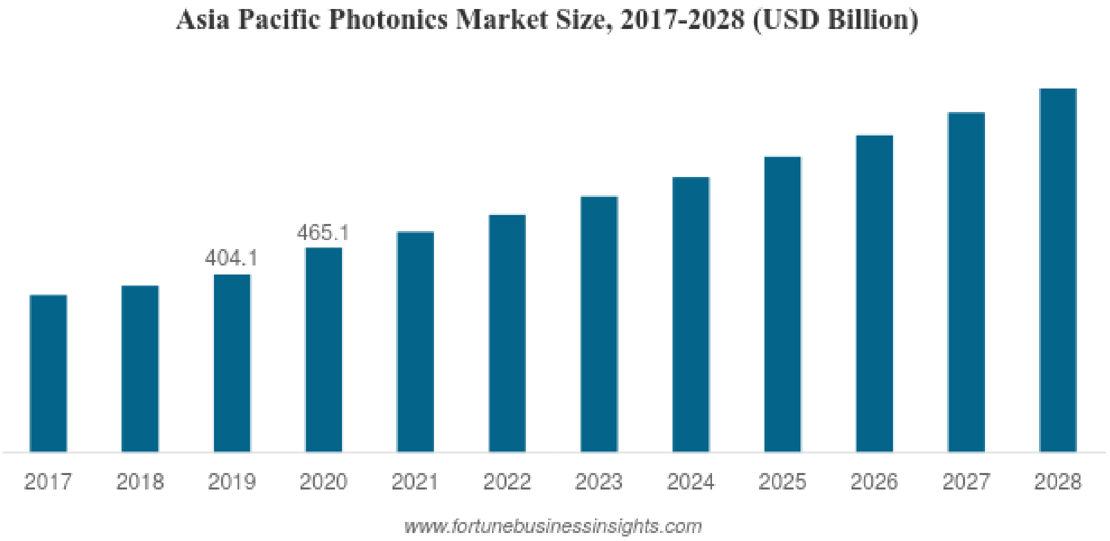
And YOU?

- Who are you?
- When did you hear Ex-Phys 5a (lecturer?)
- Topic of your Bachelor thesis
- Why are you here?
  What are your expectations?
- Special interests? Suggestions for topics?
  always: email to pohl@uni-mainz.de
-

Photonics (Wikipedia)

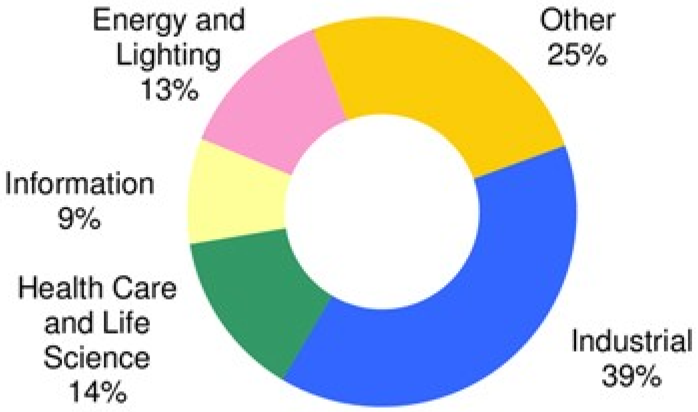
- Photonics is the physical science of **light (photon) generation**, **detection**, and **manipulation** through emission, transmission, modulation, signal processing, switching, amplification, and detection/sensing.[1][2] Though covering all light's technical applications over the whole spectrum, most photonic applications are in the range of visible and near-infrared light. The term photonics developed as an outgrowth of the first practical semiconductor light emitters invented in the early 1960s and optical fibers developed in the 1970s.

Photonics industry


Asia Pacific Photonics Market Size, 2017-2028 (USD Billion)

www.fortunebusinessinsights.com

European Photonics Production Volume 2014, by Product Segment



60 billion EUR in 2014 (3% annual growth)
2012 depression: meltdown of European photovoltaic industry (Asia)
39% industrial photonics (materials processing, lithography, image processing, …)
14% health care and sciences
13% energy and lightning
9% optical information and communication
25% optical and opto-electronic components and systems

http://optics.org/news/6/1/40

Contents of this lecture

(dynamic, this is just a proposal!)

- Intro (Refresh)
  - Atomic physics, light-atom interaction (optical Bloch equations, Rabi oscillations, Ramsey method)
- Absorption and Emission of light
  - Black body radiation, Einstein coefficients
  - classical and semi-classical description
- Spectral lines:
  - natural line width, line strength
  - AC Stark shift (light shift), DC Stark shift, Zeeman shift, ….
  - broadening mechanisms: Doppler, time-of-flight, pressure, …
- Lasers
  - types of lasers: Ruby, HeNe, YAG, Ti:Sapphire, diode laser, fiber laser, …
  - principles of operation, technical realization
- Resonators / Cavities
- Gaussian optics
- Laser stabilization
  - locking techniques: side-of-fringe, Hänsch-Couillaud, Pound-Drever-Hall, ...
- Optical devices: EOM, AOM, beat signals, mixer, spectrum analyzer, ...
- Frequency comb
- Non-linear optics: SHG, THG, SFG, DFG, OPO, ...
- Laser spectroscopy: (Saturated) absorption spectroscopy, Doppler-free spectroscopy,
- Trapping of atoms and ions (MOT, Penning traps, ….)
- Precision measurements and fundamental constants
- ……...
- And whatever else YOU want to hear about

Literature

* W. Demtröder, Laser Spectroscopy 1 & 2
(German version online on library web site)

* C.J. Foot: Atomic Physics

* H.J. Metcalf & P. van der Straten: Laser Cooling and Trapping

* P. van der Straten & H.J. Metcalf: Atoms and Molecules Interacting with Light

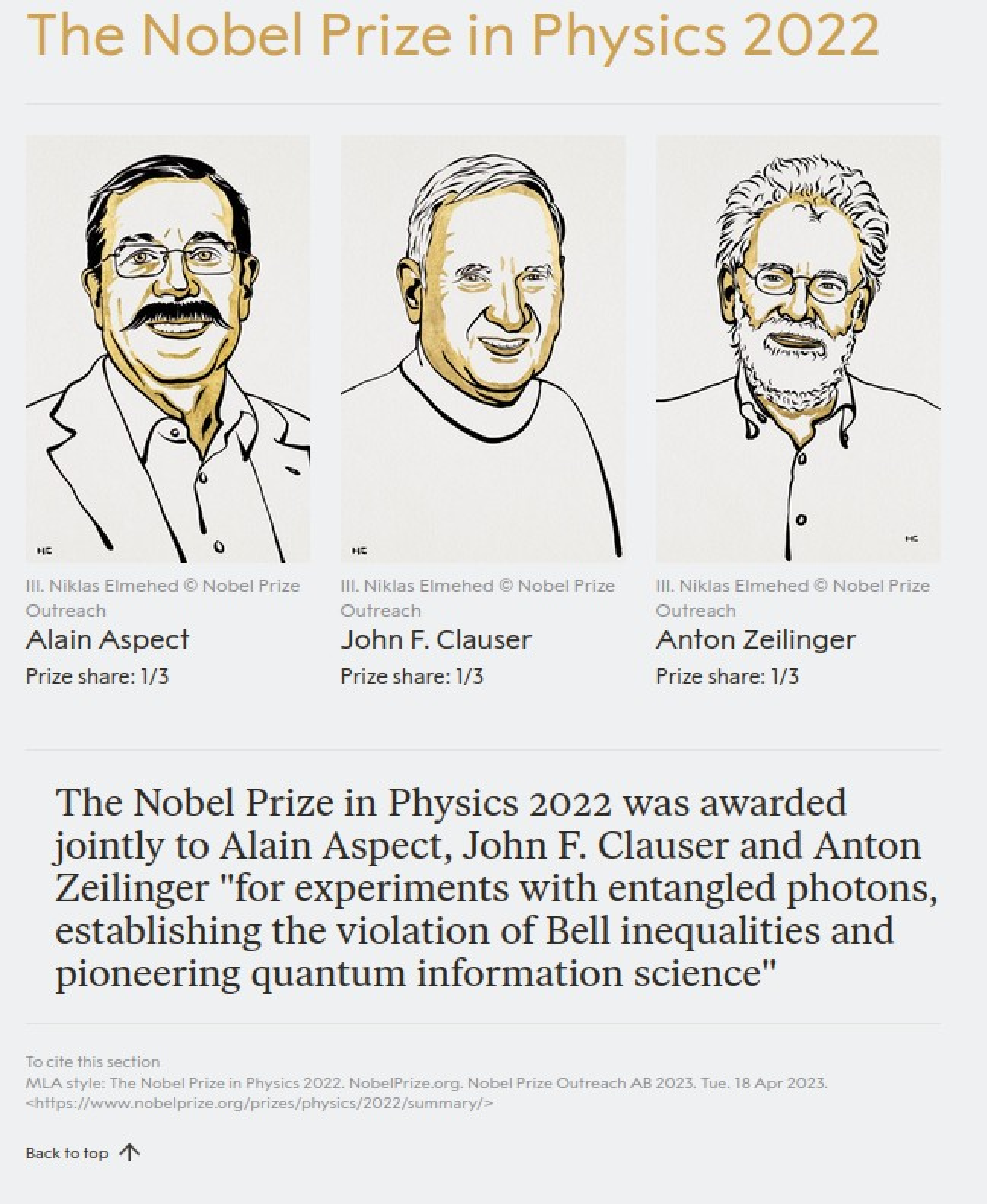
* A. Siegman: Lasers

* R. Boyd: Nonlinear Optics

* Saleh & Teich: Fundamentals of Photonics

* M. Fox: Quantum Optics – an Introduction

I will try to mention which book I used to prepare a topic



The Nobel Prize in Physics 2022

III. Niklas Elmehed © Nobel Prize Outreach

Alain Aspect

Prize share: 1/3

III. Niklas Elmehed © Nobel Prize Outreach

John F. Clauser

Prize share: 1/3

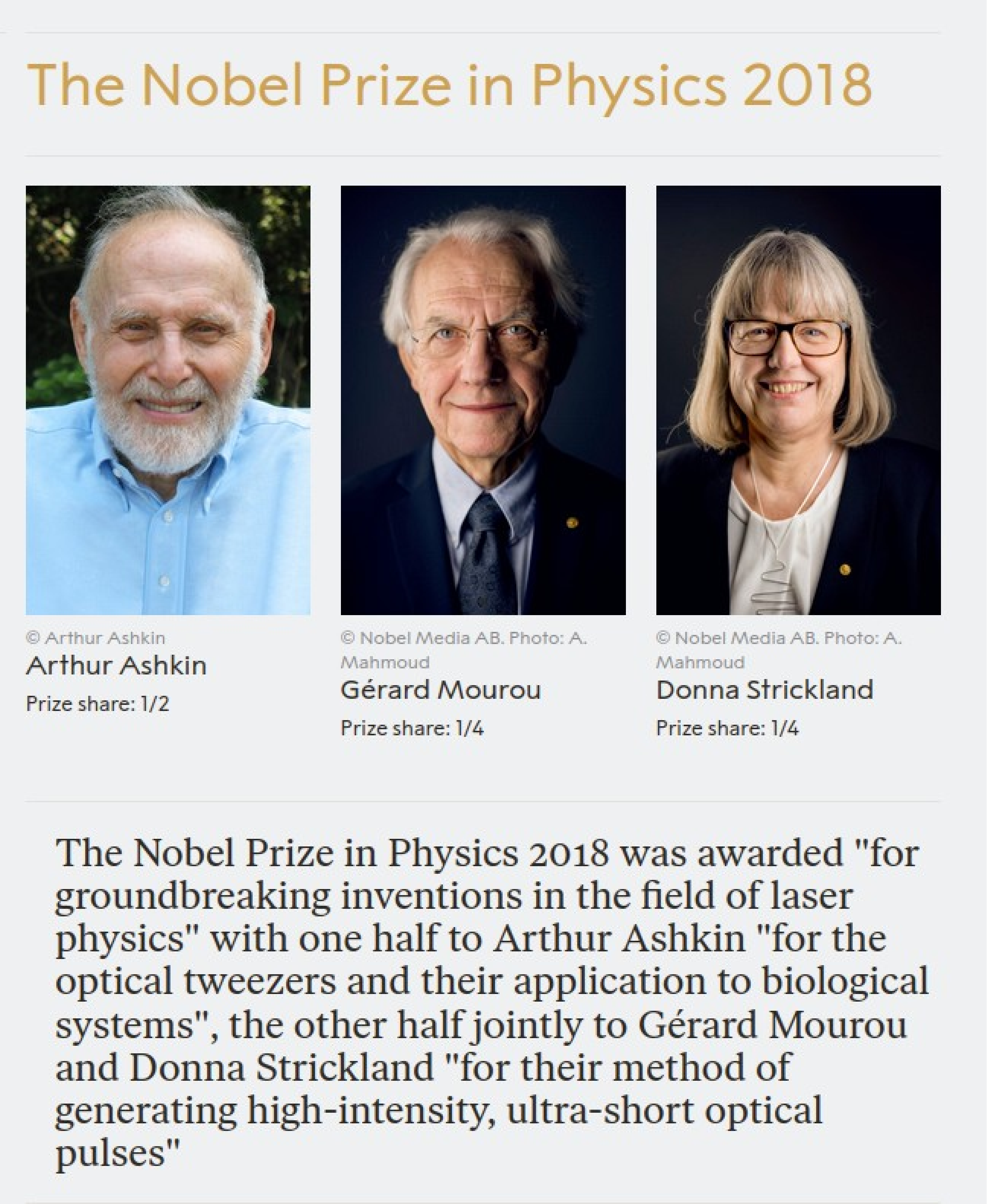
III. Niklas Elmehed © Nobel Prize Outreach

Anton Zeilinger

Prize share: 1/3

The Nobel Prize in Physics 2022 was awarded jointly to Alain Aspect, John F. Clauser and Anton Zeilinger "for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science"

To cite this section
MLA style: The Nobel Prize in Physics 2022. NobelPrize.org. Nobel Prize Outreach AB 2023. Tue. 18 Apr 2023. <https://www.nobelprize.org/prizes/physics/2022/summary/>



The Nobel Prize in Physics 2018

© Arthur Ashkin

Arthur Ashkin

Prize share: 1/2

© Nobel Media AB. Photo: A. Mahmoud

Gérard Mourou

Prize share: 1/4

© Nobel Media AB. Photo: A. Mahmoud

Donna Strickland

Prize share: 1/4

The Nobel Prize in Physics 2018 was awarded "for groundbreaking inventions in the field of laser physics" with one half to Arthur Ashkin "for the optical tweezers and their application to biological systems", the other half jointly to Gérard Mourou and Donna Strickland "for their method of generating high-intensity, ultra-short optical pulses"

The Nobel Prize in Physics 2017


Photo: Bryce Vickmark

Rainer Weiss

Prize share: 1/2

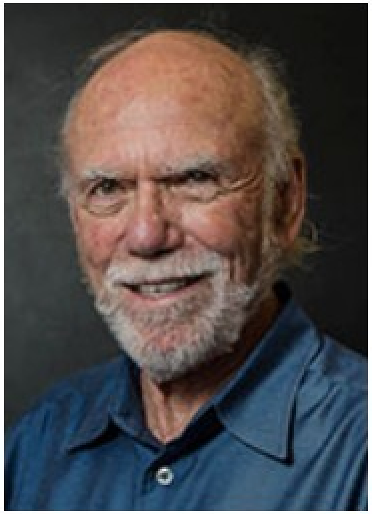


Photo: Caltech

Barry C. Barish

Prize share: 1/4


Photo: Caltech Alumni Association

Kip S. Thorne

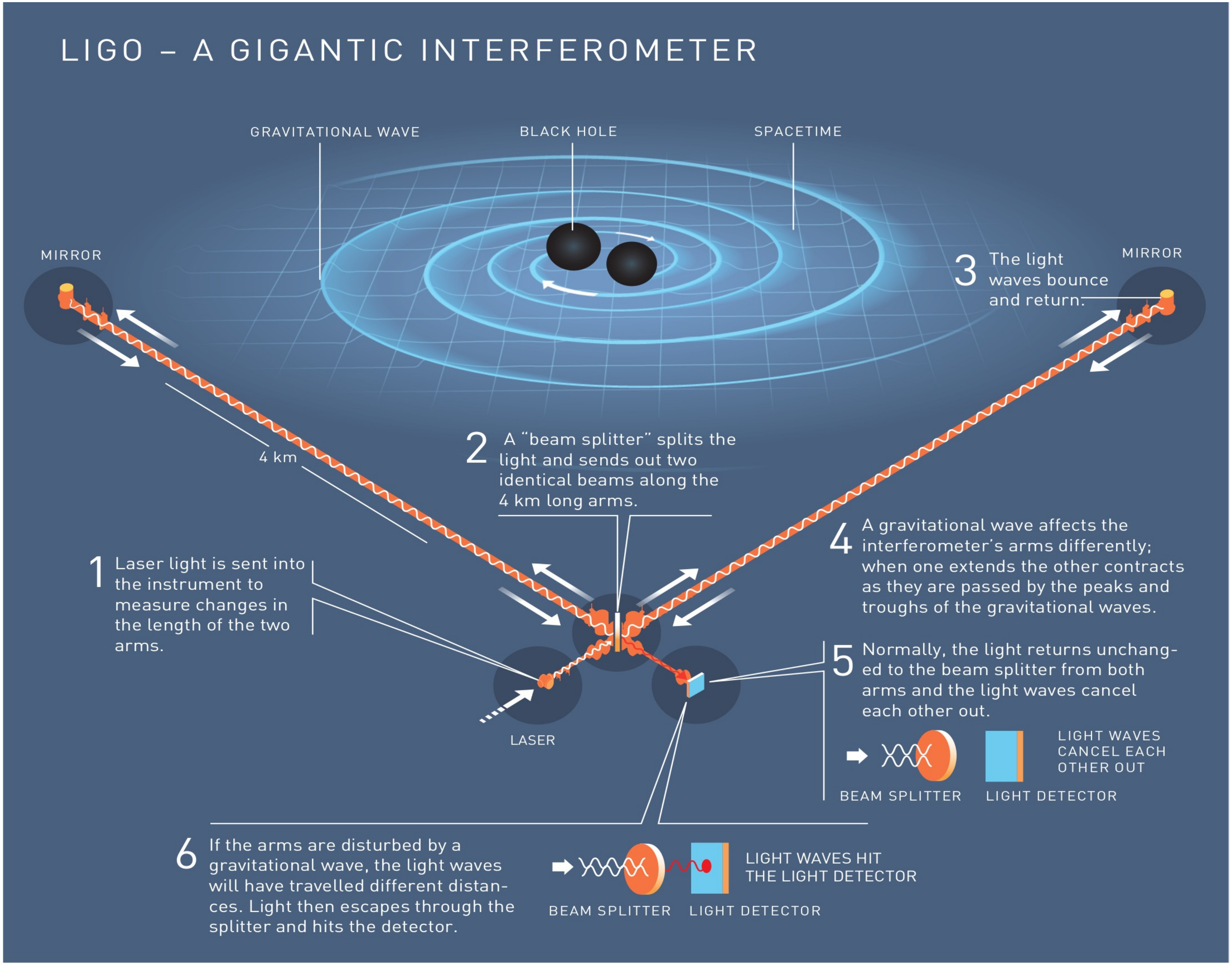
Prize share: 1/4

The Nobel Prize in Physics 2017 was divided, one half awarded to Rainer Weiss, the other half jointly to Barry C. Barish and Kip S. Thorne *"for decisive contributions to the LIGO detector and the observation of gravitational waves"*.

LIGO

www.nobelprize.org

Laser **I**nterferometer **G**ravitational-Wave **O**bservatory



LIGO – A GIGANTIC INTERFEROMETER

1 Laser light is sent into the instrument to measure changes in the length of the two arms.

2 A "beam splitter" splits the light and sends out two identical beams along the 4 km long arms.

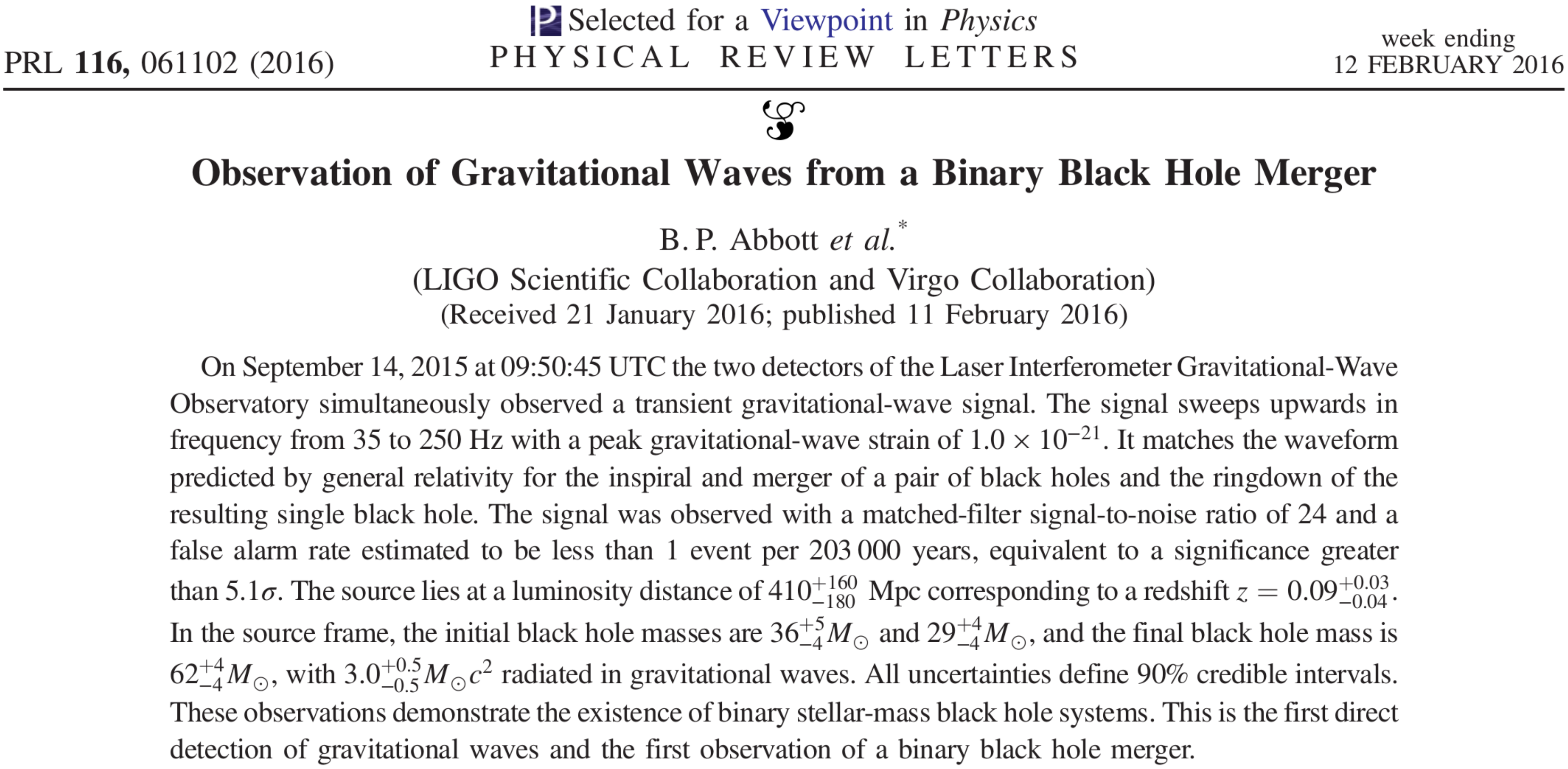
3 The light waves bounce and return.

4 A gravitational wave affects the interferometer's arms differently; when one extends the other contracts as they are passed by the peaks and troughs of the gravitational waves.

5 Normally, the light returns unchanged to the beam splitter from both arms and the light waves cancel each other out.

6 If the arms are disturbed by a gravitational wave, the light waves will have travelled different distances. Light then escapes through the splitter and hits the detector.

Gravitational waves



Selected for a Viewpoint in *Physics*
PRL **116,** 061102 (2016)
PHYSICAL REVIEW LETTERS
week ending
12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)

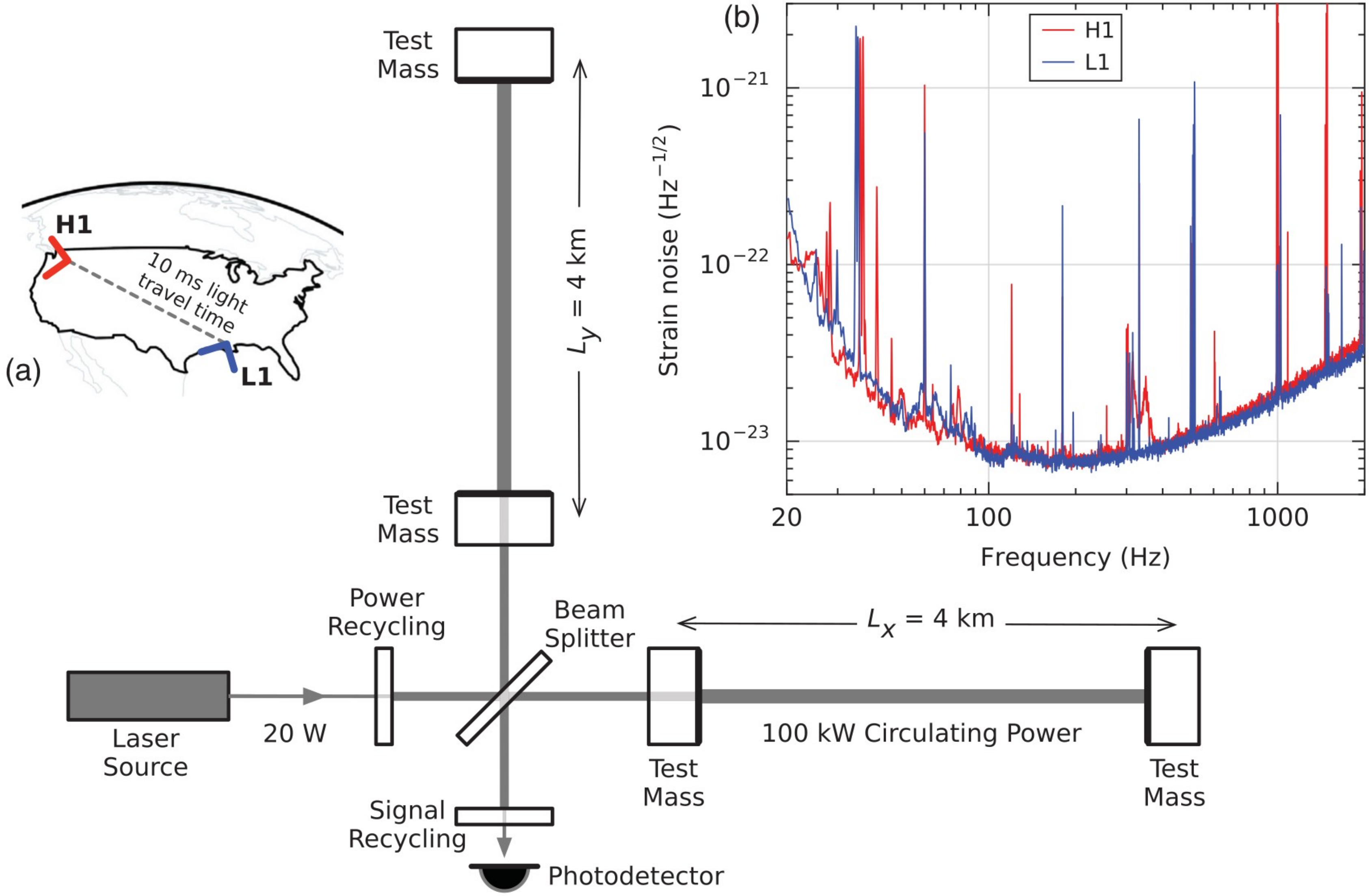
(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

LIGO: **L**aser **I**nterferometer **G**ravitational-Wave **O**bservatory

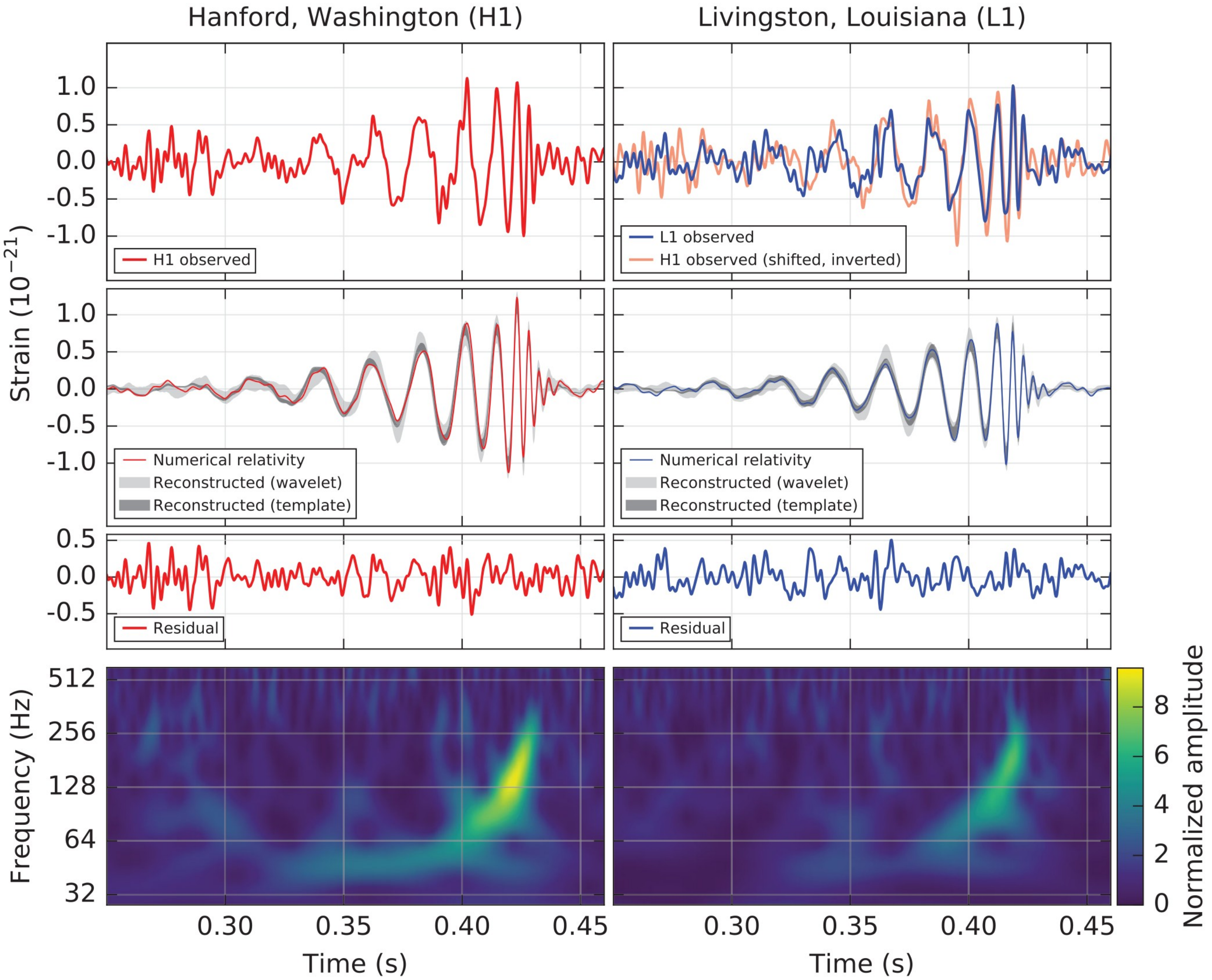
Phys. Rev. Lett. 116, 061102 (2016)

Two giant (4km!) interferometers



Phys. Rev. Lett. 116, 061102 (2016)

Gravitational waves



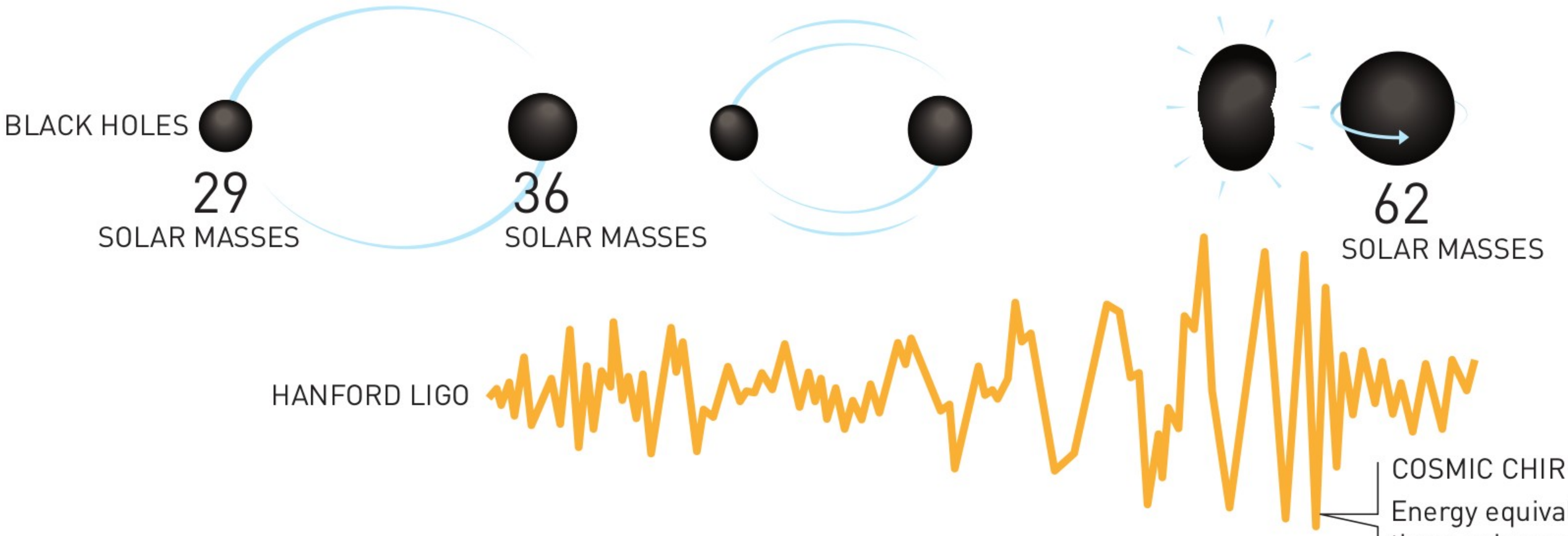
Phys. Rev. Lett. 116, 061102 (2016)

LIGO

www.nobelprize.org

Laser **I**nterferometer **G**ravitational-Wave **O**bservatory

GRAVITATIONAL WAVES FROM COLLIDING BLACK HOLES



COSMIC CHIRPS

Energy equivalent to three solar masses was emitted over a few tenths of a second.

Figure 2. The two black holes emitted gravitational waves for many million years as they rotated around each other. They got closer and closer, before merging to become one black hole in a few tenths of a second. The waves then reached a crescendo which, to us on Earth, 1.3 billion lightyears away, sounded like cosmic chirps that came to an abrupt stop.

Gravity: $29\ M_0 + 36\ M_0 = 62\ M_0$!?!? $3\ M_0$ radiated in gravitational waves!

The Nobel Prize in Physics 2014

Photo: A. Mahmoud

Isamu Akasaki

Prize share: 1/3

Photo: A. Mahmoud

Hiroshi Amano

Prize share: 1/3

Photo: A. Mahmoud

Shuji Nakamura

Prize share: 1/3

The Nobel Prize in Physics 2014 was awarded jointly to Isamu Akasaki, Hiroshi Amano and Shuji Nakamura *"for the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources"*.

The Nobel Prize in Chemistry 2014

Photo: A. Mahmoud

Eric Betzig

Prize share: 1/3

Photo: A. Mahmoud

Stefan W. Hell

Prize share: 1/3

Photo: A. Mahmoud

William E. Moerner

Prize share: 1/3

The Nobel Prize in Chemistry 2014 was awarded jointly to Eric Betzig, Stefan W. Hell and William E. Moerner *"for the development of super-resolved fluorescence microscopy"*.

The Nobel Prize in Physics 2012

Photo: U. Montan

Serge Haroche

Prize share: 1/2

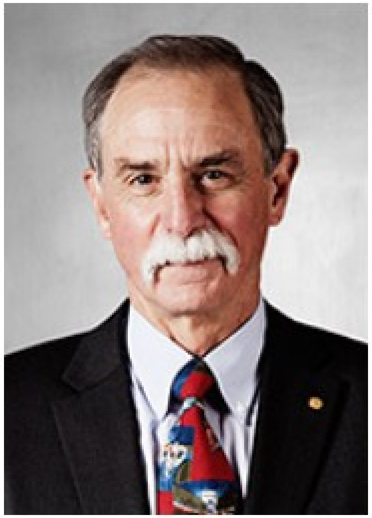


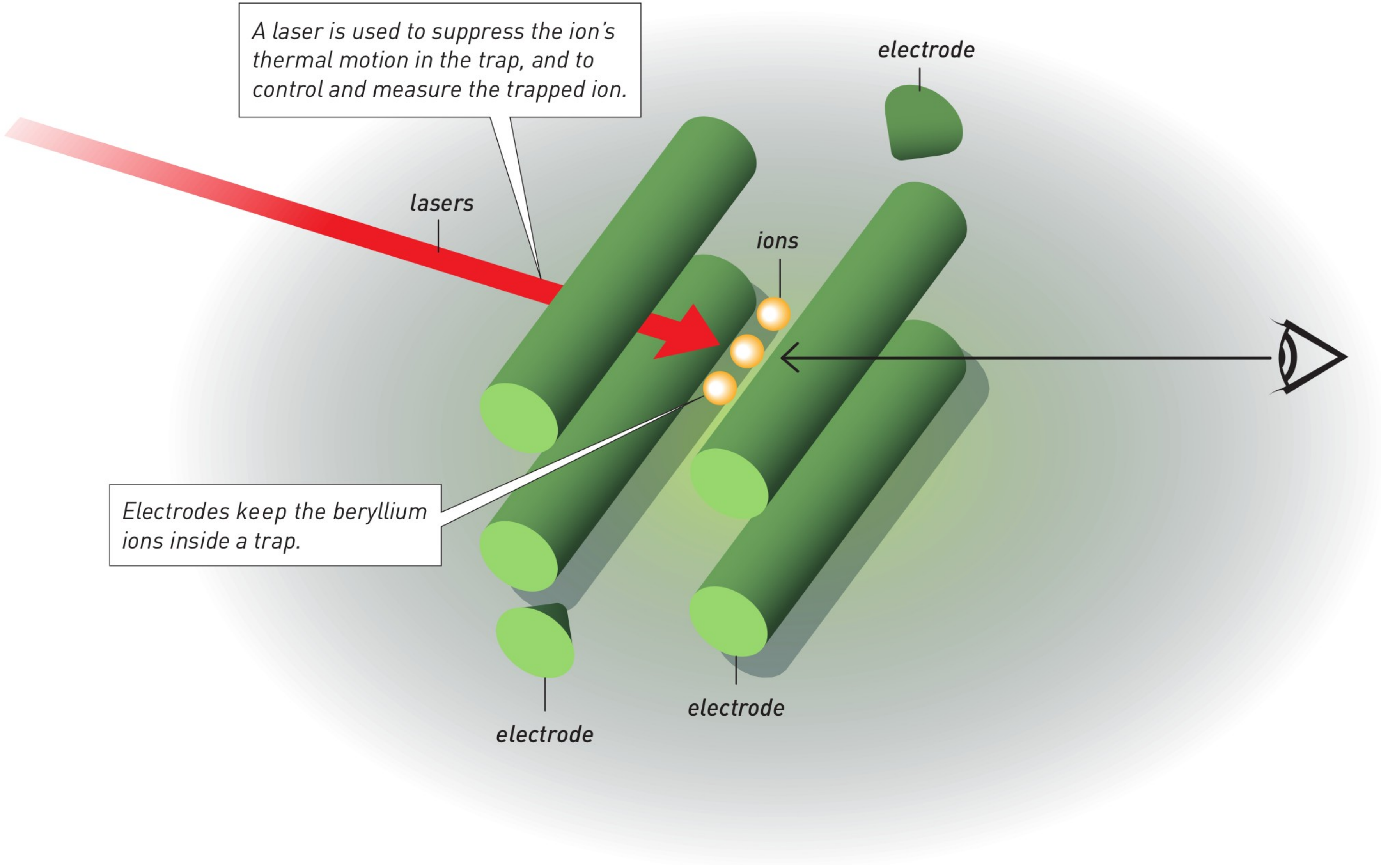
Photo: U. Montan

David J. Wineland

Prize share: 1/2

The Nobel Prize in Physics 2012 was awarded jointly to Serge Haroche and David J. Wineland *"for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems"*

Ion trap



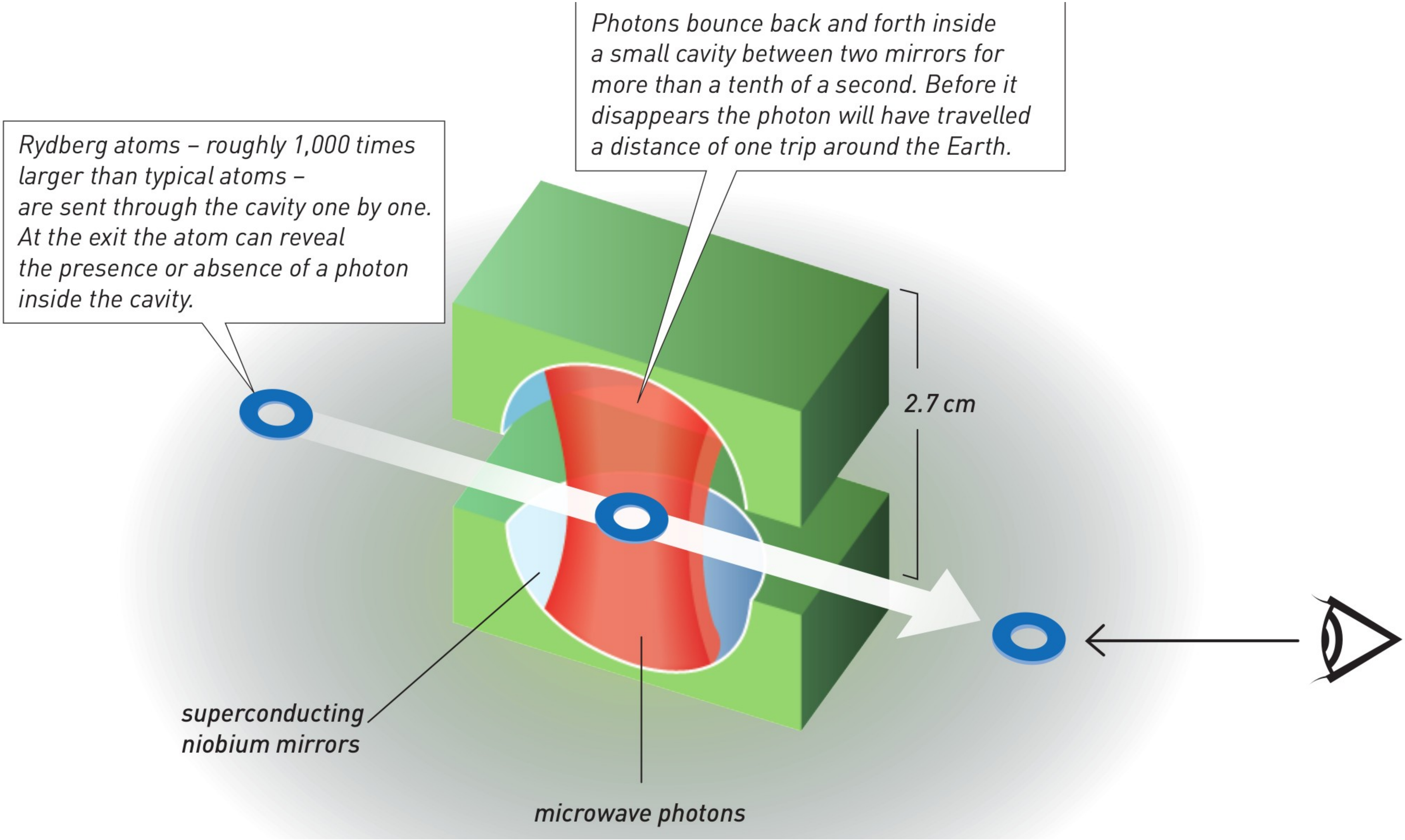
A laser is used to suppress the ion's thermal motion in the trap, and to control and measure the trapped ion.

Electrodes keep the beryllium ions inside a trap.

Wineland group

www.nobelprize.org

Cavity QED



Photons bounce back and forth inside a small cavity between two mirrors for more than a tenth of a second. Before it disappears the photon will have travelled a distance of one trip around the Earth.

Rydberg atoms – roughly 1,000 times larger than typical atoms – are sent through the cavity one by one. At the exit the atom can reveal the presence or absence of a photon inside the cavity.

Haroche group

www.nobelprize.org

The Nobel Prize in Physics 2009

Photo: U. Montan

Charles Kuen Kao

Prize share: 1/2

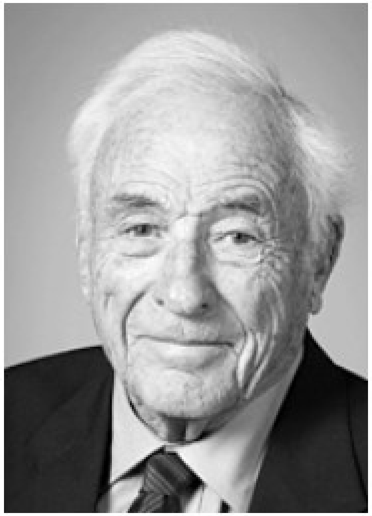


Photo: U. Montan

Willard S. Boyle

Prize share: 1/4

Photo: U. Montan

George E. Smith

Prize share: 1/4

The Nobel Prize in Physics 2009 was divided, one half awarded to Charles Kuen Kao *"for groundbreaking achievements concerning the transmission of light in fibers for optical communication"*, the other half jointly to Willard S. Boyle and George E. Smith *"for the invention of an imaging semiconductor circuit - the CCD sensor"*.

The Nobel Prize in Physics 2005

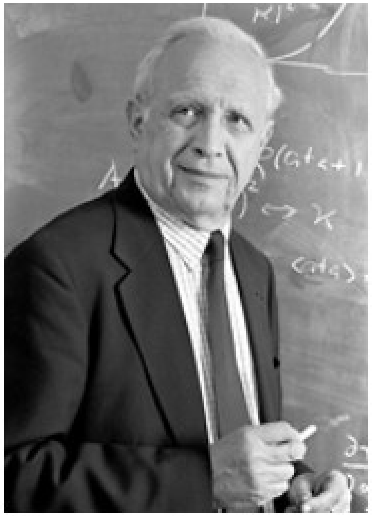


Photo: J.Reed

Roy J. Glauber

Prize share: 1/2

Photo: Sears.P.Studio

John L. Hall

Prize share: 1/4

Photo: F.M. Schmidt

Theodor W. Hänsch

Prize share: 1/4

The Nobel Prize in Physics 2005 was divided, one half awarded to Roy J. Glauber *"for his contribution to the quantum theory of optical coherence"*, the other half jointly to John L. Hall and Theodor W. Hänsch *"for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique"*.

Waves or particles?

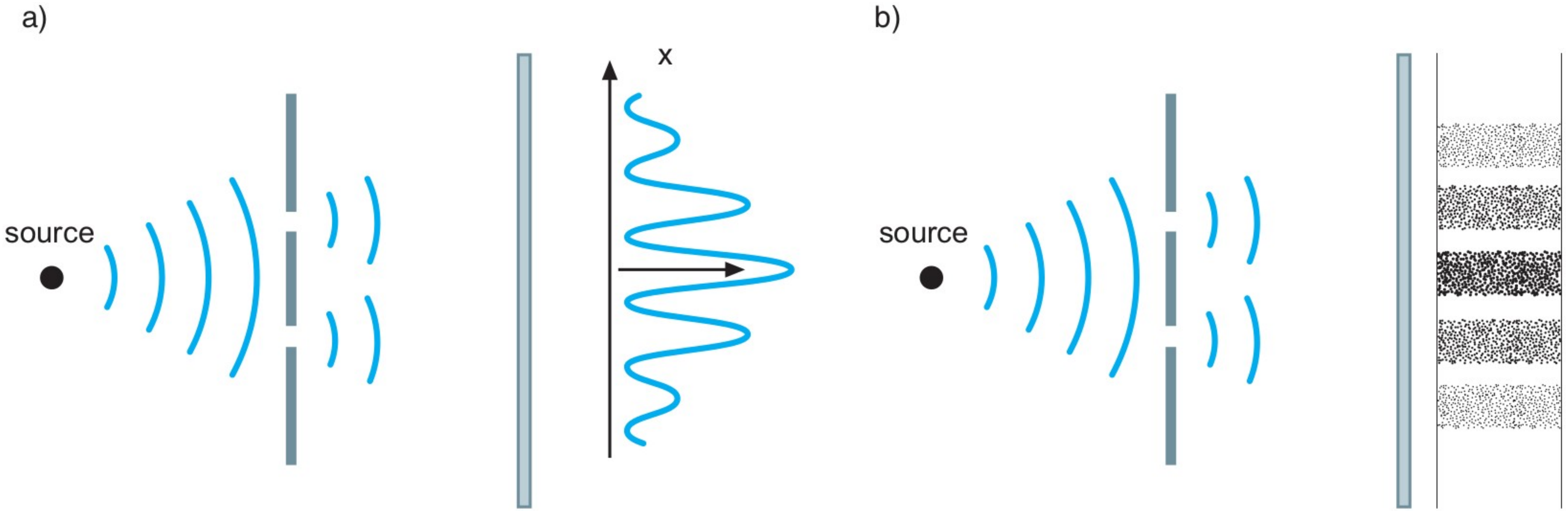
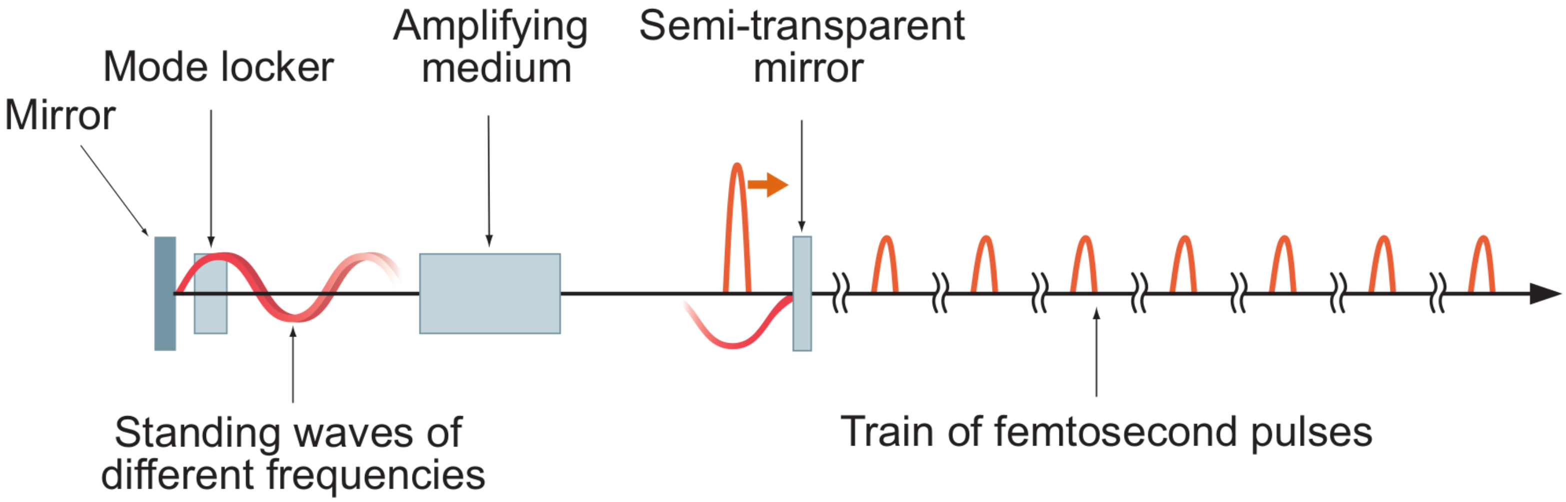
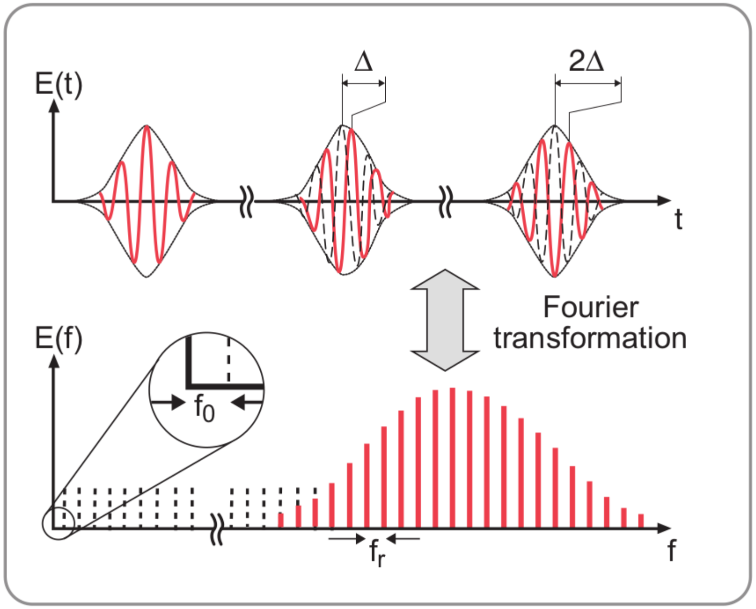


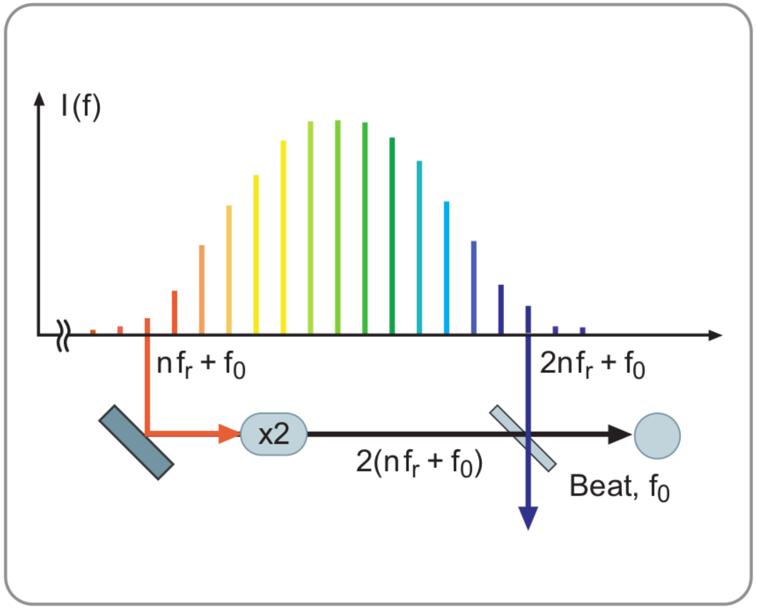
Figure 1. The difference between a classical and a quantum physics observation of light. The passage of light through two slits when it is observed as a) an electromagnetic wave motion and b) a flow of particles. Note that the same interference pattern occurs as the interaction between two waves in the first case or as the distribution of individual particles in the second case.

www.nobelprize.org

Frequency Comb







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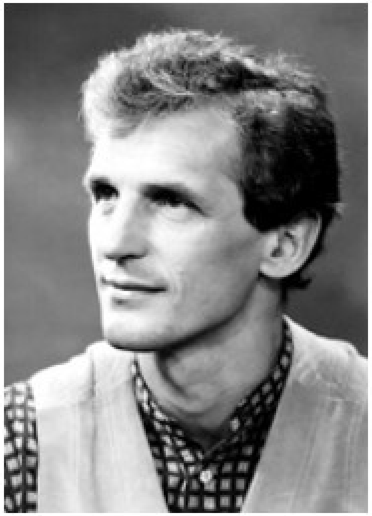
The Nobel Prize in Physics 2001

Eric A. Cornell
Prize share: 1/3

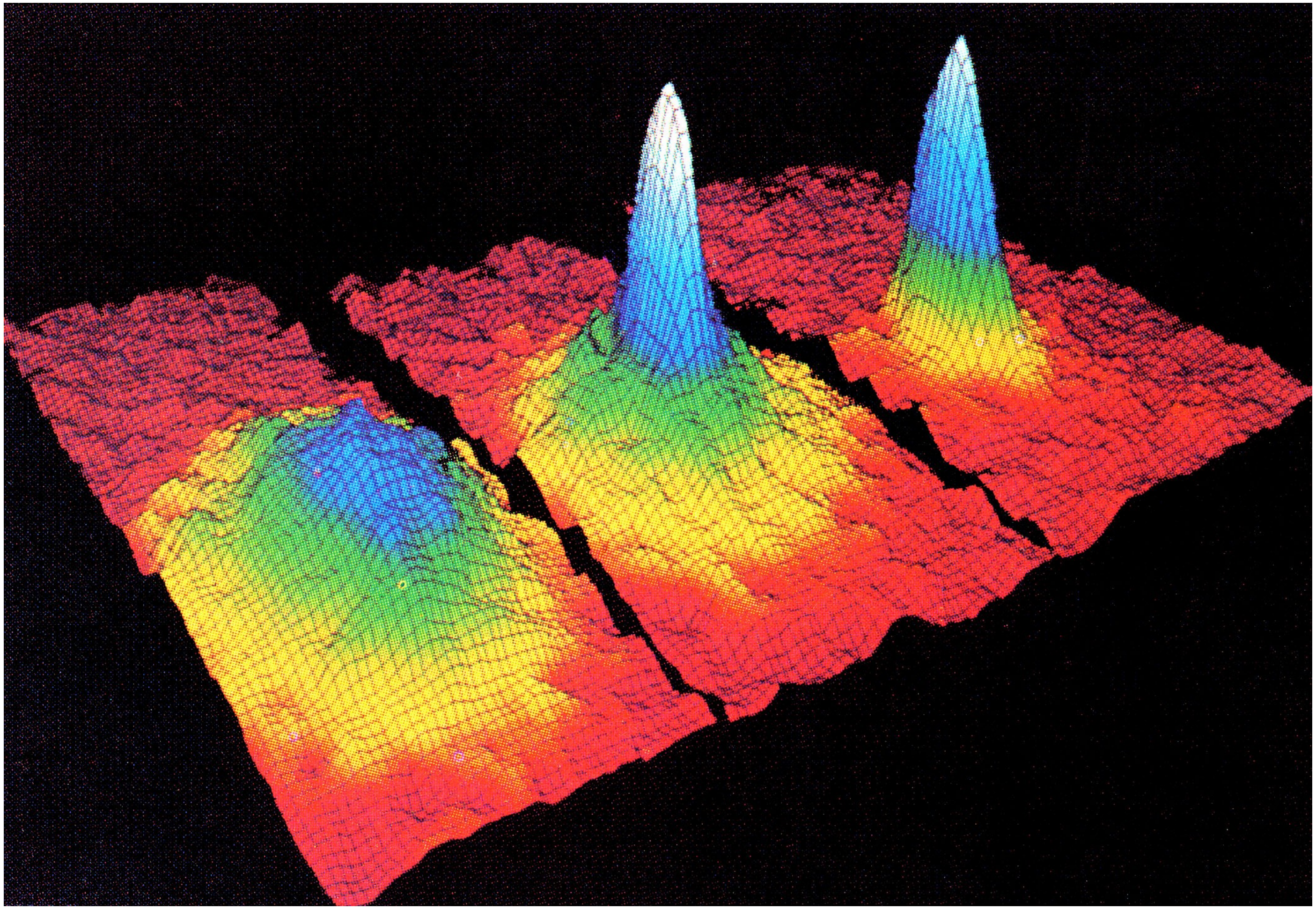


Wolfgang Ketterle
Prize share: 1/3

Carl E. Wieman
Prize share: 1/3

The Nobel Prize in Physics 2001 was awarded jointly to Eric A. Cornell, Wolfgang Ketterle and Carl E. Wieman *"for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates"*.

Bose-Einstein condensate (BEC)



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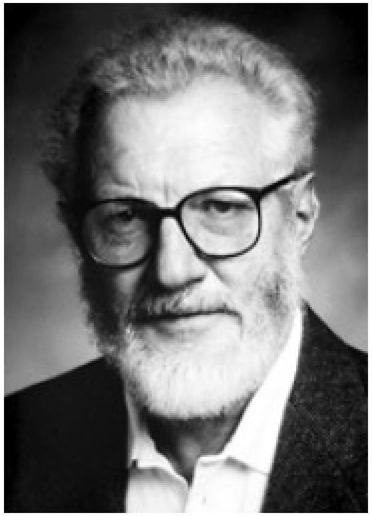
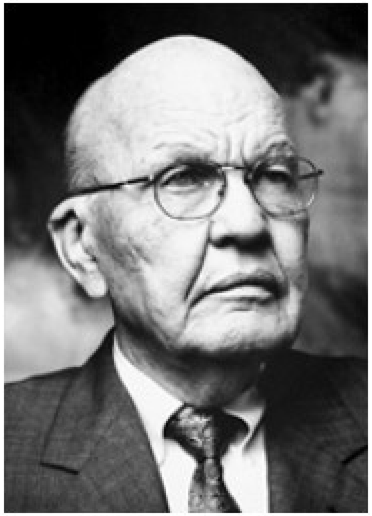
The Nobel Prize in Physics 2000

Zhores I. Alferov
Prize share: 1/4



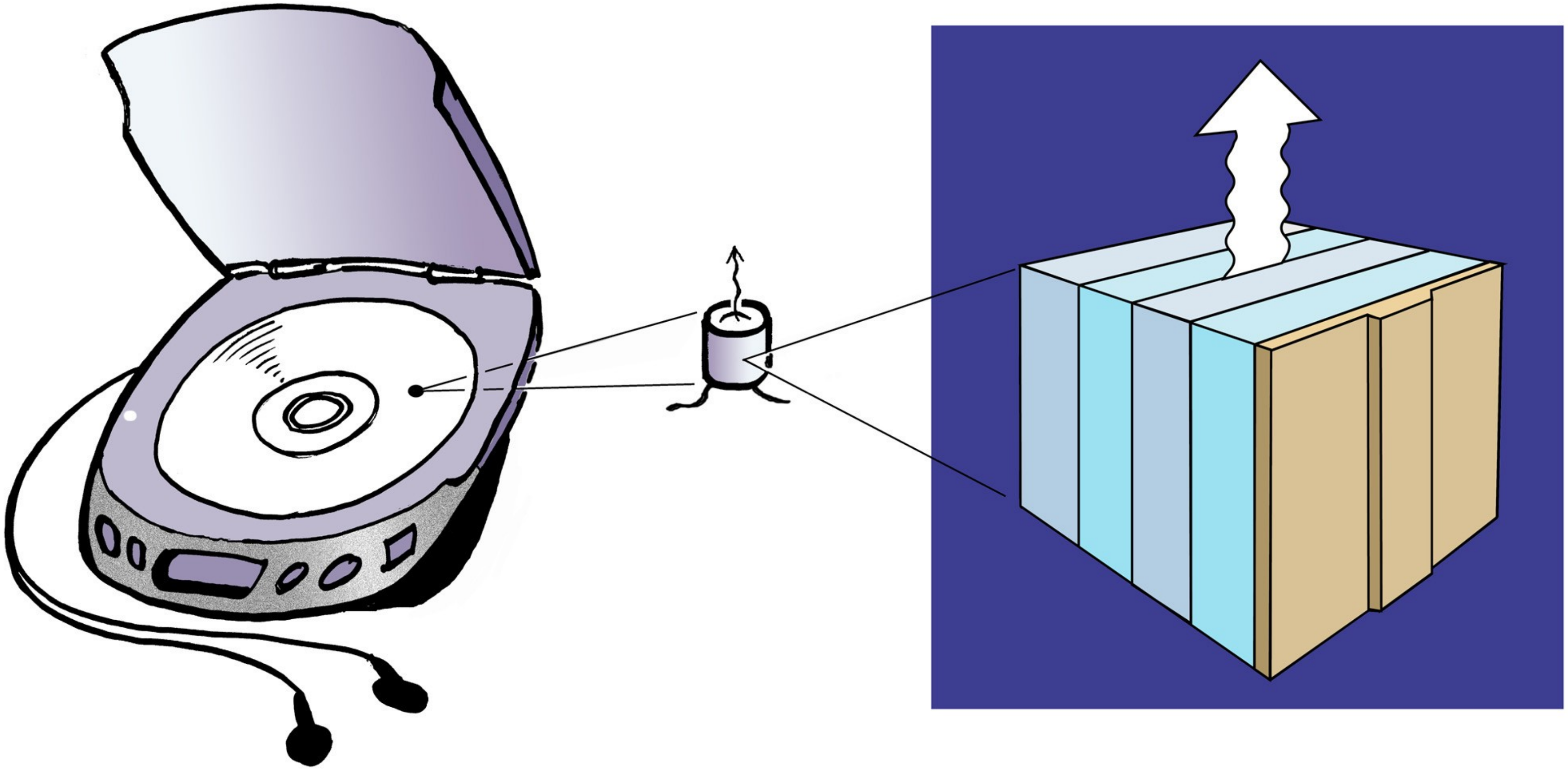
Herbert Kroemer
Prize share: 1/4



Jack S. Kilby
Prize share: 1/2

The Nobel Prize in Physics 2000 was awarded *"for basic work on information and communication technology"* with one half jointly to Zhores I. Alferov and Herbert Kroemer *"for developing semiconductor heterostructures used in high-speed- and opto-electronics"* and the other half to Jack S. Kilby *"for his part in the invention of the integrated circuit"*.

The laser diode



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The Nobel Prize in Physics 1997

Steven Chu
Prize share: 1/3

Claude Cohen-Tannoudji
Prize share: 1/3

William D. Phillips
Prize share: 1/3

The Nobel Prize in Physics 1997 was awarded jointly to Steven Chu, Claude Cohen-Tannoudji and William D. Phillips *"for development of methods to cool and trap atoms with laser light"*.

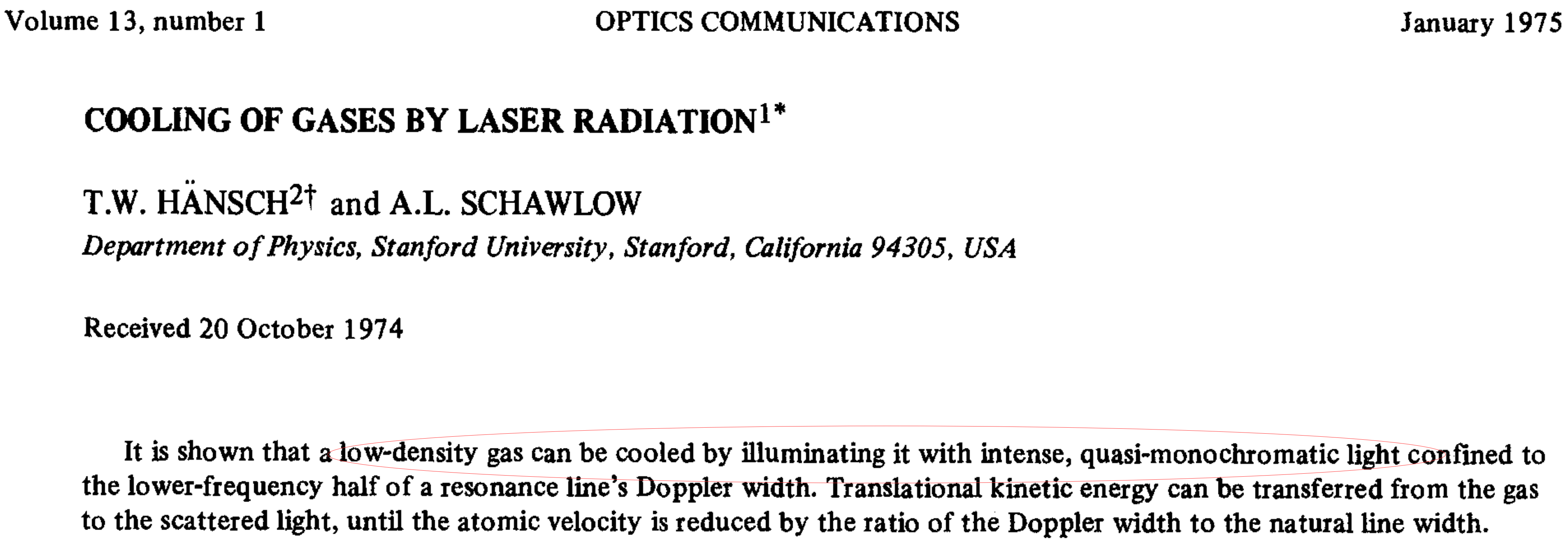
Atoms

Light acts mechanically on material objects, which means it can change their positions and velocities. This mechanical action of light is used in laser cooling and trapping to reduce the velocity spread for a collection of atoms (cooling), or to confine the atoms in a small volume (trapping).

A breakthrough was achieved in the early 1980s when **William Phillips** developed new methods of decelerating a fast atom beam. In 1985 the first reports came from experiments where the mean velocity had been reduced from 1000 m/s to zero.

www.nobelprize.org

Slowing atoms with light



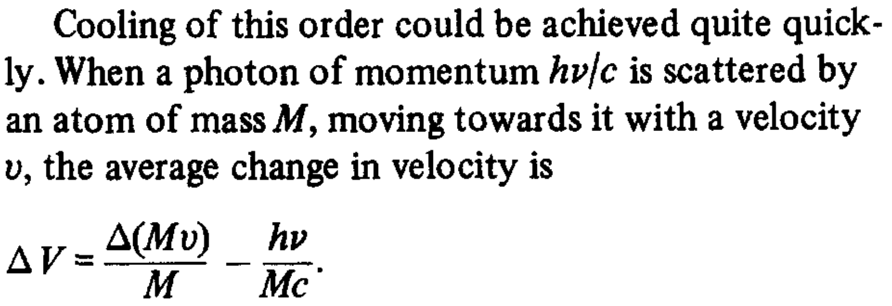
Volume 13, number 1 OPTICS COMMUNICATIONS January 1975

COOLING OF GASES BY LASER RADIATION[1*]

T.W. HÄNSCH[2†] and A.L. SCHAWLOW
Department of Physics, Stanford University, Stanford, California 94305, USA

Received 20 October 1974

It is shown that a low-density gas can be cooled by illuminating it with intense, quasi-monochromatic light confined to the lower-frequency half of a resonance line's Doppler width. Translational kinetic energy can be transferred from the gas to the scattered light, until the atomic velocity is reduced by the ratio of the Doppler width to the natural line width.



Cooling of this order could be achieved quickly. When a photon of momentum $h\nu/c$ is scattered by an atom of mass M, moving towards it with a velocity v, the average change in velocity is

$$\Delta V = \frac{\Delta(Mv)}{M} - \frac{h\nu}{Mc}.$$

Slowing atoms with light

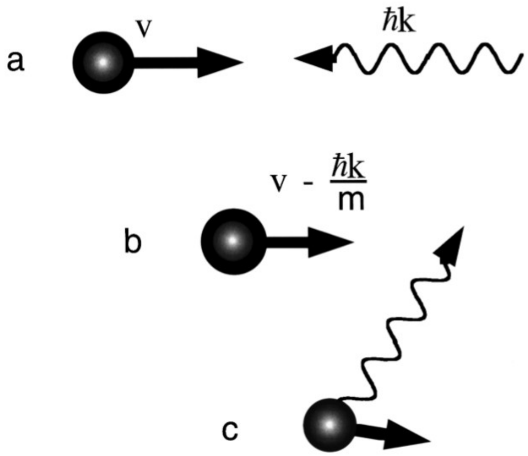


FIG. 1. (a) An atom with velocity v encounters a photon with momentum $\hbar k = h/\lambda$; (b) after absorbing the photon, the atom is slowed by $\hbar k/m$; (c) after re-radiation in a random direction, on average the atom is slower than in (a).

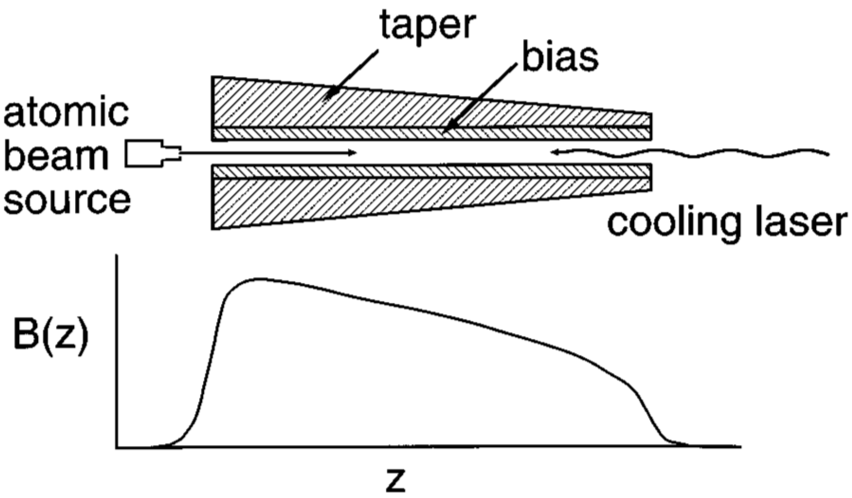


FIG. 4. Upper: Schematic representation of a Zeeman slower. Lower: Variation of the axial field with position.

„Zeeman cooling“, „Zeeman slower“

Bill Phillips, Nobel Lecture: Rev. Mod. Phys. 70, 721 (1998)

Slowing atoms with light

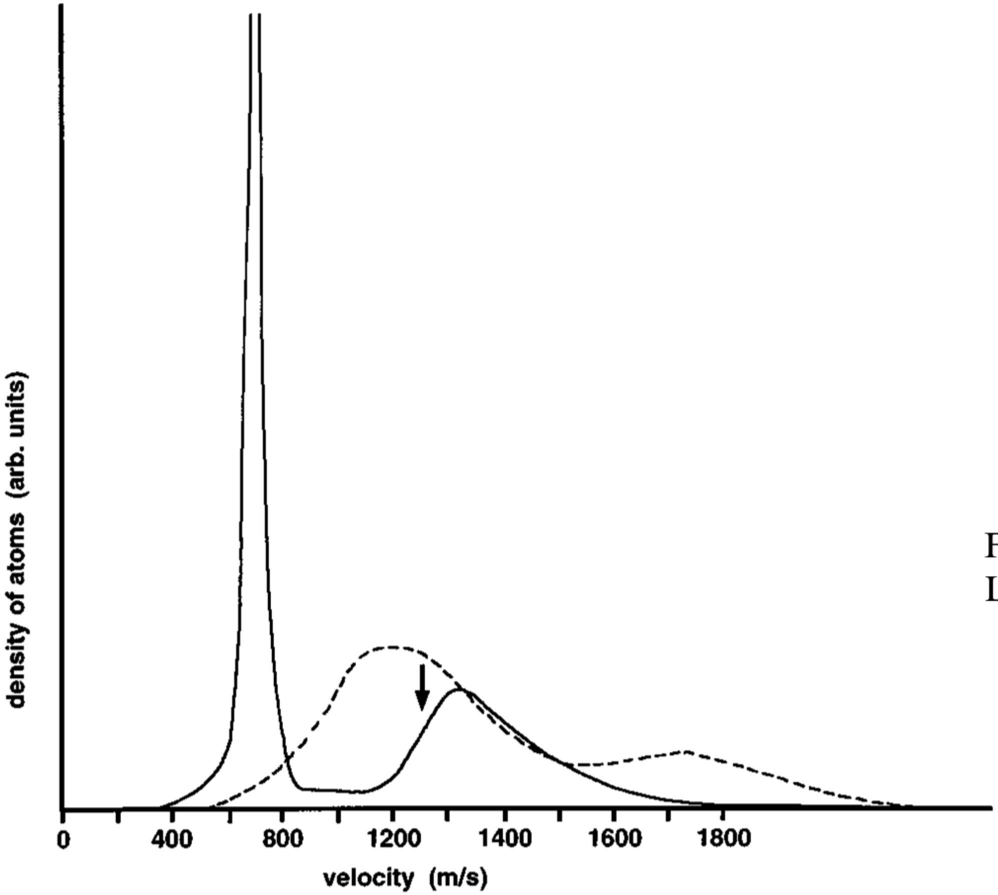


FIG. 5. Velocity distribution before (dashed) and after (solid) Zeeman cooling. The arrow indicates the highest velocity resonant with the slowing laser. (The extra bump at 1700 m/s is from $F=1$ atoms, which are optically pumped into $F=2$ during the cooling process.)

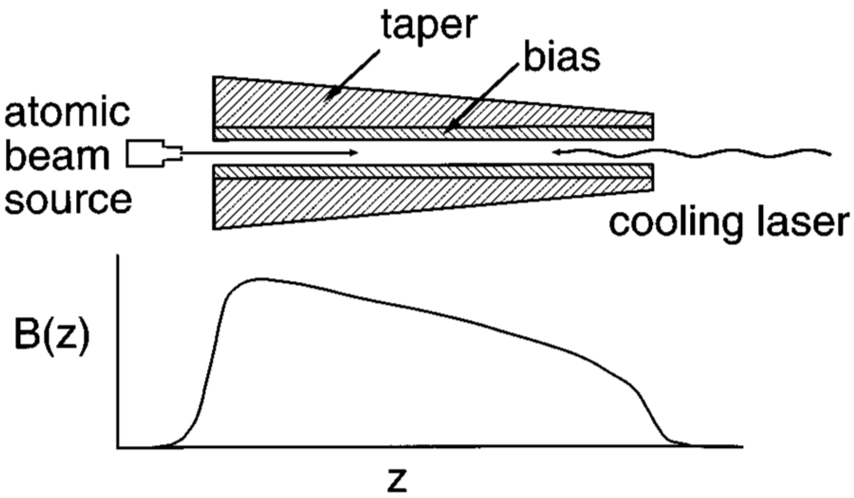
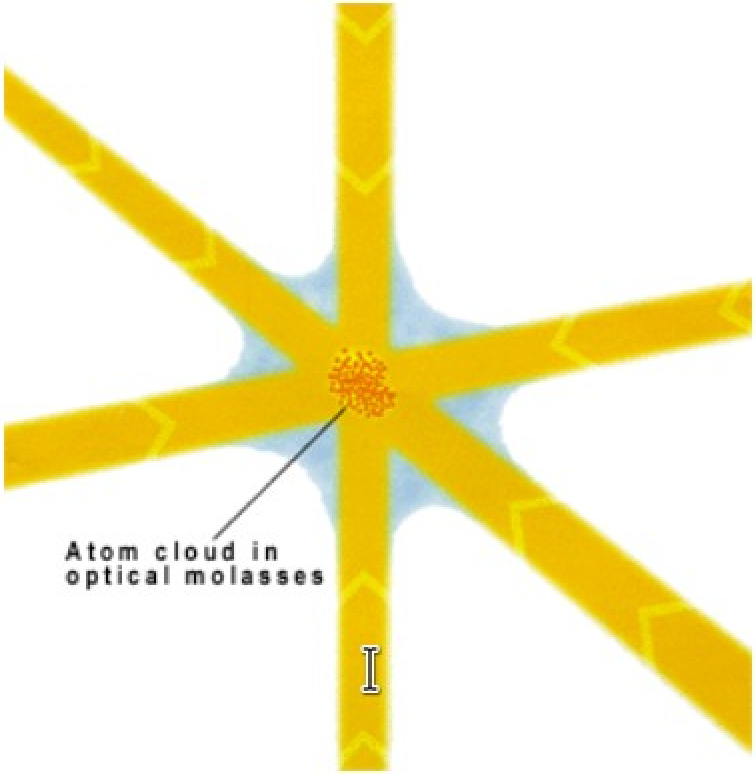
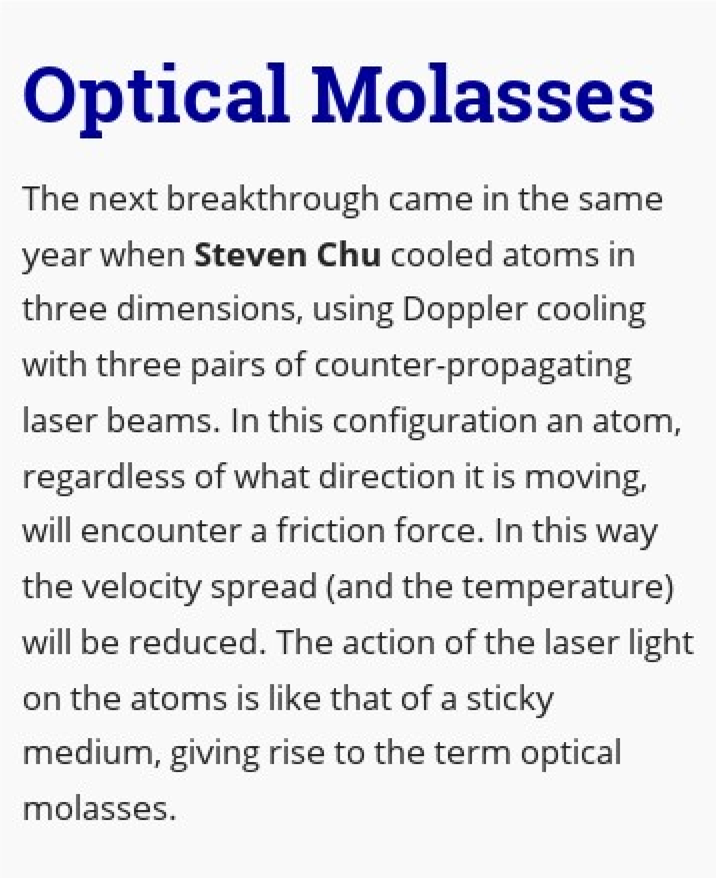


FIG. 4. Upper: Schematic representation of a Zeeman slower. Lower: Variation of the axial field with position.

Bill Phillips, Nobel Lecture: Rev. Mod. Phys. 70, 721 (1998)



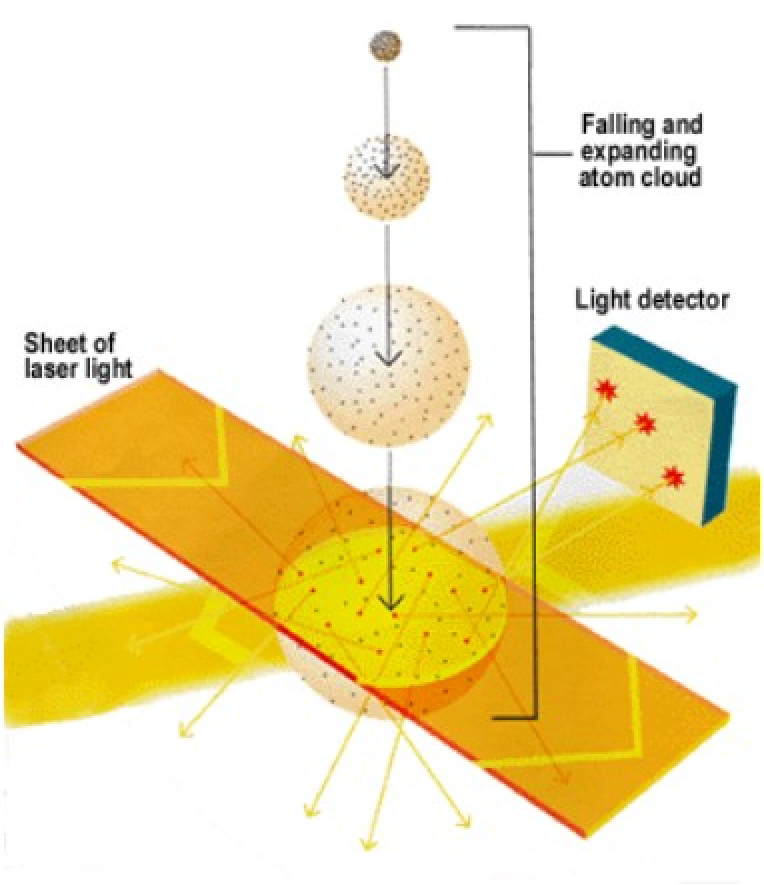
A collection of sodium atoms (yellow dot in middle of picture) trapped in a MOT.



Optical Molasses

The next breakthrough came in the same year when **Steven Chu** cooled atoms in three dimensions, using Doppler cooling with three pairs of counter-propagating laser beams. In this configuration an atom, regardless of what direction it is moving, will encounter a friction force. In this way the velocity spread (and the temperature) will be reduced. The action of the laser light on the atoms is like that of a sticky medium, giving rise to the term optical molasses.

www.nobelprize.org



Time-of-flight method

The six laser beams are switched off. The atom cloud expands in a way determined by its temperature, at the same time as the atoms fall. They fall through a sheet of laser light and the resulting fluorescence is recorded. Since the atom cloud has expanded the signal has a temporal spread. By measuring this spread the temperature of the cloud can be determined.

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The atoms are „too cold“

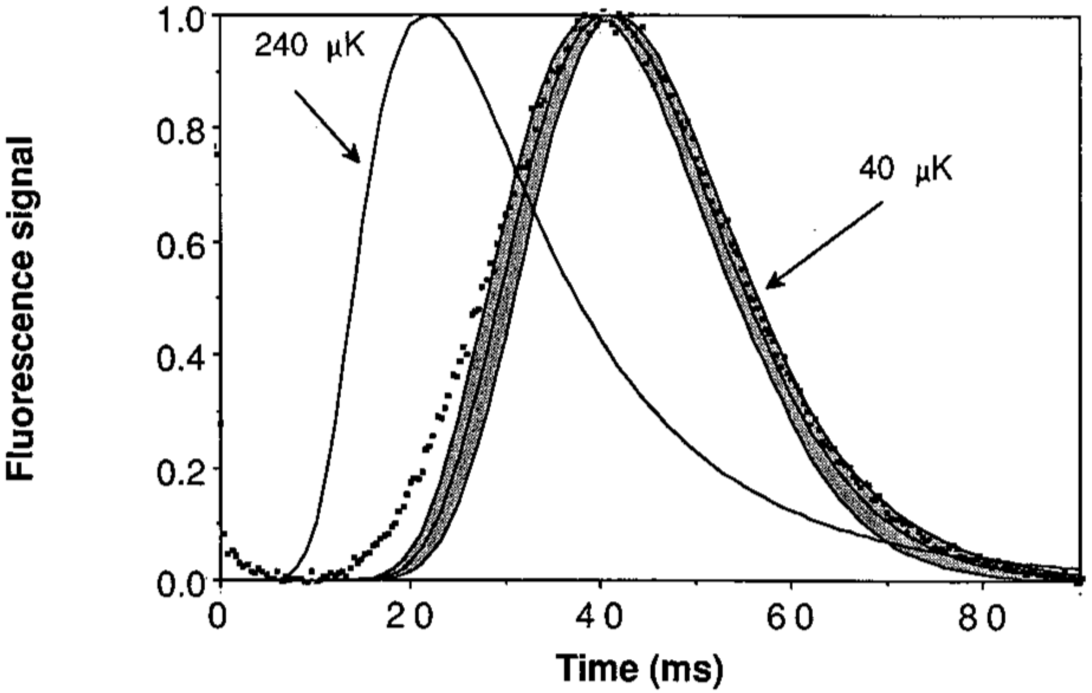
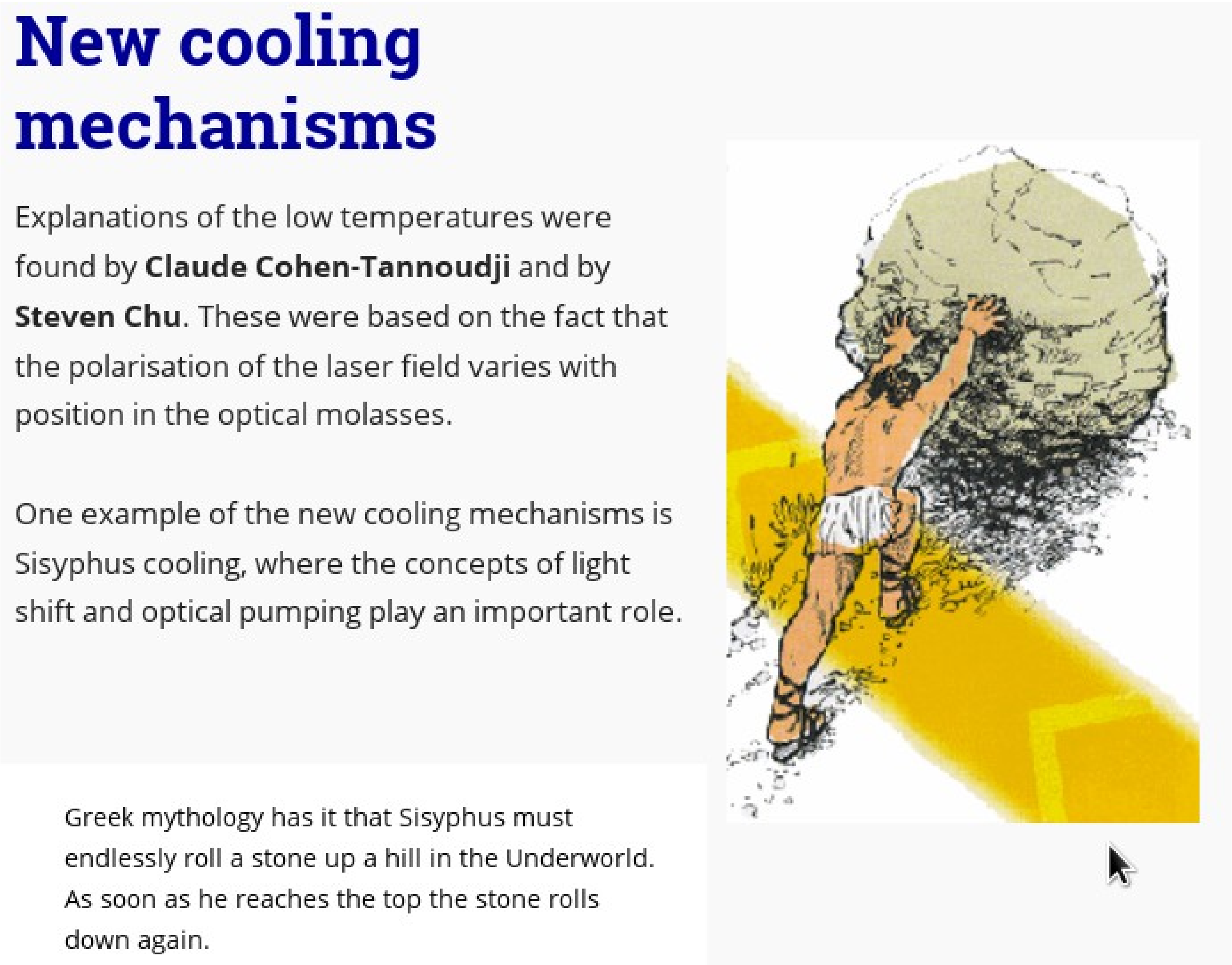


FIG. 16. The experimental TOF distribution (points) and the predicted distribution curves for 40 μK and 240 μK (the predicted lower limit of Doppler cooling). The band around the 40 μK curve reflects the uncertainty in the measurement of the geometry of the molasses and probe.

Bill Phillips, Nobel Lecture: Rev. Mod. Phys. 70, 721 (1998)



New cooling mechanisms

Explanations of the low temperatures were found by **Claude Cohen-Tannoudji** and by **Steven Chu**. These were based on the fact that the polarisation of the laser field varies with position in the optical molasses.

One example of the new cooling mechanisms is Sisyphus cooling, where the concepts of light shift and optical pumping play an important role.

Greek mythology has it that Sisyphus must endlessly roll a stone up a hill in the Underworld. As soon as he reaches the top the stone rolls down again.

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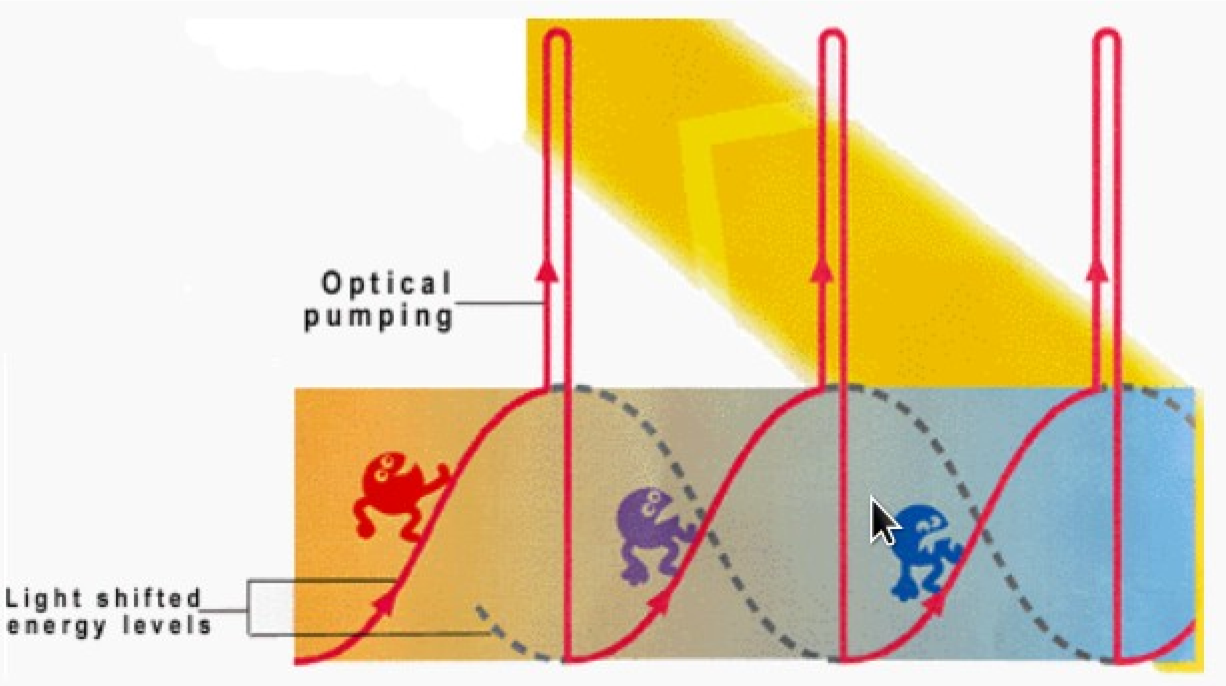
Sisyphus Cooling



Claude Cohen-Tannoudji

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Sisyphus cooling

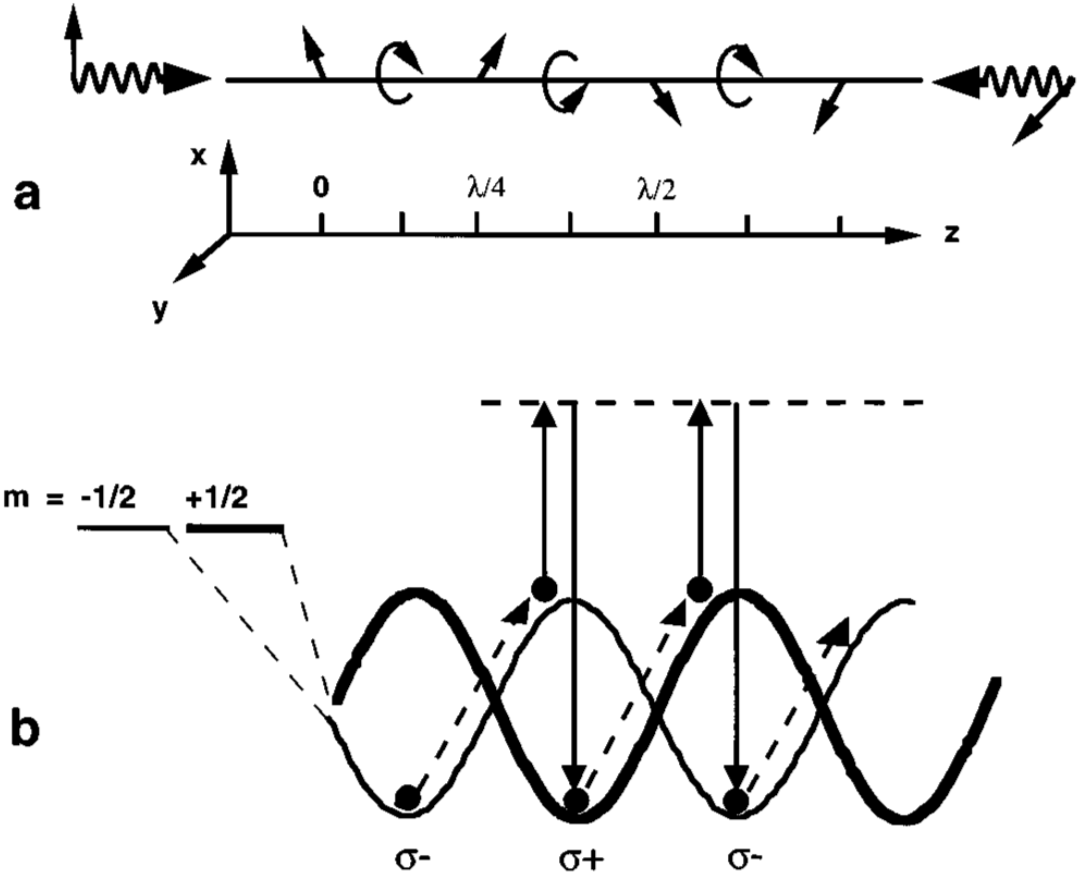
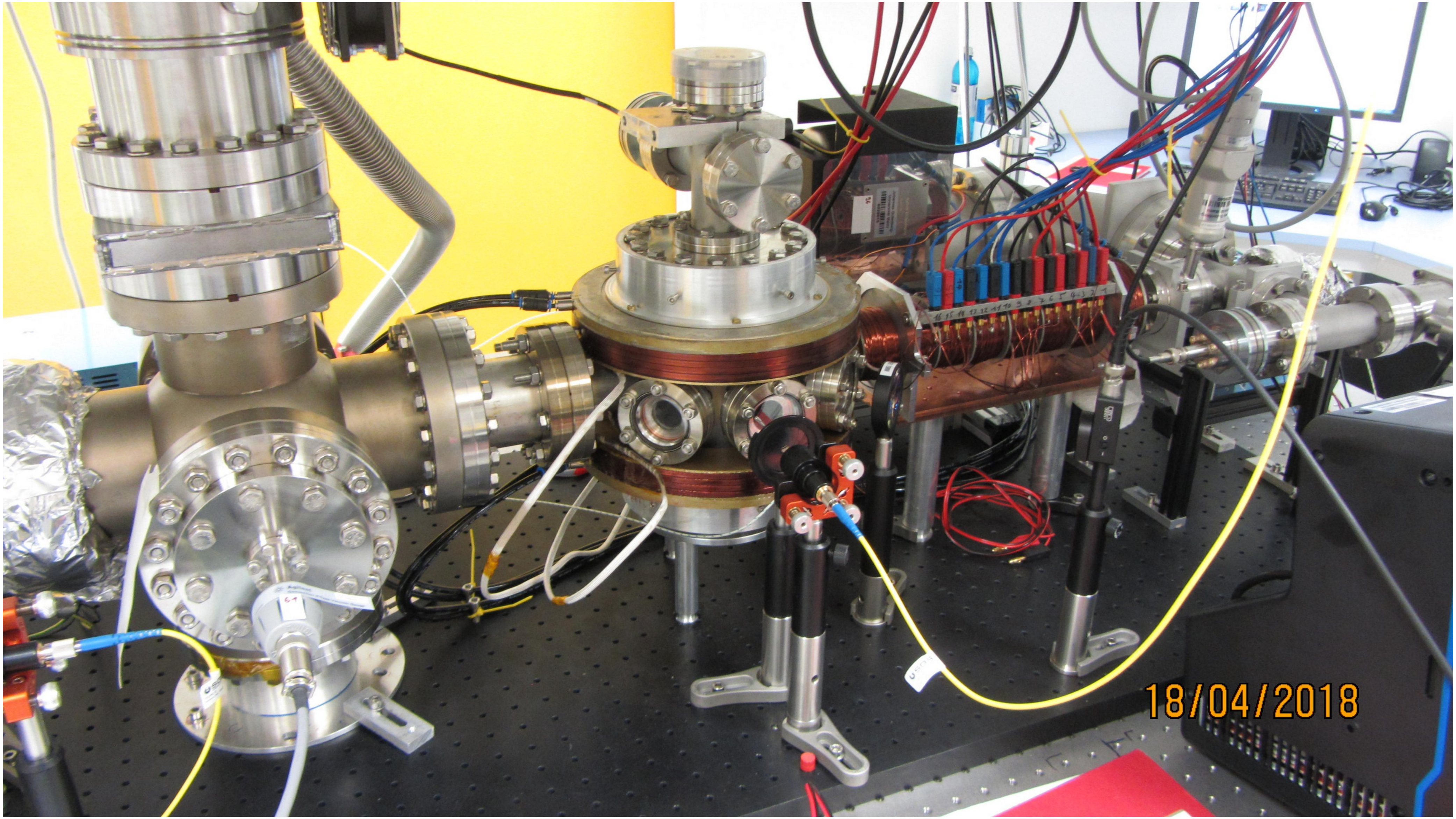


FIG. 18. (a) Interfering, counterpropagating beams having orthogonal, linear polarizations create a polarization gradient. (b) The different Zeeman sublevels are shifted differently in light fields with different polarizations; optical pumping tends to put atomic population on the lowest energy level, but nonadiabatic motion results in "Sisyphus" cooling.

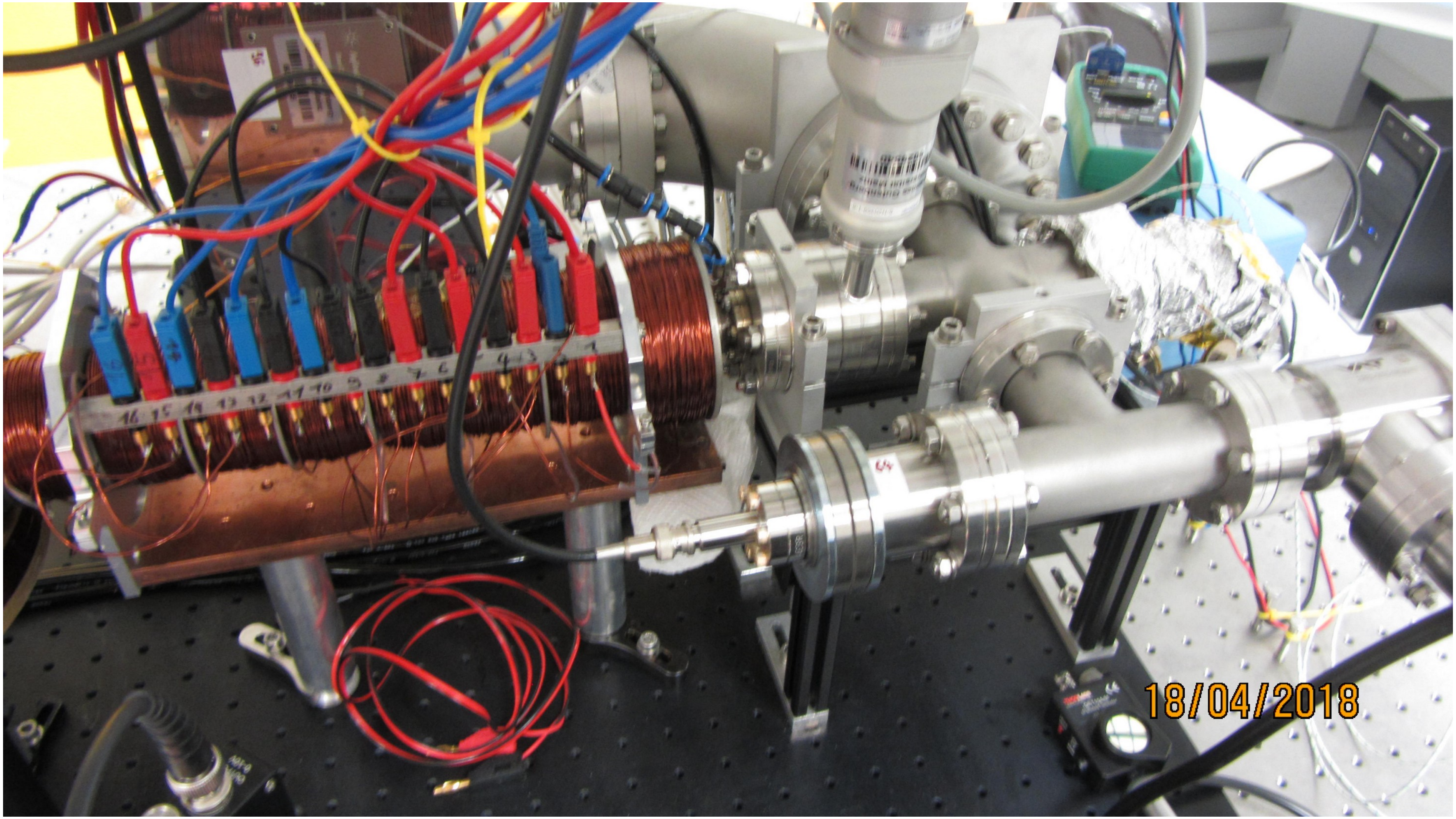
Bill Phillips, Nobel Lecture: Rev. Mod. Phys. 70, 721 (1998)

Pictures from my lab



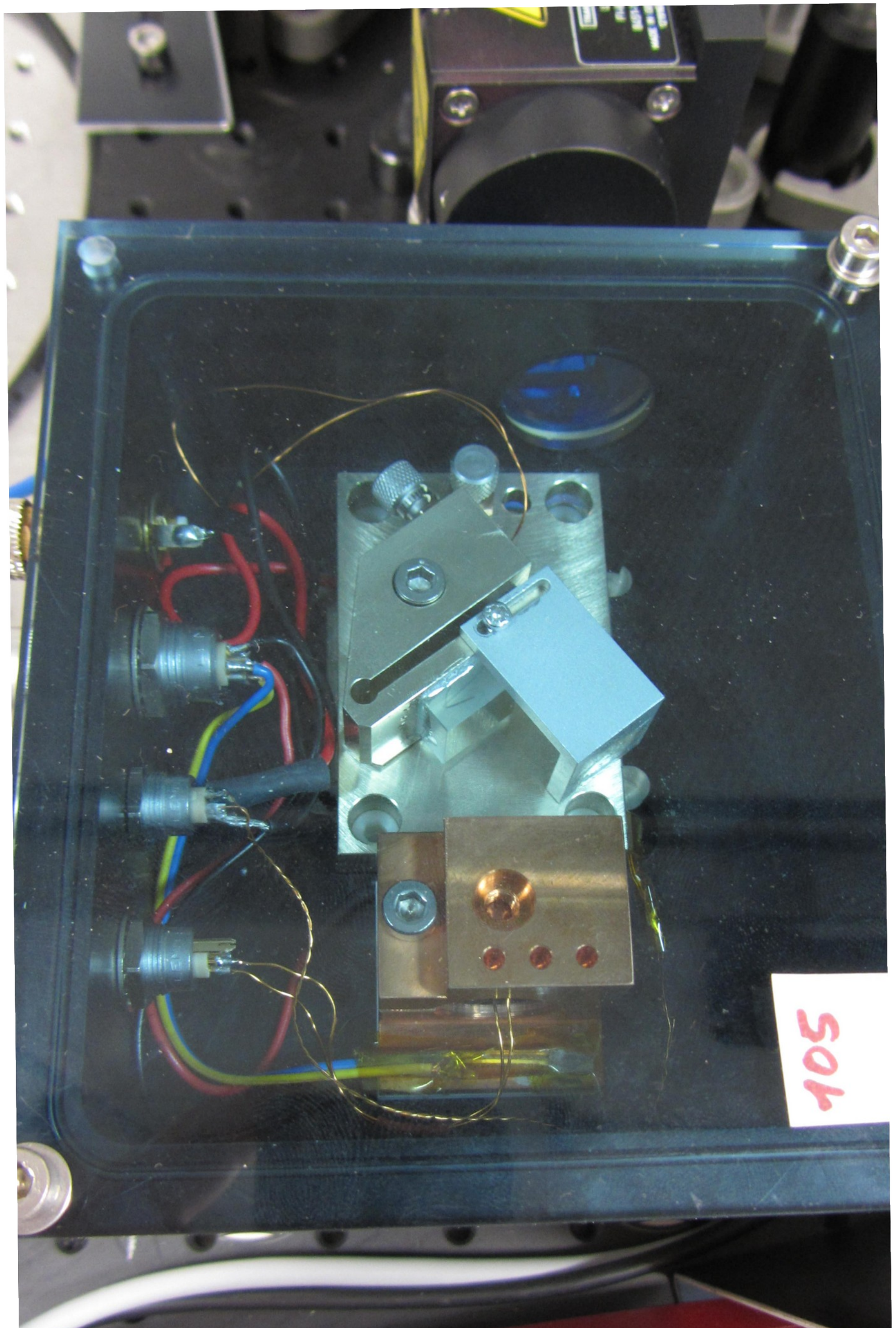
Li atomic beam and trap apparatus

Pictures from my lab



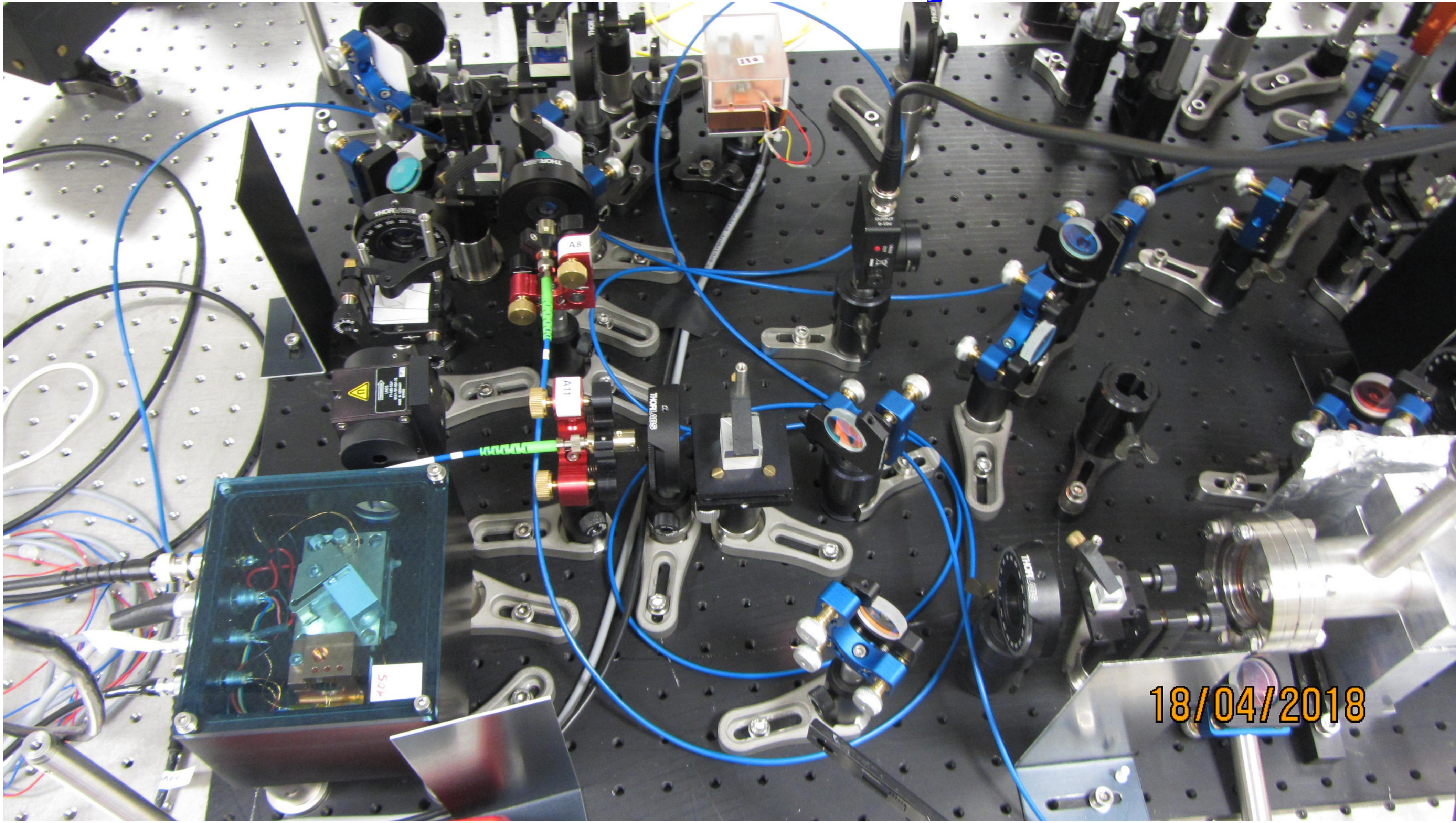
Zeeman slower

Pictures from my lab

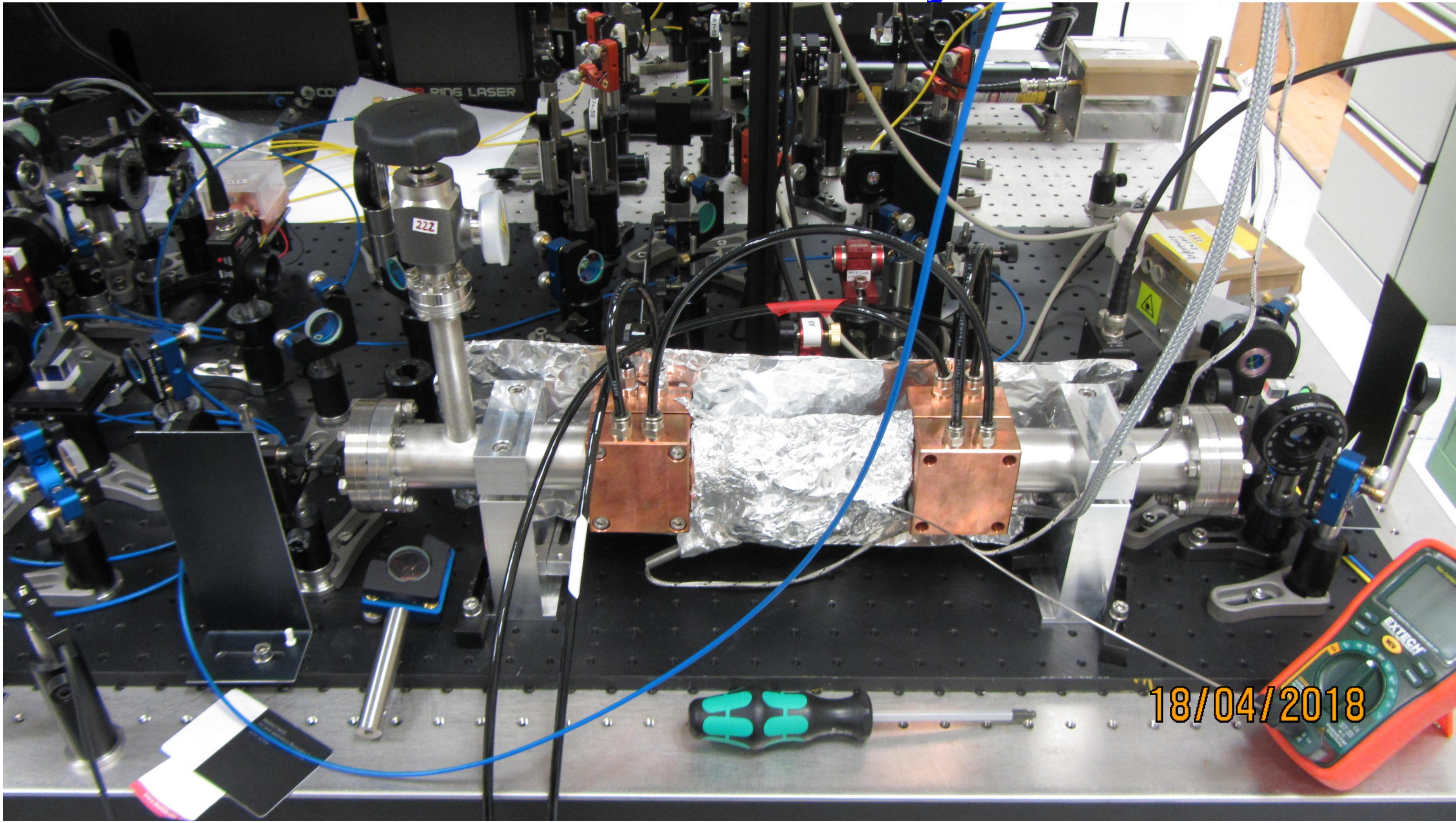


diode laser

Pictures from my lab



Pictures from my lab


18/04/2018

Li absorption cell

Thanks!

This was just a teaser!

I think we have an exciting program of wonderful physics.

This lecture is aimed at being a „practical“ lecture: You should learn stuff that you can use in a laser lab!

Most importantly, this lecture should be fun! Shout if you don‘t enjoy what I am talking about!

Tomorrow: „My“ experiment.

„What does all this have to do with reality?!“