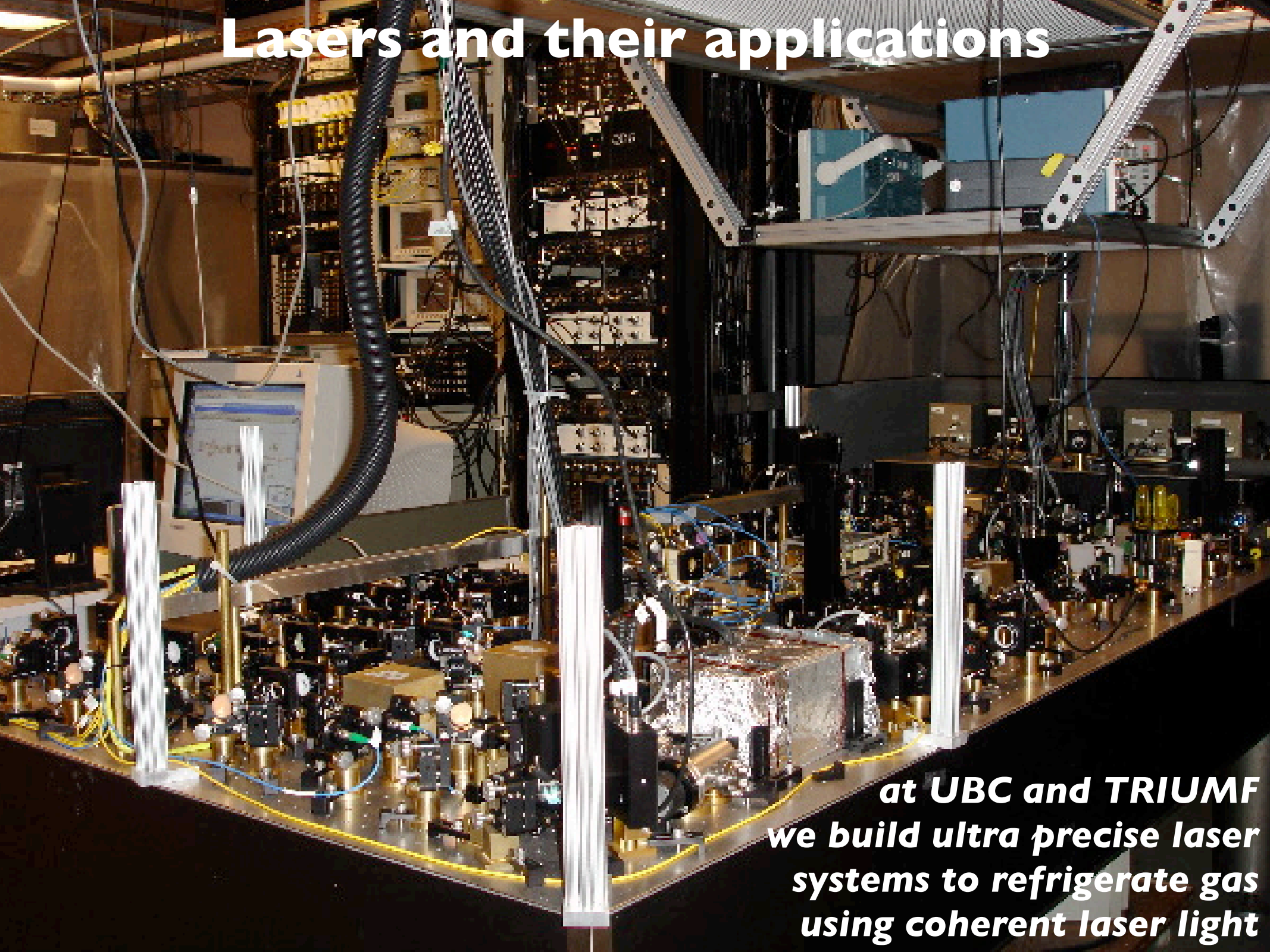
Lasers: history, properties and applications

Kirk W. Madison

University of British Columbia

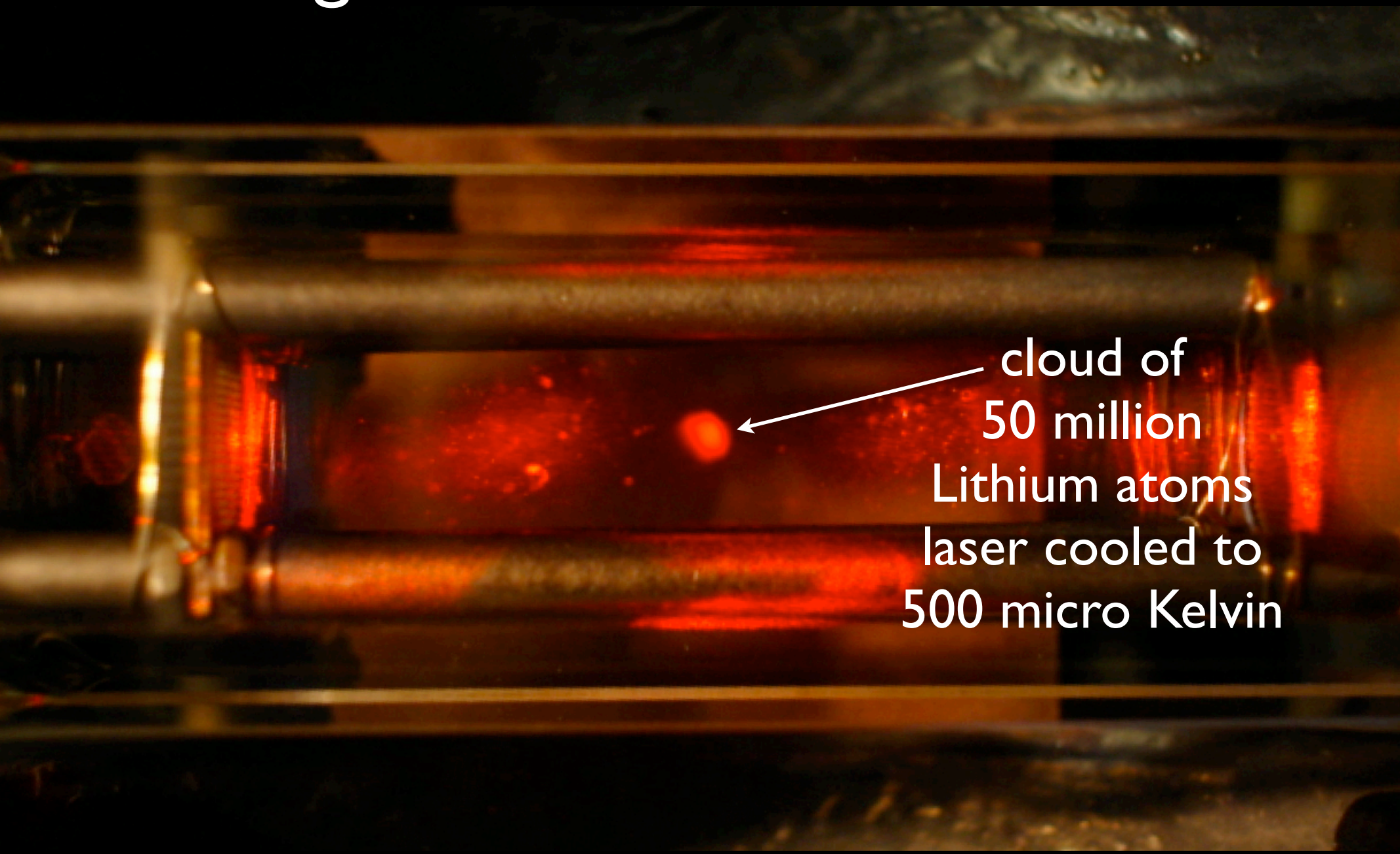
Saturday morning lecture series on Quantum Physics and Chemistry
TRIUMF, November 29, 2008

Lasers and their applications



at UBC and TRIUMF we build ultra precise laser systems to refrigerate gas using coherent laser light

Image of atomic Fluorescence



cooled with 671 nm (red) light

Why do lasers exist?

Why do lasers exist?

The work leading to the invention of lasers in 1958 was made possible because Bell Labs was supporting pure research at that time. Recalling the early work of Schawlow and Townes, a reviewer noted:

"Neither man was planning on inventing a device that would revolutionize a number of industries, from communications to medicine. They had something more straightforward in mind, developing a device to help them study molecular structures."

(from: http://www.bell-labs.com/history/laser/)

Why do lasers exist?

Schawlow and Townes had invented the **Maser** in 1958, and the first working **laser** was demonstrated on 16 May 1960 by Theodore Maiman at Hughes Research Laboratories.

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50 years later, lasers have become a multi-billion dollar industry

What are masers and lasers?

(acronyms)

Microwave **A**mplification by **S**timulated **E**mission of **R**adiation

Light **A**mplification by **S**timulated **E**mission of **R**adiation

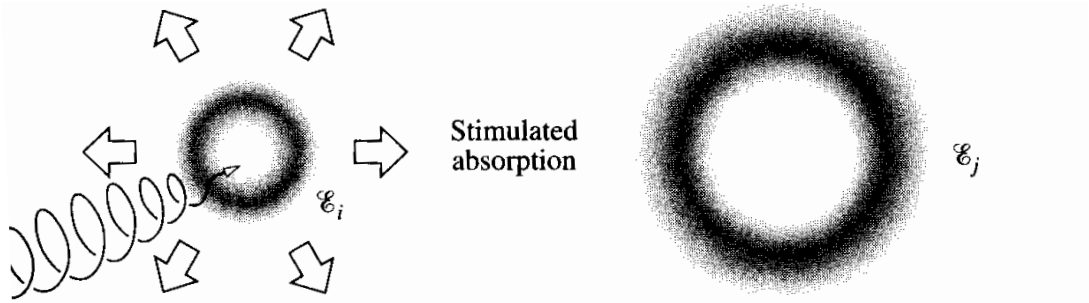
"An optical maser"

production of light (electromagnetic radiation) through a process called stimulated emission

before

after

photon in



atom in low energy state

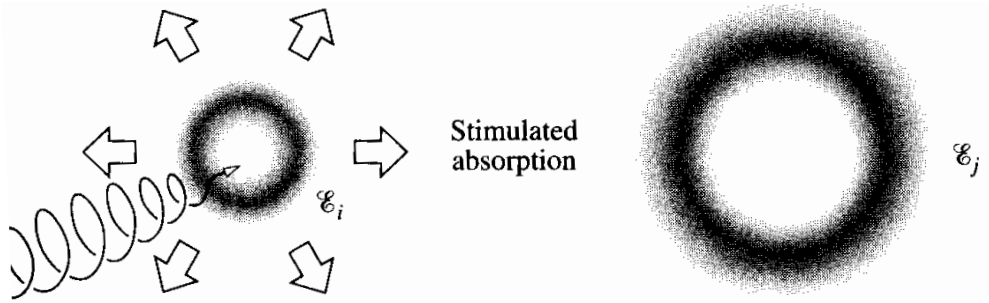
atom in high energy state

fundamental processes of atom-light interactions

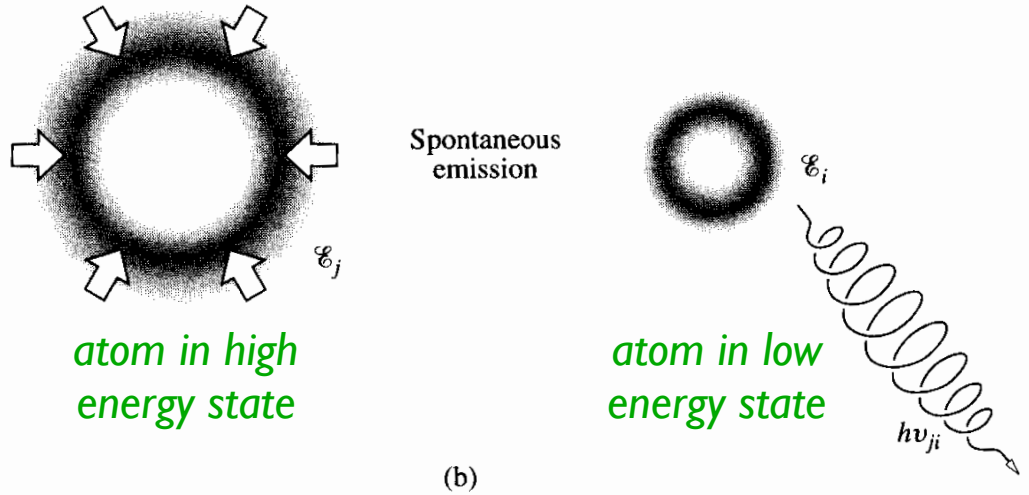
absorption and emission of light

before

after



(a)



atom in high energy state

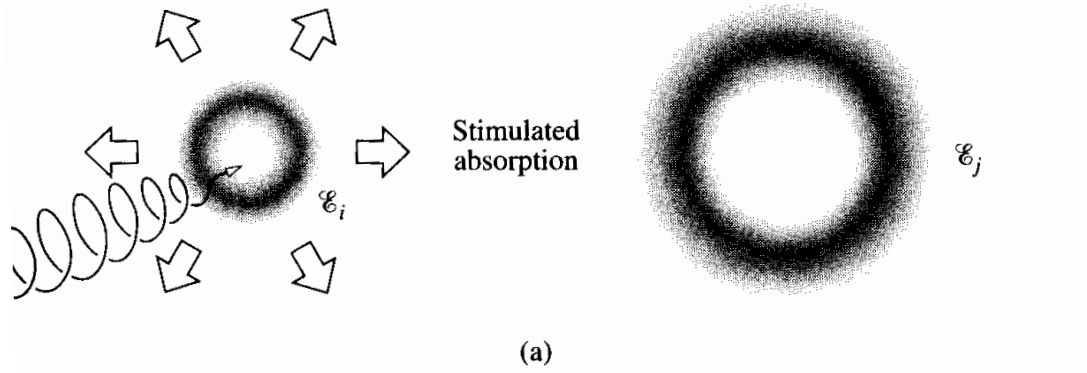
atom in low energy state

(b)

photon out (random direction)

before

after



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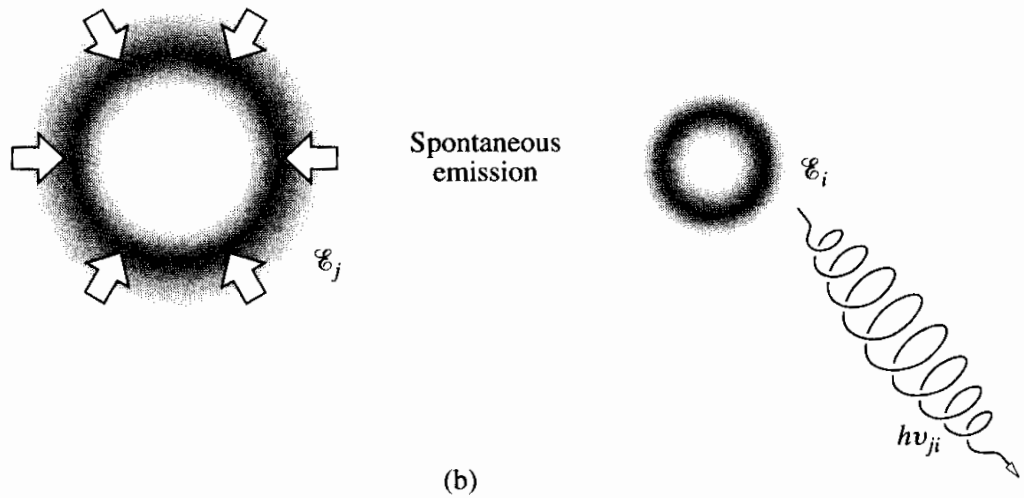
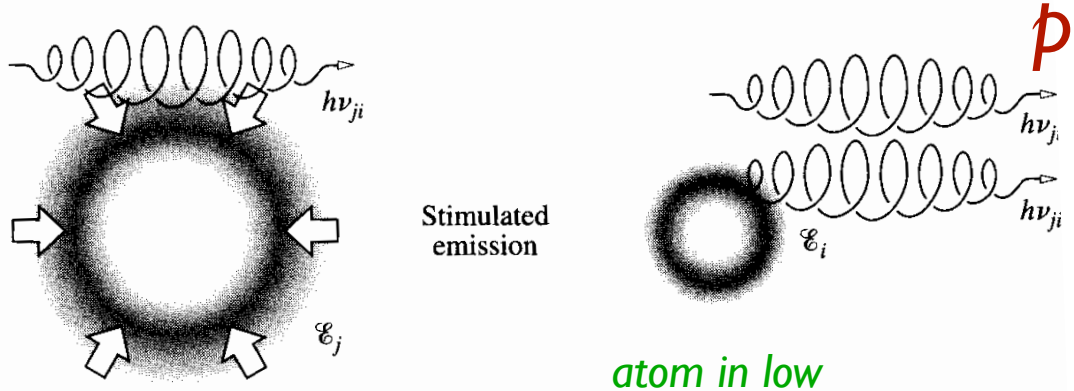


(b)

photon in



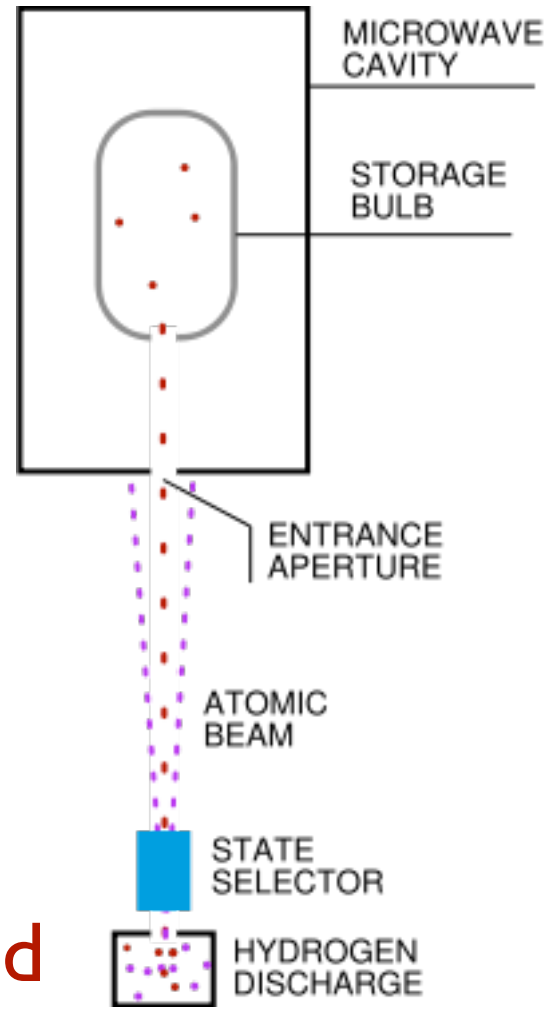
atom in high energy state

(c)

atom in low energy state

photon stimulated out into same direction as the input photon

The hydrogen maser



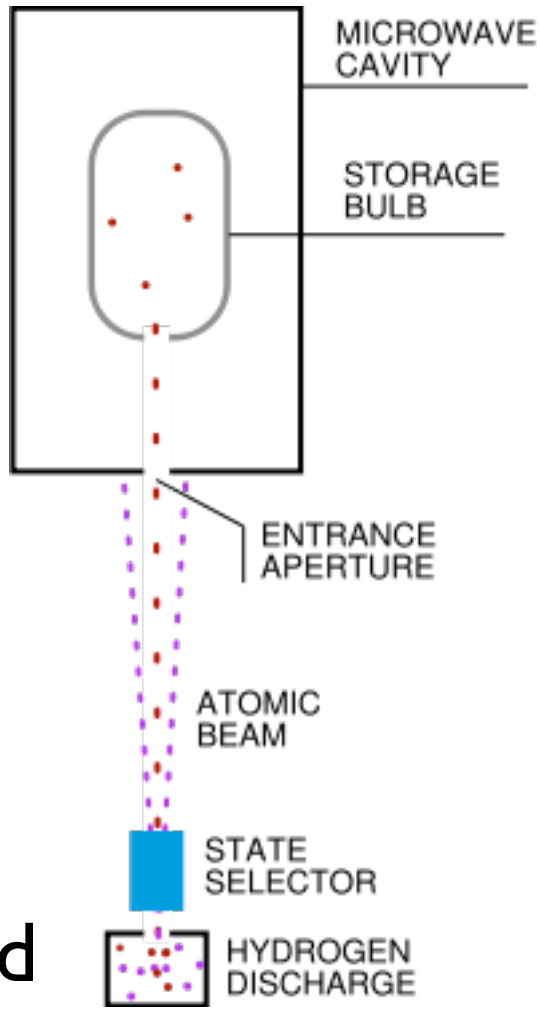
atoms are first excited

image from http://content.answers.com/

The hydrogen maser

the excited ones are selected and made to enter a cavity

atoms are first excited



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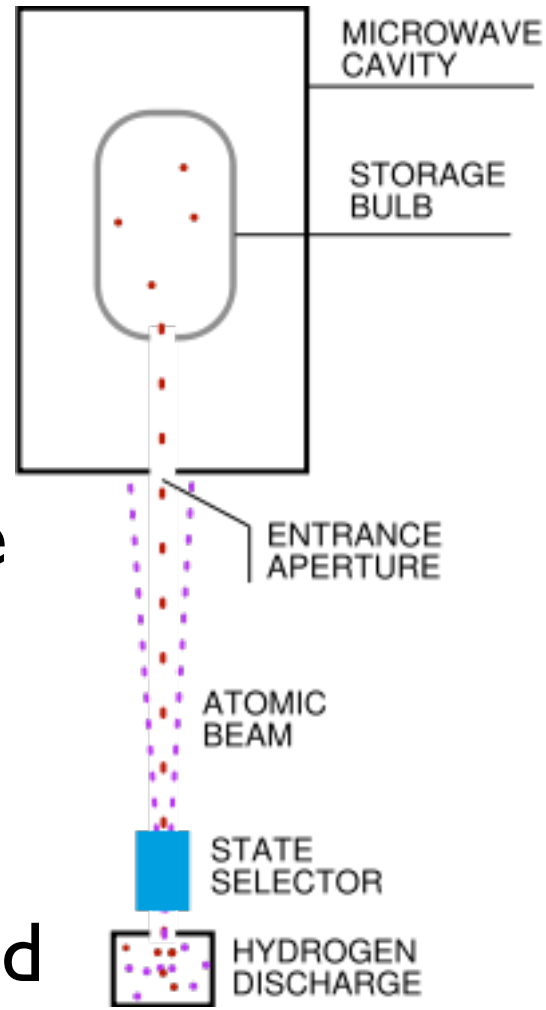
The hydrogen maser

they emit radiation
into the cavity
on its resonance

the excited ones are
selected and made
to enter a cavity

atoms are first excited



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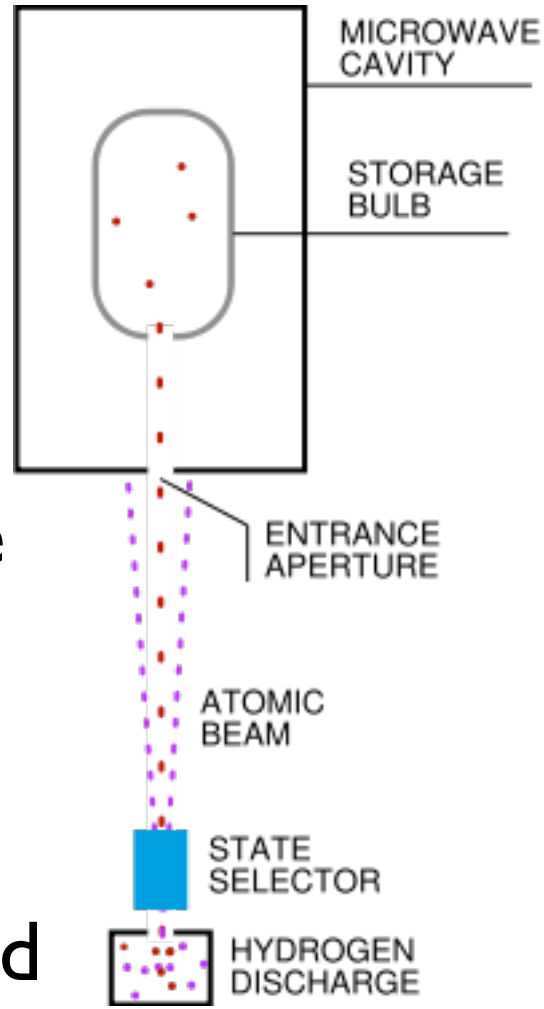

a small amount of radiation is extracted for use

image from http://content.answers.com/

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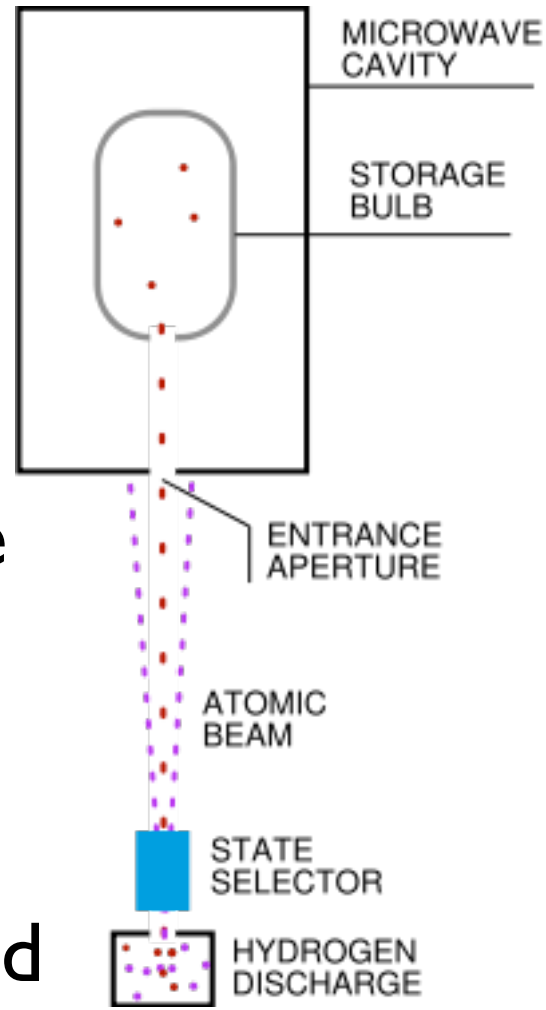


a small amount of radiation is extracted for use

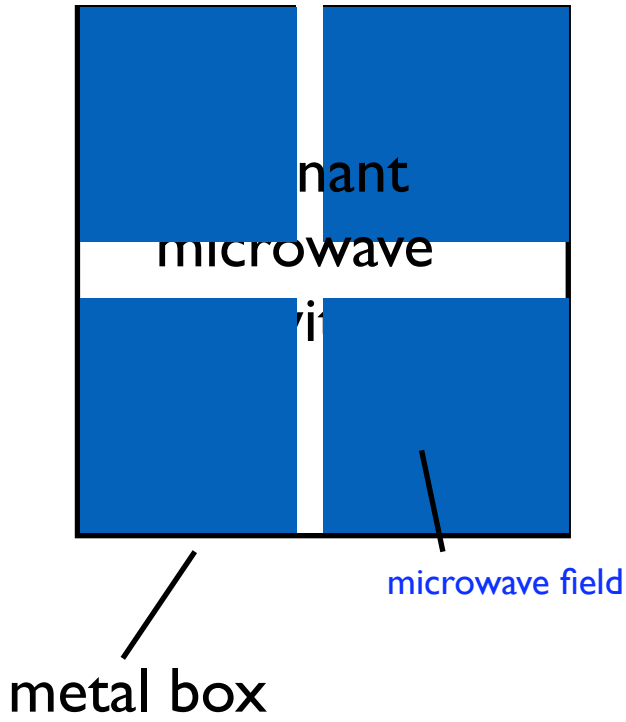
think of exciting the resonance of a bottle by blowing

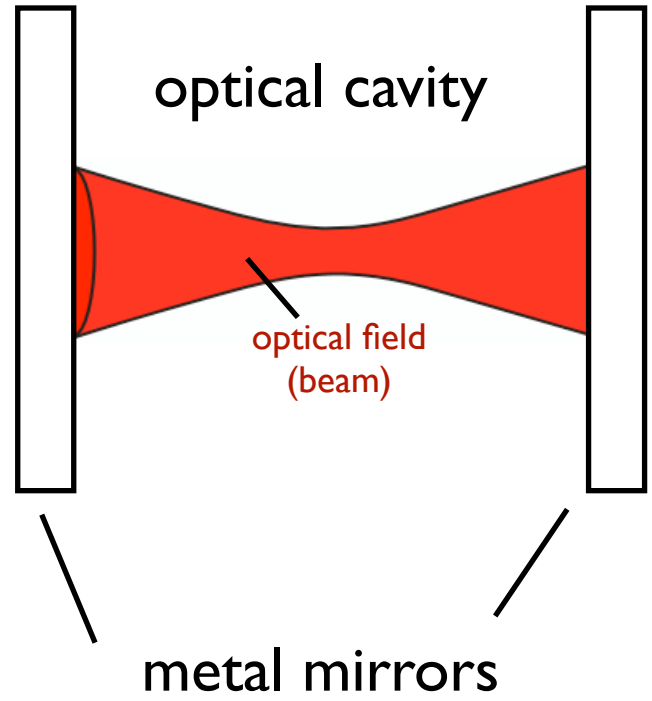
image from http://content.answers.com/

Maser

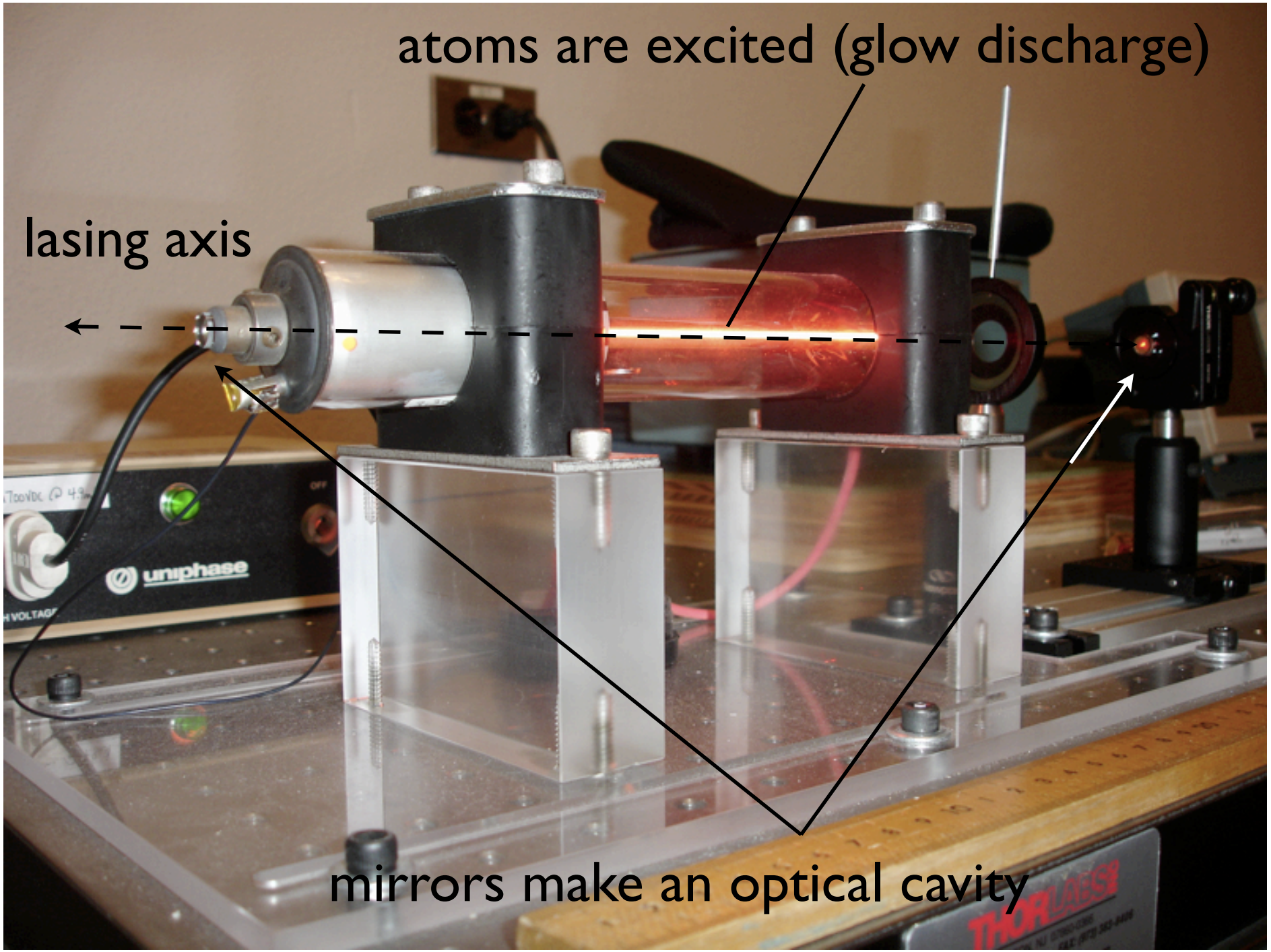
Laser

one main difference is the cavity and field shape...





The HeNe Laser



What are the properties of lasers?

the light is generated in a resonator and is therefore "coherent" - *all the photons do the same thing*.

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spatial coherence - light emitted in a narrow, low-divergence beam (all the light travels in the same direction)

temporal coherence - monochromatic or polychromatic waves with a well defined phase (all the light contributes to the same collective wave)

typically laser light is
highly directional (intense)
monochromatic (narrow spectrum)

Applications

Applications

“mainstream visible uses”

data storage and transmission

navigation and telemetry:

research:

Applications

"mainstream visible uses" [directionality, intensity]
bar code readers (grousse mountain, grocery checkout)
laser printers and laser pointers
entertainment - laser light shows
laser machining: laser inscribing, cutting, bending, and welding metal
laser surgery (eye surgery)
medical diagnostics/sensors [monochromaticity]

data storage and transmission [directionality, intensity]
CD ROM, magneto-optical disks
fiber-optic communication
quantum communication - quantum cryptography [quantum properties and coherence]

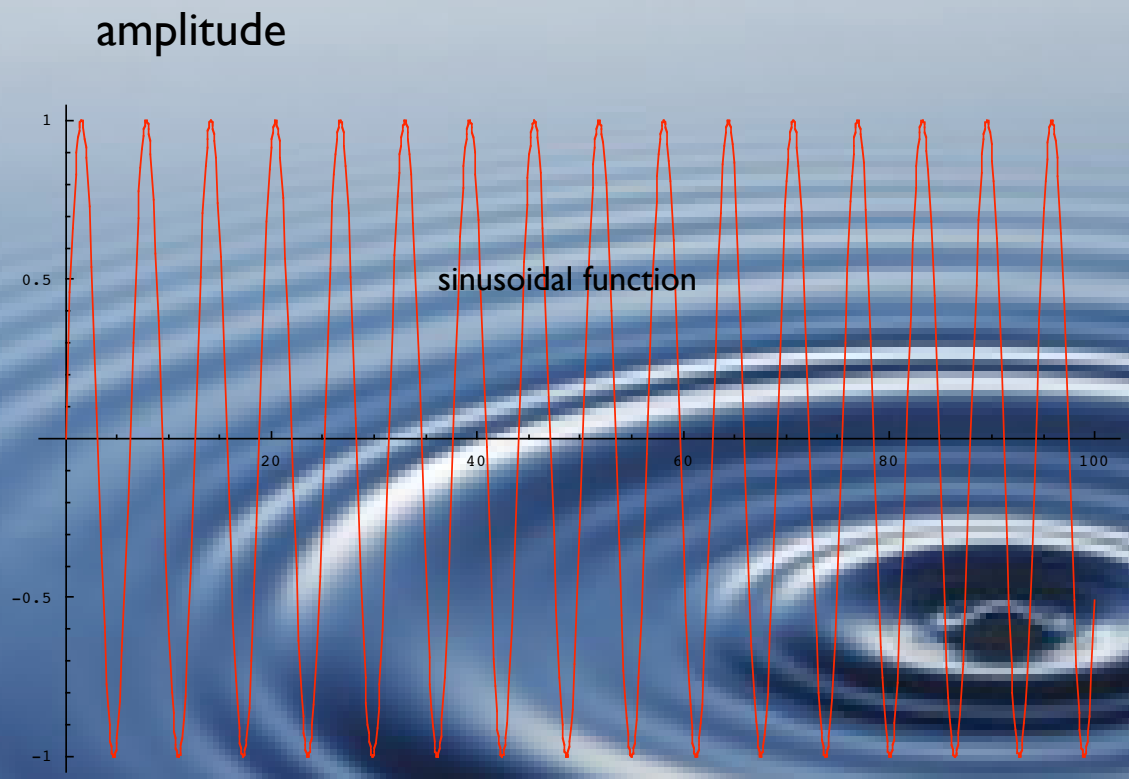
navigation and telemetry: [directionality and coherence]
laser gyroscopes
GPS and atomic clocks
LIDAR - radar but with lasers
range-finding, target designation, and illumination

research: [directionality, coherence]
biomedical: optical tweezers: cancer detection by stretching cells
laser plasma interactions - extreme forms of matter
laser cooling

Wave Coherence

Temporal Coherence

sound
pure tone



light
monochromatic

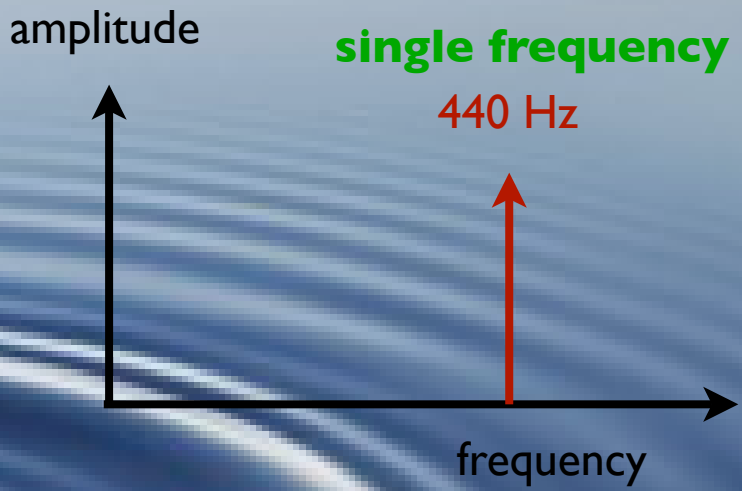
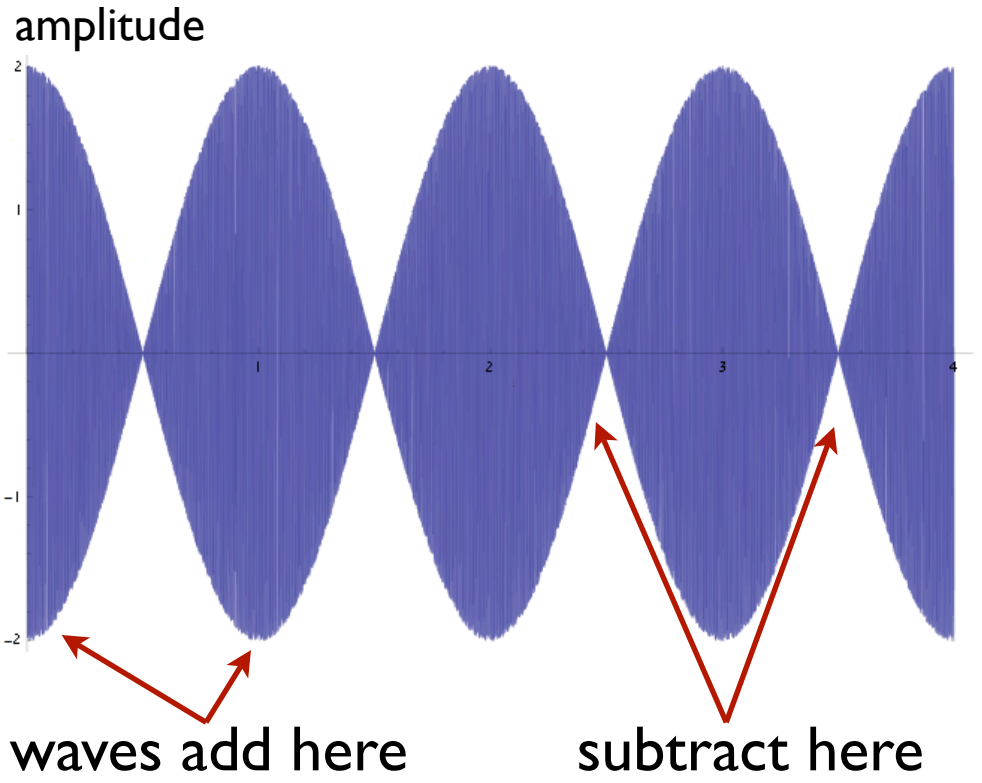


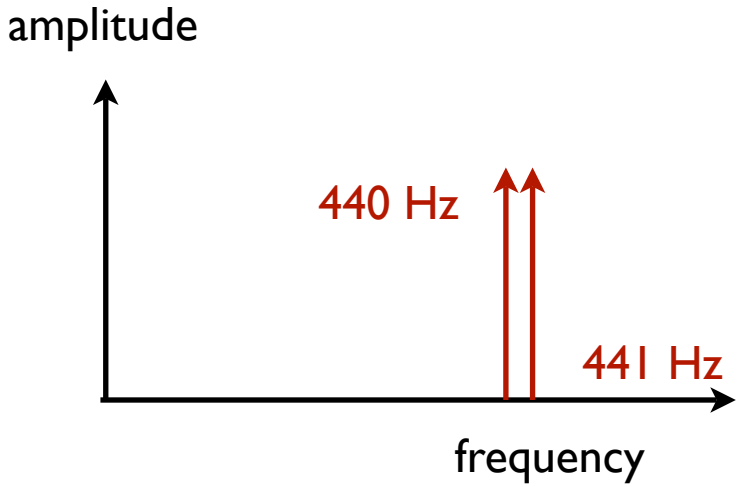
image from www.kaushik.net

Temporal Coherence

sound
two tones

light
bi-chromatic



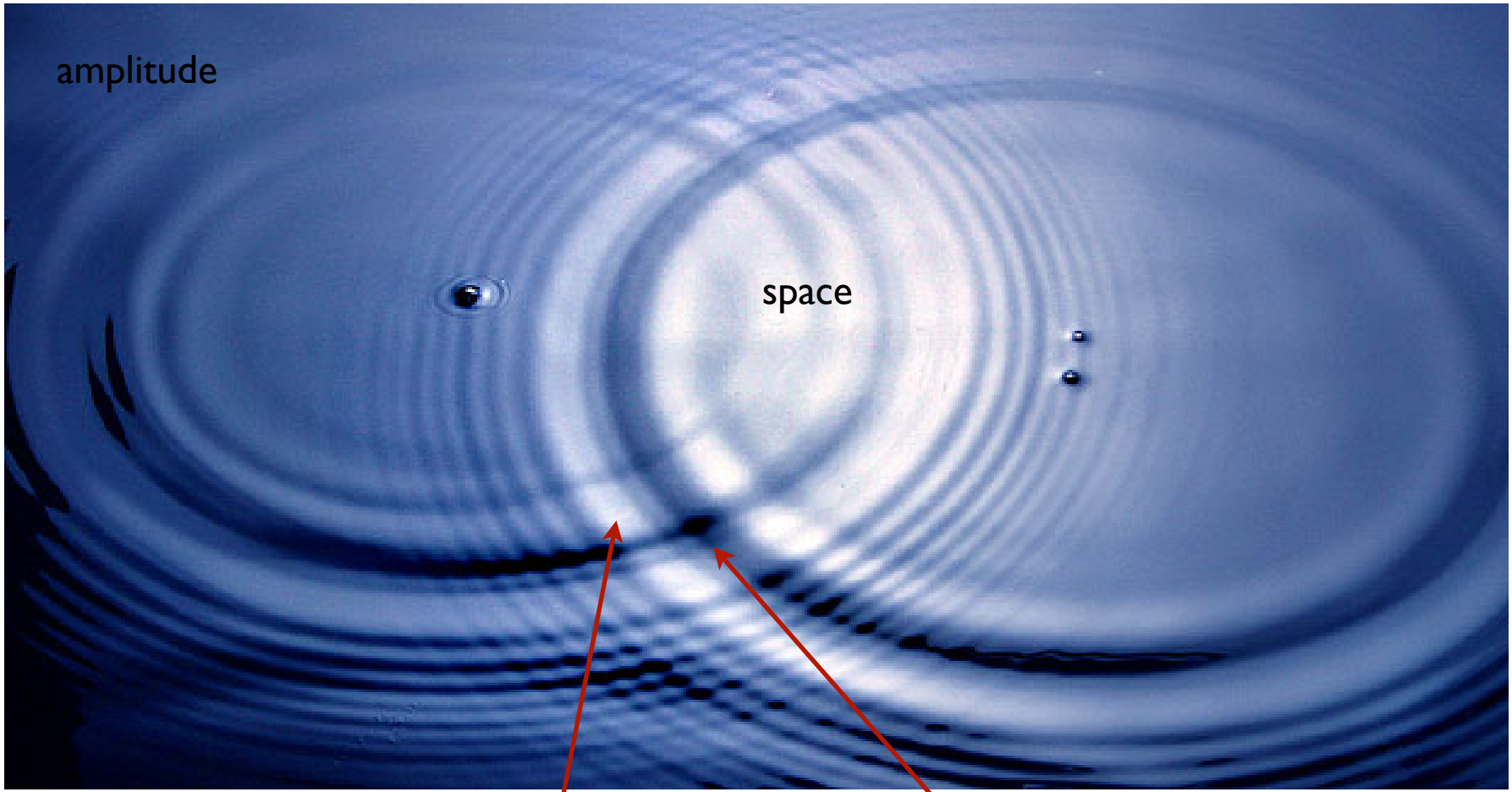


amplitude beating caused by **wave interference**

Spatial Coherence

sound
two tones

light
bi-chromatic



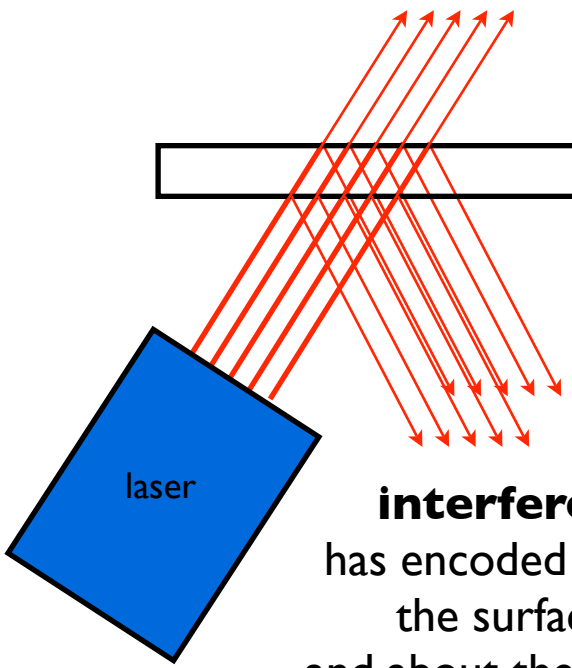
amplitude beating caused by **wave interference**

image from www.kaushik.net

Spatial Coherence

interference pattern gives a measure of spatial coherence

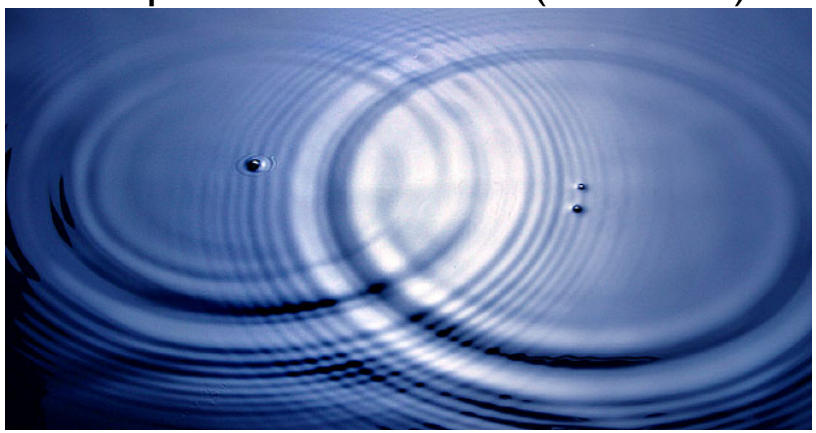
create two copies of beam with glass slide



monochromatic laser beam
"interferes" with itself

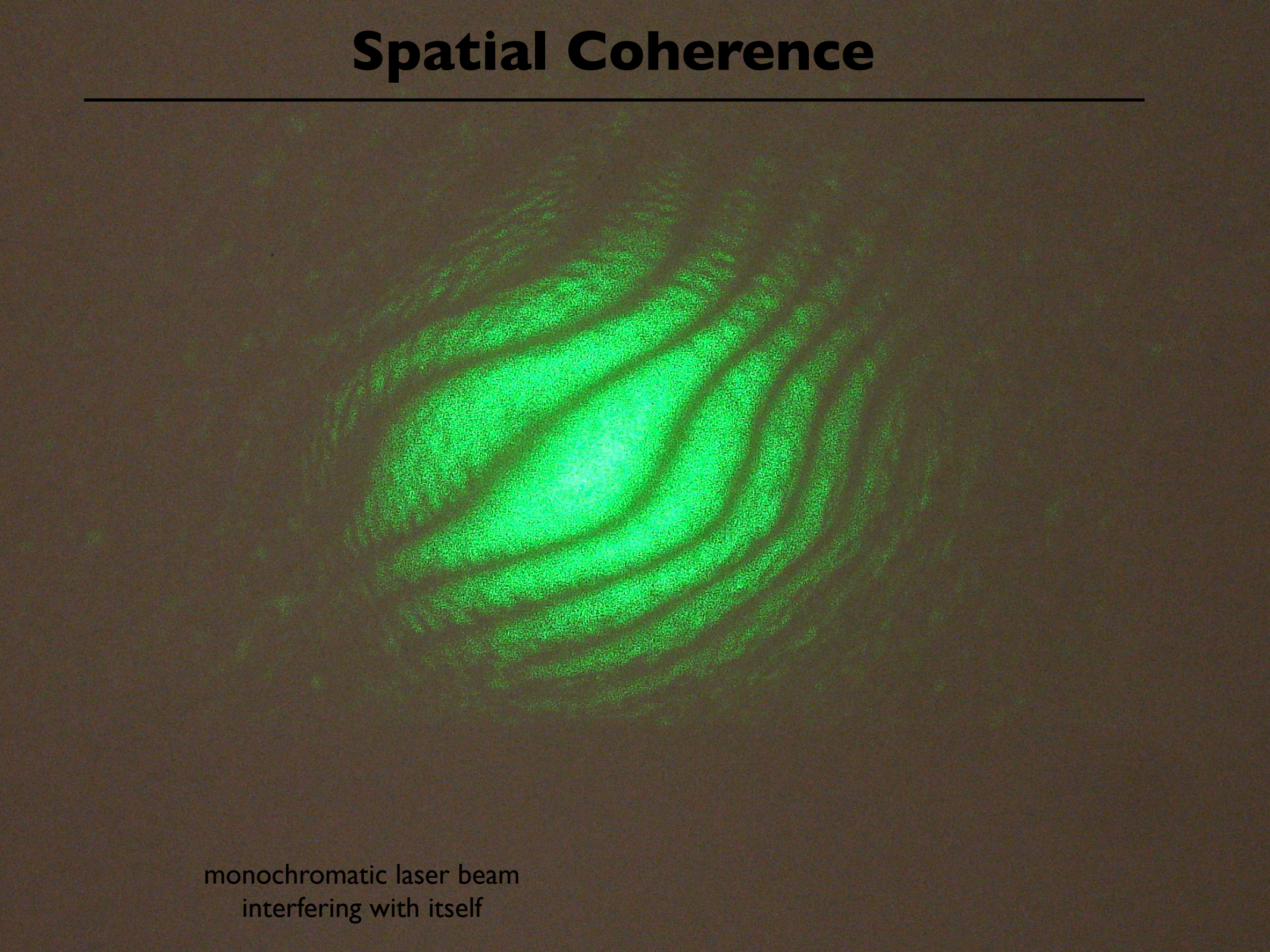
interference pattern
has encoded information about
the surfaces of the glass
and about the wavelength of light

from wavelet pattern, you can deduce
the wavelength of the waves
and position of sources (curvature)



interferometry

Spatial Coherence

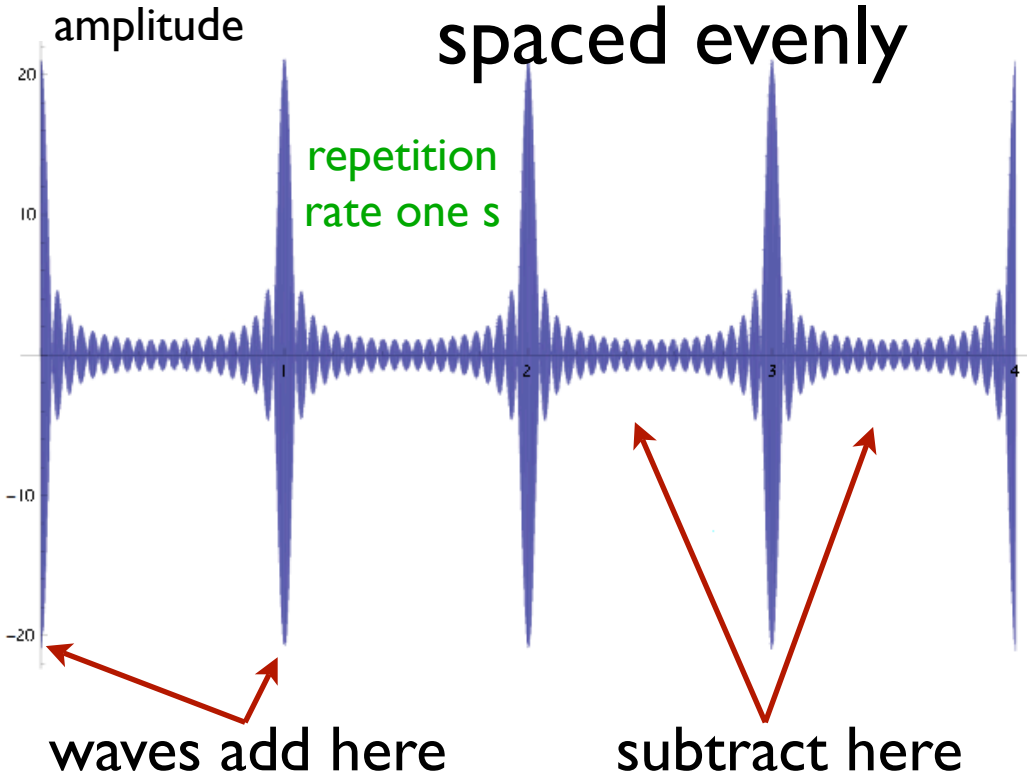


monochromatic laser beam
interfering with itself

Temporal Coherence

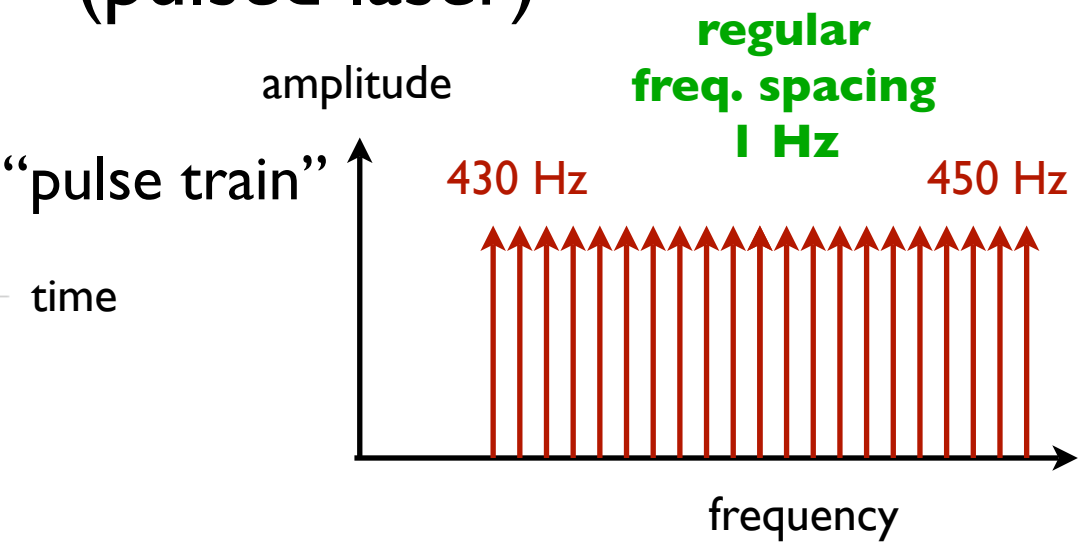
sound

multiple tones
spaced evenly



light

poly-chromatic
(pulsed laser)

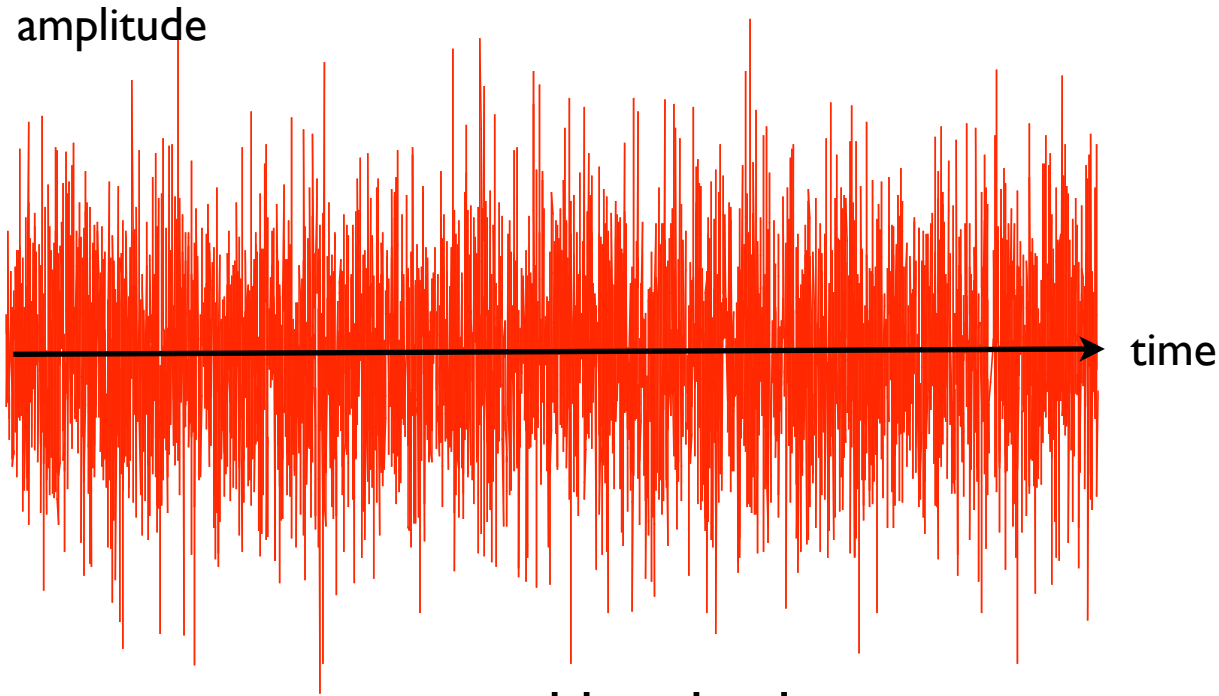


amplitude beating caused by **wave interference**

phase of waves critical to their adding correctly

Temporal Coherence

sound
"white noise"



many waves add and subtract
simultaneously producing rapid fluctuations

light
"white light"

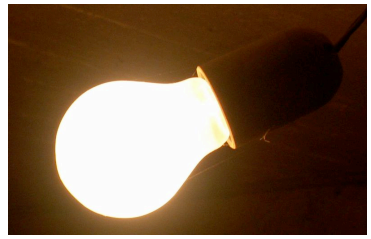
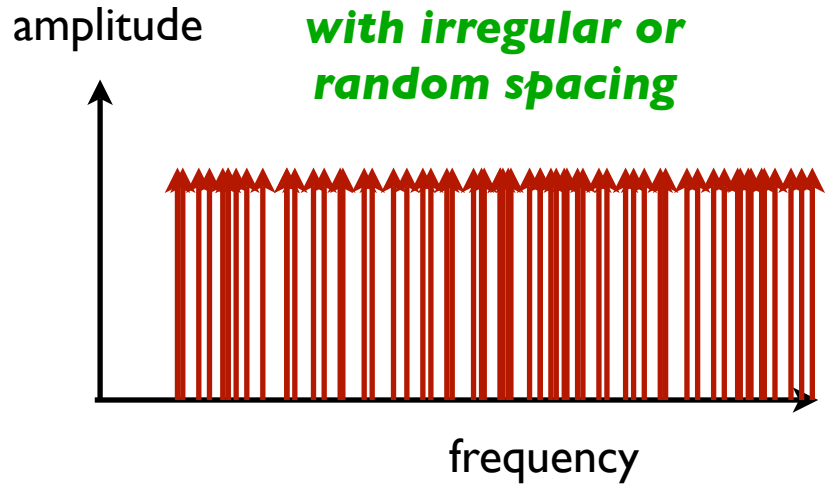


image from wikimedia.org

many frequencies with irregular or random spacing



phase of waves scrambled by random distributions of frequencies

wave interference not evident because of competing patterns

Spatial Coherence

light comes out in all directions.
each photon does something different

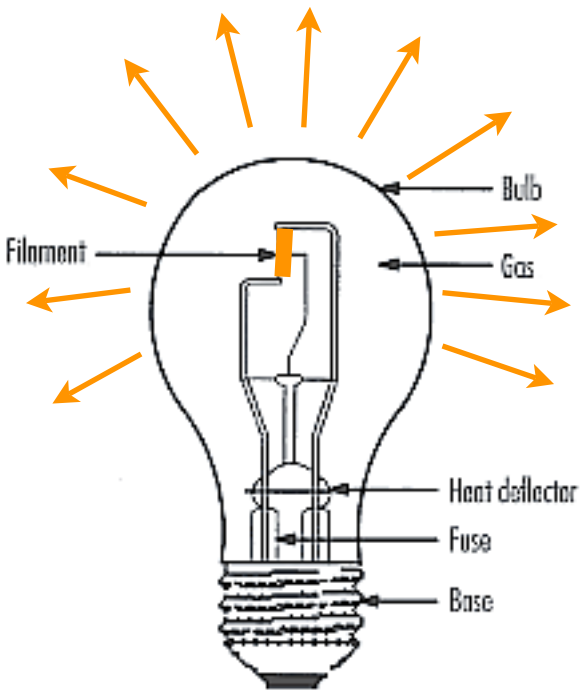
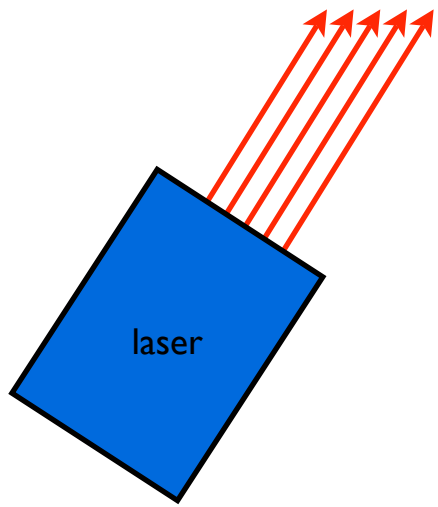


image from oee.nrcan.gc.ca

light emerges from a laser cavity in a spatially coherent beam.
each photon traveling in the same direction.



Directionality & intensity

Applications of spatial coherence: directionality, intensity, power

Laser machining

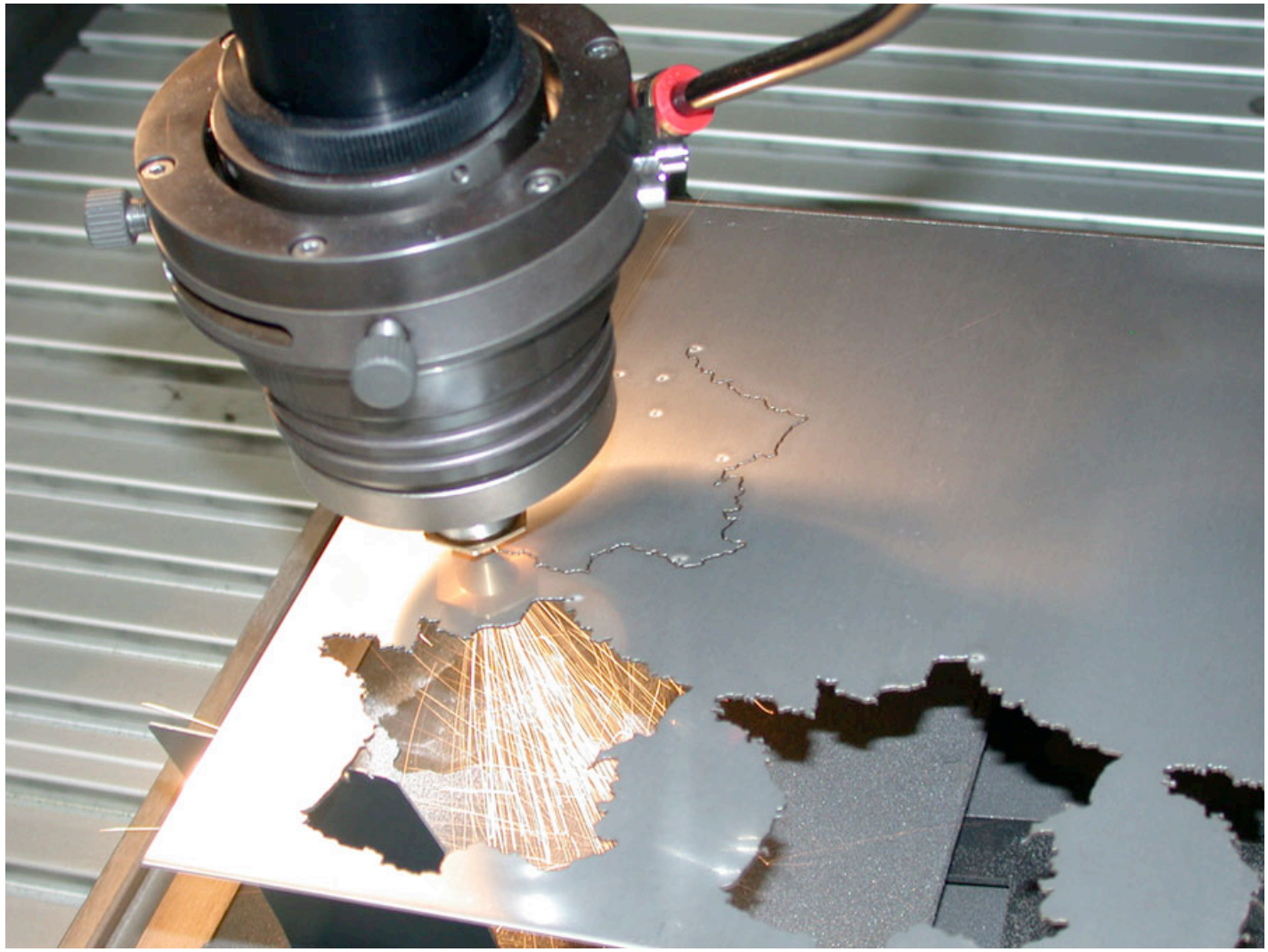


image from www.lasercheval.fr

Laser printing

A laser beam is scanned across a charged selenium drum where it removes electrostatic charges. The remaining charge holds the carbon particles of the toner and the image is transfered to paper by stretching the paper over the drum and heating.

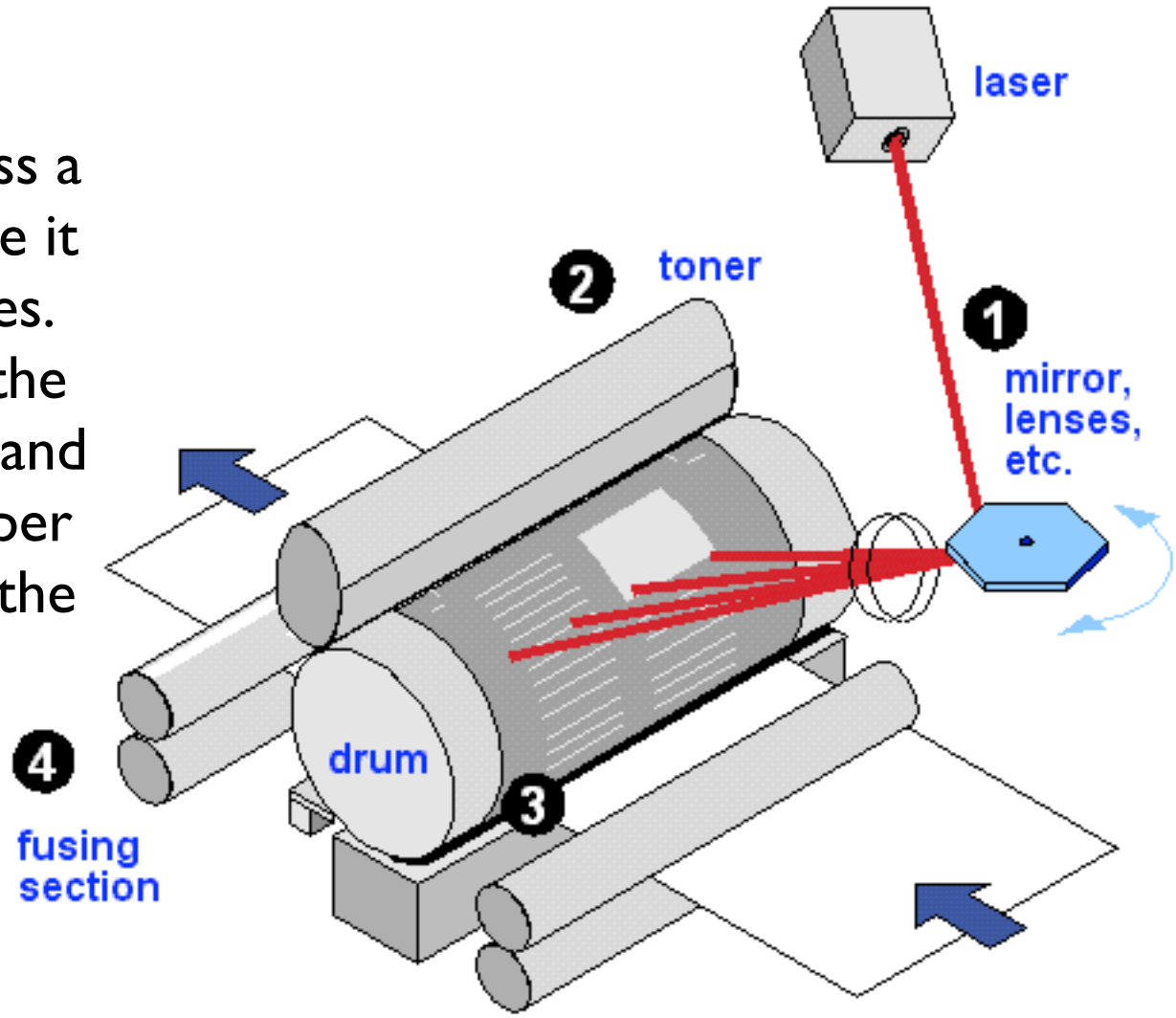
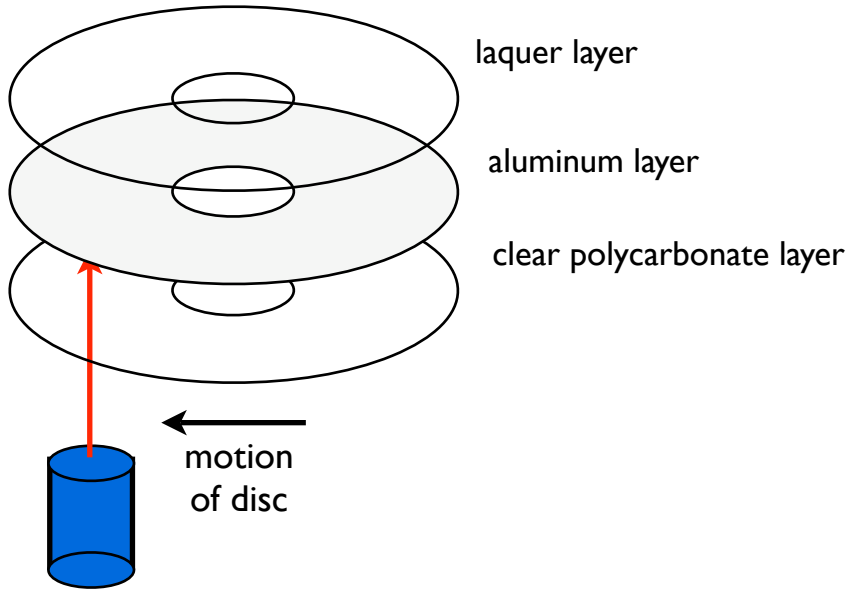
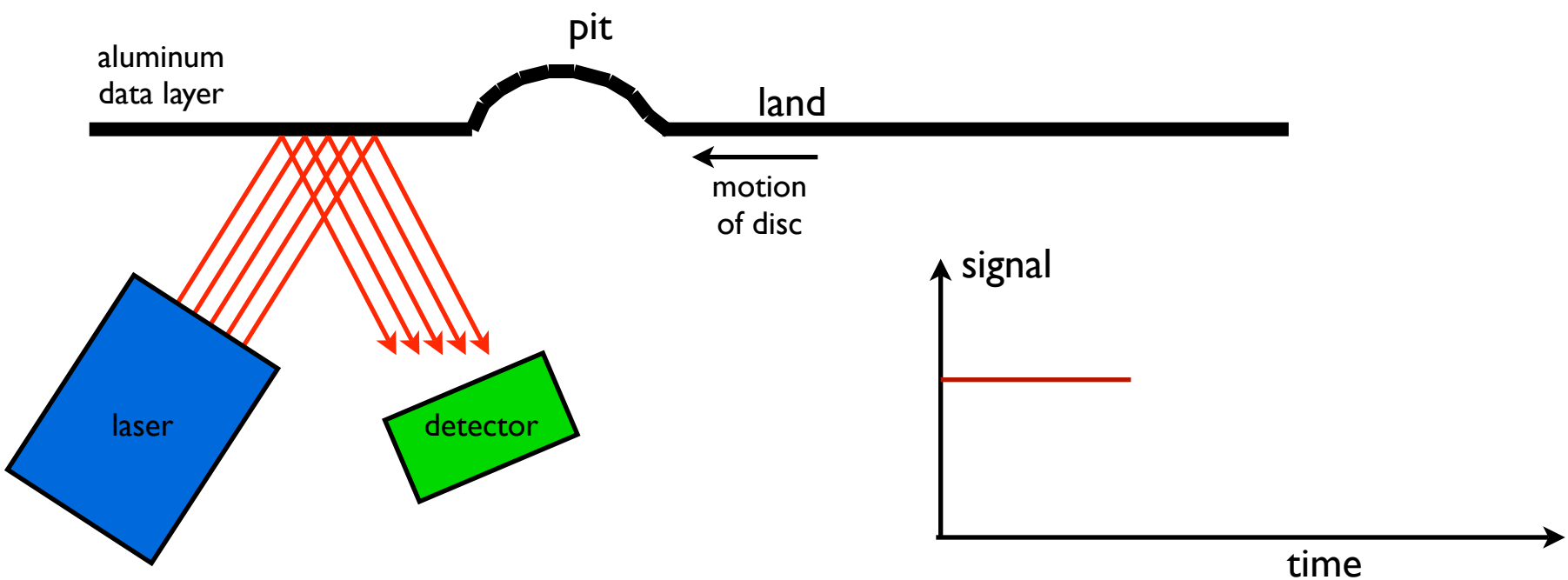


image from dictionary.zdnet.com

Data Storage

CD (compact disc)

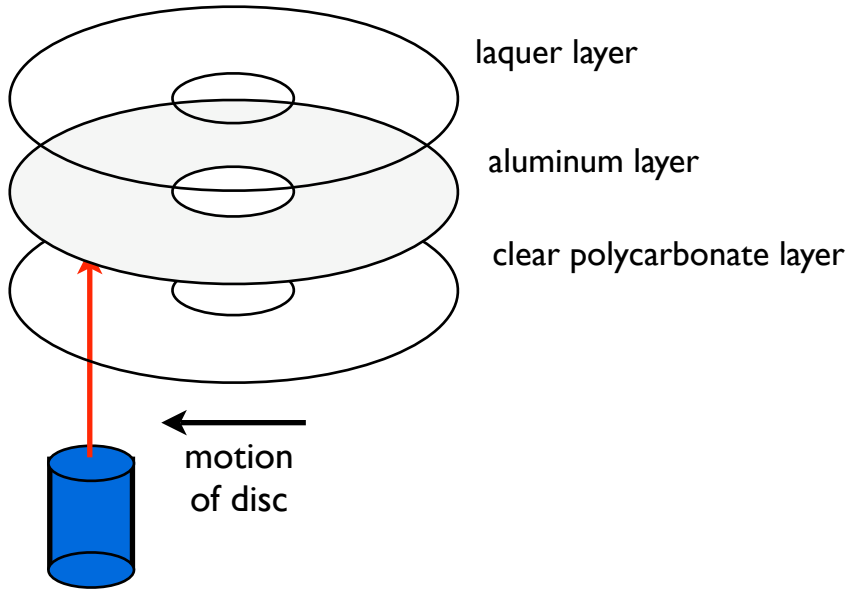


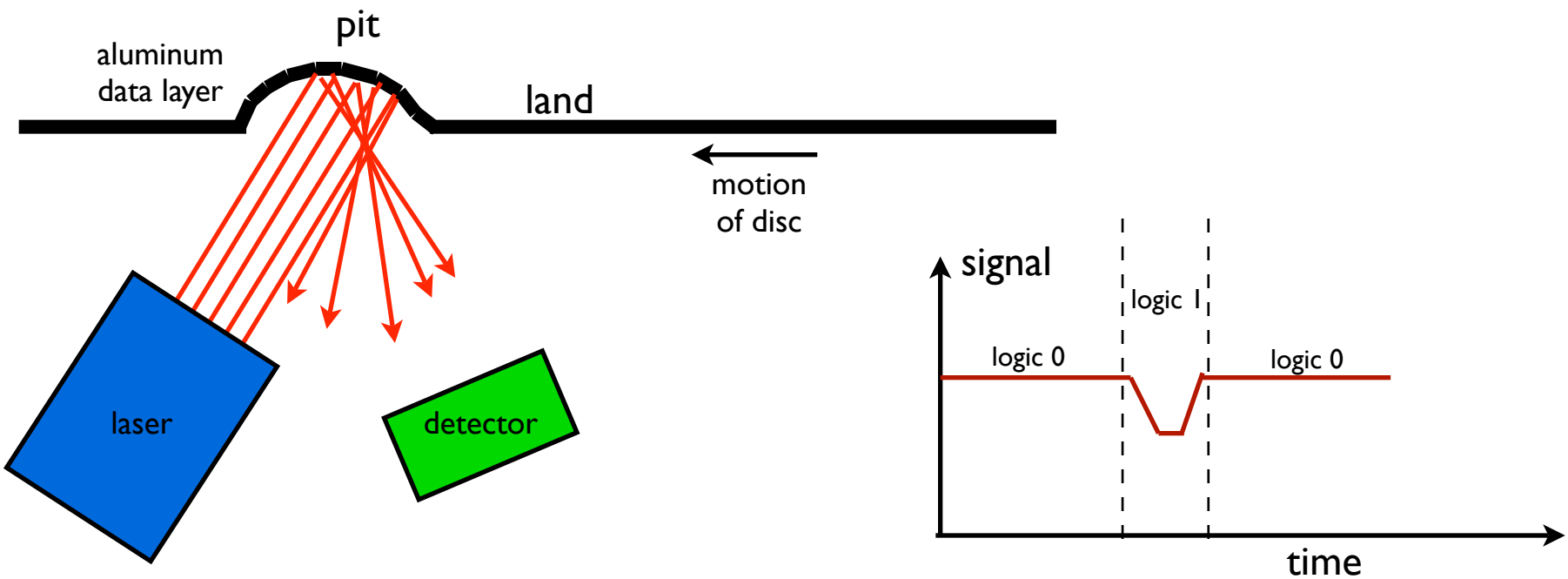


Digital data are carved into the CD-ROM as pits (low spots) and lands (high spots). As the laser shines into the moving pits and lands, a sensor detects a change in reflection when it encounters a transition from pit to land or land to pit. Each transition is a 1.

Data Storage

CD (compact disc)





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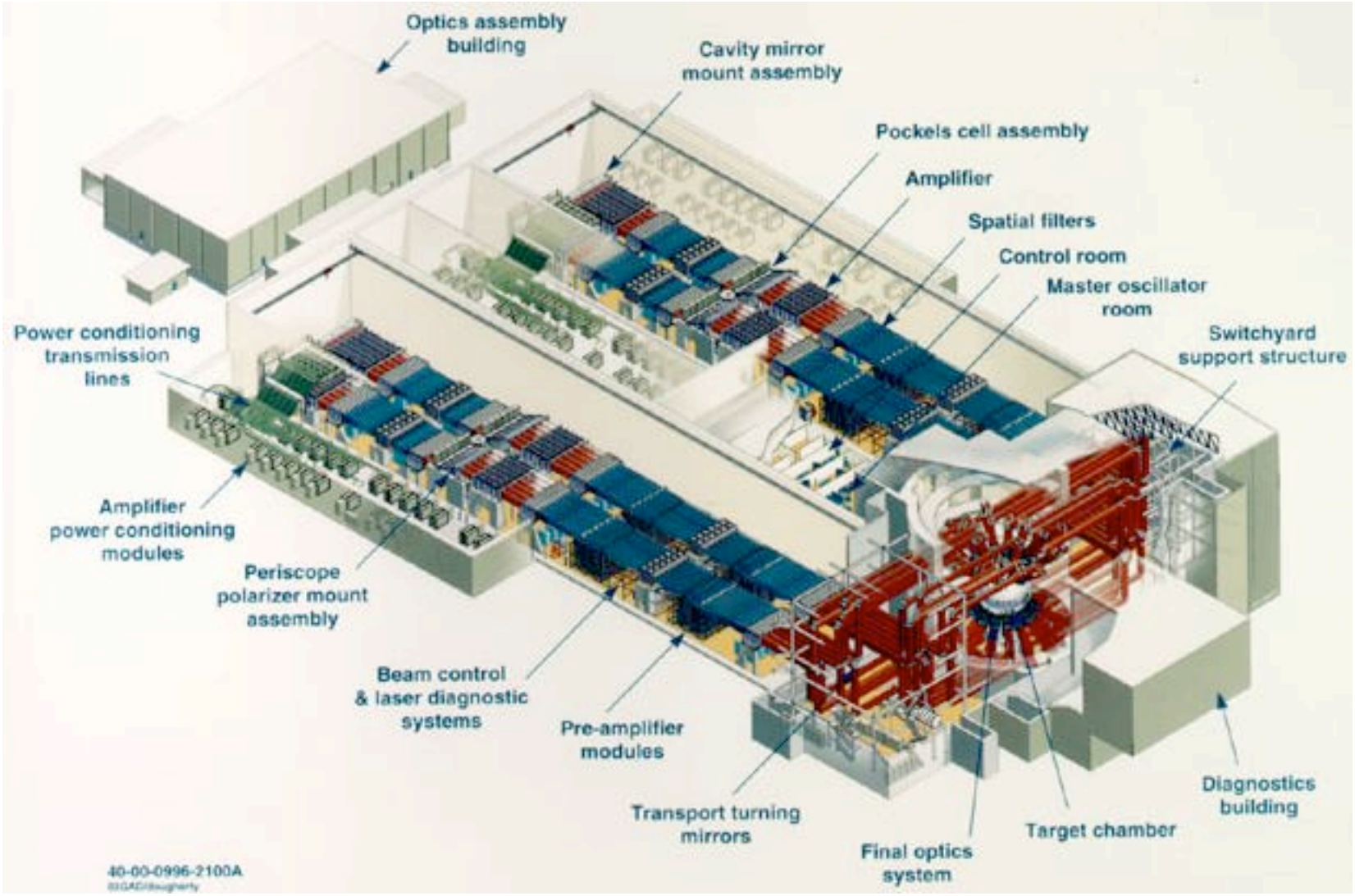
Directionality, intensity, power



National Ignition Facility (Livermore CA)

http://www.youtube.com/watch?v=dmIHD6P3rdo

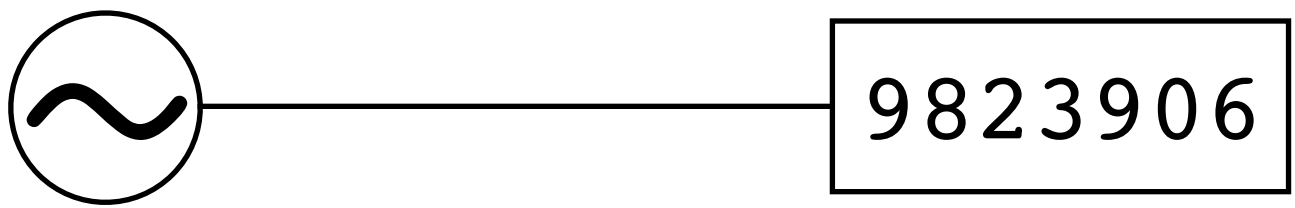
"creating supernovae in the laboratory"

Applications of temporal coherence: realizing an atomic clock

What is a clock?

An Oscillator
(Generates periodic events)

A Counter
(Counts and displays events)

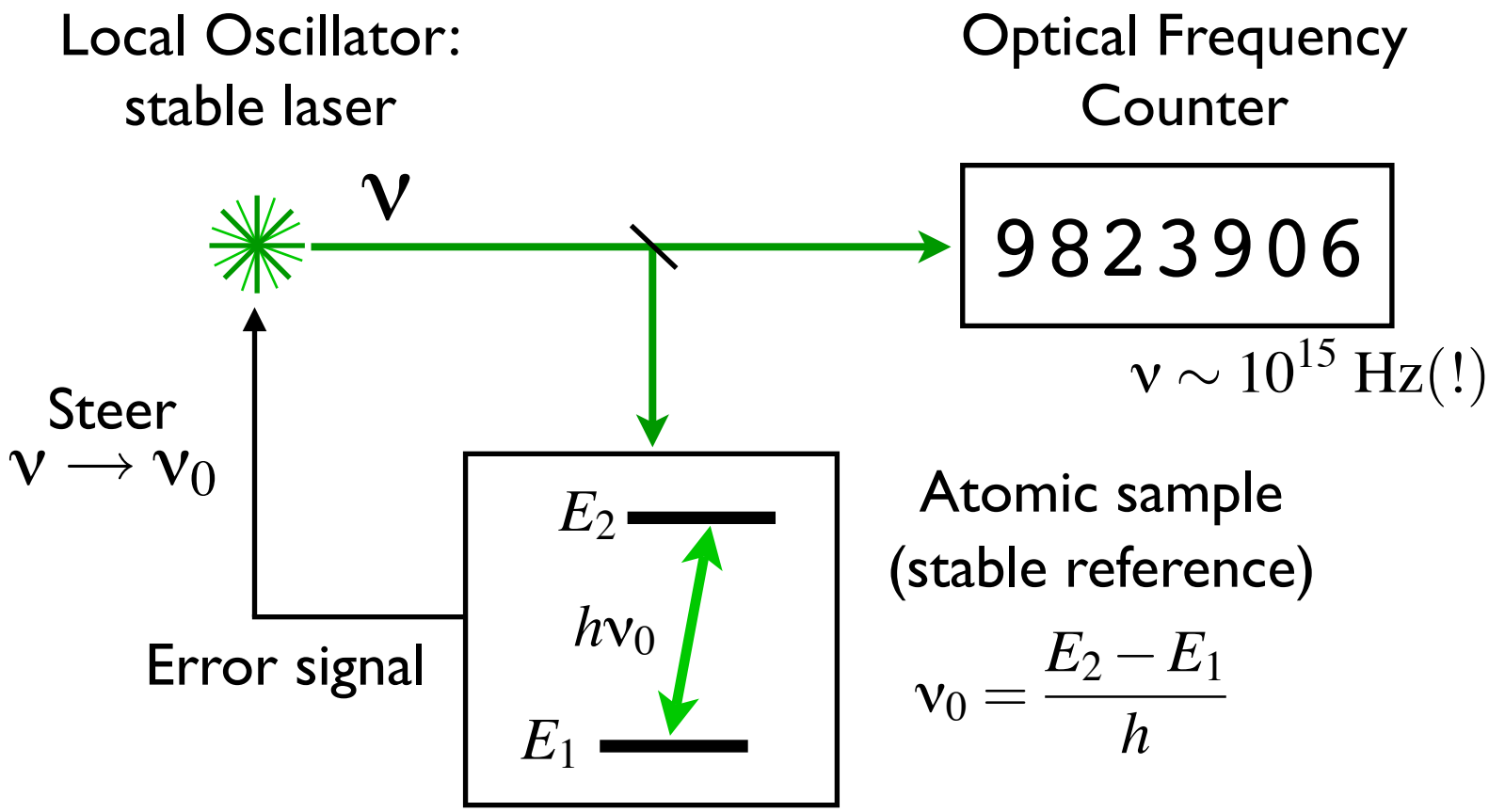


Mechanical pendulum ——— Gears and clock face

Quartz crystal ——— Electronic counter

original slide from Dr. Windell Oskay

Optical frequency clocks



- Local oscillator is stable laser (not quartz crystal)
- Need to count frequency of light
  - -Only recently practical

original slide from Dr. Windell Oskay

Applications of atomic clocks

- Precision Measurement
  - The second can be implemented more accurately than any other SI base unit
  - Meter defined in terms of second

- Navigation and positioning:
  Satellite navigation and ranging; **GPS**, etc.

- Communication
  - Network synchronization
  - High-speed communication

- Fundamental tests
  - High-resolution spectroscopy
  - Astronomical relativity tests possible through VLBI
  - Tests of quantum mechanics
  - Equivalence principle, relativity
  - Stability of fundamental constants

original slide from Dr. Windell Oskay

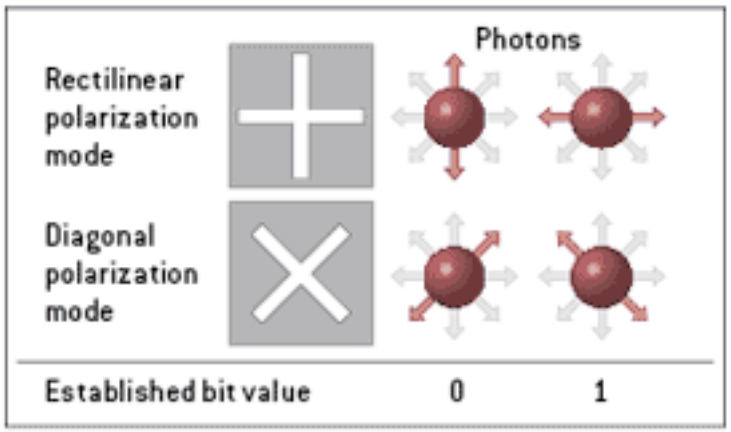
Quantum cryptography
(21st century telecommunications)

quantum mechanics lets you whisper and know you aren't being listened to

quantum mechanics lets you whisper and know you aren't being listened to

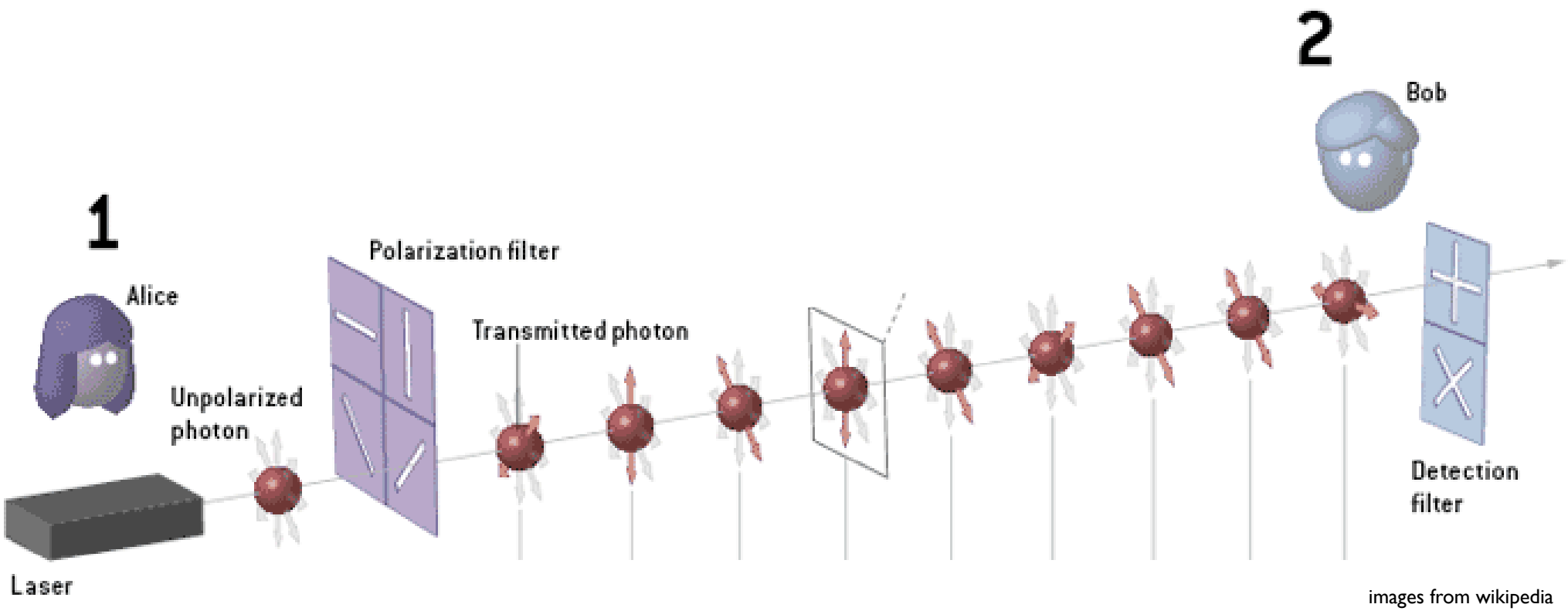
because you can talk by exchanging single photons
and if somebody takes one away or measures one,
you notice...

Quantum Cryptography



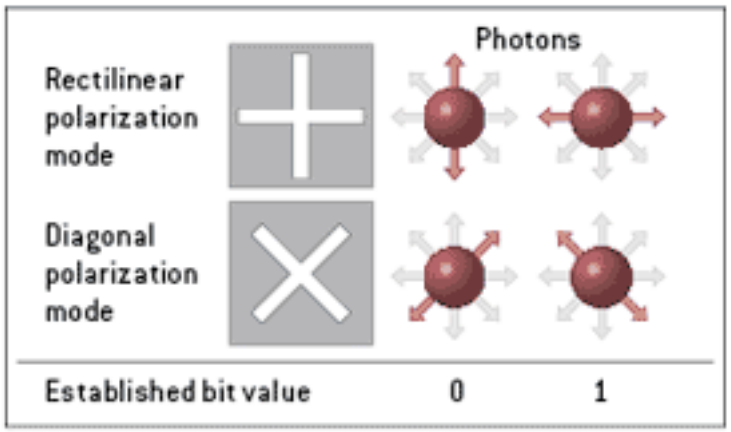
1. Alice sends a photon through either the 0 or 1 slot of either the diagonal or rectilinear polarizers. (this requires a laser)

2. For each incoming bit, Bob randomly chooses a detection filter and records the polarization and bit value

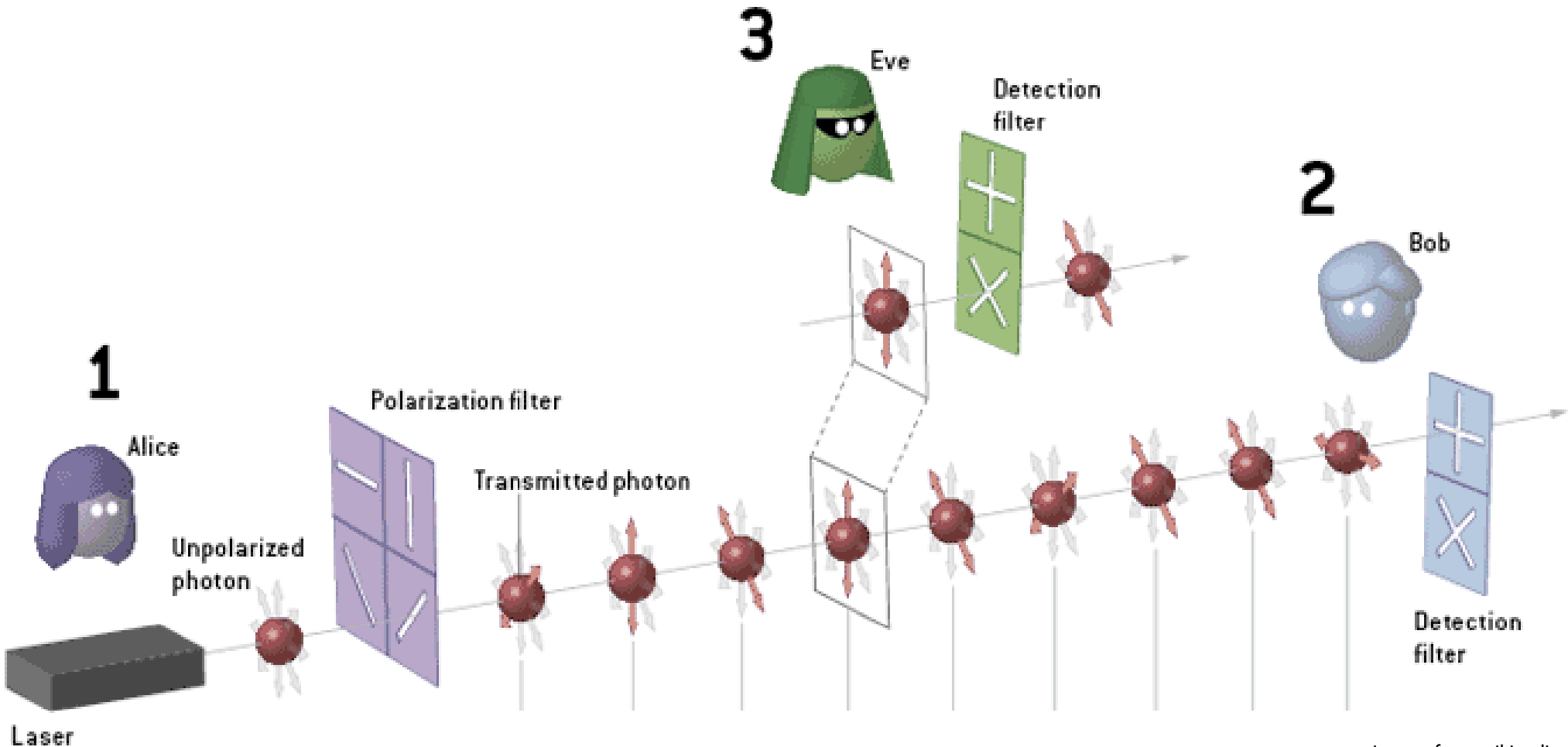


images from wikipedia

Quantum Cryptography

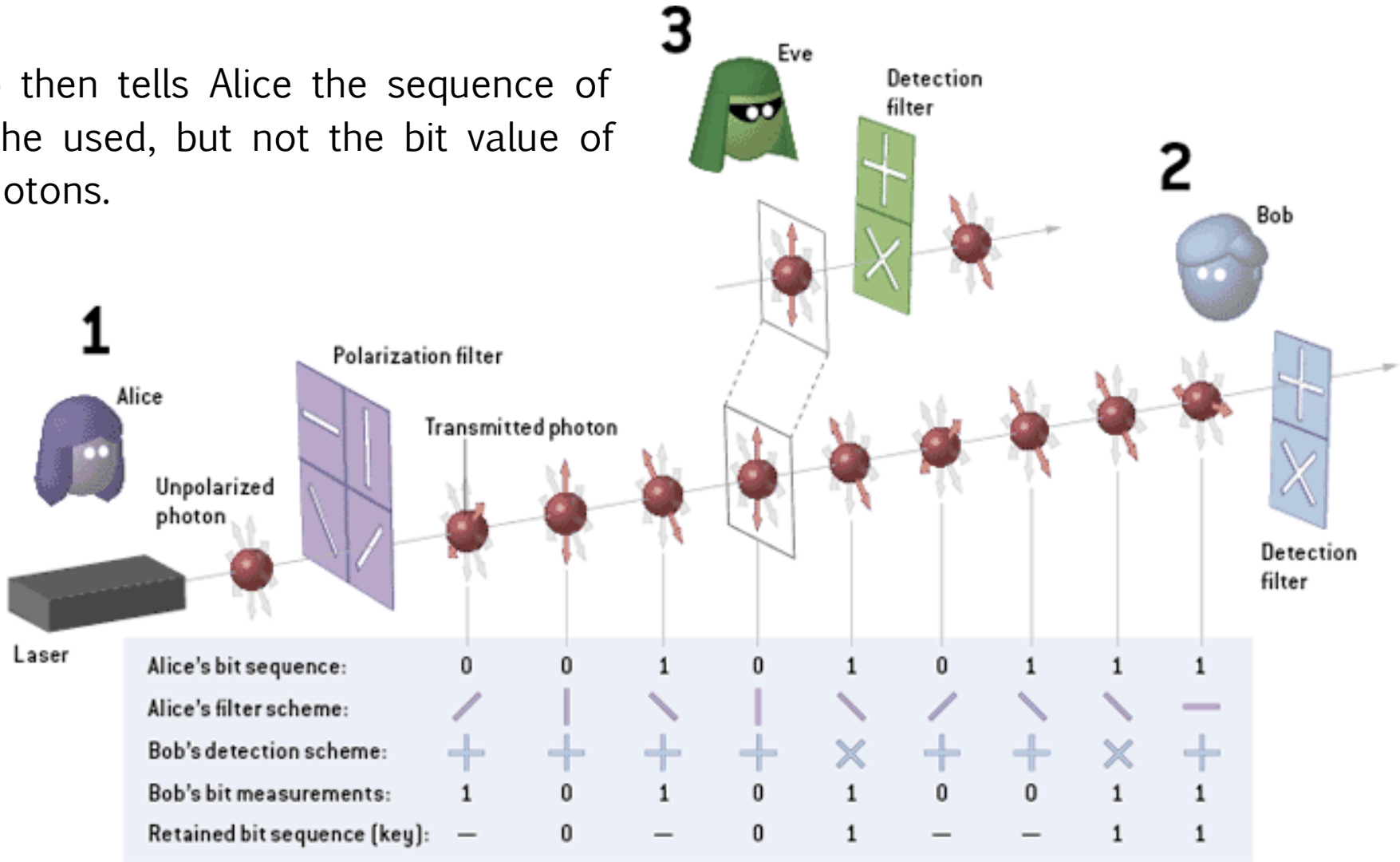


3. If Eve tries to eavesdrop, she might choose the wrong polarization filter and create errors by modifying the photon polarization.



images from wikipedia

4. Bob then tells Alice the sequence of filters he used, but not the bit value of the photons.



5. Alice then tells bob which filters he chose correctly and those instances constitute the bits that they will use to form a private key to encrypt messages

images from wikipedia

Conclusions

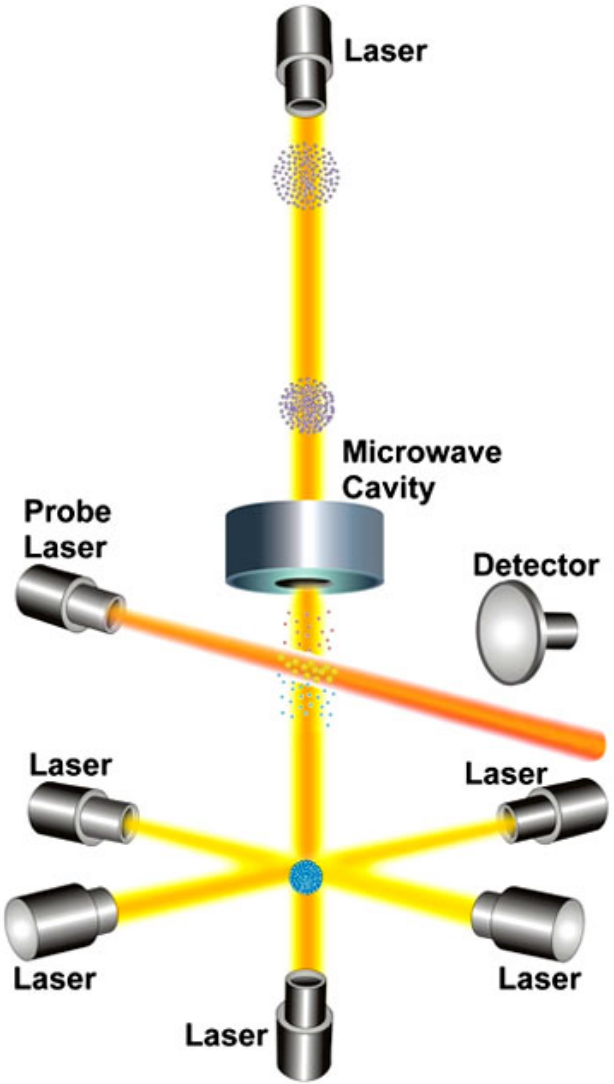
lasers are resonators and therefore sources of coherent light -
all the photons do the same thing

and (like most things of lasting worth) were born out of simple curiosity...

Recalling the early work of Schawlow and Townes, a reviewer noted:

"Neither man was planning on inventing a device that would revolutionize a number of industries, from communications to medicine. They had something more straightforward in mind, developing a device to help them study molecular structures."

Laser cooled atomic fountain clocks: the best clocks in the world



Laser cooling and trapping

Images

• *cold but not trapped*

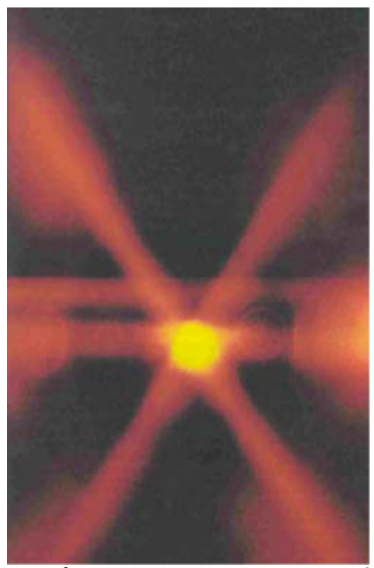
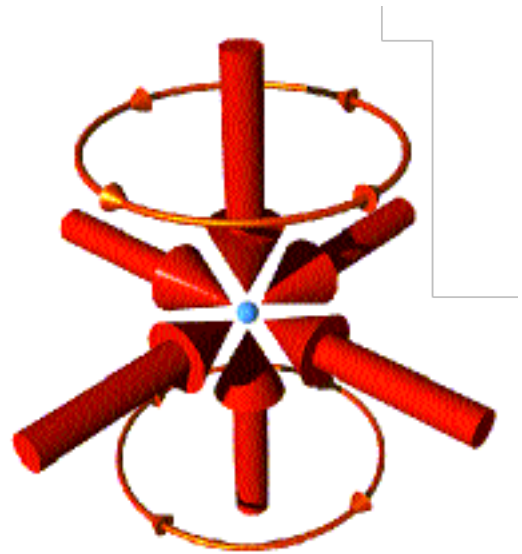


image from www-unix.oit.umass.edu

“optical molasses”



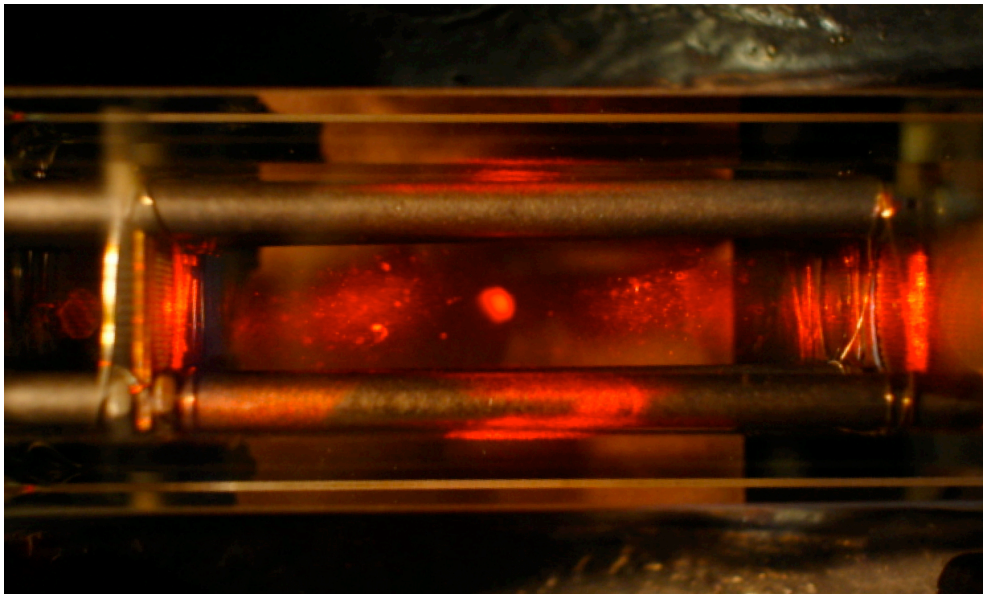
“optical molasses”
plus magnetic field gradient
cooling and confinement

graphics by Dr. Windell Oskay

Laser cooling and trapping

Images

Lithium MOT



Sodium MOT