Bern, 2008

Visions for Physics

Theodor W. Hänsch

Max-Planck-Institute of Quantum Optics, Garching,
and Ludwig-Maximilians University, Munich, Germany

Bern, June 27, 2008

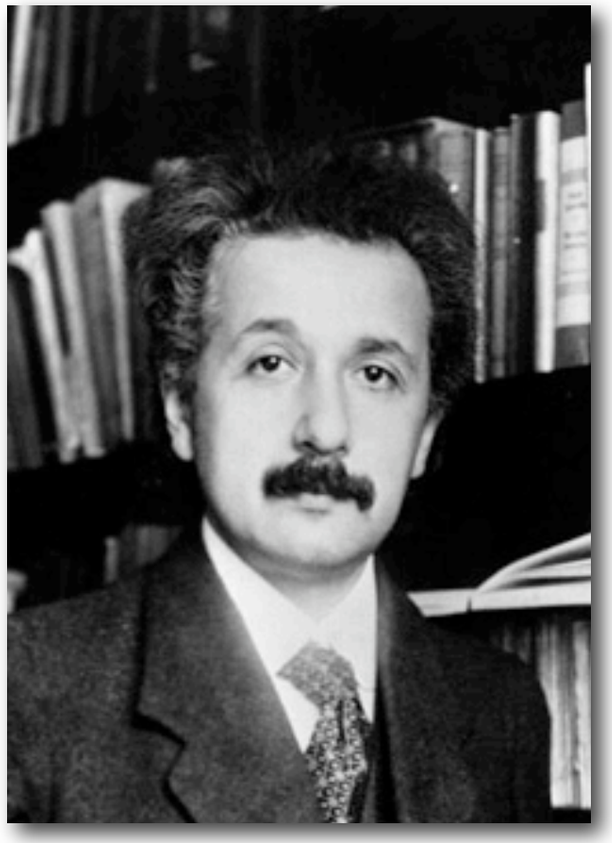
Visions for Physics

Chicago, 1894:

Albert Michelson

“The more important fundamental laws and facts of physical science have all been discovered, and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote...“

Bern, 1905:



Albert Einstein

March 17: Photoelectric effect

May 11: Brownian motion;

Quantum theory of specific heat of solids

June 30: Special theory of relativity

Arthur L. Schawlow, Stanford, 1970

„I go to conferences to see what other people are working on, so that I know what areas to stay away from.“

How to discover something new?

Try to look where no one has looked before

CERN

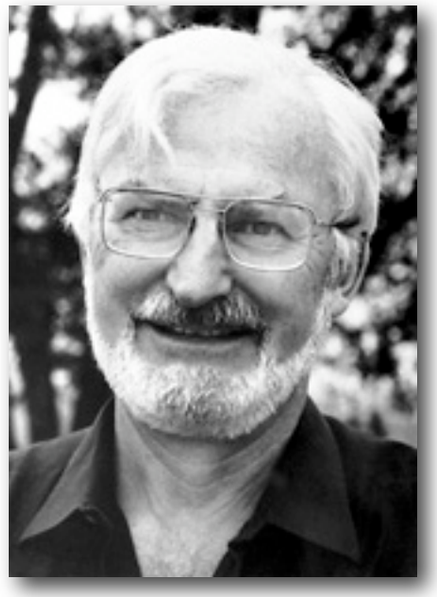
CERN

$$E \geq 10^{13} eV$$

Zürich

Nano-science

Gerd Binnig



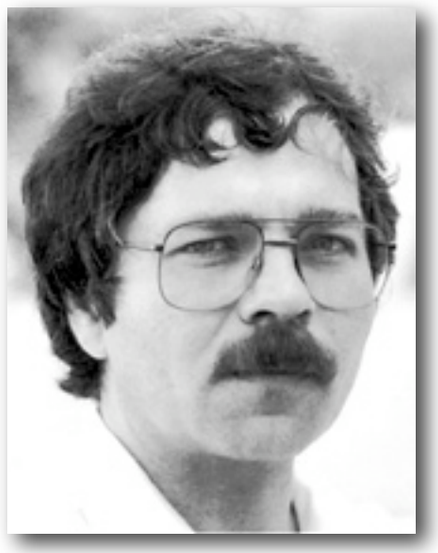
Heinrich Rohrer

Physics Nobel Prize 1986

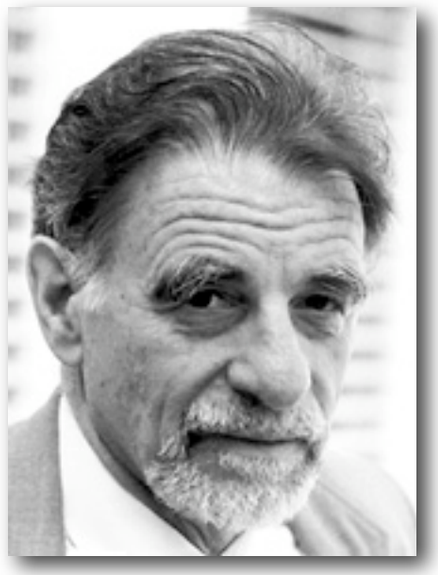
„for their design of the scanning tunneling microscope“

Zürich

Many-body quantum physics

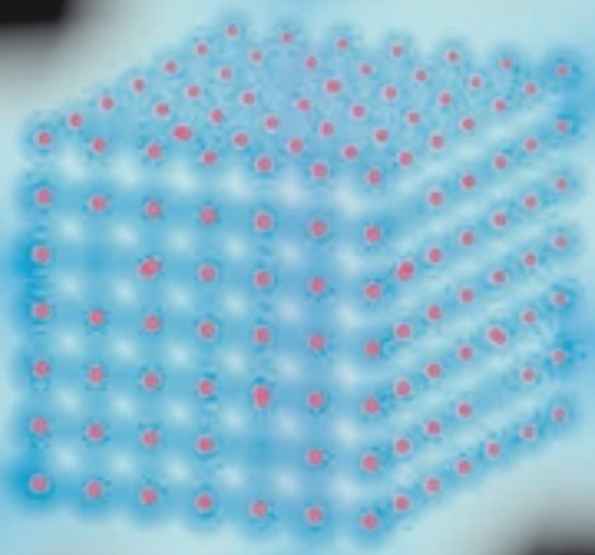


J. Georg Bednorz



K. Alexander Müller

Physics Nobel Prize 1987
"for their important break-through in the discovery of superconductivity in ceramic materials"



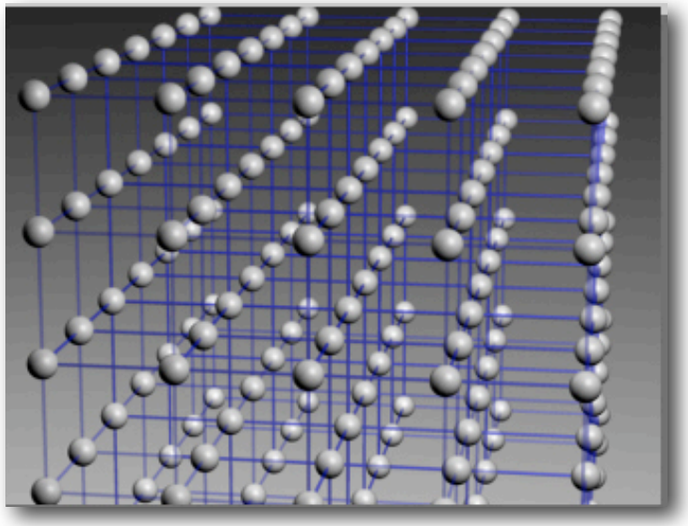
CONDENSED-MATTER PHYSICS

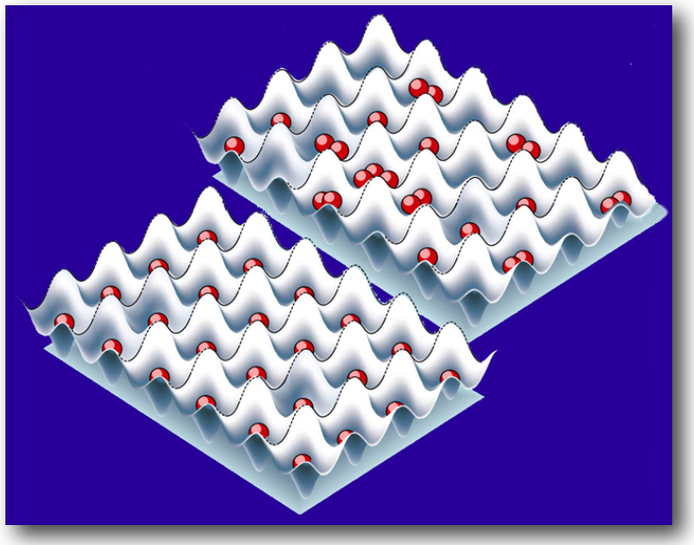
The Mad Dash to Make Light Crystals

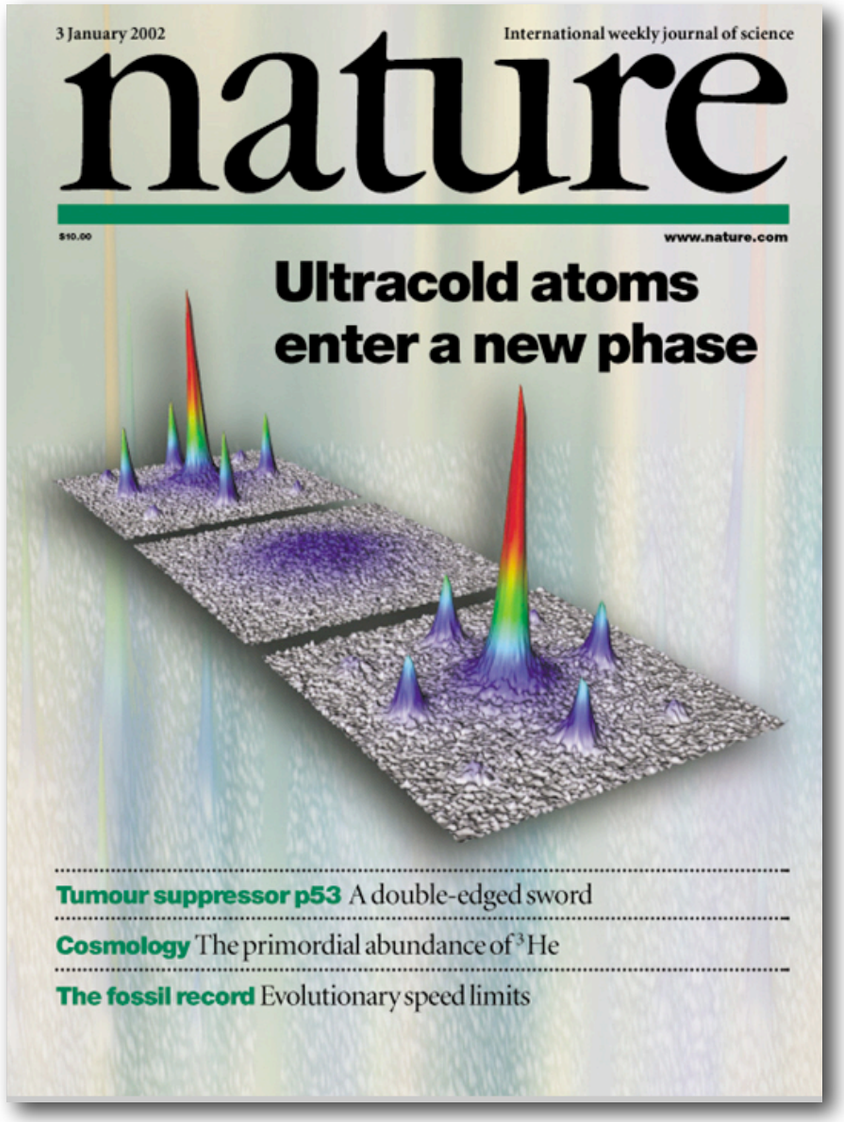
Simulations fashioned from laser light and wisps of ultracold atoms might crack the hardest problems in the physics of solids. DARPA wants them in just over a year

Quantum phase transition from a superfluid to a Mott insulator

M. Greiner et al., Nature, **415**, 39 (2002)

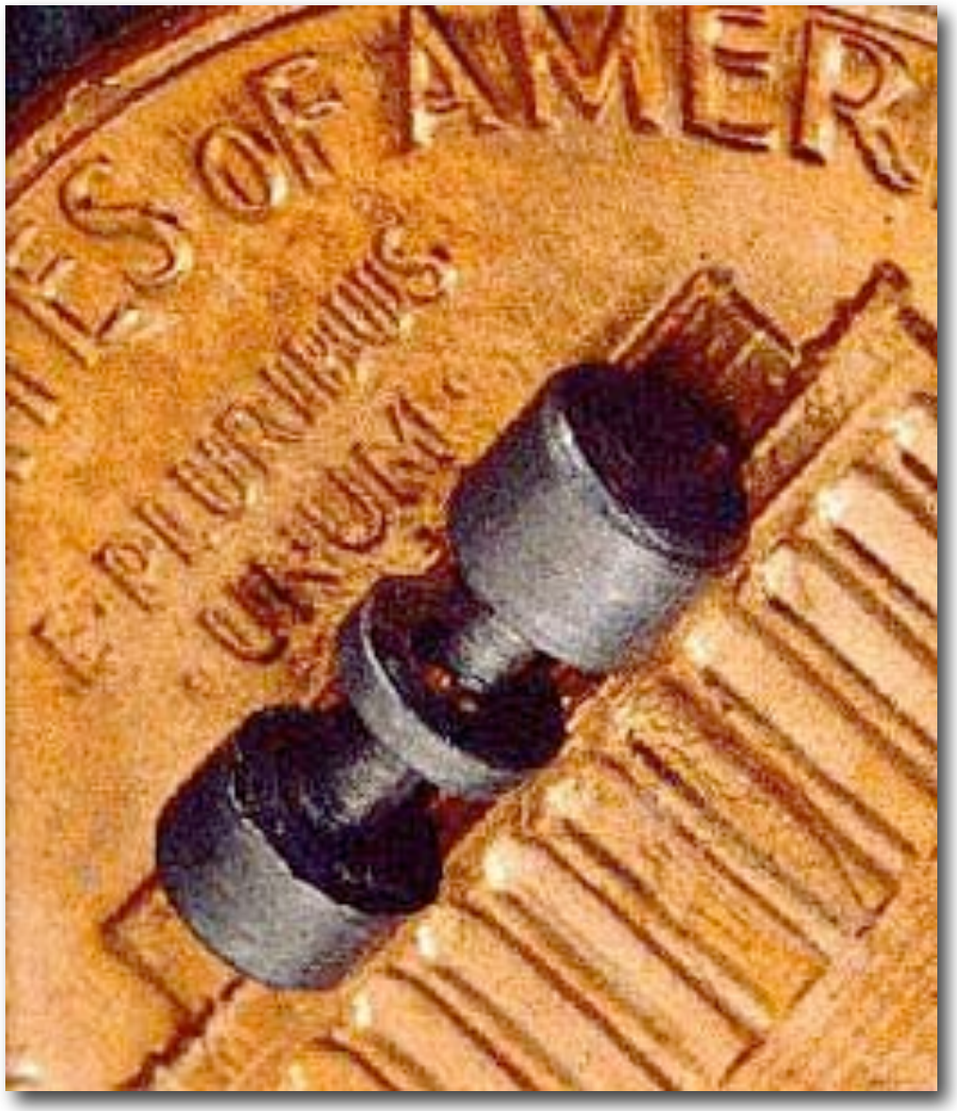






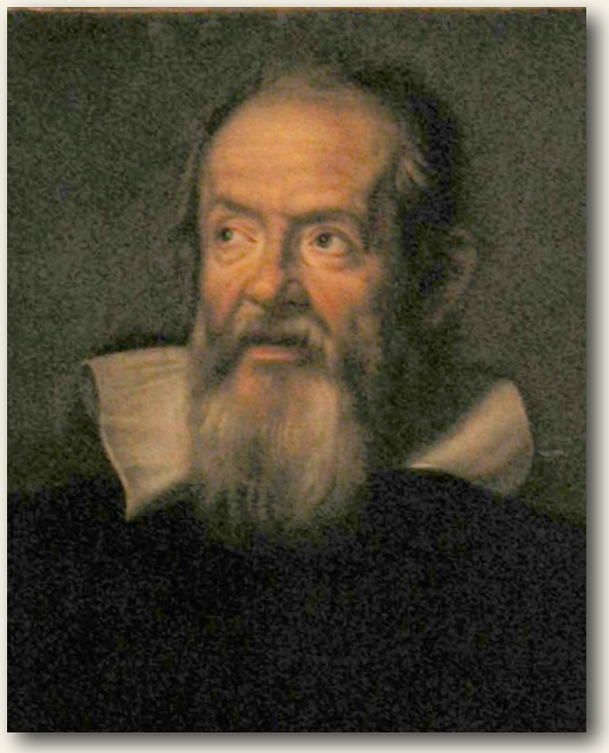
times cited: 1353
(June 20, 2008)

Passion for Precision



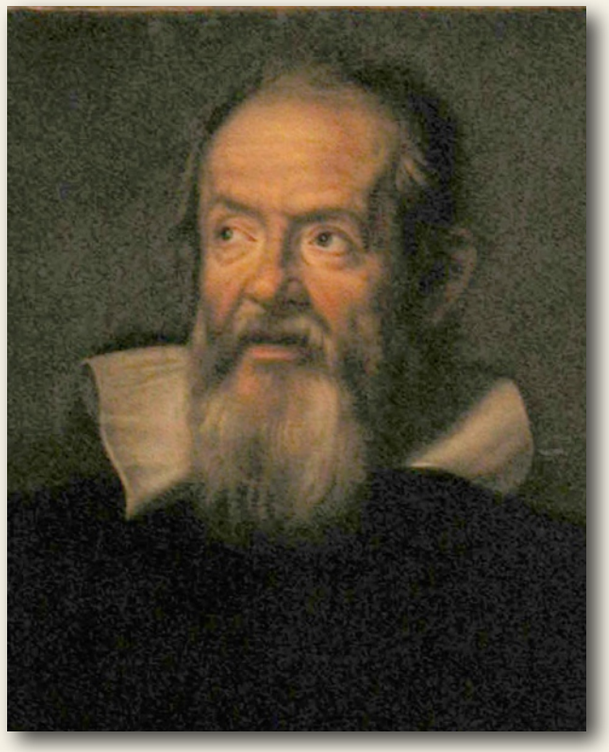
$$\frac{\Delta E}{E} \leq 10^{-16}$$

Pendulum

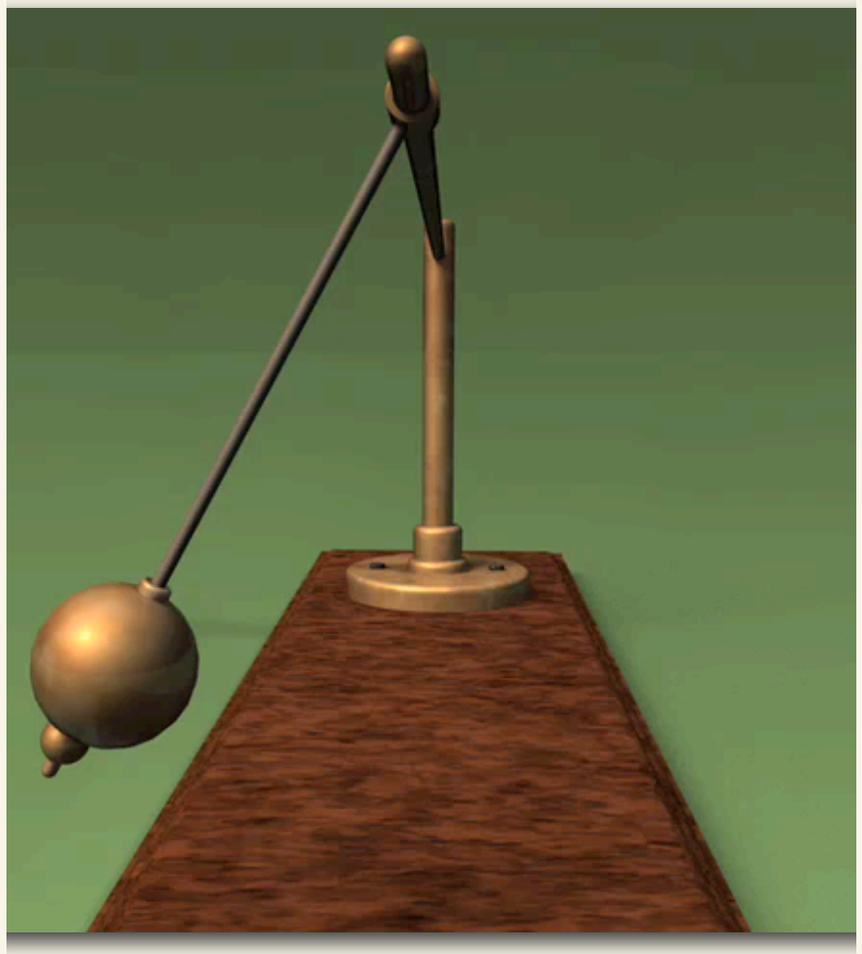


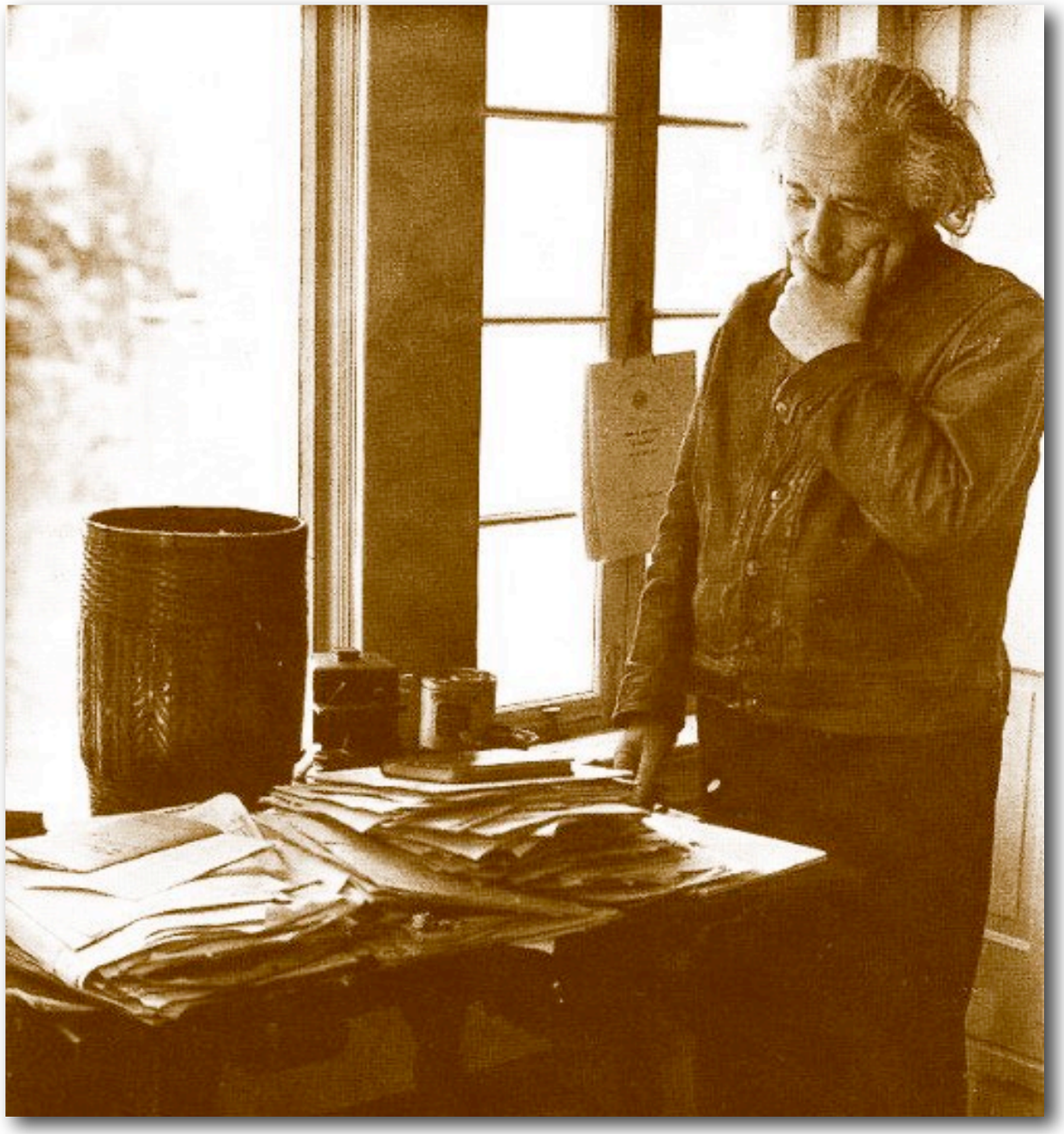
Galileo Galilei
1564 - 1642

Pendulum



Galileo Galilei
1564 - 1642



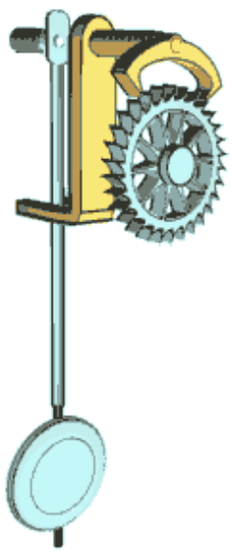


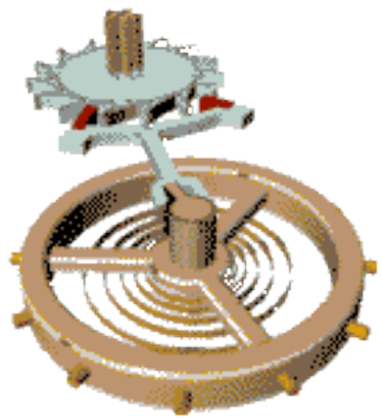
What is time?

What is space?

Time is what one measures with a clock.

Daniel Kleppner





Space must be measured with a clock

John L. Hall

Space must be measured with a clock

John L. Hall

1983, Conférence Générale des Poids et Mesures (CGPM):

One meter is the distance that light travels
during 1/299 792 456 of a second

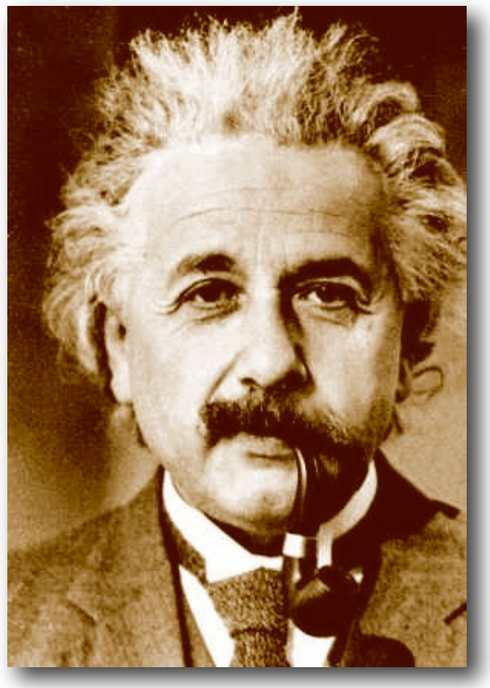
Energy should be measured with a clock

Max Planck

Energy should be measured with a clock

Max Planck

$$E = h\nu$$



Mass should be measured with a clock

Albert Einstein

$$E = mc^2 = h\nu$$

Evolution of clocks

From 3500 BC

Sun dial
one cycle per day

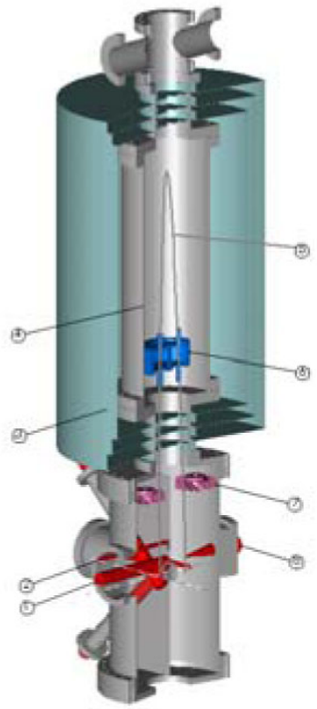
1656

Pendulum clock
1 Hz

1918

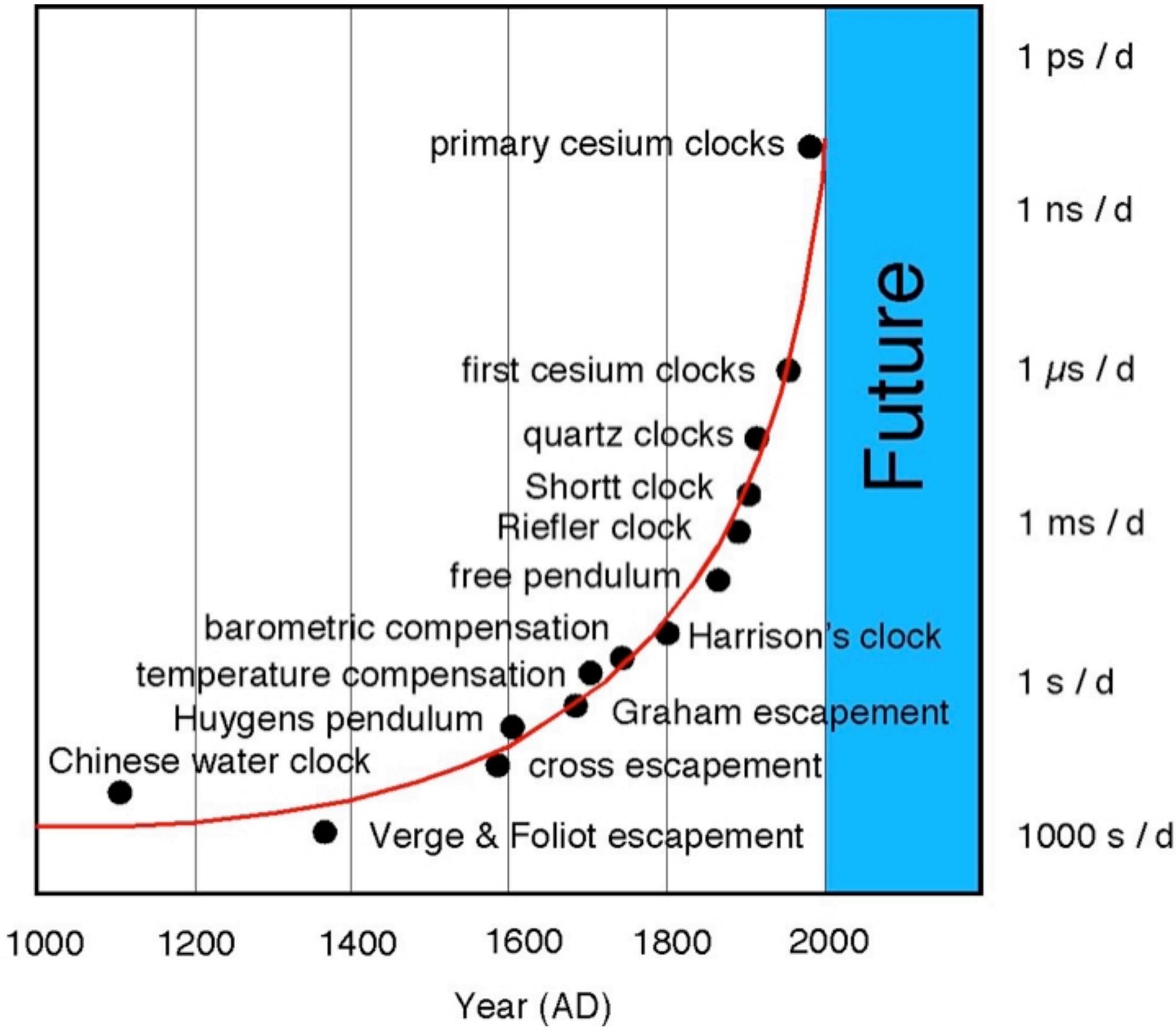
Quartz clock
32 768 Hz

1955

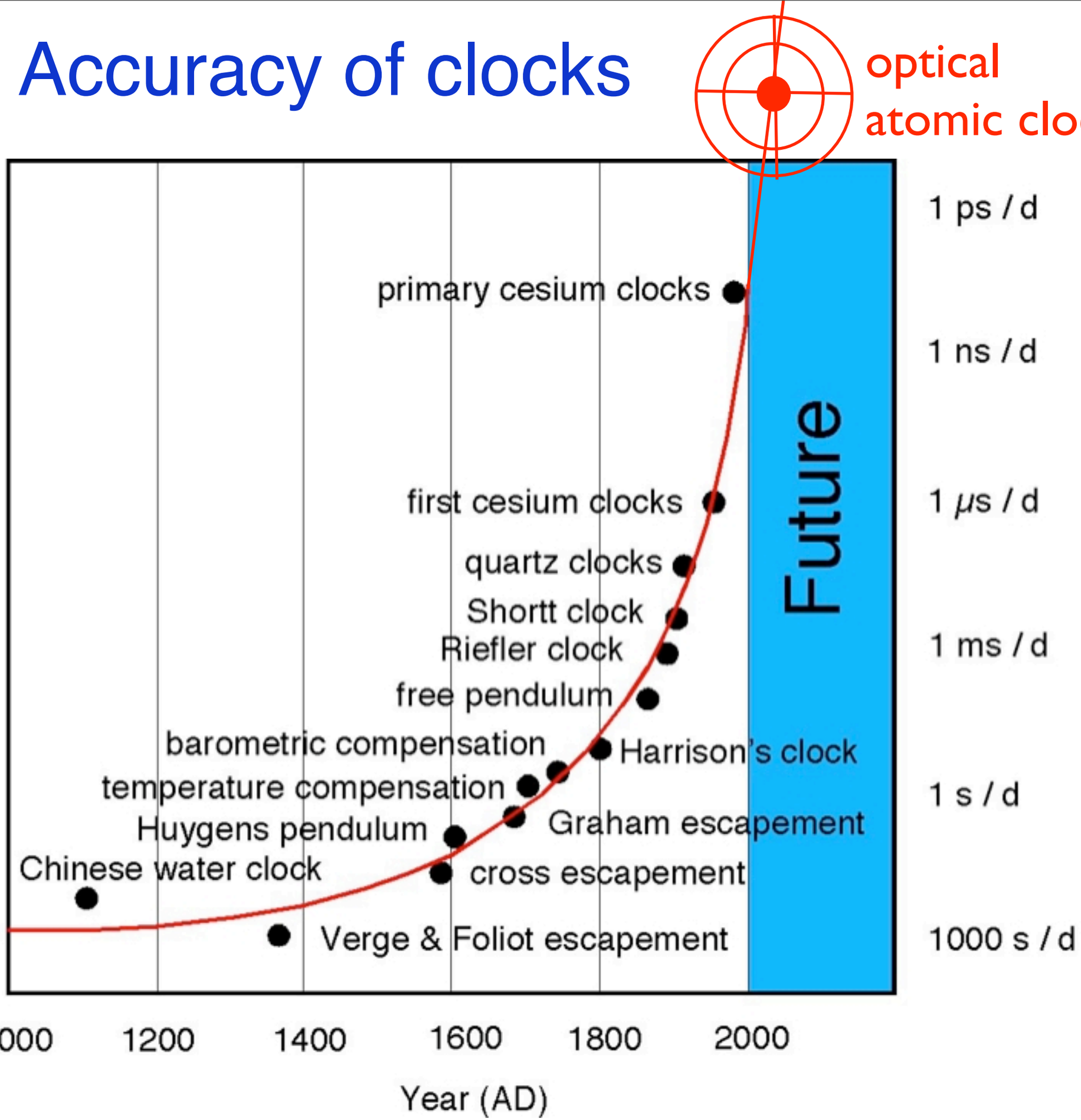


Cesium atomic clock
9 192 631 770 Hz

Accuracy of clocks



Accuracy of clocks



Clockwork for an optical atomic clock?

optical frequency comb

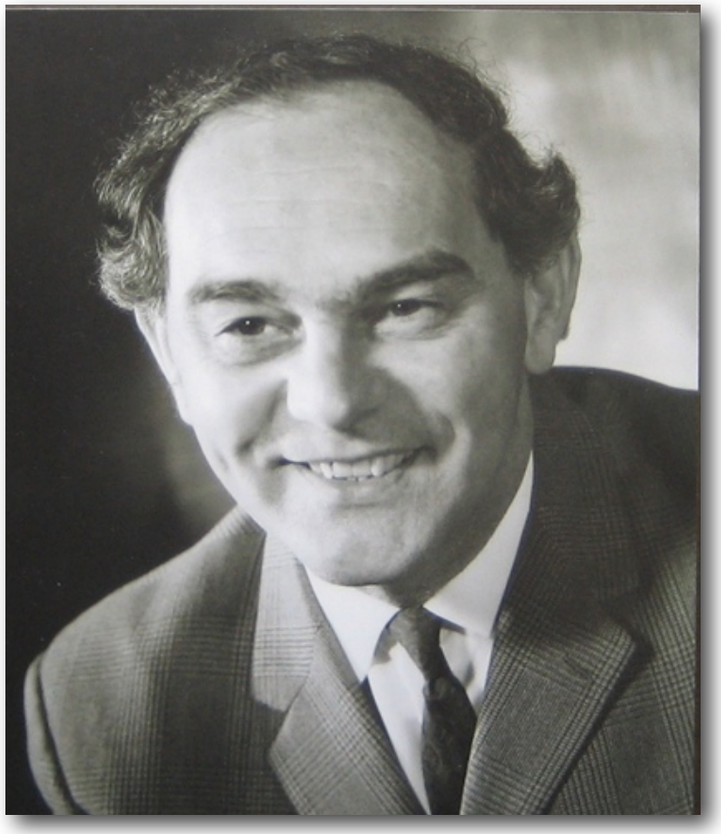
A simple tool for measuring optical
frequencies of 100's or even 1000's of THz.

A phase coherent link between
the optical and the radio-frequency region.

A clockwork mechanism for an
optical atomic clock.

"Never measure anything but frequency!"

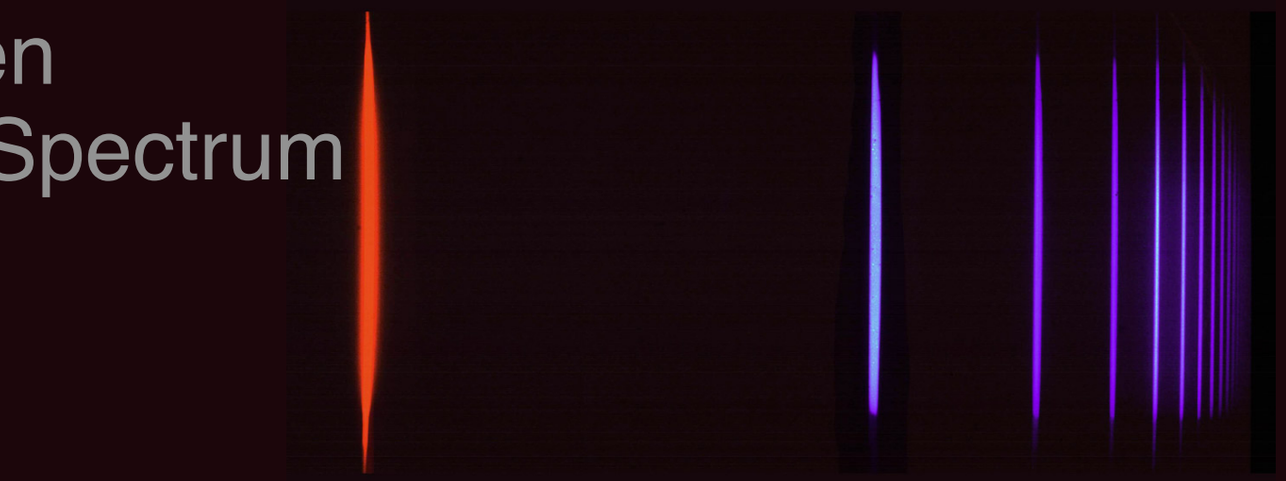
Arthur L. Schawlow



Never measure anything but hydrogen!

George W. Series

Hydrogen Balmer Spectrum



series

x 15 000

H_α

Doppler profile (300 K)

saturation spectrum

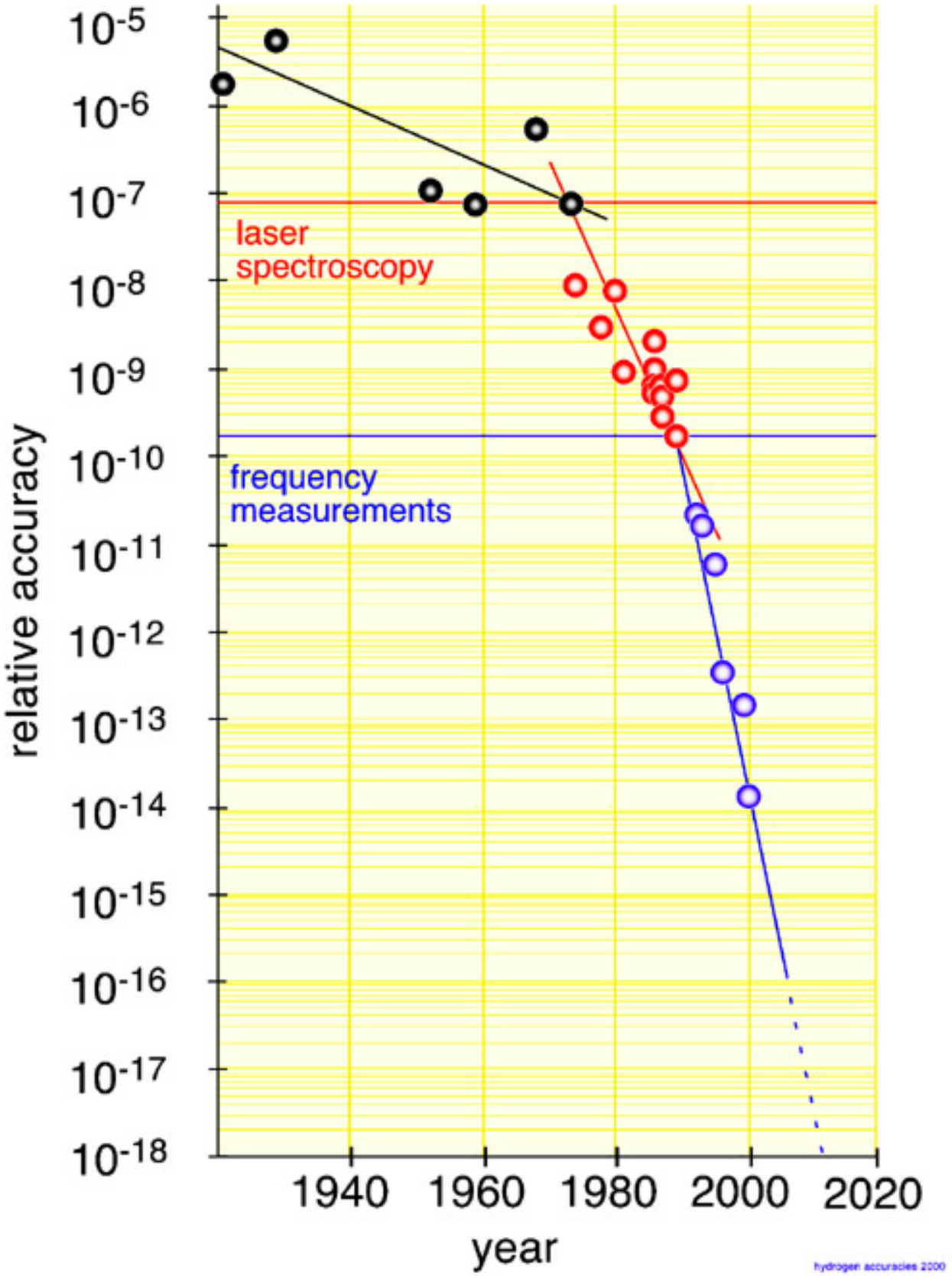
Lamb shift

0

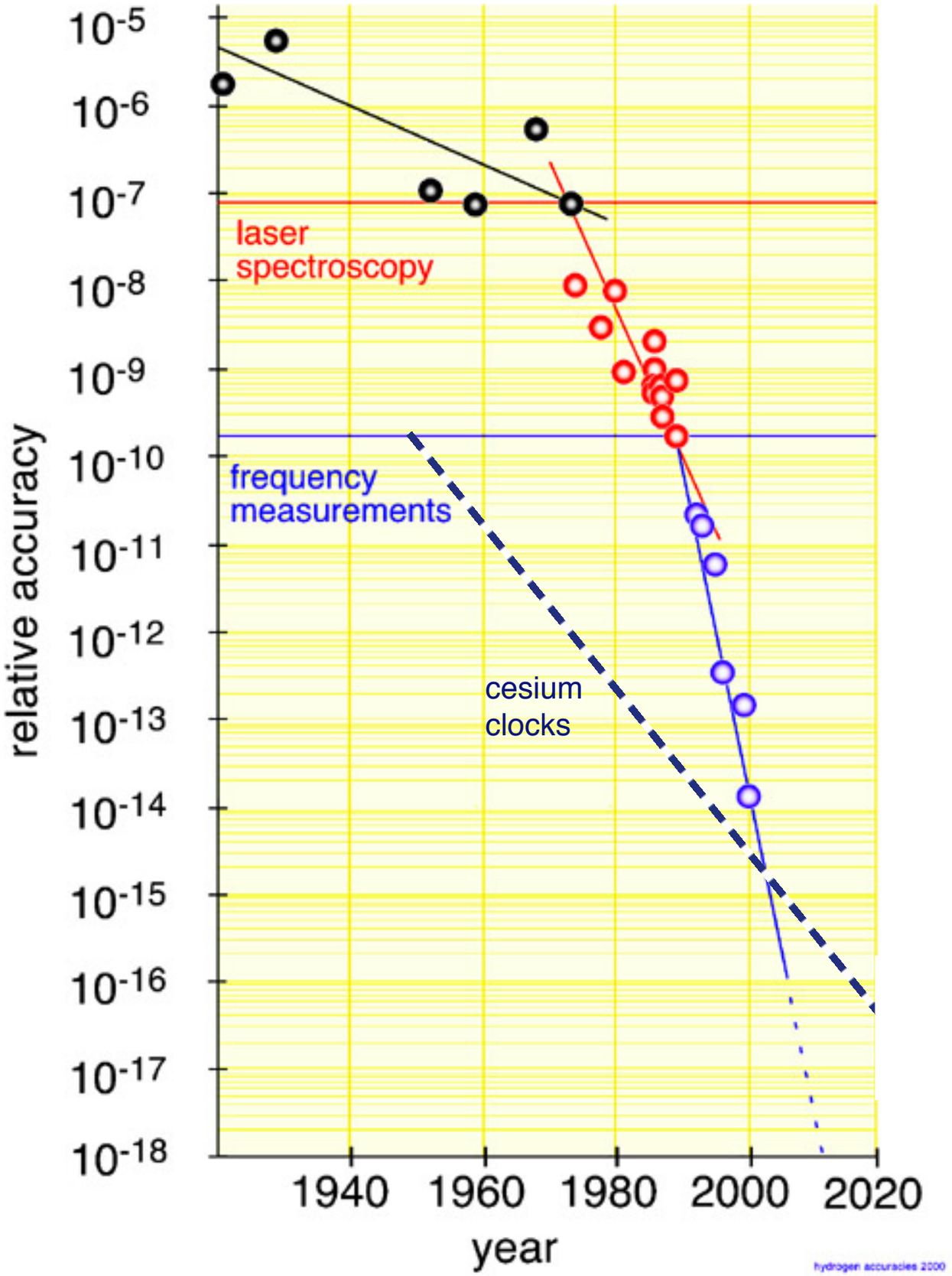
10 GHz

T.W. Hänsch, I.S. Shahin, and A.L. Schawlow, Nature **235**, 63 (1972)

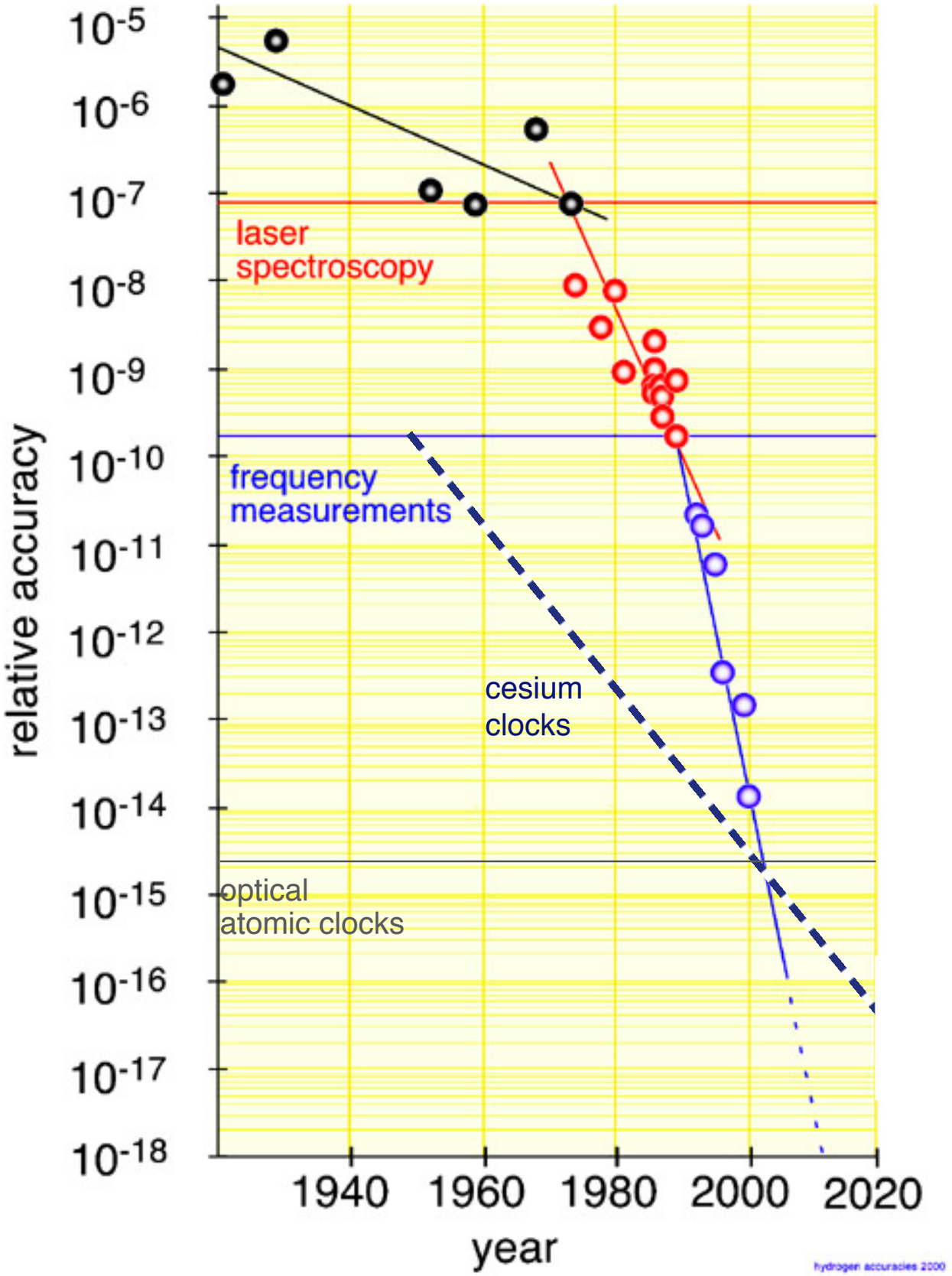
Optical Spectroscopy of Hydrogen



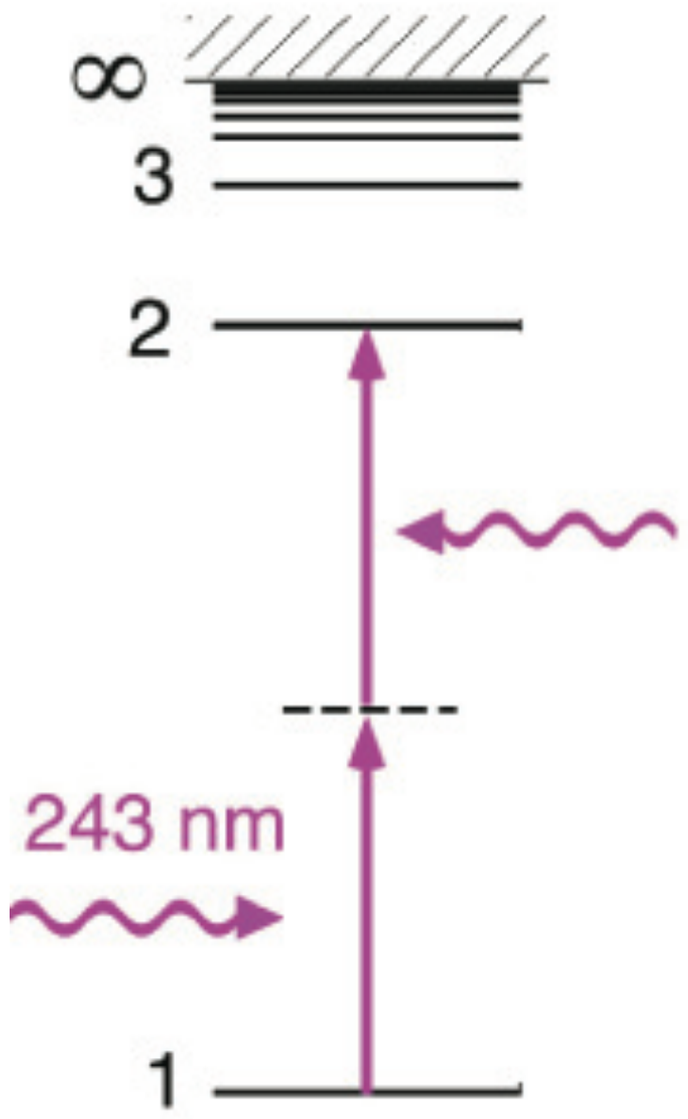
Optical Spectroscopy of Hydrogen



Optical Spectroscopy of Hydrogen



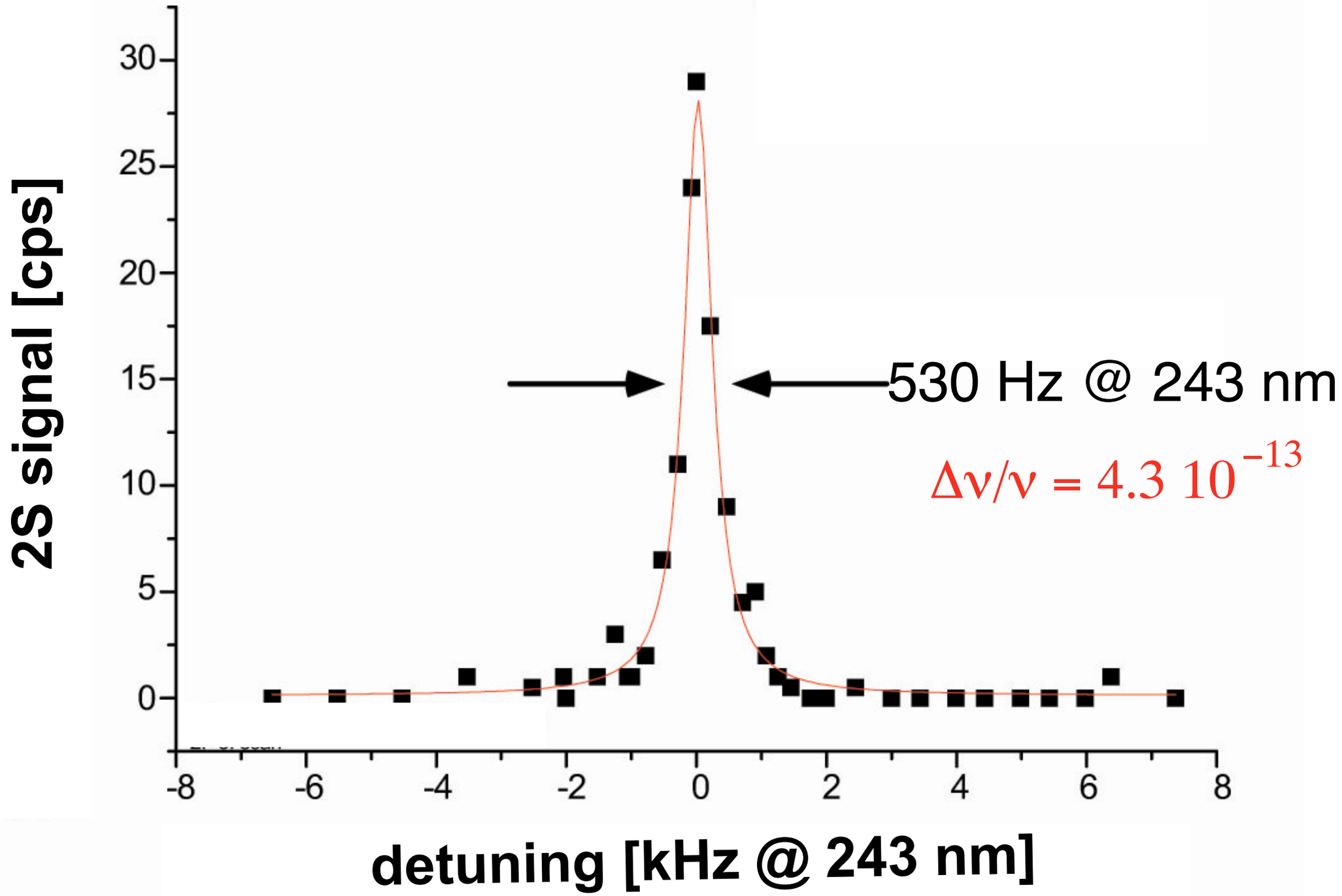
Hydrogen 1S-2S two-photon transition



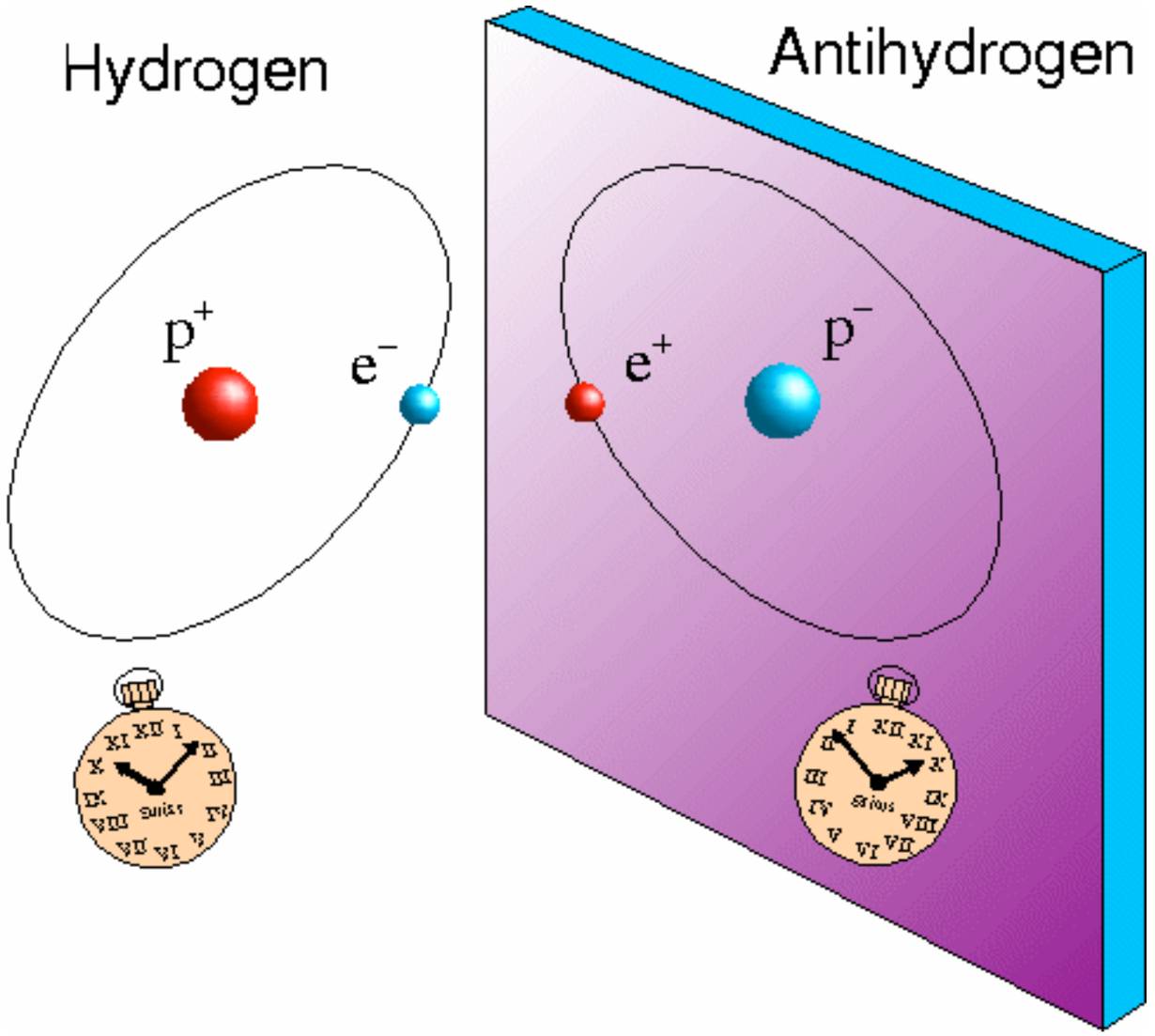
(natural line width: 1.3 Hz)

T.W. Hänsch, S.A. Lee, R. Wallenstein, and C. Wieman, Phys. Rev. Lett. **34**, 307 (1975), ...

Hydrogen 1S-2S resonance

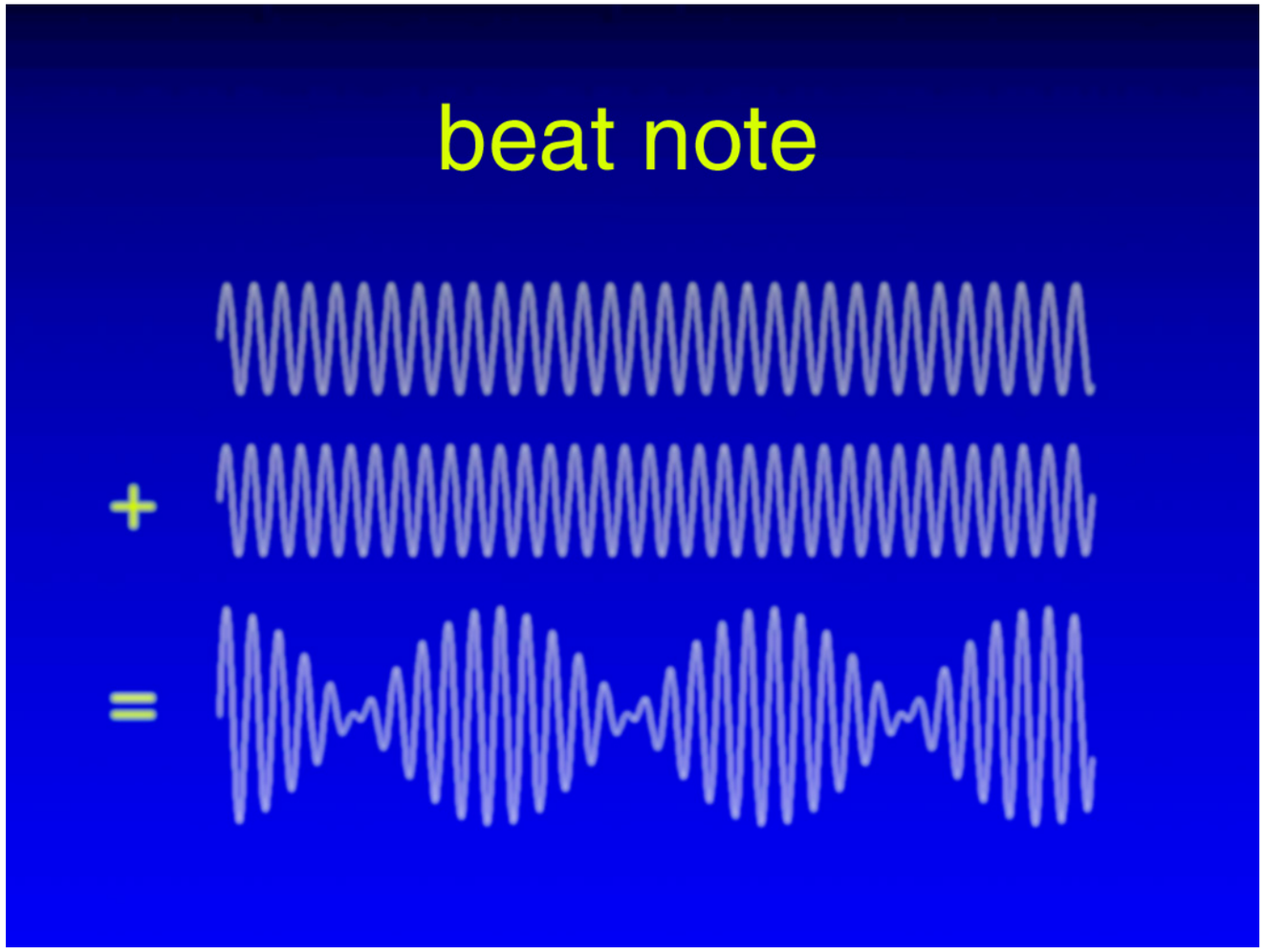


Are there detectable differences between matter and antimatter?



A dream... (Ali Javan, 1962)

Extend microwave frequency counting techniques into the optical region.



A. Javan, E.A. Ballik, and W.L. Bond,
J. Opt. Soc. Am. **7**, 553 (1962)

First Phase-Coherent Frequency Measurement of Visible Radiation

H. Schnatz, B. Lipphardt, J. Helmcke, F. Riehle, and G. Zinner
Physikalisch-Technische Bundesanstalt (PTB), D-38116 Braunschweig, Germany
(Received 10 August 1995)

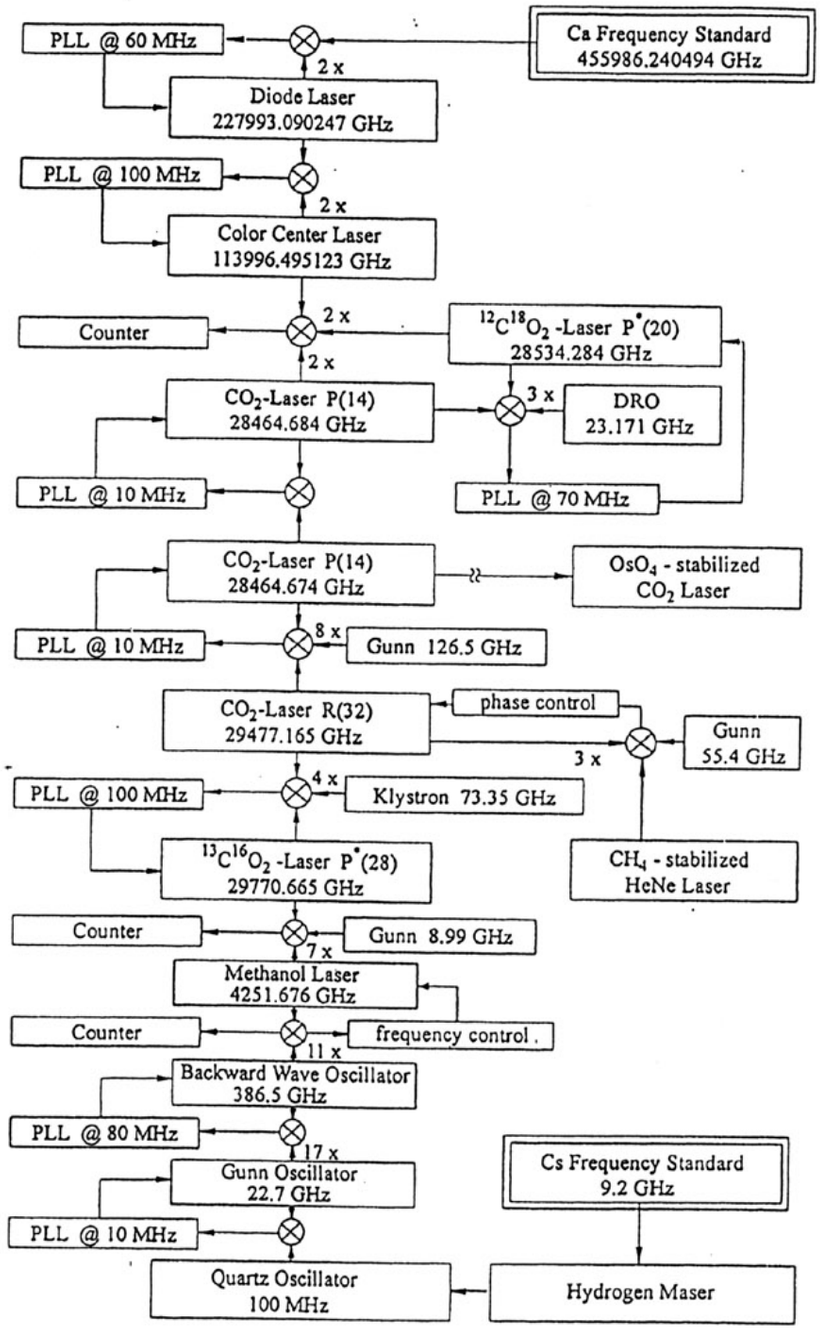
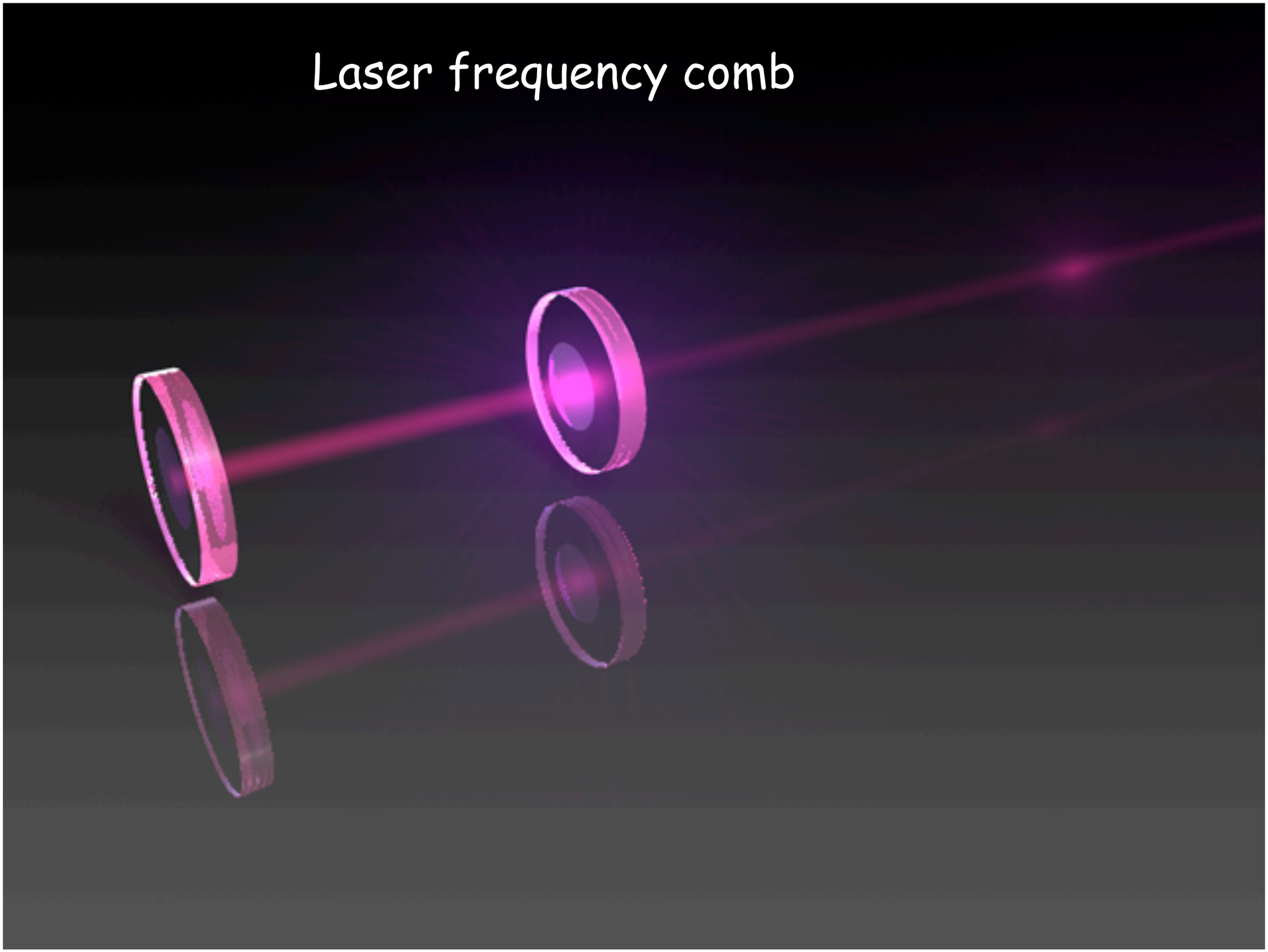


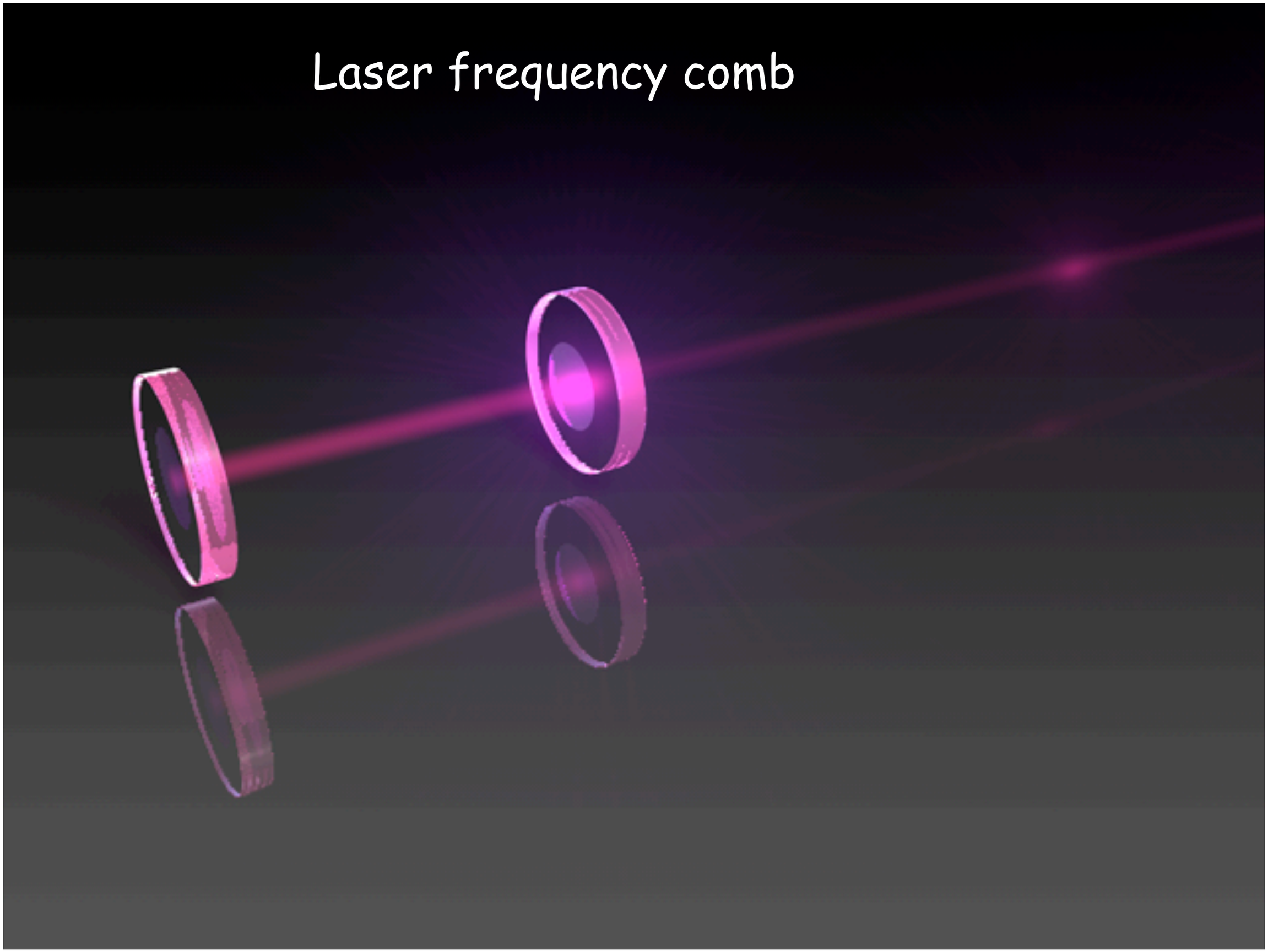
FIG. 1. PTB's frequency chain to the Ca intercombination line (PLL = phase locked loop, details are given in the text).

Laser frequency comb

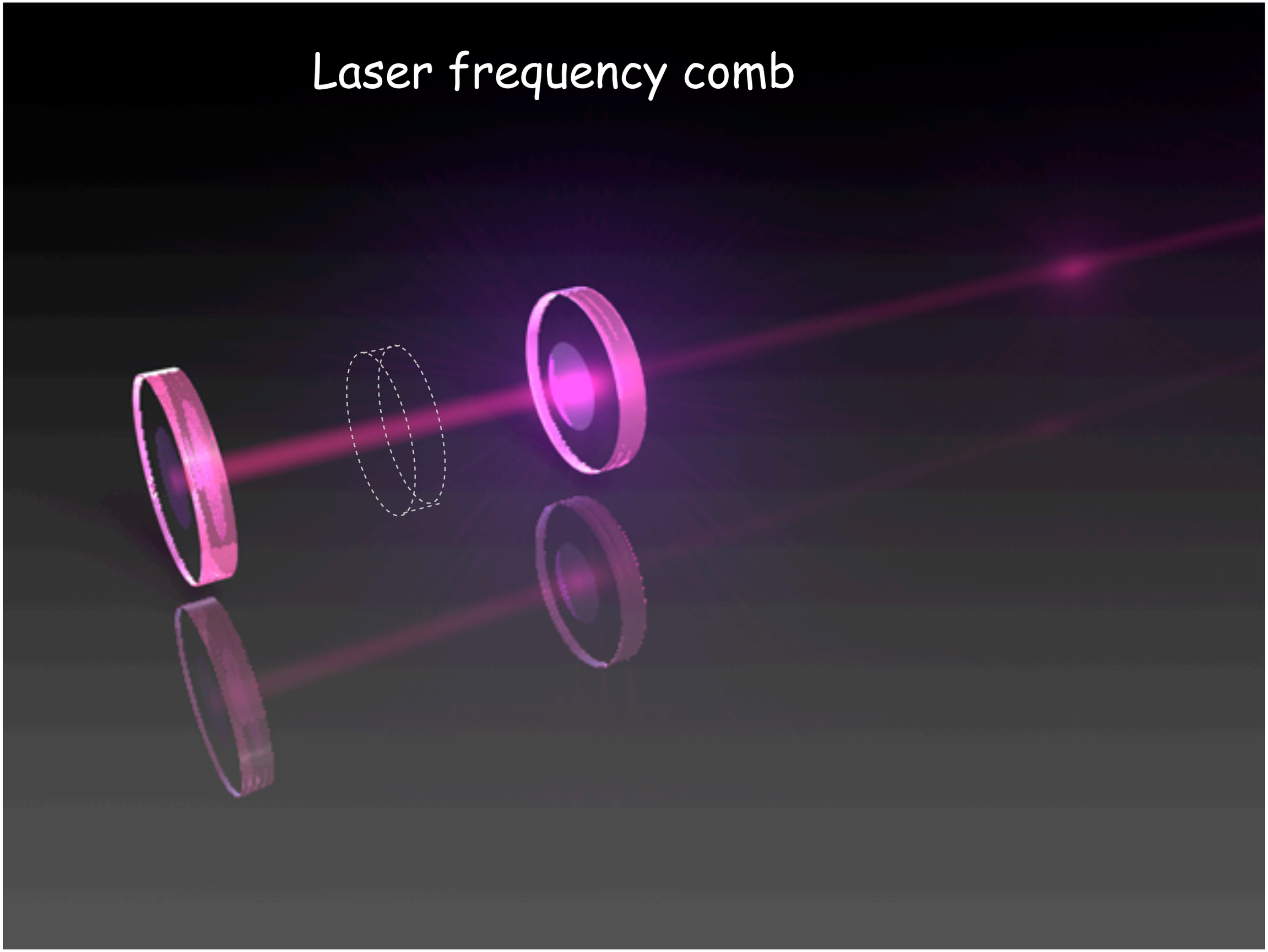


Laser frequency comb

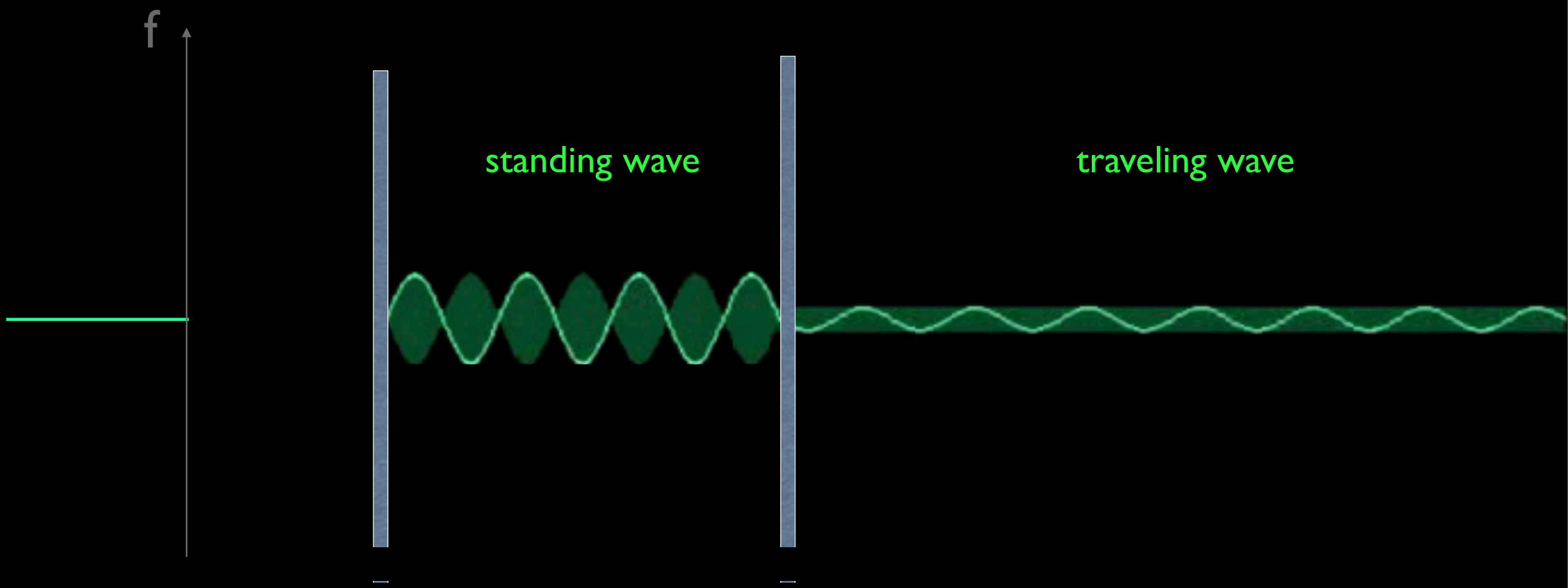
Laser frequency comb



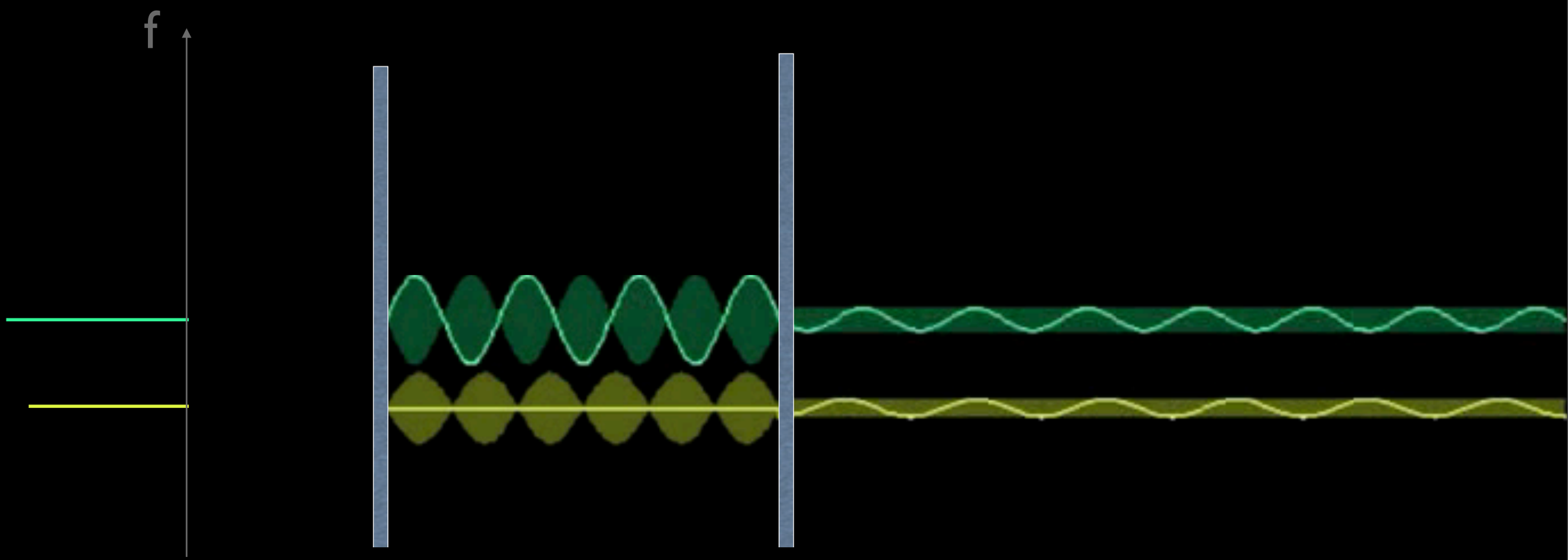
Laser frequency comb



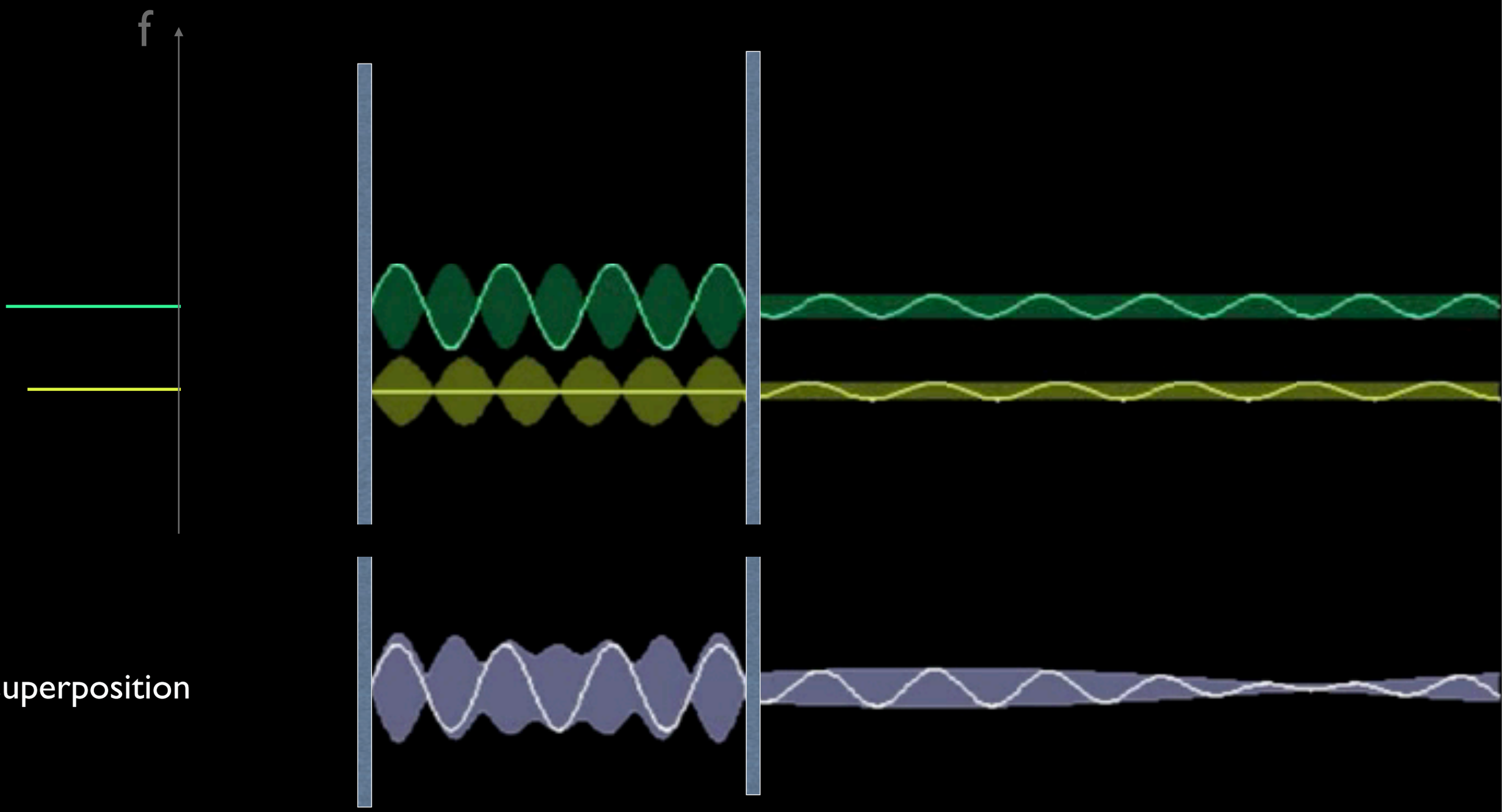
single mode



two modes

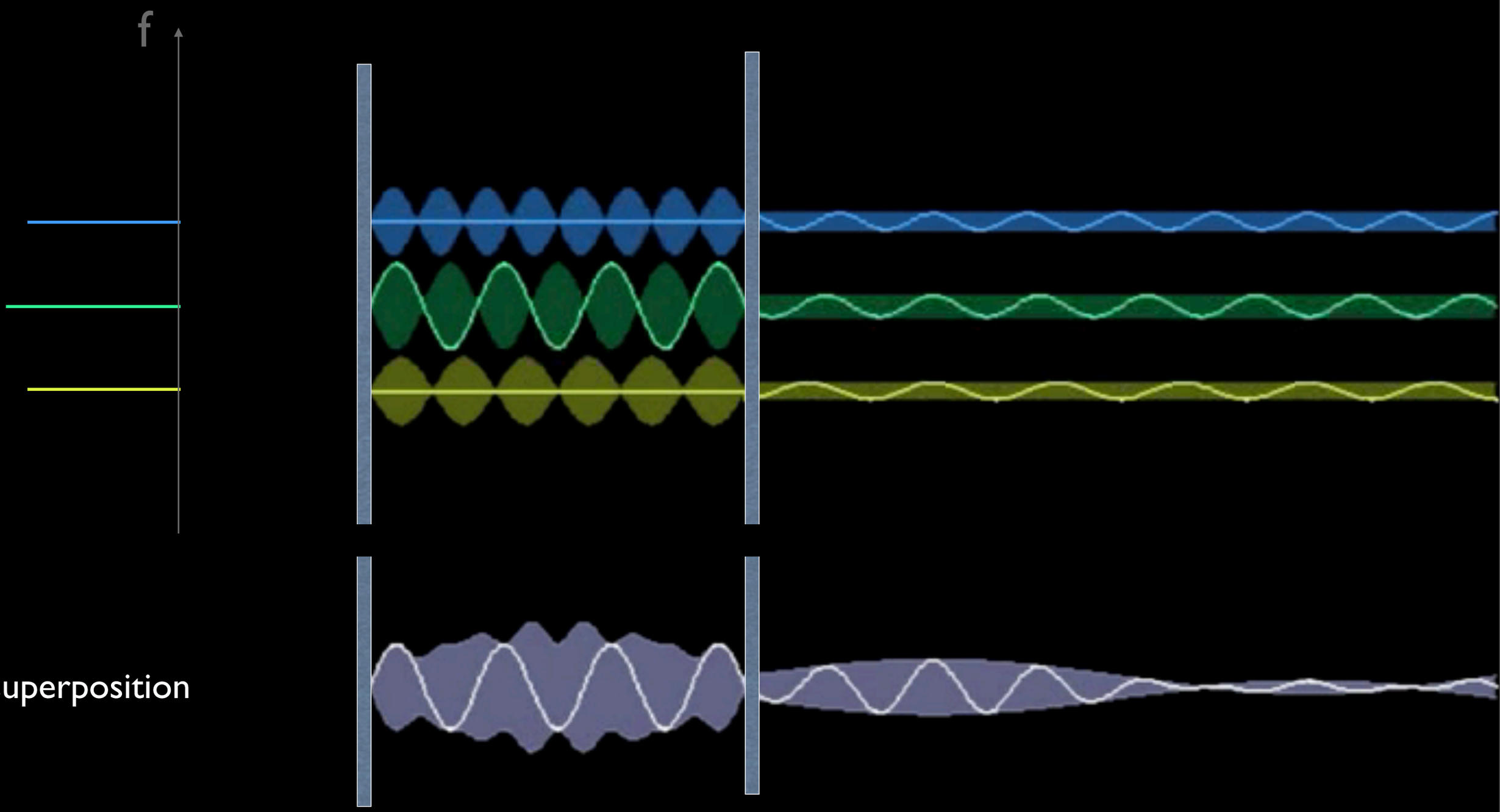


two modes



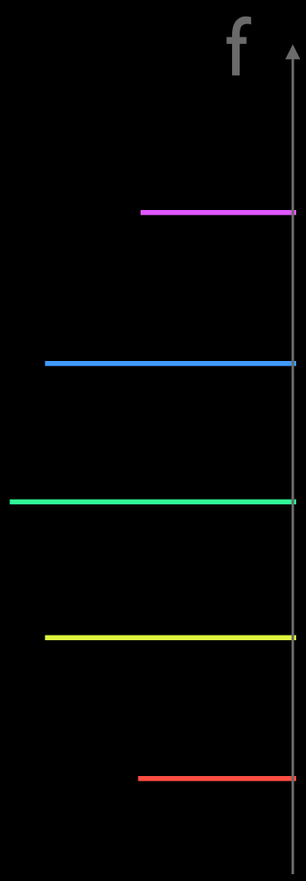
superposition

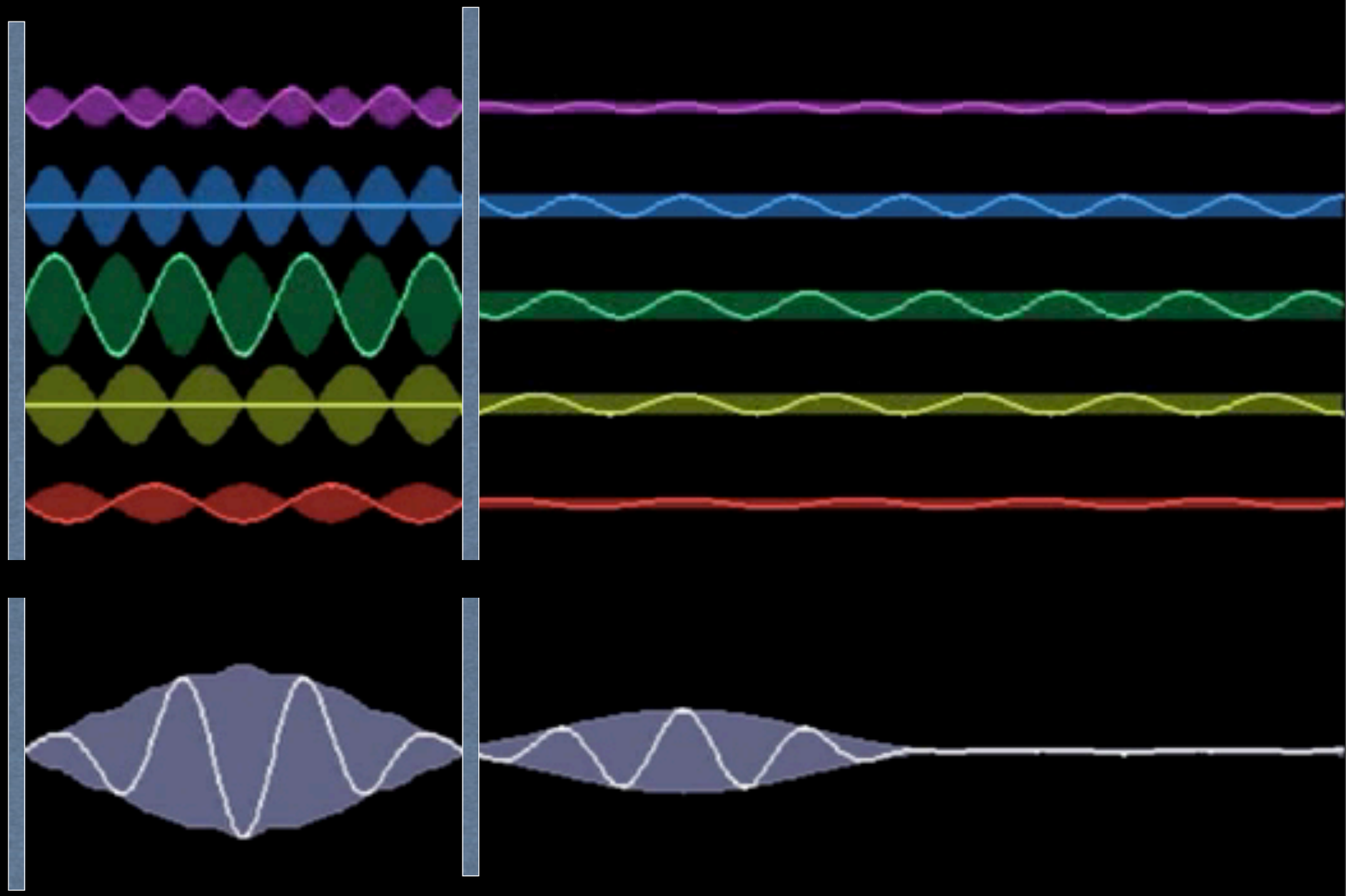
three modes



superposition

many modes

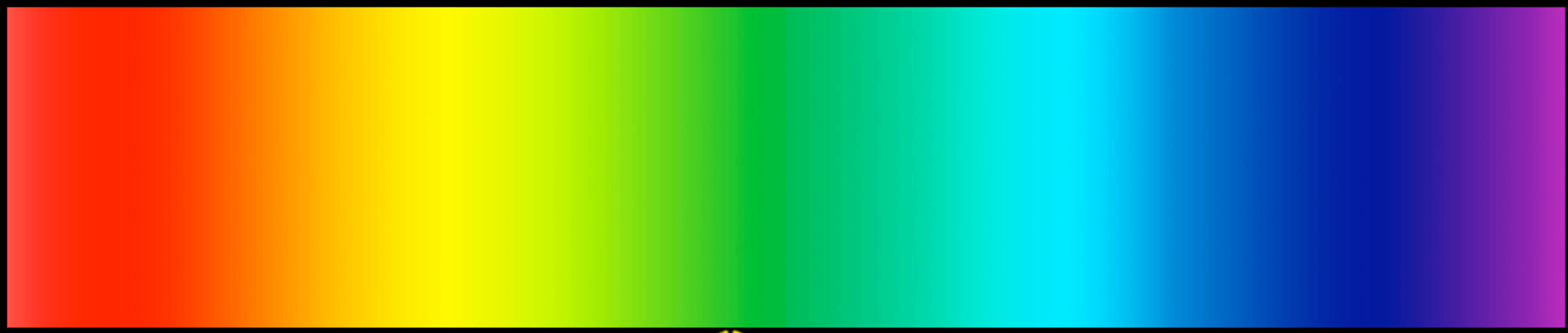




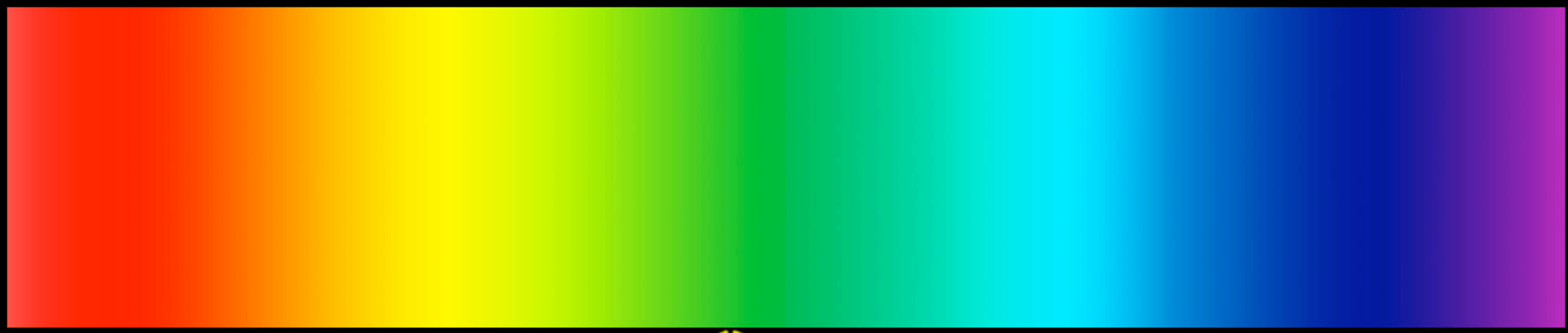
superposition

University of Bath

Optical Frequency Comb Synthesizer

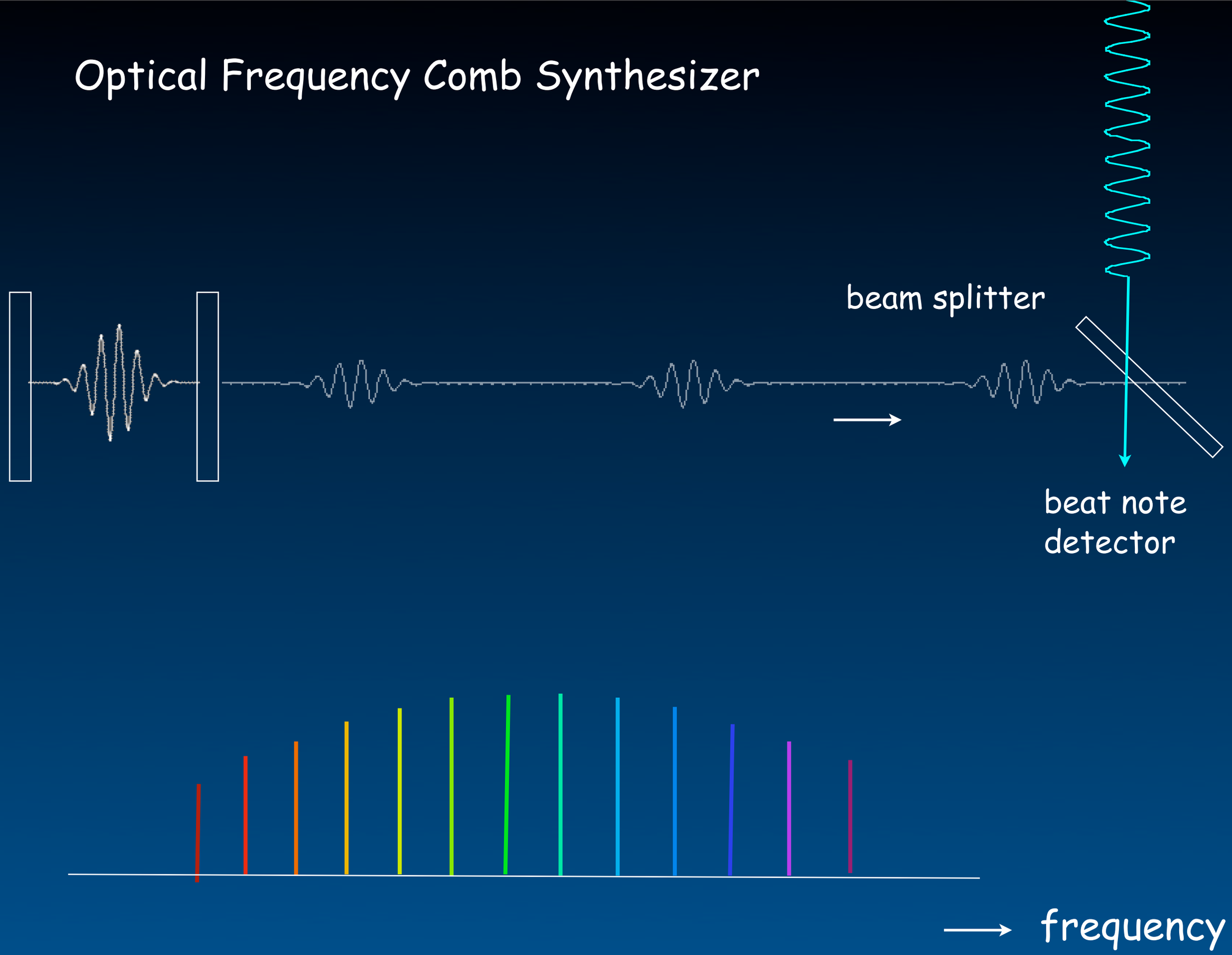


$$f_m = m\, f_{rep} \quad + f_{CEO}$$

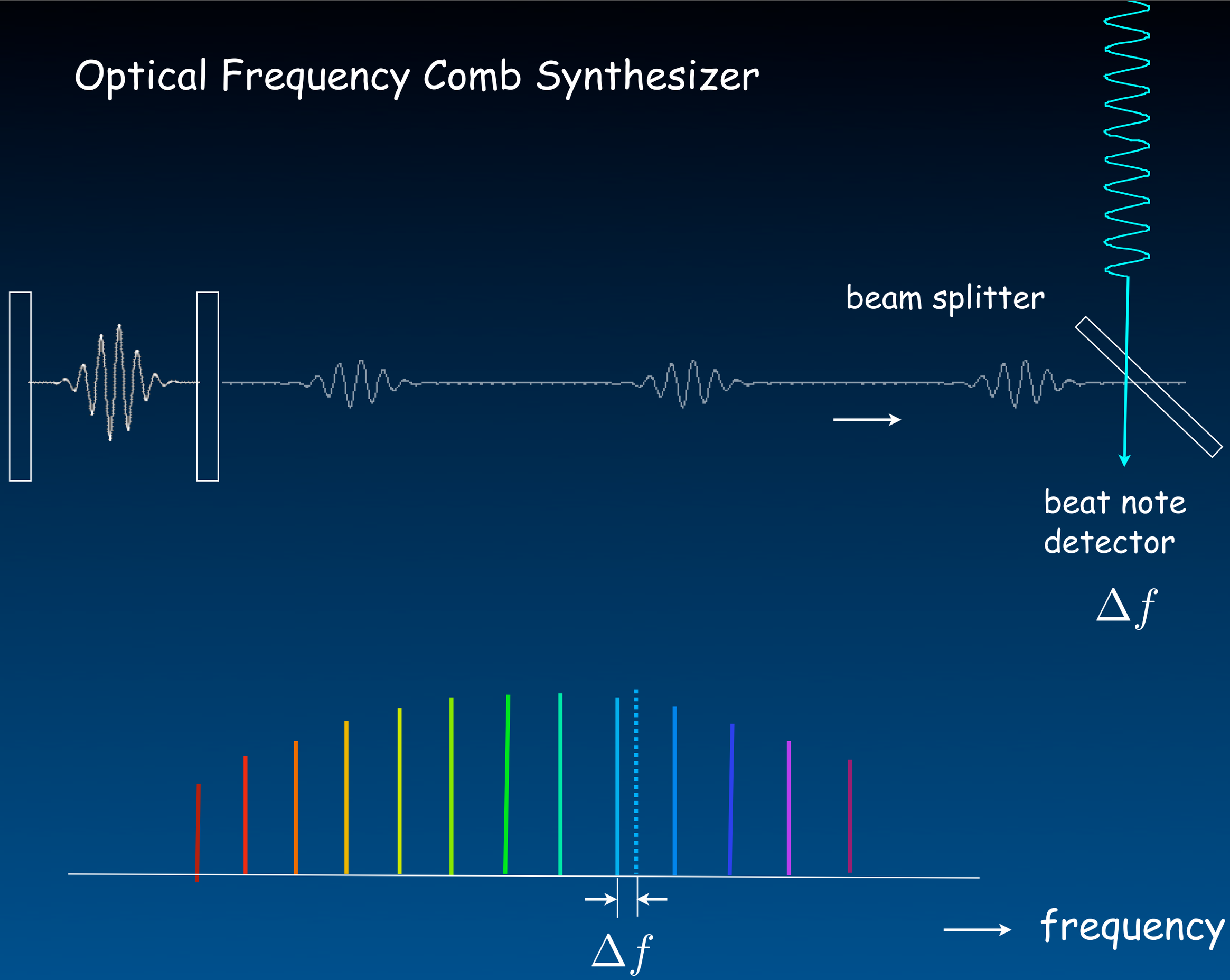


$f_m = m\, f_{rep}$

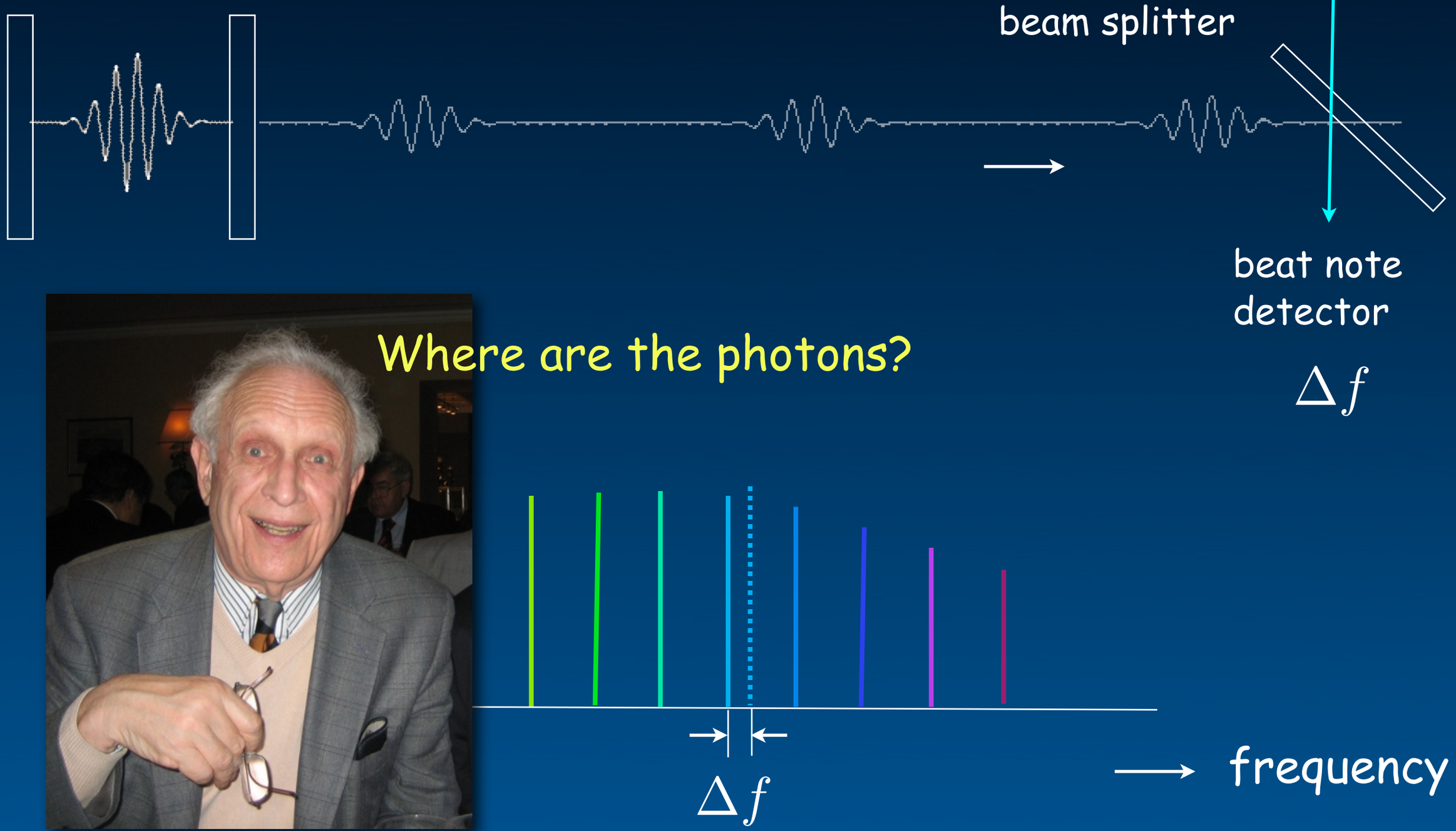
Optical Frequency Comb Synthesizer



Optical Frequency Comb Synthesizer

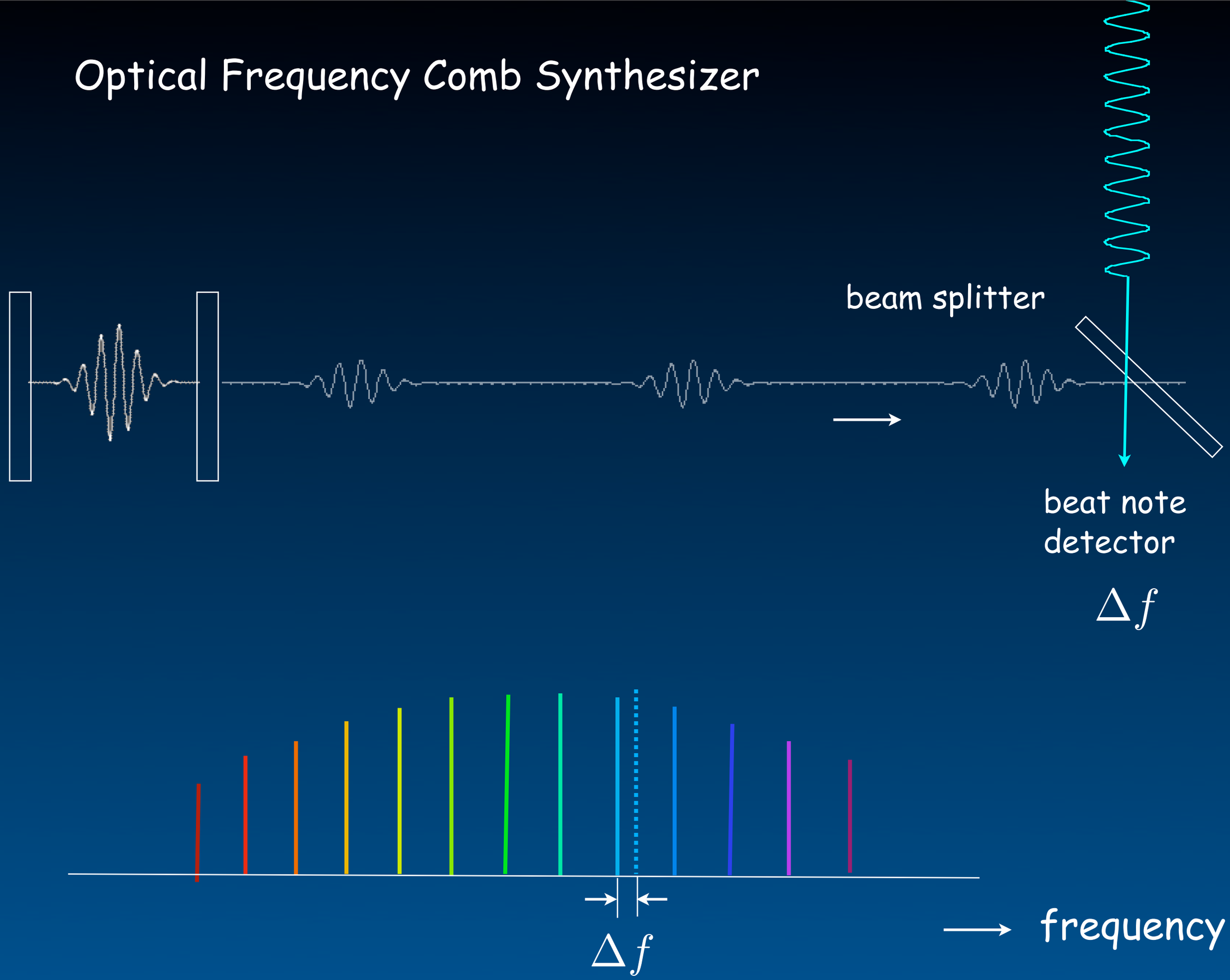


Optical Frequency Comb Synthesizer



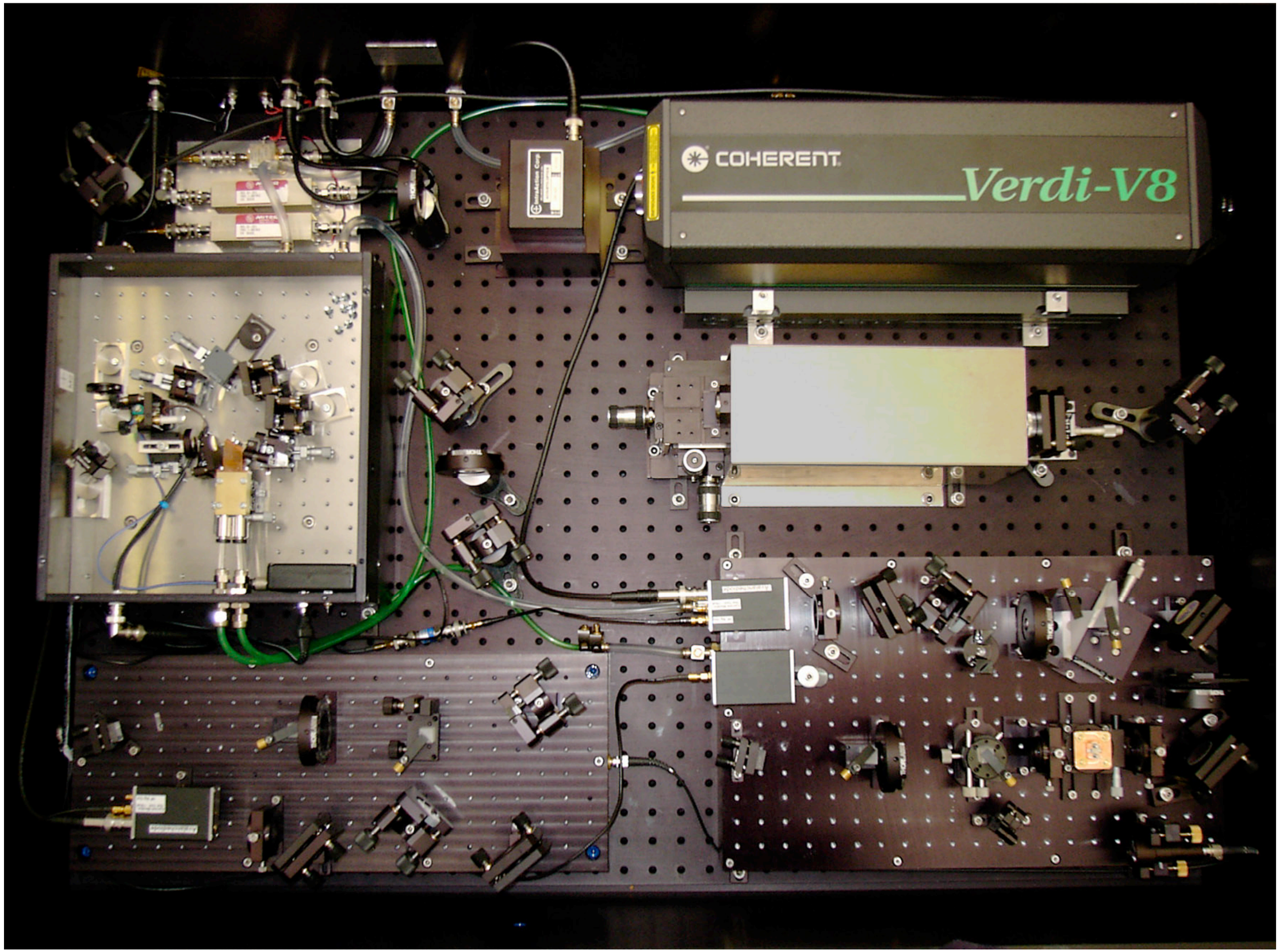
Where are the photons?

Optical Frequency Comb Synthesizer



femtosecond laser frequency comb

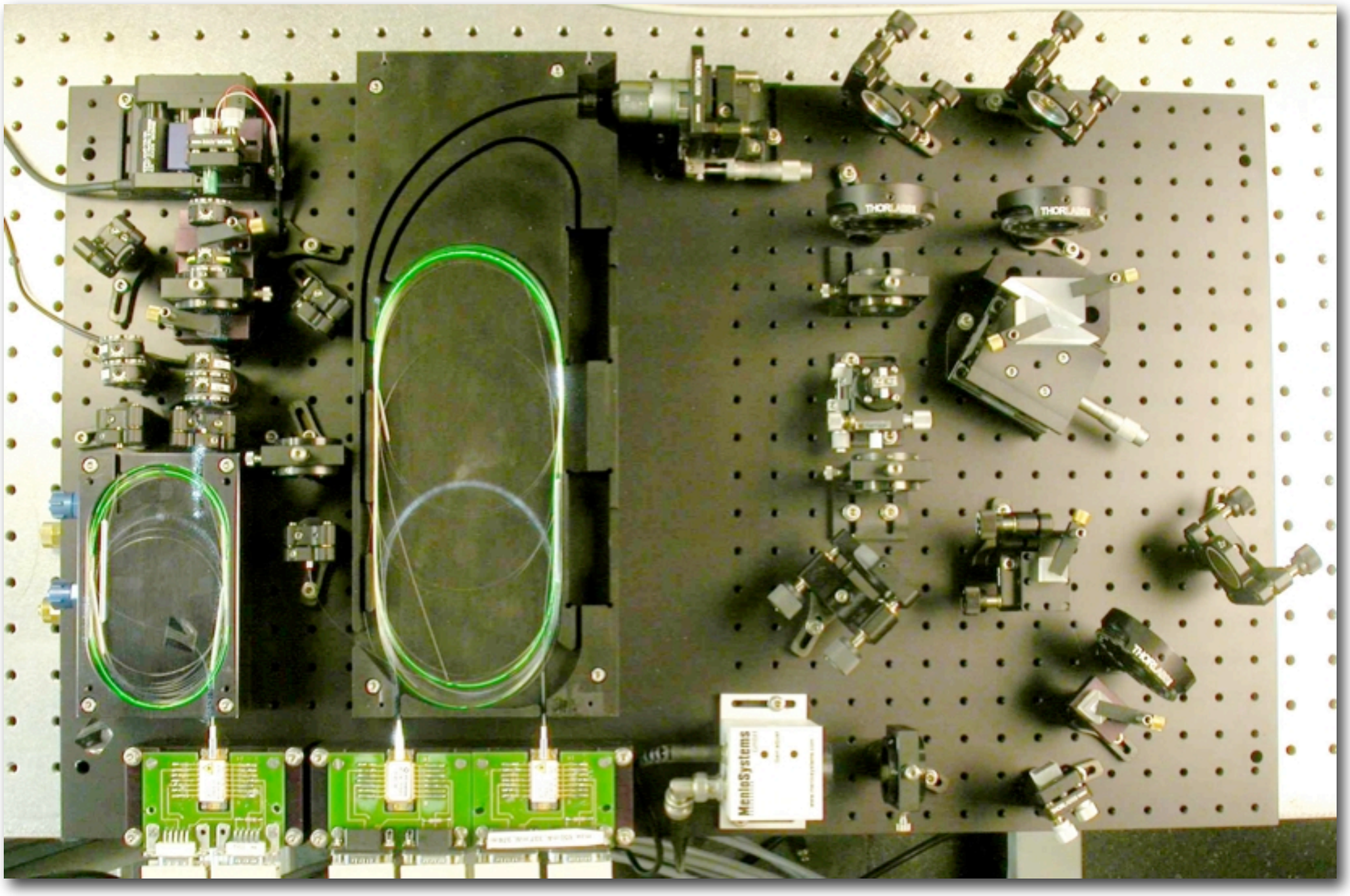
- 100 000 ultra-stable lasers at once
- revolutionary optical wave meter
- frequency counter from DC to UV
- clockwork for optical atomic clocks
- optical frequency synthesizer
- ultra-stable microwave source
- . . .
- enabling tool for fundamental measurements
- . . .
- source of phase-stabilized femtosecond pulses
- key to attosecond physics


COHERENT
Verdi-V8

Frequency Comb Generator handed over to Deutsches Museum

(Munich, June 18, 2008)

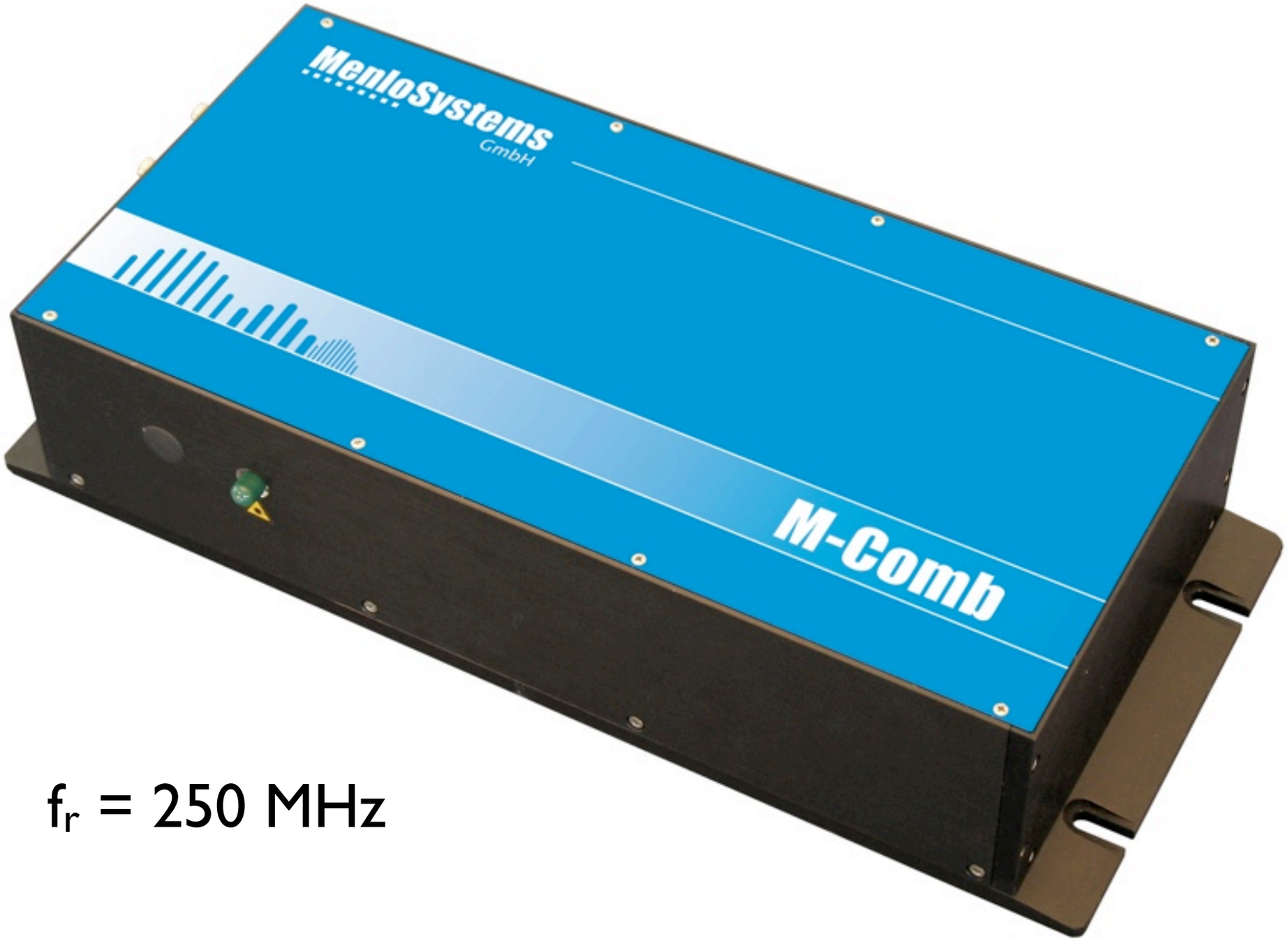
Er^+ fiber laser frequency comb synthesizer



laser oscillator amplifier nonlinear interferometer

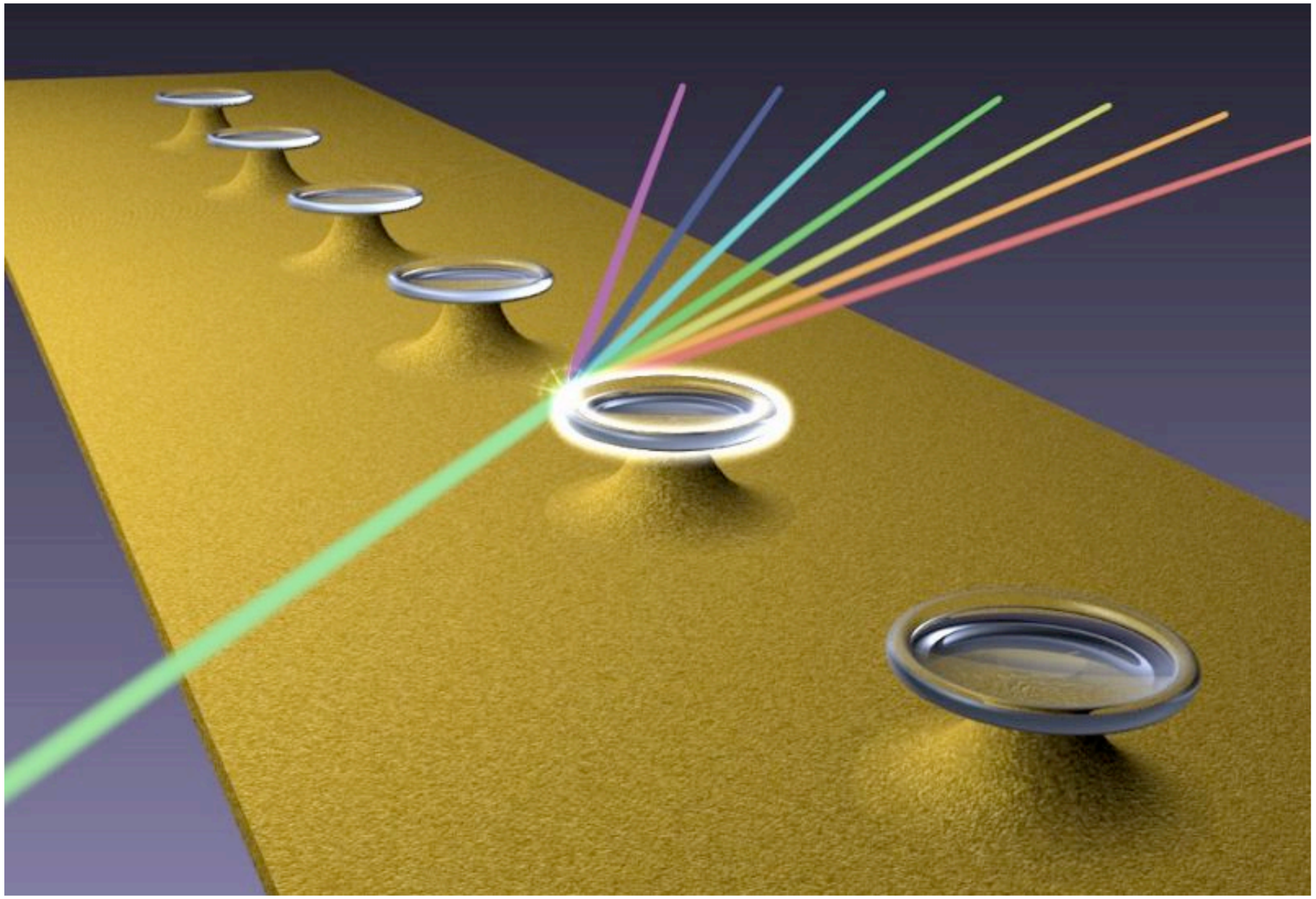
guided light: fewer adjustments, continuous operation

Er^+ fiber laser frequency comb

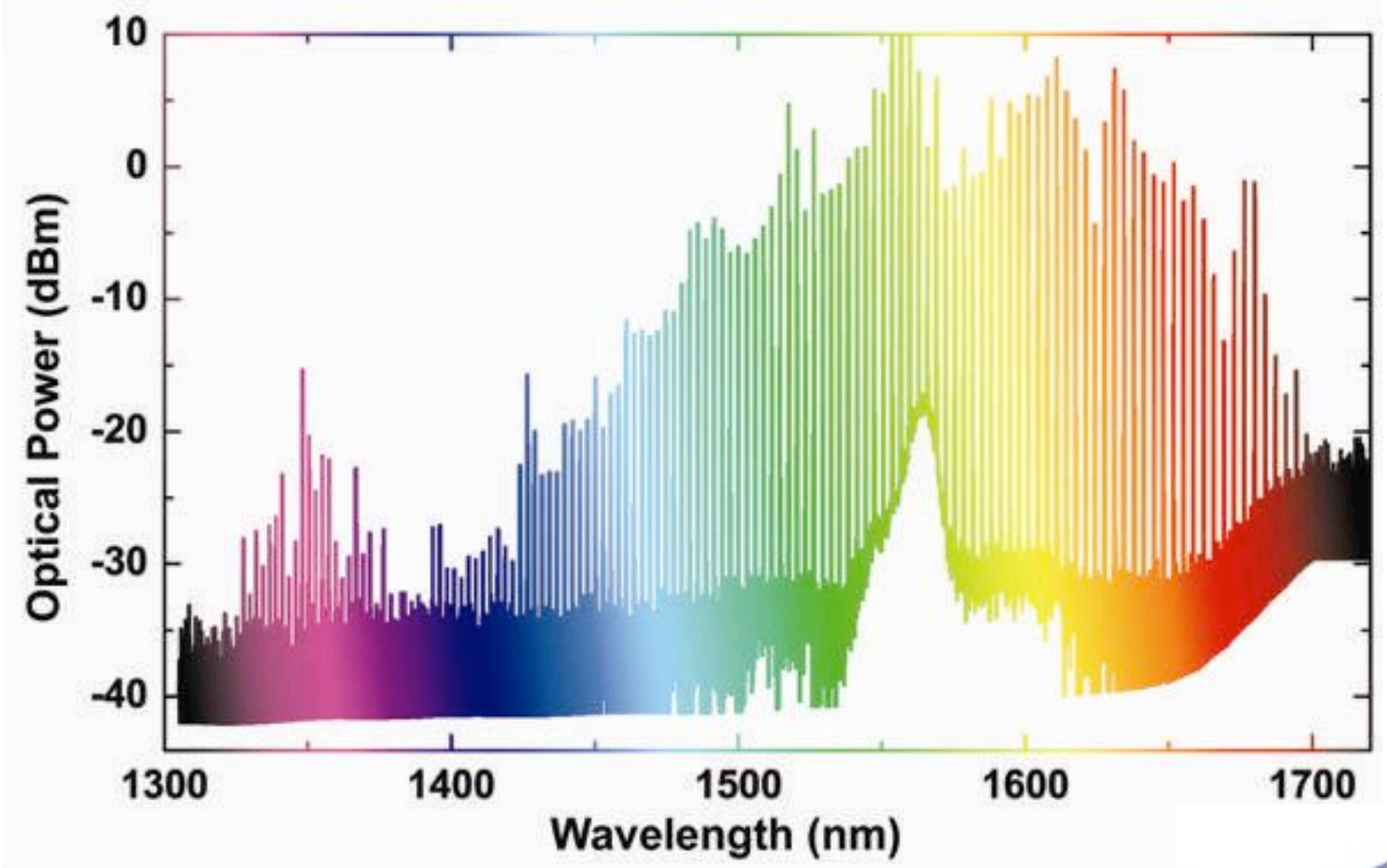


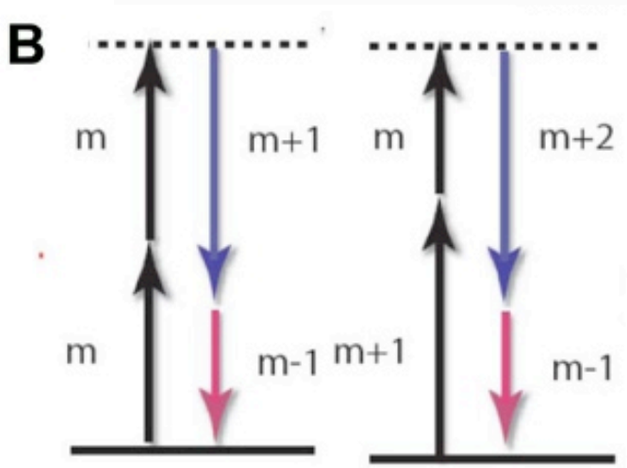
f_r = 250 MHz

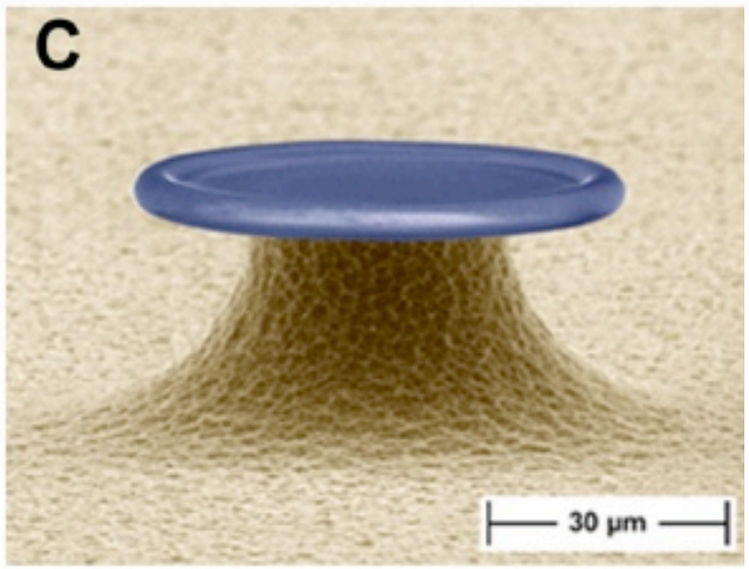
frequency combs from toroidal microresonators

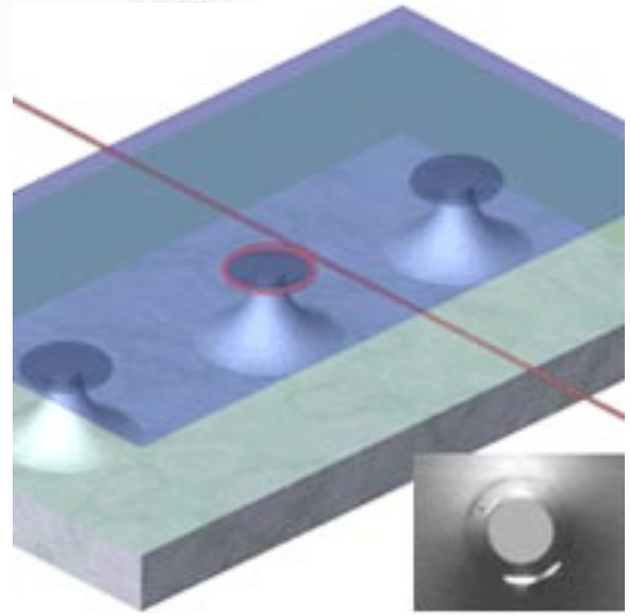


optical frequency comb generation from a monolithic microresonator



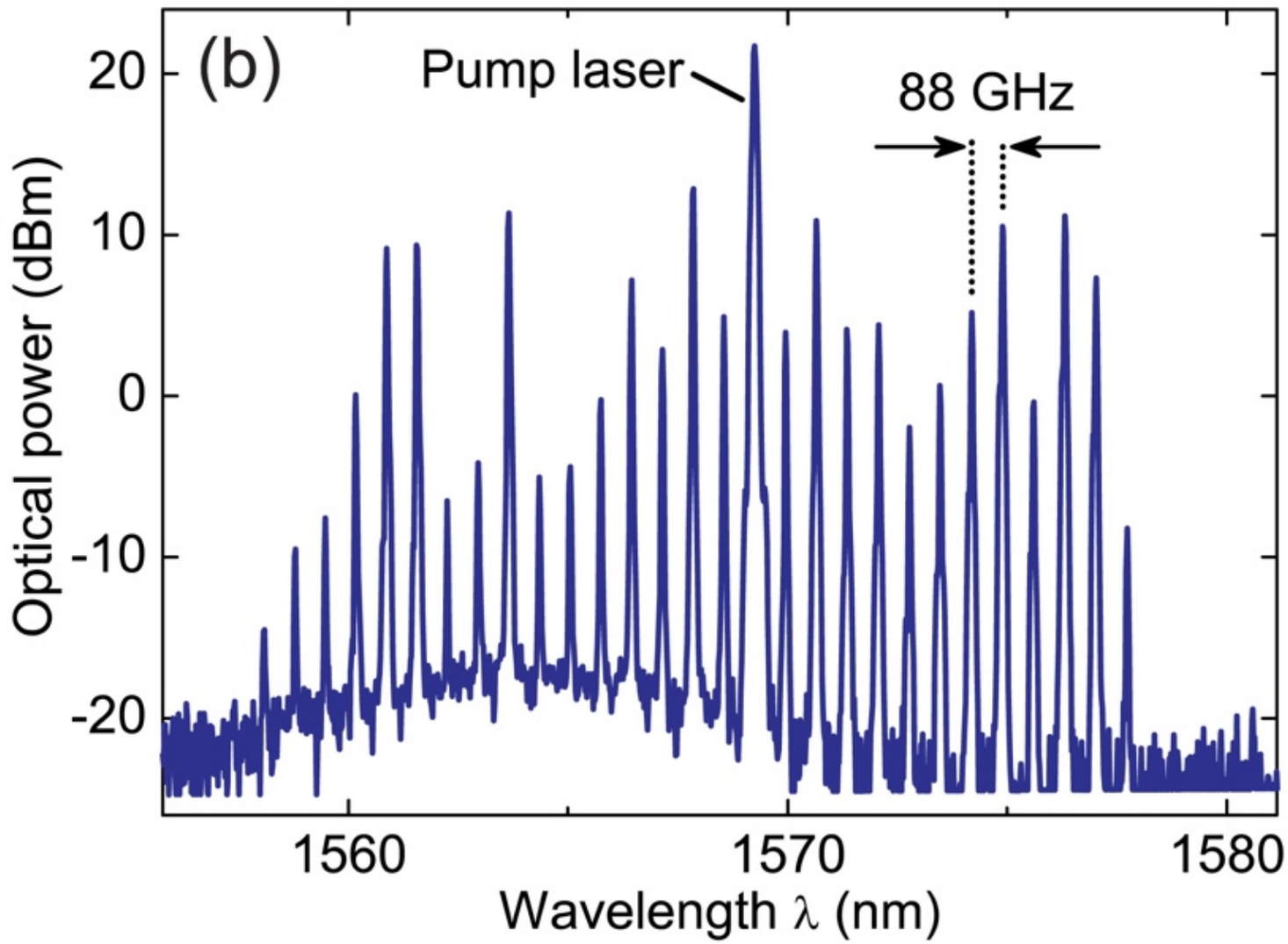




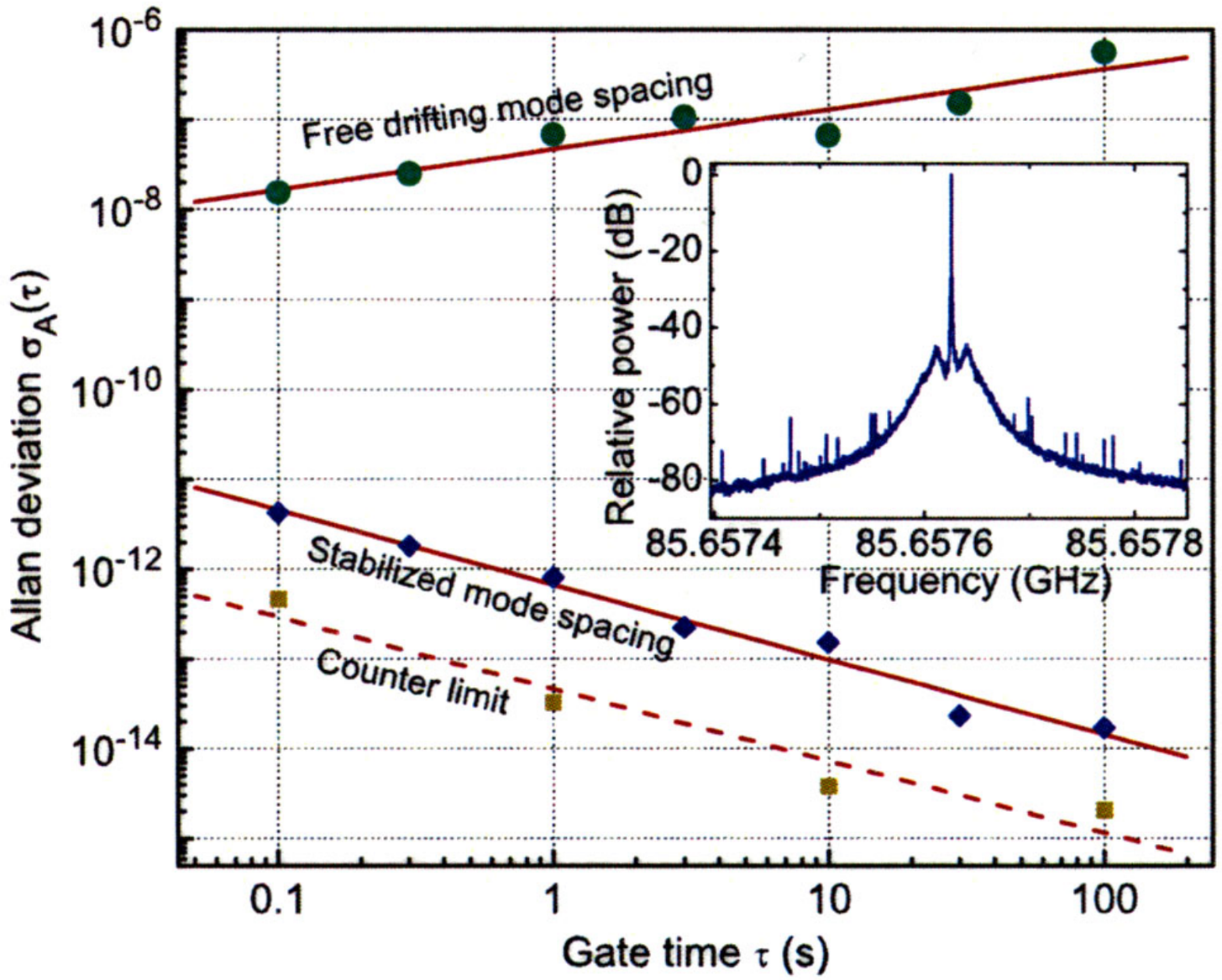


P. Del'Haye*, A. Schliesser*, T. Wilken, R. Holzwarth, T. J. Kippenberg, Nature, **450**, 1214 (2007)

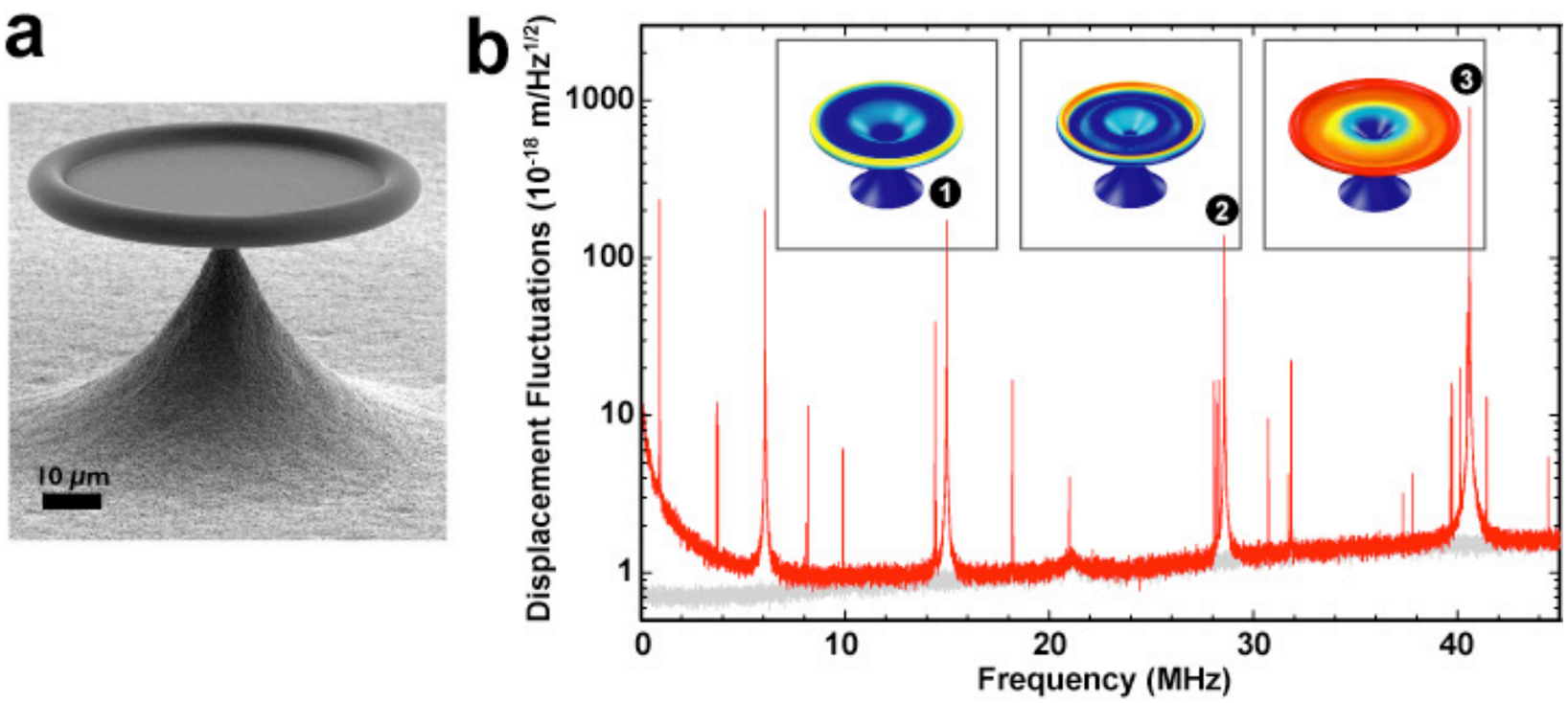
larger toroidal microresonators



pump power stabilizes mode spacing

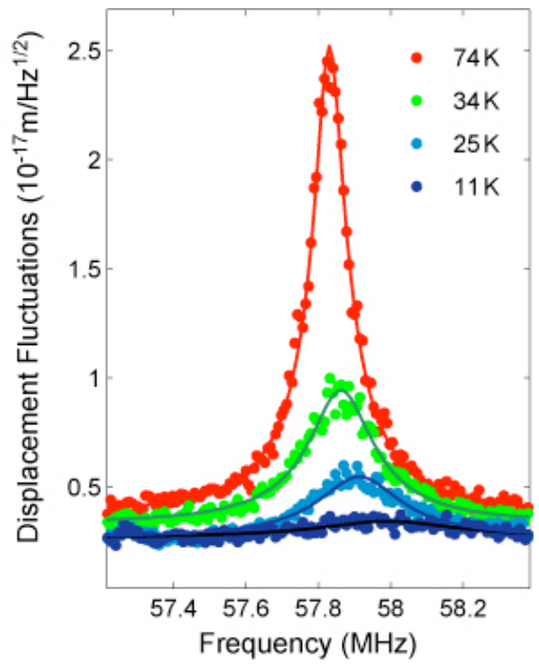


Resolved Sideband Laser Cooling of a Micromechanical Oscillator



R. Schliesser, R. Rivière, G. Anetsberger,
O. Arcizet, and T. J. Kippenberg

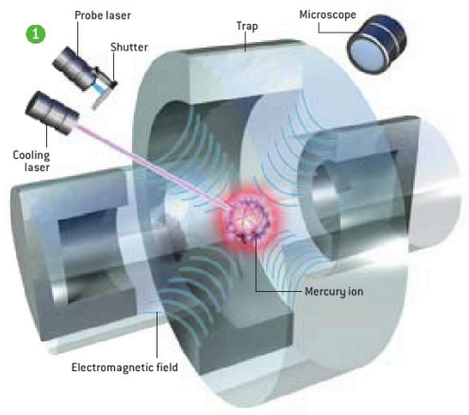
Nature Physics **4**, 415 (May 2008)



Optical clocks - some candidates

Laser-cooled trapped ions

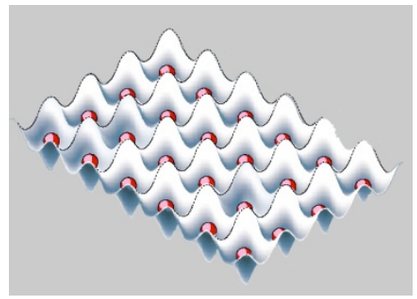
Hg^+, In^+, Yb^+, Sr^+, Ca^+, Al^+,...



Paul trap

Cold neutral atoms:

H, Ca, Sr, Yb, Ag, ...

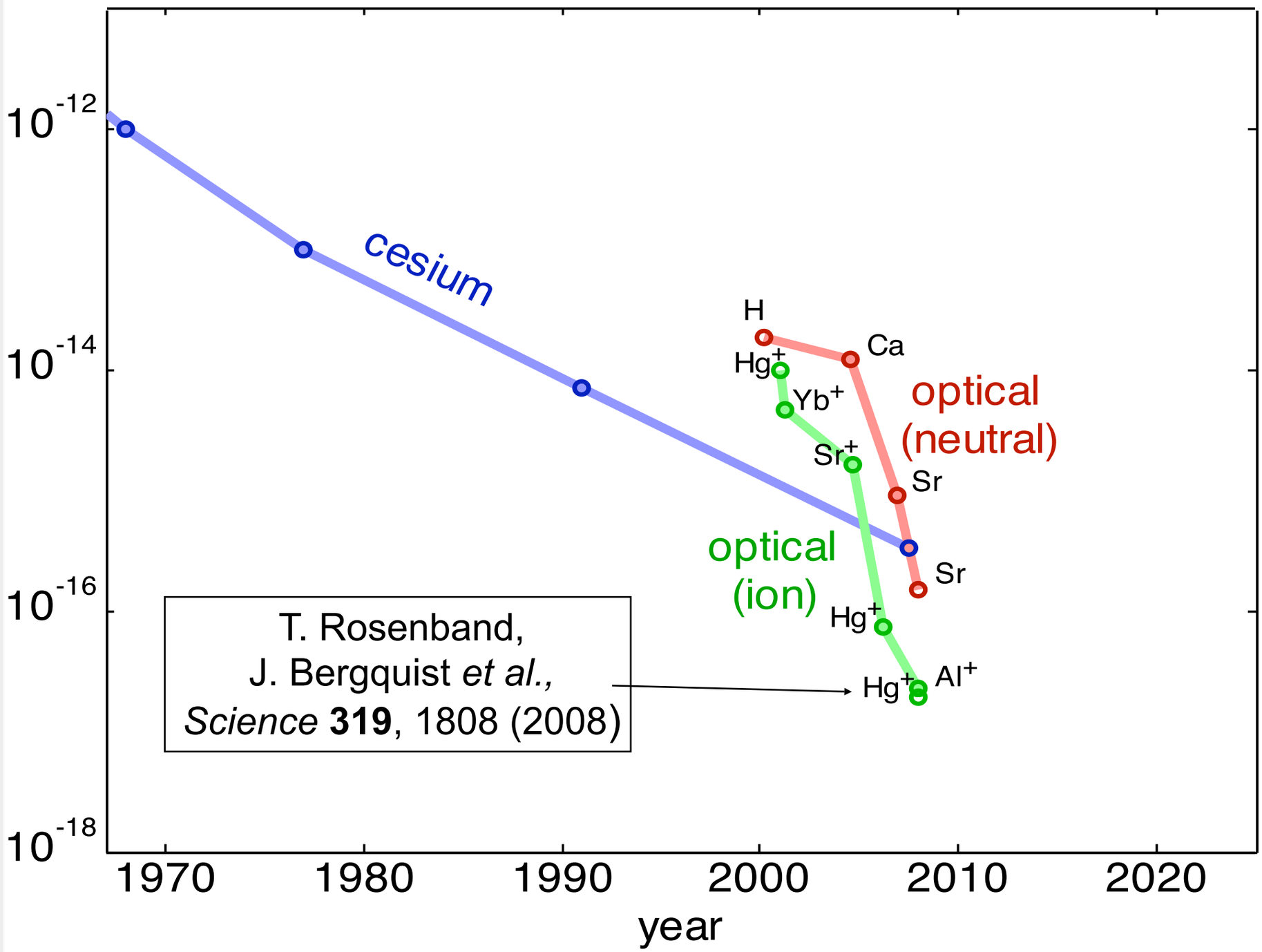


Optical lattice,
magic wavelength

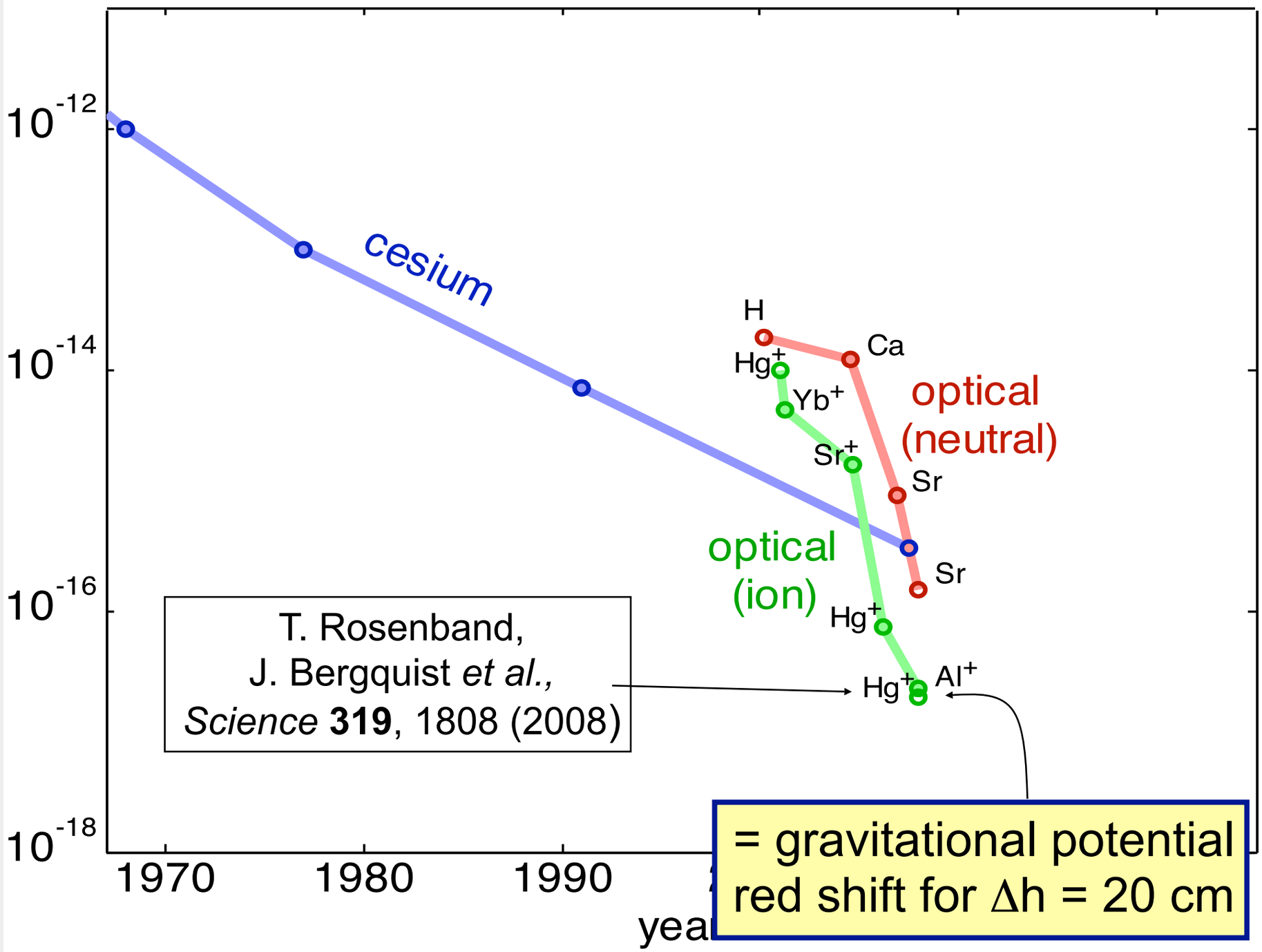
Molecules:

I_2, C_2H_4, ...

Systematic uncertainty (expressed fractionally)



Systematic uncertainty (expressed fractionally)



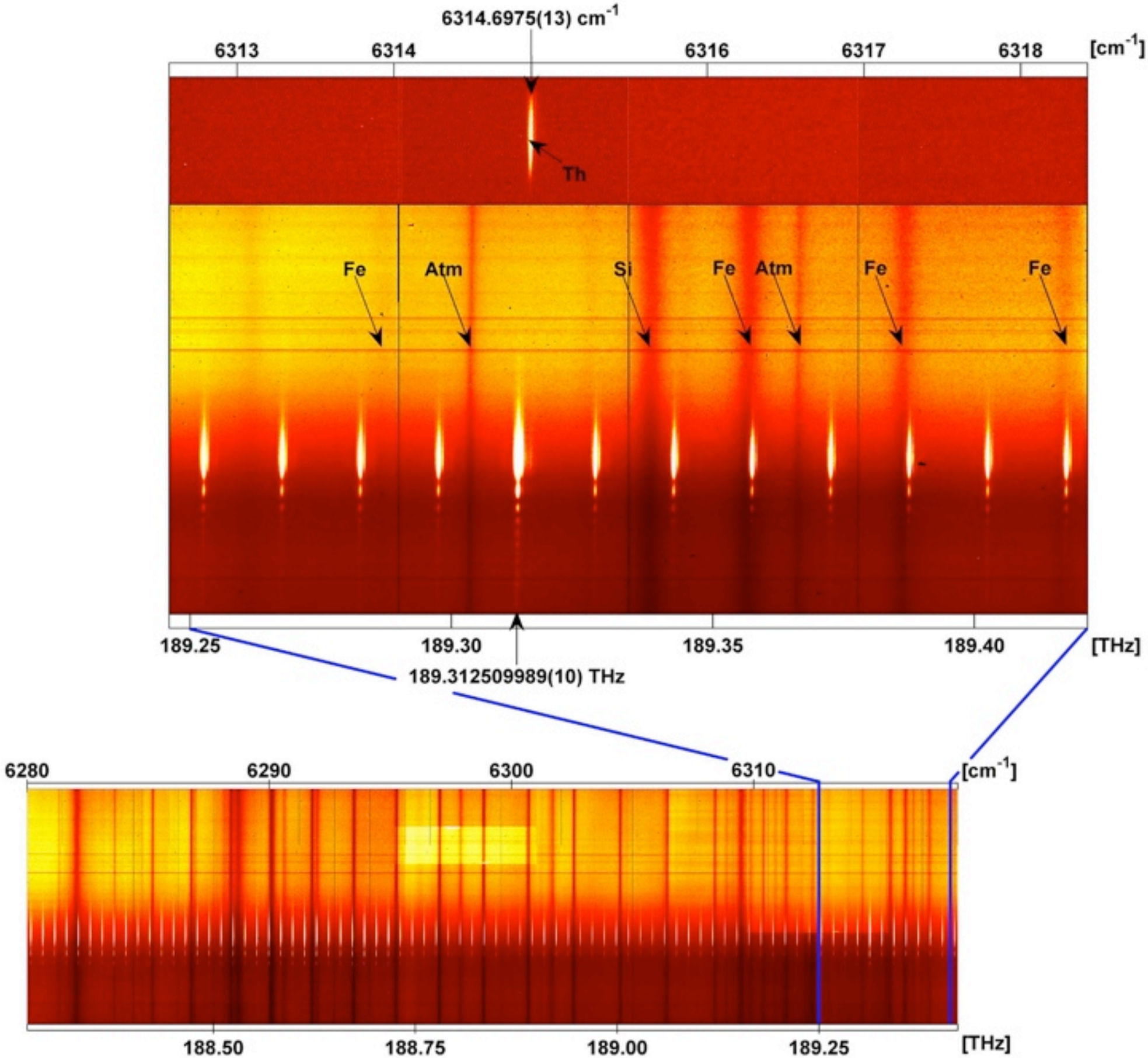
Applications for (better) Atomic Clocks

- Time and frequency metrology
- Clock synchronization over large distances
- Very long baseline interferometry (VLBI)
- Higher performance satellite navigation (Galileo)
- Precise tracking of remote space probes
- Telecommunication, network synchronization
- Variability of earth‘s rotation
- Geodesy with millimeter precision
- Mapping of the earth‘s gravitational potential
- Test of special and general relativity
- Are fundamental constants constant?
- ....

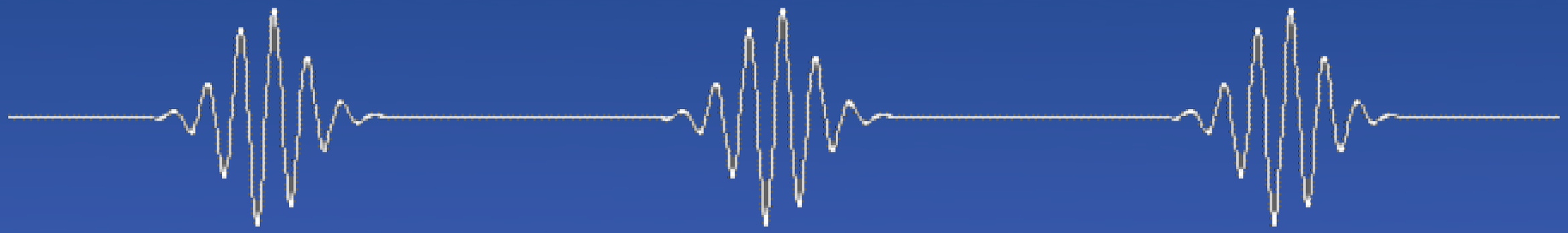
Frequency Combs in Astronomy

Calibration of large astronomical spectrographs
(ESO E-ELT, ...)
Search for earth-like planets
Search for variable fundamental constants
Direct measurement of the expansion of universe
Study of primordial nucleosynthesis (D/H, Li^6/Li^7)

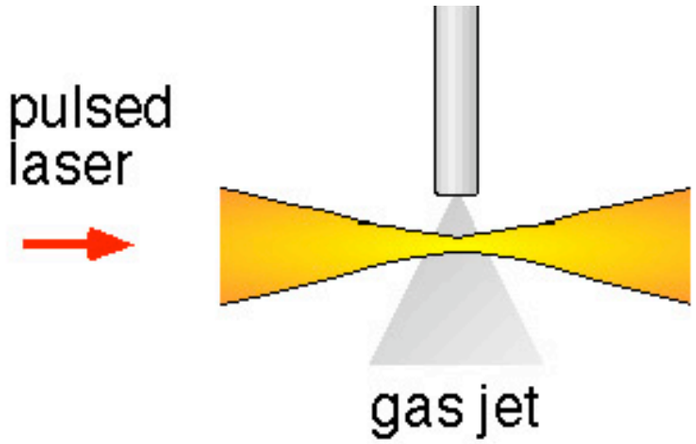
Vacuum Tower Telescope, Teide Observatory, Tenerife

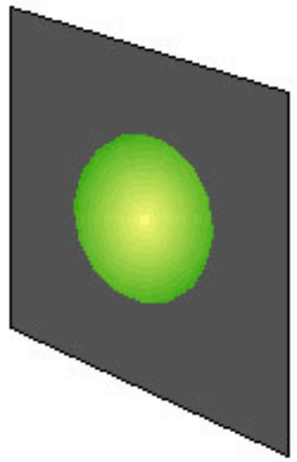

6314.6975(13) cm-1
6313
6314
6316
6317
6318
[cm-1]
Th
Fe
Atm
Si
Fe
Atm
Fe
Fe
189.25
189.30
189.35
189.40
[THz]
189.312509989(10) THz
6280
6290
6300
6310
[cm-1]
188.50
188.75
189.00
189.25
[THz]

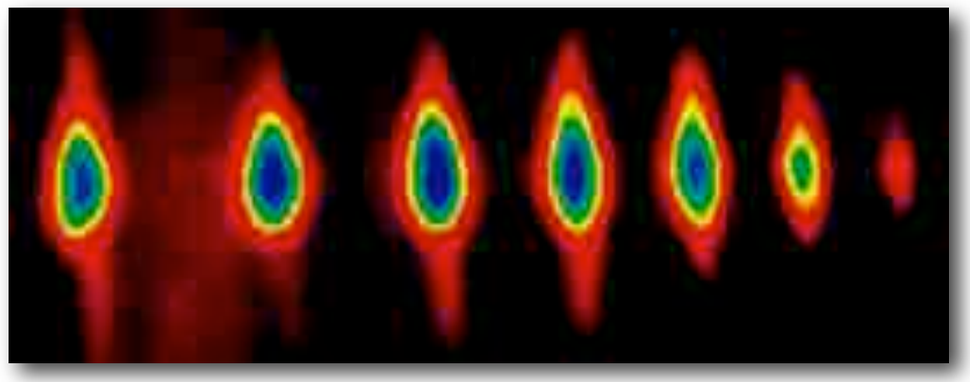
Towards frequency combs and ultraprecise spectroscopy in the extreme ultraviolet

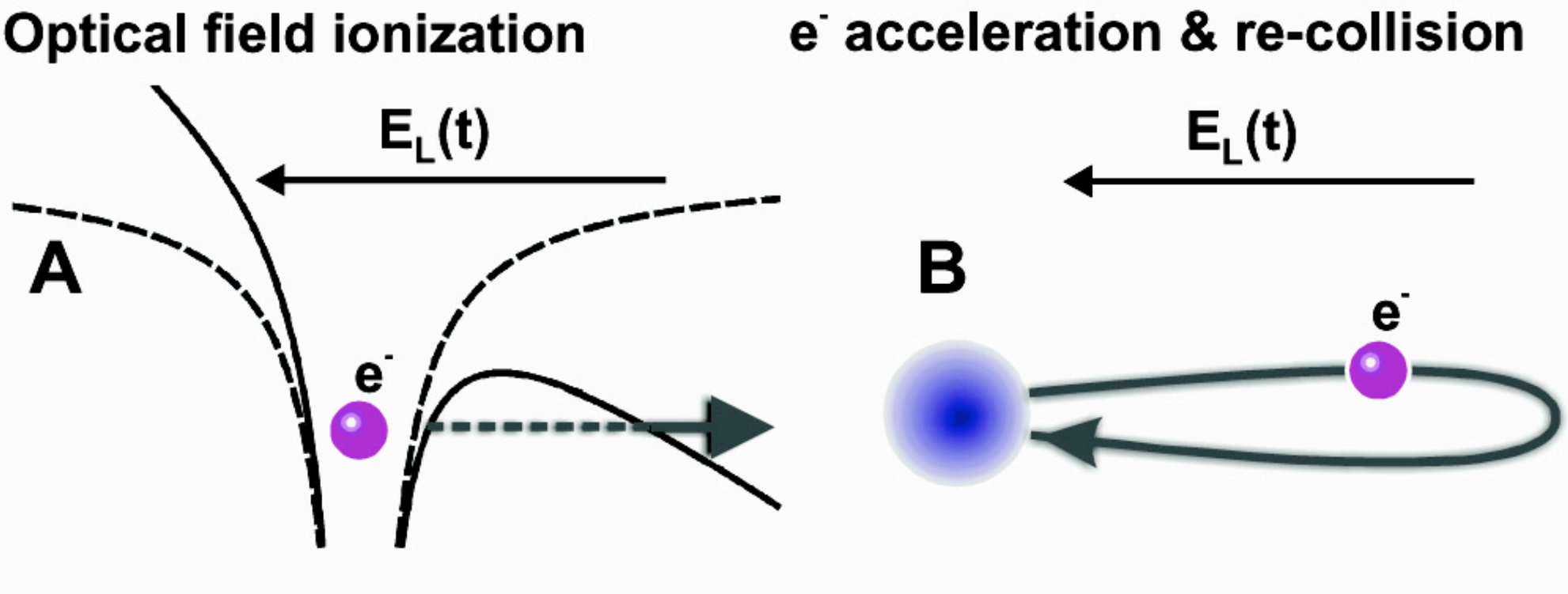


Generation of high harmonics

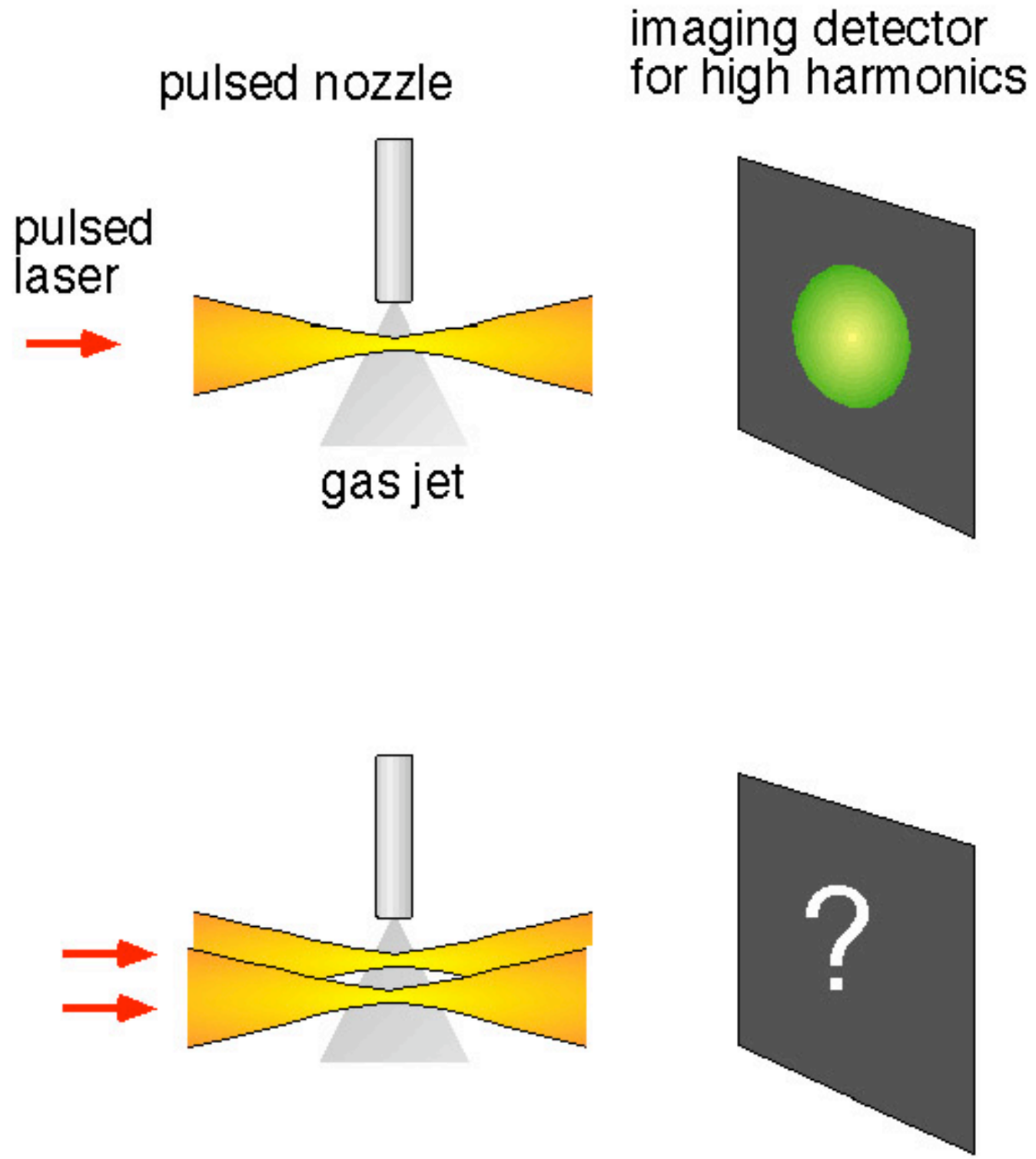




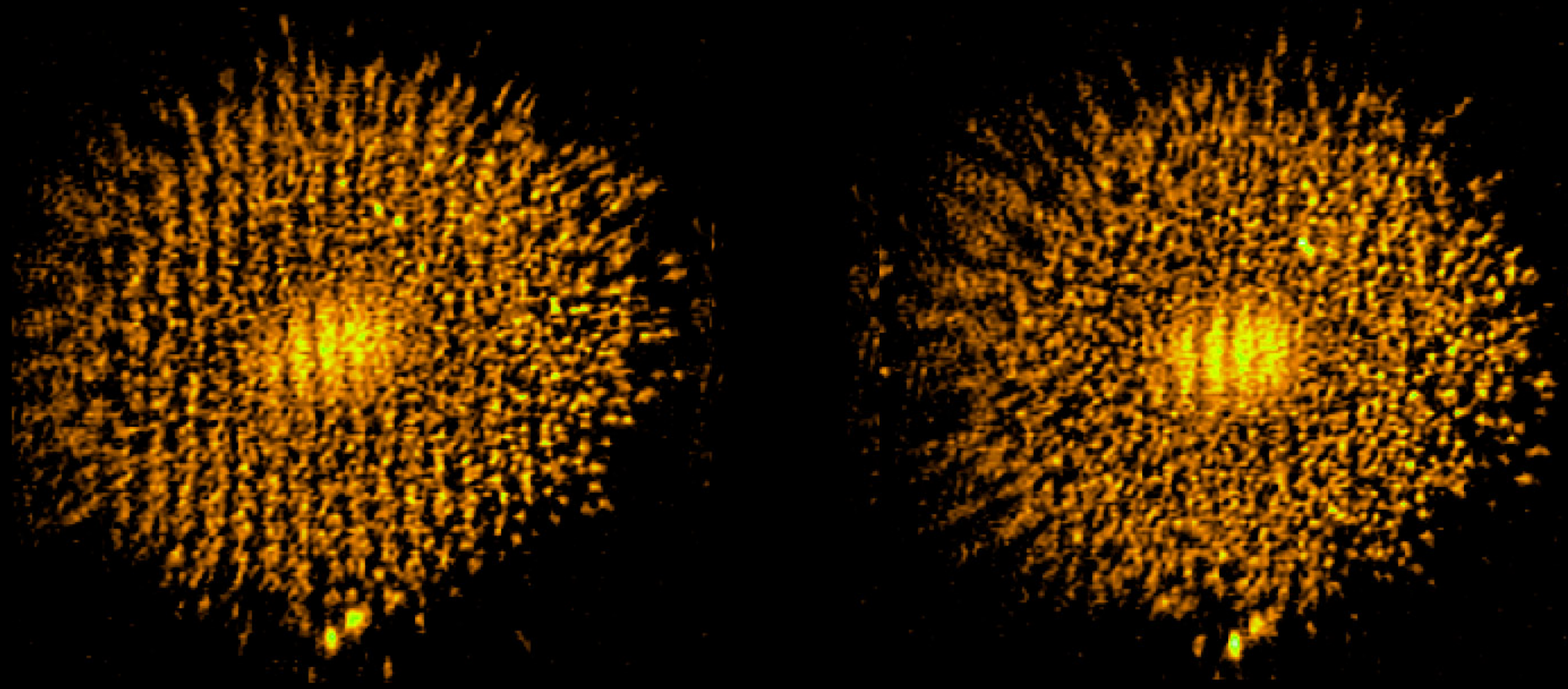




Can two high harmonics pulses interfere?



15 th harmonic (53 nm)



0 fs (delay) 15 fs

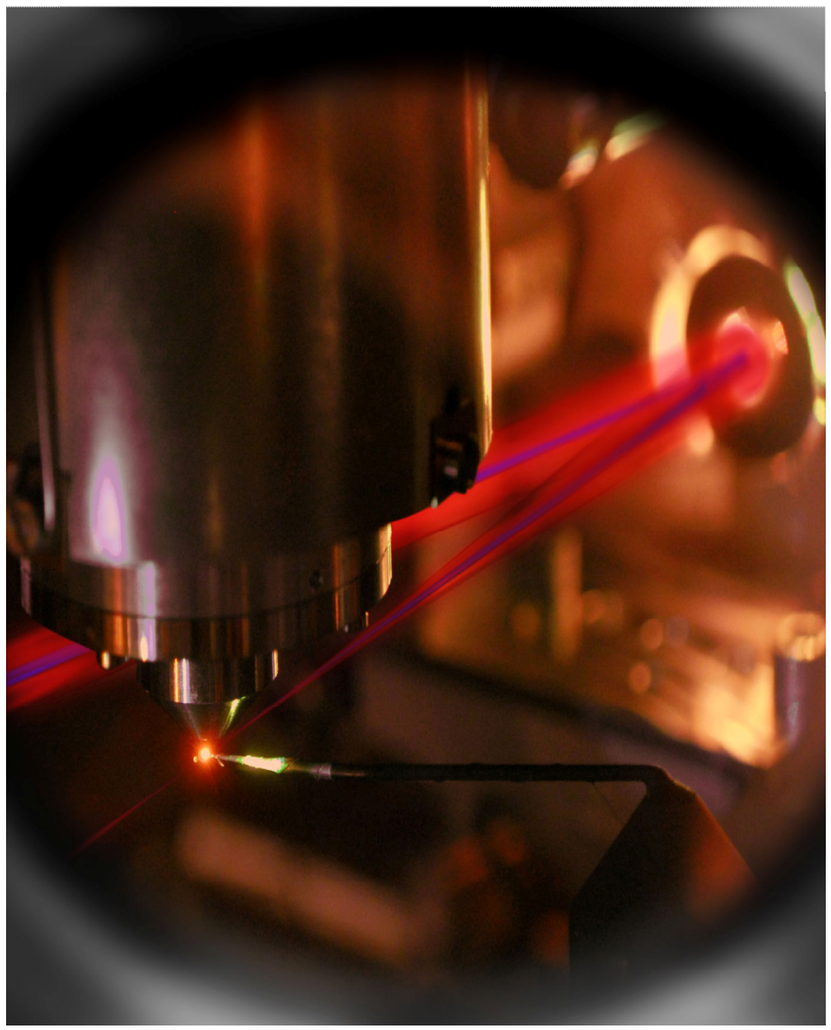
Experiments at Lund Laser Center:

R. Zerne et al., Phys. Rev. Lett. **79**, 1006 (1997)

M. Bellini et al., Phys. Rev. Lett. **81**, 297 (1998)

Single-Cycle Nonlinear Optics

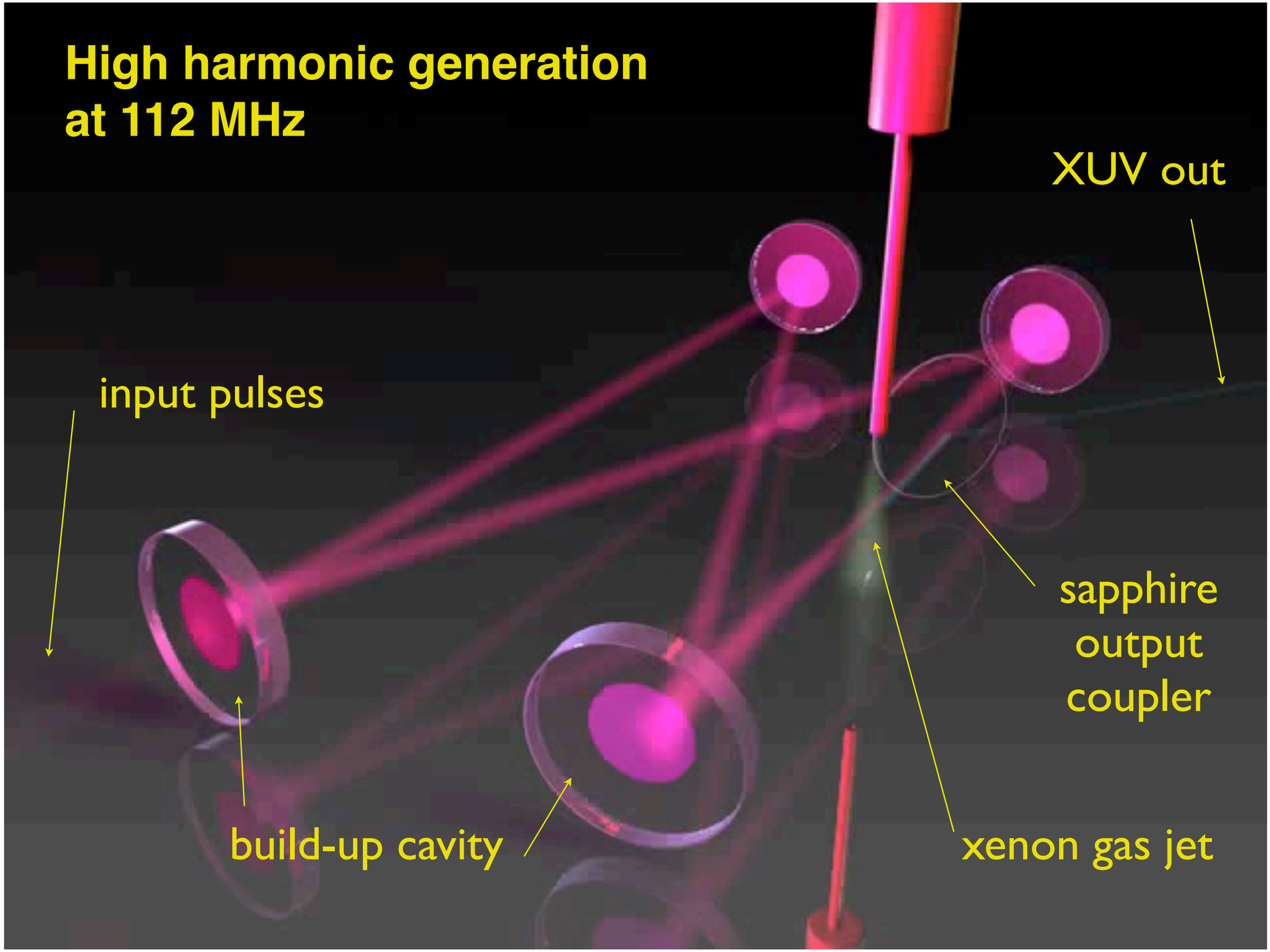
80 attosecond
XUV pulses

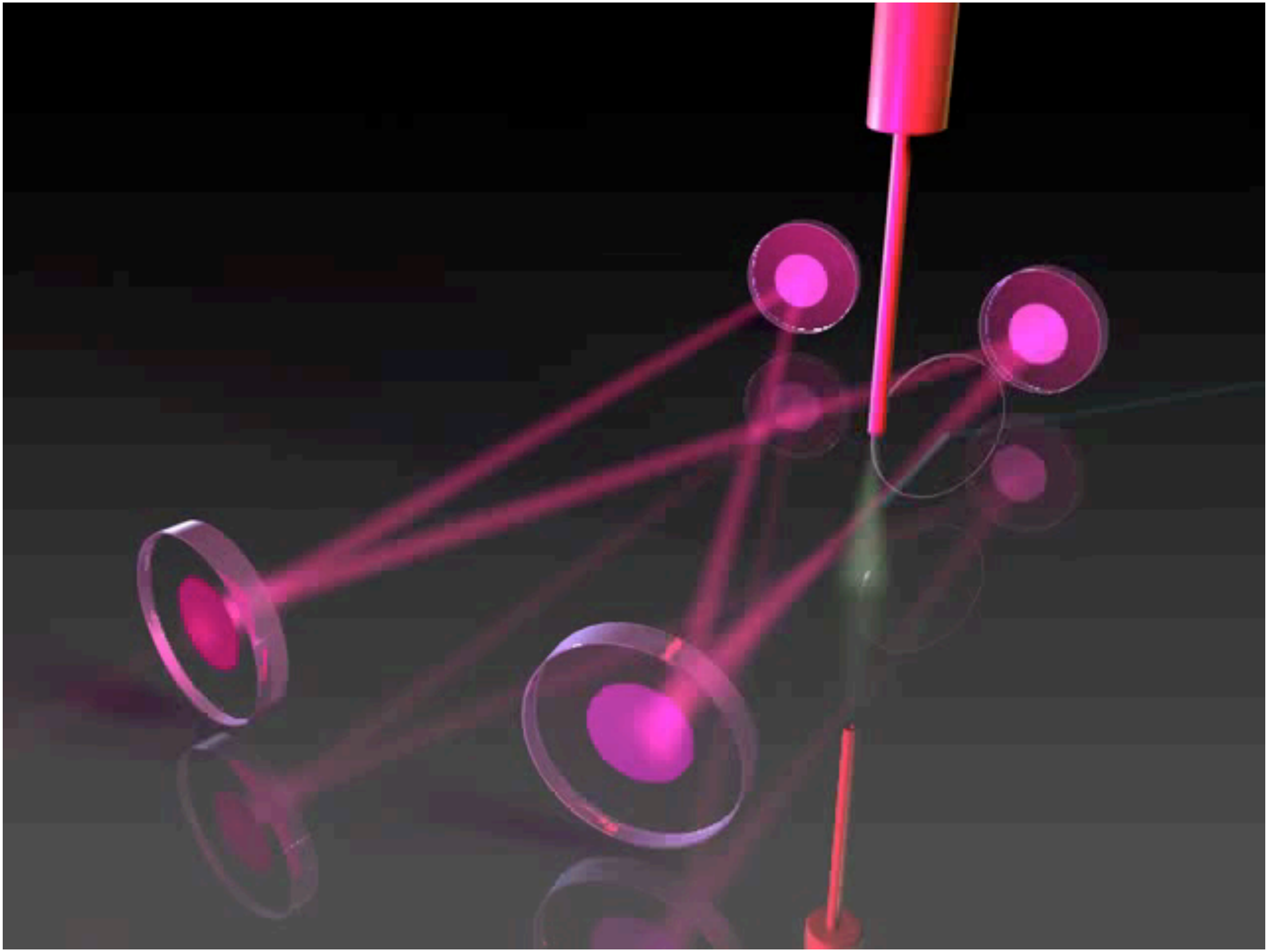


E. Goulielmakis, M. Schultze, M. Hofstetter, V. S. Yakovlev, J. Gagnon, M. Uiberacker, A. L. Aquila, E.M. Gullikson, D. T. Attwood, R. Kienberger, F. Krausz, and U. Kleineberg,

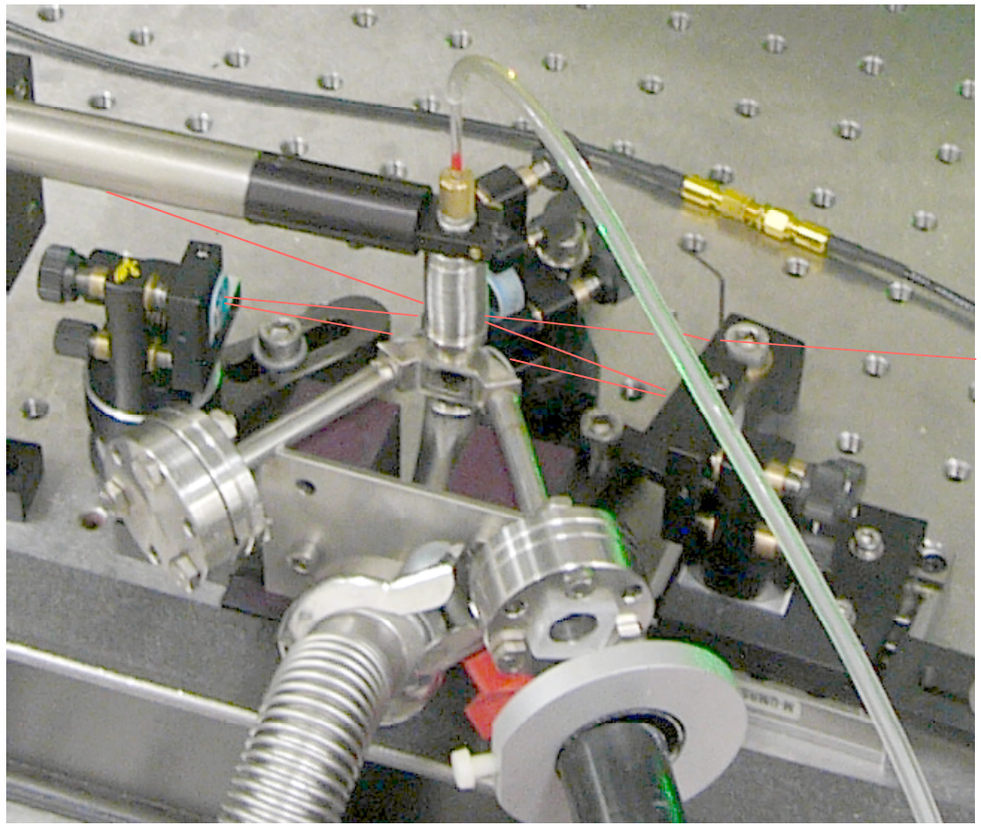
Science **20**, 1614-1617 (June 2008)

High harmonic generation at 112 MHz



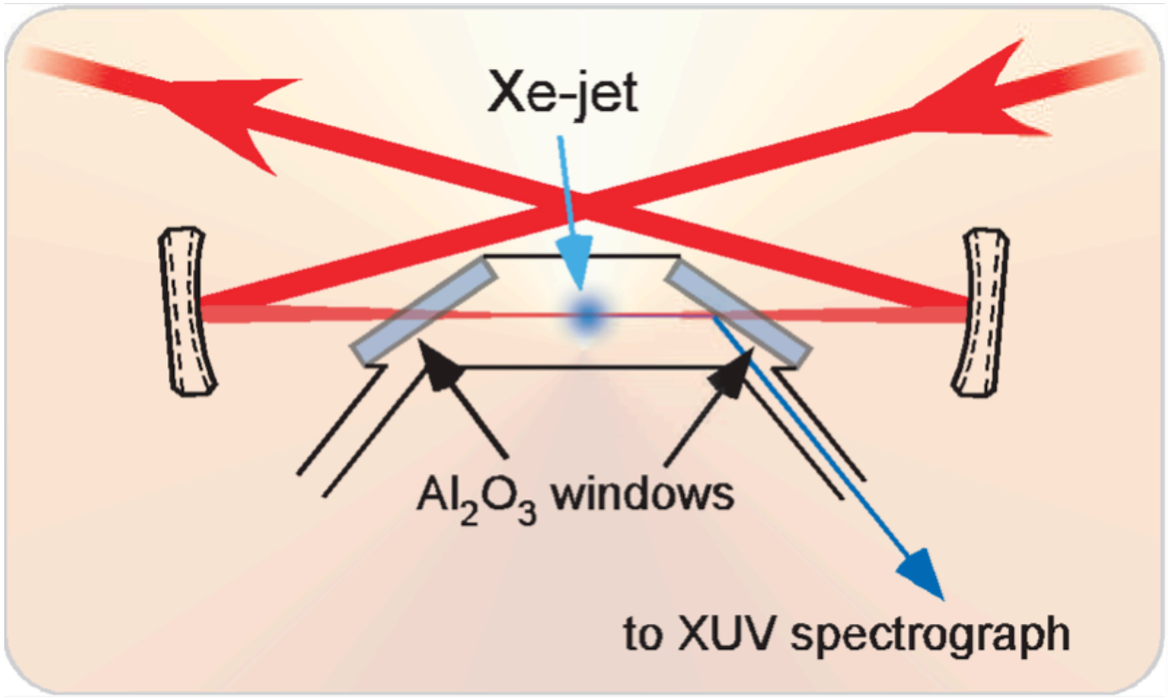


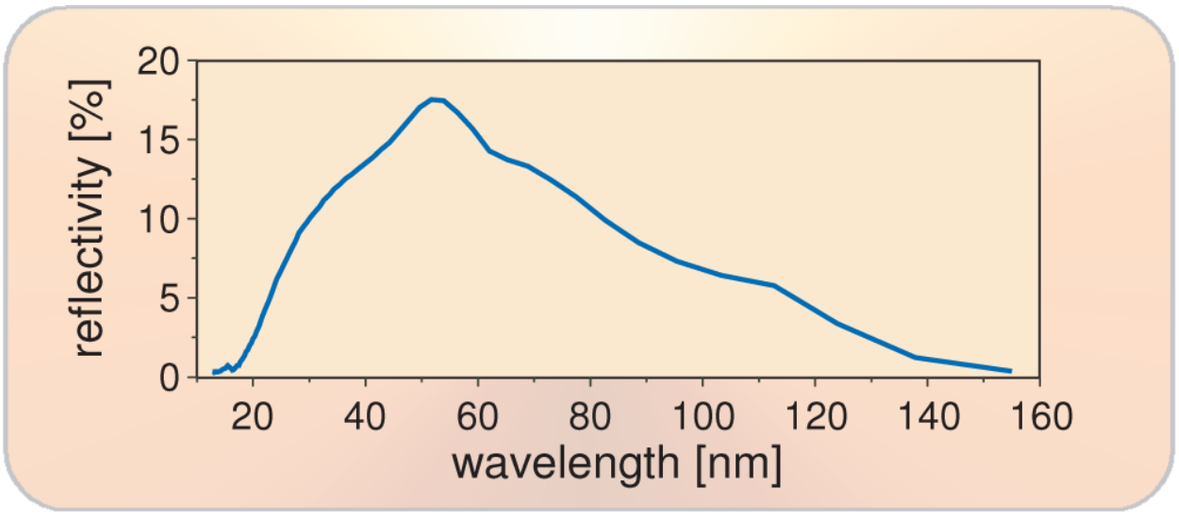
Intra-cavity high harmonic generation



injected: 22 fs pulse duration,
0.65 W average, 200 kW peak

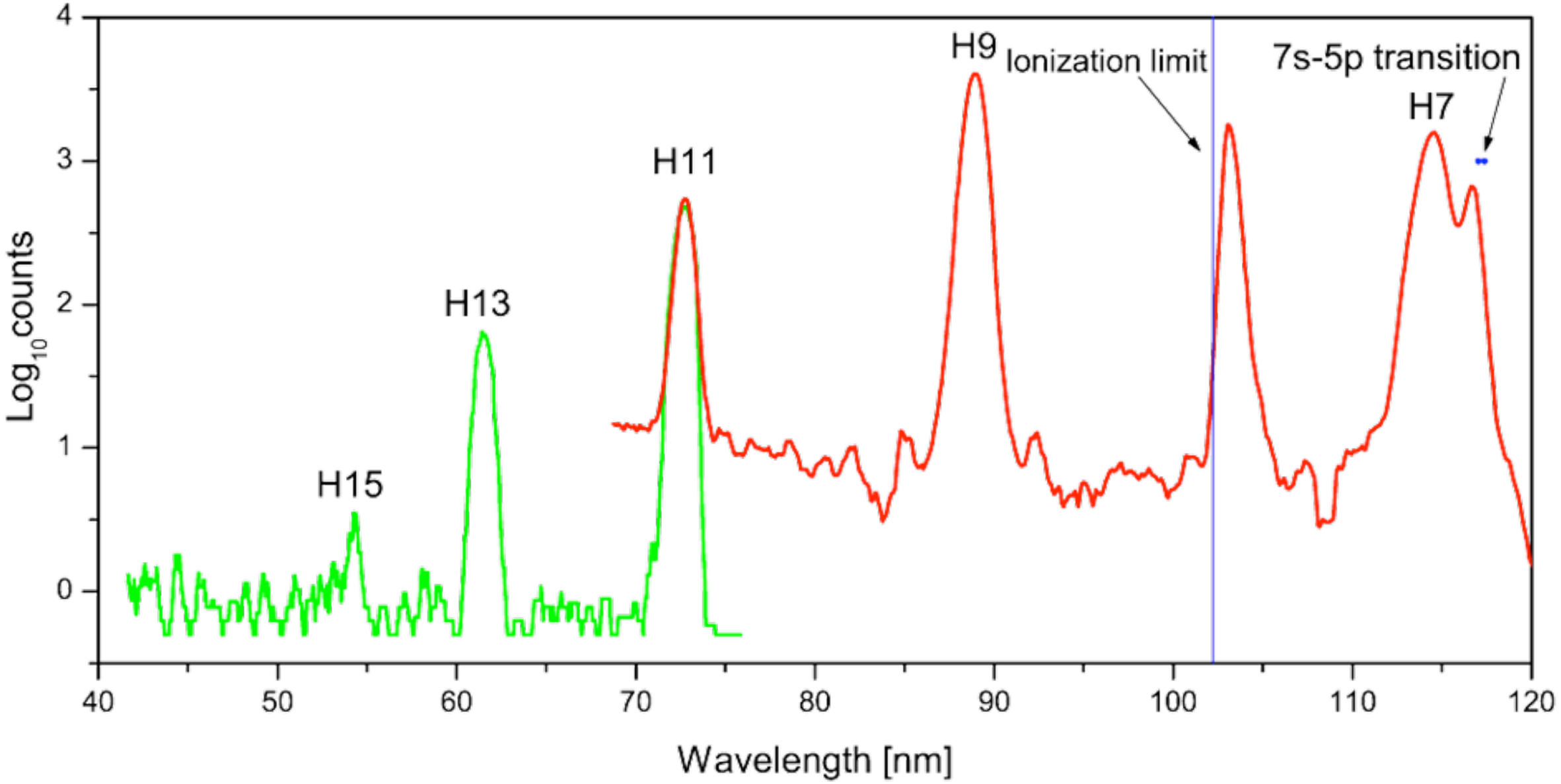
circulating: 27 fs pulse duration,
45 W average, 15 MW peak



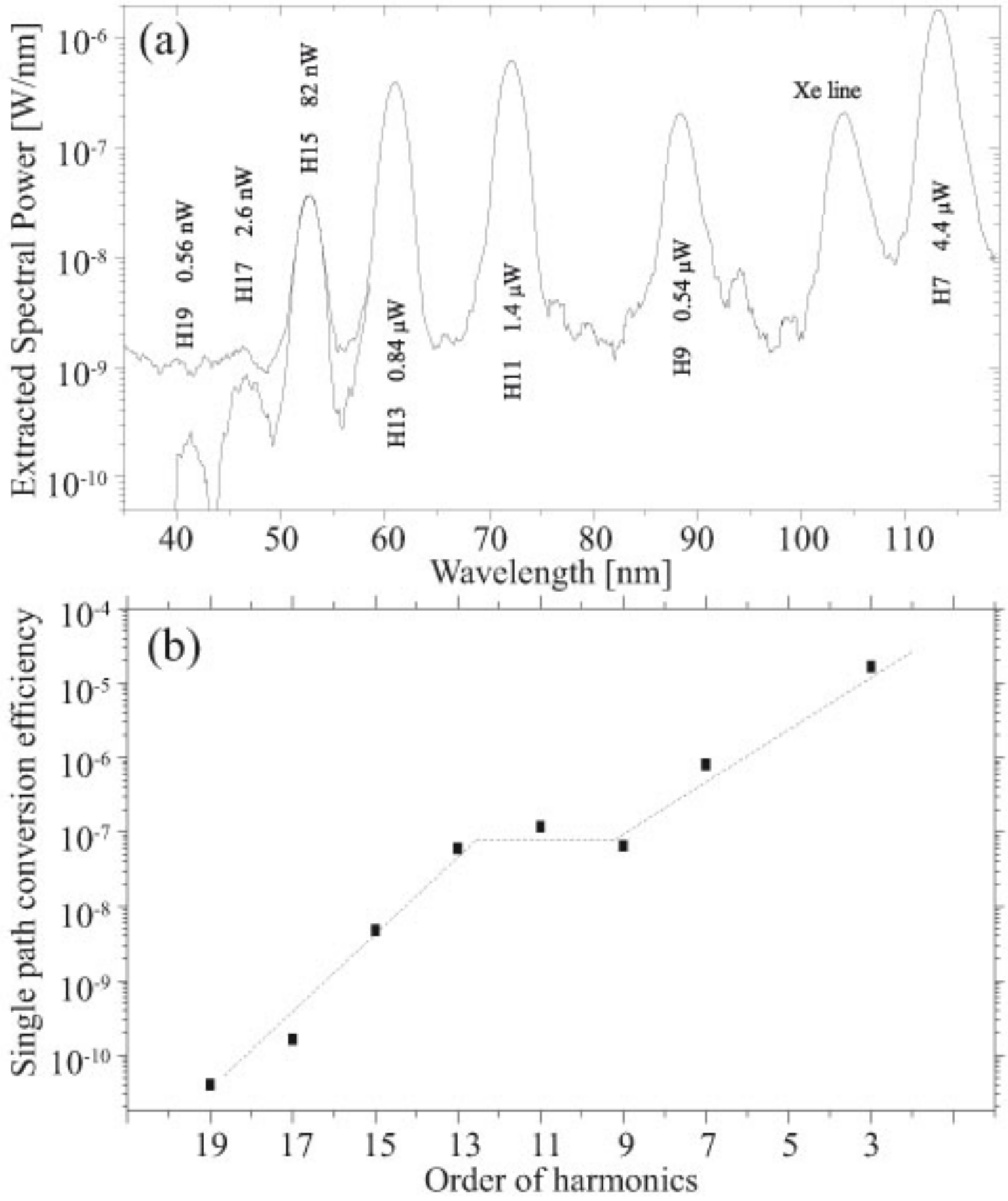


Ch. Gohle et al., Nature **436**, 234 (2005)

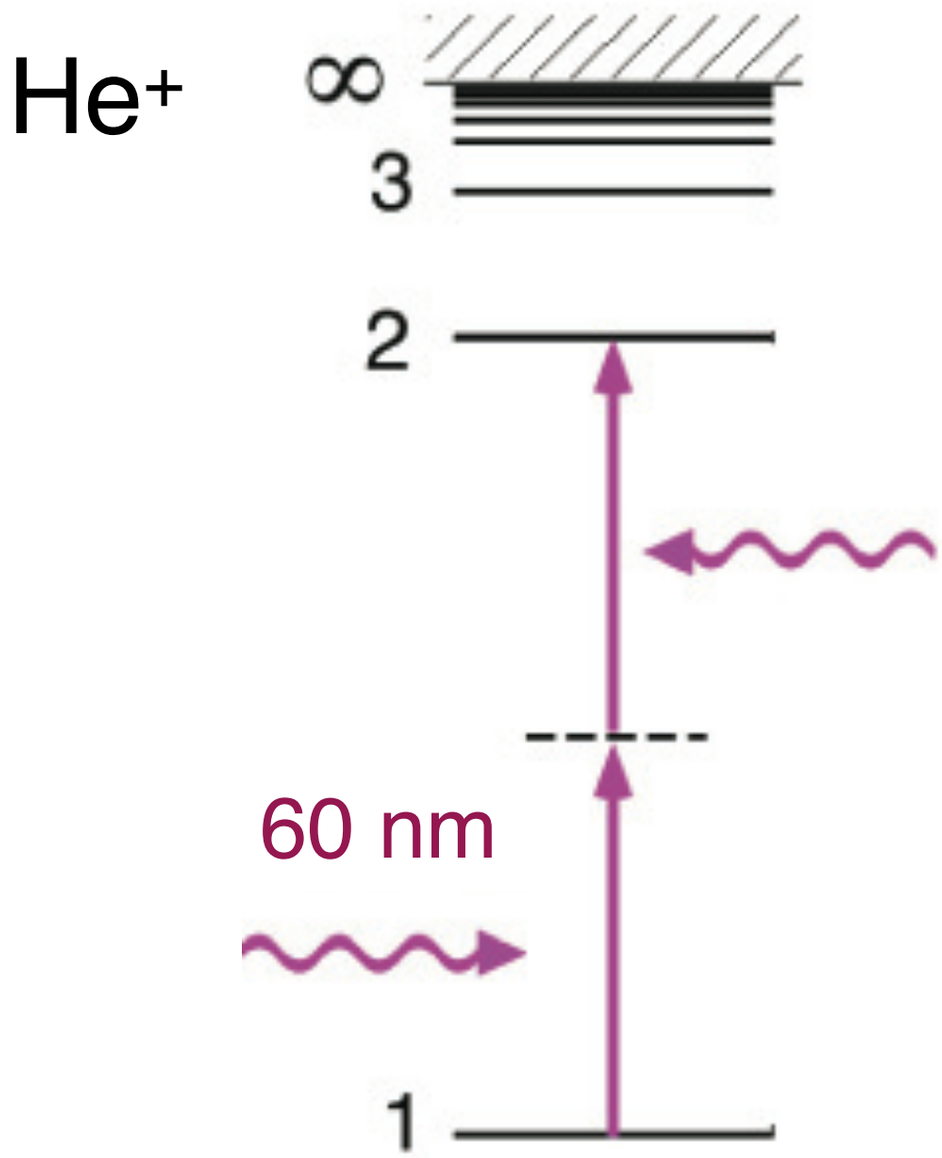
High harmonic generation at 112 MHz



Ch. Gohle et al., Nature **436**, 234 (2005)


(a)
Extracted Spectral Power [W/nm]
10-6
10-7
10-8
10-9
10-10
H19 0.56 nW
H17 2.6 nW
H15 82 nW
H13 0.84 μW
H11 1.4 μW
H9 0.54 μW
Xe line
H7 4.4 μW
40
50
60
70
80
90
100
110
Wavelength [nm]
(b)
Single path conversion efficiency
10-4
10-5
10-6
10-7
10-8
10-9
10-10
19
17
15
13
11
9
7
5
3
Order of harmonics

Two-photon spectroscopy of He^+ 1S-2S with XUV frequency comb

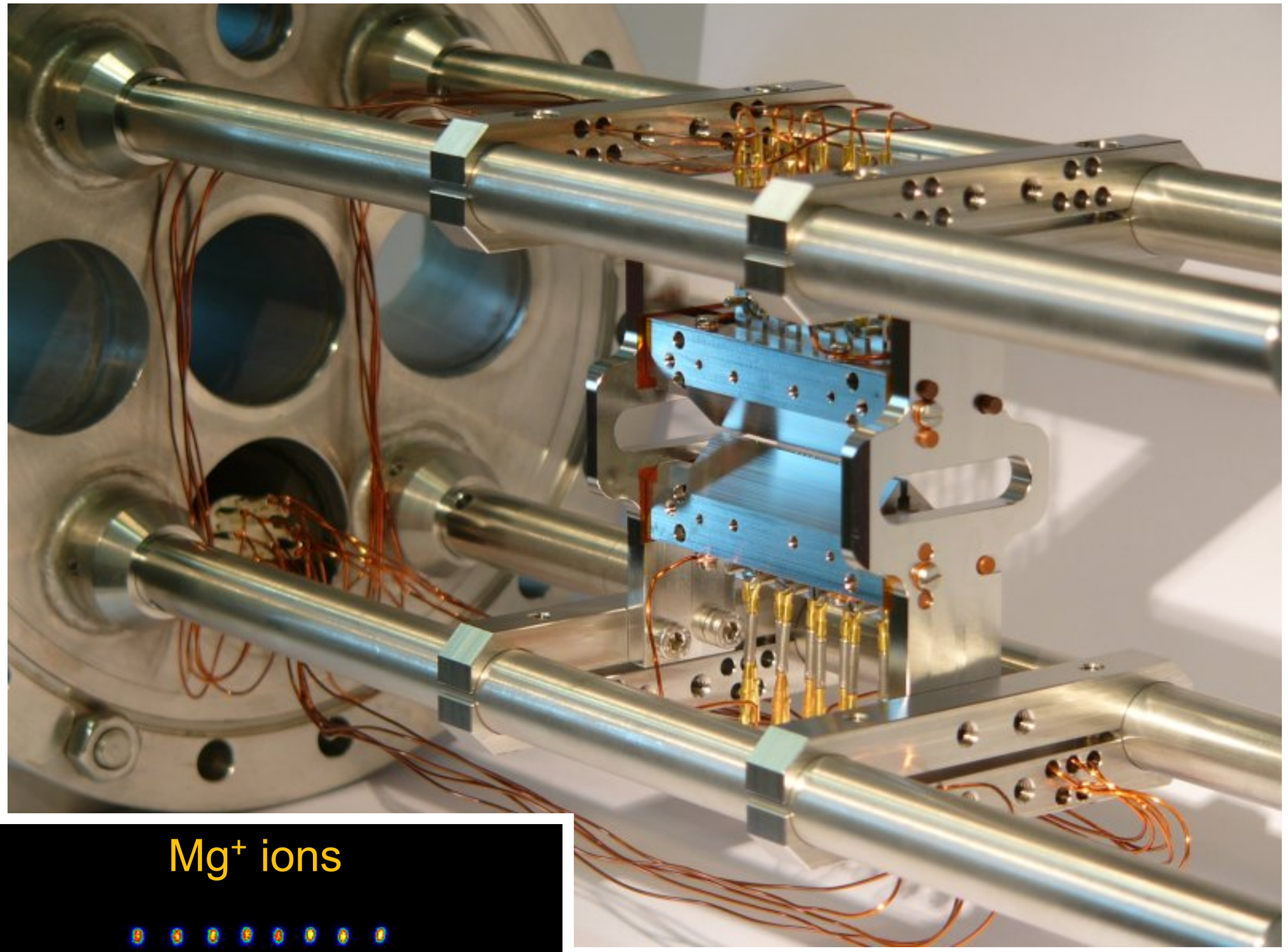


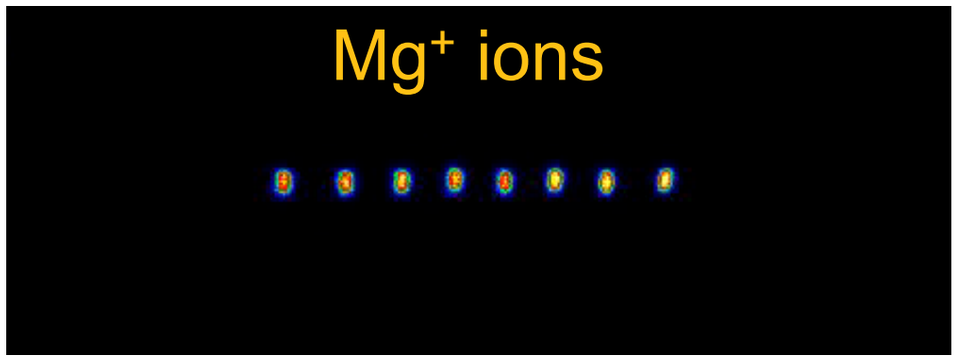
Helium ion

in Paul trap

Thomas Udem
Christoph Gohle
Maximilian Herrmann

Linear Paul trap

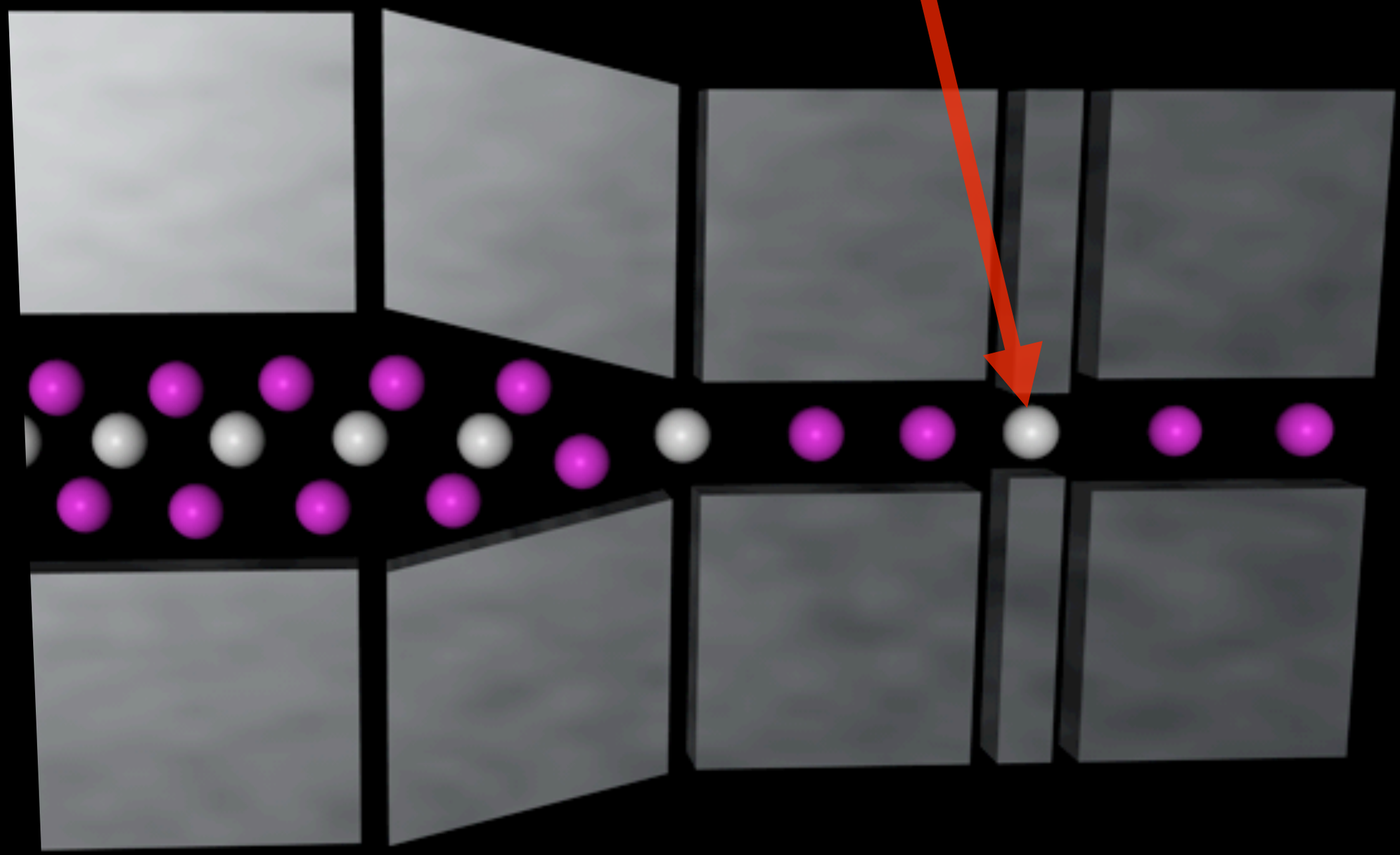




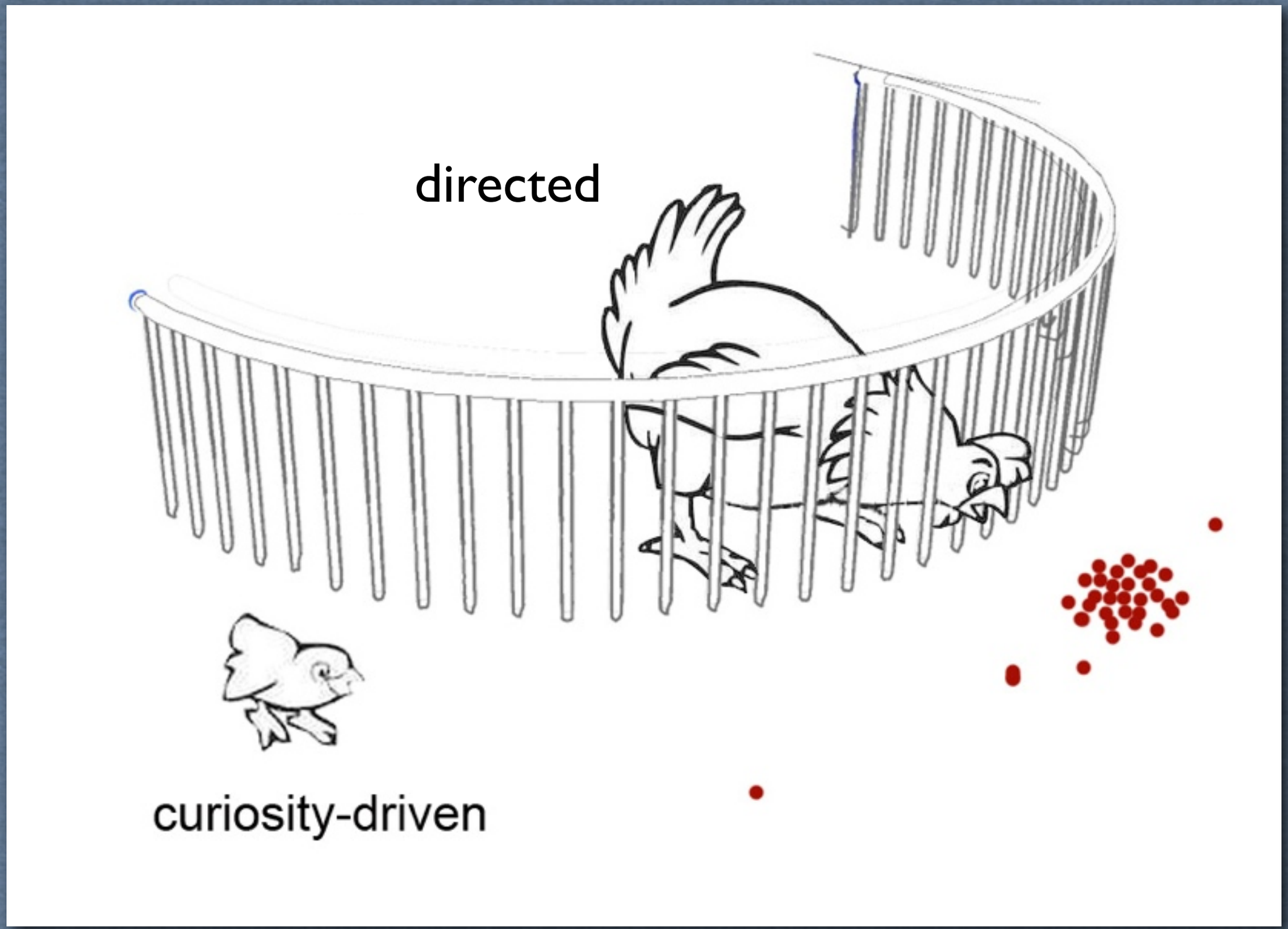
Mg^+

He^+

XUV pulse train



curiosity-driven research



M. Abgrall, P. Adel, J. Alnis, T. Andreae, R.G. Beausoleil,
M. Bellini, S. Bergesson, L.A. Bloomfield, U. Boesl, C. Bordé,
A. Clairon, B. Couillaud, S.M. Curry, P. Dabkiewicz,
K. Danzmann, J.N. Eckstein, K.S.E. Eikema, P. Fendel,
A. Ferguson, M. Fischer, C.J. Foot, H. Geiger, H. Gerhardt,
C. Gohle, J.E.M. Goldsmith, B. Gross, M. Haas, J.L. Hall,
A. Hemmerich, M. Herrmann, T. Heupel, E.A. Hildum,
R. Holzwarth, A. Huber, U. Jentschura, R. Kallenbach,
S.G. Karshenboim, J.C. Knight, W. König, N. Kolachevsky,
M. Kourogi, F. Krausz, P. Kubina, P. Laurent, S.A. Lee,
D. Leibfried,, A. Matveev, D.A. McIntyre, D. Meschede,
T. Mukai, M.H. Nayfeh, M. Niering, K. Pachucki, A. Pahl,
P. Pokasov, M. Prevedelli, J. Reichert, L. Ricci, P.St.J. Russel,
C. Salomon, A.L. Schawlow, F. Schmidt-Kaler, D. Schropp,
H.A. Schüssler, S. Seel, G.W. Series, I.S. Shahin, P. Toschek,
R. Teets, Th. Udem, W. Vassen, V. Vuletic, W.J. Wadsworth,
R. Wallenstein, J. Walz, E.Weber, M. Weitz, C. Wieman,
R. Wynands, C. Zimmermann, M. Zimmermann

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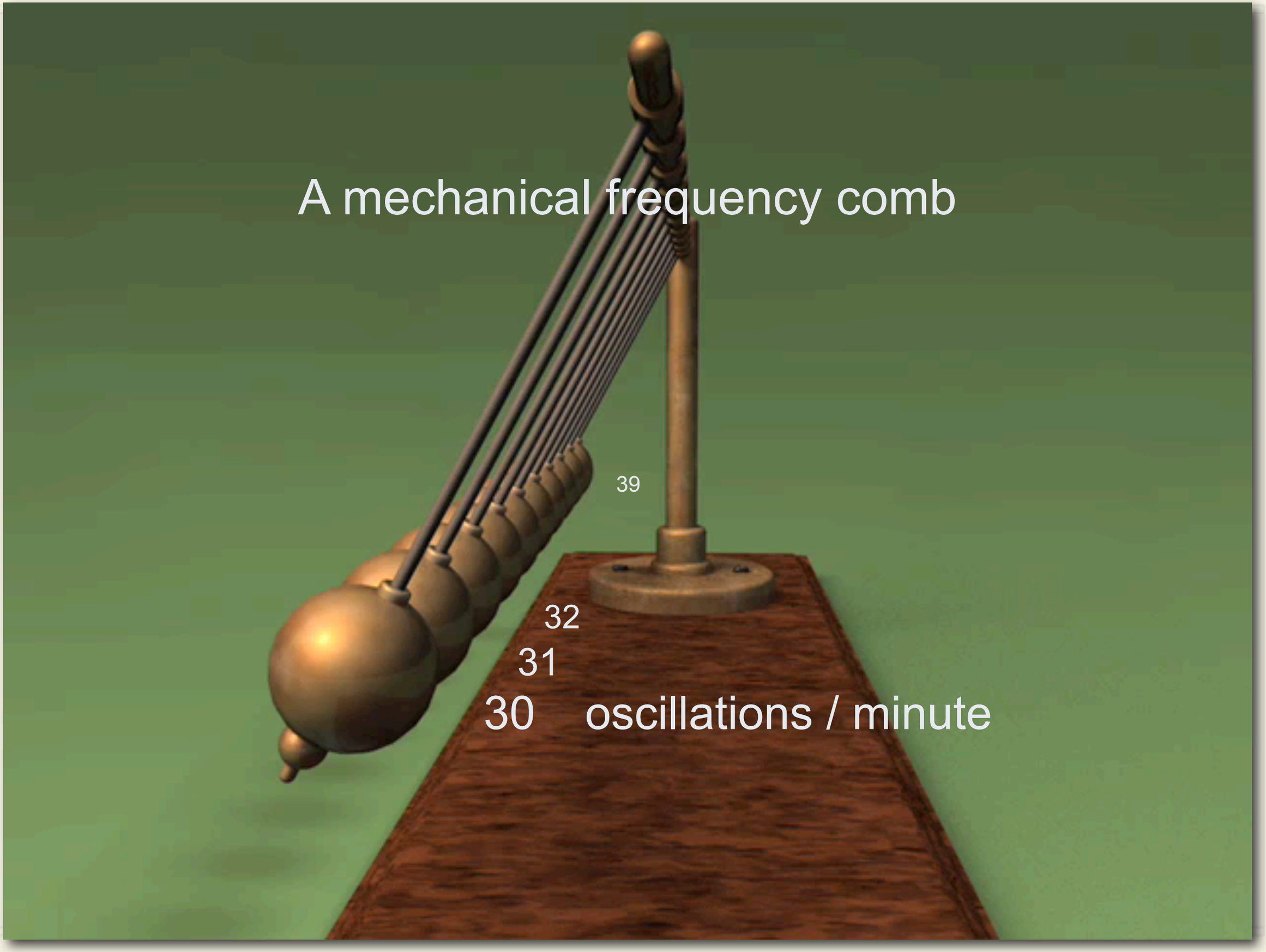
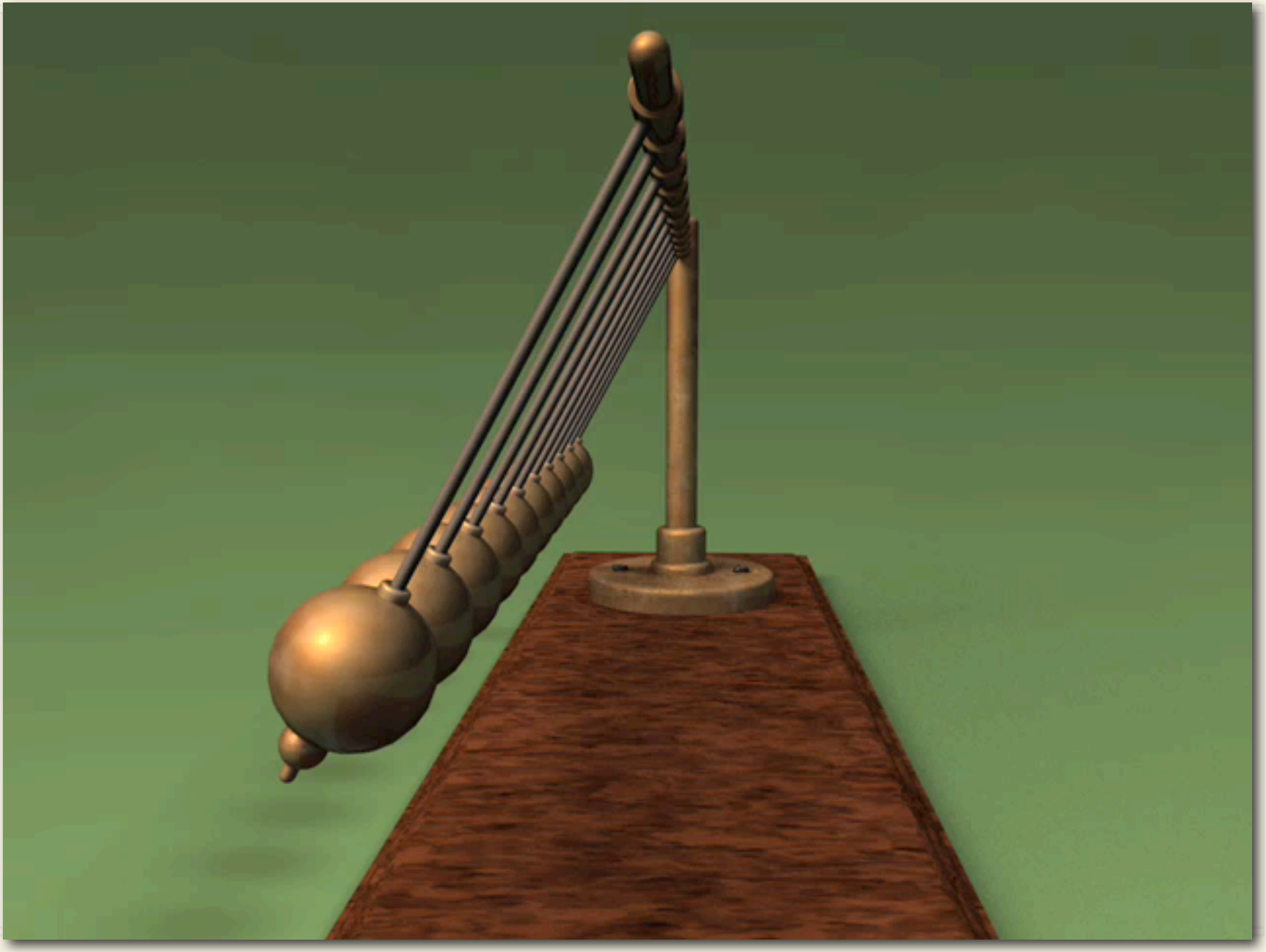
R. Wallenstein, J. Walz, E.Weber, M. Weitz, C. Wieman,
R. Wynands, C. Zimmermann, M. Zimmermann


Ronald Holzwarth
Thomas Udem
Gabriele Gschwendtner
Peter Fendel

A mechanical frequency comb





The End