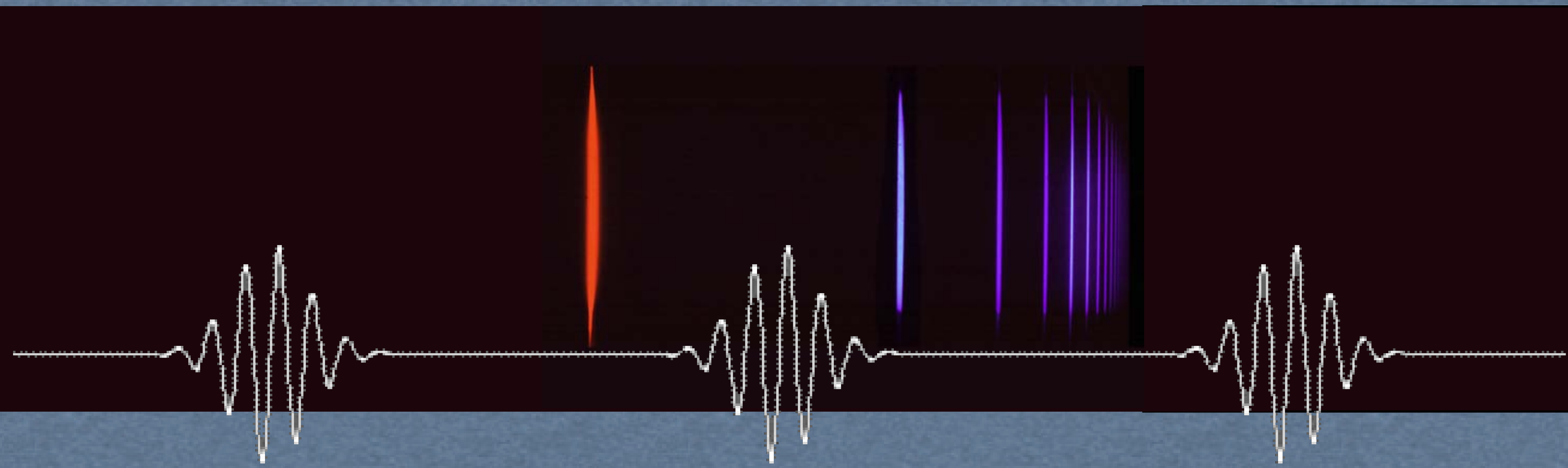
Stockholm 2005

A passion for precision

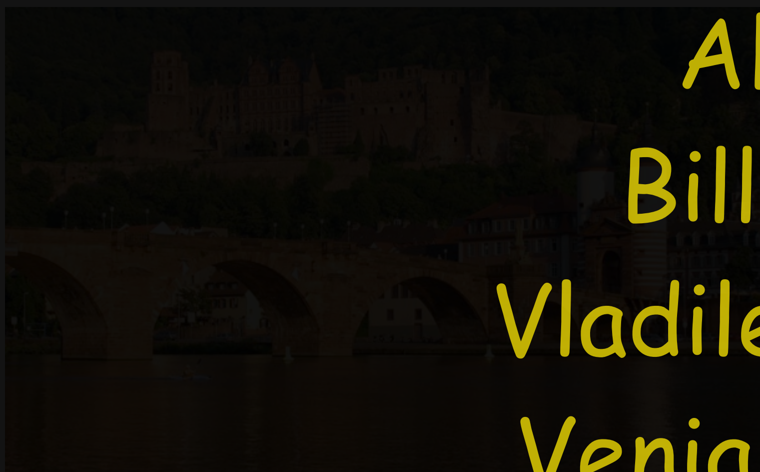


Theodor W. Hänsch

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

Stockholm, Dec. 8, 2005

University of Heidelberg, 1964 - 1970



Christoph Schmelzer

Peter Toschek

Ali Javan

Bill Bennett

Vladilen Lethokov

Venia Chebotaev

John Hall

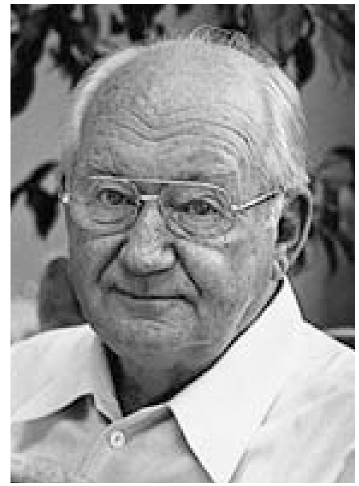
. . .

Helium-Neon gas lasers

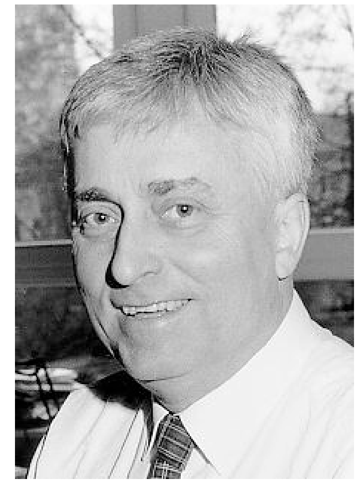
Saturation spectroscopy without Doppler broadening

Quantum interference in coupled 3-level systems

University of Heidelberg, 1964 - 1970



Christoph
Schmelzer



Peter
Toschek

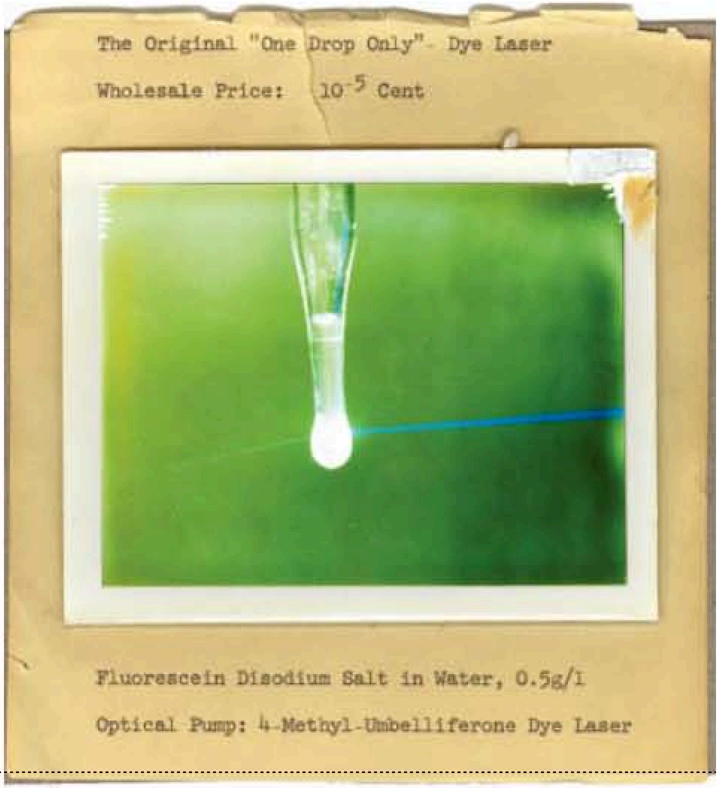
Helium-Neon gas lasers

Saturation spectroscopy without Doppler broadening

Quantum interference in coupled 3-level systems

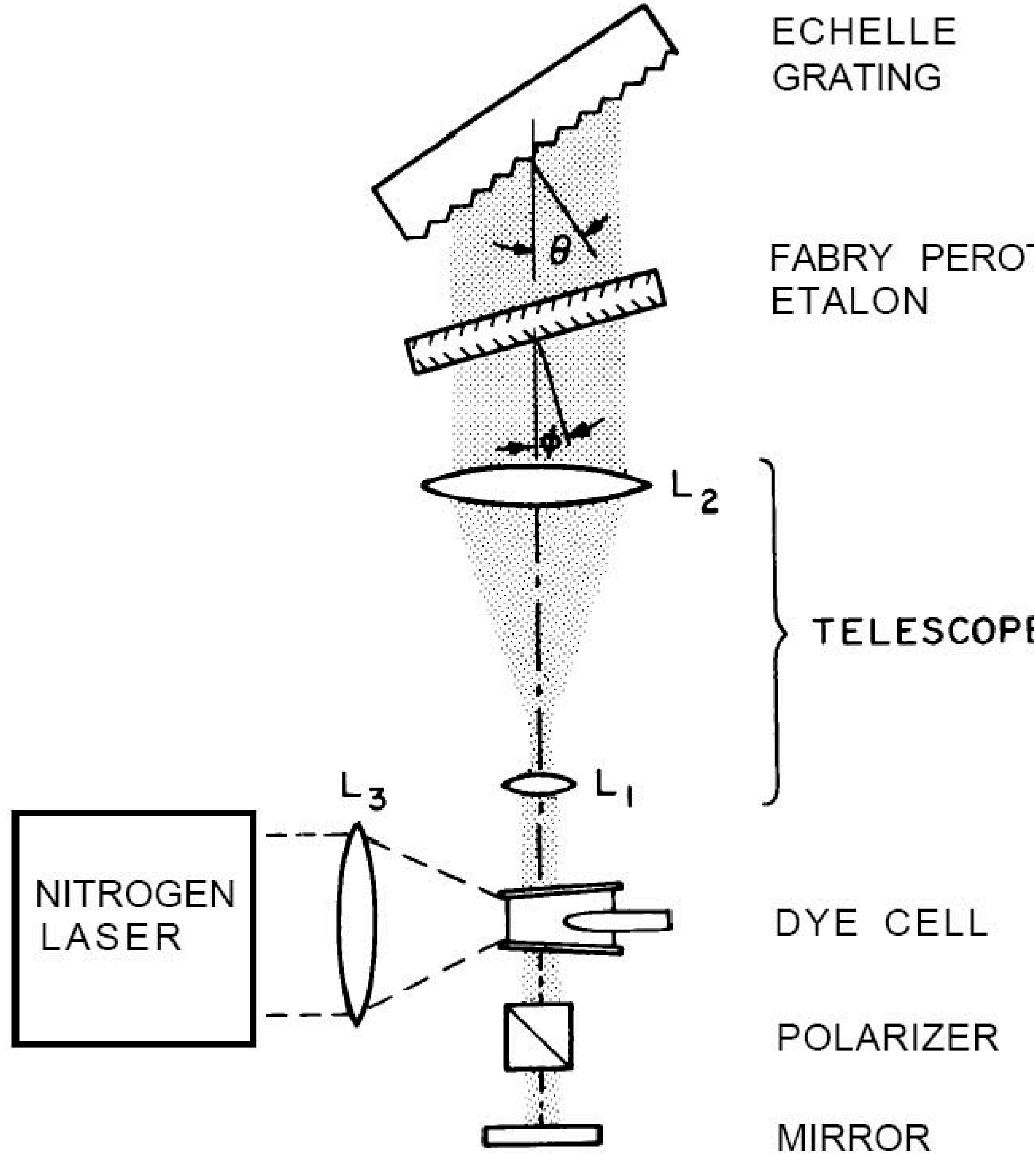
Stanford University, 1970 - 1986

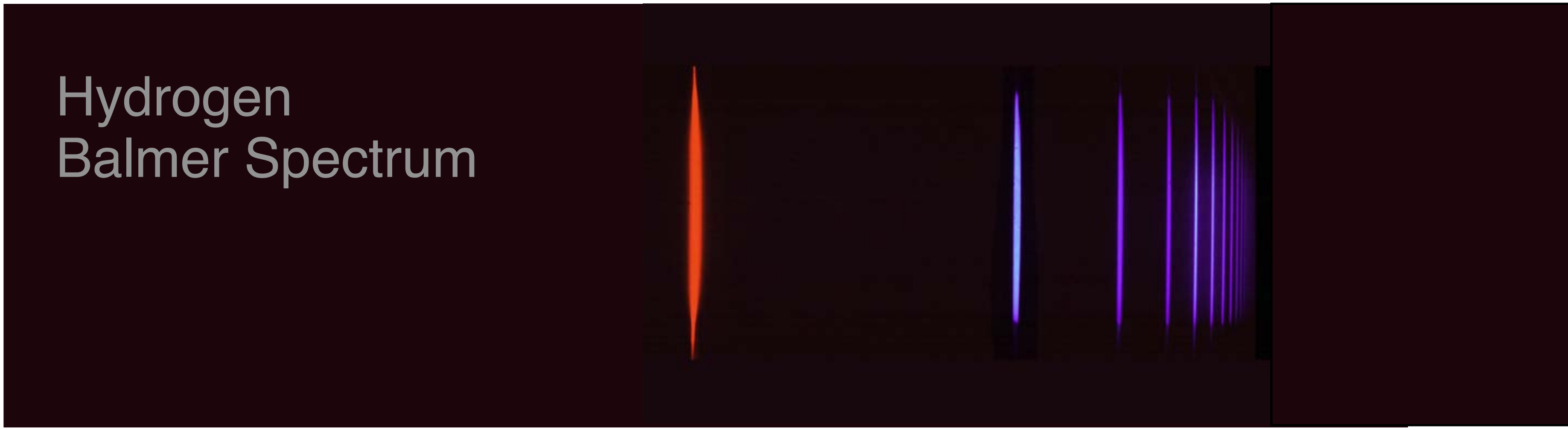
Arthur L. Schawlow

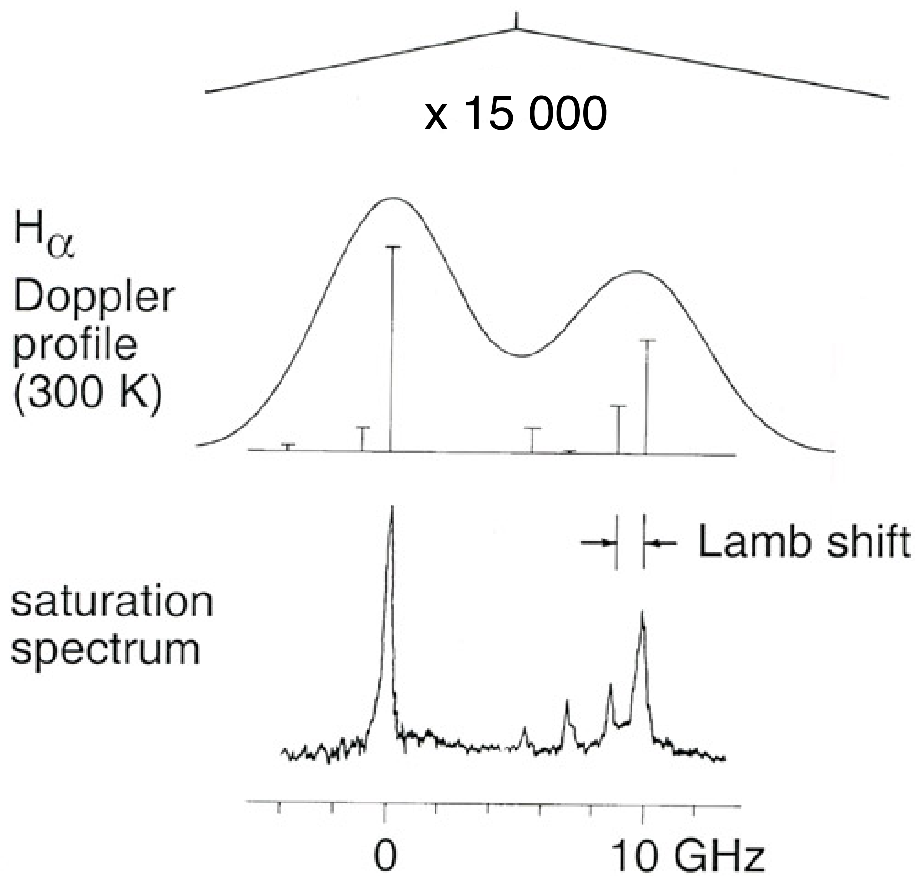


Edible Lasers and Other Delights of the 1970s

T.W.H.,
Optics and Photonics News
February 2005

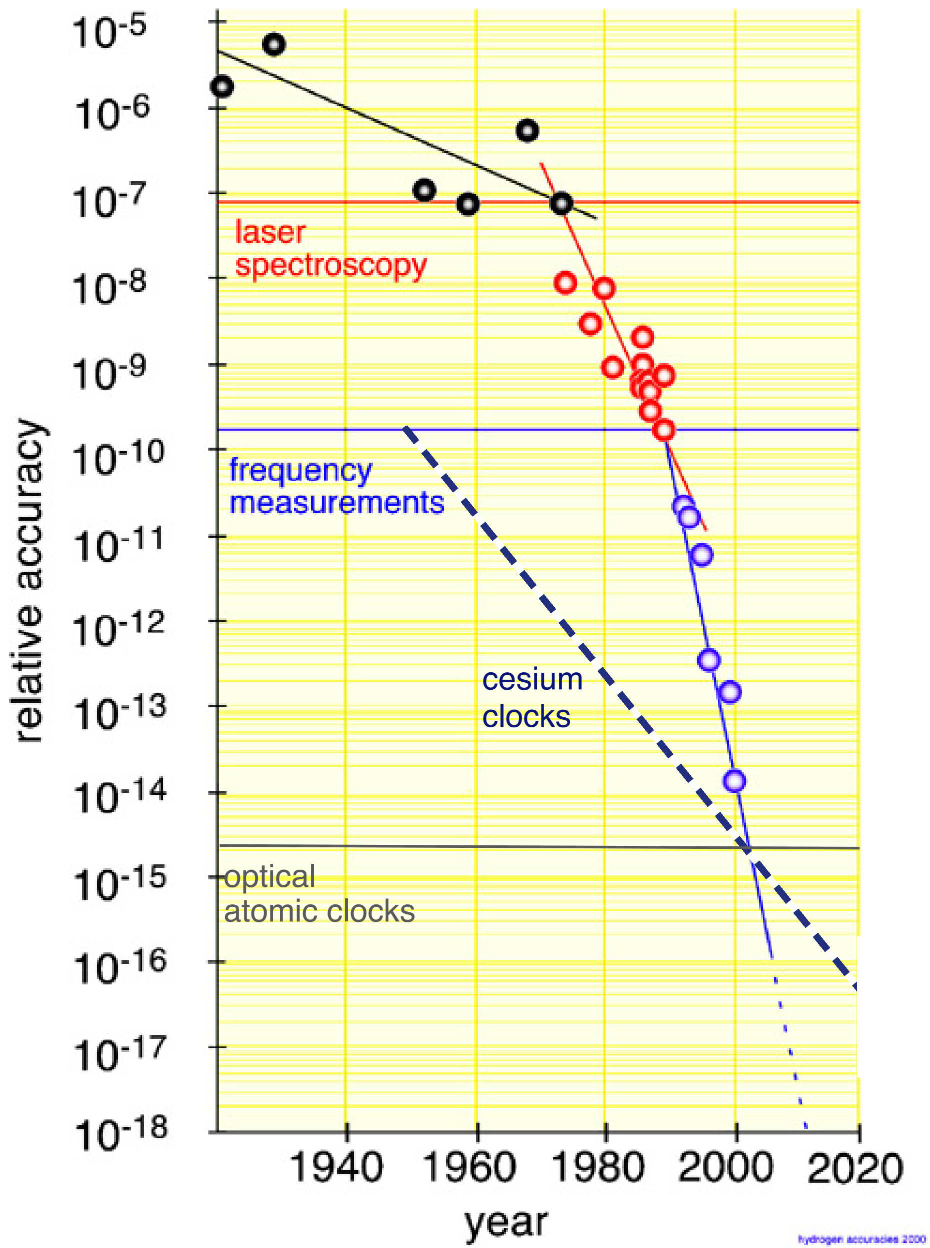




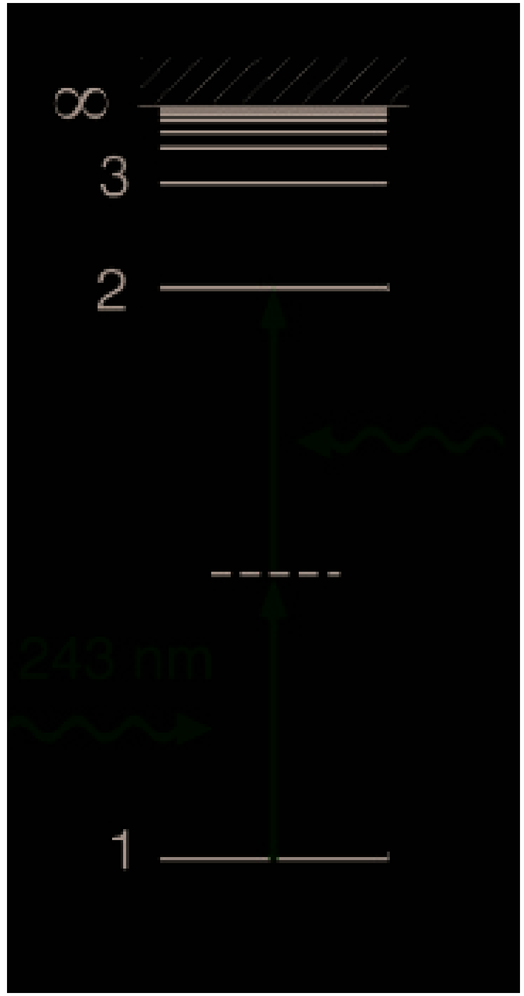


T.W. Hänsch, I.S. Shahin, and A.L. Schawlow, Nature **235**, 63 (1972)

Optical Spectroscopy of Hydrogen



Hydrogen 1S-2S two-photon transition

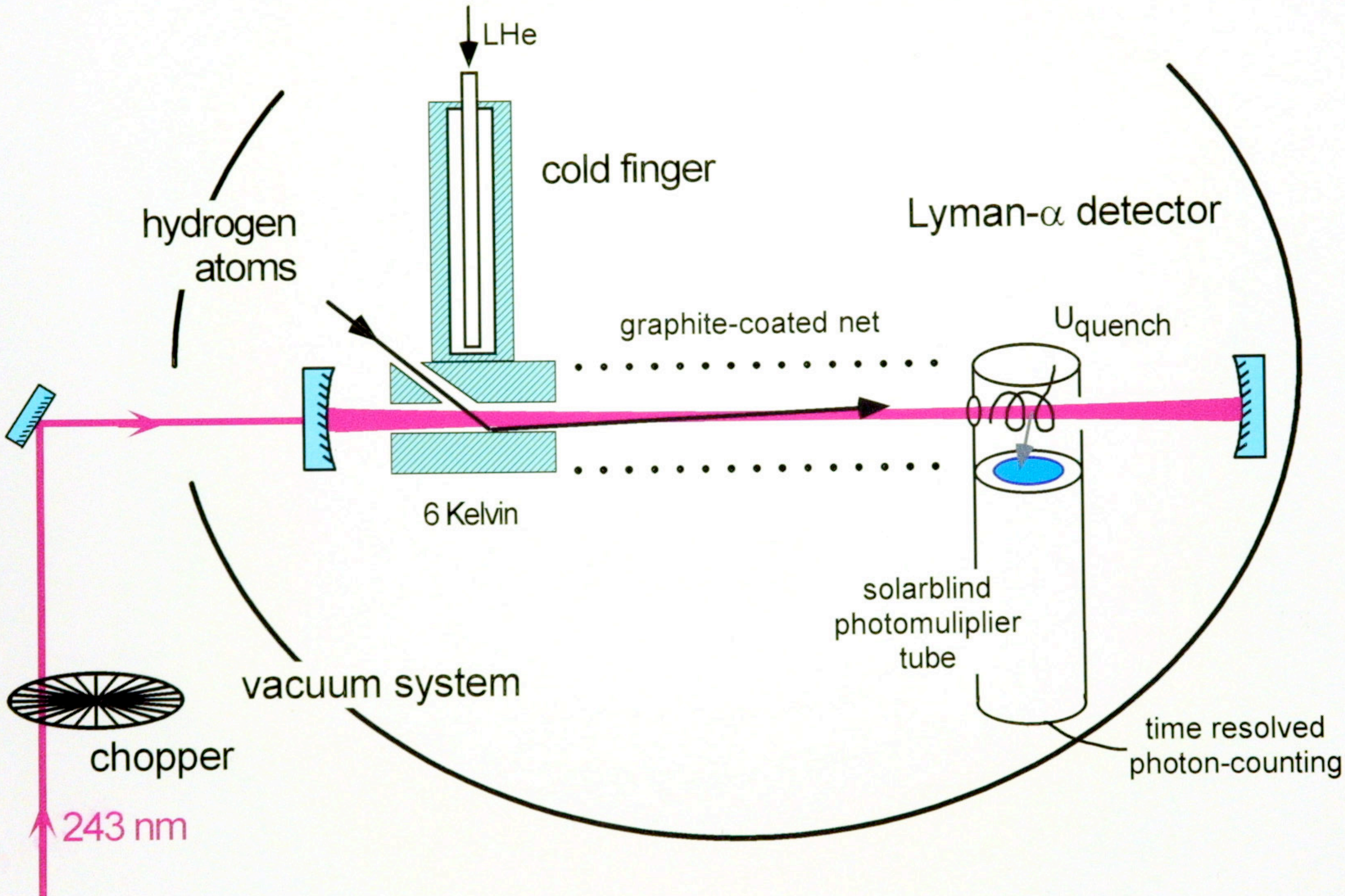


(natural line width: 1.3 Hz)

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

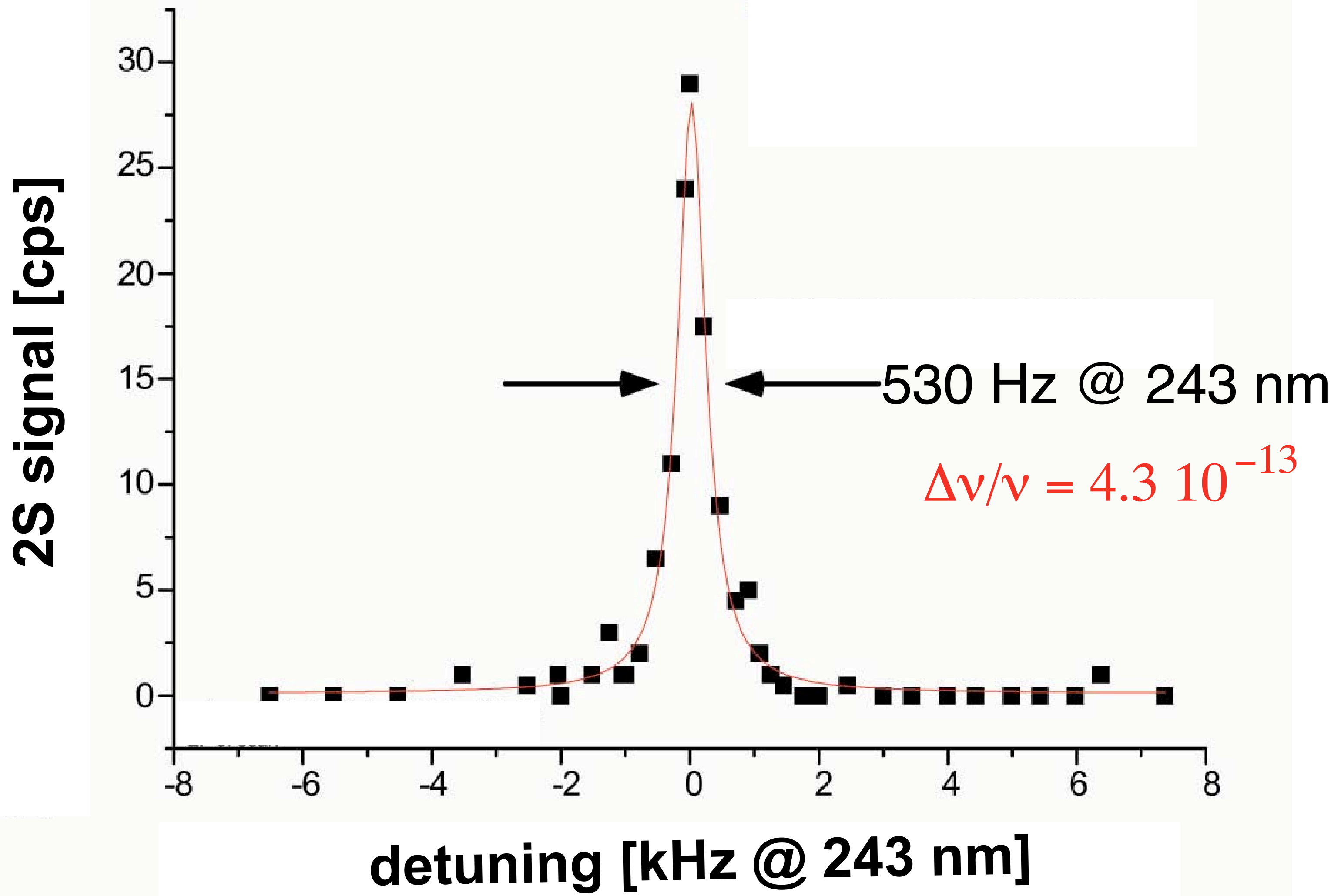
Max-Planck-Institute for Quantum Optics, Garching, and Ludwig-Maximilians-University, Munich, 1986 -

The Hydrogen Cold Atomic Beam



c:/ben/markus/vortrag/ws98_99/setup2.cvs

Hydrogen 1S-2S resonance



Hydrogen 1S-2S two-photon transition

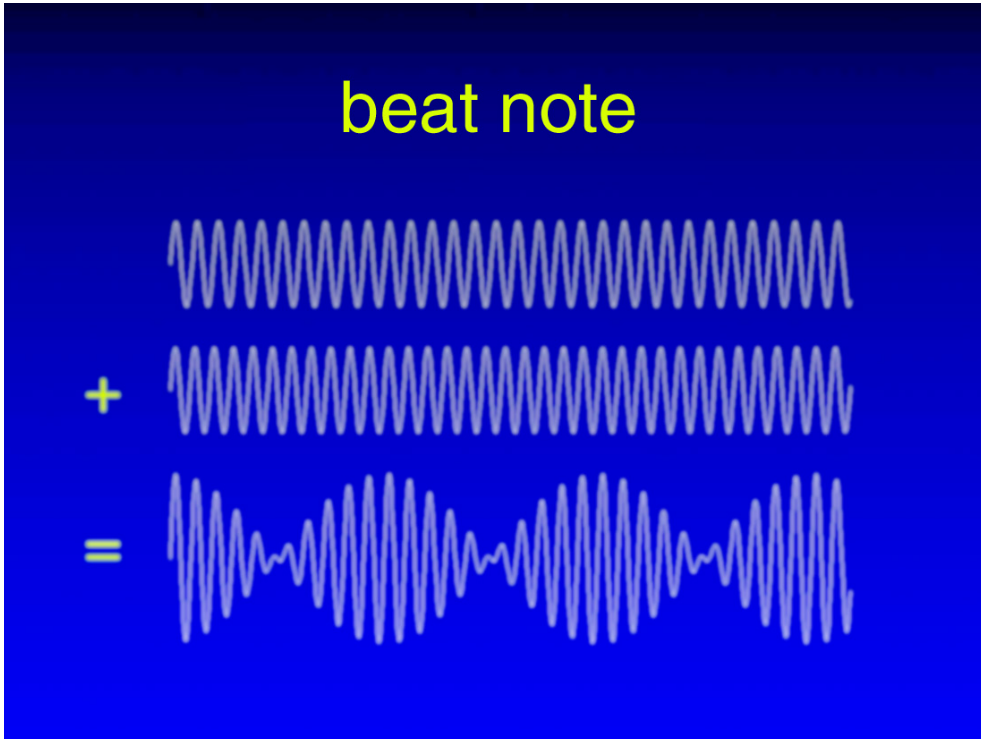
$$\nu_{\mathrm{H}}(1\mathrm{S}_{1/2} - 2\mathrm{S}_{1/2}) = \frac{3}{4}R_\infty c\left[1 - \frac{m_{\mathrm{e}}}{m_{\mathrm{p}}} + \frac{11}{48}\alpha^2 - \frac{28}{9}\frac{\alpha^3}{\pi}\ln\alpha^{-2} - \frac{14}{9}\left(\frac{\alpha R_{\mathrm{p}}}{\lambda\!\!\!^{-}_{\mathrm{C}}}\right)^2 + \cdots\right]$$

$$\begin{aligned}
\mathrm{Dirac}(1\mathrm{S}_{1/2} - 2\mathrm{S}_{1/2}) &= 2\,466\,068\,541\,018\ \mathrm{kHz}\\
\mathrm{QED}(1\mathrm{S}_{1/2} - 2\mathrm{S}_{1/2}) &= -7\,124\,736\ \mathrm{kHz}\\
\mathrm{Other}(1\mathrm{S}_{1/2} - 2\mathrm{S}_{1/2}) &= \cdots\\
\nu_{\mathrm{H}}(1\mathrm{S}_{1/2} - 2\mathrm{S}_{1/2}) &= 2\,466\,061\,413\,187\ \mathrm{kHz}
\end{aligned}$$

A cornerstone in the least squares adjustment of the fundamental constants
(P. Mohr, B. Taylor, NIST)

A dream... (Ali Javan, 1963)

Extend microwave frequency counting techniques into the optical region.



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)

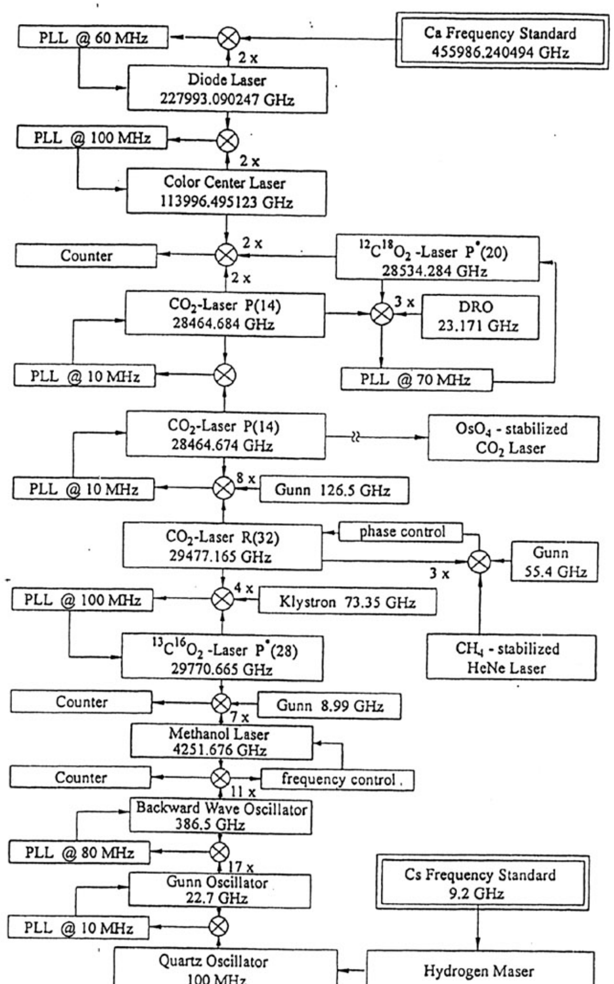
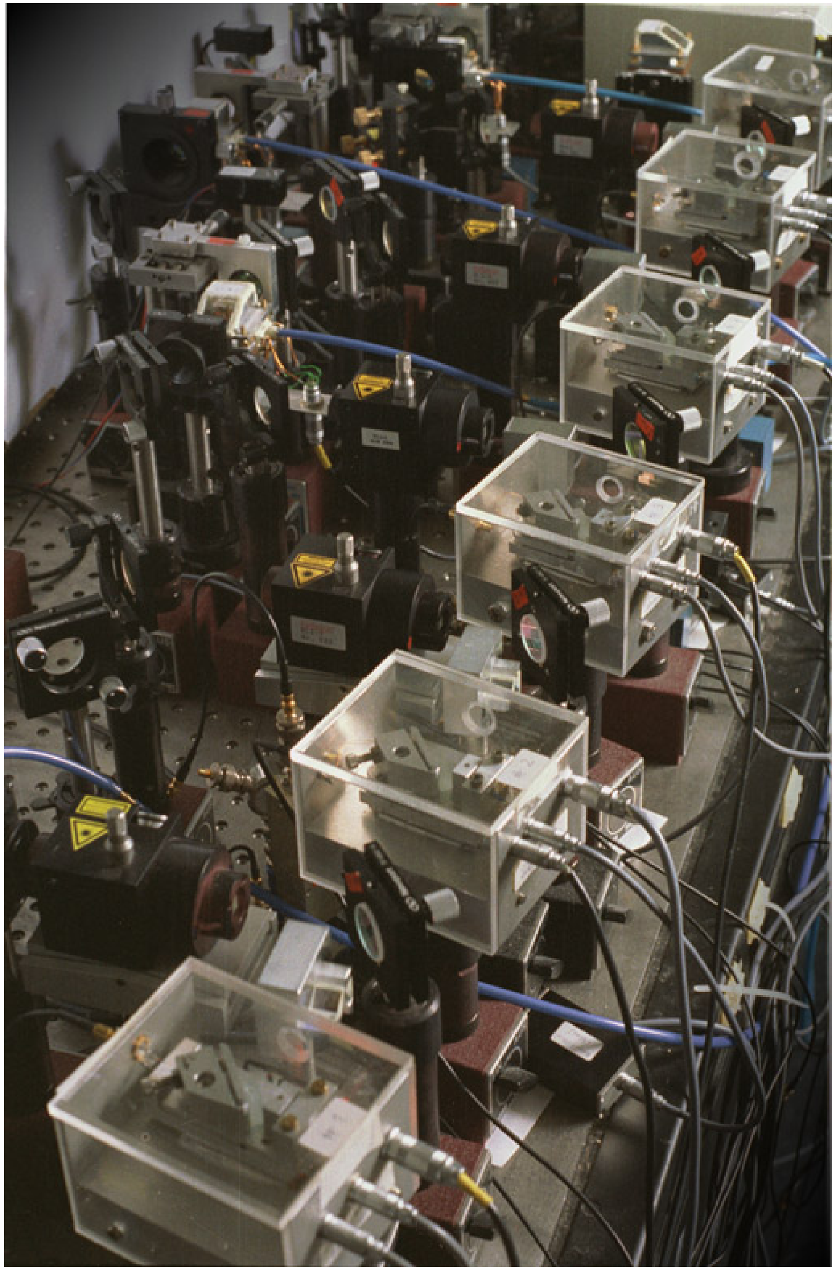
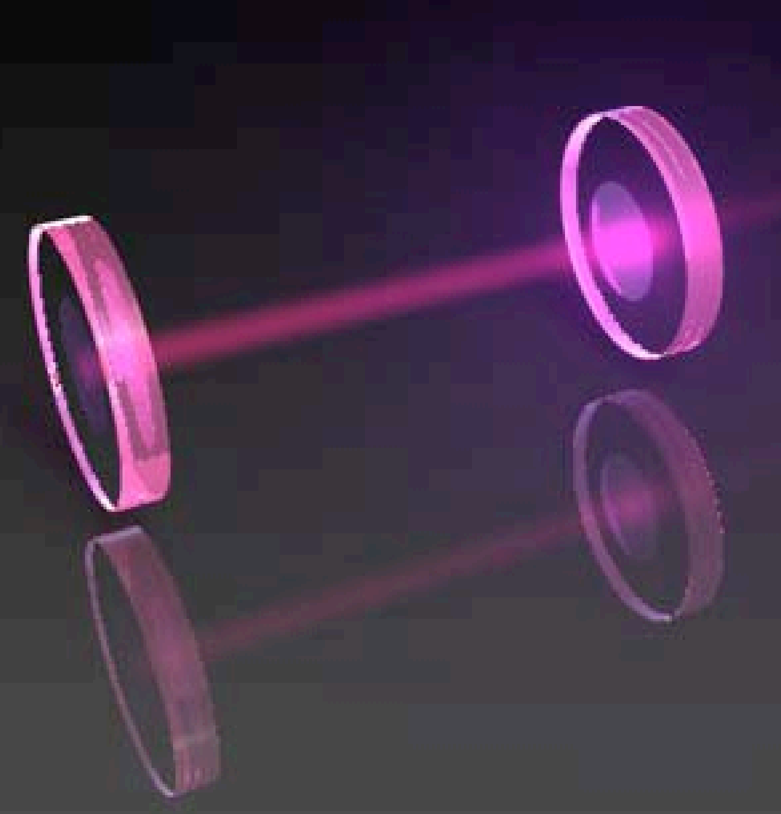


FIG. 1. PTB's frequency chain to the Ca intercombination line (PLL = phase locked loop, details are given in the text).

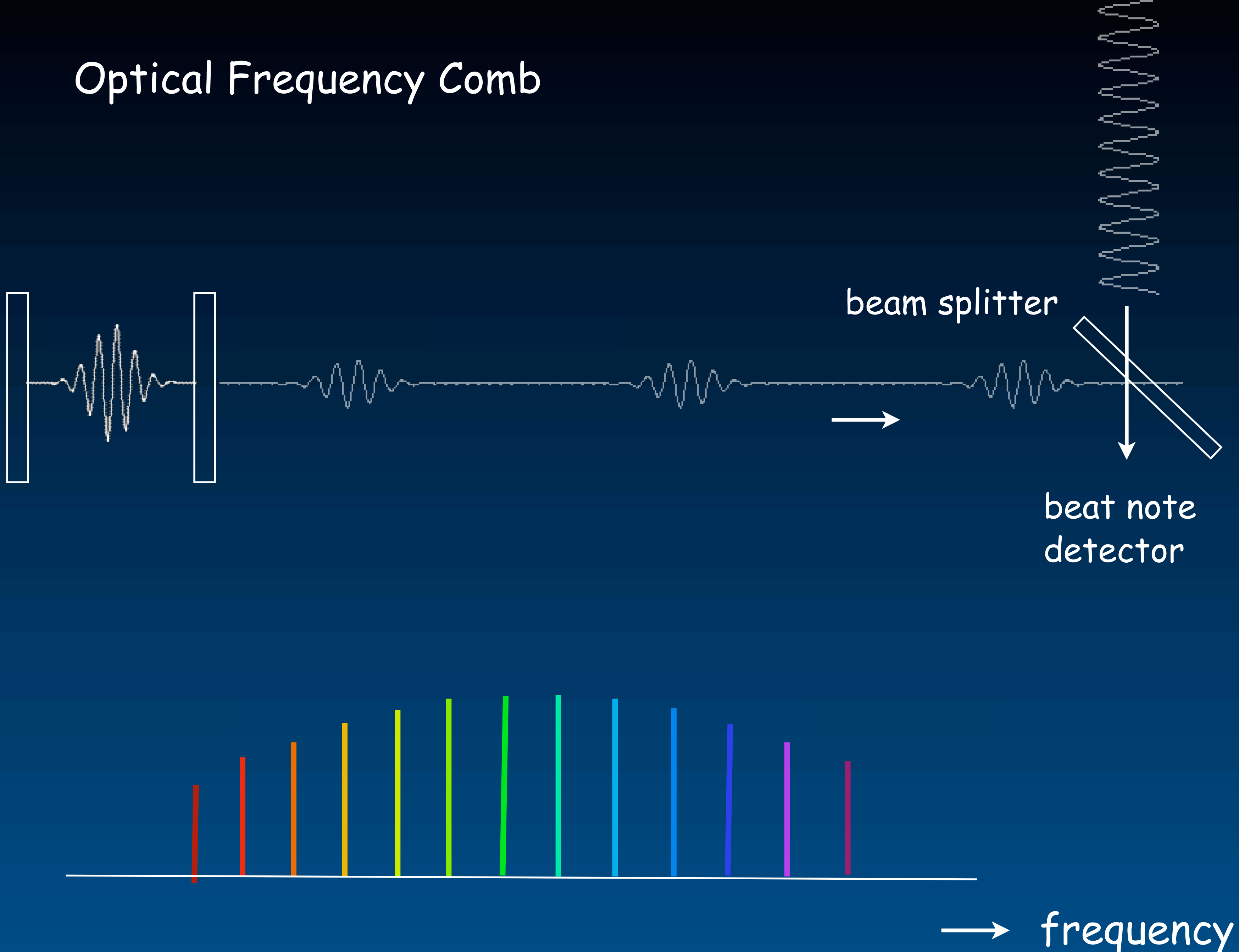
Garching frequency interval divider chain (1997)

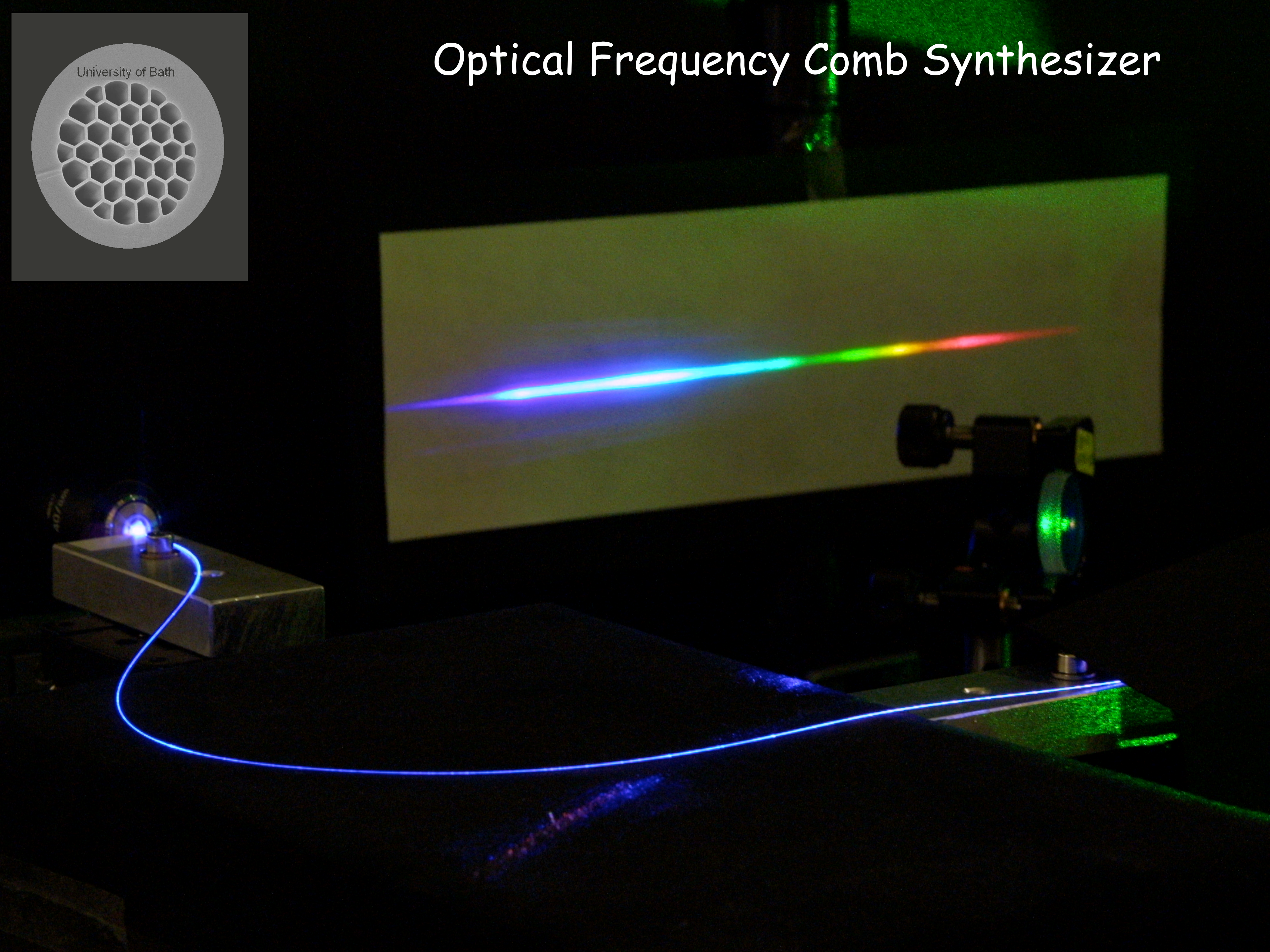


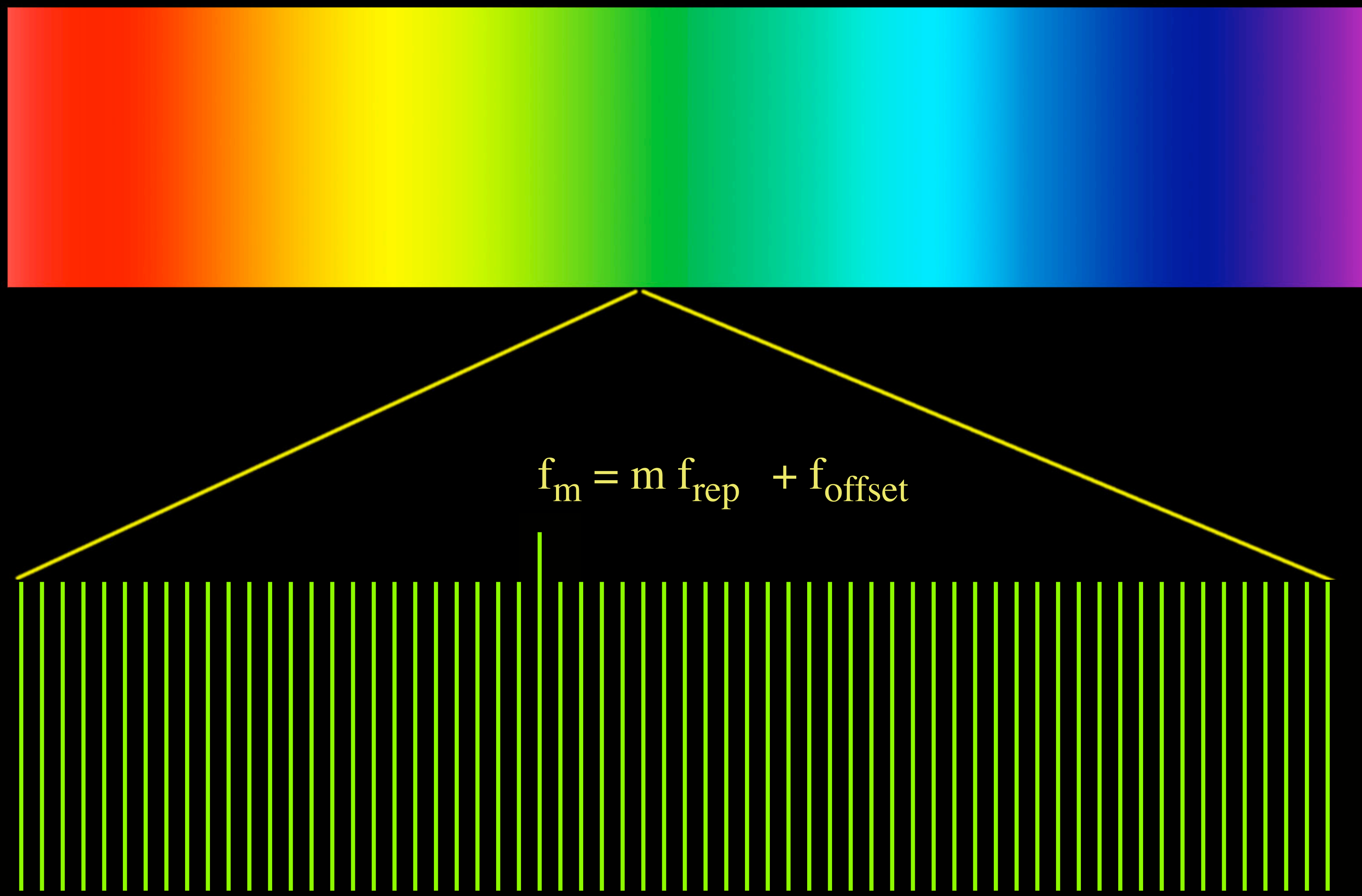
Optical frequency comb



Optical Frequency Comb




Optical Frequency Comb Synthesizer
University of Bath


$f_m = m\, f_{rep} + f_{offset}$

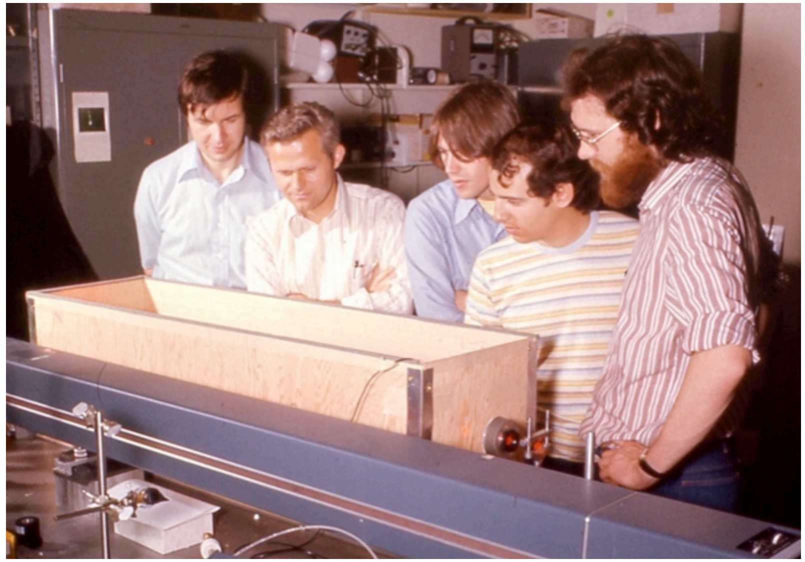
femtosecond laser frequency comb synthesizer

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

This is a simple idea!

What took so long?

Stanford, 1978: 500 GHz laser frequency comb



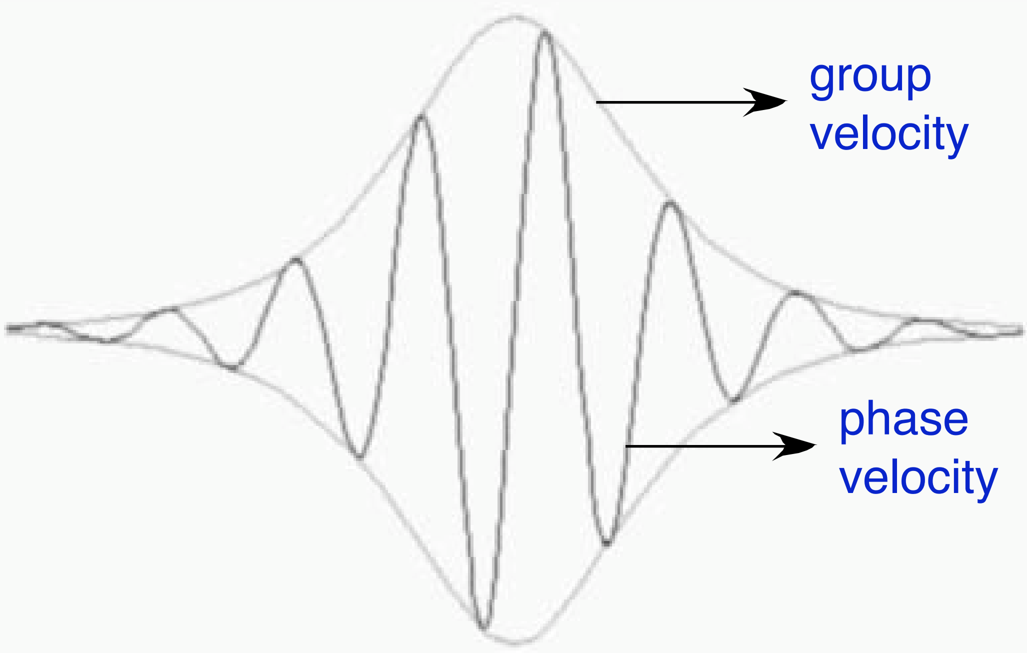
VOLUME 40, NUMBER 13 PHYSICAL REVIEW LETTERS 27 MARCH 1978

High-Resolution Two-Photon Spectroscopy with Picosecond Light Pulses

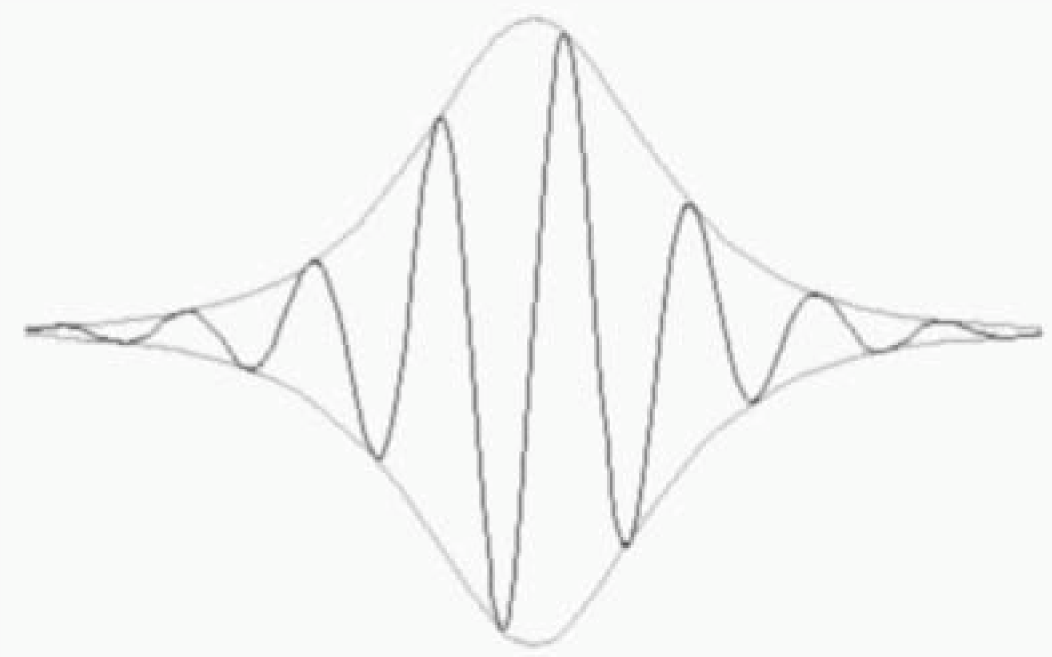
J. N. Eckstein, A. I. Ferguson, and T. W. Hänsch
Department of Physics, Stanford University, Stanford, California 94305
(Received 11 January 1978)

We have demonstrated the feasibility of Doppler-free two-photon spectroscopy with a train of picosecond standing-wave light pulses from a synchronously pumped mode-locked cw dye laser. The actively controlled mode spectrum provides a means for accurate measurements of large frequency intervals. From a multipulse spectrum of the sodium 3*s*-4*d* transition we have determined a new value of the 4*d* fine-structure splitting, 1028 ± 0.4 MHz.

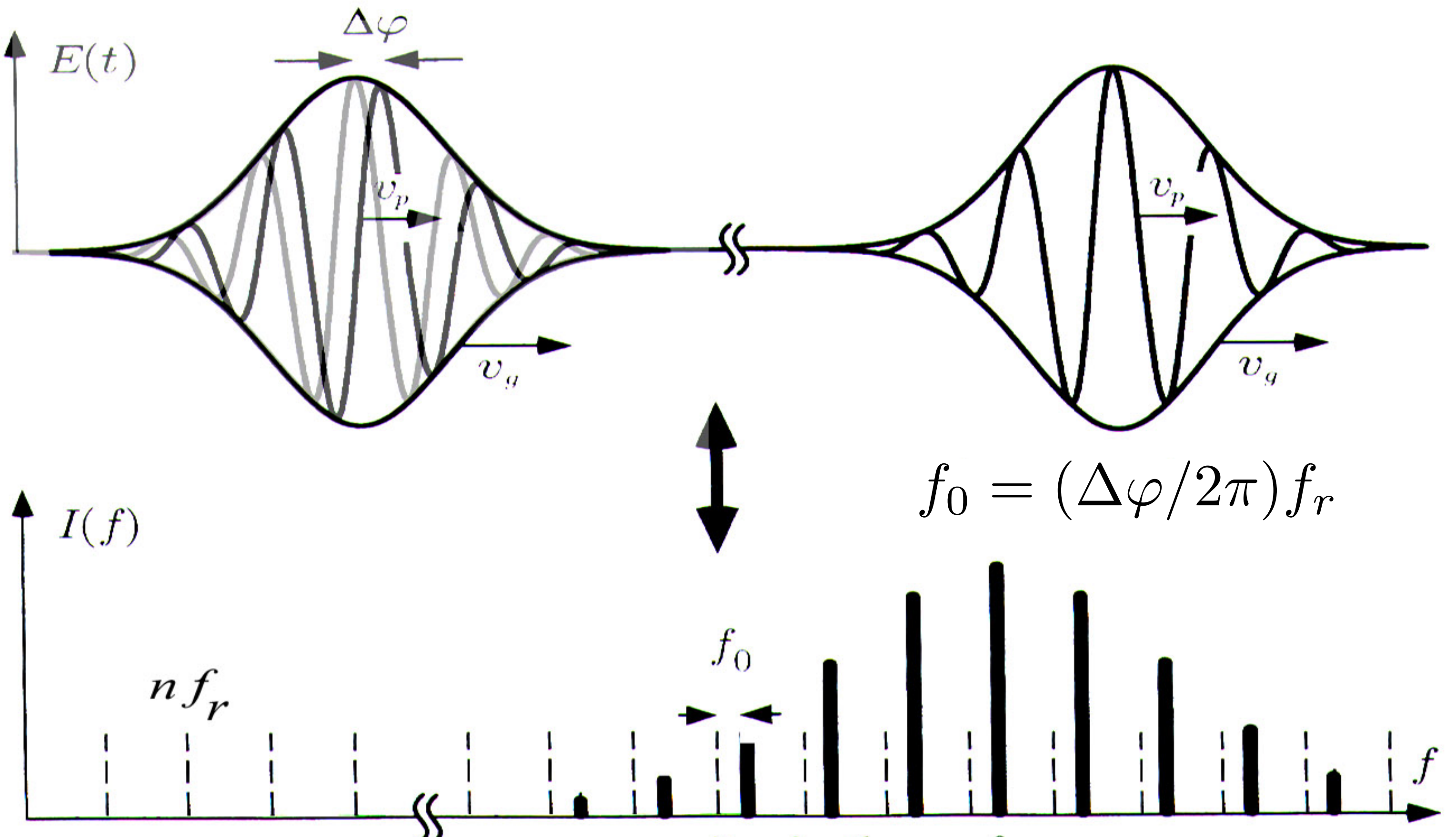
carrier-envelope phase slips



carrier-envelope phase slips



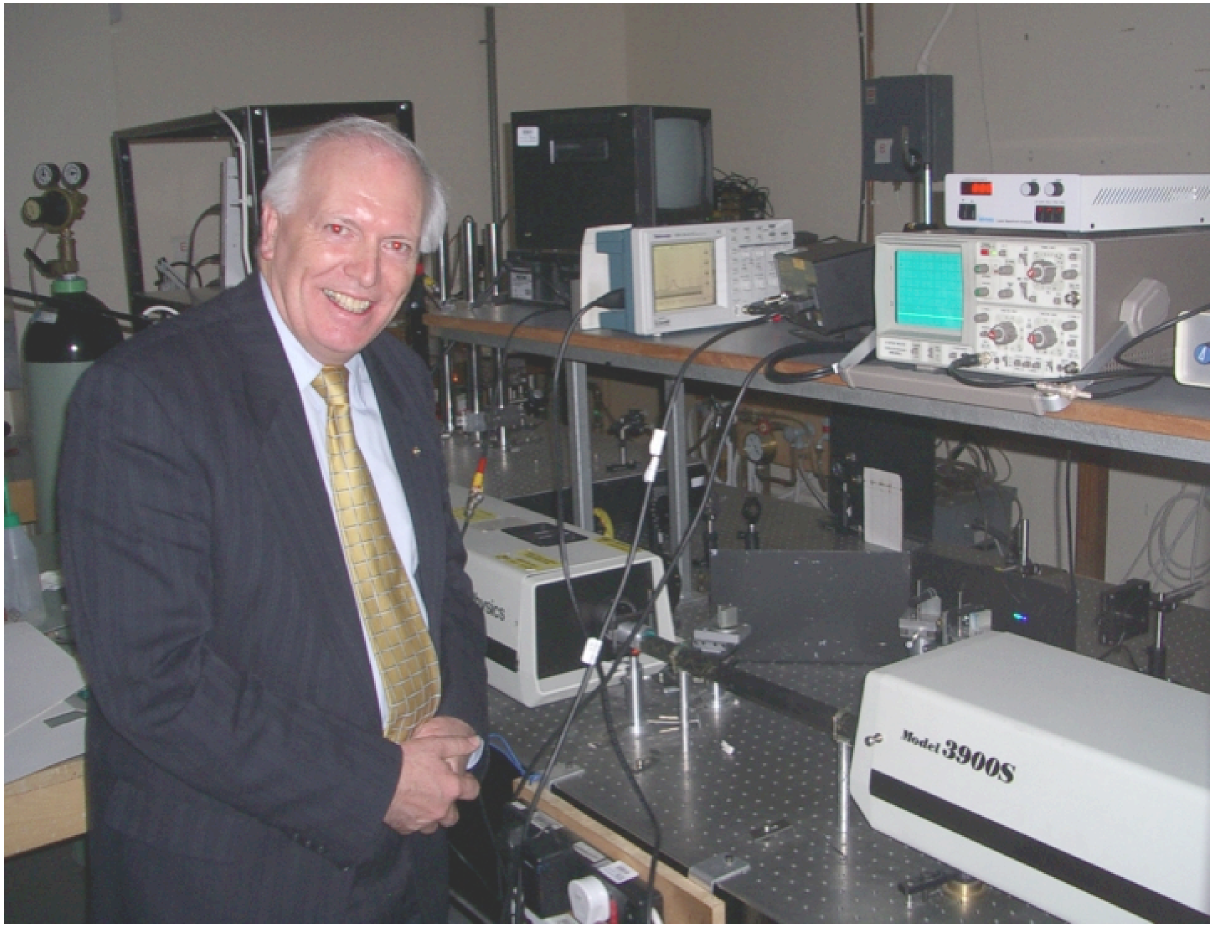
carrier-envelope phase slips and offset frequency



$$f_0 = (\Delta\varphi/2\pi) f_r$$

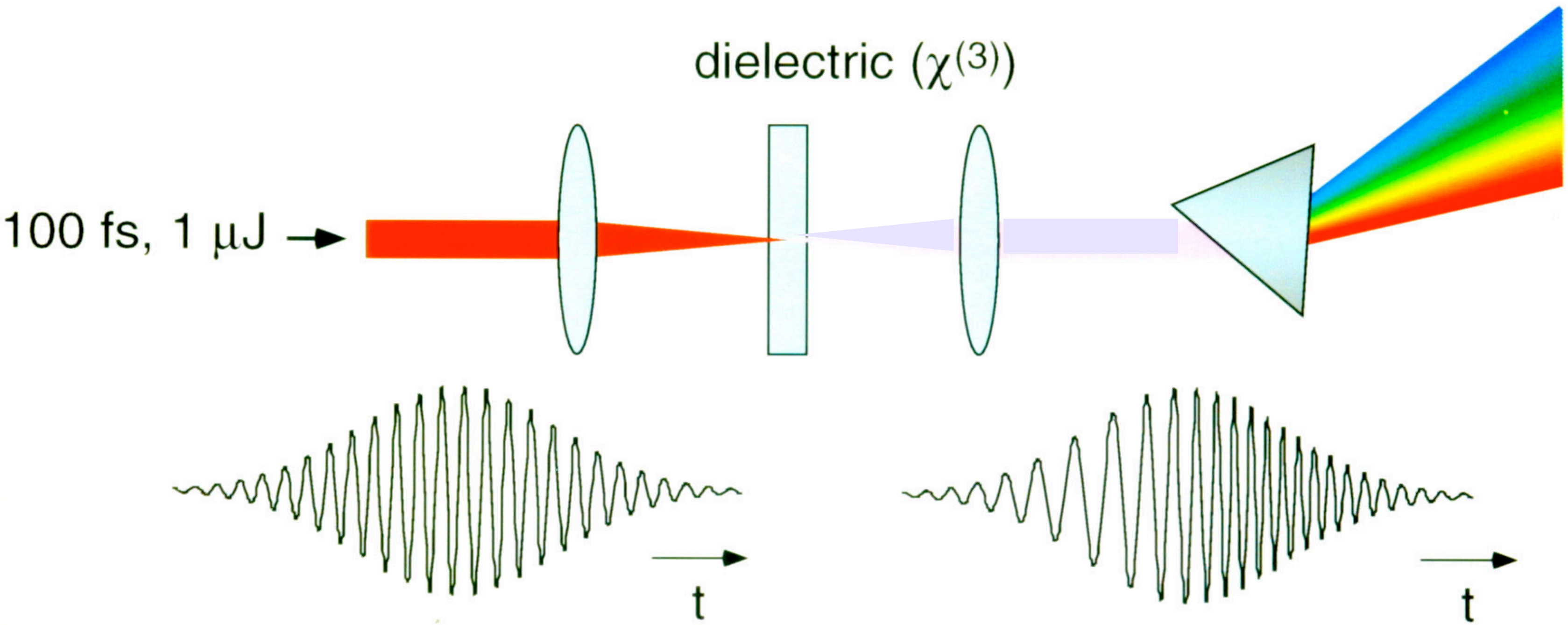
J.N. Eckstein, *Ph.D. Thesis*, Stanford University, 1978

Kerr lens mode-locking



D.E. Spencer, P.N. Kean, and W. Sibbett, Opt. Lett. 16, 42 (1991)

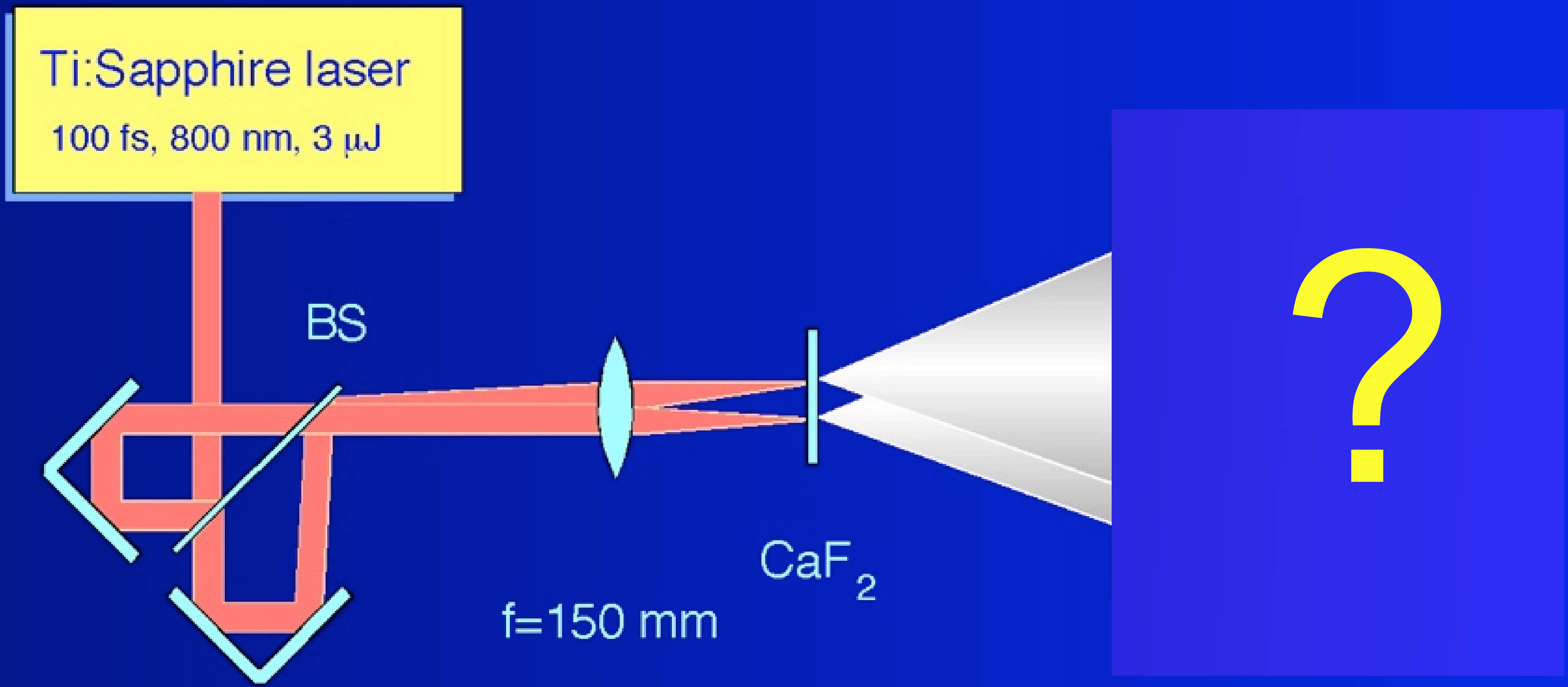
femtosecond white light continuum



intensity-dependent refractive index:
self-phase-modulation, self-focusing, shock wave formation, . . .

Florence, Italy, February 1997

Can two white light pulses interfere?



M. Bellini and T.W. Hänsch, Opt. Lett. 25, 1049 (2000)

LENS, Florence, Italy, February 1997

camcorder electronic notebook

(CONFIDENTIAL)

Proposal for a universal optical frequency comb synthesizer

T. W. Hänsch
Max-Planck-Institut für Quantenoptik

(March 30, 1997)

Abstract

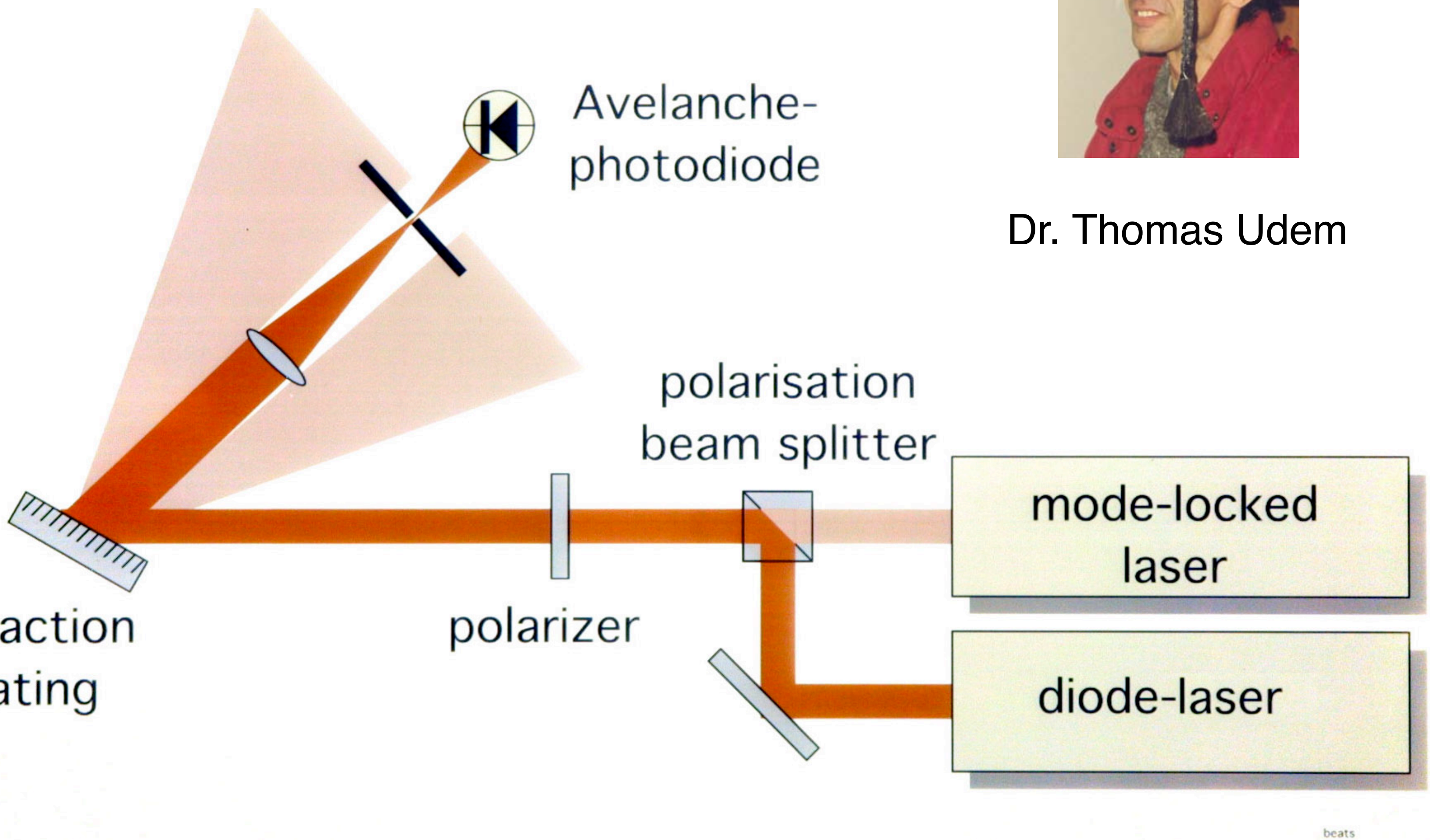
An optical frequency synthesizer is proposed which produces a wide comb of absolutely known equidistant marker frequencies throughout the infrared, visible, and ultraviolet spectral range. To this end, a white light continuum with pulse repetition rate f_p is produced by focusing the output of a mode-locked femtosecond laser into an optical fiber or bulk medium with a third order nonlinear susceptibility. The rate of phase slippage of the laser carrier relative to the pulse envelope f_s is monitored by observing a beat signal between the white light continuum and the second harmonic of the laser.

read and understood

April 4, 1997 Martin Weitz

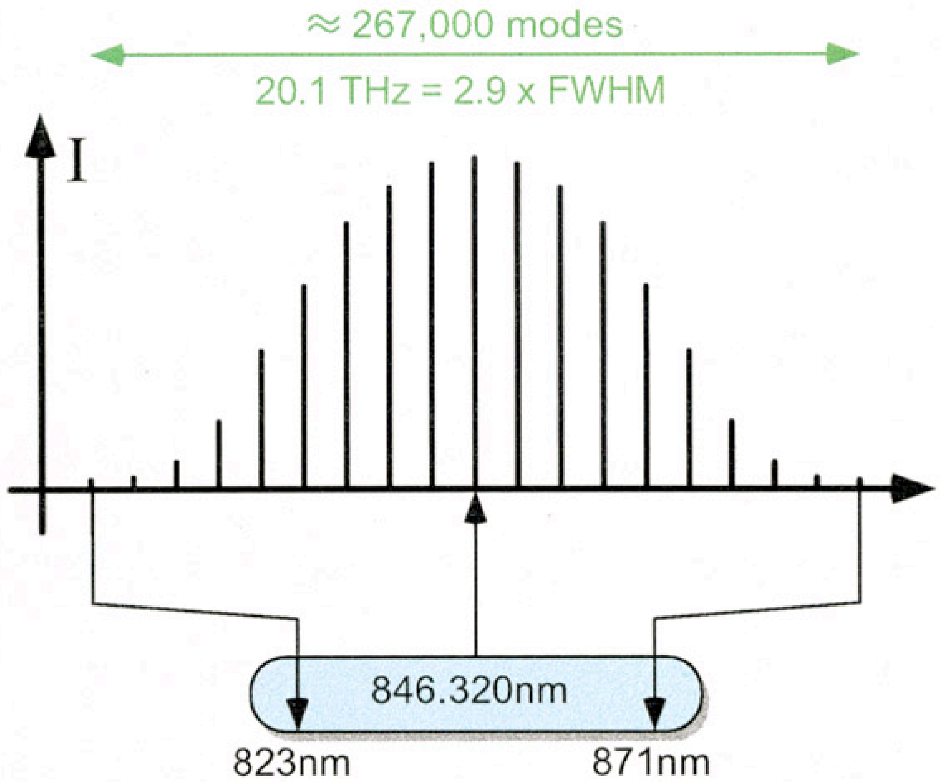
April 4, 1997 T. Udem

detection of comb lines with beat signals



Dr. Thomas Udem

Testing the uniform spacing of the comb lines



Experimental uniformity: 3×10^{-17}

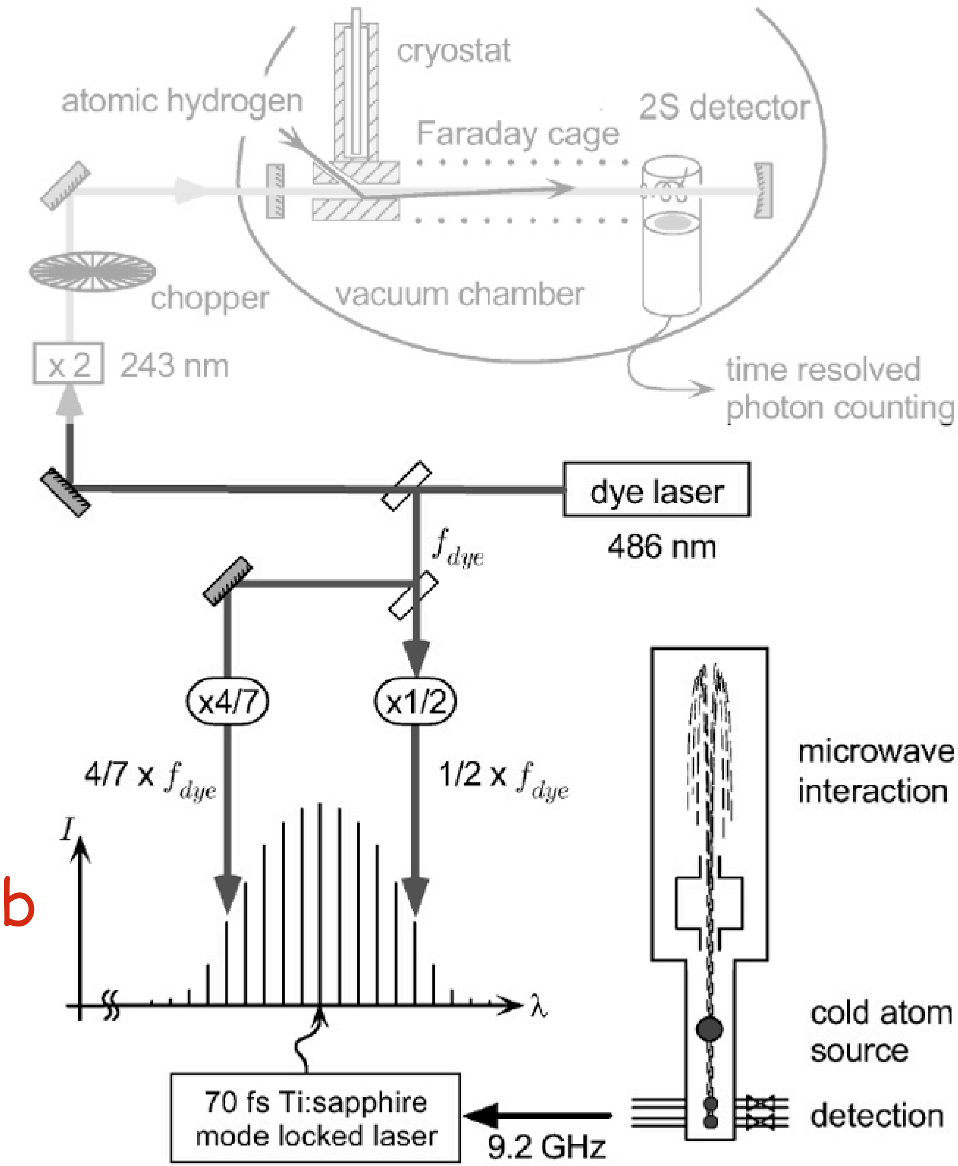
Th. Udem, J. Reichert, R. Holzwarth, and T.W. Hänsch, Opt. Lett. 24, 881 (1999)

1998: first absolute frequency measurement with a laser comb

first femtosecond pulses with controlled carrier-envelope phase

Hydrogen 1S-2S spectrometer

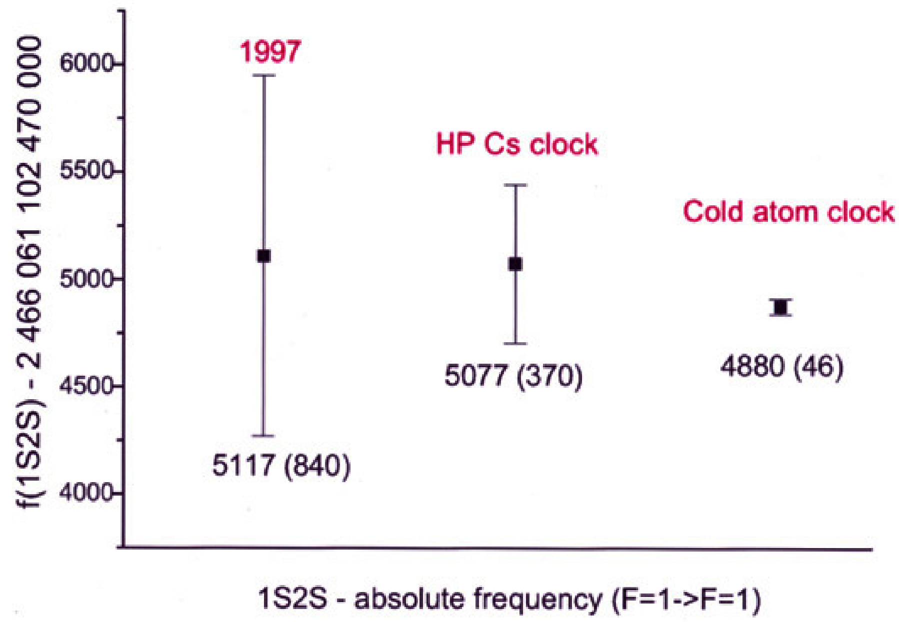
70 THz comb



October 1998:
HP Cs clock

June 1999:
Paris Cs fountain clock

Hydrogen 1S-2S Absolute Frequency



accuracy : 1.8×10^{-14}

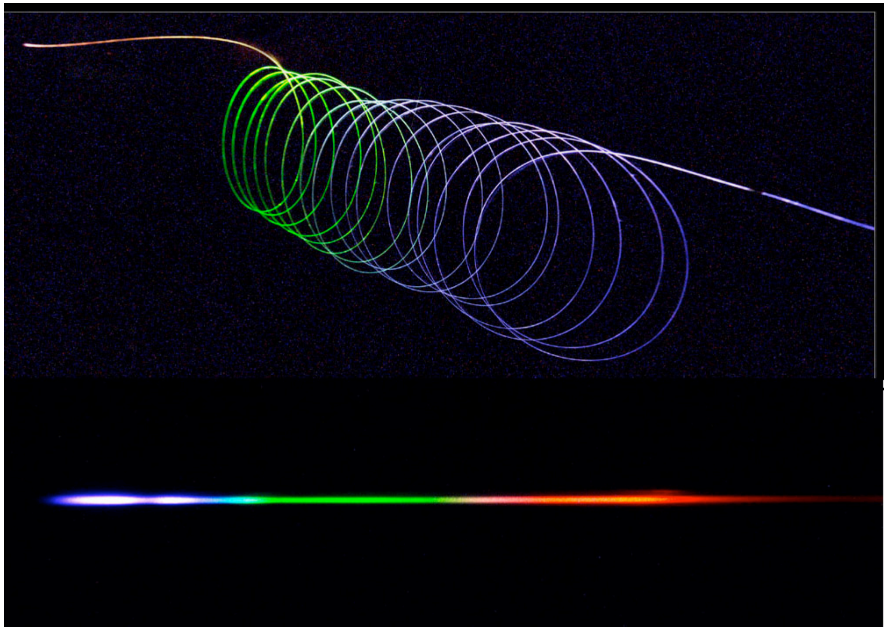
f(1S-2S) = 2 466 061 413 187 103 (46) Hz (hyperfine centroid)

Th. Udem et al., *Phys. Rev. Lett.* **79**, 2646 (1997)

J. Reichert et al., *Phys. Rev. Lett.* **84**, 3232 (2000)

M. Niering et al., *Phys. Rev. Lett.* **84**, 5496 (2000)

Octave-spanning frequency combs



„Rainbow Fiber“

(Lucent Technologies, 1999)

“Photonic Crystal Fiber”

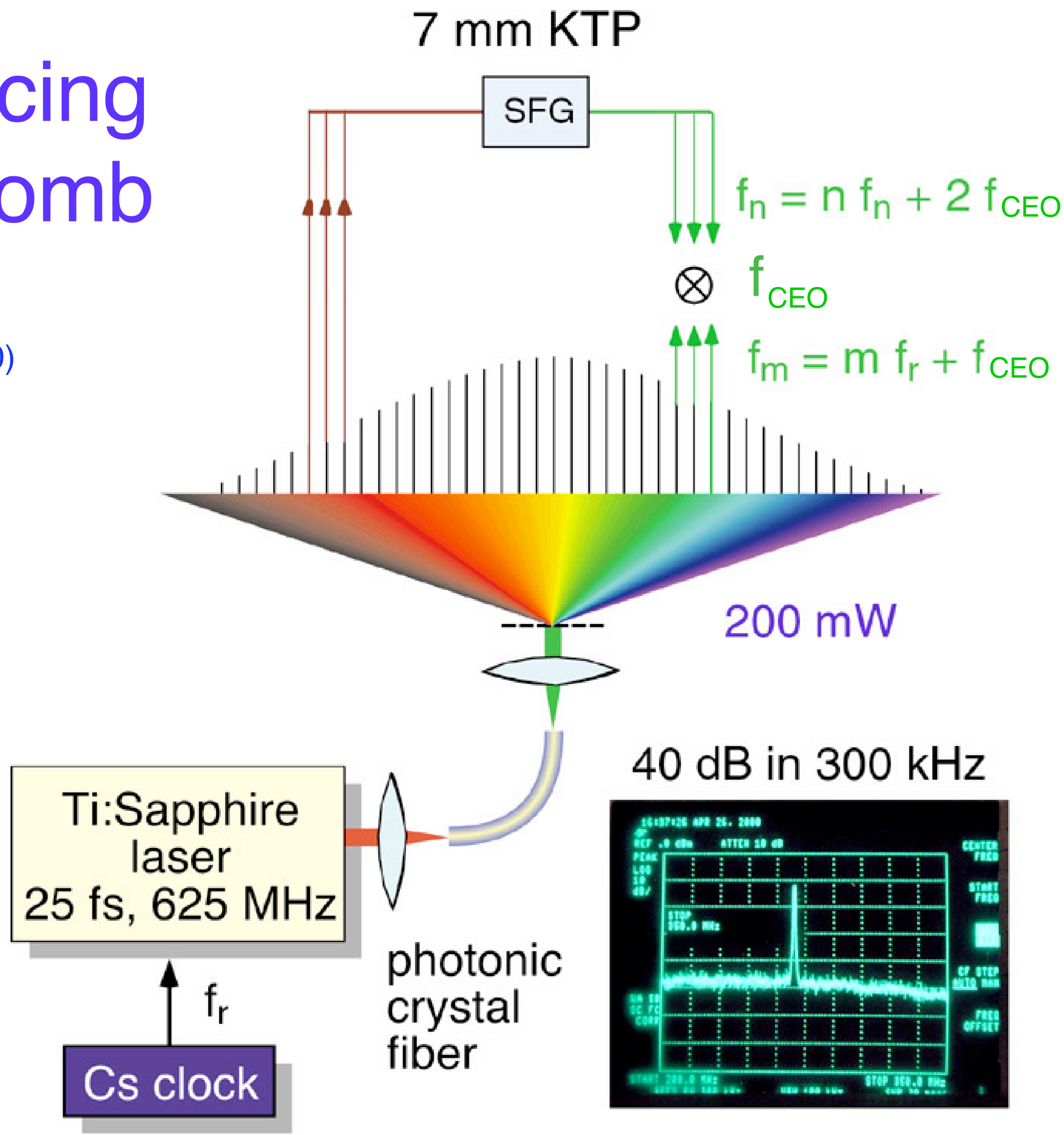
J.C. Knight, W.J. Wadsworth, P. St. Russel
University of Bath, UK

Self-referencing frequency comb

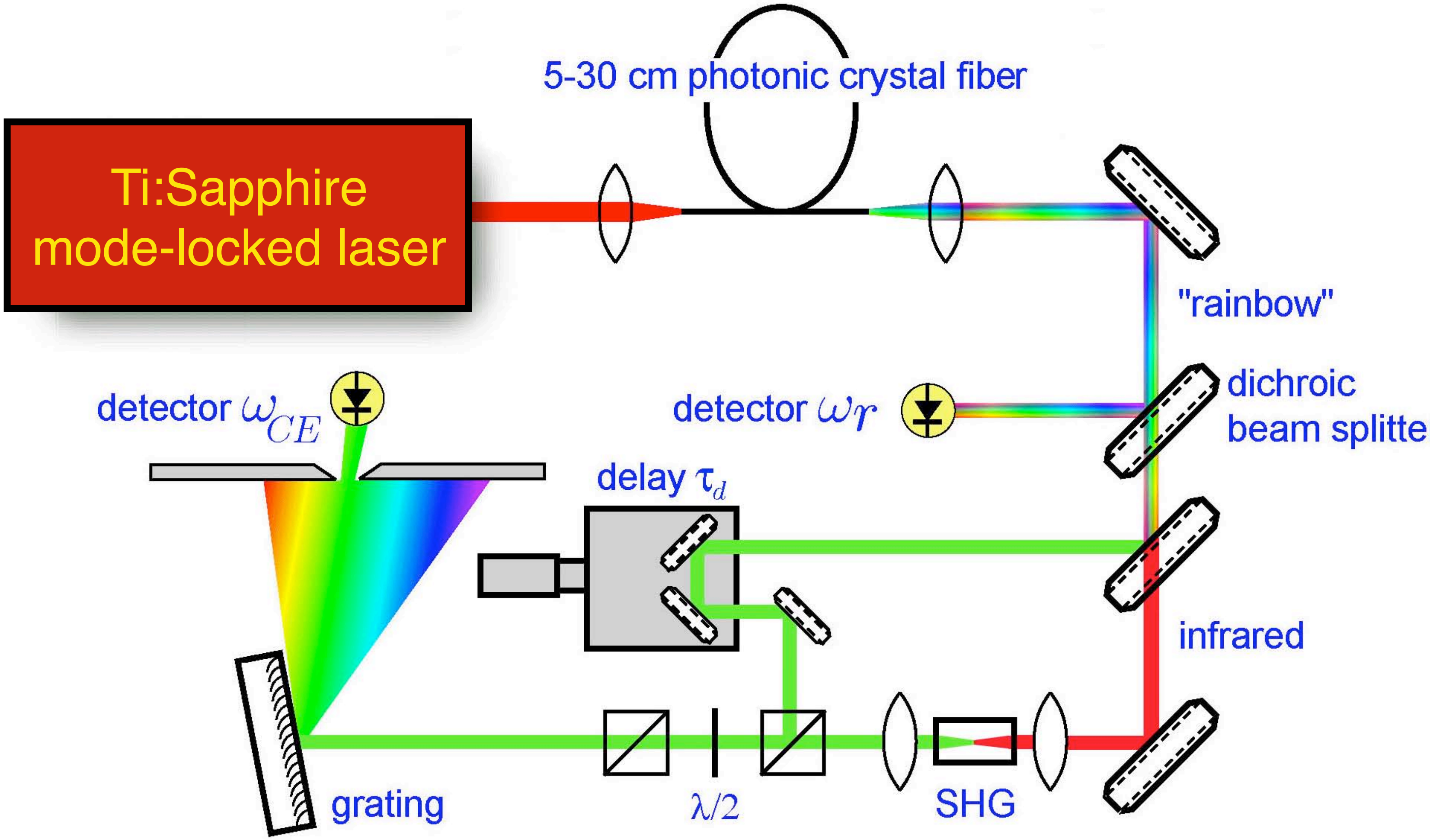
R. Holzwarth et al.,
Phys. Rev. Lett **85**, 2264 (2000)

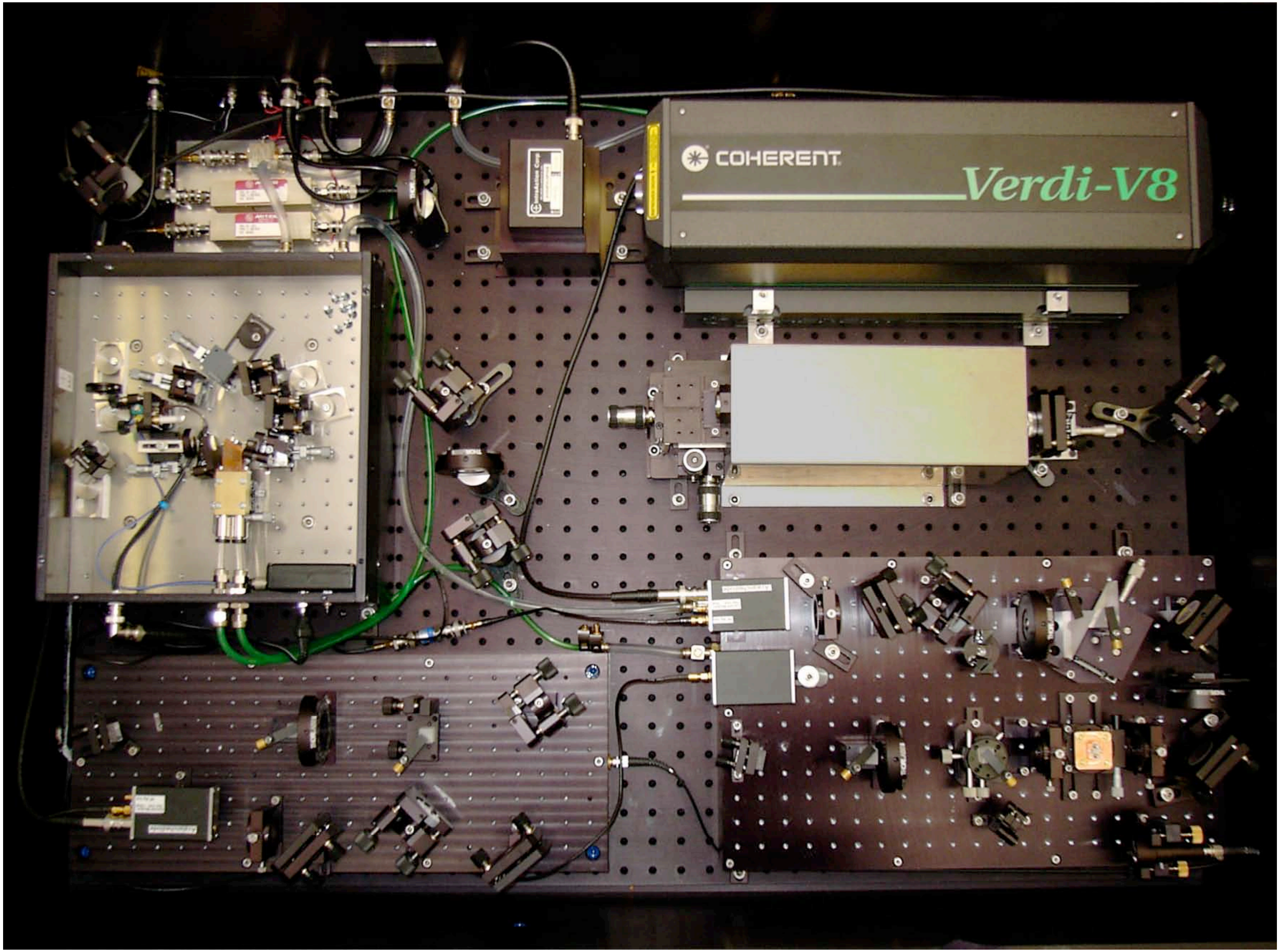
D. Jones et al.,
Science **288**, 635 (2000)

T.W. Hänsch,
Witnessed disclosure
(March 30, 1997)

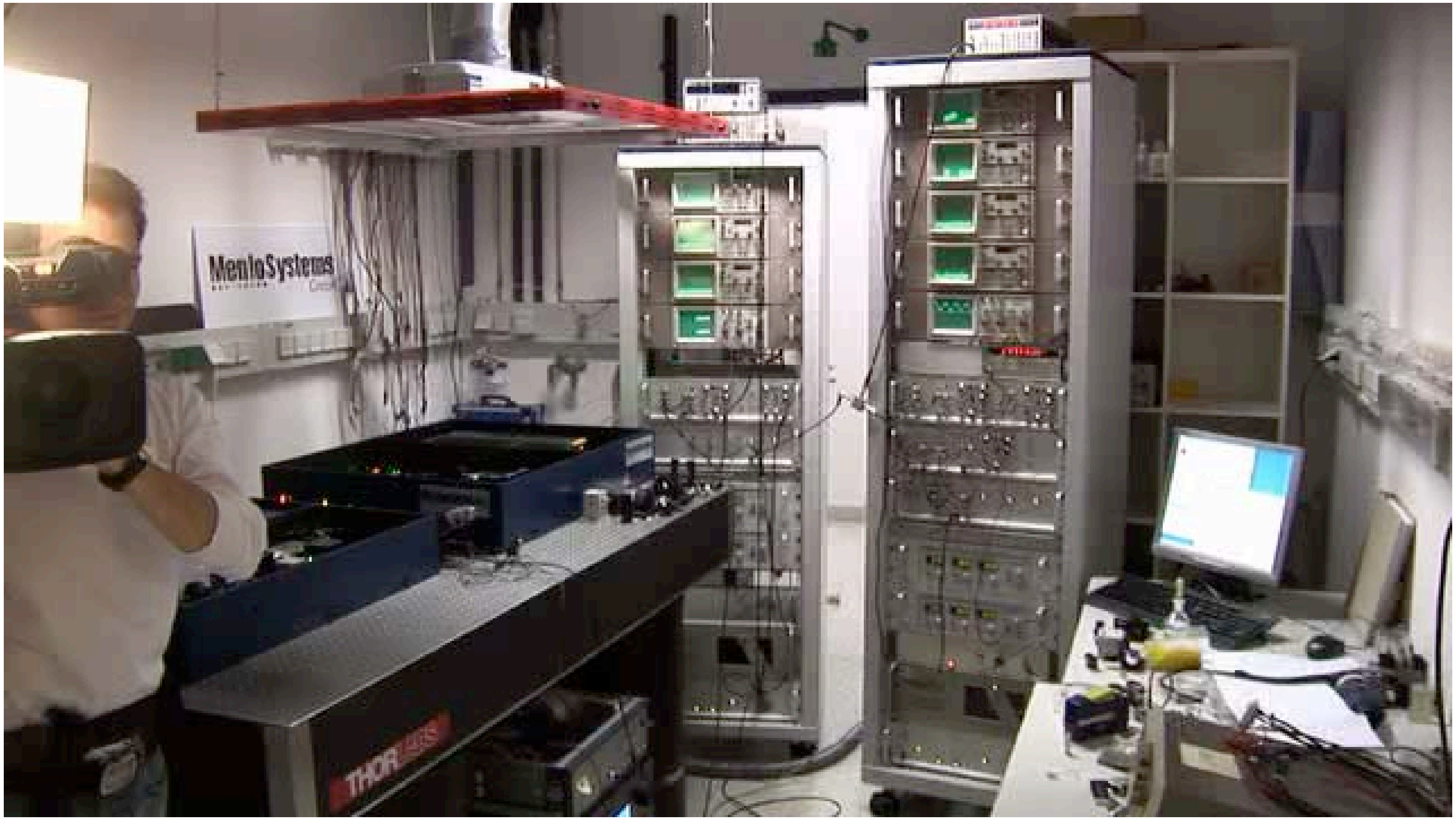


Single-Laser Optical Frequency Comb Synthesizer




COHERENT
Verdi-V8

frequency combs, 2005



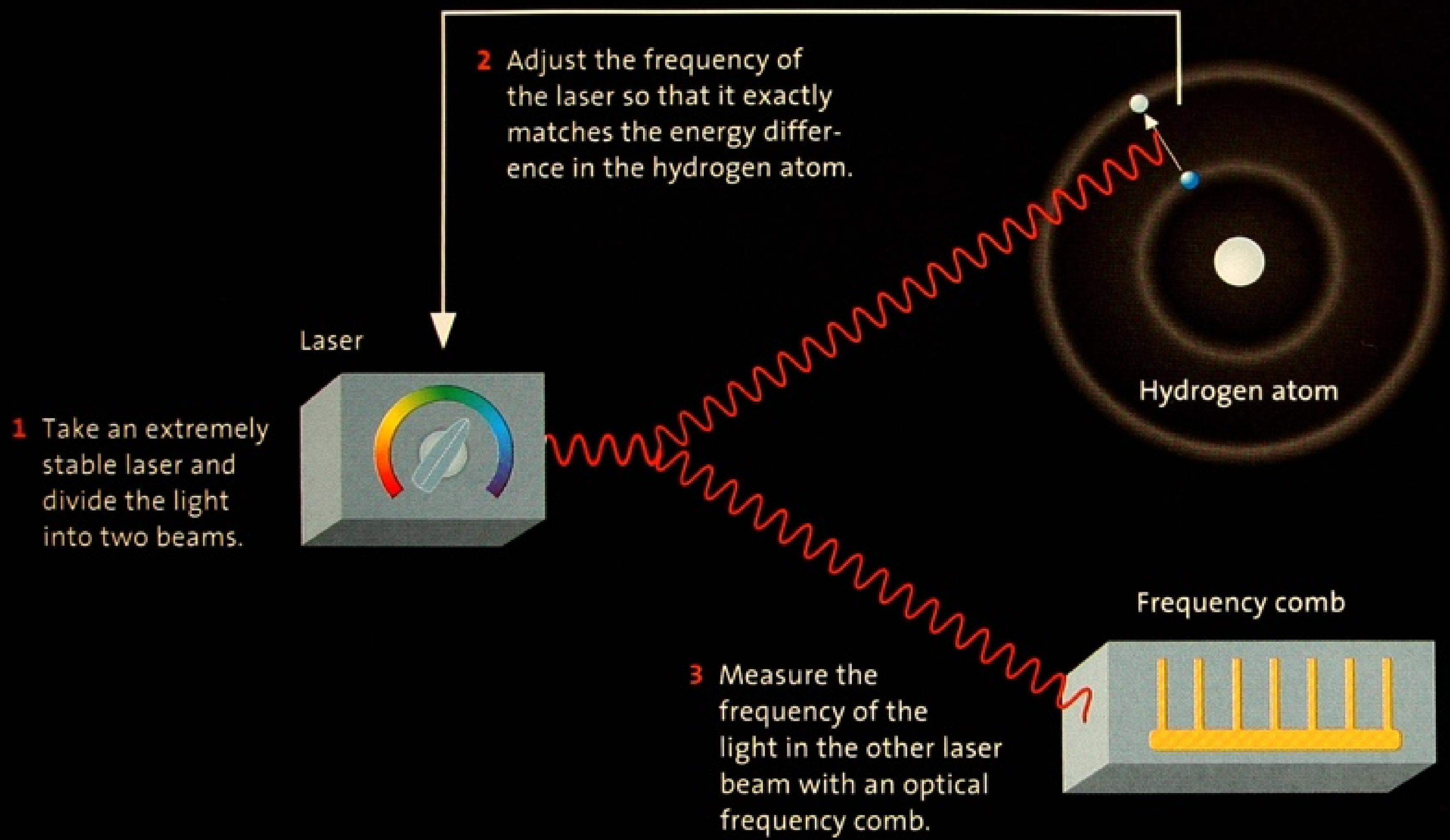
Optical Frequency Synthesis and Comparison with Uncertainty at the 10^{-19} Level

Long-Sheng Ma,[1,2*†] Zhiyi Bi,[2*] Albrecht Bartels,[3*]
Lennart Robertsson,[1] Massimo Zucco,[1] Robert S. Windeler,[4]
Guido Wilpers,[3] Chris Oates,[3] Leo Hollberg,[3]
Scott A. Diddams[3*†]

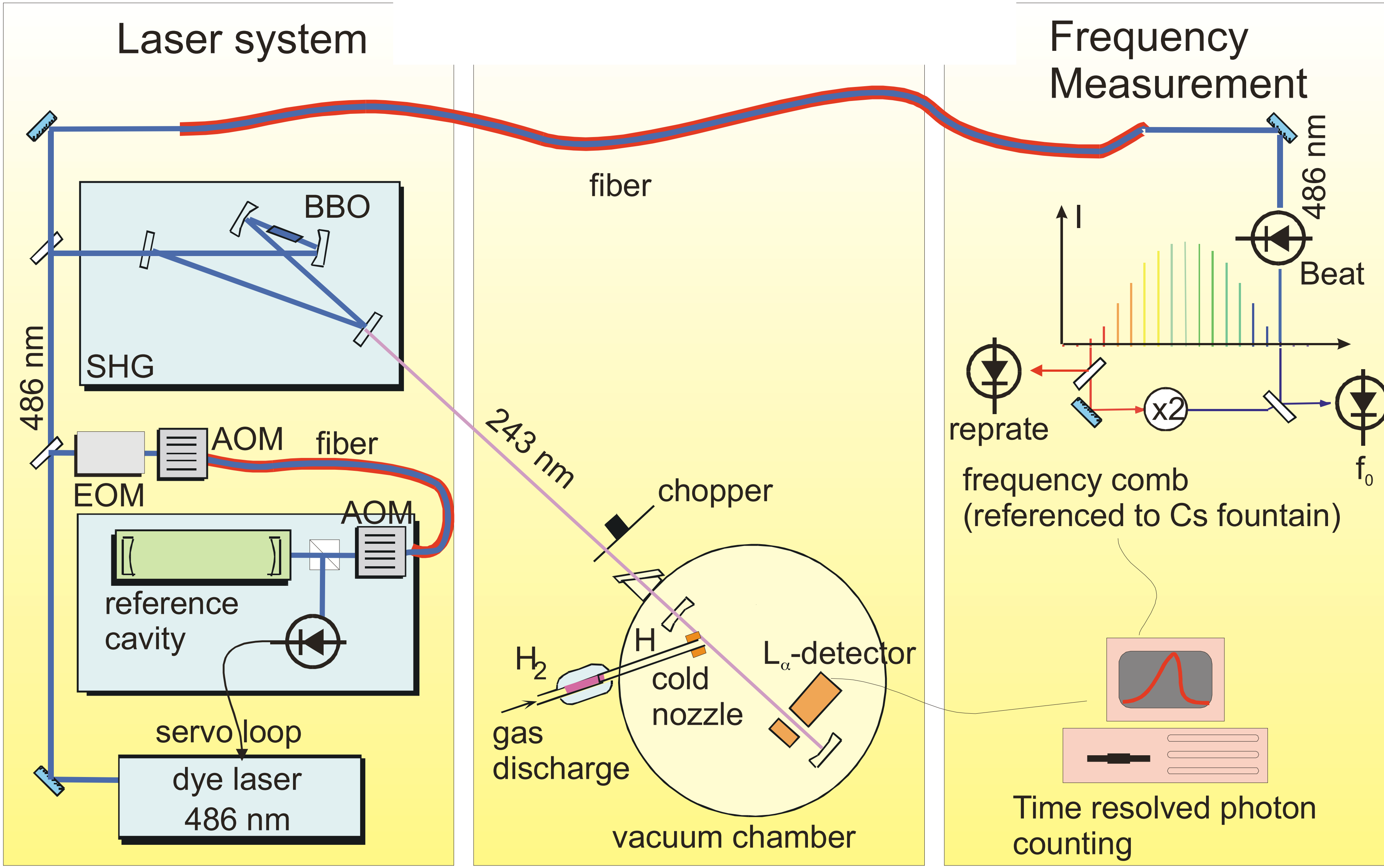
A femtosecond laser–based optical frequency synthesizer is referenced to an optical standard, and we use it to demonstrate the generation and control of the frequency of electromagnetic fields over 100 terahertz of bandwidth with fractional uncertainties approaching 1 part in 10^{19}. The reproducibility of this performance is verified by comparison of different types of femtosecond laser–based frequency synthesizers from three laboratories.

Science, **303**, 1843 (2004)

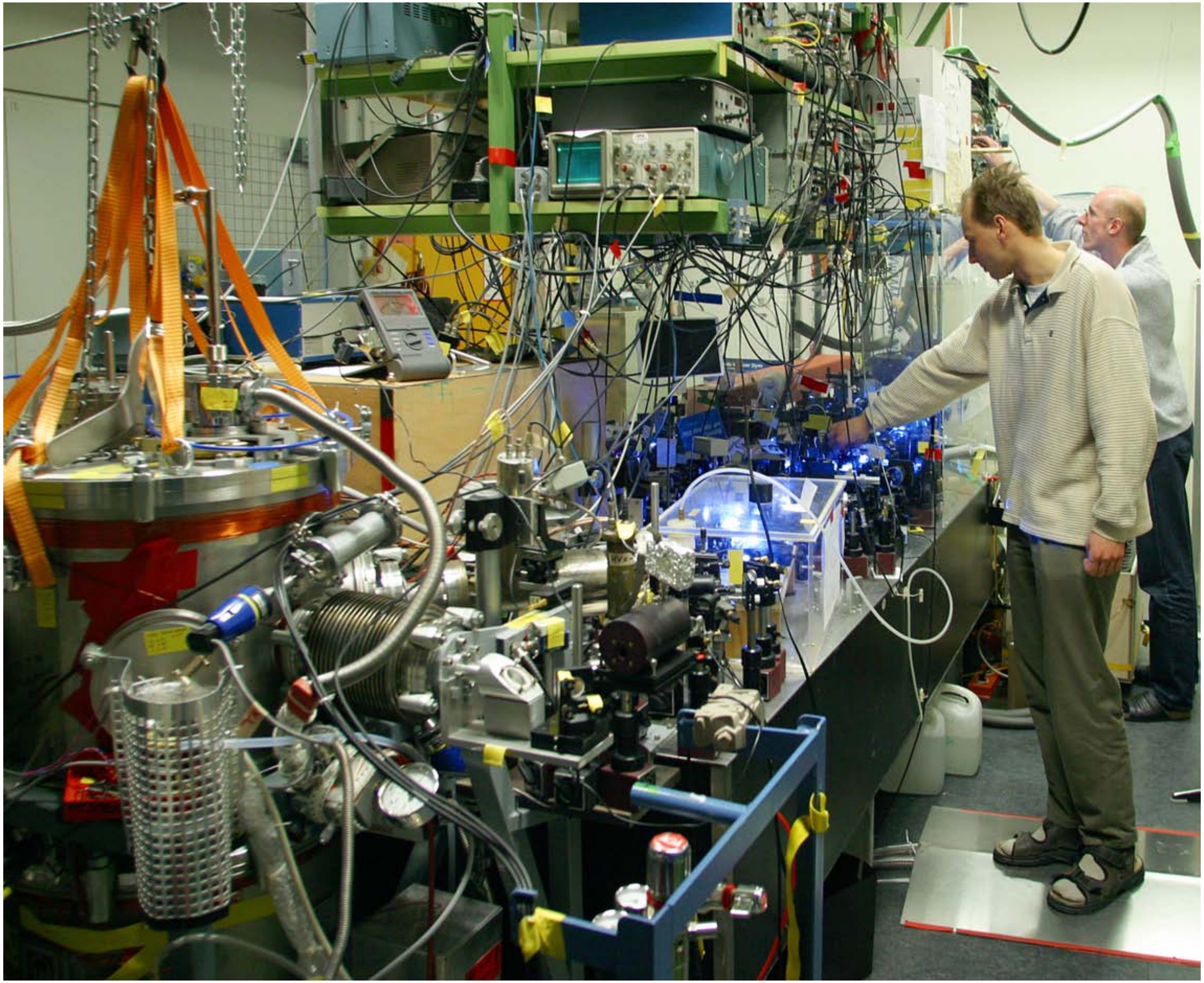
measuring the frequency of hydrogen with a laser comb



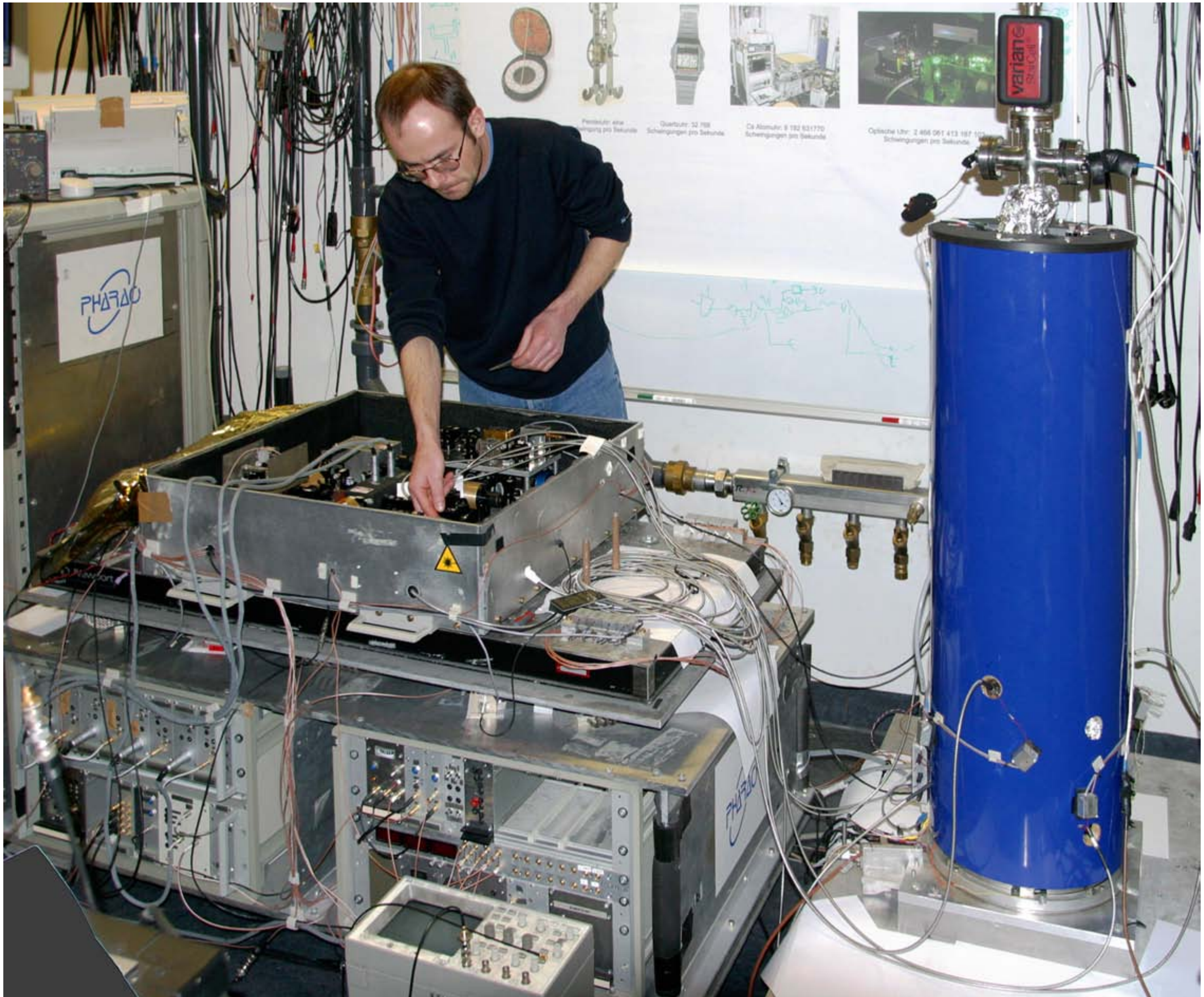
2003: Hydrogen 1S-2S spectrometer



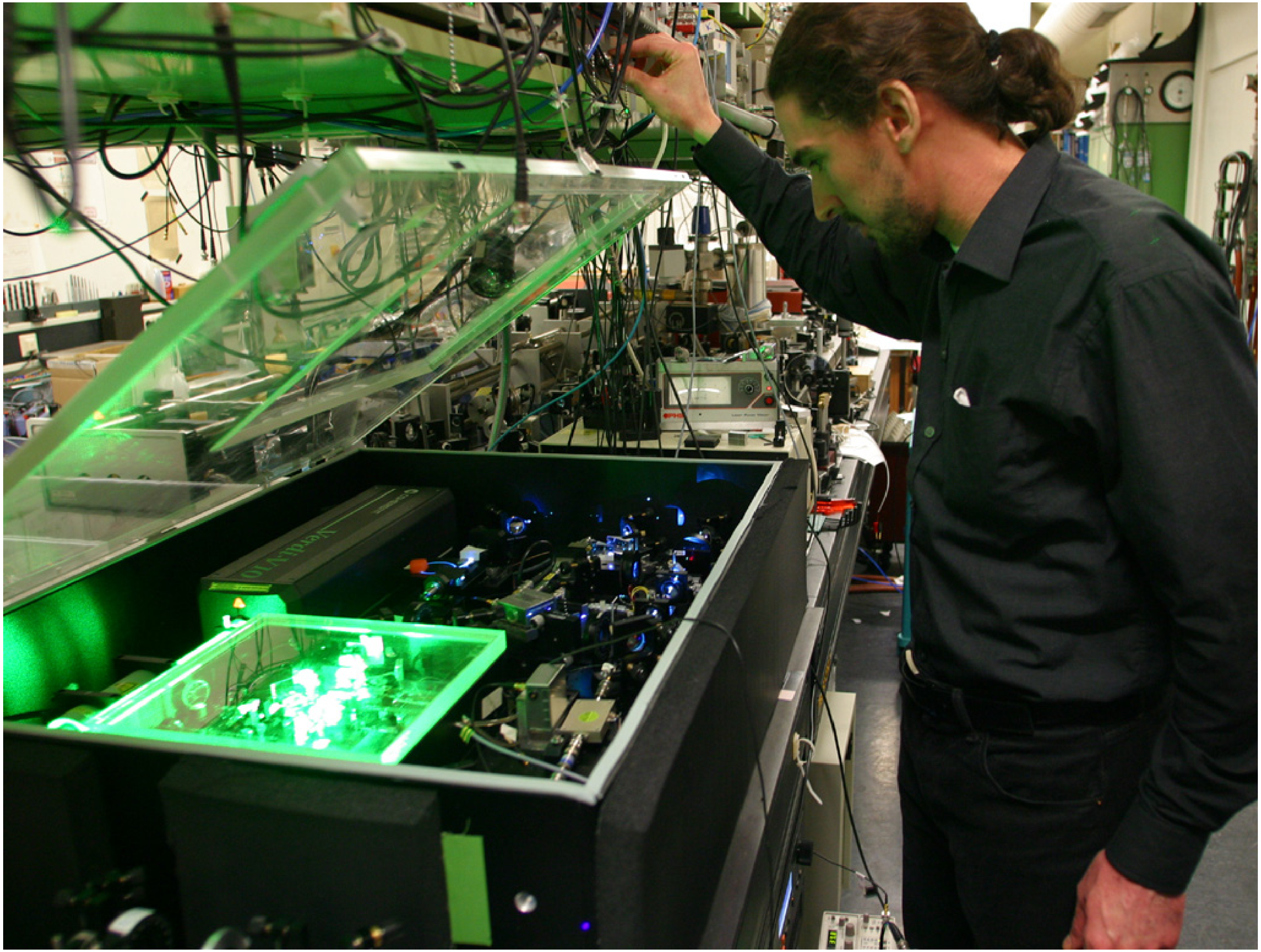
Hydrogen spectrometer, February 2003



PHARAO transportable cesium fountain clock



Frequency comb synthesizer



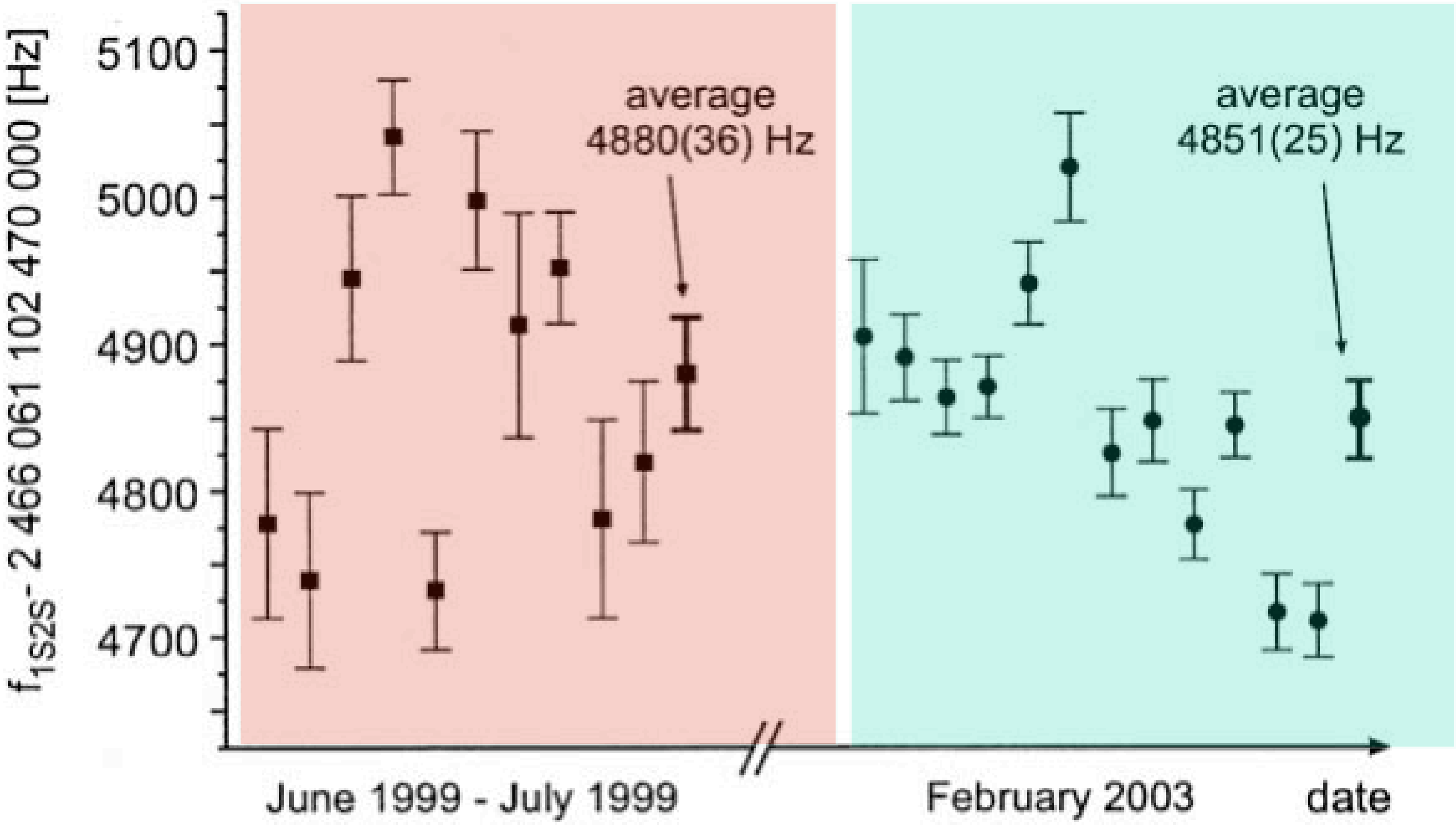


FIG. 2: *Experimental results and weighted averages for the 1999 and 2003 measurements of the absolute 1S-2S transition frequency in atomic hydrogen.*

M. Fischer et al., PRL **92**, 230802 (2004)

Hydrogen 1S-2S frequency

(F=1 to F'=1 hyperfine component)

Feb. 2003: f(1S-2S) = (2 466 061 102 474 851 $\pm$ 34) Hz

relative uncertainty: 1.4 x 10^{-14}

June 1999: f(1S-2S) = (2 466 061 102 474 870 $\pm$ 46) Hz

relative uncertainty: 1.9 x 10^{-14}

A difference of (-29 $\pm$ 57) Hz in 44 months equals a relative drift of the 1S-2S transition frequency of

(3.2 $\pm$ 6.3) x 10^{-15} per year

Further evidence for a variable fine structure constant from KECK/HIRES QSO absorption spectra

$$\dot{\alpha}/\alpha \leq +(6.4 \pm 1.35) \times 10^{-16} yr^{-1}$$

M.T. Murphy, J.K. Webb, and V.V. Flambaum, MNRAS **345**, 609 (2003)

Further evidence for a variable fine structure constant from KECK/HIRES QSO absorption spectra

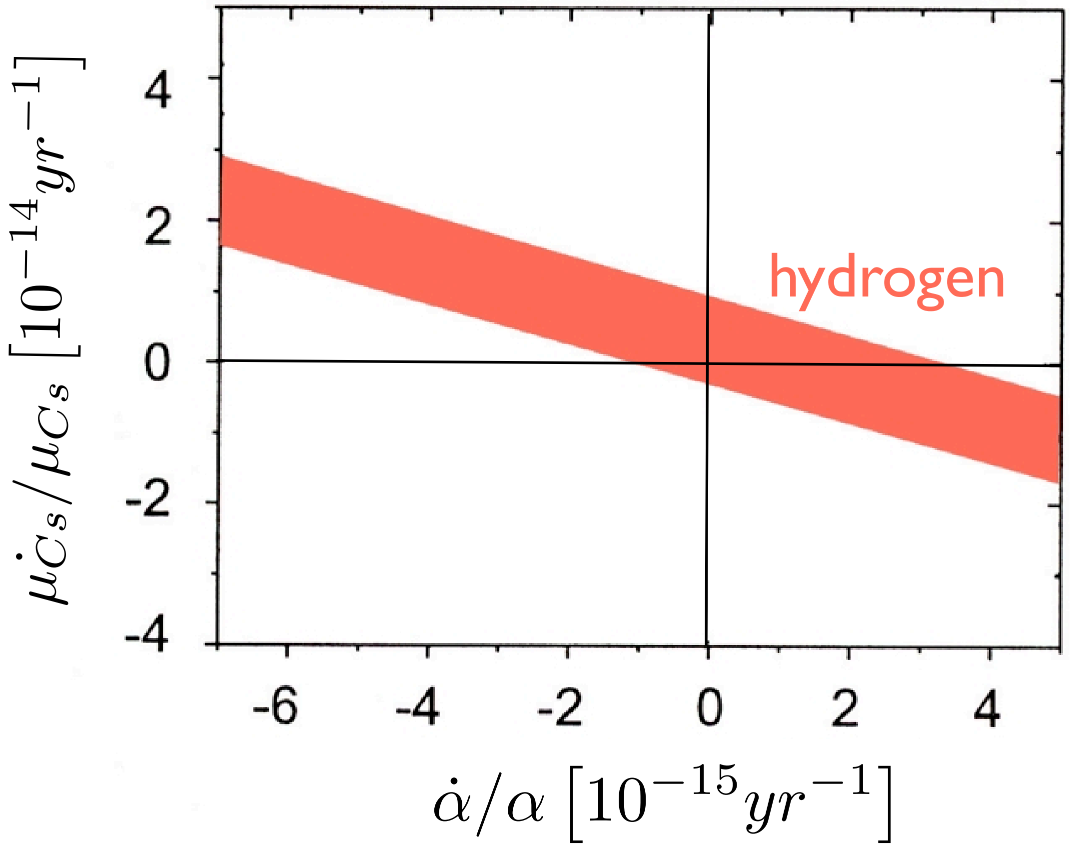
$$\dot{\alpha}/\alpha \leq +(6.4 \pm 1.35) \times 10^{-16} yr^{-1}$$

M.T. Murphy, J.K. Webb, and V.V. Flambaum, MNRAS **345**, 609 (2003)

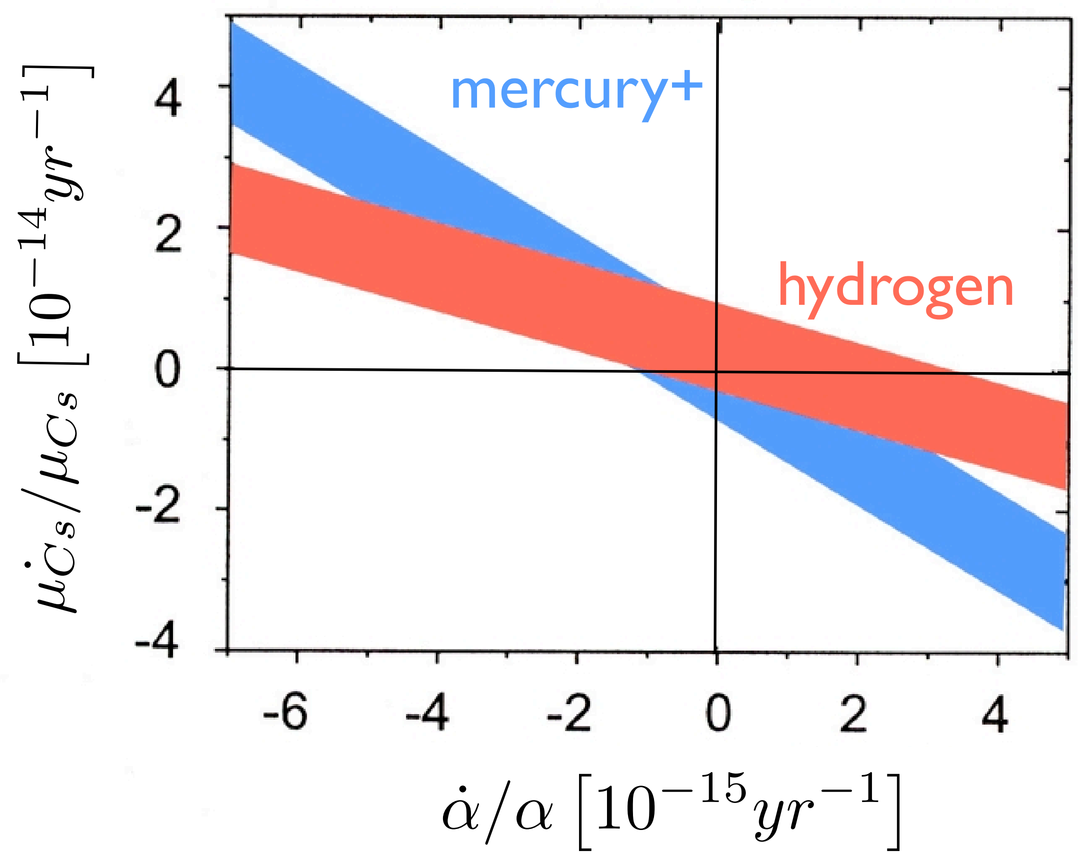
Limits on the time variation of the electromagnetic fine-structure constant in the low energy limit from absorption lines in the spectra of distant quasars

$$-2.5 \times 10^{-16} \leq \dot{\alpha}/\alpha \leq +1.2 \times 10^{-16} yr^{-1}$$

R. Srianand, H. Chand, P. Petitjean, and B. Aracil, PRL **92**, 121302 (2004)

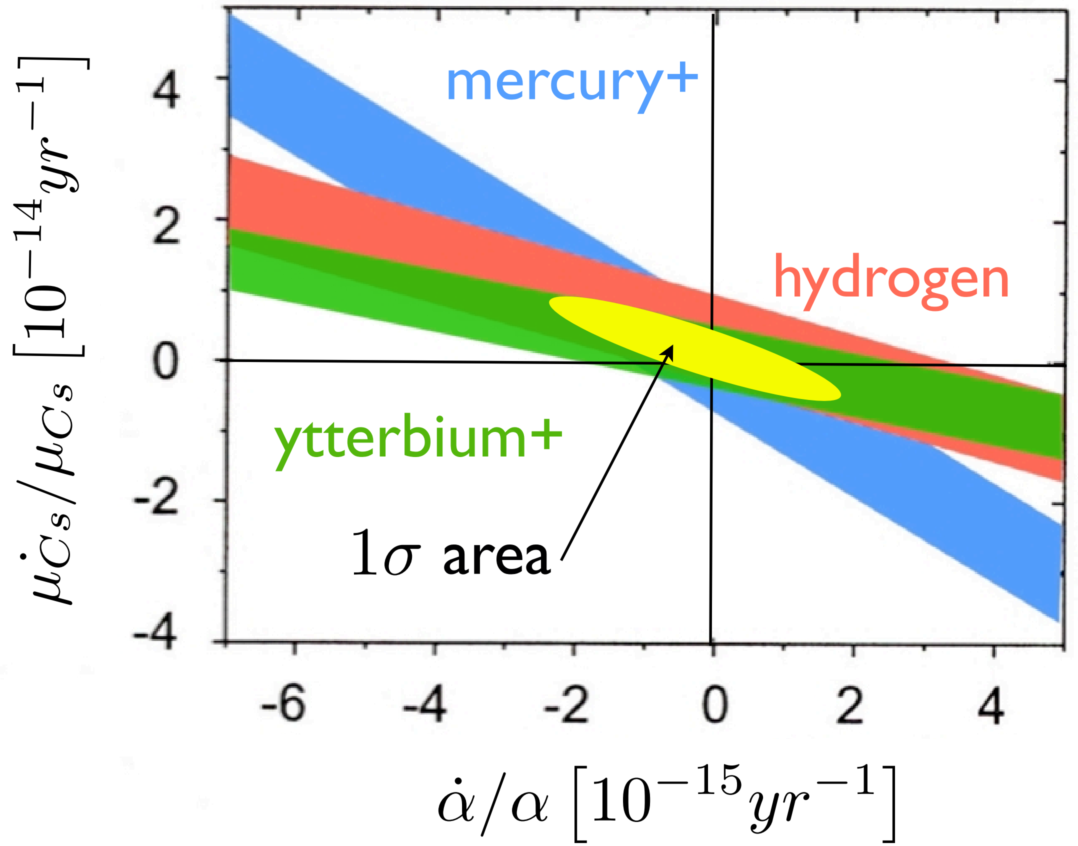


Hydrogen, 1999-2003: M. Fischer et al., PRL **92**, 230802 (2004)



Hydrogen, 1999-2003: M. Fischer et al., PRL **92**, 230802 (2004)

Mercury+, 2000-2002: S. Bize et al., PRL **90**, 150802 (2003)



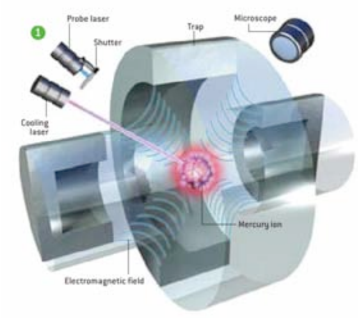
$$\dot{\alpha}/\alpha = (-0.3 \pm 2.0) \times 10^{-15} yr^{-1}$$

$$\dot{\mu_{Cs}}/\mu_{Cs} = (2.4 \pm 6.8) \times 10^{-15} yr^{-1}$$

Optical clock - some candidates

Laser-cooled trapped ions

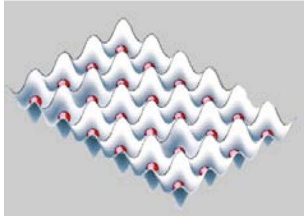
Hg^+, In^+, Yb^+, Sr^+, Ca^+, ...



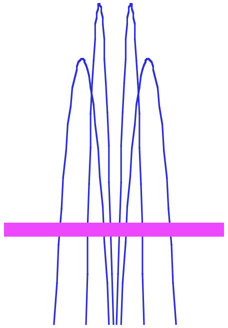
Paul trap

Cold neutral atoms:

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



Optical lattice



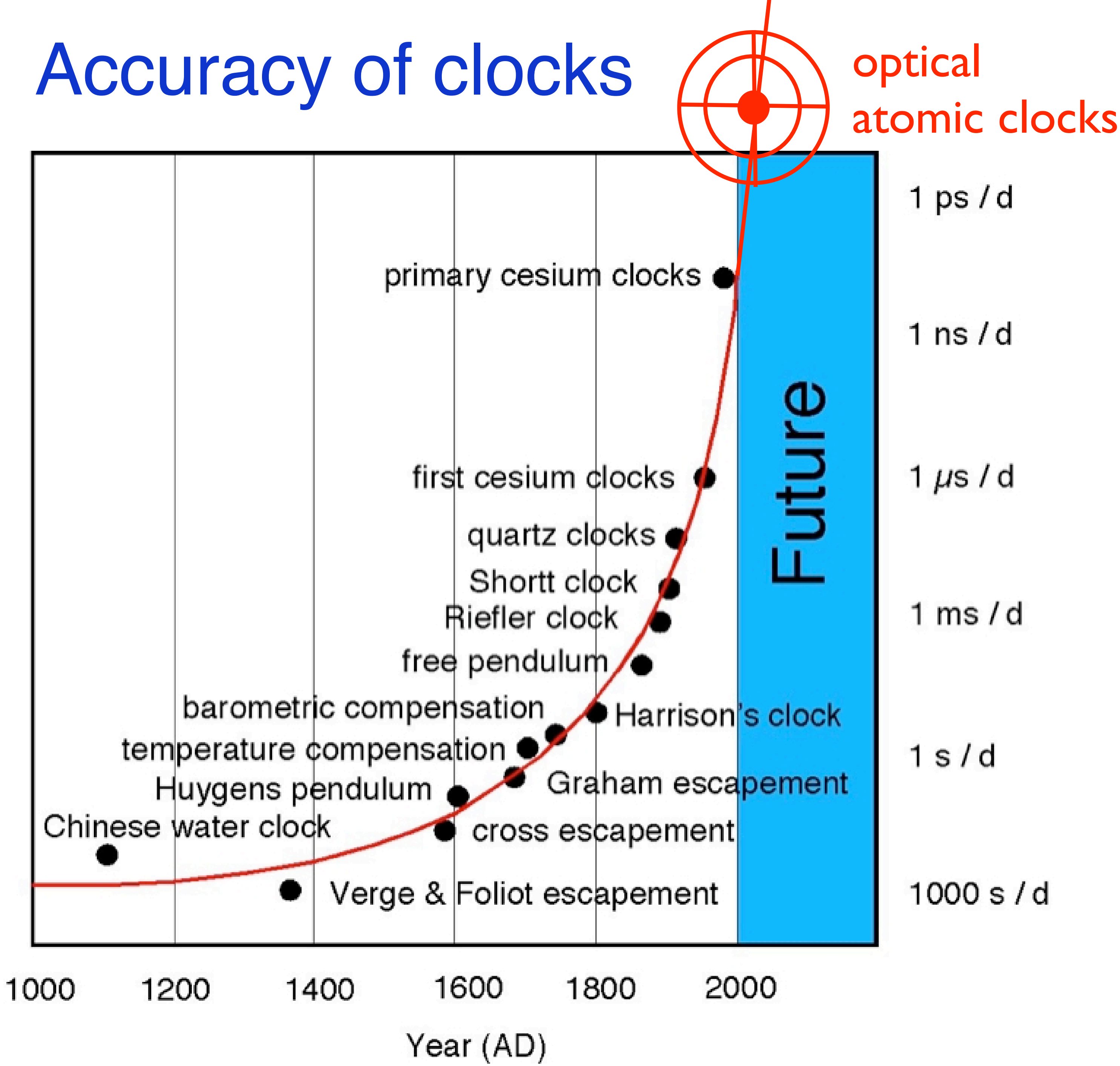
Atomic fountain

Molecules:

I_2, C_2H_4, ...

Atom chip

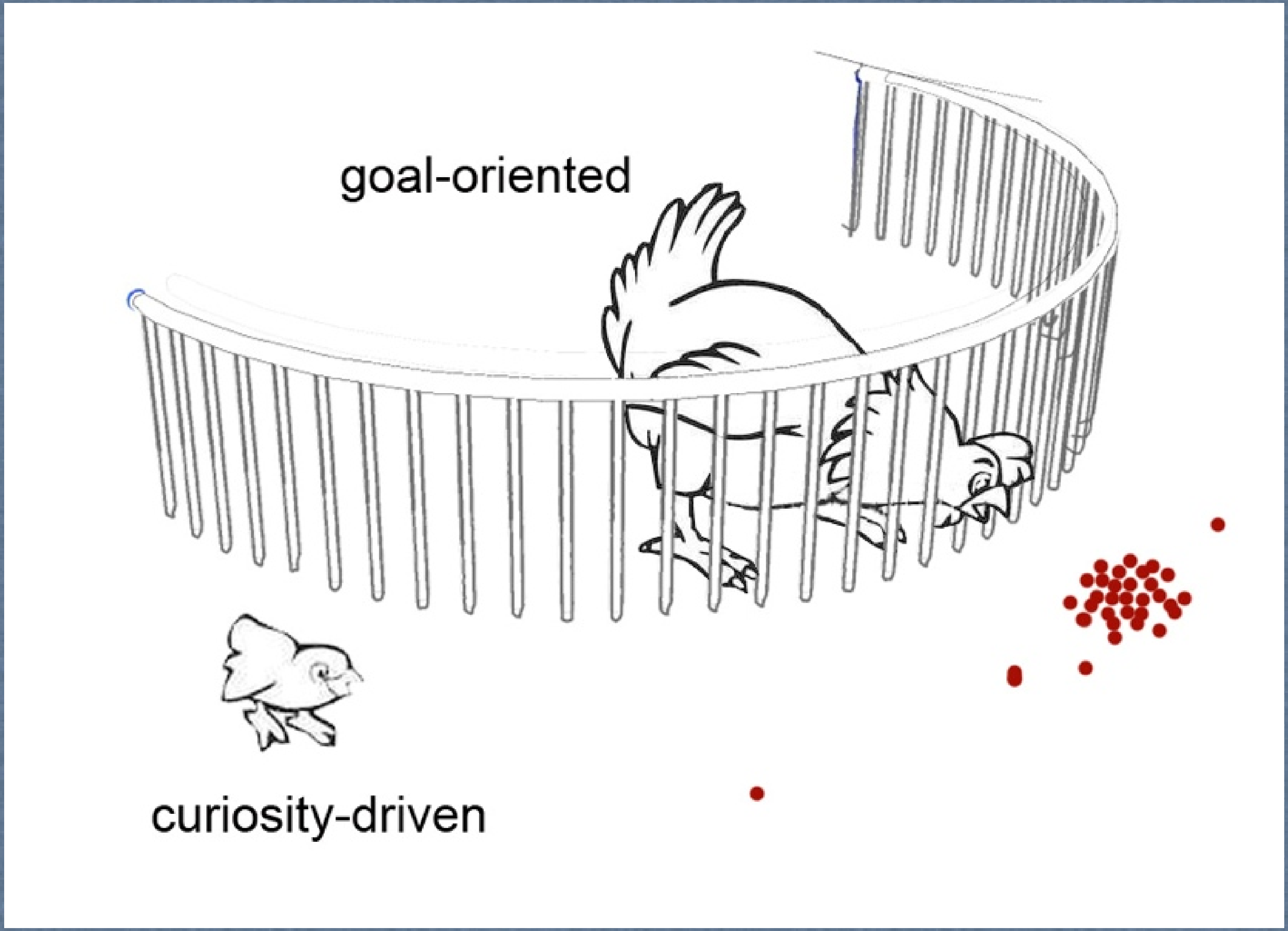
Accuracy of clocks



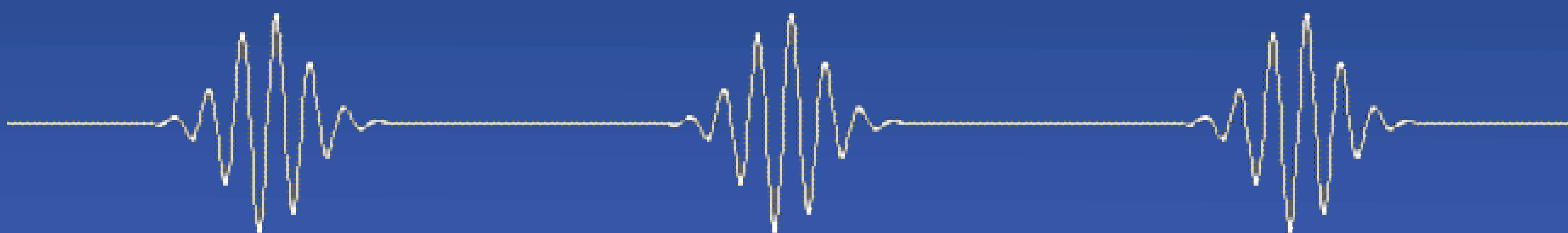
Applications for (better) Atomic Clocks

- Precision Spectroscopy
- 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
- Pulsar periods
- Test of special and general relativity
- Check constancy of fundamental constants
- ....

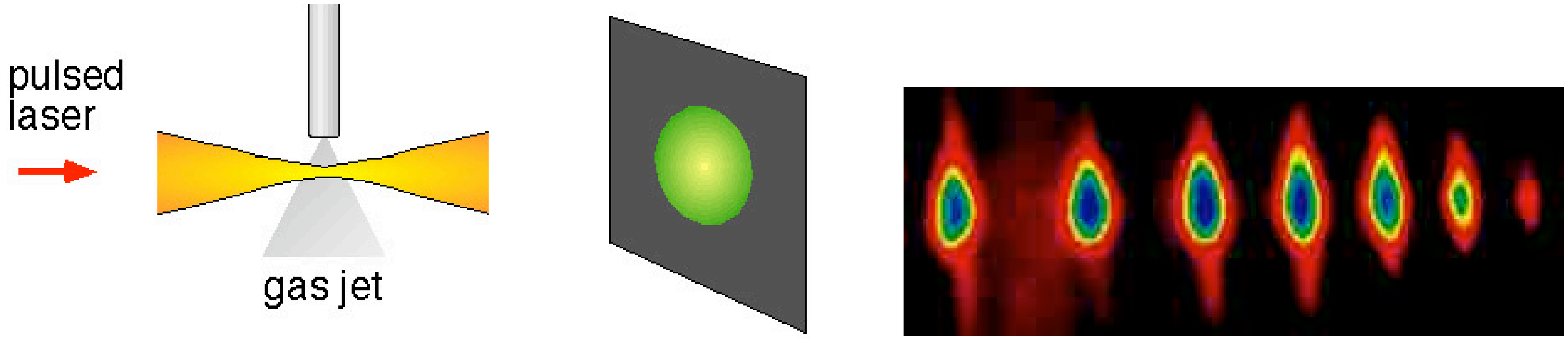
curiosity-driven research

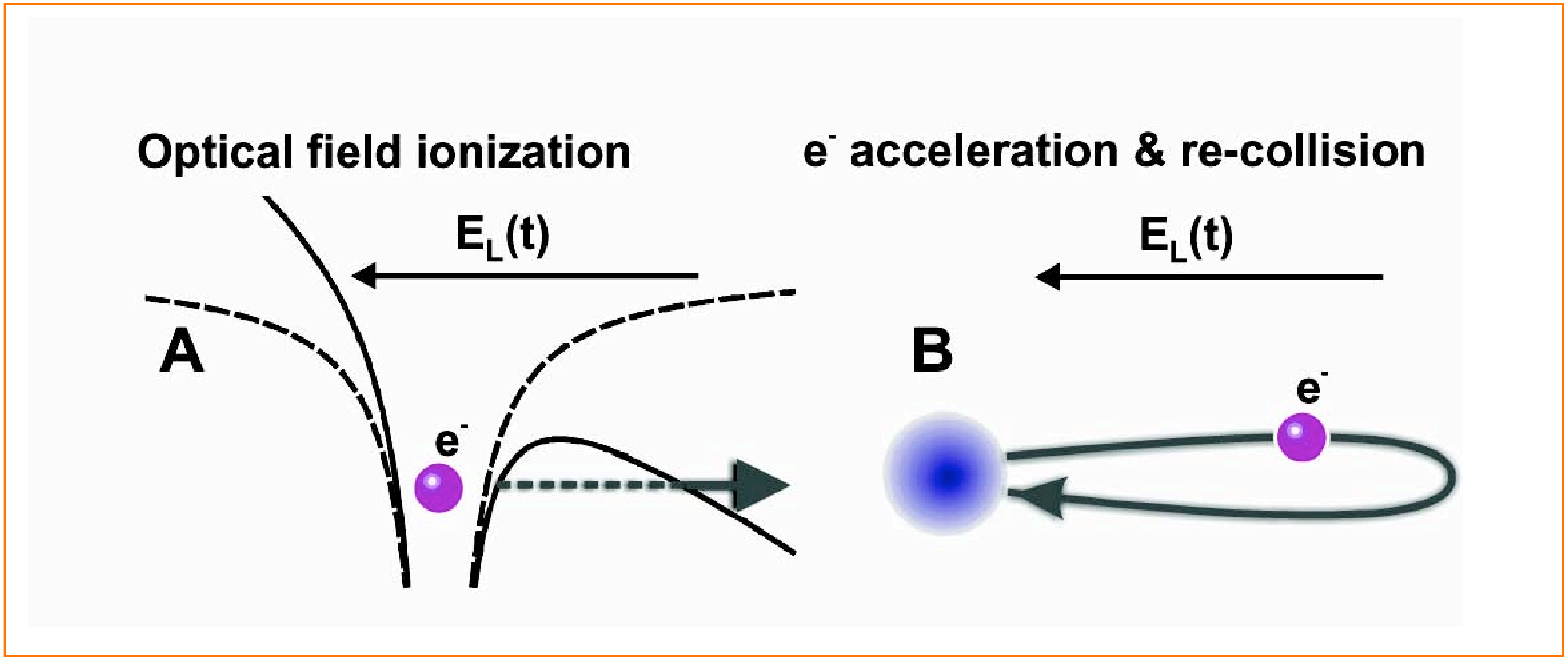


Towards frequency combs and ultraprecise spectroscopy in the extreme ultraviolet

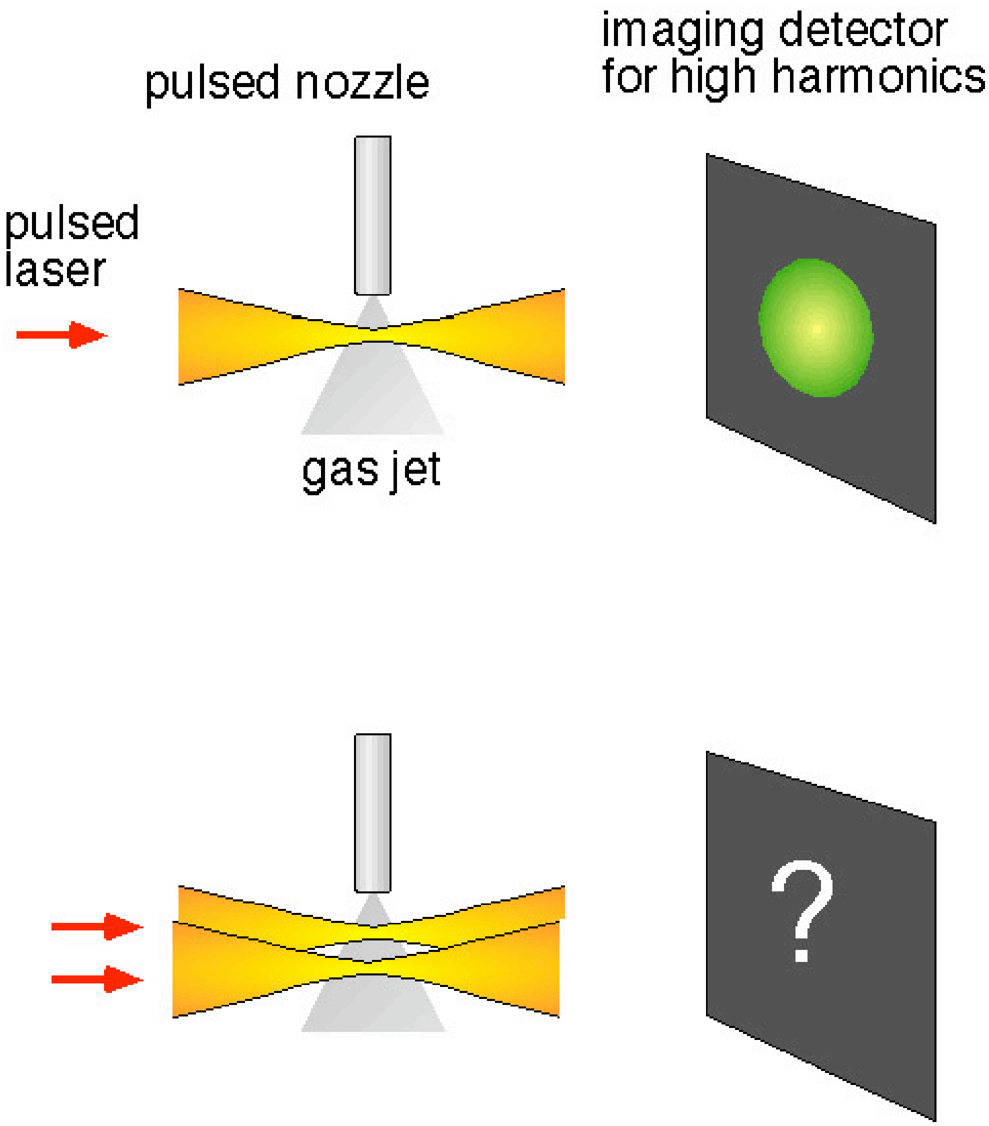


Generation of high harmonics

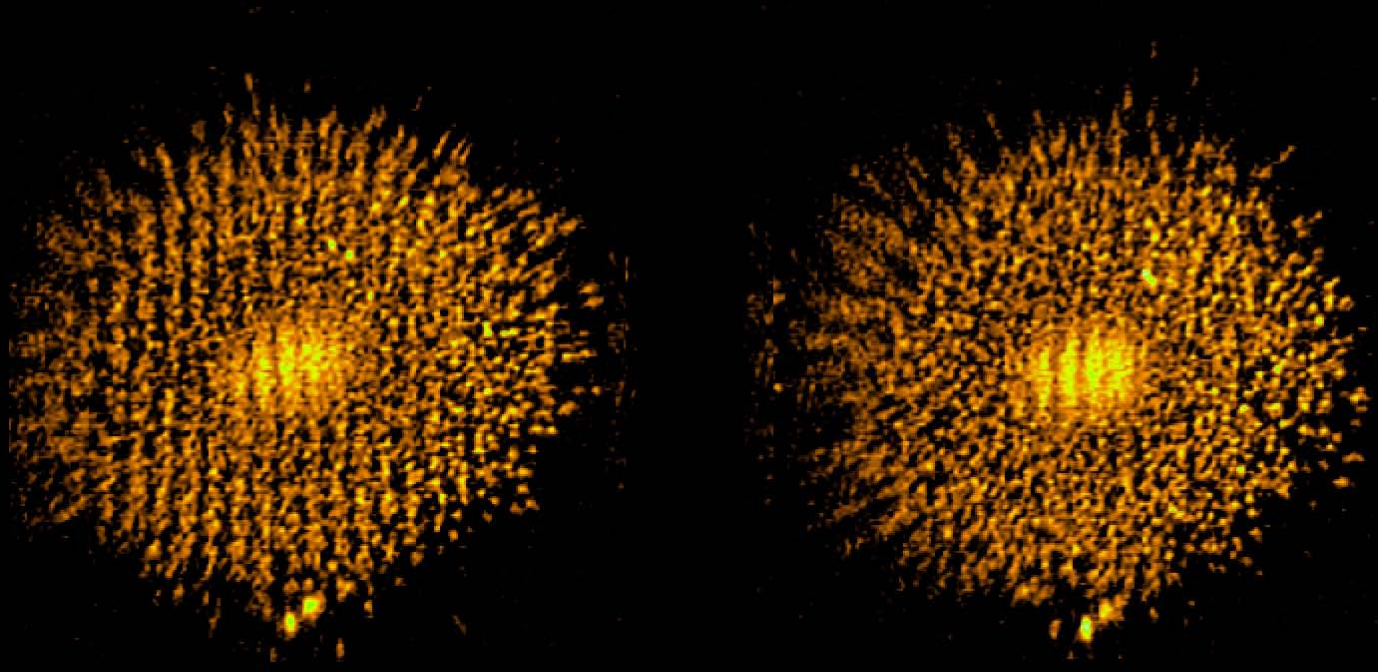




Can two high harmonics pulses interfere?



15 th harmonic (53 nm)

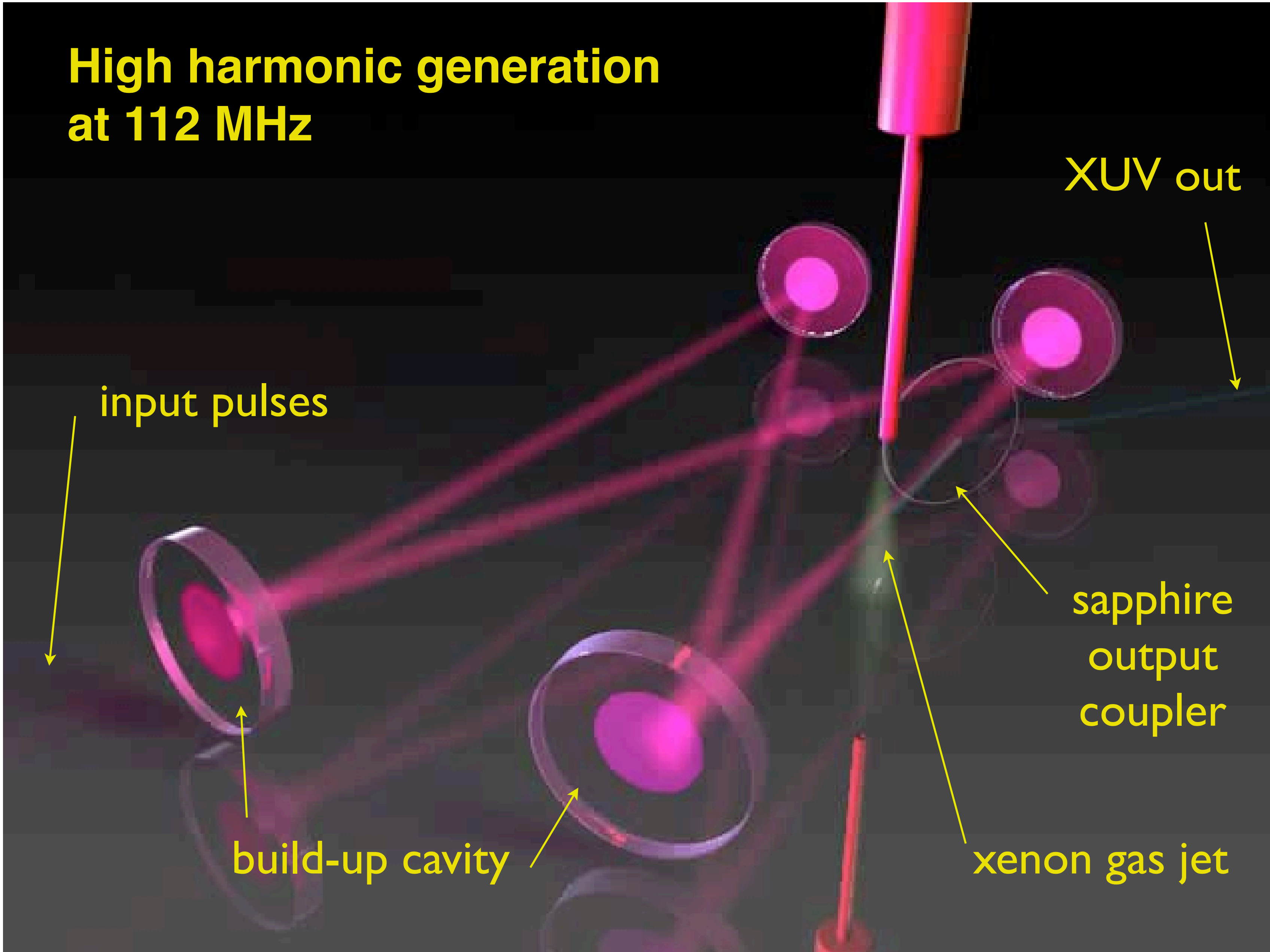


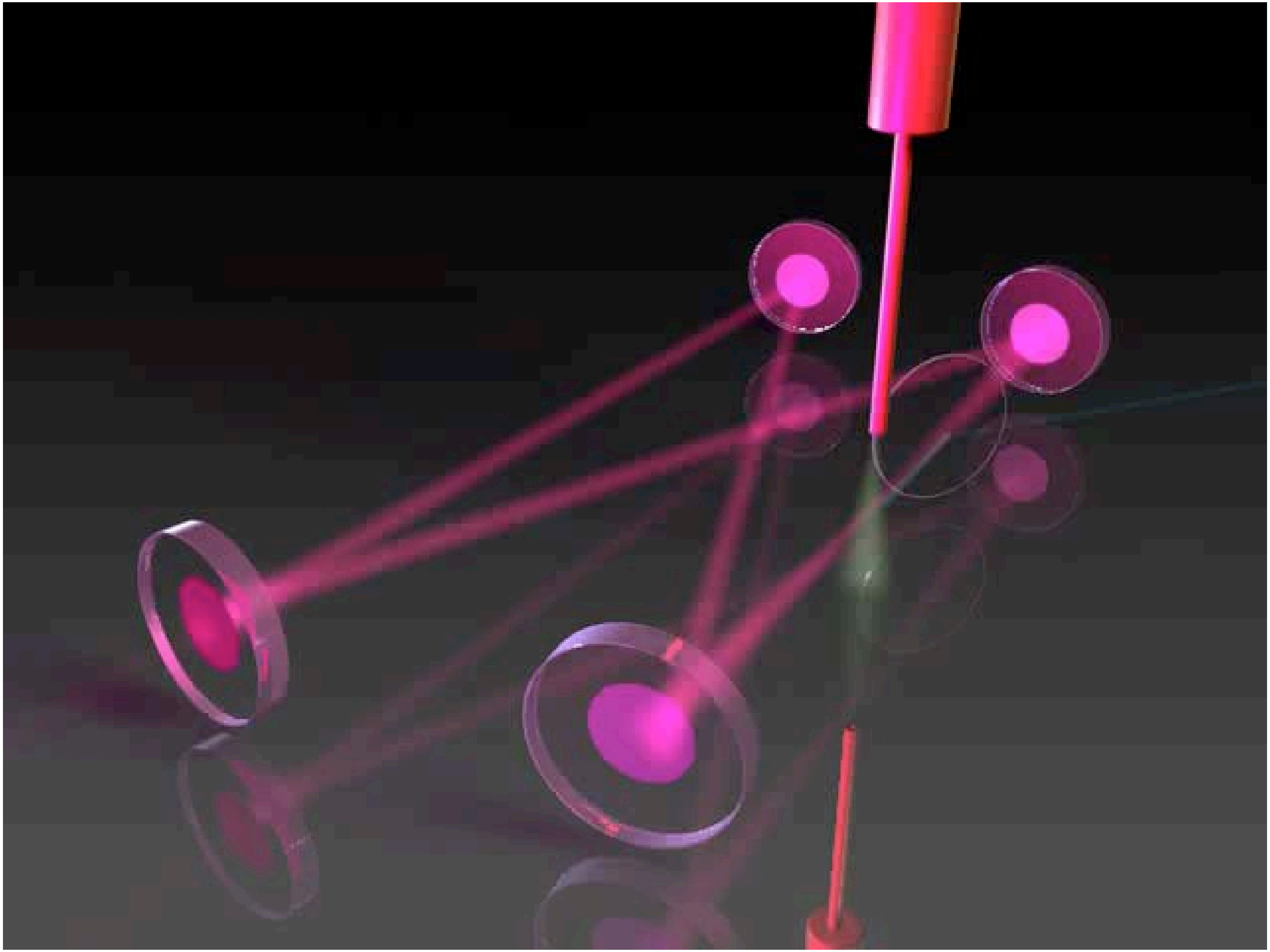
0 fs (delay) 15 fs

Experiments at Lund Laser Center:

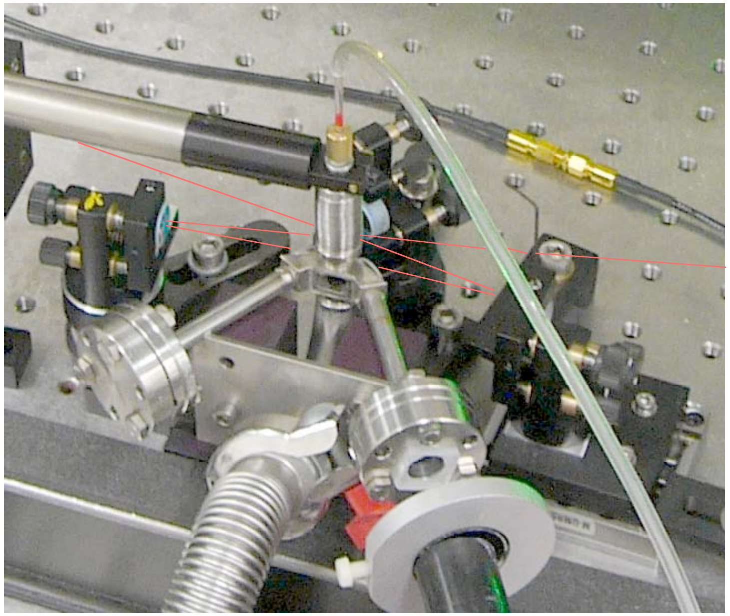
R. Zerne et al., Phys. Rev. Lett. **79**, 1006 (1997)

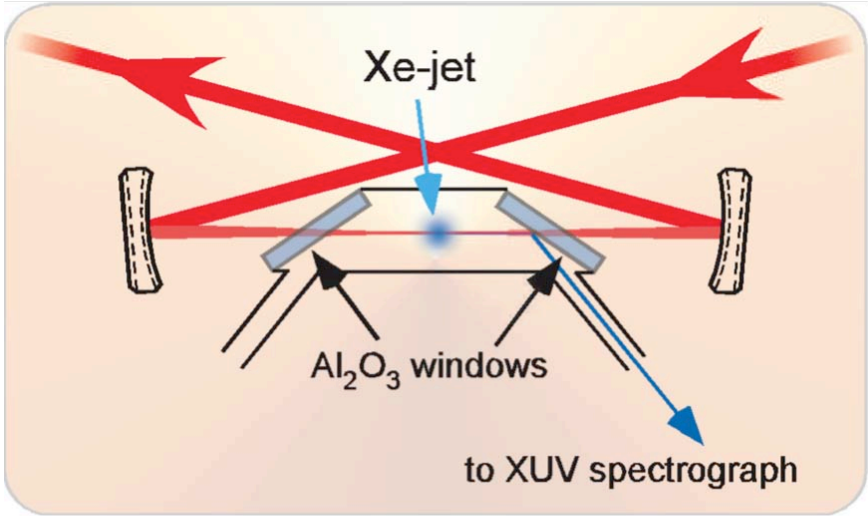
M. Bellini et al., Phys. Rev. Lett. **81**, 297 (1998)

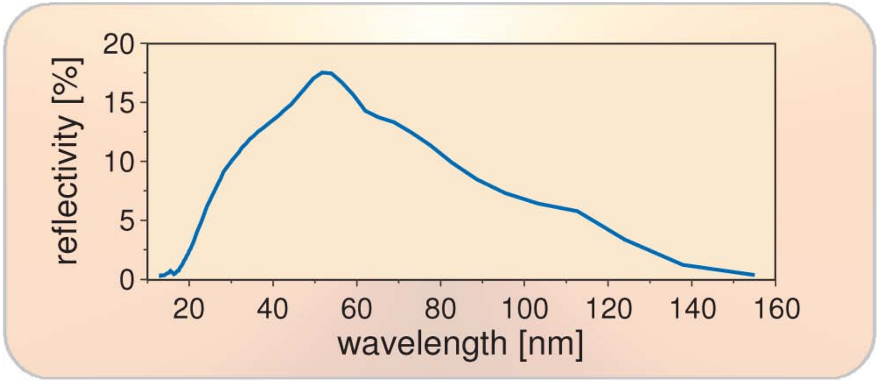

High harmonic generation
at 112 MHz
XUV out
input pulses
sapphire
output
coupler
build-up cavity
xenon gas jet



Intra-cavity high harmonic generation





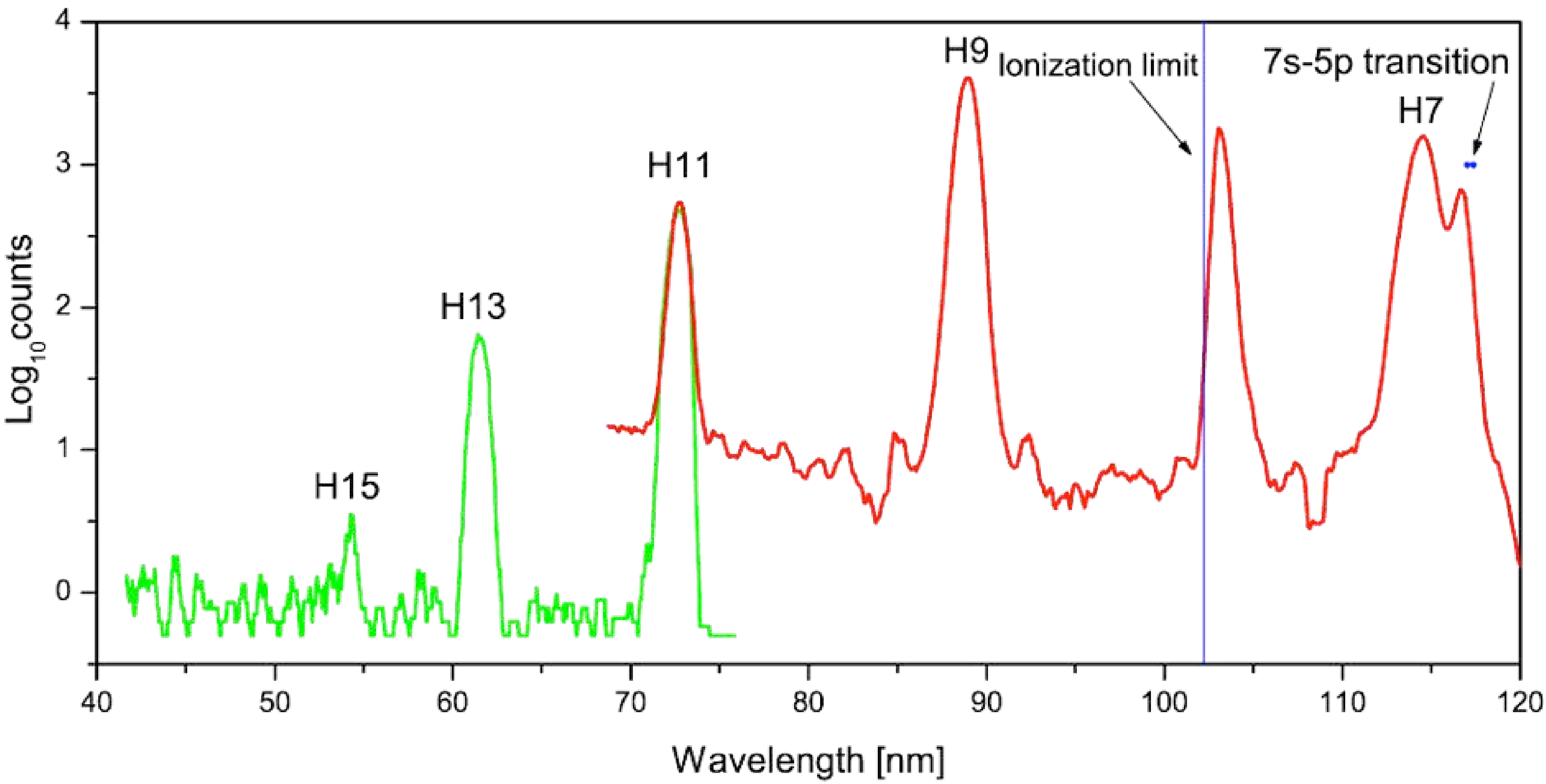


injected: 22 fs pulse duration,
0.65 W average, 200 kW peak

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

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

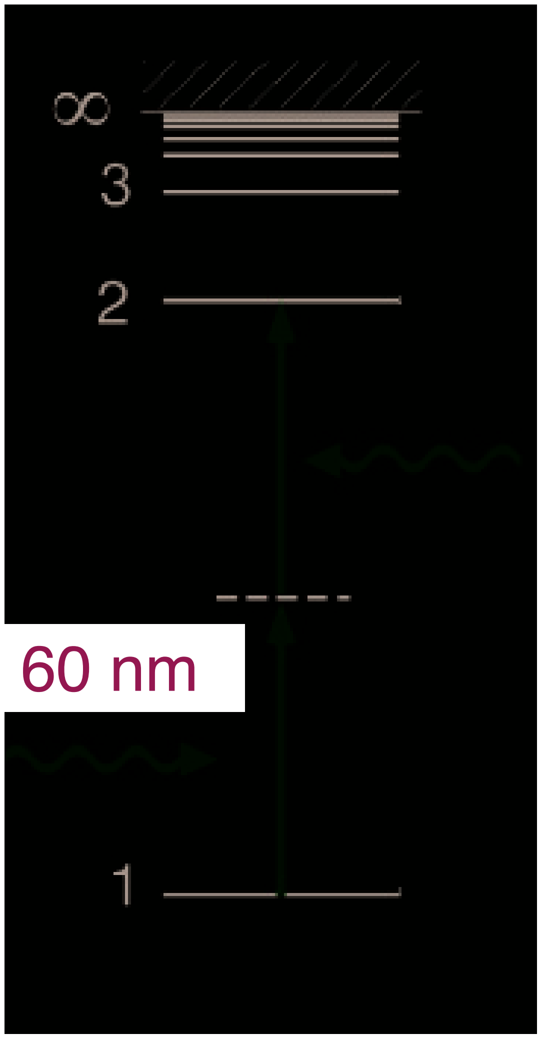
High harmonic generation at 112 MHz



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

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

He^+



Helium ion

in Paul trap

Thomas Udem
Christoph Gohle
Maximilian Herrmann

M. Abgrall, P. Adel, J. Alnis, T. Andreae, R.G. Beausoleil,
M. Bellini, S. Bergesson, L.A. Bloomfield, U. Boesl, C. Bordé,
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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,
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P. Kubina, P. Laurent, S.A. Lee, D. Leibfried, J.C. Knight,
W. König, 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,
W. Vassen, V. Vuletic, W.J. Wadsworth, R. Wallenstein, J. Walz,
E.Weber, M. Weitz, C. Wieman, R. Wynands, Th. Udem,
C. Zimmermann, M. Zimmermann

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Tack så mycket