Die genausten Uhren der Welt

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16. Schweizerischer Tag für Physik und Unterricht

ETH Zürich, 13. Nov. 2015

The International Year of Light
and Light-based Technologies
2015

INTERNATIONAL
YEAR OF LIGHT
2015

Health

Communications

Economy

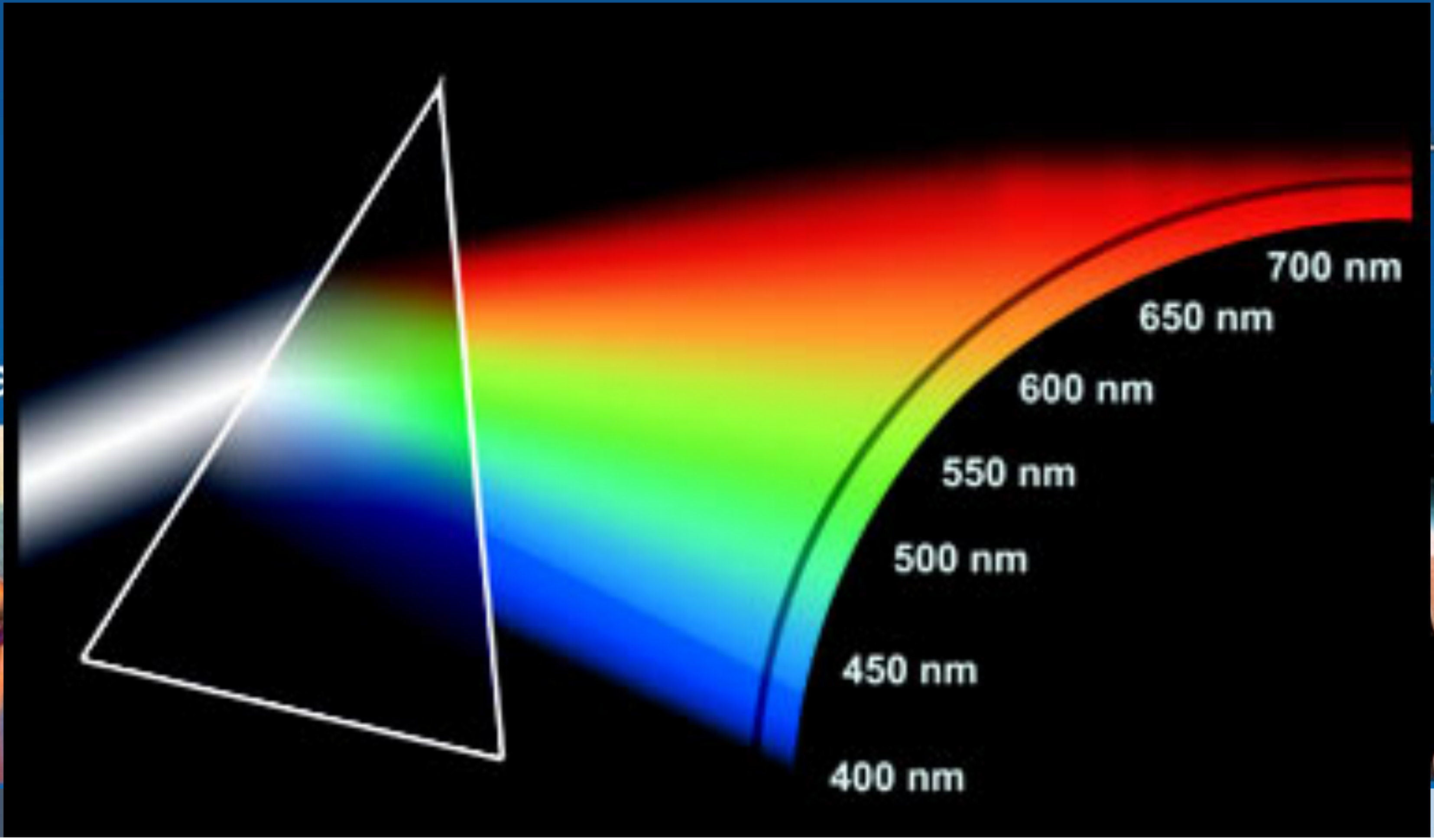
Environment

Social

The International Year of Light

and Light-based Technologies

2015



Hea

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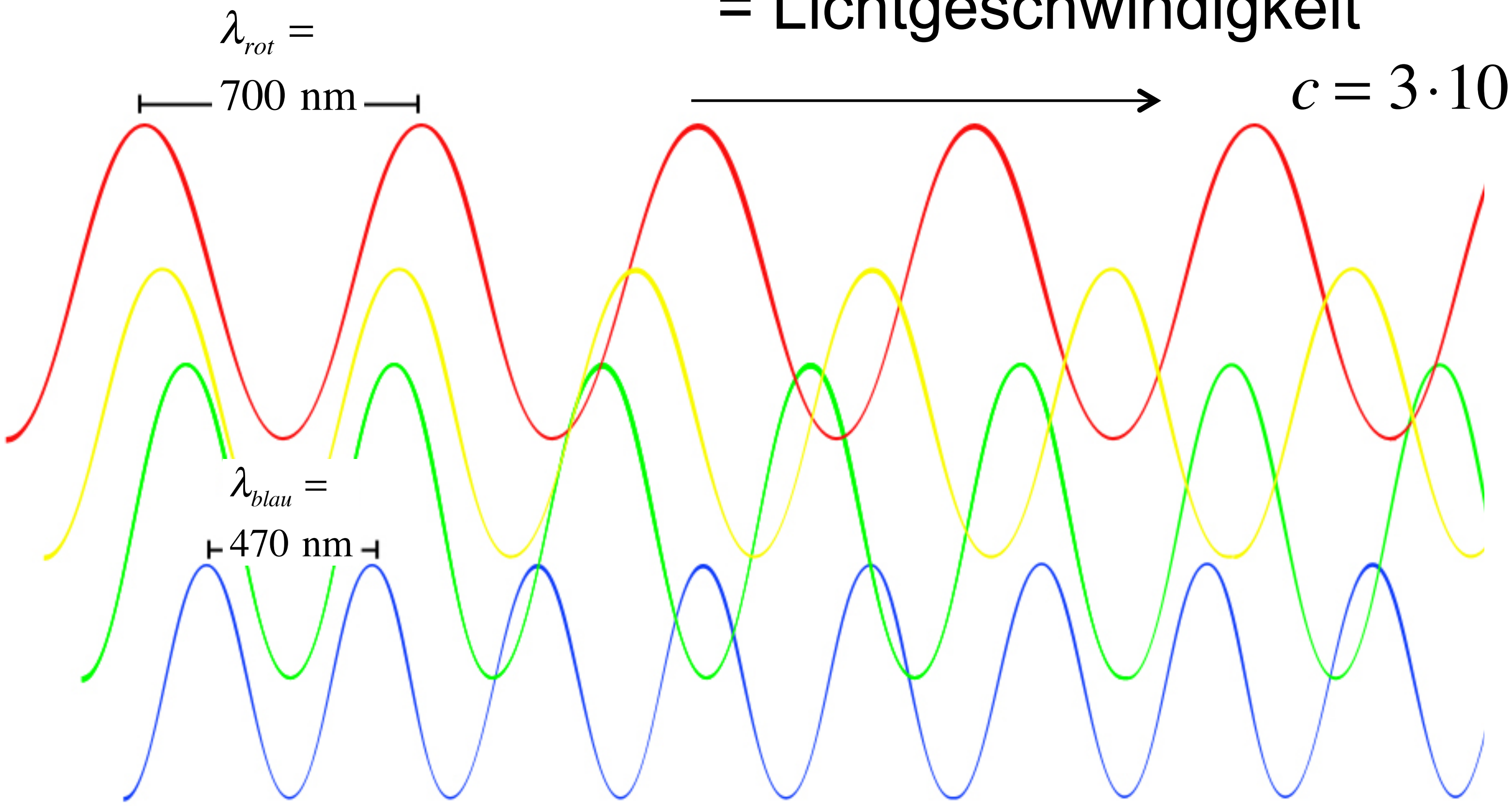
Licht

Ausbreitungsgeschwindigkeit
= Lichtgeschwindigkeit

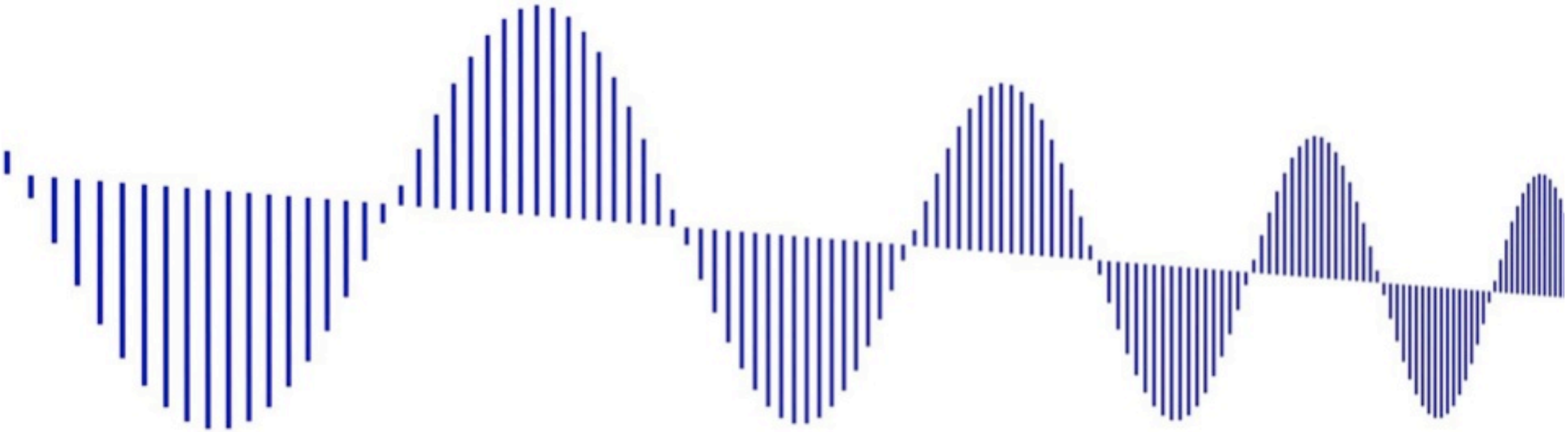
$$c = 3\cdot 10^{8}\,\frac{\mathrm{m}}{\mathrm{s}}$$

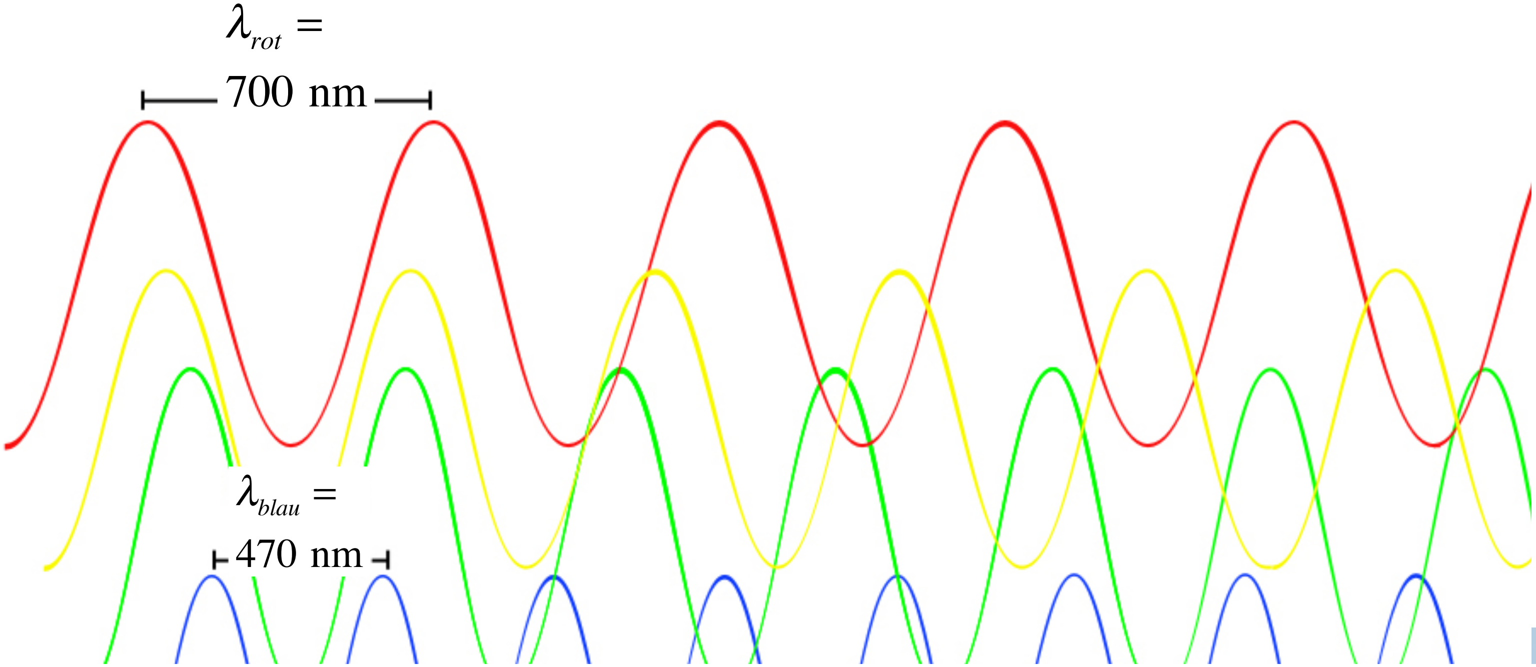


$$> 100\ \mathrm{THz}$$

Die Wellenlängen λ des Lichts
rot hat eine längere Wellenlänge – eine niedrigere Frequenz $\nu \propto \frac{1}{\lambda}$
als blau

Linear Polarisiertes Licht: Elektrischer Feldvektor oszilliert in einer Ebene

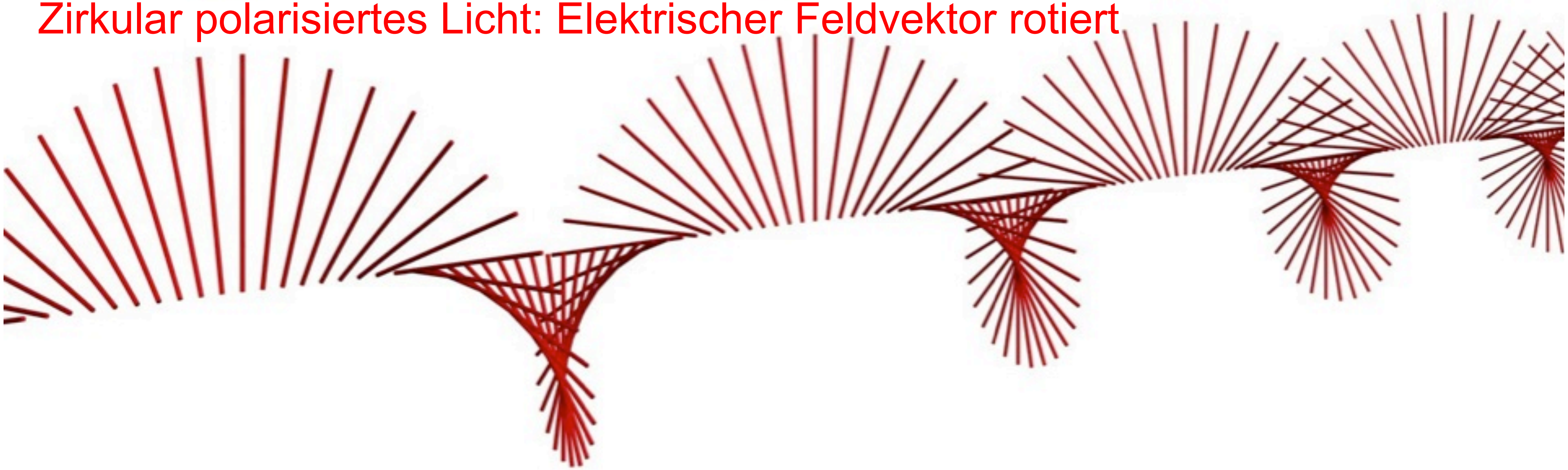




Attoclock

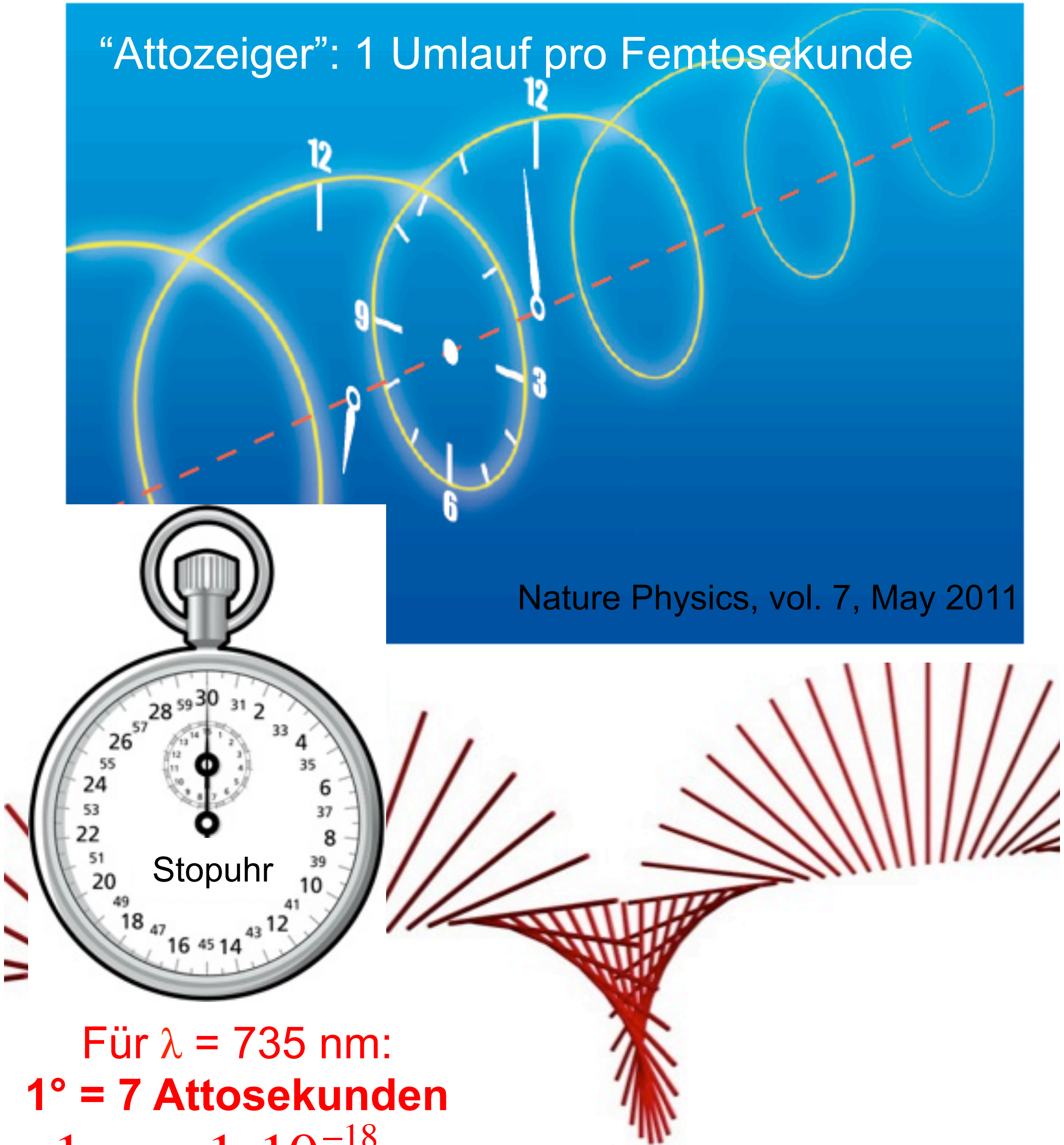
Linear Polarisiertes Licht: Elektrischer Feldvektor oszilliert in einer Ebene

Zirkular polarisiertes Licht: Elektrischer Feldvektor rotiert



P. Eckle et al., *Science* **322**, 1525 (2008)

Attoclock



“Attozeiger”: 1 Umlauf pro Femtosekunde

Nature Physics, vol. 7, May 2011

Für λ = 735 nm:

1° = 7 Attosekunden

$$1\ \text{as} = 1 \cdot 10^{-18}\ \text{s}$$

Stundenzeiger:
2 volle Rotationen pro Tag

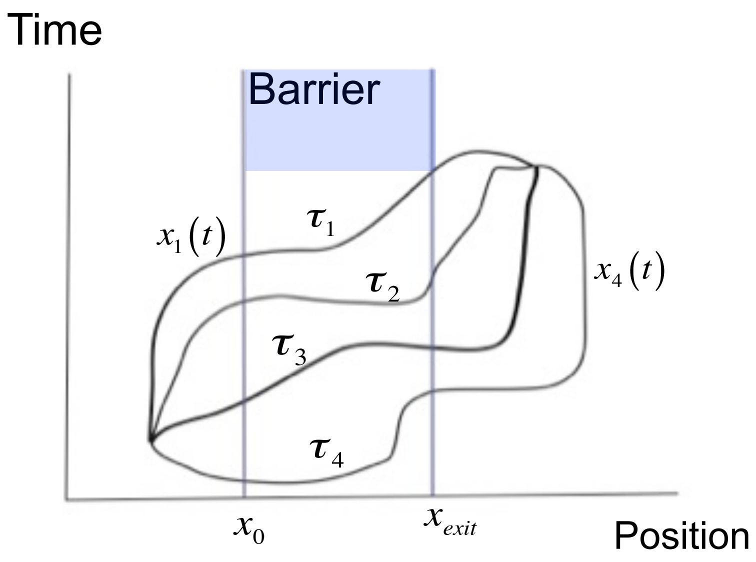
Minutenzeiger:
1 volle Rotation pro Stunde

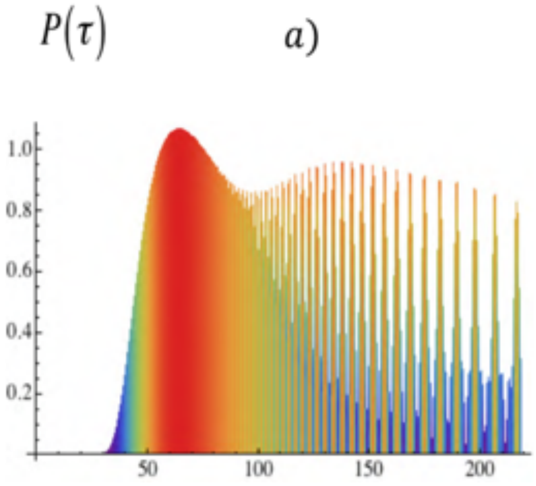
Sekundenzeiger:
1 volle Rotation pro Minute

... die Zeitmessung ist umso genauer je schneller die Rotation

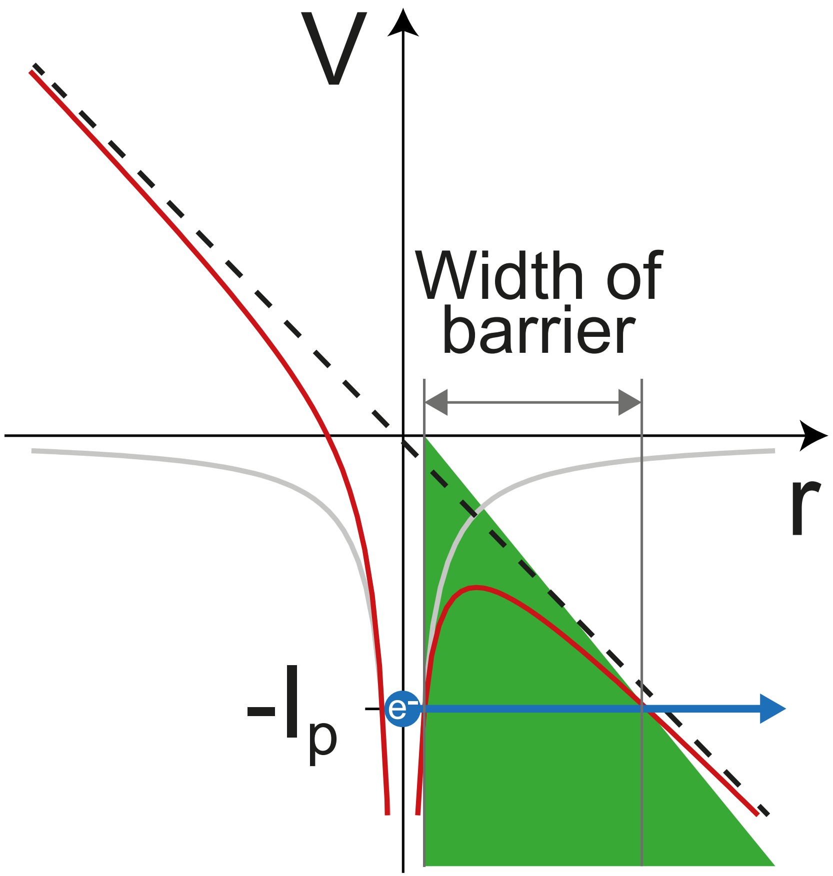
P. Eckle et al., *Science* **322**, 1525 (2008)

Wie lange braucht ein Elektron durch eine Tunnelbarriere?

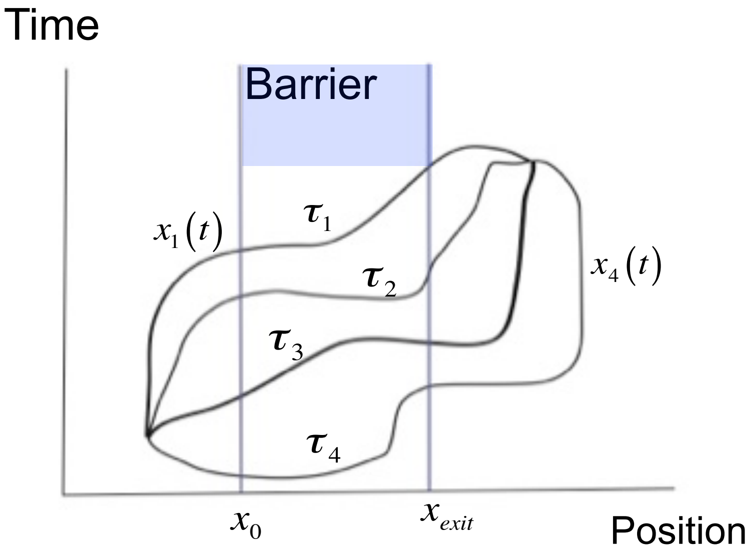


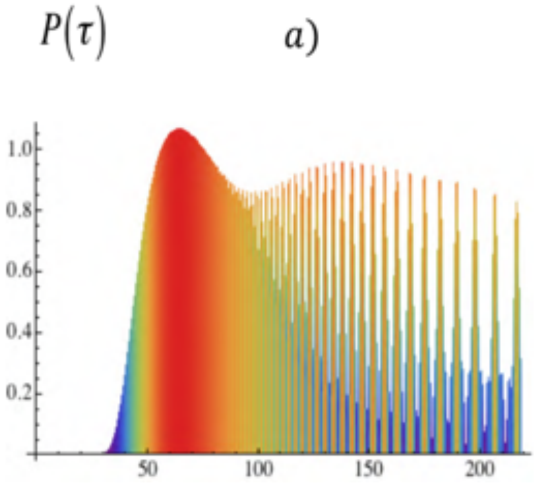


He-Atom

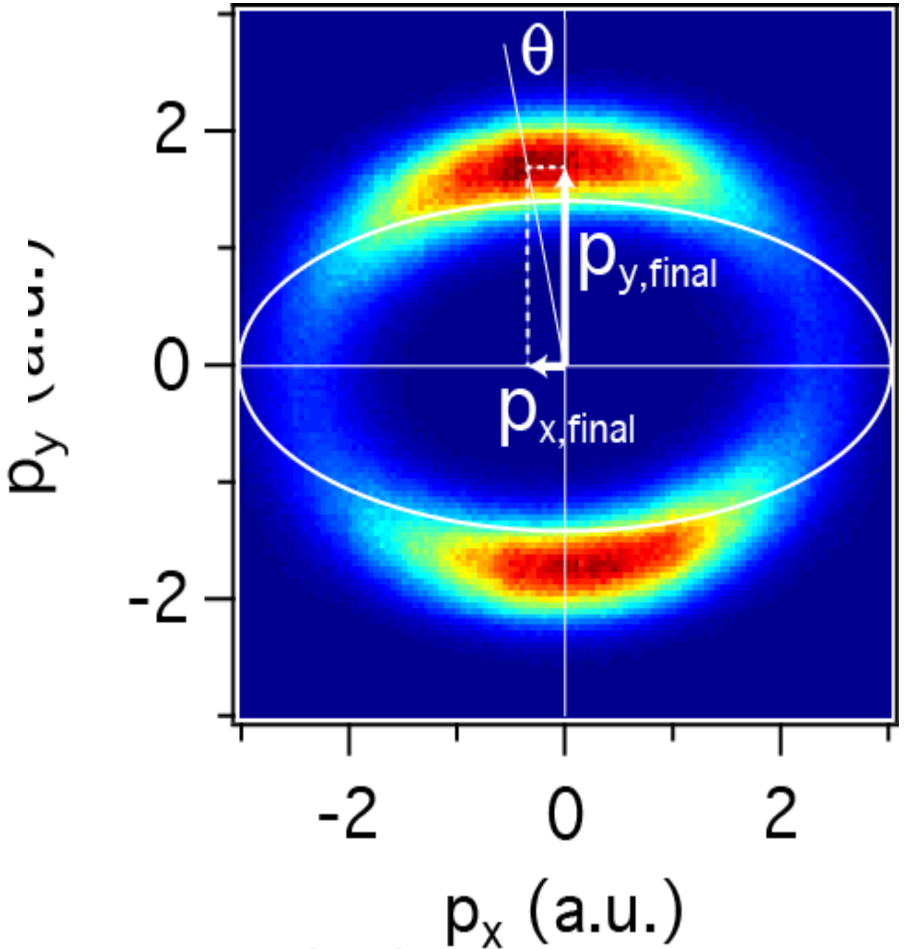


FPI and attoclock are consistent





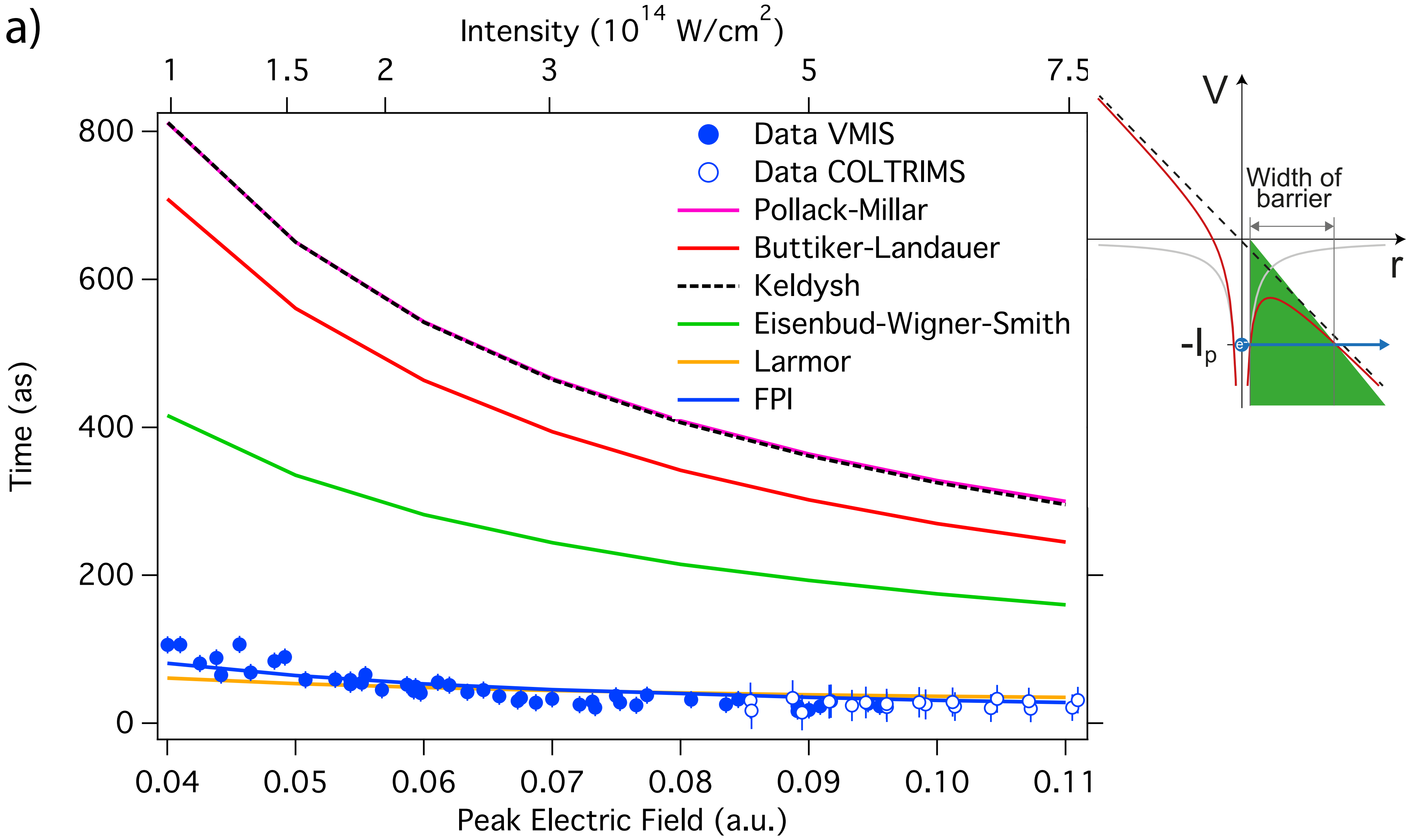
10 kHz laser system



Probability distribution for different tunneling times (FPI):
Peak of this distribution determines the "most probable trajectory" – consistent with the attoclock measurement for "peak search" (i.e. angle with highest count of electron)

Attoclock results from Helium

A. S. Landsman et al., *Optica* 1, 343, 2014



Optische Uhr

- **Gute Zeitauflösung (kurze Laserpulse)**
  Messung von schnellen Prozessen

- **Hohe Pulsrepetitionsrate**
  Frequenzkämme (1-10 GHz)
  Optische Kommunikation
  Optische Taktgeber

- **Hohe Spitzenleistung bei moderaten Energien**
  Nichtlineare Optik
  Materialbearbeitung
  Neue Energiequellen (Laser fusion)

- **Breites optisches Spektrum**
  Frequenzmessung (Frequenzkämme)
  Optische Uhren
  Optische Kohärenz-Tomographie (OCT)

Optische Uhr (>100 THz):

Zeit ist definiert durch eine gewisse Anzahl von Oszillationen innerhalb eines vorgegebenen Zeitintervalls:
„je höher die Oszillationsfrequenz, umso genauer ist die Zeitmessung und damit die Uhr“

- **0.001 Hz**: Sanduhr

- **1 Hz**: Mechanische Uhr

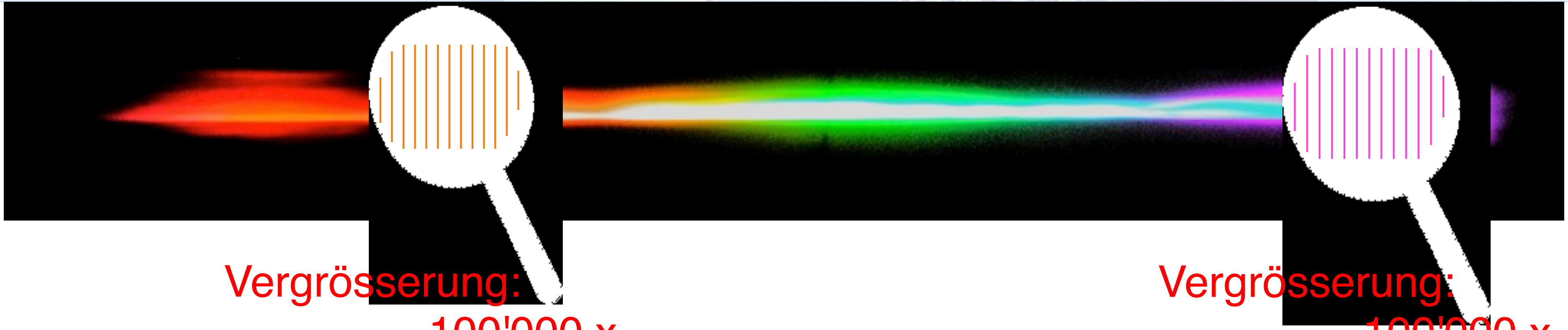
- **10 MHz**: Quarzuhr

Piezoelectric crystal resonator

- **9 GHz**: Atomuhr

GPS

Kurze Pulse und Frequenzmessung



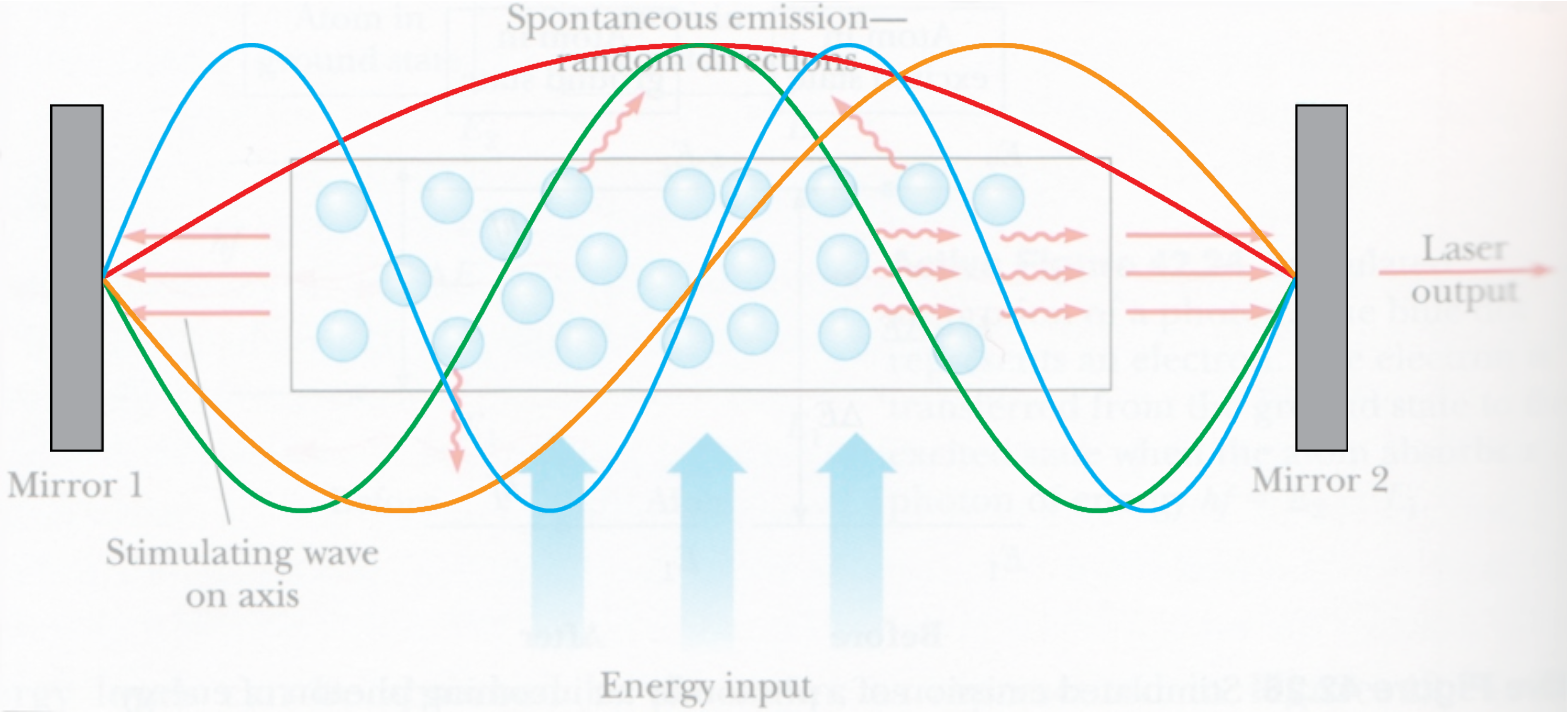
- ◆ Kurze Laserpulse haben ein breites Spektrum
- ◆ Frequenzmessung braucht feine Frequenzlinien

Kurze Pulse für Zeit- und Frequenzmessung – geht das überhaupt?

- ◆ Spektrum von einem Femtosekundenlaser besteht aus Millionen von feinen Linien

... und diese Linien haben überall den gleichen Abstand!

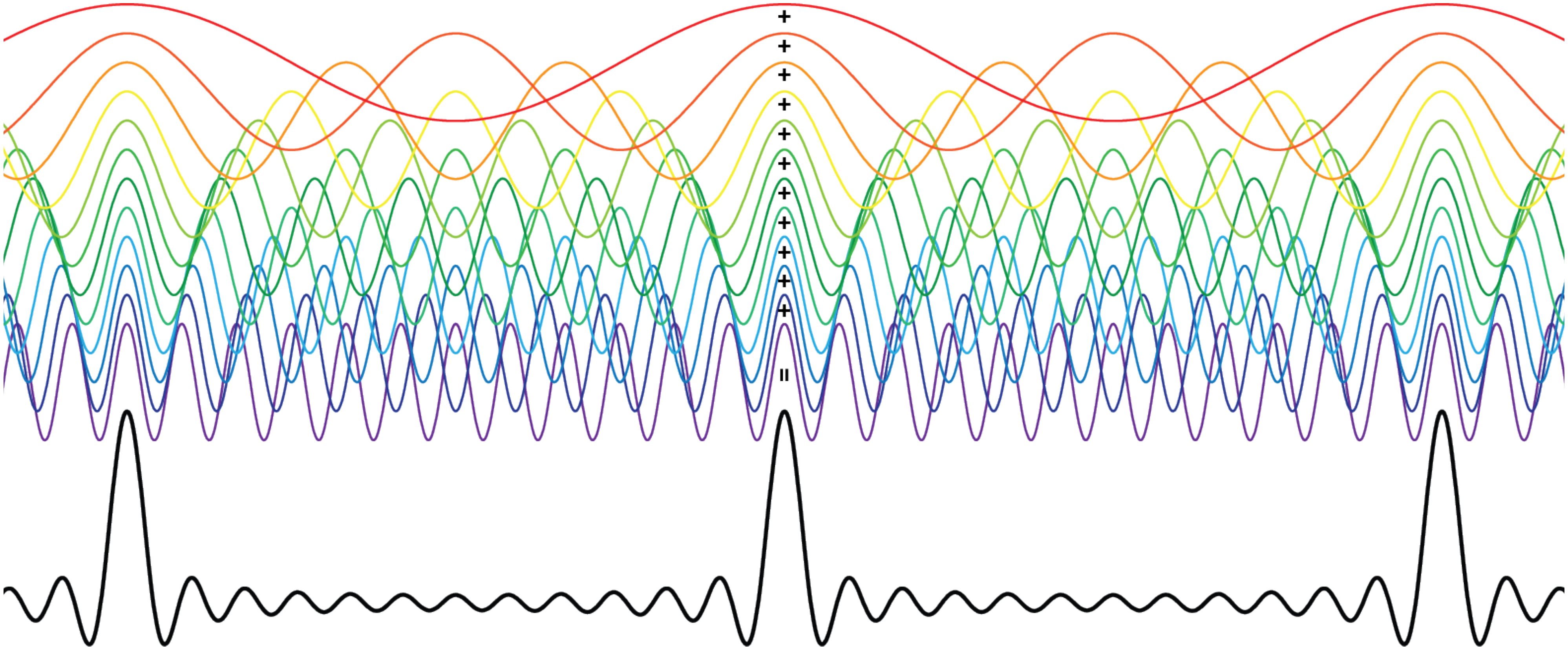
Kurze Lichtpulse aus dem Laser



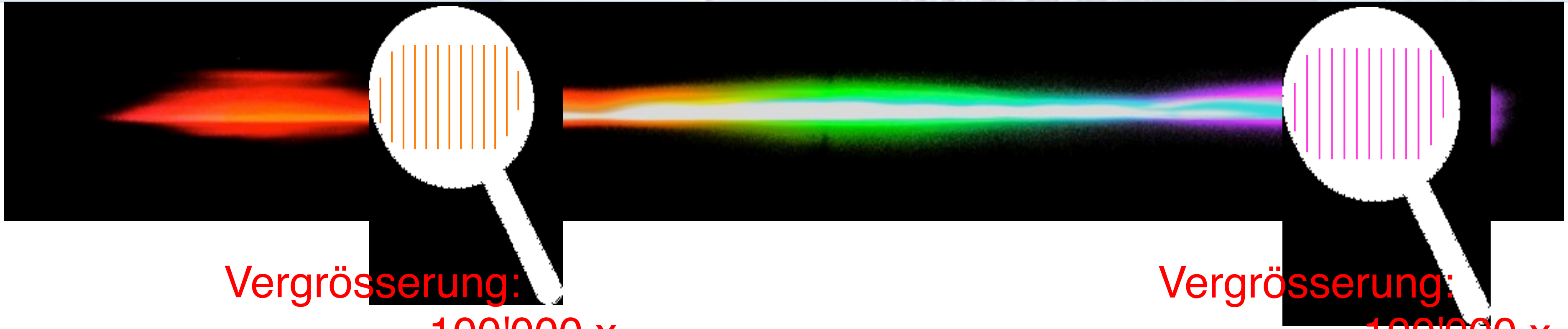
- Es passen nur Lichtwellen mit bestimmten Frequenzen in die Laserkavität (vergl. beidseitig eingespannte Saite)
- Die möglichen Wellen haben einen konstanten Frequenzabstand voneinander

Lichtpulse als Überlagerung vieler Frequenzen

- Ein kontinuierlicher Laser emittiert nur eine oder wenige dieser Frequenzen
- Lichtpulse werden dagegen als Überlagerung von Hundertausenden bis Millionen einzelner Schwingungen erzeugt



Kurze Pulse und Frequenzmessung



Vergrösserung: 100'000 x

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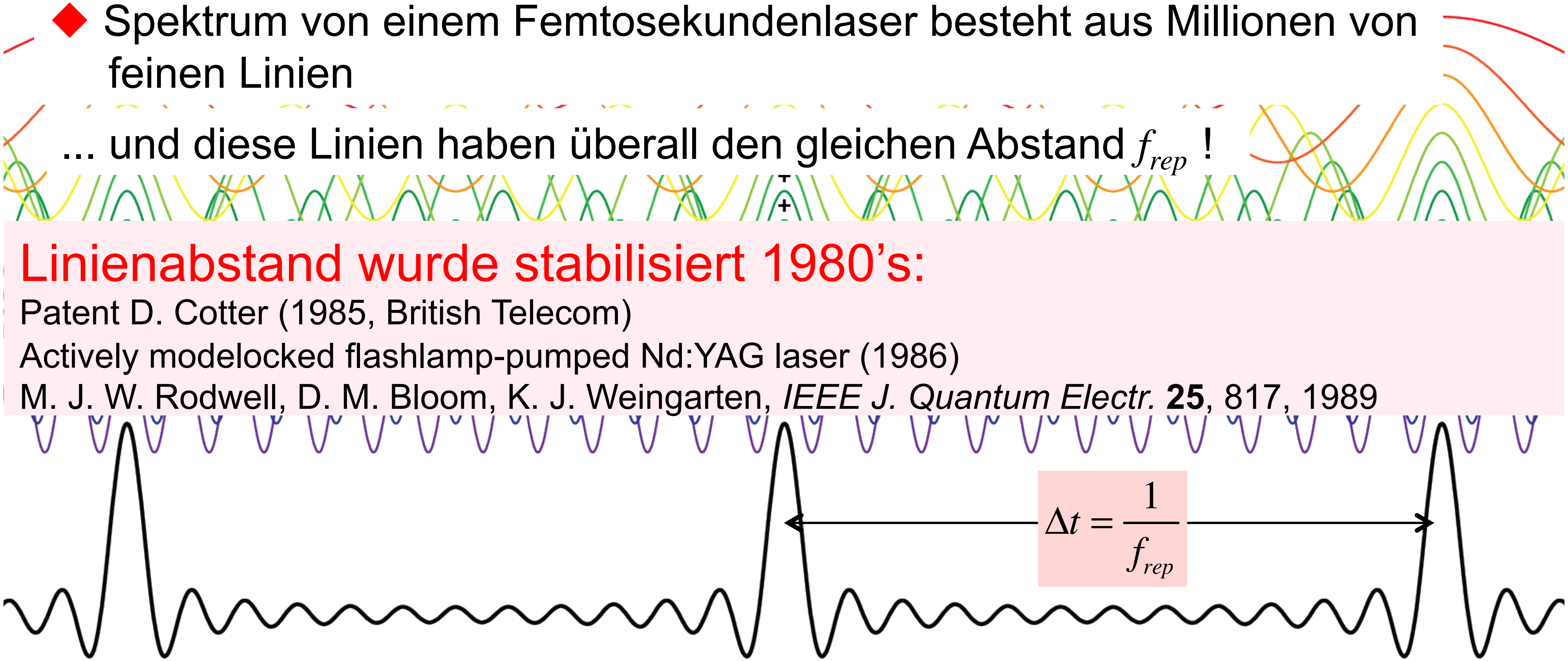


- ◆ Spektrum von einem Femtosekundenlaser besteht aus Millionen von feinen Linien

... und diese Linien haben überall den gleichen Abstand f_{rep} !

Linienabstand wurde stabilisiert 1980's:

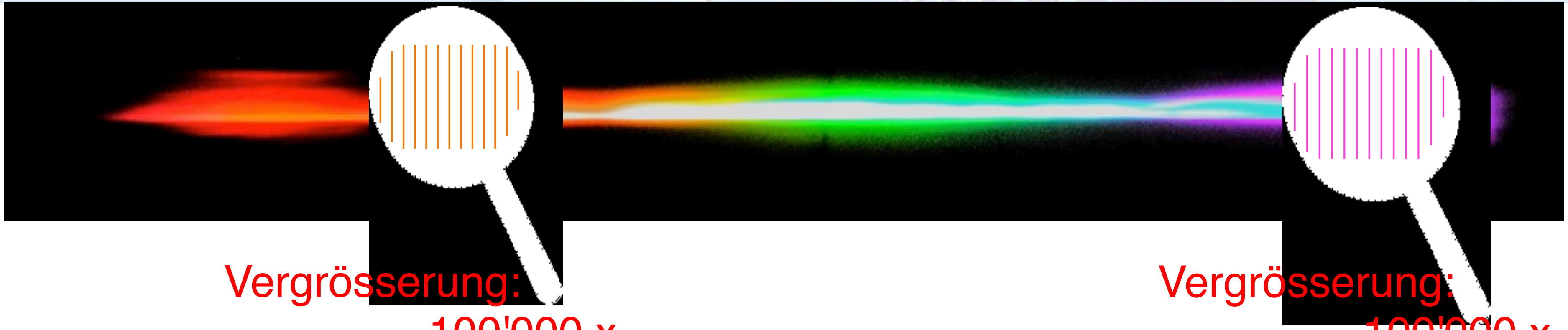
Patent D. Cotter (1985, British Telecom)

Actively modelocked flashlamp-pumped Nd:YAG laser (1986)

M. J. W. Rodwell, D. M. Bloom, K. J. Weingarten, *IEEE J. Quantum Electr.* **25**, 817, 1989

$$\Delta t = \frac{1}{f_{rep}}$$

Kurze Pulse und Frequenzmessung



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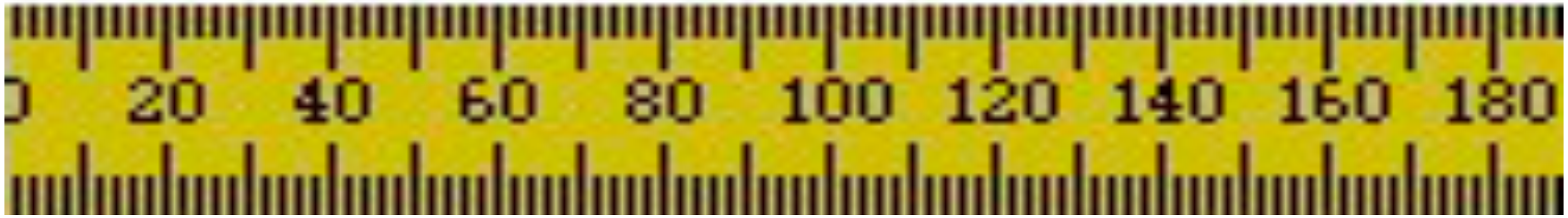


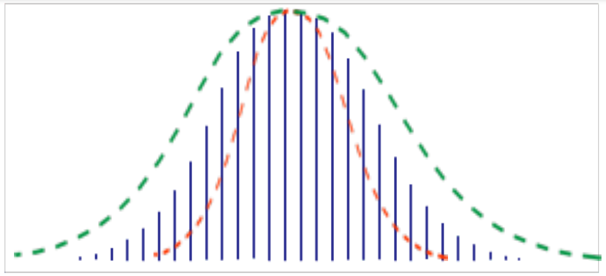
- ◆ **.... aber der „Anfang“ von diesem Lineal war nicht stabilisiert!**

Lösung gefunden 1999:

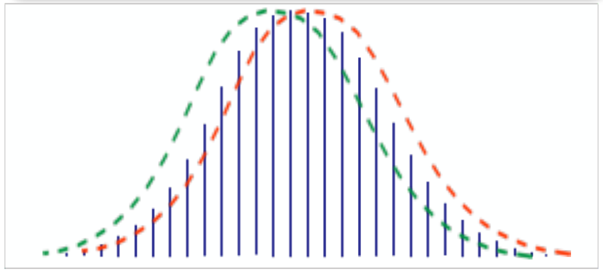
H.R. Telle, G. Steinmeyer, A. E. Dunlop, J. Stenger, D. H. Sutter, U. Keller
Appl. Phys. B **69**, 327 (1999)

Kurze Pulse und Frequenzmessung

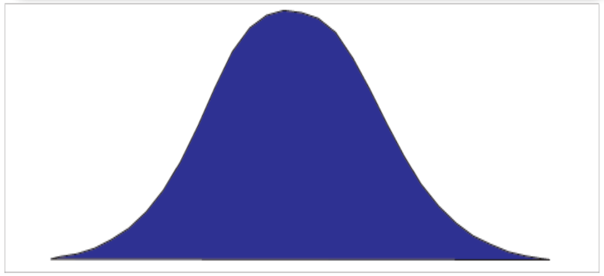
unlocked comb spacing



unlocked comb offset



time average



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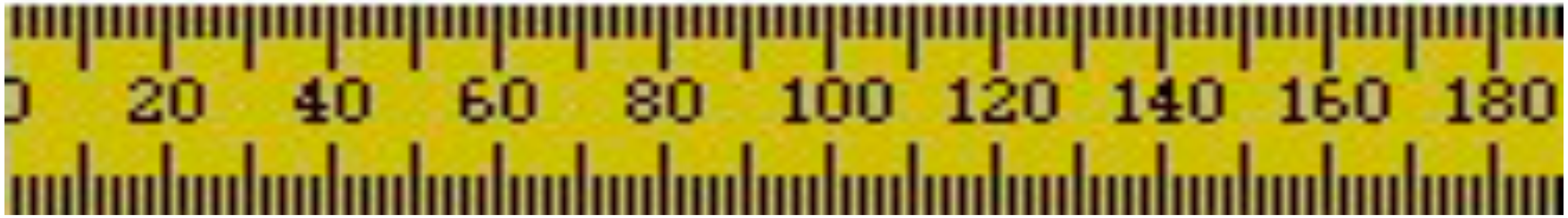

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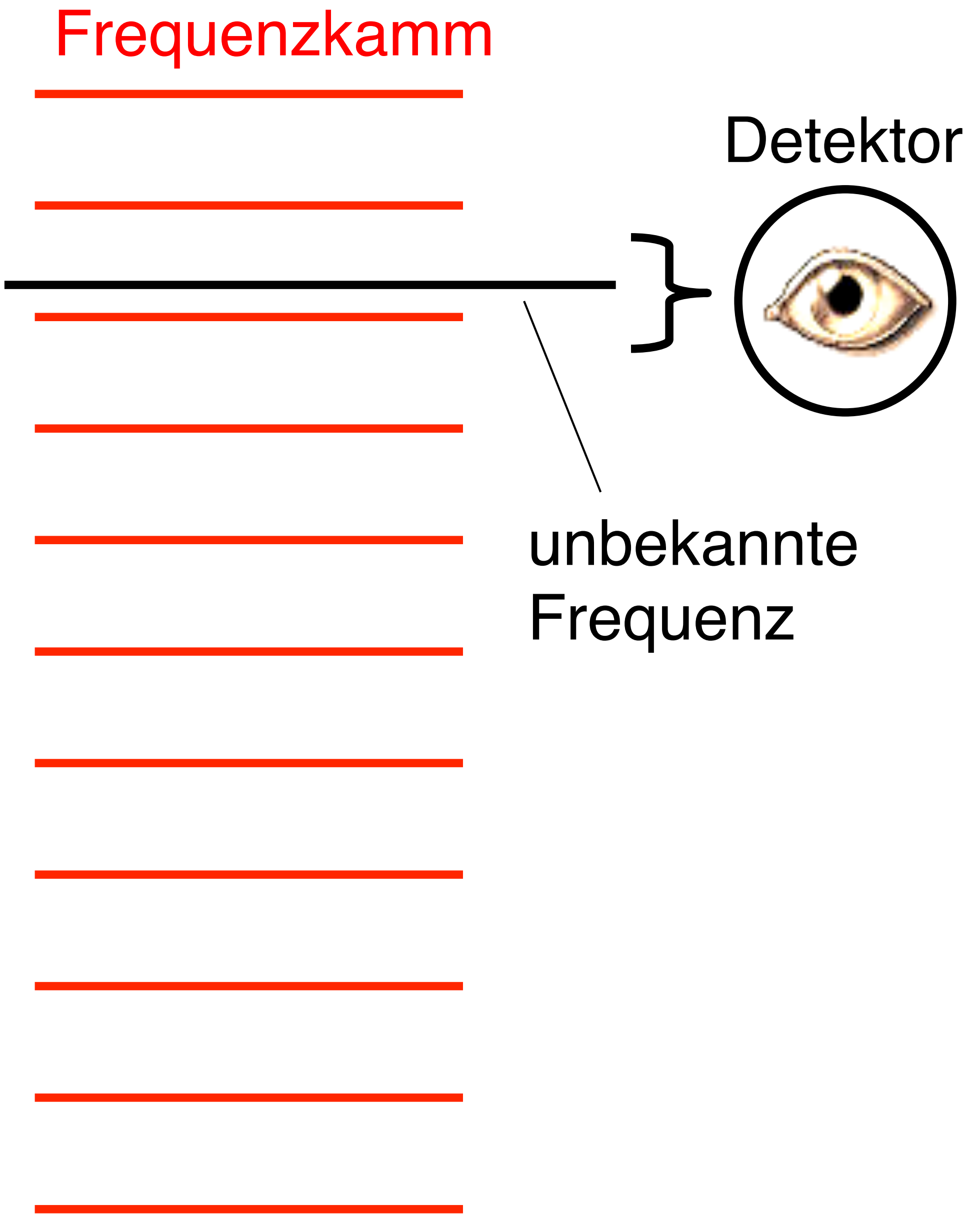
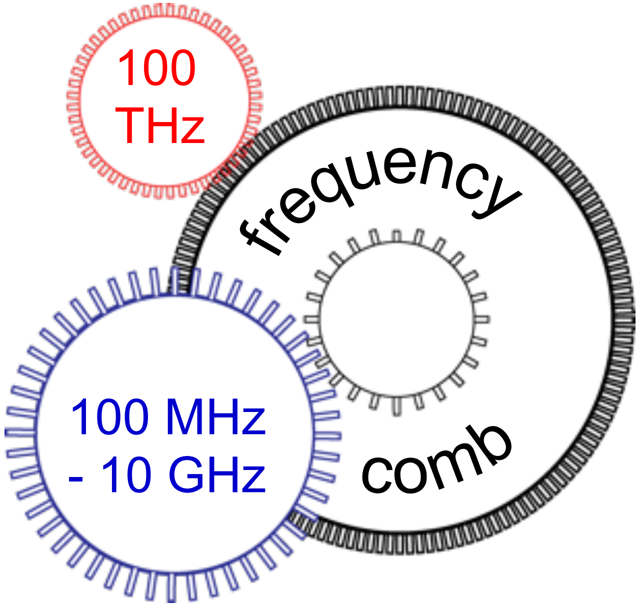
Wie kann ich mit fs-Laser Zeiten messen?



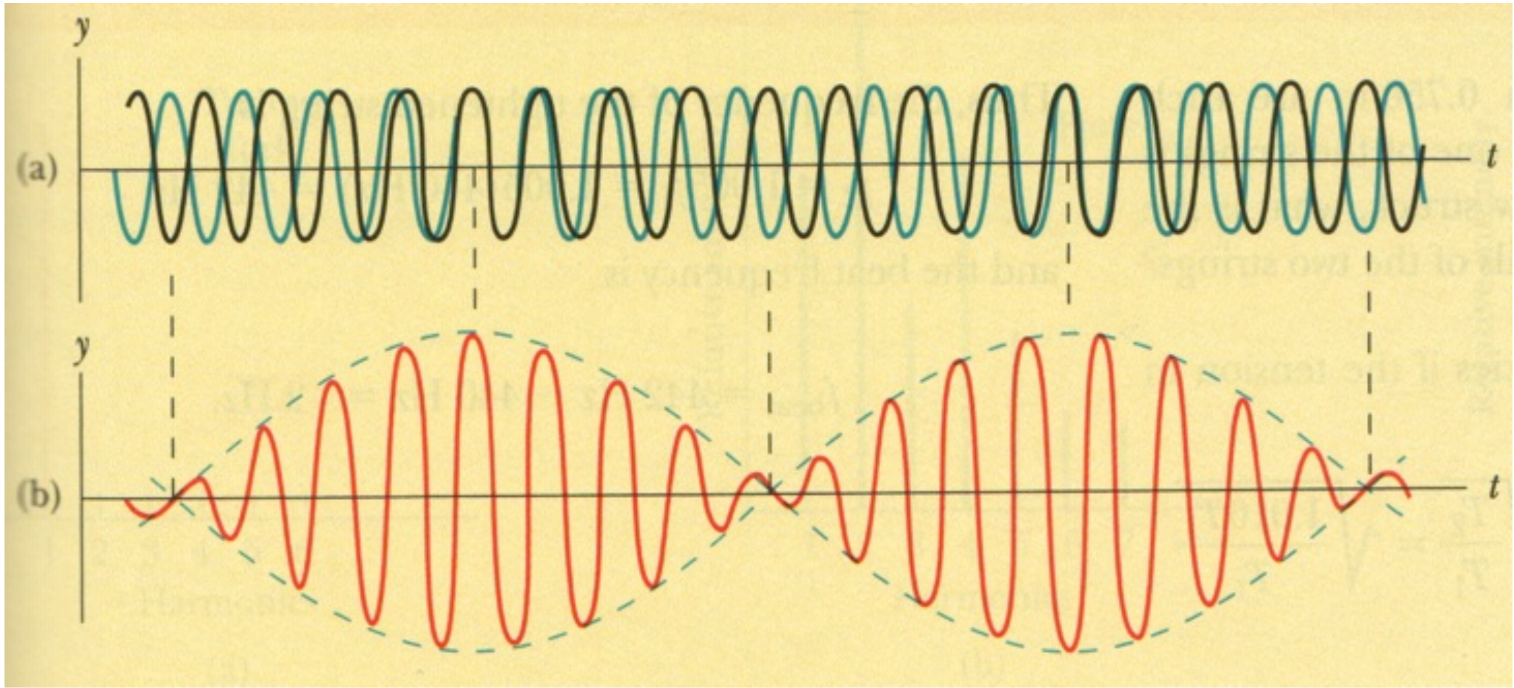
- optische Frequenzen zu hoch für direkte Messung
- Detektor misst Differenzen von Frequenzen = Schwebungssignal



Stimmgabel 1
bei der Frequenz f_1

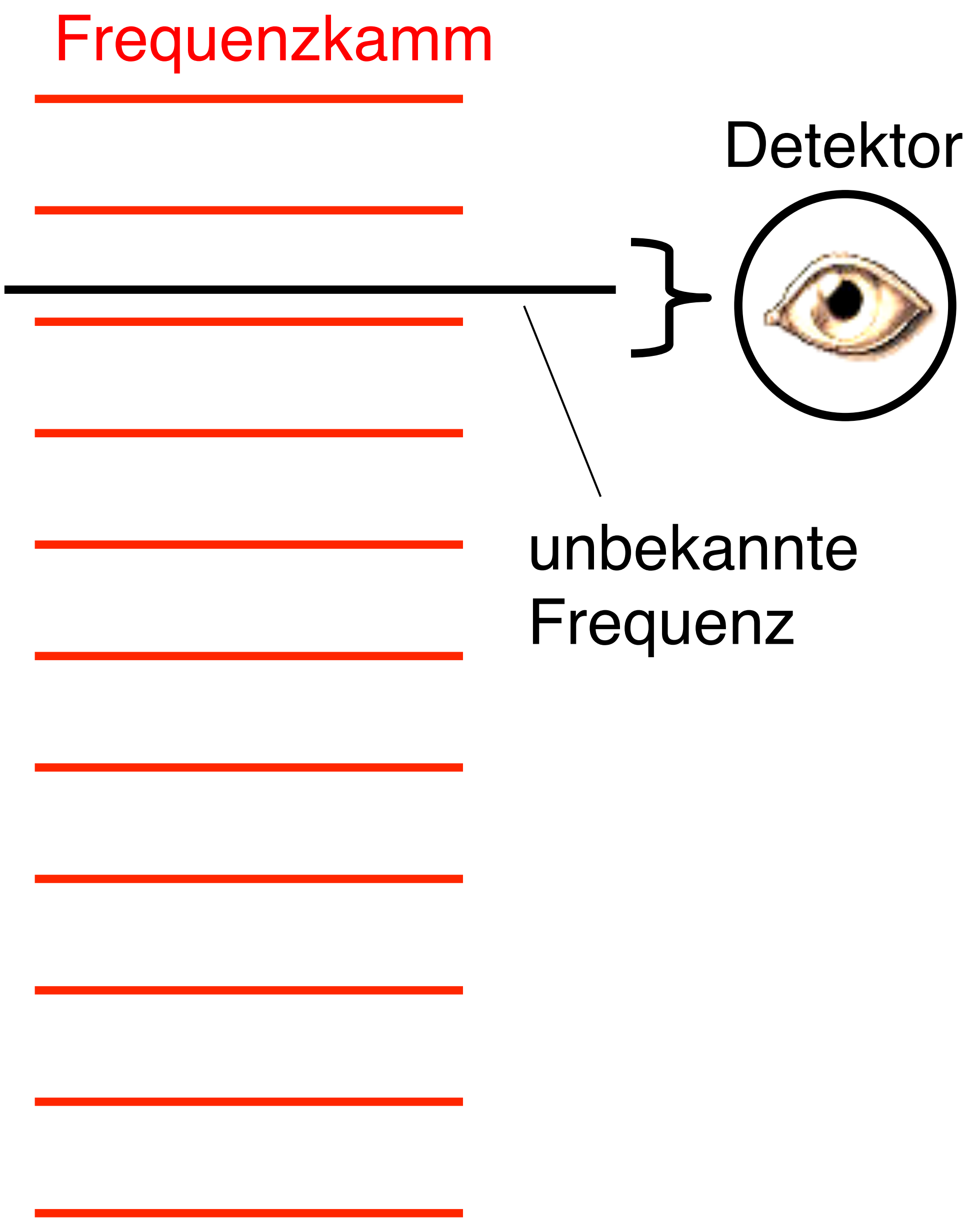
Schwebung

Stimmgabel 2
bei der Frequenz f

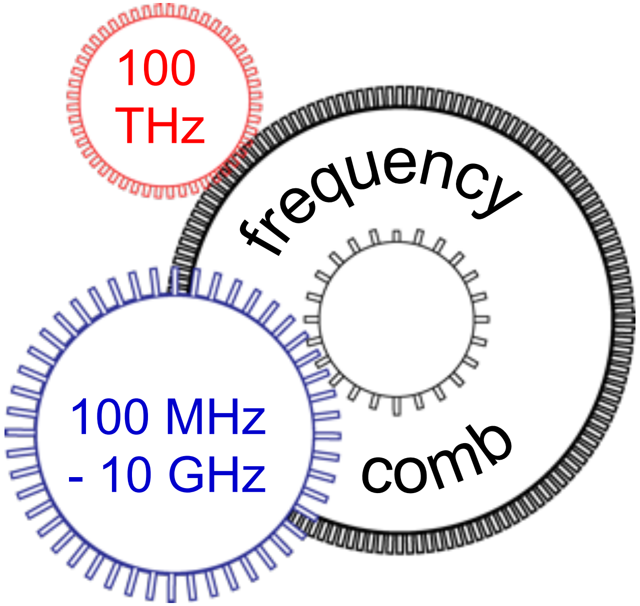


Die Überlagerung zweier benachbarter Frequenzen f_1 und f_2 auf einer Photodiode ergibt ein Schwebungssignal bei der Differenzfrequenz $f_1 - f_2$

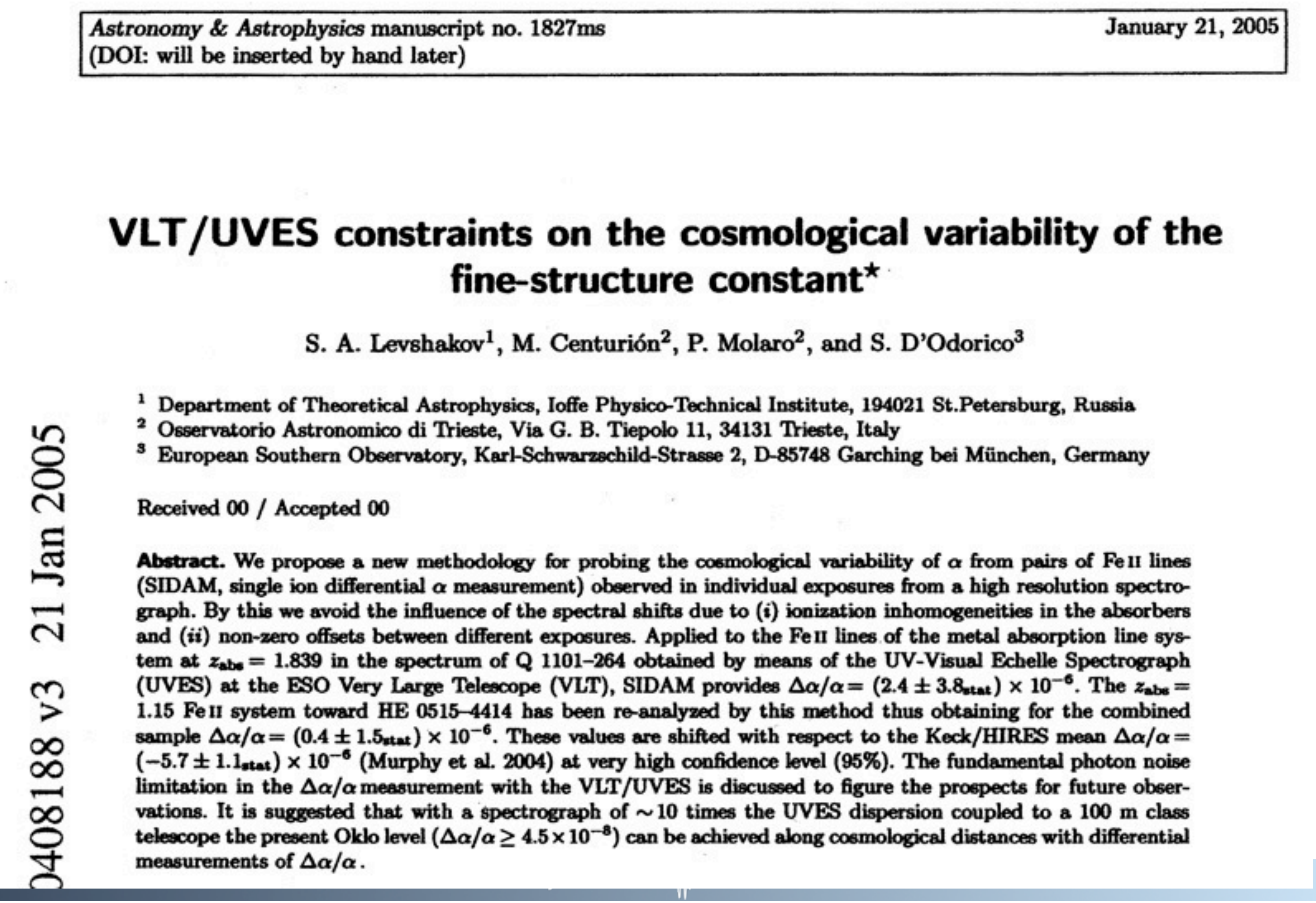
Wie kann ich mit fs-Laser Zeiten messen?



- optische Frequenzen zu hoch für direkte Messung
- Detektor misst Differenzen von Frequenzen = Schwebungssignal
- Messung des Abstandes unbekannte Frequenz – Kammlinie
- optische Frequenz wird zählbar
- damit Zeitmessung



Naturkonstanten wirklich konstant?



Astronomy & Astrophysics manuscript no. 1827ms
(DOI: will be inserted by hand later)
January 21, 2005

0408188 v3 21 Jan 2005

VLT/UVES constraints on the cosmological variability of the fine-structure constant*

S. A. Levshakov[1], M. Centurión[2], P. Molaro[2], and S. D'Odorico[3]

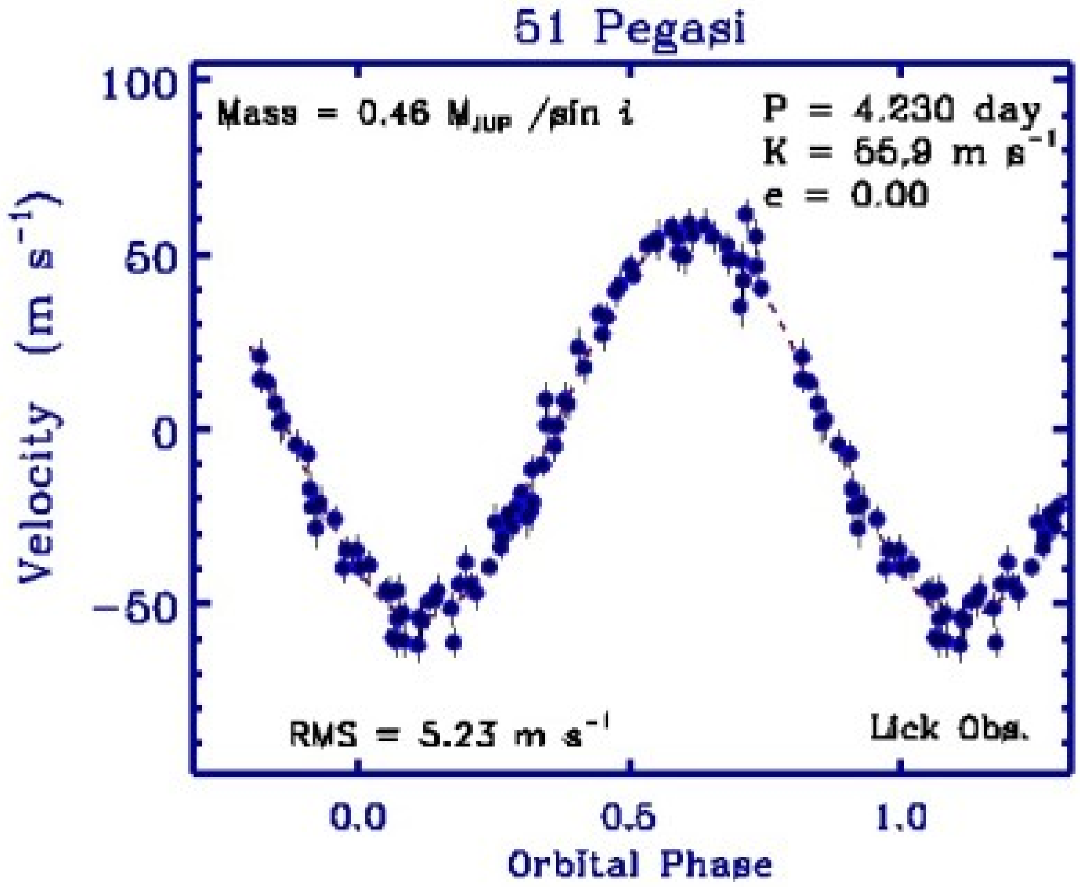
[1] Department of Theoretical Astrophysics, Ioffe Physico-Technical Institute, 194021 St.Petersburg, Russia
[2] Osservatorio Astronomico di Trieste, Via G. B. Tiepolo 11, 34131 Trieste, Italy
[3] European Southern Observatory, Karl-Schwarzschild-Strasse 2, D-85748 Garching bei München, Germany

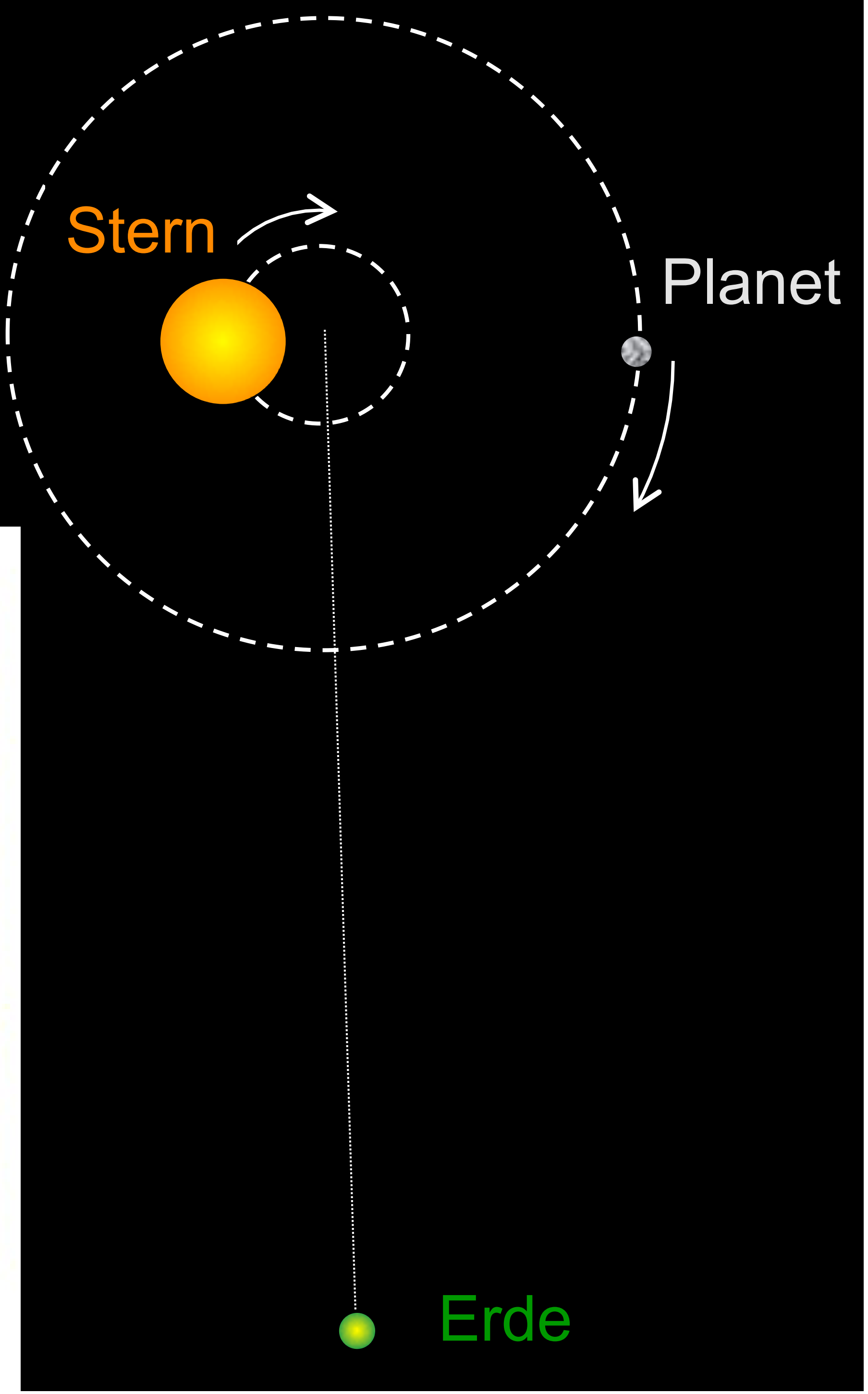
Received 00 / Accepted 00

Abstract. We propose a new methodology for probing the cosmological variability of α from pairs of Fe II lines (SIDAM, single ion differential α measurement) observed in individual exposures from a high resolution spectrograph. By this we avoid the influence of the spectral shifts due to (*i*) ionization inhomogeneities in the absorbers and (*ii*) non-zero offsets between different exposures. Applied to the Fe II lines of the metal absorption line system at $z_{\rm abs} = 1.839$ in the spectrum of Q 1101–264 obtained by means of the UV-Visual Echelle Spectrograph (UVES) at the ESO Very Large Telescope (VLT), SIDAM provides $\Delta\alpha/\alpha = (2.4 \pm 3.8_{\rm stat}) \times 10^{-6}$. The $z_{\rm abs} = 1.15$ Fe II system toward HE 0515–4414 has been re-analyzed by this method thus obtaining for the combined sample $\Delta\alpha/\alpha = (0.4 \pm 1.5_{\rm stat}) \times 10^{-6}$. These values are shifted with respect to the Keck/HIRES mean $\Delta\alpha/\alpha = (-5.7 \pm 1.1_{\rm stat}) \times 10^{-6}$ (Murphy et al. 2004) at very high confidence level (95%). The fundamental photon noise limitation in the $\Delta\alpha/\alpha$ measurement with the VLT/UVES is discussed to figure the prospects for future observations. It is suggested that with a spectrograph of $\sim$10 times the UVES dispersion coupled to a 100 m class telescope the present Oklo level ($\Delta\alpha/\alpha \geq 4.5 \times 10^{-8}$) can be achieved along cosmological distances with differential measurements of $\Delta\alpha/\alpha$.

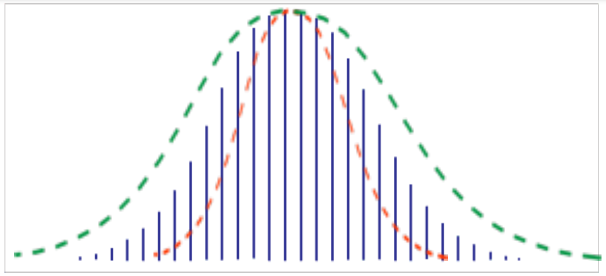
Entdeckung von Planeten

Prof. Michel Mayor, Uni Genf

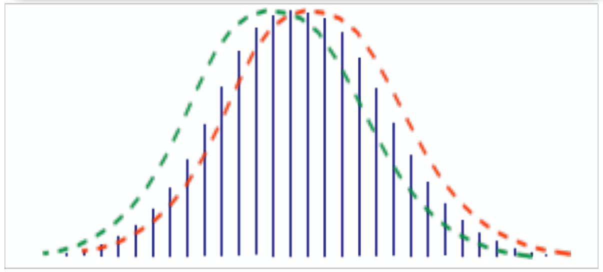




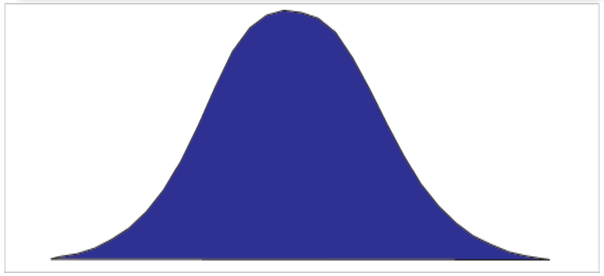
Wie kann ich den Frequenzkamm stabilisieren?



unlocked comb spacing

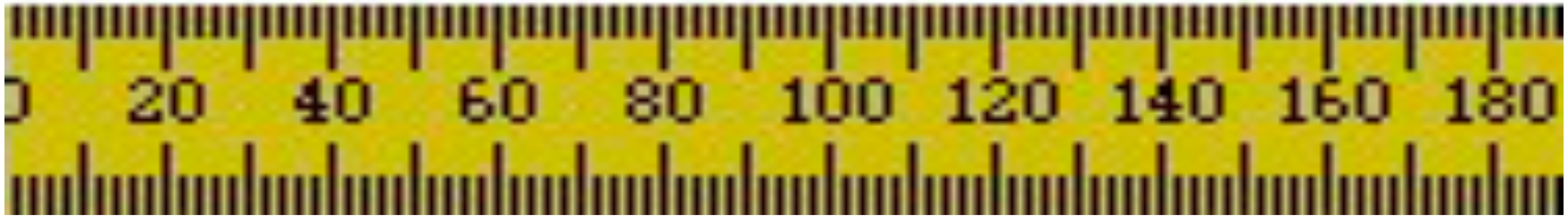


unlocked comb offset



time average

- Femtosekundenlaser ist für die Frequenzen wie ein Lineal für Längen



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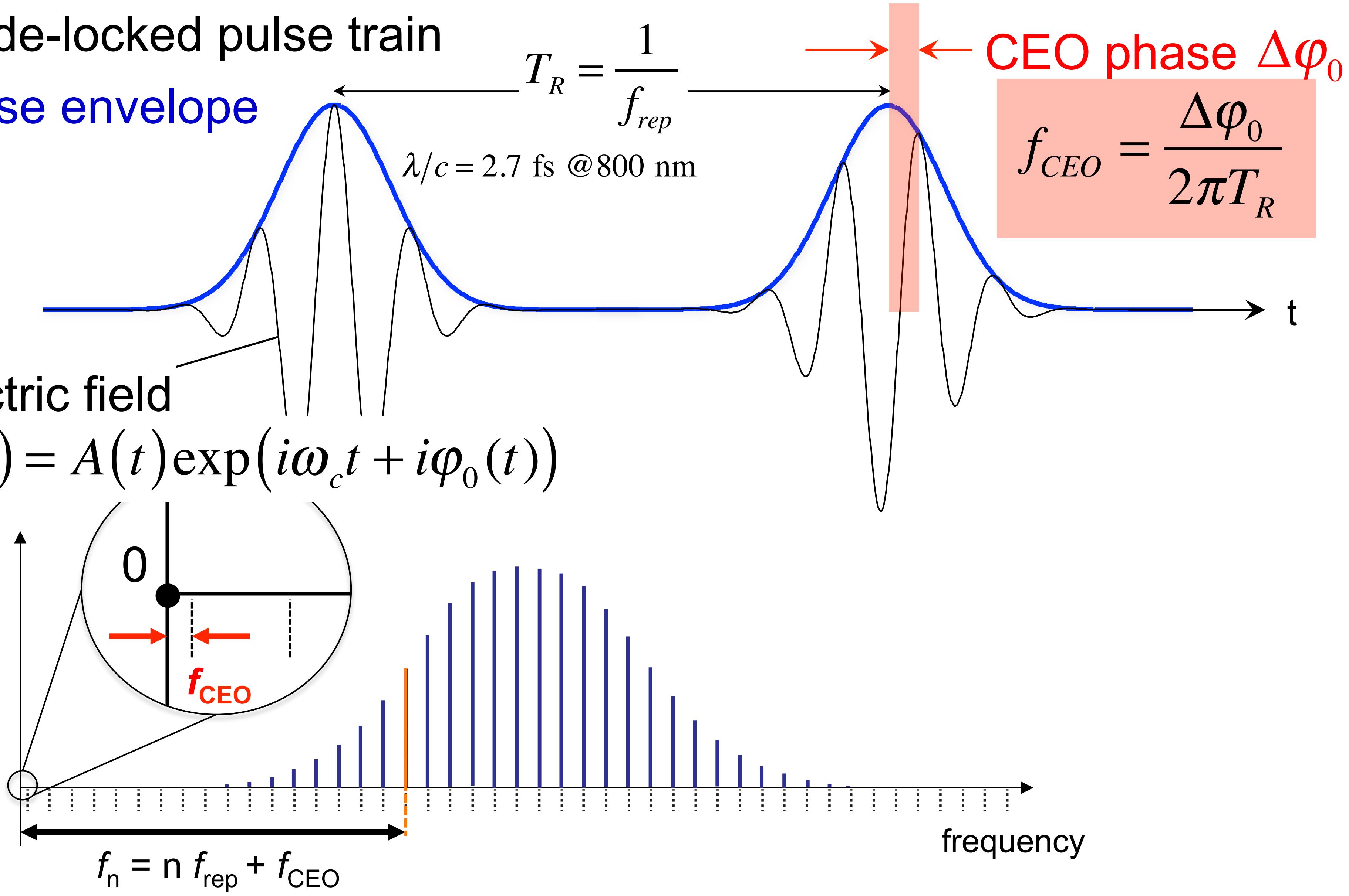
Carrier Envelope Offset (CEO)



Mode-locked pulse train

$$T_R = \frac{1}{f_{rep}}$$

Pulse envelope

$A(t)$

$\lambda/c = 2.7$ fs @800 nm

CEO phase $\Delta\varphi_0$

$$f_{CEO} = \frac{\Delta\varphi_0}{2\pi T_R}$$

Electric field

$$E(t) = A(t)\exp\left(i\omega_c t + i\varphi_0(t)\right)$$

f_{CEO}

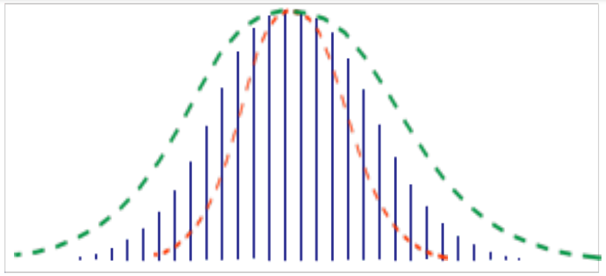
$f_n = n\, f_{rep} + f_{CEO}$

H.R. Telle, G. Steinmeyer, A.E. Dunlop, J. Stenger, D.H. Sutter and U. Keller, Appl. Phys. B 69, 327 (1999)

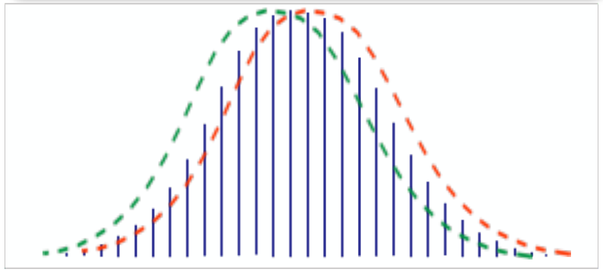
Frequency combs from modelocked lasers

free-running passively modelocked laser

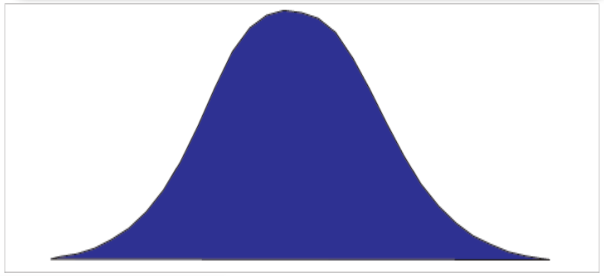
unlocked repetition rate: f_{rep}



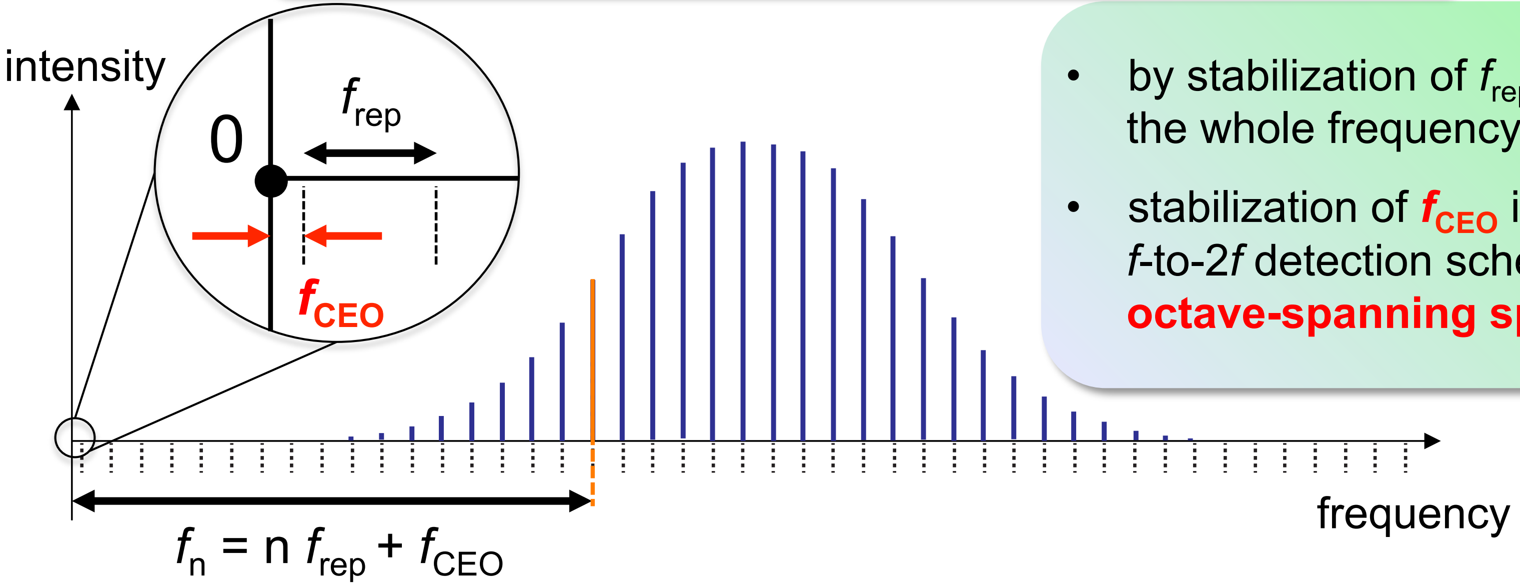
unlocked CEO: f_{CEO}



time average



phase-locked passively modelocked laser



- by stabilization of f_{rep} and f_{CEO}, the whole frequency comb is locked!
- stabilization of f_{CEO} is challenging: *f*-to-2*f* detection scheme [1] requires **octave-spanning spectrum**

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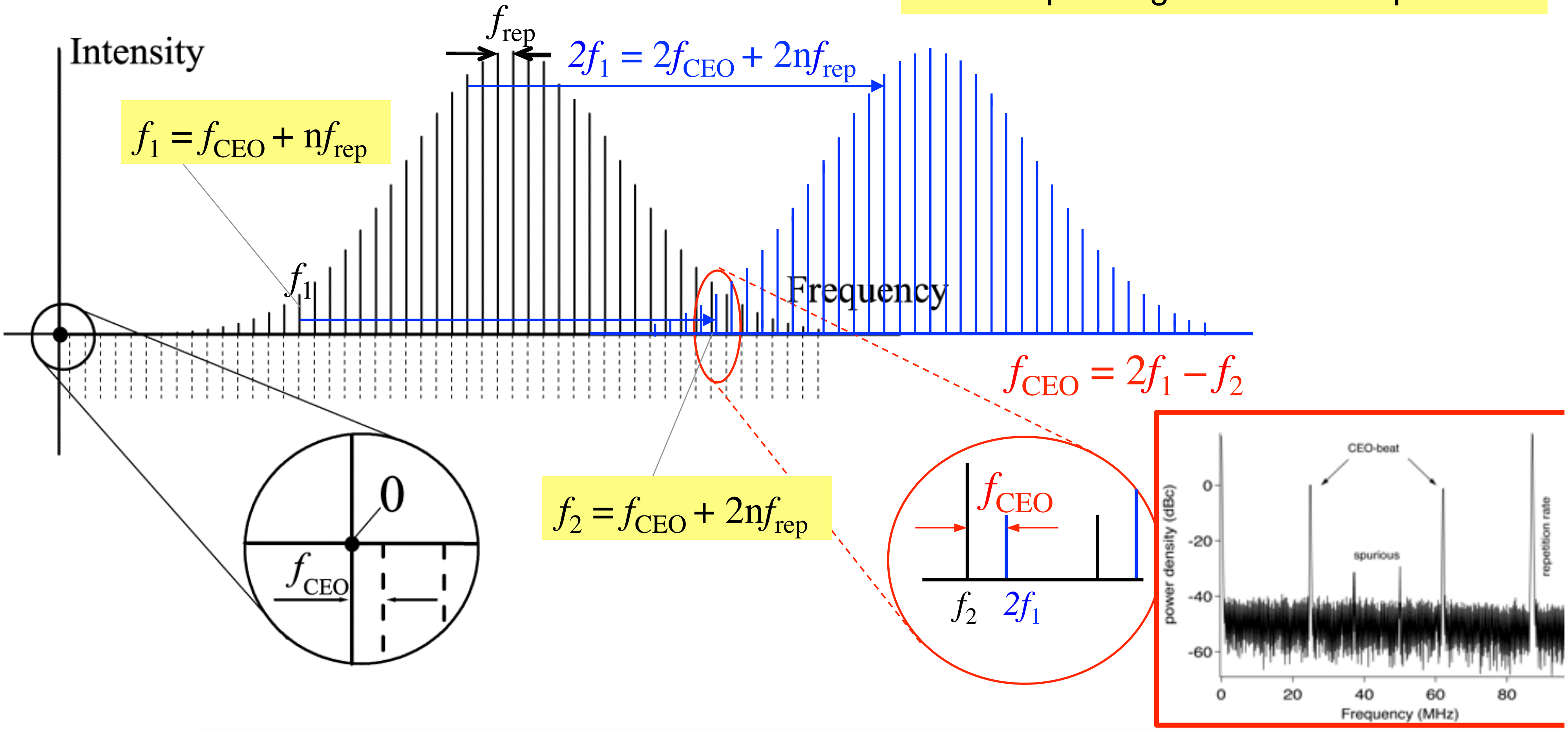
[1] comb self-referencing: H.R. Telle, G. Steinmeyer, A.E. Dunlop, J. Stenger, D.H. Sutter and U. Keller, Appl. Phys. B 69, 327 (1999)

How can we measure the frequency comb offset ?

f_{rep} : pulse repetition rate frequency , f_{CEO} : carrier envelope offset frequency

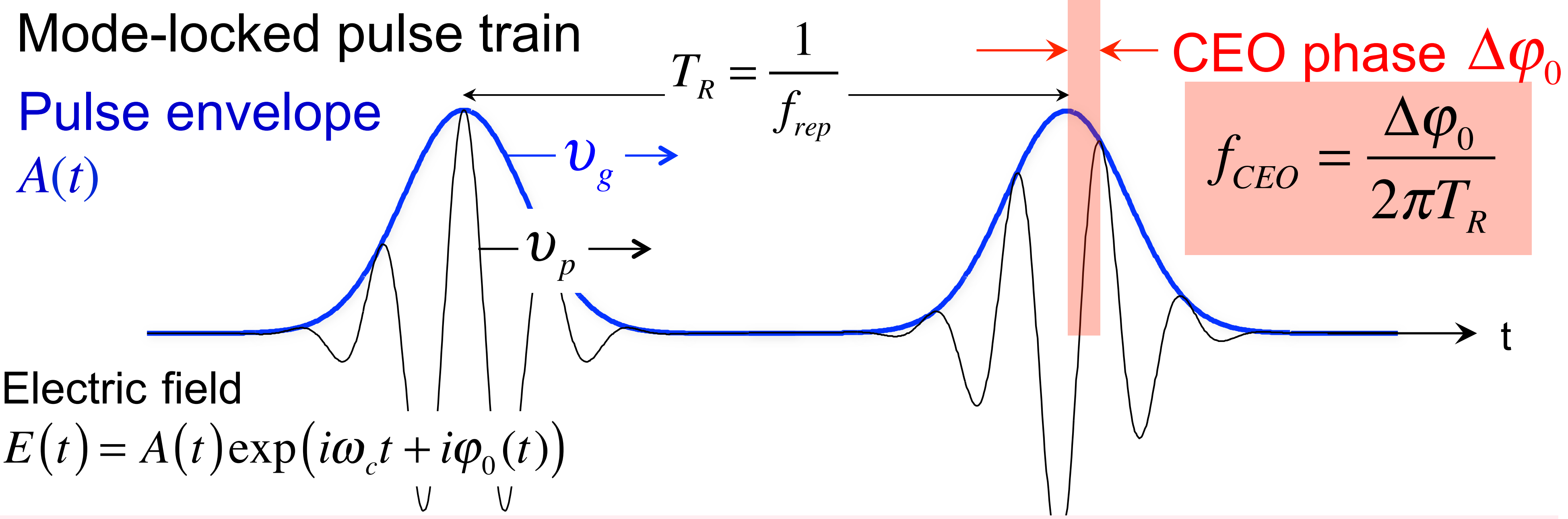
octave spanning modelocked spectrum



Mode beating of fundamental and second harmonic frequency comb
f-to-*2f* interference technique: $f_{\text{CEO}} = 2f_1 - f_2$

H.R. Telle, G. Steinmeyer, A. E. Dunlop, J. Stenger, D. H. Sutter, U. Keller, *Appl. Phys. B* **69**, 327 (1999)

How can we stabilize the frequency comb offset ?



Mode-locked pulse train

Pulse envelope $A(t)$

v_g

v_p

$T_R = \frac{1}{f_{rep}}$

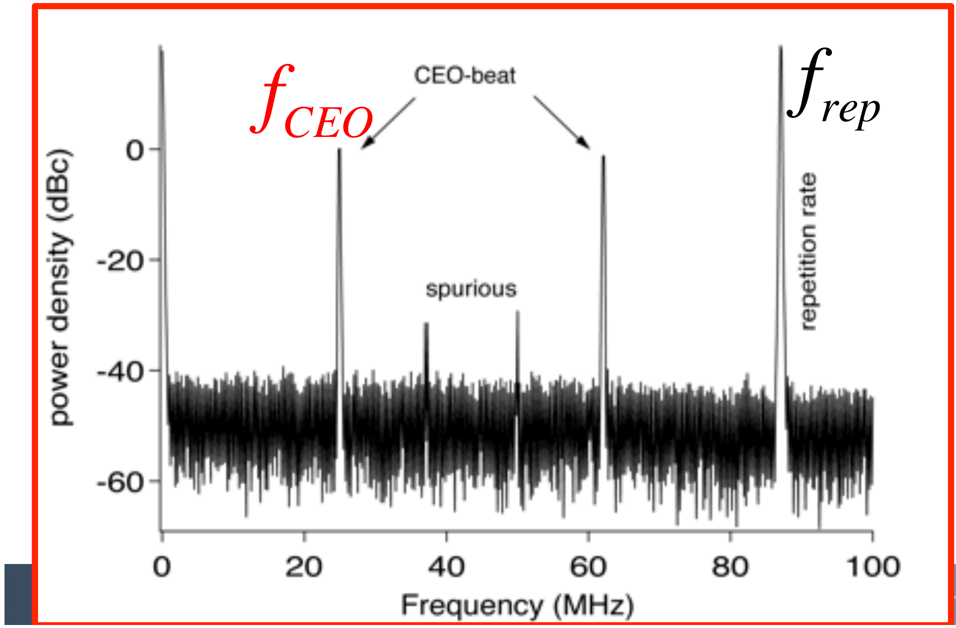
CEO phase $\Delta\varphi_0$

$$f_{CEO} = \frac{\Delta\varphi_0}{2\pi T_R}$$

Electric field

$$E(t) = A(t)\exp\left(i\omega_c t + i\varphi_0(t)\right)$$

Mode beating measured with a simple photodetector and observed on an microwave spectrum analyzer

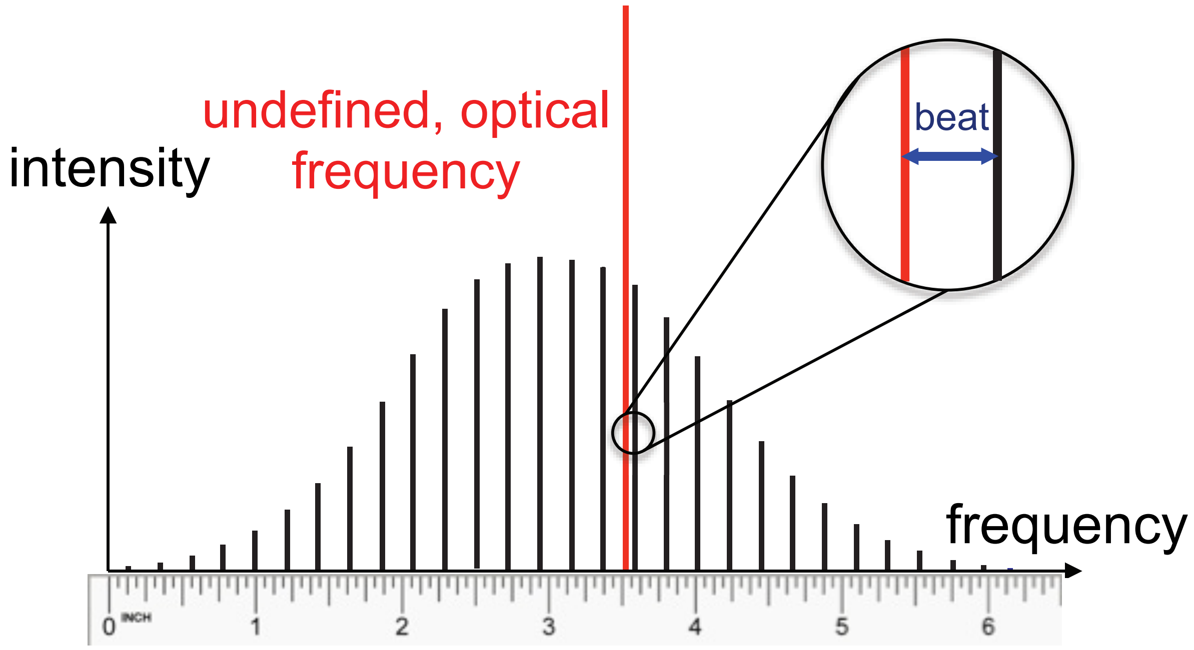


Anything where

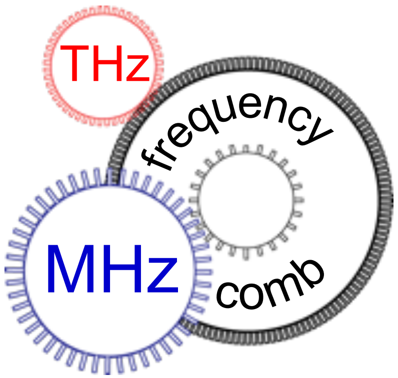
$$\Delta v_p \neq \Delta v_g$$

inside the modelocked laser

Optical Frequency Combs

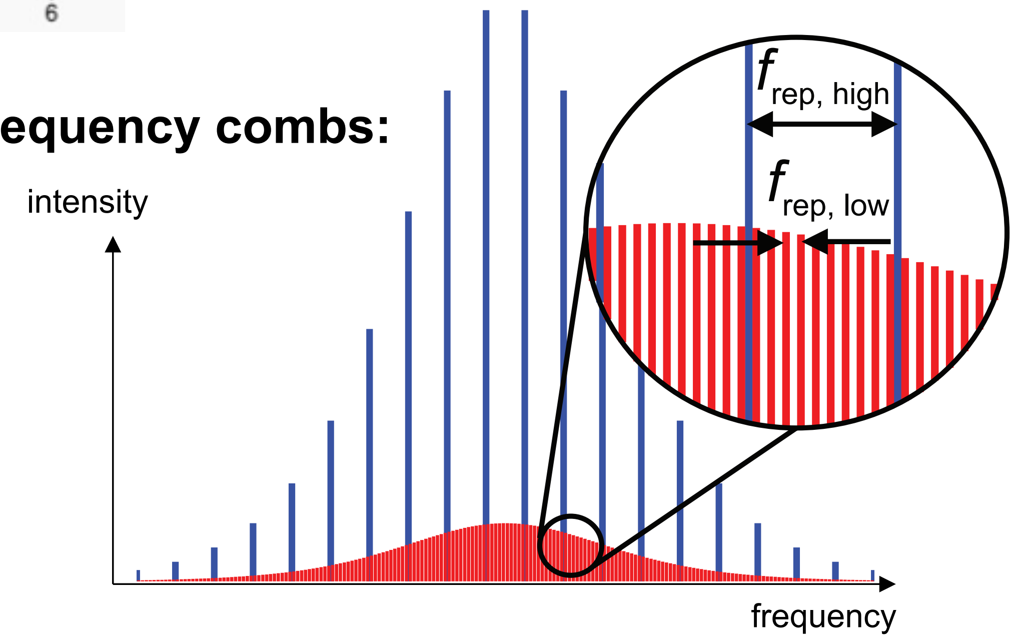


phase-stable link:
optical to microwave



High gigahertz pulse repetition rate frequency combs:

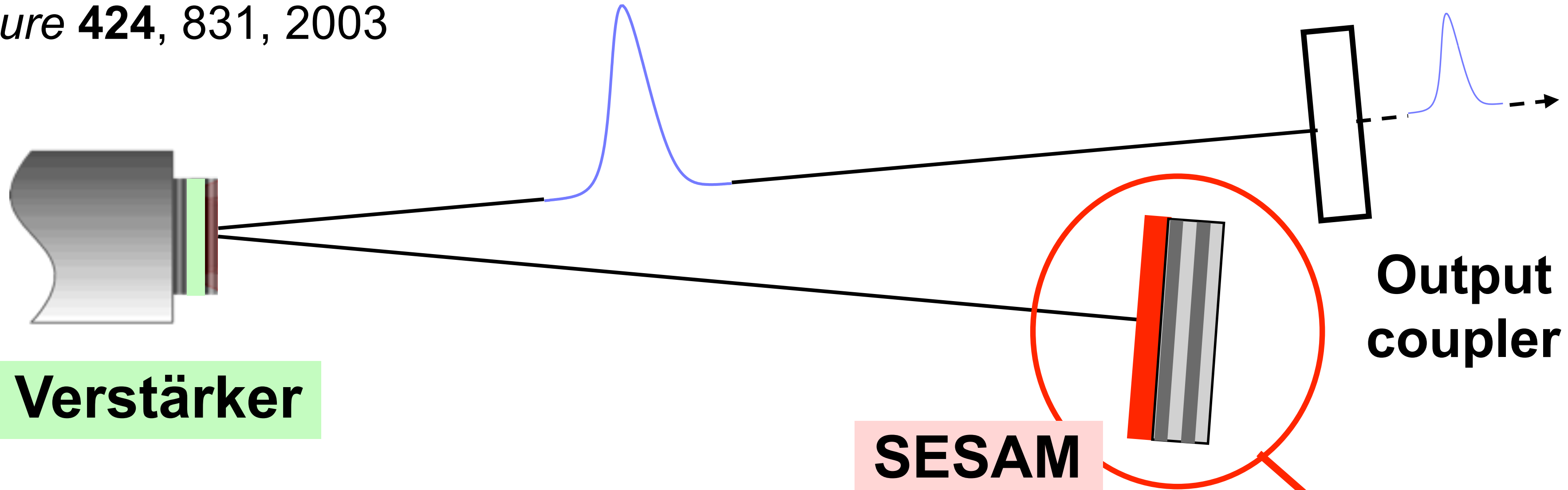
- higher power per mode
- easier to access individual lines
- more compact laser system

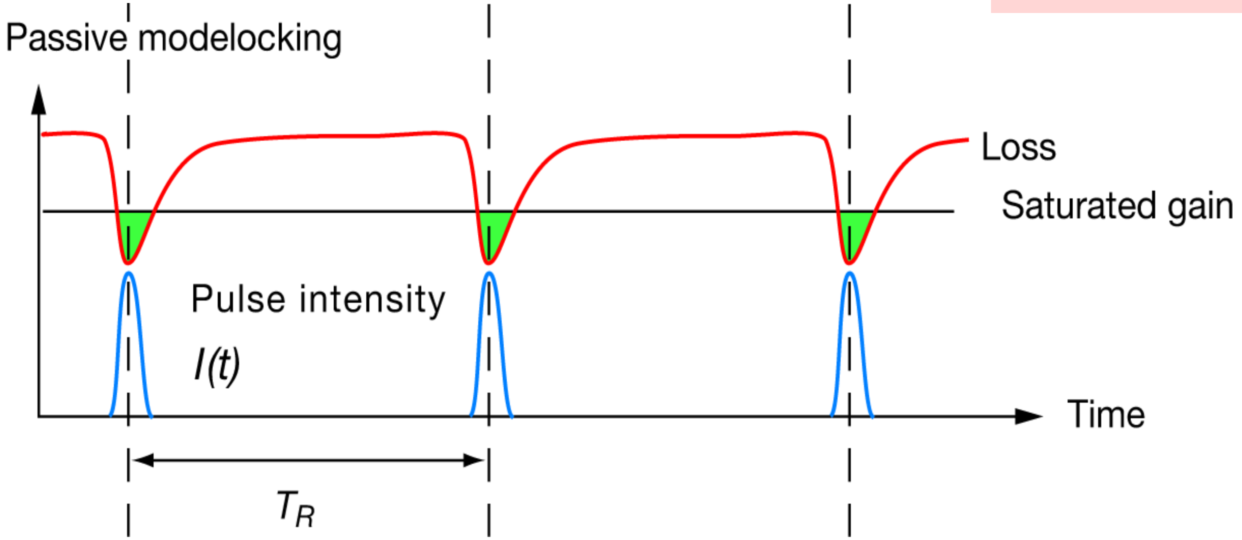


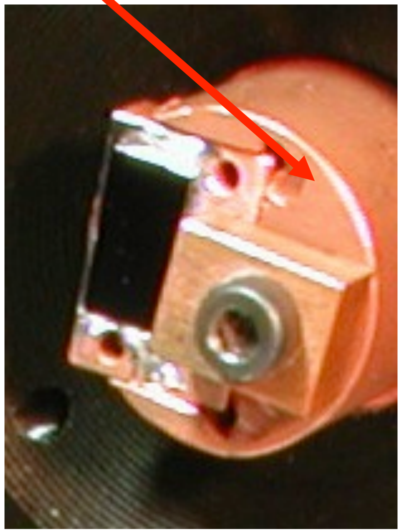
SESAM macht kurze Pulse

U. Keller et al. *Opt. Lett.* **17**, 505, 1992
IEEE JSTQE **2**, 435, 1996
Progress in Optics **46**, 1-115, 2004
Nature **424**, 831, 2003

www.ulp.ethz.ch/research/Sesam



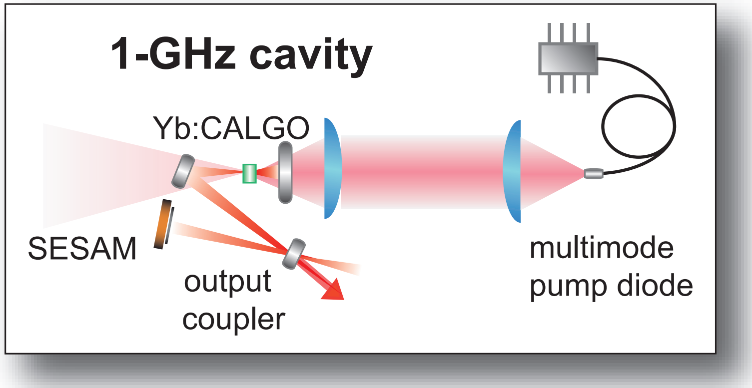


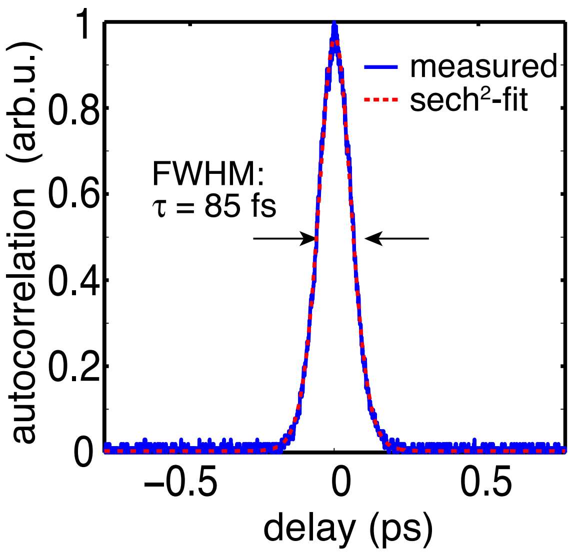


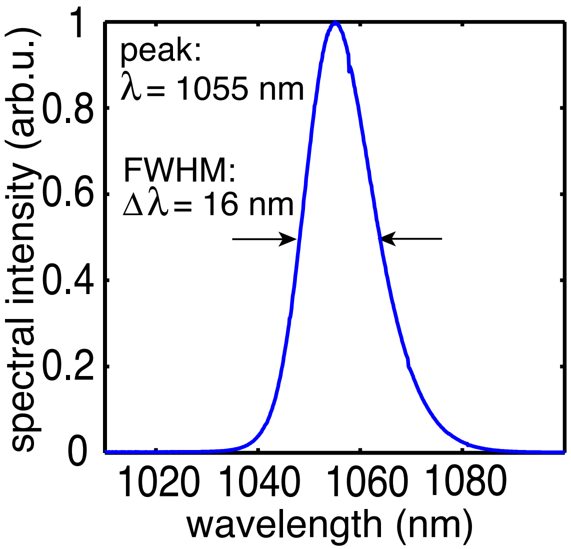
1-GHz Yb:CALGO Laser

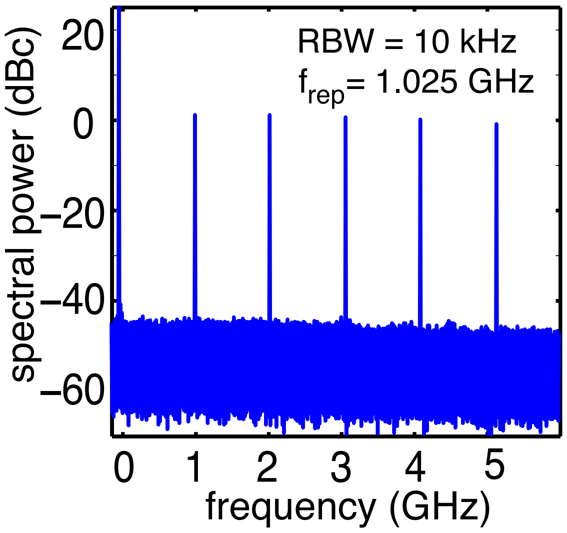
1-GHz SESAM-modelocked diode-pumped solid state laser

Repetition Rate	1.025 GHz
Gain Medium	2-mm Yb:CALGO
Output Power	< 1.7 W
Center Wavelength	1055 nm
Pulse Durations	> 63 fs









A. Klenner, S. Schilt, T. Südmeyer, and U. Keller, Opt. Express **22**, 31008-31019 (2014)

Si_3N_4 waveguide

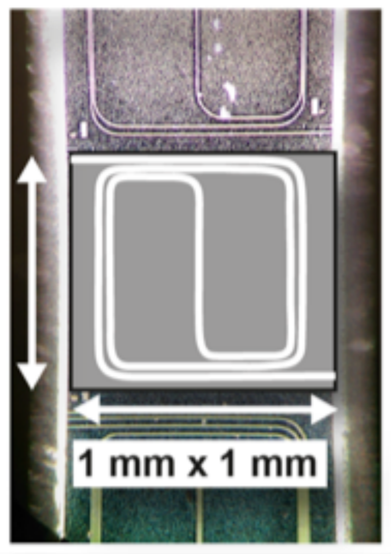
Silicon Nitride (Si_3N_4)

- VIS to 6 µm, negligible two-photon absorption at 1 µm
- 10 times higher nonlinear index n_2 than silica
- CMOS-compatible

D. J. Moss, R. Morandotti, A. L. Gaeta, and M. Lipson, Nature Photon. **7**, 597-607 (2013)

Our Si_3N_4 Waveguide:

Substrate:	Oxide-clad Silicon
Top-Cladding:	SiO_2
Cross section:	690 nm x 900 nm
Length:	7.5 mm
Bend radius:	> 100 µm
Nonlin. coeff.:	$\gamma = 3.25\ W^{-1}m^{-1}$ @1055 nm



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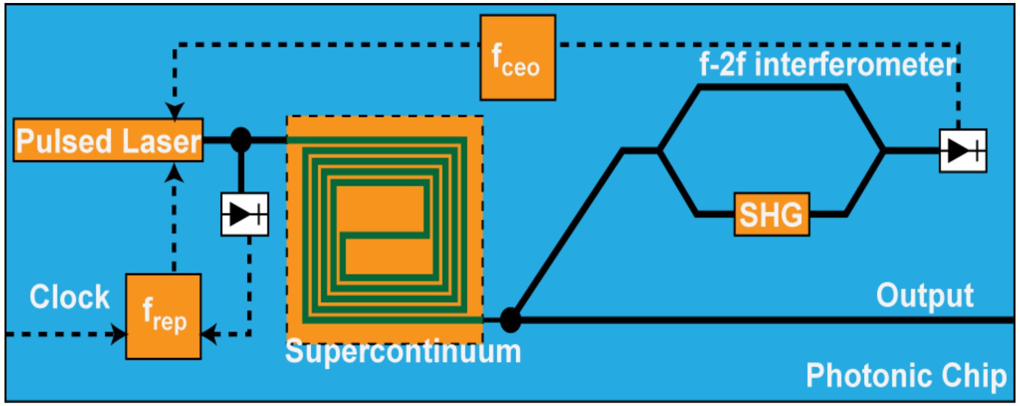
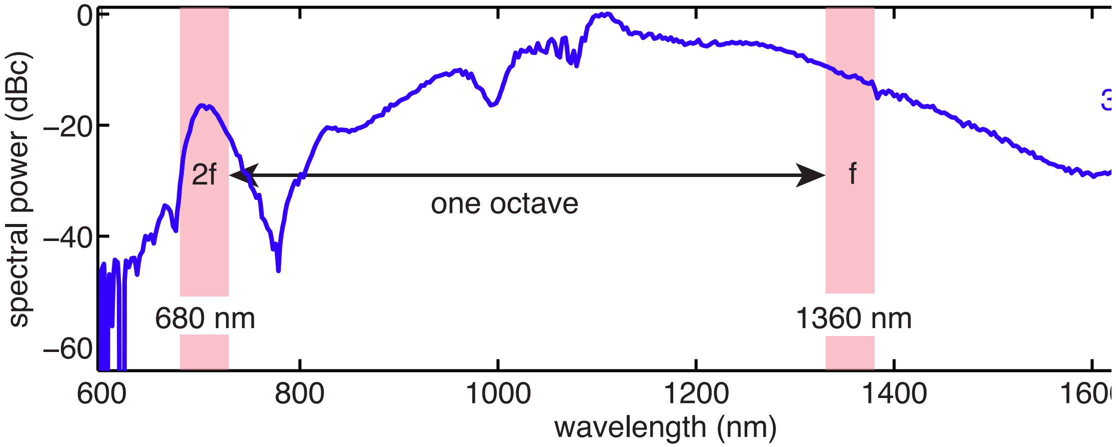
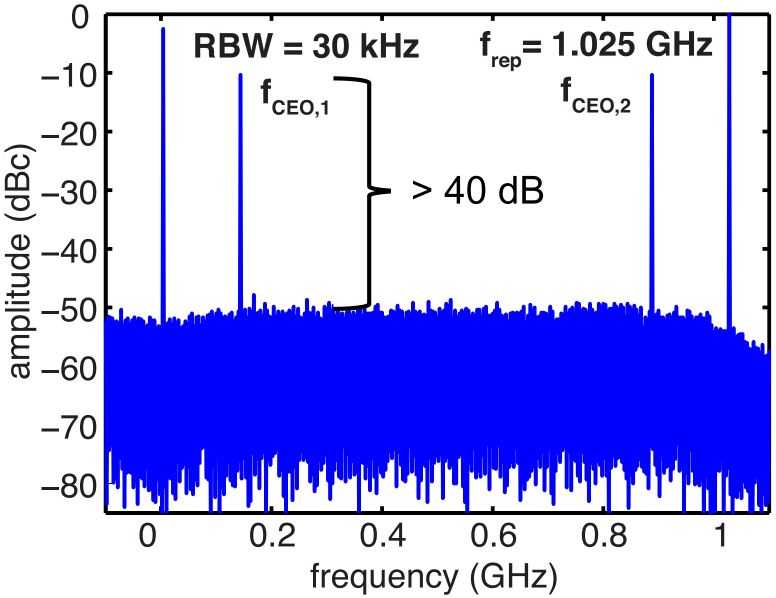
D. J. Moss, R. Morandotti, A. L. Gaeta, and M. Lipson, Nature Photon. **7**, 597-607 (2013)

Motivation: Full integration

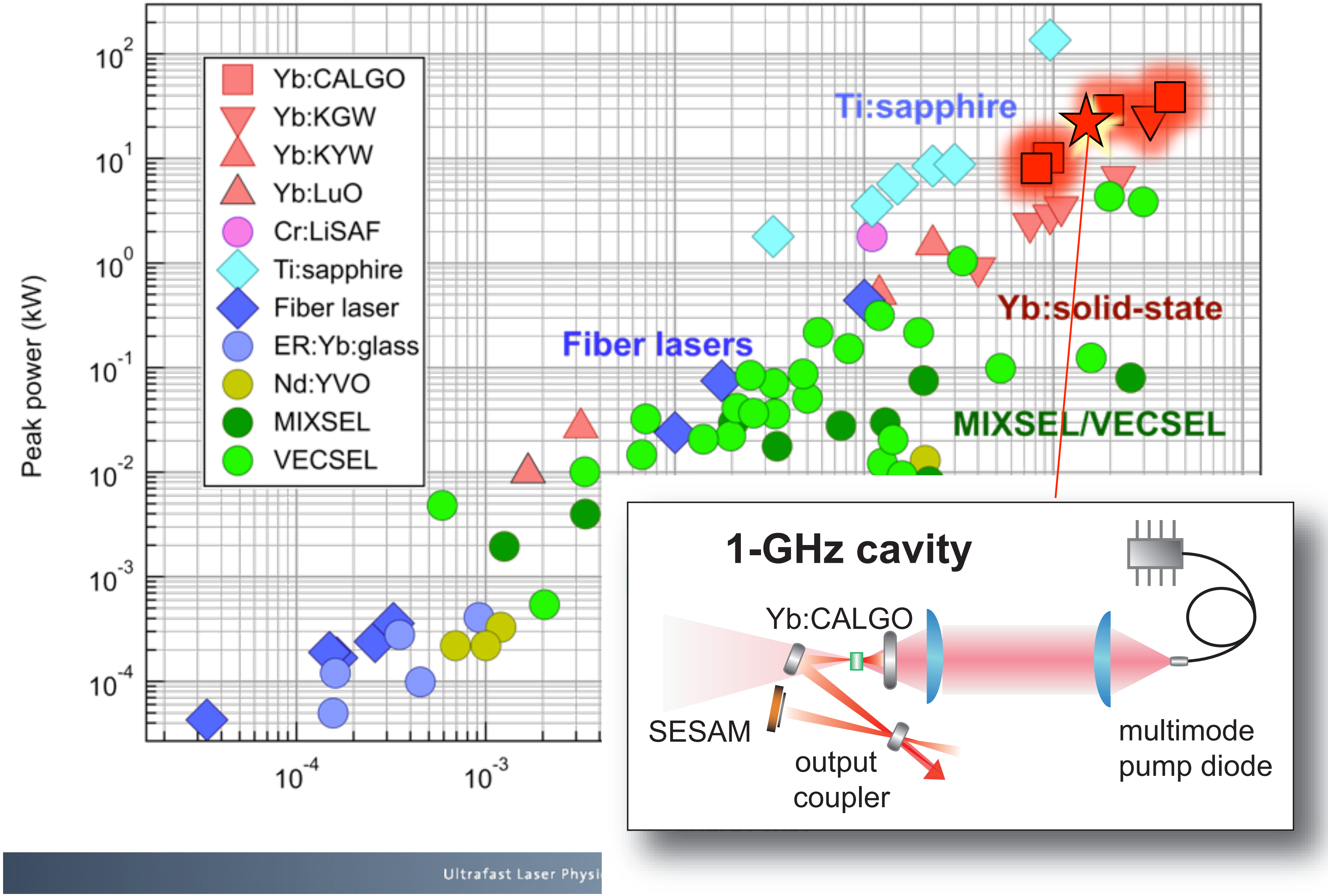






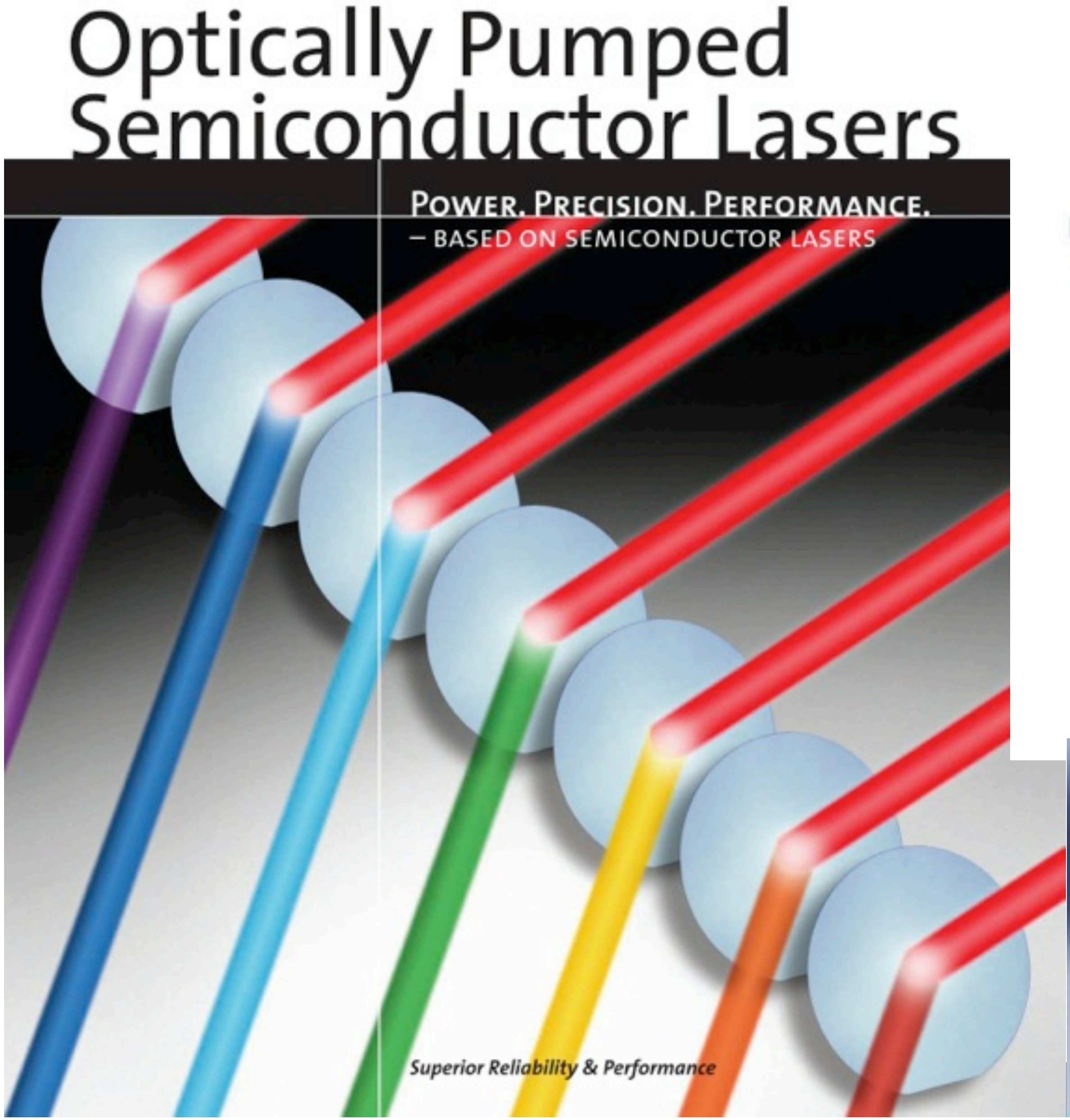
A. S. Mayer, A. Klenner, A. R. Johnson, K. Luke, M. R. E. Lamont, Y. Okawachi, M. Lipson, A. L. Gaeta, U. Keller, *Opt. Express* **23**, 15440-15451 (2015)

GHz oscillators w/o amplification or compression



COHERENT

OPSLs = OP-VECSELs



Optically Pumped Semiconductor Lasers

POWER. PRECISION. PERFORMANCE.

– BASED ON SEMICONDUCTOR LASERS

Superior Reliability & Performance

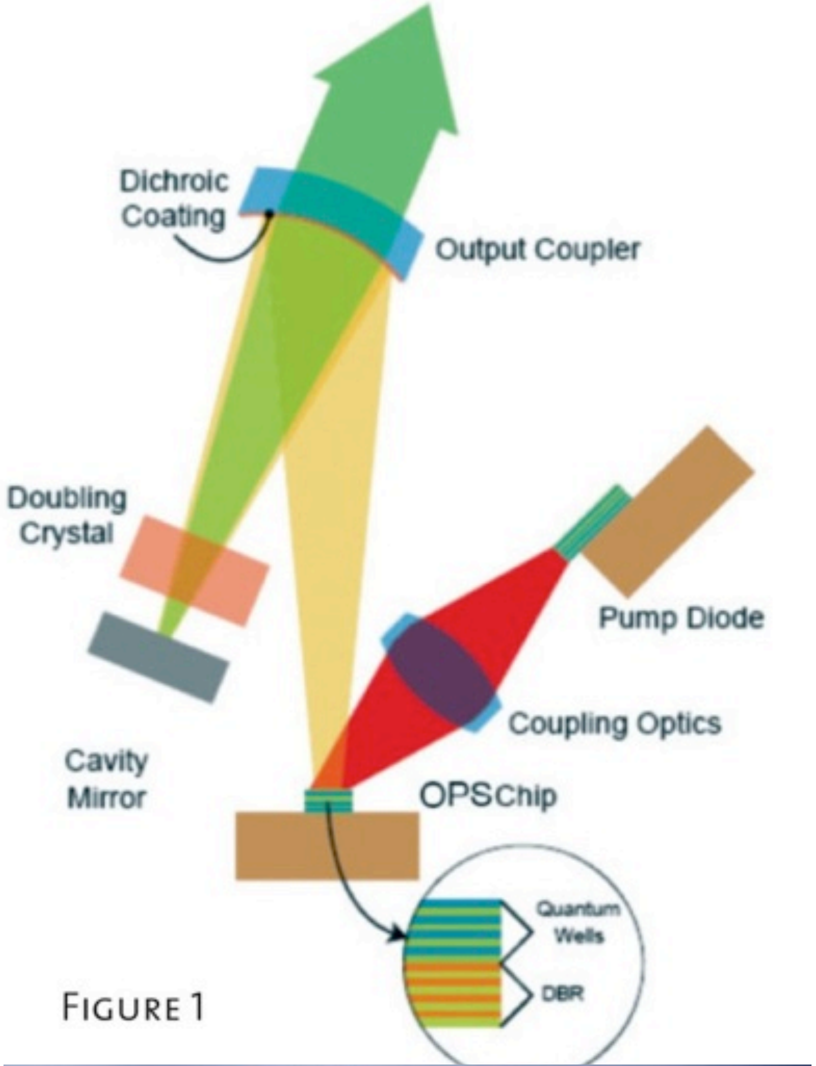
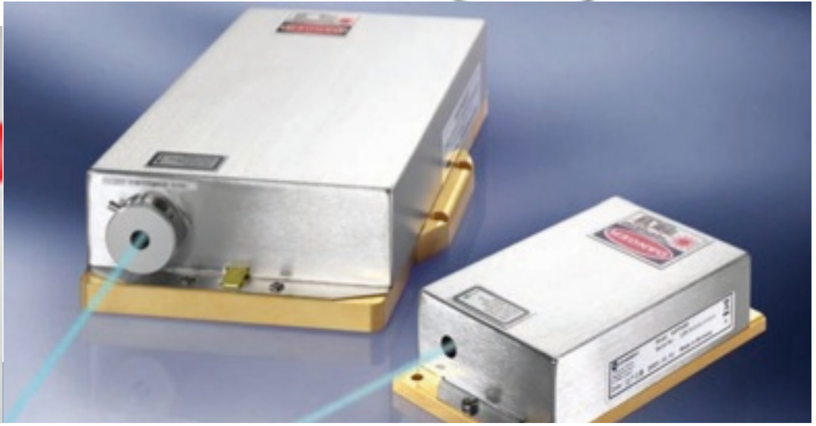
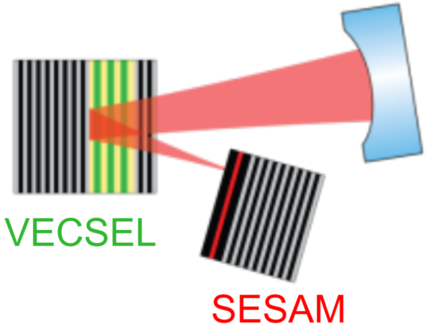


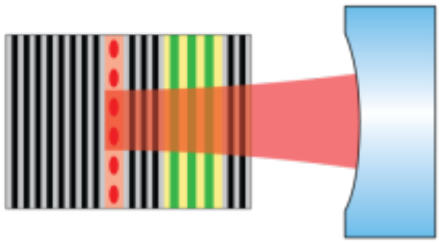
FIGURE 1



MIXSEL Concept



integration of saturable absorber



VECSEL

Vertical External Cavity Surface Emitting Laser

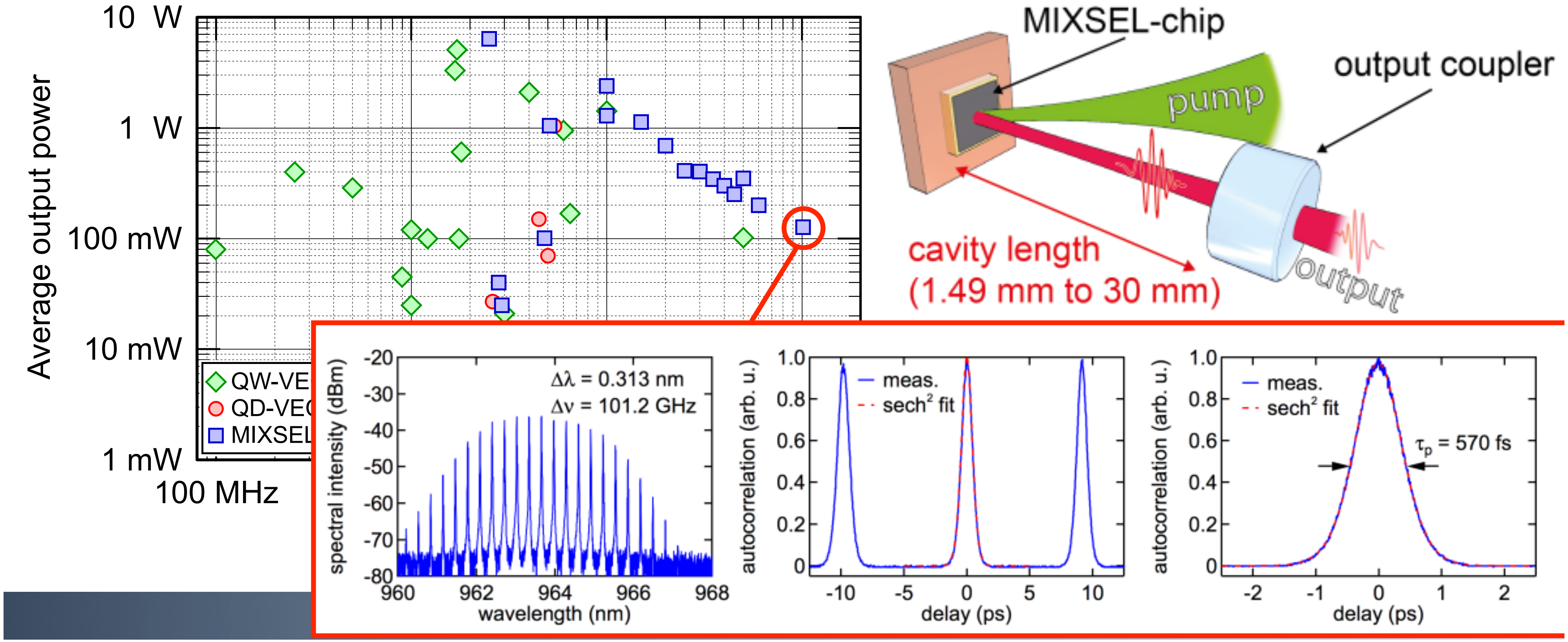
\+

SESAM

Semiconductor Saturable Absorber Mirror

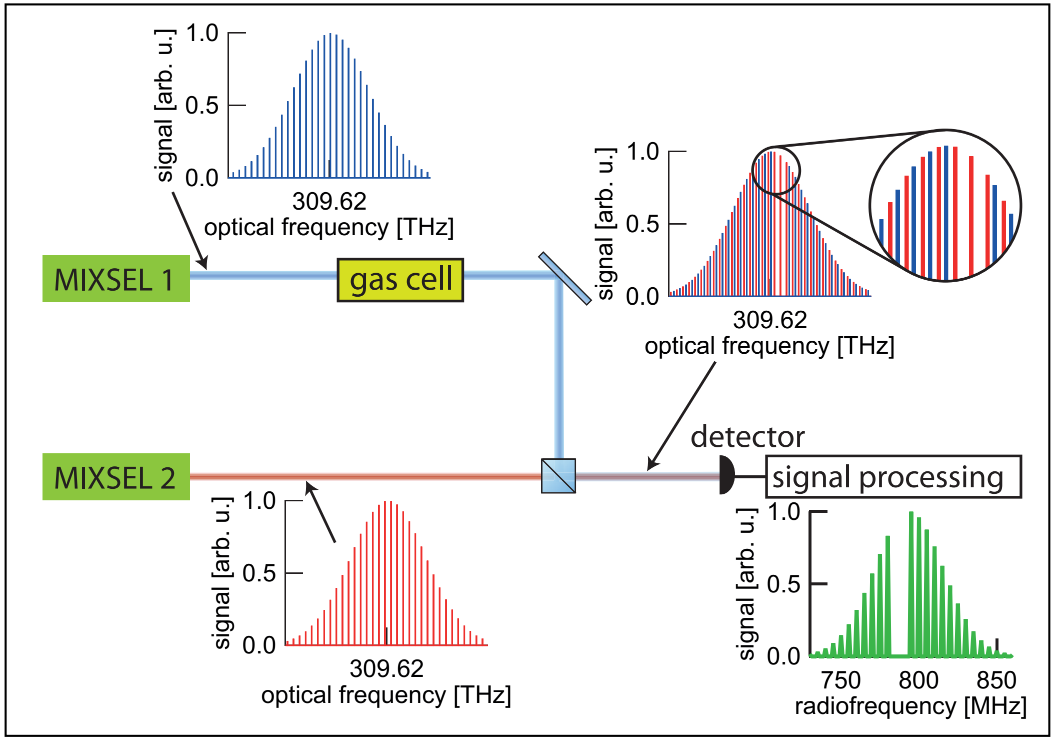
MIXSEL

Modelocked Integrated External-Cavity Surface Emitting Laser



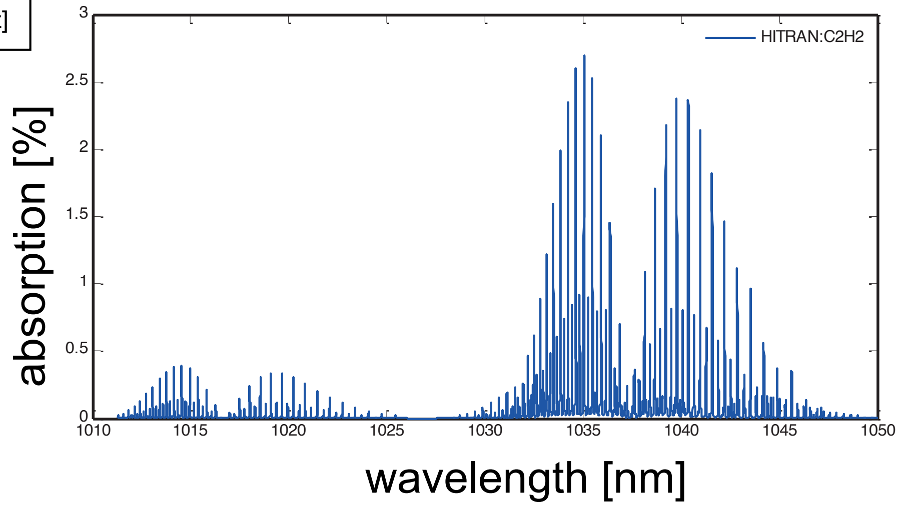
Application: Dual-comb spectroscopy

possible gas spectroscopy setup



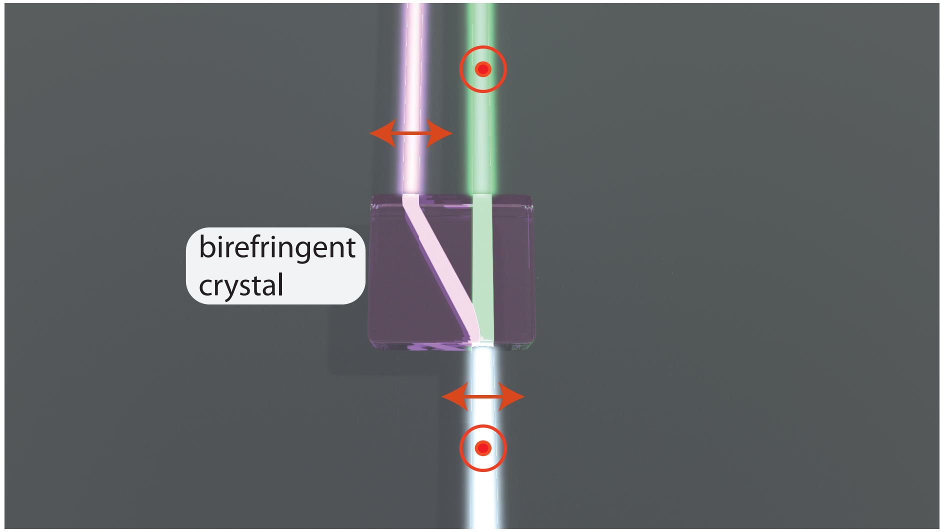
requirement: 2 modelocked lasers with slightly different pulse repetition frequencies

Acetylene has strong absorption lines in the near infrared around 1035 nm.



Dual-comb lasers

Novel concept for modelocked lasers:



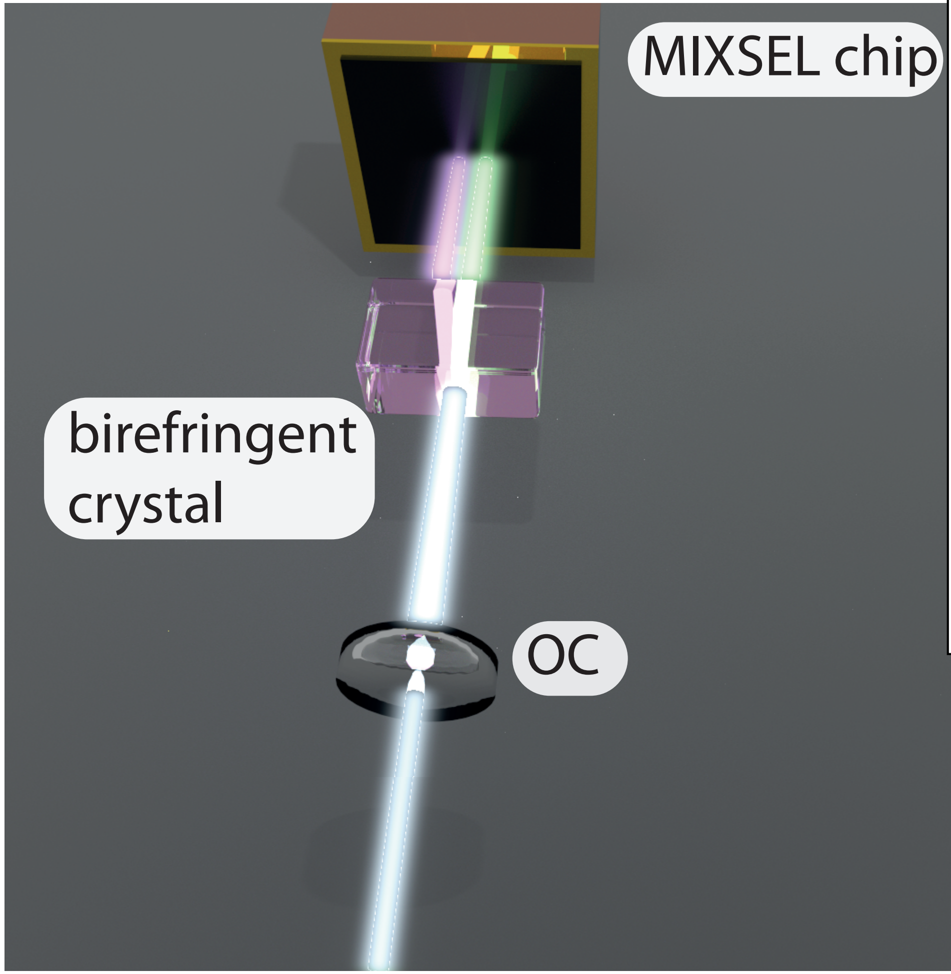
intra-cavity birefringent crystal

→ two beams:

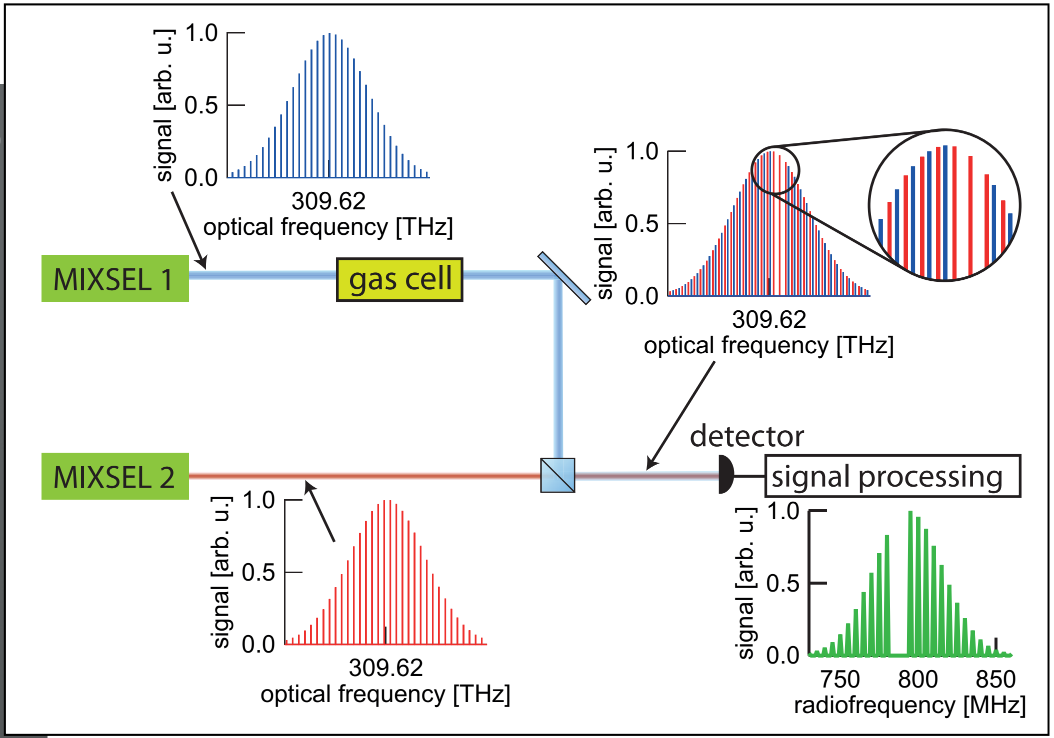
- orthogonal polarization
- spatially separated
- different optical path-length

S. M. Link, A. Klenner, M. Mangold, C. A. Zaugg, M. Golling, B. W. Tilma, U. Keller, Opt. Express, vol. 23, No. 5, pp. 5521-5531, 2015

Dual-comb laser



Dual-comb gas spectroscopy



ULP group

In general …

ULP - Ultrafast Laser Physics (Mission Statement)

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Ultrafast Laser Physics

To explore and push the frontiers in ultrafast science and technology, using interdisciplinary understanding of the physics of lasers, semiconductors, and measurement technologies. Take this competitive know-how to understand and control fundamental charge and energy transport with atomic spatial and attosecond temporal resolution.

www.ulp.ethz.ch

Ultrafast solid-state lasers

- High-power TDLs
- Semiconductor disk lasers
- High rep rate SSLs

Attosecond science

- OPCPA
- Attoline
- Attoclock (COLTRIMS)
- etc…

must

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