

Laser and Parametric Optical Frequency Combs

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Learning & Research: A continuous upward climb



Chopicalqui (6354m), Peru



Bramante Staircase, Vatican

Outline

- 1. Background: Clocks and Precise Timing**
- 2. Counting Cycles of Light**
 - **The optical frequency comb**
- 3. From Lab Scale to Chip Scale**
 - **Can we make a frequency comb on a chip?**
- 4. Applications and opportunities for frequency combs**

Boulder Colorado

25 square miles surrounded by reality



- Population of ~100k
- 30 min from Denver (1.5 M)
- Federal Research Labs: **NIST**, **NOAA**, **NCAR** (atmospheric research)
- Home of University of Colorado
- Many high-tech companies and startups

Boulder Colorado

25 square miles surrounded by reality



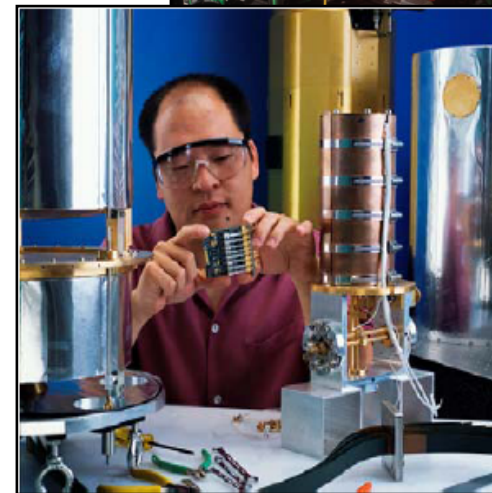
National Institute of Standards & Technology (NIST)

NIST's mission is to promote U.S. *innovation...*

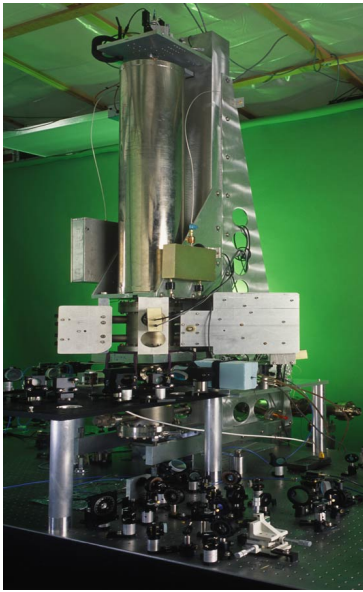
Key roles enabling innovation, education, and infrastructure for investments in the future...

NIST Boulder assets include (*approximate values*):

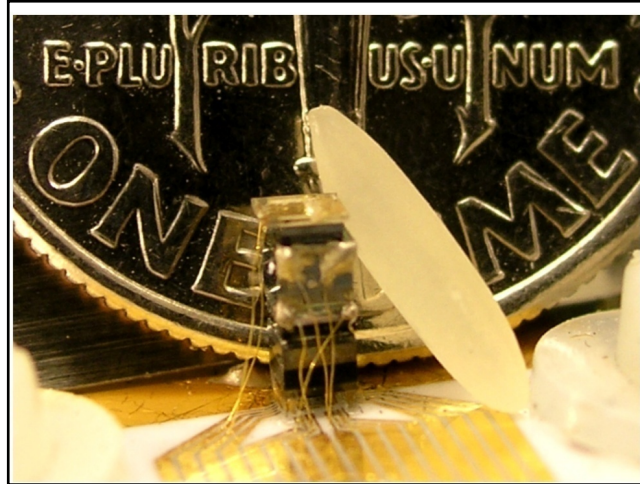
- 375 employees.
- 350 associates.
 - Postdocs, grad & undergrad students, contractors, guest researchers, etc.
- \$100 million annual operating budget.
 - Appropriations, other agency reimbursements.
- About 20% of NIST Laboratory programs overall.



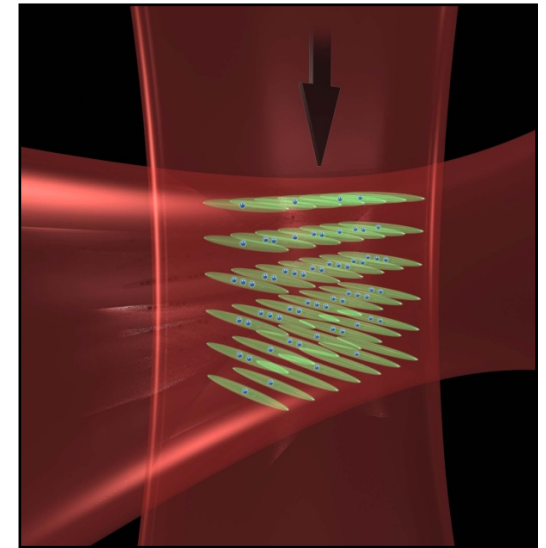
Time and Frequency Metrology



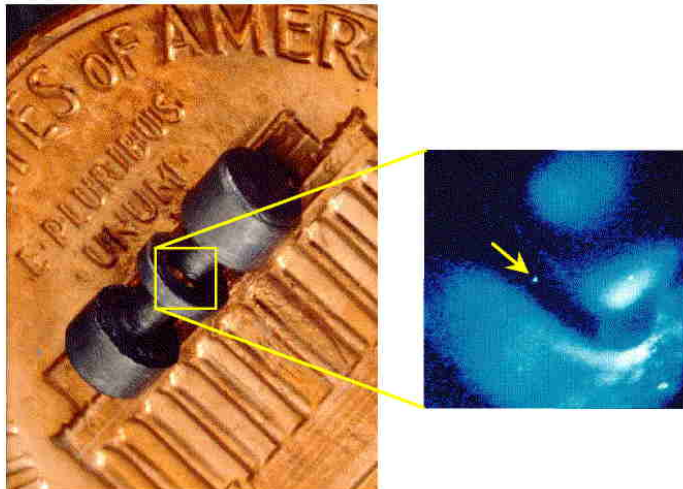
Cs Fountain Clock



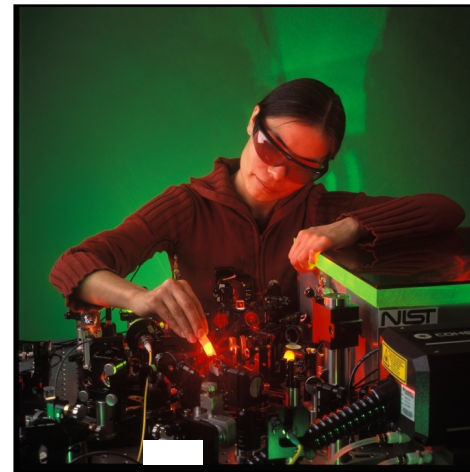
Chip-Scale Clocks



Optical lattice clocks



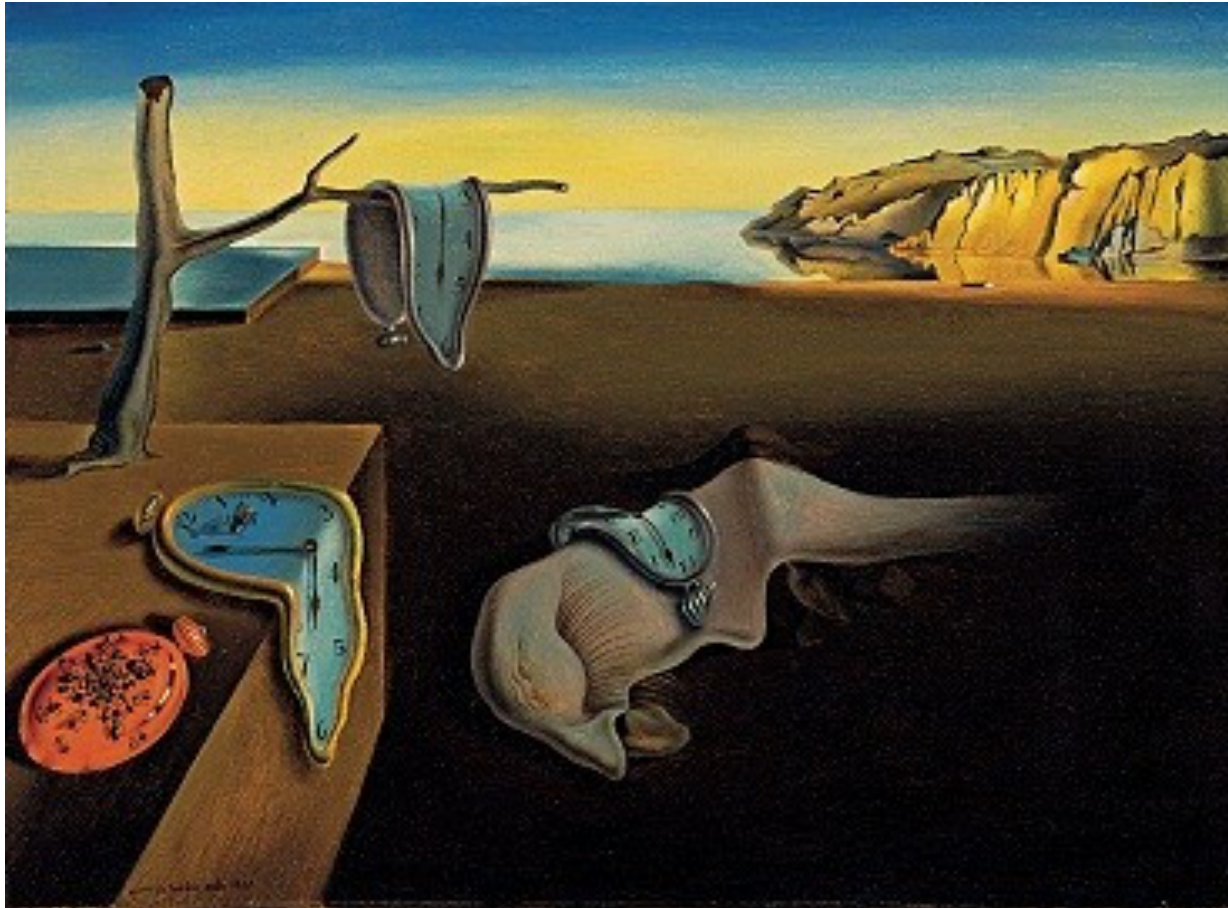
Single Ion Clocks



Optical Frequency Combs

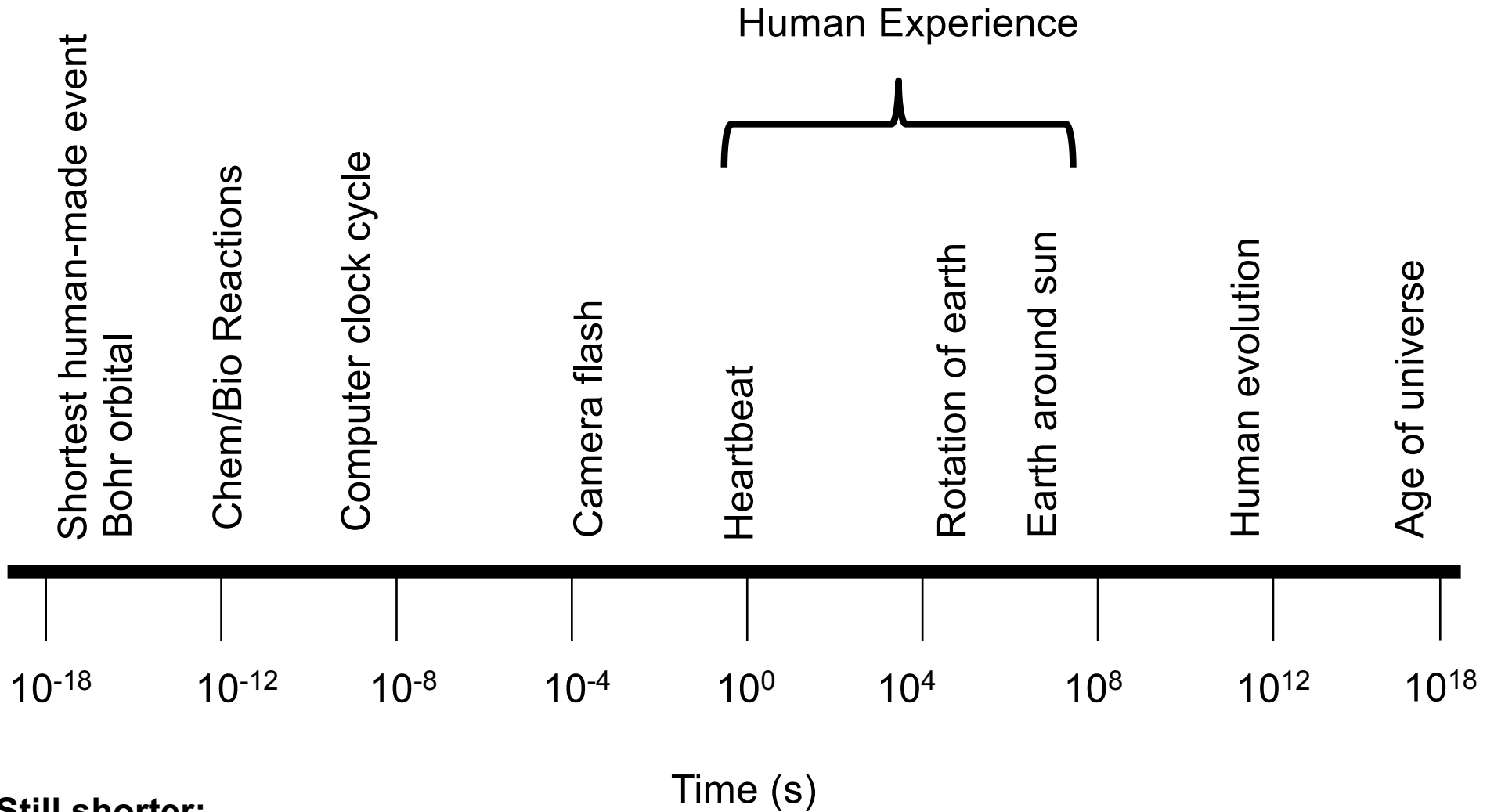


Background: Clocks and Precise Timing



Salvador Dalí: *The persistence of memory* (1931)

Timescales



Still shorter:

Top Quark lifetime: 4×10^{-25} s

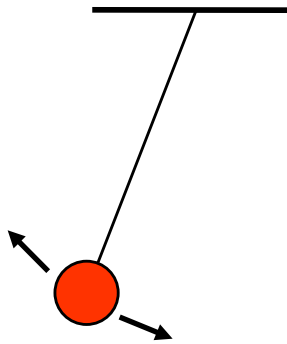
Planck time: 10^{-43} s

What Makes a Clock?

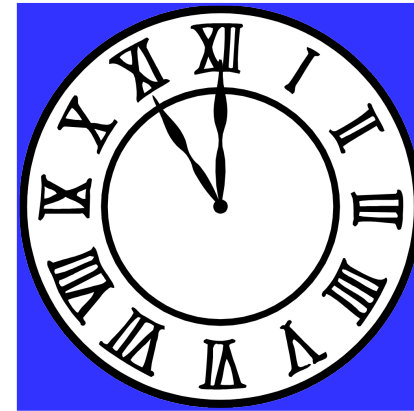
Oscillator

+

Counting Mechanism



Earth Rotation
Pendulum
Quartz Crystal



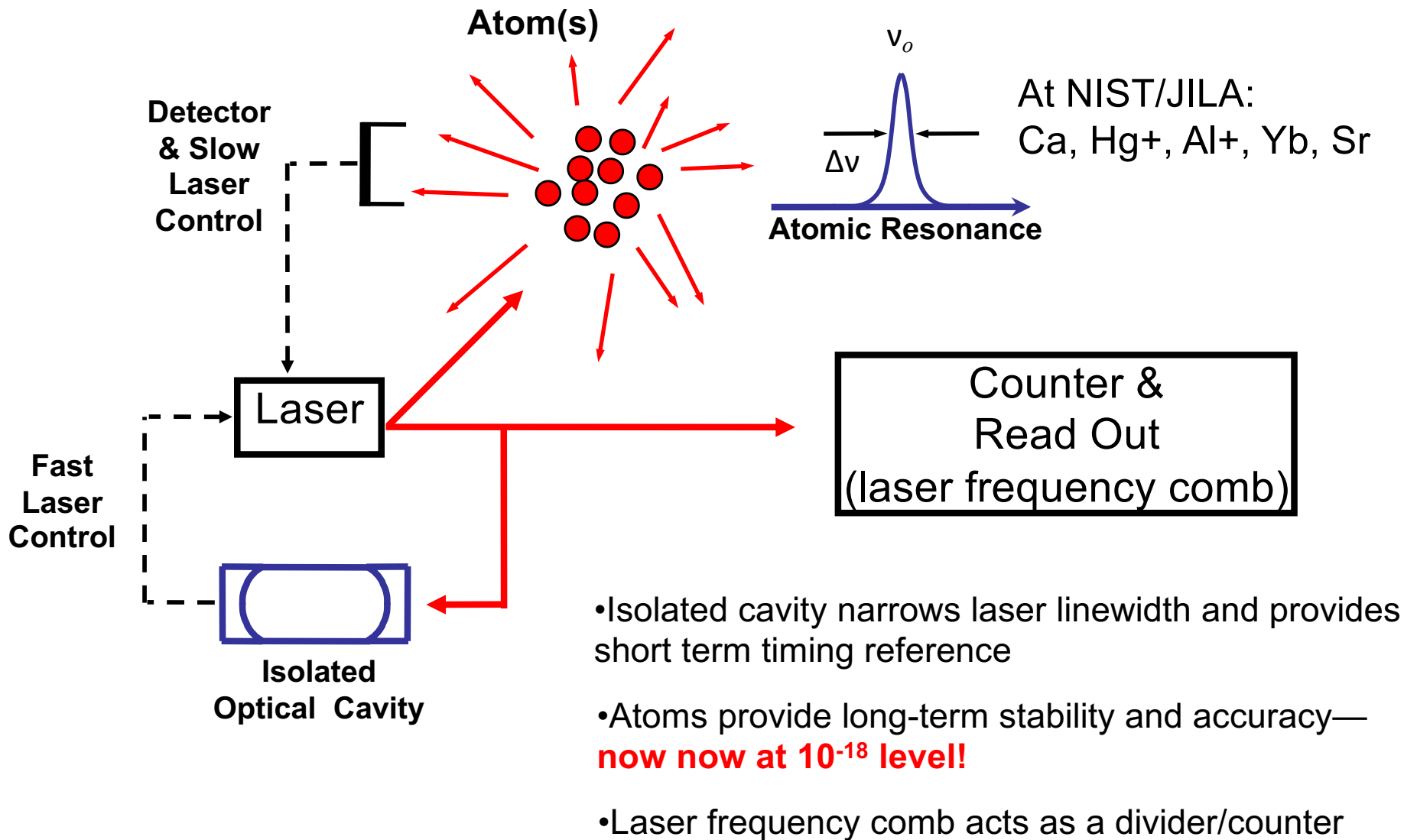
Sundial
Clock Gears/Hands
Electronic Counter

ATOMIC CLOCKS

Microwave Transition + Oscillator
Optical Transition + Laser

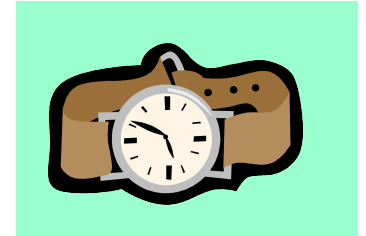
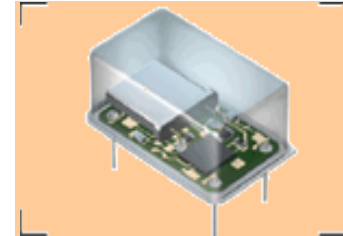
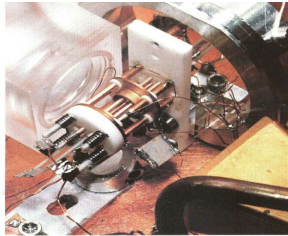
Electronic Counter
Femtosecond Laser

Optical Atomic Clocks



Types of Clocks

“Better”



**Optical
Clock**

Primary
Standard

Compact
Atomic Clock

Precision
Quartz Crystal

Wristwatch
Quartz Crystal

Loses 1 sec. in:

10^{10} yrs

10^8 yrs

1000 yrs

1 yr

1 day

Size:

laboratory

10^7 cm³

100 cm³

1 cm³

10^{-3} cm³

Stability (1s):

10^{-16}

10^{-13}

10^{-10}

10^{-11}

10^{-6}

Cost:

??

\$1 M

\$1,000

\$100

\$1



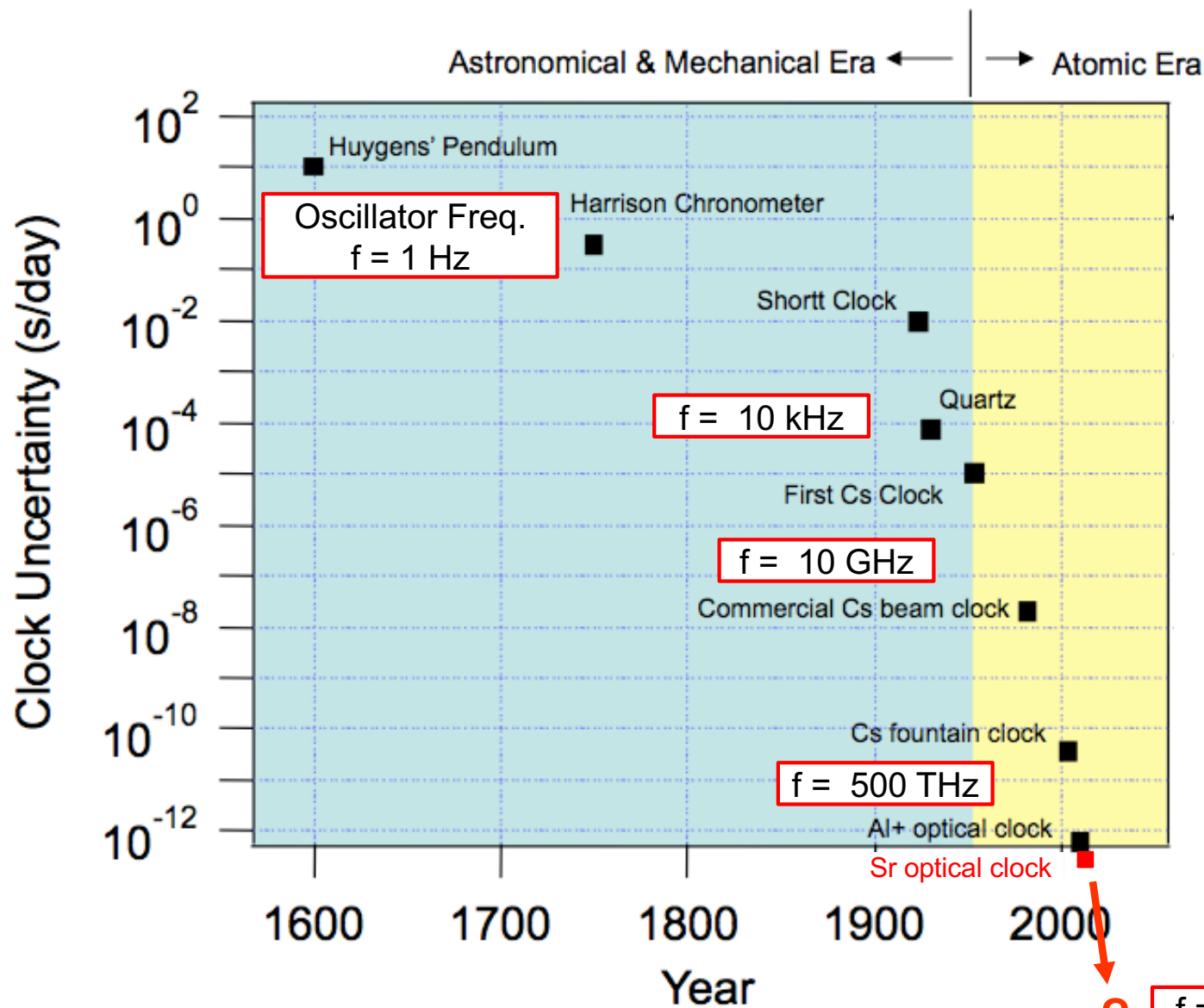
“Smaller”

All atomic clocks have:

- Reference atom
- Local oscillator (pendulum)
- Counter/gears

Figure: J. Kitching, (NIST)

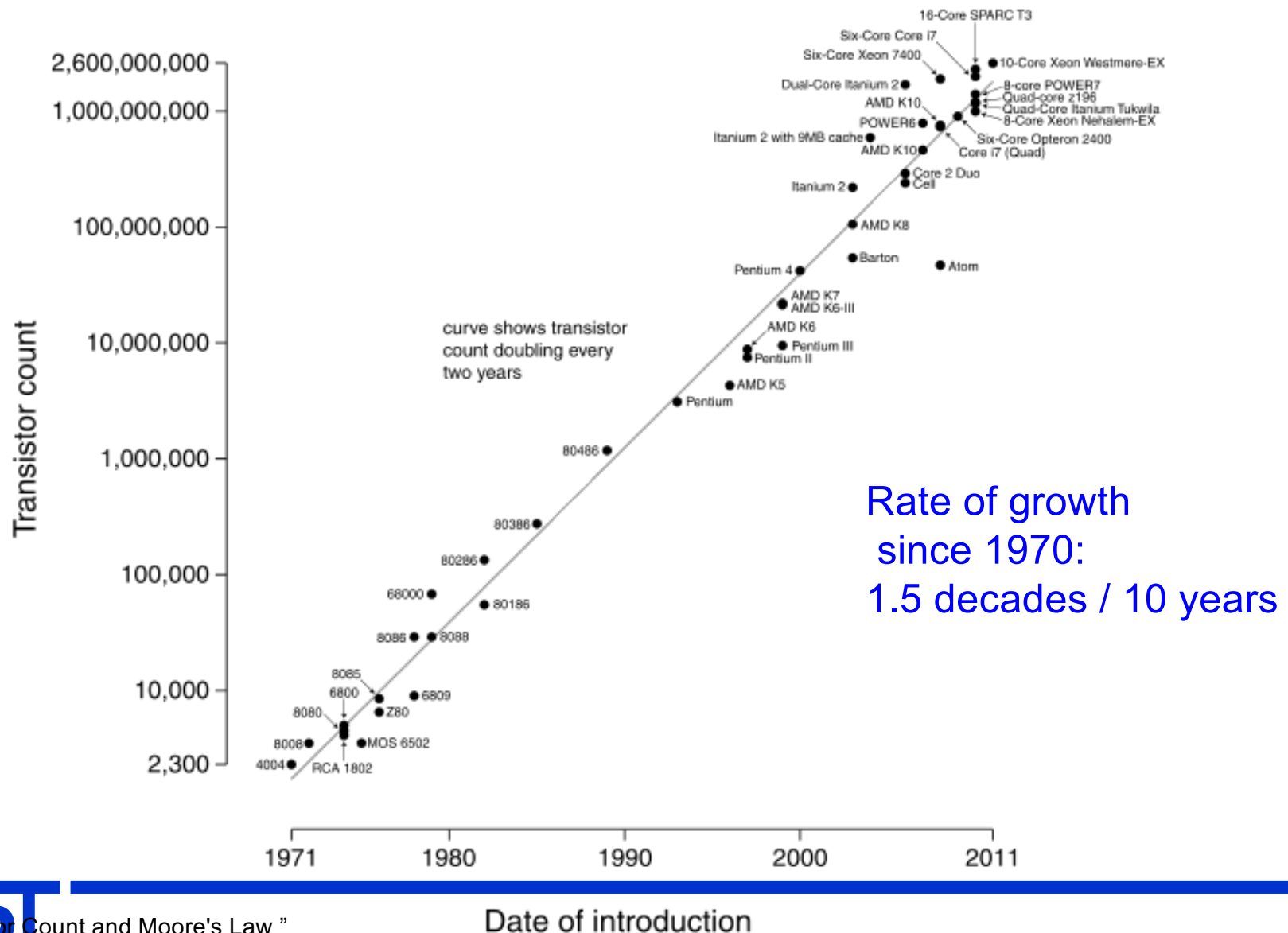
Timekeeping: The long view



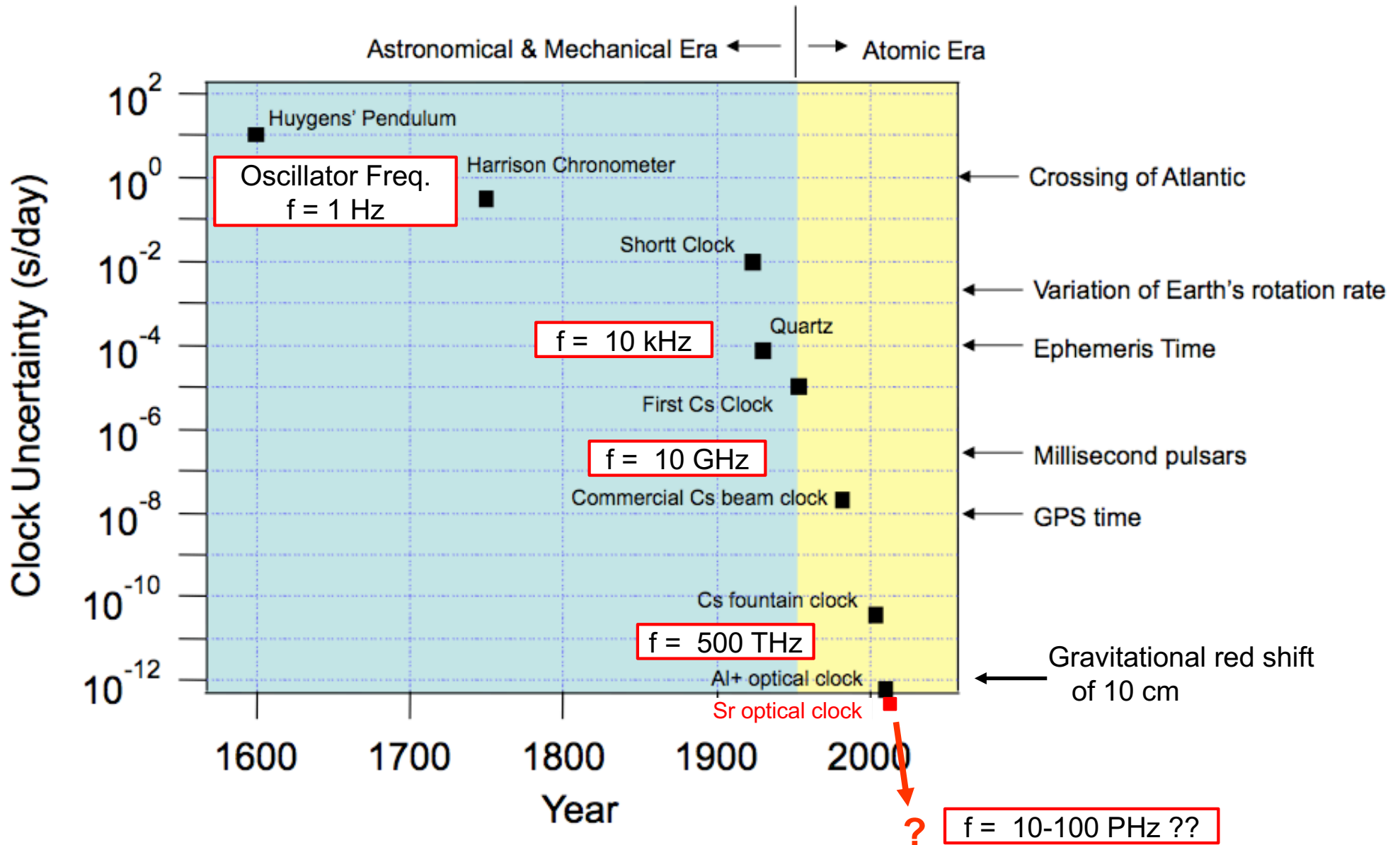
Rate of improvement since 1950:
1.2 decades / 10 years

Moore's Law for Transistors per Chip

Microprocessor Transistor Counts 1971-2011 & Moore's Law

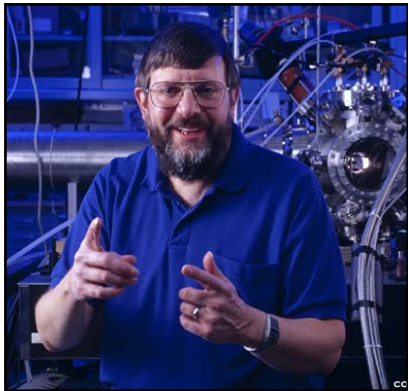


Timekeeping: Societal and Scientific Impact

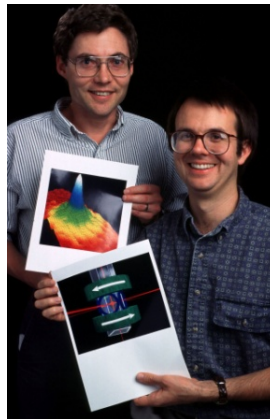


Nobel Prizes Related to Timekeeping

1943	Otto Stern	Molecular/atomic beam spectroscopy.
1944	Isidor Rabi	Atomic beam resonance technique.
1955	Polykarp Kusch	Magnetic moment of electron; early atomic clocks.
1964	Charles Townes, Nicolai Basov, Alexandr Prokhorov	Quantum electronics, including maser/laser principles.
1966	Alfred Kastler	Optical pumping methods.
1989	Norman Ramsey, Hans Dehmelt, Wolfgang Paul	Atomic clock techniques; trapped ion spectroscopy.
1997	Bill Phillips , Steven Chu, Claude Cohen-Tannoudji	Laser cooling of neutral atoms.
2001	Eric Cornell , Carl Wieman , Wolfgang Ketterle	Bose-Einstein condensate.
2005	John Hall , Ted Hansch, Roy Glauber	Femtosecond laser frequency combs.
2012	Dave Wineland , Serge Haroche	Quantum state measurement and manipulation.



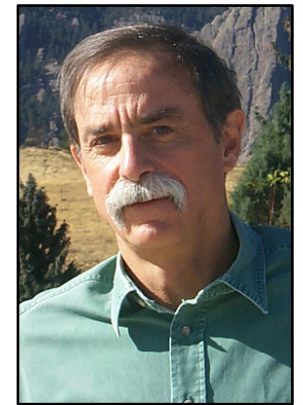
*Bill Phillips
NIST*



*Carl Wieman
JILA/CU
Eric Cornell
JILA/NIST*



*John Hall
JILA/NIST*

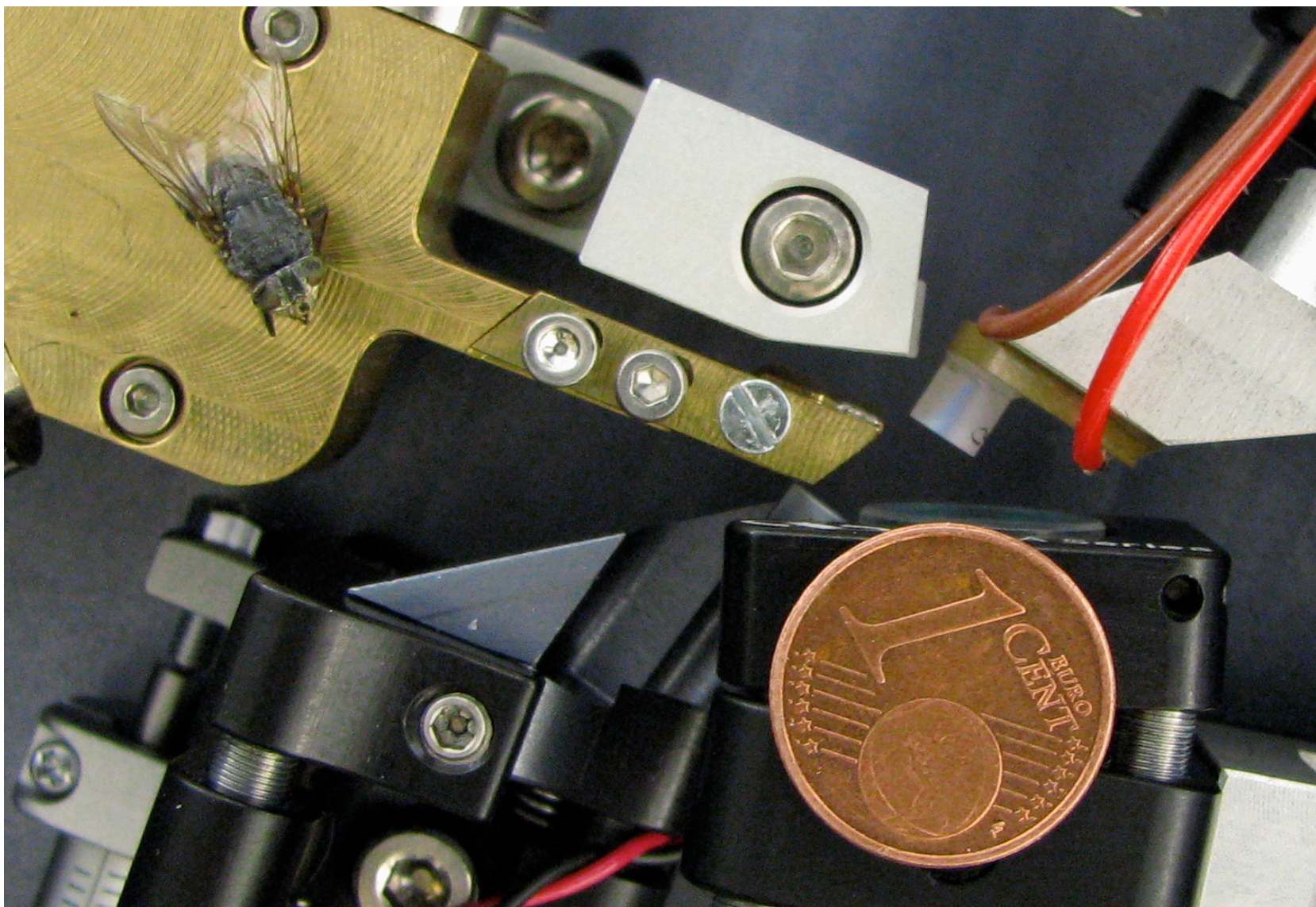


*Dave Wineland
NIST*

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Counting Cycles of Light

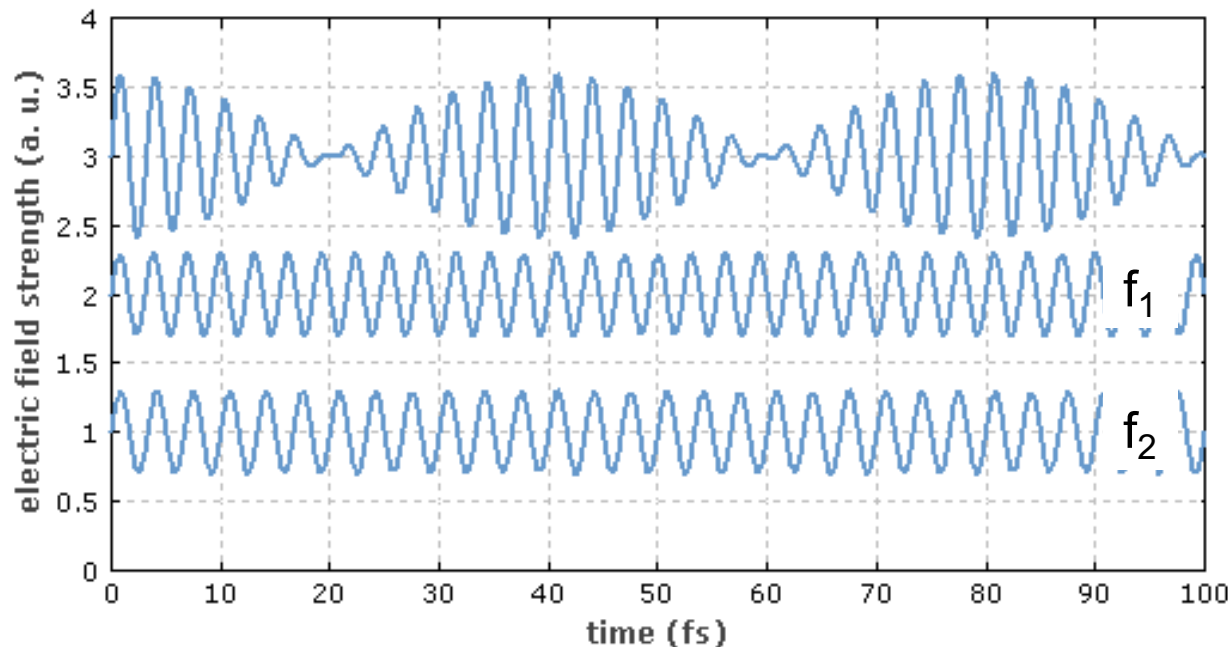


How Do You Count Optical Cycles?

Optical Frequency: $c/600 \text{ nm} = 500 \text{ THz} \rightarrow T=2 \text{ fs}$

Fastest electronics: 1 THz, 1 ps

Optical Heterodyne: Measure “beat note” between two optical frequencies



Carrier: $(f_1 + f_2)/2$

Envelope: $(f_1 - f_2)$

500,000,010,000,000 Hz

- 500,000,000,000,000 Hz

10,000,000 Hz

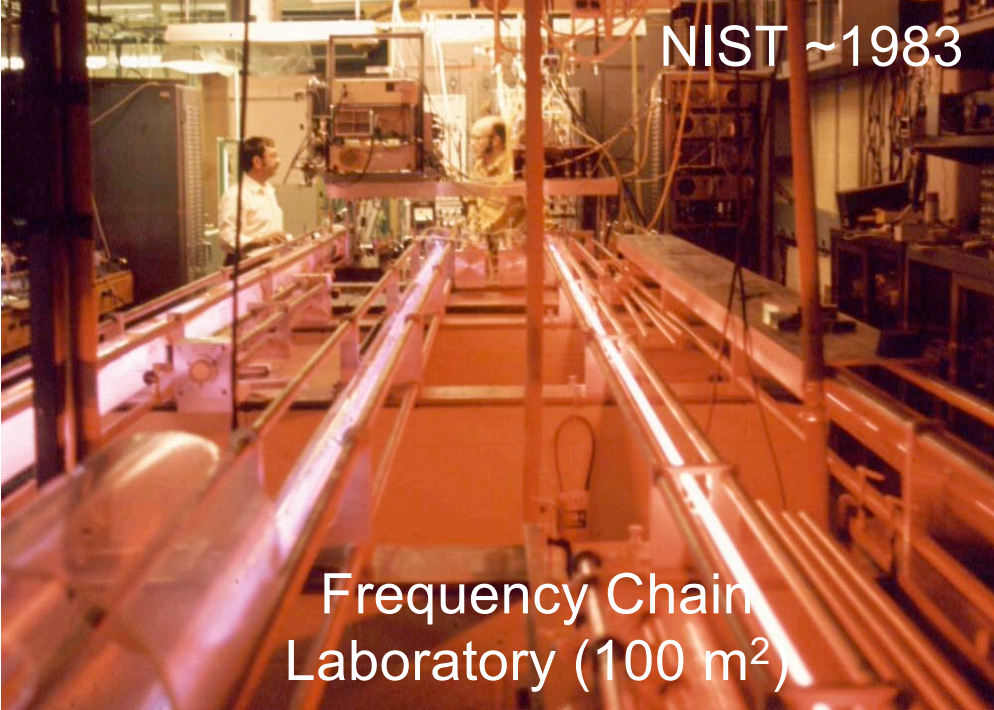
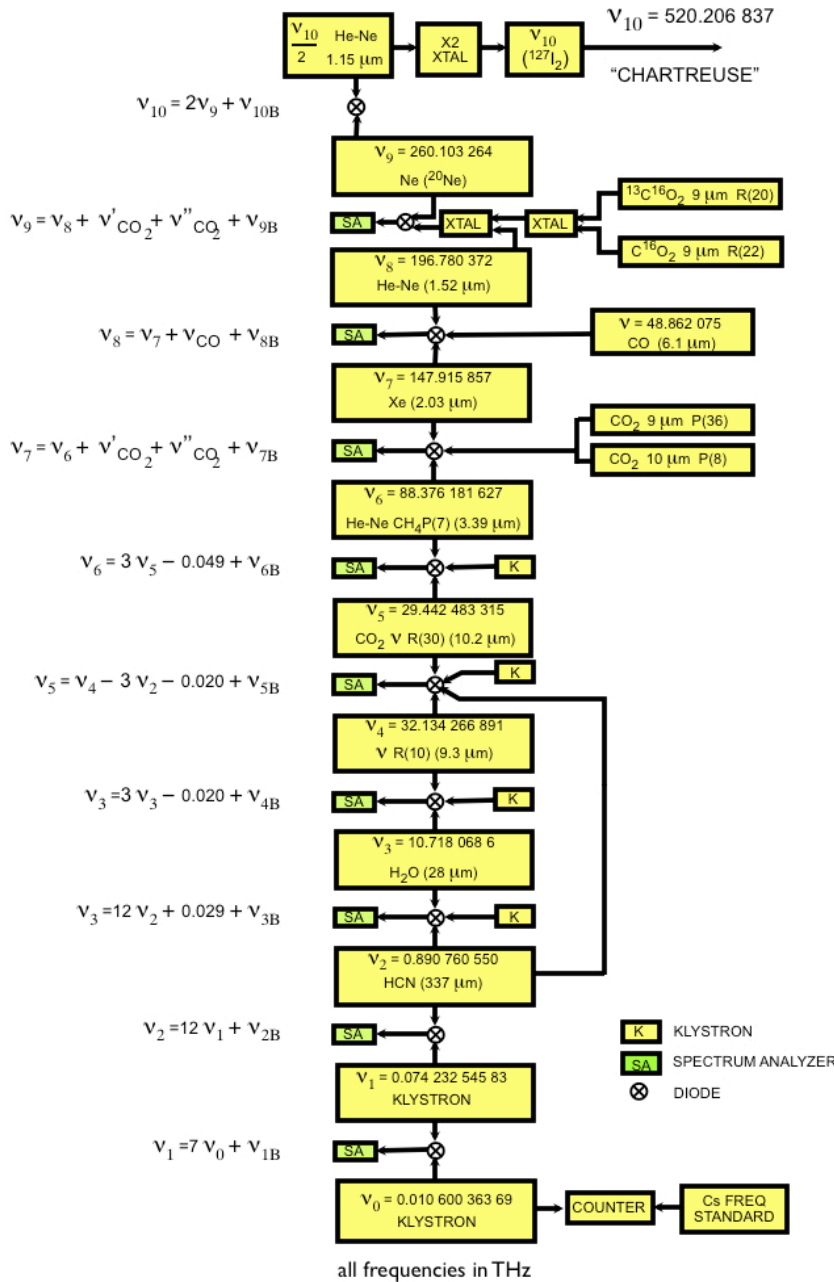
A countable frequency!

But only a relative one

Direct Multiplication

$$\frac{v_{\text{optical}}}{v_{\text{microwave}}} \approx \frac{10^{15}}{10^{10}} \approx 10^5 \approx 2^{16}$$

It worked! But not general, practical, cost effective



NBS Laser Frequency Synthesis Chain (1979)
 K. M. Evenson, D.A. Jennings, J. S. Wells, C. R. Pollock,
 F. R. Petersen, R. E. Drullinger, E. C. Beaty, J. L. Hall,
 H. P. Layer, B. L. Danielson, G.W. Day, R. L. Barger

What is a laser frequency comb??



<http://www.hairmax.com/>

Client's quote :

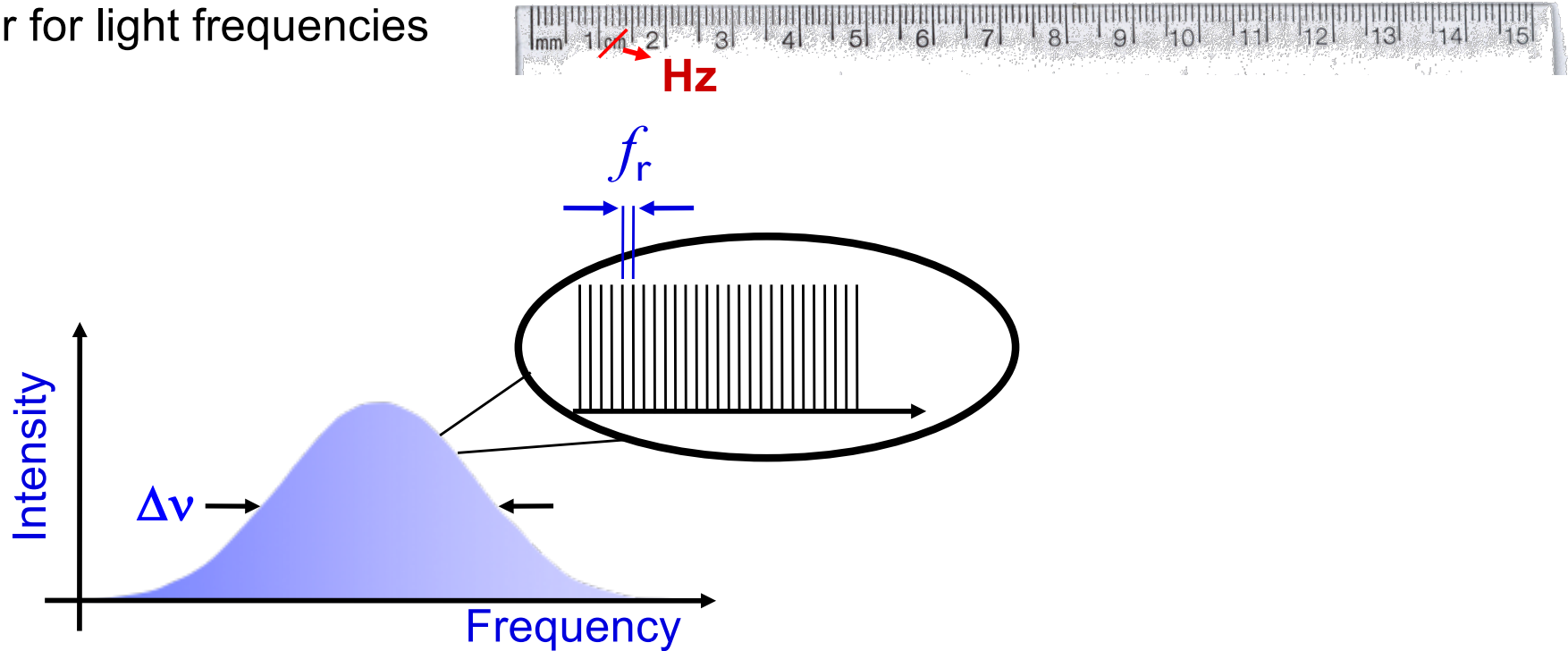
"I used to have only one or two good hair days a month. Now, every day is a good hair day."

- USER BENEFITS
- PROVEN TECHNOLOGY
- LASER RESEARCH
- LOW LEVEL LASER
- SAVE TIME & MONEY
- QUESTIONS & ANSWERS
- ABOUT LASERCOMB & US
- IN THE NEWS
- QUALITY & SAFETY
- CONTACT US
- ORDER NOW

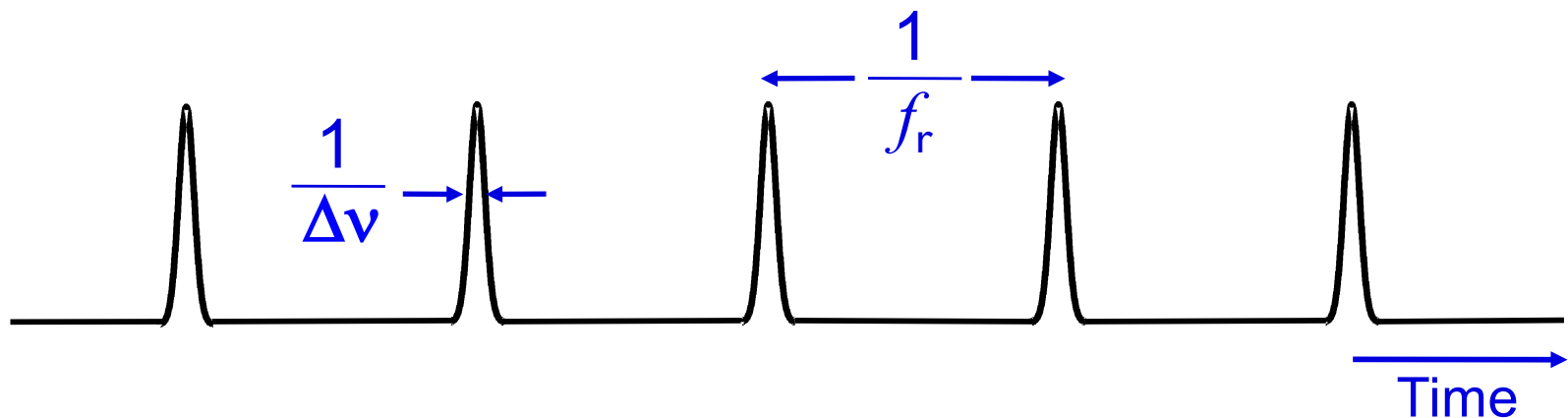


Multiple faces of a frequency comb

1. A ruler for light frequencies

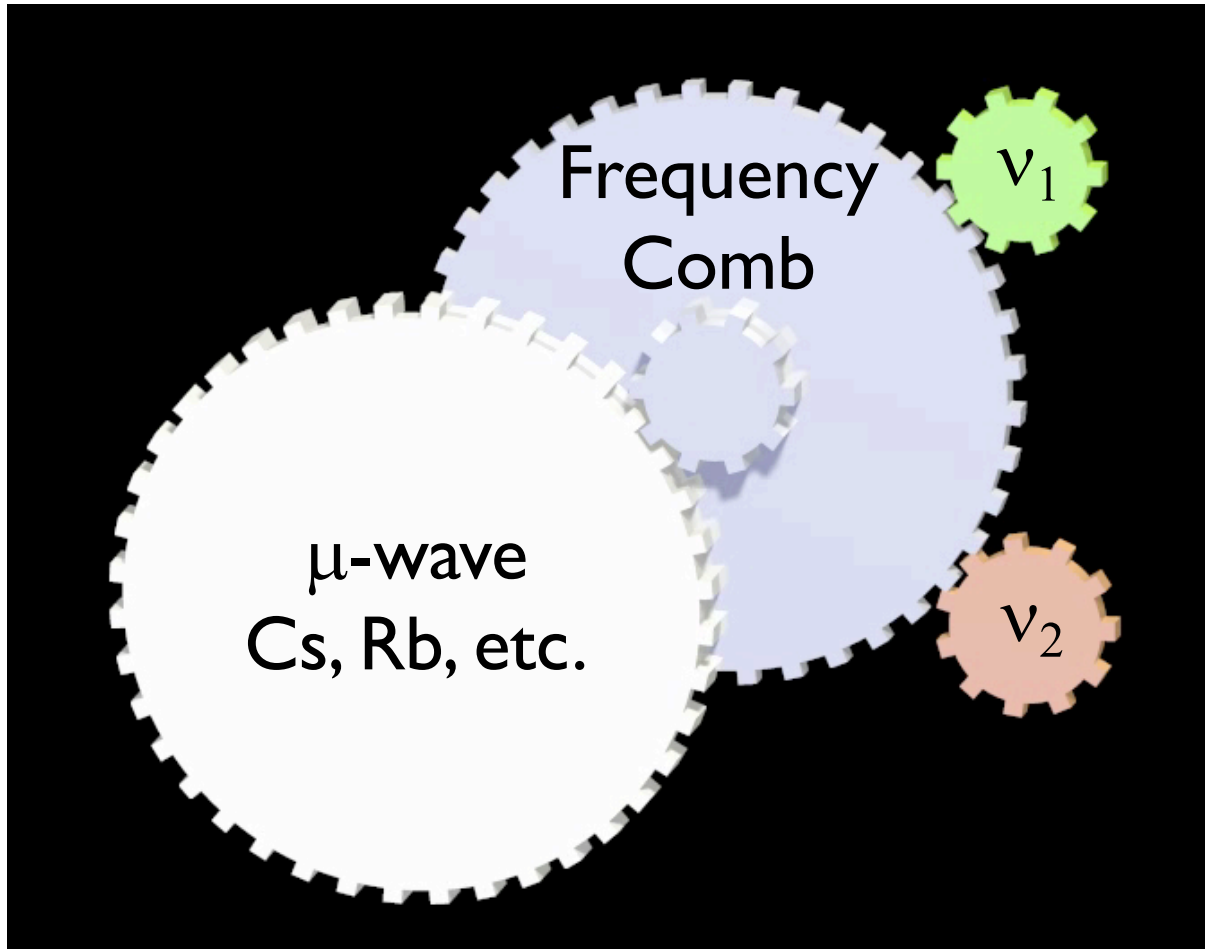


2. A perfectly-spaced train of optical pulses



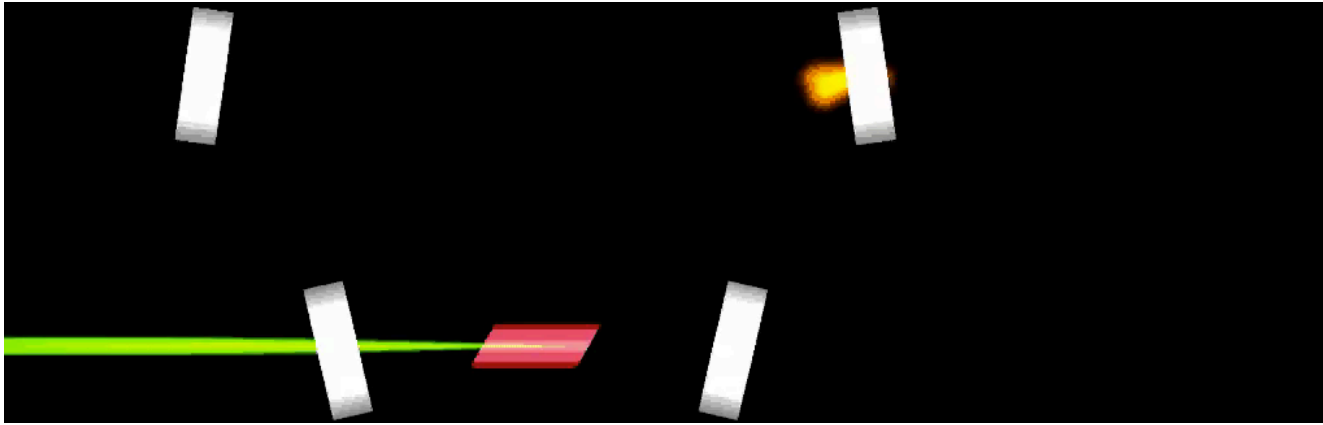
Multiple faces of a frequency comb

3. An optical clockwork

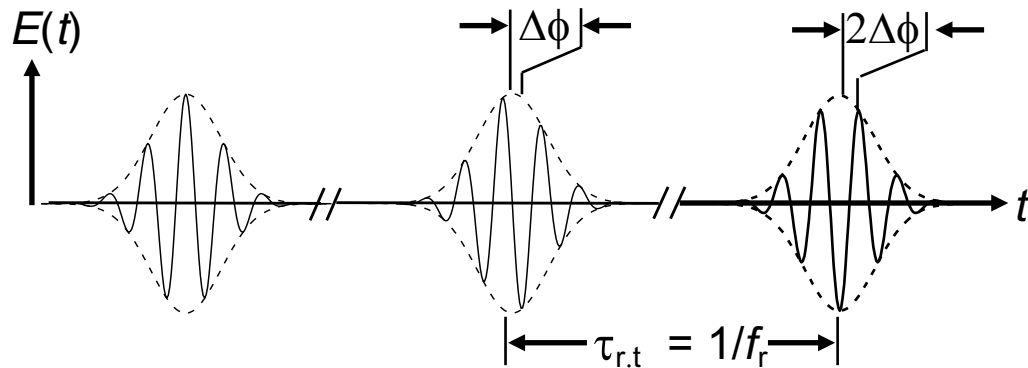


- Comb uncertainty at the 20th decimal place
- Measurement of optical ratios (e.g. $\nu_1 : \nu_2$)
- Direct connection from optical to microwave domains

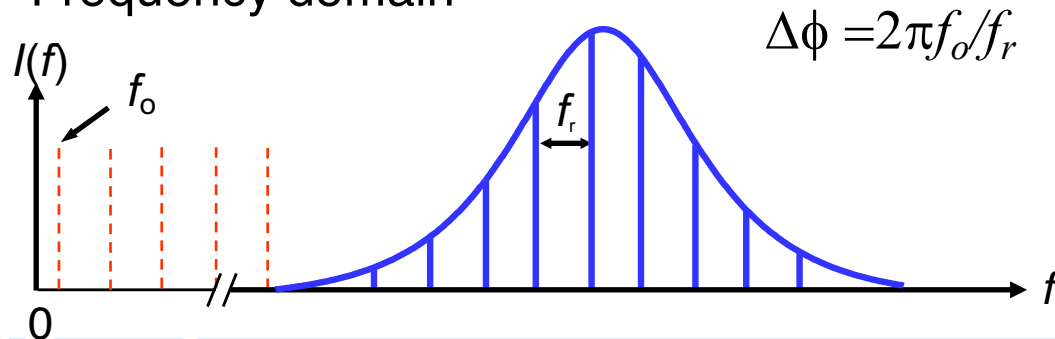
Mode-Locked Laser: Basis of the Frequency Comb



Time domain



Frequency domain



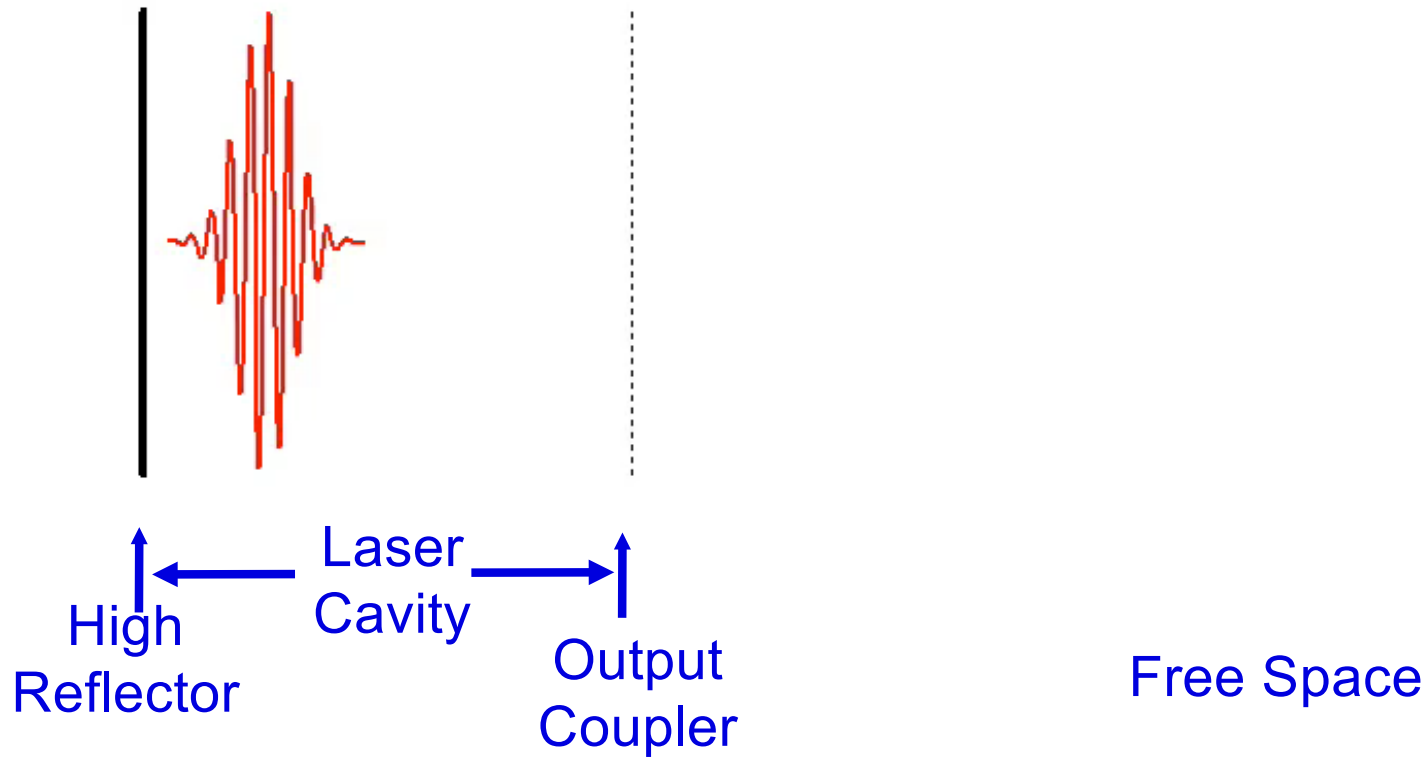
Key Concept:

Direct link between optical and microwave frequencies

$$\nu_n = n f_r + f_0$$

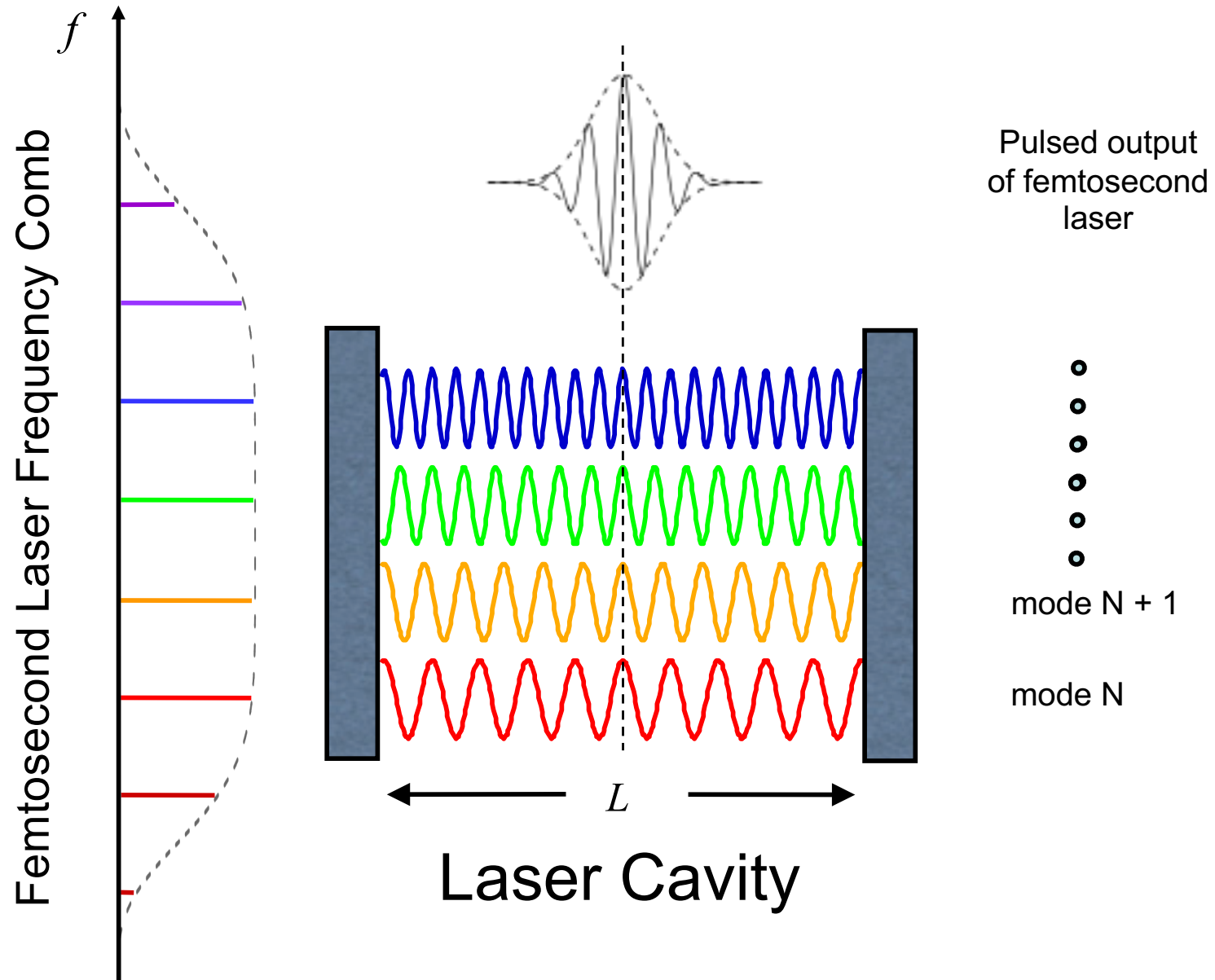
$$n \sim 10^5$$

Group and phase velocity in modelocked lasers



animation from *Steve Cundiff*

The femtosecond mode-locked laser comb



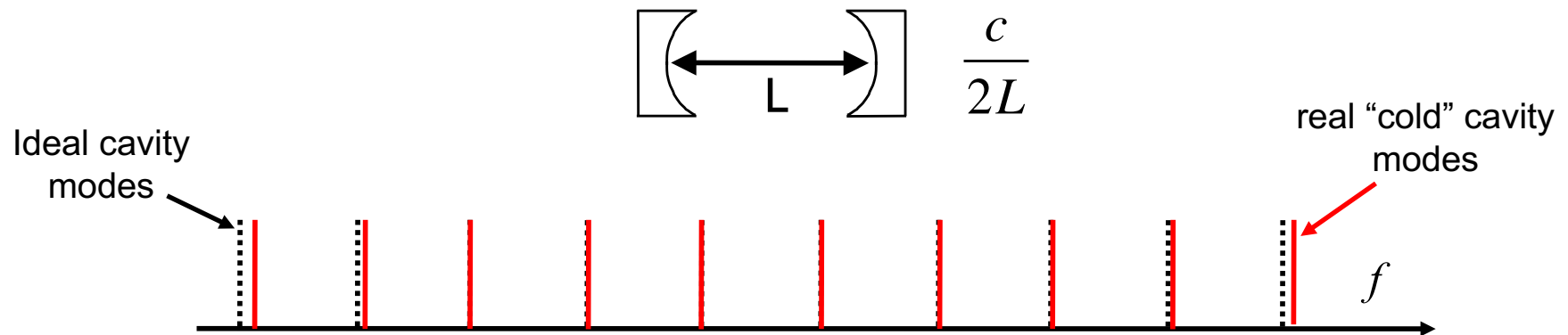
→ Cavity modes are locked in phase to generate a short pulse once every roundtrip time $2L/v_g$

How does it work?

→ All femtosecond lasers require:

- Laser cavity + broadband gain source and optical components
- **Dispersion control** → $\beta(\omega)$
- **Power-dependent gain or loss** → $n_2 I(r)$
- **Phase modulation** → $n_2 I(t)$

ideal mode spacing:



→ Due to dispersion, the cavity modes are not evenly spaced

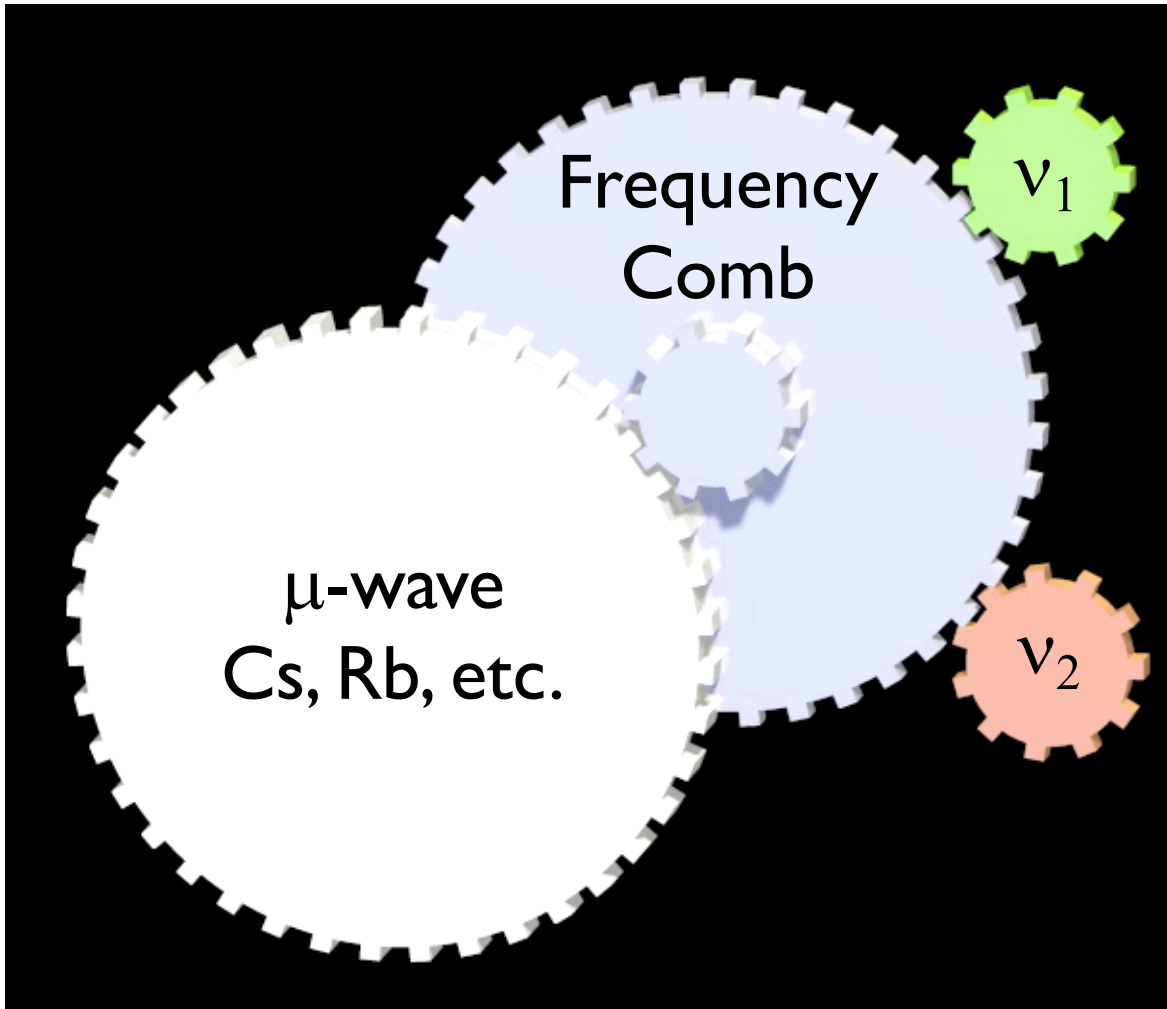
→ However, the **nonlinear phase-modulation** in a mode-locked laser provides the required synchronization of the modes.

→ Yields a strictly uniform mode comb with spacing $v_g/(2L)$

→ $\beta_2(\omega)$ and all higher orders of dispersion are compensated!

Multiple faces of a frequency comb

3. An optical clockwork



- Comb uncertainty at the 20th decimal place
- Measurement of optical ratios (e.g. $\nu_1 : \nu_2$)
- Direct connection from optical to microwave domains

Controlling the femtosecond laser comb

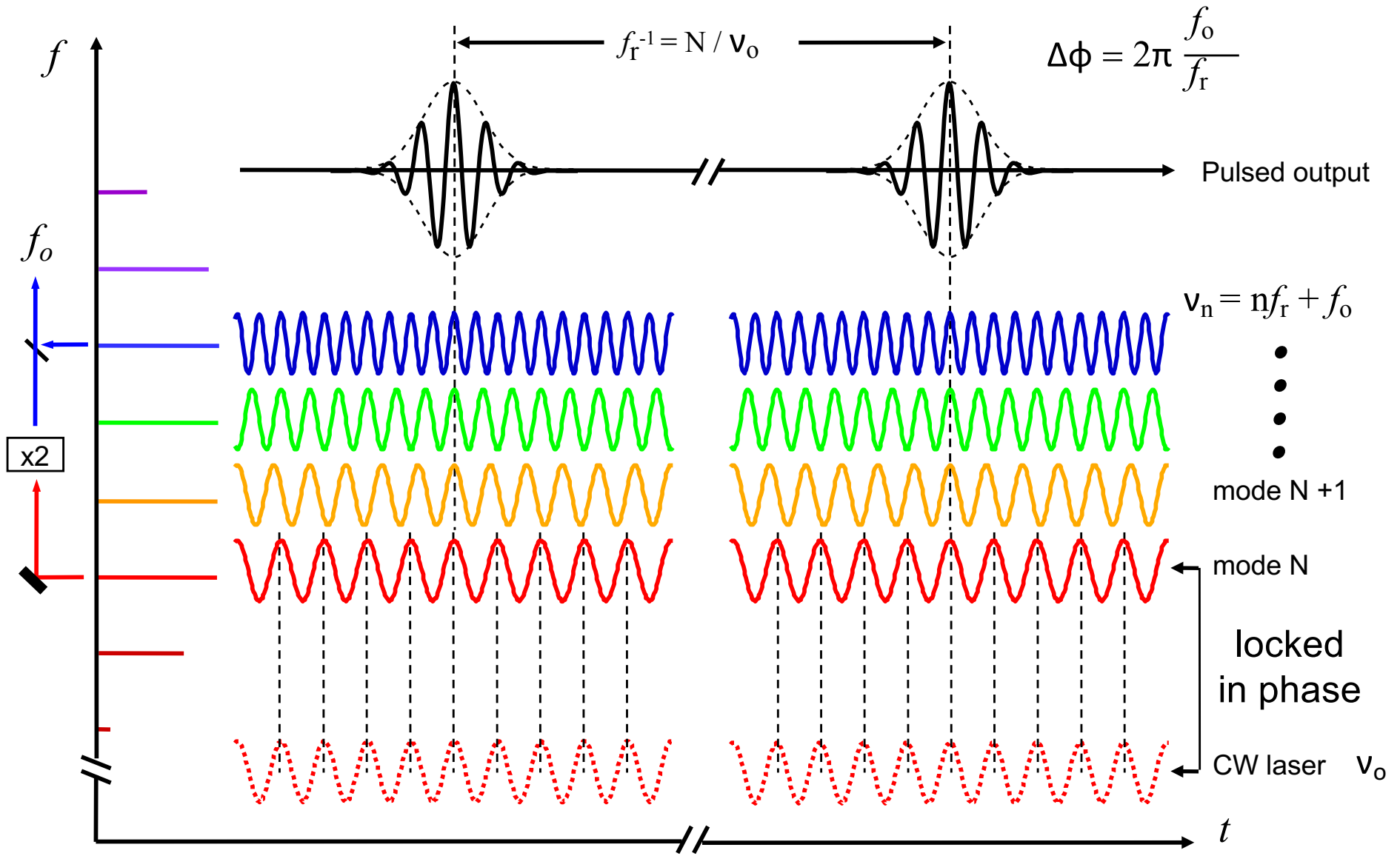
For most applications with the femtosecond laser frequency comb, we need to measure and control the two degrees of freedom of the frequency comb: f_o (offset frequency) and f_r (repetition rate)

$$f_n = n f_r + f_o$$

- f_o measured by “self-referencing”
 - Need an very broad spectrum (i.e. an octave)
- f_r controlled with a microwave source or a CW laser
- n determined by lower resolution measurement or a combination of measurements

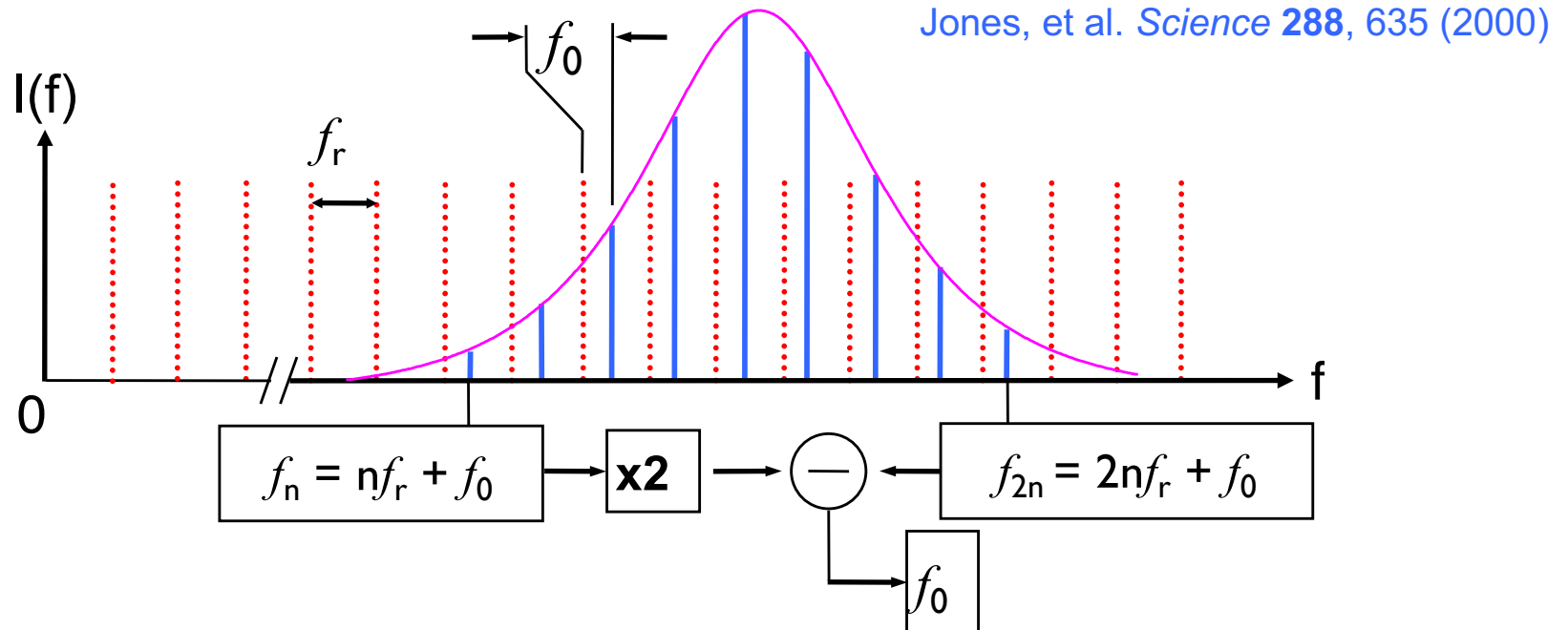
The laser comb and its control

Operational Definition: Comb = Frequency-stabilized Mode-locked Laser



Operation is fully reversible: Can lock at microwave and synthesize optical

Measuring/controlling the offset frequency: self-referencing

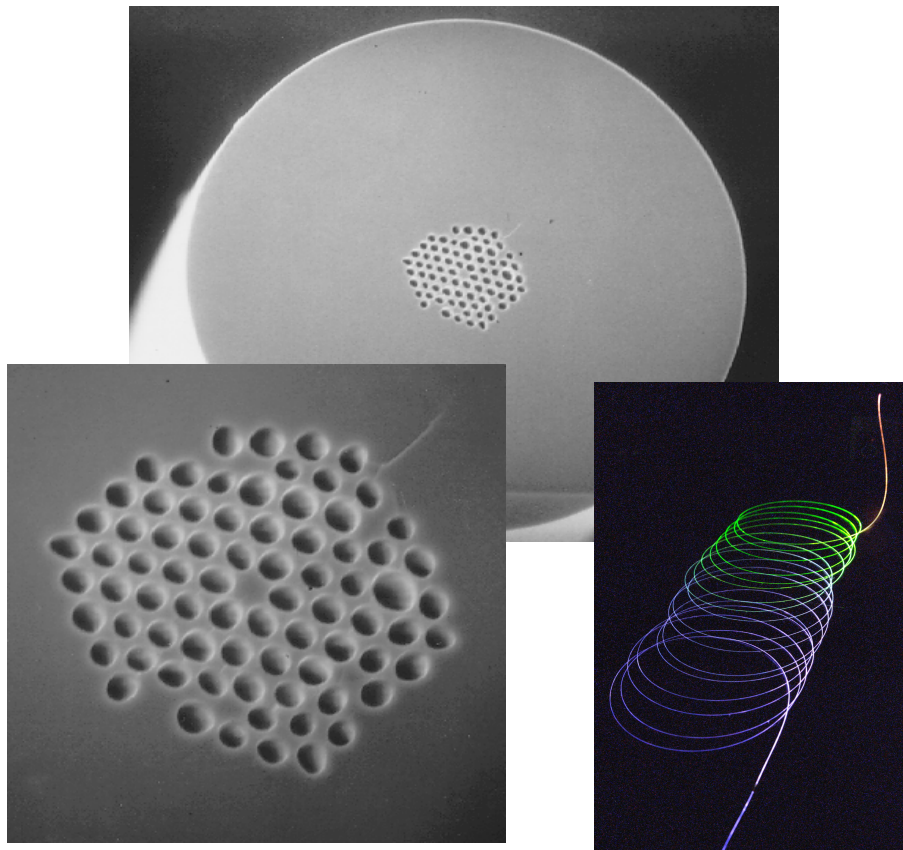


- f_0 is generated from a heterodyne beat between the second harmonic of a group of modes around the n^{th} mode and another group of modes around the $2n^{\text{th}}$ mode.

- Main Requirement: A very broad spectrum

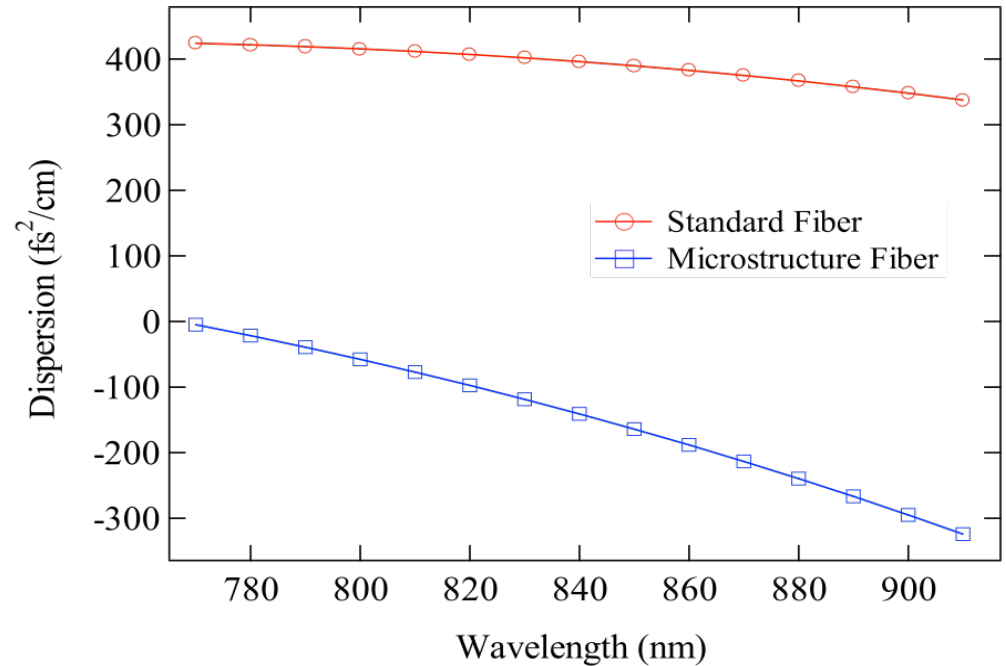
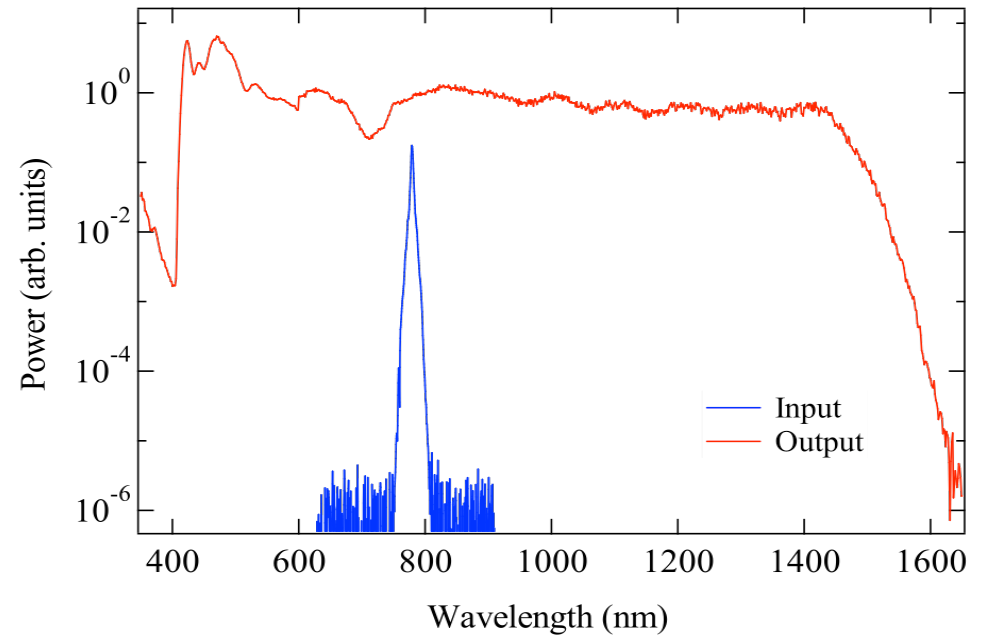
- Alternative schemes do exist, for which less than one octave is required: see H. Telle et al. *Appl. Phys. B* **69**, 327 (1999)

Microstructure optical fiber continuum generation

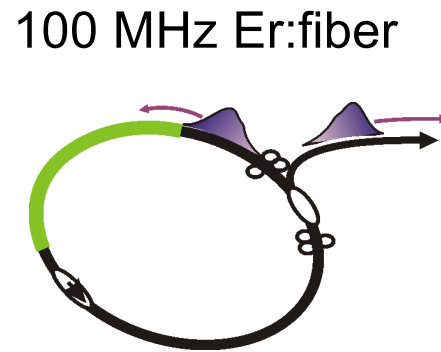
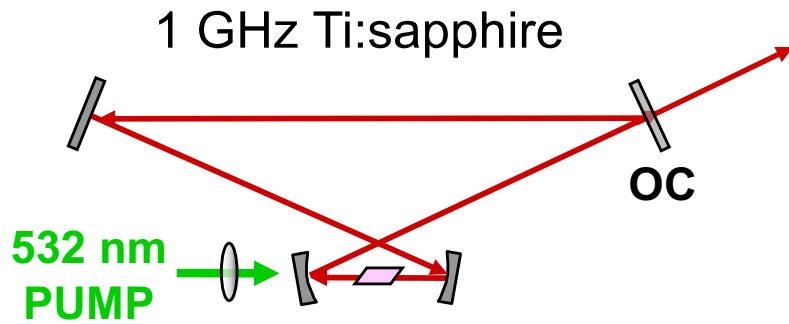


CLEO Postdeadline (CPD8) Baltimore (1999).
 J. Ranka, R. Windeler, A. Stentz, Opt. Lett. **25**, 25 (2000).

- Tight confinement of light leads to high nonlinearity and anomalous dispersion in the wavelength regime of femtosecond Ti:sapphire lasers
- Such fibers are available from commercial sources (ThorLabs, Crystal Fibre) and are developed in research labs (OFS, Univ. of Bath)



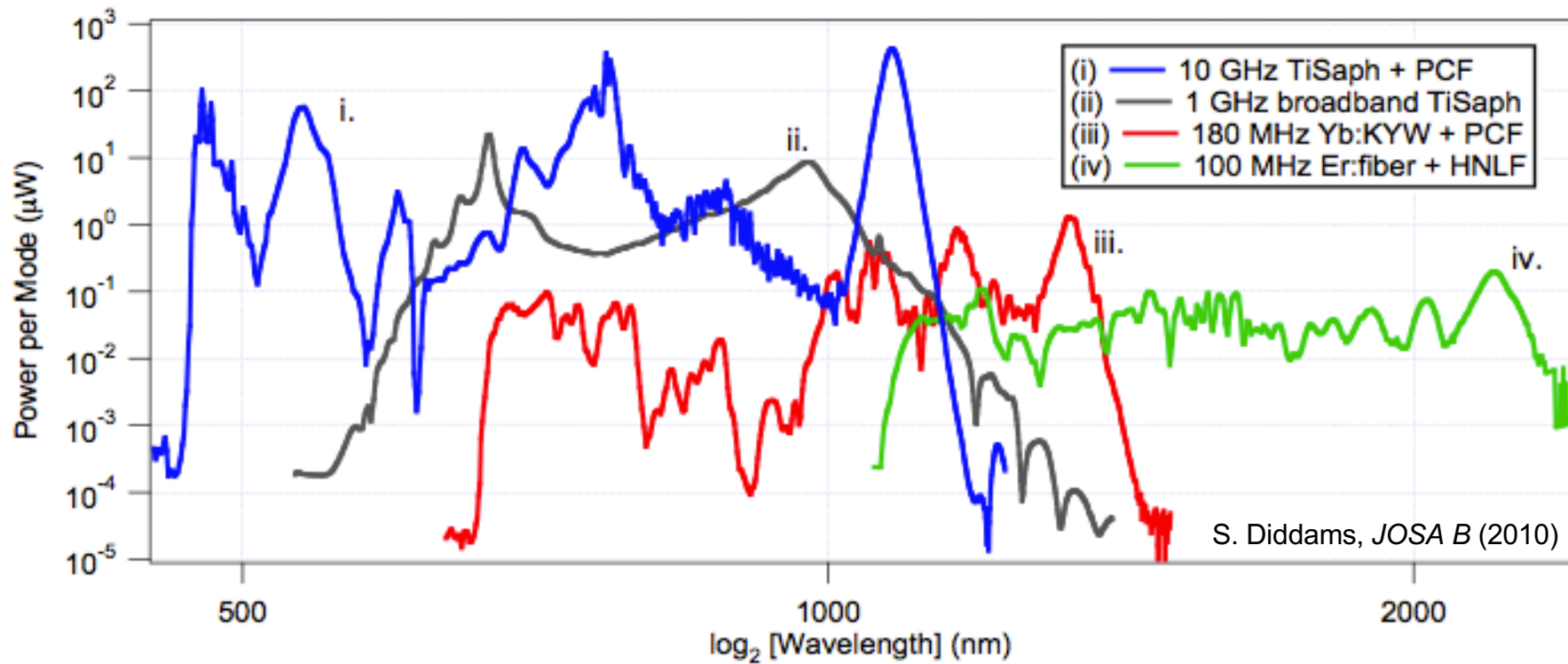
Octave-Span Supercontinuum



also....

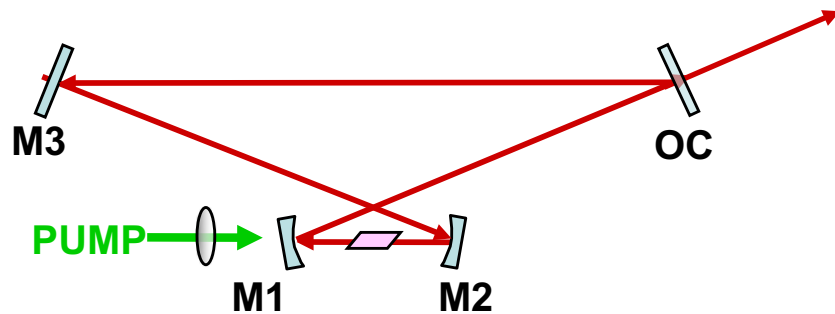
Yb:fiber
Yb:crystalline
Tm:fiber

.....

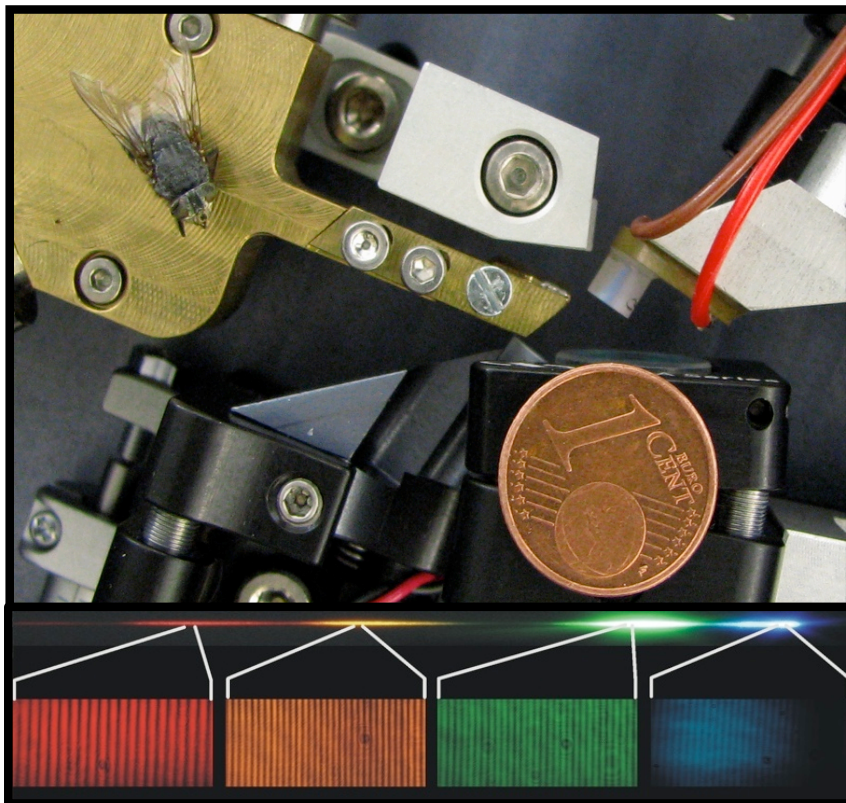


GHz Rep Rate Ti:Sapphire Combs

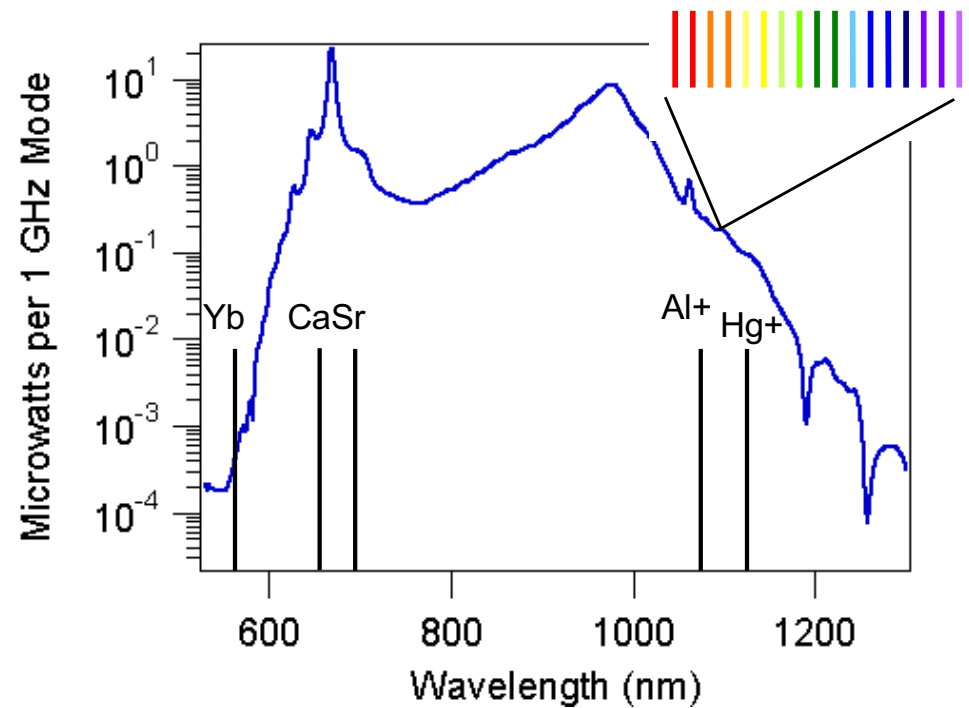
T. Fortier, A. Bartels, D. Heinecke, M. Kirchner



10 GHz Self-referenced Ti:sapphire Laser



1 GHz Octave Spanning Laser

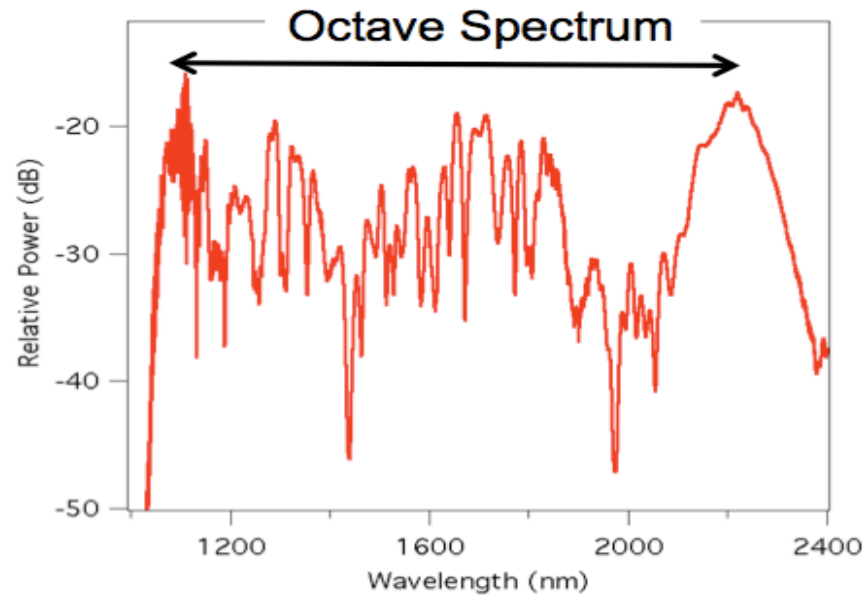
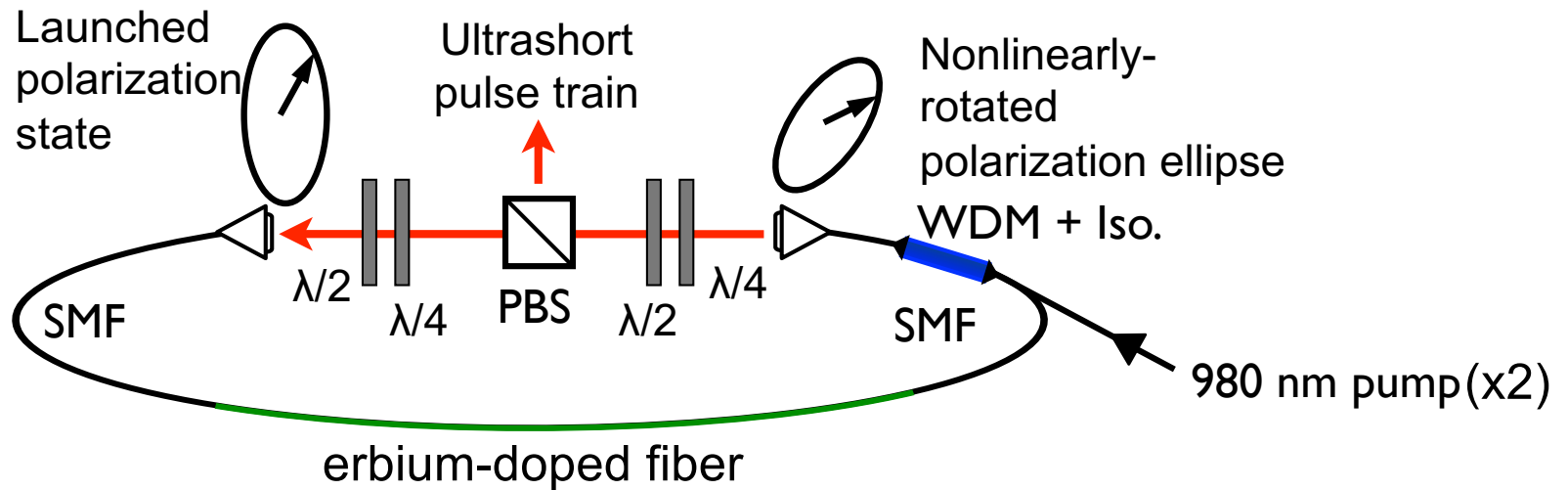


A. Bartels, H Kurz, *Opt. Lett.* 27, 1839 (2002)
T. Fortier, A. Bartels, S. Diddams, *CLEO* (2005)
T. Fortier, A. Bartels, S. Diddams, *Opt. Lett.* 31, 1011 (2006)

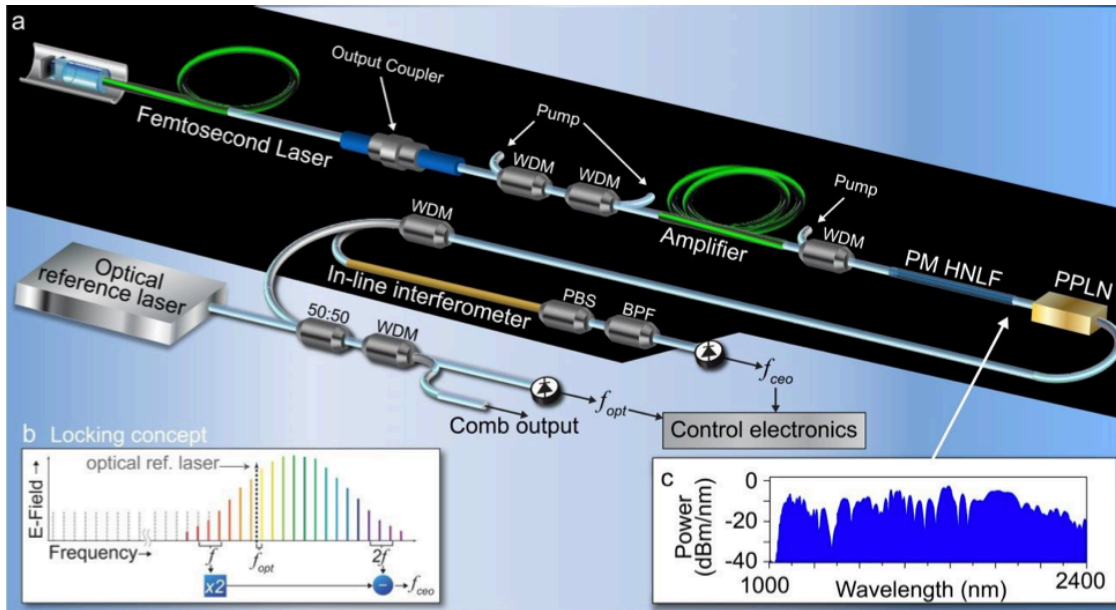
- Stabilized Comb = 10^6 Modes
- Hz-level linewidths
- Residual frequency noise at 1×10^{-19} level

Er: fiber based frequency combs

→ mode-locking based on nonlinear polarization rotation



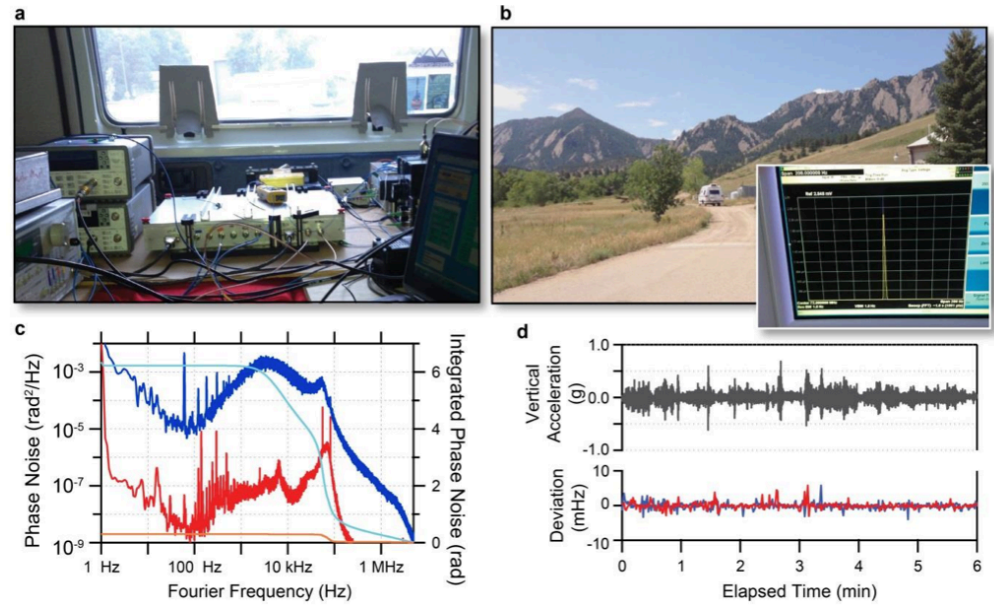
Polarization-maintaining Er: fiber laser comb



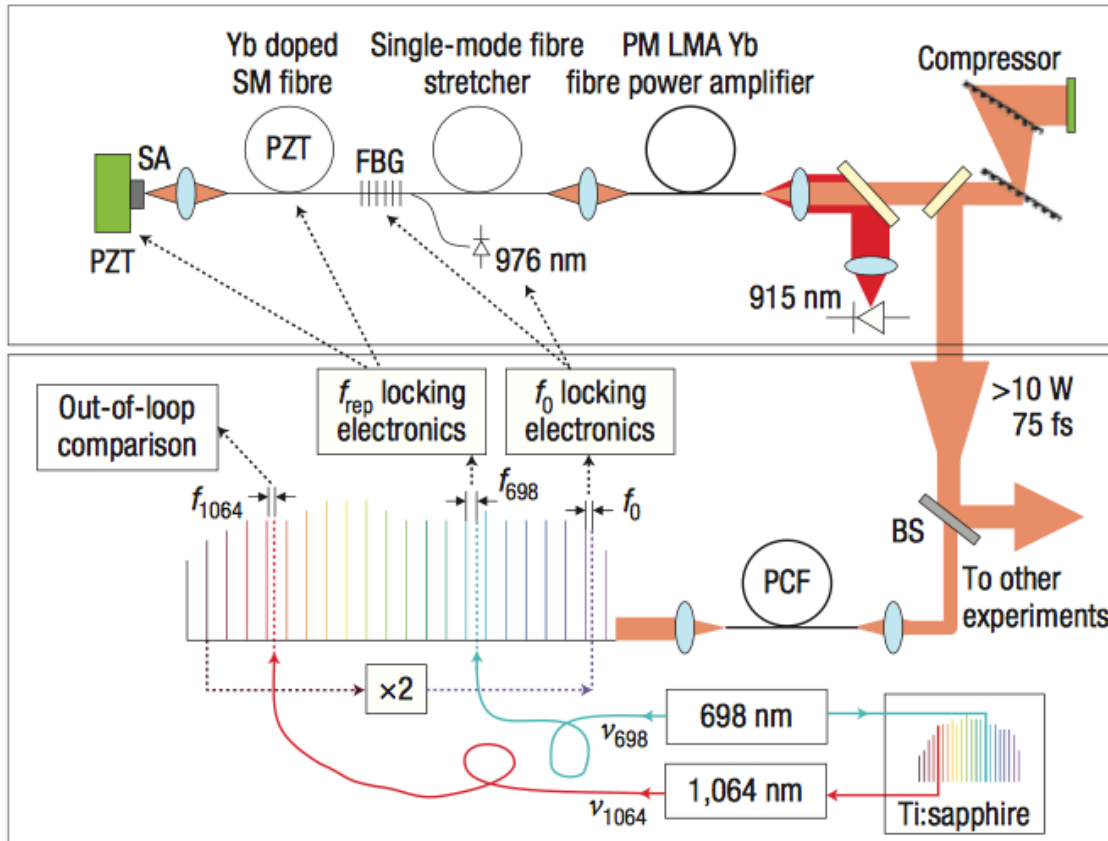
- Laser + amplifier + self-referencing are all constructed “in-line” with polarization-maintaining (PM) fiber optics.
- Laser is mode-locked with saturable absorber mirror
- Robust against environmental perturbations.

(Newbury group at NIST)

Frequency comb operates phase-locked in a moving vehicle.



High-power Yb: fiber laser frequency comb

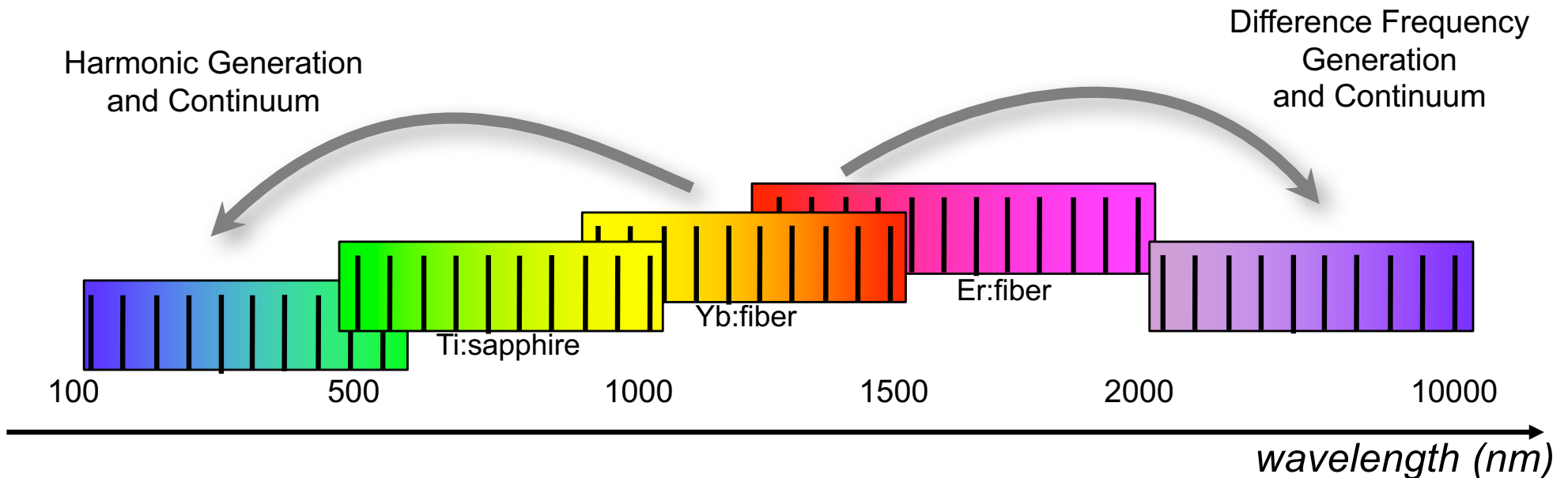


- Linear cavity design
- Saturable absorber end mirror for mode-locking
- Fiber Bragg grating provides output coupling and dispersion control
- **External amplification to ~80 W** followed by compression to ~100 femtosecond pulses
- Supports **sub Hz linewidths**

Schibli, et al. *Nature Photonics* 2, 355 - 359 (2008)

Frequency Comb Extension via Nonlinear Optics

- Using a combination of harmonic generation, difference frequency generation and super-continuum, frequency combs have been extended from the UV to the infrared



- Some examples:

- Extreme ultraviolet via harmonic generation: *Phys. Rev. Lett.* **94**, 193201 (2005); *Nature* **436**, 234-237 (2005); *Science* **307**, 400 (2005);
- Mid-infrared comb generation via OPO, DFG and supercontinuum: *Opt. Lett.* **34**, 1330 (2009); *Opt. Lett.* **37**, 1400 (2012); *Lett.* **39**, 2056 (2014); *Opt. Lett.* **36**, 2275-2277 (2011).