# Optical Frequency Combs: Nonlinear Optics and the Meeting of the Ultrafast and Ultrastable


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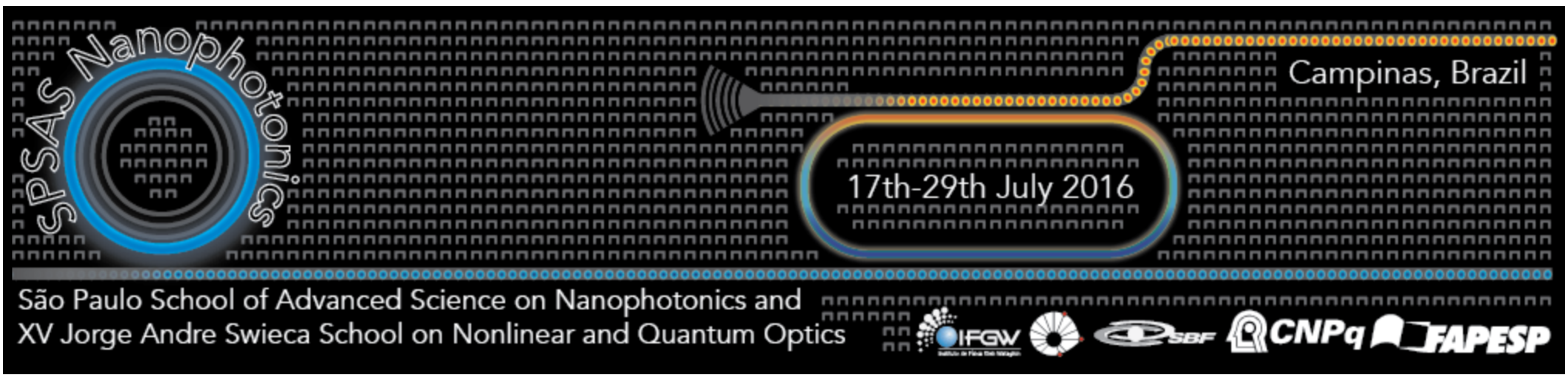

# Learning & Research: A continuous upward climb

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***

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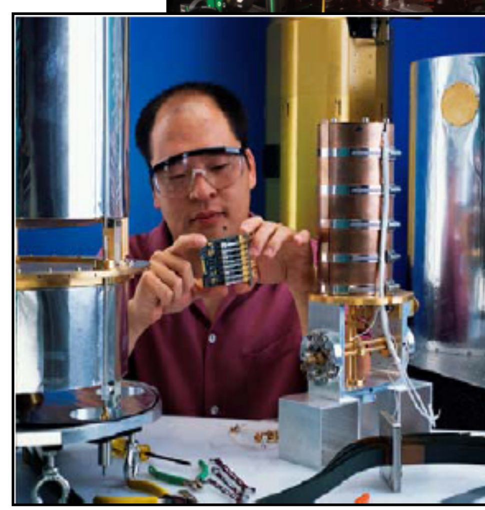
***25 square miles surrounded by reality***

# 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…*

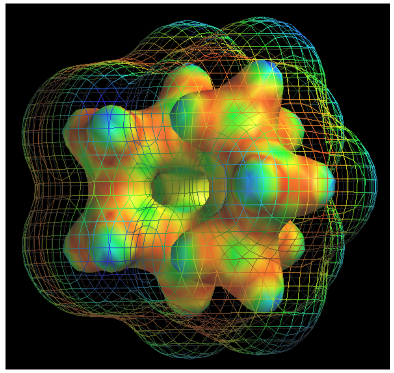



NIST Boulder assets include (*approximate* values):

- 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.

# Research at NIST Boulder

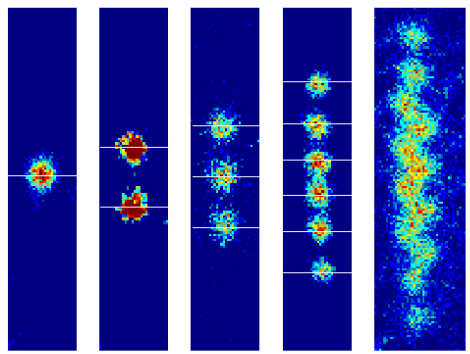
Chem-Physics



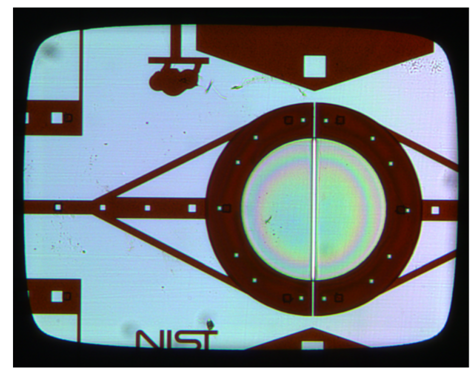
Electromagnetics

Nanotechnology

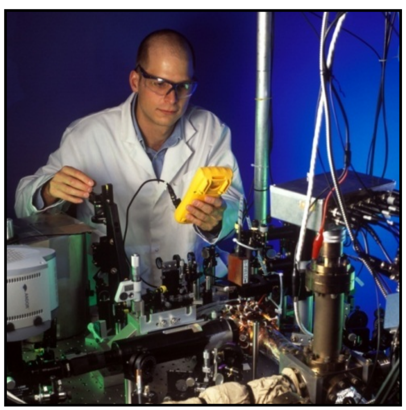
Quantum Information



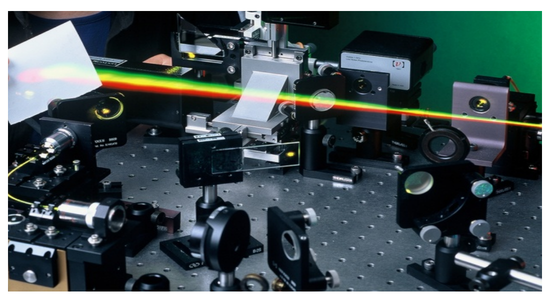
Advanced Materials



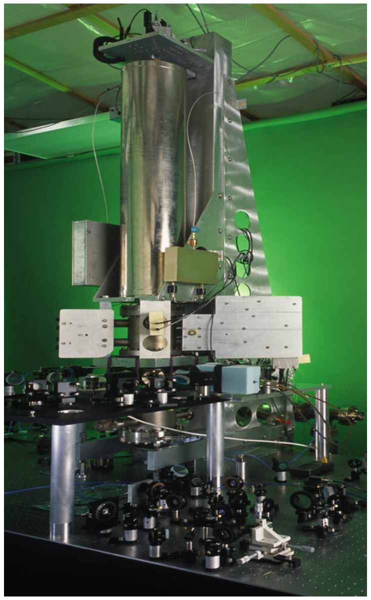
Atomic Clocks



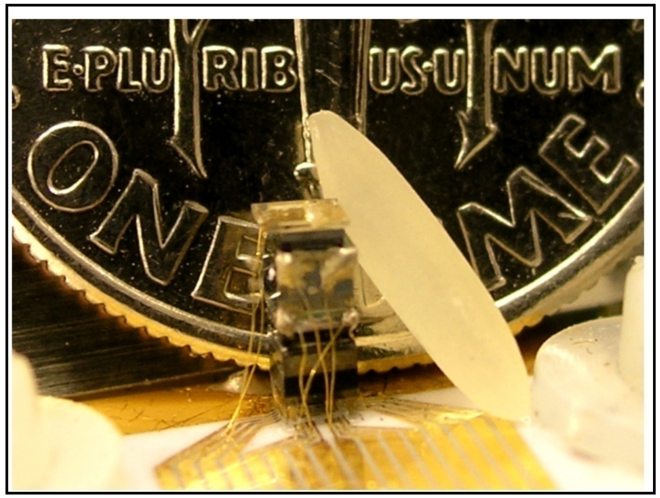
Lasers/Photonics



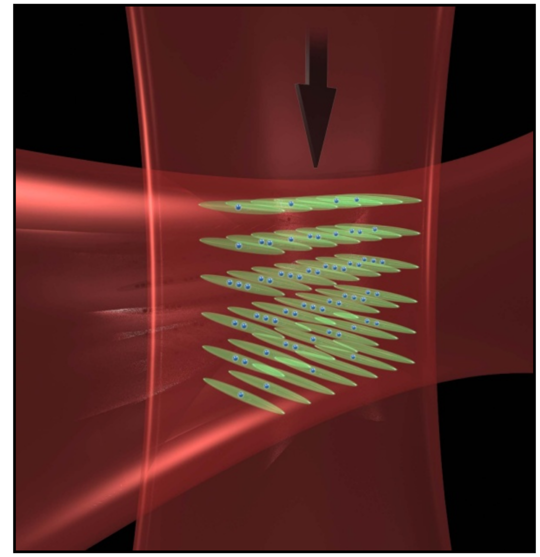
# Time and Frequency Metrology



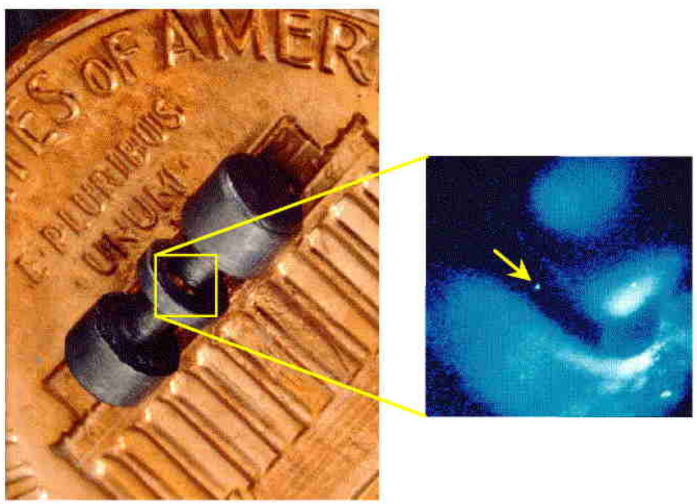
Cs Fountain Clock



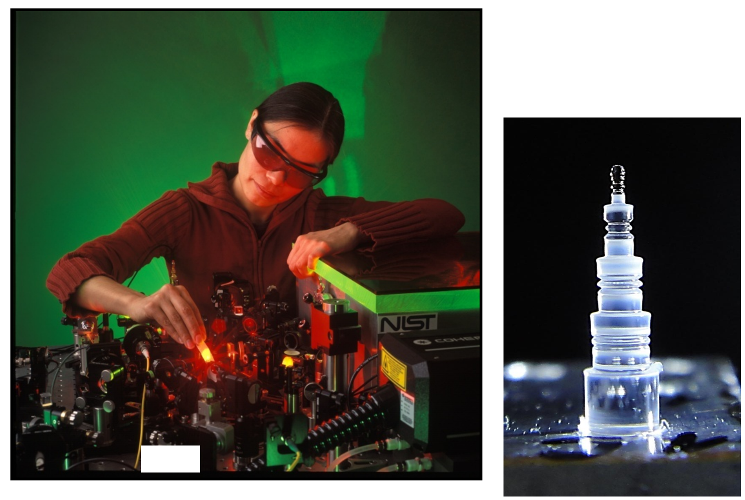

Chip-Scale Clocks



Optical lattice clocks

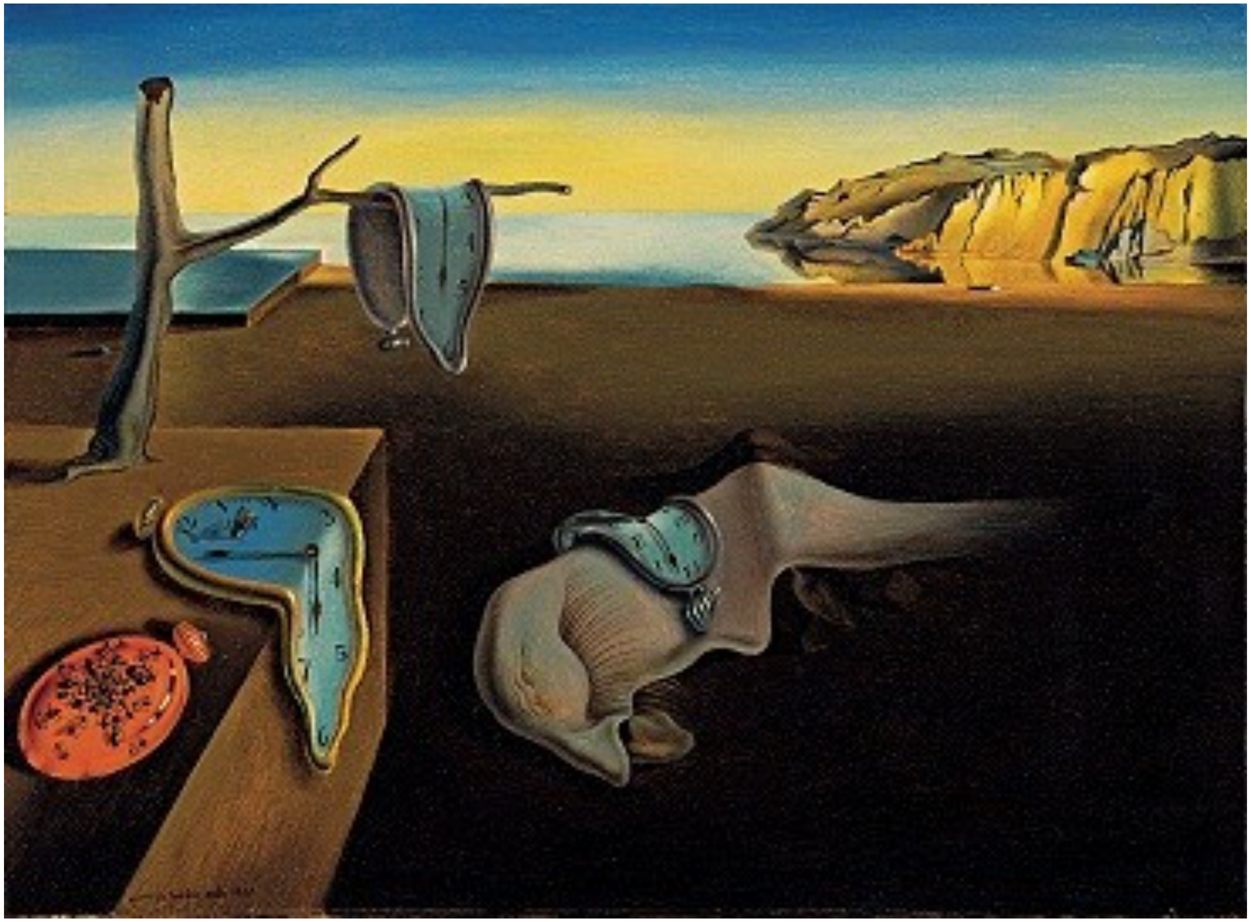


Single Ion Clocks



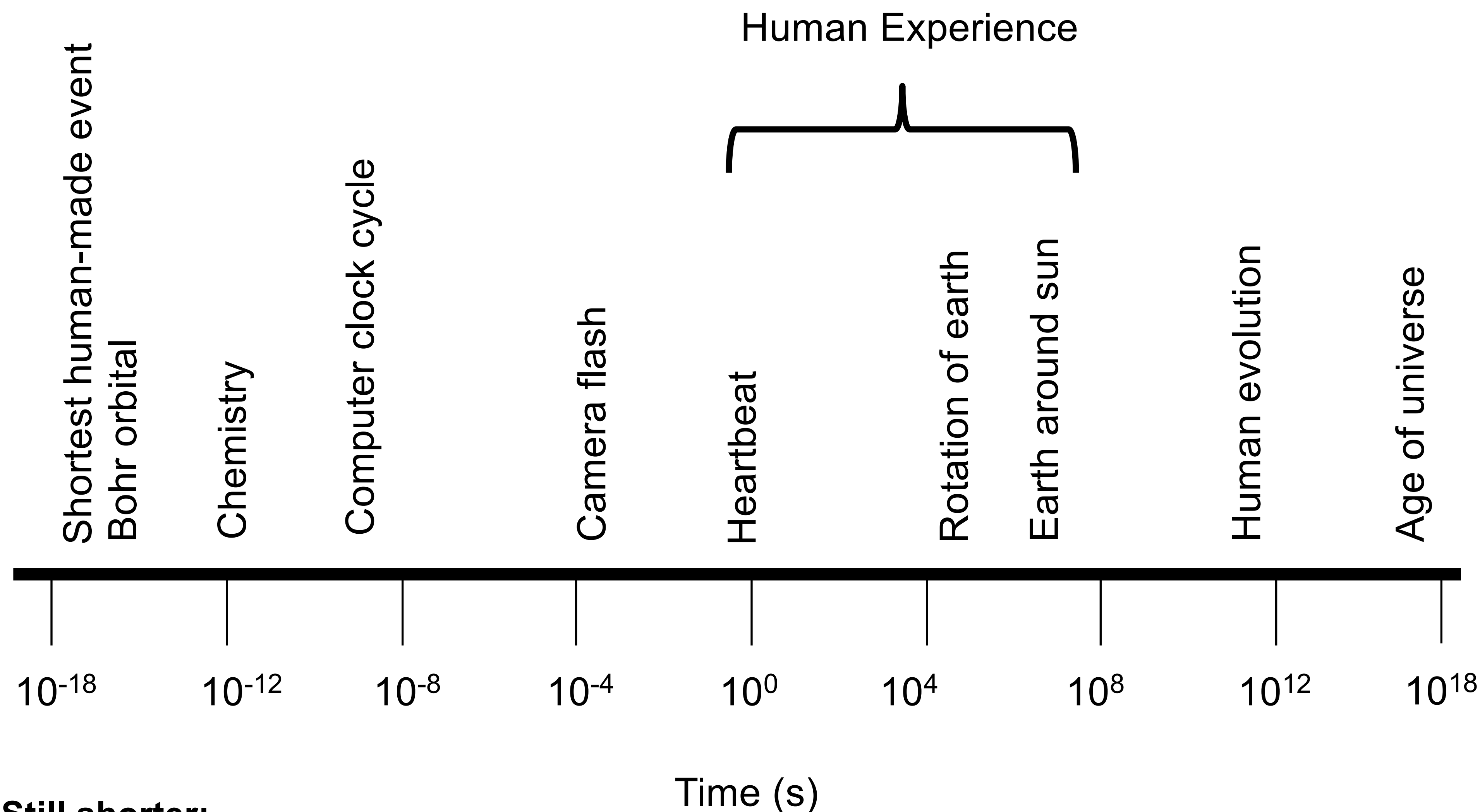
Optical Frequency Combs

# Background: Clocks and Precise Timing



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

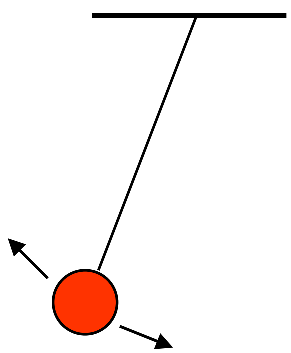
# Timescales

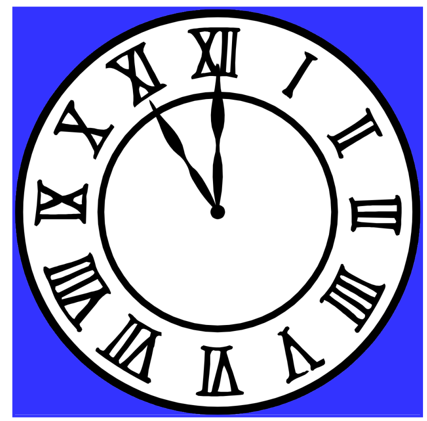



**Still shorter:**
Top Quark lifetime: $4 \times 10^{-25}$ s
Planck time: $10^{-43}$ s

# What Makes a Clock?

**Oscillator** **+** **Counting Mechanism**






Earth Rotation
Pendulum
Quartz Crystal

Sundial
Clock Gears/Hands
Electronic Counter

ATOMIC CLOCKS

Microwave Transition + Oscillator — Electronic Counter
Optical Transition + Laser — Femtosecond Laser

# 'COSMIC PENDULUM' FOR CLOCK PLANNED

## Radio Frequencies in Hearts of Atoms Would Be Used in Most Accurate of Timepieces

## DESIGN TERMED FEASIBLE

### Prof. I. I. Rabi, 1944 Nobel Prize Winner, Tells of Newest Developments

By WILLIAM L. LAURENCE

Blueprints for the most accurate clock in the universe, tuning in on radio frequencies in the hearts of atoms and thus beating in harmony with the "cosmic pendulum," were outlined yesterday at the annual New York meeting of the American Physical Society, at Columbia University, by Prof. I. I. Rabi, who delivered the Richtmyer Memorial Lecture under the auspices of the American Association of Physics Teachers.

Professor Rabi won the Nobel Prize in physics for 1944 for his epoch-making discovery of minute radio transmitting stations in the nuclei of atoms and for his devising of exceedingly delicate receiving sets for tuning in on these cosmic broadcasts and deciphering the messages that the atoms had been sending out since the beginning of time.

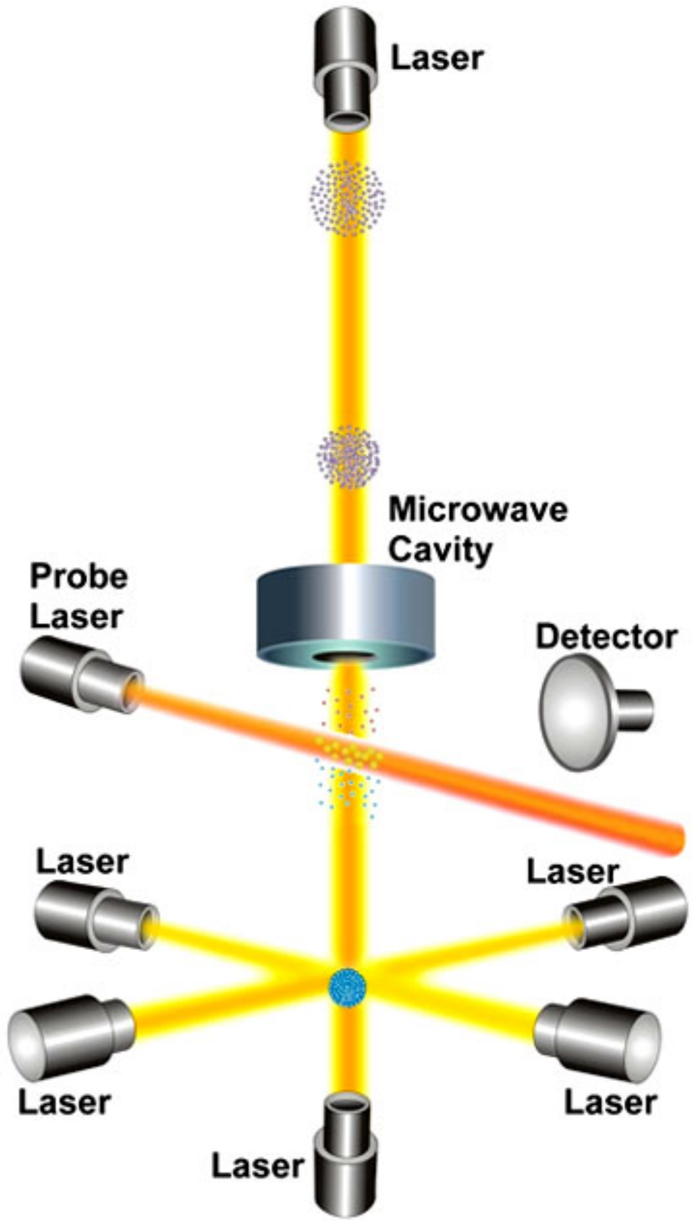
The New York Times

Jan. 21, 1945

First public description of atomic clocks given at 1945 APS/AAPT meeting and recorded by the New York Times…..

NIST

# Cs Fountain Clock: The Current Standard and the Definition of the Second



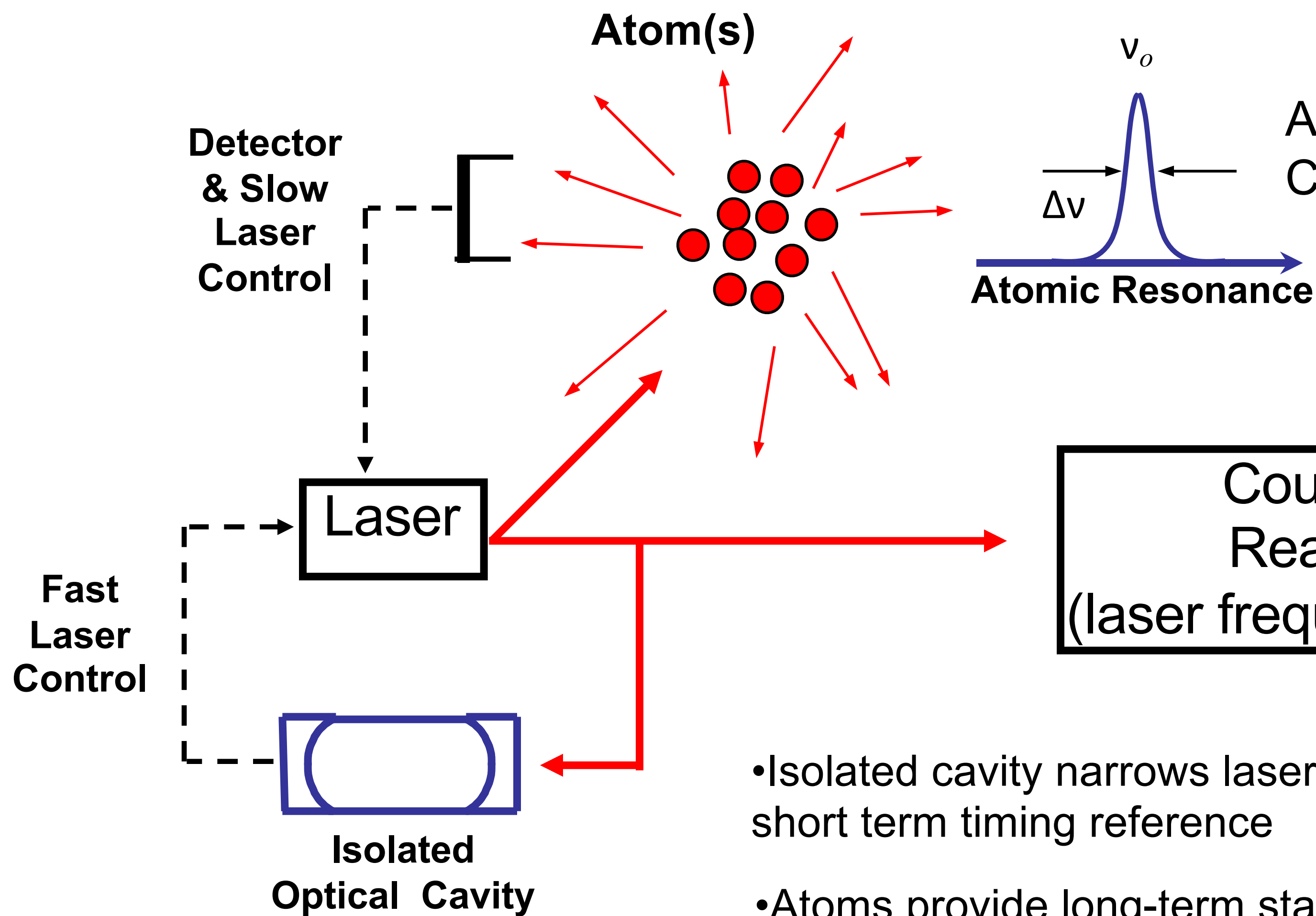

$f_{Cs}$=9,192,631,770 Hz

Total Uncertainty $\sim 1 \cdot 10^{-16}$

Cold Atoms allow long interaction times

S. Jefferts, T. Heavner, T. Parker (NIST)

# Optical Atomic Clocks




At NIST/JILA:
Ca, Hg+, Al+, Yb, Sr

Counter &
Read Out
(laser frequency comb)

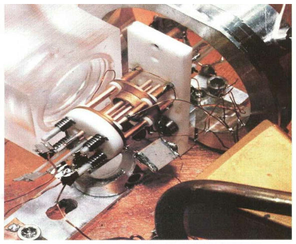
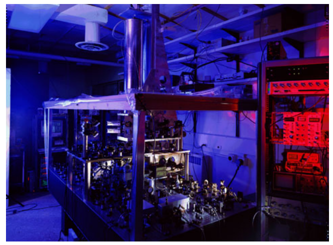
•Isolated cavity narrows laser linewidth and provides short term timing reference

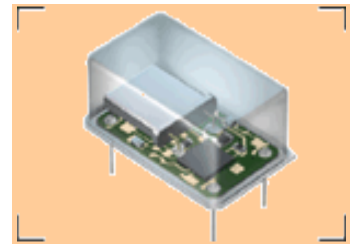
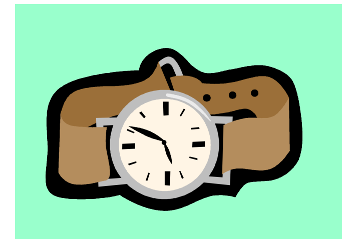
•Atoms provide long-term stability and accuracy—
**now now at $10^{-18}$ level!**

•Laser frequency comb acts as a divider/counter

# 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 | $10^{7}$ cm$^{3}$ | 100 cm$^{3}$ | 1 cm$^{3}$ | $10^{-3}$ cm$^{3}$ |
| Stability (1s): | **$10^{-16}$** | $10^{-13}$ | $10^{-10}$ | $10^{-11}$ | $10^{-6}$ |
| Cost: | **??** | $1 M | $1,000 | $100 | $1 |

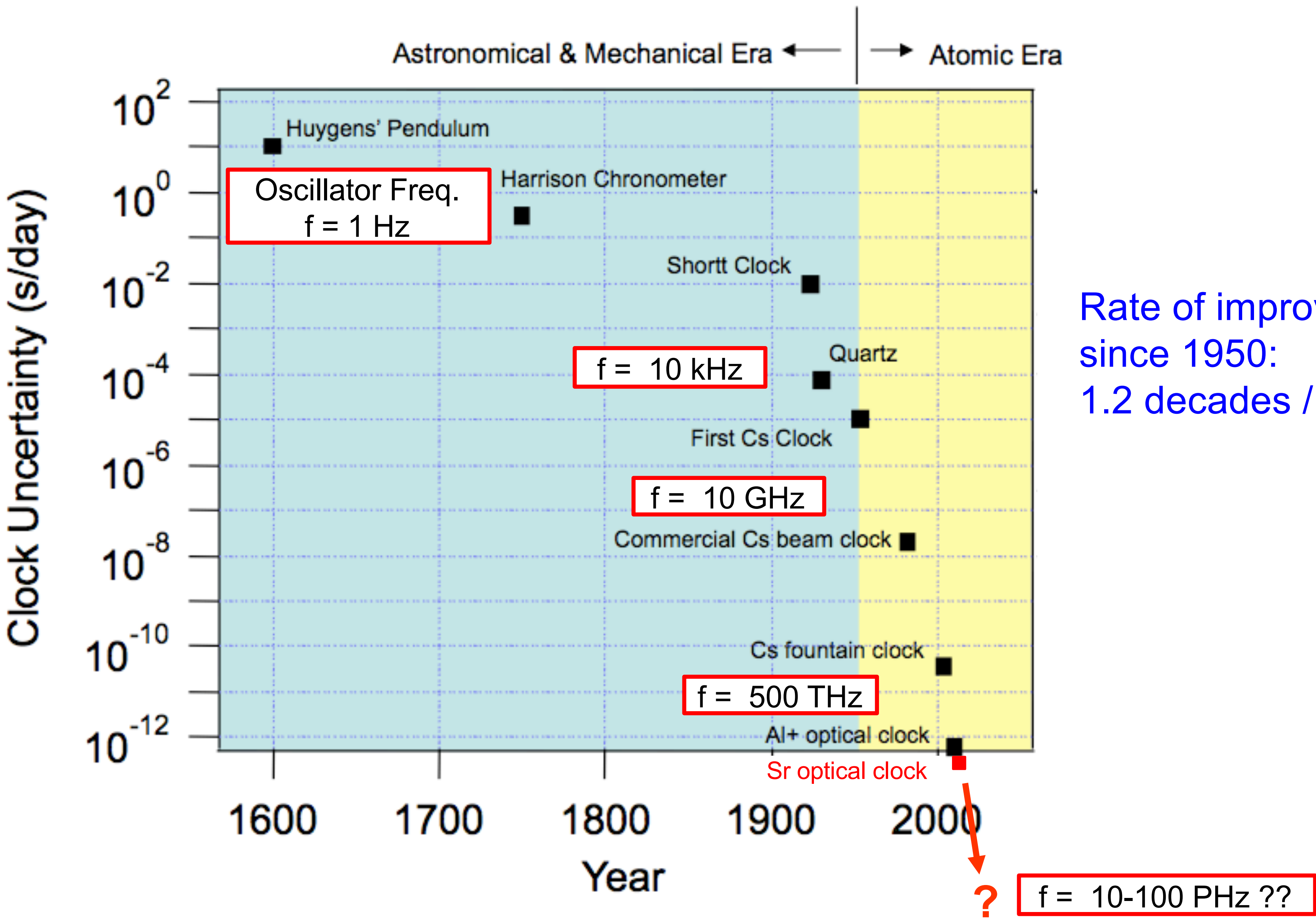
→ "Smaller"

All atomic clocks have:
- Reference atom
- Local oscillator (pendulum)
- Counter/gears

Figure: J. Kitching, (NIST)

NIST

# Timekeeping: The long view

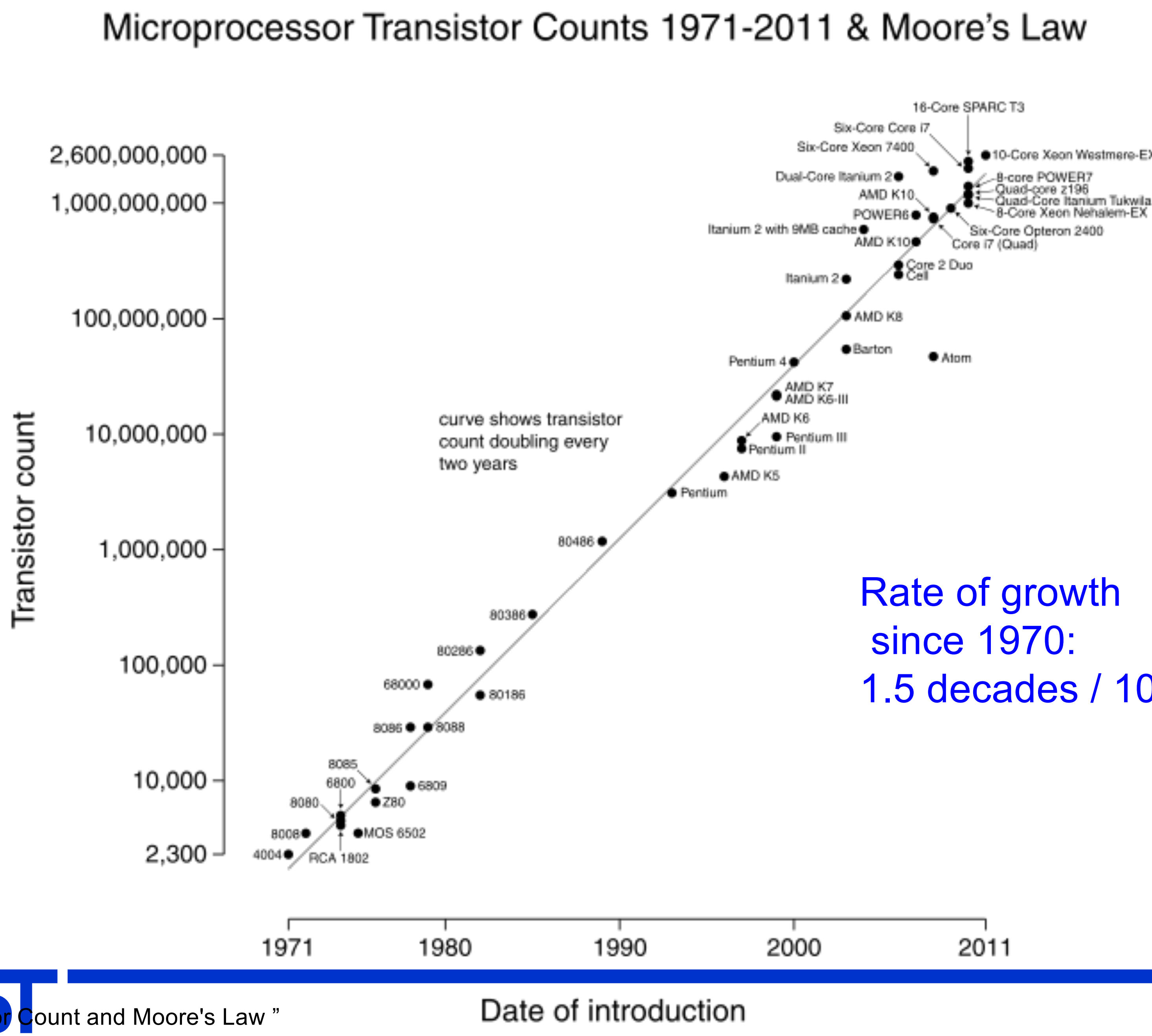



Rate of improvement since 1950:
1.2 decades / 10 years

NIST

S. Diddams, et al, Science (2004)

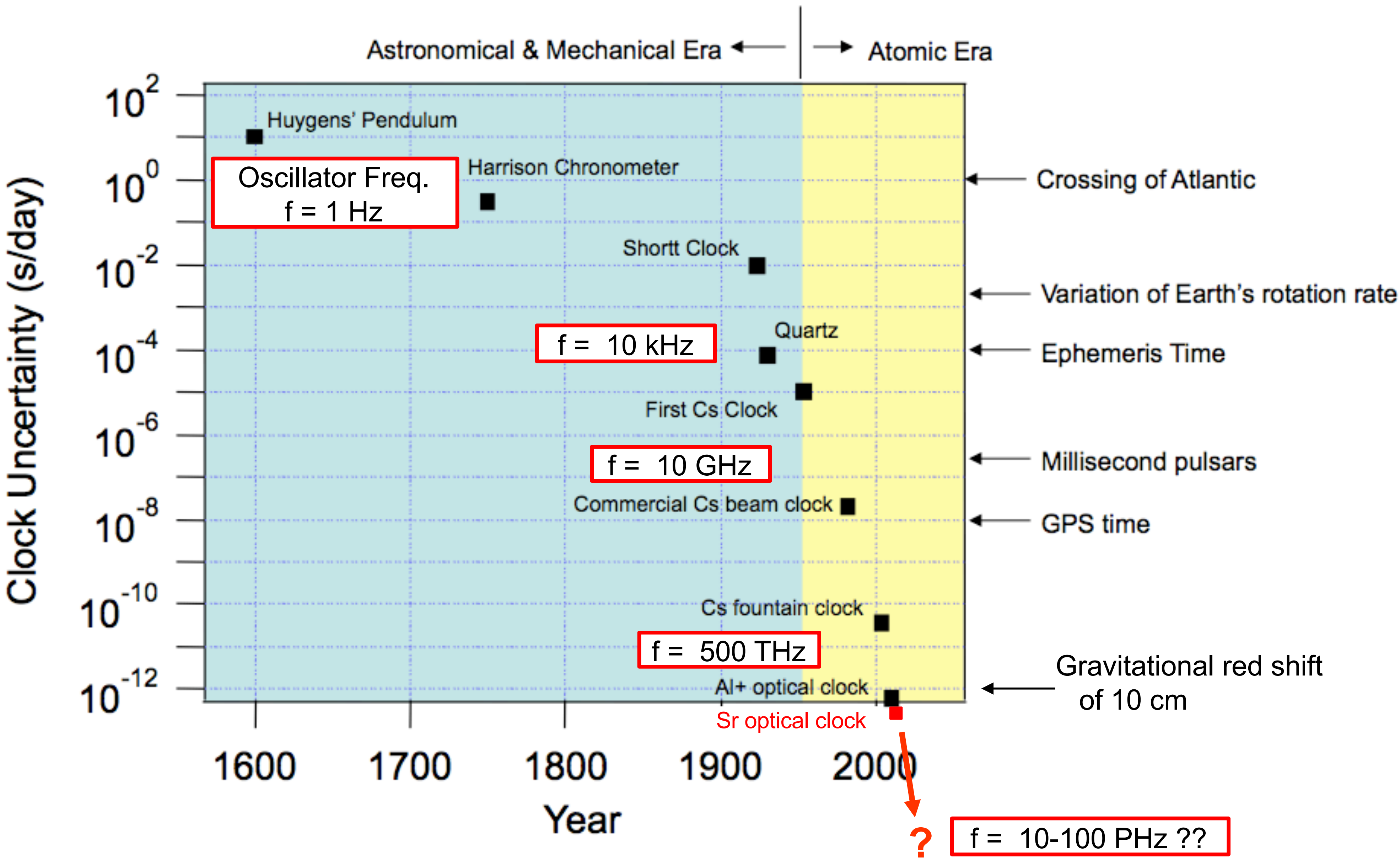
# Moore's Law for Transistors per Chip




Rate of growth
since 1970:
1.5 decades / 10 years

Wiki: "Transistor Count and Moore's Law "

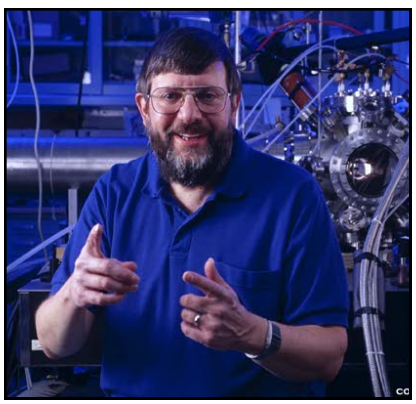
# Timekeeping: Societal and Scientific Impact



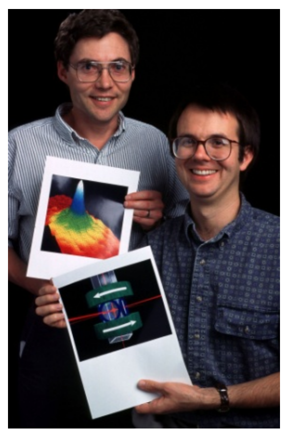

S. Diddams, et al, Science (2004)

# 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** | **Jan Hall,** Ted Hansch, Roy Glauber | Femtosecond laser frequency combs. |
| **2012** | **Dave Wineland,** Serge Haroche | Quantum state measurement and manipulation. |

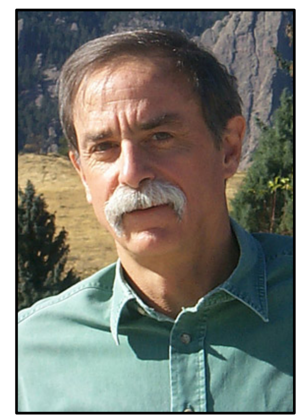


*Bill Phillips*
*NIST*



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

*Jan Hall*
*JILA/NIST*



*Dave Wineland*
*NIST*

# Why do we need better clocks?

- Time/Frequency are best known physical quantities:  The anchor of the SI (the Second impacts Length, Mass, Voltage, Current…)

- Navigation and communication

- Geodesy:  Gravitational red shift of 1 cm in earth's potential ~ $1 \times 10^{-18}$

- Probe for "New" Physics:
  - Constancy of fundamental constants
  - Local position invariance
  - Tests of QED
  - Astrophysics – millisecond pulsars

- Quantum state engineering:  In the future the best clocks will employ quantum entanglement

# Outline

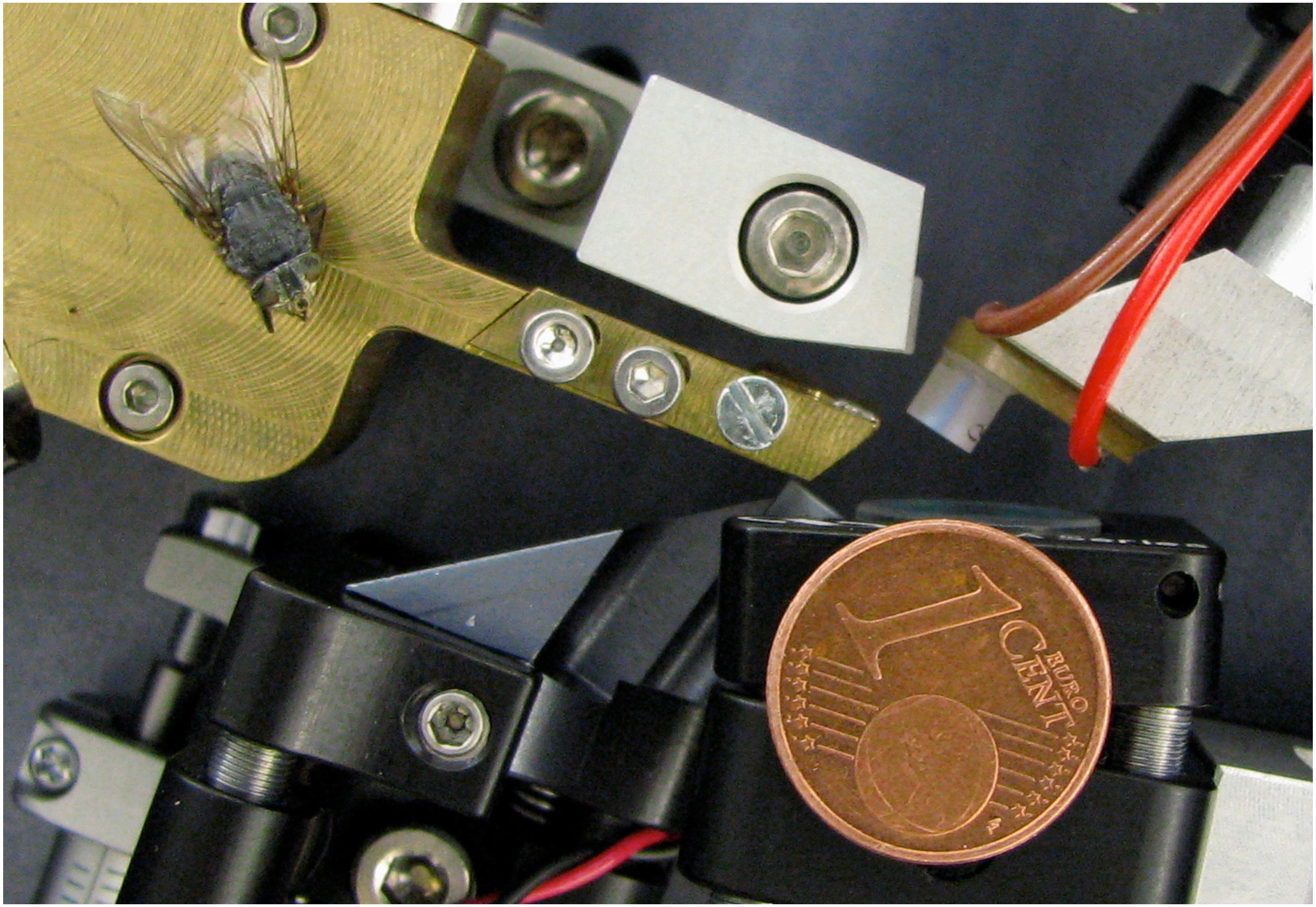
1. Background: Clocks and Precise Timing

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

# Counting Cycles of Light

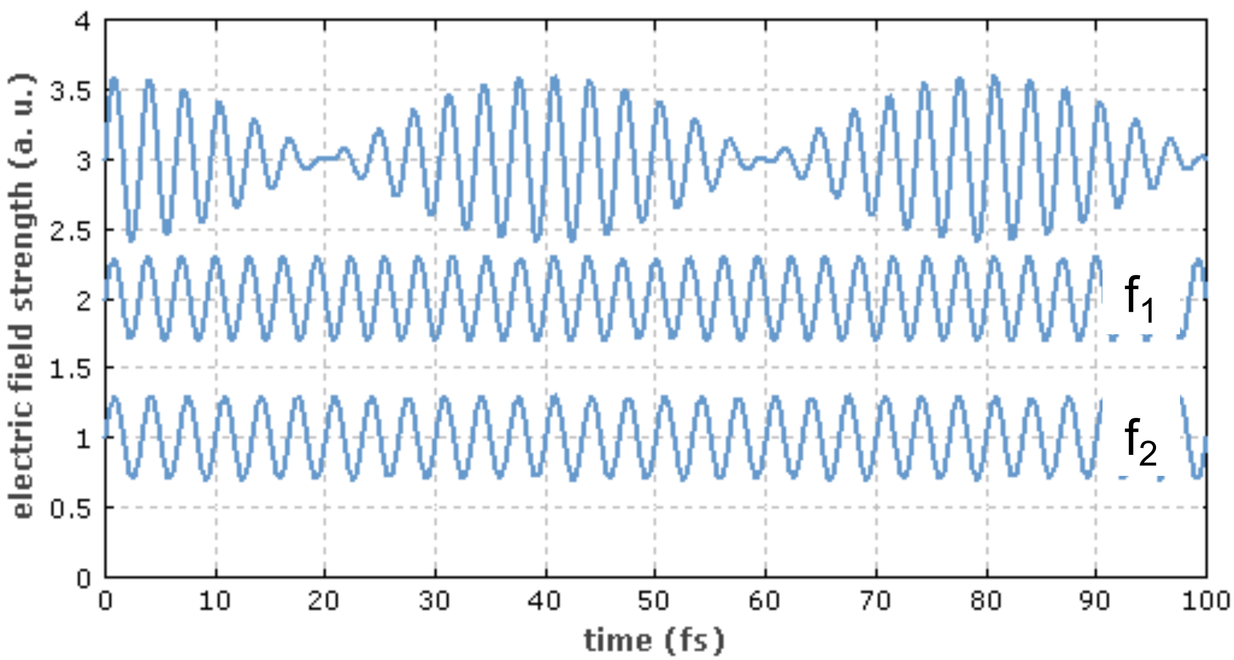


# How Do You Count Optical Cycles?

**Optical Frequency:** c/600 nm = 500 THz → **T=2 fs**

**Fastest electronics:** 1 THz, **1 ps**

**Optical Heterodyne:** Measure "beat note" between two optical frequencies



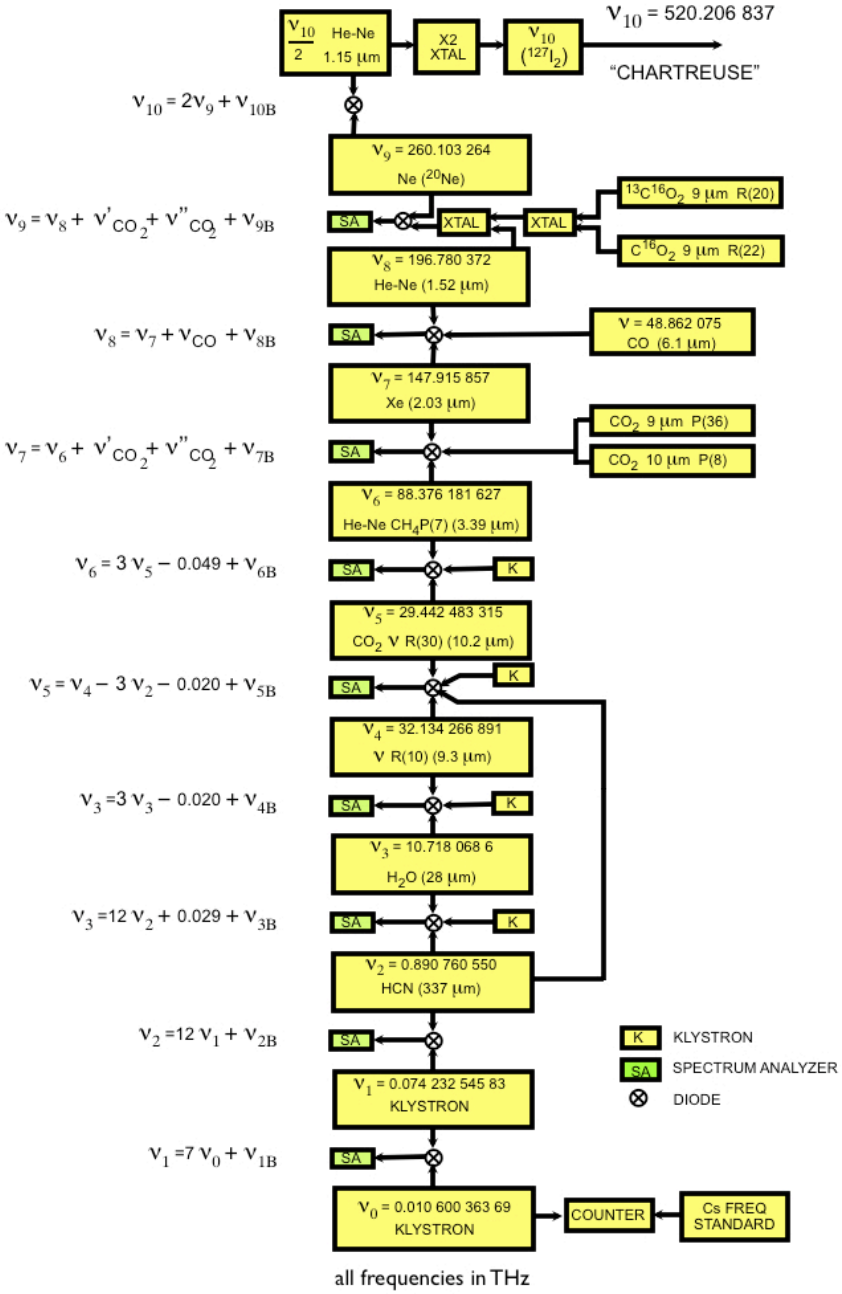

Carrier: $(f_1 + f_2)/2$

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

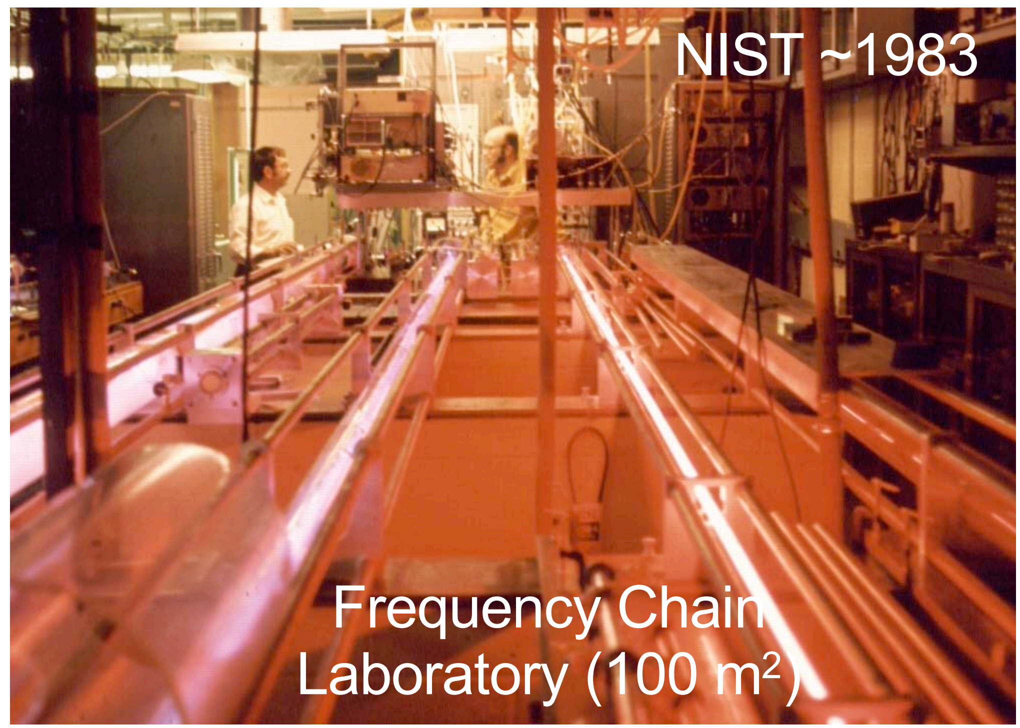
# Direct Multiplication




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

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

It worked! But not general, practical, cost effective



# What is a *laser frequency comb*??

Google

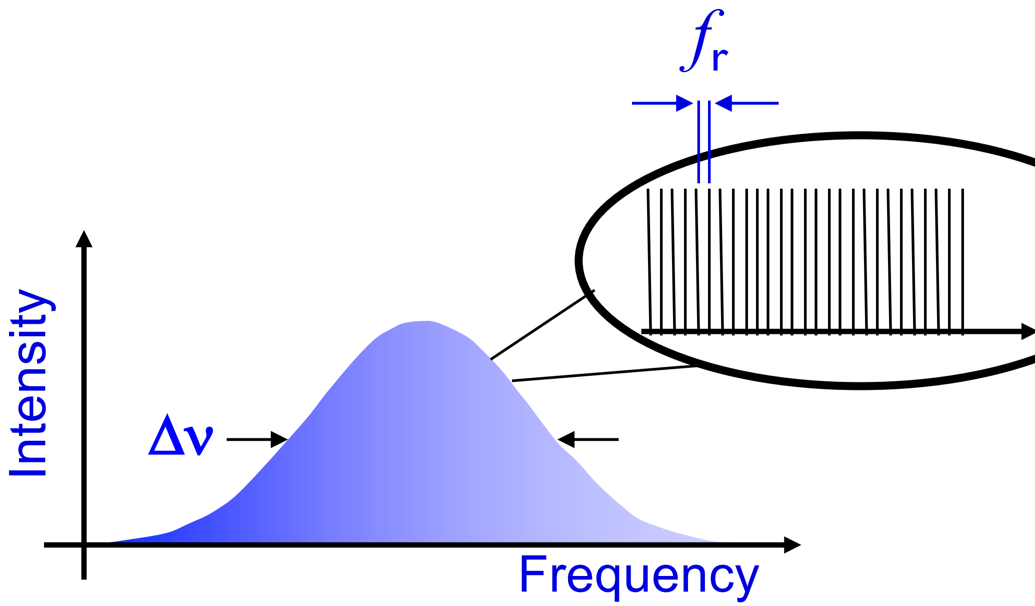
http://www.hairmax.com/


Client's quote :
**"I used to have only one or two good hair days a month. Now, every day is a good hair day."**

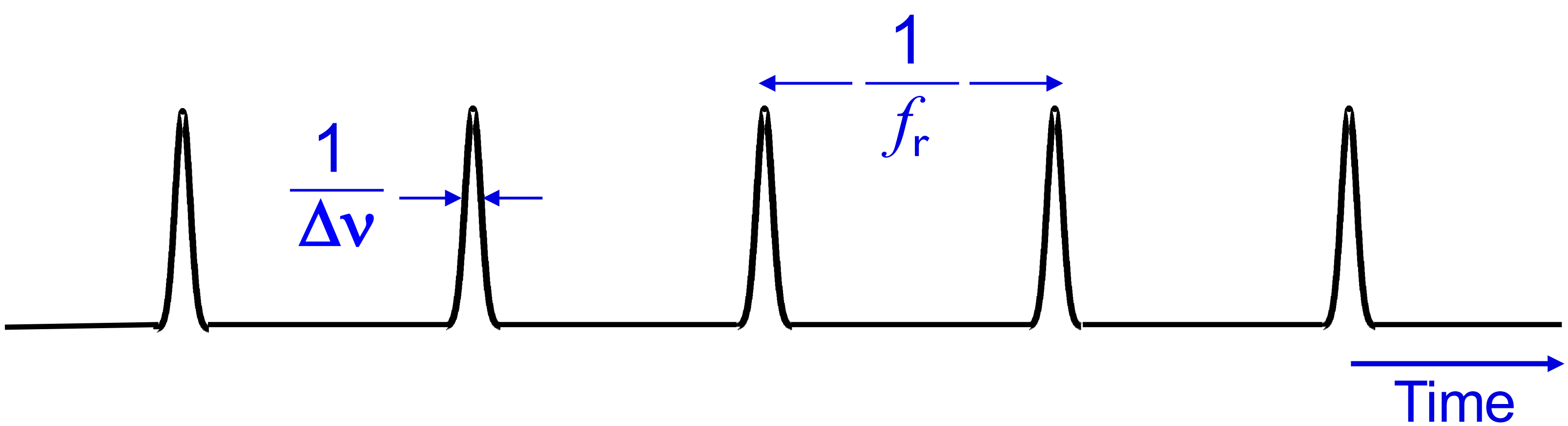
LASERCOMB Brasil
Lasercomb Brasil - Laserbras

# Multiple faces of a frequency comb

1. A ruler for light frequencies

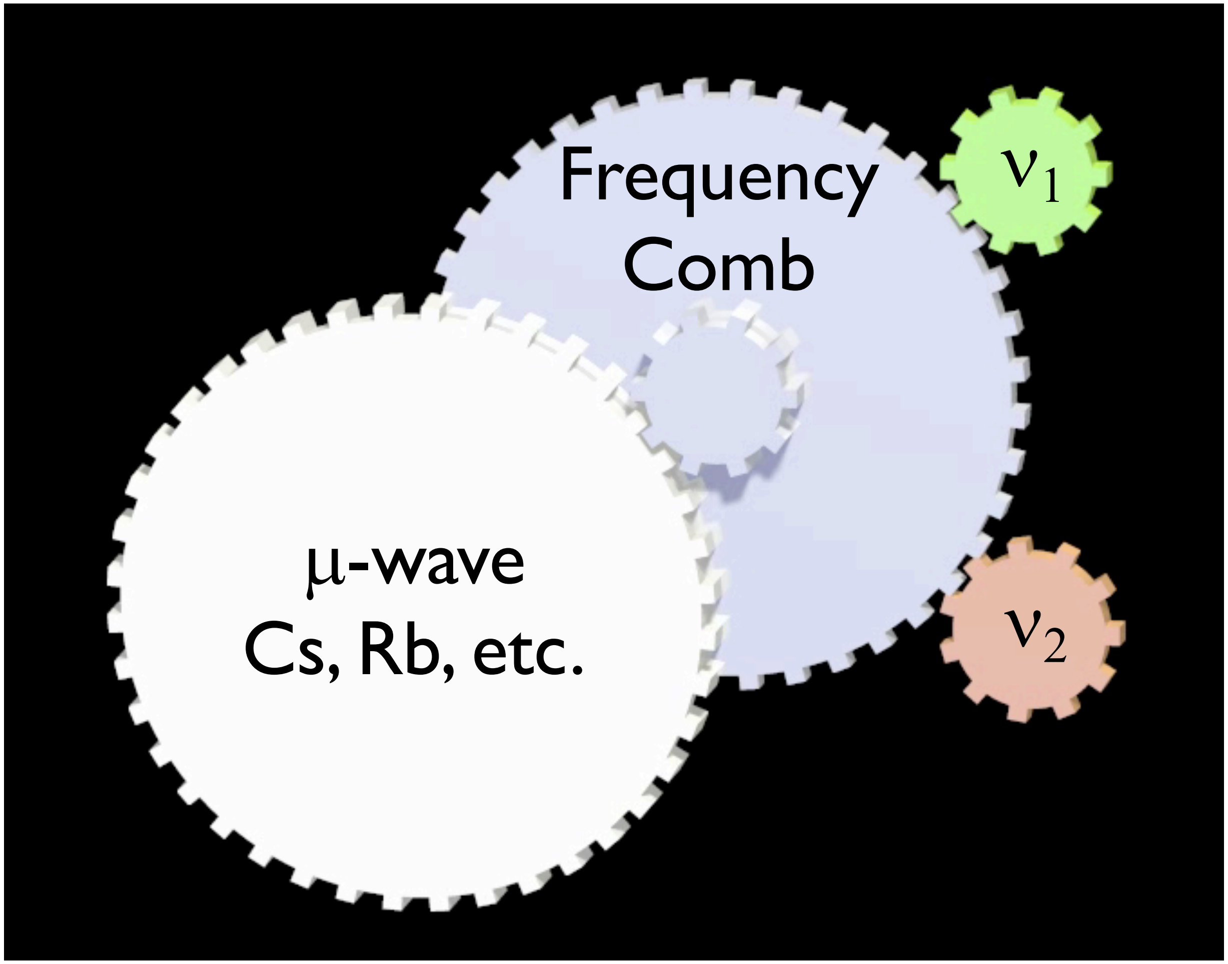




2. A perfectly-spaced train of optical pulses



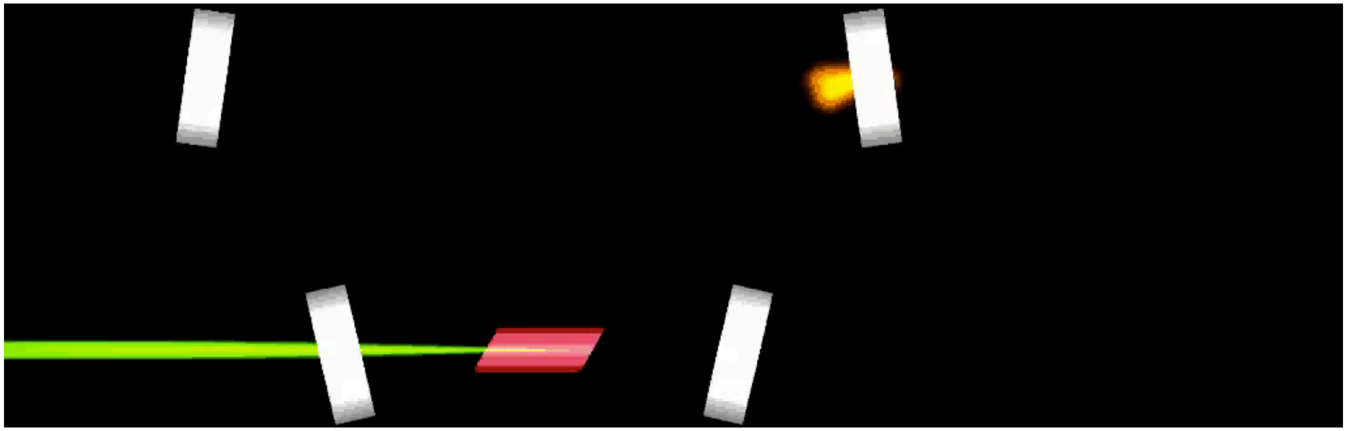
# Multiple faces of a frequency comb

3. An optical clockwork

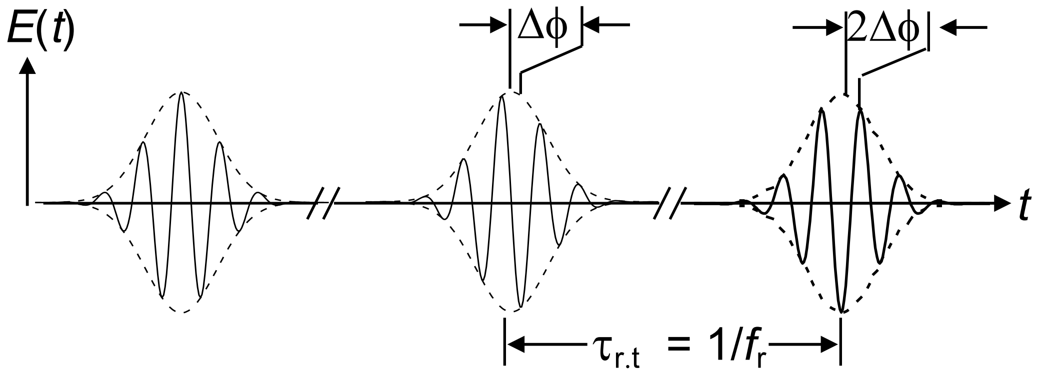



- Comb uncertainty at the 20th decimal place
- Measurement of optical ratios (e.g. $\nu_1 : \nu_2$)
- Direct connection from optical to microwave domains

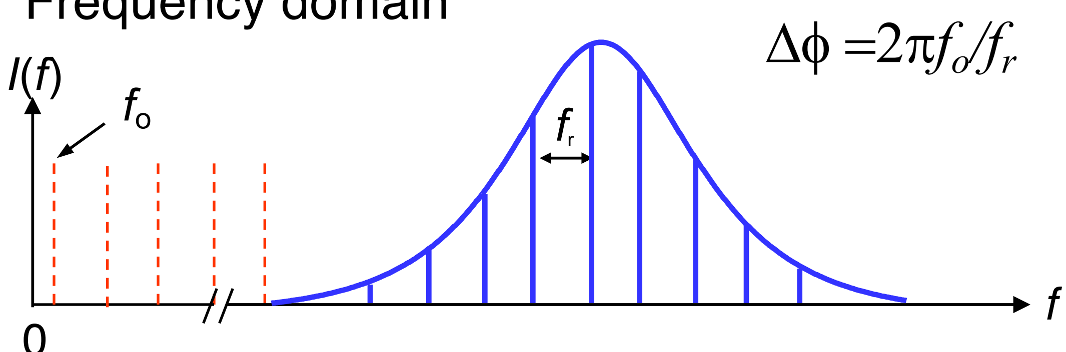
# Mode-Locked Laser:  Basis of the Frequency Comb



Time domain




Frequency domain



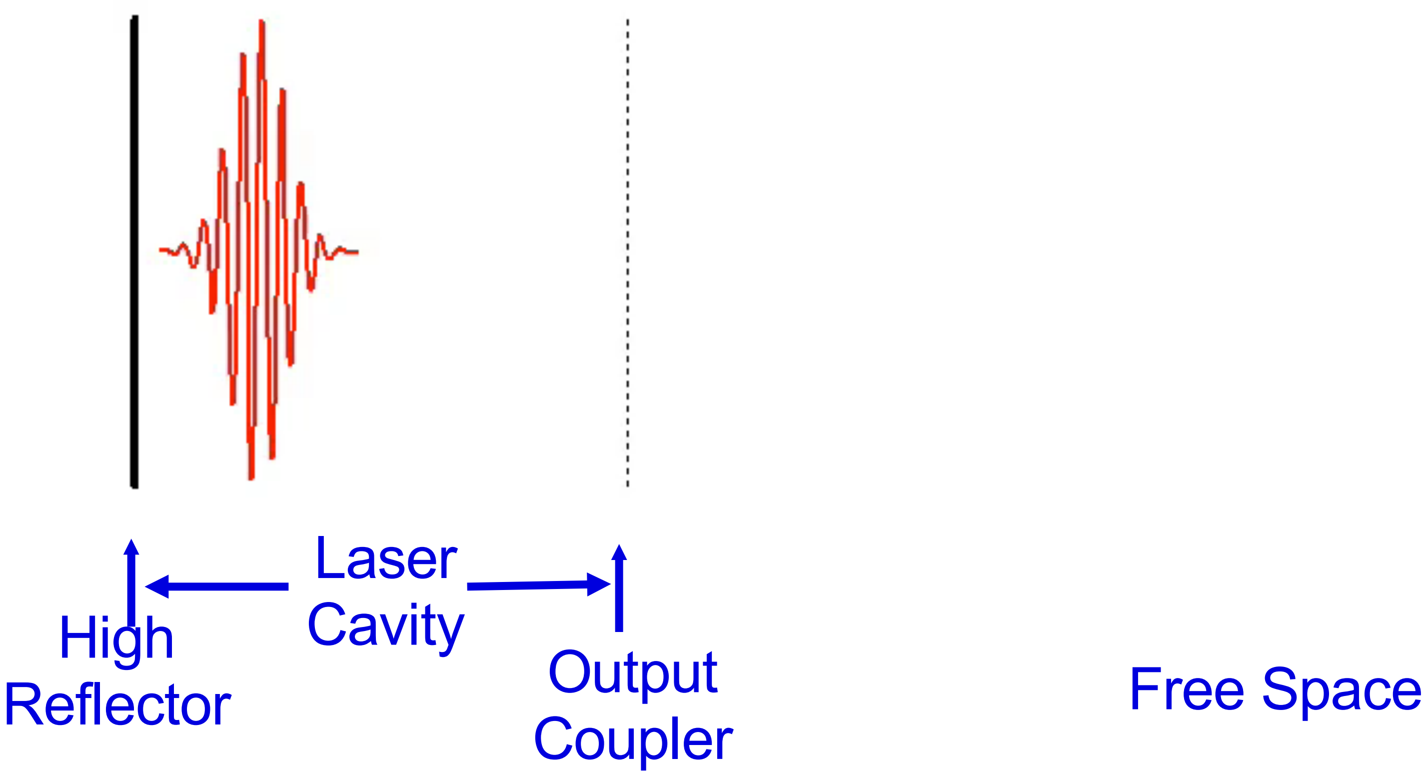

**Key Concept:**

Direct link between optical and microwave frequencies

$$\nu_n = nf_r + f_o$$

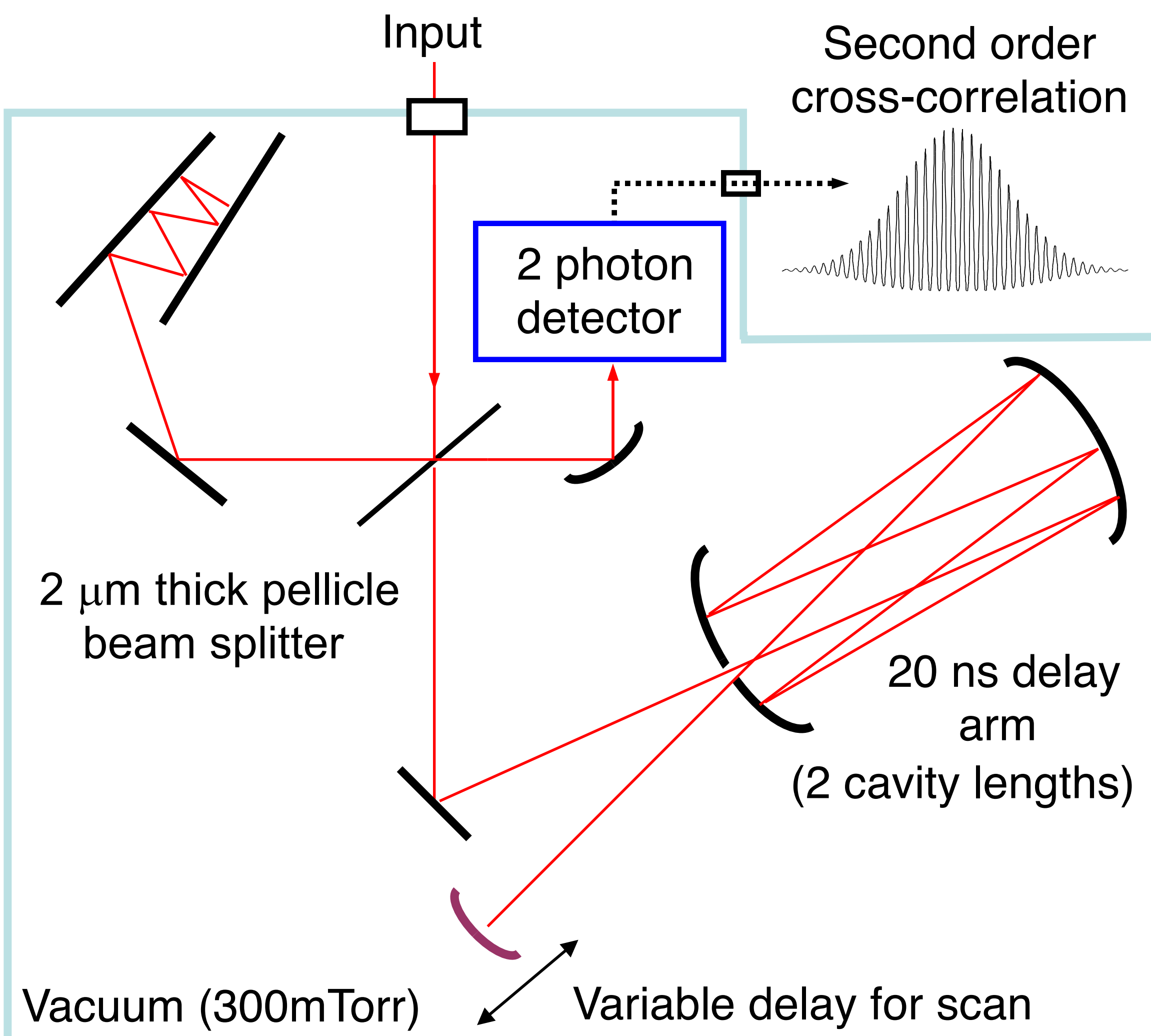
$$n \sim 10^5$$

# Group and phase velocity in modelocked lasers




animation from *Steve Cundiff*

# Direct Measurement of Carrier Envelope Phase Shift




- Correlation of pulse i and pulse i+2
- Matched number of bounces

Jones et al (2000)

# Direct Measurement of Carrier Envelope Phase Shift

$\Delta\phi = 2\pi f_o / f_r$

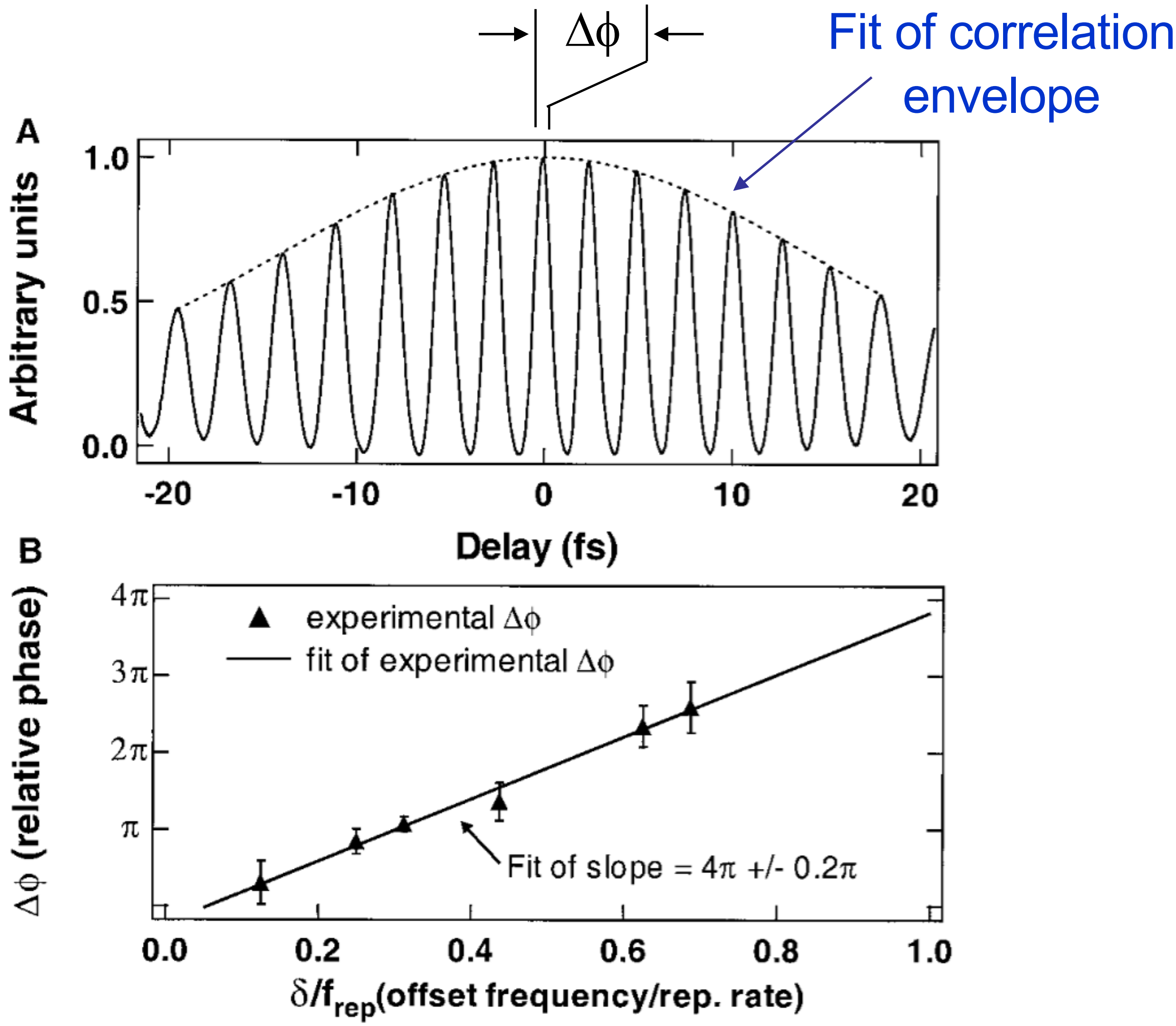
Fix

$f_o / f_r$

And measure

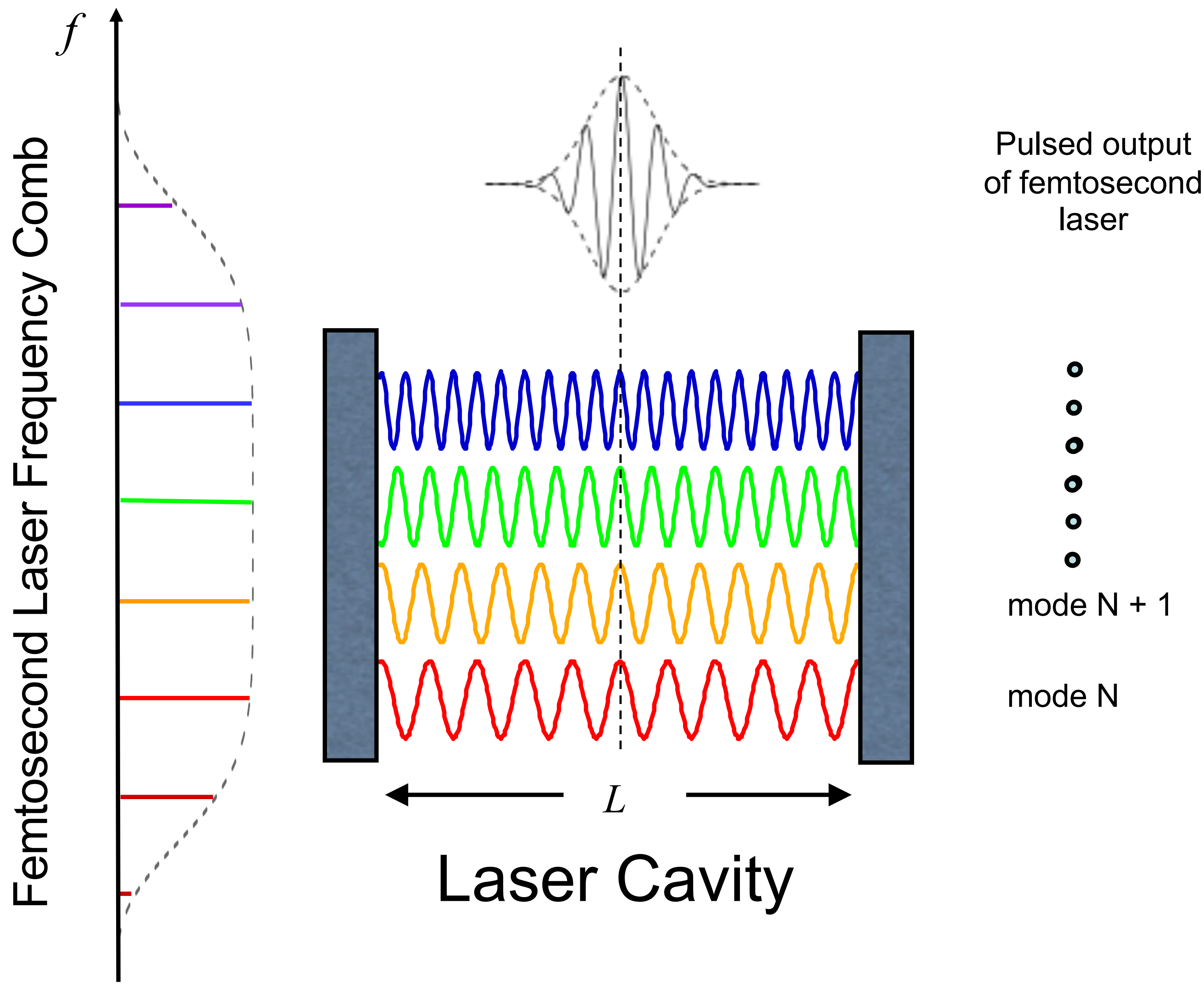
$\Delta\phi$

From interferometric autocorrelation




Jones et al (2000)

# The femtosecond mode-locked laser comb



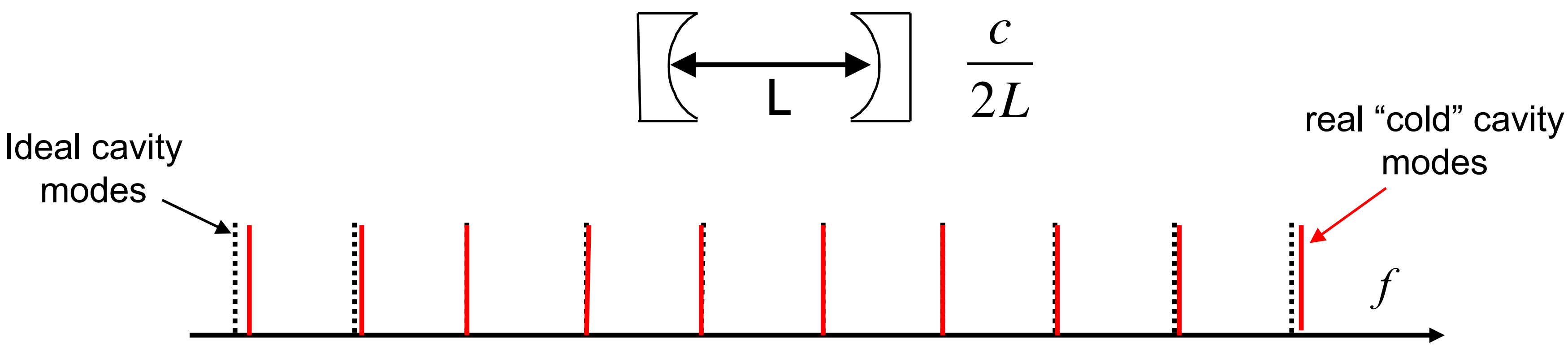

→ Cavity modes are locked in phase to generate a short pulse once every roundtrip time $2L/v_g$

# 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.

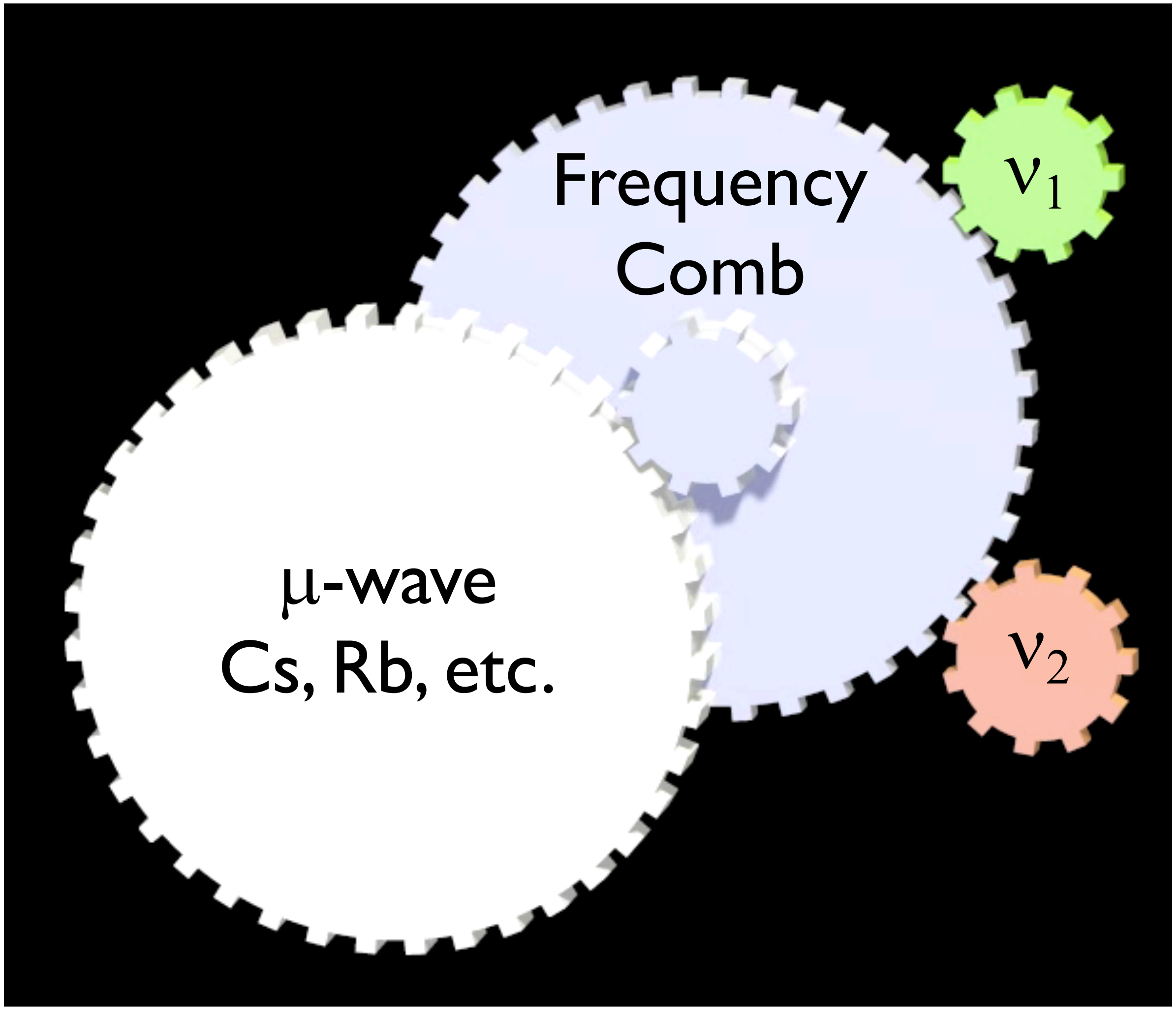
→ Yields a strictly uniform mode comb with spacing $v_g/(2L)$

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

→

# Multiple faces of a frequency comb

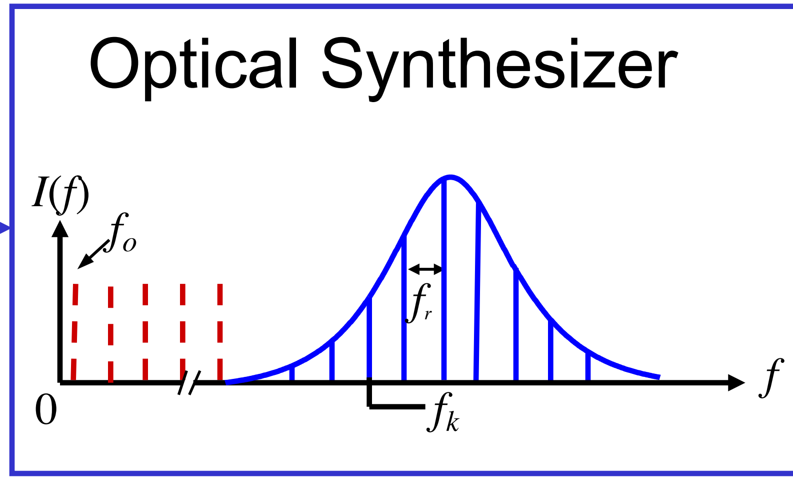
3. An optical clockwork




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

# Synthesis with an optical frequency comb

Optical ($\nu_{opt}$) or Microwave ($f_r$ , $f_o$ ) Reference




## Optical Reference

$$f_k = \nu_{opt} - f_b + \frac{k}{n_o}\left[\nu_{opt} - f_b - f_o\right]$$

$$k = n - n_o = 0, \pm 1, \pm 2....$$

and

$$f_r = \frac{\left[\nu_{opt} - f_b - f_o\right]}{n_o}$$

## Microwave Reference

$$\nu_k = kf_r + f_o$$

$$k = 1,2,3...$$

Verified to the 20th decimal place!

L.S. Ma, et al., *Science* (2004).

# 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)

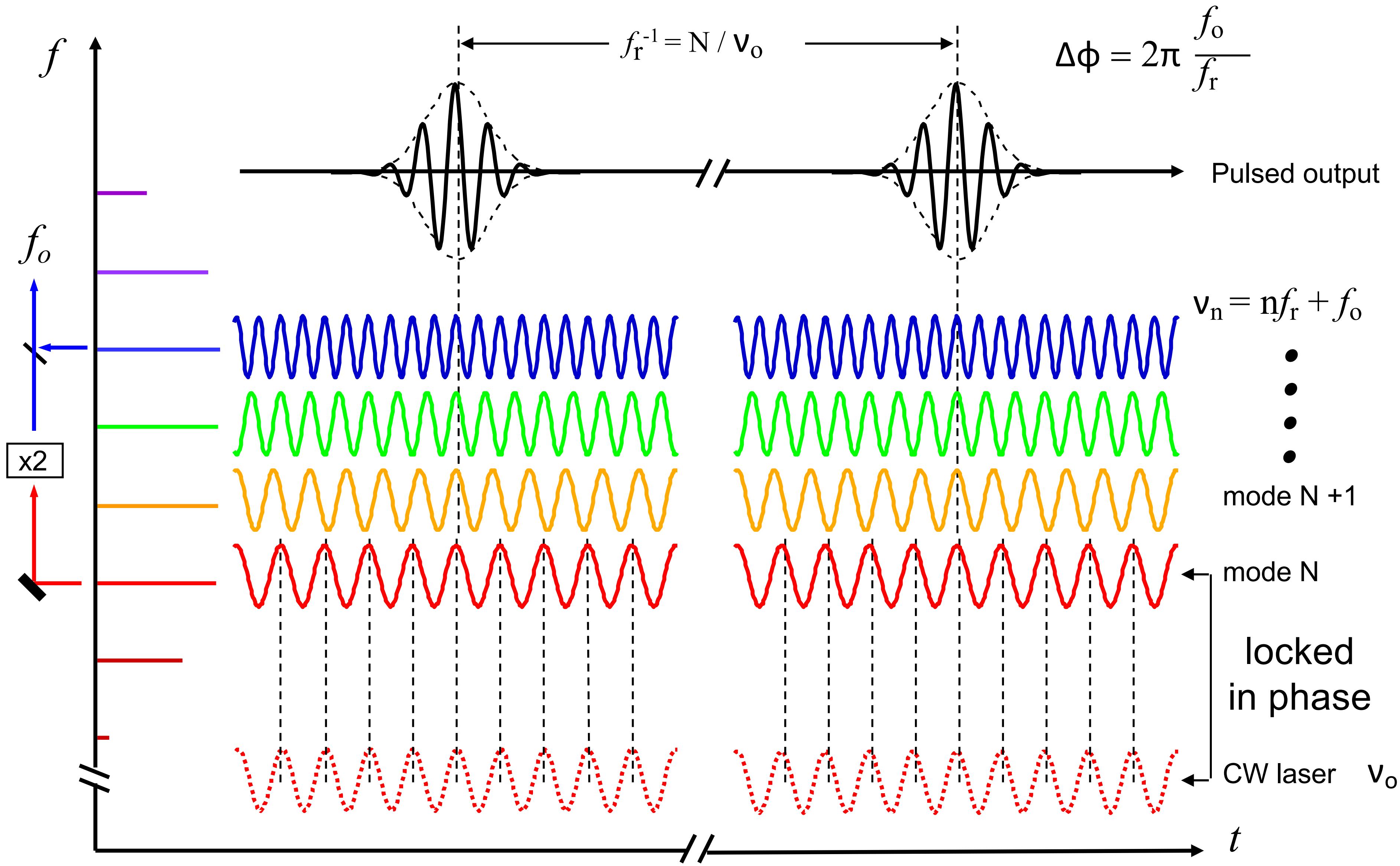
- $f_r$ controlled with a microwave source or a CW laser

- **n** determined by lower resolution measurement or a combination of measurements

NIST

# The laser comb and its control

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

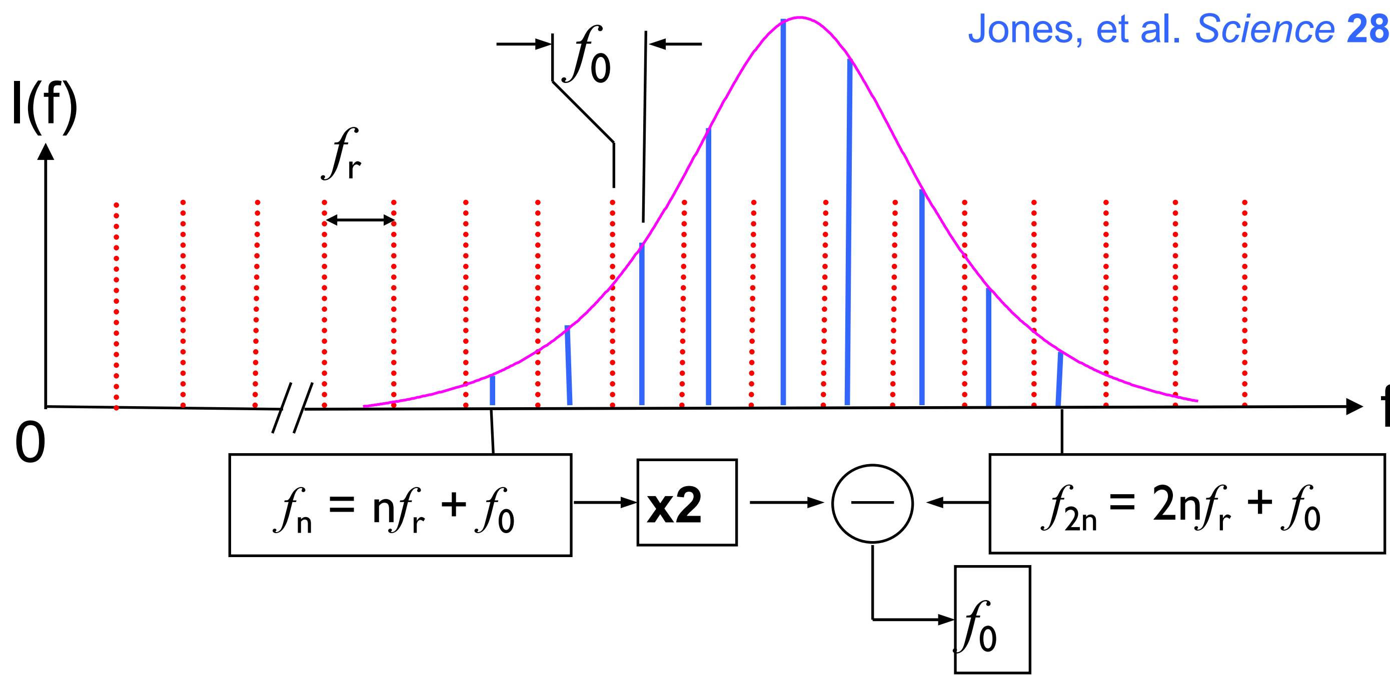



Operation is fully reversible: Can lock at microwave and synthesize optical



T. W. Hänsch and J. Hall, Nobel Lectures; D. J. Jones, et al., Science **288**, 635 (2000); S. Diddams, Th. Udem, et al., *Science* **293**, 825 (2001)

# 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$^{th}$ mode.

•Main Requirement: A very broad spectrum

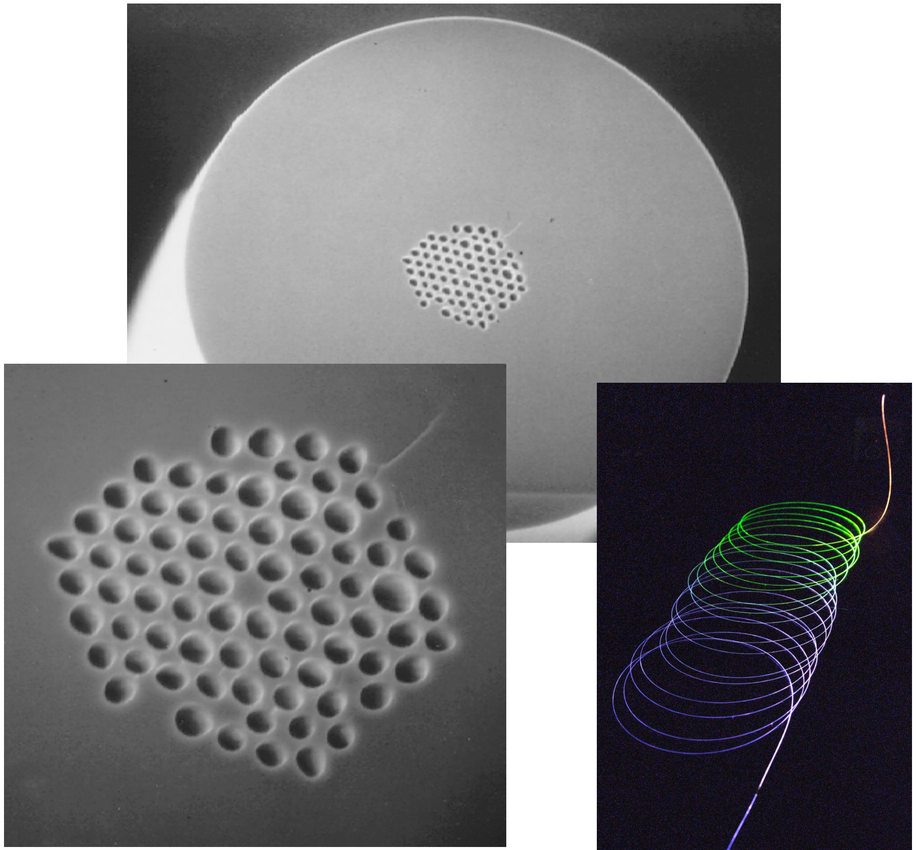
➢Alternative schemes do exist, for which less than one octave is required: see H. Telle et al. Appl. Phys. B **69,** 327 (1999)

# Getting an octave (or significant portion thereof) two routes….

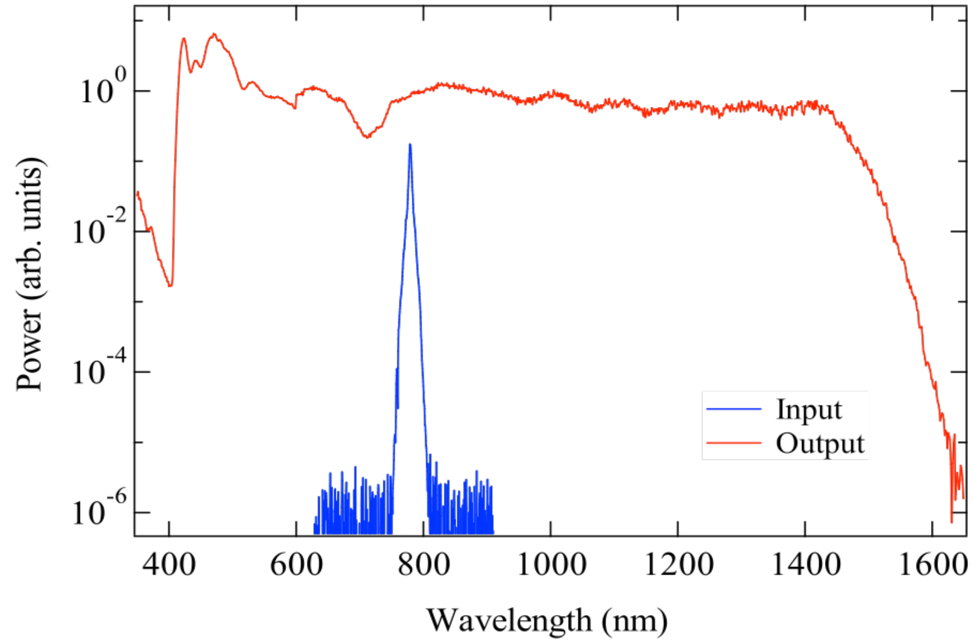
1. Start with "narrowband" femtosecond laser and use nonlinear broadening
- Advantages
  - •Nonlinear broadening in microstructured or other nonlinear (NL) fibers is now straightforward
  - •Can produce octaves about various center wavelengths
  - •HNLF for 1.5 microns provides fully-spliced and robust system.
- Disadvantages
  - •Free-space coupling to small core, highly nonlinear microstructure fibers is "tweaky" and challenging to use for long-term operation (>a few hours)
  - •Excess noise can be generated in NL fibers, which in some cases can completely erase the comb structure

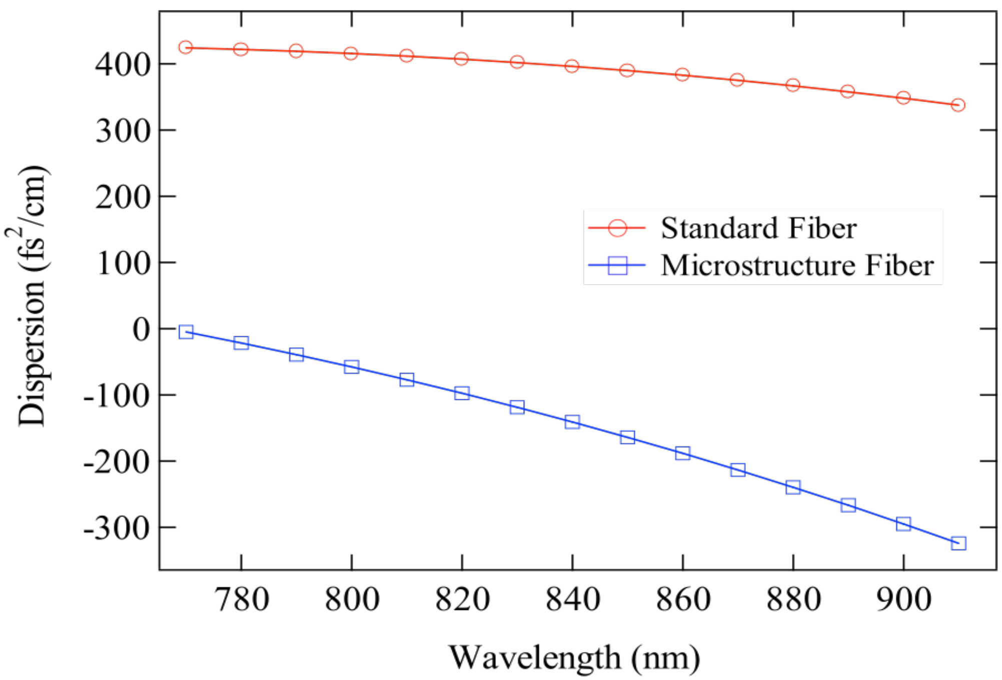
2. Generate very broadband spectra directly from the laser
- Advantages
  - •No excess fiber noise, no "tweaky" fibers
- Disadvantages
  - •Challenging laser to construct (although it is getting easier)
  - •Thus far, only works with Ti:sapphire (~550-1200 nm)

# Microstructure optical fiber continuum generation



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



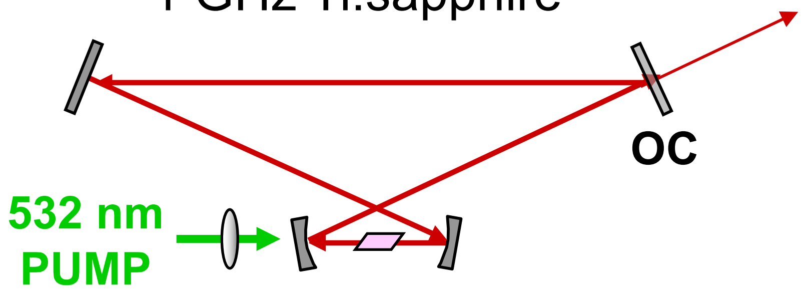




•Tight confinement of light leads to high nonlinearity and anomalous dispersion in the wavelength regime of femtosecond Ti:sapphire lasers

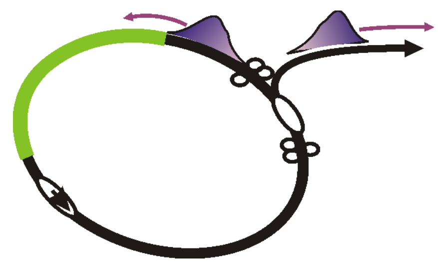
•Such fibers are available from commercial sources (ThorLabs, Crystal Fibre) and are developed in research labs (OFS, Univ. of Bath)

# Octave-Span Supercontinuum

1 GHz Ti:sapphire

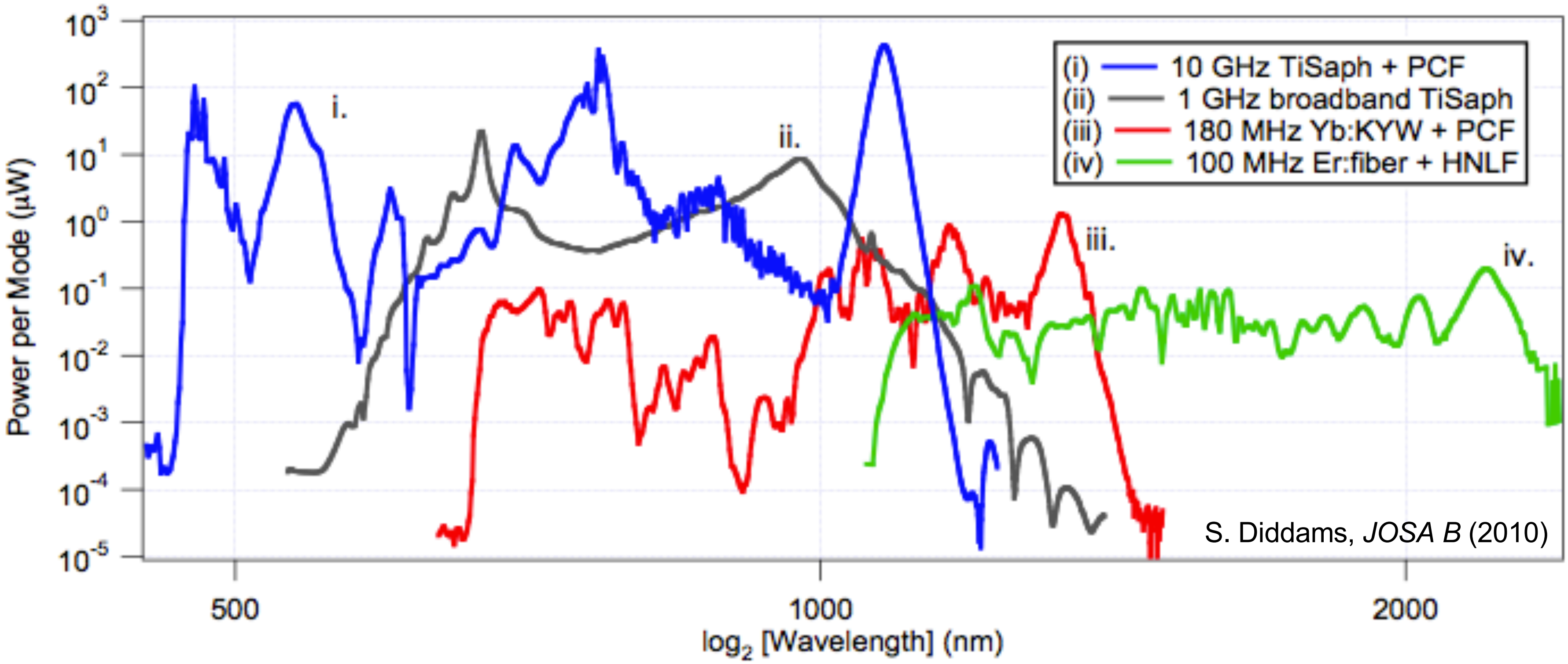



100 MHz Er:fiber



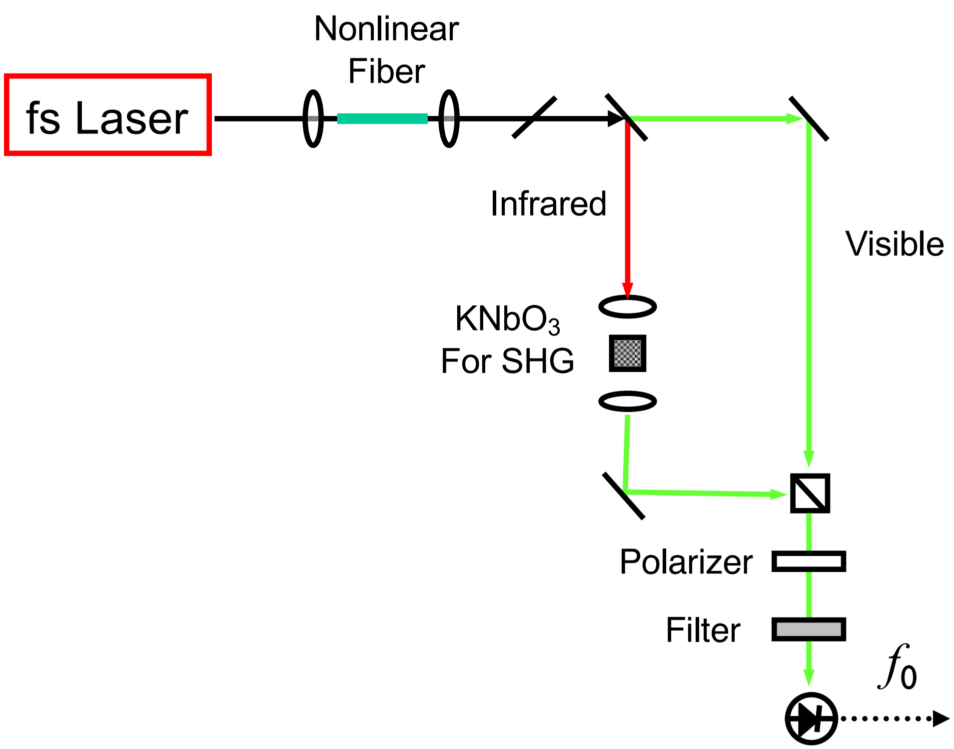
also….

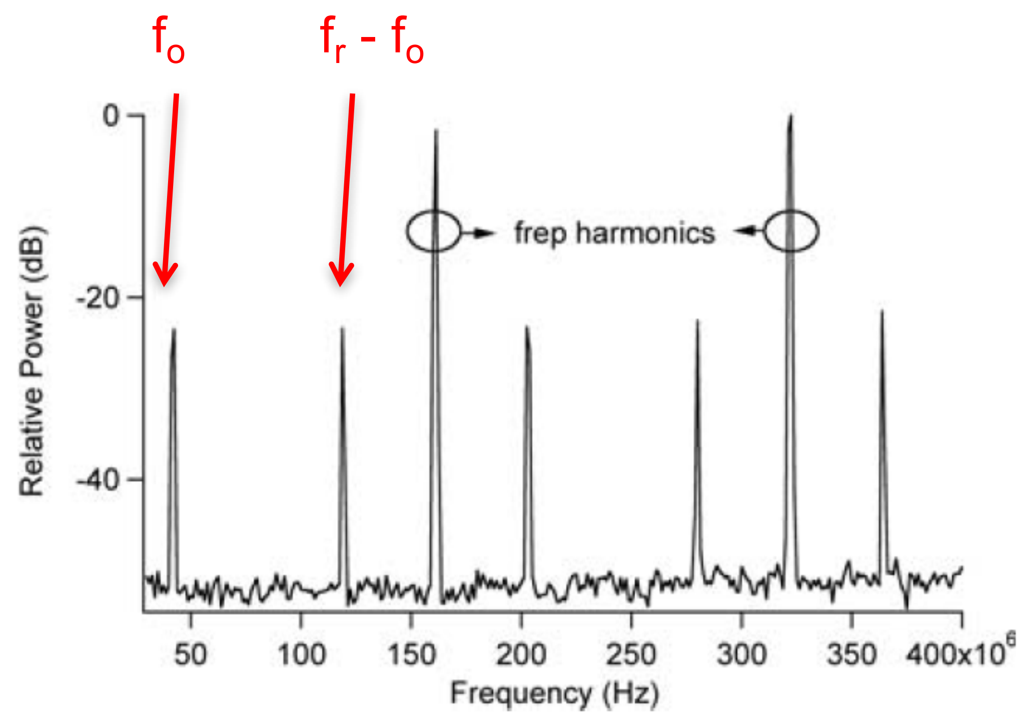
Yb:fiber
Yb:crystalline
Tm:fiber
…..




A. Bartels, H Kurz, *Opt. Lett*. **27**, 1839 (2002)
L. E. Nelson et al., *APB* **65**, (1997)

# Nonlinear interferometer for measuring $f_0$



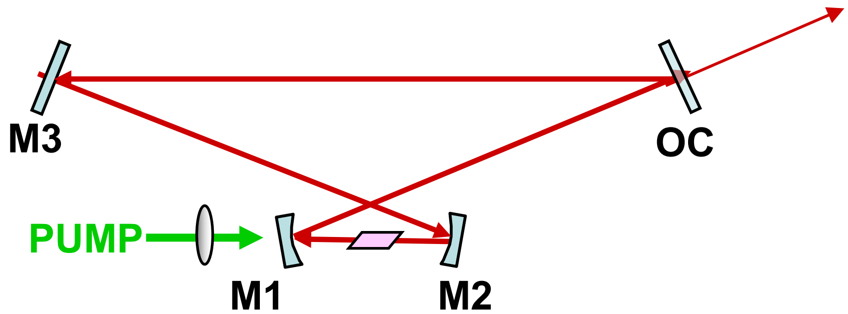




Other interferometer designs exist:

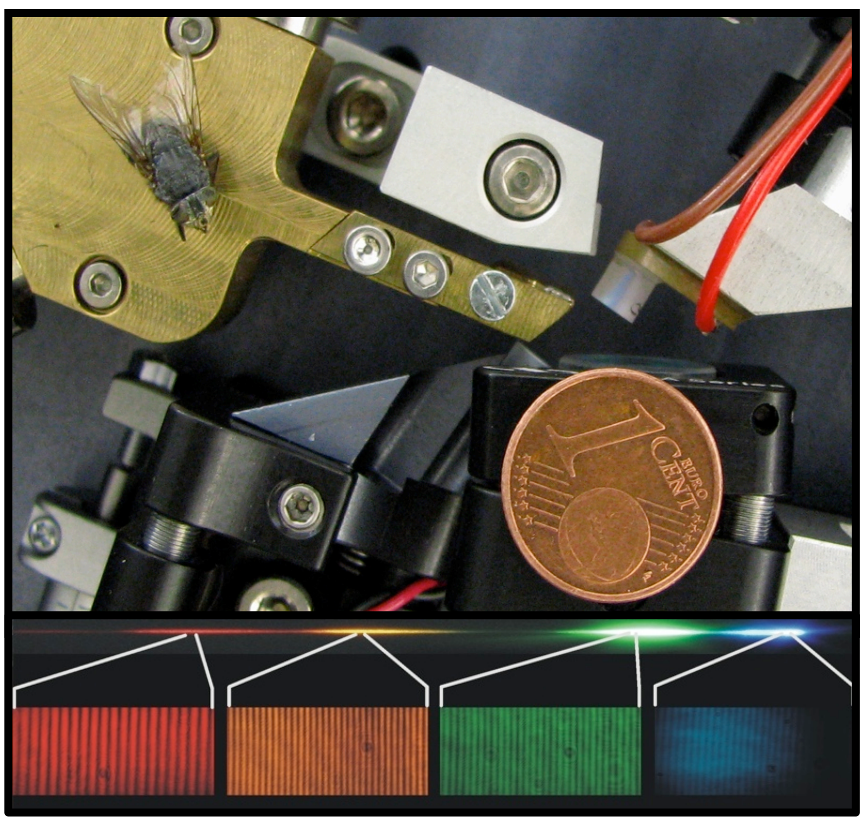
- inline with waveguide PPLN
- Michelson

# GHz Rep Rate Ti:Sapphire Combs

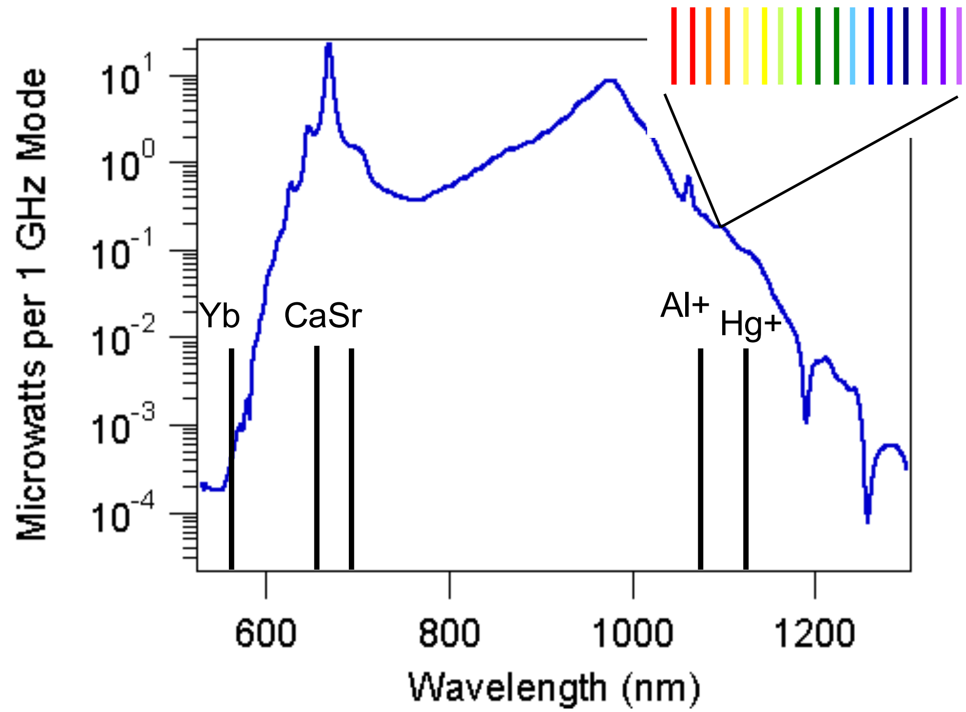
T. Fortier, A. Bartels, D. Heinecke, M. Kirchner




10 GHz Self-referenced Ti:sapphire Laser



1 GHz Octave Spanning Laser



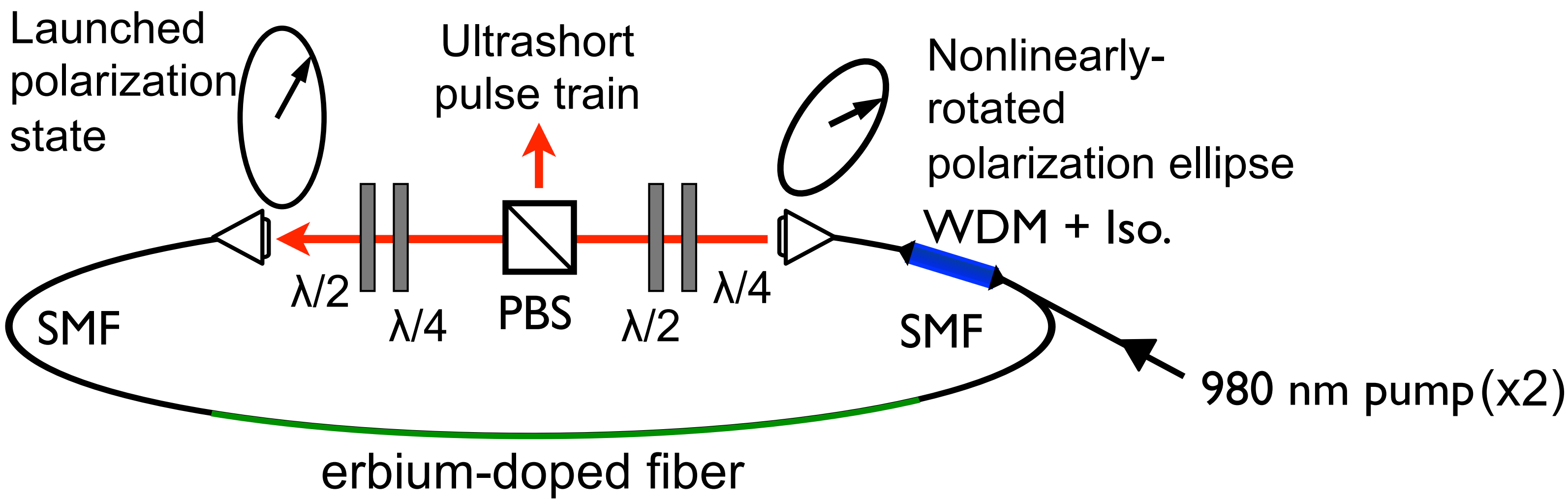

A. Bartels, H Kurz, *Opt. Lett.* 27, 1839 (2002)
T. Fortier, A. Bartels, S. Diddams, *CLEO* (2005)
T. Fortier, A. Bartels, S. Diddams, *Opt. Lett.* 31, 1011 (2006)

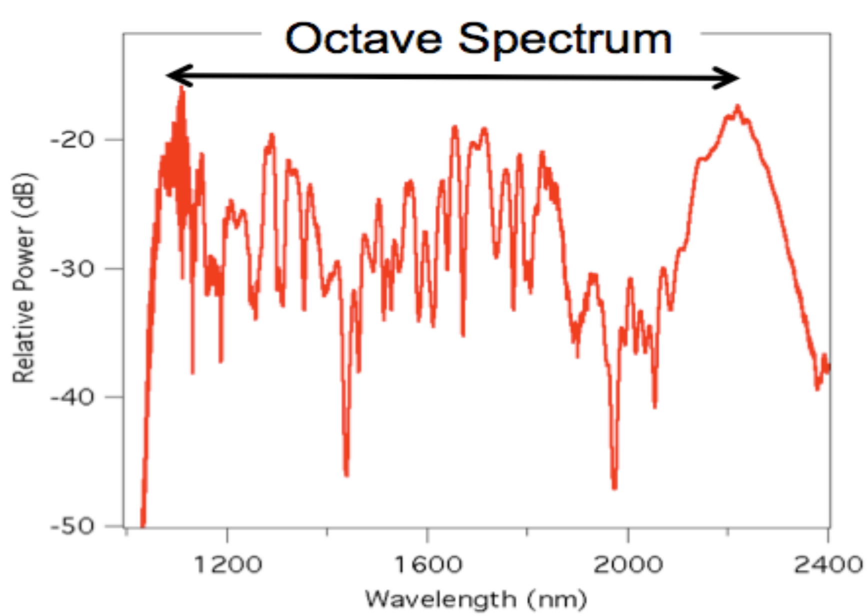
- Stabilized Comb = $10^6$ Modes
- Hz-level linewidths
- Residual frequency noise at $1 \times 10^{-19}$ level

A. Bartels, D. Heinecke, S. Diddams, *Science* **326**, 681 (2009).

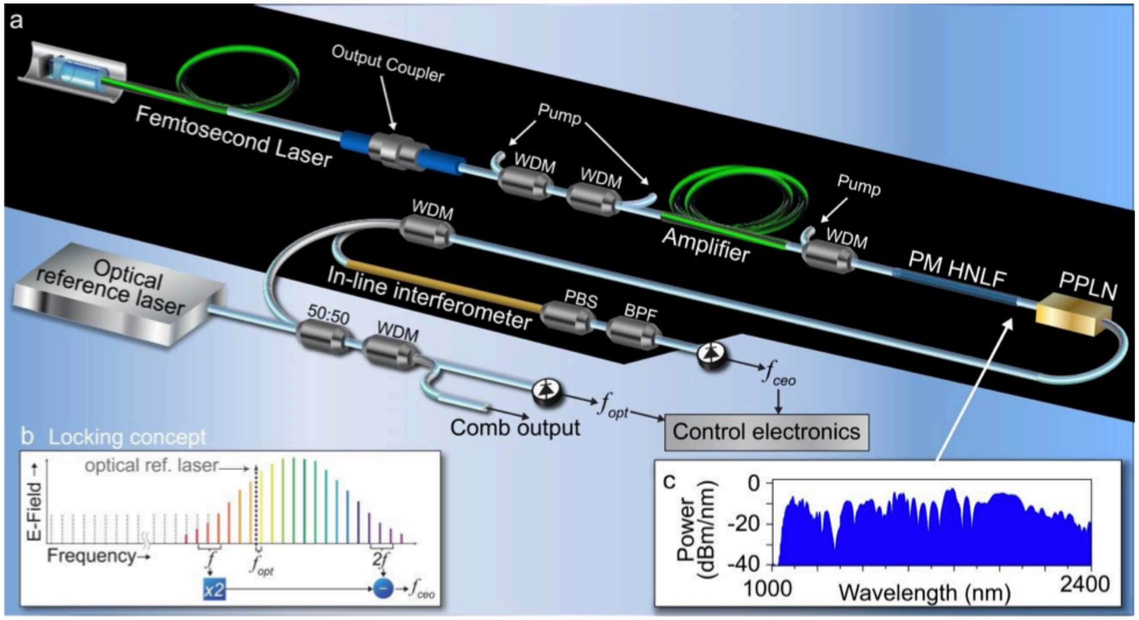
# Er:fiber based frequency combs

→ mode-locking based on nonlinear polarization rotation



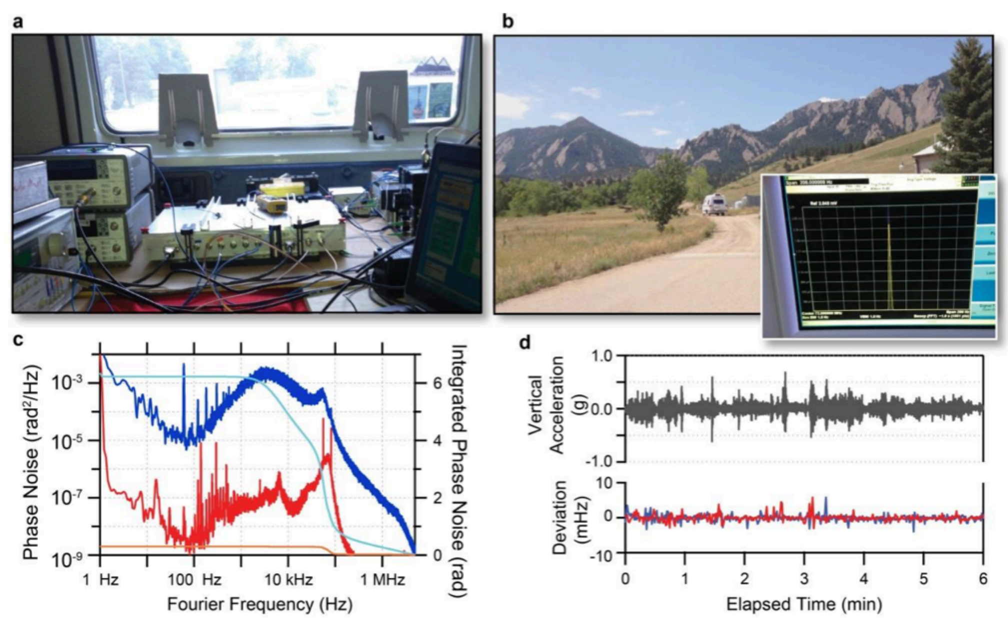
# Polarization-maintaining Er:fiber laser comb



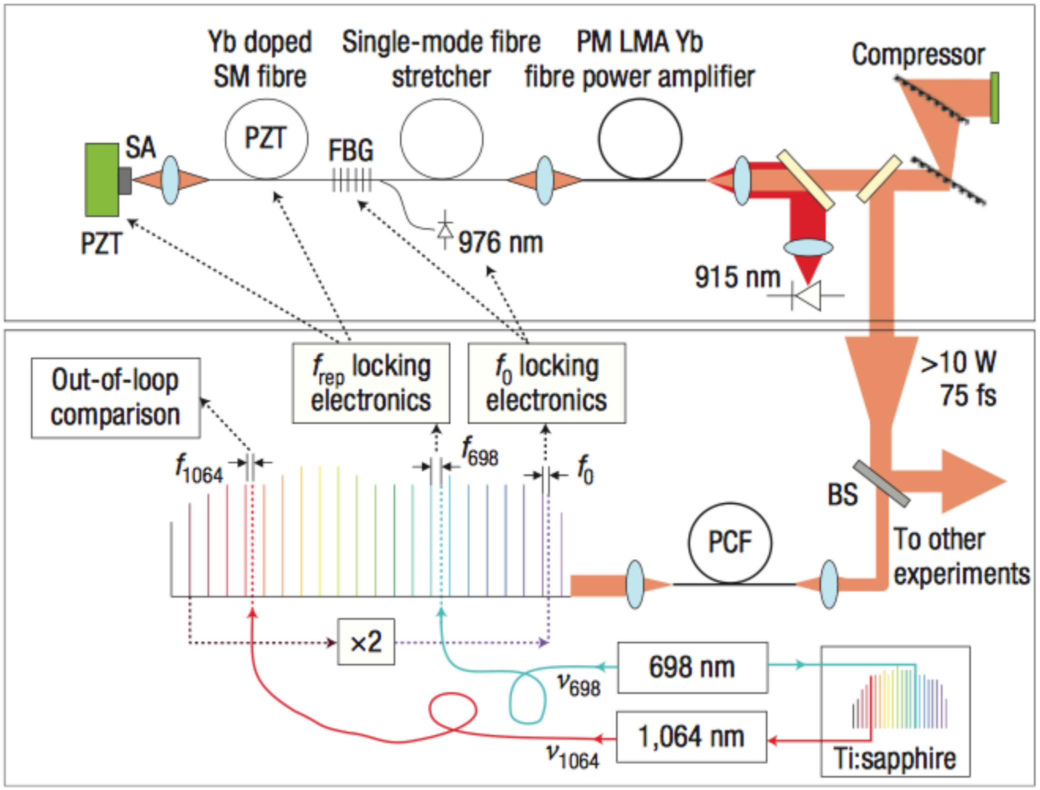

- Laser + amplifier + self-referencing are all constructed “in-line” with polarization-maintaining (PM) fiber optics.
- Laser is mode-locked with saturable absorber mirror
- Robust against environmental perturbations.

(Newbury group at NIST)

Frequency comb operates phase-locked in a moving vehicle.



# High-power Yb:fiber laser frequency comb

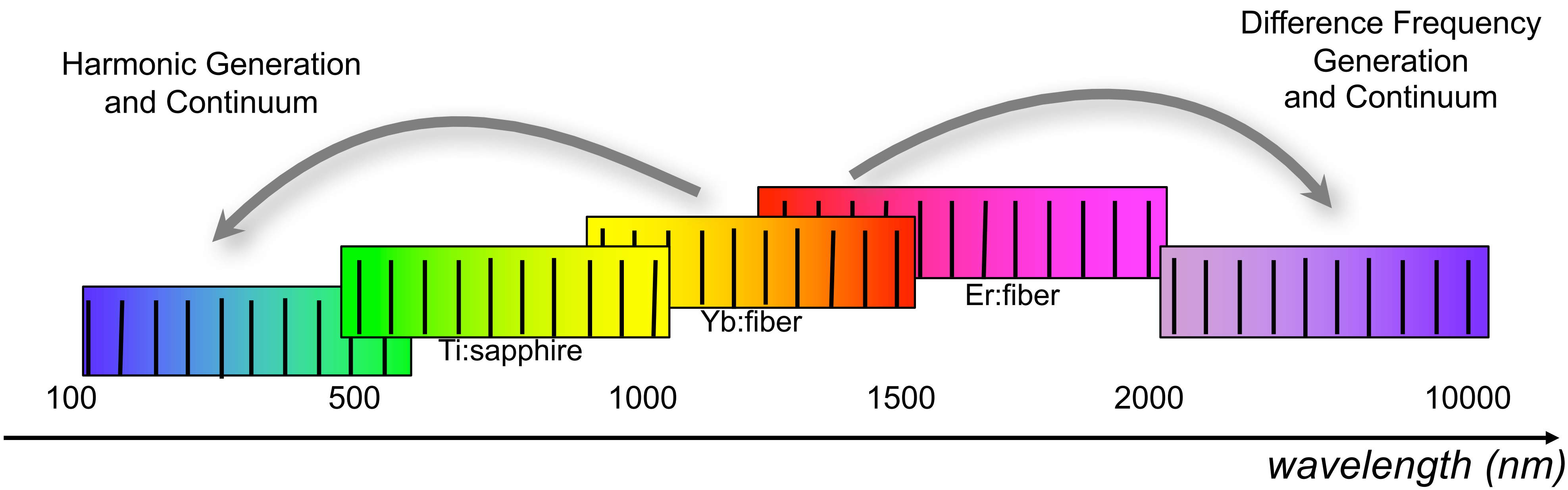



- Linear cavity design
- Saturable absorber end mirror for mode-locking
- Fiber Bragg grating provides output coupling and dispersion control
- **External amplification to ~80 W** followed by compression to ~100 femtosecond pulses
- Supports **sub Hz linewidths**

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).