# Femtosecond Lasers for Precision Frequency and Distance Metrology

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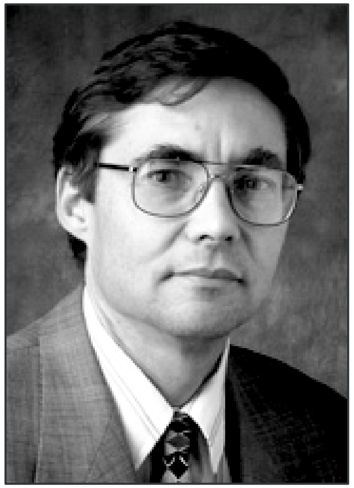
# The essence of precision

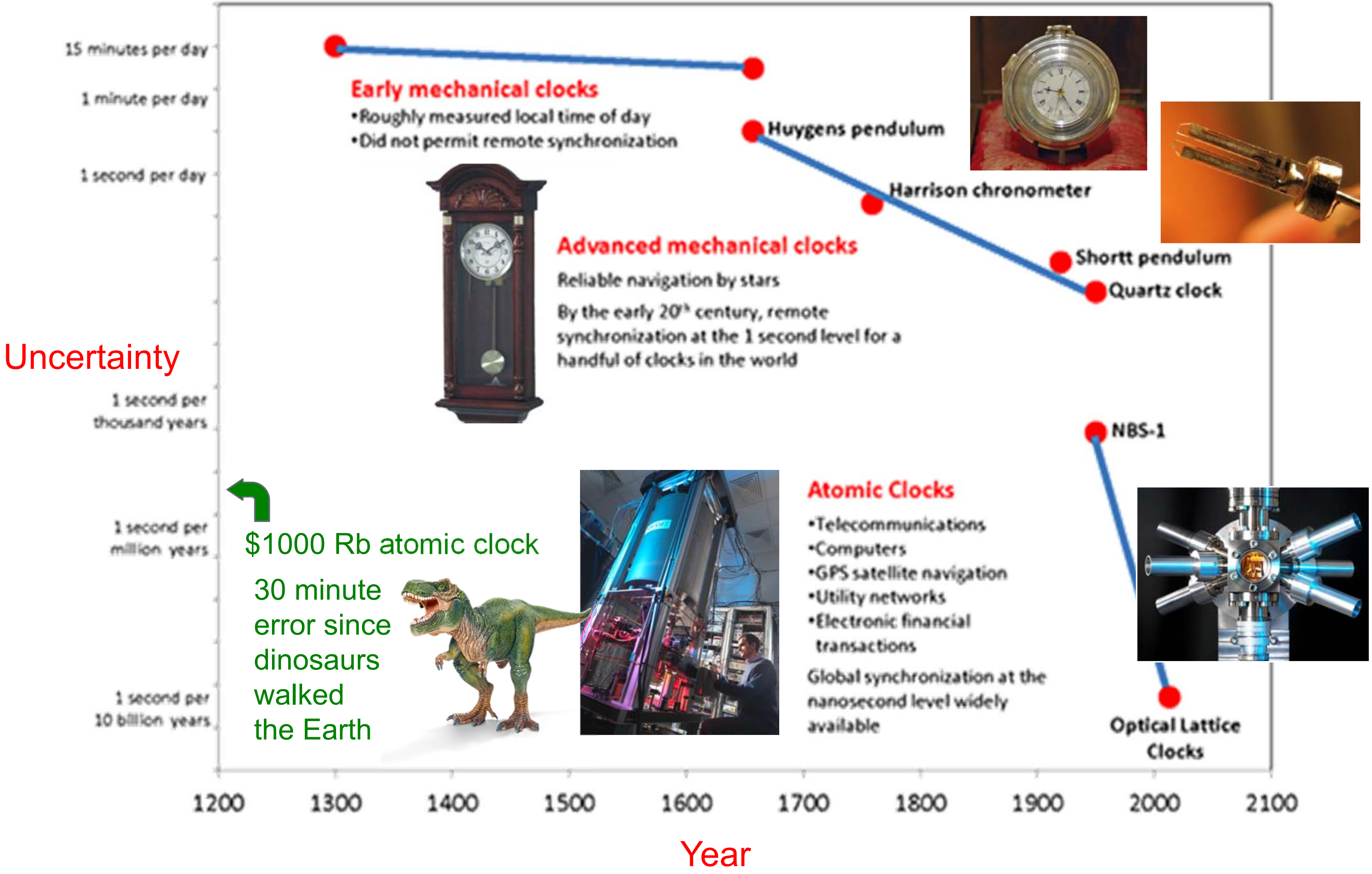


***“ in experimental physics, a precision measurement is almost always a frequency measurement ”***

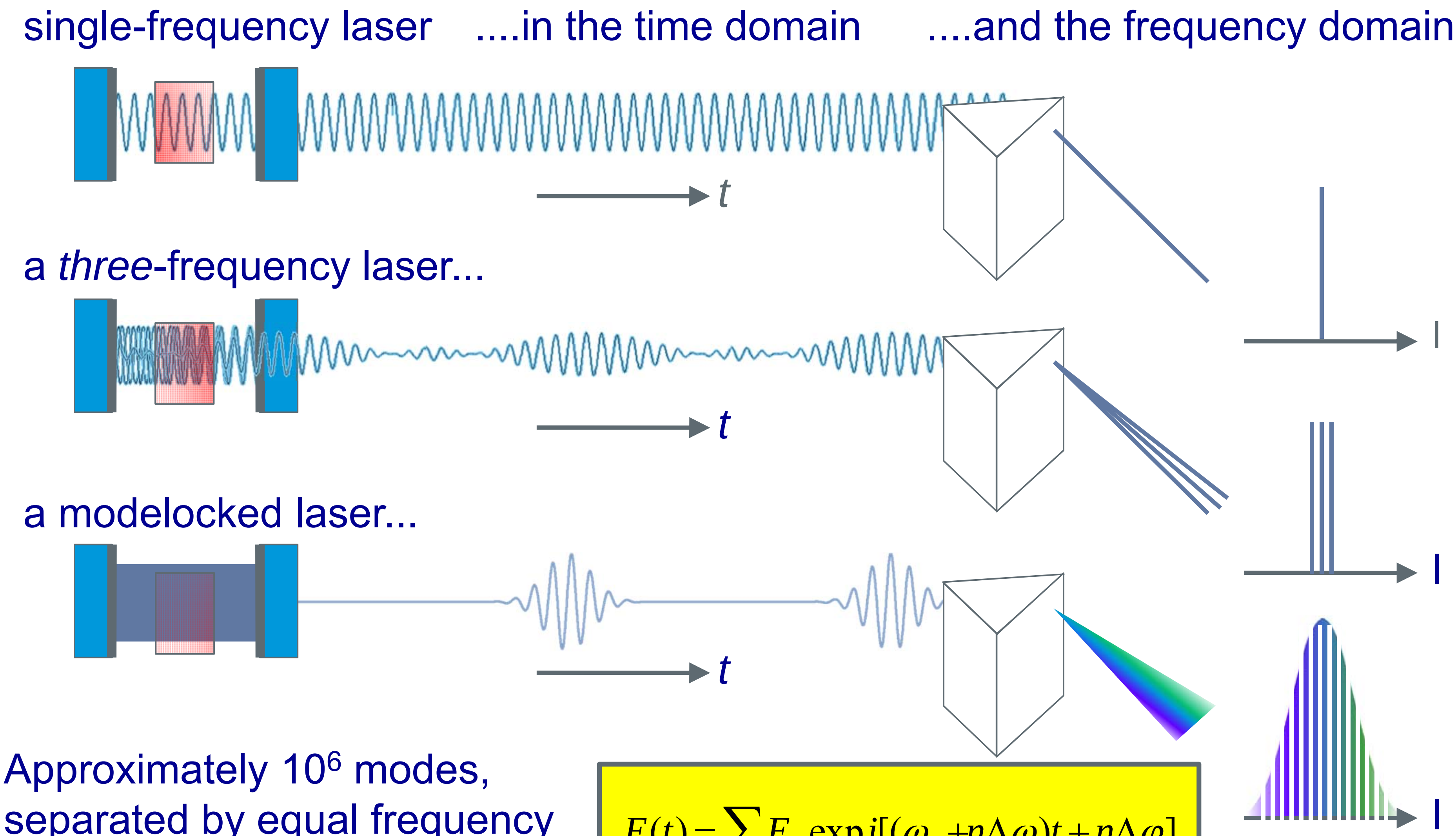
Carl Edwin Wieman, Nobel Laureate

- ❖ The SI second is the most precisely realised unit (to about 1 in $10^{15}$)
- ❖ ...Always measure frequency where possible

# Time and Frequency Precision



# The frequency comb explained



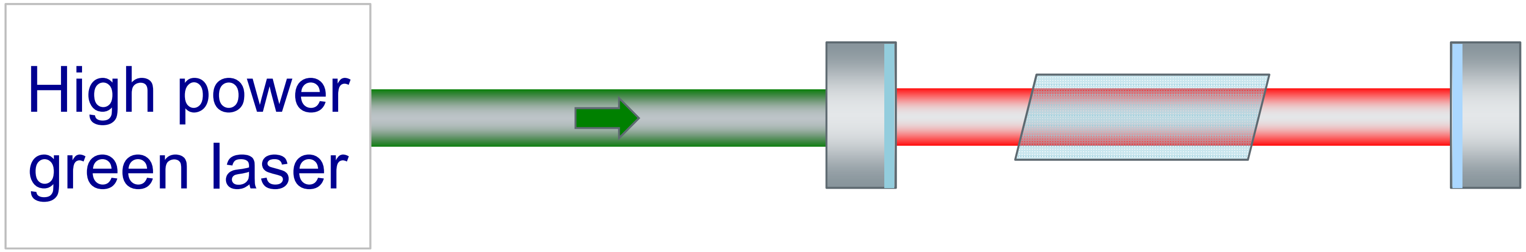

Approximately $10^6$ modes, separated by equal frequency and phase intervals:

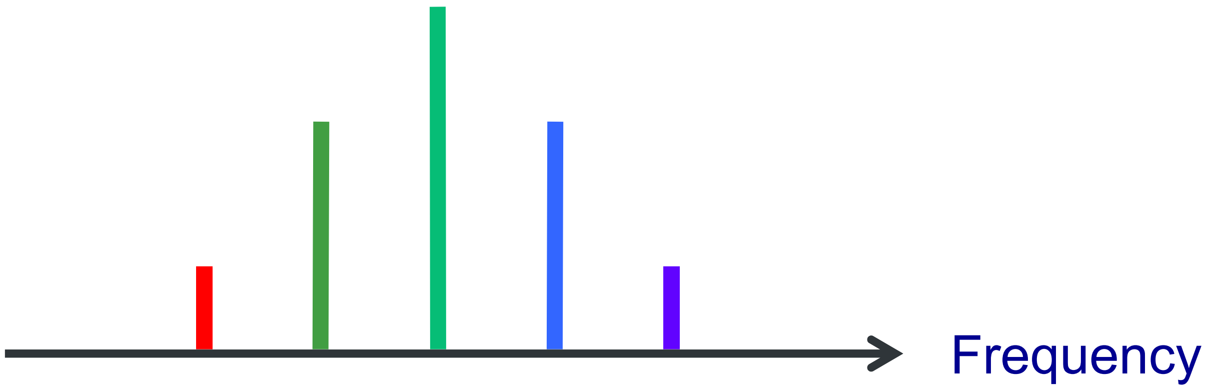
$$E(t) = \sum_n E_n \exp i[(\omega_o + n\Delta\omega)t + n\Delta\varphi]$$

# The frequency comb explained

audio_frequency_comb.m

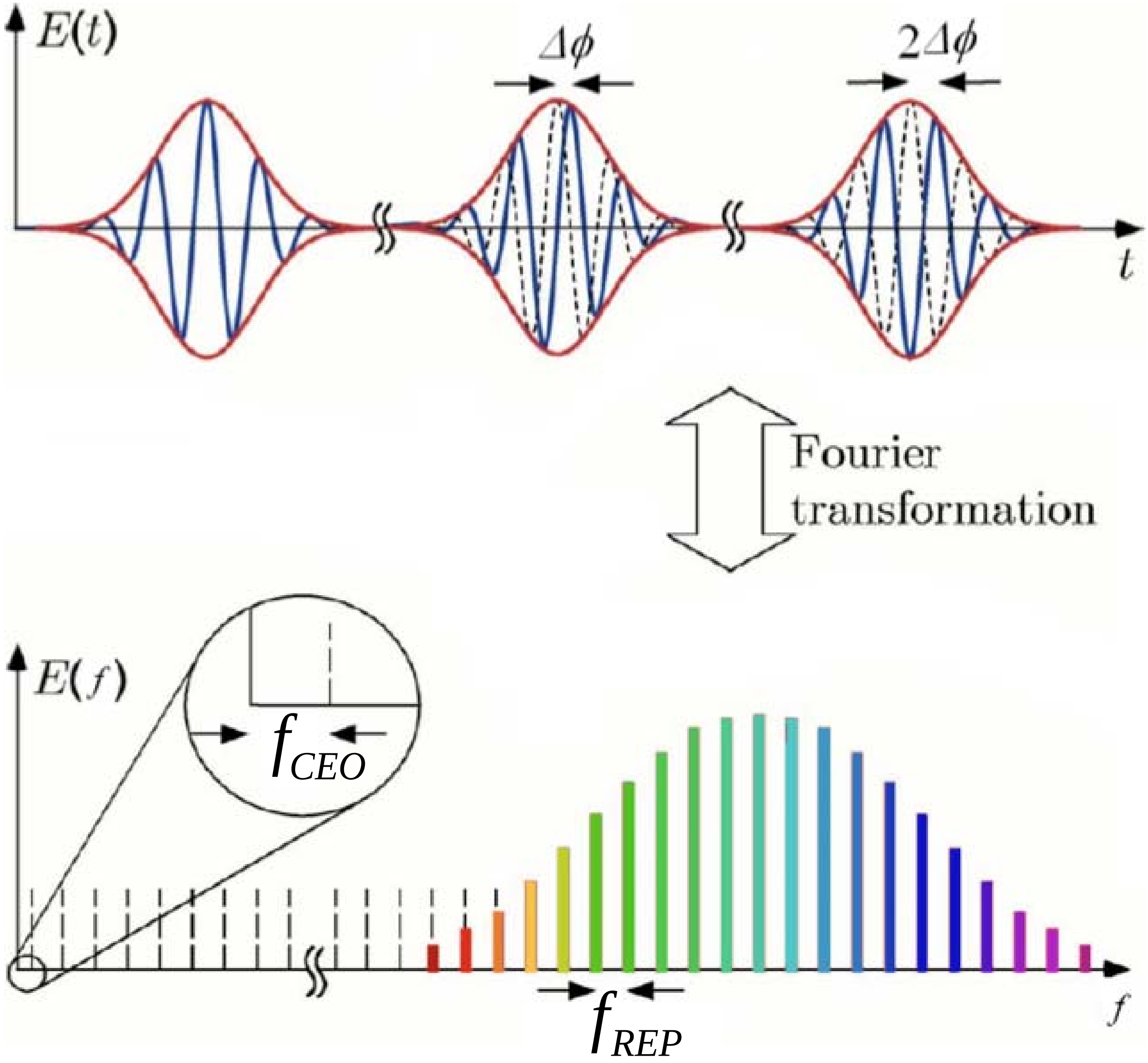
# Degree of Freedom #1: Comb spacing ($f_{REP}$)



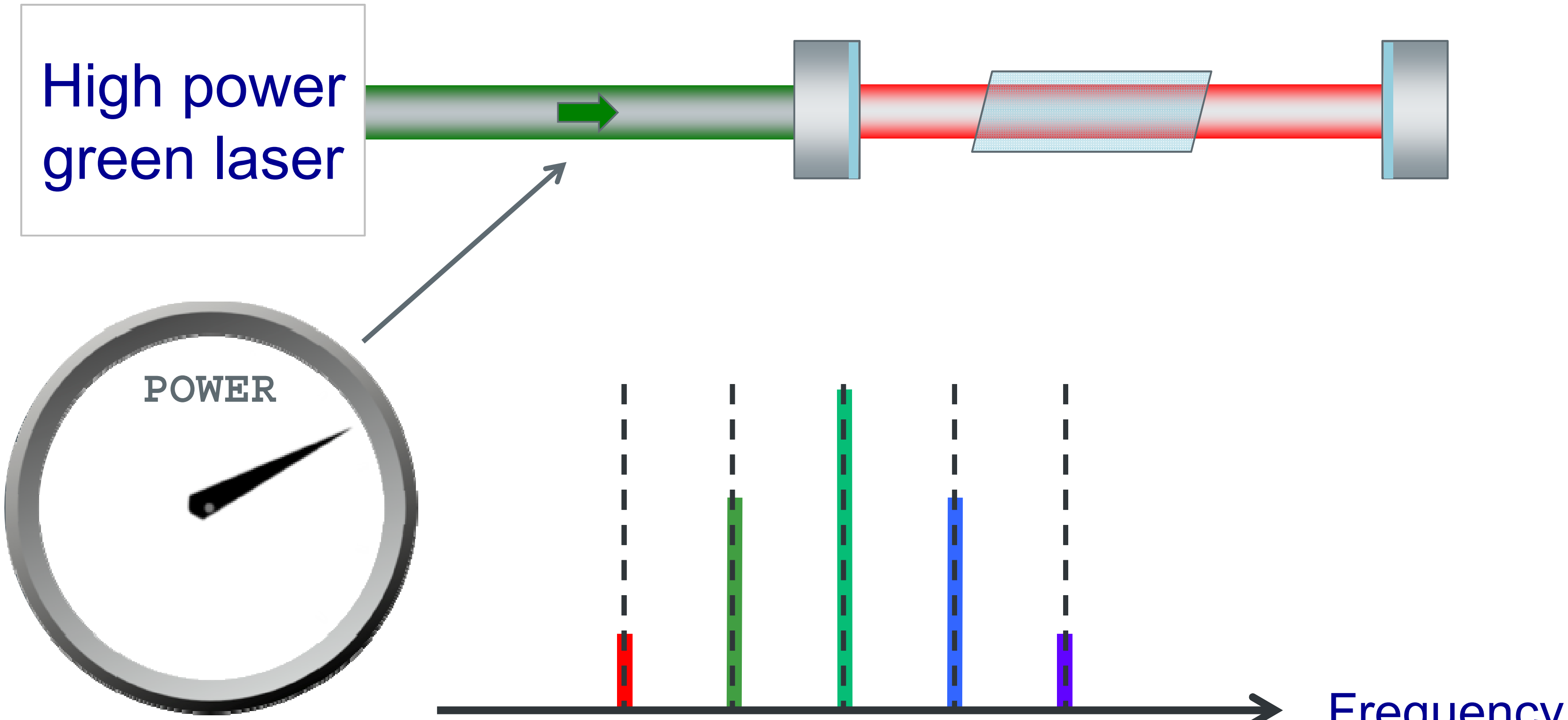



# Degree of Freedom #2: Comb offset ($f_{CEO}$)

$$f_{CEO} = \frac{\Delta\phi / 2\pi}{\Delta t}$$



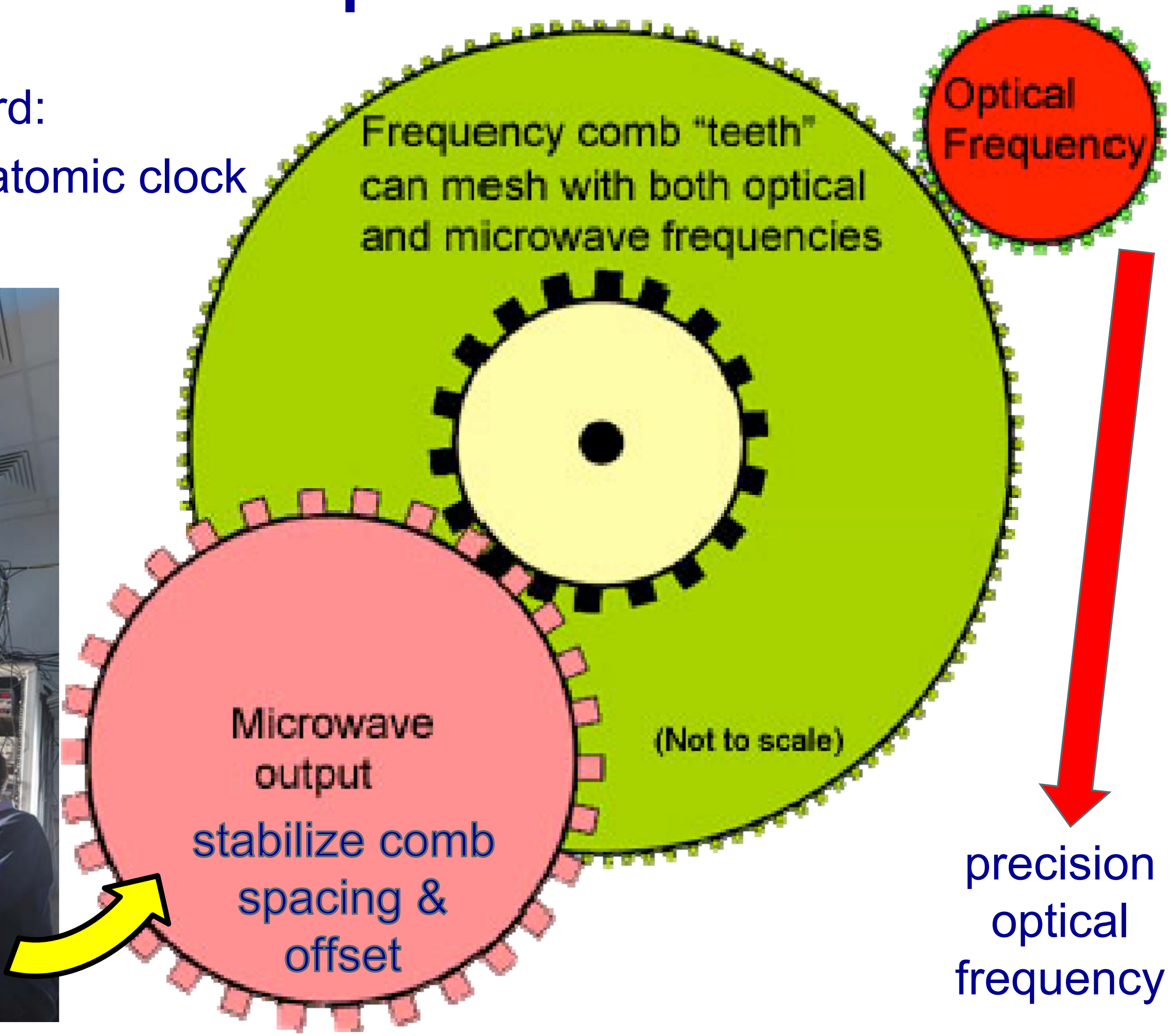
# Degree of Freedom #2:
# Comb offset ($f_{CEO}$)



# Combs connect electrical and optical frequencies

The UK's time standard:

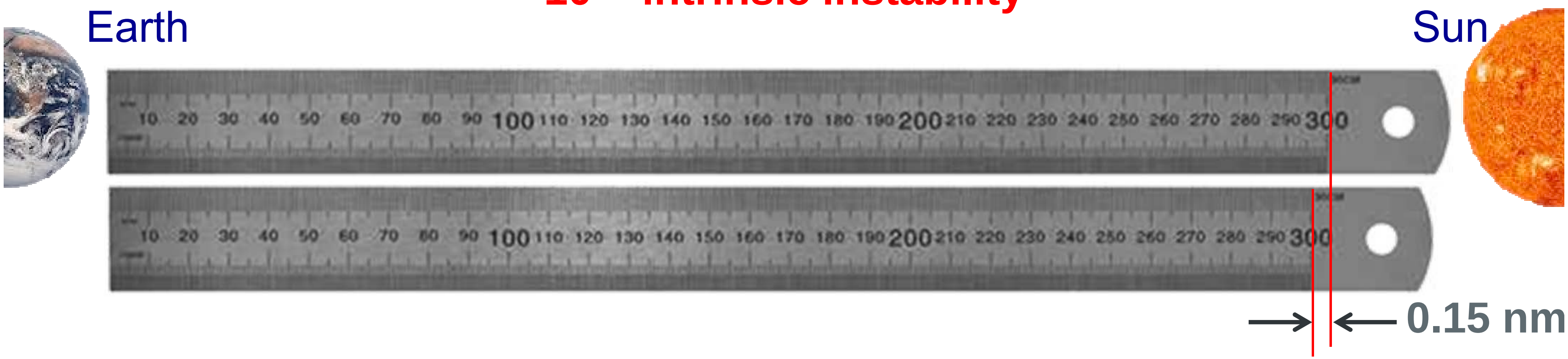
9.2-GHz Cs-fountain atomic clock



# Frequency-Comb Precision

- The world's most precise lasers:

**$10^{-21}$ intrinsic instability**




- Applications in:

  **Precision optical metrology**

  **Precision spectroscopy (e.g for astronomy)**

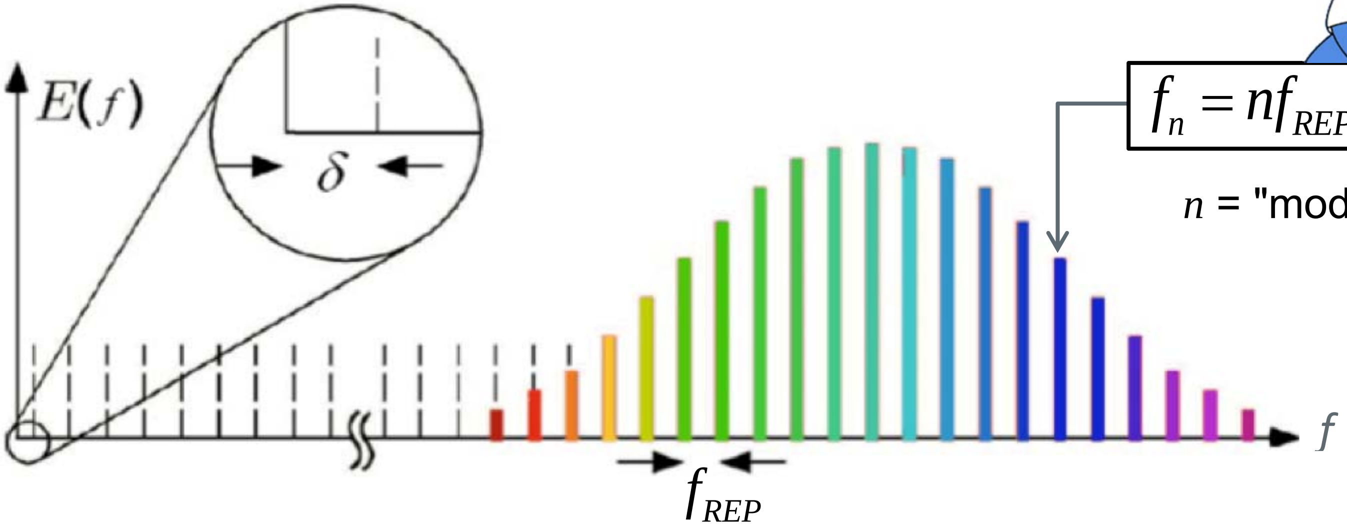
  **Precision distance metrology**

  Much more, e.g. clocks, atomic physics, soft-X-ray generation...

# Factors affecting frequency-comb precision & accuracy

Ferreiro et al., Opt. Express **19**, 24159 (2011)

How accurately can the positions of the modes in a frequency comb be controlled?




$$f_n = n f_{REP} + f_{CEO}$$

$n$ = "mode order"

The frequency of the $n^{th}$ mode $f_n$ determined by 2 parameters:

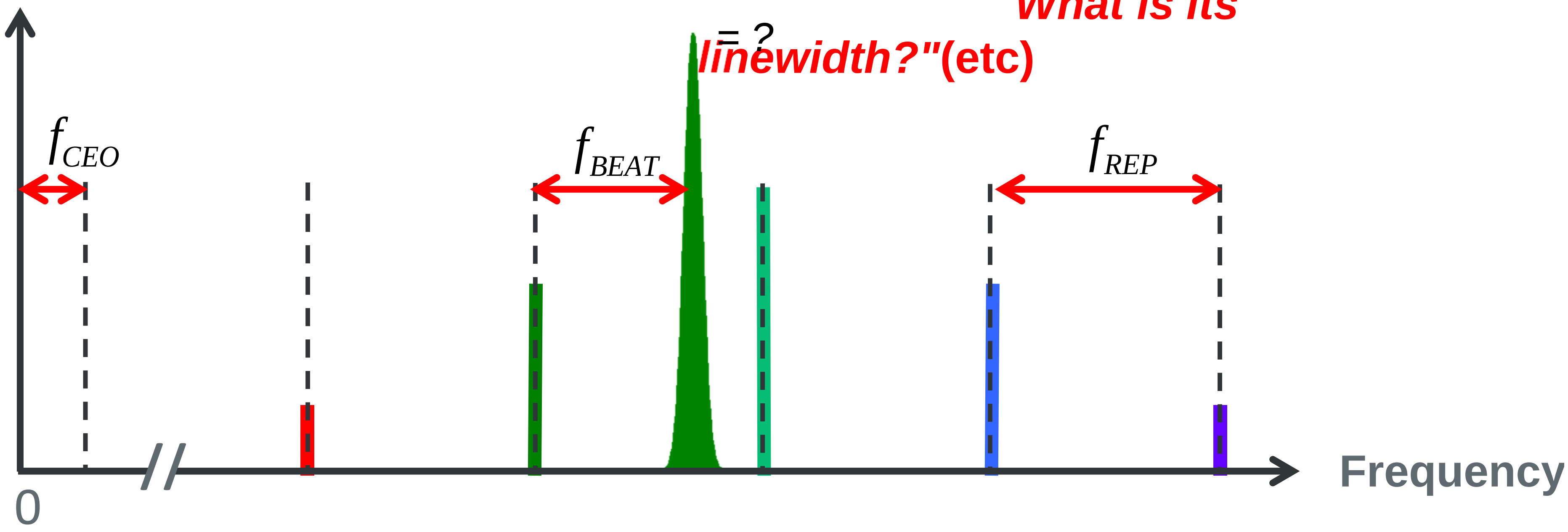
- $f_{REP}$ : sub-mHz stability (~$10^{-13}$), but uncertainty in $f_n$ multiplied by $n$ ~ $10^6$
- $f_{CEO}$ : sub-Hz level stability (~$10^{-10}$), contributing only additively to $f_n$ uncertainty

# Precision optical metrology with a frequency comb

❖ Answering the most basic questions of, ***"What is this frequency?"***

***"How stable is it?"***

***"What is its linewidth?"*** **(etc)**

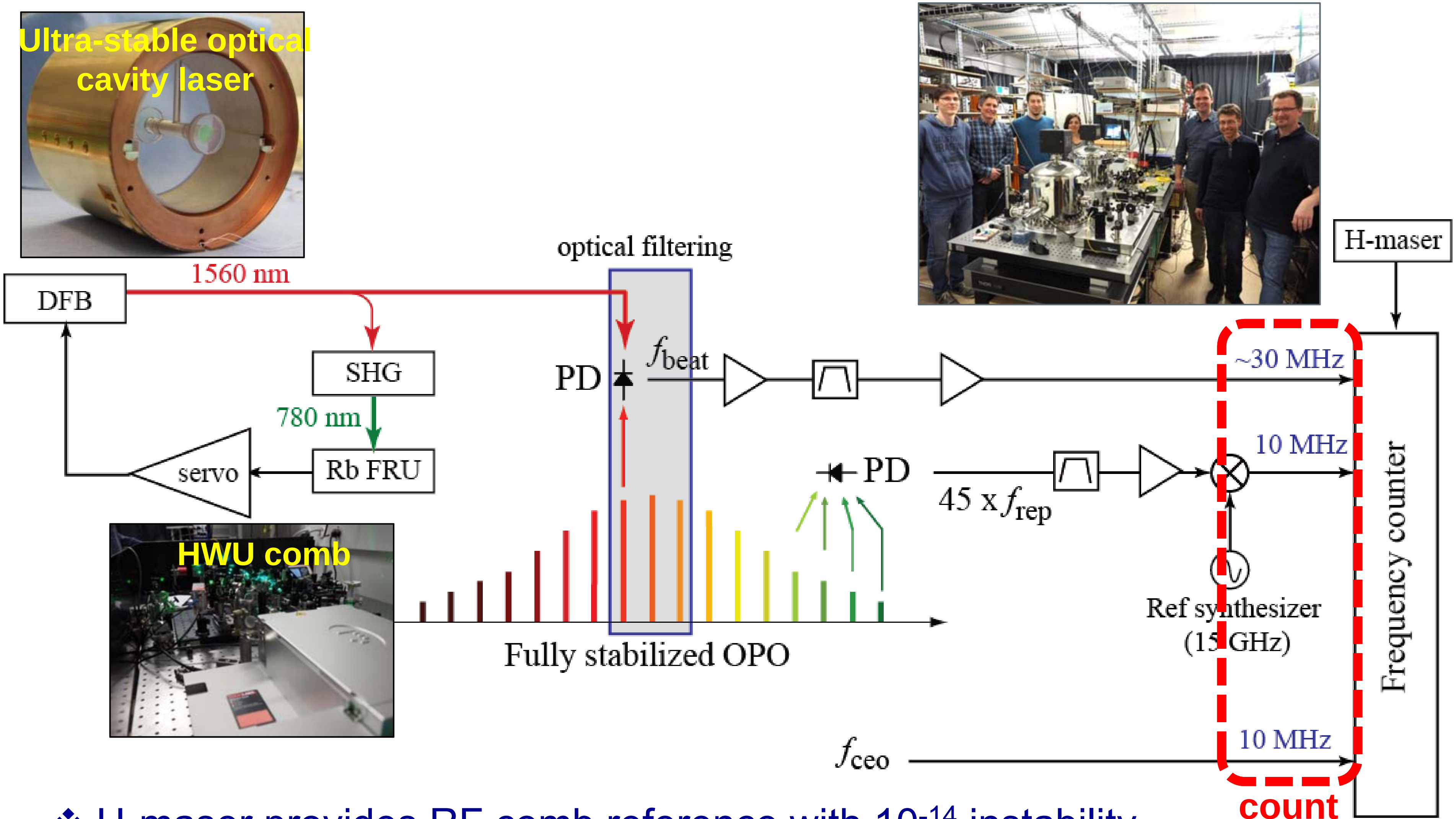



❖ By recording $f_{BEAT}$, $f_{CEO}$ and $f_{REP}$ we can determine the unknown frequency

❖ Measurement precision is limited only by the instability of the comb reference frequencies

# Ultra-precision frequency measurement using HWU frequency comb

Balskus et al., Opt. Express 24(8), 8370-8381 (2016)

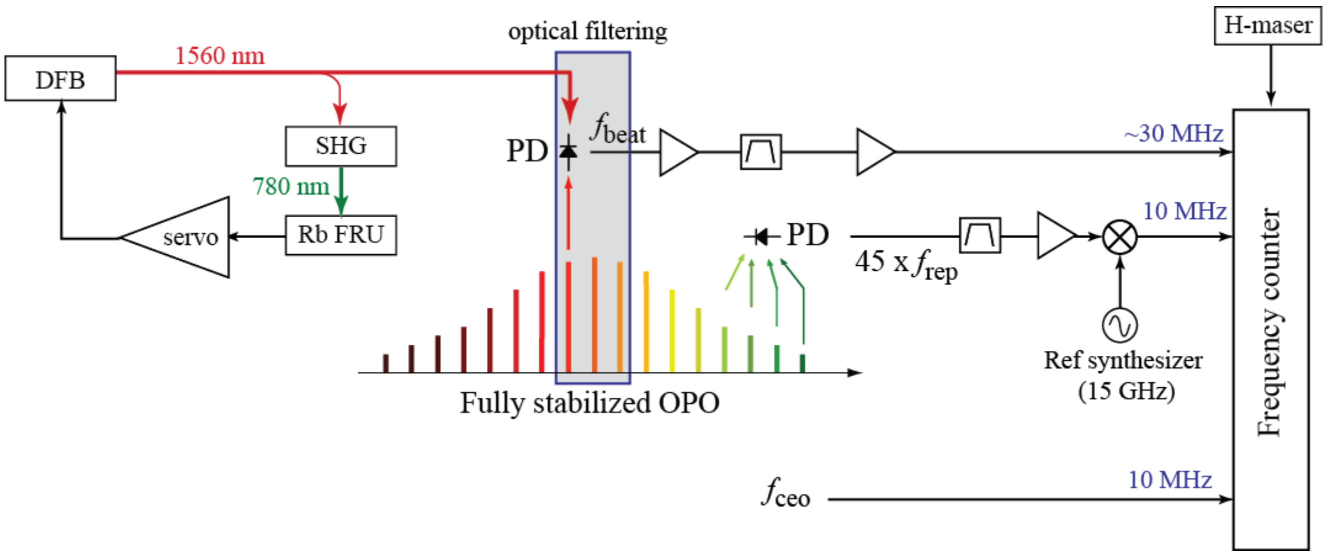



❖ H-maser provides RF comb reference with $10^{-14}$ instability

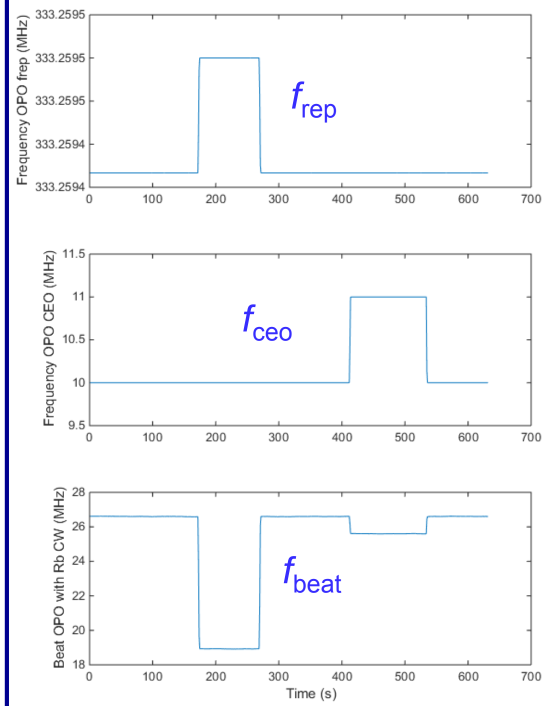
# Ultra-precision frequency measurement using HWU frequency comb

Balskus et al., Opt. Express 24(8), 8370-8381 (2016)

- Measurement of the optical frequency of a 1560 nm laser, frequency-doubled and locked to a Rb transition by saturation spectroscopy
- Simultaneous recording of $f_{REP}$, $f_{CEO}$ and $f_{BEAT}$ with dead-time-free counters (FXM50 from Menlo)
- Determination of the signs of the beats ($f_{CEO}$ and $f_{BEAT}$
- Optical frequency: $\dfrac{\nu_{Rb}}{2} = N \cdot f_{REP} + f_{CEO} + f_{BEAT}$




### Beat sign determination



# Ultra-precision frequency measurement using HWU frequency comb

Balskus et al., Opt. Express 24(8), 8370-8381 (2016)

| Parameter | OPO measurement 1 | OPO measurement 2 | Menlo comb measurement |
|---|---|---|---|
| $f_{rep}$ [Hz] | 333’261’086.66666 ± 0.00046 | 333’260’610.66667 ± 0.00046 | 250’000’413.00000 ± 0.00039 |
| $f_{ceo}$ [Hz] | 10’000’000.000 ± 0.084 | 10’000’000.001 ± 0.172 | 20’000’000.000 ± 2.271 |
| $f_{beat}$ [Hz] | 28’785’300.558 ± 37’478.230 | -30’036’067.888 ± 7680 | 29’731’235 ± 28’500 |
| *N* (calculated) | 576’446 (576’446.999906) | 576’446 (576’467.999784) | 768’455 (768’454.999844) |
| Measured frequency [Hz] | 192’114’057’632’772 ± **37’500** | 192’114’057’673’724 ± **7’680** | 192’114’057’640’680 ± **28’500** |
| Theoretical value [Hz] | 192’114’057’601’610.0 | | |
| Frequency offset [Hz] | **+31’200** | **+72’100** | **+39’070** |

- Agreement between independent measurements to 10 significant figures
- Similar agreement with expected (theoretical) value
- Short-term noise on the measured optical frequency at the kHz level, mainly limited by the MHz linewidth of the cw laser
- Measurement also yields the mode number of the exact comb mode heterodyned with the unknown frequency

# Precision distance metrology with a frequency comb

nature photonics

ARTICLES

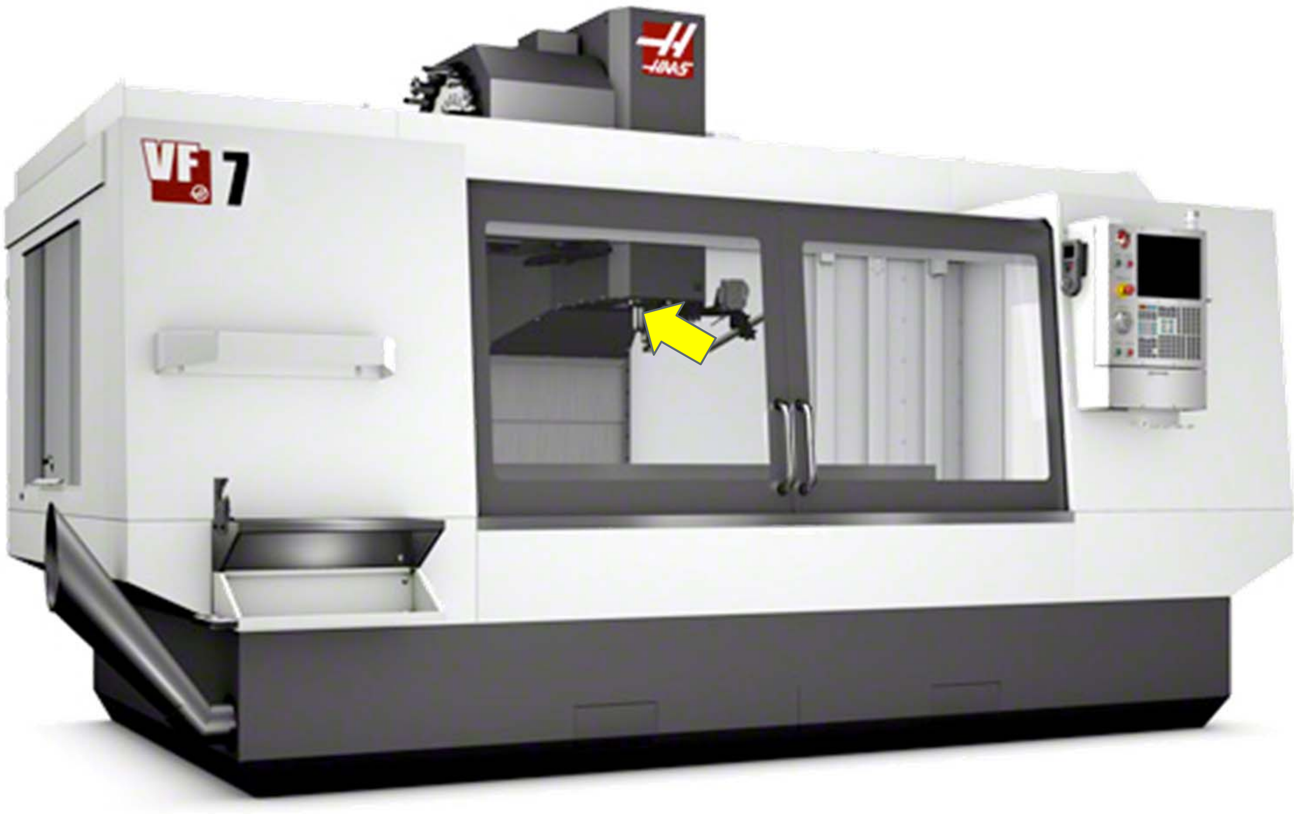
PUBLISHED ONLINE: 24 MAY 2009 | DOI: 10.1038/NPHOTON.2009.94

## Rapid and precise absolute distance measurements at long range

I. Coddington*, W. C. Swann, L. Nenadovic and N. R. Newbury*

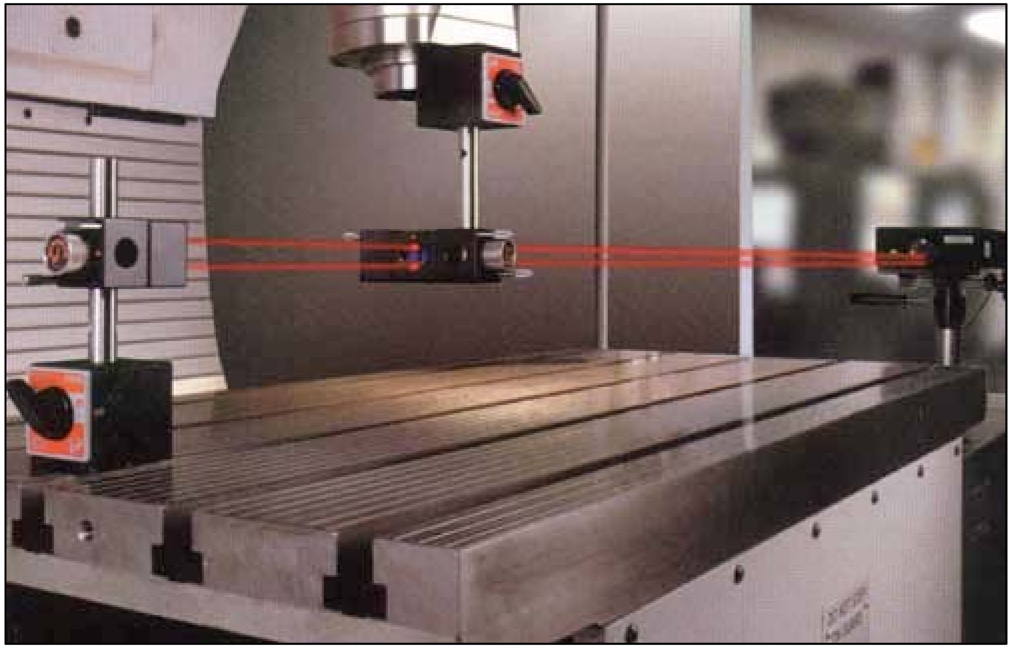
- Introduced a new way of exploiting the precision of frequency combs ***in distance measurements***
- Using this technique, frequency combs present intriguing opportunities for use in ***manufacturing metrology...***

# The metrology problem




- Is that machine tool always going to the right place?
- How far has it moved?
- Will it "home" to the same position every time?

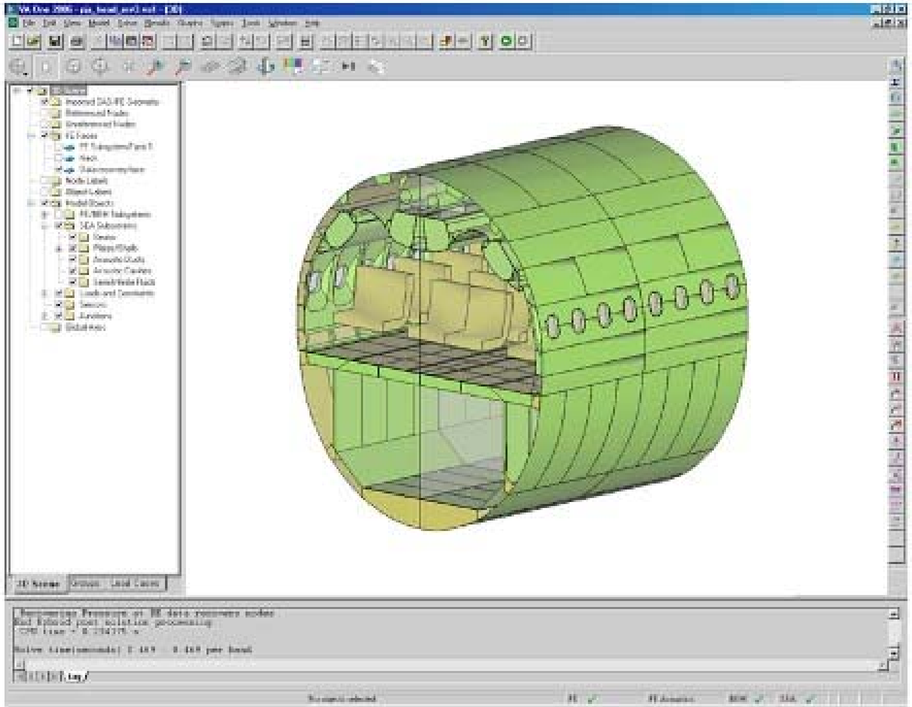
# The metrology problem



- ❖ Can use laser interferometry to calibrate position
- ❖ A movement of $\lambda/4$ changes a fringe on a detector from dark to bright
- 🙂 Good at measuring changes in position
- 🙂 nm precision
- ☹ No absolute ranging (must count fringes to measure large distances)
- ☹ Measurement compromised if beam blocked... re-home and start again

# The metrology problem


? =



- ❖ Did we make it right?
- ❖ Is the size and shape of what we made the same as the CAD model?
- ❖ Fuselages, telescope mirrors, turbine blades, buildings...
- ❖ Photogrammetry or laser ranging methods used to answer this question
- ❖ Resolution limited to ~ 1mm level

# The metrology problem


- Solutions: photogrammetry or laser ranging

- Gives absolute position
- Limited resolution (mm)

# The metrology problem

**Accuracy**
*"am I measuring the correct value?"*

*trade-off*

**Precision**
*"what is the uncertainty in my value?"*

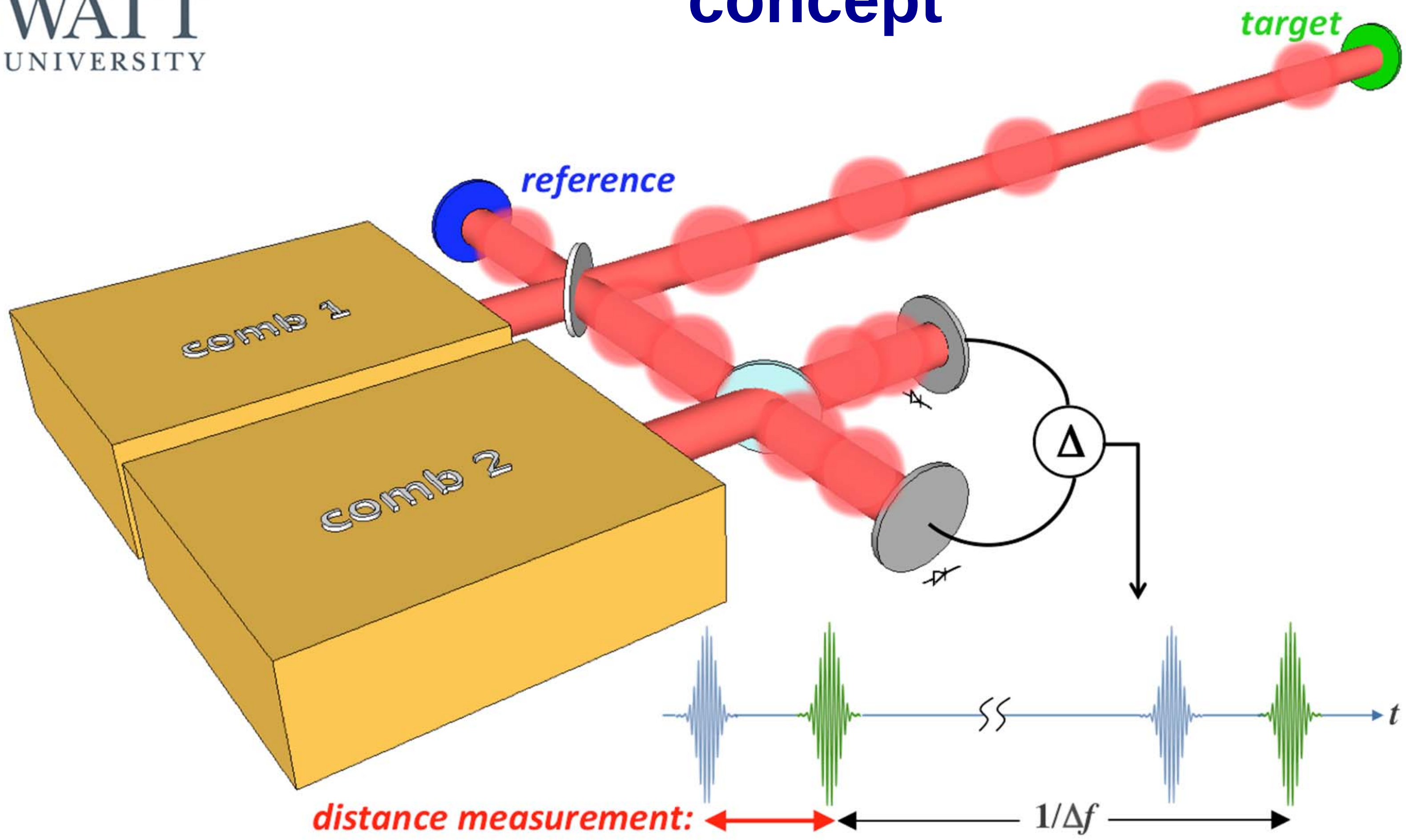
Time-of-flight ranging

Interferometry

## "Dual-comb" distance metrology

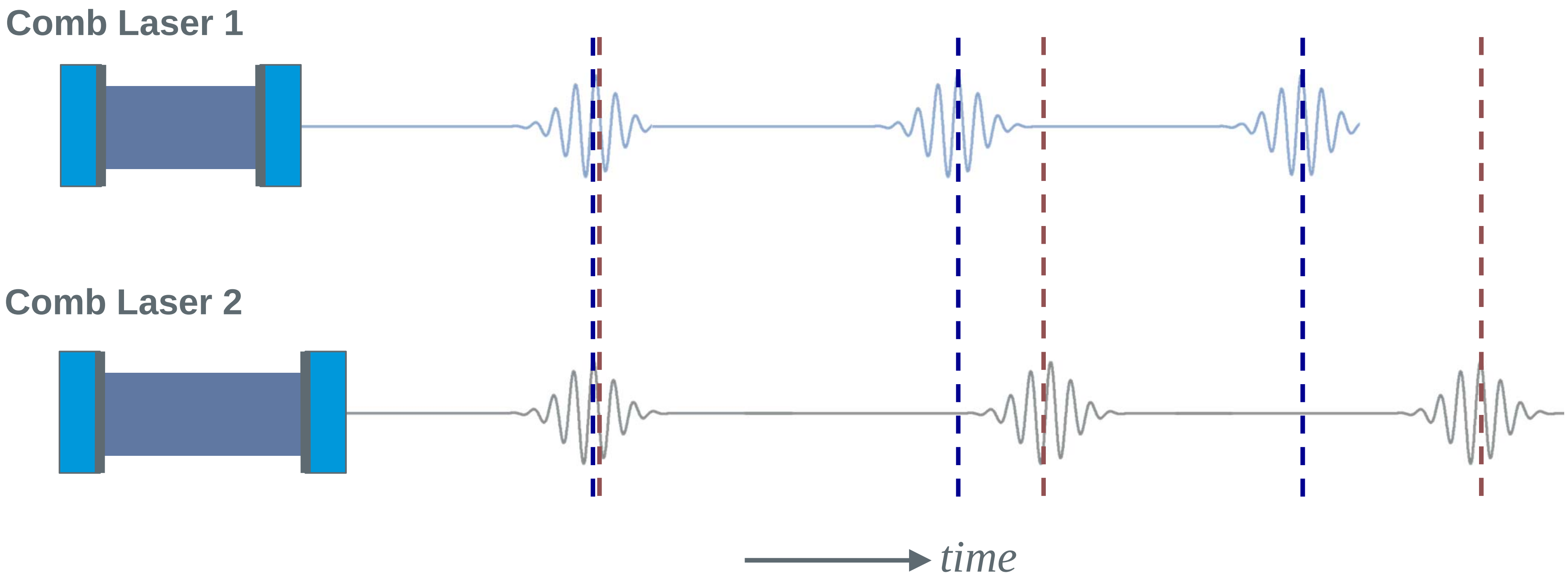
- The envelope of the pulse gives an absolute arrival time ***...like time-of-flight***
- The phase of the pulse gives nanometre precision ***...like laser interferometry***

# Dual-comb distance metrology concept




- ❖ Pulses (comb 1) are launched into interferometer reference and target arms
- ❖ Pulses from a second comb (comb 2) coherently gate the first pulses in time, yielding data revealing the absolute target position with interferometric accuracy.

# Dual-comb distance metrology concept




- ❖ Dual-comb metrology uses two modelocked lasers operating at slightly different pulse repetition frequencies
- ❖ Resembles a Vernier scale in time: the gap between the two pulse envelopes gives absolute distance
- ❖ When phase-locked (true "frequency combs") their phase difference gives accuracy to sub-wavelength

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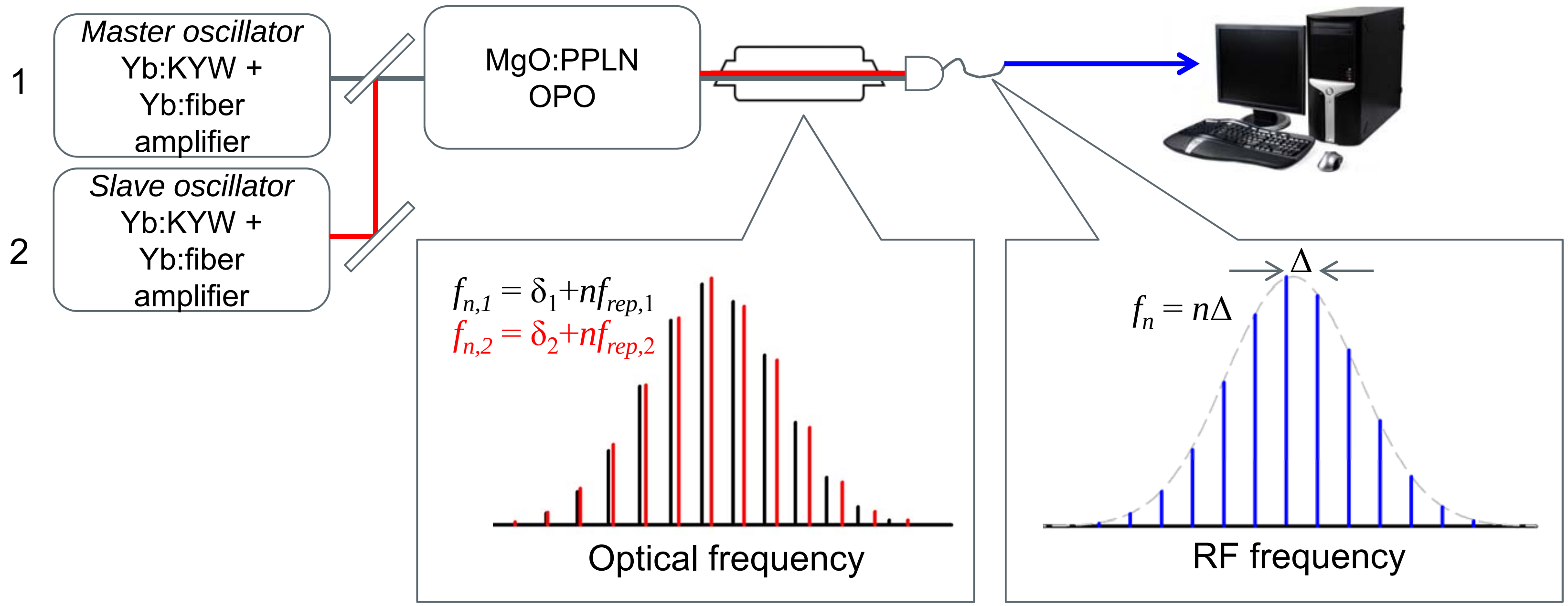
# Frequency-comb enabled metrology for manufacturing (EPSRC EP/N002547/1)

- Er:fibre laser and Ti:sapphire laser developmen
- Some RF electronics and locking loops to stabilise the two lasers
- Lab measurements to develop and calibrate dual-comb metrology technique
  - "ground truth" from HeNe interferometer
  - envelope extraction algorithms
  - extending the ambiguity range:
    - Vernier techniques
    - phase-meters
    - single-photon counting
- Field measurements
  - extended-range performance
  - challenging objects, including large optics for astronomy

# Mid-infrared asynchronous OPO frequency-comb spectroscopy

- **Coherent** but **asynchronous** pulses from 2 frequency combs can be used to "mimic" Fourier-transform spectroscopy[1–4]
- Compared with conventional FTIR spectrometer,
- No moving parts, so it is **robust**, and **high spectral resolution (< 0.01 cm$^{-1}$)** data can be obtained **rapidly** (in only a few ms).

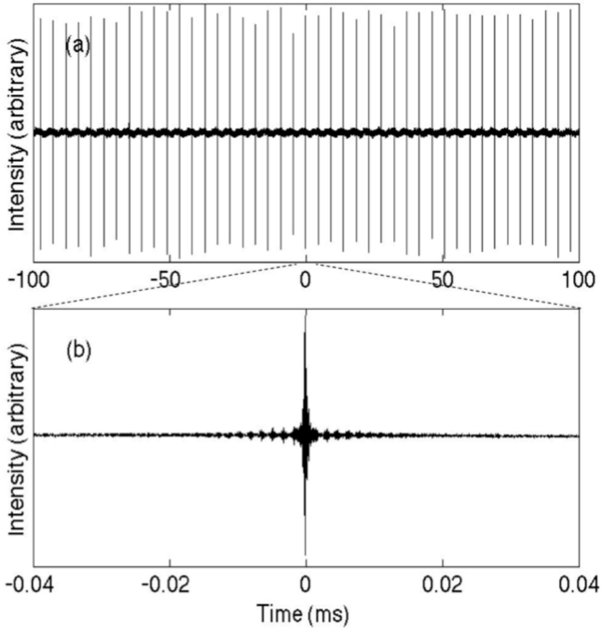


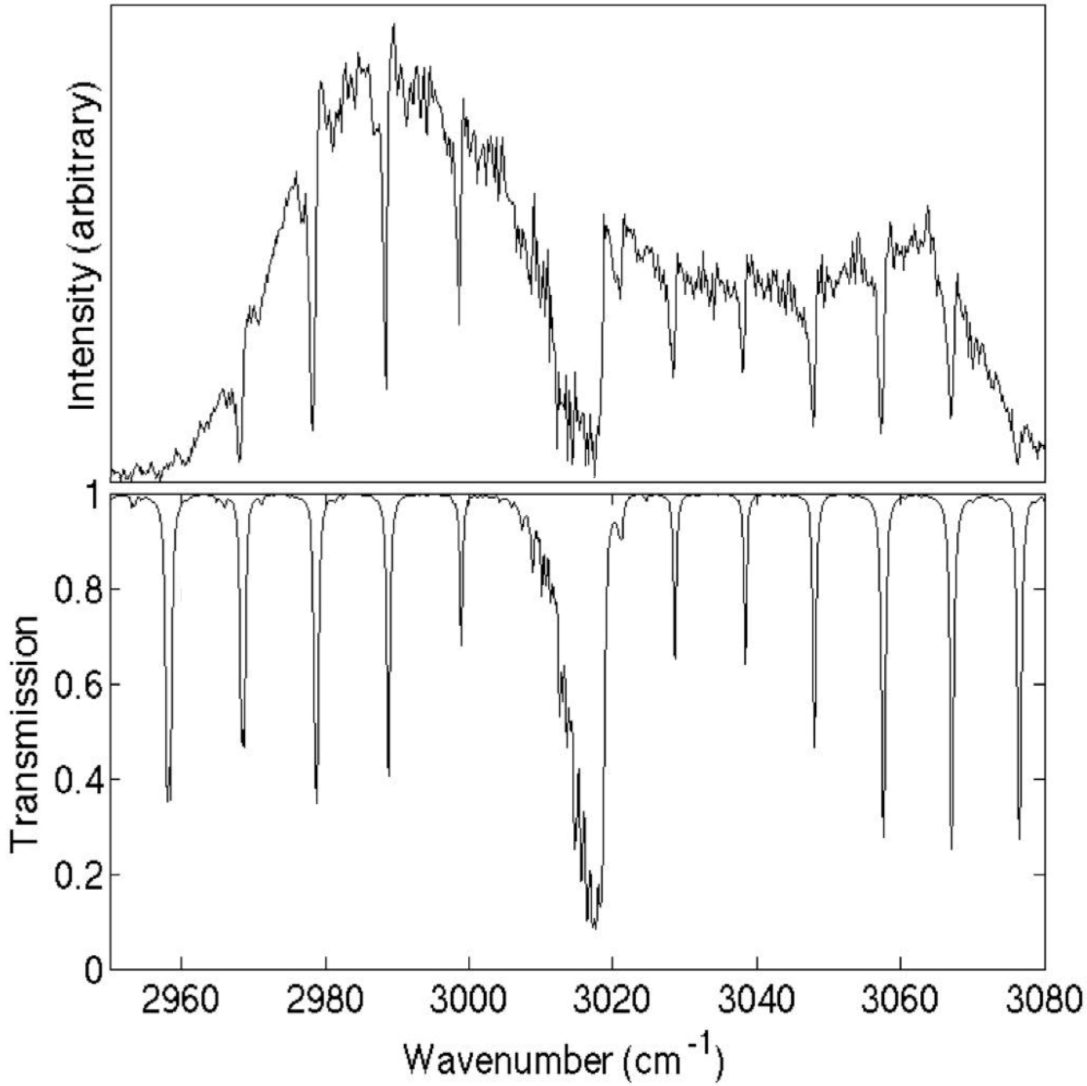

1. Keilmann et al, Opt. Lett. **29**, 1542 (2004)
2. Schliesser, et al., Opt. Express **13**, 9029-9038 (2005)
3. Coddington, et al, Phys. Rev. Lett. **100**, 013902 (2008)
4. Baumann, et al., Phys. Rev. A **84**, 062513 (2011)

# Mid-infrared asynchronous OPO frequency-comb spectroscopy

Z. Zhang et al, Optics Letters 38, 3148-3150 (2013)
Kara et al., CLEO (2016)

- Dual-comb methane absorption




- HITRAN fit parameters: 0.65% $CH_4$ at 1 atm, 20 cm cell, Res = 0.2 cm$^{-1}$

# Precision astronomical spectroscopy with a frequency comb

THE SCOTSMAN
SCOTLAND on SUNDAY

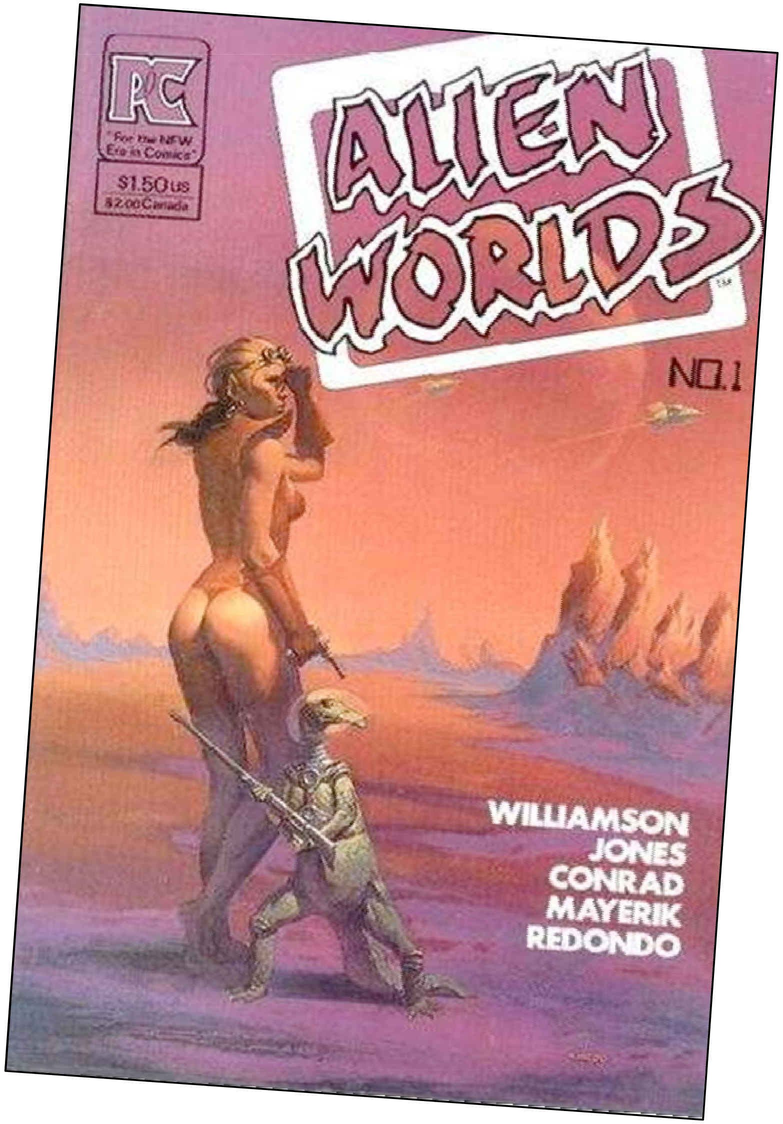
Friday 31st January 2014 | Heavy rain 1°C / 4°C

Scotland | UK | World | Politics | Transport | Education | Sci-Tech | Environment | Health | Celebrity | Odd | Opin

Top stories | Edinburgh, East & Fife | Glasgow & West | North East | Tayside & Central | Inverness & Highlands | Sou

## Scottish scientists to search for alien life

Artists impression of EELT in its enclosure on Cerro Armazones in Chiles Atacama Desert. Picture: Contributed



# Precision astronomical spectroscopy with a frequency comb

exoplanet

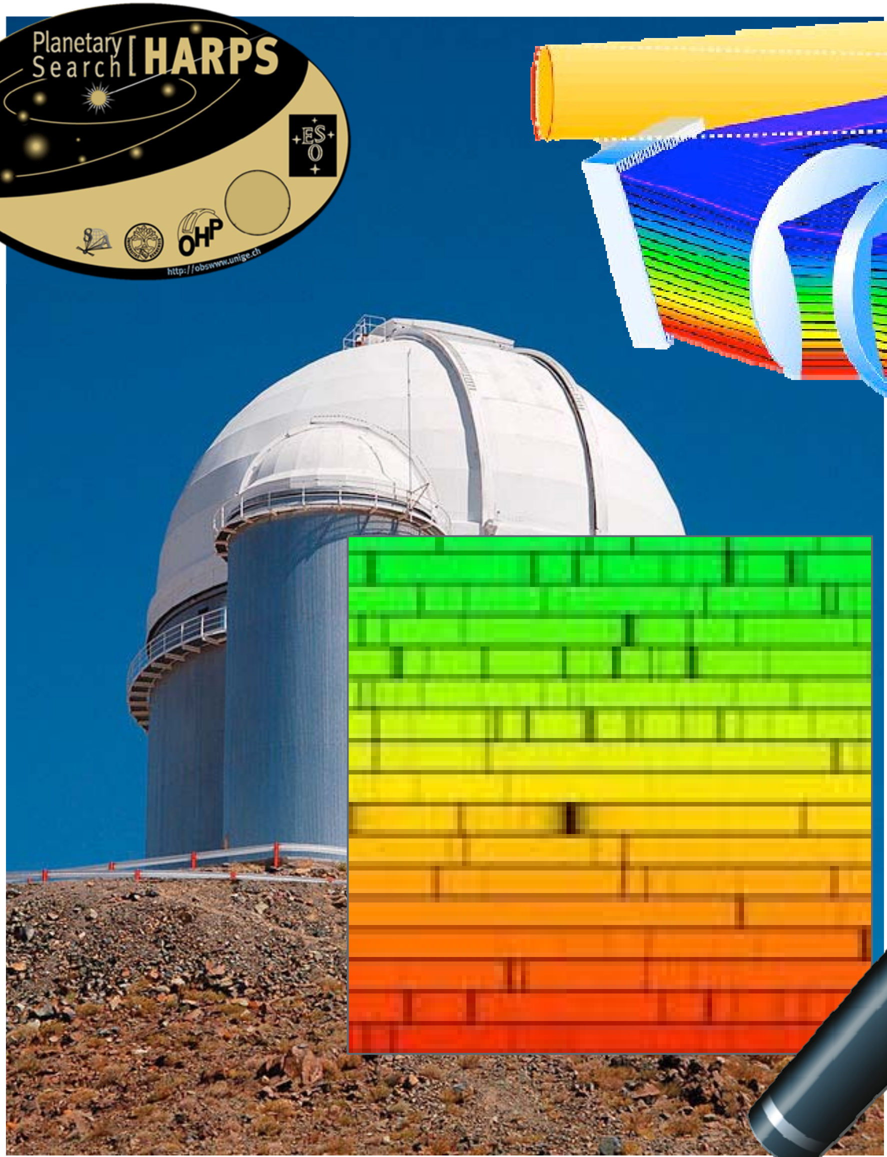
/ˈɛksəʊplanɪt/

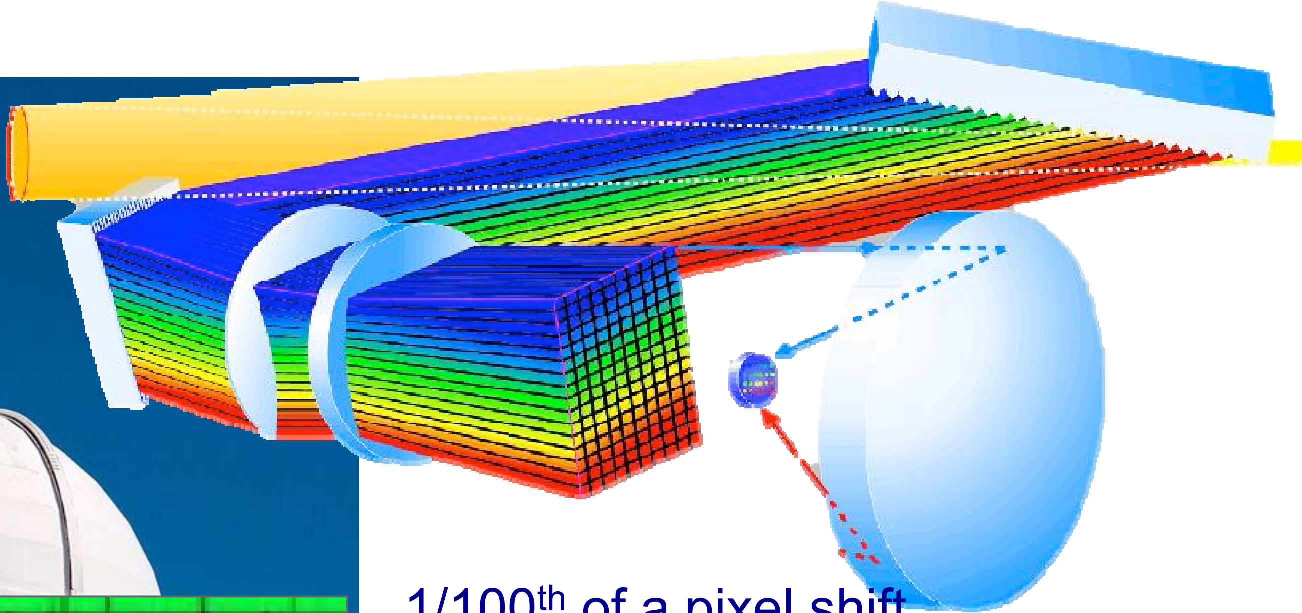
*noun*

a planet which orbits a star outside the solar system.

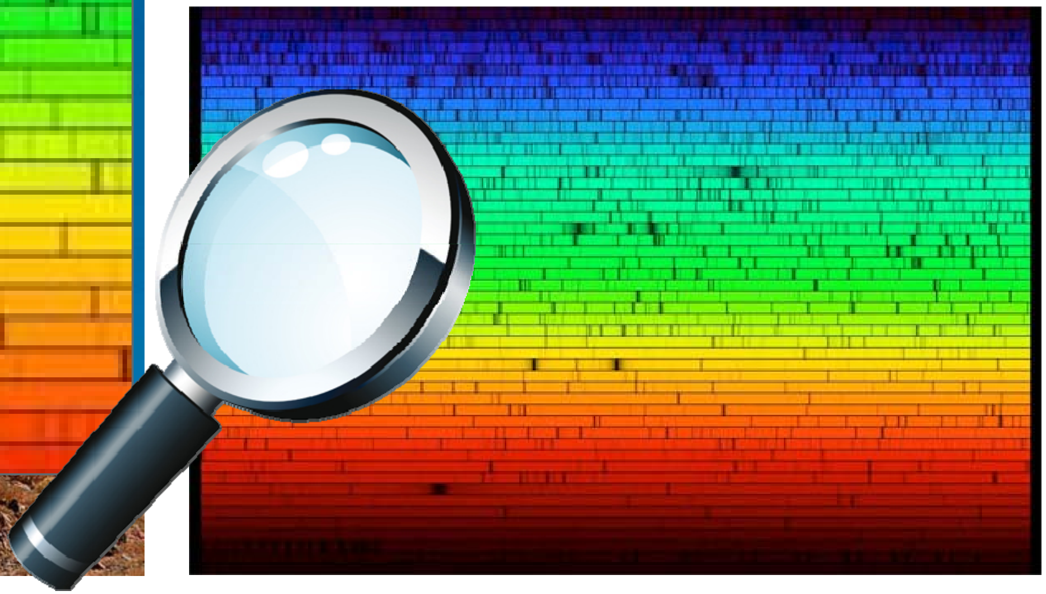
www.eso.org

# Starlight's colour change is tiny!





1/100$^{th}$ of a pixel shift

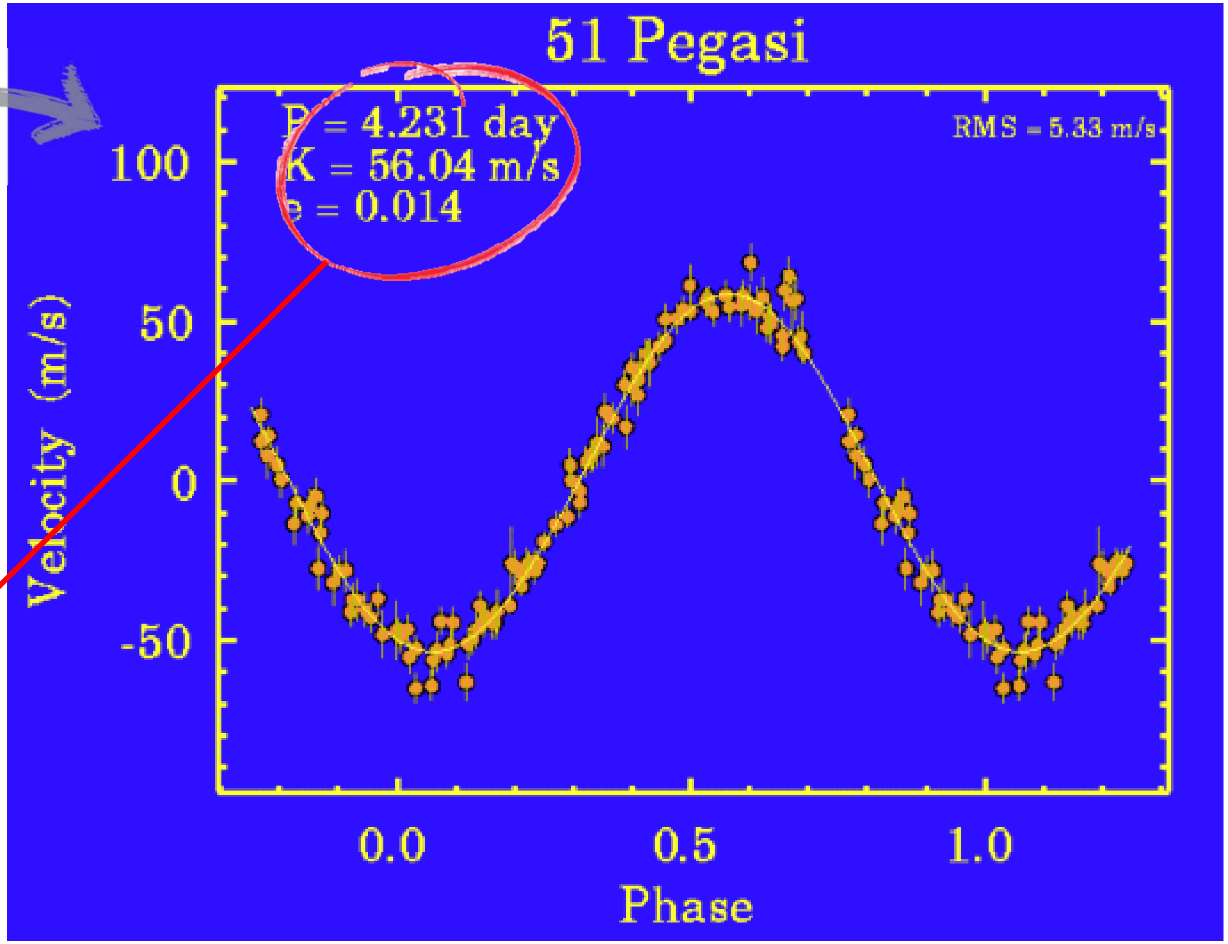


# First exoplanet discovered

Real data from the first exoplanet ever discovered

Orbiting planet similar in size to Jupiter

Remember this velocity!



# Radial velocity exoplanet search

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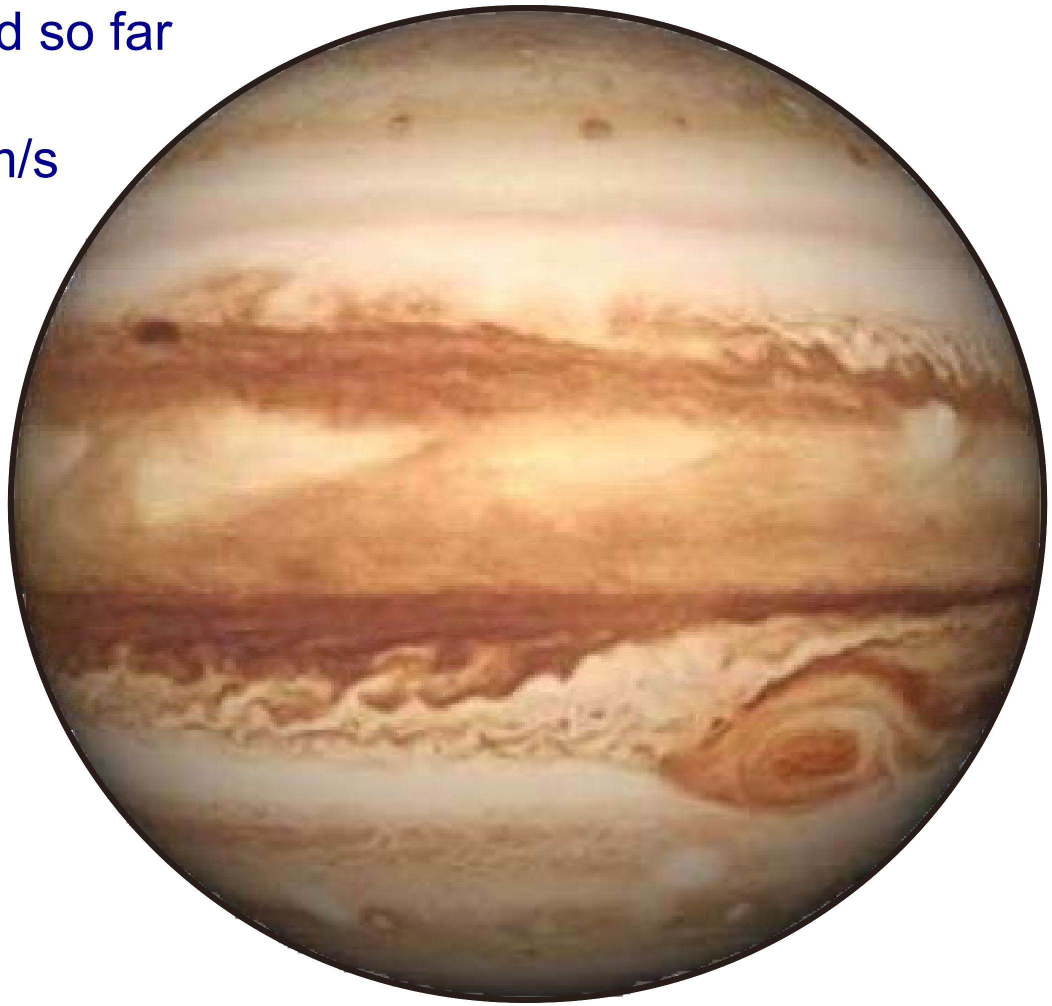
(Broadly speaking)
what we've found so far

Jupiter  K > 50 m/s



What we're looking for

Earth
K = 3 cm/s

# SALT – THE SOUTHERN AFRICAN LARGE TELESCOPE

# SALT astrocomb architecture

*electronic locks*

photonic crystal fibre

**Ti:sapphire laser**

1.2W and 25 fs
$\lambda$ = 770 – 830 nm
$f_{REP}$ = 1 GHz

**continuous-wave laser**

50 mW
$\lambda$ = 780.2 nm

**super-continuum**

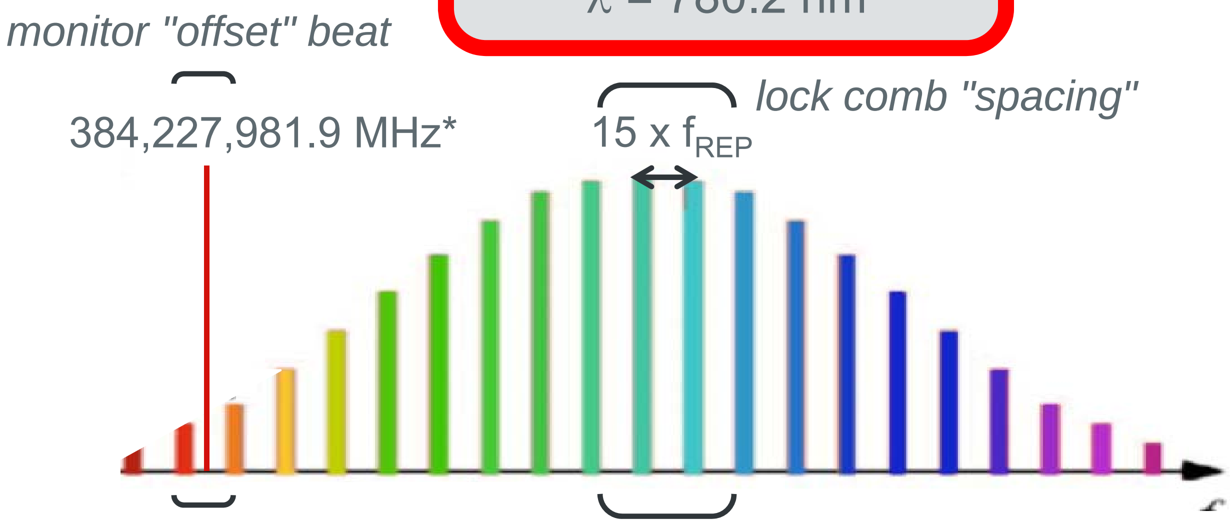
75 – 200 mW
$\lambda$ = 500 – 1000 nm
$f_{REP}$ = 1 GHz

**Fabry-Pérot**

5 – 13 mW
$\lambda$ = 500 – 1000 nm
$f_{REP}$ = 15 GHz

**delivery fibre**

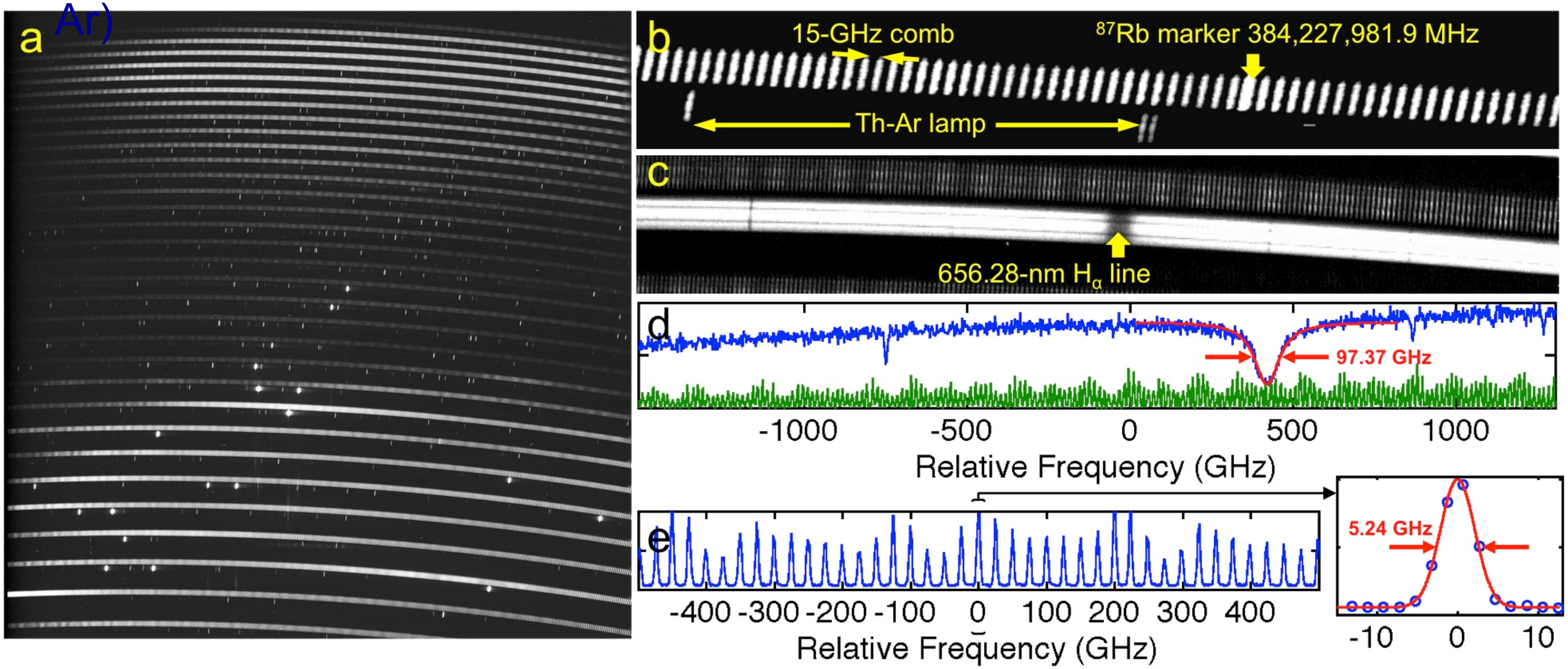
0.5 – 1.5 mW
$\lambda$ = 500 – 1000 nm
$f_{REP}$ = 15 GHz




*Ye et al, Opt. Lett. 21, 1280 (1996).

# Precision astrocomb spectroscopy from SALT high-resolution spectrograph

- ❖ Comb observed from 555-890 nm with factor-of-a-few intensity variation
- ❖ Rb-referenced 780-nm laser gives a precise frequency marker to 10 sig. fig.
- ❖ Massive increase in calibration lines over Th-Ar lamp
- ❖ Comb-calibrated on-sky data from LTT7379 shows expected $H_a$ linewidth
- ❖ Comb linewidth gives spectrograph R = 67,355 (64,600 previously using Th-Ar)



# The European Extremely Large Telescope (E-ELT)

ESO
European
Southern
Observatory

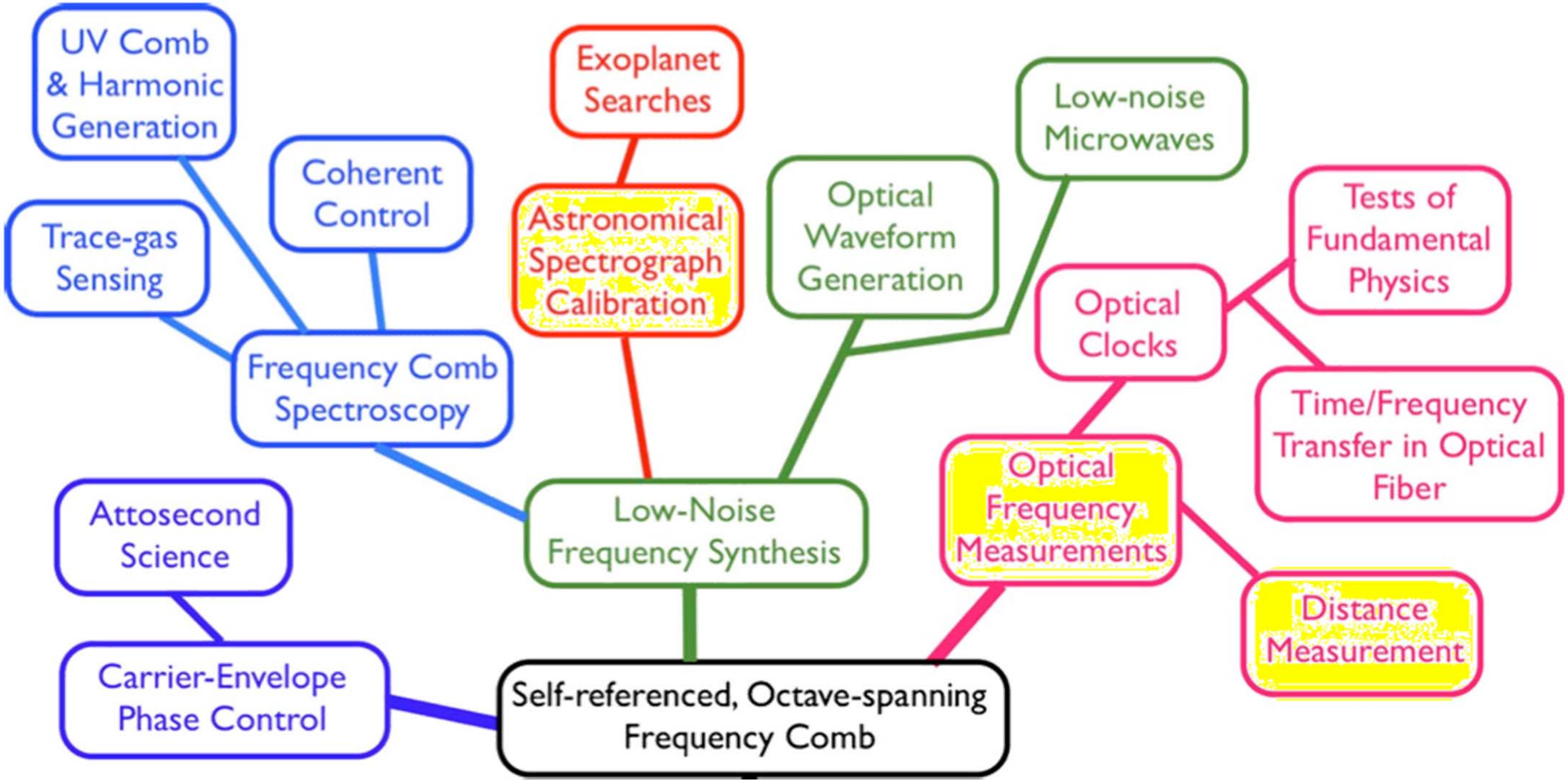
HIRES spectrograph

UK consortium: UK ATC (Edinburgh), Cambridge, Durham, Oxford, Heriot-Watt

Wavelength coverage: 0.4–2.4 μm

# Conclusions

❖ Wide range of precision metrology applications for frequency combs:




From Diddams, "**The evolving optical frequency comb**," J. Opt. Soc. Am, B **57**, B51

# Conclusions

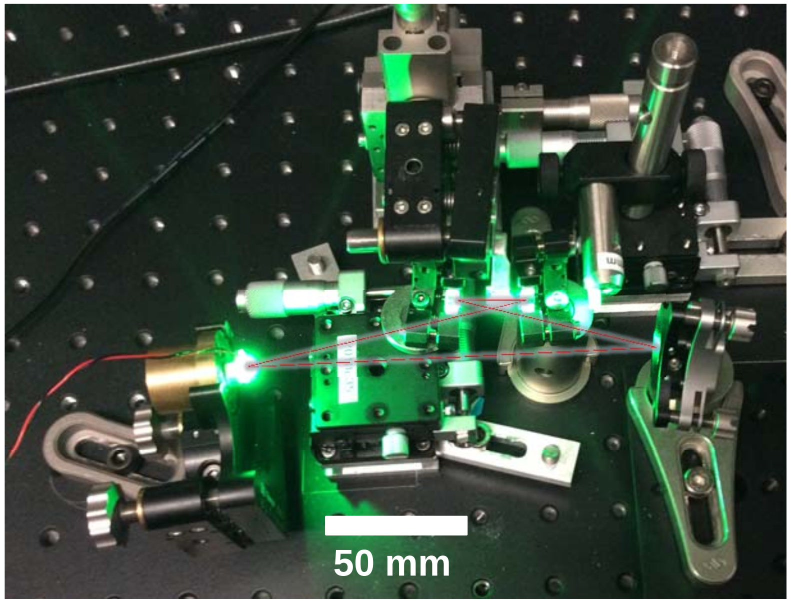
- Frequency combs represent the worlds most accurate measuring devices
  - absolute accuracy, when referenced to a frequency "gold standard" (e.g. GPS)
  - ultra-high intrinsic precision
  - traceability from one measurement to another

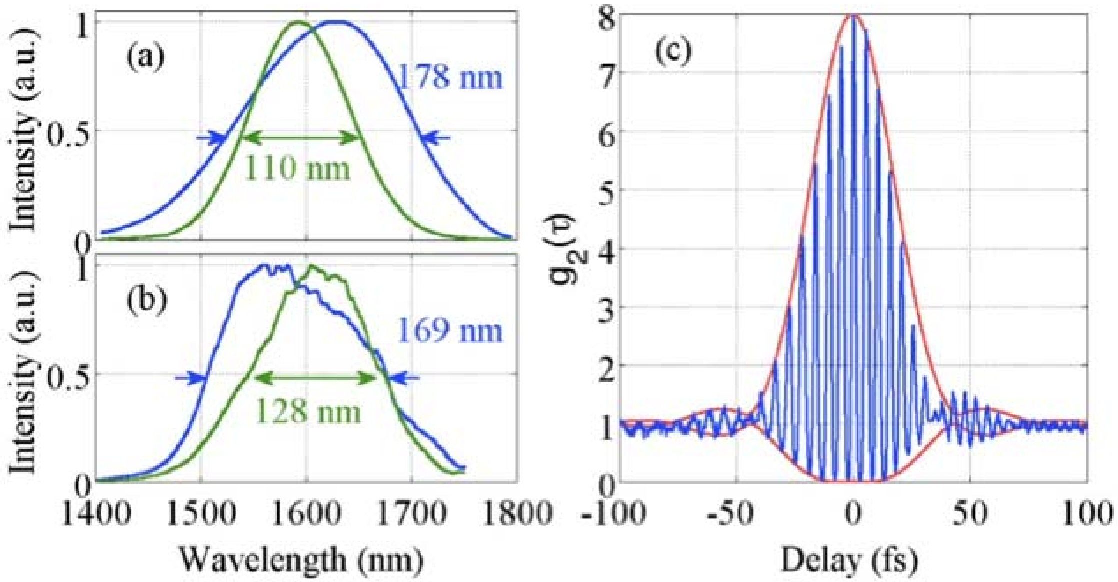

# Acknowledgements

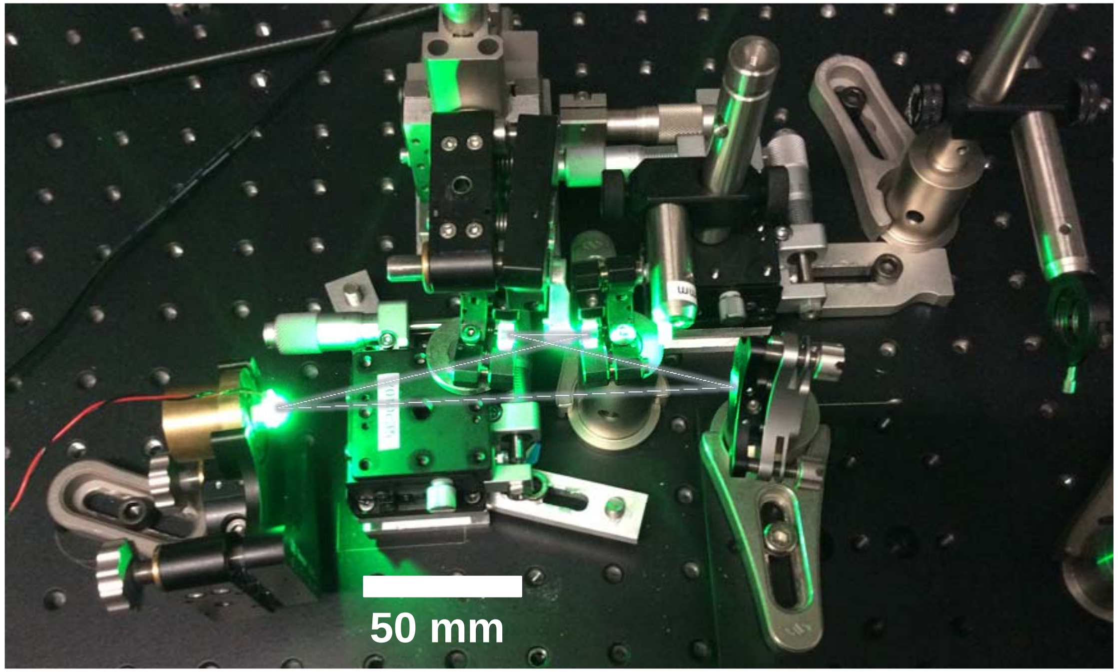
# Doubly-resonant degenerate 1-GHz OPO comb

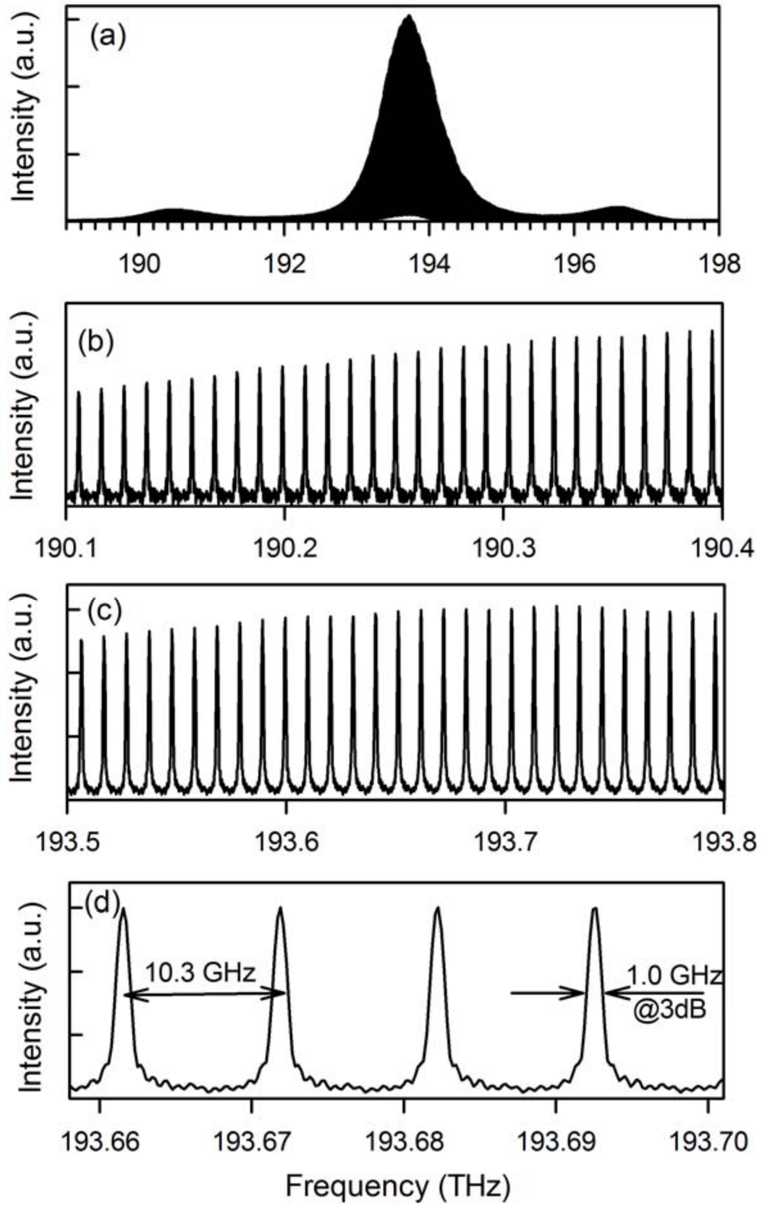
McCracken et al. "Few-cycle near-infrared pulses from a degenerate 1 GHz optical parametric oscillator," Opt. Lett. 40, 4102-4105 (2015)

- ❖ Five-cycle optical pulse generated at 1.6 µm
- ❖ Duration 23 fs and bandwidth 169 nm (full coverage from 1.4 – 1.8 µm)
- ❖ Peak power requirements are compatible with direct 10-GHz laser pumping
- ❖ Self-referenced locking the 805-nm pump laser leaves plenty power for OPO



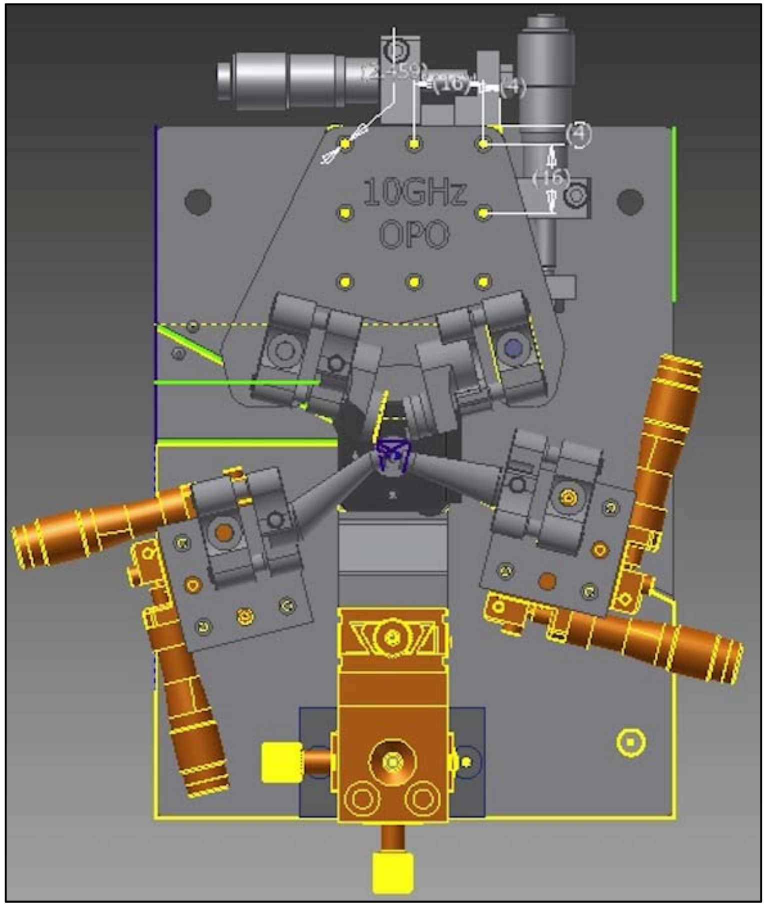

50 mm

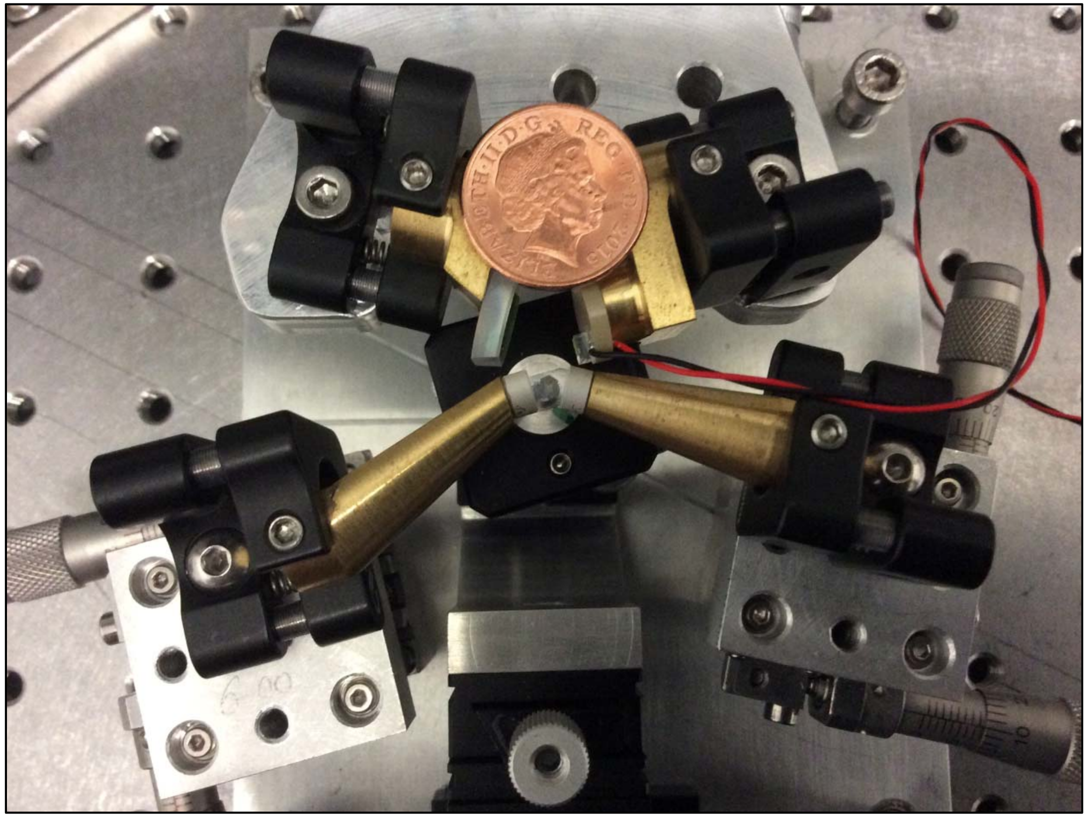

(a)
Intensity (a.u.)
190
192
194
196
198
(b)
Intensity (a.u.)
190.1
190.2
190.3
190.4
(c)
Intensity (a.u.)
193.5
193.6
193.7
193.8
(d)
Intensity (a.u.)
10.3 GHz
1.0 GHz
@3dB
193.66
193.67
193.68
193.69
193.70
Frequency (THz)

# Doubly-resonant degenerate 10-GHz OPO comb

HWU + Laser Quantum (Bartels): 1.6-µm fs OPO (oscillation achieved late August 2015).

*OPO shown beside a 1 pence coin*

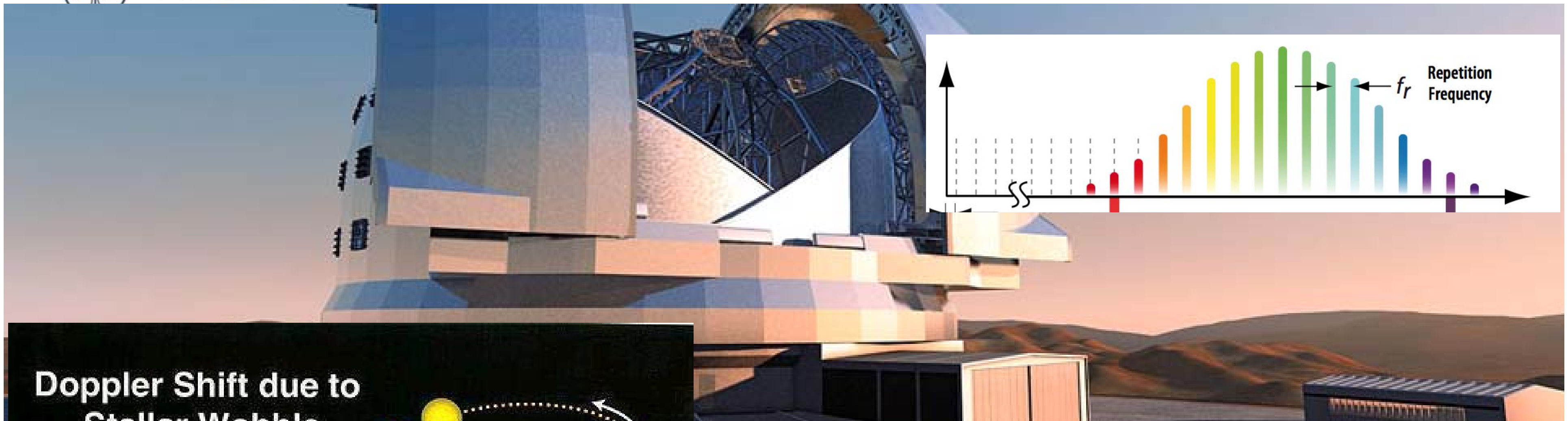


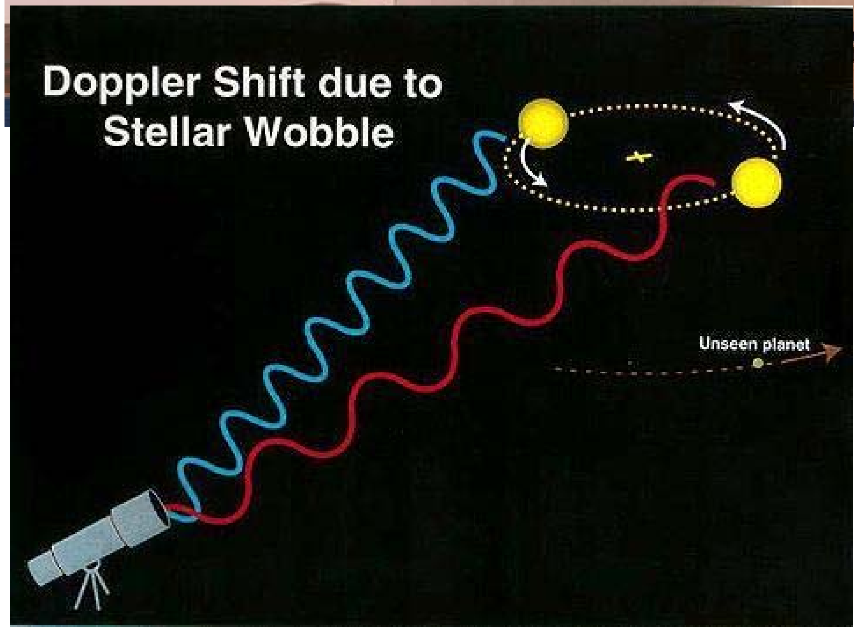



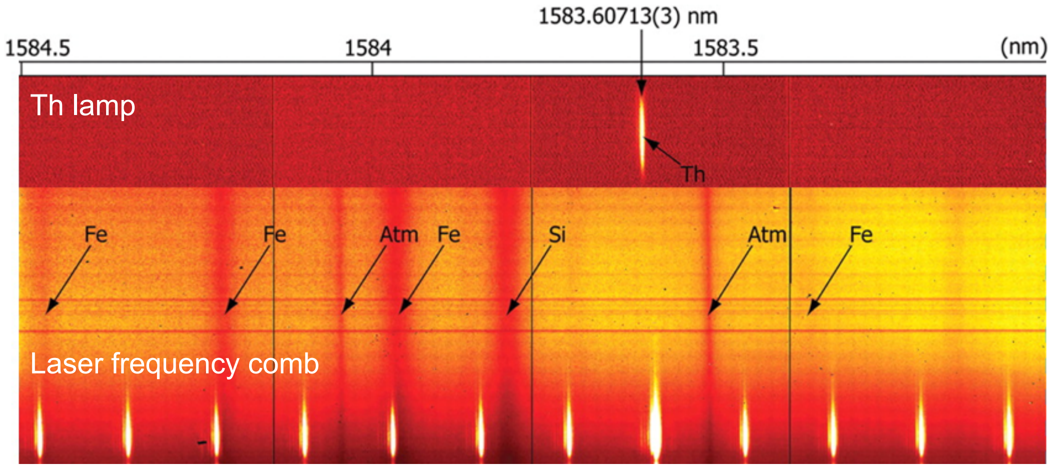
# GPS time makes the clock + comb system more compact



# Astronomy applications of femtosecond lasers




❖ Femtosecond laser provides extremely accurate frequency scale to measure tiny changes in the wavelength of starlight