Frequency Combs for Astronomy

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Optical Frequency Combs

Harmonic Frequency Chains

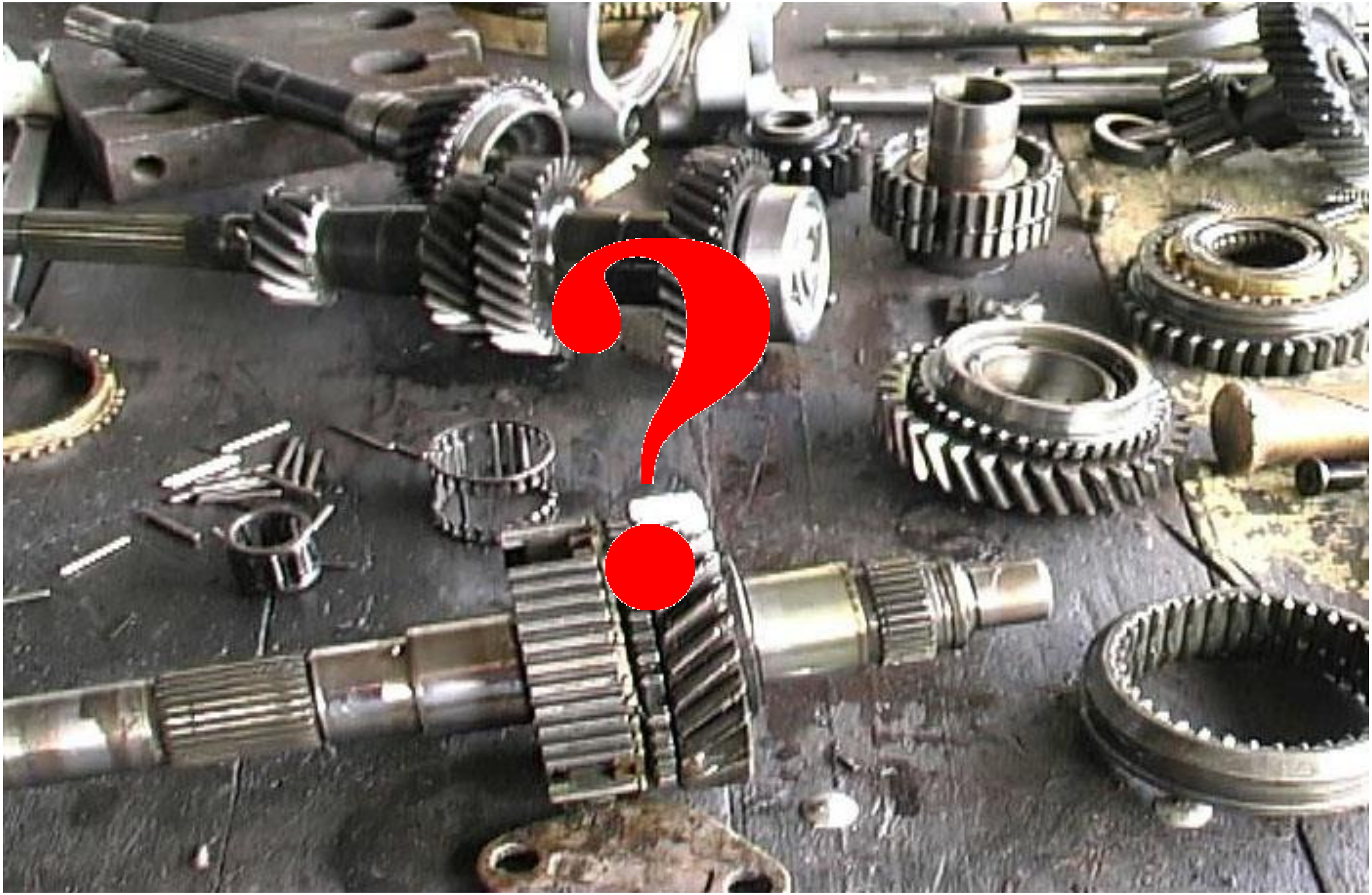
VOLUME 76, NUMBER 1 PHYSICAL REVIEW LETTERS 1 JANUARY 1996

First Phase-Coherent Frequency Measurement of Visible Radiation

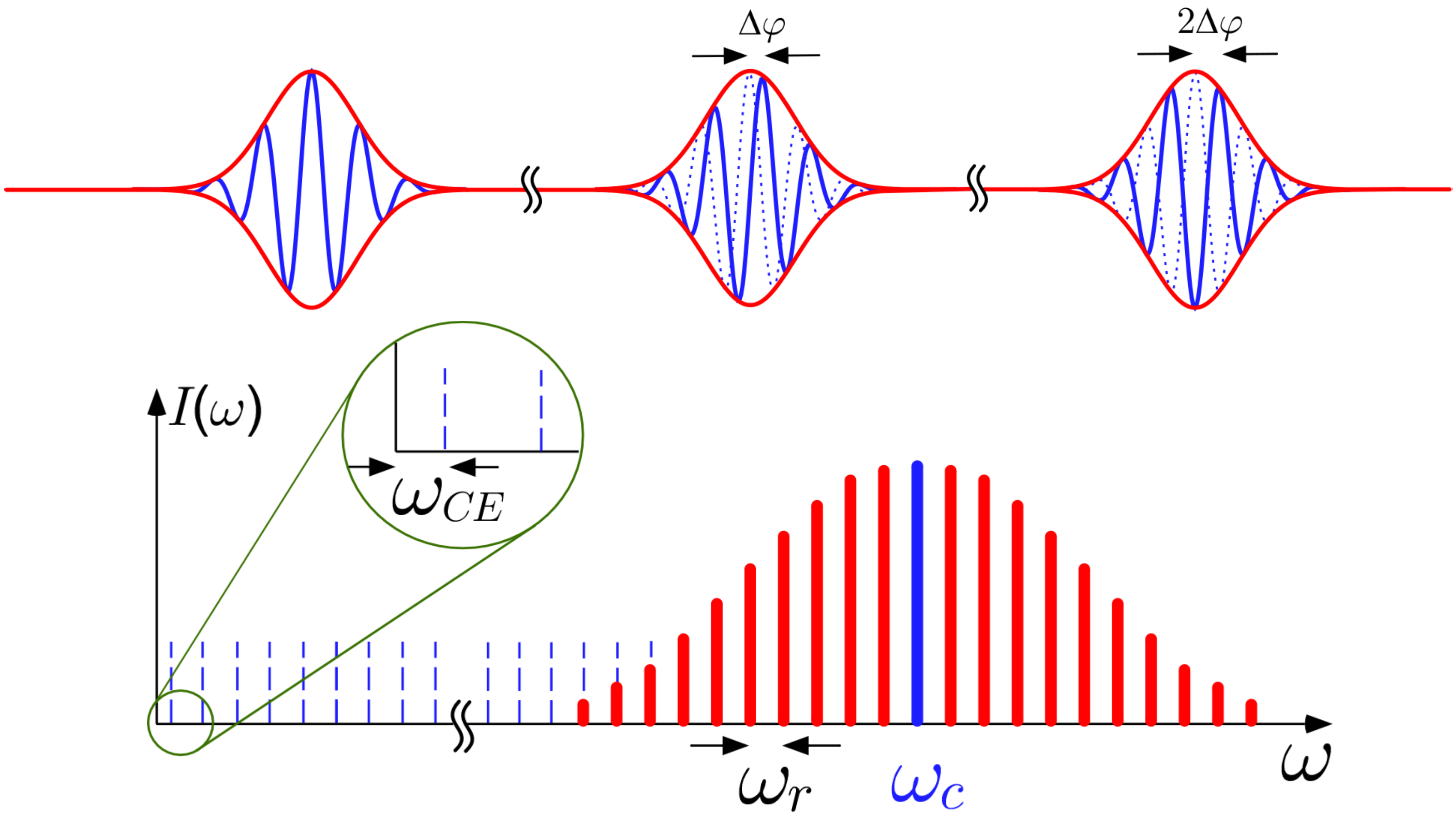
H. Schnatz, B. Lipphardt, J. Helmcke, F. Riehle, and G. Zinner
Physikalisch-Technische Bundesanstalt (PTB), D-38116 Braunschweig, Germany
(Received 10 August 1995)

We have determined the frequency of the $^3P_1$-$^1S_0$ intercombination transition of atomic ^{40}Ca stored in a magneto-optical trap to be $\nu = 455\,986\,240\,493.95$ kHz with an estimated standard uncertainty of 0.43 kHz ($\delta\nu/\nu < 10^{-12}$) using a phase-coherent optical frequency chain from the Cs atomic clock to the visible. This allows the realization of the SI-unit meter according to its definition by visible radiation with 25-fold reduced uncertainty compared to previous measurements.

How to improve the Optical Counter



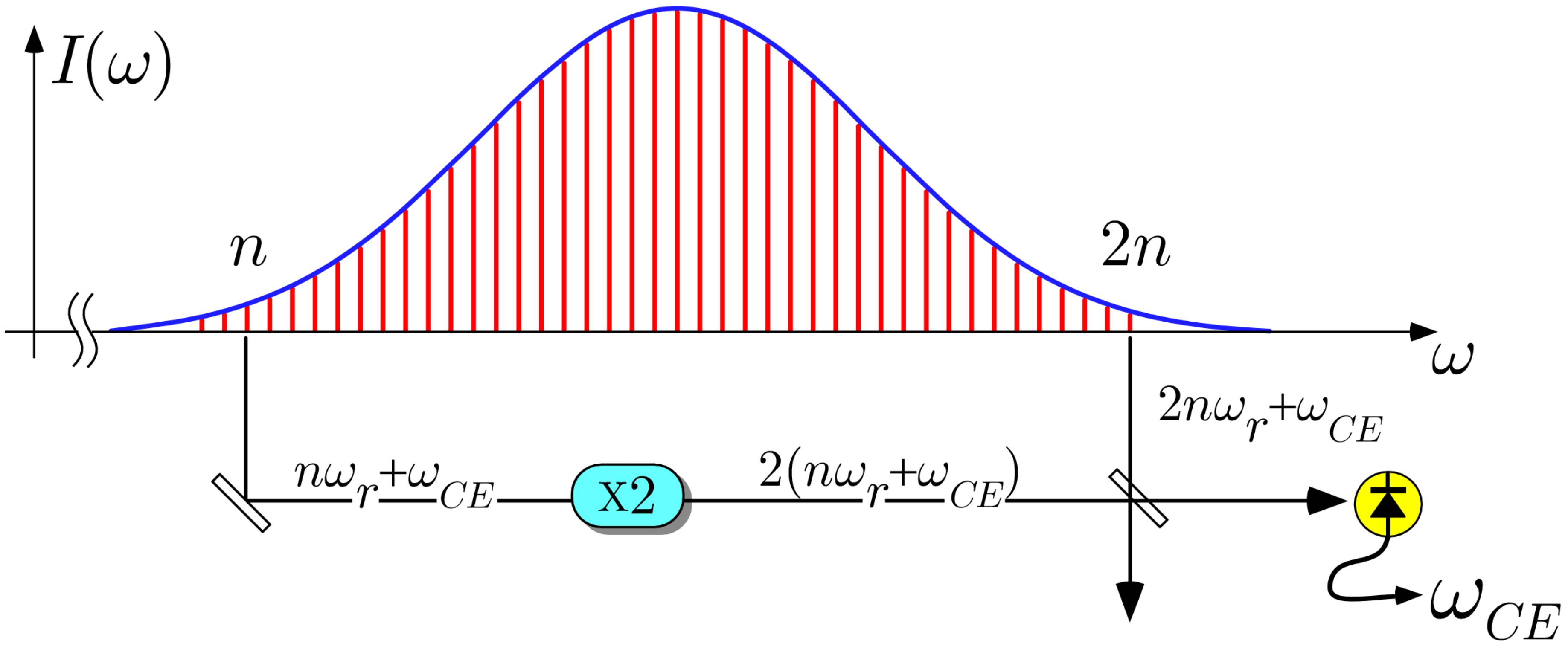
Mode Locked Laser



$$\omega_n = n\omega_r + \omega_{CE} \;\text{ with }\; \omega_{CE} < \omega_r$$

Self Referencing

Self Referencing

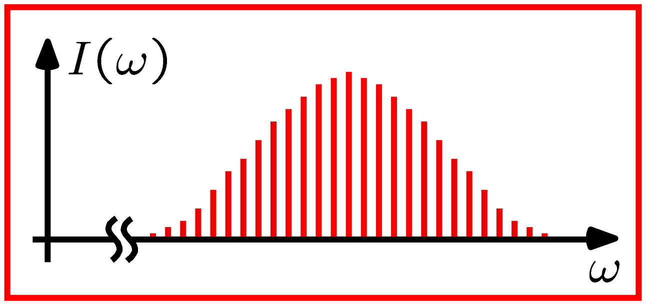


$$\omega_{CE} = 2(n\omega_r + \omega_{CE}) - (2n\omega_r + \omega_{CE})$$

Phys. Rev. Lett. 84, 5102 (2000) & Phys. Rev. Lett. 84, 3232 (2000)

Frequency Conversions with the Comb

radio frequency
or
optical frequency



radio frequency
or
optical frequency

radio frequency → optical frequency

locked to a Cs clock ($n\omega_r$ and ω_{CE})

$$\omega_n = n\omega_r + \omega_{CE}$$

optical frequencies (ω_n)

optical frequency → radio frequency

locked to a stable laser (ω_n)

locked to ω_r (ω_{CE})

$$\omega_n = n\omega_r + \omega_{CE}$$

countable clock output (ω_r)

optical frequency → optical frequency

locked to a stable laser (ω_n)

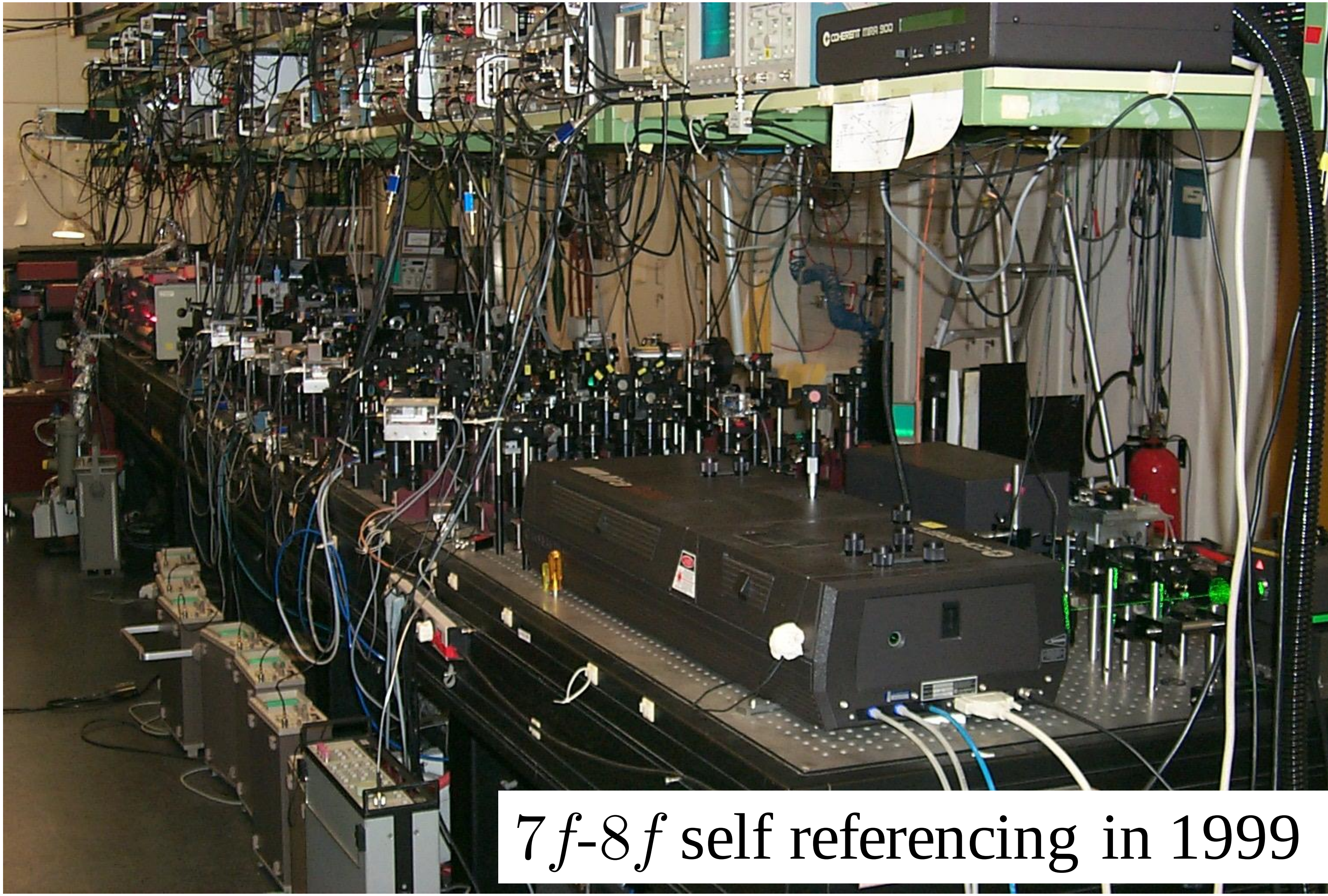
locked to ω_r (ω_{CE})

$$\omega_n = n\omega_r + \omega_{CE}$$

measure another laser (ω_n)

Science 293, 825 (2001)

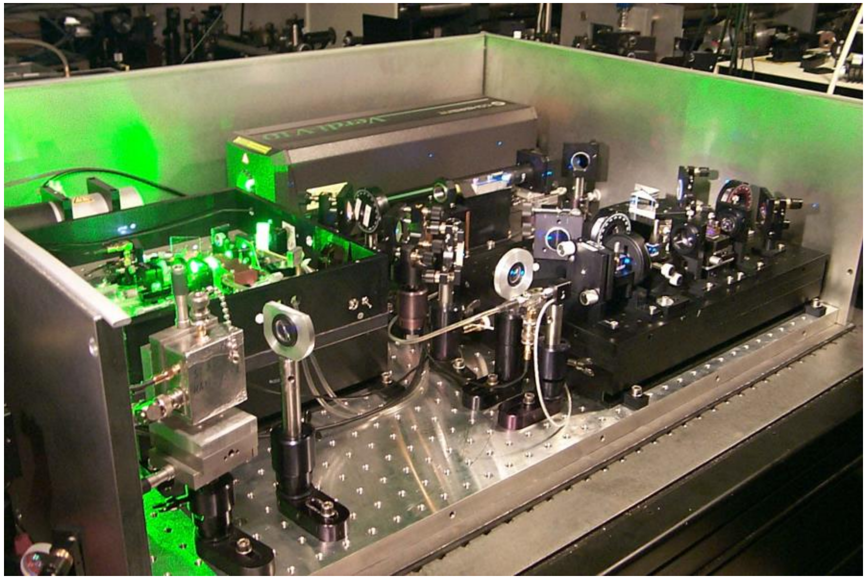
First Self Referenced Frequency Comb



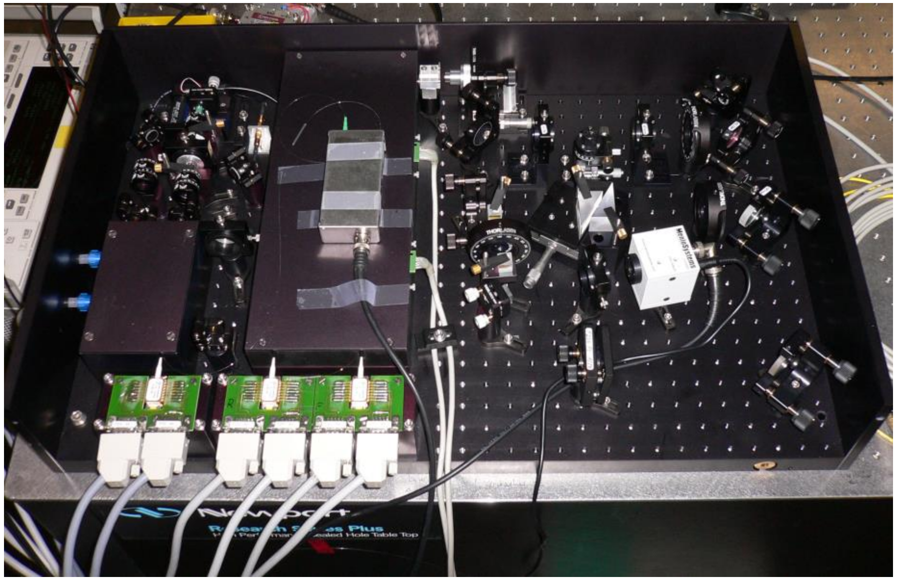
$7f$-$8f$ self referencing in 1999

EFTF-FCS Besancon 1999; Opt.Commun. 172, 59 (1999); Phys. Rev. Lett. 84, 3232 (2000) & Phys. Rev. Lett. 84, 5496 (2000)

Optical Frequency Comb



With 800 MHz Ti:sapphire ring laser
Albrecht Bartels (GigaOptics)



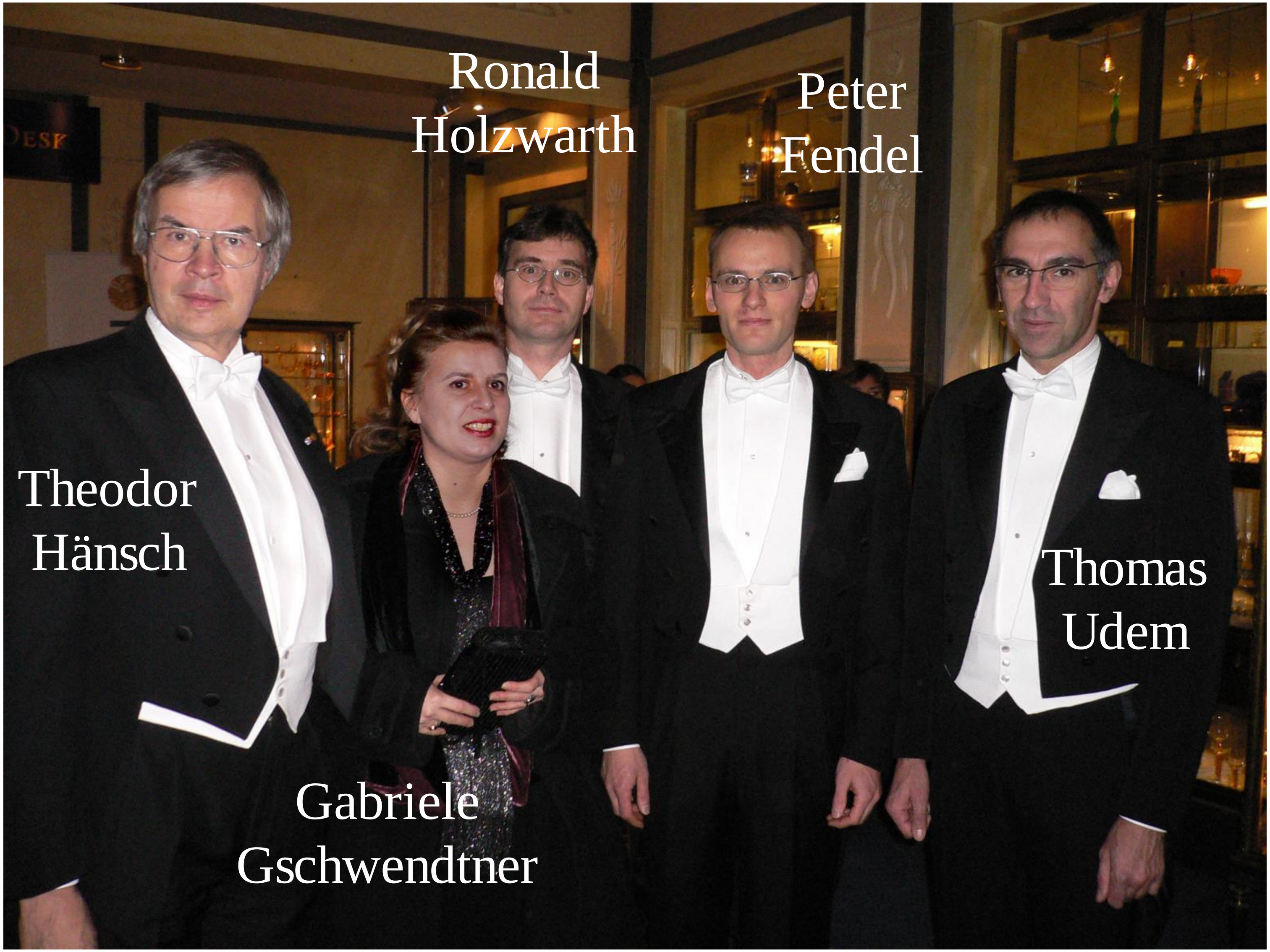
With Er-doped fiber laser
Ronald Holzwarth (MenloSystems)

Replaces large and complex laser harmonic frequency chains.

One system to measure virtually any optical frequency.

Up to now no systematic effects detected (tested down to 10^{-16}).

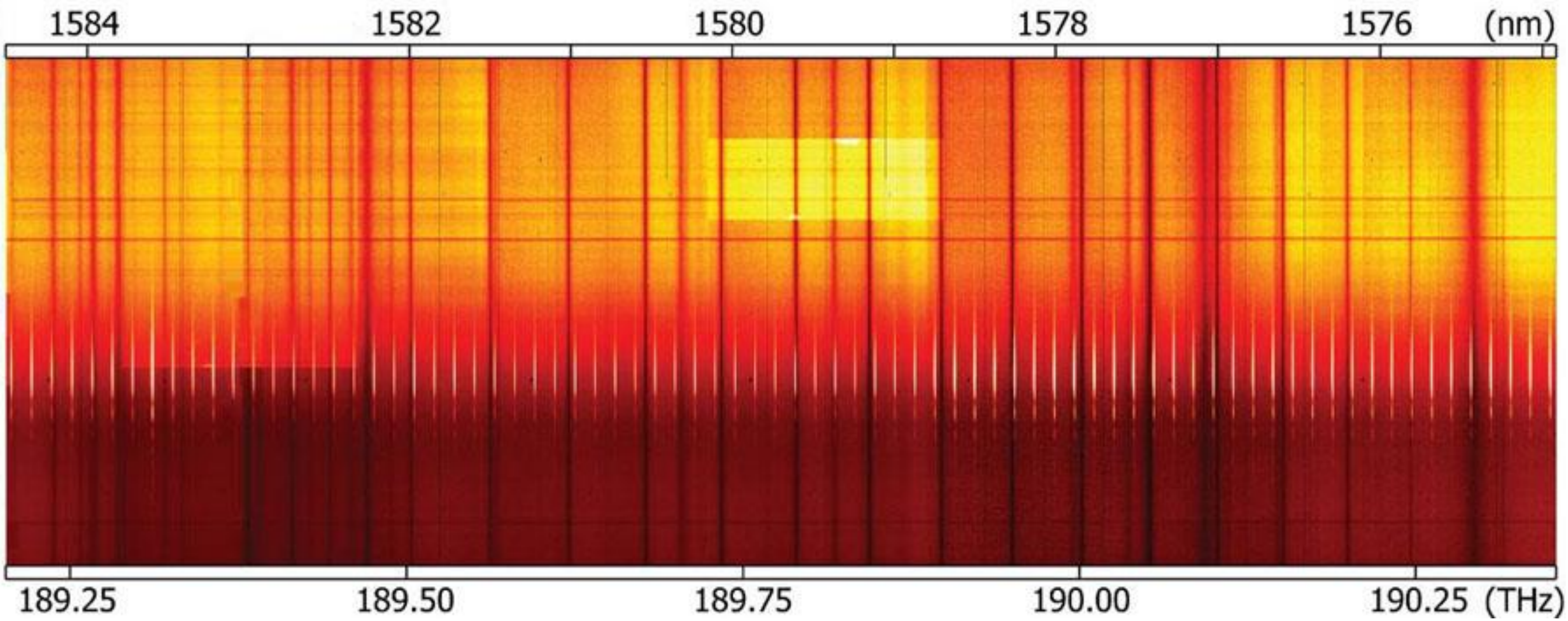
A Trip to Stockholm in 2005



Applications

- High resolution laser spectroscopy
  - testing QED
  - testing special relativity
  - determination of fundametal constants
  - detect or limit slow time evolution of these constants
- Optical atomic clocks
- Controlling the electric field transients of pulses
  - generation attosecond pulses
- Direct comb spectrocopy
  - high resolution XUV laser spectroscopy
- Calibration of astronomical spectrographs
  - detecting extra-solar planets
  - temporal evolution of constants on cosmological time scales
  - confirm or rule out existence of dark energy
  - solar gravitationla red shift

Solar Spectrum with Frequency Comb



Science 321, 1335 (2008)

Requirements for the Frequency Comb

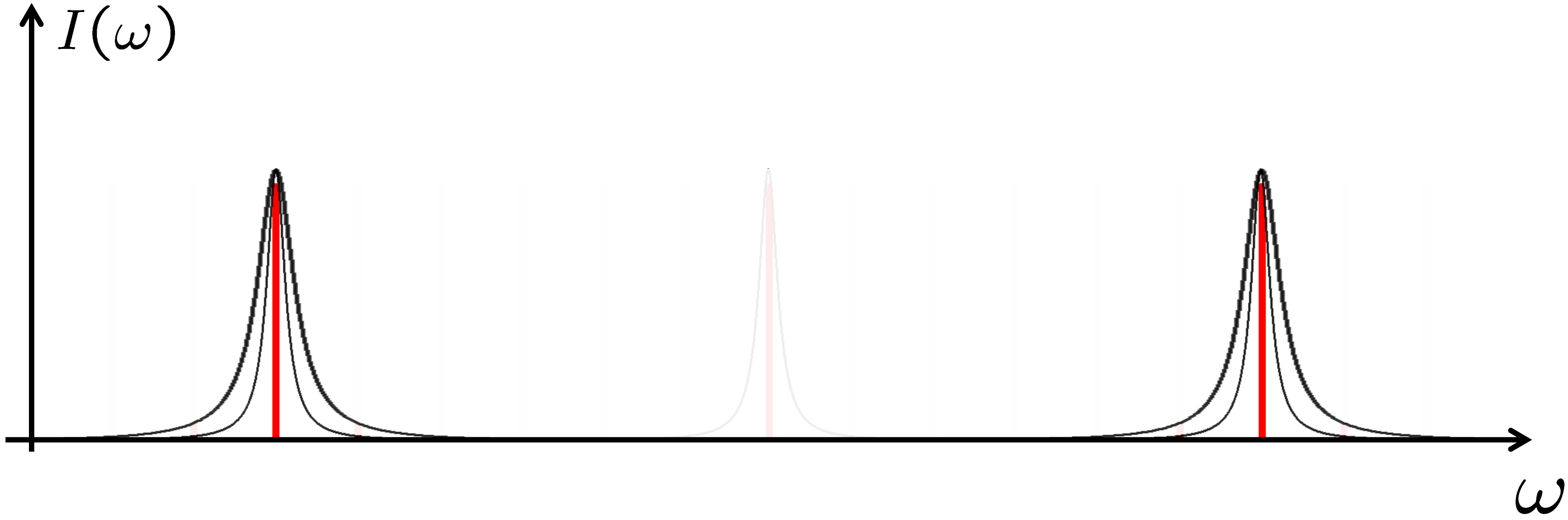
- octave 400nm-800nm
- modes resolvable

repetition rate > 10 GHz

repetition rate < 2 GHz (large pulse energy)

mode filter Fabry-Perot cavity

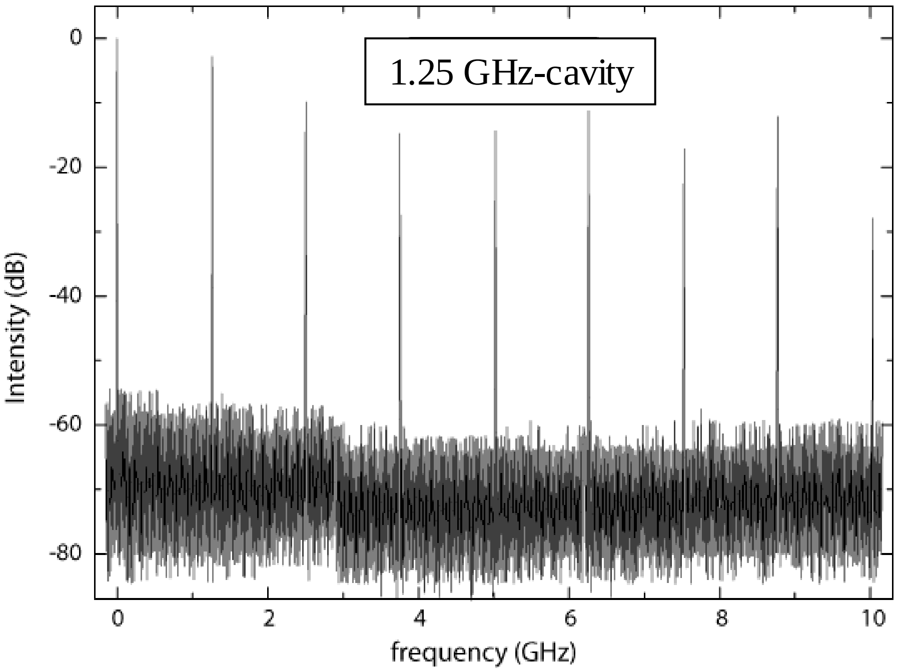
Mode Filter Cavity



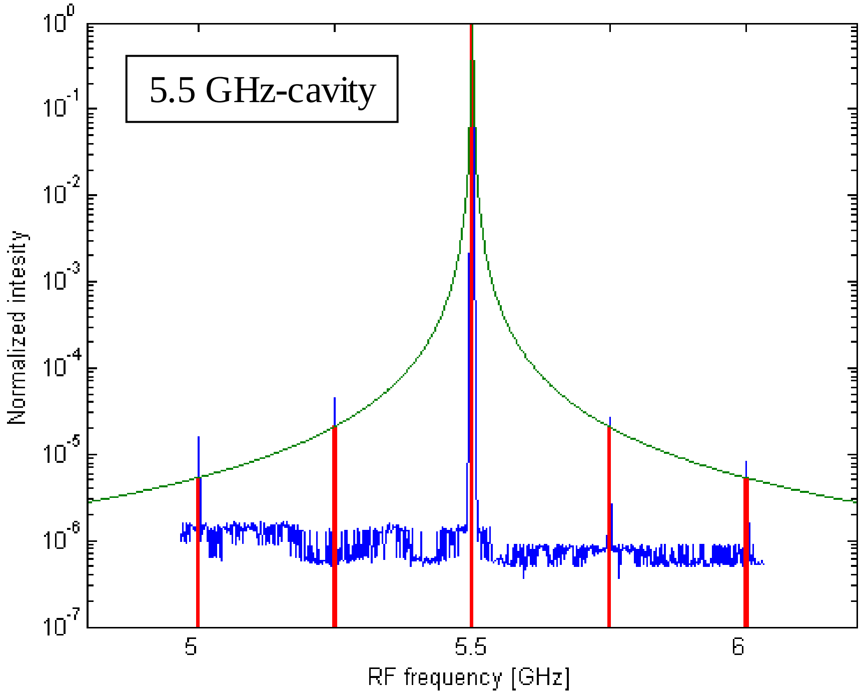
Science 321, 1335 (2008), see also Li *et al.* Nature 425, 610 (2008) & D.A Braje *et al.* Euro. Phys. J. D 48, 57 (2008).

Mode Suppression with 250 MHz Mode Locked Laser

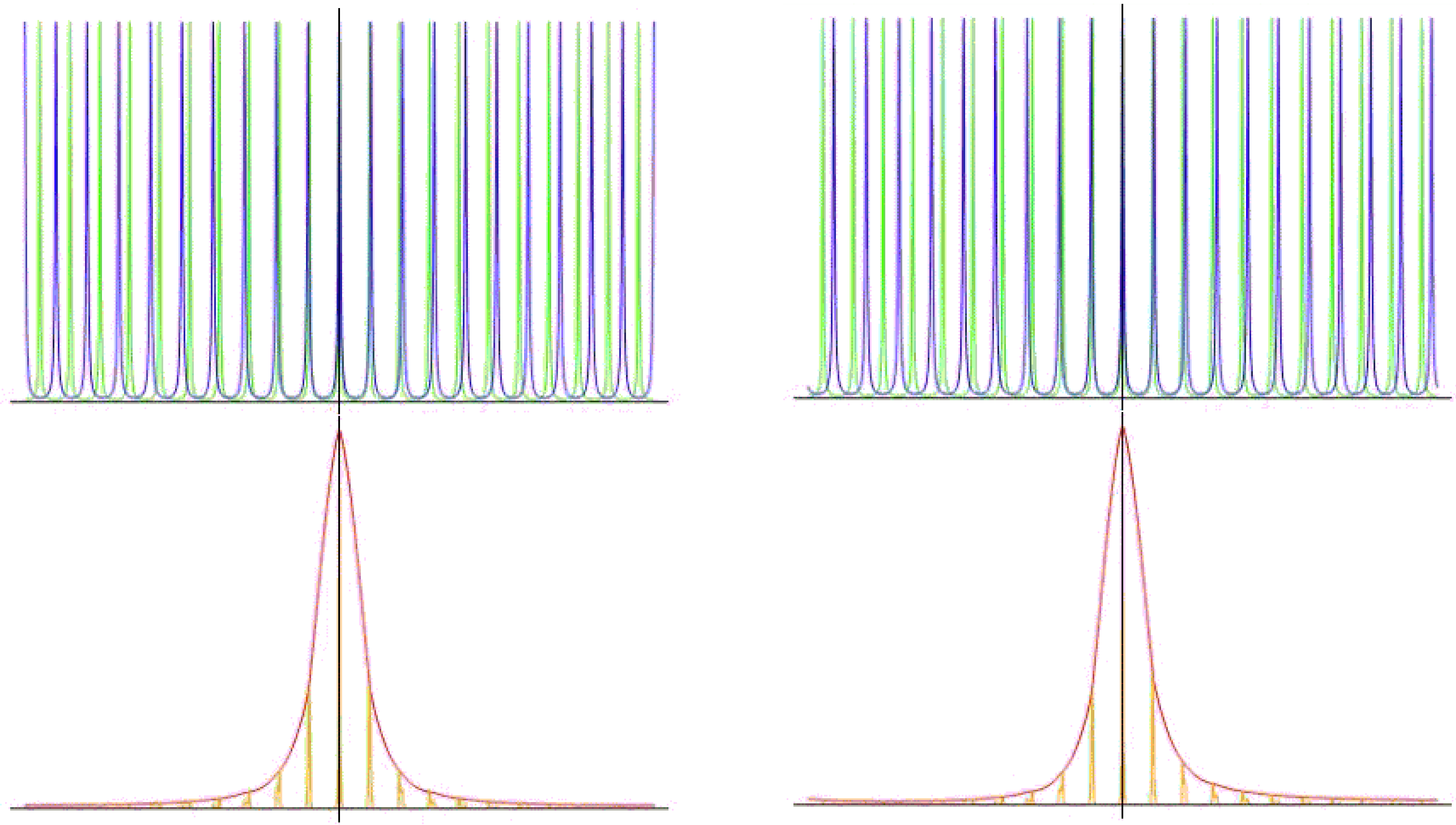
1:5 filter ratio



1:22 filter ratio

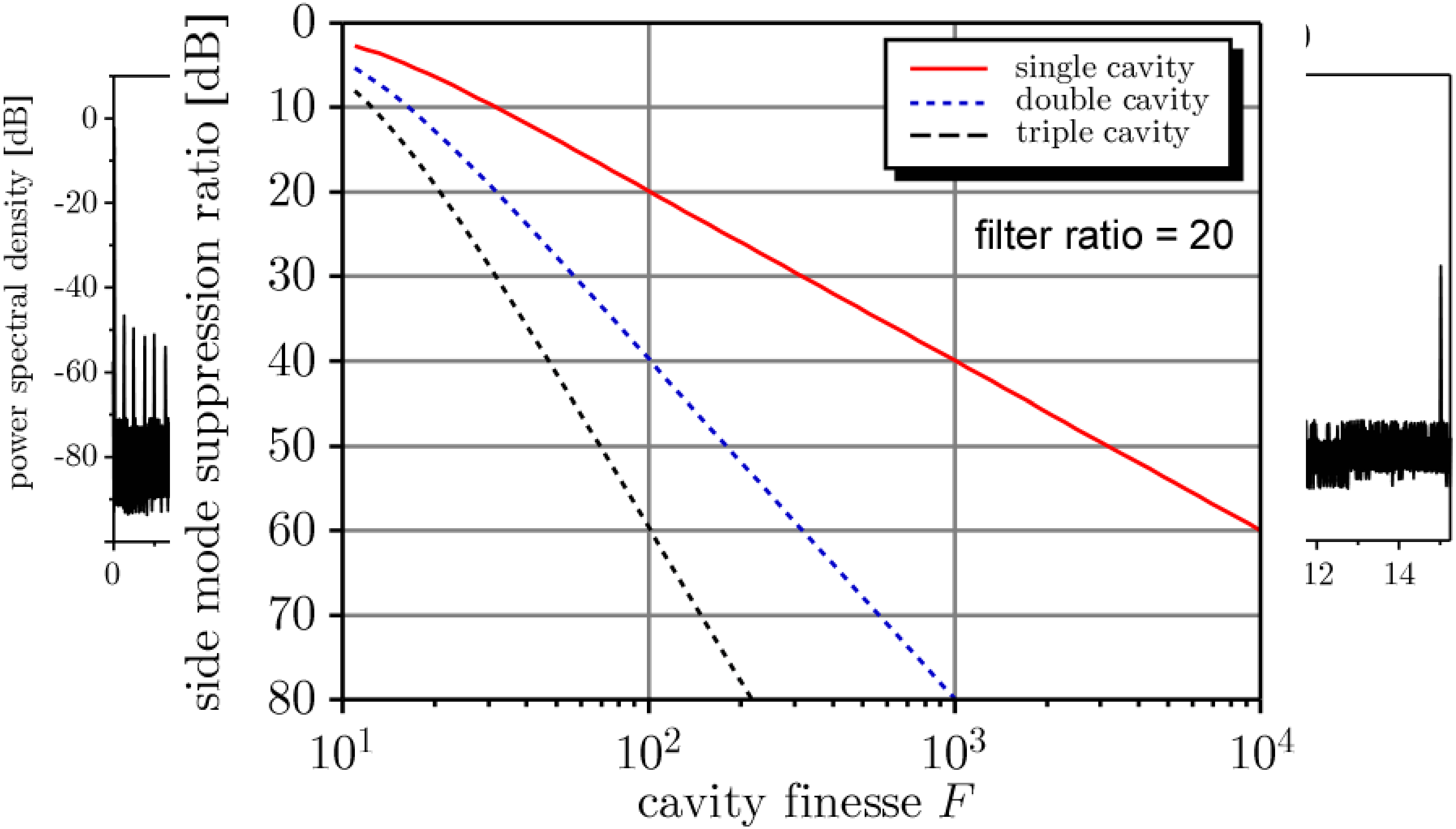


Matching up the Modes

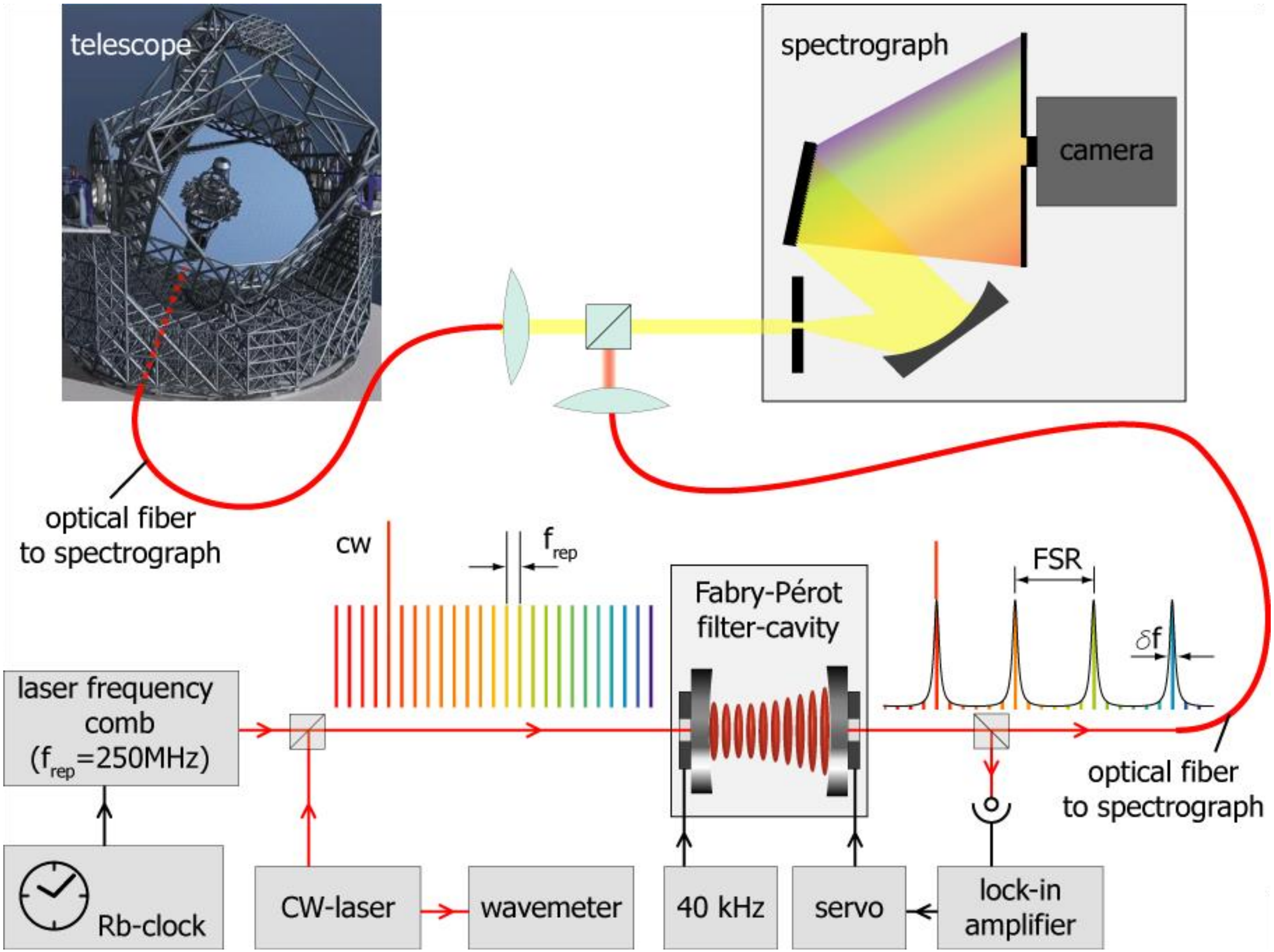


Filter Cavities in Series

Filter Cavities in Series

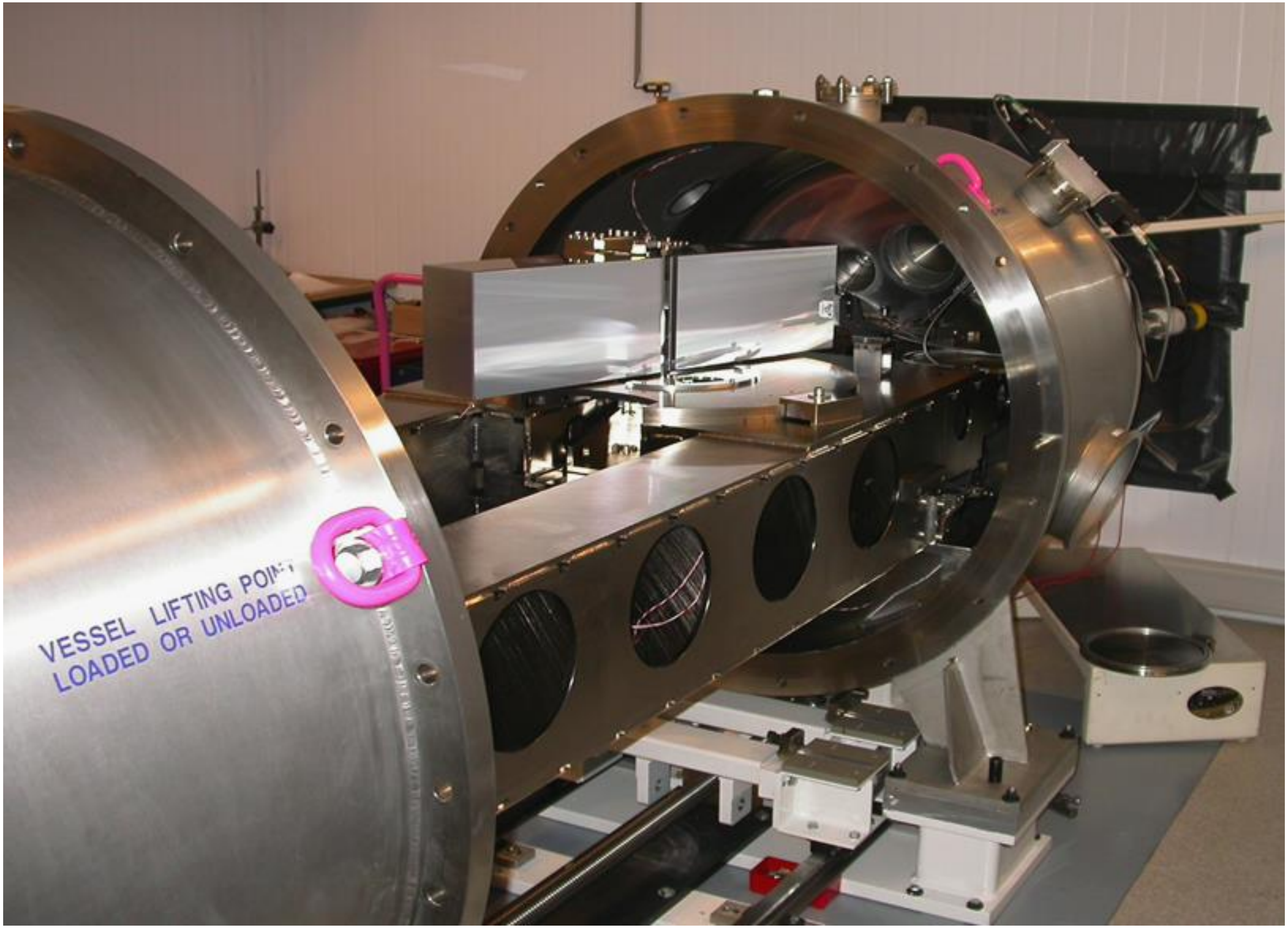


Setup

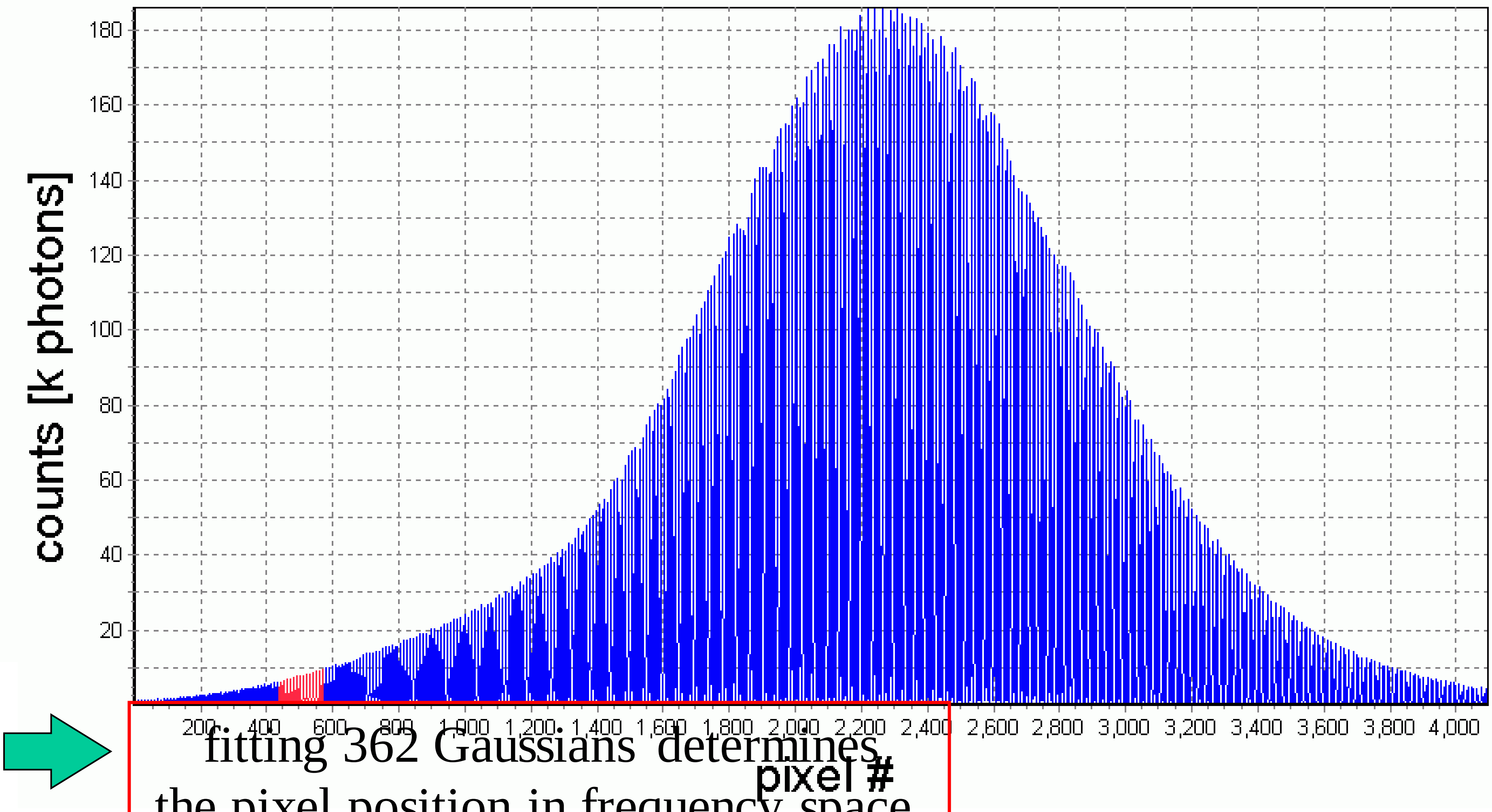


telescope
spectrograph
camera
optical fiber
to spectrograph
cw
f_{rep}
FSR
δf
Fabry-Pérot
filter-cavity
laser frequency
comb
(f_{rep}=250MHz)
optical fiber
to spectrograph
Rb-clock
CW-laser
wavemeter
40 kHz
servo
lock-in
amplifier

“High Accuracy Radial Velocity Planet Searcher” (HARPS)

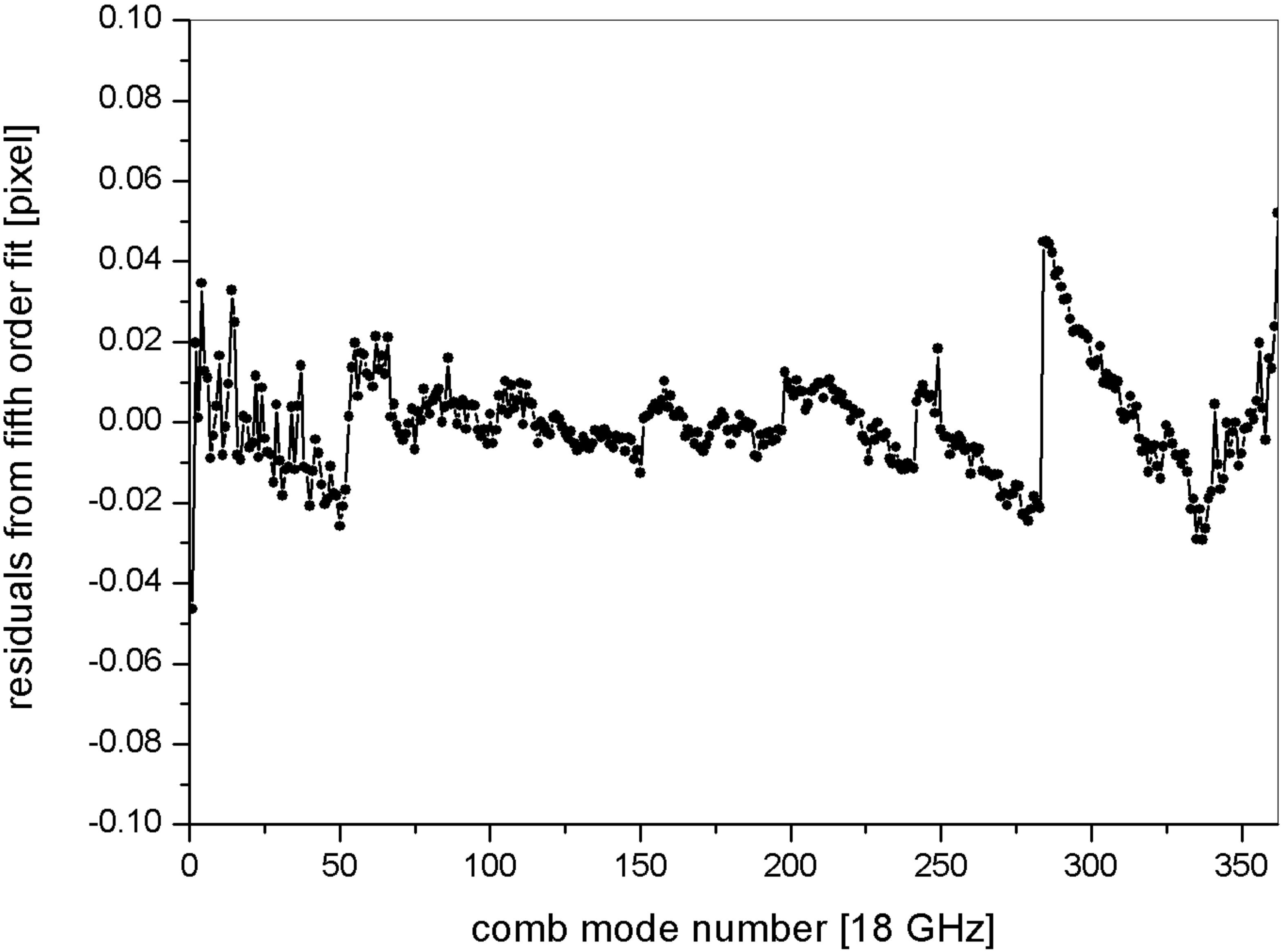


Determine the Calibration Curve

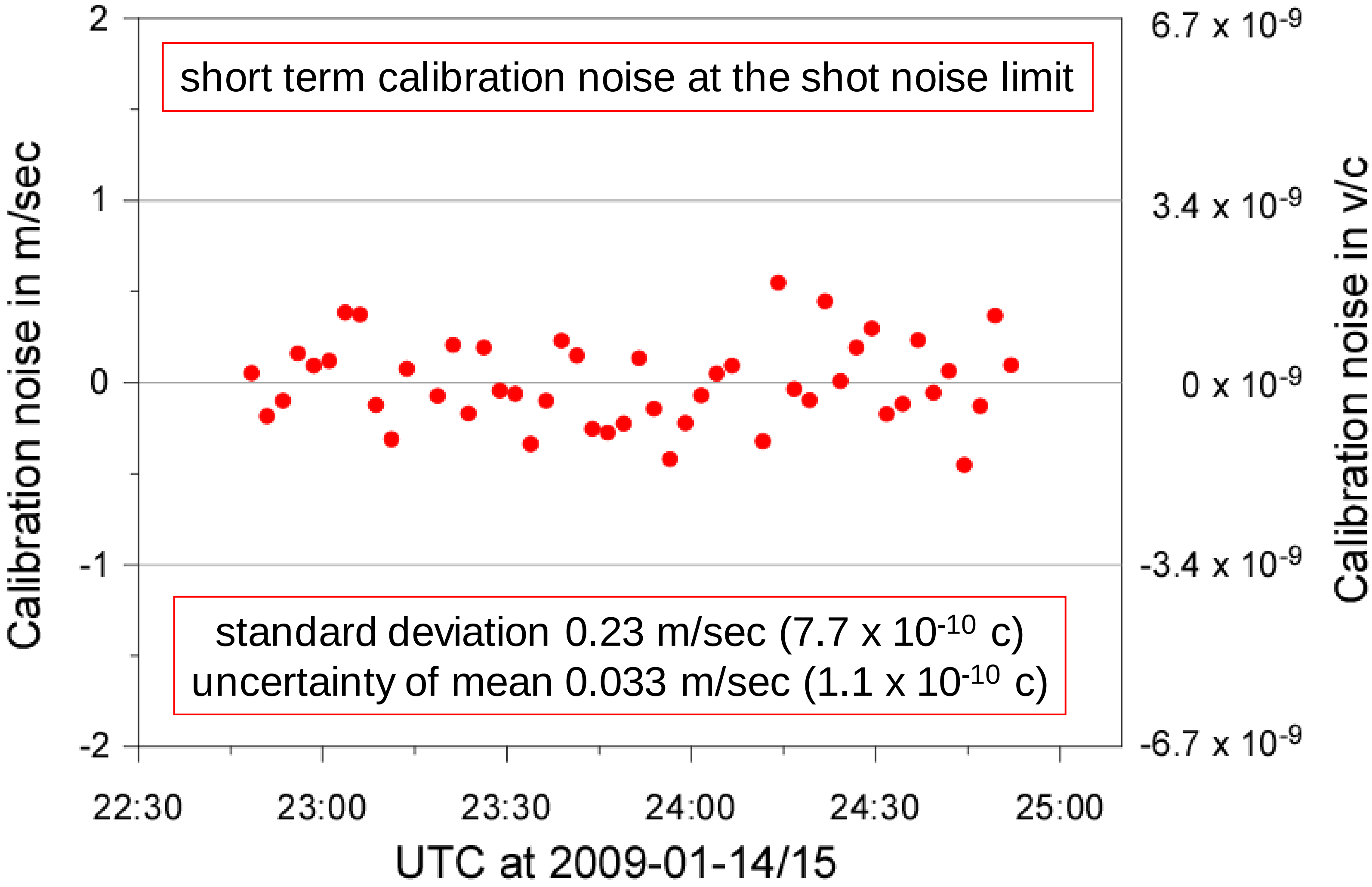


fitting 362 Gaussians determines the pixel position in frequency space.

Determine the Calibration Curve



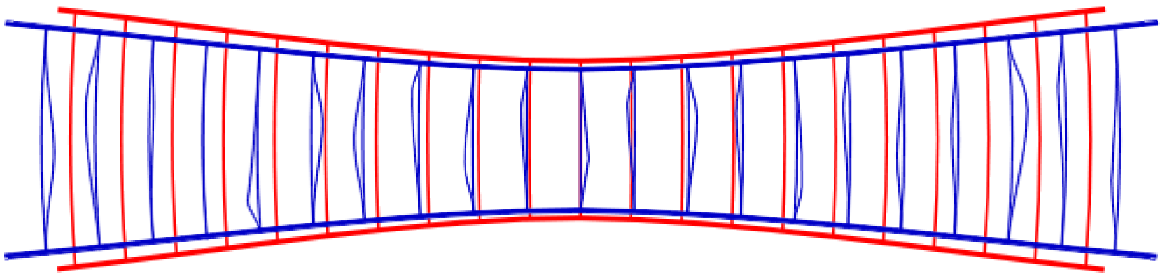
Short Term Repeatability of Calibration



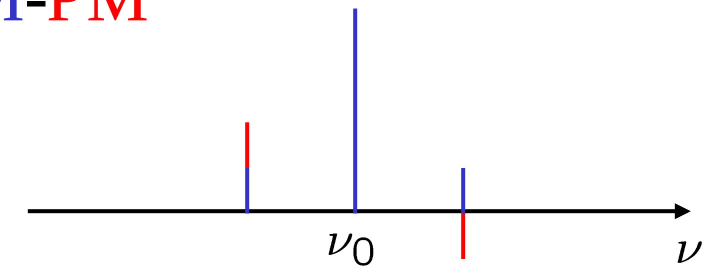
Long Term Repeatability of Doppler Calibration

Factors that may limit term repeatability:

- non-perfect mode matching

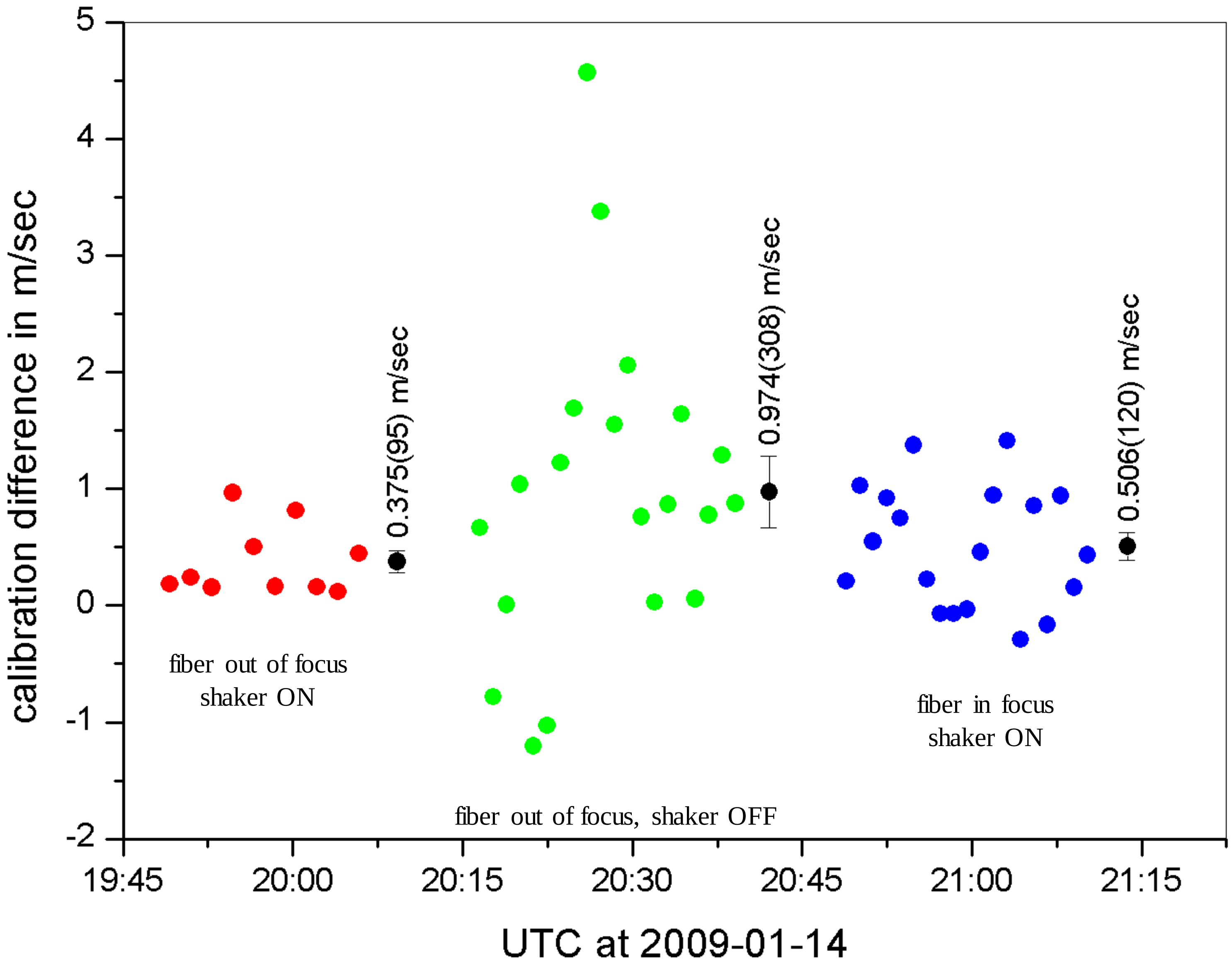


- correlated AM-PM



preliminary upper limit: 50m/sec

Calibration Reproducibility



Astronomical Problems

Precision Astronomy

- Temporal variation of constants ……….. $5x10^{-9}$
- Extra solar planets ..…………………….. $3x10^{-10}$ (9 cm/sec)
- Cosmic acceleration ………………………. $3x10^{-11}$ (over 20 years)
- Solar gravitational redshift ..……………….. $3x10^{-12}$

Fundamental Constants

Fundamental Constants

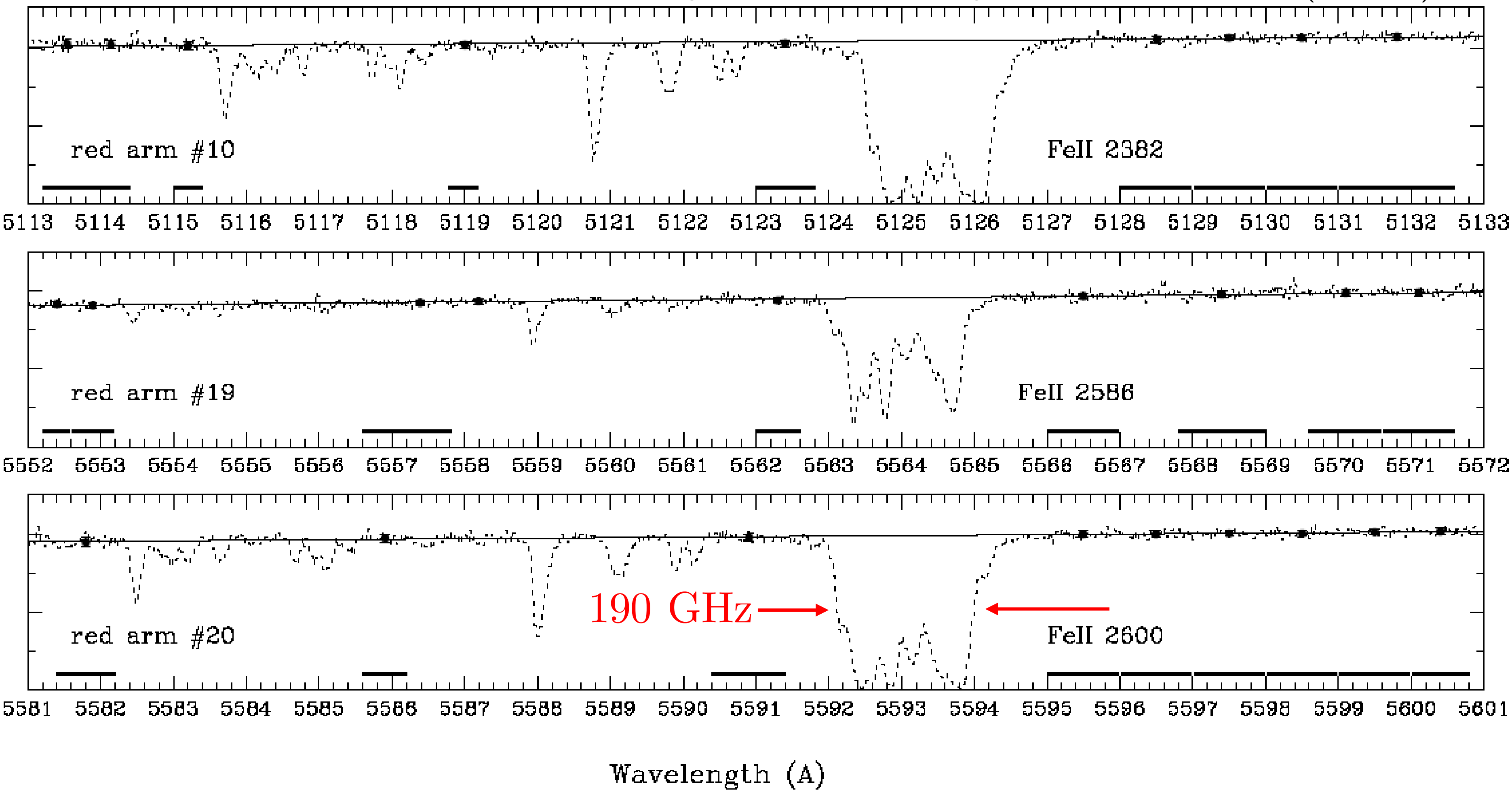
- Why do the constants have the observed values?
- Can‘t be calculated ➡ standard model is incomplete.
- Look for phenomena beyond the standard model.
- A complete theory should produce small numbers

Dirac 1937: The age of the universe in atomic units divided by the electromagnetic force between an electron and a proton measured in units of their gravitational force is such a small number (believed to be ≈ 3 in 1937).

➡ **Almost every „constant“ could vary in time.**

Quasar Absorption Spectra

S. A. Levshakov Astronomy & Astrophysics 449, 879 (2006)

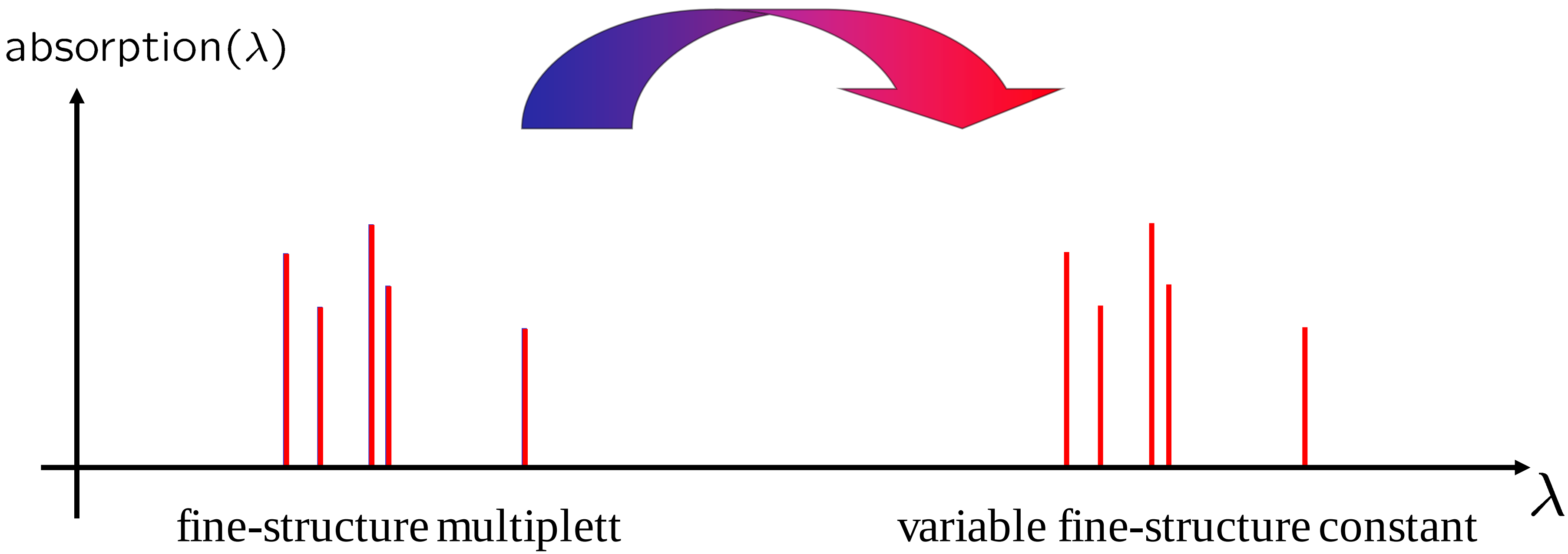


redshift $z = 1.15$ i.e. λ(observed) $= \lambda$(emitted) $(z{+}1)$

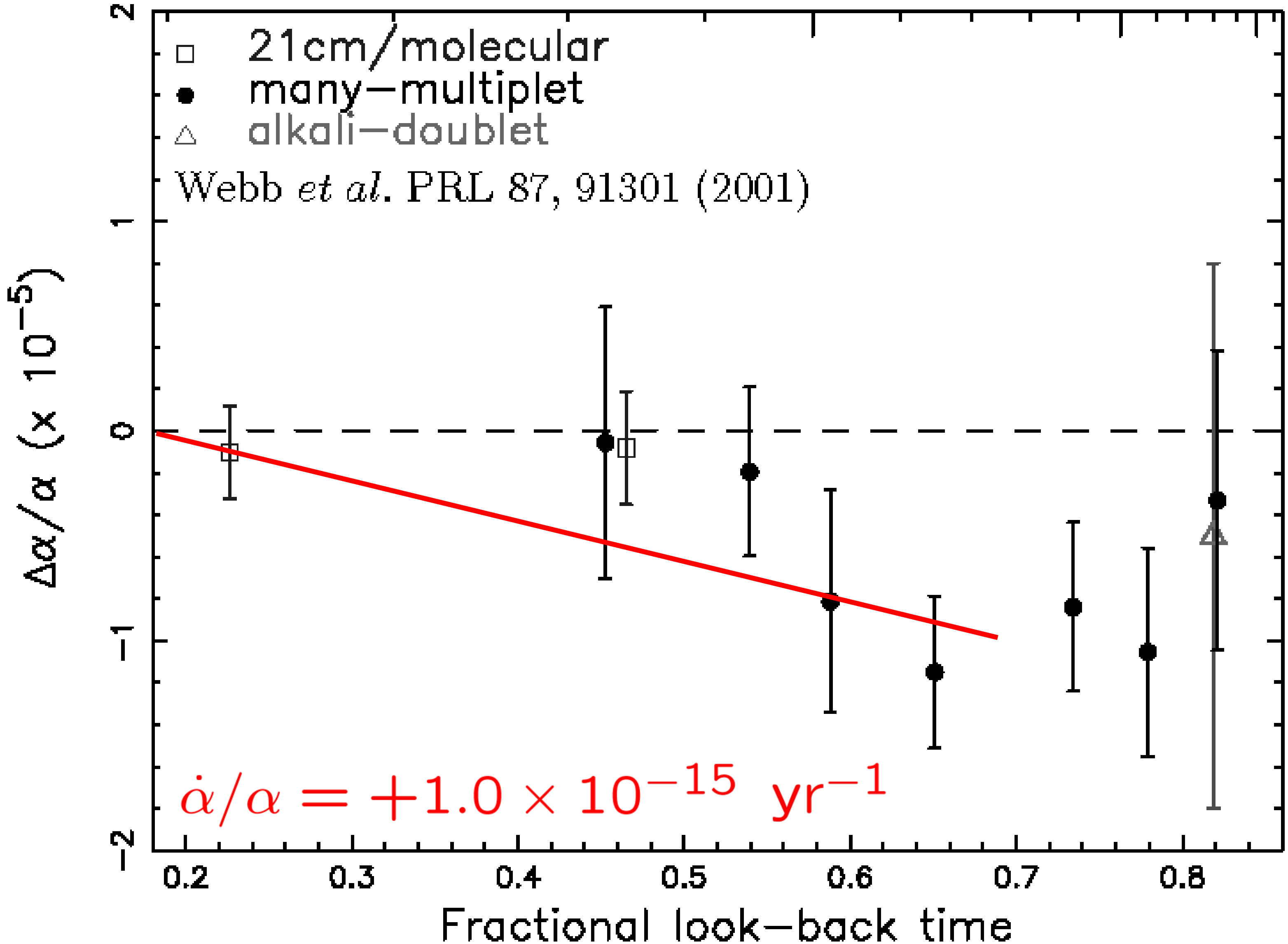
Quasar Spectra

cosmological redshift:

$$z = \frac{\lambda_{\text{receiver}} - \lambda_{\text{sender}}}{\lambda_{\text{sender}}} = \frac{R(t_0)}{R(t_1)} - 1$$



Possible Drift of the Fine Structure Constants



Frequency Ratio

optical frequency ⇨ optical frequency

locked to a stable laser

locked to ω_r

$$\omega_n = n\omega_r + \omega_{CE}$$

measure another laser

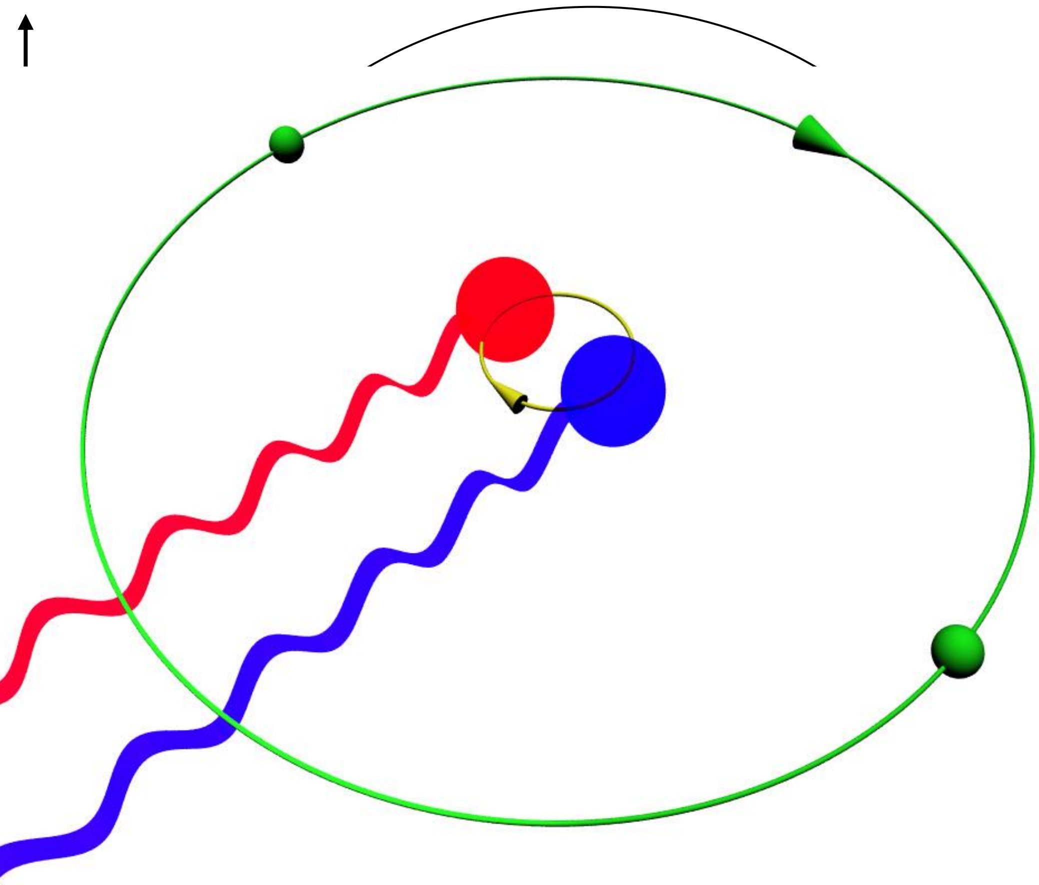
T. Rosenband *et al.* Science 319, 1808 (2008):

$$\dot{\alpha}/\alpha = -1.6 \pm 2.3 \times 10^{-17}\ \mathrm{yr}^{-1}$$

Extra-Solar Planets

Planet Recoil

Planet Recoil



$$\frac{d_2}{d_1} = \frac{M_1}{M_2} \Rightarrow d_1 = 3000 \text{ km}$$

$$v_{\text{Sun}} = 9 \text{ cm/sec}$$

$$\text{Doppler shift} = \frac{v_{\text{Sun}}}{c} = 3 \times 10^{-10}$$

HARPS Radial Velocity Method

C.Lovis *et al*. Nature 441, 305 (2006)

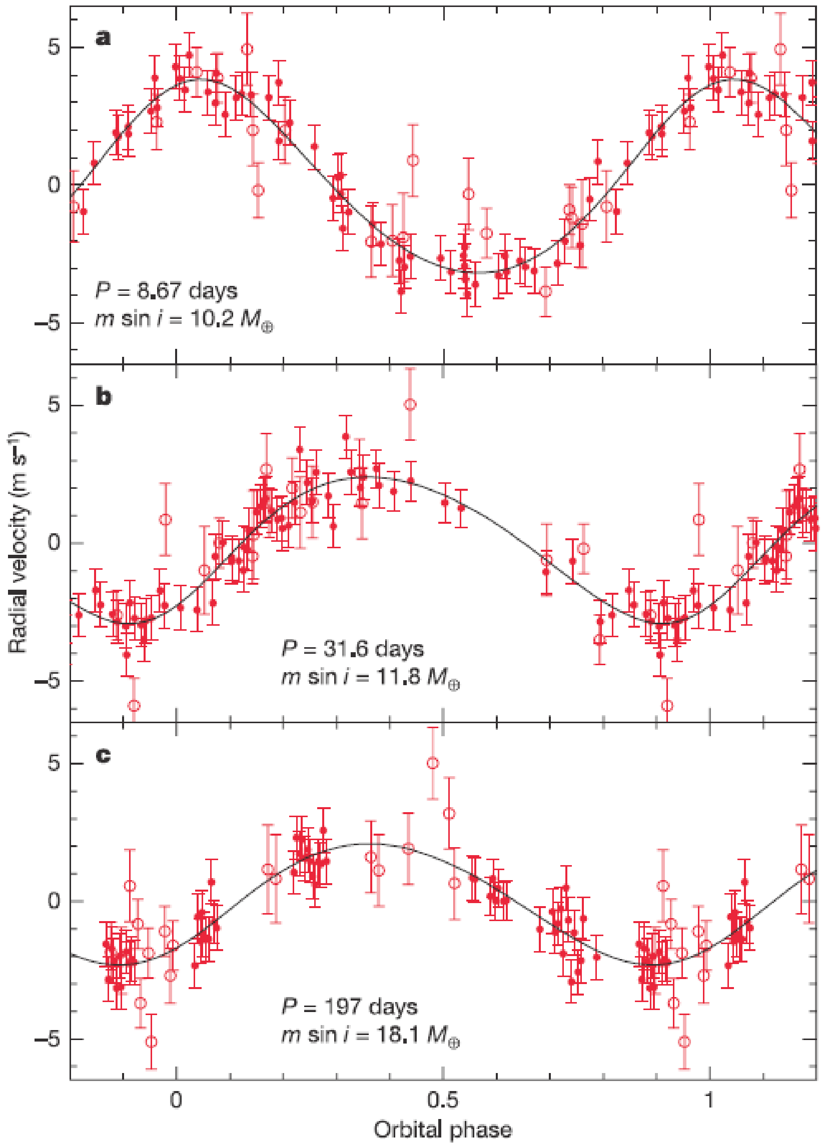
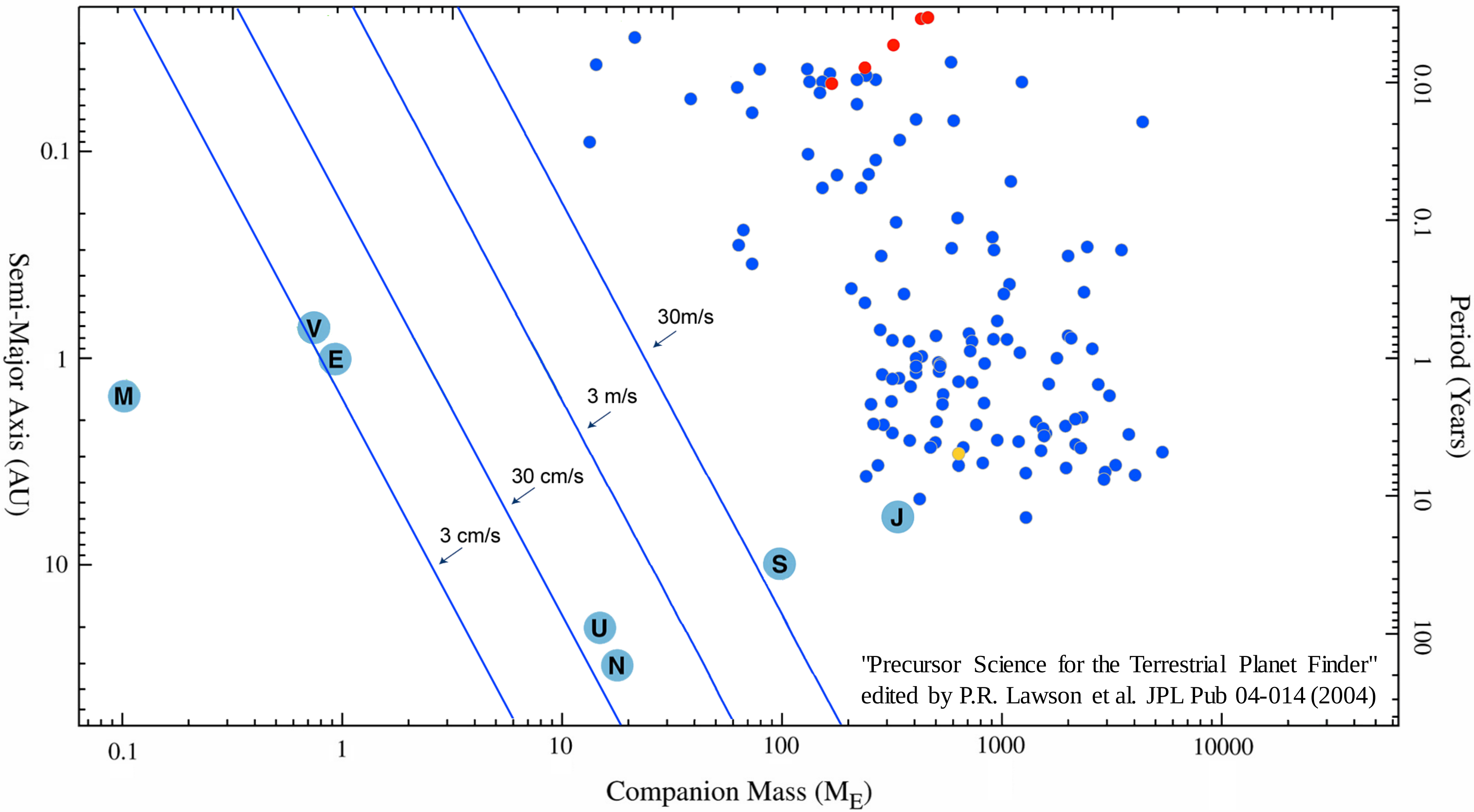


Figure 1 | Phase-folded radial velocity curves for the three planets. In each case, the contribution of the two other planets has been subtracted. The orbital periods, P, are 8.67, 31.6 and 197 days, for the inner (**a**), intermediate (**b**) and outer (**c**) planet, respectively. The radial velocity semi-amplitudes range from 3.5 to 2.2 m s^{-1}, corresponding to minimum masses $m\sin i$ of 10.2 $M_{\oplus}$, 11.8 $M_{\oplus}$ and 18.1 $M_{\oplus}$ (here $M_{\oplus}$ is the Earth's mass, m is the actual planetary mass and i is the inclination angle of the system). The integration time was 4 min on average for the first 18 measurements (shown as open circles), and was increased to 15 min for the remaining points (filled circles). The latter measurements are of much higher quality for the following reasons: lower photon noise (from 0.4 to 0.2 m s^{-1}), improved guiding accuracy (from ~1.0 to 0.3 m s^{-1}), lower wavelength calibration error (from 0.8 to ~0.3 m s^{-1}) and better averaging of the stellar p-mode oscillations (which have characteristic periods of a few minutes and individual amplitudes of a few tens of cm s^{-1} that may add up to a few m s^{-1})[9,15]. For the K0 dwarf HD 69830, we estimate that the oscillation noise is between 0.2 and 0.8 m s^{-1} depending on the exposure time. Combining all these error sources in quadrature, we obtain final 1σ error bars between 0.7 and 1.5 m s^{-1}.

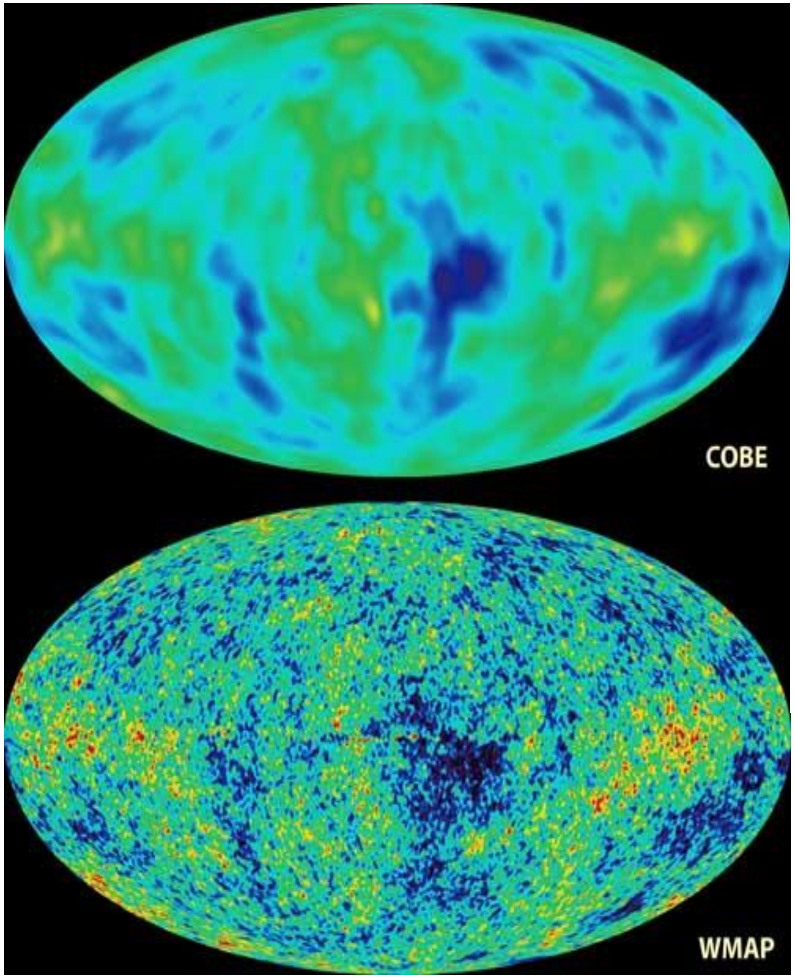
Extra Solar Planets Discovered so Far



Planets discovered by radial velocity (blue), transit (red) and microlensing (yellow)

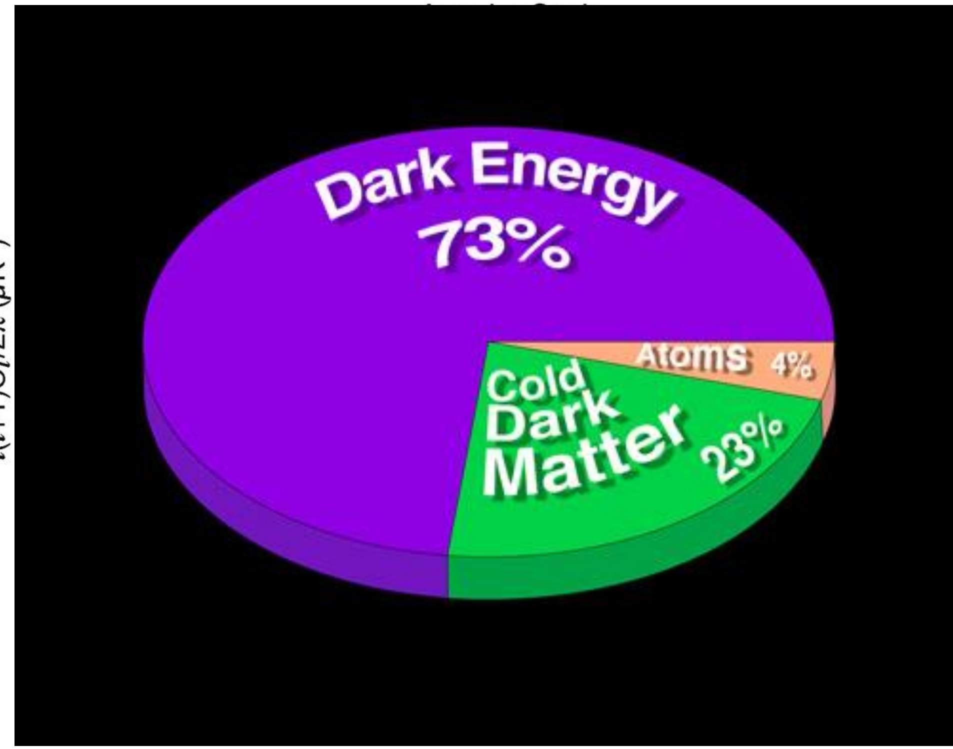
Cosmic Expansion

Microwave Background



temperature picture of the Universe
at the age of 397.000 years

$l(l+1)C_l/2\pi\ (\mu K^2)$



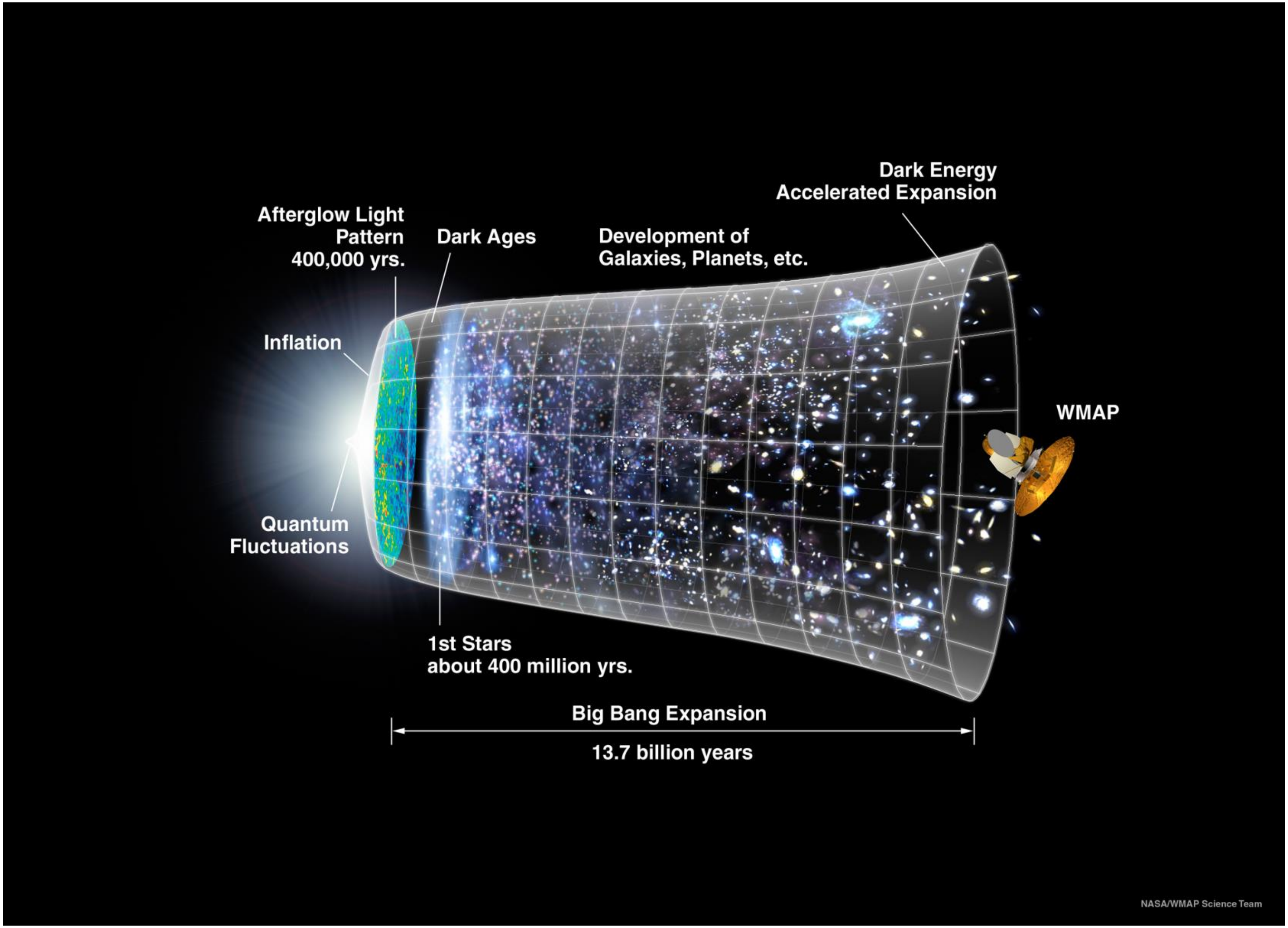
theory with $\Omega_{tot} = \Omega_m + \Omega_{dm} + \Omega_\Lambda$

generates peak at $l = 200/\sqrt{\Omega_{tot}}$

$\Rightarrow \Omega_{tot} = 1$

(+other structure, spatially flat Universe…)

Constituents of the Universe



Vacuum Energy?

$$\rho_{vac} \propto \int_0^{L_p} d^3k \frac{\hbar\omega}{2} \approx 5 \times 10^{93} \ \frac{\mathrm{Kg}}{\mathrm{m}^3}$$

where to cut off?

Planck length: $L_p = \sqrt{\frac{Gh}{c^3}} = 4.1 \times 10^{-35}\,\mathrm{m}$

about 120 orders of magnitude too large!*

*Greatest embarrassment in all of theoretical physics. (Michael Turner *Physics Today* 4/2003)

Thank you for your Attention

The Oklo Nuclear Reactor

$^{149}\mathrm{Sm} + n \rightarrow\ ^{150}\mathrm{Sm}$

resonance stable within 0.05 eV for 2×10^9 yrs.

Light Curve

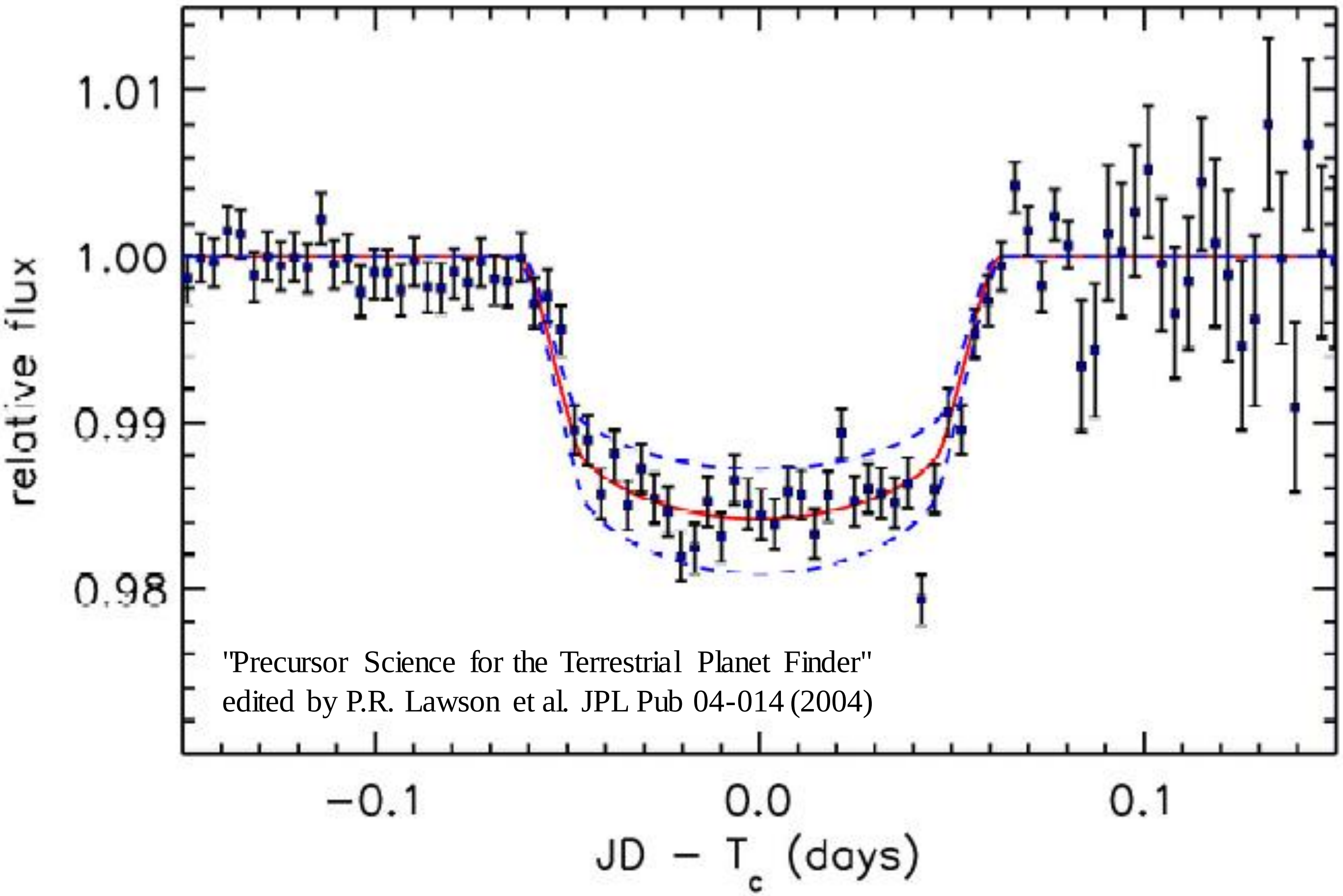


Figure 7. Light curve for the transit of HD 209458. The solid line is the transit shape that would occur for the best-fit model. The lower and upper dashed lines are the transit curves for planets 10% larger and smaller in radius, respectively.

“High Accuracy Radial Velocity Planet Searcher” (HARPS)

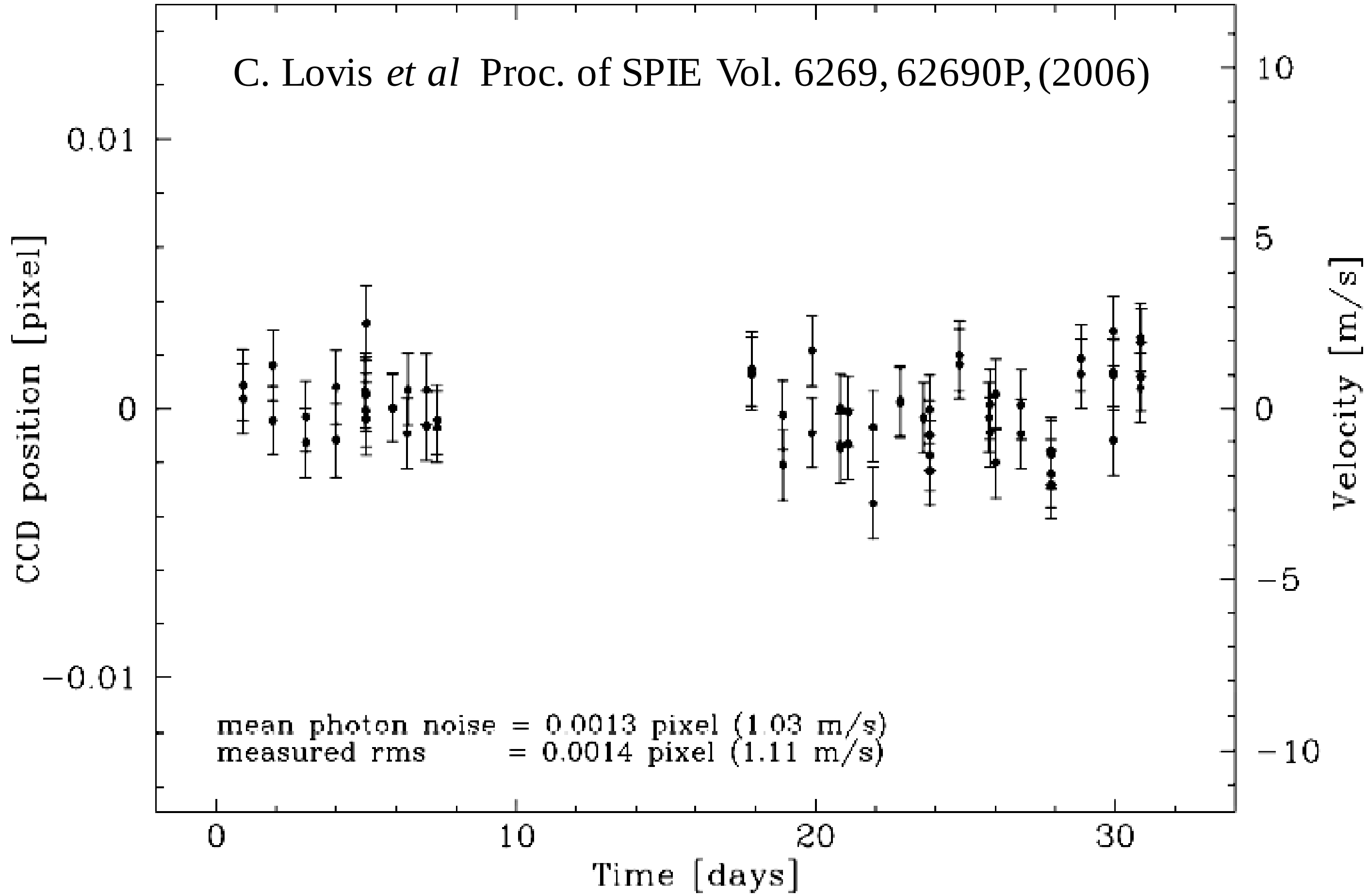
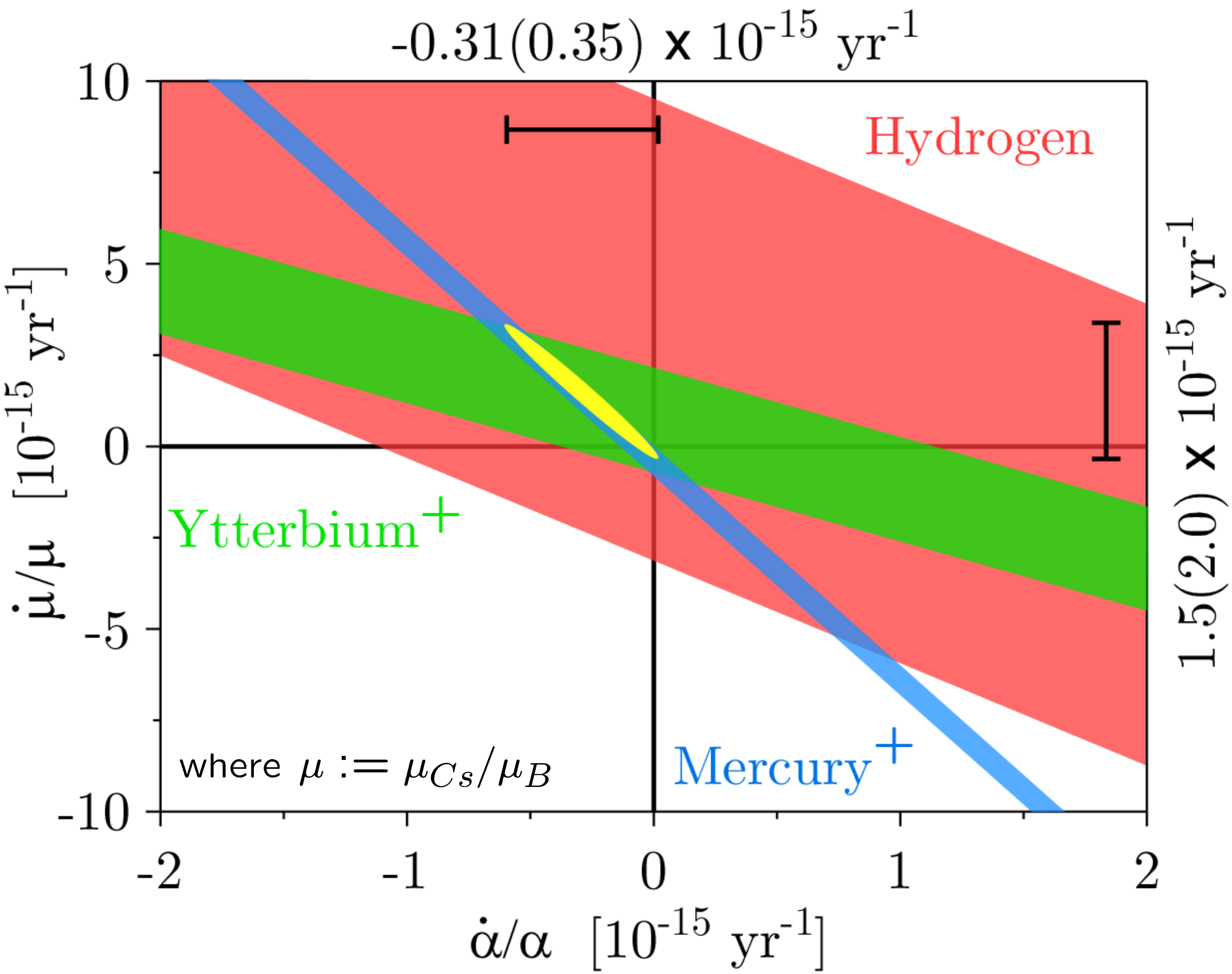


Fig. 3. Measured absolute position of a typical, strong Th line on the CCD as a function of time. The dispersion of 1.4 milli-pixels corresponds to 1.1 m s^{-1} in radial velocity and is photon-noise limited. This shows that the spectrograph extremely stable over about one month.

Possible Drift of the Natural Constants



Hg: T.M.Fortier PRL 98, 070801 (2007) Yb: E.Peik arXiv:physics/0611088 (2006) H: M.Fischer PRL 92, 230802 (2004).

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