Frequency Combs for Astronomy

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Frequency Combs for Astronomy

Frequency Combs for Astronomy

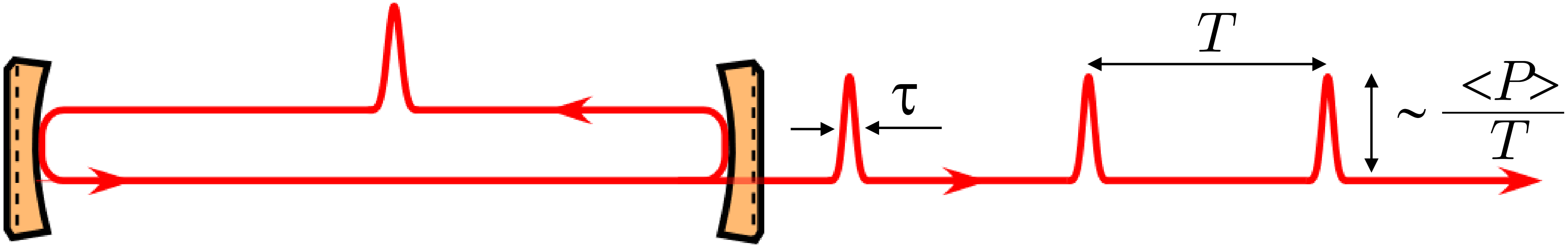
- Frequency combs have been used for the most accurate measurements in all experimental physics

- What is it?

- What could be the advantages?

- What is the current status?

Basic Features of a Mode Locked Laser



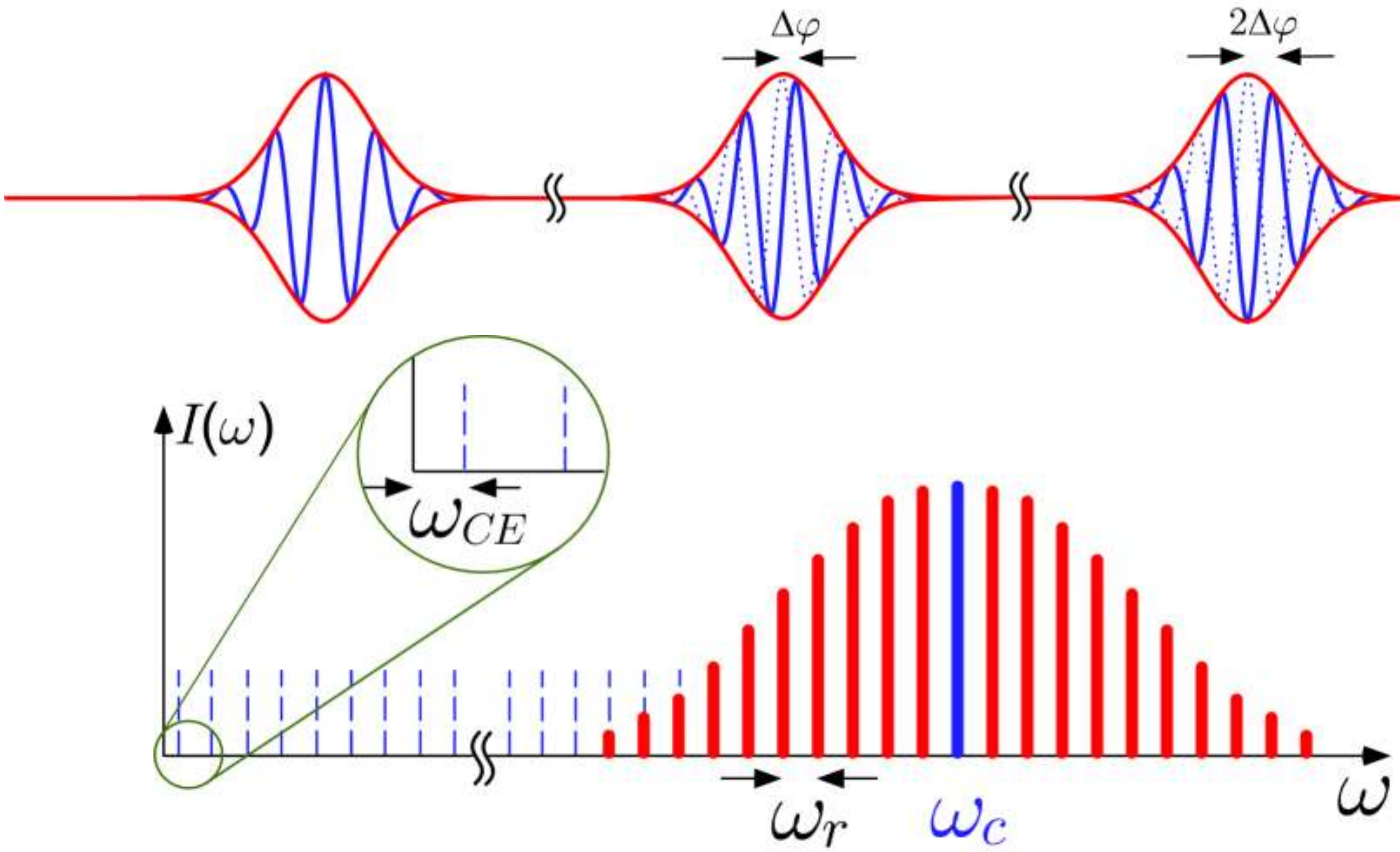
Typical mode locked laser:

- pulse repetition rate $T^{-1} = 100$ MHz
- pulse duration $\tau = 100$ fs
- spectral width $= 1/\tau = 10$ THz ($\Delta\lambda = 35$nm)
- peak power ~ 1/repetition rate

Various types of mode locked lasers:

- some fiber lasers can operate un-attended for months

Mode Locked Laser



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

Controlling the Frequency Comb

locked to an atomic clock

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

every mode can be used for calibration

- we can measure **and** control ω_r **and** ω_{CE}
- a million stabilized lasers in a single beam
- accurate to at least 10^{-16} (in frequency!)
- scan modes across each individual pixels

Requirements for HARPS

- spectral coverage 400 nm-800 nm
- modes resolvable

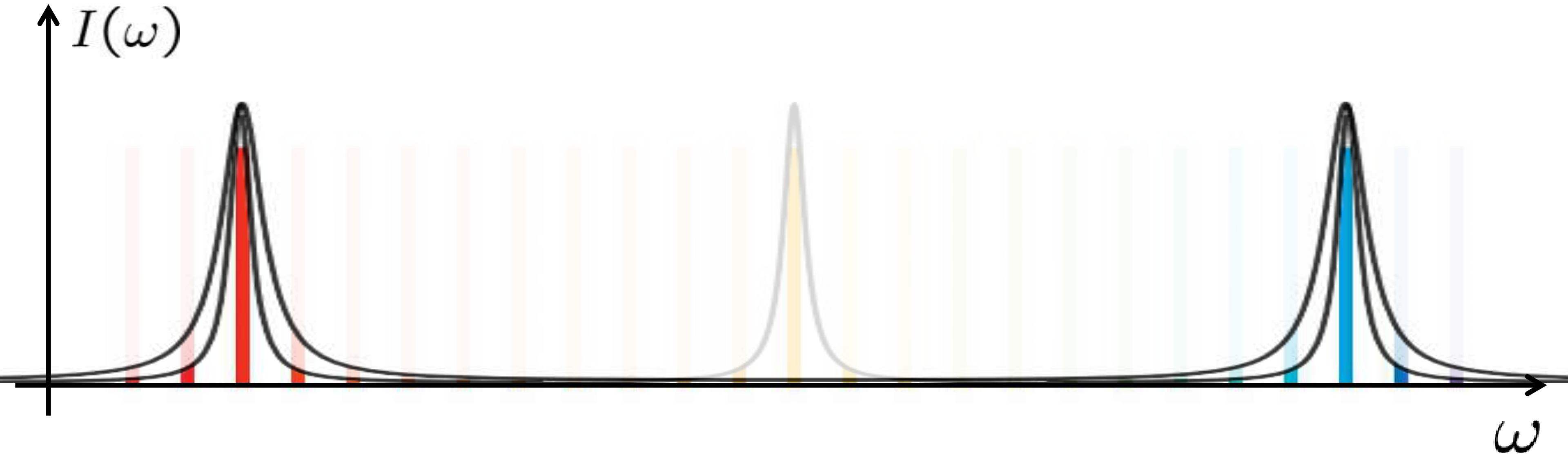
high repetition rate, say > 20 GHz

low repetition rate, i.e. high peak intensity (depends on average power)

mode filter Fabry-Perot cavity is an option

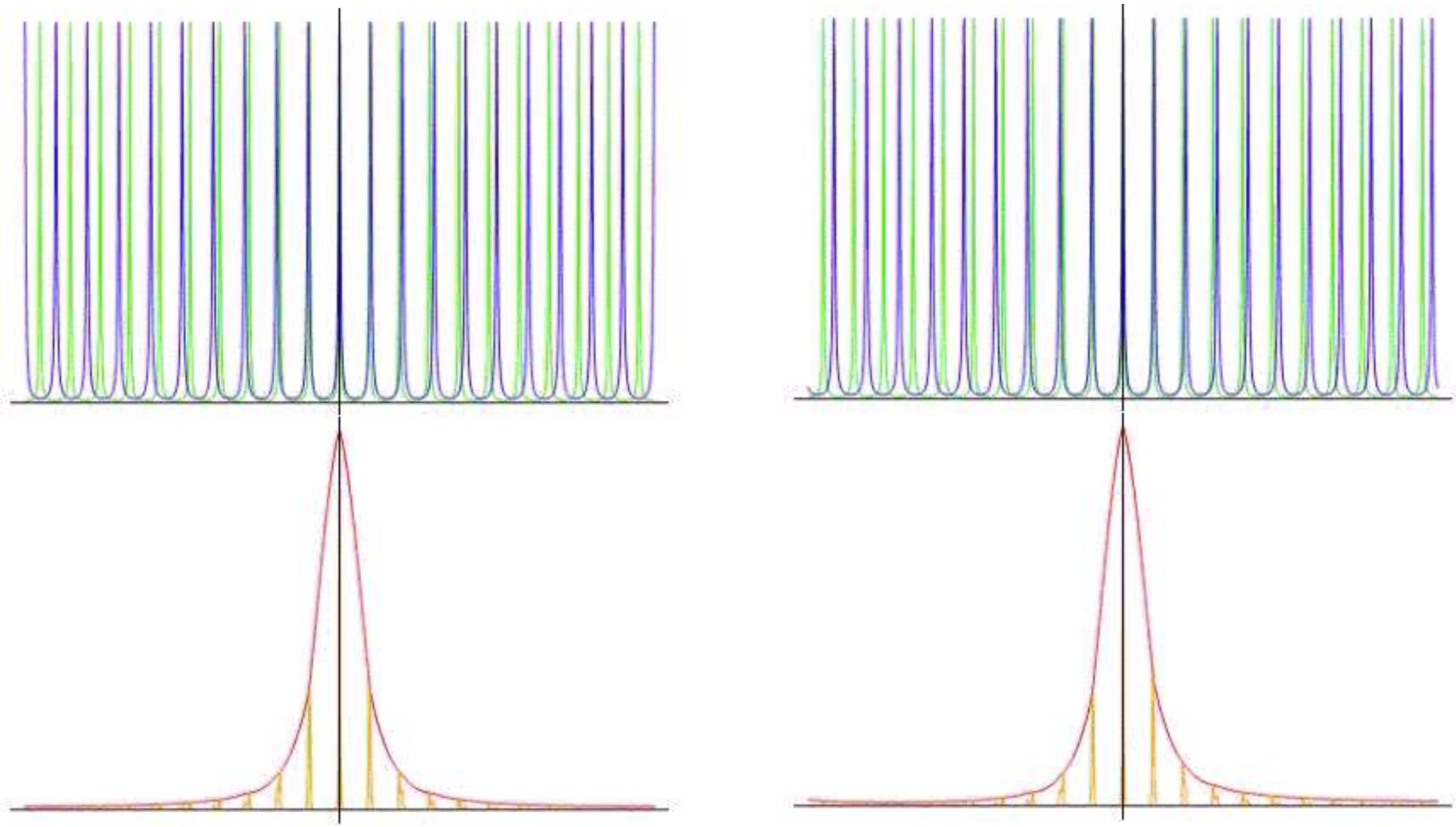
Mode Filter

Mode Filter

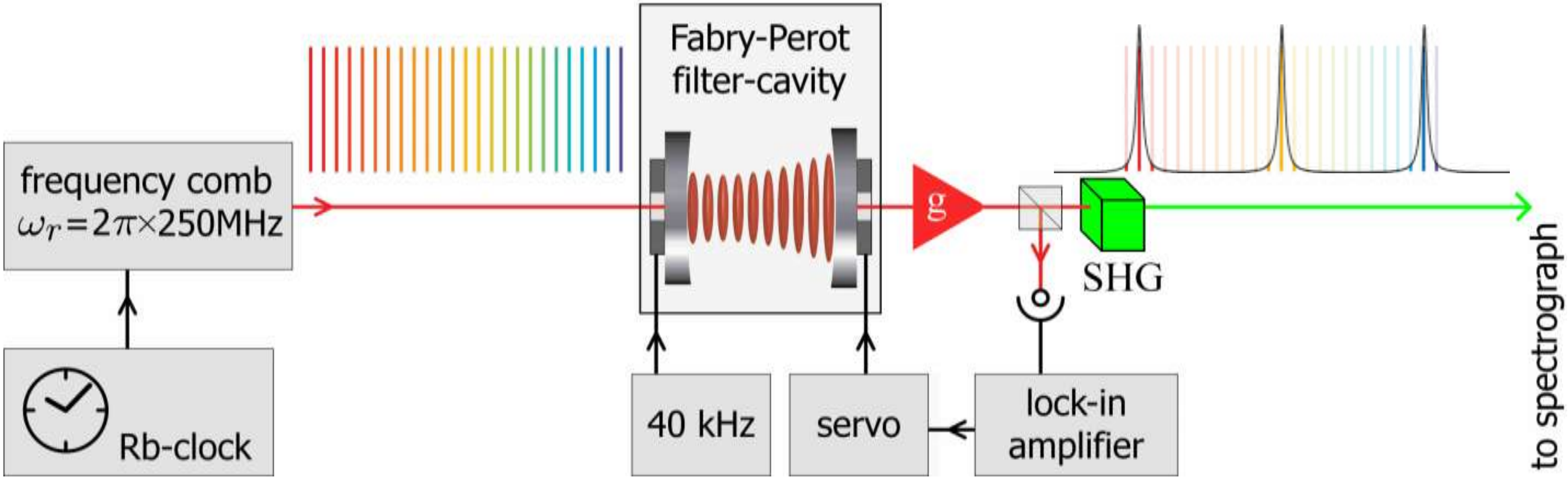


Science 321, 1335 (2008), see also Li *et al.* Nature 425, 610 (2008) & D.A Braje *et al.* Euro. Phys. J. D 48, 57 (2008).

Matching up the Modes

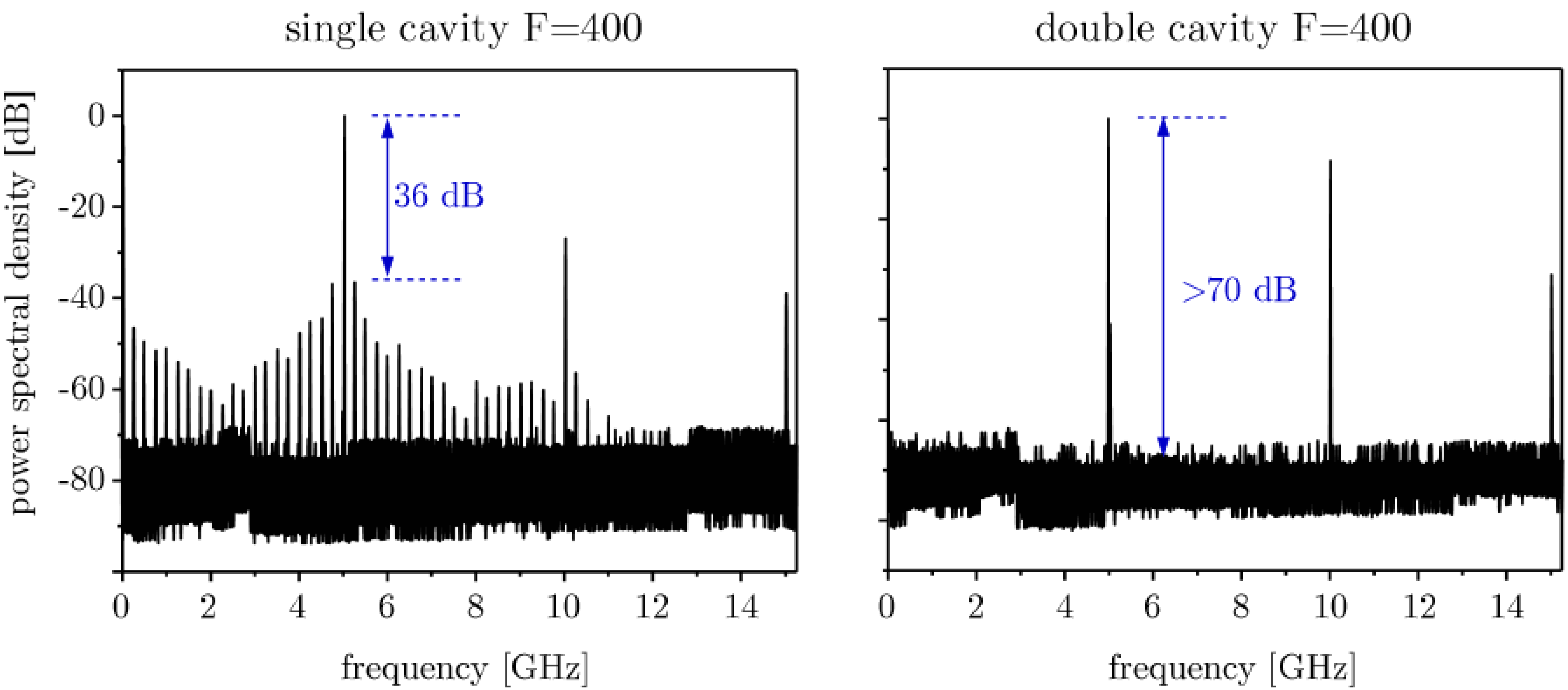


Setup 1

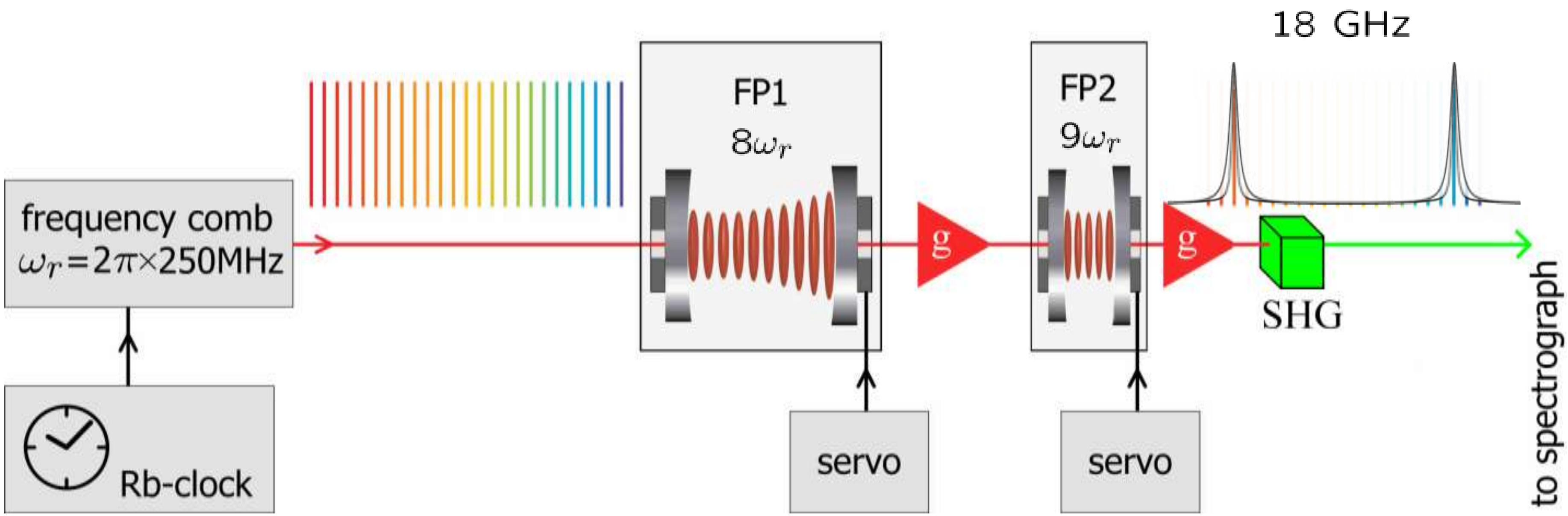


$$\text{SHG:} \quad E_{\text{out}}(t) = \chi^{(2)} E_1(t) E_2(t) = \chi^{(2)} E_1 e^{\pm i\omega_1 t} E_2 e^{\pm i\omega_2 t}$$

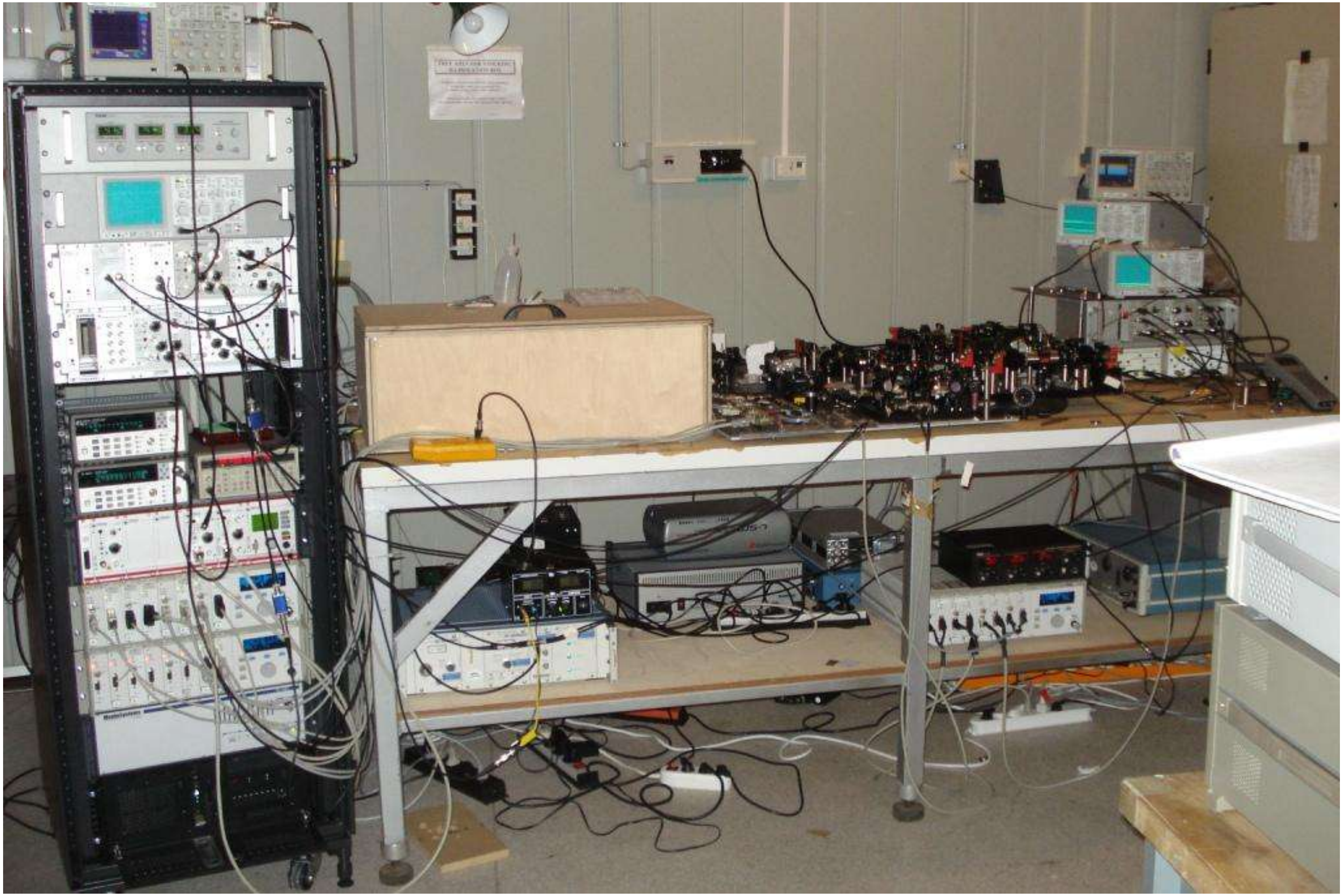
Filter Cavities in Series



Setup 2

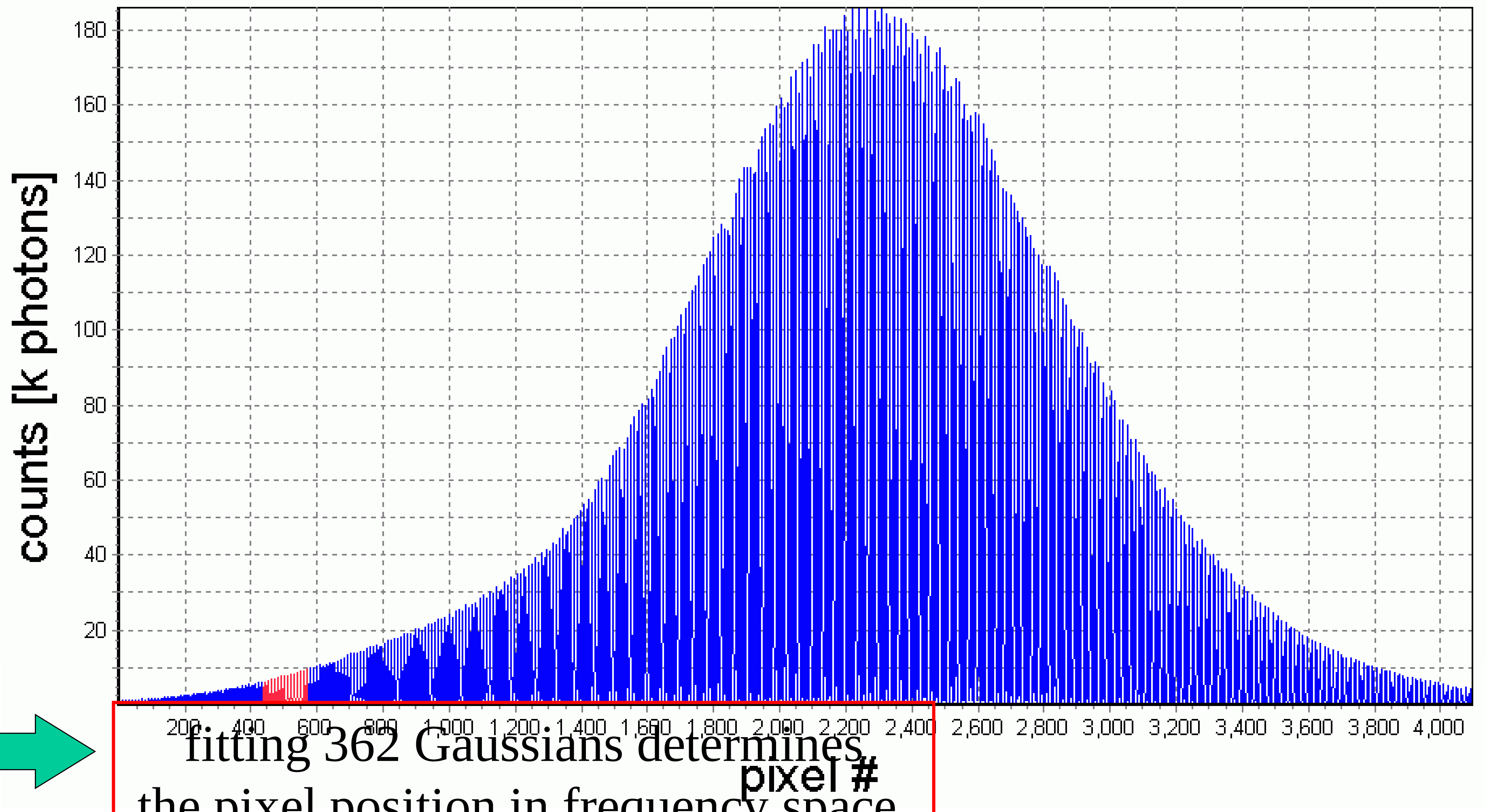

18 GHz
FP1
$8\omega_r$
FP2
$9\omega_r$
frequency comb
$\omega_r = 2\pi \times 250$MHz
g
g
SHG
to spectrograph
Rb-clock
servo
servo

La Silla 2009



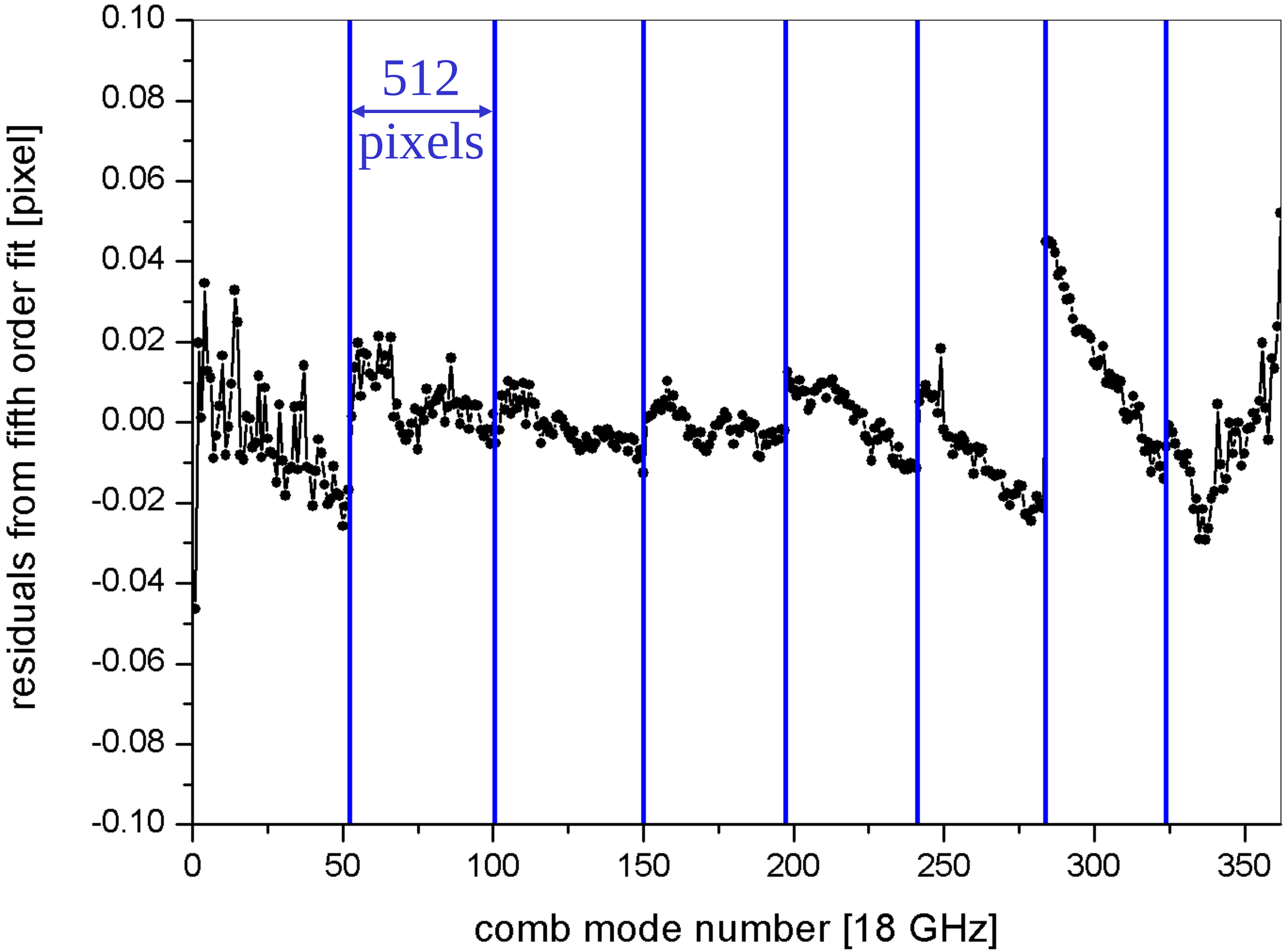
Determine the Calibration Curve

Determine the Calibration Curve



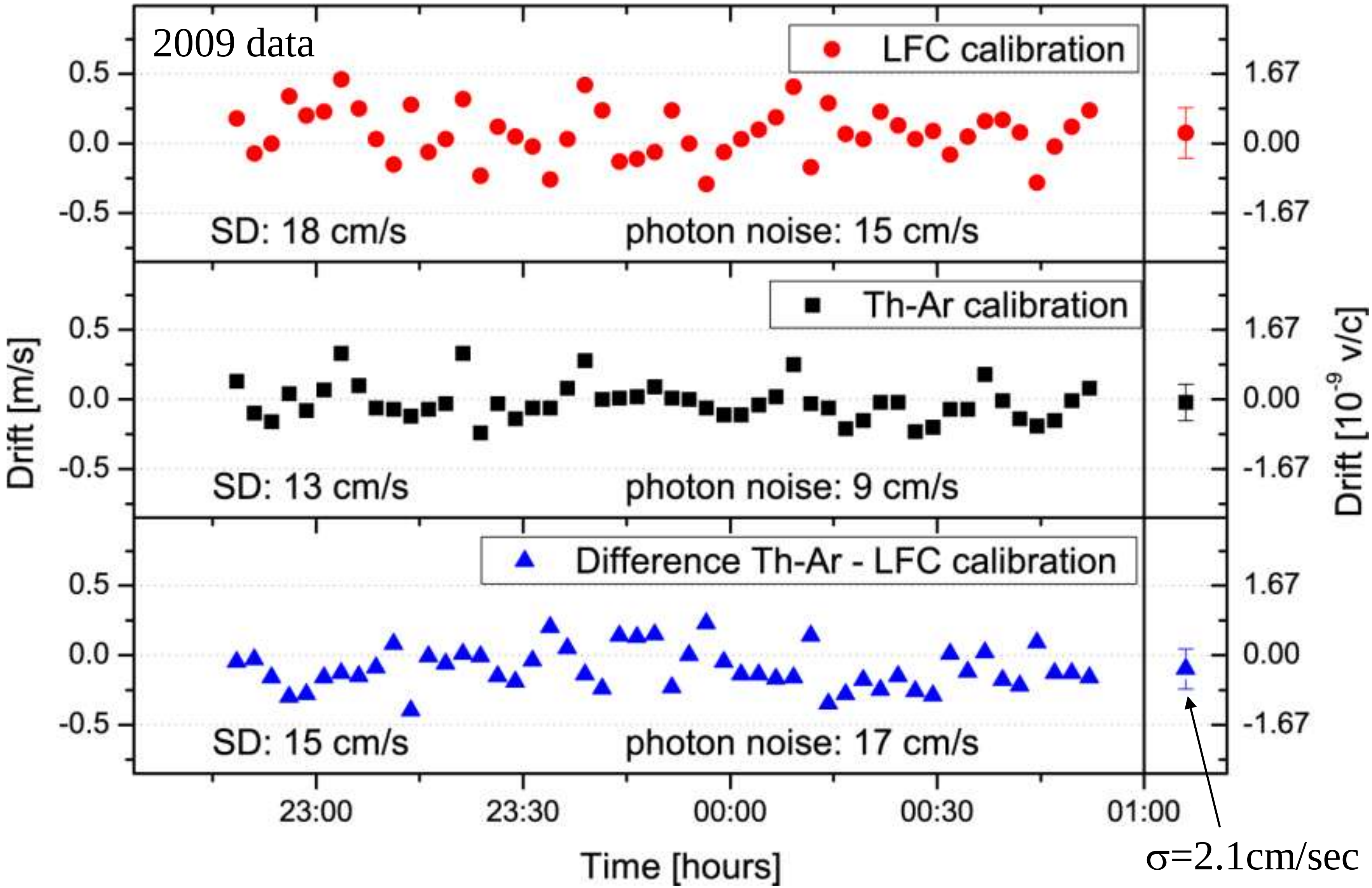
fitting 362 Gaussians determines
the pixel position in frequency space.

Determine the Calibration Curve



T. Wilken *et al.* Mon. Not. R. Astron. Soc. Lett. 405, L16 (2010)

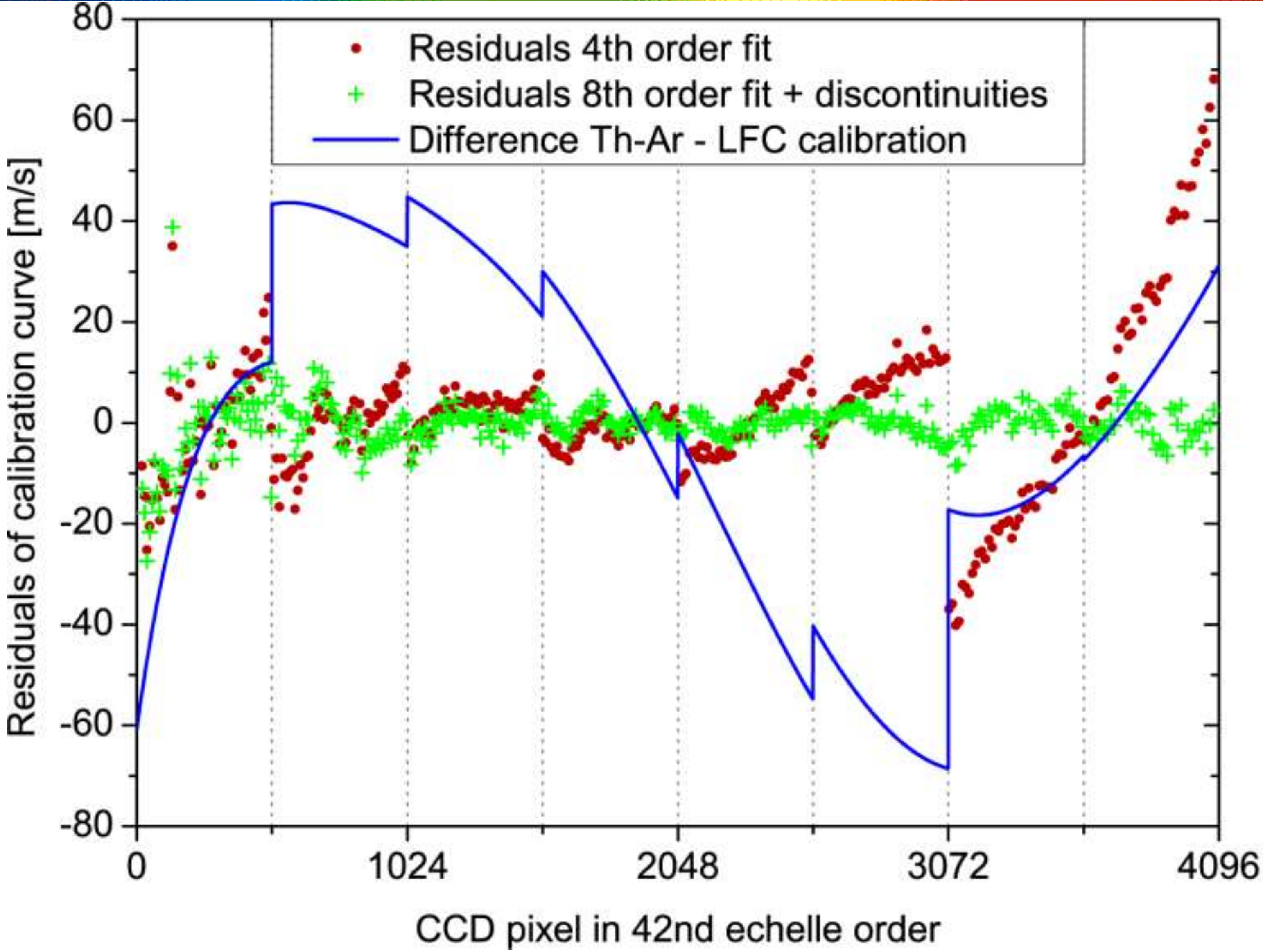
Short Term Repeatability of Calibration



σ=2.1cm/sec

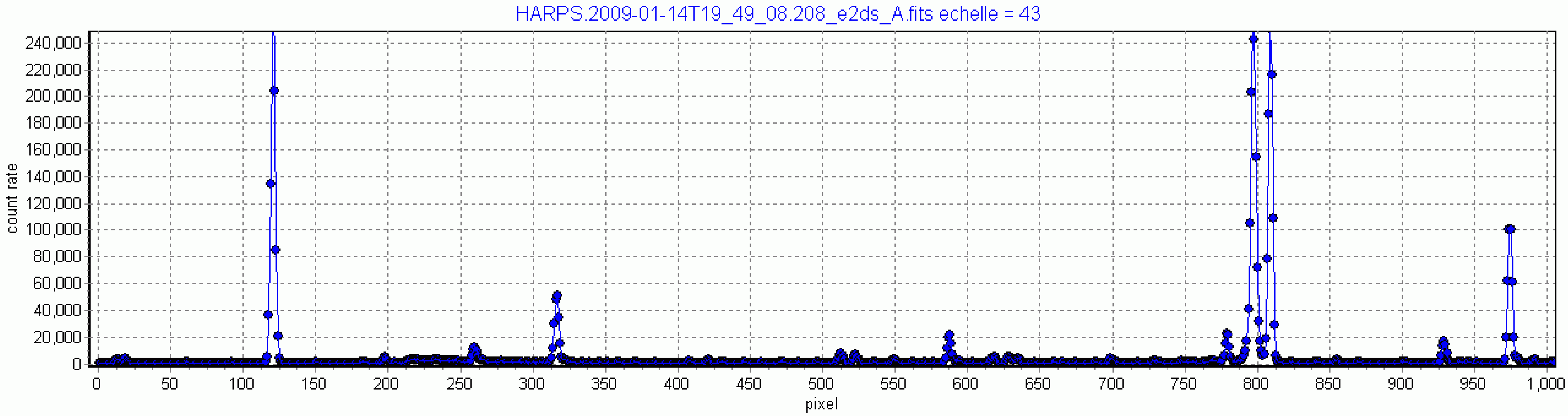
T. Wilken *et al.* Mon. Not. R. Astron. Soc. Lett. 405, L16 (2010)

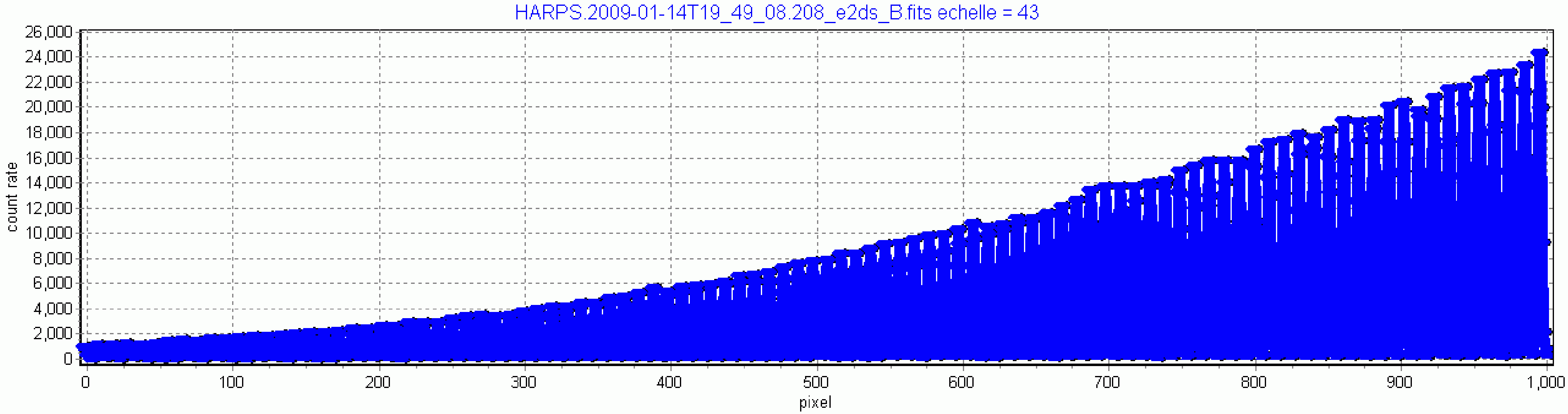
Comparision with Th-Ar



T. Wilken *et al.* Mon. Not. R. Astron. Soc. Lett. 405, L16 (2010)

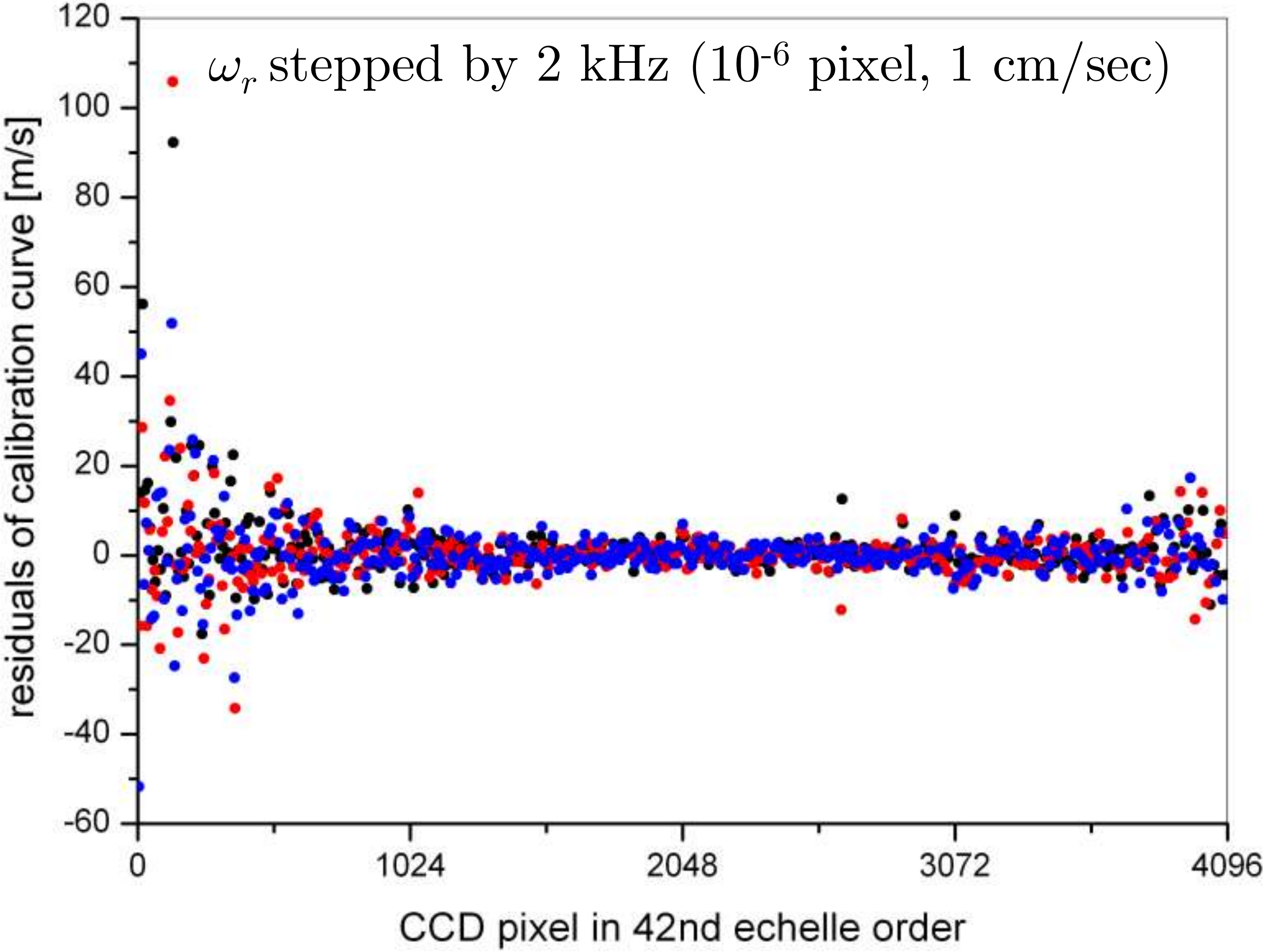
Scanning the Comb





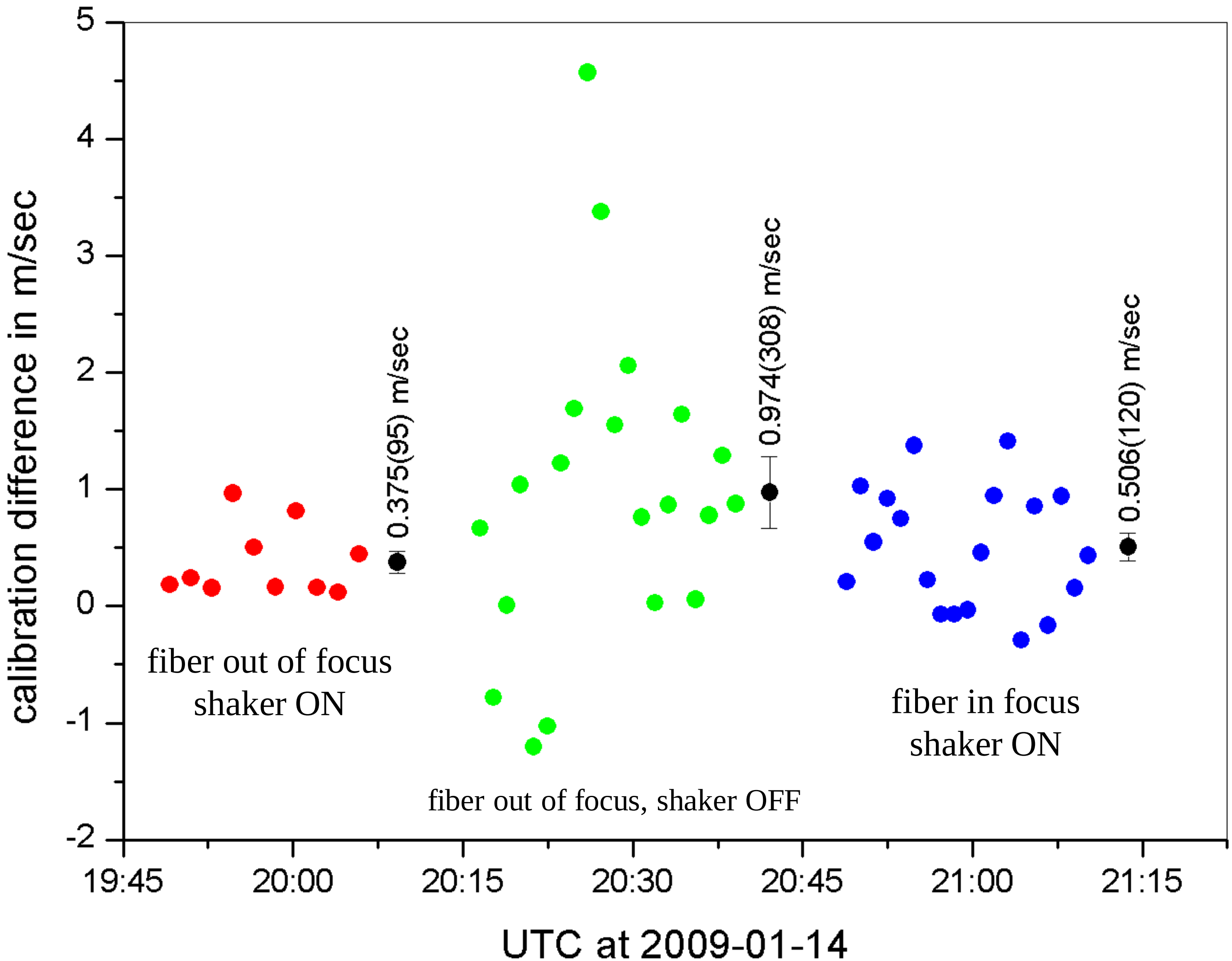
Scanning the Comb

Scanning the Comb



Current Problems

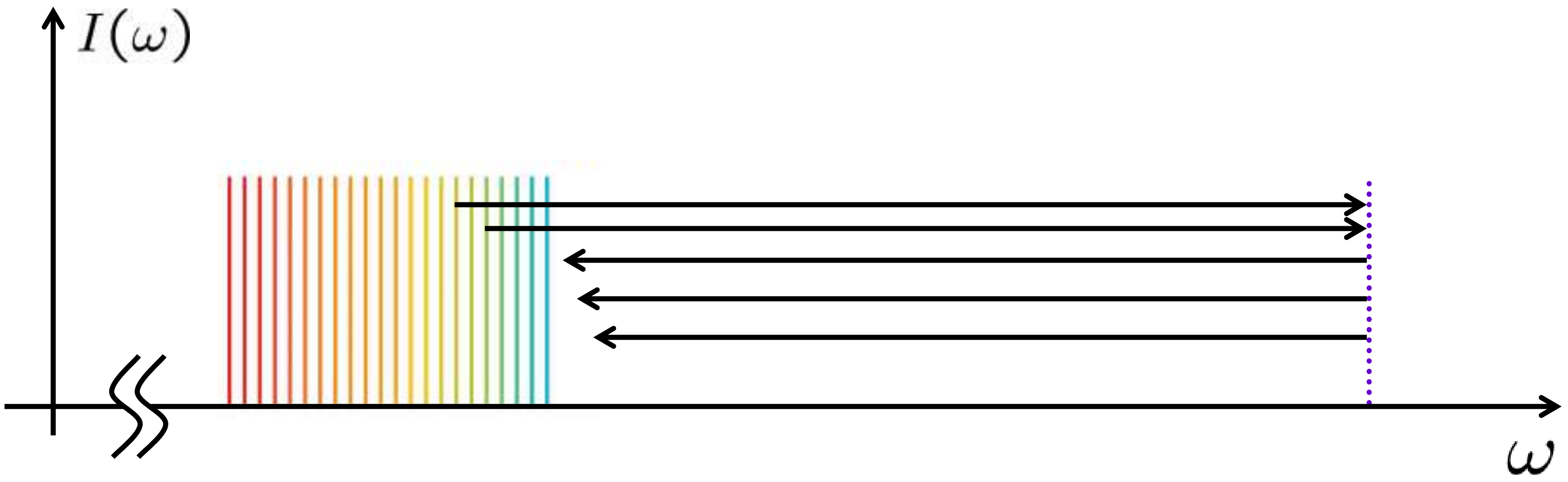
Calibration Repeatability



Spectral Broadenening by Self-Phase Modulation

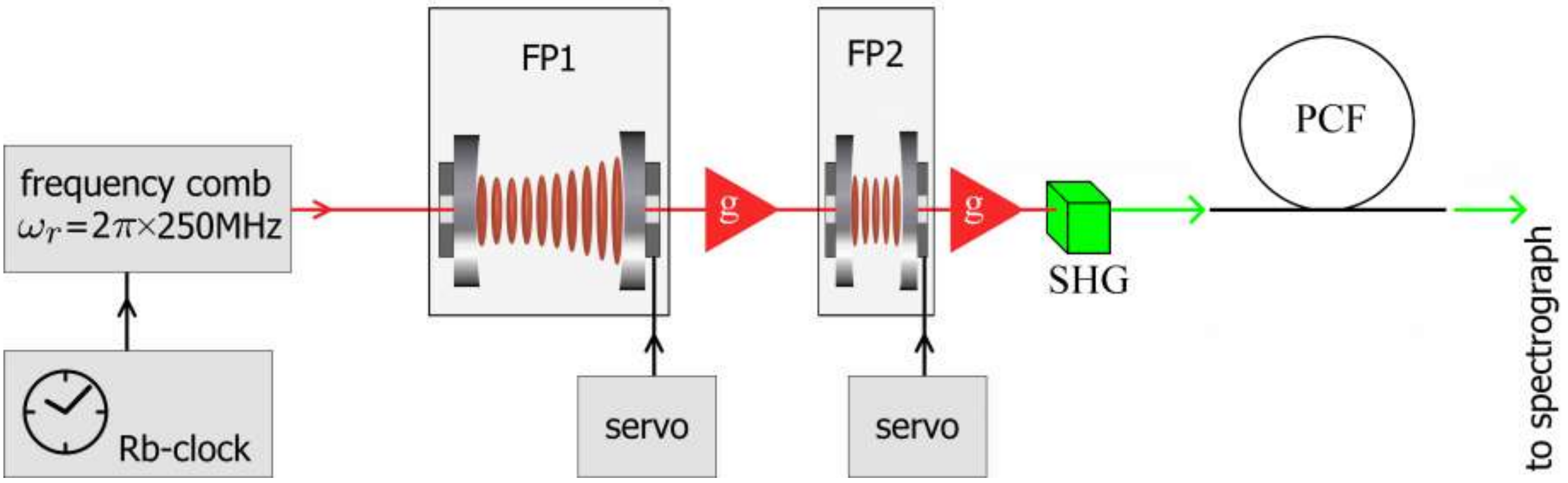
Four wave mixing:

$$E_{\text{out}}(t) = \chi^{(3)} E_1(t) E_2(t) E_3(t) = \chi^{(2)} E_1 e^{\pm i\omega_1 t} E_2 e^{\pm i\omega_2 t} E_3 e^{\pm i\omega_3 t}$$

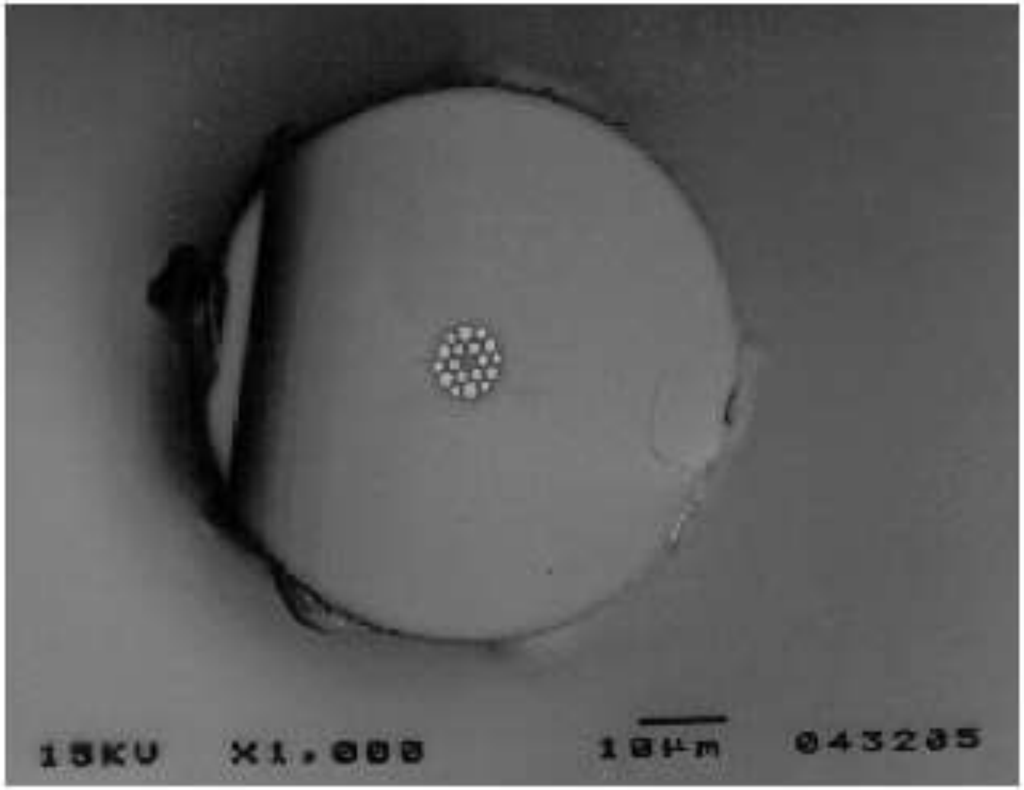


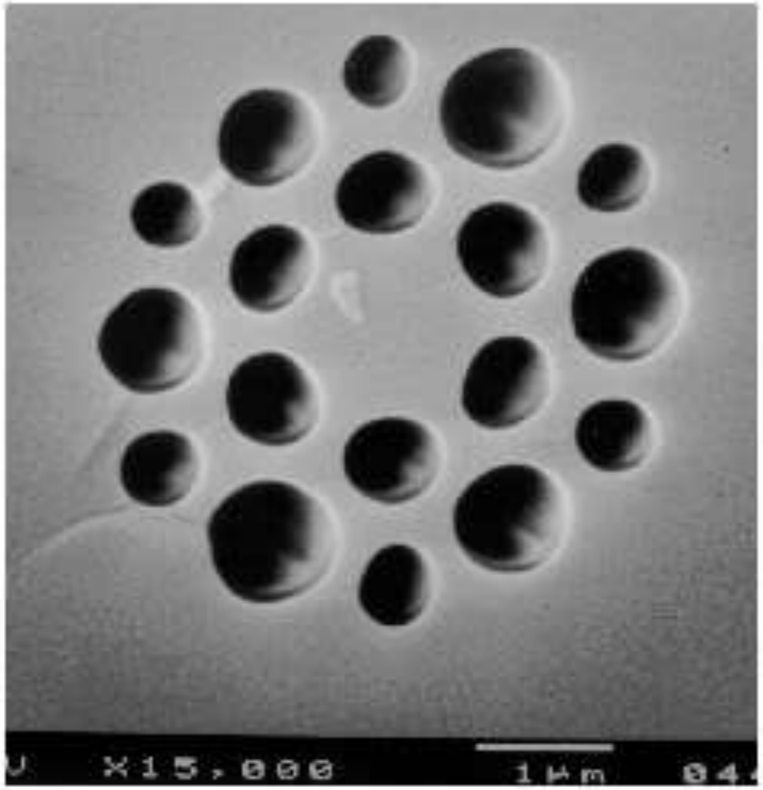
four wave mixing adds modes to the comb

Setup 3

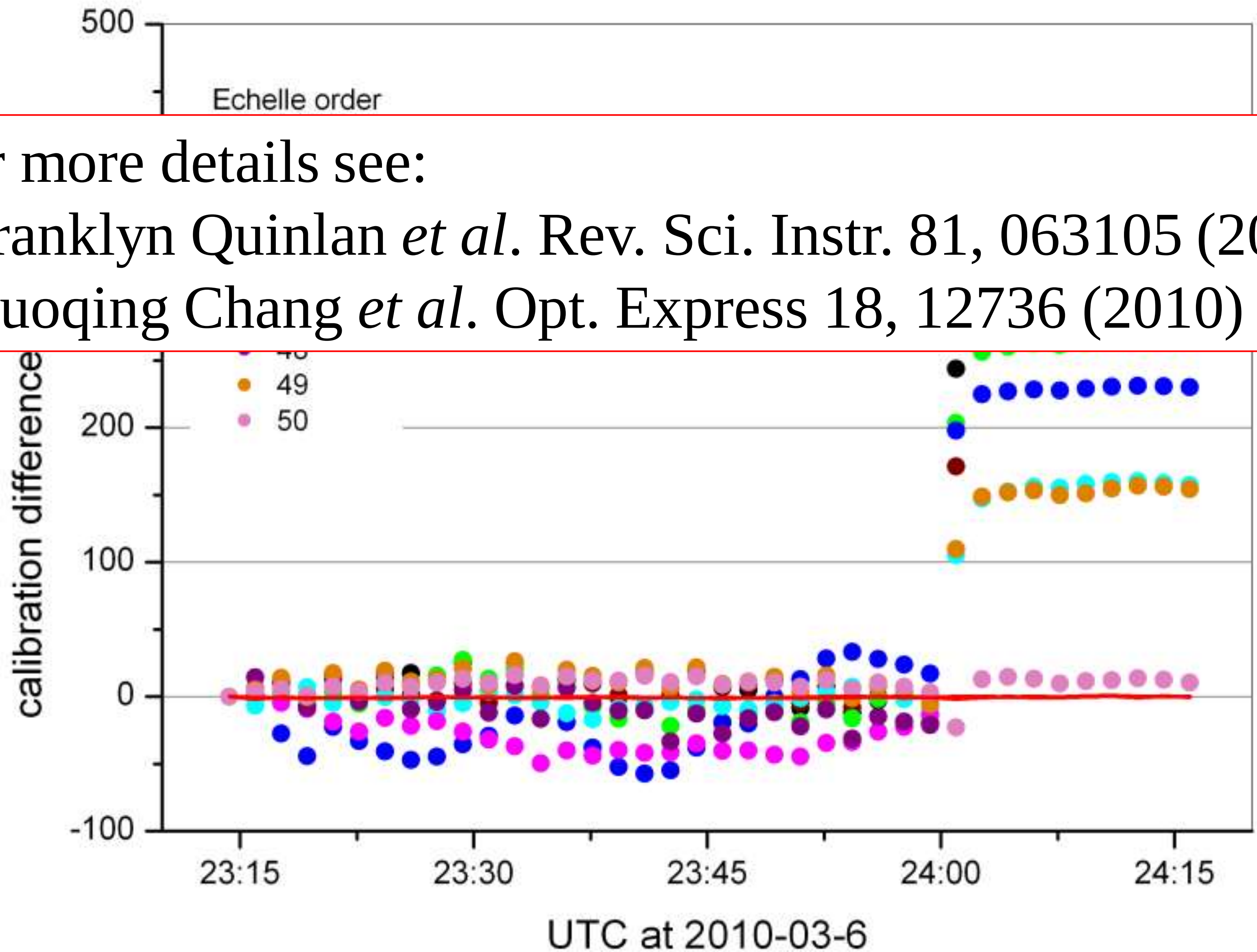

frequency comb
$\omega_r = 2\pi \times 250$MHz
Rb-clock
FP1
FP2
g
g
servo
servo
SHG
PCF
to spectrograph

Photonic Crystal Fiber from Bath University





Calibration Repeatability with Spectral Broadening



For more details see:

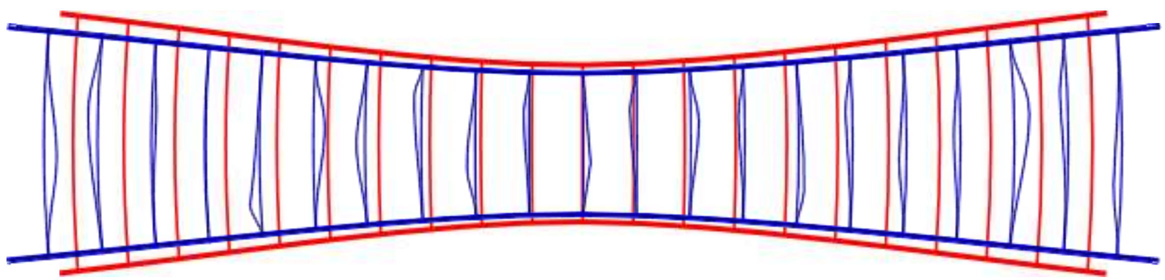
- Franklyn Quinlan *et al*. Rev. Sci. Instr. 81, 063105 (2010)
- Guoqing Chang *et al*. Opt. Express 18, 12736 (2010)

Thank you for your attention

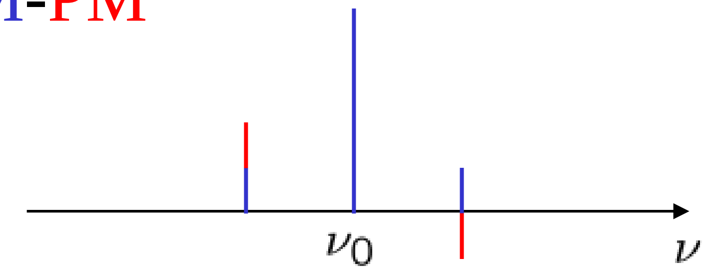
Long Term Repeatability of Doppler Calibration

Factors that may limit term repeatability:

- non-perfect mode matching

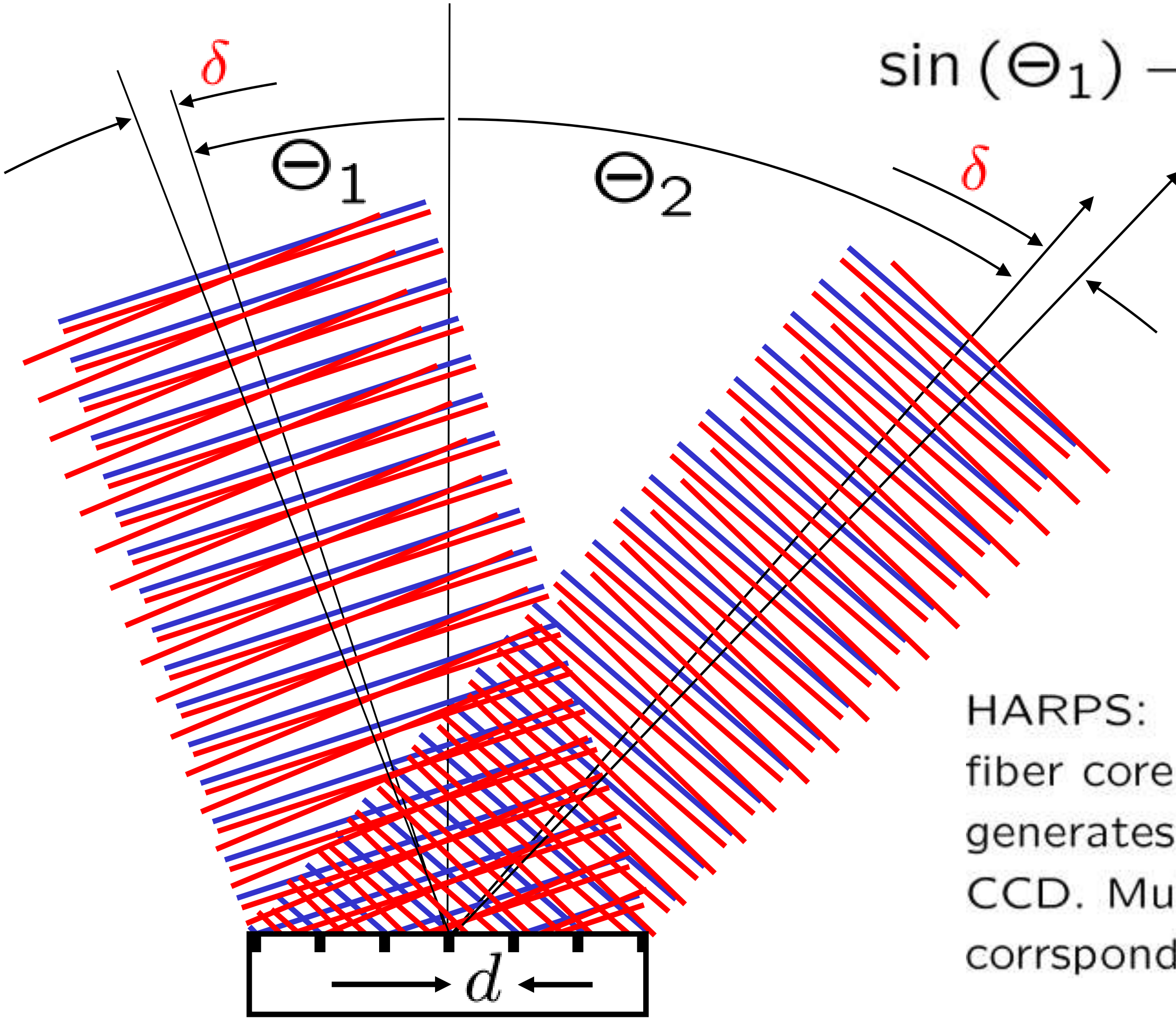


- correlated AM-PM



preliminary upper limit: 50m/sec

Comparing Wavelength rather than Frequency



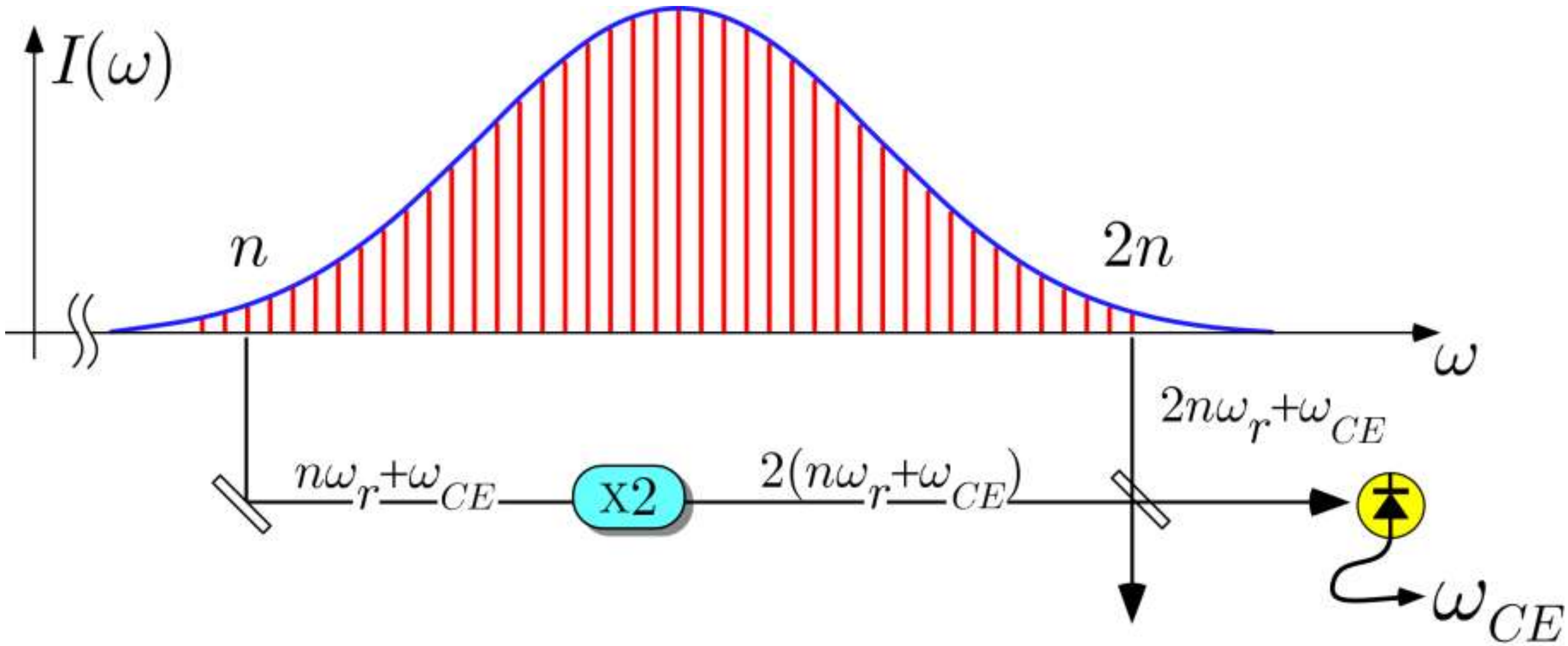
$$\sin(\Theta_1) - \sin(\Theta_2) = \frac{n\lambda}{d}$$

$\Rightarrow \Theta_2(\lambda)$

$\Rightarrow \Theta_2(\lambda) \rightarrow \delta$

HARPS:
fiber core diameter = 70 μm generates a 45 μm spot on the CCD. Mulitimode induced δ corrsponds to 2.5 km/sec.

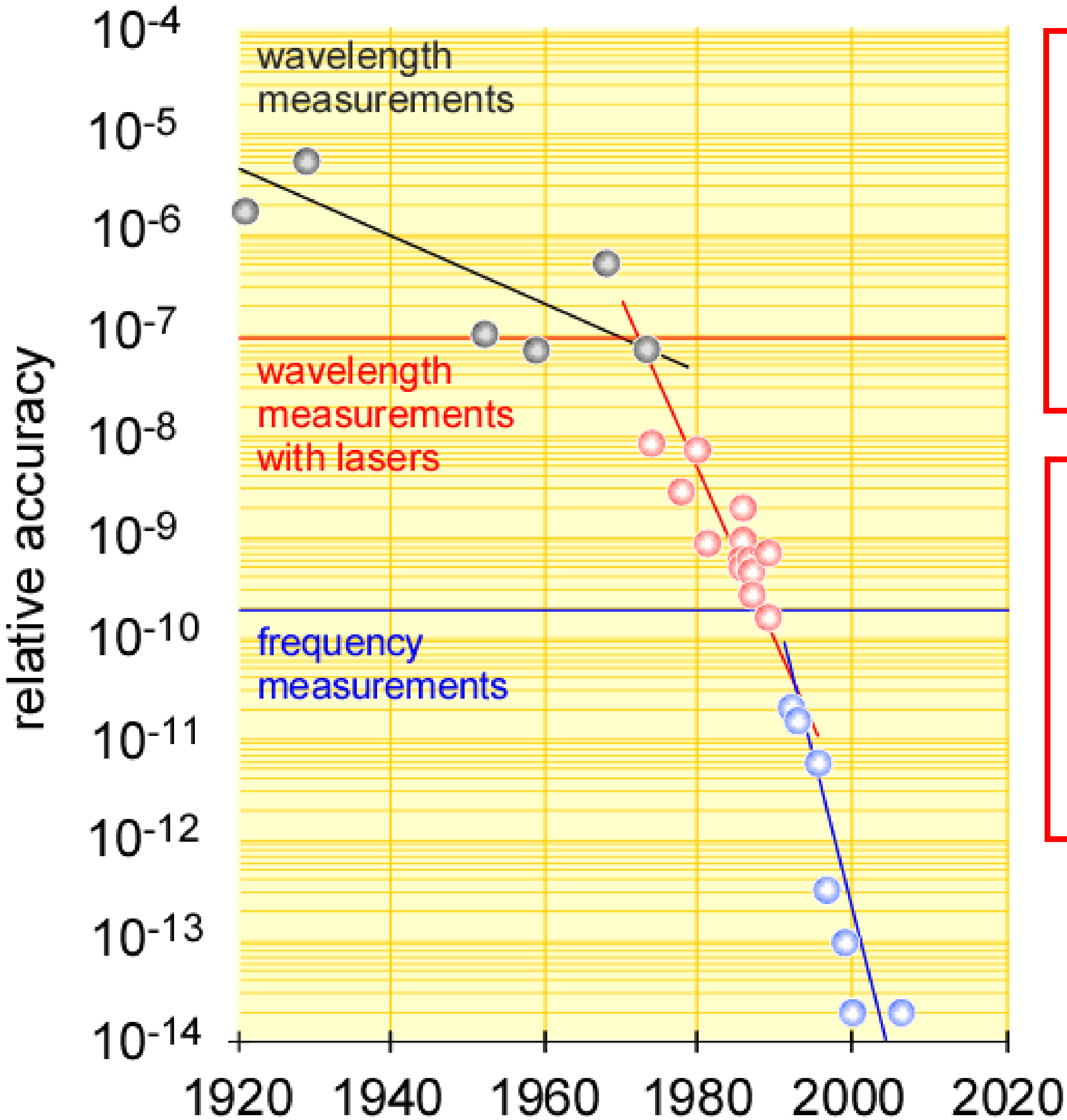
Self Referencing



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

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

Hydrogen History

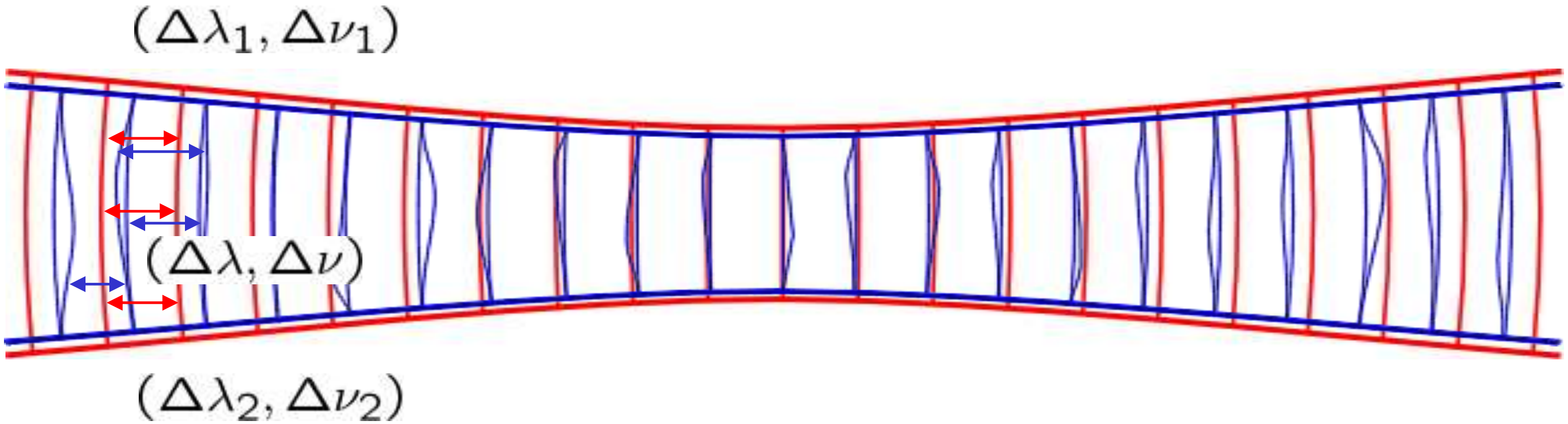


Best wavelength comparisions ever using laser beams coupled through single mode fibers: 10^{-10} (3 cm/sec)

But: Astronomy needs precission (reprodicibility) rather than accuracy and uses many lines simultanously.

Comparing Wavelengths

Assuming a perfect spectrometer...

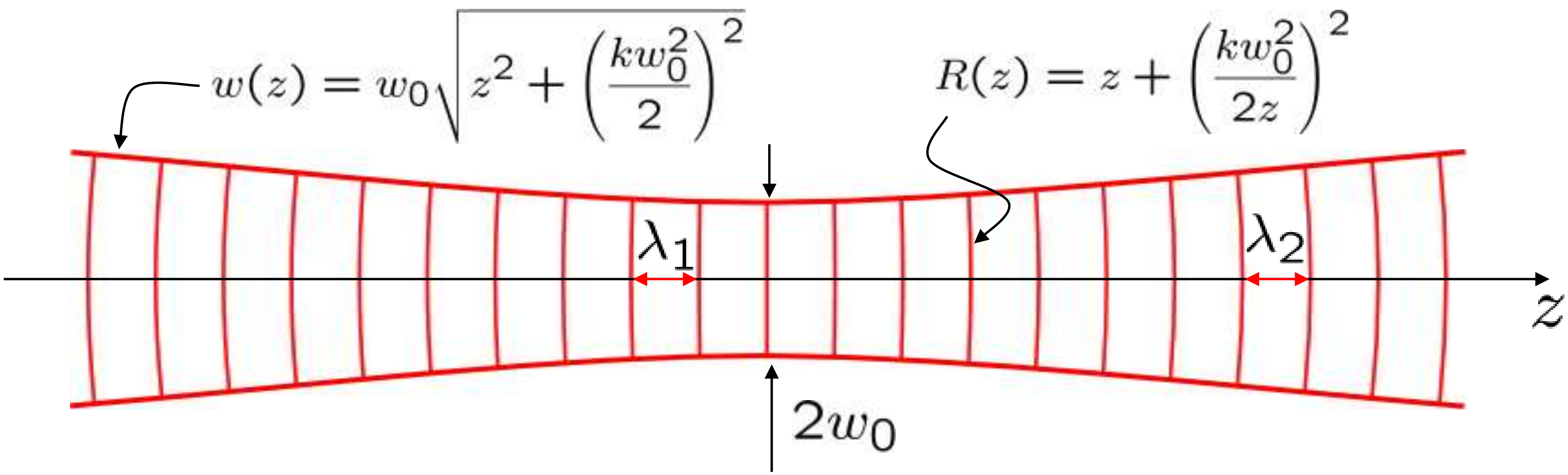


Wavefront deformations lead to $\Delta\lambda_1 \neq \Delta\lambda_2$ but $\Delta\nu_1 = \Delta\nu_2$.

Comparing Wavelengths

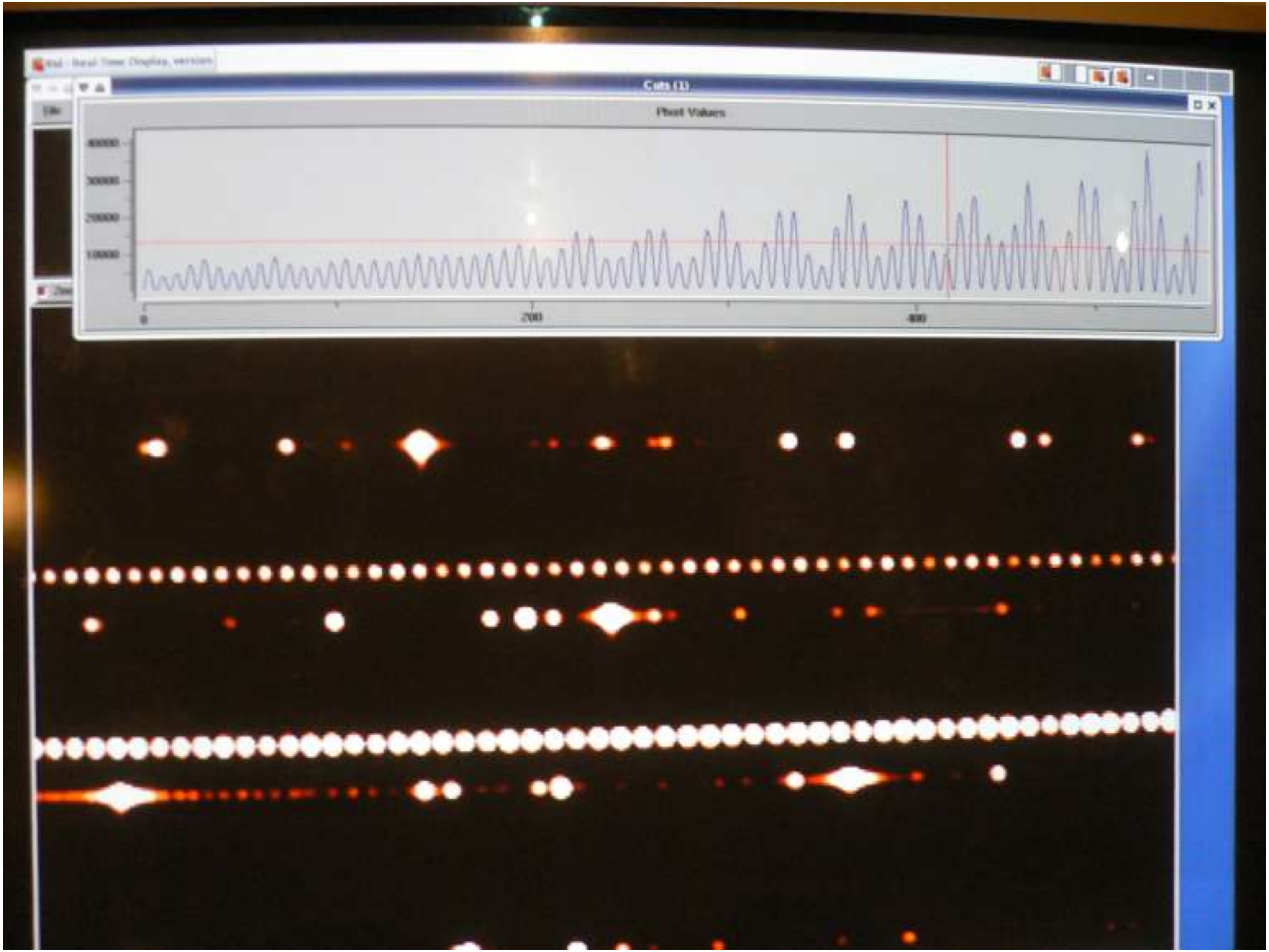
Now assuming a perfect spectrometer and a perfect wavefront ...

Gaussian mode: $E \propto \exp\left(-\frac{r^2}{w^2(z)} - i\frac{kr^2}{2R(z)} + ikz - i\,\mathrm{arctan}\left(\frac{2z}{kw_0^2}\right)\right)$



$$\lambda_1 \neq \lambda_2 \neq \frac{c}{\nu} \quad \text{but} \quad \frac{\Delta z}{z} \approx \frac{1}{(kw_0)^2}$$

Spectral Interference due to Spatial Mode Beating



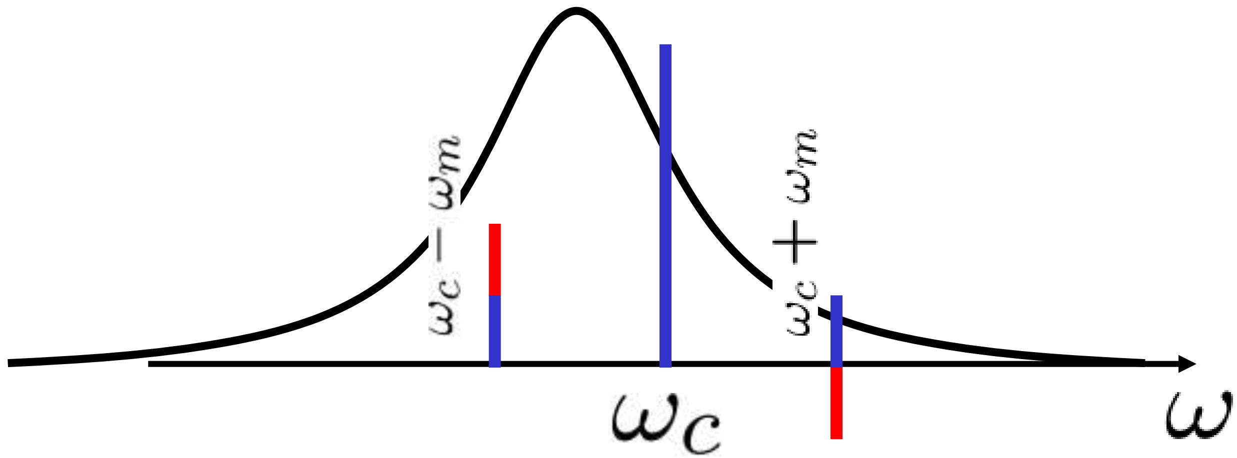
Correlated AM-PM noise

- Amplitude modulation AM:

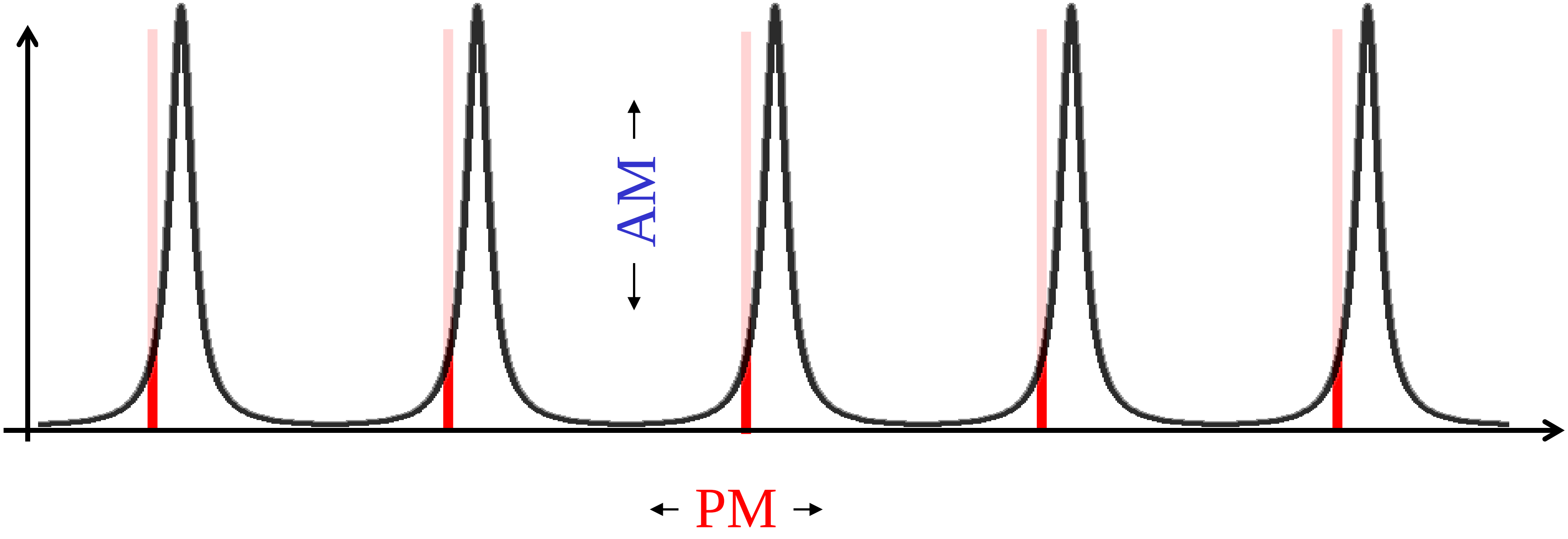
$$\cos(\omega_c t)\,[1 + 2a_m \cos(\omega_m t)]$$
$$= \cos(\omega_c t) + a_m\,[\cos((\omega_c + \omega_m)t) + \cos((\omega_c - \omega_m)t)]$$

- Frequency (Phase) modulation PM:

$$\cos(\omega_c t + M \sin(\omega_m t)) = \sum_{n=-\infty}^{+\infty} J_n(M) \cos(\omega_c t + n\omega_m t)$$
$$\approx \cos(\omega_c t) + J_1(M)\,[\cos((\omega_c + \omega_m)t) - \cos((\omega_c - \omega_m)t)]$$

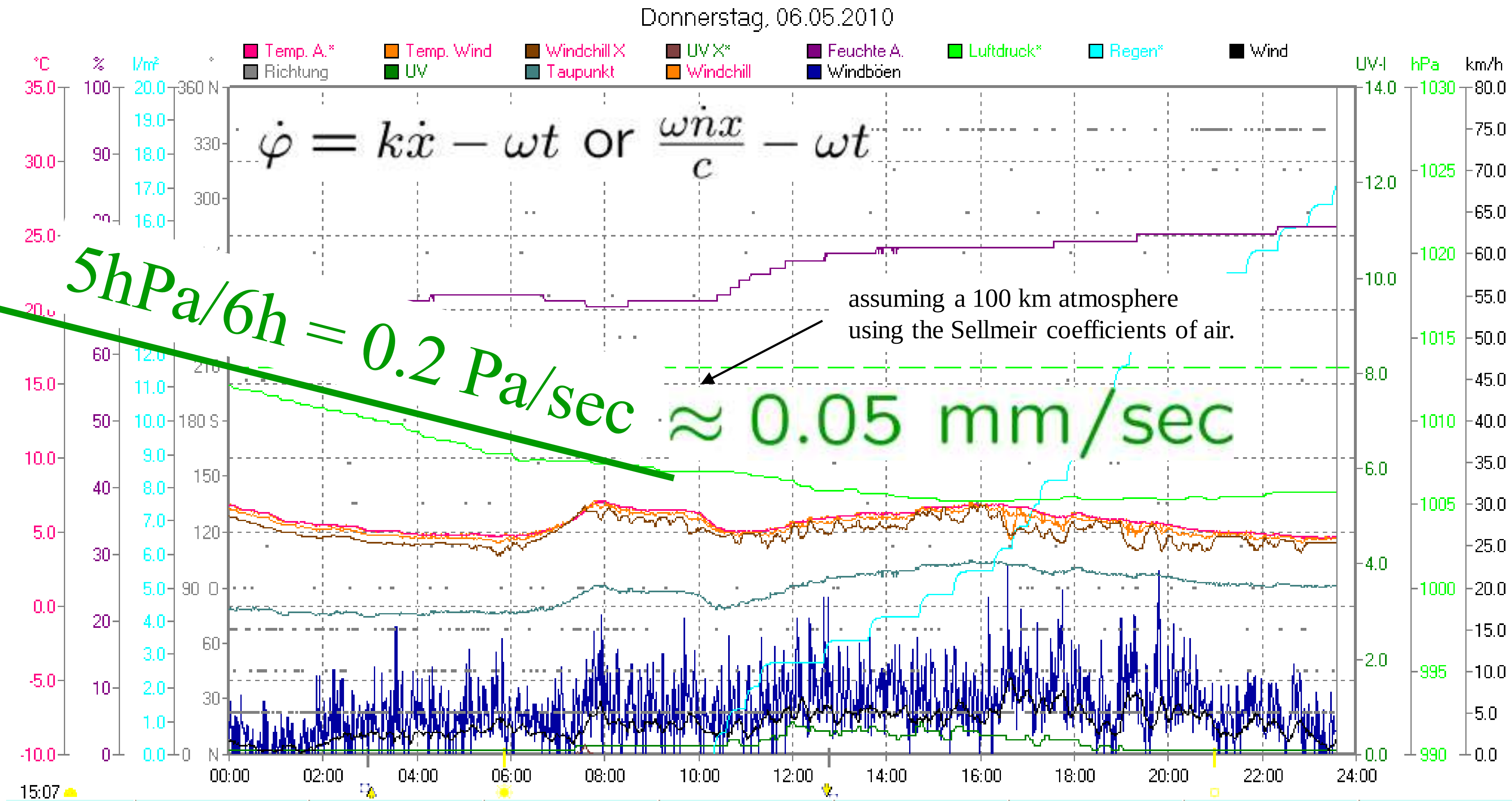


Correlated AM-PM noise



Pressure Drifts

Pressure Drifts



Sensor	Temp. A.	°C	Feuchte A.	%	Luftdruck	hPa	Wind	km/h	Feuchte I.	%	Regen	l/m²	Windböen	km/h	UV	UV-I
MinWert	22:49	4.6	00:00	61	15:03	1005.2	Ø 10 min.	1.2	20:38	56			Ø 10 min.	3.3	00:00	0.1
MaxWert	07:46	7.1	22:19	79	00:00	1012.1	16:38	O-SO 9.2	10:10	61	10:20	0.7	16:35	N-NO 22.5	11:58	0.7
Durchschnitt		5.71		72	^1.0hPa/h	1007.1		3.6		59	Gesamt:	17.2		5.5		0.2
06.05. 23:35		**4.7**	5.26 g/m³	**79**	veränderlich	**1005.7**	1 Bft N	**1.8**	10.27 g/m³	**57**	17.2 l/m²	**0.0**	1 Bft N	**2.9**		**0.1**

Filter Cavities in Series