# Comb generation for metrology

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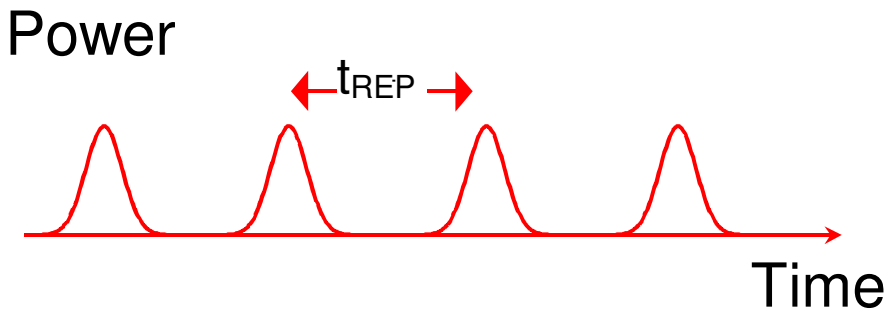
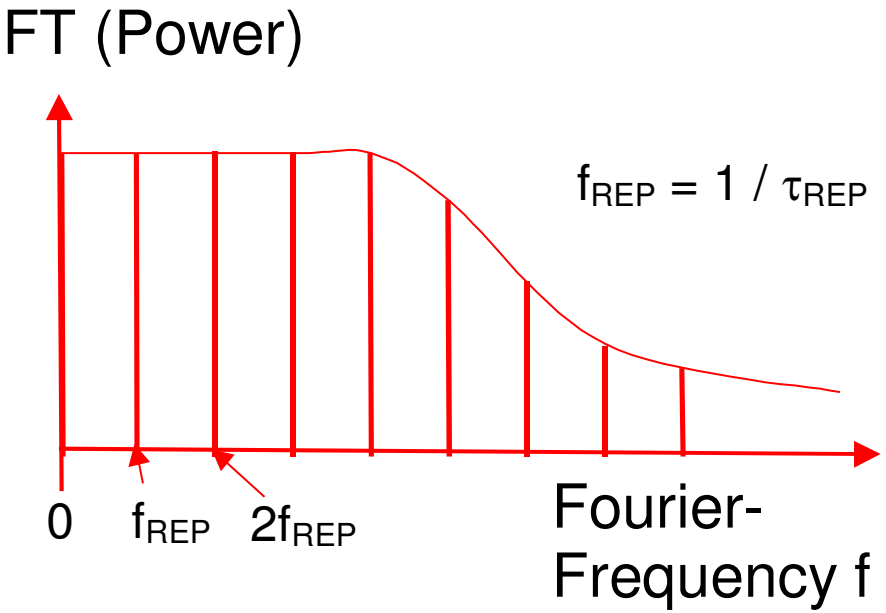
- Femtocombs in frequency metrology
- Possible noise contributions and countermeasures
- Supercontinuum generation
- Outlook

# Periodic train of light pulses, e. g. from a LED



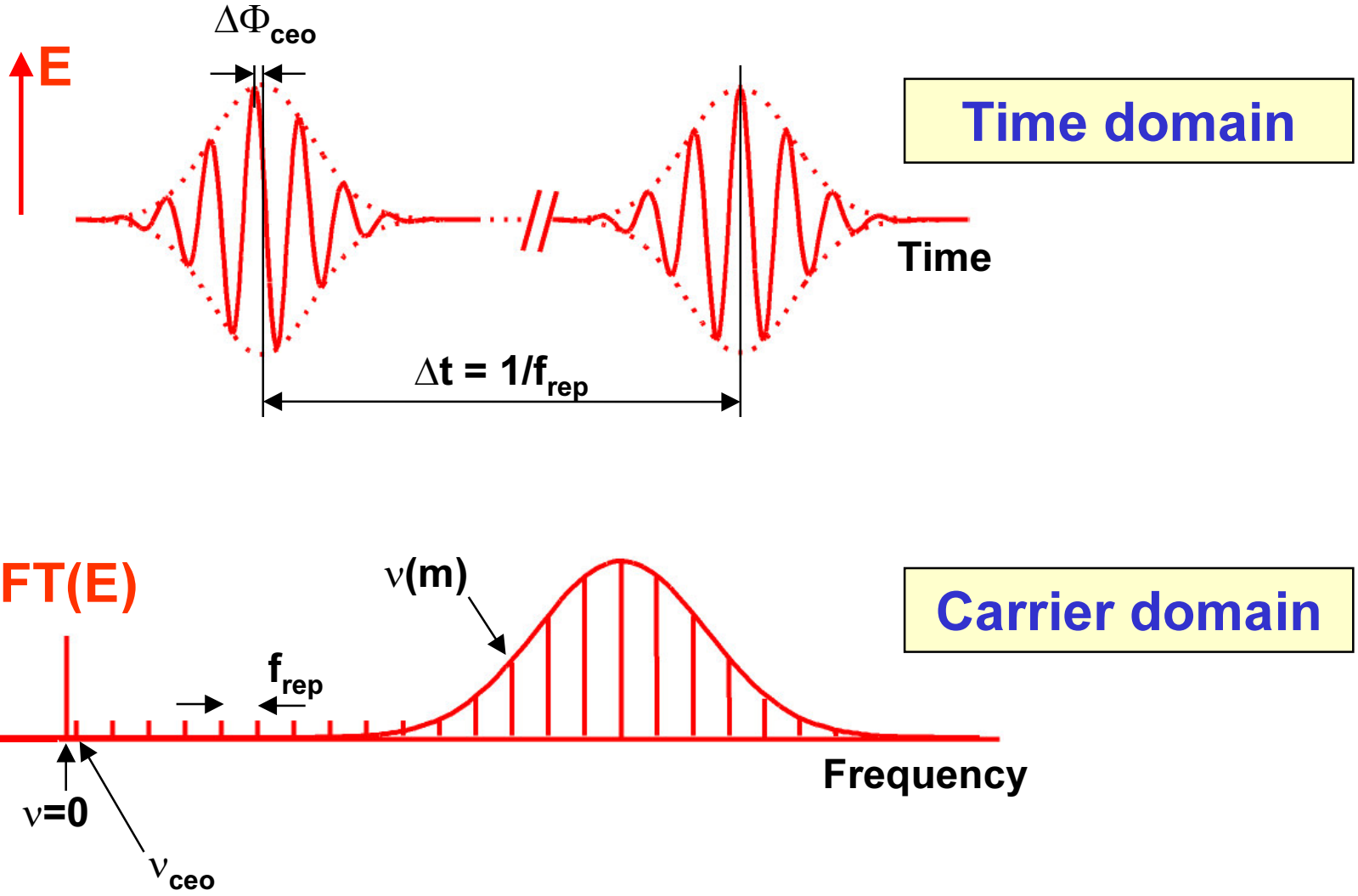

**Time domain**




**Baseband domain**

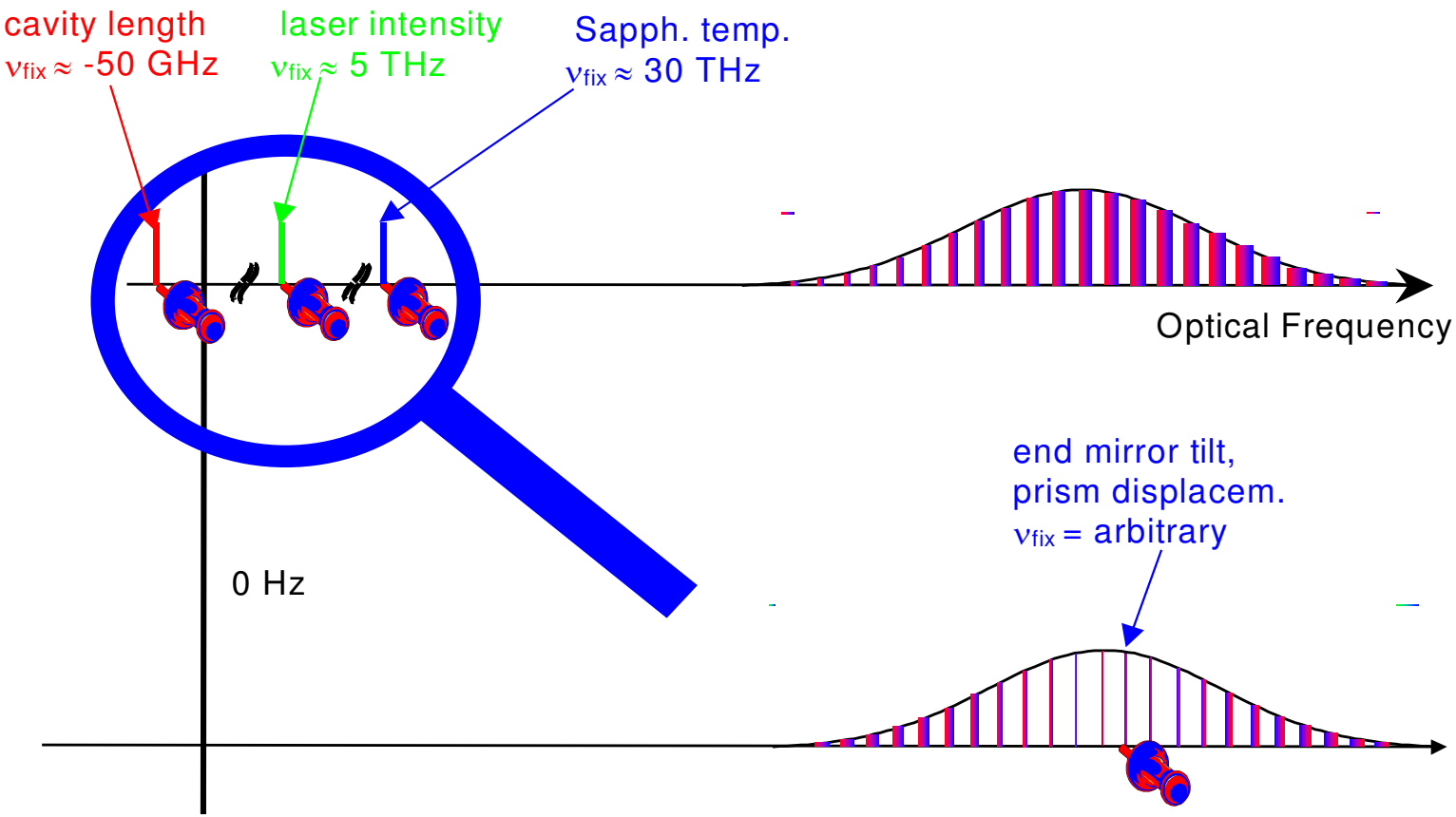
**In general no comb spectrum in carrier domain !**

# Periodic train of light pulses with coherent carrier

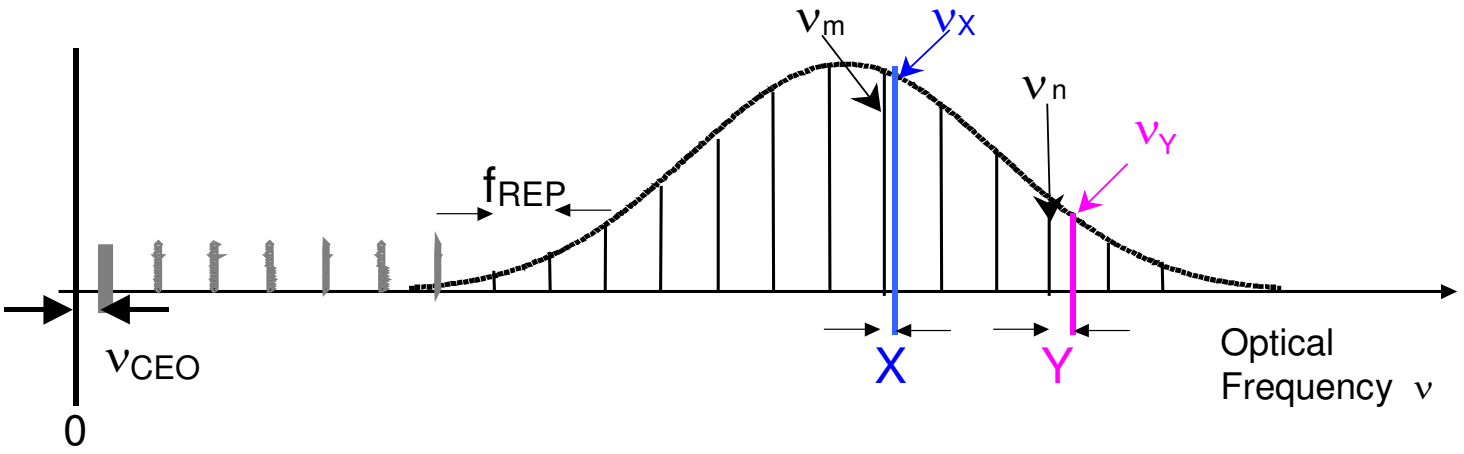



$\nu(m) = \nu_{ceo} + m\, f_{rep}$ , Elastic tape picture

# Fixed point of ’elastic tape’

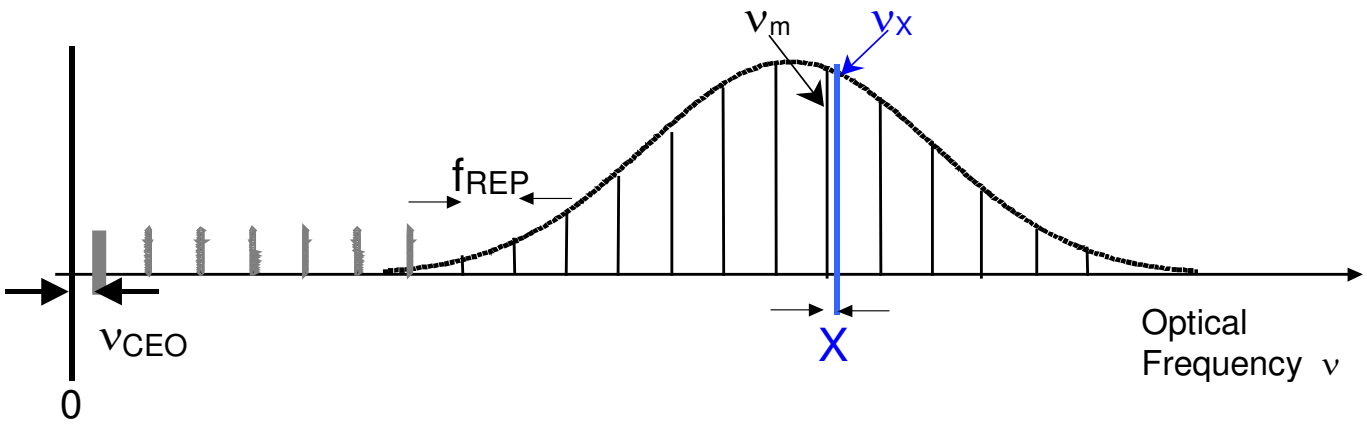


# Applications of Femtocombs in Frequency Metrology




| Task | Detection of | Applications |
|---|---|---|
| Link the difference of 2 optical frequencies to MW | beat-note X<br>beat-note Y<br>$f_{REP}$ | MW generation<br>IR-metrology<br>IR-synthesis |
| Link 1 optical frequency to MW | CEO-frequency<br>beat-note X<br>$f_{REP}$ | absolute frequency measurement<br>optical frequency synthesis<br>MW generation |
| Link 2 optical frequencies | CEO-frequency<br>beat-note X<br>beat-note Y | optical frequency ratios<br>optical frequency synthesis |

# Phase-coherent measurement: detection of phase angles




$\nu_X = \nu_m + X = \nu_{ceo} + m\, f_{rep} + X$

**Assumption:** $\varphi_m(t) = \varphi_{ceo}(t) + m\,\varphi_{rep}(t) + \Phi(t,m)$

**Elastic tape picture holds even for phases,** $\Phi(t,m) < \infty$

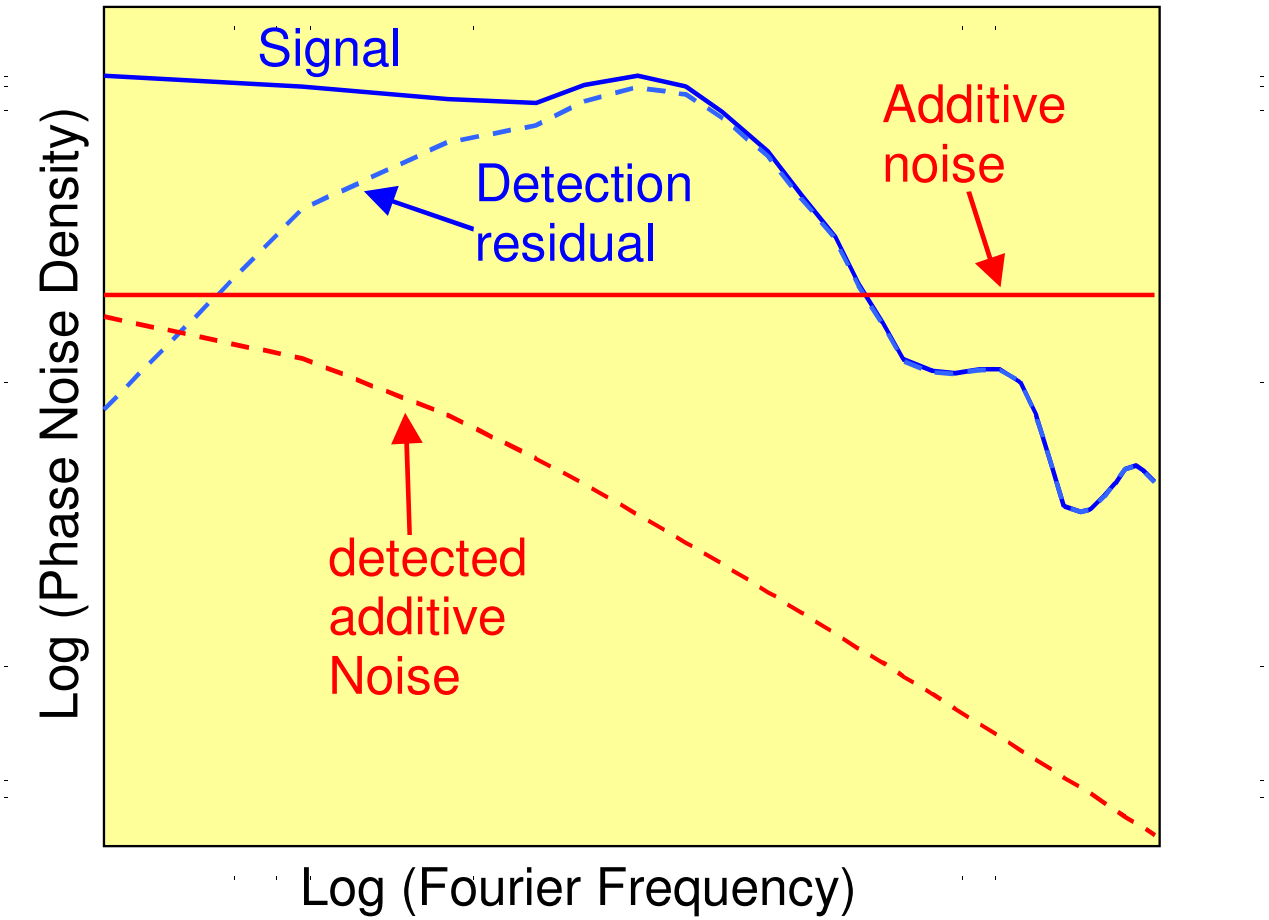
$\Rightarrow$ **Detection of** $\varphi_m(t)$, $\varphi_{CEO}(t)$, $\varphi_{REP}(t)$

# Detection of $\varphi_m$, $\varphi_{CEO}$, $\varphi_{REP}$

**Possible noise contributions**

- **optimum bandwidth $\Rightarrow$ detection residual**
- **additive noise, e. g. electronic noise, shot noise**
- **noise cross conversion, e.g. AM $\rightarrow$ PM**
- **external multiplicative noise, e. g. thermal delay time noise**

# Noise contributions (schematic)




Signal ≡ fluctuations of references and femtocomb !

# Detection of $\varphi_m$, $\varphi_{CEO}$, $\varphi_{REP}$

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# Data processing

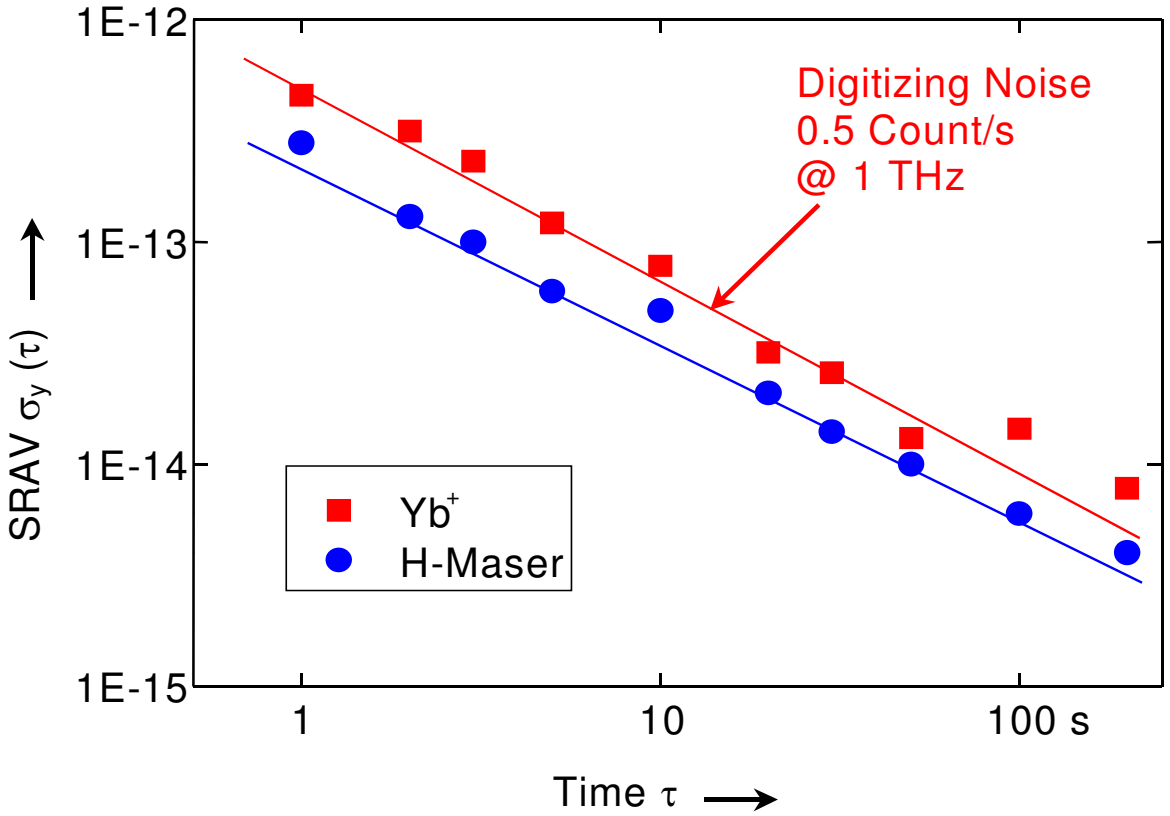
## Possible noise contributions

- Counting & digitizing noise
- Servo cross conversion
- Imperfect compensation of detection residuals due to different filtering during detection process

## Countermeasures

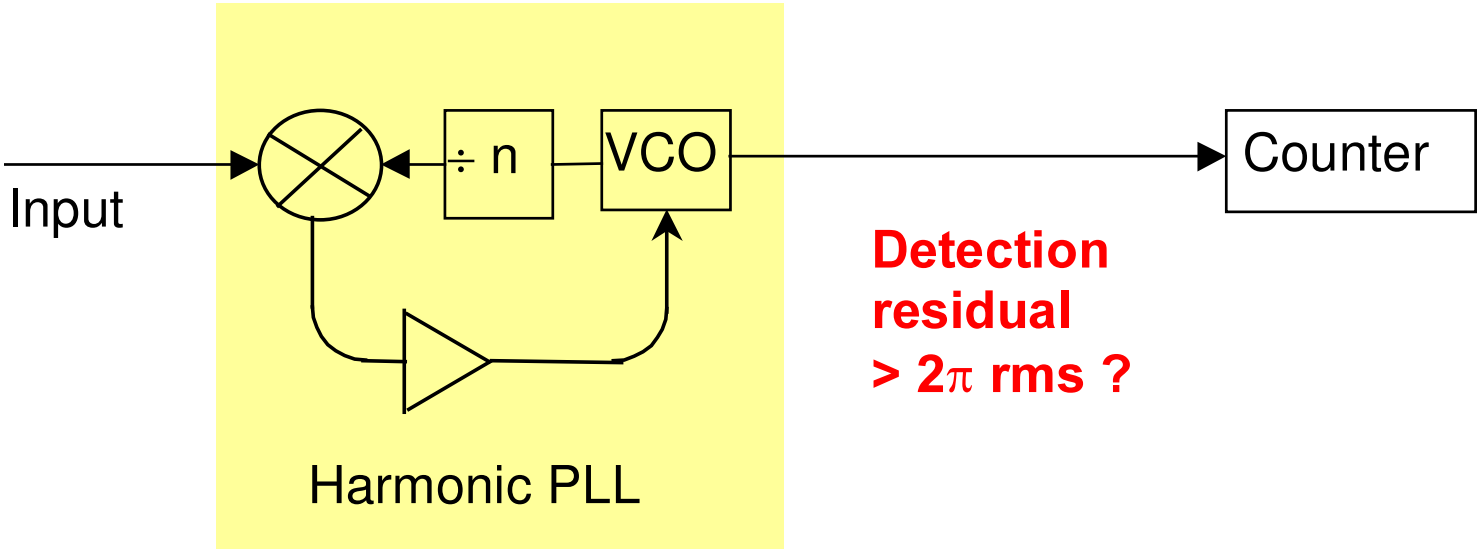
- Phase interpolation
- Totalizing frequency counters
- Broadband detection of all instantaneous phase angles with optimum post-filtering of processed signal (transfer concept)

# Countig of $_{REP}$: Digitizing noise




⇒ **Phase interpolation essential !**

# Phase interpolation by frequency multiplication




**Detection residual > 2π rms ?**

**⇒ Totalizing frequency counter essential !**

# Data processing

## Possible noise contributions

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# Detection of $\varphi_m$, $\varphi_{CEO}$, $\varphi_{REP}$

**Elastic tape picture for Fourier components of phase fluctuations:**

$$\varphi_m(t) = \varphi_{ceo}(t) + m\,\varphi_{rep}(t) + \text{const} \quad \Rightarrow \quad \tilde{\varphi}_m(f) = \tilde{\varphi}_{CEO}(f) + m\,\tilde{\varphi}_{REP}(f) + \text{const}$$

**Elastic tape model in general NOT valid for detected quantities**

$H_m(f)\ \tilde{\varphi}_m(f)$

$H_{CEO}(f)\ \tilde{\varphi}_{CEO}(f)$

$H_{REP}(f)\ \tilde{\varphi}_{REP}(f)$

H complex transfer functions ≠ 1,
e. g. PLL loop filter, delay times
$H_m(f) \neq H_{CEO}(f) \neq H_{REP}(f)$

# Real-time data processing (transfer concept)

**Example: Measurement of** $\nu_X / f_{MW}$

$\nu_X$ **optical frequency**

$f_{MW}$ **microwave reference**

**Measured quantities:** $H_X X$ , $H_Y Y$ , $H_{CEO}\,\varphi_{CEO}$

$X = \varphi_X - \varphi_m$, $Y = \varphi_{REP} - \varphi_{MW}$

**Real time data processing:**

$$\Sigma = H_X X + H_{CEO}\varphi_{CEO} + m\, H_Y Y$$

**Narrow-band post filtering:**

$$H_x(f) = H_Y(f) = H_{CEO}(f) = 1, \quad f \text{ small}$$

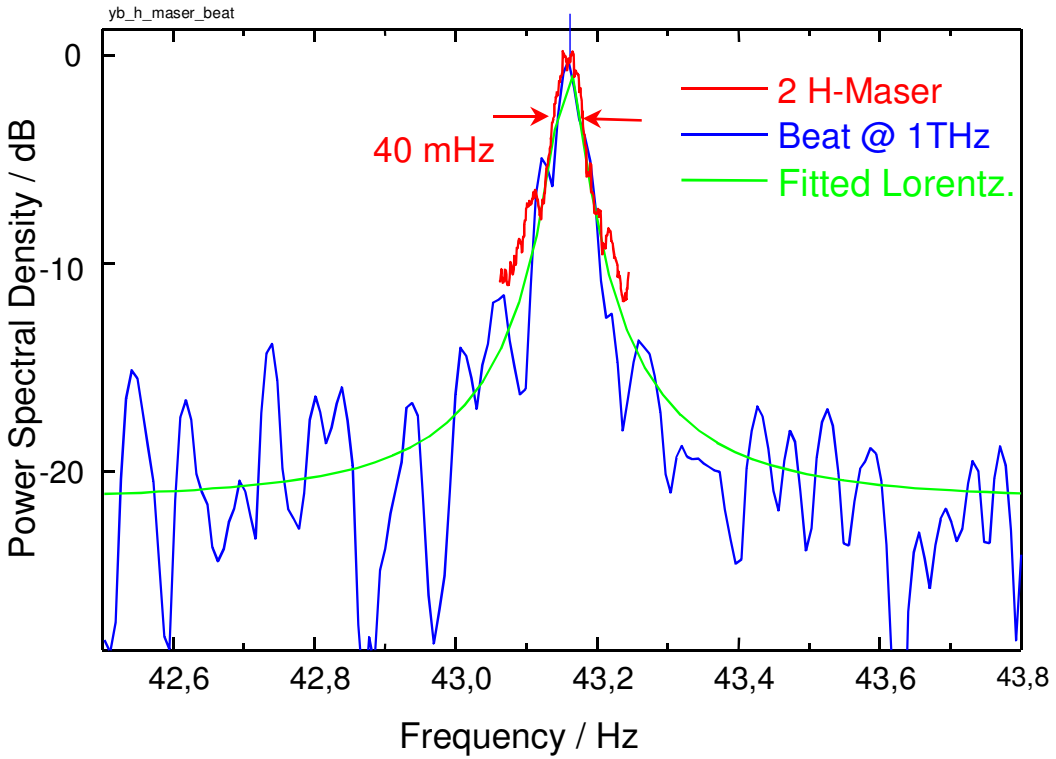
**Elastic tape:** $\varphi_{CEO} + m\,\varphi_{REP} - \varphi_m = \text{const}$

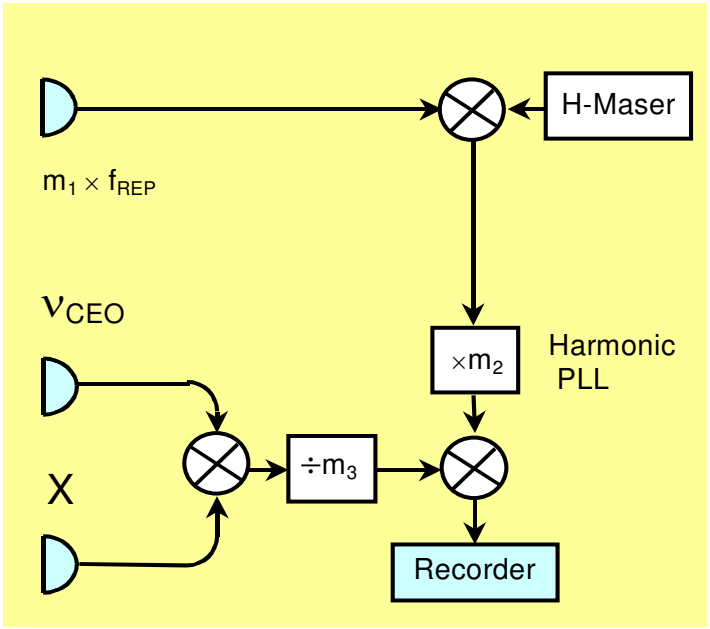
$$\Sigma = \varphi_X - m \times \varphi_{MW}$$

$\Rightarrow$ **independent of femtocomb**
**detection residuals cancel out !**

# Transfer between microwave and optical range

Virtual frequency: 989 GHz

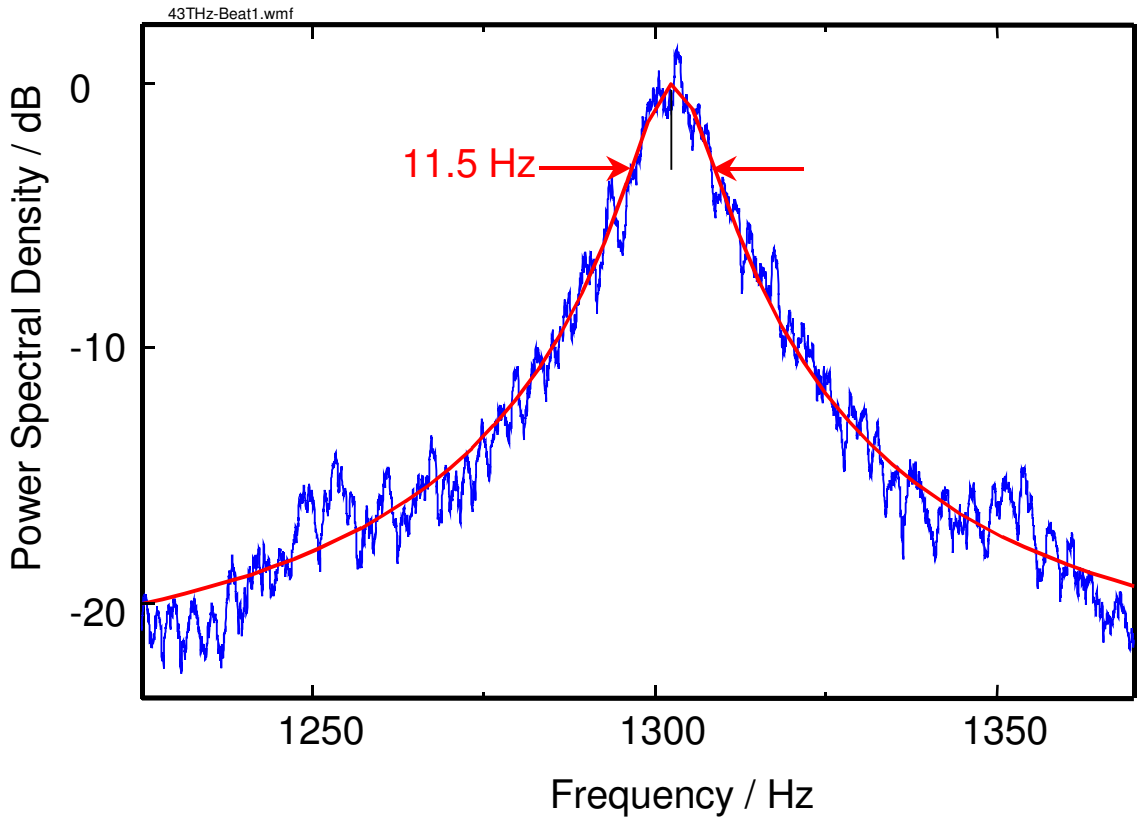



**Phase locking of beat: optical or MW synthesizer**

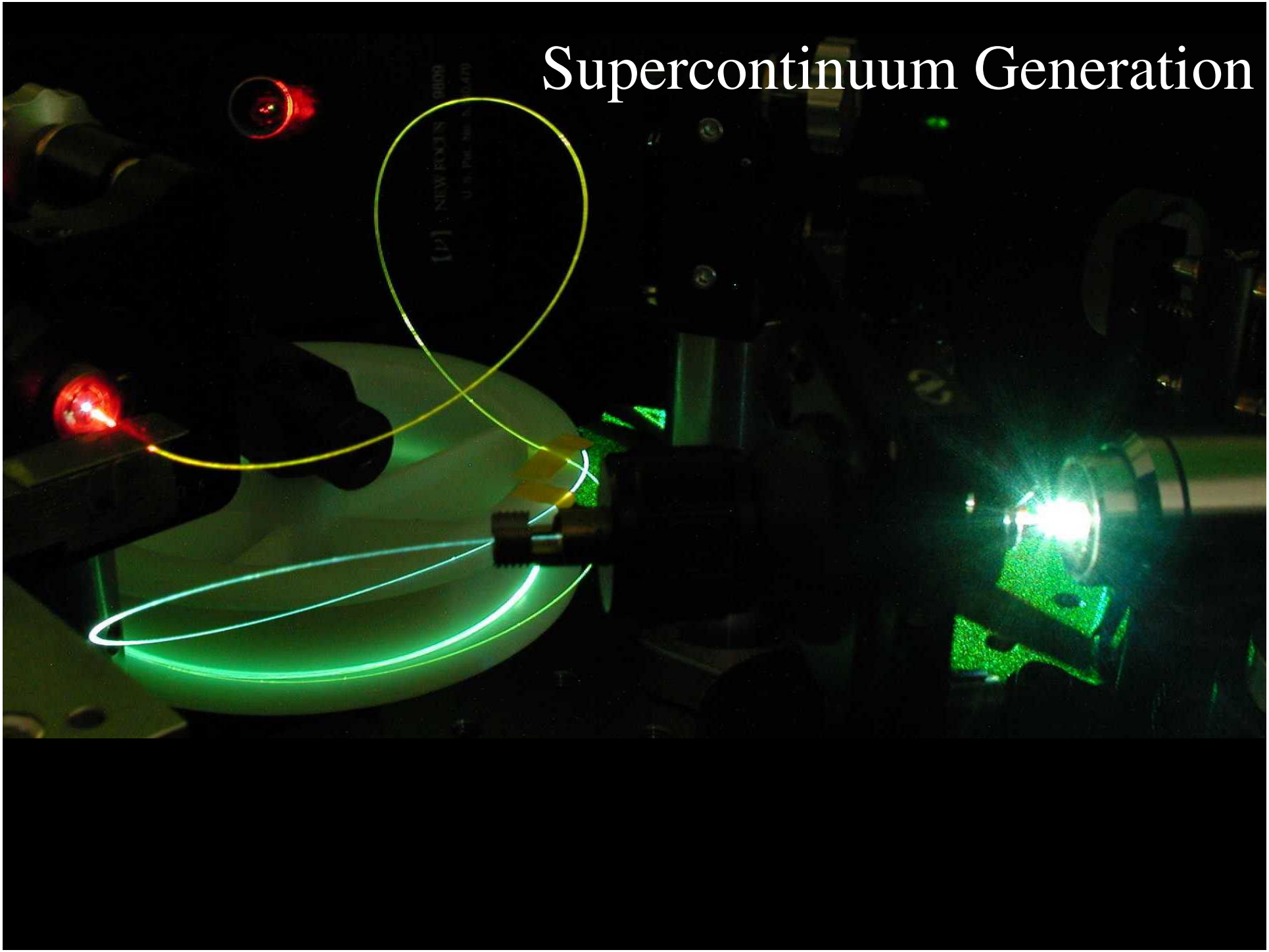
# Transfer between two optical frequencies ($I_2$ and $Yb^+$ clock laser)

Virtual frequency: 43 THz




**phase-locking:**
**optical synthesizer**

# Supercontinuum Generation

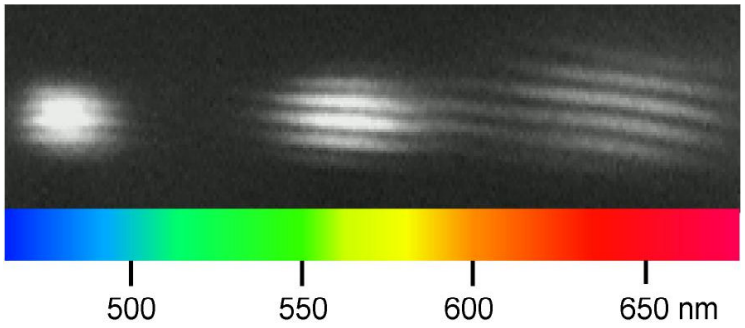


## Noise in microstructure fibers

**Is supercontinuum generation in MS fibers a deterministic process ?**

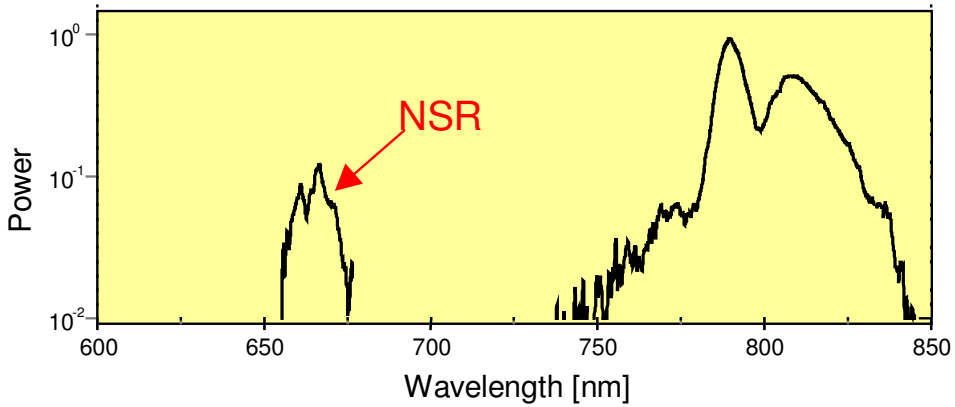
**Propagation time noise due to fluctuations of pump pulse parameters ?**

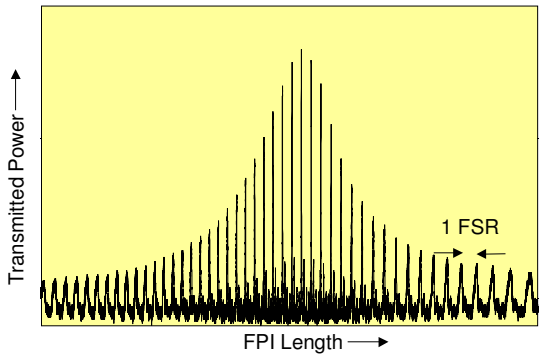
# Is supercontinuum generation a deterministic process ?



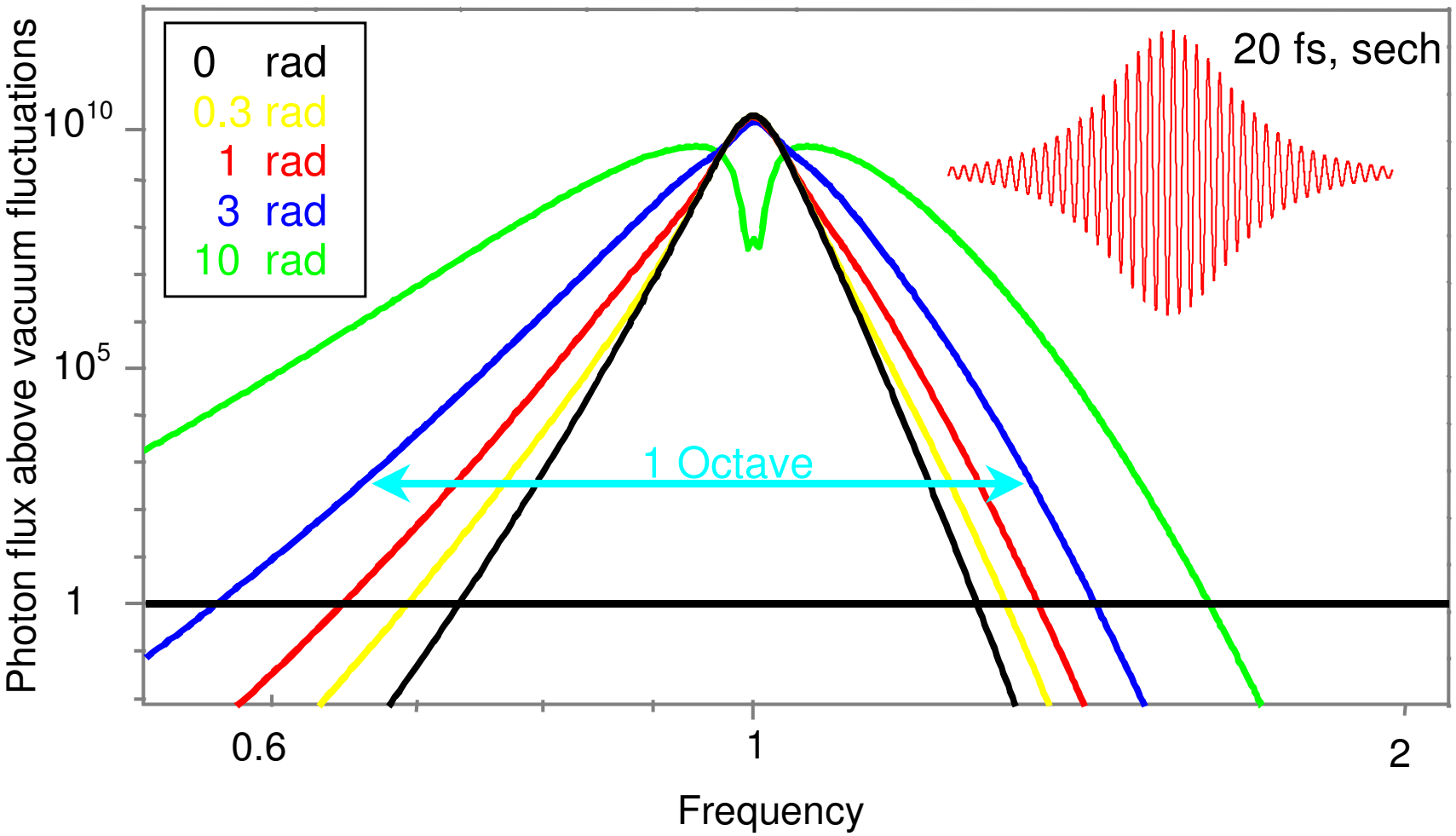

**Interference of subsequent pulses**

**Comb spectra even for discrete spectral components (NSR)**



# Self-phase-modulation as seeding process



# Noise of propagation time

$AM \rightarrow \Delta\tau_{Prop}$ - coefficient: 4000 rad / 100% [1)]

$\Delta P / P \approx 10^{-3}$ (1 s),

$\Delta P / P \approx 10^{-1}$ ($10^4$ s)

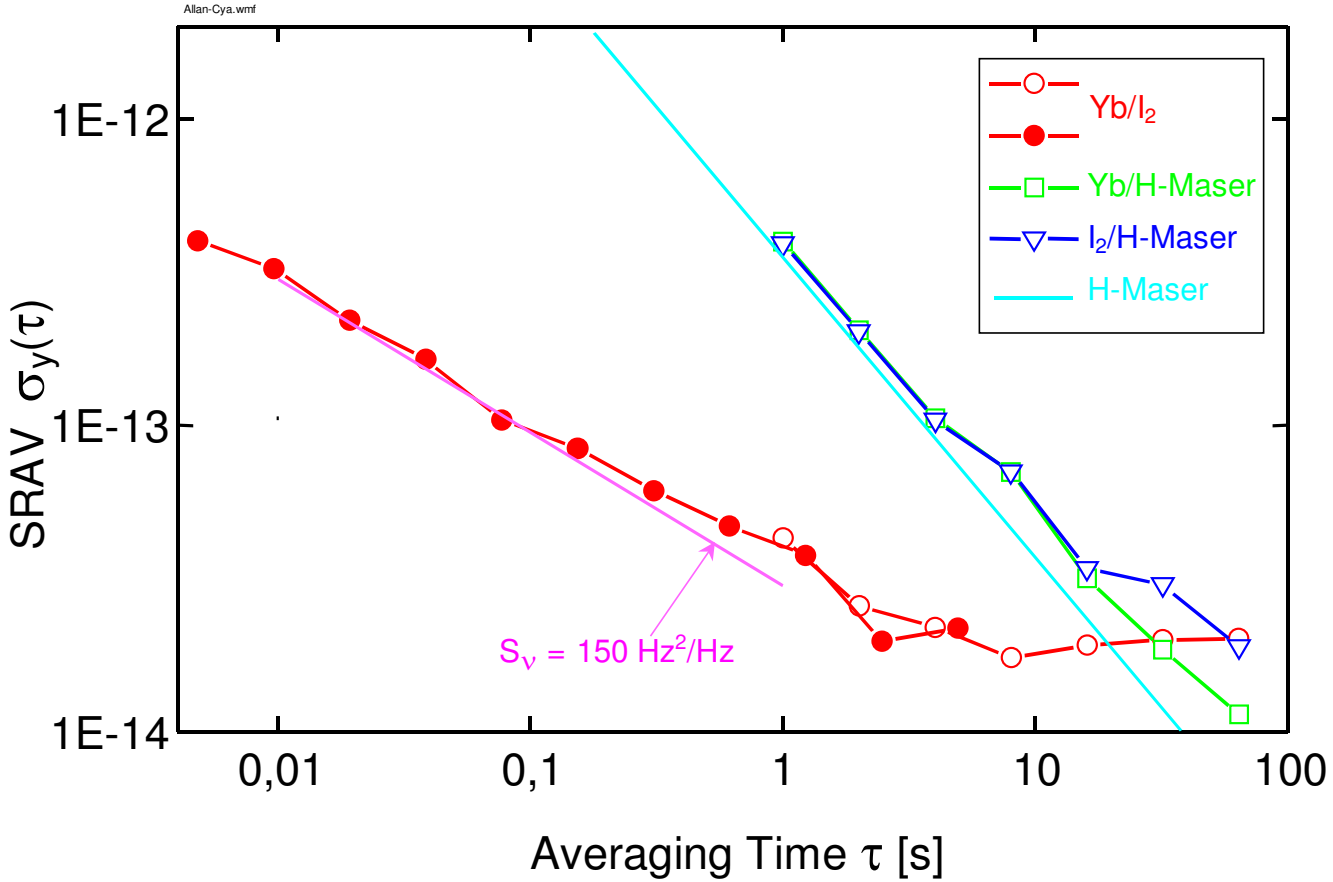
$\Rightarrow \sigma_y(1\ s) \approx 10^{-15}$

$\sigma_y(10^4\ s) \approx 10^{-17}$

BW 20 MHz (cavity dumper)
Shot-noise -150 dBc / Hz

T. M. Fortier et al, Optics Lett. 27, 445 (2002)

# Short-term instability




H. R. T. et al, Appl. Phys. B 74, 1 (2002)

## Summary / Outlook

- No cycle slipping - no principal frequency uncertainty
- Supercontinuum generation is deterministic for short pulses
- Instability < $10^{-15}$ (1s) realistic for arbitrary frequencies
- Experiments on a $10^{-17}$ level feasible, e. g. alpha dot

## Acknowledgement

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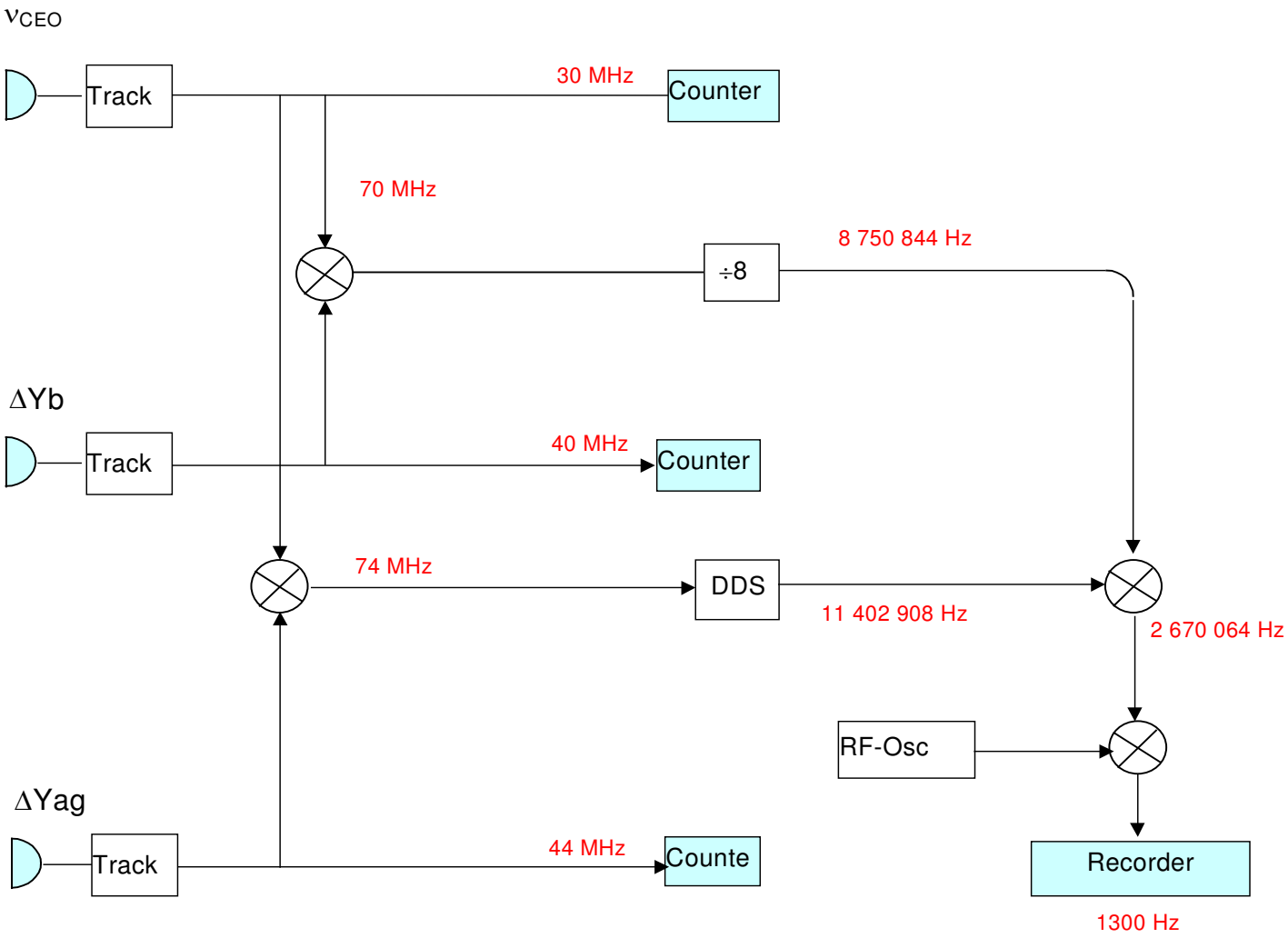
DFG
SFB 407


νCEO
Track
30 MHz
Counter
70 MHz
÷8
8 750 844 Hz
ΔYb
Track
40 MHz
Counter
74 MHz
DDS
11 402 908 Hz
2 670 064 Hz
RF-Osc
ΔYag
Track
44 MHz
Counte
Recorder
1300 Hz

# H - maser linewidth vs. frequency multiplication factor