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Lasers, Optics and Photonics 2014 – Philadelphia, USA, Sept. 9, 2014

# Linear optical methods as ultrashort pulse diagnostics


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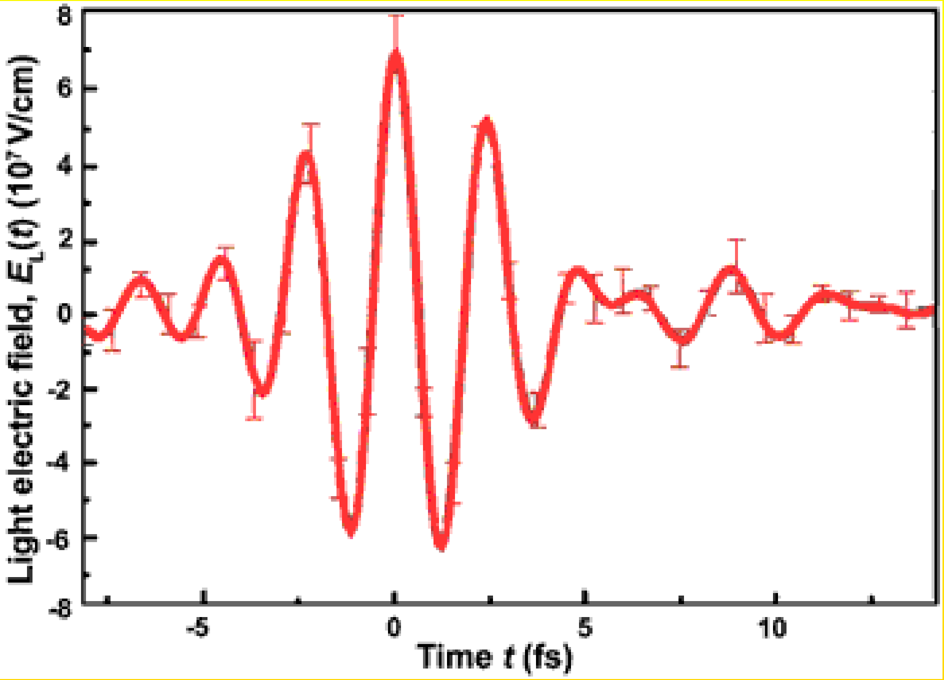
***CE Optics Research and Development Ltd.,*** *Hungary*

# Ultrashort laser pulses

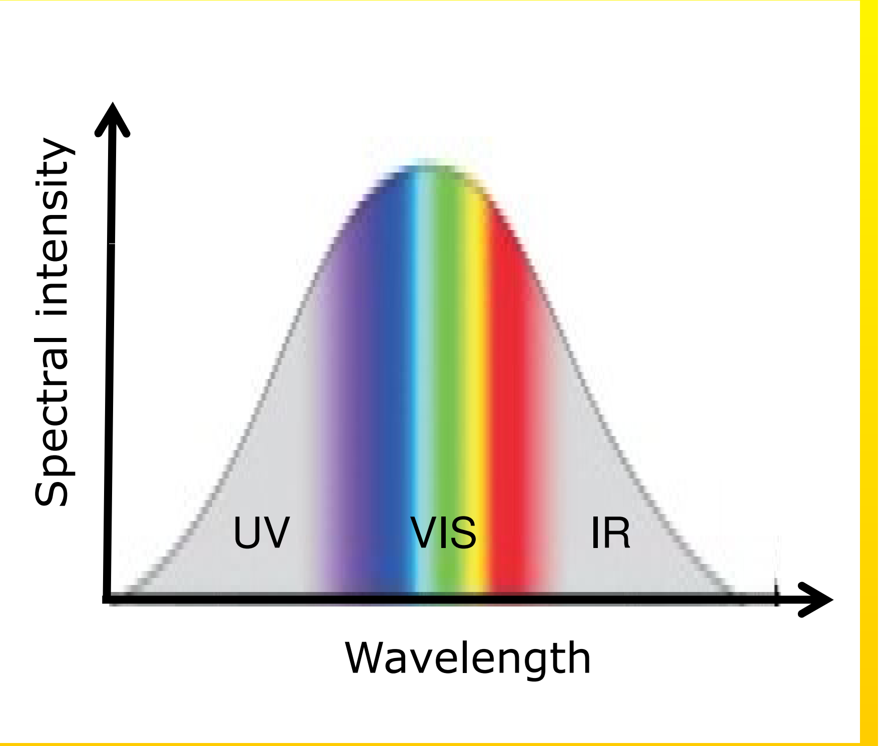
## Only a few optical cycles under the pulse envelope




$$E(t,z)=\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty}\tilde{E}(\omega)\exp\left[i\omega(t-n(\omega)\cdot z/c)\right]d\omega.$$

**Where the spectral phase is**

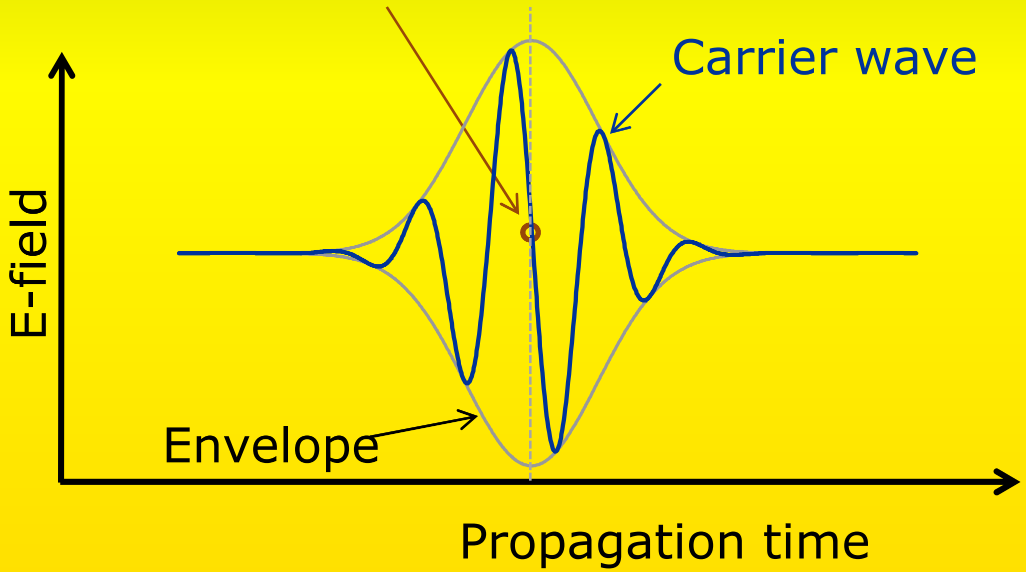
$$\varphi(\omega,z)=\omega\cdot n(\omega)\cdot z/c$$




**Fourier analysis suggests that short pulses have broadband spectra**

# Phase relations of ultrashort pulses

**Carrier-envelope phase:** relation between the carrier wave and the pulse envelope.



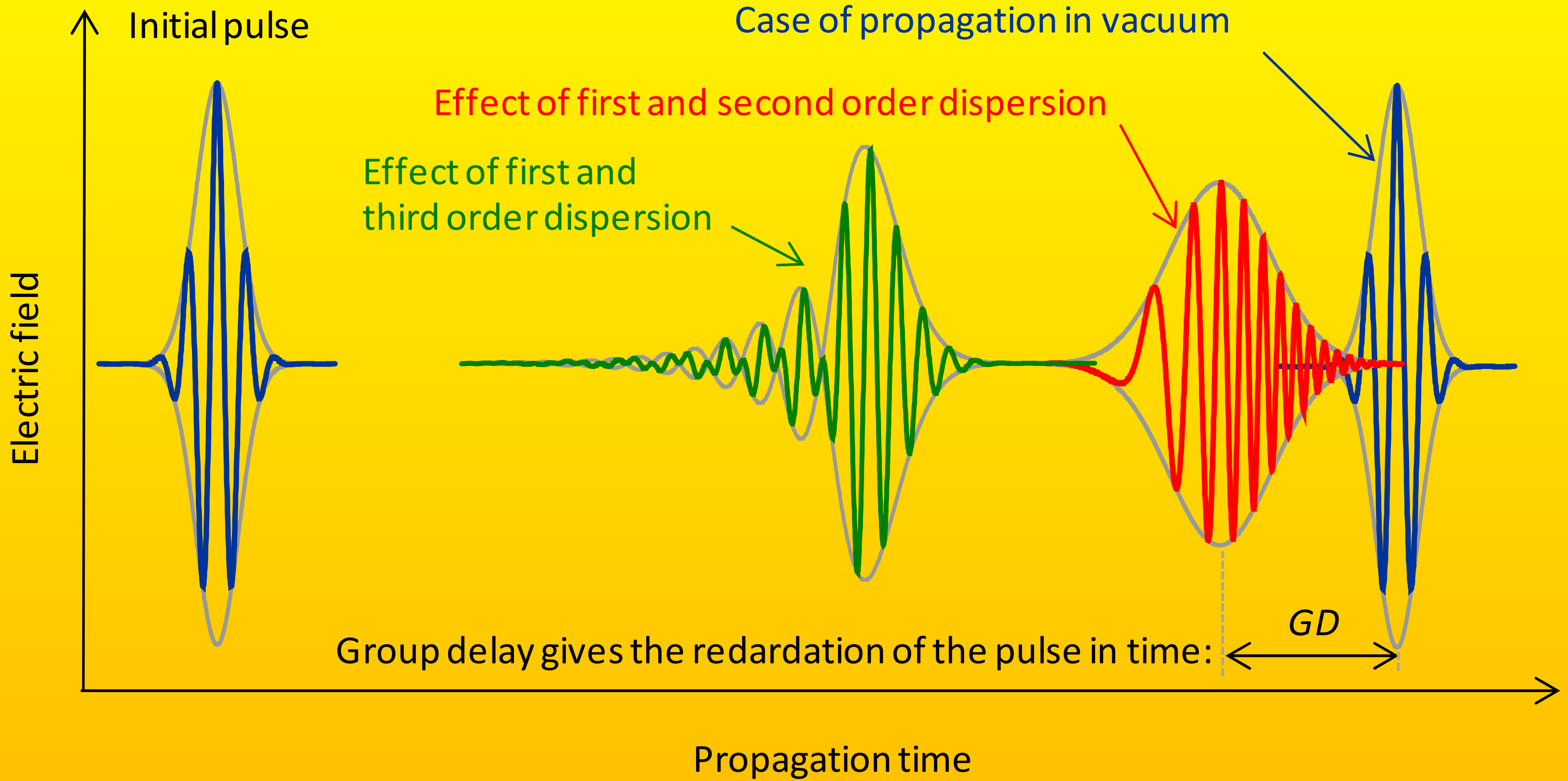

**Use of CEP stabilized pulses**

- Attosecond physics and high-harmonic generation
- High precision optical frequency and time measurements (by stable ”frequency-comb”)
- High precision refractive index measurements
- Calibration of astronomical mirrors

# Time-domain pulse distortions

**Dispersion of the spectral phase** related strongly to the pulse shape:

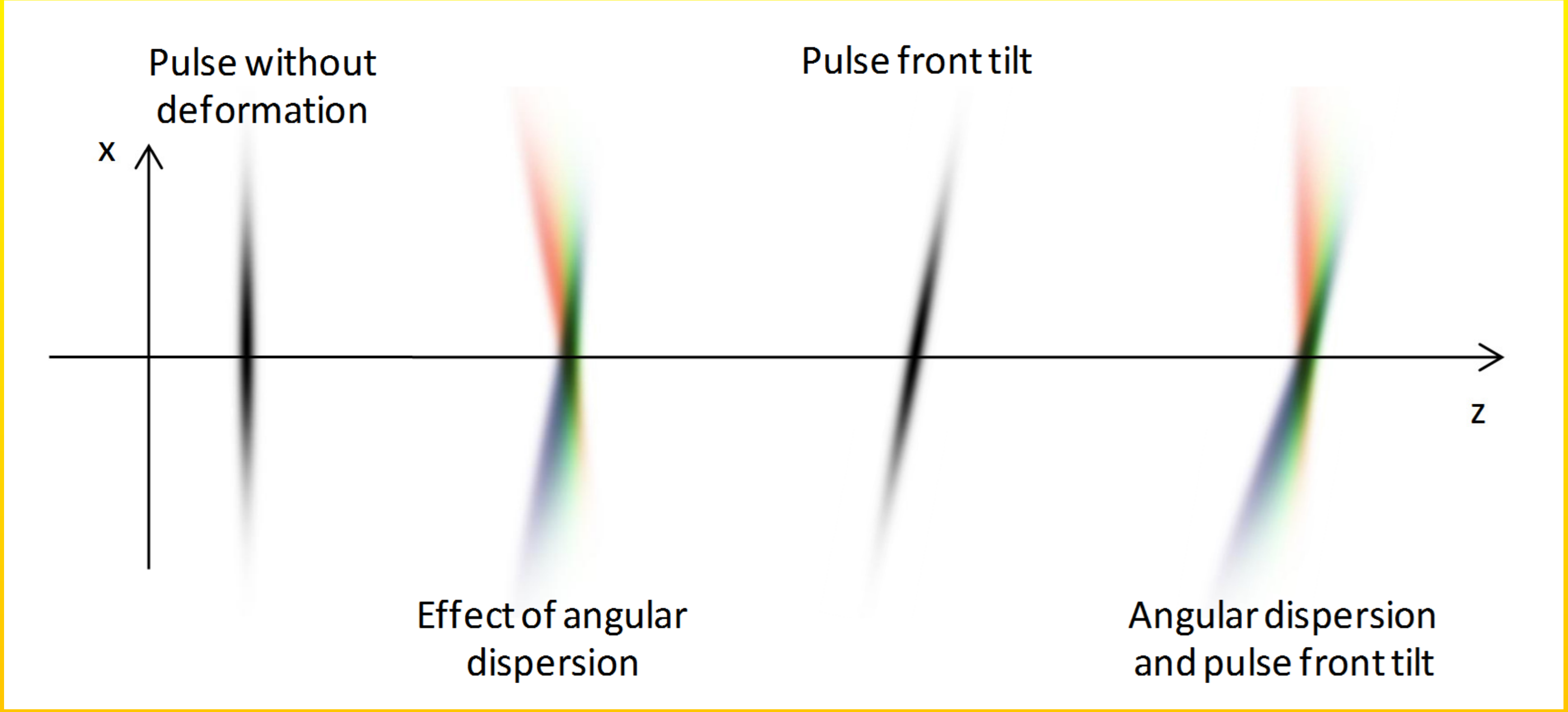
$$\varphi(\omega,z)=\varphi(\omega_0,z)+\left.\frac{d\varphi(\omega,z)}{d\omega}\right|_{\omega_0}\cdot(\omega-\omega_0)+\frac{1}{2}\left.\frac{d^2\varphi(\omega,z)}{d\omega^2}\right|_{\omega_0}\cdot(\omega-\omega_0)^2+\frac{1}{6}\left.\frac{d^3\varphi(\omega,z)}{d\omega^3}\right|_{\omega_0}\cdot(\omega-\omega_0)^3+\ldots$$



# Space-domain pulse distortions

**Spectral components of the pulse** propagate to different directions

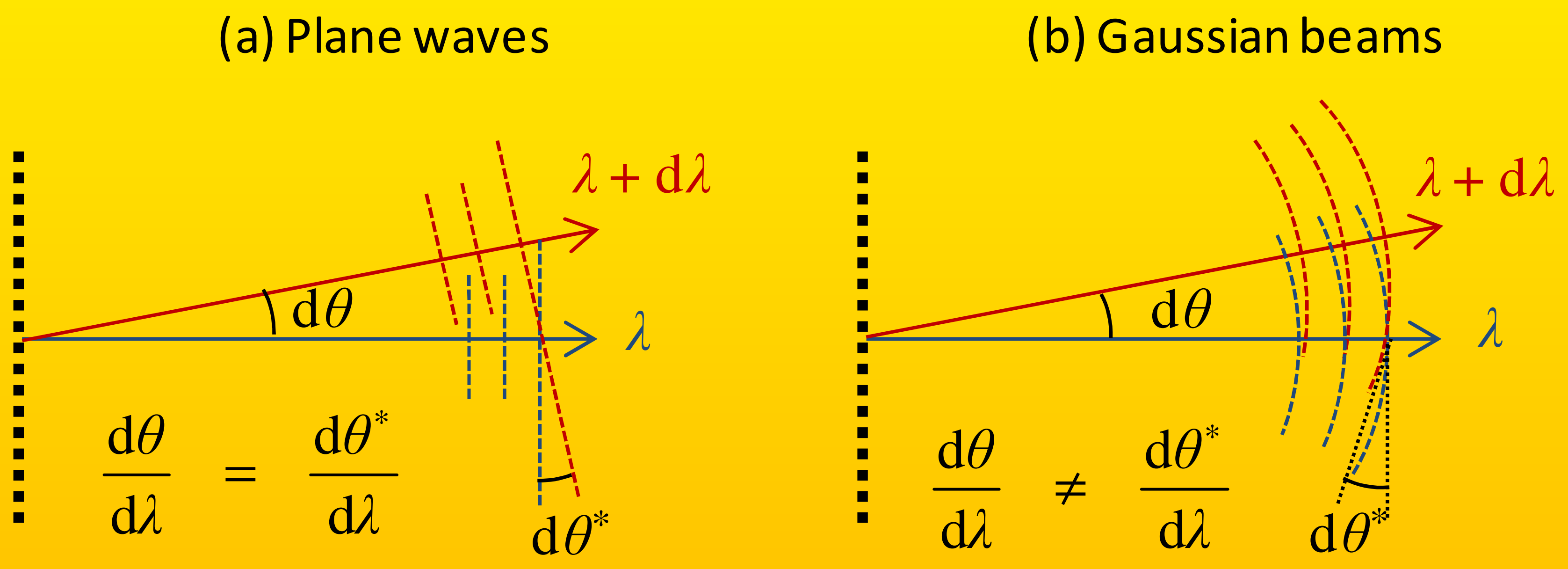
- Various spatiotemporal pulse deformations
- Also possible to tailor the pulse length in a controlled way: stretcher-compressor systems of chirped pulse amplifiers



# Space-domain pulse distortions

**Two different definitions of angular dispersion**

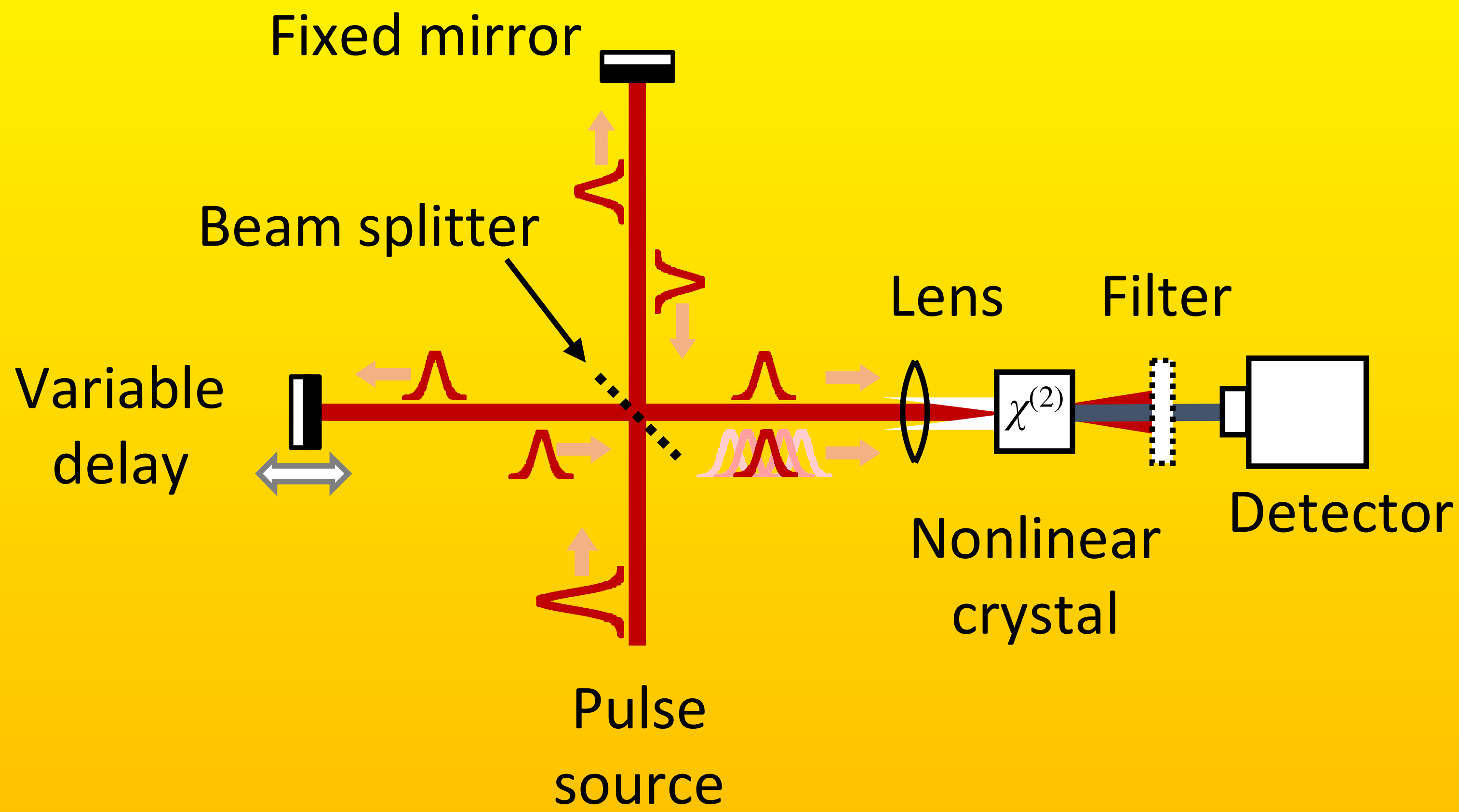
- Propagation direction of spectral components
- Spectral phase fronts of spectral components
- Same for plane waves
- Different for Gaussian beams, phase front angular dispersion slowly diminishes during propagation



# Self-referenced pulse measurements

**Based on frequency conversion of the autocorrelation signal**

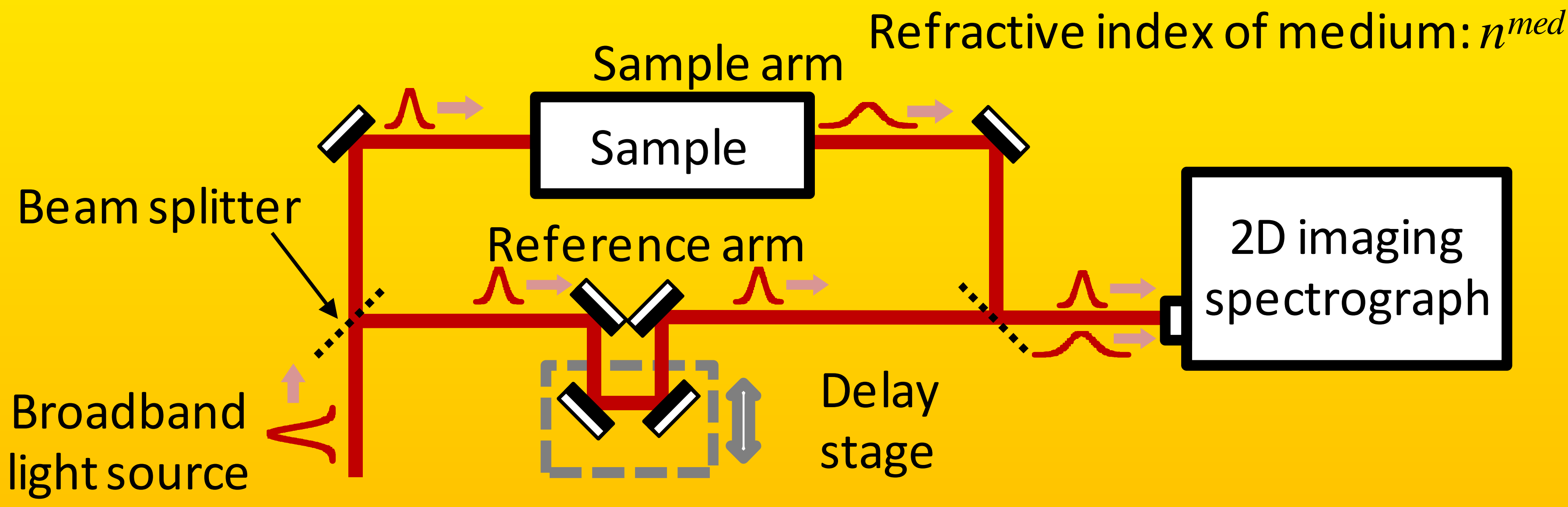
- Typical methods: FROG, SPIDER, WIZZLER, etc.
- Requires nonlinear process
- Usually difficult and iterative algorithms



# Linear optical methods

**Spectrally (and spatially) resolved interferometry**

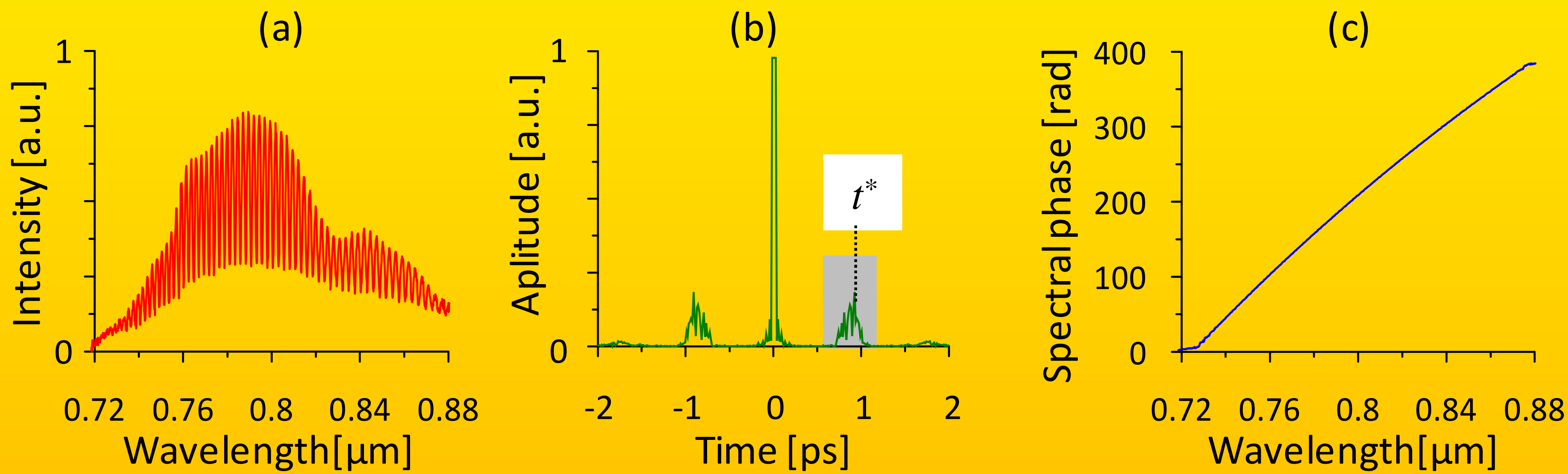
- Based on the combination of a two-beam interferometer and an imaging spectrograph
- No need for nonlinear processes
- Easy and straightforward algorithm
- High precision easily achievable
- In some cases, it is restricted to measure relative values only



# Fourier-transformation algorithm

**Evaluation is based on Fourier-domain filtering**

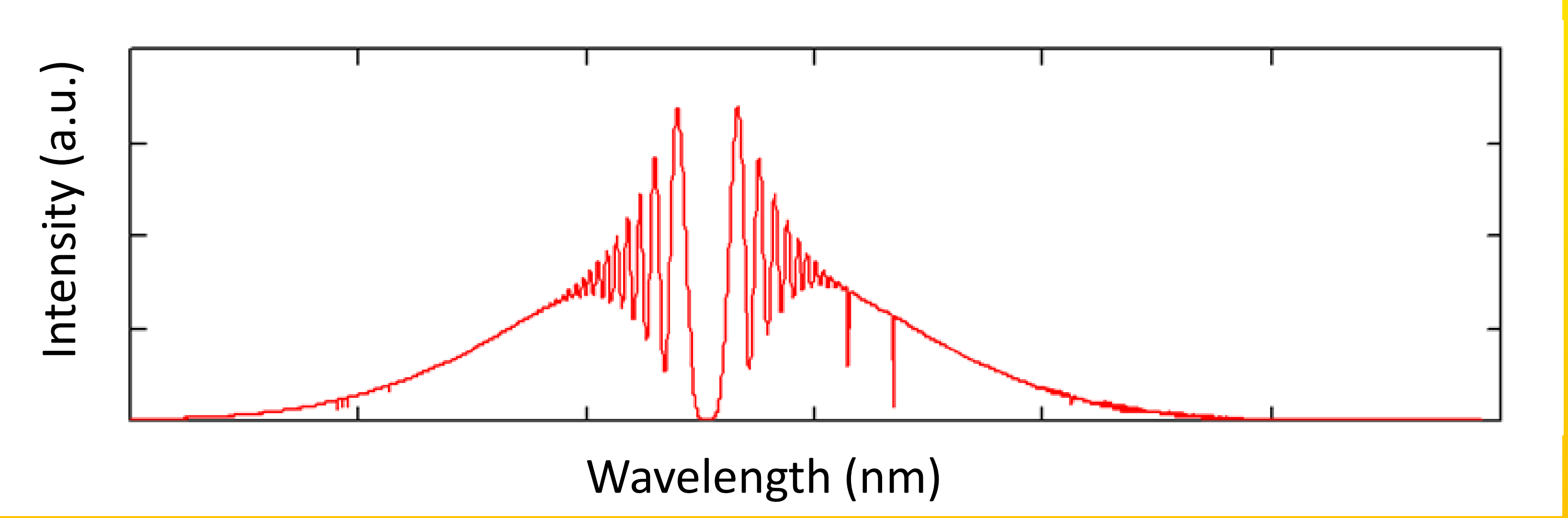
- Record the spectrally resolved interferogram
- Keep only the relevant part in the Fourier domain
- Apply inverse Fourier-transformation
- Complex angle of the received spectrum gives the phase
- Phase derivatives calculated from polynomial fitting



# Stationary Phase Point Method

**Effective when the sample pulse is much longer than the reference**

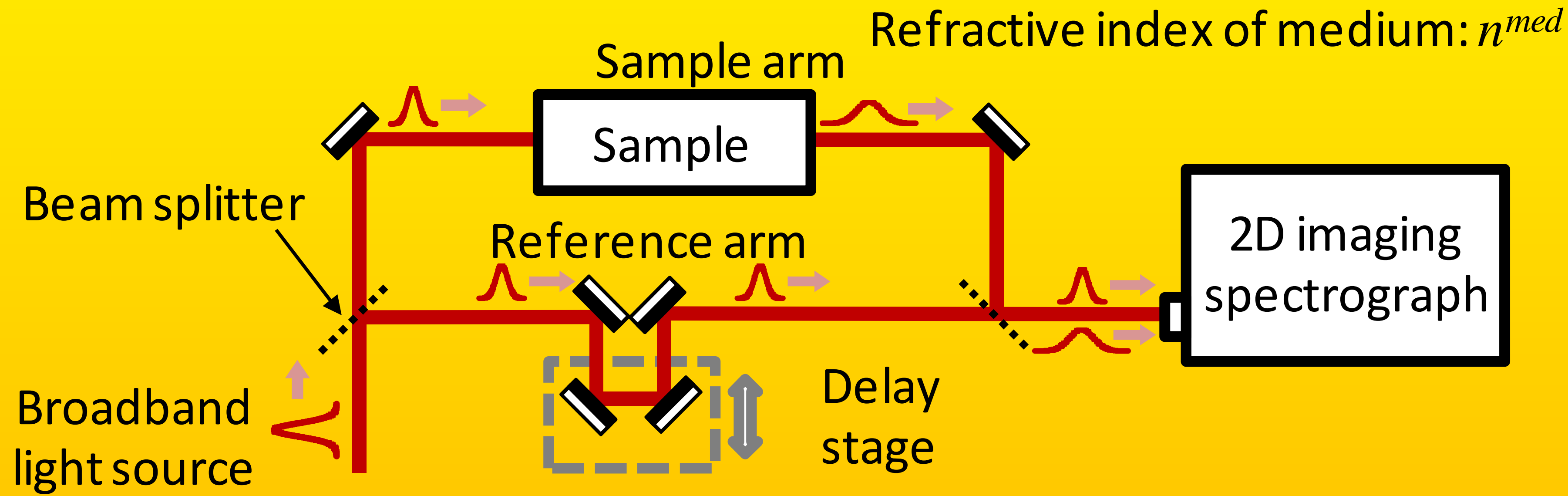
- Can be used to characterize stretchers/compressors
- Short pulse is only coherent in a small spectral region
- Stationary phase point is where the modulation minimal
- SPP can be scanned through the spectrum by changing the delay of the reference pulse
- Delayed between the edges of the spectrum tells the length of the stretched pulse



# Spectrally and spatially resolved interferometry

**A bit more general description of the SRI**

- Based on the combination of a two-beam interferometer and an <u>two-dimensional</u> imaging spectrograph
- A small angle between the incoming beams at the spectrograph's slit helps the algorithm and visualizes the spectral phase



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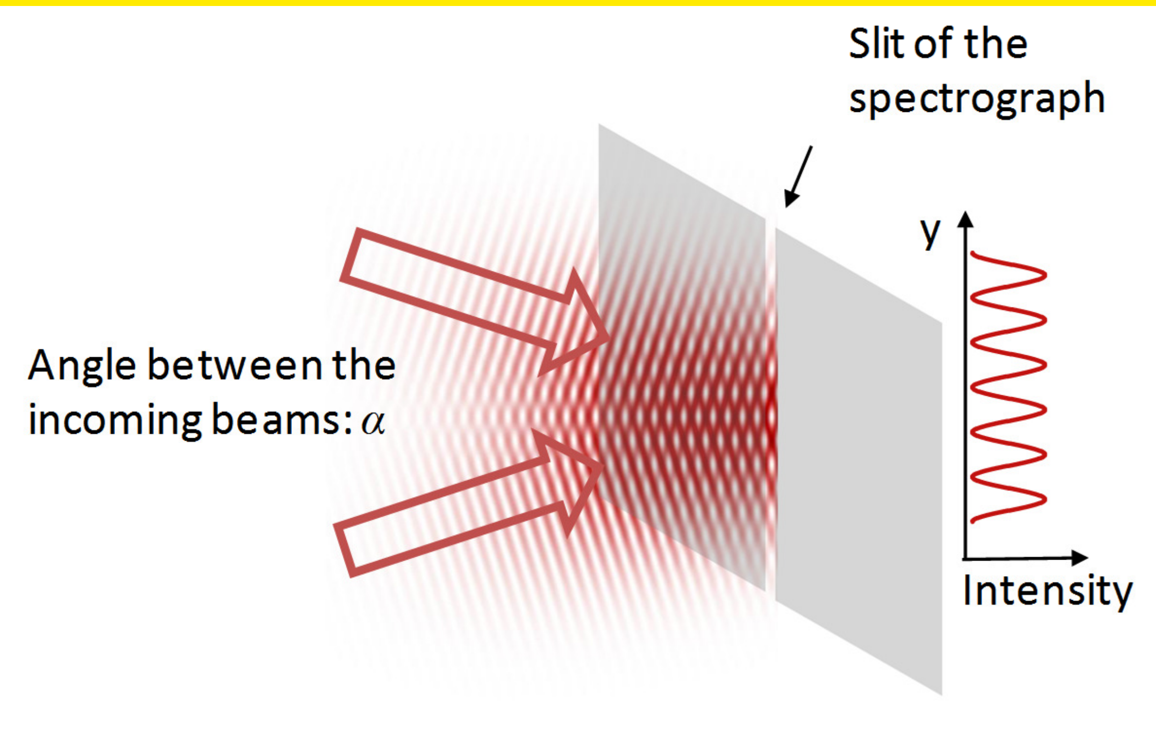
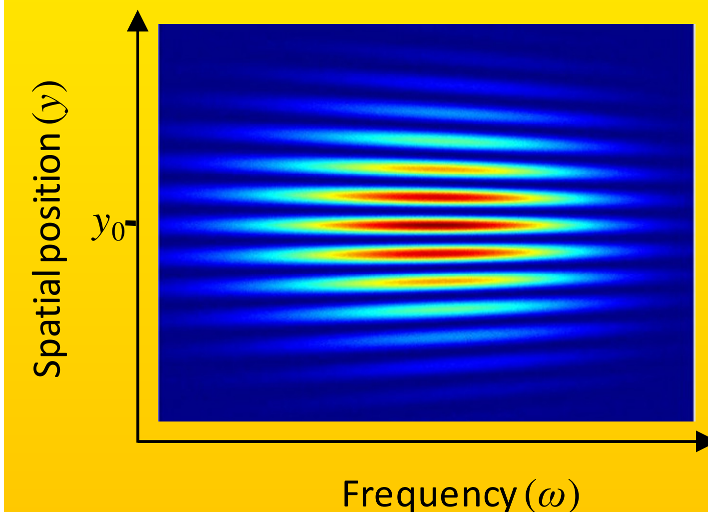


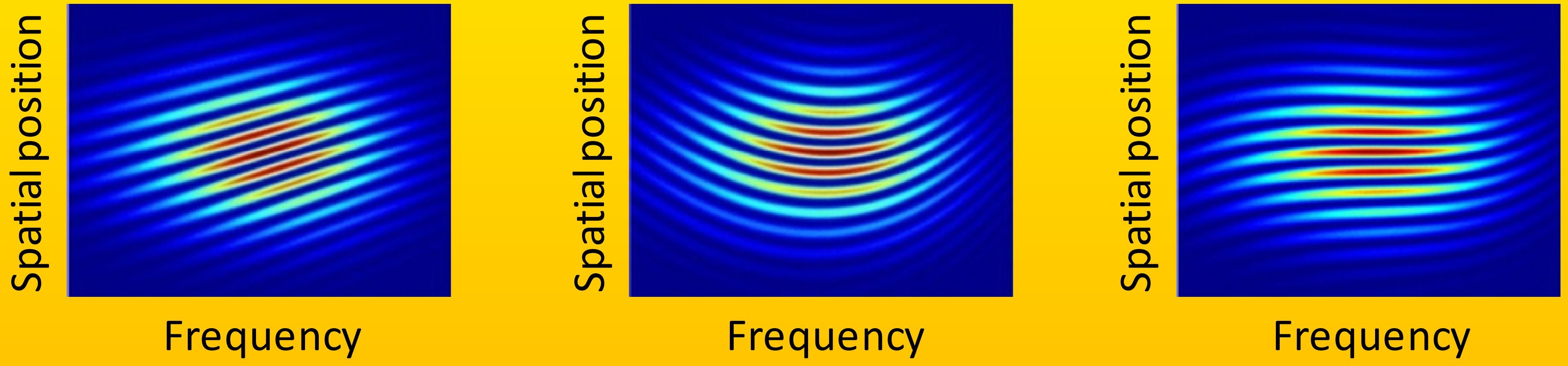
# 2D Fourier-transformation algorithm

**The 2D implementation of the Fourier-domain filtering works well**

The shape of the spectral phase translates directly to the shape of the fringes

(a) First order dispersion only (**group delay**)
(b) Second order dispersion only (**group delay dispersion**)
(c) Third order dispersion only (**third order dispersion**)

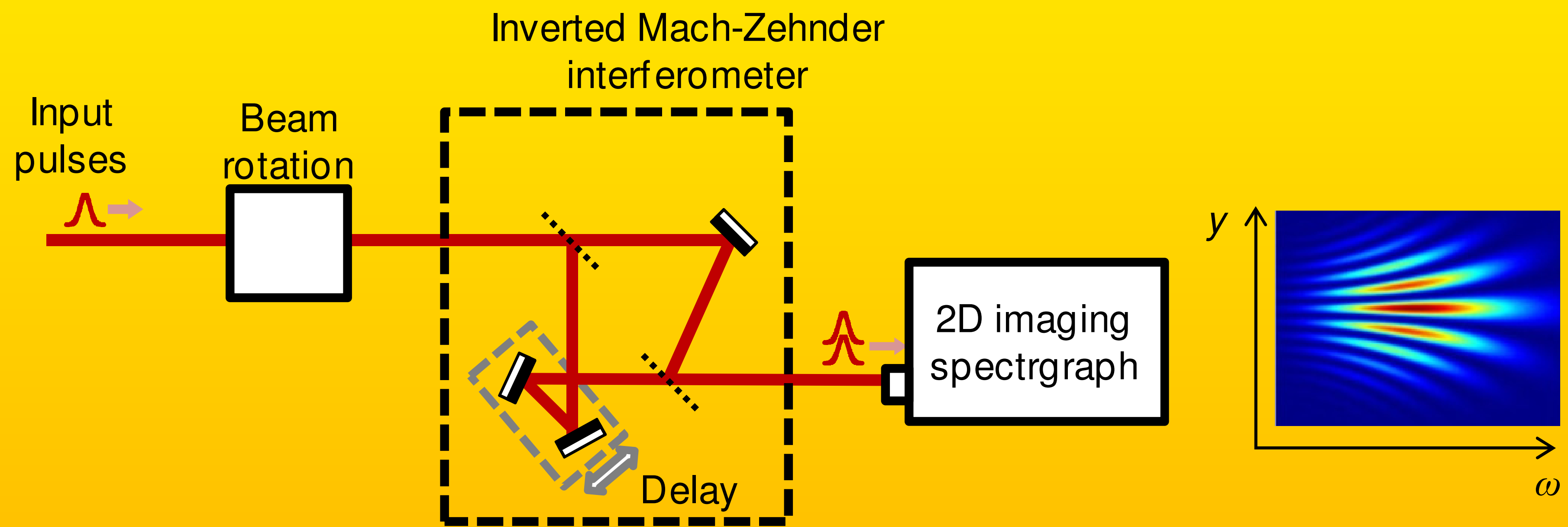
(a) (b) (c)



# Angular dispersion measurement

**Slight modification of the general SSRI setup**

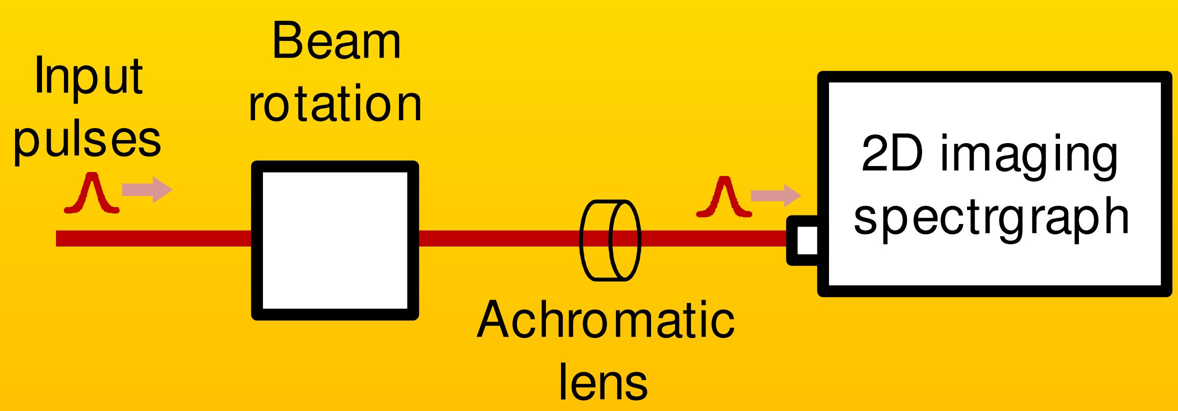
- The interfering beams are mirrored (e.g. one more reflection)
- Spectral density of the fringes correspond to the angle between the interfering beams
- If the beam has angular dispersion, the mirroring effect doubles the spectral dependence of the phase front direction
- The absolute phase front angular dispersion can be measured

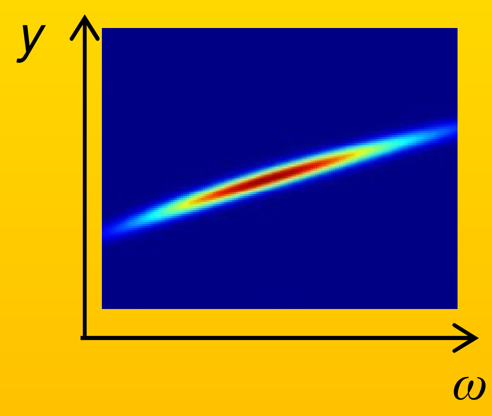


# Alternative angular dispersion measurement

**Requires a 2D spectrograph, a beam rotation stage and a focusing element only**

- Focus the beam onto the slit of the spectrograph
- The angle of the spectral components translated to position
- Spectral components with different position means angular dispersion
- Spectrograph resolves the beam spectrally
- The tilt of the spectrogram tells the angular dispersion
- Polarization (beam orientation) rotation needed for full characterization

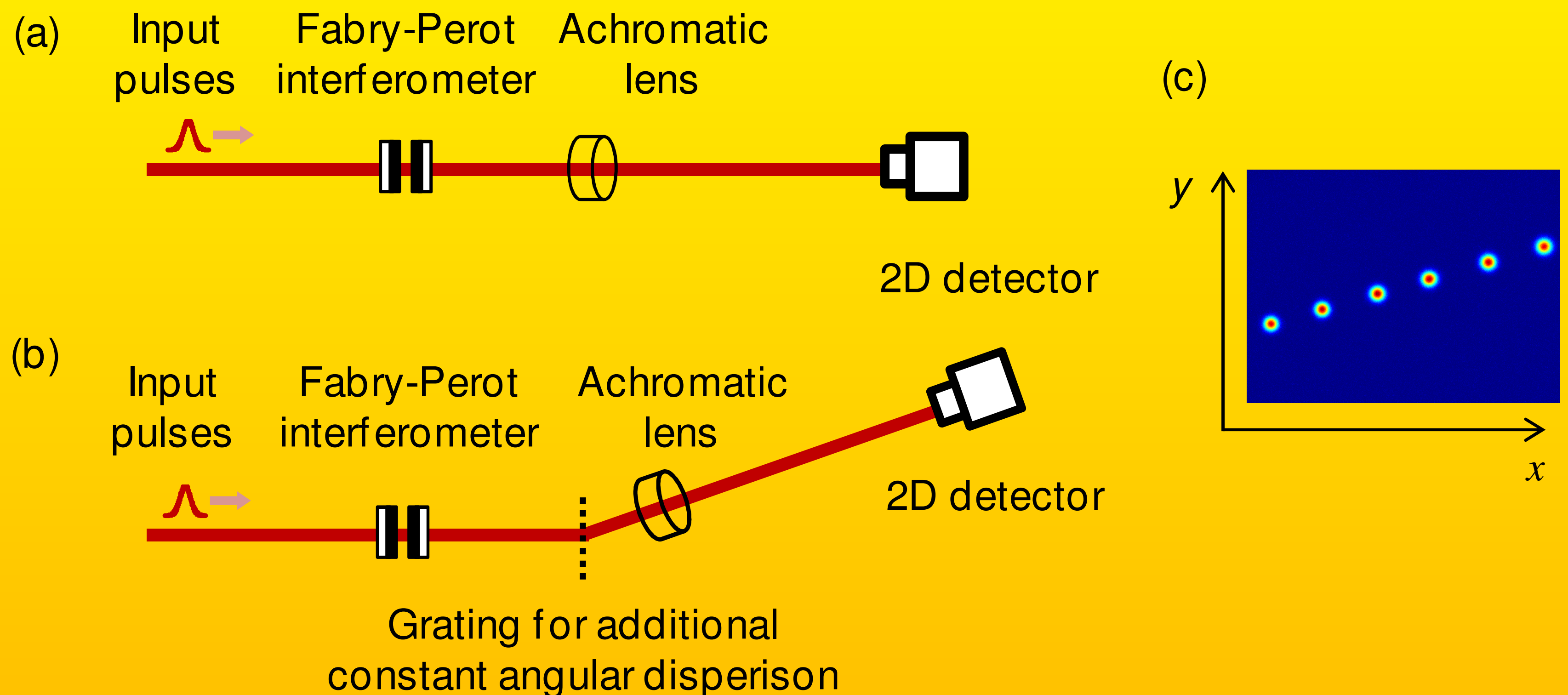


# Alternative 2D angular dispersion measurement

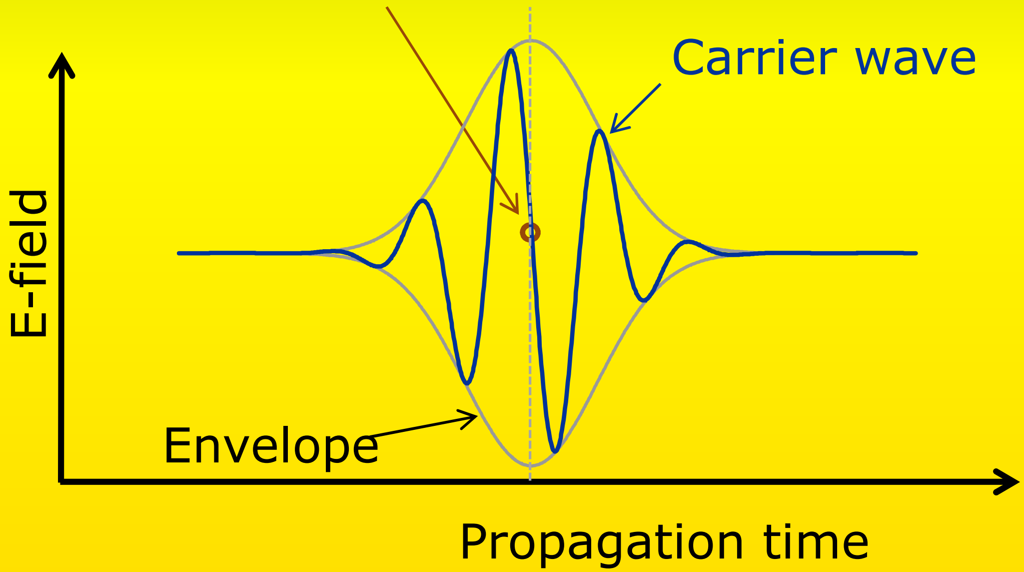
**Neither spectrograph, nor beam rotation needed**

- Calibrated spectral filtering (e.g. Fabry-Perot etalon) creates well defined, separated spectral peaks
- Focusing element translates angle into position
- Spot distances gives the angular dispersion in 2D



# Phase relations of ultrashort pulses

**Carrier-envelope phase:** relation between the carrier wave and the pulse envelope.




**Use of CEP stabilized pulses**

- Attosecond physics and high-harmonic generation
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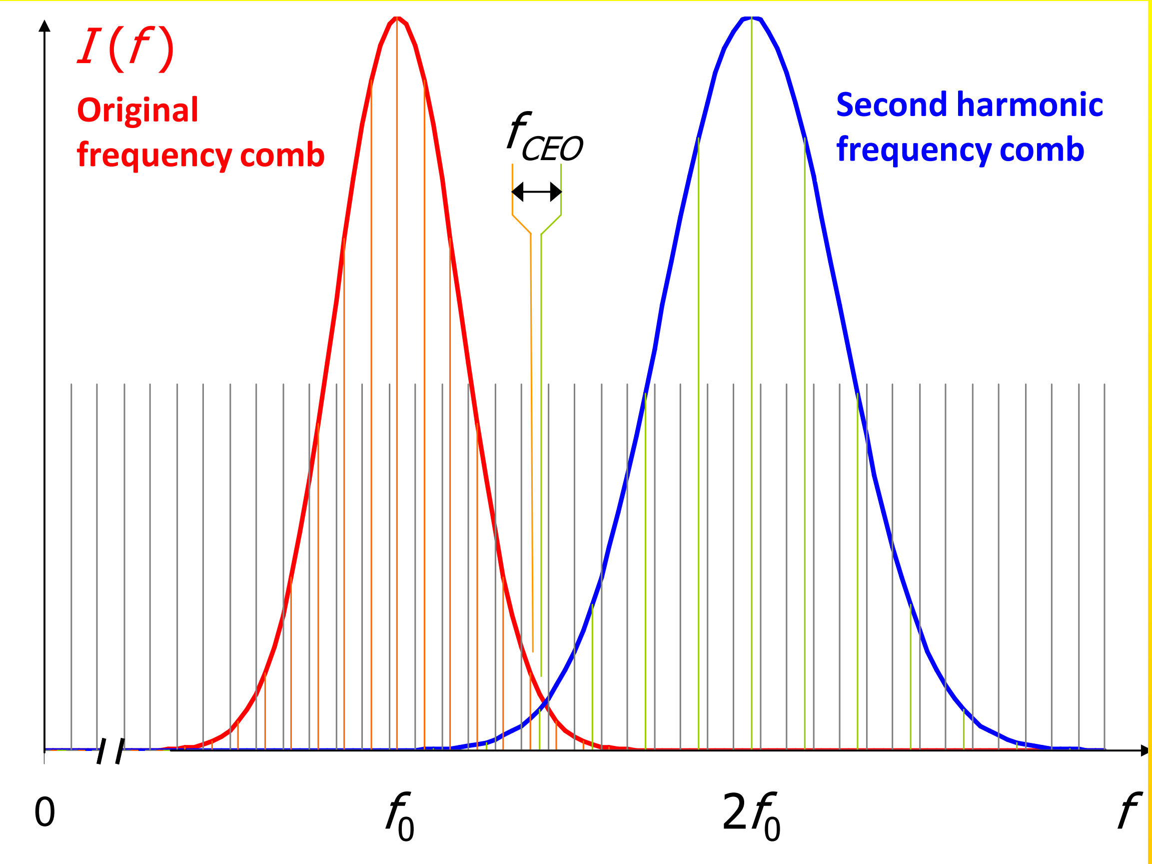
# Methods to measure CEP drift

## The f-to-2f scheme – the nonlinear way




$$f_1 = f_{CEO} + n \cdot f_{rep}$$

$$f_2 = 2 \cdot (f_{CEO} + m \cdot f_{rep})$$

$$f_{beat} = f_2 - f_1 = f_{CEO}$$

$$\varphi_{CEO} = 2\pi \cdot f_{CEO} / f_{rep}$$

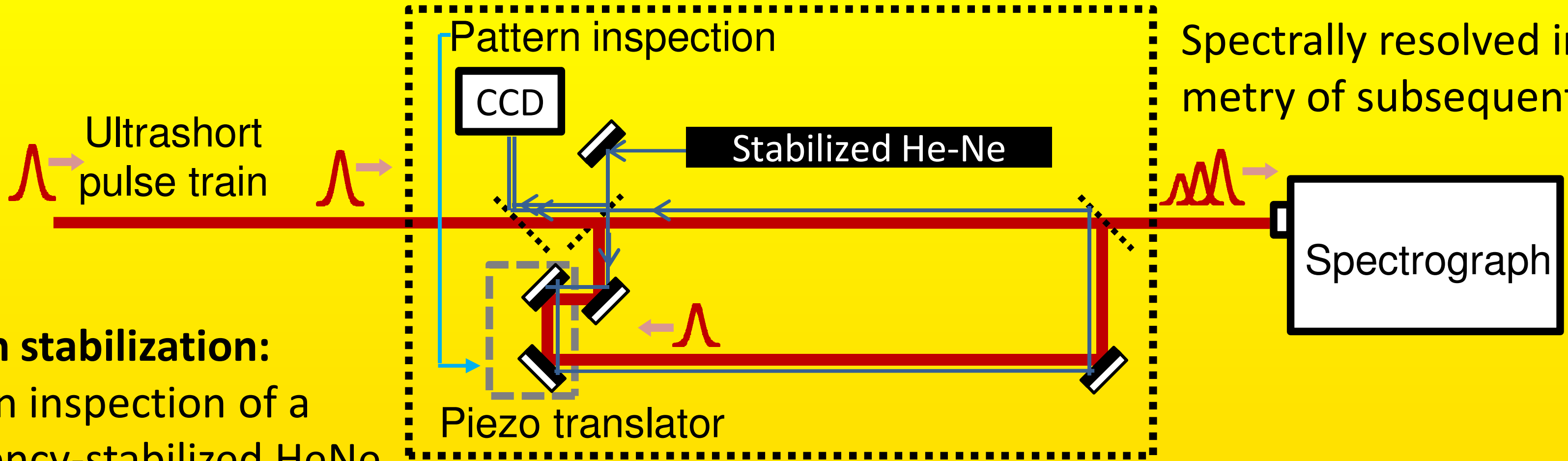
**Requirements:**

- Octave-broad bandwidth
- $2^{nd}$ harmonic generation

H.R. Telle et al., Appl.Phys. B. **69**, 327 (1999).

# Methods to measure CEP drift

## Multiple-beam interferometer – the linear way



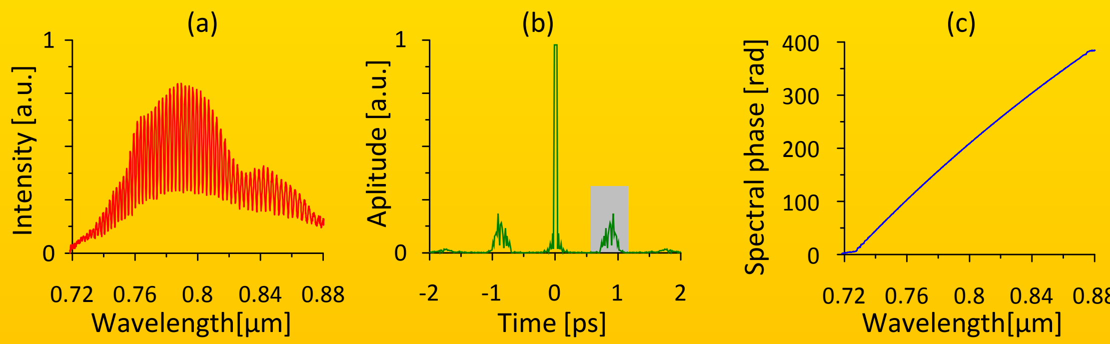

**Detection:**
Spectrally resolved interferometry of subsequent pulses

**Length stabilization:**
Pattern inspection of a frequency-stabilized HeNe

K. Osvay et al., Opt.Lett. **32**, 3095 (2007).

**Evaluation steps:**

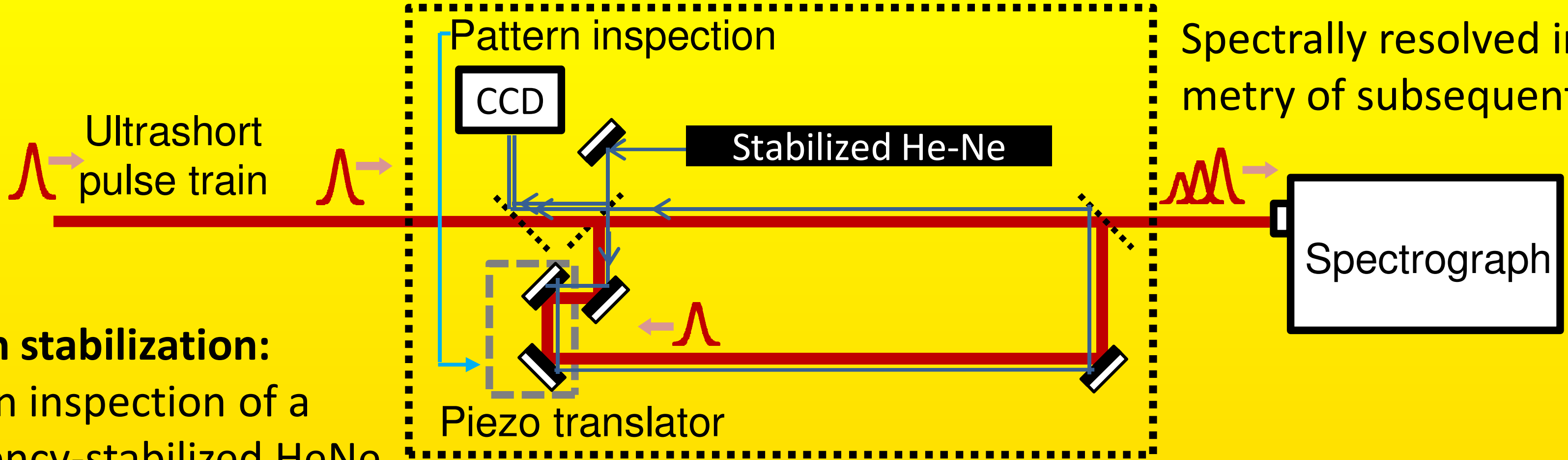
(1) Record interference pattern
(2) FFT and filter the spectrum
(3) Inverse FFT
(4) Complex angle gives the spectral phase difference
(5) Fitting Taylor-series
(6) Calculate CEP = $\phi_0 - GD \cdot \omega_0$




L. Lepetit et al., JOSA B **12**, 2467 (1995).

# Methods to measure CEP drift

## Multiple-beam interferometer – the linear way



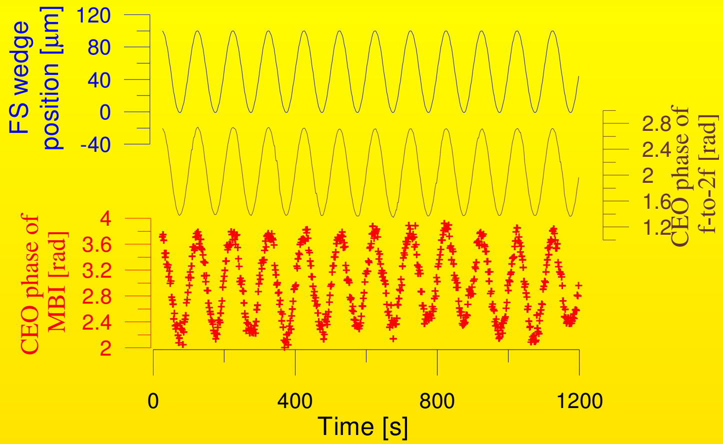

**Detection:**
Spectrally resolved interferometry of subsequent pulses

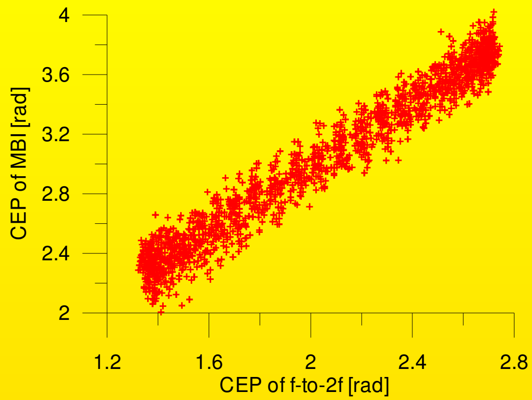
**Length stabilization:**
Pattern inspection of a frequency-stabilized HeNe

- **Linear**
- **Scalable**
- **Bandwidth independent**
- **UV and far infrared lasers**
- **Applicable to a wide range of lasers:**
- **(sub-)picosecond lasers**

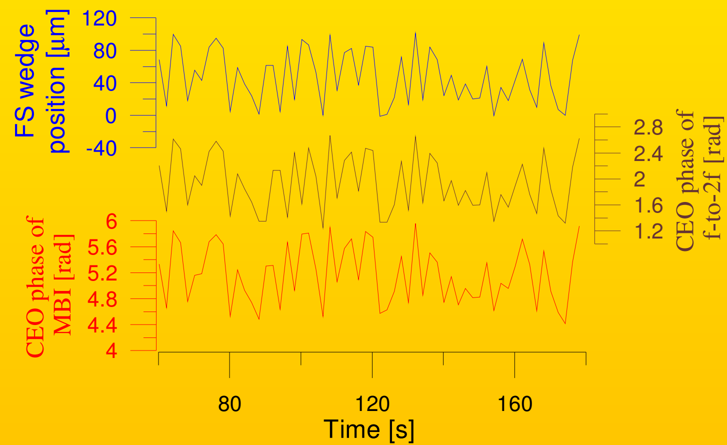
# Cross-calibration with f-to-2f method

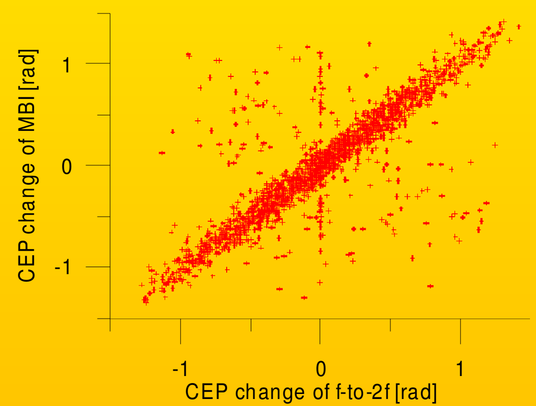
## Sinusoidal intracavity modification of CEP drift




## Random intracavity modification of CEP drift

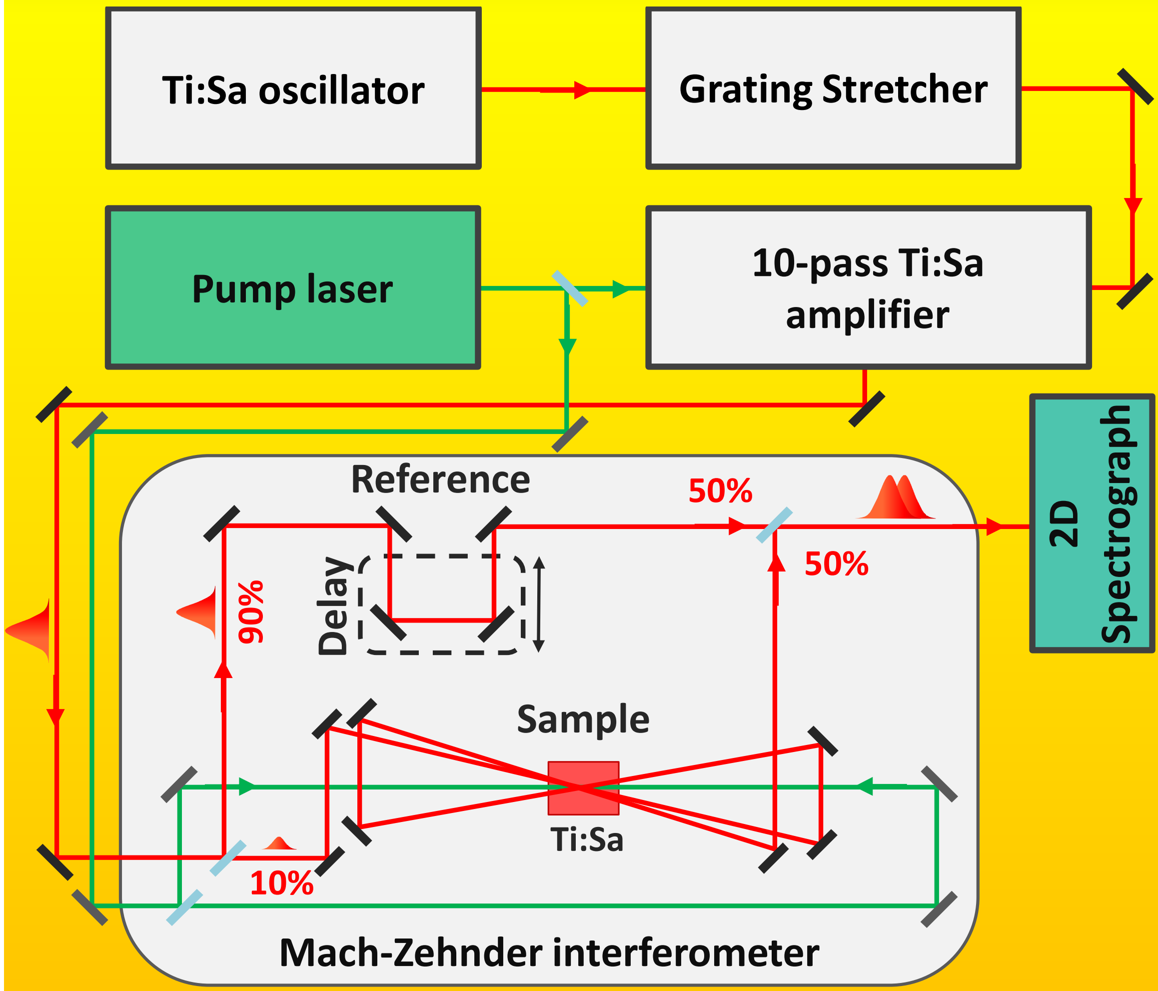



P. Jojart et al., Opt.Lett. **37**, 836 (2012).

# CEP drift noise in a Ti:S amplifier

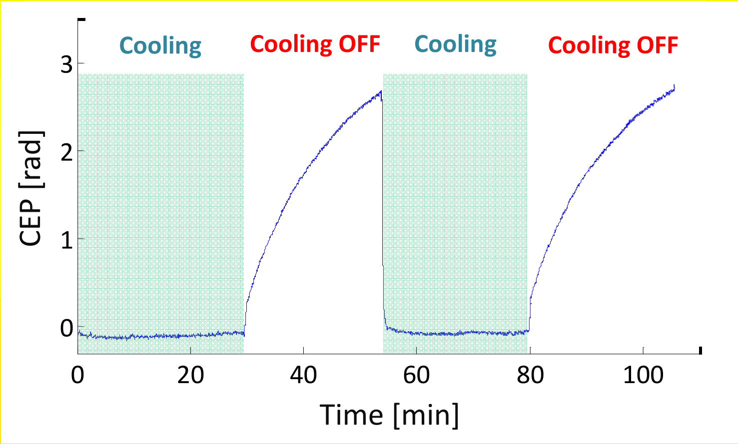
## Spectrally resolved interferometry – relative CEP change



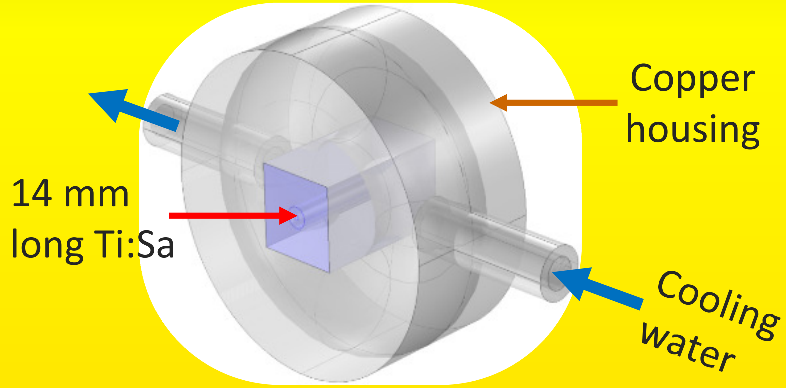

- General setup of the measurement (Mach-Zehnder interferometer)
- Method: Spectrally Resolved Interferometry (SRI)
- Main source of CEP change: Ti:S amplifier crystal
- Measuring the change in CEP between non- and amplified pulses

# CEO noise and drift measurement

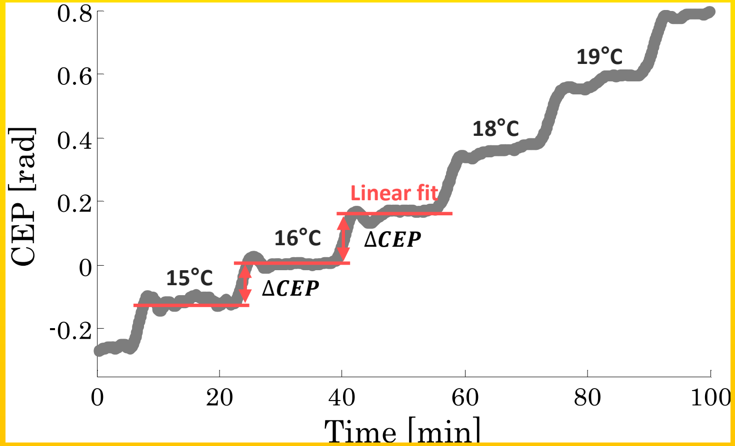
- **Effect of crystal cooling on CEP stability:**




Crystal cooling mount

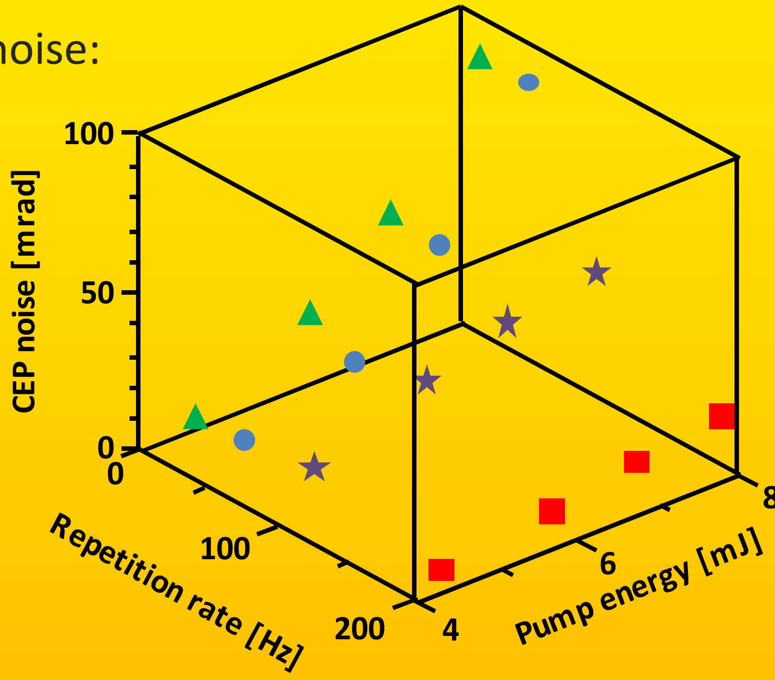



- **Coolant temperature:**




*Temperature values are related to the cooling water*

CEP noise:



# Further developments

• **Spectrally resolved interferometry is an efficient linear optical method of ultrashort pulse measurement**

• **Most effective if used together with self-referenced characterization techniques**

**Thank you for your attention!**

**Acknowledgements:**
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