Lecture Series Buenos Aires

18-3-2024 until 22-3-2024

Lecture F3 – Pulse characterization

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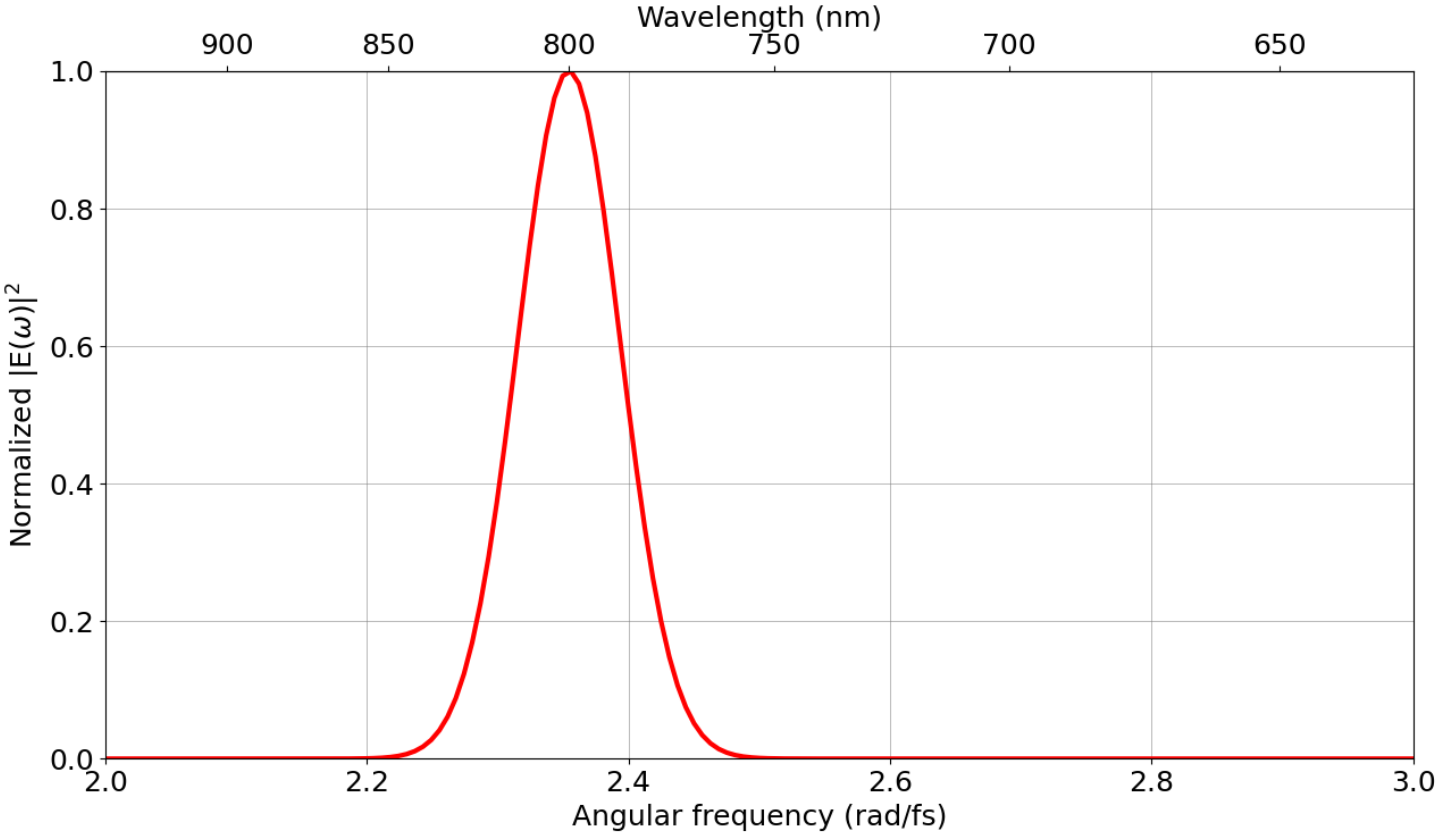
Pulse Characterization

Bandwidth and pulse duration

Does the spectrum determines the pulse shape and duration???

$$|\tilde{E}^{+}(\omega)|^2 = S(\omega) \quad \text{pulse spectrum}$$

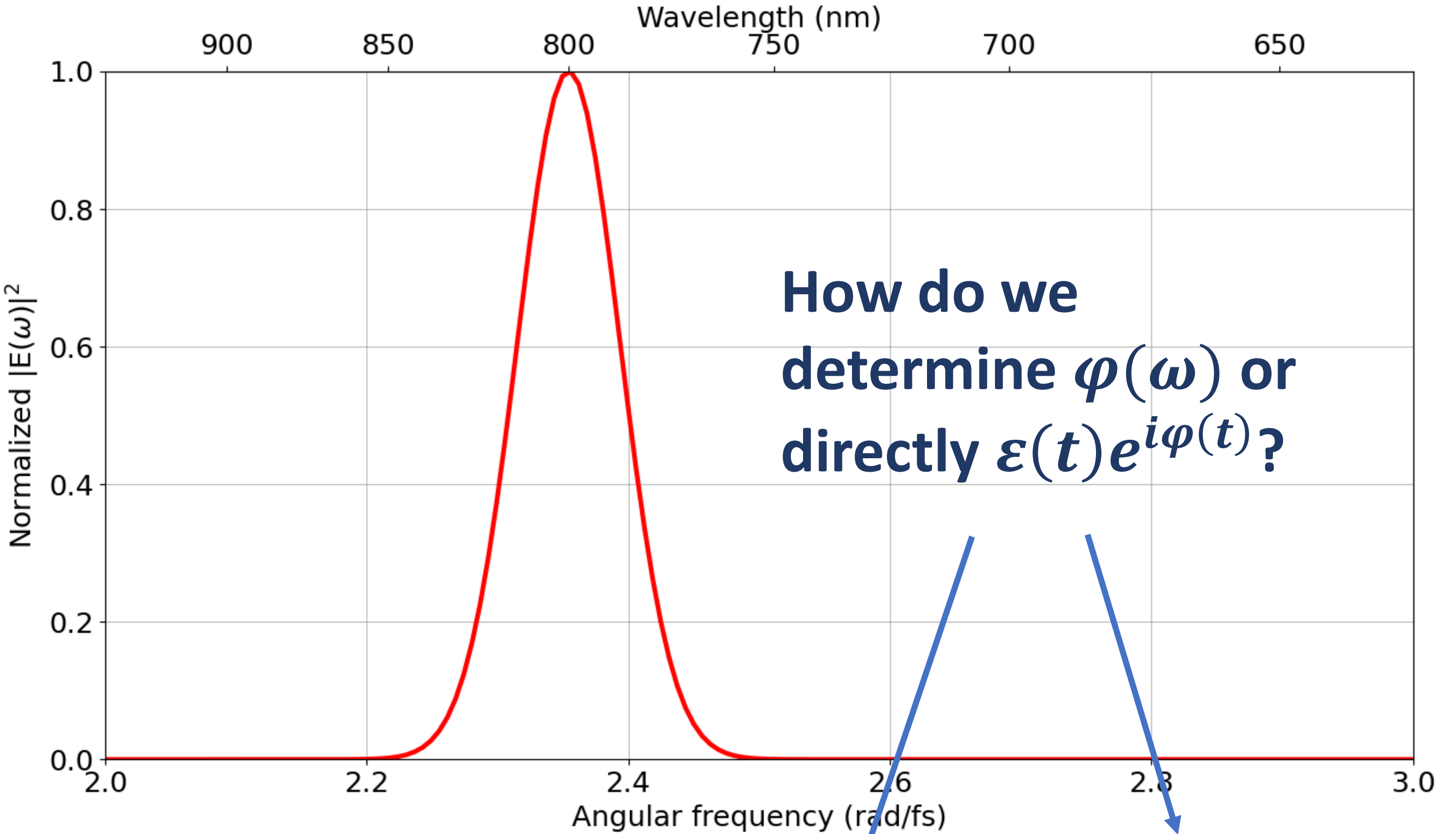


$$\tilde{E}^{+}(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} |\tilde{E}^{+}(\omega)| e^{i\omega t + i\varphi(\omega)} d\omega = \frac{1}{2}\varepsilon(t) e^{i\varphi(t)} e^{i\omega_l t}$$

Bandwidth and pulse duration

Does the spectrum determines the pulse shape and duration???

$|\tilde{E}^{+}(\omega)|^{2} = S(\omega)$ pulse spectrum



How do we determine $\varphi(\omega)$ or directly $\varepsilon(t)e^{i\varphi(t)}$?

$$\tilde{E}^{+}(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty}|\tilde{E}^{+}(\omega)|e^{i\omega t + i\varphi(\omega)}d\omega = \frac{1}{2}\varepsilon(t)e^{i\varphi(t)}e^{i\omega_l t}$$

Intensity autocorrelation

Lots of methods have been developed. We will:

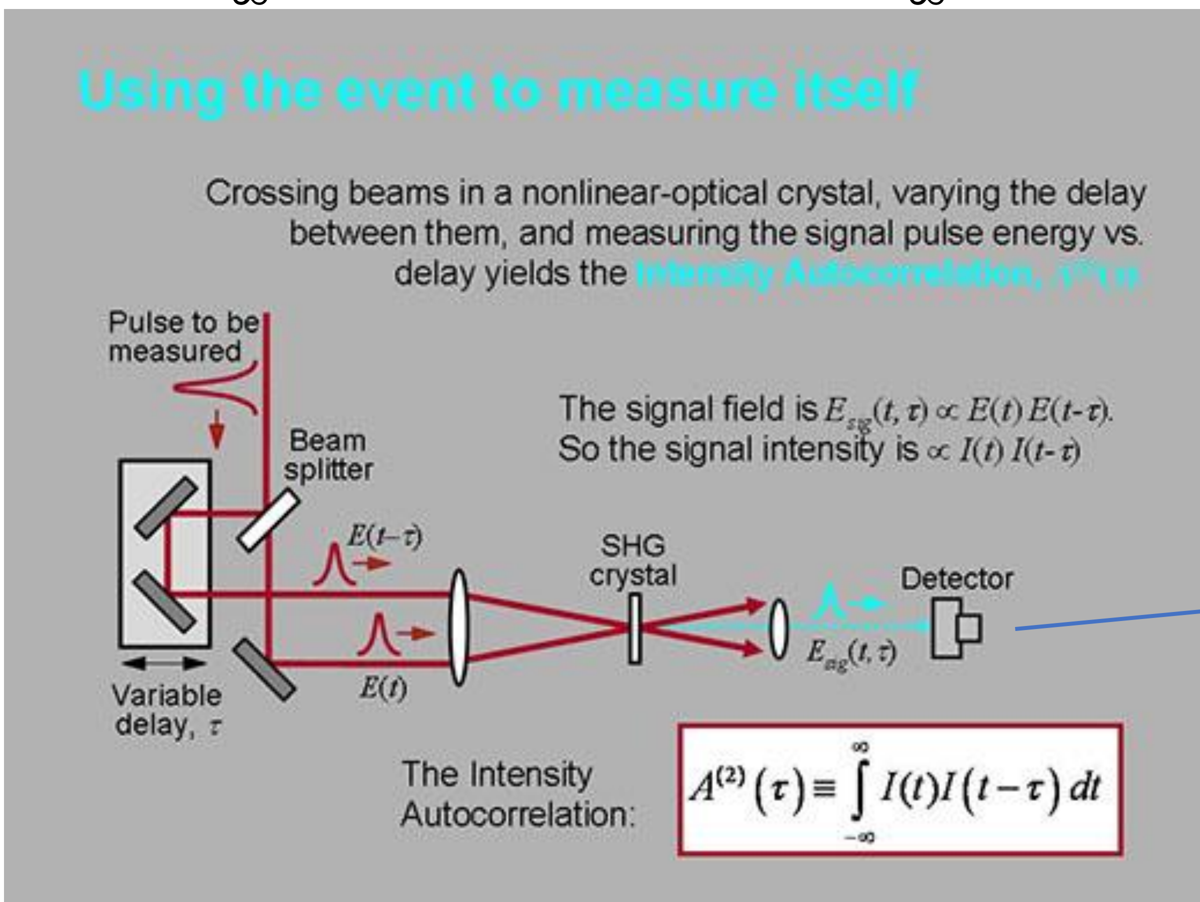
- Introduce the most widely implemented methods
  - Autocorrelation
  - FROG
  - SPIDER

- Examples of extension to spatio-temporal (or spatio-spectral) characterization

Intensity autocorrelation

Use nonlinear process (e.g. second harmonic generation (SHG)) to generate a pulse appearing only when the pulses meet in space and time and interact (nonlinearly) in a material

Signal: $I(\tau)_{IAC} = \int_{-\infty}^{+\infty} |E(t)E(t-\tau)|^2 dt = \int_{-\infty}^{+\infty} I(t)I(t-\tau)dt$



Power of SHG

Taken from https://frog.gatech.edu/tutorial.html

Intensity autocorrelation

No information about the spectral phase or pulse shape

Need to assume a pulse shape to retrieve a pulse duration

$$\tau_p \cong \begin{cases} \tau_{AC}/_{1.414} & for\ e^{-t^2} \\ \tau_{AC}/_{1.543} & for\ \operatorname{sech}(t)^2 \end{cases}$$

Taken from https://en.wikipedia.org/wiki/Optical_autocorrelation

Intensity autocorrelation

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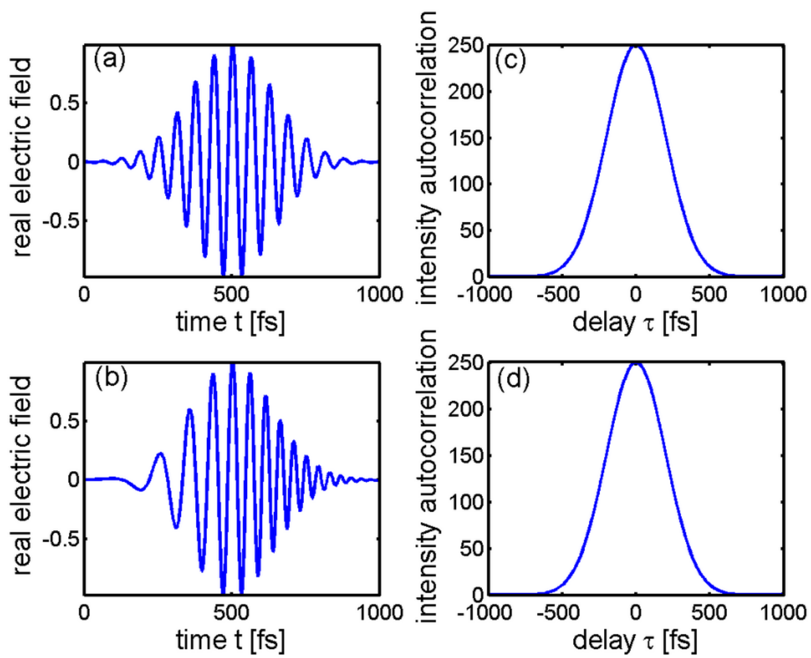

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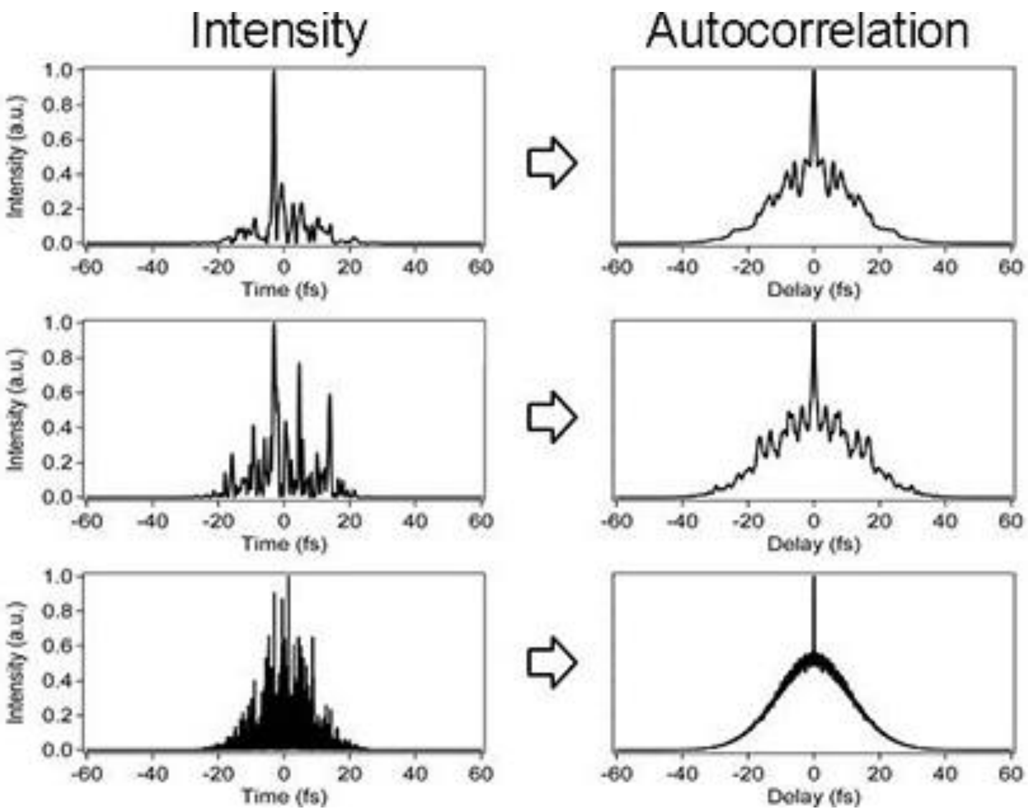
Intensity autocorrelation

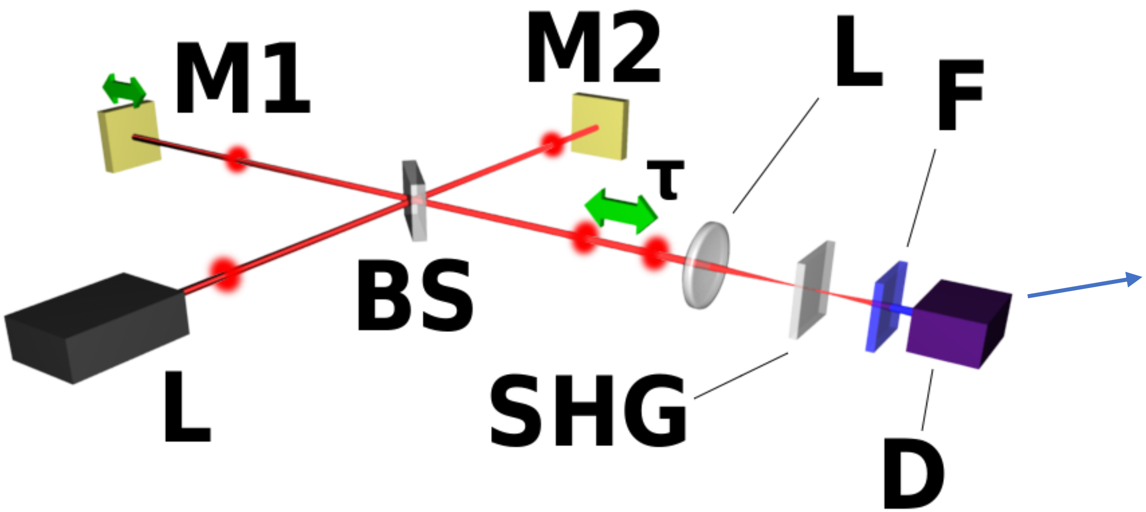
Can lead to very misleading results for complex pulse shapes



Taken from https://frog.gatech.edu/tutorial.html

Interferometric autocorrelation

Similar configuration but collinear geometry gives rise to interferometric signal: $I(\tau)_{IAC} = \int_{-\infty}^{+\infty} |(E(t) + E(t-\tau))^2|^2 dt$

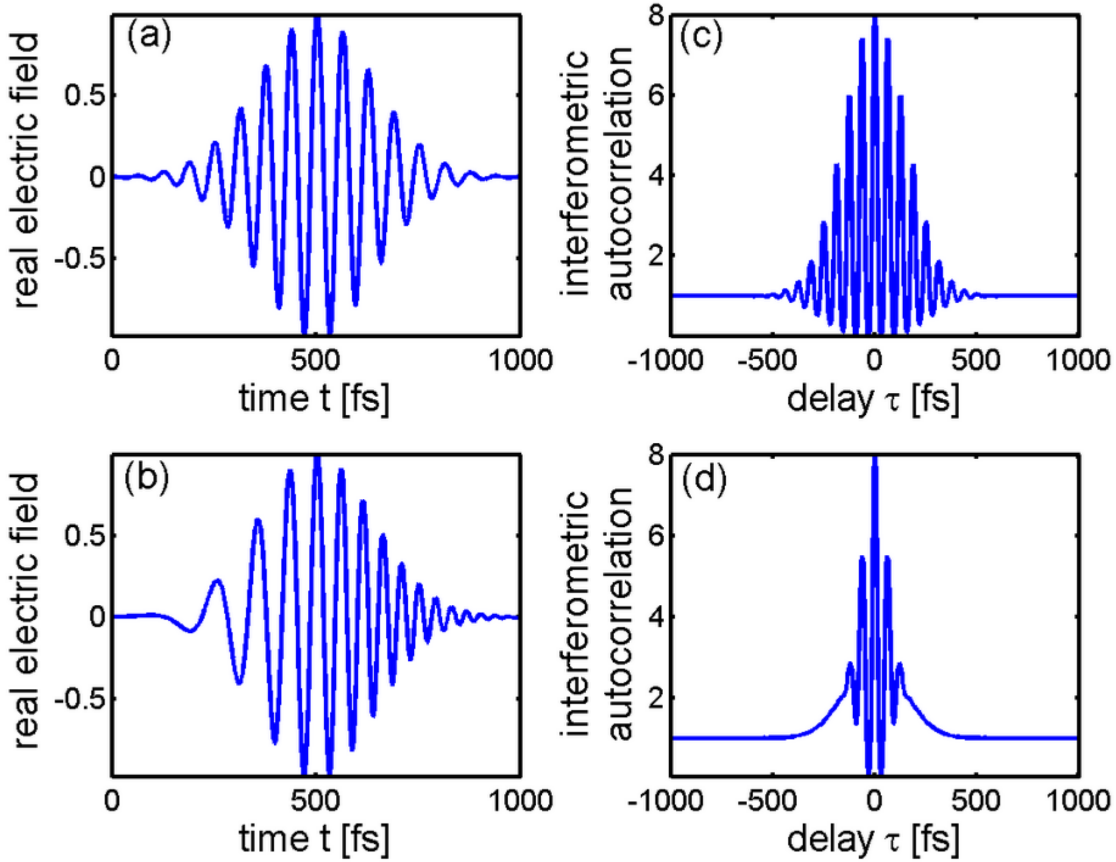


Power of SHG

Taken from https://en.wikipedia.org/wiki/Optical_autocorrelation

Interferometric autocorrelation

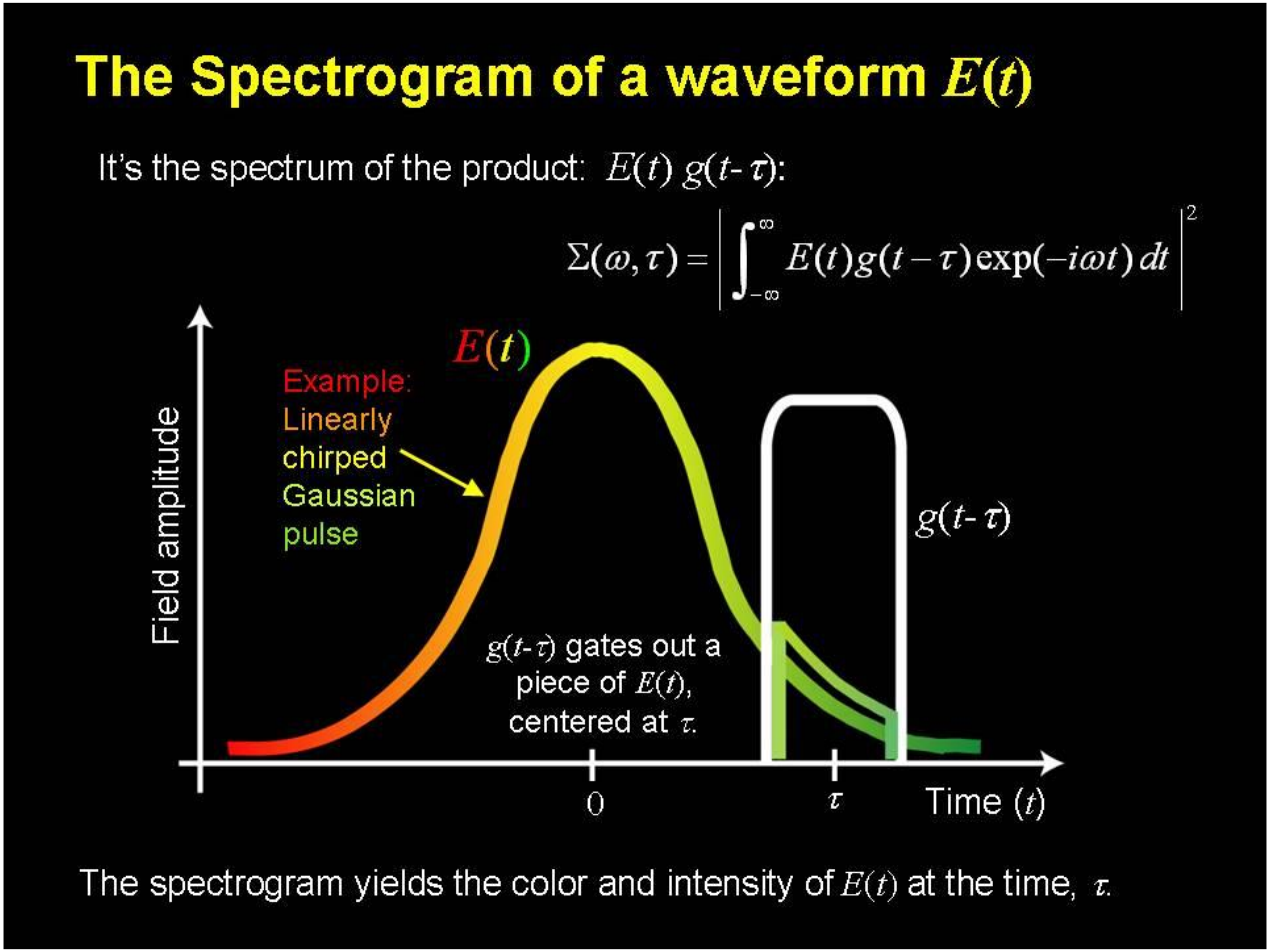
No pulse or phase retrieval, but some information about pulse structure: e.g. Chirp washes away fringes



Taken from https://en.wikipedia.org/wiki/Optical_autocorrelation

FROG: Frequency-Resolved Optical Gating

We want to measure *E(t)* using a gating function *g(t)*



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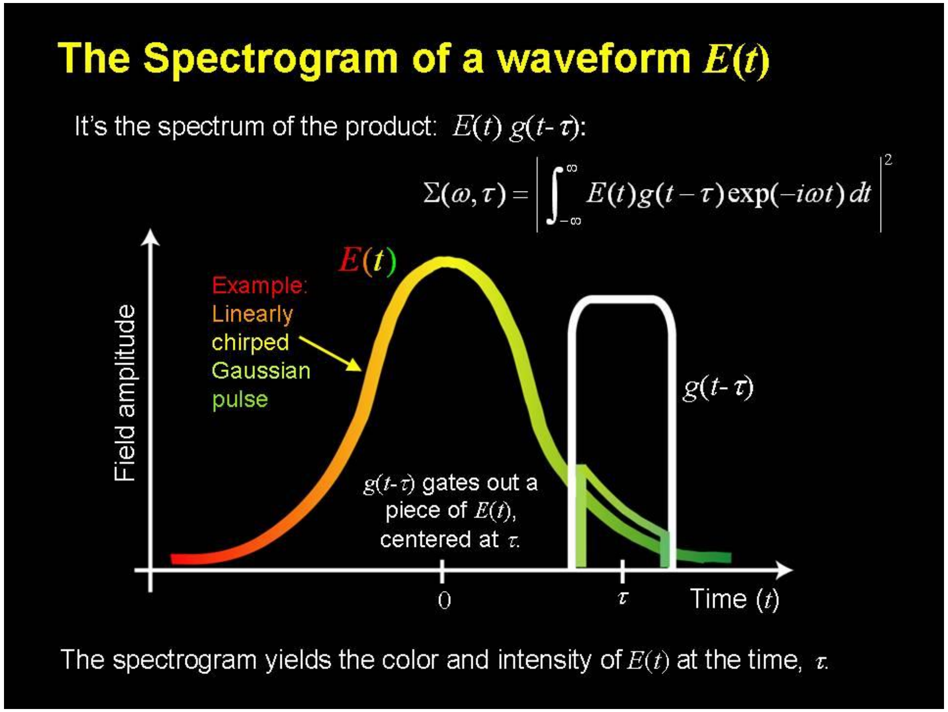
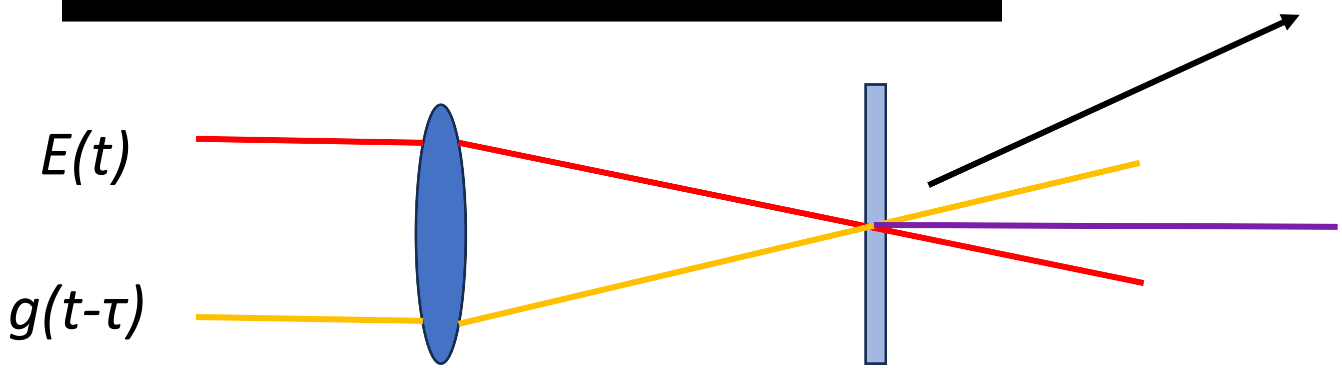


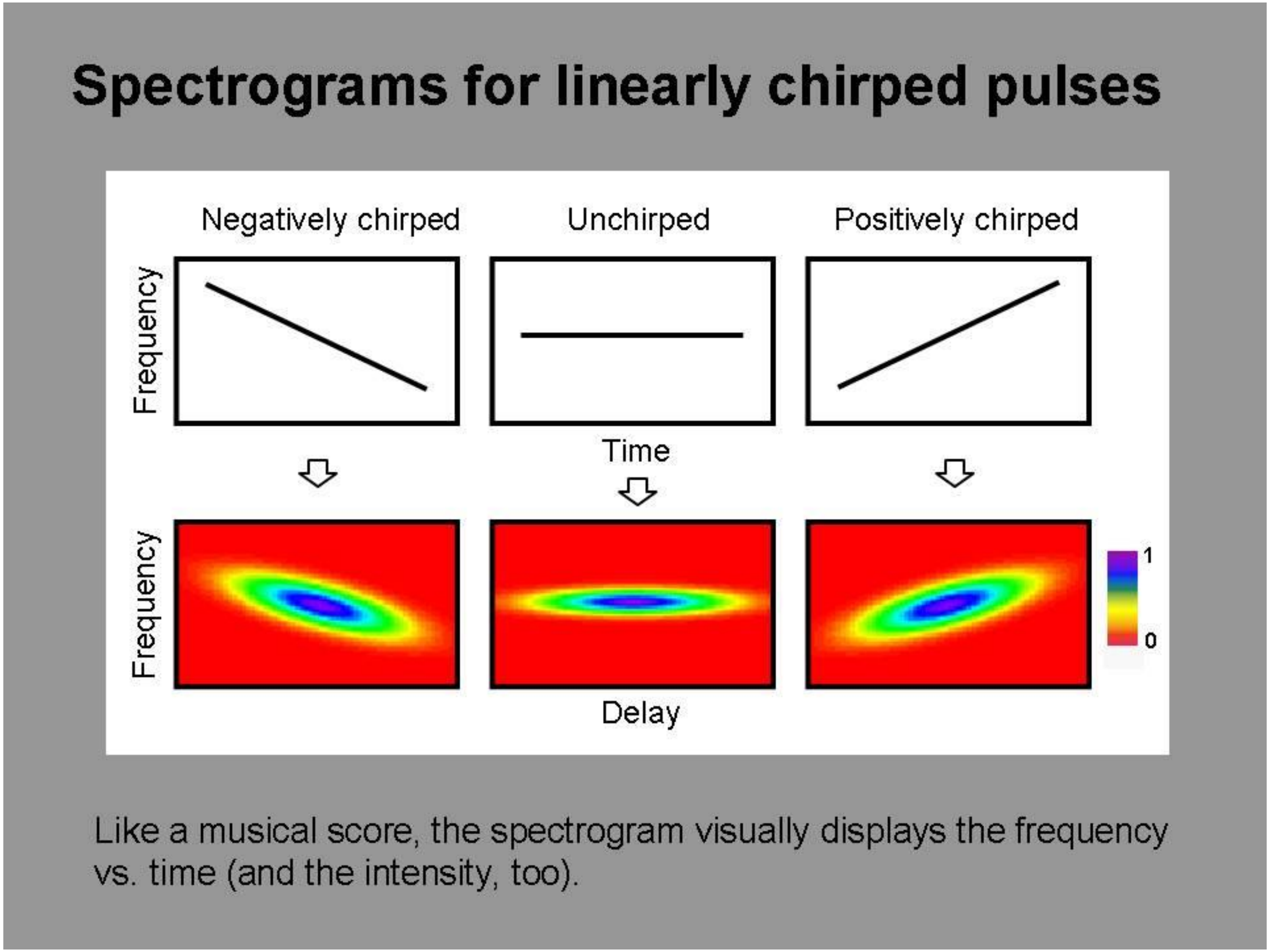
Gating process: Nonlinear interaction leading to frequency mixing when *E(t)*, *g(t)* overlap. e.g., sum-frequency generation (SFG)



Generated signal via SFG $\omega_{SFG} = \omega_g + \omega_E$ depends on τ

Taken from https://frog.gatech.edu/tutorial.html

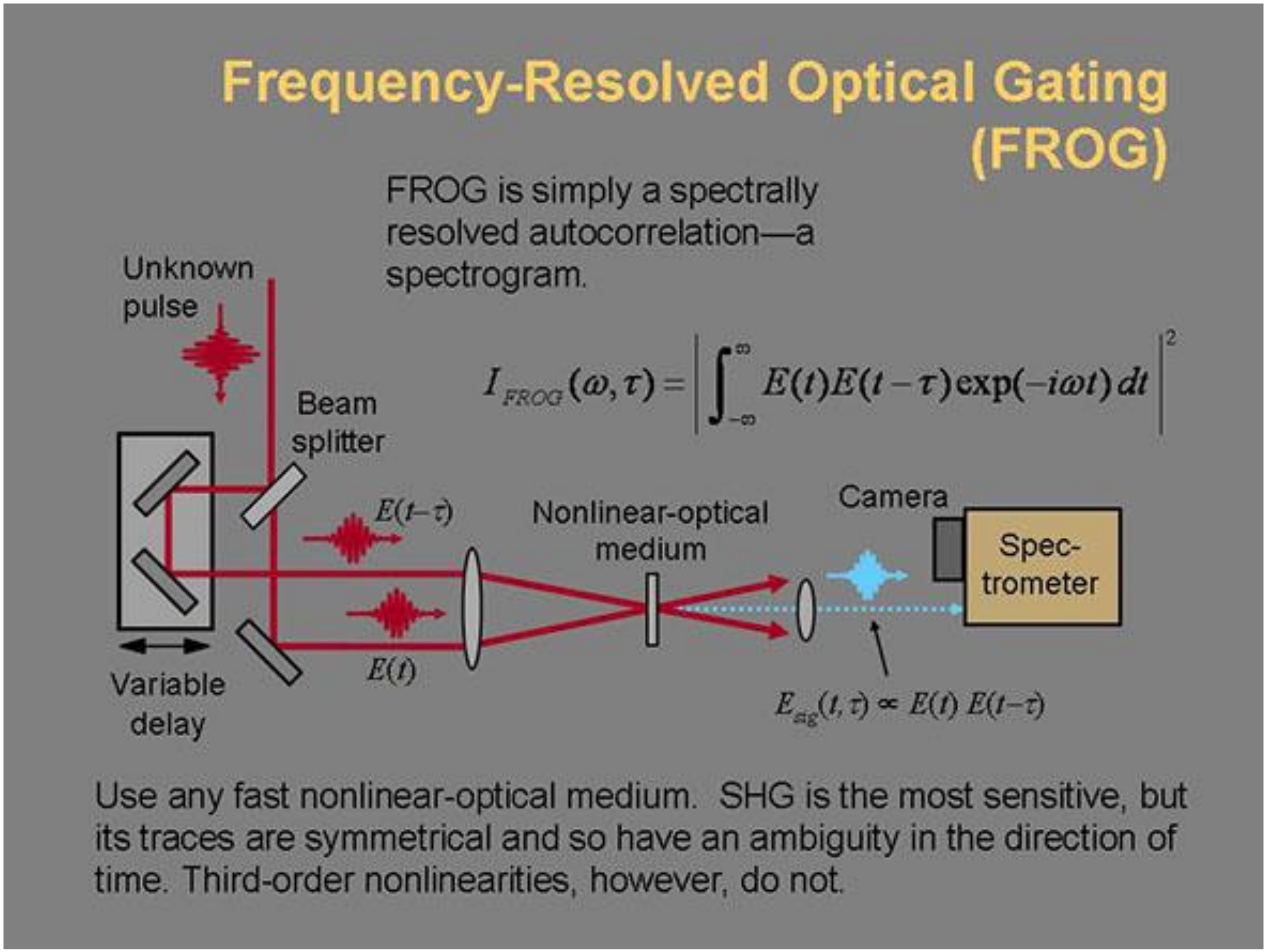
FROG: Frequency-Resolved Optical Gating



Taken from https://frog.gatech.edu/tutorial.html

FROG: Frequency-Resolved Optical Gating

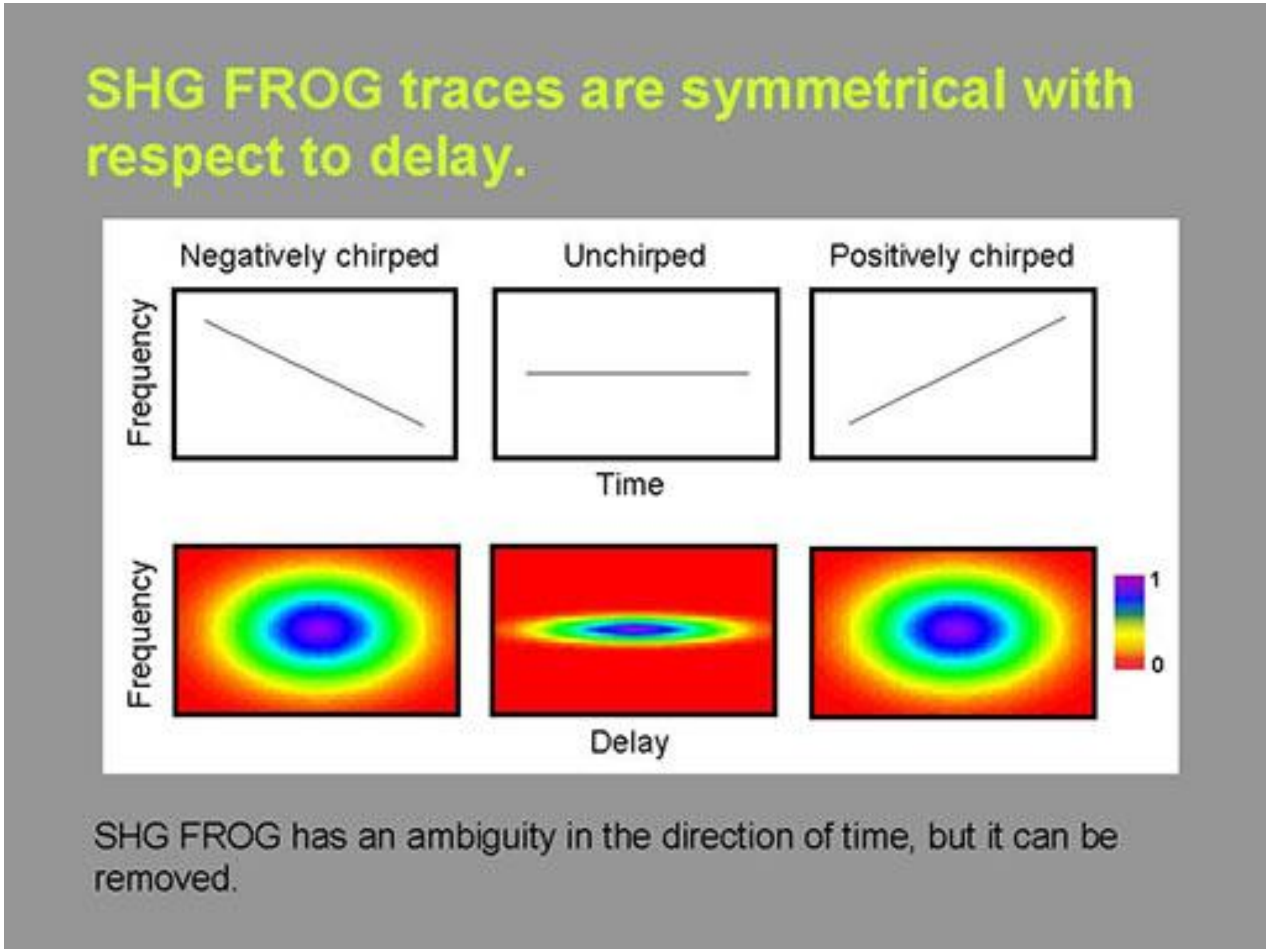
Problem: No access to *g(t)* much shorter than *E(t)*… we use *E(t)* itself



Taken from https://frog.gatech.edu/tutorial.html

FROG: Frequency-Resolved Optical Gating

$$I_{FROG}(\tau,\omega) = \left|\int_{-\infty}^{+\infty} E(t)E(t-\tau)\, e^{-i\omega t}\, dt\right|^2$$



Taken from https://frog.gatech.edu/shg-frog-traces.html

FROG algorithm

Iterative algorithm using the measured trace $I_{FROG}(\tau,\omega) = \left| \int_{-\infty}^{+\infty} E(t)E(t-\tau)\, e^{-i\omega t} dt \right|^2$

Initial guess for *E(t)*

$E(t)E\,(t-\tau)$

Fourier Transform in t

$E_{sig}(\omega,\tau) = A(\omega,\tau)e^{i\theta(\omega,\tau)}$

Replace $A(\omega,\tau)$ with $\sqrt{I_{FROG}(\tau,\omega)}$

$E_{sig}(\omega,\tau)$

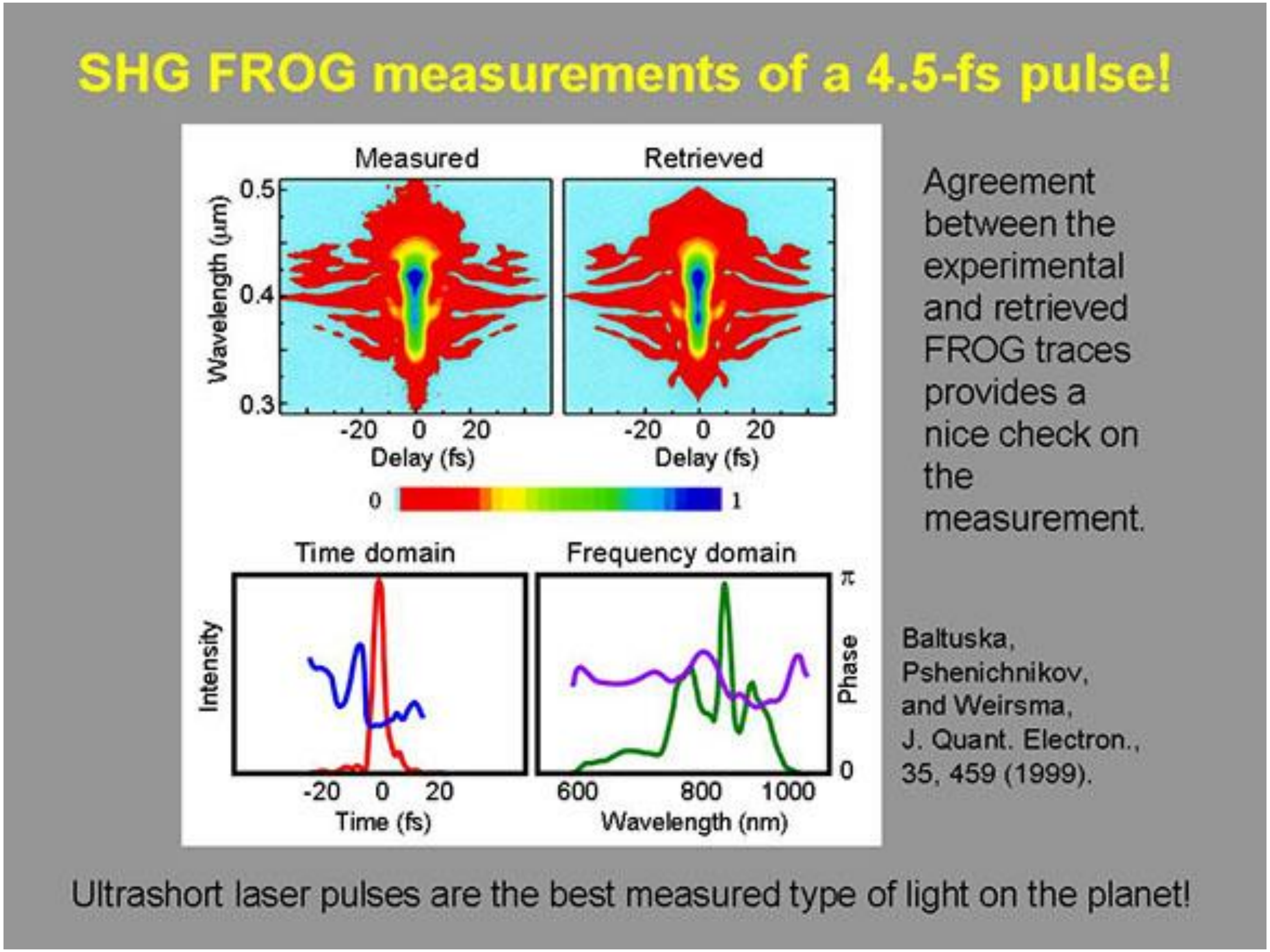
Fourier Transform in ω

$E_{sig}(t,\tau)$

$$E\,(t) = \int_{-\infty}^{+\infty} E_{sig}(t,\tau)\, d\tau$$

Adapted from Kane and Trebino, Opt. Lett. 18, 823 (1993)

FROG: Frequency-Resolved Optical Gating



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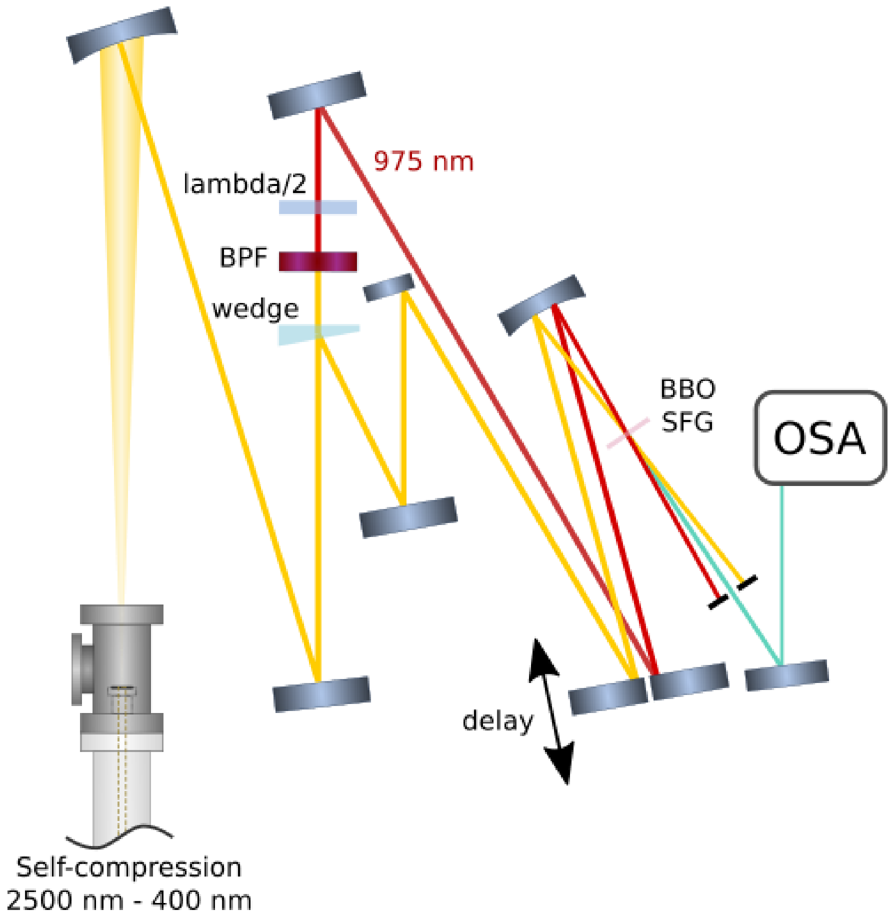
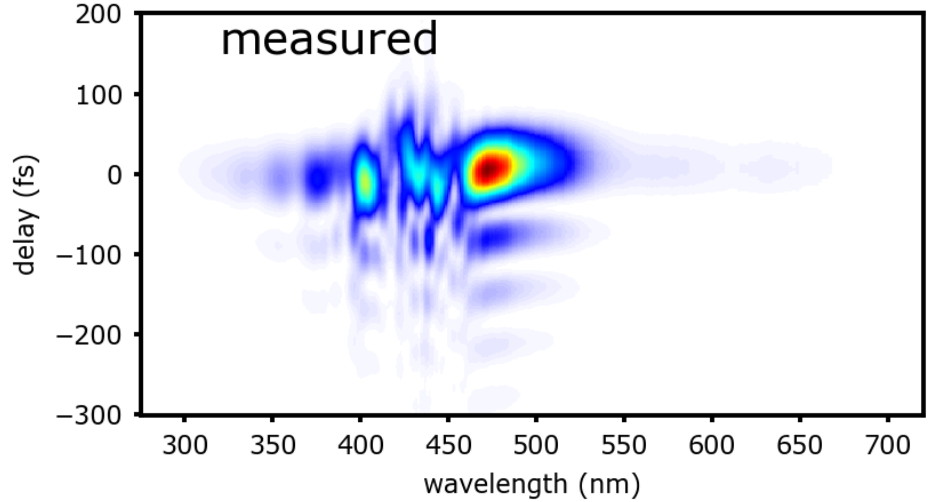
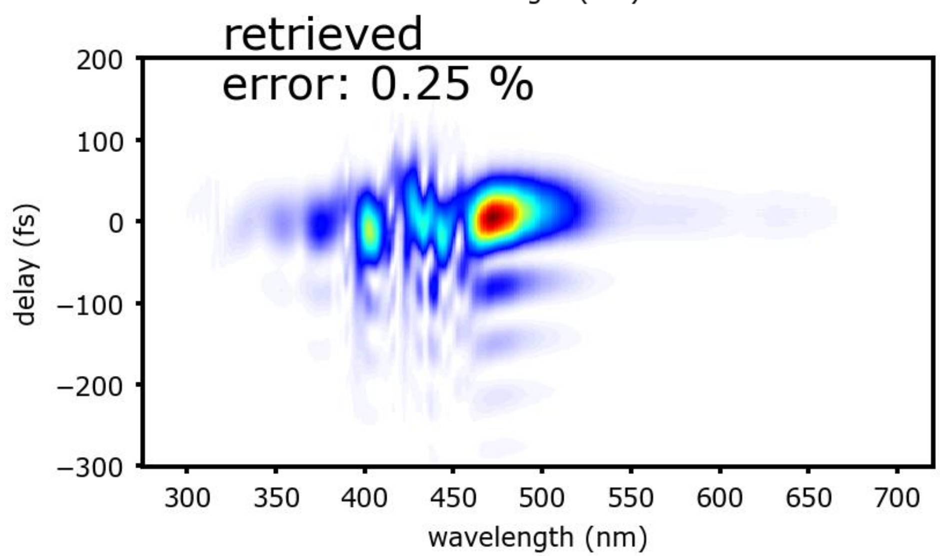
FROG: Frequency-Resolved Optical Gating

Spectral broadening and self-compression of 40 fs pulses from Ti:Sapphire laser in gas-filled hollow capillary







Unpublished data from J. Cardoso de Andrade (MBI)

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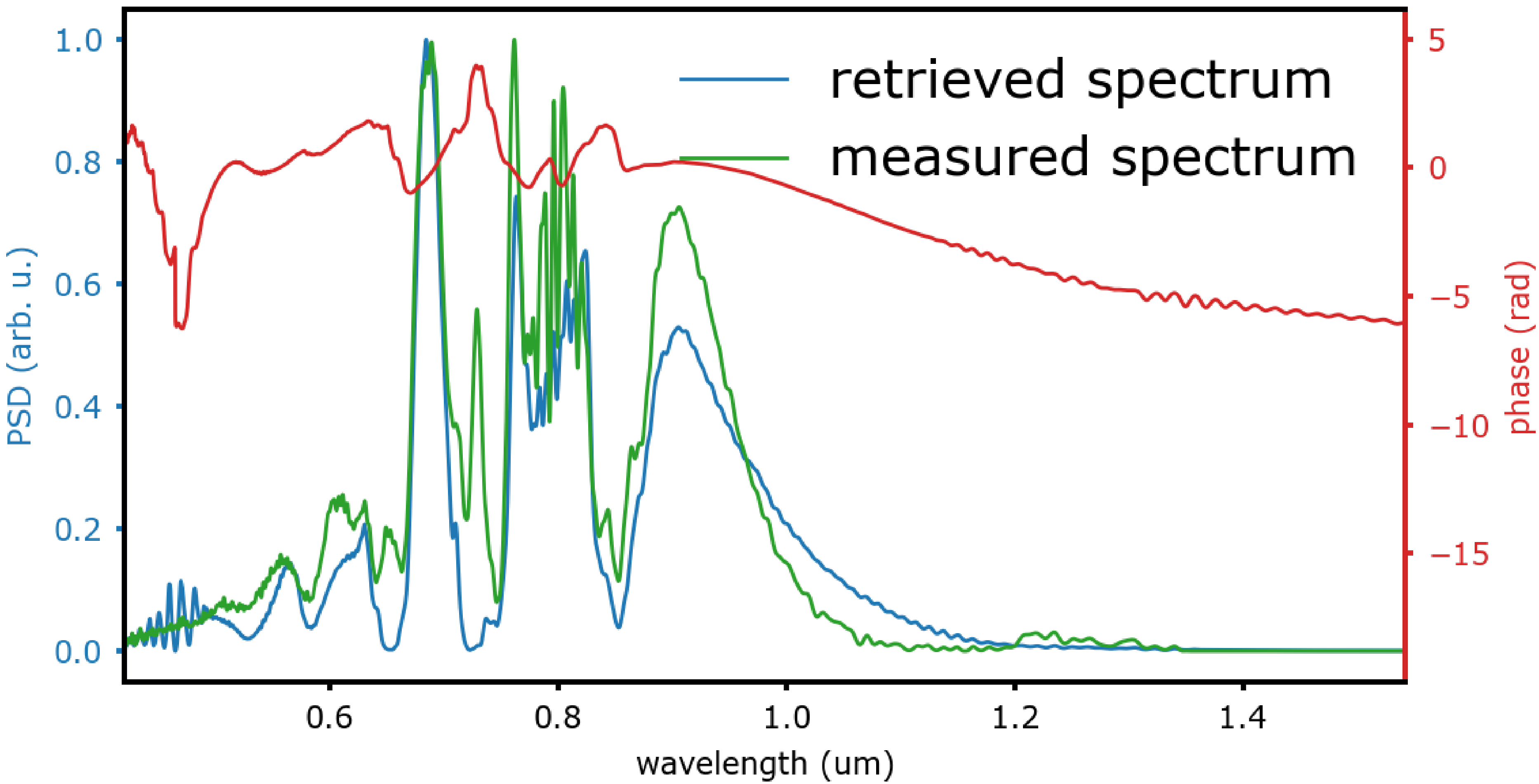

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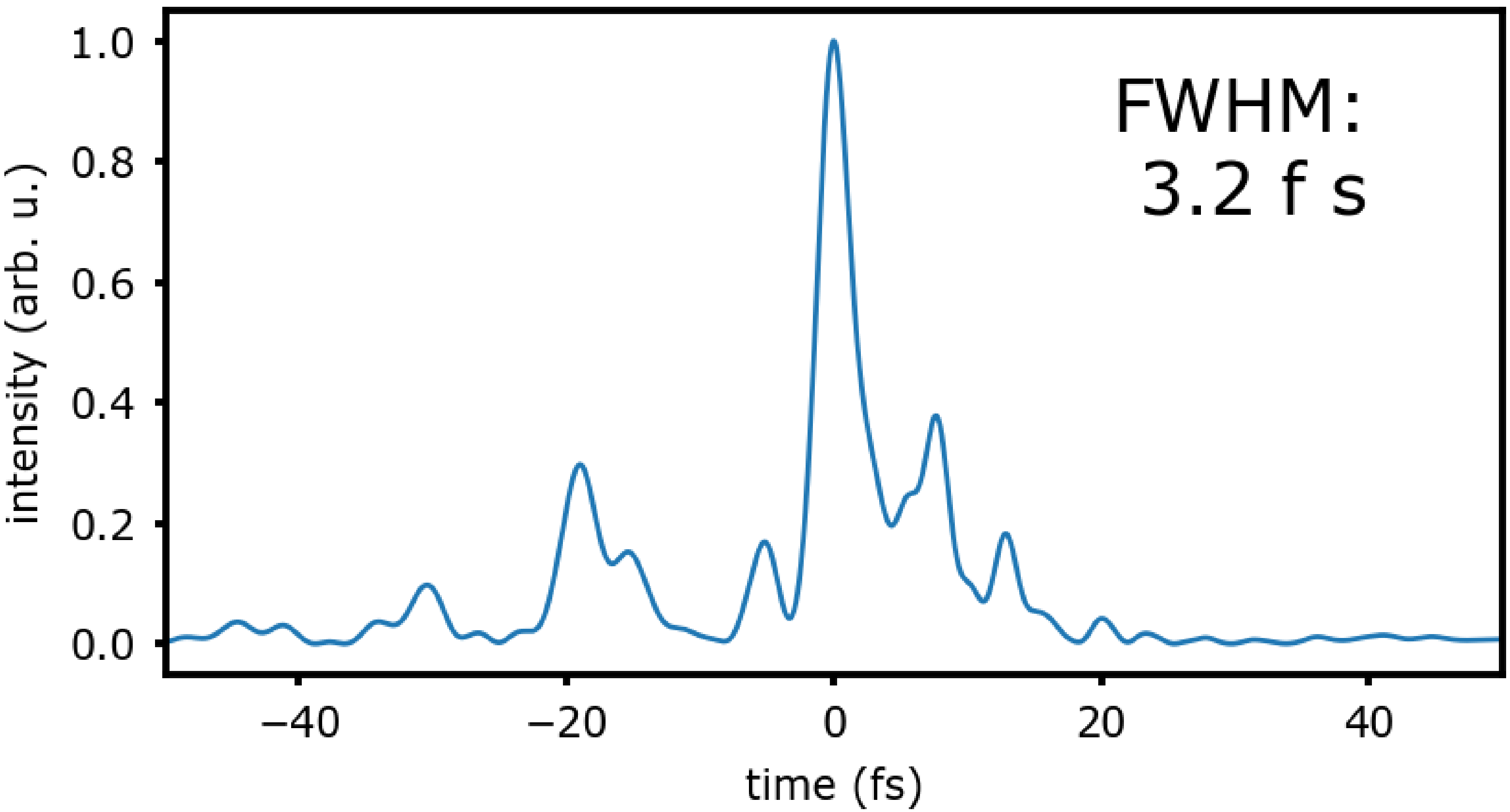

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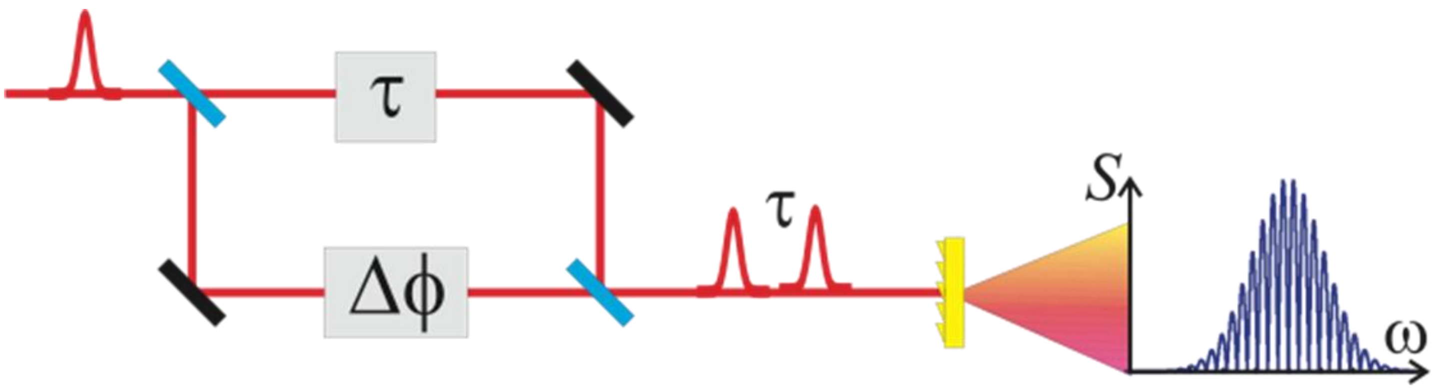
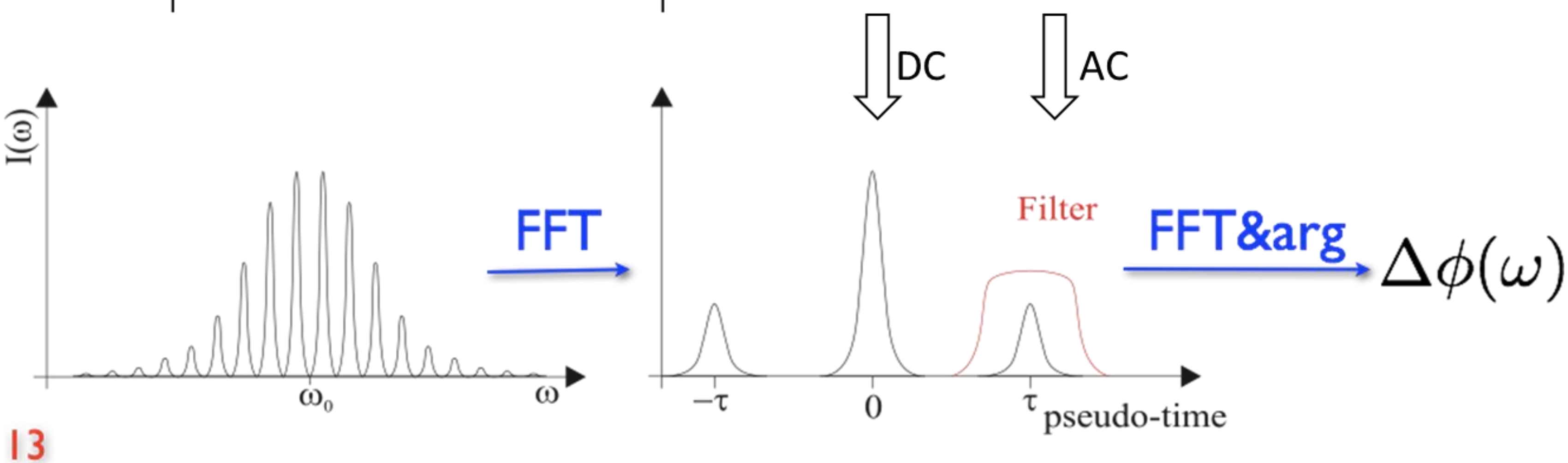
Spectral interferometry

single-shot measurement of phase difference



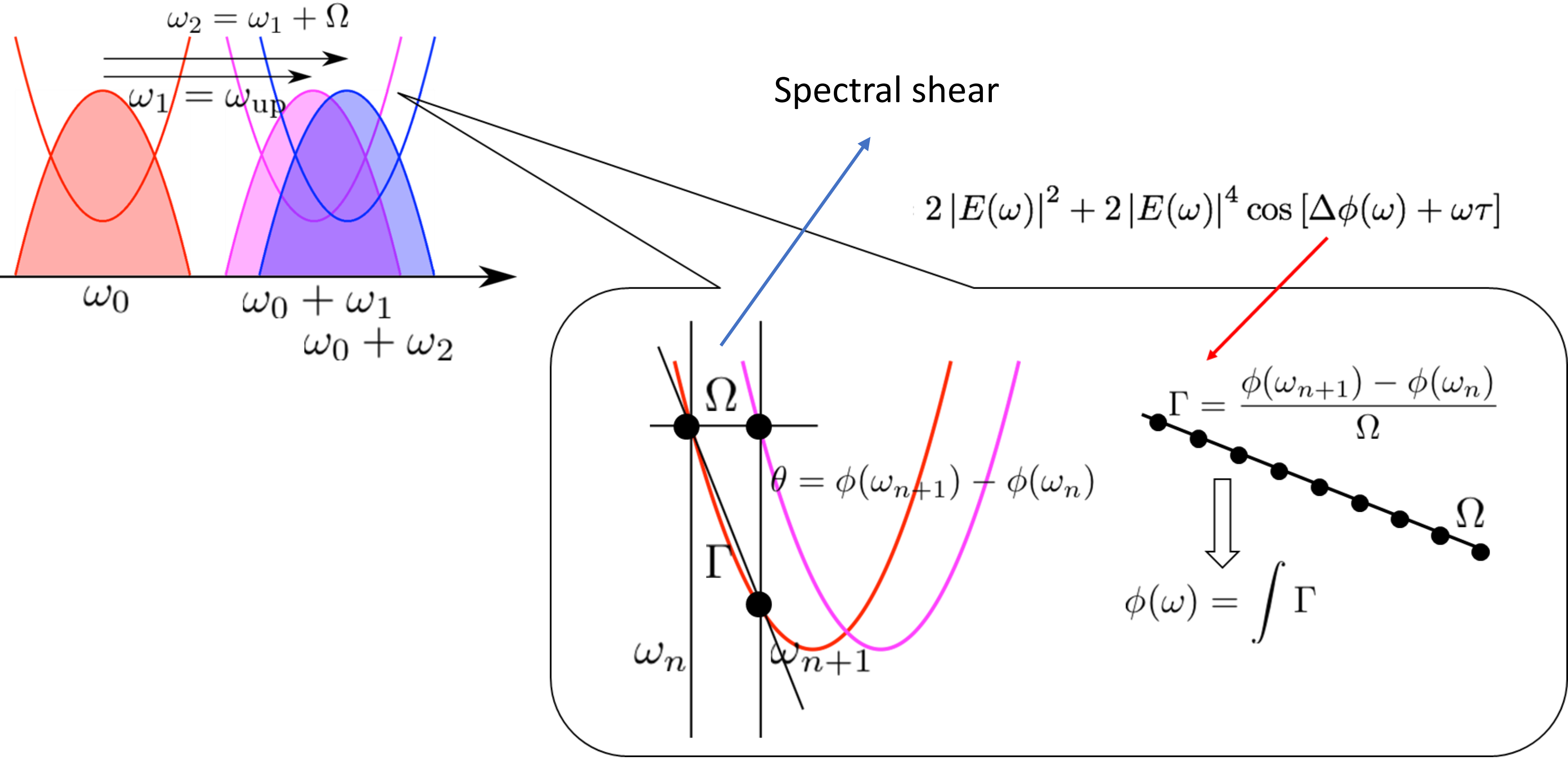
$$S(\omega) = \left| E(\omega) + E(\omega) e^{i\Delta\phi(\omega)} e^{i\omega\tau} \right|^2 = 2\left|E(\omega)\right|^2 + 2\left|E(\omega)\right| \cos\left[\Delta\phi(\omega) + \omega\tau\right]$$



Material from Dr. Tobias Witting (MBI)

Spectral shear interferometry

Single-shot measurement of phase difference
Measurement of discrete derivative of spectral phase



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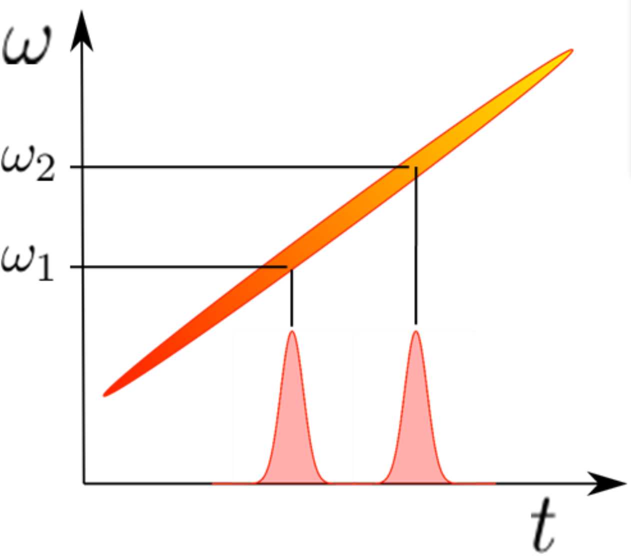
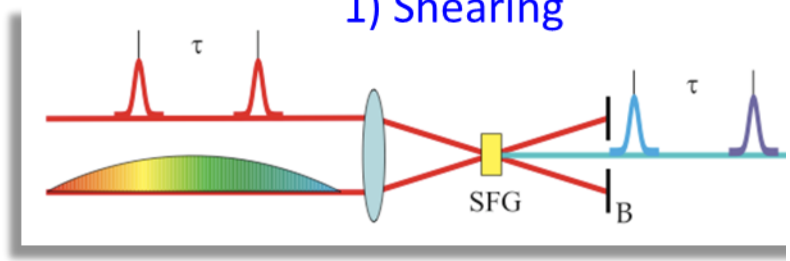
SPIDER: Spectral Phase Interferometry for Direct Electric-field Reconstruction

Single-shot measurement of pulse. Spectral phase retrieved “directly” from data



1) Shearing



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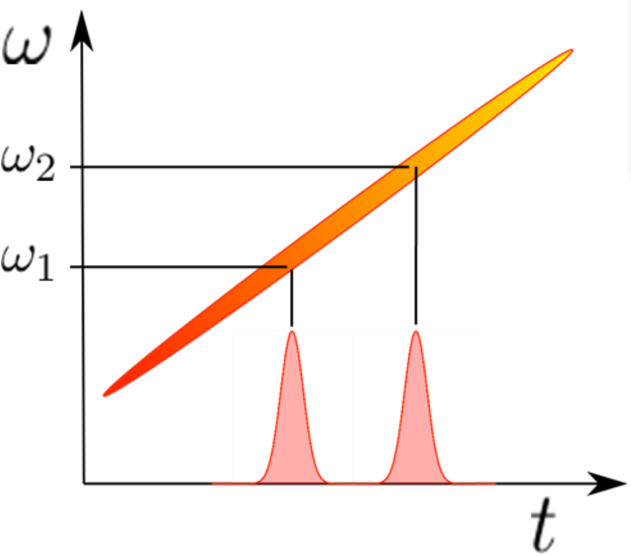

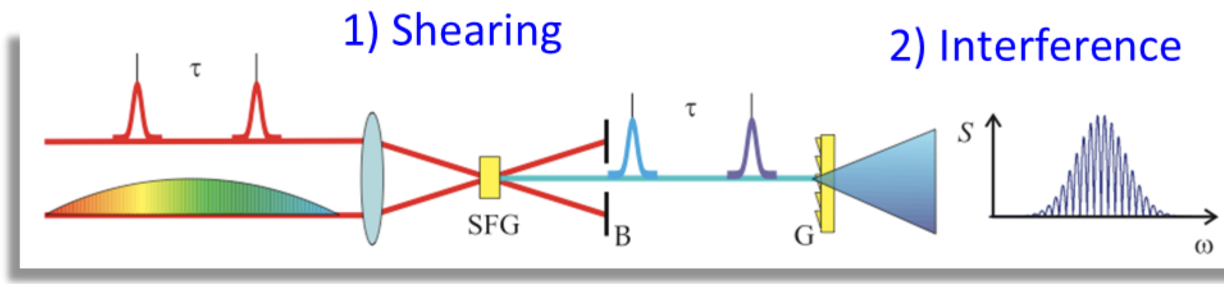

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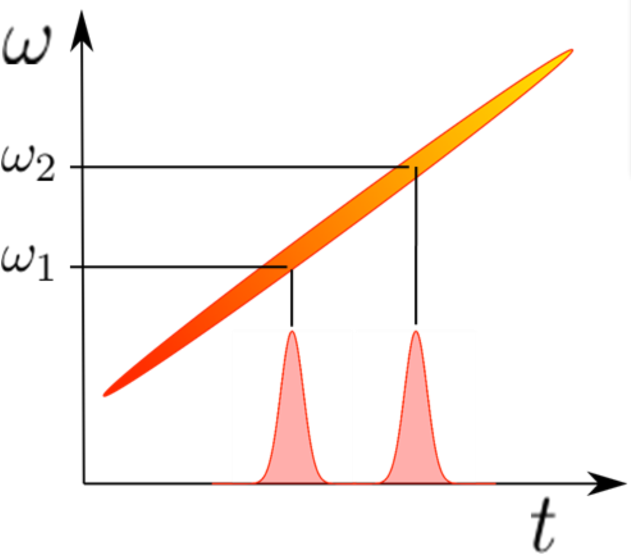

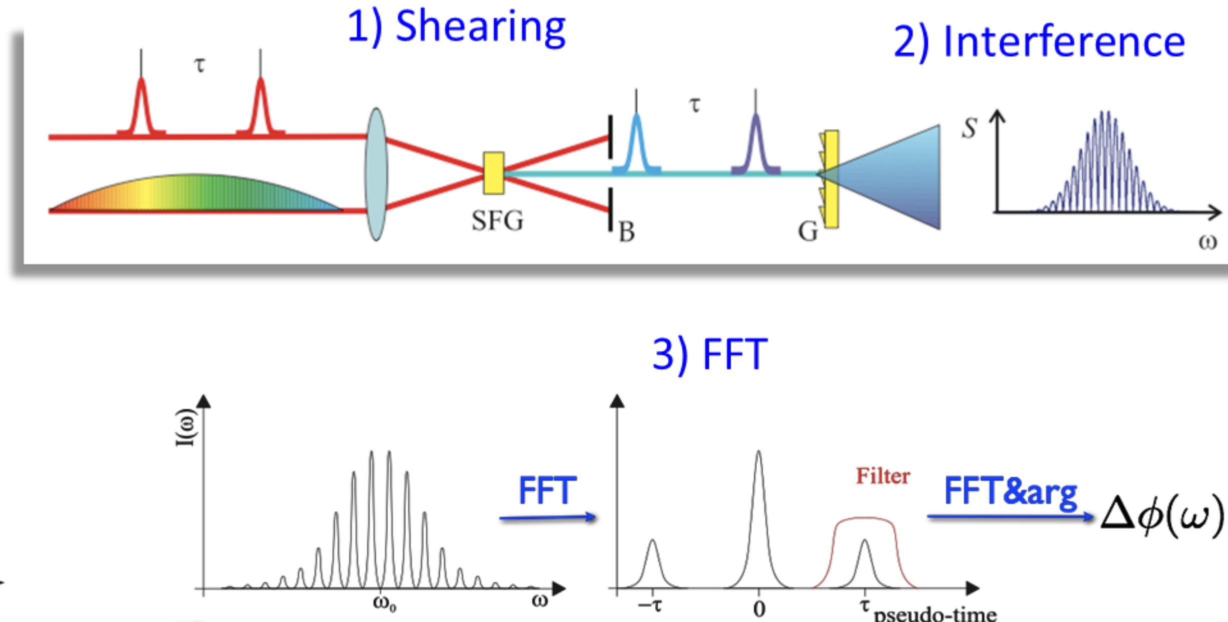

13

Material from Dr. Tobias Witting (MBI)

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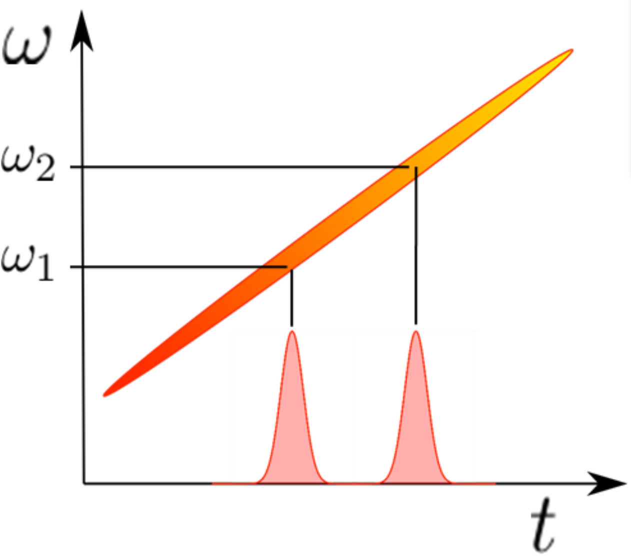
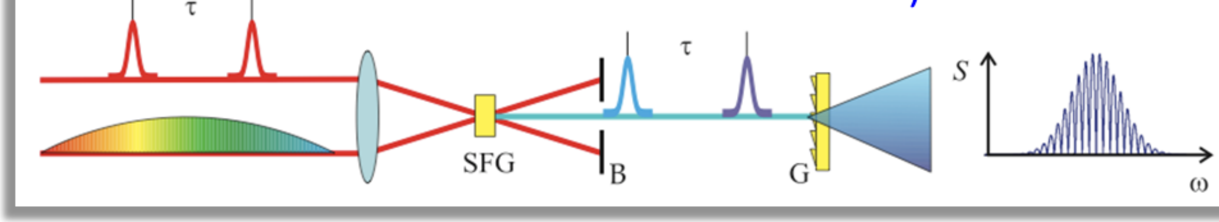
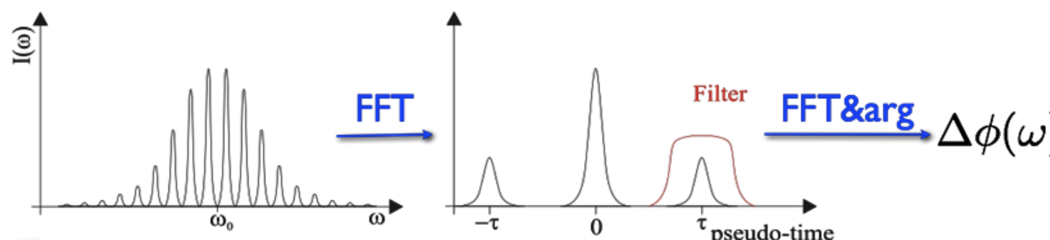


1) Shearing

2) Interference



3) FFT



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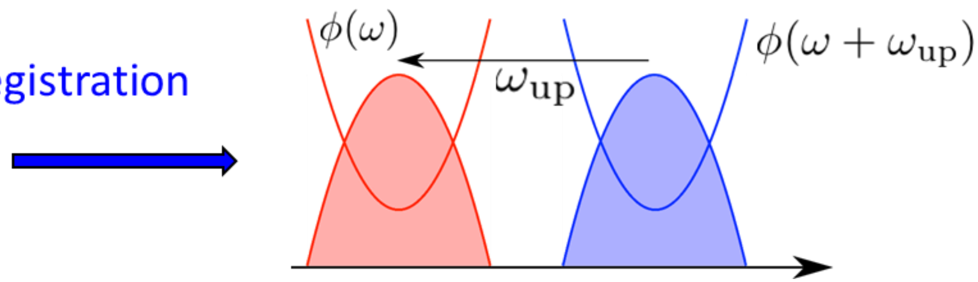
4) registration



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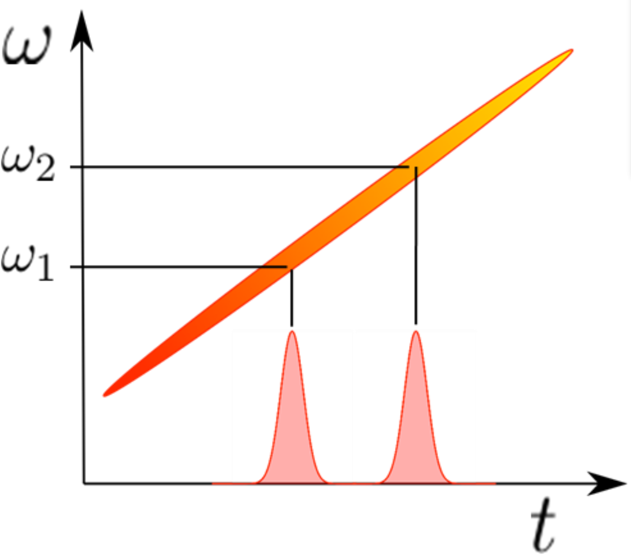

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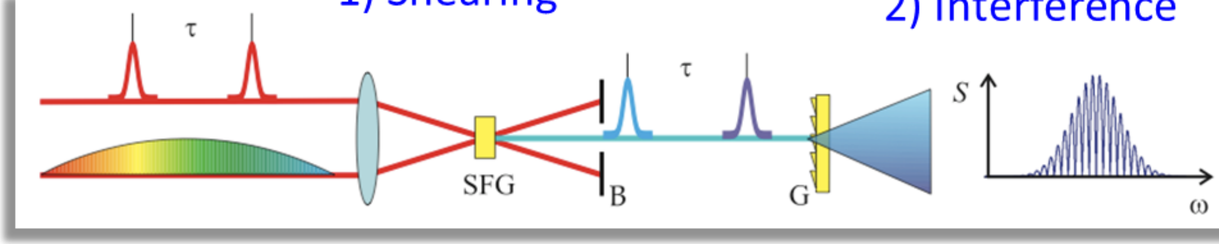

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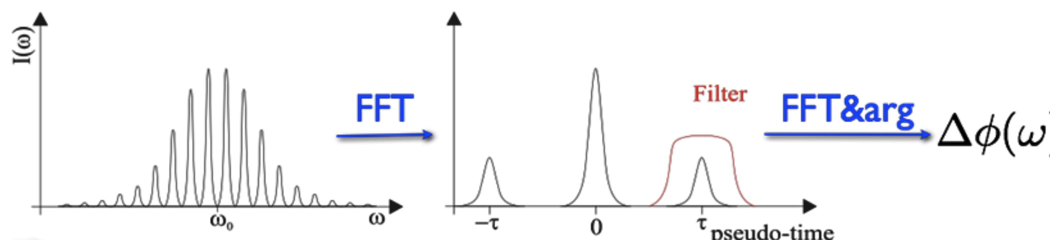

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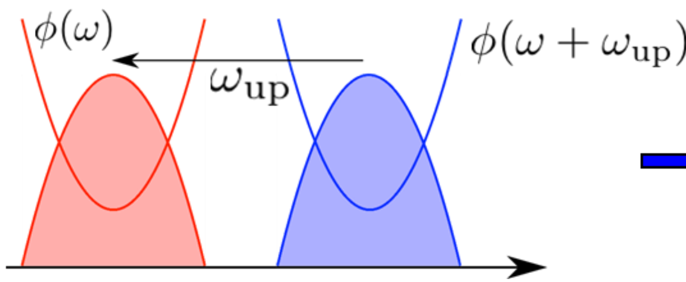


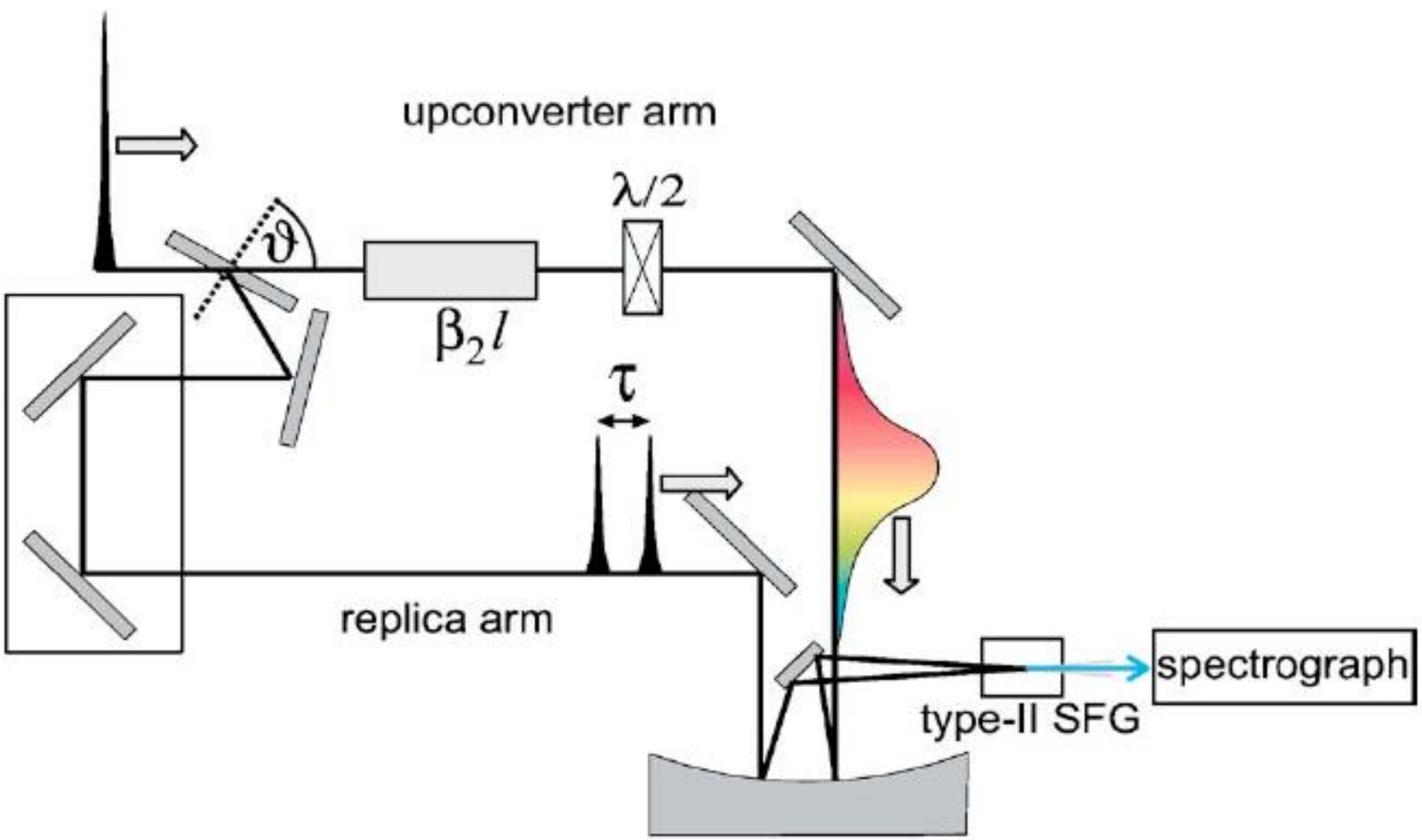
5) FFT

End product:
Time domain pulse

$$E(t) = \mathrm{FFT}\left[\sqrt{I(\omega)}e^{i\phi(\omega)}\right]$$

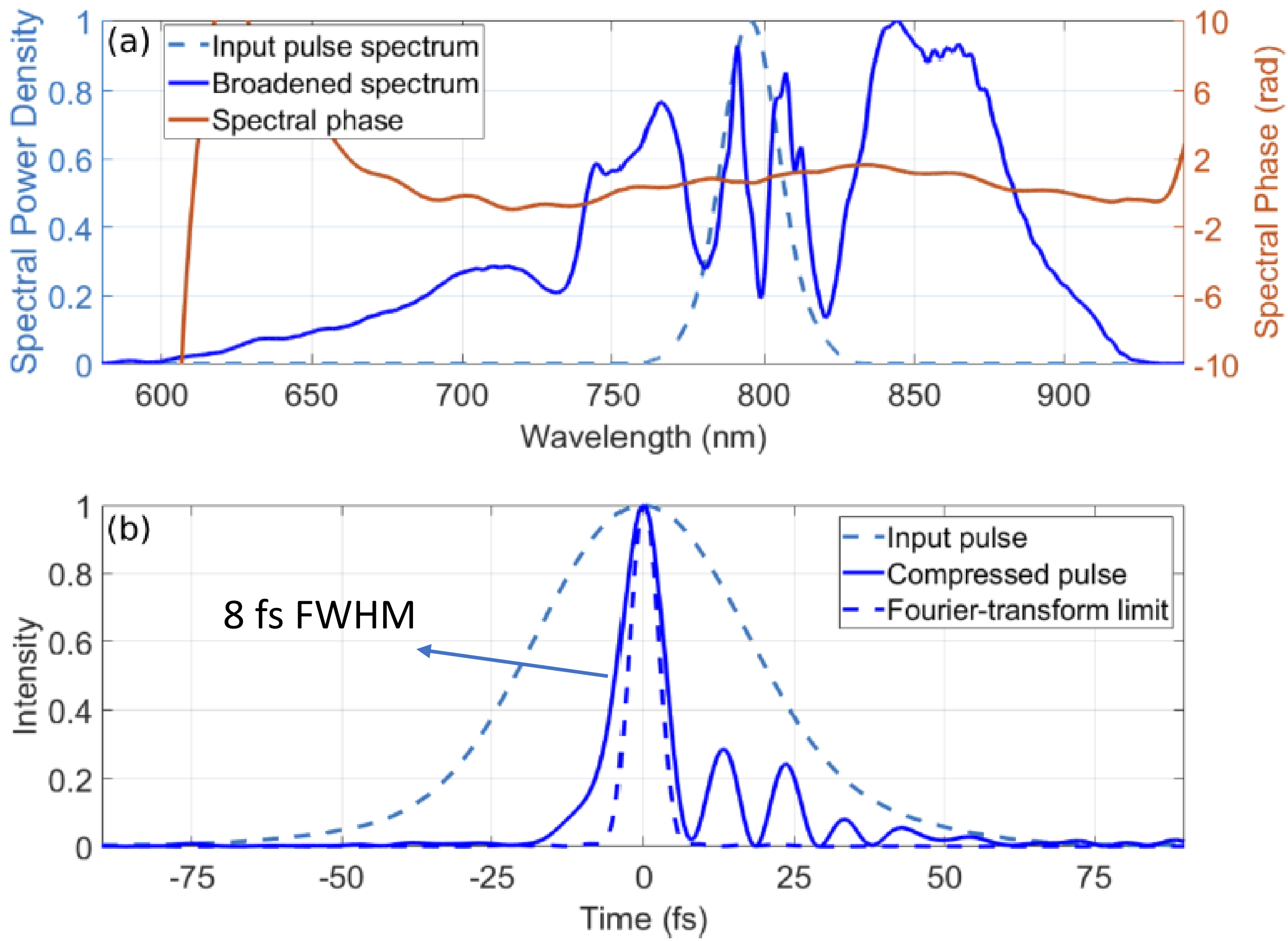
Material from Dr. Tobias Witting (MBI)

SPIDER: Spectral Phase Interferometry for Direct Electric-field Reconstruction



Stibenz and Steinmeyer, Rev. Sci. Inst. 77, 073105 (2006)

SPIDER: Spectral Phase Interferometry for Direct Electric-field Reconstruction



Rueda et al, Opt. Exp. 29, 27004 (2021)

Spatially-resolved SPIDER

- What we think we have and can do:

$$E(x, y, t) = E(x, y)E(t)$$

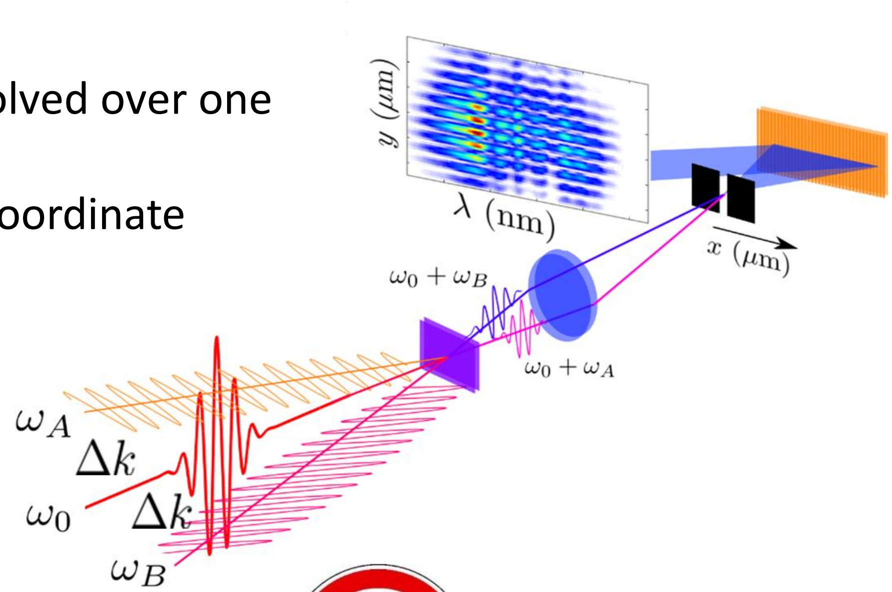
Camera

FROG, SPIDER, dscan =>

Material from Dr. Tobias Witting (MBI)

Spatially-resolved SPIDER

- Single-shot pulse measurement spatially resolved over one spatial coordinate
- Interference pattern encoded in the spatial coordinate



❑ What we think we have and can do:

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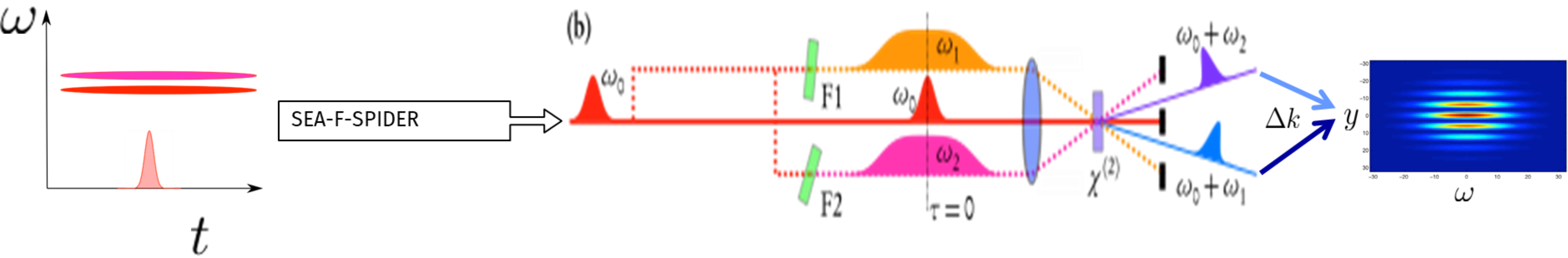
FROG, SPIDER, dscan =>

Kosik et al. OL 30, 326 (2005)
Wyatt et al. OL 31, 1914 (2006)
Witting et al. OL 34, 881 (2009)

Material from Dr. Tobias Witting (MBI)

Spatially-resolved SPIDER



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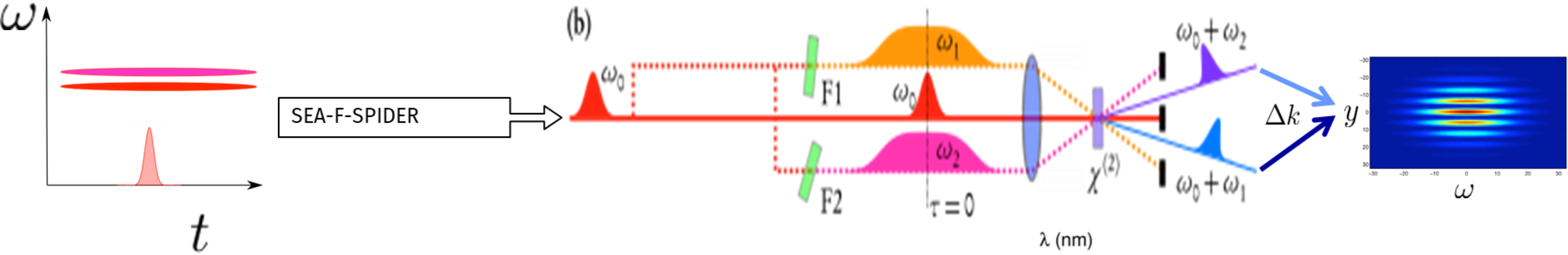
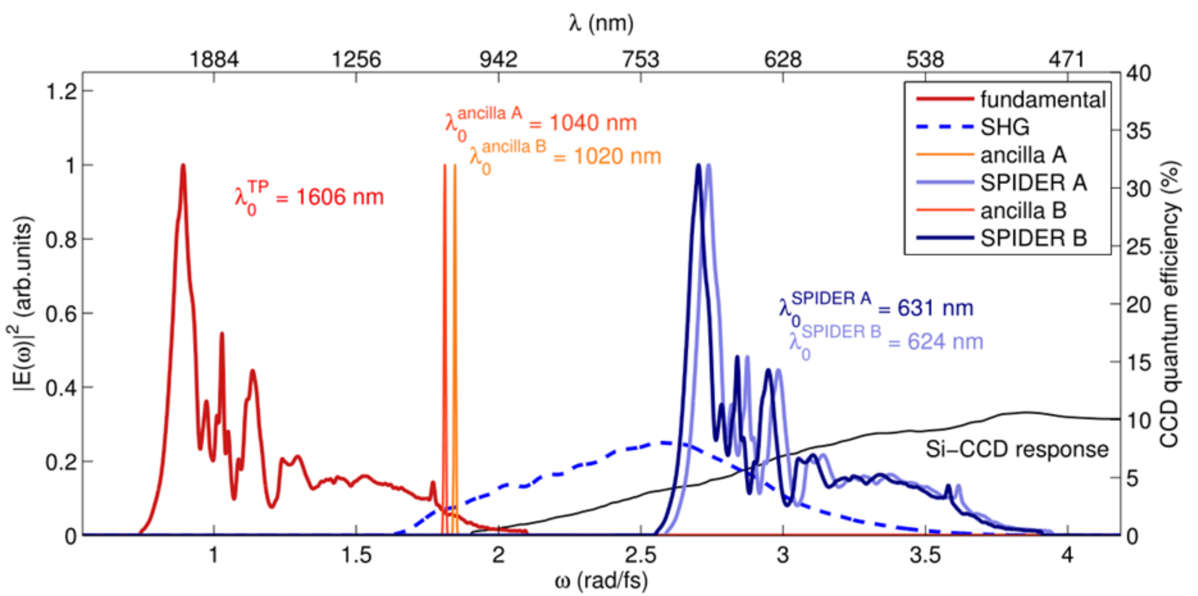


- Direct spectral filtering to achieve monochromaticity of ancillae.
- Spectral shear easy to calibrate and change.
- SFG reproduces fundamental spectrum faithfully.



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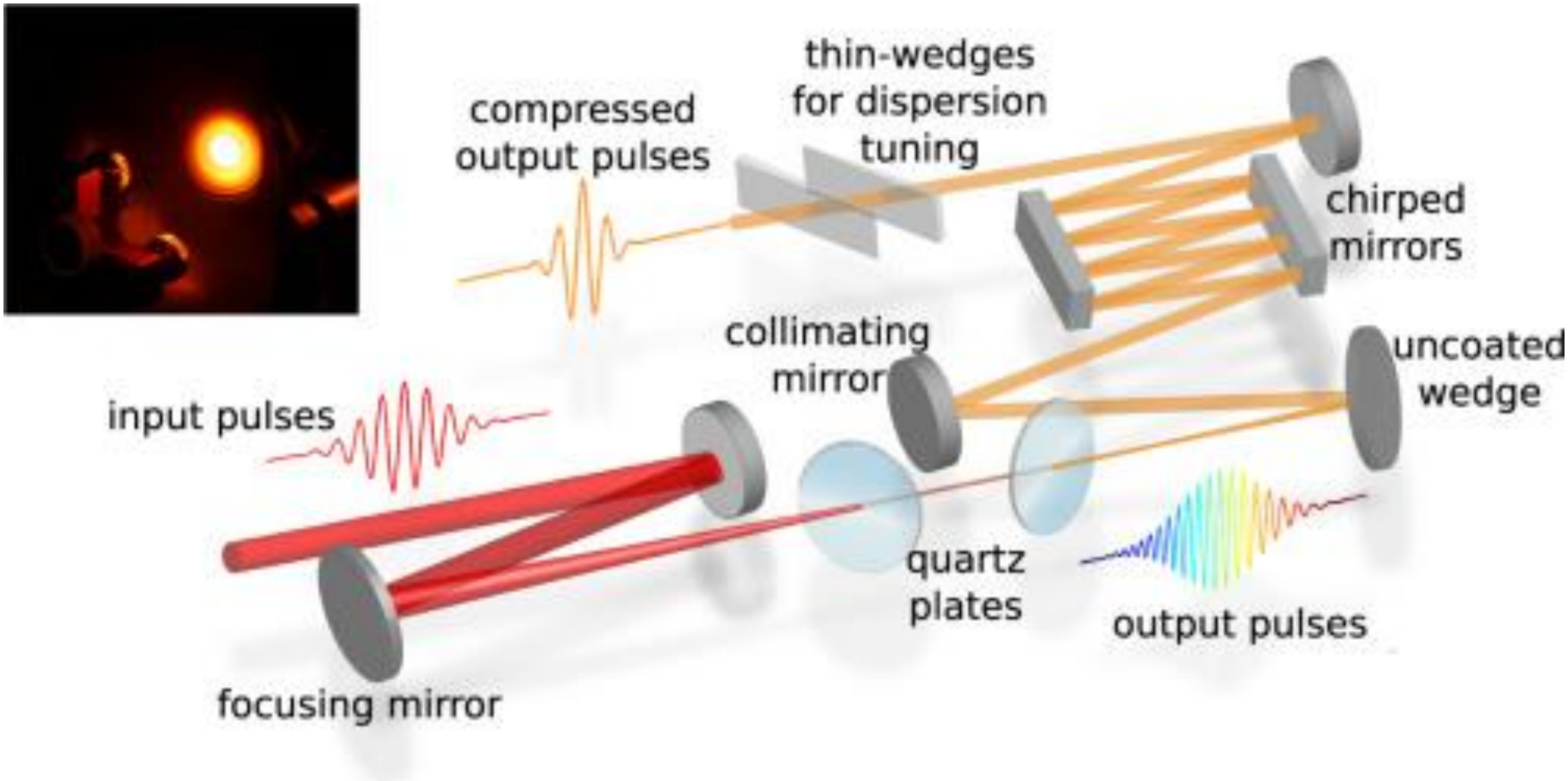
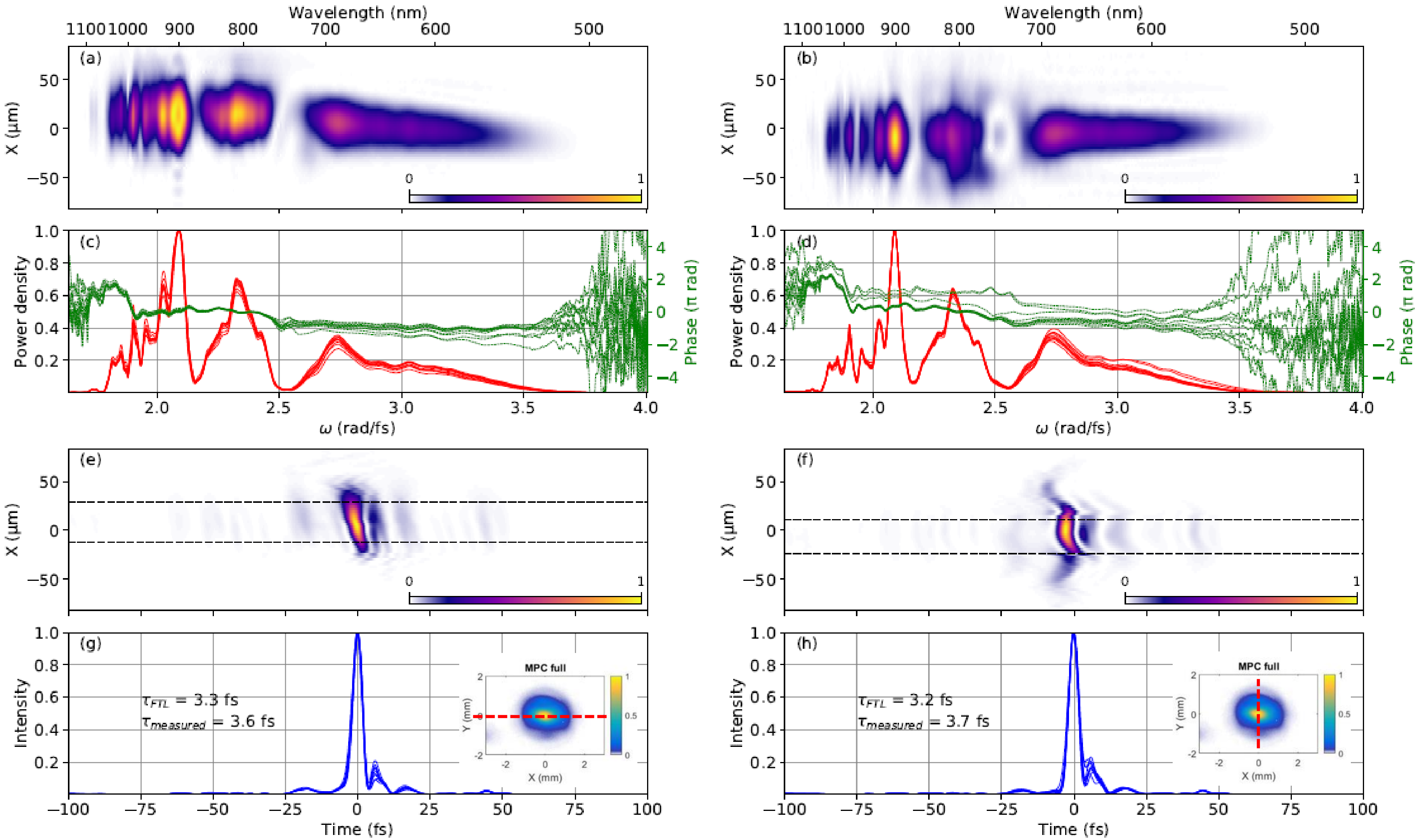
Spatially-resolved SPIDER: near single cycle pulses with space-time couplings



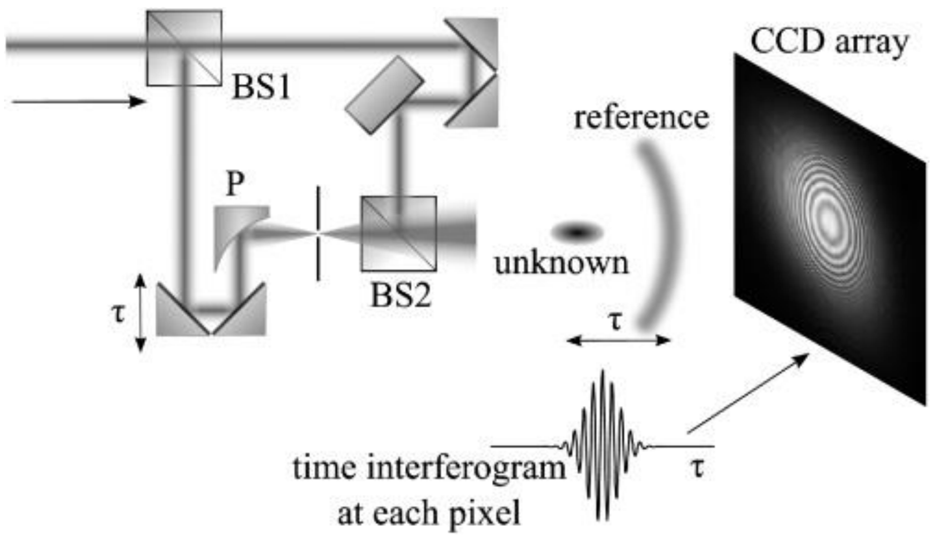
Lu et al., Opt. Exp. 26, 8941 (2018)

Spatially-resolved SPIDER



Data from Lu et al., Opt. Exp. 26, 8941 (2018)

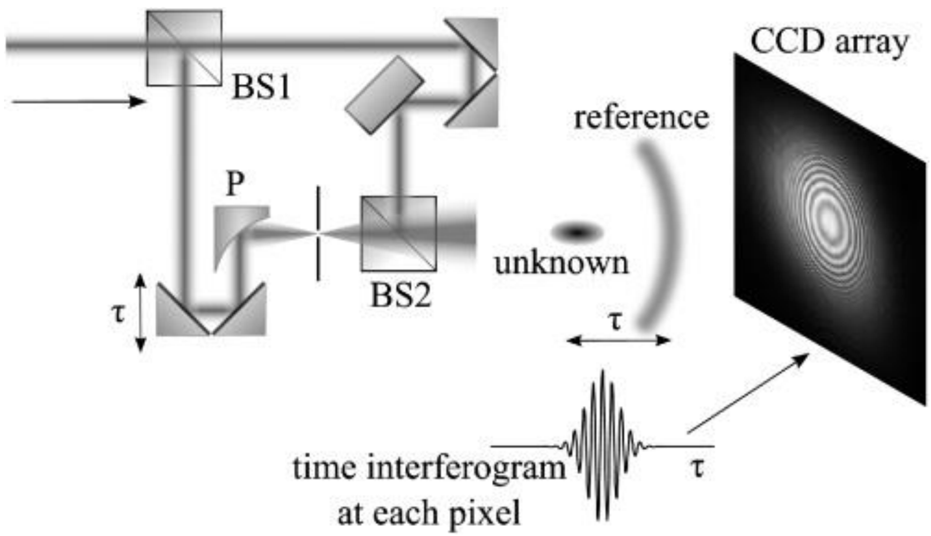
(almost) Full-3D characterization



Fourier-Transform spectrometry at each pixel of the CCD

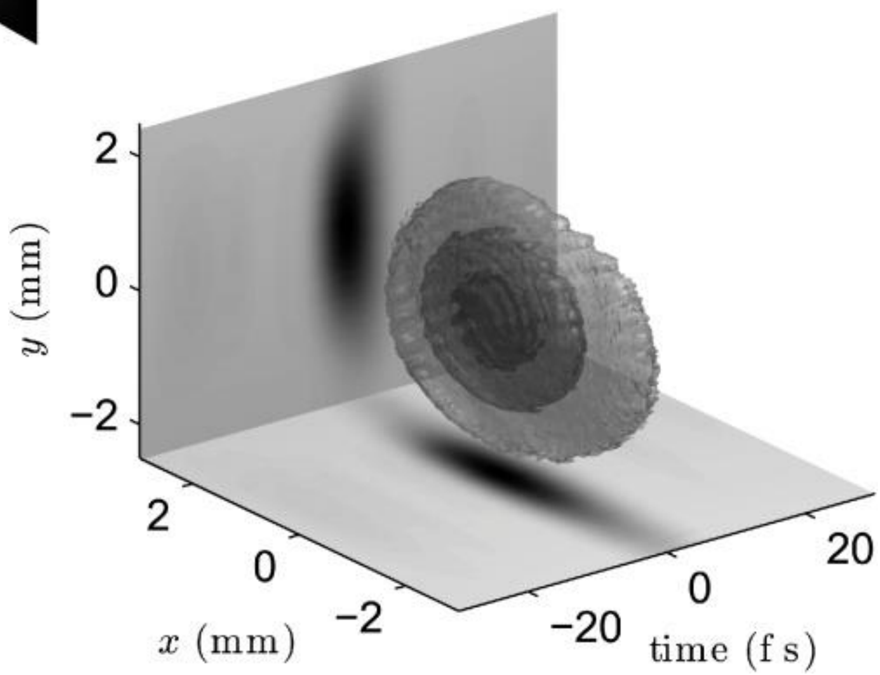
Miranda et al., Opt. Lett. 1, 400 (2018)

(almost) Full-3D characterization



Fourier-Transform spectrometry at each pixel of the CCD

+ 1D pulse characterization at one point (x_o,y_o) e.g. with d-scan



Miranda et al., Opt. Lett. 1, 400 (2018)

Suggested literature

J.-C. Diels and W. Rudolph, *Ultrashort Laser Pulse Phenomena,* (Academic Press, 2006)

Ian A. Walmsley and Christophe Dorrer, "Characterization of ultrashort electromagnetic pulses," Adv. Opt. Photon. 1, 308-437 (2009)

https://frog.gatech.edu/tutorial.html

Spencer W Jolly, Olivier Gobert and Fabien Quéré, "Spatio-temporal characterization of ultrashort laser beams: a tutorial," Journal of Optics, Volume 22, Number 10 (2020)