How to deal with femtosecond pulses

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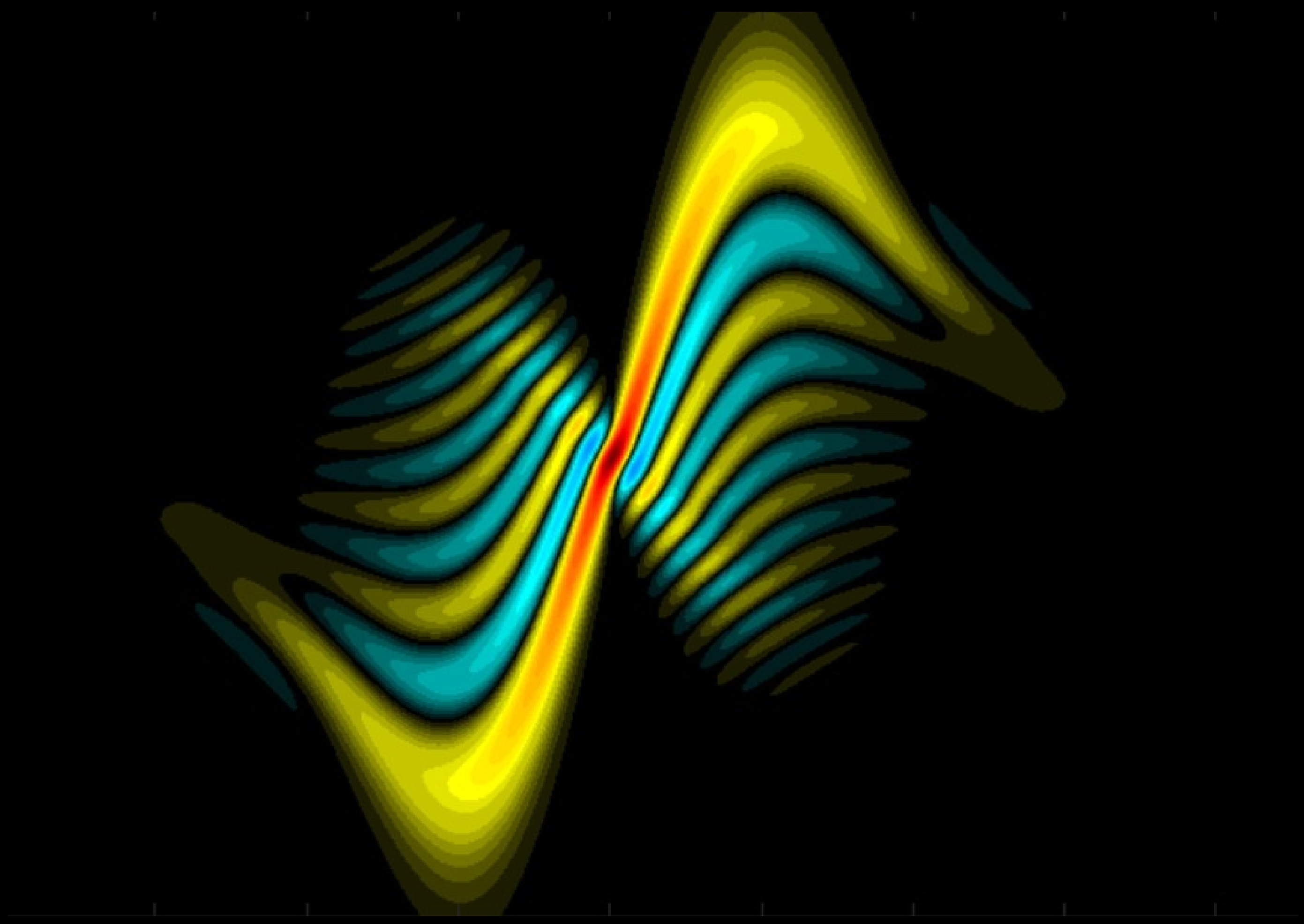
Sébastien Weber, CEMES Toulouse, CNRS

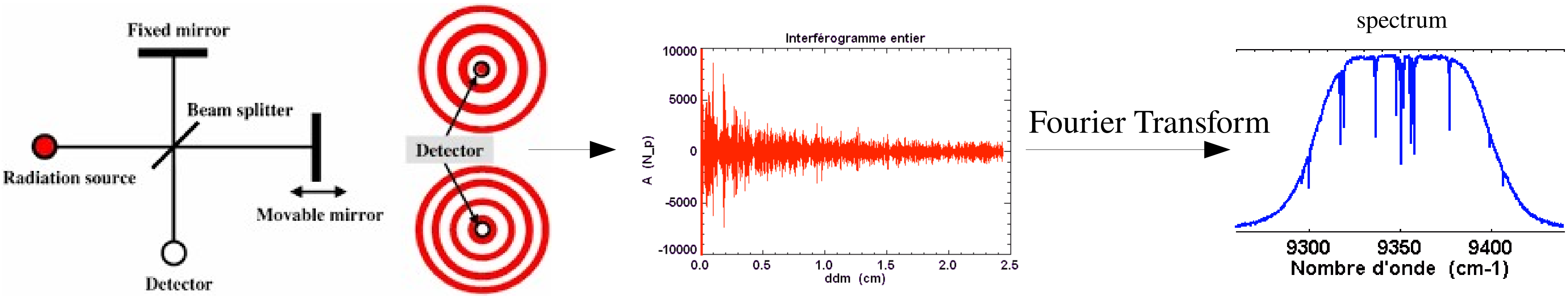
II – Characterization



Time and spectrum

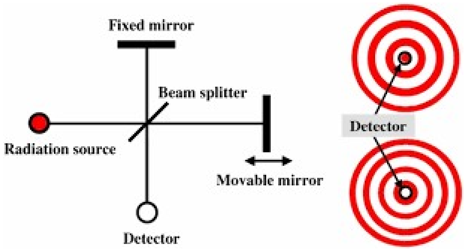
The spectral width of a light source defines its **coherence time** $\tau_c = 1/\Delta\nu$
(coherence = ability to produce interferences)

Measurement: linear (field) autocorrelation = Fourier transform spectroscopy



No temporal information in the field autocorrelation ?

A few examples of field autocorrelation



Measurement : slow detector → Measures the intensity of the total field

$$I_{tot}(\tau) = \int |E_{tot}(t)|^2 dt$$

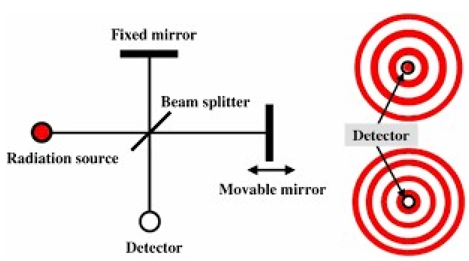
$$I_{tot}(\tau) = \int |E(t) + E(t-\tau)|^2 dt = \int |E(t)|^2 \, dt + \int |E(t-\tau)|^2 \, dt + 2 \int E(t) E^*(t-\tau) dt$$

$$I_{tot}(\tau) = 2 \int |E(t)|^2 \, dt + 2A(\tau)$$

$$A(\tau) = \int E(t) E^*(t-\tau) dt$$

Field autocorrelation function

A few examples of field autocorrelation



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$$I_{tot}(\tau) = 2\int |E(t)|^2 dt + 2A(\tau)$$

$$A(\tau) = \int E(t)E^*(t-\tau)dt$$

Field autocorrelation function

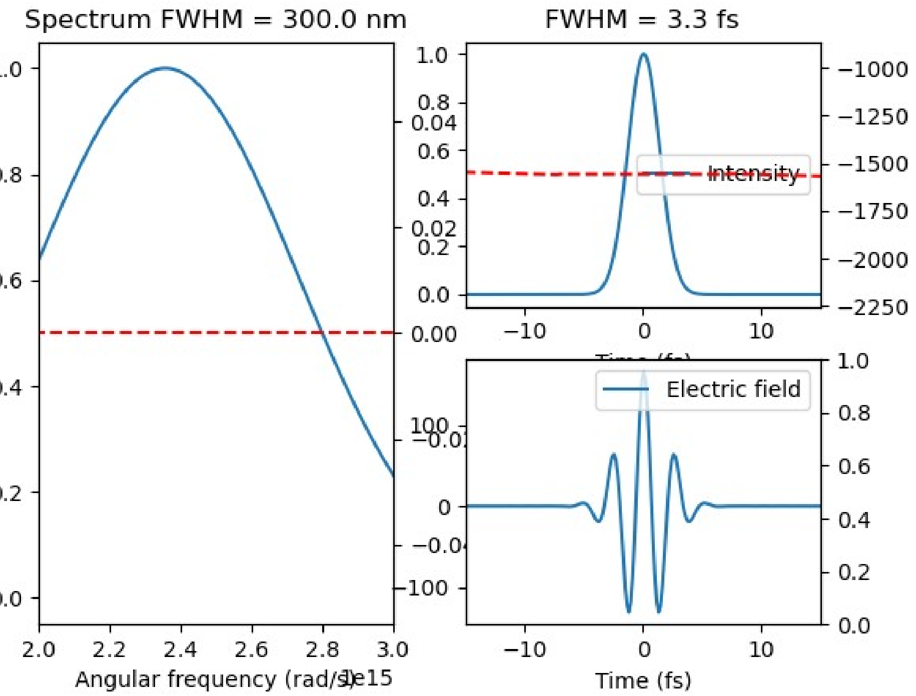
4 cases :

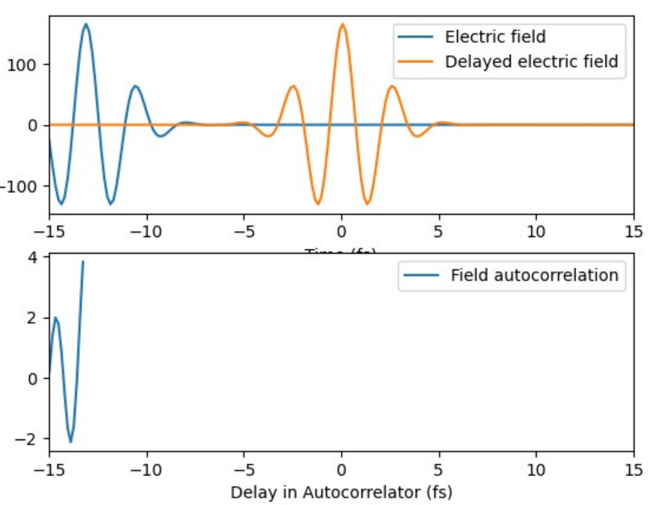
- Broaband Fourier-Limited pulse
- Broadband Chirped pulse
- Broadband High-order Spectral Phase pulse
- Narroband Fourier Limited pulse

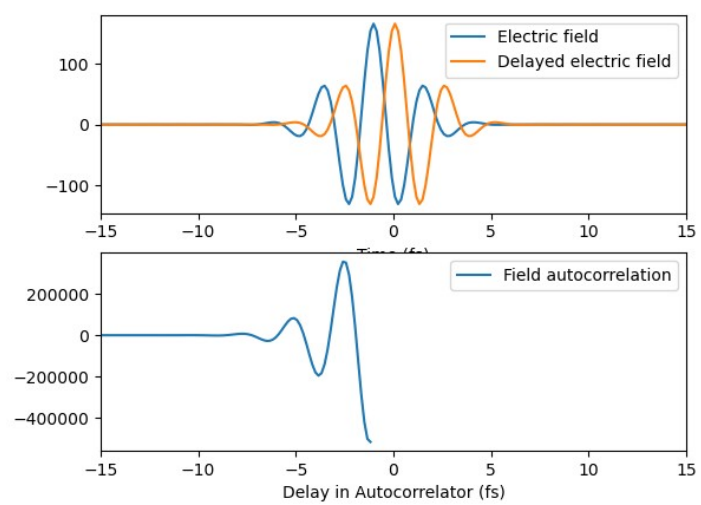
```
A[i0+i]=sum((E_t_0)*roll(conjugate(E_t_0),i0+i-round(size(t)/2)))
```

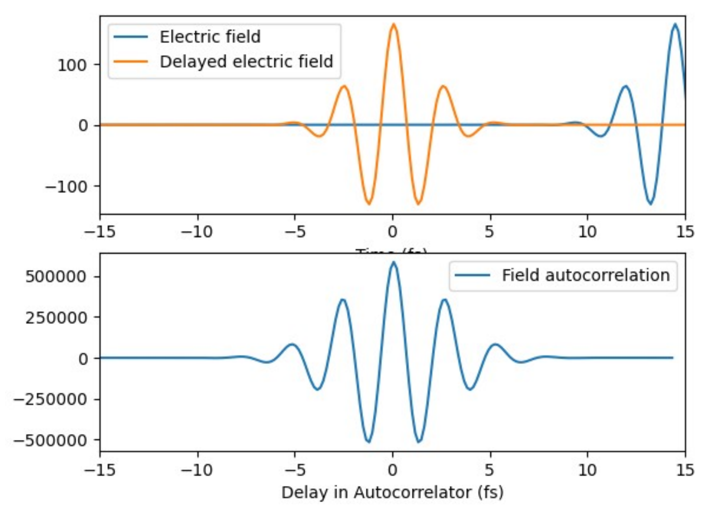
A few examples of field autocorrelation

Broadband Fourier-Limited pulse



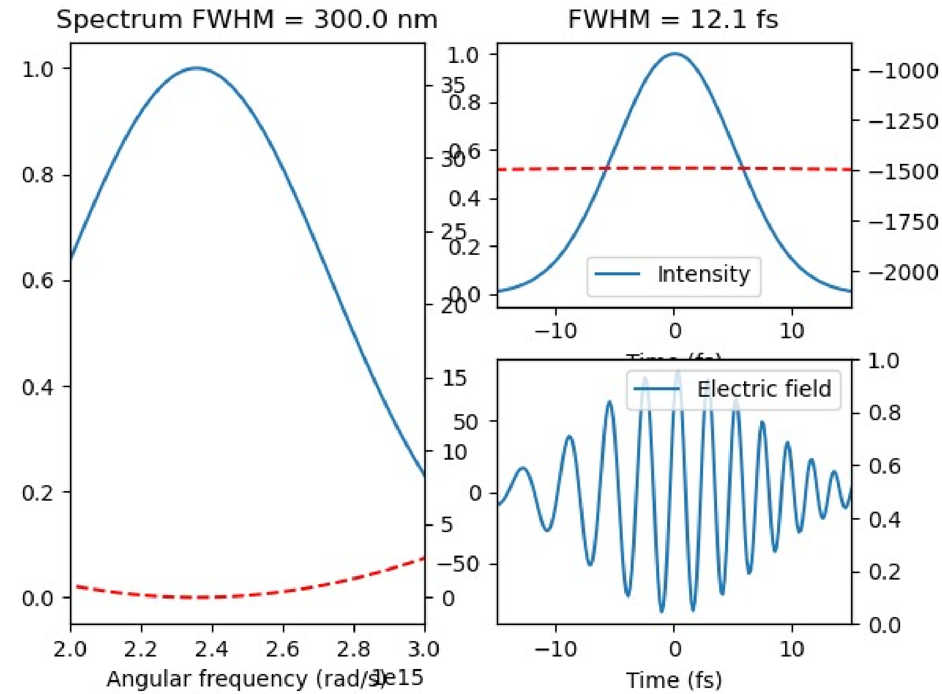


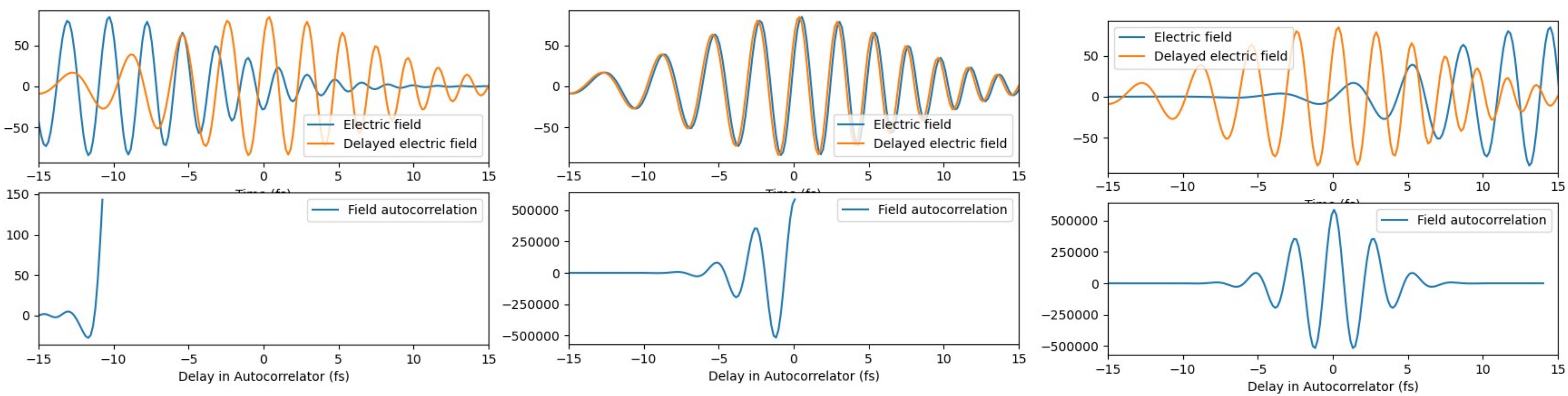




A few examples of field autocorrelation

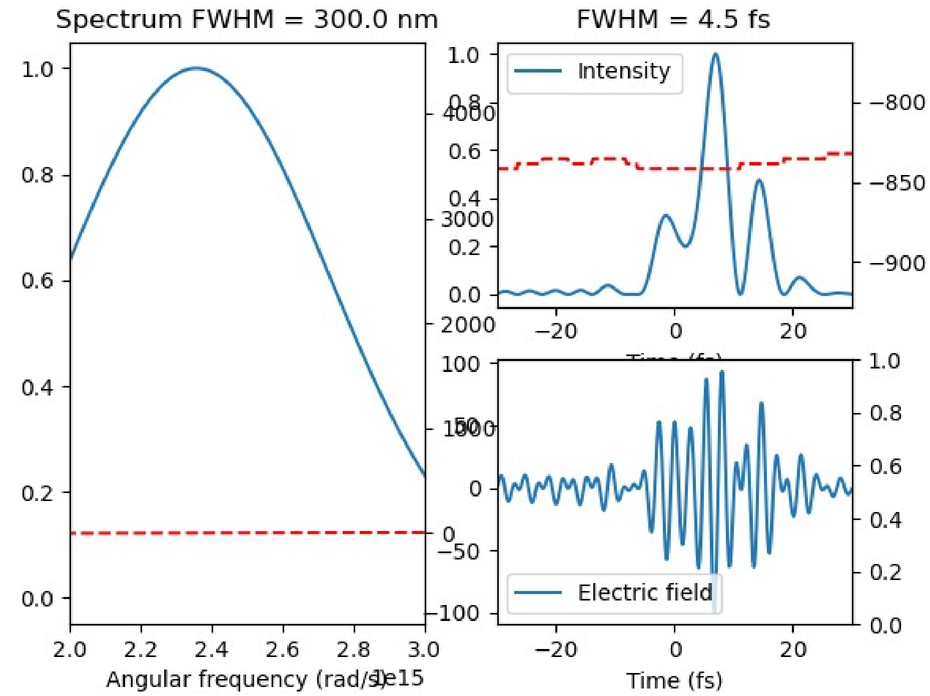
Broadband Chirped pulse

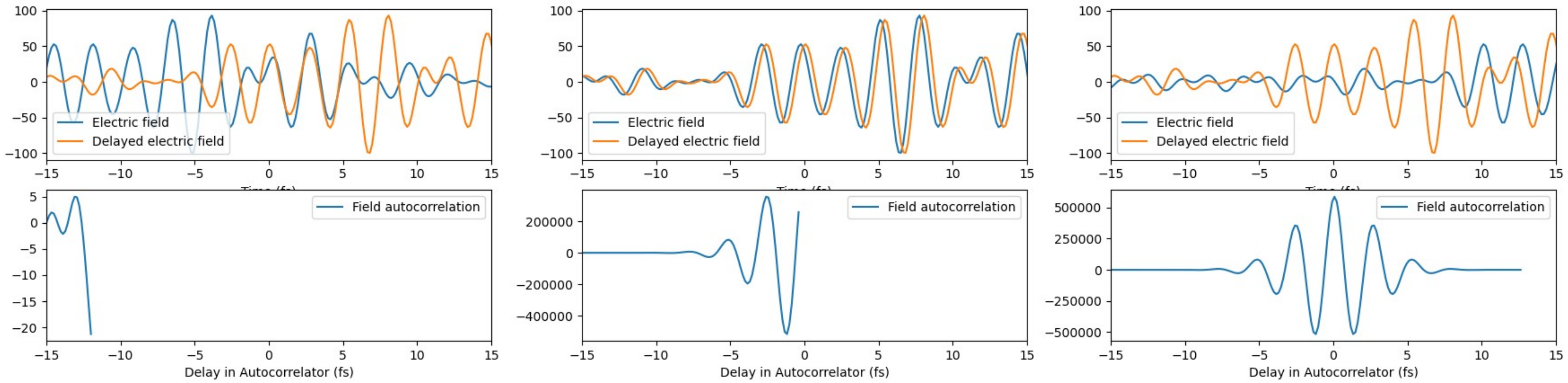




A few examples of field autocorrelation

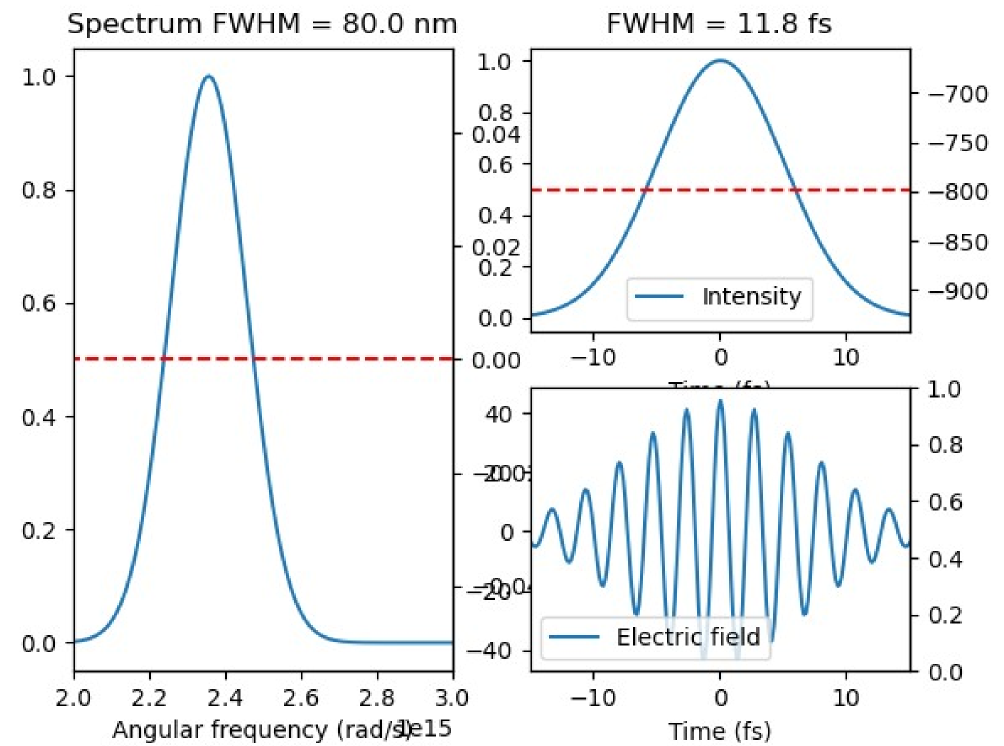
Broadband High-order Spectral Phase pulse

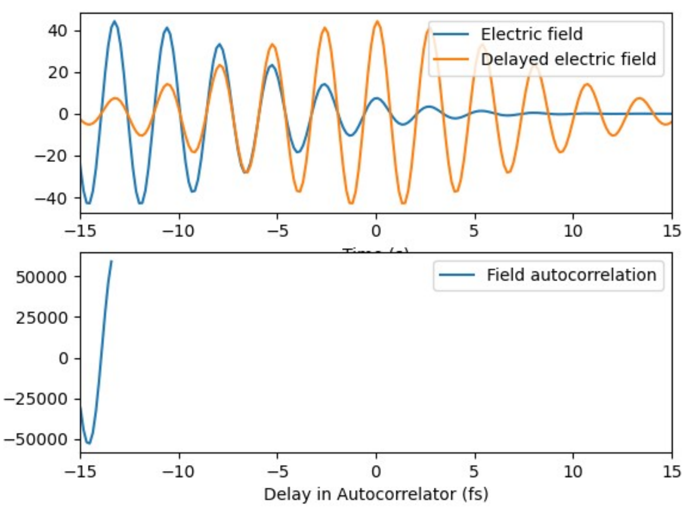


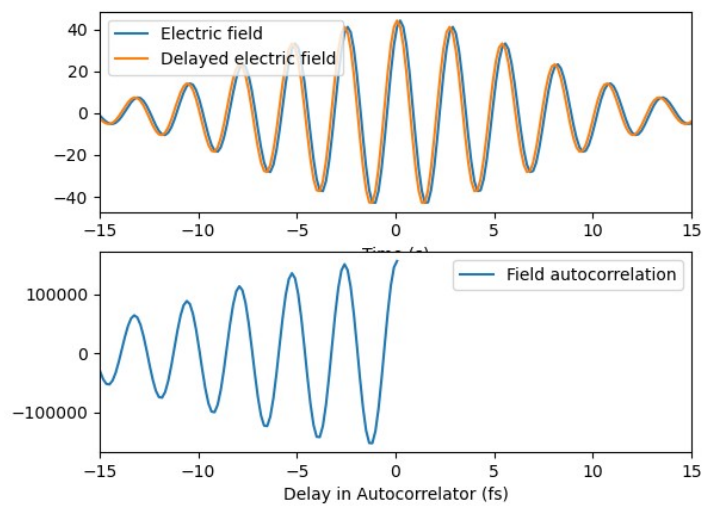


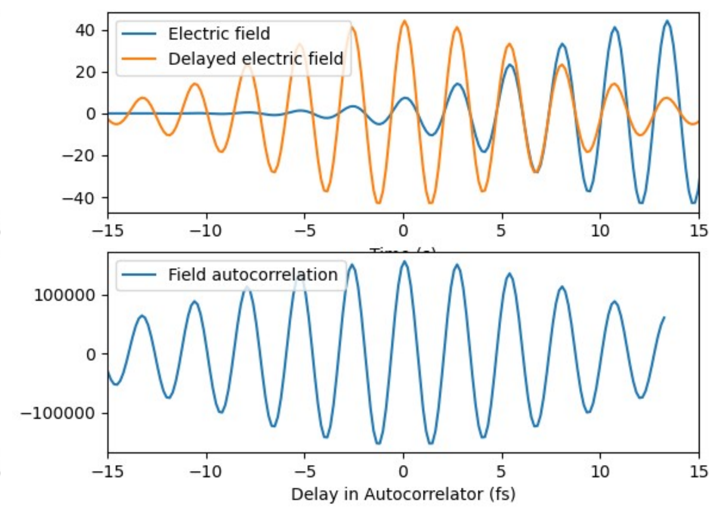
A few examples of field autocorrelation

Narroband Fourier Limited pulse

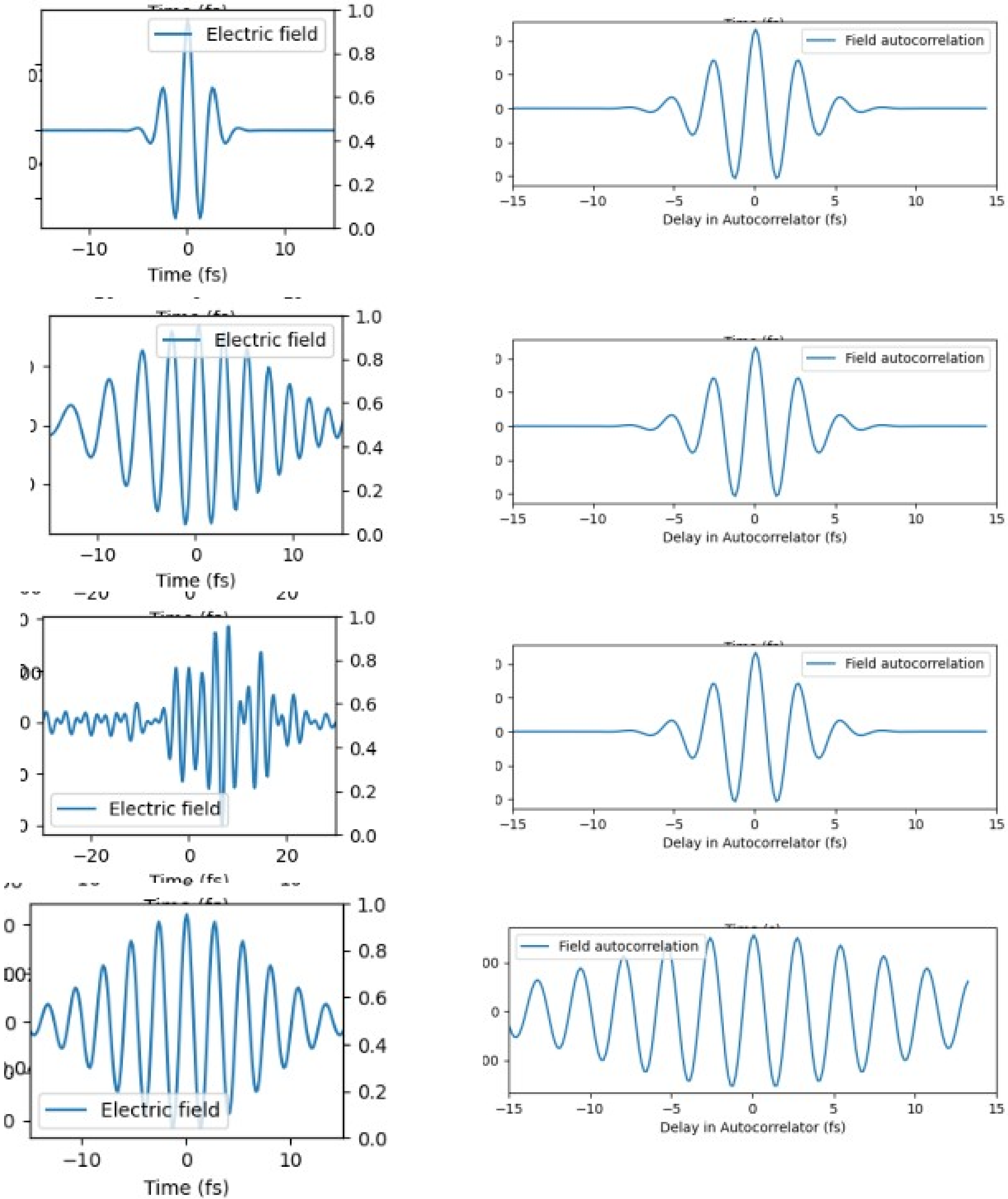








Recap



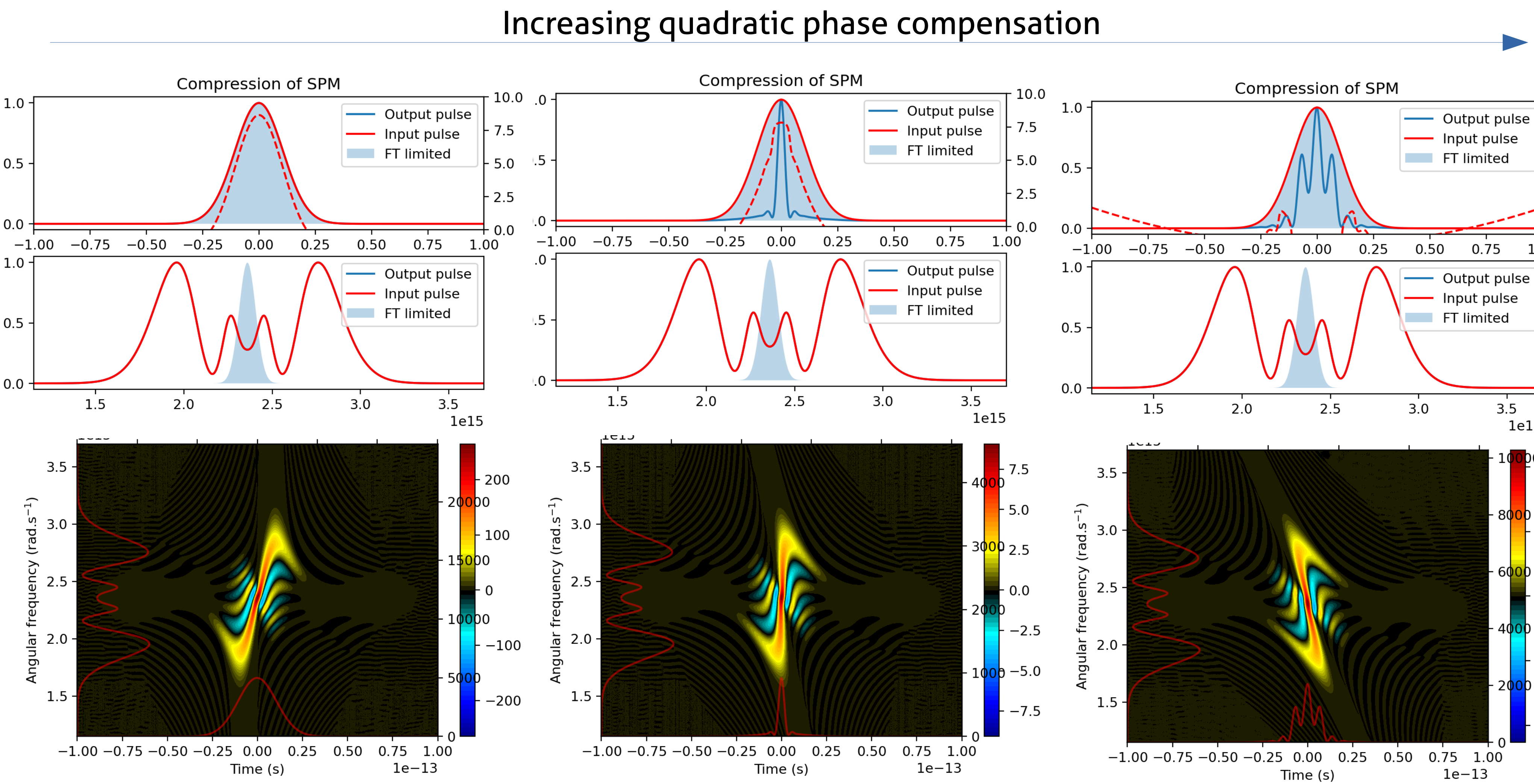
The only information contained
in the field autocorrelation
is the spectrum

Wiener Khinchin theorem

How can we get access to spectral phase or temporal profile ?

What we can easily measure : Spectrum

Adding spectral phase does not modify the spectrum



$$S = \int_{-\infty}^{+\infty} |E'(t)|^2 dt = \int_{-\infty}^{+\infty} |E'(\omega)|^2 \frac{d\omega}{2\pi}$$

Case of a linear and stationnary filter, with response R(t,t') :

$$E'(t) = \int_{-\infty}^{+\infty} R(t,t')E(t')dt' = \int_{-\infty}^{+\infty} R(t-t')E(t')dt'$$

$\longrightarrow$ $E'(\omega) = R(\omega)E(\omega)$ (Transfert function)

$$\longrightarrow \quad S = \int_{-\infty}^{+\infty} |R(\omega)|^2 |E(\omega)|^2 \frac{d\omega}{2\pi}$$

The spectrum is simply modified by the filter’s spectral response

→ A nonlinear or a non-stationnary filter is necessary

Different measurement schemes

Characterization of ultrashort electromagnetic pulses

Ian A. Walmsley[1] and Christophe Dorrer[2]

[1]Department of Physics, University of Oxford, Clarendon Laboratory, Parks Road, Oxford, OX1 3PU, UK, walmsley@physics.ox.ac.uk

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Ultrafast optics has undergone a revolution in the past two decades, driven by new methods of pulse generation, amplification, manipulation, and measurement. We review the advances made in the latter field over this period, indicating the general principles involved, how these have been implemented in various experimental approaches, and how the most popular methods encode the temporal electric field of a short optical pulse in the measured signal and extract the field from the data. © 2009 Optical Society of America

OCIS codes: 320.7100, 140.7090.

Advances in Optics and Photonics 1, 308–437 (2009) doi:10.1364/AOP.1.000308 308
1943-8206/09/020308-130/$15.00 © OSA

Interferometry → directly measure the spectral phase (SPIDER…)
Spectrography → Measure a spectrogram (FROG…)
Tomography → Measure projections of the Wigner distribution and retrieve it

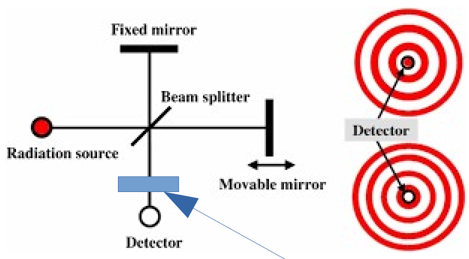
Autocorrelations

FROG

D-scan

Time-domain strong field methods

Second order interferometric autocorrelation



Let's add a frequency doubling crystal here

Measurement : slow detector → Measures the intensity of the total field

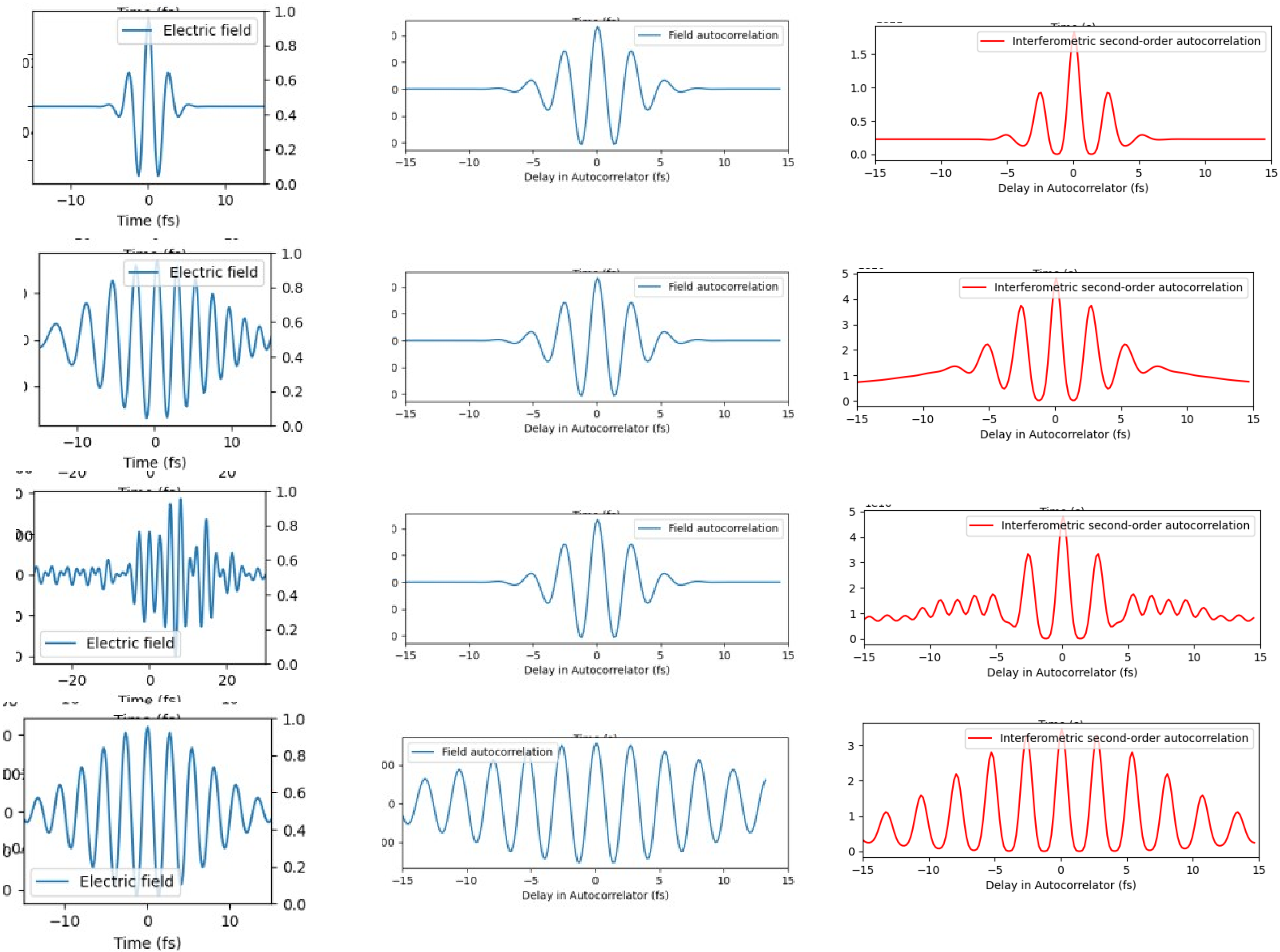
$$I_{tot}(\tau) = \int \left|(E(t) + E(t-\tau))^2\right|^2 dt$$

4 cases :

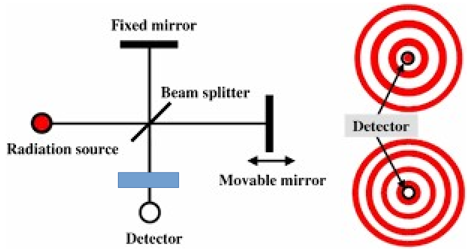
- Broaband Fourier-Limited pulse
- Broadband Chirped pulse
- Broadband High-order Spectral Phase pulse
- Narroband Fourier Limited pulse

```
IA[i0+i]=sum(abs((E_t_0+roll((E_t_0),i0+i-round(size(t)/2)))**2)**2)
```

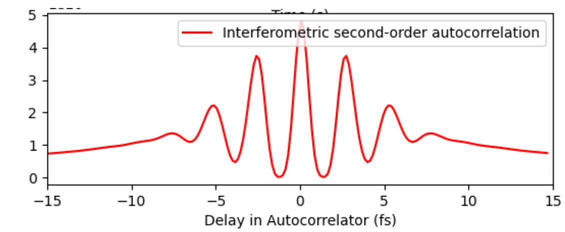
Recap


Electric field
Time (fs)
Field autocorrelation
Delay in Autocorrelator (fs)
Interferometric second-order autocorrelation
Delay in Autocorrelator (fs)

Intensity autocorrelation



The second-order interferometric autocorrelation mixes information on duration and coherence



More straightforward observable ?

Go non-colinear

Extract the signal coming from the product of E(t) and E(t-τ)

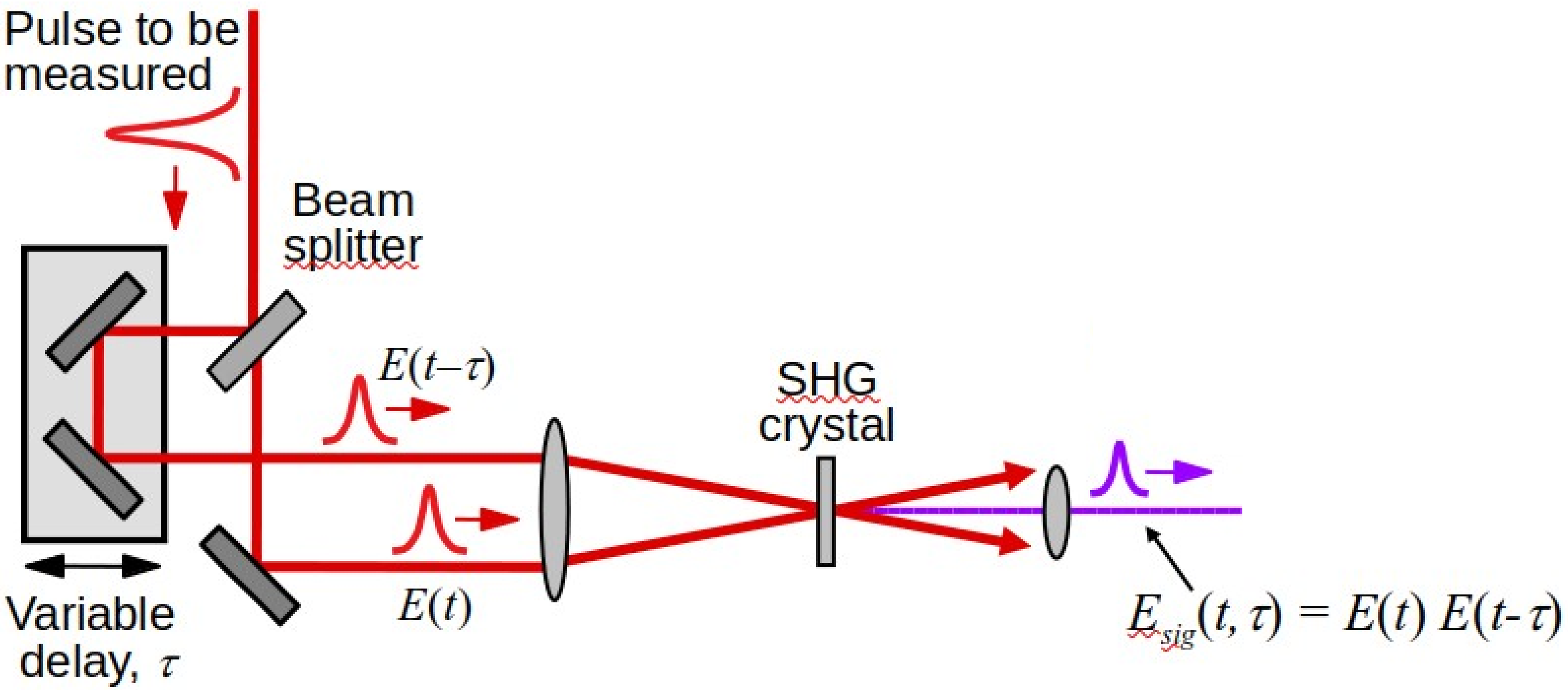
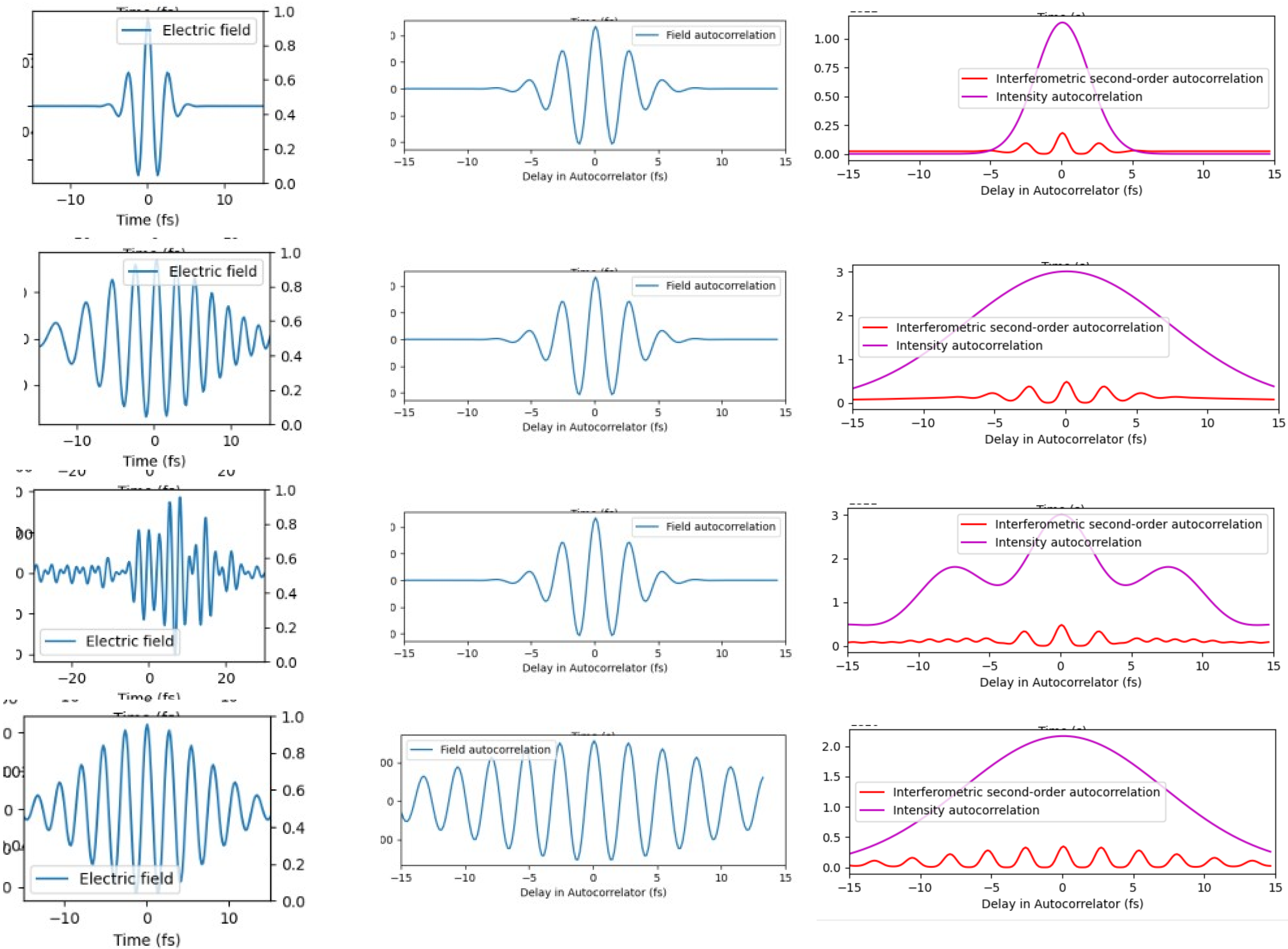


Figure from Rick Trebino's lectures : https://frog.gatech.edu/lectures.html

$$I_{tot}(\tau) = \int |E(t)E(t-\tau)|^2 dt = \int I(t)I(t-\tau)dt$$

Recap



Electric field
Time (fs)
Field autocorrelation
Delay in Autocorrelator (fs)
Interferometric second-order autocorrelation
Intensity autocorrelation
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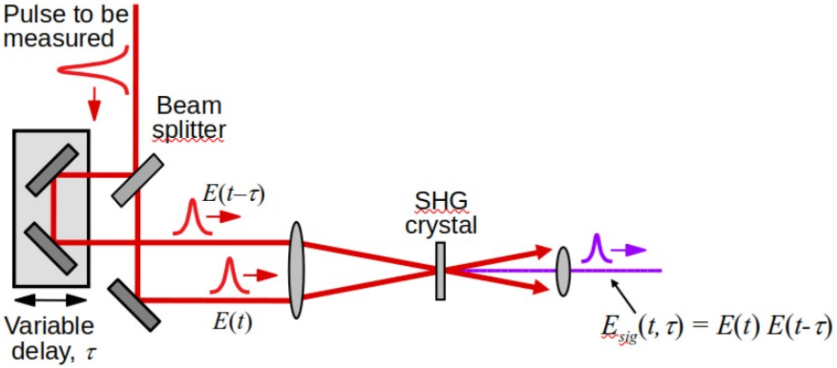
Intensity autocorrelation



Very easy to implement
Can do single shot measurements
Rather straightforward interpretation

Intensity autocorrelation

Generation of high energy 10 fs pulses by a new pulse compression technique

M. Nisoli, S. De Silvestri, and O. Svelto
Centro di Elettronica Quantistica e Strumentazione Elettronica–CNR, Dipartimento di Fisica, Politecnico, Piazza L. da Vinci 32, 20133 Milano, Italy

(Received 12 January 1996; accepted for publication 11 March 1996)

An optical compression technique which is particularly suitable for ultrashort pulses of high energy is presented. Spectral broadening is achieved by pulse propagation along a hollow-core fused silica waveguide filled with noble gases at high pressure. Pulse compression is then obtained in a prisms dispersive delay line. Experiments performed with pulses of 140 fs duration and 660 μJ energy from a Ti:sapphire laser demonstrate the generation of compressed pulses of 10 fs duration and 240 μJ energy. © *1996 American Institute of Physics.* [S0003-6951(96)03920-4]

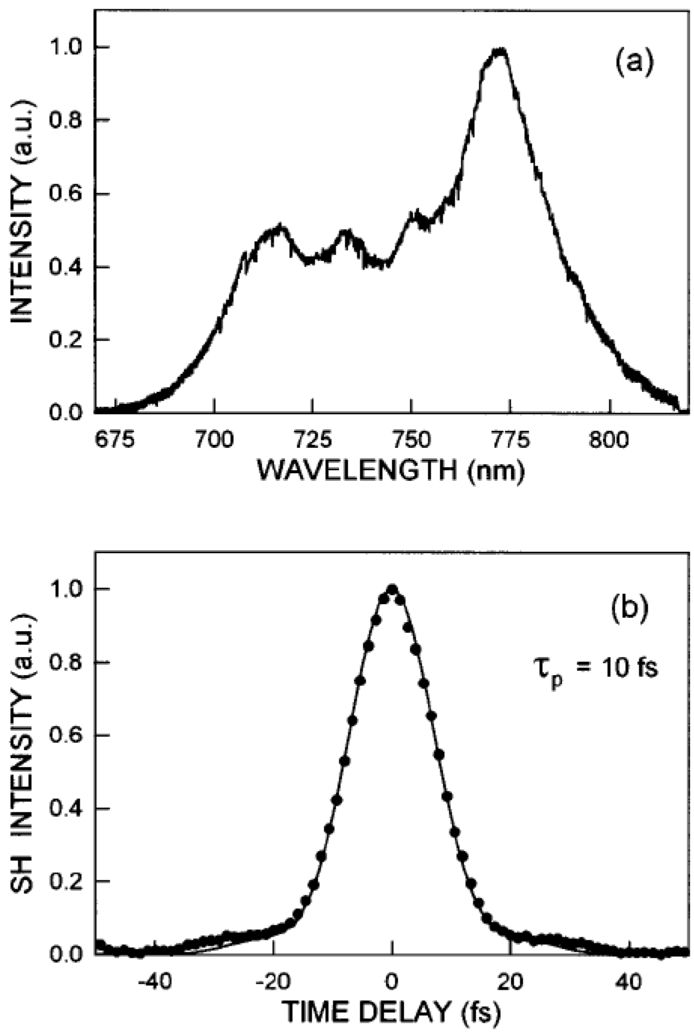
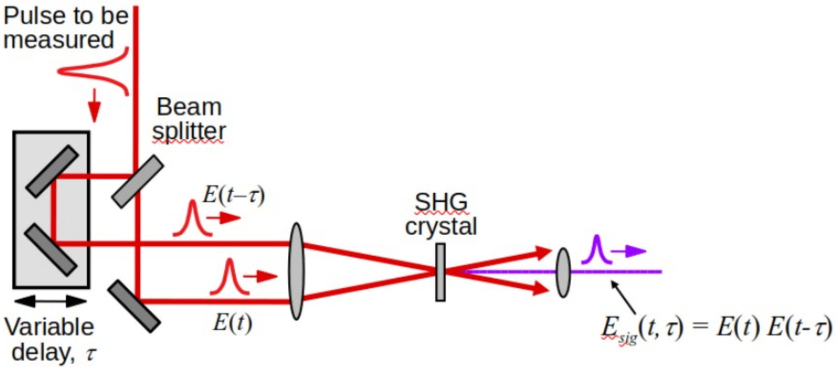


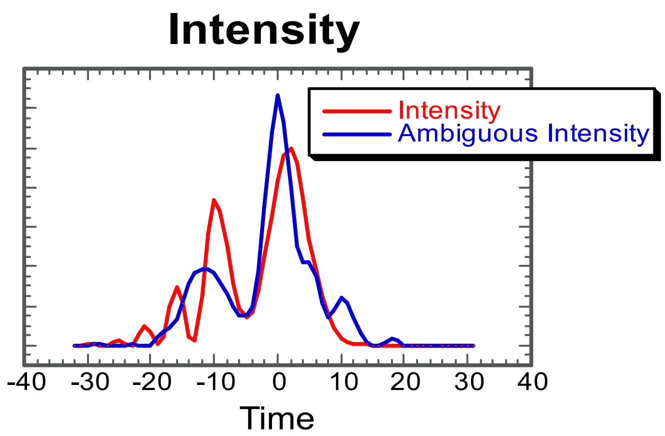
FIG. 3. (a) Selected portion of the spectrum obtained with krypton at $p=2$ atm and $P_0=3.5$ GW; (b) SH intensity autocorrelation function (dots) of the compressed pulses and autocorrelation trace (solid curve) of the pulses obtained by taking the inverse Fourier transform of the spectrum in (a). Pulse duration τ_p was estimated assuming a sech^2 pulse shape.

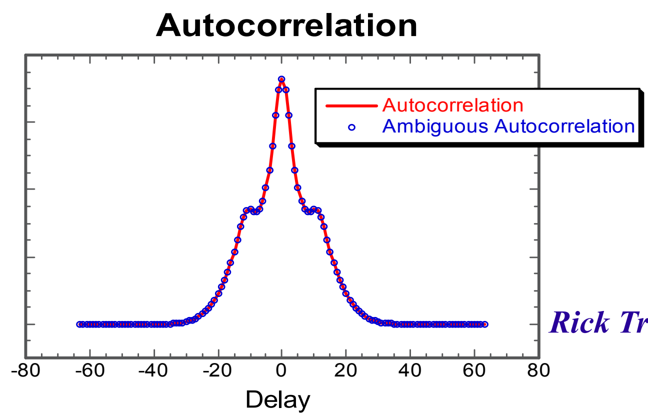
Intensity autocorrelation



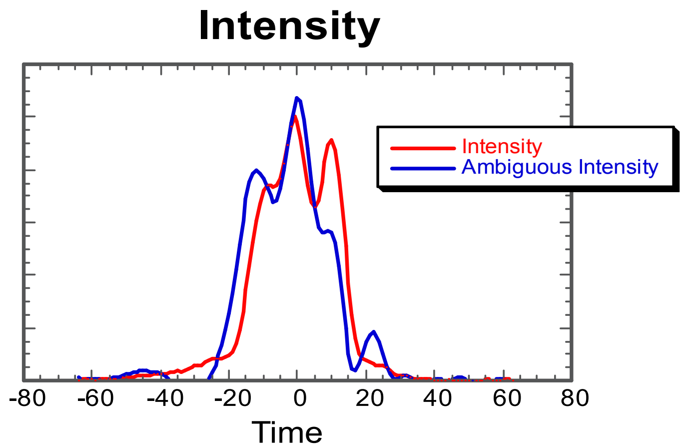
Very easy to implement
Can do single shot measurements
Rather straightforward interpretation

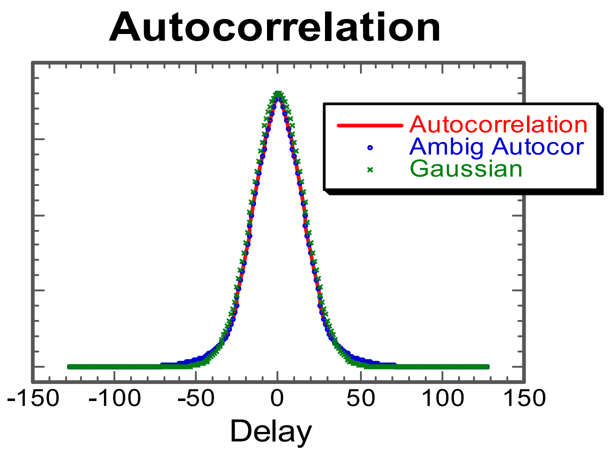
BUT :
Dont use this with complicated pulse shapes





Rick Trebino, GaTech University





Autocorrelations

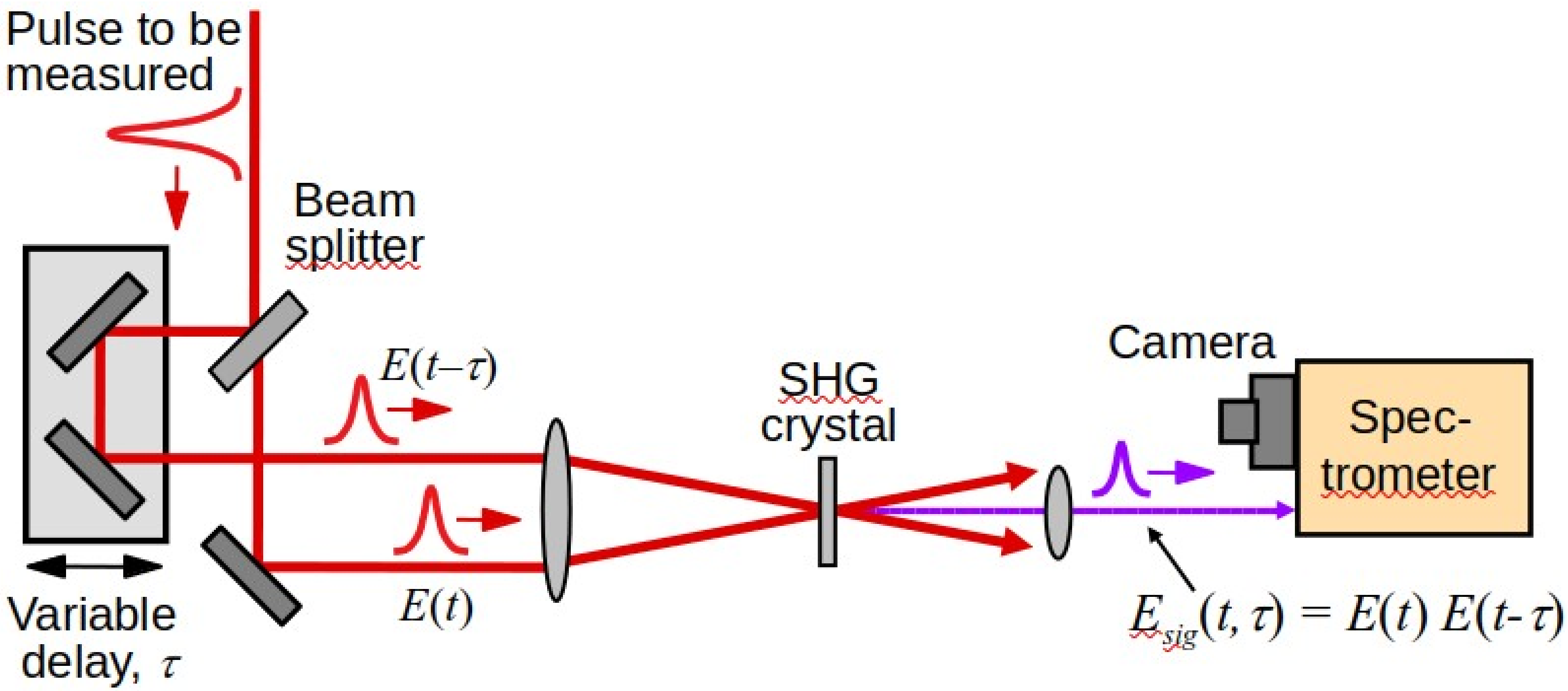
FROG

d-Scan

Time-domain strong field methods

Beyond autocorrelation ?

Add a spectrometer to resolve the spectrum of the signal



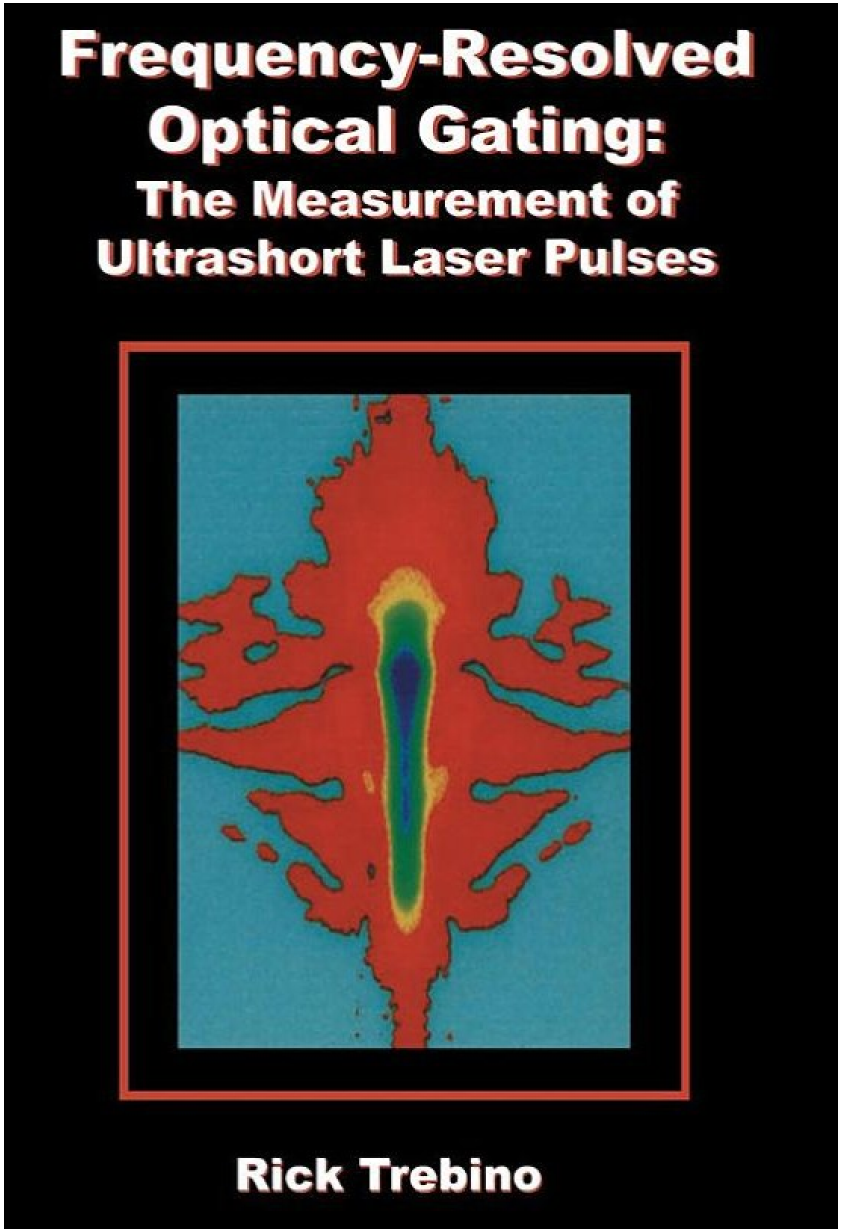
$$S(\omega,\tau) = \left| \int E(t)E(t-\tau)e^{i\omega t}dt \right|^2$$

$$S(\omega,\tau) = \left| \int E(t)G(t-\tau)e^{i\omega t}dt \right|^2$$

This is a spectrogram in which the pulse gates itself

Frequency-Resolved Optical Gating – FROG

FROG



$$S(\omega,\tau) = \left| \int E(t)E(t-\tau)e^{i\omega t}dt \right|^2$$

$$S(\omega,\tau) = \left| \int E(t)G(t-\tau)e^{i\omega t}dt \right|^2$$

Key idea : the generated spectrograms encode all the information on the temporal and spectral complex properties of the pulse
(except the carrier-envelop phase)

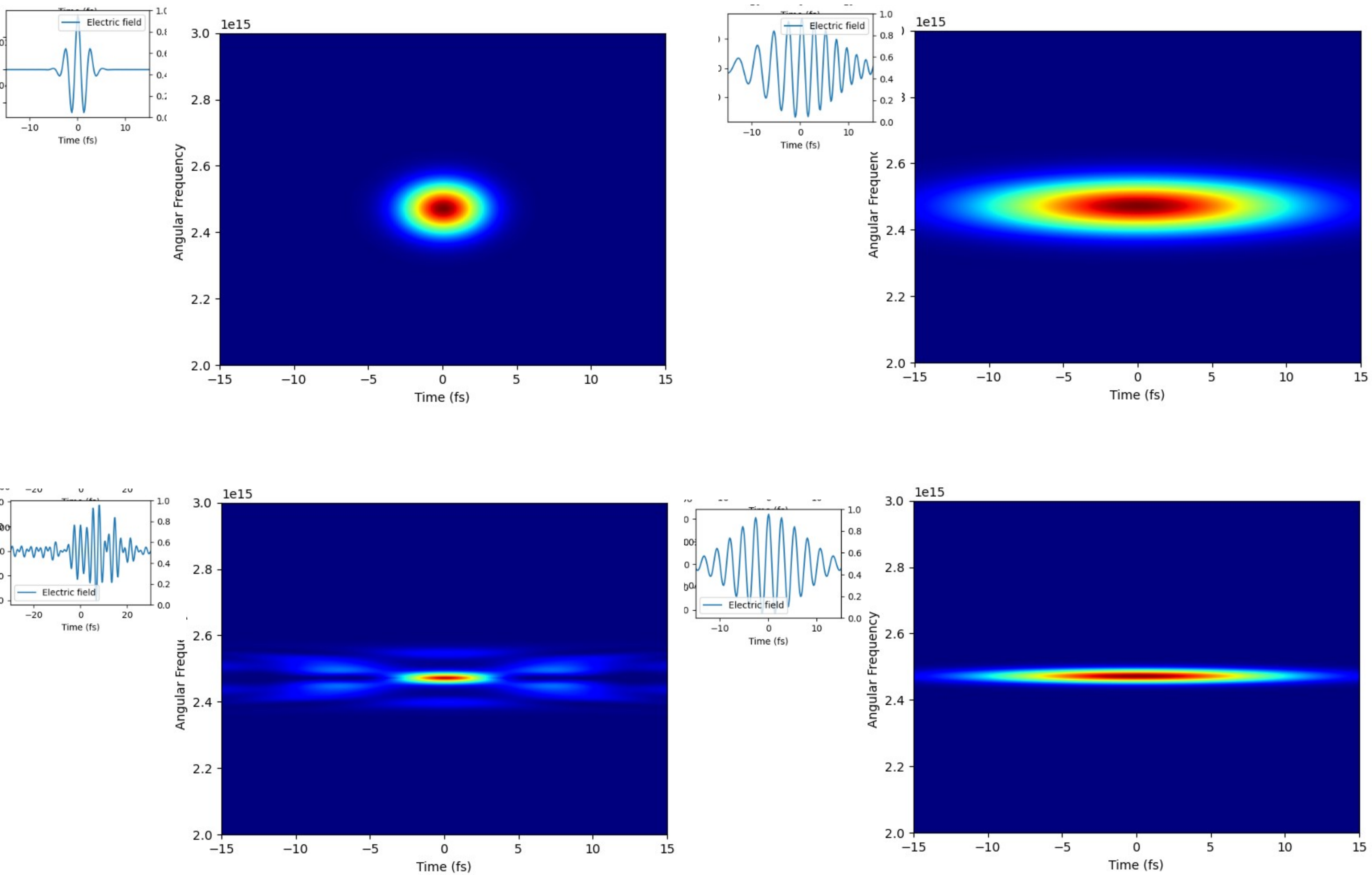
Beyond autocorrelation ?

Add a spectrometer to resolve the spectrum of the signal

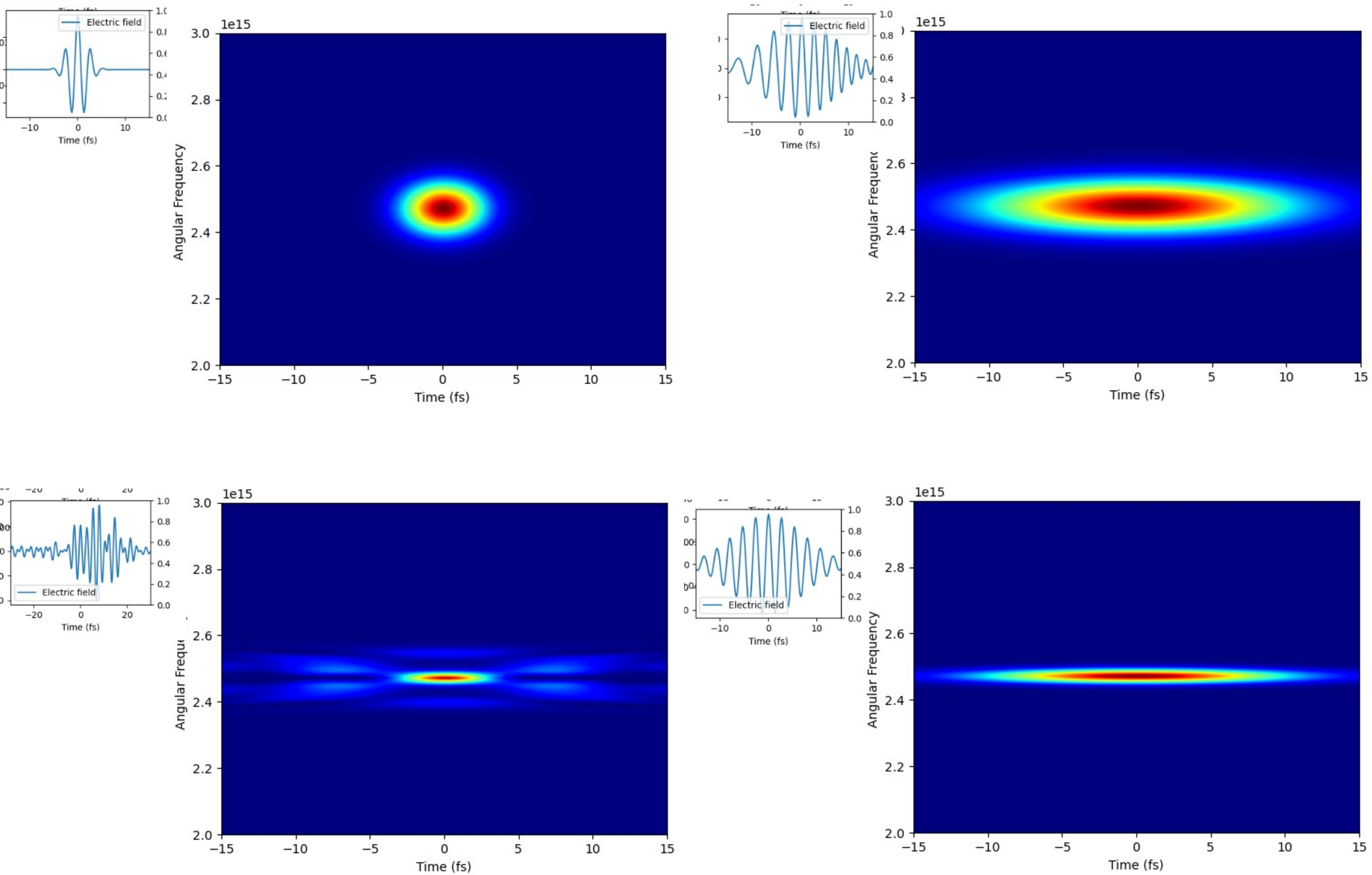
$$S(\omega,\tau) = \left| \int E(t)E(t-\tau)e^{i\omega t}dt \right|^2$$

```
def shgfrog(t,E_t,zp):
    S=zeros((len(t),zp),dtype=complex)
    for i,tau in enumerate(t):
        S[i,:]=ifftshift(ifft(E_t*roll(E_t,i-round(size(t)/2)),zp))
    return transpose(S)
```

Calculating SHGFROG traces



Calculating SHGFROG traces



Information not as straightfoward as in Gabor analysis, because of the SHG process
Other versions of FROG provide more intuitive traces (THG, PG…)

Pulse reconstruction

The pulse and gate can be retrived from S(ω,τ)

How can the phase of E(t) et G(t) be retrieved?

In 1D, this problem cannot be solved : the phase of a pulse cannot be retrived from its spectrum S(ω).

In 2D, this problem can be solved, and has been solved for a long time in image processing

Stark, Image Recovery, Academic Press, 1987.

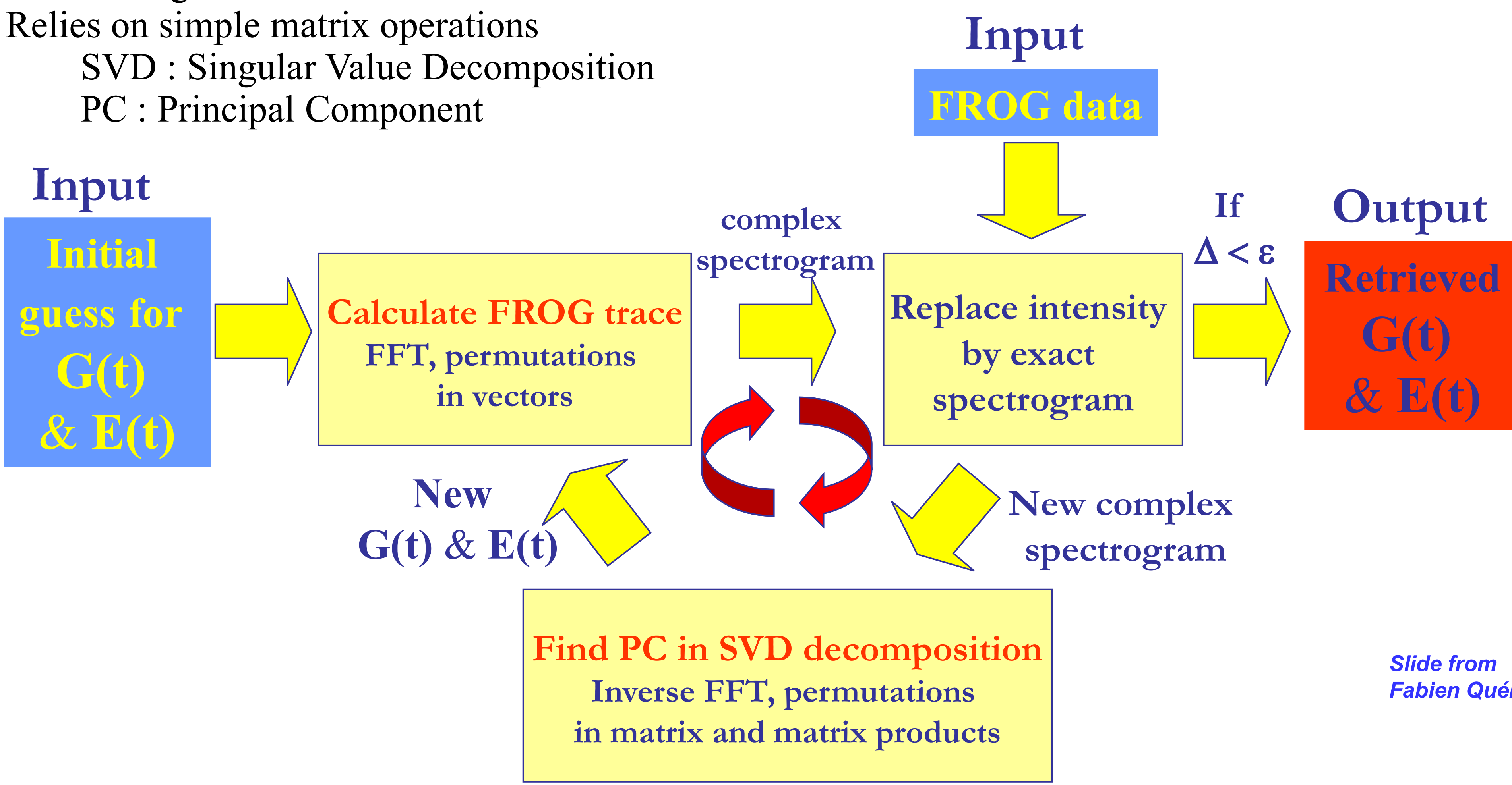
Example : Principal Component Generalized Projections Algorithm

*D. Kane, IEEE J. Quant. Elec. **35**, 421 (1999)*

Iterative algorithm

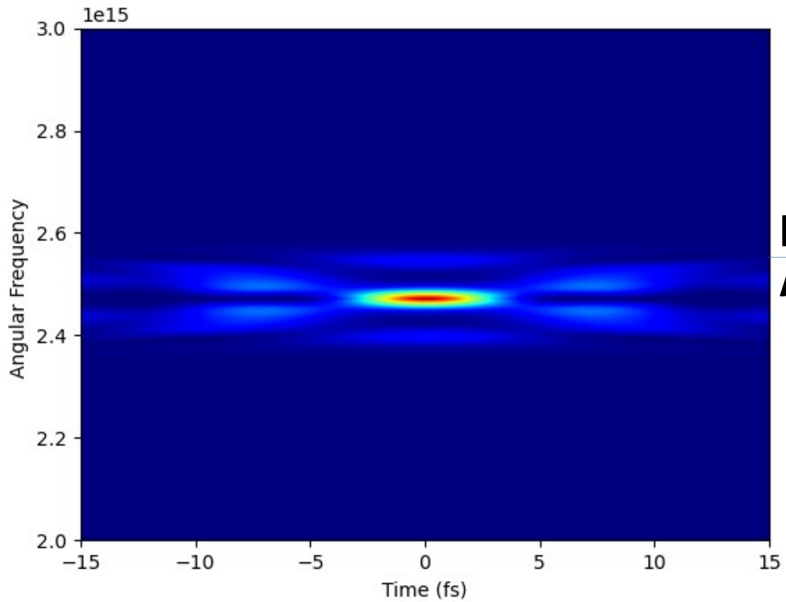
Relies on simple matrix operations

- SVD : Singular Value Decomposition
- PC : Principal Component

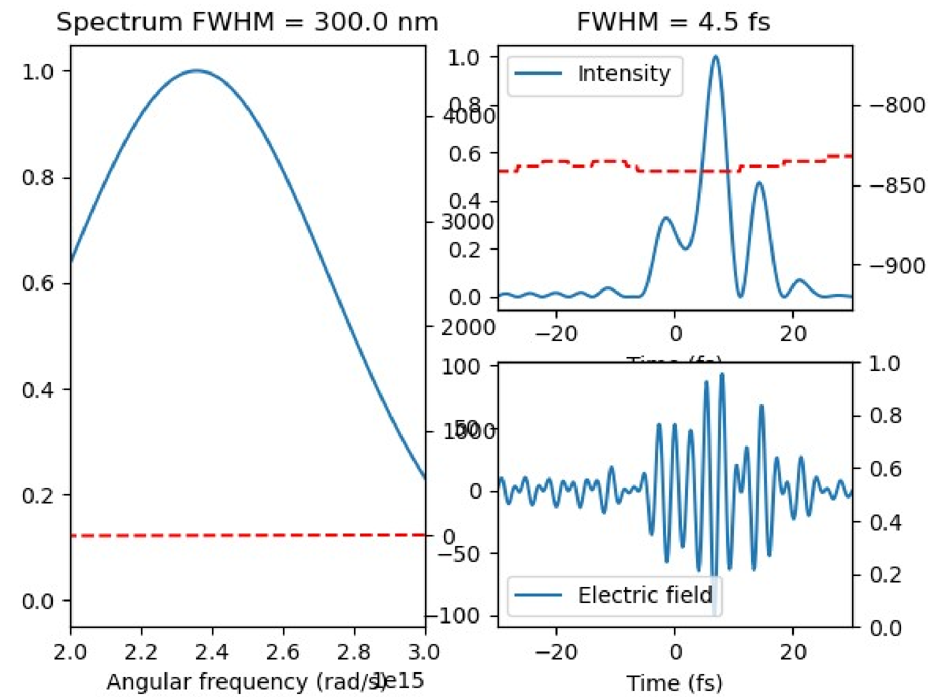


Slide from Fabien Quéré

Pulse reconstruction



Iterative Algorithm



Complete reconstruction of the pulse :

spectrum + spectral phase / temporal intensity + temporal phase

Need to retrieve N amplitudes and N phases, from a N^2 points trace

→ High redundancy of information

→ Robust against noise

Pulse reconstruction

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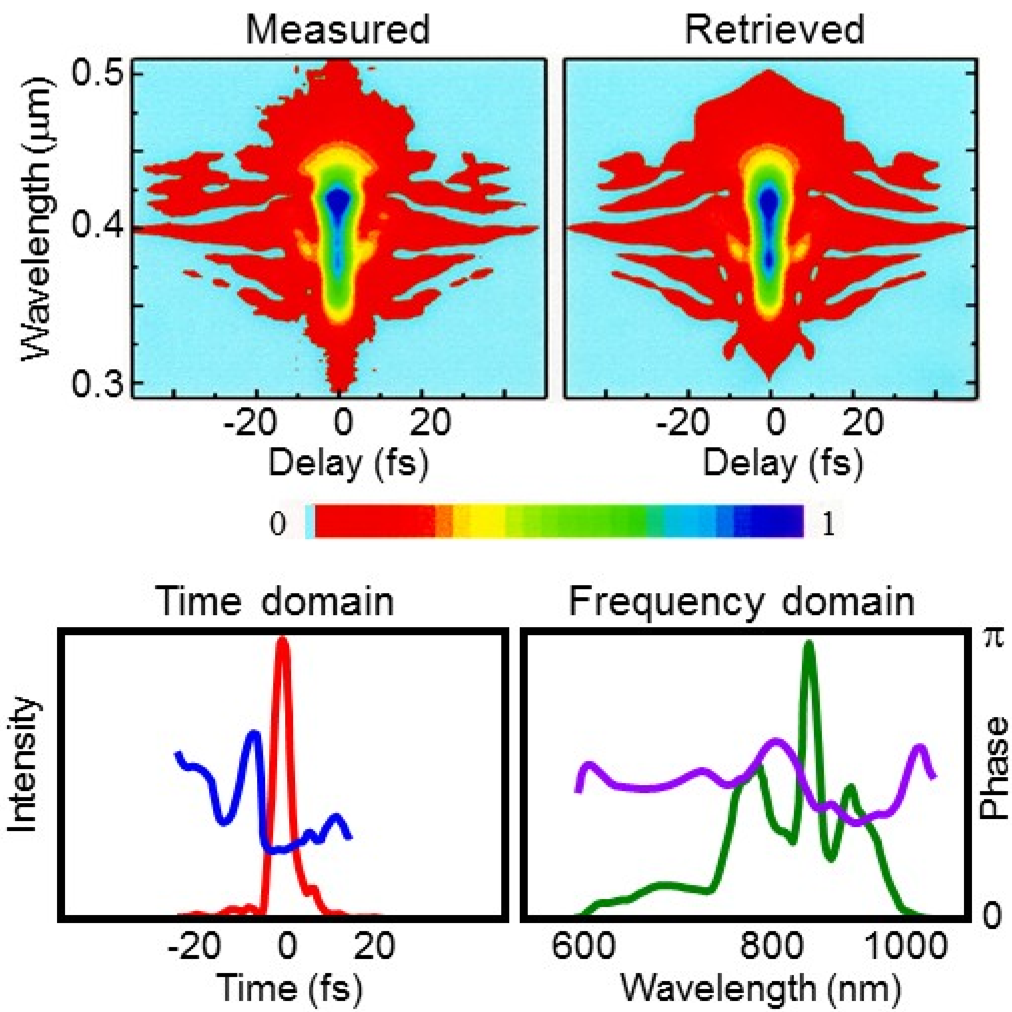
Second-Harmonic Generation Frequency-Resolved Optical Gating in the Single-Cycle Regime

Andrius Baltuška, Maxim S. Pshenichnikov, and Douwe A. Wiersma

(Invited Paper)



4.5 fs FWHM

The quality of the retrieval tells you if your measurement is ok
→ Detection of measurement artifacts

Pulse reconstruction

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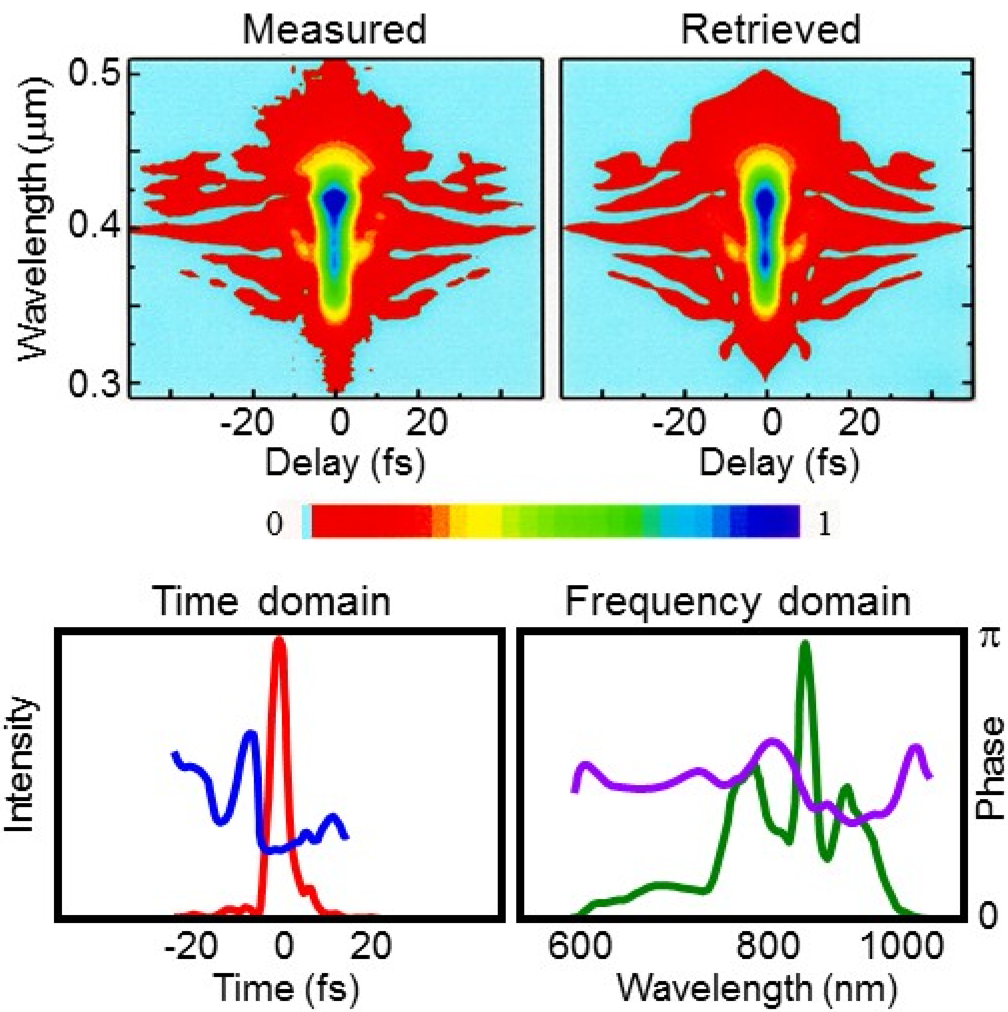

4.5 fs FWHM

The quality of the retrieval tells you if your measurement is ok
→ Detection of measurement artifacts

Additional checks : measure 'marginals'
= FROG trace summed along τ or ω

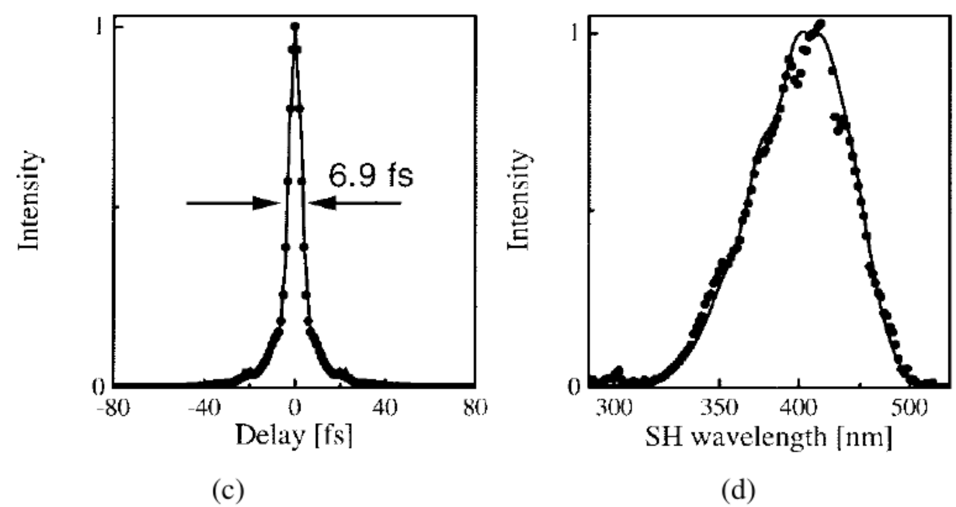

Fig. 17. The results of SHG FROG characterization of compressed pulses. (a) Experimental and (b) retrieved traces. (c) Temporal marginal (filled circles) and independently measured autocorrelation of 4.5-fs pulses (solid curve). (d) Frequency marginal (filled circles) and autoconvolution of the fundamental spectrum (solid curve).

Pulse reconstruction

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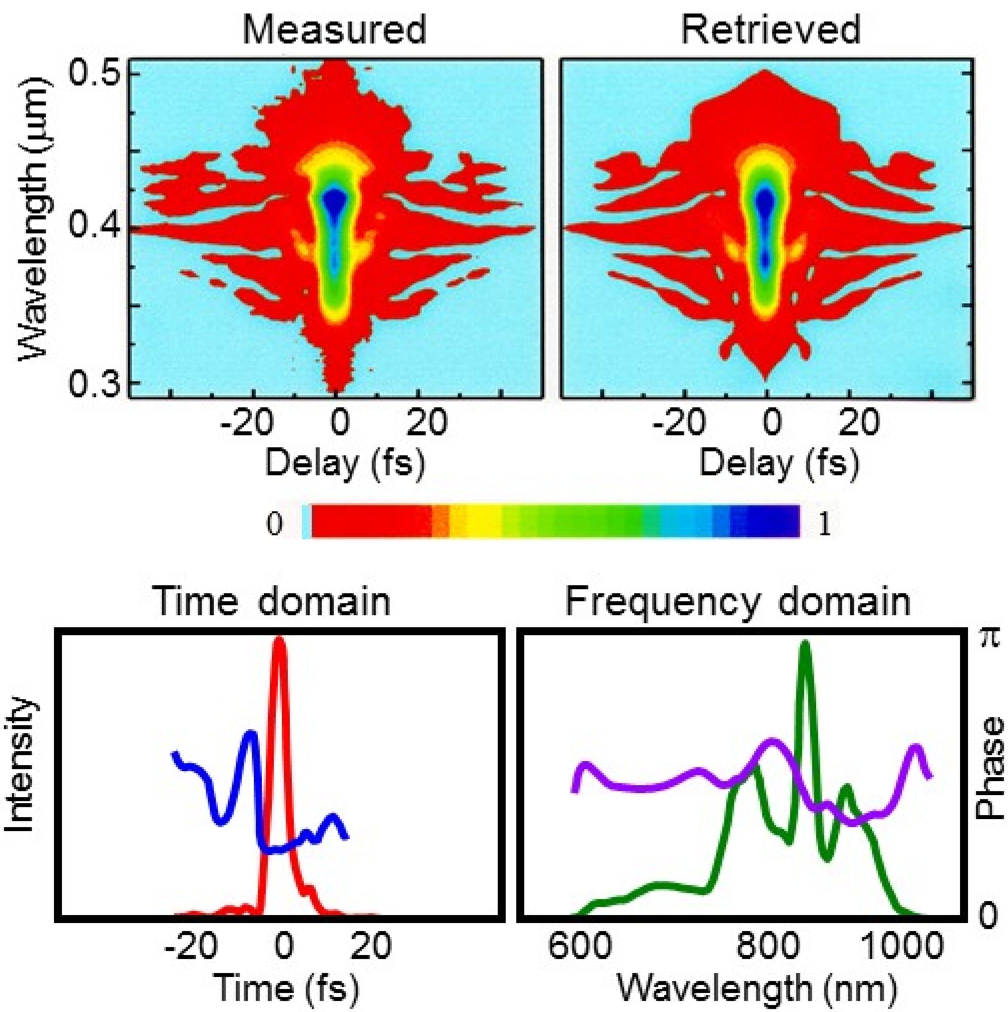


4.5 fs FWHM

The quality of the retrieval tells you if your measurement is ok
→ Detection of measurement artifacts

Note : the few-cycle regime is challenging :
The SHG process must not distort the spectrum, which is very broad

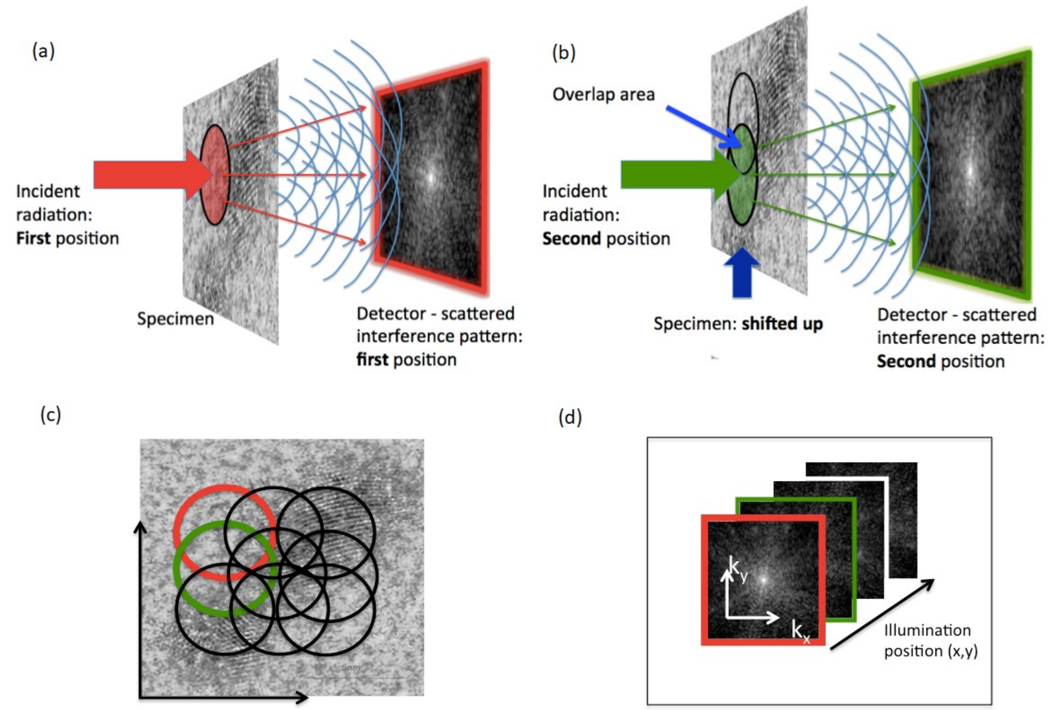
In this paper, we have developed the SHG FROG description that includes phase matching in the SHG crystal, noncollinear beam geometry, and dispersion of the second-order nonlinearity. The derived master equation is valid down to single-cycle pulses. Furthermore, the numerical simulations have shown that the conventional description of FROG in the case of Type I phase matching can be readily used even for the single-cycle regime upon spectral correction of the FROG traces, provided the beam geometry, the finite crystal thickness, and phase-matching bandwidth are chosen correctly.

Better algorithm : ptychography

Ptychography = Coherent Diffraction Imaging technique

Ptychography

From Wikipedia, the free encyclopedia



ADVANCES IN IMAGING AND ELECTRON PHYSICS, VOL. 150

Ptychography and Related Diffractive Imaging Methods

J.M. RODENBURG

Department of Electronic and Electrical Engineering, University of Sheffield, Mappin Street, S1 3JD, United Kingdom

Move a gate over an object, and measure the Fourier transform
Similar to FROG :

$$S(\omega,\tau) = \left| \int E(t)G(t-\tau)e^{i\omega t}dt \right|^2$$

Better algorithm : ptychography

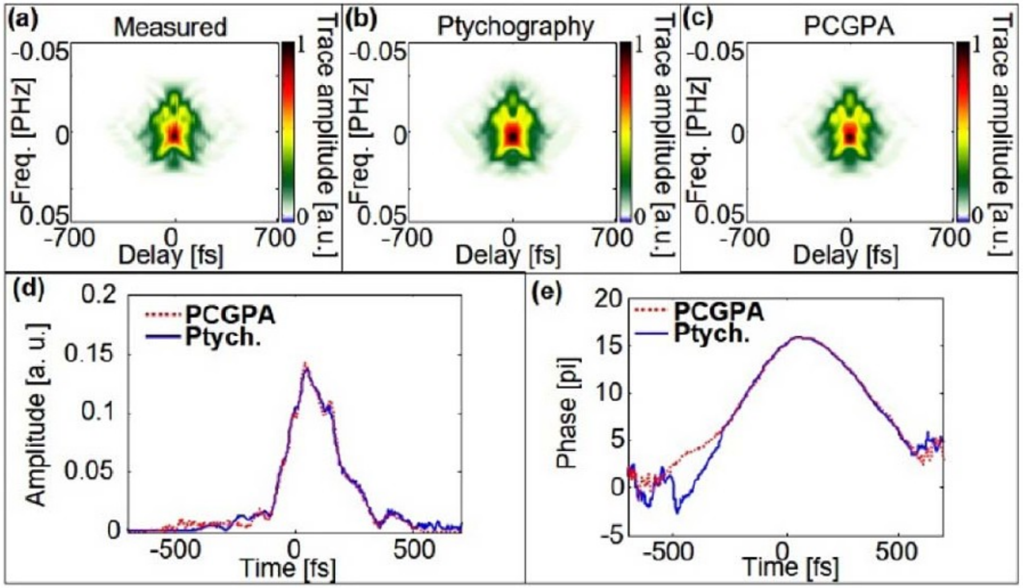


Fig. 3. Demonstration of ptychographic-based reconstruction using experimental SHG FROG data. (a) Measured FROG trace. (b) and (c) are traces recovered by ptychgraphic-based algorithm and PCGPA algorithm, respectively. Amplitude (d) and phase (e) of the recovered pulse by ptychographic-based algorithm (solid blue curve) and PCGPA algorithm (red dashed curve), respectively.

Research Article Vol. 3, No. 12 / December 2016 / *Optica* 1320

optica

Ptychographic reconstruction algorithm for frequency-resolved optical gating: super-resolution and supreme robustness

Pavel Sidorenko,[1,2] Oren Lahav,[1] Zohar Avnat,[1] and Oren Cohen[1,3]

[1]*Department of Physics and Solid State Institute, Technion, Haifa 32000, Israel*

Can do as good as PCGPA

Better algorithm : ptychography

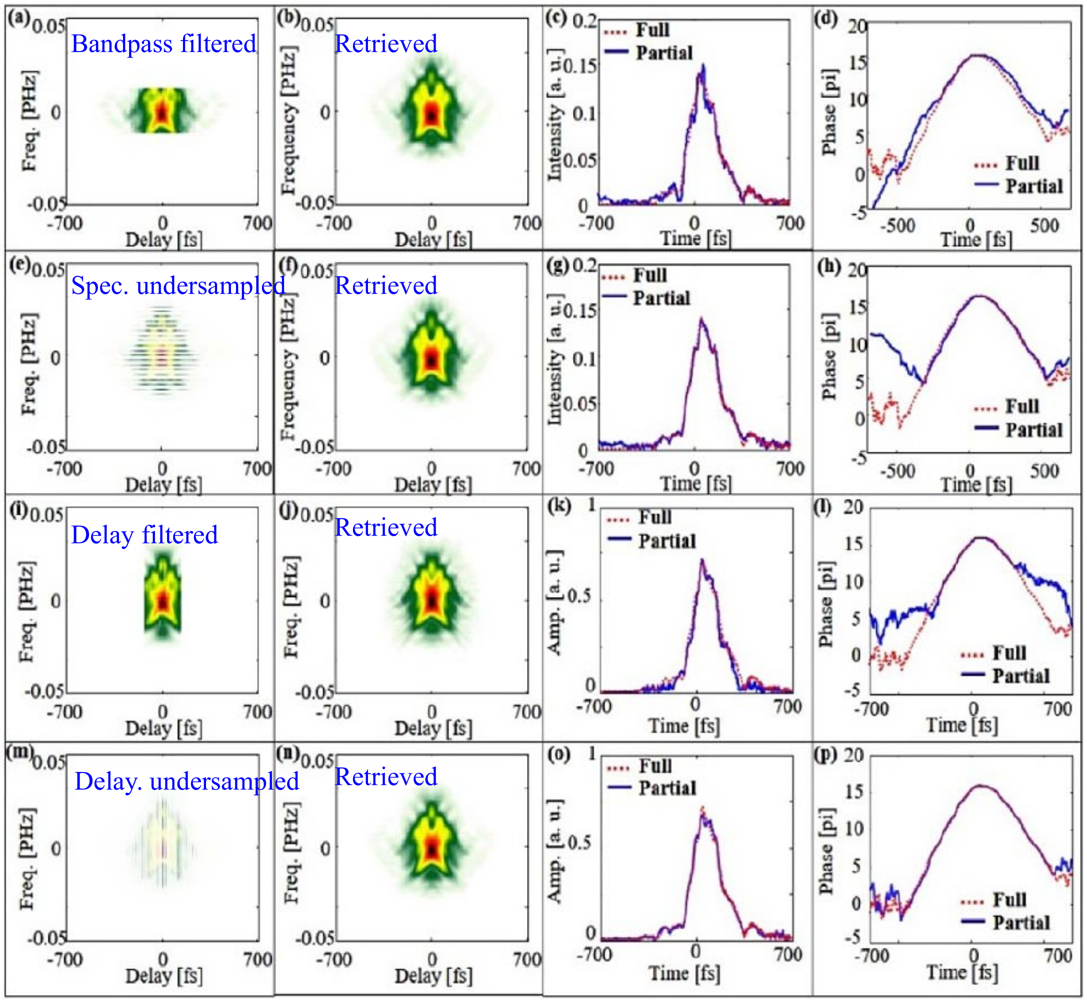
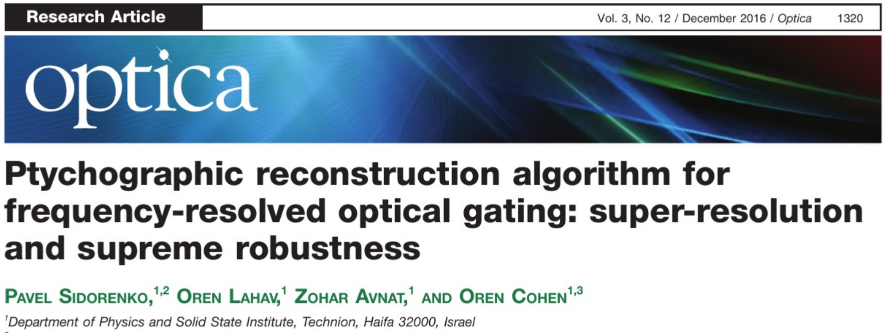


Fig. 4. Experimental pulse reconstructions from incomplete FROG traces. First horizontal panel (a)–(d) presents reconstruction from low-



Research Article Vol. 3, No. 12 / December 2016 / Optica 1320
optica

Ptychographic reconstruction algorithm for frequency-resolved optical gating: super-resolution and supreme robustness

Pavel Sidorenko,[1,2] Oren Lahav,[1] Zohar Avnat,[1] and Oren Cohen[1,3]
[1]Department of Physics and Solid State Institute, Technion, Haifa 32000, Israel

Can do as good as PCGPA
But does not need the full trace !

Autocorrelations

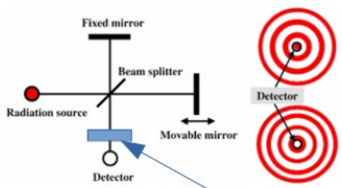
FROG

D-scan

Time-domain strong field methods

Bringing non-linearity in the measurement

Reminder : going from autocorrelation to non-linear autocorrelation led us to temporal characterization

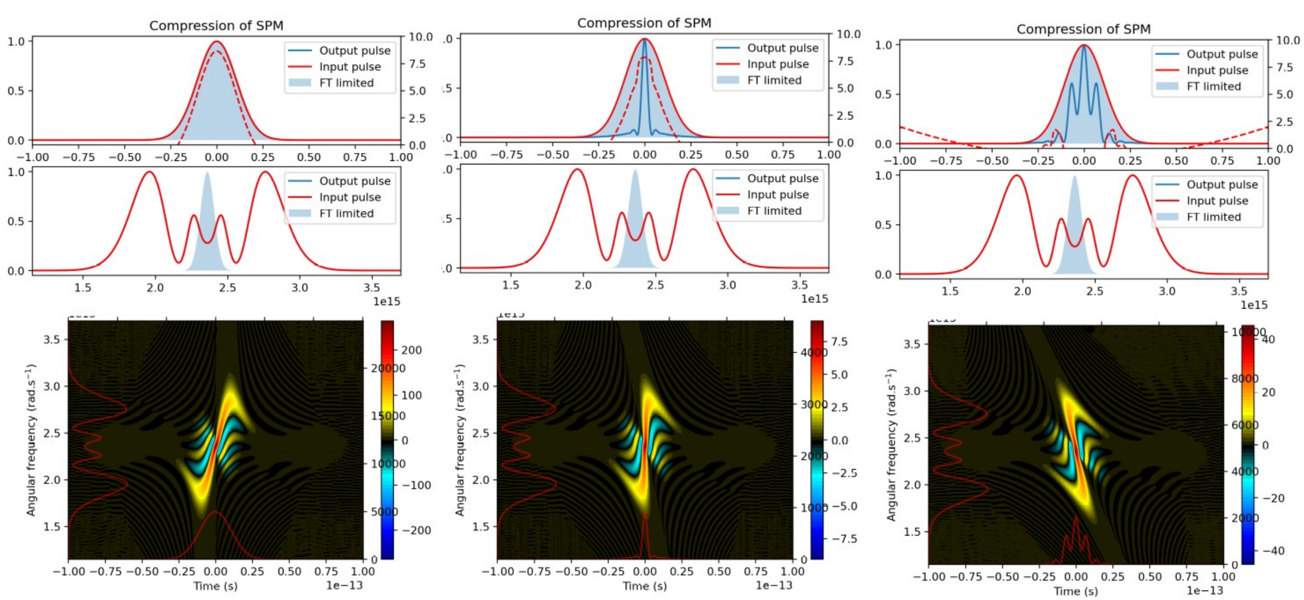


Let's add a frequency doubling crystal here

Same idea for dispersion scans ?

Adding spectral phase does not modify the spectrum

Increasing quadratic phase compensation



Let's add a frequency doubling crystal
The SHG spectrum will vary with the amount of quadratic phase

D-Scan

Simultaneous compression and characterization of ultrashort laser pulses using chirped mirrors and glass wedges

Miguel Miranda,[1,2,*] Thomas Fordell,[2] Cord Arnold,[2] Anne L'Huillier,[2] and Helder Crespo[1]

[1]*IFIMUP-IN and Departamento de Física e Astronomia, Universidade do Porto, Rua do Campo Alegre 687, 4169-007 Porto, Portugal*
[2]*Department of Physics, Lund University, P.O. Box 118, SE-221 00 Lund, Sweden*
[*]*mmiranda@fc.up.pt*

#156410 - $15.00 USD Received 14 Oct 2011; revised 18 Nov 2011; accepted 18 Nov 2011; published 23 Dec 2011
 2 January 2012 / Vol. 20, No. 1 / OPTICS EXPRESS 688

Scan the dispersion of your pulse

using the grating compressor or changing the amount of dispersion (pair of SiO2 wedges)

Frequency double your beam

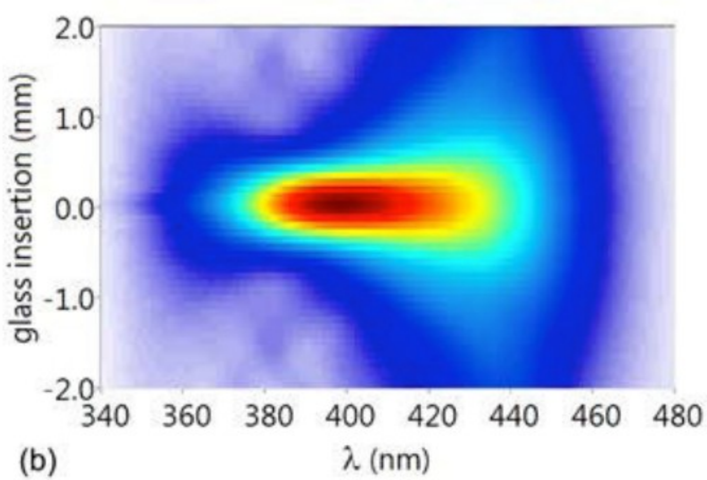
using a SHG crystal

Signal will maximize when the pulse is Fourier limited

principle of MIIPS, Multiphoton Intrapulse Interference Phase Scan

V. V. Lozovoy, I. Pastirk, and M. Dantus, "Multiphoton intrapulse interference. IV. Ultrashort laser pulse spectral phase characterization and compensation," Opt. Lett. **29**(7), 775–777 (2004).

Measure the spectrum



Dscan trace

Iterative algorithm
→ complete characterizaton of the pulse

D-Scan

190 Vol. 34, No. 1 / January 2017 / Journal of the Optical Society of America B Research Article

Journal of the Optical Society of America B

OPTICAL PHYSICS

Fast iterative retrieval algorithm for ultrashort pulse characterization using dispersion scans

Miguel Miranda,[1,*] João Penedones,[2,3] Chen Guo,[1] Anne Harth,[1] Maïté Louisy,[1] Lana Neoričić,[4] Anne L'Huillier,[1] and Cord L. Arnold[1]

[1]Department of Physics, Lund University, P.O. Box 118, SE-221 00 Lund, Sweden
[2]Fields and Strings Laboratory, Institute of Physics, EPFL, CH-1015 Lausanne, Switzerland
[3]Centro de Fisica do Porto, Universidade do Porto, Rua do Campo Alegre 687, 4169-007 Porto, Portugal
[4]ELI-ALPS, Dugonics tér 13, 6720 Szeged, Hungary

2D data → highly redundant → robust (like in FROG)

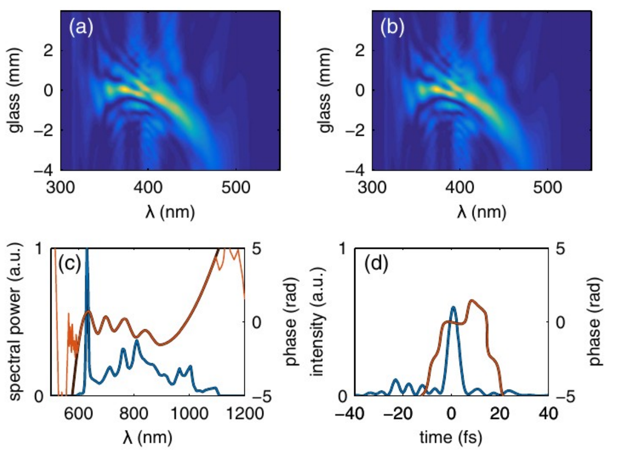


Fig. 1. Example of (a) simulated and (b) retrieved d-scan traces. (c) Both spectral intensity (blue) and phase (orange) are precisely retrieved, as well as the corresponding pulse in the time domain. (d) Retrieved fields are plotted in lighter colors. Note that in this plot the simulated and retrieved fields overlap almost exactly and cannot be easily distinguished.

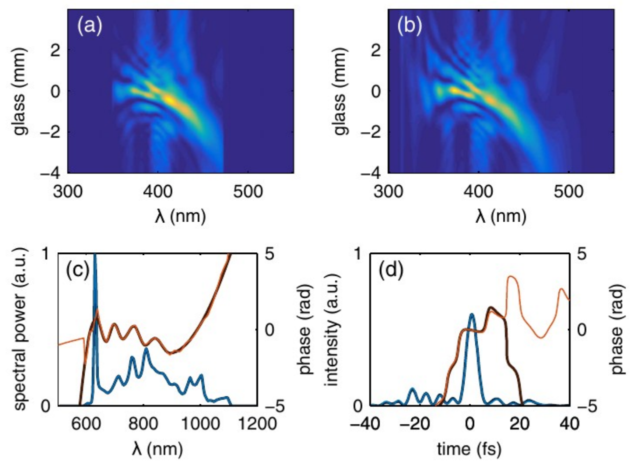


Fig. 3. Example of (a) simulated trace where a spectral filter was applied, simulating phase-matching and clipping. The algorithm uses the known fundamental spectrum (c) and retrieves a trace (b) very similar to the original trace. The corresponding pulse in the time domain is shown in (d).

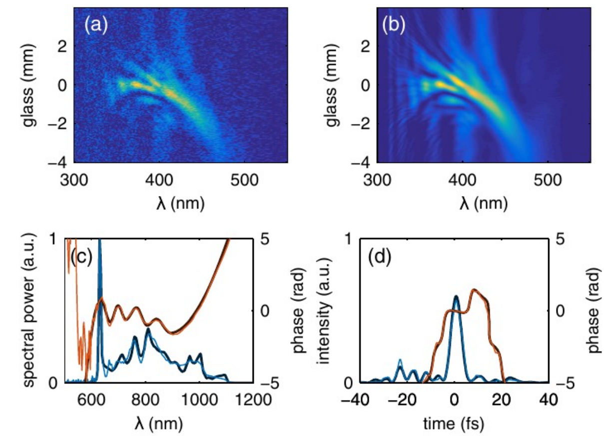


Fig. 4. Example of (a) simulated trace with added noise and (b) corresponding retrieved trace.

D-Scan

Ouillé et al. *Light: Science & Applications* (2020)9:47
https://doi.org/10.1038/s41377-020-0280-5

Official journal of the CIOMP 2047-7538
www.nature.com/lsa

ARTICLE Open Access

Relativistic-intensity near-single-cycle light waveforms at kHz repetition rate

Marie Ouillé[1,2], Aline Vernier[1], Frederik Böhle[1], Maïmouna Bocoum[1], Aurélie Jullien[1], Magali Lozano[1], Jean-Philippe Rousseau[1], Zhao Cheng[1], Dominykas Gustas[1], Andreas Blumenstein[3], Peter Simon[3], Stefan Haessler[1], Jérôme Faure[1], Tamas Nagy[4] and Rodrigo Lopez-Martens[1]

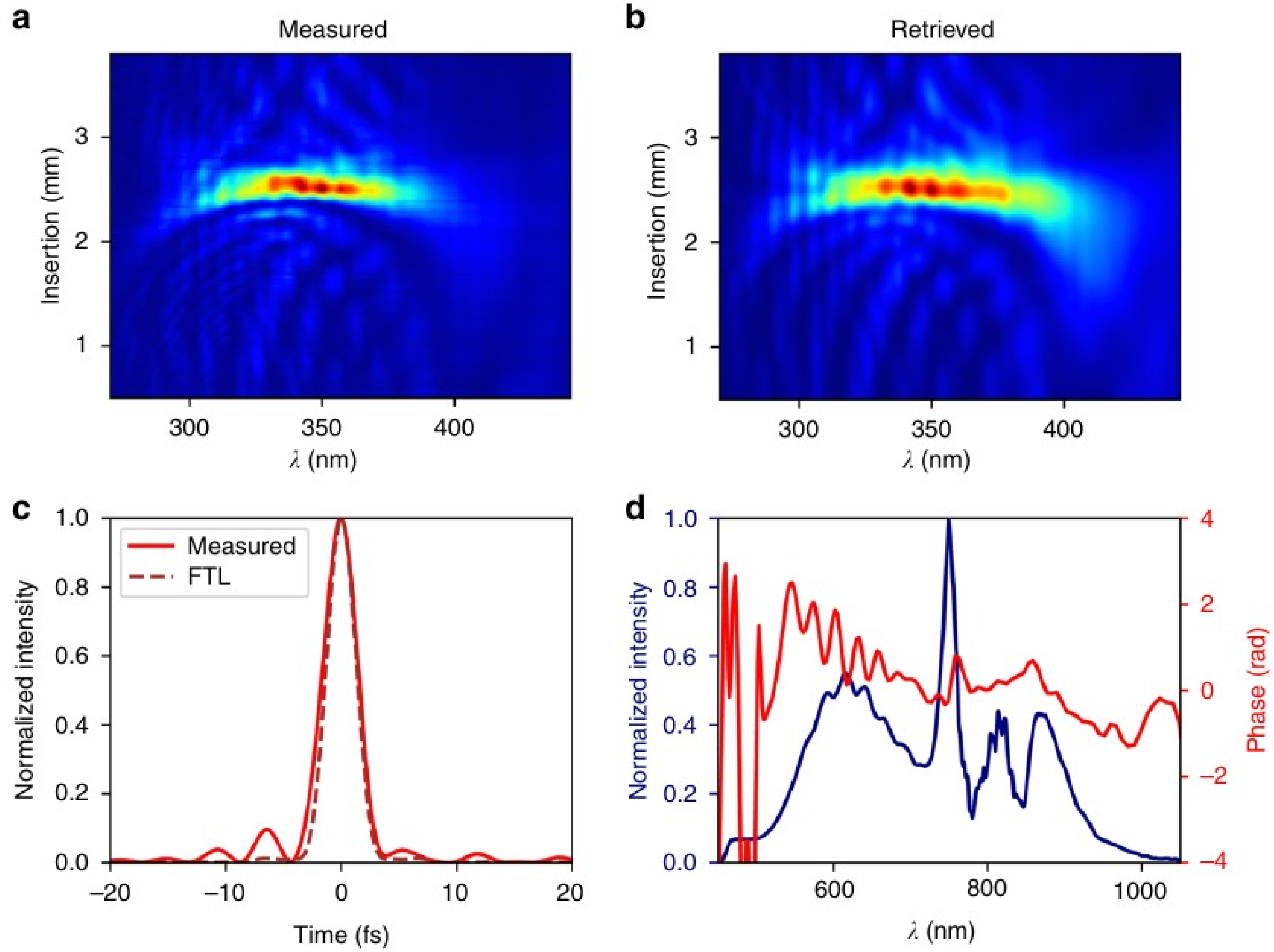


Fig. 2 D-scan measurement for 1.3 bar helium pressure. Measured (**a**) and retrieved (**b**) d-scan traces. Reconstructed temporal profile (**c**): the retrieved temporal pulse profile is shown in red (3.4 fs FWHM). The ideal Fourier transform-limited shape (2.9 fs FWHM) is indicated by the brown dotted line. Measured spectral intensity and phase (**d**). Relative CEP stability (each point averaged over 30 shots) (**e**) and pulse energy at the fiber exit

Autocorrelations

FROG

d-Scan

Time-domain strong field methods

Timescales

Oscillation of the electric field : 2.7 fs at 800 nm

Used to be impossible to resolve temporally

But possible now with attosecond spectroscopy

→ Use an attosecond XUV pulse to measure the electric field in the time domain
Attosecond streak camera / FROGCRAB

VOLUME 88, NUMBER 17 PHYSICAL REVIEW LETTERS 29 APRIL 2002

Attosecond Streak Camera

J. Itatani,[1] F. Quéré,[1] G. L. Yudin,[1] M. Yu. Ivanov,[1] F. Krausz,[2] and P. B. Corkum[1]
[1]*Steacie Institute for Molecular Sciences, National Research Council of Canada, Ottawa, Ontario, Canada K1A 0R6*
[2]*Institute für Photonik, Technische Universität Wien, Gusshausstrasse 27, A-1040 Wien, Austria*

Example :

PHYSICAL REVIEW A **71**, 011401(R) (2005)

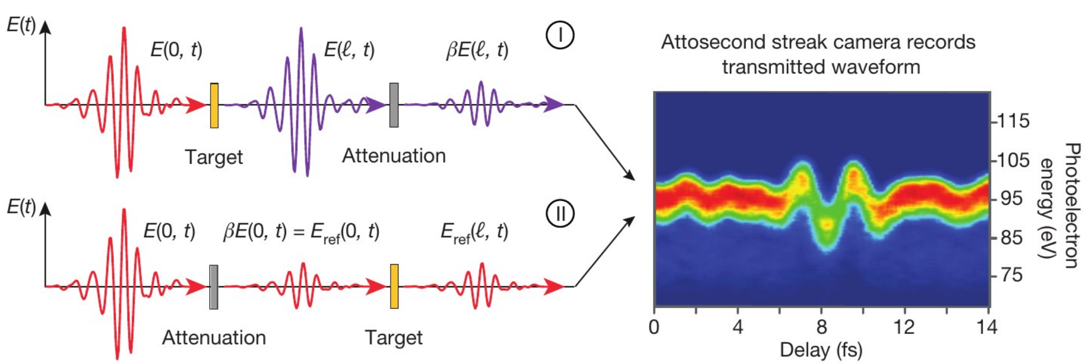
Frequency-resolved optical gating for complete reconstruction of attosecond bursts

Y. Mairesse and F. Quéré
DSM-DRECAM–Service des Photons, Atomes et Molécules, CEA Saclay, 91191 Gif-sur-Yvette Cedex, France

LETTER doi:10.1038/nature17650

Attosecond nonlinear polarization and light–matter energy transfer in solids

A. Sommer[1*], E. M. Bothschafter[1,2*†], S. A. Sato[3], C. Jakubeit[1], T. Latka[1], O. Razskazovskaya[1], H. Fattahi[1], M. Jobst[1], W. Schweinberger[1,2], V. Shirvanyan[1], V. S. Yakovlev[1,4], R. Kienberger[5], K. Yabana[3,6], N. Karpowicz[1], M. Schultze[1,2] & F. Krausz[1,2]



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VOLUME 88, NUMBER 17 PHYSICAL REVIEW LETTERS 29 APRIL 2002

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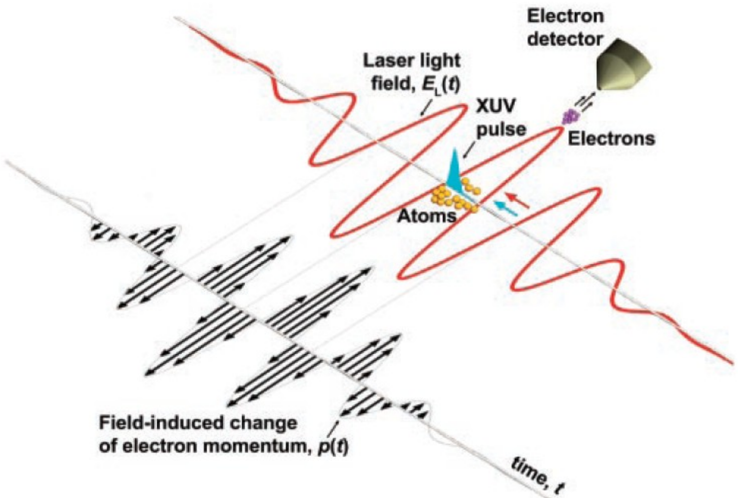
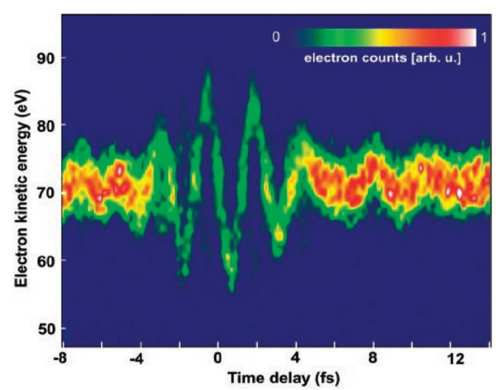
Principle:





*E. **Goulielmakis** et al, Science **305**, 1267 (2004)*

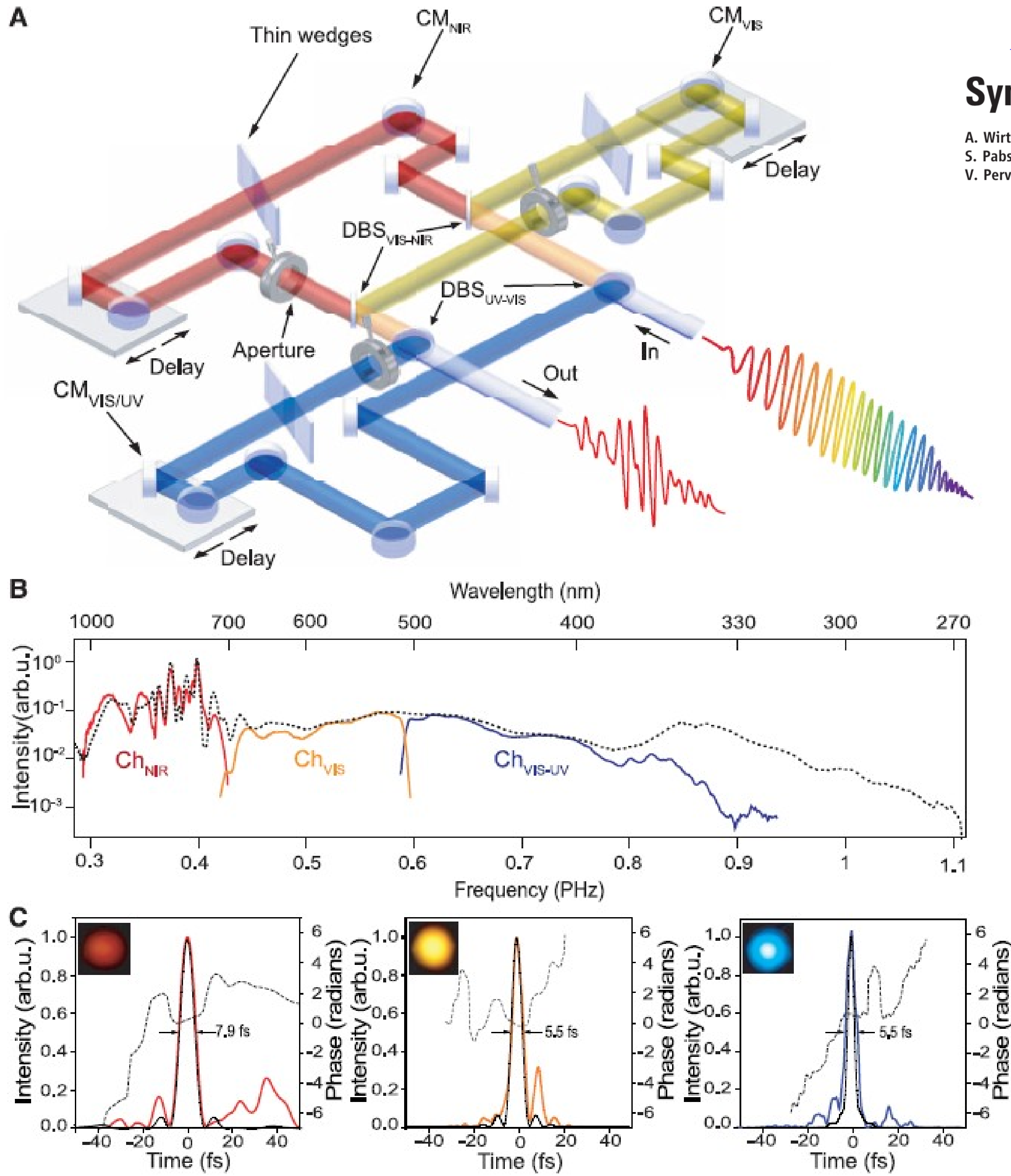
Measuring complex ultrabroadband electric fields

Very broadband laser pulse. The electric field can be finely taylored.

A. Wirth et al, Science 334, 194 (2012)

Synthesized Light Transients

A. Wirth,[1] M. Th. Hassan,[1,2] I. Grguraš,[1] J. Gagnon,[1] A. Moulet,[1] T. T. Luu,[1] S. Pabst,[3,4] R. Santra,[3,4] Z. A. Alahmed,[2] A. M. Azzeer,[2] V. S. Yakovlev,[1,5] V. Pervak,[5] F. Krausz,[1,5] E. Goulielmakis[1]*



Measuring complex ultrabroadband electric fields

A. Wirth et al, Science 334, 194 (2012)

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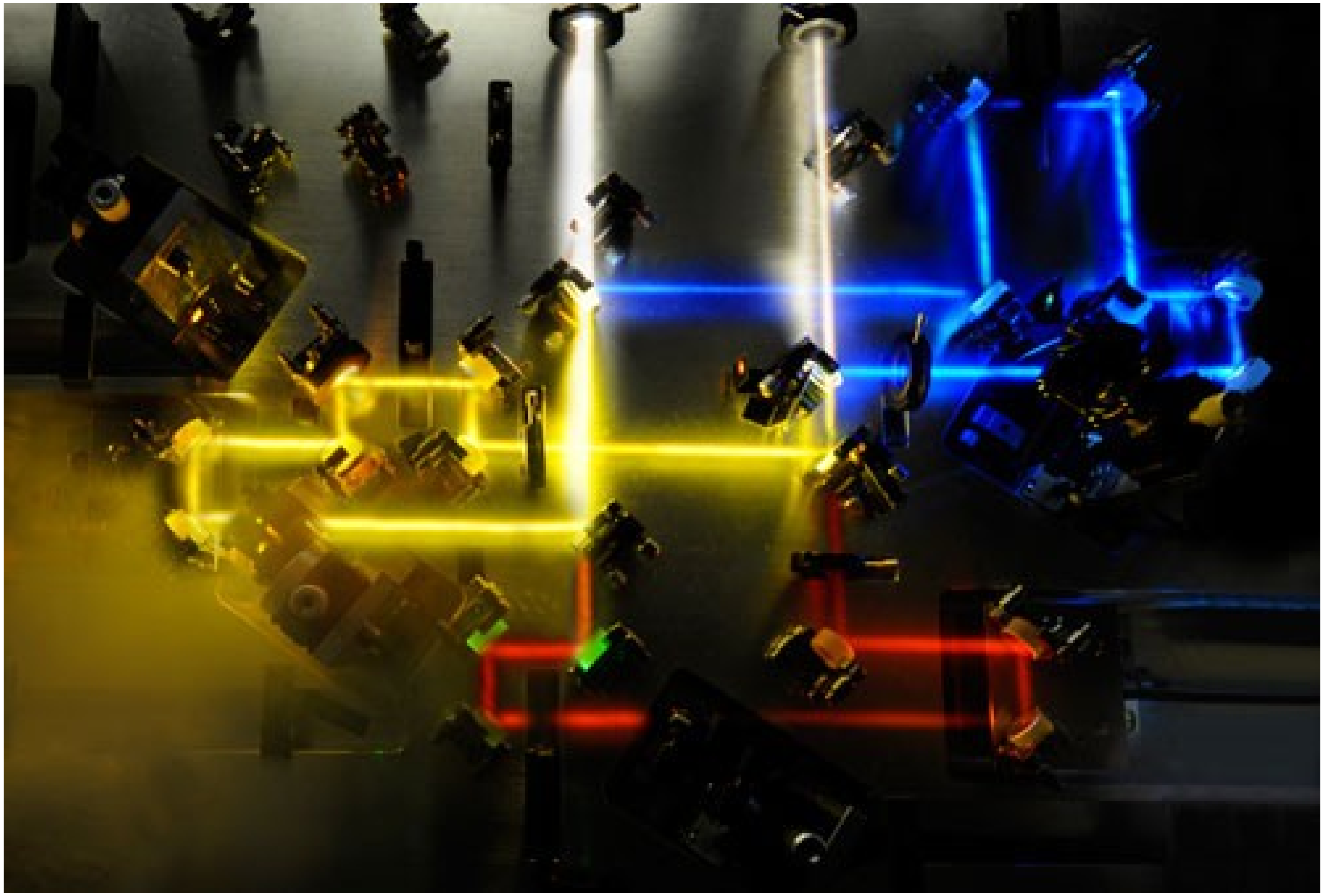

Measuring complex ultrabroadband electric fields

A. Wirth et al, Science 334, 194 (2012)

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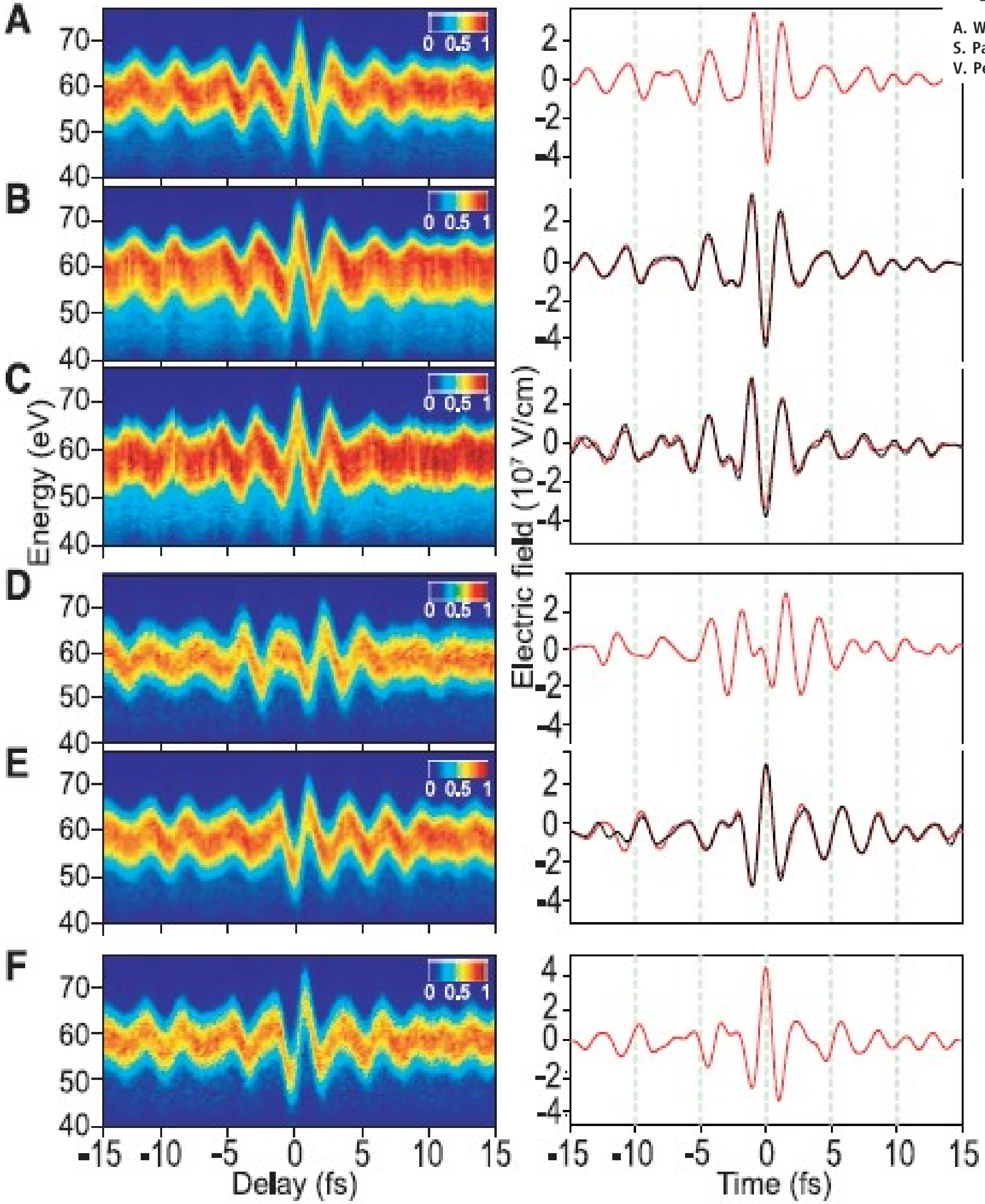


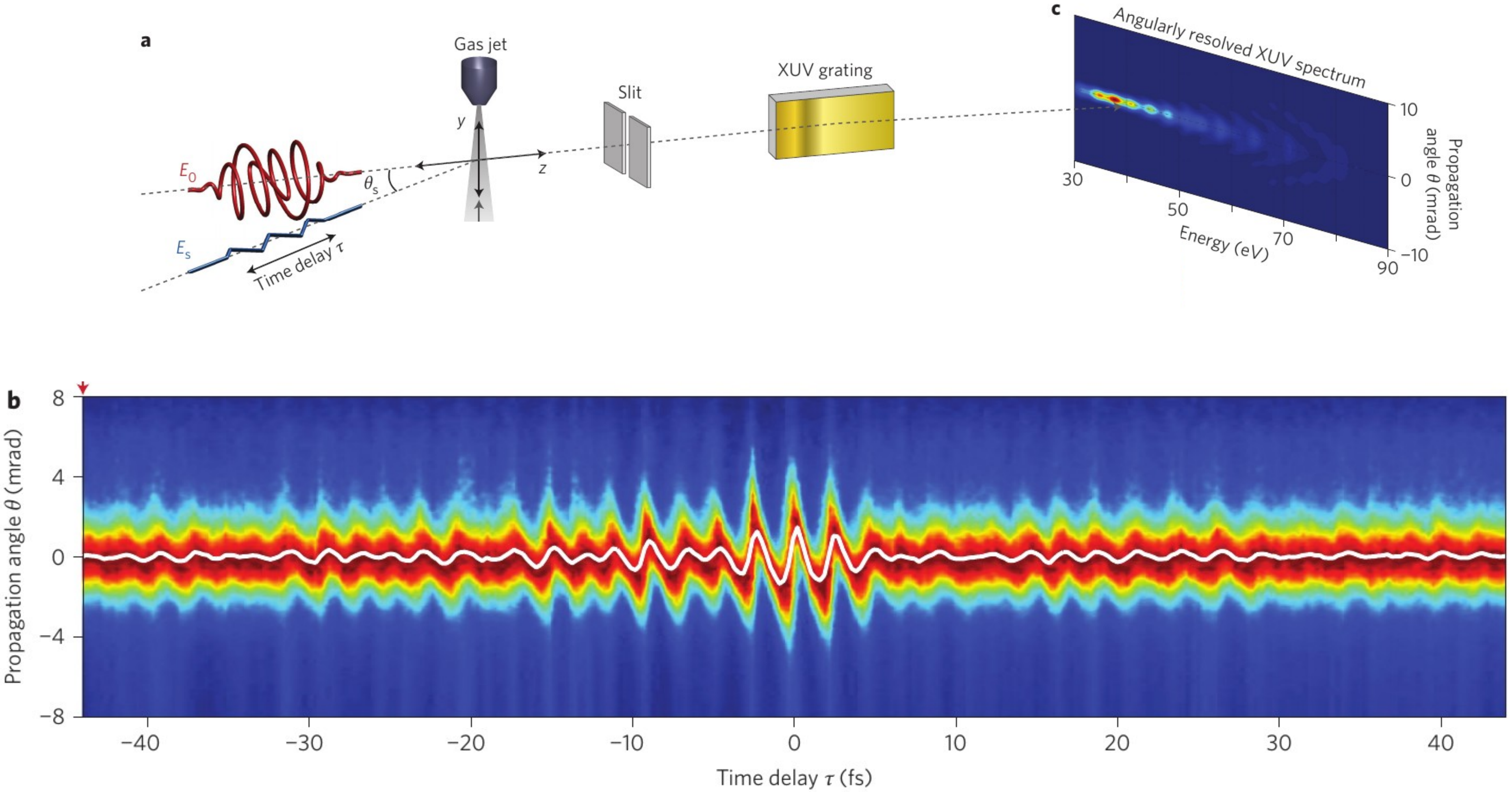
Other strong field methods

LETTERS
PUBLISHED ONLINE: 3 NOVEMBER 2013 | DOI: 10.1038/NPHOTON.2013.286
nature photonics

Petahertz optical oscilloscope

Kyung Taec Kim[1], Chunmei Zhang[1], Andrew D. Shiner[1], Bruno E. Schmidt[2], François Légaré[2], D. M. Villeneuve[1] and P. B. Corkum[1]*

High-order harmonic generation perturbed by the field to be measured

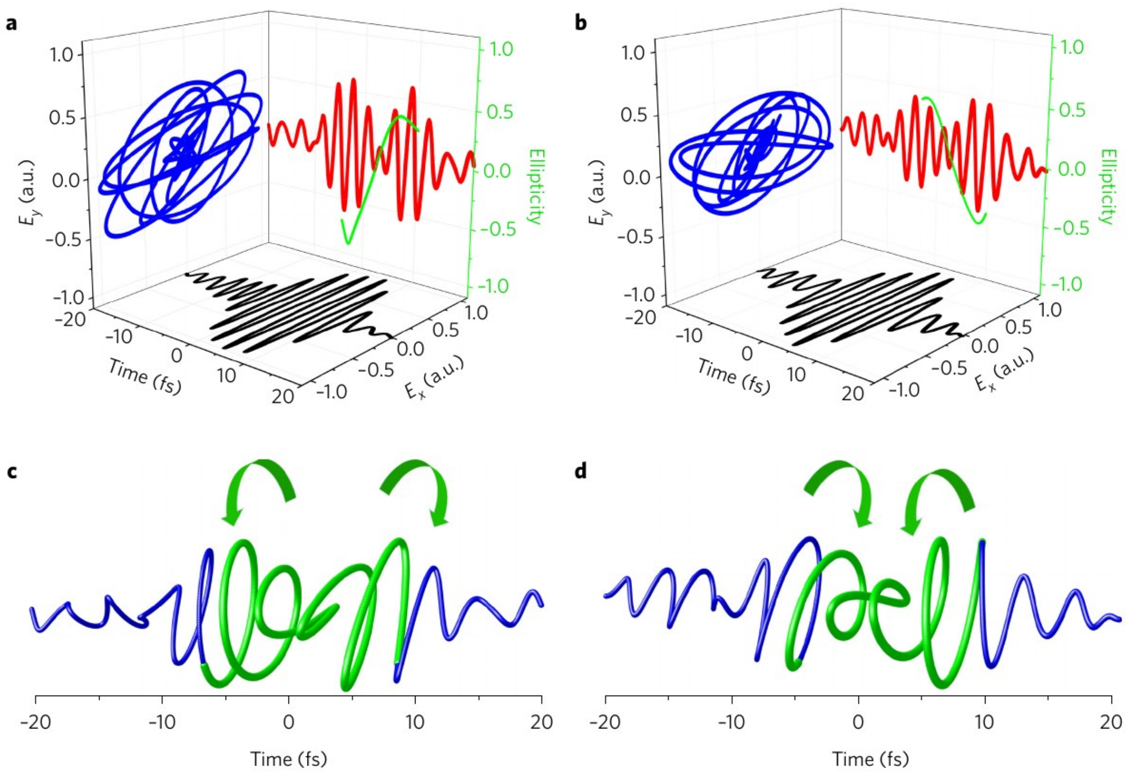


nature photonics
ARTICLES
PUBLISHED ONLINE: 29 MAY 2017 | DOI: 10.1038/NPHOTON.2017.73

Vectorial optical field reconstruction by attosecond spatial interferometry

P. Carpeggiani[1,2†], M. Reduzzi[1,2†], A. Comby[1†], H. Ahmadi[1,3], S. Kühn[4], F. Calegari[2,5,6], M. Nisoli[1,2], F. Frassetto[7], L. Poletto[7], D. Hoff[8], J. Ullrich[9], C. D. Schröter[10], R. Moshammer[10], G. G. Paulus[8] and G. Sansone[1,2,4,11★]

High-order harmonic interferometry perturbed by the field to be measured



Other strong field methods

Research Article Vol. 5, No. 4 / April 2018 / Optica 402

optica

Direct sampling of a light wave in air

Seung Beom Park,[1] Kyungseung Kim,[1] Wosik Cho,[1,2] Sung In Hwang,[1] Igor Ivanov,[1] Chang Hee Nam,[1,2] and Kyung Taec Kim[1,2,*]

SCIENTIFIC REPORTS
natureresearch

OPEN

Temporal characterization of femtosecond laser pulses using tunneling ionization in the UV, visible, and mid-IR ranges

Wosik Cho[1,2], Sung In Hwang[1], Chang Hee Nam[1,2], Mina R. Bionta[3,5], Philippe Lassonde[3], Bruno E. Schmidt[4], Heide Ibrahim[3], François Légaré[3] & Kyung Taec Kim[1,2*]

Strong field ionization perturbed by the field to be measured
TIPTOE

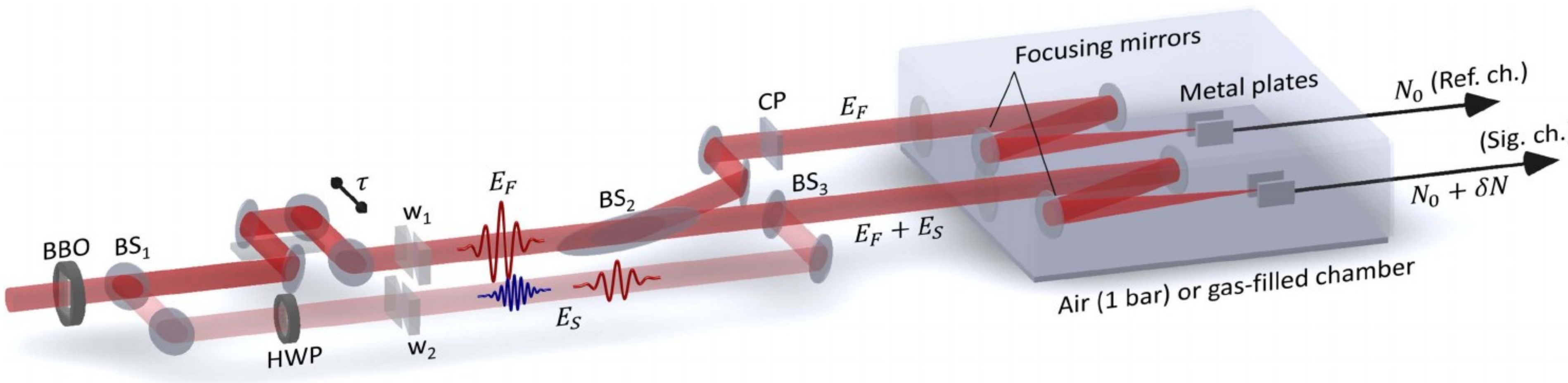


Fig. 2. Incident laser pulse is separated into two pulses: the fundamental pulse E_F and the signal pulse E_S. The fundamental pulse is divided into two identical pulses again by a beam splitter (BS2). One of these components is superposed with the signal pulse by another beam splitter (BS3). A part of the fundamental (730 nm, 5 fs pulses) or second-harmonic (355 nm) pulse can be selected as a signal pulse since the pulses are temporally separated. In the reference channel, the ionization yield N_0 is measured using only the fundamental pulse. In the signal channel, the ionization yield $N_0 + \delta N$ is measured using the fundamental and signal pulses. The details of the setup are provided in Section 4 (Methods).

Other strong field methods

Research Article Vol. 5, No. 4 / April 2018 / Optica 402
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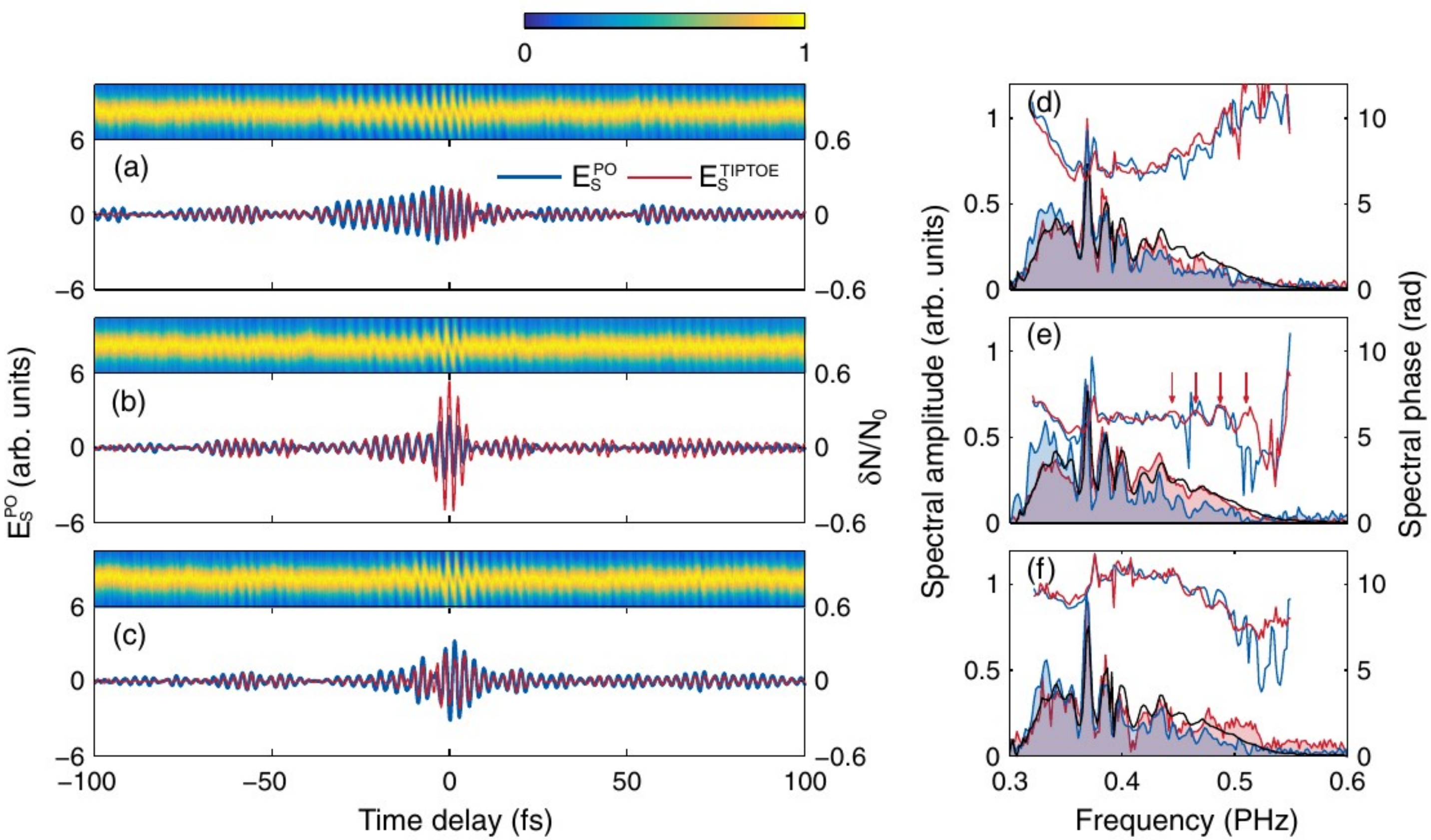

Autocorrelations

FROG

d-Scan

Time-domain strong field methods

Conclusions

Many methods, and many more

Trade off between simplicity and accuracy

- Many people still use intensity autoco on a day to day basis, and its ok in many cases

FROG and Dscan are well established and robust

Time-domain methods based on strong fields are becoming commercial (eg TIPTOE)

What are the limitations ?

- bandwidth of the crystals ?
- methods for UV, VUV pulses ?
- CEP characterization ?

+ Space time couplings ! – Need to measure the spatial phase in addition to the temporal phase

And how does it work in practice ? → Sébastien