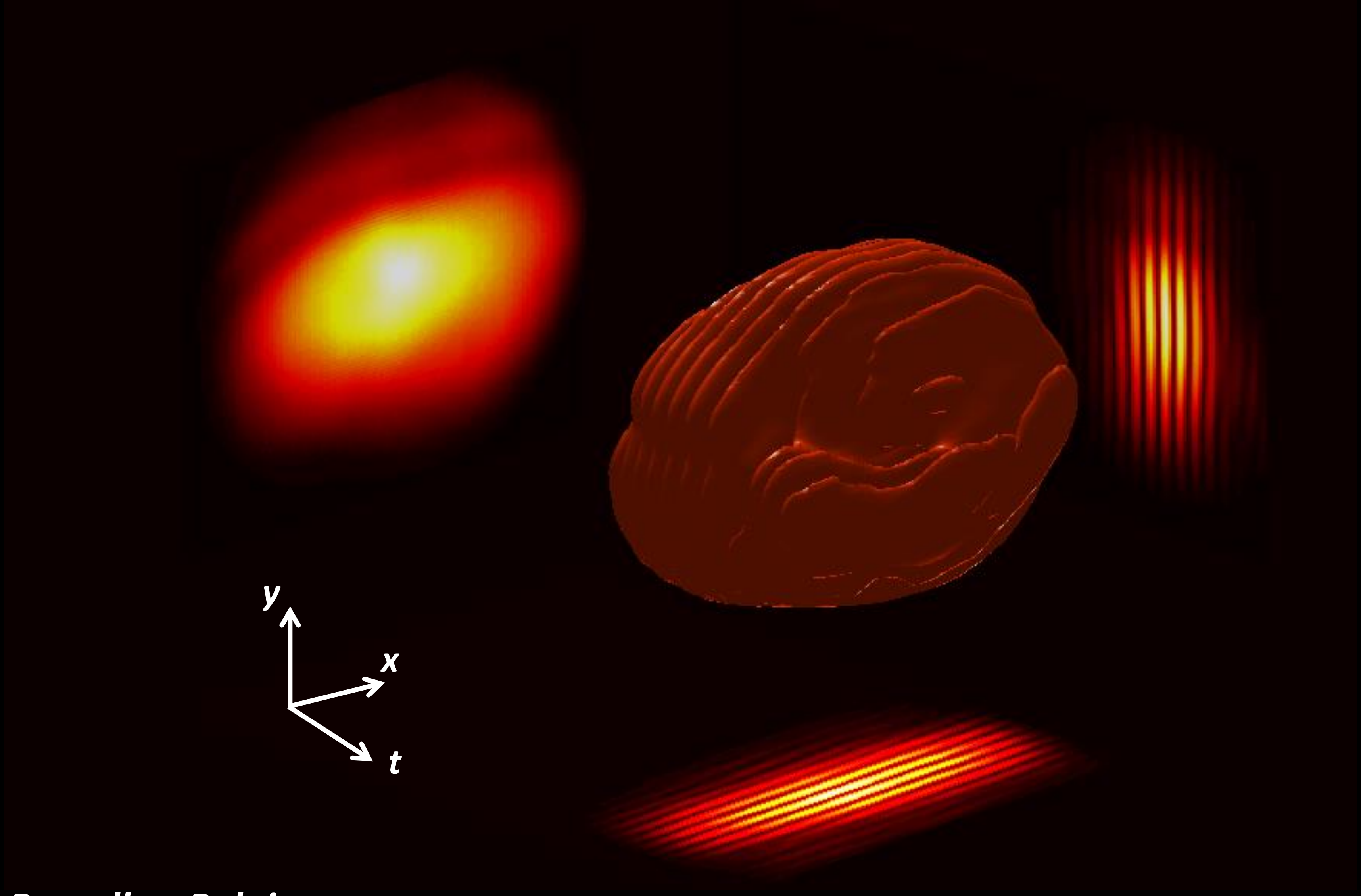
ADVANCES IN SPATIO-TEMPORAL PULSE CHARACTERIZATION

Réseau FEMTO // Journée Caractérisation – November 10th, 2023



Spencer W. Jolly
Université libre de Bruxelles, Belgium

About me

Work performed while at:

(until Nov 2019)

→ Many slides taken from Fabien Quéré

Where I am now:

(since 01 Oct 2022)

My project:
"StructULB"
Structured Ultrafast Light Beams for fundamental science and applications in micromachining, particle acceleration, integrated photonics, and photo-chemistry

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 801505.

Disclaimer: This is not new

Volume 59, number 3 OPTICS COMMUNICATIONS 1 September 1986

PULSE DISTORTIONS IN TILTED PULSE SCHEMES FOR ULTRASHORT PULSES

Oscar Eduardo MARTINEZ [1]

Ceilap, Citefa Conicet, Zufriategui y Varela, 1603 V. Martelli, Buenos Aires, Argentina

Received 5 March 1986

OPTICS LETTERS / Vol. 26, No. 2 / January 15, 2001

Spatially resolved amplitude and phase characterization of femtosecond optical pulses

L. Gallmann, G. Steinmeyer, D. H. Sutter, and T. Rupp

Ultrafast Laser Physics Laboratory, Institute of Quantum Electronics, Swiss Federal Institute of Technology, ETH Hönggerberg–HPT, CH-8093 Zürich, Switzerland

C. Iaconis and I. A. Walmsley

The Institute of Optics, University of Rochester, Rochester, New York 14627

U. Keller

Ultrafast Laser Physics Laboratory, Institute of Quantum Electronics, Swiss Federal Institute of Technology, ETH Hönggerberg–HPT, CH-8093 Zürich, Switzerland

Received July 6, 2000

High-order pulse front tilt caused by high-order angular dispersion

Yasuo Nabekawa and Katsumi Midorikawa

RIKEN (The Institute of Physical and Chemical Research)
2-1 Hirosawa, Wako-shi, Saitama 351-0198, Japan
tel:+81-48-467-9503, fax:+81-48-462-4682

Received October 31, 2003; Revised November 25, 2003
15 December 2003 / Vol. 11, No. 25 / OPTICS EXPRESS 3365

Spatio-temporal characterization of few-cycle pulses obtained by filamentation

A. Zaïr[1*], A. Guandalini[1], F. Schapper[1], M. Holler[1], J. Biegert[1,1], L. Gallmann[1], A. Couairon[2], M. Franco[3], A. Mysyrowicz[3], and U. Keller[1]

[1] *ETH Zurich, Physics Department / Institute of Quantum Electronics, 8093 Zurich, Switzerland*
[2] *Centre de Physique Théorique, CNRS, École Polytechnique, F-91128 Palaiseau, France*
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30 April 2007 / Vol. 15, No. 9 / OPTICS EXPRESS 5394

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Outline

- **Why is STC characterization necessary?**
- What are STCs?
- Overview of history and of standard techniques
- More recent measurements and techniques
- Very recent progress in exotic STCs

Standard characterization routine for UHI lasers

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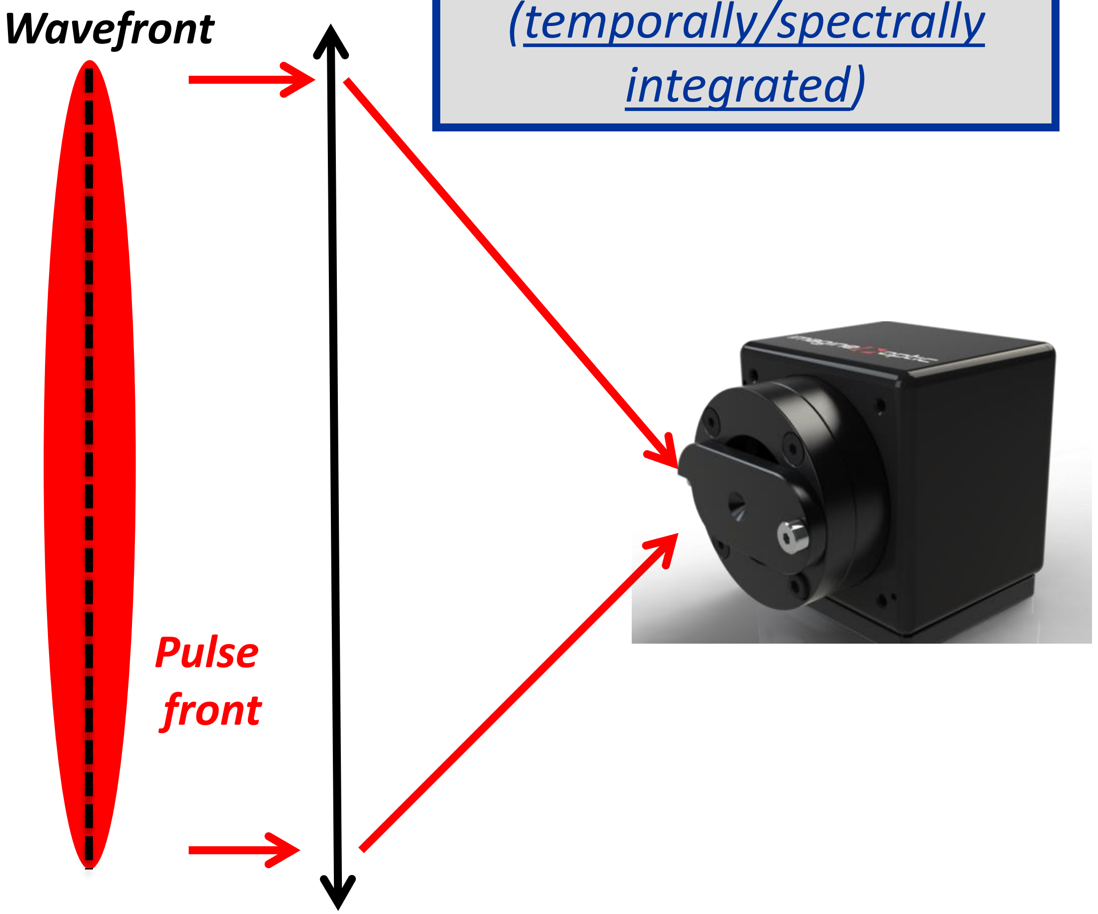
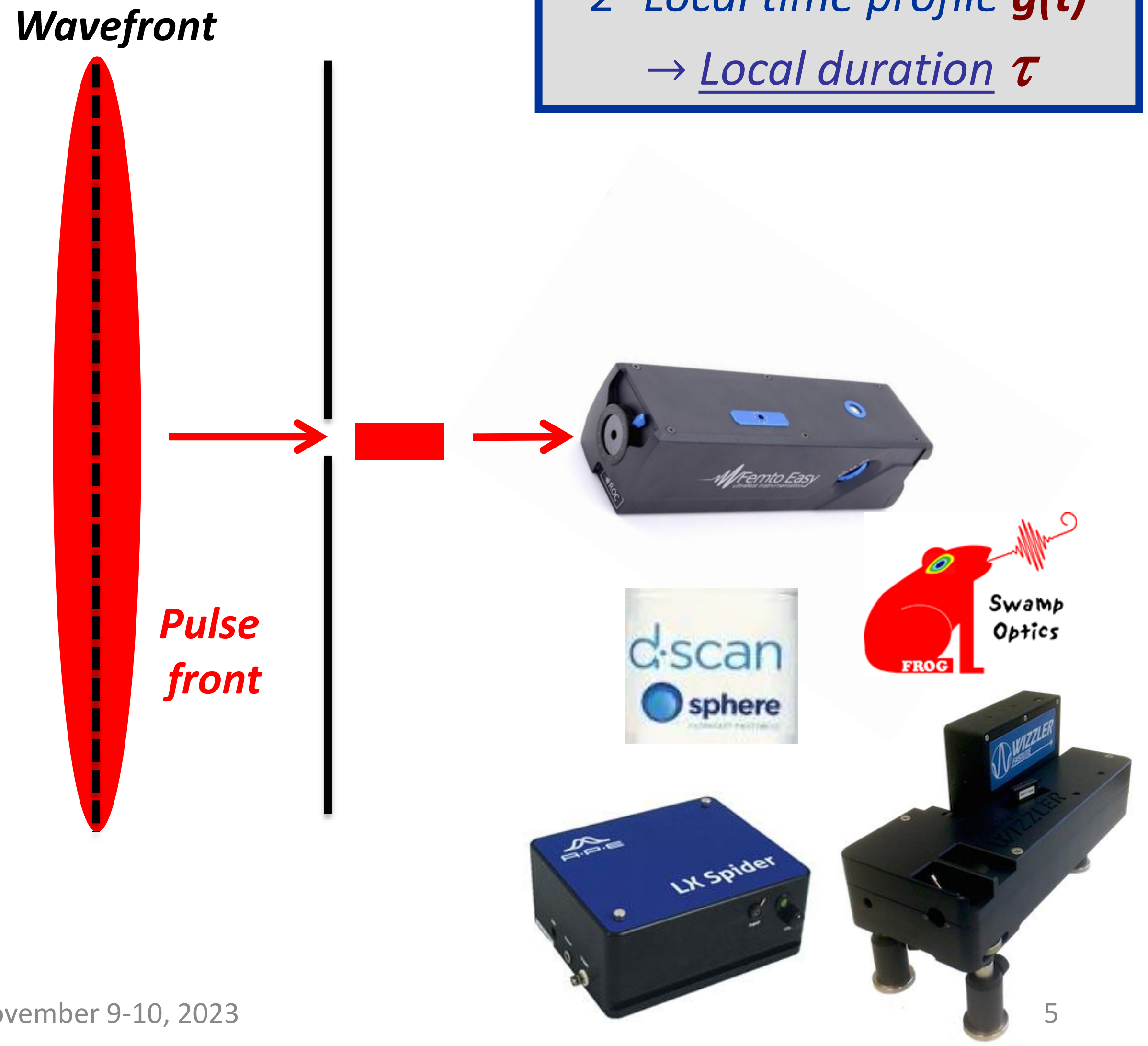
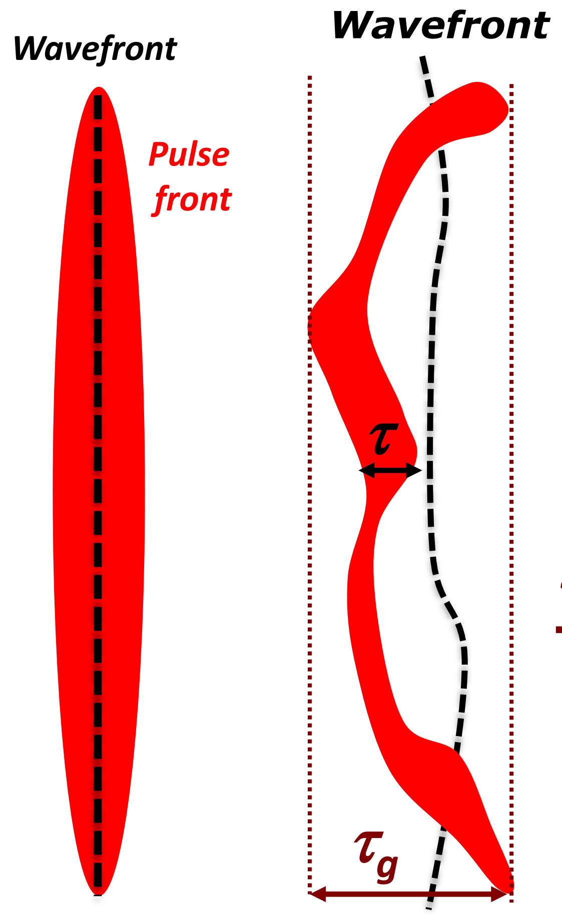
*1- Spatial profile **f(x,y)***
(temporally/spectrally integrated)



*2- Local time profile **g(t)***
*→ Local duration **τ***



Where does it go wrong?



1- Spatial profile ***f(x,y)*** *(temporally/spectrally averaged)*

2- Local time profile ***g(t)*** *→ Local duration* τ

E(x,y,t) = f(x,y).g(t)

→ $P=E/\tau$ **Estimated peak power**

This neglects Spatio-temporal couplings (STC)

$E(x,y,t) \neq f(x,y).g(t)$

→ $P=E/\tau_g$ **Real peak power**

Spatial dependence of the temporal (or spectral) properties

OR

Temporal (or spectral) dependence of the spatial properties

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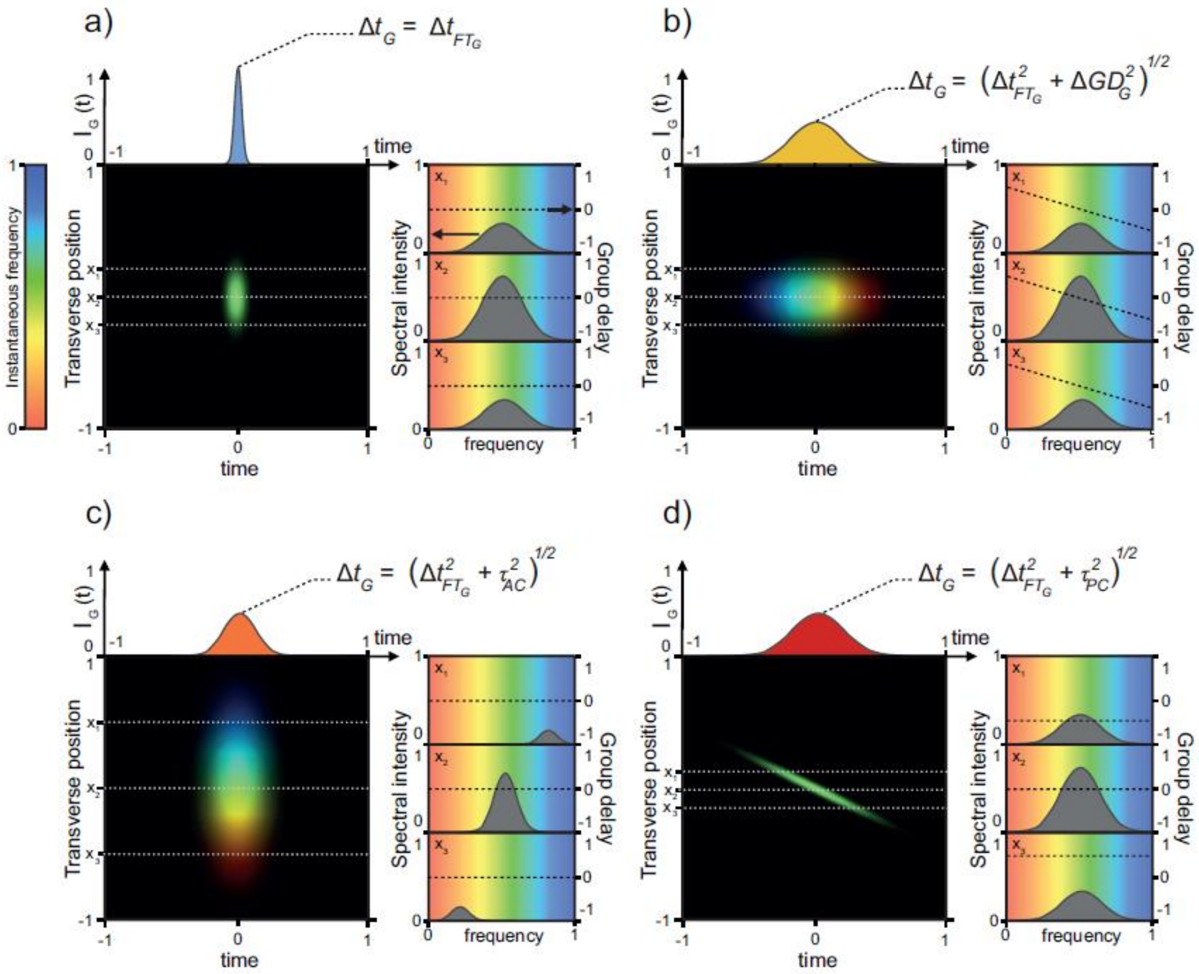
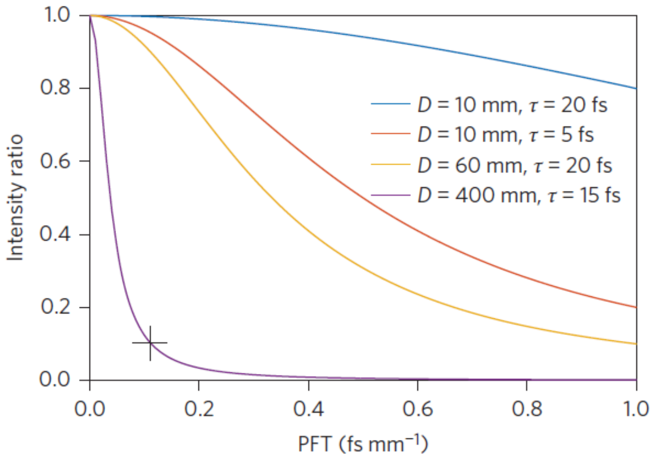
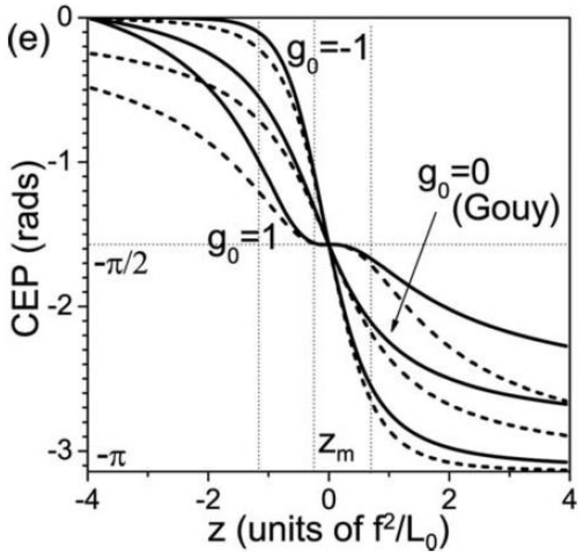
Clear effect on duration/intensity





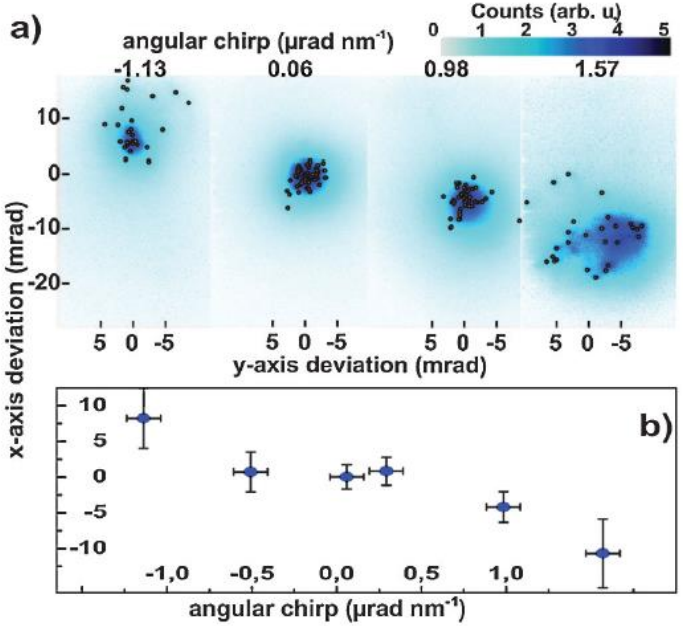
→ very relevant for the big lasers that drive laser-plasma acceleration

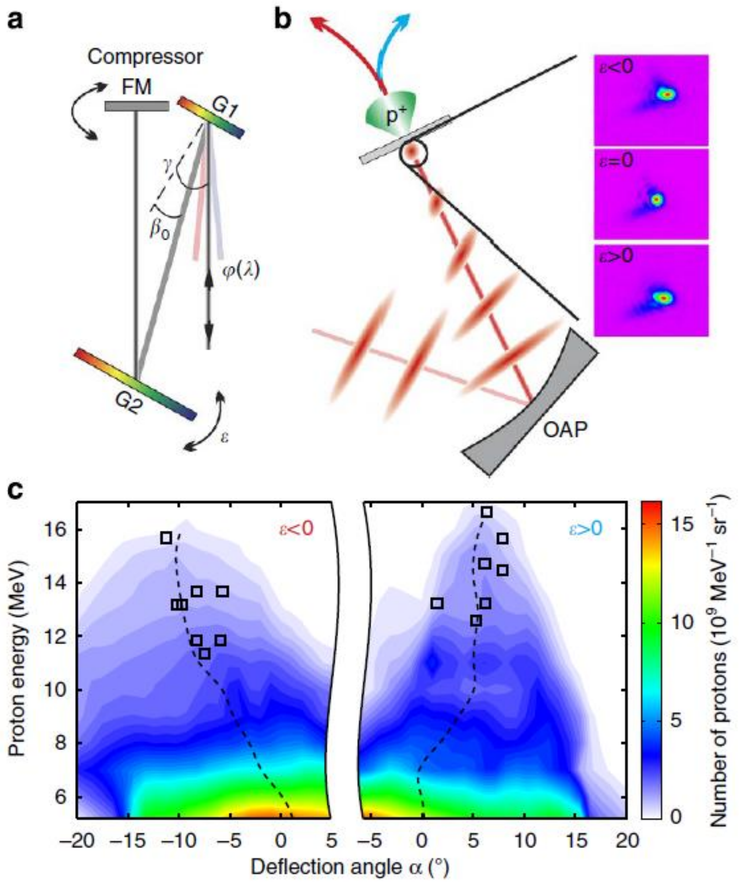


→ Potentially relevant for the shortest lasers that drive HHG, photoionization etc.

C. Bourassin-Bouchet et al., Opt. Express **19**, 17357 (2011).
G. Pariente et al., Nat. Phot. **10**, 547 (2016).
M. A. Porras, Opt. Lett. **34**, 1546 (2009).

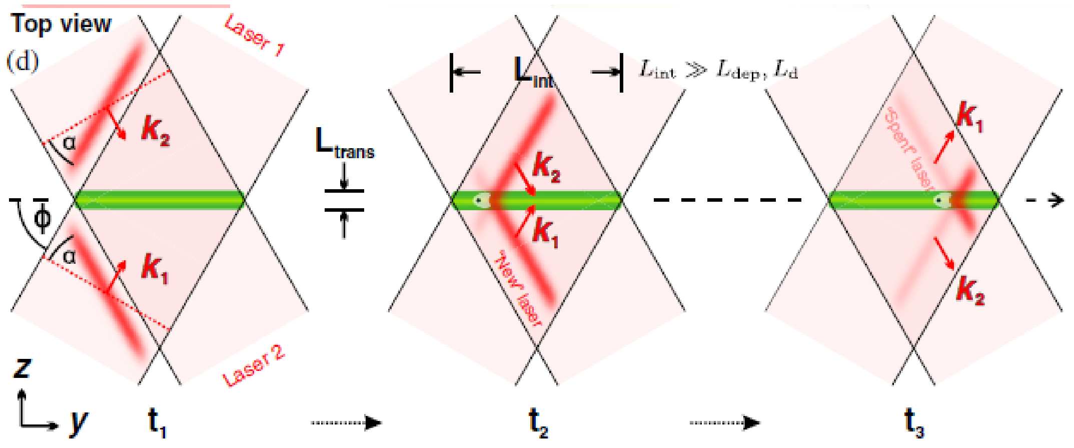
Steering laser-plasma acceleration

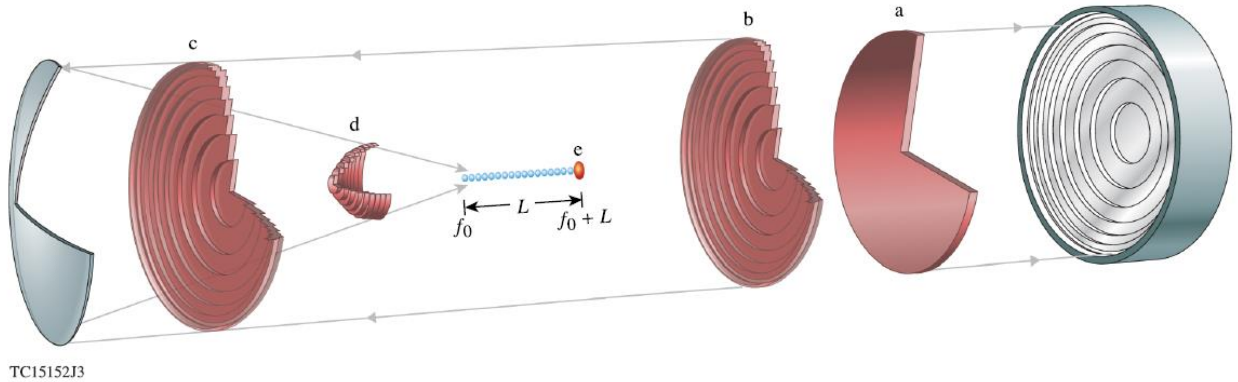


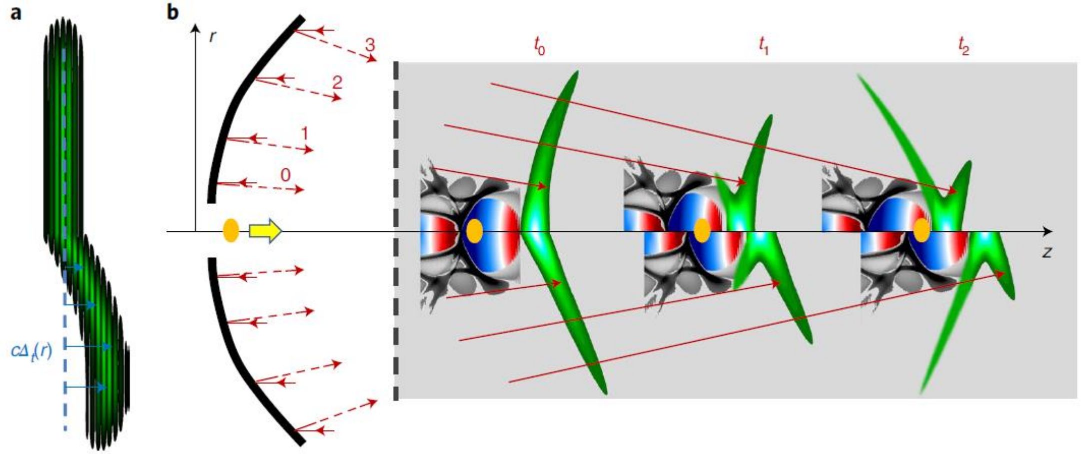


A. Popp et al., PRL **105**, 215001, (2010).
K. Zeil et al., Nat. Comm. **3**, 874 (2012).

Optimizing laser-plasma acceleration

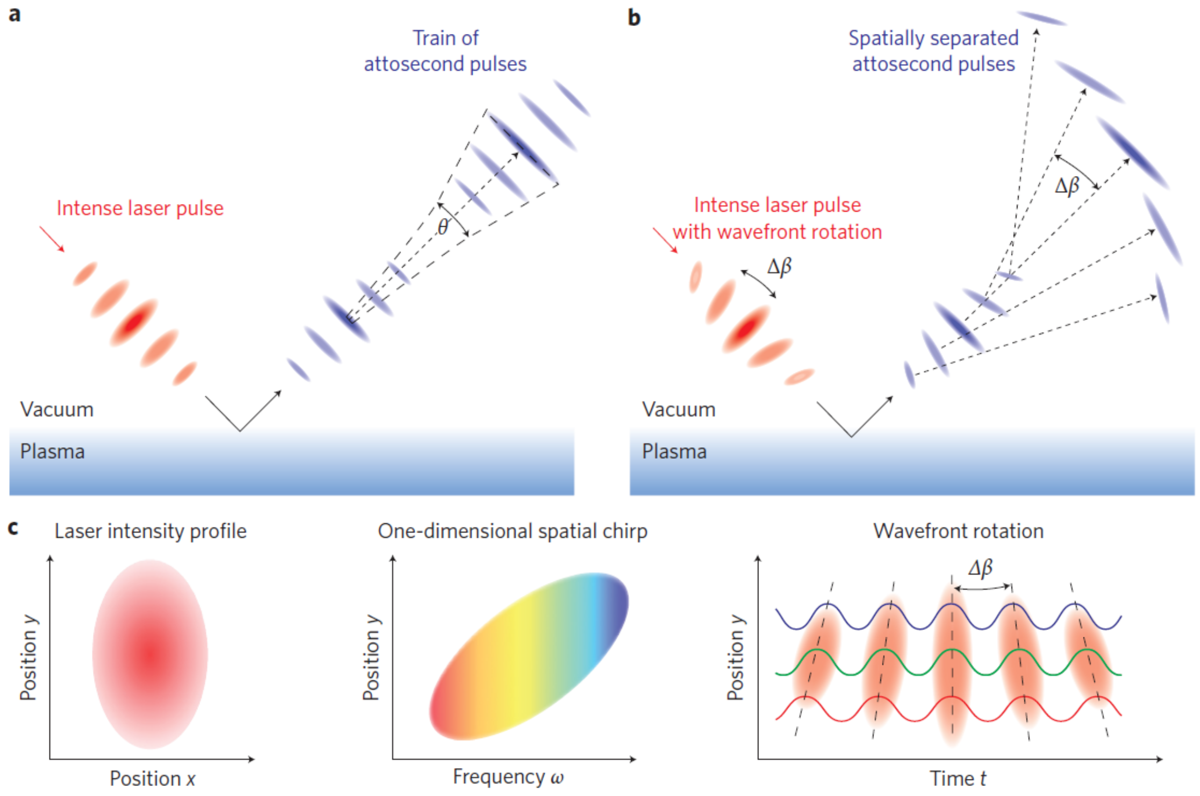


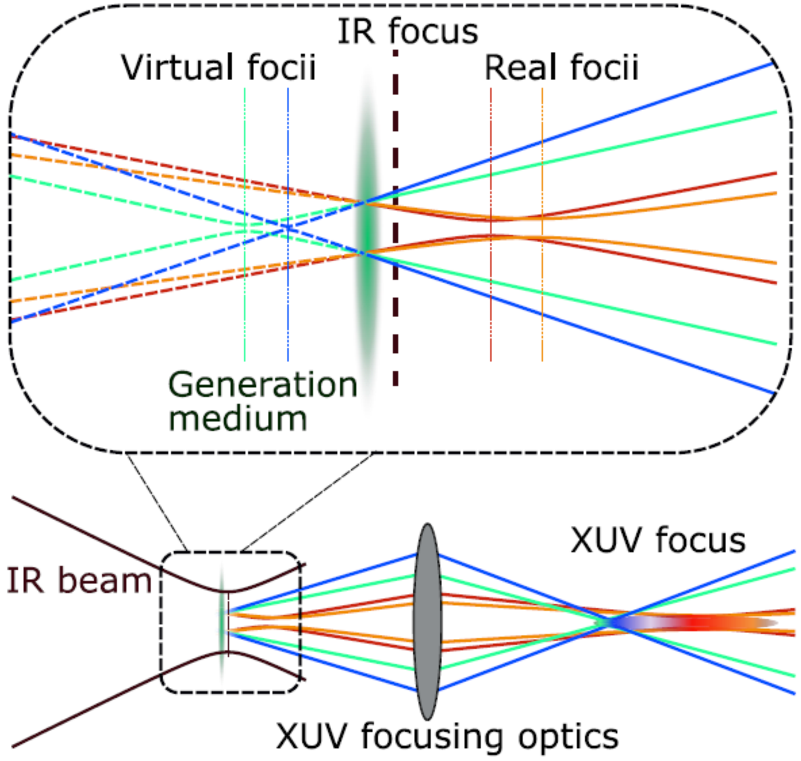




A. Debus et al., PRX **9**, 031044, (2019).
J. P. Palastro et al., PRL **124**, 134802, (2020).
C. Caizergues et al., Nat. Phot. **14**, 475 (2020).

Applications to attosecond science





Wimark et al., PNAS **116**, 4779 (2019).

H. Vincenti & F. Quéré, PRL **108**, 113904 (2012).
J. H. Wheeler et al., Nat. Phot. **6**, 829, (2012).
K. T. Kim et al., Nat. Phot. **7**, 651 (2013).

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Outline

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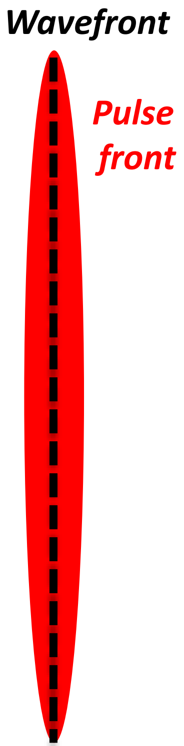
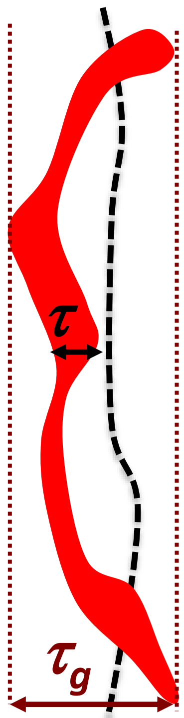
Spatio-temporal couplings (STCs)

- Anything where spatial and temporal properties are unseparable
- Often more easily explained with chromatic aberrations





spatial chirp

Simultaneous spatio-temporal focusing

wavefront rotation

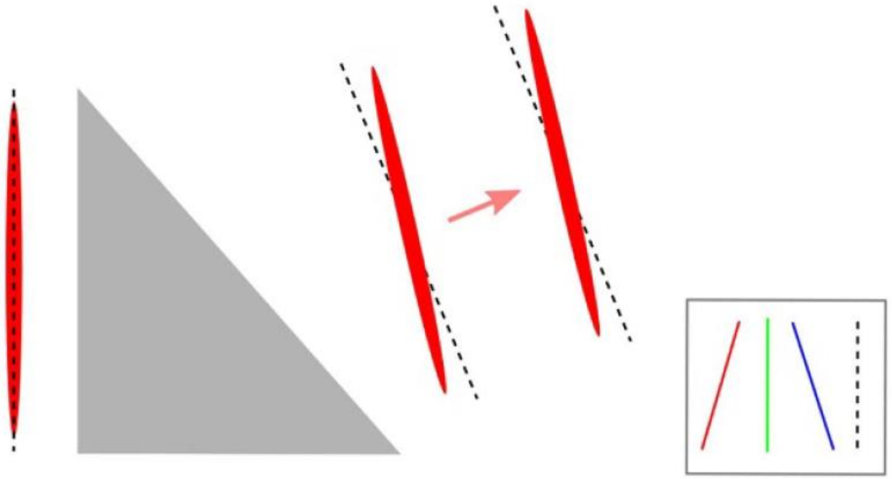
spatially-varying spectral phase

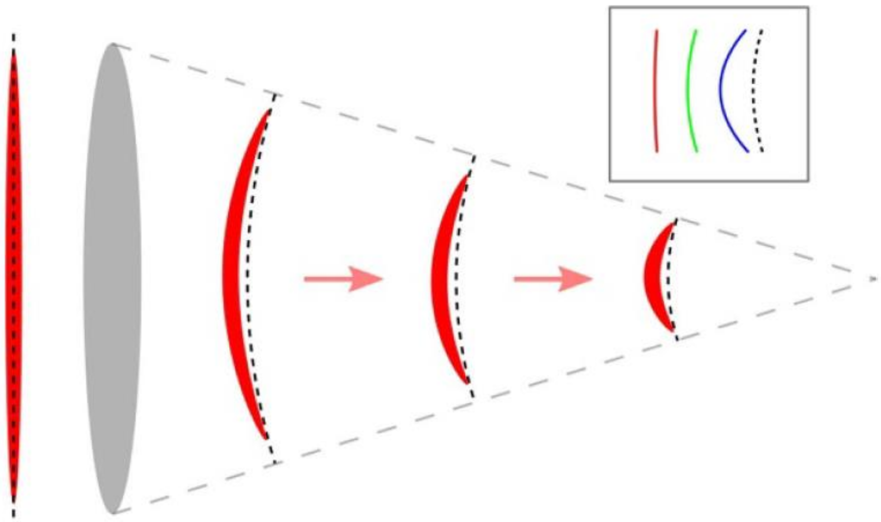
A. G. Kostenbauder, IEEE JQE **26**, 1148 (1990).
Q. Lin, Optical and Quantum Electronics **27**, 679 (1995).
S. Akturk et al., Opt. Exp. **13**, 8642 (2005).
S. Akturk et al., J. Opt. **12**, 093001 (2010).

Standard and well-known STCs

Often due to dispersive optics that aren't flat

→Dispersive prisms, dispersive lenses





Z. Bor et al., Opt. Eng. **32**, 2501 (1993).
Z. Bor, Optics Letters **14**, 119 (1989).

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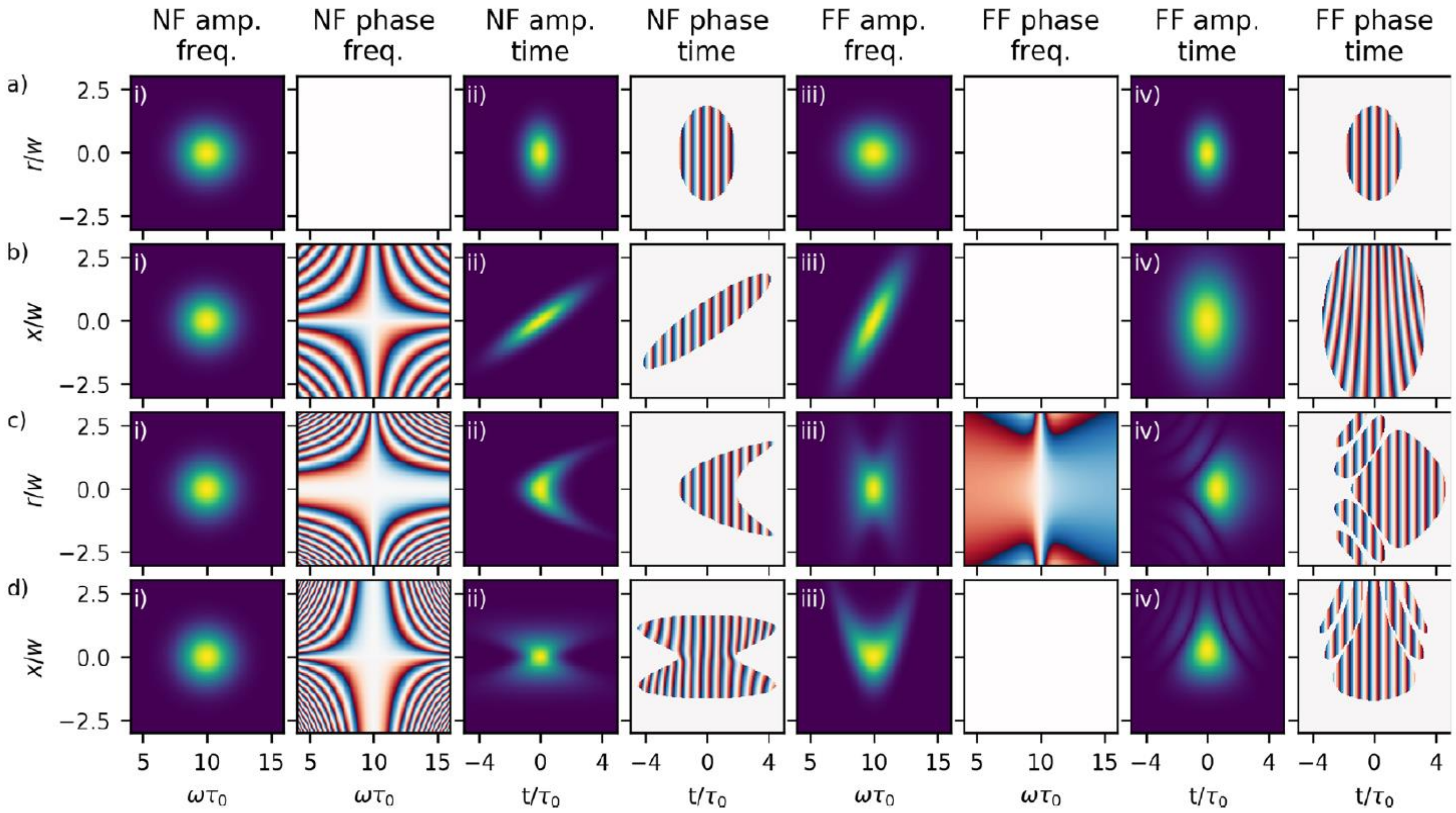
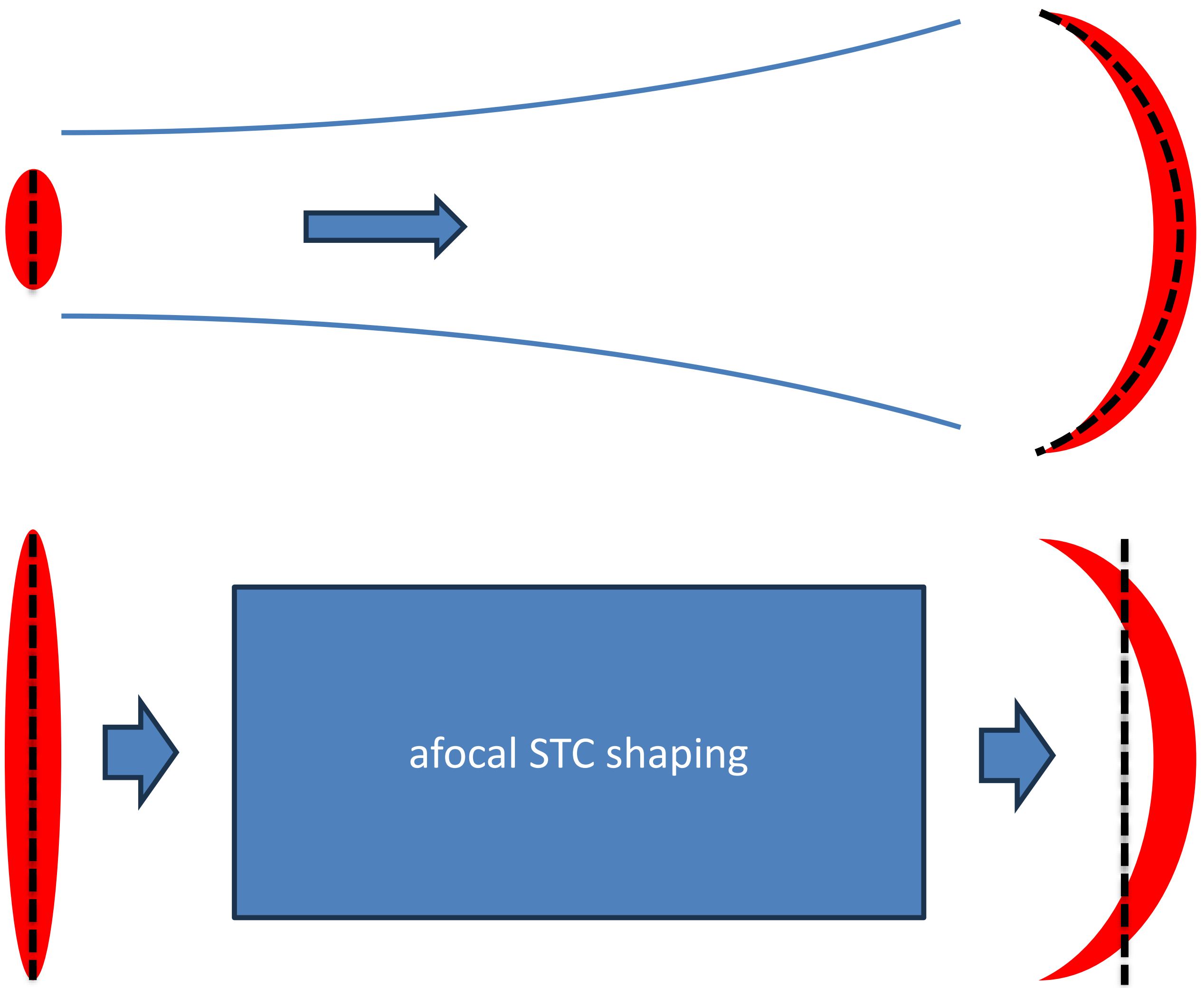
Important to understand come concepts



“Inherent” and “Imposed” STCs



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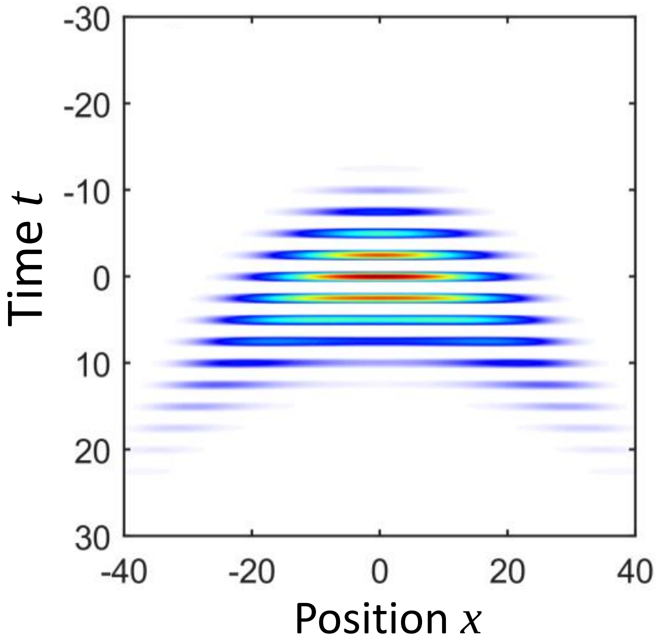
Spatio-temporal amplitude and phase



A beam can be locally short everywhere,
BUT globally long!

We need to determine

$$E(t,\mathbf{r}) = A(t,\mathbf{r})e^{i\phi(t,\mathbf{r})}$$

$\Updownarrow$

$$\hat{E}(\omega,\mathbf{r}) = \hat{A}(\omega,\mathbf{r})e^{i\varphi(\omega,\mathbf{r})}$$

$$= \sqrt{I(\omega,\mathbf{r})}e^{i\varphi(\omega,\mathbf{r})}$$

Spatio-spectral intensity: *'Easily' measured*

Spatio-spectral Phase: *Challenging!*

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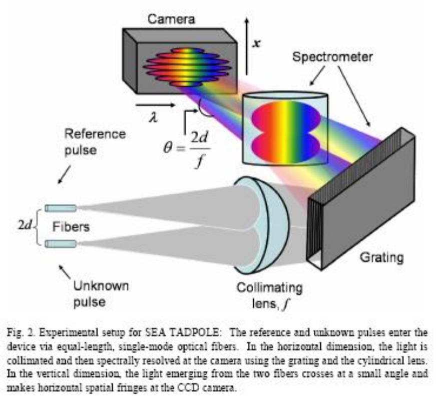
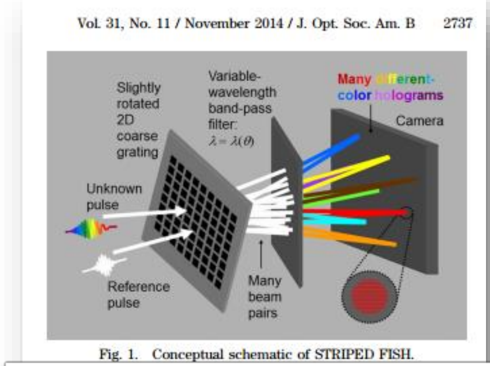
Spatio-temporal metrology: many techniques

SEA TADPOLE

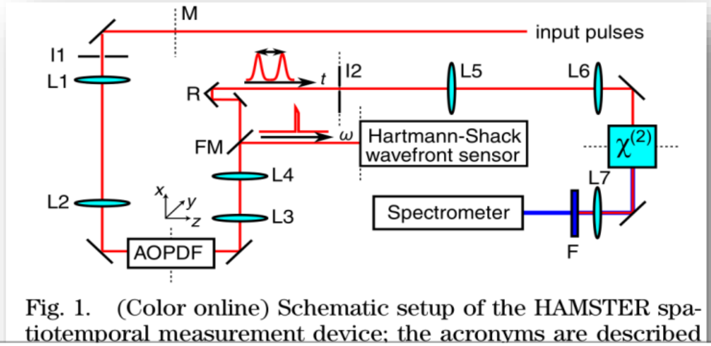


Bowlan *et al., 2006*

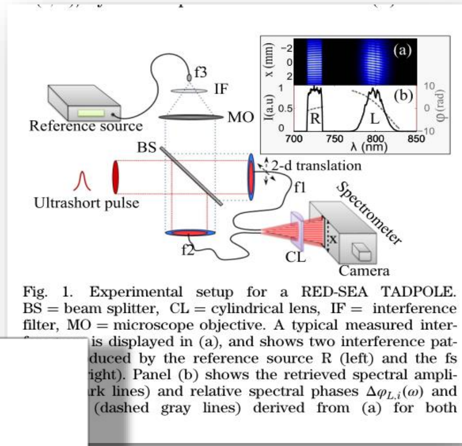
STRIPED FISH



HAMSTER



RED-SEA TADPOLE



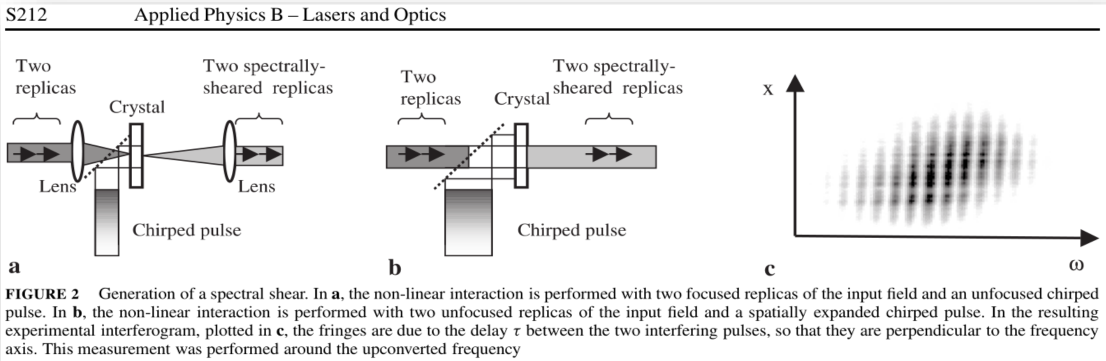
...llet *et al., 2014*

See recent overviews:

C. Dorrer, IEEE Journal of Sel. Topics in Quan. Elec. **25**, 1 (2019).

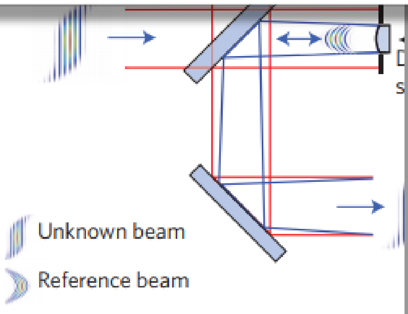
S. W. Jolly, O. Gobert, & F. Quére, Journal of Optics **22**, 103501 (2020).

SPIDER 2D

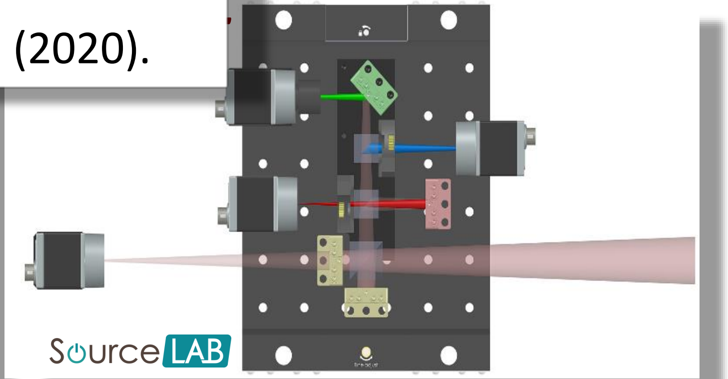


Dorrer *et al., 2001*

TERMITES



M. Miranda, et al, Opt. Lett. 39, 5142 (2014)
PhD thesis V. Gallet, (2014)
Gallet, Pariente, Quéré, patent (2014)
Pariente et al, Nature Pho. 10, 547–553 (2016)



A. Borot, *et al.*, Opt. Exp. 26, 26444 (2018).
https://www.sourcelab-plasma.com/laser-shaping/beam-shaping-catalog/insight/

Take a step back

- Is it 2-D or 3-D?
- Is it single-shot or scanning?
- Is there some type of hard limit on resolution?
- Is there a required (perfect) reference beam?
- Is it truly a space-time device or “just” space-spectrum?

“different techniques just shift the hard part of the measurement to a different subsystem”

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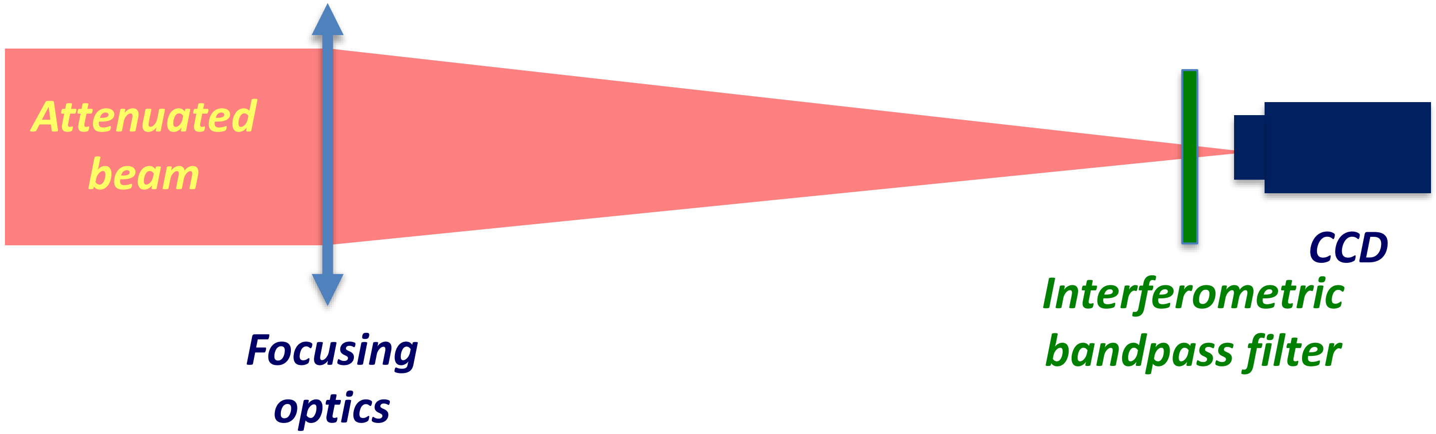
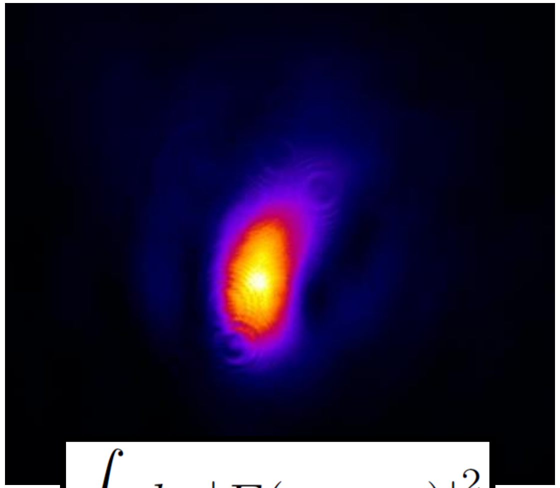
Simple but partial measurement example (1/2)

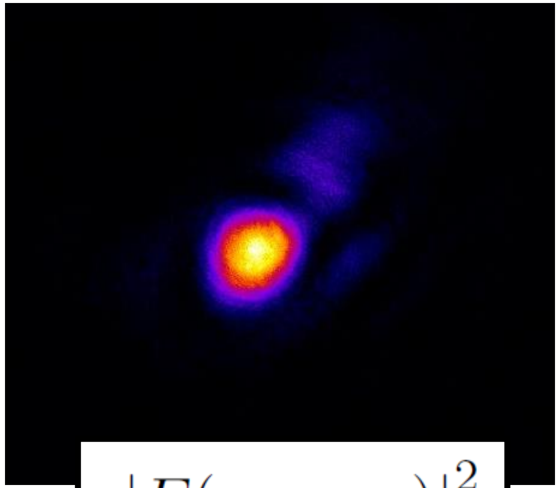


Focal spot image with full spectrum
(≈70 nm FWHM @ 800 nm)



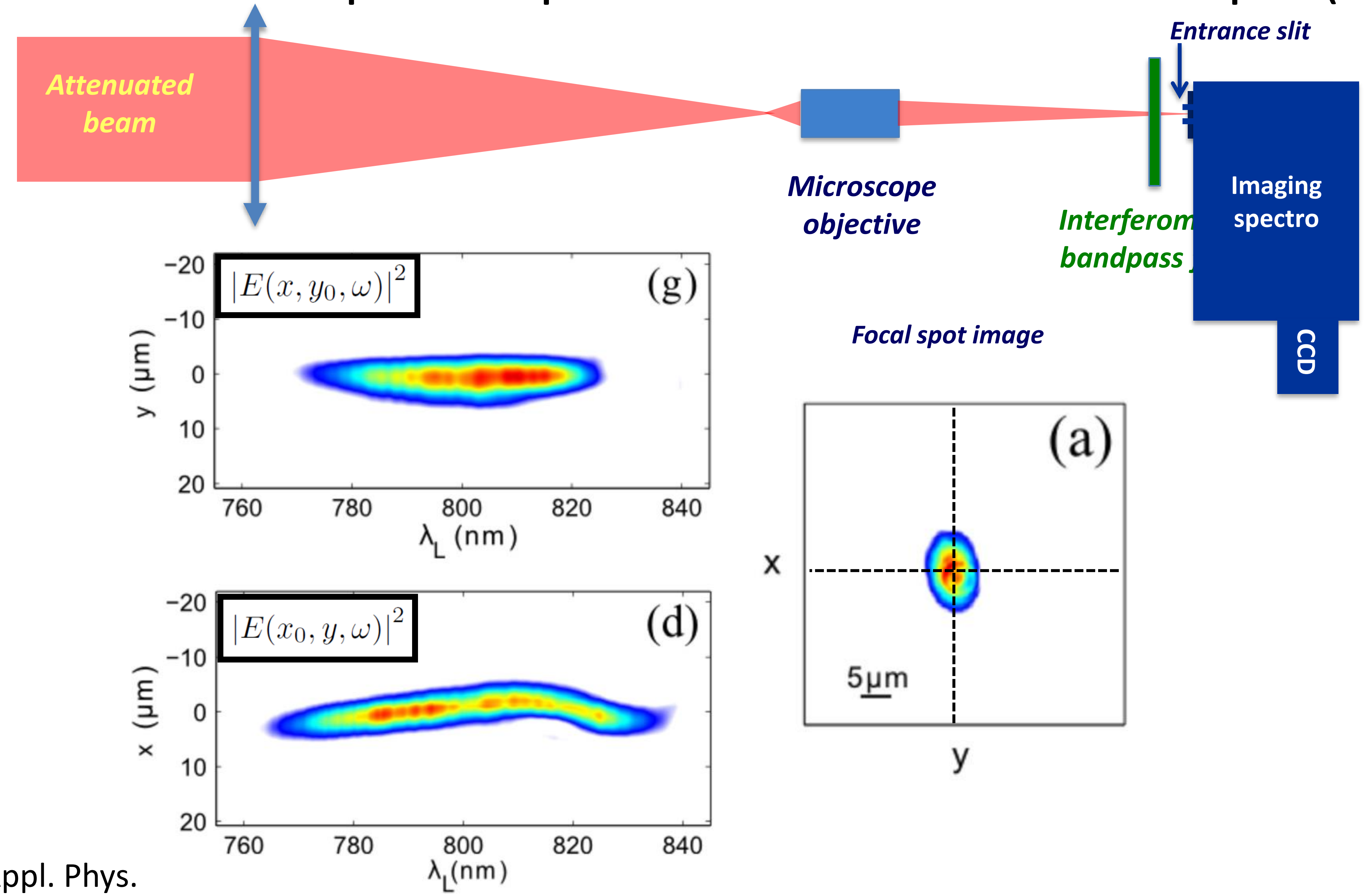
$$\int d\omega \, |E(x, y, \omega)|^2$$

Focal spot image with bandpass filter
(≈10 nm FWHM @ 800 nm)



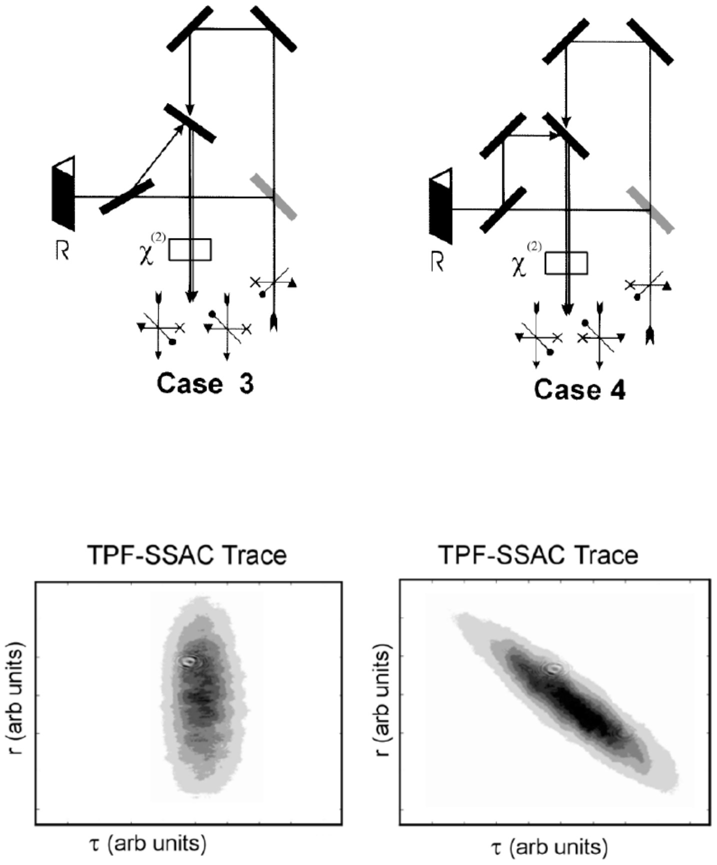
$$|E(x, y, \omega_0)|^2$$

Simple but partial measurement example (2/2)

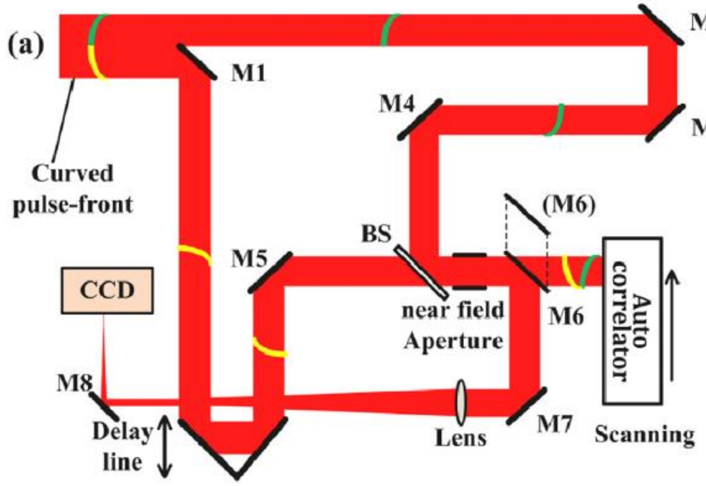


S. Kahaly et al., Appl. Phys. Lett. **104**, 054103 (2014)

Modified single-shot autocorrelators



Z. Sacks et al., Opt. Lett. **26**, 462 (2001).



F. Wu et al., Opt. Comm. **367**, 259 (2016).

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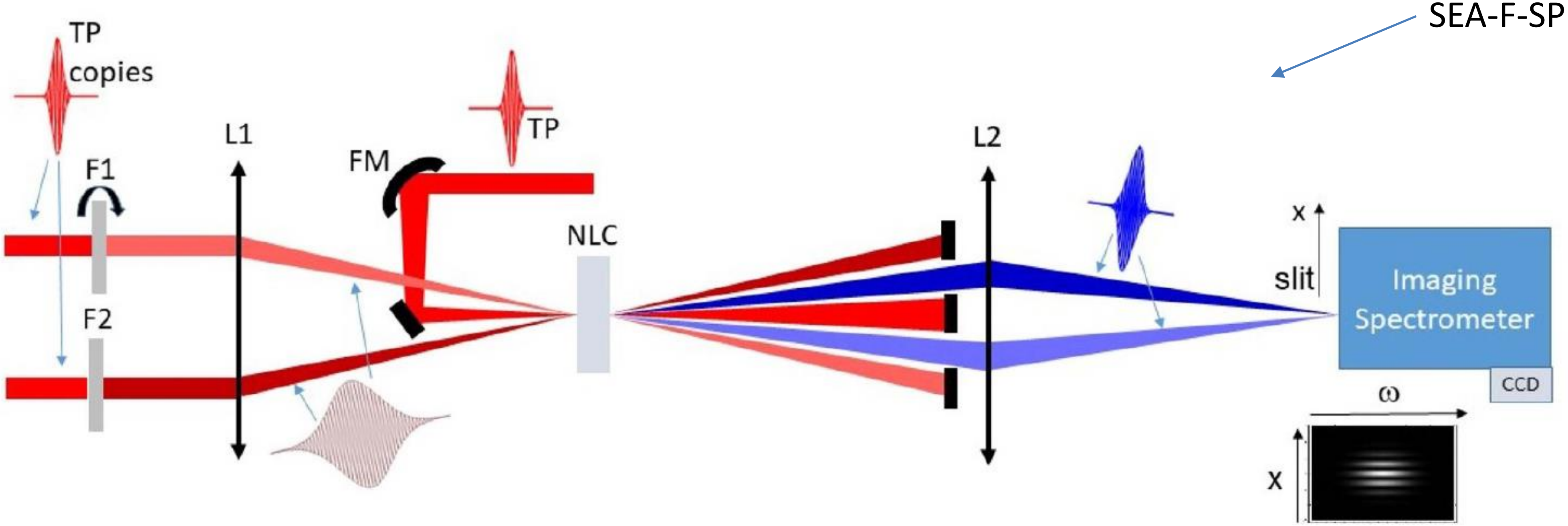
2D versions of SPIDER

SPIDER-2D
SEA-SPIDER
SEA-F-SPIDER



C. Dorrer et al., Opt. Lett. **27**, 462 (2002).
T. Witting et al., Opt. Lett. **34**, 881 (2009).

Towards "complete" measurements

#1 – Spatially-resolving a spectral measurement

#2 – Spectrally-resolving a spatial measurement

Yes, these are really different

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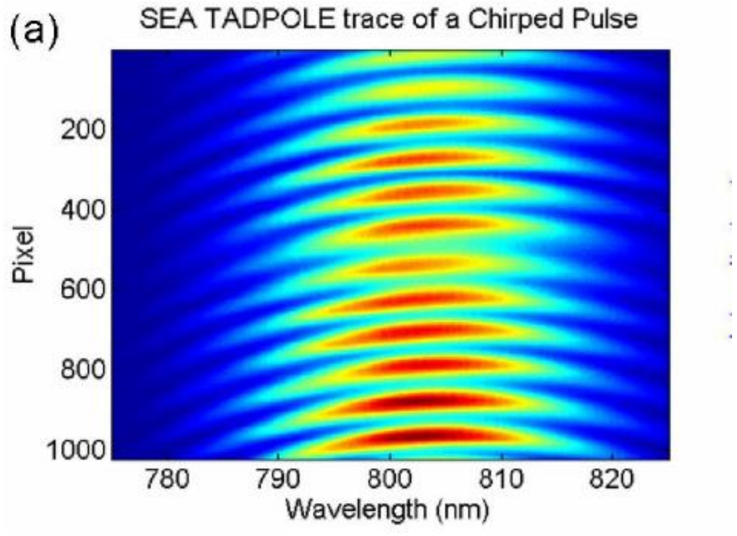
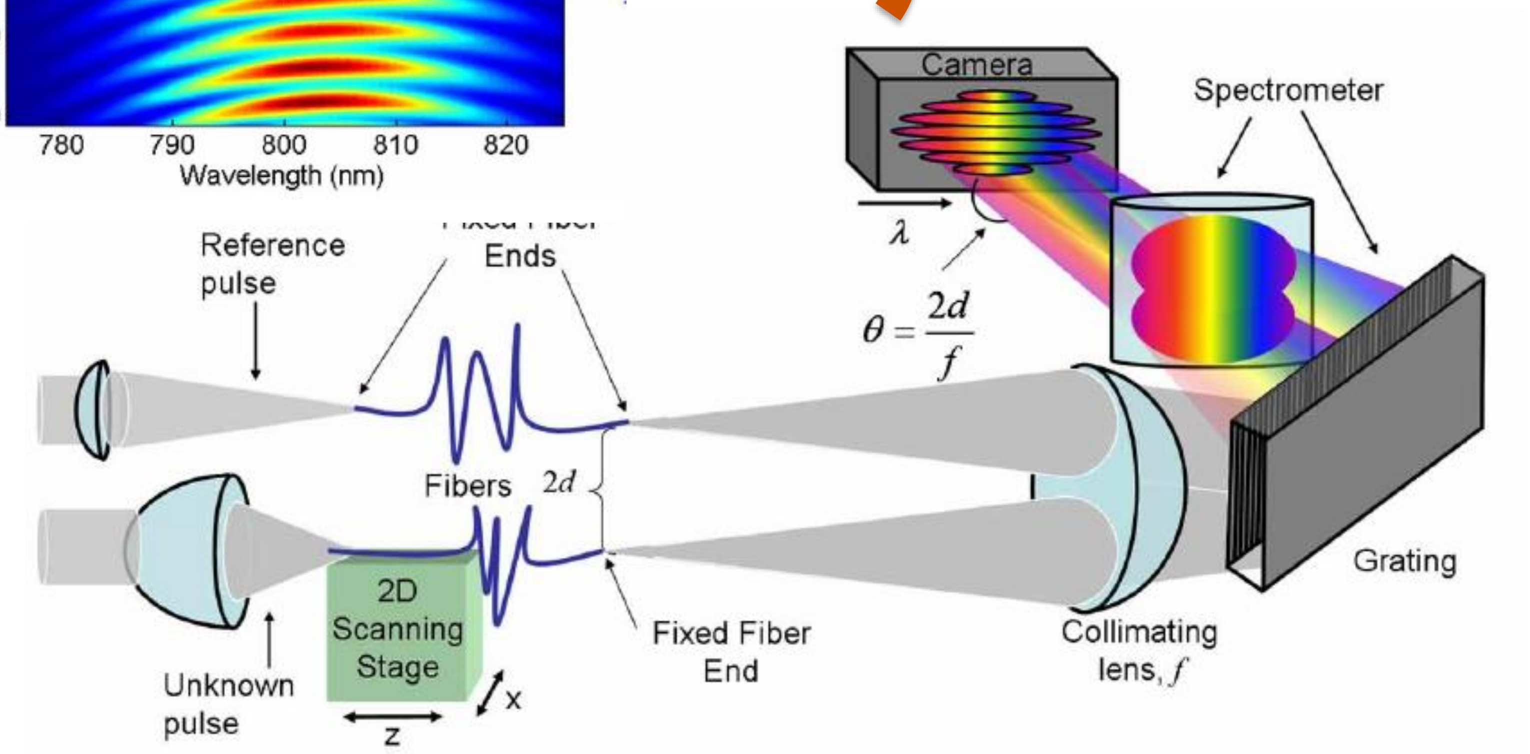
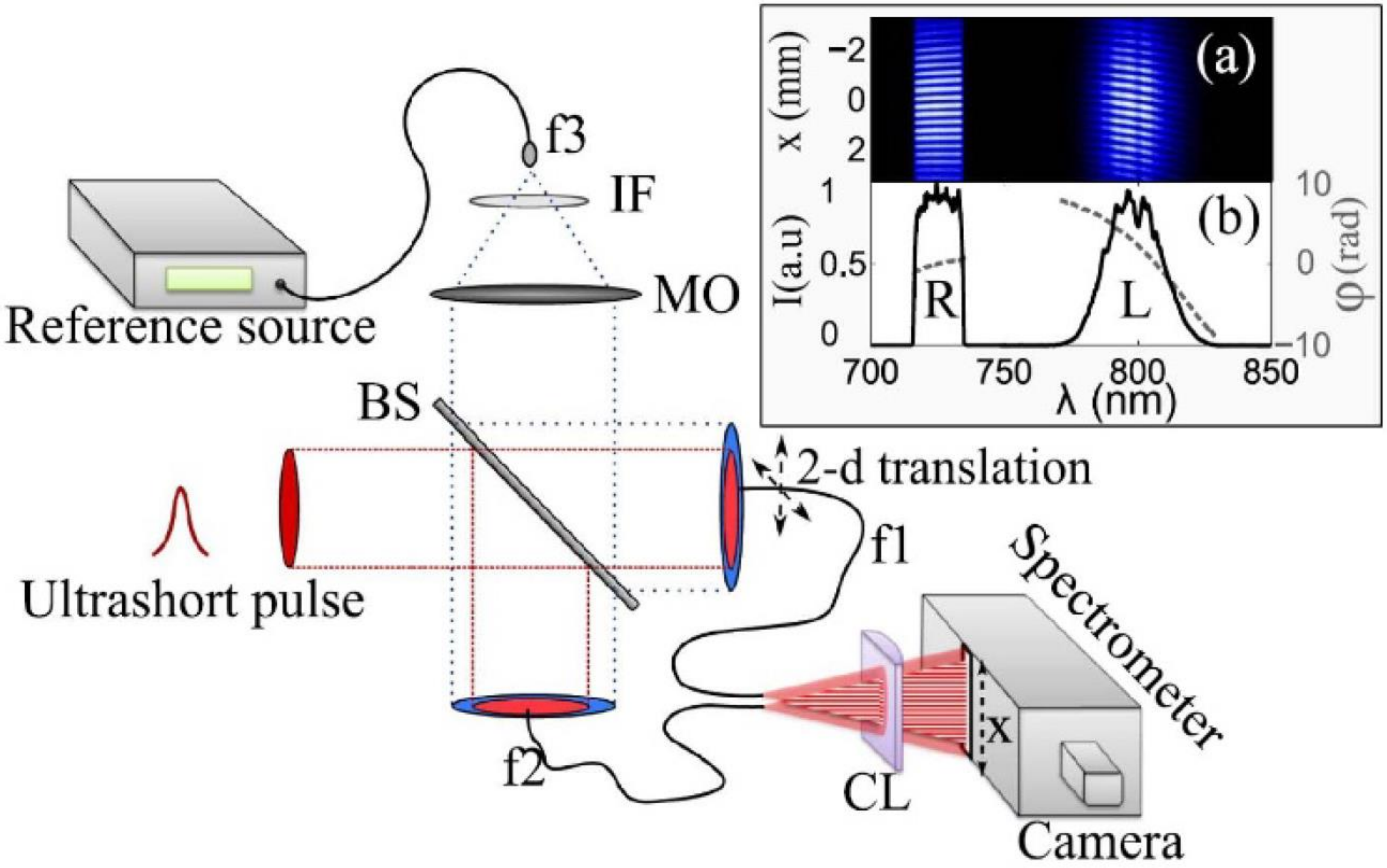
SEA-TADPOLE and STARFISH





P. Bowlan et al., Opt. Express **14**, (2006)
P. Bowlan et al., Opt. Express **15**, (2007)
B. Alonso et al., JOSA B **27**, 933 (2010).

RED-SEA-TADPOLE



V. Gallet et al., Opt. Lett. **39**, 4687 (2014).

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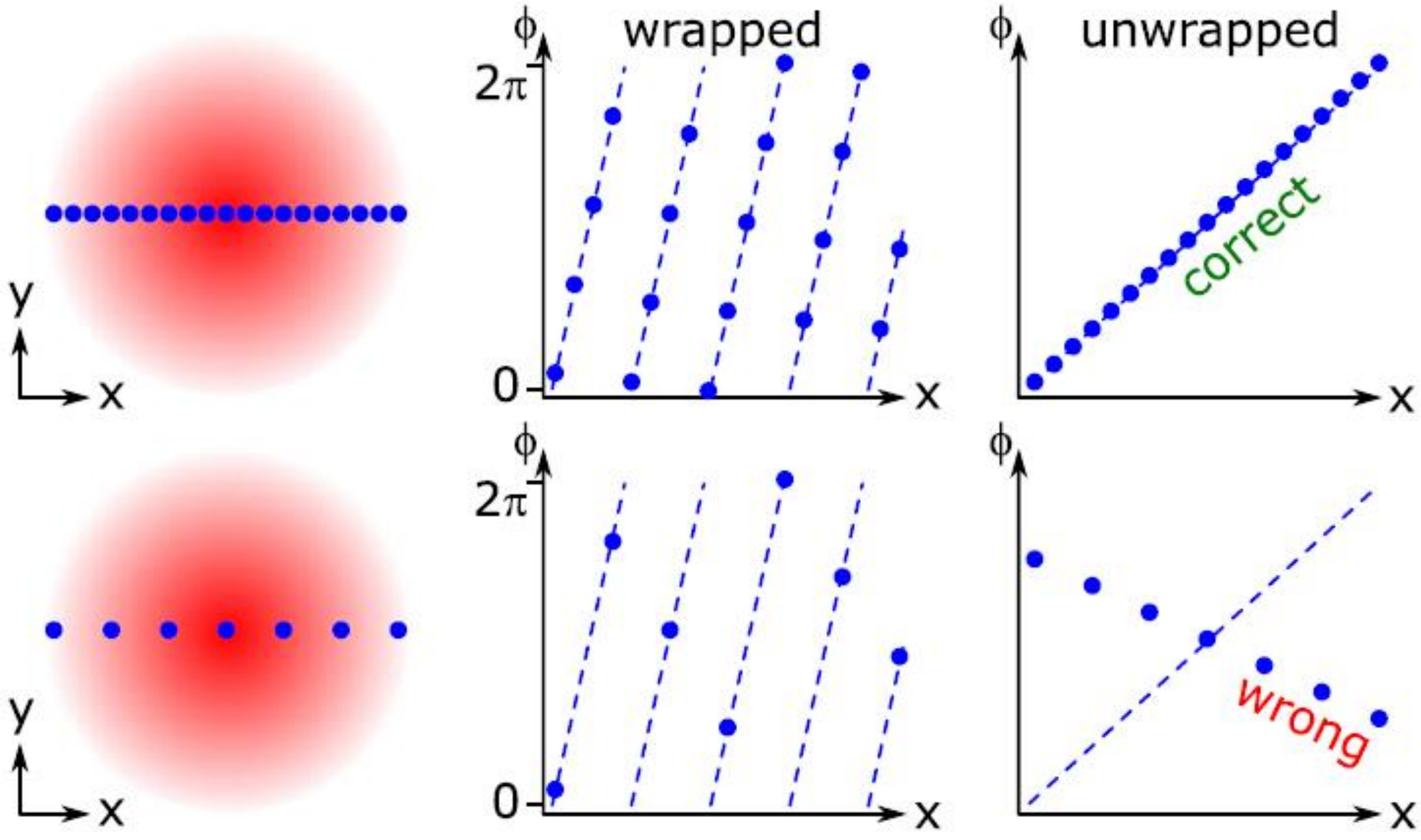
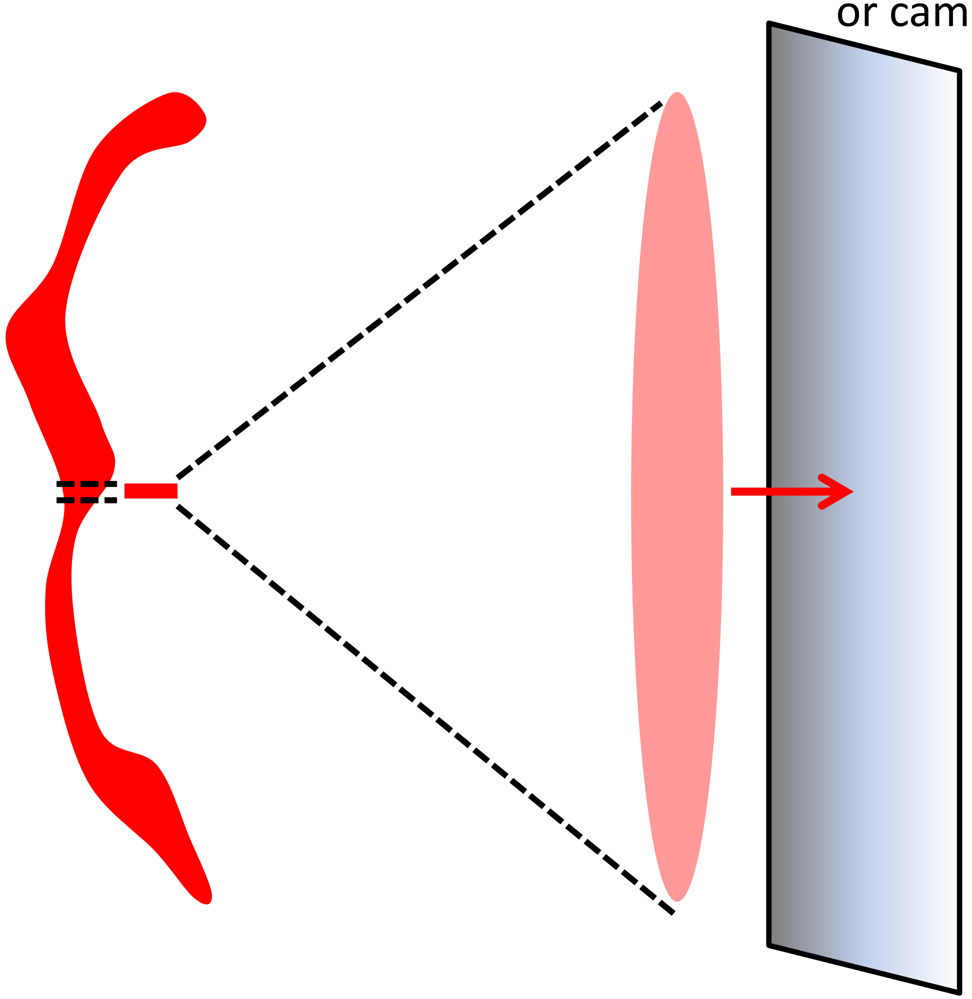
Weakness in spatial sampling



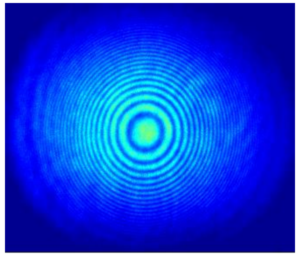
From SEA-TADPOLE to TERMITES

$$E_R(t) \;=\; E(t, \mathbf{r}_0)$$

Screen
or camera

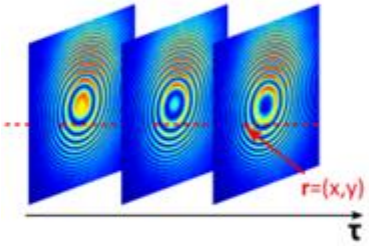


Measure 2D interference pattern



$$S(\tau, \mathbf{r}) = \int dt\, |E(t, \mathbf{r}) + E_R(t-\tau)|^2$$

Measure as a function of τ

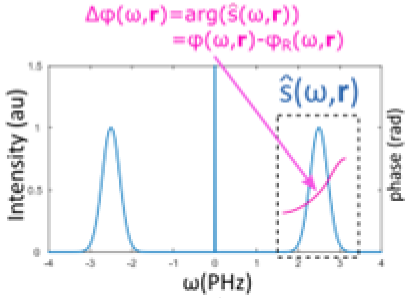


$$s(\tau, \mathbf{r}) = \int dt E(t, \mathbf{r}) E_R^*(t-\tau)$$

FFT with respect to τ

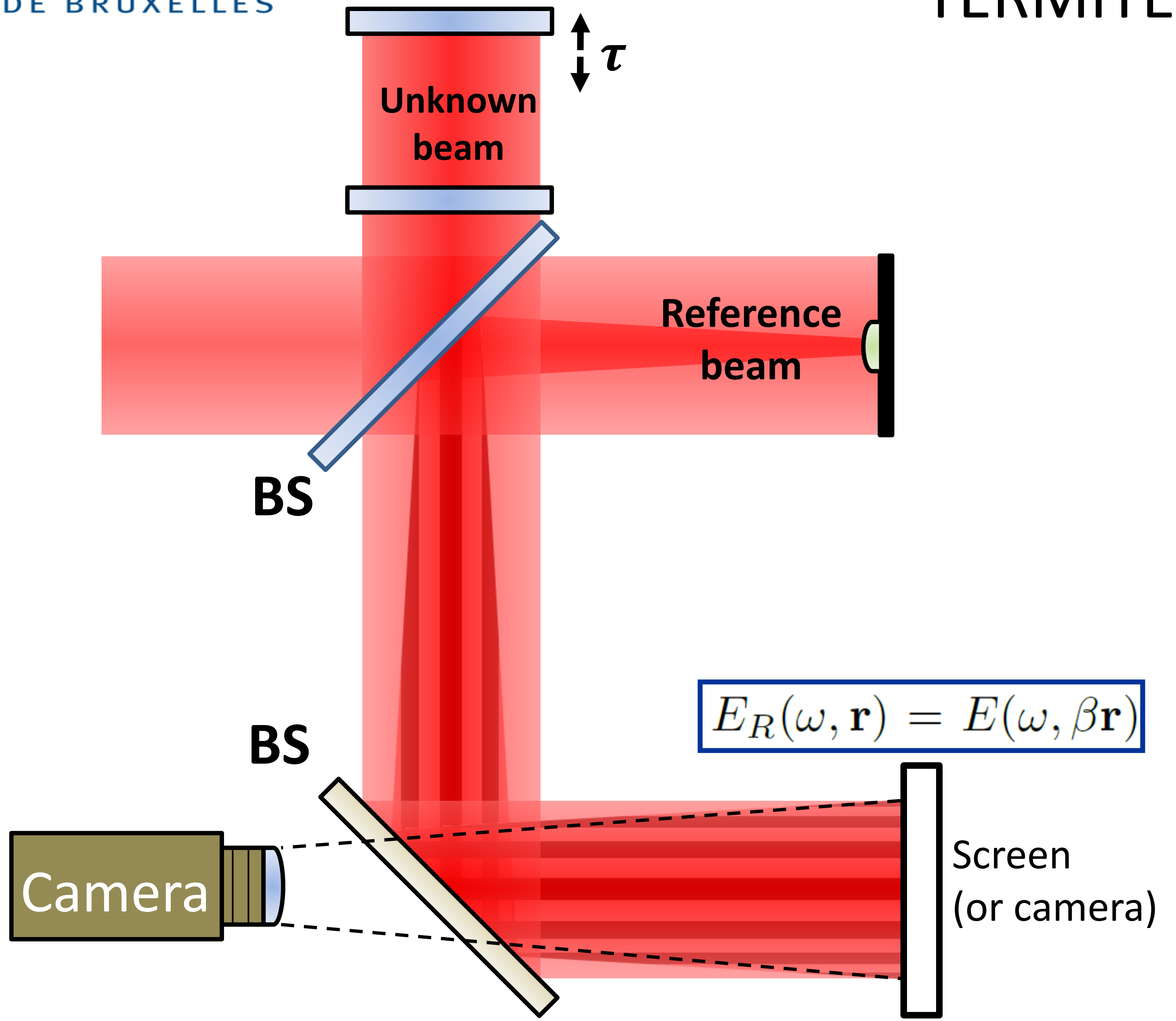
According to Wiener–Khintchine's theorem:

$$s(\omega, \mathbf{r}) \;=\; E(\omega, \mathbf{r}) E_R^*(\omega)$$

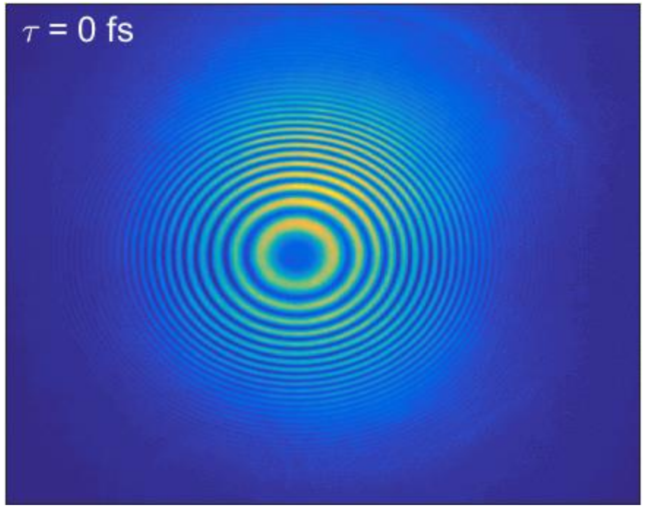


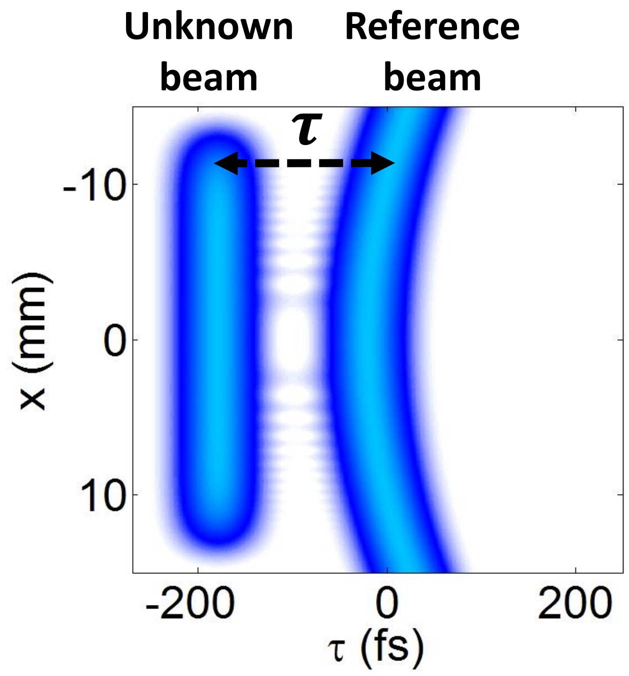
M. Miranda et al., Opt. Lett. **39**, 5142 (2014).
G. Pariente et al., Nat. Phot. **10,** 547 (2016).

TERMITES



$$E_R(\omega, \mathbf{r}) = E(\omega, \beta\mathbf{r})$$





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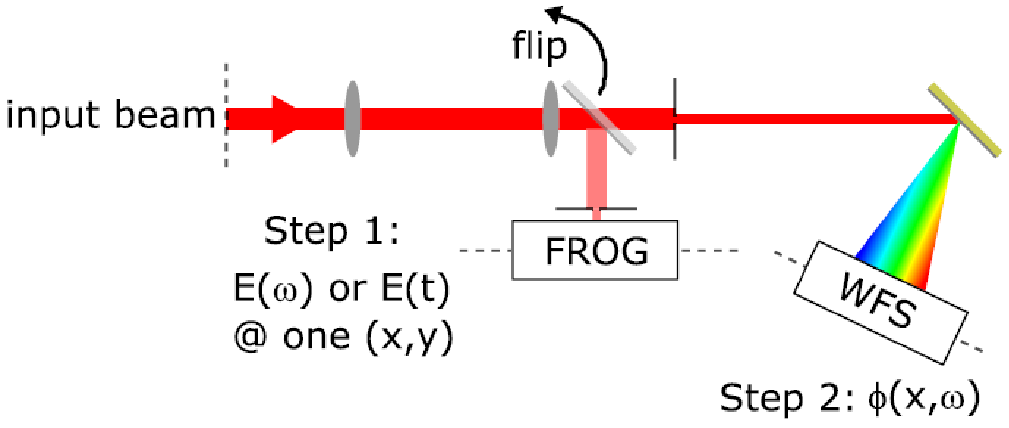
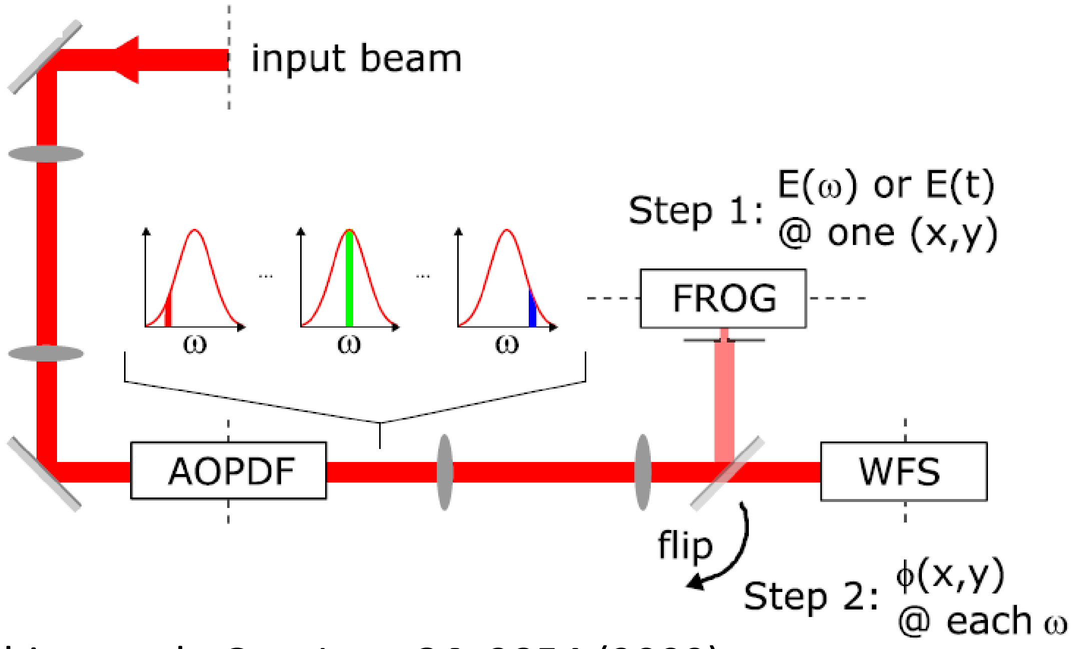
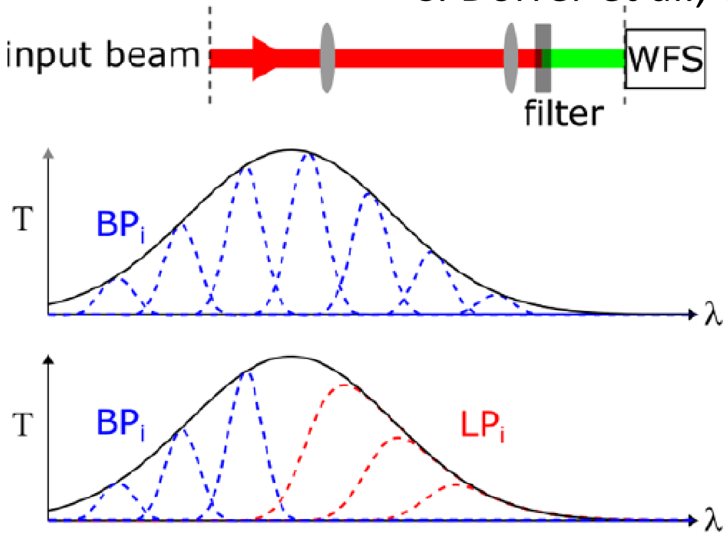
Frequency-resolved wavefront measurements

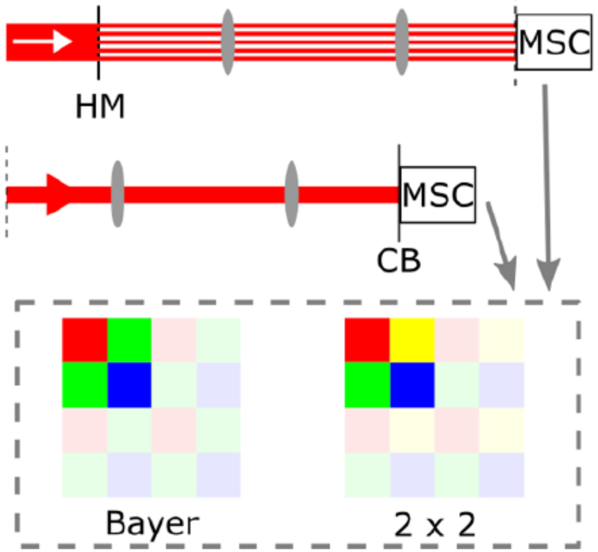
E. Kueny et al., Opt. Exp. **26**, 31299 (2018).
L. Ranc et al., OSA Laser Congress (2019).
C. Dorrer et al., Opt. Exp. **26**, 33387 (2018).





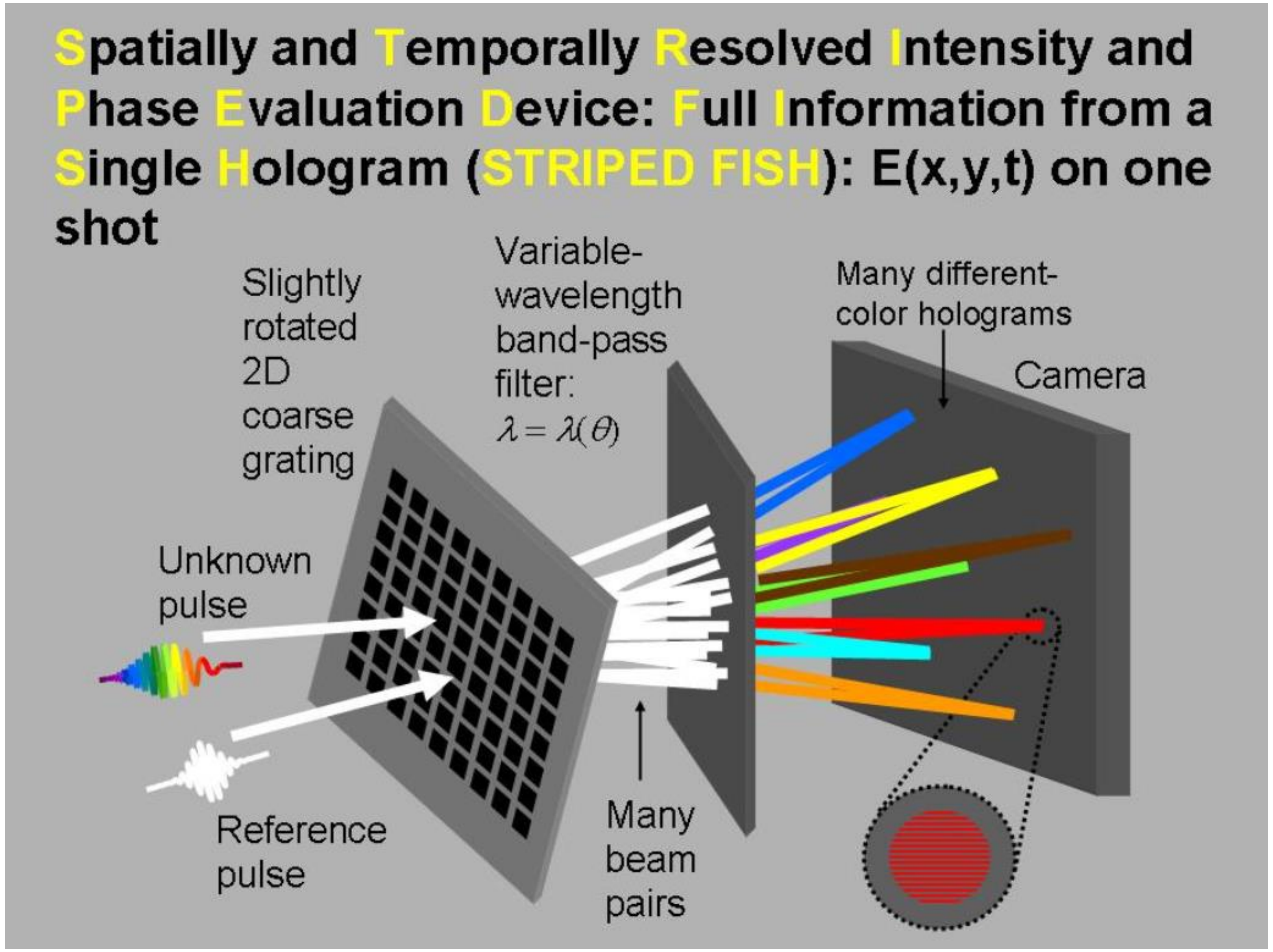


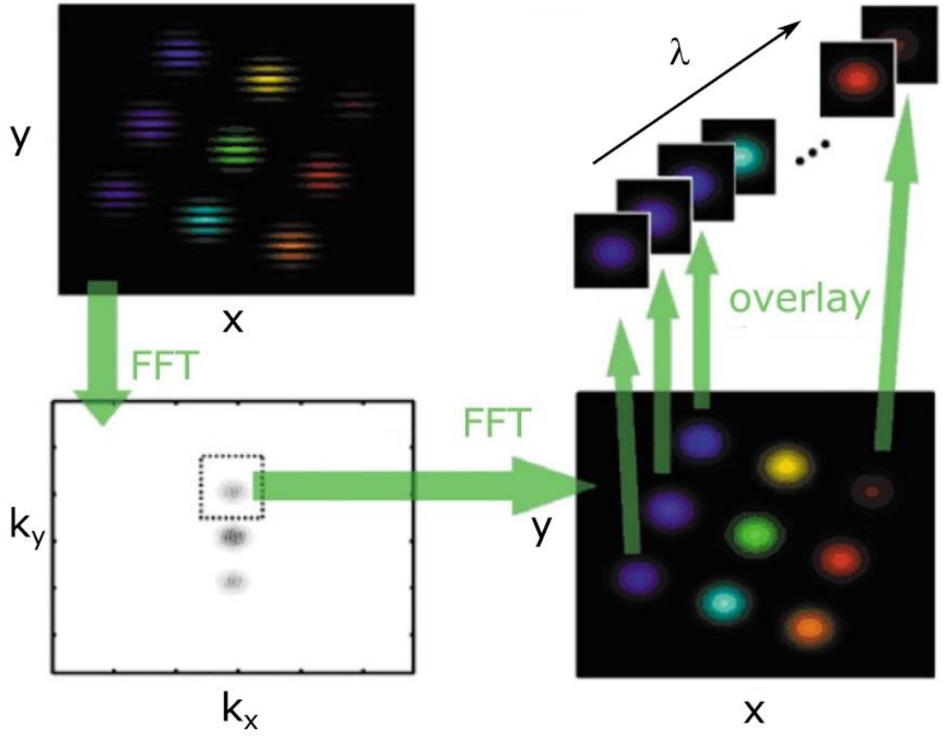
imagine optic
HASO Multispectral



E. Rubino et al., Opt. Lett. **34**, 3854 (2009)
S. Cousin et al., Opt. Lett. **37**, 3291 (2012).

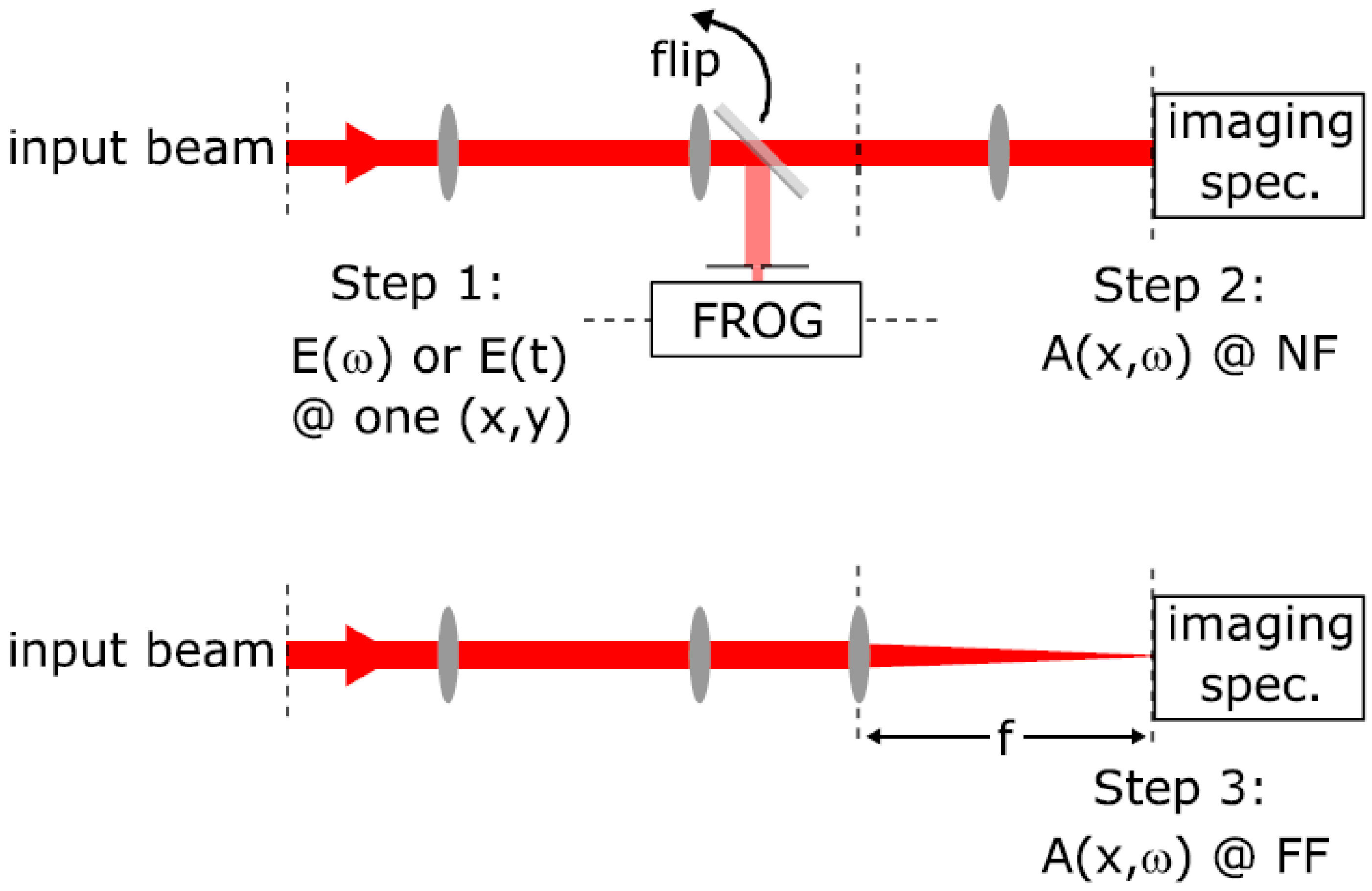
STRIPED-FISH





Gabolde and Trebino, Optics Express **14**, 11460 (2006).

CROAK technique



F. Bragheri et al., Opt. Lett. **33**, 2952 (2008).

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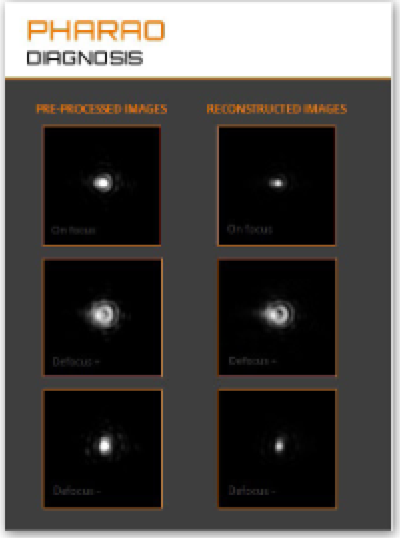
Insight: a reference-free, phase retrieval approach

imagine optic™

PHARAO EXTENSION

Focal spot optimization

Phase Retrieval algorithm PhaRAO is an optional extension of WaveTune. With the help of a simple far field camera, PharAO enables users to control and optimize the focal spot directly in the interaction chamber.



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Insight: a reference-free, phase retrieval approach

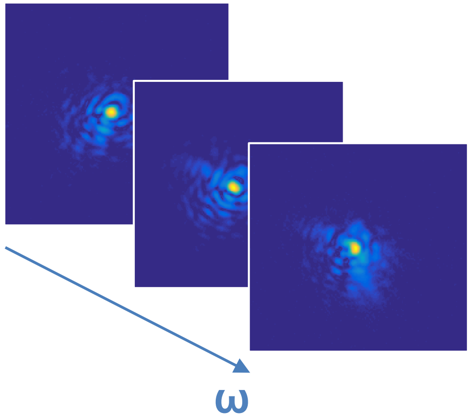
$$E(x,y,\omega) = A(x,y,\omega) * e^{i\varphi(x,y,\omega)}$$

Frequency-dependent amplitude profile

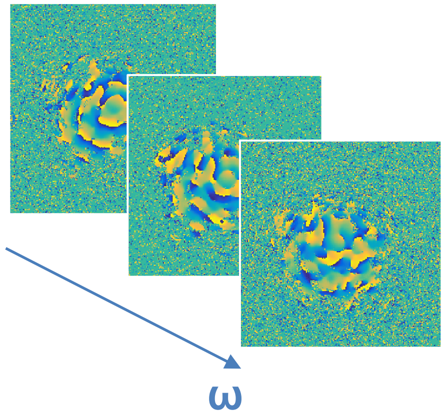
Frequency-dependent phase profile

INSIGHT

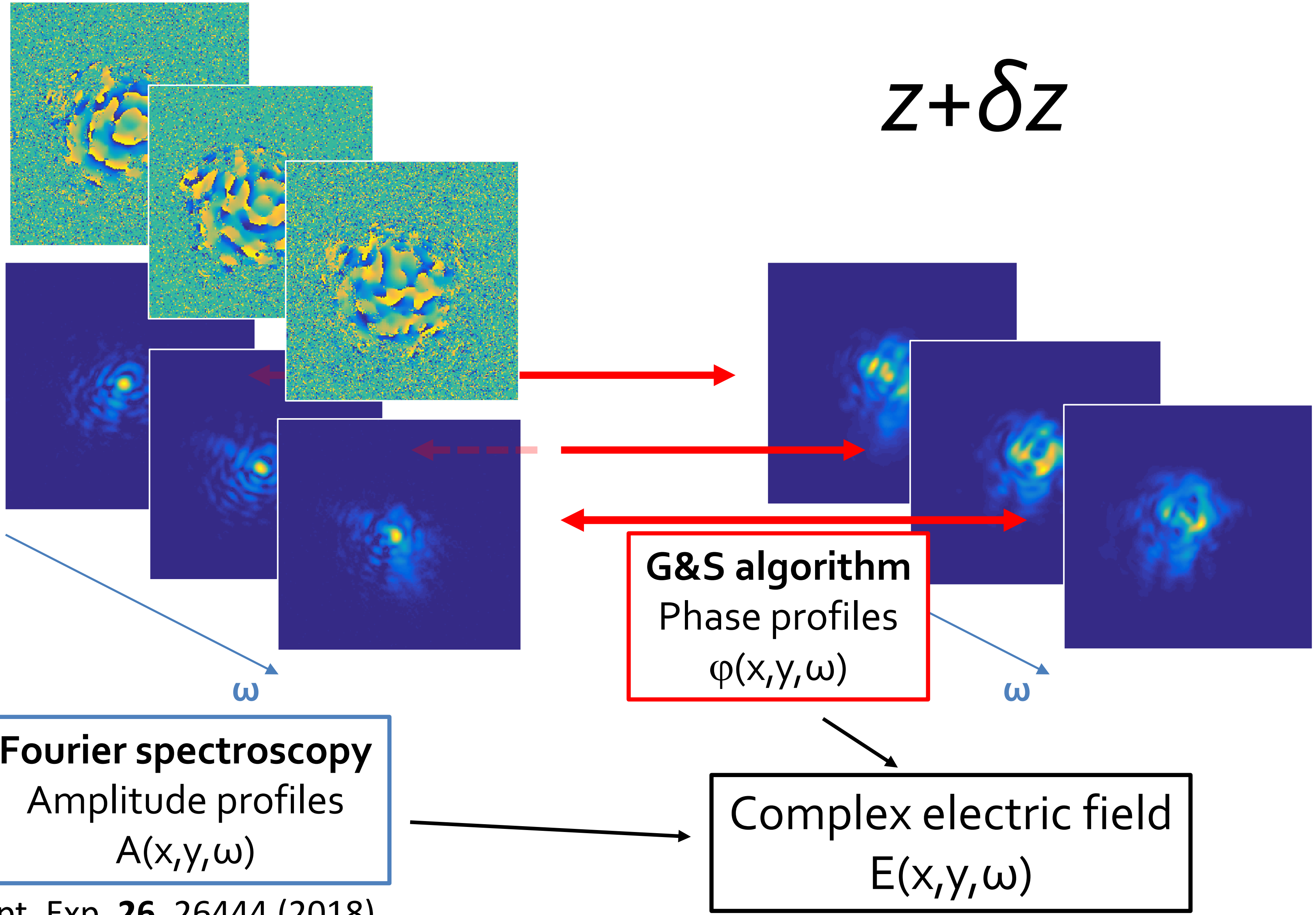
Spatially-resolved Fourier spectroscopy



Spectrally-resolved phase retrieval algorithm

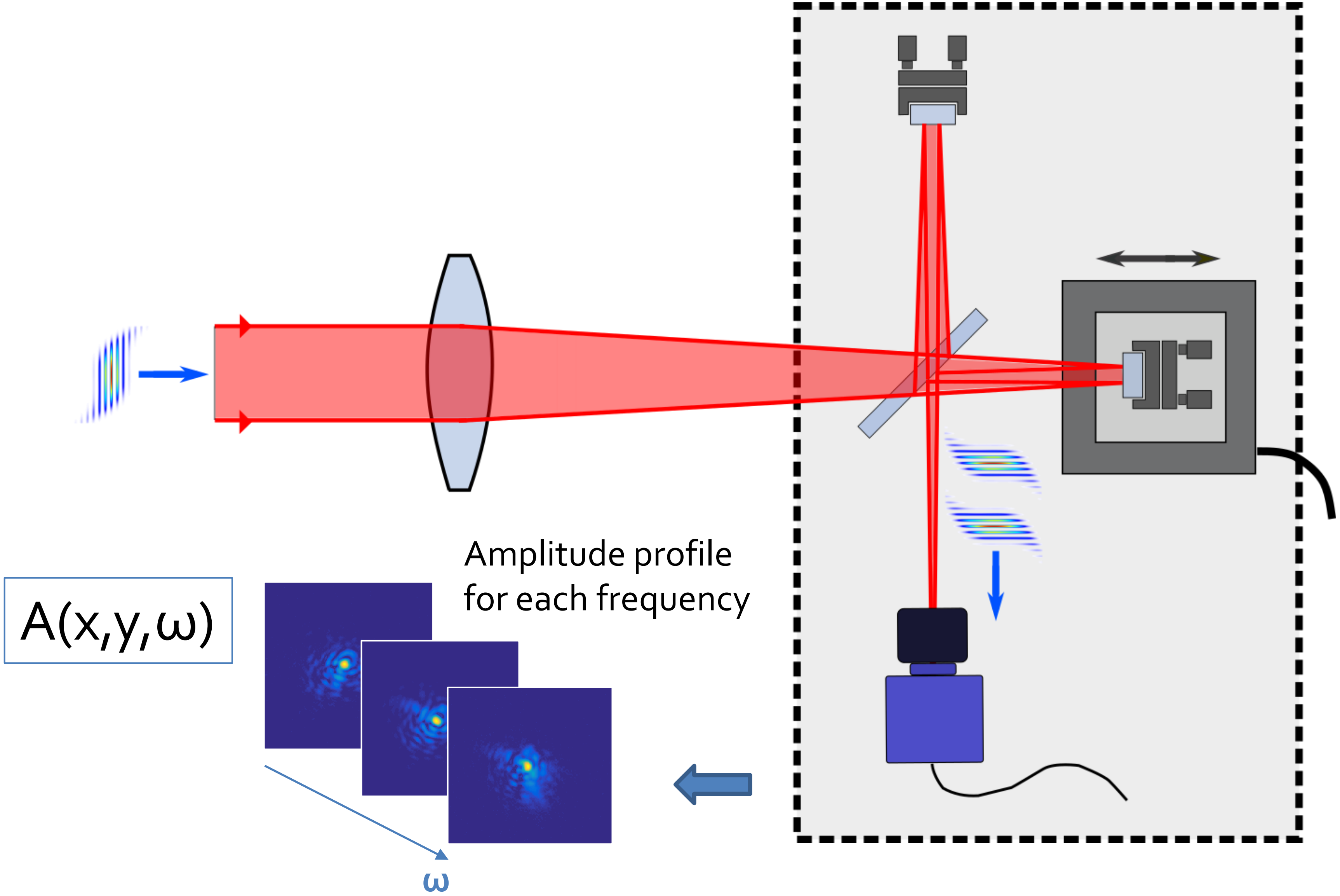


Insight in one glance



A. Borot and F. Quéré, Opt. Exp. **26**, 26444 (2018).

Experimental setup of Insight



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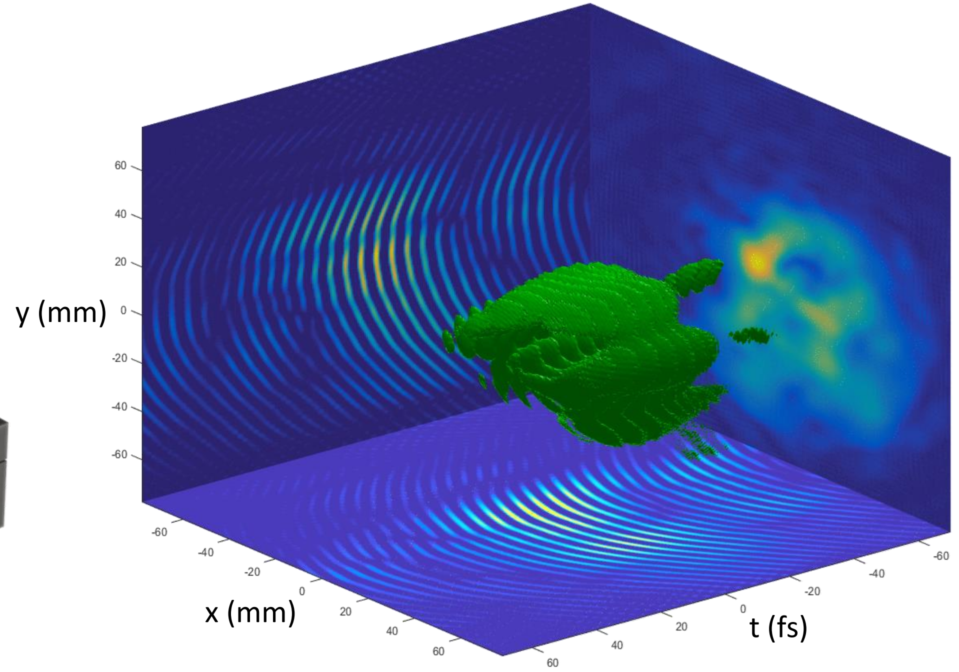
Insight: Spatio-spectral imager at the focus



@1 Hz : 12 min
@10 Hz : 2 min

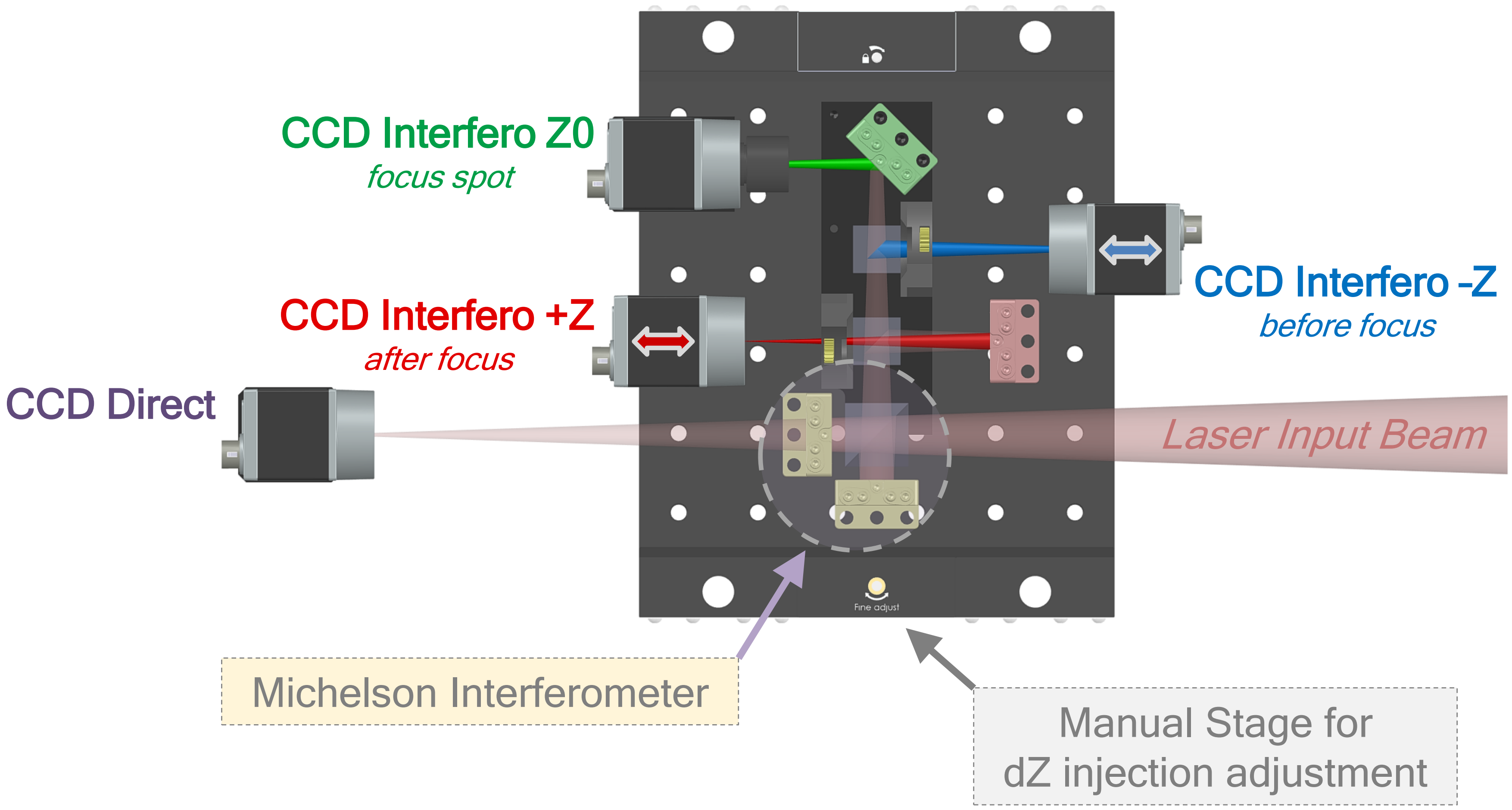
SourceLAB

https://www.sourcelab-plasma.com/laser-shaping/beam-shaping-catalog/insight/

Outline

- Why is STC characterization necessary?
- What are STCs?
- Overview of history and of standard techniques
- **More recent measurements and techniques**
- Very recent progress in exotic STCs

New: Insight Quadro



https://www.sourcelab-plasma.com/laser-shaping/beam-shaping-catalog/insight/

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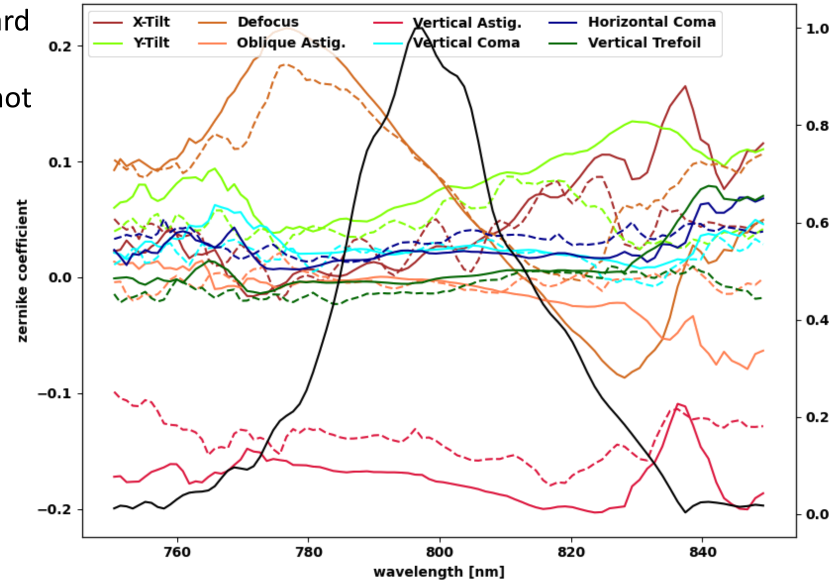
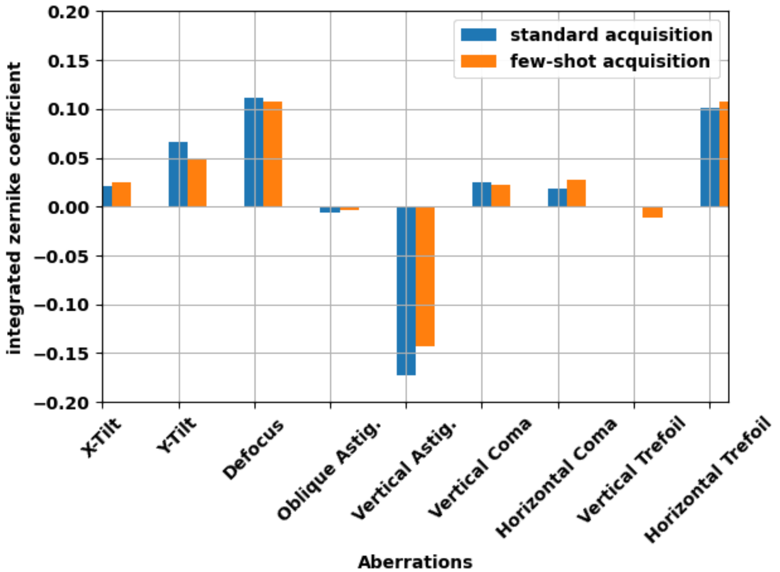
New: Few-shot plugin

As INSIGHT is **a scanning device**, it is well suited for > 10 Hz laser system for a fast acquisition. For repetition rate < 10 Hz (in particular few shots/min laser system), a powerful Few-Shot plugin **is now available**.

Solid: standard acquisition
Dash: few-shot acquisition



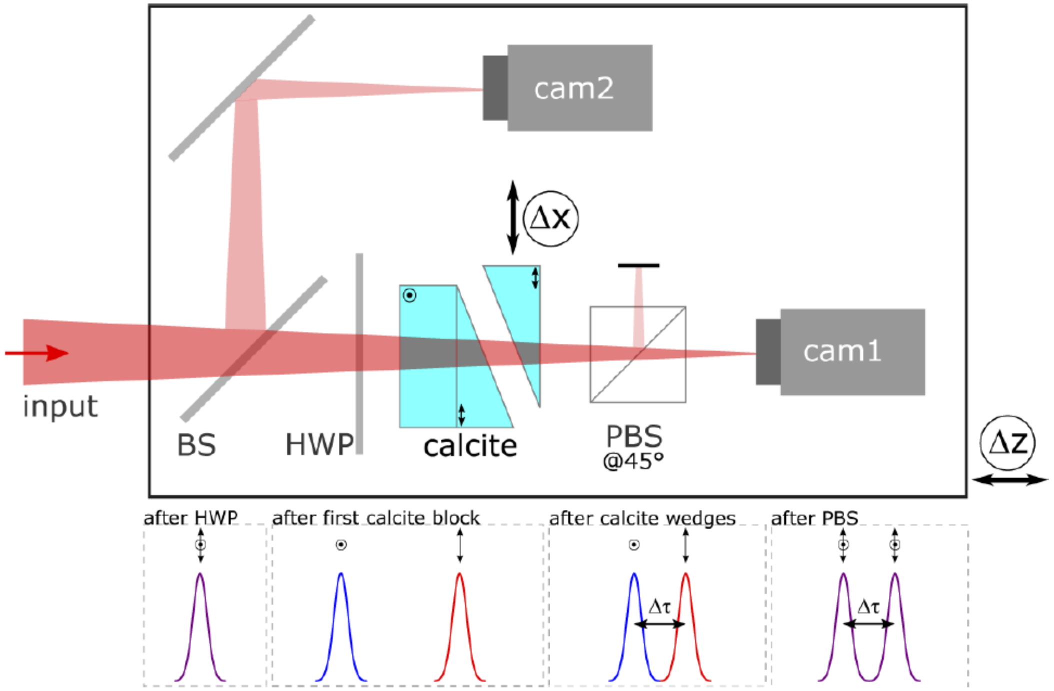


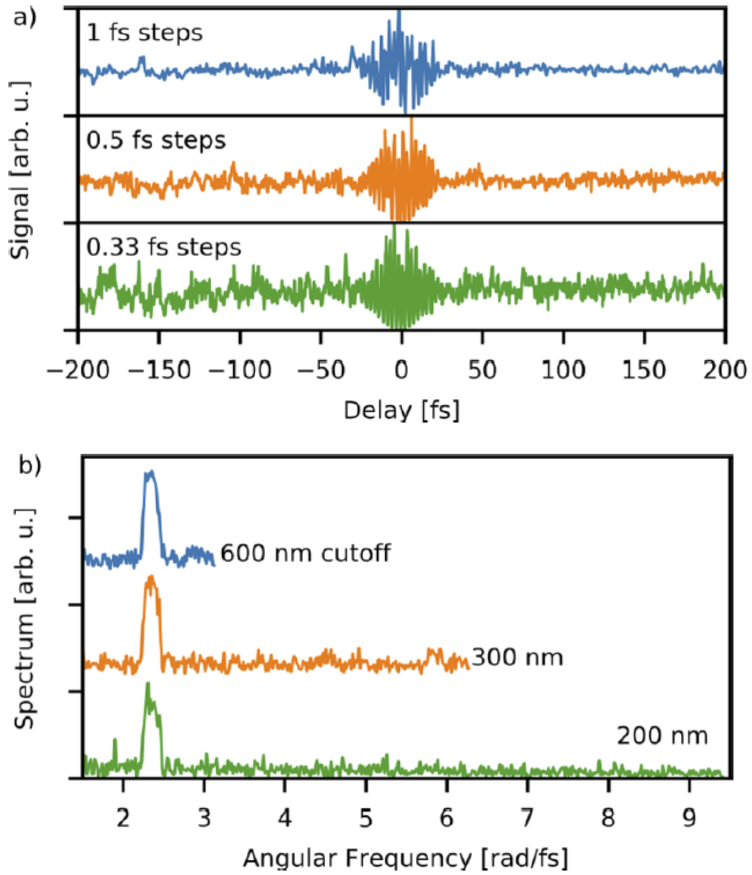
- Can extract quantitatively the spectrally resolved Zernike coefficients, about **10 times faster** than the standard procedure in INSIGHT.
- Particularly useful for **quasi-real time** iterative alignment of complex components (e.g. compressor gratings).

SourceLAB

https://www.sourcelab-plasma.com/laser-shaping/beam-shaping-catalog/insight/

A new version of Insight with birefringent prisms





Higher precision for delay steps

→shorter wavelengths (limited only by optics)

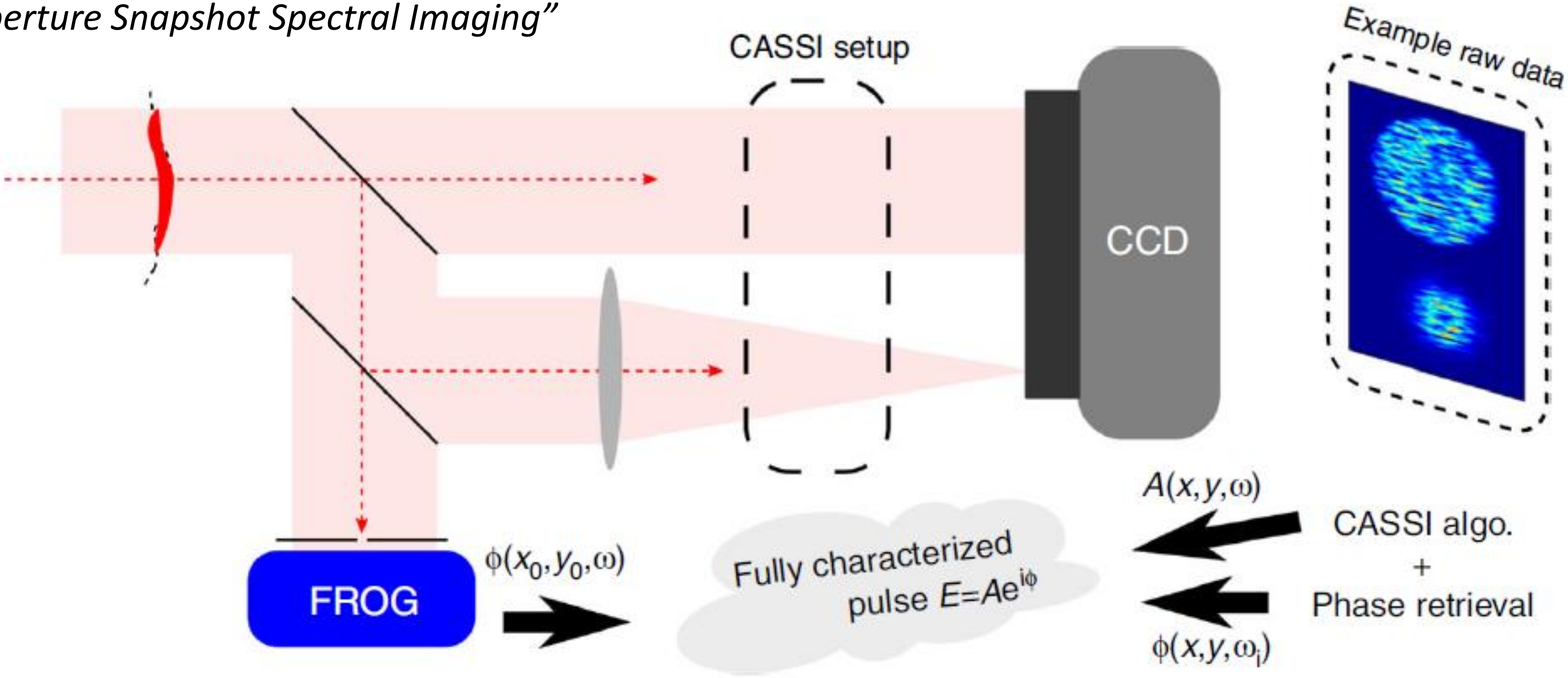
→One avenue towards compressed sensing (fewer shots)

→removes noise due to fluctuation of the delay

S. W. Jolly et al., OSA Continuum **4**, 2044 (2021).

CASSI + phase retrieval

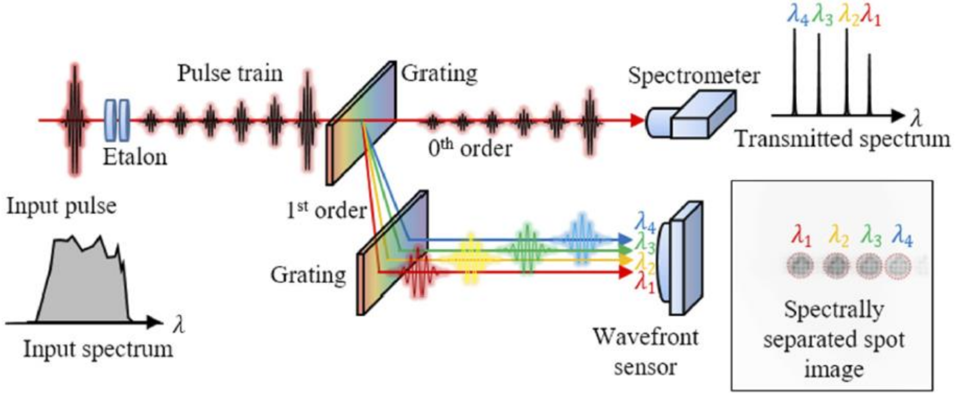
"Coded-Aperture Snapshot Spectral Imaging"

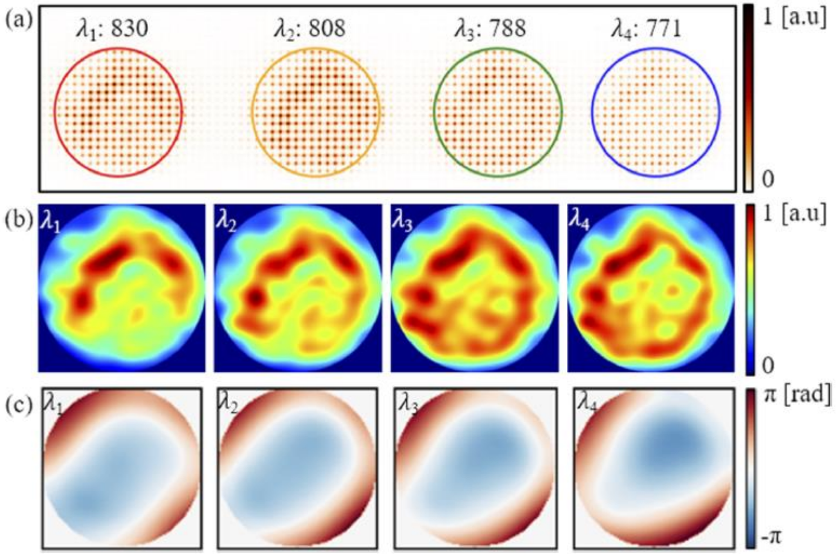


H. Tang et al., Light: Sci. App. **11**, 244 (2022).

Single-shot measurements at CoReLS in Korea

"multispectral wavefront sensor"

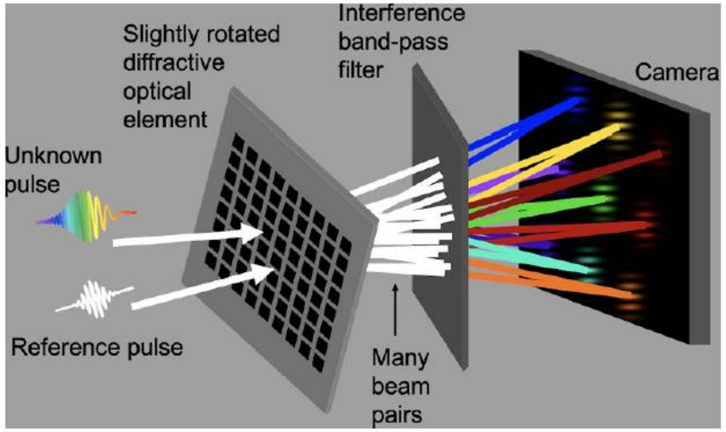


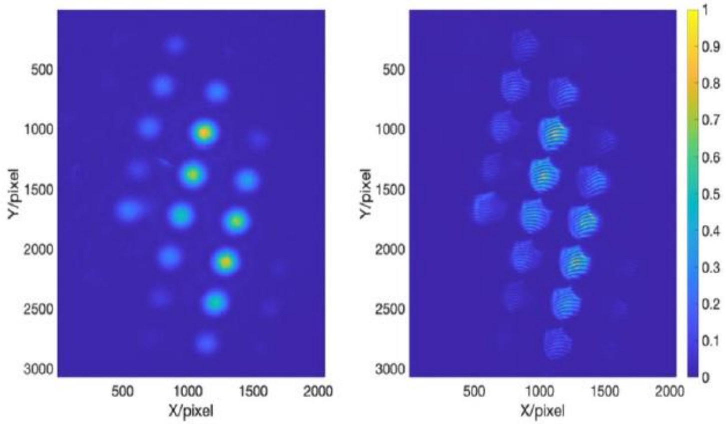


J. W. Yoon et al., Optica **8**, 630 (2021).
Y. G. Kim et al., Opt. Express **29**, 19506 (2021).

Single-shot measurements at LLNL(+GT) in USA

STRIPED-FISH technique





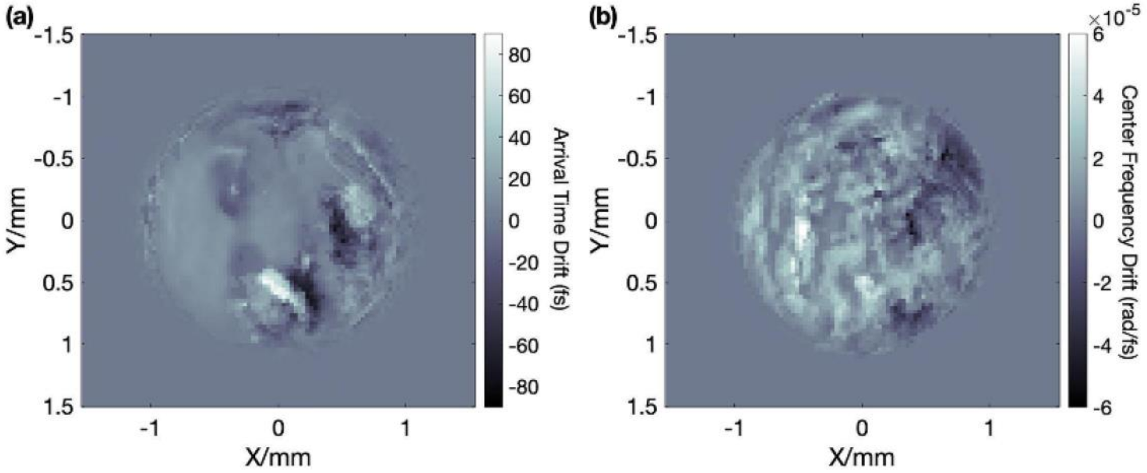
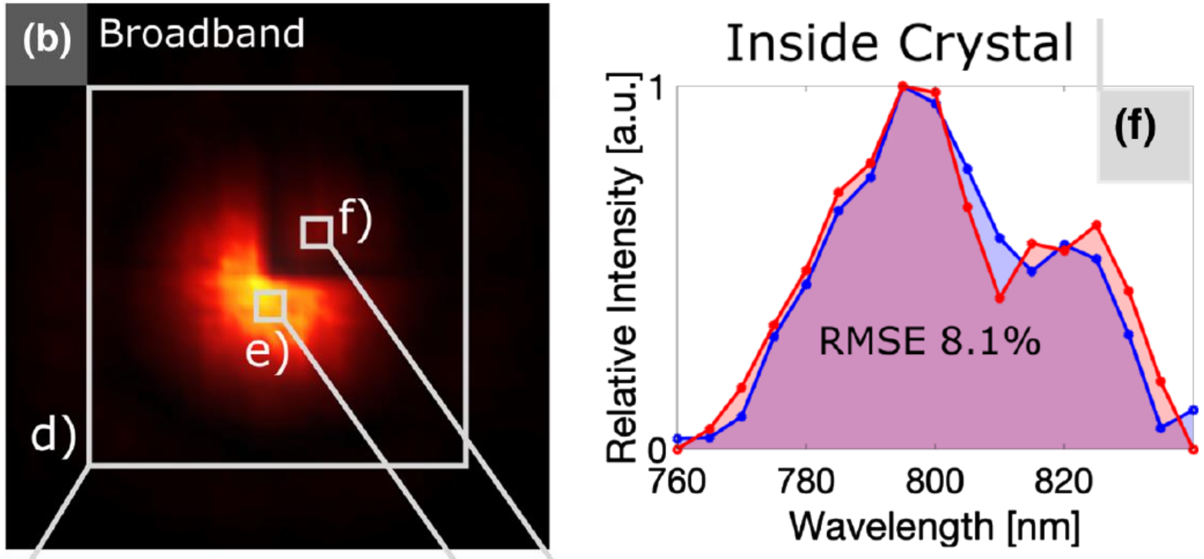


Figure 7. Drift over the course of the shot day in the arrival time (a) and center frequency (b).

E. Grace et al., J. Opt. **23**, 075505 (2021).

Broadband ptychography



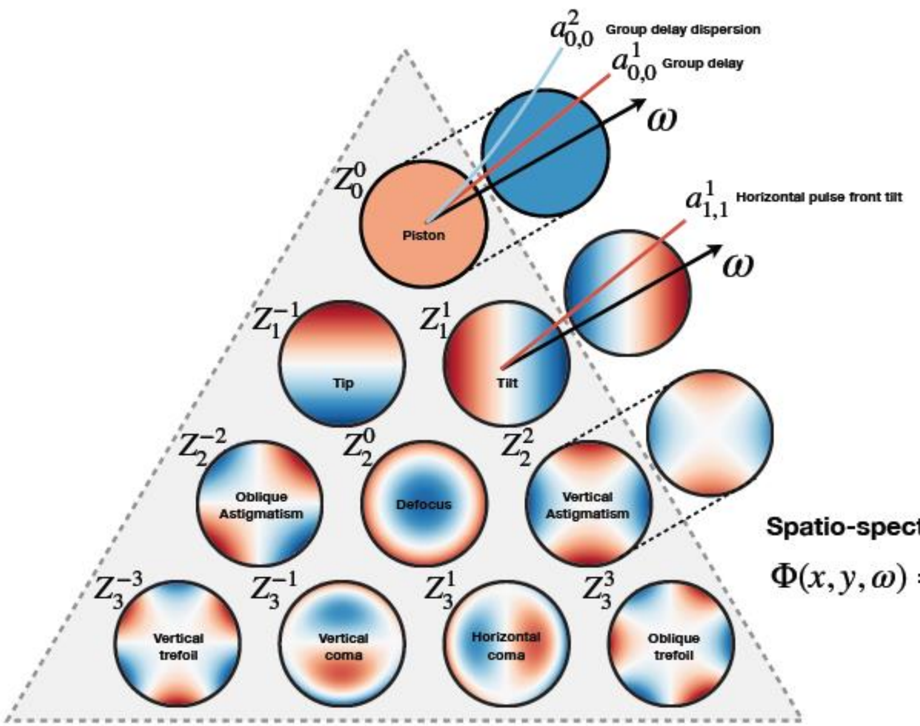
D. Goldberger et al., Opt. Express **28**, 18887 (2020).

D. Goldberger et al., Opt. Express **29**, 32474 (2021).

D. Goldberger et al., Optica **9**, 894 (2022).

D. Goldberger et al., Opt. Lett. **48**, 3455 (2023).

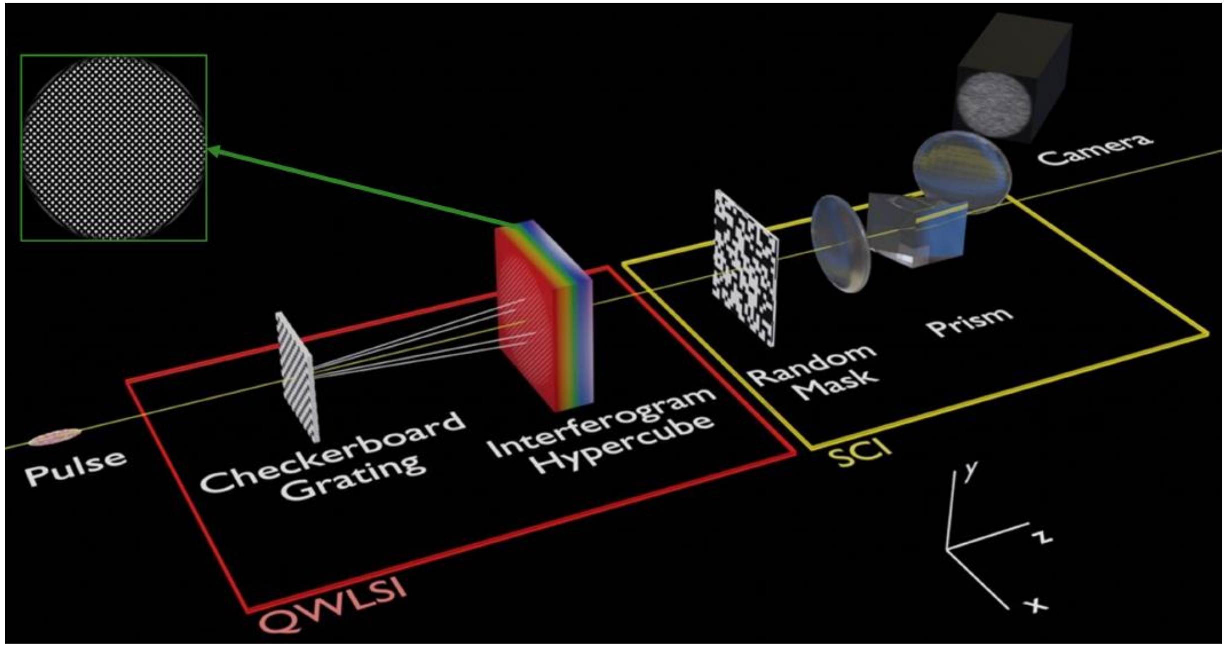
Hyperspectral wavefront + advanced algorithms

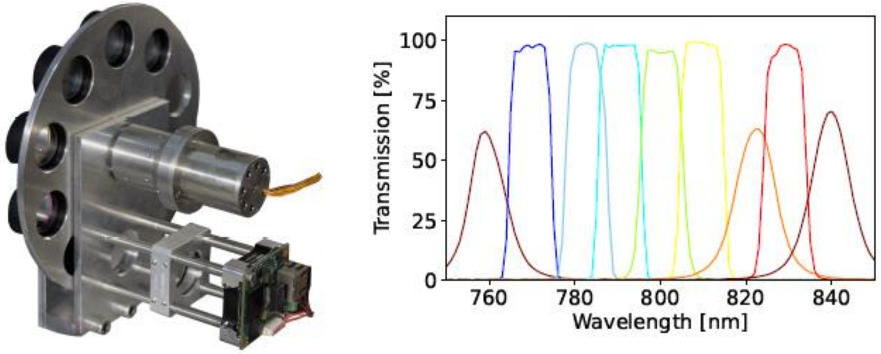


Spatio-spectral phase

$$\Phi(x,y,\omega) = \sum_{m,n,i} a_{m,n}^i (\omega - \omega_0)^i Z_n^m(x,y)$$

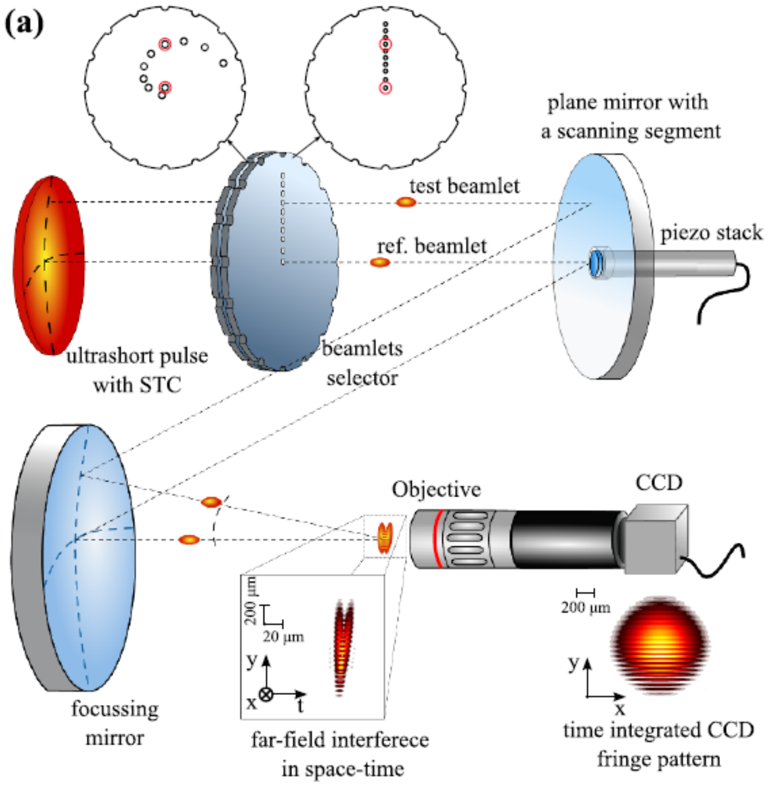
Spatial phase $\varphi(x,y) = \sum_{m,n} a_{m,n} Z_n^m(x,y)$.

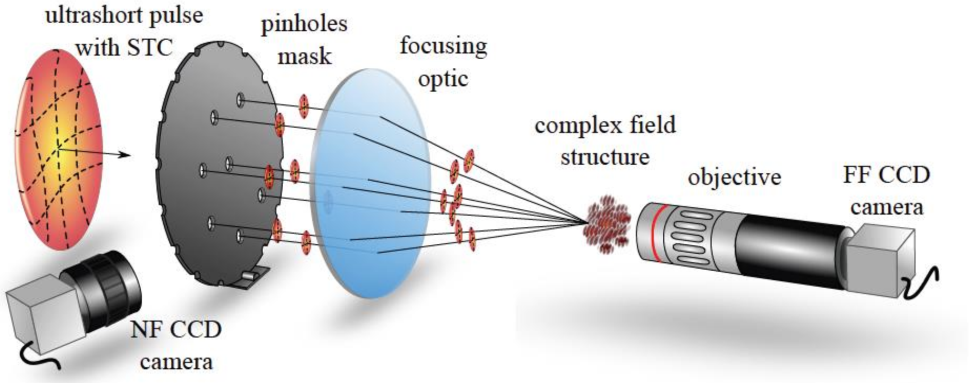




S. Howard et al., HPLS&E **11**, e32 (2023).
N. Weiße et al., Opt. Express **31**, 19733 (2023).

Beamlet cross-correlation





S. Smartsev et al., J. Opt. **24**, 115503 (2022).

S. Smartsev et al., arXiv:2307.15799

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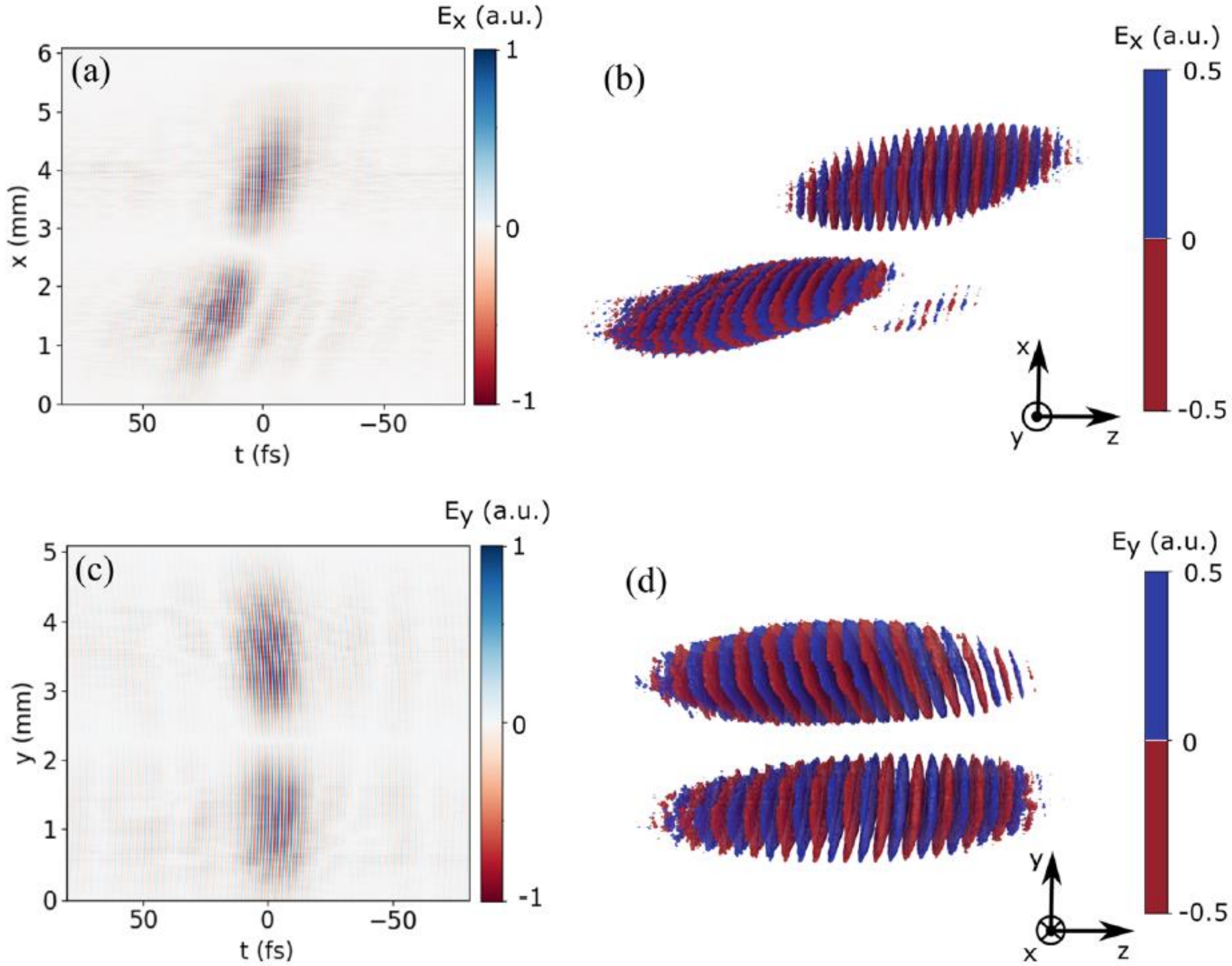
Space-time-polarization measurements

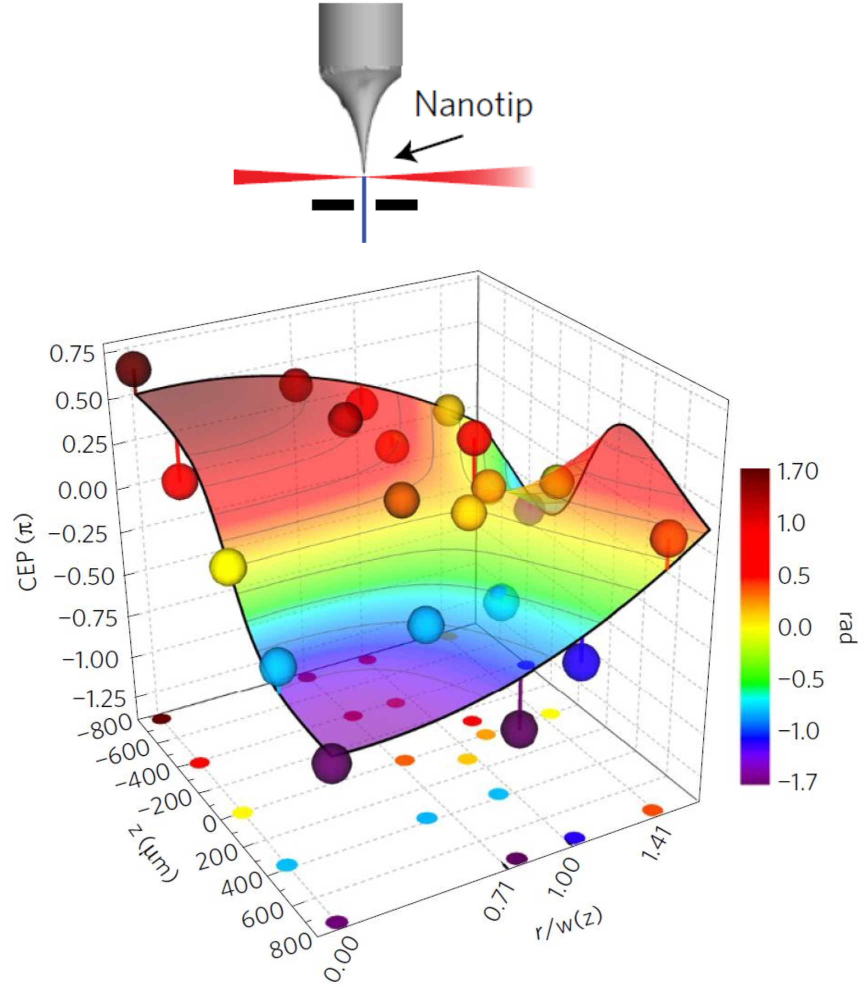


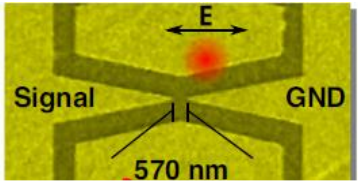
B. Alonso et al., Comm. Physics **3**, 151 (2020).

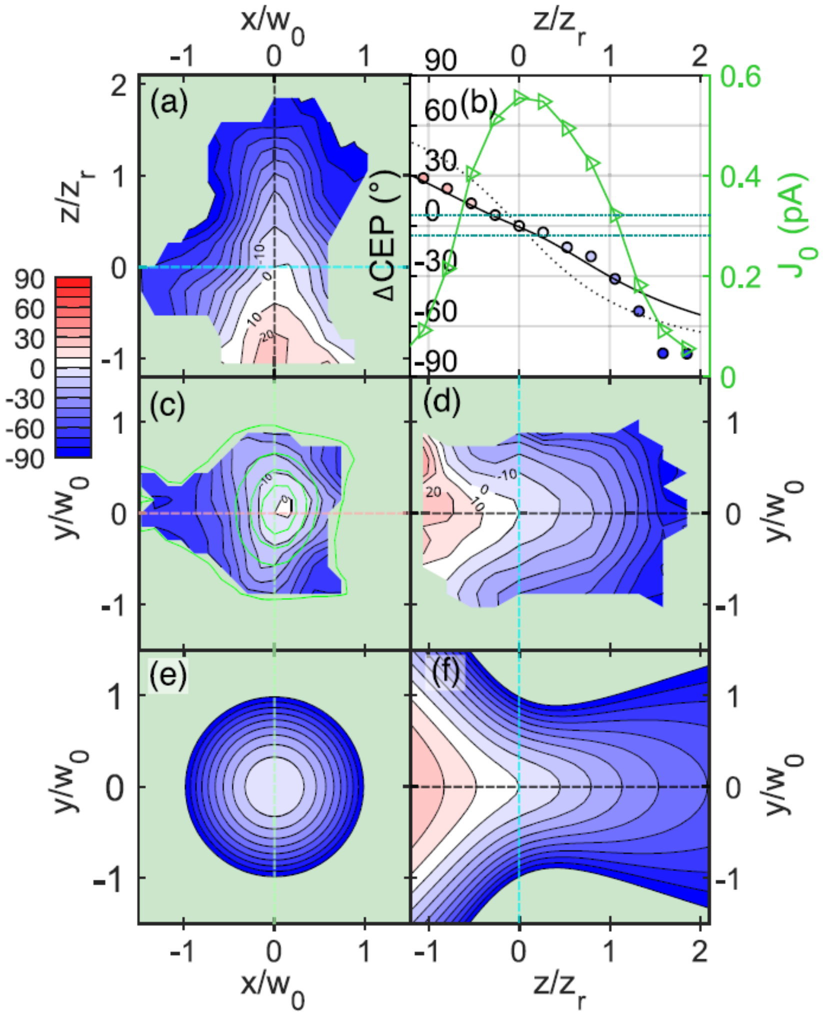
A. Zdagkas et al., APL Photonics **6**, 116103 (2021).

D. Goldberger et al., Optica **9**, 894 (2022).

Spatial measurement of CEP







D. Hoff et al., Nat. Phys. **13**, 947 (2017).

V. Hanus et al., Nat. Comm. **14**, 5068 (2023).

Take a step back (again)

- Is it 2-D or 3-D?
- Is it single-shot or scanning?
- Is there some type of hard limit on resolution?
- Is there a required (perfect) reference beam?
- Is it truly a space-time device or "just" space-spectrum?

usually related

this can be a big limitation

this usually doesn't matter

adding polarization or looking at a non-standard wavelength will generally affect all of the above

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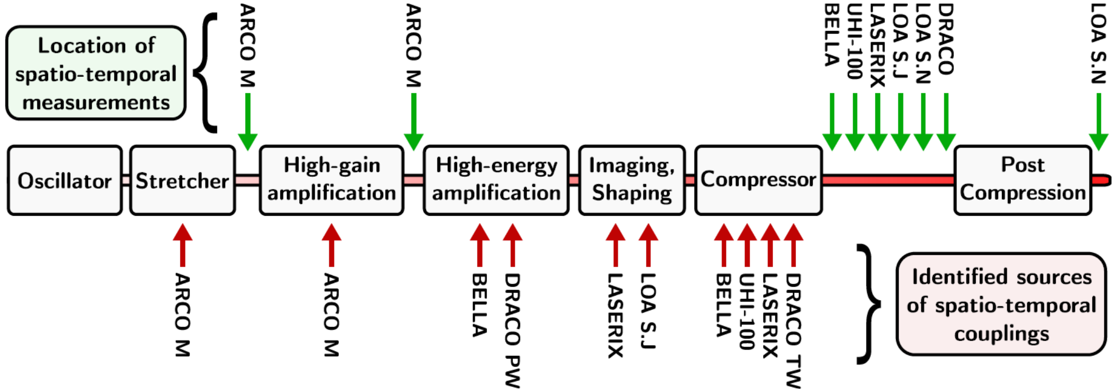
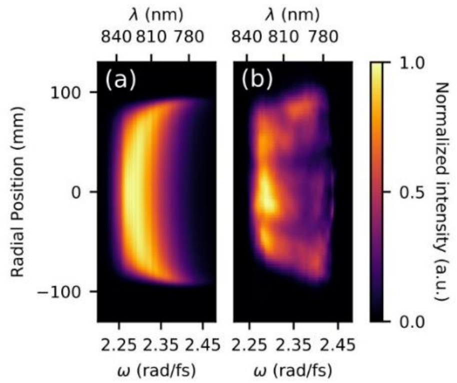
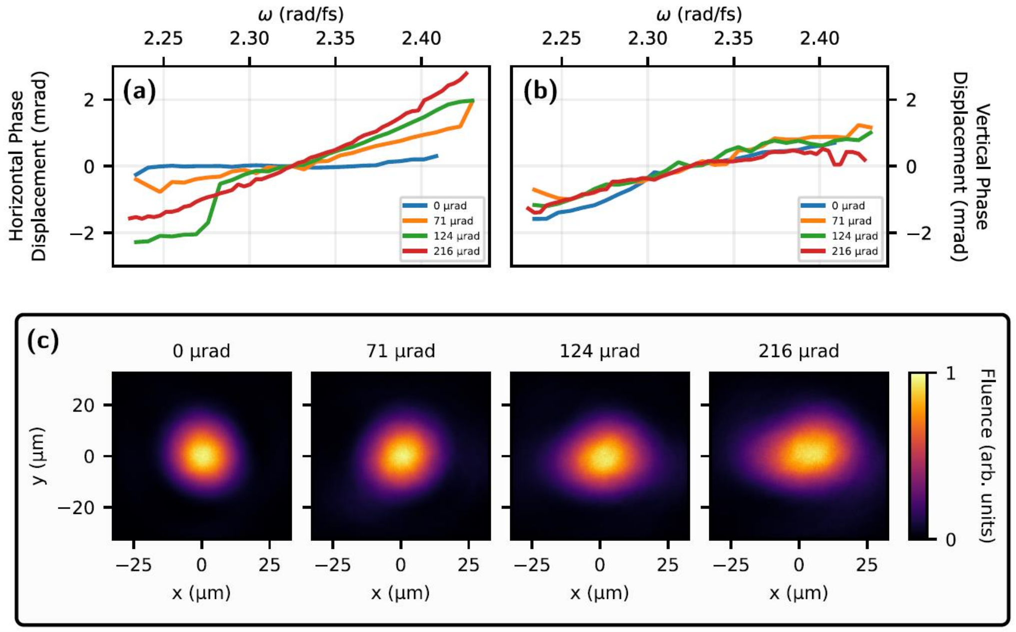
Survey of couplings on many systems



Joule-level amplifier physics





Big collaboration:
Salle Jaune & Salle Noire @ LOA
UHI-100 @ CEA
BELLA @ Berkeley Lab
DRACO TW & PW @ HZDR
Industrial system @ Amplitude
LASERIX @ Orsay

A. Jeandet et al., JPhys: Photonics **1**, 035001 (2019).
A. Jeandet et al., Opt. Express **30**, 3262 (2022).

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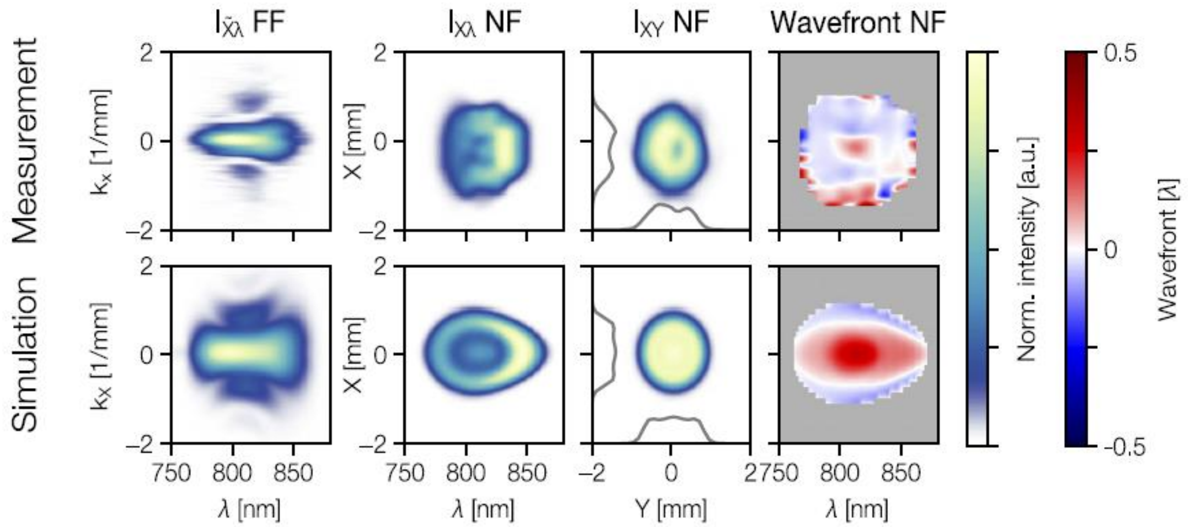
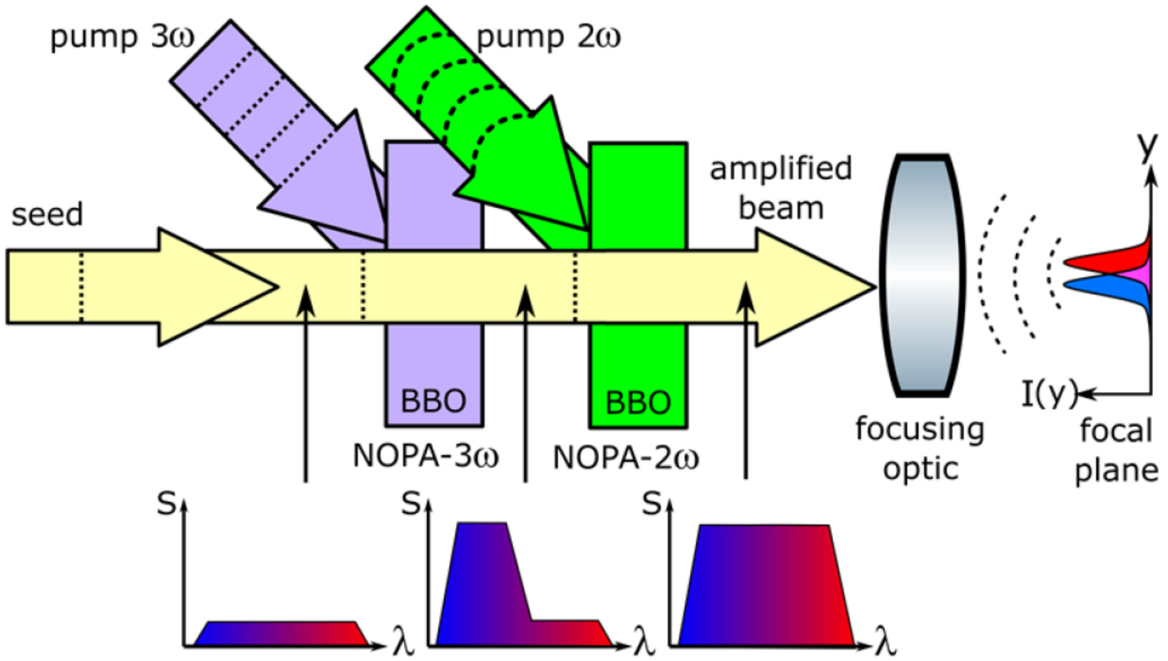
Couplings in saturated OPCPAs





T. Eichner et al., Opt. Express **30**, 3404 (2022).
A. De Andres et al., Opt. Exp. **31**, 12036 (2023).

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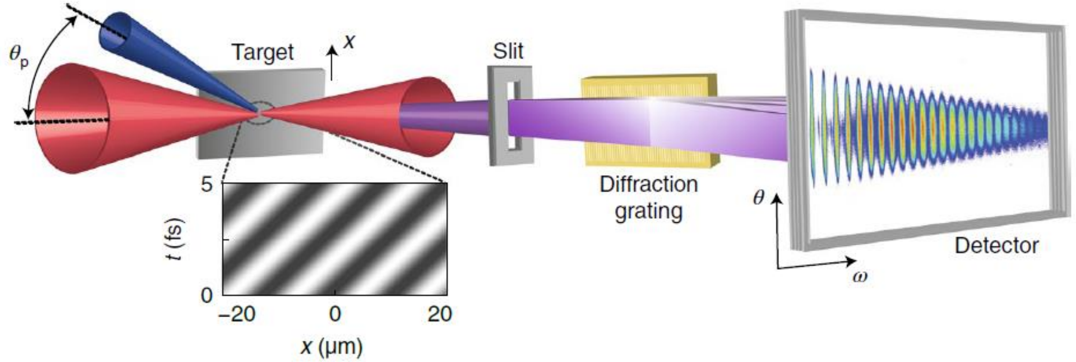
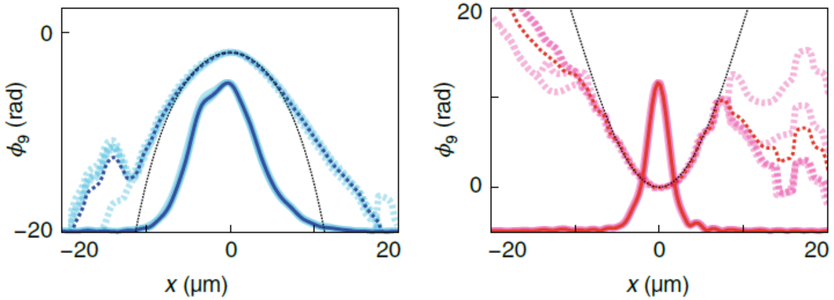
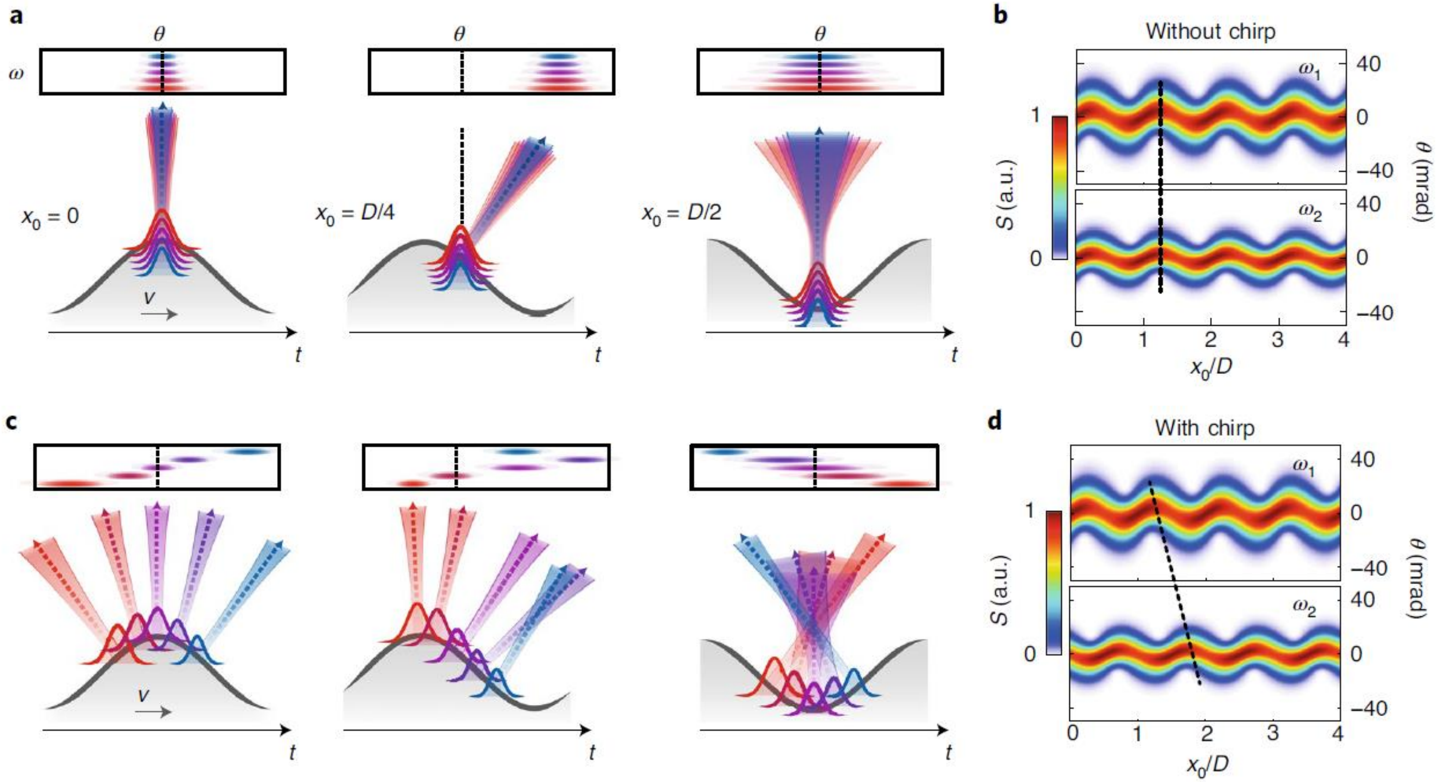
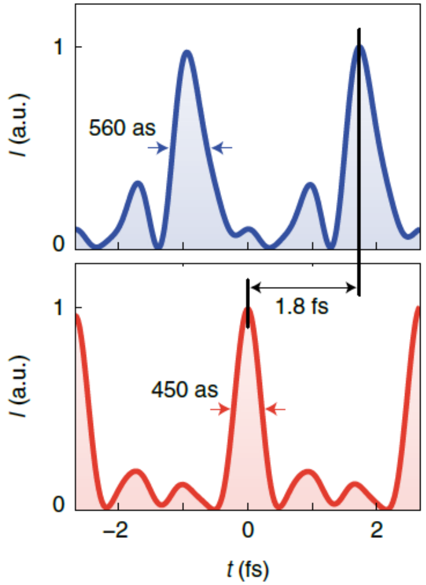
Space-time measurements of attosecond beams









L. Chopineau et al., Nat. Physics **17**, 968 (2021).

Outline

- Why is STC characterization necessary?
- What are STCs?
- Overview of history and of standard techniques
- More recent measurements and techniques
- **Very recent progress in exotic STCs**

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(Small advertisement 1/4)

Research Article Vol. 31, No. 6 / 13 Mar 2023 / *Optics Express* 10237

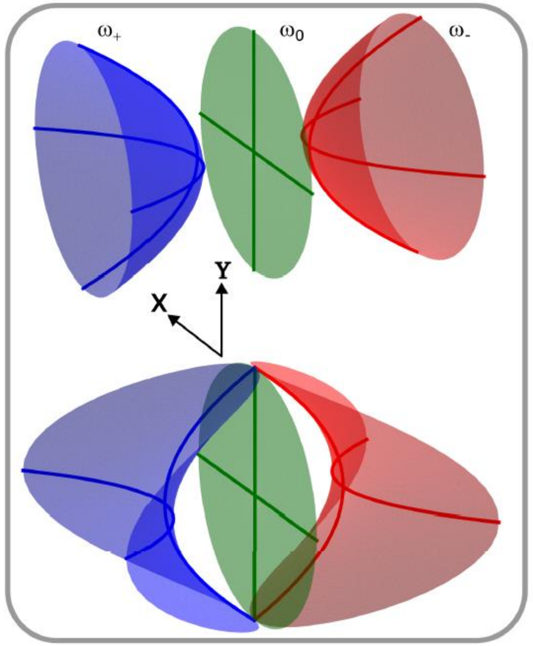
Optics EXPRESS

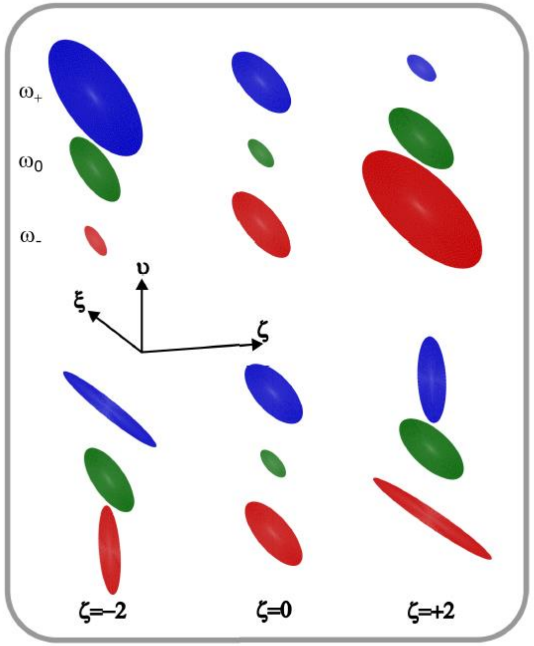
Ultrashort laser pulses with chromatic astigmatism

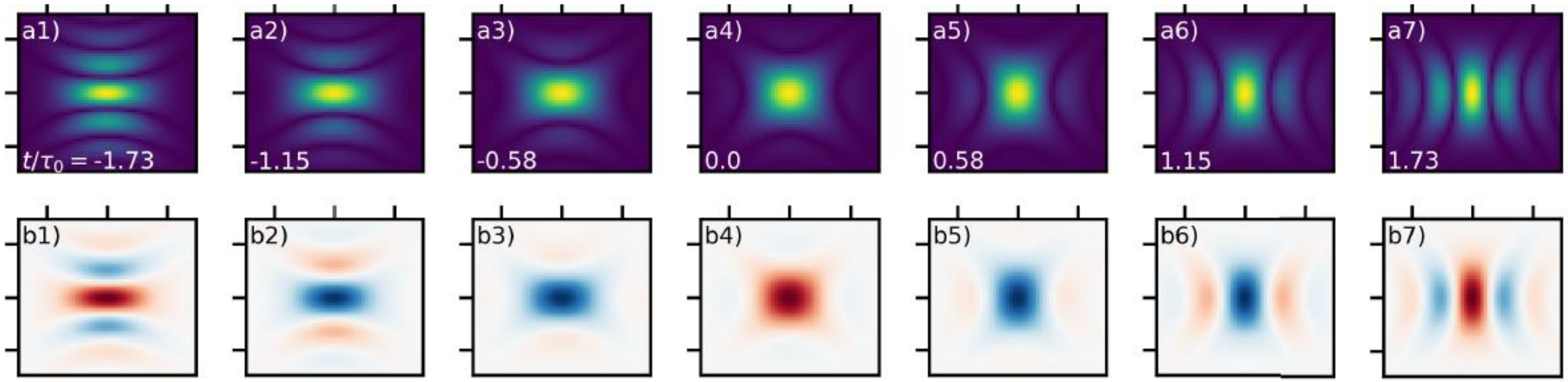
SPENCER W. JOLLY*

Service OPERA-Photonique, Université libre de Bruxelles (ULB), Brussels, Belgium

*spencer.jolly@ulb.be







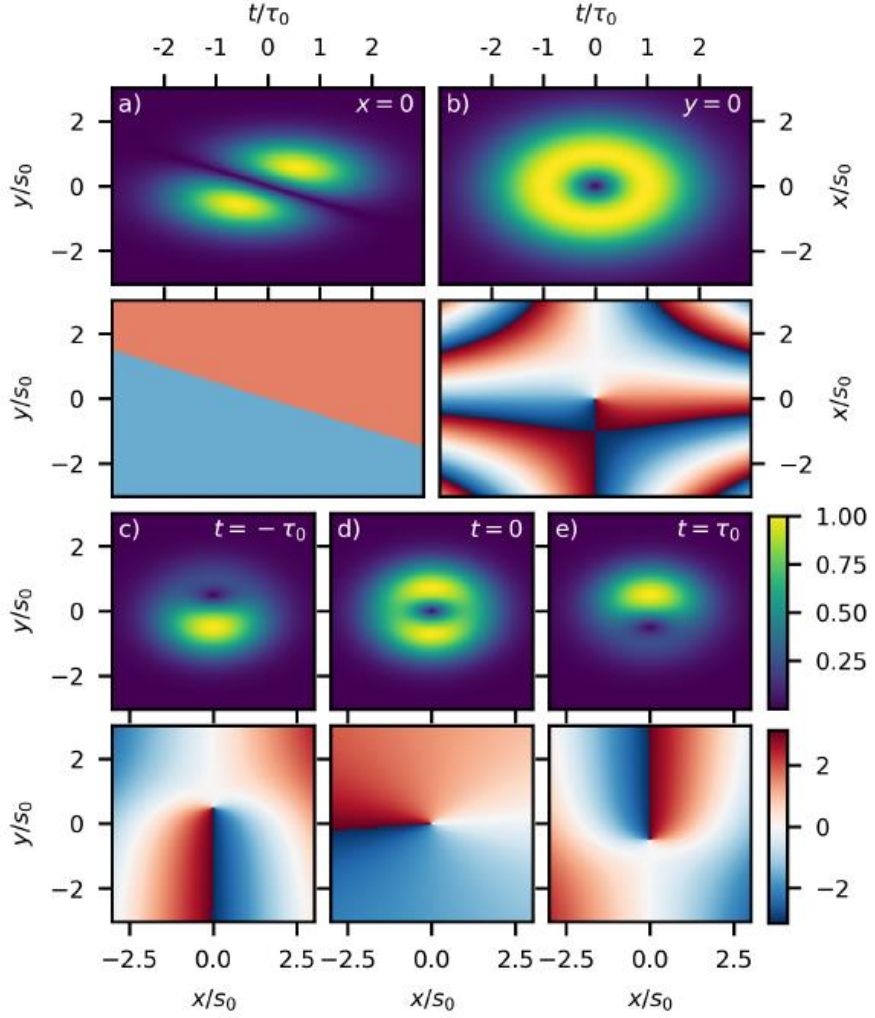
S. W. Jolly, Opt. Express **31**, 10237 (2023).

(Small advertisement 2/4)

Control of vortex orientation of ultrashort optical pulses using spatial chirp

MIGUEL A. PORRAS[1,*] AND SPENCER W. JOLLY[2,3]

[1] Grupo de Sistemas Complejos, ETSIME, Universidad Politécnica de Madrid, Rios Rosas 21, 28003 Madrid, Spain
[2] Service OPERA-Photonique, Université libre de Bruxelles (ULB), Brussels, Belgium
[3] Email: spencer.jolly@ulb.be
[*] Corresponding author: miguelangel.porras@upm.es



Accepted to Optics Letters

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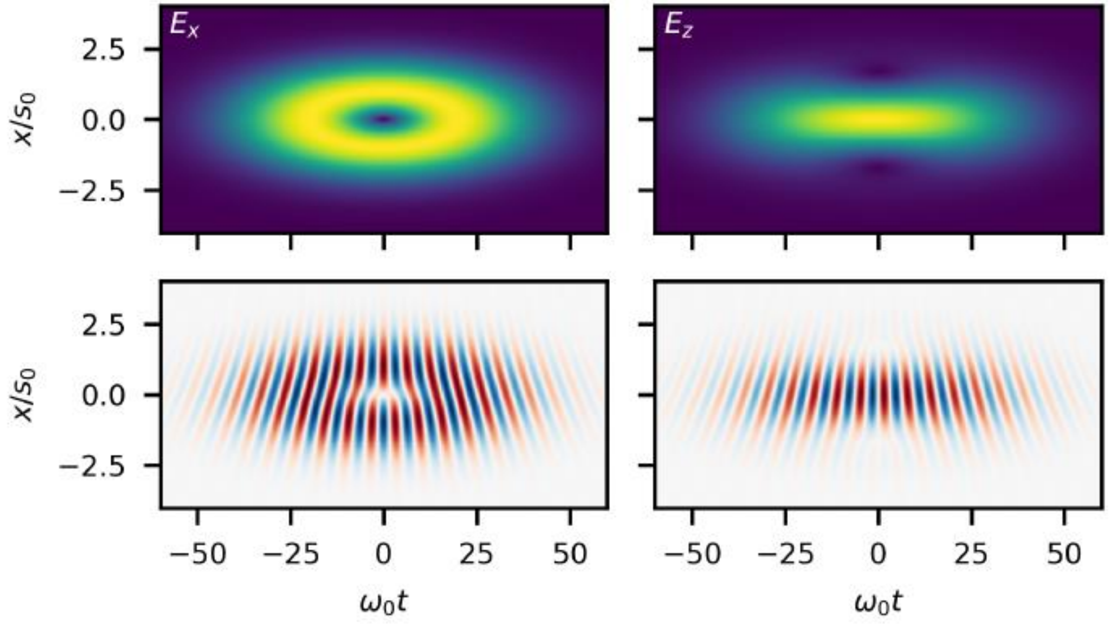
(Small advertisement 3/4)

Analytical fields of an ultrashort radially polarized laser with spatial chirp

SPENCER W. JOLLY[1,*] AND MIGUEL A. PORRAS[2,3]

[1] Service OPERA-Photonique, Université libre de Bruxelles (ULB), Brussels, Belgium
[2] Grupo de Sistemas Complejos, ETSIME, Universidad Politécnica de Madrid, Rios Rosas 21, 28003 Madrid, Spain
[3] Email: miguelangel.porras@upm.es
[*] Corresponding author: spencer.jolly@ulb.be



Submitted to JOSA B

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IOP Publishing
Journal of Optics
J. Opt. 25 (2023) 093001 (59pp)
https://doi.org/10.1088/2040-8986/ace4dc

Roadmap

Roadmap on spatiotemporal light fields

Yijie Shen[1,2,29,*], Qiwen Zhan[3,4,29,*], Logan G Wright[5,6], Demetrios N Christodoulides[7], Frank W Wise[6], Alan E Willner[8], Kai-heng Zou[8], Zhe Zhao[8], Miguel A Porras[9], Andy Chong[10], Chenhao Wan[3,11], Konstantin Y Bliokh[12,13,14], Chen-Ting Liao[15], Carlos Hernández-García[16], Margaret Murnane[15], Murat Yessenov[7], Ayman F Abouraddy[7], Liang Jie Wong[17], Michael Go[17], Suraj Kumar[17], Cheng Guo[18], Shanhui Fan[19], Nikitas Papasimakis[2], Nikolay I Zheludev[1,2], Lu Chen[20,21], Wenqi Zhu[20,21], Amit Agrawal[20,21], Mickael Mounaix[22], Nicolas K Fontaine[23], Joel Carpenter[22], Spencer W Jolly[24], Christophe Dorrer[25], Benjamín Alonso[16], Ignacio Lopez-Quintas[16], Miguel López-Ripa[16], Íñigo J Sola[16], Junyi Huang[26], Hongliang Zhang[26], Zhichao Ruan[26], Ahmed H Dorrah[27], Federico Capasso[27] and Andrew Forbes[28]

14. Measuring ultrashort spatiotemporal structures

Spencer W Jolly[1] *and Christophe Dorrer*[2]

[1] Service OPERA-Photonique, Université libre de Bruxelles (ULB), Brussels, Belgium
[2] Laboratory for Laser Energetics, University of Rochester, 250 East River Road, Rochester, NY 14623-1299, United States of America

15. Characterization of complex vector pulses

Benjamín Alonso, Ignacio Lopez-Quintas, Miguel López-Ripa and Íñigo J Sola

Grupo de Investigación en Aplicaciones del Láser y Fotónica, Departamento de Física Aplicada, Universidad de Salamanca, 37008 Salamanca, Spain

Y. Shen et al., Journal of Optics **25**, 093001 (2023).

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LASY

LASY : LAser manipulations made eaSY

A simple coding structure to model complex laser pulses and input them to a range of codes
→ "standardization"

1) Theoretical input of STCs (me)

2) Experimental input of STCs (SourceLab)

https://github.com/LASY-org/lasy

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Perspectives

The direct benefits of STC metrology

- Assess the real performance of ultrashort lasers (e.g. PW lasers)
  → Manage expectations
- Optimize laser performance
  → fix problems in real time, save $$

The advanced benefits of STC *control*

- New inputs for simulations codes (e.g. Particle-in-Cell codes)
  → **LASY : LAser manipulations made easy**
- EXPLOITING STCs for the control of laser-matter interactions
  → dephasingless laser wakefield acceleration

nanophotonics

Attosecond physics

nonlinear optics

micro-machining

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