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Basics of ultrashort pulses and propagation and Complex pulse shaping and metrology

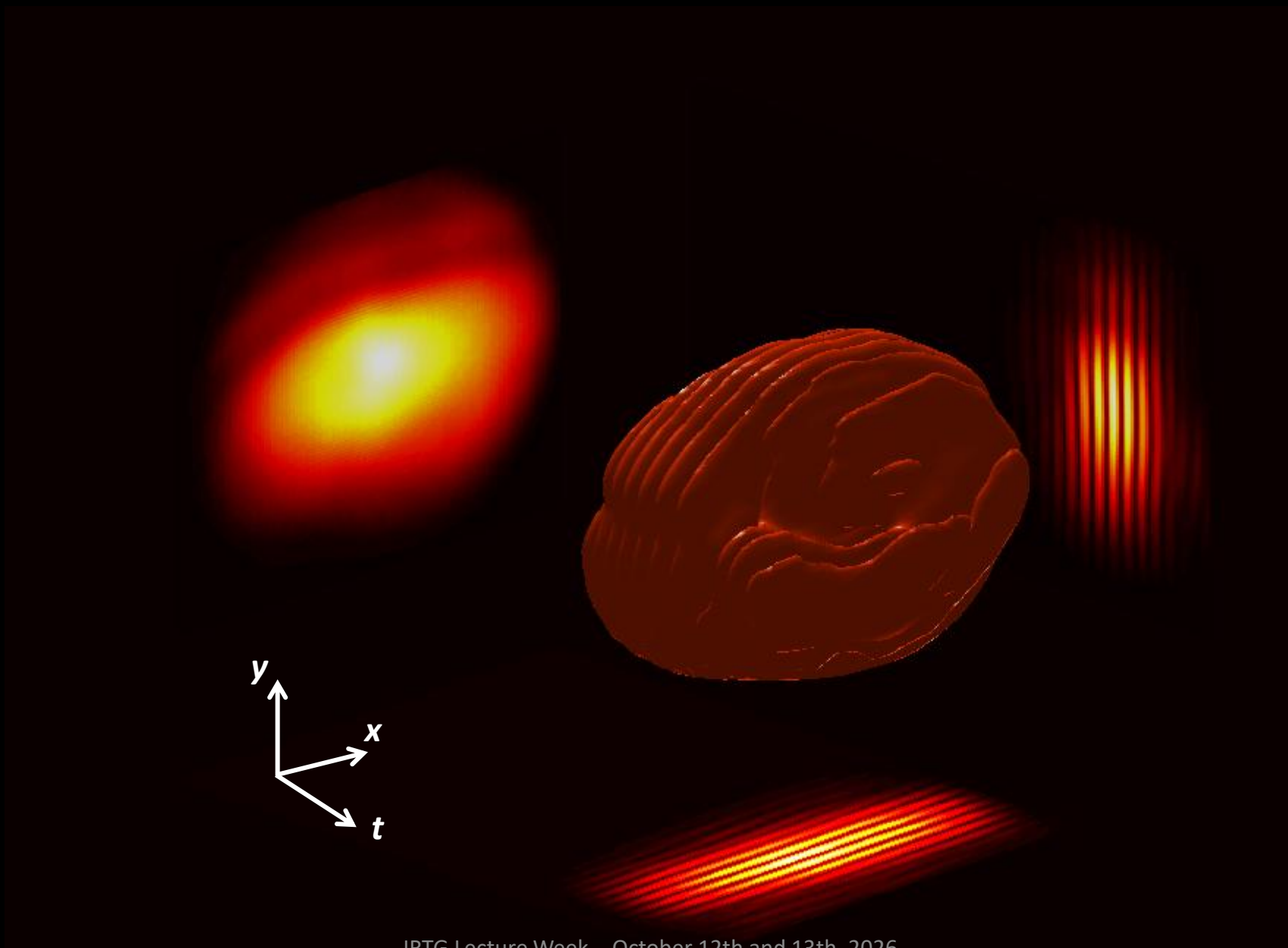
space-time effects in ultrashort light pulses

Spencer W. Jolly

Université libre de Bruxelles, Belgium

IRTG Lecture Week – October 12th and 13th, 2026

The lecture week is supported by Project ELI-RO/DFG/2025_013
IATP-NP 2.0 funded by the Institute of Atomic Physics, Romania



Bachelors in 2012



Masters in 2014



About me



PhD (Aug 2014 - Jan 2018)



First Postdoc (Jan 2018 - Nov 2019)



B-PHOT
BRUSSELS
PHOTONICS

Second Postdoc (Dec 2020 - Sep 2021)



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Third Postdoc (since Oct 2021)

fnrs
LA LIBERTÉ DE CHERCHER



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.

Since Oct. 2025, permanent Assistant Professor:

Structured Ultrafast Light Beams for fundamental science and applications in micromachining, particle acceleration, integrated photonics, and multimode nonlinear optics.

(don't forget 2019 review from C. Dorrer)

J. Opt. **22** (2020) 103501 (33pp)

<https://doi.org/10.1063/1.5131111>

Spatio-temporal characterization of ultrashort laser beams: a tutorial

Spencer W Jolly , Olivier Gobert and Fabien Quéré 

LIDYL, CEA, CNRS, Université Paris-Saclay, CEA Saclay, Gif-sur-Yvette 91191, France

Space-time characterization of ultrashort laser pulses: A perspective

Cite as: APL Photon. **9**, 070901 (2024); doi: [10.1063/5.0219447](https://doi.org/10.1063/5.0219447)

Submitted: 17 May 2024 • Accepted: 23 June 2024 •

Published Online: 16 July 2024



Benjamín Alonso,^{1,2} , Andreas Döpp,³  and Spencer W. Jolly^{4,a)} 

AFFILIATIONS

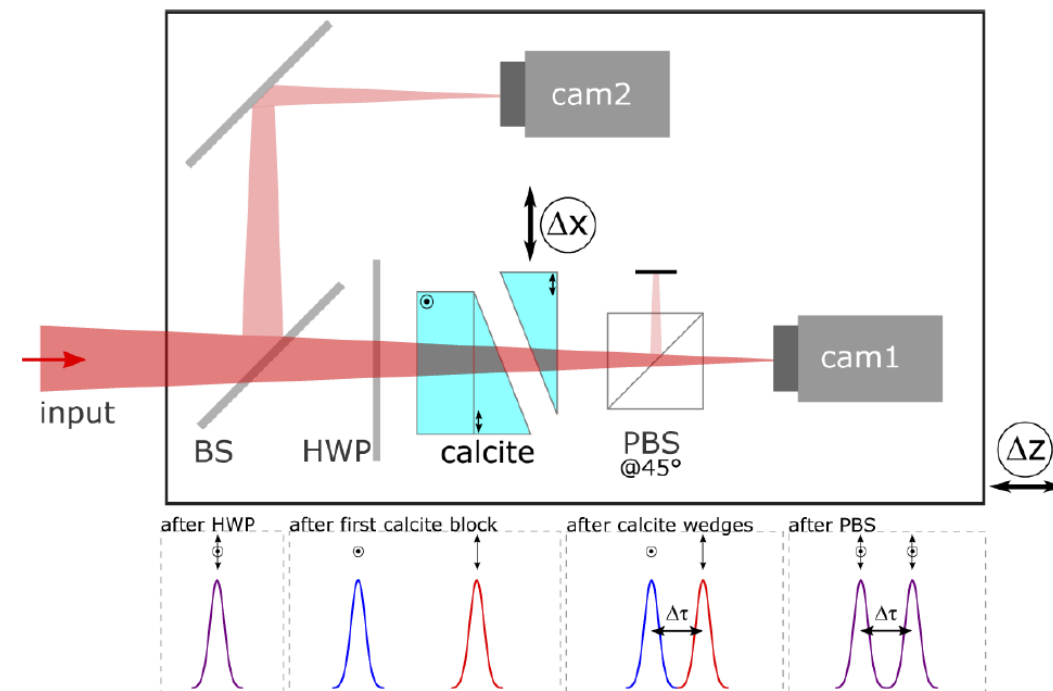
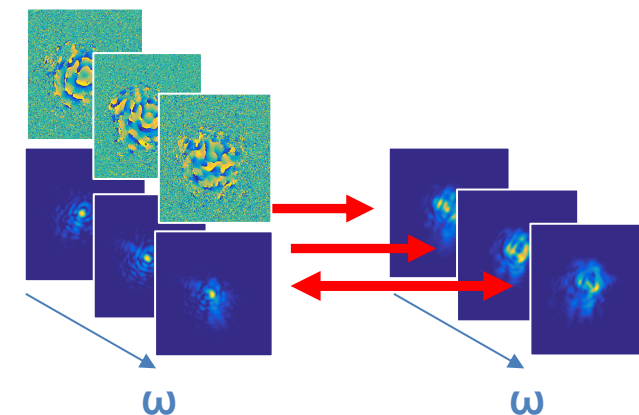
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²Unidad de Excelencia en Luz y Materia Estructuradas (LUMES), Universidad de Salamanca, Salamanca, Spain

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SourceLAB



What message do I want to pass on?

- Yes, we are all human !
- There is no typical career !
- My job here is to demystify things for you
 - Sometimes things are actually complicated and very hard to describe
 - Sometimes things are simple but hidden behind complicated terminology
 - Sometimes things are *relatively* simple, but hidden behind *overly* simplified explanations
- Trust your scientific instincts and never get rid of skepticism

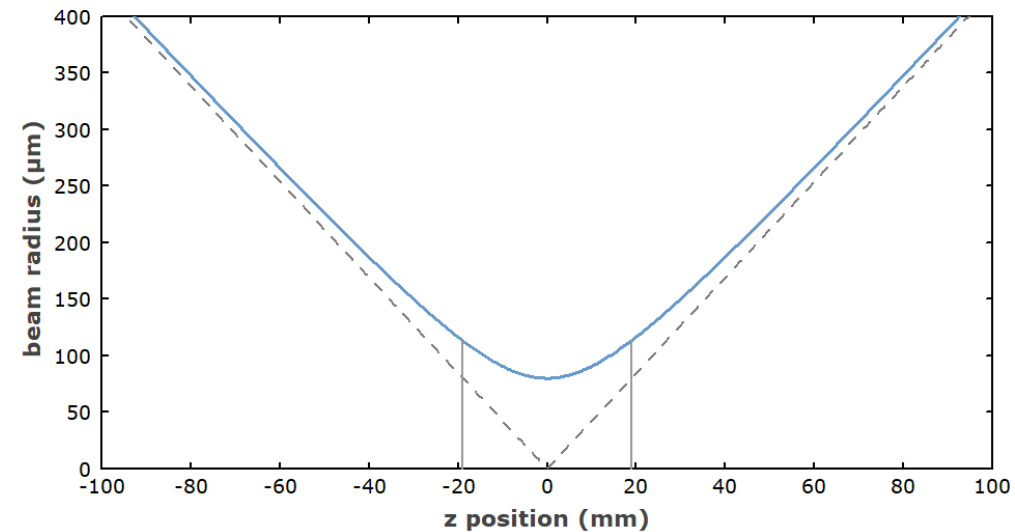
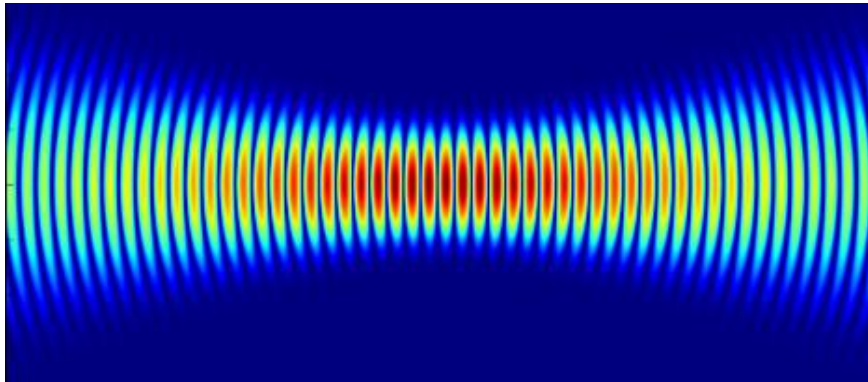
Outline

- Laser beams and laser pulses – the basics
- Shaping and measuring laser beams and laser pulses – the basics
- Going to space and time: what are STCs?
- Why STCs? And why is characterization difficult?
- Overview of history and of standard techniques
- More recent measurements, techniques, and exotic concepts

The Gaussian beam

everything starts from Maxwell's equations!

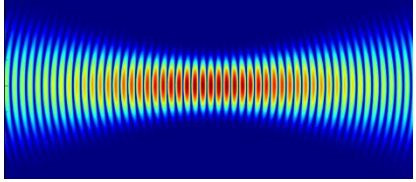
$$\mathbf{E}(r, z) = E_0 \hat{\mathbf{x}} \frac{w_0}{w(z)} \exp\left(\frac{-r^2}{w(z)^2}\right) \exp\left(-i \left(kz + k \frac{r^2}{2R(z)} - \psi(z)\right)\right)$$



https://en.wikipedia.org/wiki/Gaussian_beam

https://www.rp-photonics.com/gaussian_beams.html

There are different ways to write the same thing



Wikipedia:

$$\mathbf{E}(r, z) = E_0 \hat{\mathbf{x}} \frac{w_0}{w(z)} \exp\left(\frac{-r^2}{w(z)^2}\right) \exp\left(-i \left(kz + k \frac{r^2}{2R(z)} - \psi(z)\right)\right)$$

$$k = \frac{2\pi n}{\lambda} = \omega/c$$

https://en.wikipedia.org/wiki/Gaussian_beam

Gaussian beam in space

q parameter:

$$E(r, z) = \frac{e^{-ikr^2/2q(z)}}{1 - z/q_0} e^{-ikz}$$

$$q(z) = q_0 + z$$

$$q_0 = iz_R$$

$$k = \omega/c$$

$$E(r, z) = \frac{e^{ikr^2/2q(z)}}{1 + z/q_0} e^{ikz}$$

$$q(z) = q_0 + z$$

$$q_0 = -iz_R$$

$$k = \omega/c$$

https://en.wikipedia.org/wiki/Complex_beam_parameter

Just depends on definition of Fourier transform

Another way:

$$E(r, z) = f e^{-f\rho^2} e^{-ikz}$$

$$f = \frac{i}{i + z/z_R}$$

$$\rho = r/w_0$$

$$k = \omega/c$$

$$E(r, z) = f e^{-f\rho^2} e^{ikz}$$

$$f = \frac{i}{i - z/z_R}$$

Authors usually just choose the easiest one for their application, or the one they are most used to.

Hermite-Gaussian beams

a) *Modes in Cartesian Coordinates:* For a system with a rectangular (x, y, z) geometry one can try a solution for (11) of the form

$$\psi = g\left(\frac{x}{w}\right) \cdot h\left(\frac{y}{w}\right) \cdot \exp\left\{-j\left[P + \frac{k}{2q}(x^2 + y^2)\right]\right\} \quad (30)$$

where g is a function of x and z , and h is a function of y and z . For real g and h this postulates mode beams whose intensity patterns scale according to the width $2w(z)$ of a Gaussian beam. After inserting this trial solution into (11) one arrives at differential equations for g and h of the form

$$\frac{d^2 H_m}{dx^2} - 2x \frac{dH_m}{dx} + 2mH_m = 0. \quad (31)$$

This is the differential equation for the Hermite polynomial $H_m(x)$ of order m . Equation (11) is satisfied if

$$g \cdot h = H_m\left(\sqrt{2} \frac{x}{w}\right) H_n\left(\sqrt{2} \frac{y}{w}\right) \quad (32)$$

where m and n are the (transverse) mode numbers. Note that the same pattern scaling parameter $w(z)$ applies to modes of all orders.

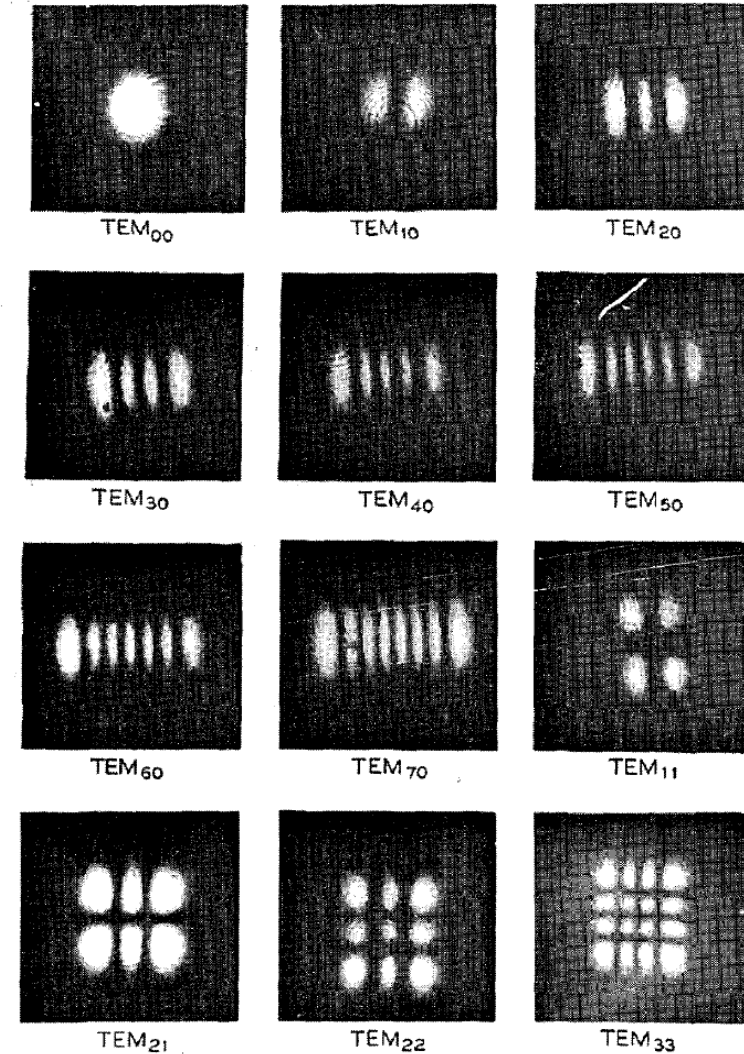


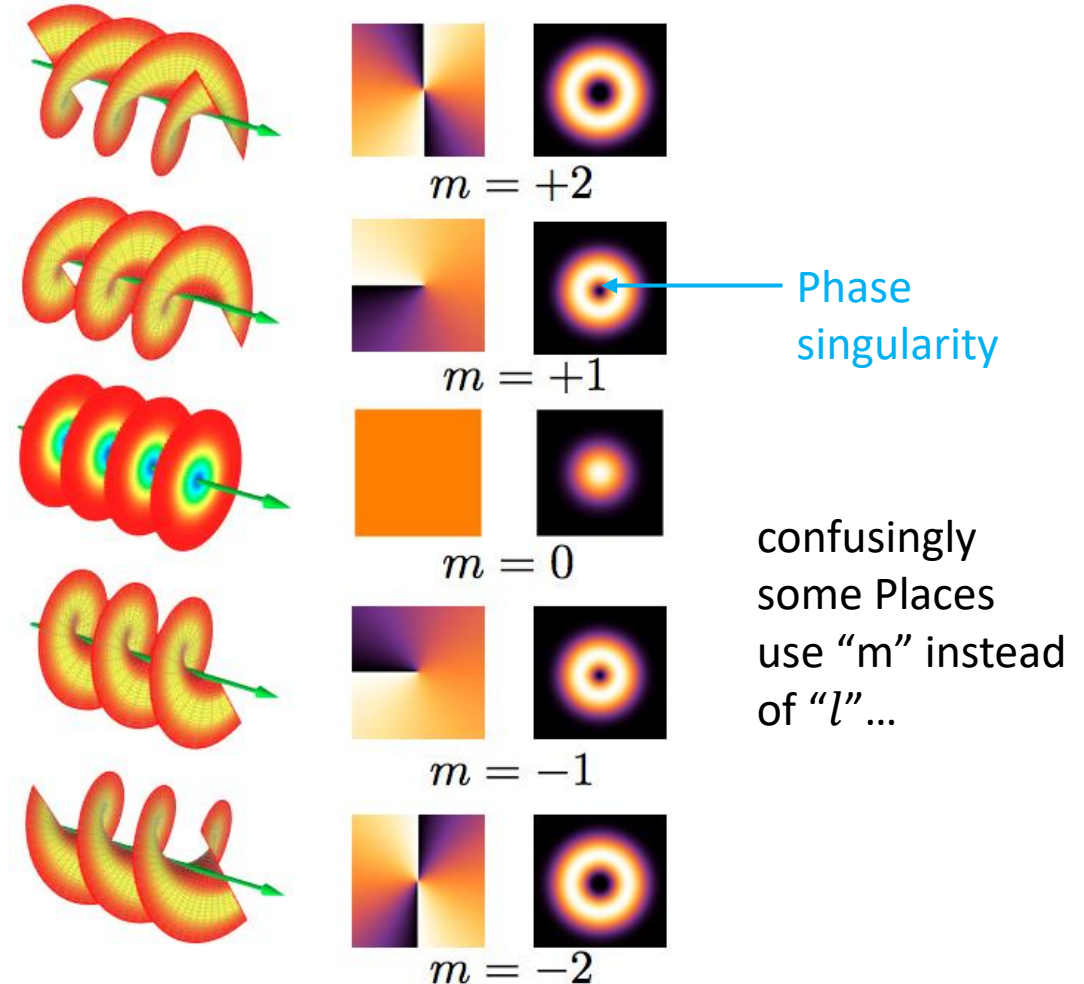
Fig. 7. Mode patterns of a gas laser oscillator (rectangular symmetry).

H. Kogelnik and T. Li, Applied Optics 5, 1550 (1966).

Vortex beams

Simply the Laguerre-Gaussian solution with l nonzero $\rightarrow$ “spiral phase”

$$u(r, \phi, z) = C_{lp}^{LG} \frac{w_0}{w(z)} \left(\frac{r\sqrt{2}}{w(z)} \right)^{|l|} \exp\left(-\frac{r^2}{w^2(z)}\right) L_p^{|l|} \left(\frac{2r^2}{w^2(z)} \right) \times \exp\left(-ik\frac{r^2}{2R(z)}\right) \exp(-il\phi) \exp(i\psi(z)),$$



H. Kogelnik and T. Li, Applied Optics **5**, 1550 (1966).

https://en.wikipedia.org/wiki/Gaussian_beam#Laguerre-Gaussian_modes

https://en.wikipedia.org/wiki/Optical_vortex

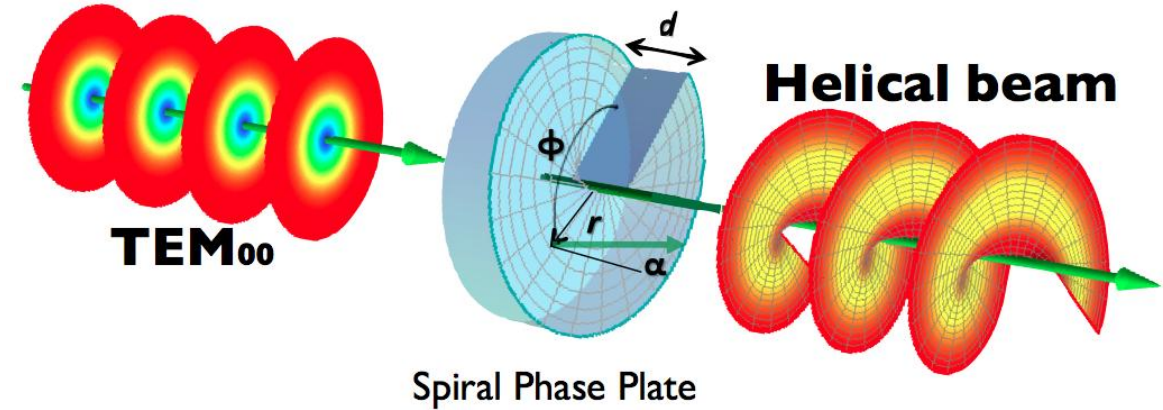
Vortex beams as a superposition

$$\begin{array}{c} \text{↓} \quad \text{↑} \\ \text{10} \end{array} + i \begin{array}{c} \text{↑} \\ \text{↓} \\ \text{01} \end{array} = \begin{array}{c} \text{3D helical beam} \end{array} \quad \begin{array}{c} \text{Phase plot} \quad \text{Intensity plot} \\ m = +1 \end{array}$$

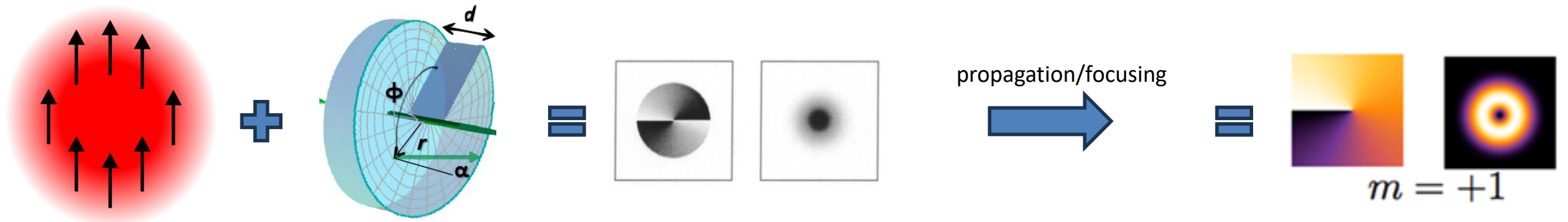
The diagram illustrates the superposition of two vortex beams to form a higher-order vortex beam. On the left, two beams are shown: the first, labeled '10', has a downward-pointing red arrow on the left and an upward-pointing red arrow on the right; the second, labeled '01', has an upward-pointing red arrow on the left and a downward-pointing red arrow on the right. These are added together with a phase factor i . The result, indicated by an equals sign, is a 3D visualization of a helical beam (a vortex) and its corresponding 2D phase and intensity profiles. The phase plot shows a π phase shift across the beam, and the intensity plot shows a central vortex core. The label $m = +1$ indicates the topological charge of the resulting vortex beam.

Making vortex beams in real life

A simple way to think about it:

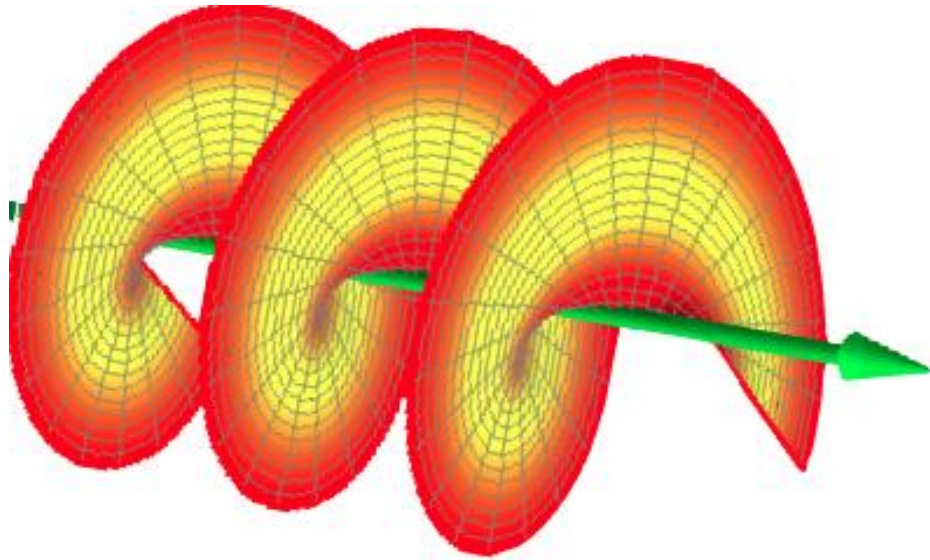


The truth:



+a background from the diffraction of the central part

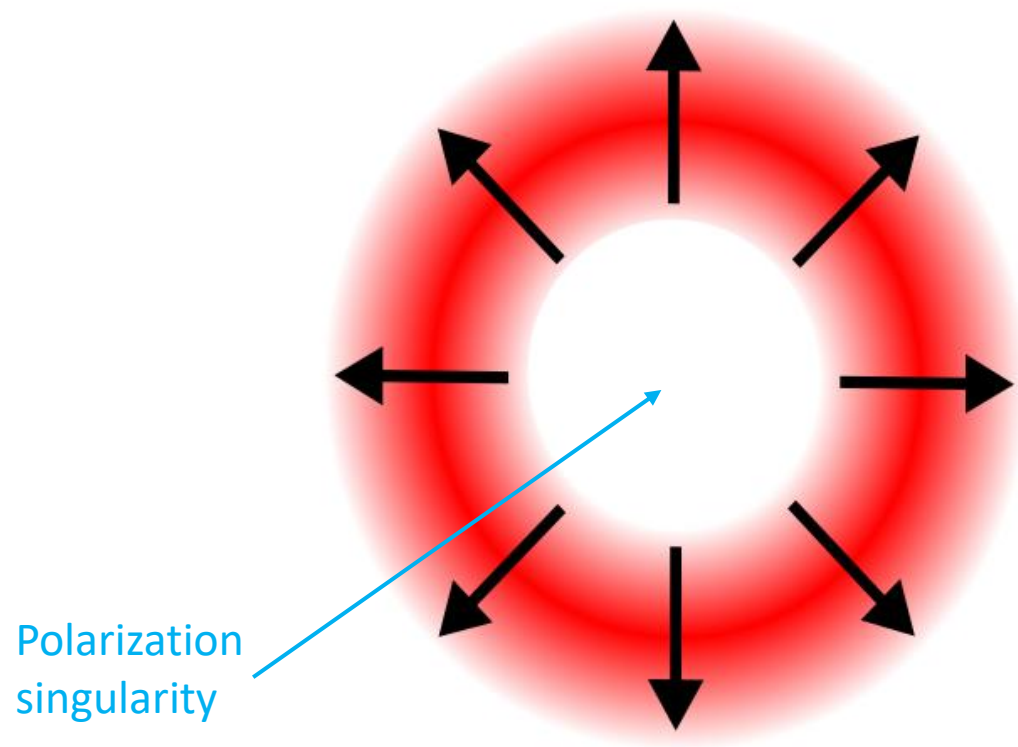
Vortex beams and angular momentum



- A global property of the beam, an orbital angular momentum proportional to the topological charge " l "
- BUT showing this requires invoking non-paraxial parts of the field (at least indirectly via the vector potential)

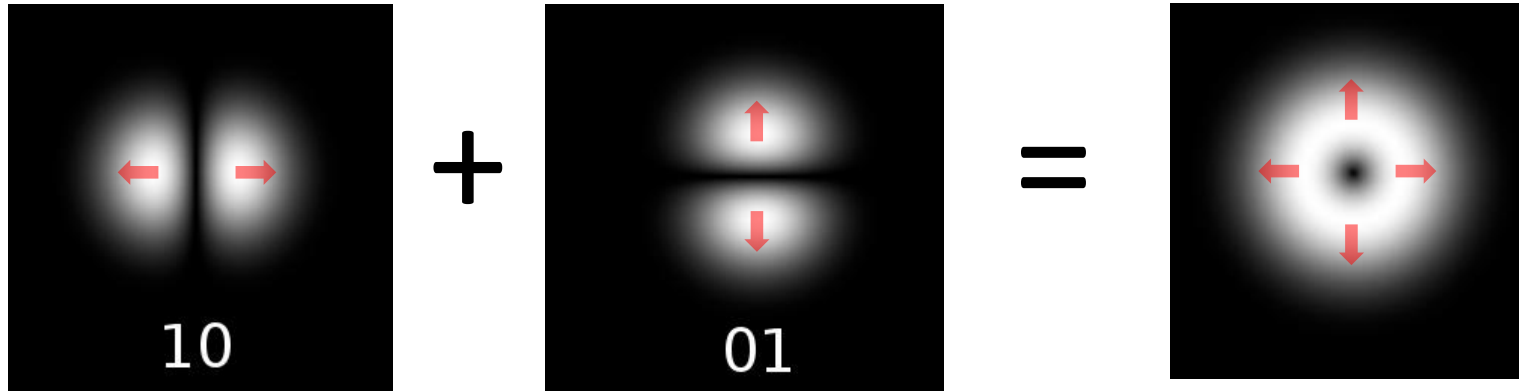
Vector beams

polarization that depends on space



- Some will also consider circular or elliptical polarization as vector beams, even though there is no spatial variation
- The canonical vector beam is the radially-polarized beam
- Of course, there are more complicated versions

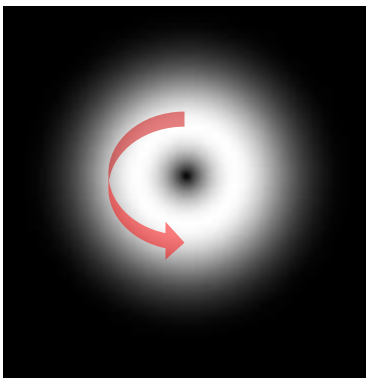
Vector beams as a superposition



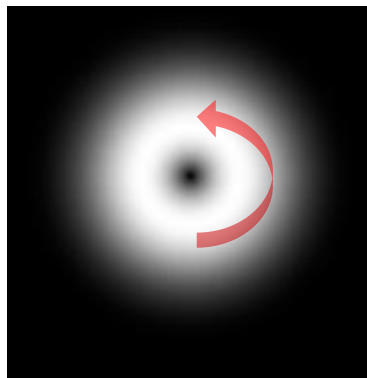
$$H_1(x)\hat{e}_x + H_1(y)\hat{e}_y \propto r\hat{e}_r$$

Authors usually just choose the easiest one for their application, or the one they are most used to.

$l=1$, RHCP

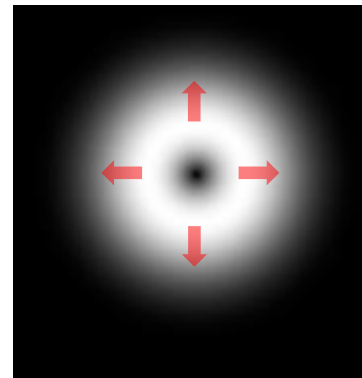


$l=-1$, LHCP



+

=



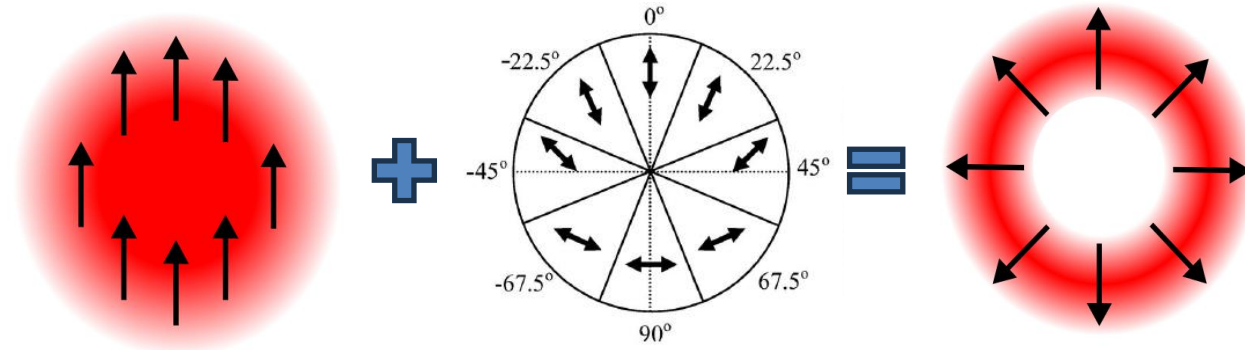
There are interesting and sometimes mysterious connections between different kinds of beams

$$\frac{\psi_r(\rho, \zeta)}{\sqrt{2}} \left[e^{-i\theta} \left(\frac{\mathbf{e}_x + i\mathbf{e}_y}{\sqrt{2}} \right) + e^{i\theta} \left(\frac{\mathbf{e}_x - i\mathbf{e}_y}{\sqrt{2}} \right) \right] e^{i\eta}$$

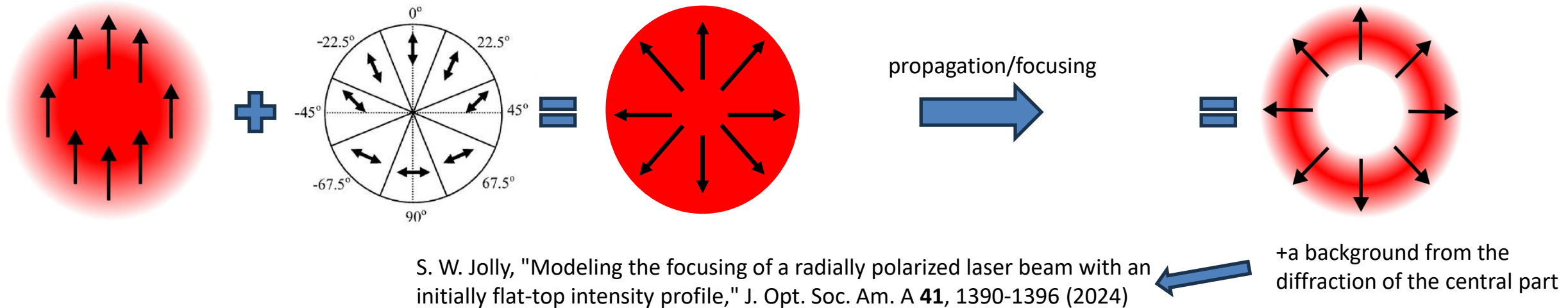
$$= \psi_r(\rho, \zeta) e^{i\eta} \mathbf{e}_r = E_r \mathbf{e}_r,$$

Making vector beams in real life

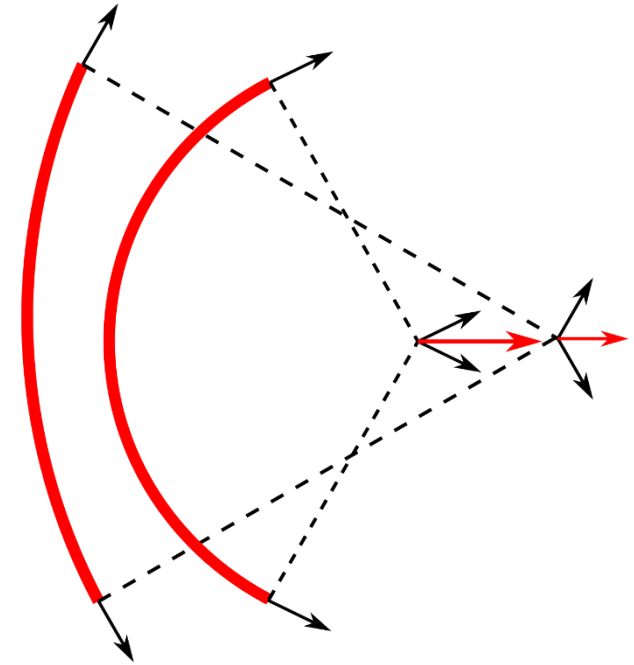
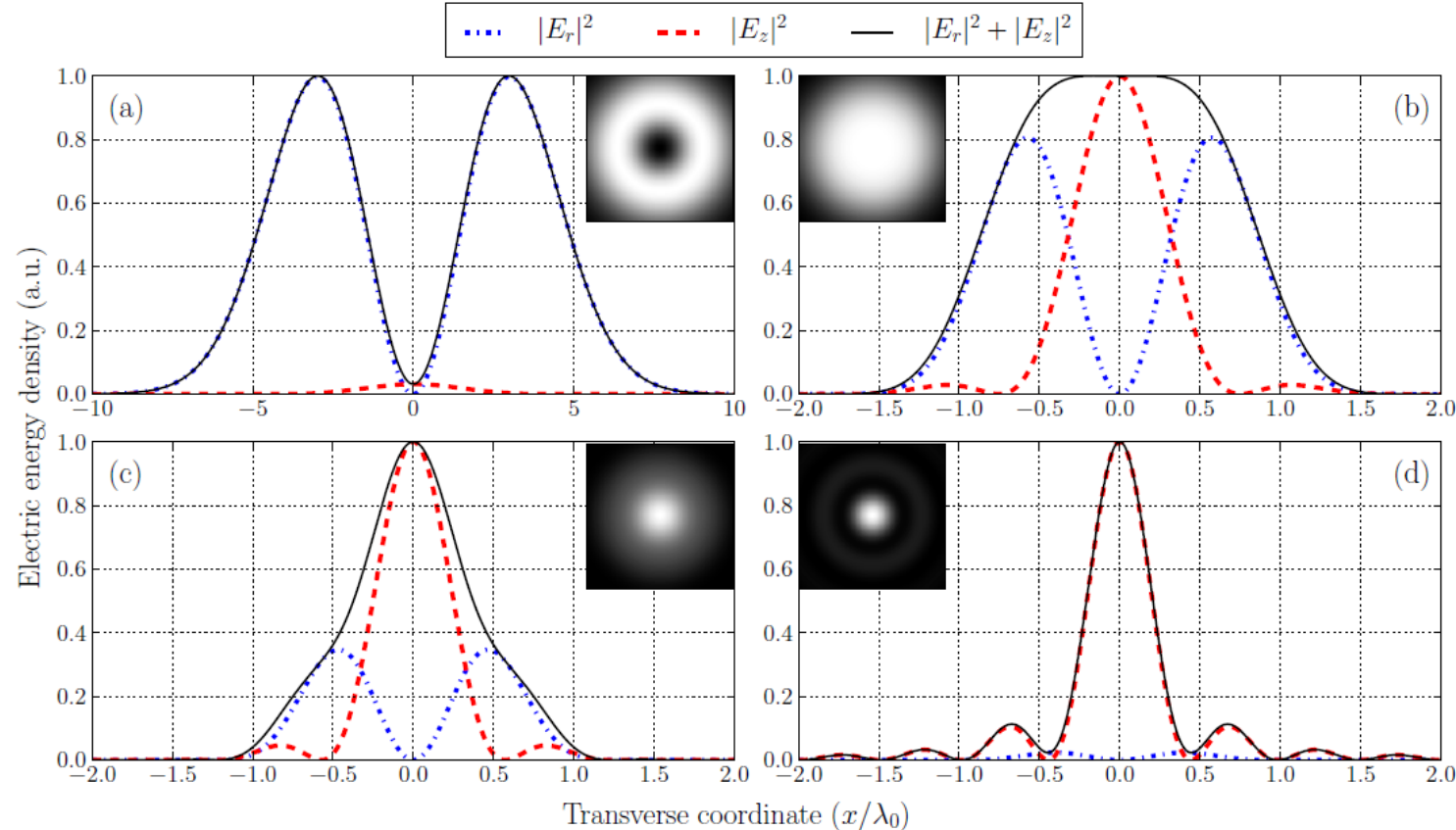
A simple way to think about it:



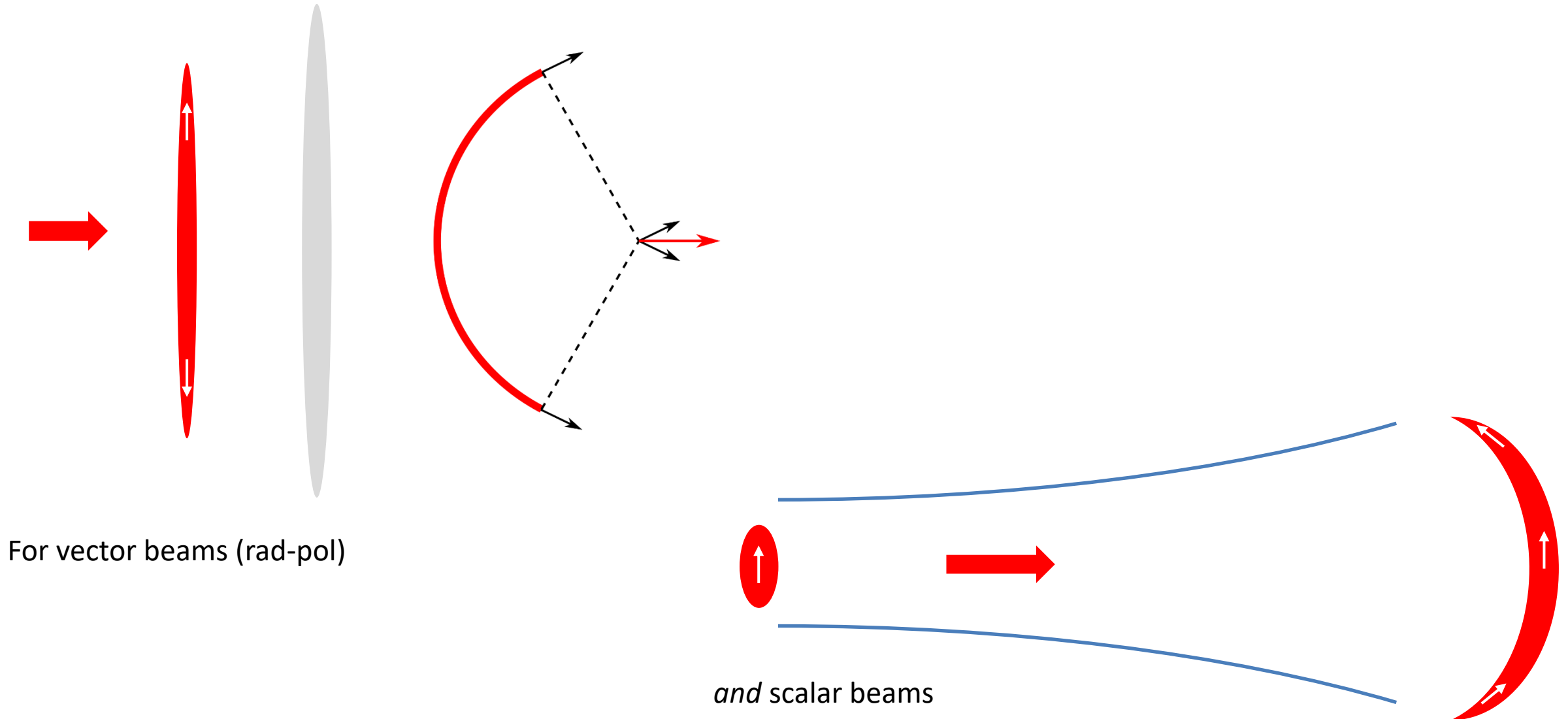
The truth:



Radial-polarization and longitudinal field



Focusing and diffraction are vectorial operations!



Gaussian beam beyond the paraxial approximation



Gauss's law!

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0}$$

$$E_z = \frac{i}{k_0} \frac{\partial E_x}{\partial x}$$

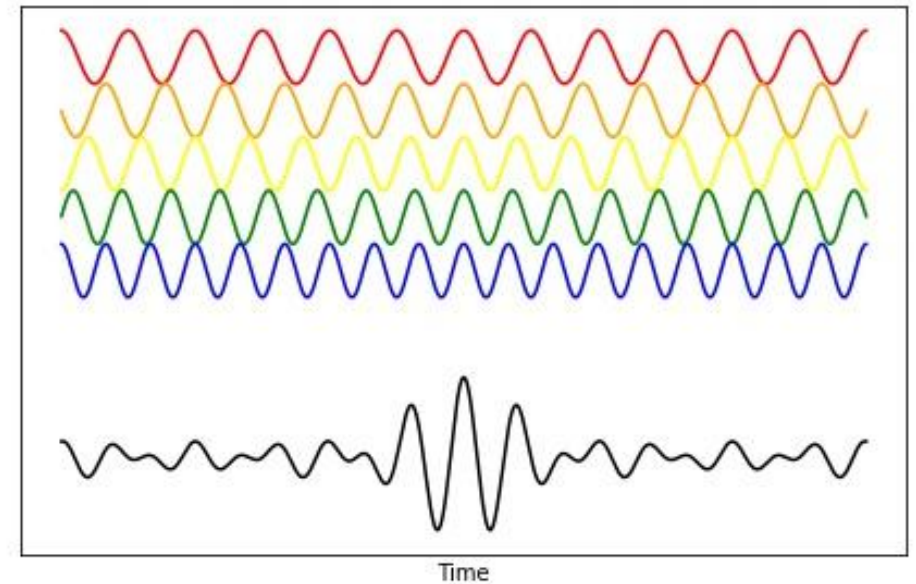
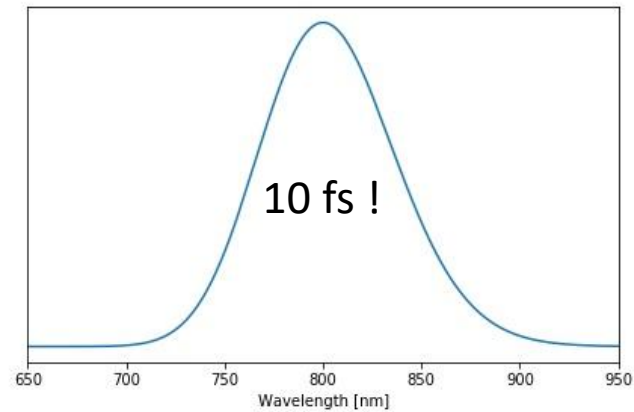
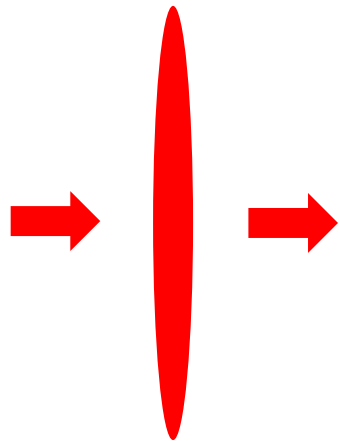
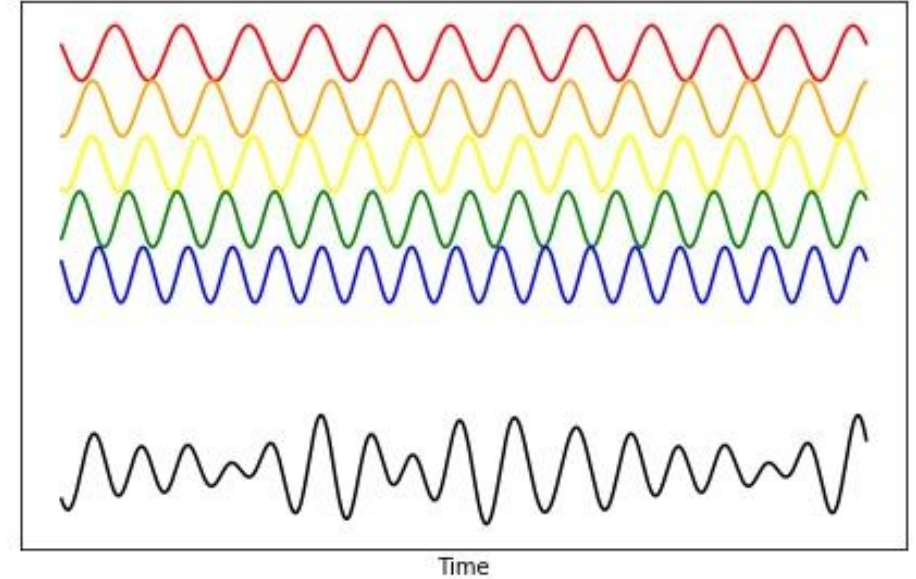
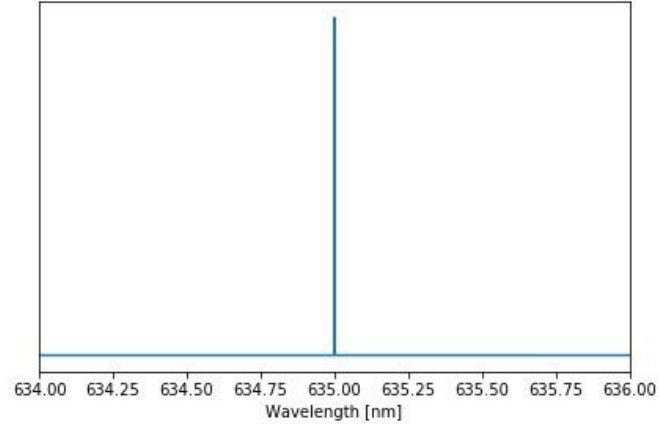
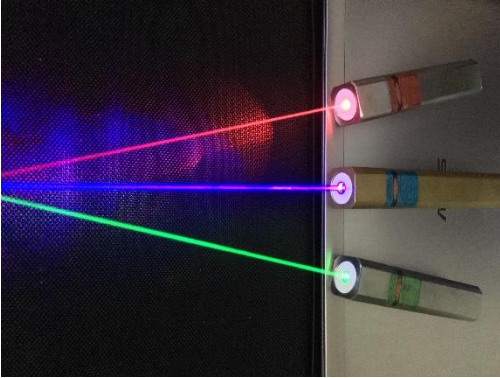


We accepted this as a scalar and fundamental solution to the wave equation, but it actually violates Maxwell's equations!

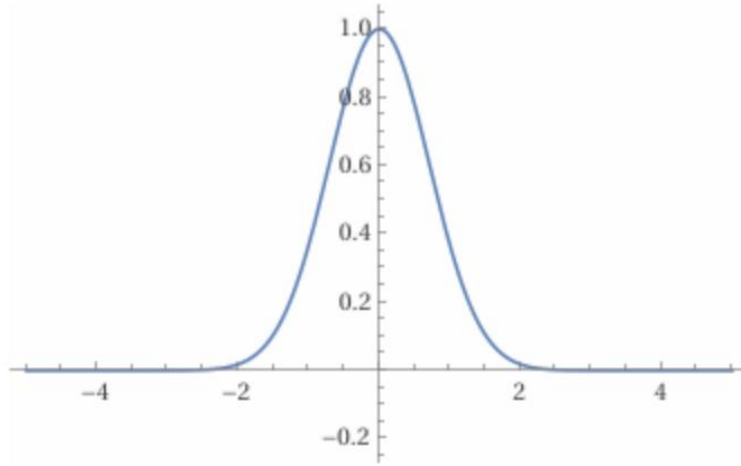
Which one?

The longitudinal field is a Hermite-Gauss

What are light pulses?



Pulses: please do not be afraid of integrals!



$$\int_{-\infty}^{\infty} e^{-x^2} dx = \sqrt{\pi}$$



$$\int_{-\infty}^{\infty} e^{-(x-x_0)^2} dx = \sqrt{\pi}$$



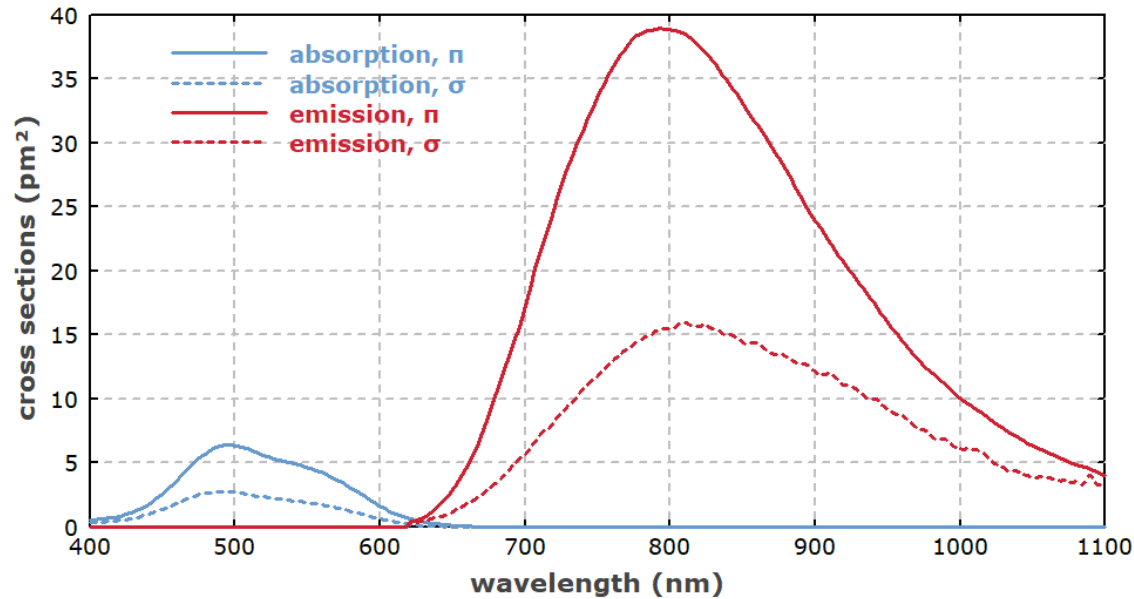
Fourier transform $\rightarrow$

$$\int_{-\infty}^{\infty} e^{-i\omega t} e^{-(\omega-\omega_0)^2/\Omega_0^2} d\omega = e^{-i\omega_0 t} \int_{-\infty}^{\infty} e^{-i\Omega t} e^{-\Omega^2/\Omega_0^2} d\Omega = e^{-i\omega_0 t} e^{-\Omega_0^2 t^2/4} \int_{-\infty}^{\infty} e^{-(\Omega/\Omega_0 + it\Omega_0/2)^2} d\Omega$$

$$= \sqrt{\pi} \Omega_0 e^{-i\omega_0 t} e^{-\Omega_0^2 t^2/4} \rightarrow \text{Gaussian profile in frequency and time}$$

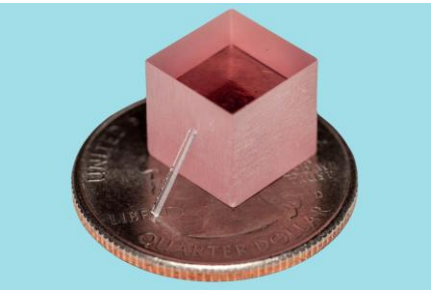
How to make ultrashort pulses

Making all of the colors



Making them “align” with each other

- Q-switching
- Mode-locking
 - Saturable absorber
 - Kerr-lens
 - Etc, etc.

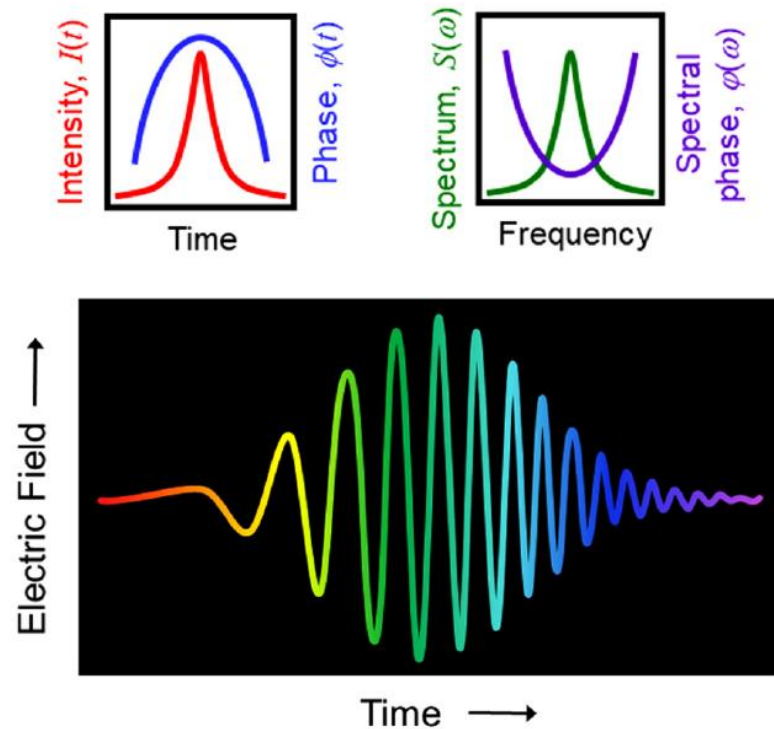


The field is excited about Yb-based lasers

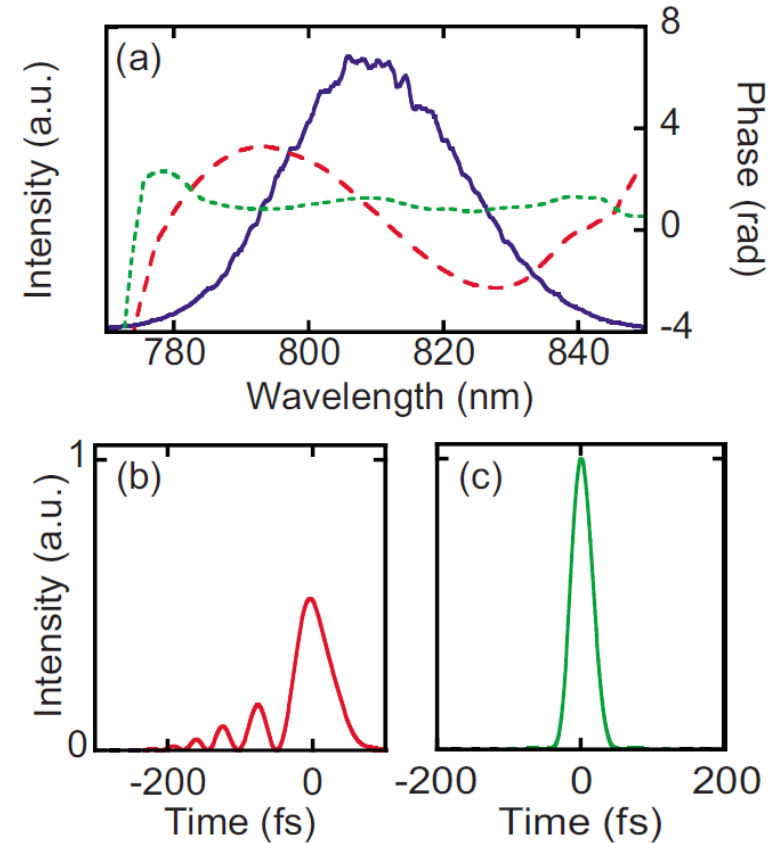


https://www.rp-photonics.com/titanium_doped_laser_gain_media.html

Spectral phase



R. Trebino et al., J. Appl. Phys. **128**, 171103 (2020); doi: 10.1063/5.0022552



Walmsley & Dorrer, Adv. in Opt. and Phot. **1**, 308–437 (2009); doi:10.1364/AOP.1.000308

Another view of chirp and spectral phase

GDD ϕ_2

↓

$$\int_{-\infty}^{\infty} e^{-i\omega t} e^{-(\omega-\omega_0)^2/\Omega_0^2} e^{-i\phi_2(\omega-\omega_0)^2/2} d\omega = e^{-i\omega_0 t} \int_{-\infty}^{\infty} e^{-i\Omega t} e^{-\Omega^2/\Omega_1^2} d\Omega = e^{-i\omega_0 t} e^{-\Omega_1^2 t^2/4} \int_{-\infty}^{\infty} e^{-(\Omega/\Omega_1 + i t \Omega_1/2)^2} d\Omega$$

$$\frac{1}{\Omega_1^2} = \frac{1}{\Omega_0^2} + i \frac{\phi_2}{2} \quad \longrightarrow \quad \frac{\Omega_1^2}{\Omega_0^2} = \frac{1}{1 + i \frac{\Omega_0^2 \phi_2}{2}} = \frac{1 - i \frac{\Omega_0^2 \phi_2}{2}}{1 + \frac{\Omega_0^4 \phi_2^2}{4}}$$

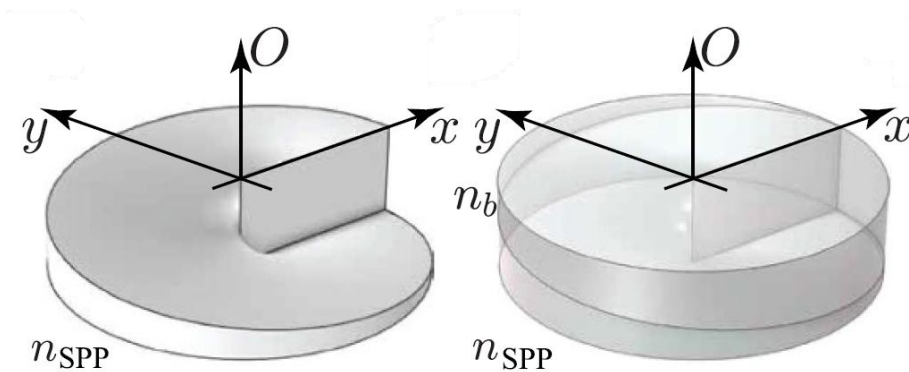
$$= \sqrt{\pi} \Omega_1 e^{-i\omega_0 t} e^{-\Omega_1^2 t^2/4} = \sqrt{\pi} \Omega_1 e^{-i(\omega_0 t - A t^2)} e^{-\Omega_0^2 t^2/4B}$$

You don't need to know calculus!

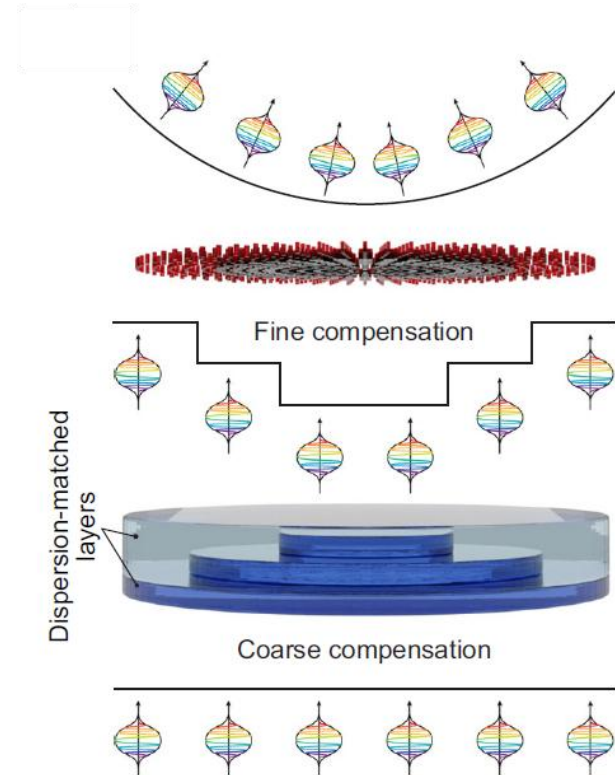
Looking back at optics but for pulses

Now you need to care about the behavior across the bandwidth!

For vortex beams:



For meta-lenses:



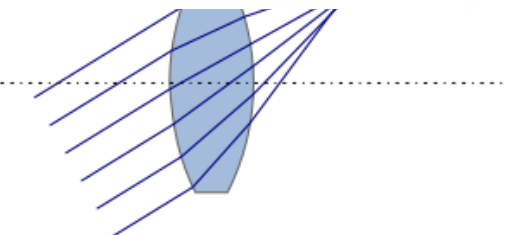
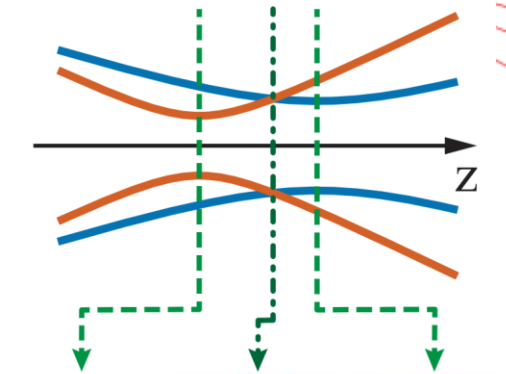
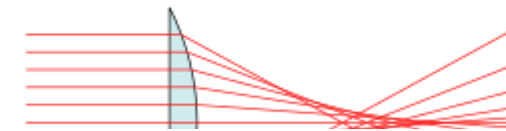
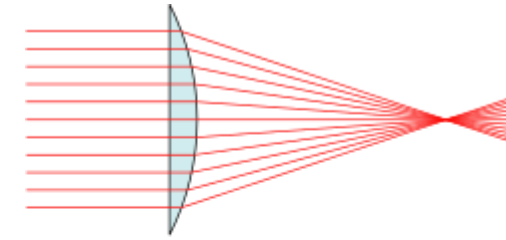
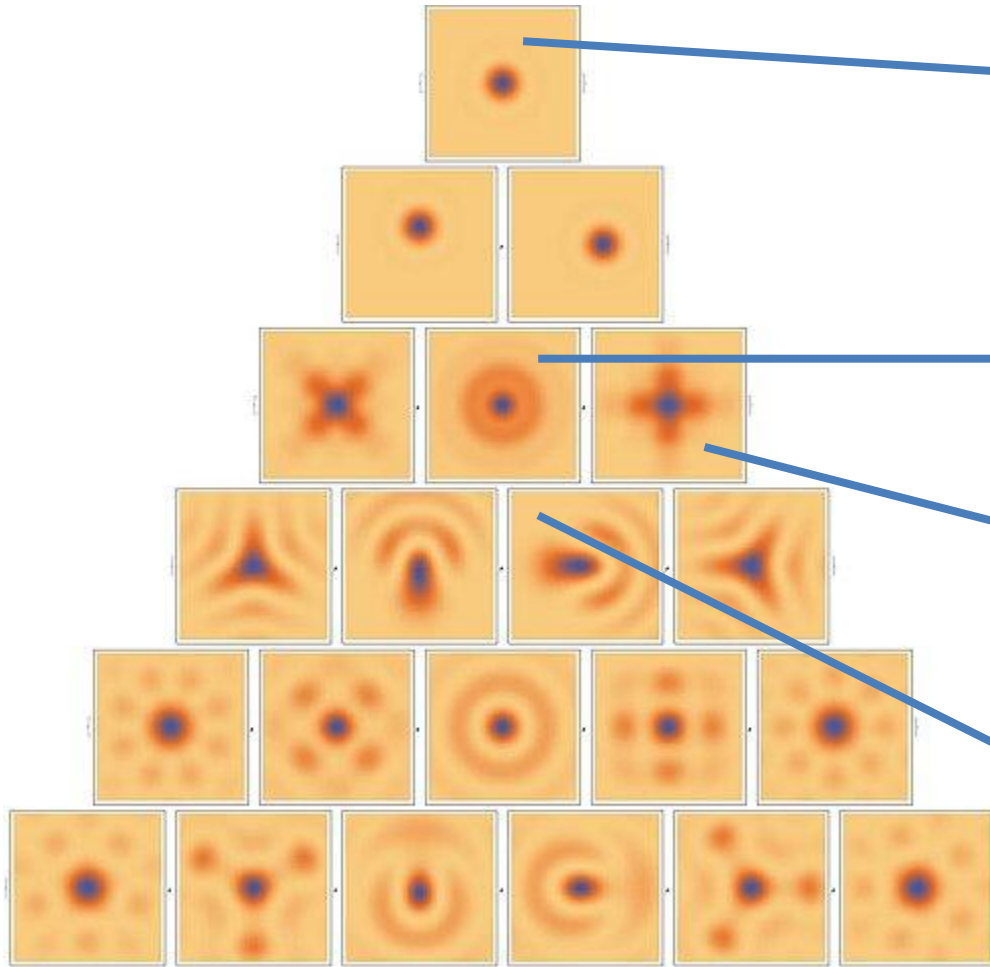
G. A. Swartzlander, *Optics Letters* **31**, 2042 (2006).
E. R. Baca-Montero et al., *J. Phys. Photonics* **8** 035028 (2026).

S. Chang et al., *Nature Communications* **15**, 9627 (2024).

Outline

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- **Shaping and measuring laser beams and laser pulses – the basics**
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Phase aberrations

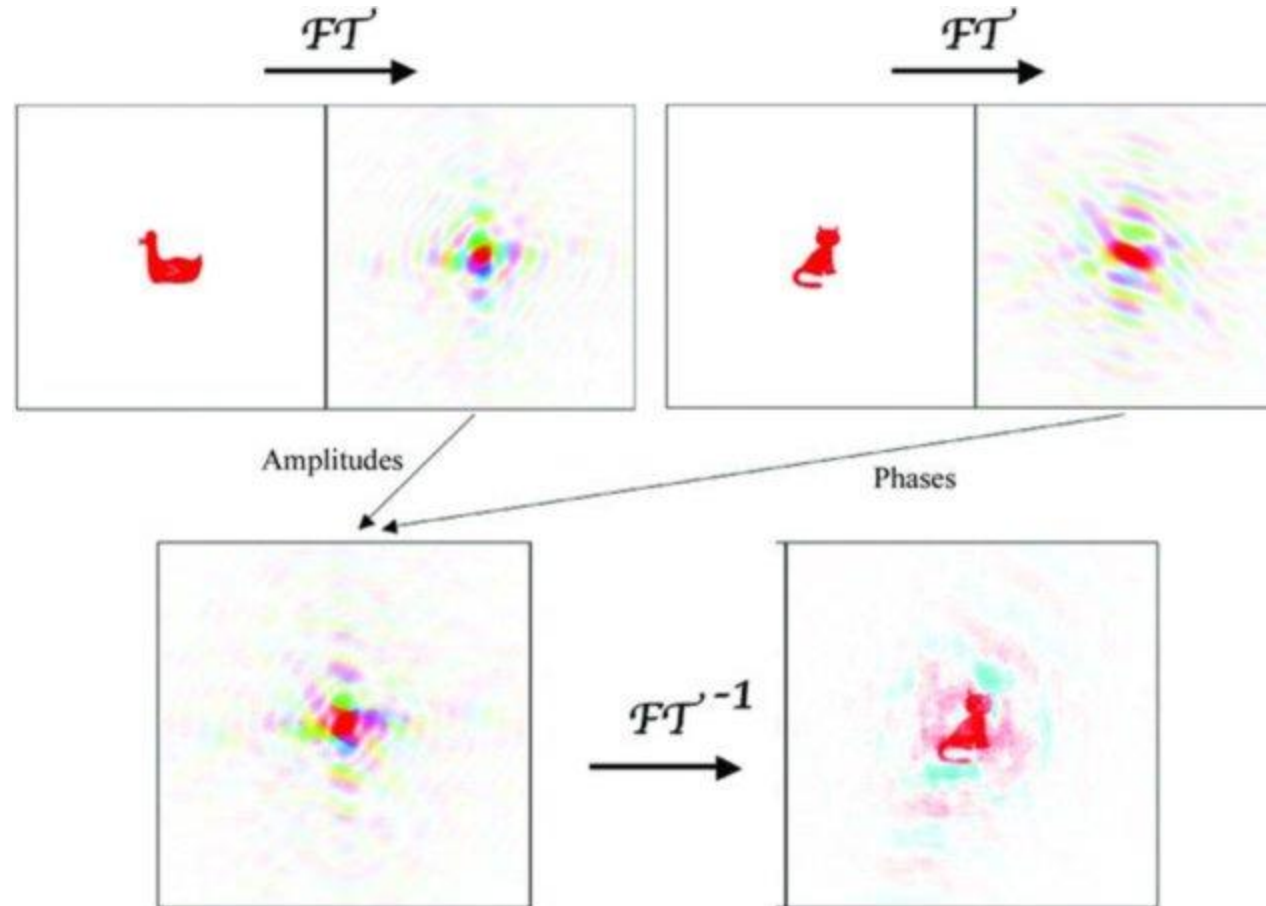


https://en.wikipedia.org/wiki/Optical_aberration

https://en.wikipedia.org/wiki/Spherical_aberration

https://en.wikipedia.org/wiki/Coma_%28optics%29

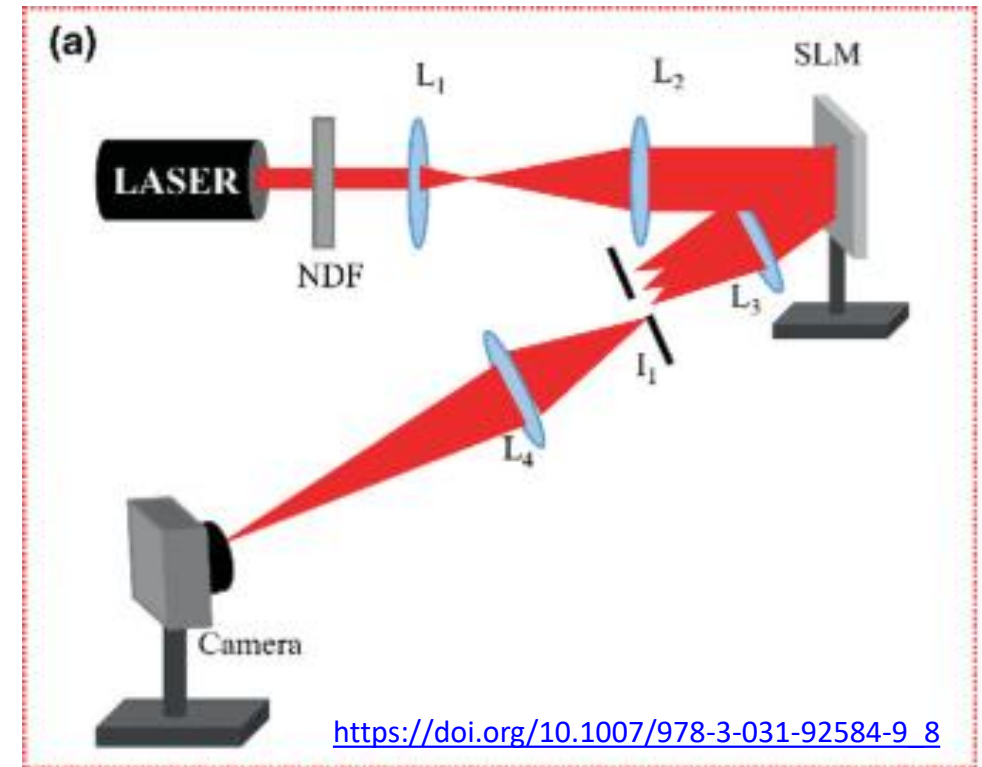
The connection between phase and intensity



<http://www.ysbl.york.ac.uk/~cowtan/fourier/magic.html>

Arbitrary spatial shaping: SLMs, etc.

- Pixelized shaping of amplitude or phase (and even polarization)
- In reflection or transmission
- Can be based on a number of materials and methods
- Extremely powerful and mature
- Deep connections to metasurfaces
 - Low damage threshold?
 - Artefacts from pixelization?



https://en.wikipedia.org/wiki/Spatial_light_modulator

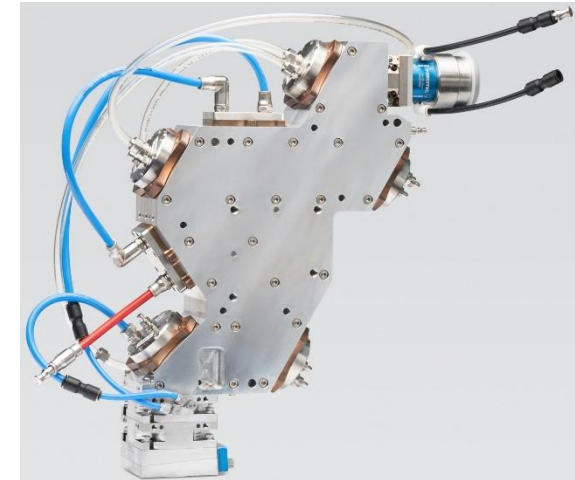
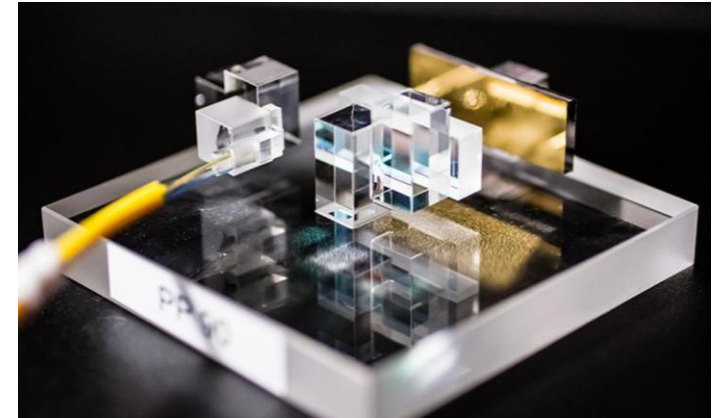
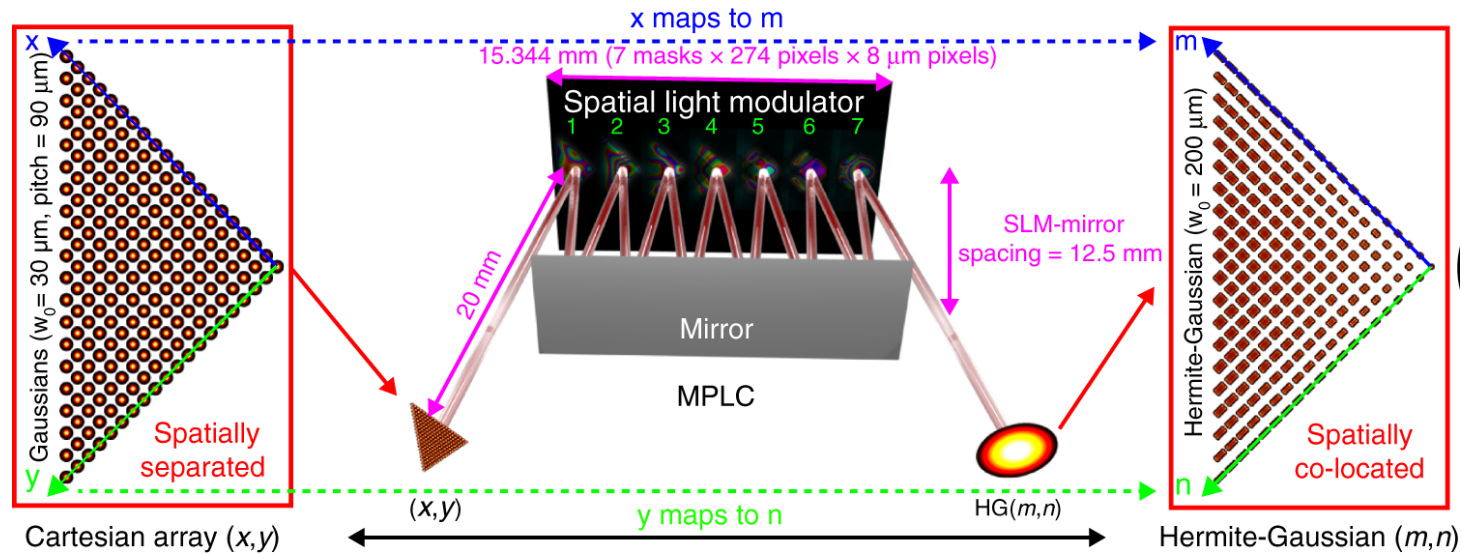
https://en.wikipedia.org/wiki/Digital_micromirror_device

https://en.wikipedia.org/wiki/Electromagnetic_metasurface



Arbitrary spatial shaping: MPLC

Input position couples to output spatial mode



G. Labroille et al., Opt. Express **22**, 15599 (2014).
N. Fontaine et al., Nat Comm. **10**, 1865 (2019).

cailabs

SHAPING THE LIGHT

One slide on laser beam characterization

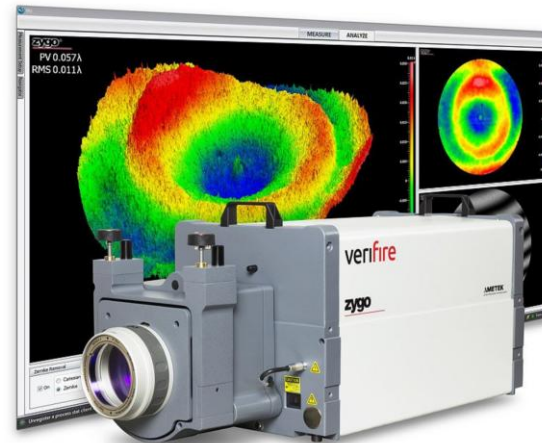
One wants to measure the spatial profile and the wavefront



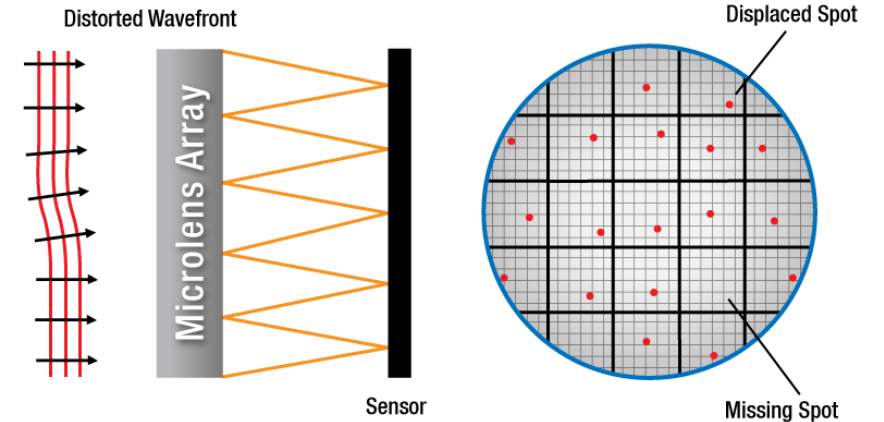
amplitude

phase

$$F(x, y, z_0) = A(x, y, z_0)e^{i\phi(x, y, z_0)}$$



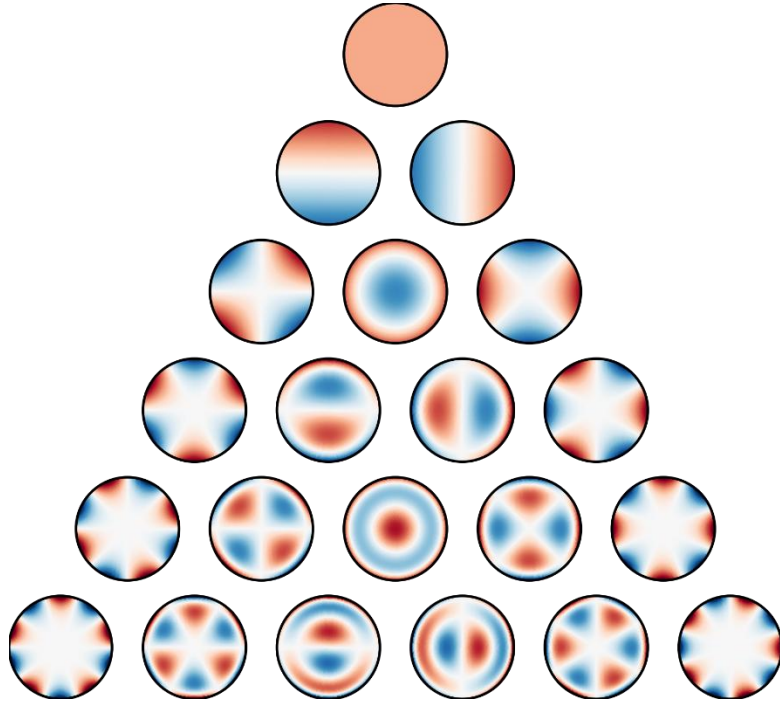
zygoTM



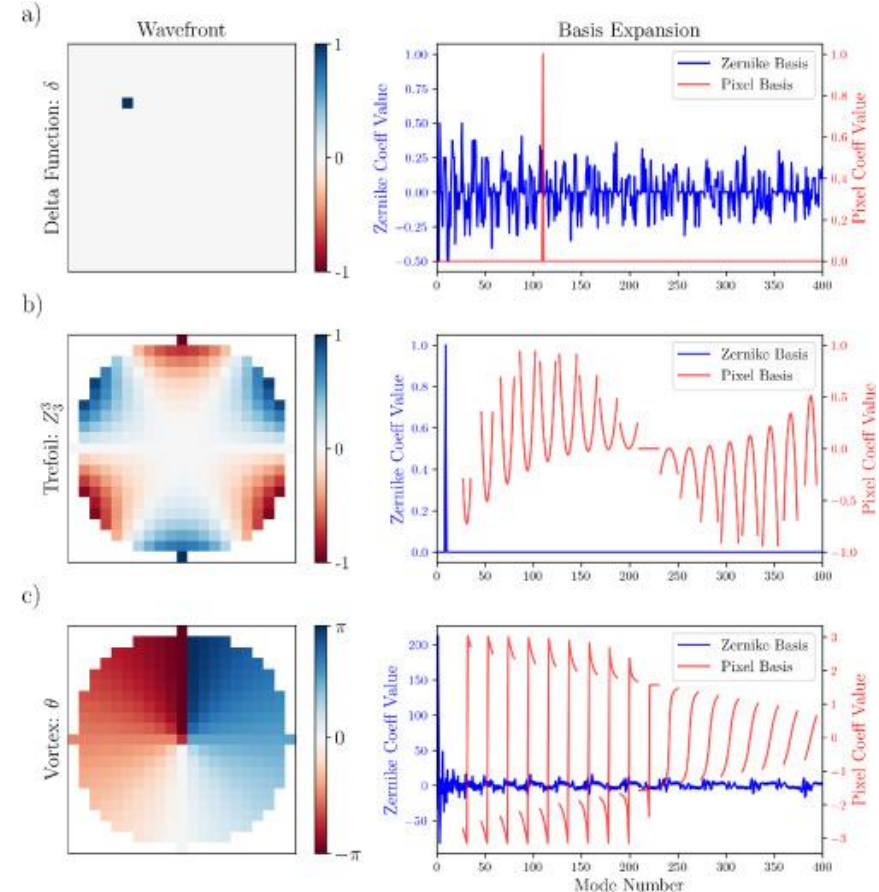
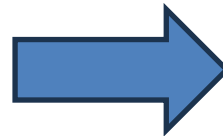
imagine  **optic**TM

 **Phasics**

My word on the Zernike polynomials



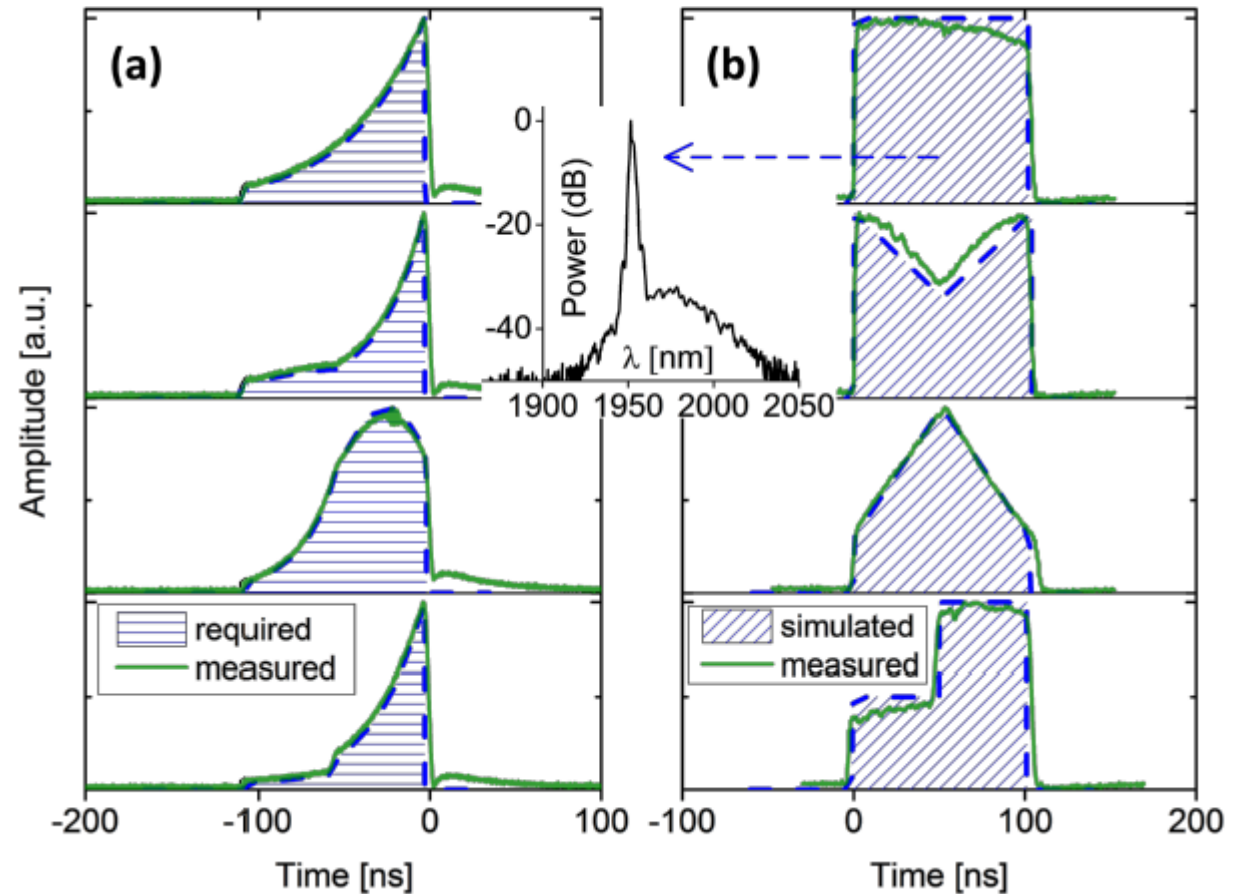
Great for common optical aberrations, but not necessarily for all types of beams. Simple phases like axicon $\propto r$, cubic $\propto r^3$, or vortex $\propto l\theta$ require many high-order Zernike coeffs.



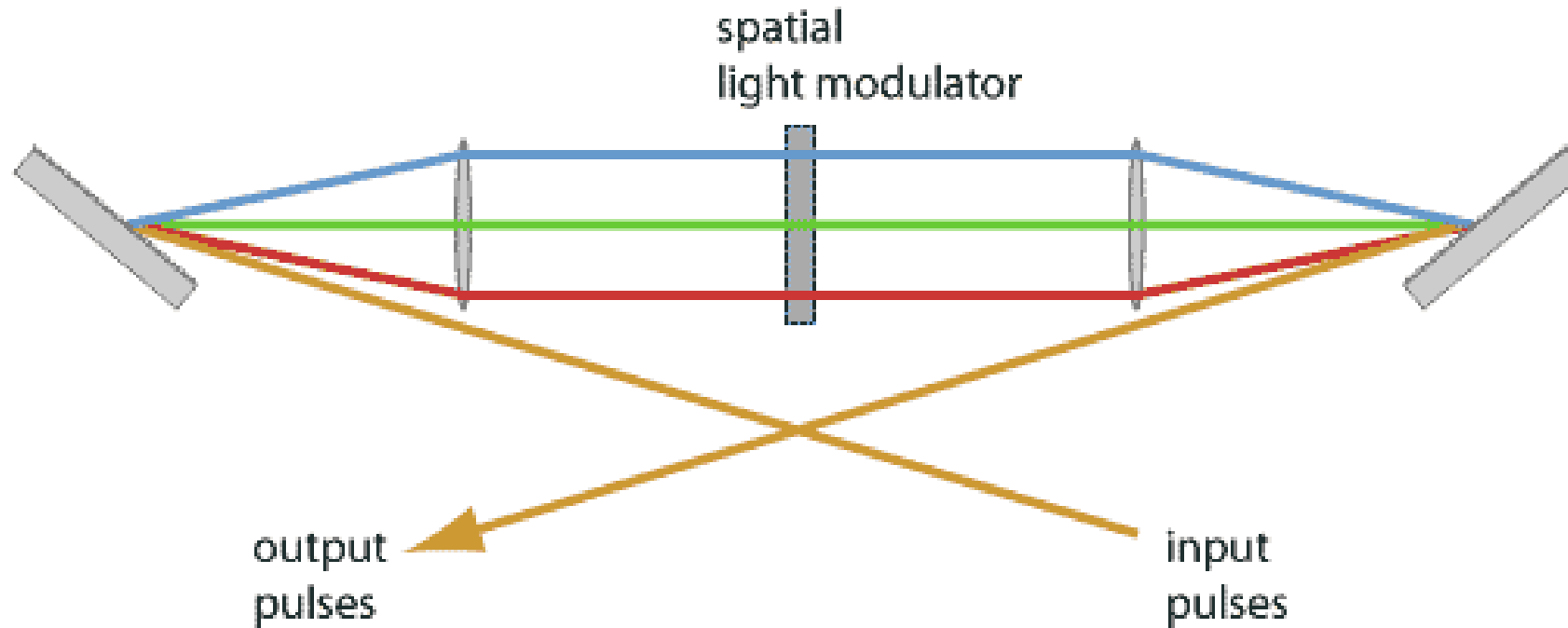
S. Howard, N. Weisse, J. Schröder, C. Barbero, B. Alonso, Í. Sola, P. Norreys, and A. Döpp, "Sparse reconstruction of wavefronts using an over-complete phase dictionary," Opt. Express **33**, 12939-12952 (2025).

Shaping “long” pulses

- Slow enough time-scale to be done with electronics
- Can be within the laser cavity or after the laser is further amplified
- Used for a very long time and very robust



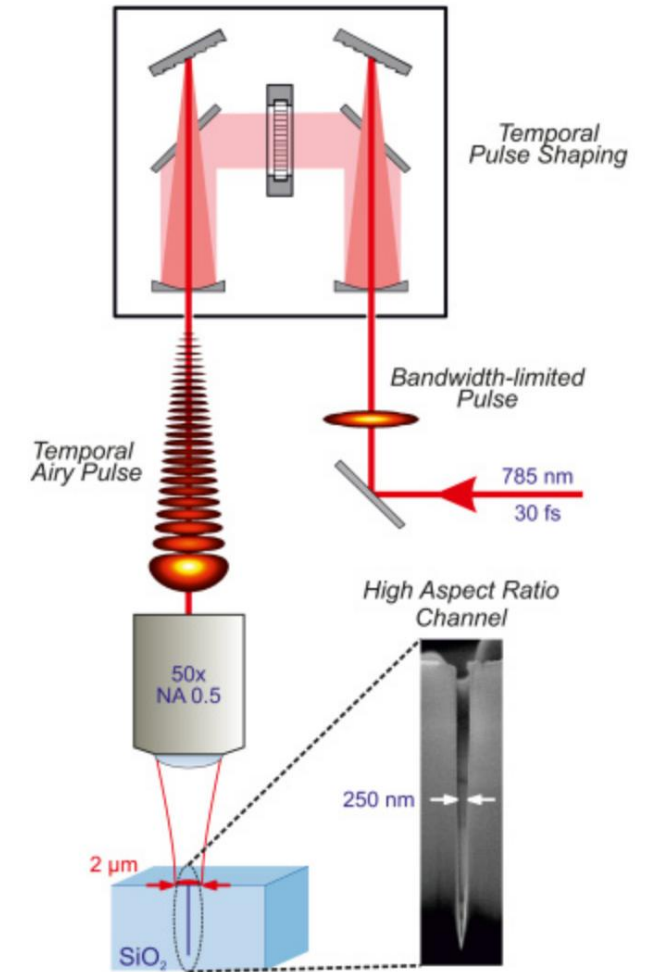
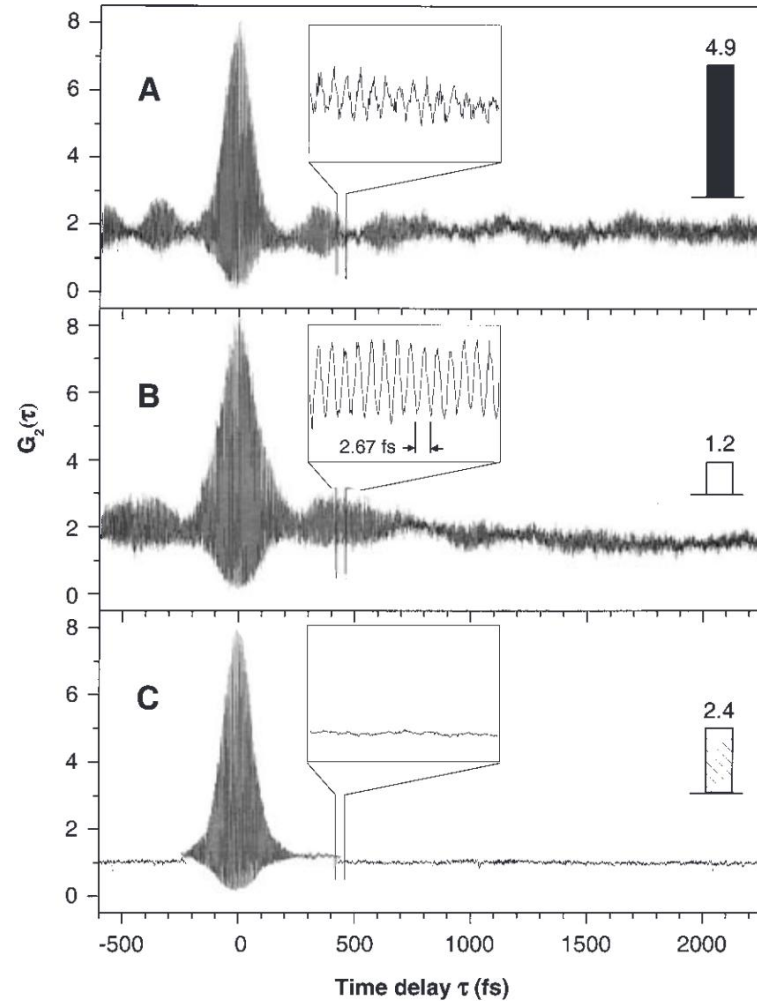
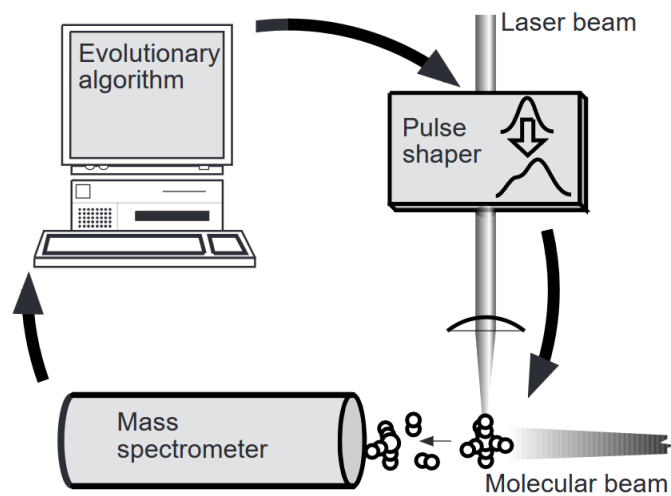
fs shaping → the 4-f pulse shaper



https://www.rp-photonics.com/pulse_shapers.html

https://en.wikipedia.org/wiki/Femtosecond_pulse_shaping

Applications of temporal shaping



The “picosecond problem”

- Nanosecond pulse shaping is with electronics
- Femtosecond pulse shaping is with dispersion and filters, etc.
- Picosecond pulses?
 - Too fast for electronics
 - Too narrowband for dispersive pulse-shaping

This is an ongoing research problem!

Randy Lemons, Jack Hirschman, Hao Zhang, Charles Durfee, Sergio Carbajo.
Nonlinear Shaping in the Picosecond Gap. *Ultrafast Science* **5**, 0112 (2025).

Sidenote: I'm going fast here ...

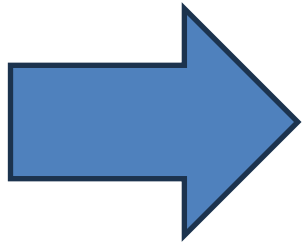
IOP PUBLISHING

JOURNAL OF PHYSICS B: ATOMIC, MOLECULAR AND OPTICAL PHYSICS

J. Phys. B: At. Mol. Opt. Phys. **43** (2010) 103001 (34pp)

[doi:10.1088/0953-4075/43/10/103001](https://doi.org/10.1088/0953-4075/43/10/103001)

PhD TUTORIAL



A newcomer's guide to ultrashort pulse shaping and characterization

Antoine Monmayrant^{1,2}, Sébastien Weber³ and Béatrice Chatel³

¹ CNRS-LAAS, 7 avenue du colonel Roche, F-31077 Toulouse, France

² Université de Toulouse, UPS, INSA, INP, ISAE ; LAAS, F-31077 Toulouse, France

³ CNRS-Université de Toulouse; UPS, Laboratoire Collisions, Agrégats Réactivité, IRSAMC, F-31062 Toulouse, France.

E-mail: beatrice.chatel@irsamc.ups-tlse.fr

A. Monmayrant, et al., J. Phys. B **43**, 103001 (2010).

One slide on temporal characterization

One wants to measure the temporal profile, but also E-field

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

↕

$$\tilde{E}(\omega) = \tilde{A}(\omega)e^{i\phi(\omega)}$$

amplitude phase

→ Most techniques in fact measure the spectrum and the spectral phase, which together can uniquely determine the electric field, but there are limitations!



Walmsley & Dorrer, Adv. in Opt. and Phot. **1**, 308–437 (2009); doi:10.1364/AOP.1.000308

R. Trebino et al., J. Appl. Phys. **128**, 171103 (2020); doi: 10.1063/5.0022552

How to make a pulse more powerful?

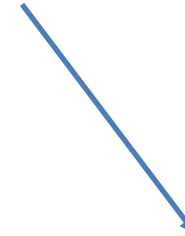
$$P = \frac{E}{\tau}$$



Make the pulse more energetic or shorter (or both ☺)



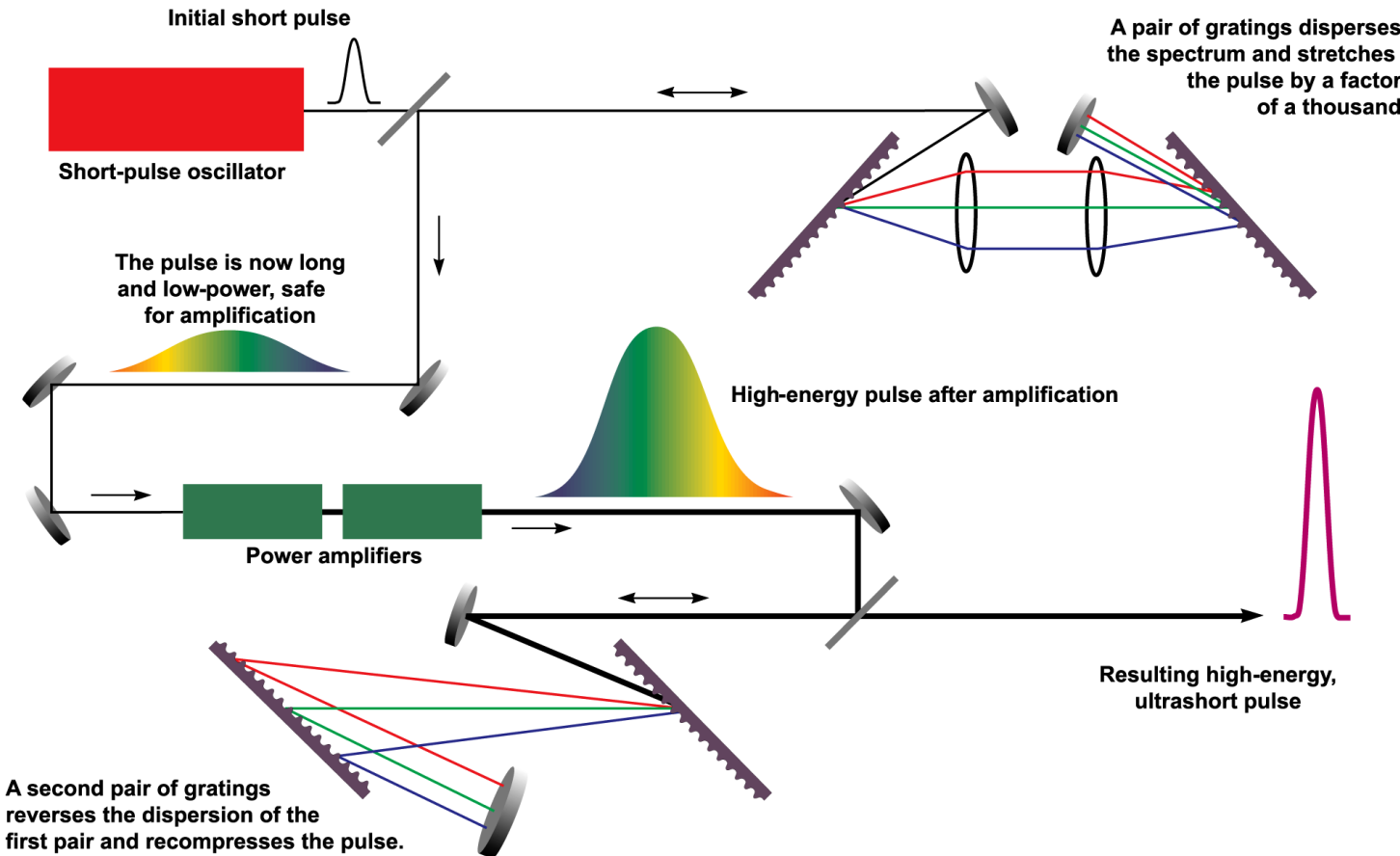
amplification



make the spectrum broader

Spectral phase still important !

Chirped-Pulse Amplification (CPA)

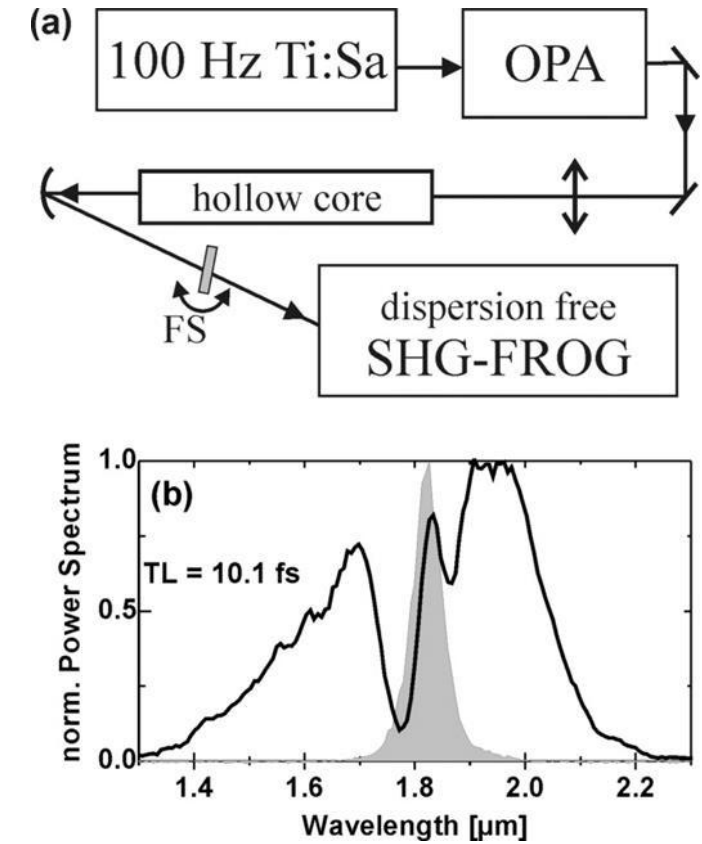
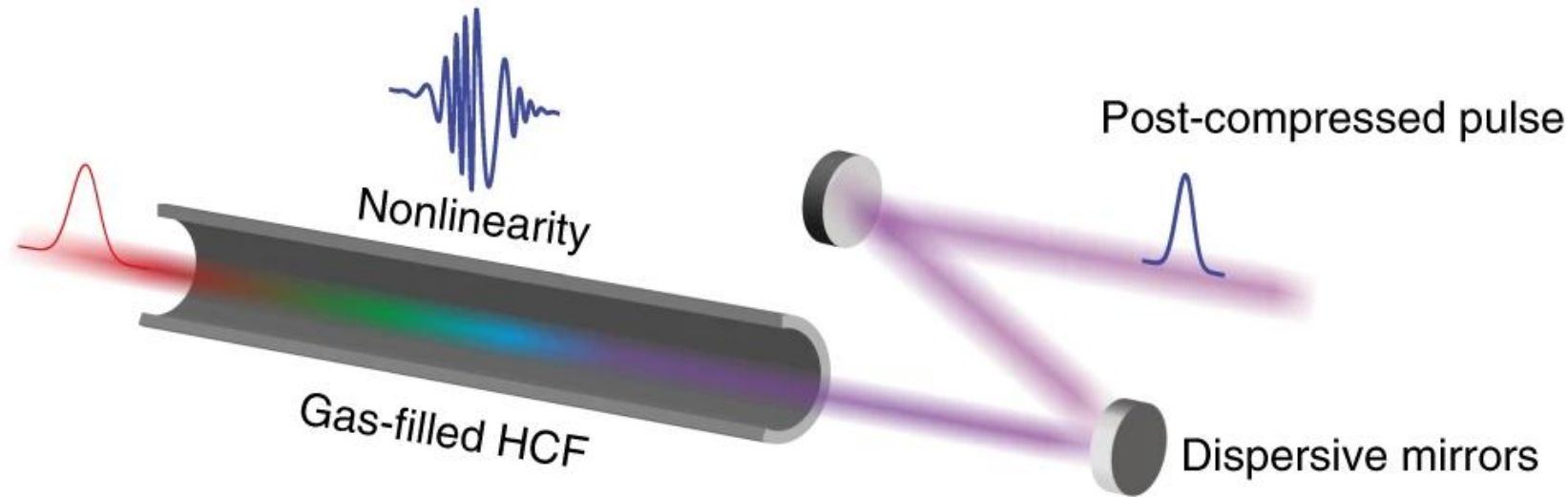


https://en.wikipedia.org/wiki/Chirped_pulse_amplification



BELLA @ Berkeley, USA
1 PW-35 fs-40 J
1 Hz -800 nm

Nonlinear pulse broadening



<https://www.nature.com/articles/s41566-019-0416-4>

<https://doi.org/10.1063/1.3359458>

https://www.rp-photonics.com/pulse_compression.html

Comparing the two processes

	Ω	τ
Dispersion only	Constant	Changes
Nonlinear process	Changes	$\sim$ Constant

CPA = short pulse $\rightarrow$ add dispersion to make longer $\rightarrow$ amplify $\rightarrow$ remove dispersion to compress

SPM broadening = short pulse $\rightarrow$ nonlinear process to broaden spectrum $\rightarrow$ remove dispersion to compress

Results → High-field science



(2002)

https://en.wikipedia.org/wiki/Attosecond_physics



(2004)

https://en.wikipedia.org/wiki/Plasma_acceleration

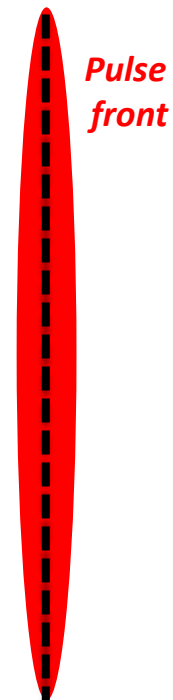
Outline

- Laser beams and laser pulses – the basics
- Shaping and measuring laser beams and laser pulses – the basics
- **Going to space and time: what are STCs?**
- Why STCs? And why is characterization difficult?
- Overview of history and of standard techniques
- More recent measurements, techniques, and exotic concepts

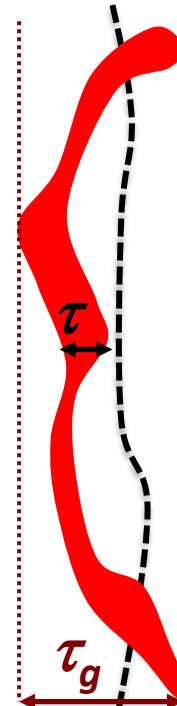
Spatio-temporal couplings (STCs)

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

Wavefront



*Pulse
front*



spatial chirp

Simultaneous
spatio-temporal
focusing

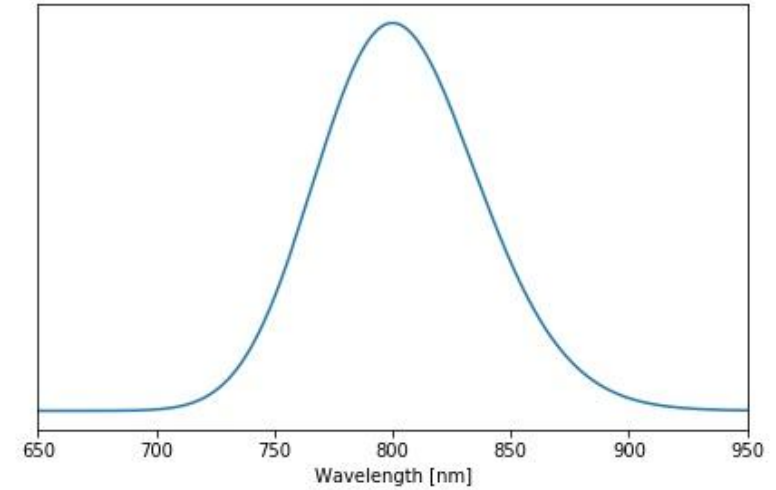
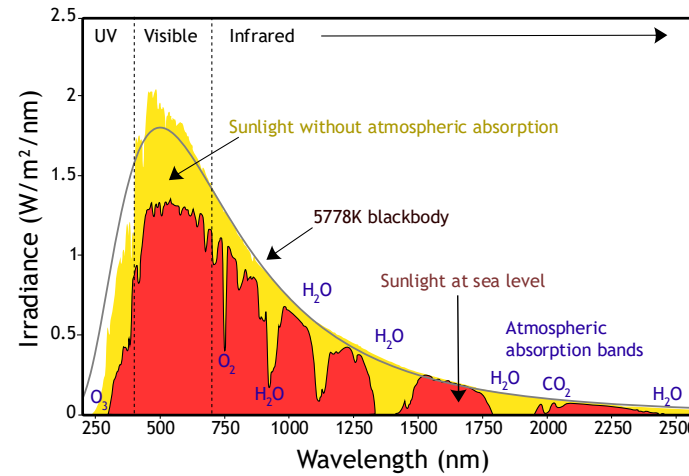
wavefront rotation

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).

Making a link to imaging

Spectrum of Solar Radiation (Earth)



An STC

https://en.wikipedia.org/wiki/Chromatic_aberration

Disclaimer: STCs are not new

Volume 59, number 3

OPTICS COMMUNICATIONS

1 September 1986

JOURNAL OF MODERN OPTICS, 1988, VOL. 35, NO. 12, 1907–1918

PULSE DISTORTIONS IN TILTED PULSE SCHEMES FOR ULTRASHORT PULSES

Oscar Eduardo MARTINEZ¹

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

Received 5 March 1986

Distortion of femtosecond laser pulses in lenses and lens systems

Z. BOR†

Max-Planck Institut für biophysikalische Chemie,
Abteilung Laserphysik, Postfach 2841,
D-3400 Göttingen, F.R. Germany

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. Guandalini¹, F. Schapper¹, M. Holler¹, J. Biegert^{1,2}, L. Gallmann¹,
A. Couairon², M. Franco³, A. Mysyrowicz³, and U. Keller¹

¹ETH Zurich, Physics Department / Institute of Quantum Electronics, 8093 Zurich, Switzerland

²Centre de Physique Théorique, CNRS, École Polytechnique, F-91128 Palaiseau, France

³Laboratoire d'Optique Appliquée, École Nationale Supérieure des Techniques Avancées—École Polytechnique, F-91761 Palaiseau Cedex, France

*Corresponding author: zair@phys.ethz.ch

Received 13 Mar 2007; revised 9 Apr 2007; accepted 10 Apr 2007; published 18 Apr 2007
30 April 2007 / Vol. 15, No. 9 / OPTICS EXPRESS 5394

One of the first mentions I have found

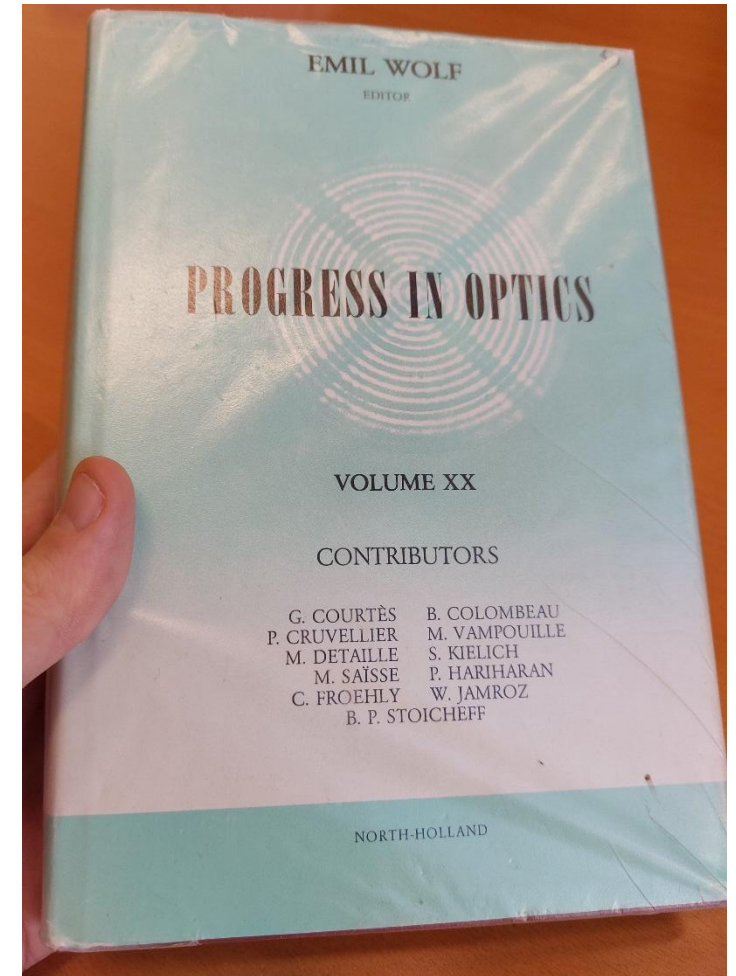
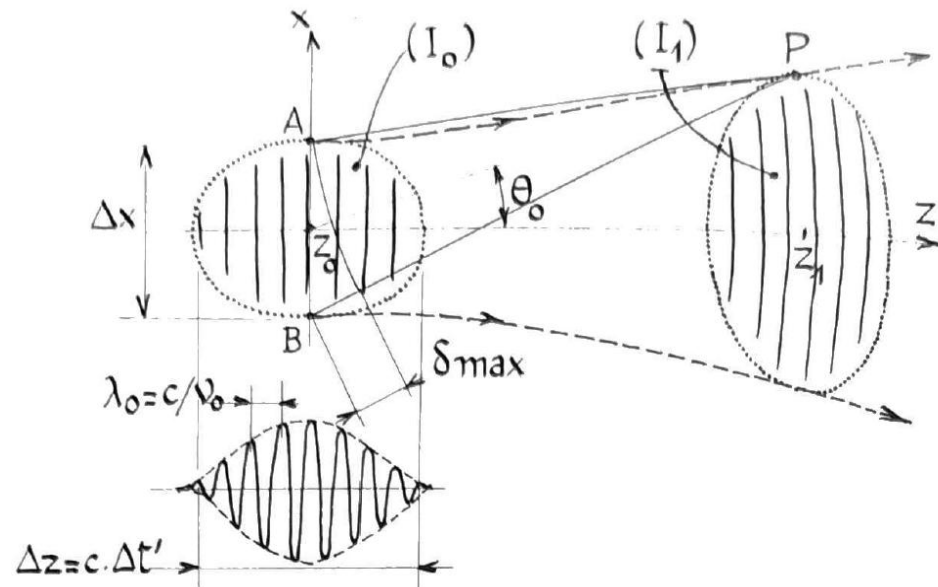
II

SHAPING AND ANALYSIS OF PICOSECOND LIGHT PULSES

BY

C. FROEHLY, B. COLOMBEAU and M. VAMPOUILLE

*U.E.R. des Sciences, Laboratoire d'Optique, E.R.A. CNRS 535, 123 Rue Albert Thomas,
87060 Limoges-Cedex, France*



1983

Going even further in the past

Nouv. Rev. Optique, 1973, t. 4, n° 4, p. 183-196

LABORATOIRE DE PHYSIQUE GÉNÉRALE ET OPTIQUE
Faculté des Sciences et des Techniques — F-25030 Besançon Cedex

NOTIONS DE RÉPONSE IMPULSIONNELLE ET DE FONCTION DE TRANSFERT TEMPORELLES DES PUPILLES OPTIQUES, JUSTIFICATIONS EXPÉRIMENTALES ET APPLICATIONS

par
Cl. FROEHLI, A. LACOURT,
et J. Ch. VIÉNOT

MOTS CLÉS :
Techniques de Fourier
Cohérence temporelle
KEY WORDS :
Fourier techniques
Time coherence

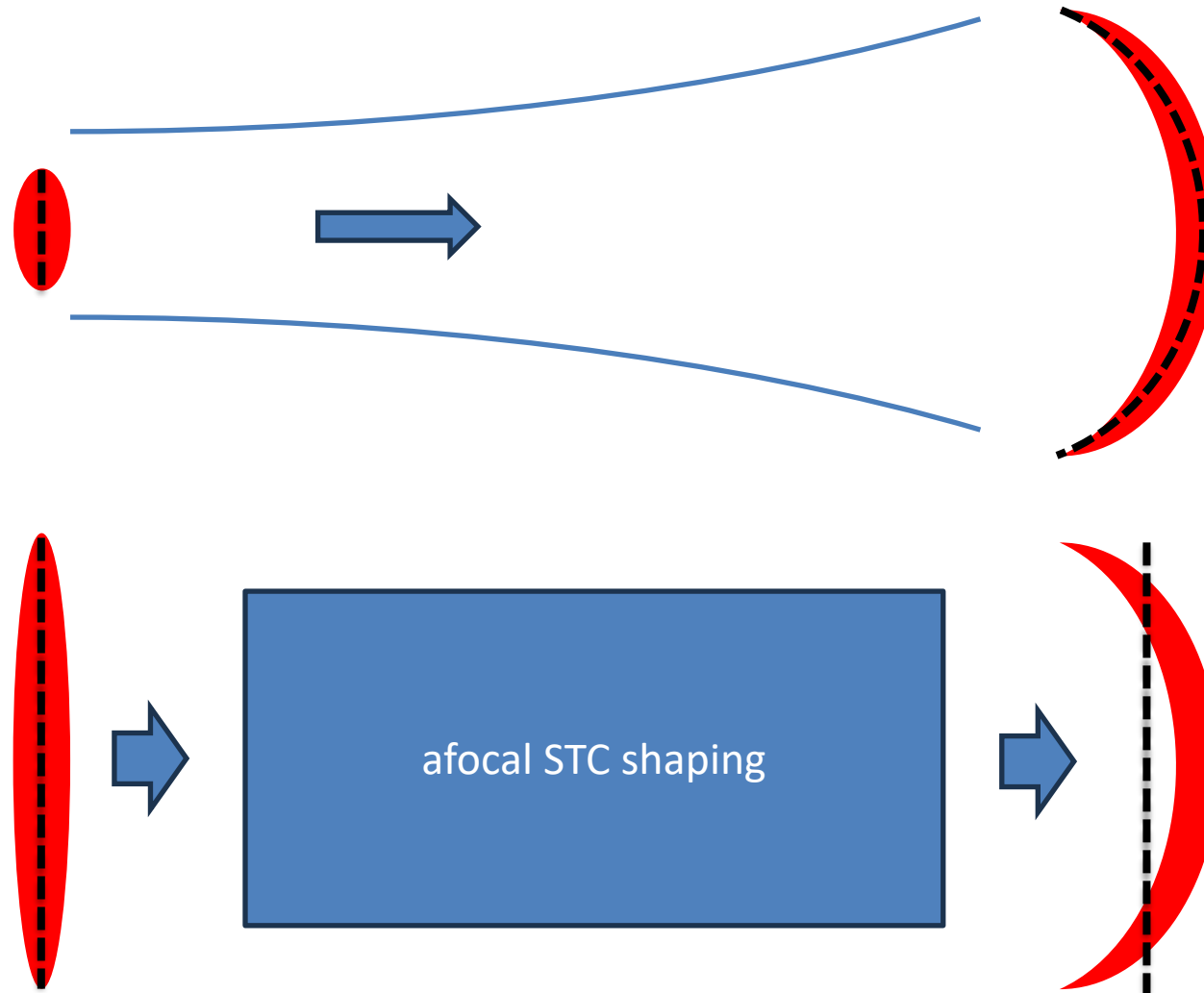
1973

RÉPONSE PERCUSSIONNELLE SPATIOTEMPORELLE EN DIFFRACTION POLYCHROMATIQUE

par
Georges BONNET
Professeur à la Faculté des Sciences *

1975

“Inherent” and “Imposed” STCs



Ultrashort Gaussian-Gaussian Pulse-Beam

Monochromatic at ω

$$E = \frac{-iz_R}{q} e^{i\omega r^2/2cq} e^{-i\omega t'}$$

$$q(z) = z - iz_R$$

$$t' = t - z/c$$

Multiply by envelope
in time

Gaussian pulse at ω_0

$$E = \frac{-iz_R}{q} e^{i\omega_0 r^2/2cq} e^{-i\omega_0 t'} e^{-(t'/\tau_0)^2}$$

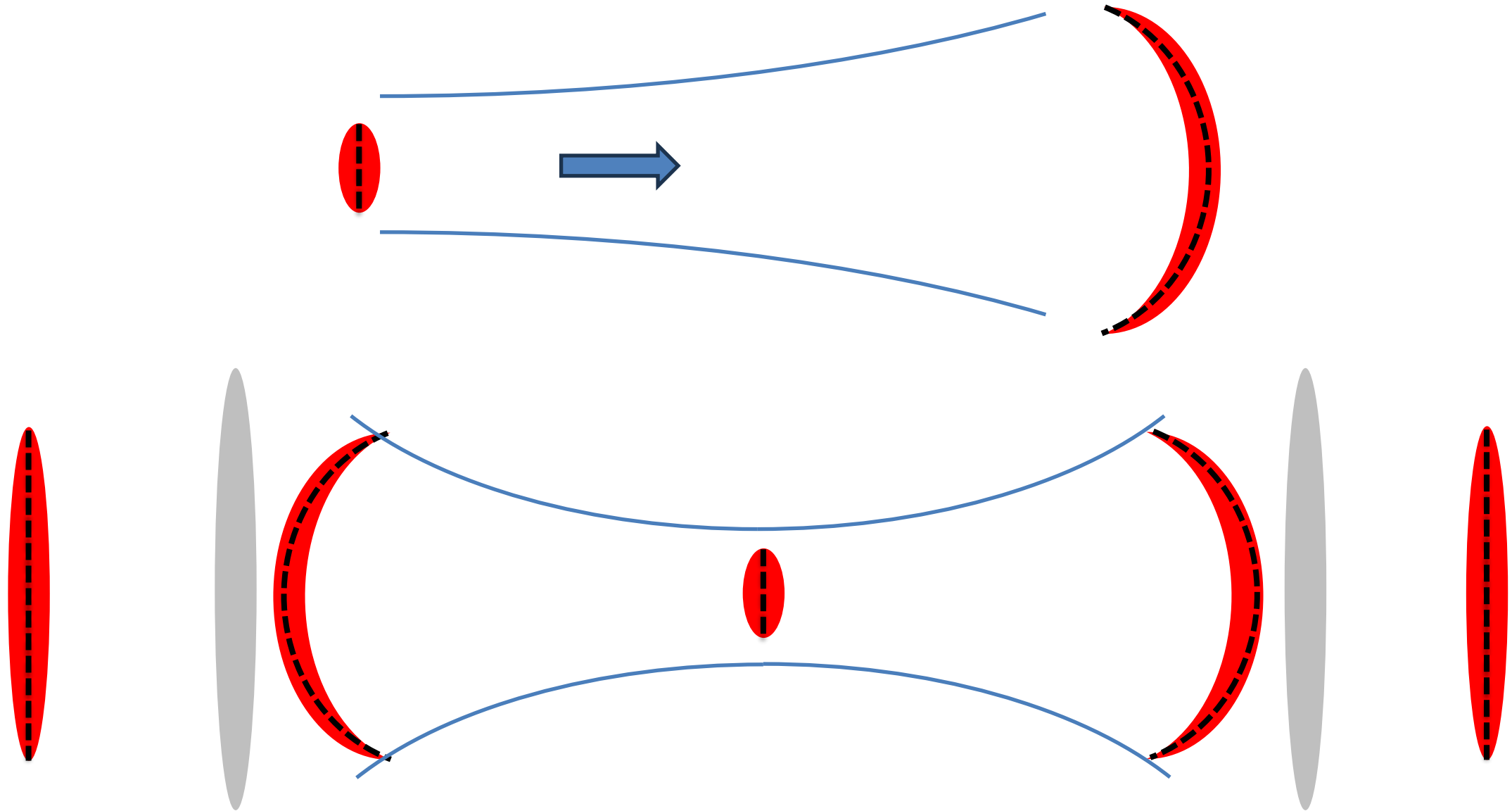
Superposition
in freq. space

$$\hat{E} = \frac{-iz_R}{q} e^{i\omega r^2/2cq} e^{i\omega z/c} e^{-(\omega - \omega_0)^2/\Omega_0^2}$$

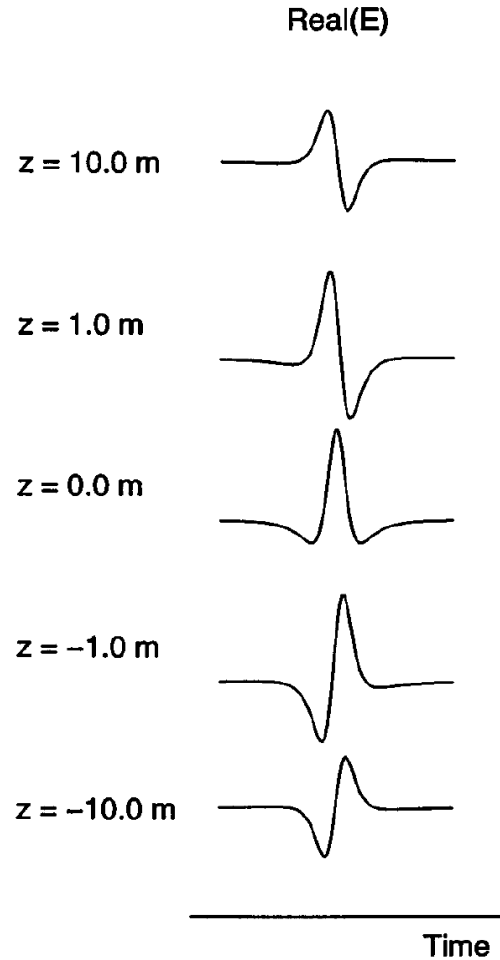
(Fourier transform)

$$E = \frac{-iz_R}{\sqrt{\pi}\tau_0 q} e^{i\omega_0 r^2/2cq} e^{-i\omega_0 t'} e^{-(t' - \underline{r^2/2cq})^2/\tau_0^2} \quad (\tau_0 = 2/\Omega_0)$$

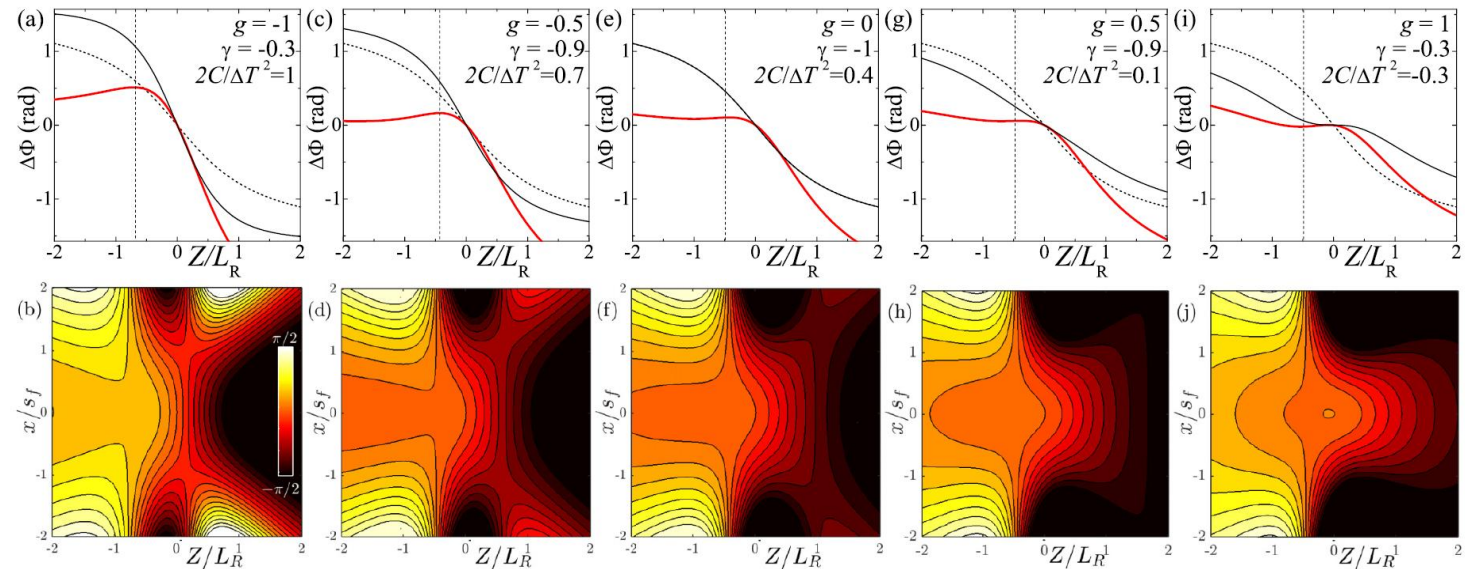
Can we reconcile this with a focusing lens/mirror?



Few-cycle pulses are fully reshaped in S-T



Initial space-time distribution (g_0), chromatic lenses (γ), and chirp (C), lead to CEP reshaping in *space-time*



M. Porras, Opt. Lett. **34**, 1546 (2009).

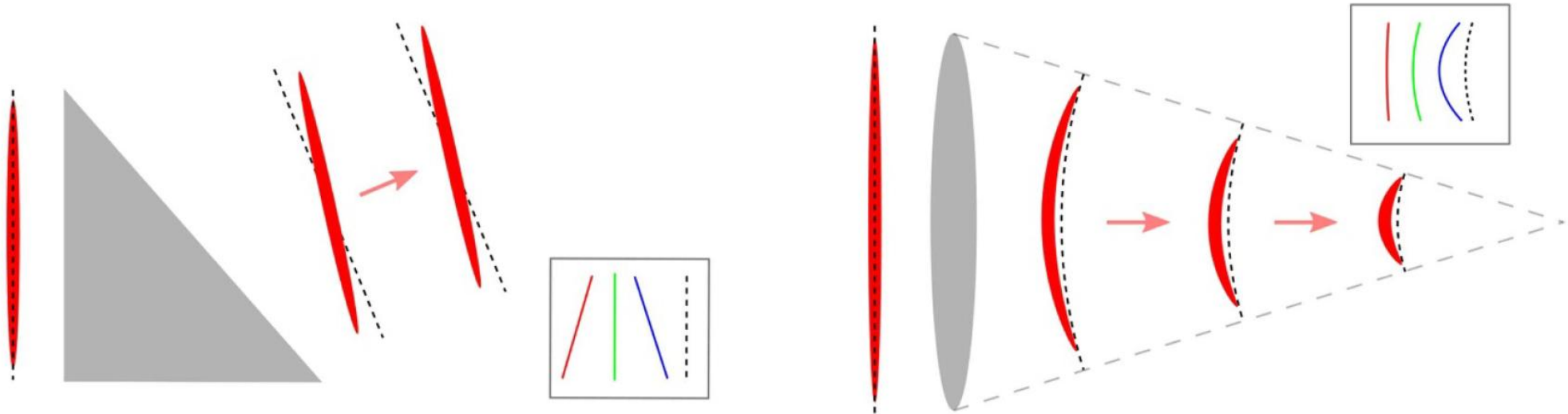
M. Porras, et al., Phys. Rev. A **98**, 063819 (2018).

First shown with THz pulses:

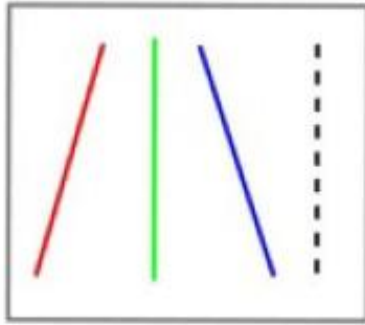
Feng & Winful, Opt. Lett. **23**, 385 (1998).

Standard and well-known “imposed” STCs

Often due to dispersive optics that aren't flat
→ Dispersive prisms, dispersive lenses



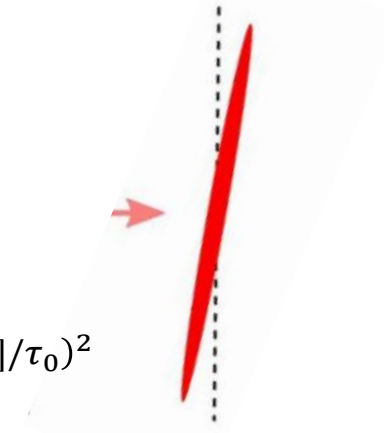
Connecting frequency and time



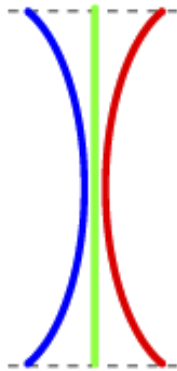
$$\tilde{E} = e^{-(r/w_0)^2} e^{-(\omega - \omega_0)^2 / \Omega^2} e^{i\alpha x (\omega - \omega_0)}$$



$$E = e^{-(r/w_0)^2} e^{-i\omega_0 t} e^{-([t - \alpha x] / \tau_0)^2}$$



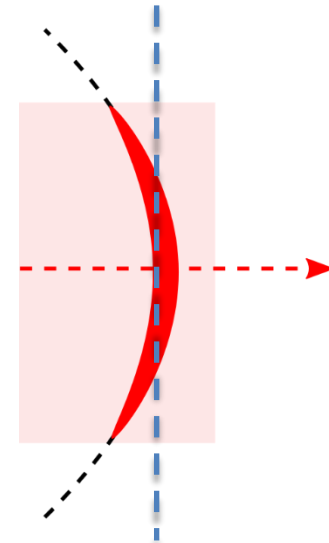
Angular dispersion (frequencies having different tilt directions) is equivalent to a pulse-front tilt



$$\tilde{E} = e^{-(r/w_0)^2} e^{-(\omega - \omega_0)^2 / \Omega^2} e^{i\alpha r^2 (\omega - \omega_0)}$$



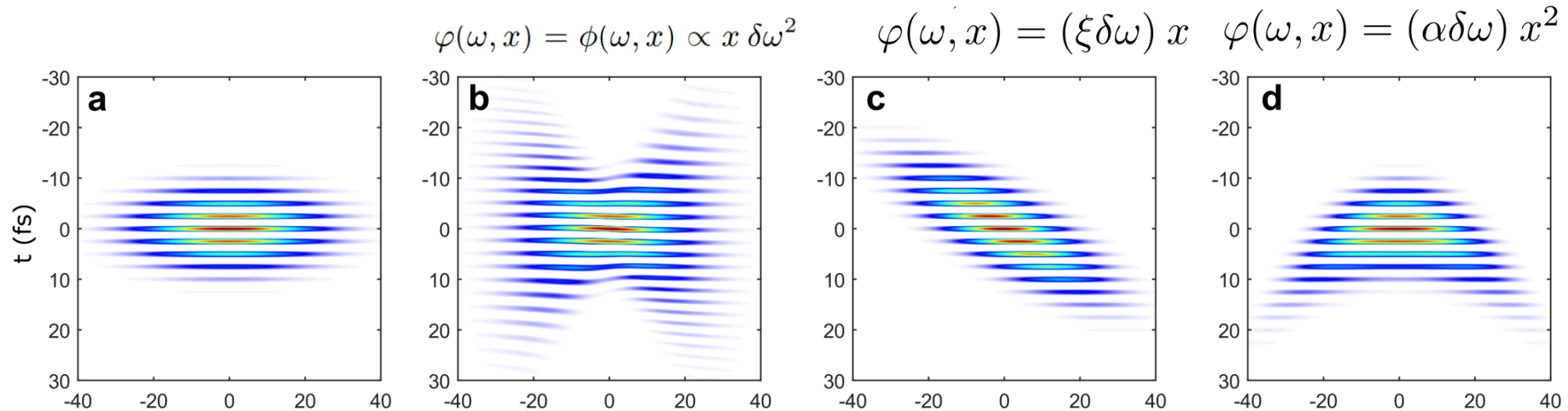
$$E = e^{-(r/w_0)^2} e^{-i\omega_0 t} e^{-([t - \alpha r^2] / \tau_0)^2}$$



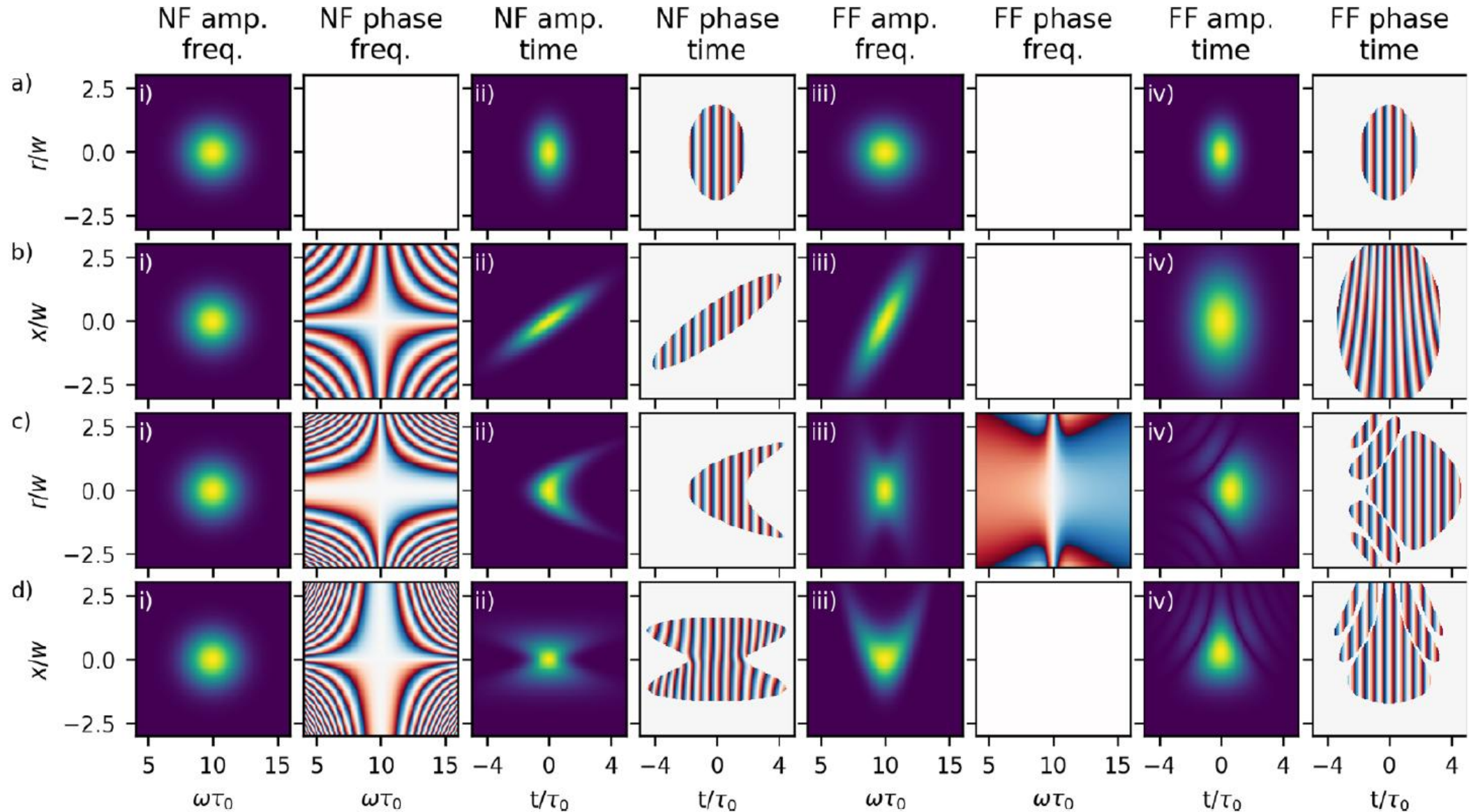
Chromatic curvature (frequencies having different focusing) is equivalent to a pulse-front curvature

Connecting frequency and time

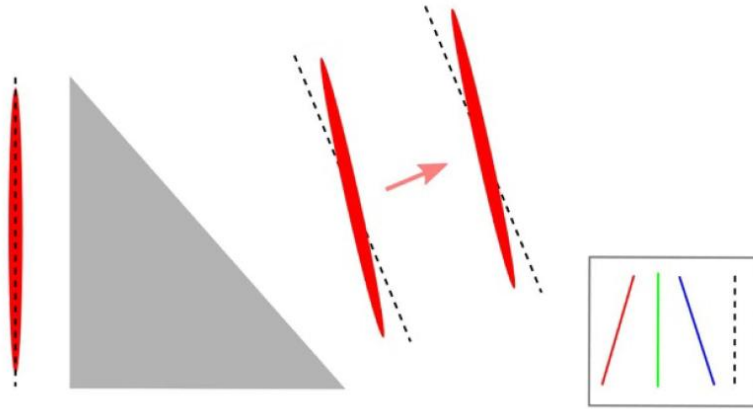
$$\varphi(\omega, \mathbf{r}) = \varphi(\omega_0, \mathbf{r}) + \frac{\partial \varphi(\omega_0, \mathbf{r})}{\partial \omega} \delta \omega + \phi(\omega, \mathbf{r})$$



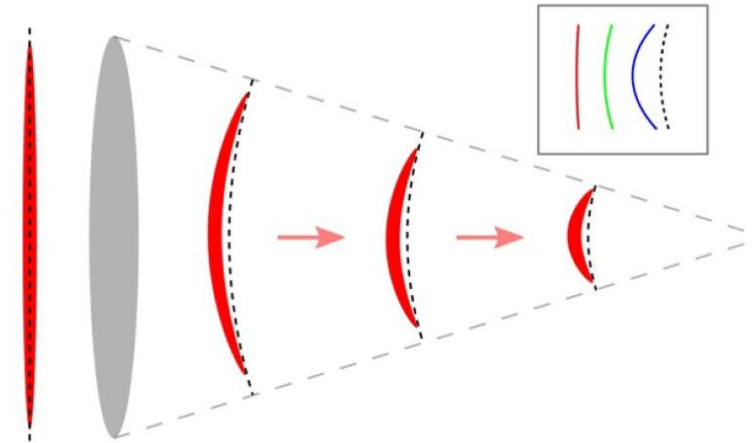
Connecting near-field and far-field



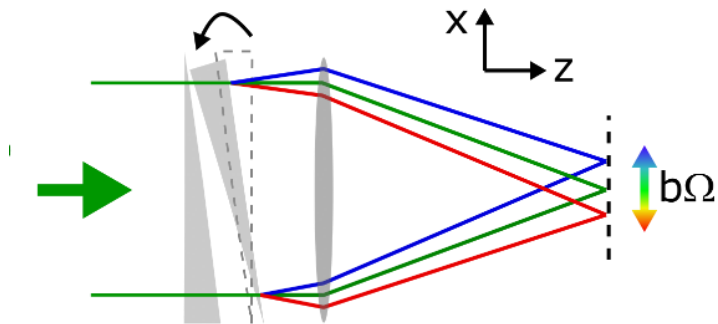
Another useful comparison



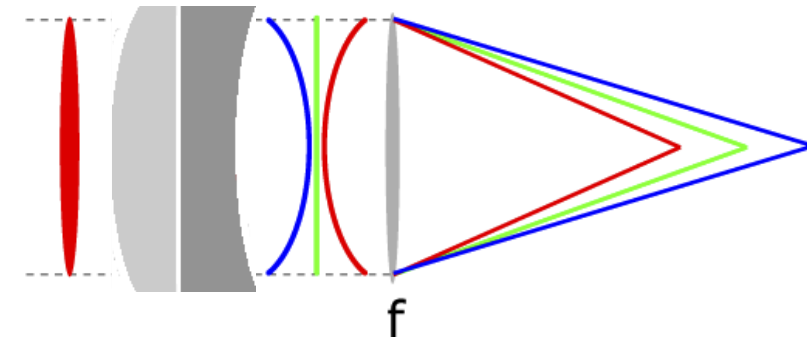
A prism imparts angular dispersion, and also an overall tilt



A singlet lens imparts chromatic curvature, and also an overall focusing



- A pair of prisms (one tilted) imparts angular dispersion with no overall tilt
- When a beam with angular dispersion is focused, there is spatial chirp in the focus



- A pair of lenses (different glasses) imparts chromatic curvature with no overall focus
- When a beam with chromatic curvature is focused, there is longitudinal chromatism in the focus

Analytically modeling an STC

$$\hat{E} = \frac{-iZ_R}{q} e^{i\omega r^2/2cq} e^{i\omega z/c} e^{-(\omega-\omega_0)^2/\Omega_0^2}$$

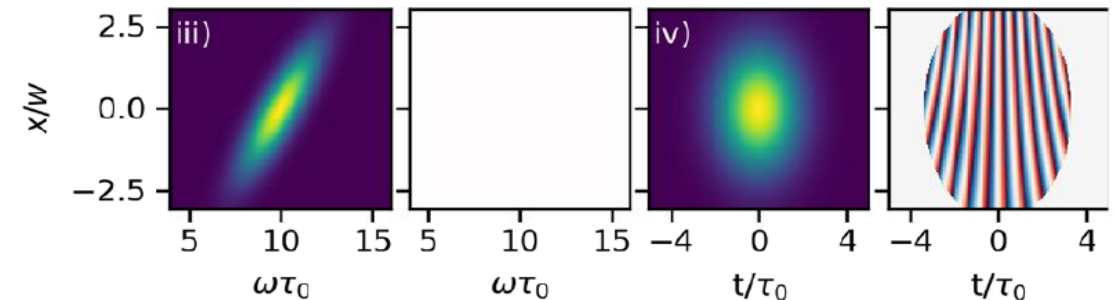
(spatial chirp)

$$\hat{E} = \frac{-iZ_R}{q} e^{i\omega([x-b(\omega-\omega_0)]^2+y^2)/2cq} e^{i\omega z/c} e^{-(\omega-\omega_0)^2/\Omega_0^2}$$

(Fourier transform)

$$E = \frac{-iZ_R}{2\sqrt{\pi}\alpha q} e^{i\omega_0 r^2/2cq} e^{-i\omega_0 t'} e^{-(t'-(r^2-\underline{2\omega_0 bx})/2cq)^2/4\alpha^2}$$

$$\alpha = \sqrt{\frac{1}{\Omega_0^2} - \frac{i(\omega_0 b^2 - 2bx)}{2cq}}$$



Numerically modeling an STC

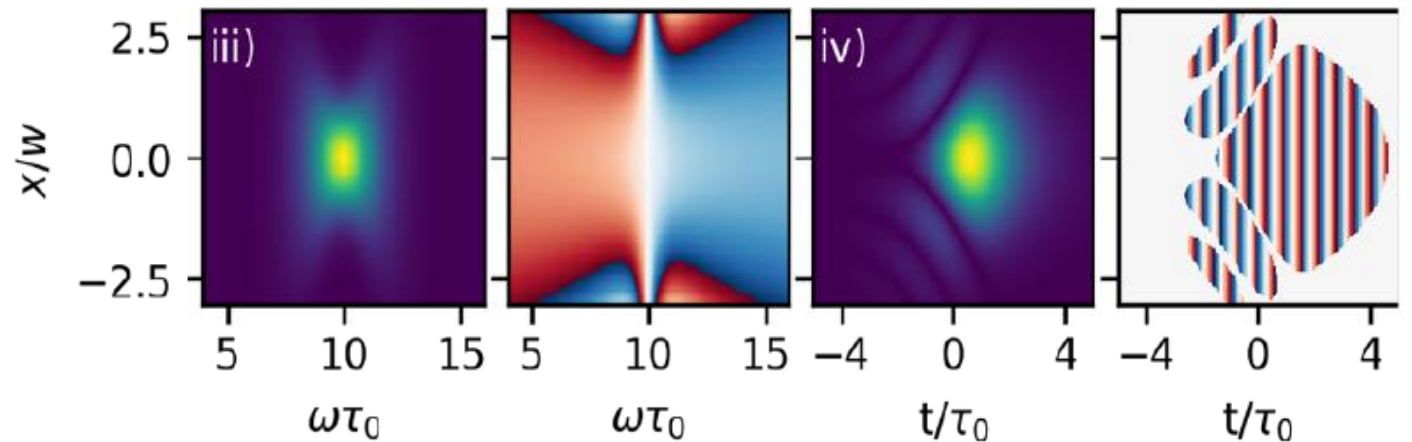
$$\hat{E} = \frac{-iz_R}{q} e^{i\omega r^2/2cq} e^{i\omega z/c} e^{-(\omega-\omega_0)^2/\Omega_0^2}$$

(longitudinal chromatism)

$$\hat{E} = \frac{-iz_R}{q - \alpha(\omega - \omega_0)} e^{i\omega r^2/2c[q - \alpha(\omega - \omega_0)]} e^{i\omega z/c} e^{-(\omega-\omega_0)^2/\Omega_0^2}$$

No integral solution!

(Numerical Fourier transform)



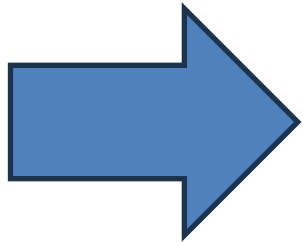
Even here I can't go through all the details!



Progress in Optics

Available online 21 February 2026

[In Press, Corrected Proof](#) [? What's this?](#)



Analytical models for ultrashort laser pulses with space-time couplings

Spencer W. Jolly  

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<https://doi.org/10.1016/bs.po.2026.01.001> 

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A new rigorous way to define STCs?

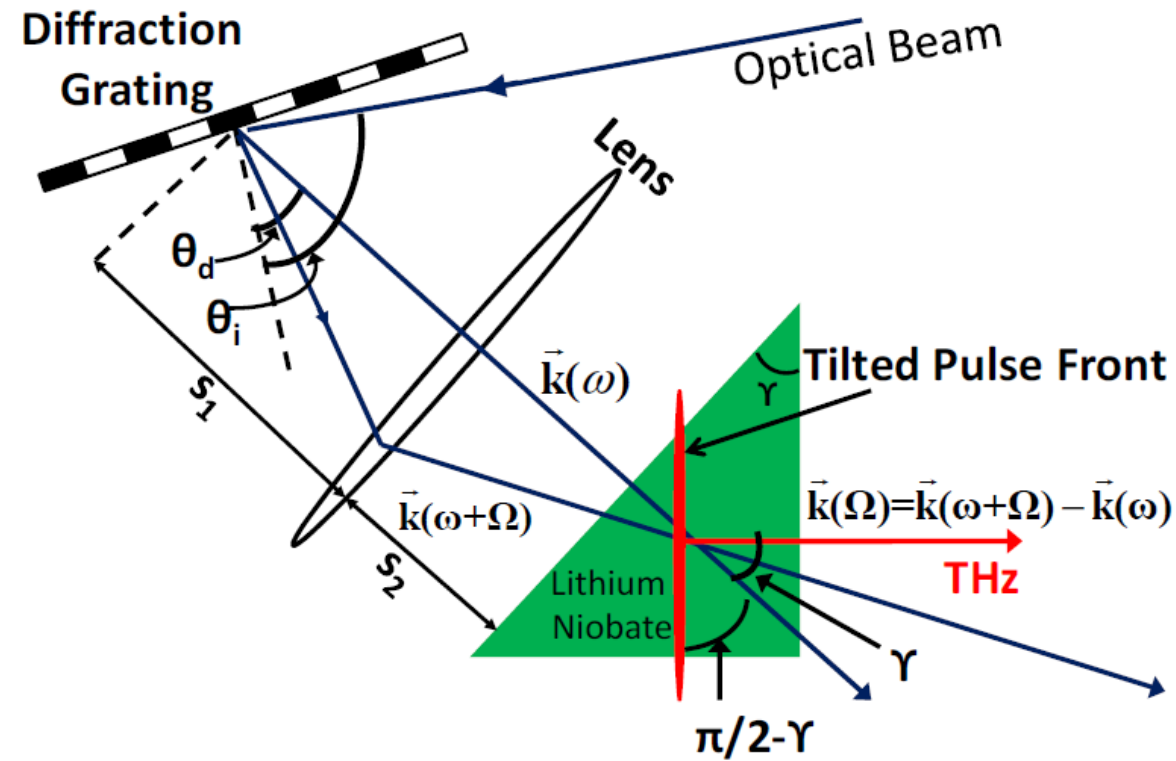


- Basically, if the field interfering with any other part of itself produces always the same spectrum, then it is NOT space-time coupled
- It seems that this is fully general and rigorous

Outline

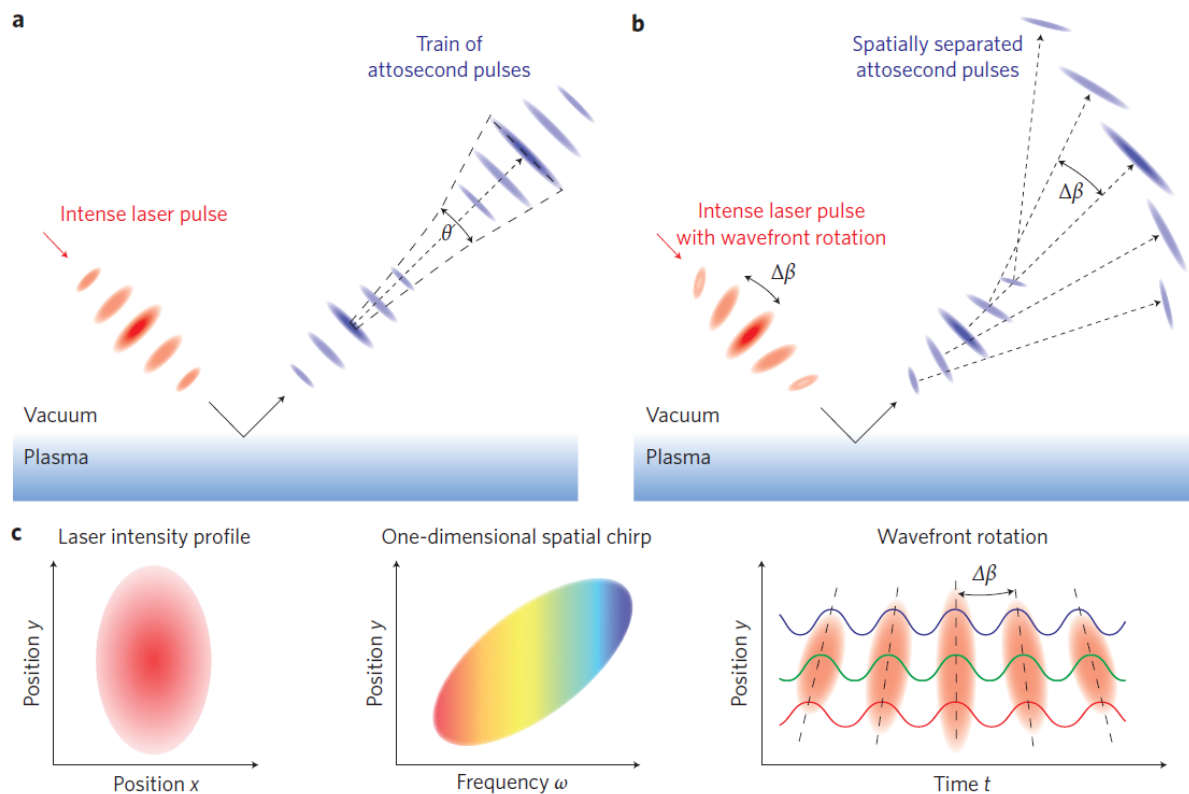
- Laser beams and laser pulses – the basics
- Shaping and measuring laser beams and laser pulses – the basics
- Going to space and time: what are STCs?
- **Why STCs? And why is characterization difficult?**
- Overview of history and of standard techniques
- More recent measurements, techniques, and exotic concepts

Terahertz generation



Koustuban Ravi, W. Ronny Huang, Sergio Carbajo, Xiaojun Wu, and Franz Kärtner, "Limitations to THz generation by optical rectification using tilted pulse fronts," Opt. Express **22**, 20239-20251 (2014).

Applications to attosecond science

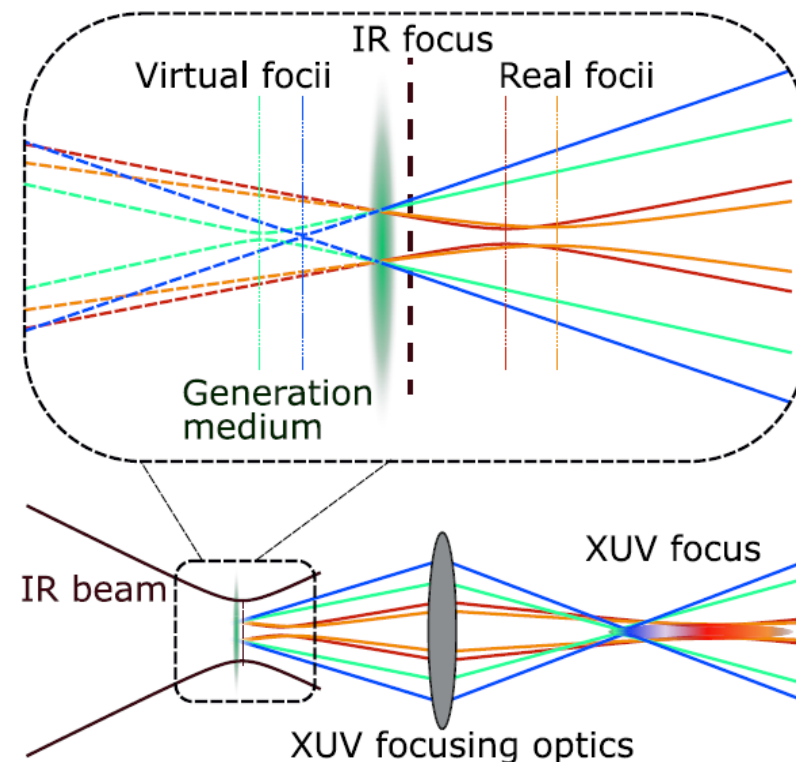


H. Vincenti & F. Quéré, PRL **108**, 113904 (2012).

J. H. Wheeler et al., Nat. Phot. **6**, 829, (2012).

K. T. Kim et al., Nat. Phot. **7**, 651 (2013).

This is not even mentioning higher-level structured light for HHG (now going towards space-time as well): T. Ruchon, C. Hernandez-Garcia, Kapetyn-Murnane, C. Durfee, etc.



E. Frumker et al., Opt. Express **20**, 13870 (2012).

H. Wikmark et al., PNAS **116**, 4779 (2019).

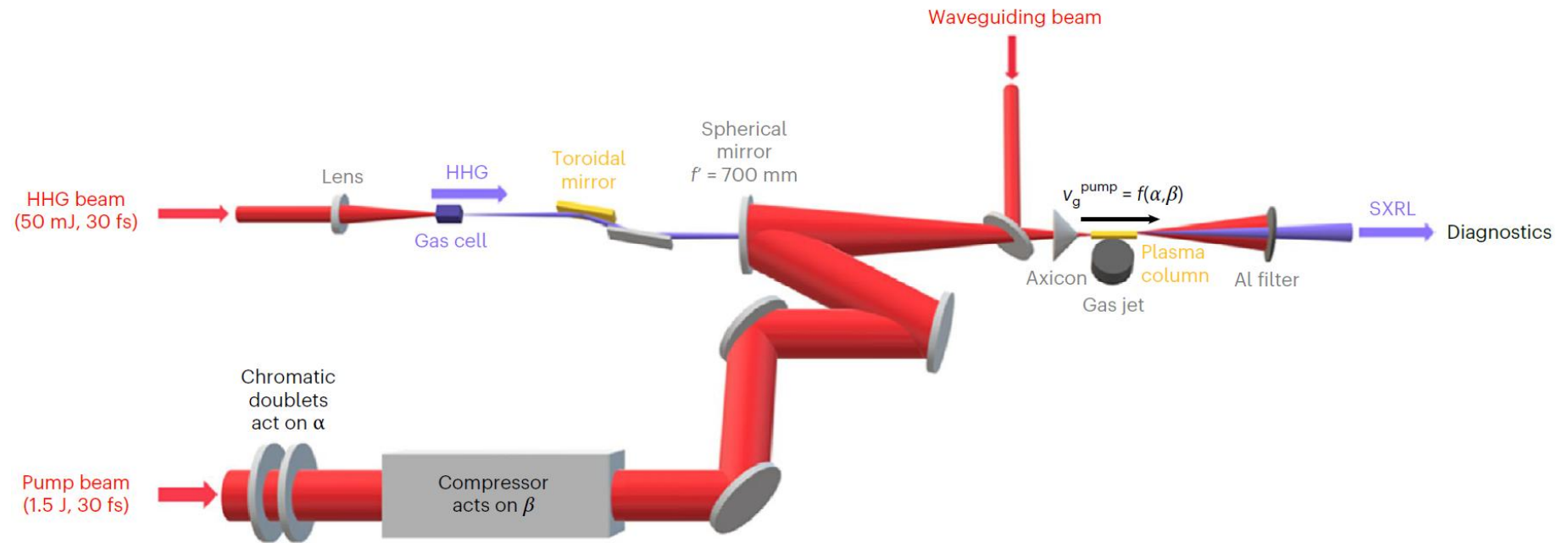
M. Hoflund et al., Ultrafast Sci. 9797453 (2021).

K. Veyrinas et al., New. J. Phys. **25**, 023017 (2023).

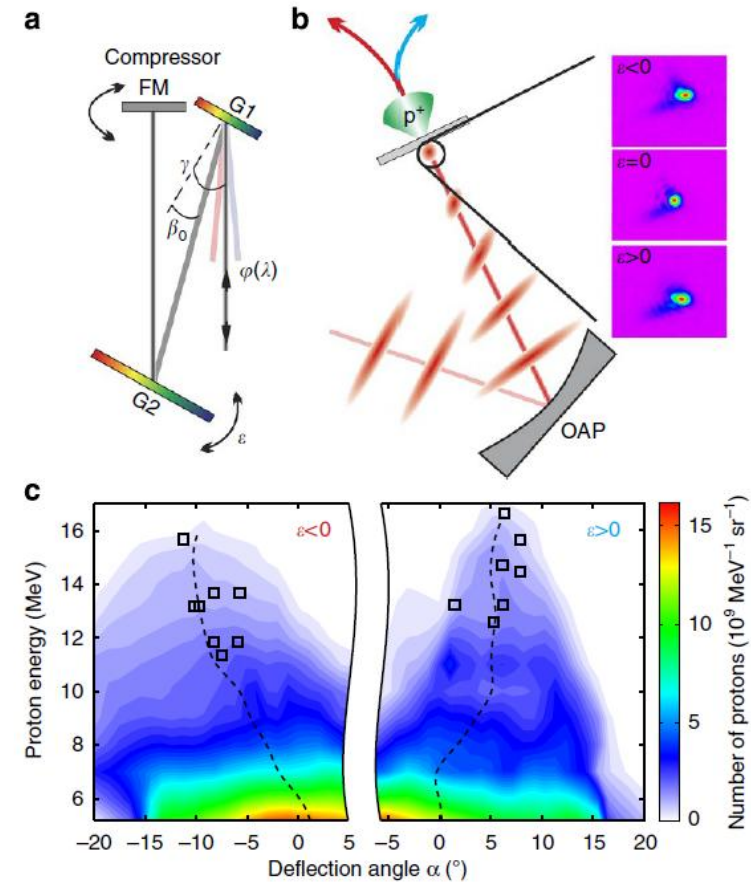
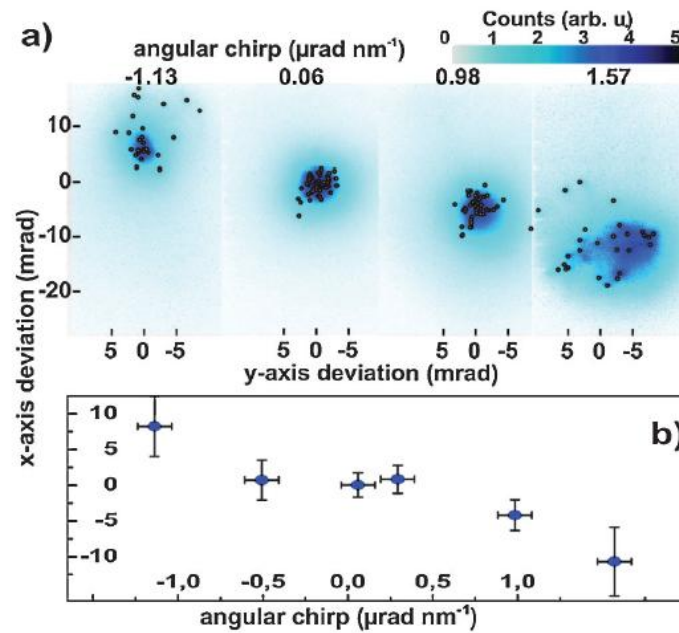
X. Liu et al., Phys. Rev. Research **5**, 043100 (2023).

R. Martín-Hernández, et al., arXiv:2507.04550

HHG-pumped X-ray lasers

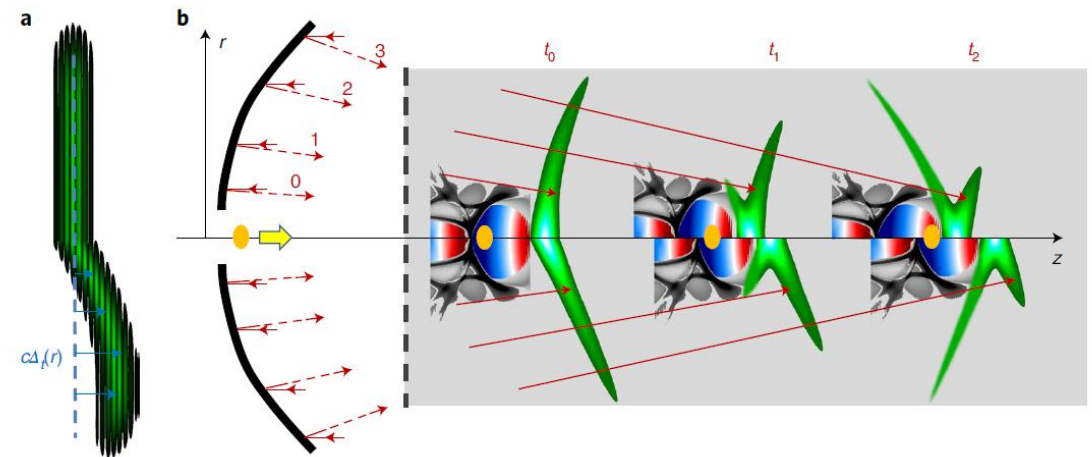
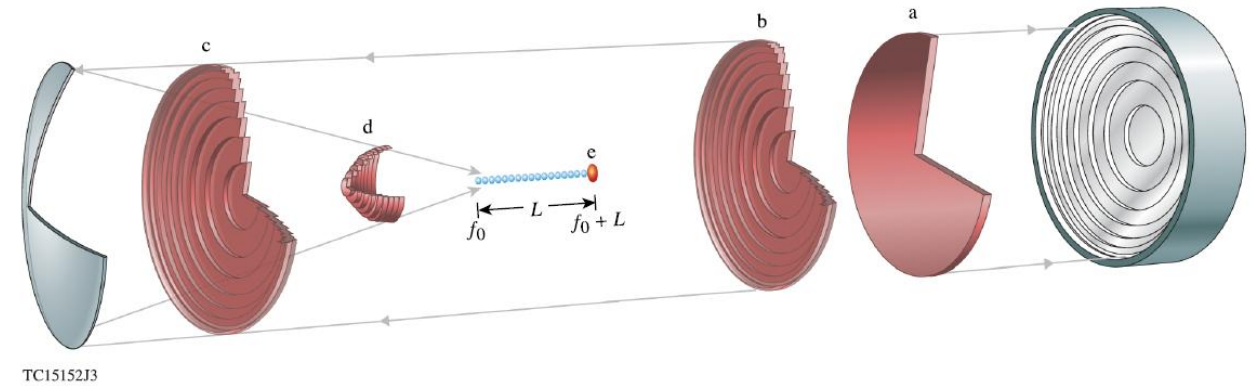
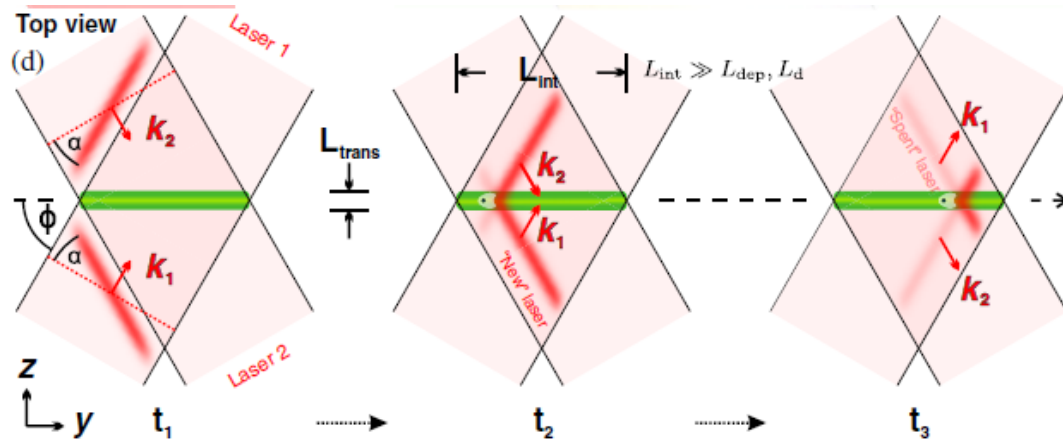


Steering laser-plasma acceleration



Optimizing laser-plasma acceleration

Recently demonstrated also experimentally!

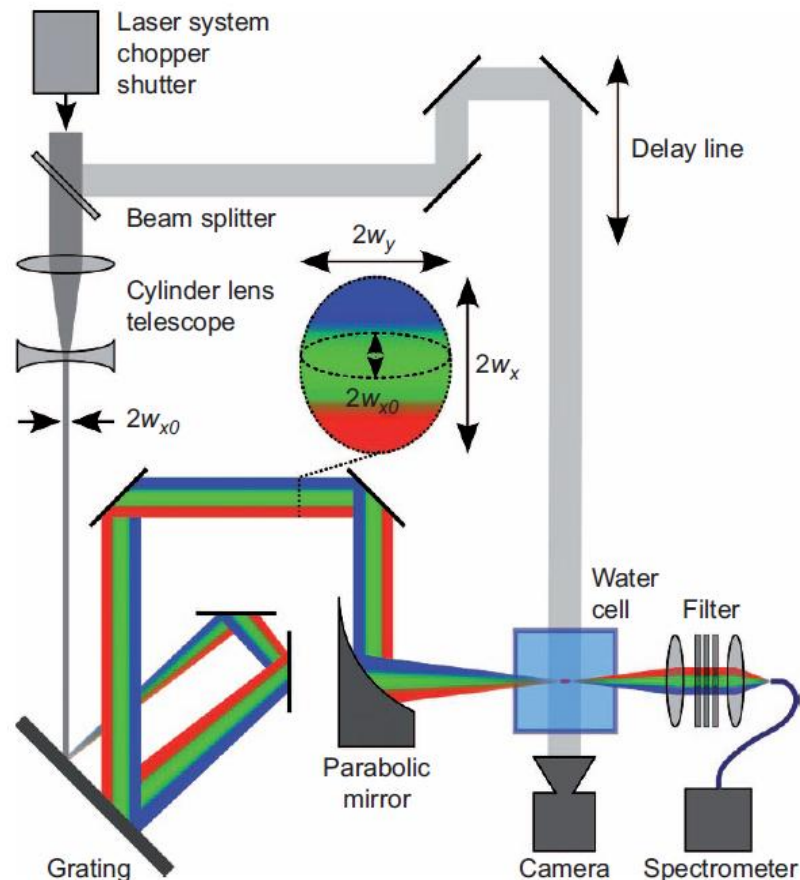


- A. Debus et al., PRX **9**, 031044, (2019).
 J. P. Palastro et al., PRL **124**, 134802, (2020).
 C. Caizergues et al., Nat. Phot. **14**, 475 (2020).

Space-time light and micromachining

Enhancing precision in fs-laser material processing by simultaneous spatial and temporal focusing

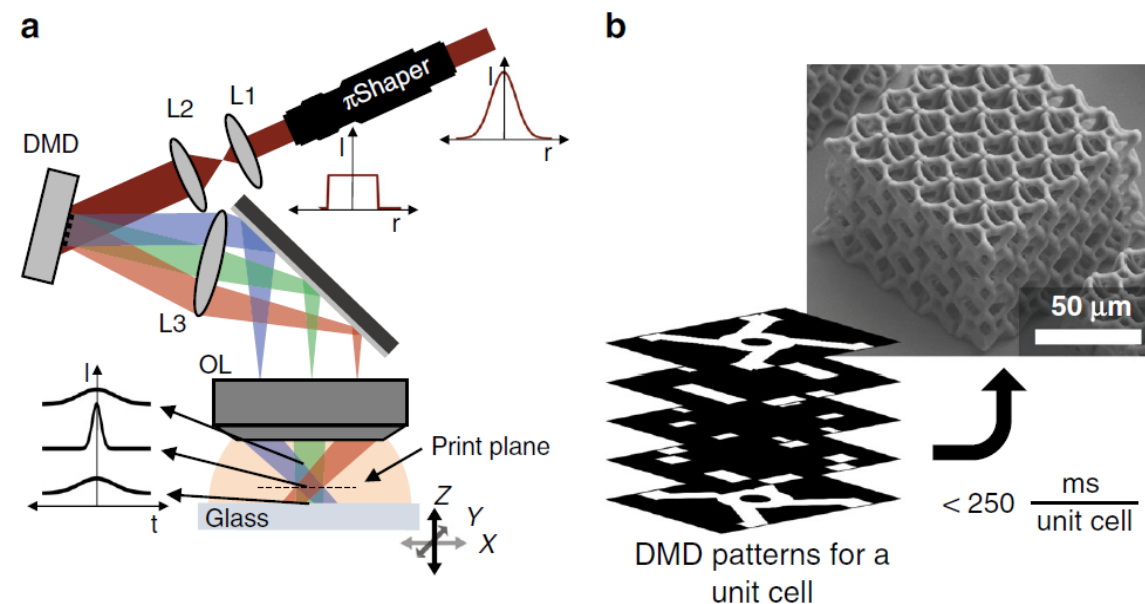
Robert Kammel¹, Roland Ackermann¹, Jens Thomas^{1,2}, Jörg Götze³, Stefan Skupin^{3,4,5}, Andreas Tünnermann^{1,6} and Stefan Nolte^{1,6}



SSTF = Simultaneous Spatial and Temporal Focusing

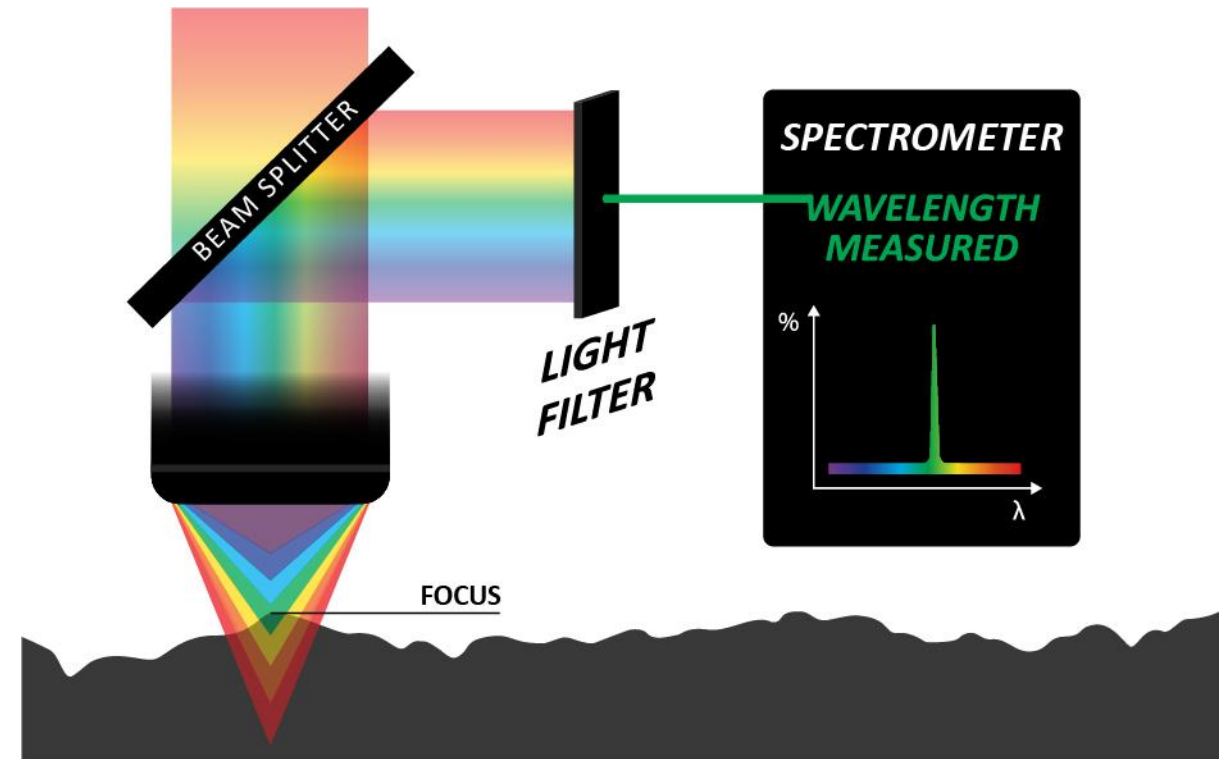
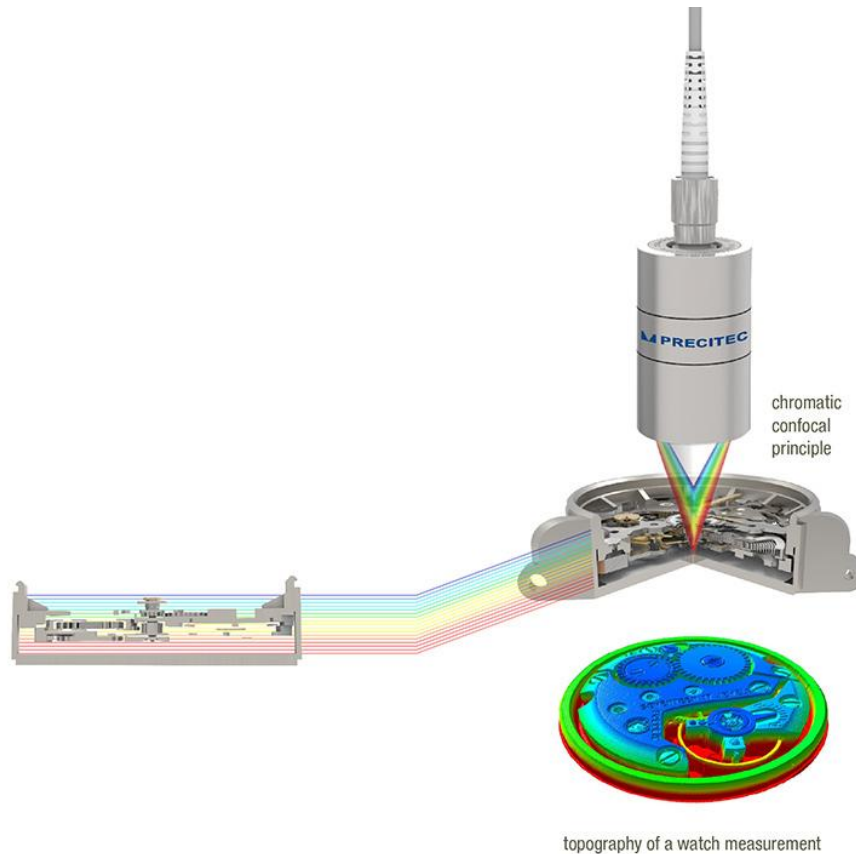
Rapid, continuous projection multi-photon 3D printing enabled by spatiotemporal focusing of femtosecond pulses

Paul Somers¹, Zihao Liang², Jason E. Johnson¹, Bryan W. Boudouris^{2,3}, Liang Pan¹ and Xianfan Xu¹



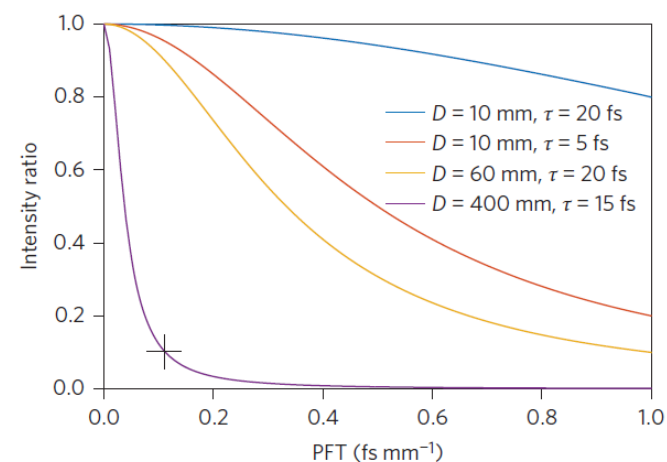
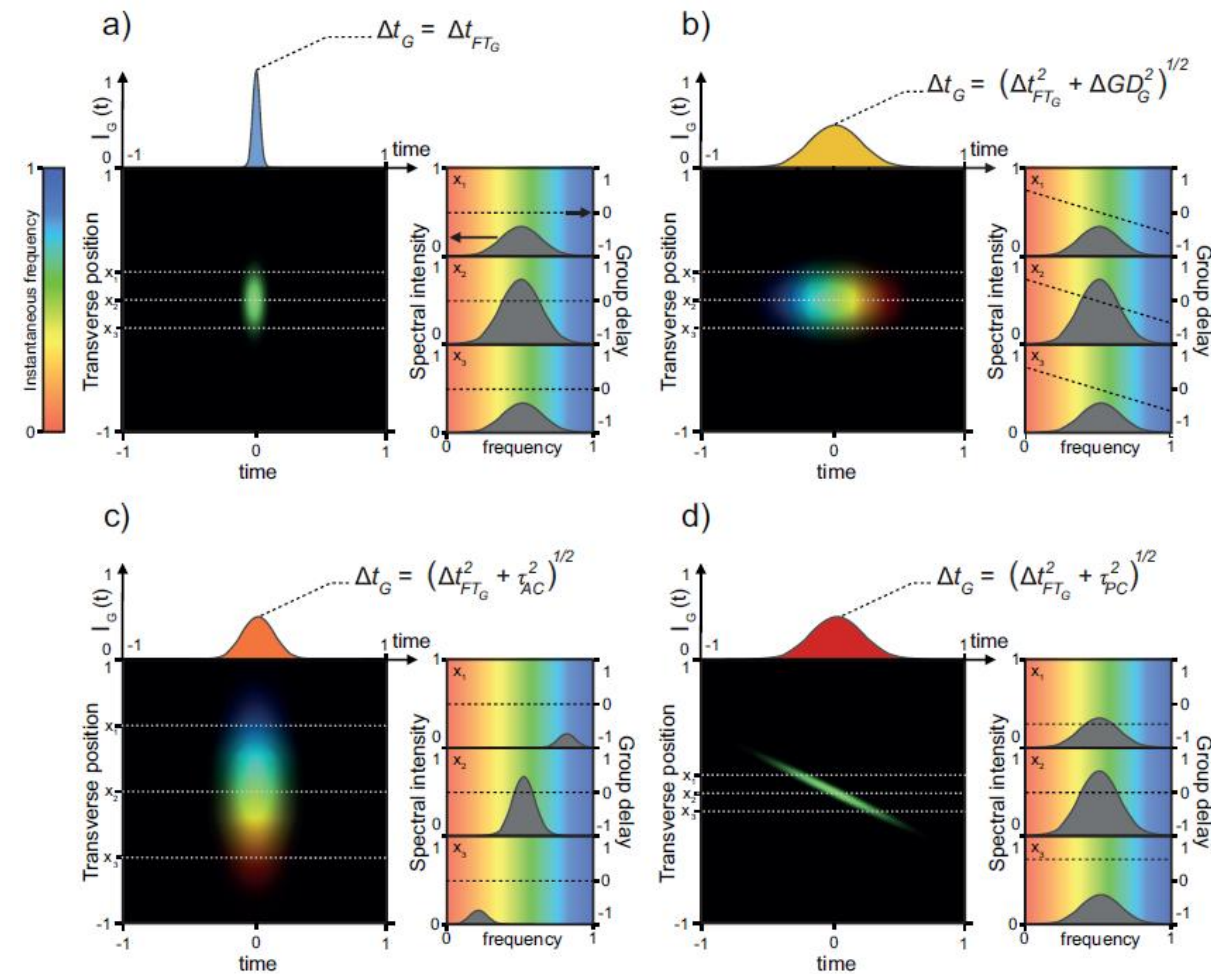
G. Zhu, et al., Optics Express **13**, 2153 (2005).
R. Kammel, et al., Light: S. & A **3**, e169 (2014).
P. Somers, et al., Light: S. & A **10**, 199 (2021).

Chromatic confocal microscopy?

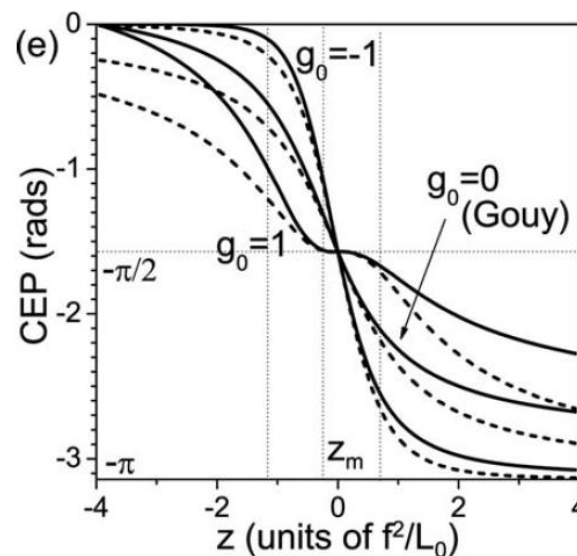


*But the light doesn't need to be temporally coherent here, only broadband
→ is there a coherent/nonlinear version of chromatic microscopy?*

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.

M. Porras, Z. Horváth, B. Major, Phys. Rev. A **98**, 063819 (2018).

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).

STCs also come from high rep-rate

Optics EXPRESS

Wavefront degradation of a 200 TW laser from heat-induced deformation of in-vacuum compressor gratings

VINCENT LEROUX,^{1,2,*} SPENCER W. JOLLY,^{1,2} MATTHIAS SCHNEPP,¹ TIMO EICHNER,¹ SÖREN JALAS,¹ MANUEL KIRCHEN,¹ PHILIPP MESSNER,¹ CHRISTIAN WERLE,¹ PAUL WINKLER,^{1,3} AND ANDREAS R. MAIER¹

¹Center for Free-Electron Laser Science & Department of Physics, Universität Hamburg, Hamburg, Germany

²Institute of Physics of the ASCR, ELI-Beamlines project, Prague, Czech Republic

³Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

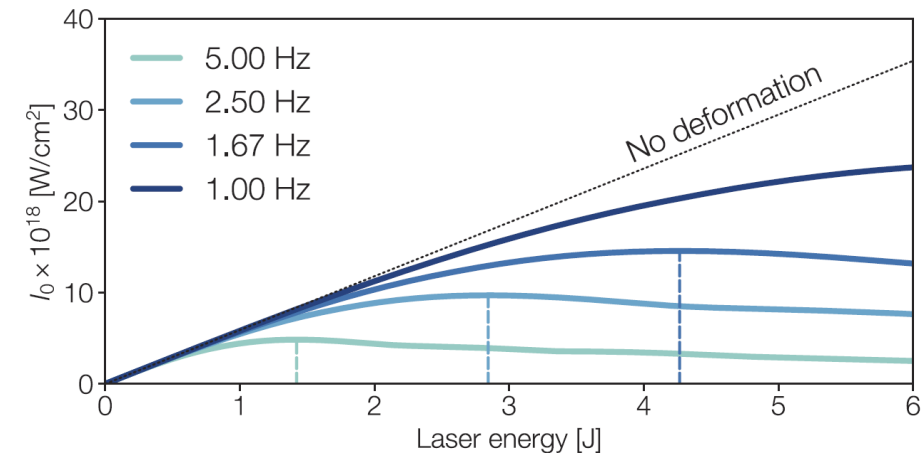
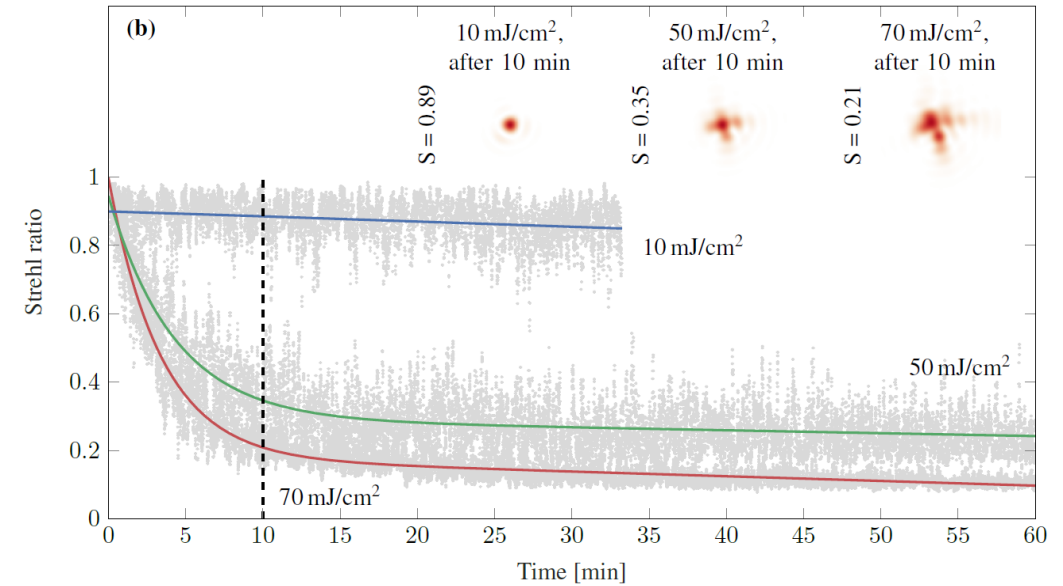
Optics EXPRESS

Description of spatio-temporal couplings from heat-induced compressor grating deformation

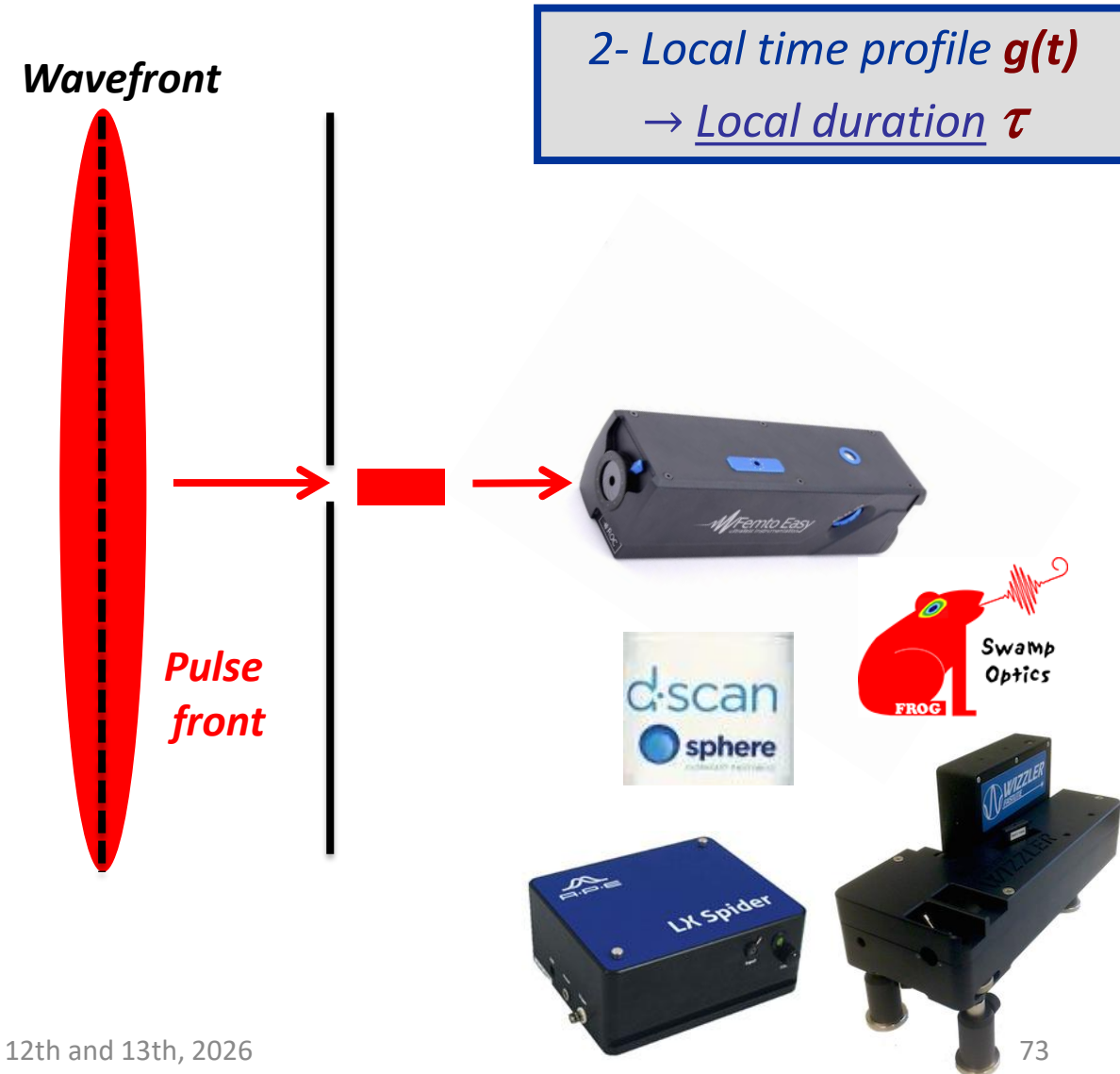
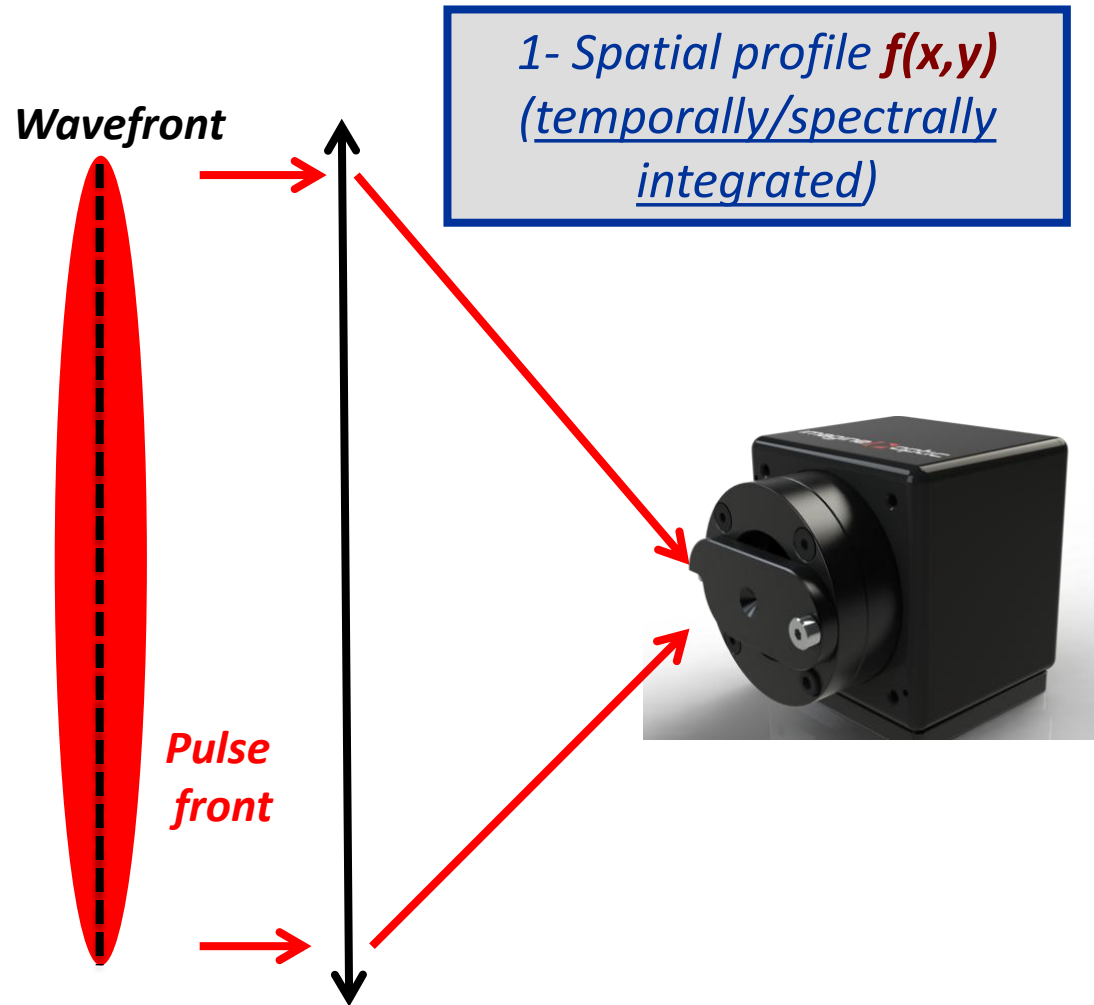
VINCENT LEROUX,^{1,2}  TIMO EICHNER,^{2,*} AND ANDREAS R. MAIER^{2,1} 

¹Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

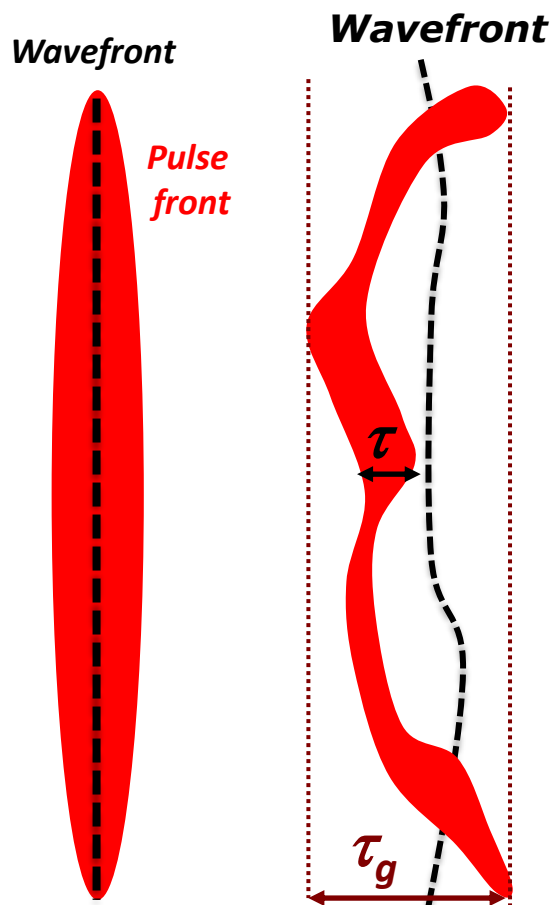
²Center for Free-Electron Laser Science & Department of Physics Universität Hamburg, Hamburg, Germany



Standard characterization routine for pulse-beams



Where does it go wrong?



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

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

$$E(x,y,t) = f(x,y) \cdot g(t)$$

➔ $P = E/\tau$
Estimated
peak power

This neglects Spatio-temporal couplings (STC)

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

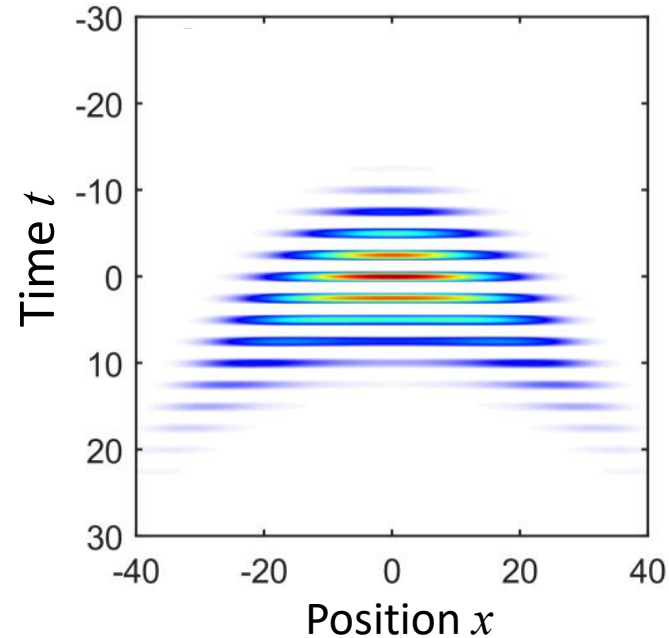
➔ $P = E/\tau_g$
Real
peak power

Spatial dependence
of the temporal (or spectral)
properties

OR

Temporal (or spectral)
dependence of the spatial
properties

Spatio-temporal amplitude and phase



We need to determine

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



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

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

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

Spatio-spectral
intensity:

'Easily' measured

Spatio-spectral
Phase:

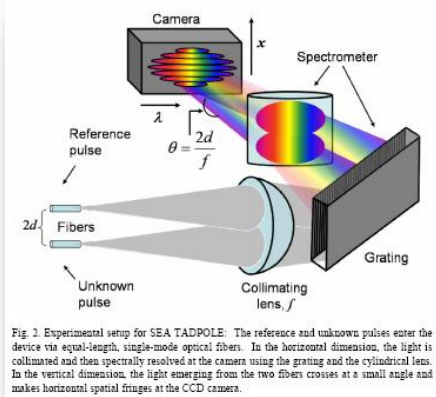
Challenging!

Outline

- Laser beams and laser pulses – the basics
- Shaping and measuring laser beams and laser pulses – the basics
- Going to space and time: what are STCs?
- Why STCs? And why is characterization difficult?
- **Overview of history and of standard techniques**
- More recent measurements, techniques, and exotic concepts

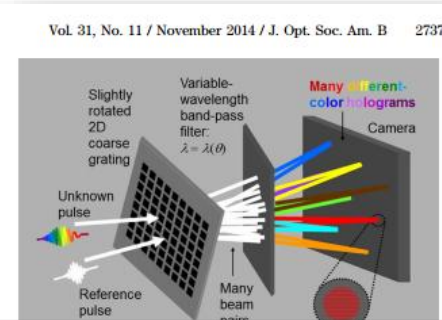
Spatio-temporal metrology: many techniques

SEA TADPOLE

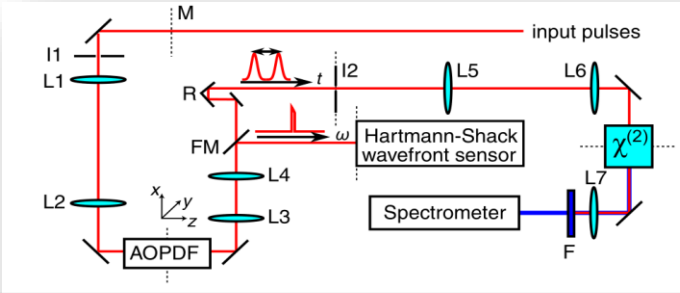


Bowlan et al., 2006

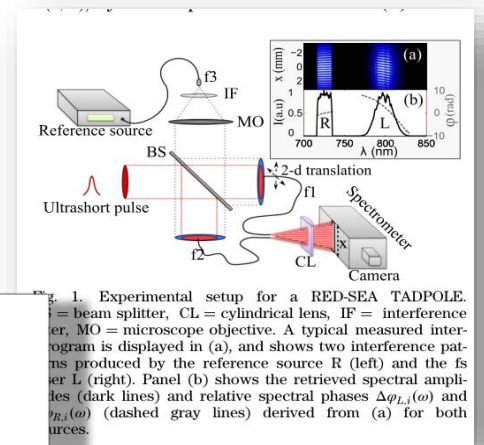
STRIPED FISH



HAMSTER



RED-SEA TADPOLE



Gallet et al., 2014

See recent overviews:

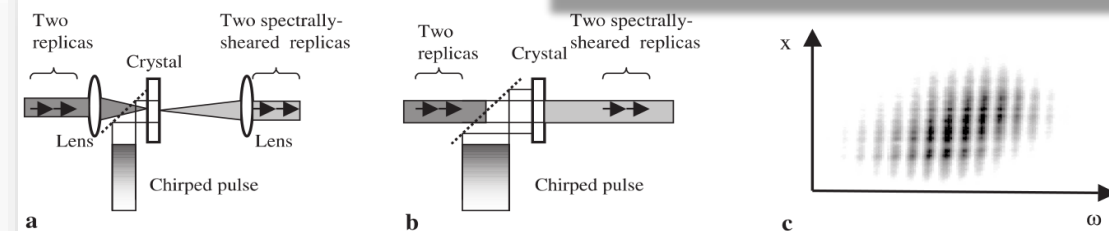
C. Dorrer, IEEE Journal of Sel. Topics in Quan. Elec. **25**, 1 (2019).

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

B. Alonso, A. Döpp, & S. W. Jolly, APL Photonics **9**, 070901 (2024).

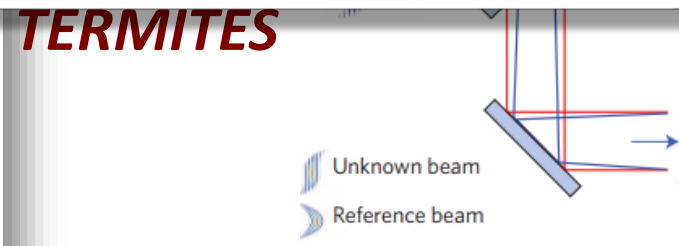
SPIDER 2D

S212 Applied Physics B – Lasers and Optics

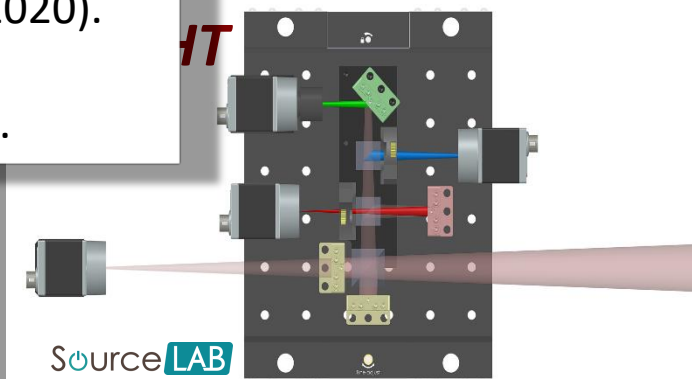


Dorrer et al., 2001

TERMITES



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



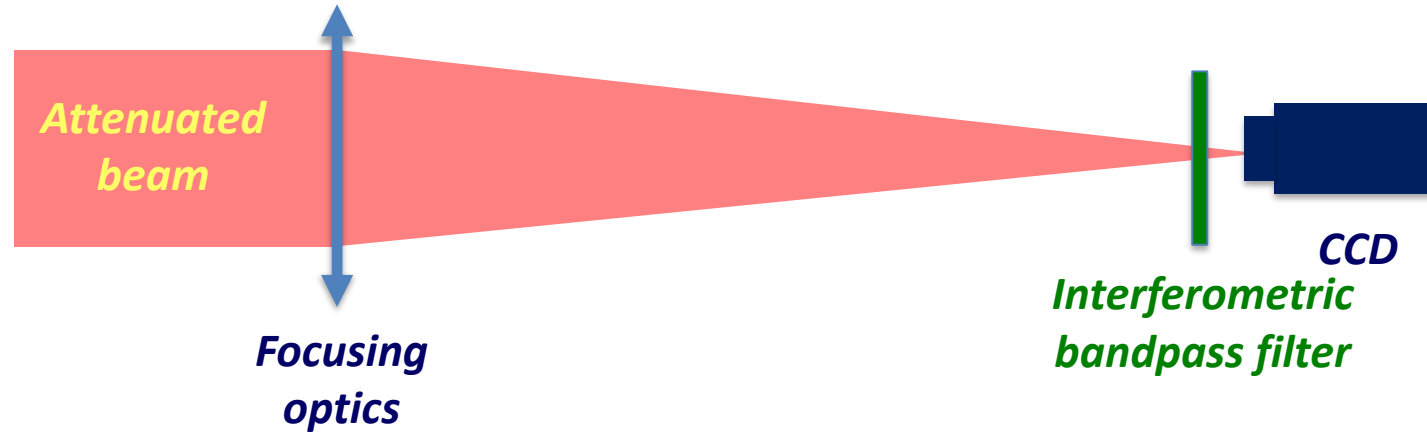
A. Borot, et al., Opt. Exp. **26**, 26444 (2018).
<https://www.sourcelab-plasma.com/laser-shaping/beam-shaping-catalog/insight/>

Take a step back

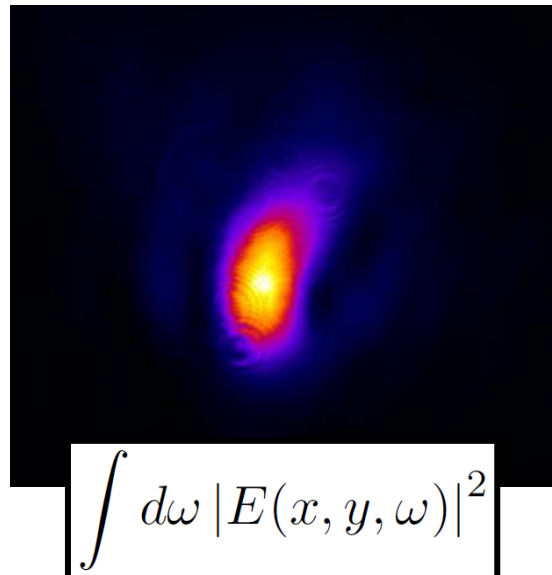
- Is it 2-D or 3-D?
- Is it single-shot or scanning?
- Is there some type of hard limit on resolution?
- Is there a required (perfect) reference beam?
- Is it truly a space-time device or “just” space-spectrum?

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

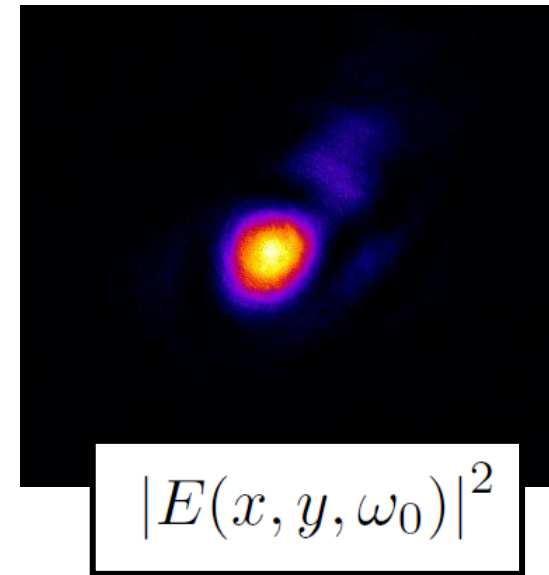
Simple but partial measurement example (1/2)



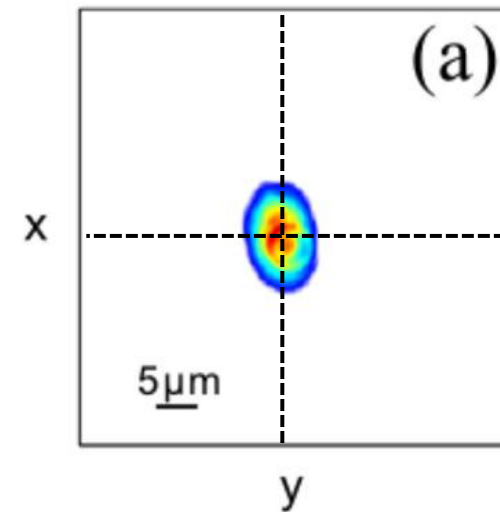
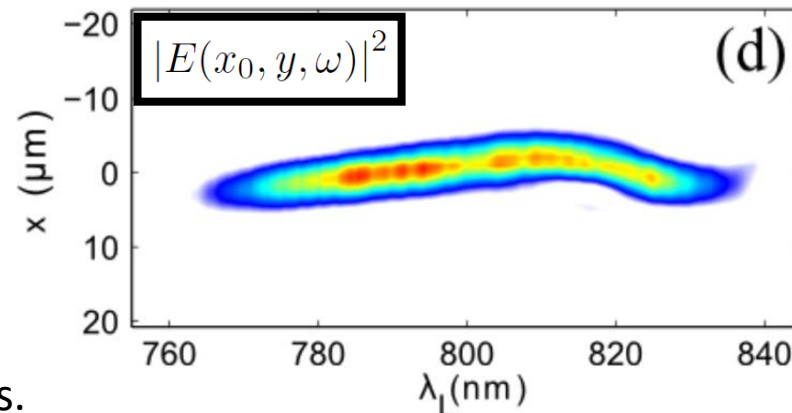
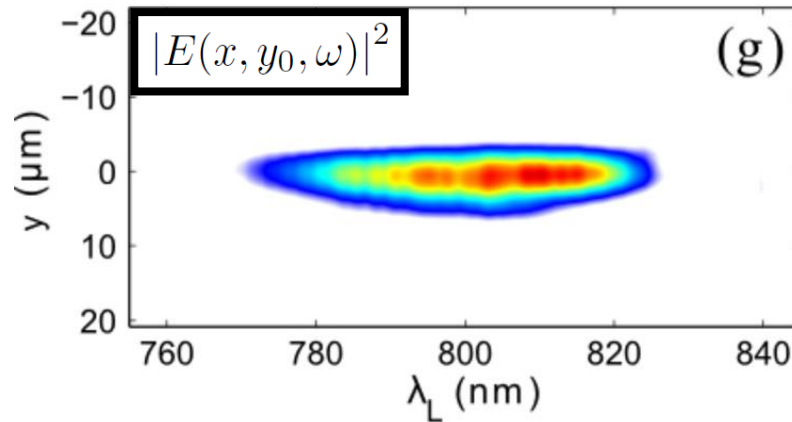
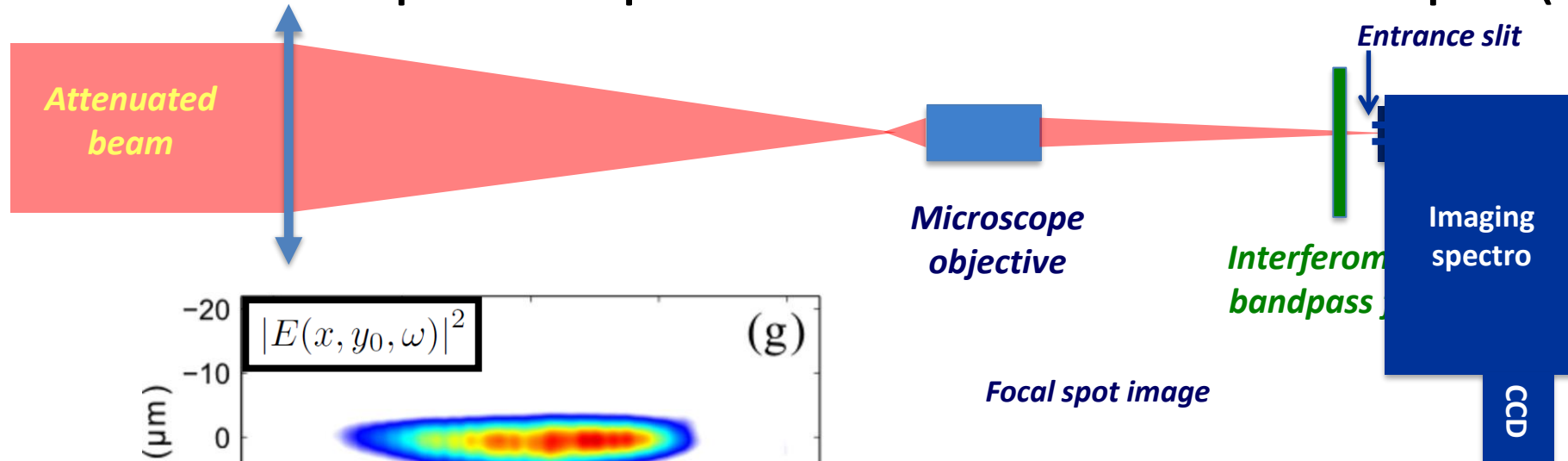
Focal spot image **with full spectrum**
 (≈ 70 nm FWHM @ 800 nm)



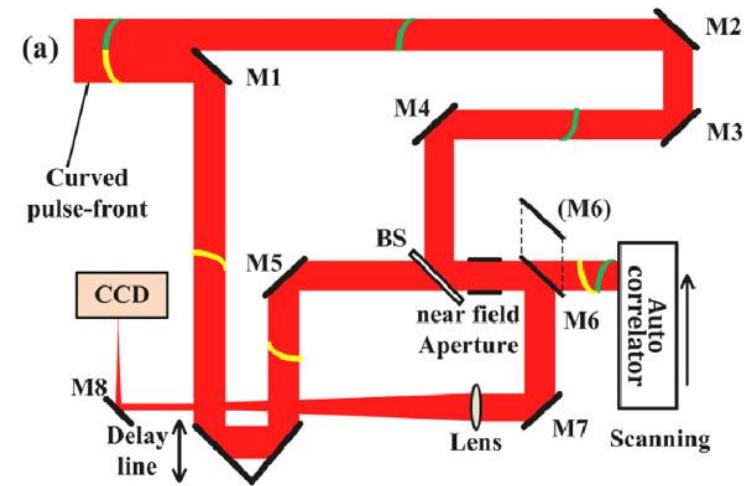
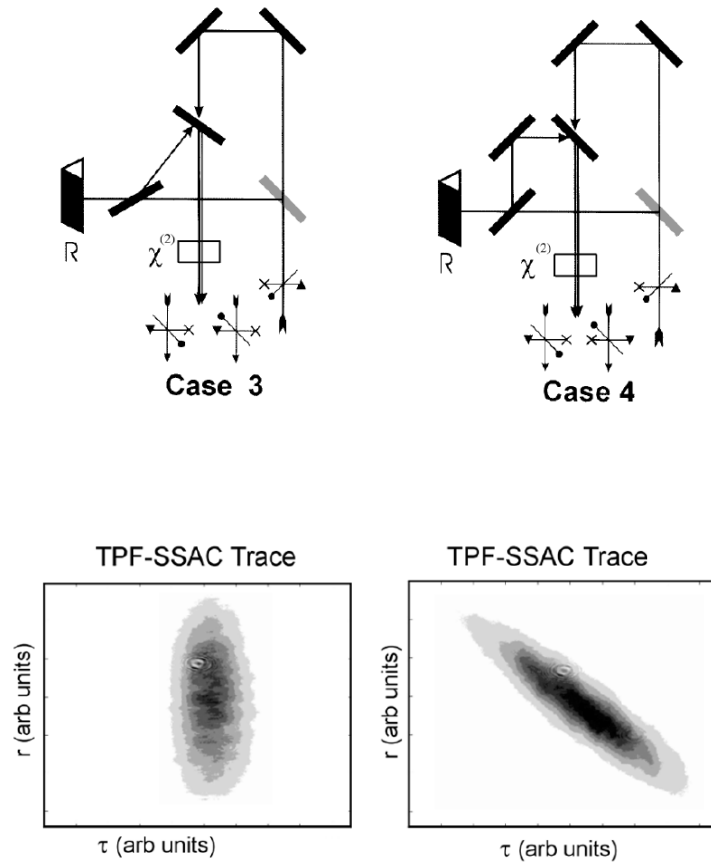
Focal spot image **with bandpass filter**
 (≈ 10 nm FWHM @ 800 nm)



Simple but partial measurement example (2/2)



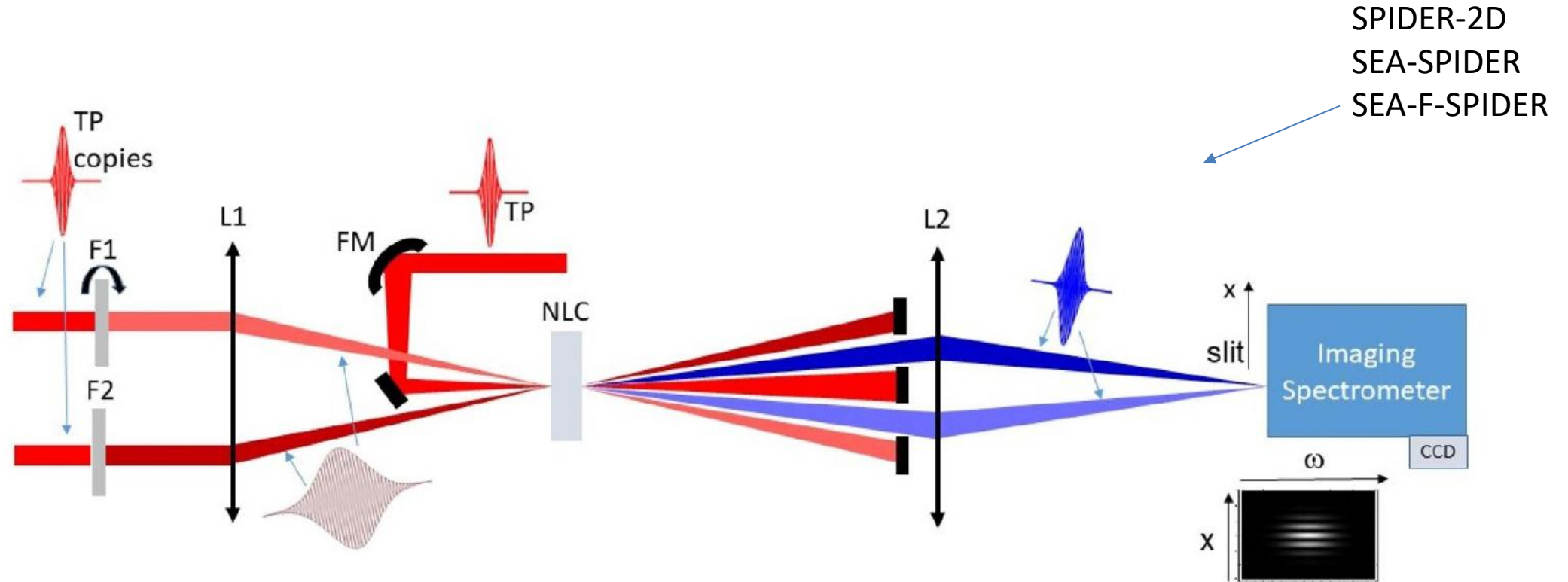
Modified single-shot autocorrelators



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

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

2D versions of SPIDER



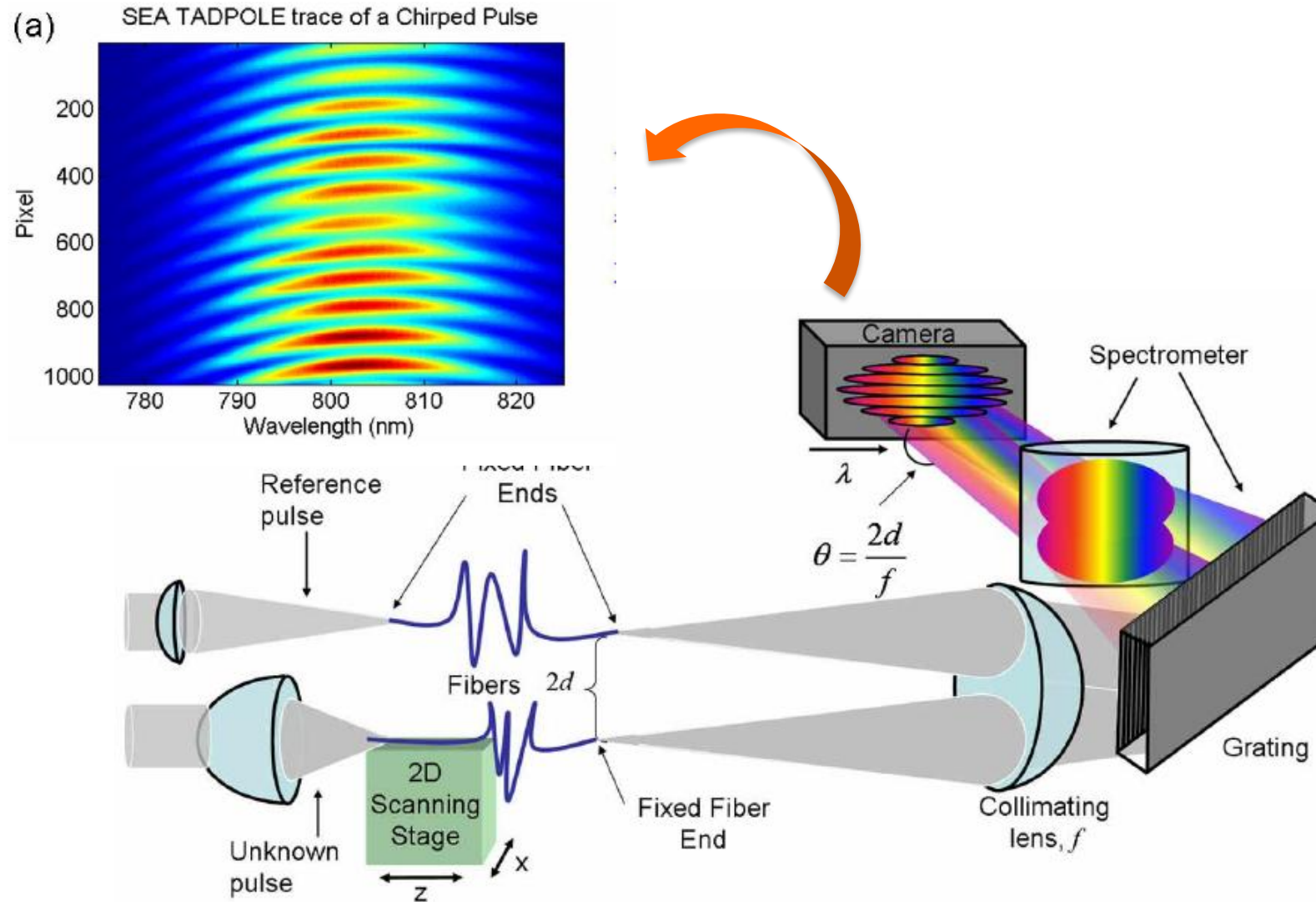
Towards “complete” measurements

#1 – Spatially-resolving a
spectral measurement

#2 – Spectrally-resolving a
spatial measurement

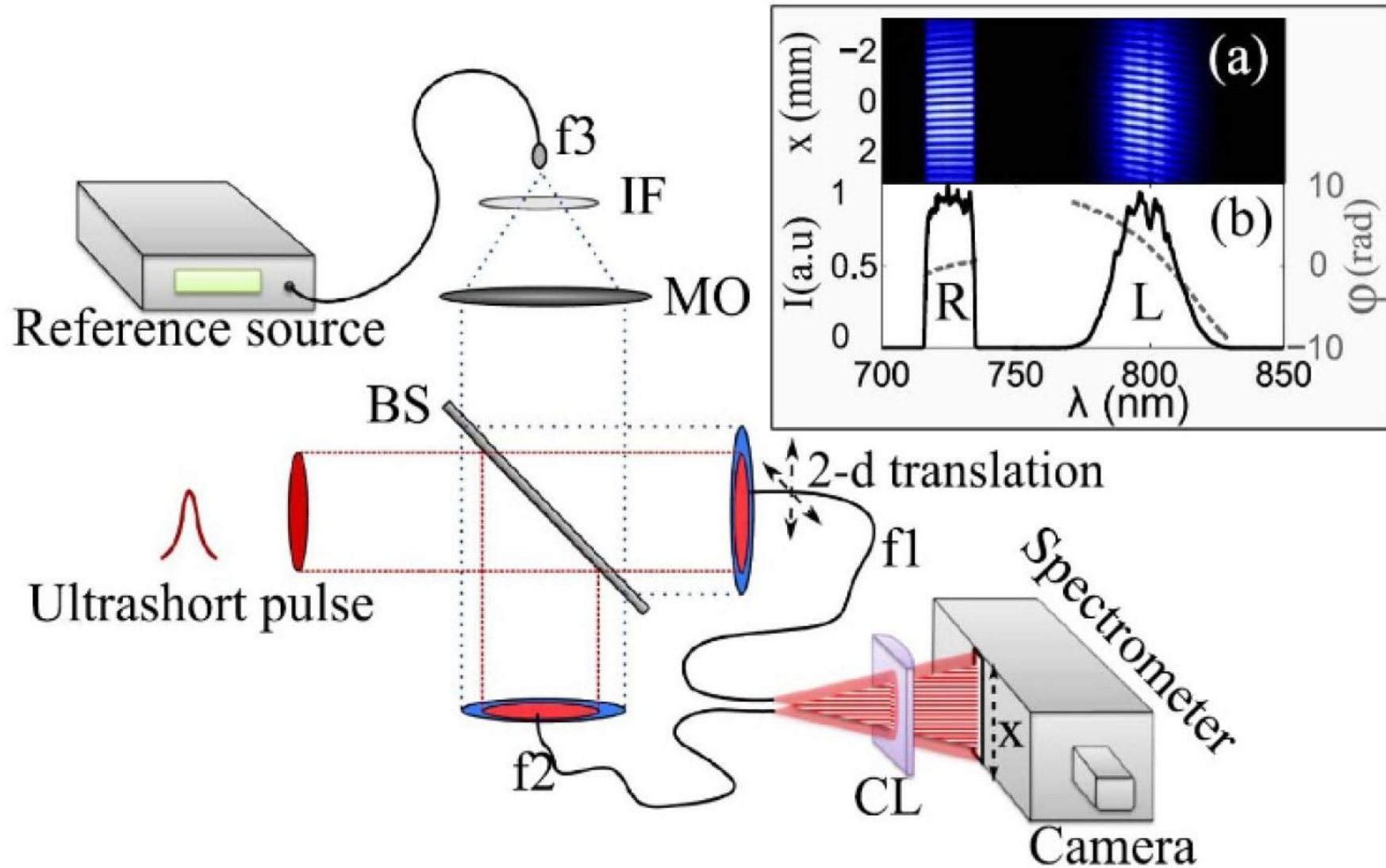
Yes, these are really different

SEA-TADPOLE and STARFISH

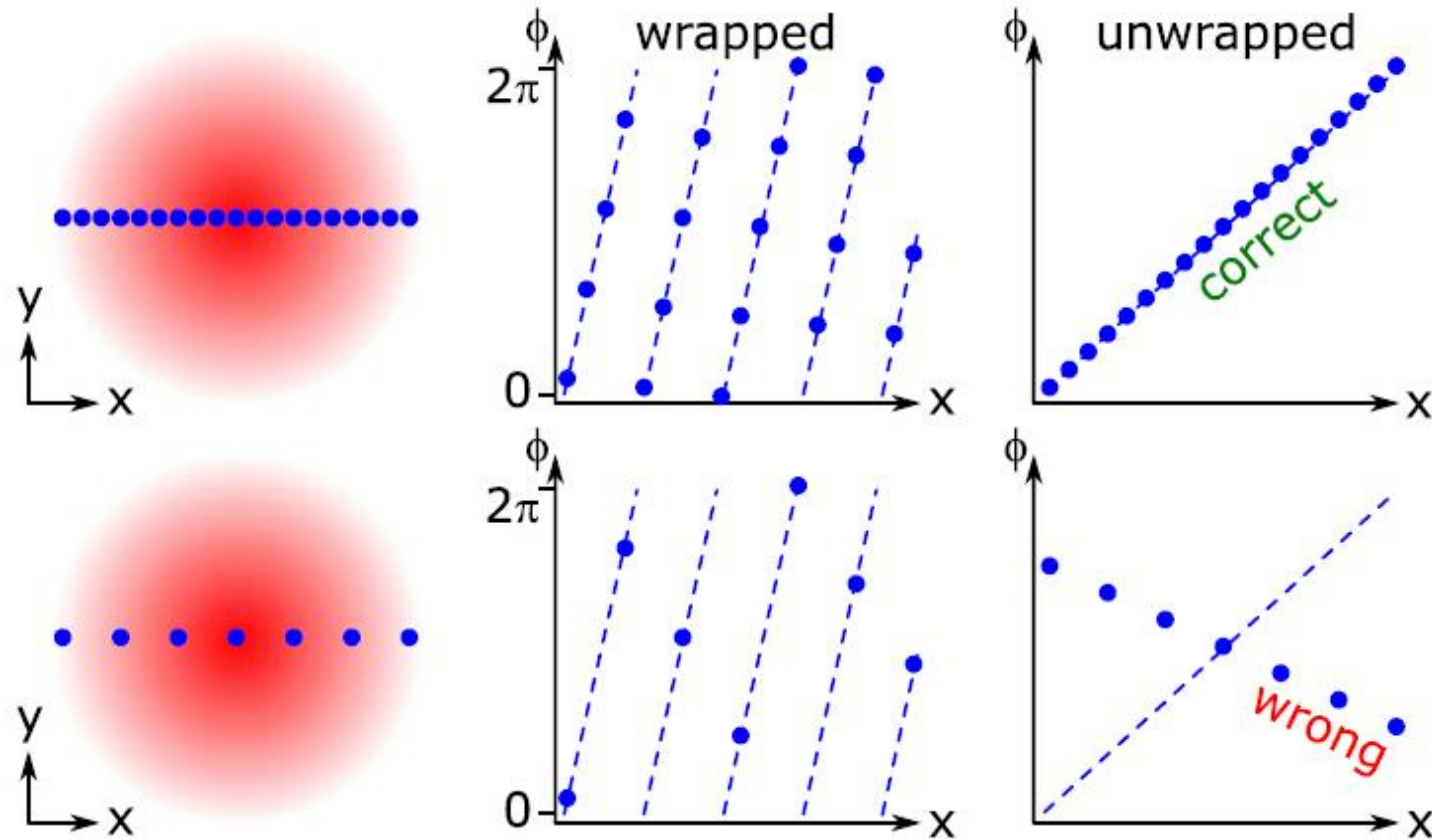


- P. Bowlan et al., Opt. Express **14**, (2006)
P. Bowlan et al., Opt. Express **15**, (2007)
B. Alonso et al., JOSA B **27**, 933 (2010).

RED-SEA-TADPOLE

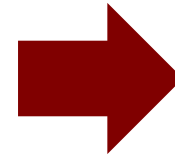
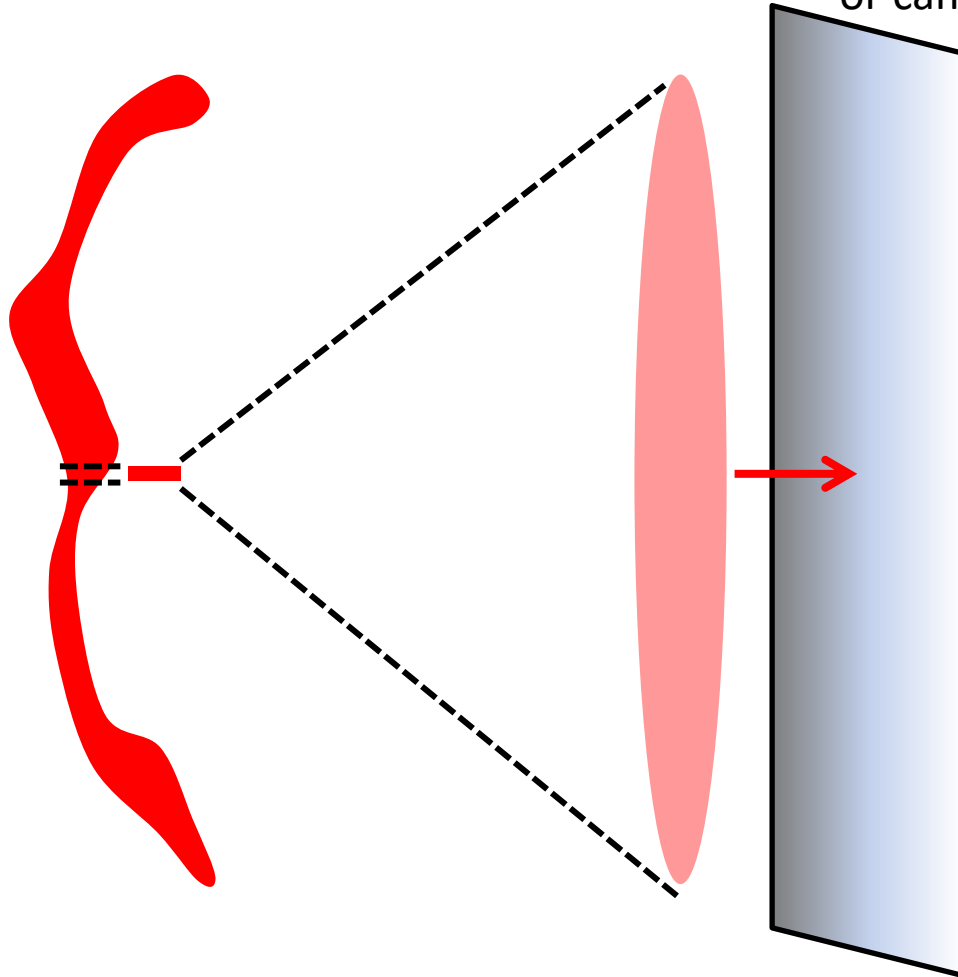


Weakness in spatial sampling



From SEA-TADPOLE to TERMITES

$$E_R(t) = E(t, \mathbf{r}_0) \quad \text{Screen or camera}$$



**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**



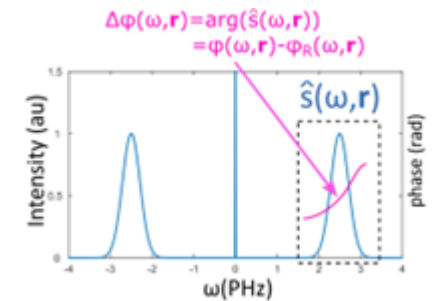
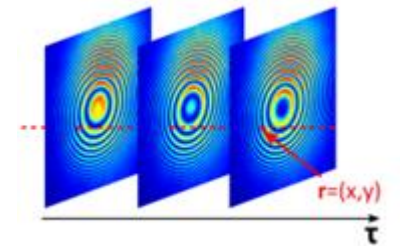
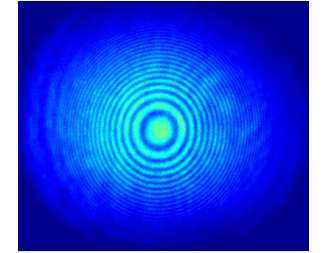
$$s(\tau, \mathbf{r}) = \int dt E(t, \mathbf{r}) E_R^*(t - \tau)$$

**FFT with
respect to τ**

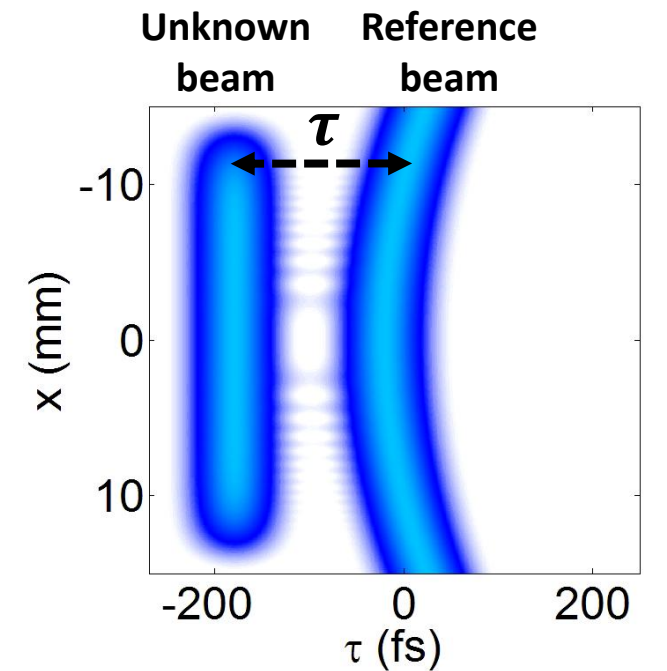
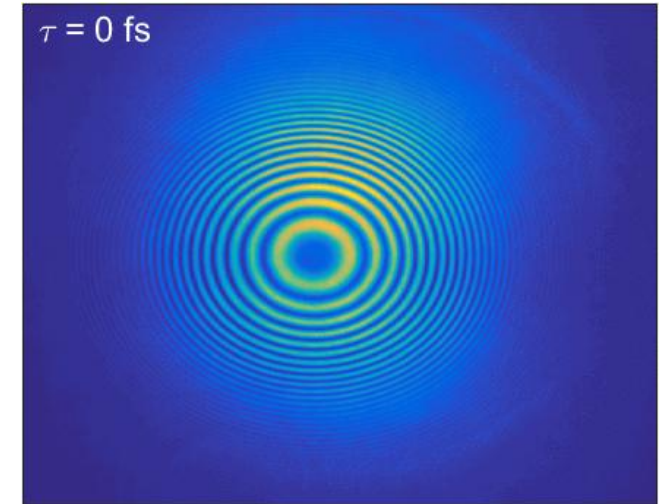
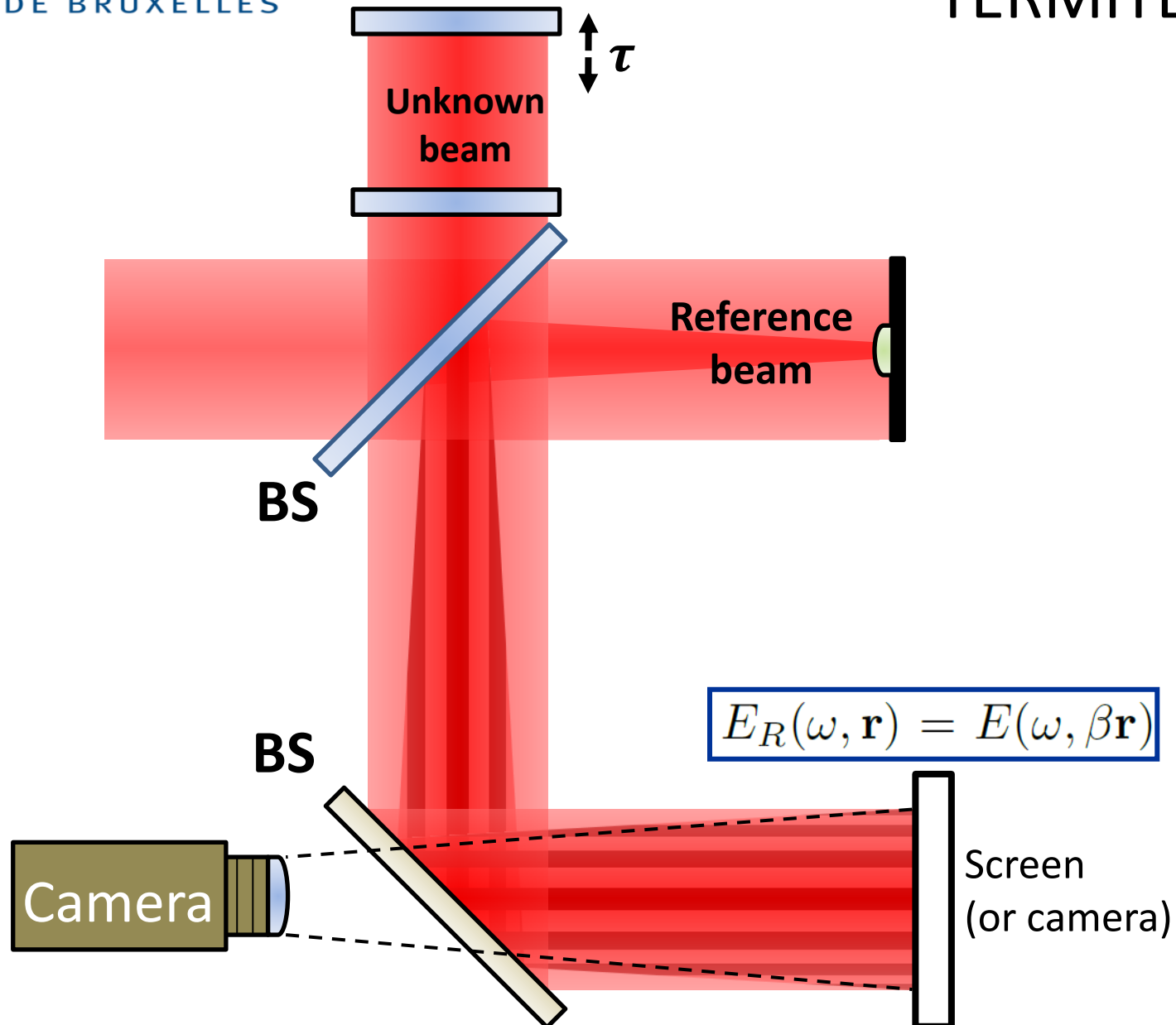


According to Wiener–Khinchine's theorem:

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



TERMITES

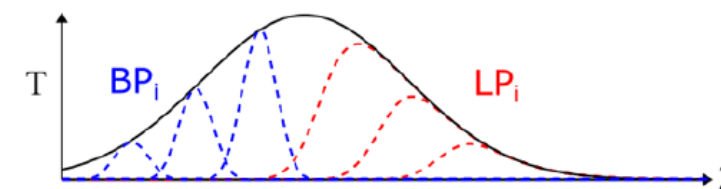
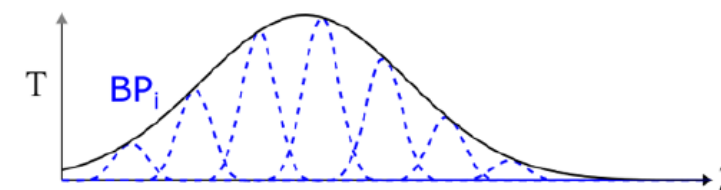
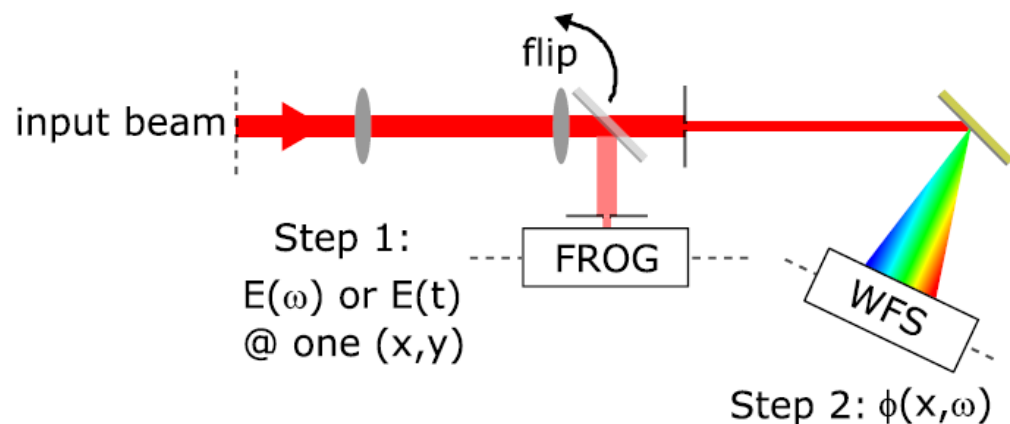


Frequency-resolved wavefront measurements

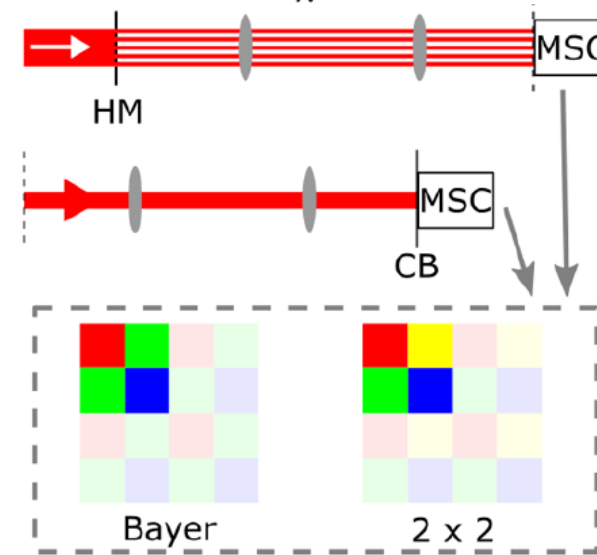
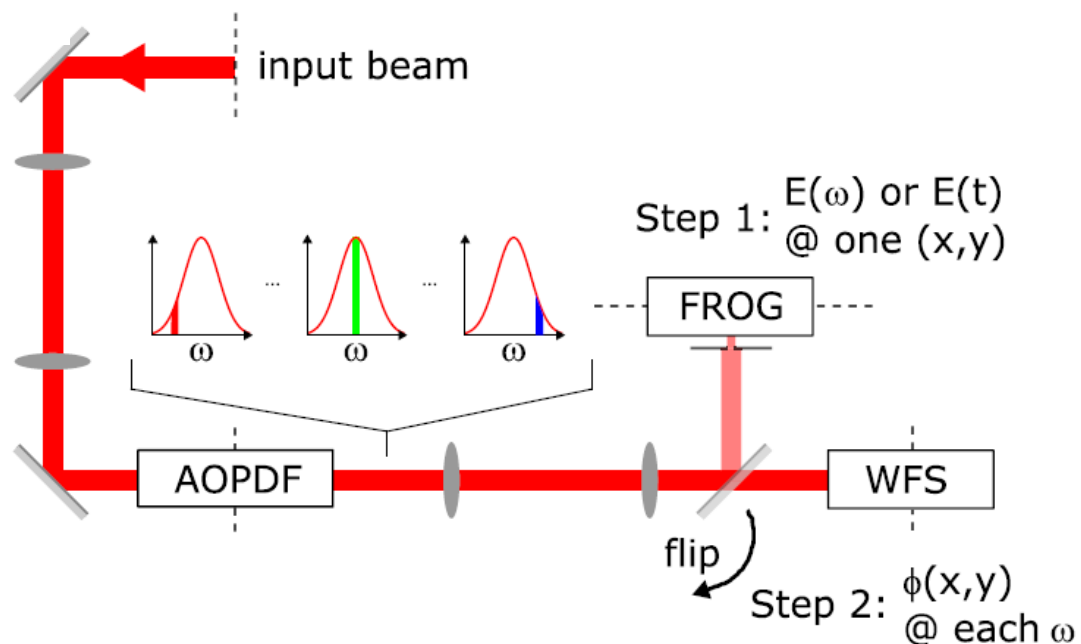
E. Kueny et al., Opt. Exp. **26**, 31299 (2018).

L. Ranc et al., OSA Laser Congress (2019).

C. Dorrer et al., Opt. Exp. **26**, 33387 (2018).



Imagine Optic
HASO Multispectral

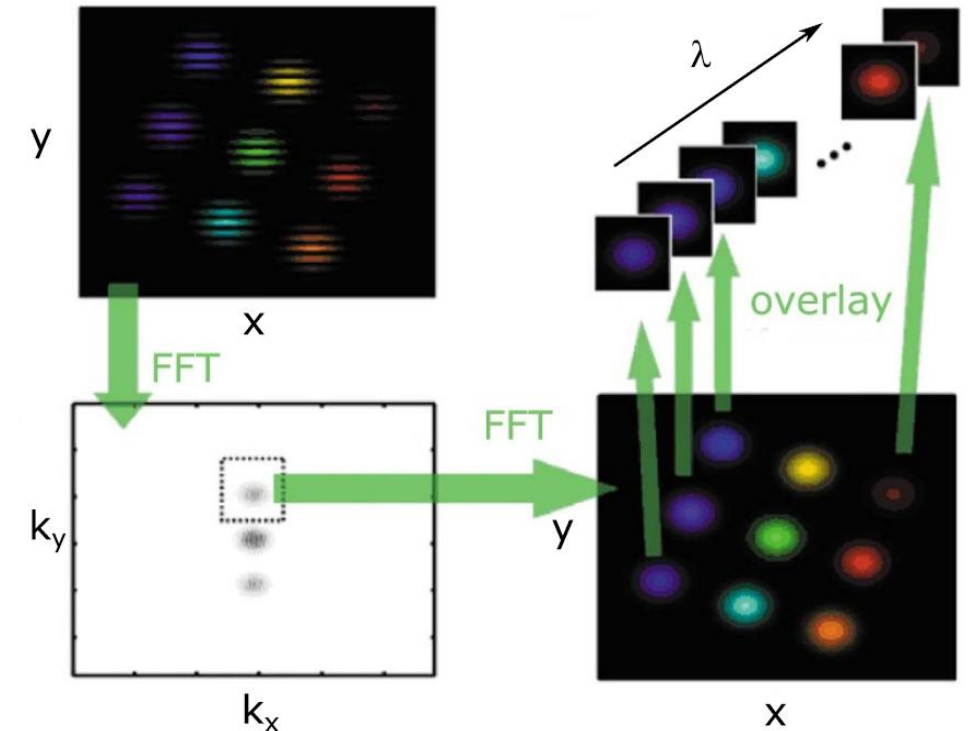
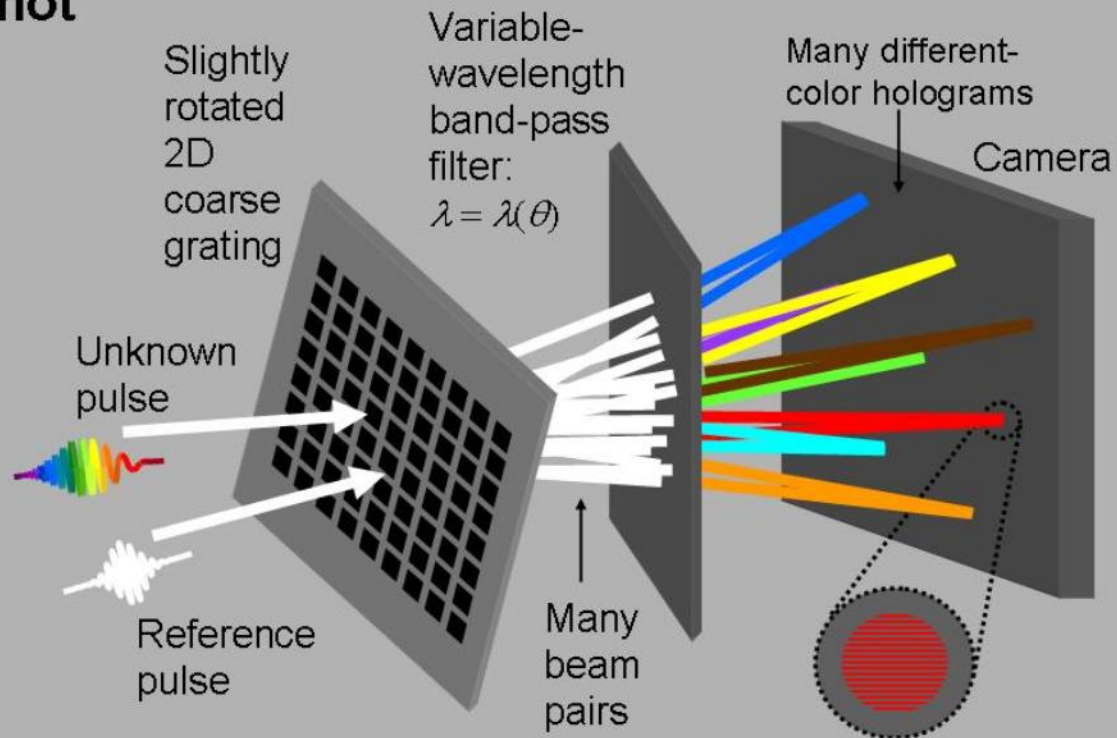


E. Rubino et al., Opt. Lett. **34**, 3854 (2009)

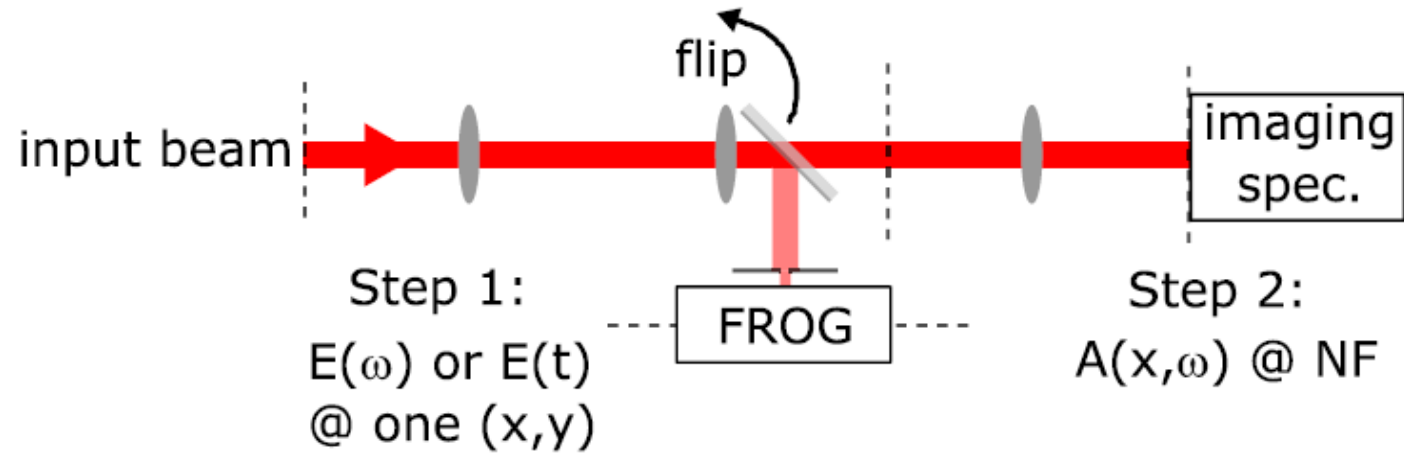
S. Cousin et al., Opt. Lett. **37**, 3291 (2012).

STRIPED-FISH

Spatially and Temporally Resolved Intensity and Phase Evaluation Device: Full Information from a Single Hologram (STRIPED FISH): $E(x,y,t)$ on one shot



CROAK technique



Insight: a reference-free, phase retrieval approach

$$F(x, y, z)$$

imagine  **optics™**

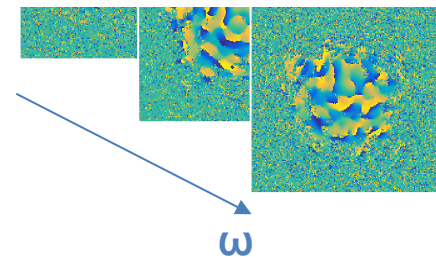
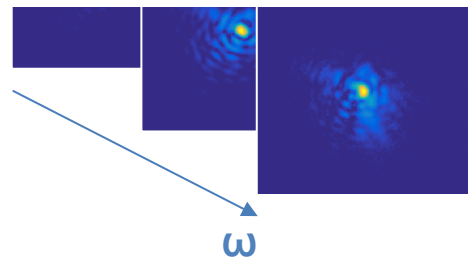
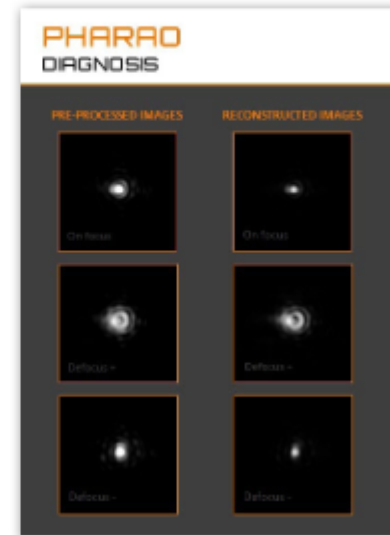
PHARAO EXTENSION

Frequency
amplitude

Focal spot optimization

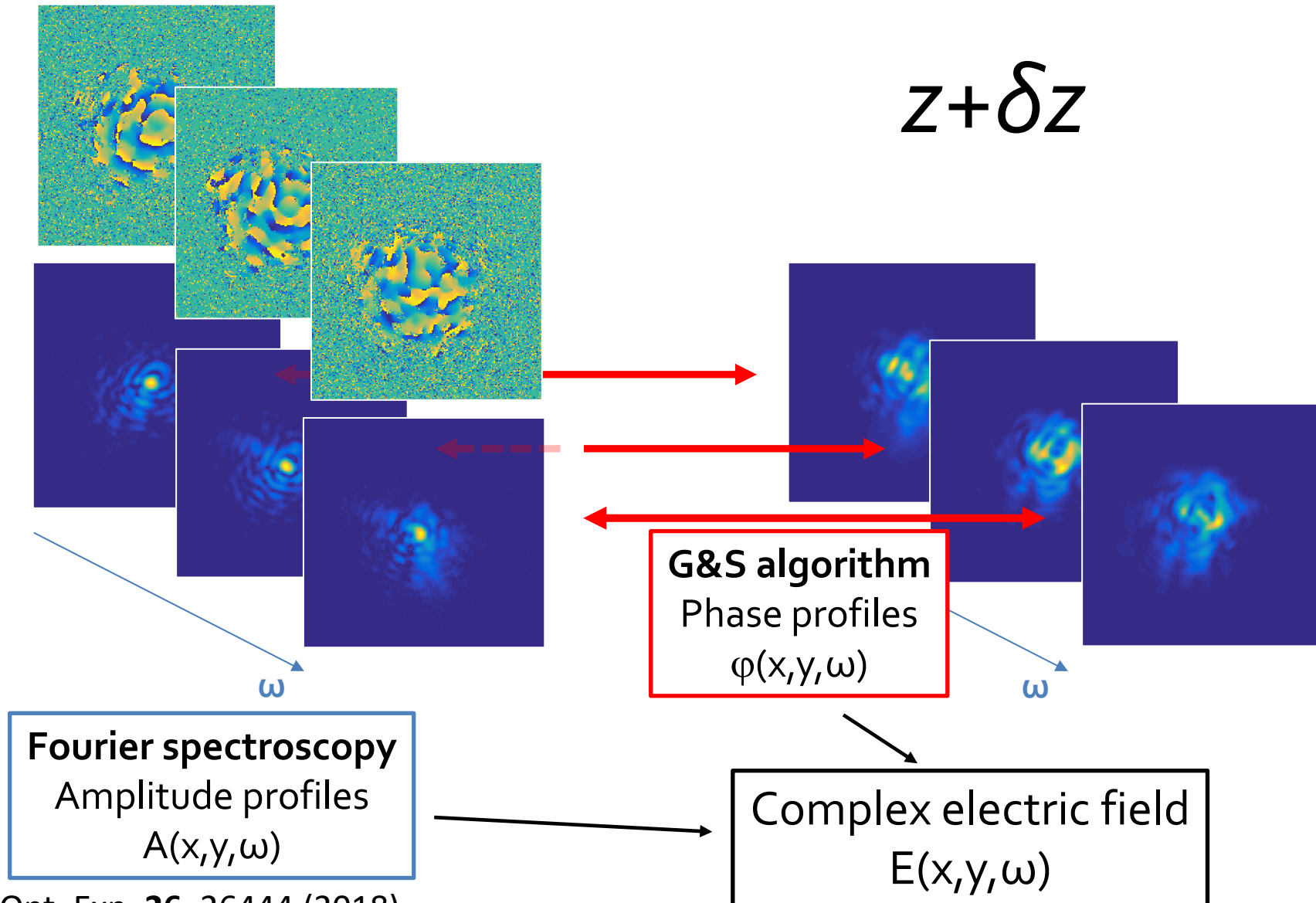
dependent

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.

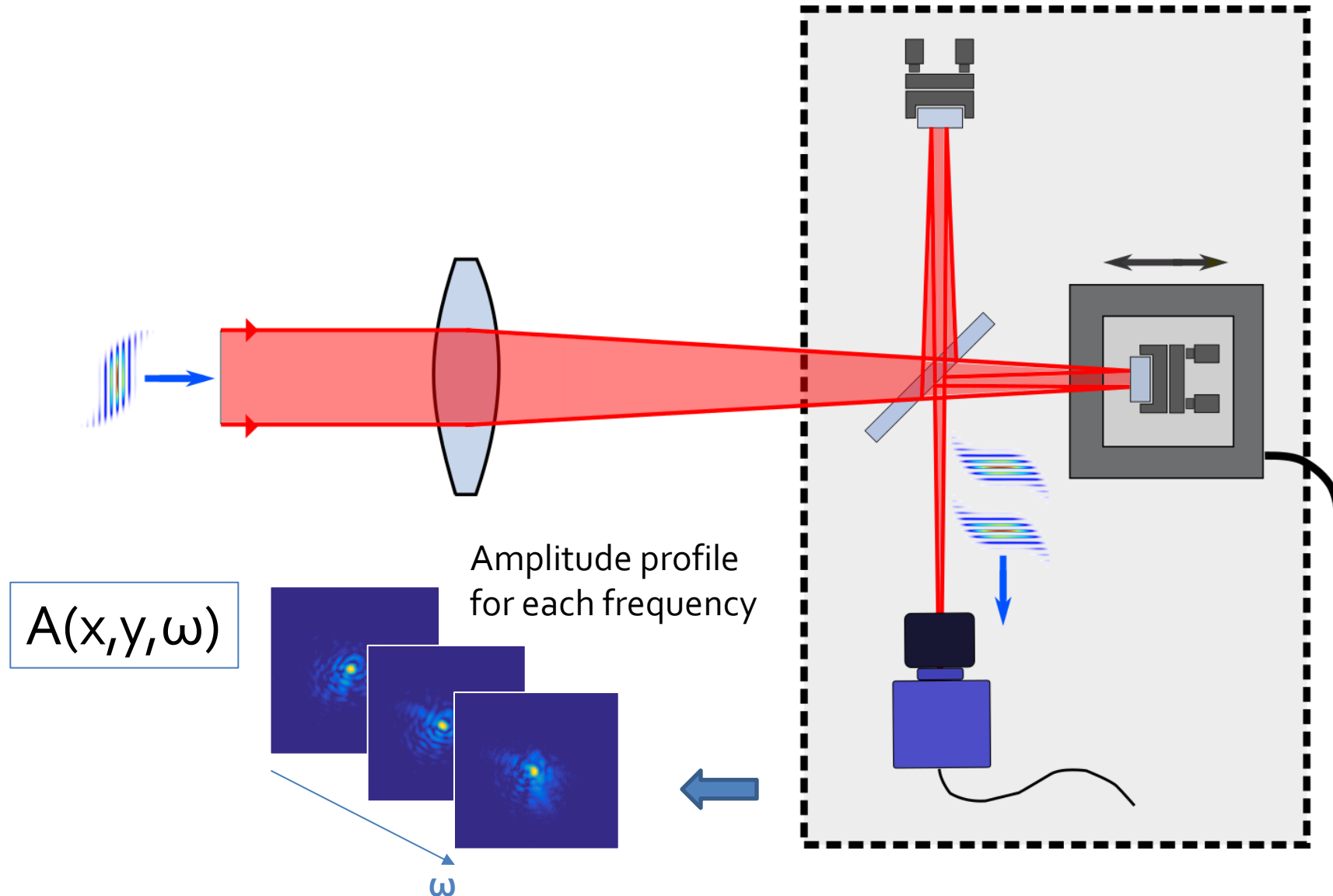


Insight in one glance

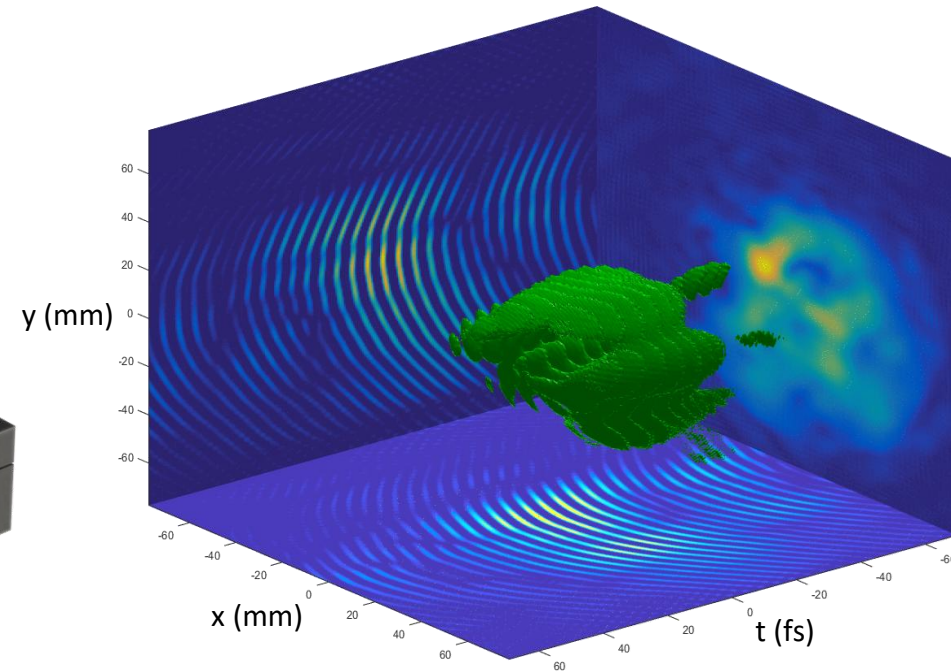
$$z + \delta z$$



Experimental setup of Insight



Insight: Spatio-spectral imager at the focus



@1 Hz : 12 min

@10 Hz : 2 min

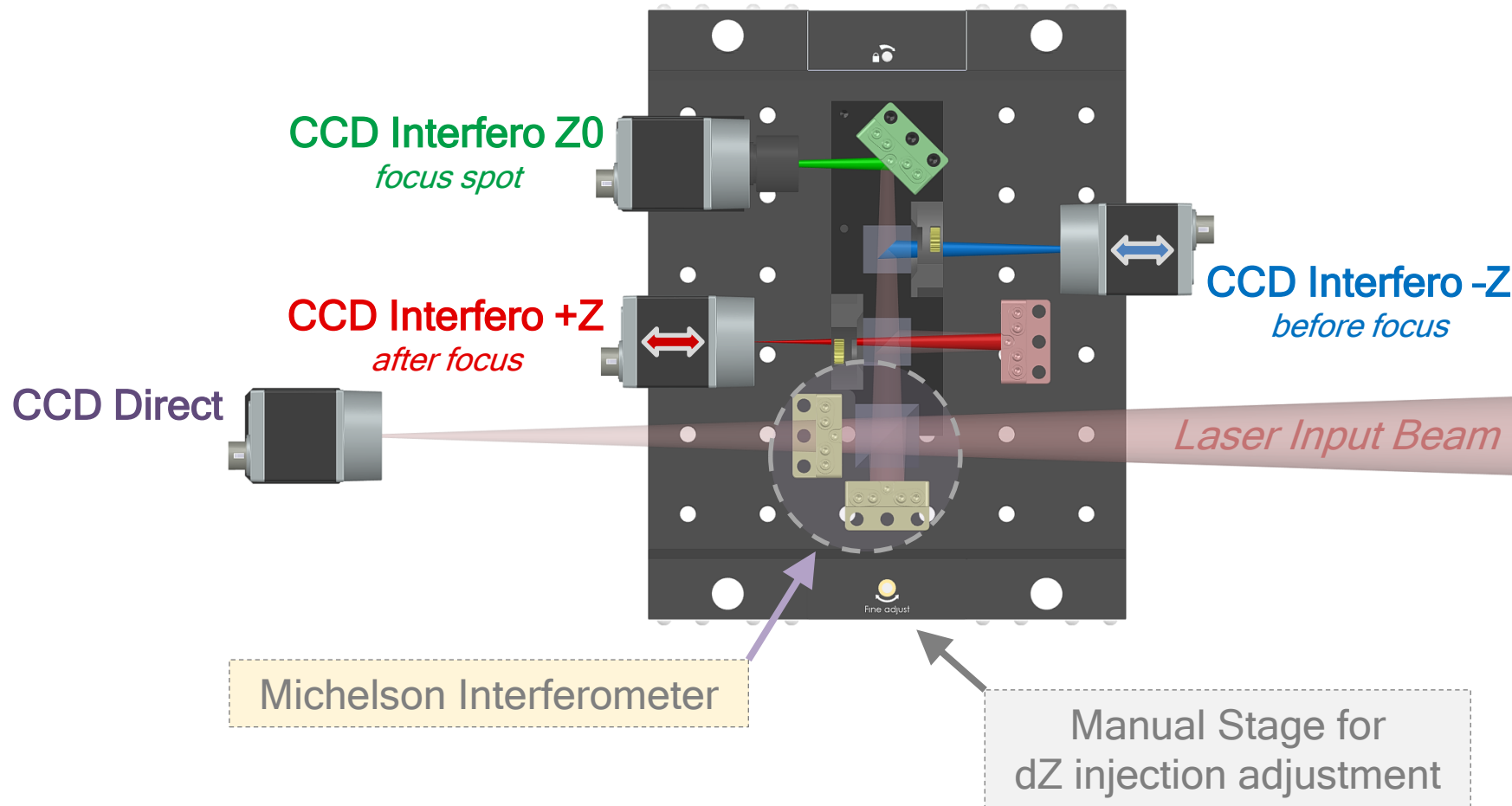
SourceLAB

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

Outline

- Laser beams and laser pulses – the basics
- Shaping and measuring laser beams and laser pulses – the basics
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- Why STCs? And why is characterization difficult?
- Overview of history and of standard techniques
- **More recent measurements, techniques, and exotic concepts**

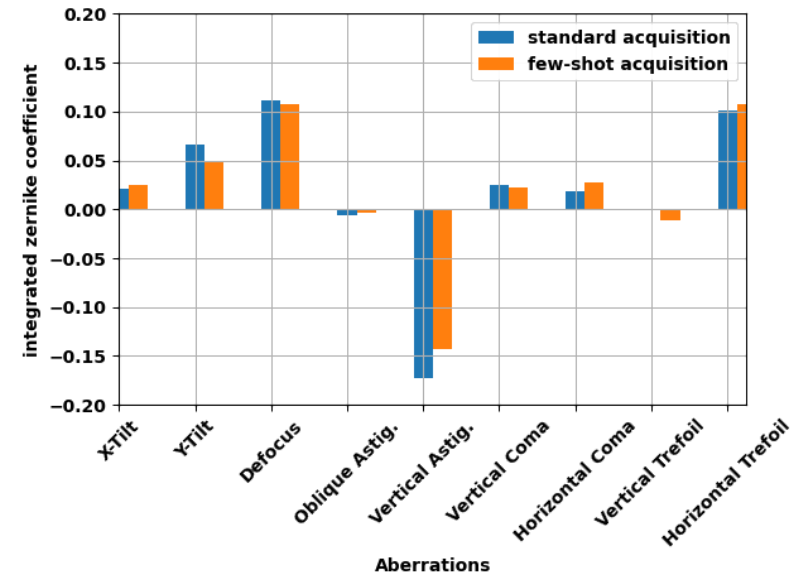
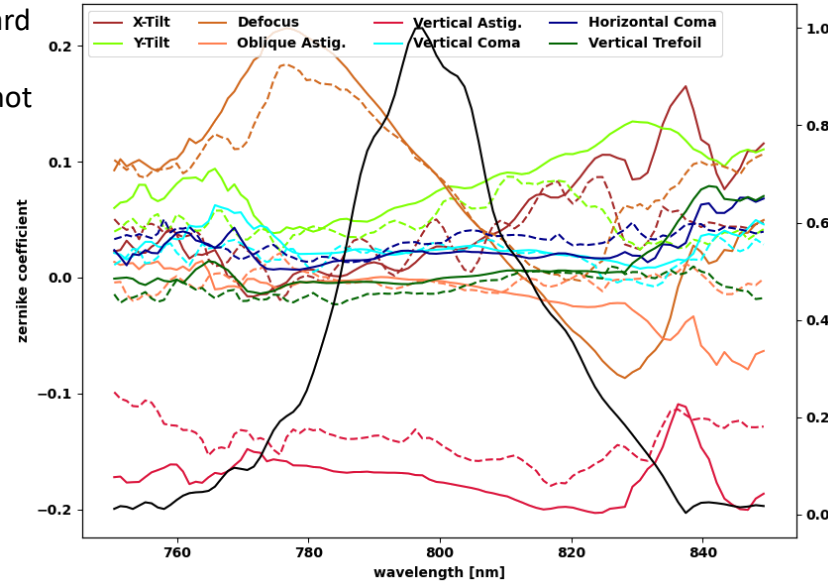
New: Insight Quadro



New: Few-shot plugin

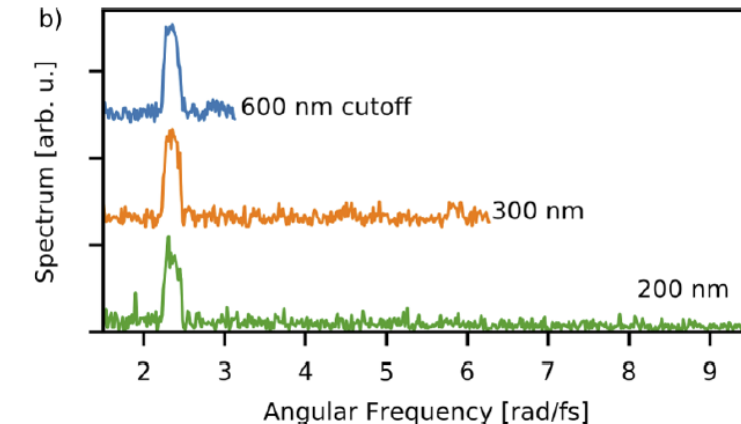
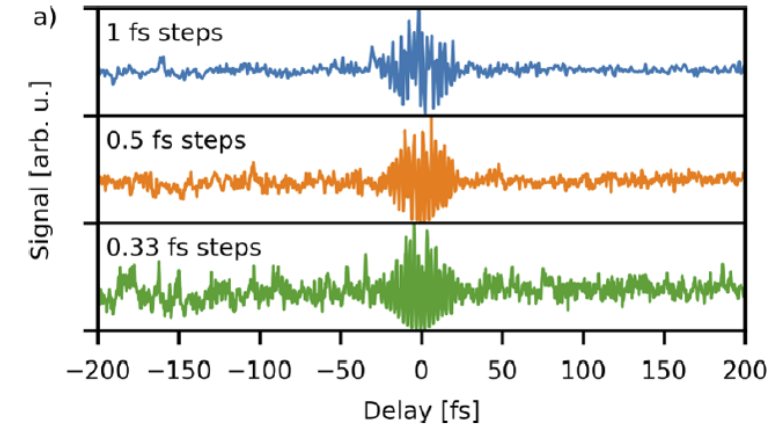
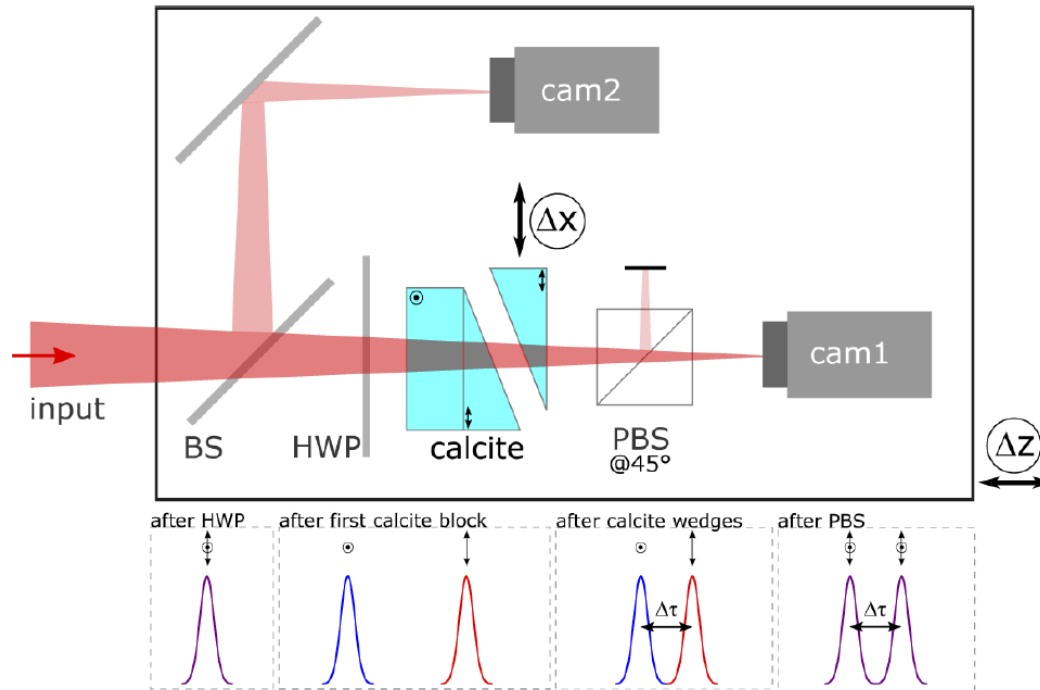
As INSIGHT is a **scanning device**, it is well suited for > 10 Hz laser system for a fast acquisition. For repetition rate < 10 Hz (in particular few shots/min laser system), a powerful Few-Shot plugin is **now available**.

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).

A new version of Insight with birefringent prisms



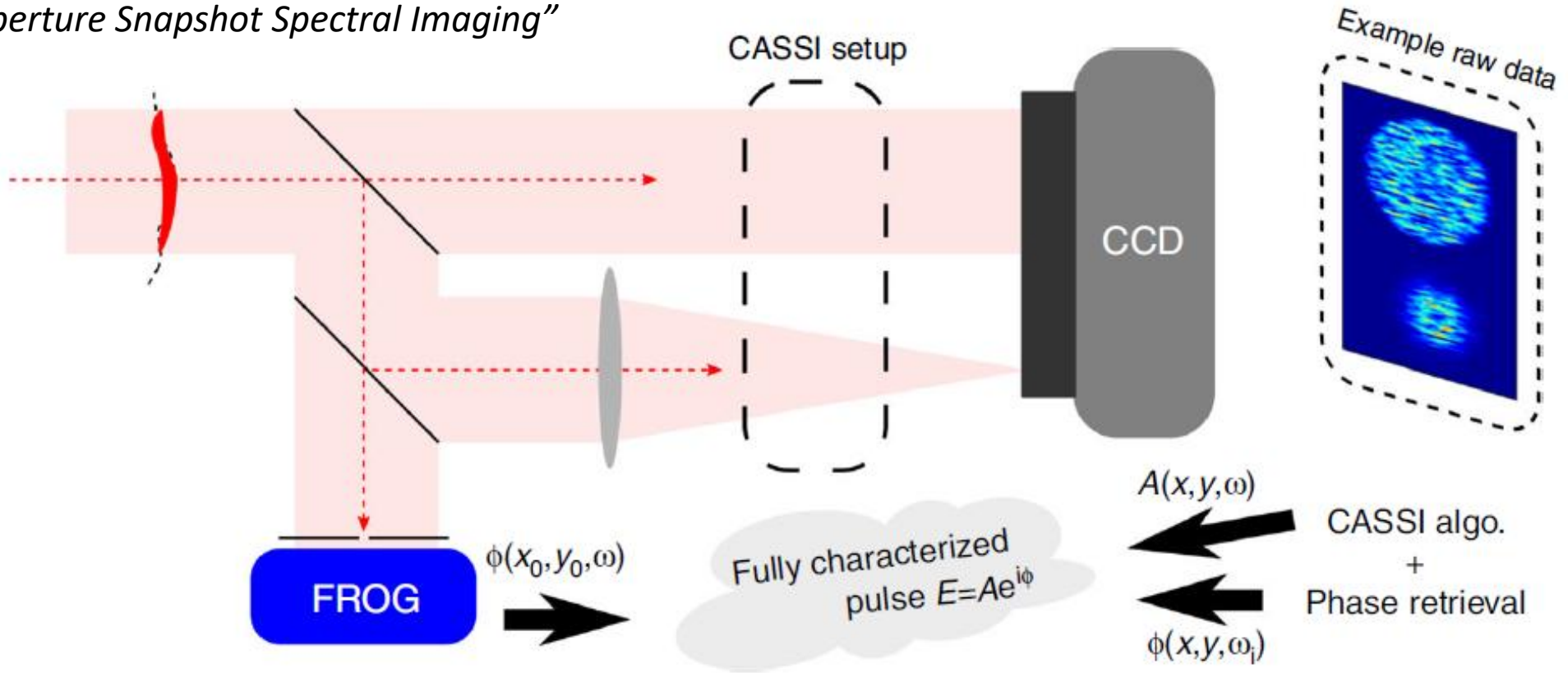
Higher precision for delay steps

- shorter wavelengths (limited only by optics)
- One avenue towards compressed sensing (fewer shots)
- removes noise due to fluctuation of the delay

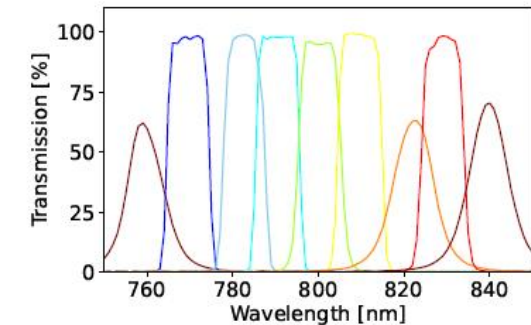
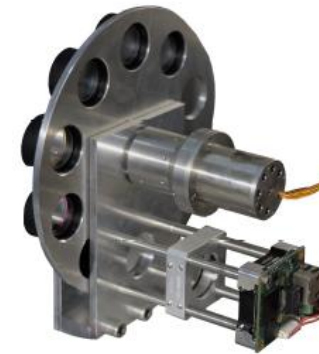
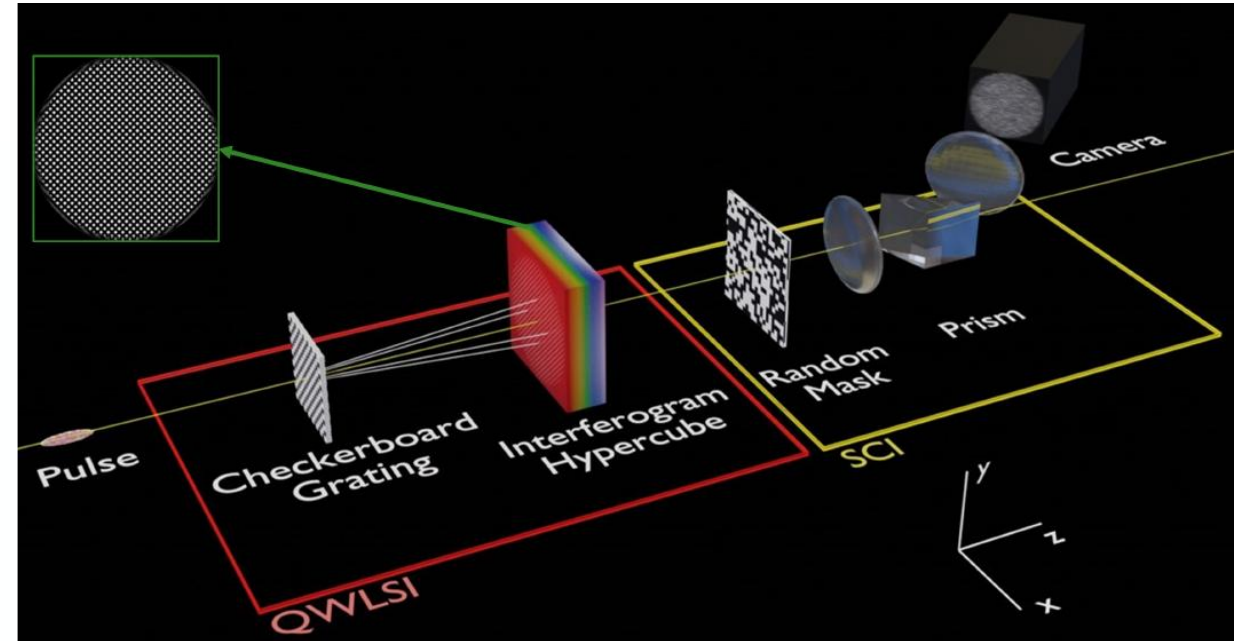
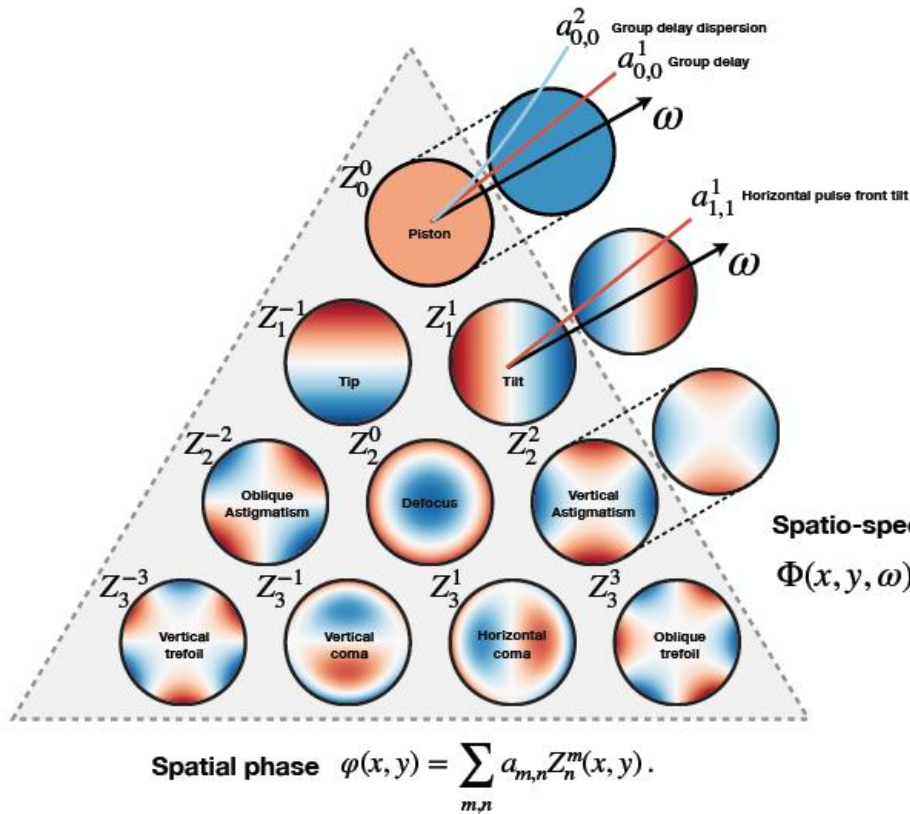


CASSI + phase retrieval

“Coded-Aperture Snapshot Spectral Imaging”

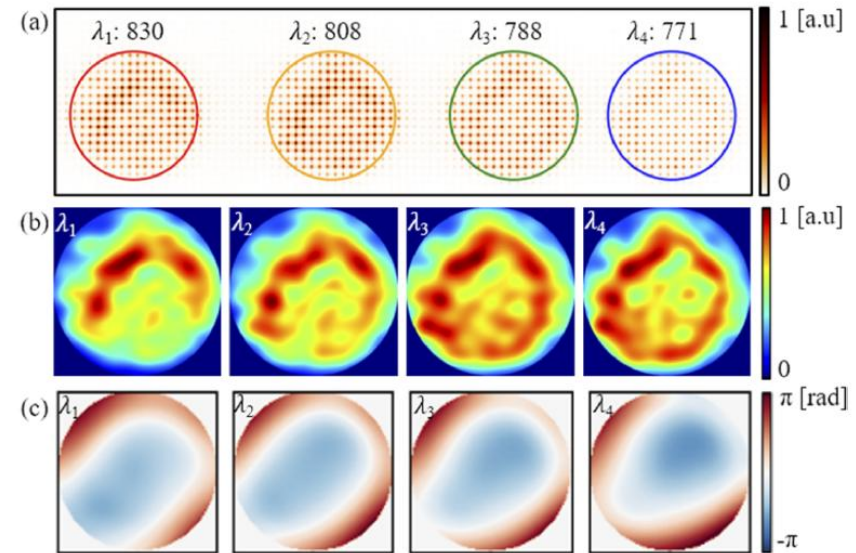
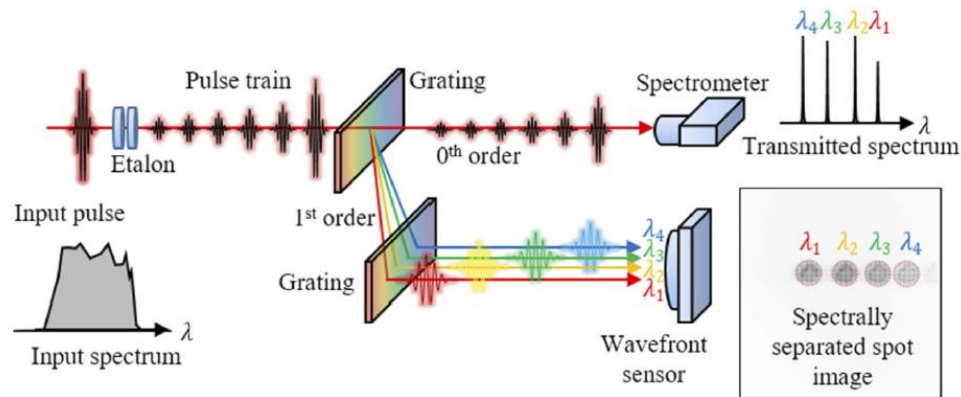


Hyperspectral wavefront + advanced algorithms



Single-shot measurements at CoReLS in Korea

“multispectral wavefront sensor”



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

STRIPED-FISH technique

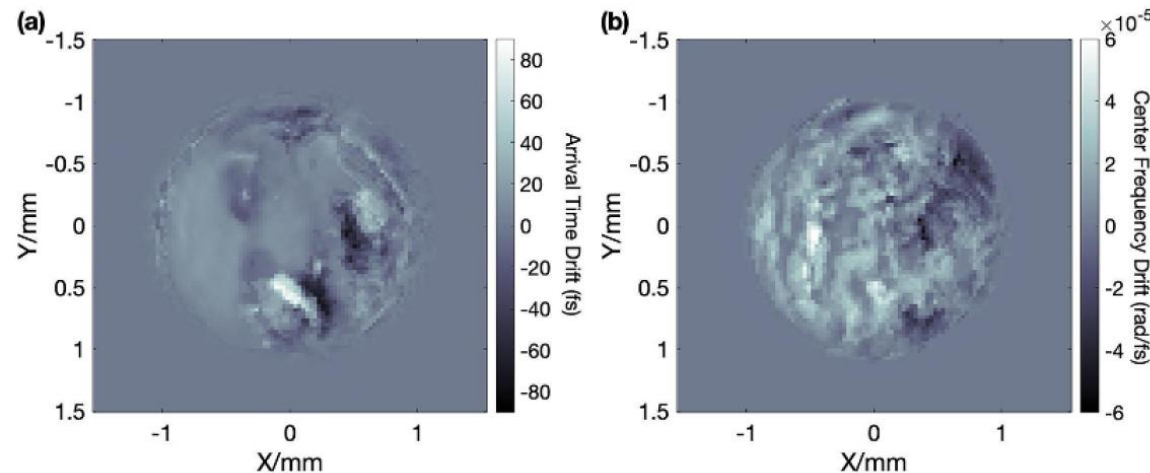
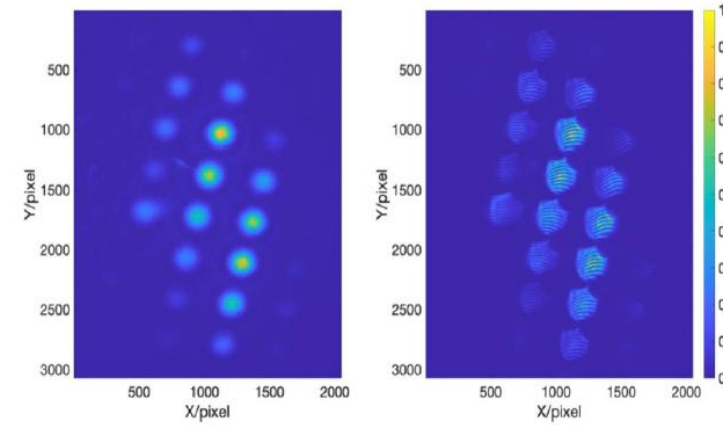
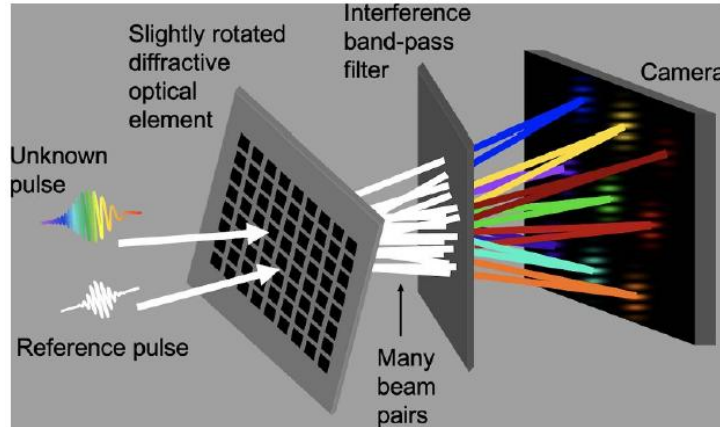
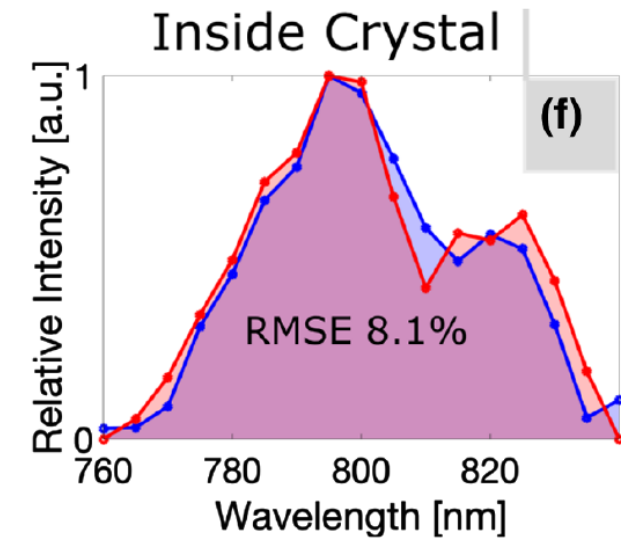
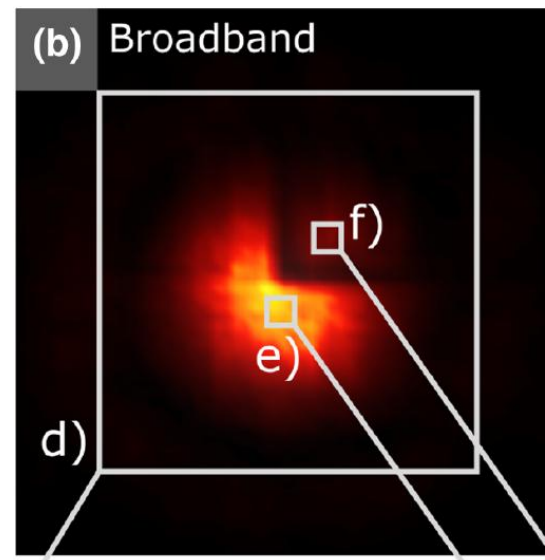


Figure 7. Drift over the course of the shot day in the arrival time (a) and center frequency (b).

Broadband ptychography



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

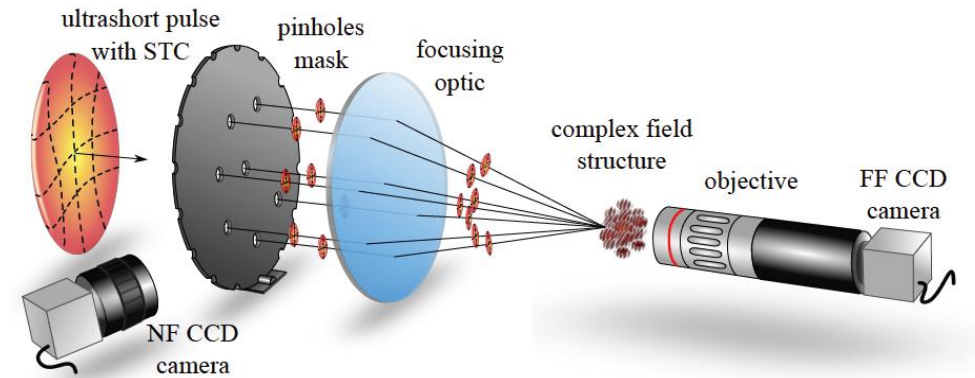
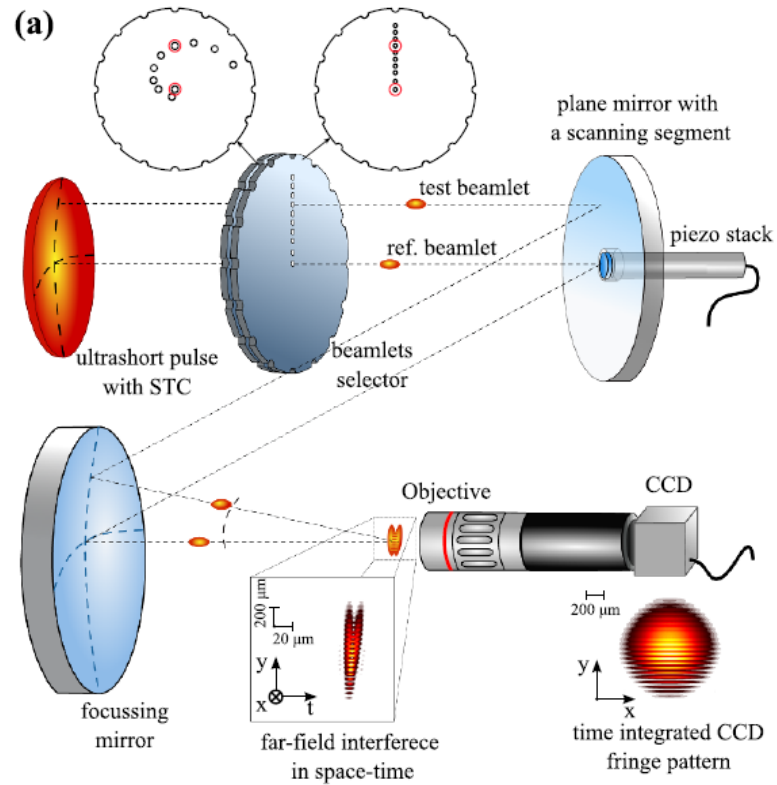
D. Goldberger et al., Opt. Express **29**, 32474 (2021).

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

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

IRTG Lecture Week – October 12th and 13th, 2026

Beamlet cross-correlation



S. Smartsev et al., Opt. Lett. **49**, 1900 (2024).

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

“IMPALA”



Single-shot hyperspectral wavefront imaging

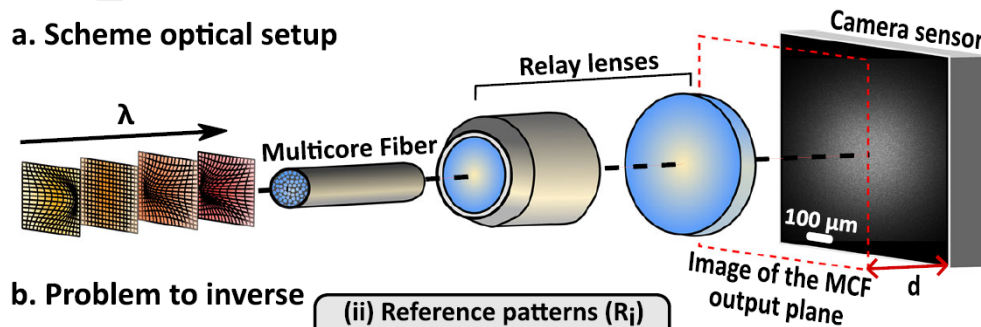
Received: 21 November 2024

Accepted: 17 November 2025

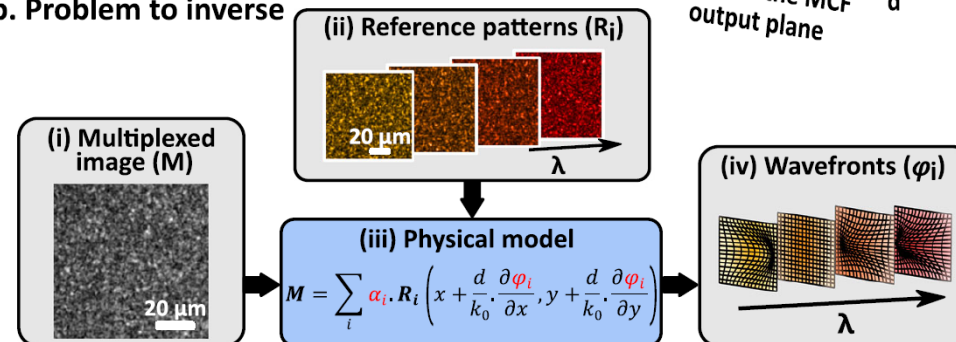
Published online: 04 December 2025

Baptiste Blochet¹✉, Nathalie Lebas², Pascal Berto^{1,3,4},
Dimitrios Papadopoulos² & Marc Guillon^{1,4,5}✉

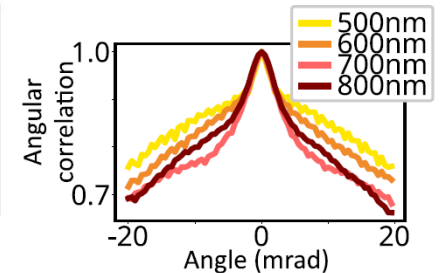
a. Scheme optical setup



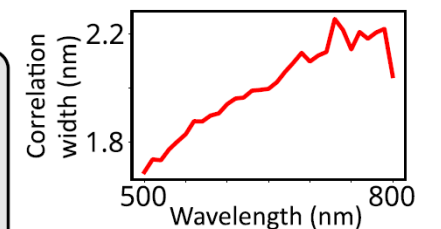
b. Problem to inverse



c. Angular memory effect



d. Spectral correlation width

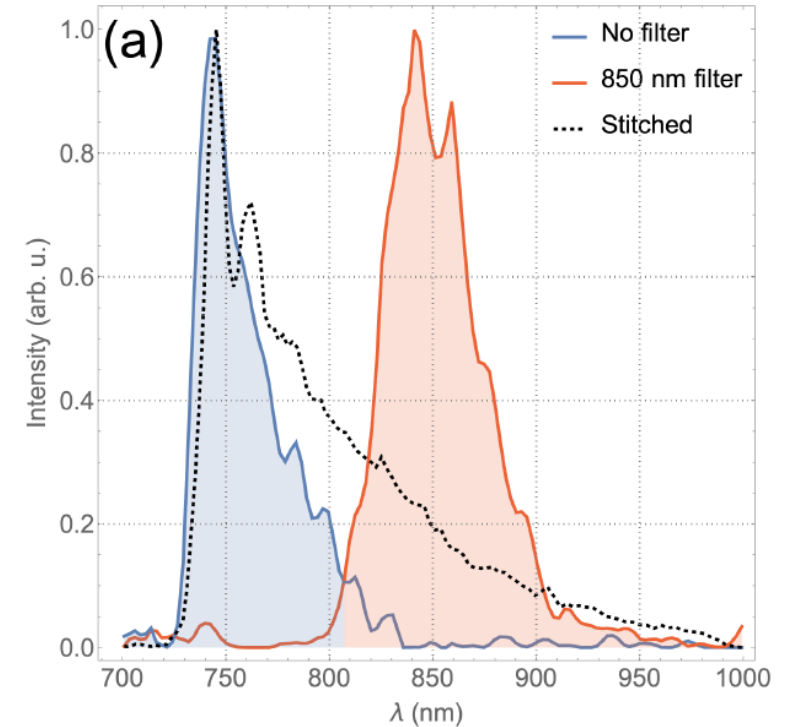


Article submitted to: *High Power Laser Science and Engineering*, 2026

Enhanced dynamic range spatio-spectral metrology of few-cycle laser pulses

Cristian Alexe^{1,2,3,*}, Aaron Liberman^{4,*}, Saga Westerberg⁵, Andrea Angella⁵, Anda-Maria Talposi⁴, Ann-Kathrin Raab⁵, Erik Löfquist⁵, Alice Dumitru^{1,2,3}, Andrew H. Okukura^{1,2,3}, Flanish D'Souza⁵, Cornelia Gustafsson⁵, Anders Persson⁵, Chen Guo⁵, Cord Arnold⁵, Olle Lundh⁵, Victor Malka^{1,4}, and Daniel Ursescu^{1,2,3,†}

¹*Extreme Light Infrastructure - Nuclear Physics, National Institute for Physics and Nuclear Engineering Horia Hulubei, 30 Reactorului str., Măgurele, 077125, Ilfov, Romania*



Systematic comparison of commercial devices for temporal characterization of few-cycle laser pulses in the 500-1000 nm spectral range

VIKTOR PAJER,[†]  JÁNOS BOHUS,^{†,*}  ABDOLLAH MALAKZADEH, 
LEVENTE LEHOTAI, MIKHAIL KALASHNIKOV, IMRE SERES,
BARNABÁS GILICZE, BÁLINT KISS, ÁDÁM BÖRZSÖNYI, KATALIN
VARJÚ, GÁBOR SZABÓ, AND ROLAND NAGYMIHÁLY 

ELI ALPS, ELI-HU Non-Profit Ltd., Wolfgang Sandner utca 3., Szeged, H-6728, Hungary

[†]These authors contributed equally to this work

*Janos.Bohus@eli-alps.hu

Poster

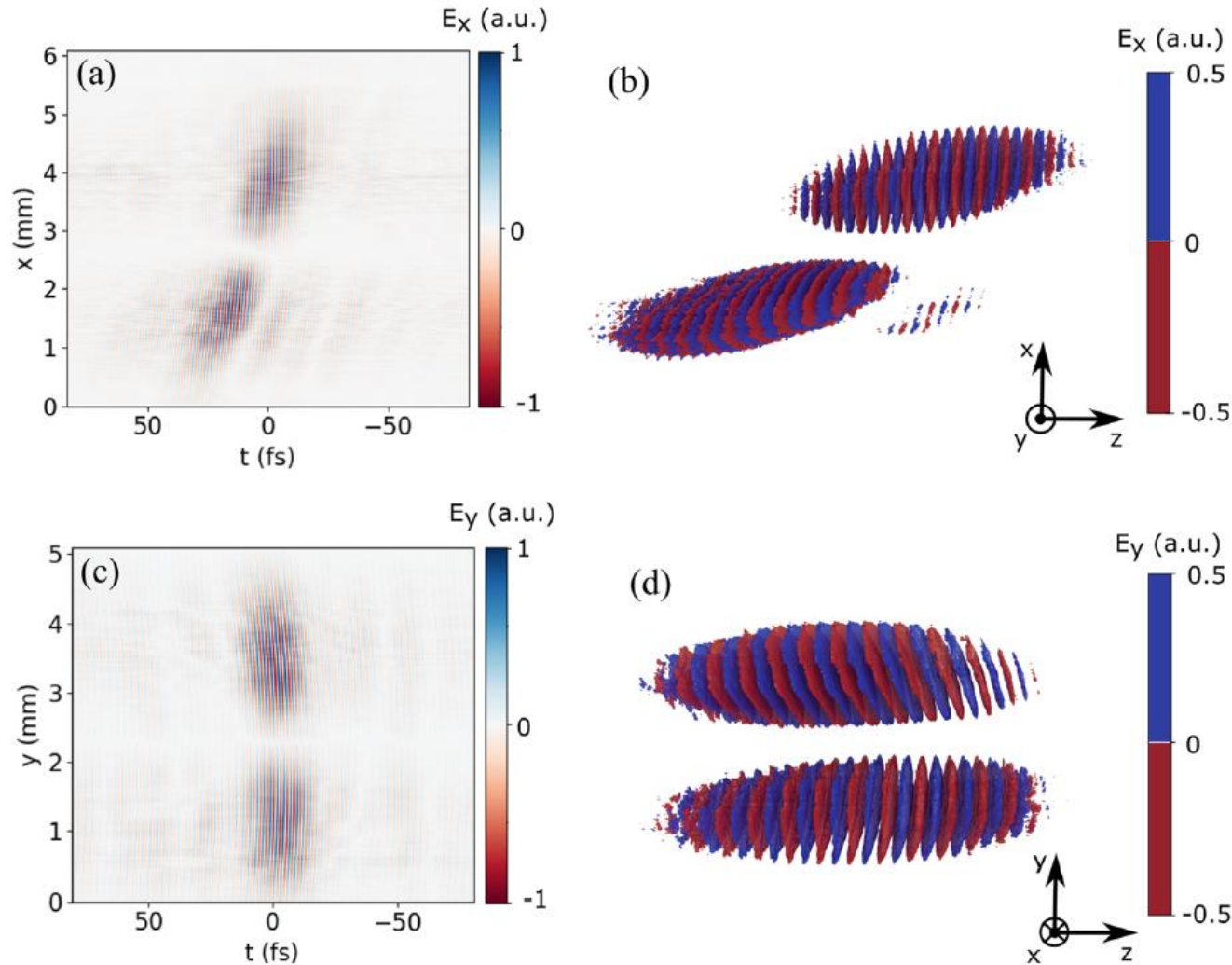
Systematic comparison of spatio-temporal coupling characterization techniques

September 2024

Conference: ICUIL 2024

 Levente Lehotai ·  Roland Sándor Nagymihály ·  Viktor Pajer · [Show all 6 authors](#) · Ádám Börzsönyi

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).

S. Howard et al., Nat. Photonics **19**, 898 (2025).

single shot

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More sophisticated statistical methods

- Decrease the resolution of the device to allow for single-shot with a simple device
- Decrease your expectations for how “complete” you want/need your measurement to be
- Make assumptions on how complex your laser beam is
- Update your uncertainty based on past measurements

RESEARCH ARTICLE | PHYSICS



A Bayesian perspective on single-shot laser characterization

J. Esslinger , N. Weiße, C. Eberle, J. Schröder , S. Howard, P. Norreys , S. Karsch, and A. Döpp [Authors](#)

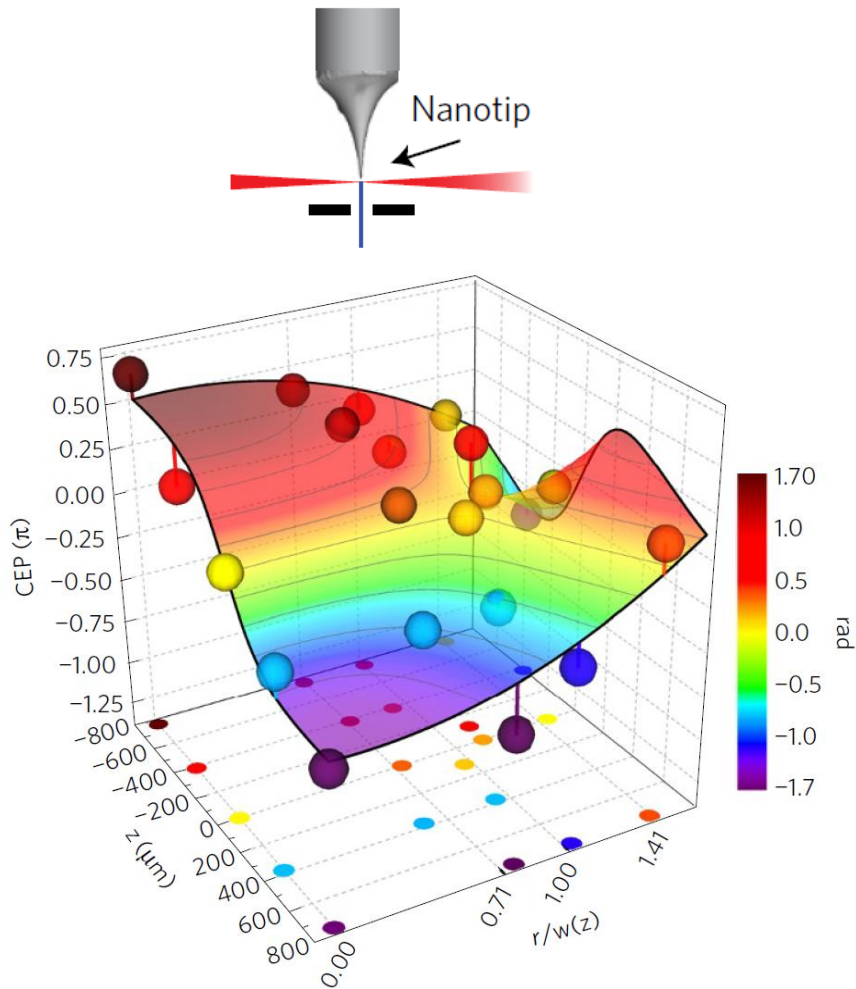
[Info & Affiliations](#)

Edited by Victor Malka, Weizmann Institute of Science, Rehovot, Israel; received April 29, 2025; accepted September 2, 2025 by Editorial Board Member Hui Cao

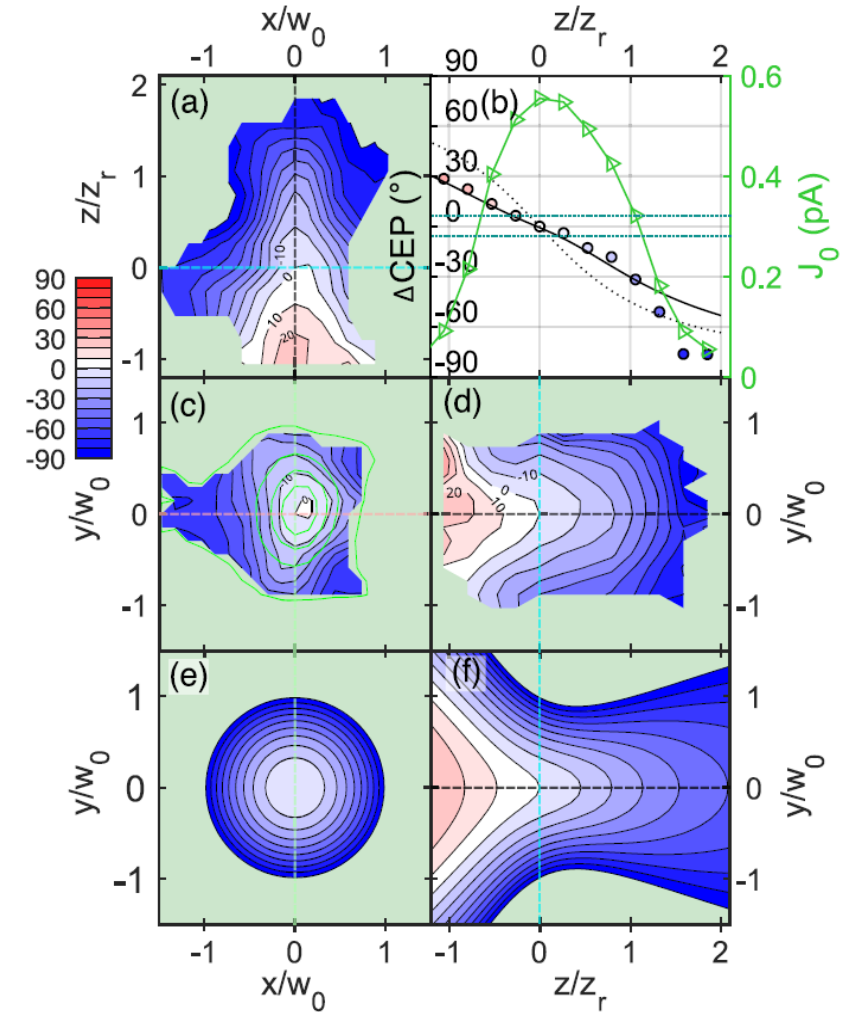
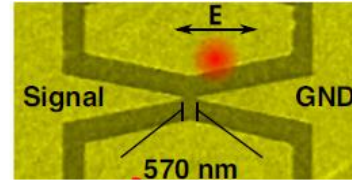
October 24, 2025 | 122 (43) e2510645122 | <https://doi.org/10.1073/pnas.2510645122>

J. Esslinger, et al., A Bayesian perspective on single-shot laser characterization, *Proc. Natl. Acad. Sci. U.S.A.* 122 (43) e2510645122, <https://doi.org/10.1073/pnas.2510645122> (2025).

Spatial measurement of CEP



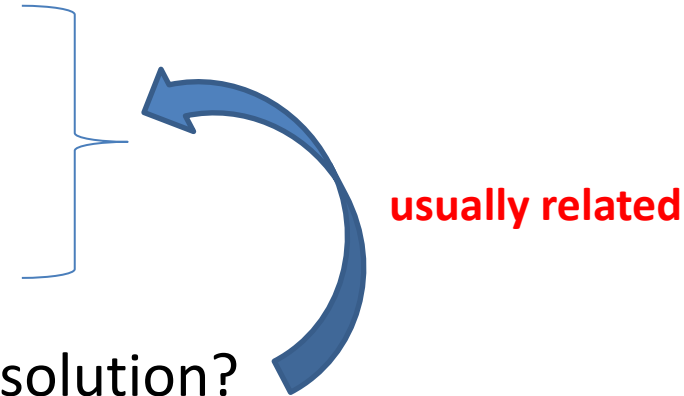
D. Hoff et al., Nat. Phys. **13**, 947 (2017).



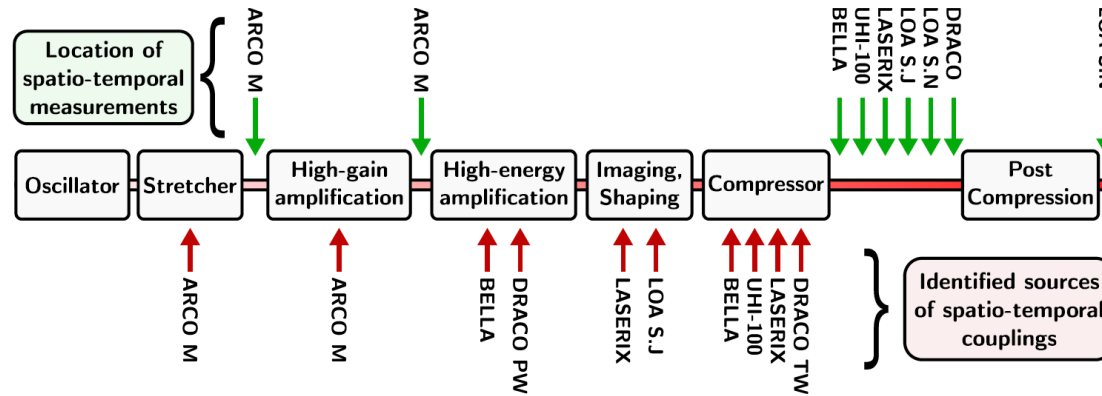
V. Hanus et al., Nat. Comm. **14**, 5068 (2023).

Take a step back (again)

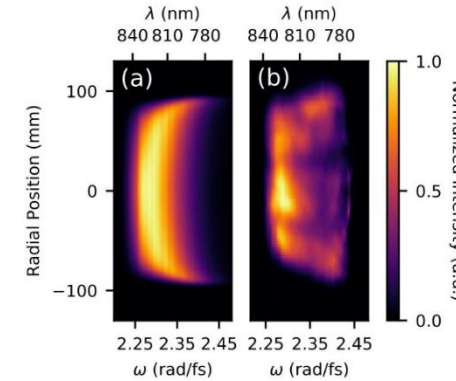
- Is it 2-D or 3-D?
 - Is it single-shot or scanning?
 - Is there some type of hard limit on resolution?
 - Is there a required (perfect) reference beam?
this can be a big limitation
 - Is it truly a space-time device or “just” space-spectrum?
this usually doesn't matter
- adding polarization or looking at a
non-standard wavelength will
generally affect all of the above**



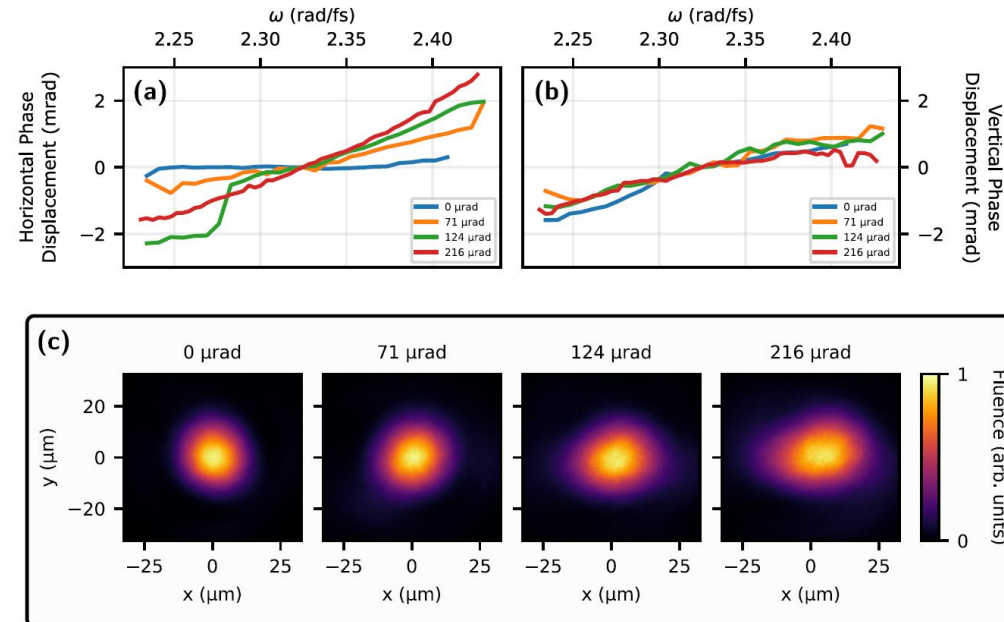
Survey of couplings on many systems



Joule-level amplifier physics

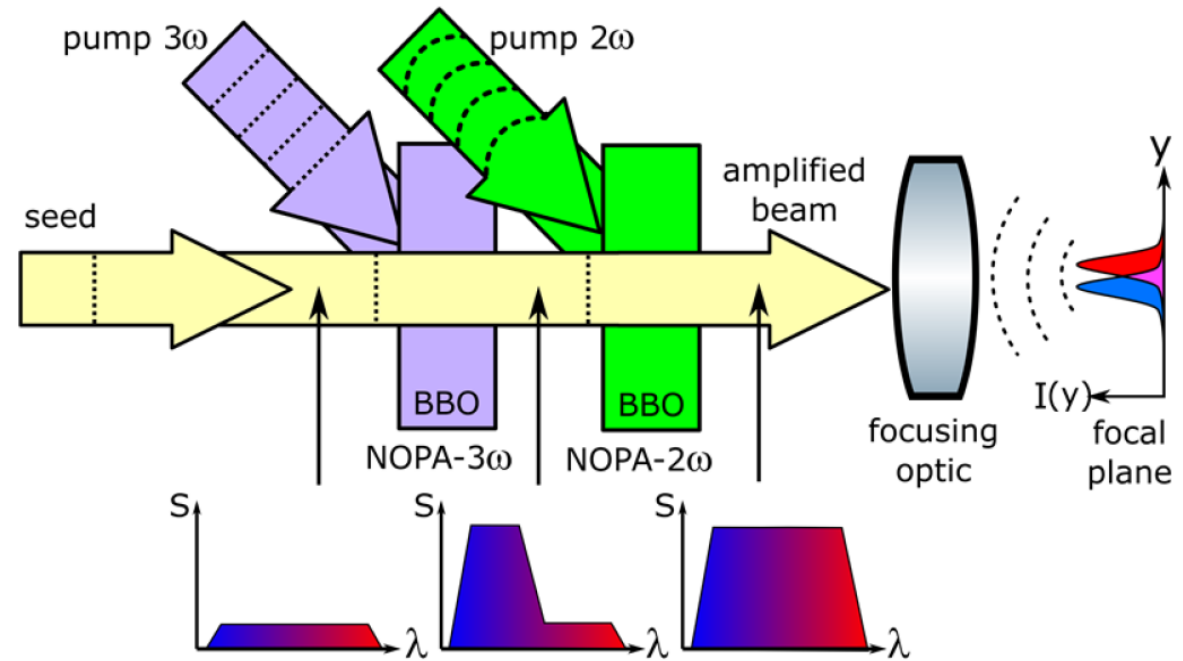
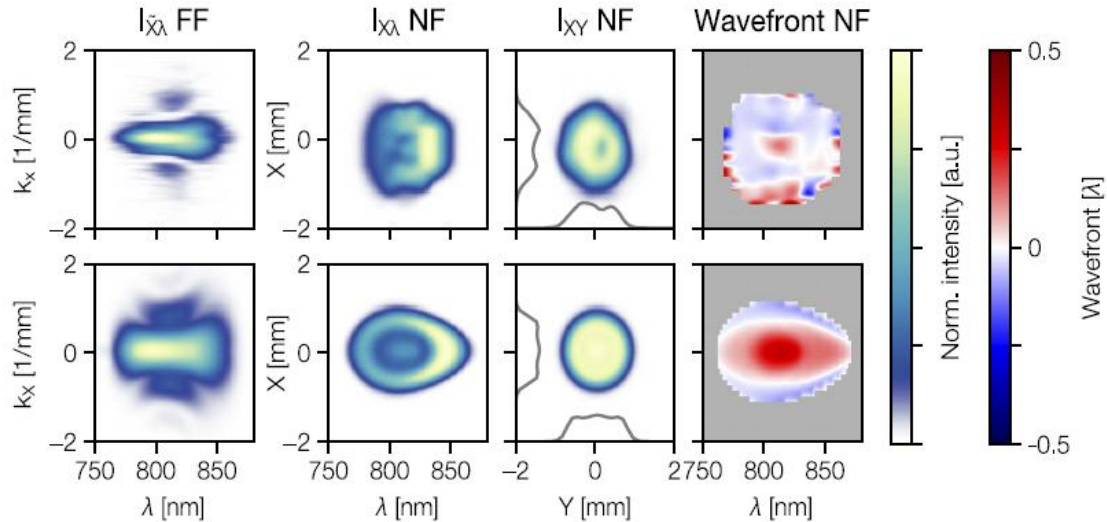


Big collaboration:
Salle Jaune & Salle Noire @ LOA
UHI-100 @ CEA
BELLA @ Berkeley Lab
DRACO TW & PW @ HZDR
Industrial system @ Amplitude
LASERIX @ Orsay



Couplings in saturated OPCPAs

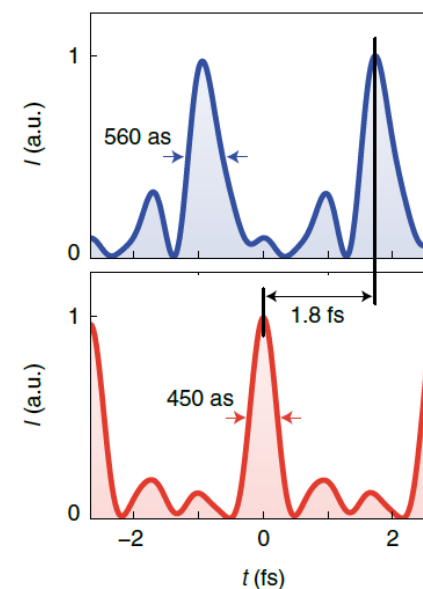
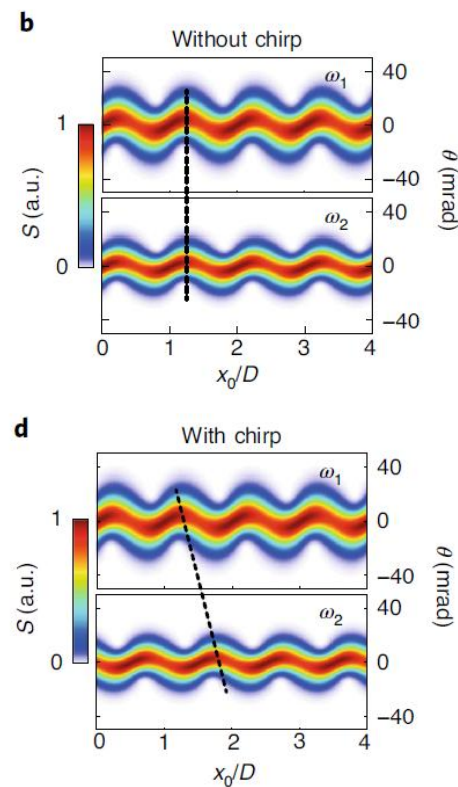
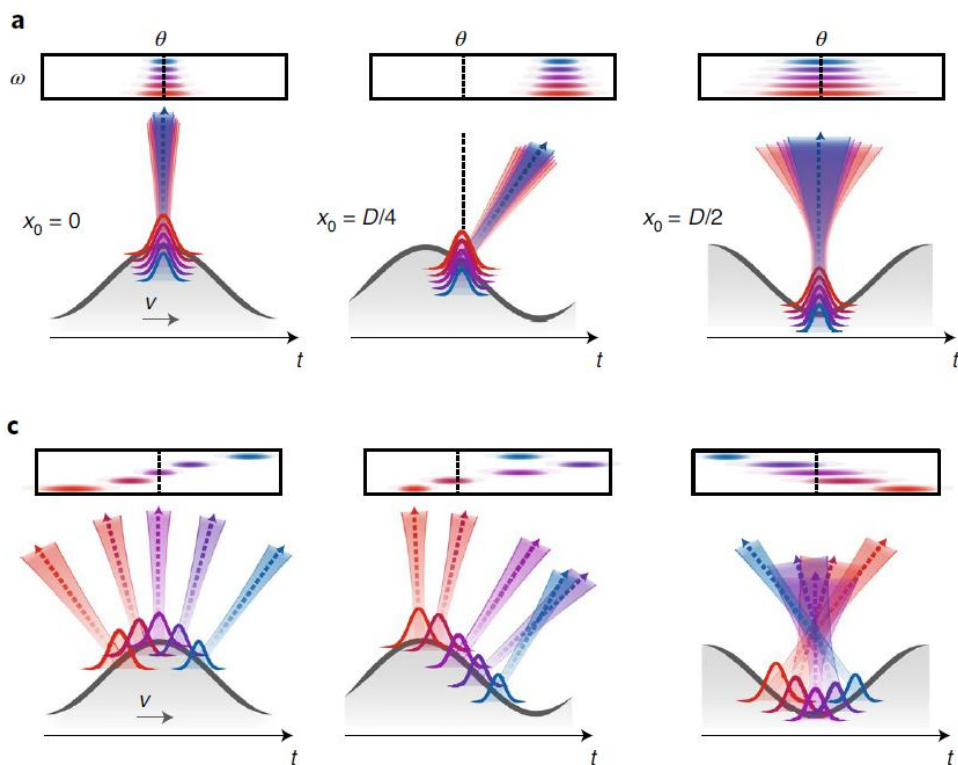
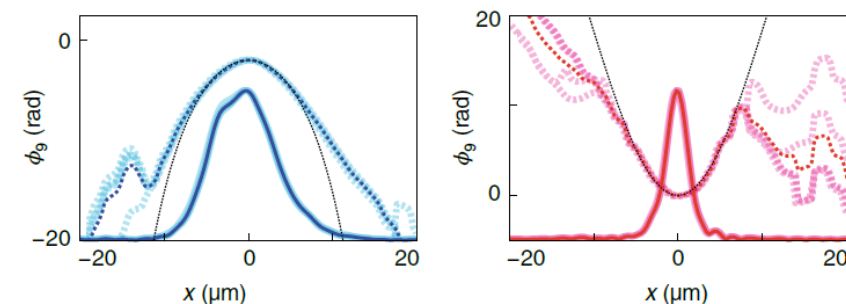
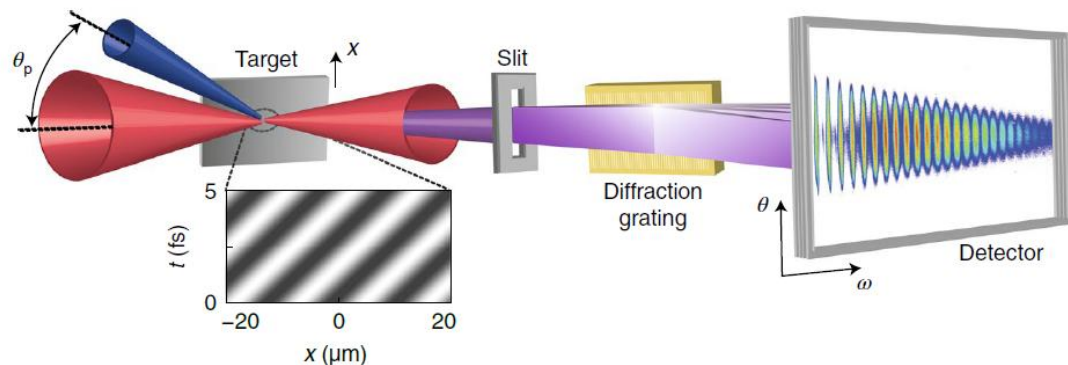
Simulation Measurement



T. Eichner et al., Opt. Express **30**, 3404 (2022).

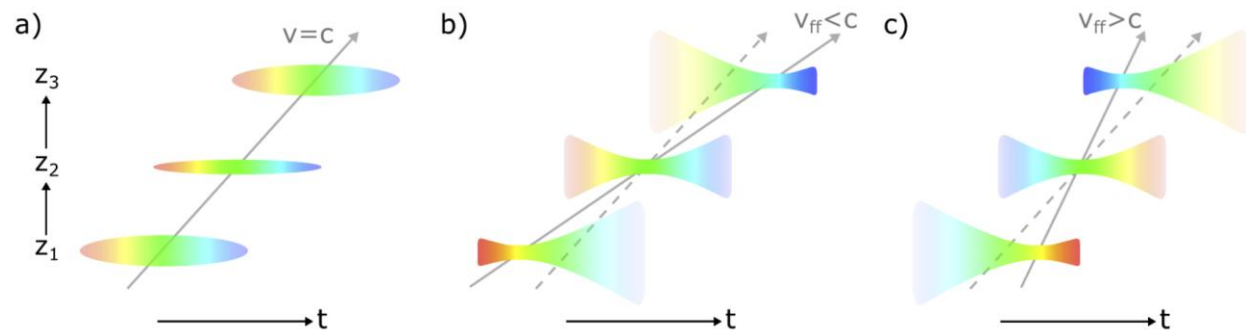
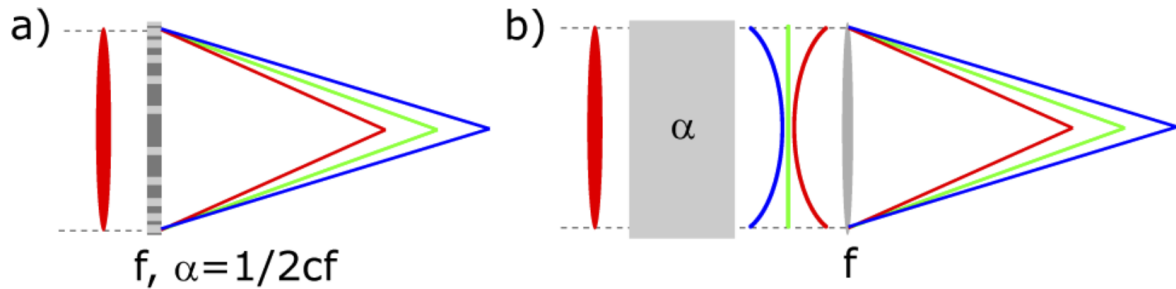
A. De Andres et al., Opt. Exp. **31**, 12036 (2023).

Space-time measurements of attosecond beams

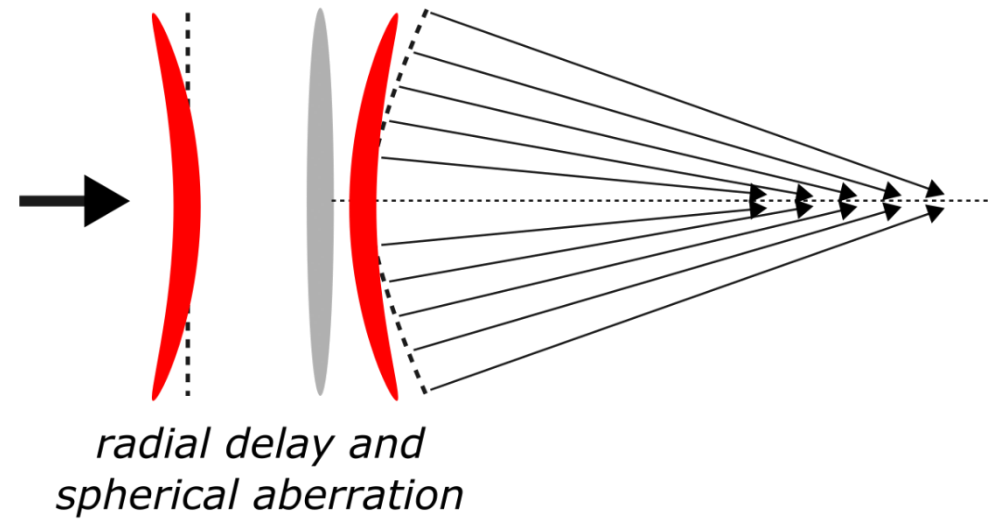


The flying focus

“Chromatic” version



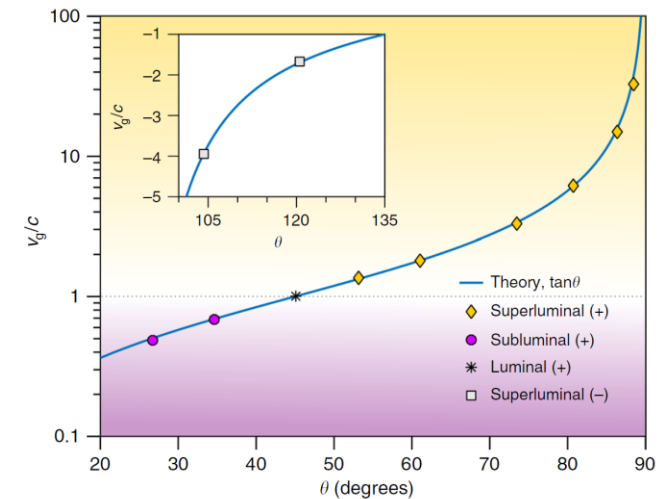
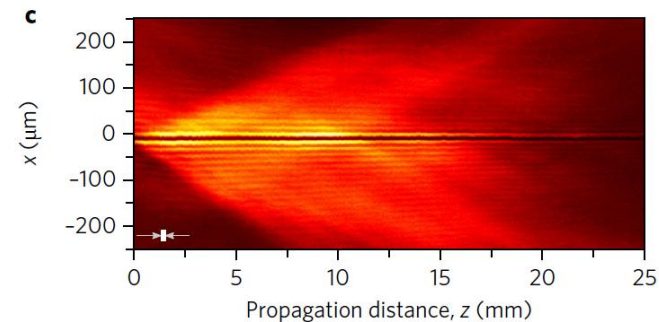
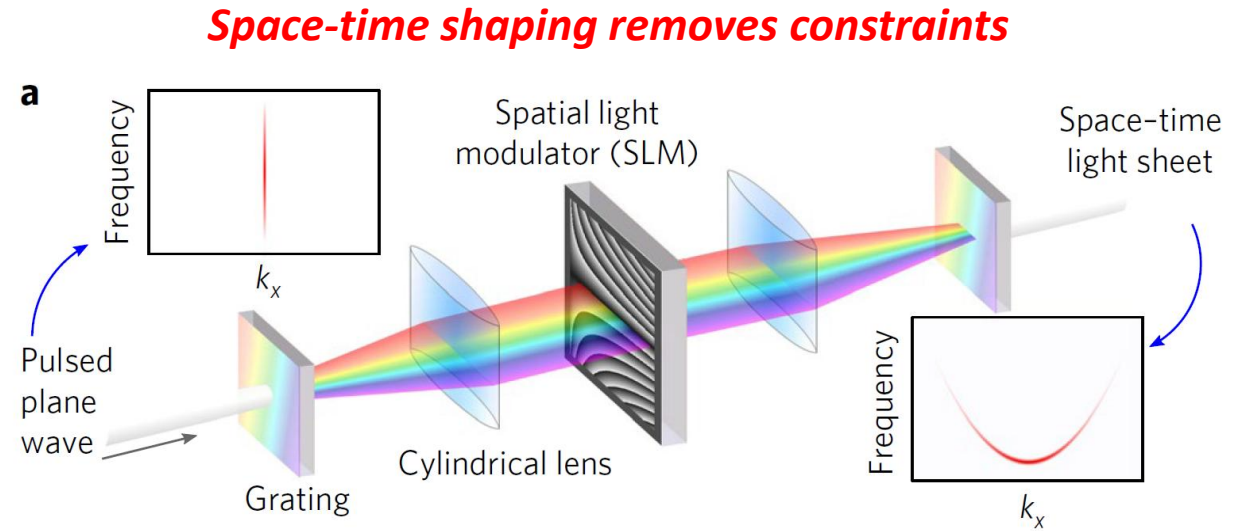
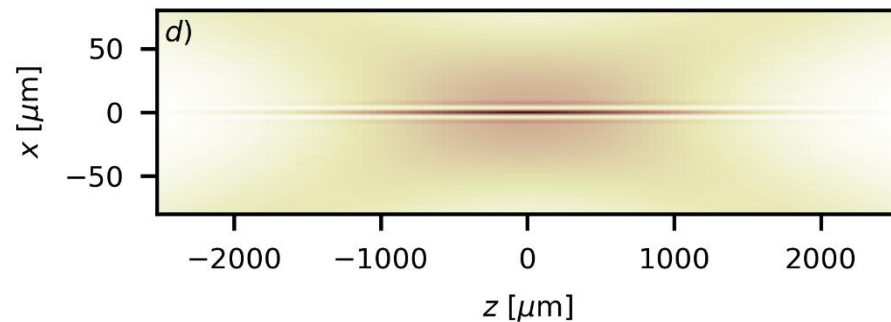
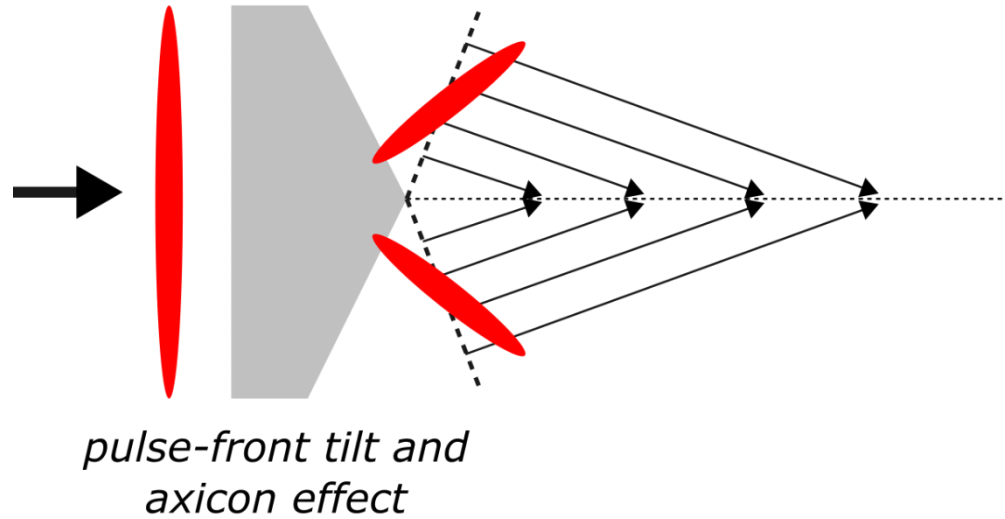
“Ultrashort” version



Intensity peak that travels at a velocity wildly different than “c”

- A. Saint-Marie, et al., *Optica* **4**, 1298 (2017).
- D. Froula, et al., *Nat. Photonics* **12**, 262 (2018).
- S. W. Jolly et al., *Opt. Express* **28**, 4888 (2020).
- M. Ambat et al., *Opt. Express* **31**, 31354 (2023).

Non-diffracting space-time beams

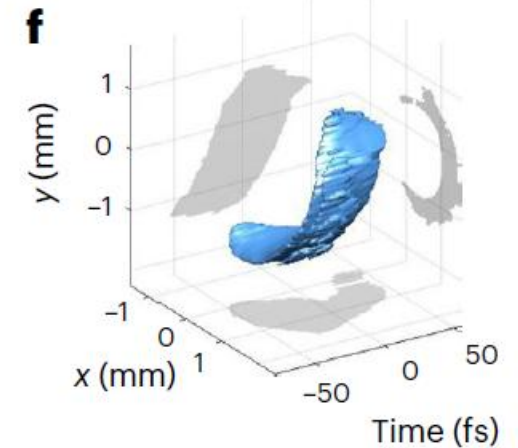
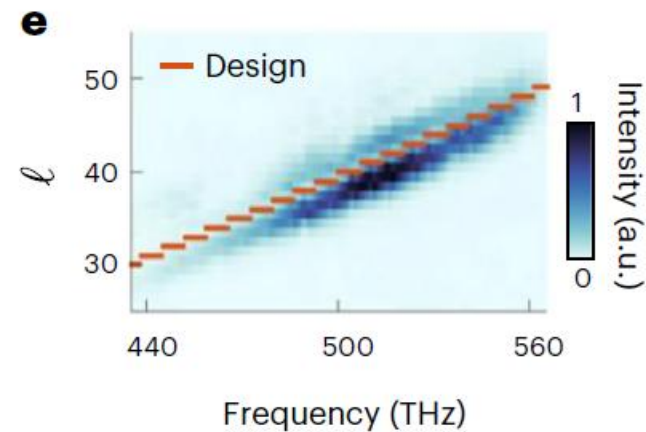


P. Saari et al., Phys. Rev. Lett. **79**, 4135 (1997).
 Kondakci et al., Nat. Phot. **11**, 733 (2017).
 Kondakci et al., Nat. Comm. **10**, 929 (2019)
 Bhaduri et al., Optica **6**, 139 (2019).
 Bahduri et al., Nat. Phot. **14**, 416 (2020).
 Yessenov et al., Nat. Comm. **13**, 4573 (2022).

Spatiotemporal light springs

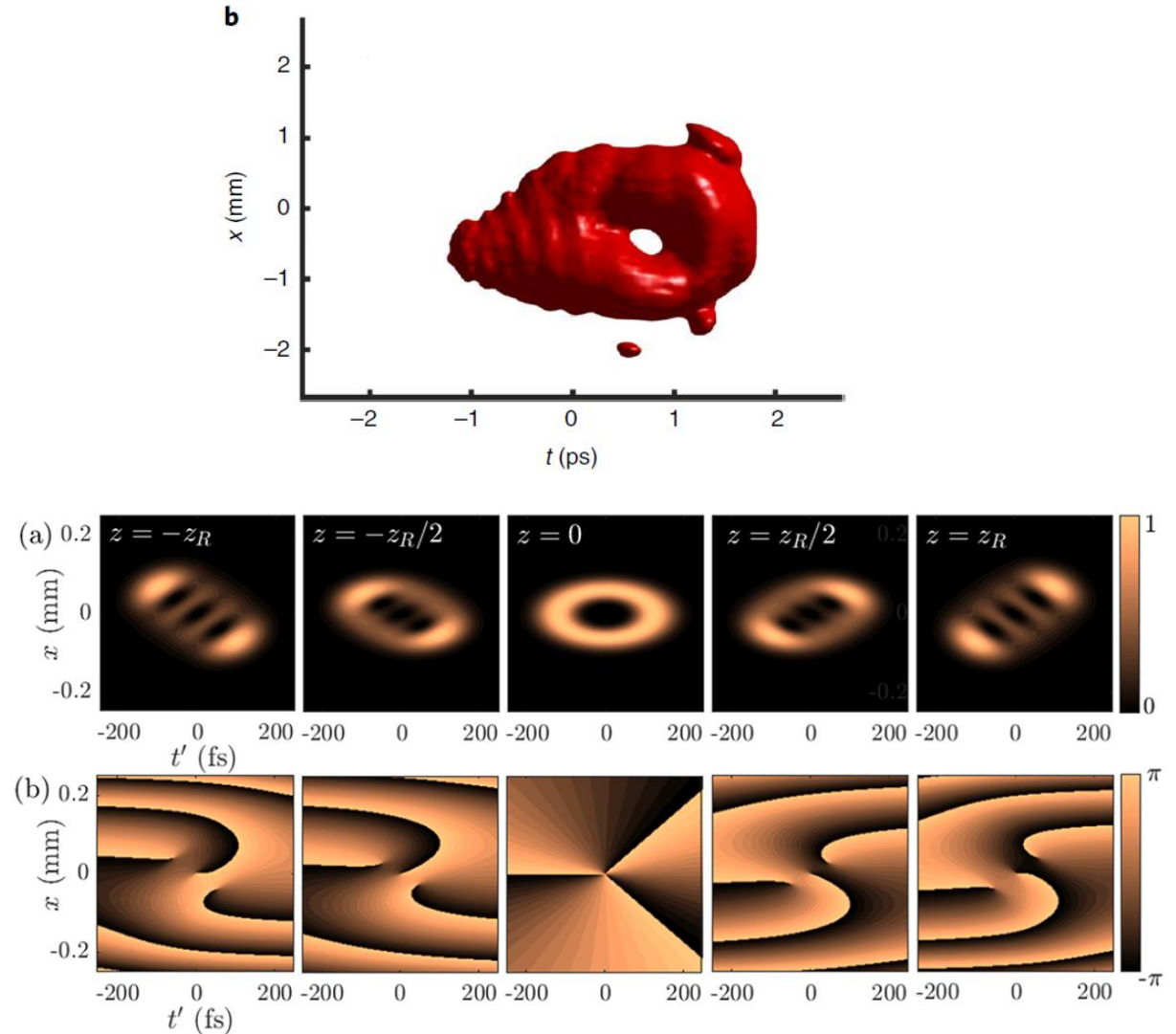
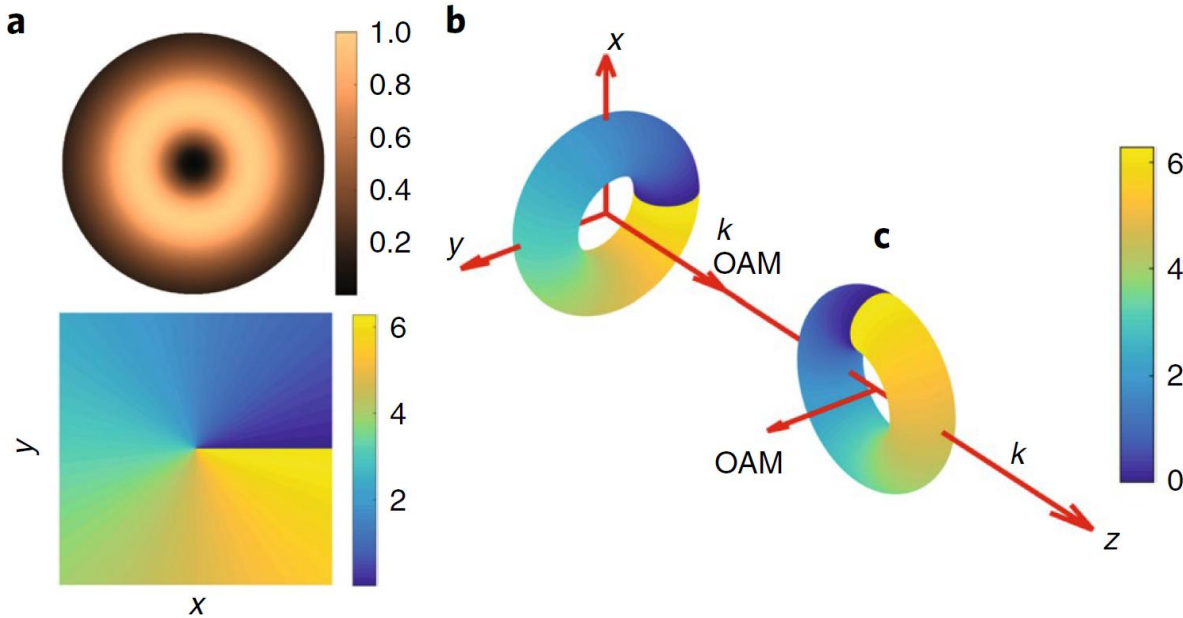
$$u(r, \phi, z) = C_{lp}^{LG} \frac{w_0}{w(z)} \left(\frac{r\sqrt{2}}{w(z)} \right)^{|l|} \exp\left(-\frac{r^2}{w^2(z)}\right) L_p^{|l|} \left(\frac{2r^2}{w^2(z)} \right) \times \\
 \exp\left(-ik\frac{r^2}{2R(z)}\right) \underline{\exp(-il\phi) \exp(i\psi(z))},$$

Can one make this depend on frequency?
 → azimuthal intensity arrival time



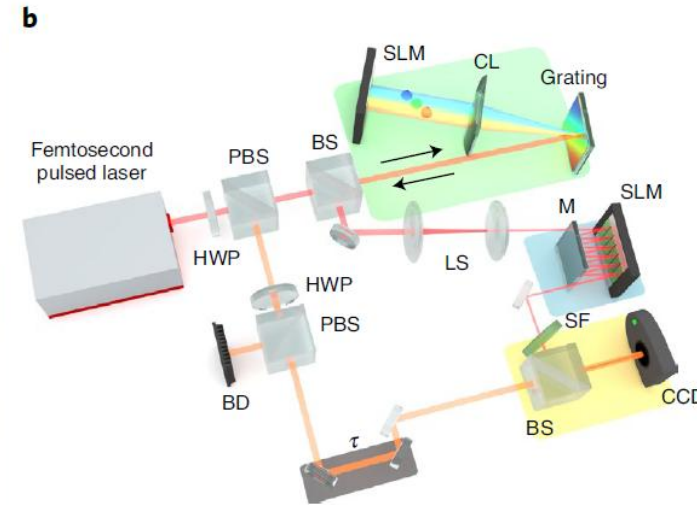
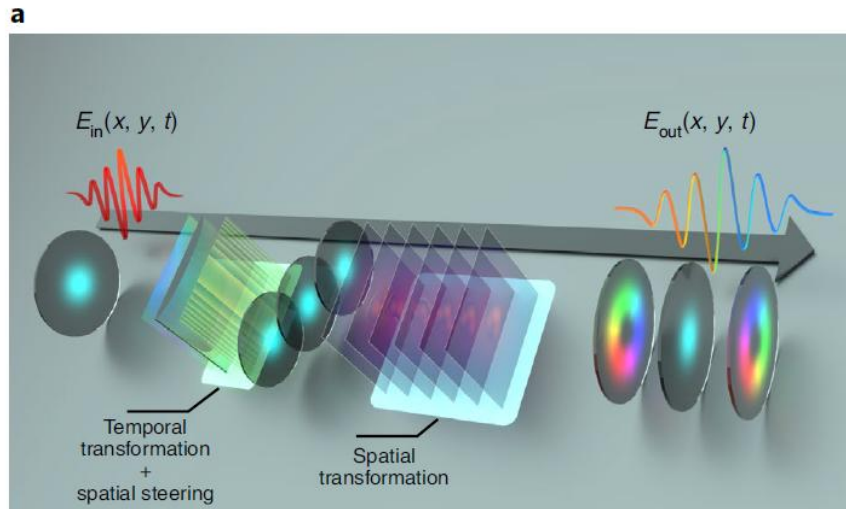
- G. Pariente & F. Quéré, Opt. Lett. **40**, 2037 (2015).
 L. Chen et al., Sci. Advances **8**, eabq8314 (2022).
 M. Piccardo et al., Nat. Photonics **17**, 822 (2023).

Spatiotemporal optical vortex



- N. Jhajj et al., Phys. Rev. X **6**, 031037 (2016).
 S. Hancock et al., Optica **6**, 1547 (2019).
 A. Chong et al., Nat. Phot. **14**, 350 (2020).
 S. Hancock et al, Phys. Rev. Lett. **127**, 193901 (2021).
 M. Porras, Opt. Lett. **48**, 367 (2023).
 C. Wan et al., eLight **3**, 11 (2023).
 A. Bekshaev, APL Photonics **9**, 110806 (2024).

But you can almost do what you want these days



Examples :

- M. Mounaix et al., Nat. Comm. **11**, 5813 (2020).
- D. Cruz-Delgado, et al., Nat. Photonics **16**, 686 (2022).
- X. Liu et al., Nat. Comm. **15**, 5435 (2024).
- Q. Cao et al., Nat. Comm. **15**, 7821 (2024).
- S. Huang et al., Sci. Advances **10**, eadn6206 (2024).
- W. Chen et al., Nat. Comm. **16**, 2818 (2025).



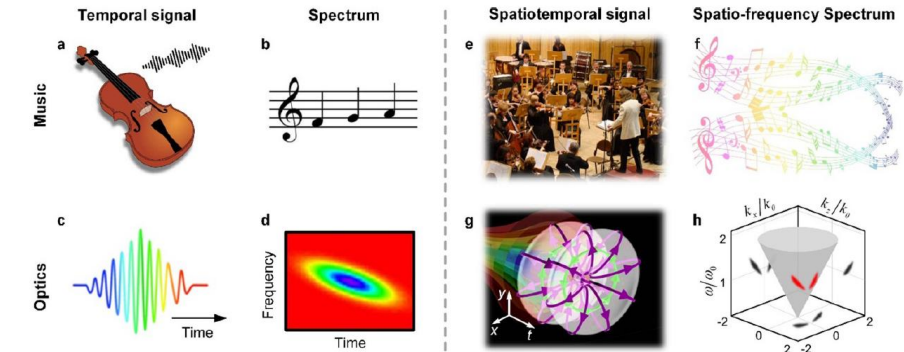
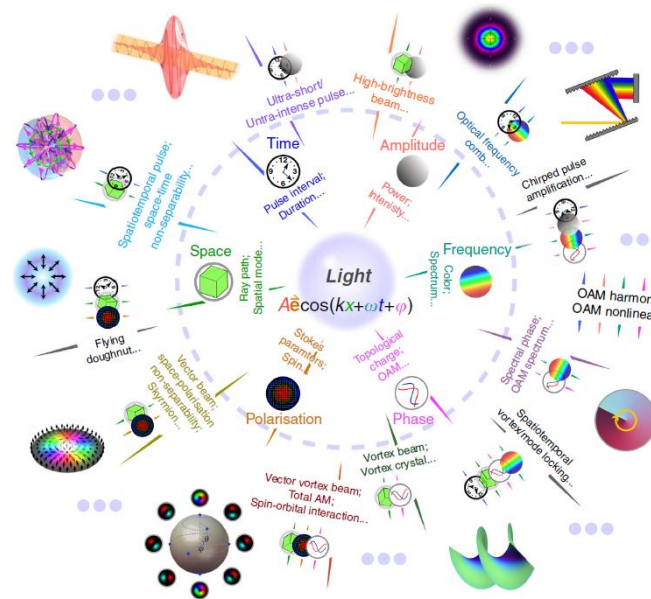
Tutorials :

- Qiwen Zhan, "Spatiotemporal sculpturing of light: a tutorial," Adv. Opt. Photon. **16**, 163-228 (2024).
- Murat Yessenov and Ayman F. Abouraddy, "Optical spatiotemporal Fourier synthesis: tutorial," J. Opt. Soc. Am. A **42**, 1295-1315 (2025).

Towards higher-dimensional structured light

Roadmap

Roadmap on spatiotemporal light fields



Higher-order Zernike STC

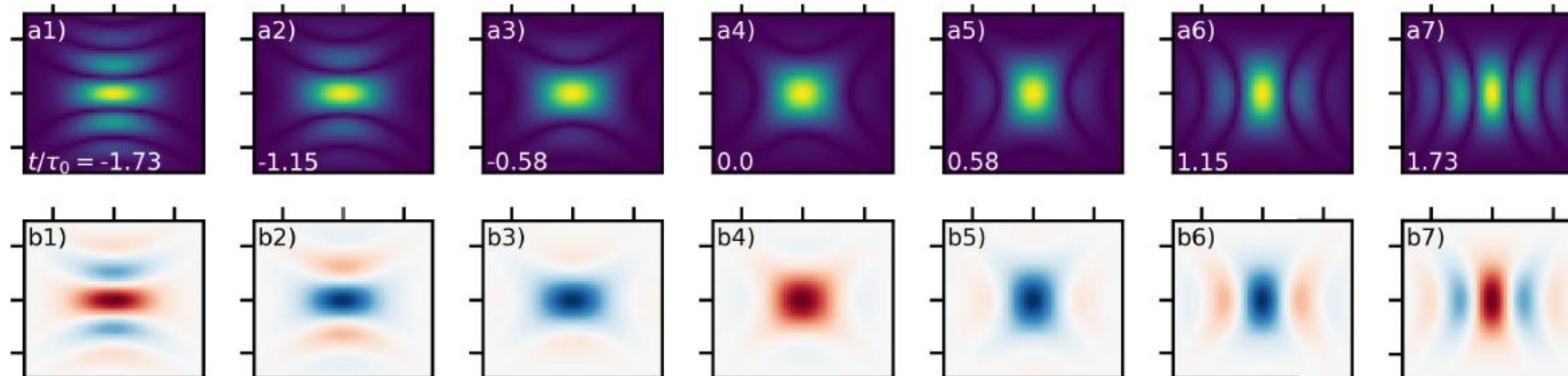
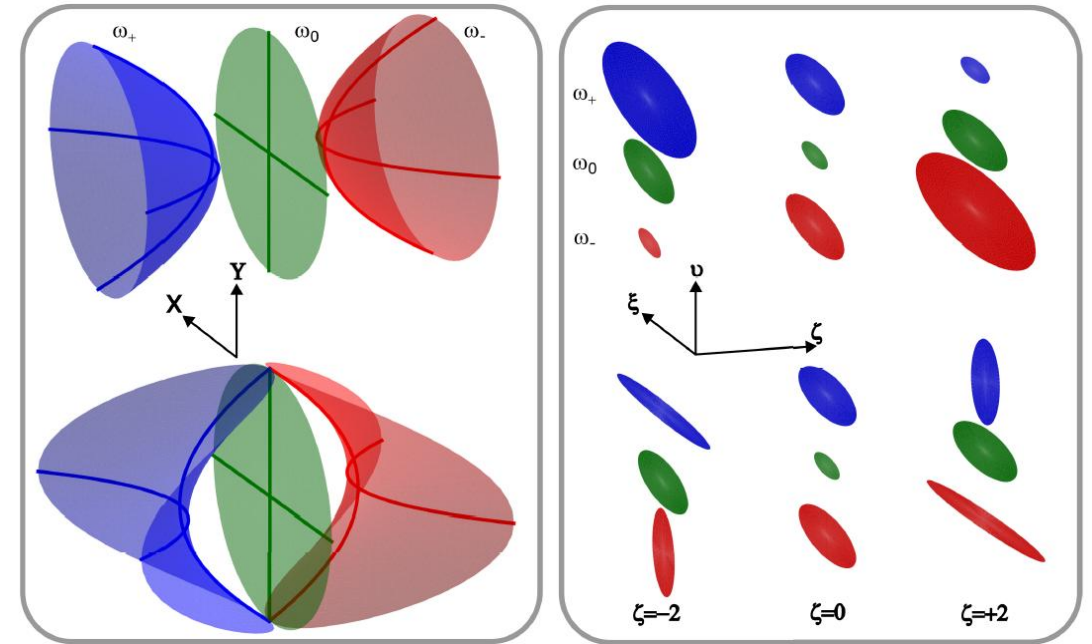
Research Article Vol. 31, No. 6/13 Mar 2023 / *Optics Express* 10237

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



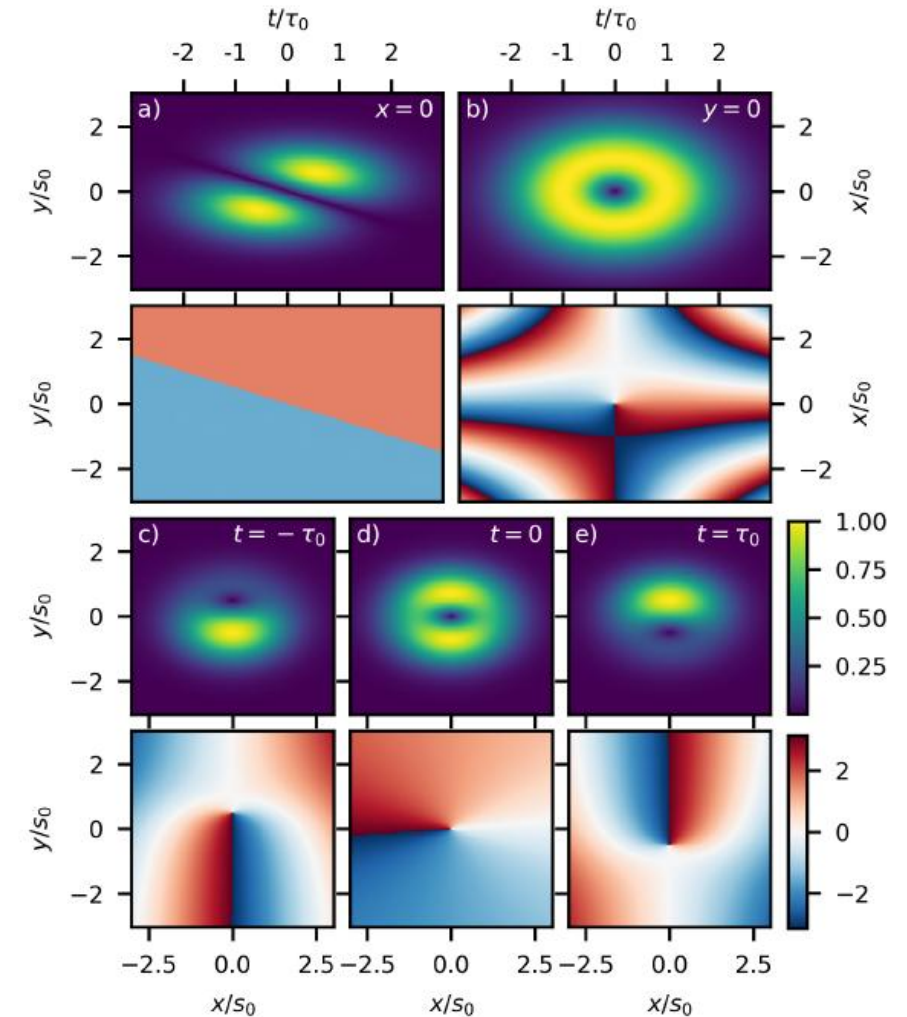
Vortex with spatial chirp



Article

Influence of Spatio-Temporal Couplings on Focused Optical Vortices

Anda-Maria Talposi^{1,2} , Vicentiu Iancu^{1,2}  and Daniel Ursescu^{1,2,*} 



A.-M. Talposi et al., *Photonics* **9**, 389 (2022).

M. A. Porras & S. W. Jolly, *Opt. Lett.* **48**, 6448 (2023).

Analytically modeling a vortex with spatial chirp

$$\hat{E} = \frac{w_0}{w(z)} e^{-i(l+1)\psi(z)} \left(\frac{\sqrt{2}(x \pm iy)}{w(z)} \right)^l e^{i\omega r^2/2cq} e^{i\omega z/c} e^{-(\omega-\omega_0)^2/\Omega_0^2}$$

(spatial chirp)

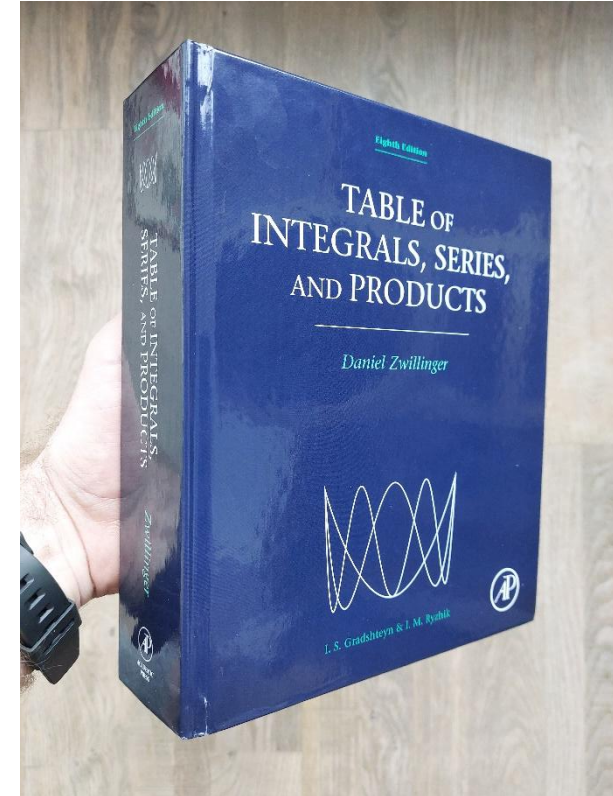
$$\hat{E} = \frac{w_0}{w(z)} e^{-i(l+1)\psi(z)} \left(\frac{\sqrt{2}(x - b\Omega \pm iy)}{w(z)} \right)^l e^{i\omega([x-b\Omega]^2+y^2)/2cq} e^{i\omega z/c} e^{-(\omega-\omega_0)^2/\Omega_0^2}$$

(Fourier transform)

$$E = \frac{E_0}{\alpha\Omega_0} e^{-i(l+1)\psi} \frac{s_0}{s} e^{\frac{i\omega_0(x^2+y^2)}{2cq}} e^{-\frac{(t'+\omega_0 bx/cq)^2}{4\alpha^2}} \left(\frac{\sqrt{2} ib}{s \alpha} \right)^l \\ \times \frac{1}{2^l} H_l \left\{ \left(\frac{\alpha}{ib} \right) \left[x \left(1 + \frac{i\omega_0 b^2}{\alpha^2 2cq} \right) \pm iy + i \frac{b}{2\alpha^2} t' \right] \right\} e^{-i\omega_0 t'}$$

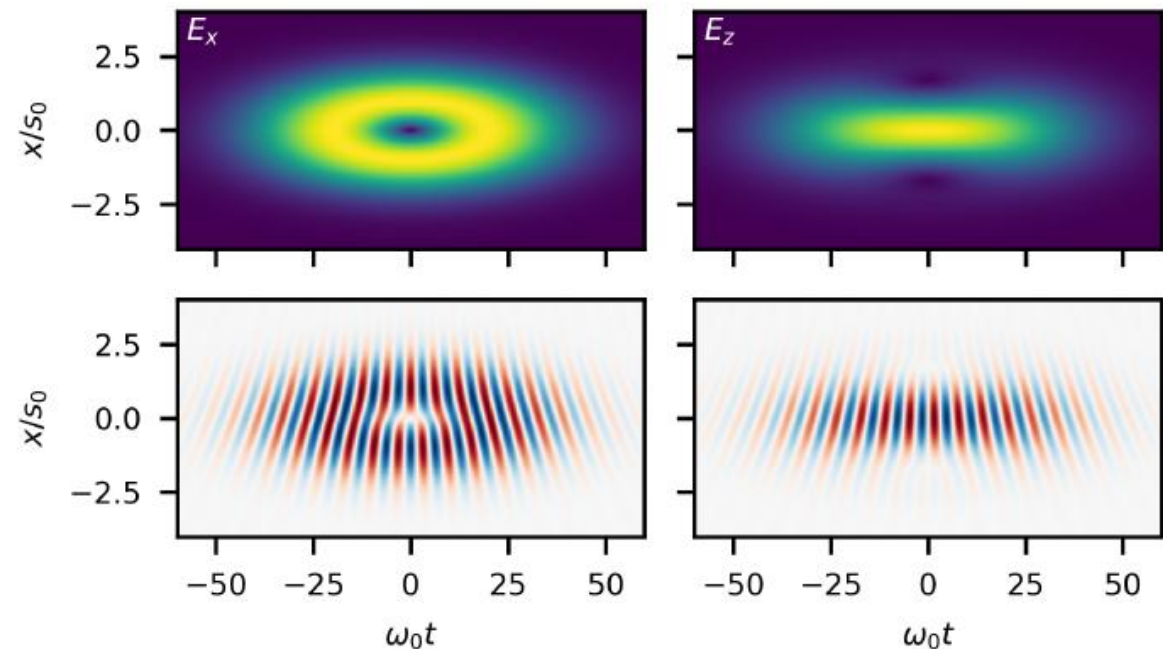
where

$$\alpha = \sqrt{\frac{1}{\Omega_0^2} - \frac{i\omega_0 b^2}{2cq}},$$



Analytical fields of ultrashort radially polarized laser beams with spatial chirp

SPENCER W. JOLLY^{1,*}  AND MIGUEL A. PORRAS^{2,3} 



S. W. Jolly & M. A. Porras, *JOSA B* **41**, 577 (2024).

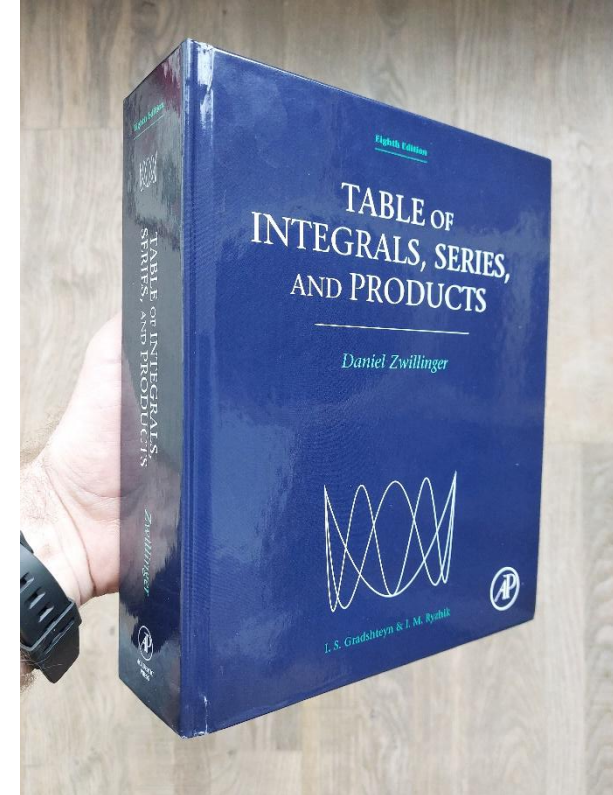
Analytically modeling a rad-pol with spatial chirp

$$E_x(x, y, z, t) = \frac{A}{\alpha s_0} e^{-(t'')^2/4\alpha^2} \left(x + i \frac{bt''}{2\alpha^2} \right),$$

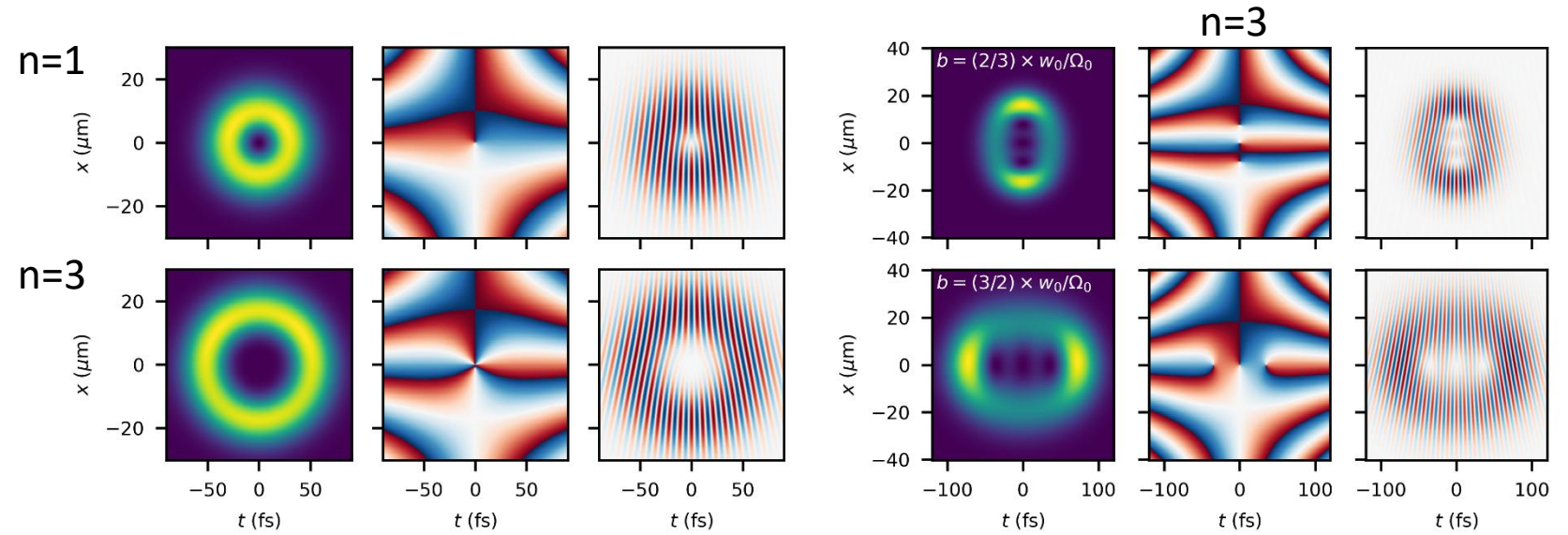
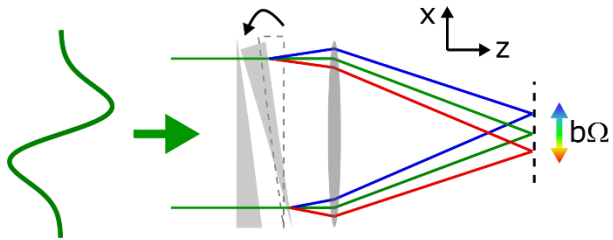
$$E_y(x, y, z, t) = \frac{A}{\alpha s_0} e^{-(t'')^2/4\alpha^2} y,$$

$$E_z(x, y, z, t) = \frac{iA}{\alpha z_R} e^{-(t'')^2/4\alpha^2} \times \left\{ 1 - \frac{e^{-i\psi_G(z)}}{s_0 s(z)} \times \left[x^2 + y^2 + \frac{b^2}{2\alpha^2} + \frac{ibt''x}{\alpha^2} - \frac{b^2(t'')^2}{4\alpha^4} \right] \right\},$$

$$t'' = t - \frac{z}{c} - \frac{(x^2 + y^2 - 2\omega_0 bx)}{2cq}.$$



Hermite-Gaussian with spatial chirp



Matched spatial chirp:
 A similar space-time vortex-
 like structure, but simpler
 than previous cases

Larger or smaller spatial chirp:
 An array of space-time
 vortices along x or t

Analytically modeling H-G with spatial chirp

$$\hat{E} = \frac{-iz_R}{q} \left(\frac{q^*}{4q} \right)^{n/2} e^{i\omega r^2/2cq} e^{i\omega z/c} e^{-(\omega-\omega_0)^2/\Omega_0^2} H_n \left(\frac{\sqrt{2}x}{w(z)} \right)$$

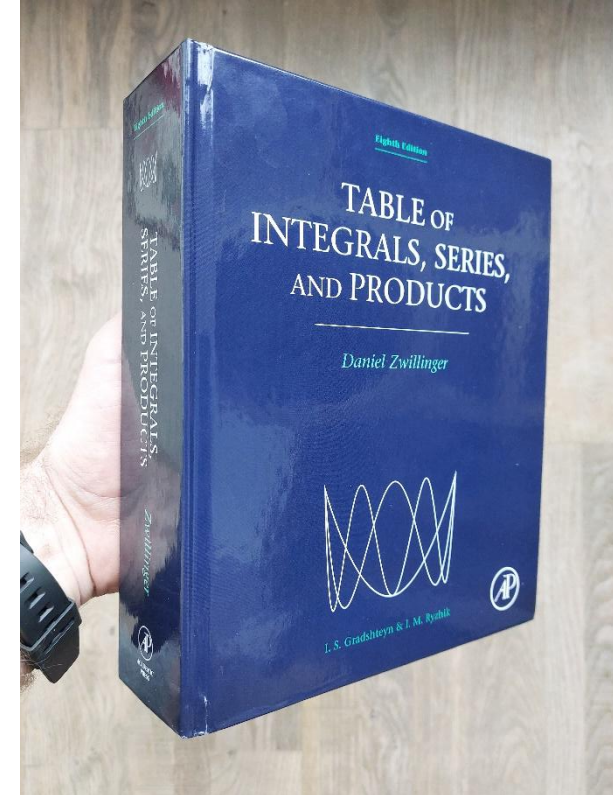
(spatial chirp)

$$\hat{E} = \frac{-iz_R}{q} \left(\frac{q^*}{4q} \right)^{n/2} e^{i\omega([x-b\Omega]^2+y^2)/2cq} e^{i\omega z/c} e^{-(\omega-\omega_0)^2/\Omega_0^2} H_n \left(\frac{\sqrt{2}[x-b\Omega]}{w(z)} \right)$$

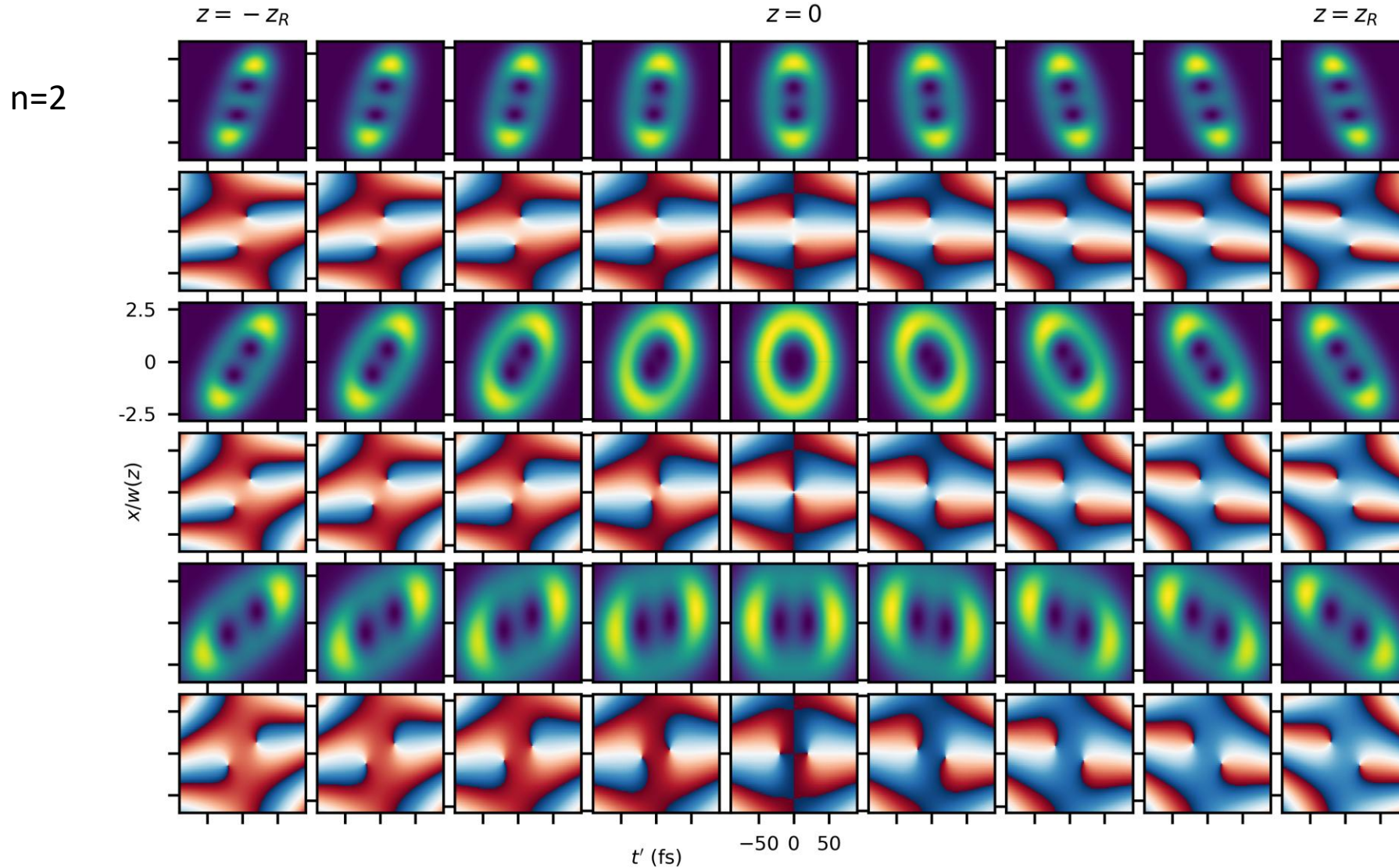
(Fourier transform)

$$E = \frac{iz_R}{q} \left(\frac{q^*}{4q} \left(1 - \frac{2b^2}{\alpha^2 w(z)^2} \right) \right)^{n/2} \times \frac{e^{-i\omega_0 t'}}{2\pi\alpha} e^{i\omega_0(x^2+y^2)/2cq} e^{-(t'')^2/4\alpha^2} \times H_n \left(\frac{\frac{\alpha x}{b} + \frac{i}{2\alpha} t''}{\sqrt{\frac{\alpha^2 w(z)^2}{2b^2} - 1}} \right),$$

$$t'' = t - \frac{z}{c} - \frac{(x^2 + y^2 - 2\omega_0 b x)}{2cq}.$$

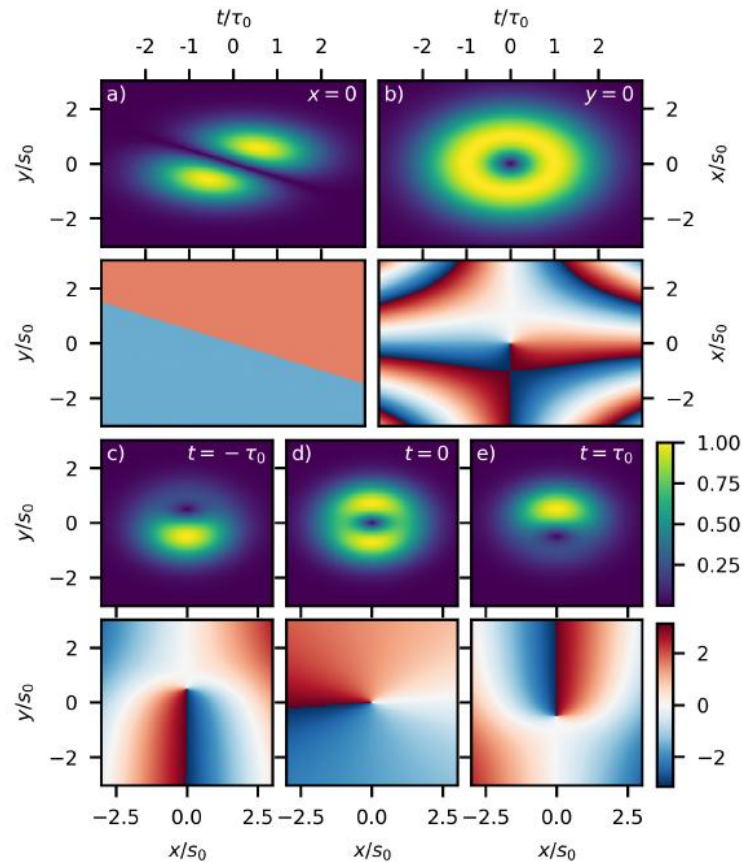


Propagation

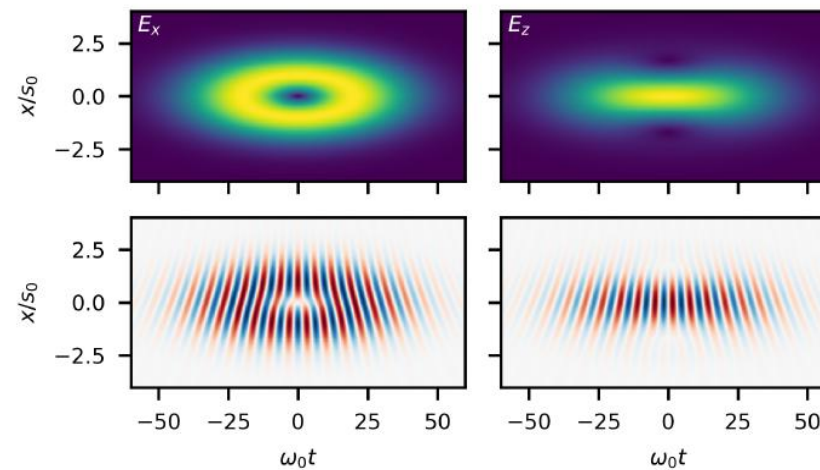


Notice something in common?

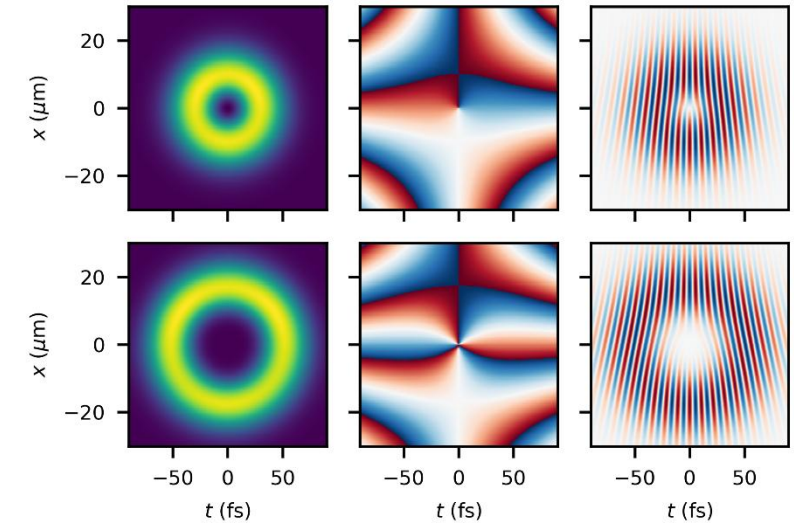
Vortex (LG) with spatial chirp



Rad-pol with spatial chirp

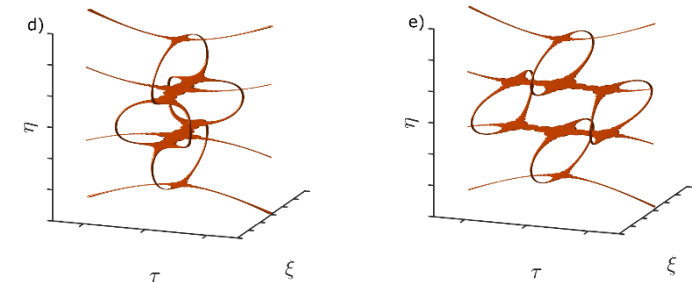
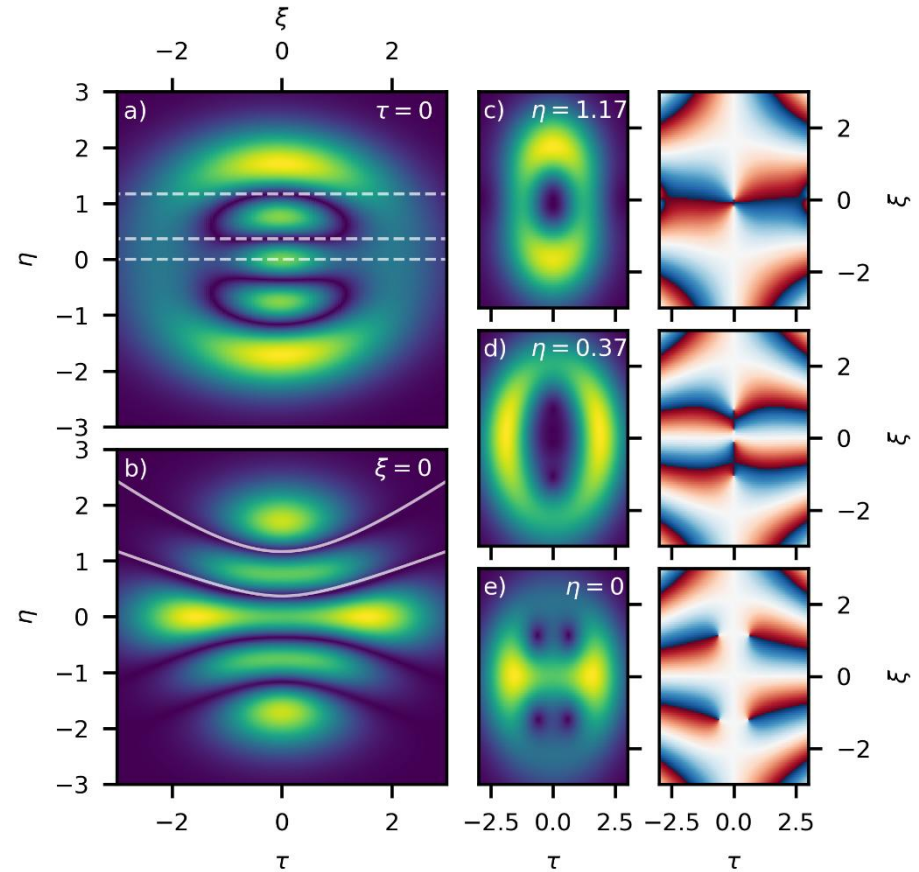
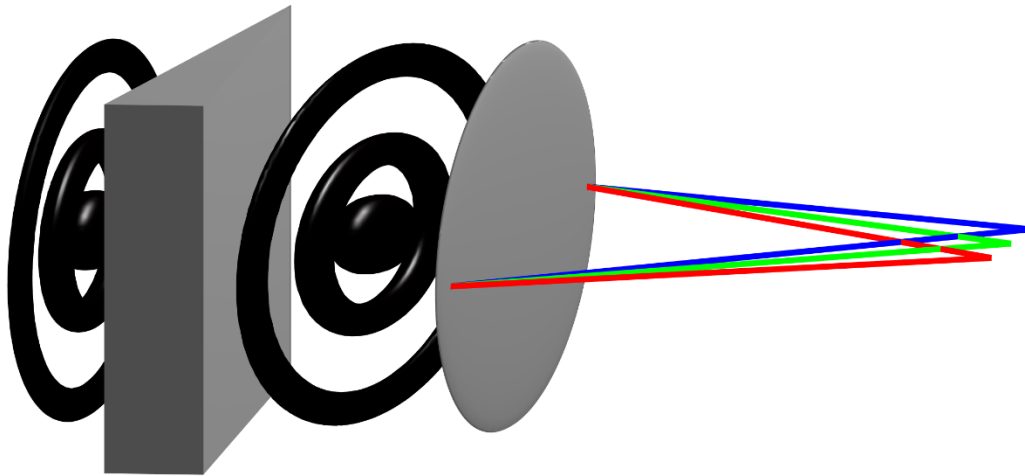


HG with spatial chirp

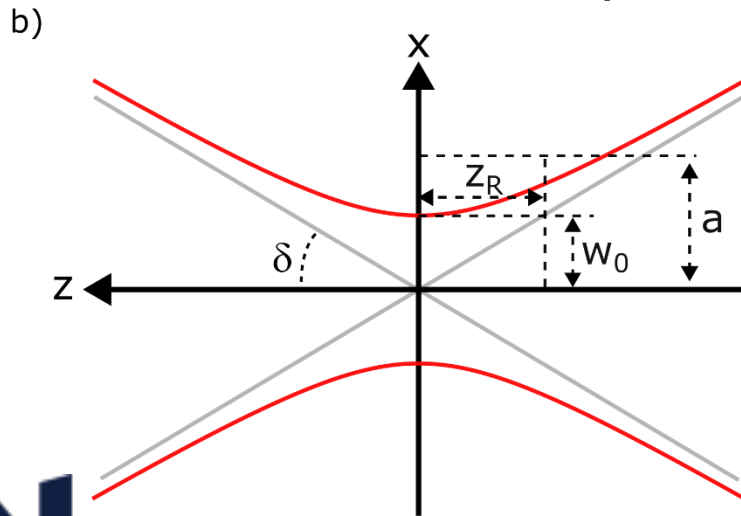
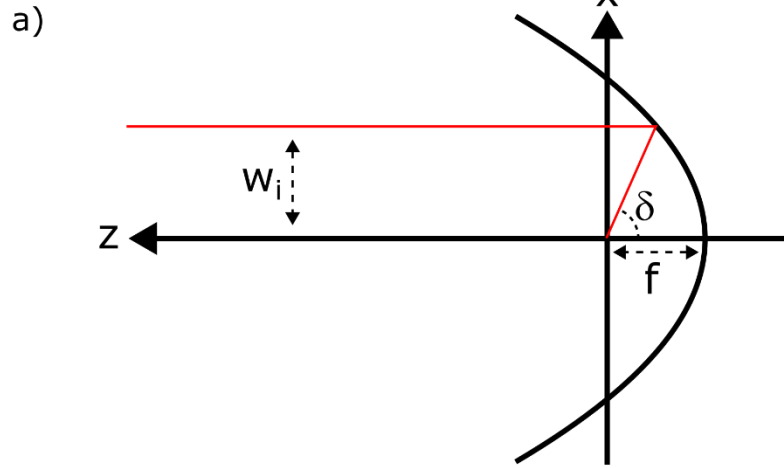


There is also some sort of mystical connection here, like for CW vector and LG/HG beams, but now it is via spatial chirp and space-time vortices.

Recent work with general Laguerre-Gaussian beams



Going Further → highly non-paraxial case



- Previous solutions are not accurate with high NA
- Spherical waves, complex source model, Hertz potentials, ... , ... , numerical Fourier transform
- The scaling of space-time effects [NF→FF] changes
- Vector components are complicated
- Compare to diffraction-integral methods (some overlap with Q. Zhan's work)

→ Nanometric SSTF or flying focus

→ Important for focusing to high intensity

→ Nanophotonics!

→ Atomic or molecular control?

Similar model and approach for non-paraxial STOVs

J. Opt. **26** (2024) 095607 (12pp)

<https://doi.org/10.1088/204>

Closed forms for spatiotemporal optical vortices and sagittal skyrmionic pulses

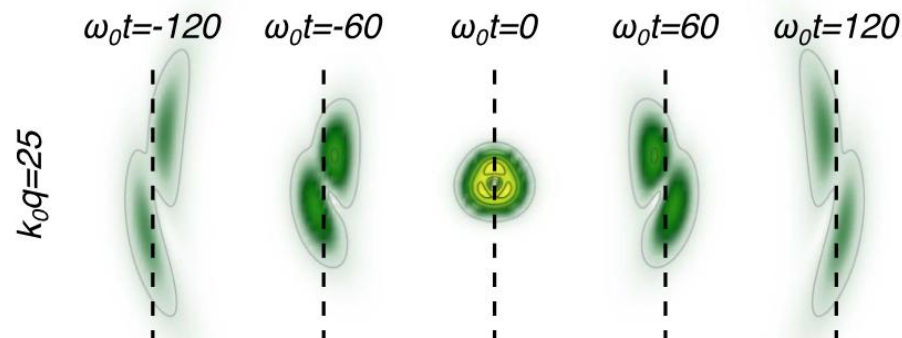
S Vo¹, R Gutiérrez-Cuevas²  and M A Alonso^{1,3,4,*} 

¹ The Institute of Optics, University of Rochester, Rochester, NY 14627, United States of America

² Institut Langevin, ESPCI Paris, Université PSL, CNRS, 75005 Paris, France

³ Aix Marseille Univ, CNRS, Centrale Med, Institut Fresnel, UMR 7249, Marseille Cedex 20, 13397, France

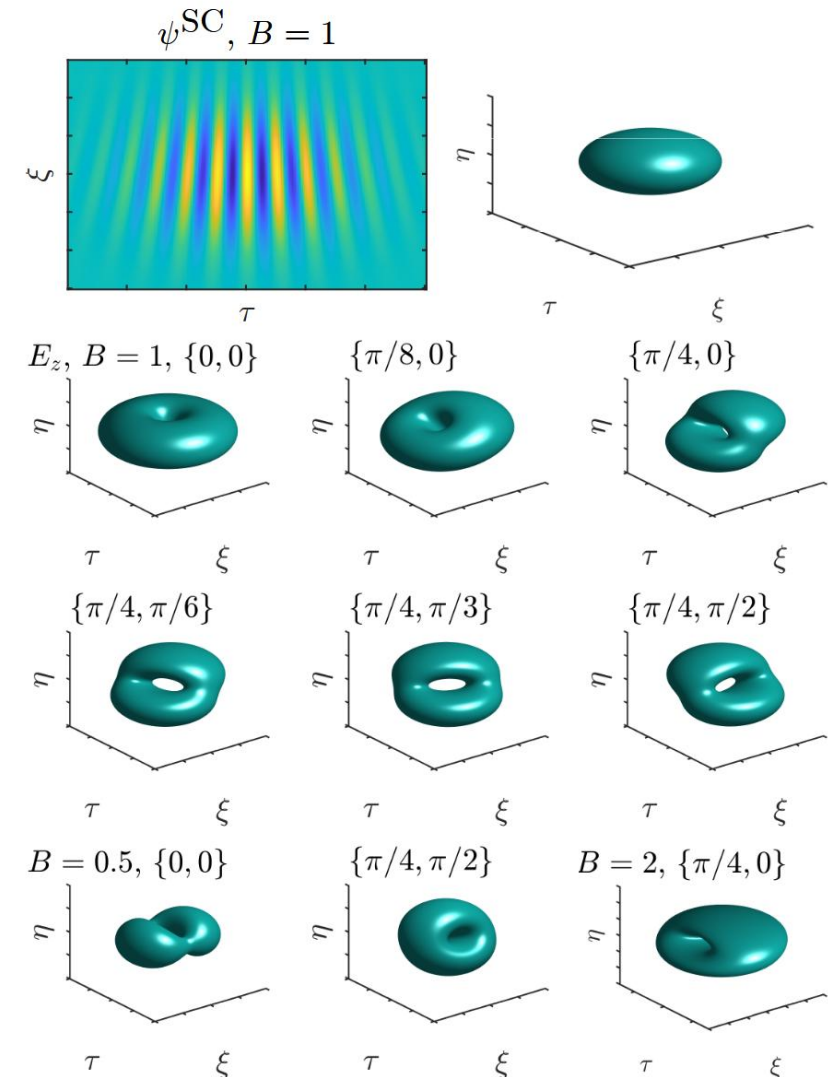
⁴ Laboratory for Laser Energetics, University of Rochester, Rochester, NY 14627, United States of America



- Using the same complex-source model as the previous slide
- Constructing non-paraxial STOVs from a sum of the “basic” solution and temporal and spatial derivatives of itself
- Then enforcing that the STOV is round

Taking a step back

- We went right to combing “structured light” or “higher-order” beams with spatial chirp
- But actually, even looking at a Gaussian beam is interesting
- One last complication, let’s consider an elliptically-polarized Gaussian beam with spatial chirp



(Small advertisement ...)

LASY

LASY : LAsEr manipulations made eaSY



Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG



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

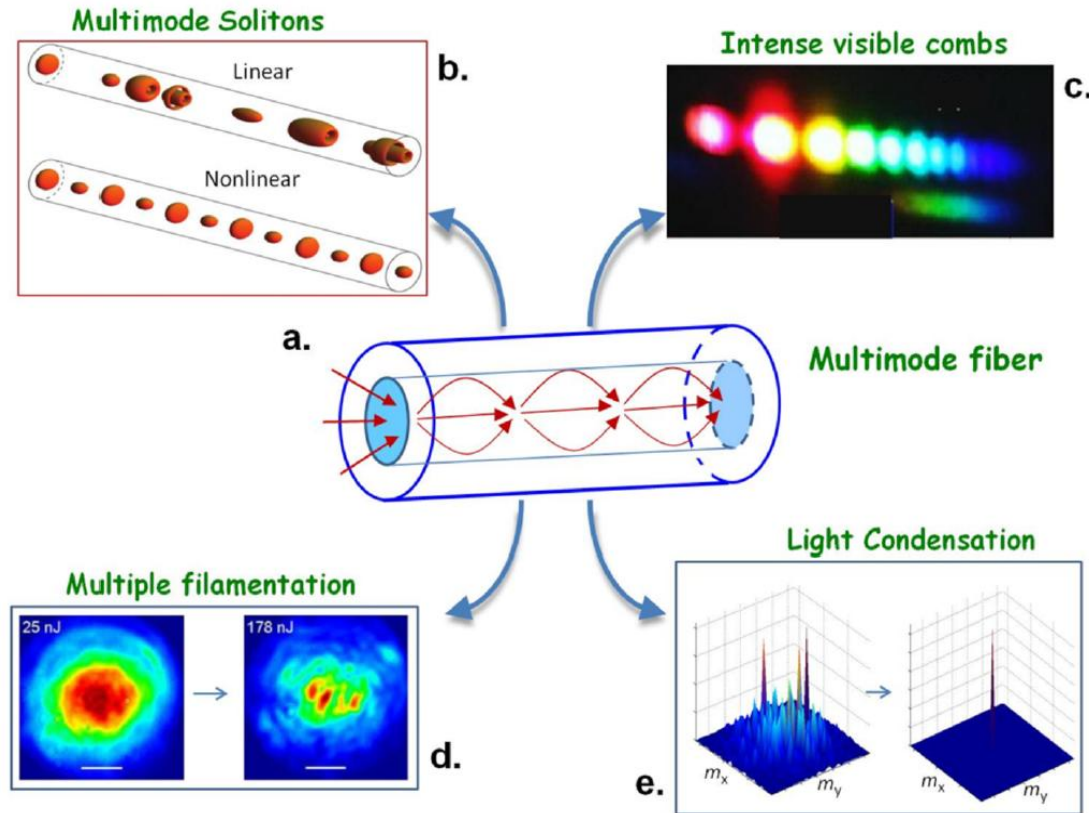
1) Theoretical input of STCs (me and others)

2) Experimental input of STCs (SourceLab SAS)

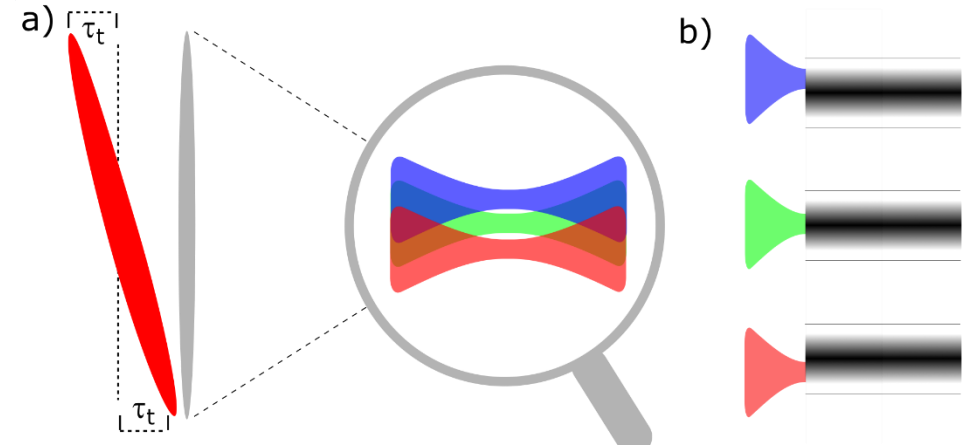


Another part of my work → multimode fibers

Like space-time effects, BUT with discrete spatial modes (and their propagation constants), in a rich nonlinear environment



Pumping MM fibers with space-time light



Z. Guang & Y. Zhang, Appl. Opt. **57**, 9835 (2018).

Q. Cao et al., Adv. Photonics **5**, 036002 (2023).

C. Zhang et al., Photonics **11**, 328 (2024).

D. Cruz-Delgado et al., Nat. Comm. **16**, 6081 (2025).

My "team" :

S. W. Jolly & P. Kockaert, J. Opt. **25**, 054002 (2023).

J. Dechanxhe et al., Opt. Continuum **4**, 1489 (2025).

S. W. Jolly et al., J. Opt. **27**, 075503 (2025).

Review papers:

K. Krupa et al., APL Photonics **4**, 110901 (2019).

L. G. Wright et al., Optica **9**, 824 (2022).

L. G. Wright et al., Nat. Phys. **18**, 1018 (2022).

Feel free to contact me → spencer.jolly@ulb.be

QUESTIONS?