AN INTRODUCTION TO FEMTOSECOND LASER SCIENCE

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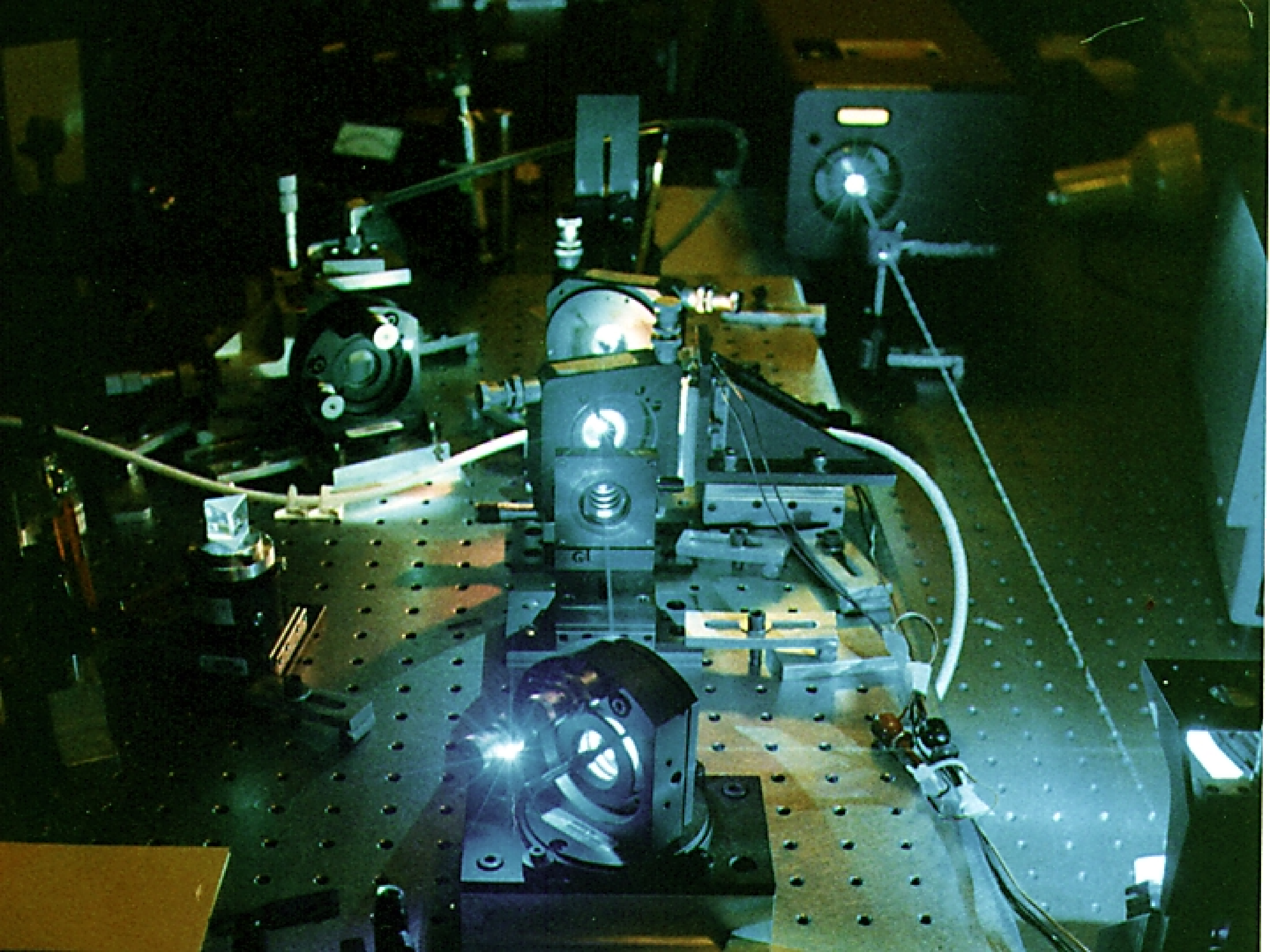
Harvard University

Short Course SC101
OSA Annual Meeting 2003, Tucson AZ



Outline

- **linear and nonlinear propagation**
- **femtosecond measurements**
- **examples**

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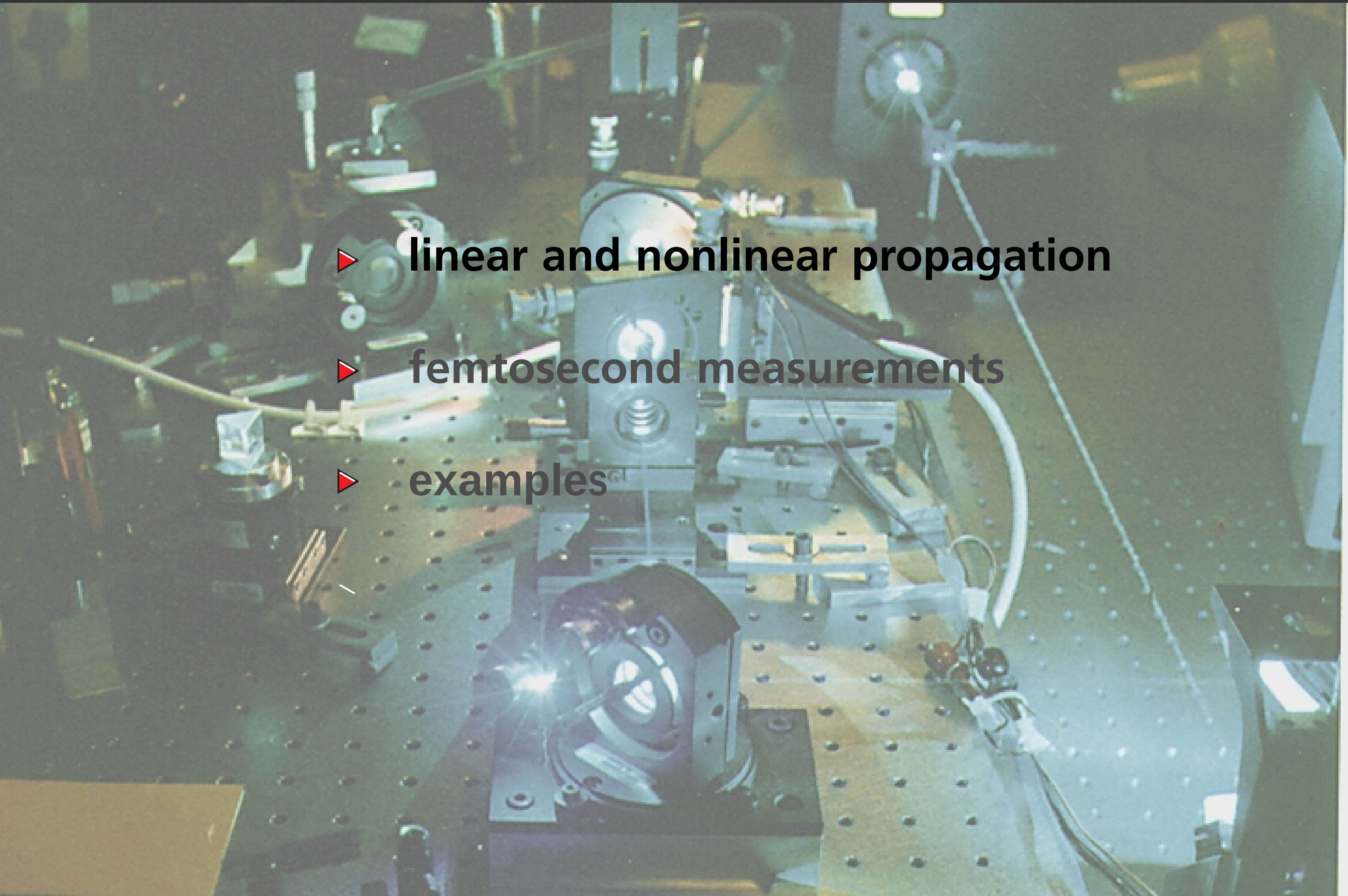

- **linear and nonlinear propagation**
- femtosecond measurements
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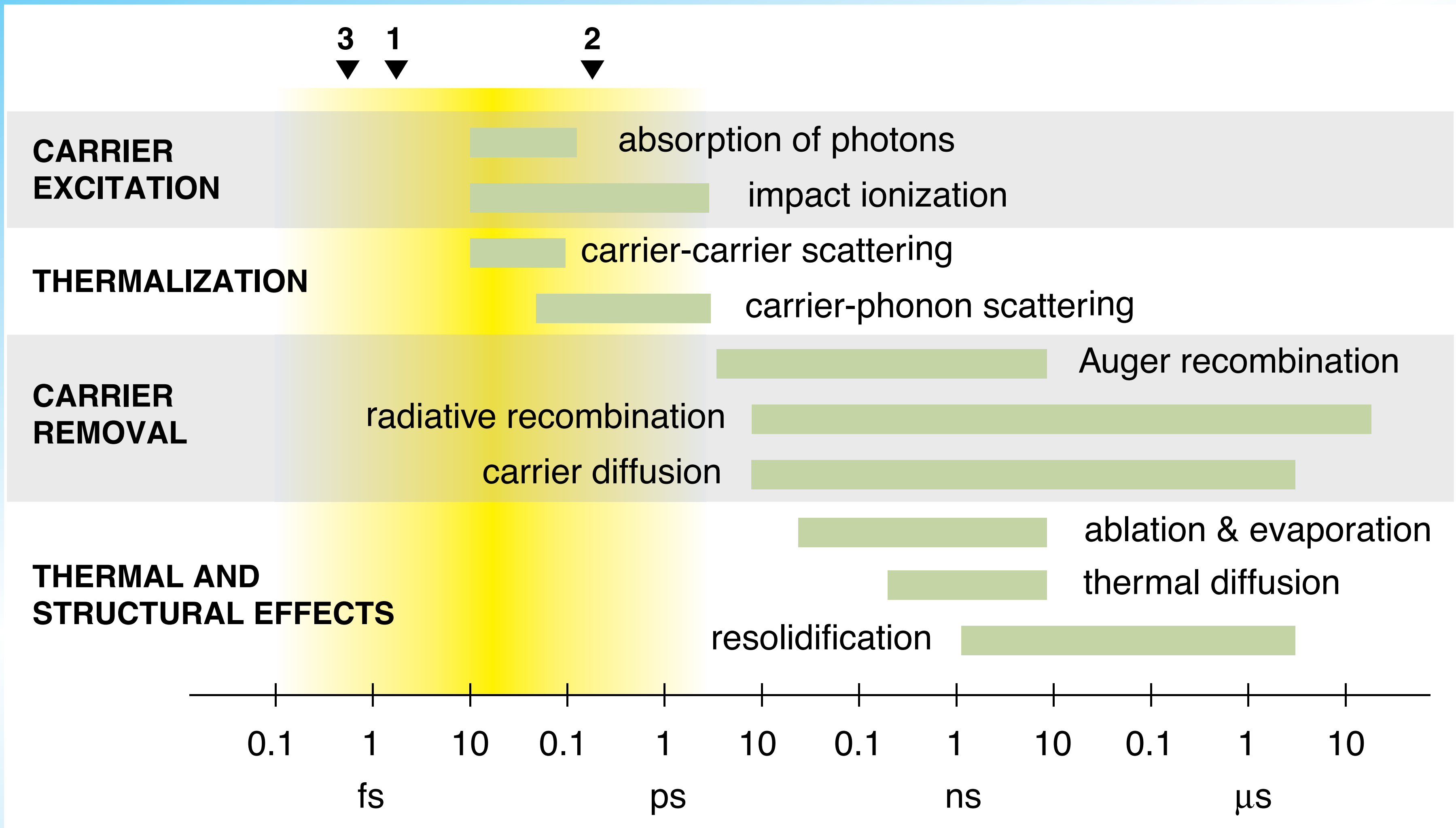
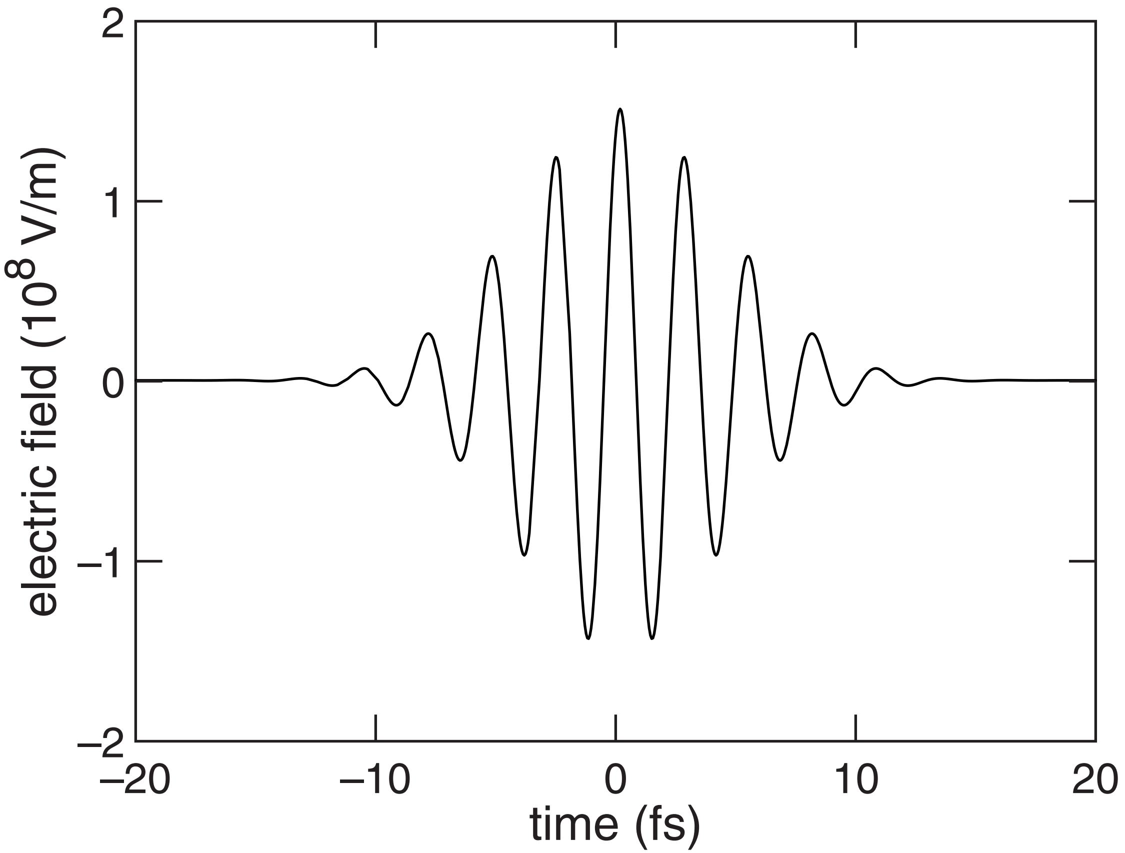
Introduction



Introduction



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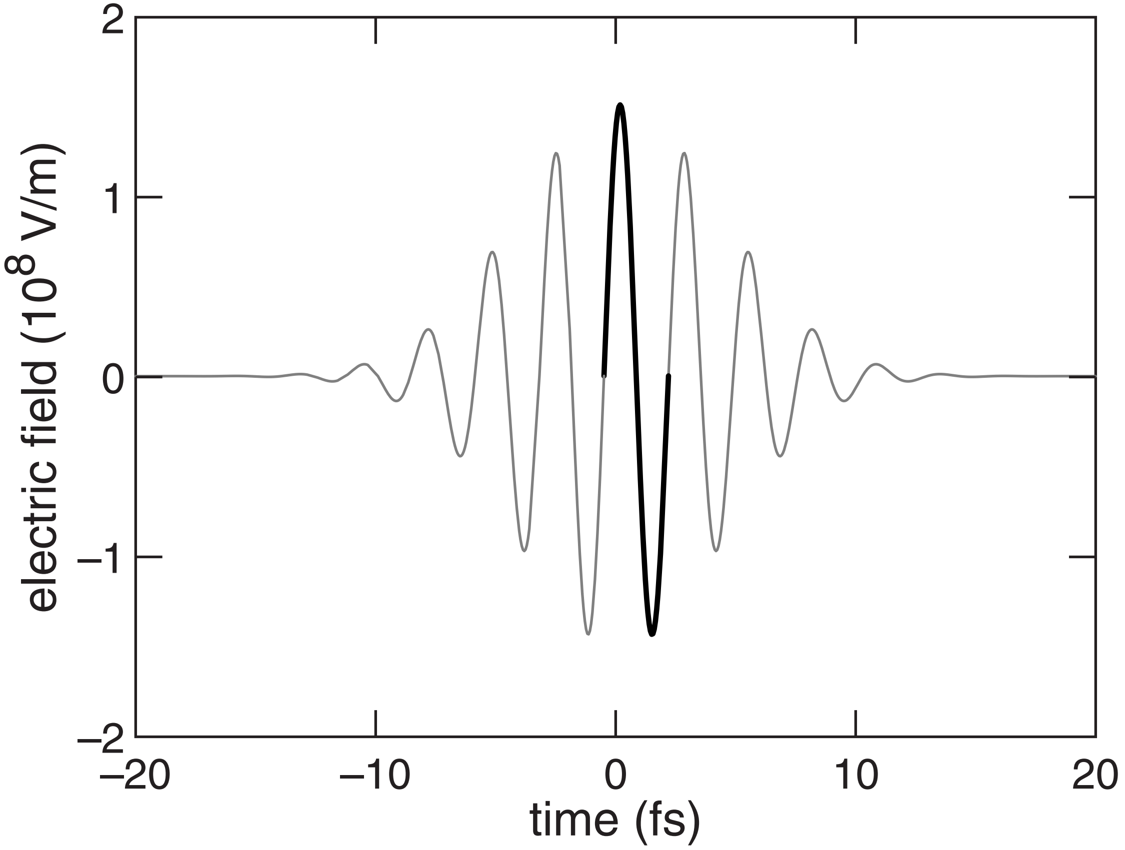

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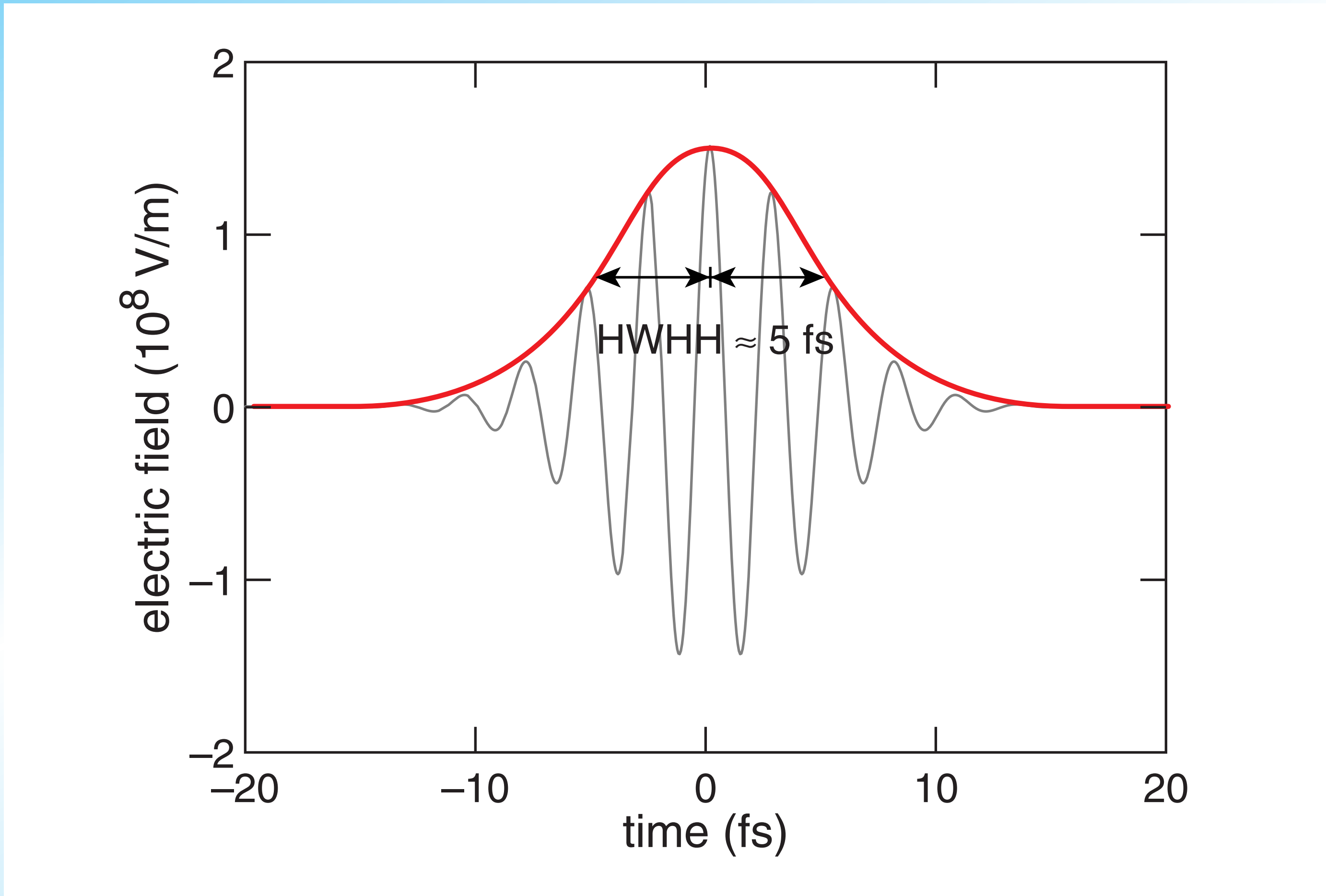

Introduction

- time resolution
- high intensity
- nonlinear optics
- new physics

Propagation of EM waves through medium

Governed by wave equation

$$\nabla^2 \vec{E} - \frac{\mu\epsilon}{c^2}\frac{\partial^2 \vec{E}}{\partial t^2} = 0$$

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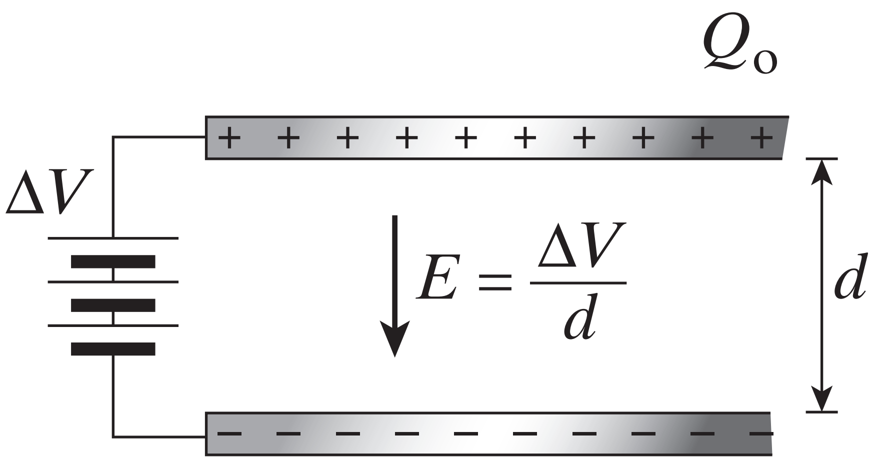
In non-ferromagnetic media $\mu \approx 1$**, and so** $n \approx \sqrt{\epsilon}$**.**

In dispersive media $n = n(\omega)$**.**

Propagation of EM waves through medium

Dielectric constant measures increase in capacitance

$$\epsilon = \frac{C_d}{C_o}$$



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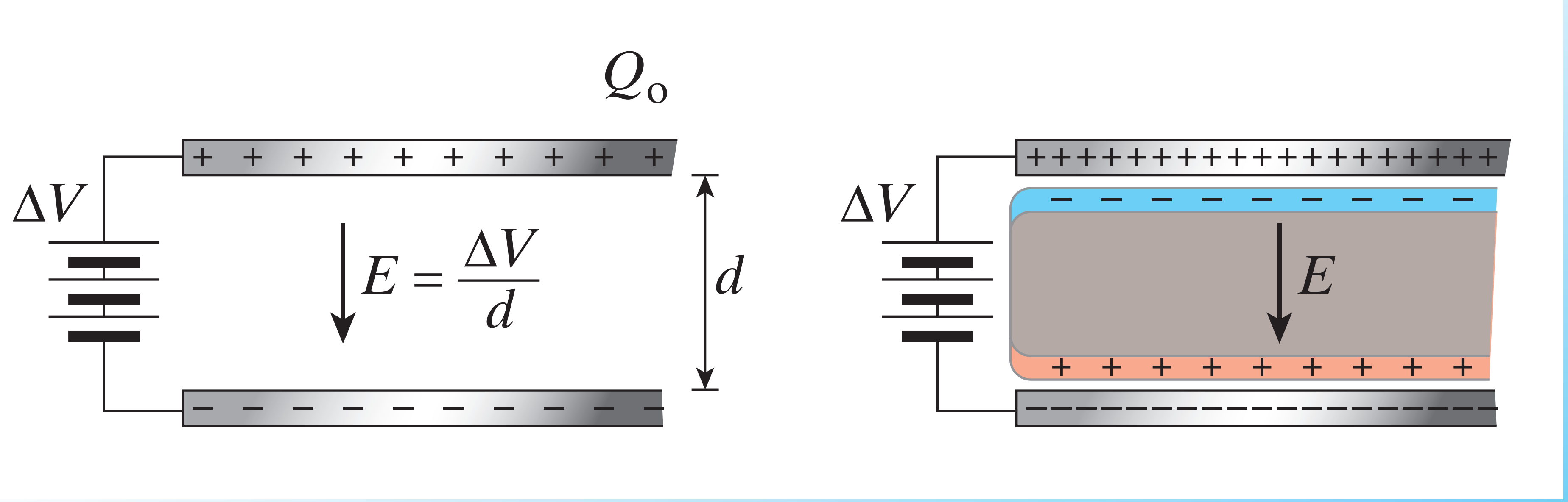

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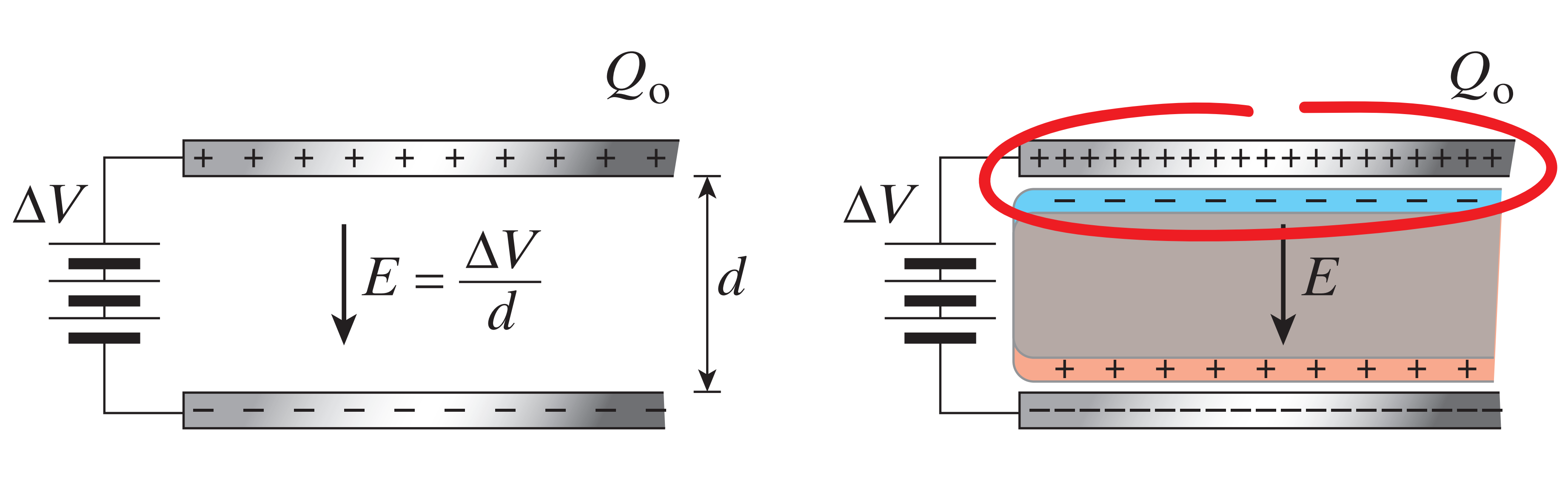

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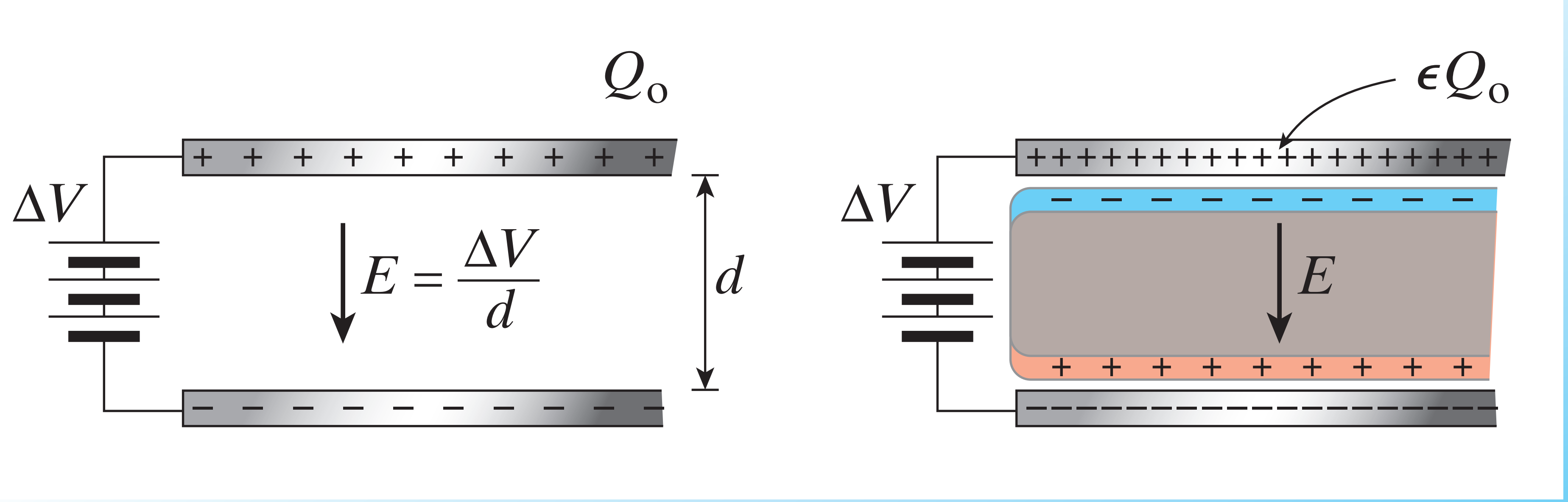
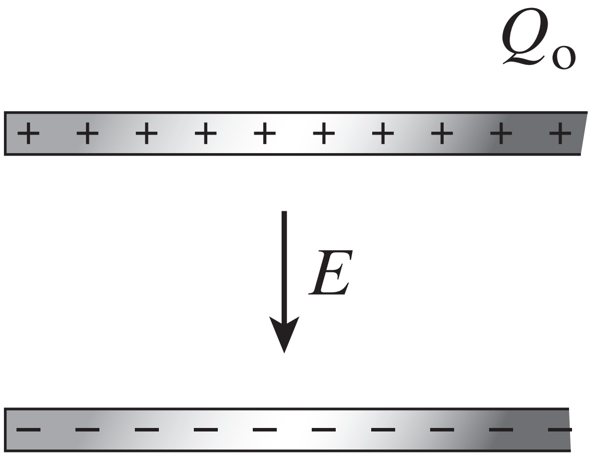


Propagation of EM waves through medium

Alternatively, ϵ is measure of the attenuation of the field



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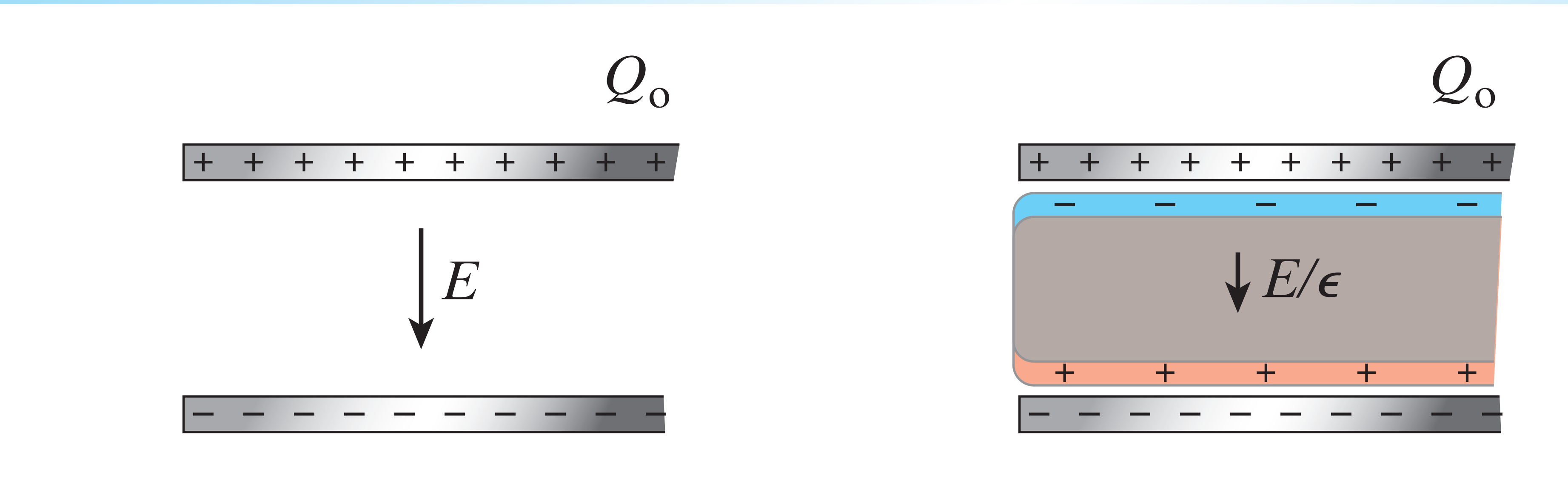
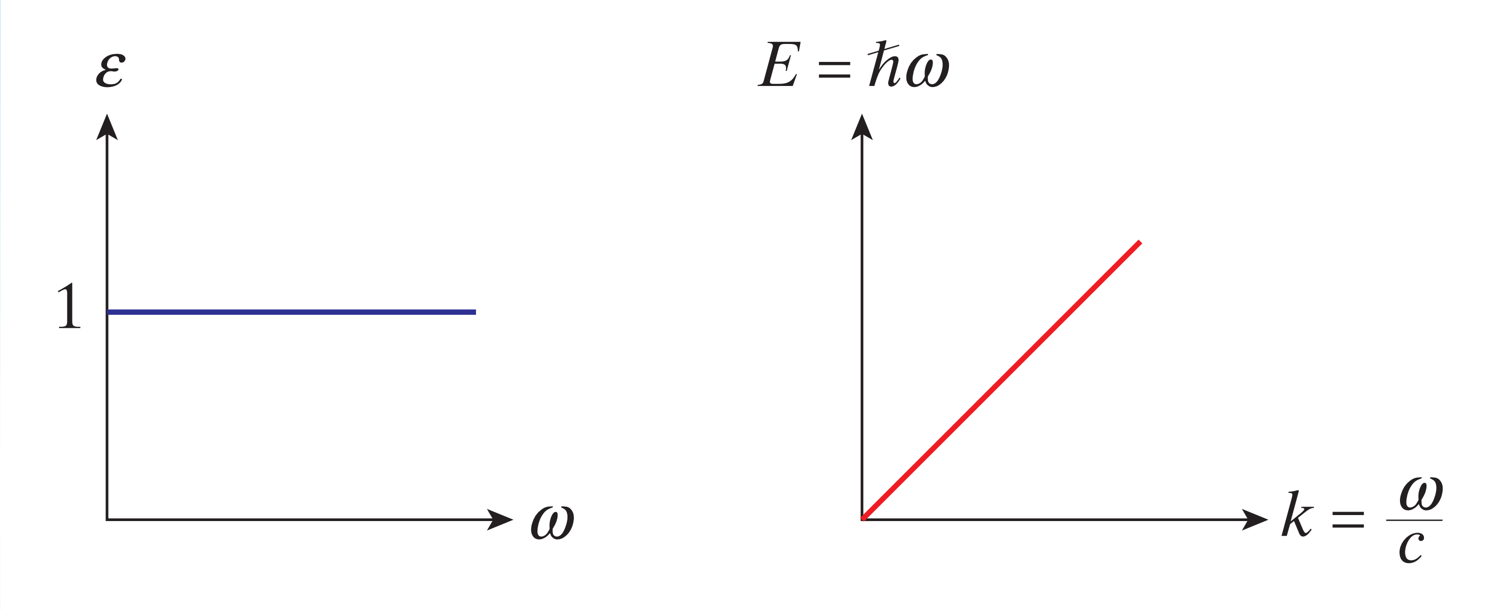


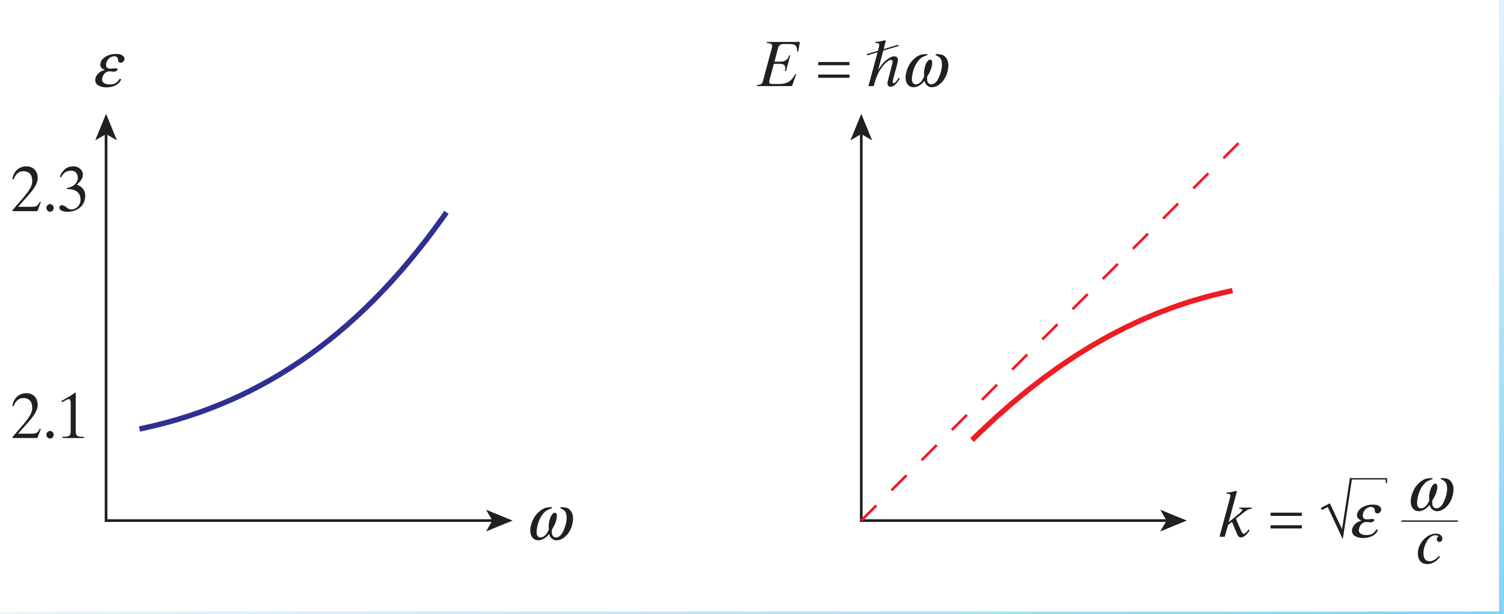
Propagation of EM waves through medium

In vacuum: $f\lambda = \dfrac{\omega}{k} = c \quad \Rightarrow \quad \omega = c\,k$

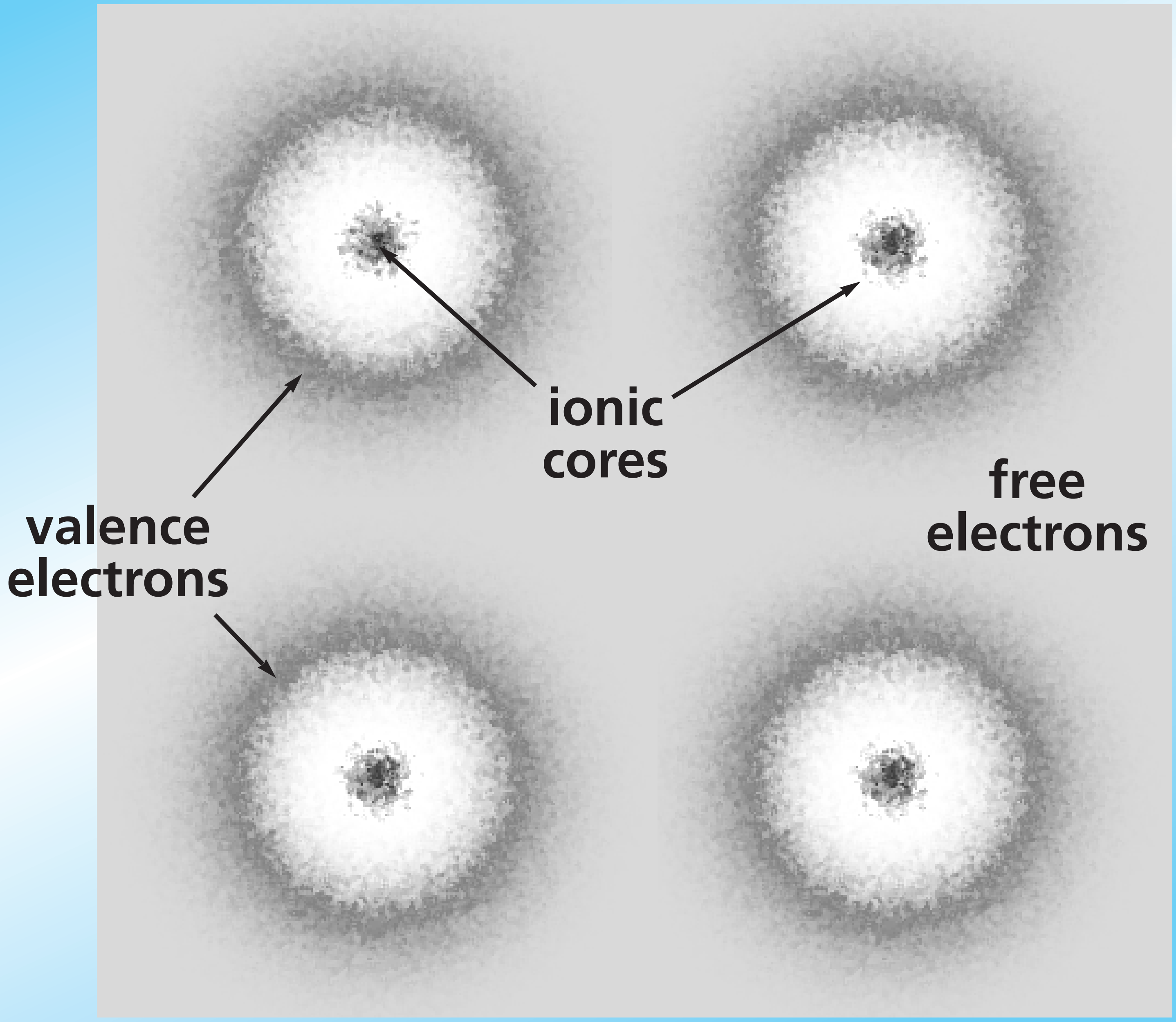


Propagation of EM waves through medium

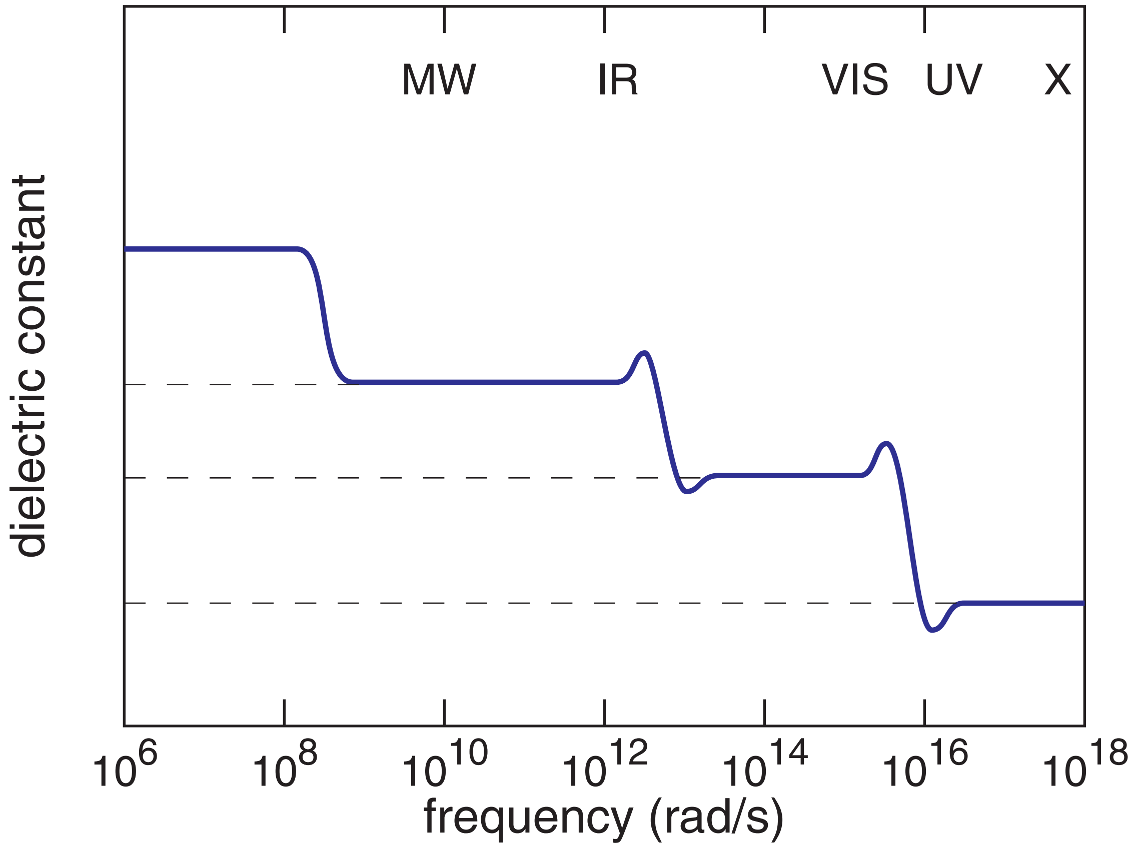
In medium: $$v = \frac{c}{\sqrt{\epsilon(\omega)}} = \frac{c}{n} \quad \Rightarrow \quad \omega = \frac{c}{\sqrt{\epsilon}} k$$



Which charges participate?



Dielectric function



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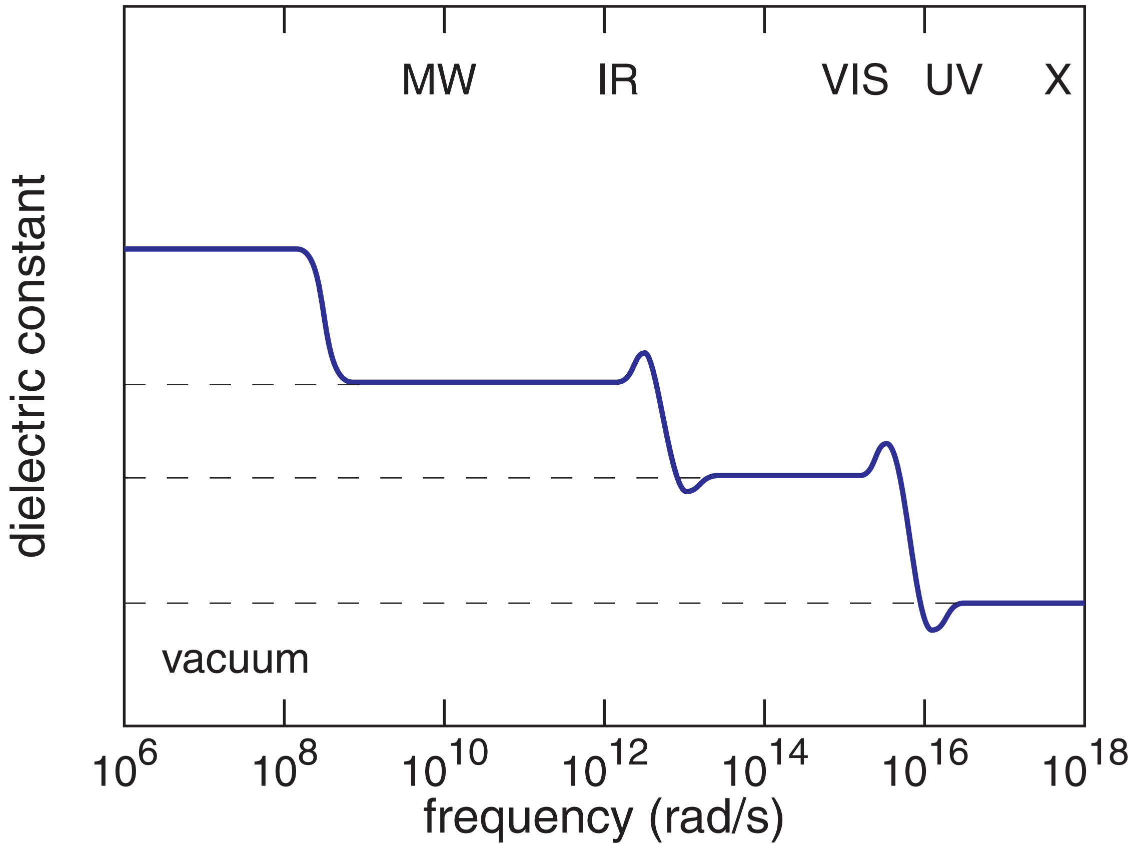

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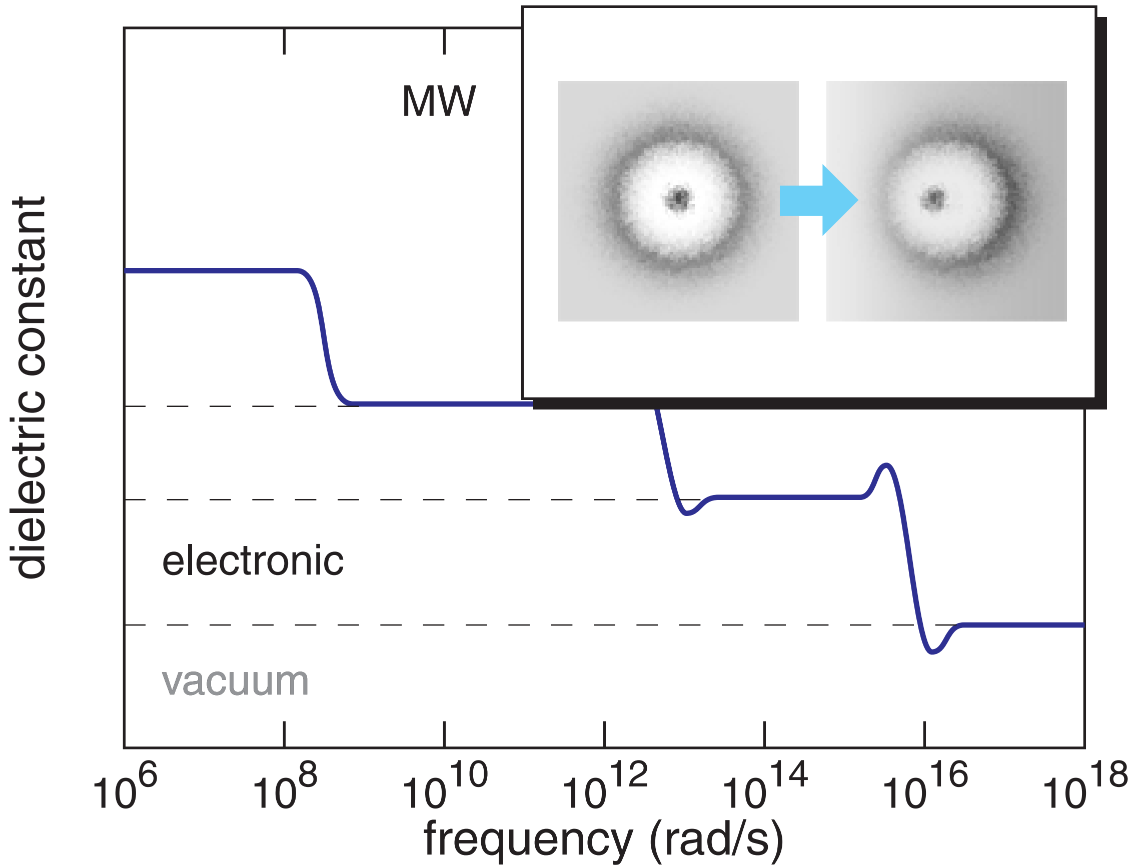

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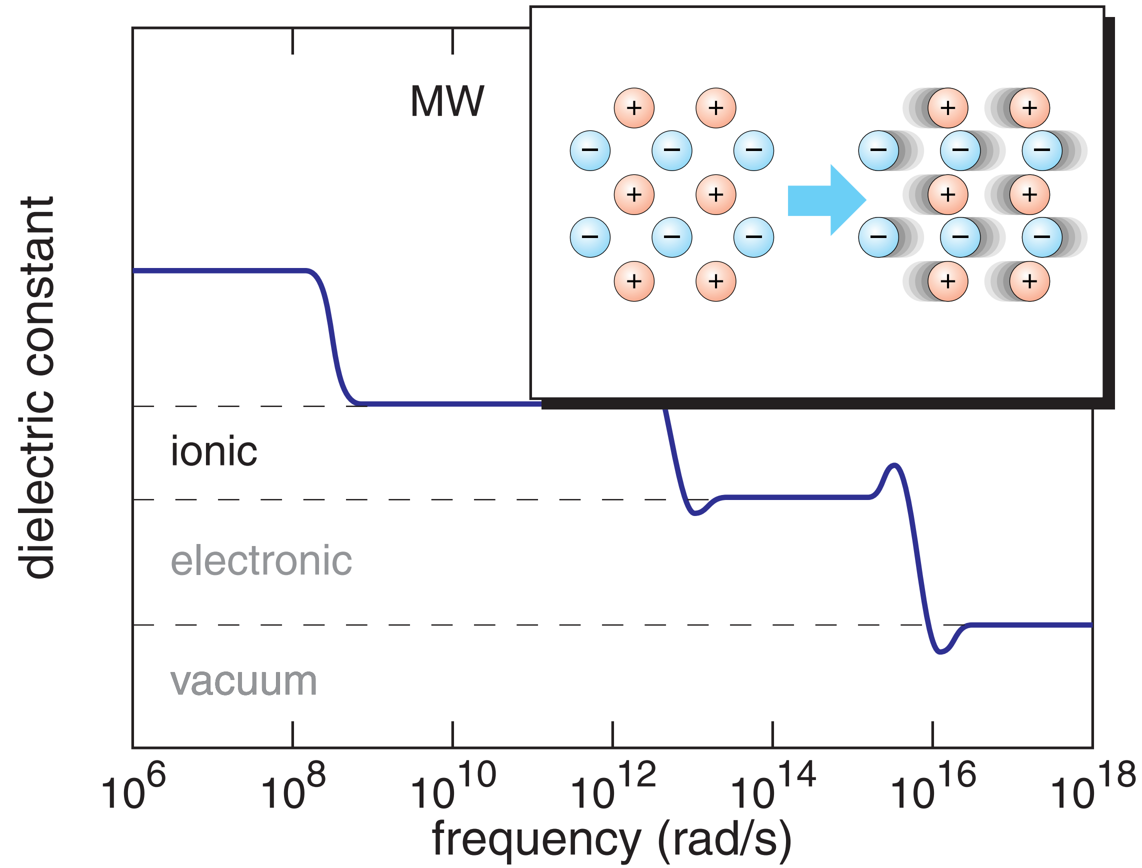

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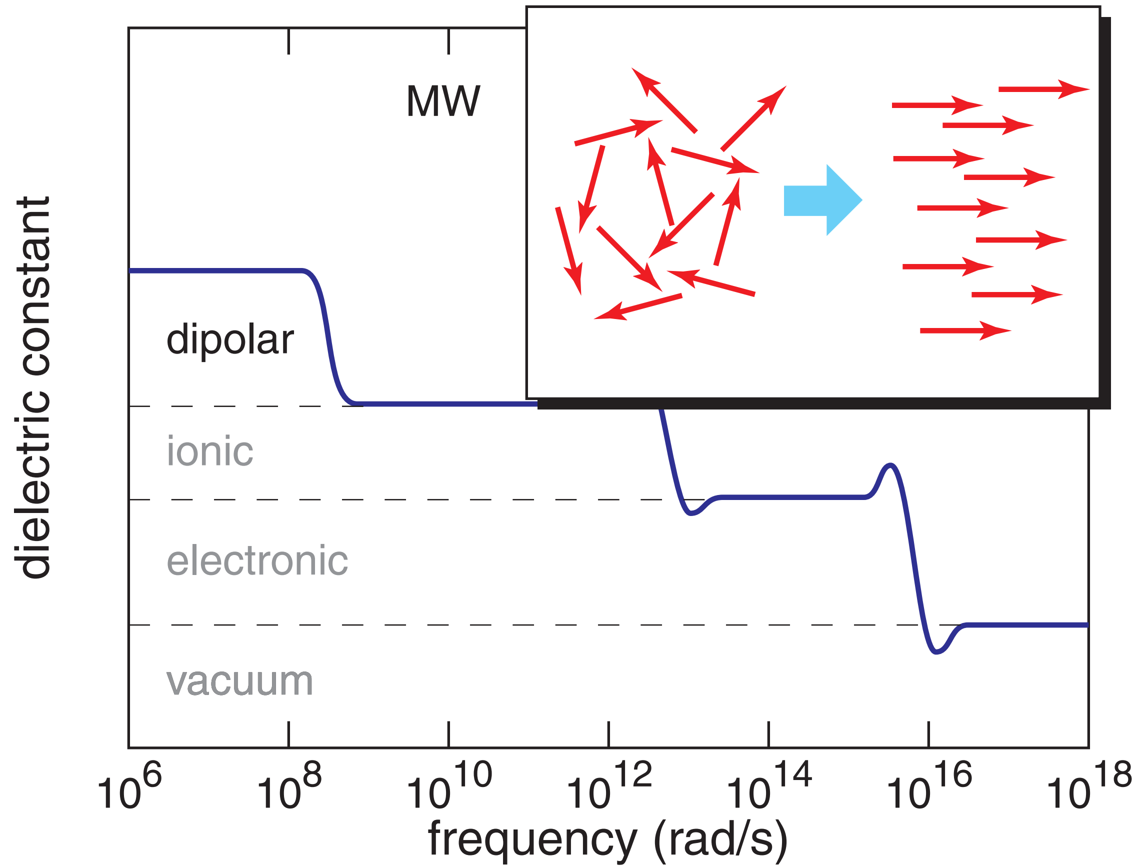

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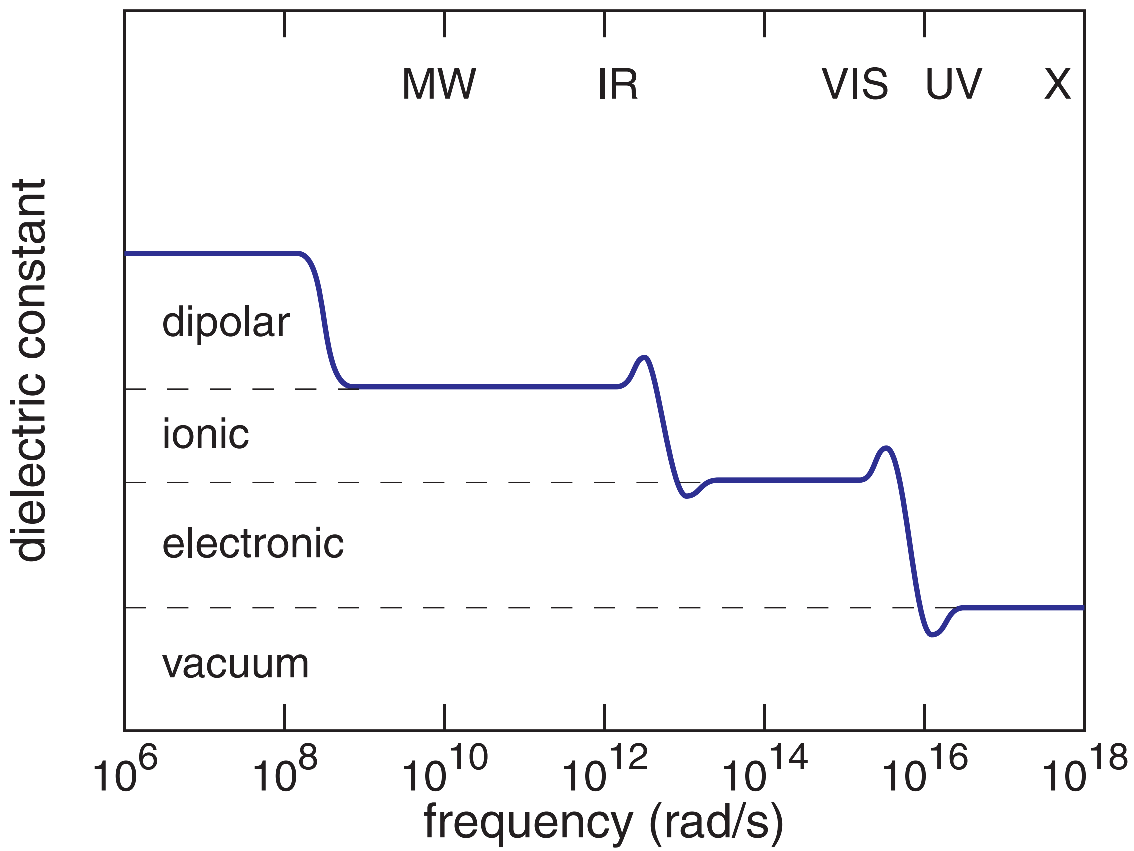

Electron on a string:

$$F_{binding} = -m_e \omega_o^2 x$$

Bound electrons

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$$m\frac{d^2x}{dt^2} + m\gamma\frac{dx}{dt} + m\omega_o^2 x = -eE$$

Bound electrons

Steady state: electron oscillates at driving frequency

$$x(t) = x_o e^{-i\omega t} \qquad x_o = -\frac{e}{m}\frac{1}{(\omega_o^2 - \omega^2) - i\gamma\omega}E_o$$

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Oscillating dipole

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Polarization

$$P(t) = \left(\frac{Ne^2}{m}\right)\sum_j \frac{f_j}{(\omega_j^2 - \omega^2) - i\gamma_j\omega}E(t) \equiv \epsilon_o\chi_e E(t)$$

Dielectric function

$$\epsilon(\omega) \equiv 1 + \chi_e = 1 + \frac{Ne^2}{\epsilon_o m} \sum_j \frac{f_j}{(\omega_j^2 - \omega^2) - i\gamma_j \omega}$$

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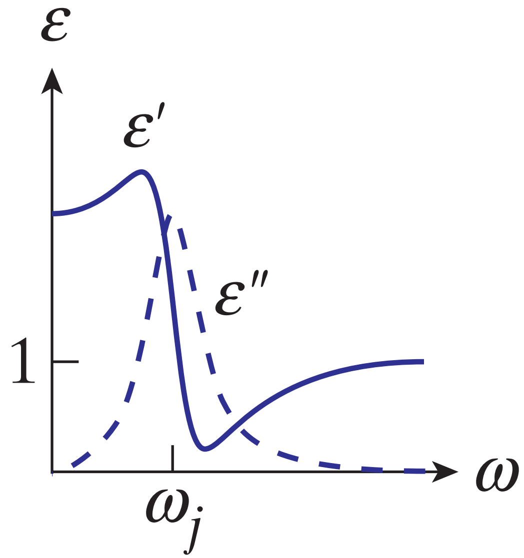
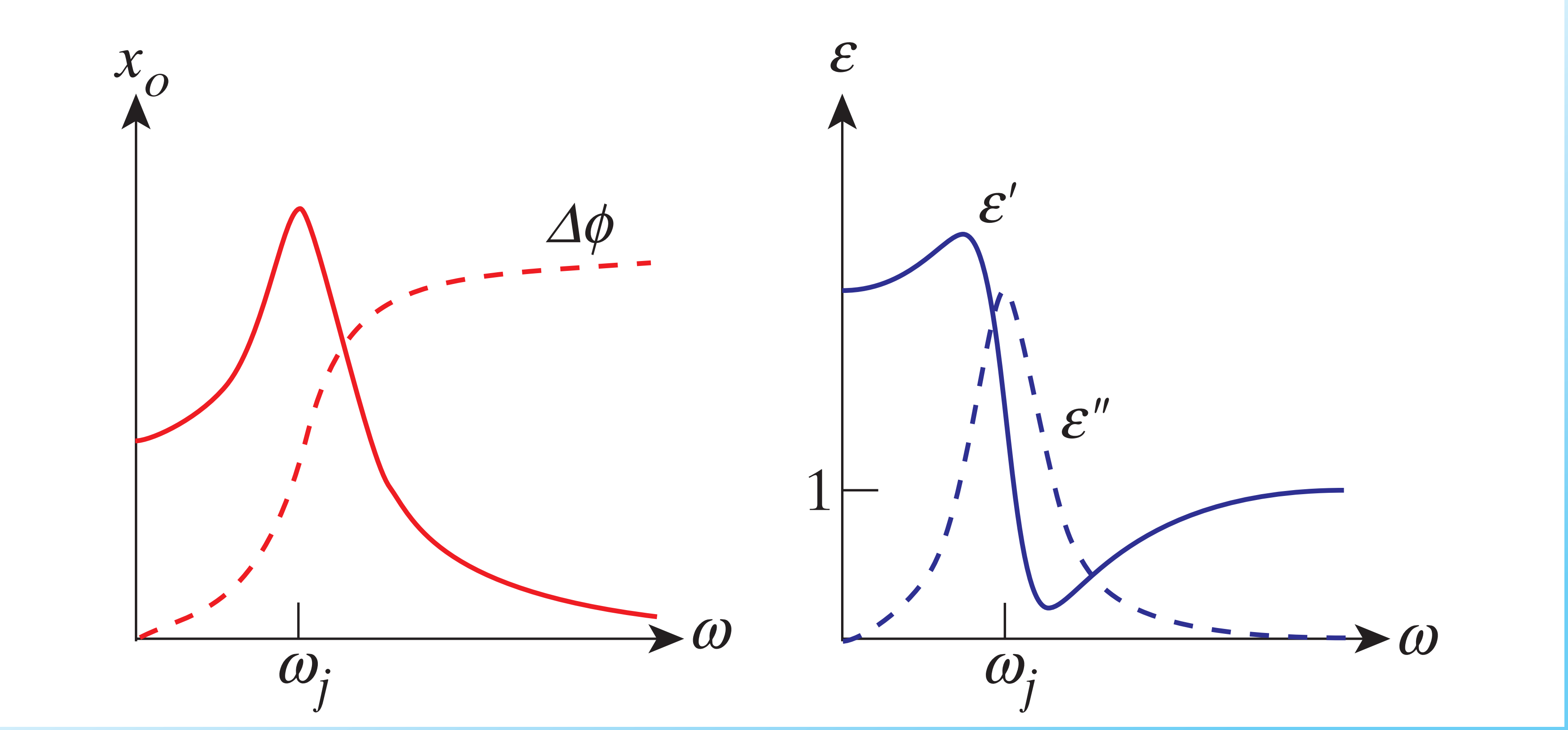


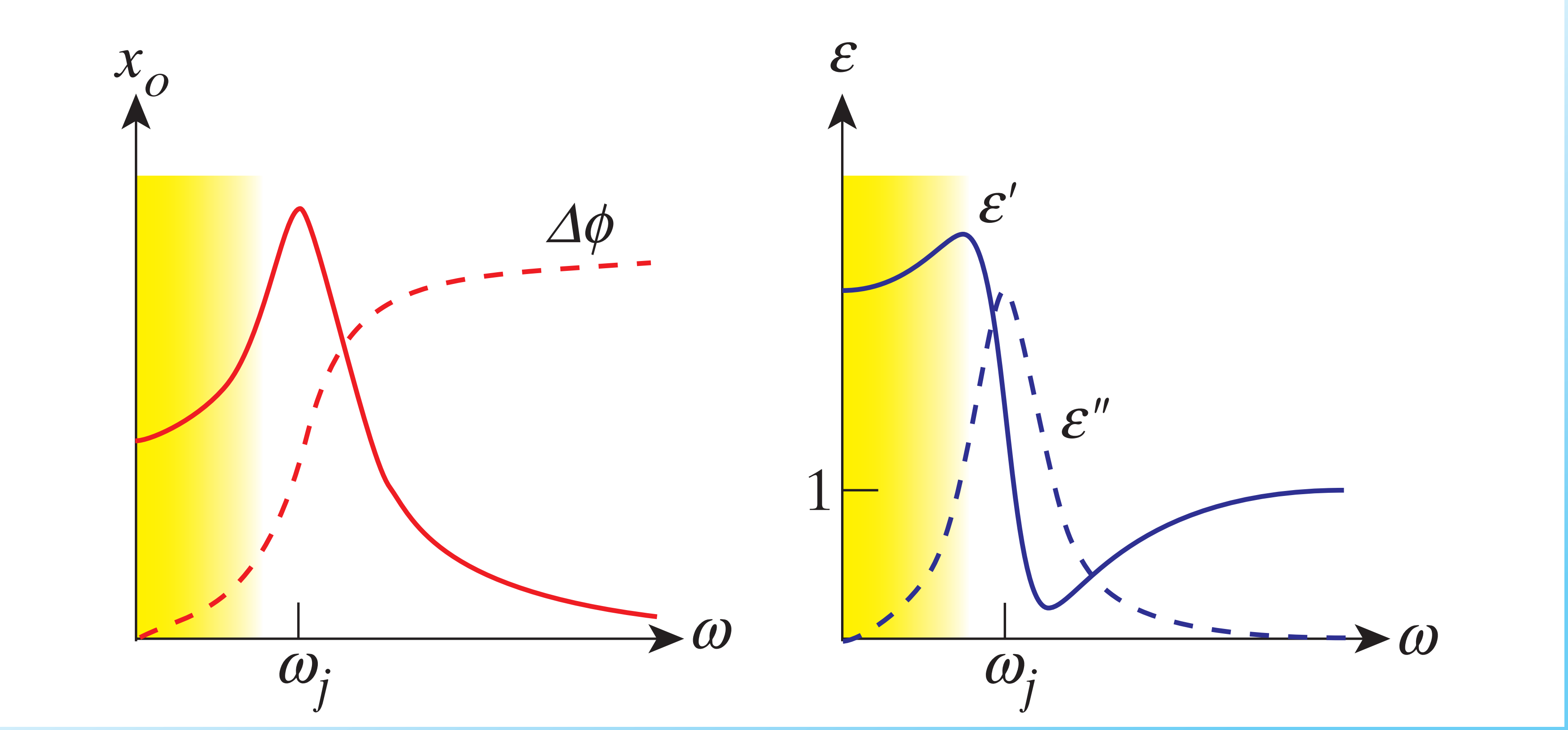
Bound electrons

amplitude of bound charge oscillation



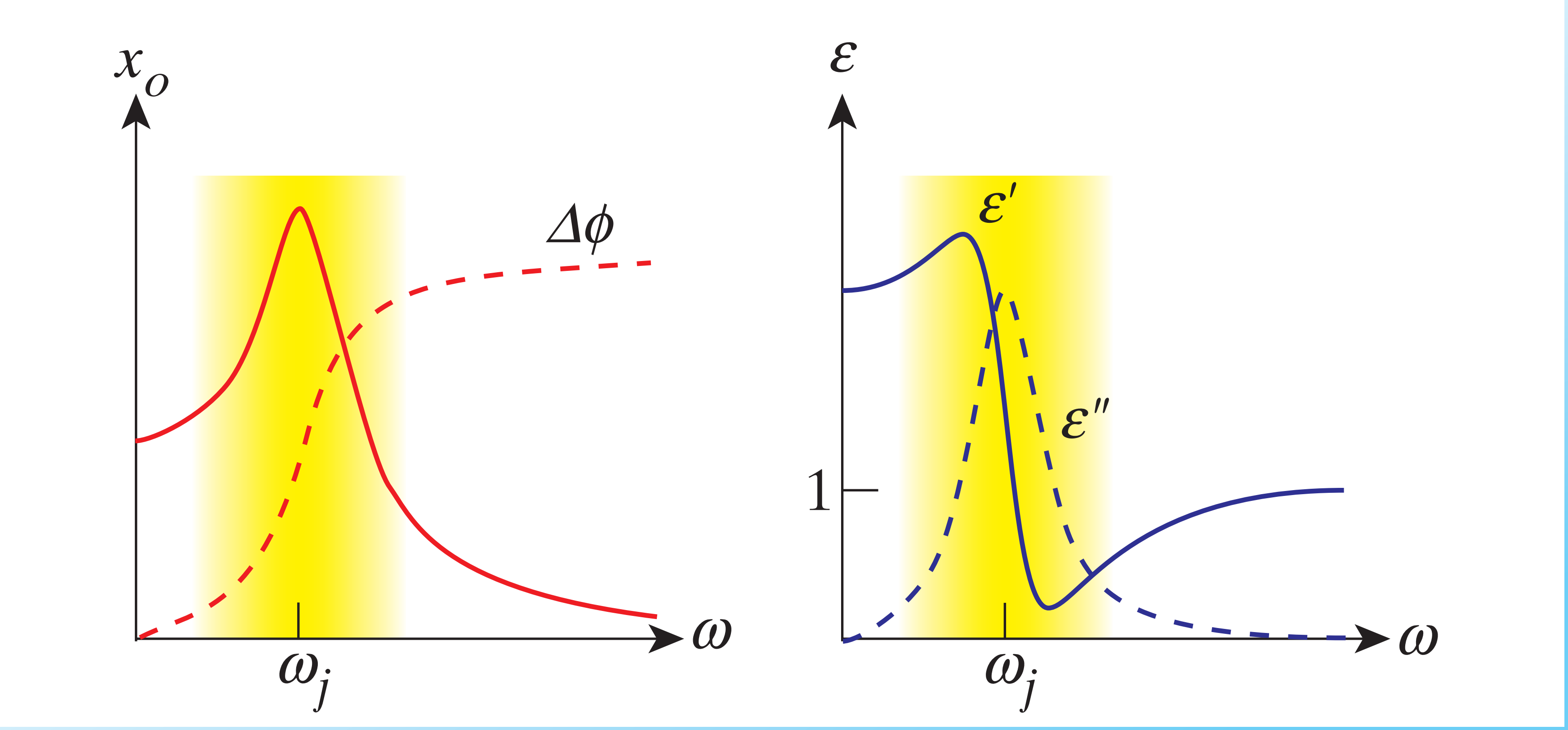
Bound electrons

Below resonance: bound charges keep up with driving field ⇒ field attenuated, wave propagates more slowly

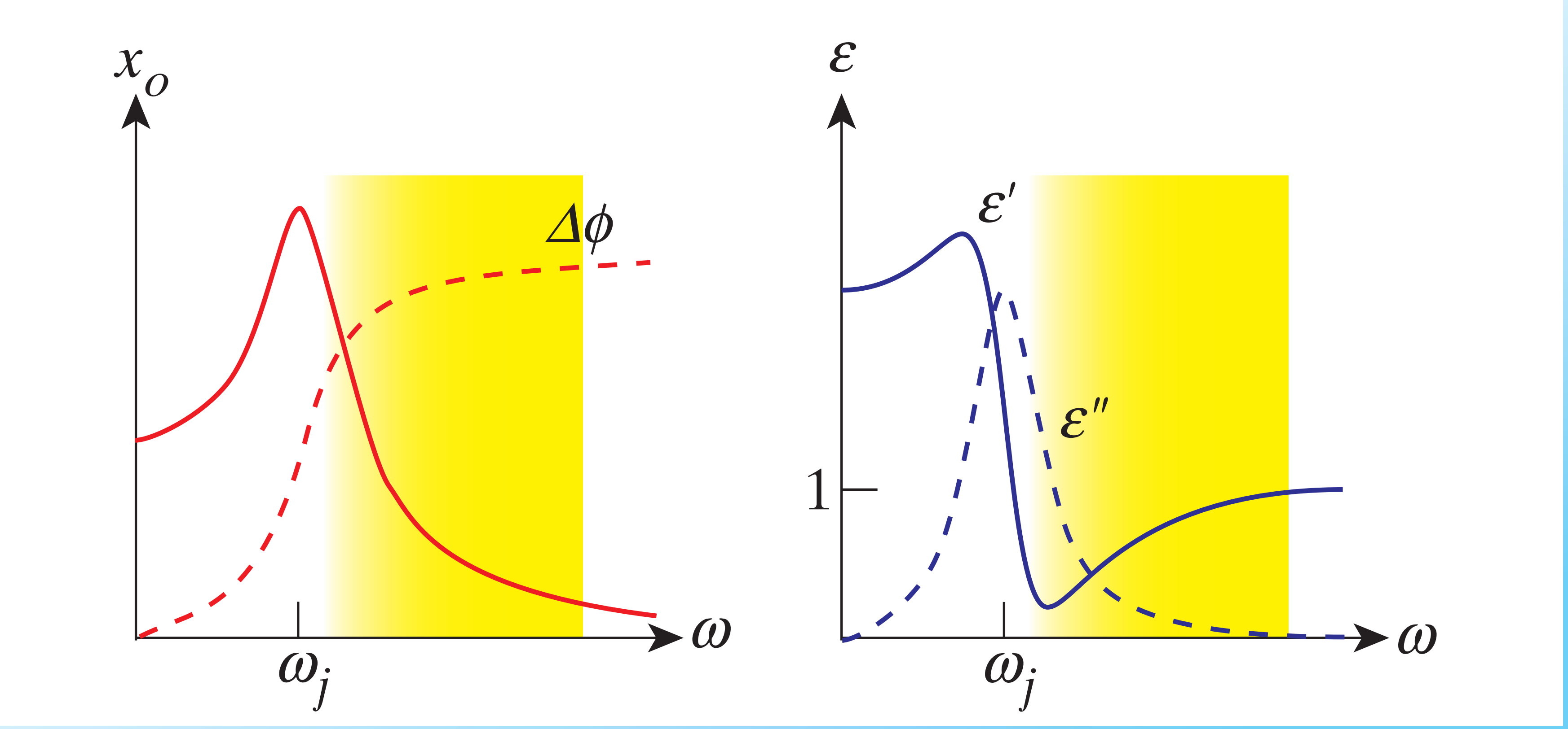


Bound electrons

At resonance: energy transfer from wave to bound charges ⇒ wave attenuates (absorption)



Above resonance: bound charges cannot keep up with driving field ⇒ dielectric like a vacuum



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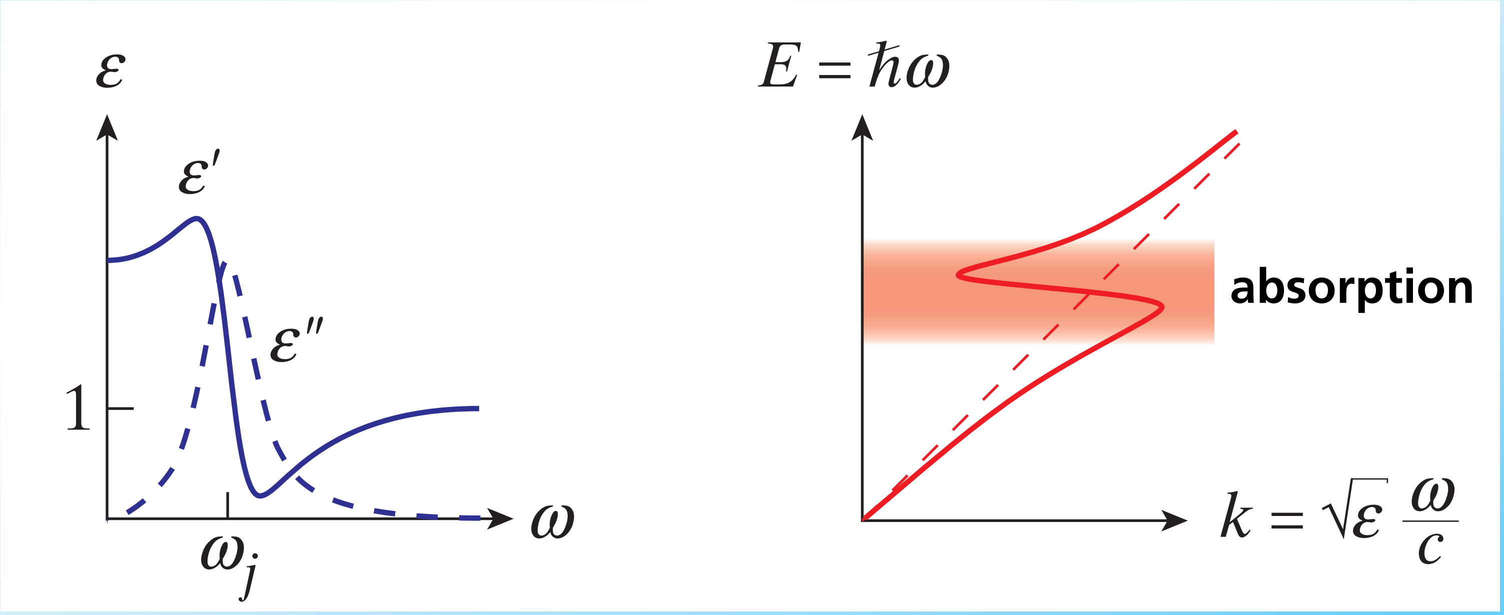

Free electrons

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Solution: $x(t) = \frac{e}{m}\frac{1}{\omega^2 + i\gamma\omega}E(t)$ **(no resonance)**

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Low frequency ($\omega \ll 1$**)** $\Rightarrow$ **current generated**

$$J = -Ne\frac{dx}{dt} = \frac{Ne^2}{m}\frac{1}{\gamma - i\omega}E \approx \frac{Ne^2}{m\gamma}E \equiv \sigma E$$

Free electrons

$\omega \gg \gamma$**:** σ **complex** $\Rightarrow$ J **out of phase with** E

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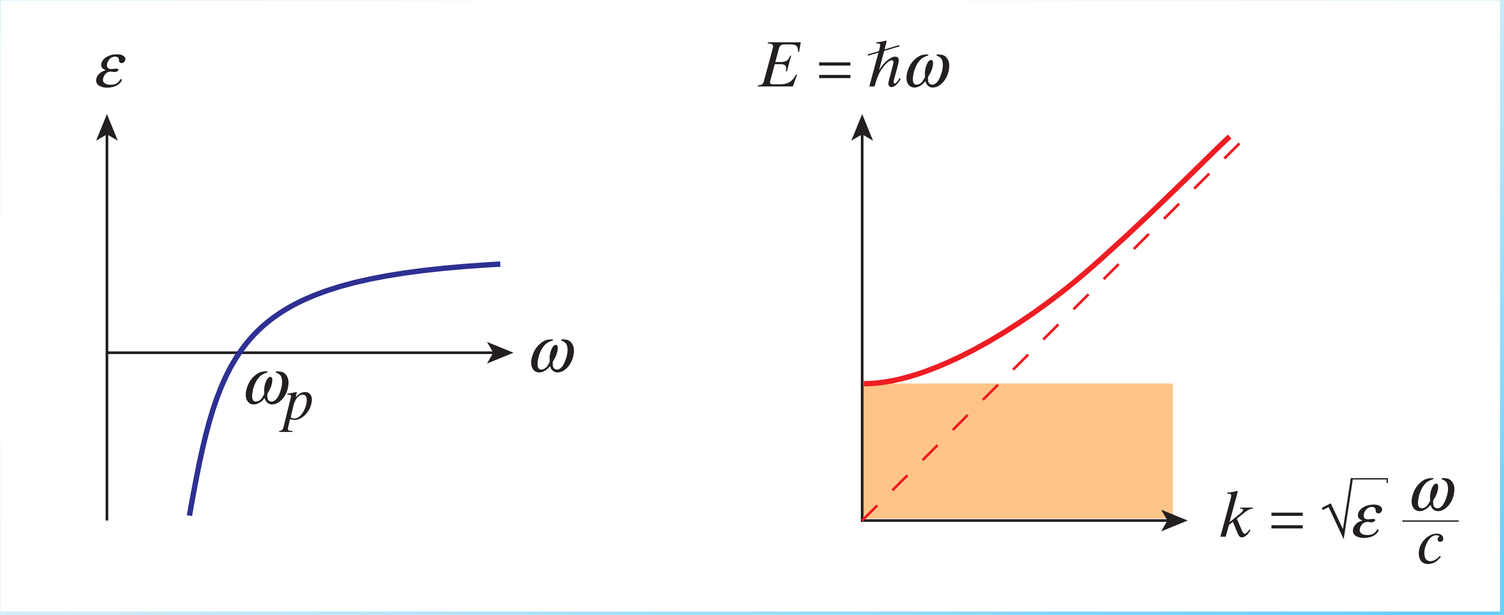
Dielectric function

$$\epsilon(\omega) \equiv 1 + \chi_e = 1 - \frac{Ne^2}{m\epsilon_o}\frac{1}{\omega^2 + i\gamma\omega} = \epsilon'(\omega) + i\epsilon''(\omega)$$

Plasma

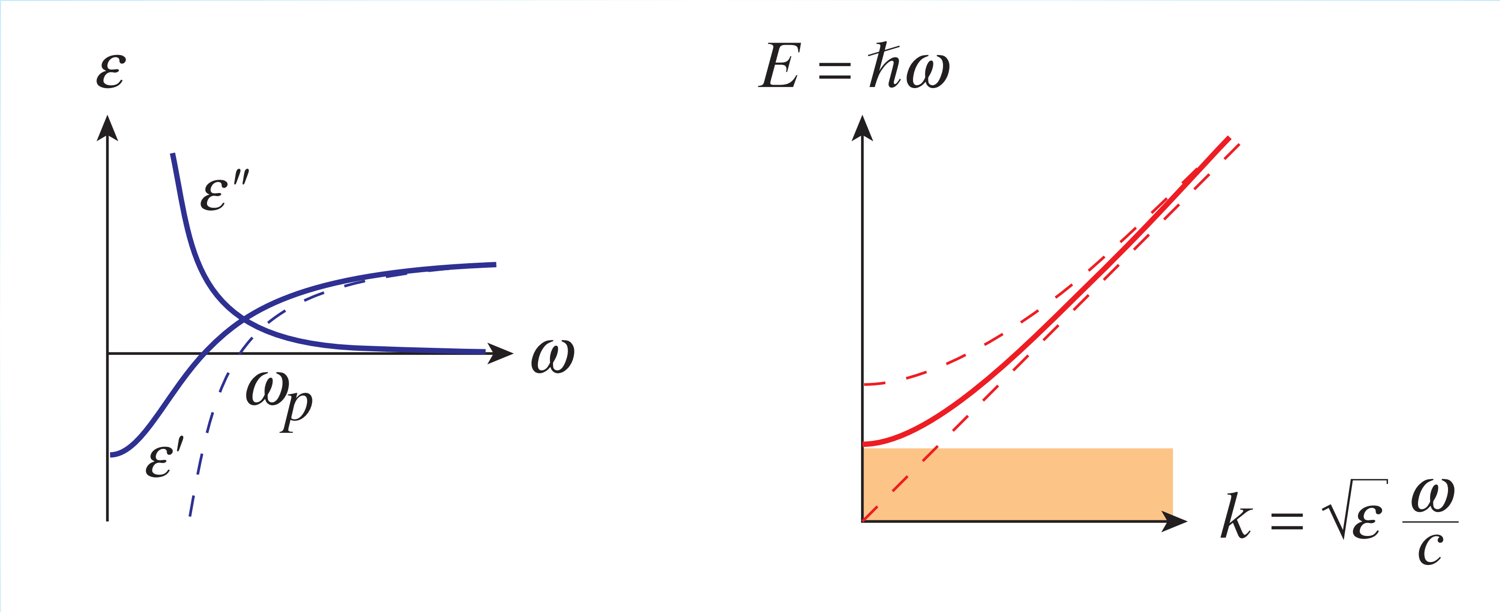
$$\gamma \approx 0 \qquad \Rightarrow \quad \epsilon'' = 0$$

$$\epsilon'(\omega) = 1 - \frac{Ne^2}{m\epsilon_o}\frac{1}{\omega^2} \equiv 1 - \frac{\omega_p^2}{\omega^2}$$



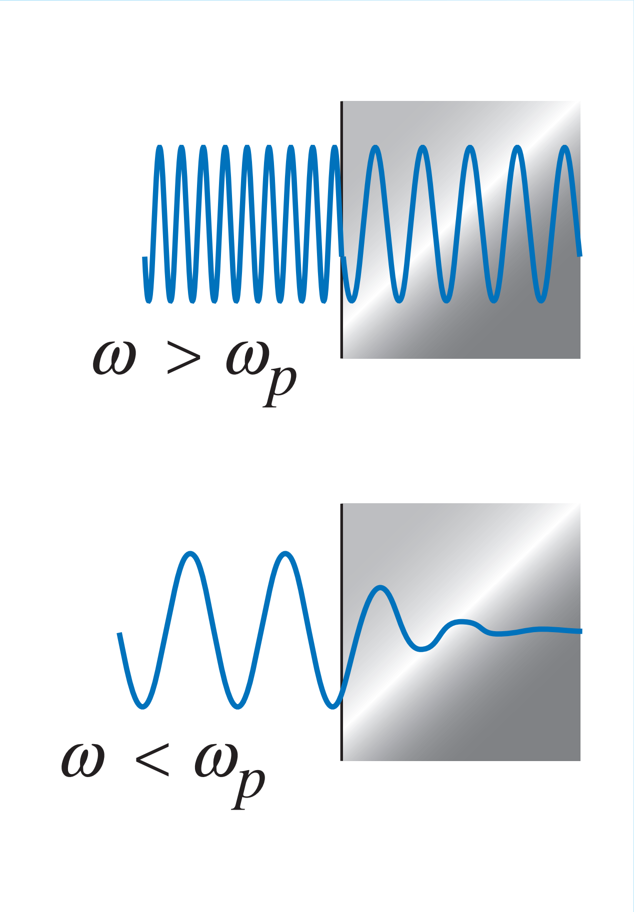
Plasma

Add damping $\gamma \lesssim \omega_p$



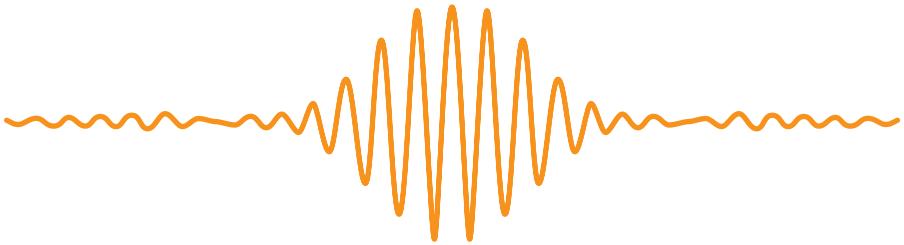
Plasma

Plasma acts like a high-pass filter:



log N (cm^{-3})	ω_p (rad s^{-1})	λ_p
22	6 x 10^{15}	330 nm
18	6 x 10^{13}	33 μm
14	6 x 10^{11}	3.3 mm
10	6 x 10^{9}	0.33 m

Pulse dispersion



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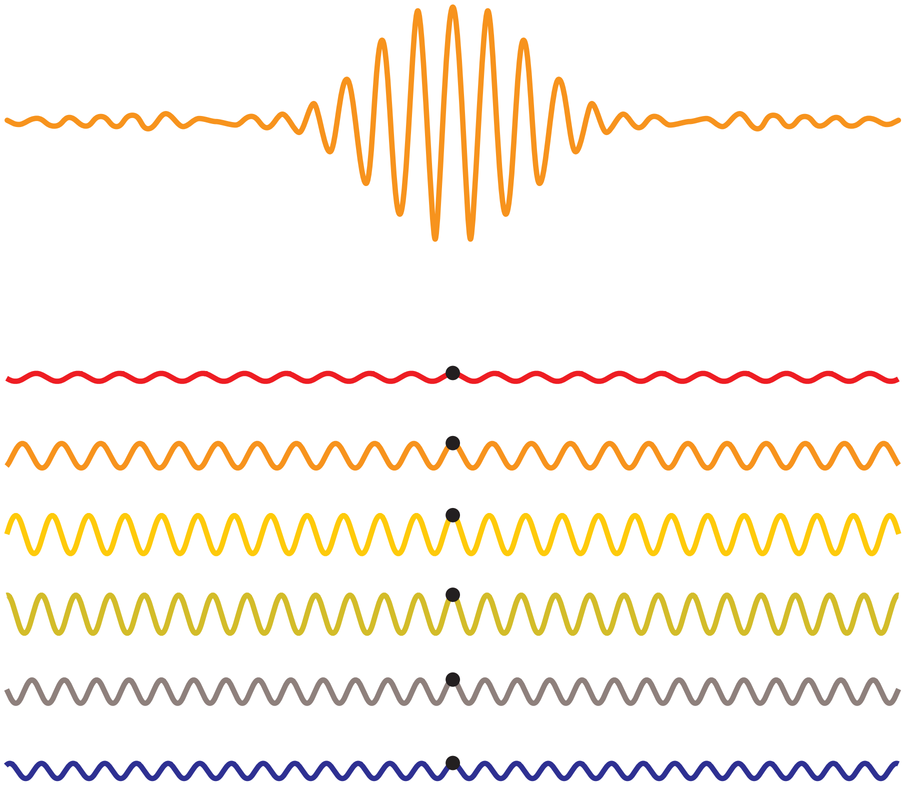

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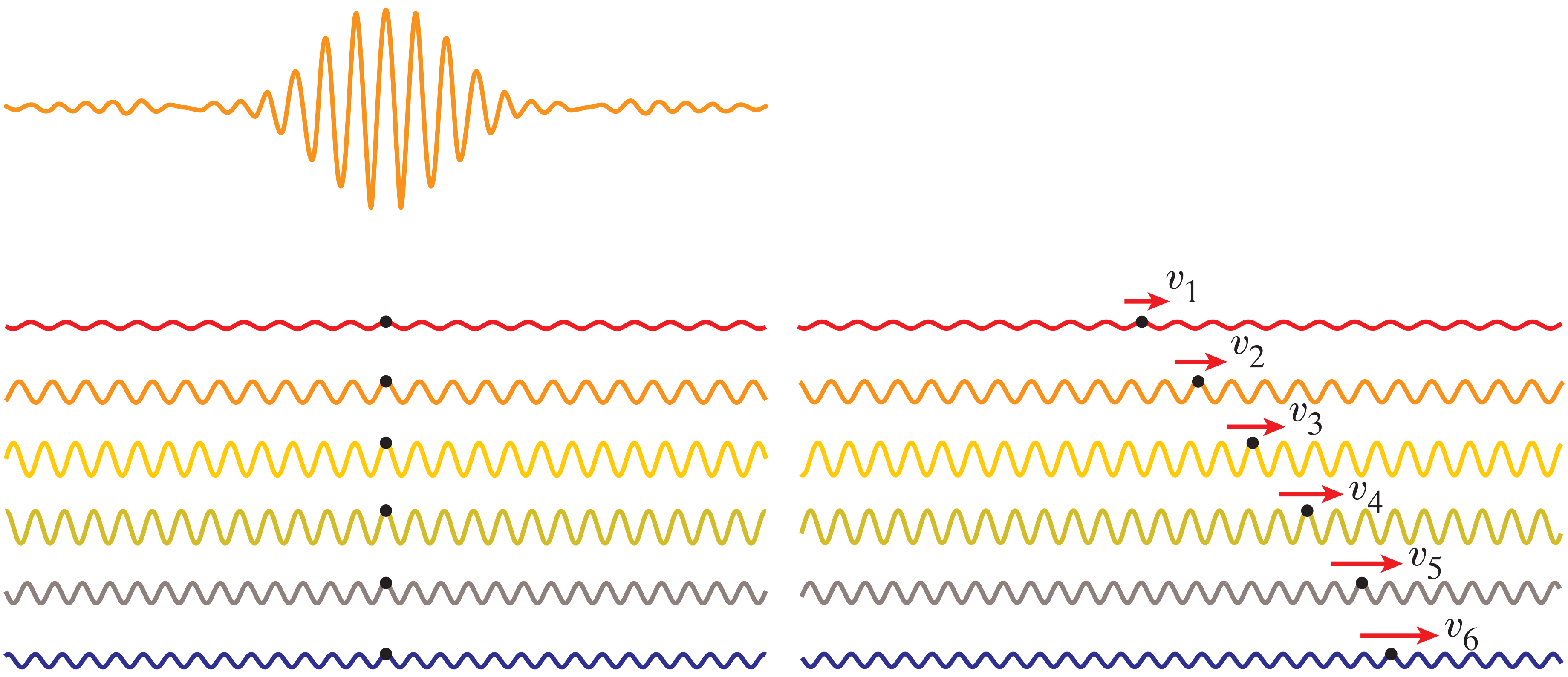

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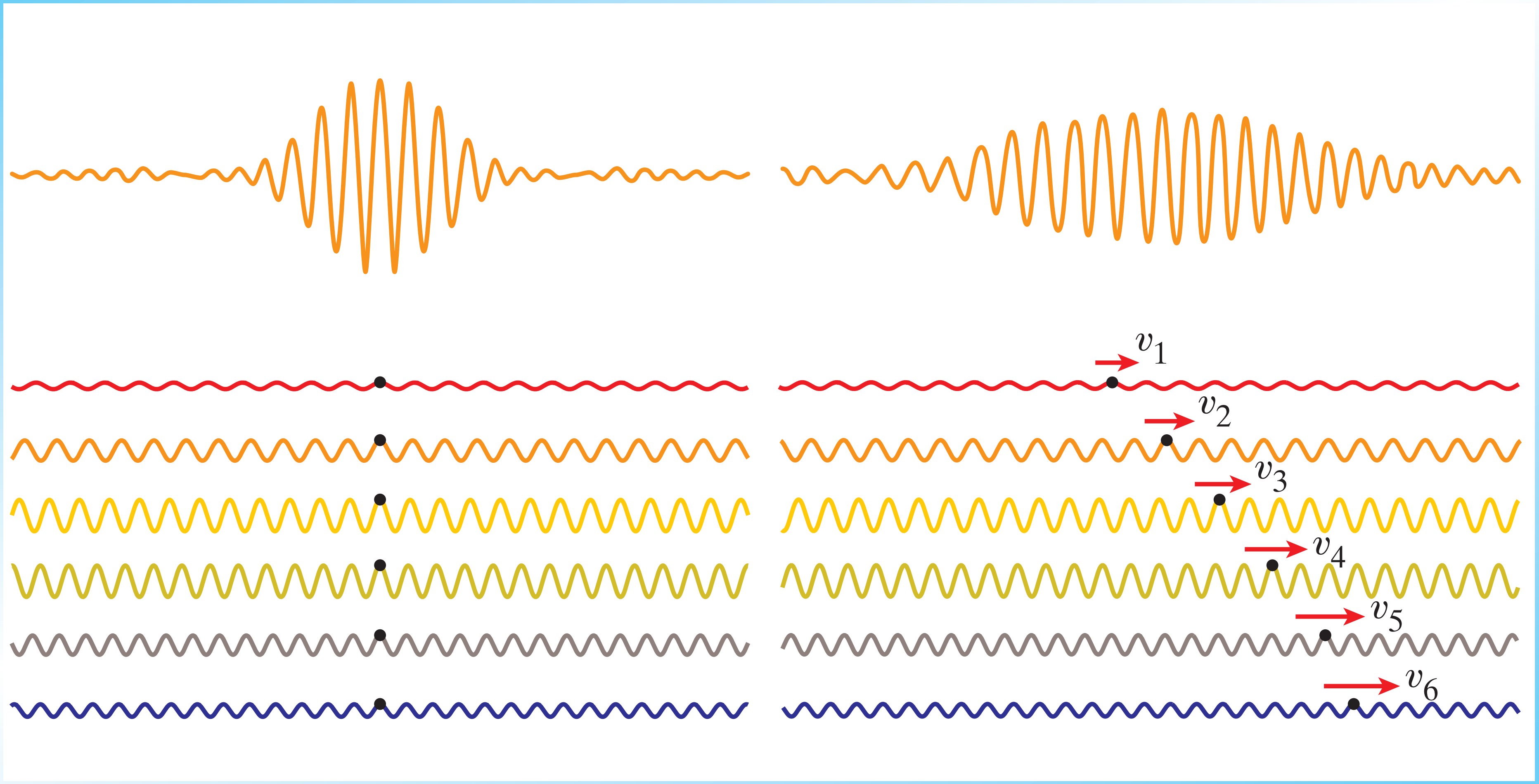

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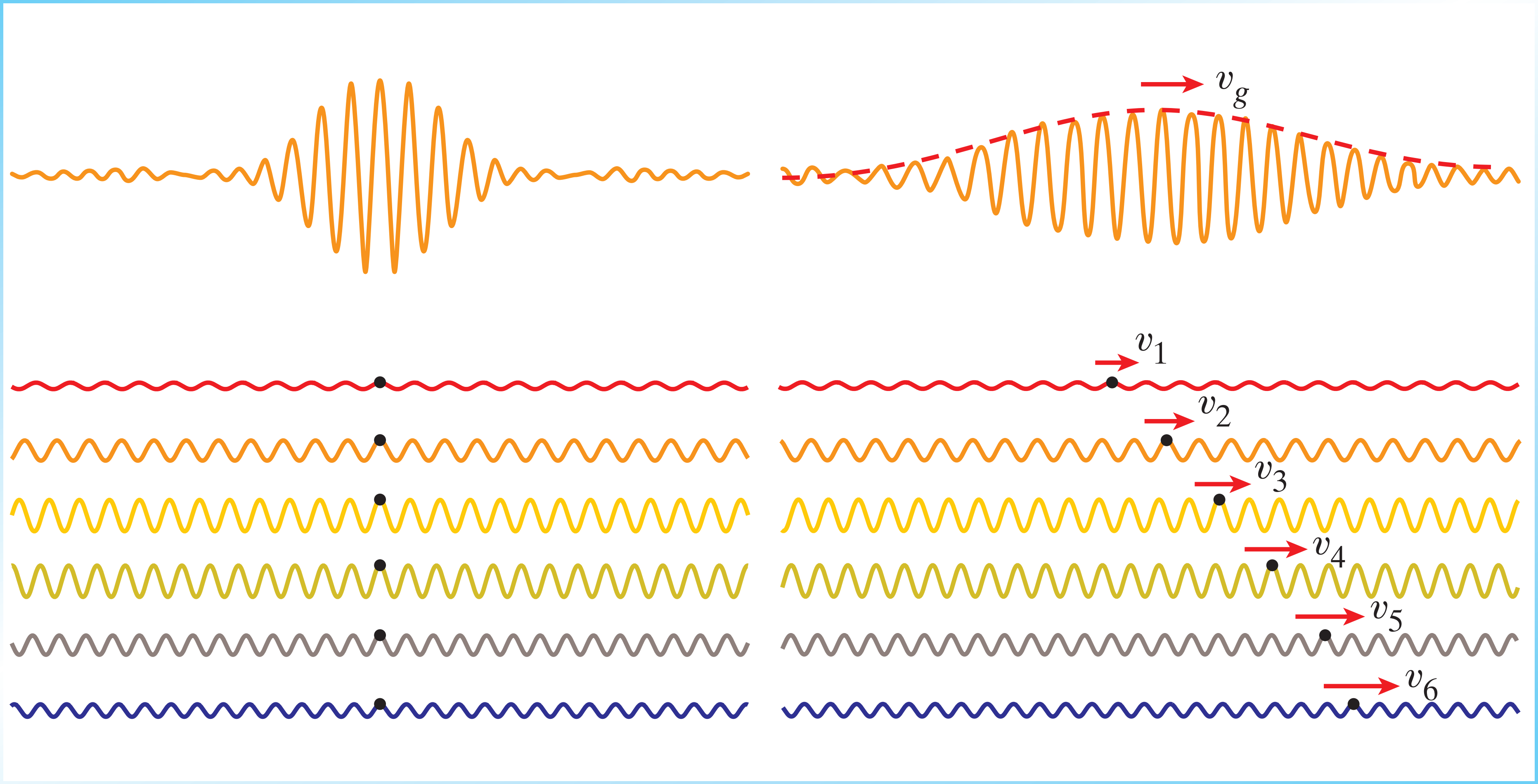
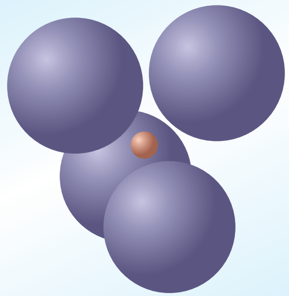


Nonlinear optics

Linear response $$P(t) = \epsilon_o \chi_e E(t)$$



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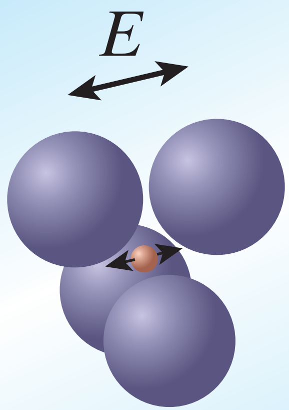

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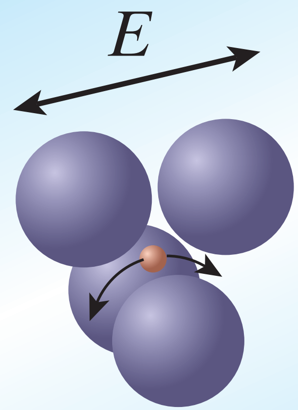

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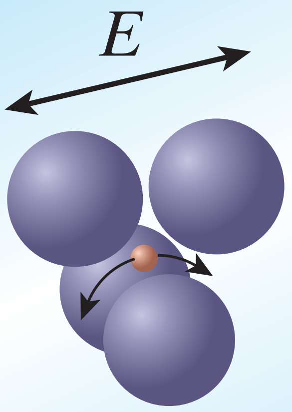
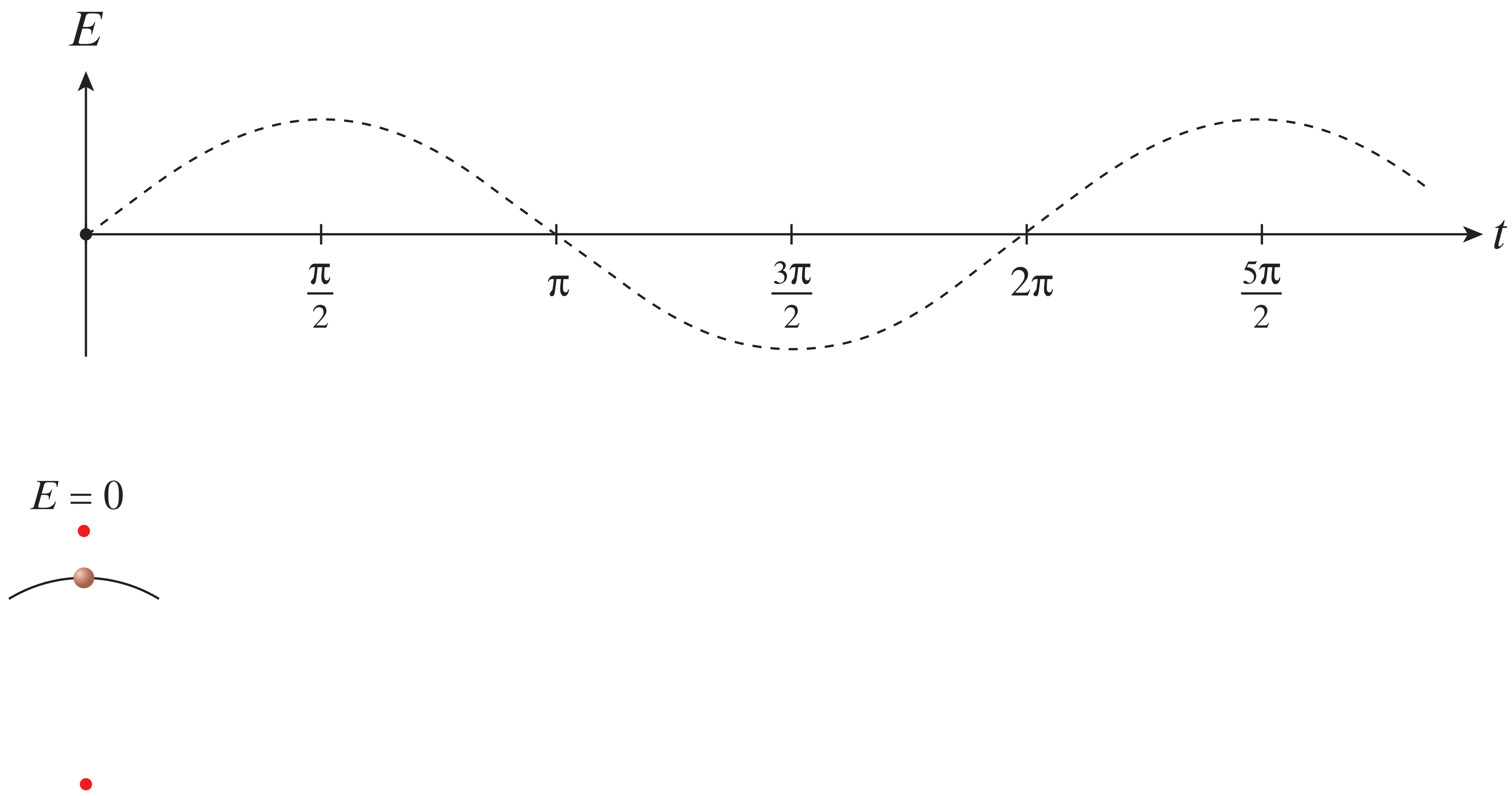


Nonlinear polarization:

$$P = \chi^{(1)}E + \chi^{(2)}E^2 + \chi^{(3)}E^3 + \ldots$$

$$P = P^{(1)} + P^{(2)} + P^{(3)} + \ldots$$

Nonlinear optics



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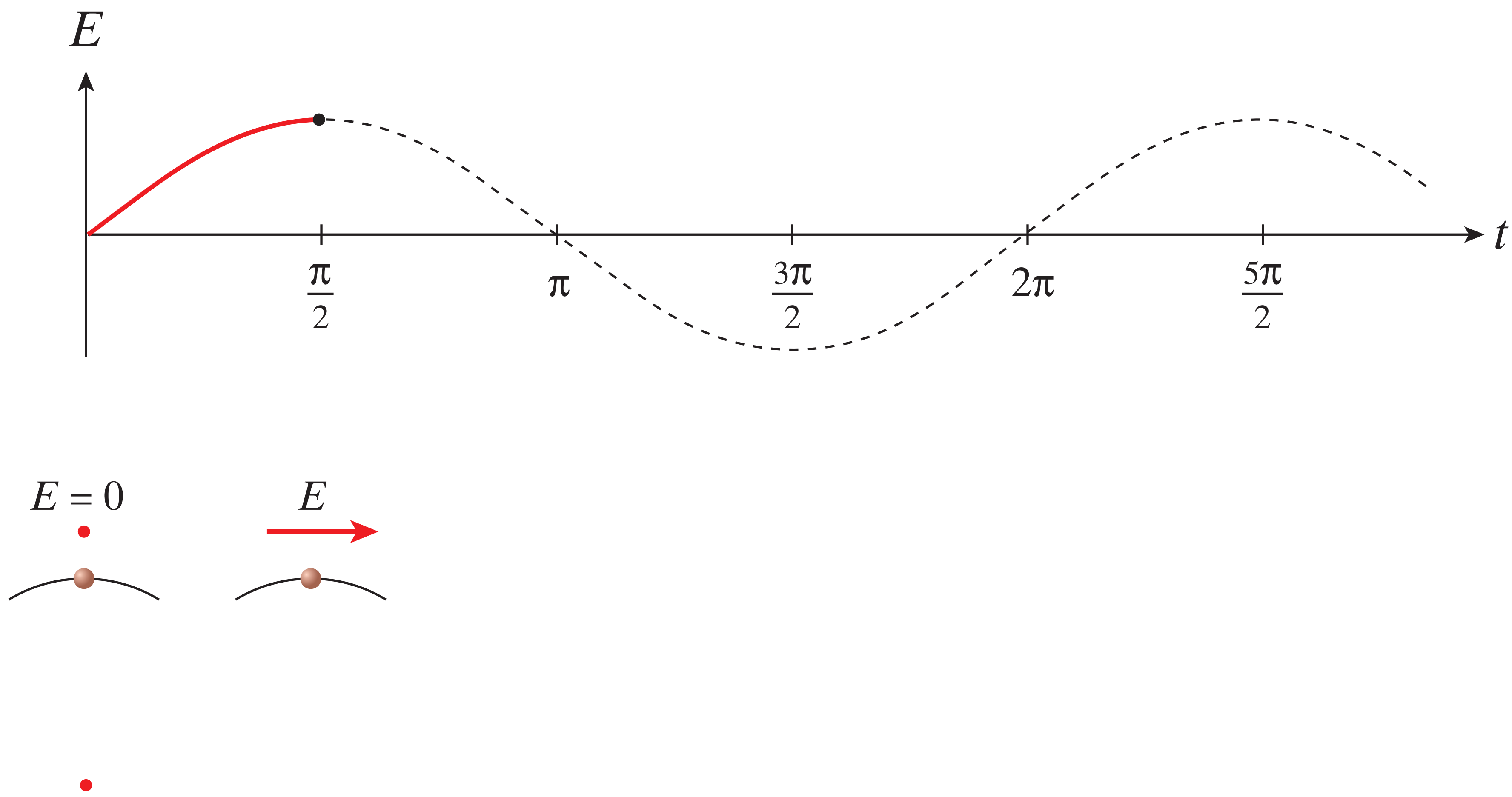

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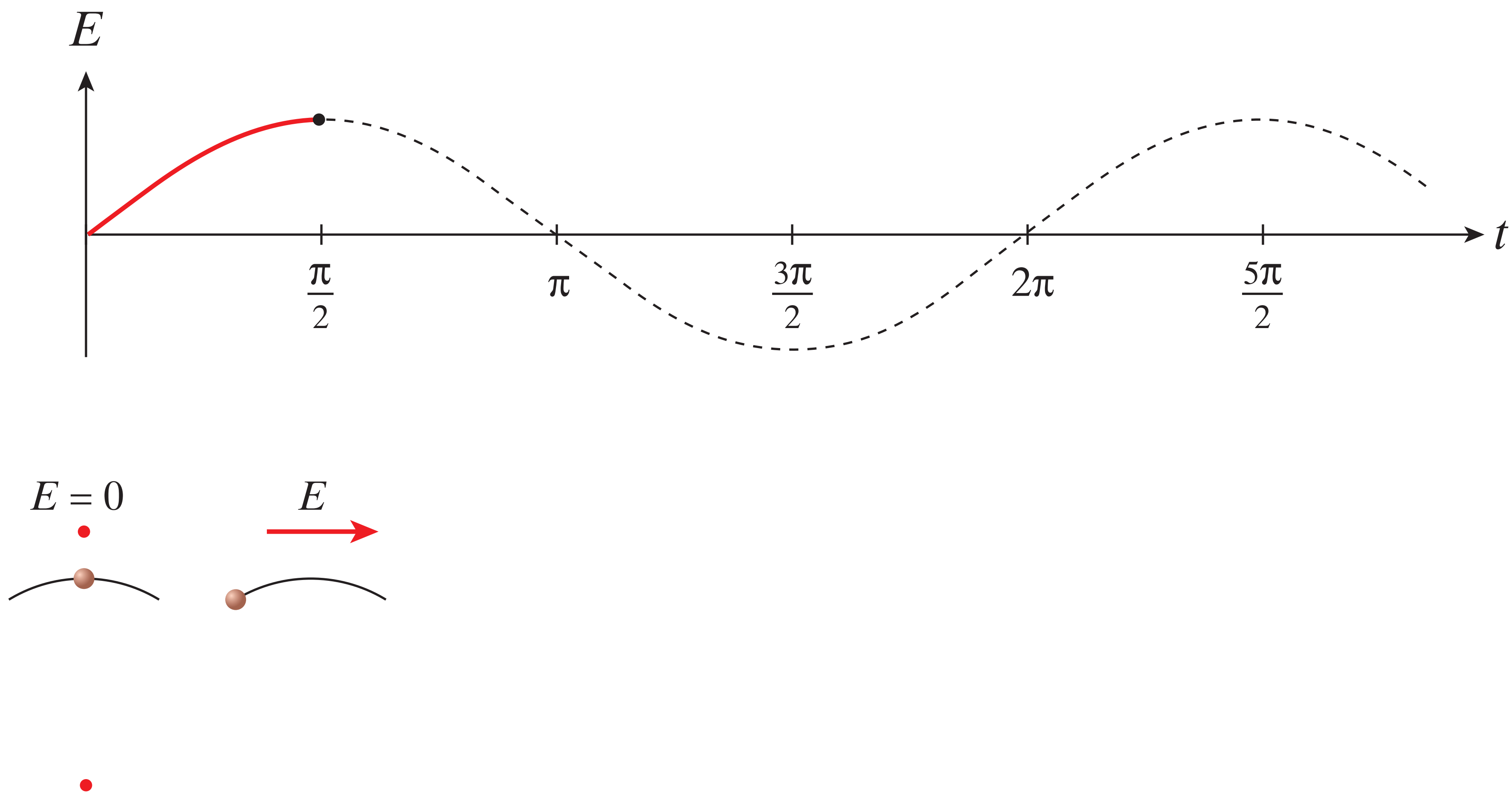

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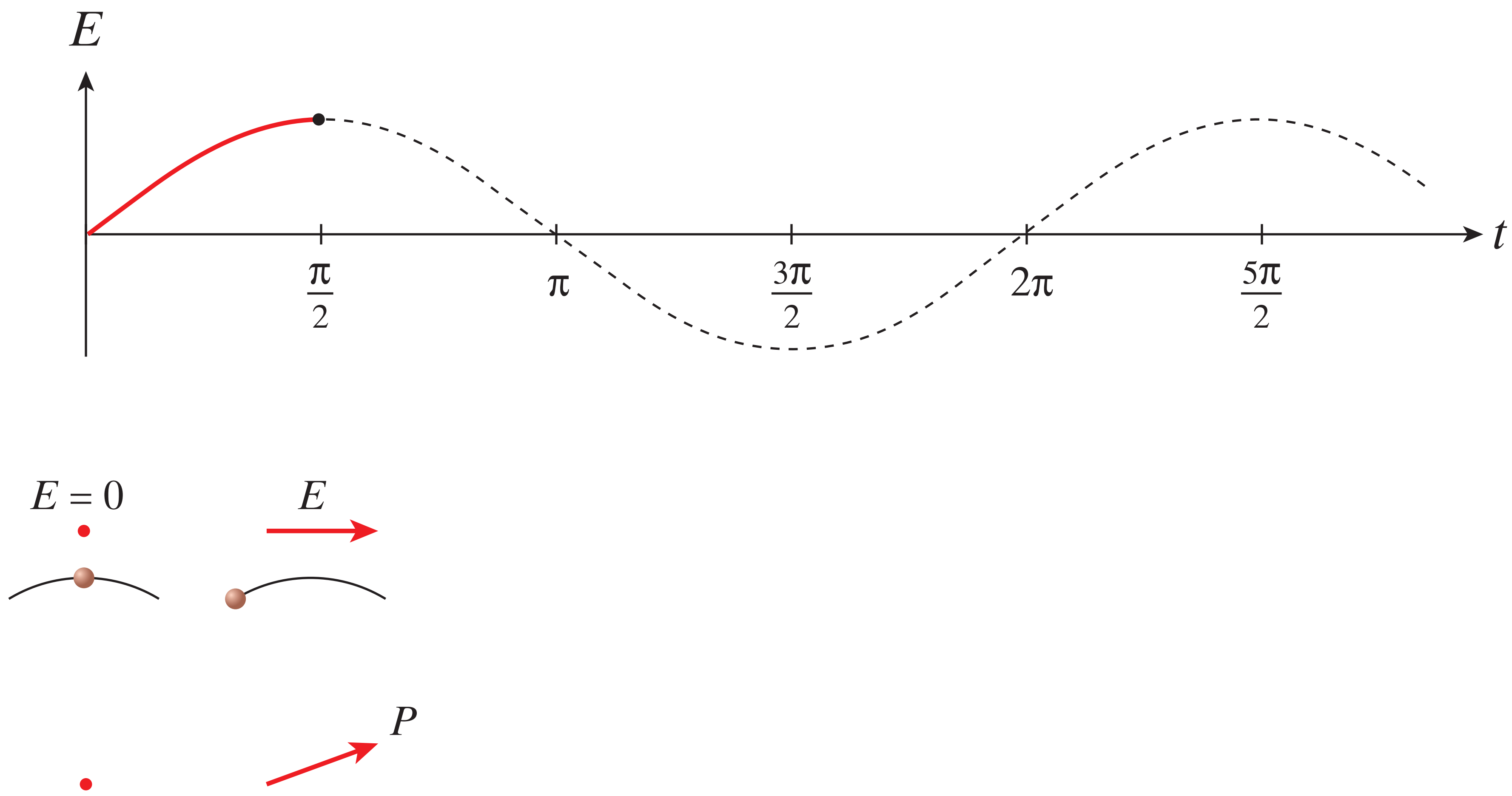

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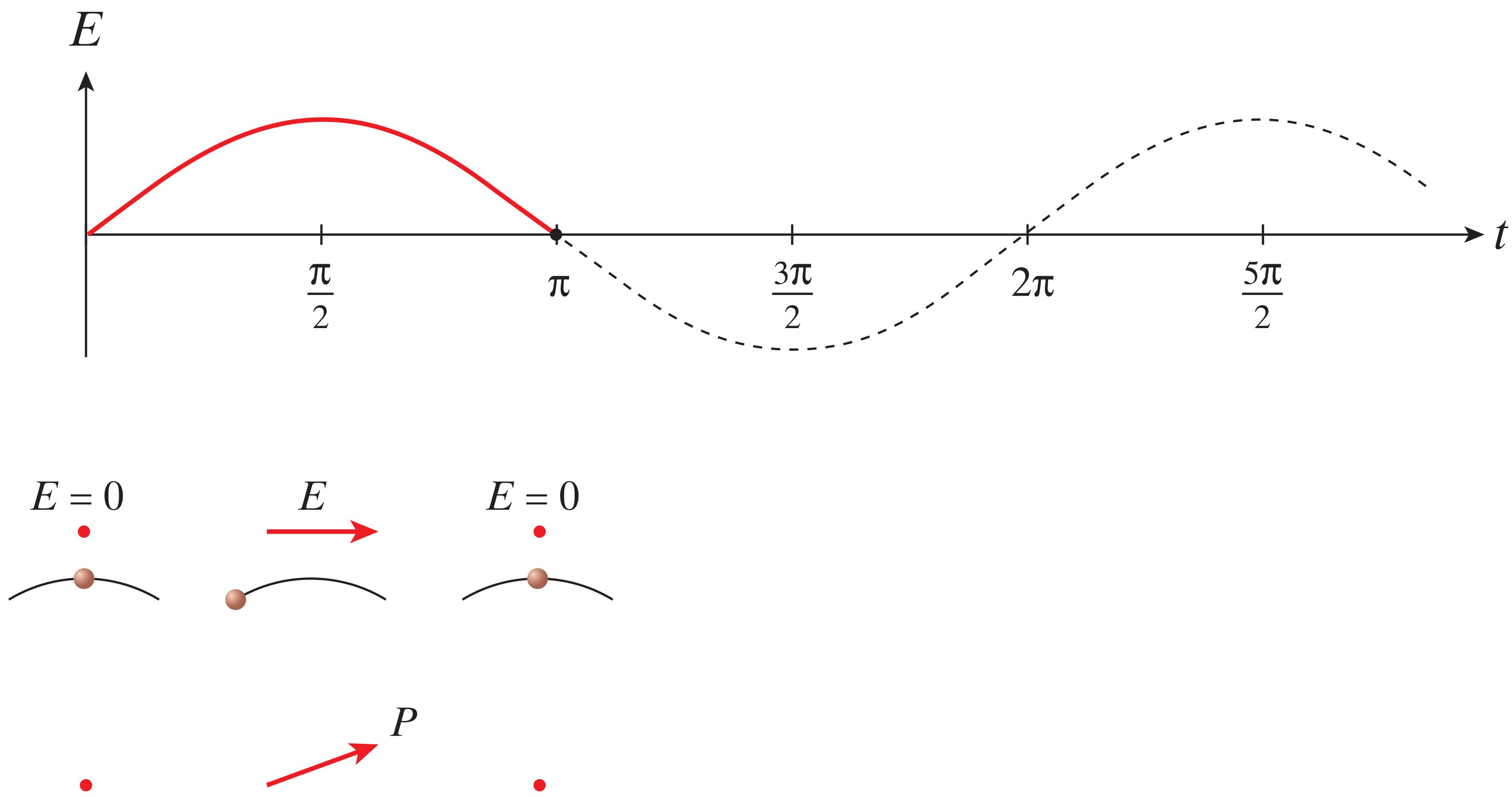

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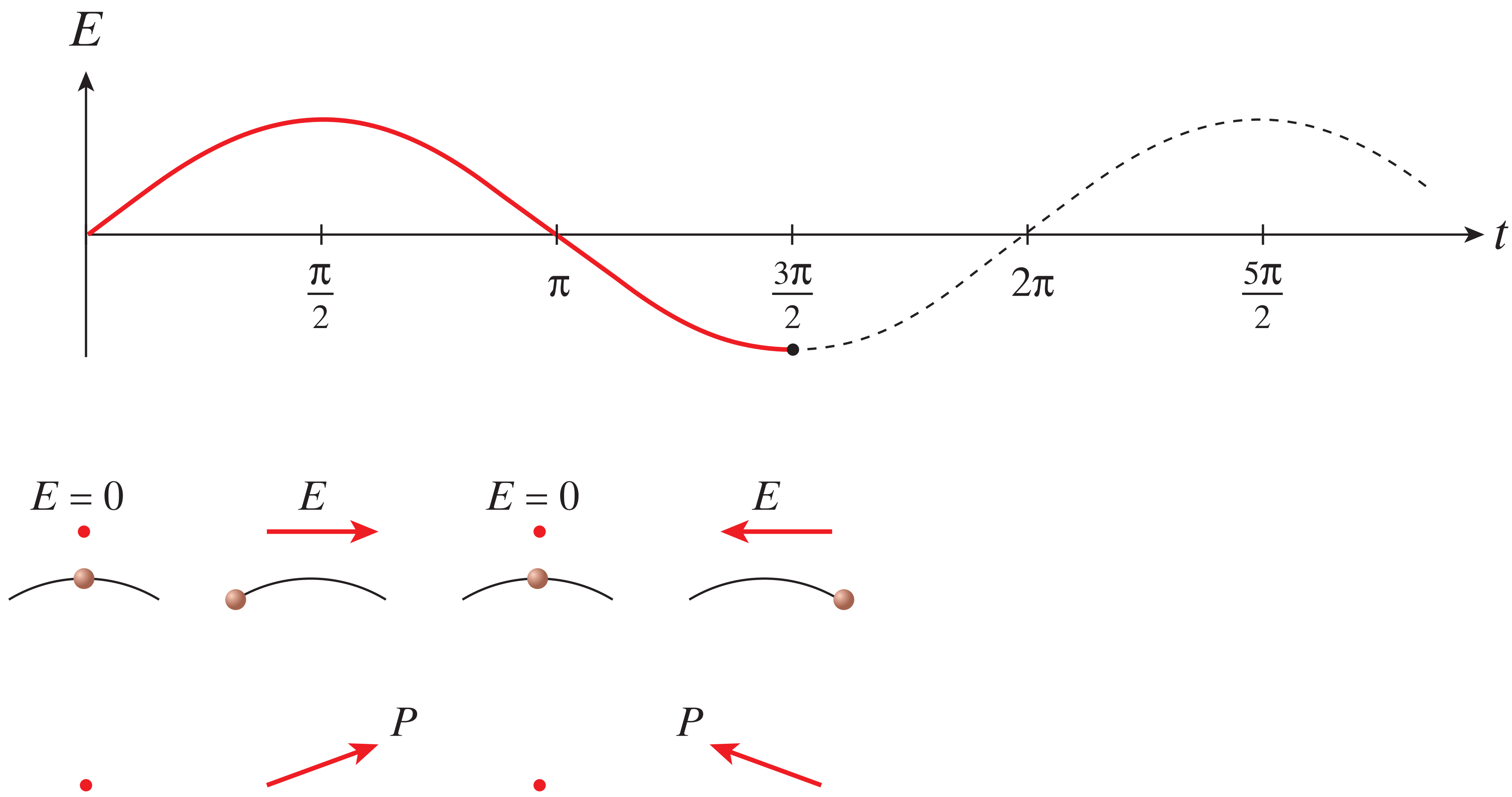

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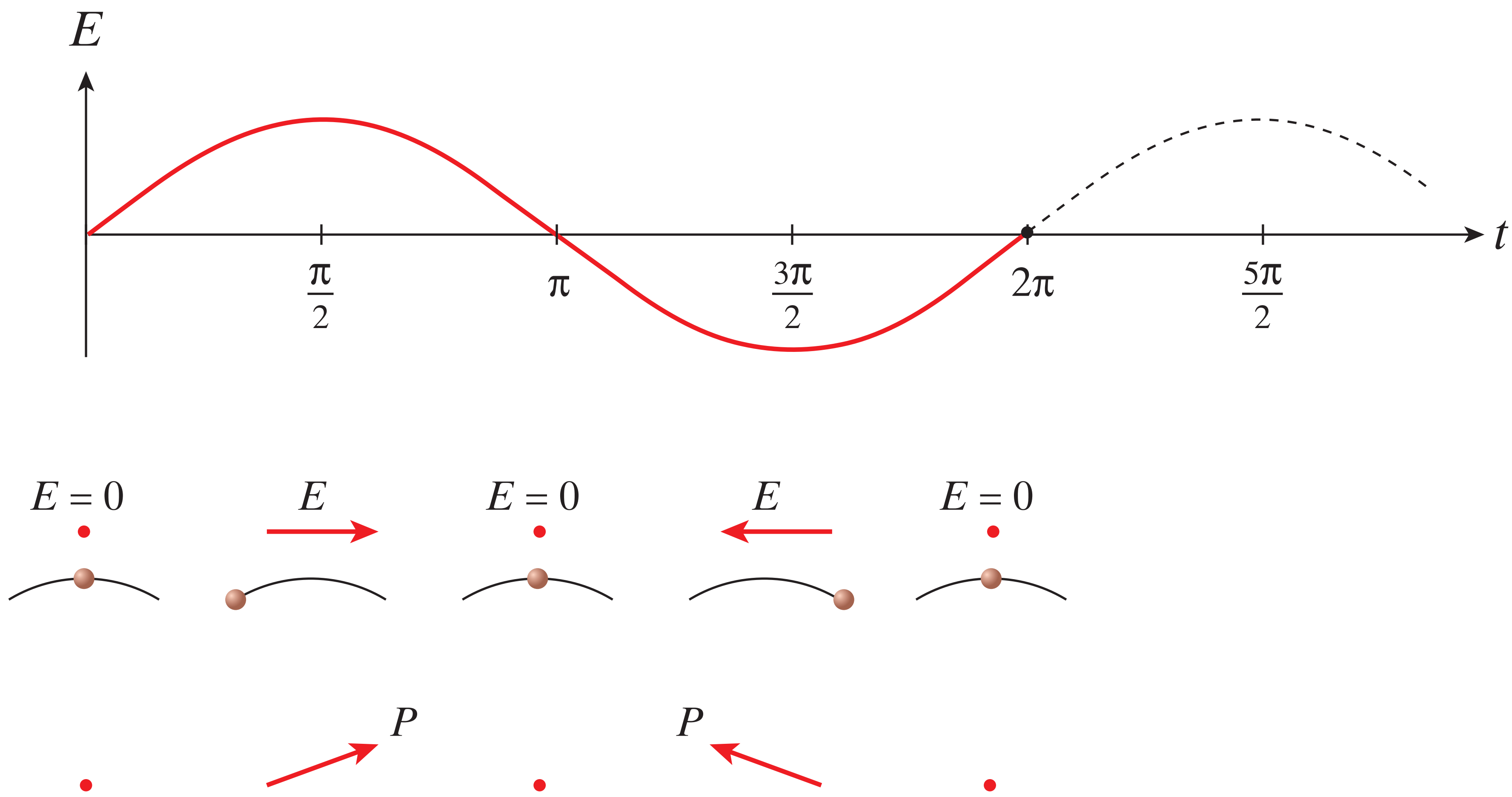

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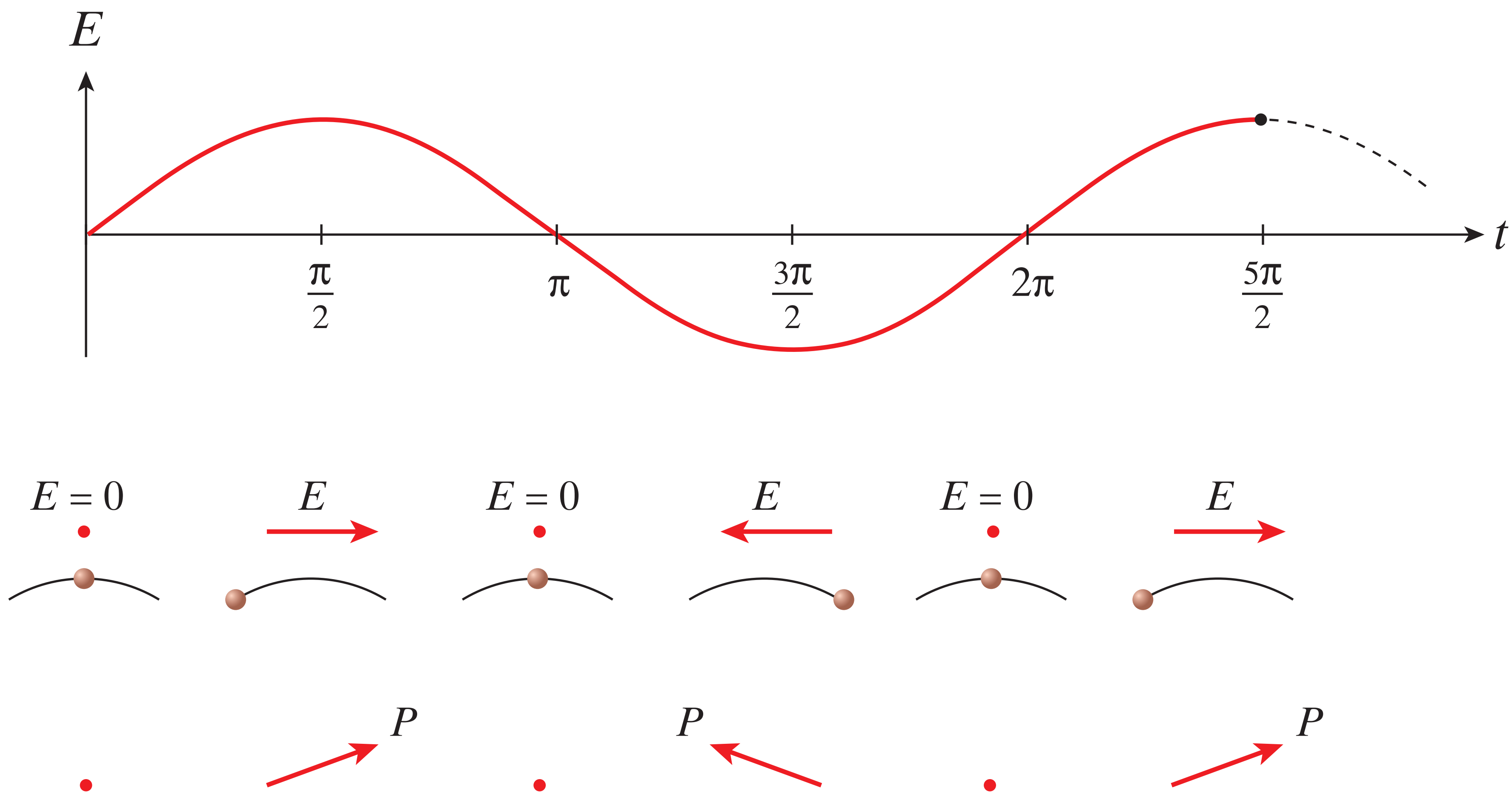

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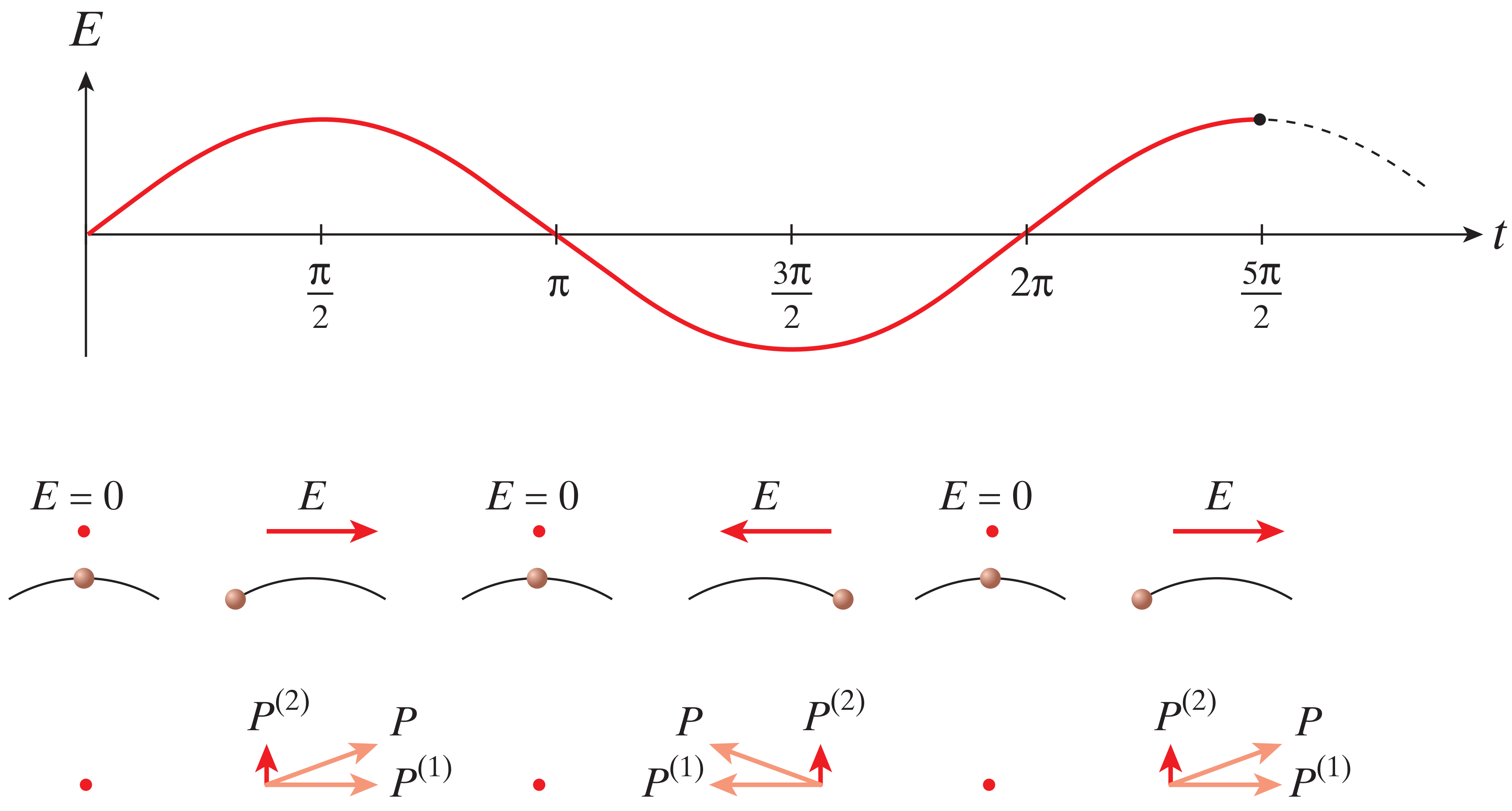
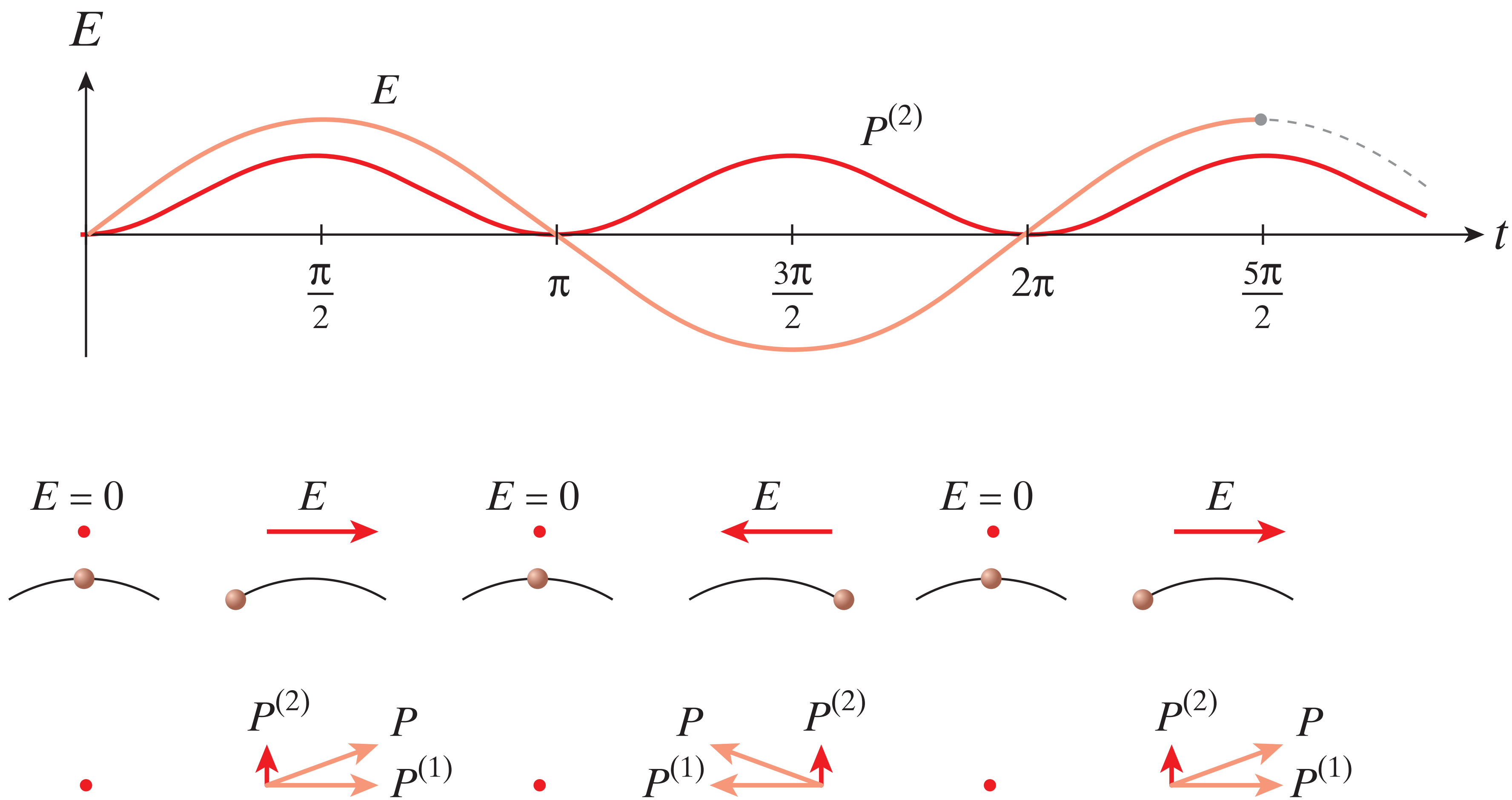


Nonlinear optics



In medium with inversion symmetry

$$\vec{P}^{(2)} = \overset{\rightrightarrows}{\chi}^{(2)} : \vec{E}\,\vec{E} \quad \Rightarrow \quad -\vec{P}^{(2)} = \overset{\rightrightarrows}{\chi}^{(2)} : (-\vec{E})(-\vec{E})$$

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Nonlinear optics

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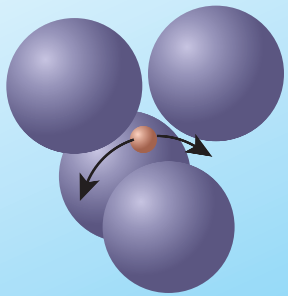
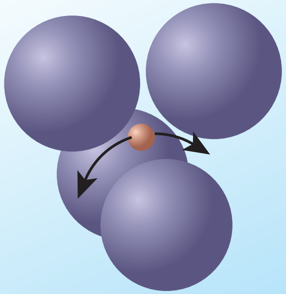
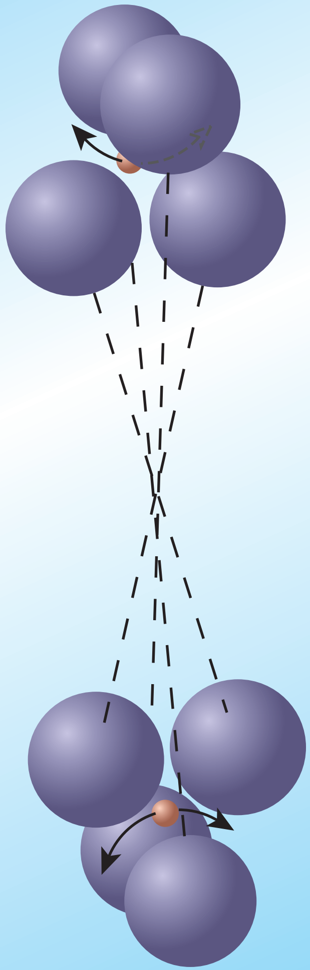
… but …



How to reconcile $\chi^{(2)} = -\chi^{(2)} = 0$ **with**  **?**

Nonlinear optics



Nonlinear optics

Nonlinear polarization:

$$P = \chi^{(1)}E + \chi^{(3)}E^3 + \ldots$$

Nonlinear polarization:

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Nonlinear optics

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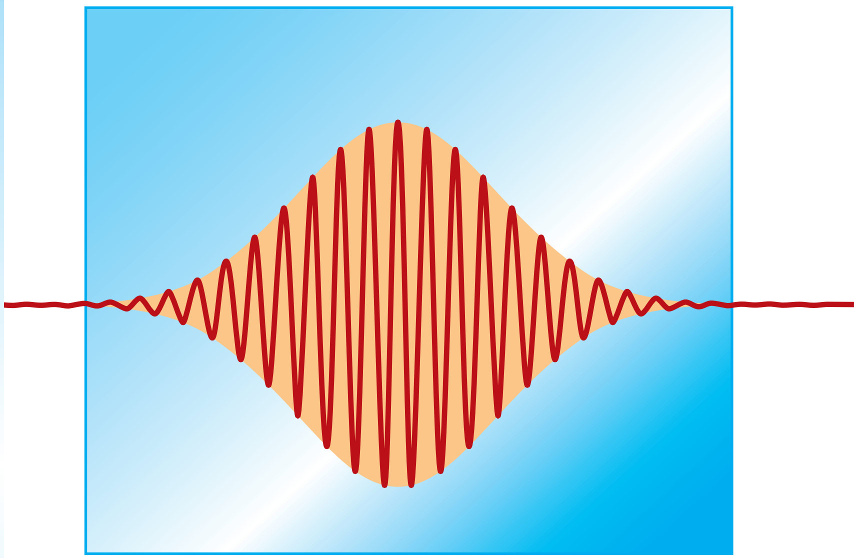
$$n = \sqrt{\epsilon} = \sqrt{1 + \chi_{eff}} \approx \sqrt{1 + \chi^{(1)}} + \tfrac{1}{2}\frac{\chi^{(3)}I}{\sqrt{1 + \chi^{(1)}}} = n_o + n_2 I$$

Nonlinear optics

Intensity dependent index of refraction:

$$n = n_o + n_2 I$$



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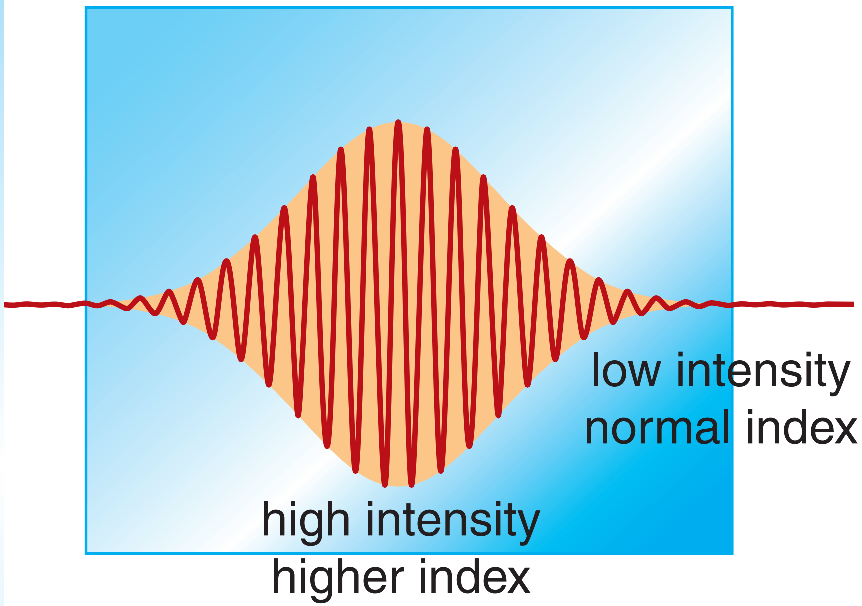

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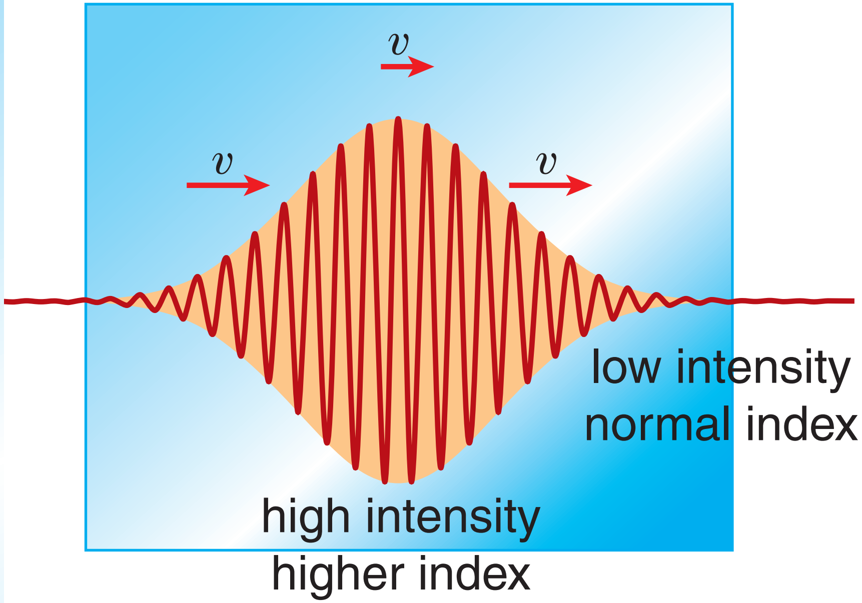

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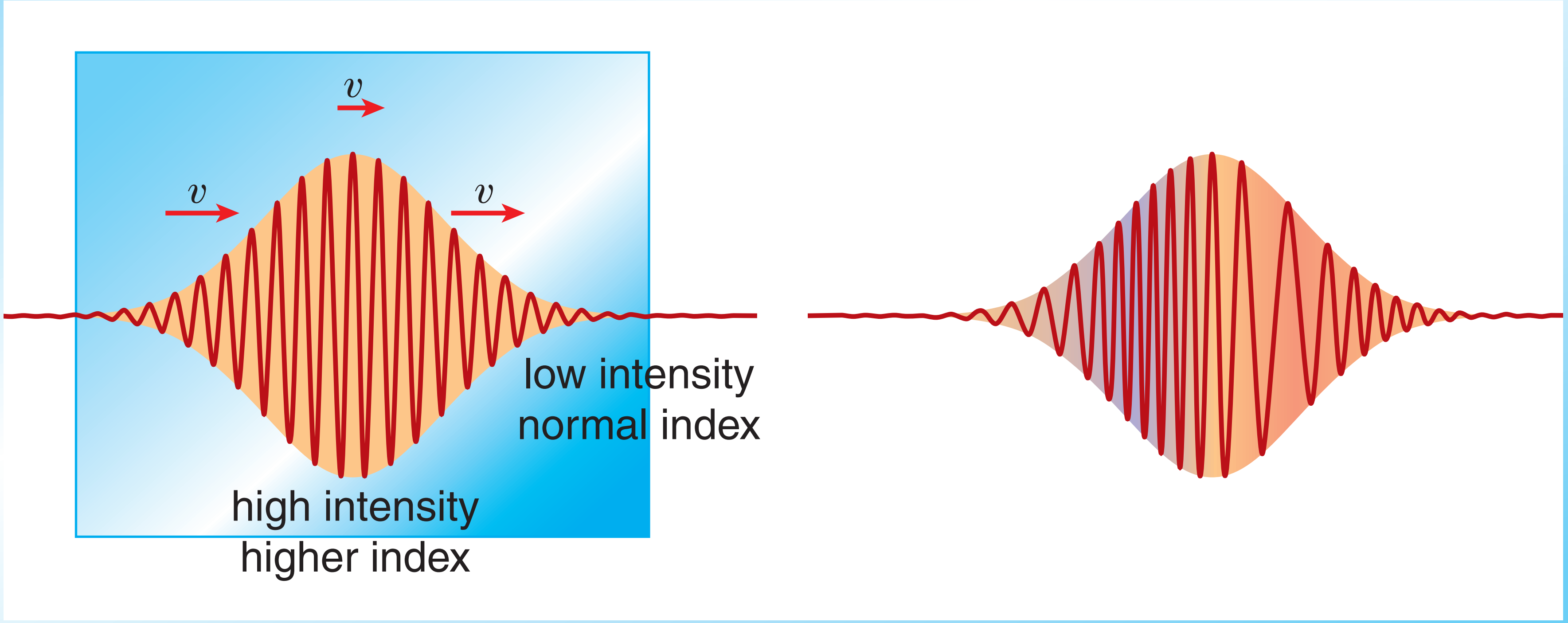

Nonlinear optics

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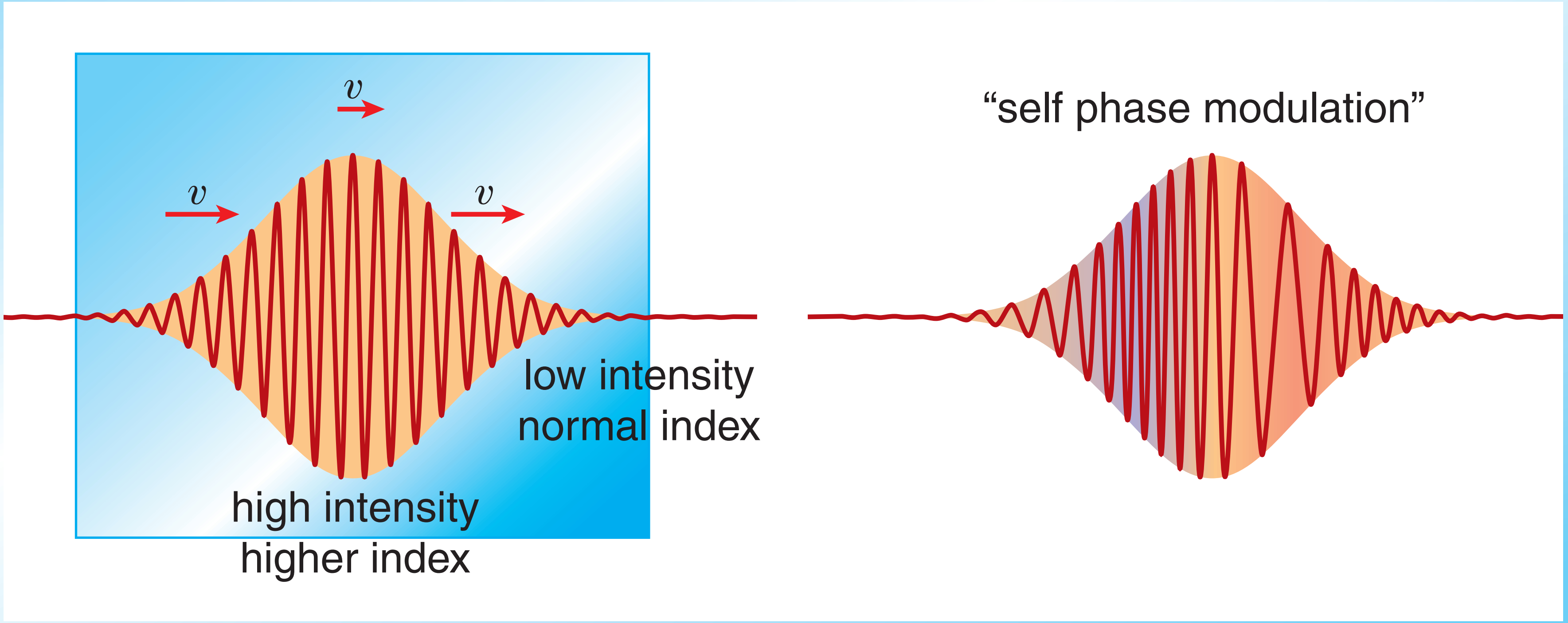

Nonlinear optics

Phase:

$$\frac{\phi}{2\pi} = \frac{nL}{\lambda}$$

Nonlinear optics

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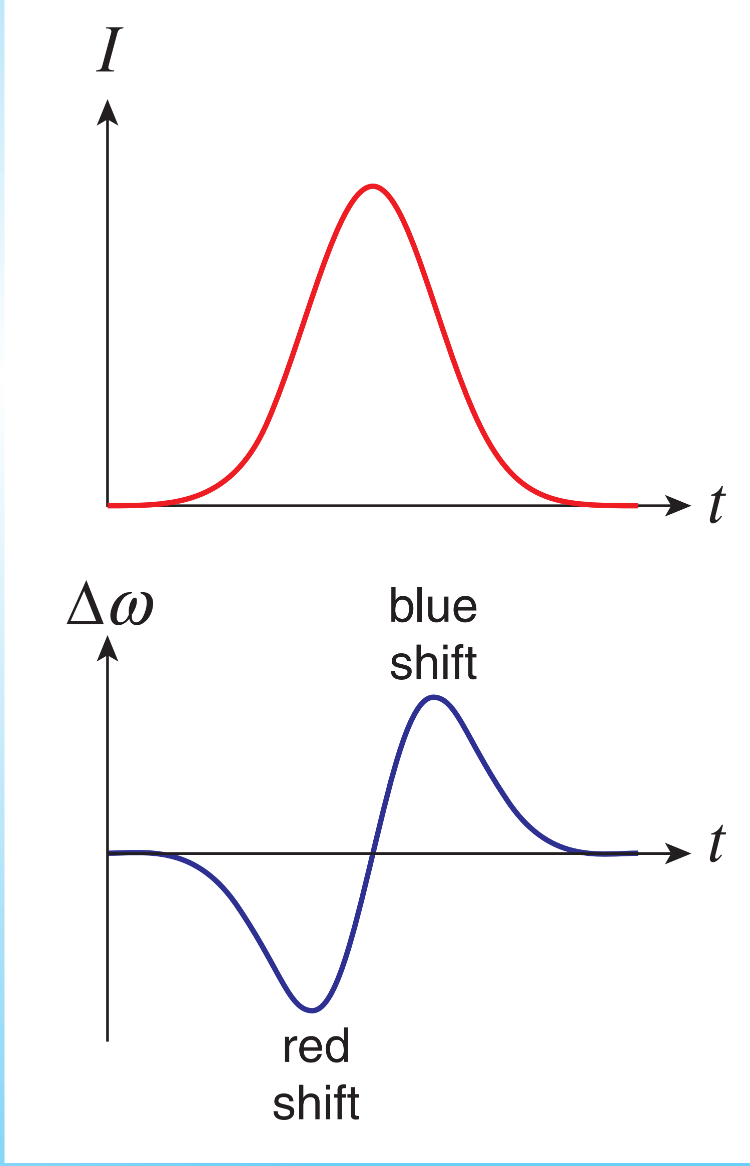
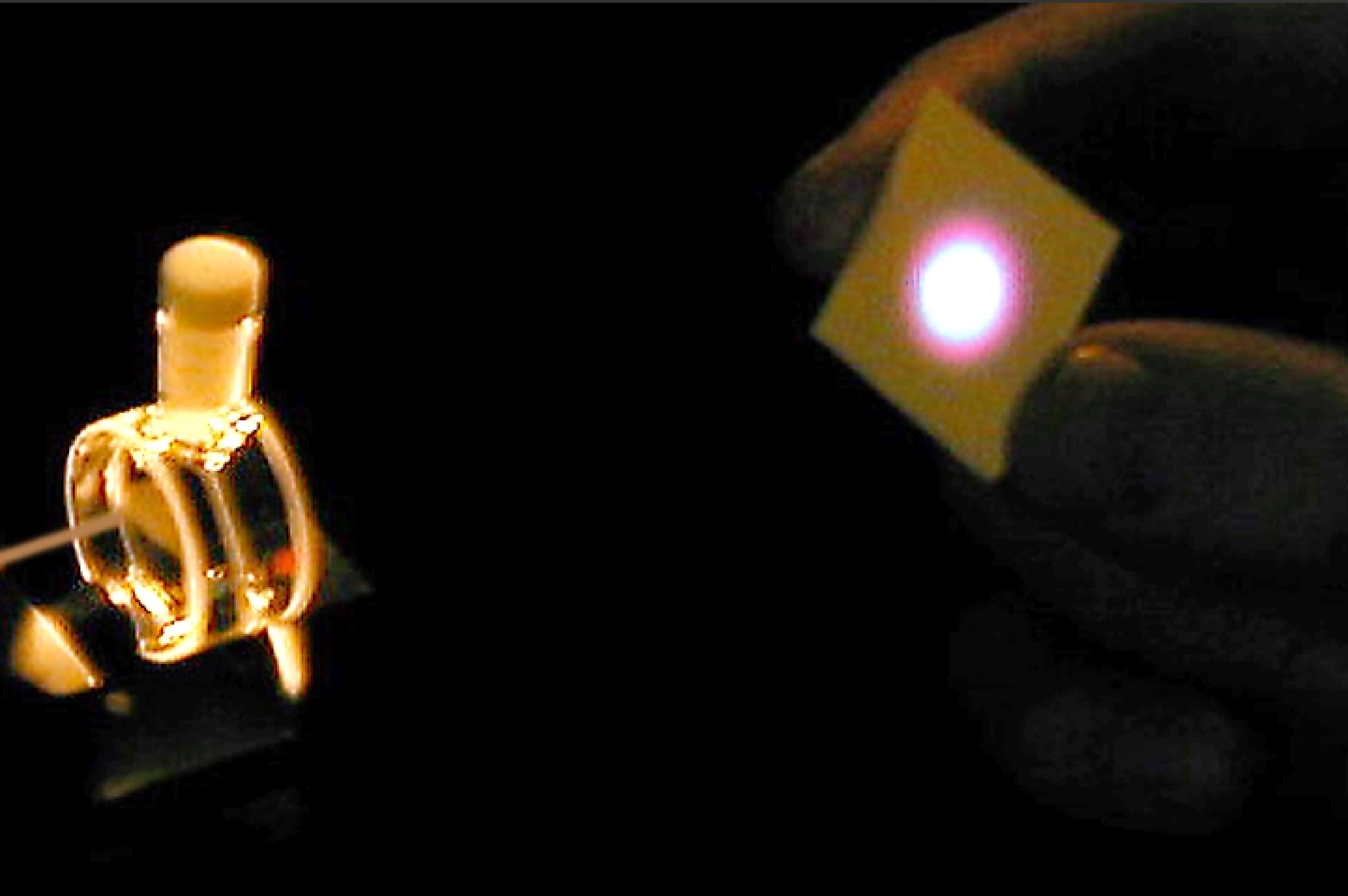
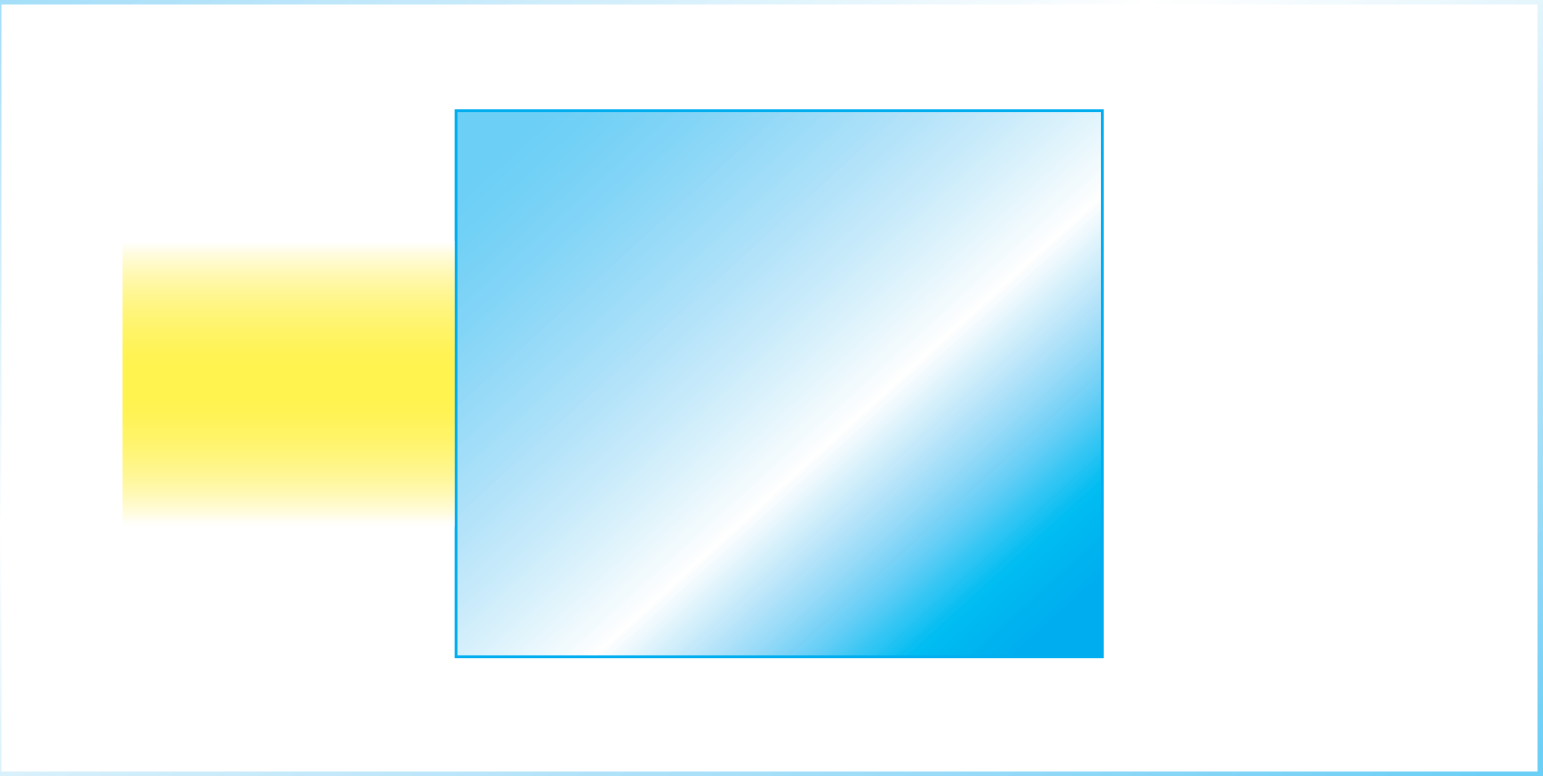


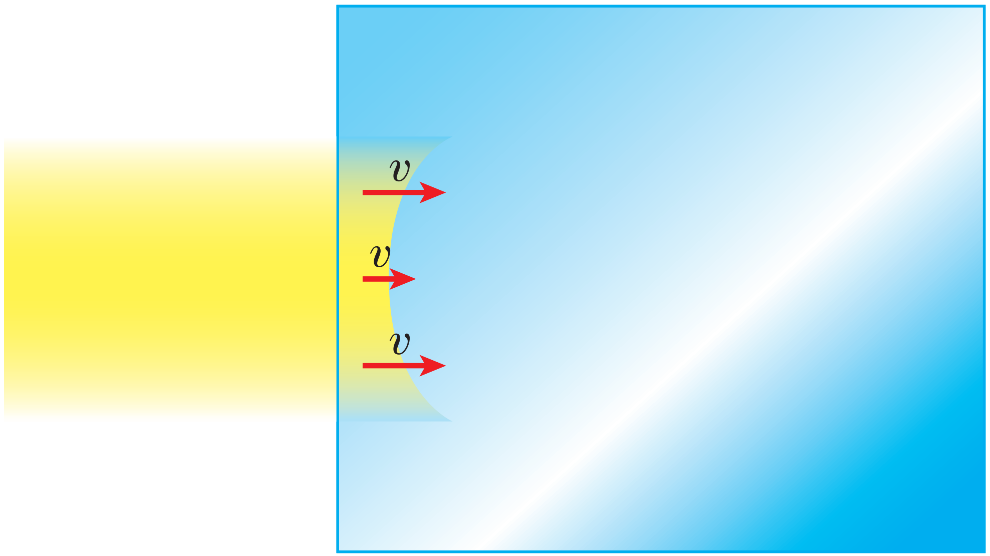
Nonlinear optics



Spatial intensity profile…

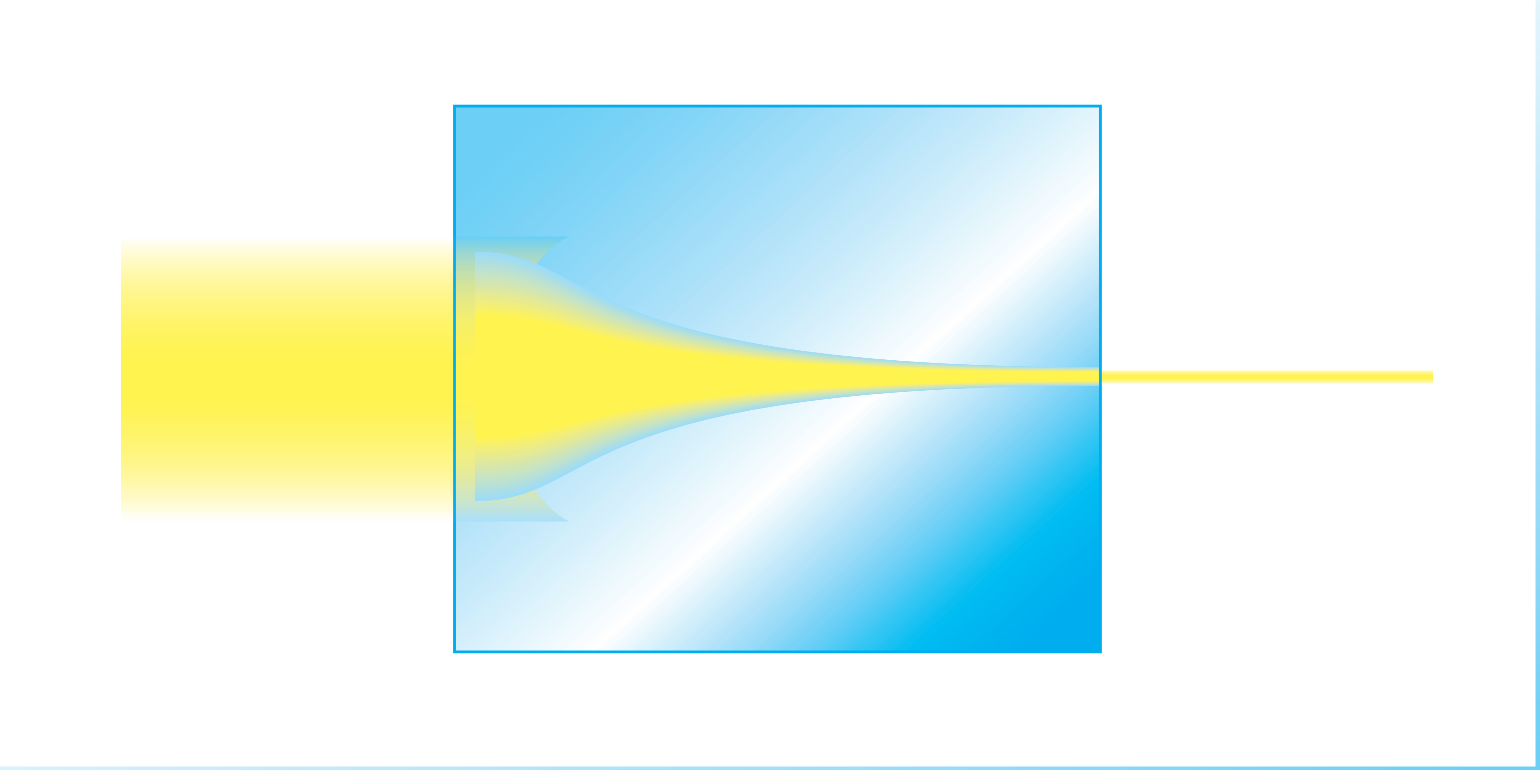


Spatial intensity profile…



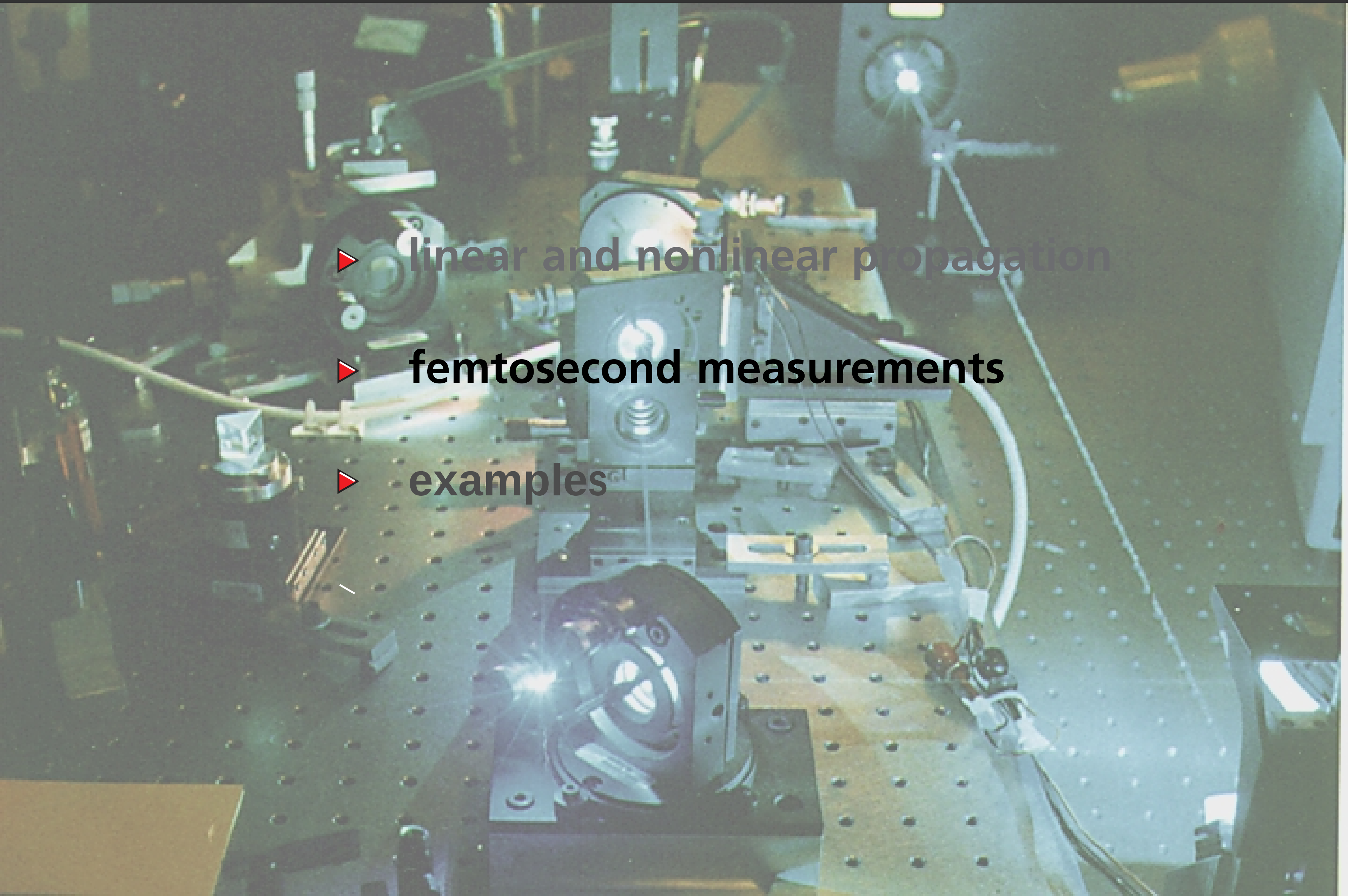
Nonlinear optics

…causes self-focusing

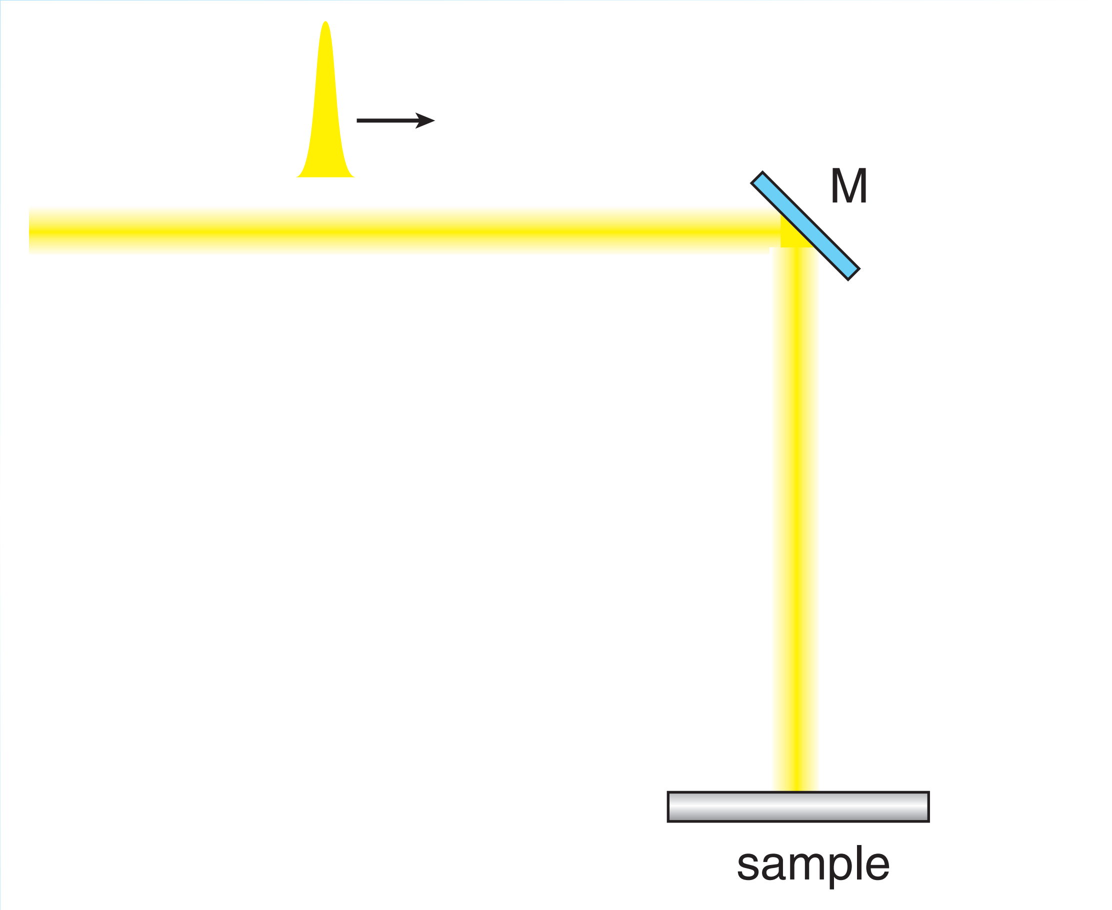


Outline

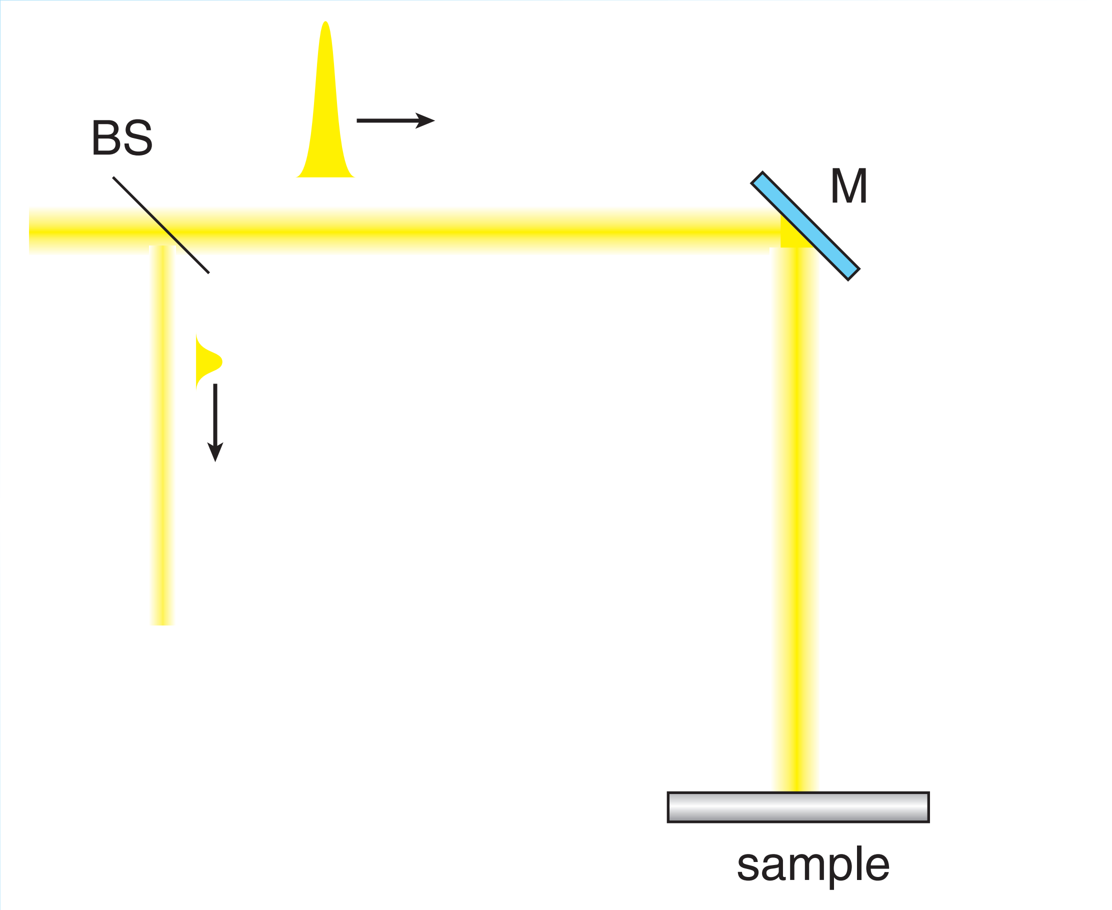
- linear and nonlinear propagation
- **femtosecond measurements**
- examples



How to measure on the femtosecond time scale?



Use pump-probe technique



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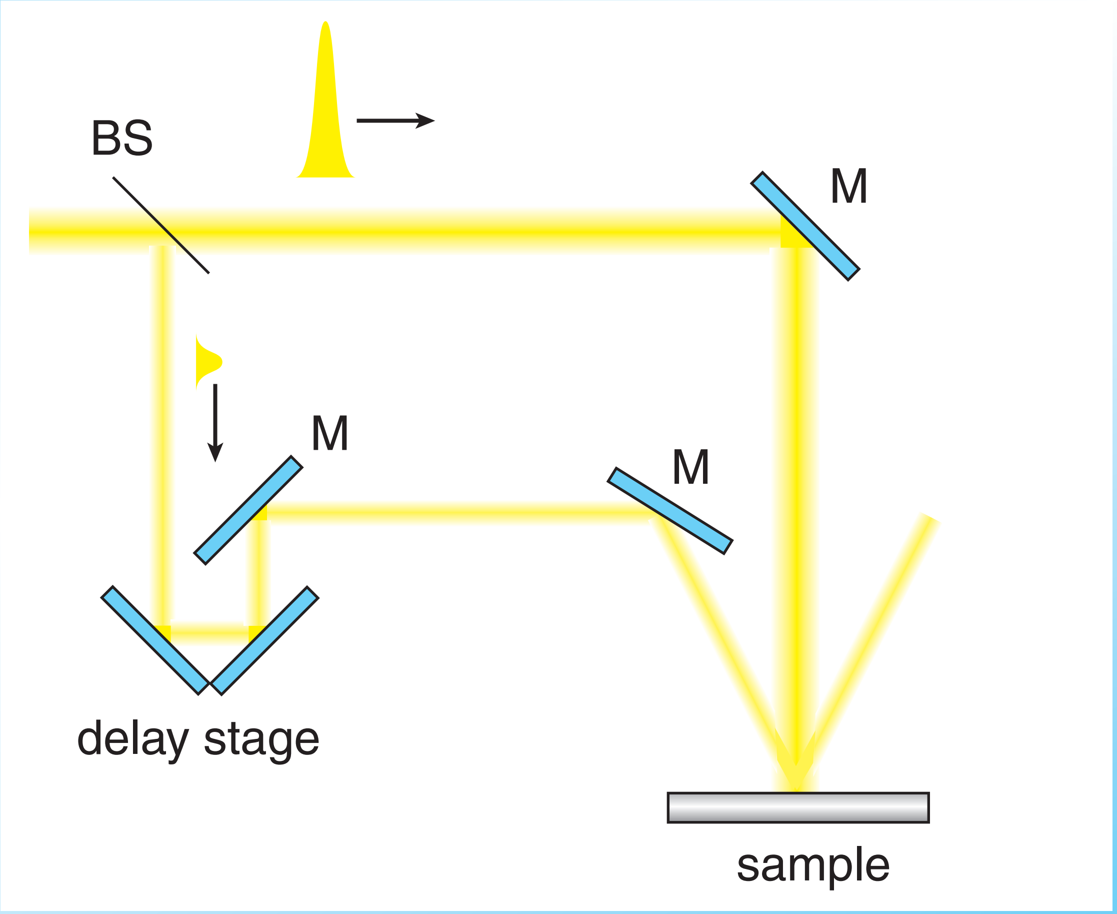

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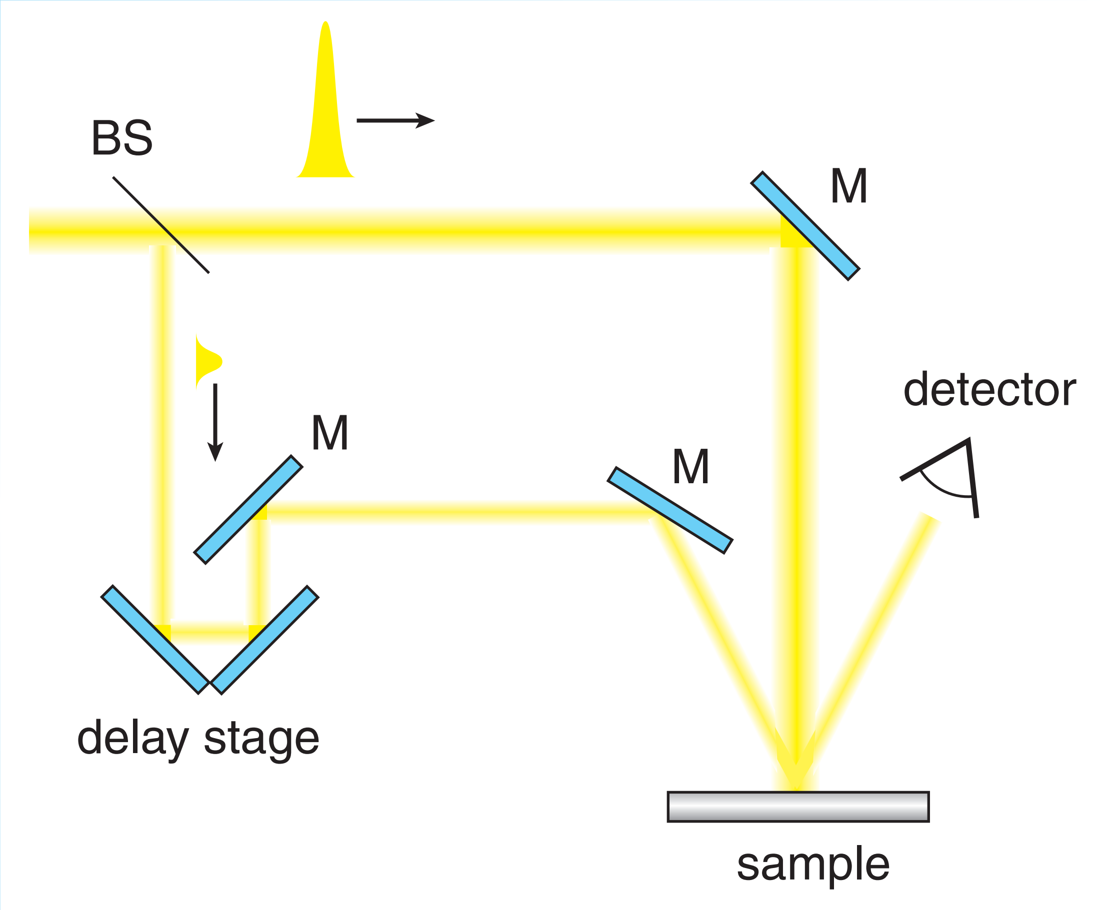
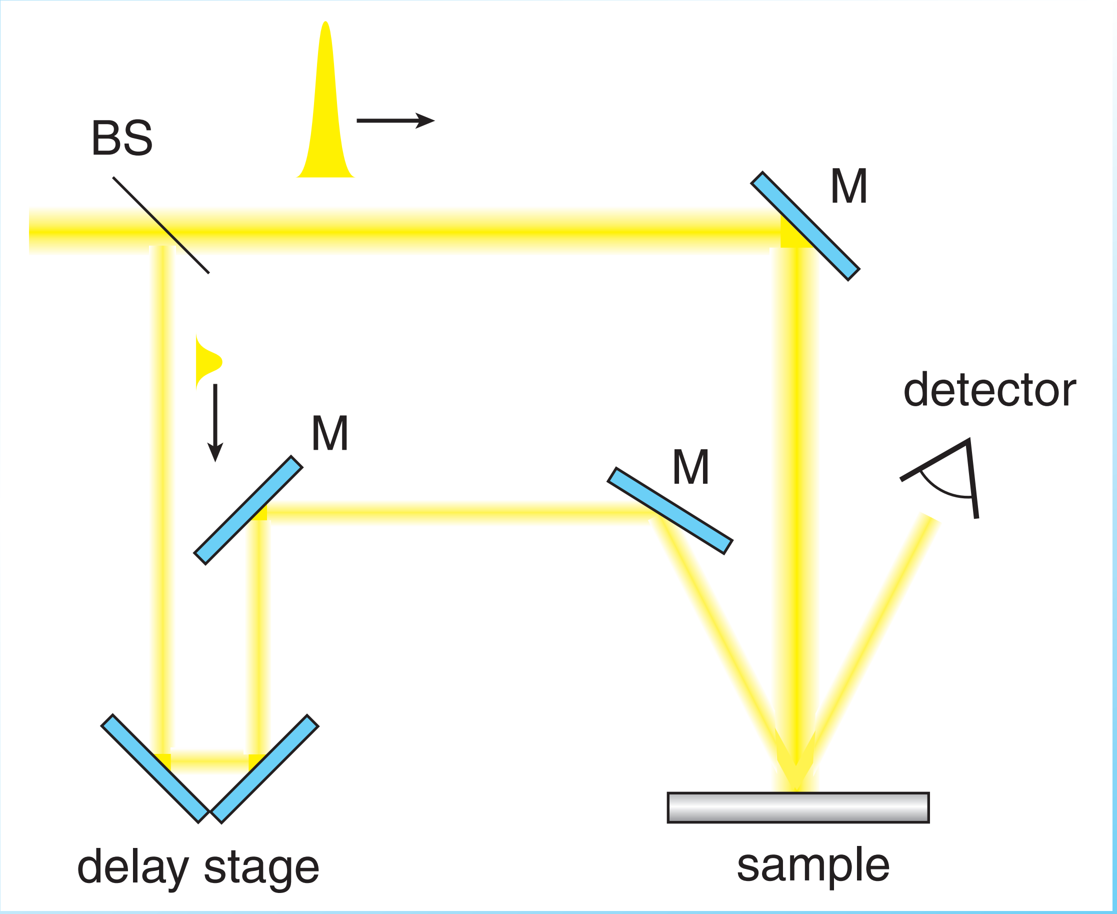
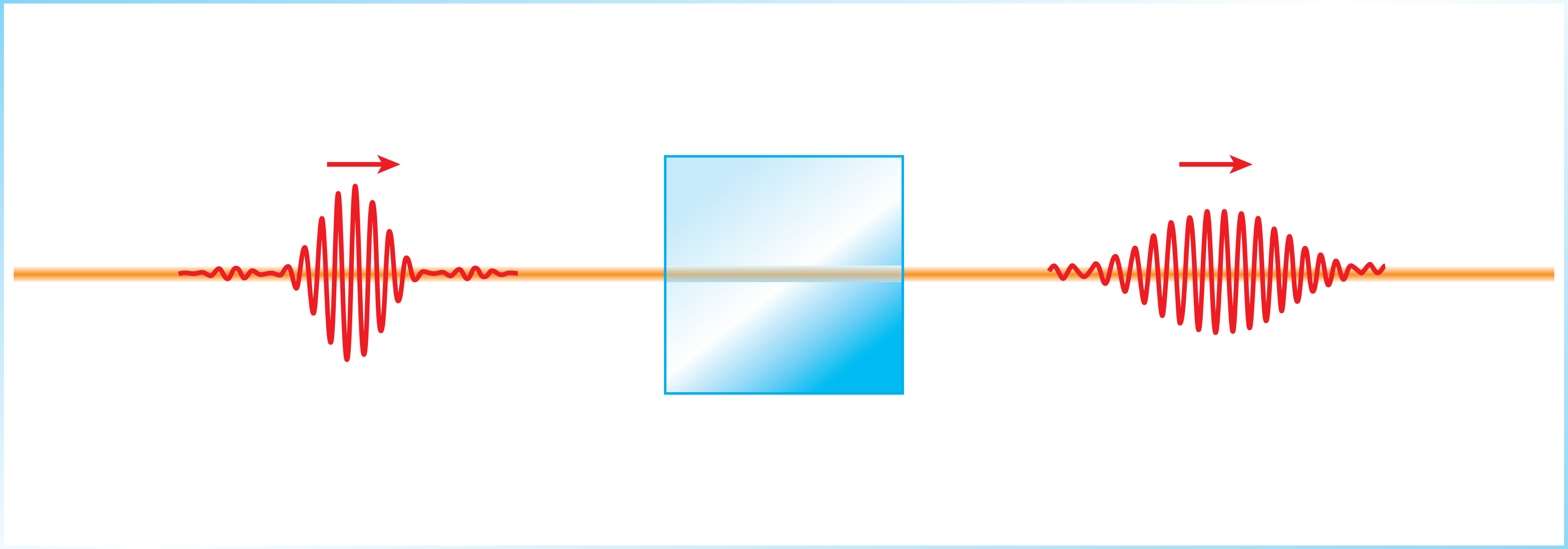


Vary delay to get time resolution



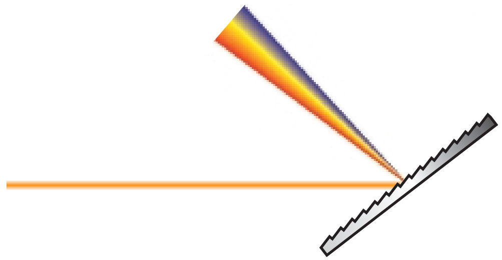
Dispersion compensation

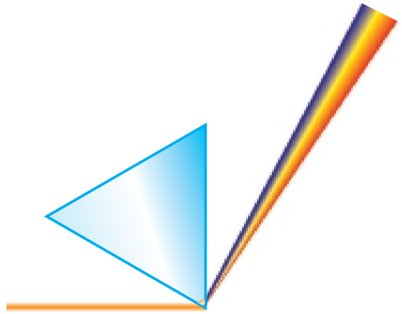
Dispersion stretches the pulse



Compensate by rearranging spectral components!

Dispersion compensation





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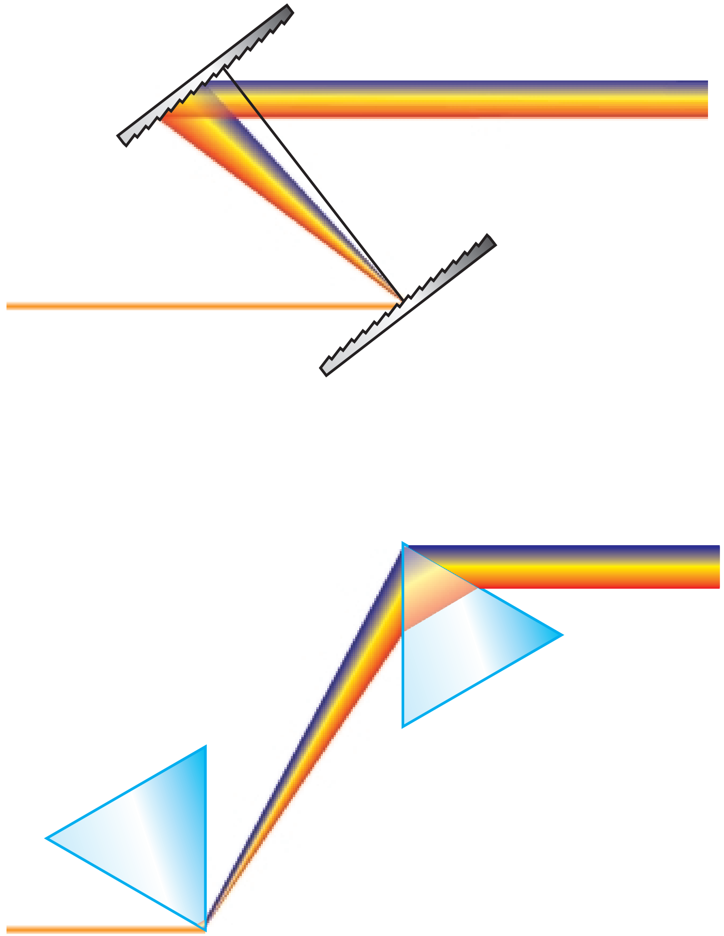

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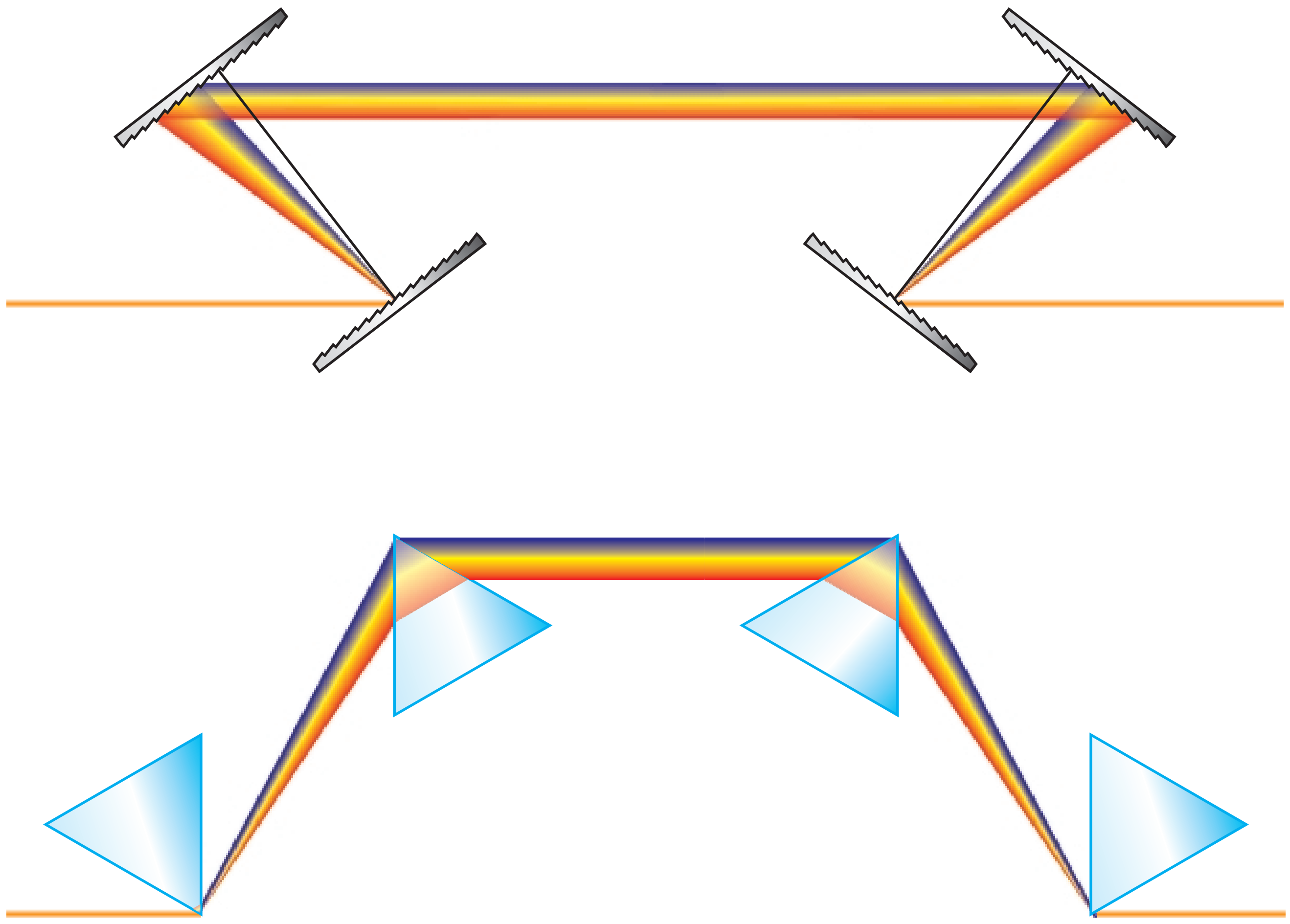
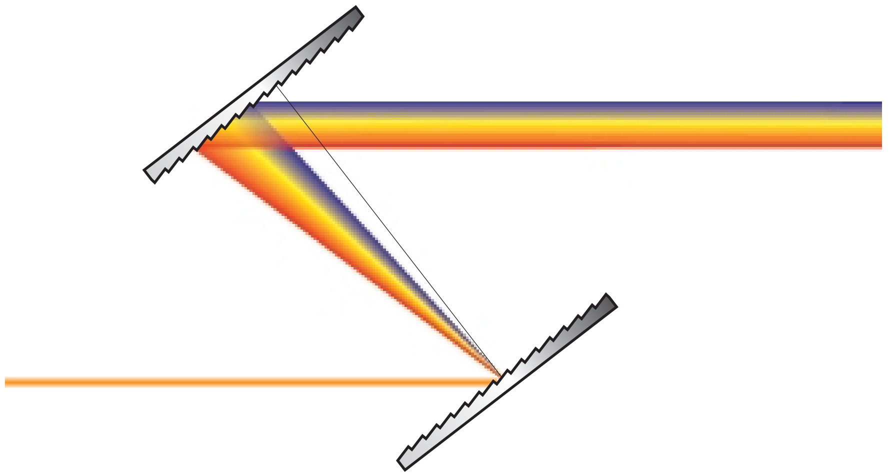


Dispersion compensation

How do these arrangements work?

Dispersion compensation

Does path length difference compensate?



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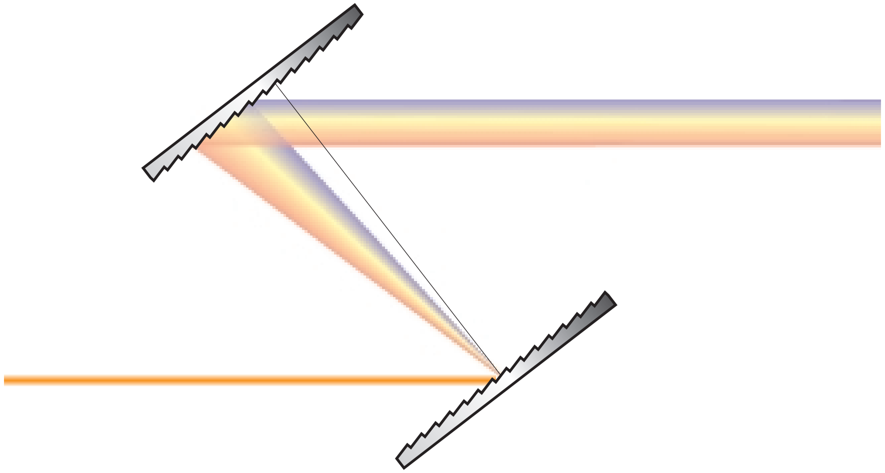

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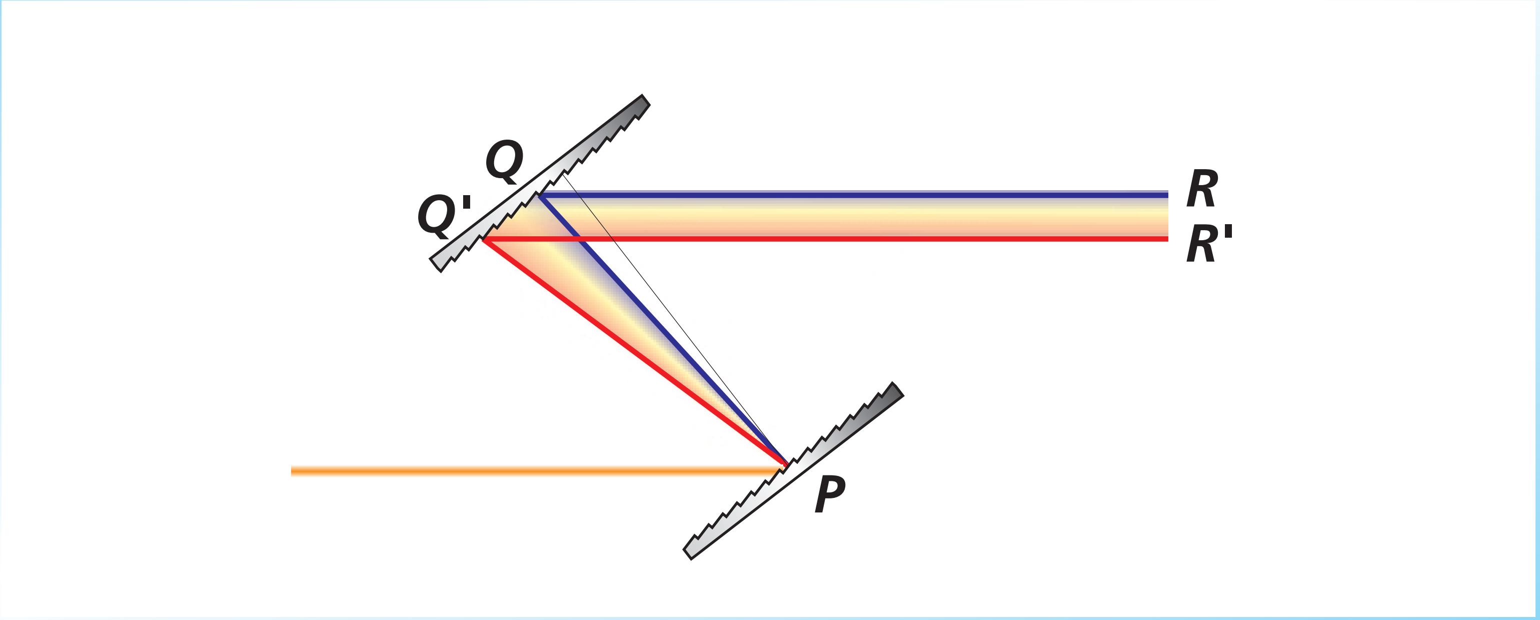

Grating gives low frequency longer path length…

Dispersion compensation

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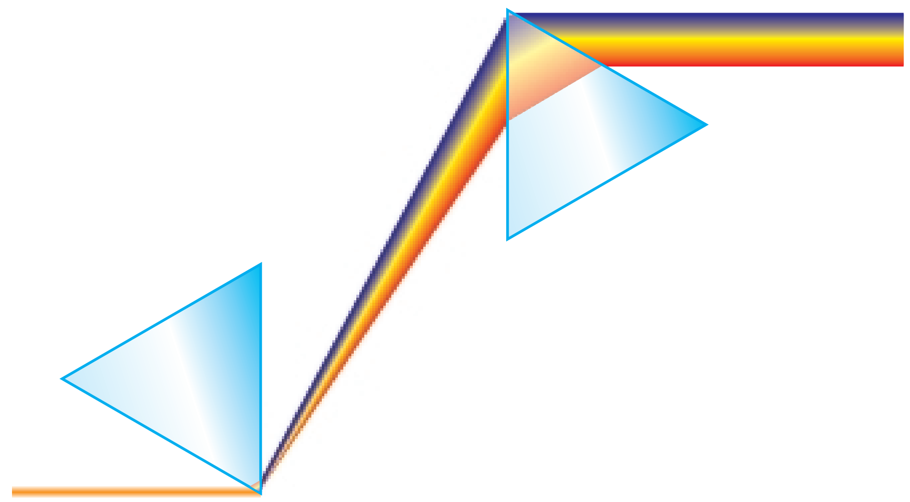

Dispersion compensation

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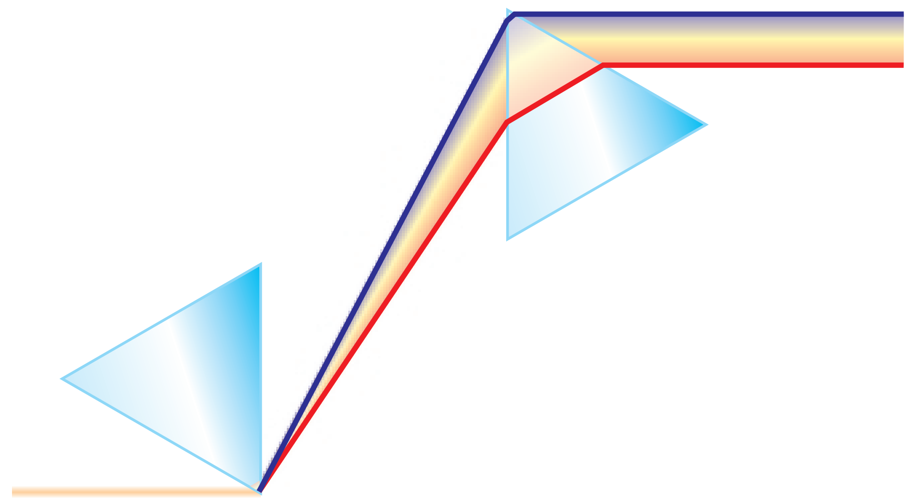

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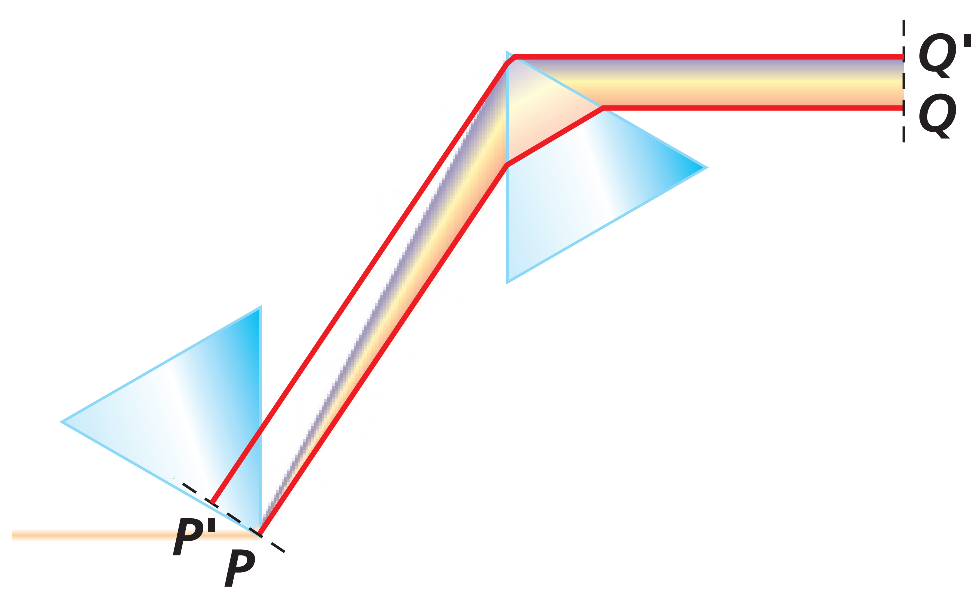
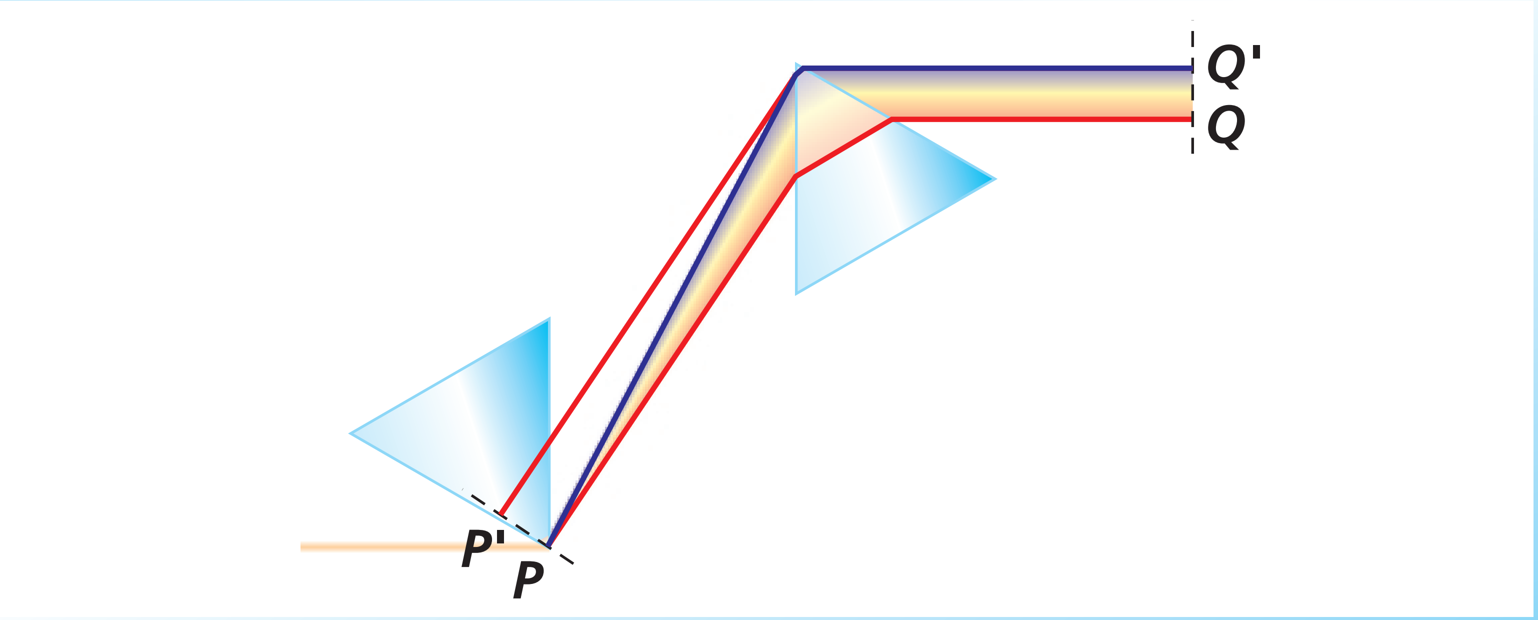


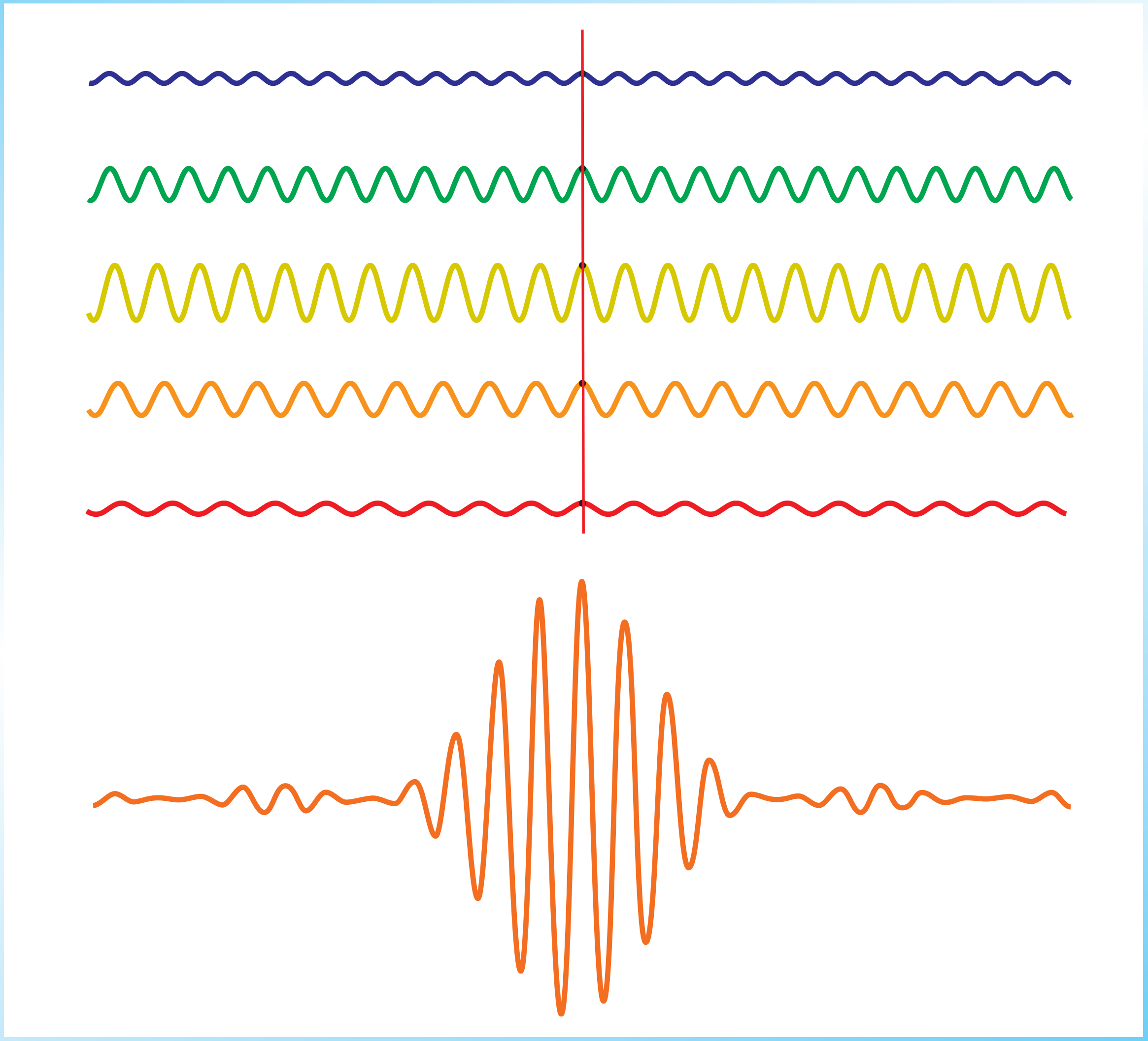
Dispersion compensation

Does path length difference compensate?

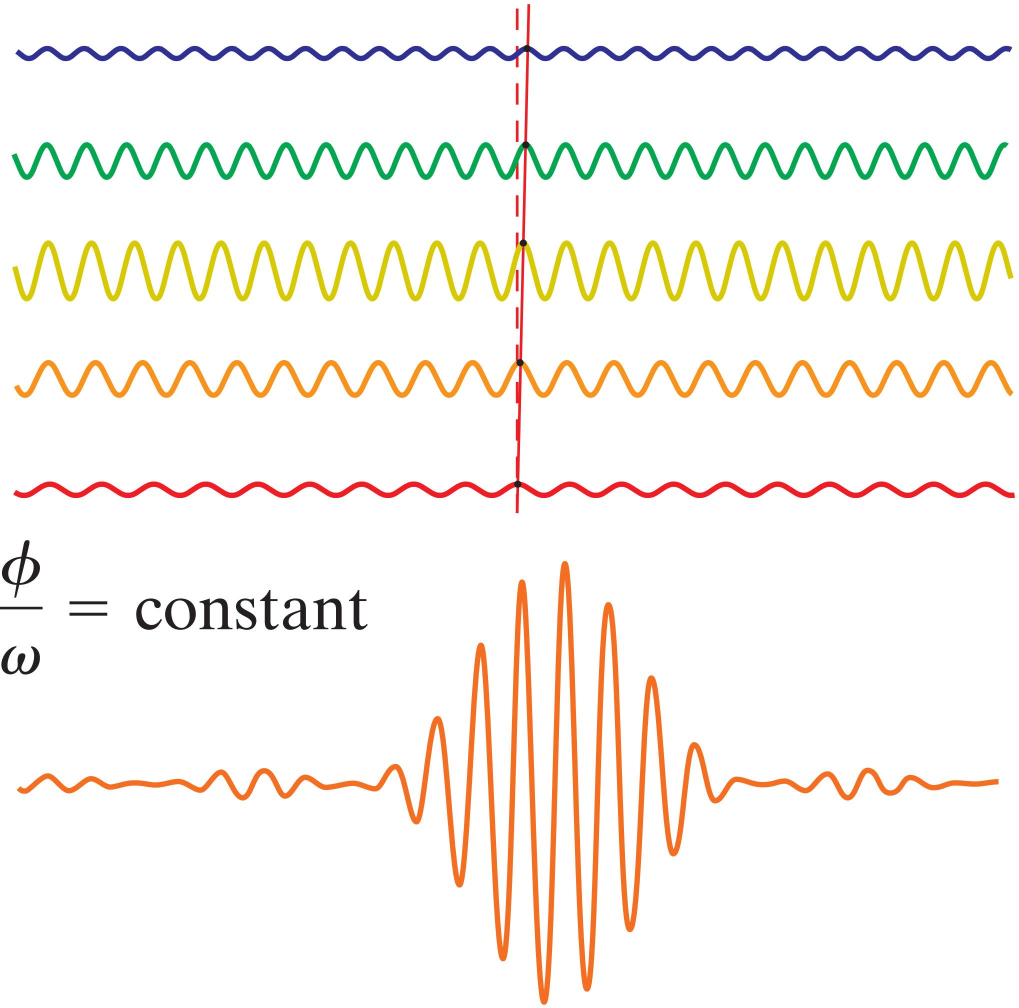


…so prism gives low frequency *shorter* path length…

Dispersion compensation

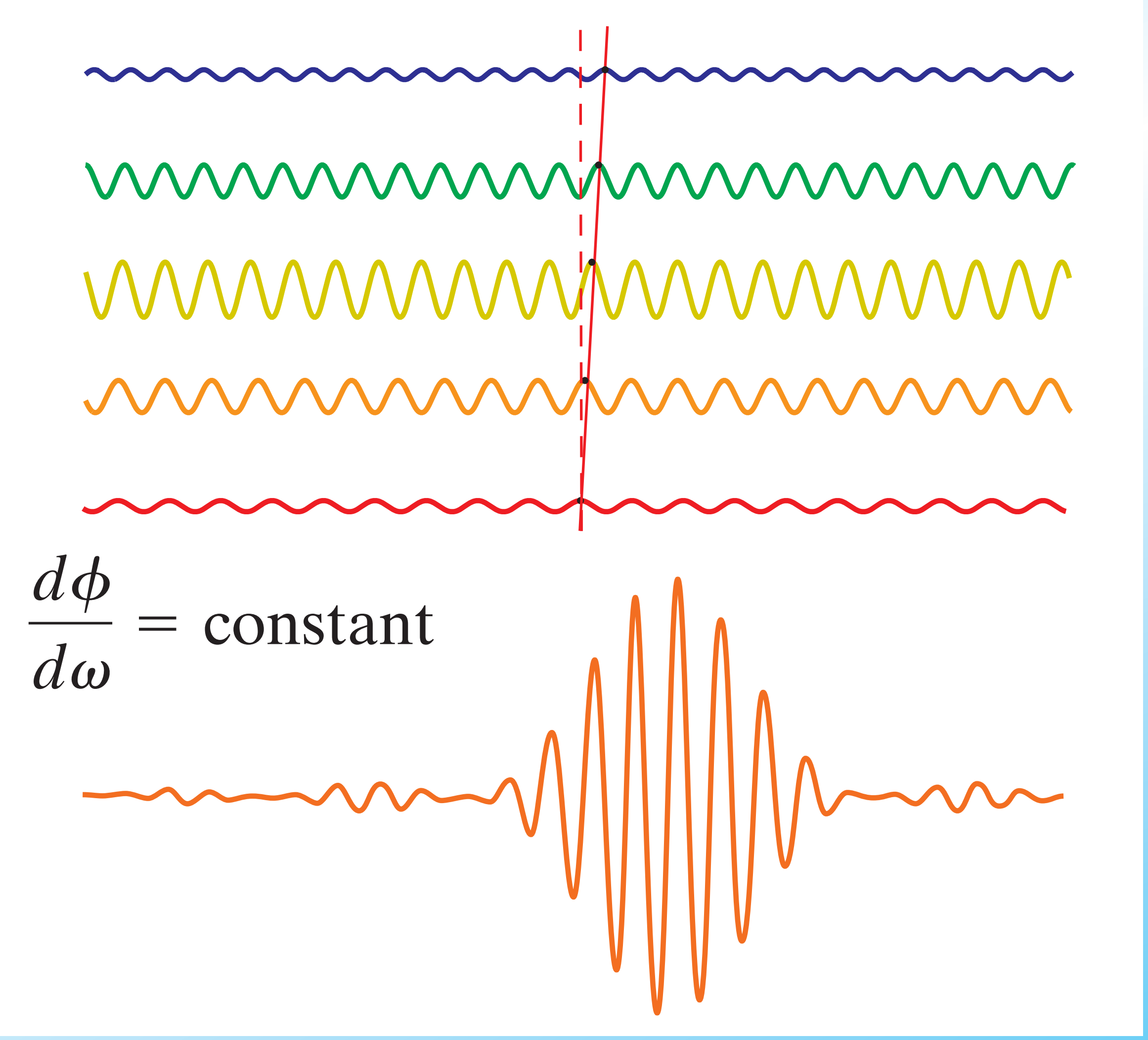


Dispersion compensation

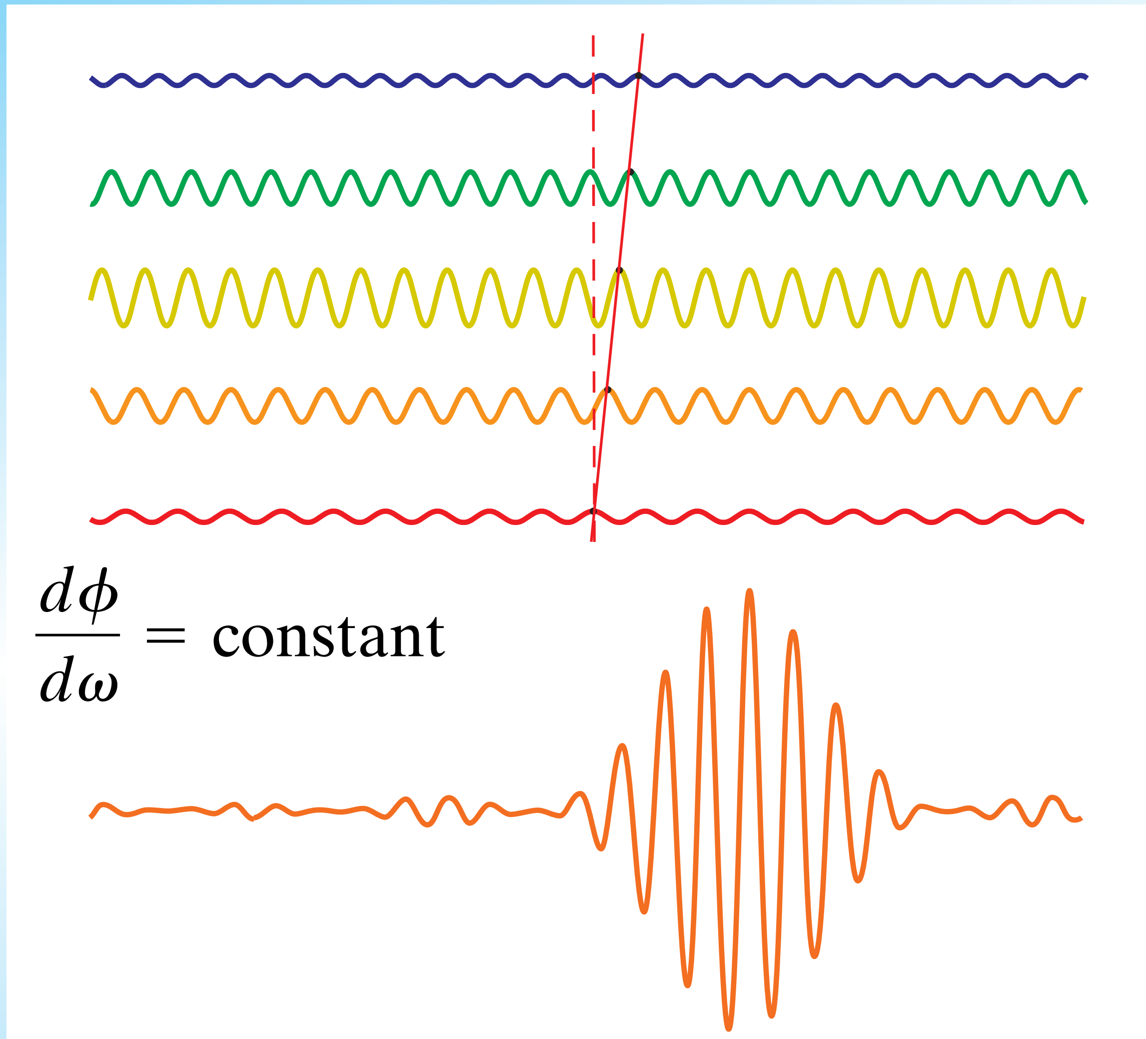


$$\frac{d\phi}{d\omega} = \text{constant}$$

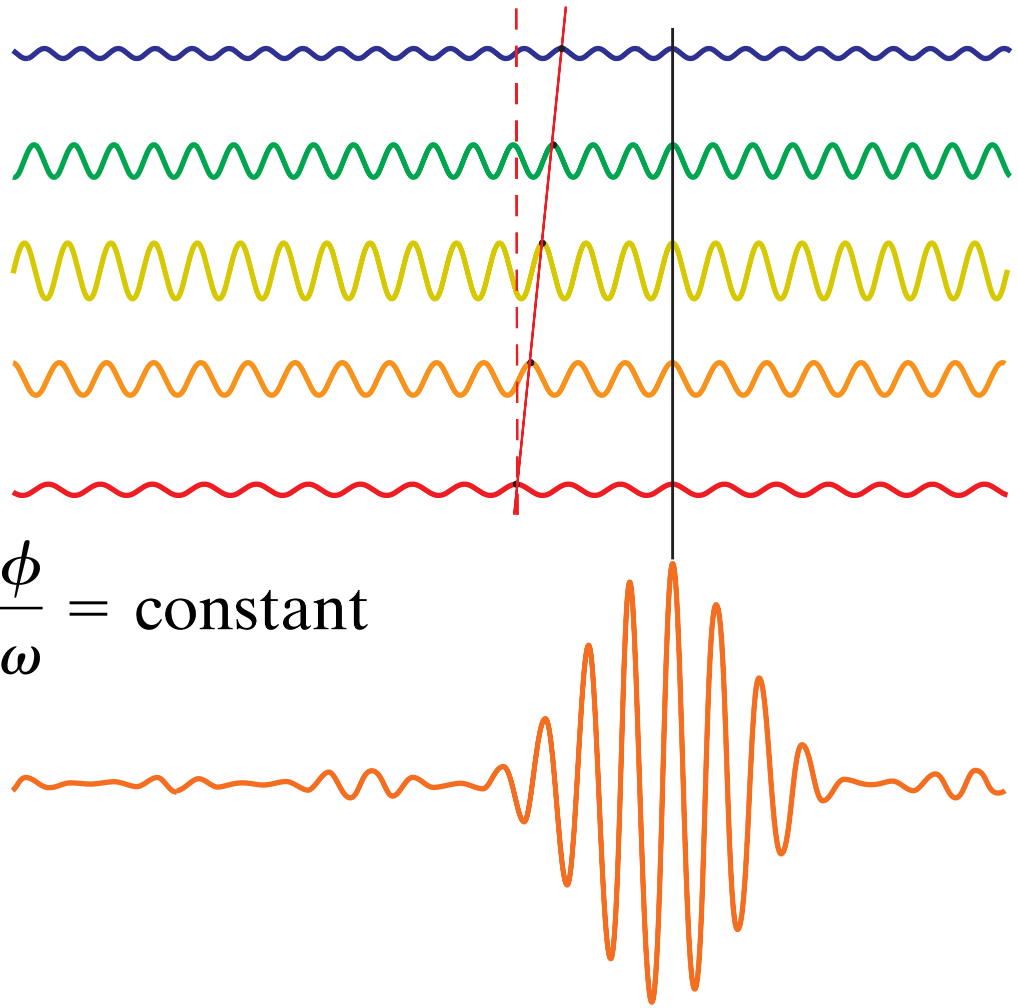
Dispersion compensation



Dispersion compensation



Dispersion compensation



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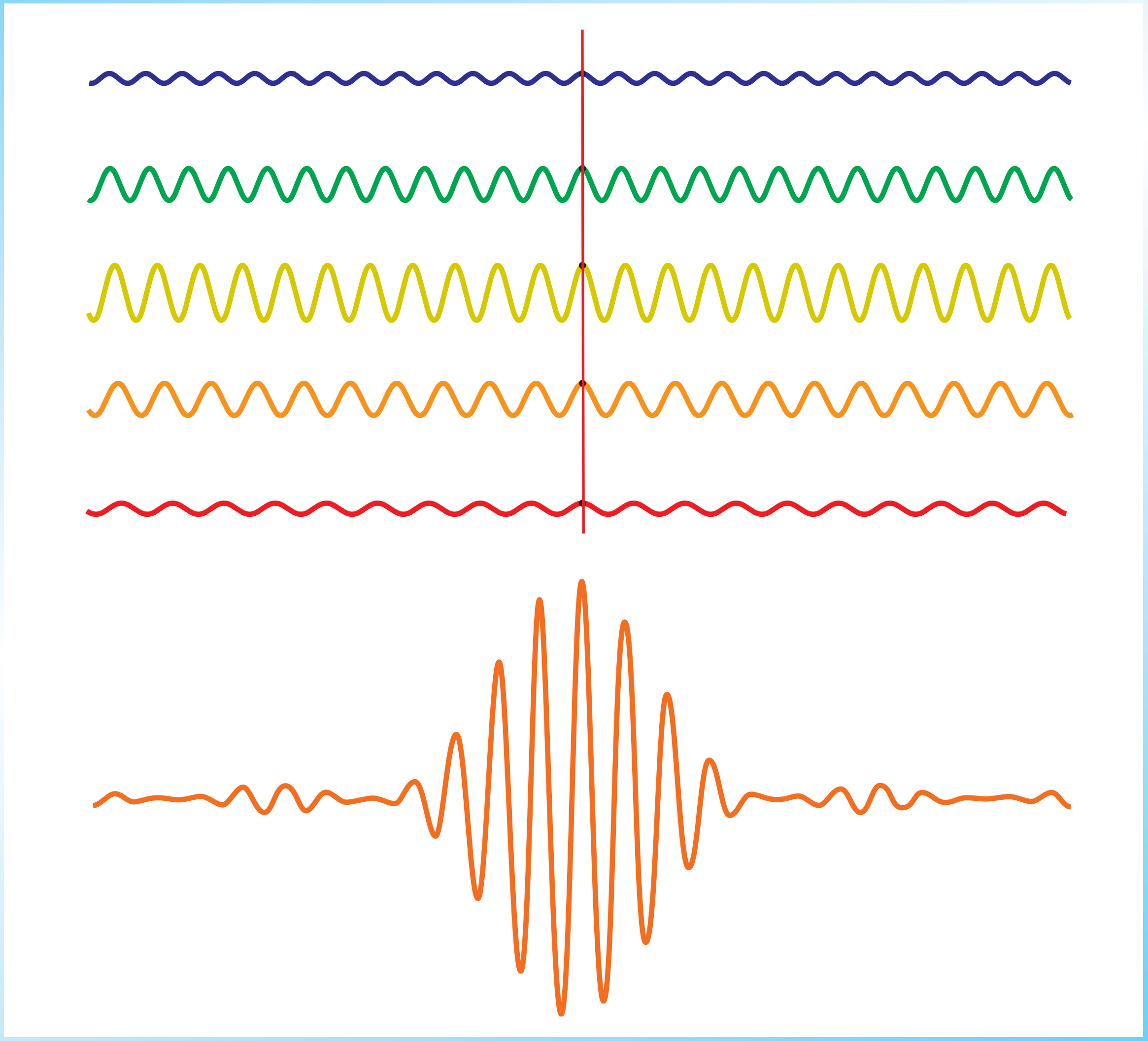

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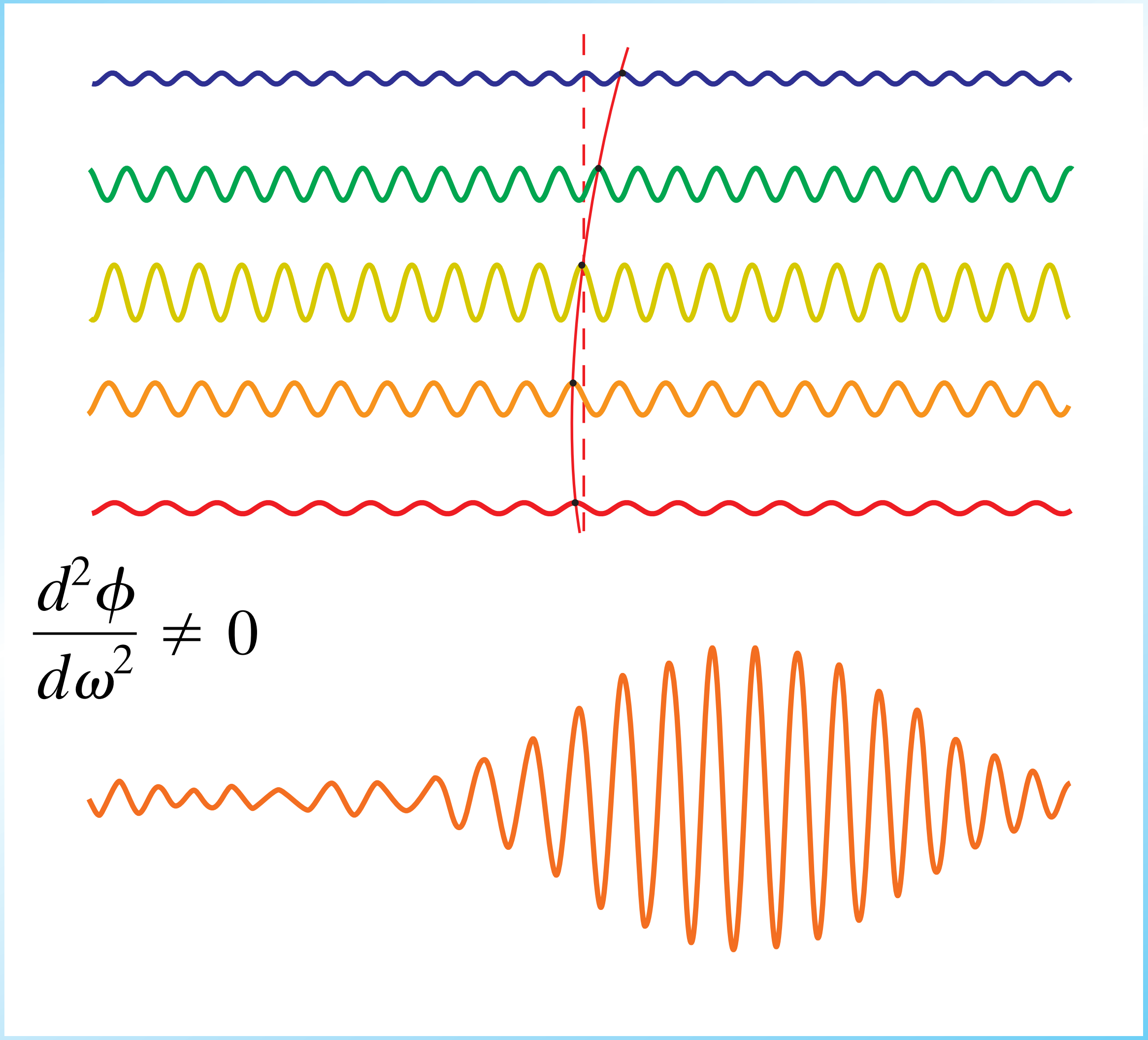
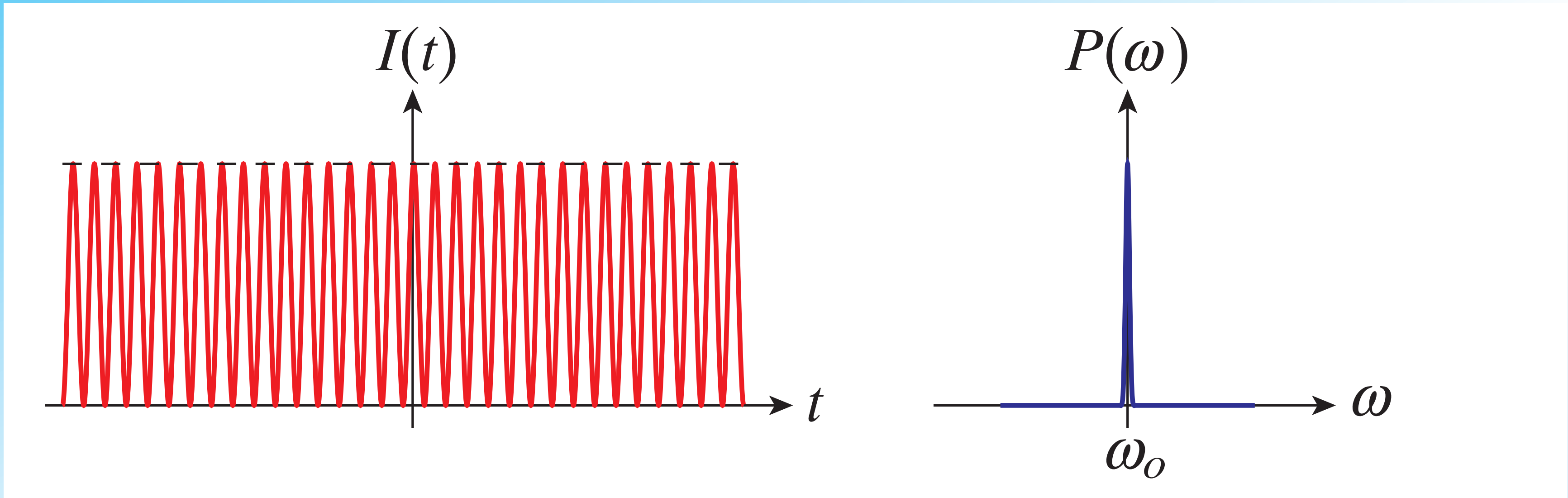


Dispersion compensation

So not path length but $\frac{d^2\phi}{d\omega^2}$ matters!

	$\frac{dl_{eff}}{d\omega}$	$\frac{d^2\phi}{d\omega^2}$
dispersion	+	+
gratings	–	–
prisms	+	–

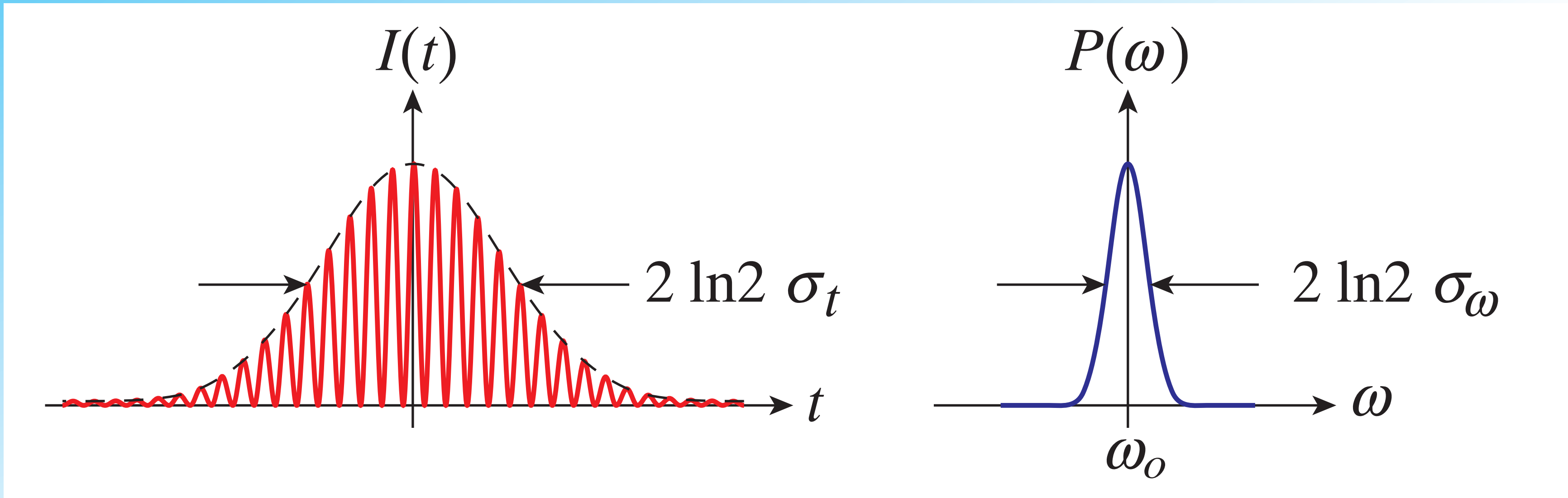
Representation of pulses



Spectrum of sinusoidal intensity is a delta function

$$I(t) = \cos^2(\omega_o t) \quad \Rightarrow \quad P(\omega) = \delta(\omega - \omega_o)$$

Representation of pulses



Modulate amplitude

$$I(t) = \exp\left[-\frac{t^2}{\sigma_t^2}\right]\cos^2(\omega_o t)$$

Representation of pulses

Fourier relations:

$$E(t) = \exp\left[-\frac{t^2}{2\sigma_t^2} - i\omega_o t\right]$$

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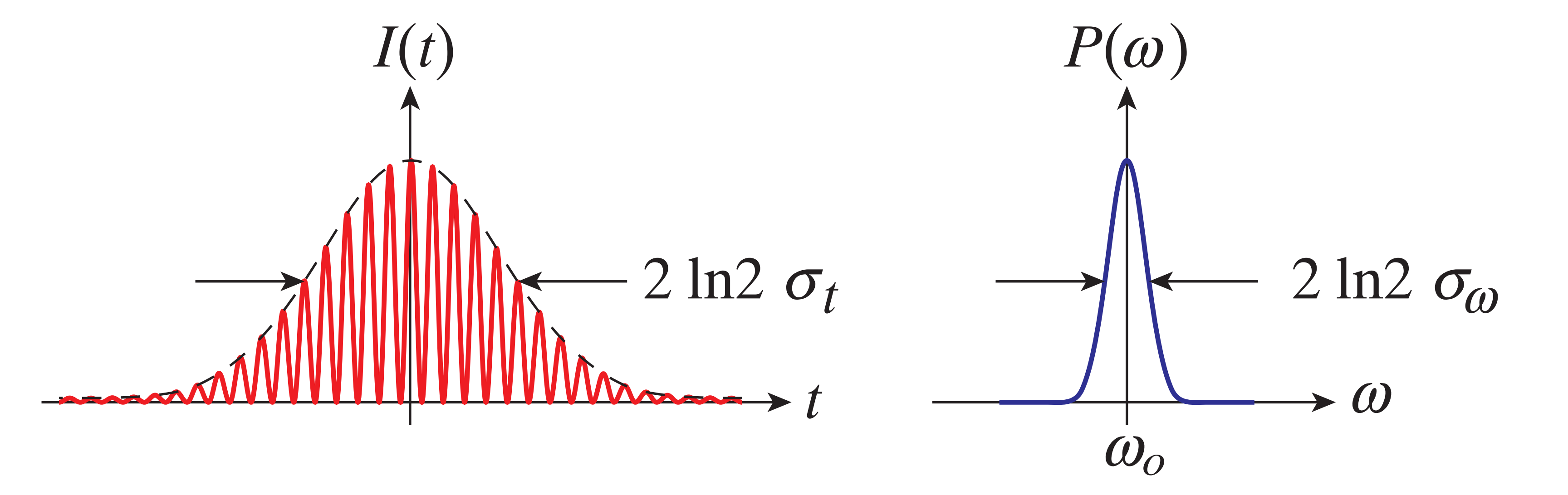
$$= \sigma_t \exp\left[-\frac{\sigma_t^2(\omega-\omega_o)^2}{2}\right] \equiv \sigma_t \exp\left[-\frac{(\omega-\omega_o)^2}{2\sigma_\omega^2}\right]$$

Representation of pulses



Pulse duration-bandwidth product: $\sigma_t \sigma_\omega = 1$

$$I(t) = [\mathrm{Re}\, E(t)]^2 \propto \exp\left[-\frac{t^2}{\sigma_t^2}\right] \cos^2(\omega_o t)$$

$$P(\omega) = E(\omega)E^*(\omega) = \exp\left[-\frac{(\omega-\omega_o)^2}{\sigma_\omega^2}\right]$$

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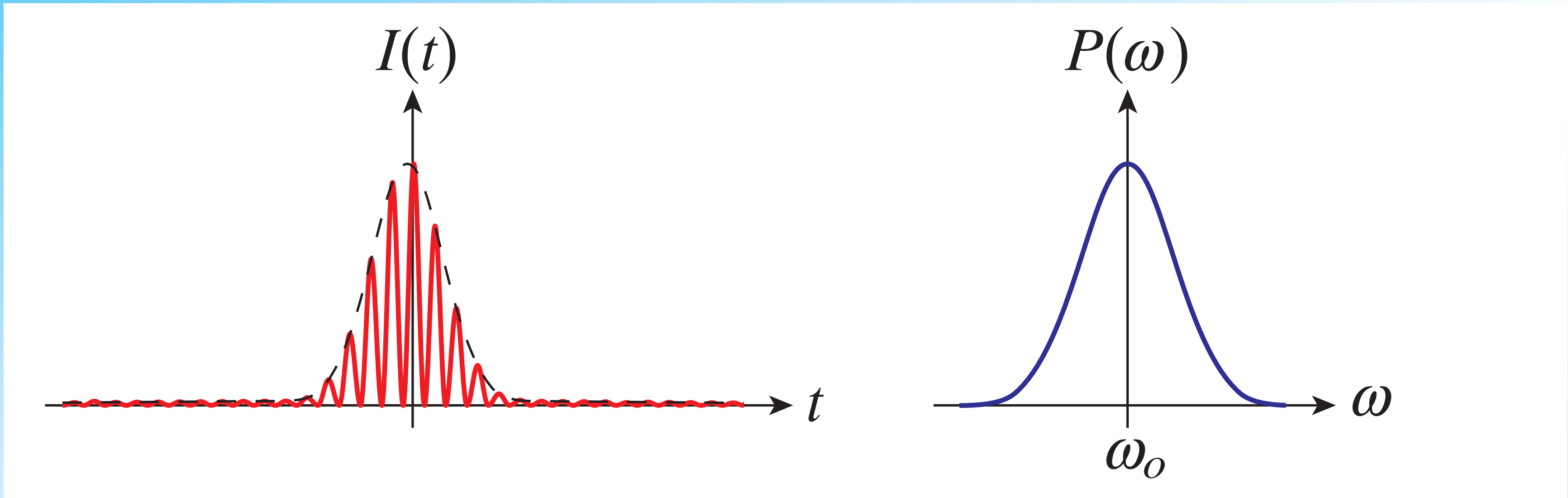

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Wigner representation:

$$W(t,\omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty} E\left(\omega + \frac{\omega'}{2}\right)E^*\left(\omega - \frac{\omega'}{2}\right)e^{-i\omega' t}d\omega' =$$

$$= \int_{-\infty}^{\infty} E\left(t + \frac{t'}{2}\right)E^*\left(t - \frac{t'}{2}\right)e^{-i\omega t'}\,dt'$$

Joint time-frequency representation

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Joint time-frequency representation

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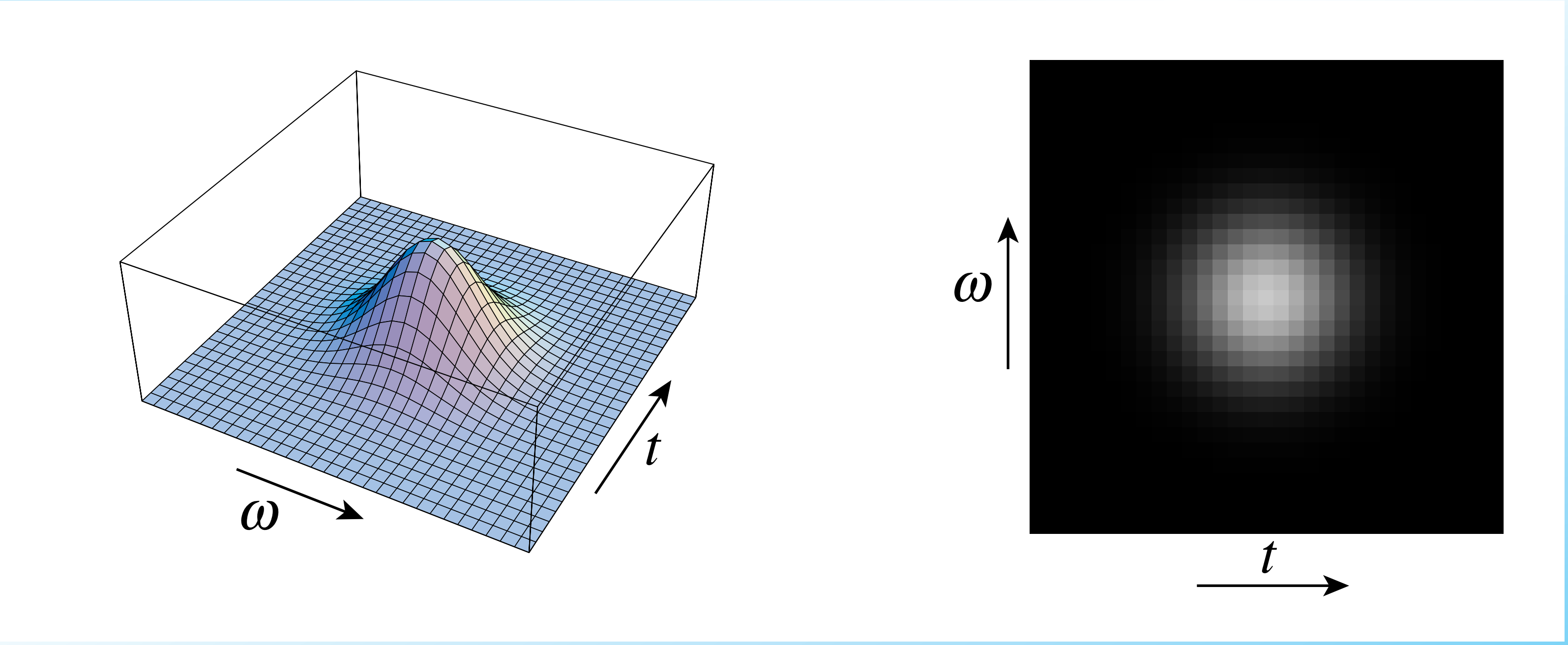
Joint time-frequency representation

Energy: $$\frac{1}{2\pi}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} W(t,\omega)\; dt\; d\omega$$



Joint time-frequency representation

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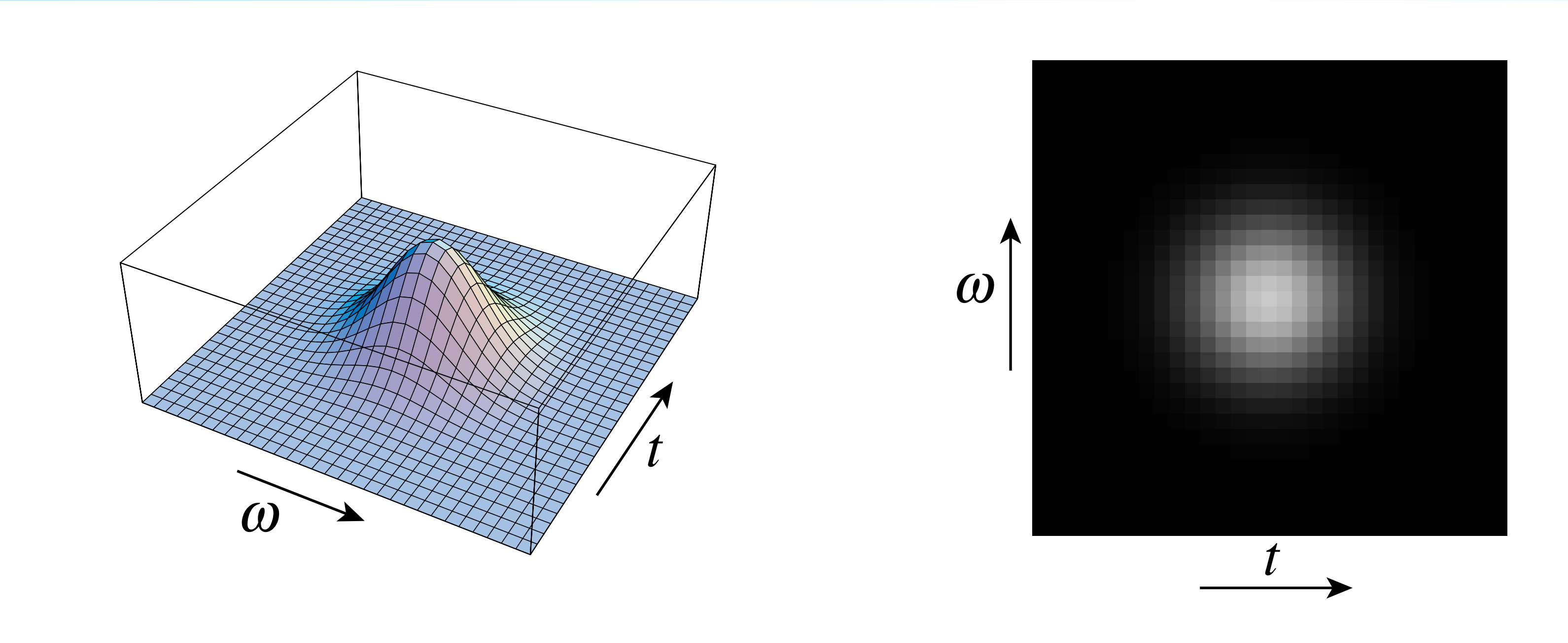
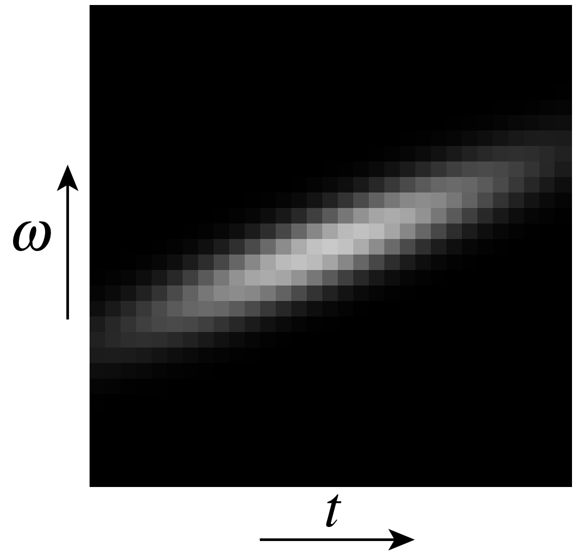


$W(t,\omega)$ **must be nonzero in phase-space area larger than** π

Joint time-frequency representation

Energy: $$\frac{1}{2\pi}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} W(t,\omega)\, dt\, d\omega$$

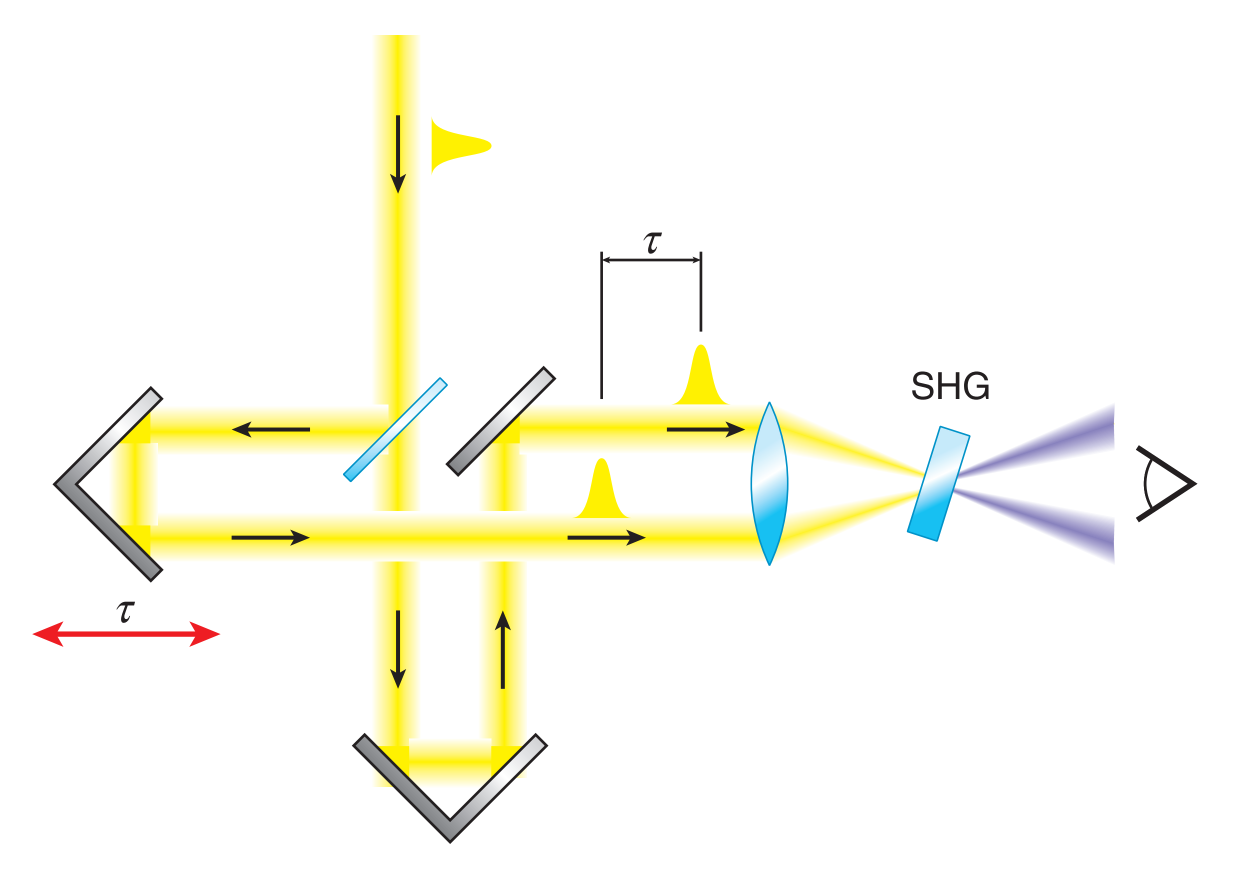
chirped pulse



$W(t,\omega)$ **must be nonzero in phase-space area larger than** π

Temporal characterization

Use pulse to measure itself…



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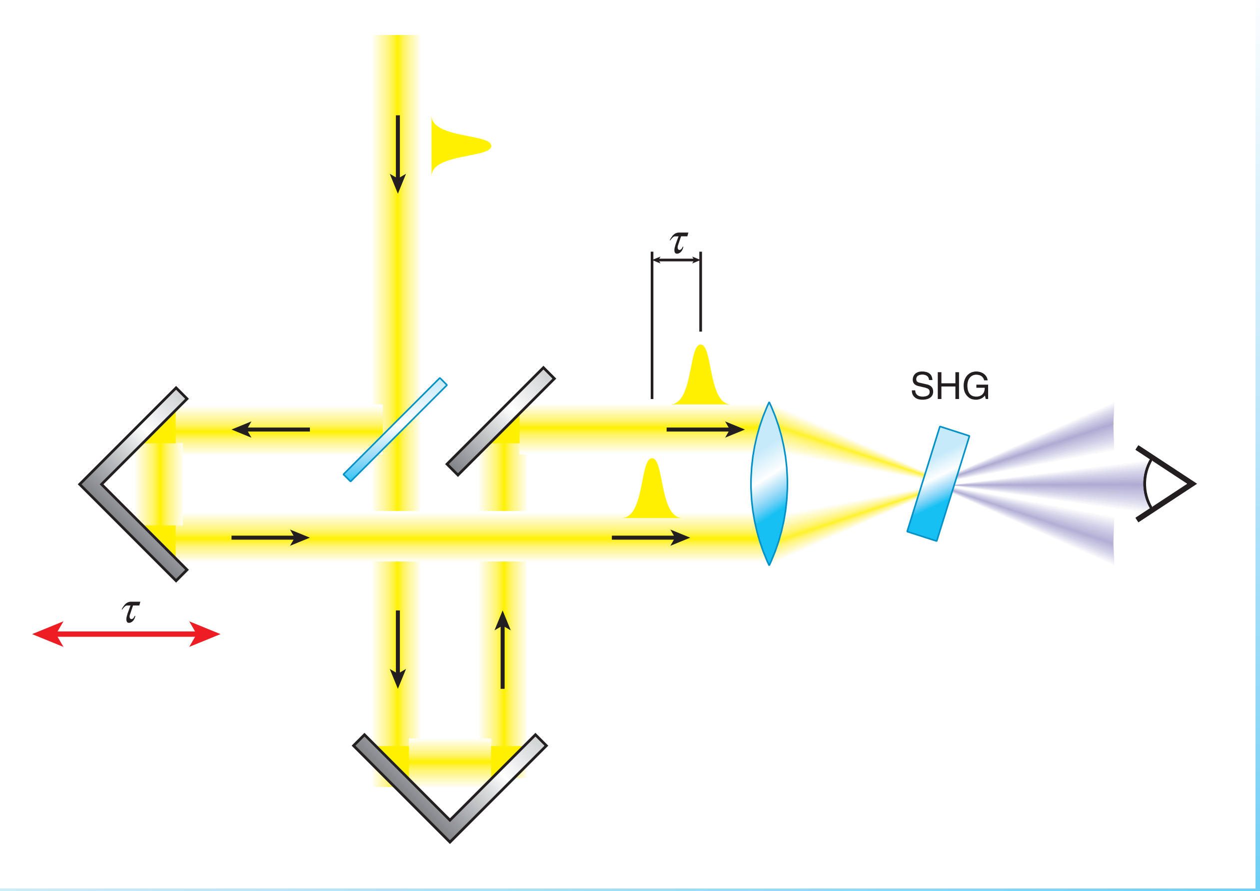

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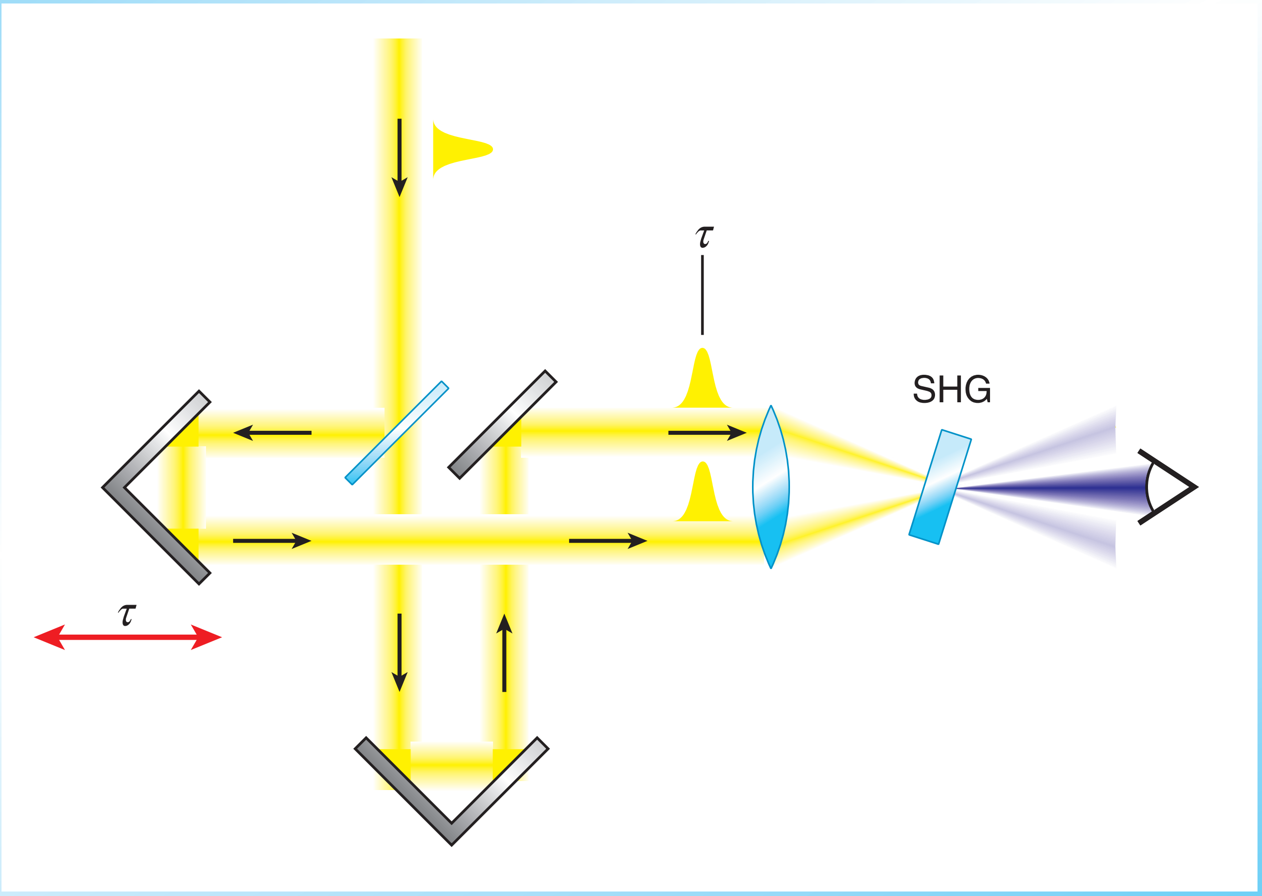

Temporal characterization

Electric field at SHG crystal

$$E_{tot}(t,\tau) = \frac{1}{\sqrt{2}}E_1(t) + \frac{1}{\sqrt{2}}E_2(t + \tau)$$

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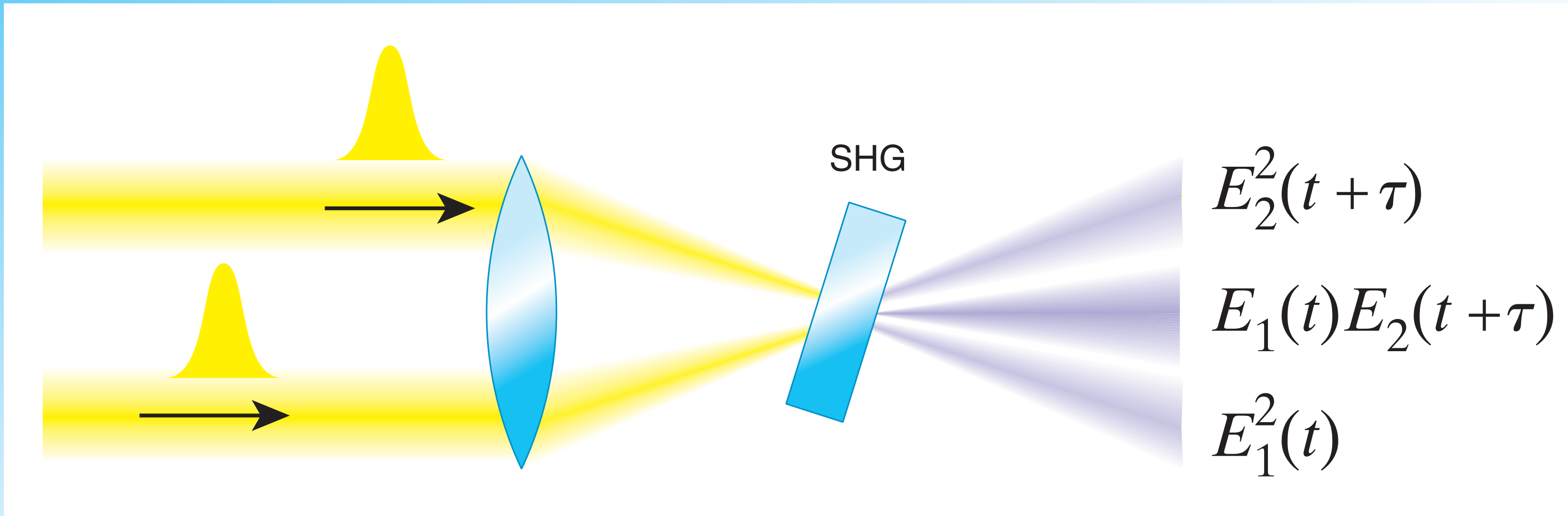
Second harmonic intensity

$$I_{2\omega}(t,\tau) \propto \left|\chi^{(2)}\right|^2 \left|E_{tot}^2\right|^2 = \left|\chi^{(2)}\right|^2 \left|E_1^2(t) + 2E_1(t)E_2(t+\tau) + E_2^2(t+\tau)\right|^2$$

Temporal characterization



Second harmonic intensity

$$I_{2\omega}(t,\tau) \propto |\chi^{(2)}|^2\, |E_{tot}^2|^2 = |\chi^{(2)}|^2 |E_1^2(t) + 2E_1(t)E_2(t+\tau) + E_2^2(t+\tau)|^2$$

detector selects middle term

Integrated detector signal yields intensity autocorrelation

$$A(\tau) = \int I_{2\omega}(t,\tau)dt \propto \int \left|\chi^{(2)}\right|^2 4\left|E_1(t)\right|^2 \left|E_2(t+\tau)\right|^2 dt$$

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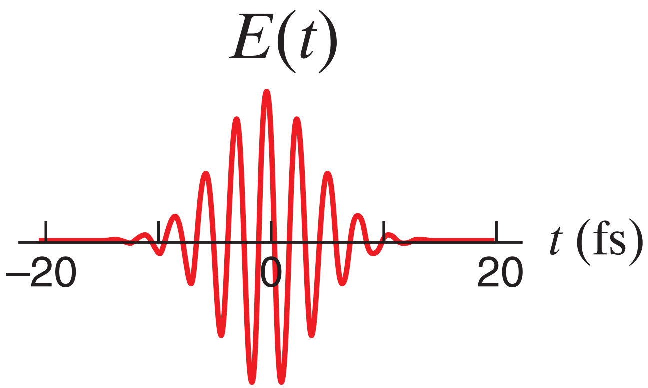

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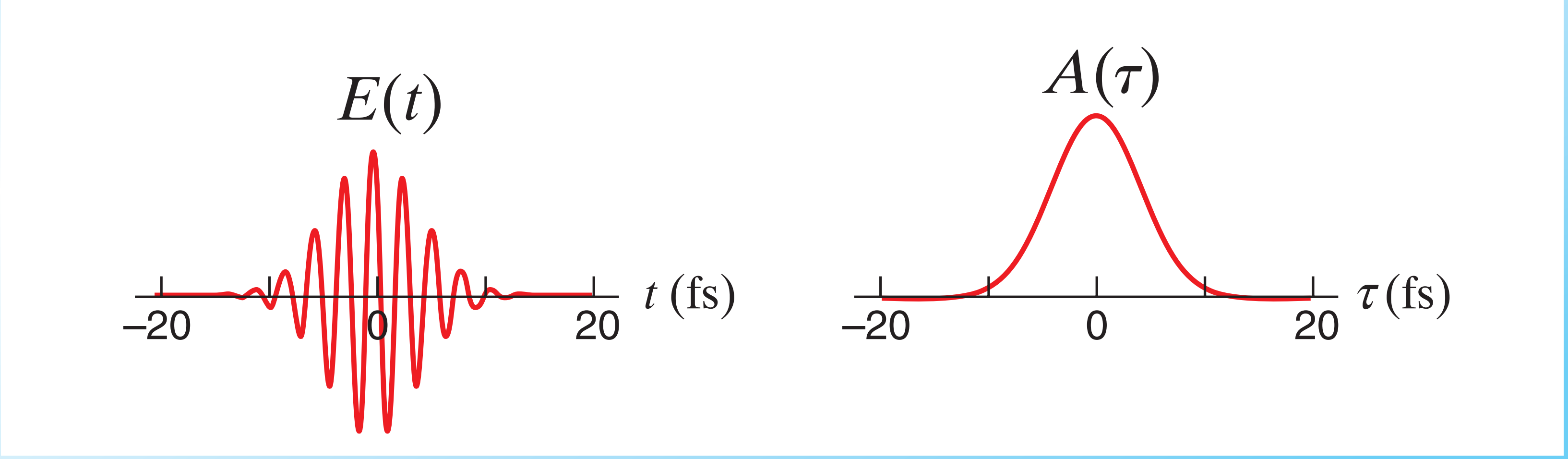
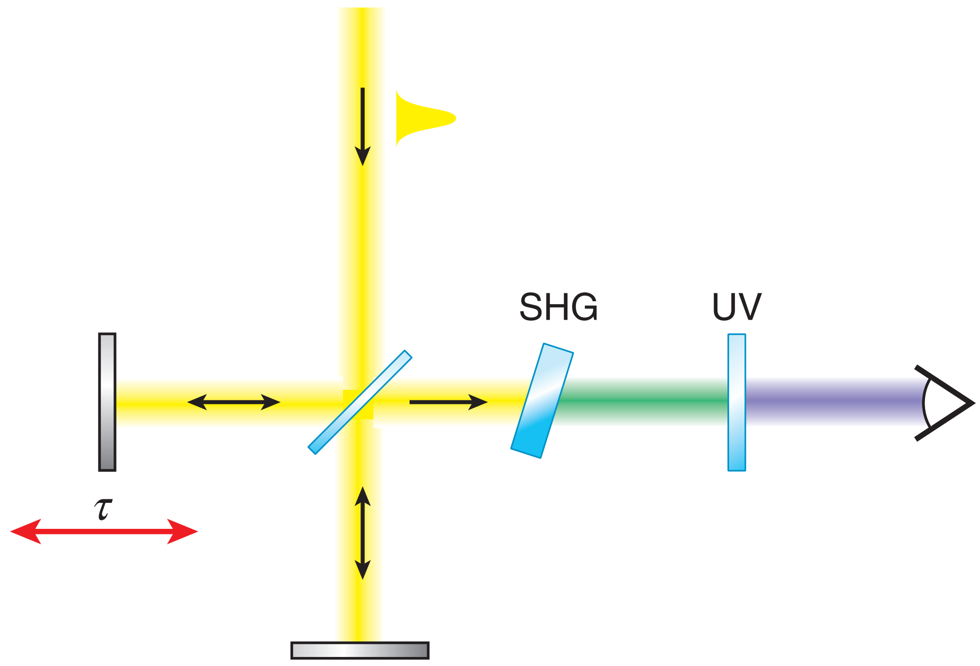


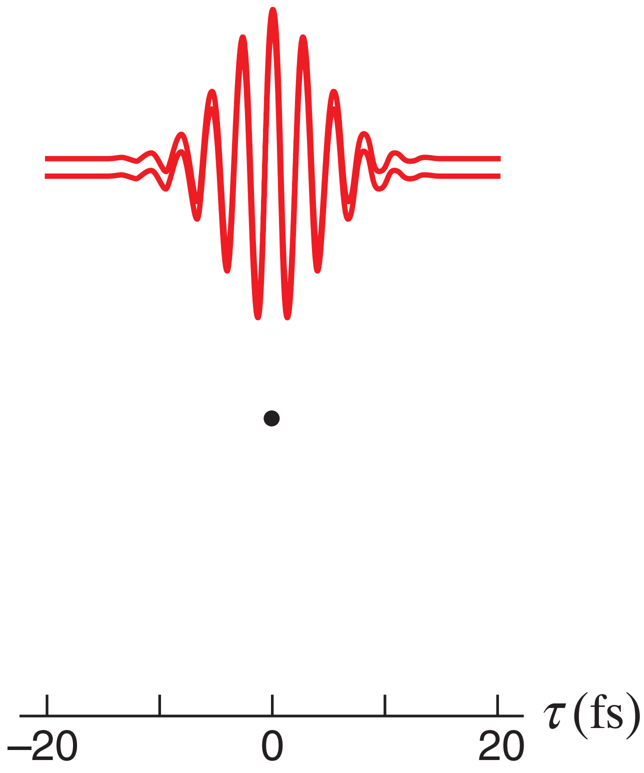
Temporal characterization

Alternative colinear geometry



All terms now contribute:

$$I_{2\omega}(t,\tau) \propto \left|\chi^{(2)}\right|^2 \left|E_{tot}^2\right|^2 = \left|\chi^{(2)}\right|^2 \left|E_1^2(t) + 2E_1(t)E_2(t+\tau) + E_2^2(t+\tau)\right|^2$$



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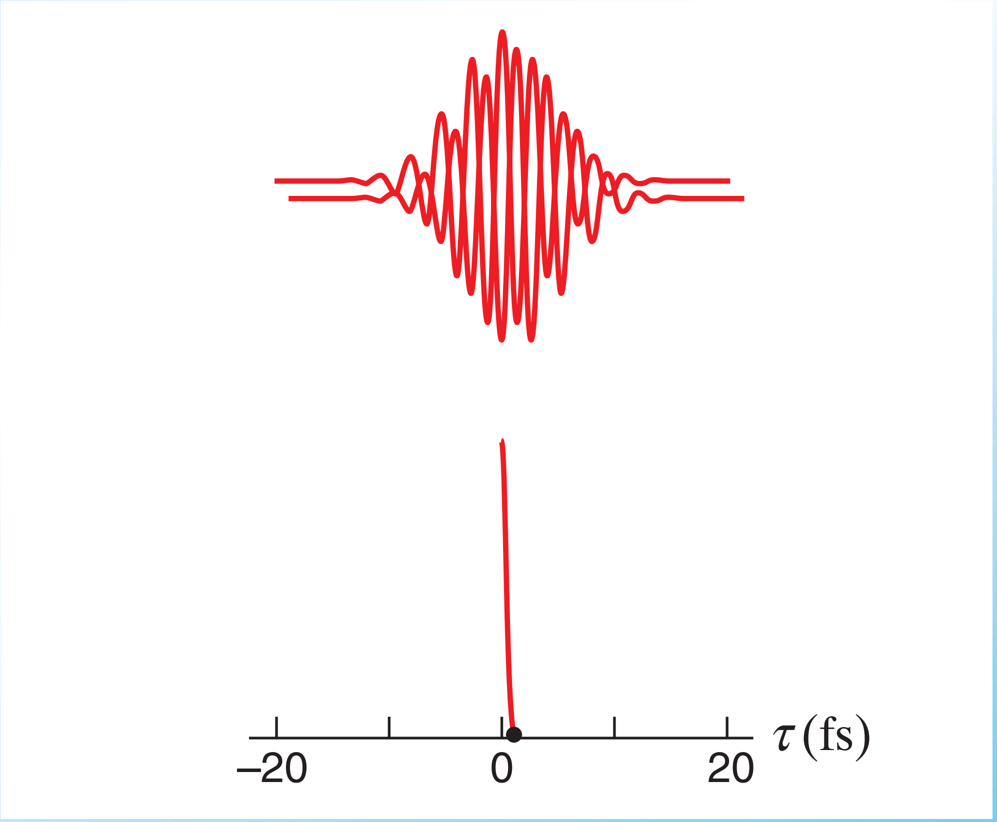

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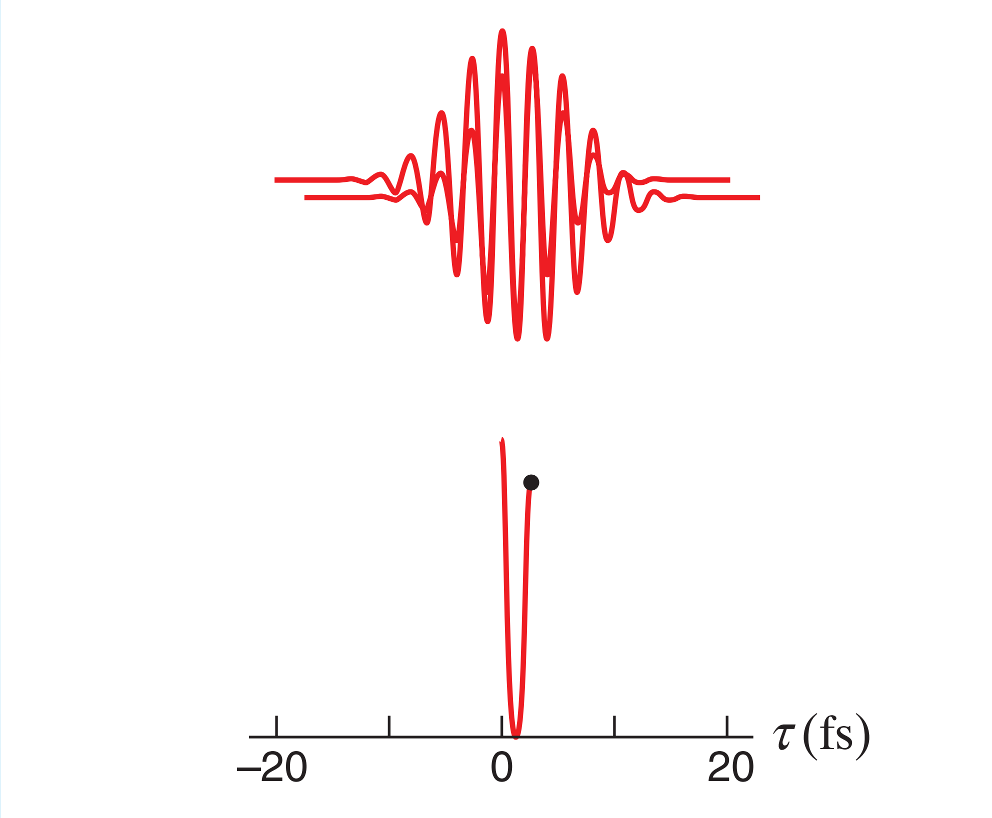

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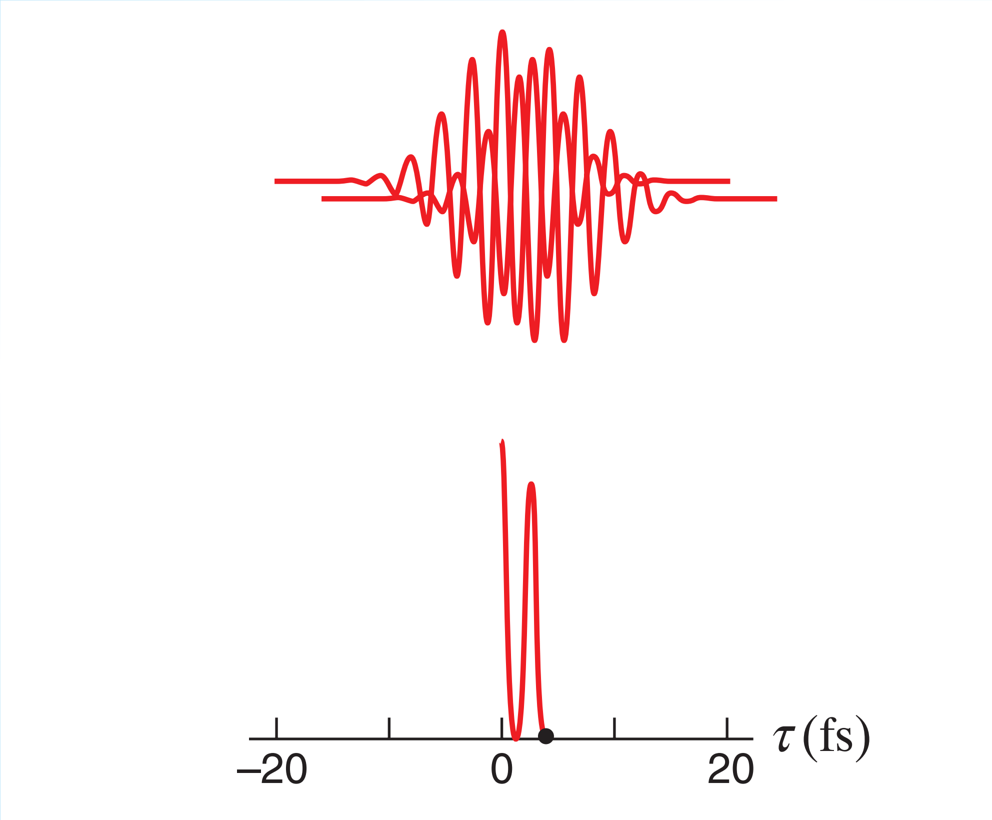

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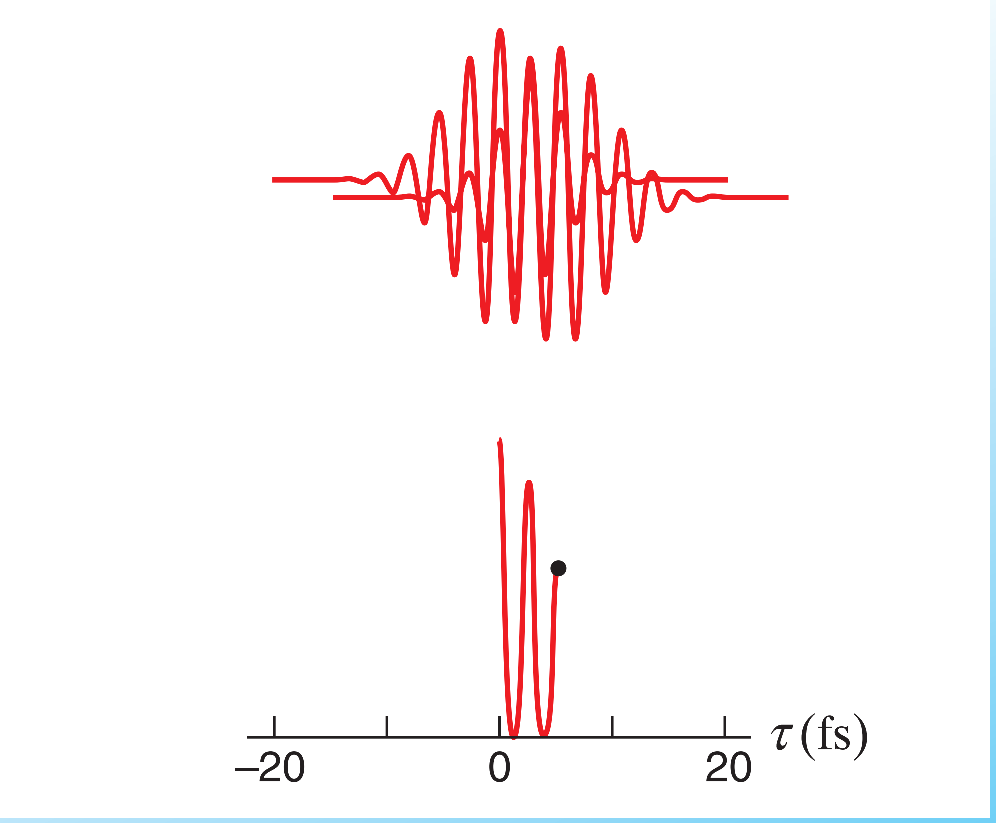

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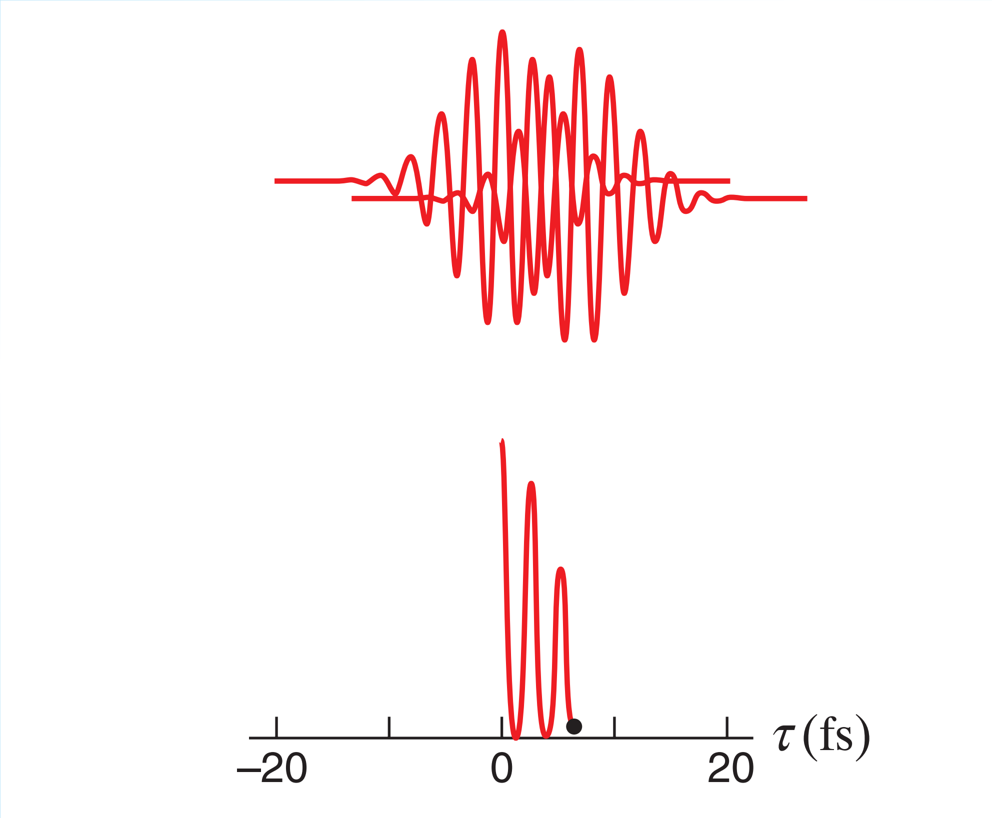

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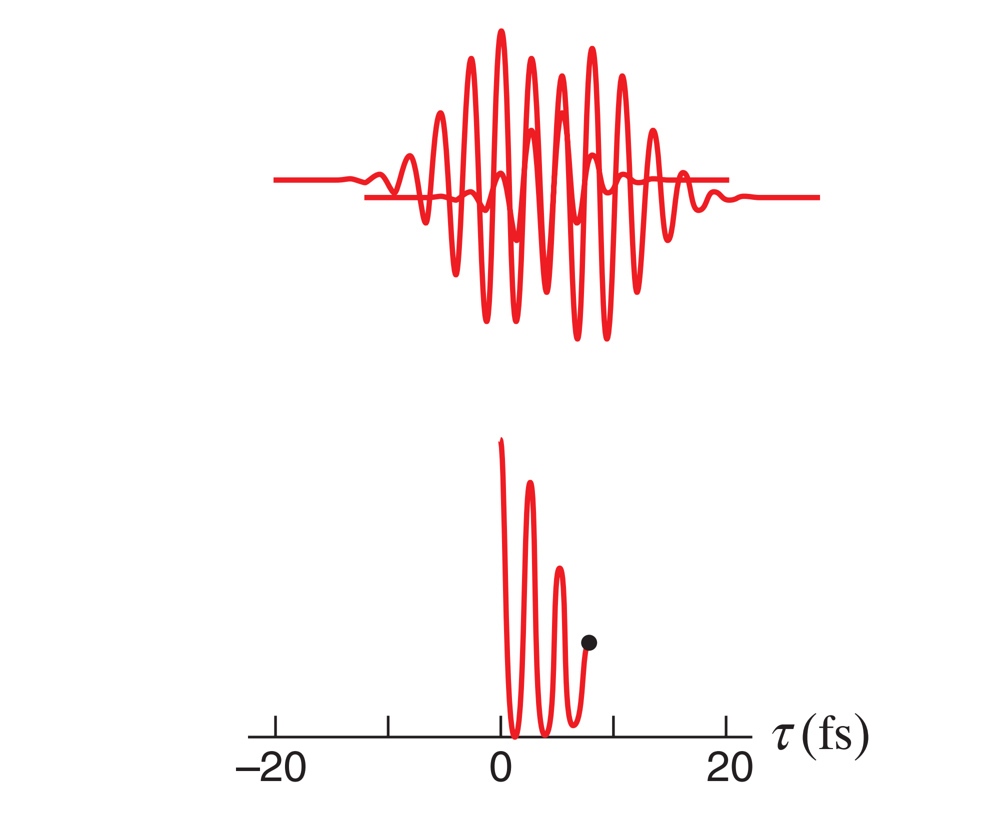

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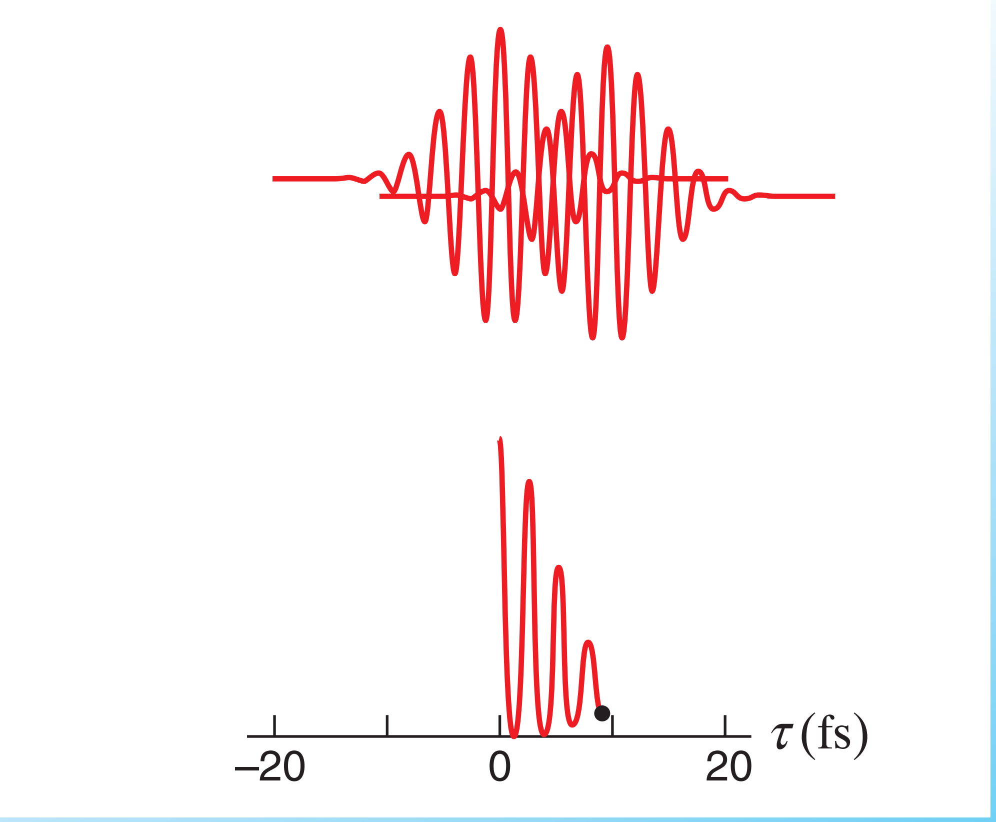

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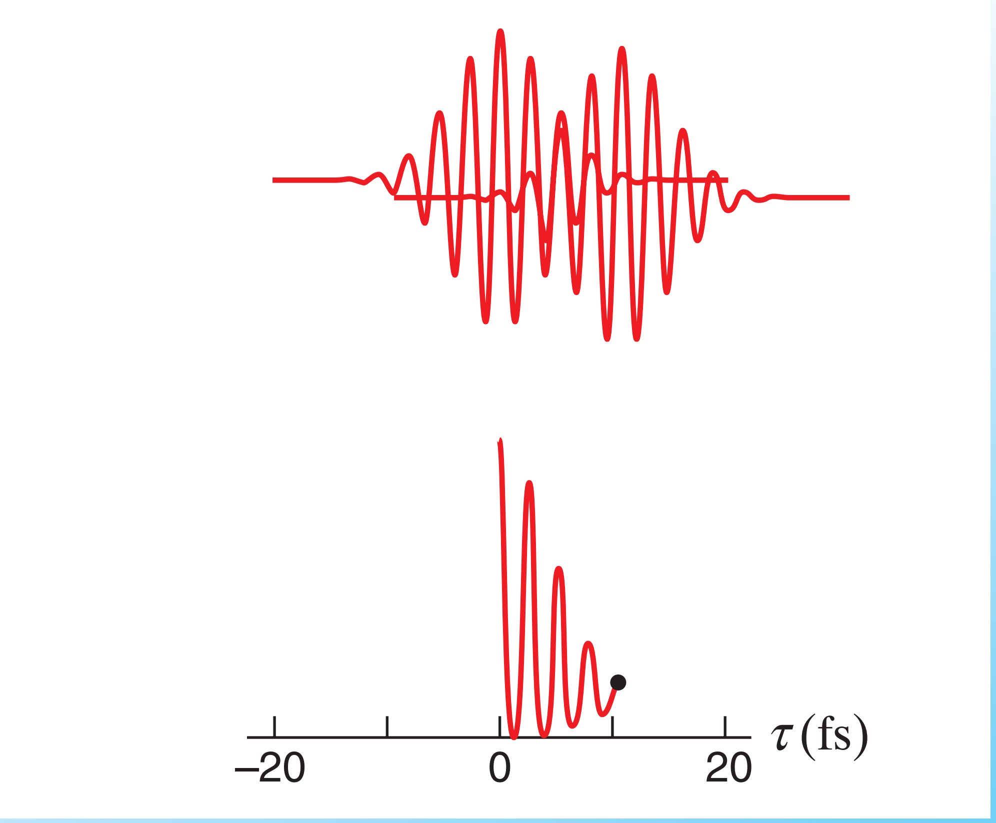

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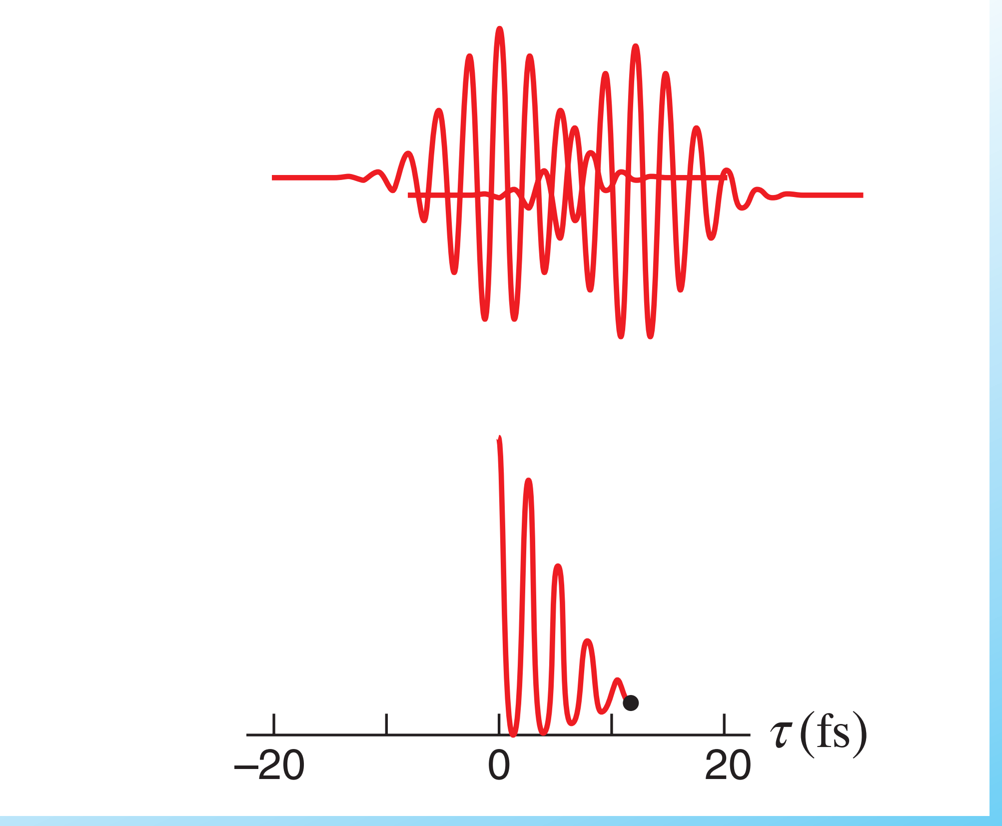

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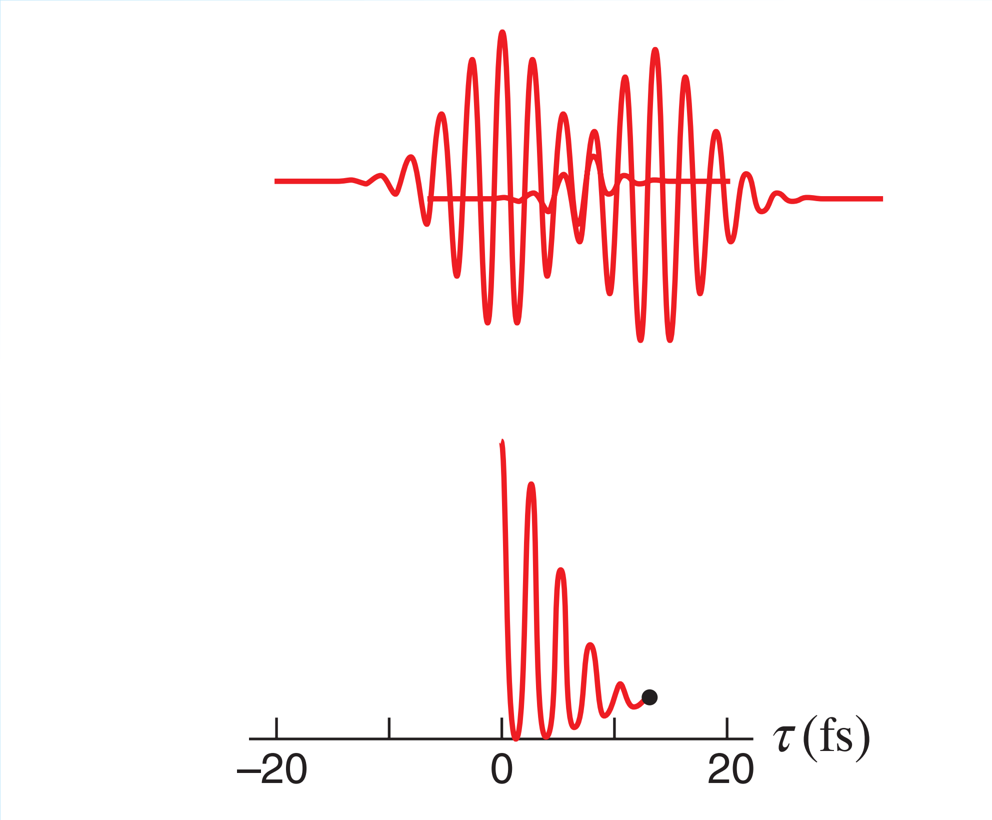

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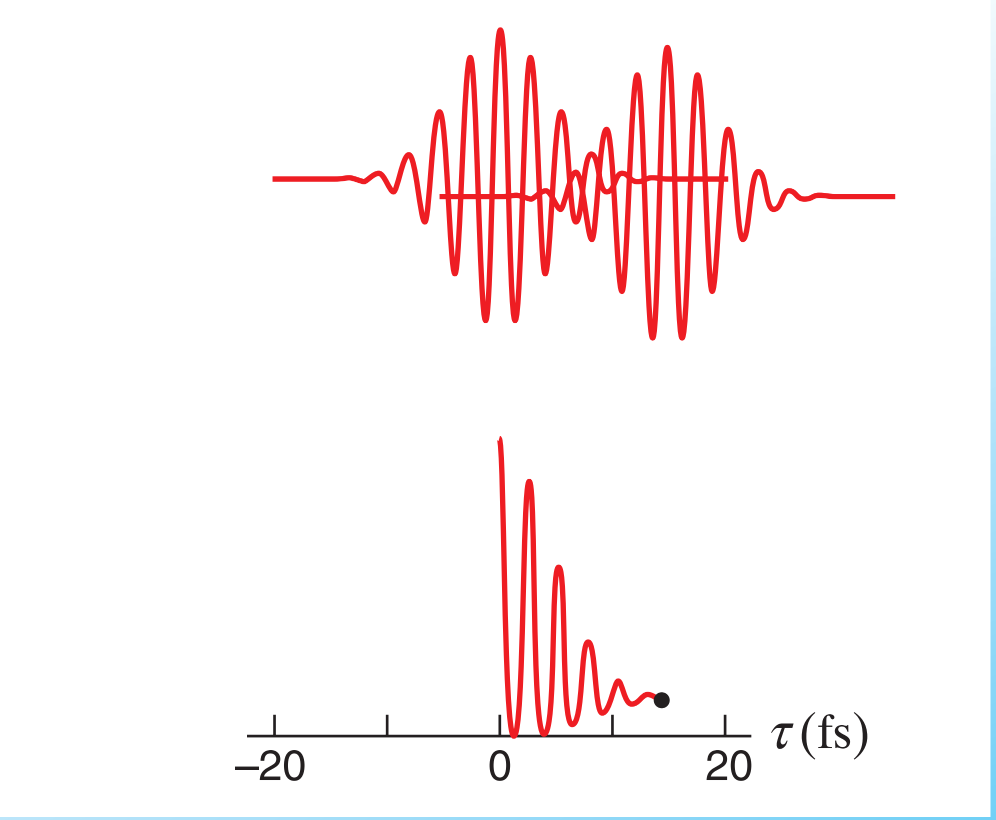

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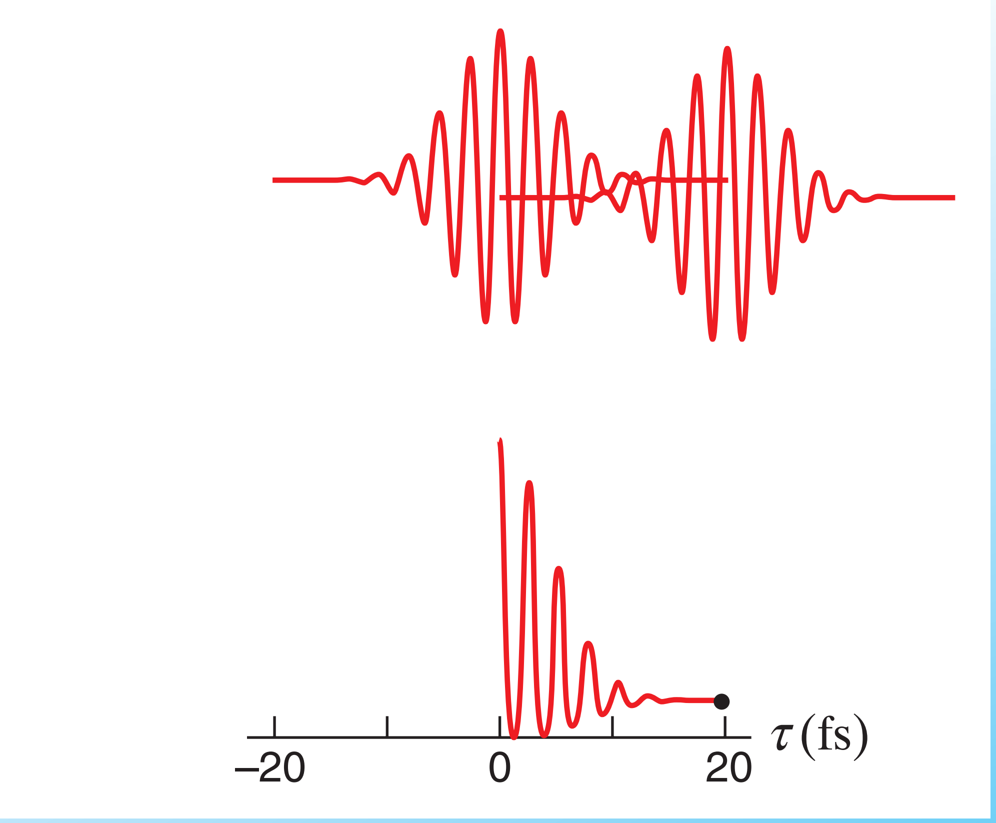

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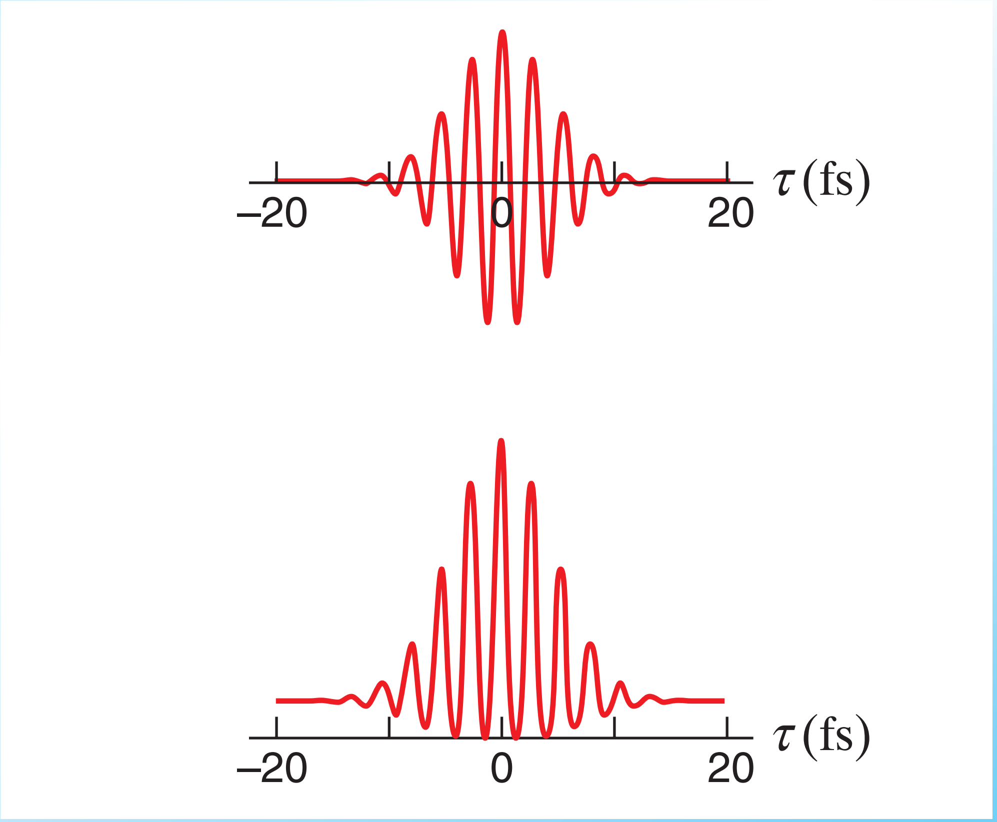

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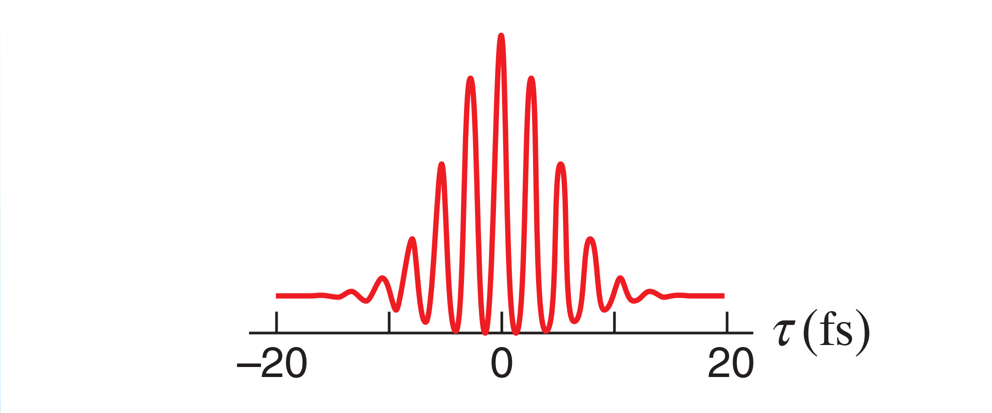
at $\tau = 0$**:** $$I_{2\omega}(t,\tau) \propto 16E^4(t)$$



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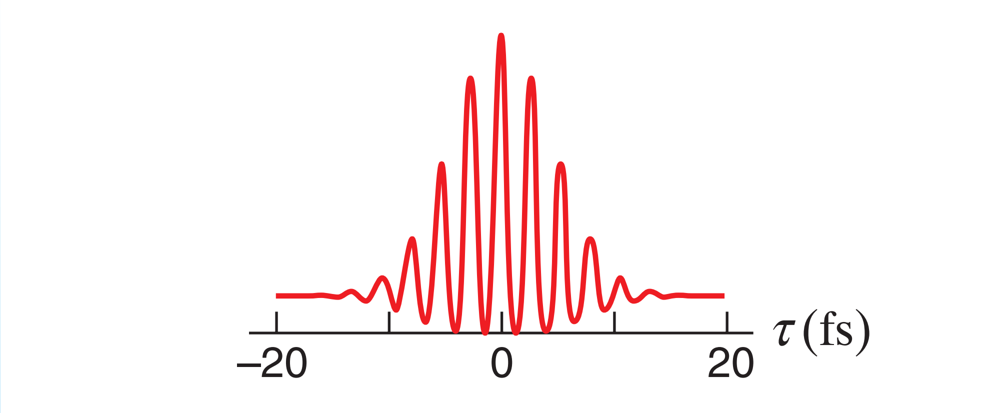

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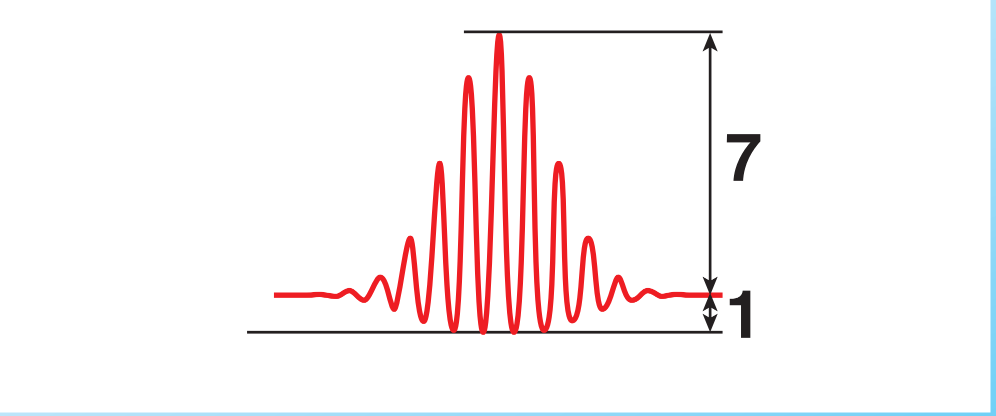
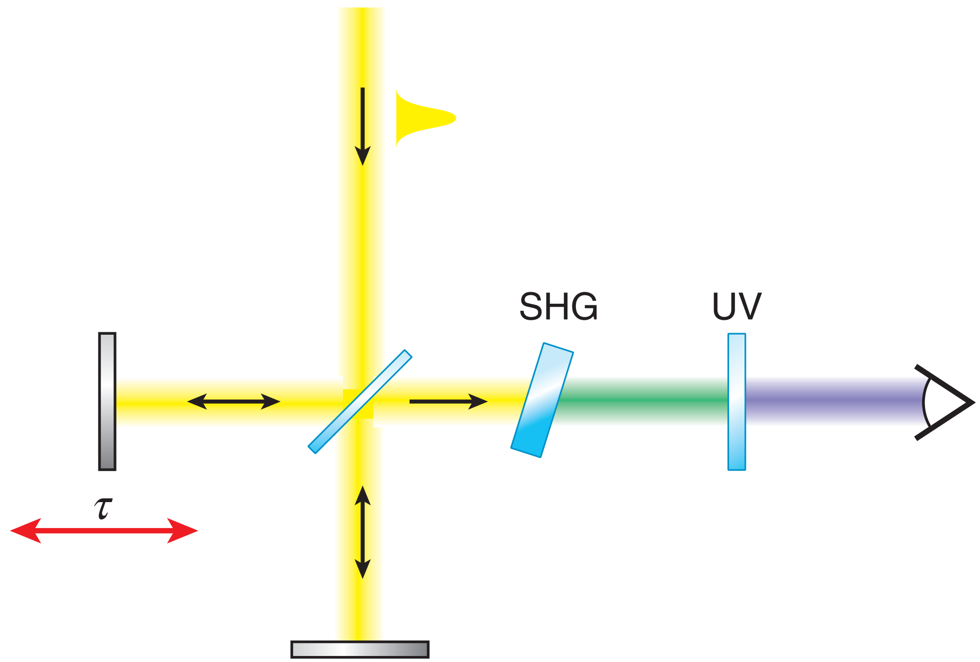


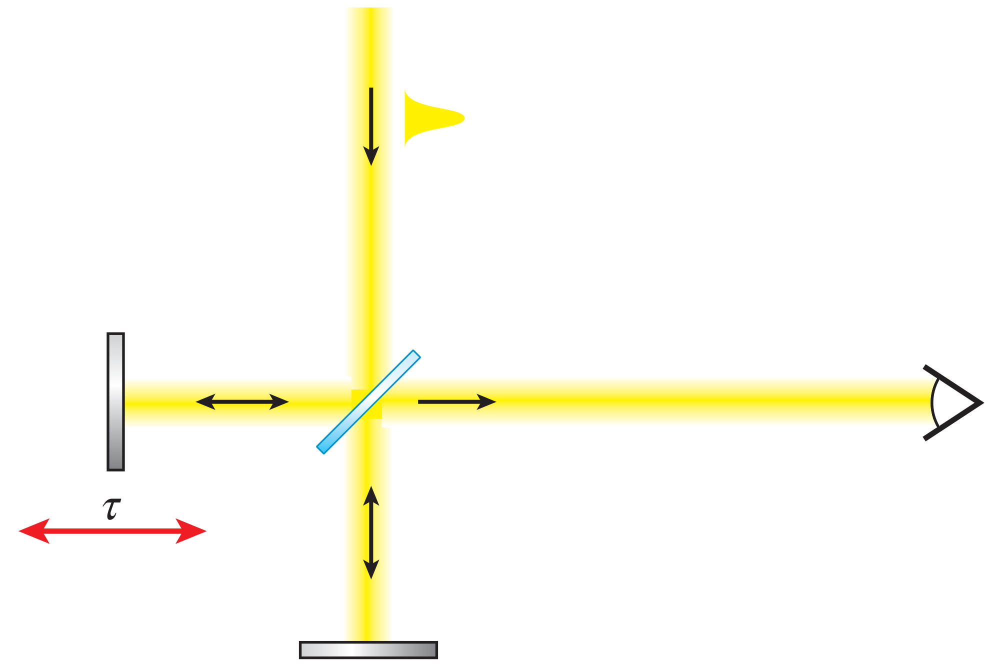
Temporal characterization

Do we really need the second-harmonic crystal…?



Temporal characterization

Would this work?



Temporal characterization

Intensity at detector

$$I_\omega(t,\tau) \propto \left| E_1(t) + E_2(t+\tau) \right|^2$$

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Temporal characterization

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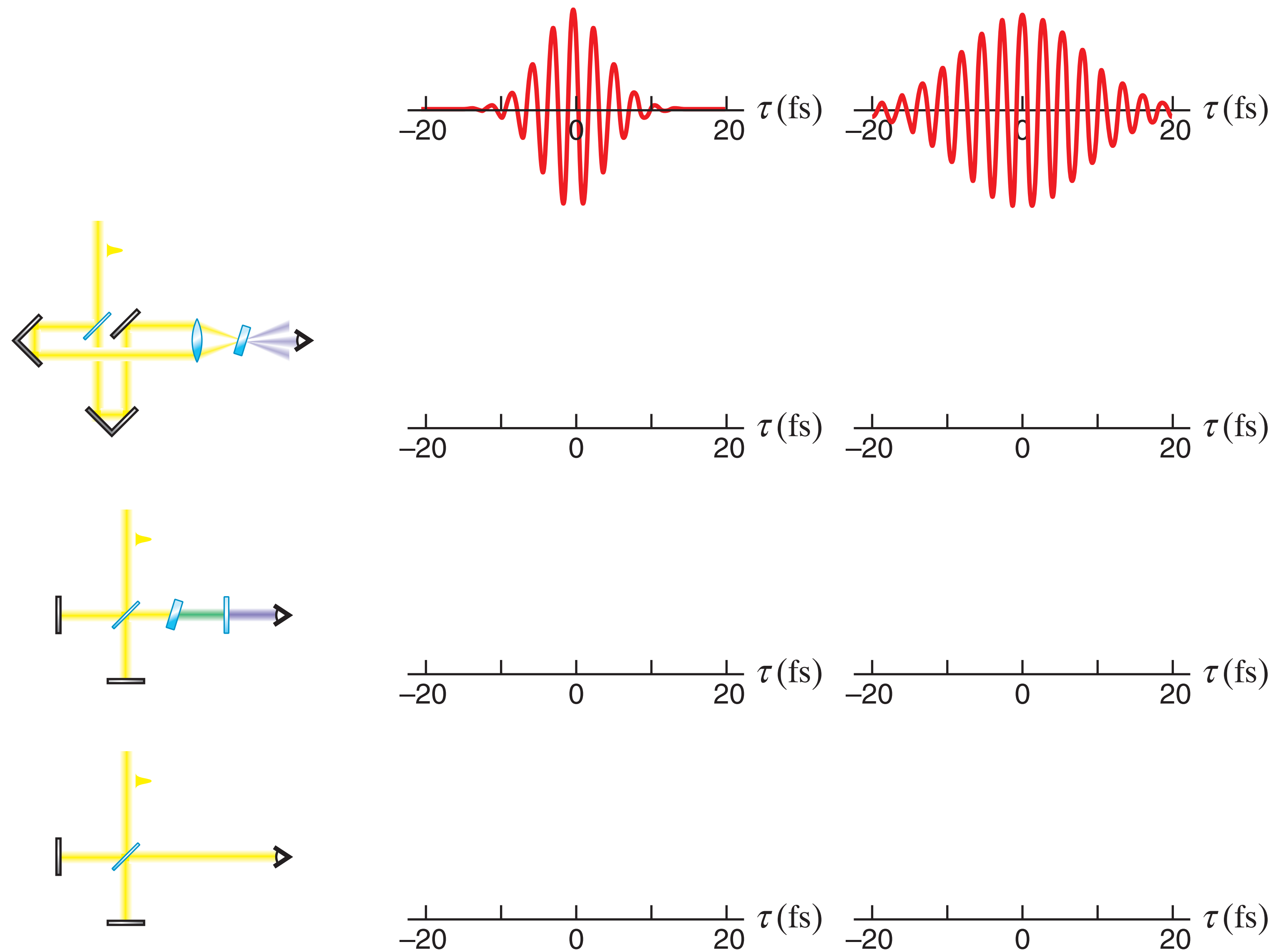
so

$$S_\omega(\tau) \propto \int \left\{ \left|E_1(t)\right|^2 + \left|E_2(t+\tau)\right|^2 + E_1(t)E_2{}^*(t+\tau) + E_1{}^*(t)E_2(t+\tau) \right\} dt$$

Temporal characterization



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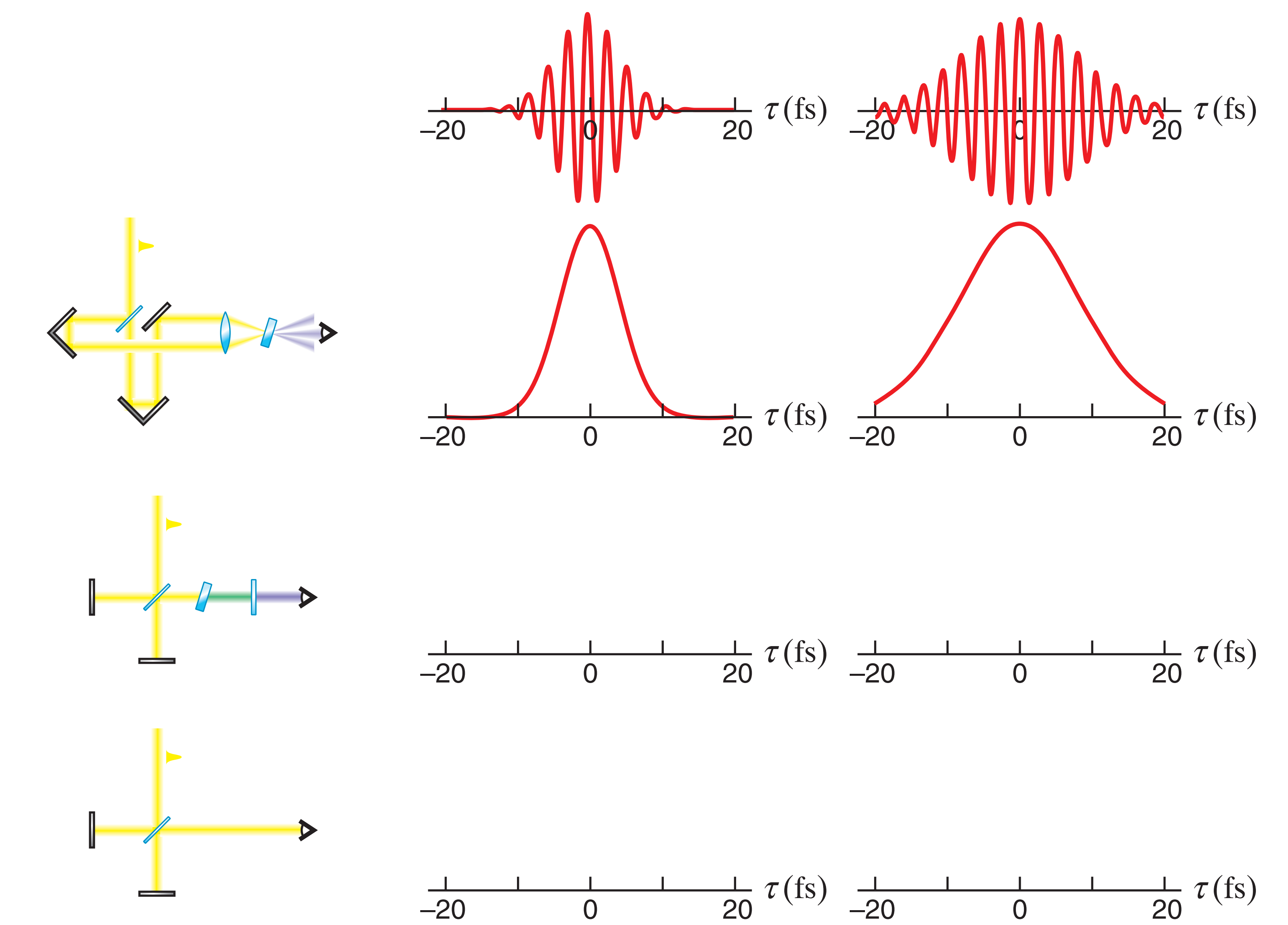

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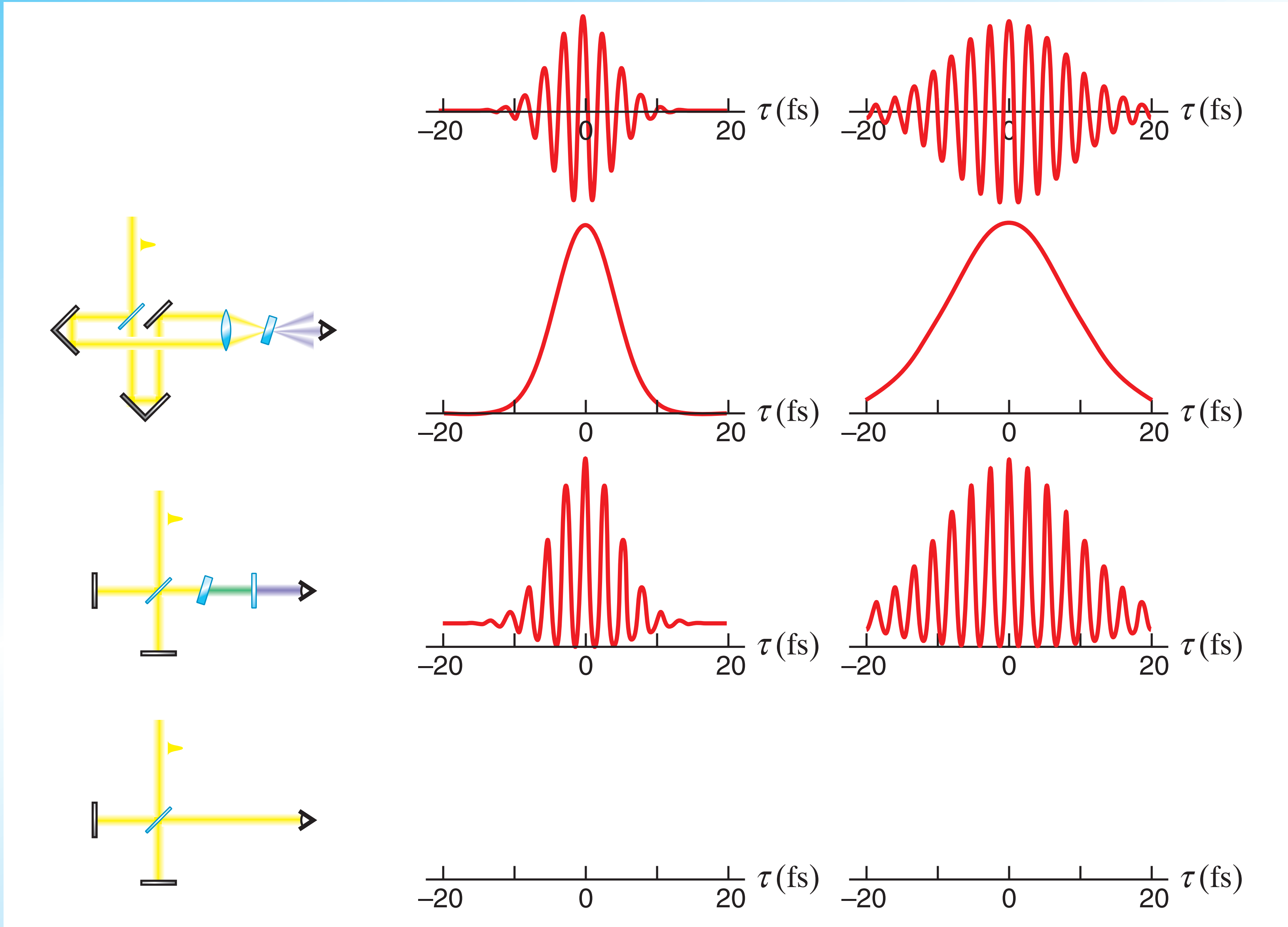

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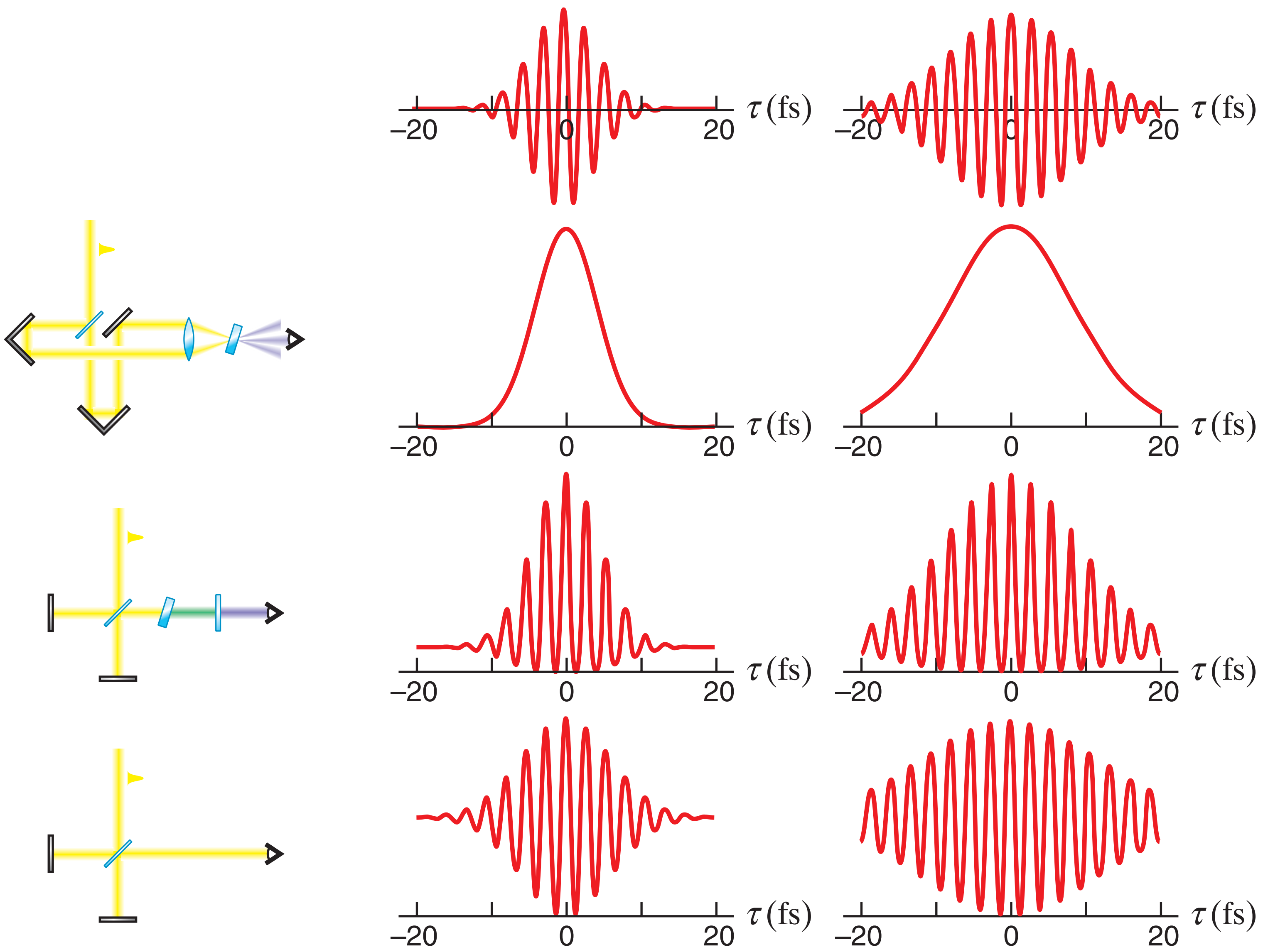
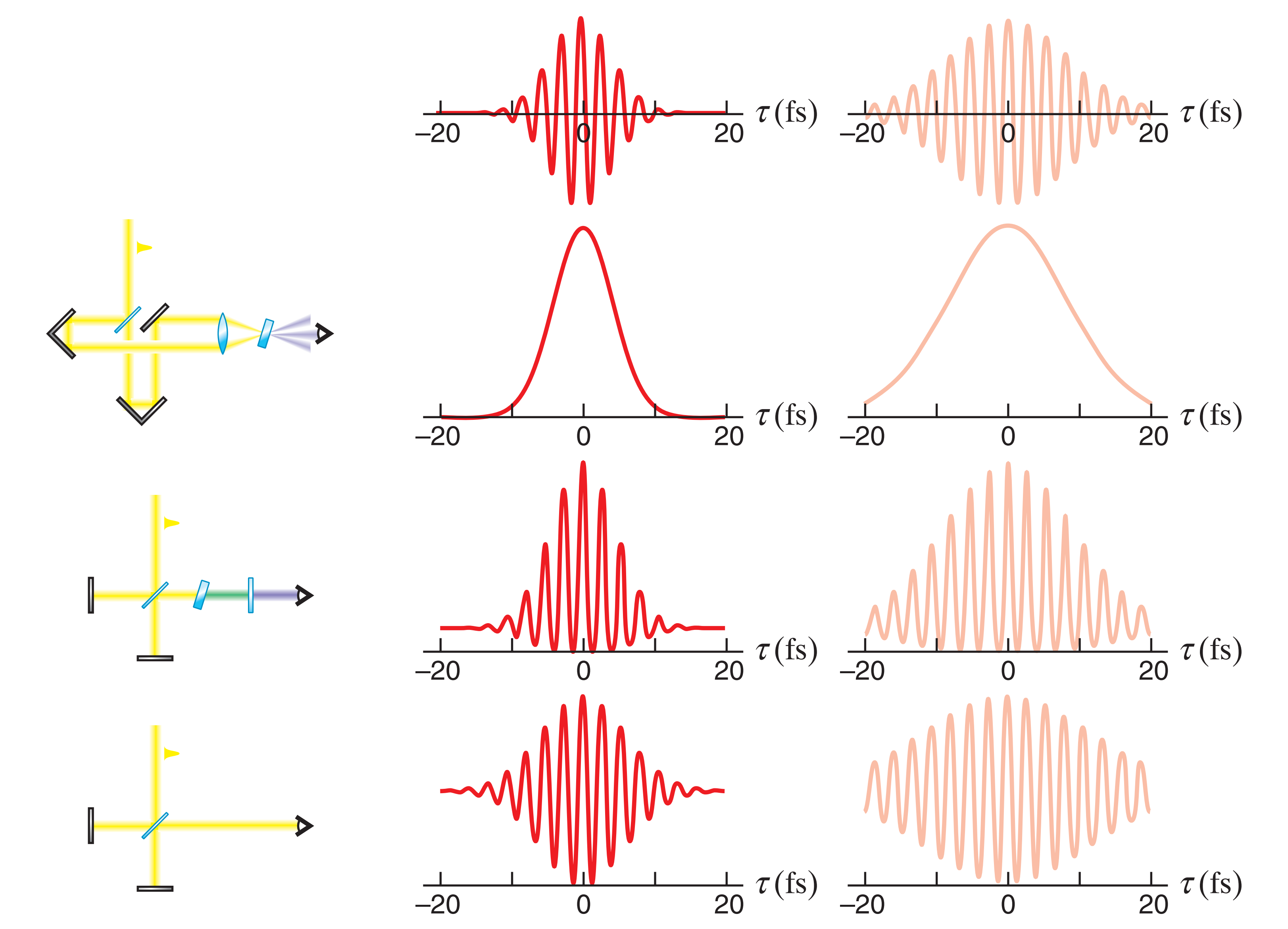


Temporal characterization

But what about dispersion?

Temporal characterization



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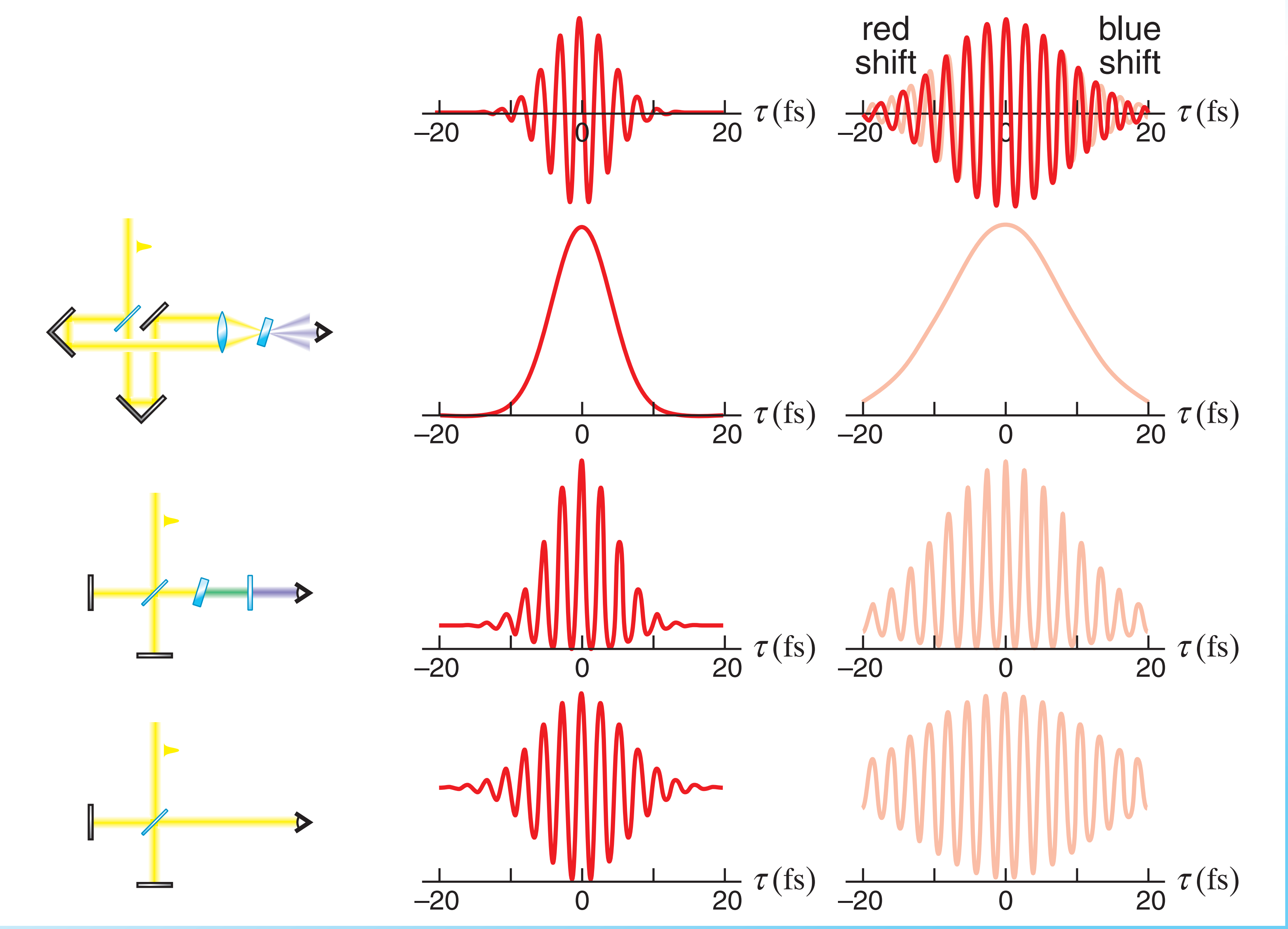

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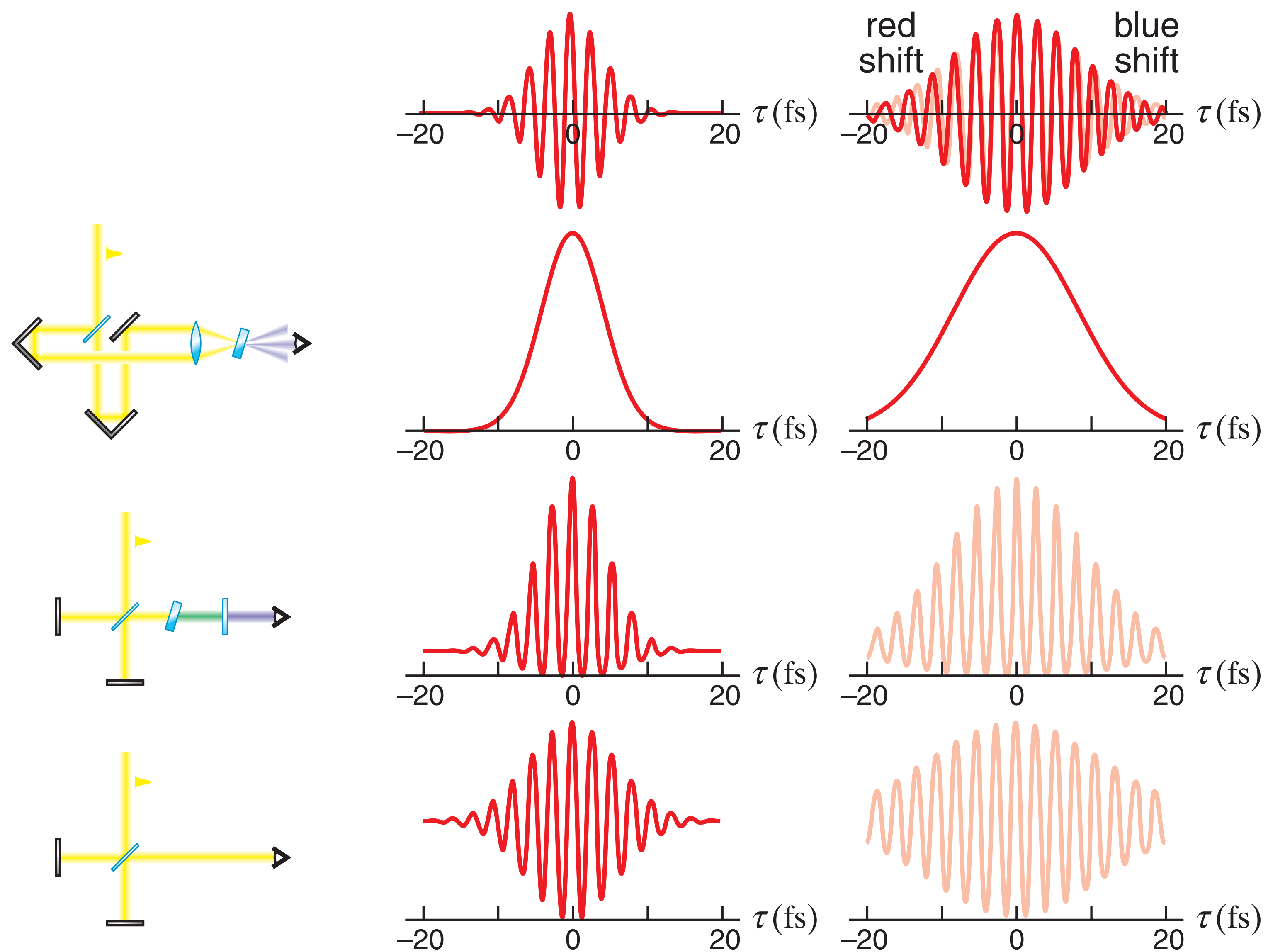

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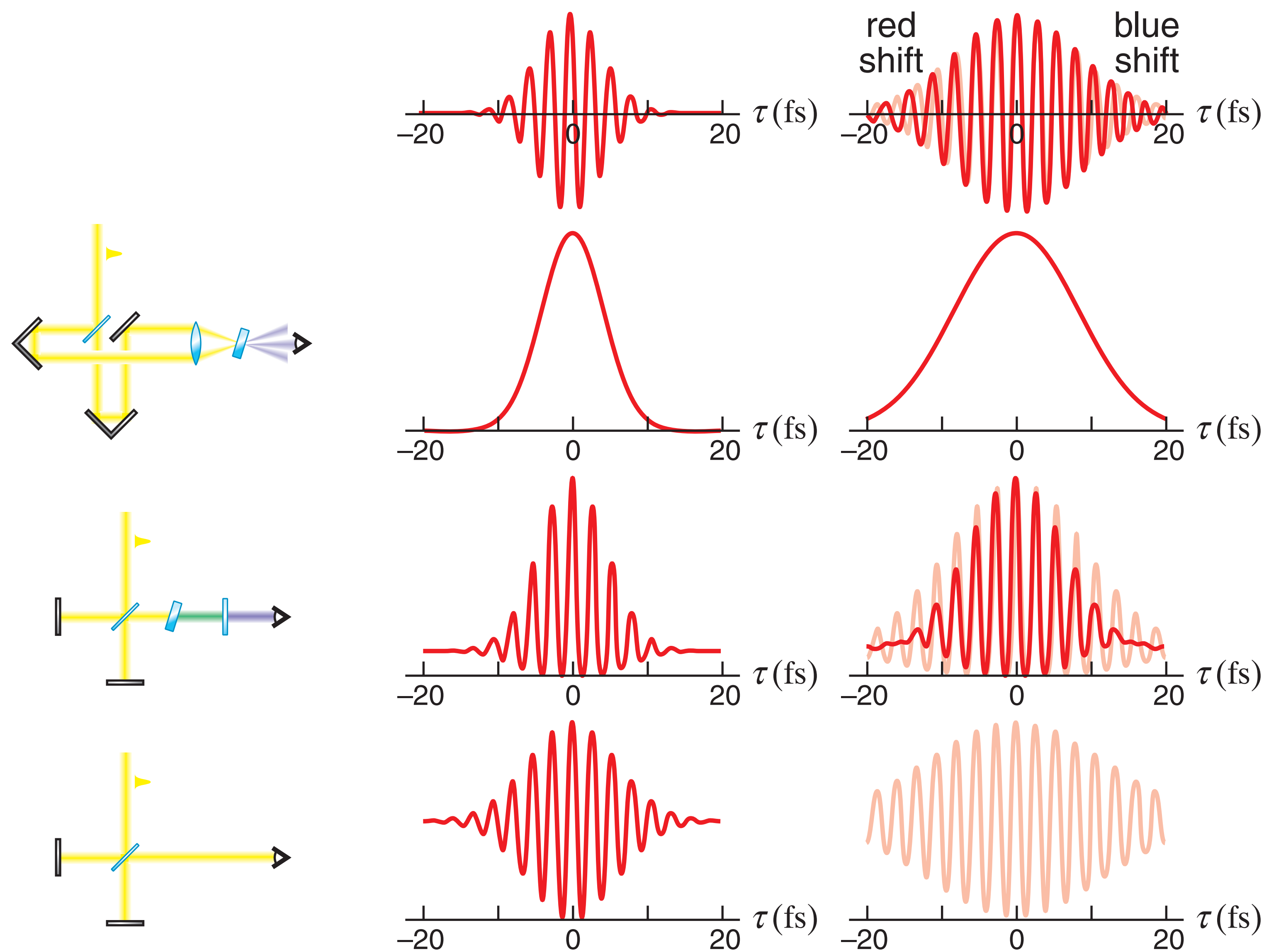

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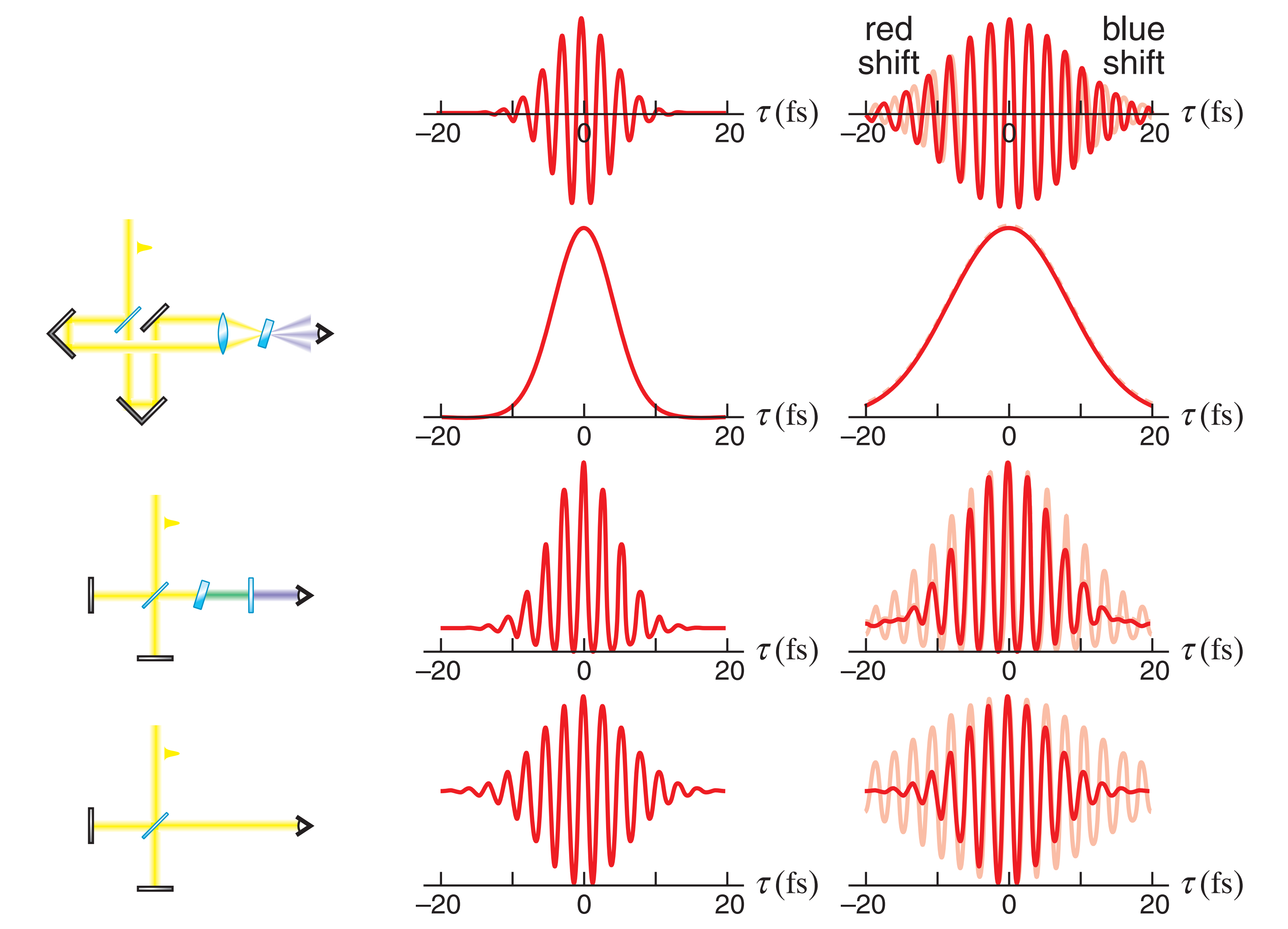

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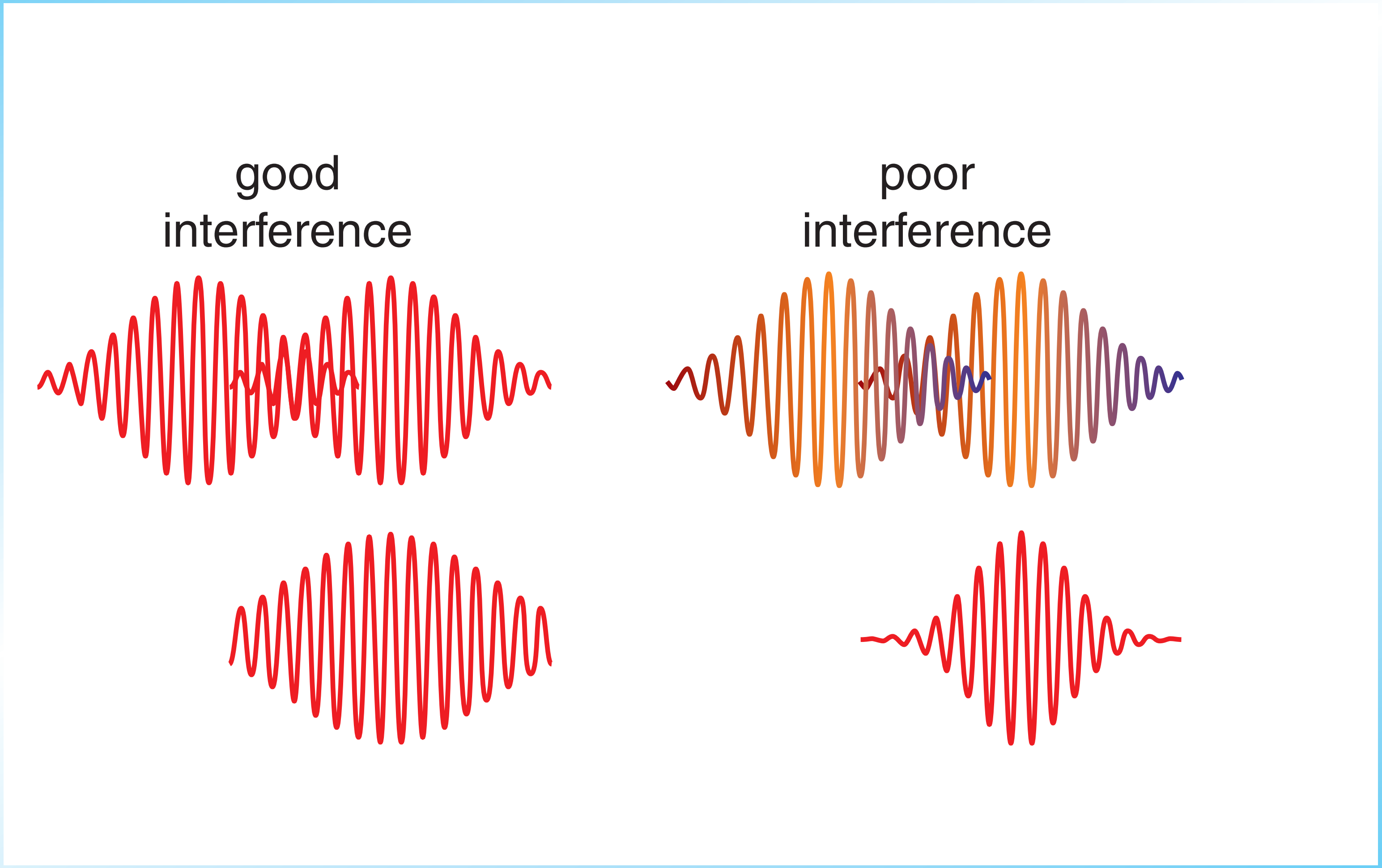

Temporal characterization

Let $E_{disp}(\omega) = E_{orig}(\omega)e^{-i\phi(\omega)}$**.**

Temporal characterization

Let $E_{disp}(\omega) = E_{orig}(\omega)e^{-i\phi(\omega)}$**. Convolution theorem**

$$f_1(t) \otimes f_2(t) \equiv \int f_1(t+\tau) f_2{}^*(t)\, dt = \mathscr{F}^{-1}\{f_1(\omega) f_2{}^*(\omega)\}$$

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Interference term in linear autocorrelation:

$$\int E_{disp}(t+\tau)E^*_{disp}(t)\,dt = \mathcal{F}^{-1}\{E_{disp}(\omega)E^*_{disp}(\omega)\} =$$

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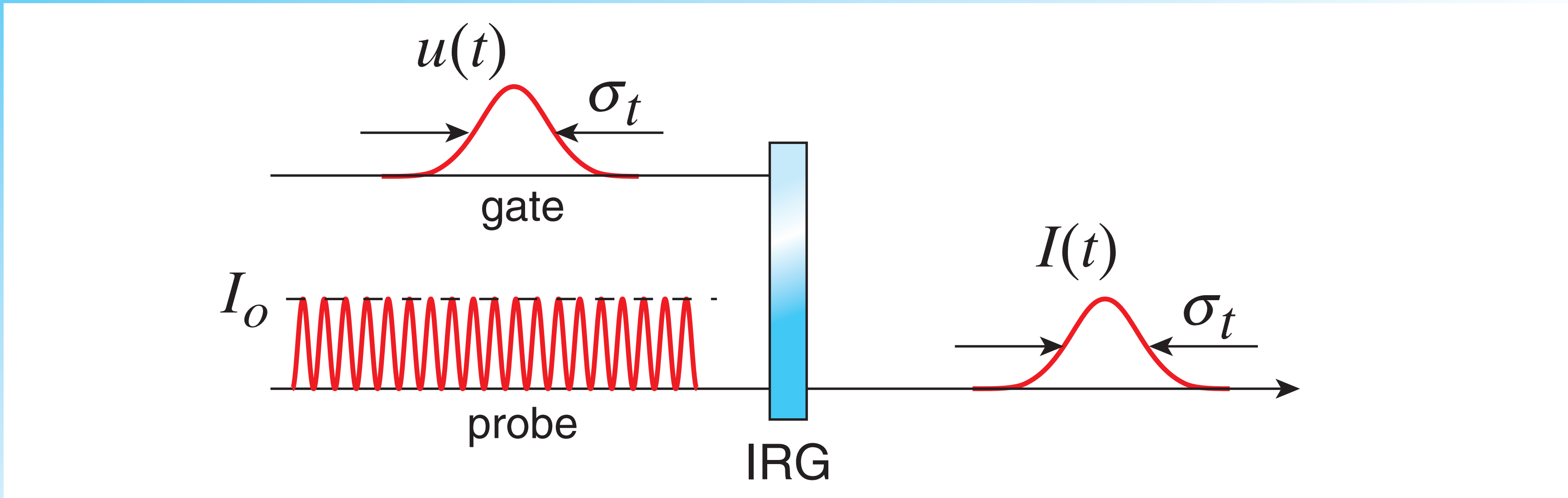
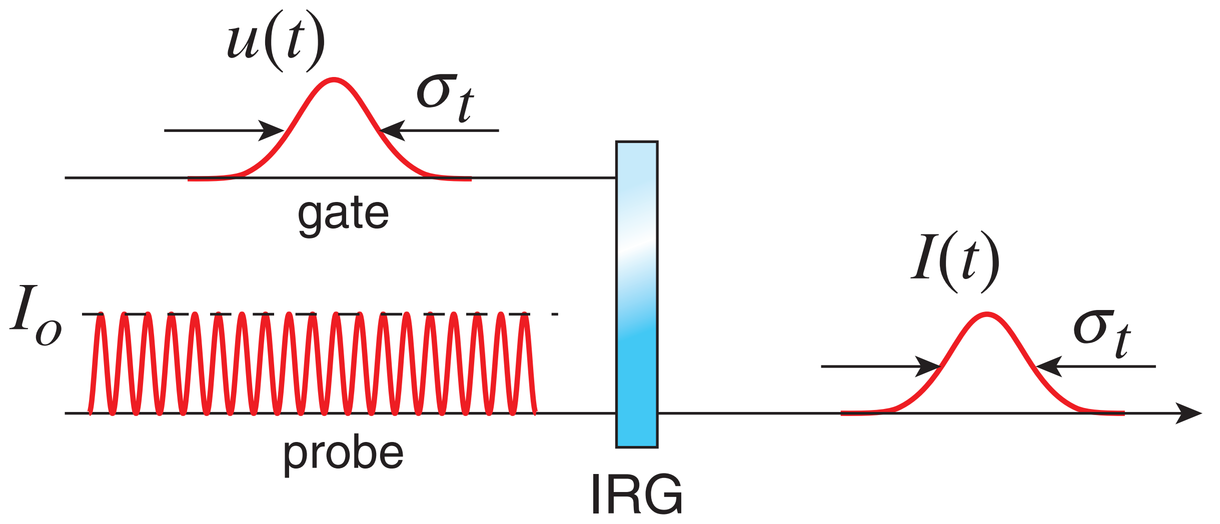
Joint time-frequency measurements



IRG ("instantaneous response gate"): device whose transmittance of a weak probe pulse is proportional to the intensity envelope of the pump ("gate")

$$T(t) = u(t)$$

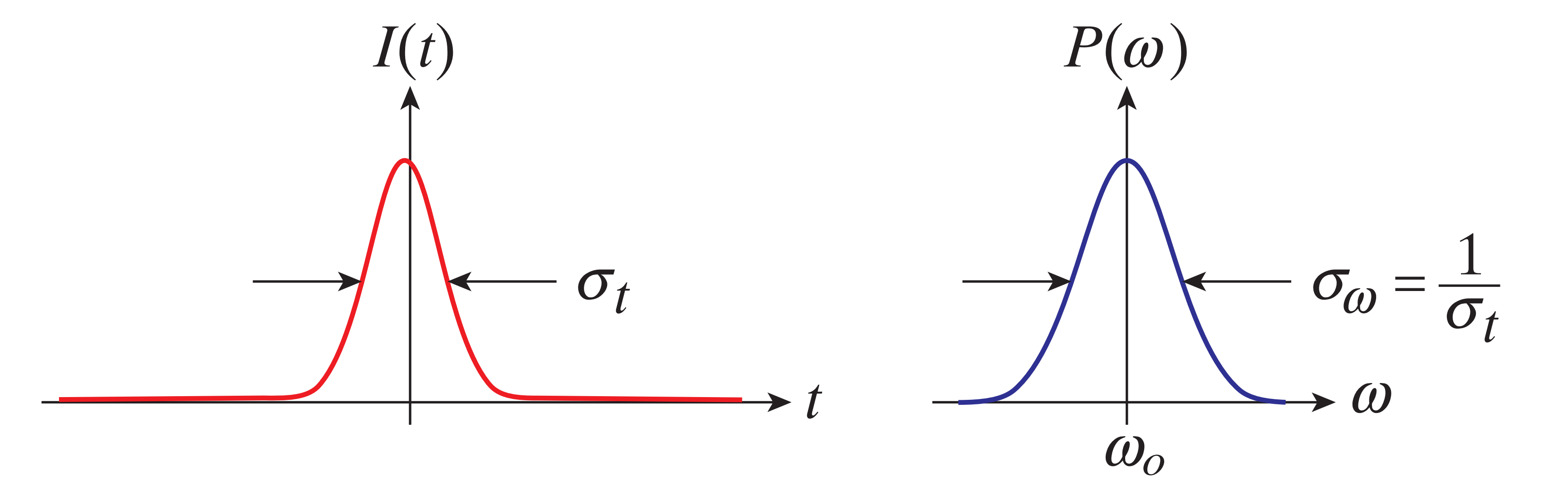
Joint time-frequency measurements



Transmitted intensity

$$I(t) = I_o T(t) = I_o u(t) = I_o \exp\left[-\frac{t^2}{\sigma_t^2}\right]$$

Joint time-frequency measurements



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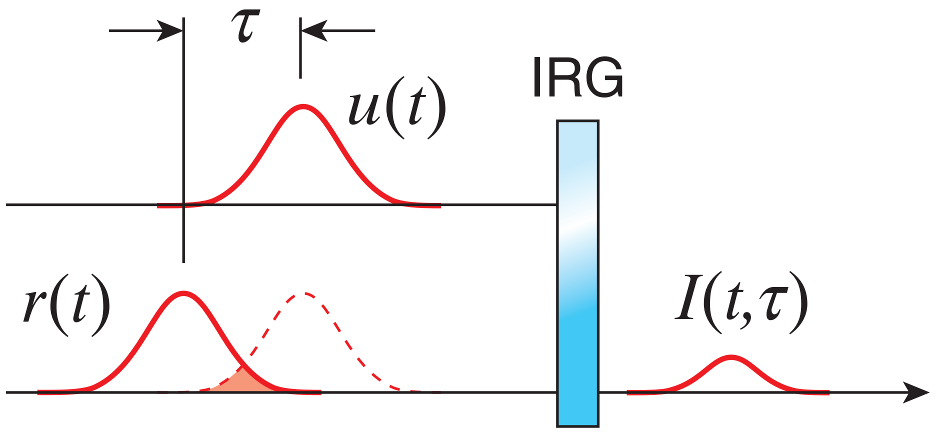
$$\sigma_t \sigma_\omega = 1$$

Joint time-frequency measurements

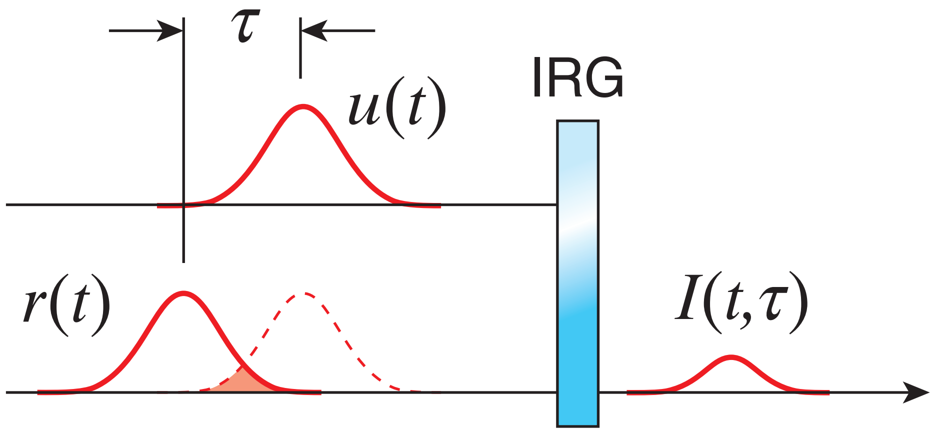


Transmitted intensity

$$I(t,\tau) = u(t)r(t+\tau) = \exp\left[-\frac{t^2}{\sigma^2}\right]\exp\left[-\left(\frac{t+\tau}{\sigma}\right)^2\right] =$$

$$= \exp\left[-\frac{2t^2+2t\tau+\tau^2}{\sigma^2}\right] = \exp\left[-\frac{2t^2+2t\tau+\tau^2/2}{\sigma^2}\right]\exp\left[-\frac{\tau^2}{2\sigma^2}\right] =$$

Joint time-frequency measurements

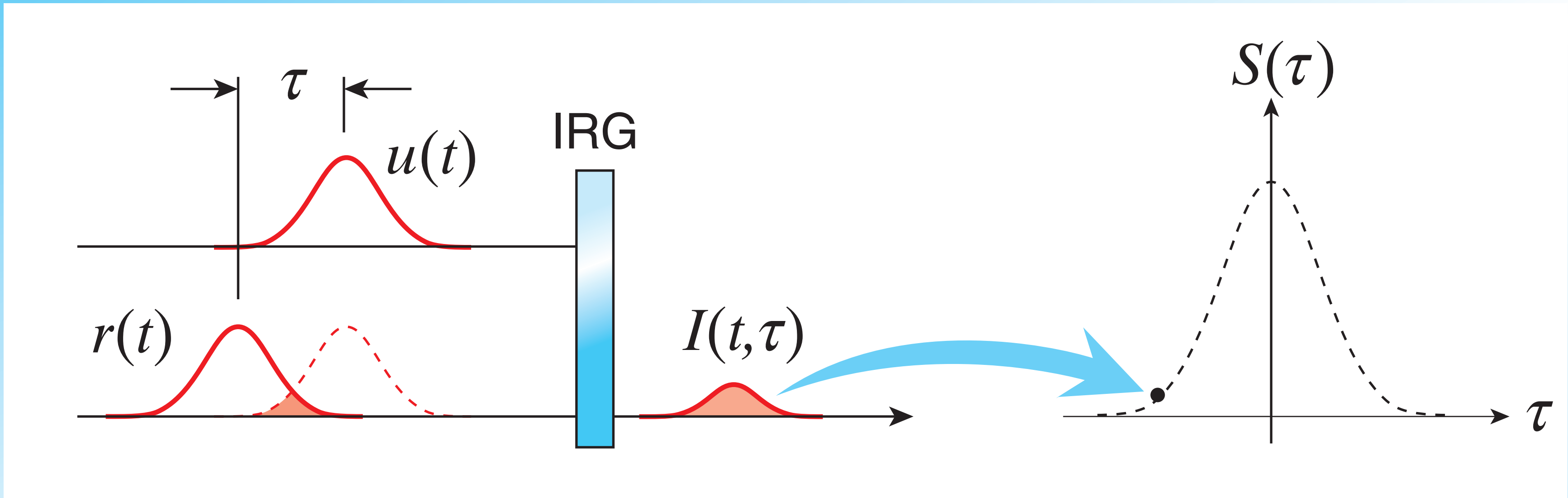


Transmitted intensity

$$I(t,\tau) = \exp\left[-\frac{\tau^2}{2\sigma^2}\right]\exp\left[-\left(\frac{t+\tau/2}{\sigma/\sqrt{2}}\right)^2\right]$$

so $I(t,\tau)$ **narrowed by** $\sqrt{2}$

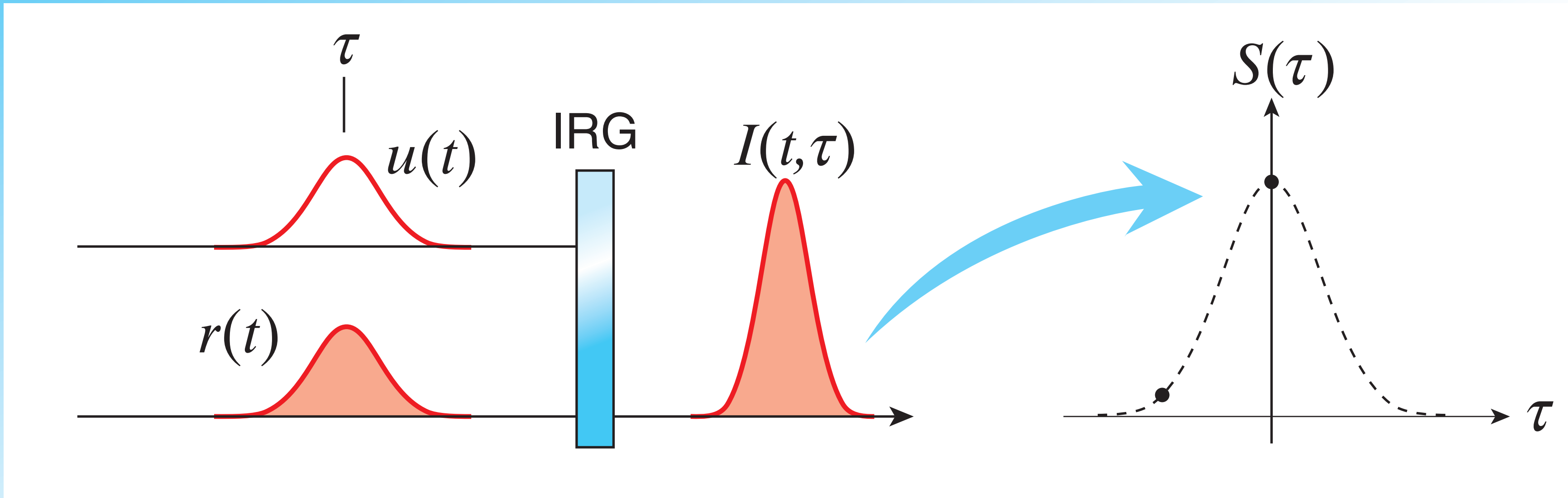
Joint time-frequency measurements



…but detector integrates $I(t,\tau)$**:**

$$S(\tau) = \int_{-\infty}^{\infty} I(t,\tau)\,dt = \int_{-\infty}^{\infty} \exp\left[-\frac{\tau^2}{2\sigma^2}\right] \exp\left[-2\left(\frac{t+\tau/2}{\sigma^2}\right)^2\right] dt$$

Joint time-frequency measurements



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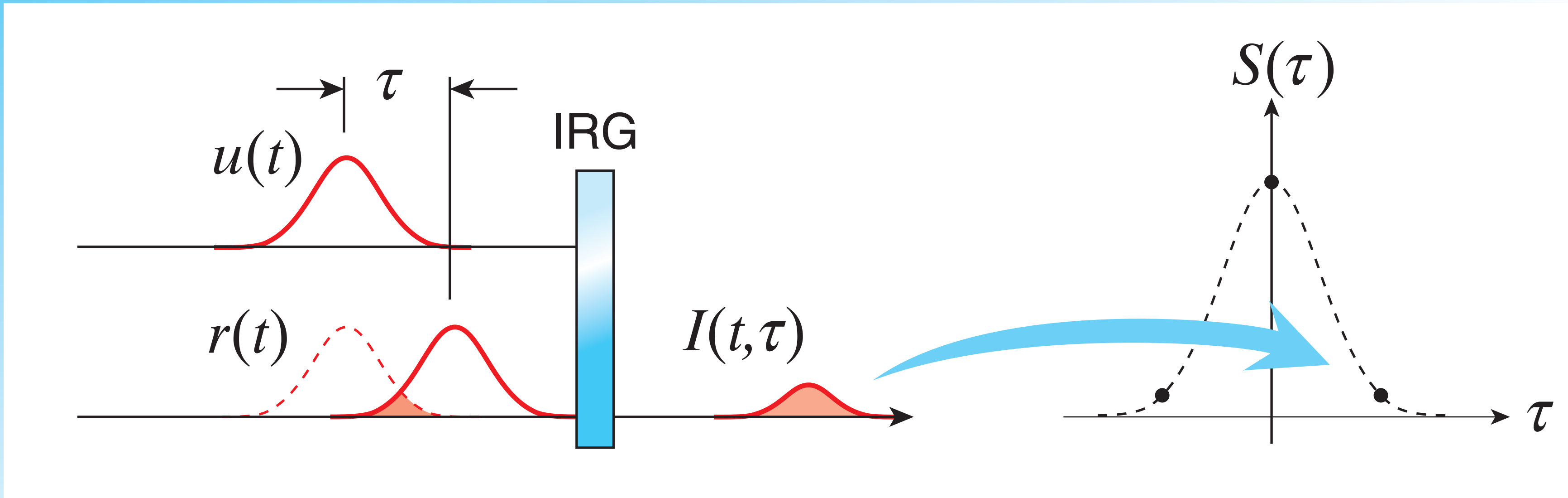

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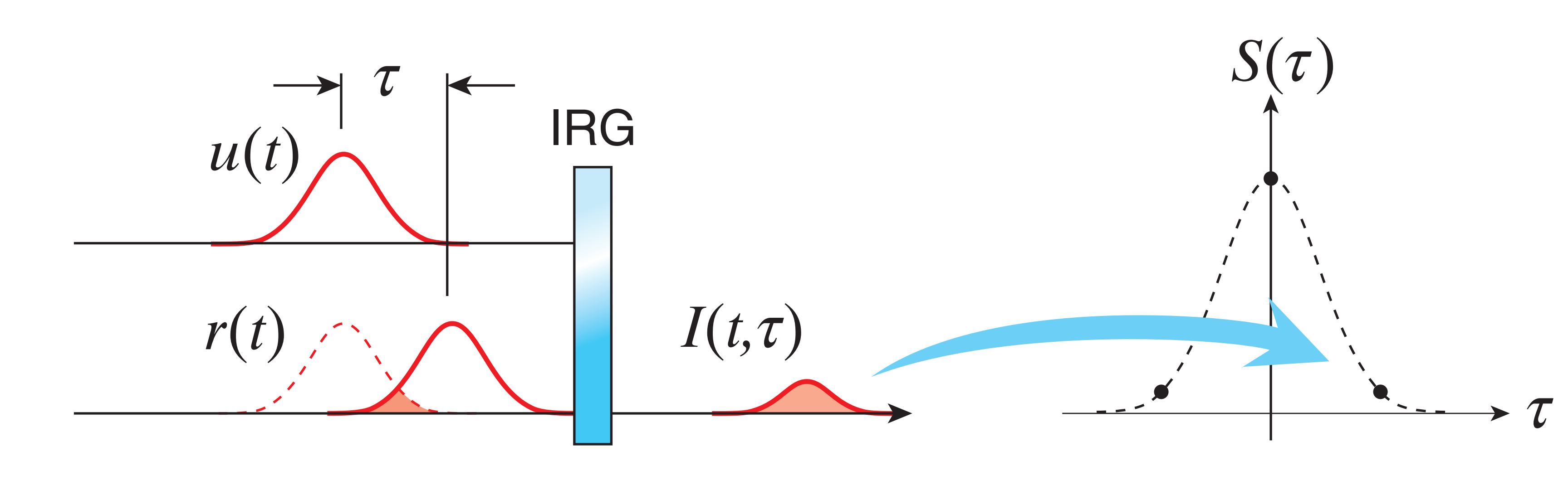
Joint time-frequency measurements



…but detector integrates $I(t,\tau)$:

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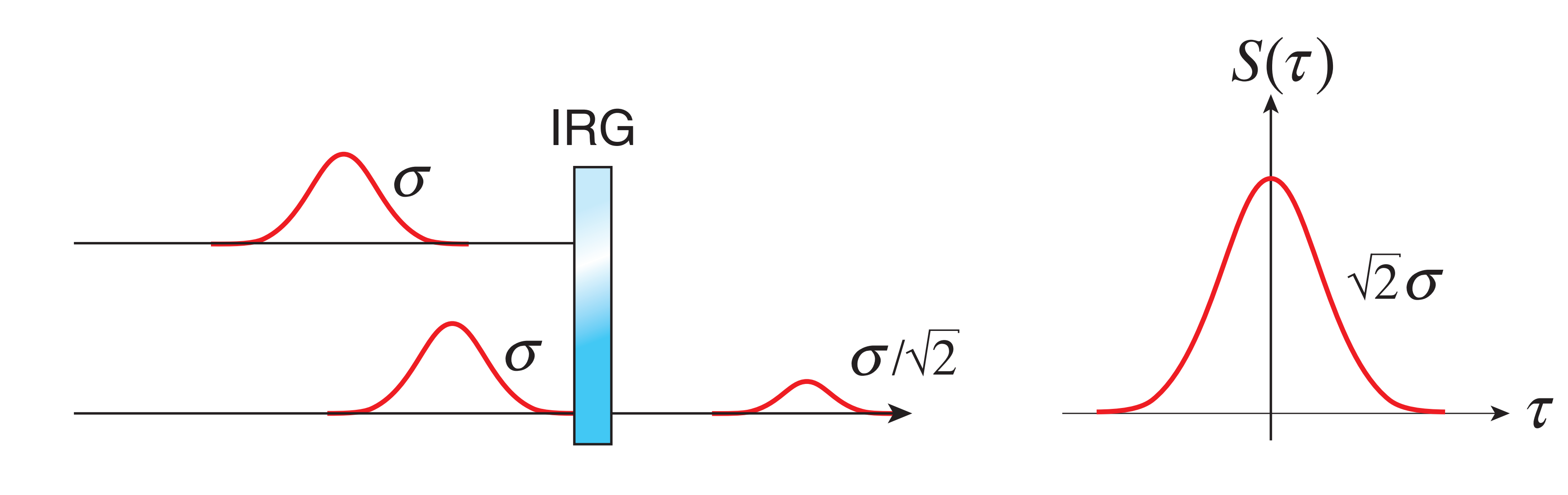
$$= \exp\left[-\frac{\tau^2}{2\sigma^2}\right] \int_{-\infty}^{\infty} \exp\left[-\frac{2u^2}{\sigma^2}\right] du = \sqrt{\frac{\pi}{2}}\,\sigma \exp\left[-\frac{\tau^2}{(\sigma\sqrt{2})^2}\right]$$

Joint time-frequency measurements



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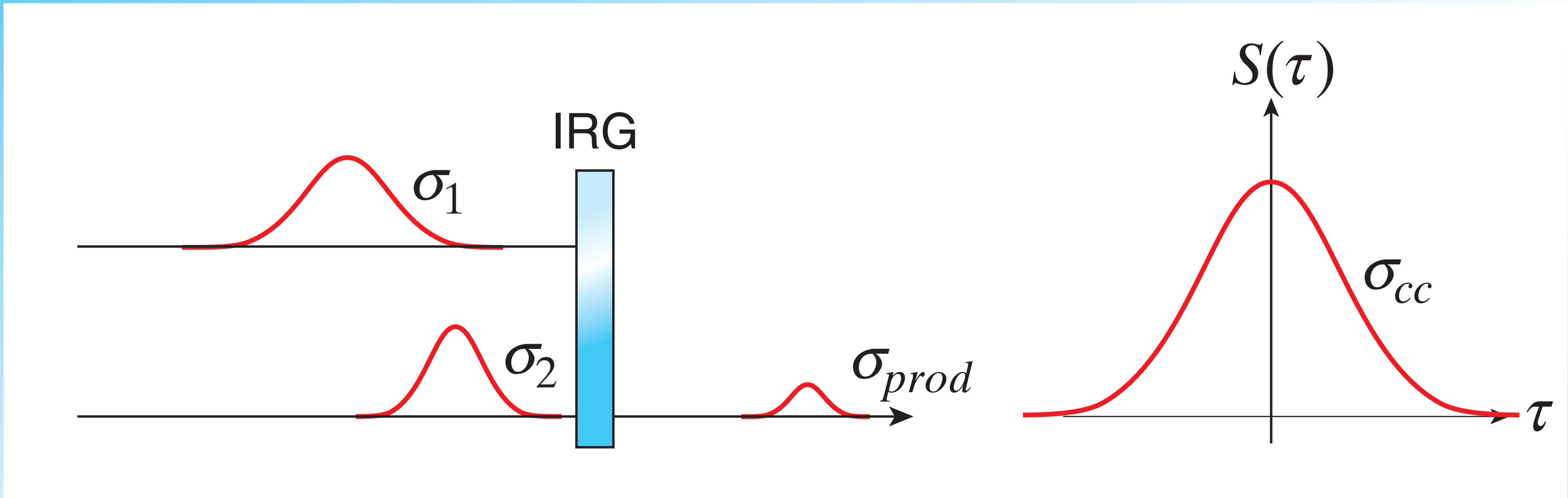
Joint time-frequency measurements

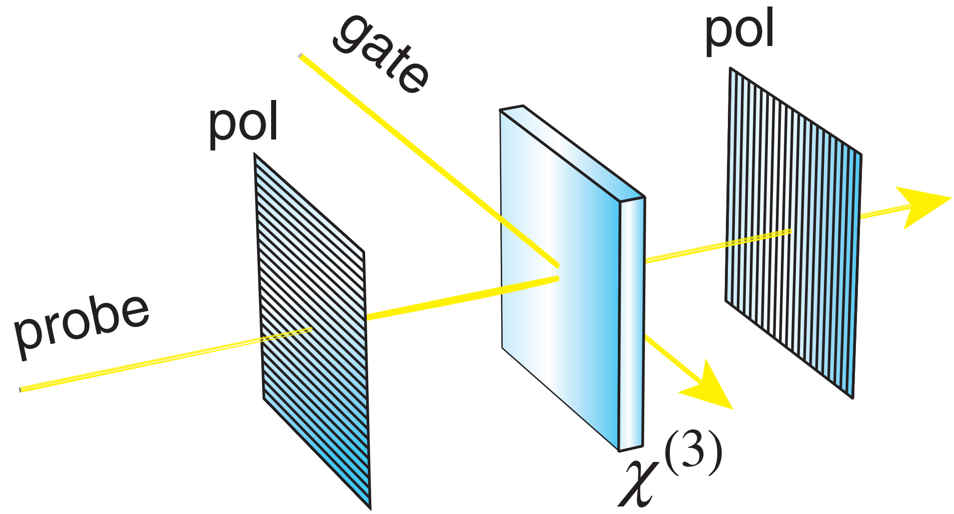


If gate and probe unequal:

$$\sigma_{prod}^2 = \frac{\sigma_1^2 \sigma_2^2}{\sigma_1^2 + \sigma_2^2}$$ **(narrower than both)**

$$\sigma_{cc}^2 = \sigma_1^2 + \sigma_2^2$$ **(wider than both)**

Joint time-frequency measurements

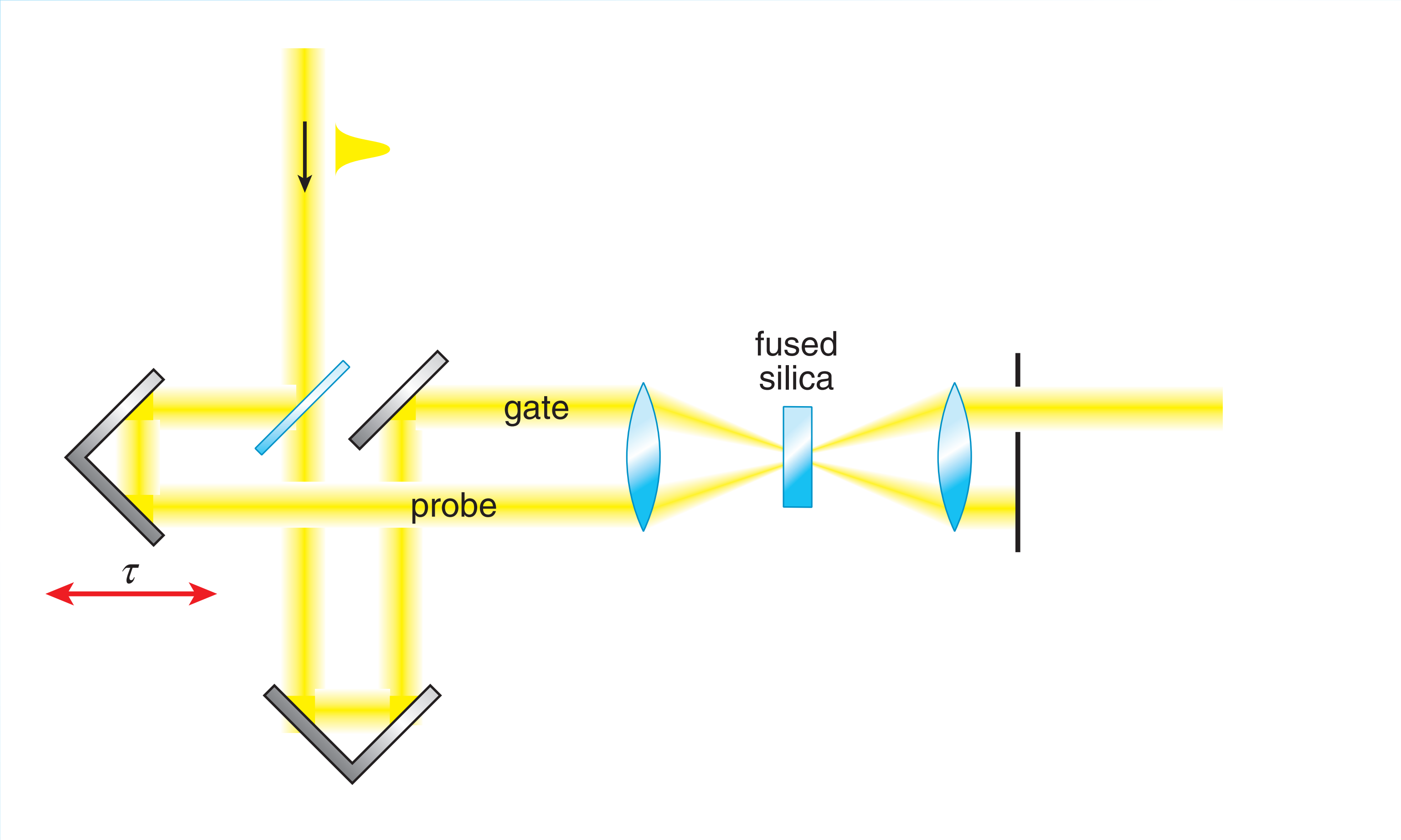


Transmitted field:

$$E_{trans}(t,\tau) \propto \chi^{(3)} E_{probe}(t) \left| E_{gate}(t+\tau) \right|^2$$

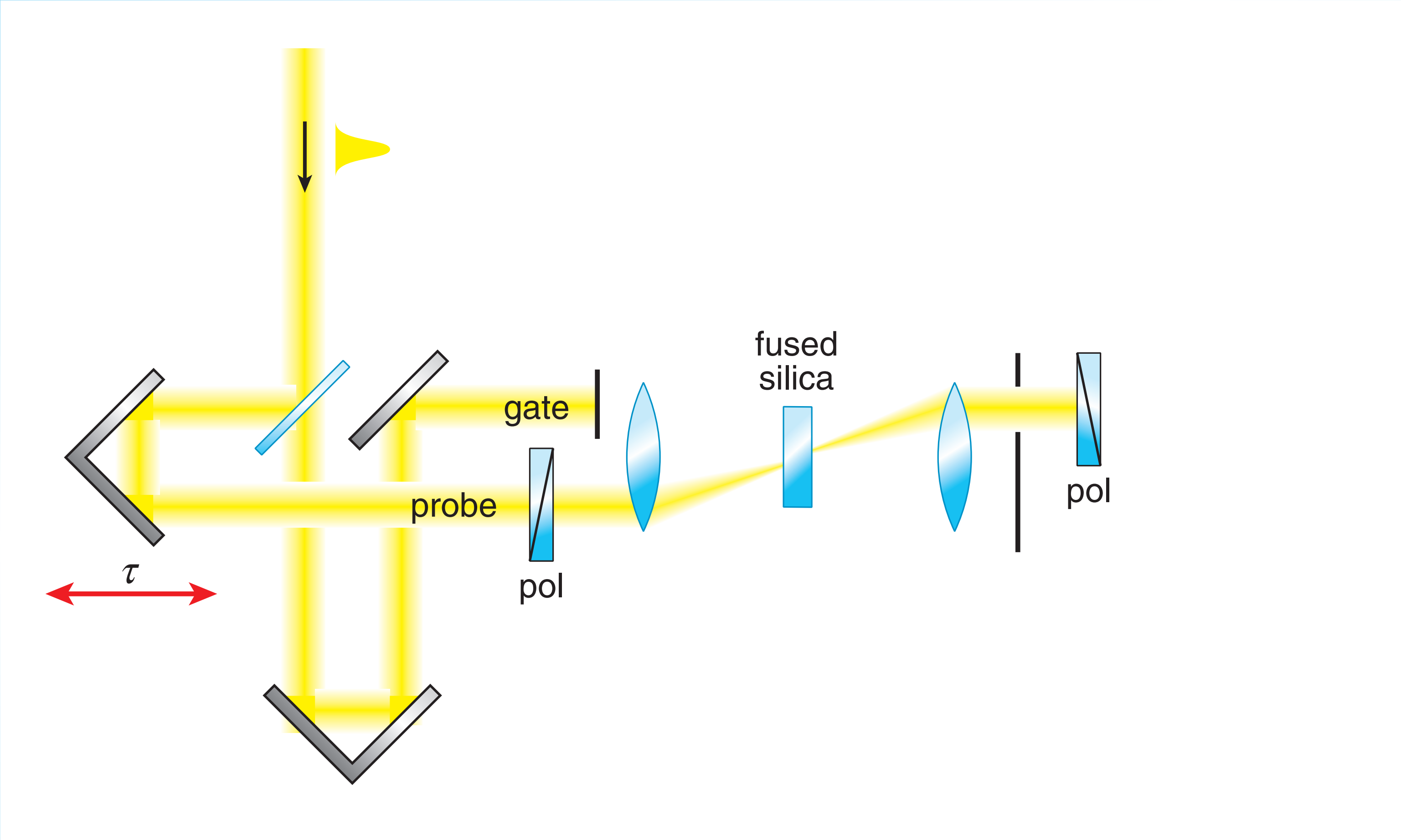
Joint time-frequency measurements

FROG: frequency-resolved optical gating



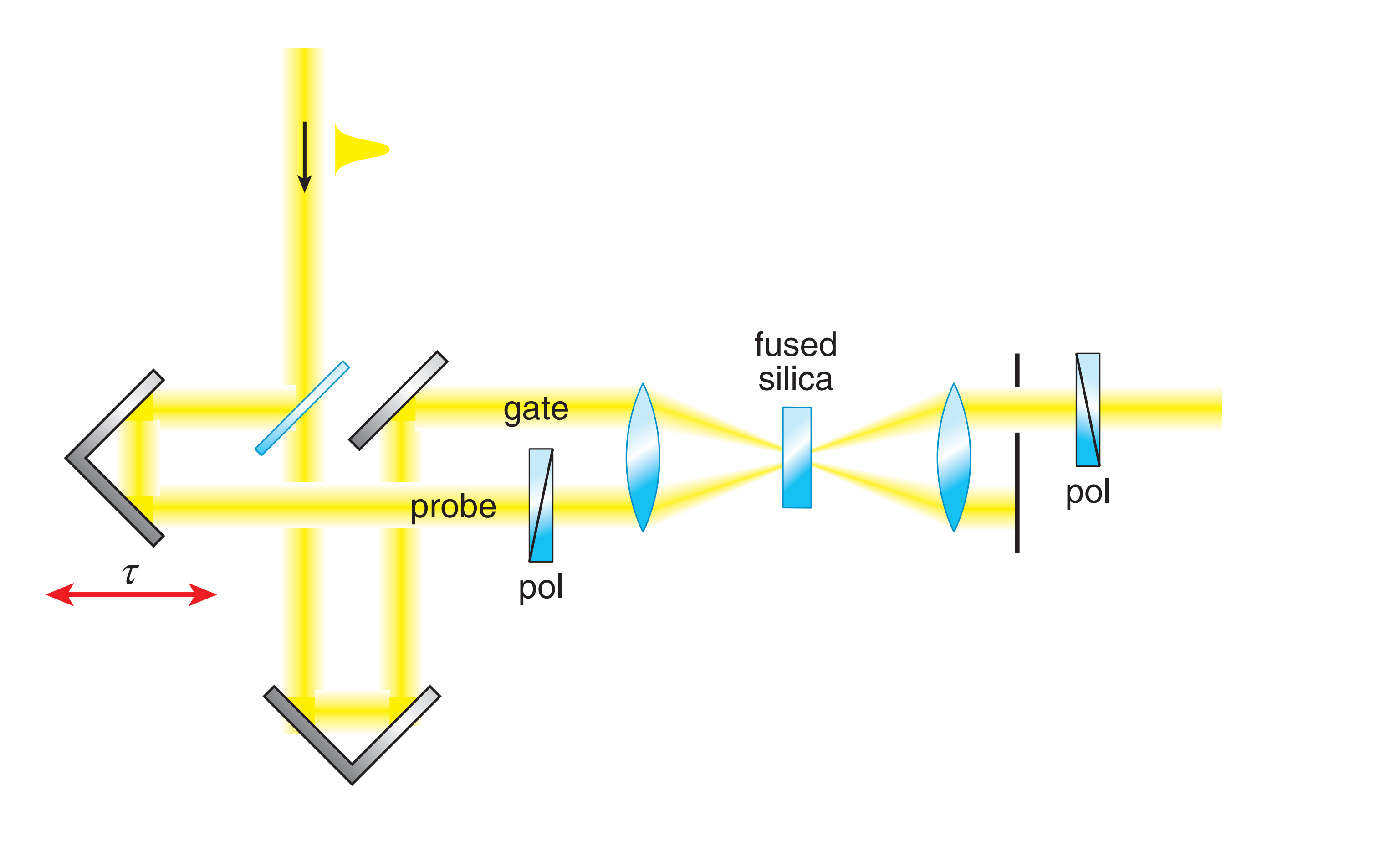
Joint time-frequency measurements

FROG: frequency-resolved optical gating



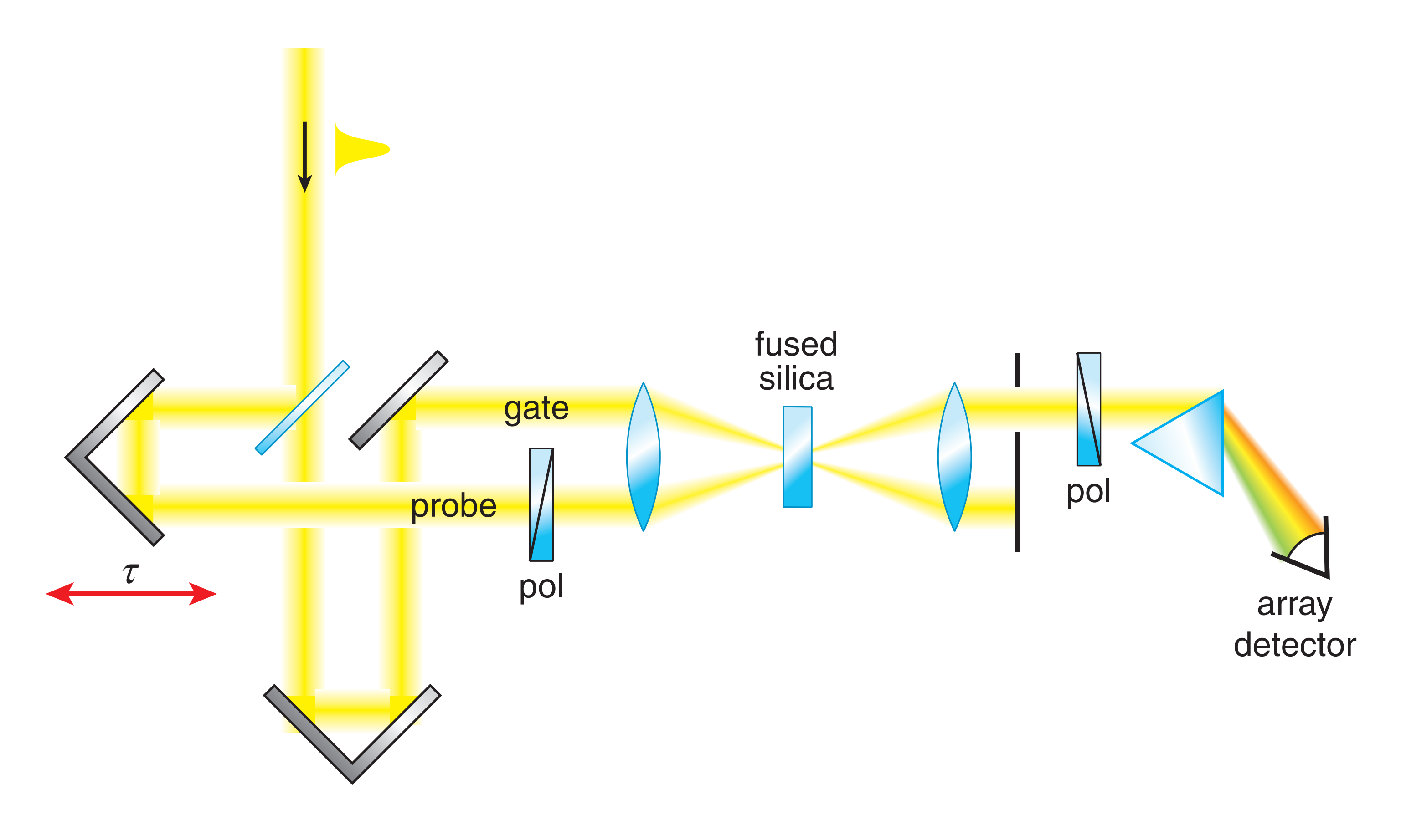
Joint time-frequency measurements

FROG: frequency-resolved optical gating

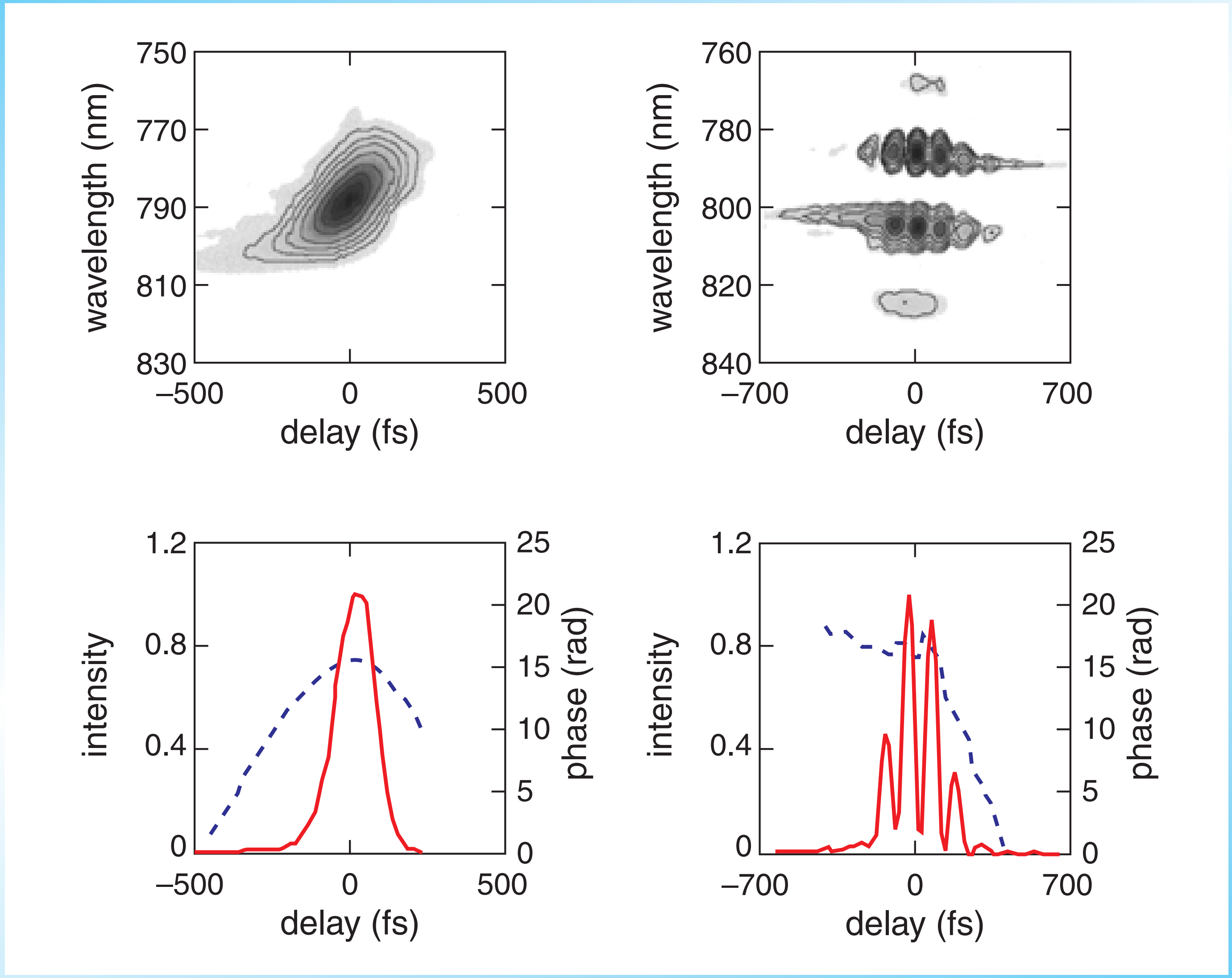


Joint time-frequency measurements

FROG: frequency-resolved optical gating

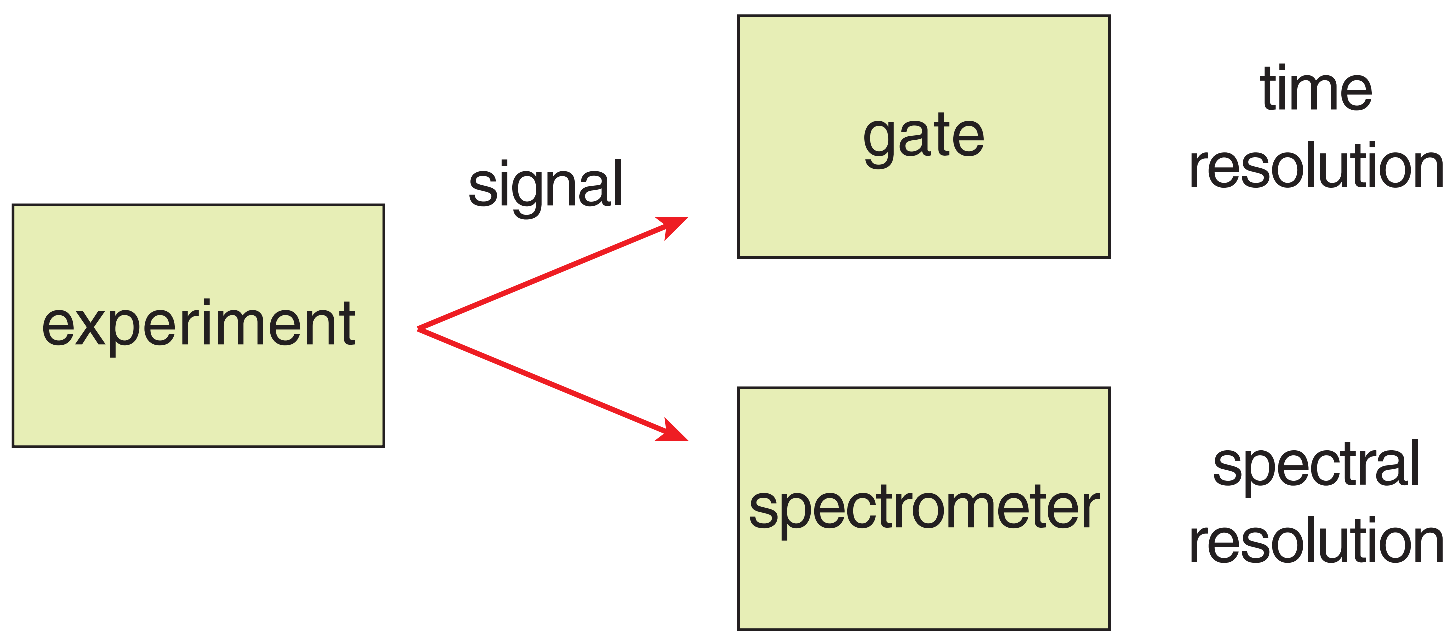


Joint time-frequency measurements



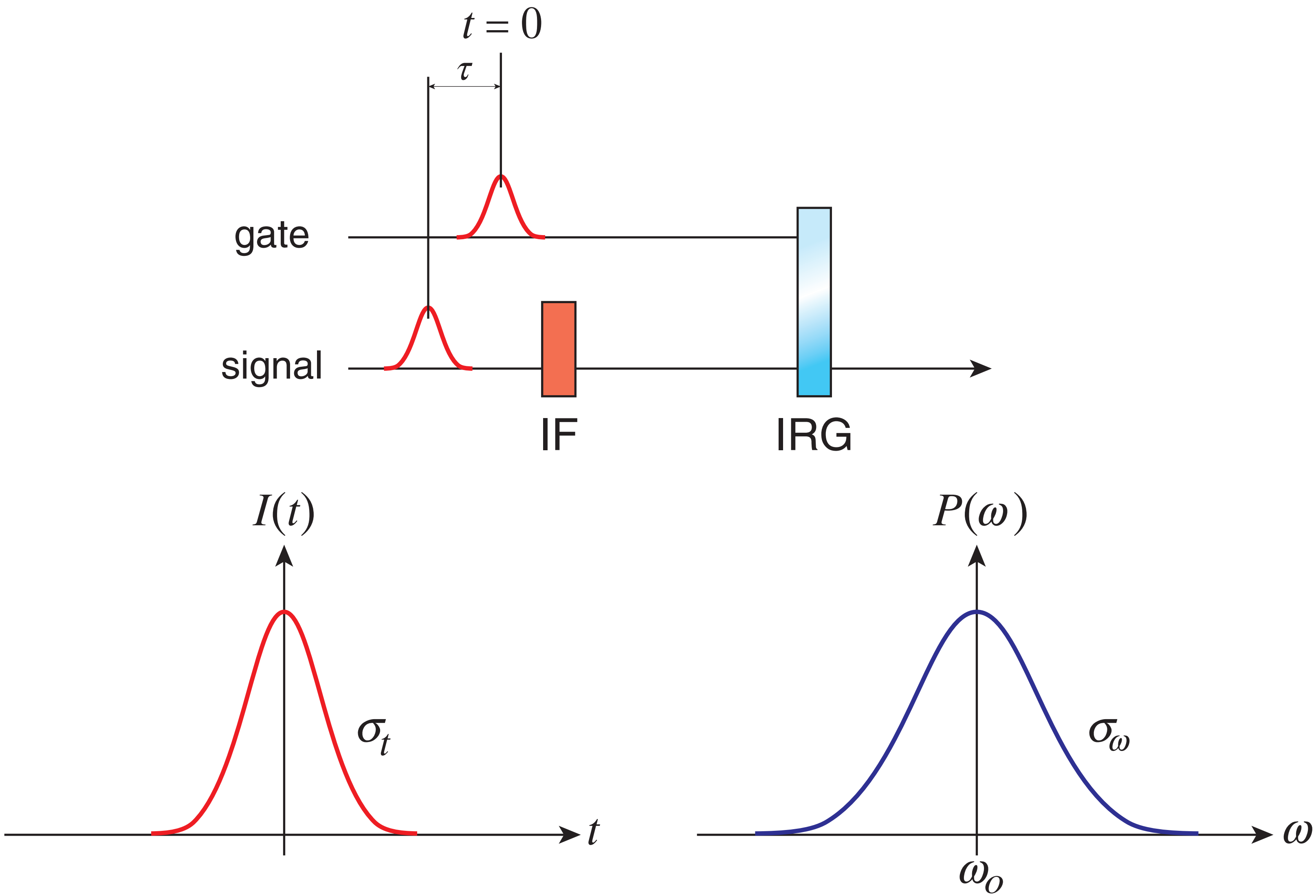
R. Trebino, *et al.*, Rev. Sci. Instrum. 68, 3277 (1997)

Joint time-frequency measurements

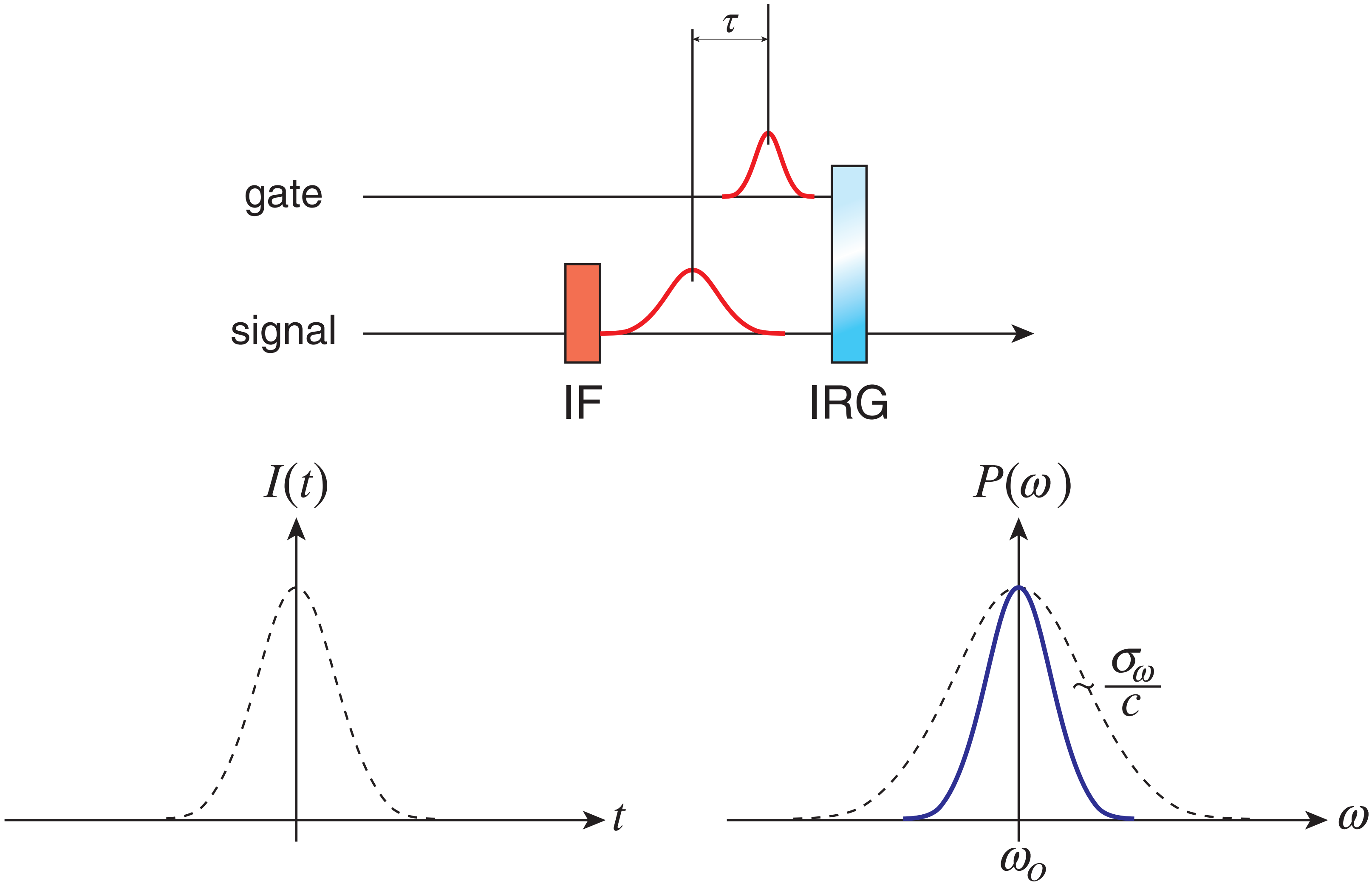


What are the resolution limits?

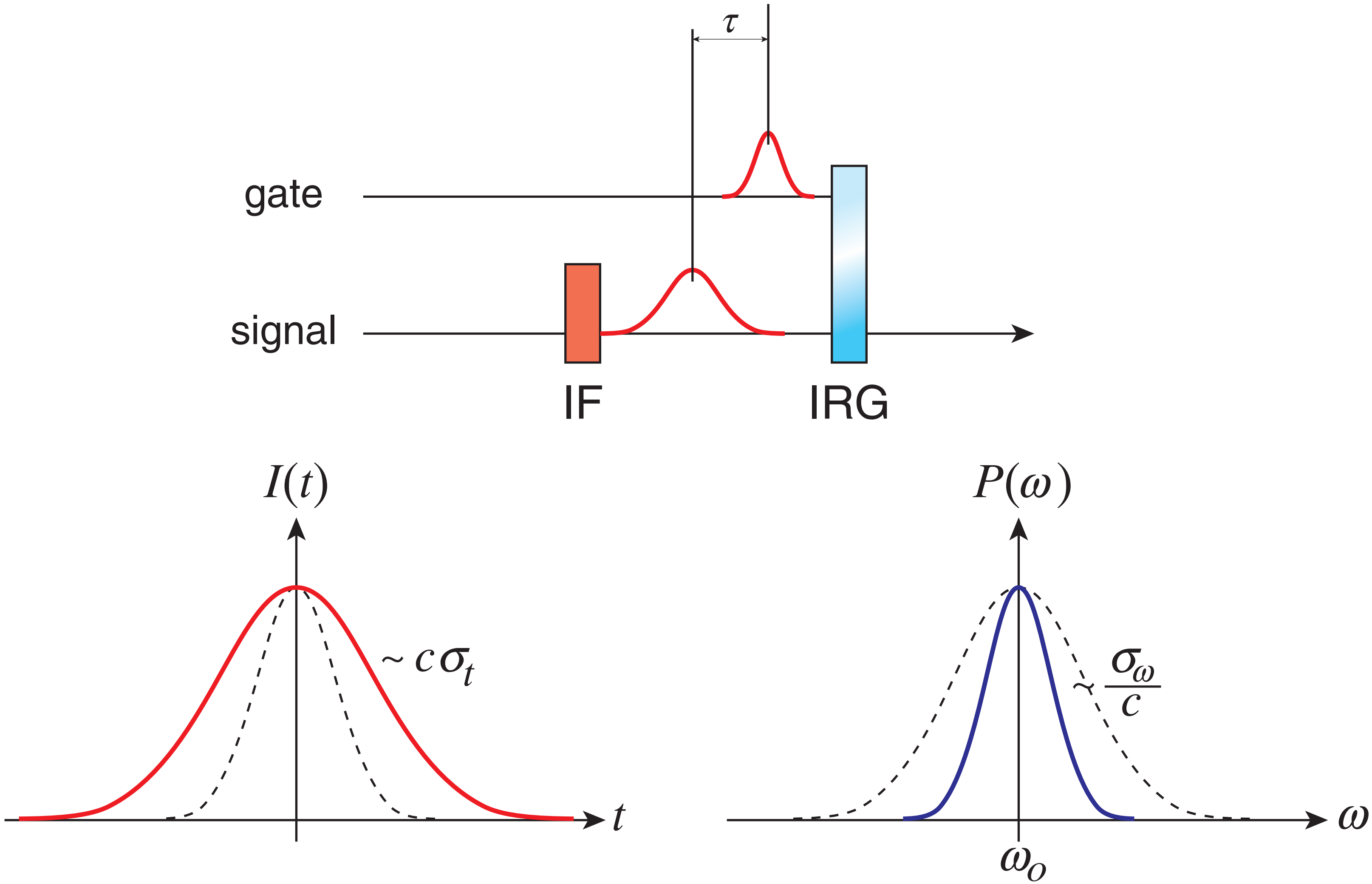
Experiment 1



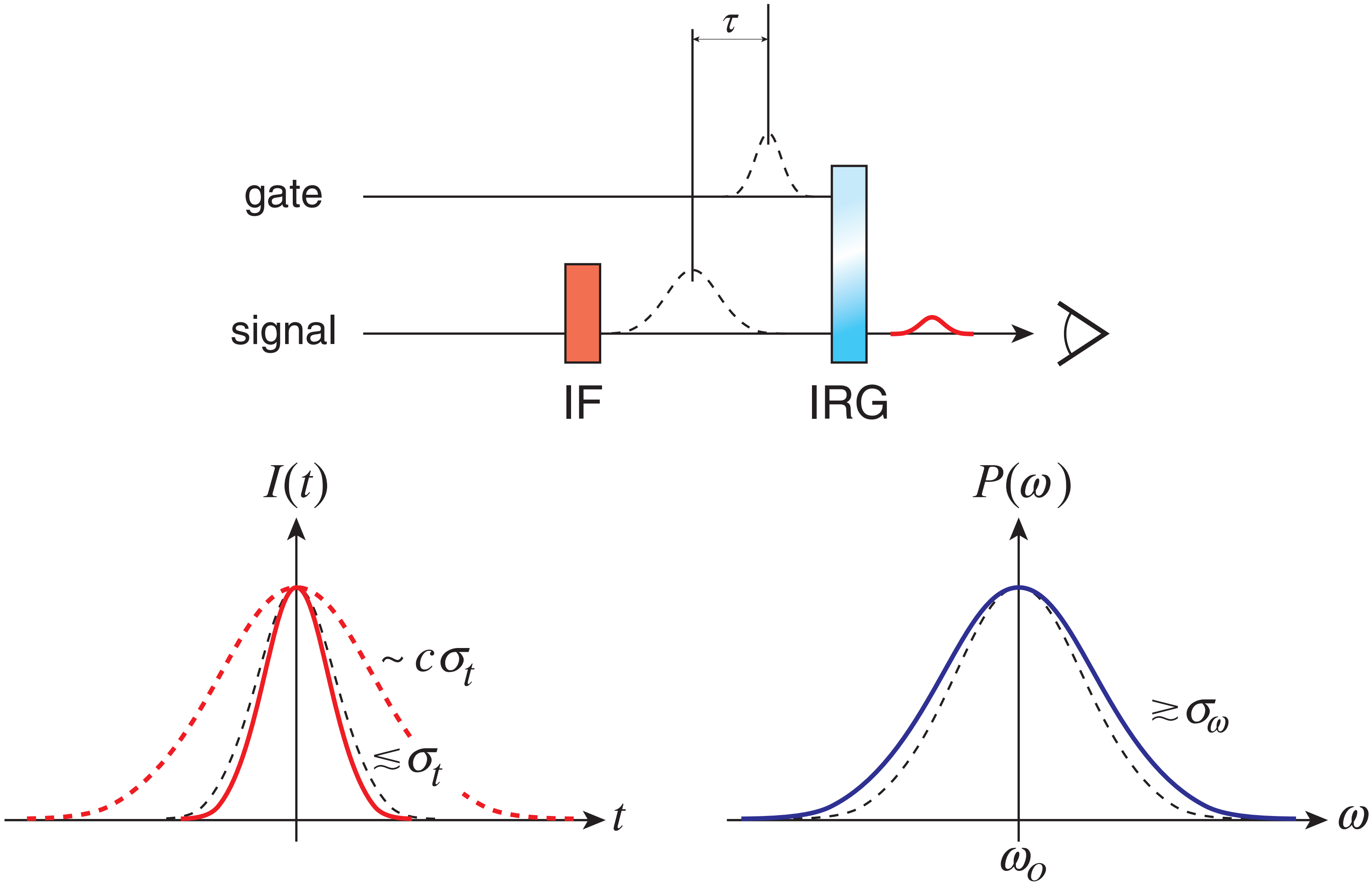
Experiment 1



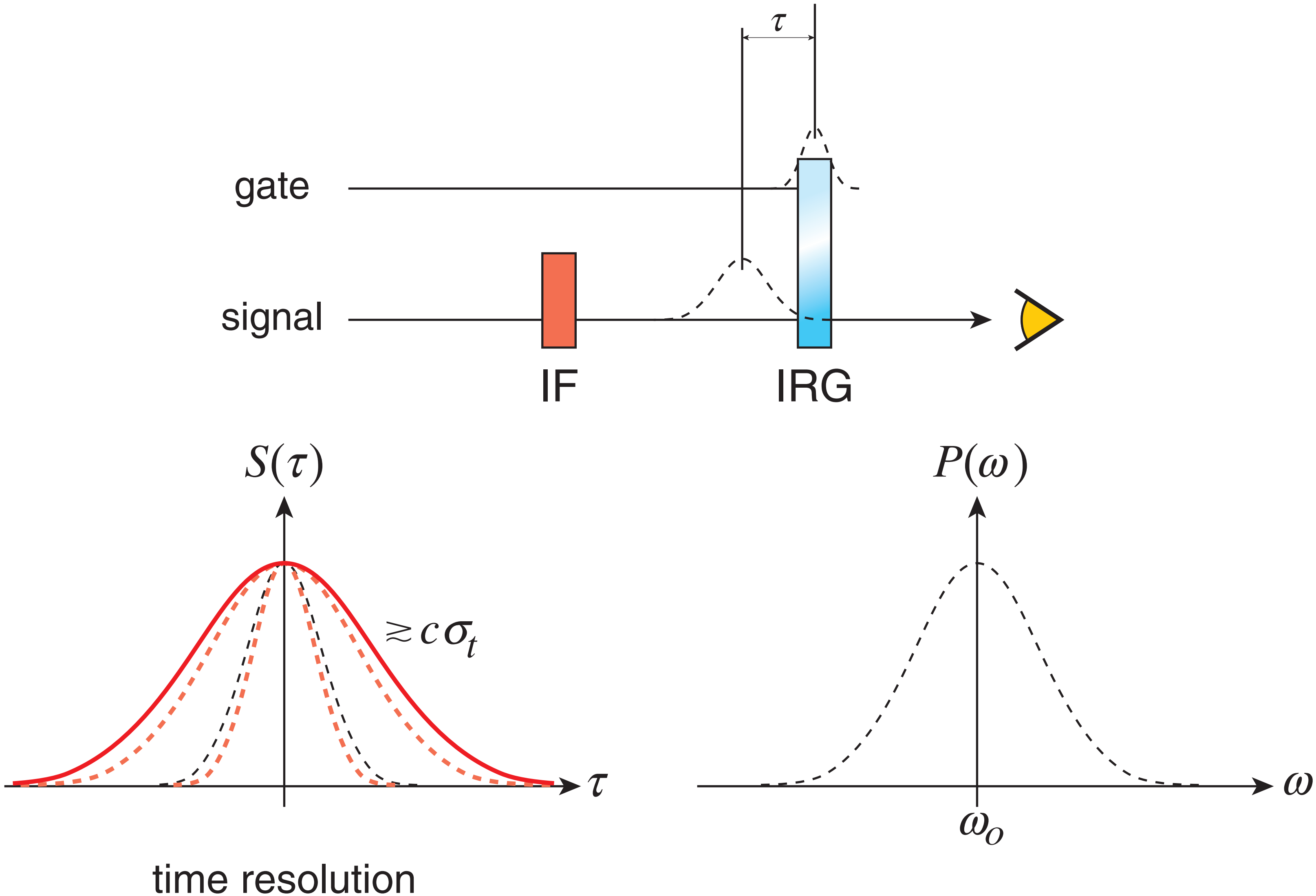
Experiment 1



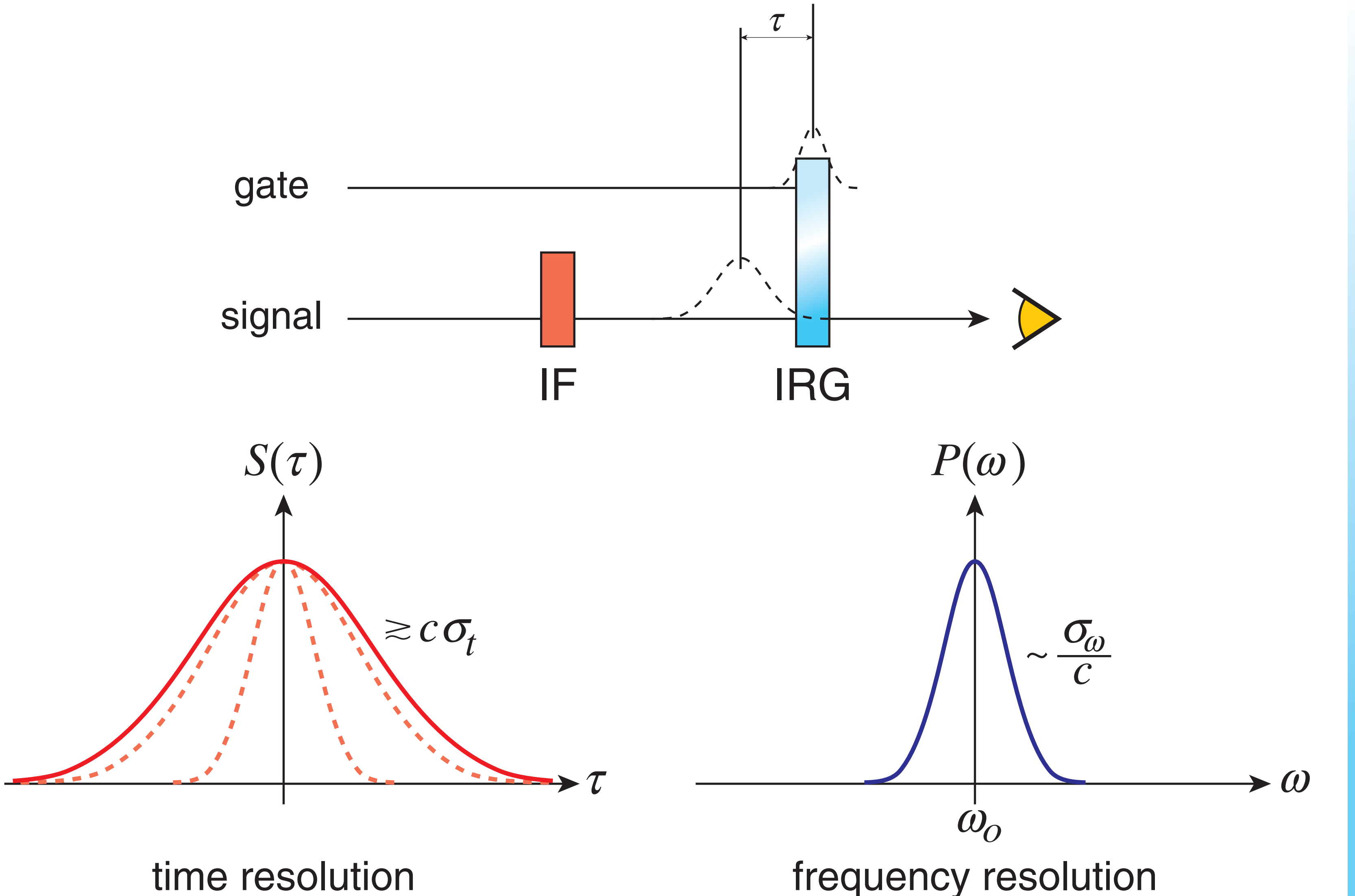
Experiment 1



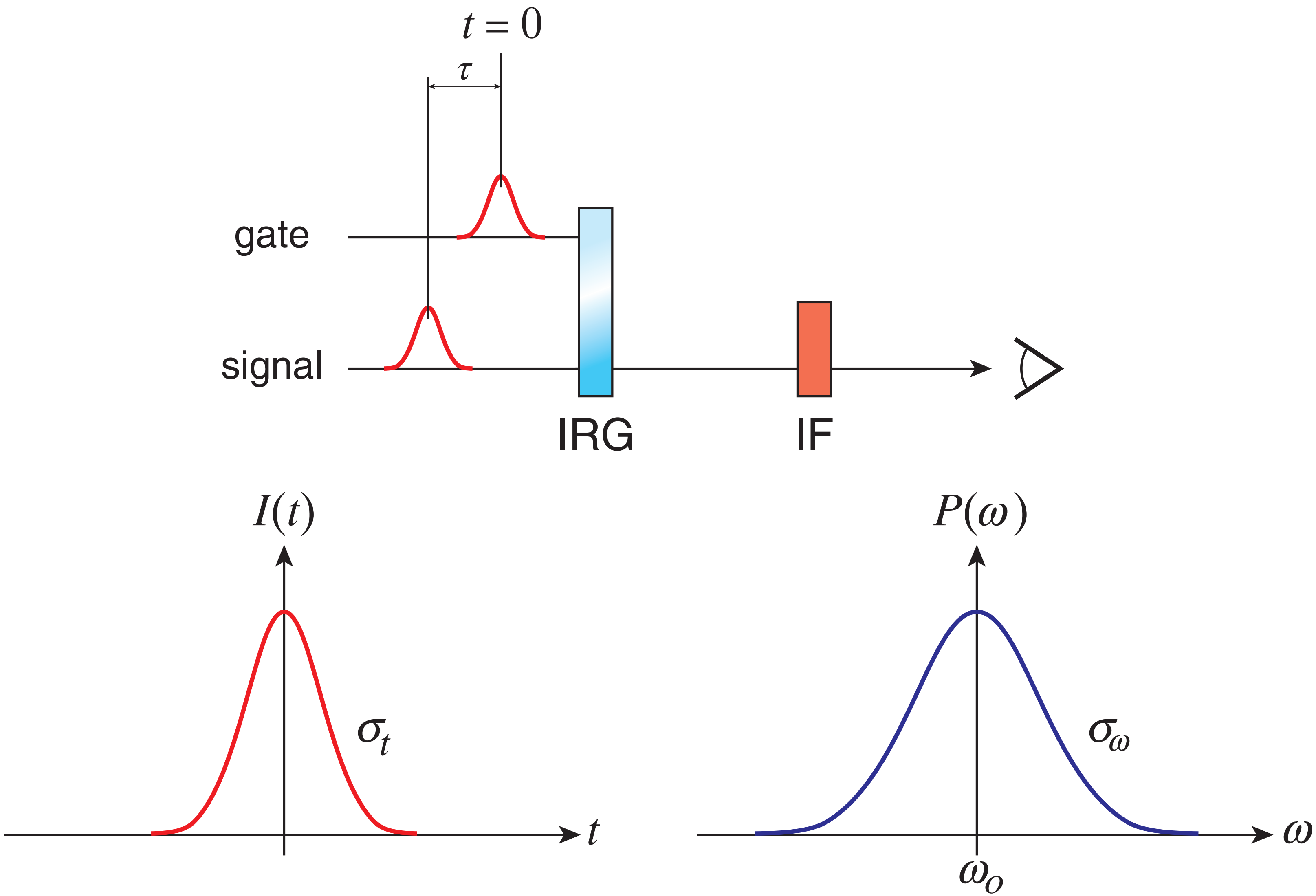
Experiment 1



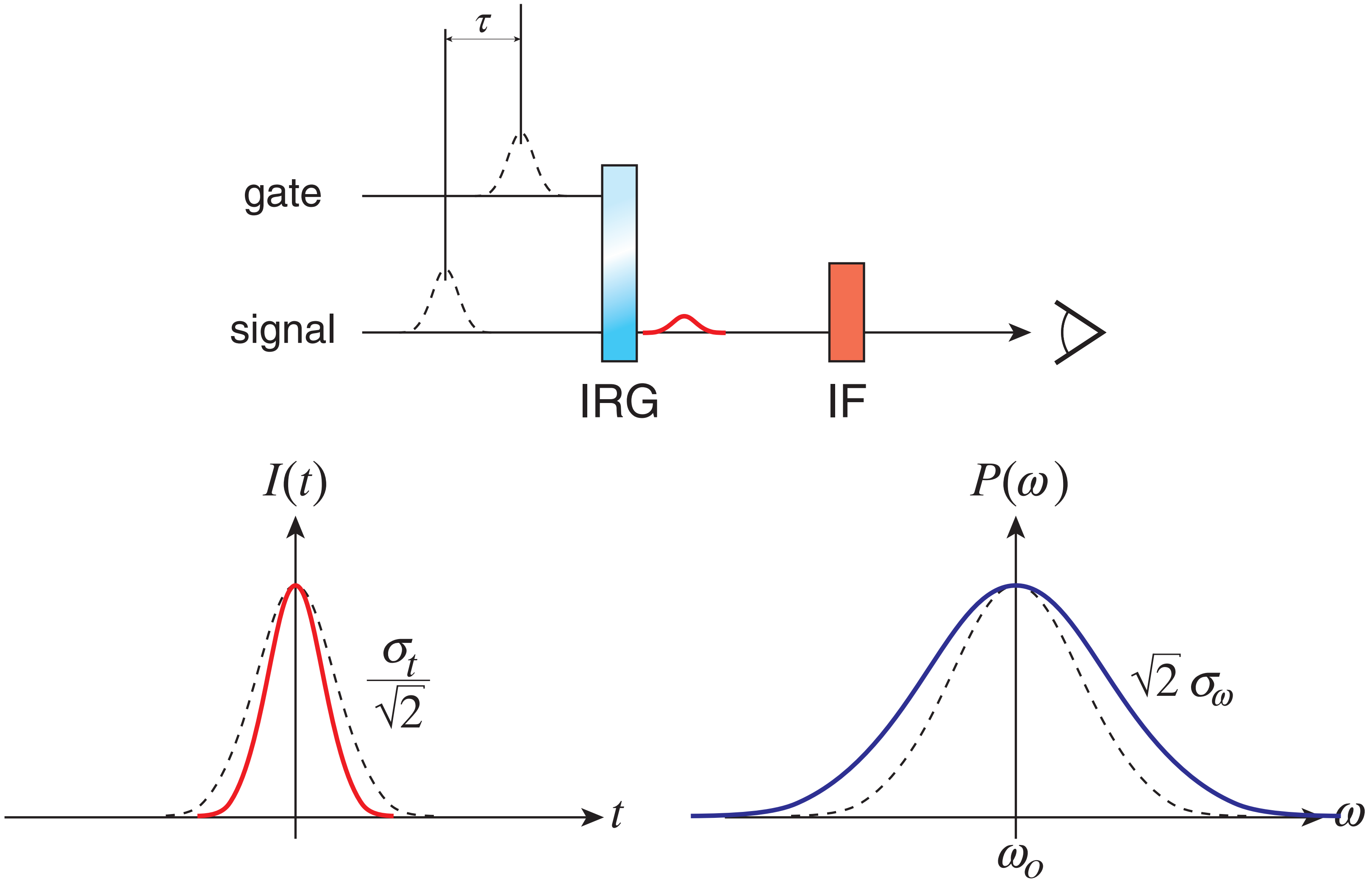
Experiment 1



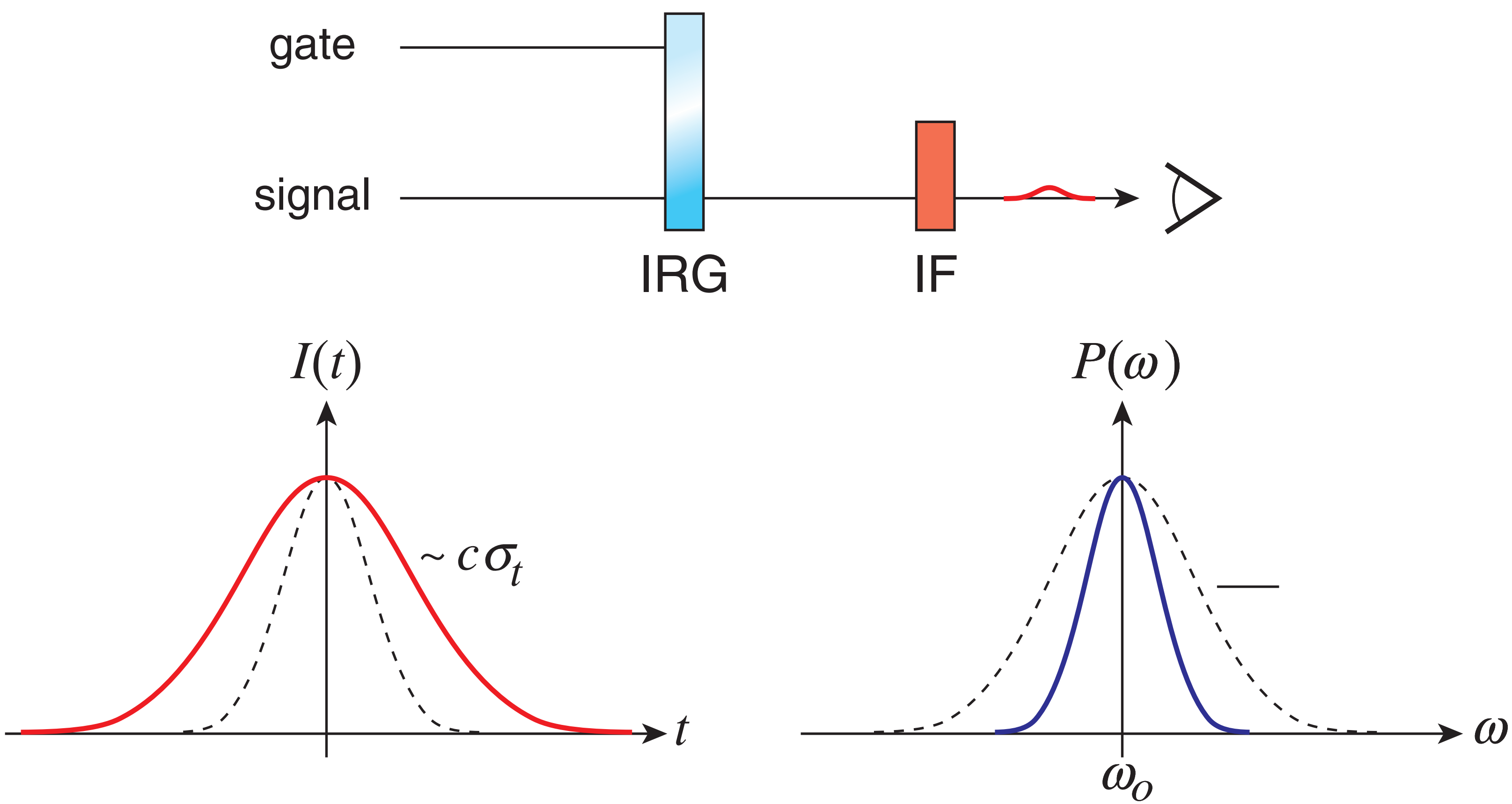
Experiment 2



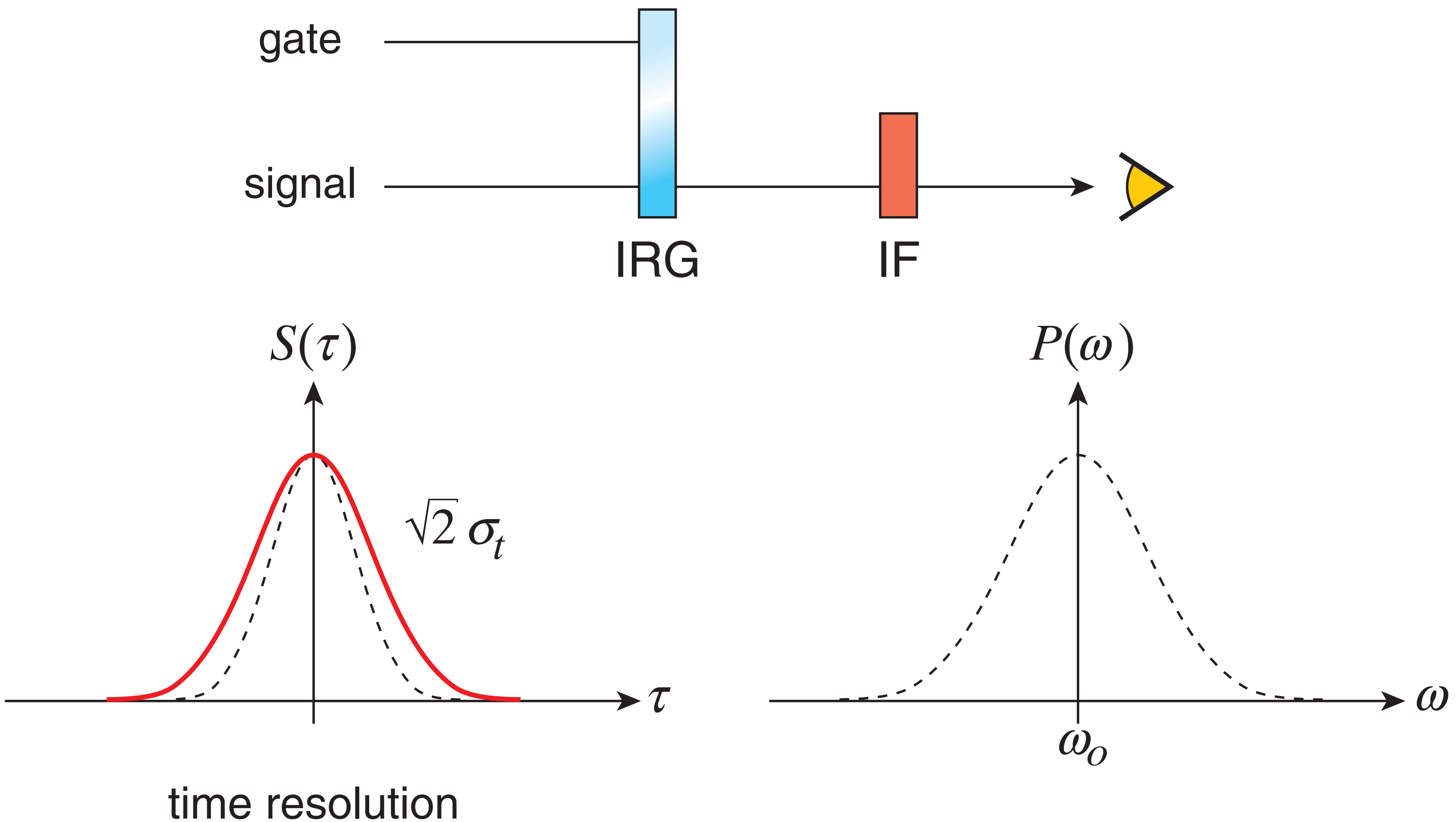
Experiment 2



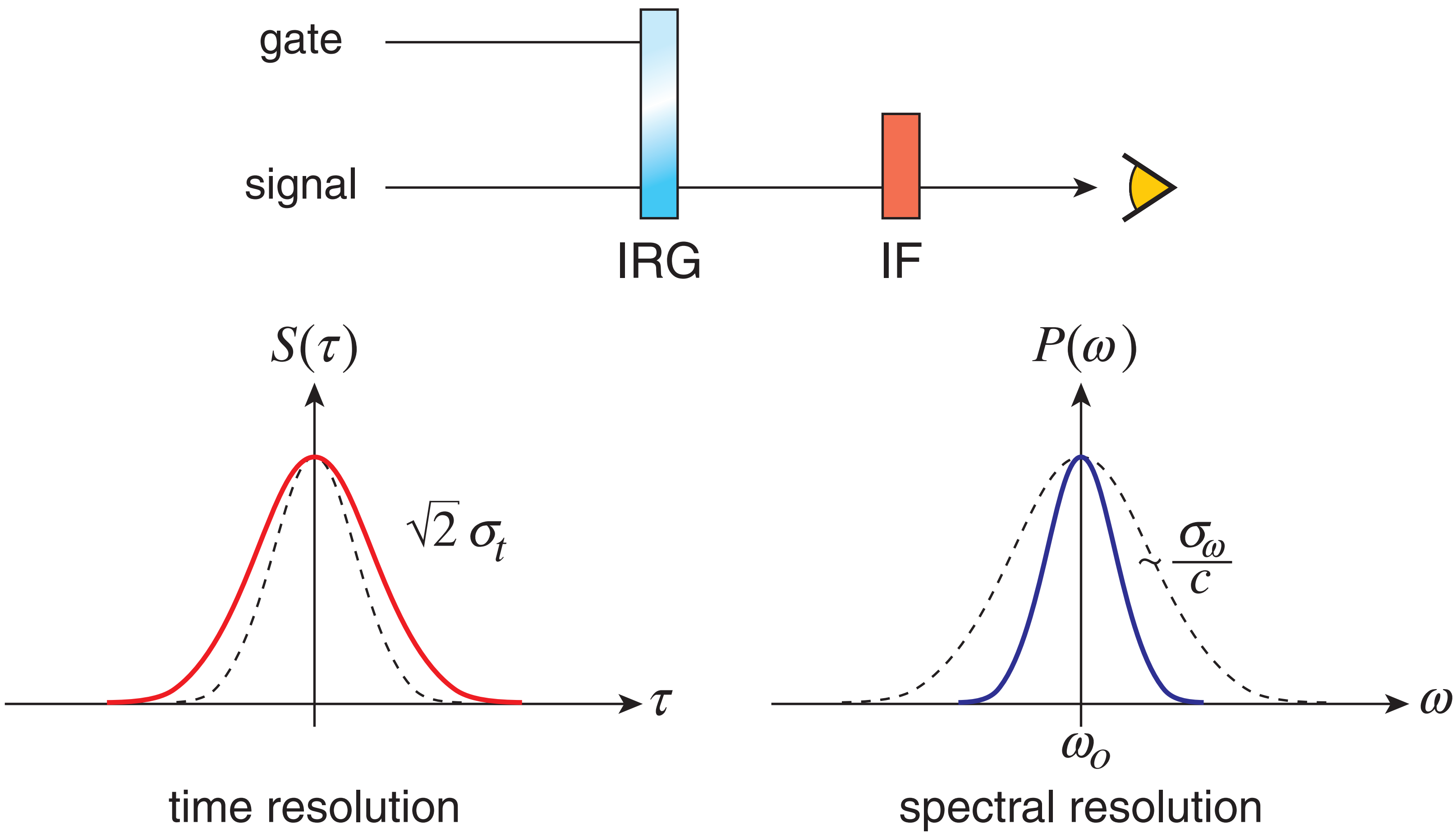
Experiment 2



Experiment 2

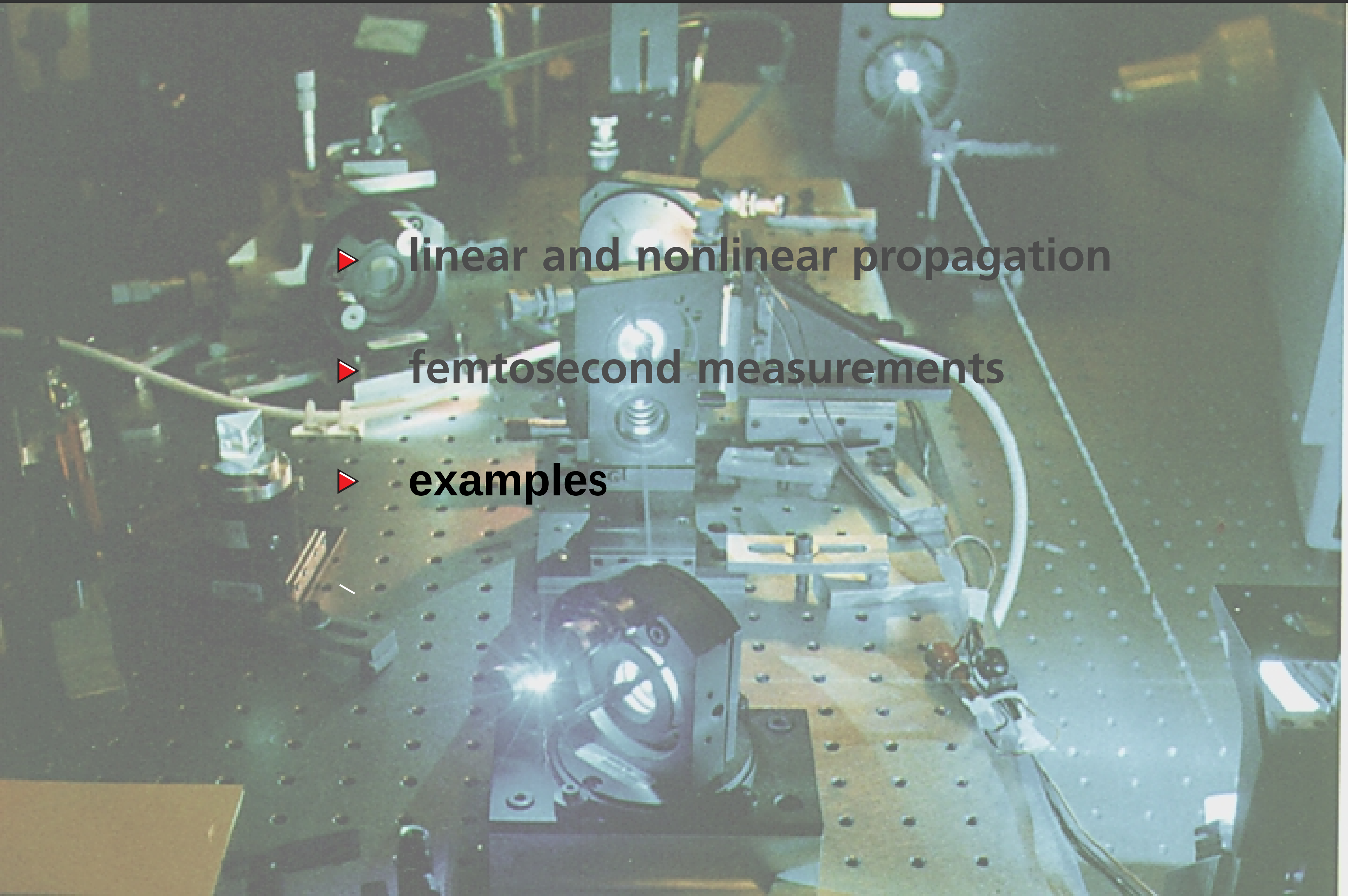


Experiment 2



Outline

- linear and nonlinear propagation
- femtosecond measurements
- **examples**

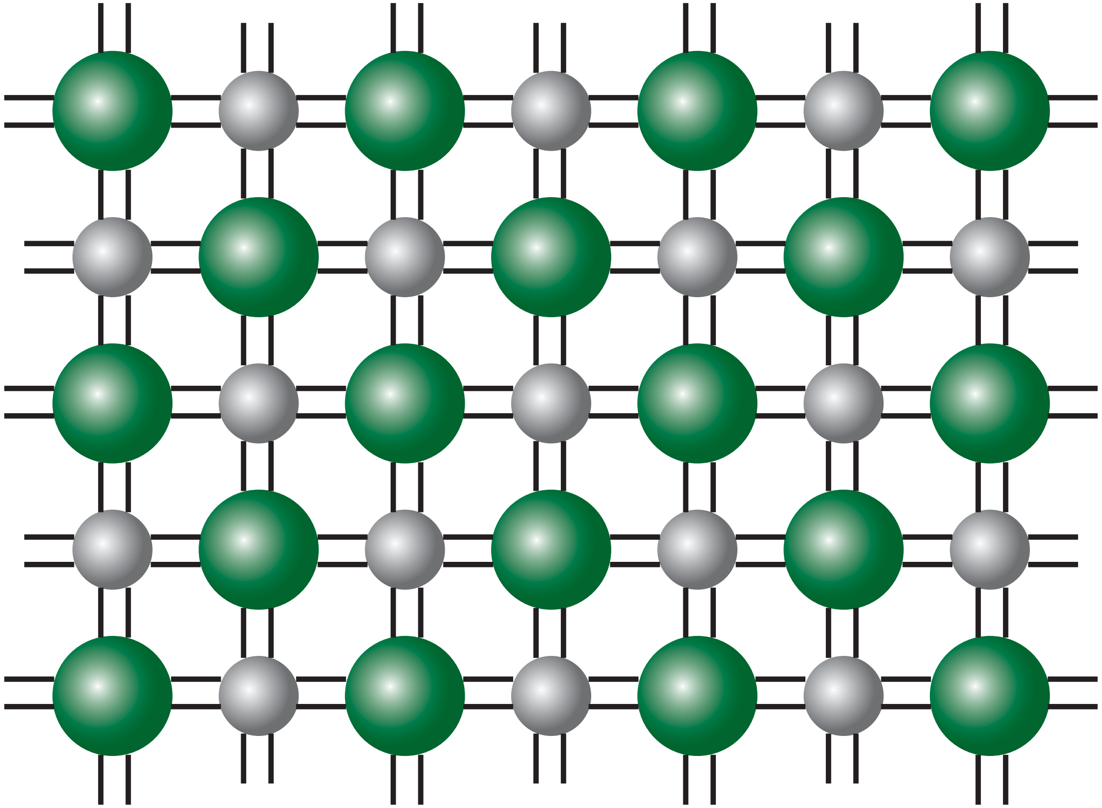


Introduction

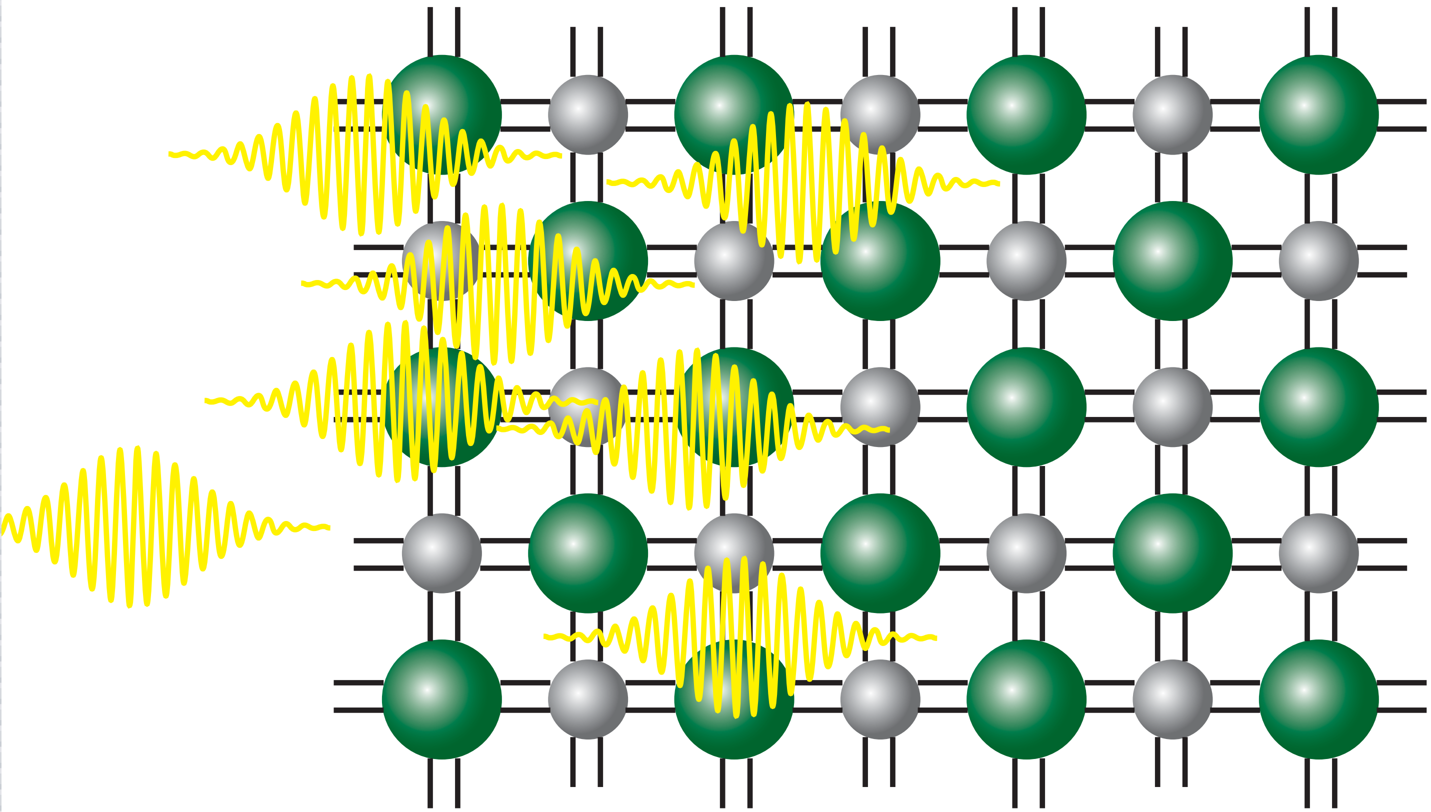
short laser pulses can drive structural transitions

Introduction

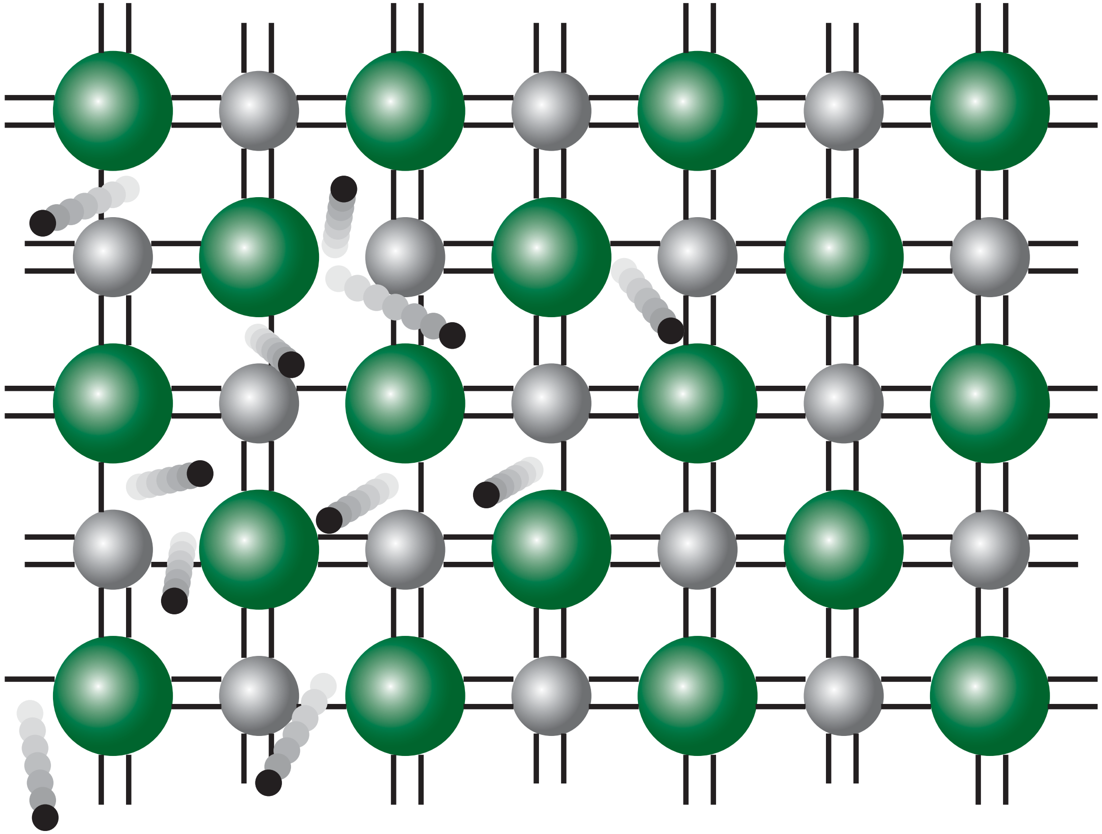
how do femtosecond laser pulses alter a solid?



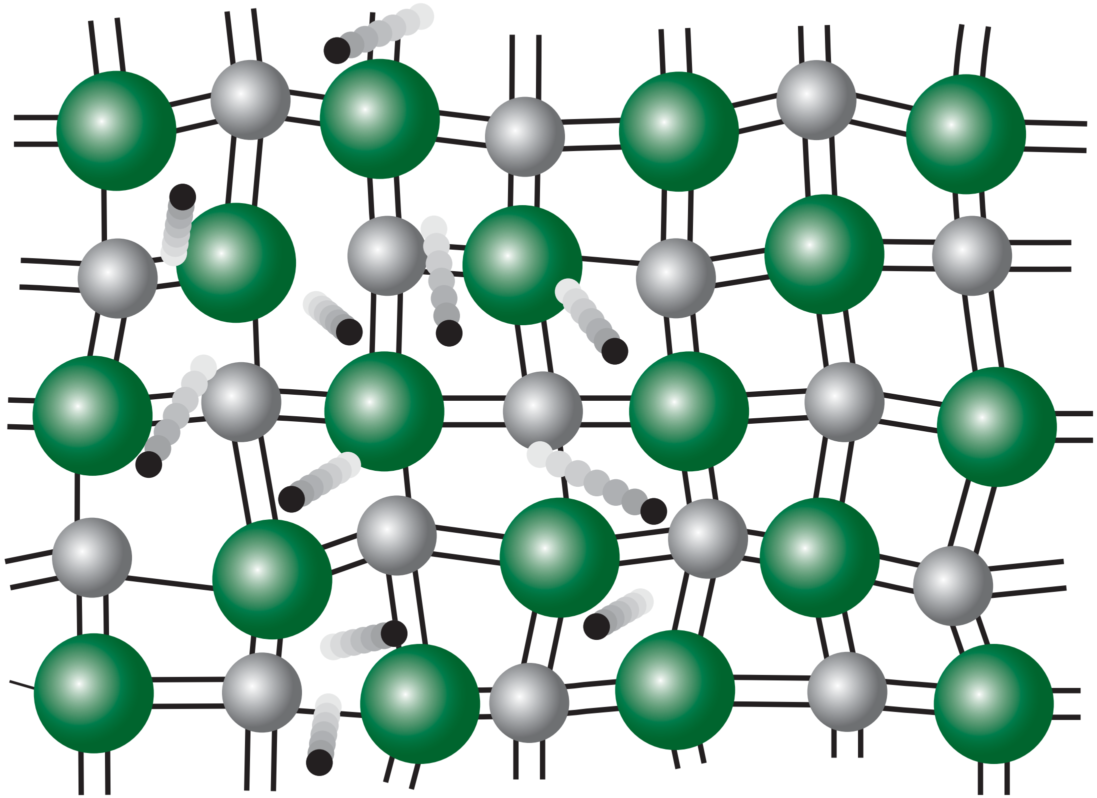
photons excite valence electrons…



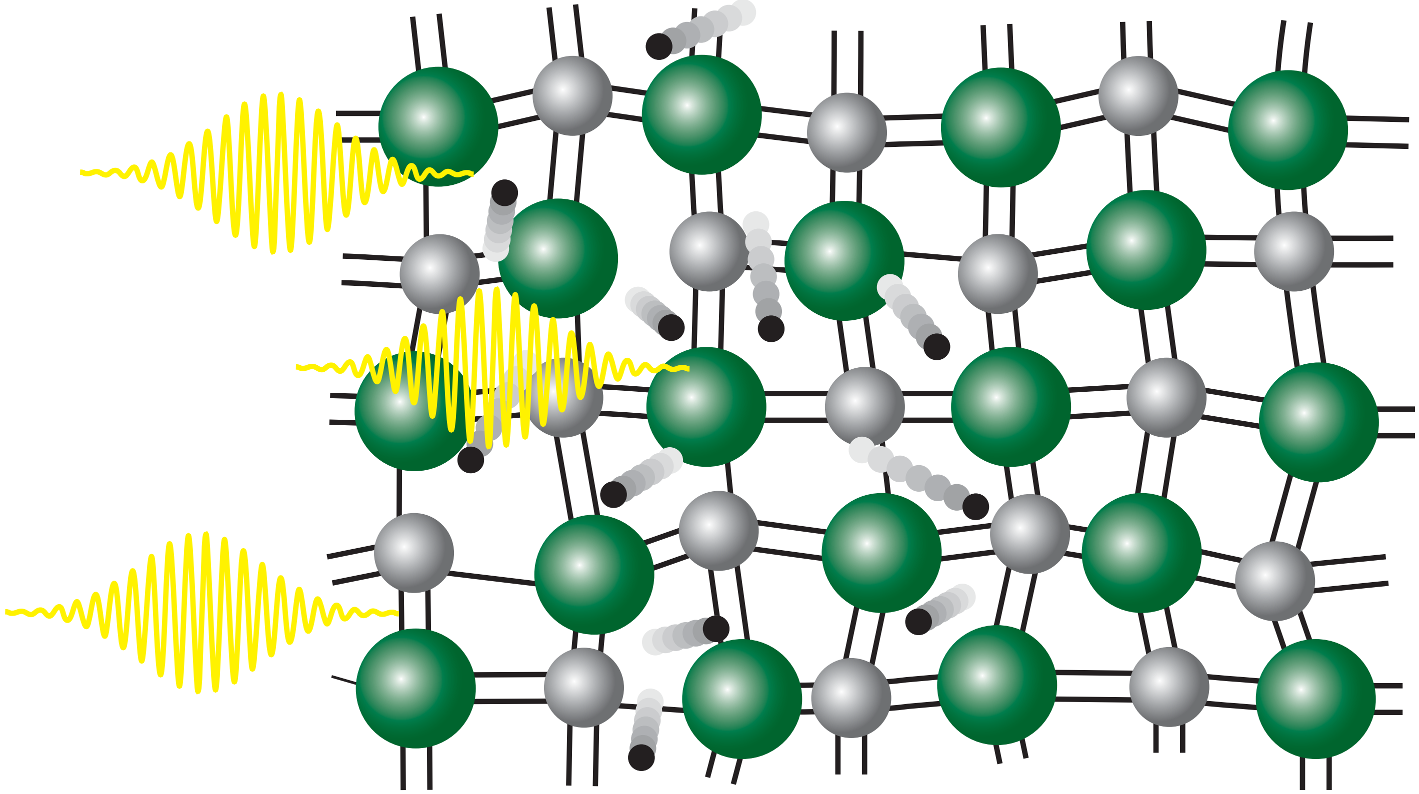
… and create free electrons…



… causing electronic and structural changes…

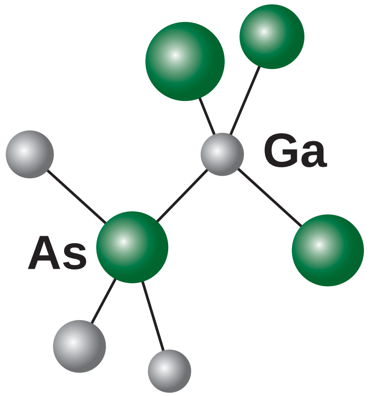


… which we detect with a second laser pulse



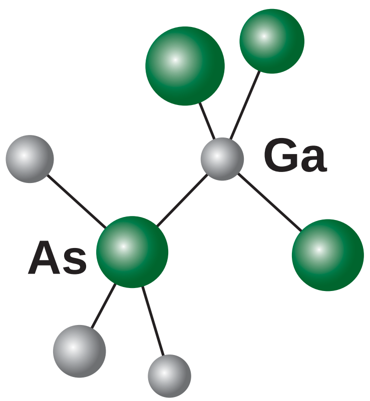
Introduction

structure

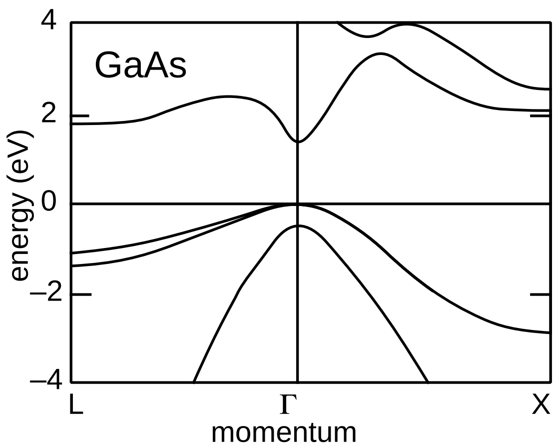


Introduction

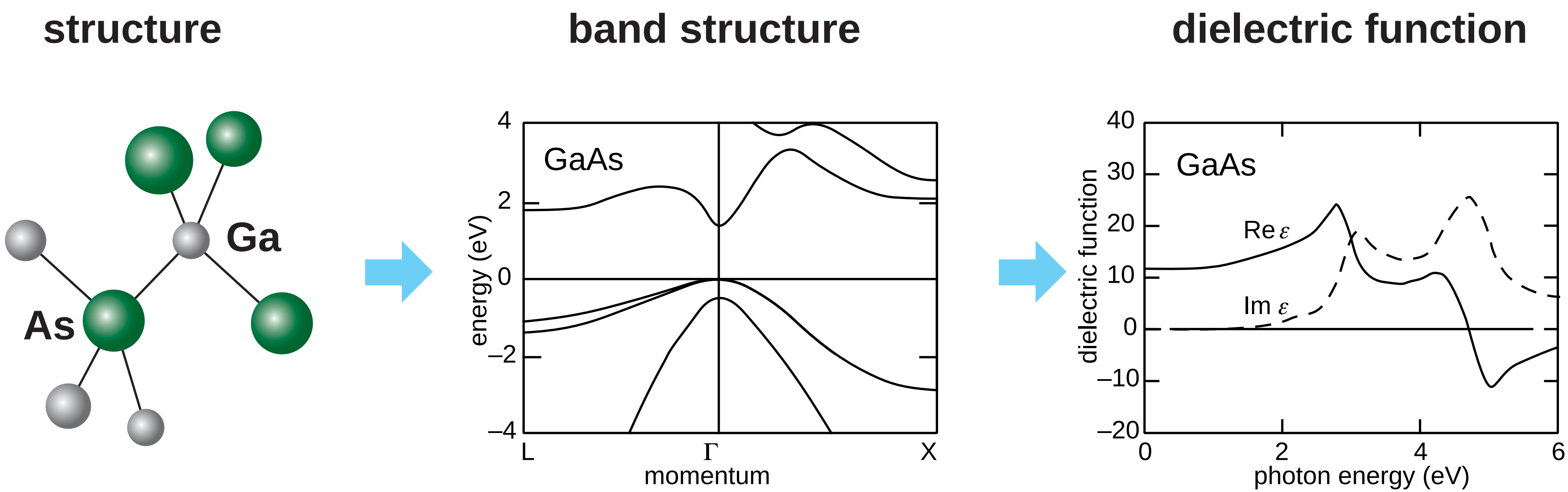
structure



band structure

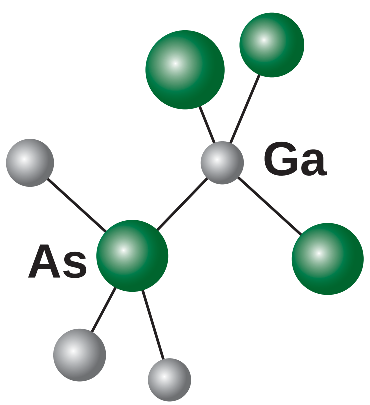


Introduction

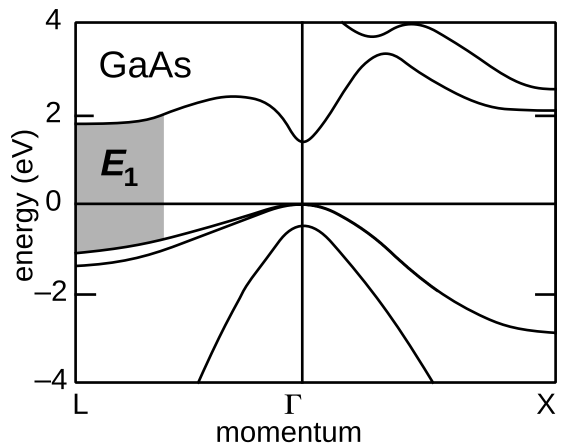


Introduction

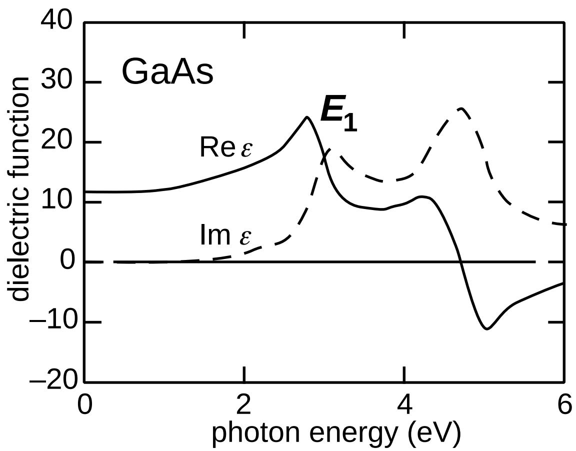
structure



band structure

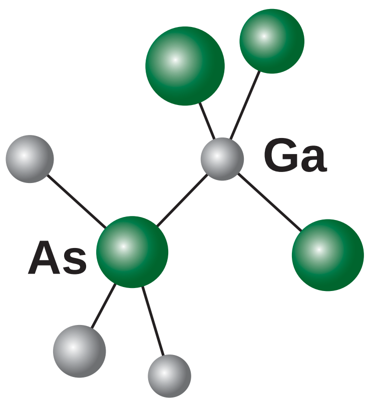


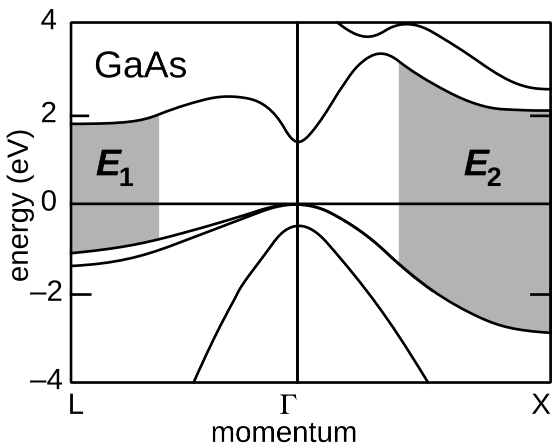
dielectric function

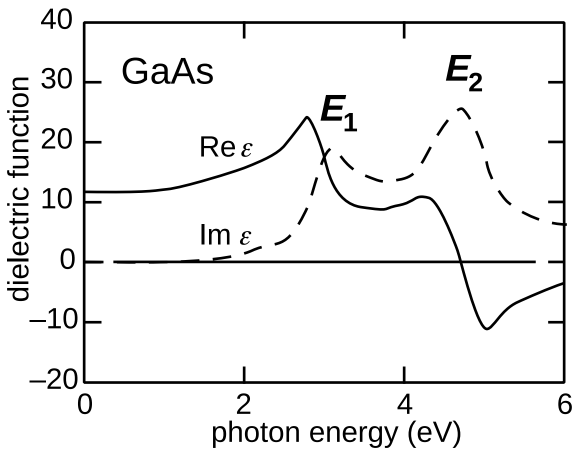


Introduction

structure | **band structure** | **dielectric function**

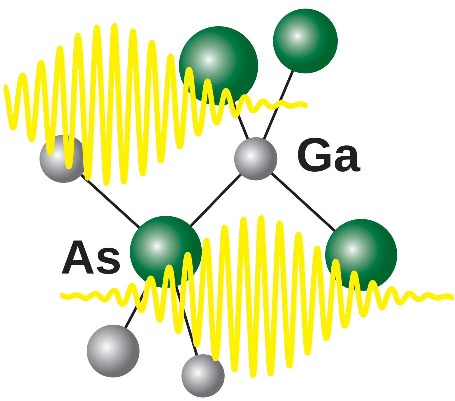




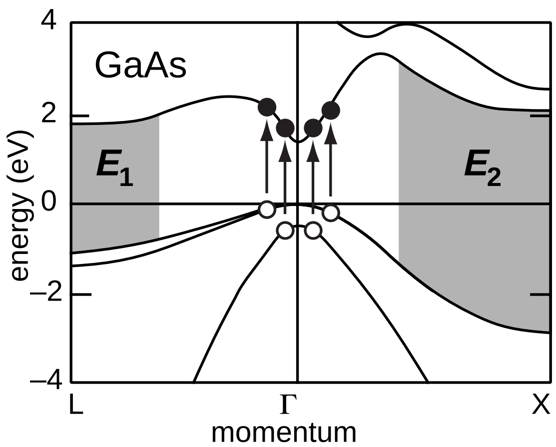


Introduction

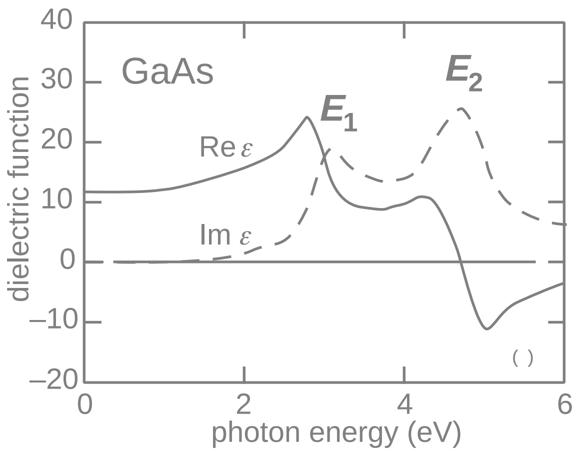
structure



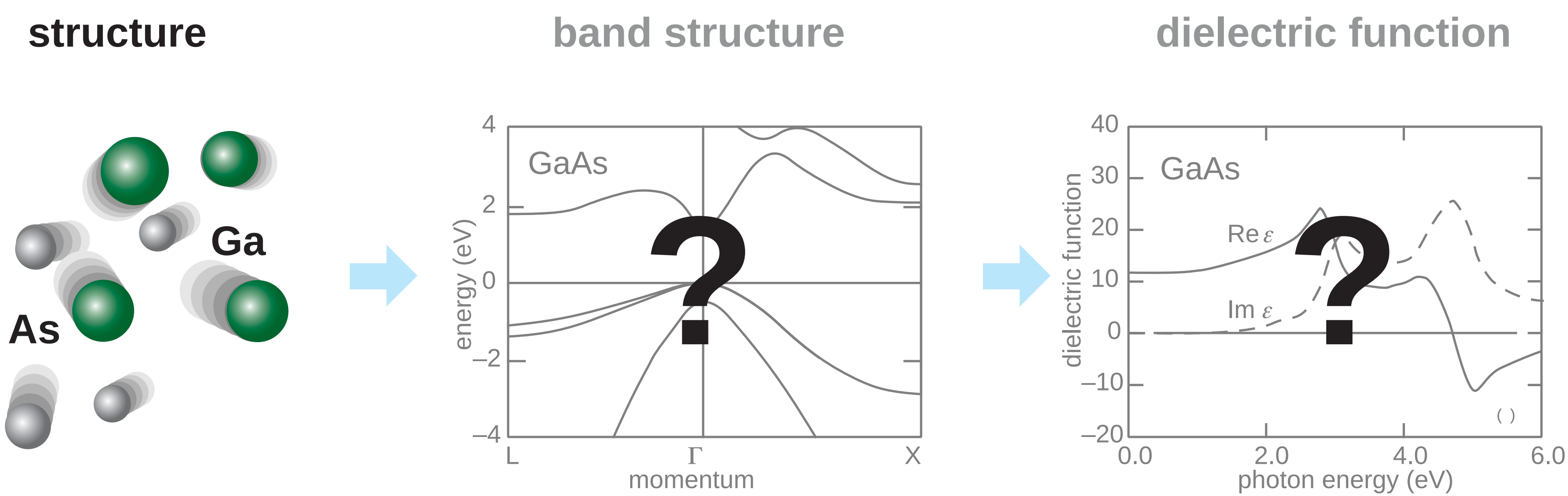
band structure



dielectric function

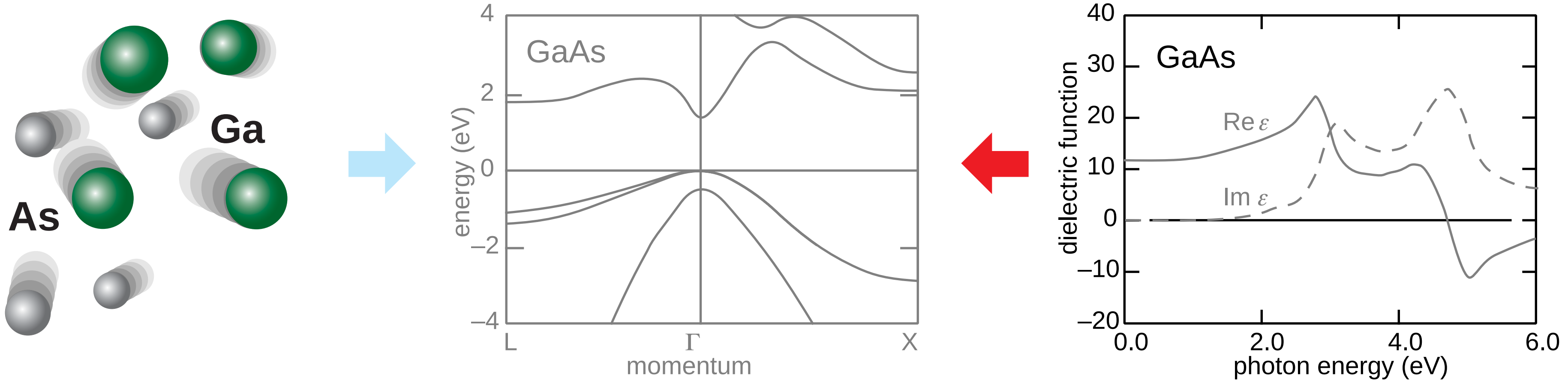


Introduction



Introduction

structure | **band structure** | **dielectric function**



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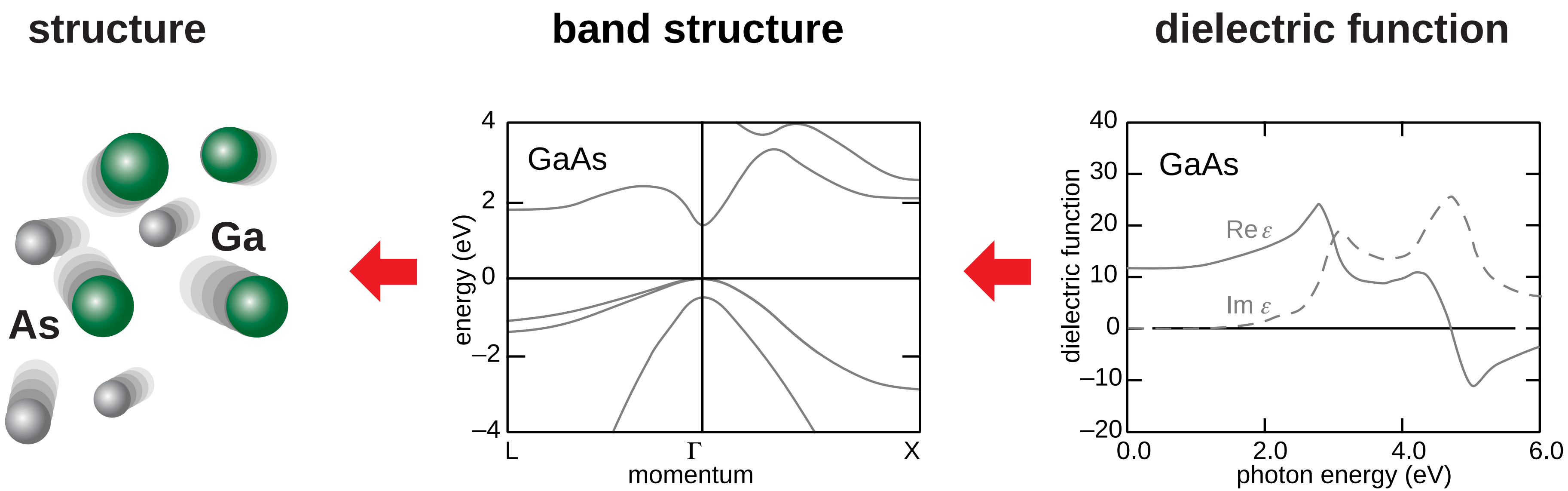
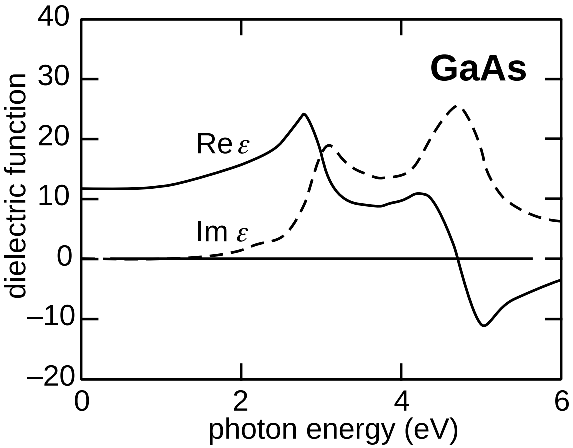


Introduction



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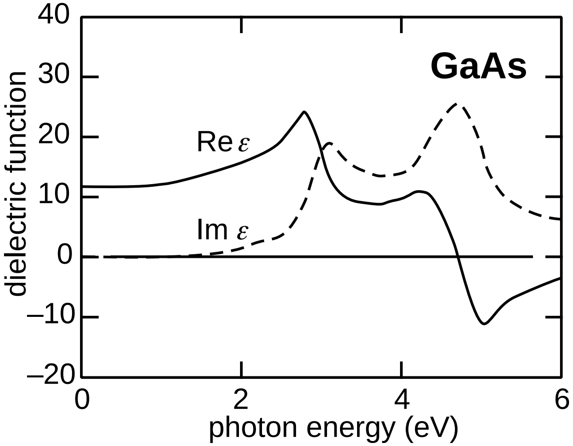
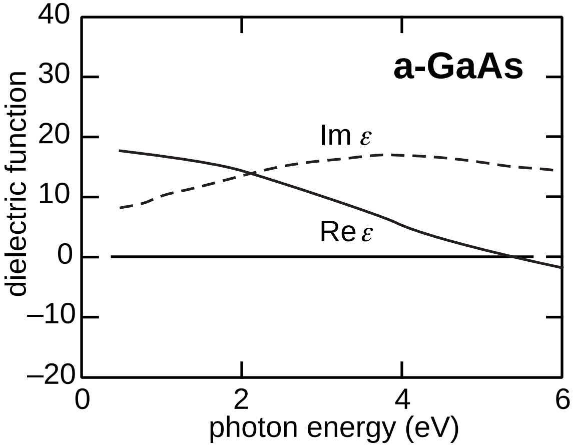
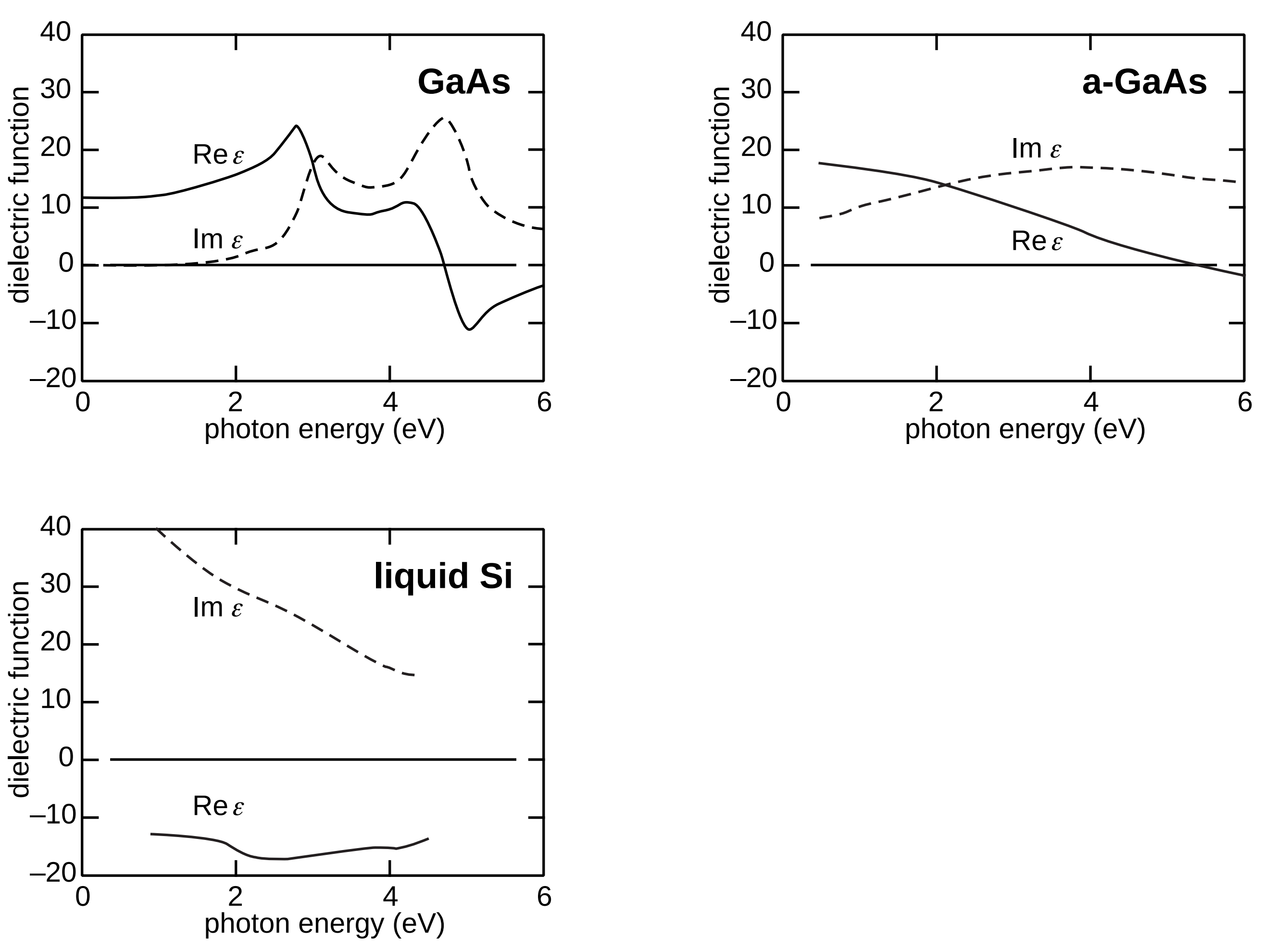




Introduction



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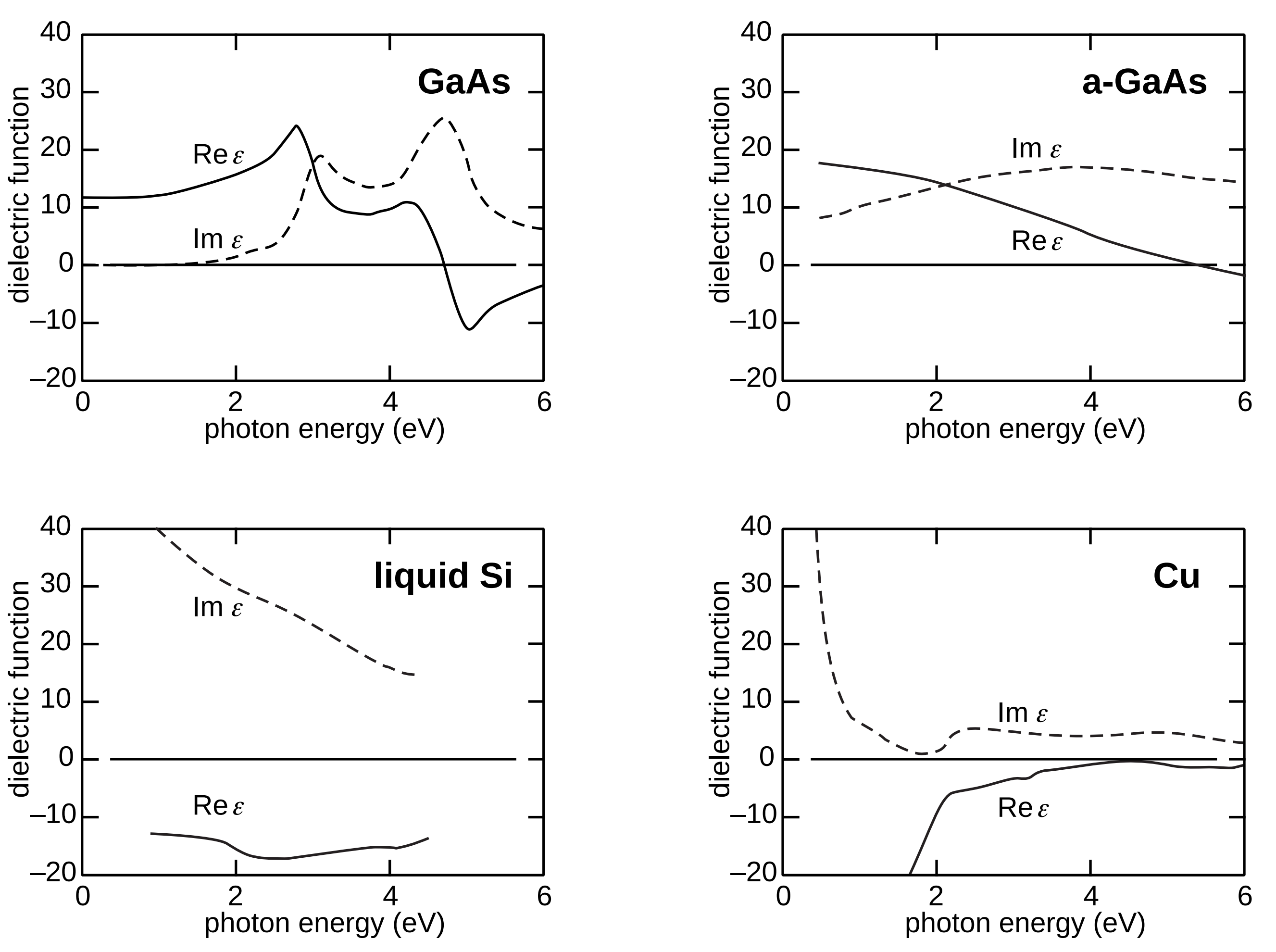
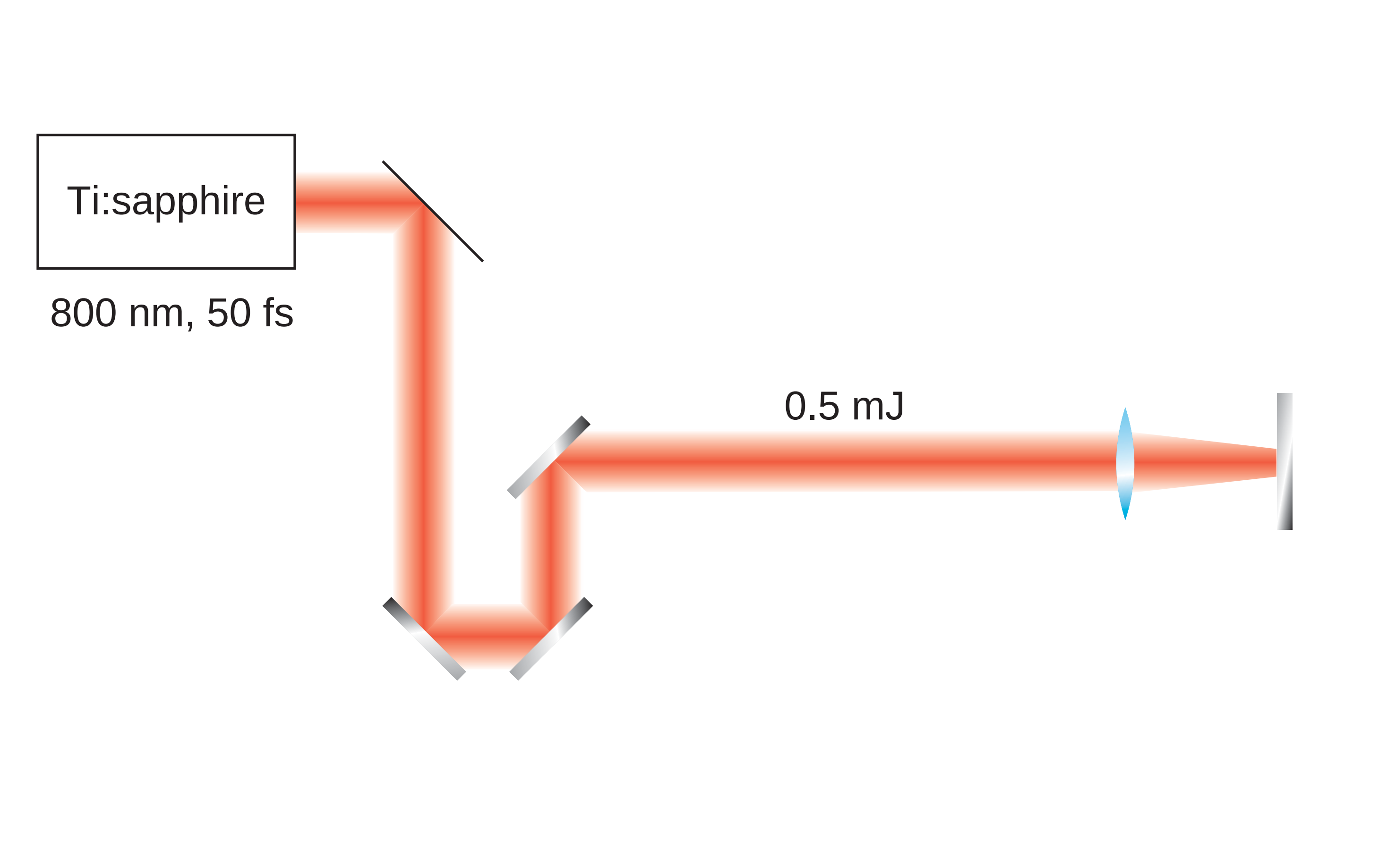


broadband time-resolved ellipsometry



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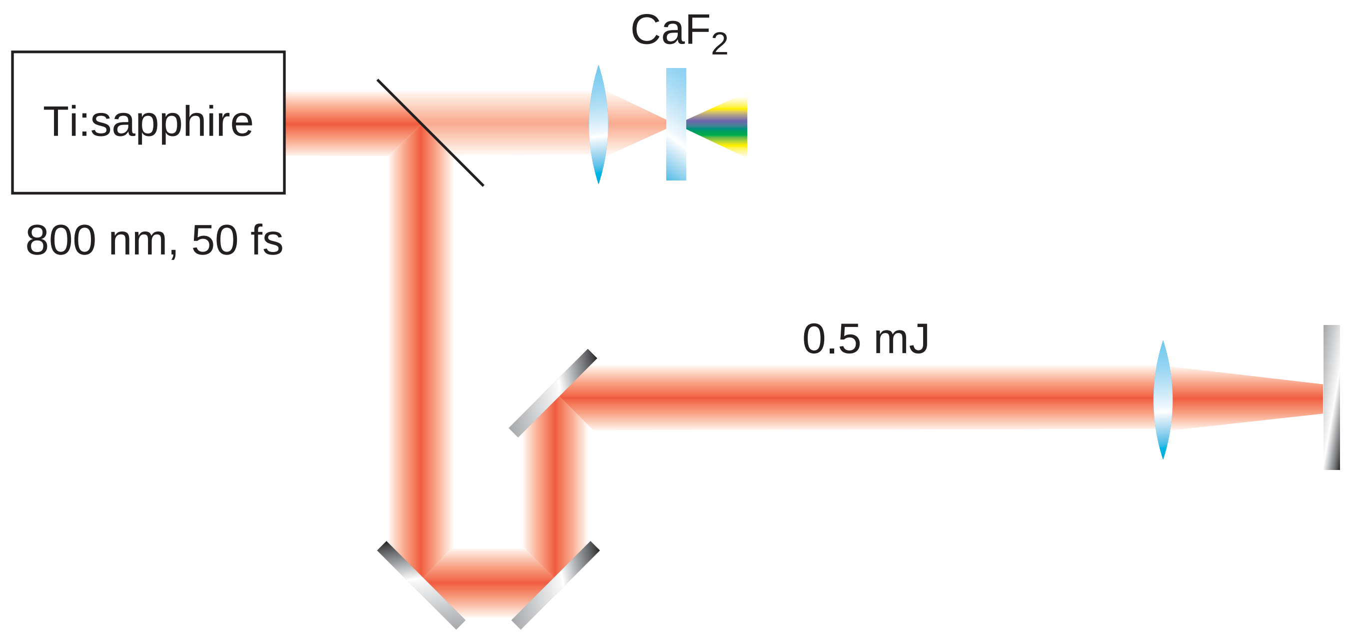
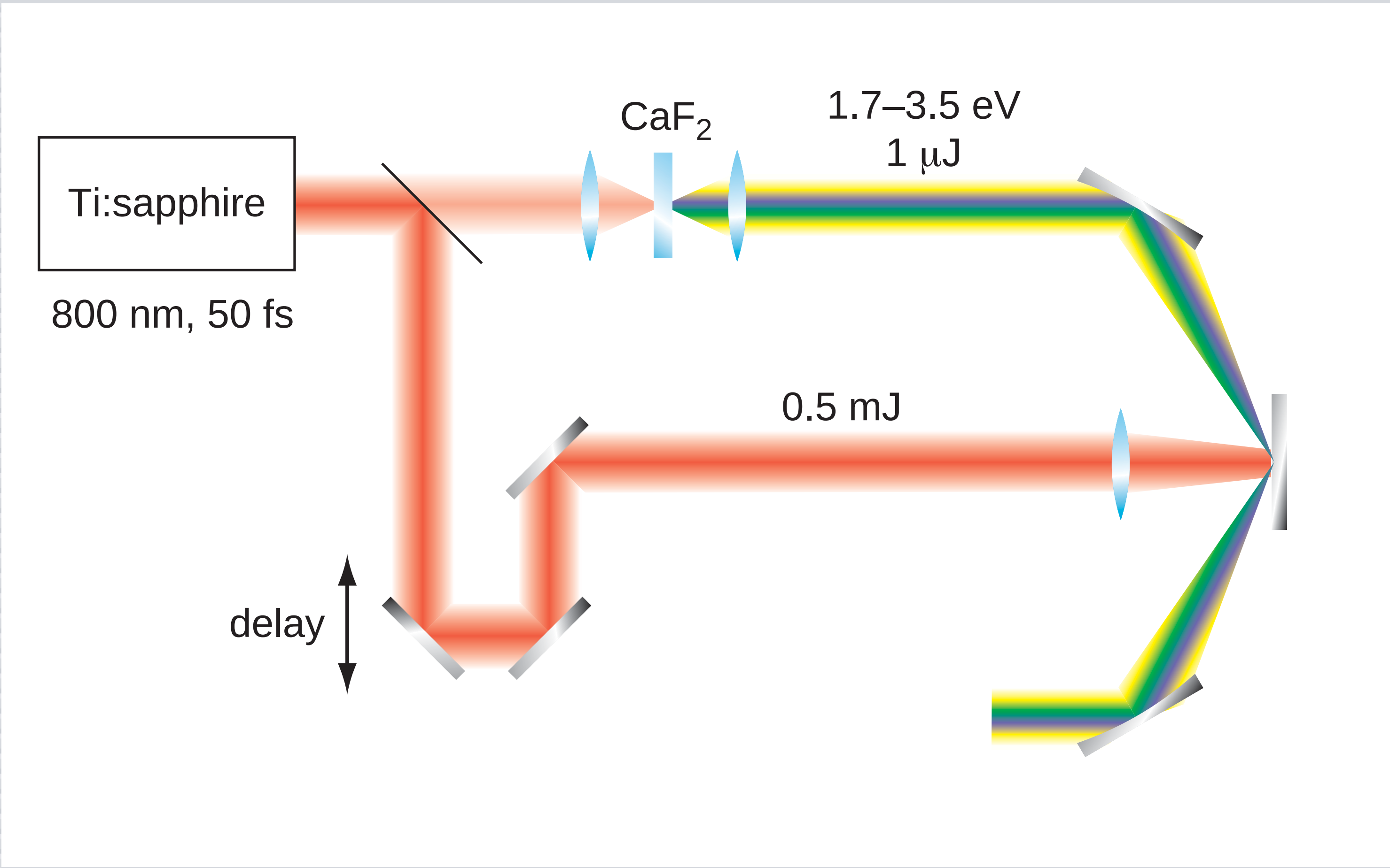
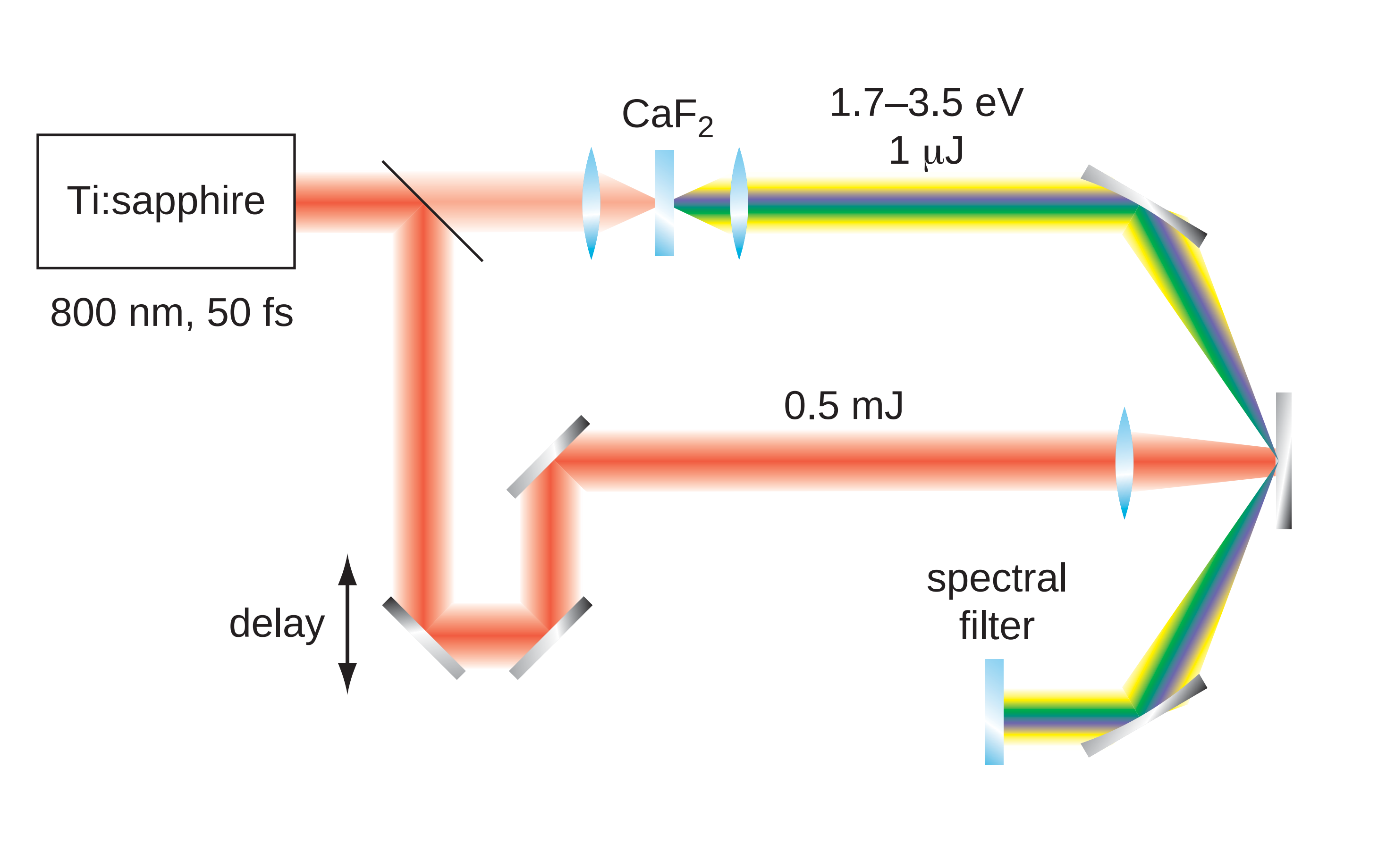


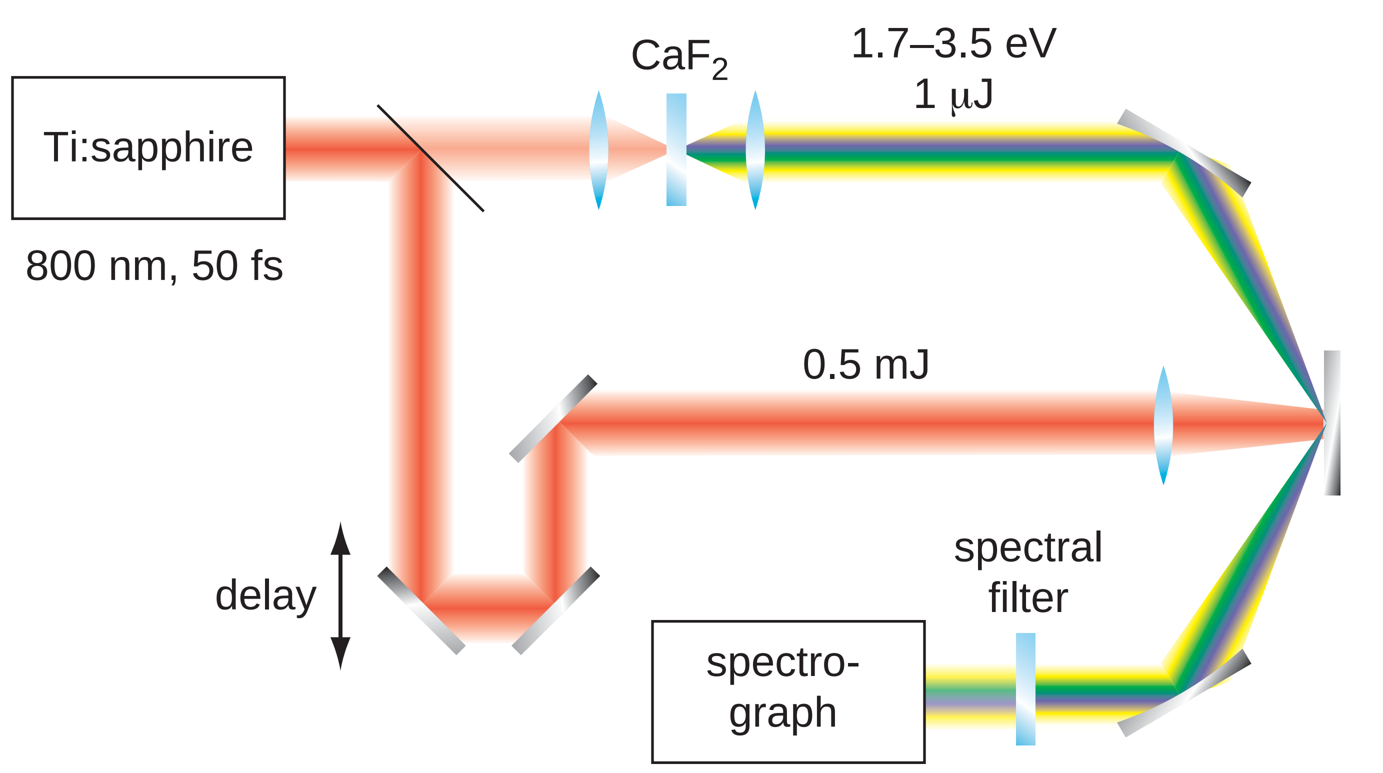
broadband time-resolved ellipsometry



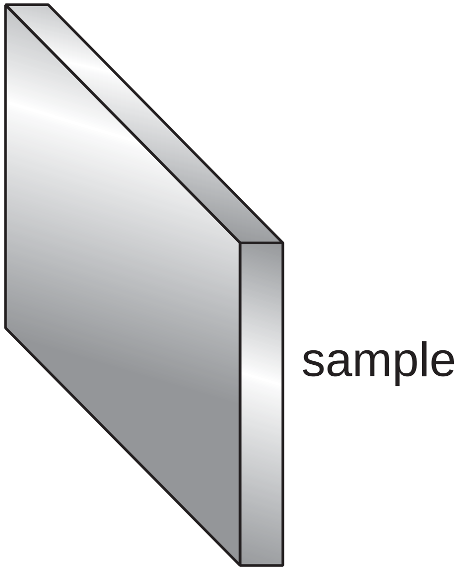
broadband time-resolved ellipsometry



broadband time-resolved ellipsometry

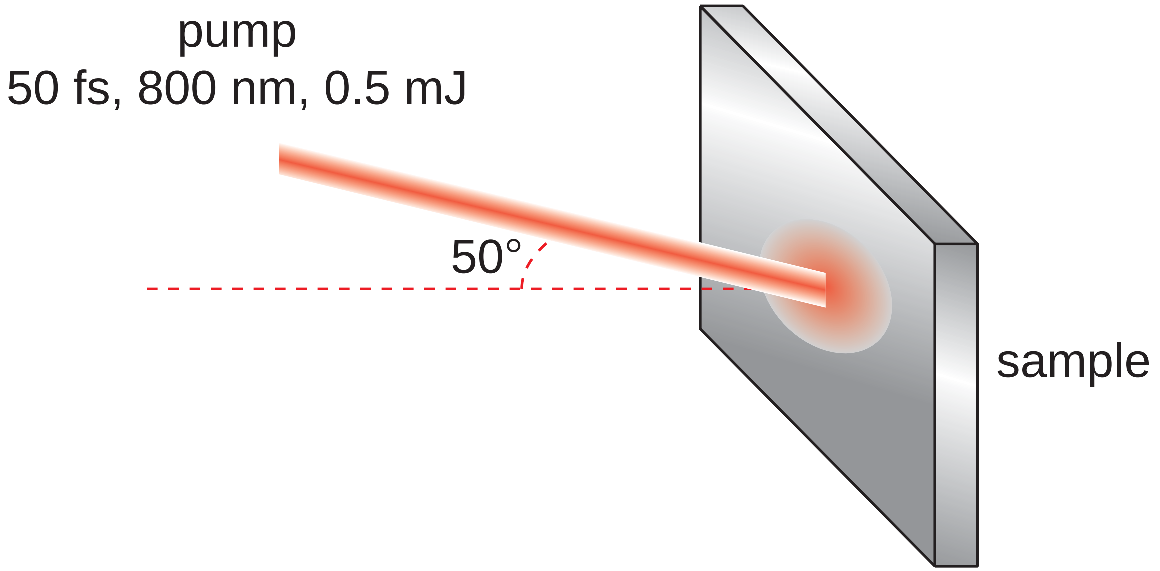


broadband time-resolved ellipsometry

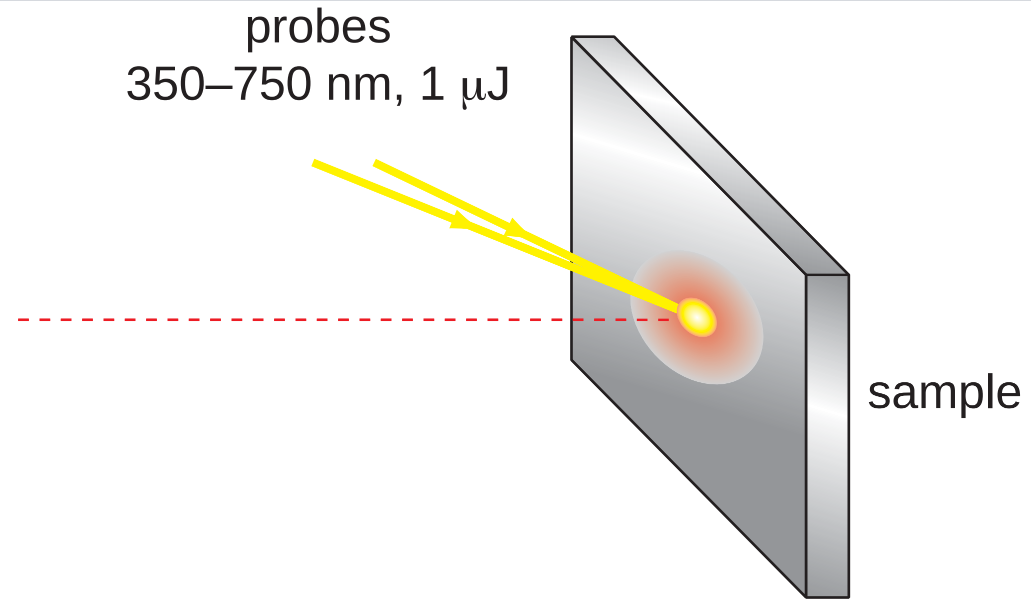


Technique

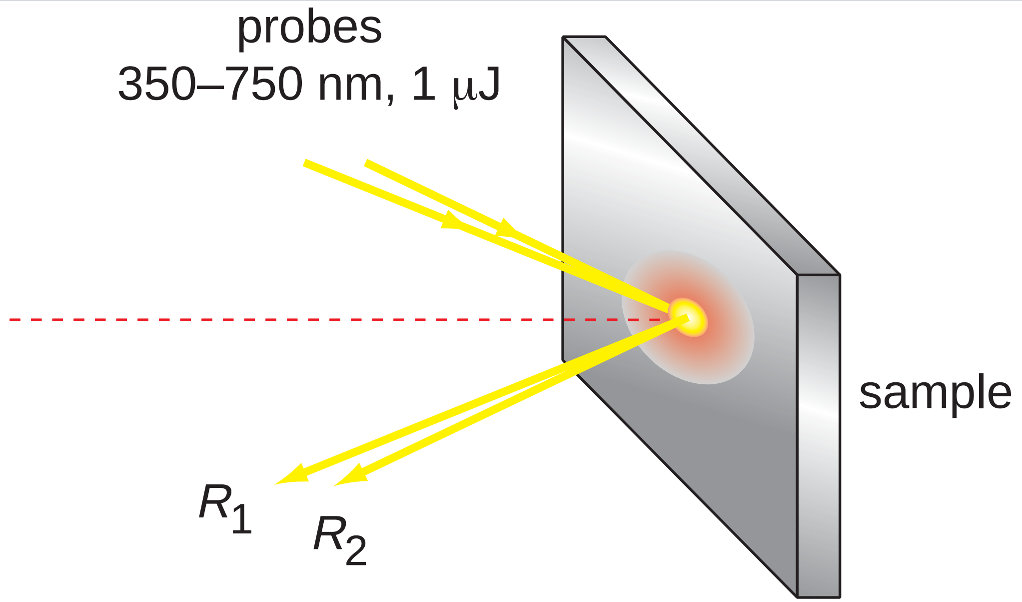
broadband time-resolved ellipsometry



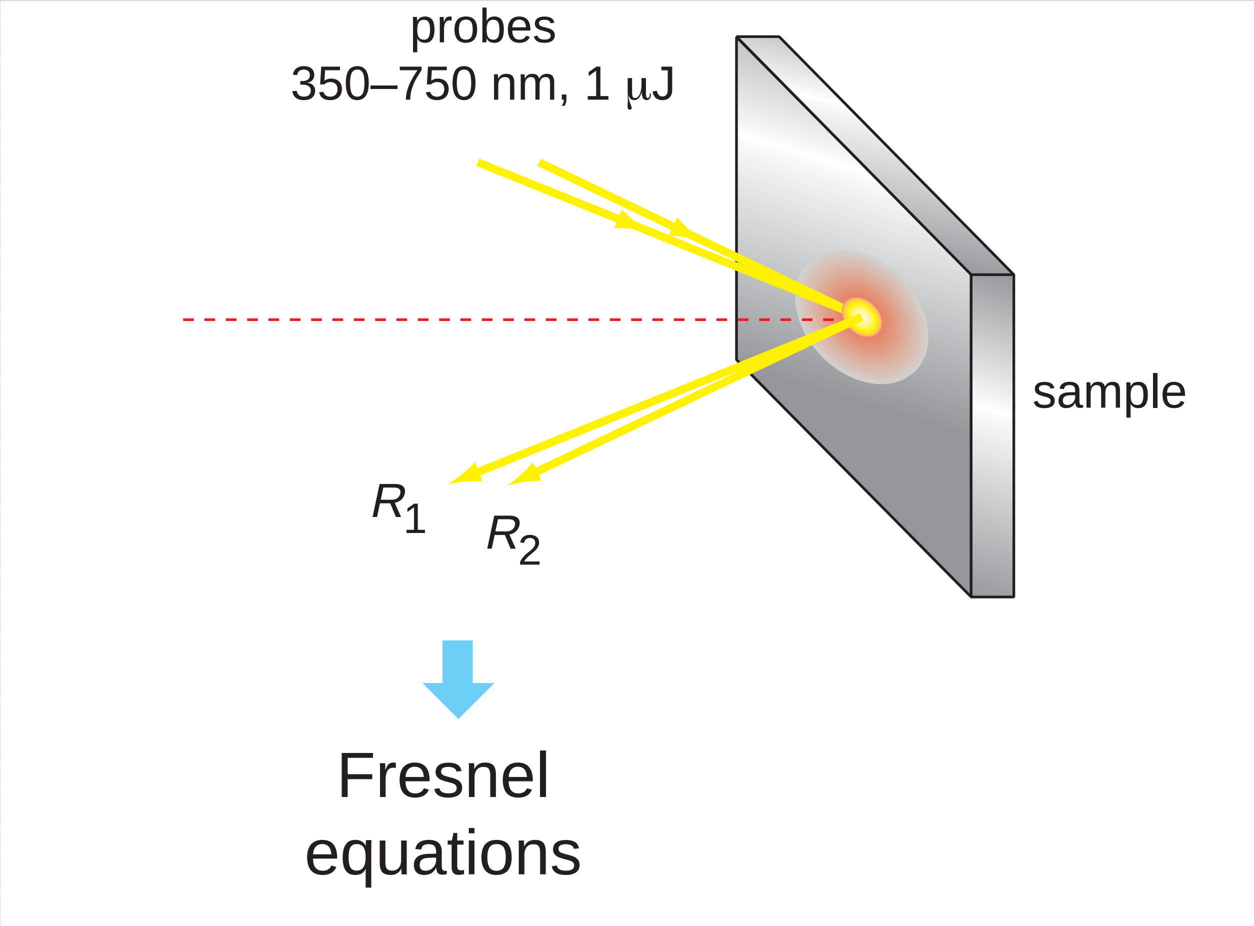
broadband time-resolved ellipsometry



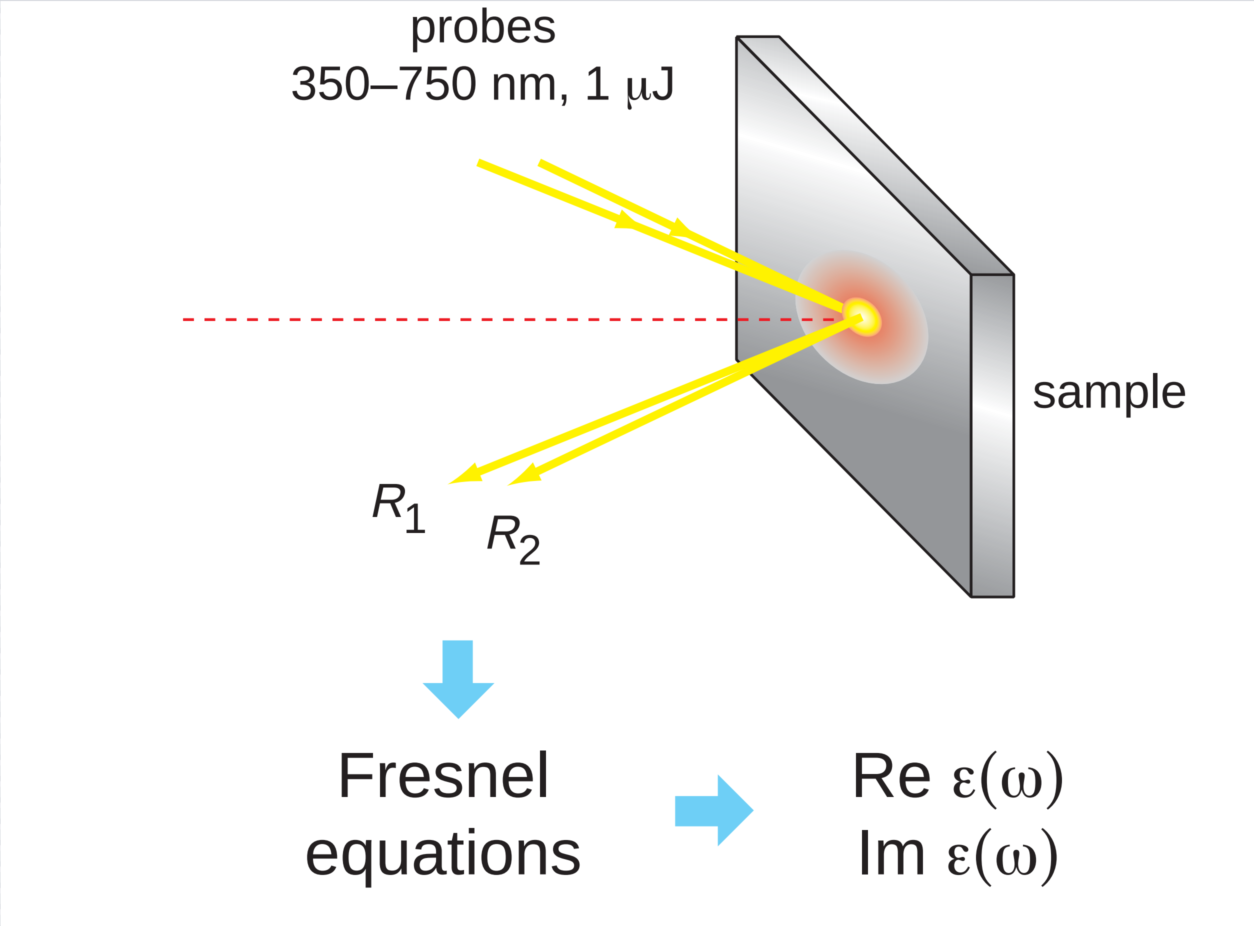
broadband time-resolved ellipsometry



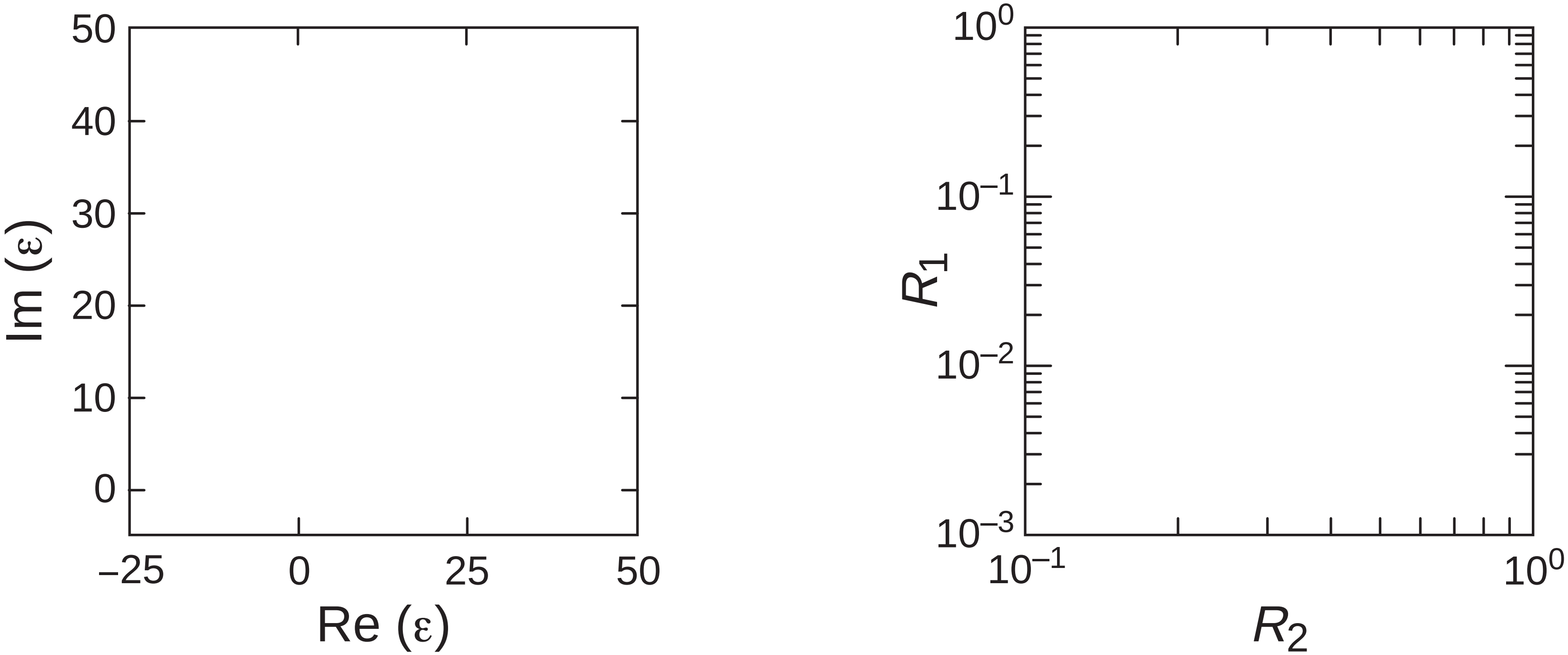
broadband time-resolved ellipsometry



broadband time-resolved ellipsometry

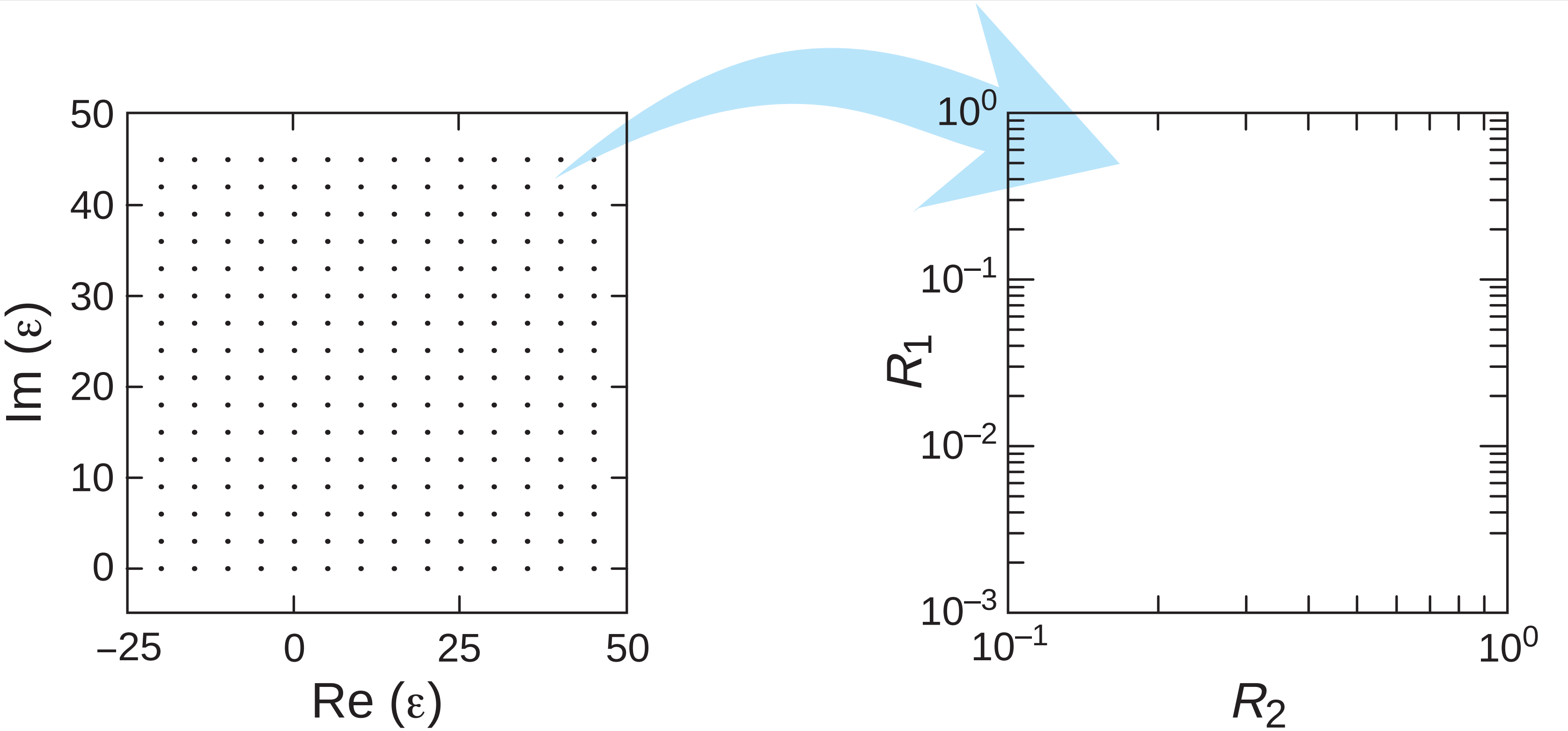


choice of angles



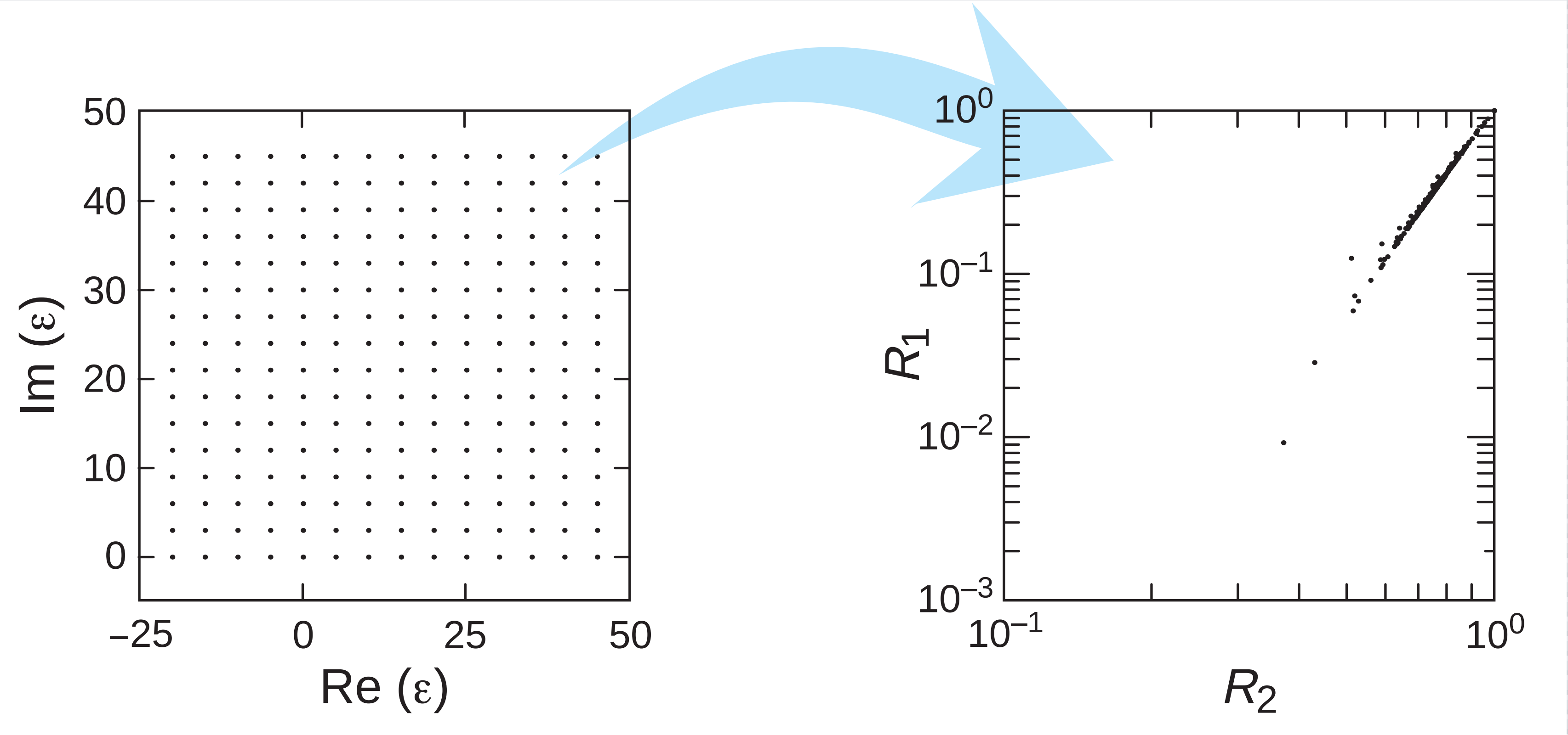
Fresnel equations cannot be inverted analytically

choice of angles



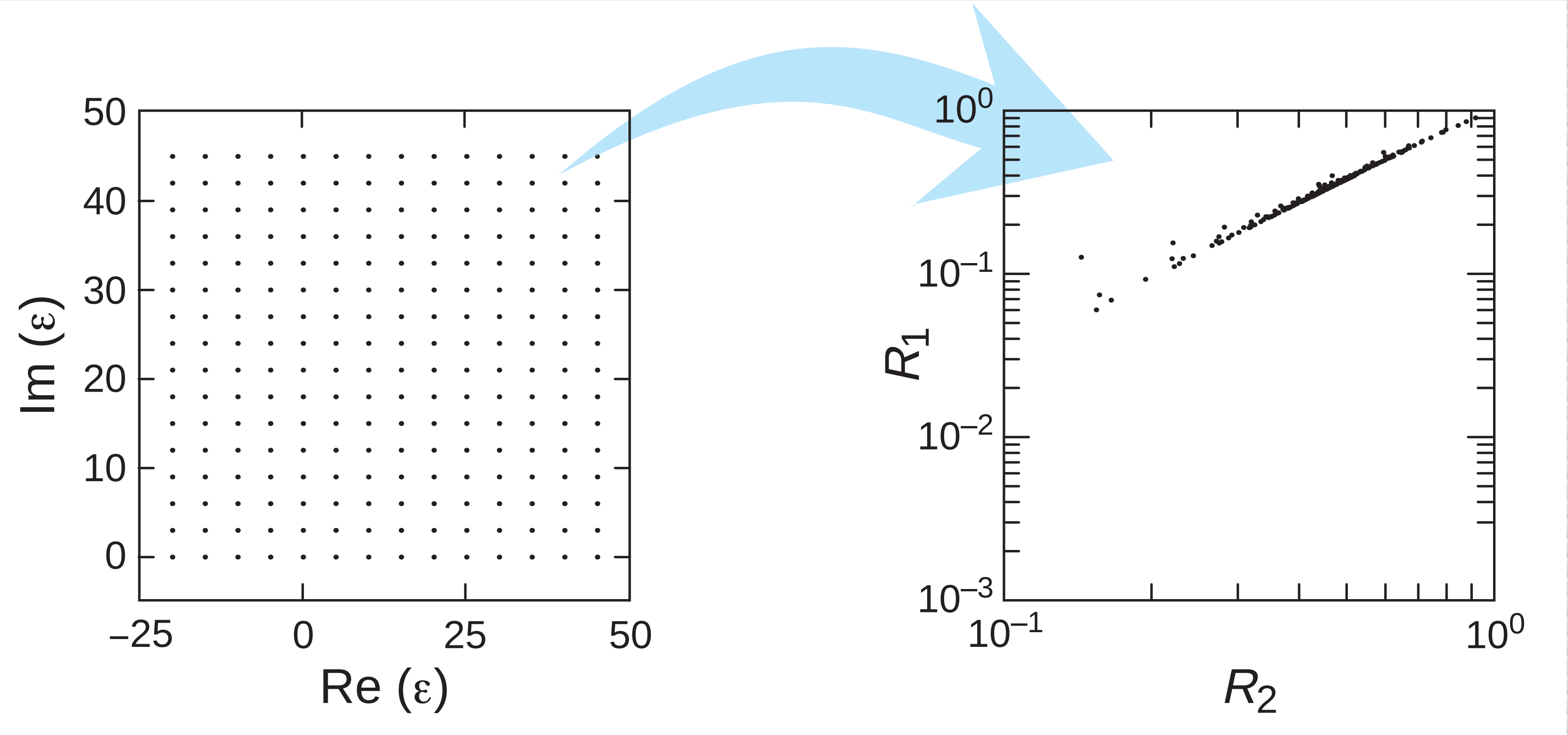
need numerical inversion

choice of angles



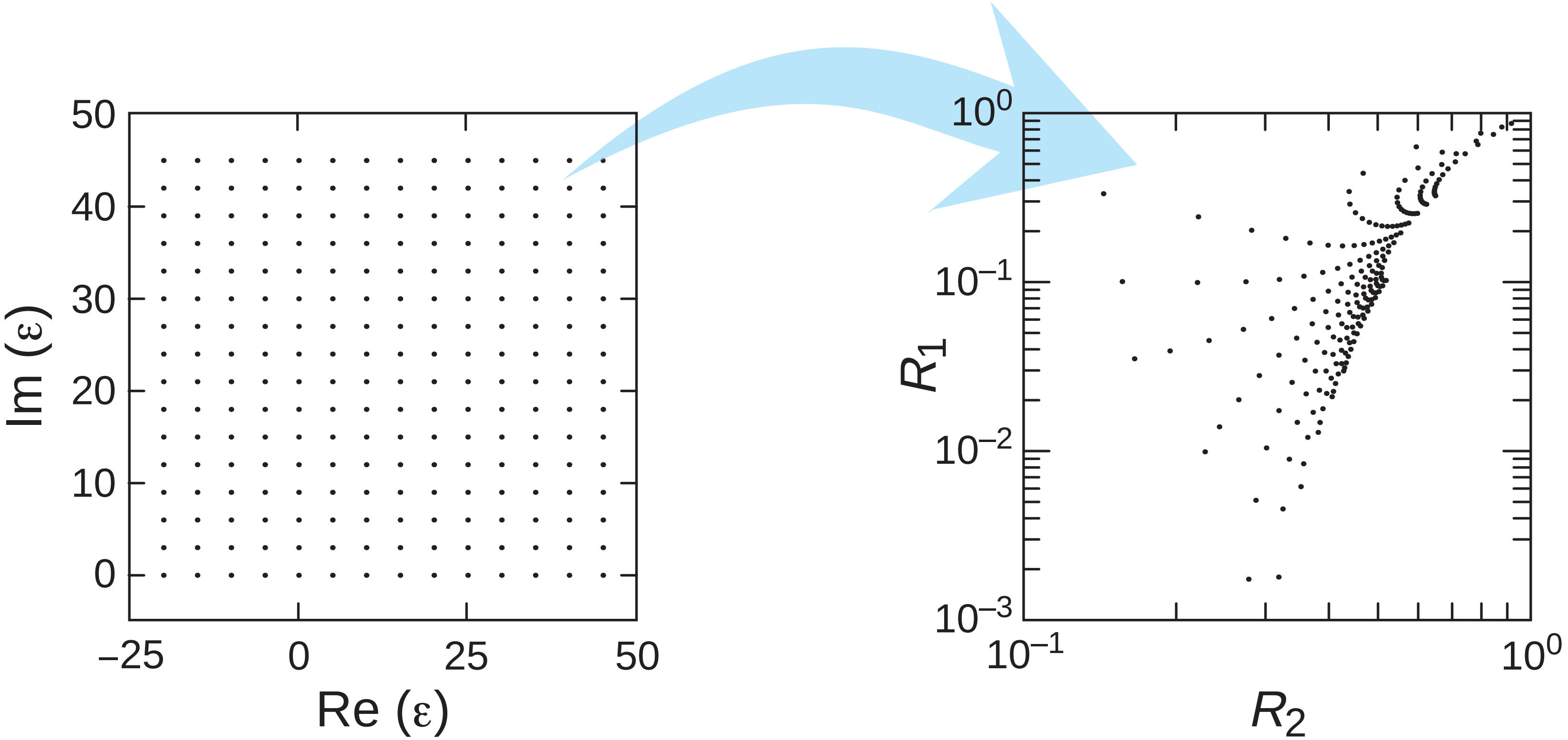
R_1 = 45° *p*-pol, R_2 = 45° *s*-pol

choice of angles



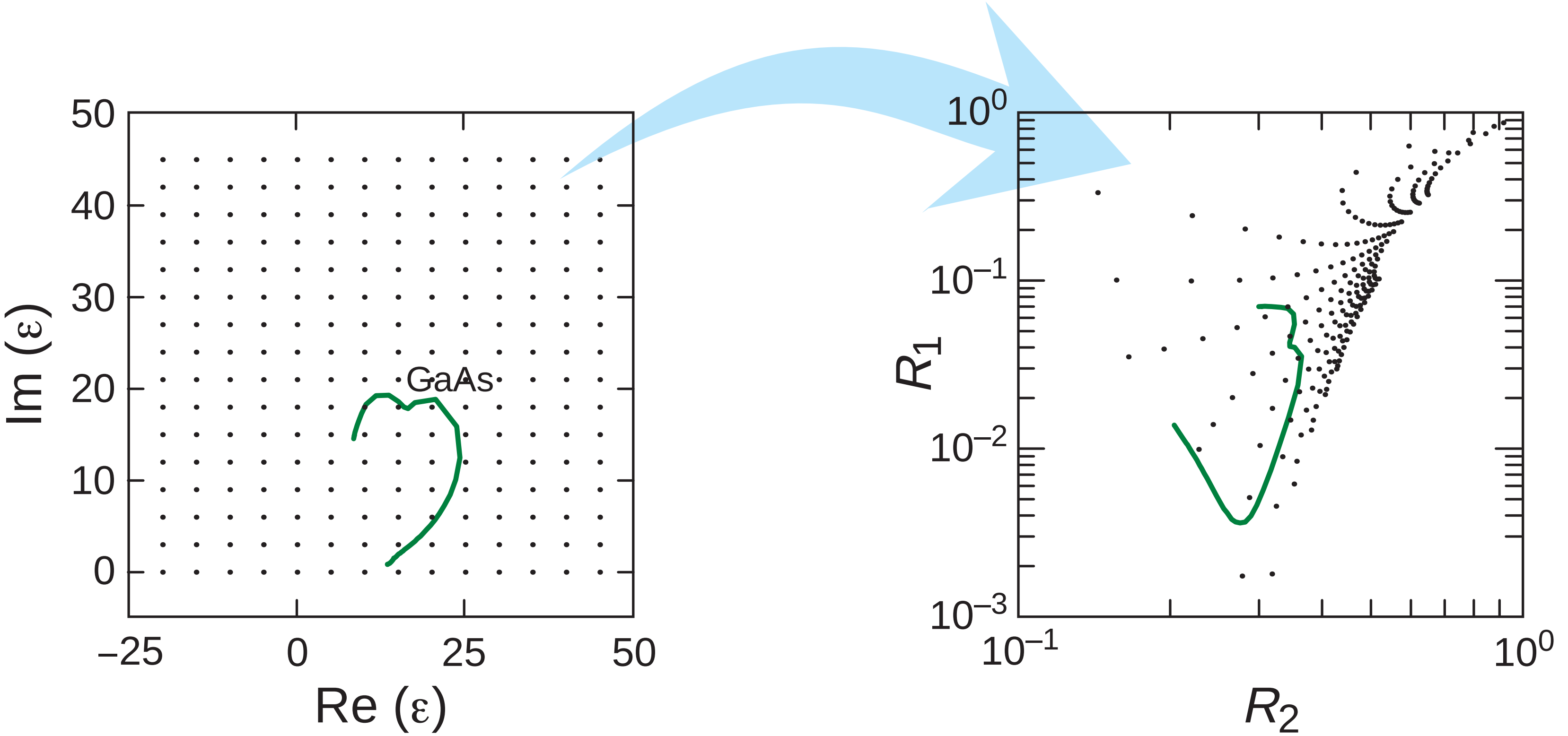
R_1 = 60° *p*-pol, R_2 = 45° *p*-pol

choice of angles



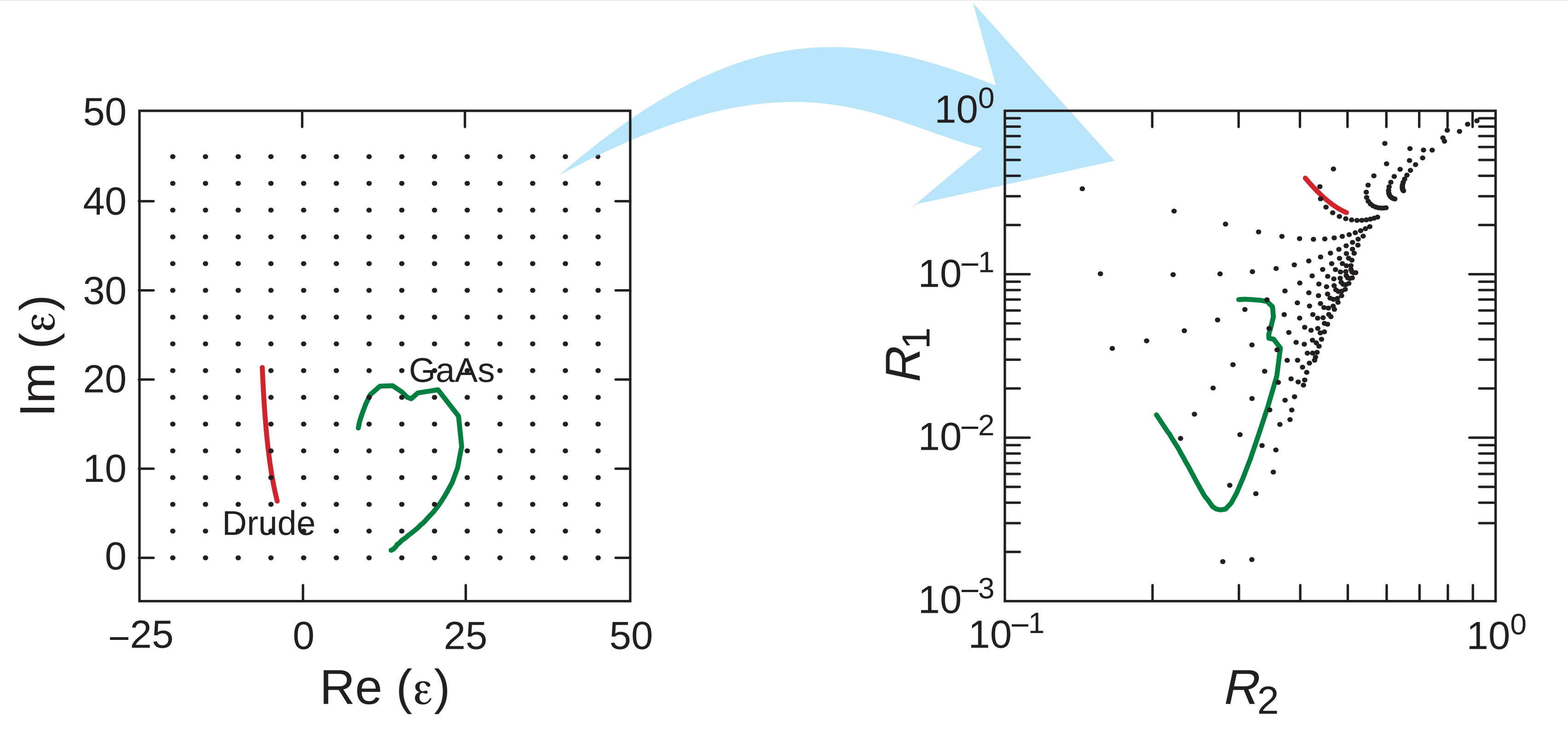
R_1 = 78° *p*-pol, R_2 = 45° *p*-pol

choice of angles



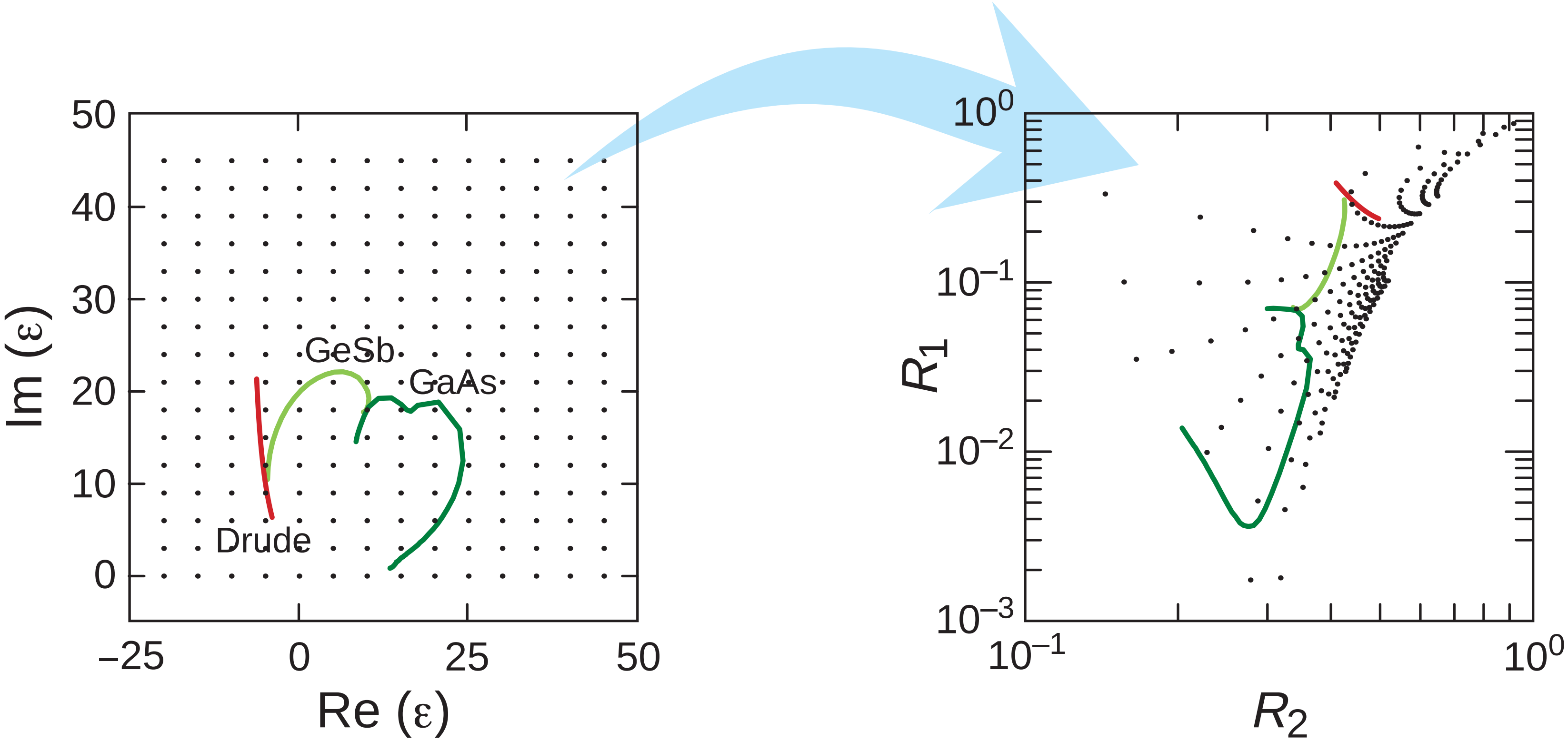
R_1 = 78° *p*-pol, R_2 = 45° *p*-pol

choice of angles



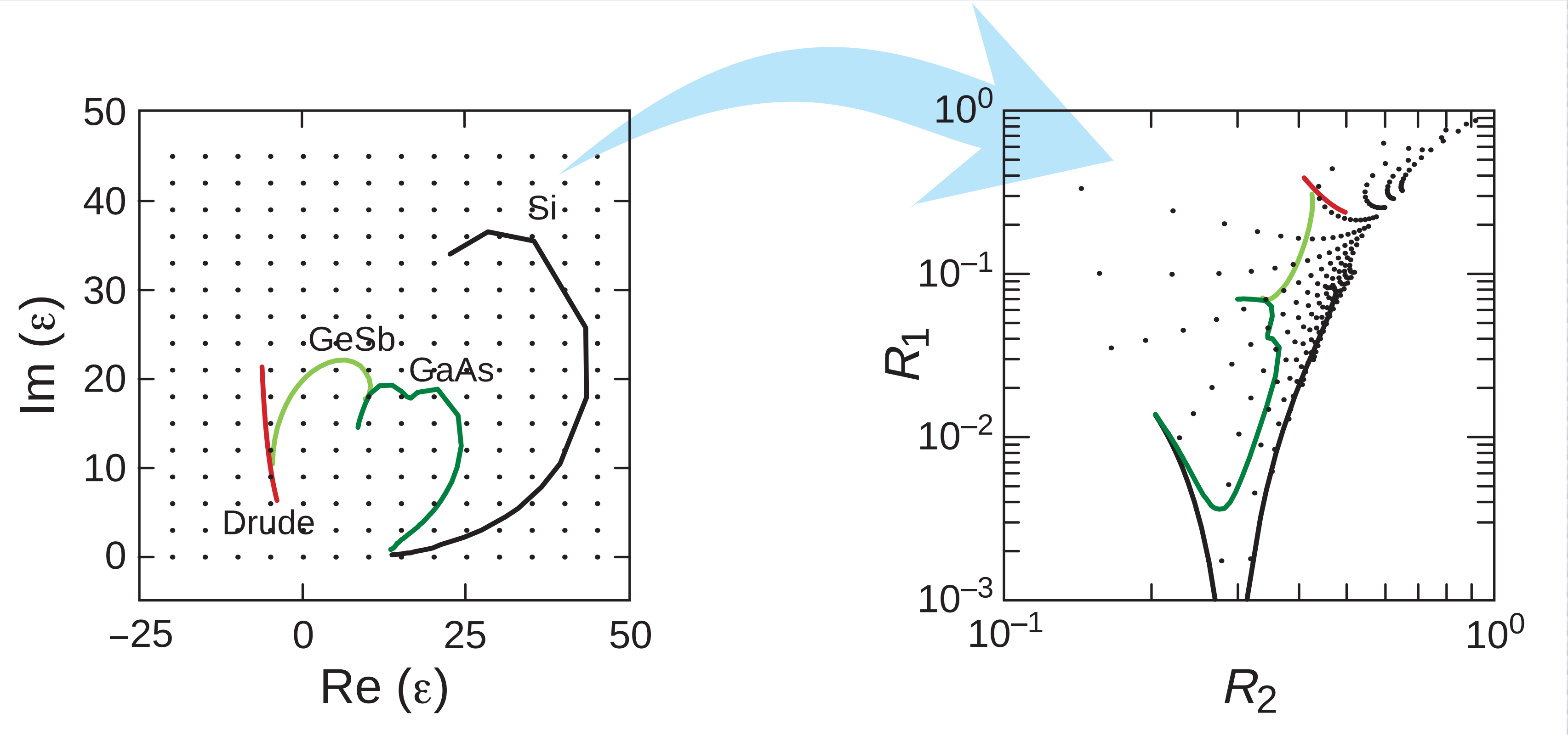
R_1 = 78° *p*-pol, R_2 = 45° *p*-pol

choice of angles



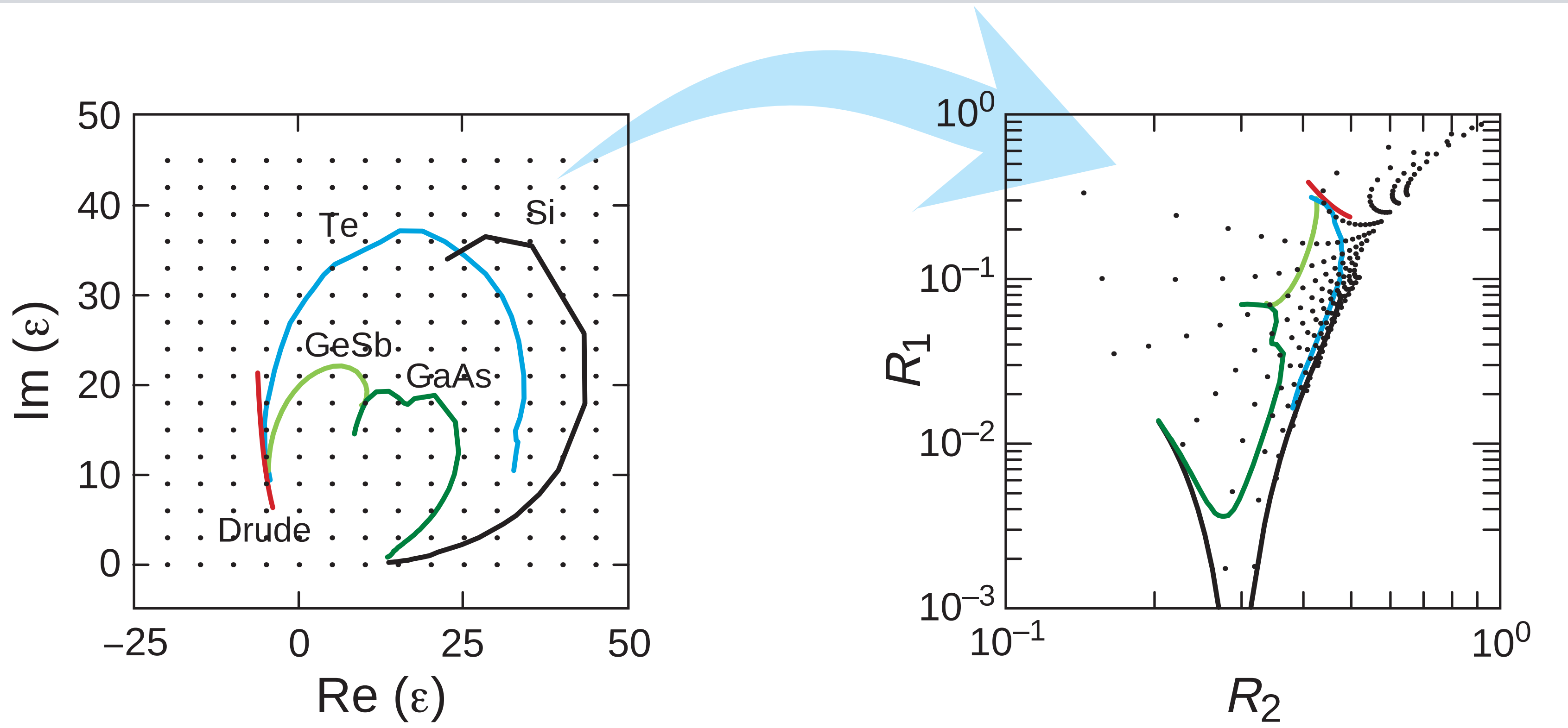
R_1 = 78° *p*-pol, R_2 = 45° *p*-pol

choice of angles



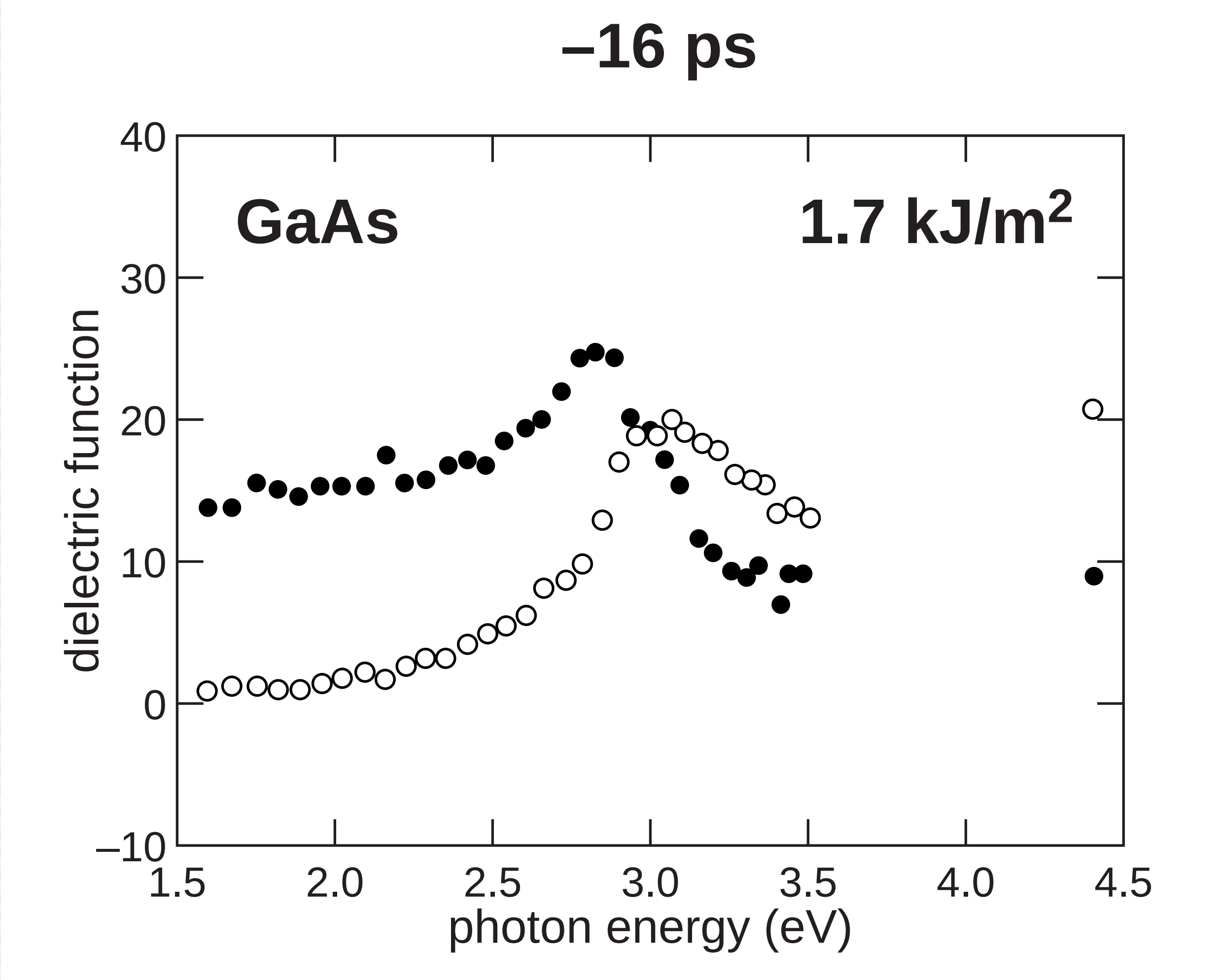
R_1 = 78° *p*-pol, R_2 = 45° *p*-pol

choice of angles



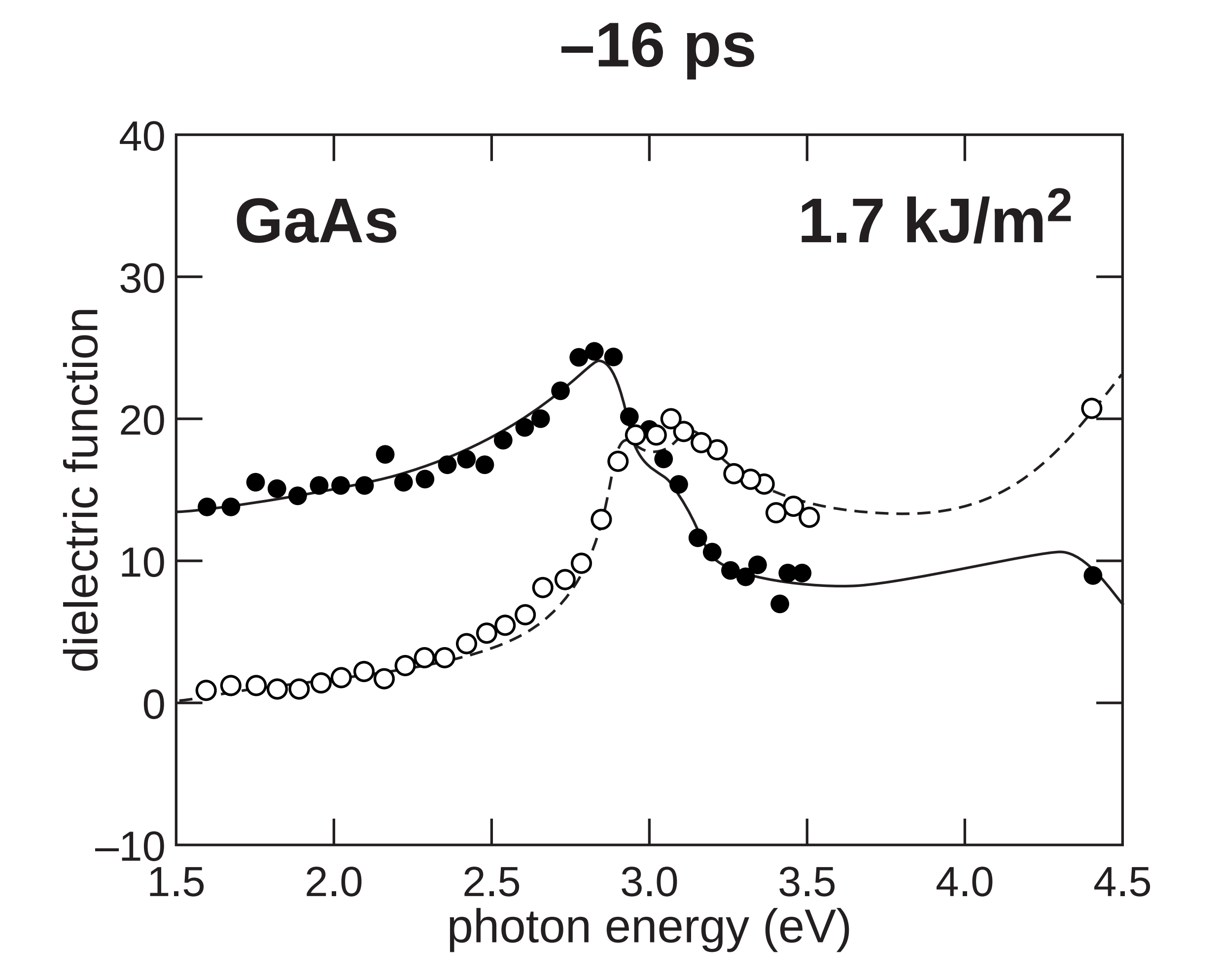
R_1 = 78° *p*-pol, R_2 = 45° *p*-pol

Technique



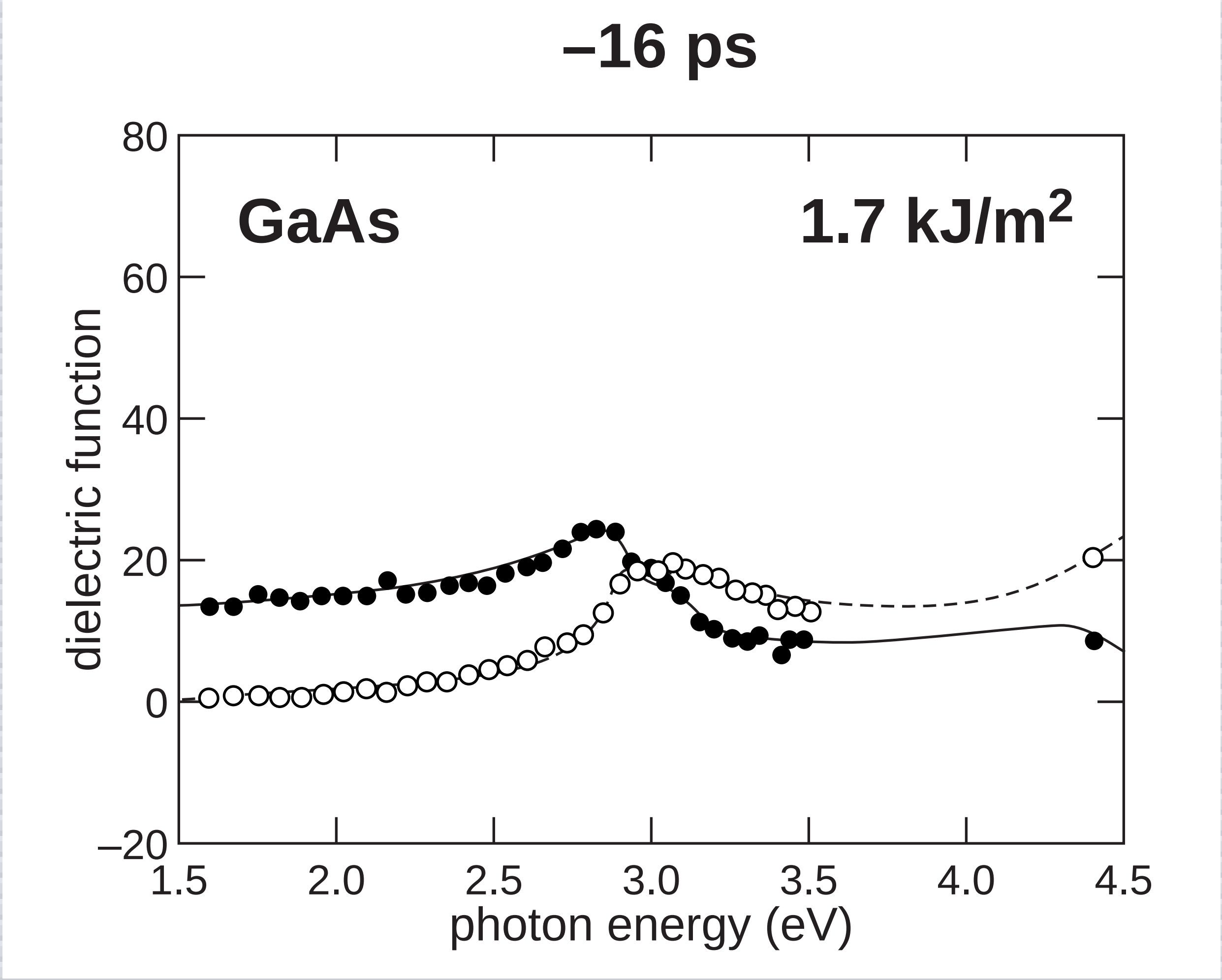
Phys. Rev. Lett. 80, 185 (1998)

Technique



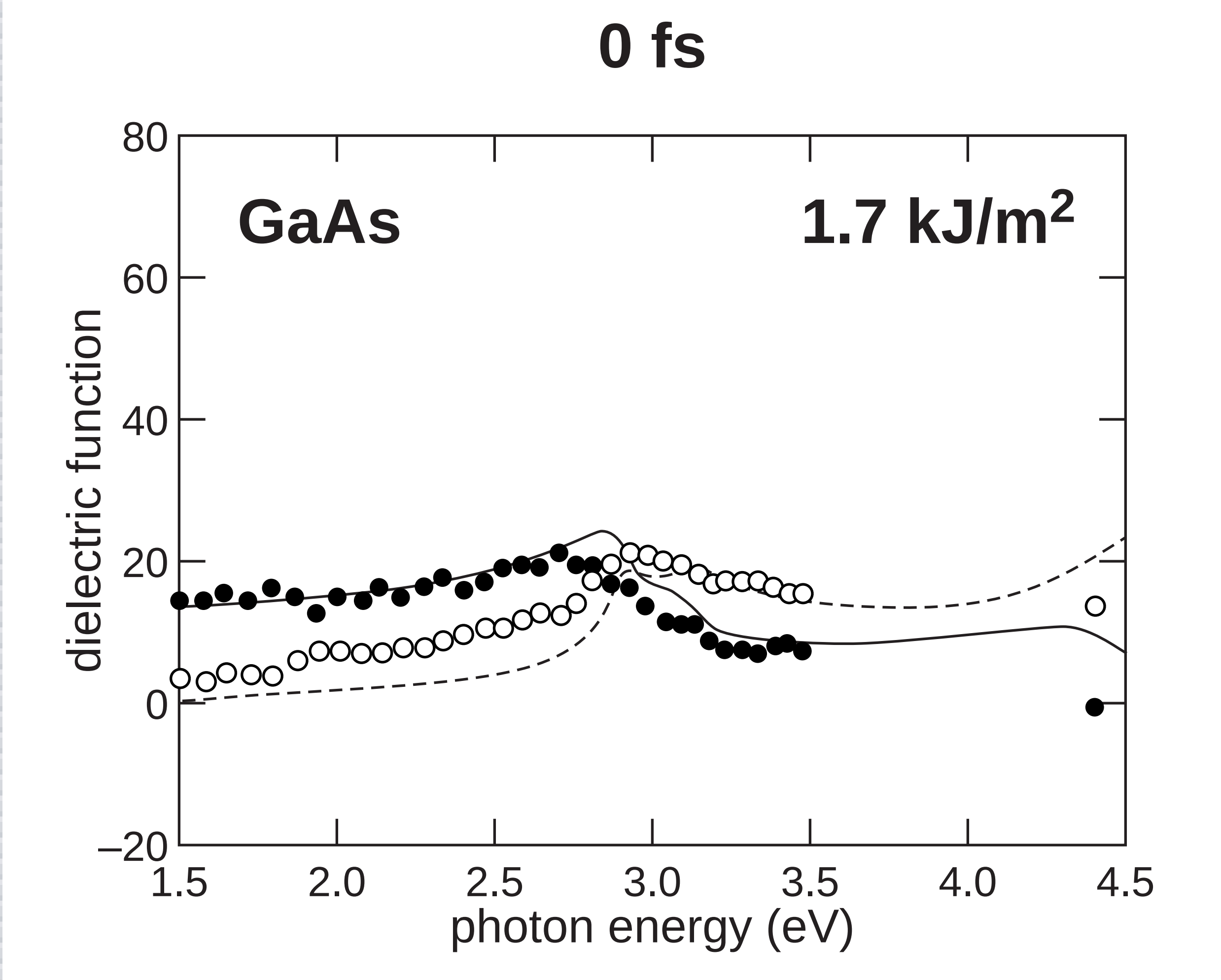
Phys. Rev. Lett. 80, 185 (1998)

Technique



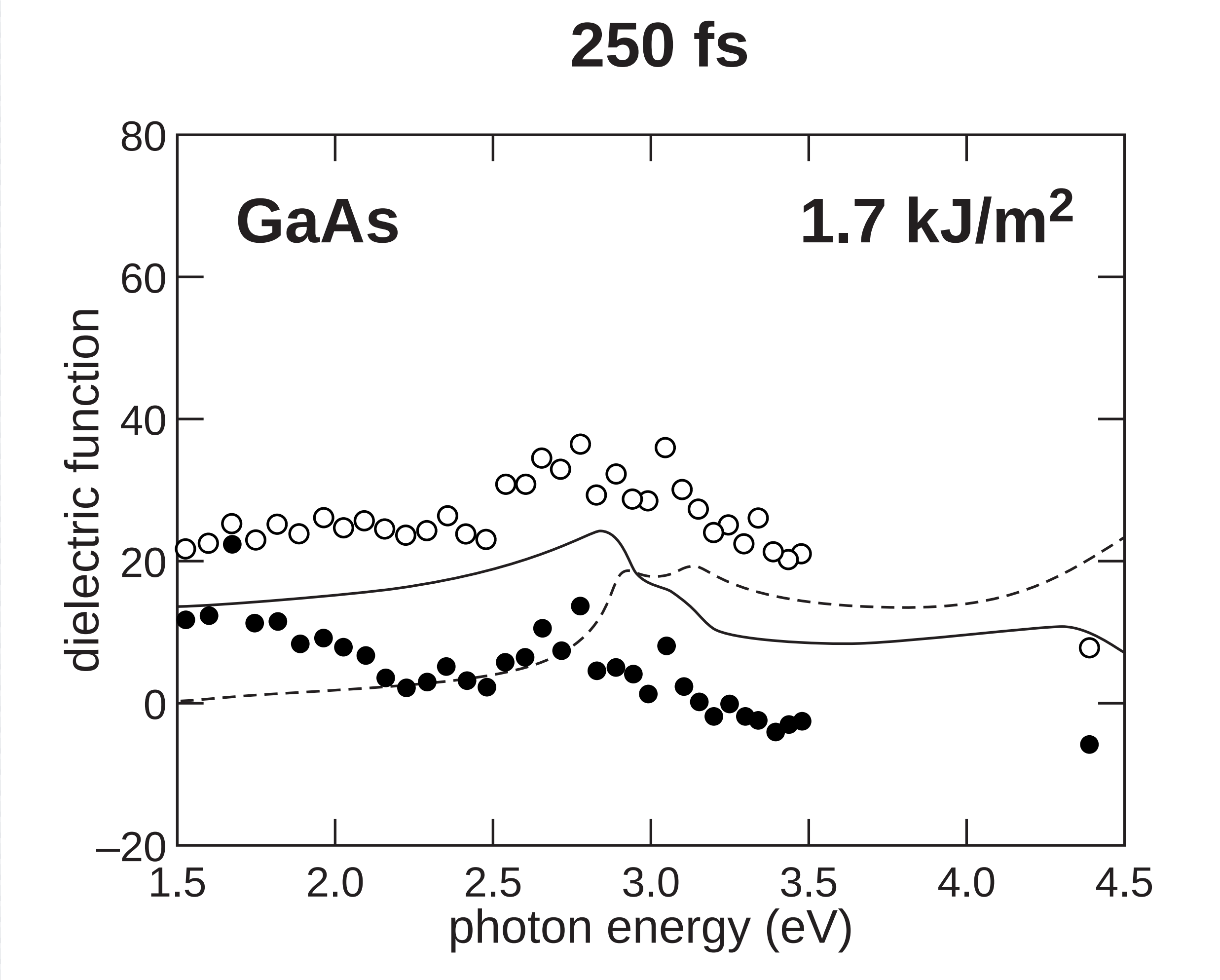
***Phys. Rev. Lett.* 80, 185 (1998)**

Technique



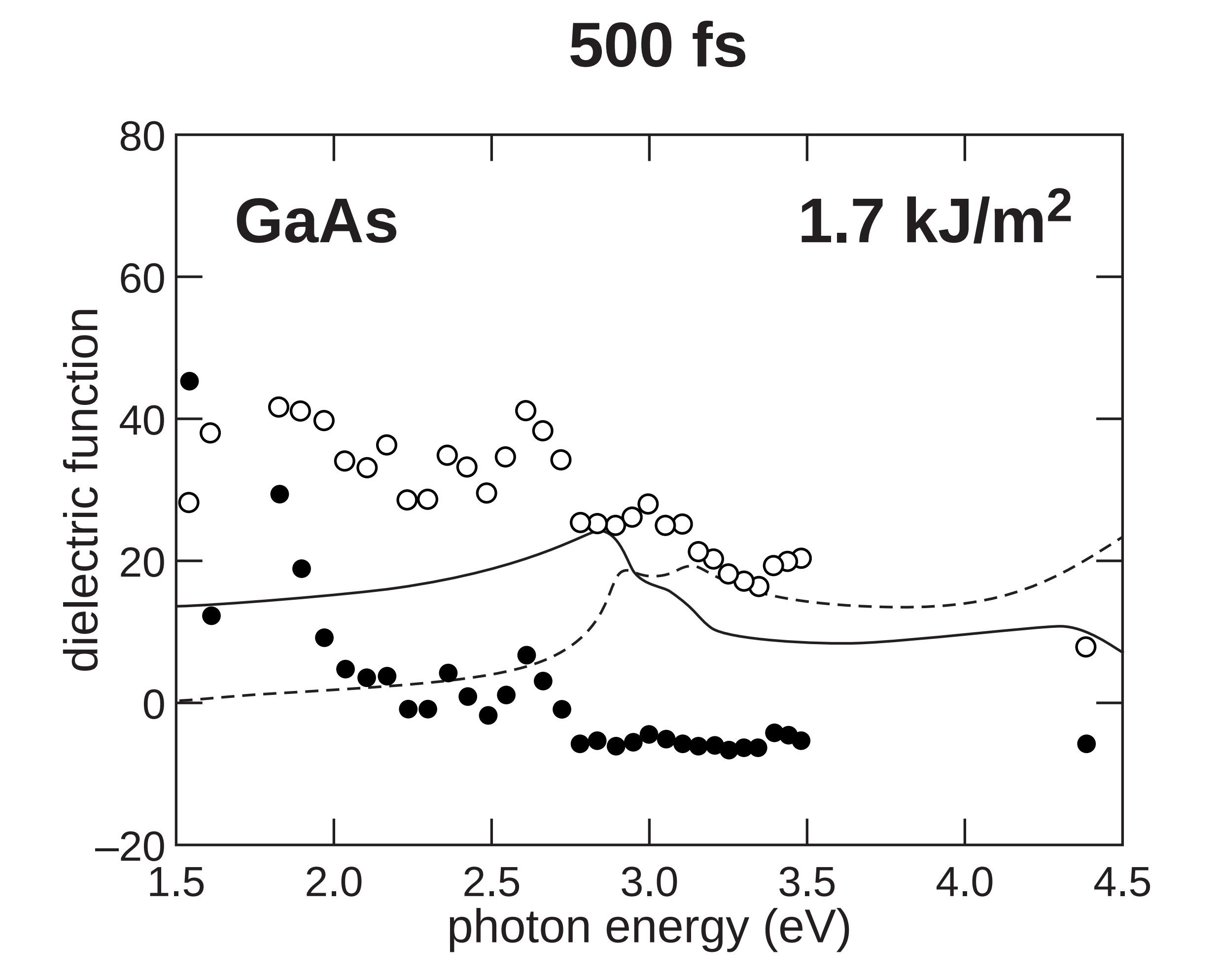
***Phys. Rev. Lett.* 80, 185 (1998)**

Technique



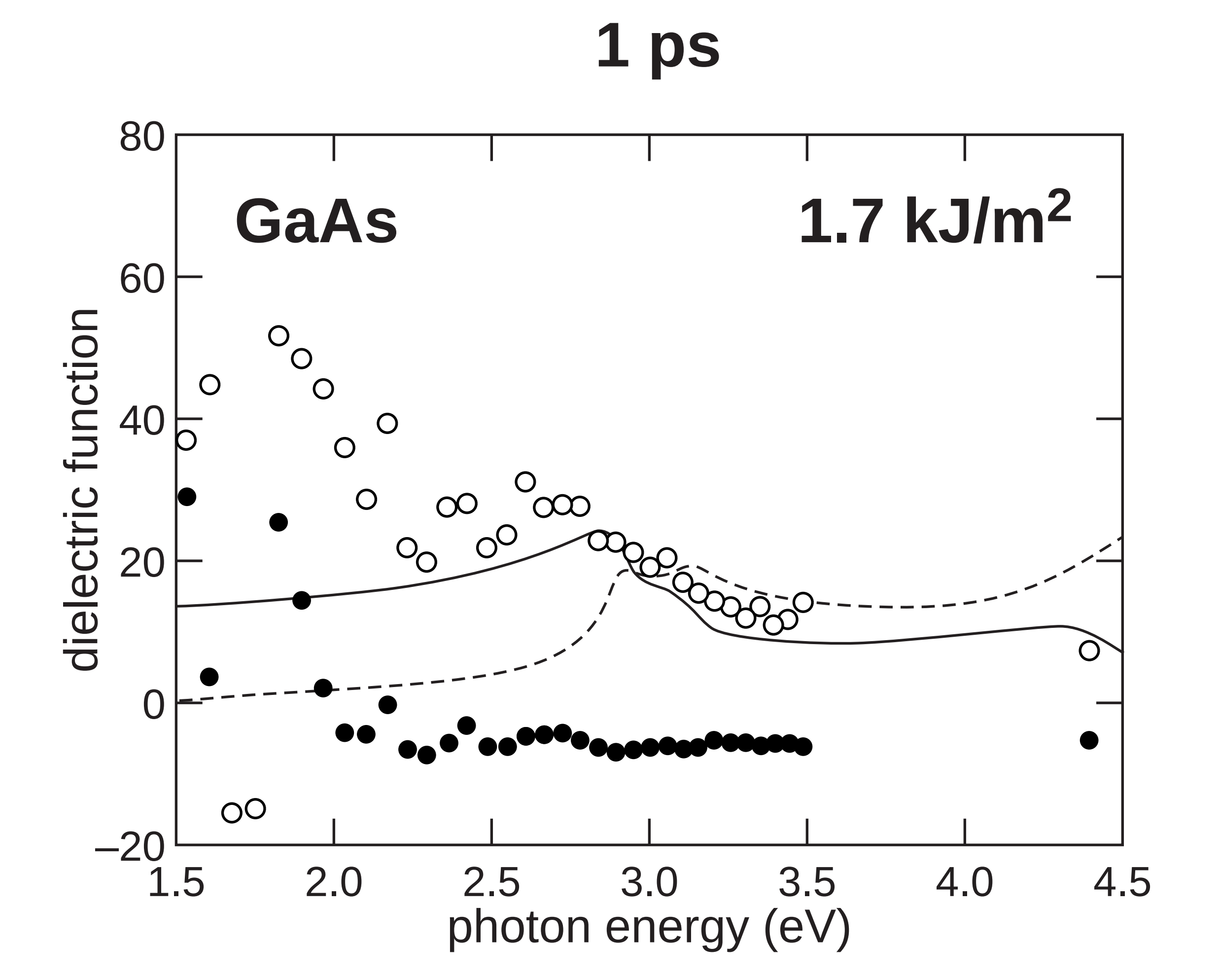
Phys. Rev. Lett. 80, 185 (1998)

Technique



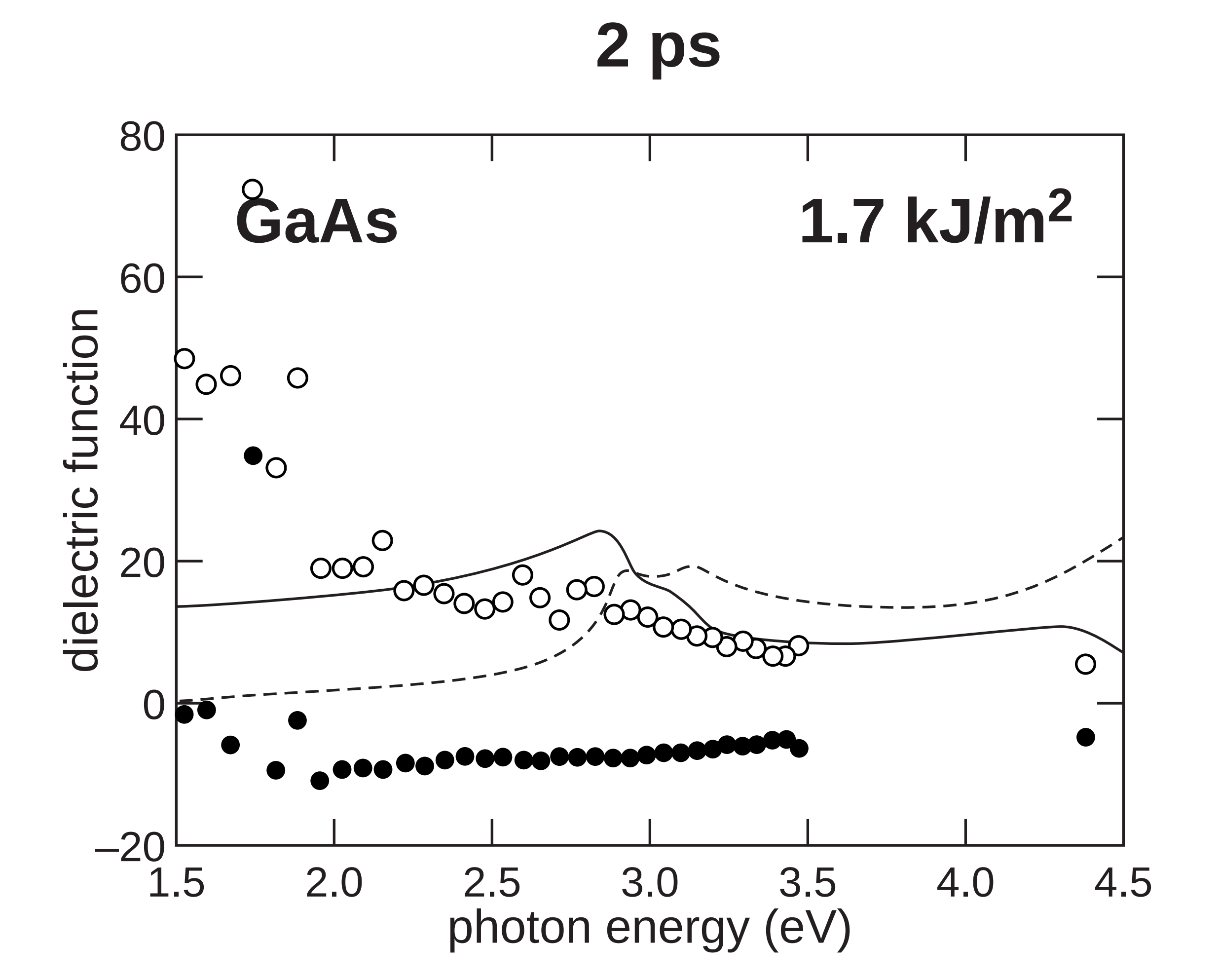
Phys. Rev. Lett. 80, 185 (1998)

Technique



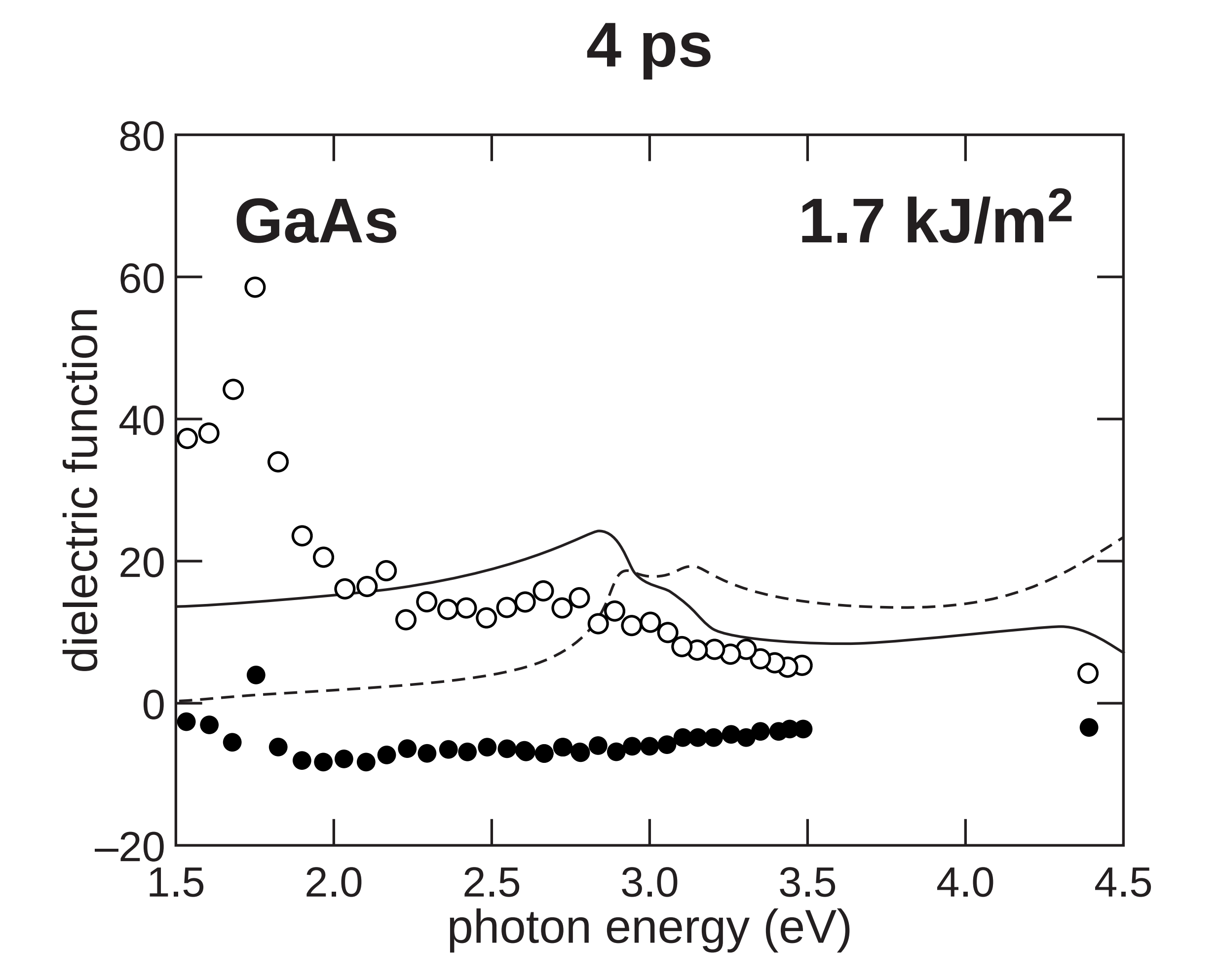
Phys. Rev. Lett. 80, 185 (1998)

Technique



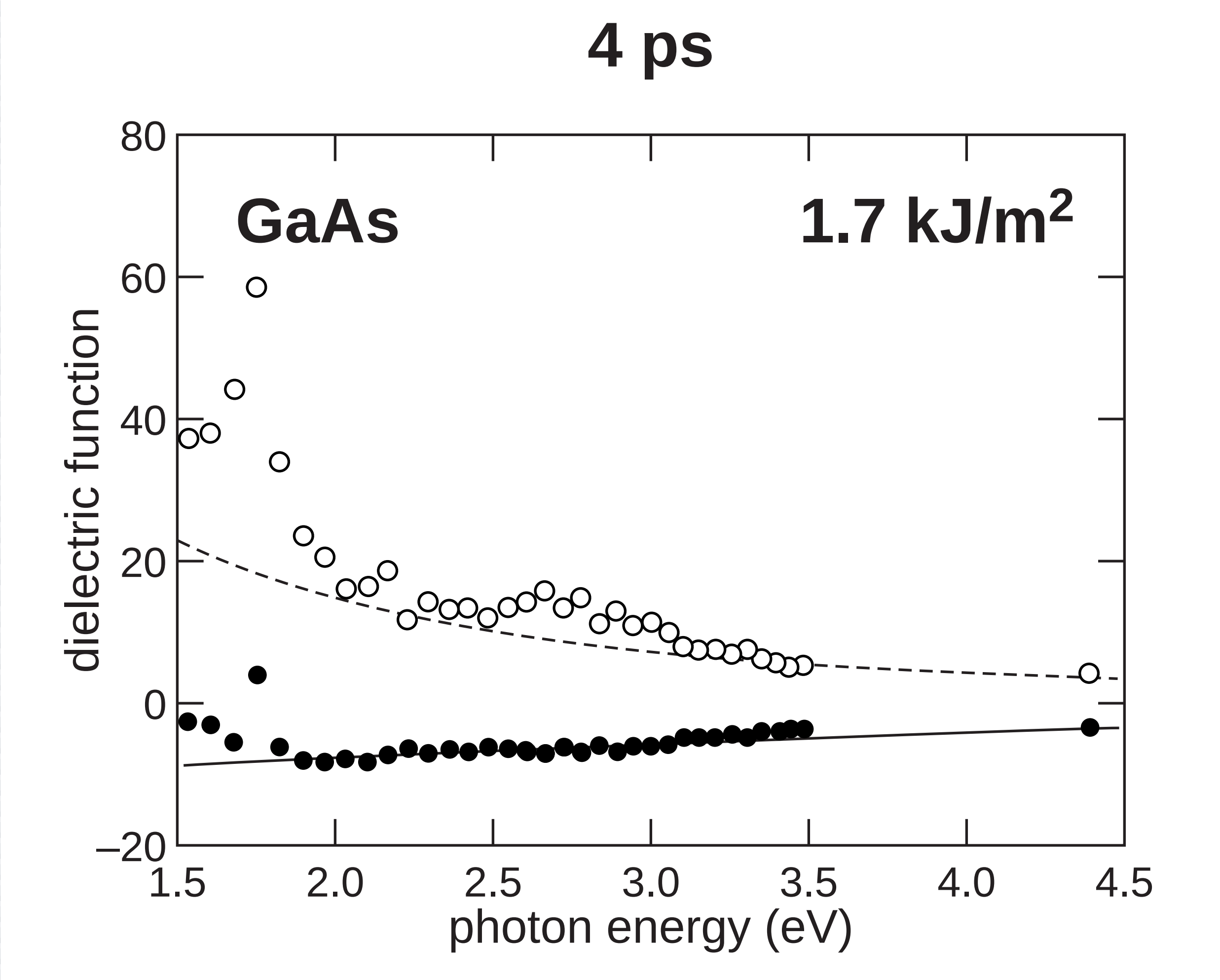
Phys. Rev. Lett. 80, 185 (1998)

Technique



Phys. Rev. Lett. 80, 185 (1998)

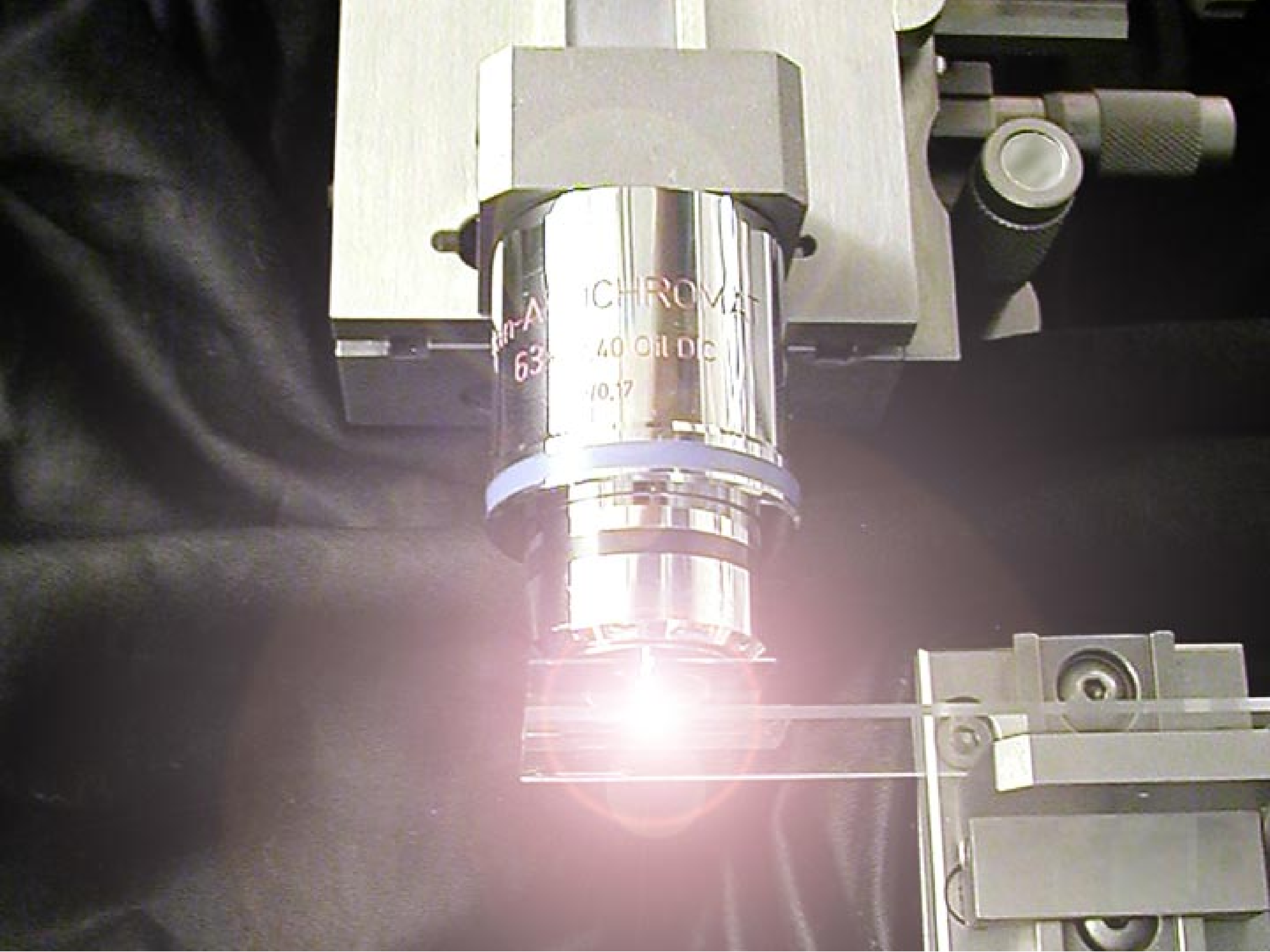
Technique



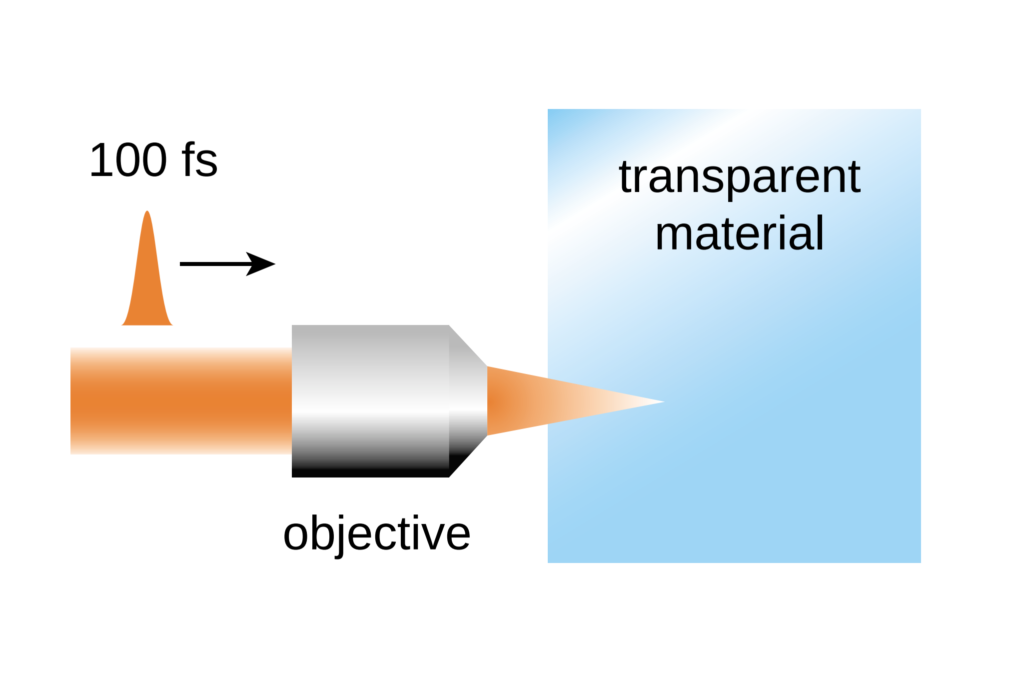
***Phys. Rev. Lett.* 80, 185 (1998)**

Technique

- **direct observation of semiconductor-to-metal transition**
- **order-disorder transition**
- **transition structural, not electronic**

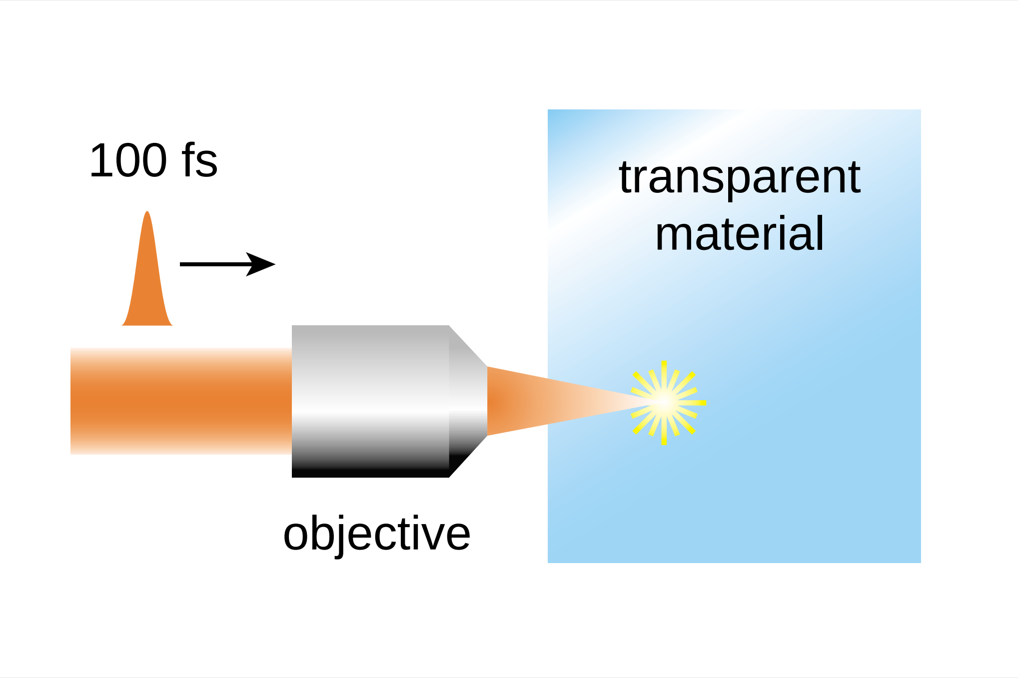

40 Oil DIC
/0.17

Processing with fs pulses



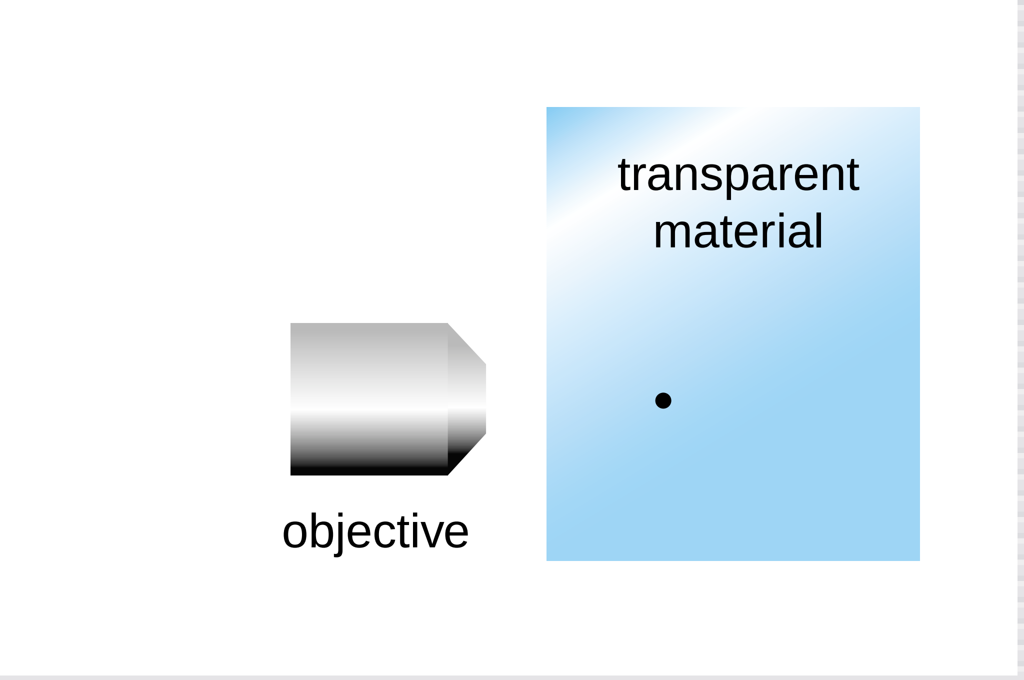
high intensity at focus…

Processing with fs pulses



… causes nonlinear ionization…

Processing with fs pulses



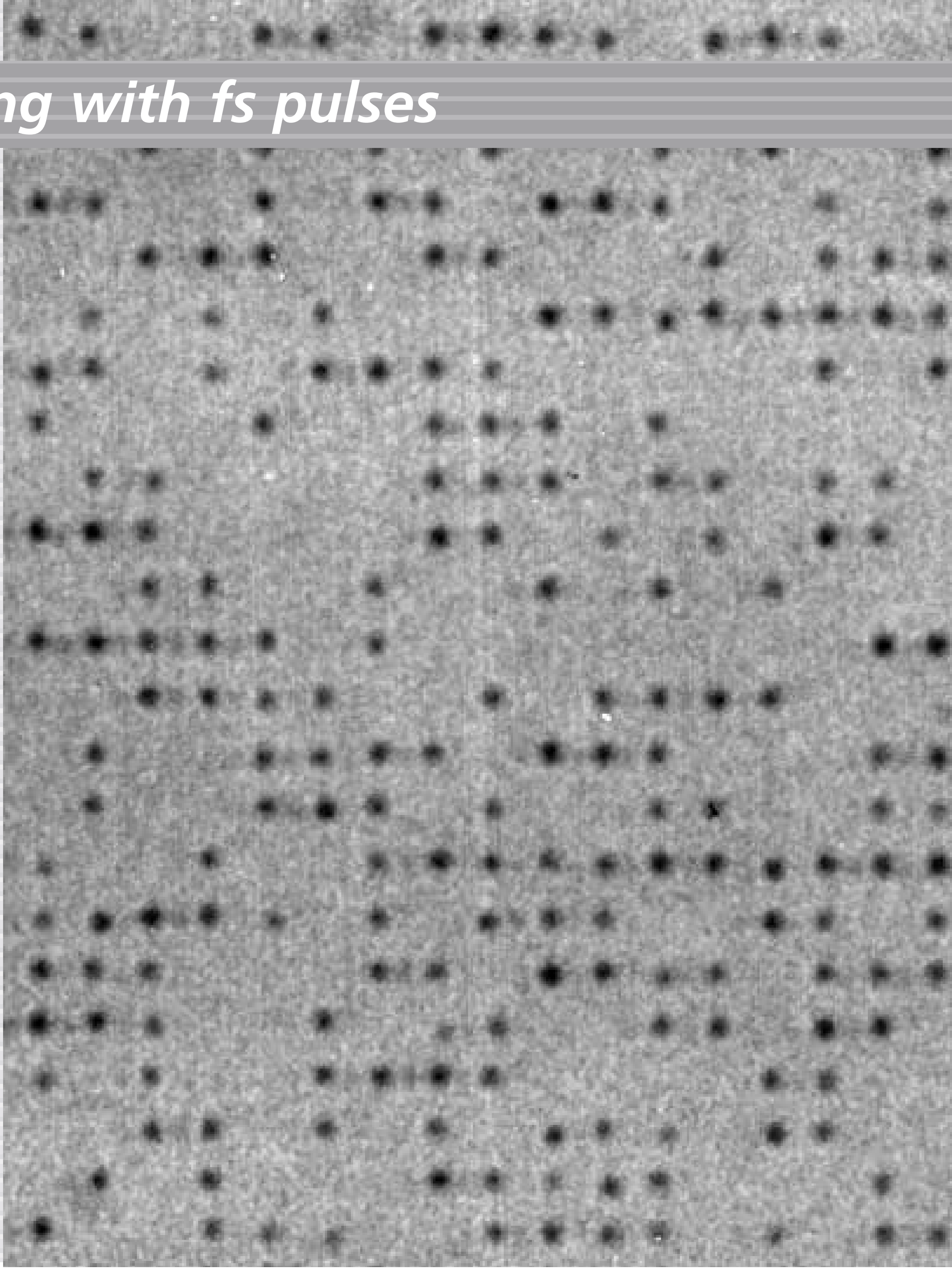
and 'microexplosion' causes microscopic damage

Processing with fs pulses

2 x 2 μm array

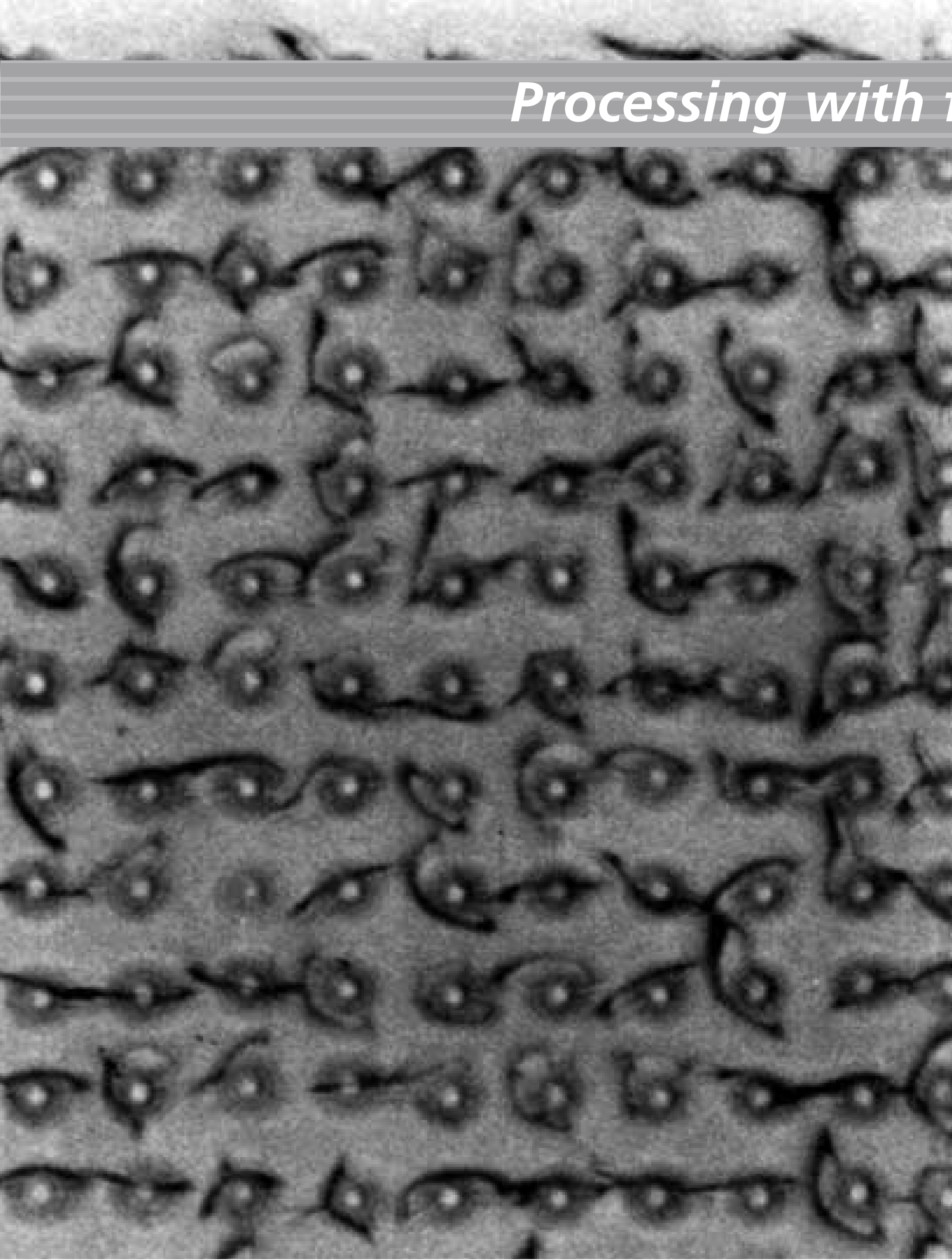
fused silica, 0.65 NA

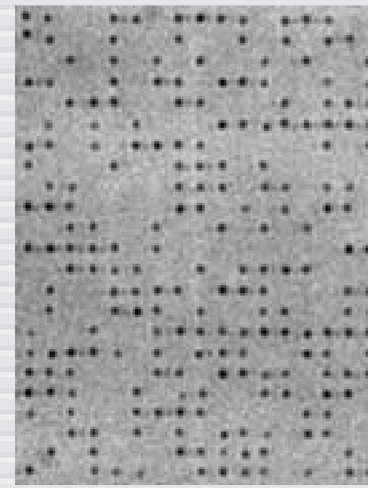
0.5 μJ, 100 fs, 800 nm



***Opt. Lett.* 21, 2023 (1996)**

Processing with fs pulses

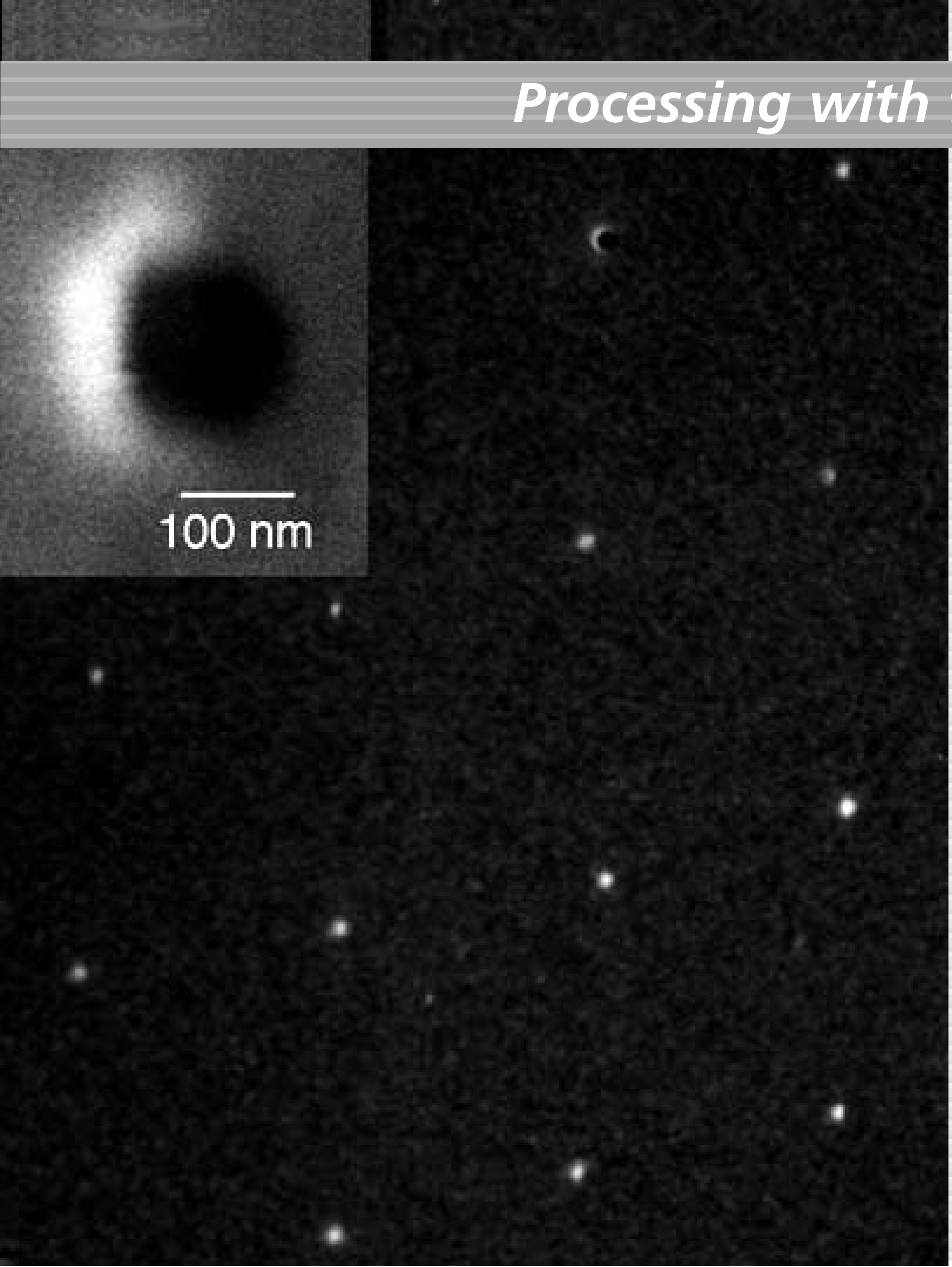




100 fs
0.5 μJ

200 ps
9 μJ

Processing with fs pulses



5 x 5 μm array

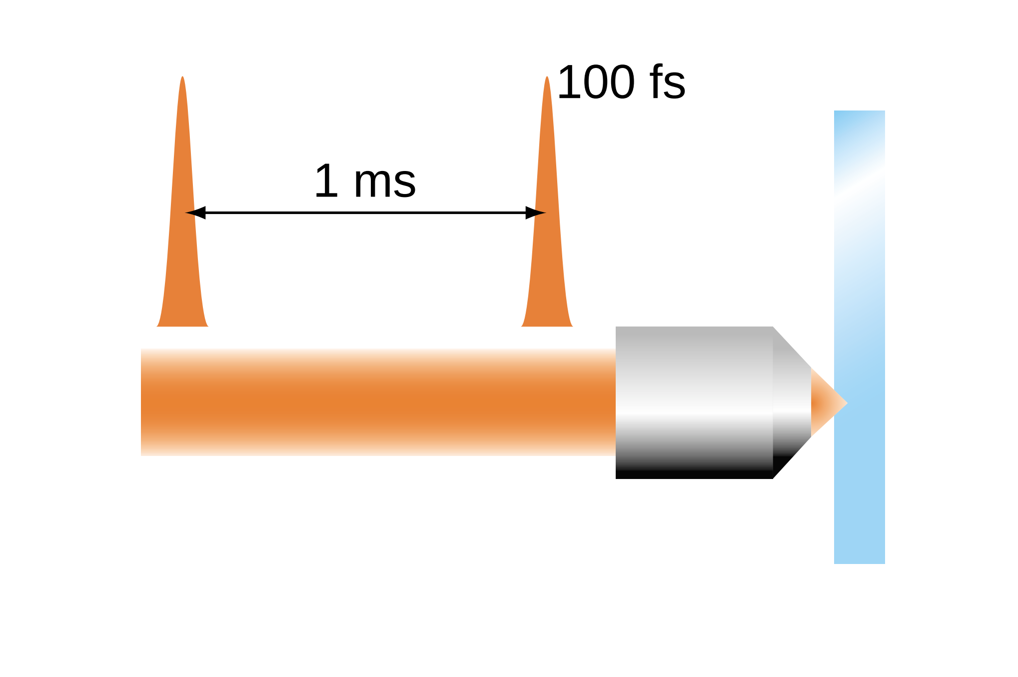
fused silica, 0.65 NA

0.5 μJ, 100 fs, 800 nm

***Opt. Lett.* 21, 2023 (1996)**

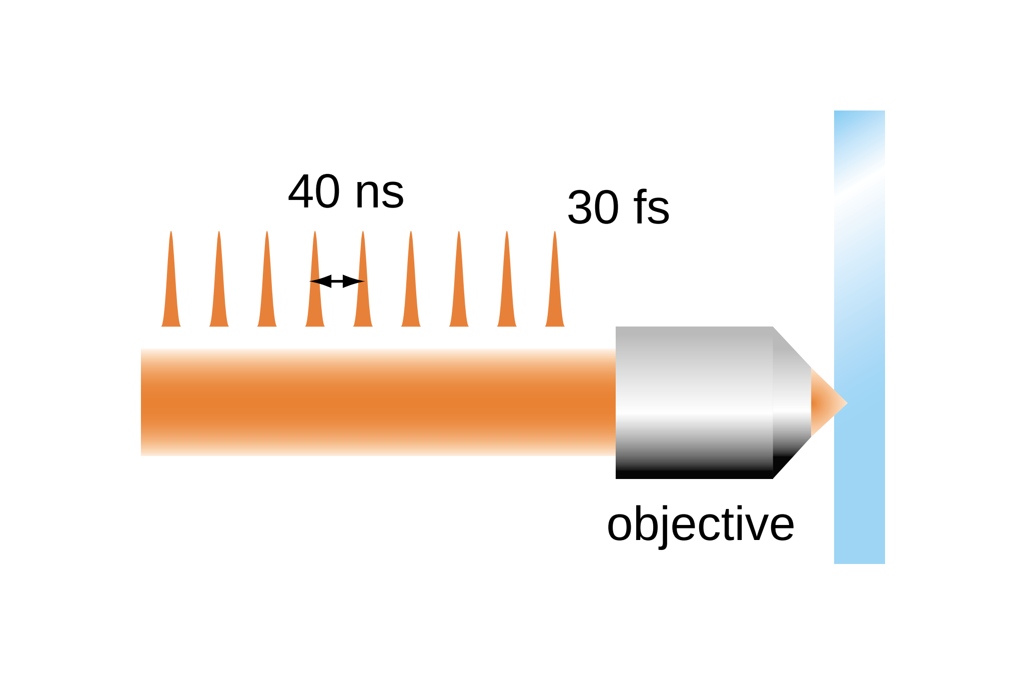
Low-energy processing

amplified laser



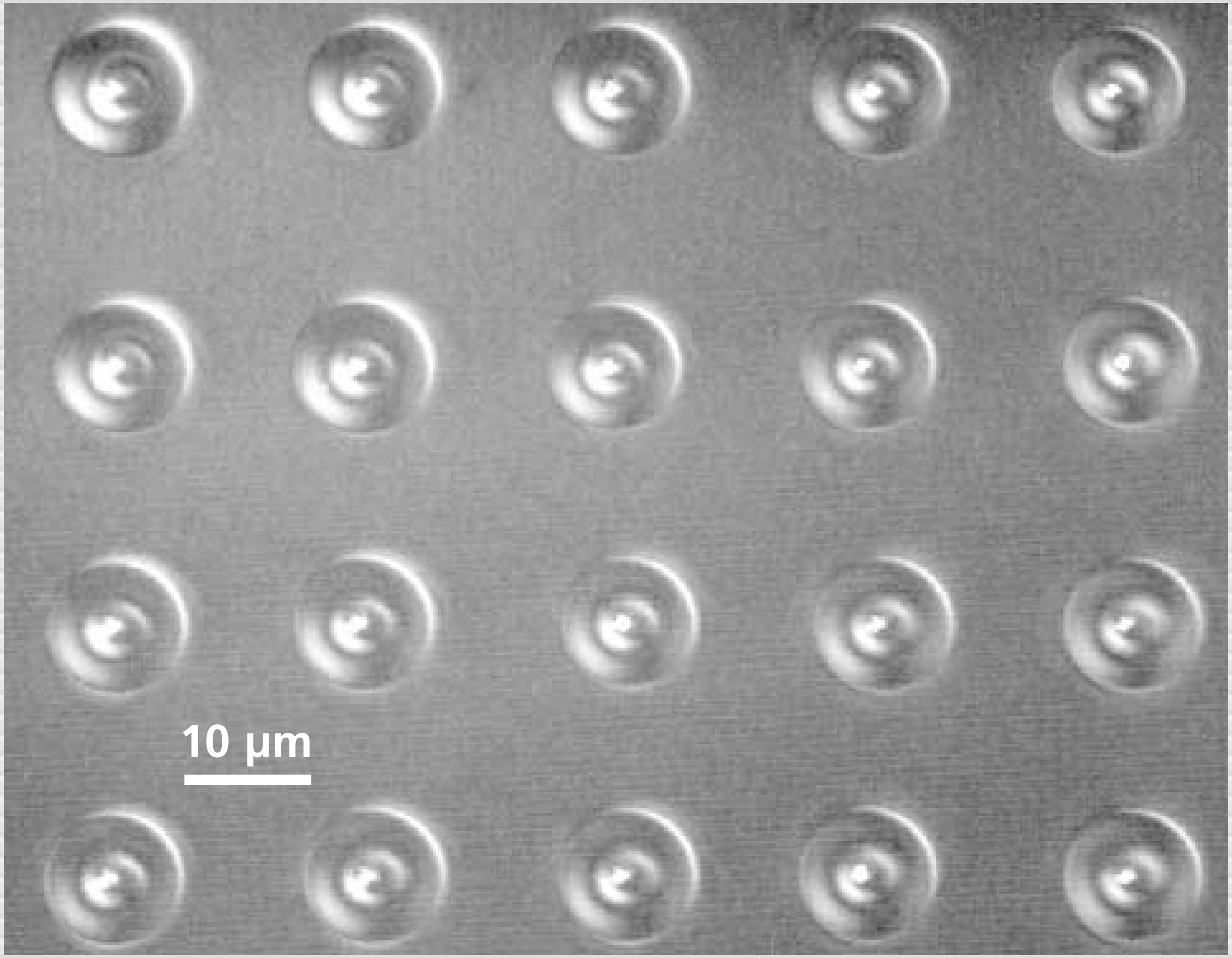
heat-diffusion time: $\tau_{diff} \approx 1\ \mu s$

long-cavity Ti:sapphire oscillator

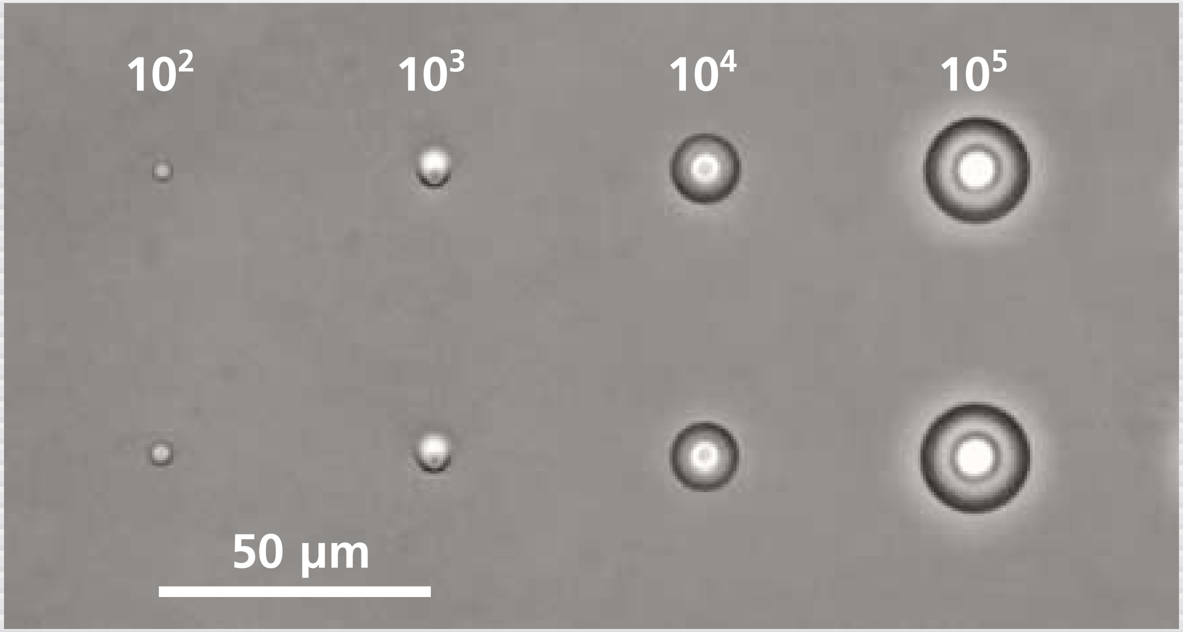


heat-diffusion time: $\tau_{diff} \approx 1\ \mu s$

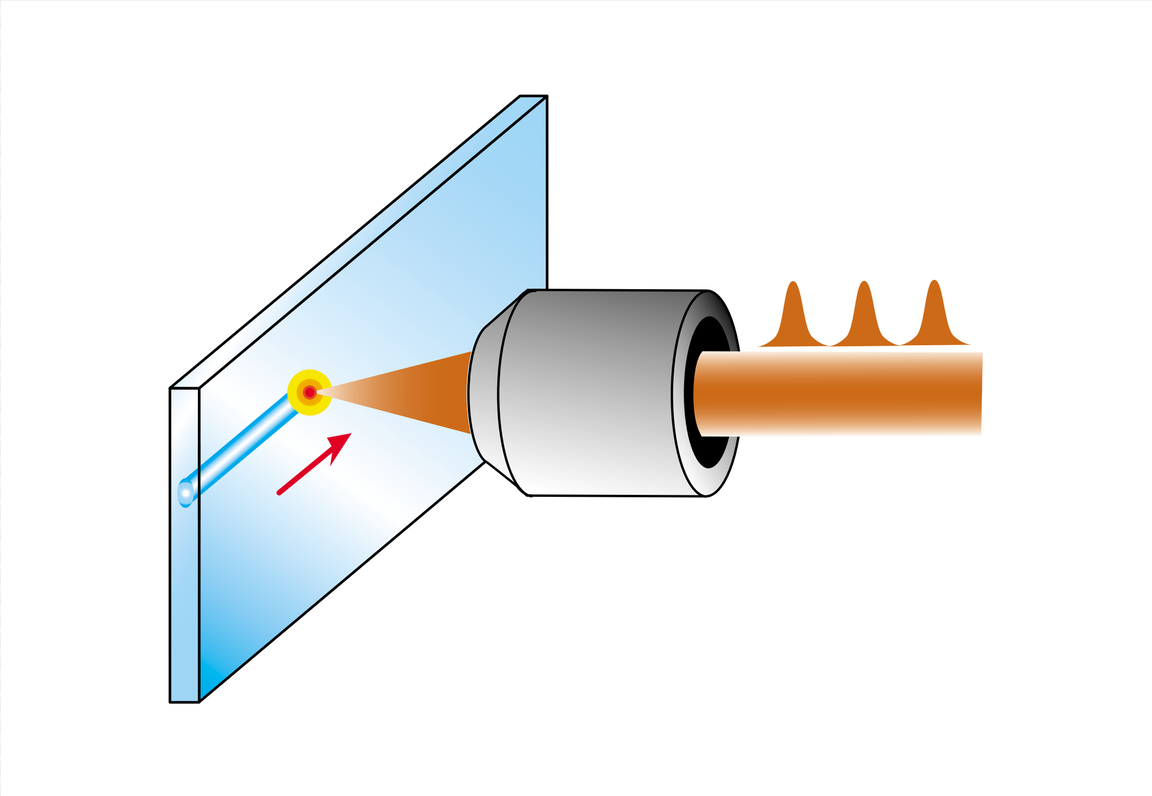
Low-energy processing



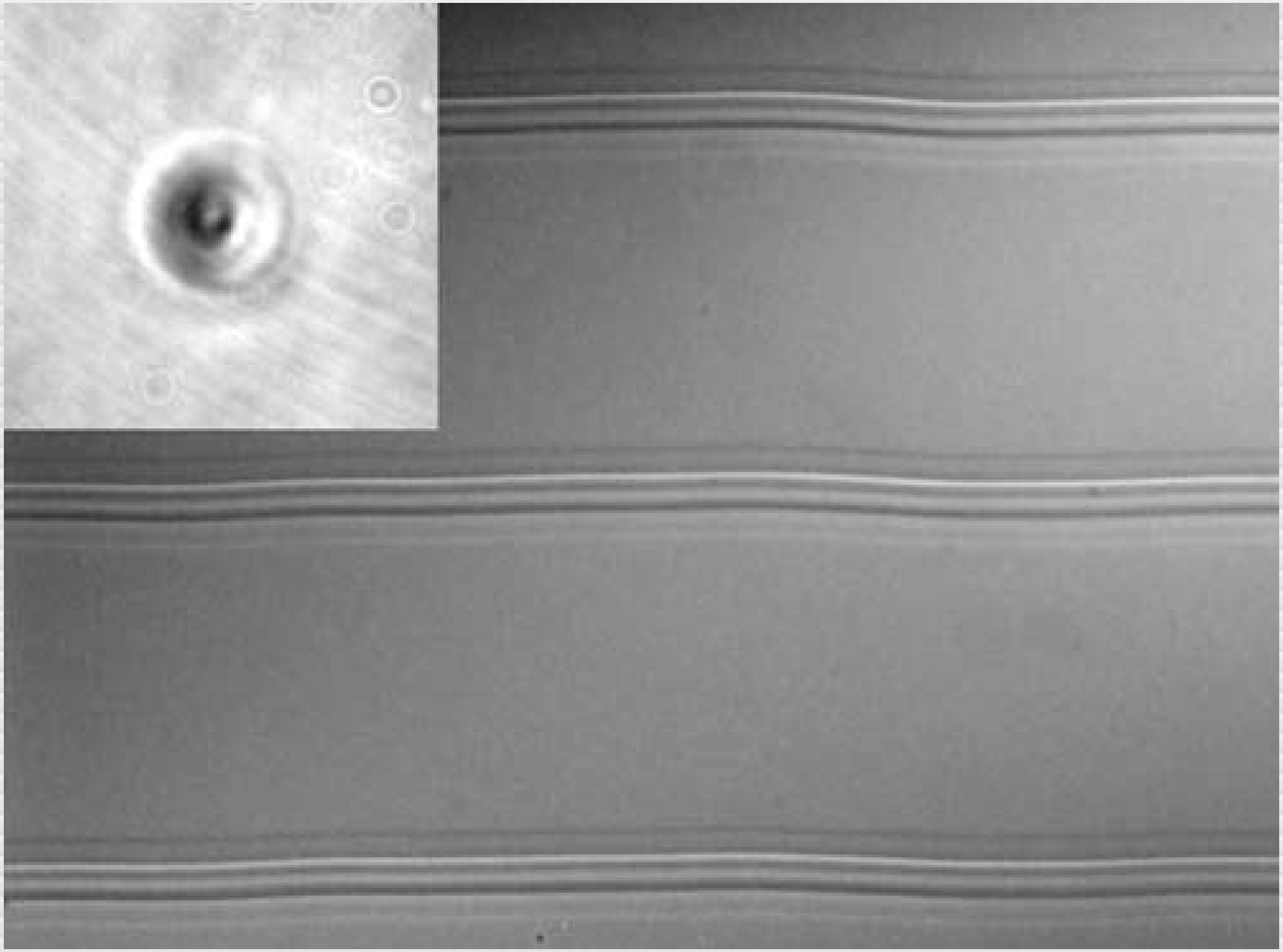
Low-energy processing



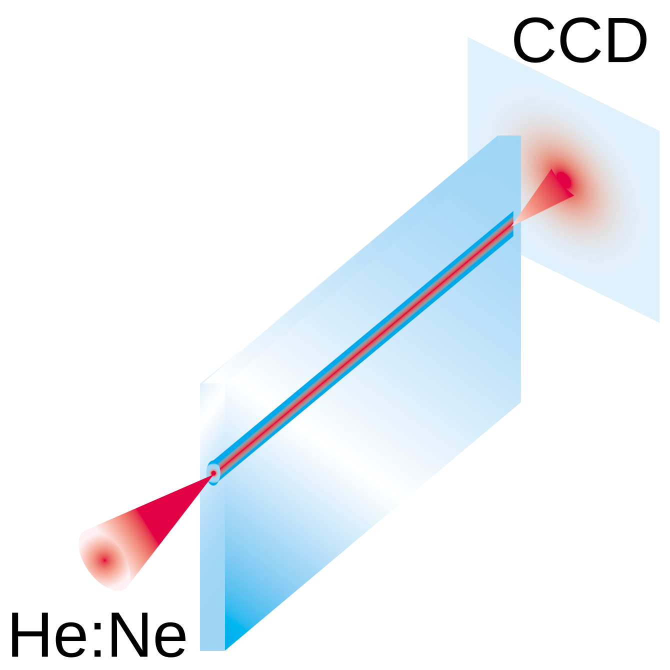
waveguide machining



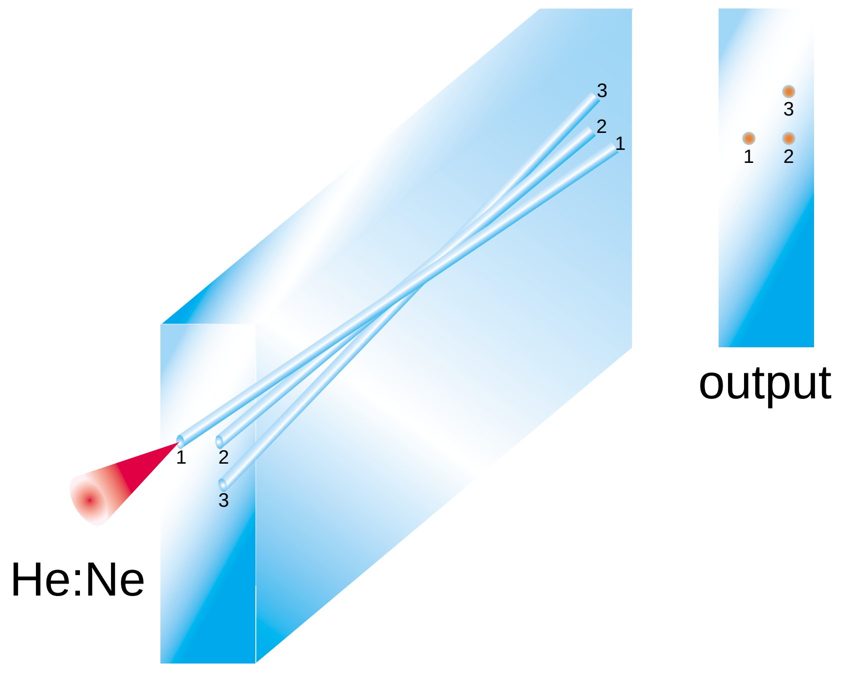
waveguide machining



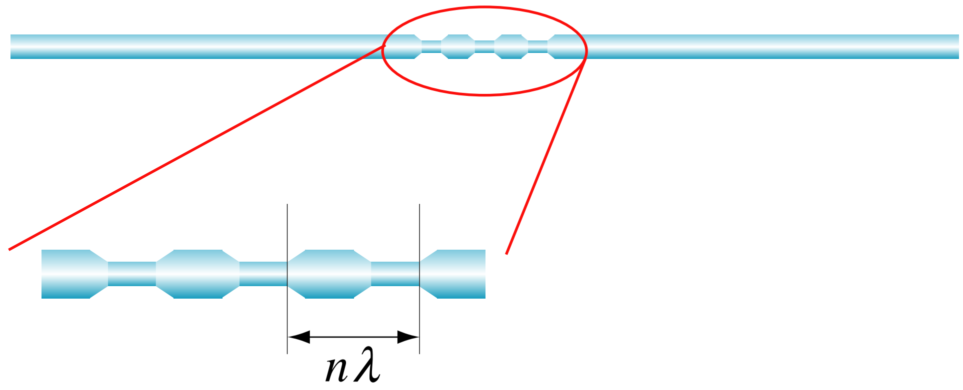
waveguide mode analysis



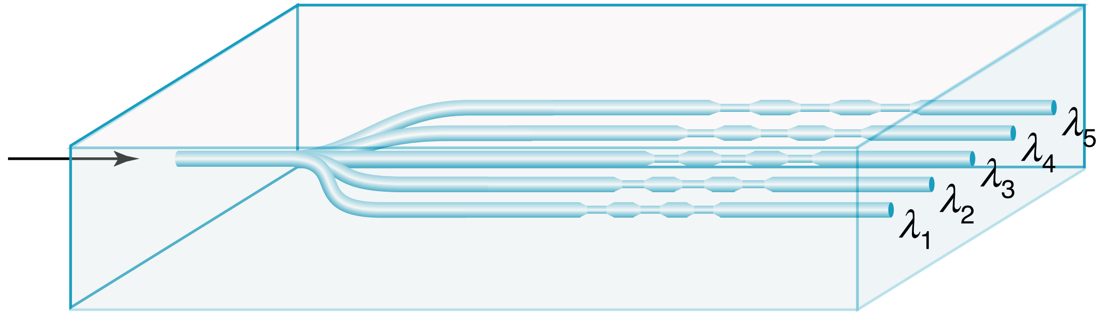
3D wave splitter



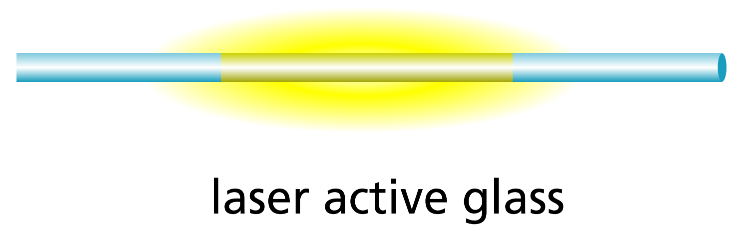
Bragg grating



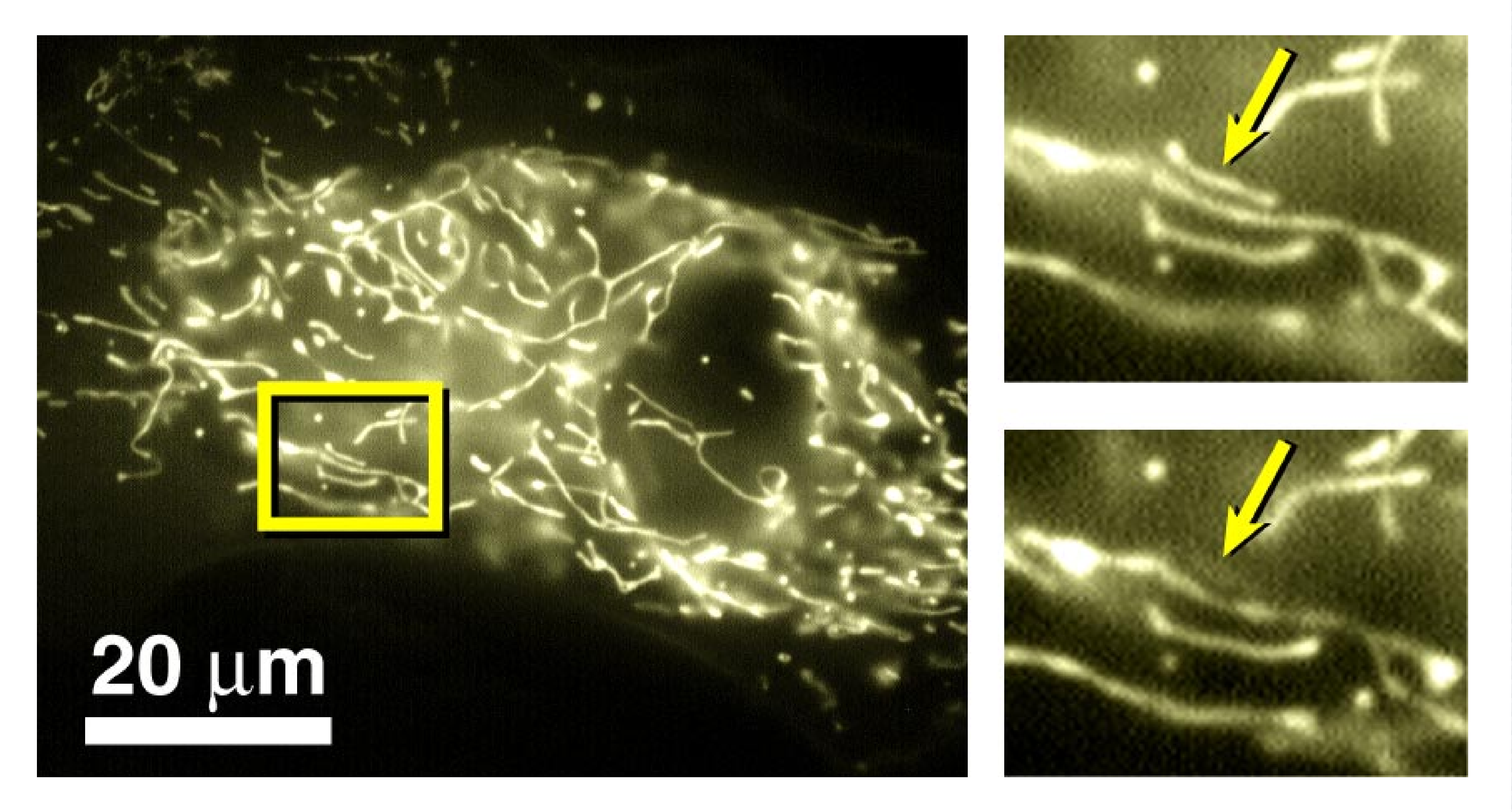
Bragg grating



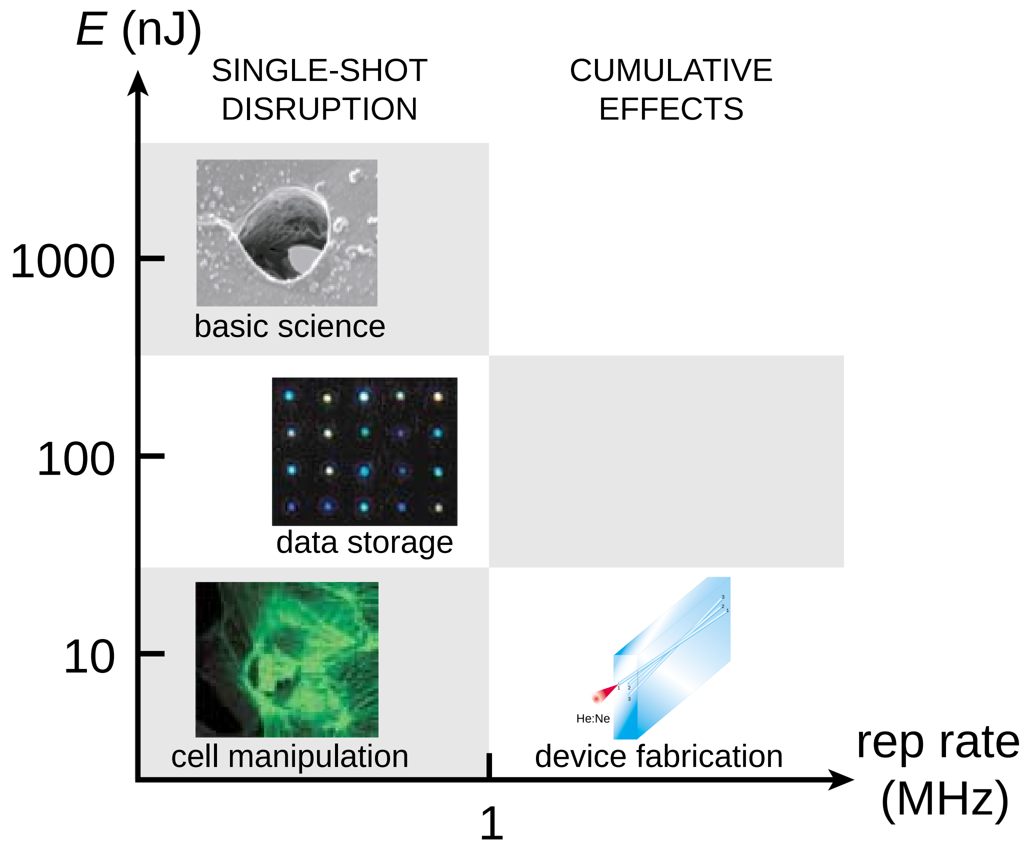
monolithic amplifier



Low-energy processing



Summary


E (nJ)
SINGLE-SHOT DISRUPTION
CUMULATIVE EFFECTS
1000
100
10
basic science
data storage
cell manipulation
He:Ne
device fabrication
1
rep rate (MHz)

Conclusion

- **wiring optoelectronics circuits of the future**
- **manipulating the machinery of life**

Summary

Femtosecond laser pulses offer:

- **Unprecedented view into dynamics**
- **Extreme conditions with little energy**
- **New opportunities for research and processing**

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Prof. H. Ehrenreich
Prof. T. Kaxiras

For a copy of this talk and additional information, see:

http://mazur-www.harvard.edu