An introduction to femtosecond laser science

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Harvard University

Short course 541
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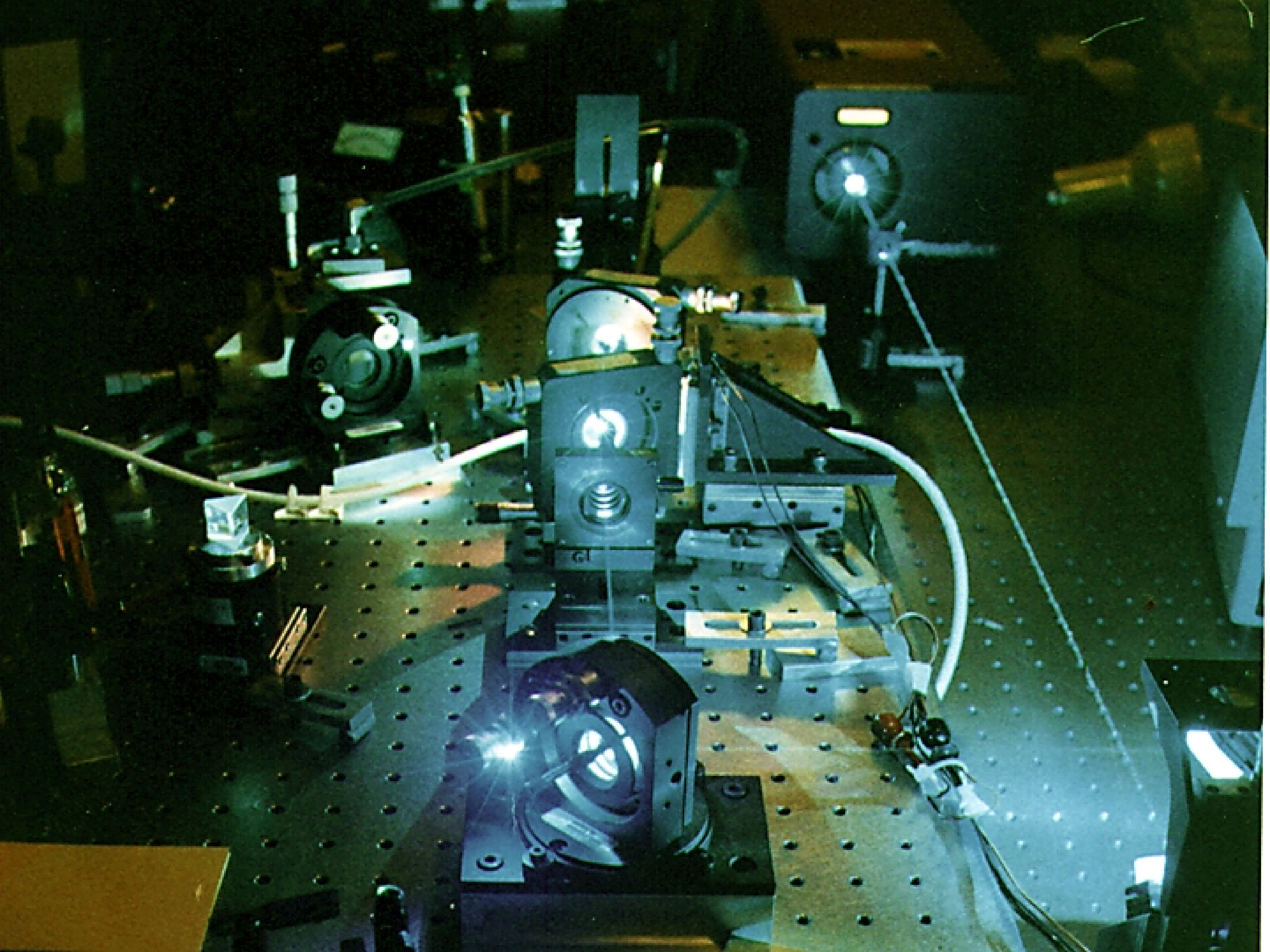

Outline

- linear and nonlinear propagation
- femtosecond measurements
- examples

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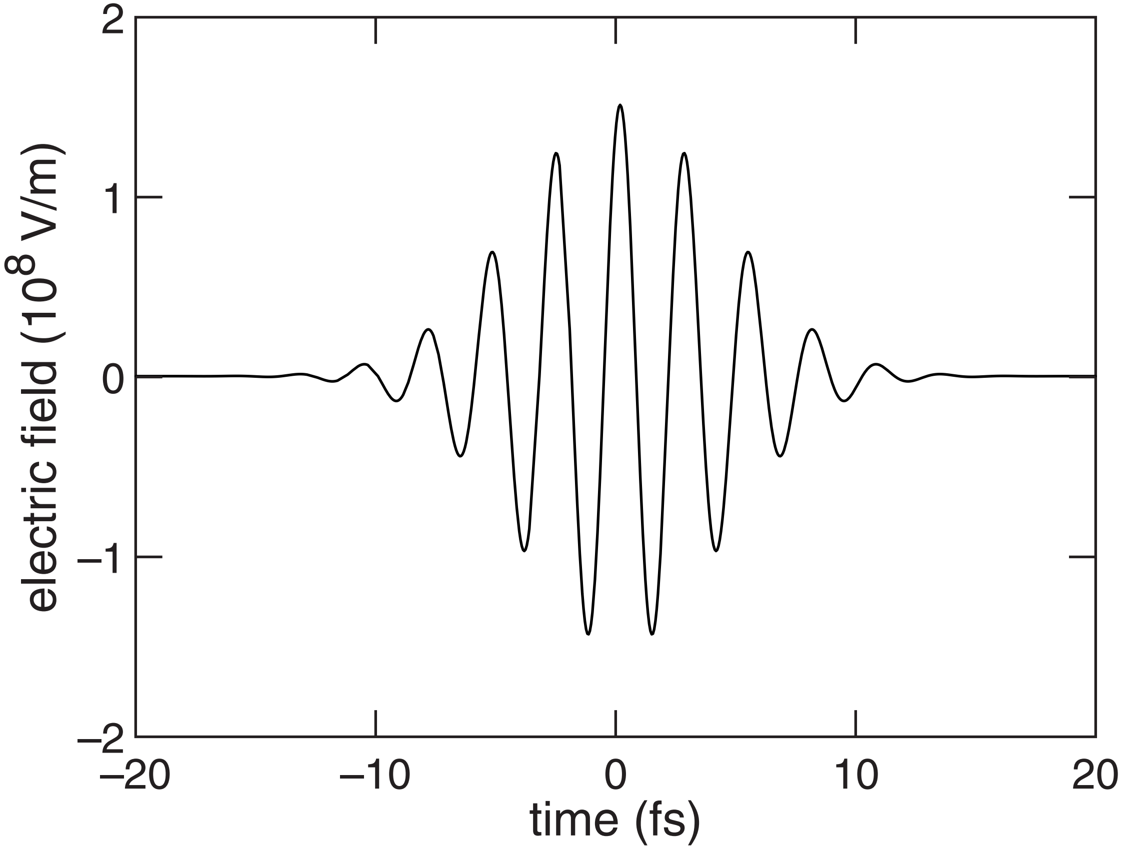
- **linear and nonlinear propagation**
- **femtosecond measurements**
- **examples**

Introduction



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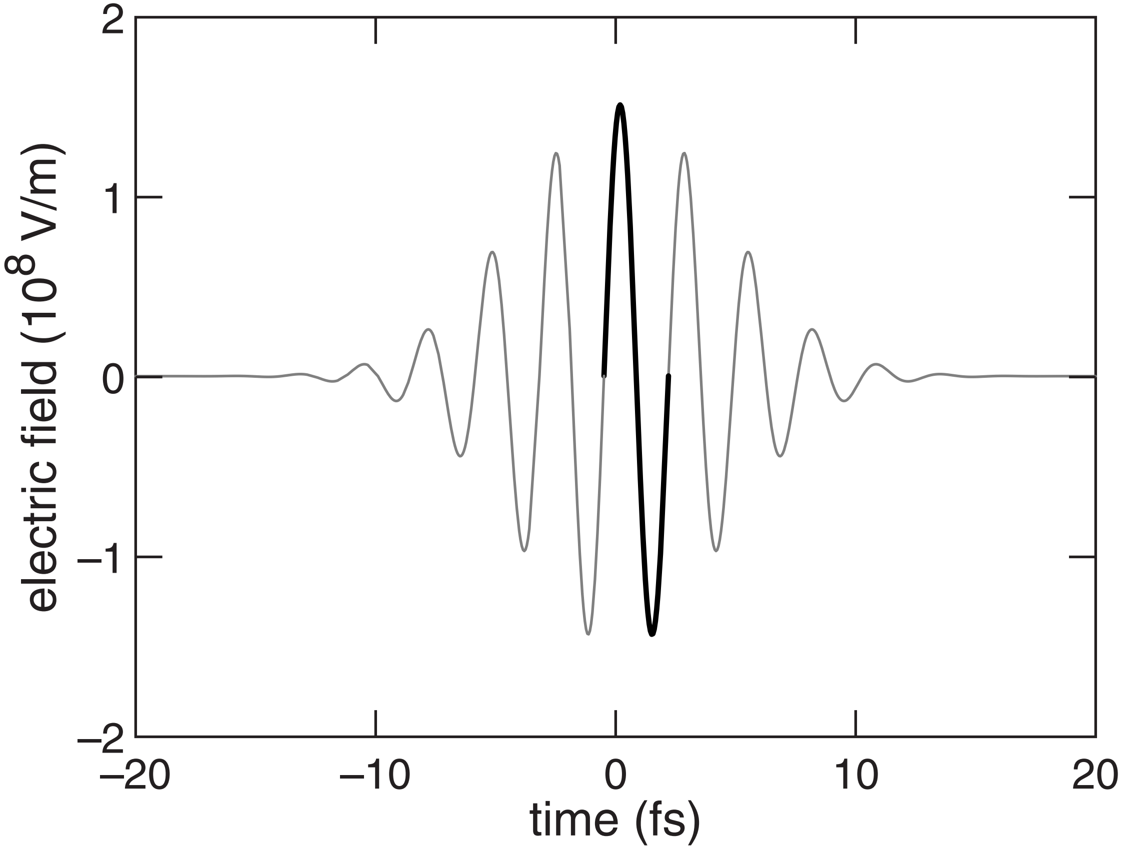

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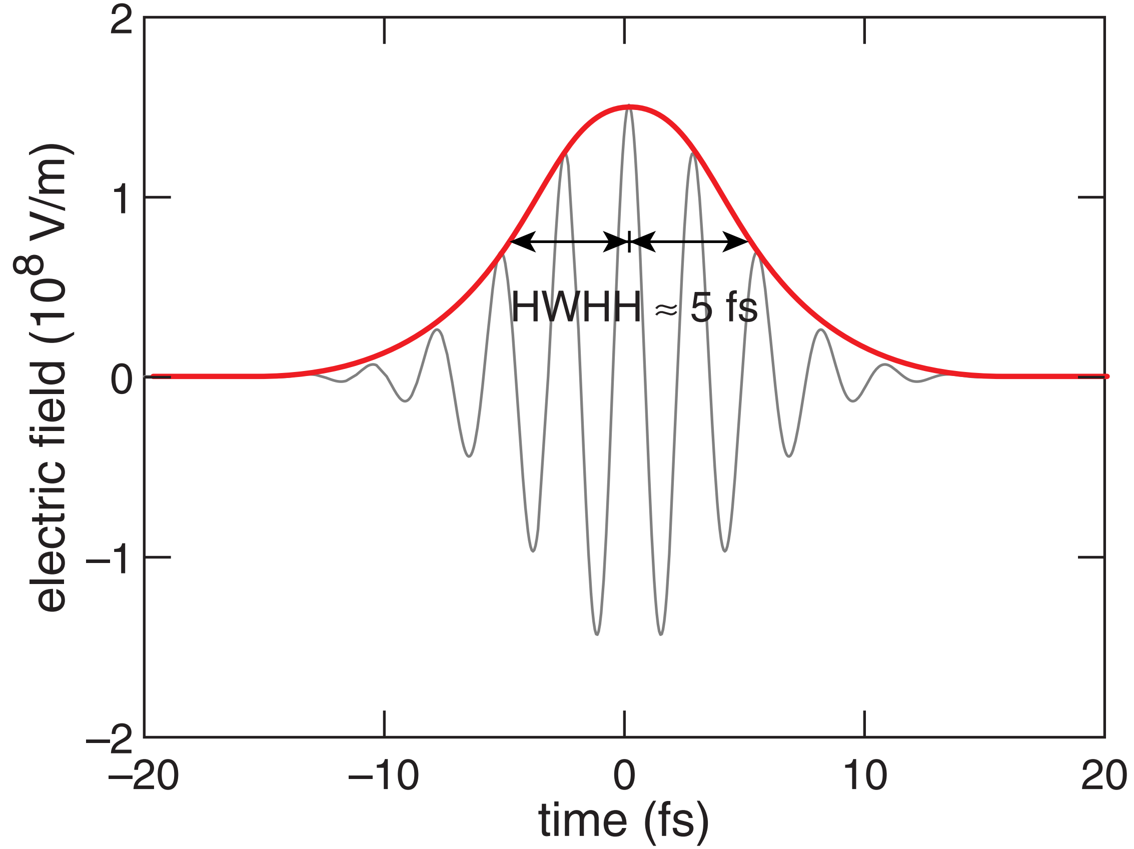

Introduction

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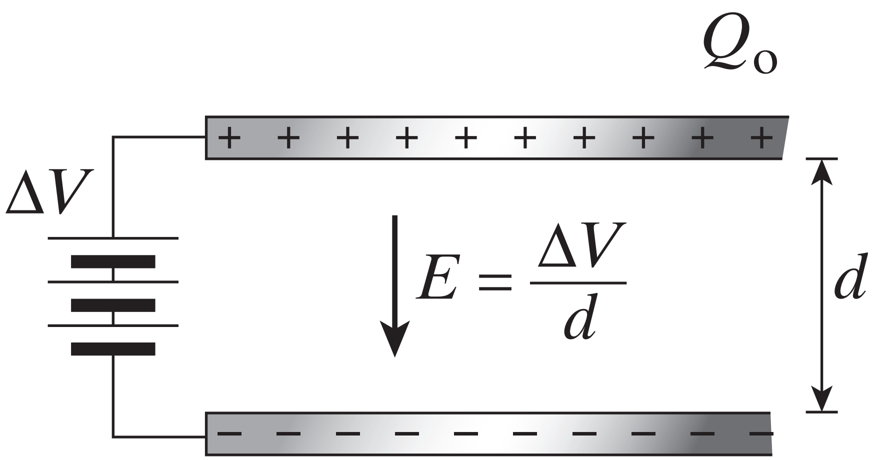
In non-ferromagnetic media $\mu \approx 1$**, and so** $n \approx \sqrt{\epsilon}$**.**

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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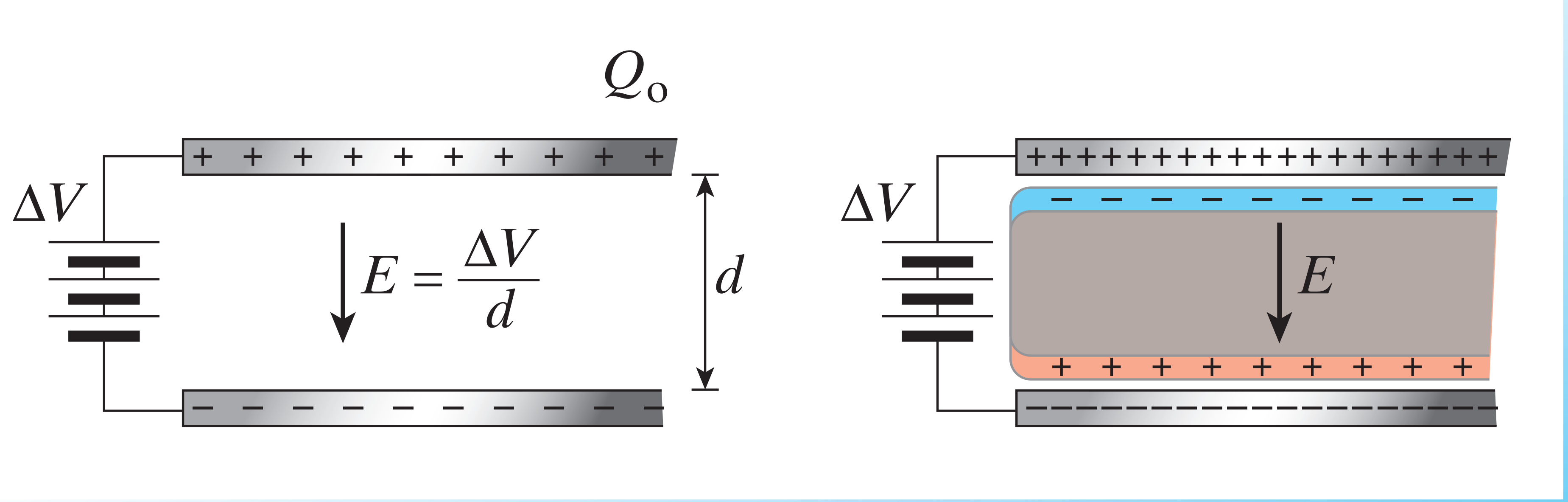

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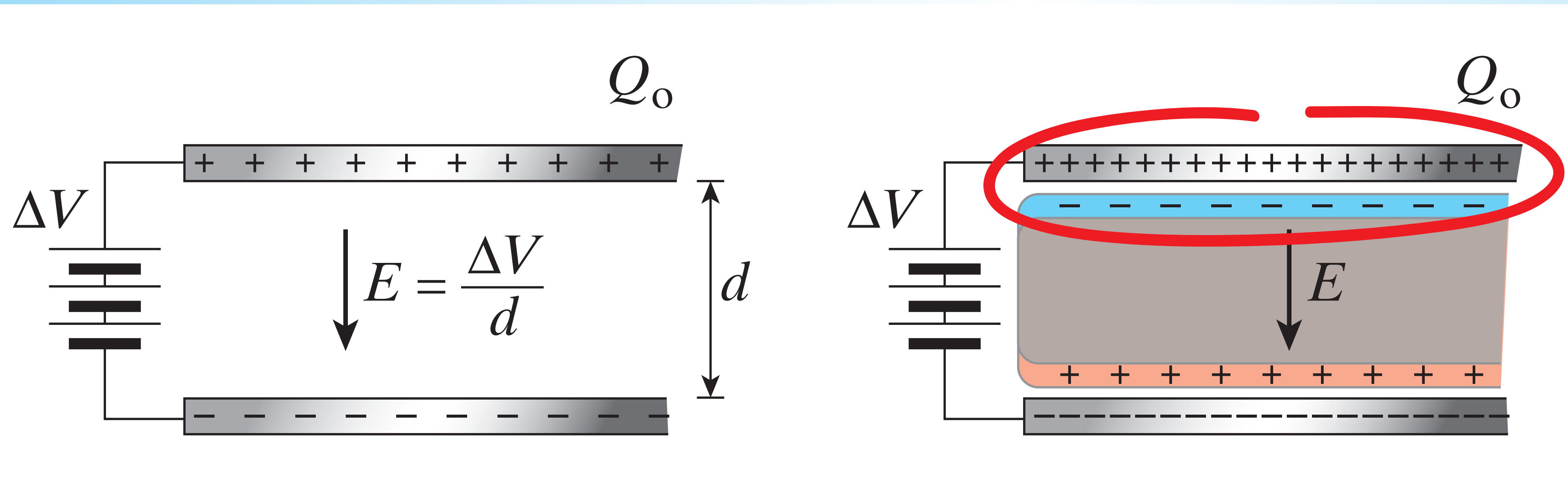

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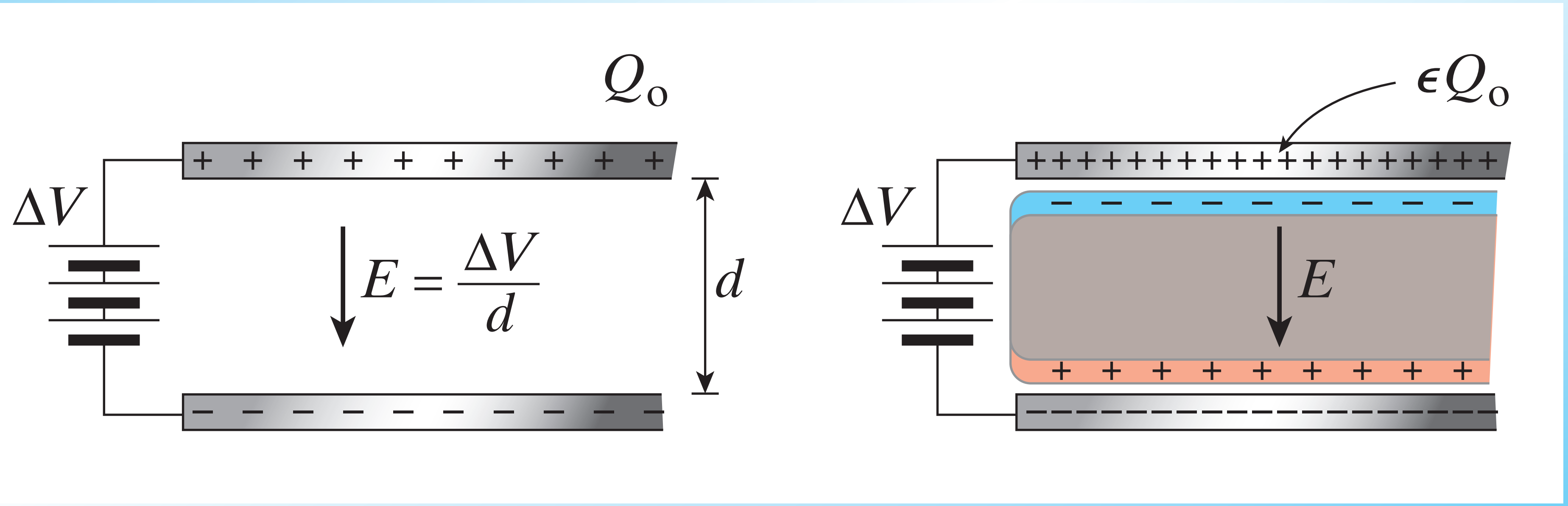
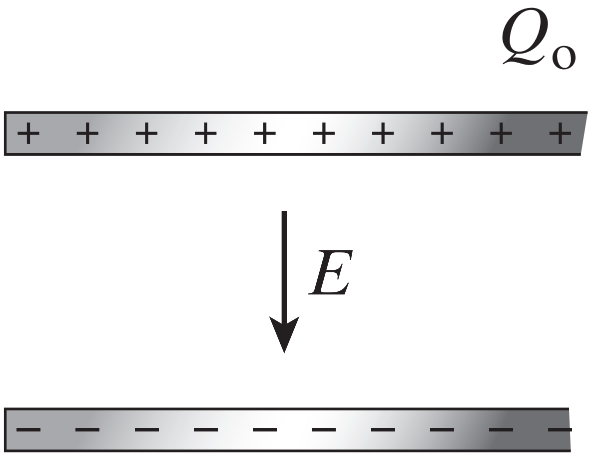


Propagation of EM waves through medium

Alternatively, ϵ is measure of the attenuation of the field



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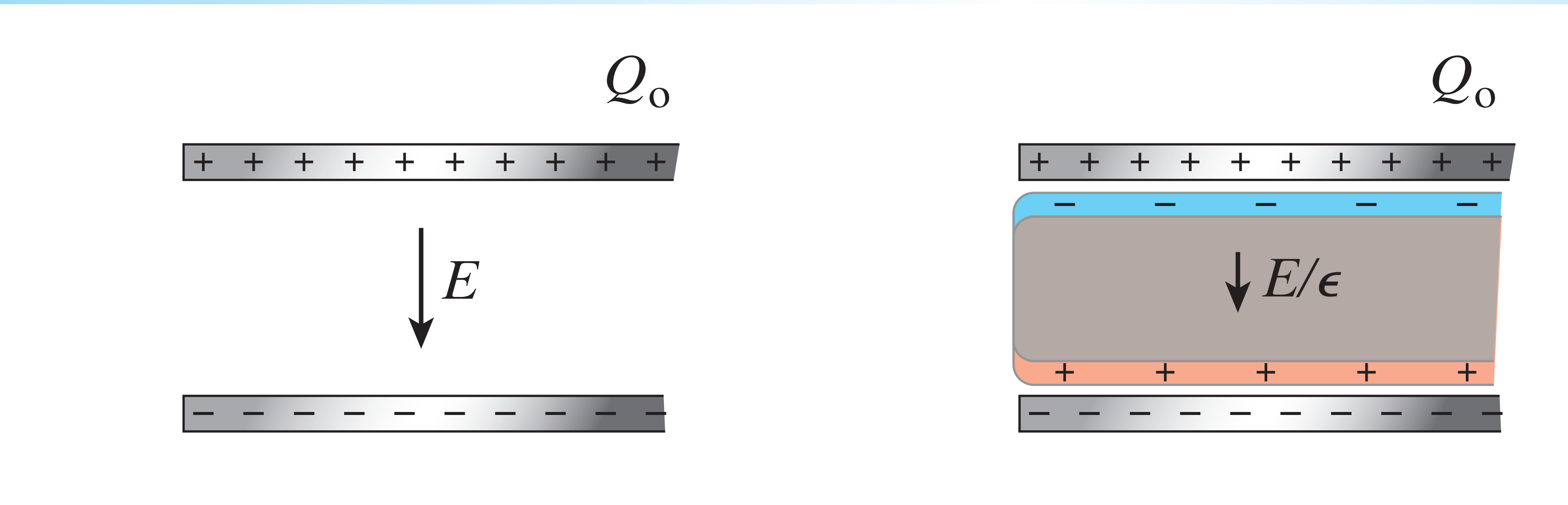
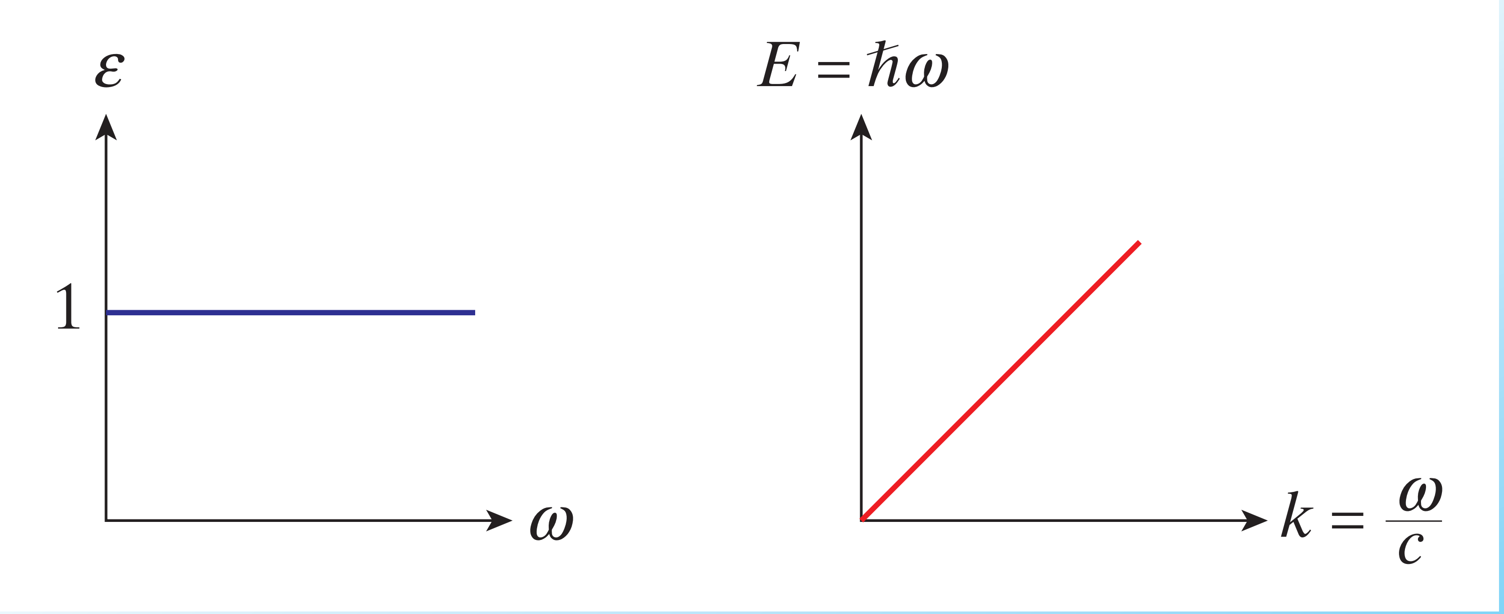


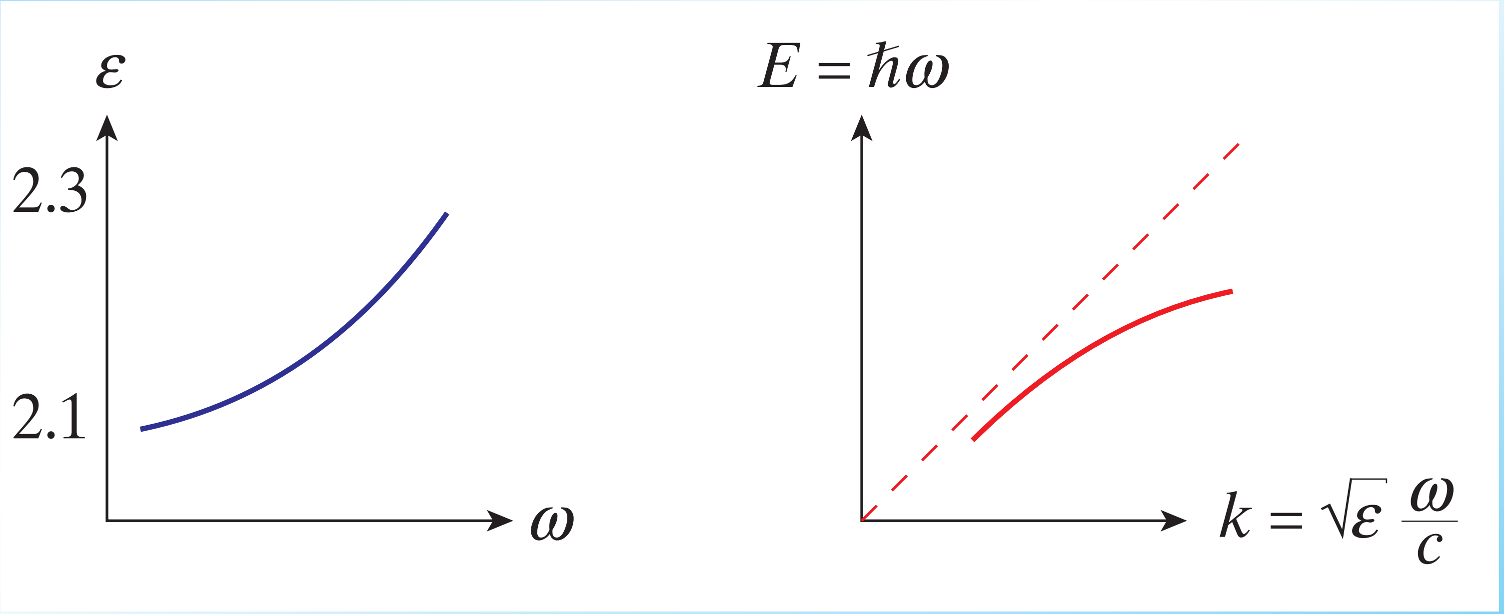
Propagation of EM waves through medium

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

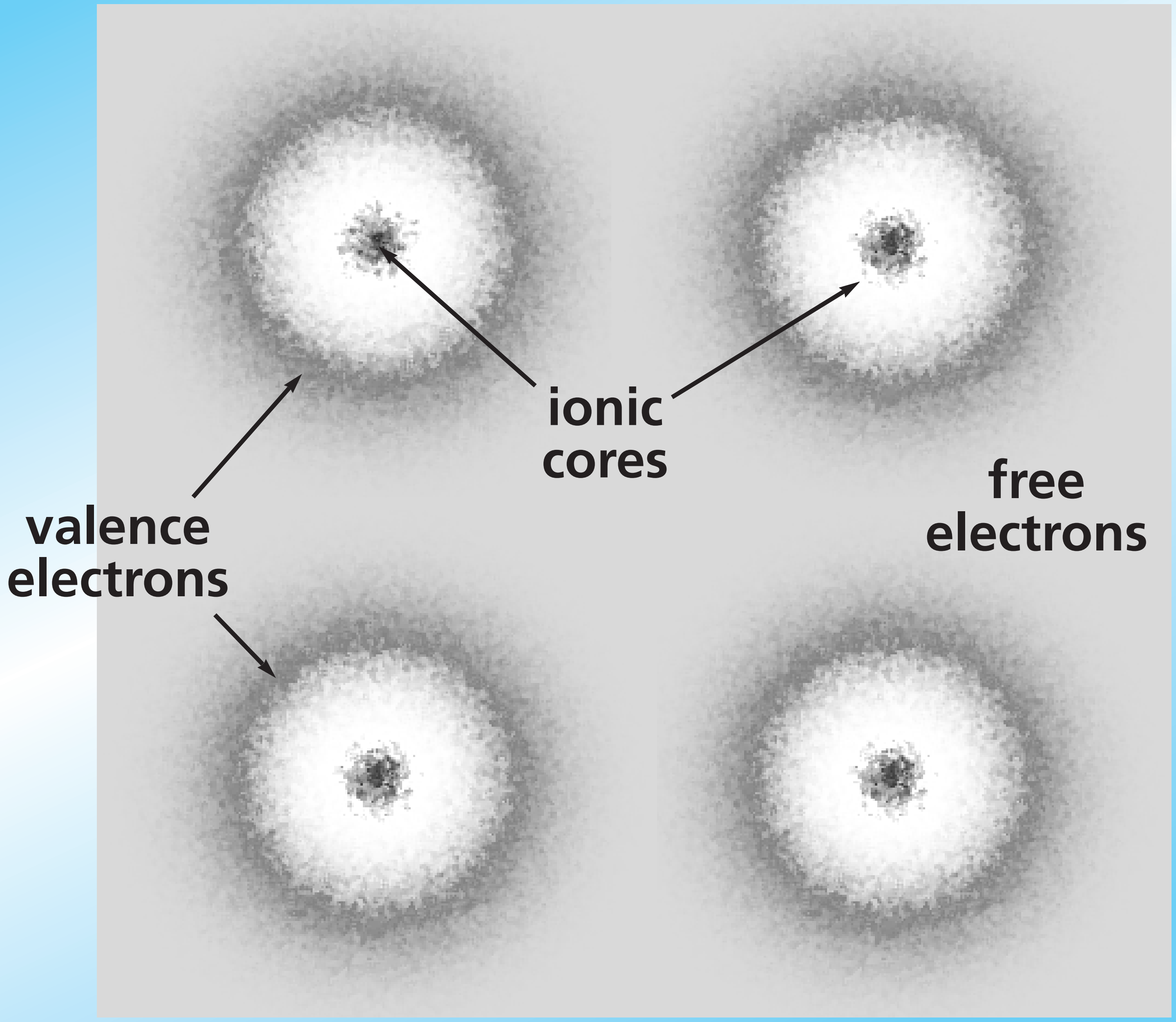


Propagation of EM waves through medium

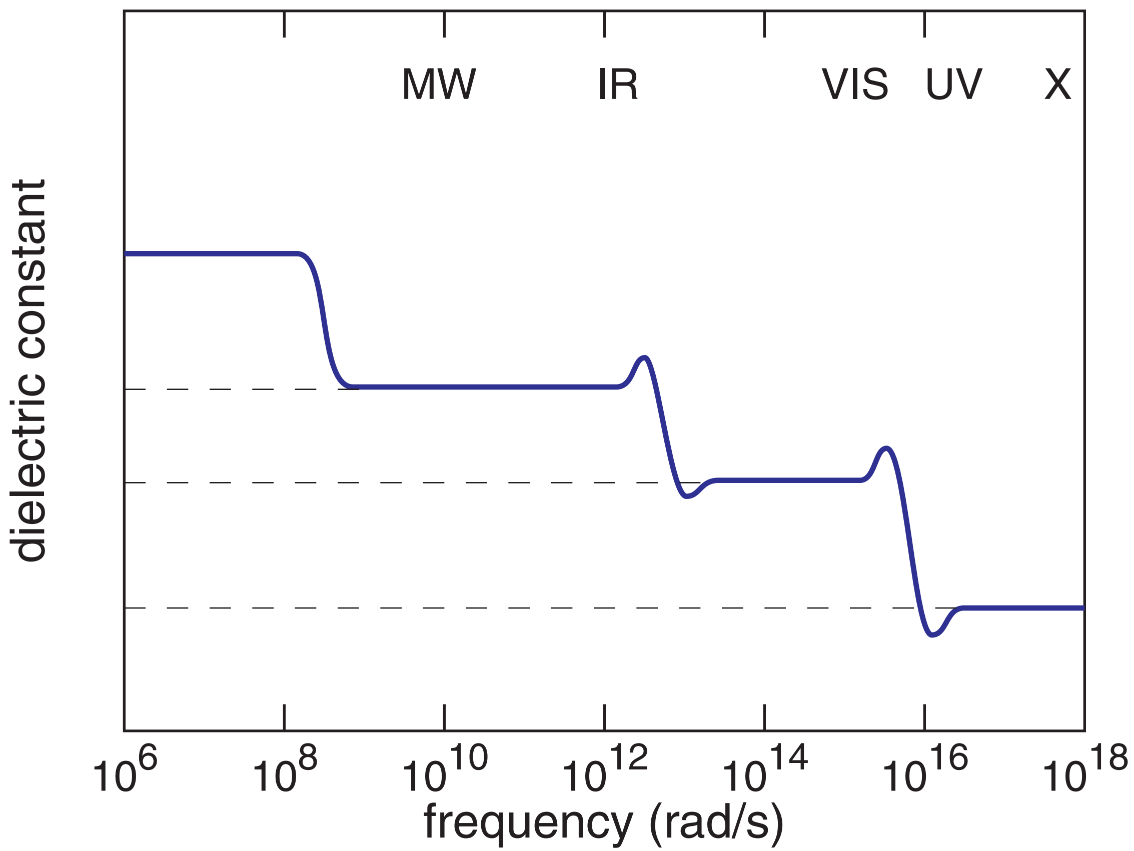
In medium: $$v = \frac{c}{\sqrt{\epsilon(\omega)}} = \frac{c}{n} \quad \Rightarrow \quad \omega = \frac{c}{\sqrt{\epsilon}} k$$



Which charges participate?



Dielectric function



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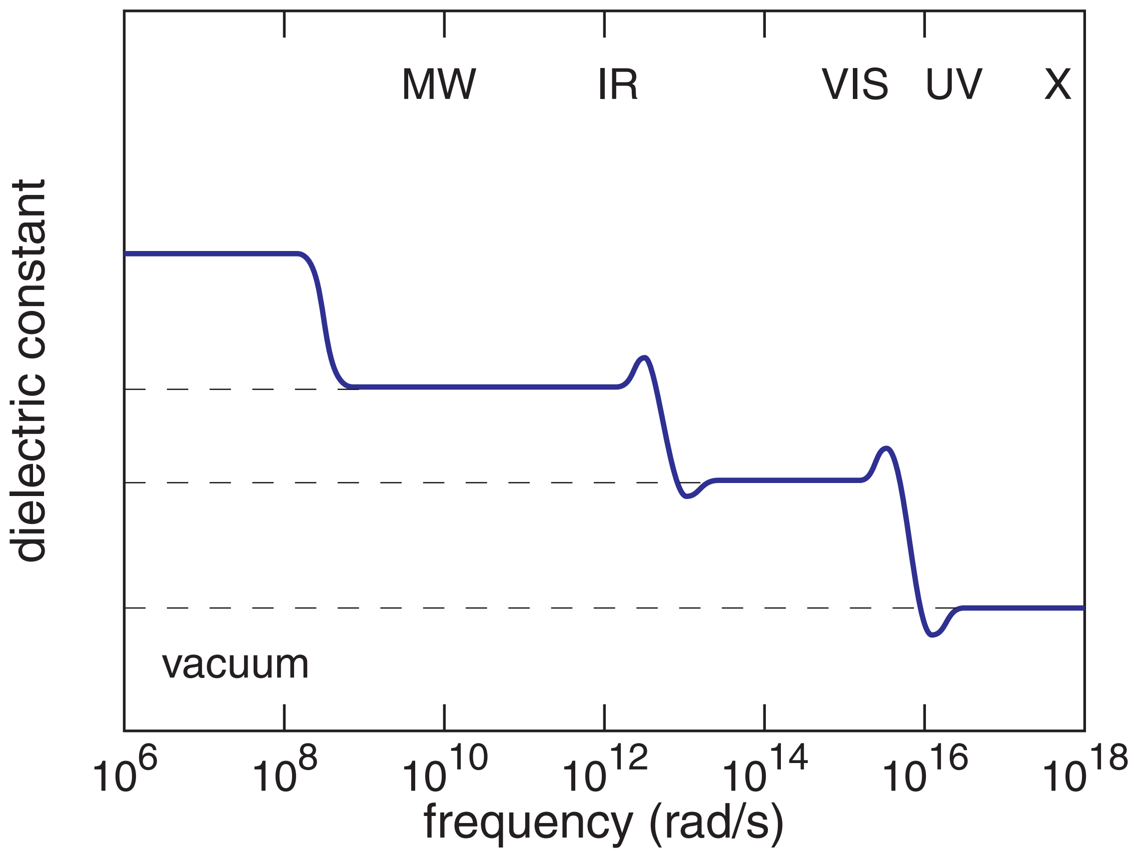

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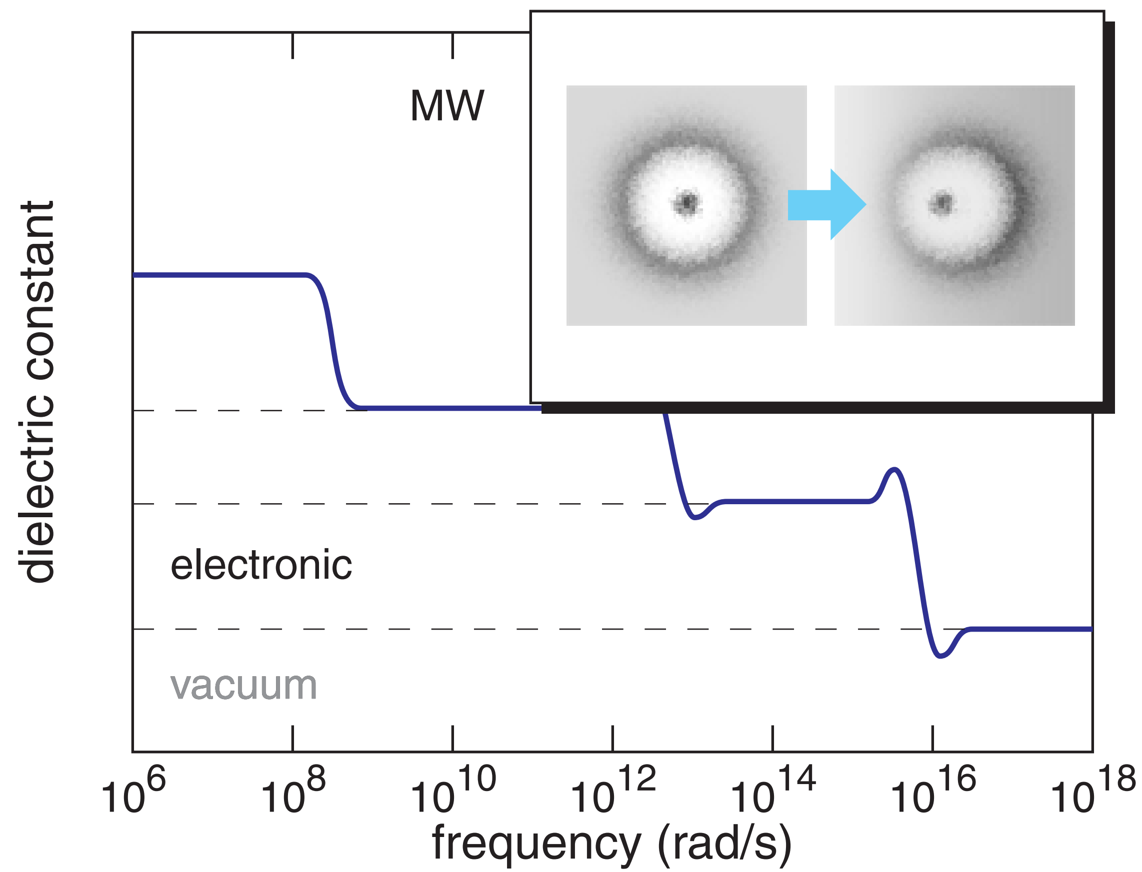

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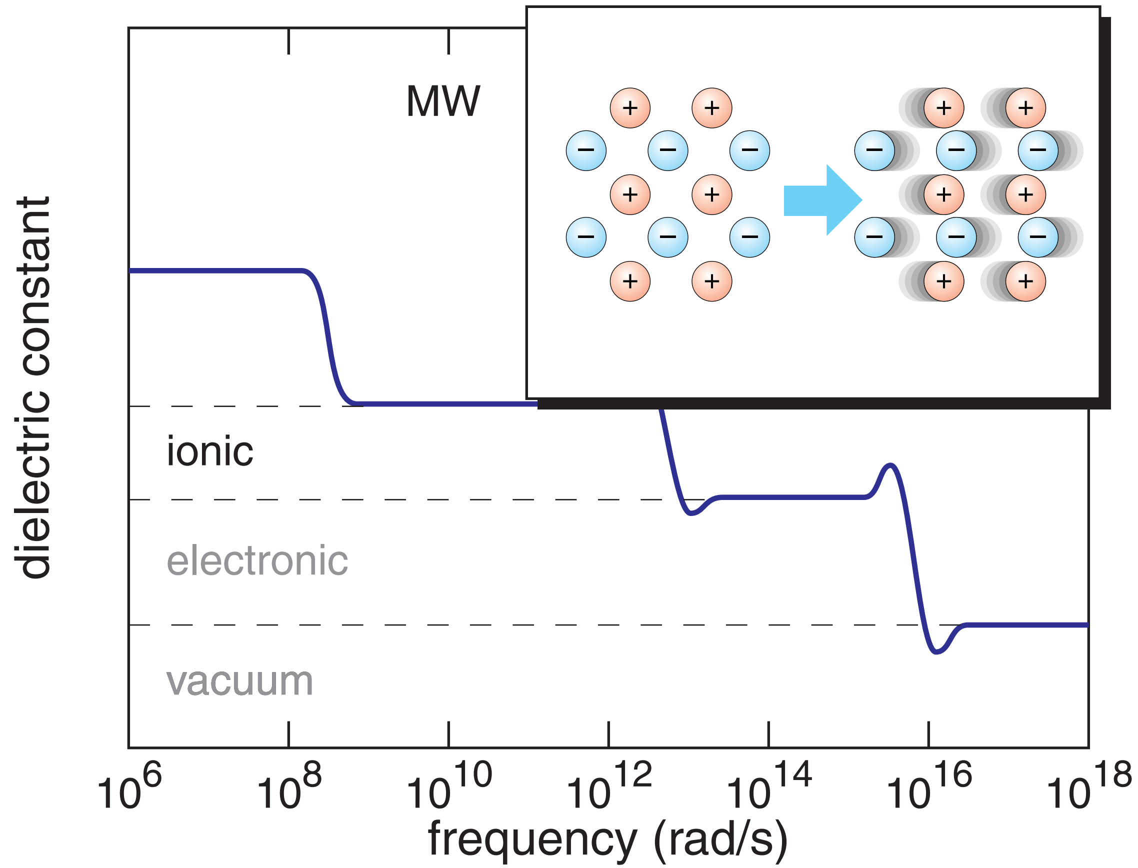

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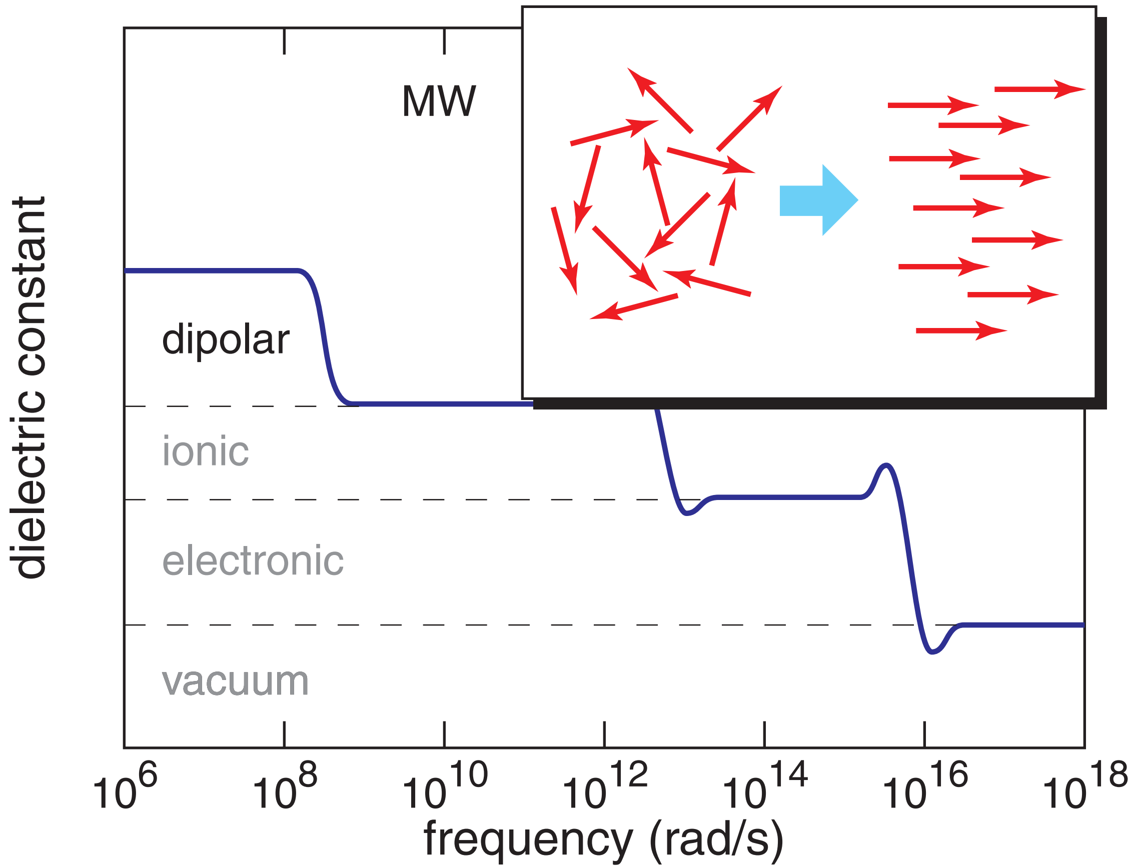

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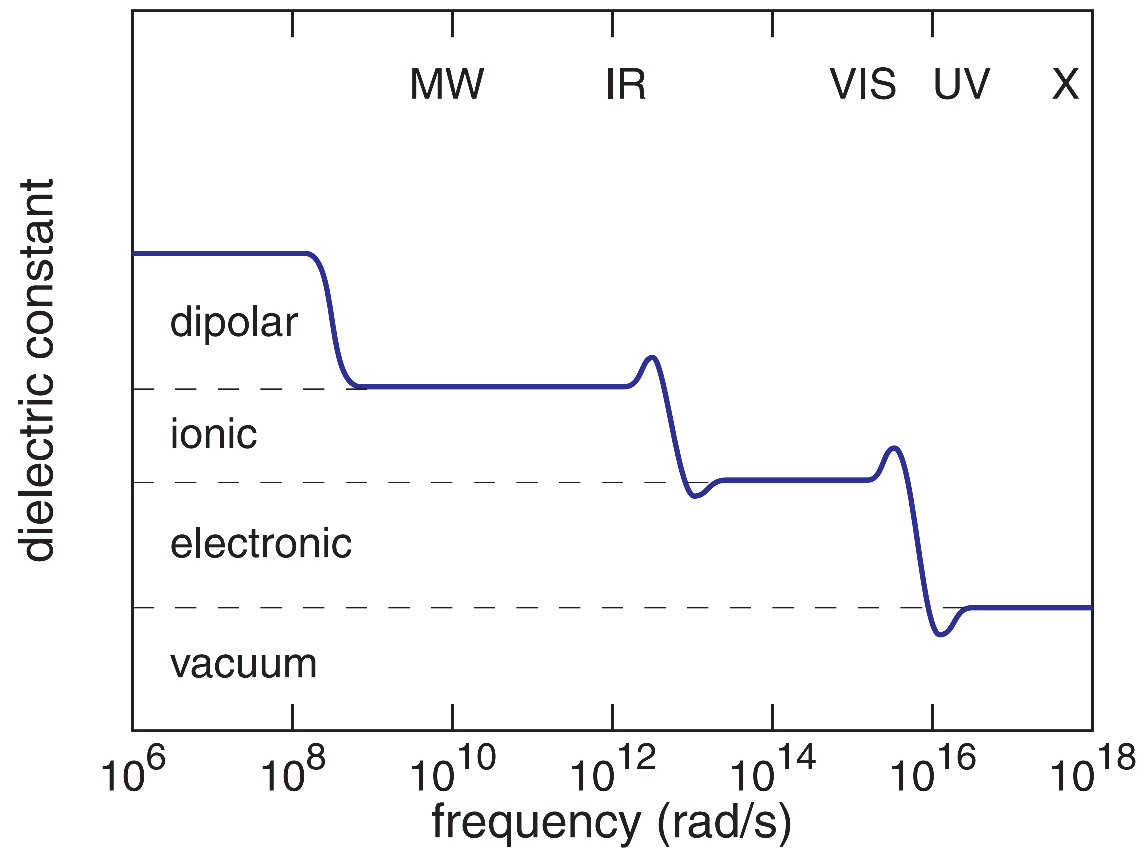

Bound electrons

Electron on a string:

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

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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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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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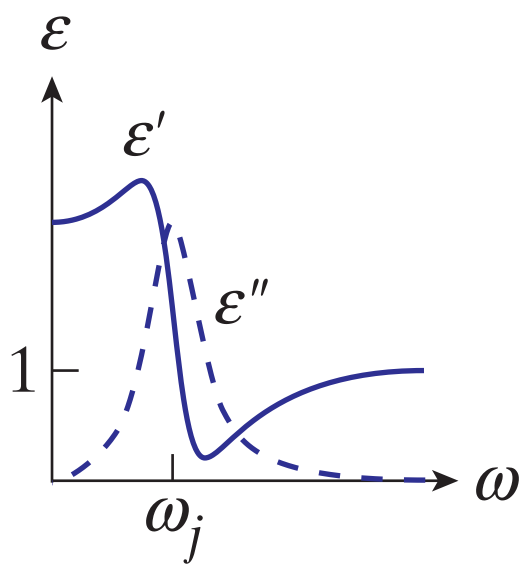
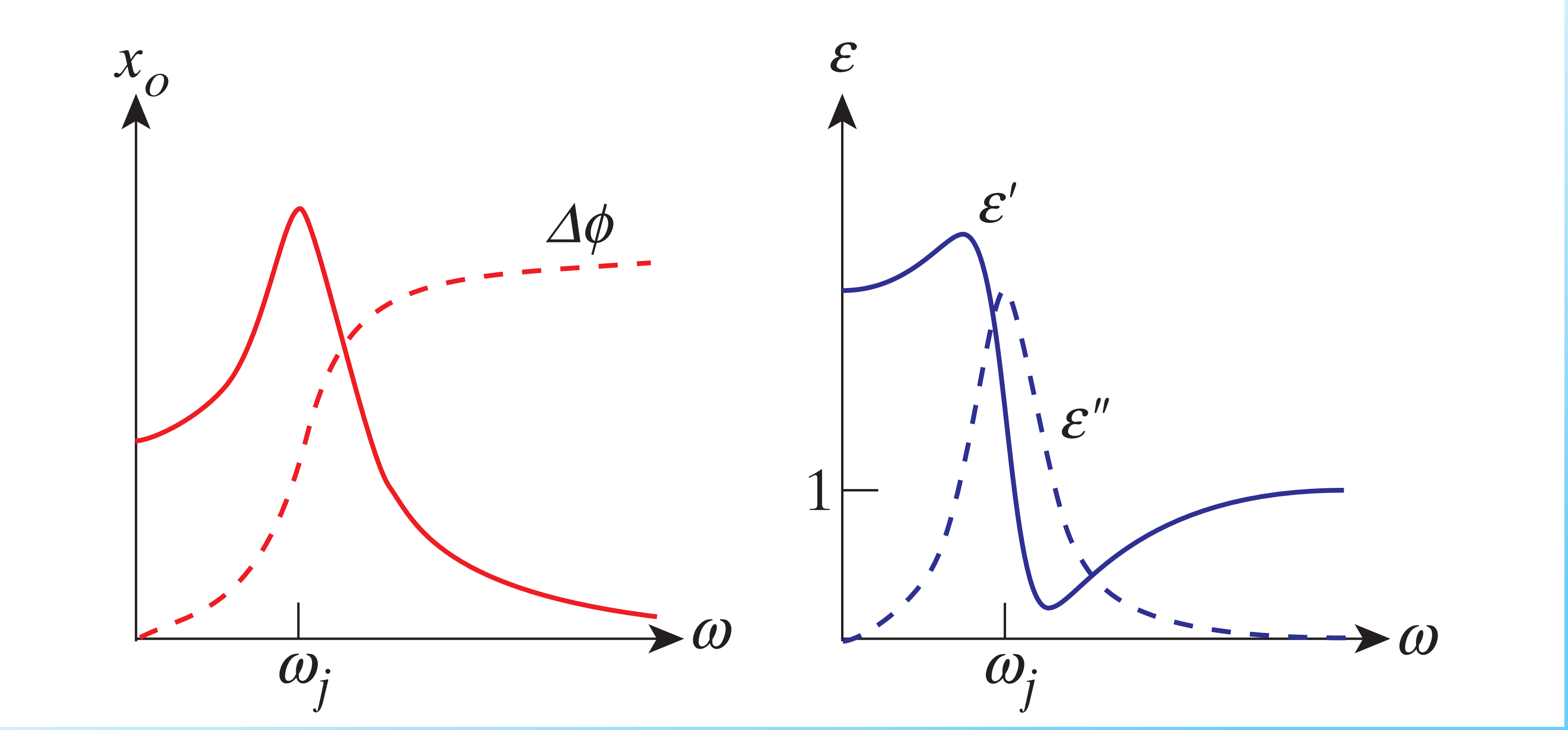
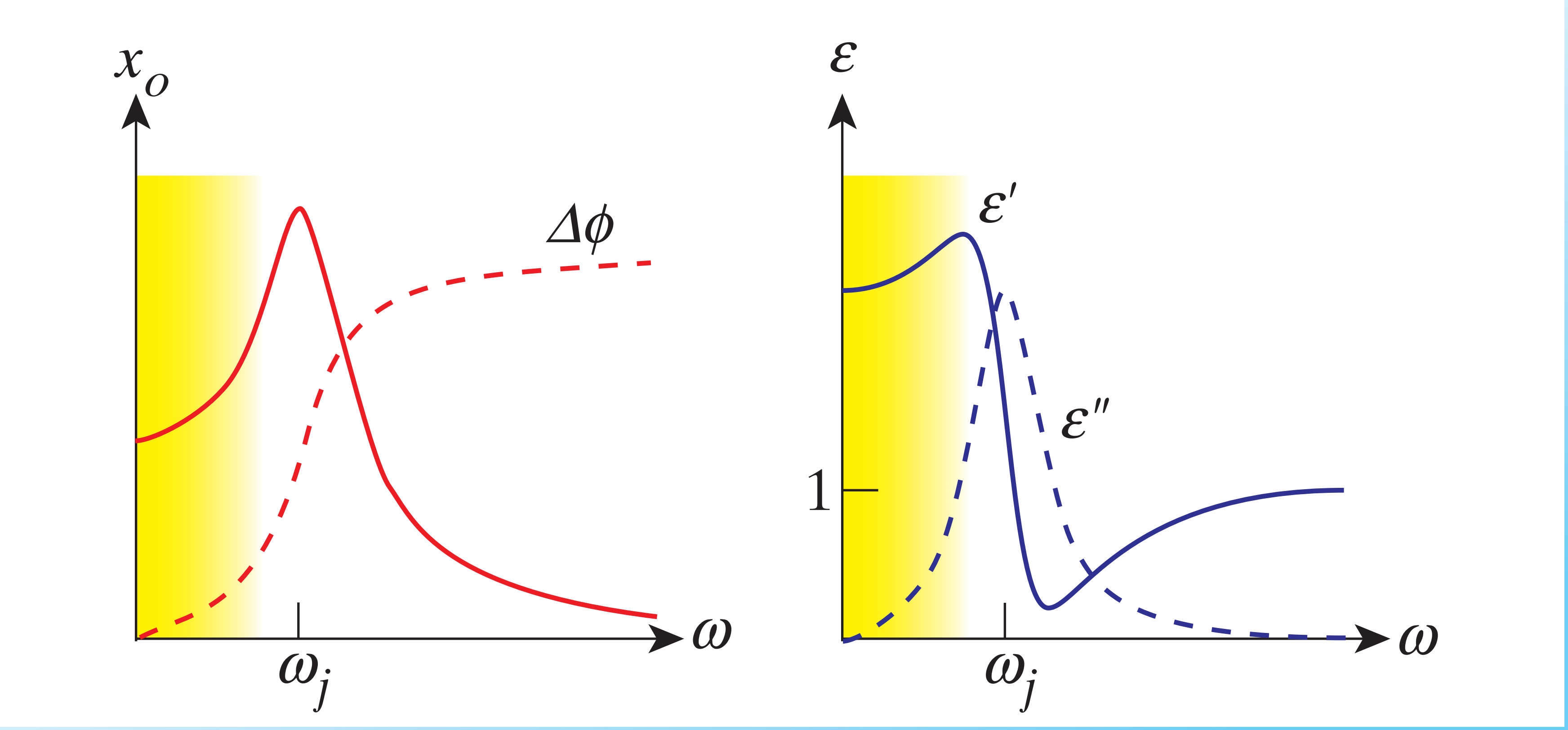


amplitude of bound charge oscillation



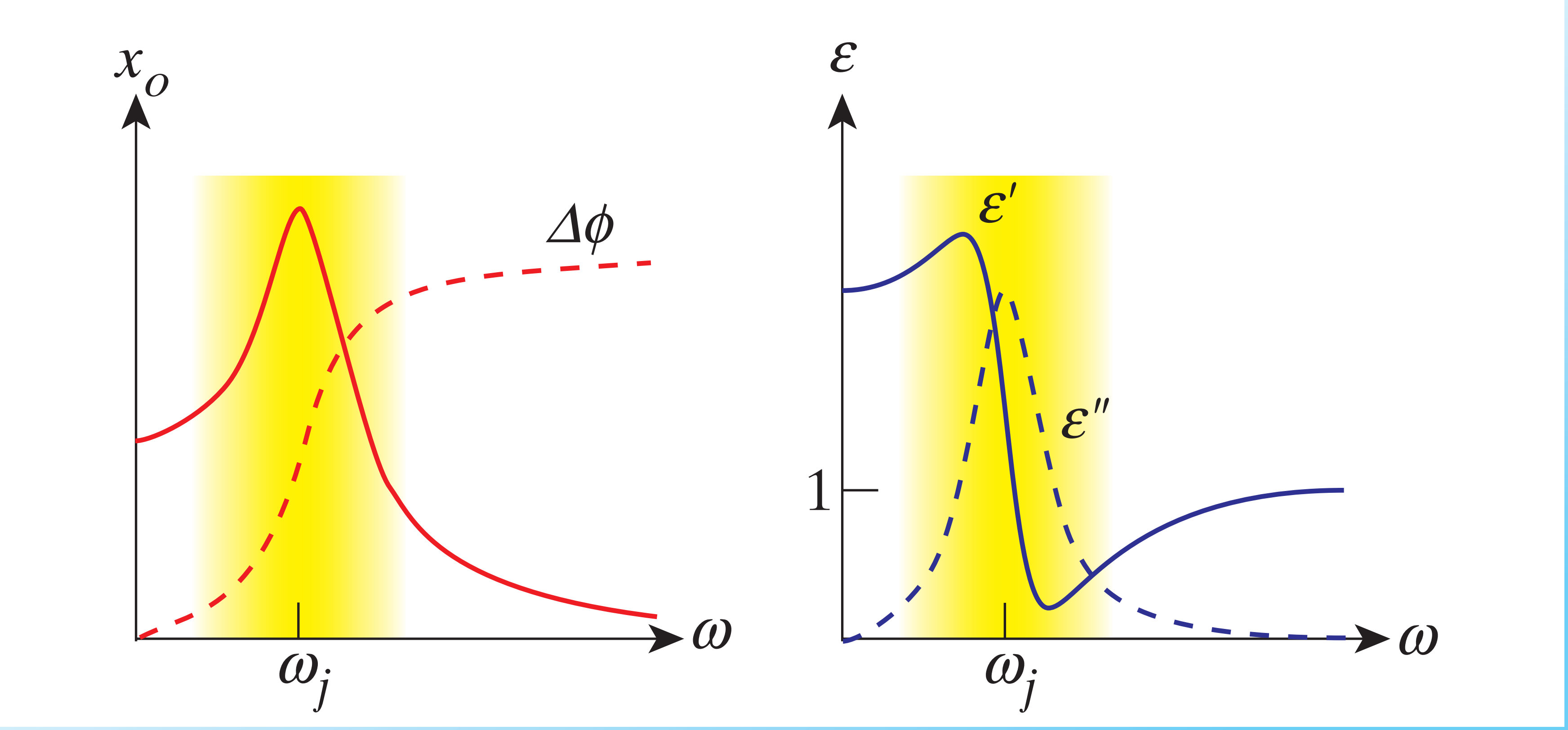
Bound electrons

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



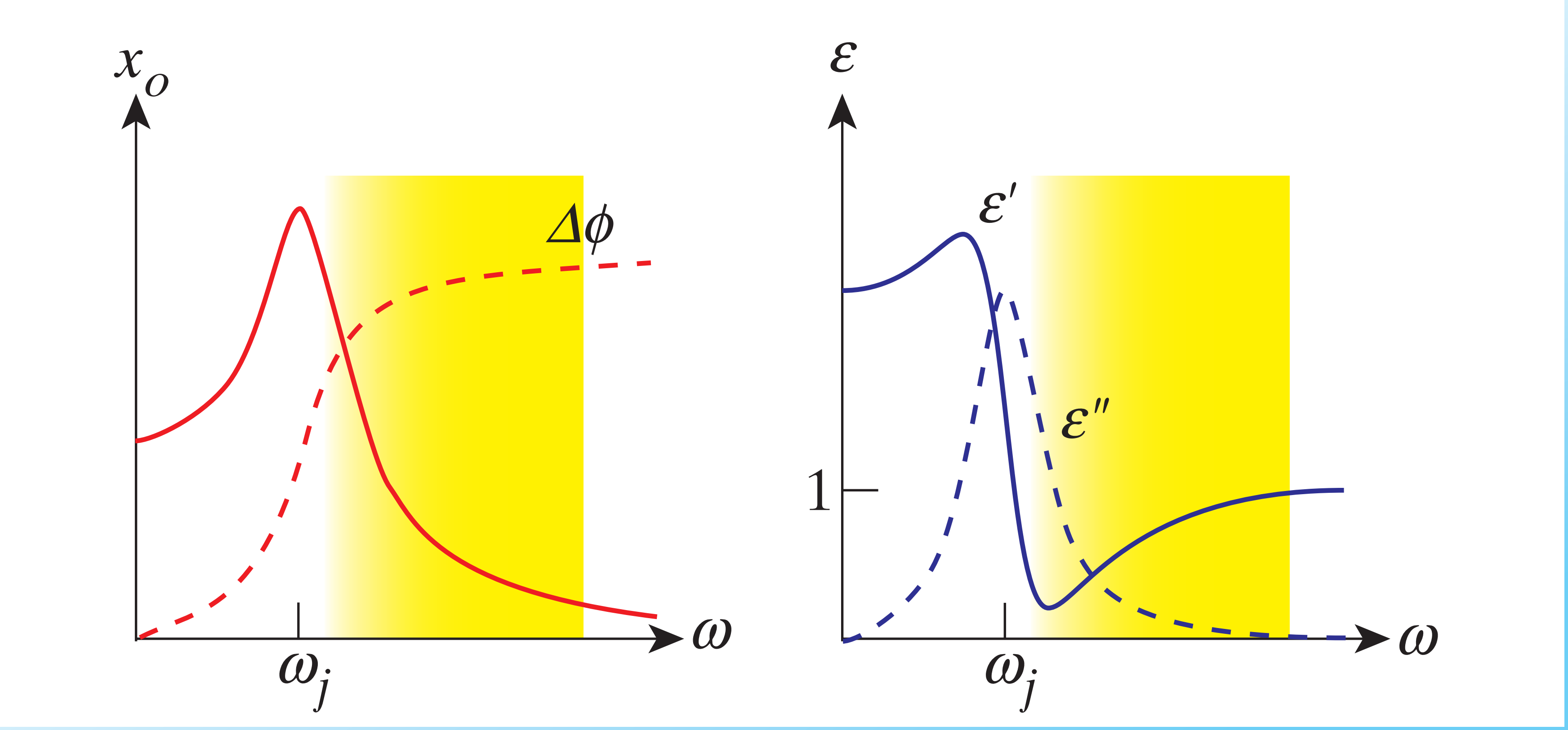
Bound electrons

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



Bound electrons

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



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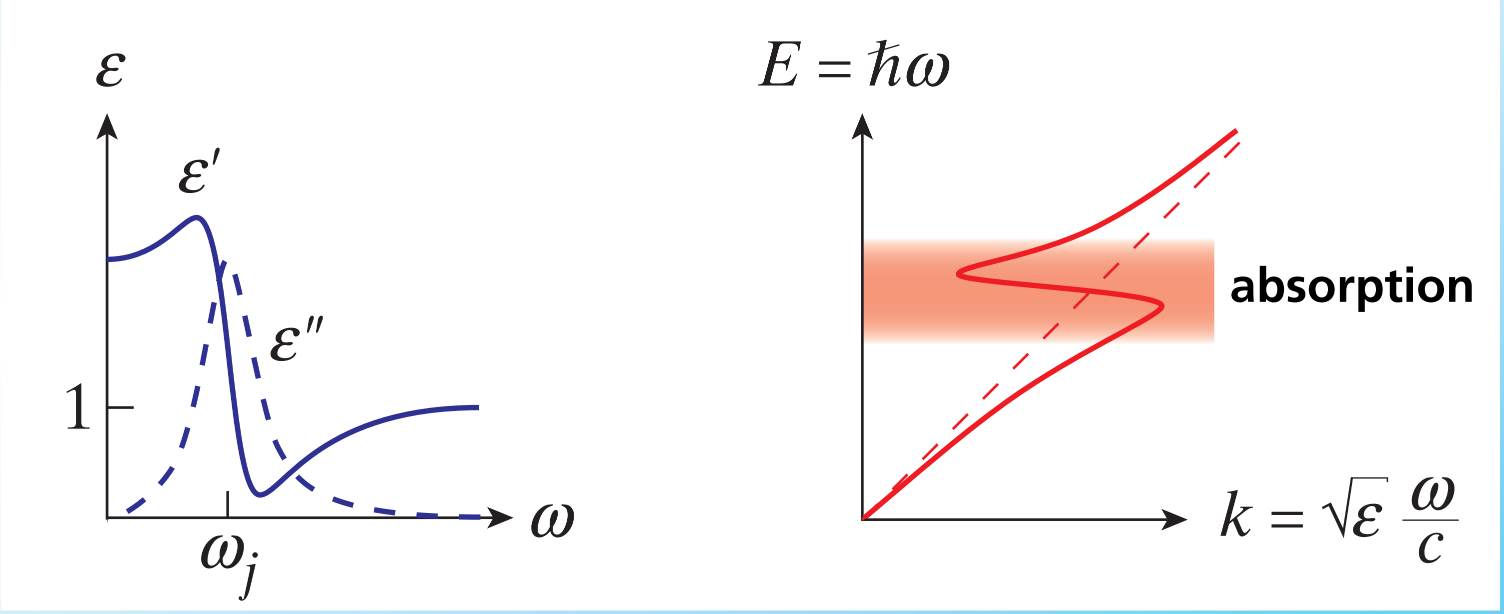

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Low frequency ($\omega \ll 1$) $\Rightarrow$ current generated

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

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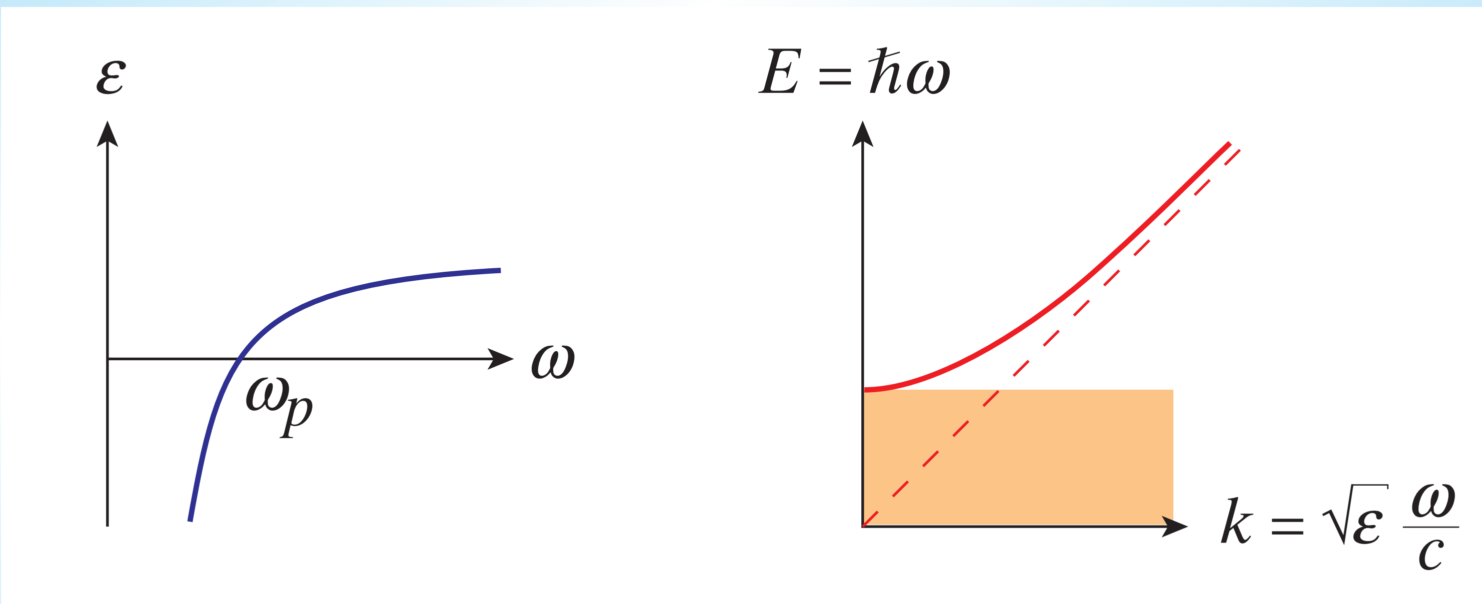
$$\epsilon(\omega) \equiv 1 + \chi_e = 1 - \frac{Ne^2}{m\epsilon_o}\frac{1}{\omega^2 + i\gamma\omega} = \epsilon'(\omega) + i\epsilon''(\omega)$$

Plasma

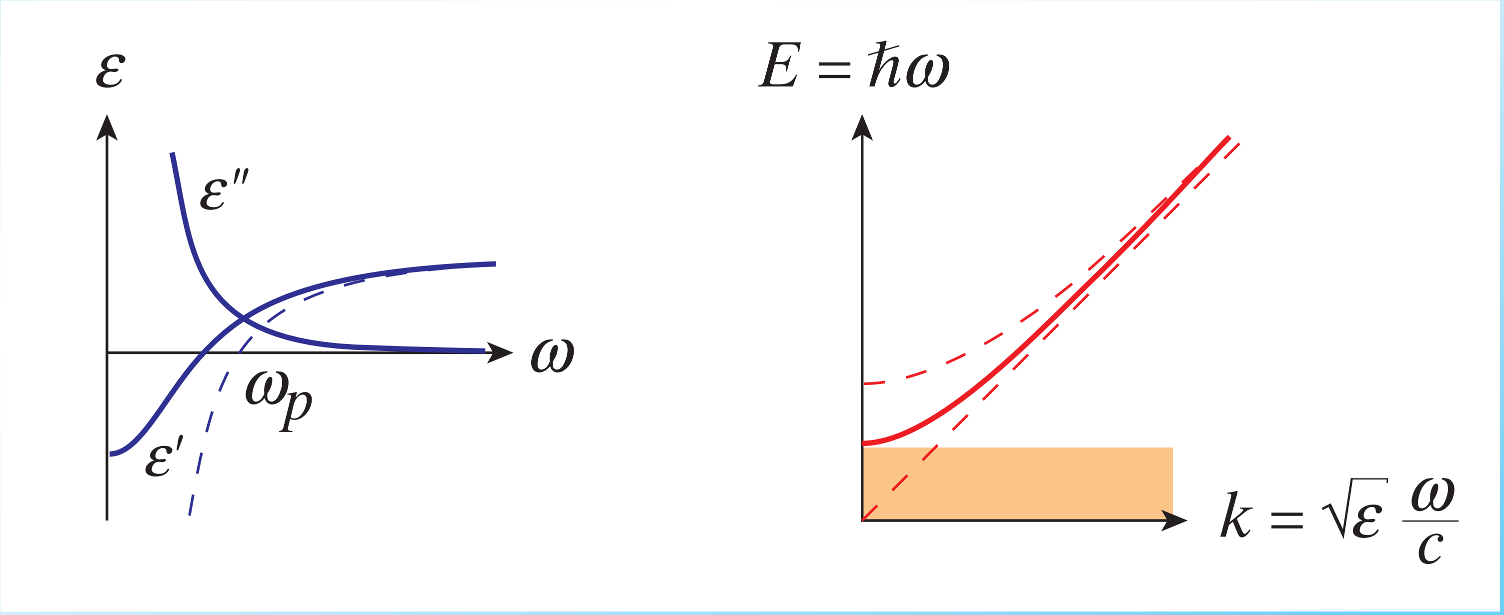
$$\gamma \approx 0 \qquad \Rightarrow \quad \epsilon'' = 0$$

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



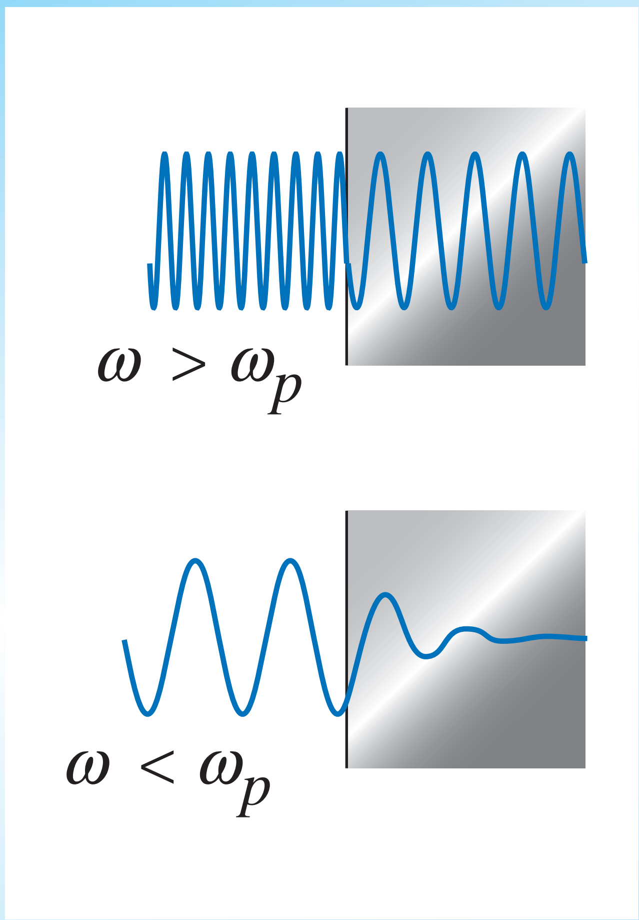
Plasma

Add damping $\gamma \lesssim \omega_p$



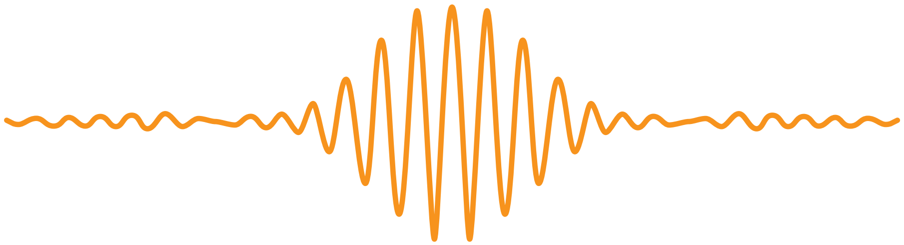
Plasma

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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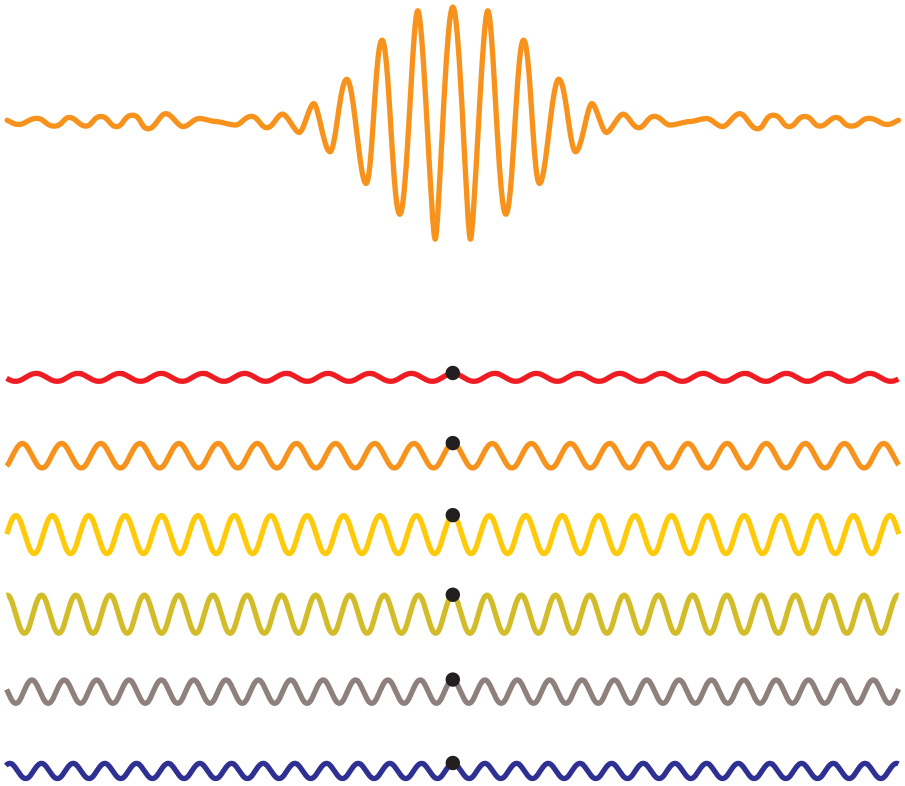

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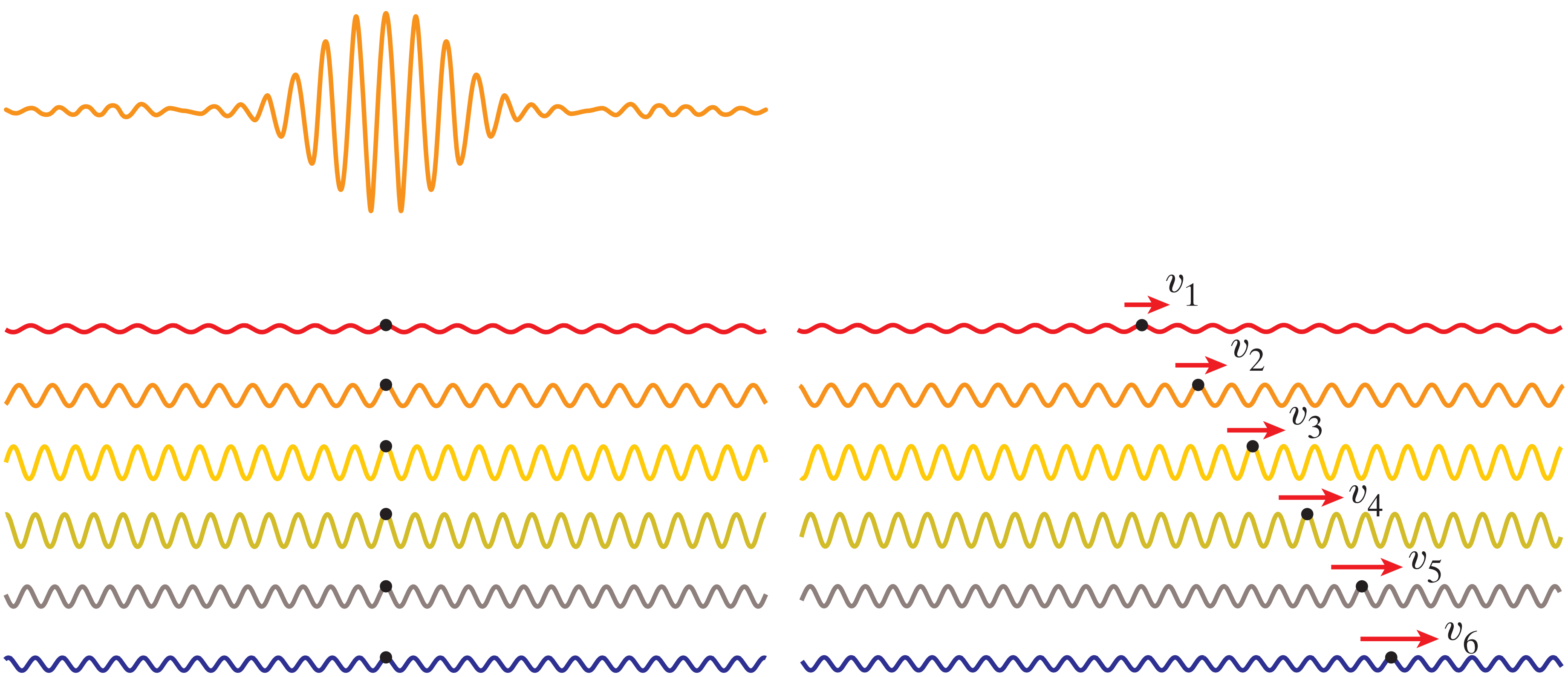

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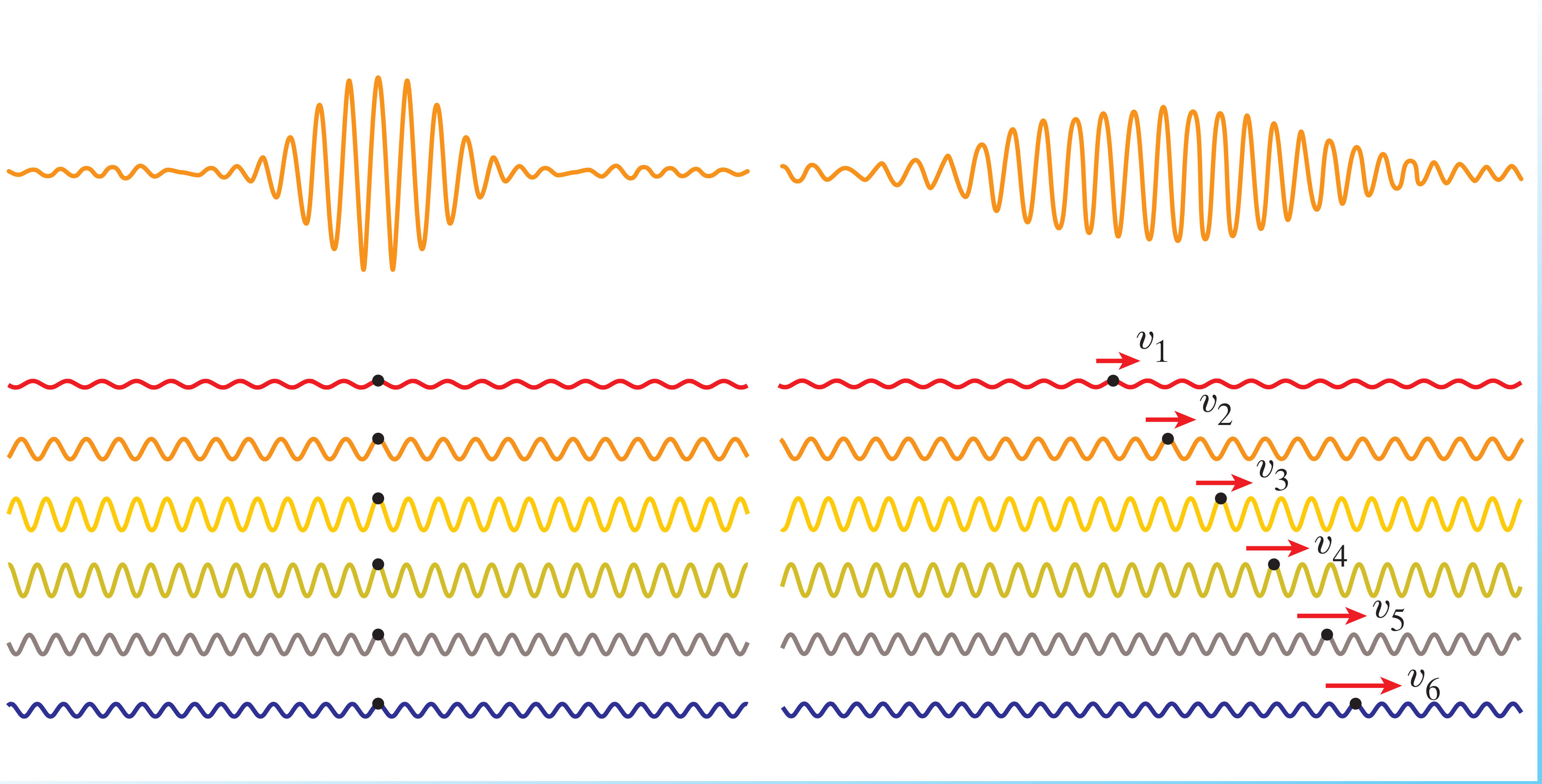

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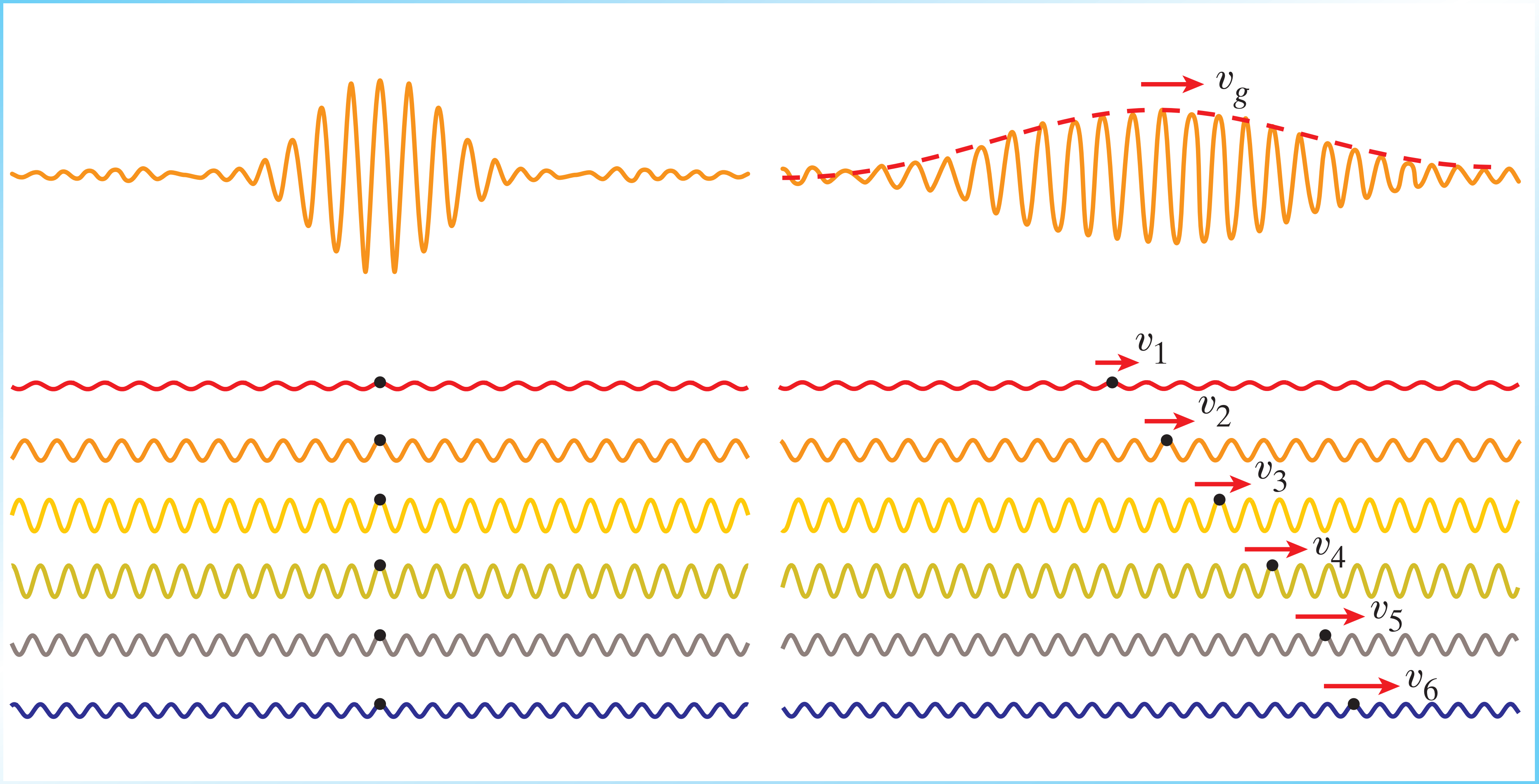
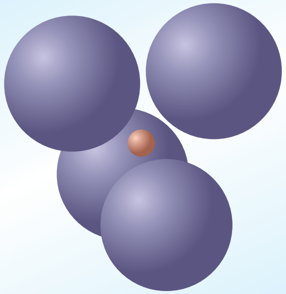


Nonlinear optics

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



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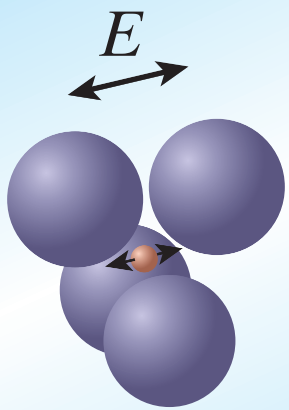

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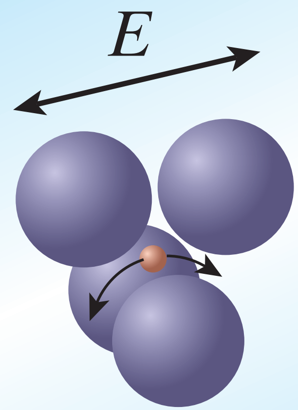

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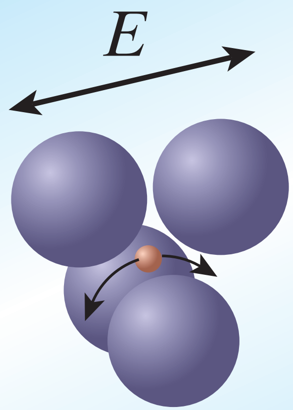
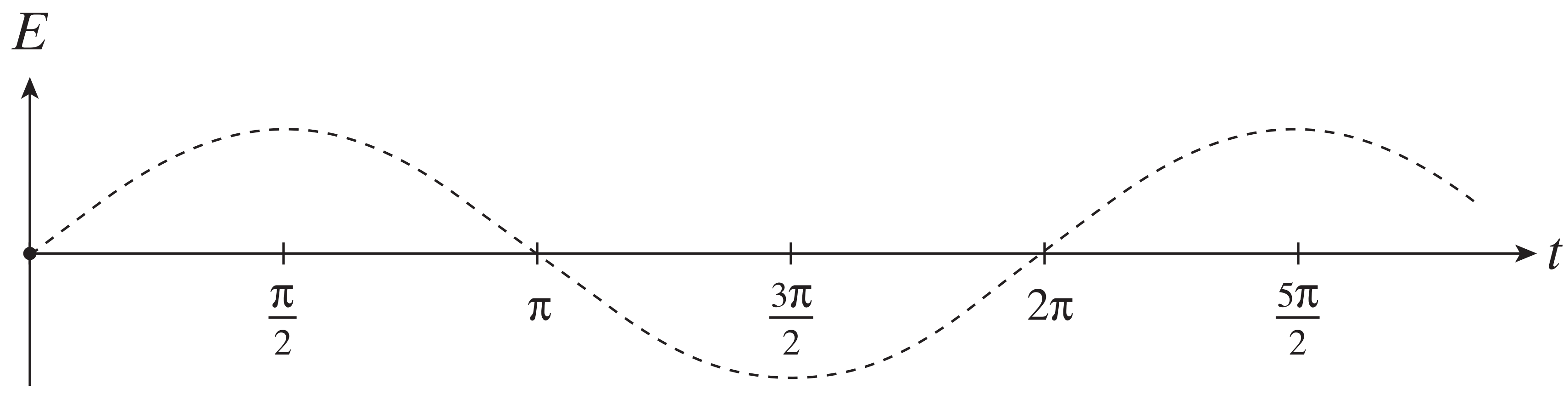


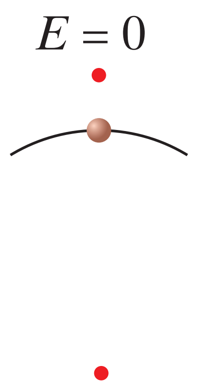
Nonlinear polarization:

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

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

Nonlinear optics





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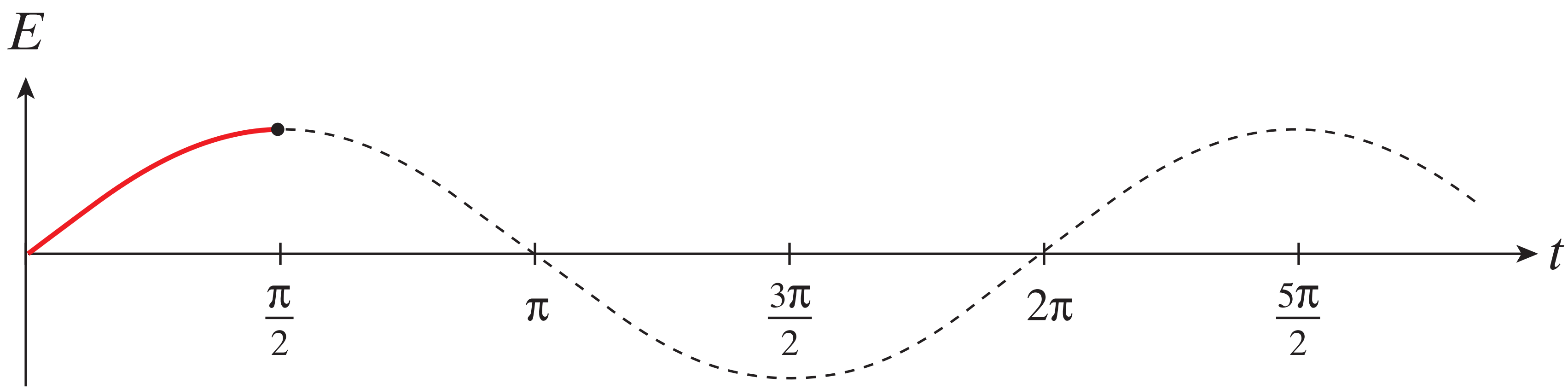

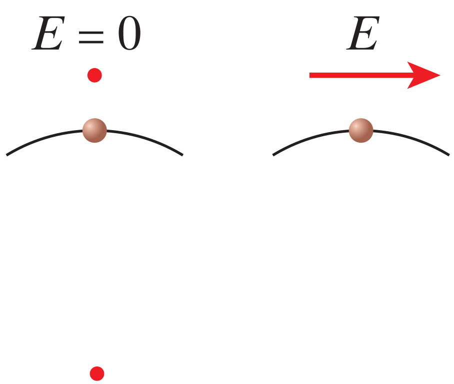

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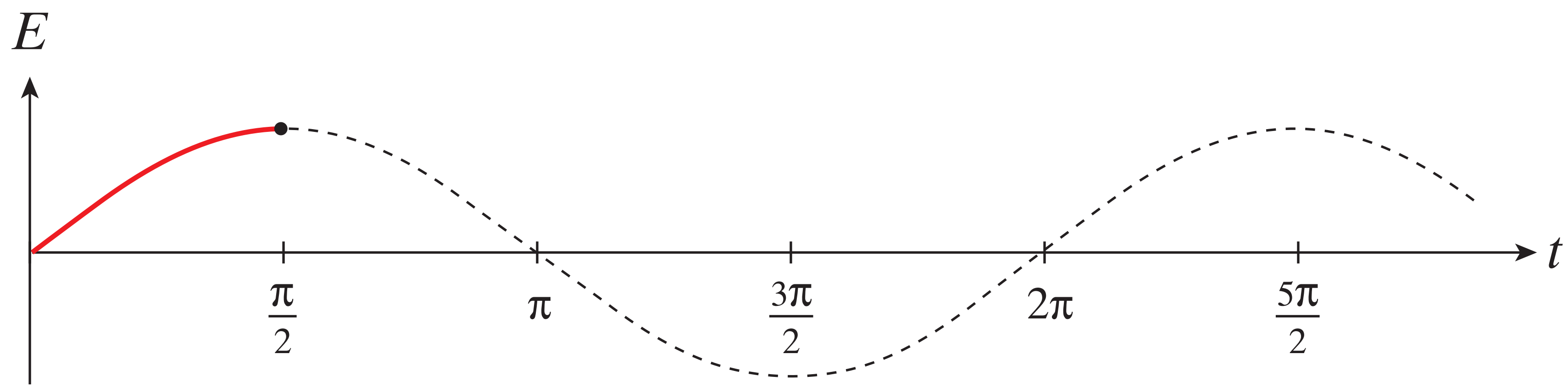

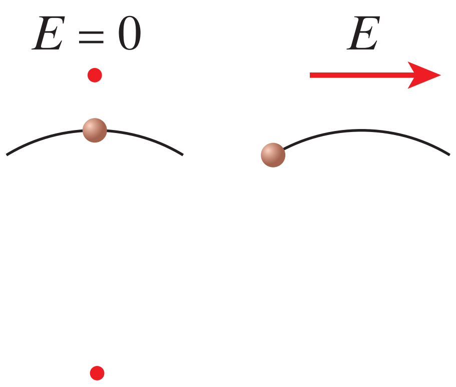

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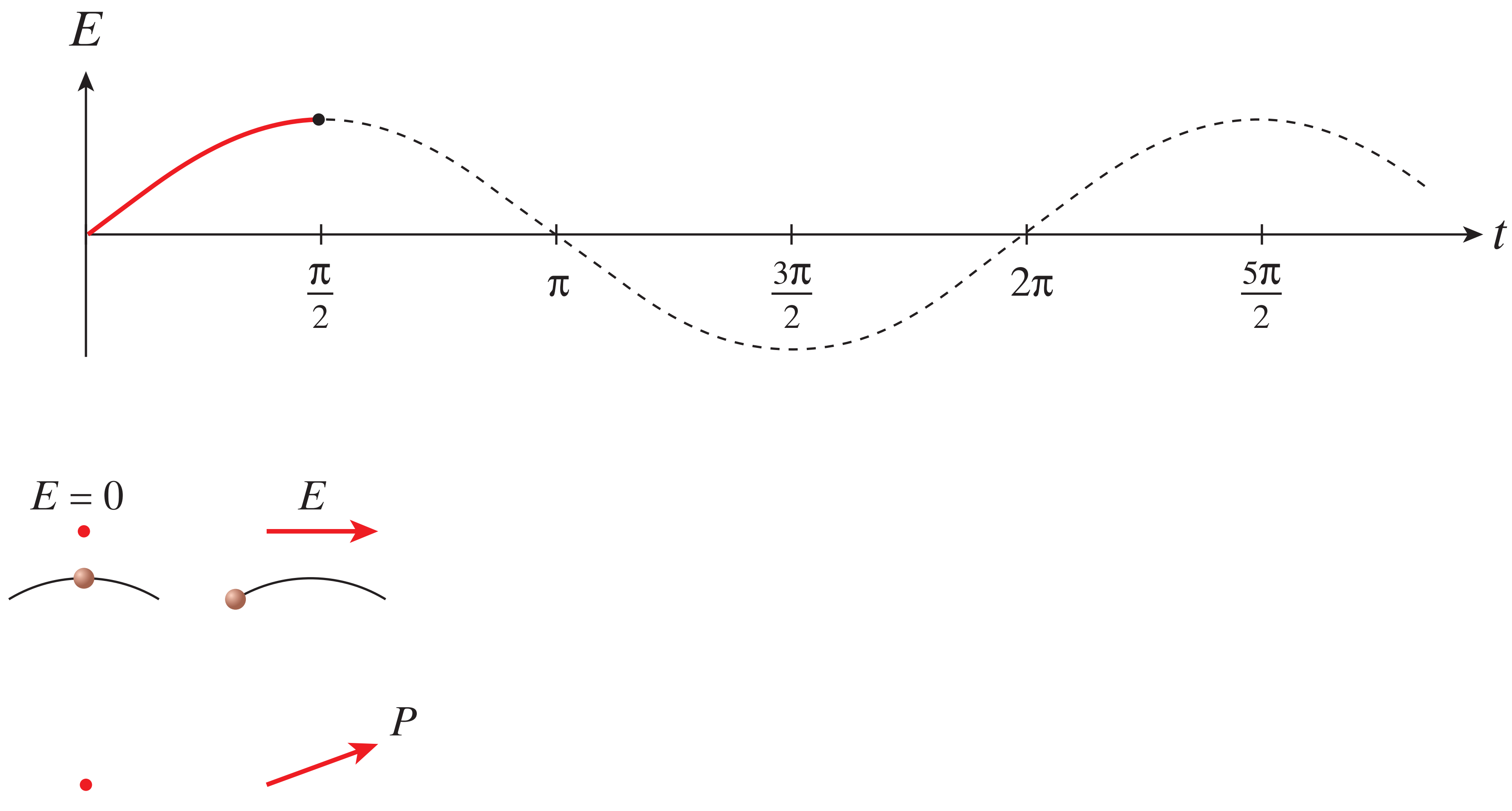

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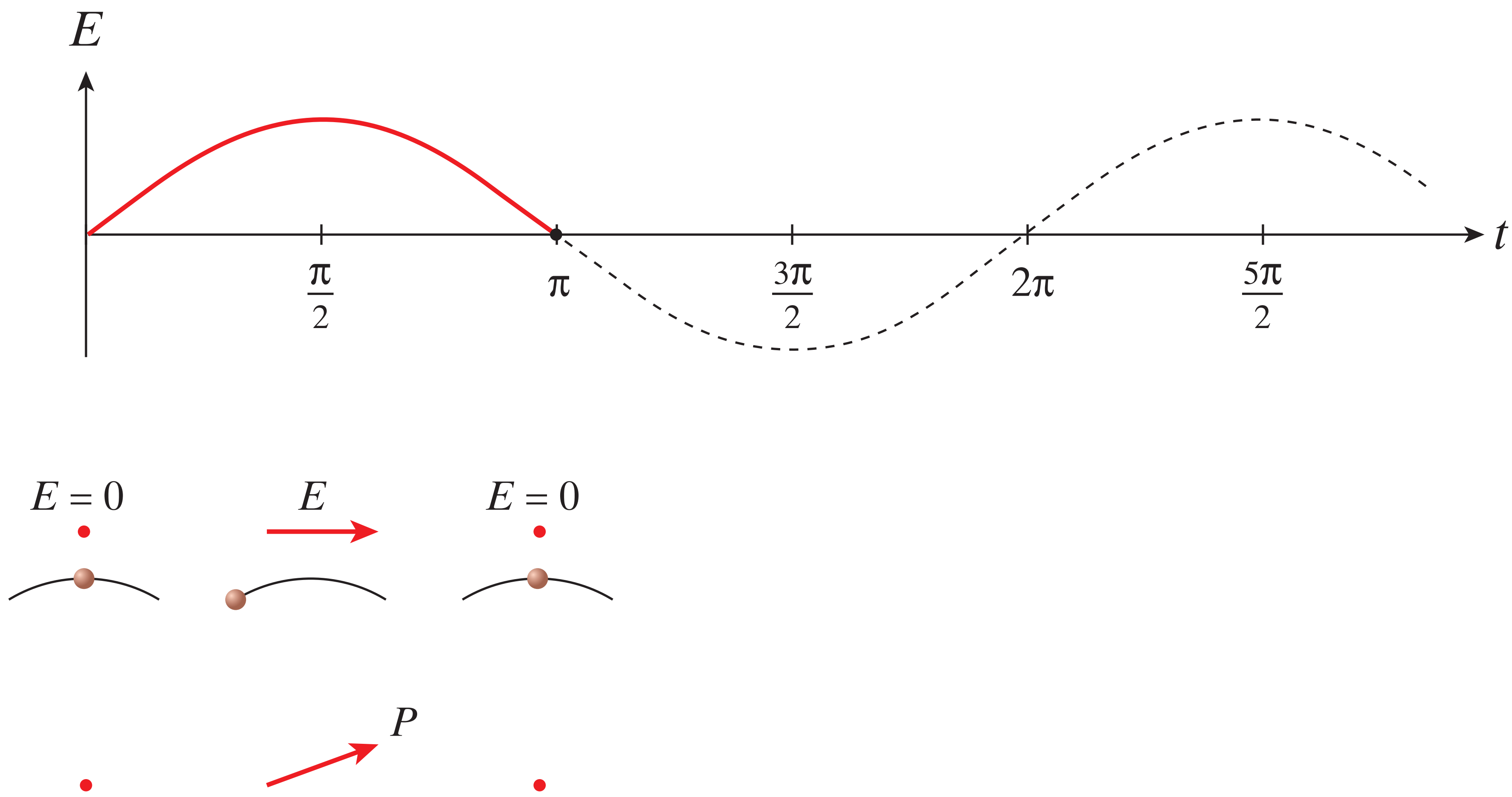

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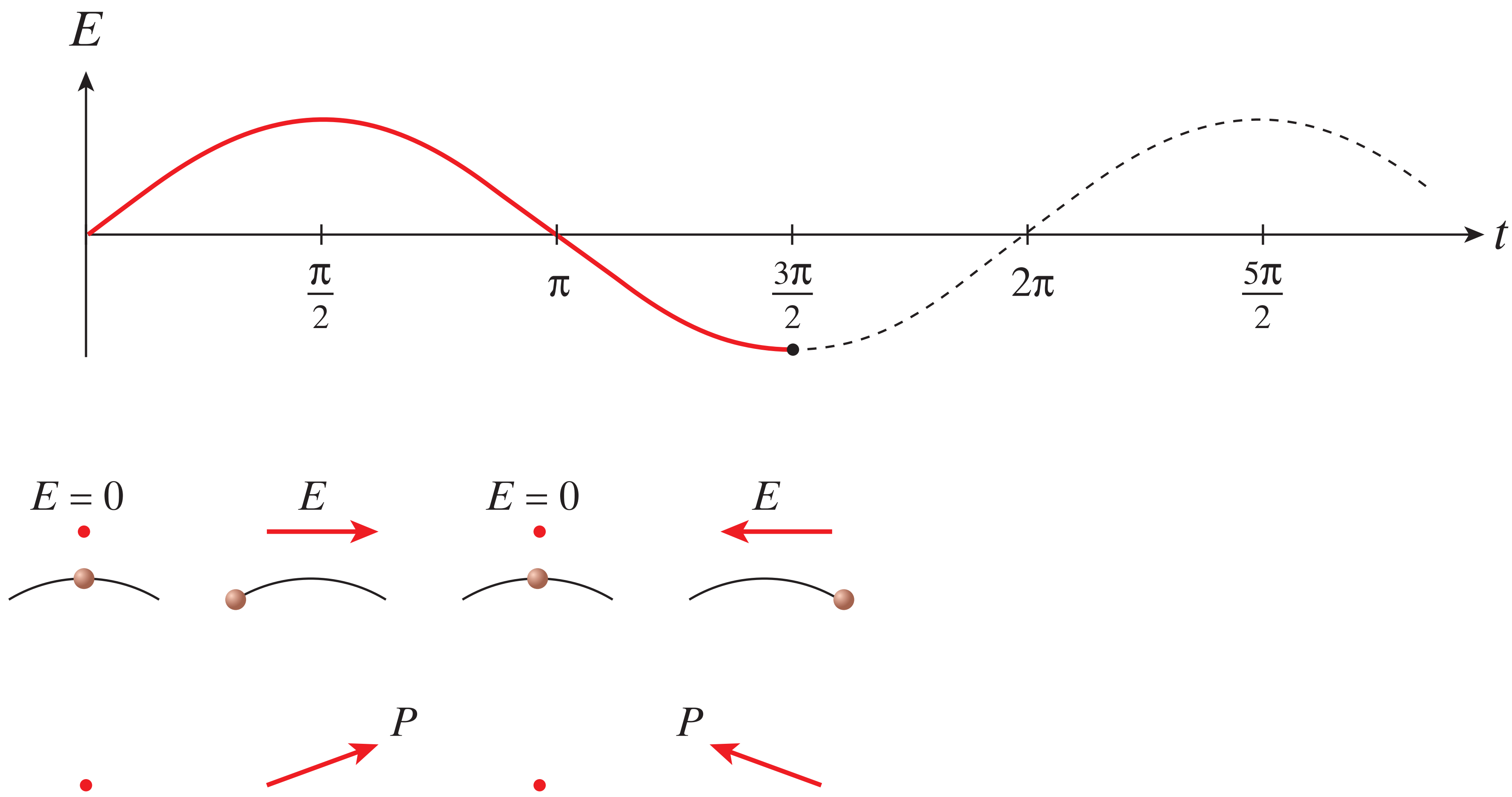

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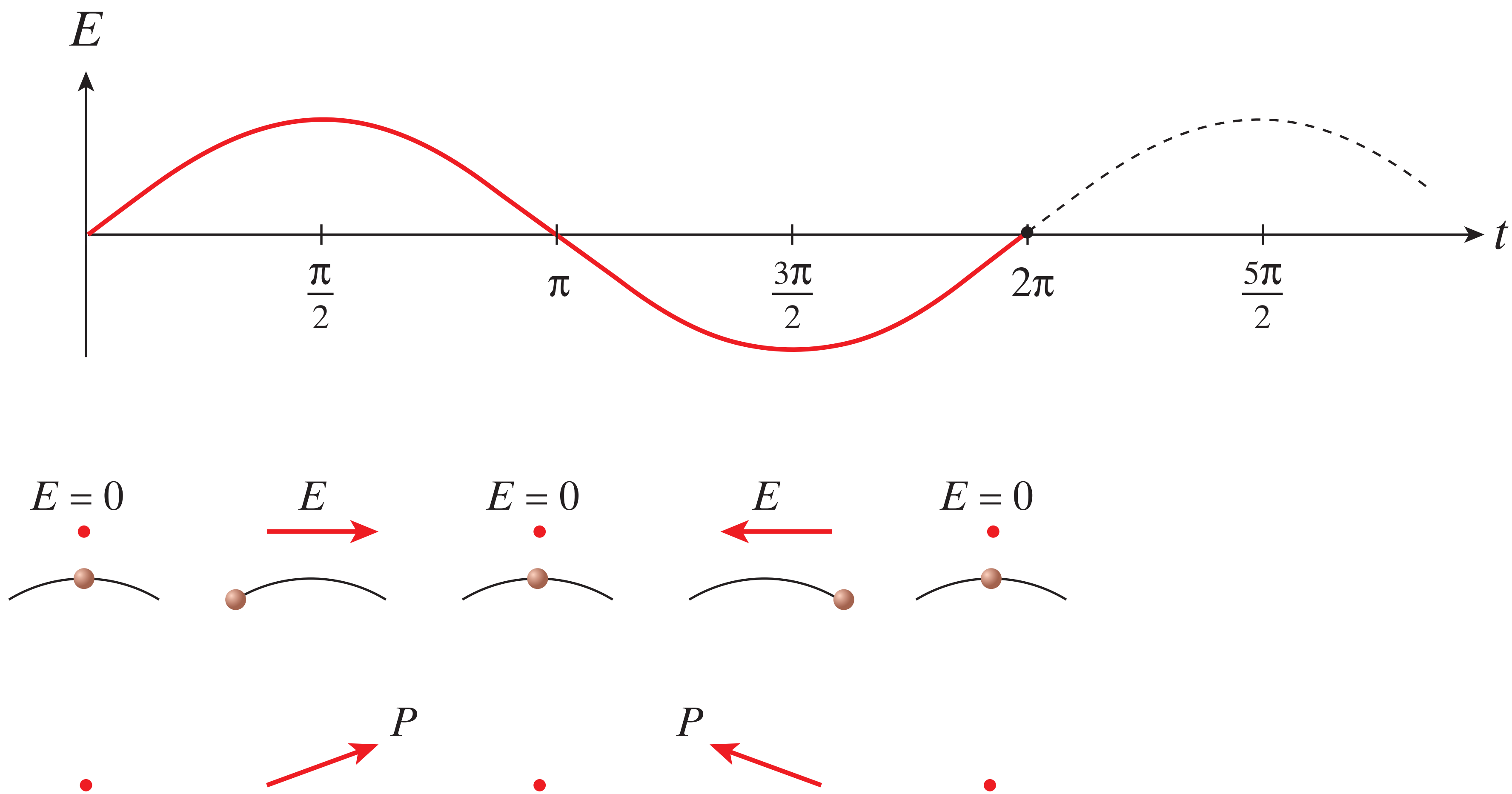

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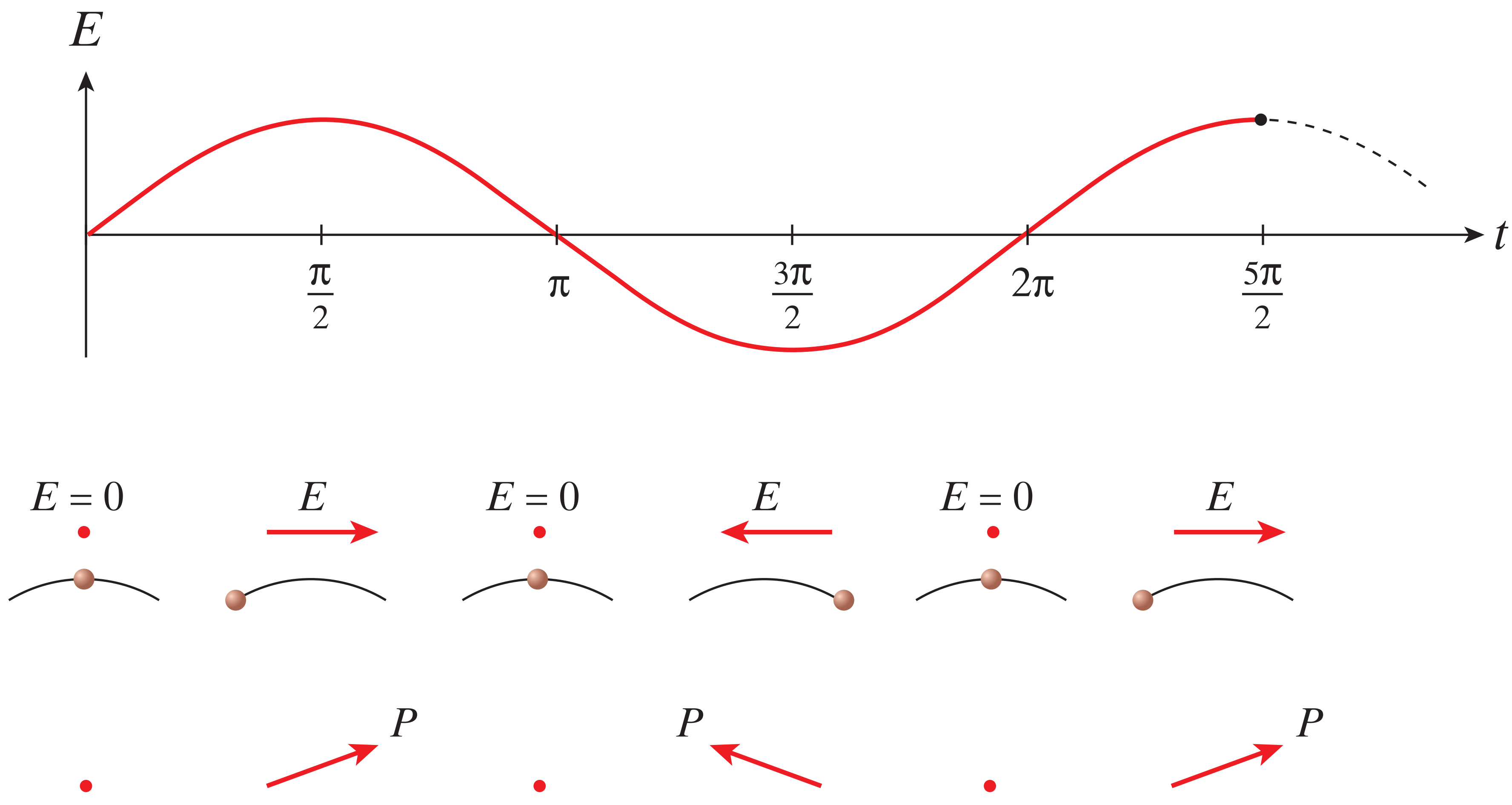
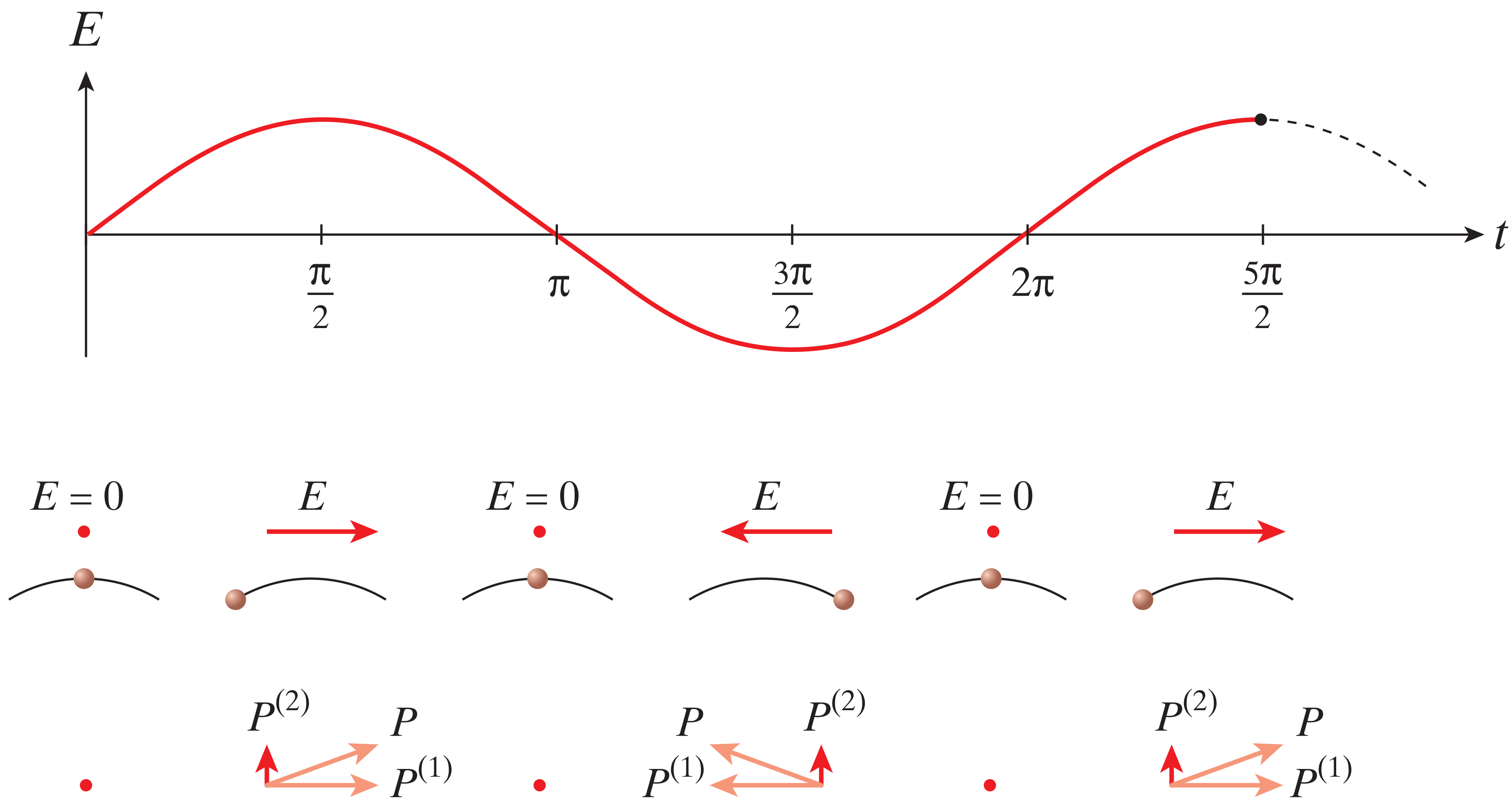
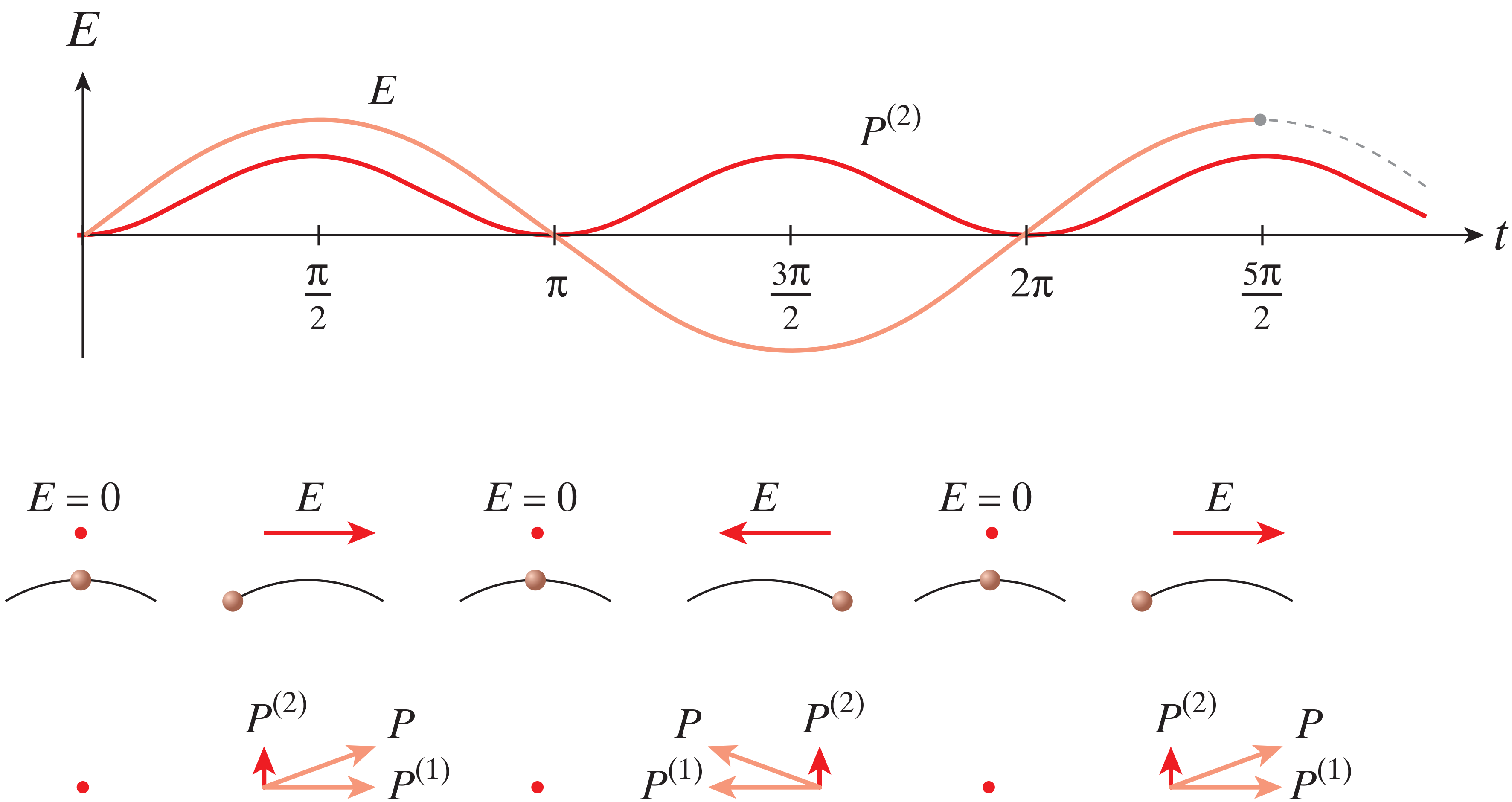


Nonlinear optics



Nonlinear optics



In medium with inversion symmetry

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

Nonlinear optics

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In medium with inversion symmetry

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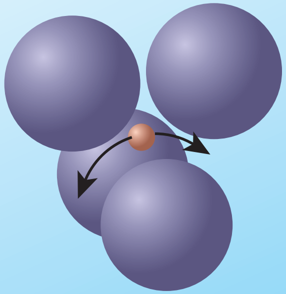
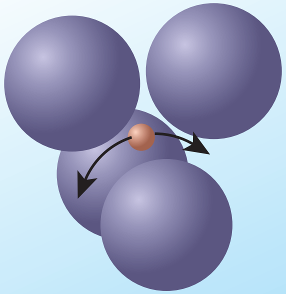
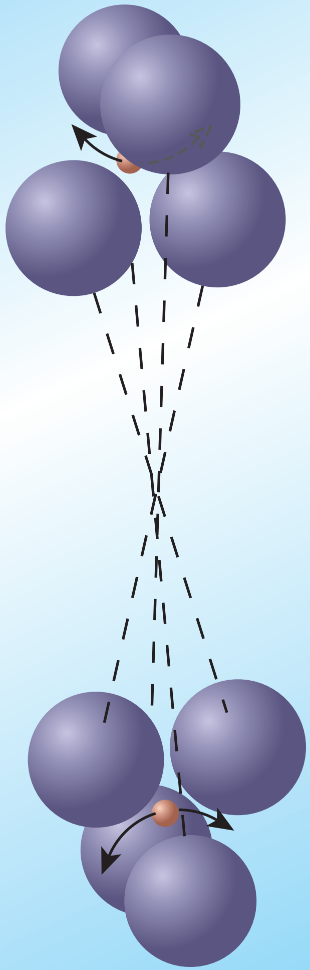
… but …



Nonlinear optics

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 optics

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Third order polarization

$$P^{(3)}(t) = \chi^{(3)}E(t)E^*(t)E(t) = \chi^{(3)}I(t)E(t)$$

Nonlinear optics

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Nonlinear optics

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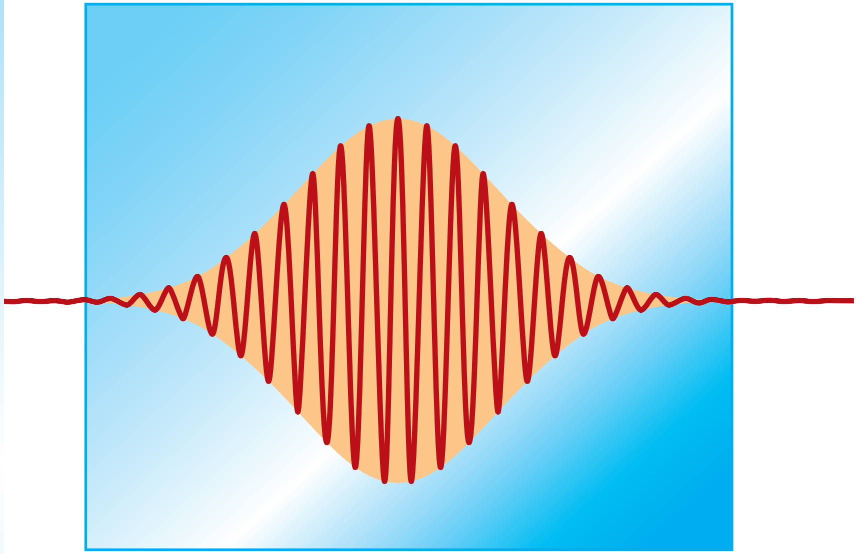
$$n = \sqrt{\epsilon} = \sqrt{1 + \chi_{eff}} \approx \sqrt{1 + \chi^{(1)}} + \frac{1}{2}\frac{\chi^{(3)}I}{\sqrt{1 + \chi^{(1)}}} = n_o + n_2 I$$

Intensity dependent index of refraction:

$$n = n_o + n_2 I$$



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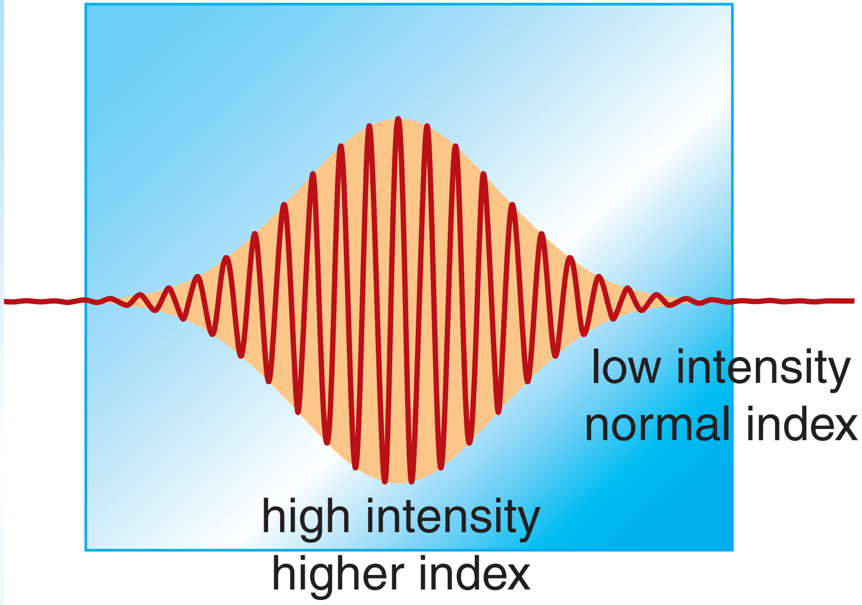

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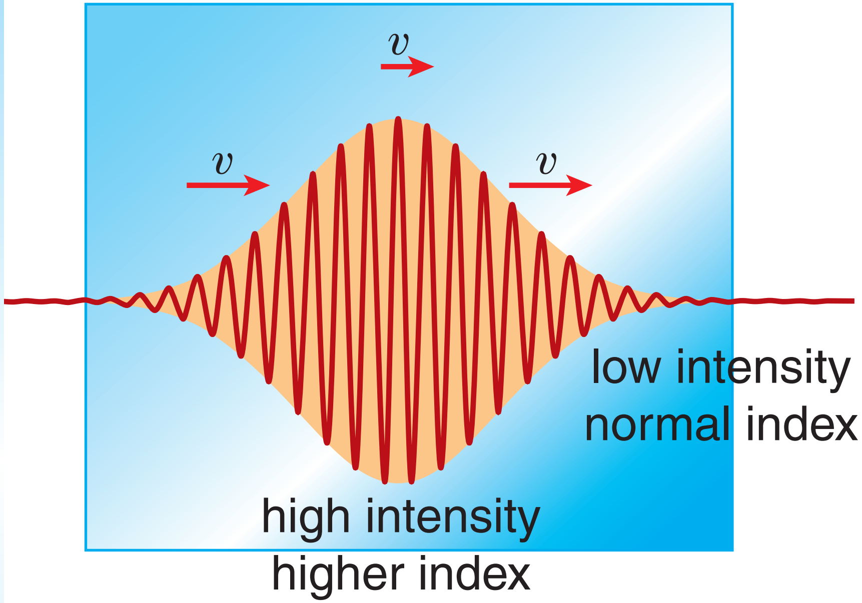

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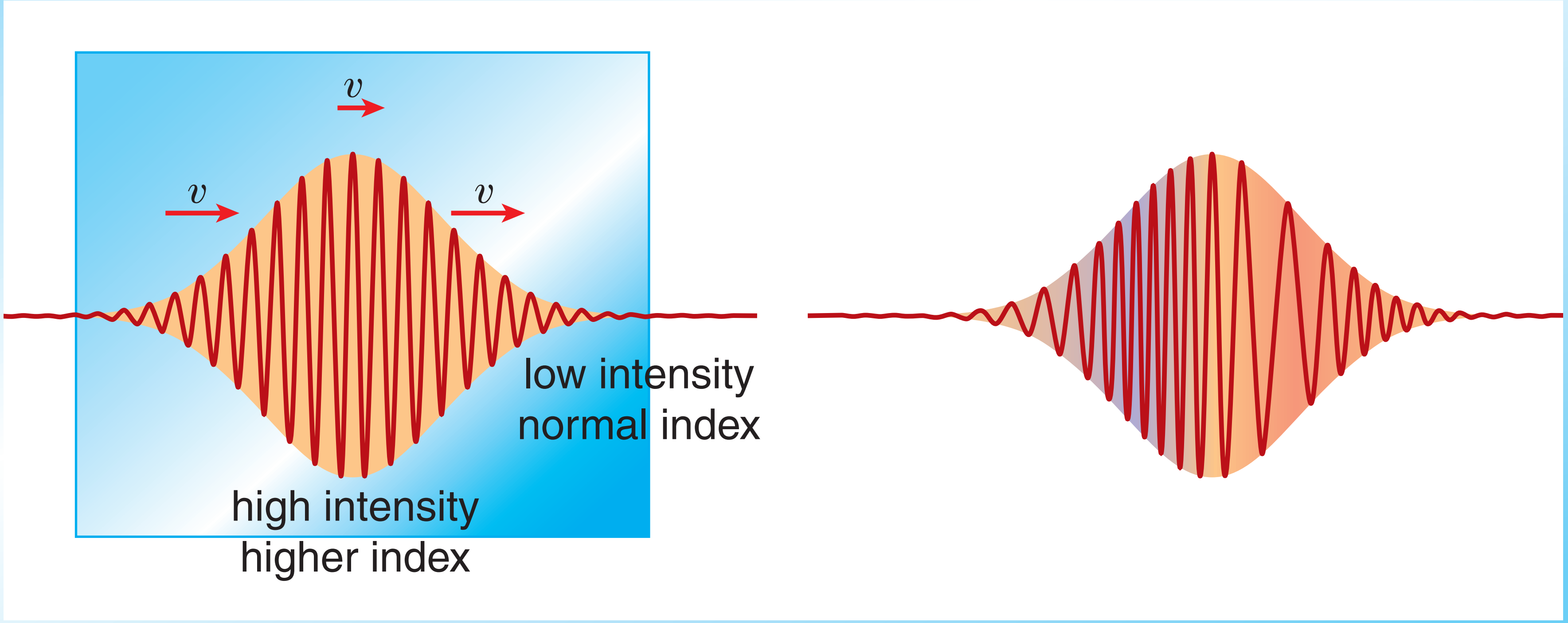

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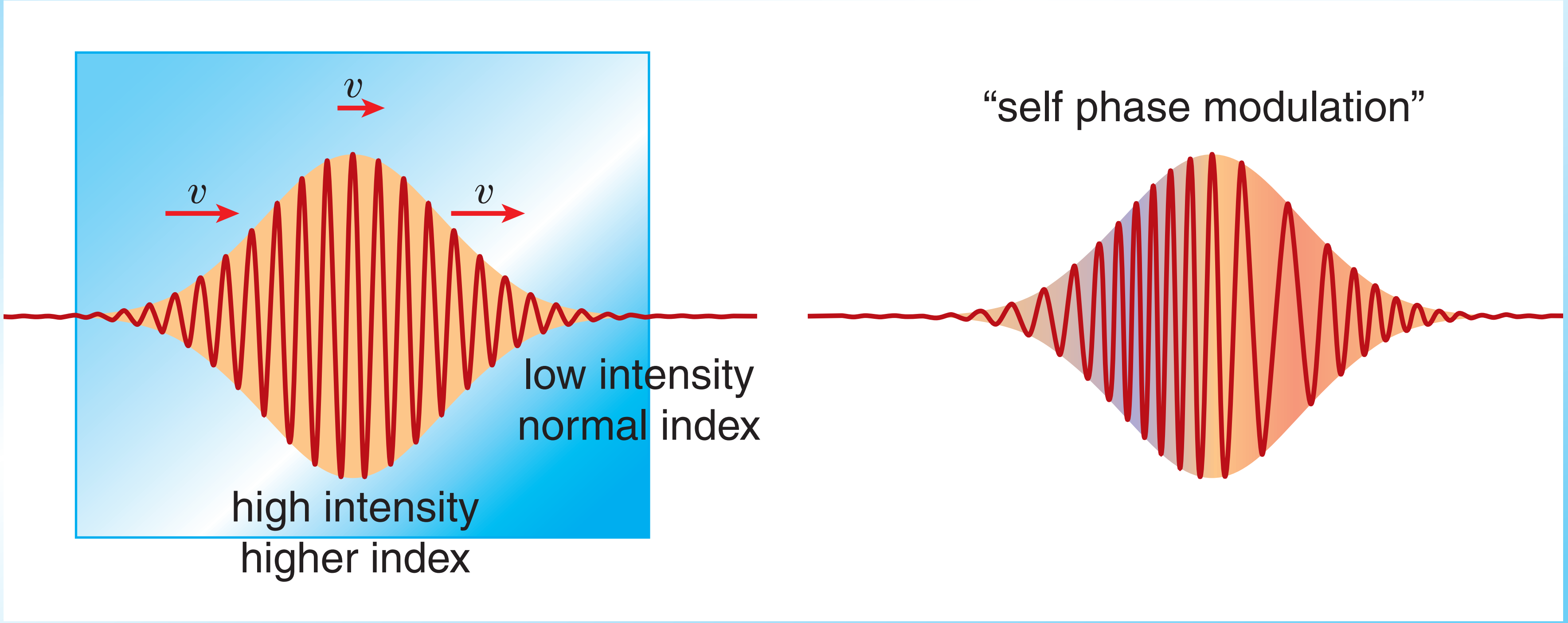

Phase:

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

Nonlinear optics

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$$\phi = \frac{2\pi}{\lambda} L(n_o + n_2 I)$$

Nonlinear optics

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$$\Delta\omega = -\frac{d\phi}{dt} = \frac{-2\pi}{\lambda} L n_2 \frac{dI}{dt}$$

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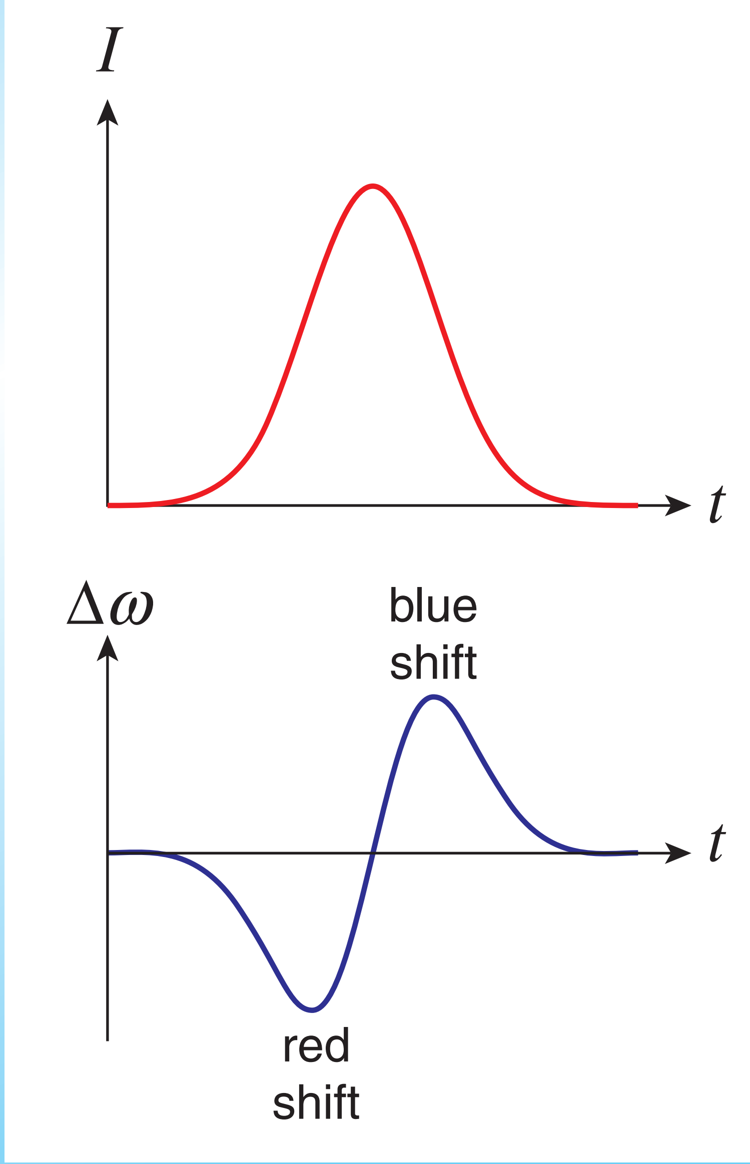
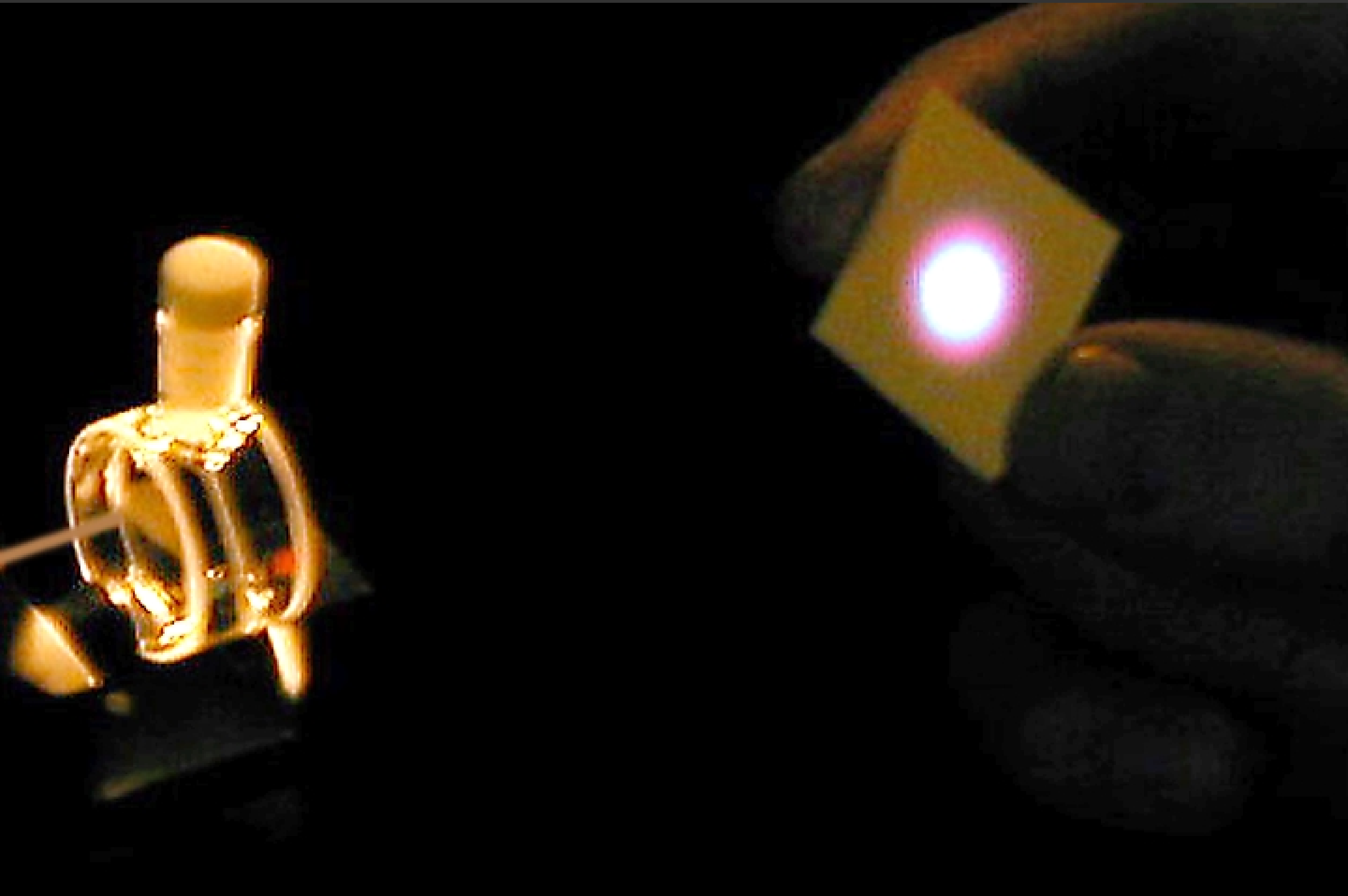
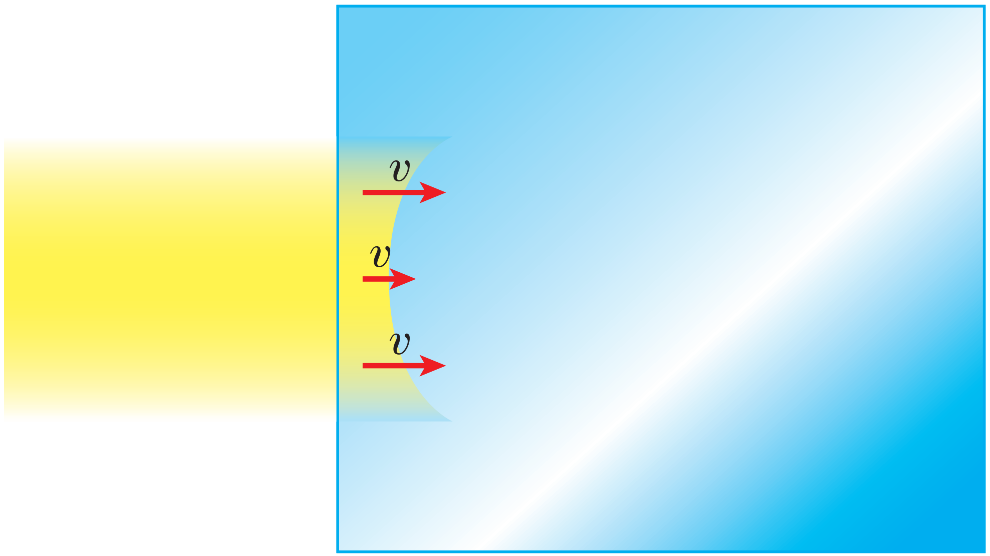


Nonlinear optics

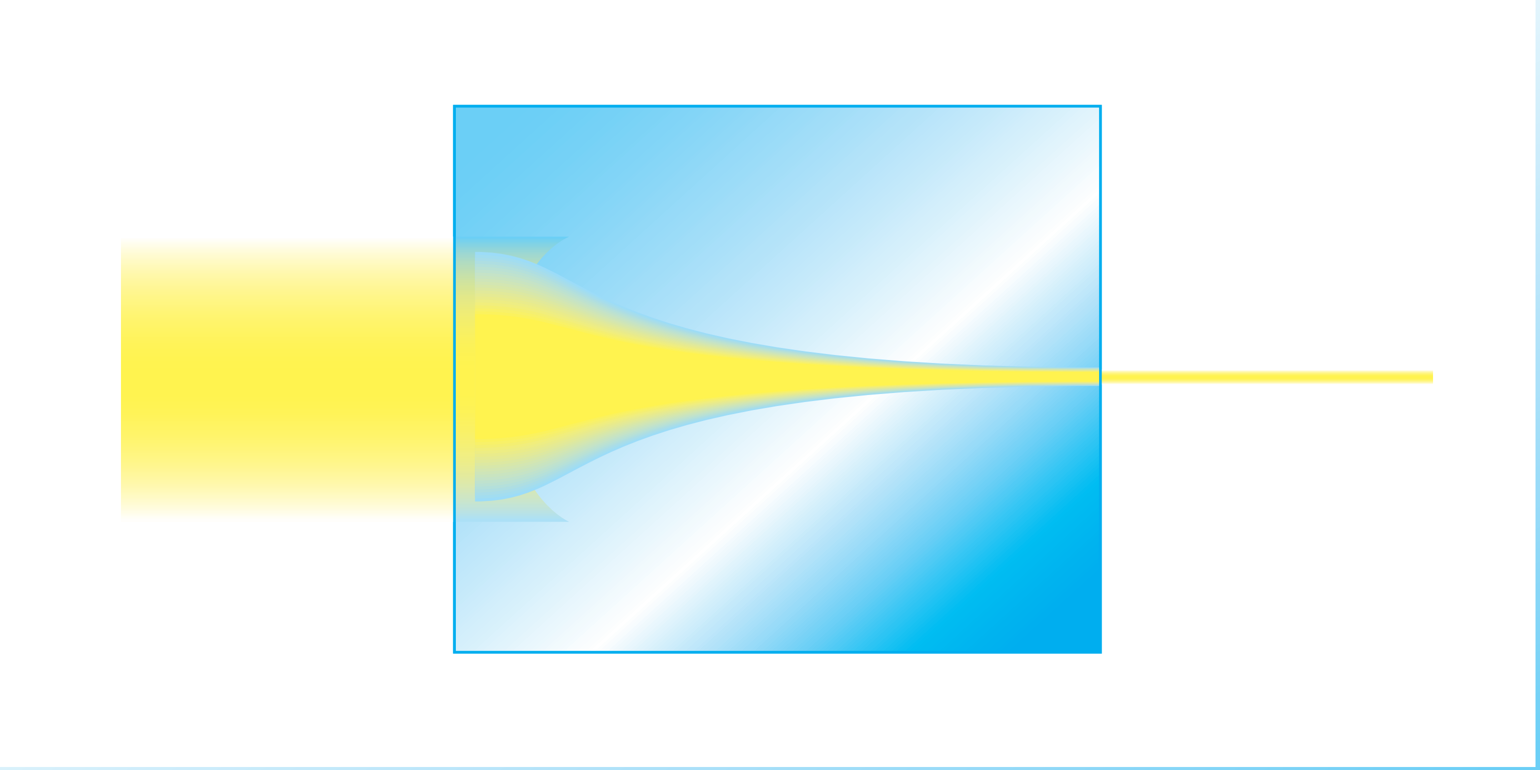


Spatial intensity profile…

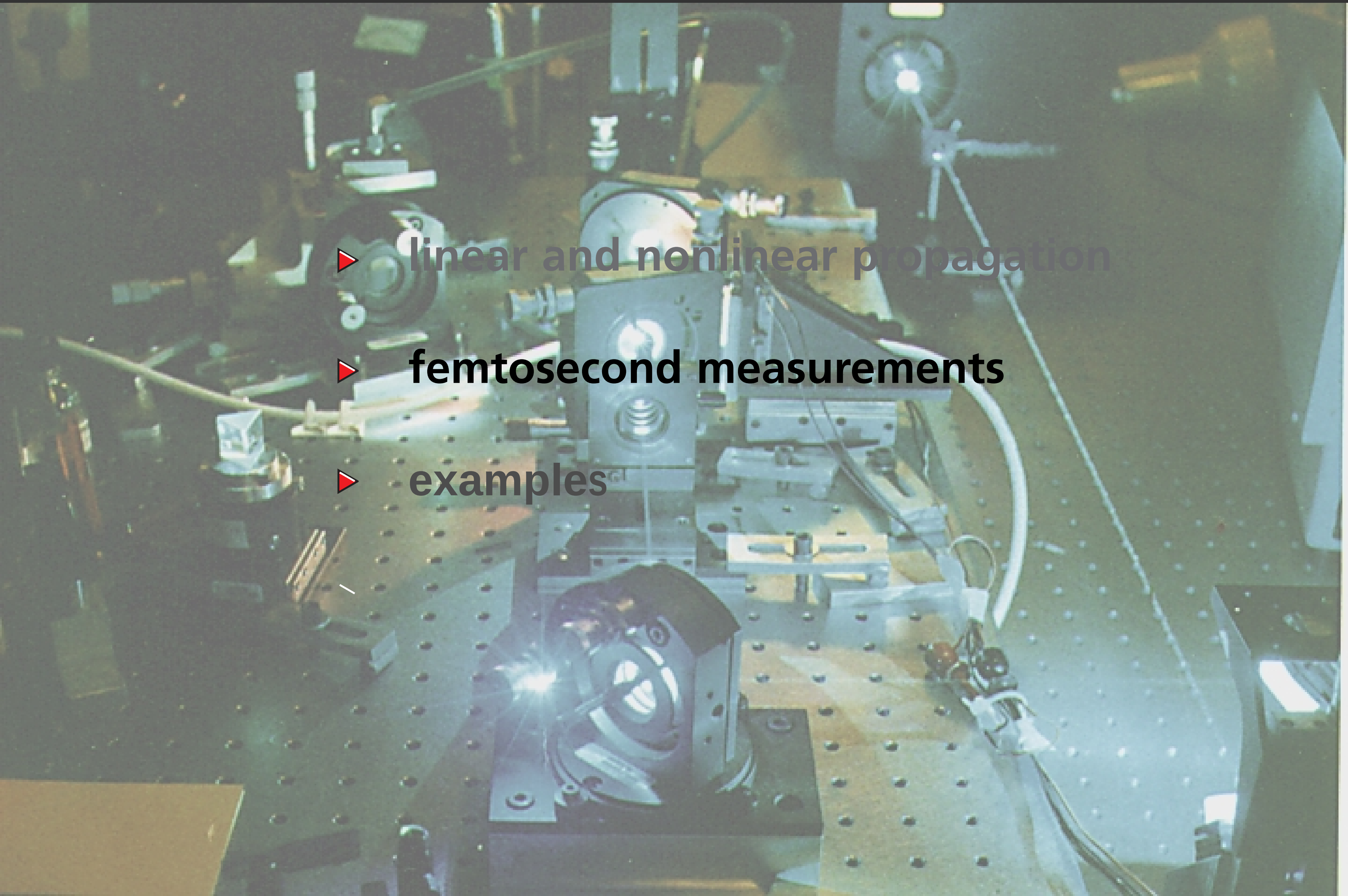
Spatial intensity profile…



…causes self-focusing



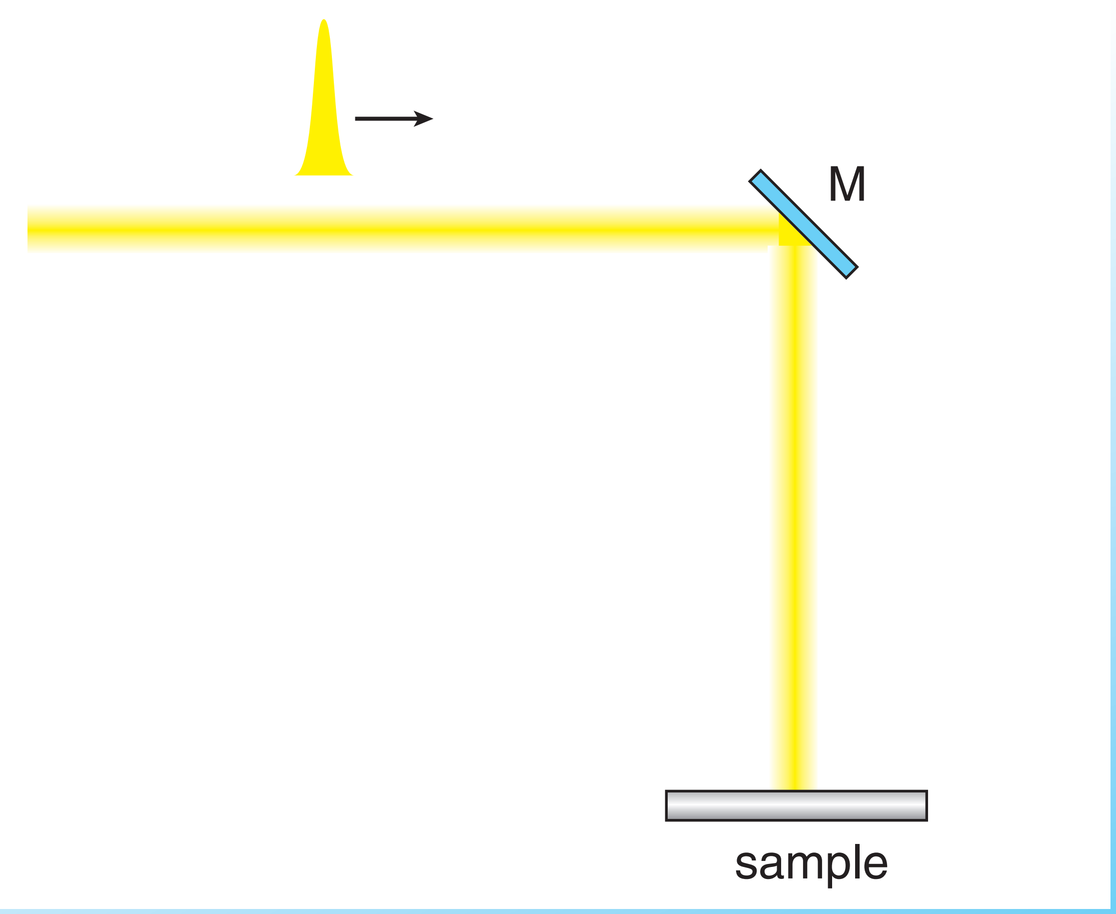
Outline



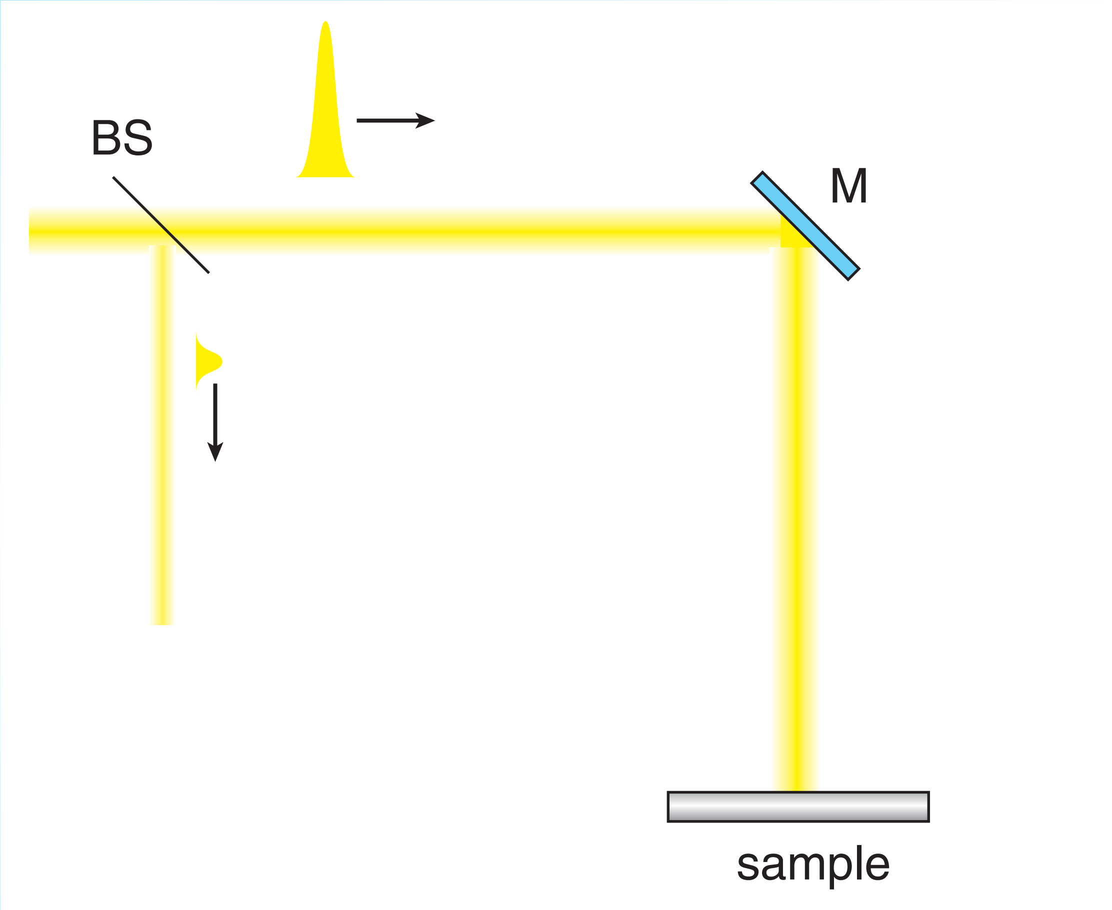
- linear and nonlinear propagation
- **femtosecond measurements**
- examples

Introduction

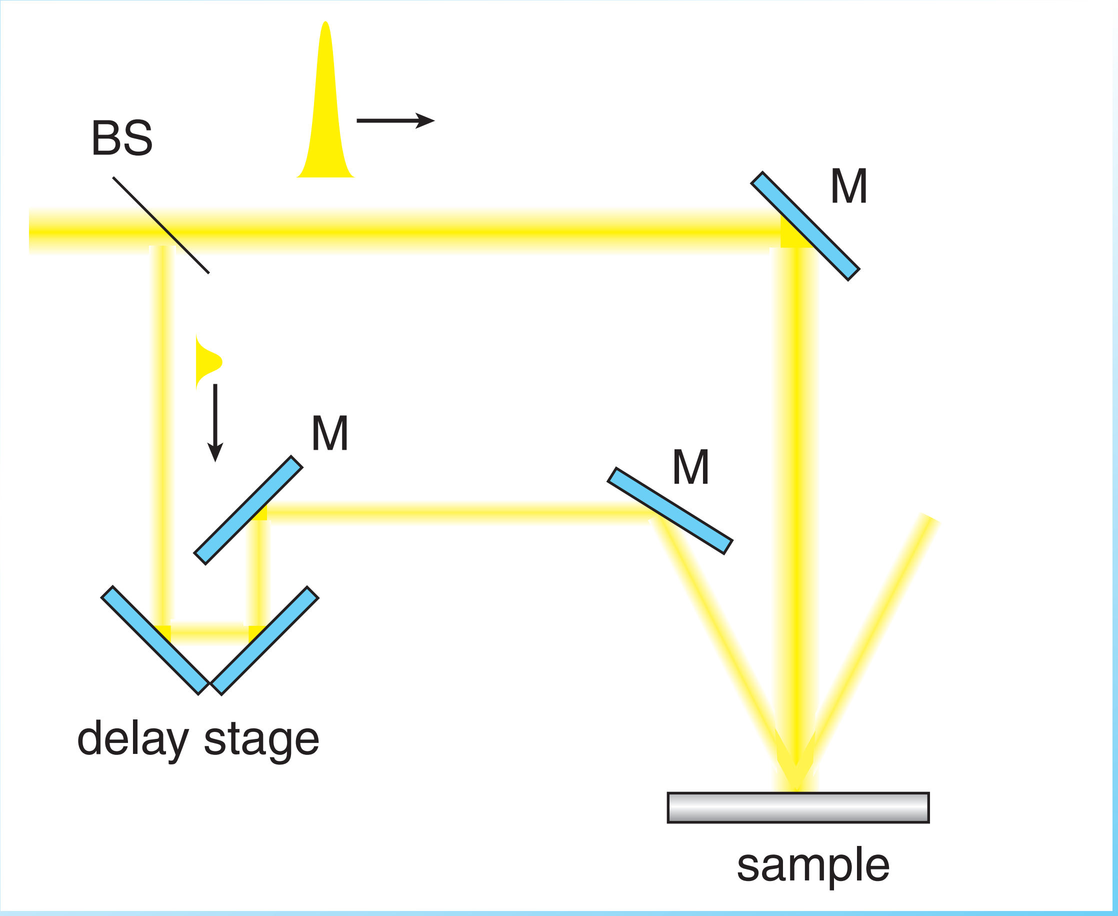
How to measure on the femtosecond time scale?



Use pump-probe technique

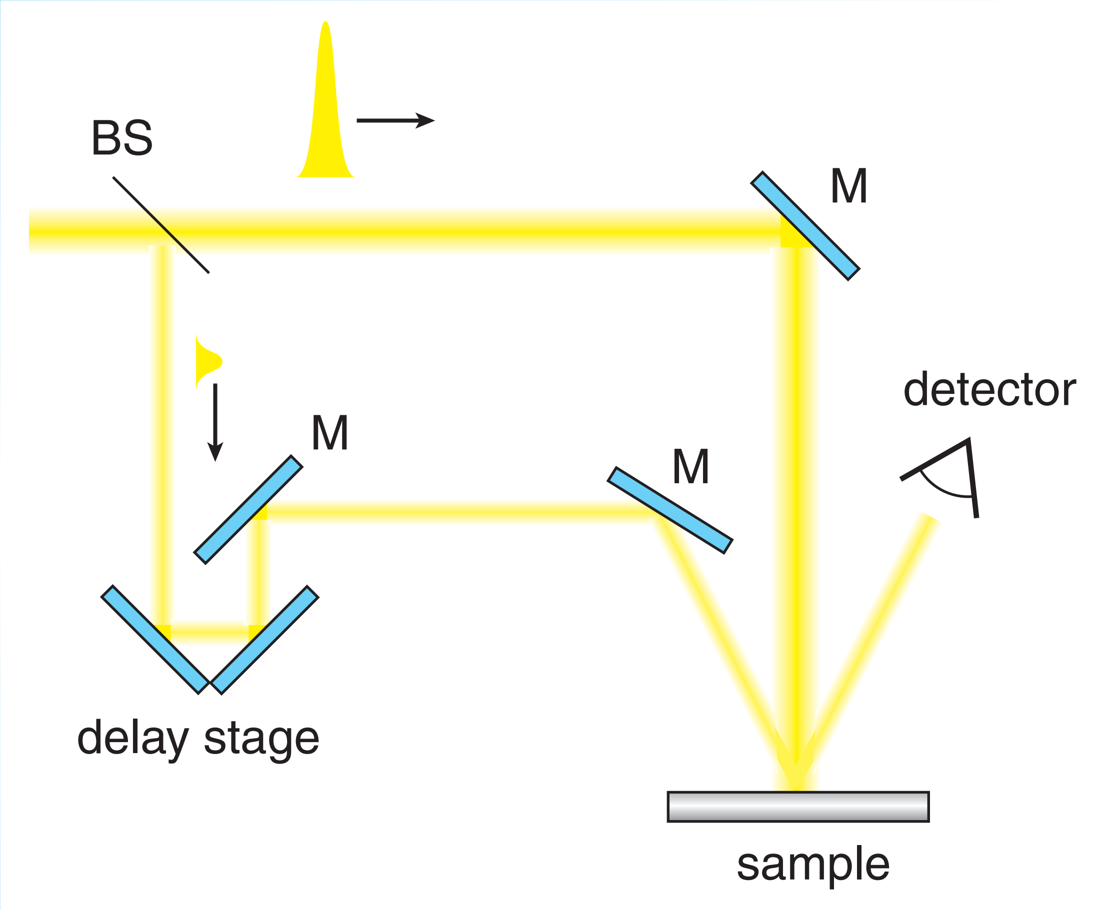


Use pump-probe technique

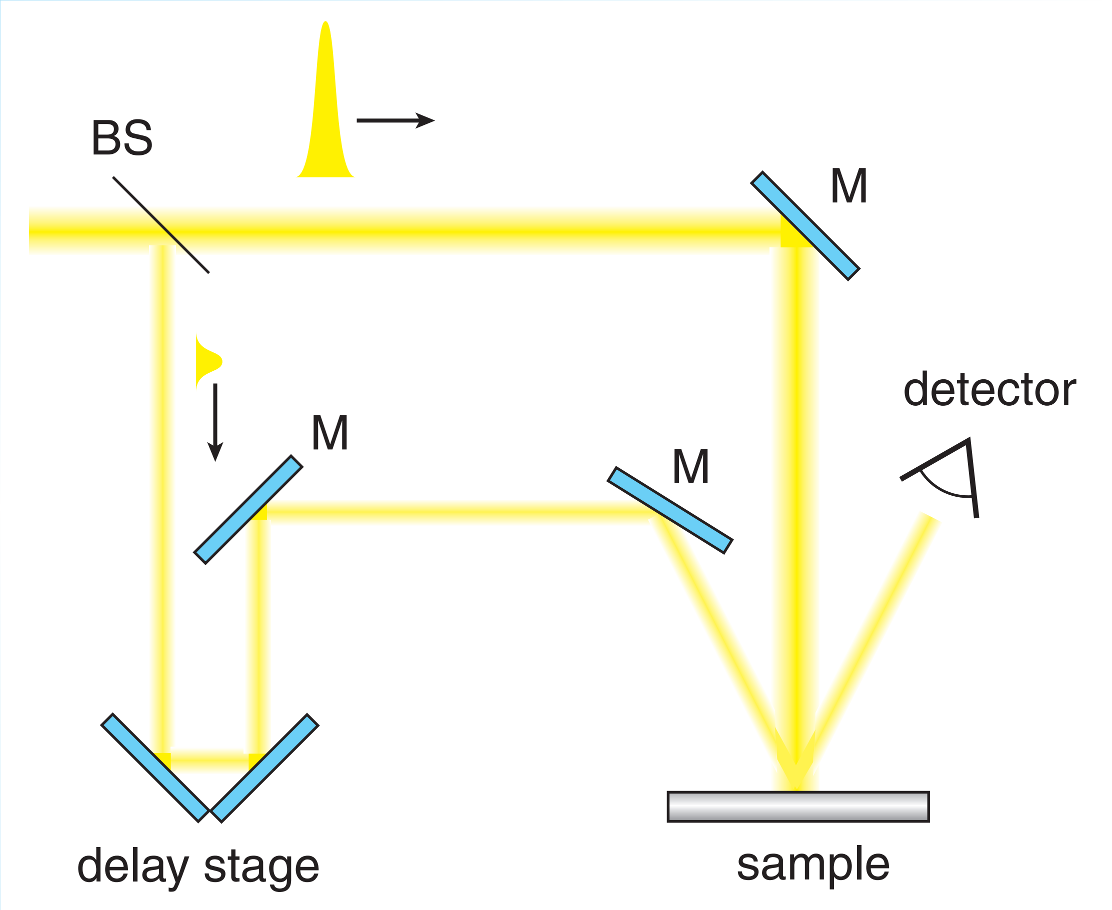


Introduction

Use pump-probe technique

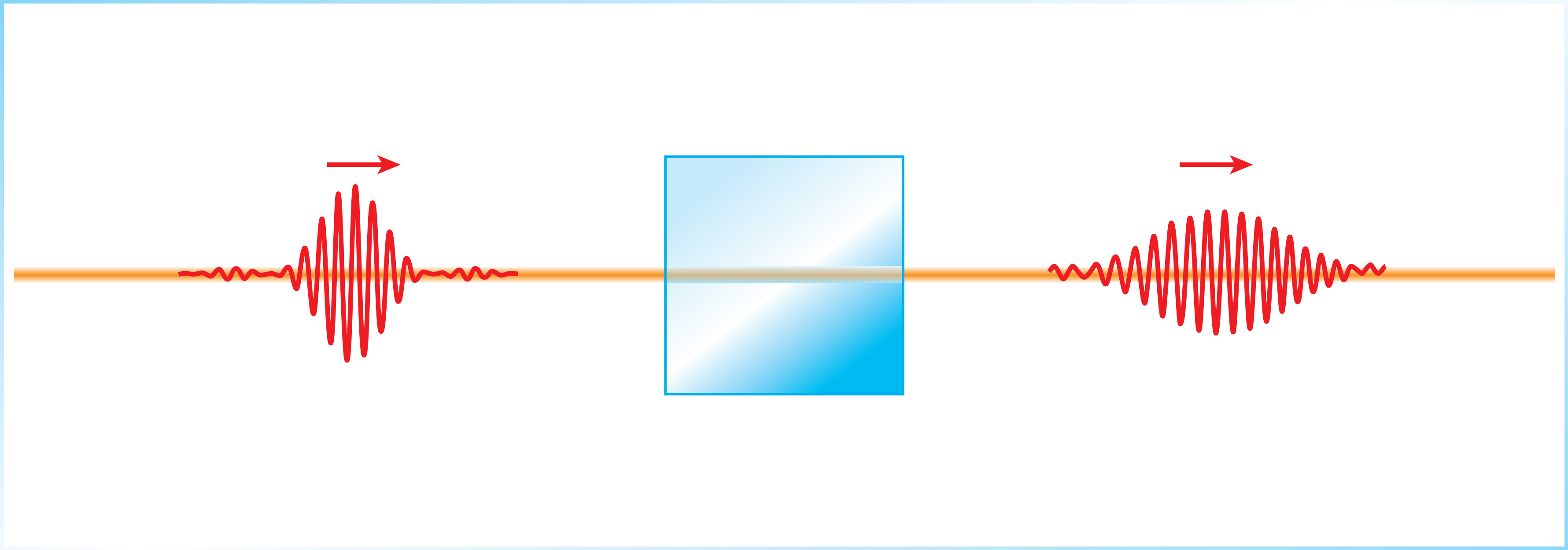


Vary delay to get time resolution



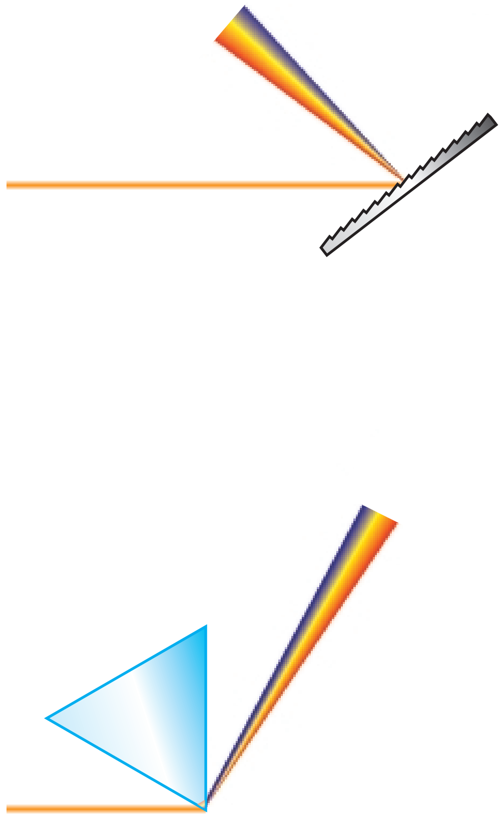
Dispersion compensation

Dispersion stretches the pulse

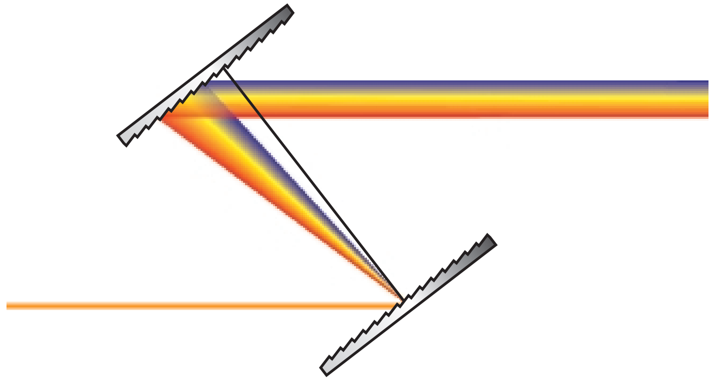


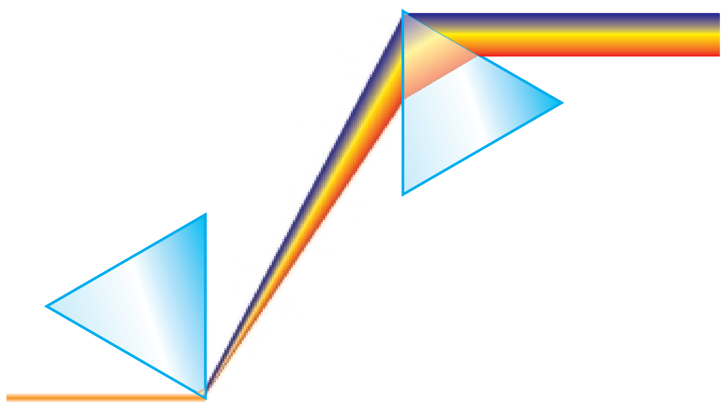
Compensate by rearranging spectral components!

Dispersion compensation

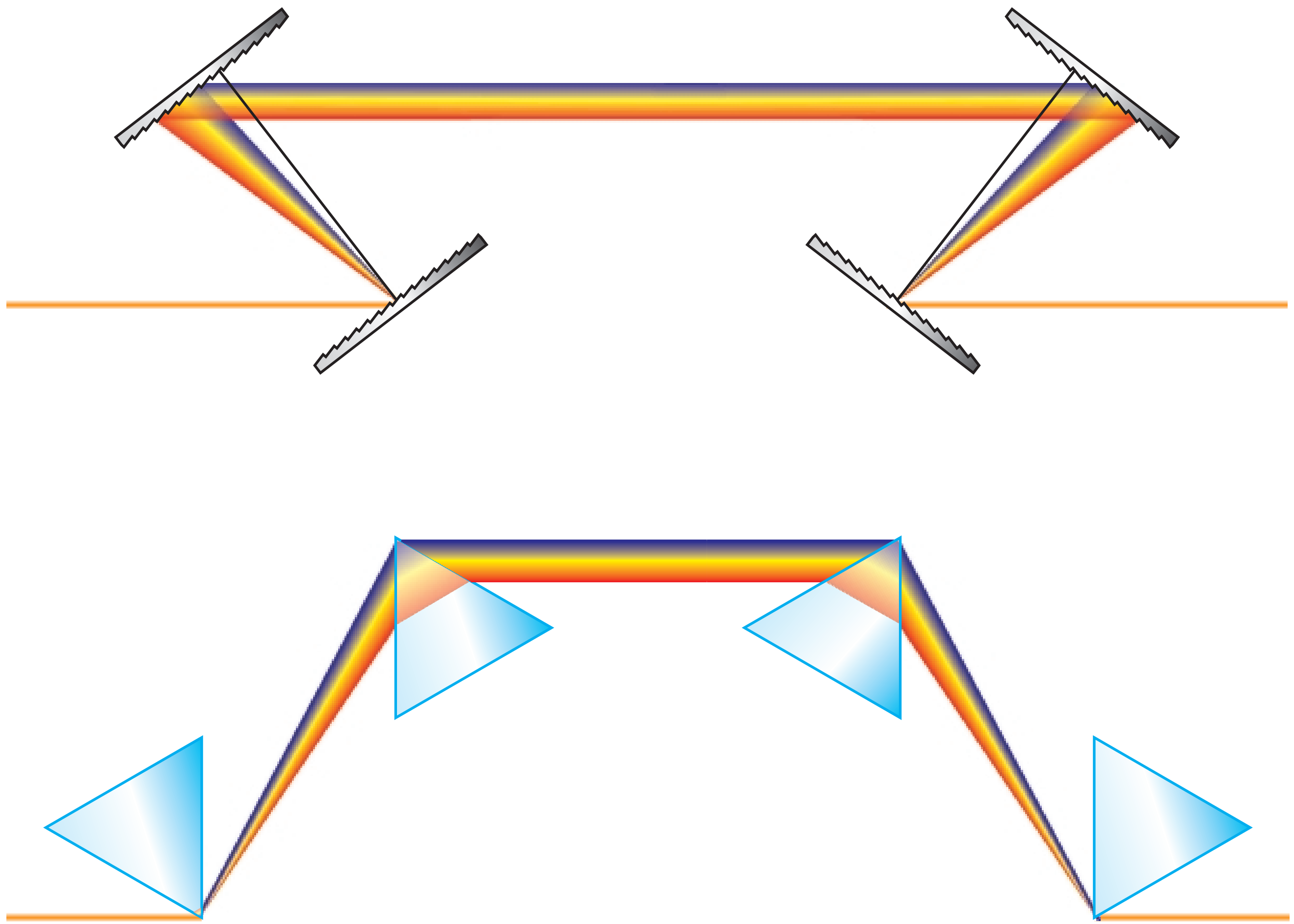


Dispersion compensation





Dispersion compensation

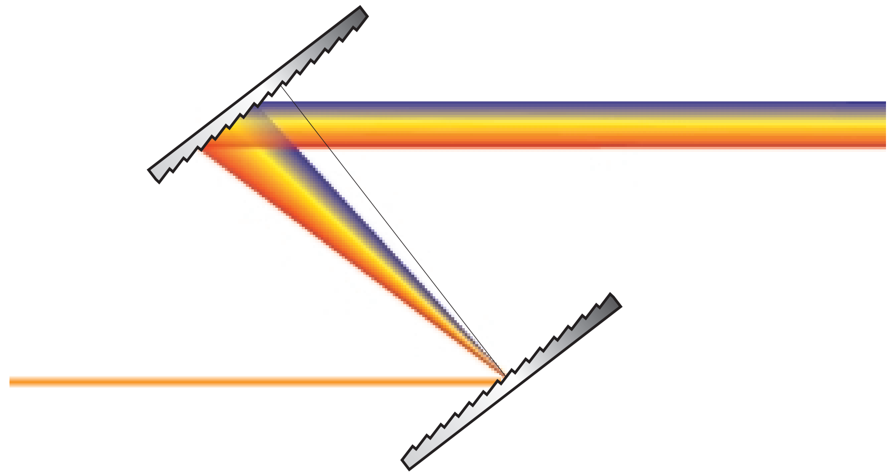


Dispersion compensation

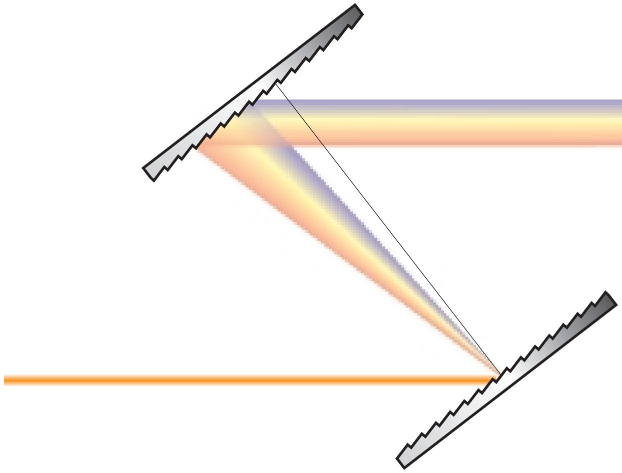
How do these arrangements work?

Dispersion compensation

Does path length difference compensate?



Does path length difference compensate?



Dispersion compensation

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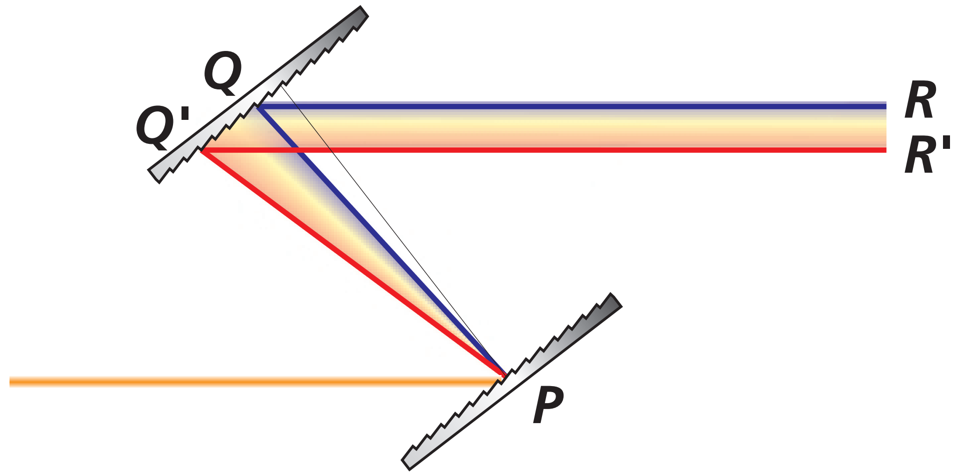
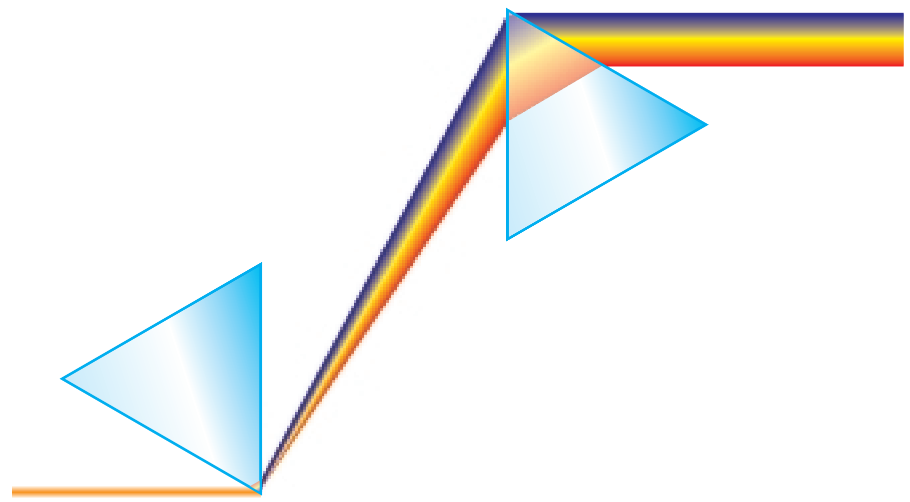


Grating gives low frequency longer path length…

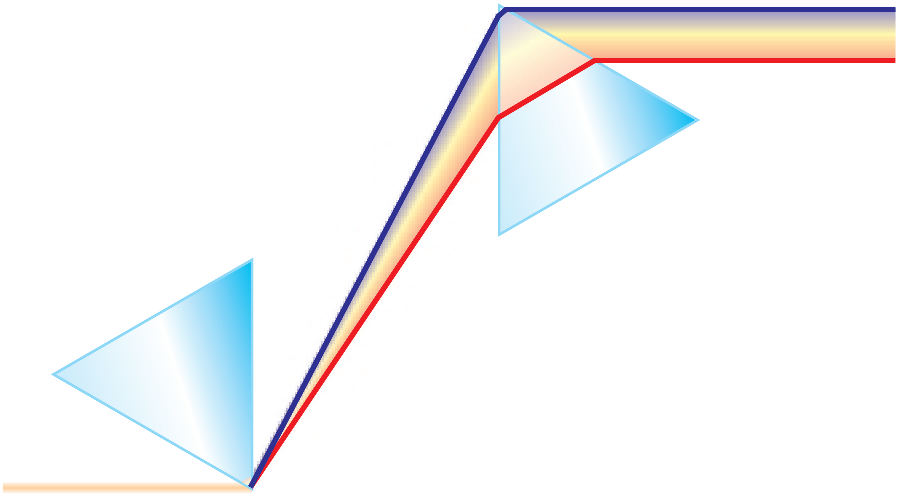
Dispersion compensation

Does path length difference compensate?



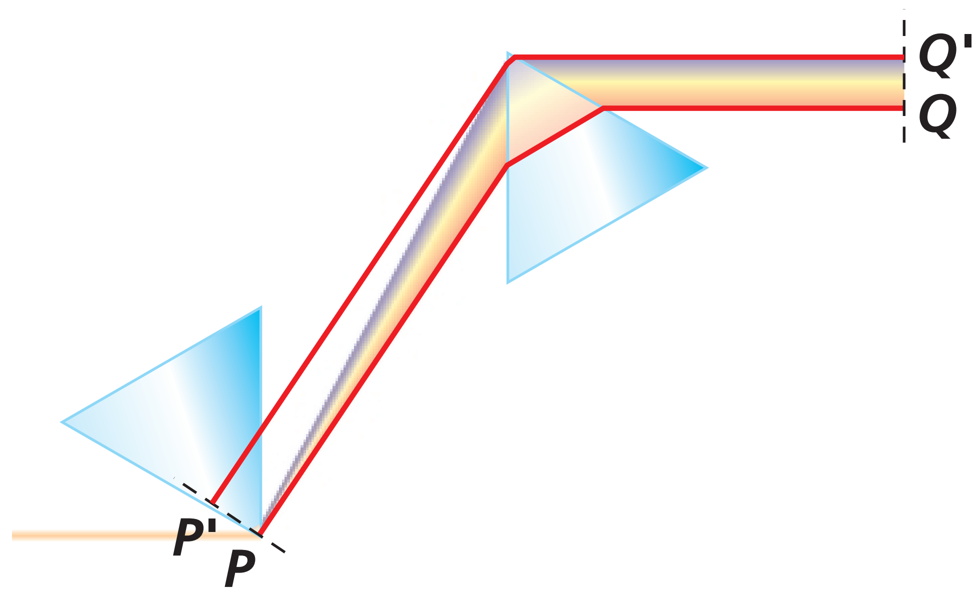
Dispersion compensation

Does path length difference compensate?



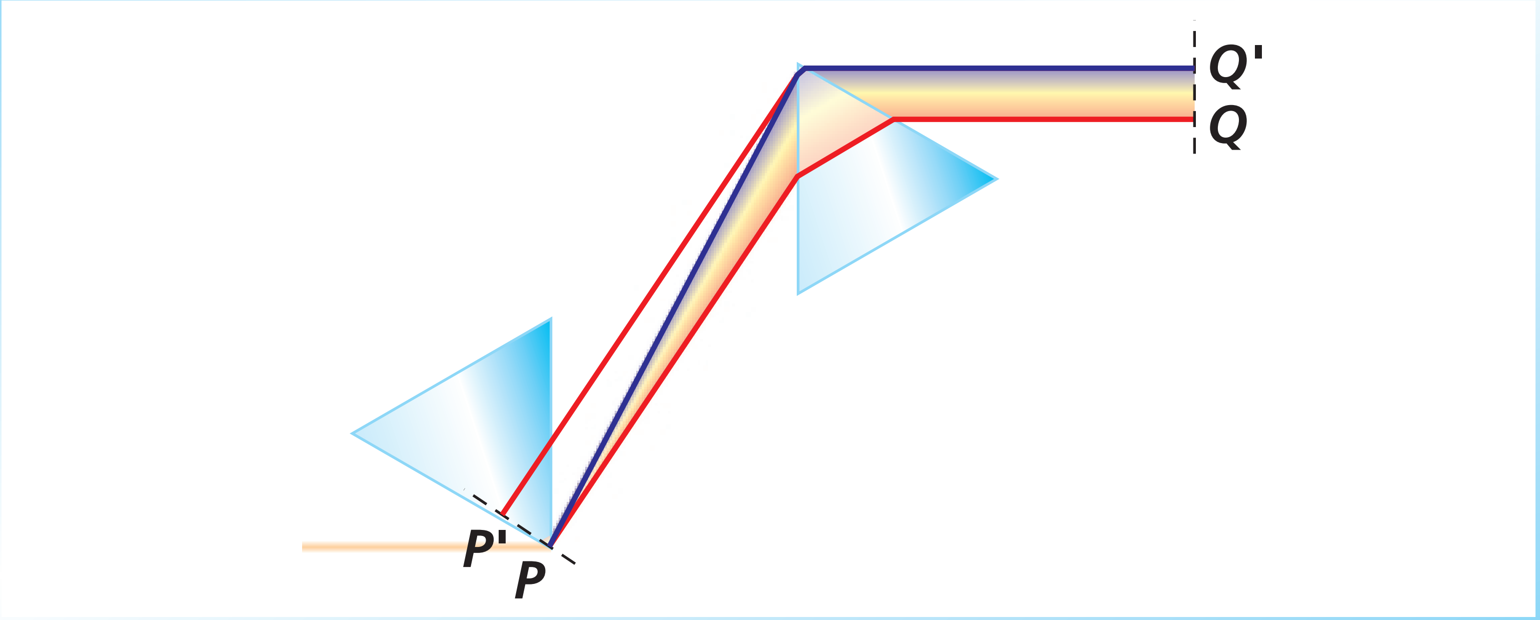
Dispersion compensation

Does path length difference compensate?



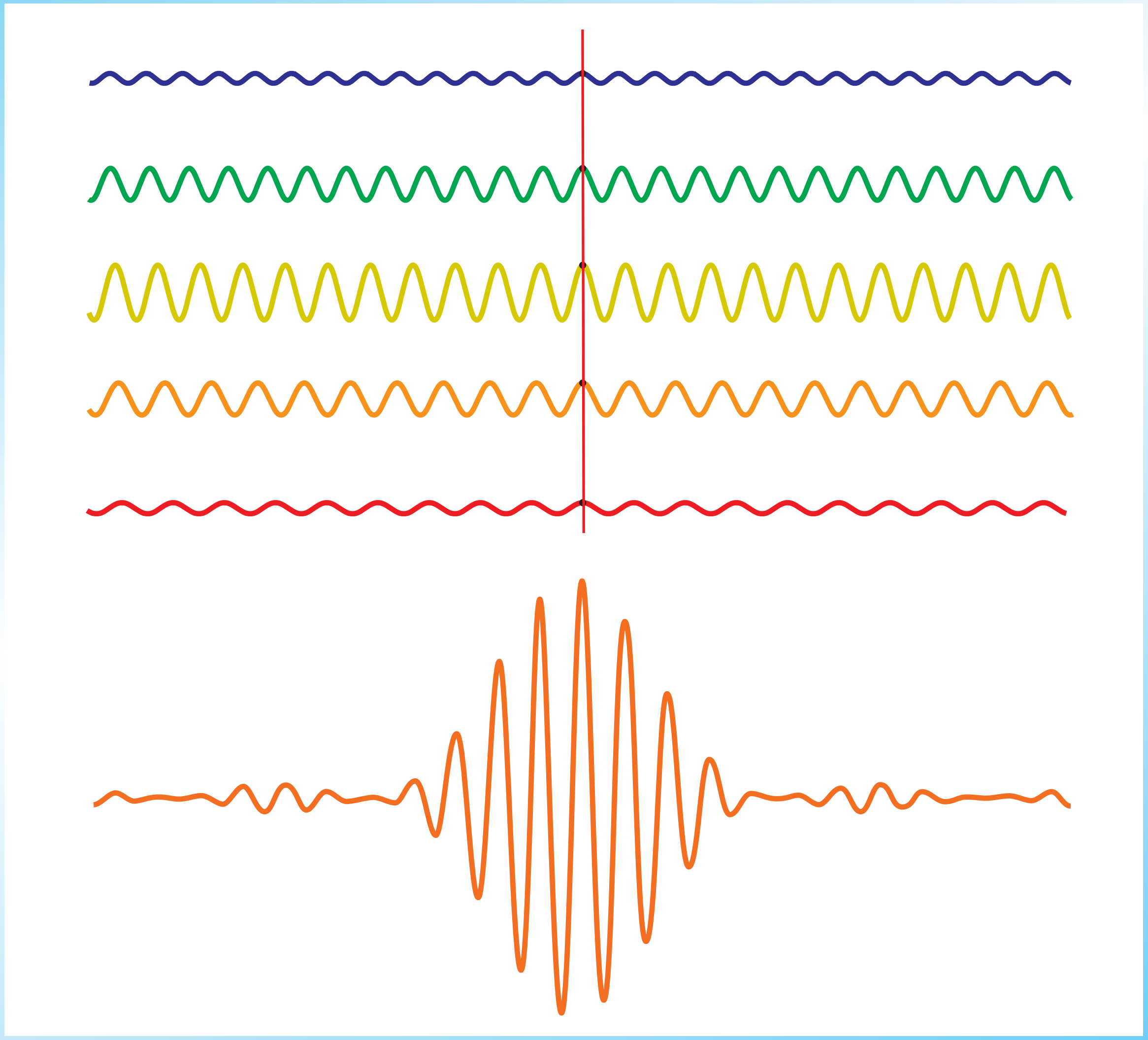
Dispersion compensation

Does path length difference compensate?

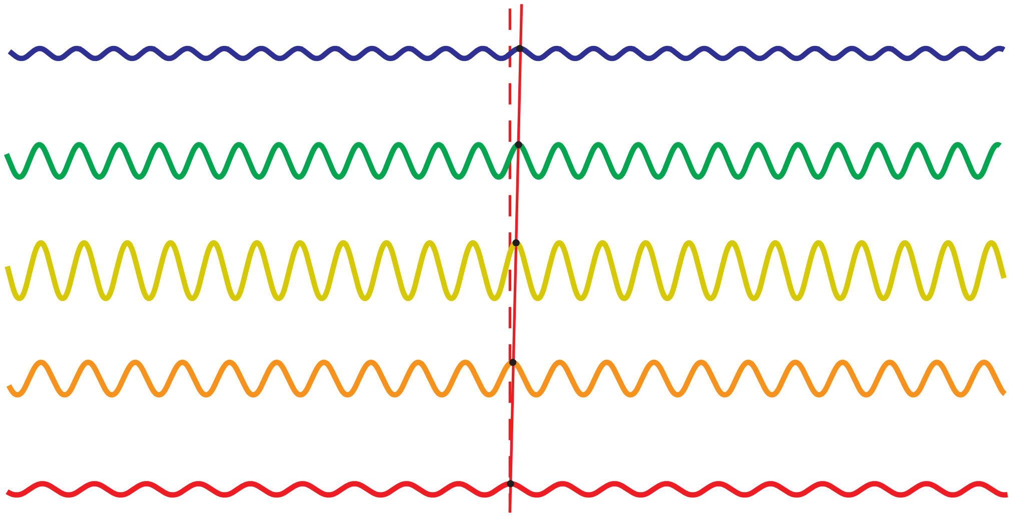


…so prism gives low frequency *shorter* path length…

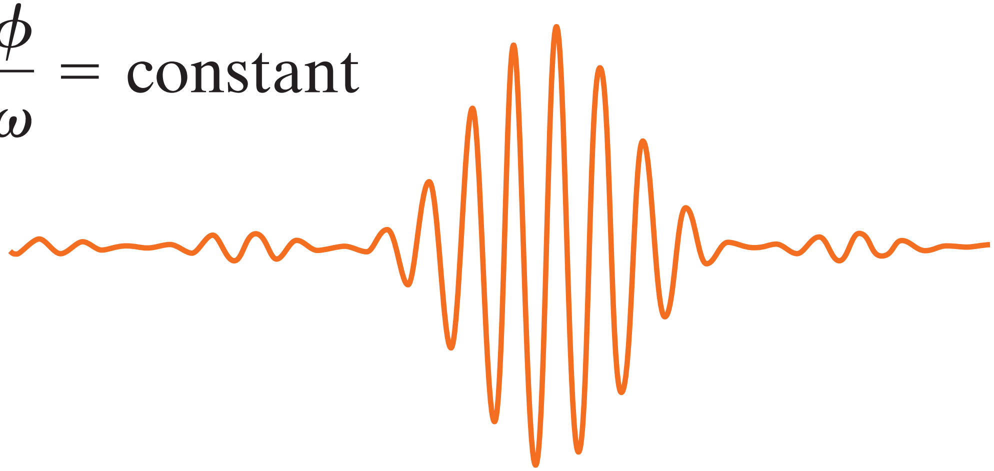
Dispersion compensation



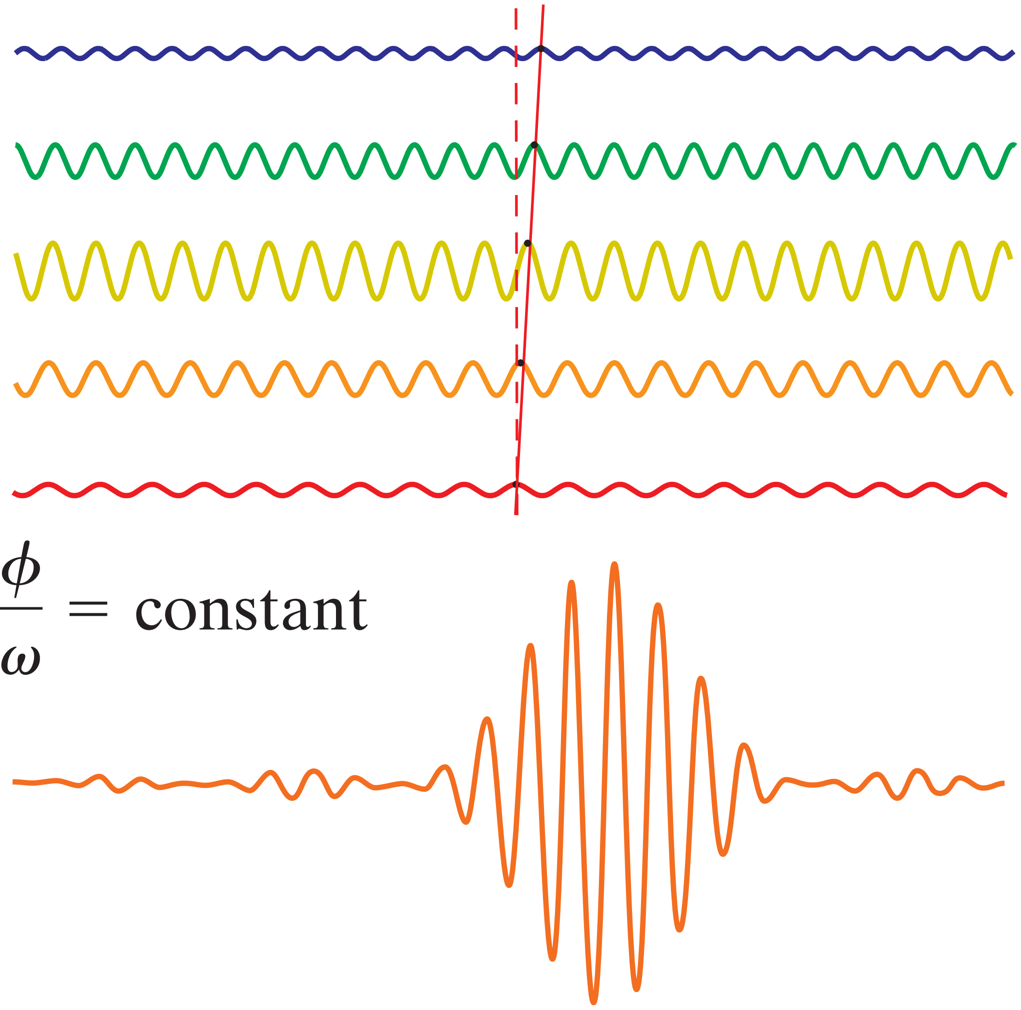
Dispersion compensation



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



Dispersion compensation



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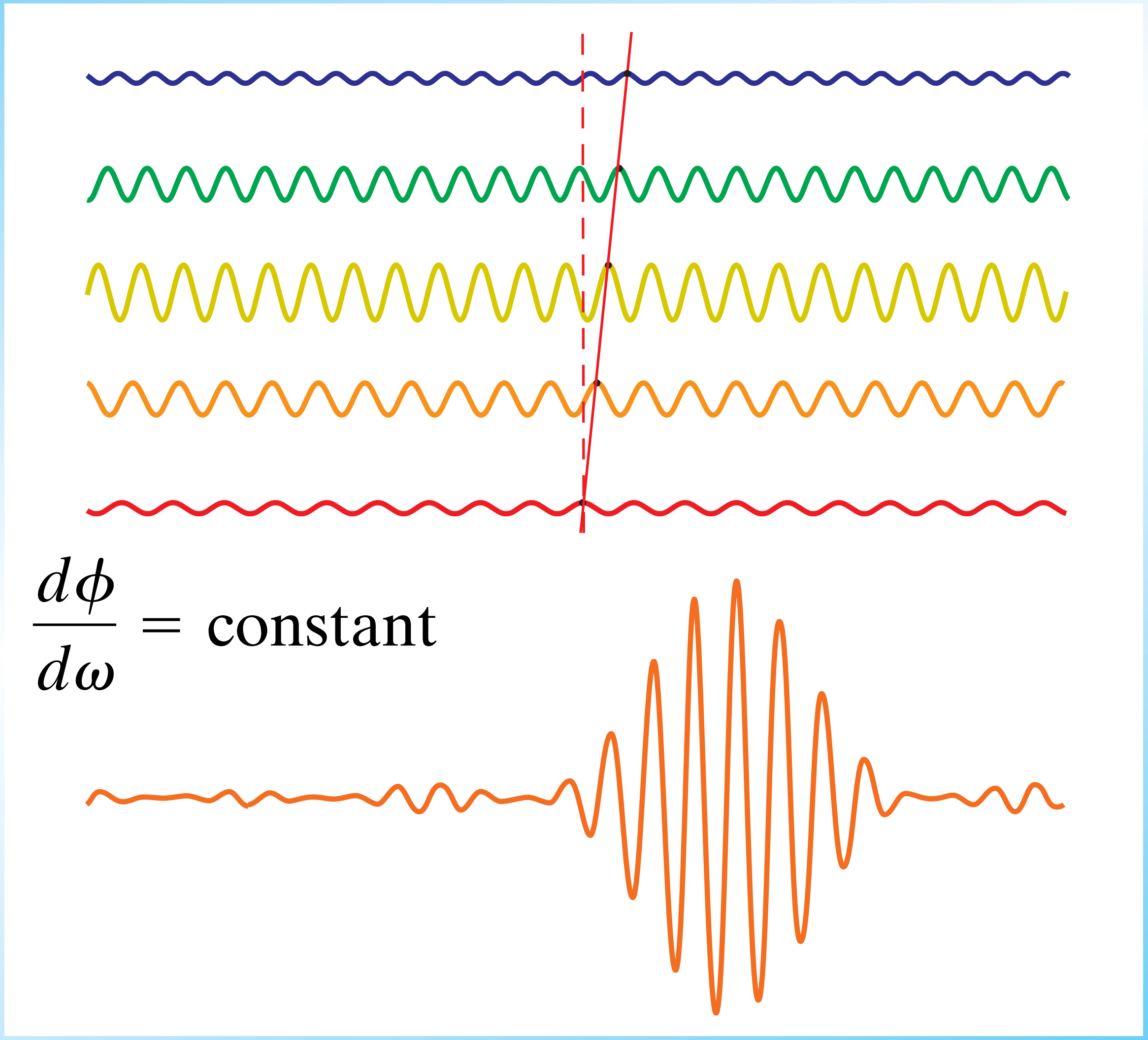
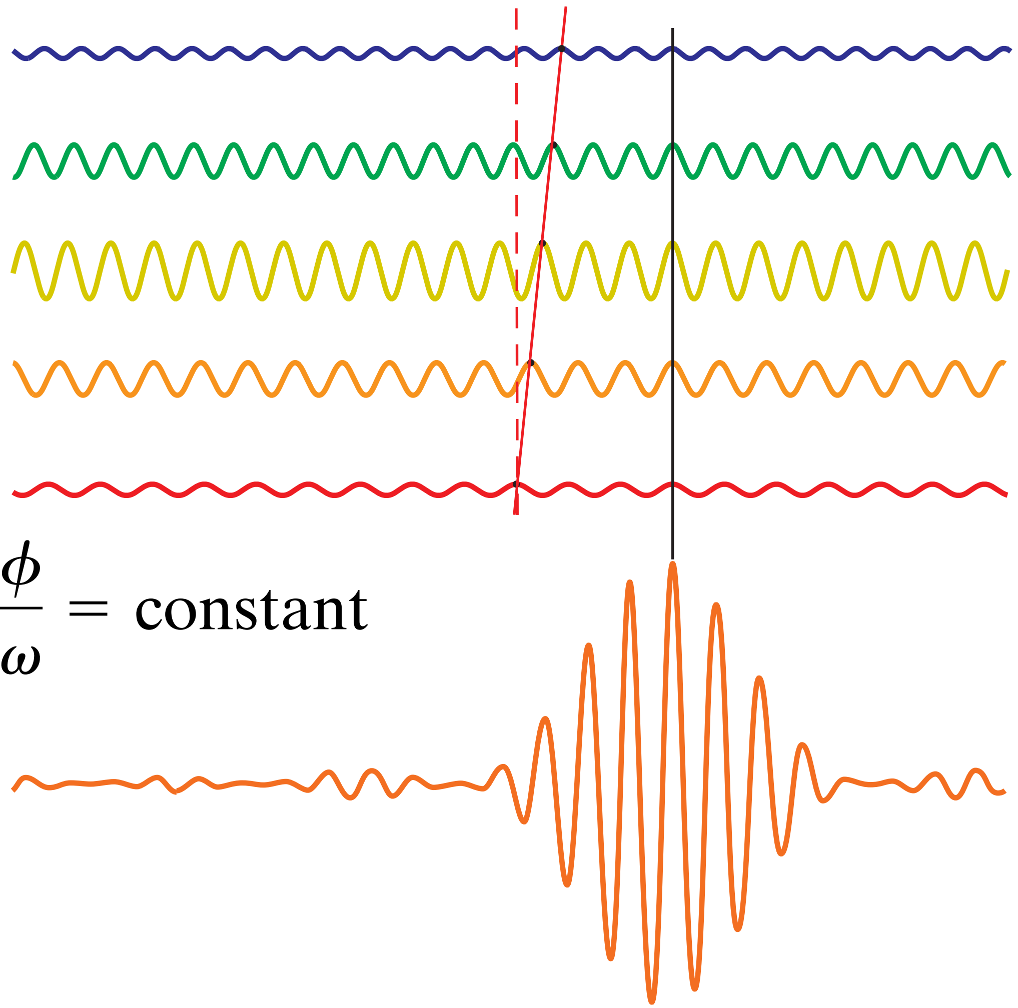


Dispersion compensation



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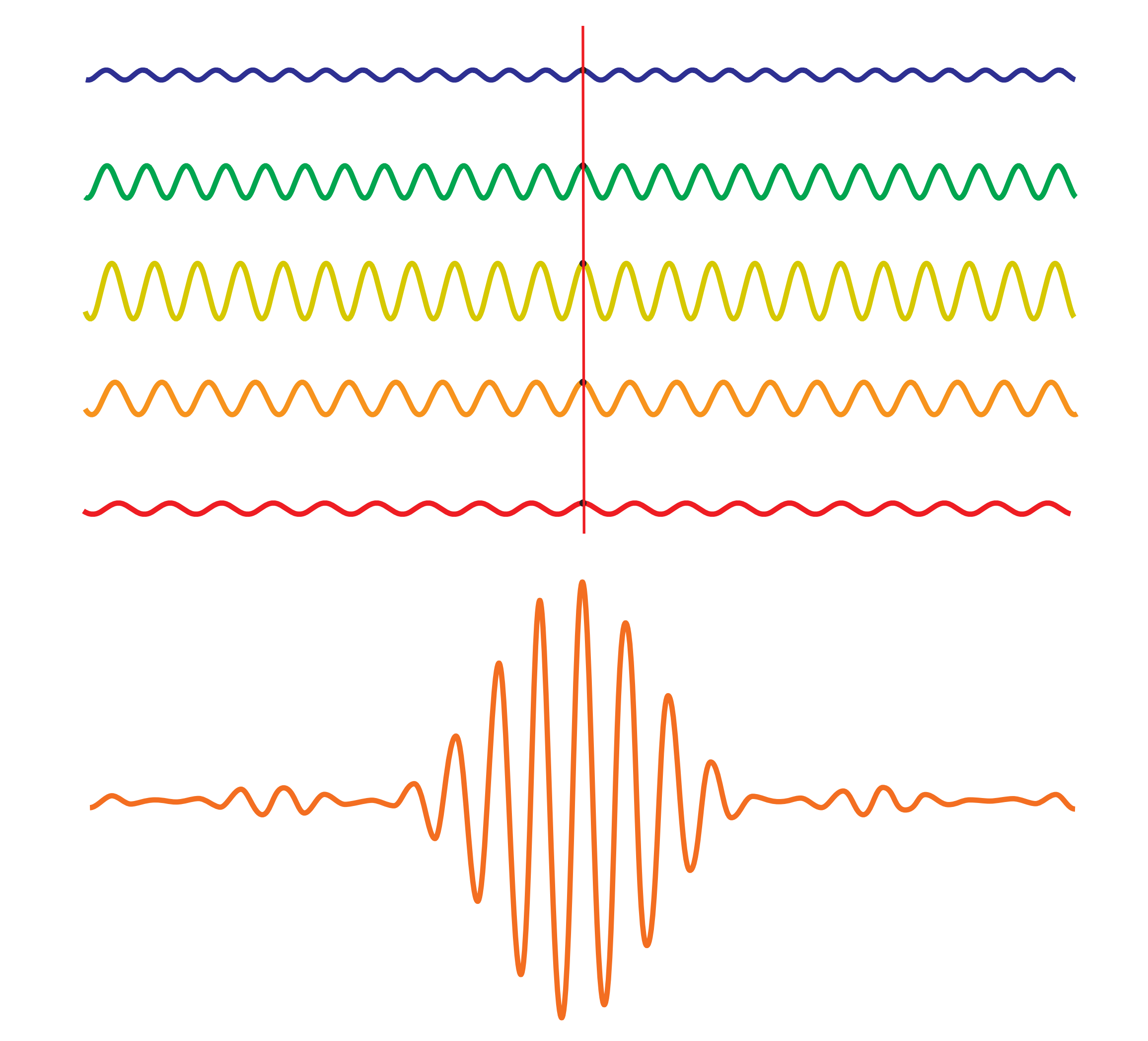
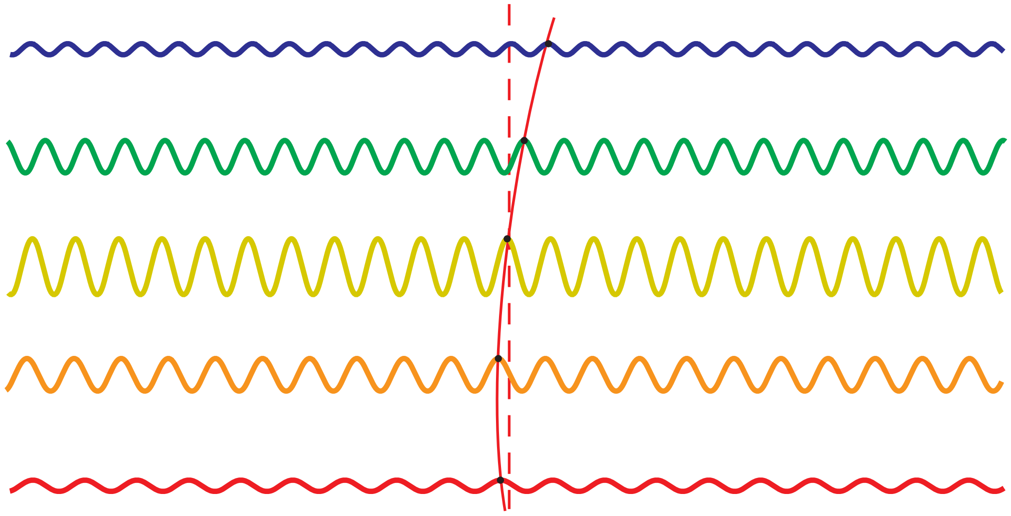
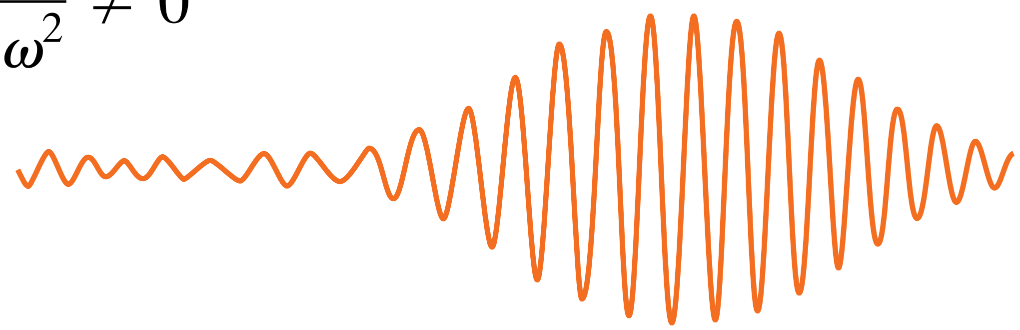


Dispersion compensation



$$\frac{d^2\phi}{d\omega^2} \neq 0$$

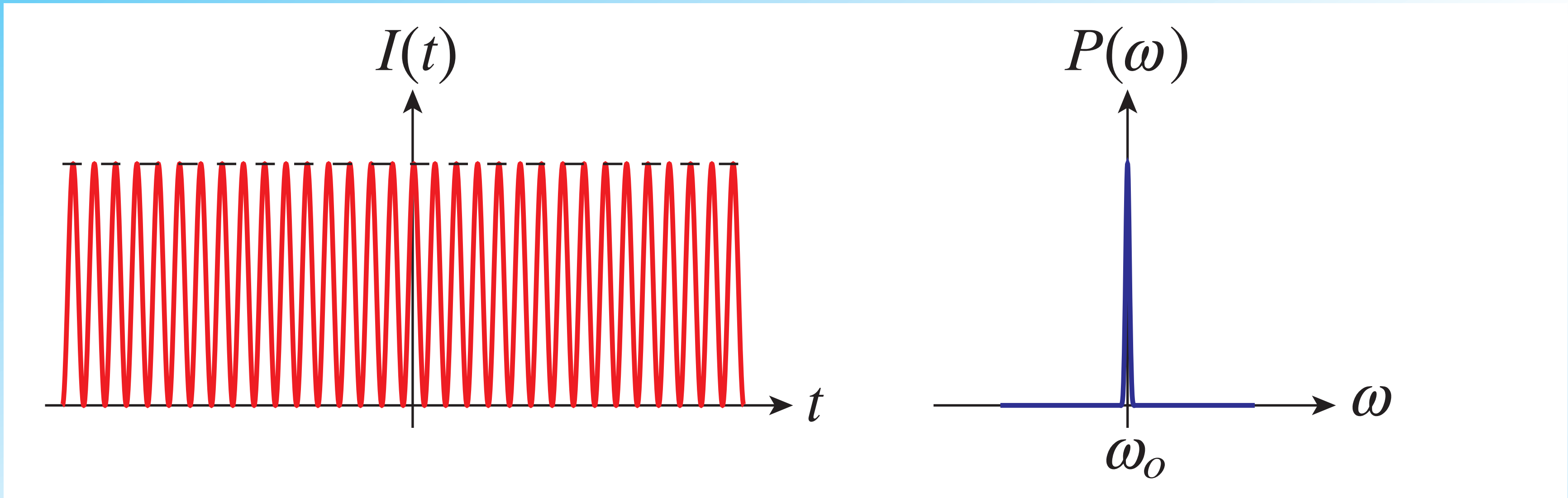


Dispersion compensation

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	+	–

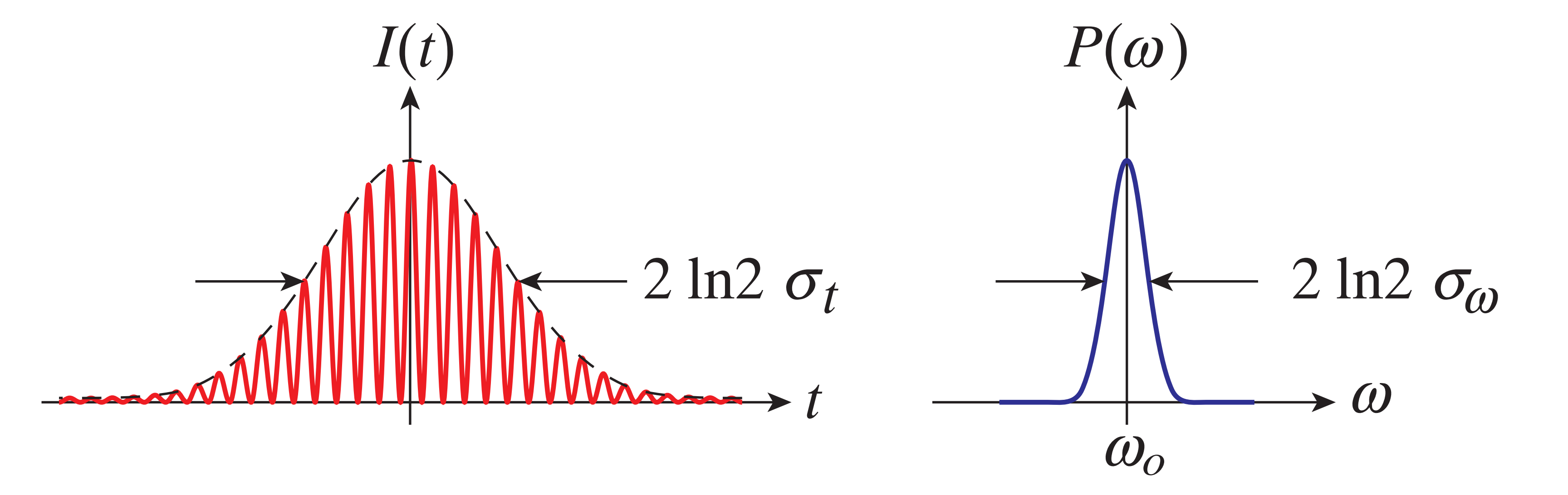
Representation of pulses



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

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

Fourier relations:

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

Representation of pulses

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$$= \frac{1}{\sqrt{2\pi}} \exp\left[-\frac{\sigma_t^2(\omega - \omega_o)^2}{2} \right] \int_{-\infty}^{\infty} \exp - \left[\frac{t}{\sqrt{2}\sigma_t} - i\,\frac{(\omega - \omega_o)\sigma_t}{\sqrt{2}} \right]^2 dt =$$

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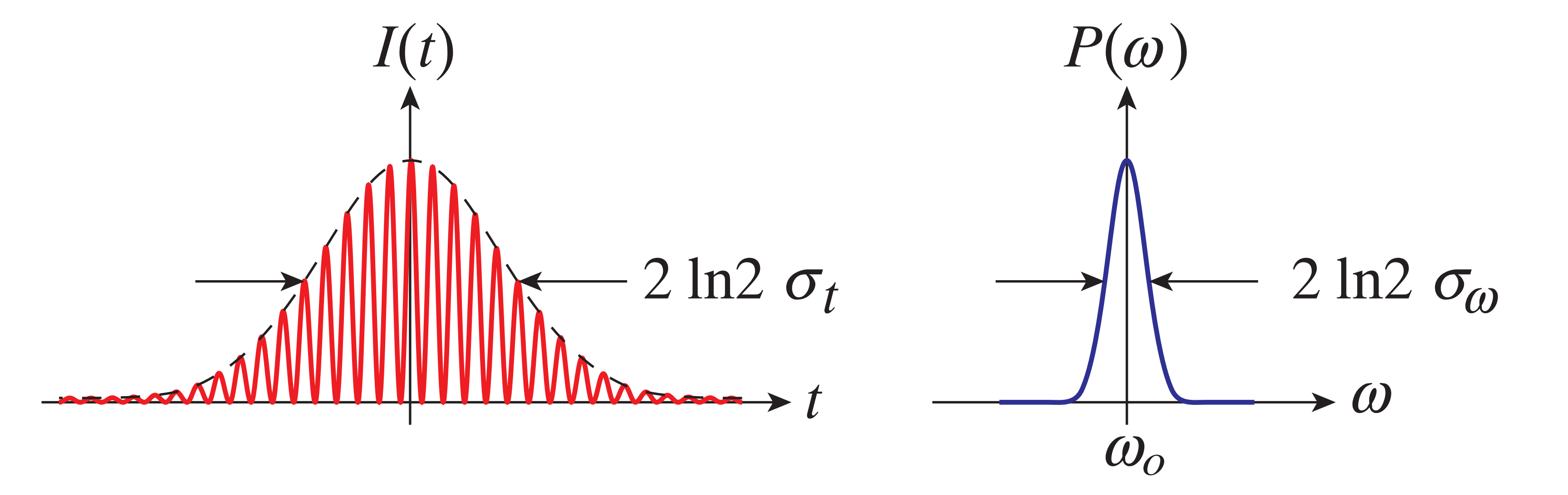
$$= \sigma_t\exp\left[-\frac{\sigma_t^2(\omega-\omega_o)^2}{2}\right] \equiv \sigma_t\exp\left[-\frac{(\omega-\omega_o)^2}{2\sigma_\omega^2}\right]$$

Representation of pulses

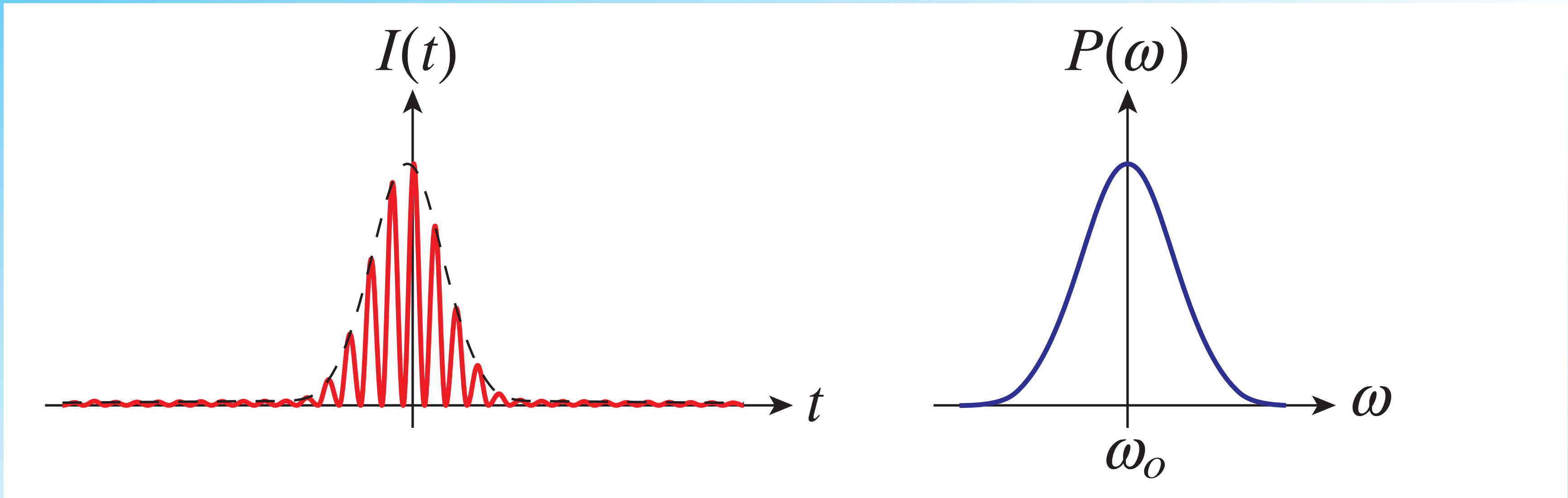


Pulse duration-bandwidth product: $\sigma_t \sigma_\omega = 1$

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

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

Representation of pulses



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Joint time-frequency representation

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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$$\frac{1}{2\pi}\int_{-\infty}^{\infty} W(t,\omega)\, d\omega = \left| E(t) \right|^2 = I(t)$$

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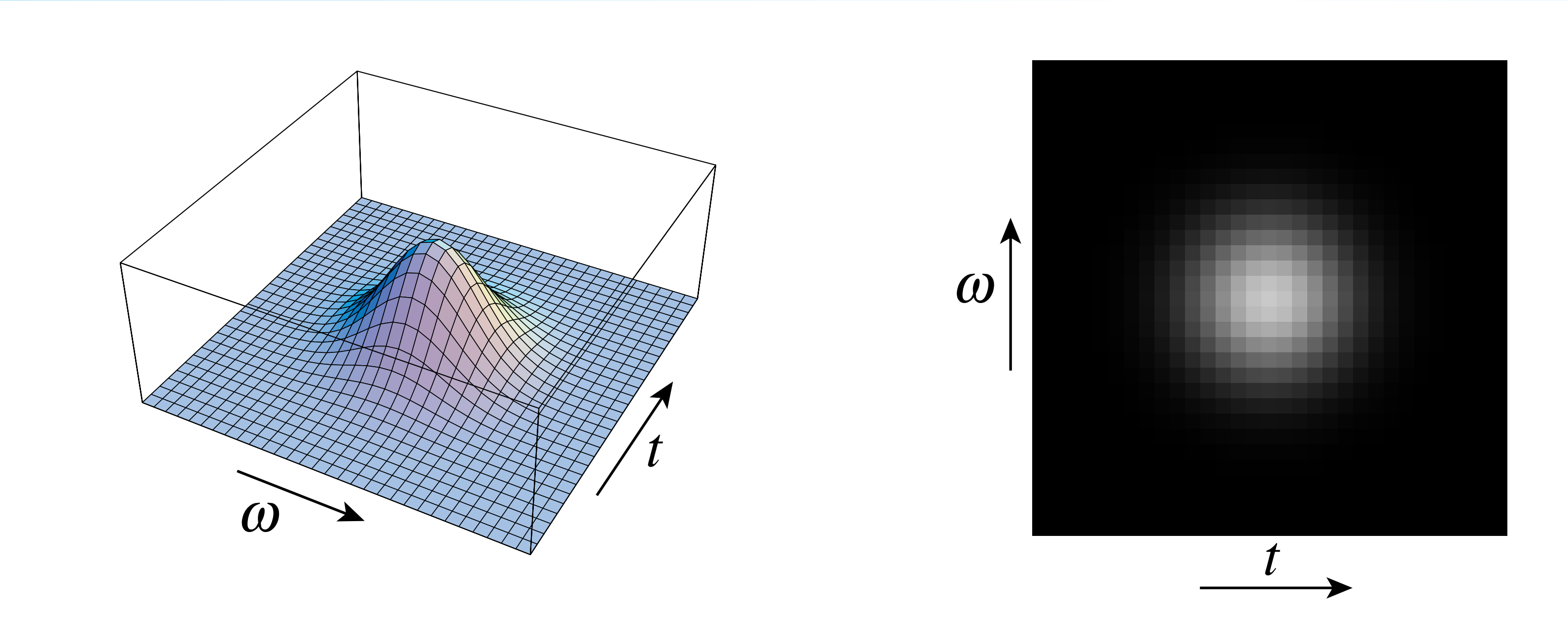
$$\int_{-\infty}^{\infty} W(t,\omega)\,dt = |\,E(\omega)\,|^2 = I(\omega)$$

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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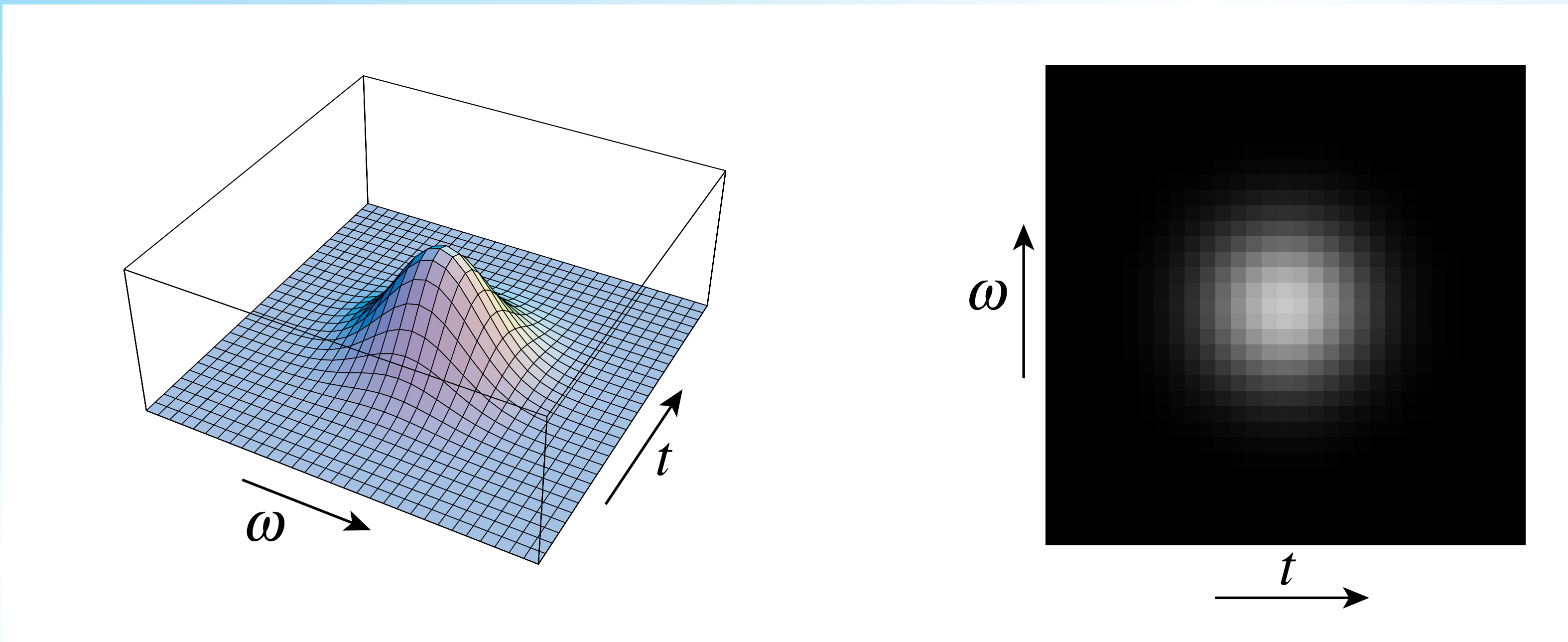
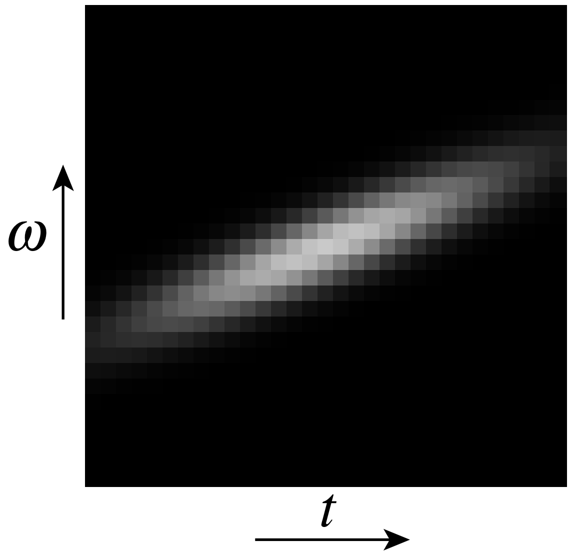


$W(t,\omega)$ **must be nonzero in phase-space area larger than** π

Joint time-frequency representation

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

chirped pulse



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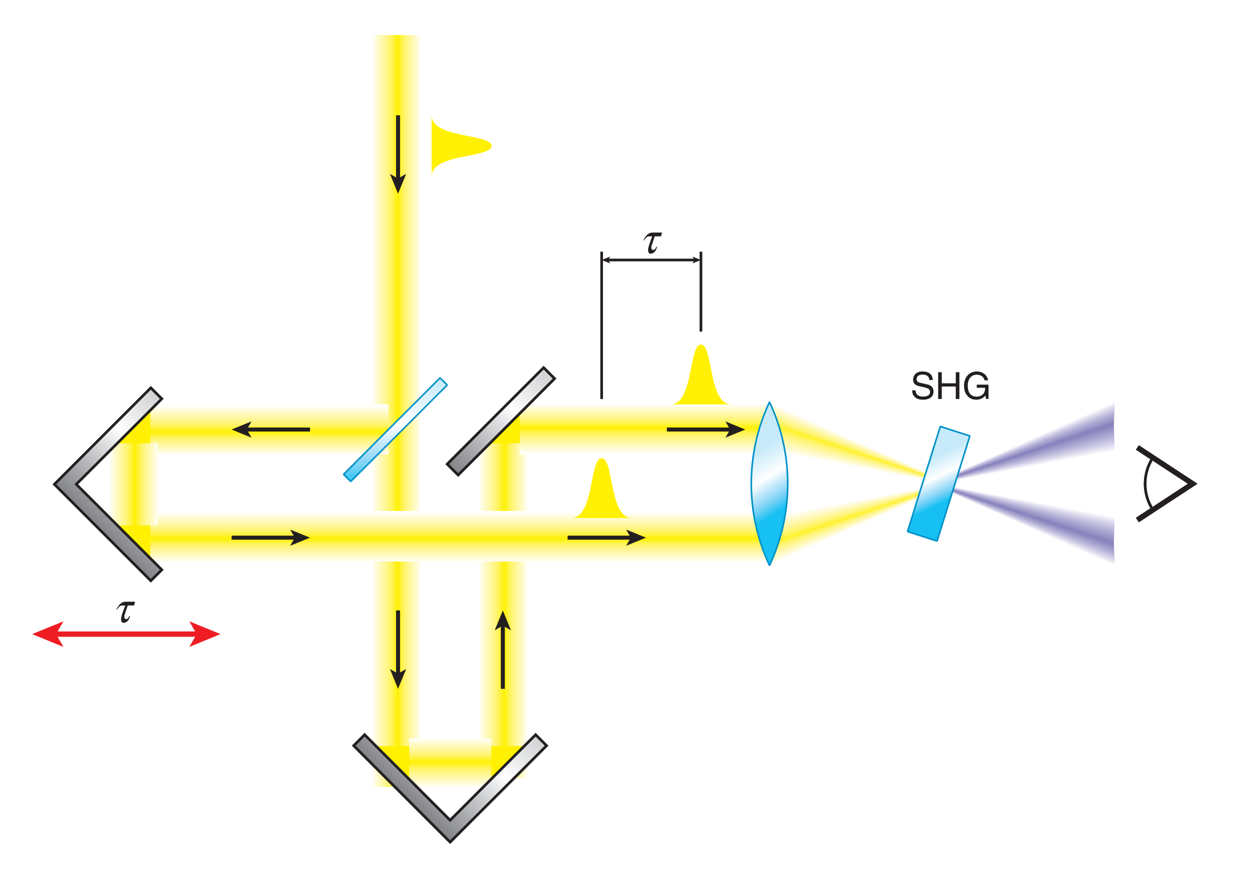
Temporal characterization

Use pulse to measure itself…



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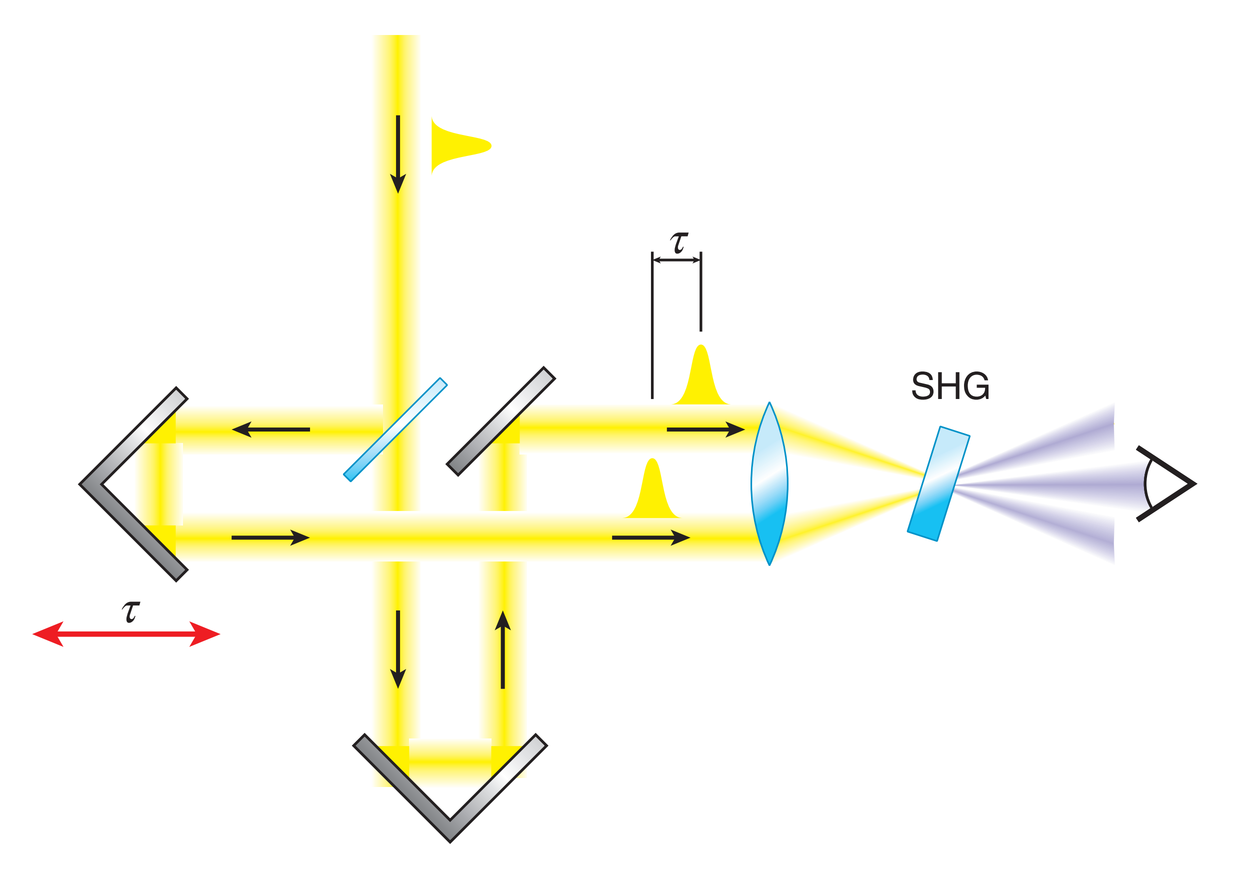

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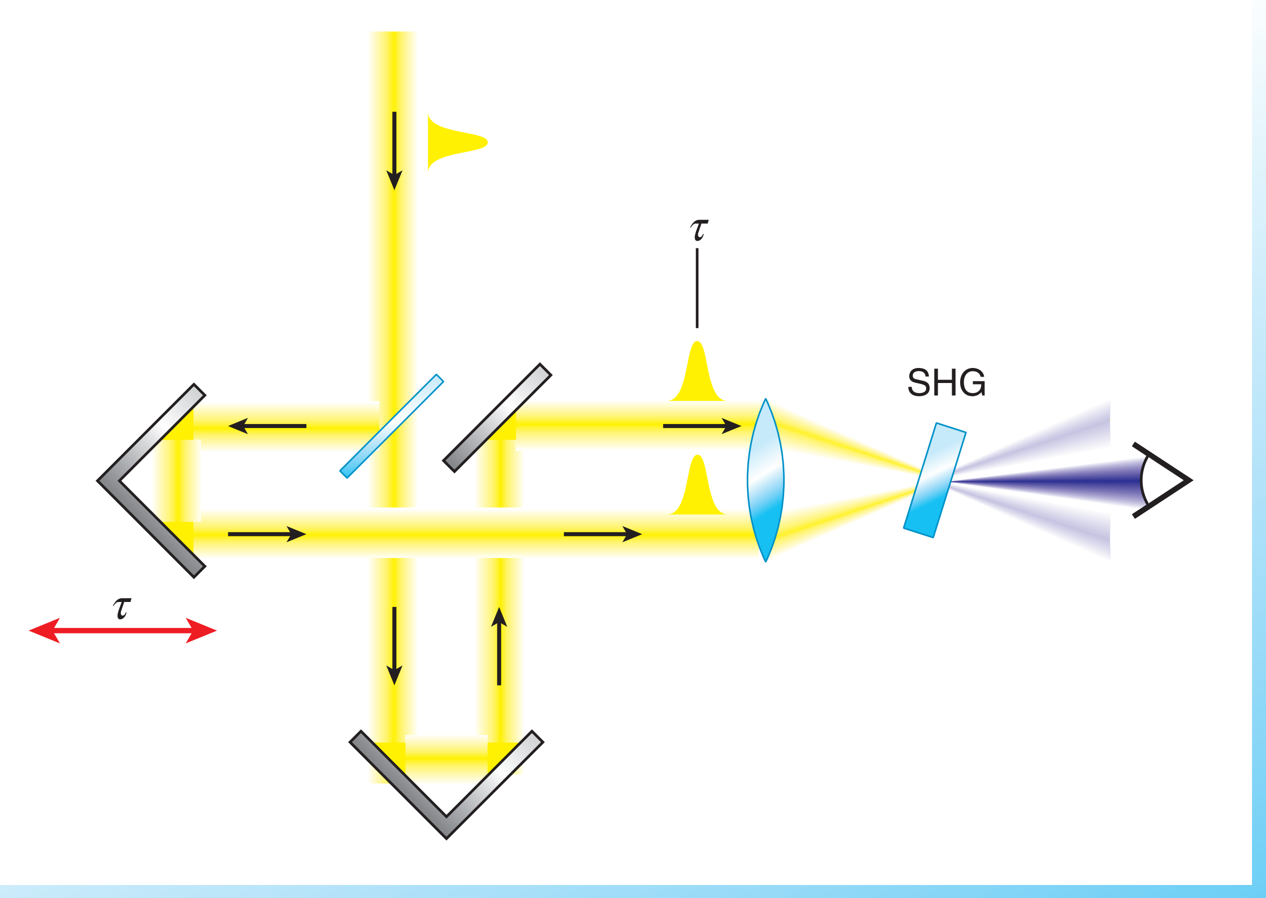

Temporal characterization

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 field

$$E_{2\omega} \propto \chi^{(2)}E_{tot}^2$$

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Second harmonic intensity

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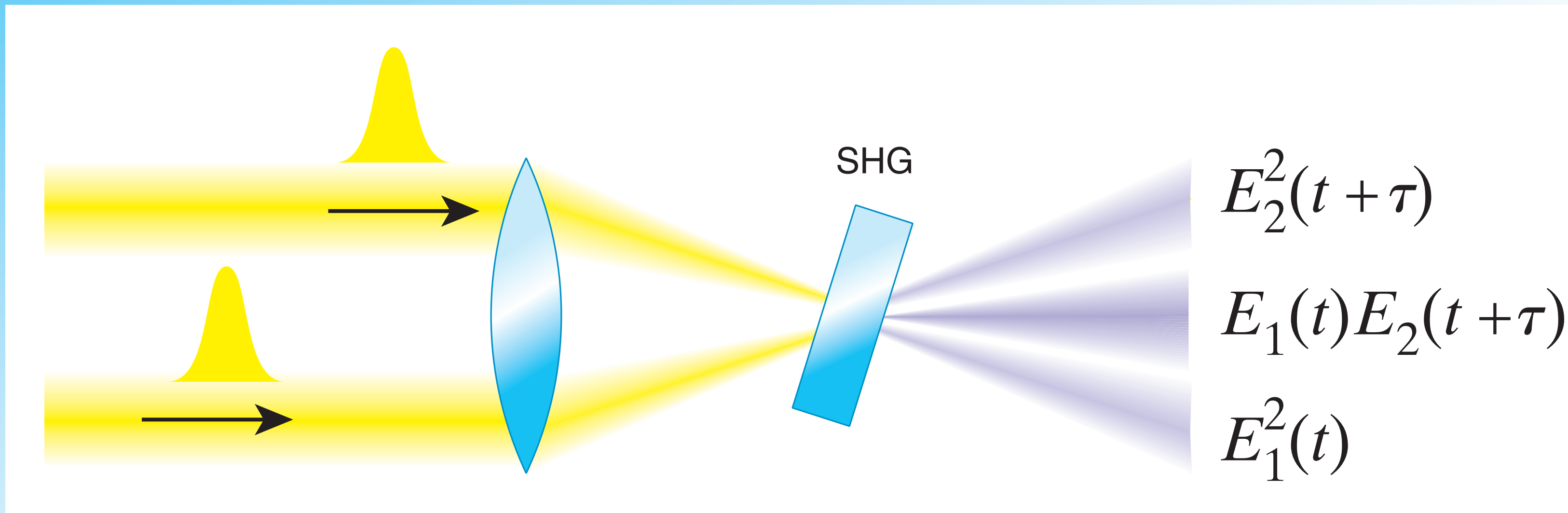
Temporal characterization



Second harmonic intensity

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detector selects middle term

Temporal characterization

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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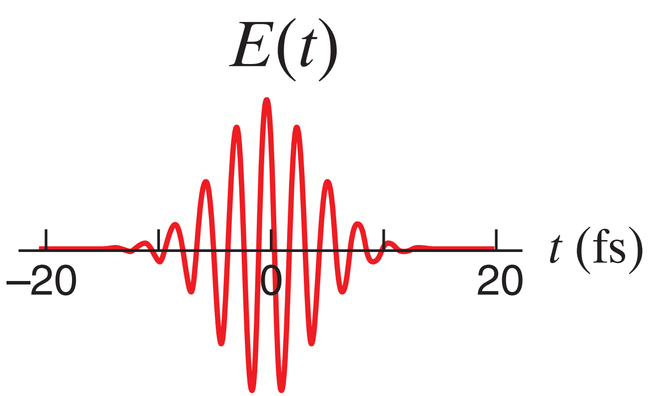

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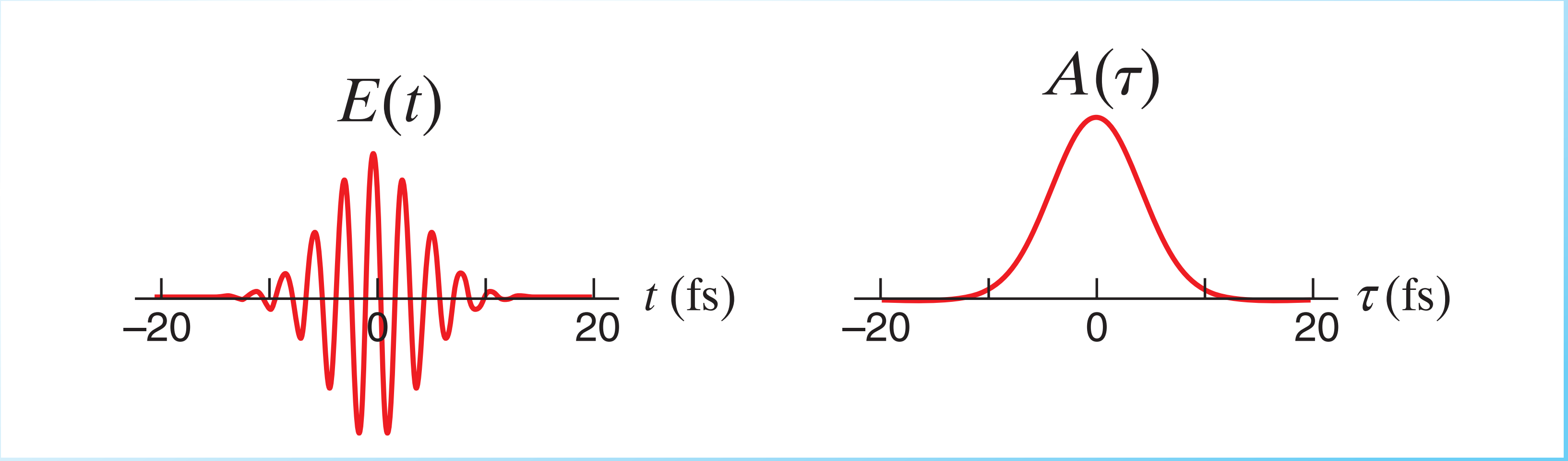
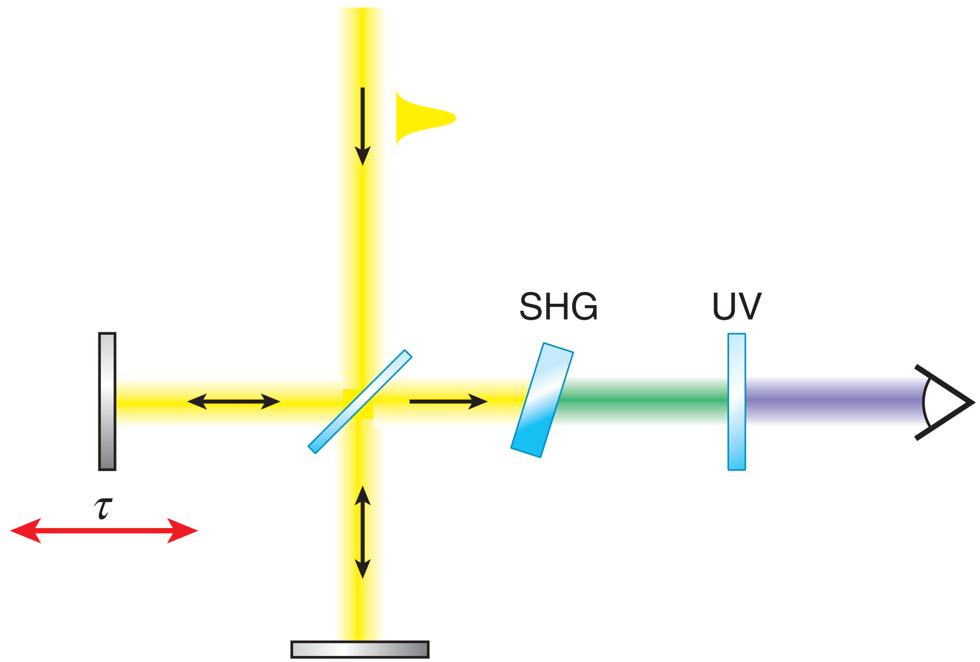


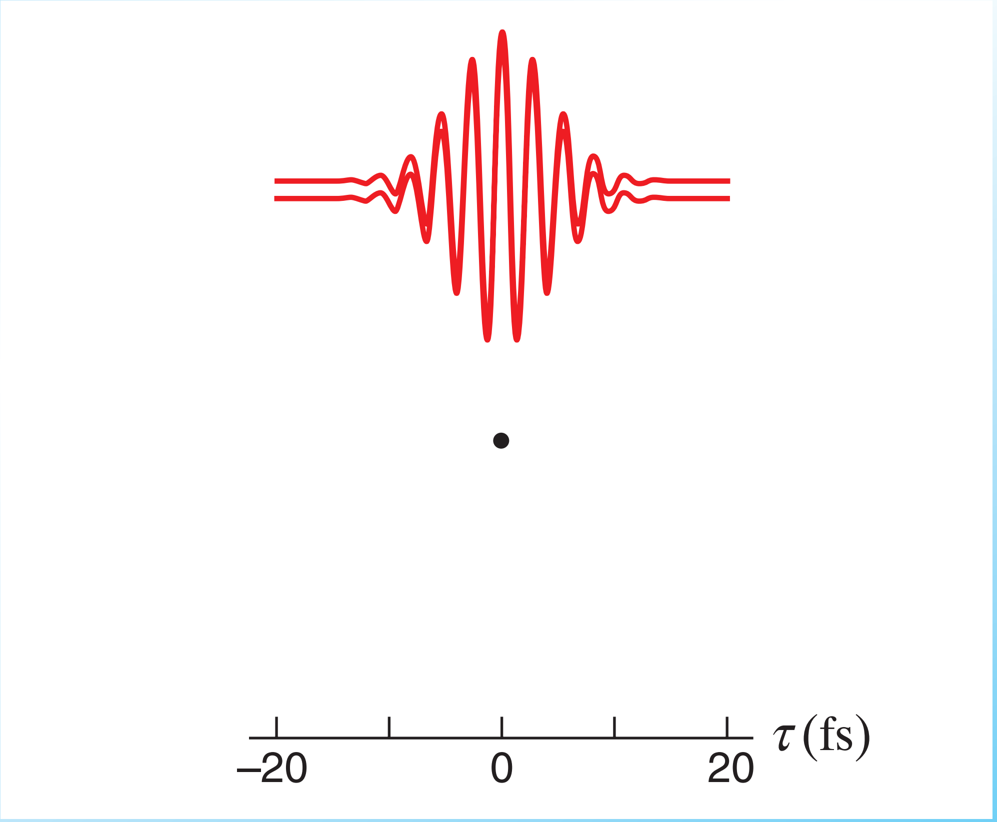
Temporal characterization

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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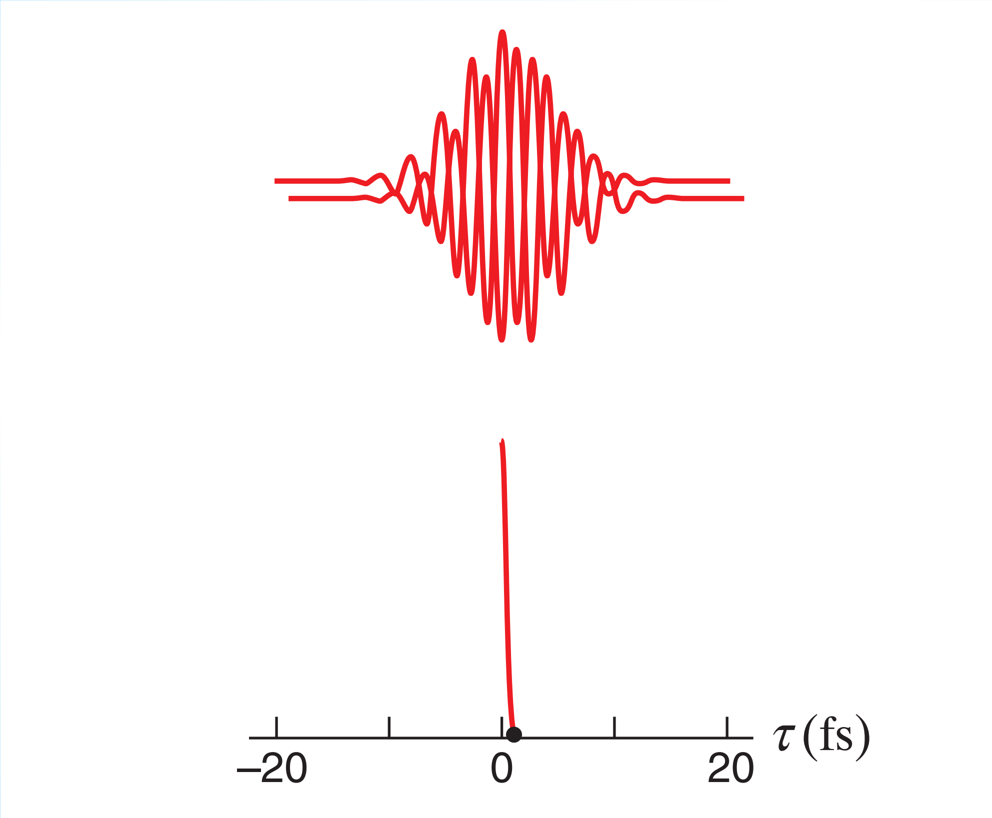

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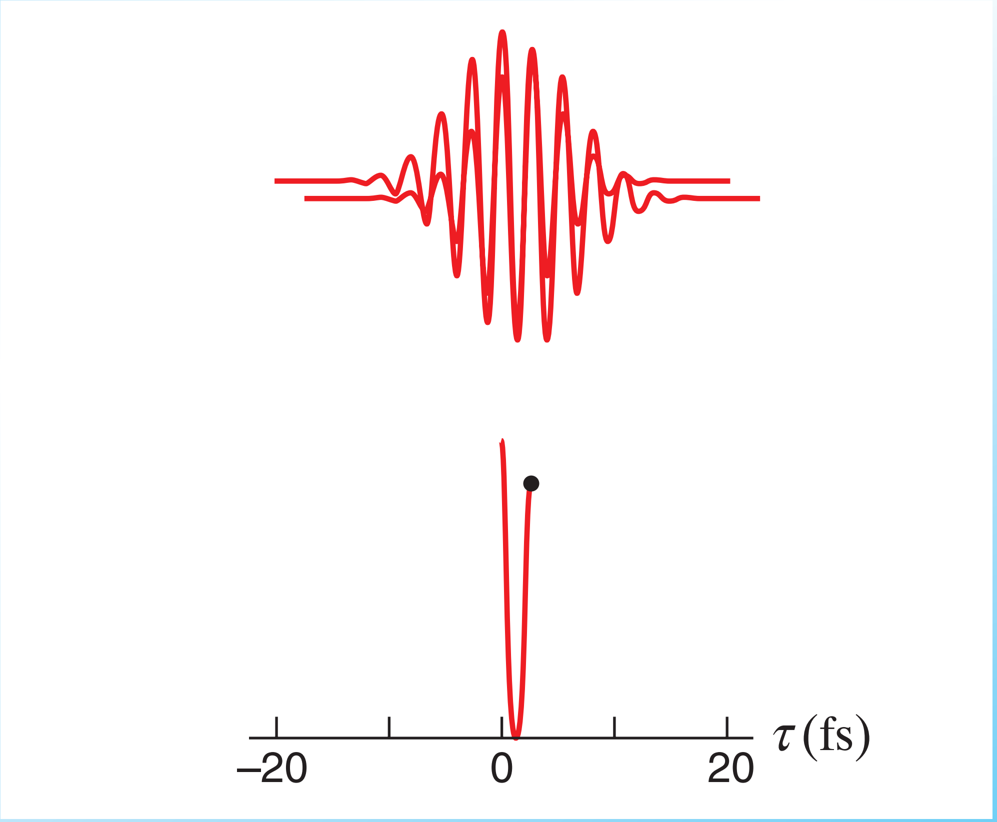

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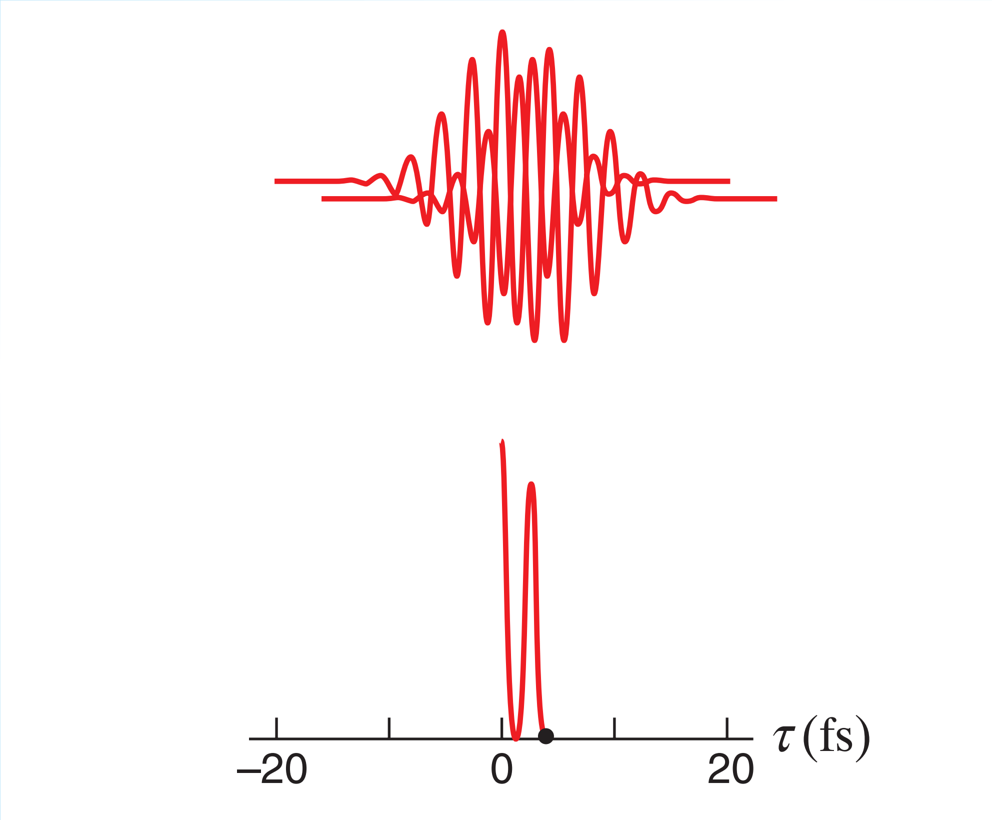

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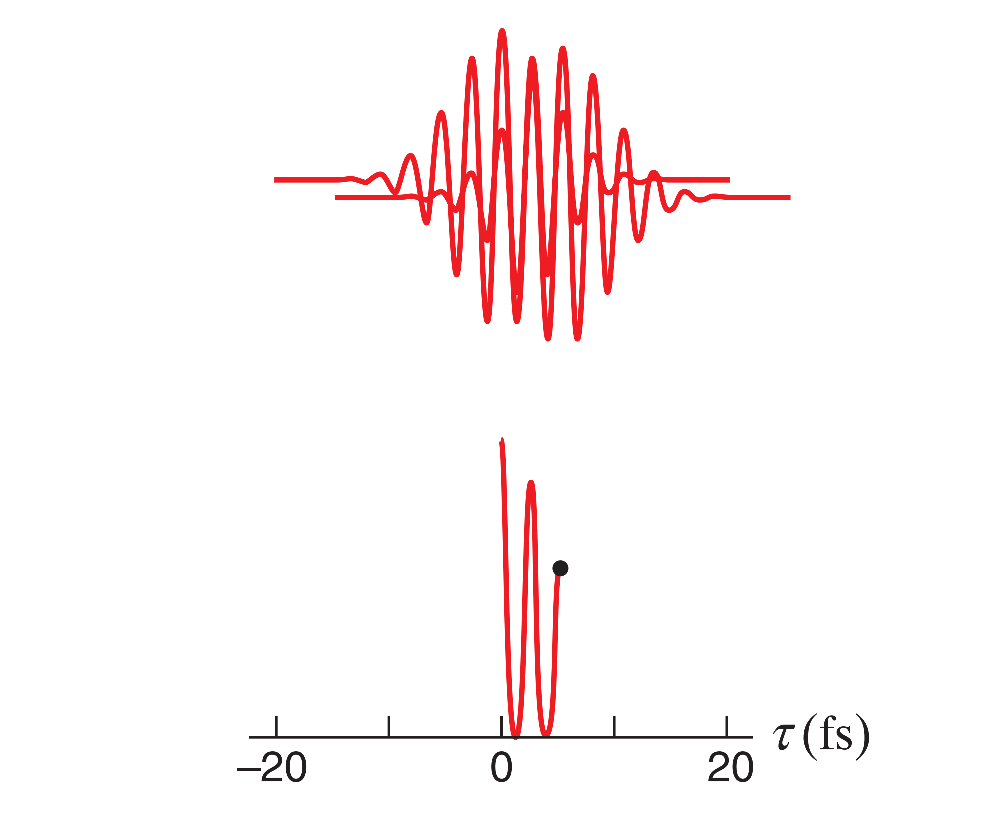

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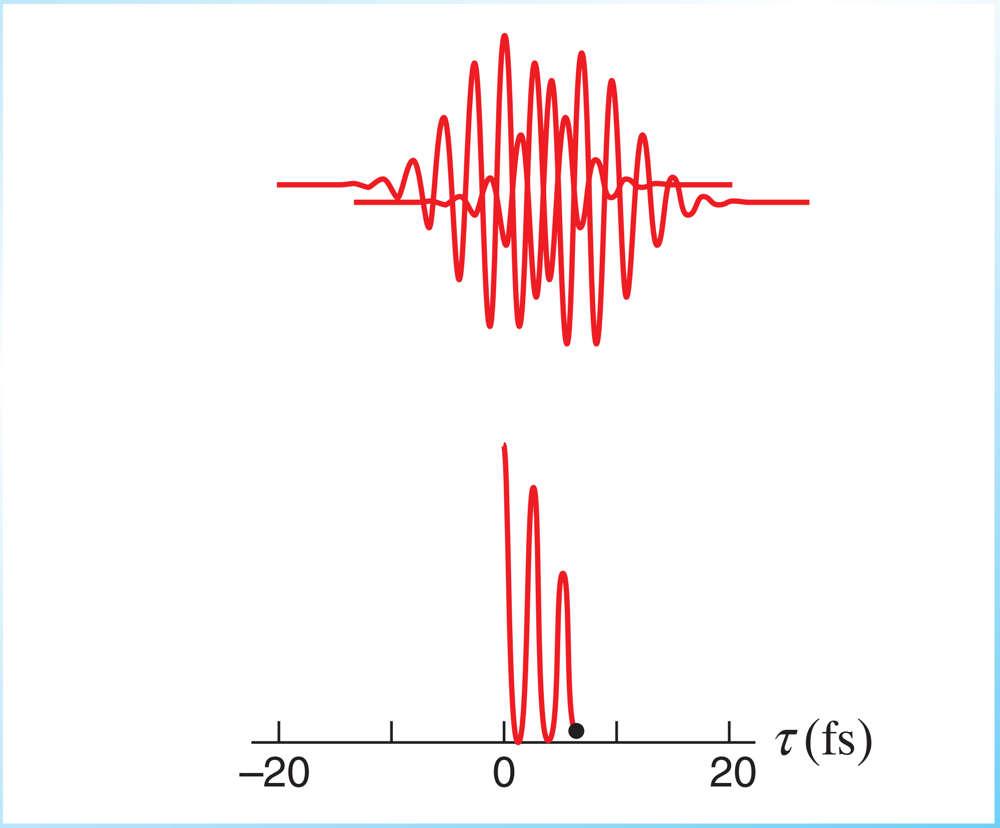

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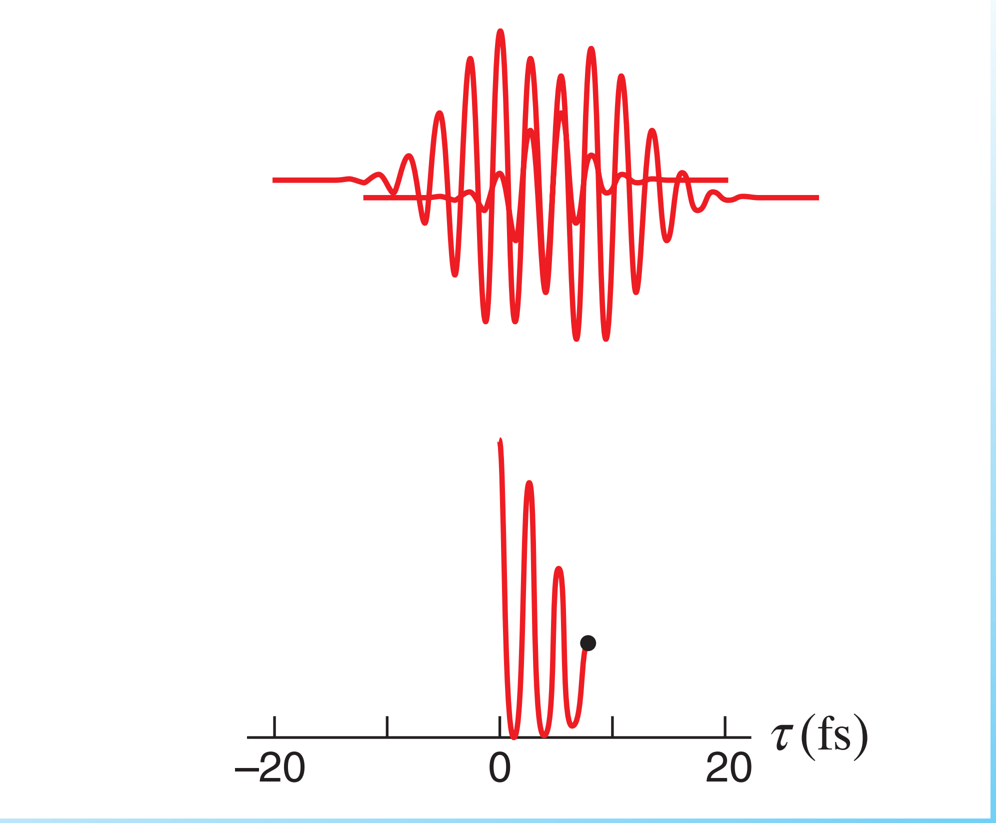

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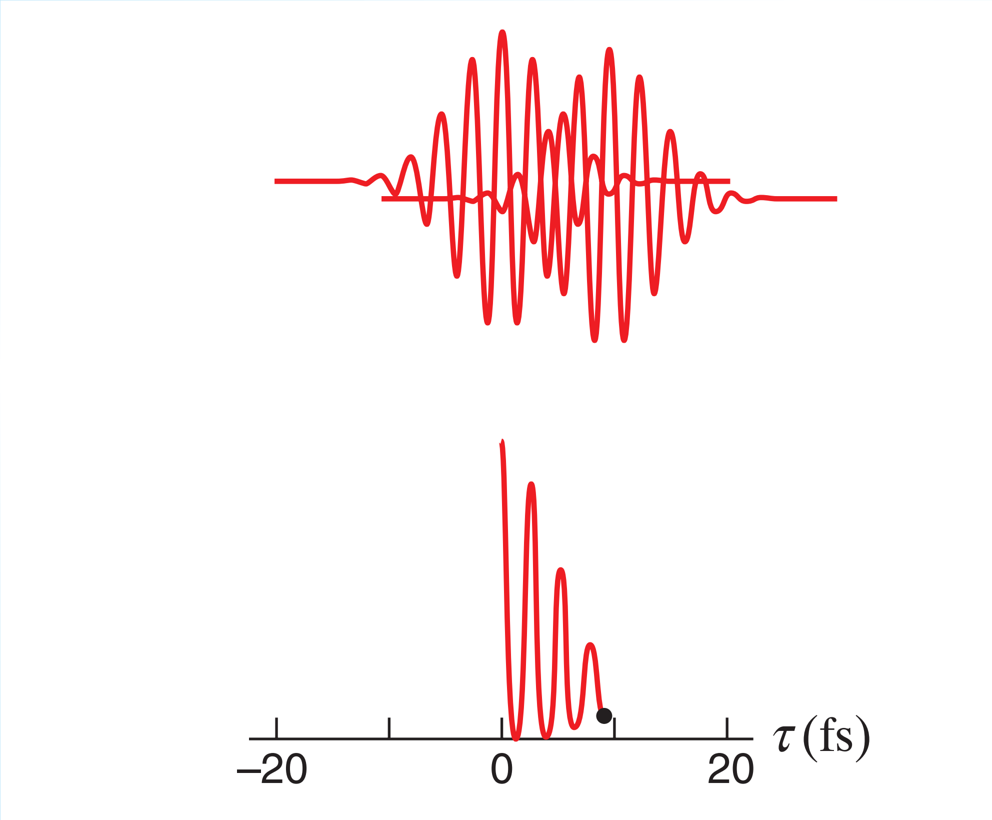

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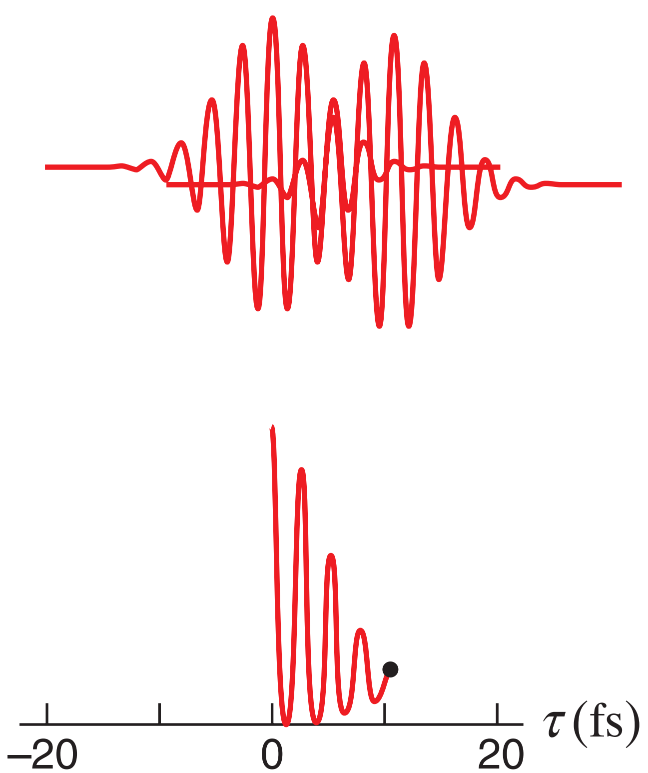

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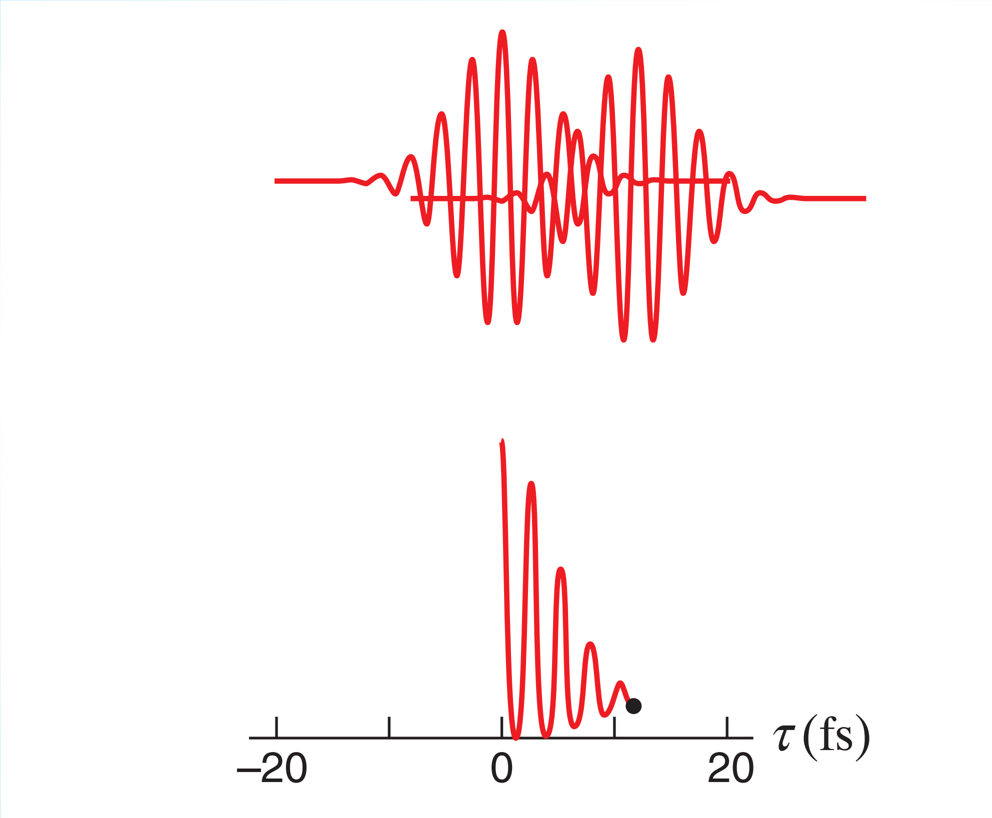

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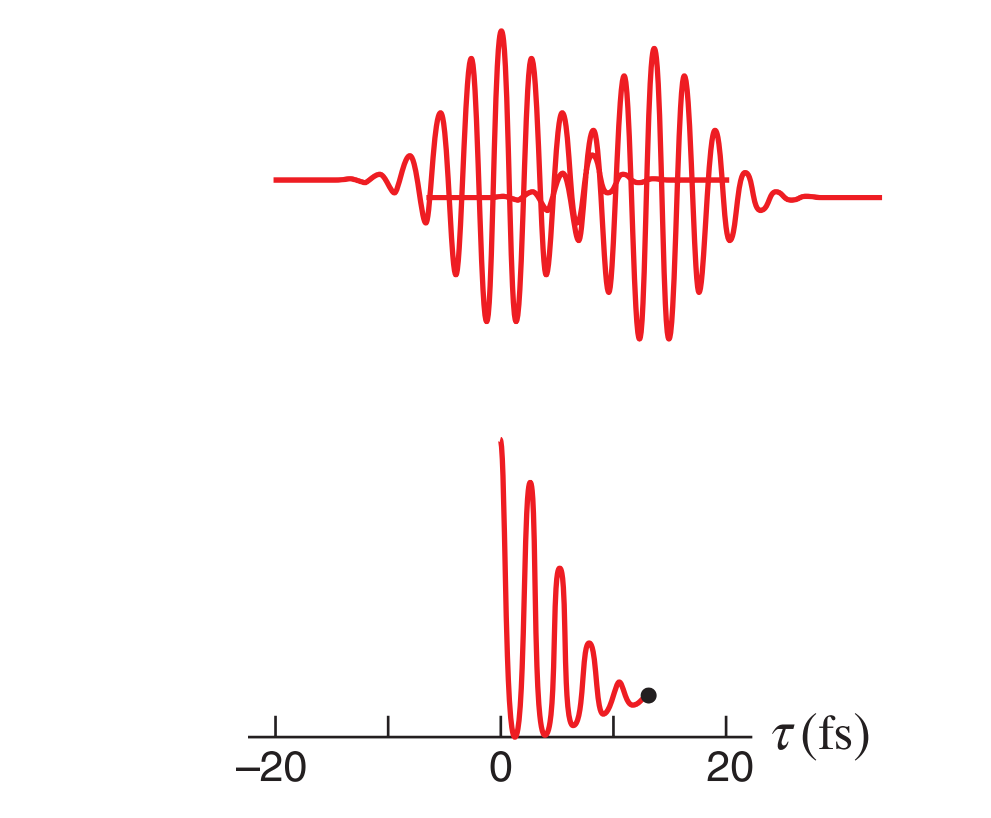

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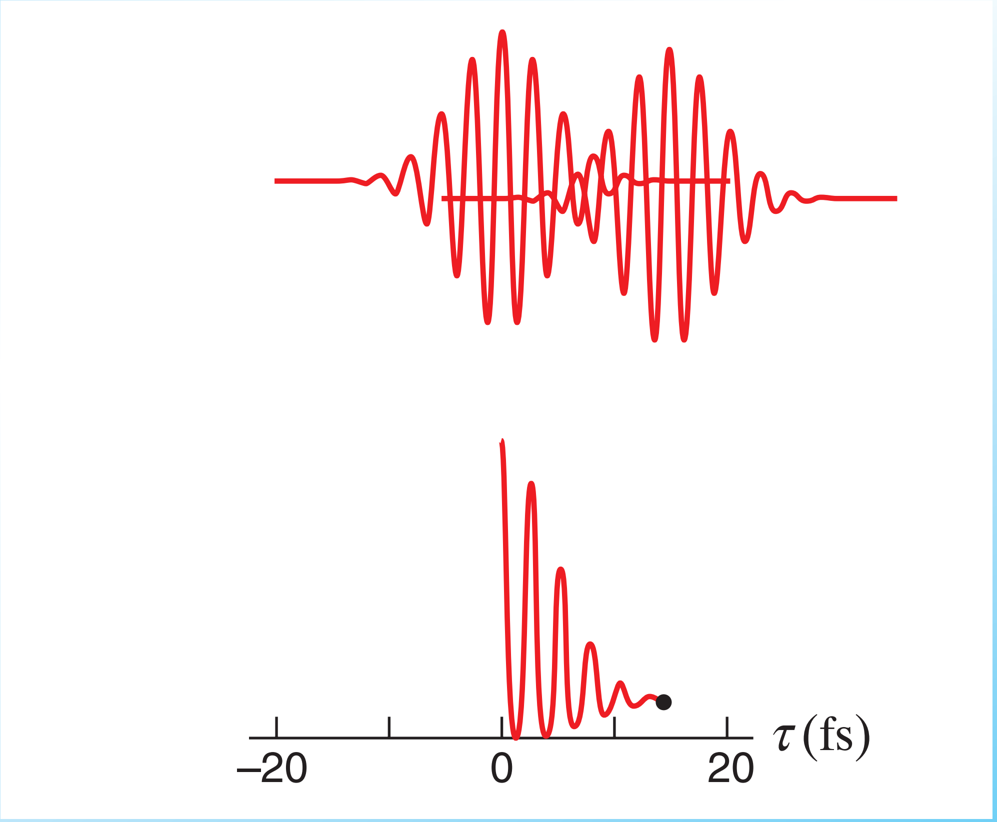

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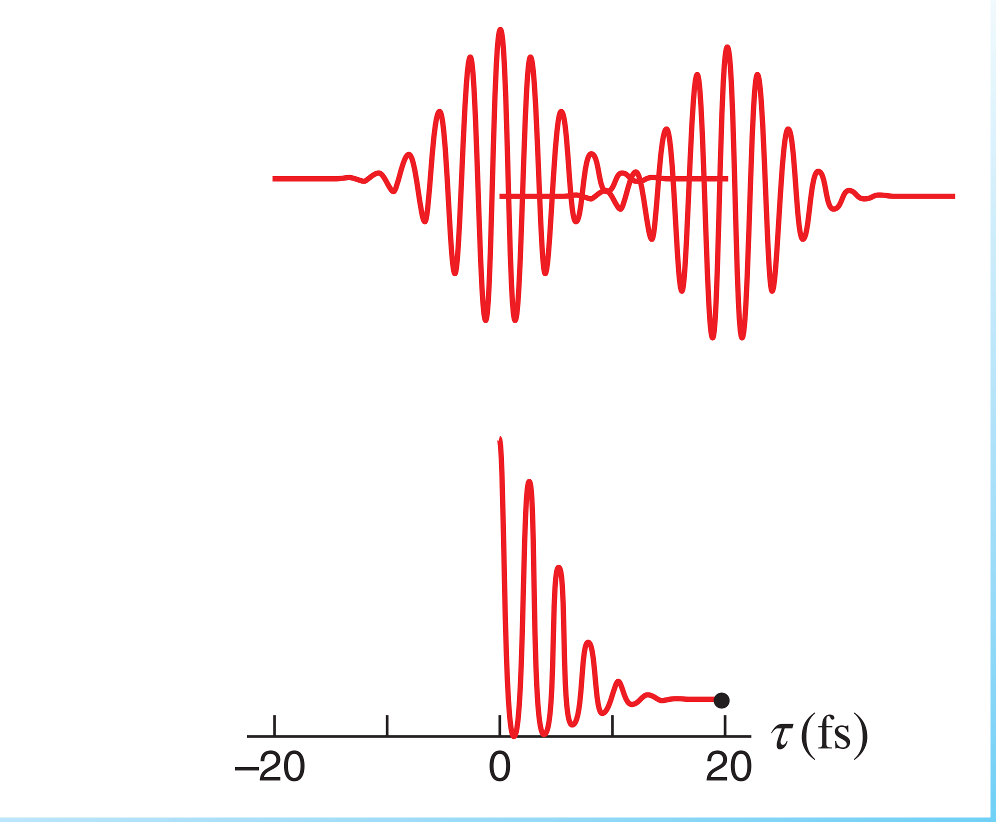

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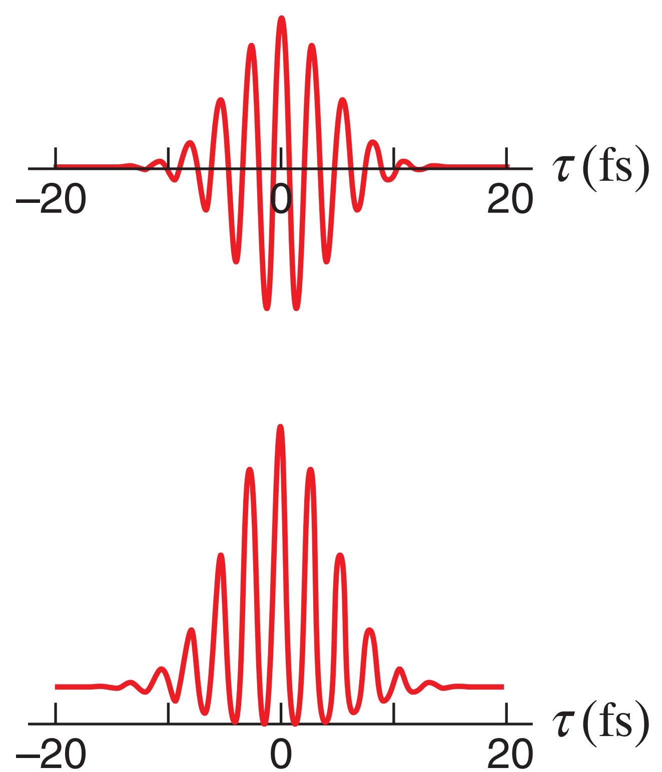

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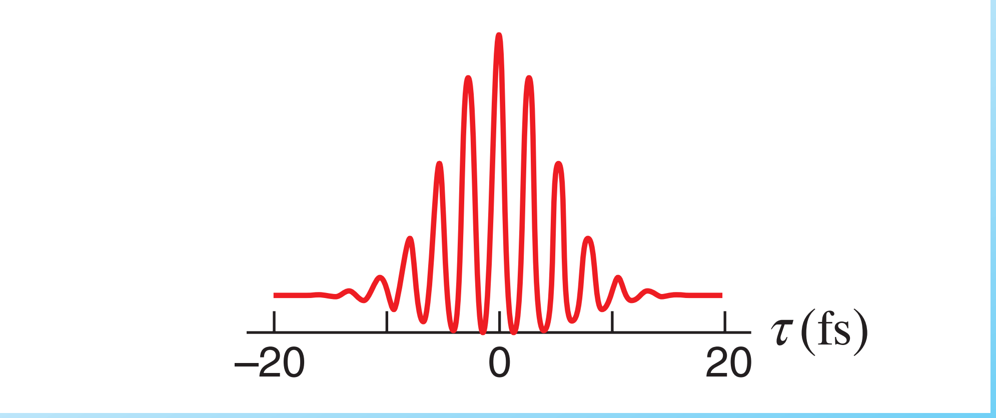
at $\tau = 0$**:** $$I_{2\omega}(t,\tau) \propto 16E^4(t)$$



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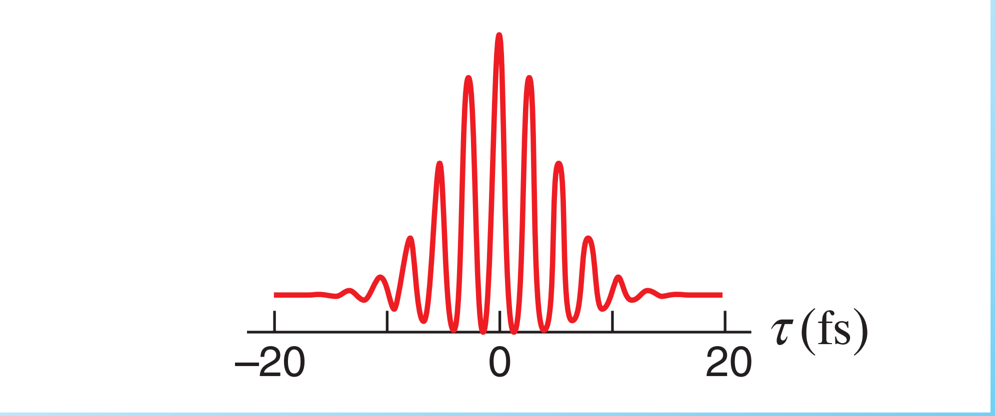
as $\tau \to \pm\infty$**:** $$I_{2\omega}(t,\tau) \propto 2E^4(t)$$



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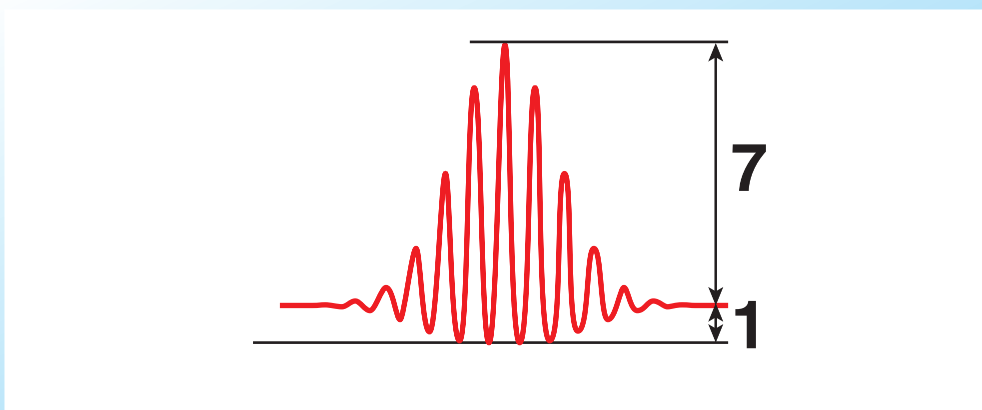
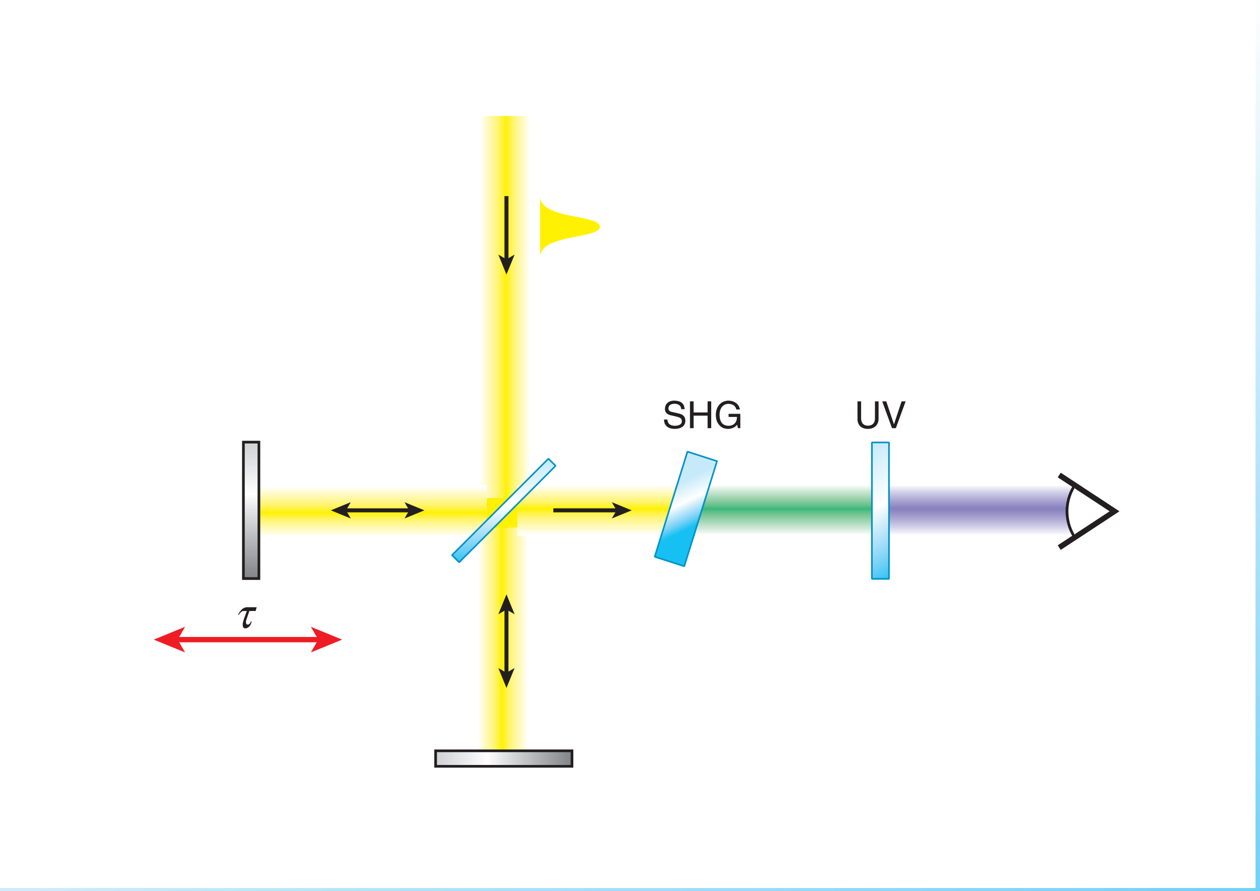


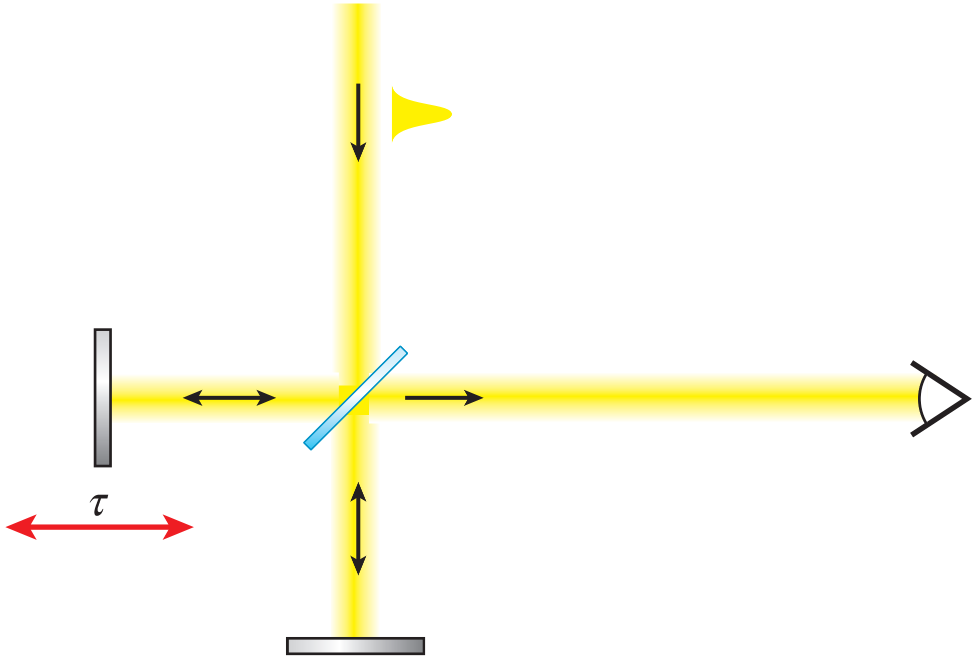
Temporal characterization

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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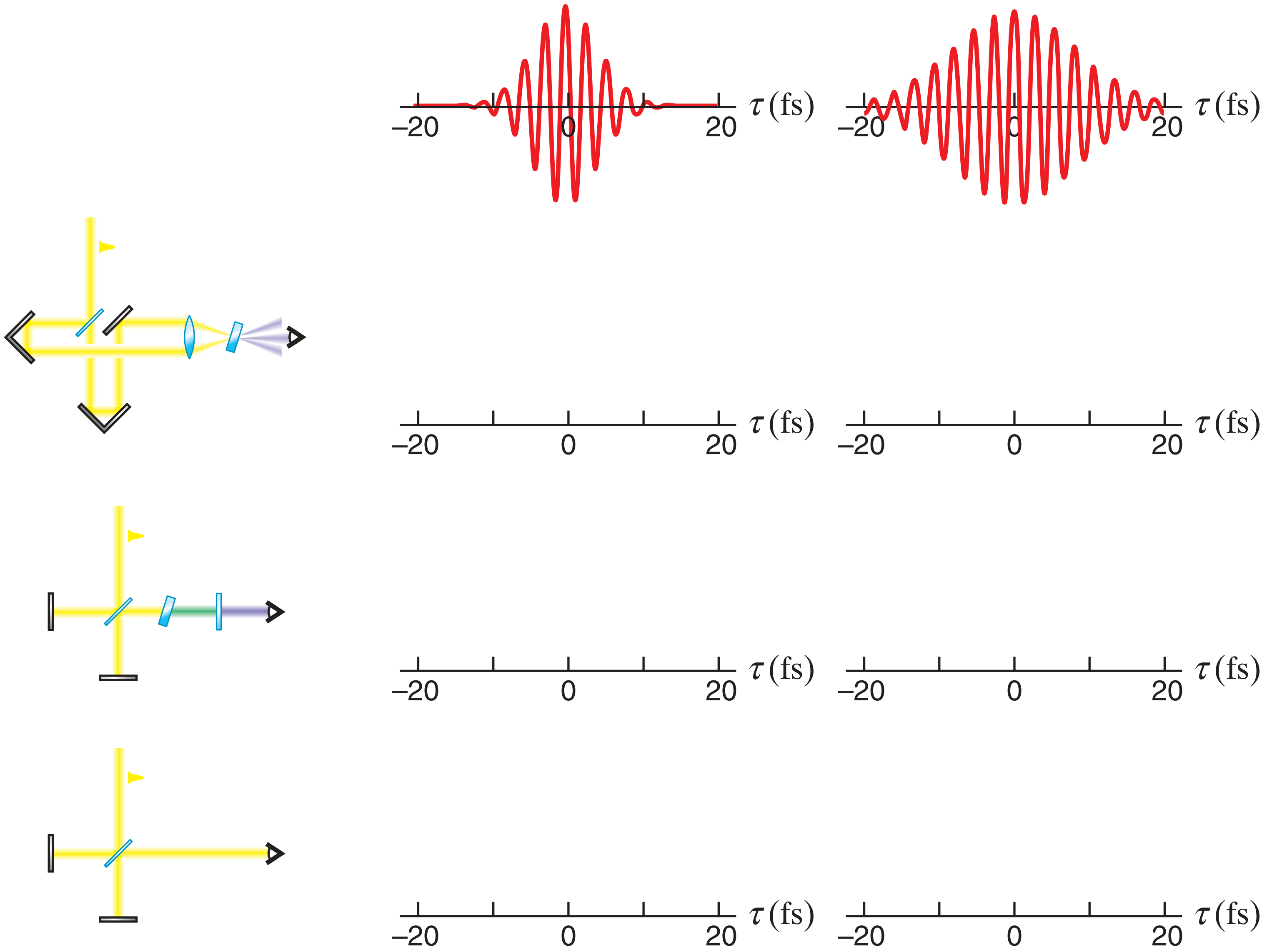
so

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

Temporal characterization



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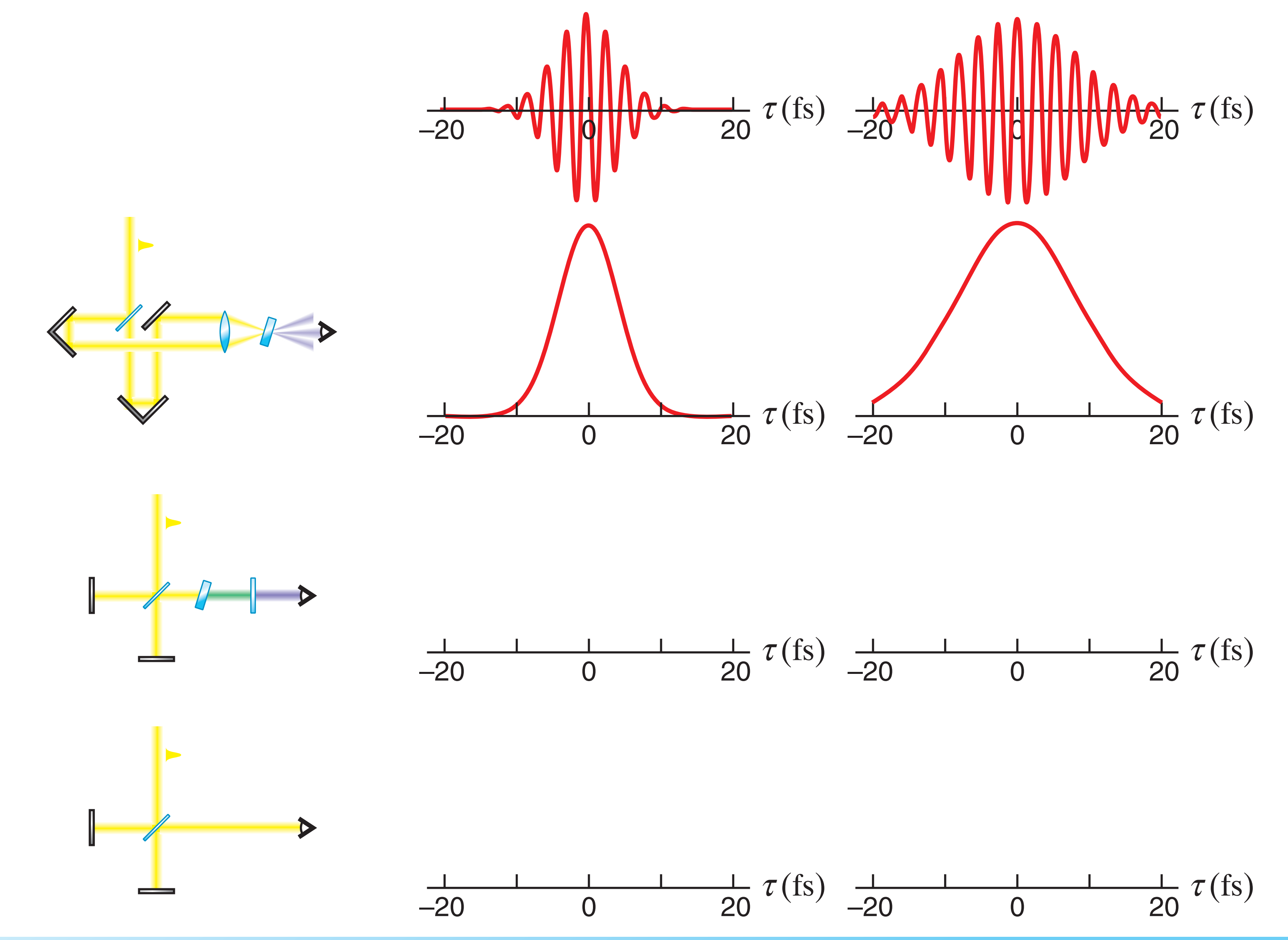

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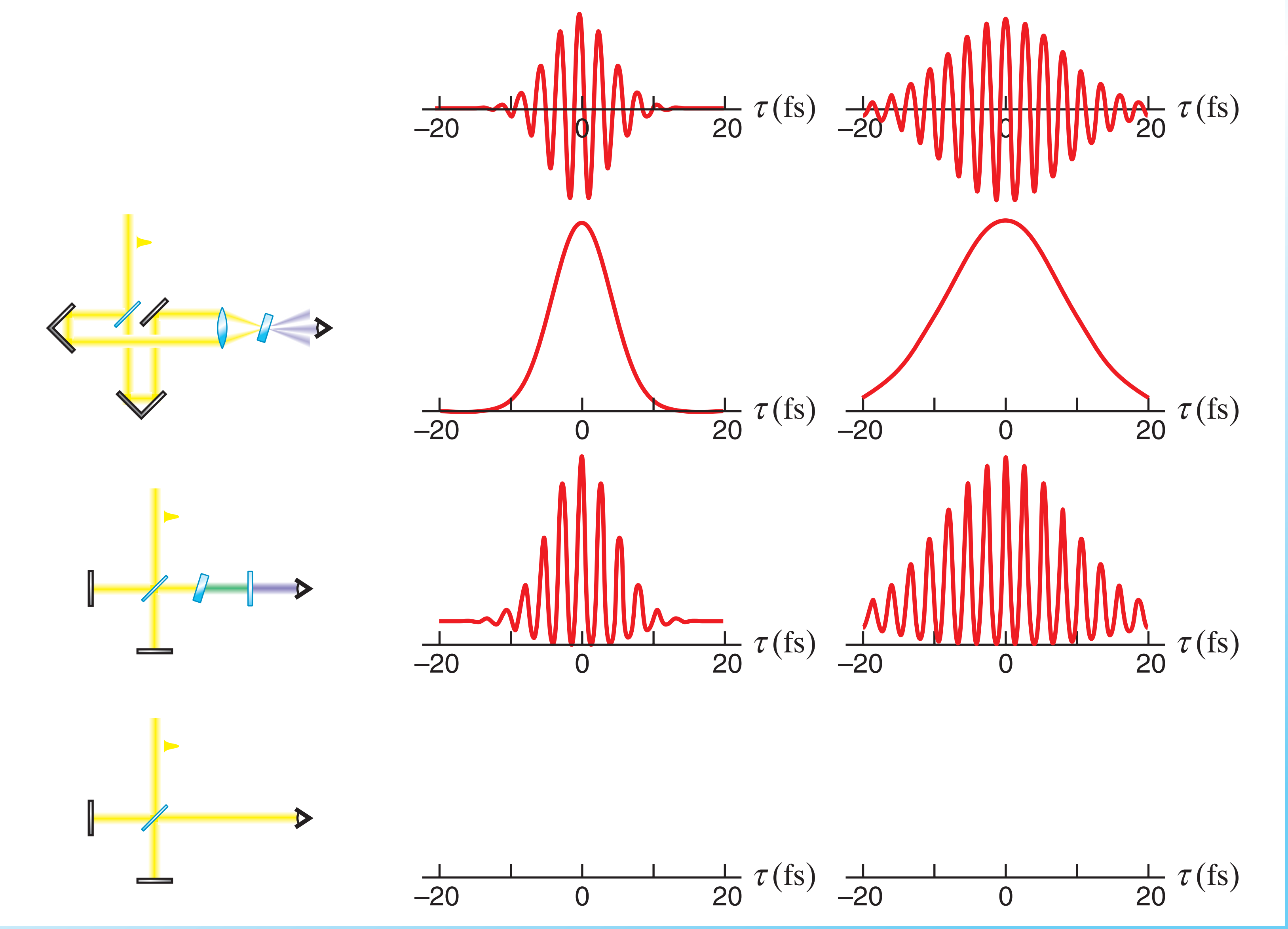

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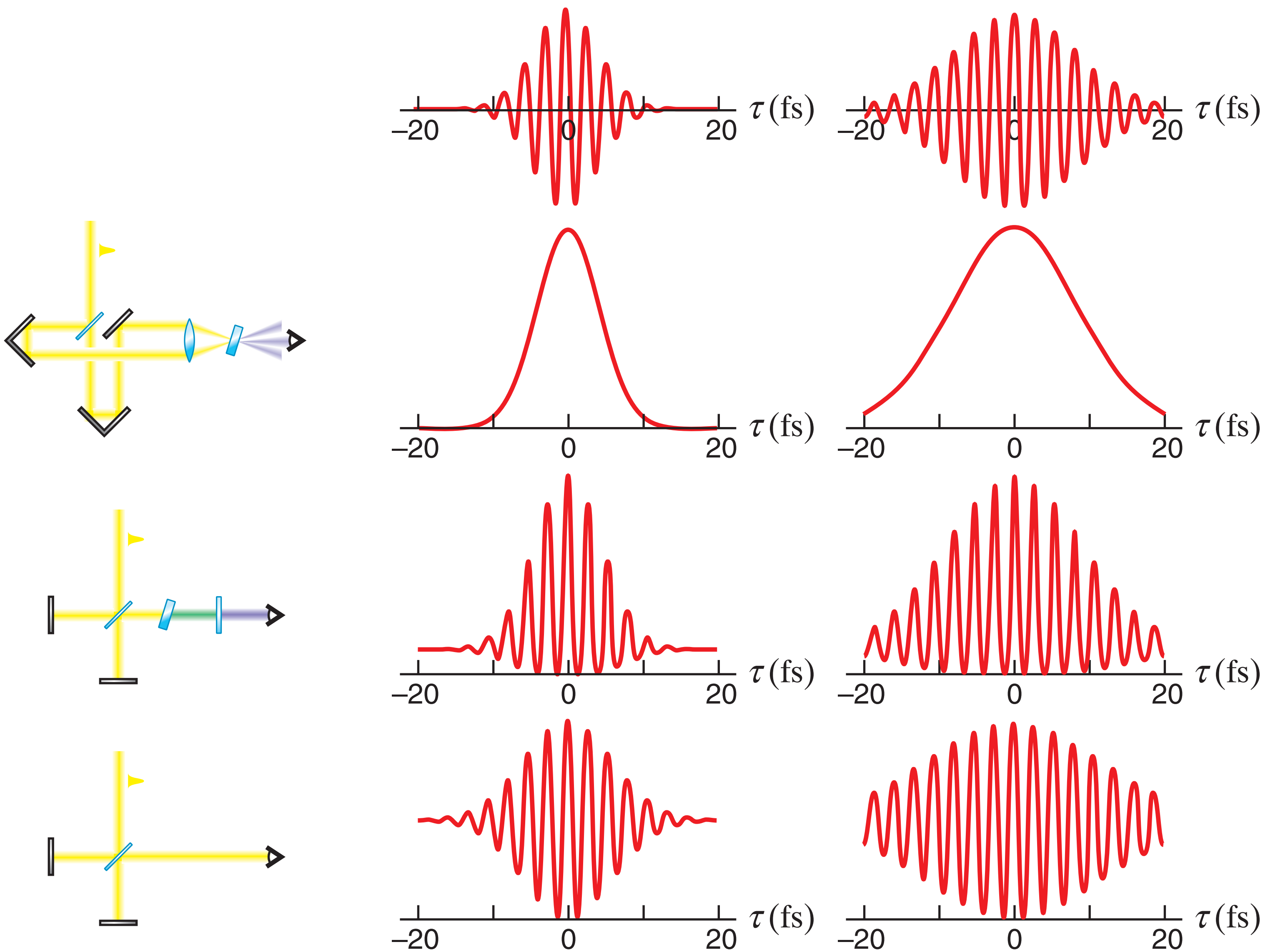
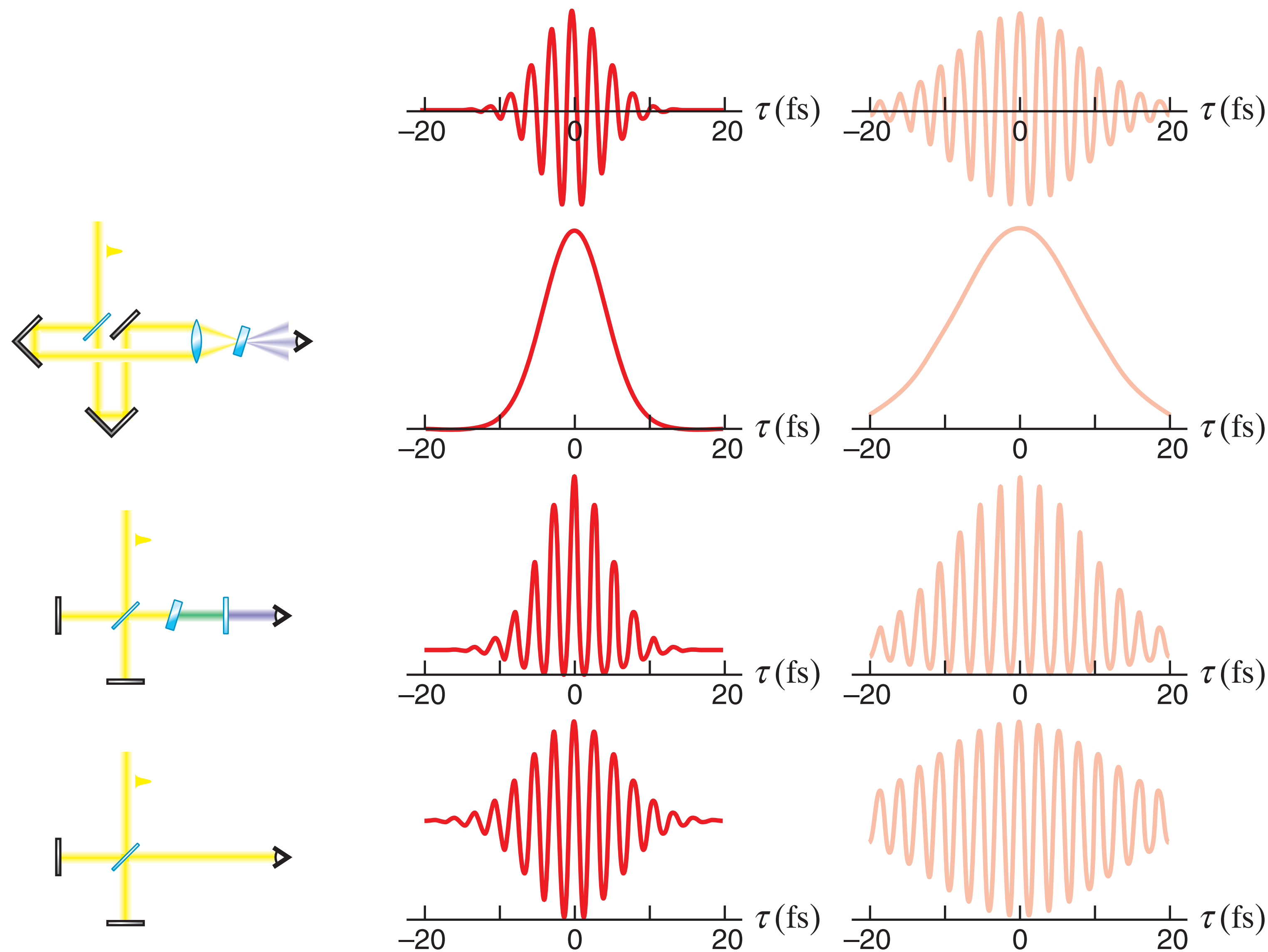


Temporal characterization

But what about dispersion?

Temporal characterization



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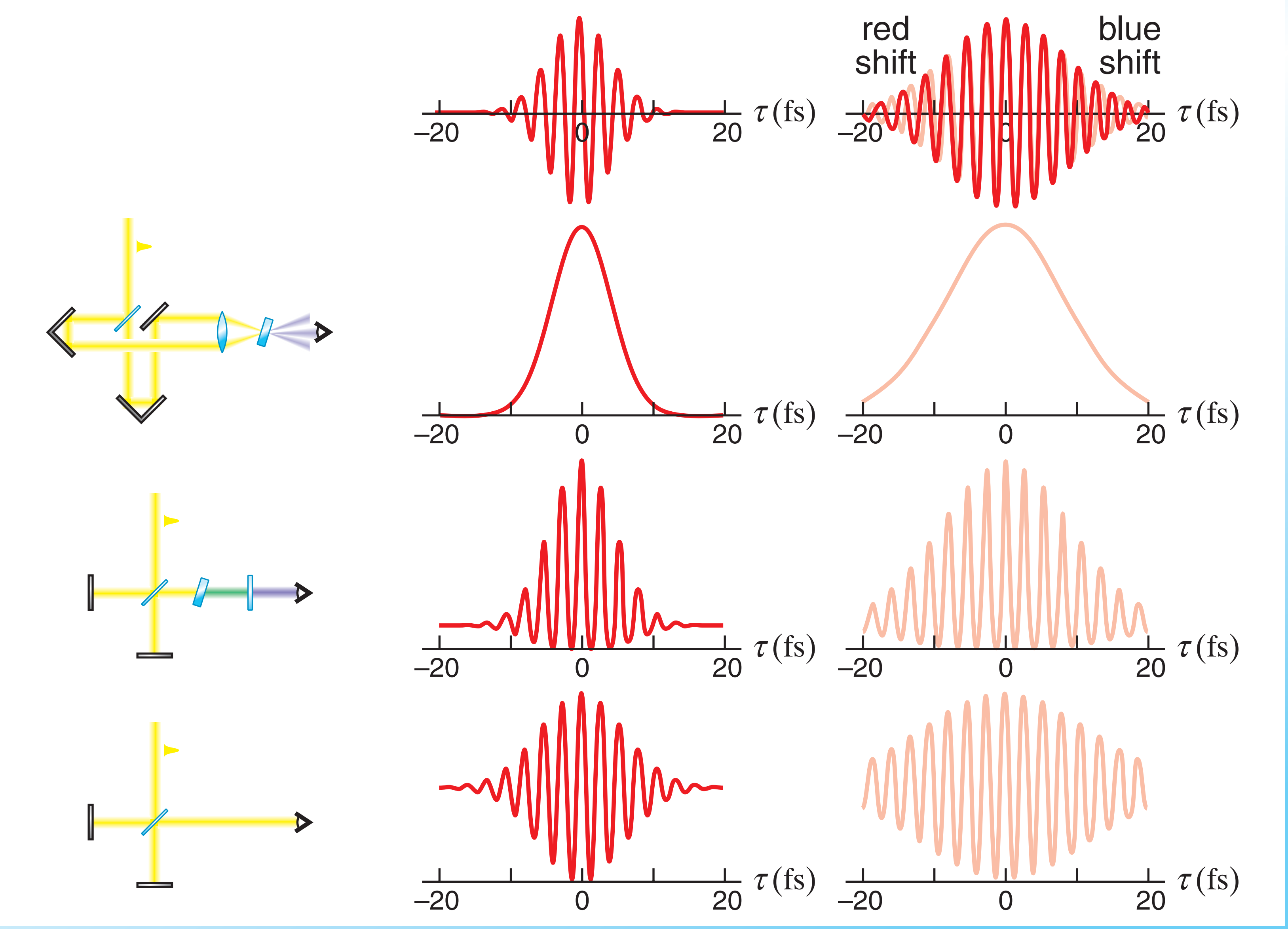

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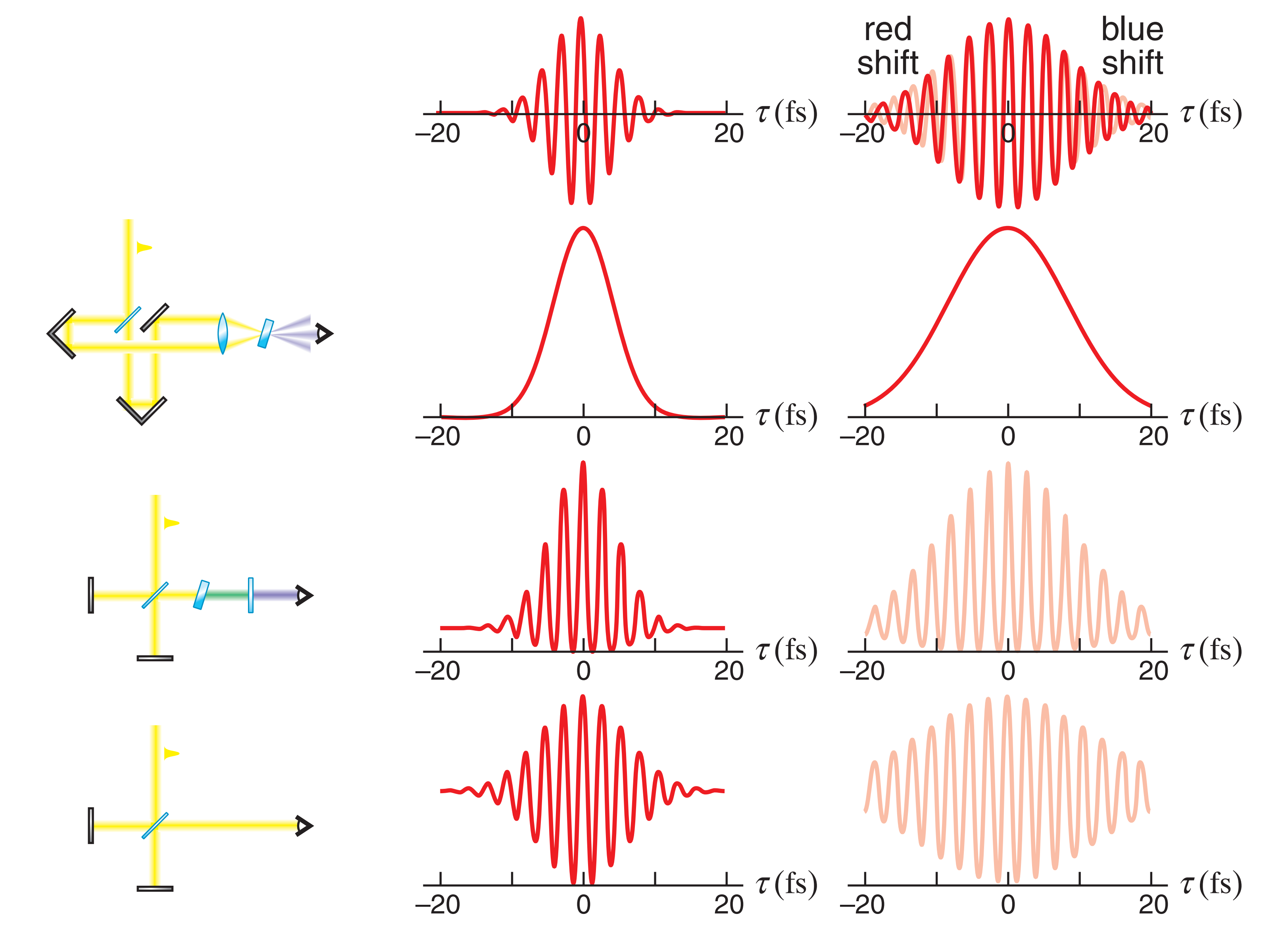

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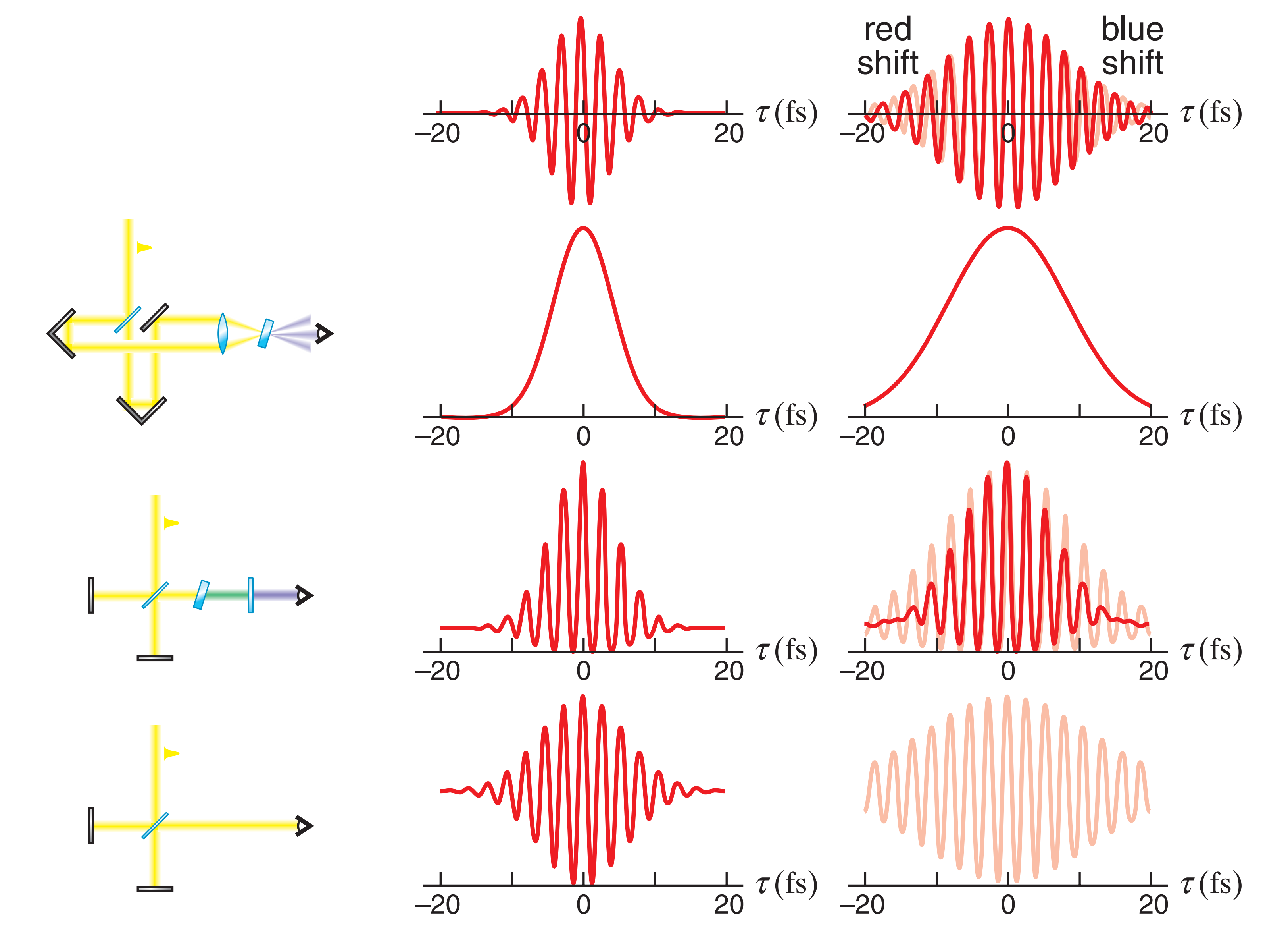

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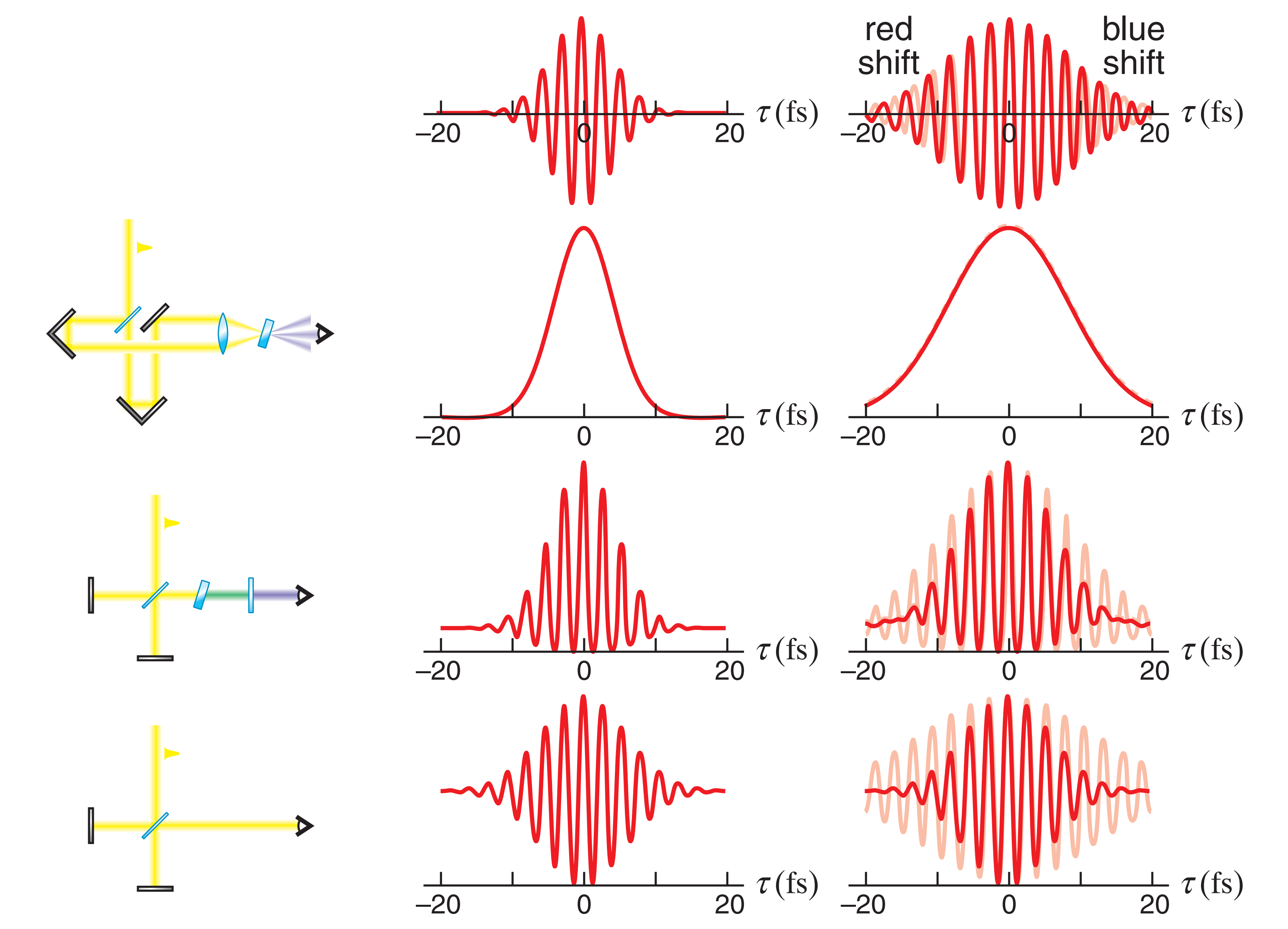

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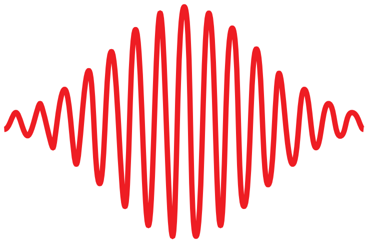

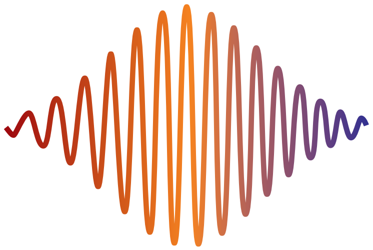

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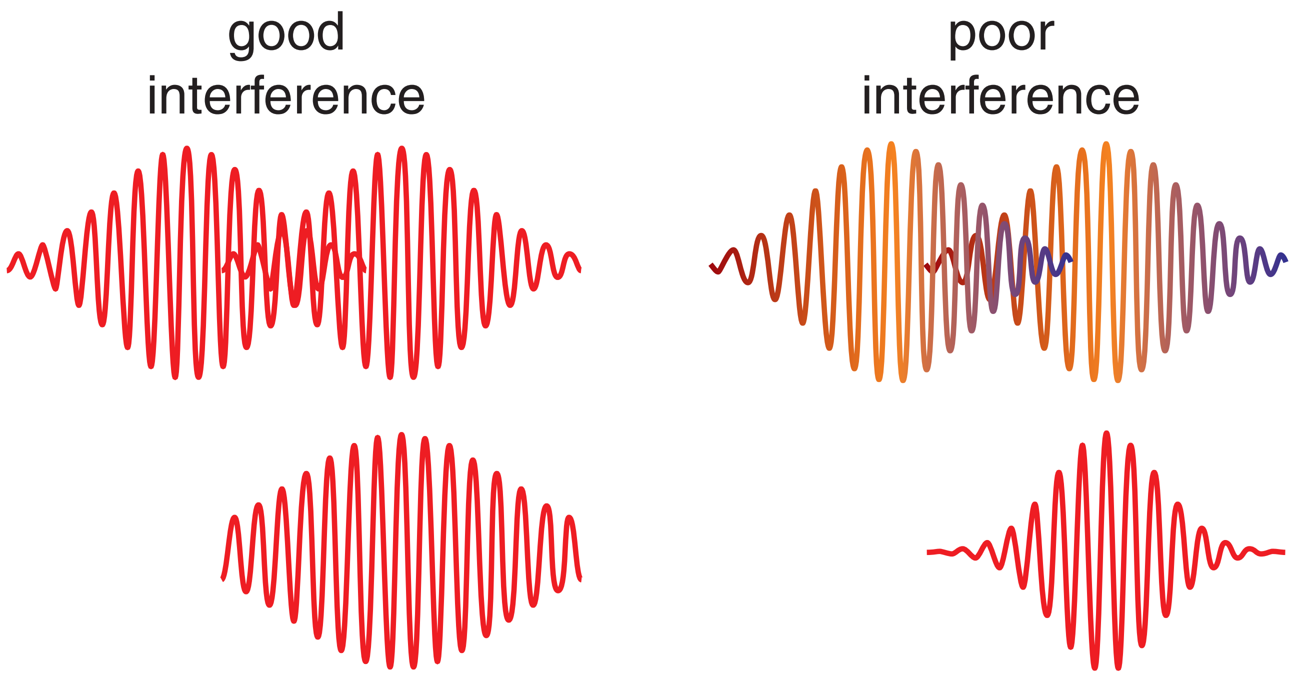

Temporal characterization

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

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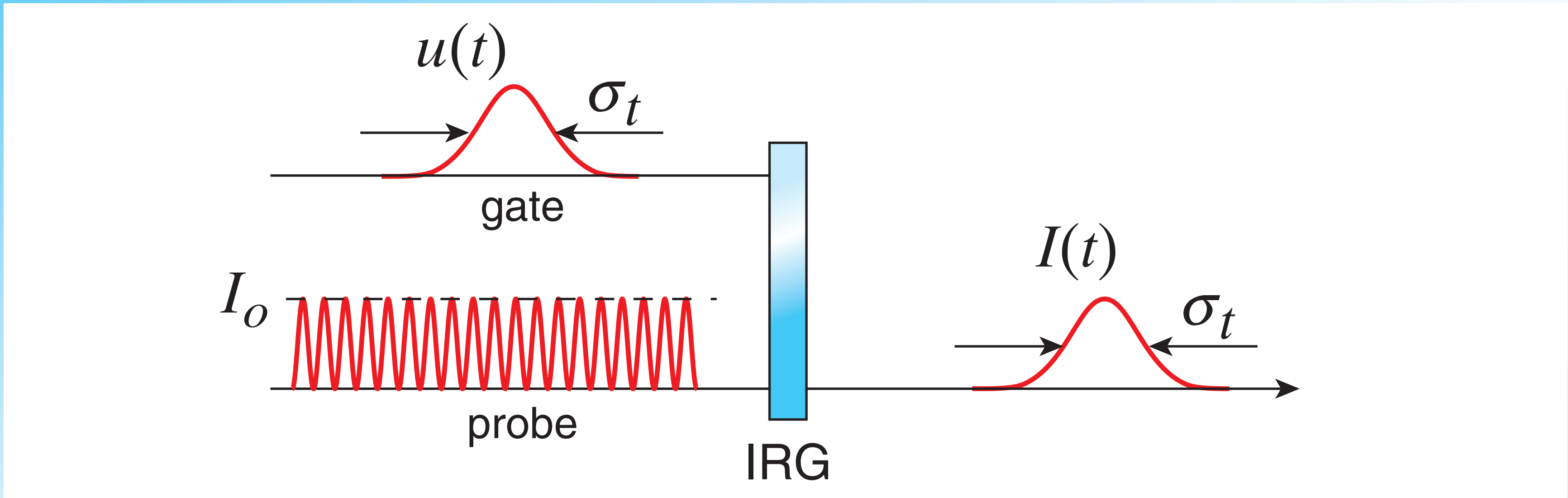
$$= \mathcal{F}^{-1}\{E_{orig}(\omega) E^*_{orig}(\omega)\} = \int E_{orig}(t+\tau)\, E_{orig}{}^*(t)\, dt$$

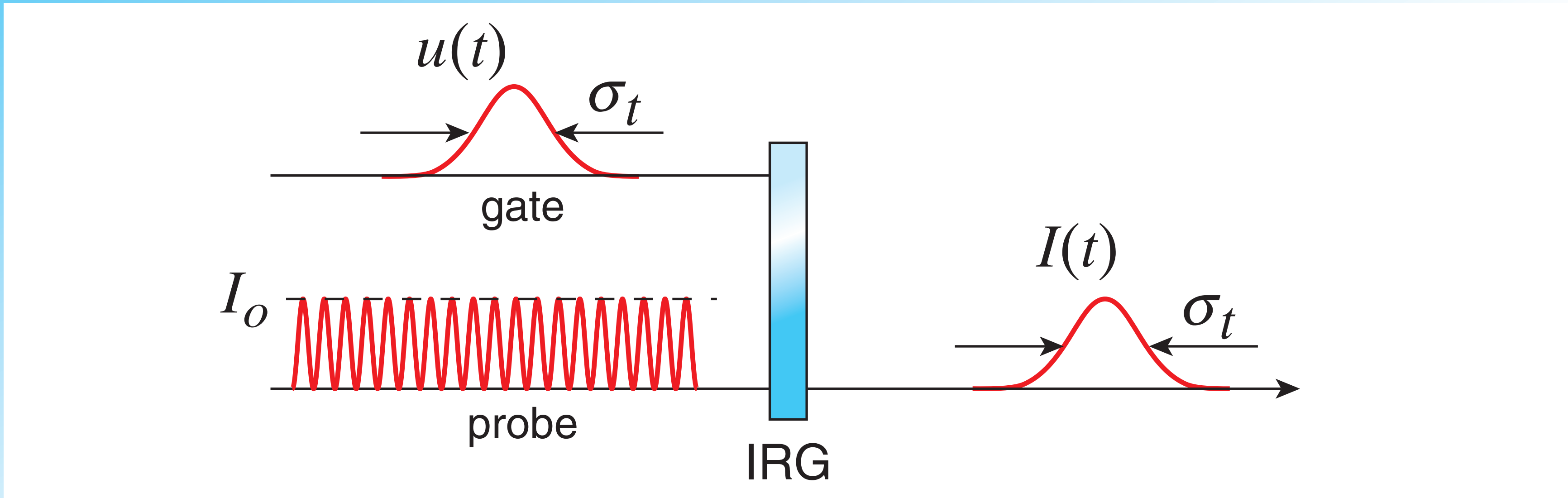
Joint time-frequency measurements



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

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

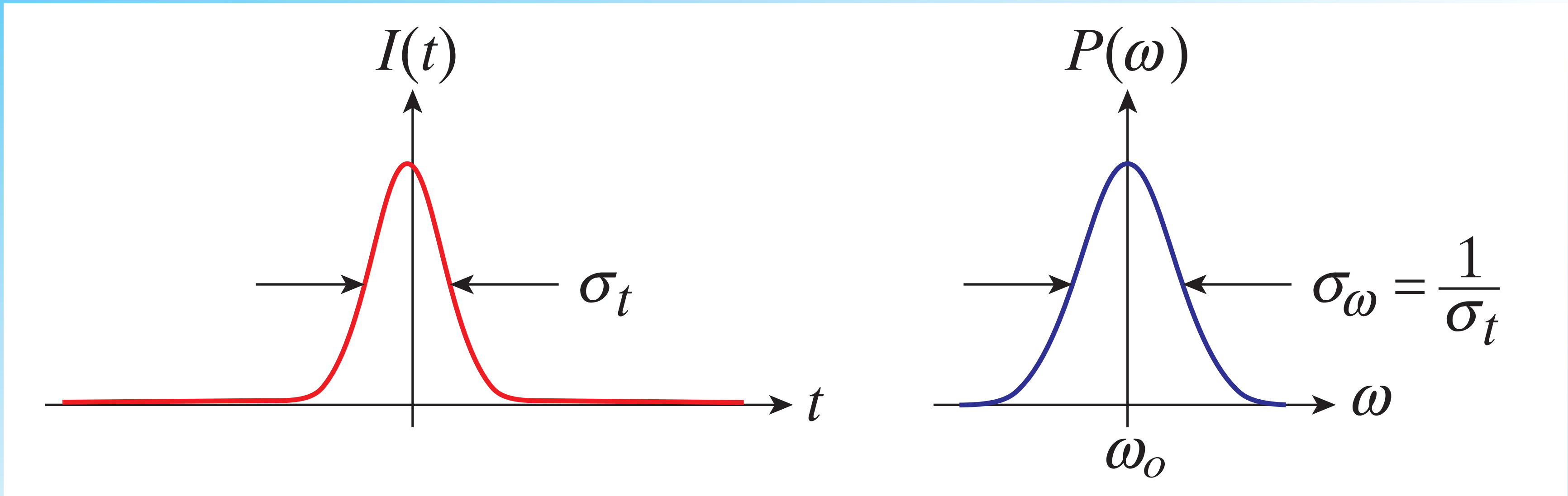
Joint time-frequency measurements



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

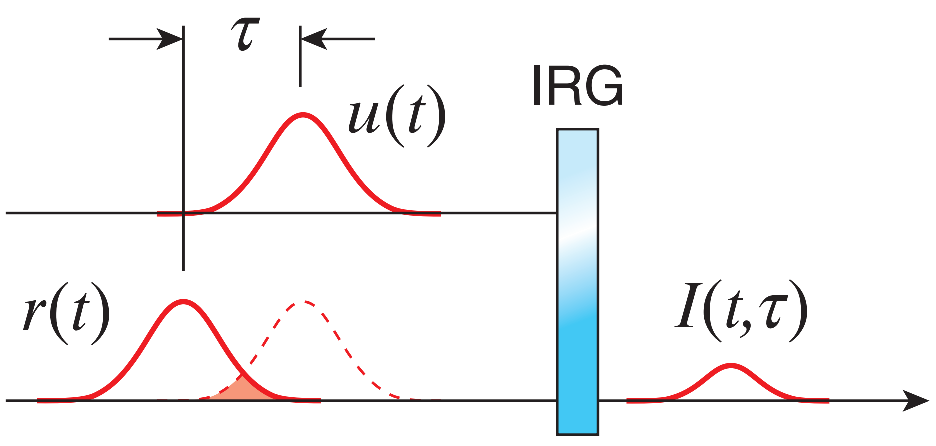


Transmitted intensity

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

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

Joint time-frequency measurements

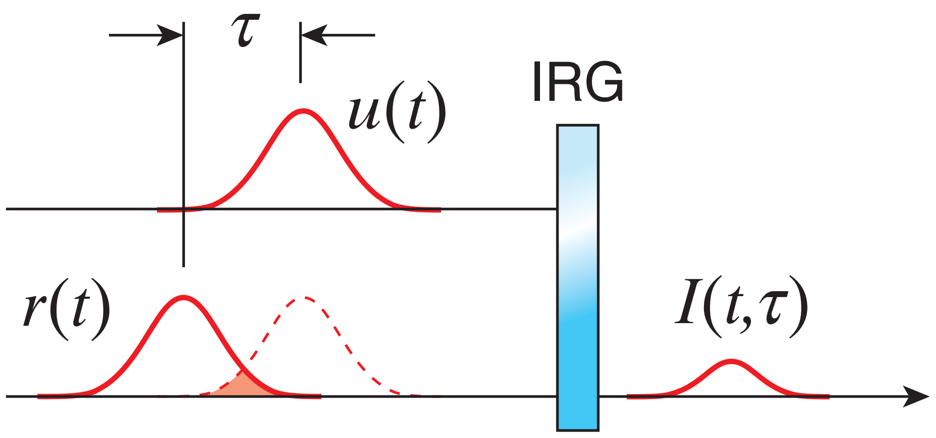


Transmitted intensity

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

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

Joint time-frequency measurements

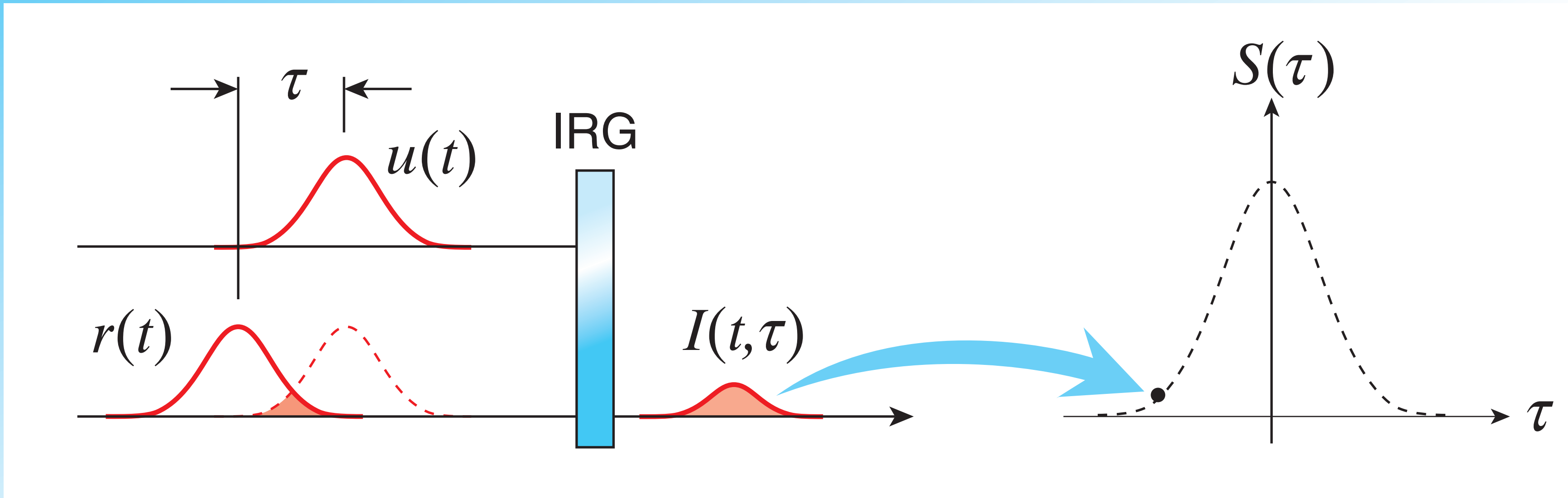


Transmitted intensity

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

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

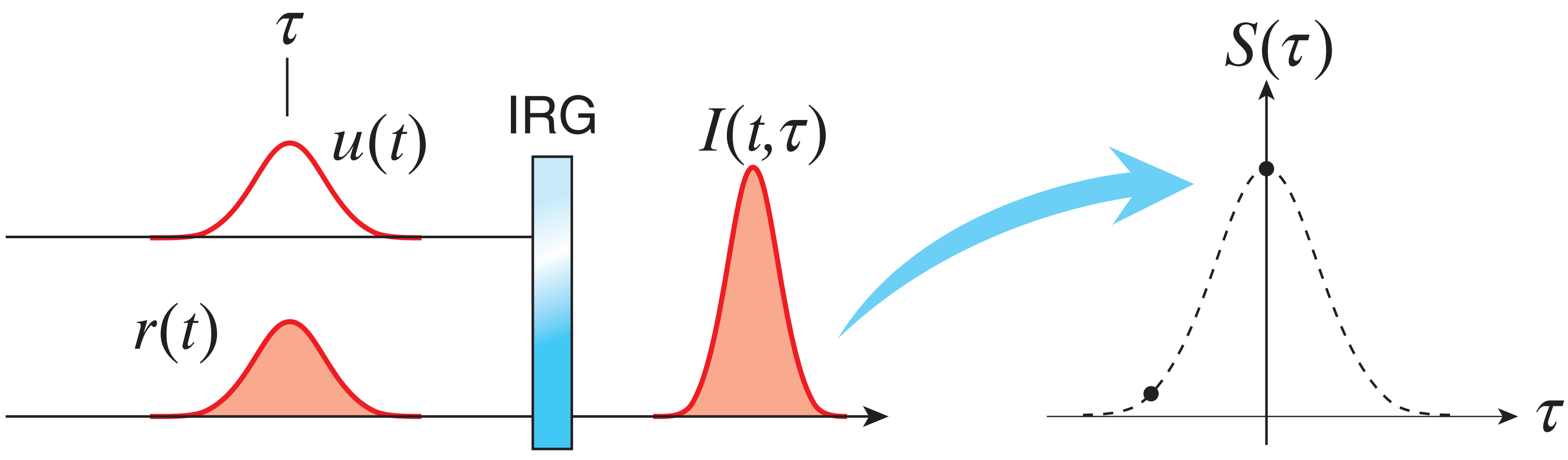
Joint time-frequency measurements



…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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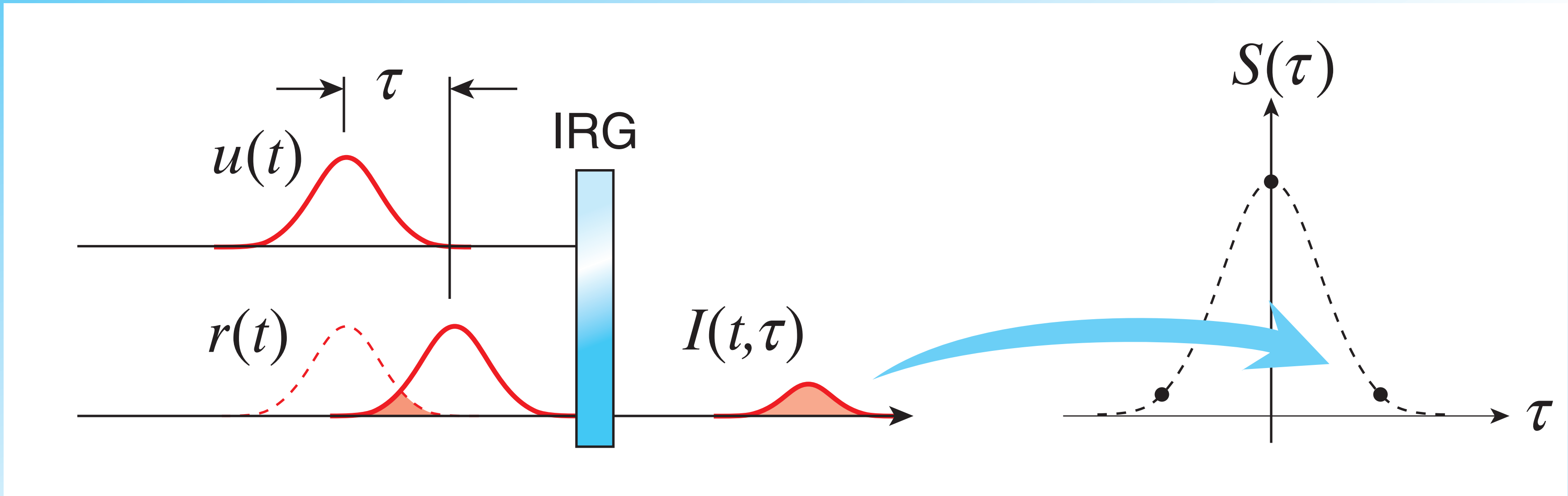

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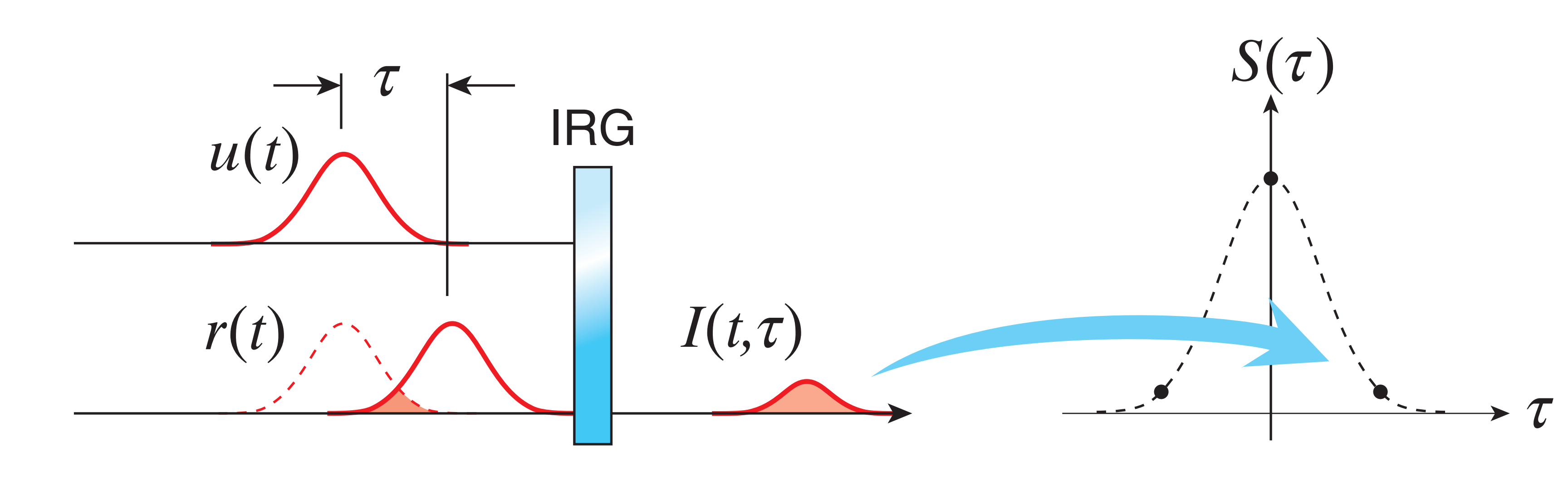
Joint time-frequency measurements



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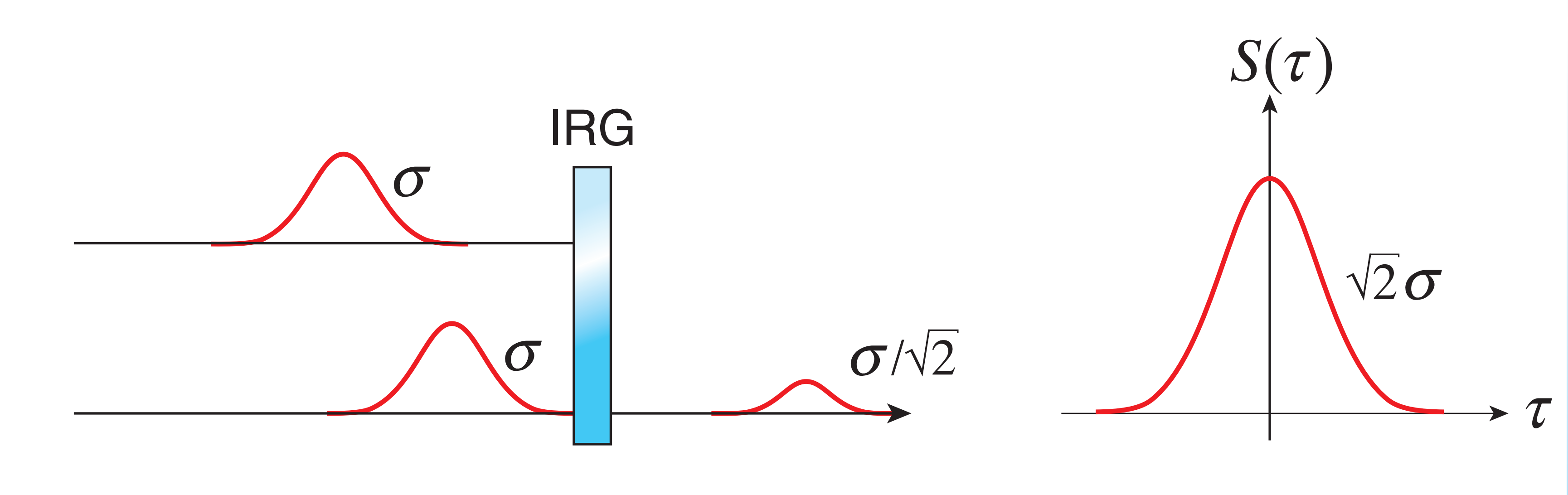
$$= \exp\left[-\frac{\tau^2}{2\sigma^2}\right] \int_{-\infty}^{\infty} \exp\left[-\frac{2u^2}{\sigma^2}\right] du = \sqrt{\frac{\pi}{2}}\,\sigma \exp\left[-\frac{\tau^2}{(\sigma\sqrt{2})^2}\right]$$

Joint time-frequency measurements



…but detector integrates $I(t,\tau)$:

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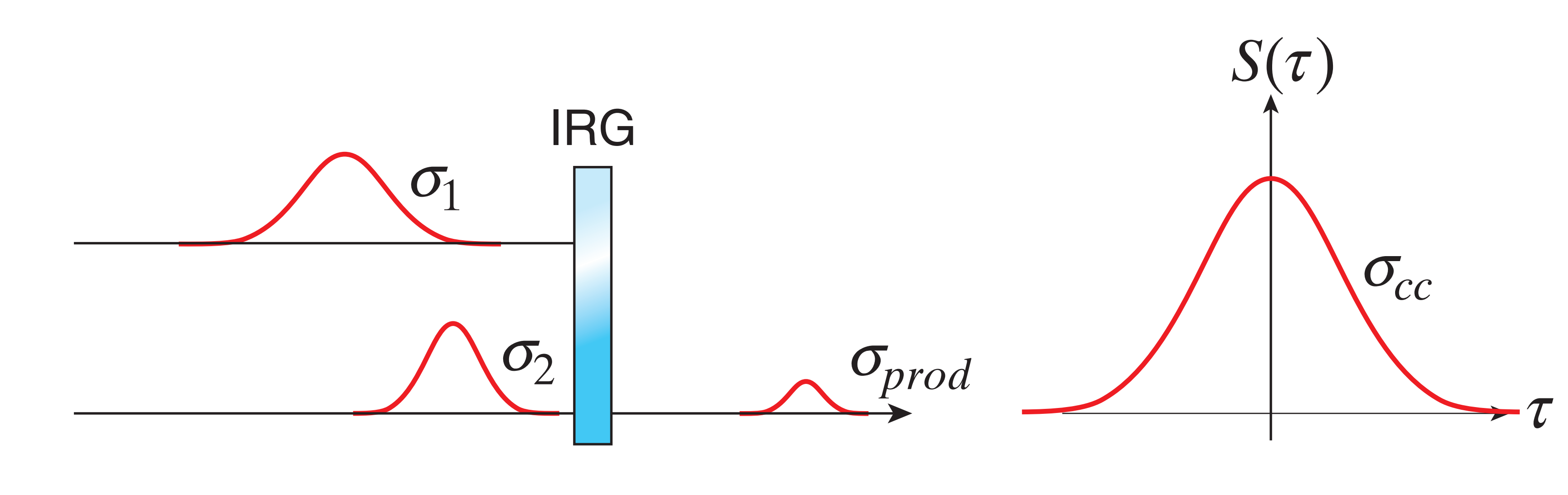
Joint time-frequency measurements

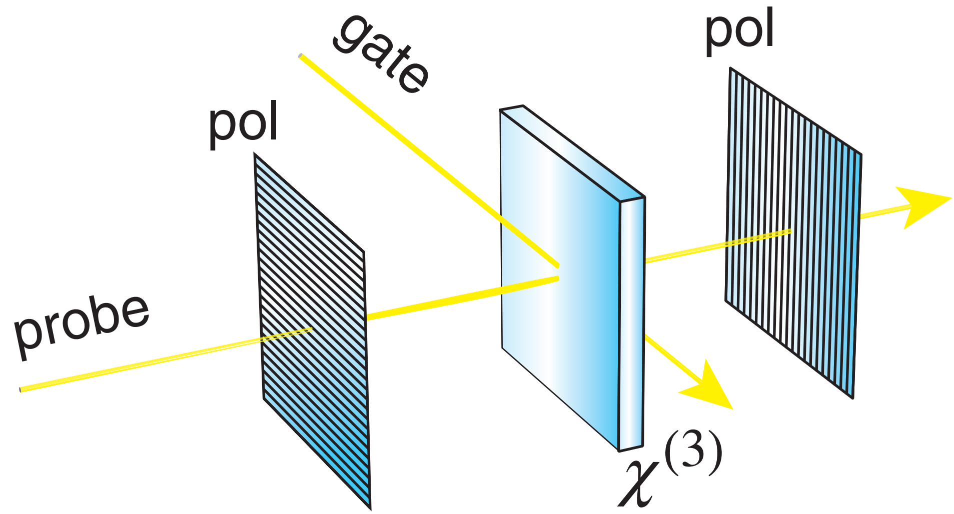


If gate and probe unequal:

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

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

Joint time-frequency measurements

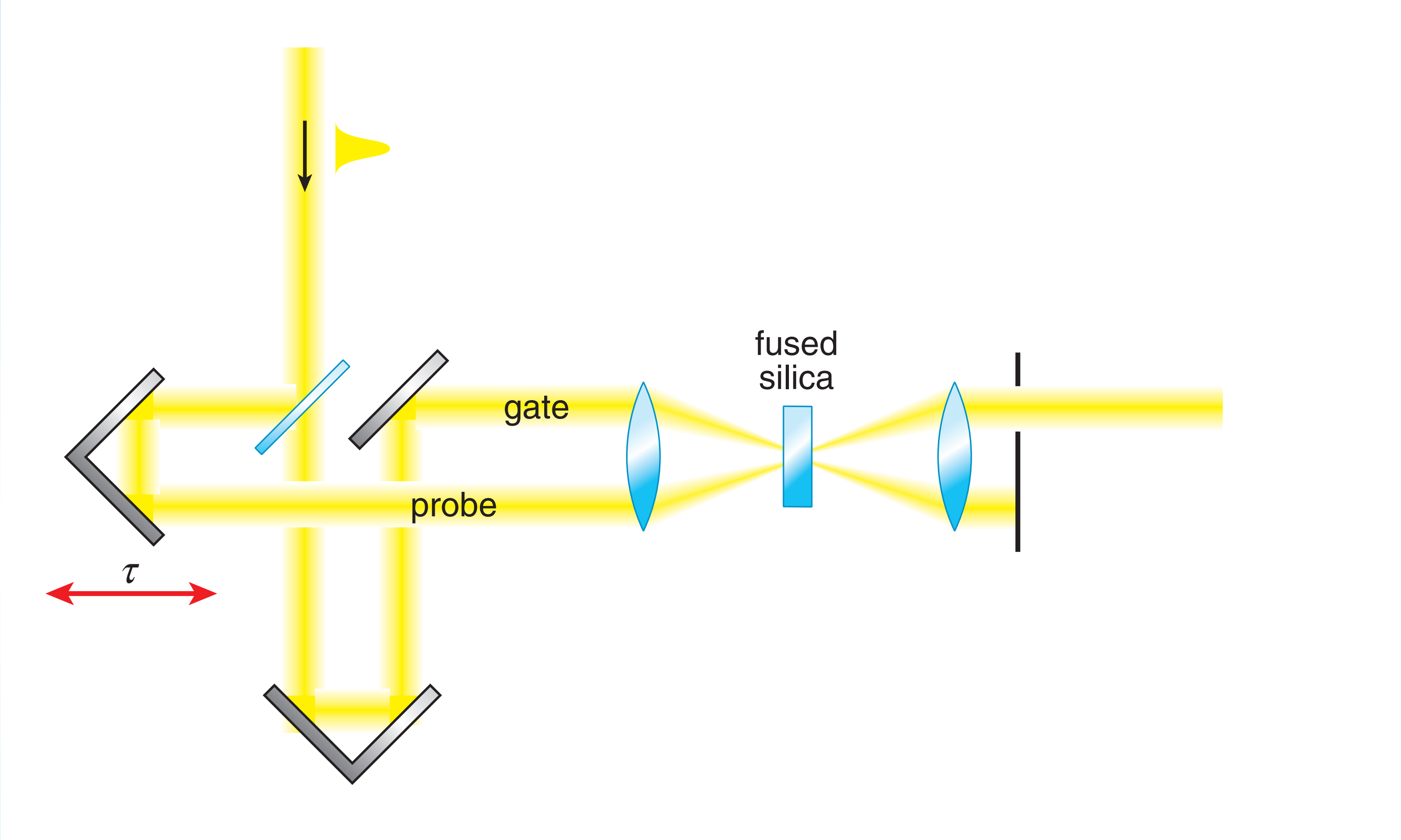


Transmitted field:

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

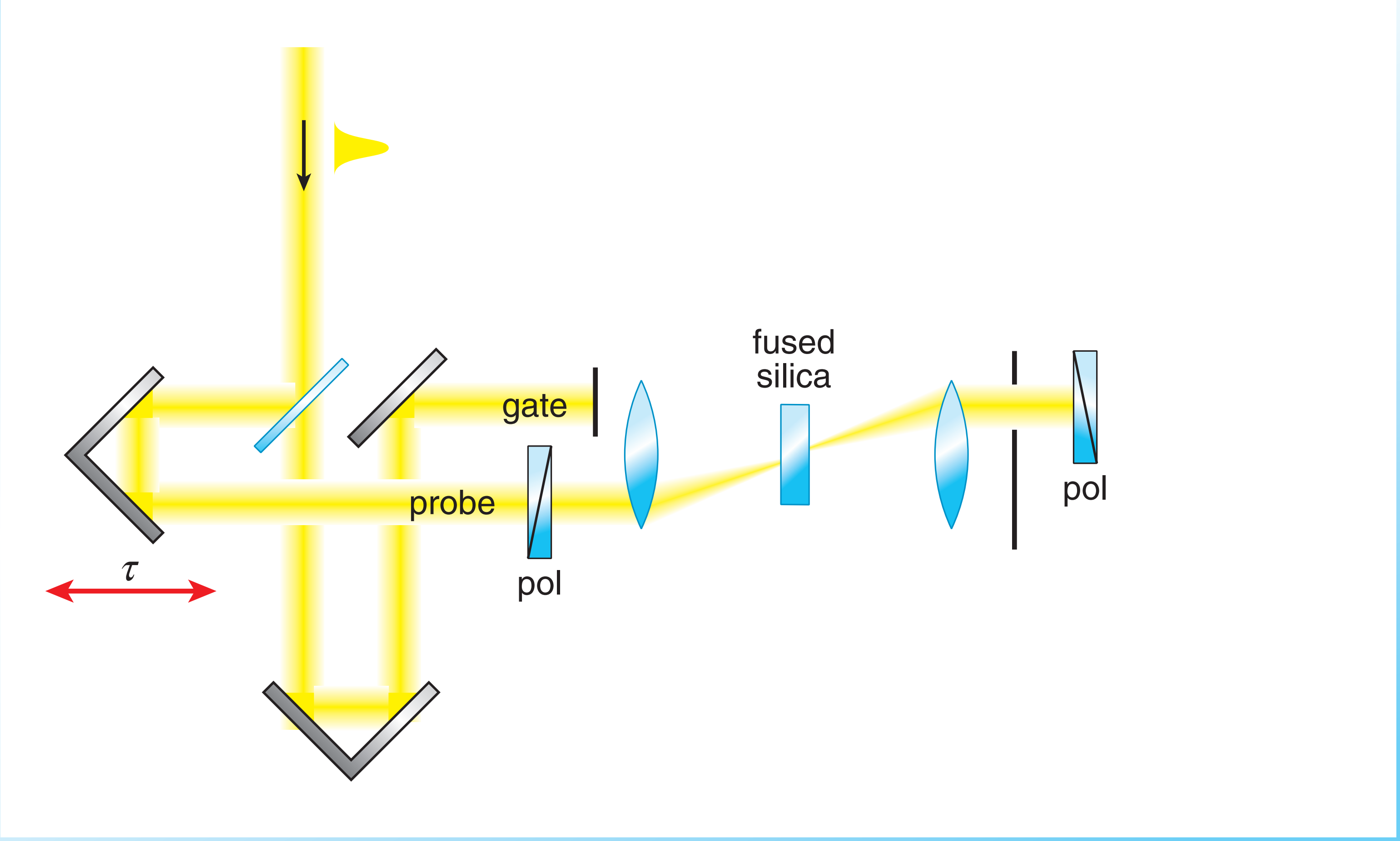
Joint time-frequency measurements

FROG: frequency-resolved optical gating



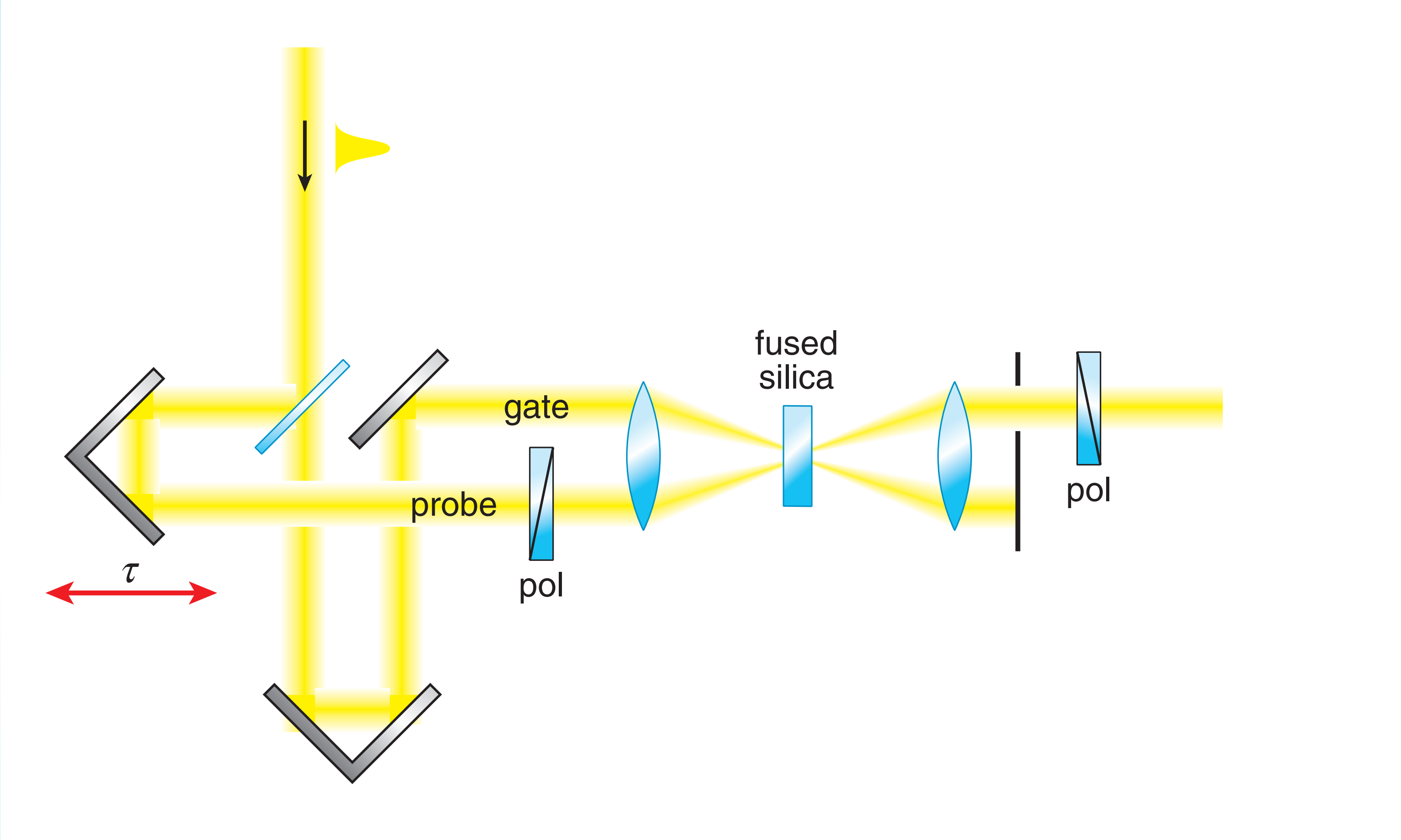
Joint time-frequency measurements

FROG: frequency-resolved optical gating



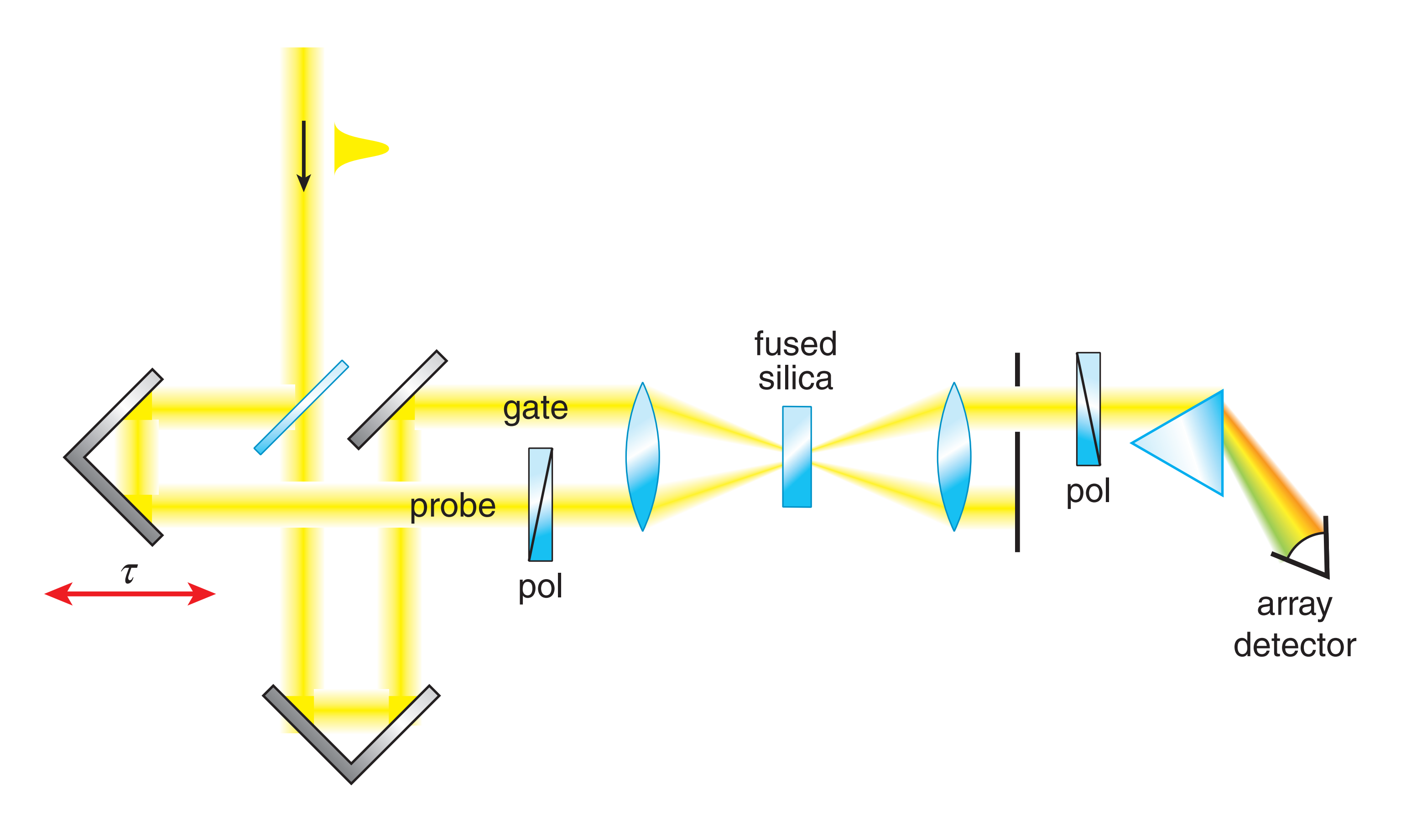
Joint time-frequency measurements

FROG: frequency-resolved optical gating

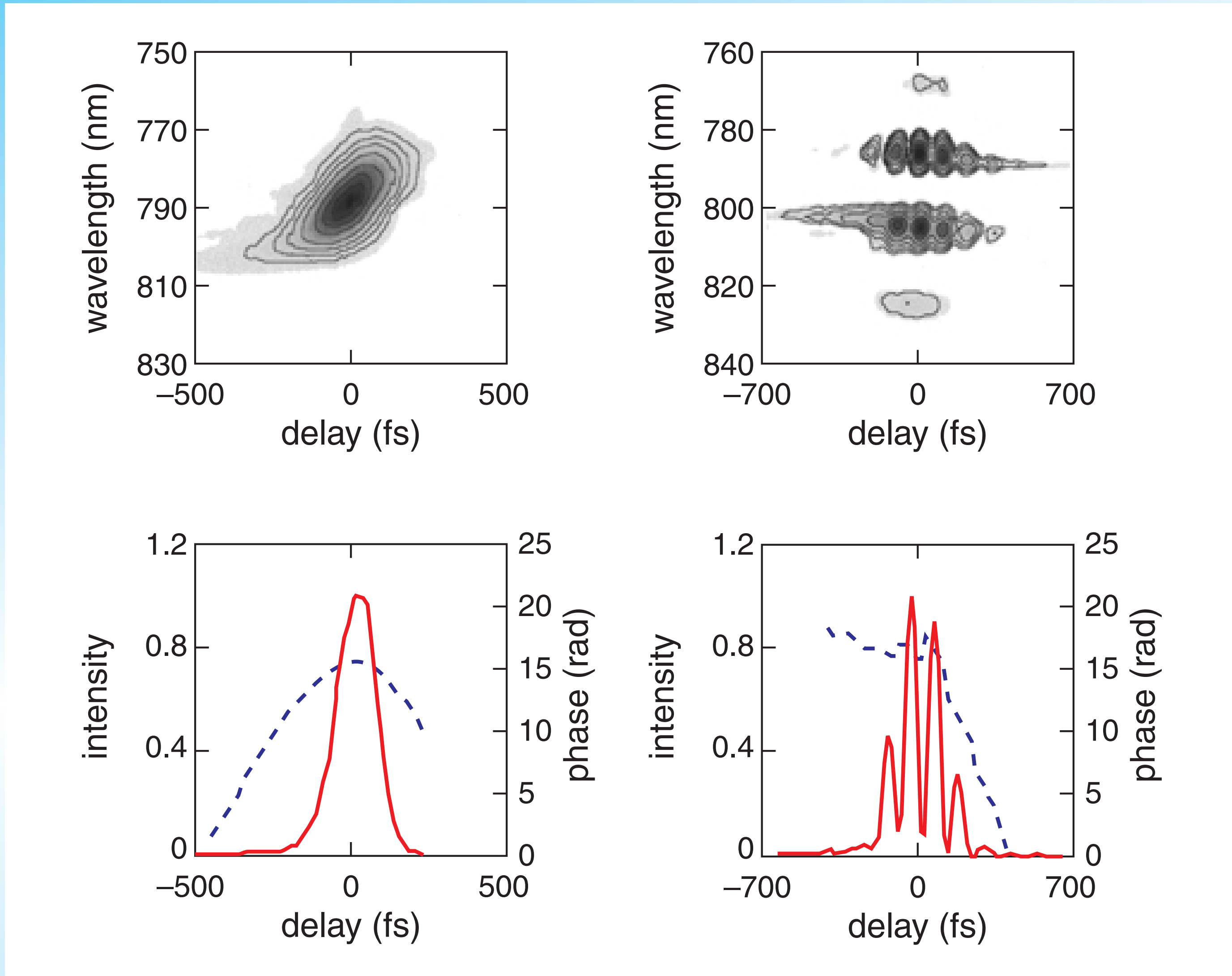


Joint time-frequency measurements

FROG: frequency-resolved optical gating

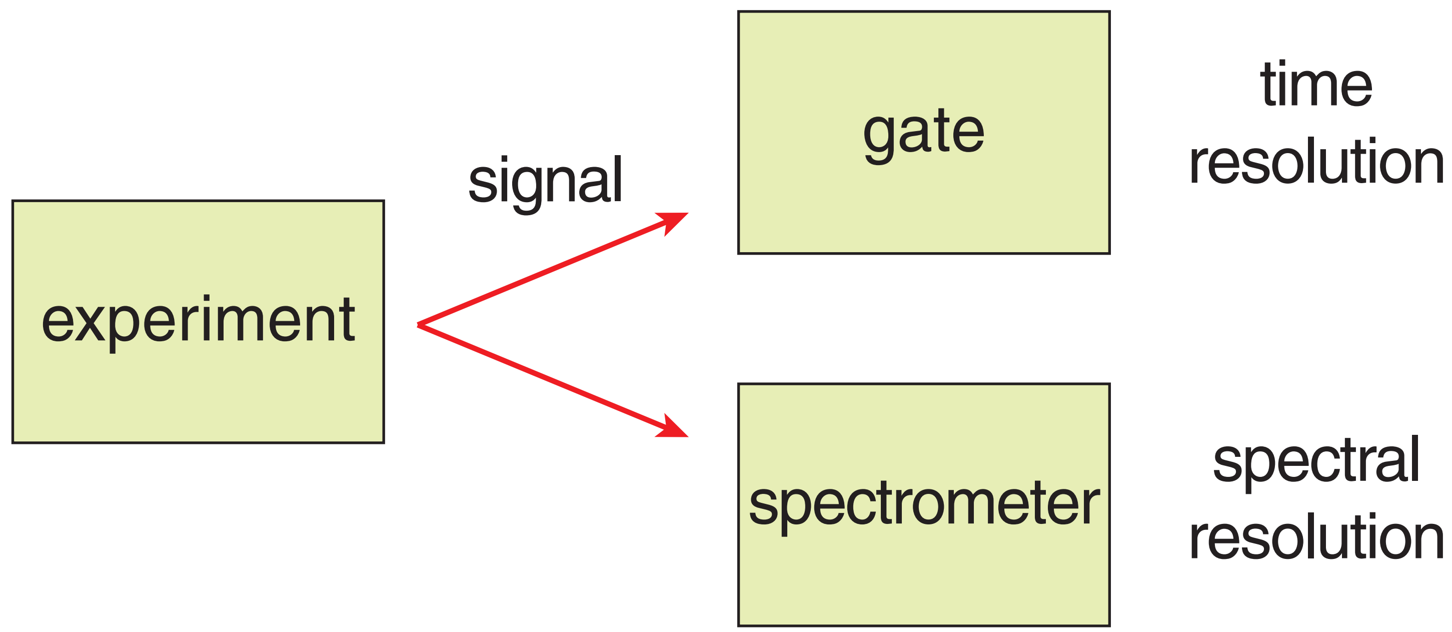


Joint time-frequency measurements



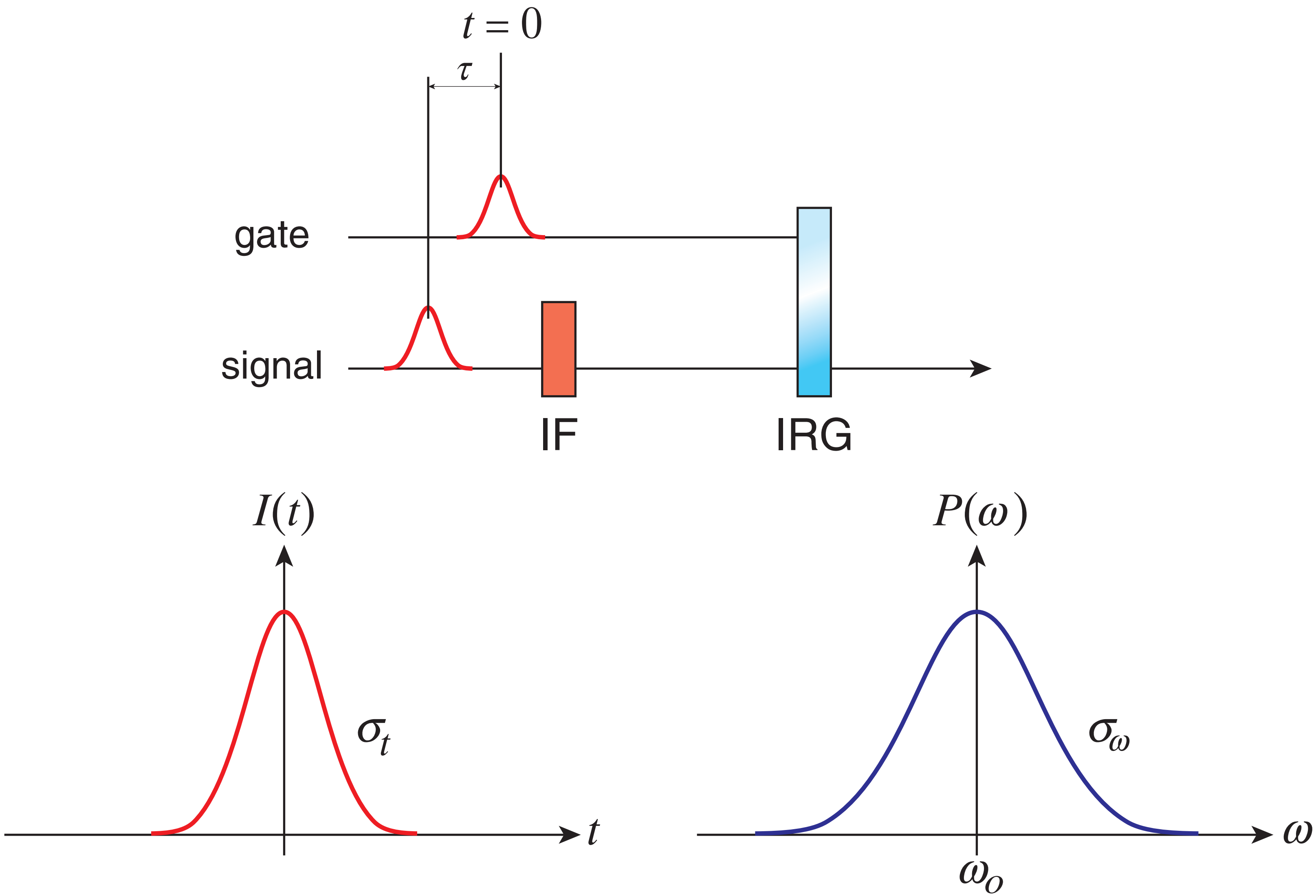
R. Trebino, *et al.*, Rev. Sci. Instrum. 68, 3277 (1997)

Joint time-frequency measurements

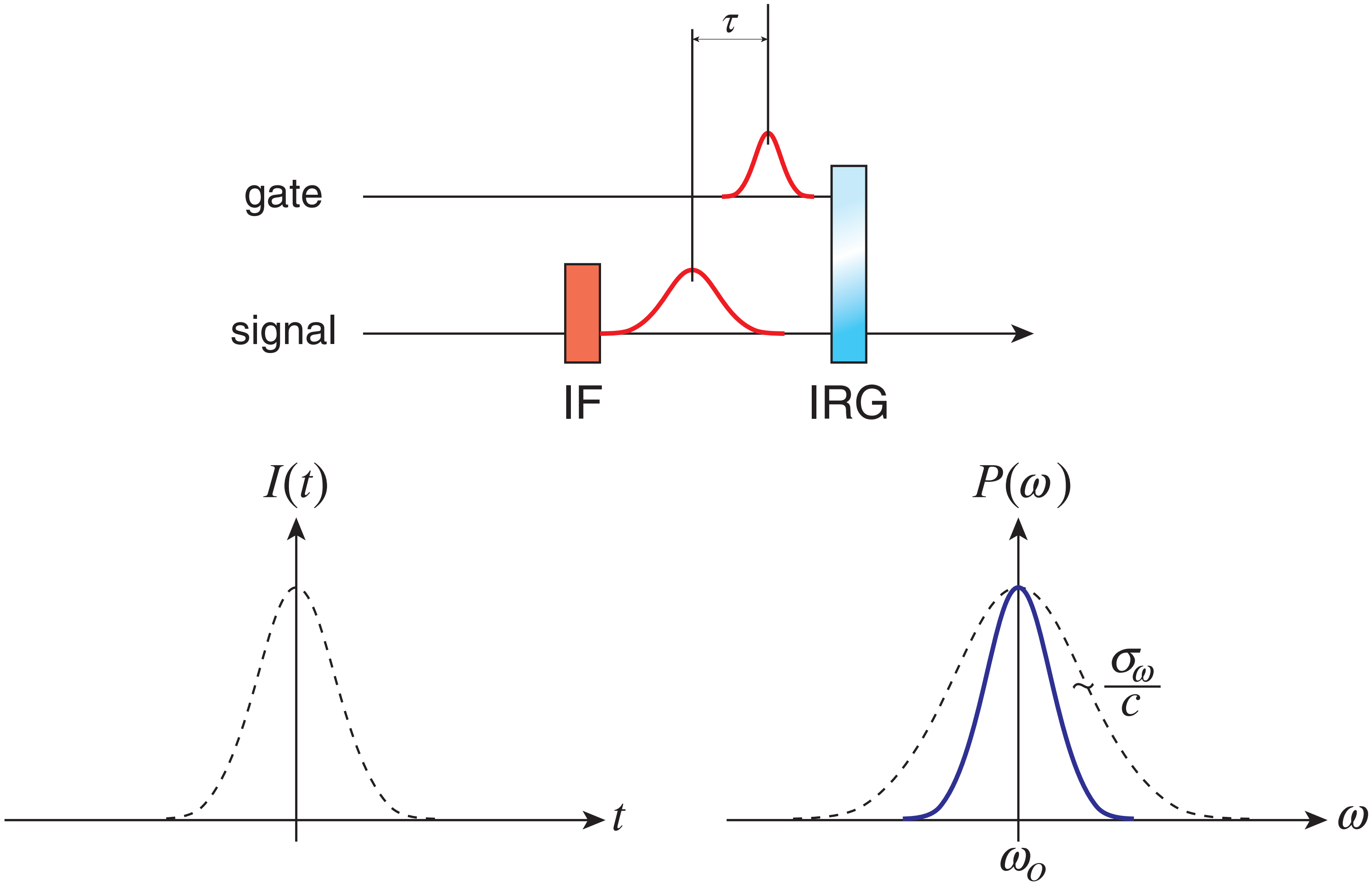


What are the resolution limits?

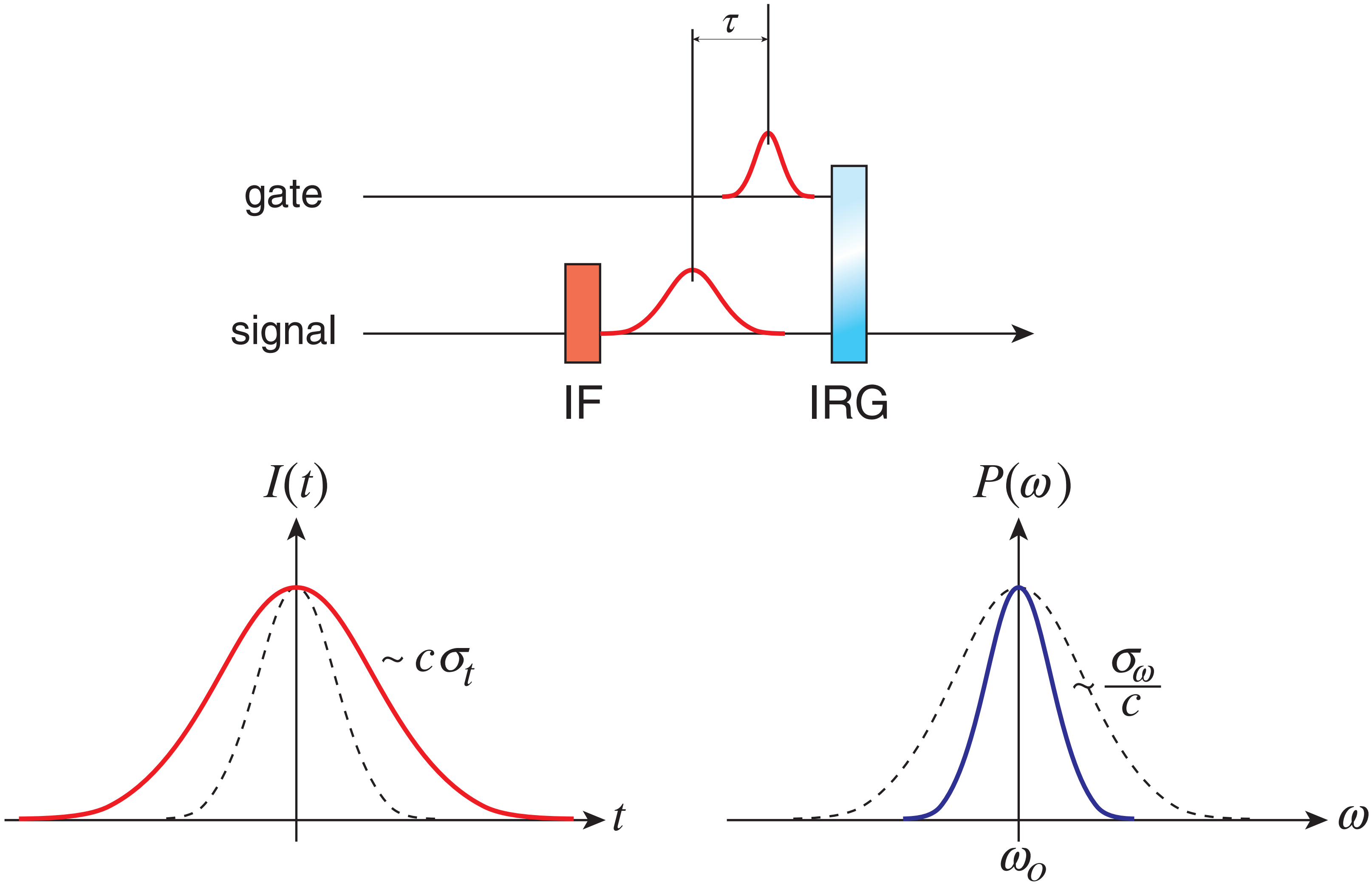
Experiment 1



Experiment 1



Experiment 1



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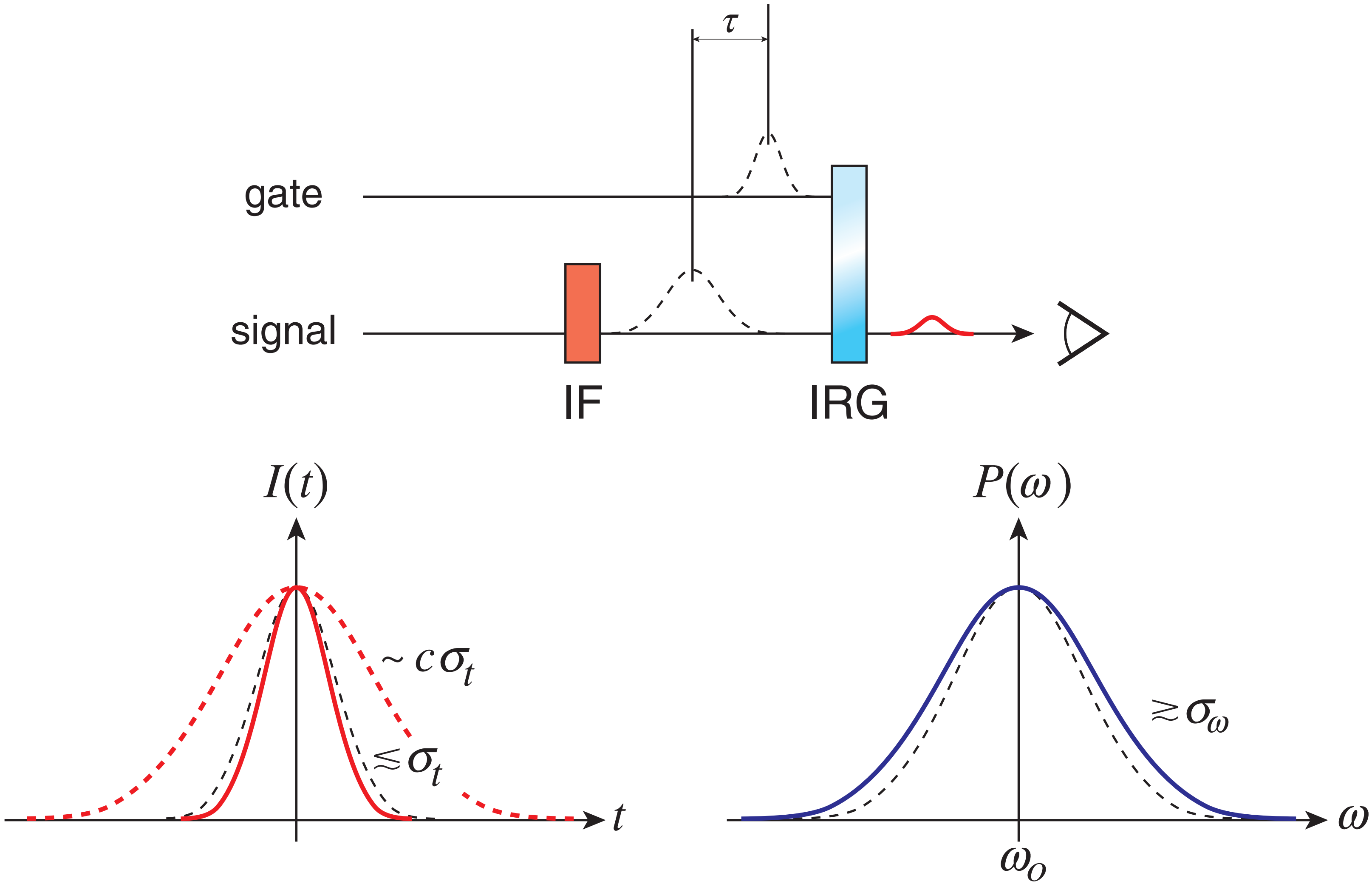

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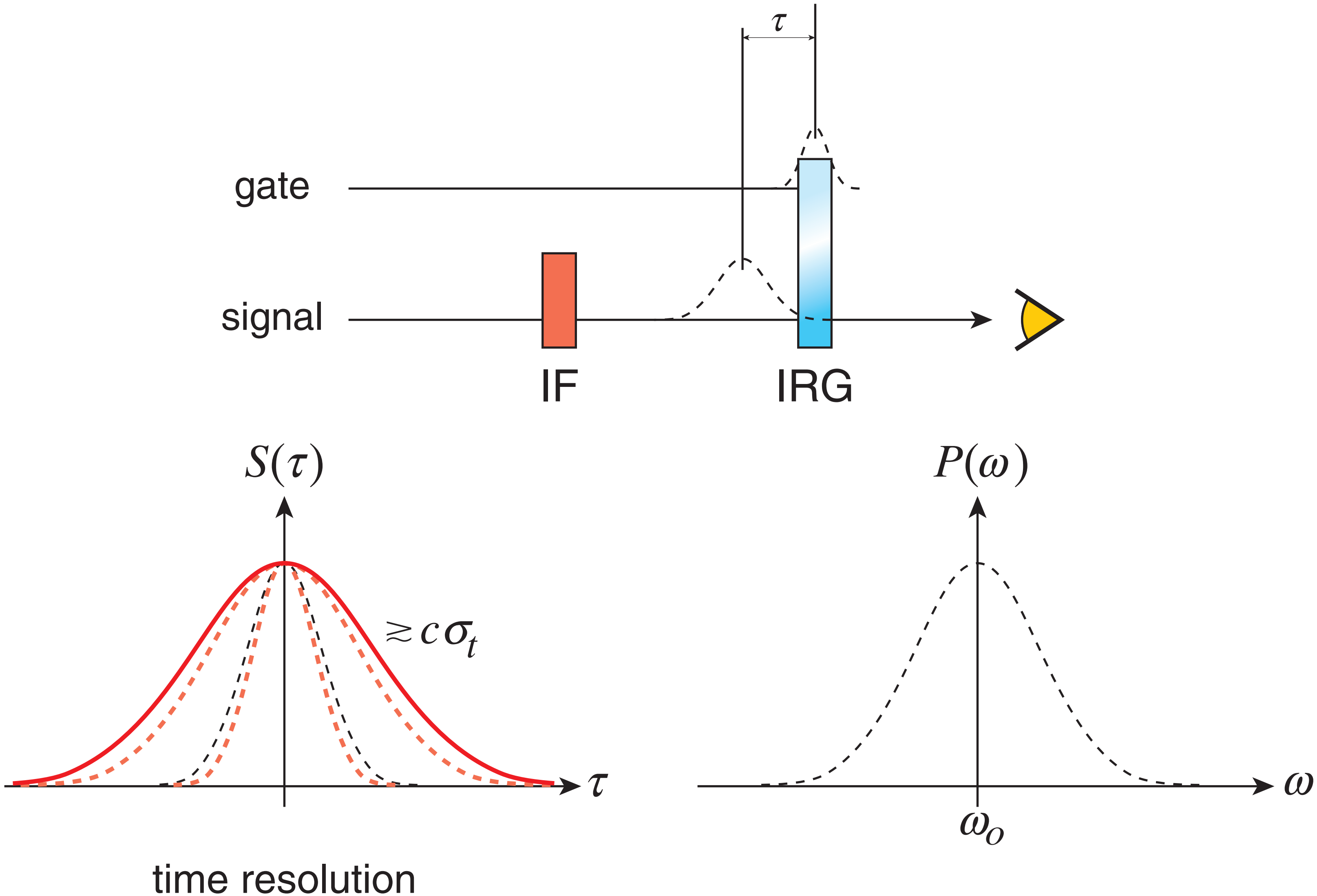

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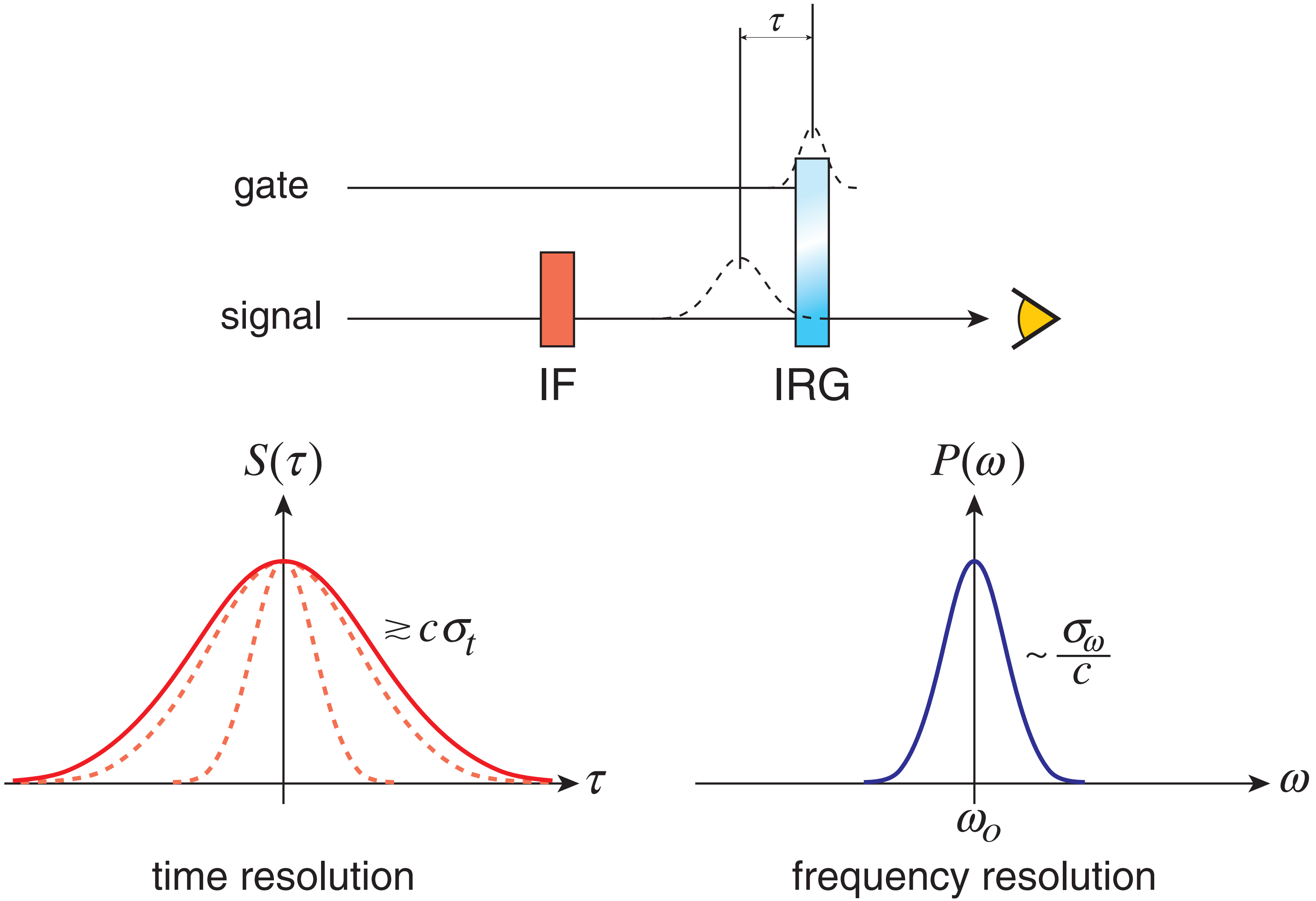
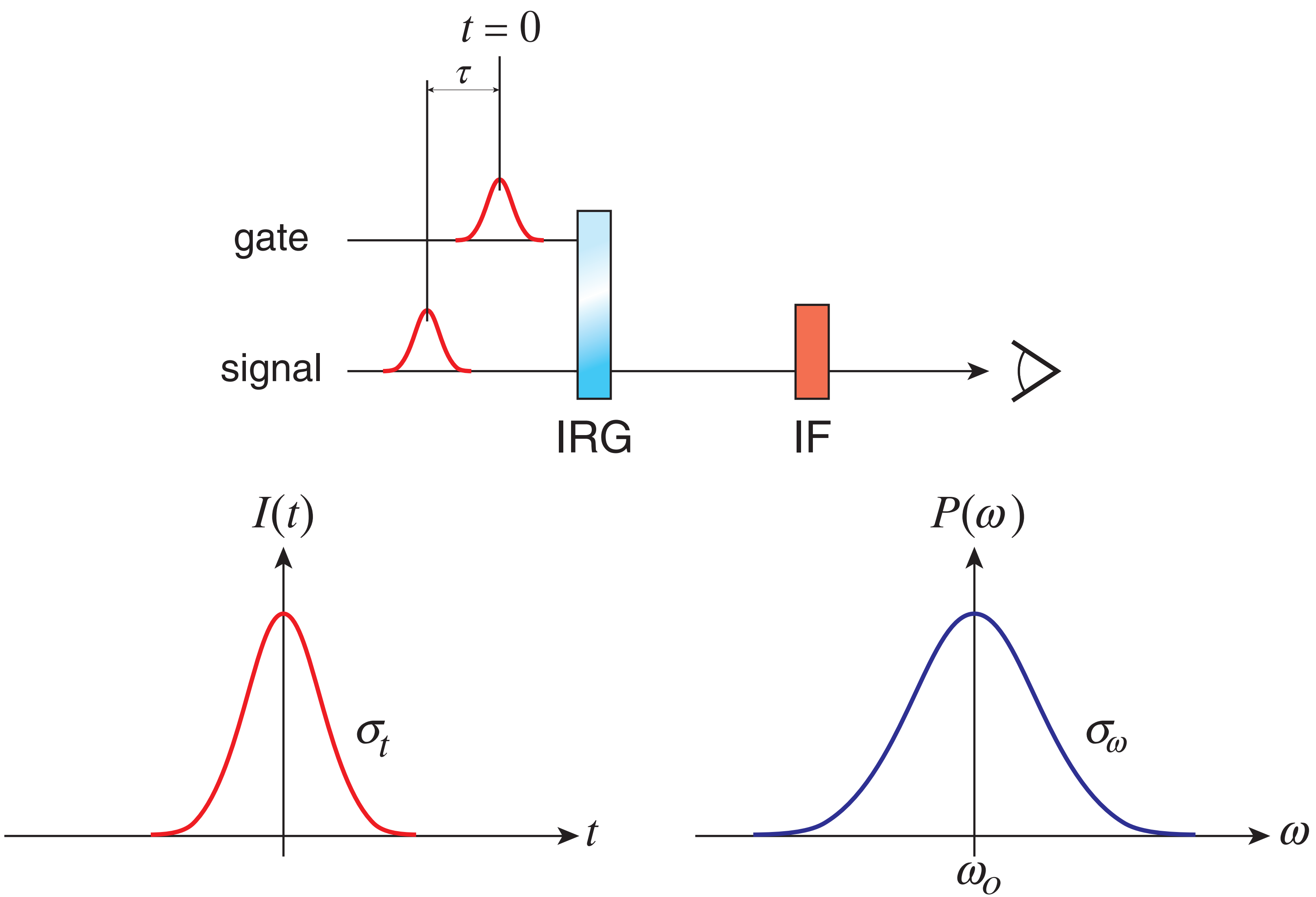
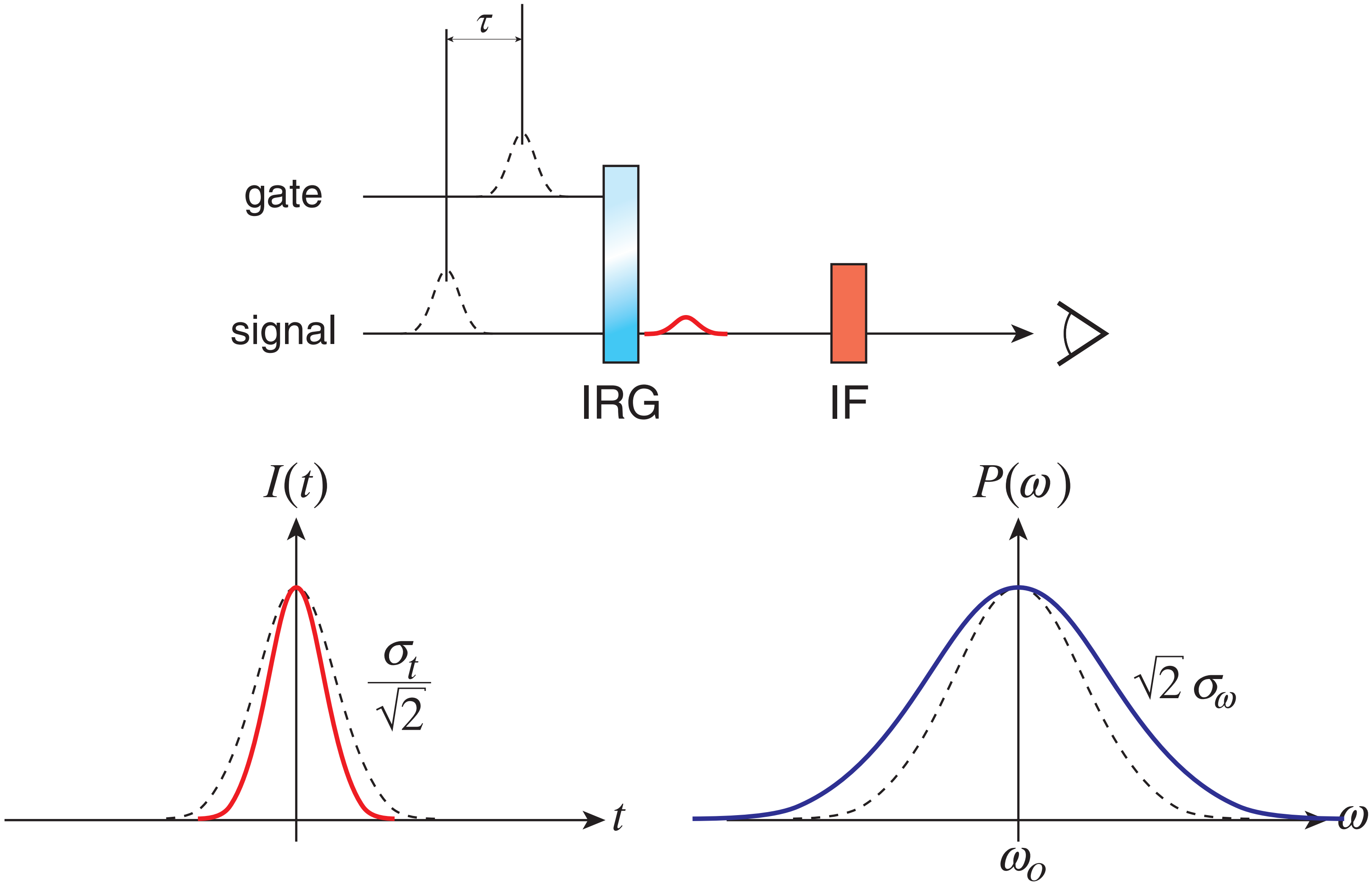


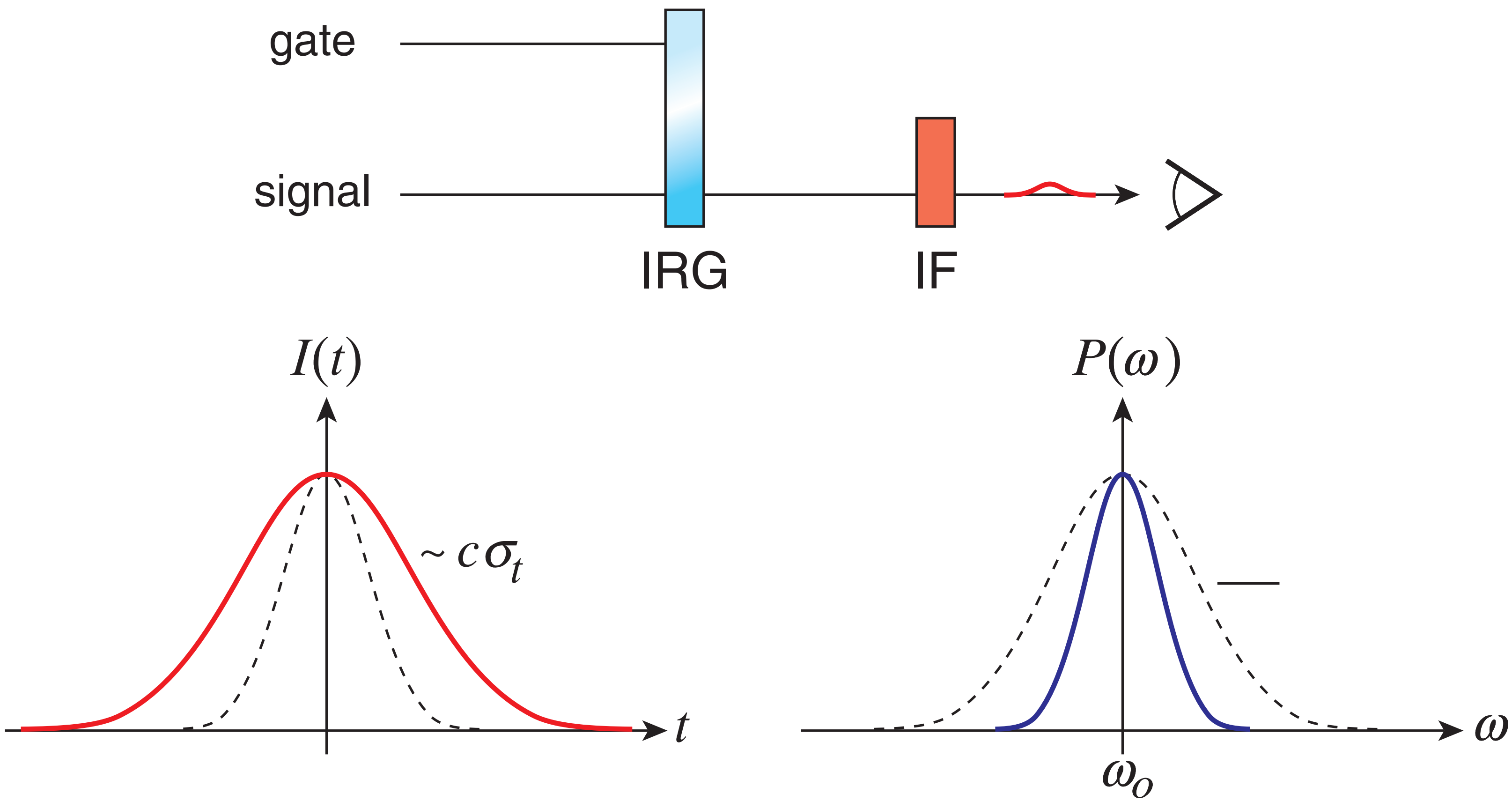
Experiment 2



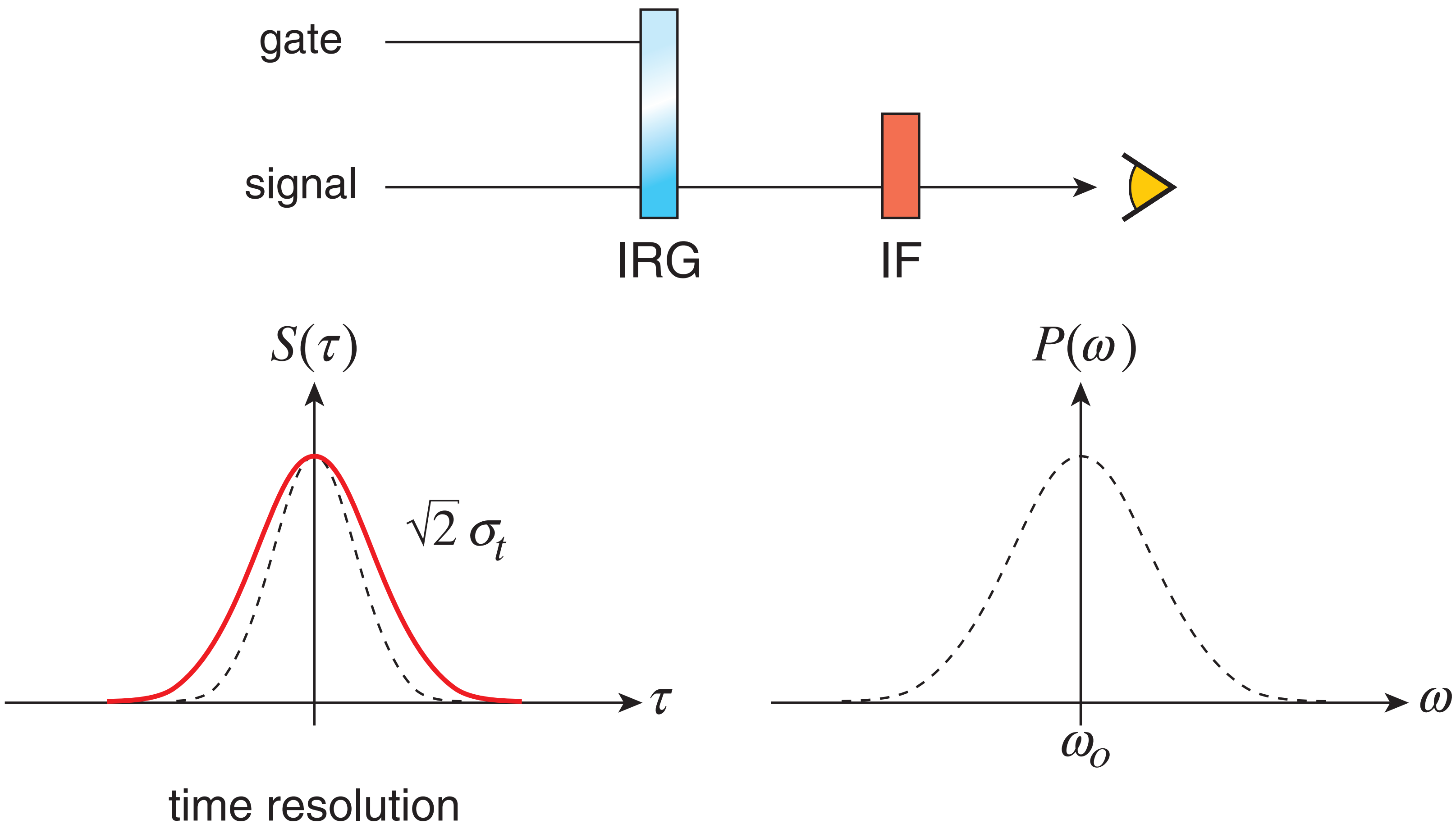
Experiment 2



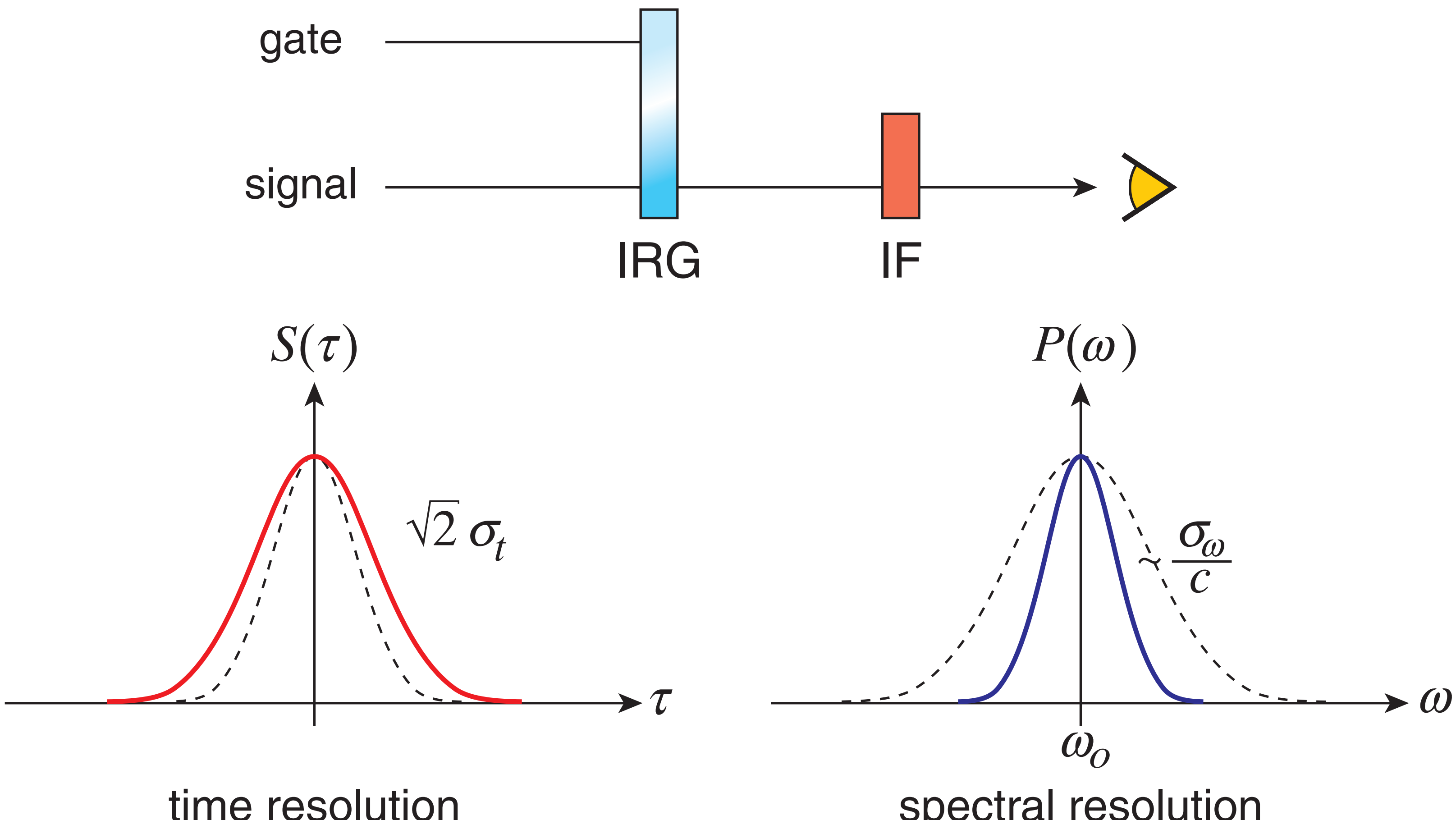
Experiment 2



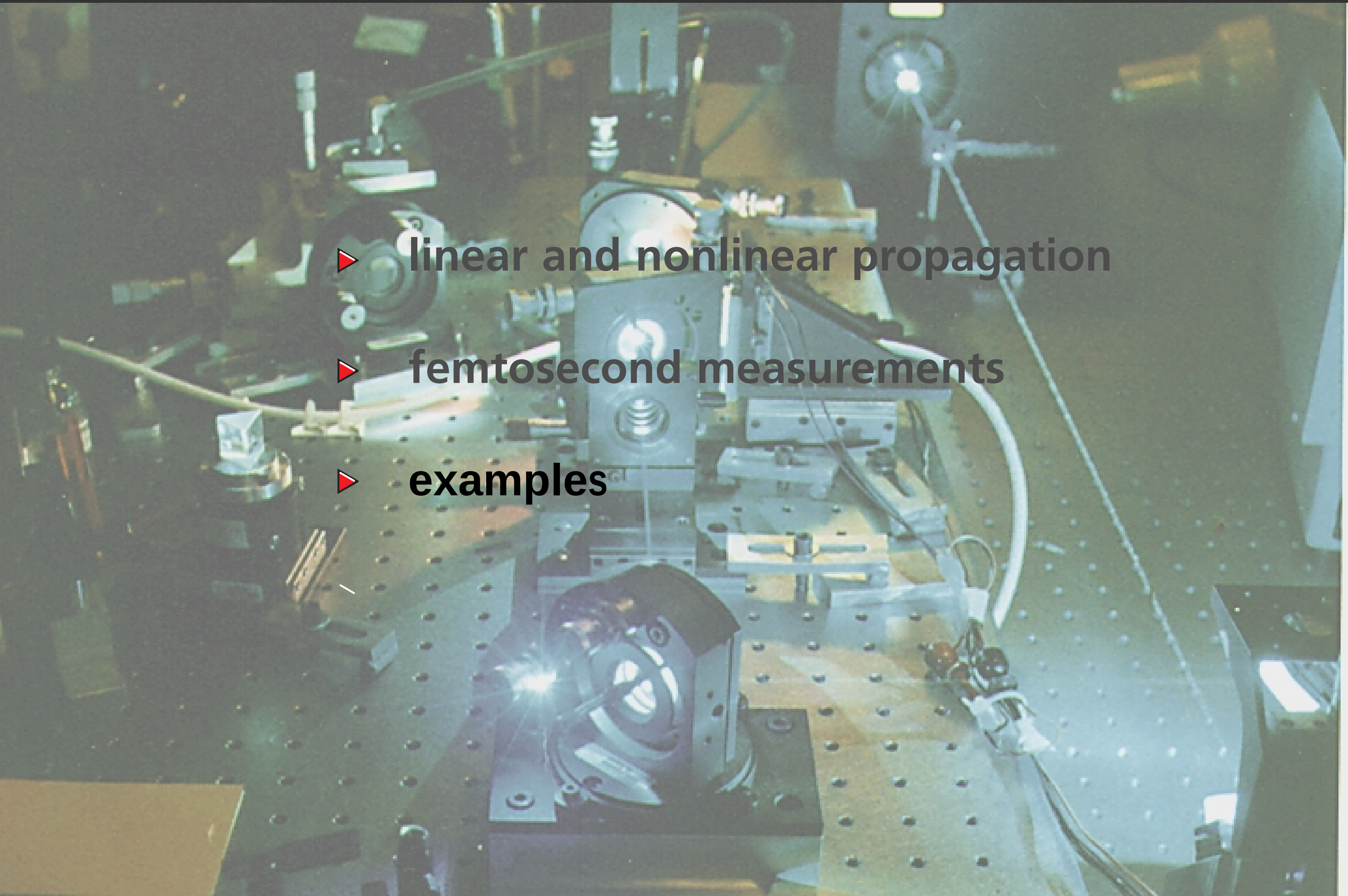
Experiment 2



Experiment 2



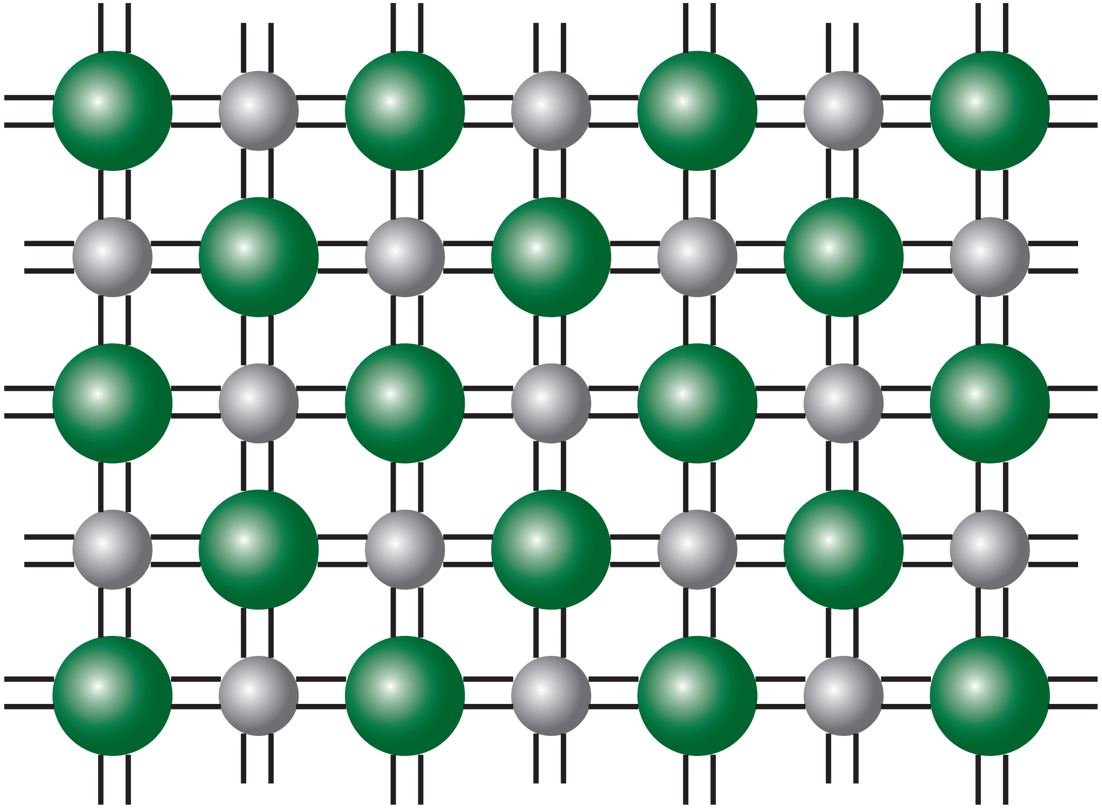
Outline



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

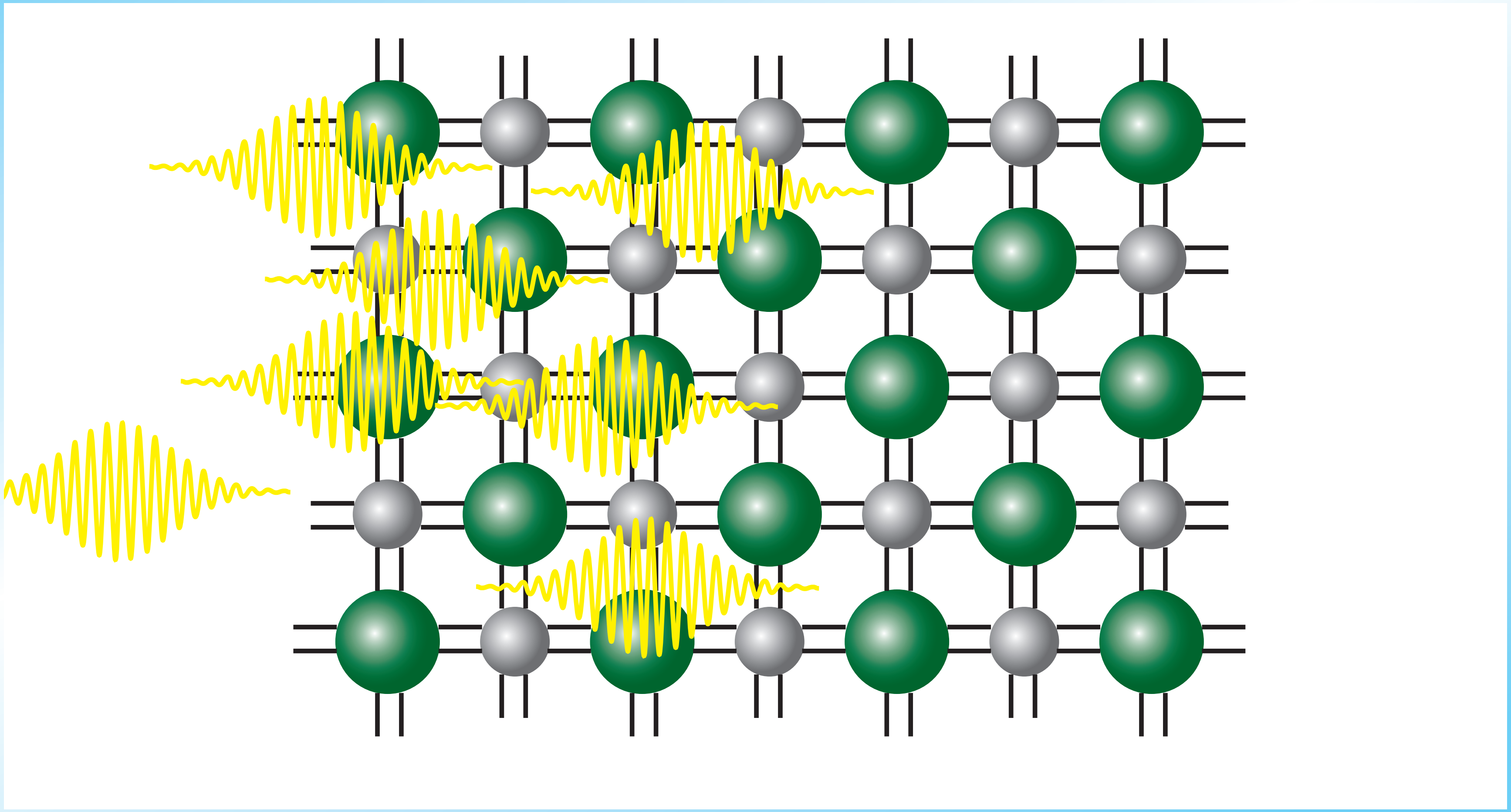
Dielectric function measurements

how do femtosecond laser pulses alter a solid?



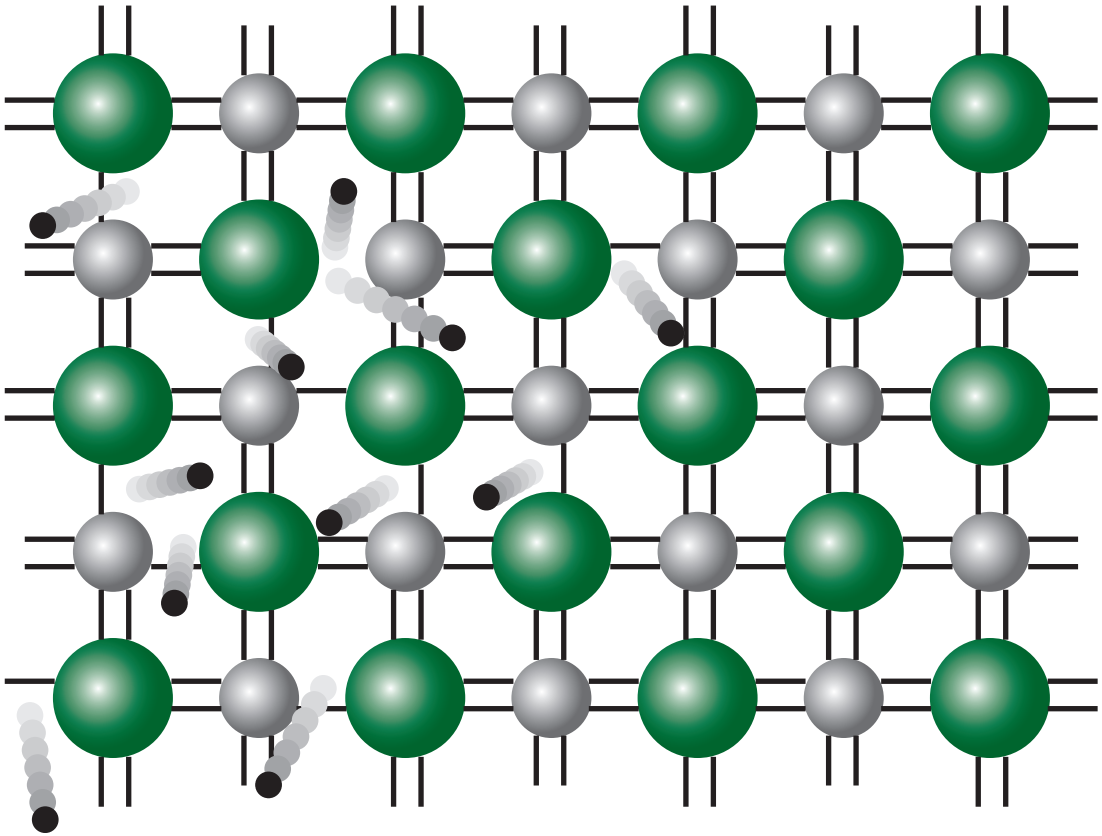
Dielectric function measurements

photons excite valence electrons…



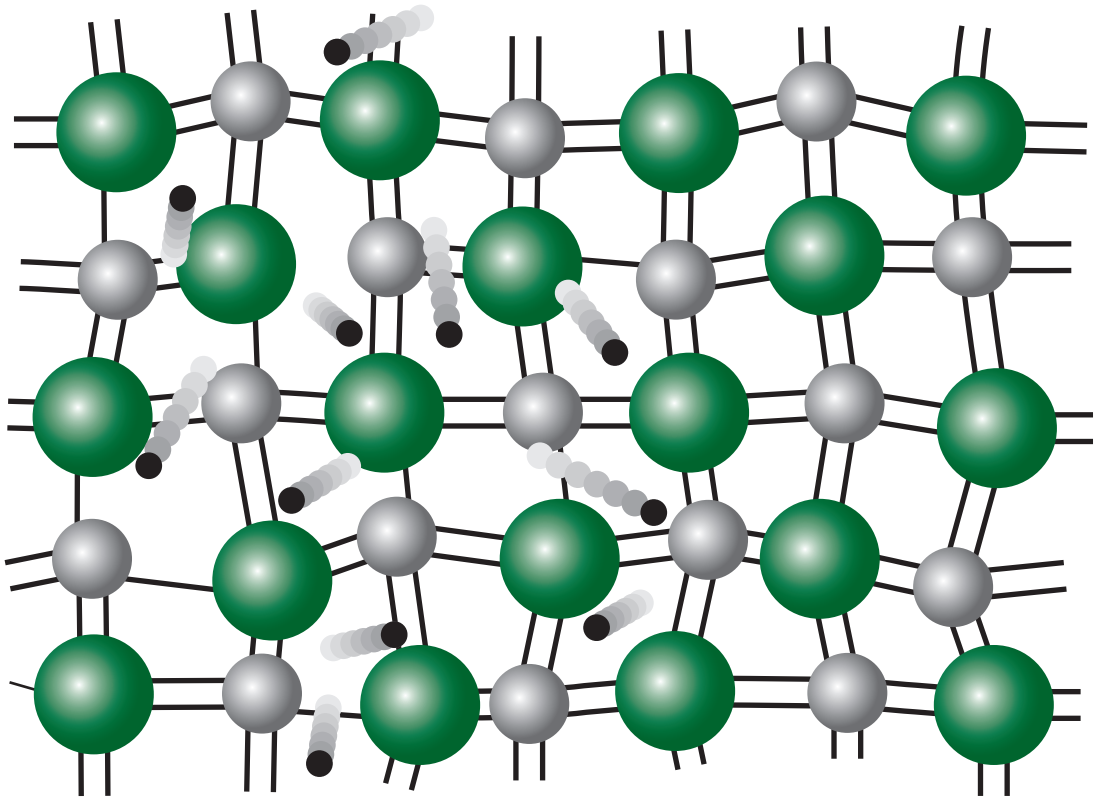
Dielectric function measurements

…and create free electrons…



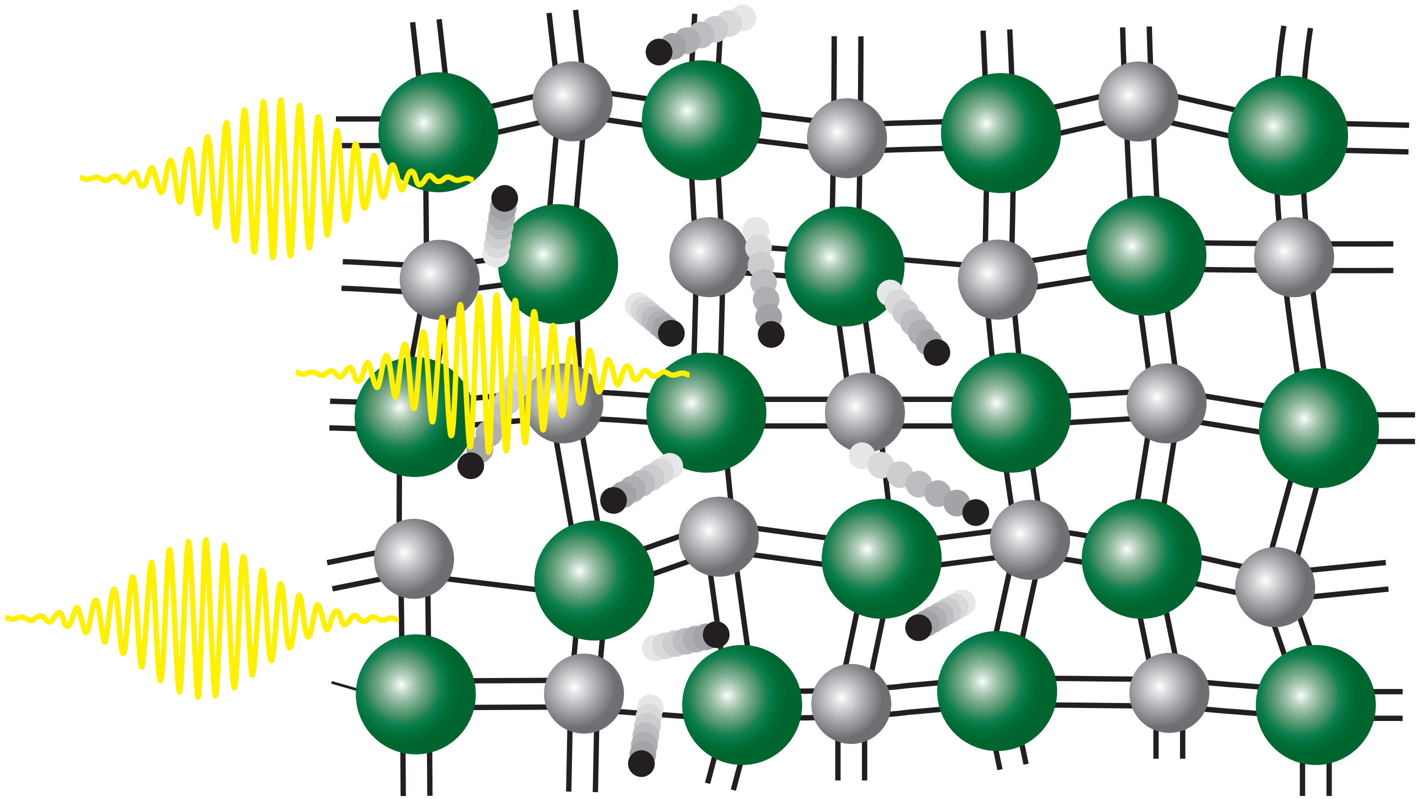
Dielectric function measurements

…causing electronic and structural changes…

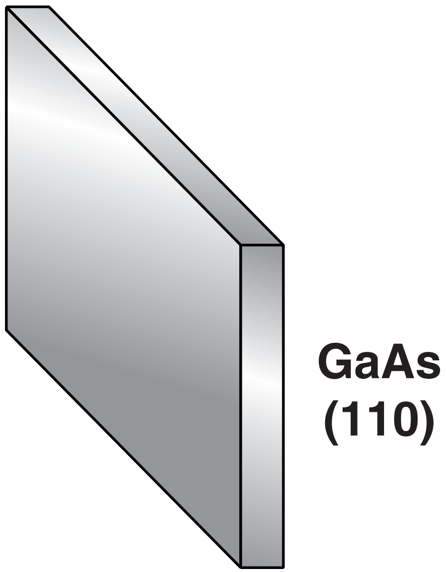


Dielectric function measurements

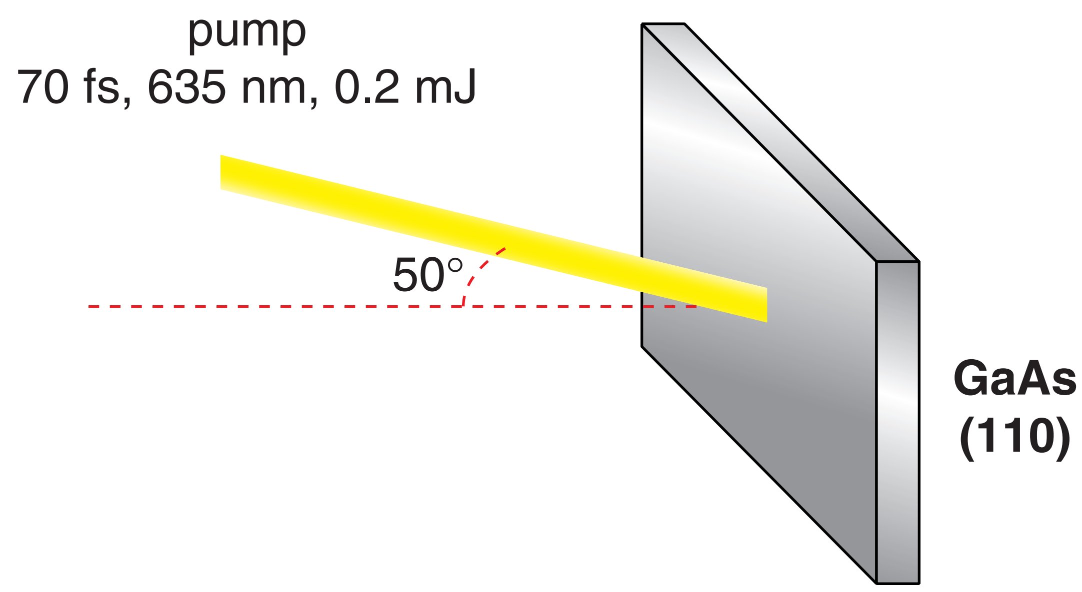
…which we measure with another pulse



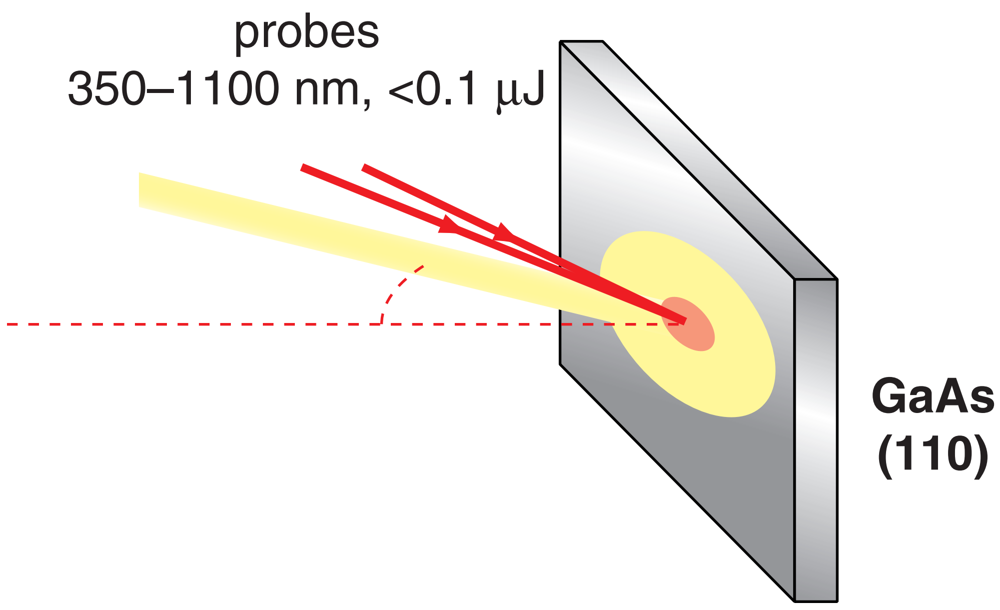
Dielectric function measurements



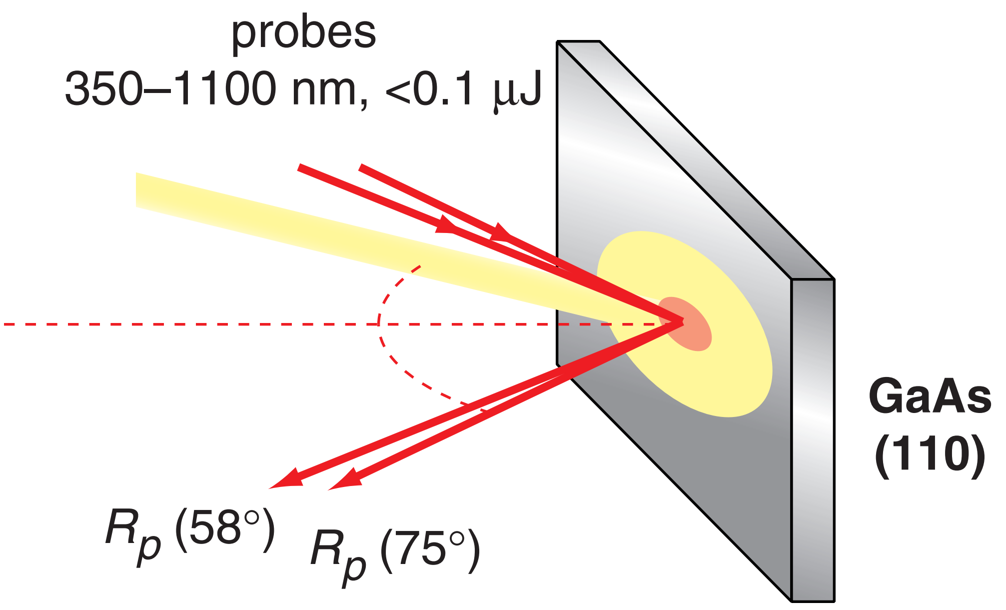
Dielectric function measurements



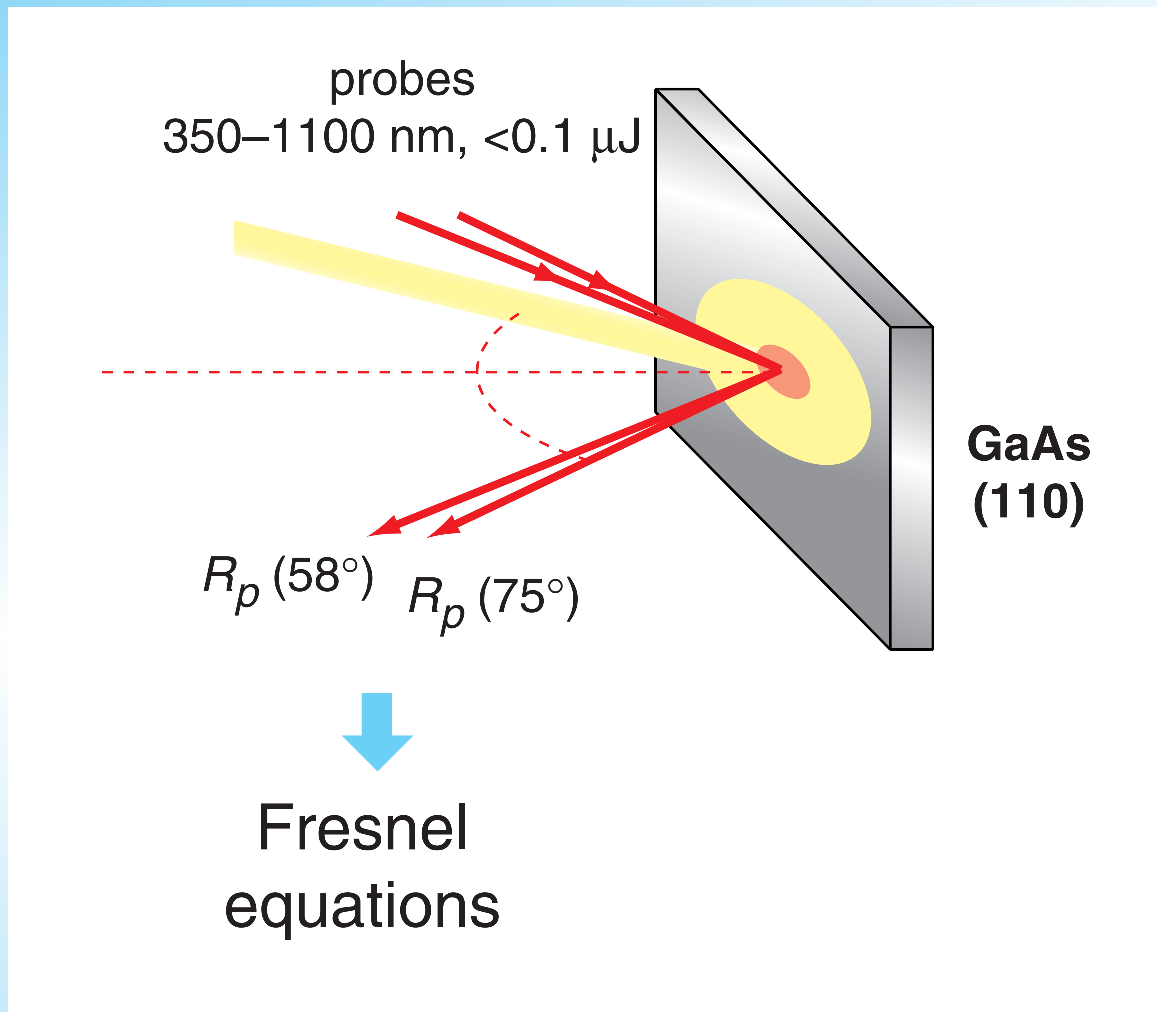
Dielectric function measurements



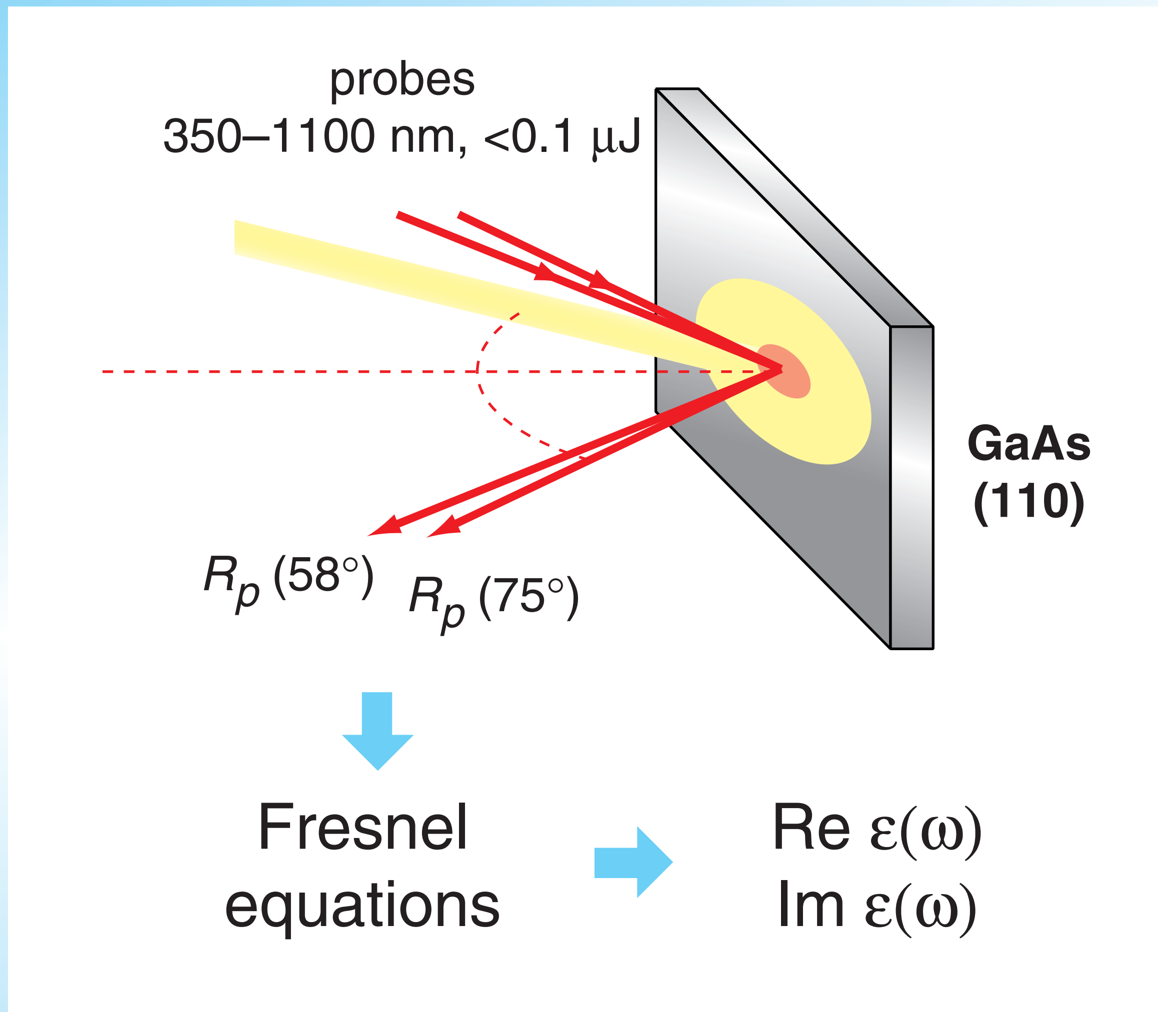
Dielectric function measurements



Dielectric function measurements



Dielectric function measurements



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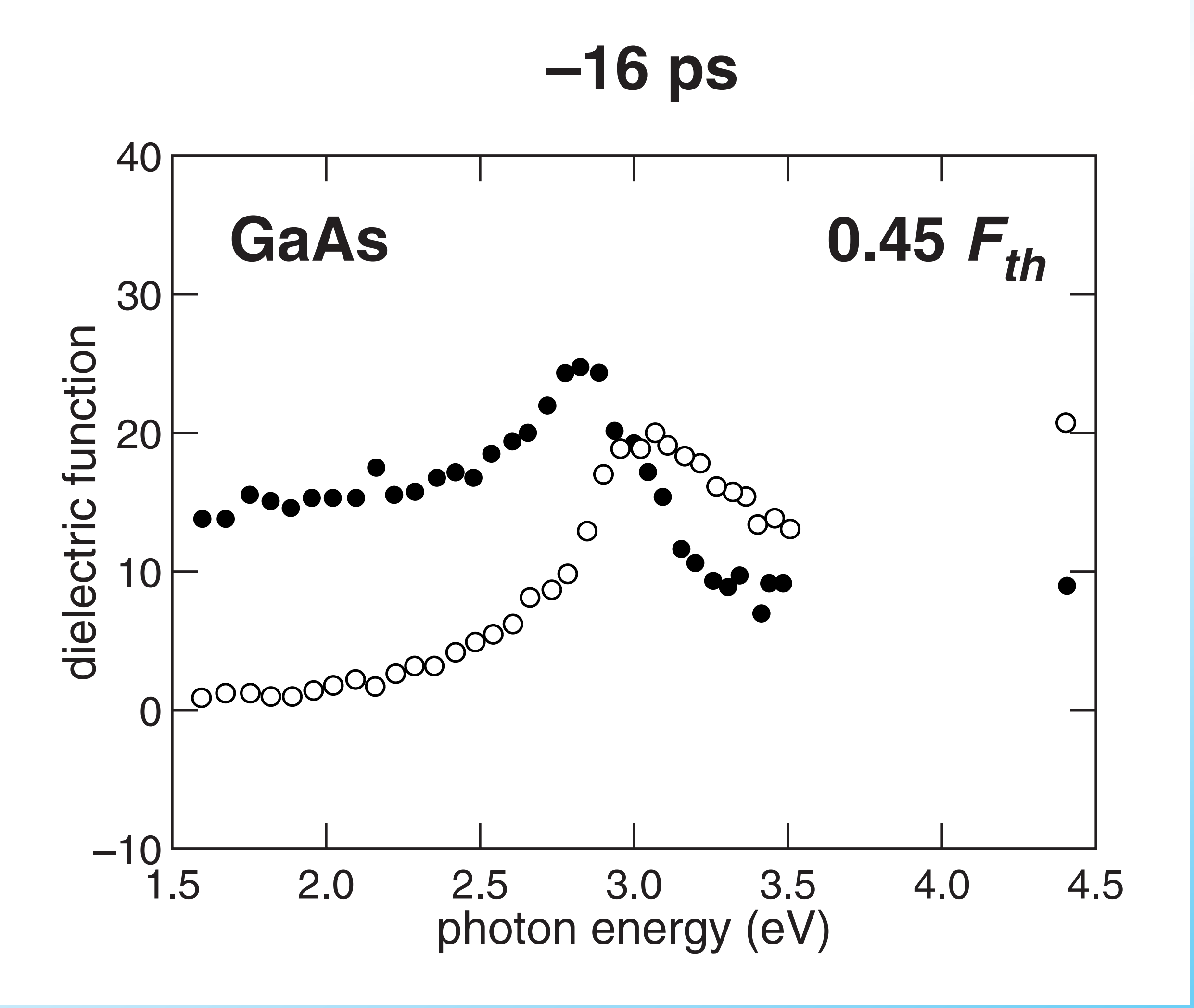

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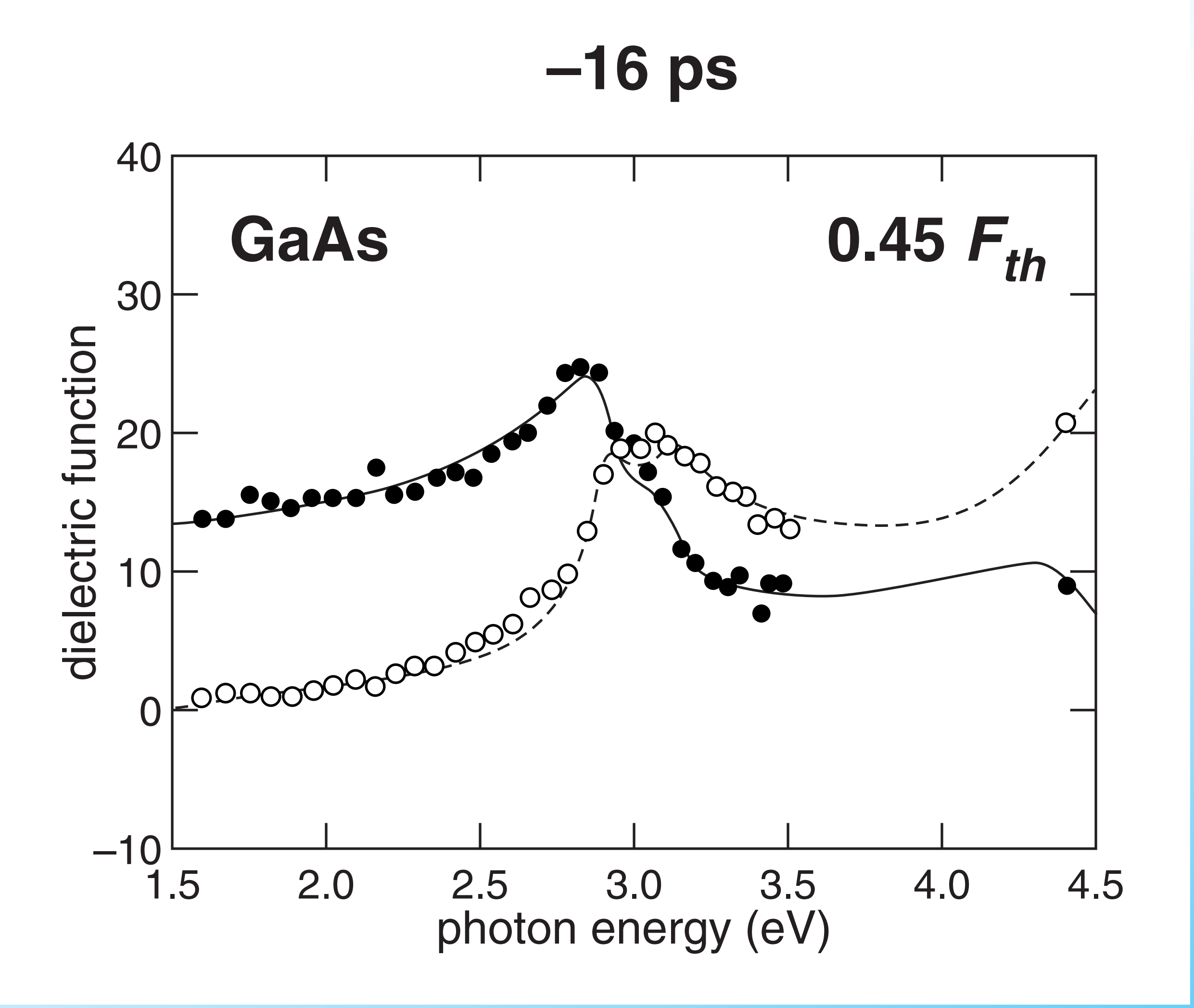
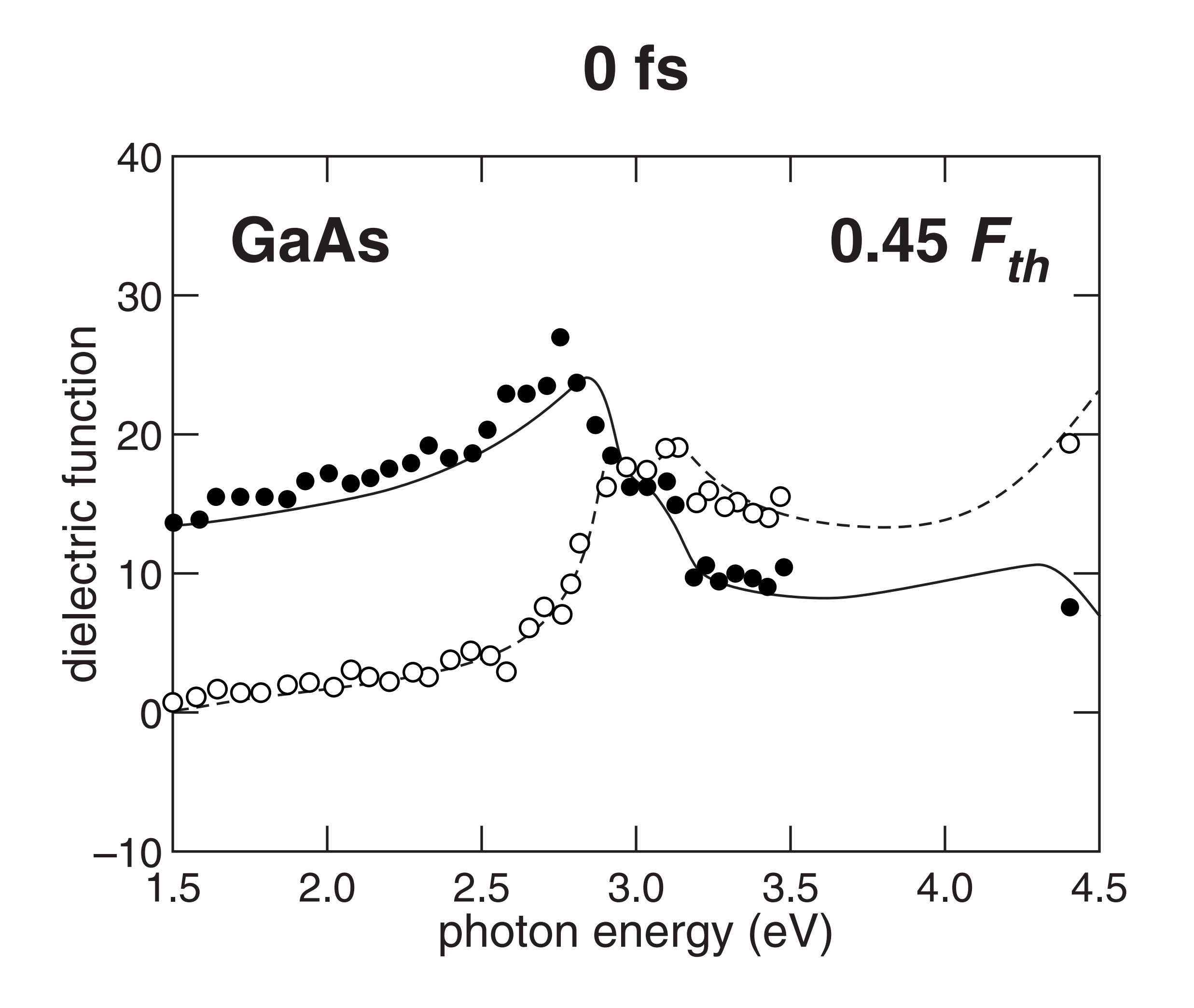


Dielectric function measurements



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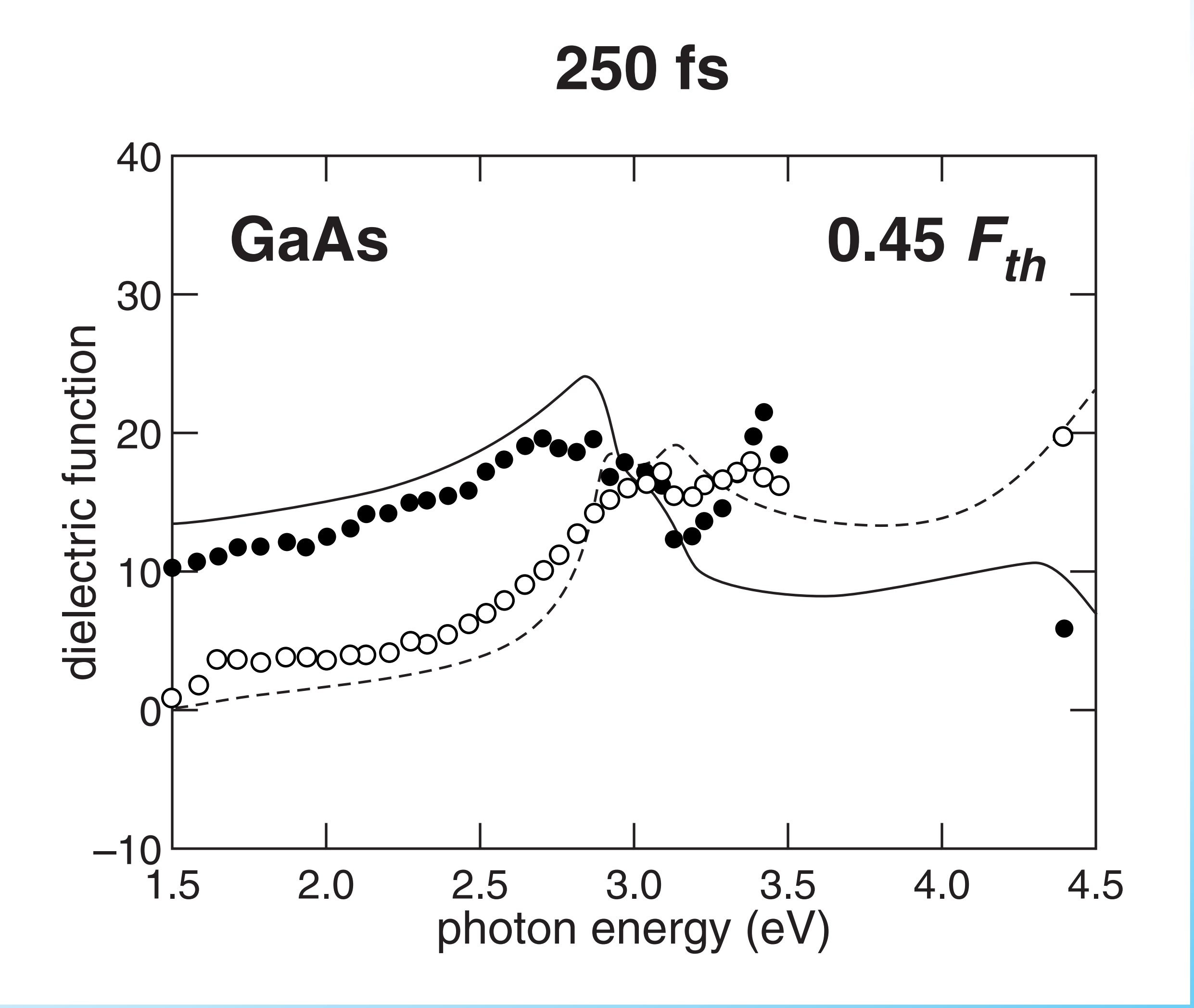
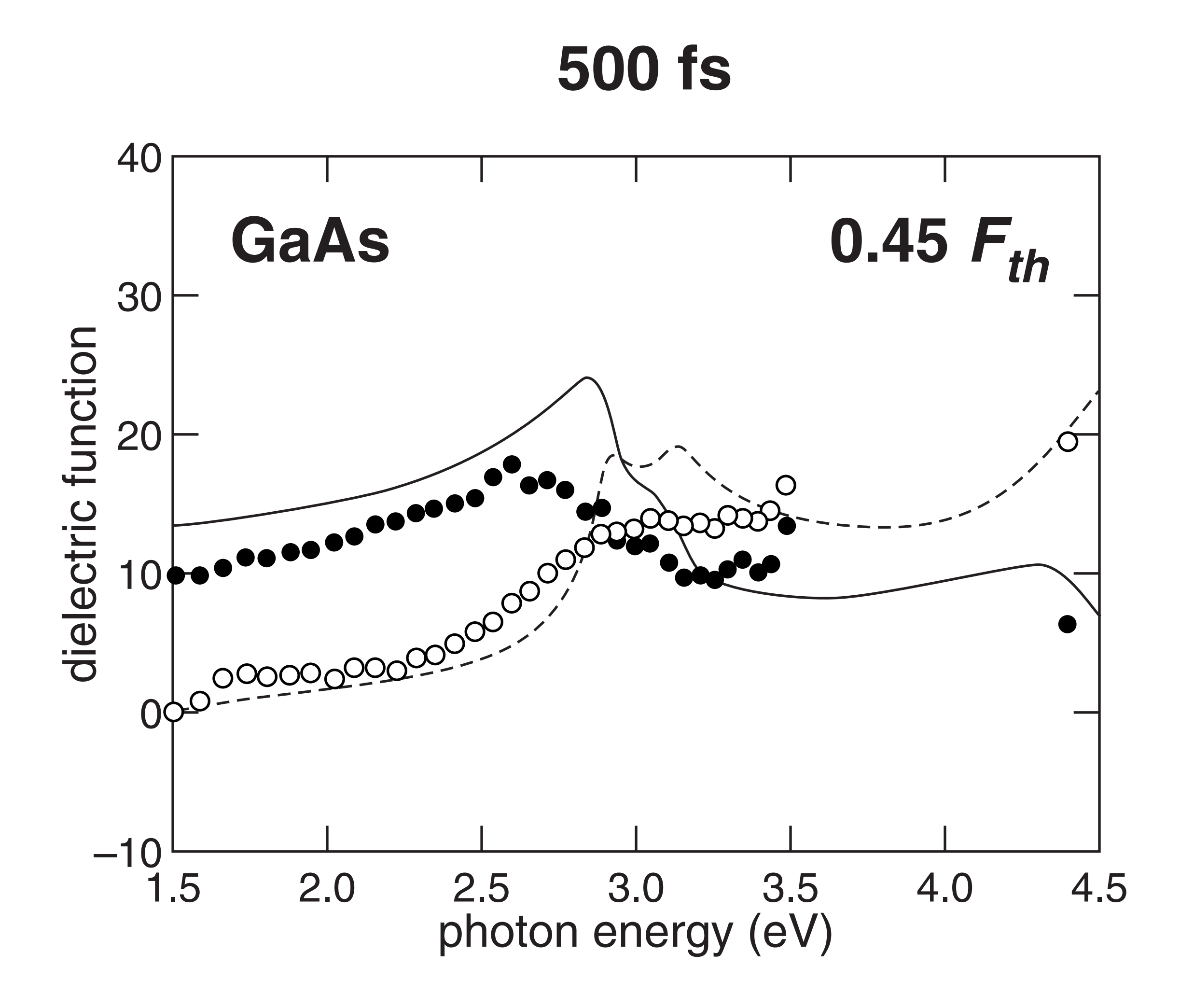


Dielectric function measurements



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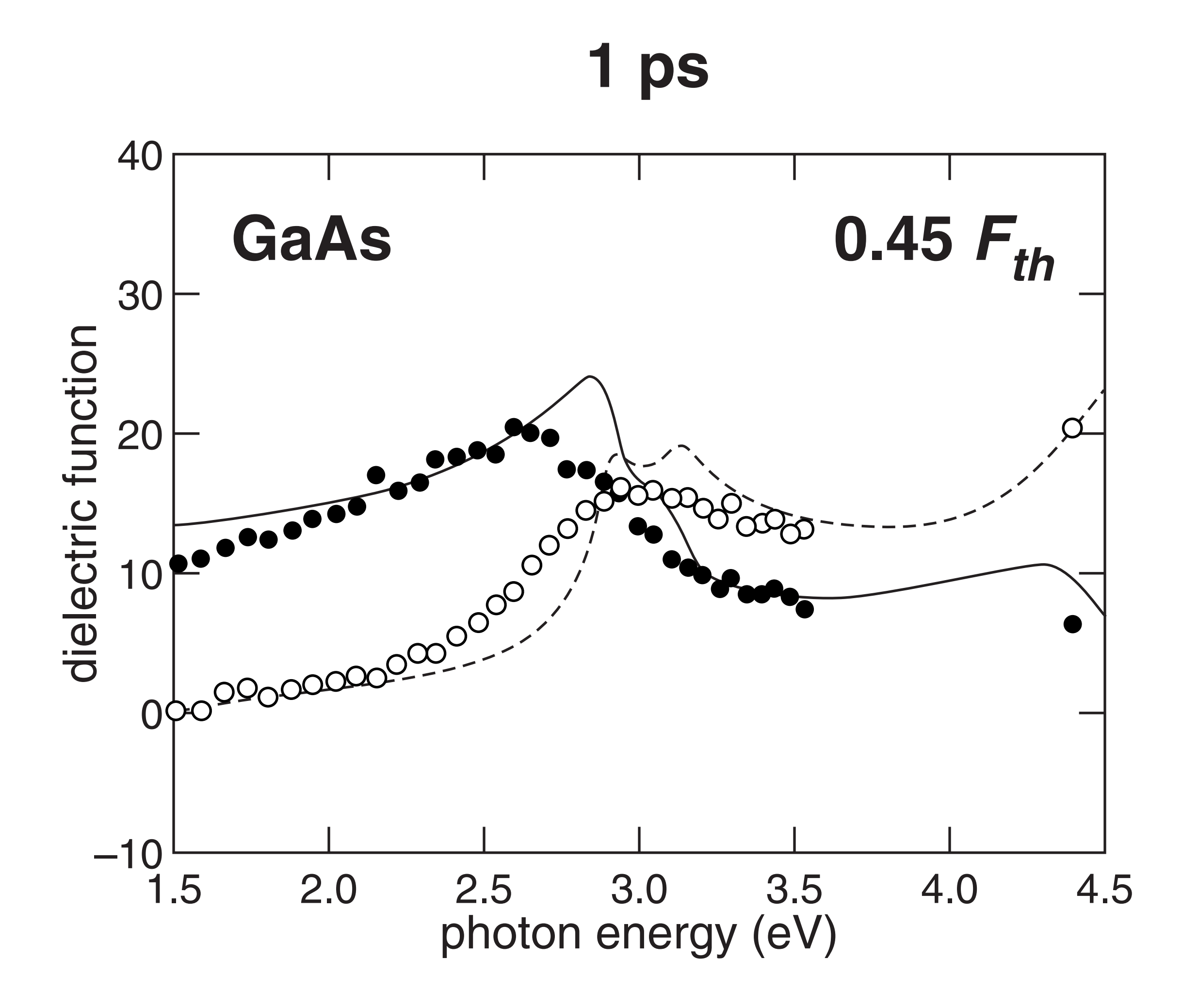

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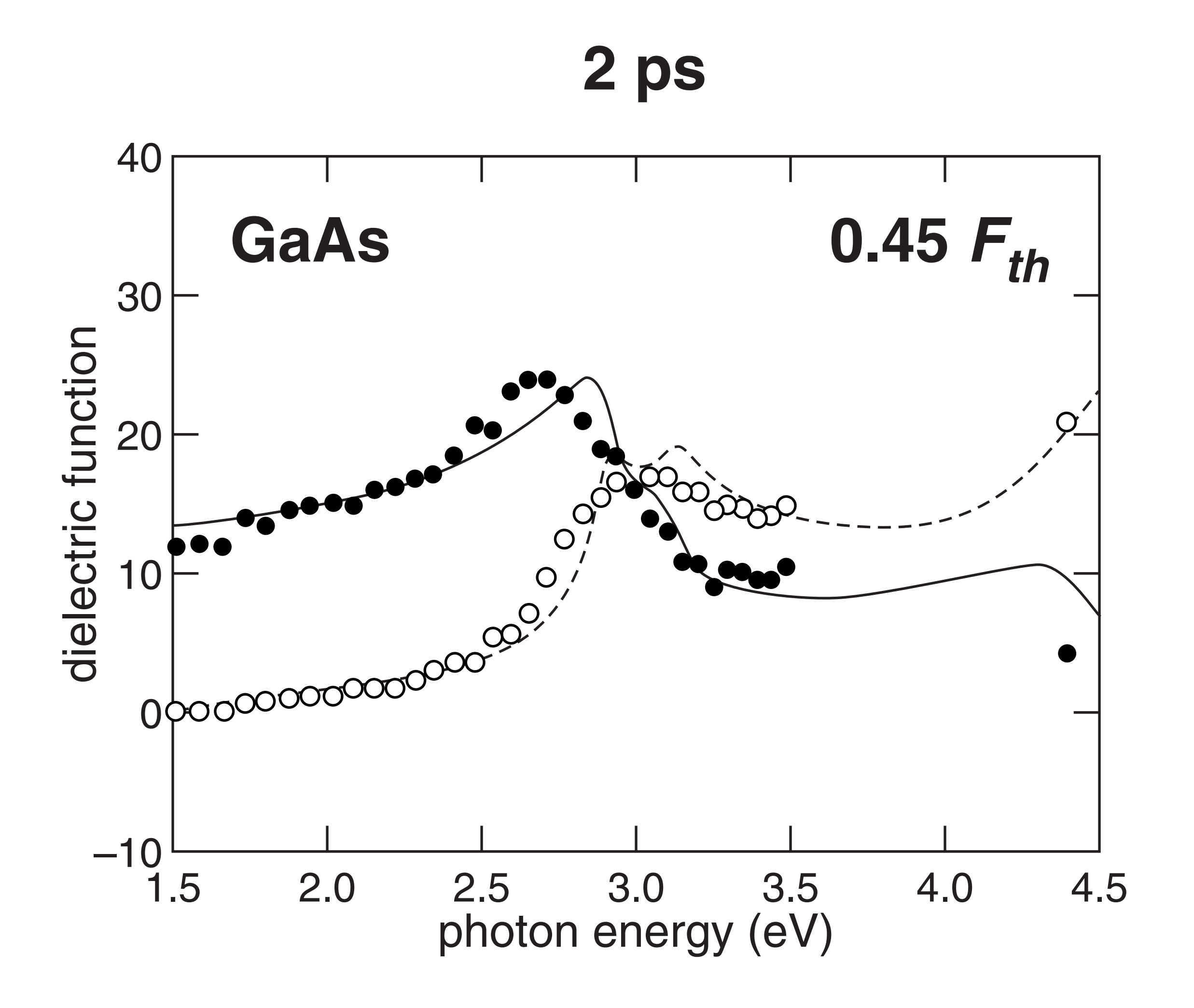

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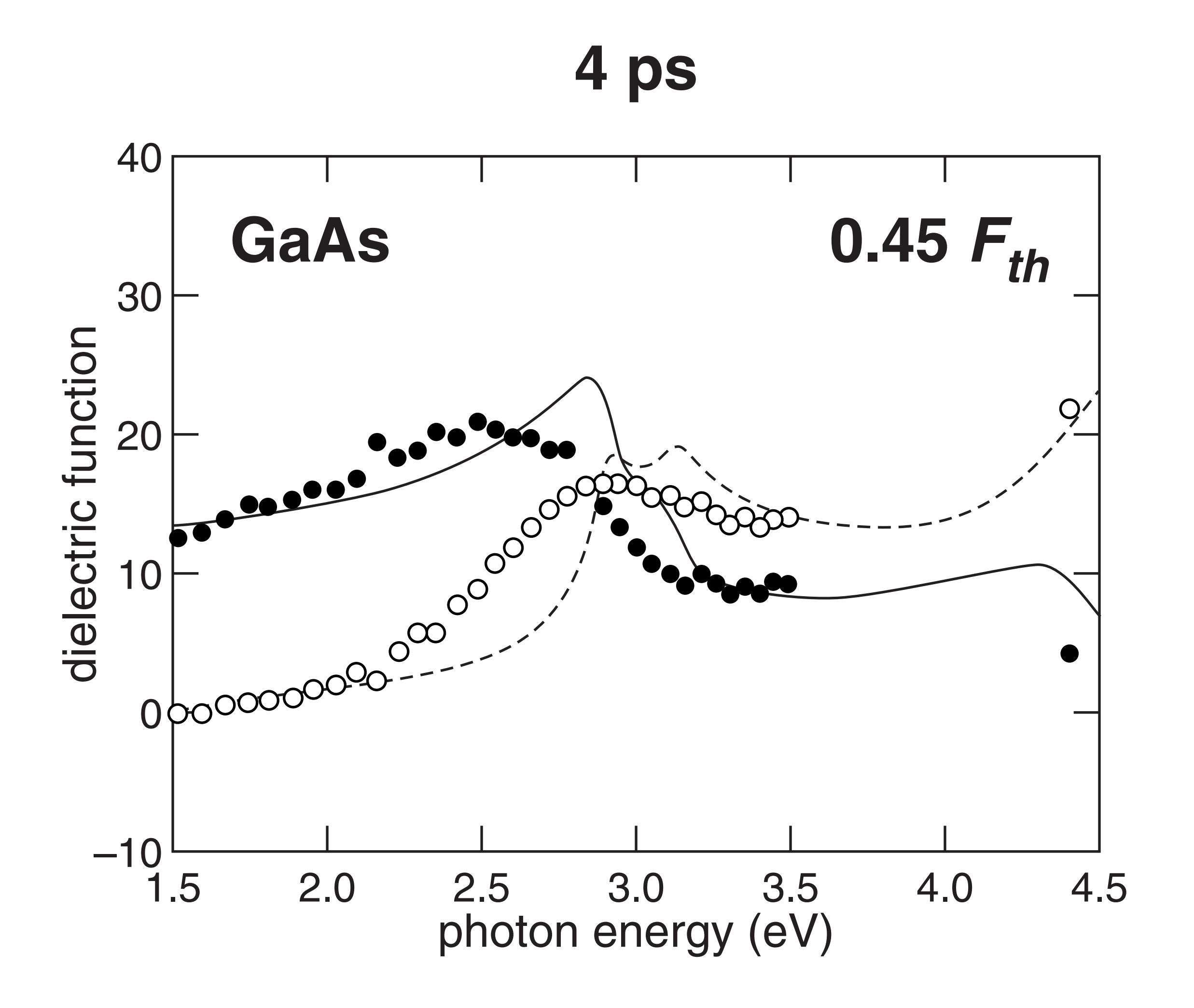

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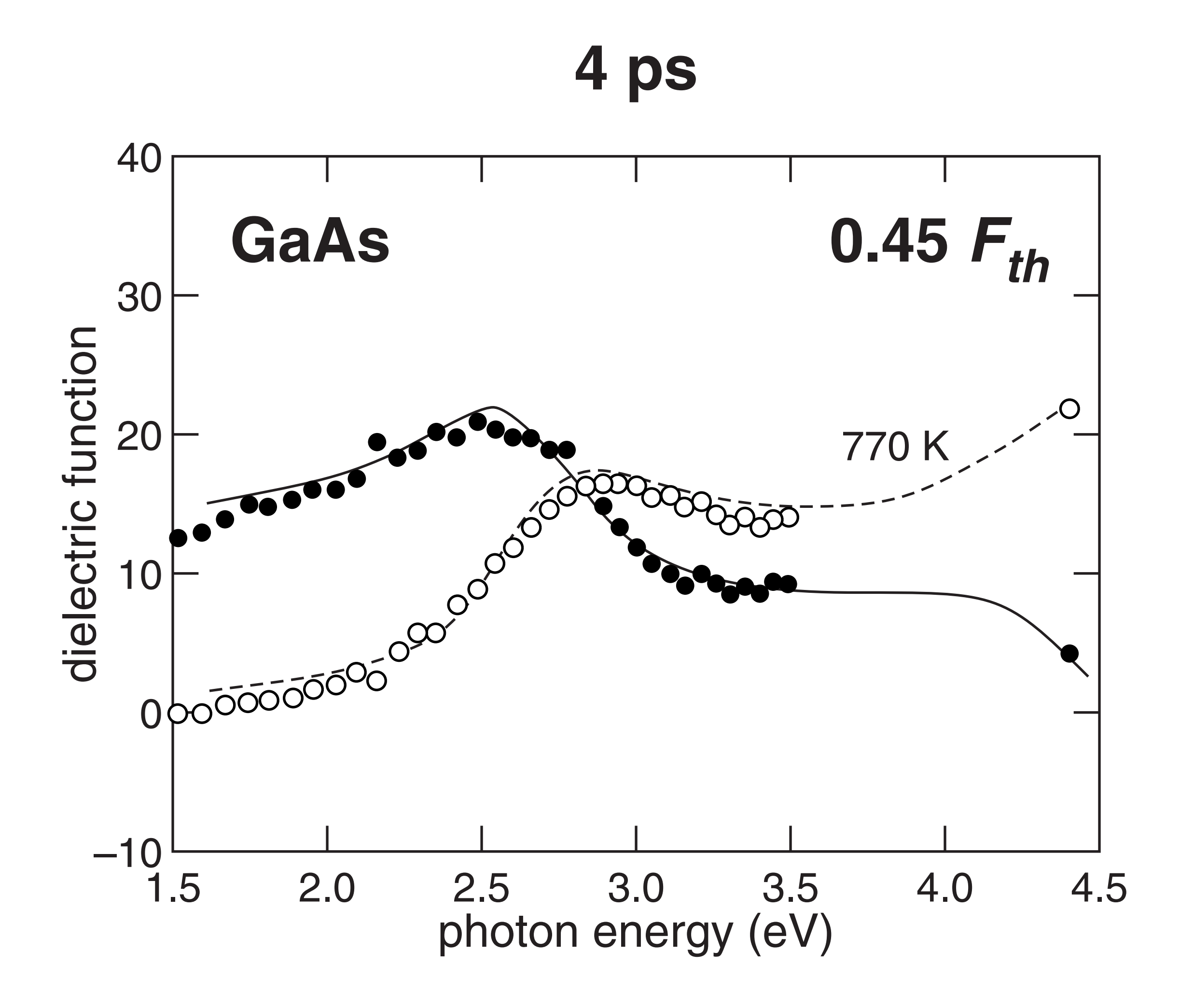

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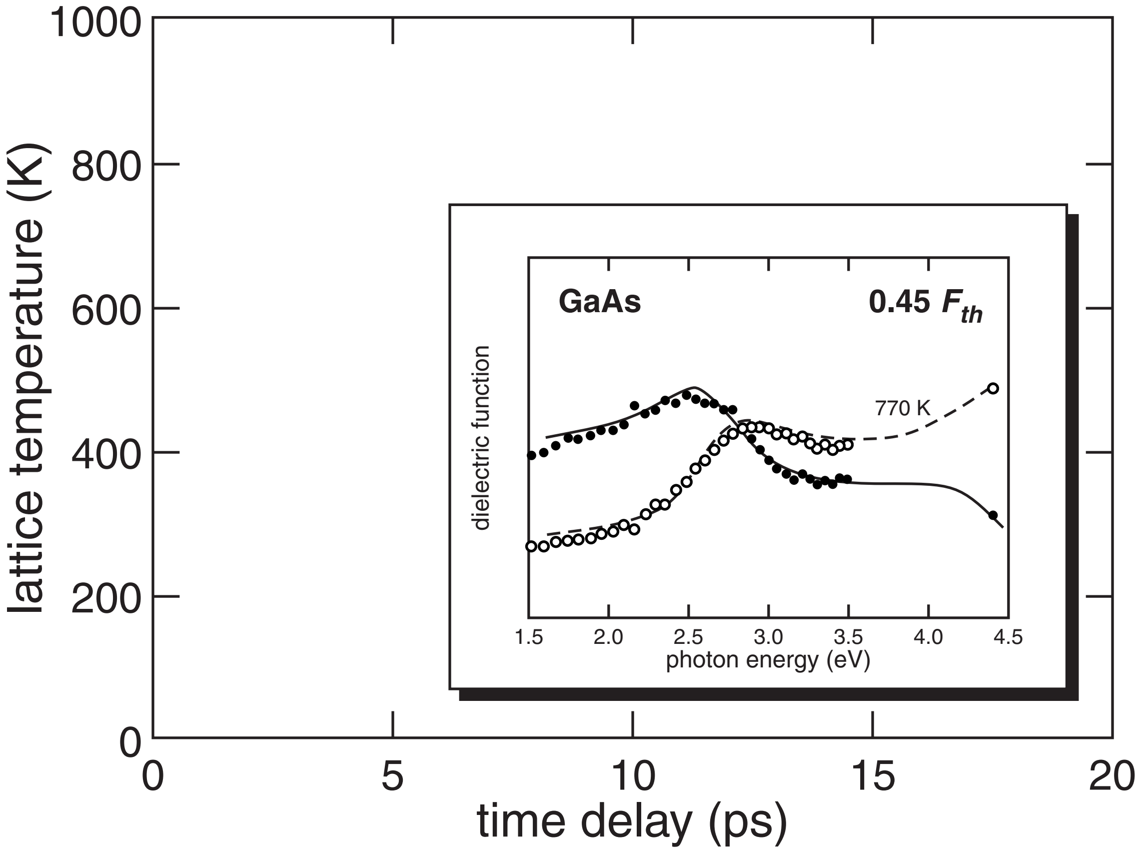

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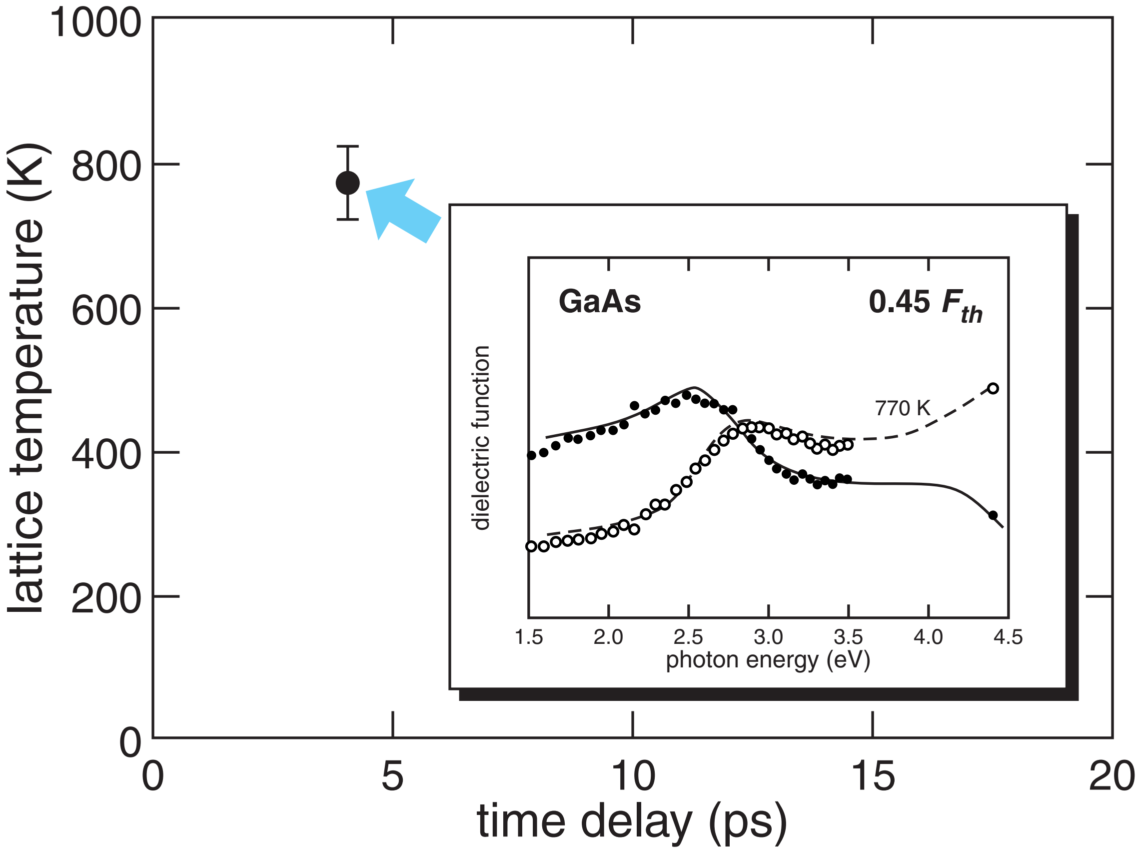
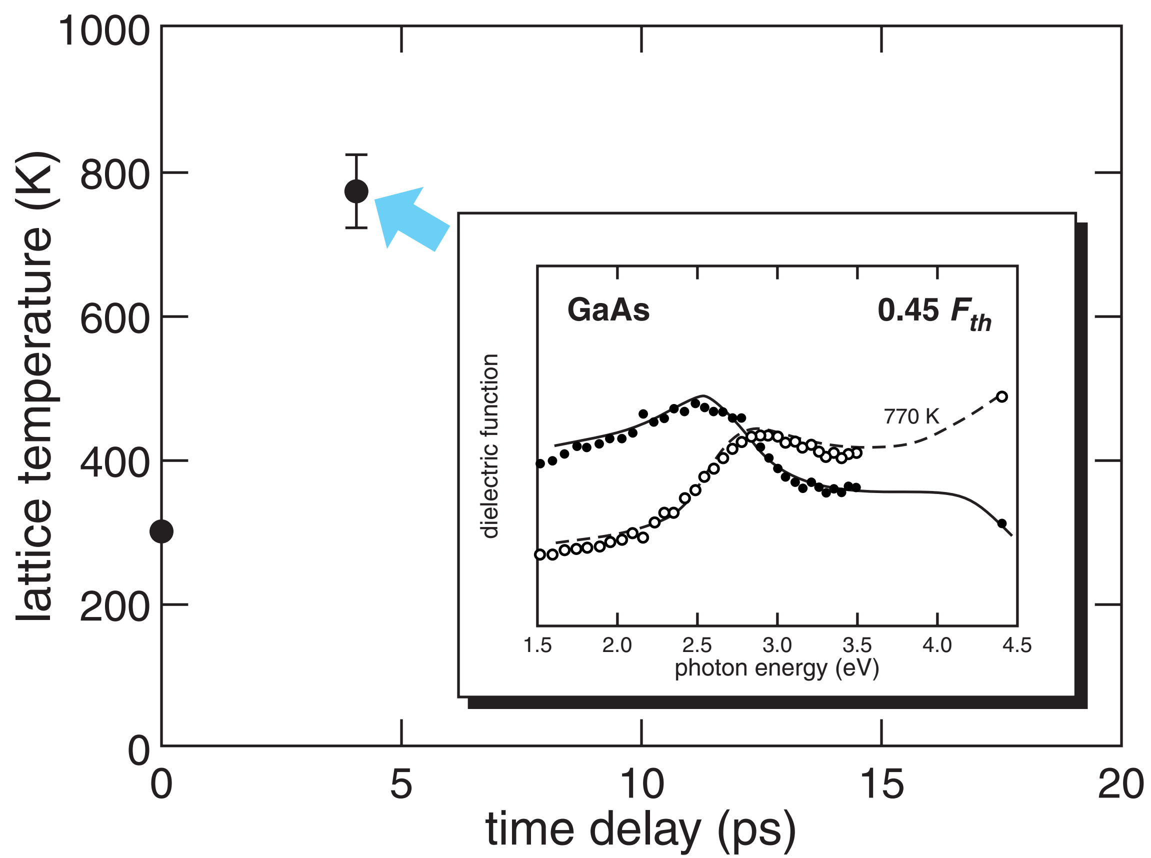
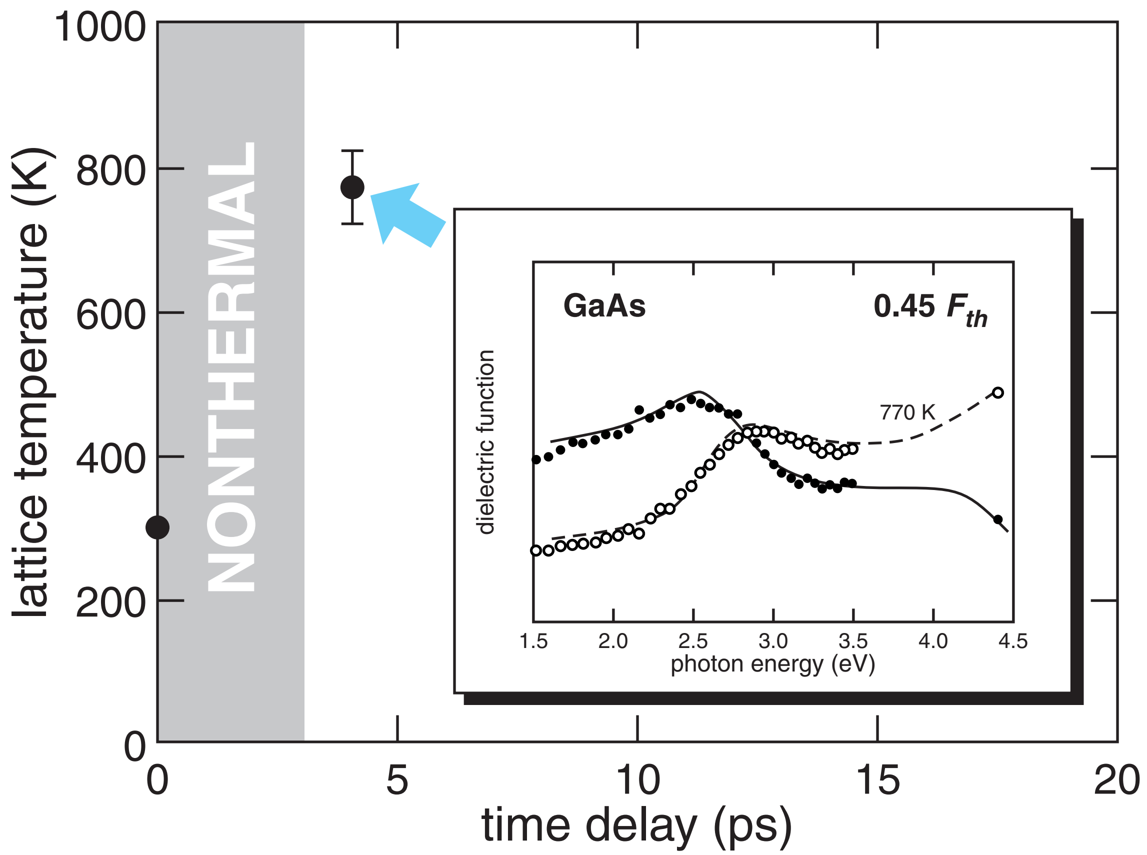


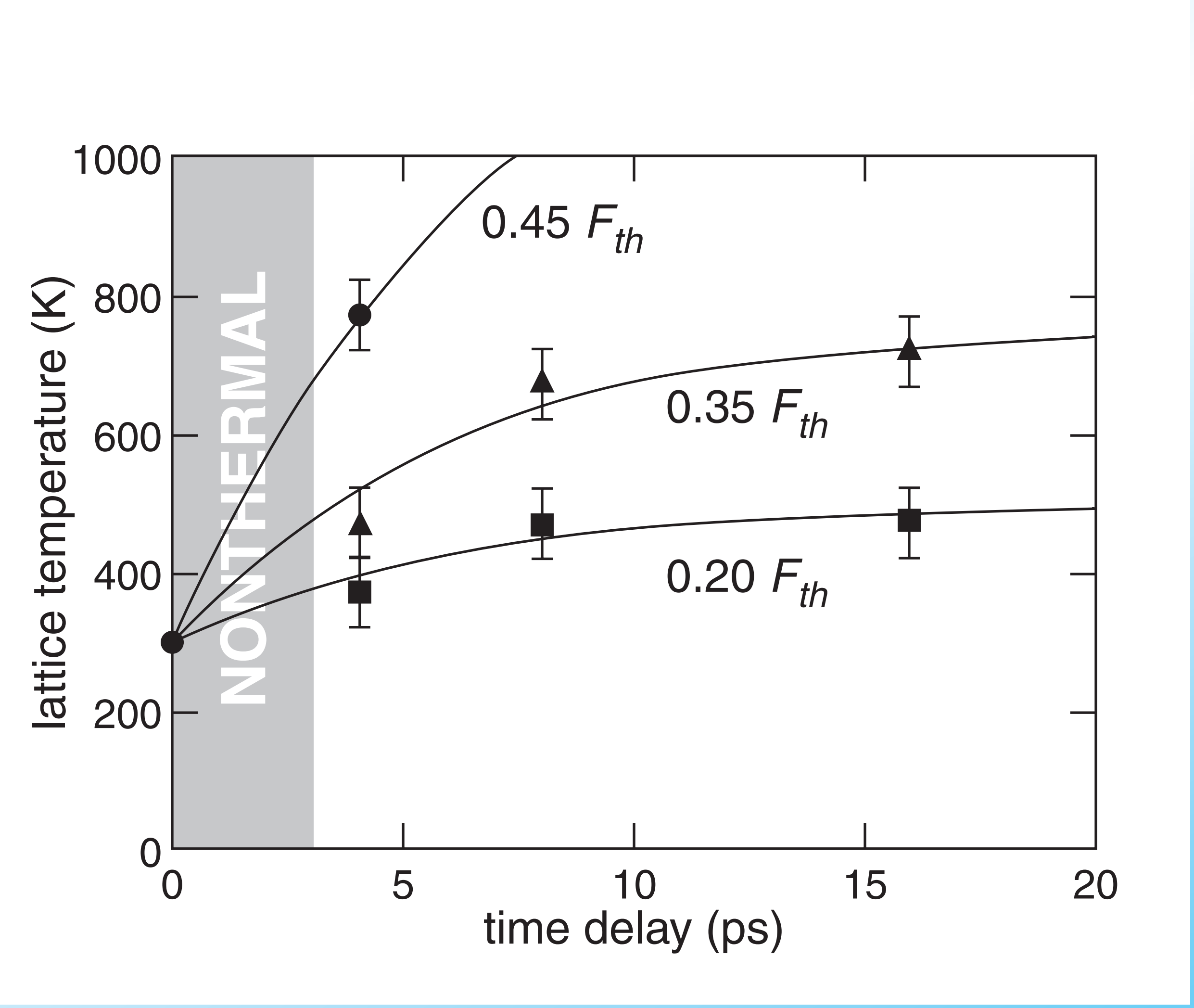
Dielectric function measurements



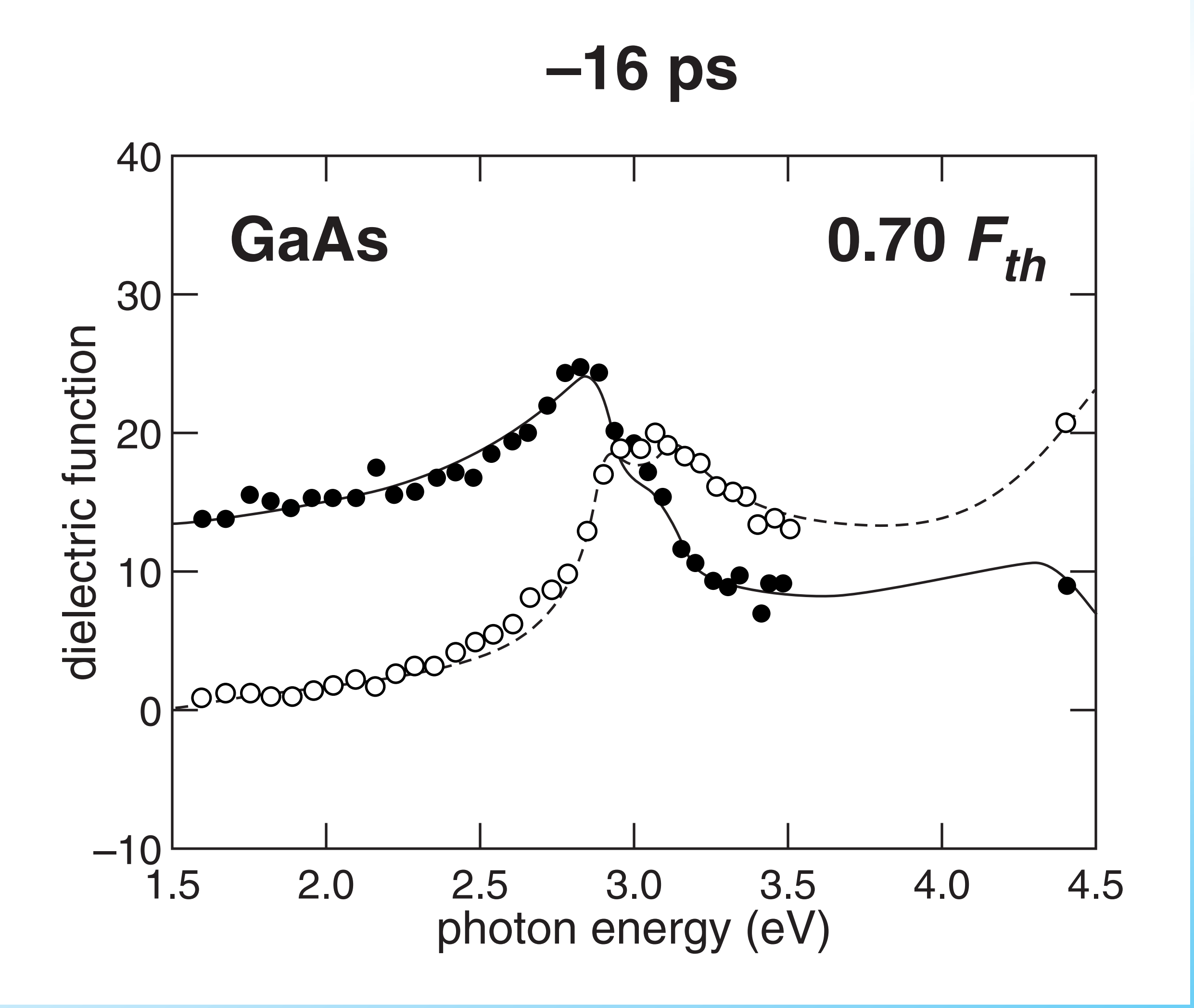
Dielectric function measurements



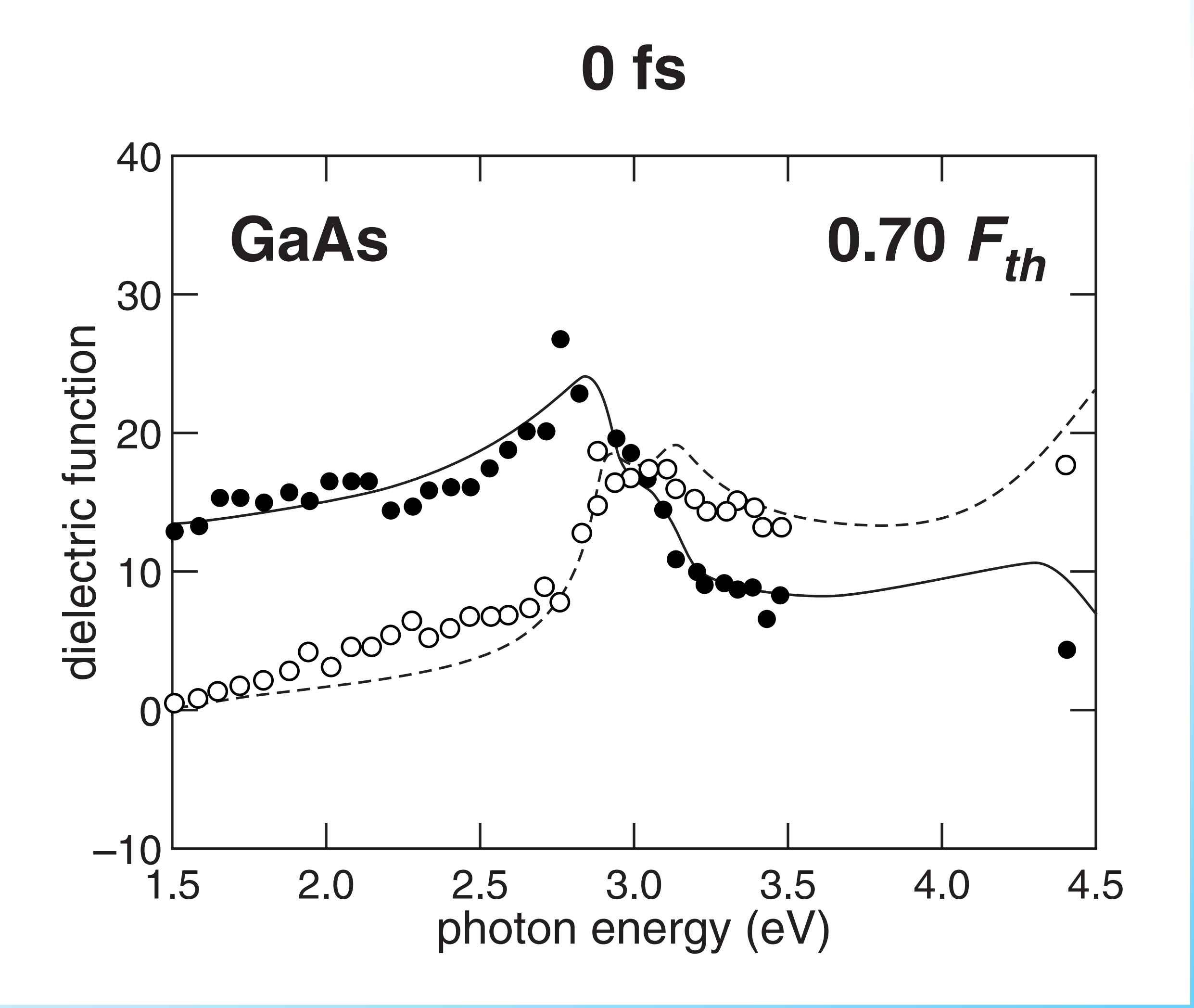
Dielectric function measurements



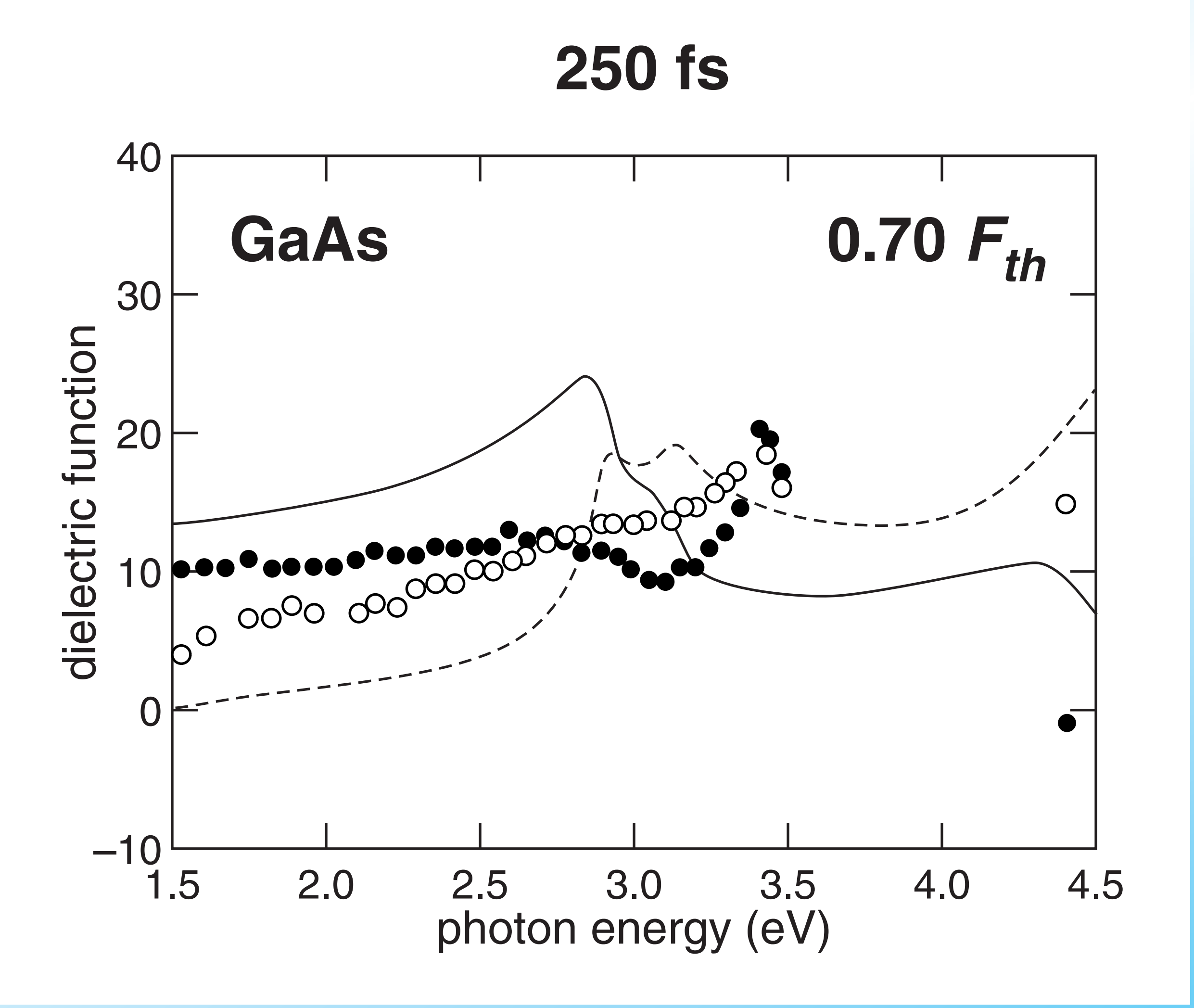
Dielectric function measurements



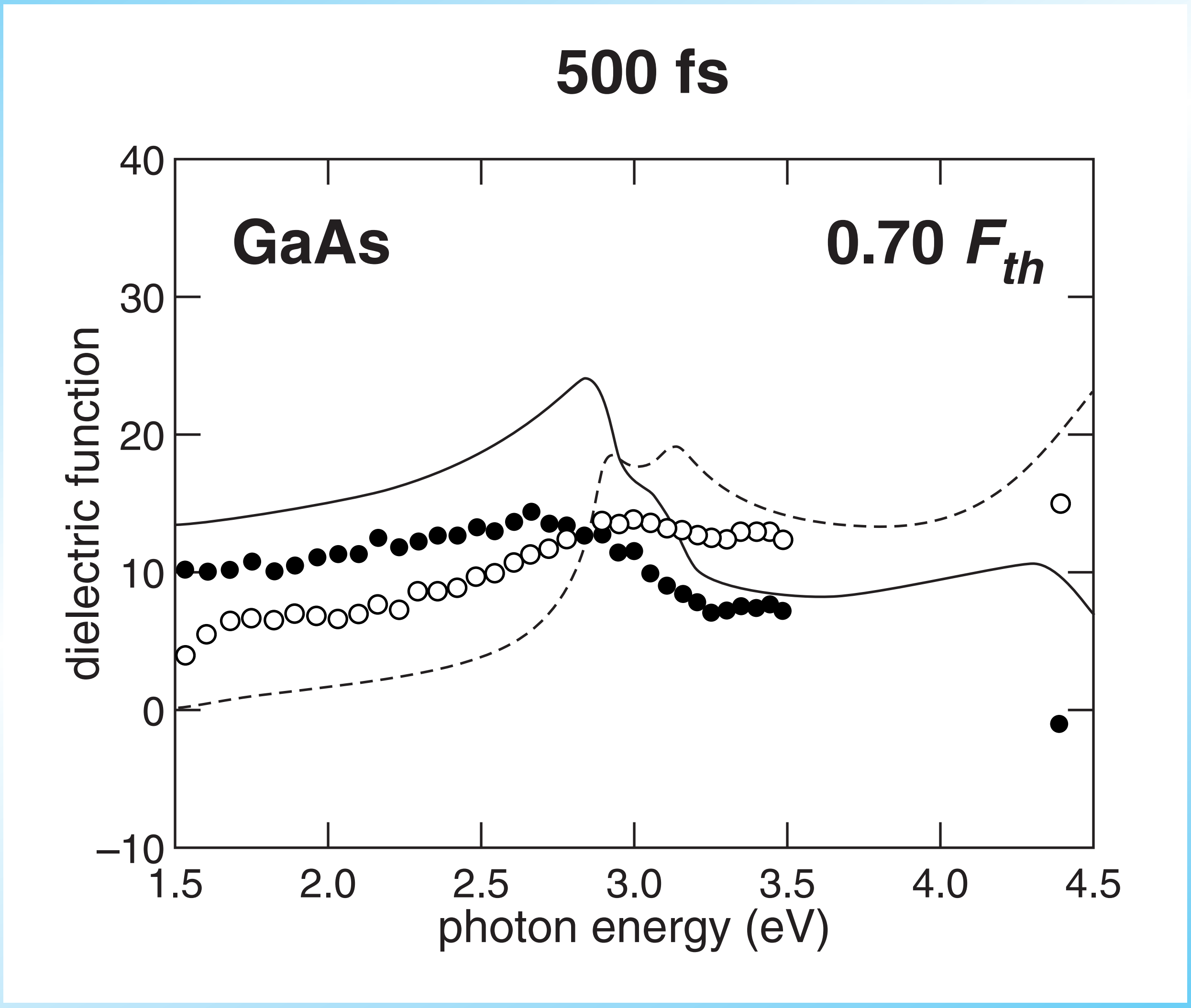
Dielectric function measurements



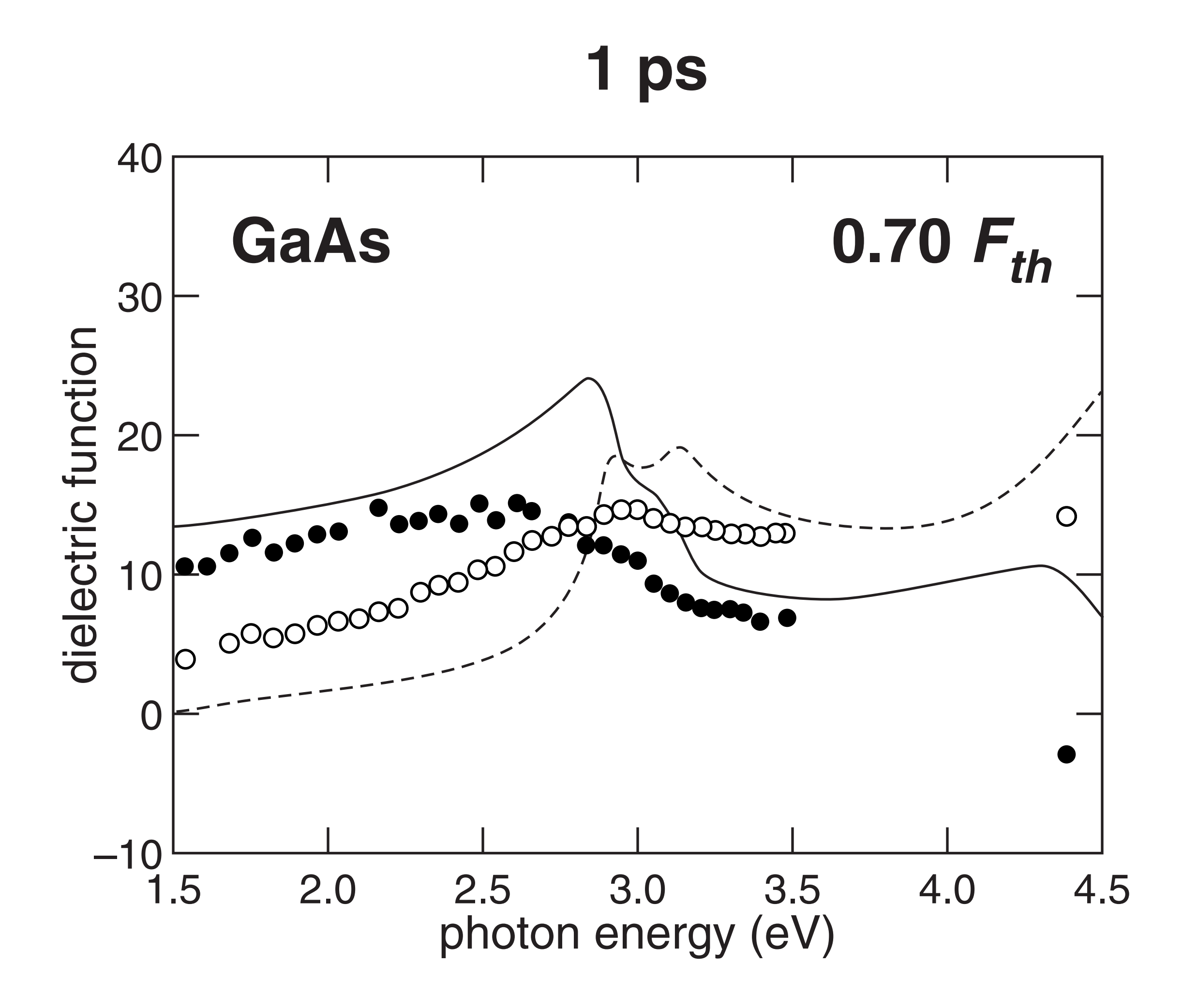
Dielectric function measurements



Dielectric function measurements



Dielectric function measurements



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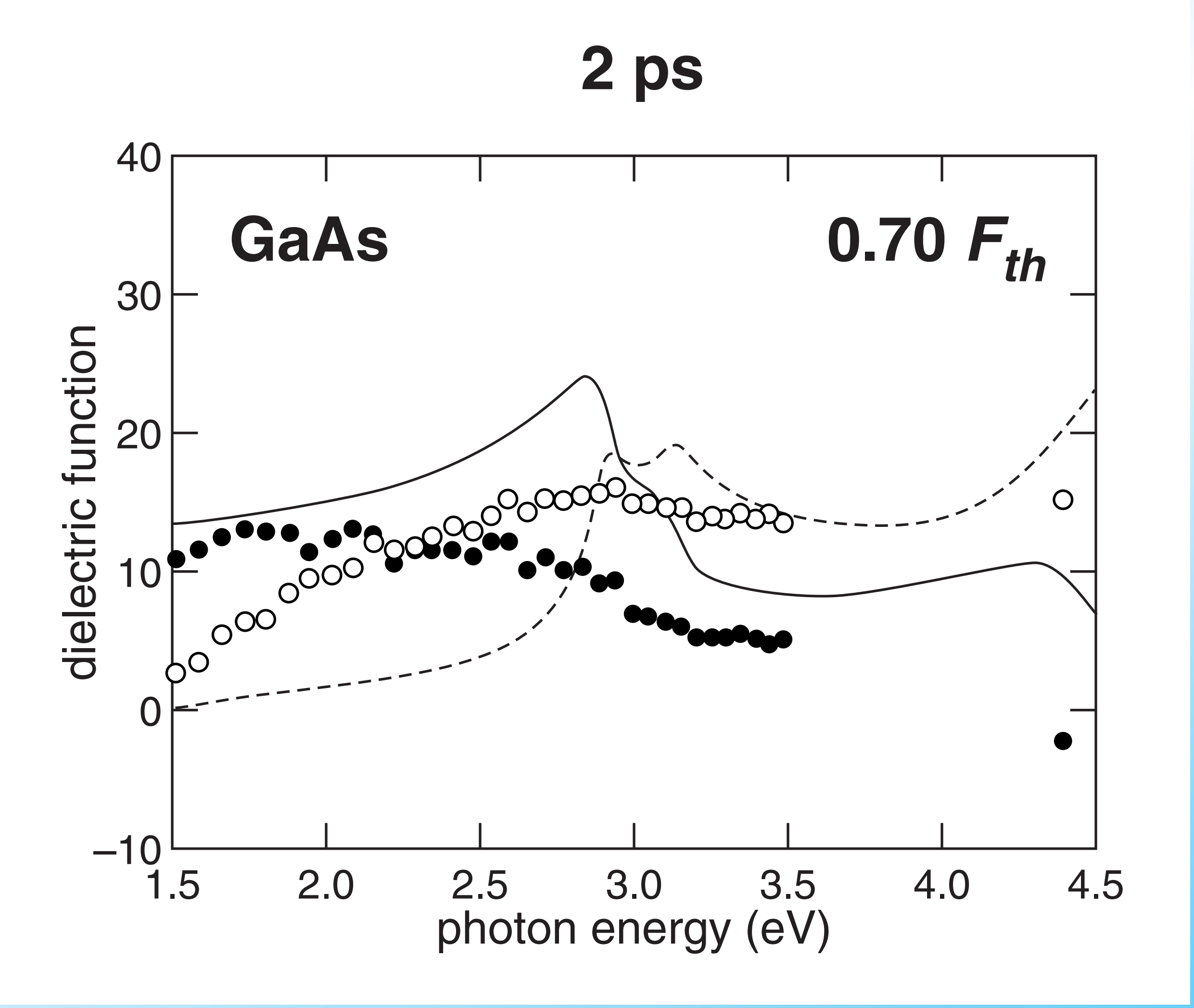
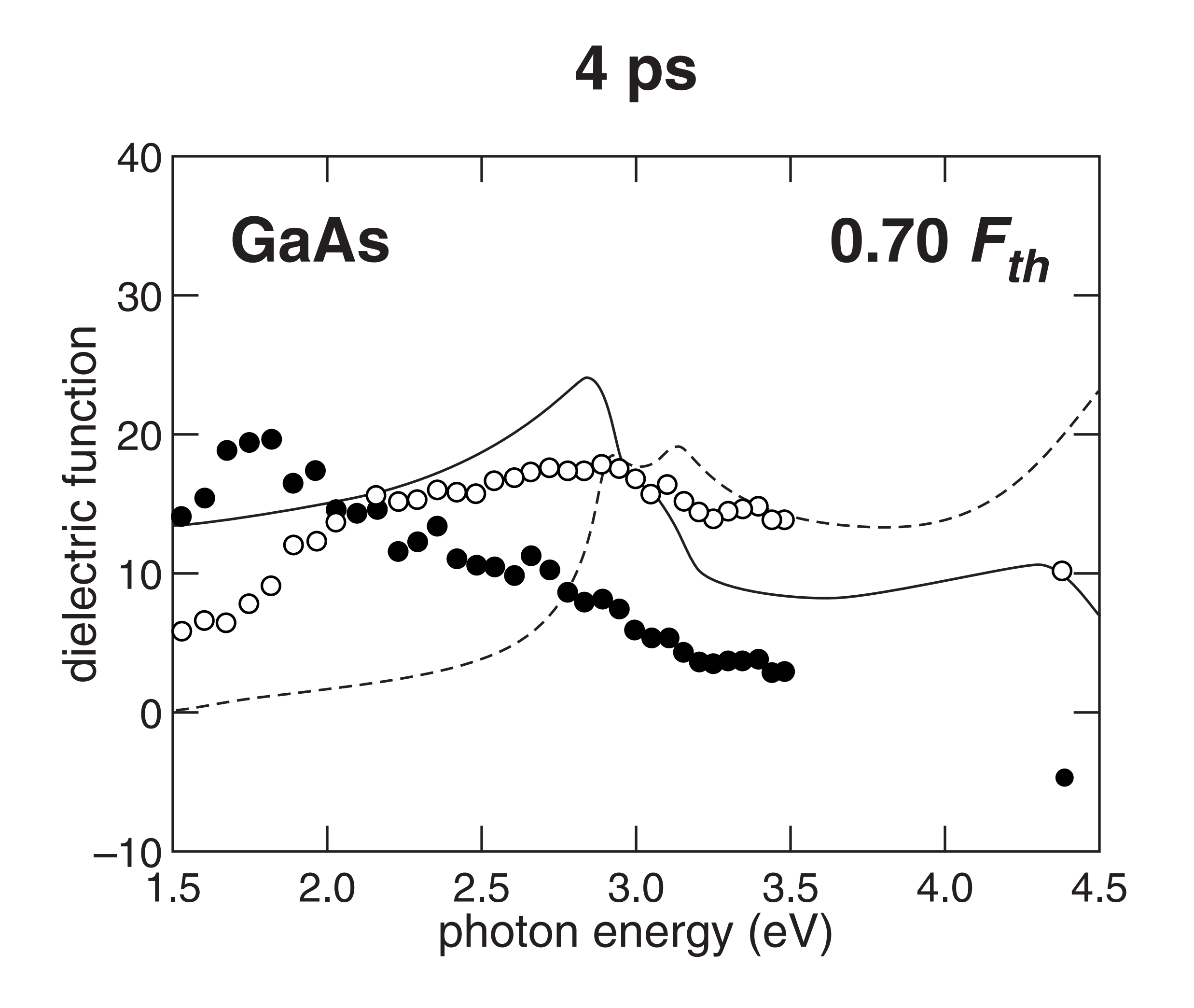
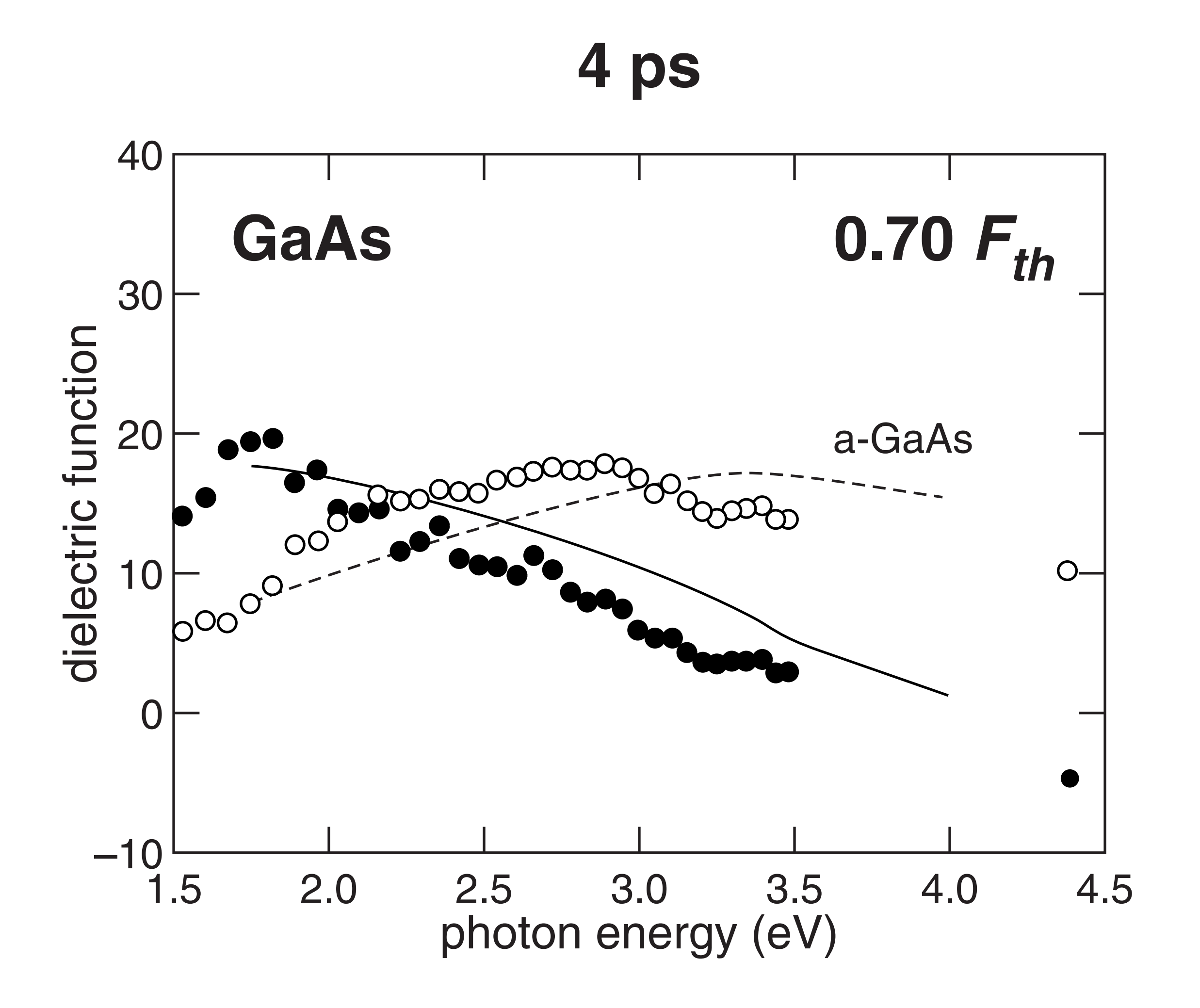


Dielectric function measurements

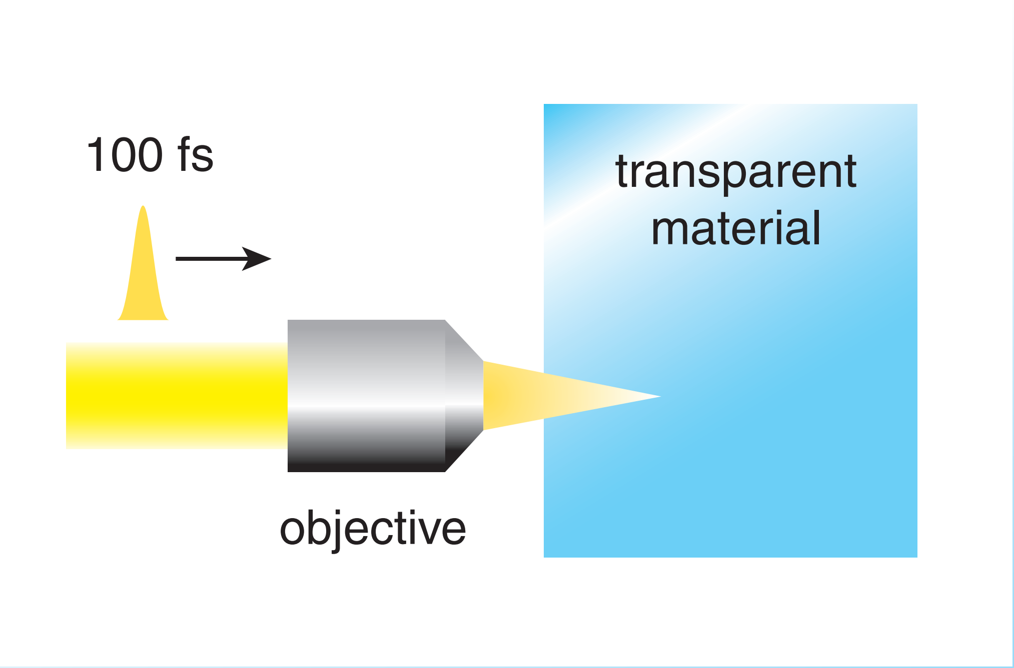


Dielectric function measurements



Extreme nonlinear optics

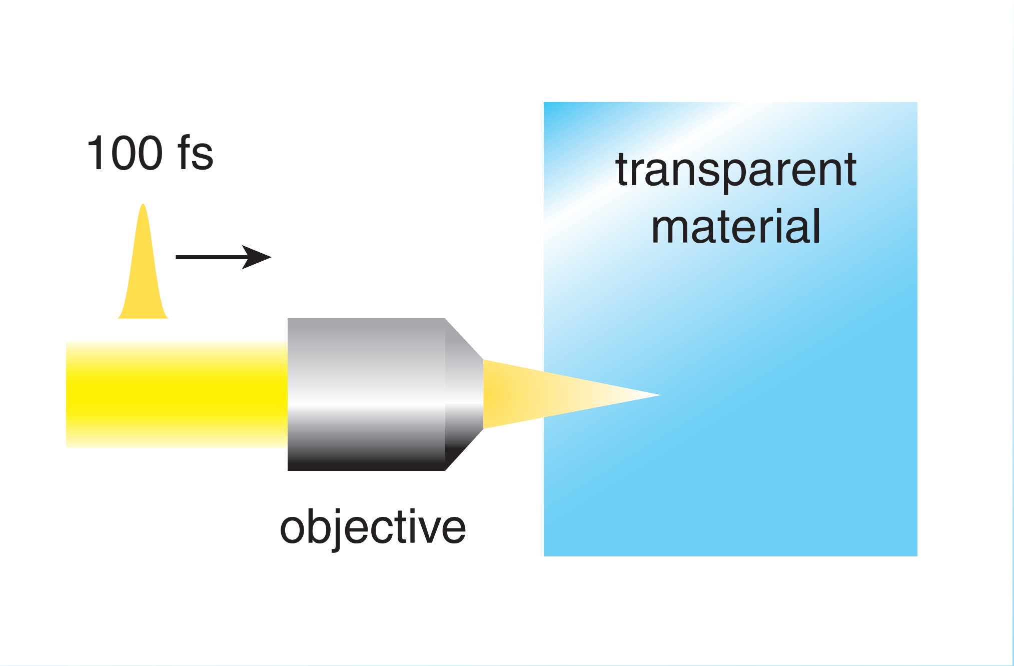
focus laser beam inside material…



Glezer, *et al.*, *Opt. Lett.* 21, 2023 (1996)

Extreme nonlinear optics

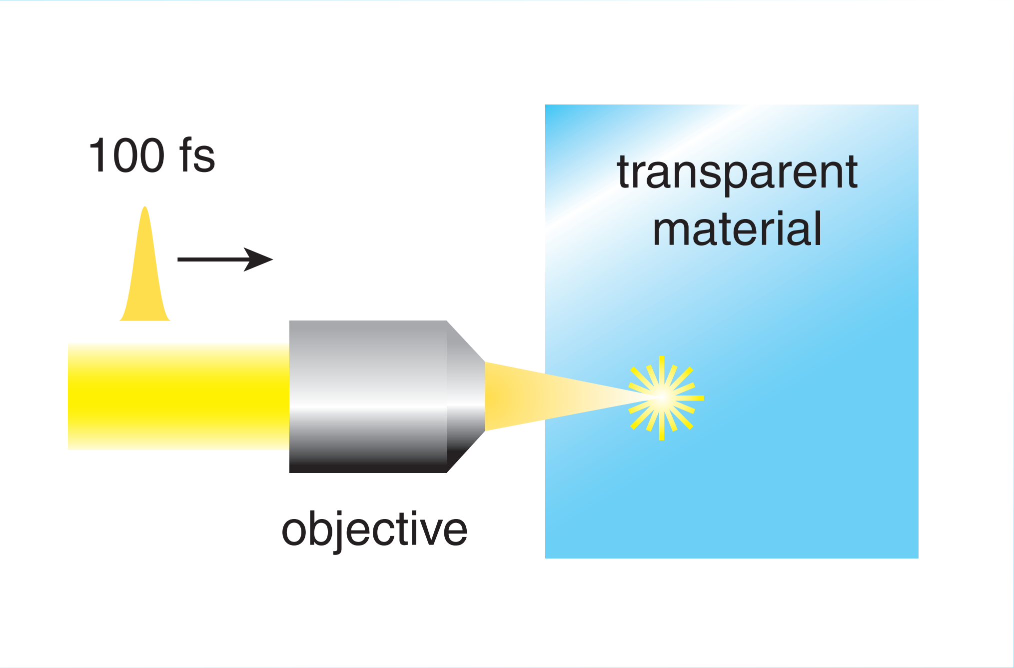
high intensity at focus…



Glezer, *et al.*, *Opt. Lett.* 21, 2023 (1996)

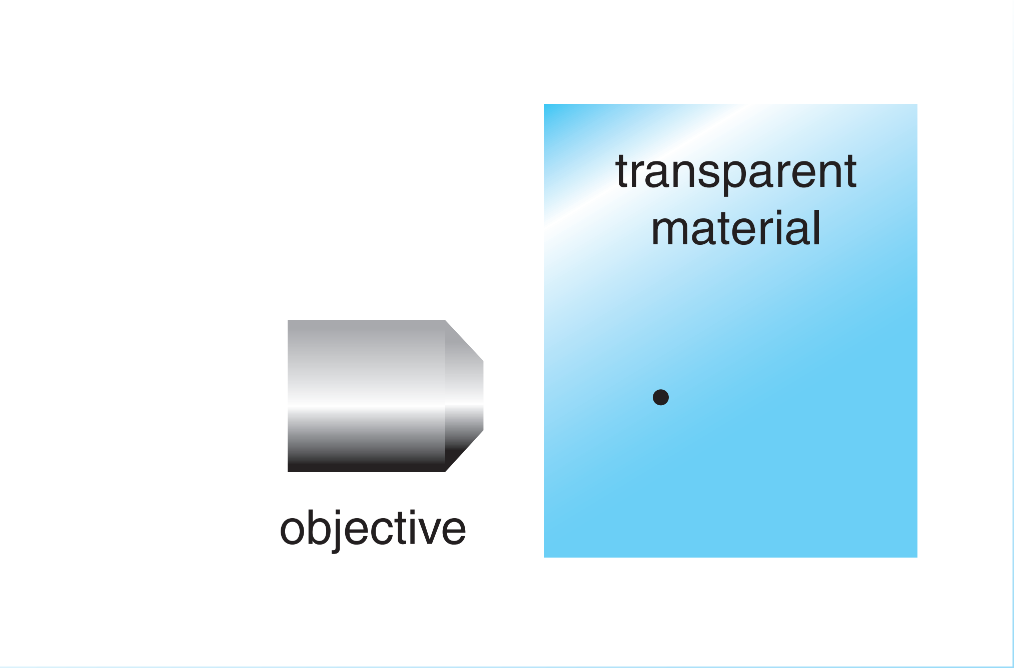
Extreme nonlinear optics

… causes nonlinear ionization…



Glezer, *et al.*, *Opt. Lett.* 21, 2023 (1996)

and microscopic bulk damage



Glezer, *et al.*, *Opt. Lett.* 21, 2023 (1996)

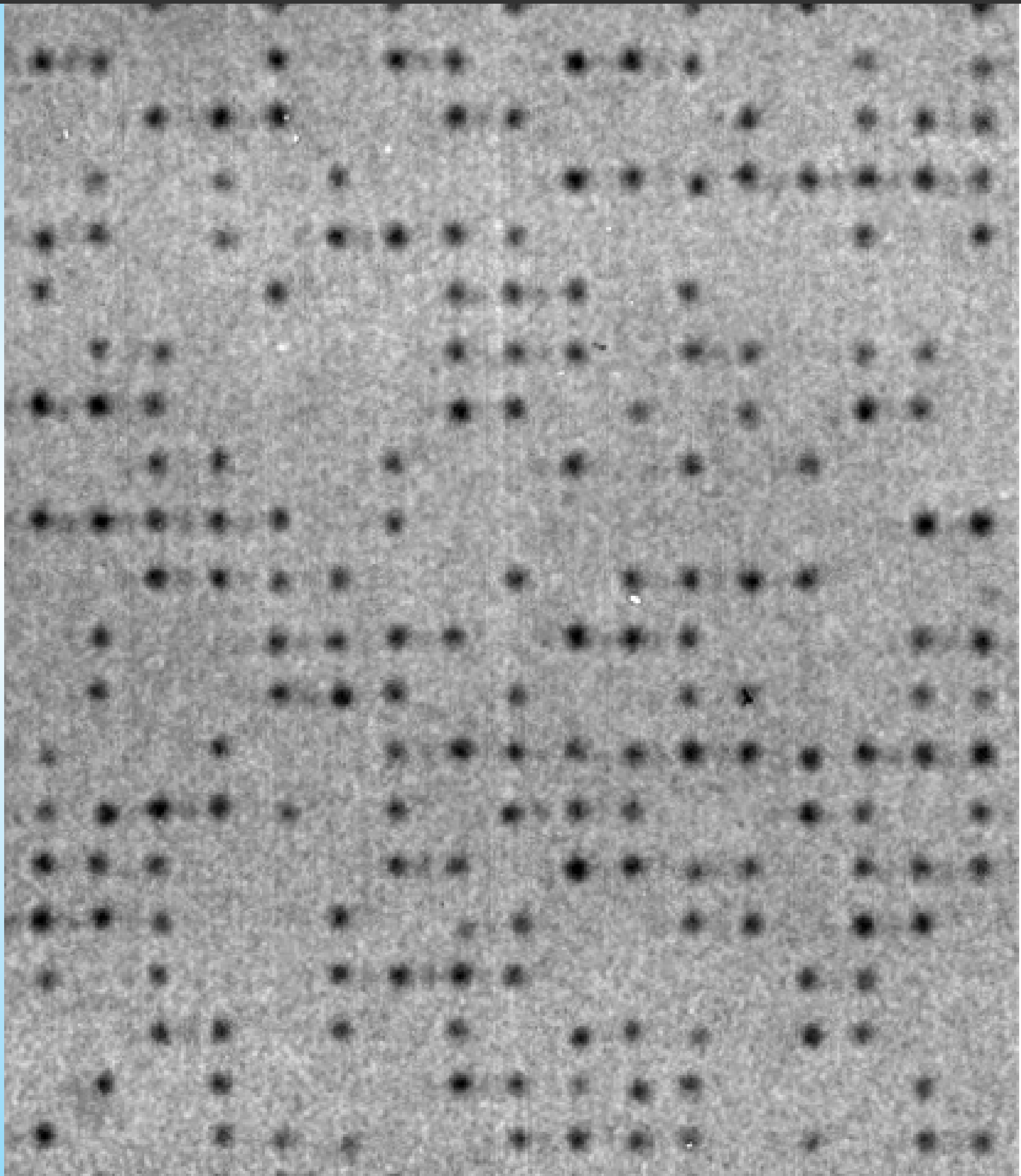
Extreme nonlinear optics

optical microscopy

2 x 2 μm array

fused silica

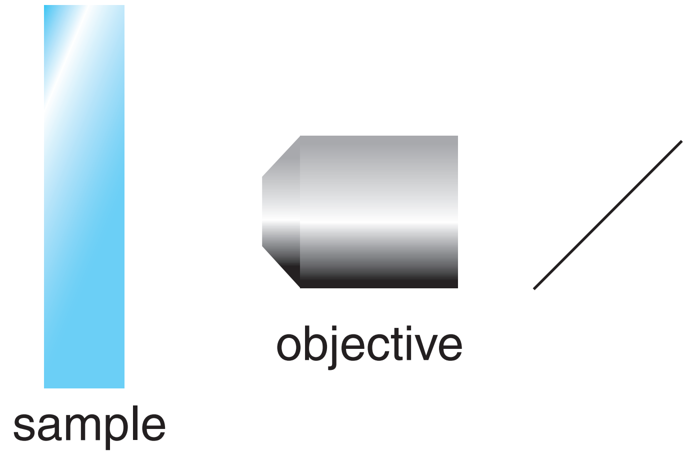
0.5 μJ, 100 fs, 800 nm



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

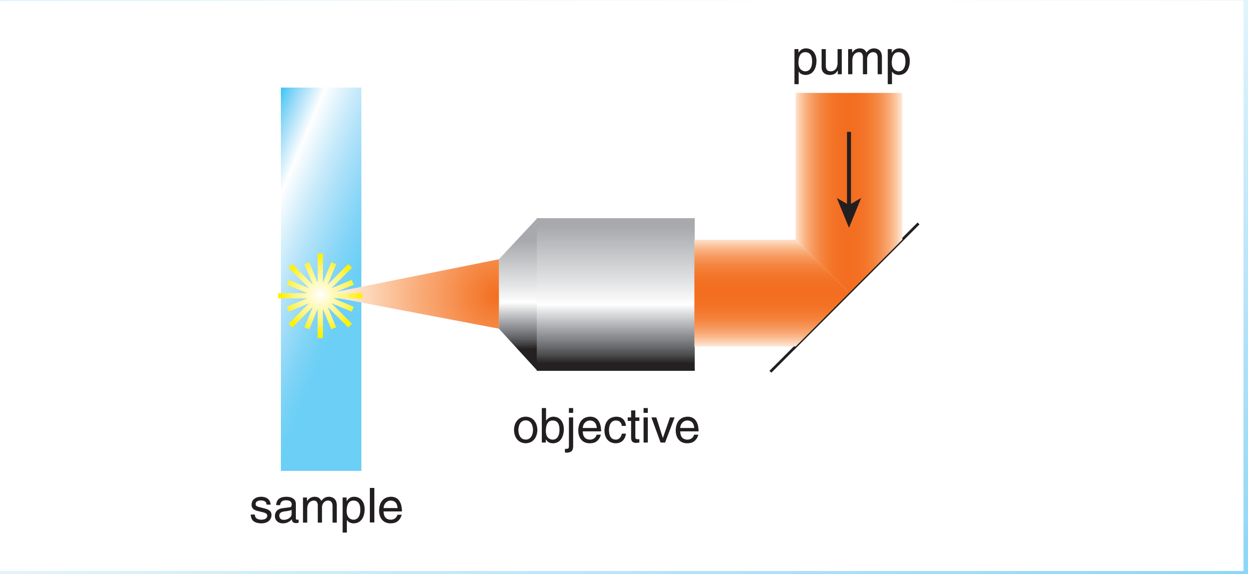
Extreme nonlinear optics

imaging setup



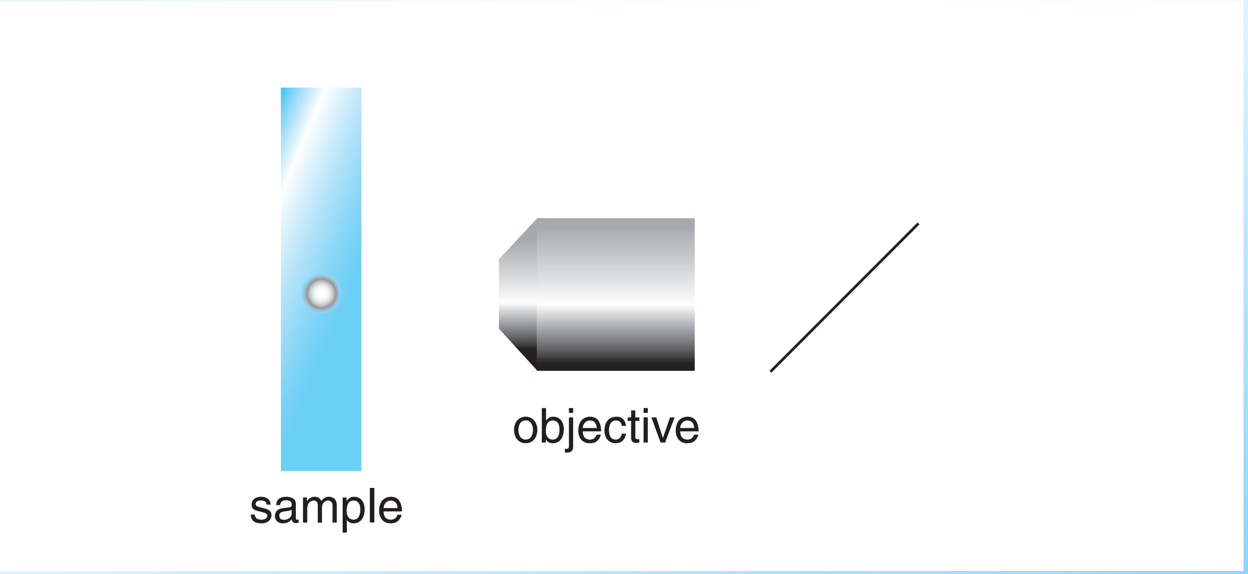
Extreme nonlinear optics

imaging setup

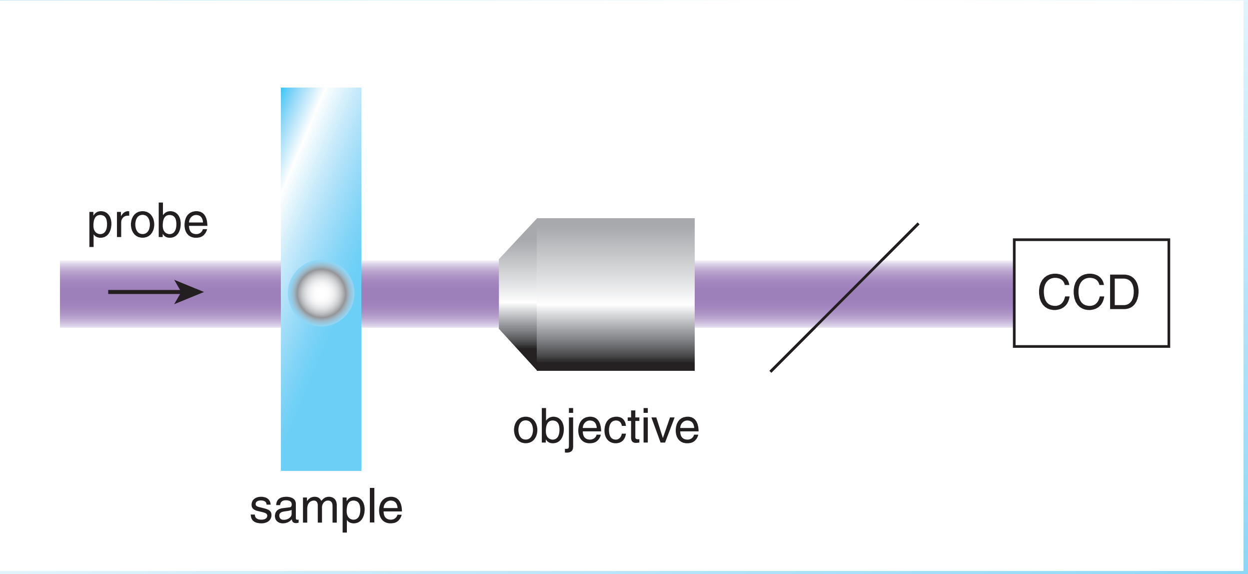


Extreme nonlinear optics

imaging setup



imaging setup



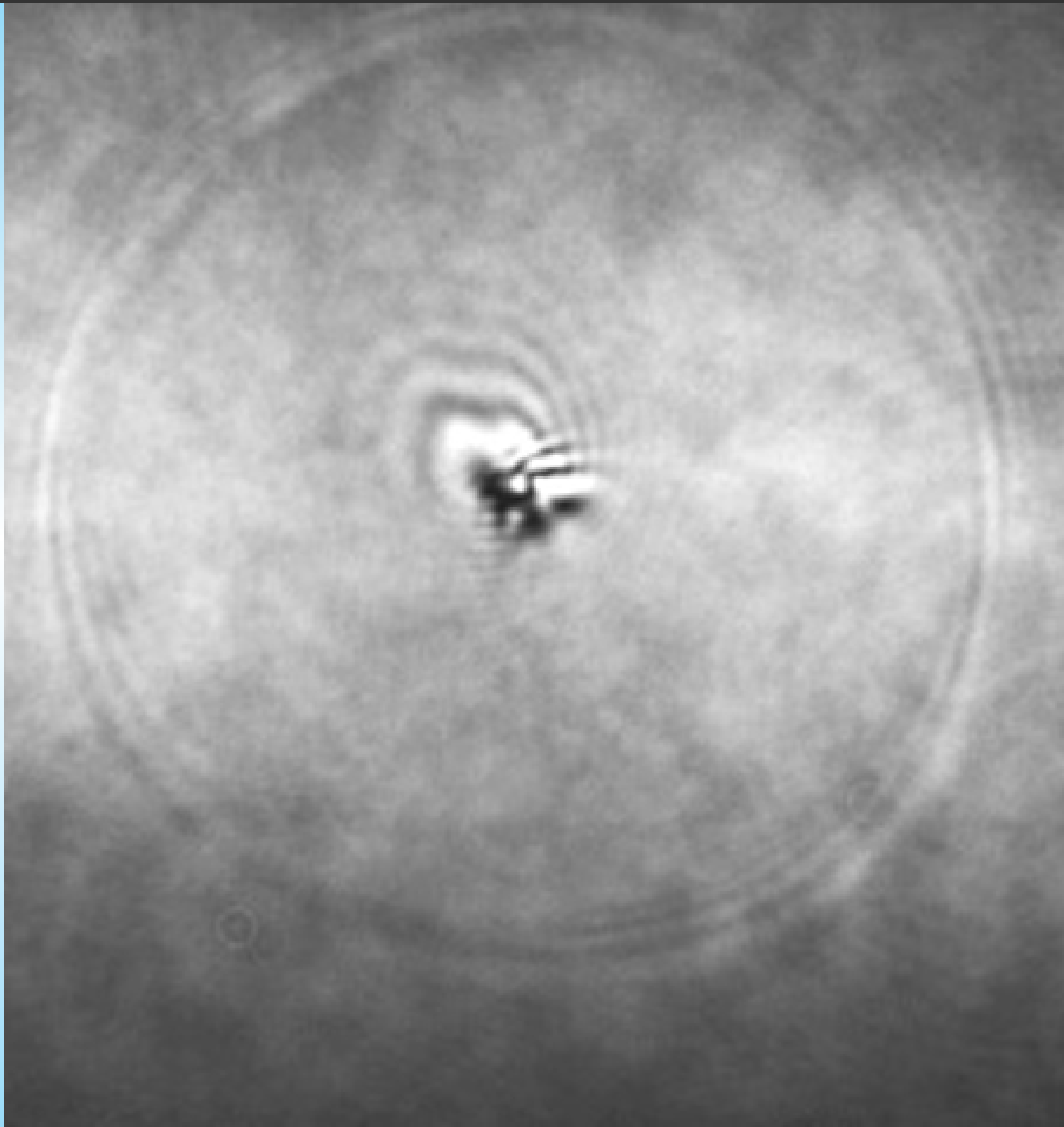
Extreme nonlinear optics

sapphire

3 μJ pulse

3.8 ns delay

40 μm radius



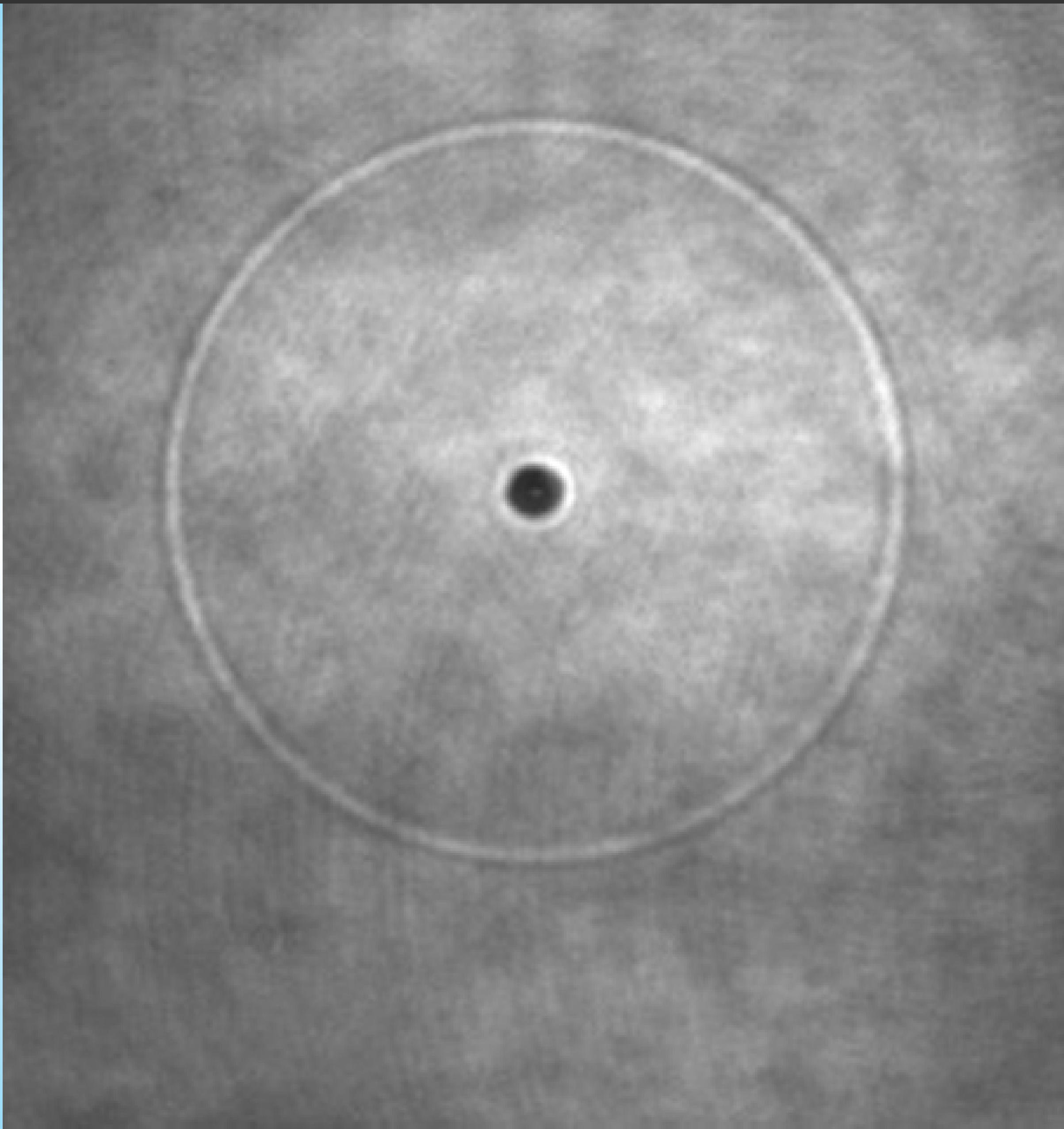
Extreme nonlinear optics

water

1.0 μJ pulse

35 ns delay

58 μm radius



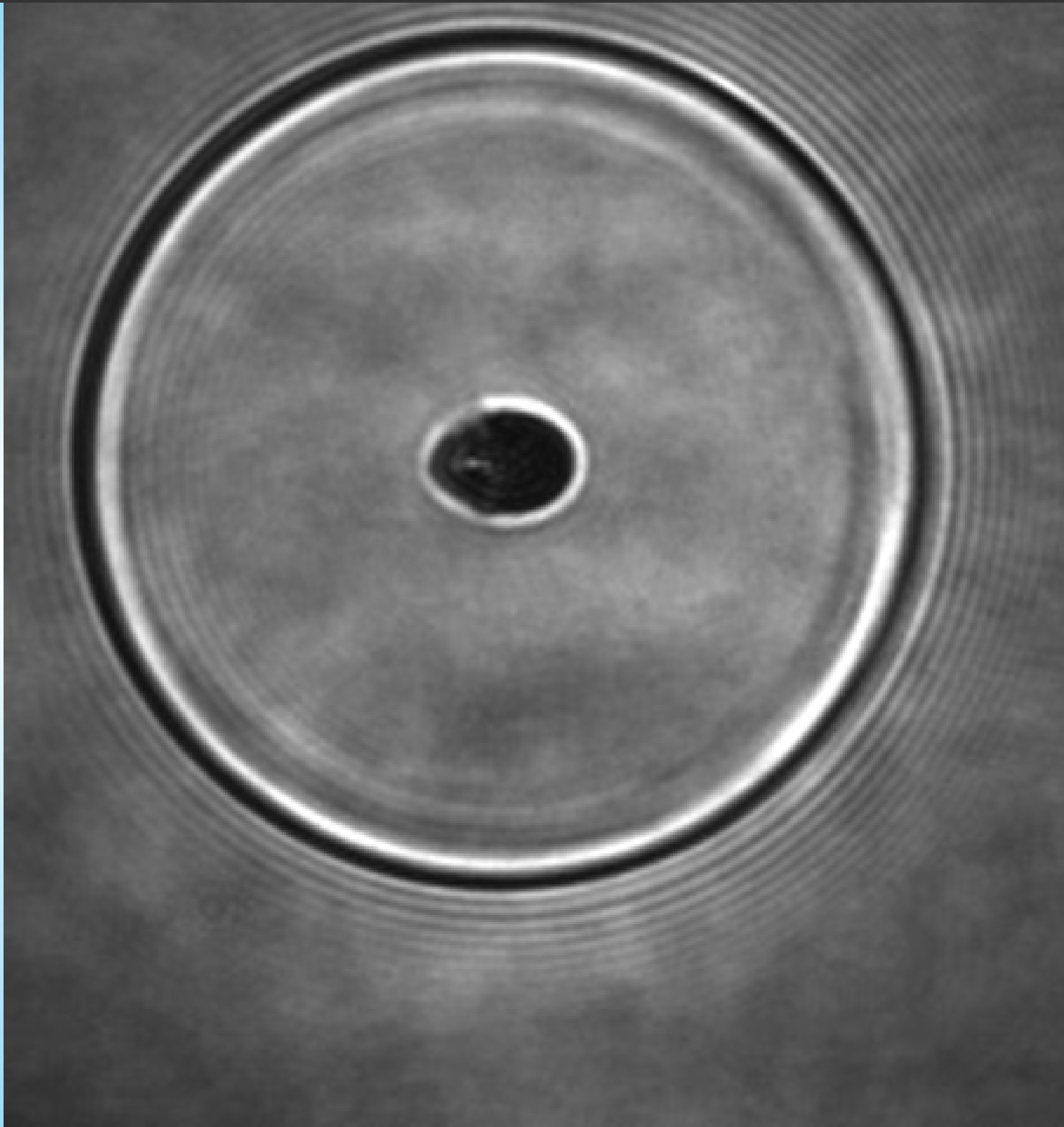
Extreme nonlinear optics

water

14 μJ pulse

35 ns delay

64 μm radius



Extreme nonlinear optics

Summary

Femtosecond lasers offer:

- **unprecedented view into dynamics**
- **extreme conditions with very little energy**
- **new research in materials science**

Many exciting talks in Symposium Q!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For a copy of this talk and additional information, see:

http://mazur-www.harvard.edu