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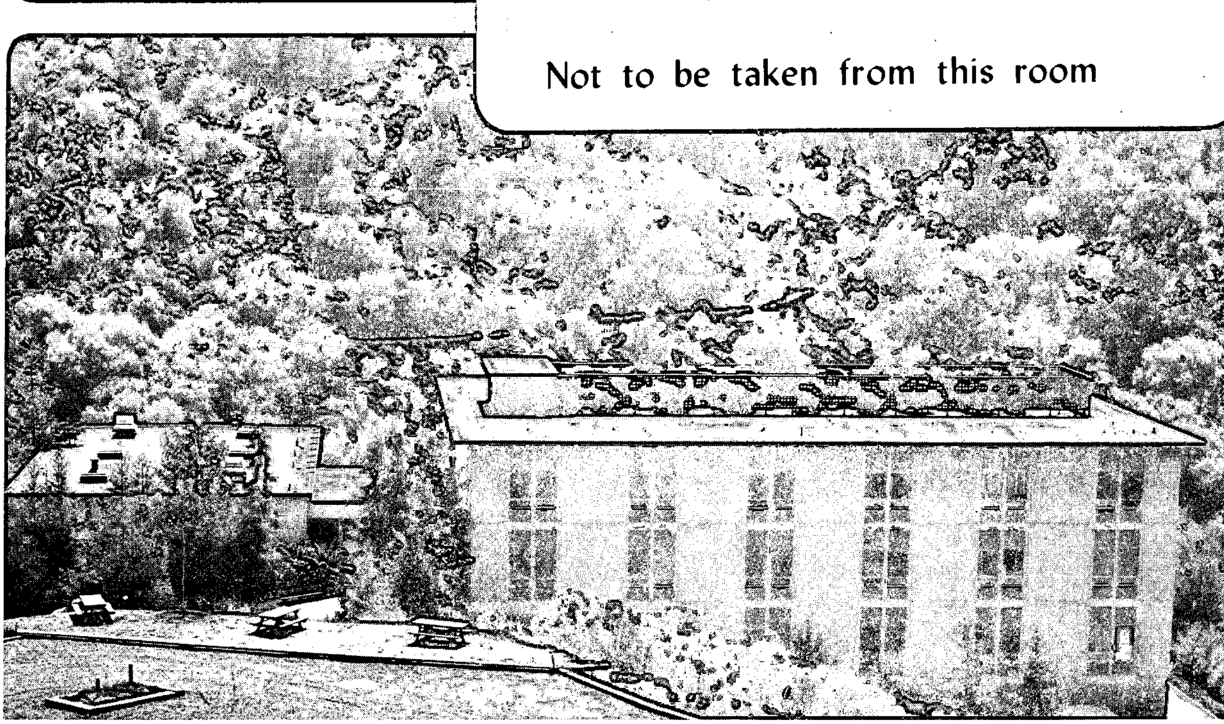

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ABSTRACT

We present solutions for the semiconductor Bloch equations under different excitation conditions. By exciting far above the band gap we provide clear theoretical evidence for a photon echo in the absorption continuum of a semiconductor.

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The theory of photon echoes has been intensively investigated for interaction-free particles since 1979 [1]. Numerical calculations for semiconductors, excited at or below the band edge, have been reported [2]. However, a very important configuration for ultrashort pulse experiments corresponds to excitation in the continuum or simultaneous excitation of bound and continuum states as shown in Fig. 1. To the best of our knowledge, this configuration has never been studied theoretically, despite the fact that one can expect marked differences between the response of bound and continuum states.

We have solved the semiconductor Bloch equations,

$$i\hbar\frac{\partial}{\partial t}n(\mathbf{r},t) = [\,H(\,.\,,t)*,\,n(\,.\,,t)\,](\mathbf{r}) + i\hbar\left(\frac{\partial\,n(\mathbf{r},t)}{\partial t}\right)_{\mathbf{deph}}$$

$$H(\mathbf{r},t) = \begin{pmatrix} -\frac{\hbar^2}{4\,m}\Delta & -\mu\,E(t) \\ -\mu^* E^*(t) & -\frac{\hbar^2}{4\,m}\Delta \end{pmatrix}\delta(\mathbf{r}) - V(\mathbf{r})\,[\,n(\mathbf{r},t) - n(\mathbf{r},-\infty)\,]\,;\quad m = \frac{m_\mathrm{e}\,m_\mathrm{h}}{m_\mathrm{e}+m_\mathrm{h}}$$

$$V(\mathbf{r}) = \frac{e^2}{4\pi\varepsilon_0\varepsilon r}\,;\quad n(\mathbf{r},-\infty) = \mathrm{diag}(\,0\,,\,1\,)\,\delta(\mathbf{r})\,;\quad \left(\frac{\partial\,n_{ij}(\mathbf{r},t)}{\partial t}\right)_{\mathbf{deph}} = \begin{cases} 0 & \text{for } i=j \\ -\epsilon\,n_{ij}(\mathbf{r},t) & \text{for } i\neq j \end{cases},$$

up to the third order in the field for a four-wave-mixing (FWM) geometry for various conditions of the excitation. The pulses are assumed to have a Gaussian form, $E(t) = \bar{E}\,\frac{1}{\sqrt{2\pi\sigma^2}}\,e^{\frac{t^2}{2\sigma^2}}\,e^{-i\bar{\omega}t}$, and the second pulse is delayed by Δt.

For all explicit results, excitonic units are used (GaAs: $1\,\mathrm{Ry} = 7.4\,\mathrm{meV}\,;\ \hbar/\mathrm{Ry} = 120\,\mathrm{fs}$), and we assume a phenomenological homogeneous linewidth $\hbar\epsilon = \hbar/T_2 = 0.2\,\mathrm{Ry}$. Figure 1 shows the linear spectrum and the power spectra $|\tilde{E}(\omega)|^2$ of the laser pulse for different excitation conditions.

In Fig. 2 time integrated FWM signals $\int_{-\infty}^{+\infty} dt\,|P^{(3)}(t)|^2$ are plotted on a logarithmic scale versus time delay Δt for $\hbar\bar{\omega} = -1$, 0, and +1 Ry and $\sigma = 2.5\,\hbar/\mathrm{Ry}$ (dashed lines in Fig. 1). For excitation at the exciton, the signal is proportional to $\exp(-2\,\epsilon\,\Delta t)$ for $t \rightarrow +\infty$ and

$\exp(4\,\epsilon\,\Delta t)$ for $t \rightarrow -\infty$. The behavior for negative time delay is due to polarization interference [3]. In the continuum case, the signal shows a decay with $\exp(-4\,\epsilon\,\Delta t)$ for $t \rightarrow +\infty$ that indicates that the signal is delayed by $2\,\Delta t$.

In Fig. 3 the creation of a photon echo is demonstrated for excitation high in the continuum with $\hbar\omega = 7\,\mathrm{Ry}$, $\sigma = 0.5\,\hbar/\mathrm{Ry}$ (dotted line in Fig. 1), and $\Delta t = 4\hbar/\mathrm{Ry}$. The time-resolved signal $|P^{(3)}(t)|^2$ is plotted versus time t. A photon echo appears that has approximately a Gaussian shape and a maximum at $t = 2\,\Delta t - 4\,\epsilon\,\sigma^2$.

In conclusion, we have provided convincing theoretical evidence for a photon echo in a homogeneous broadened semiconductor excited in the absorption continuum.

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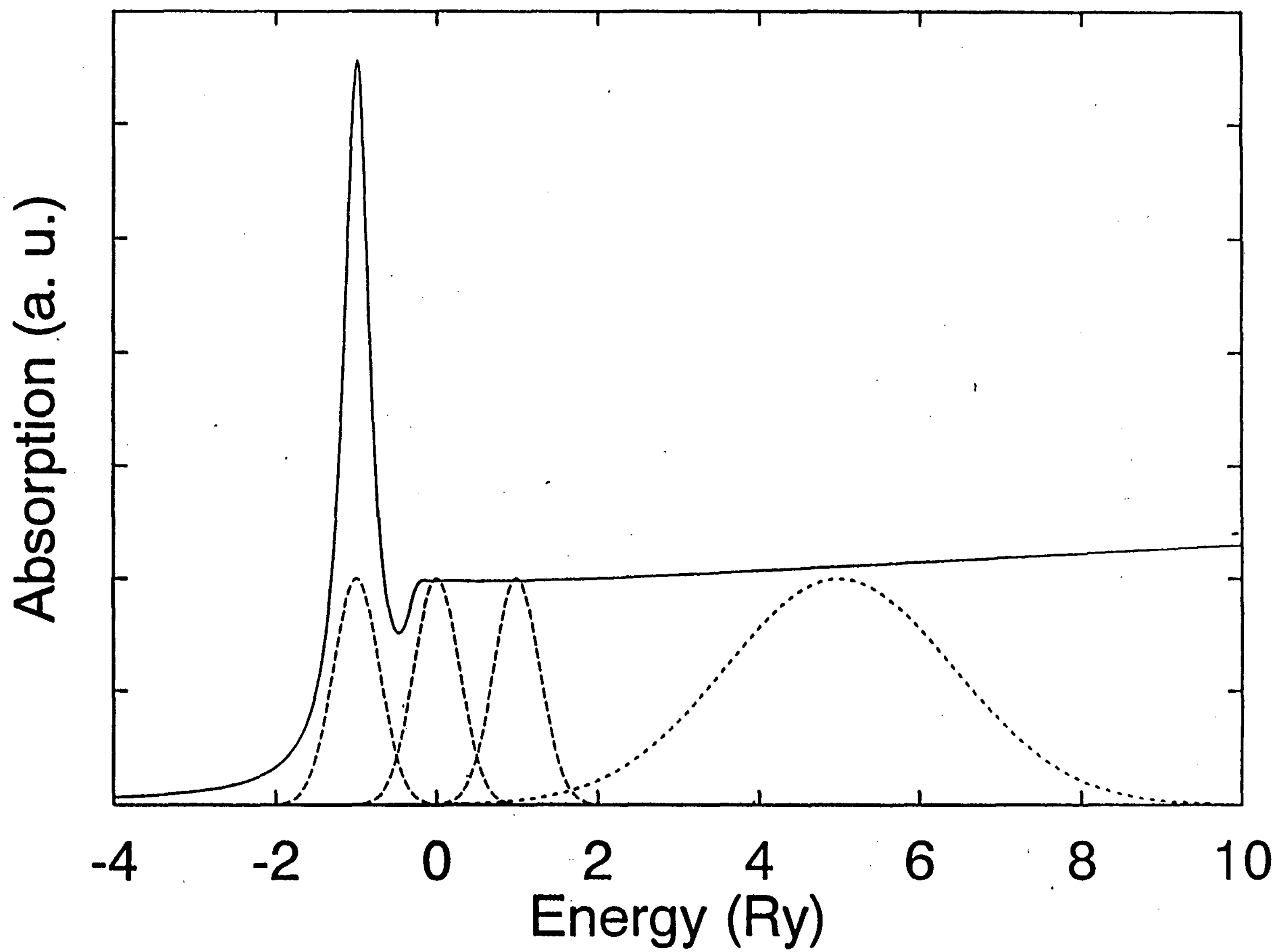
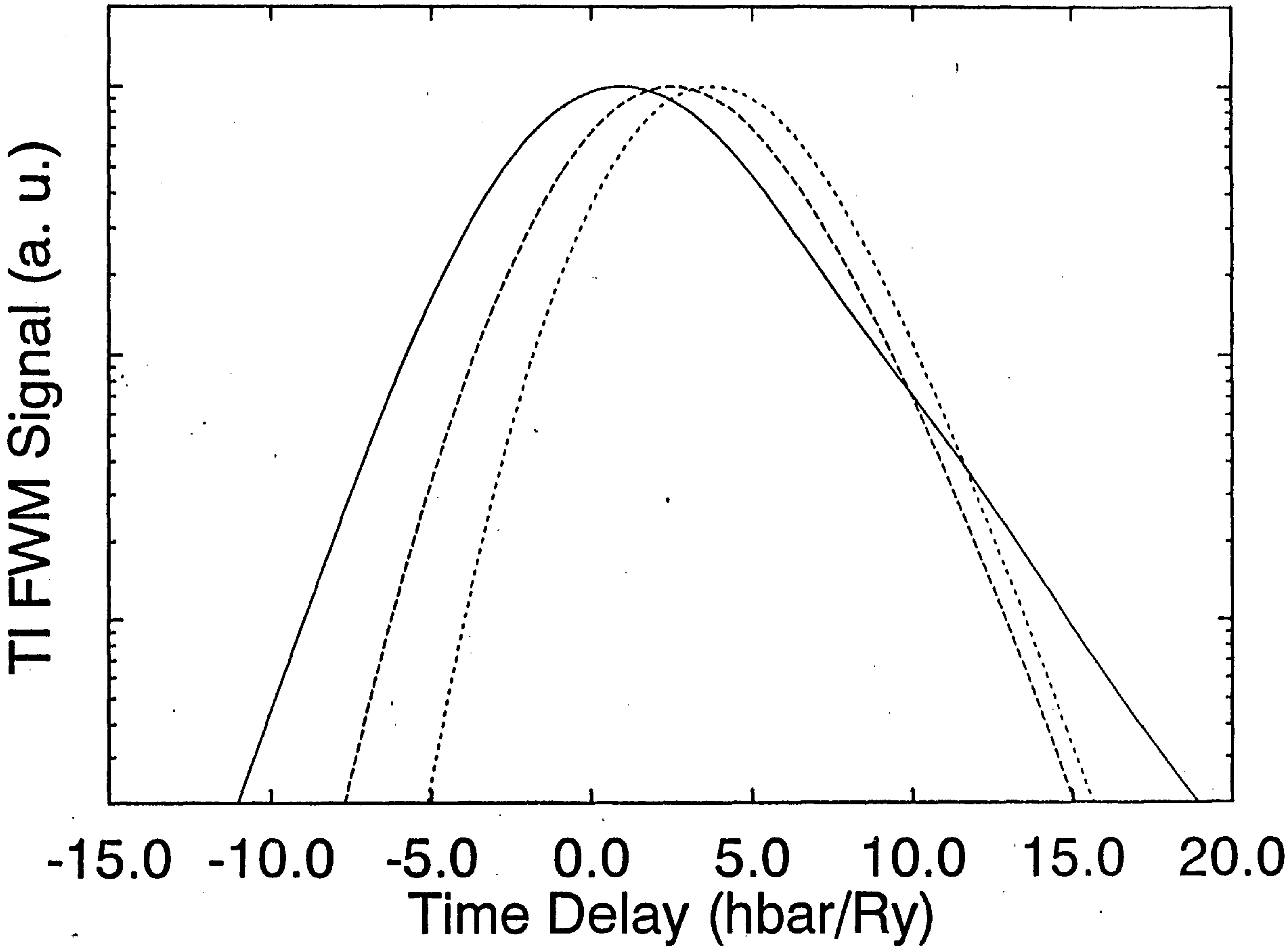
FIGURES

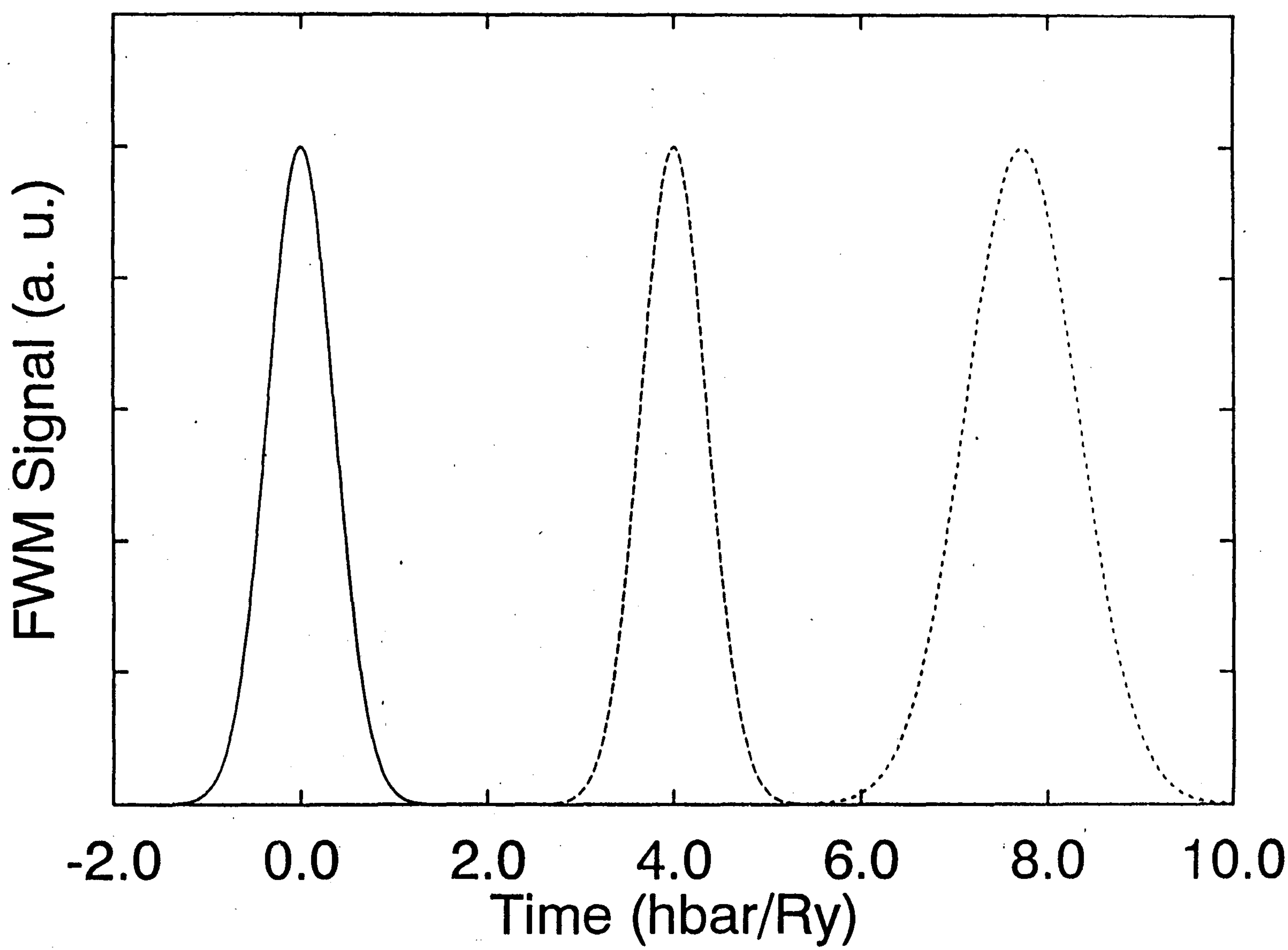
FIG.1: Absorption spectrum (solid line) and power spectra for different excitation conditions $\sigma = 2.5\,\hbar/\mathrm{Ry}$, $\hbar\omega = -1$, 0, and +1 Ry (dashed line); and $\sigma = 0.5\,\hbar/\mathrm{Ry}$, $\hbar\omega = +7\,\mathrm{Ry}$ (dotted line).

FIG.2: Time-integrated FWM signal on a logarithmic scale vs. time delay for $\sigma = 2.5\,\hbar/\mathrm{Ry}$ and $\hbar\omega = -1$ (solid line), 0 (dashed line), and +1 Ry (dotted line).

FIG.3: Intensities $|E_1(t)|^2$ (solid line), $|E_2(t)|^2$ (dashed line) and time-resolved FWM signal (dotted line) on a linear scale for $\sigma = 0.5\,\hbar/\mathrm{Ry}$, $\hbar\omega = +7\,\mathrm{Ry}$ and $\Delta t = 4\,\hbar/\mathrm{Ry}$.


Absorption (a. u.)
-4
-2
0
2
4
6
8
10
Energy (Ry)


TI FWM Signal (a. u.)
-15.0
-10.0
-5.0
0.0
5.0
10.0
15.0
20.0
Time Delay (hbar/Ry)


FWM Signal (a. u.)
-2.0
0.0
2.0
4.0
6.0
8.0
10.0
Time (hbar/Ry)

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