Photon-photon scattering in collisions of laser pulses

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  Heisenberg-Euler Lagrangian

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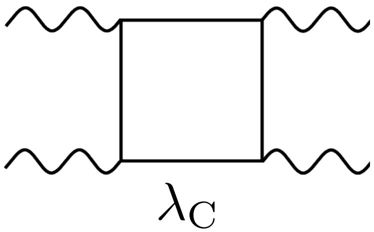
Vacuum Polarisation

Vacuum Polarisation



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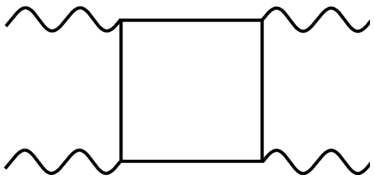

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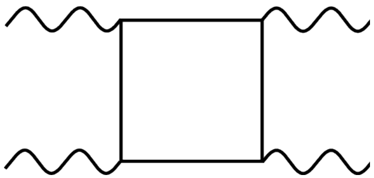

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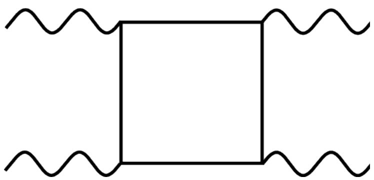

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D. Bernard (LPNHE) et al.
EPJD **10**, 141-145 (2000)

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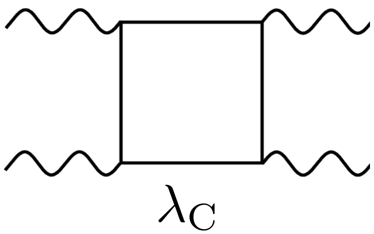

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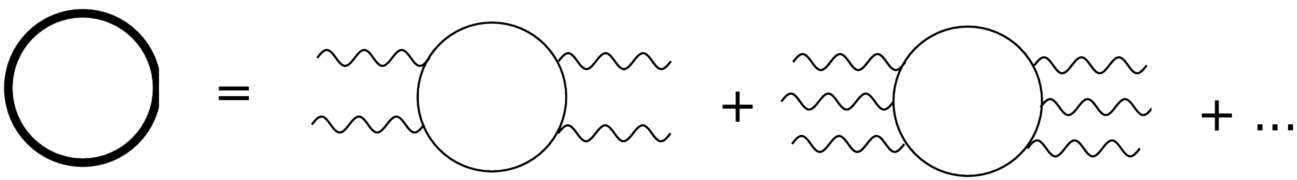

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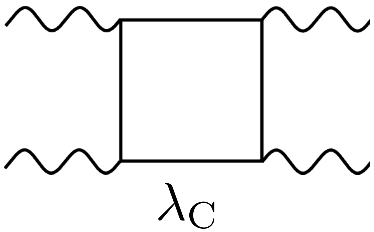

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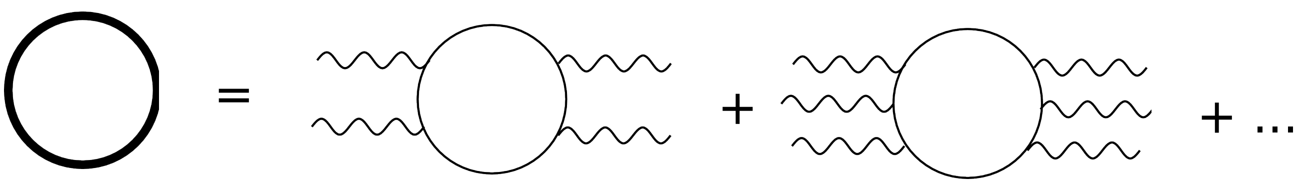

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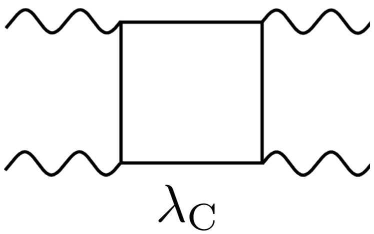

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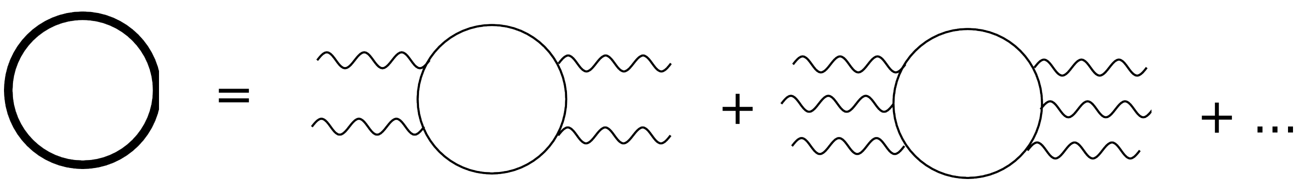

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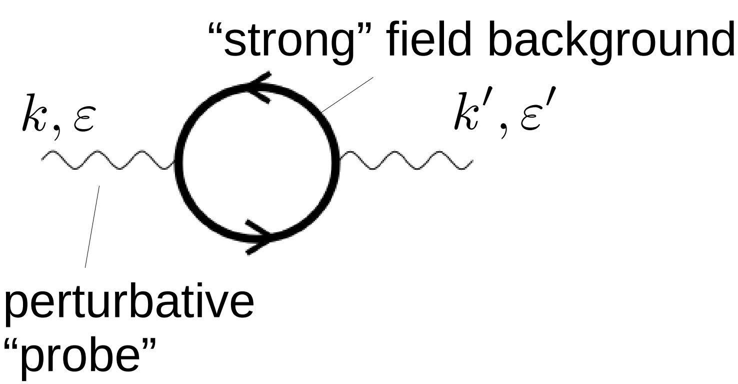

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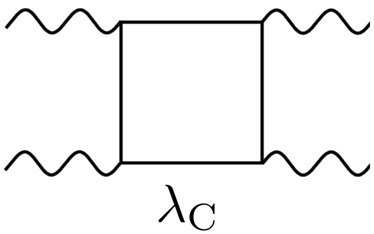

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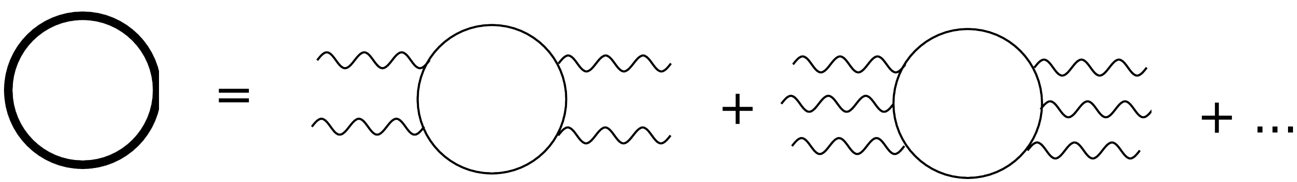

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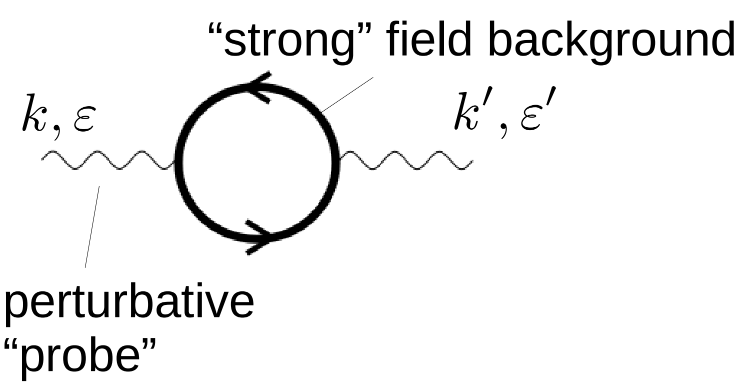

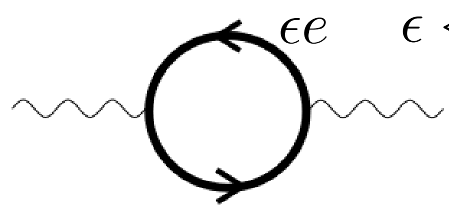

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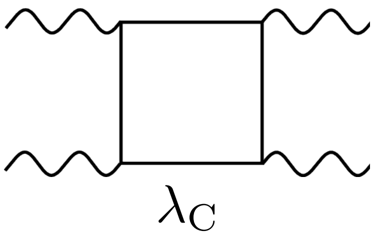

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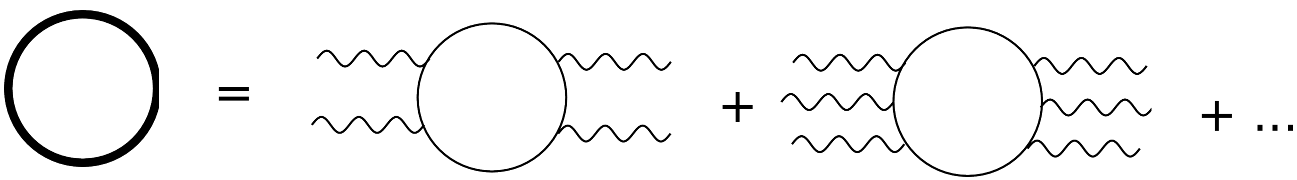

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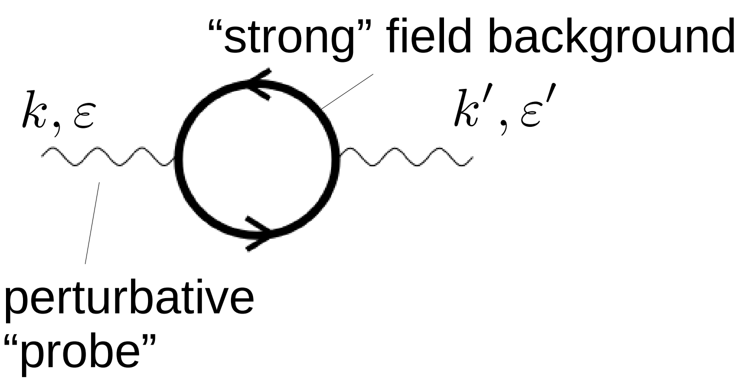

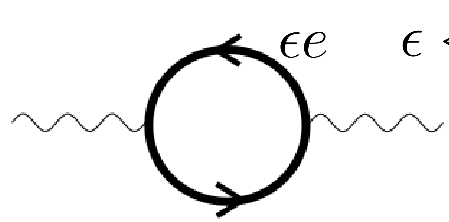

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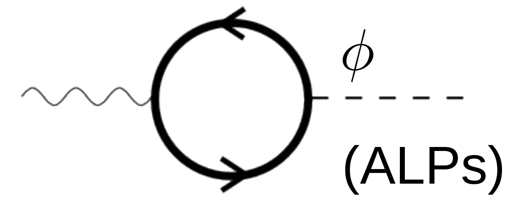
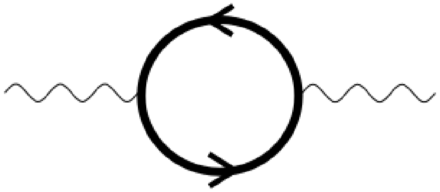


Photon-photon scattering

$\hbar\omega \ll mc^2 \qquad (\lambda \ll \lambda_C)$

$\hat{A} \to A$



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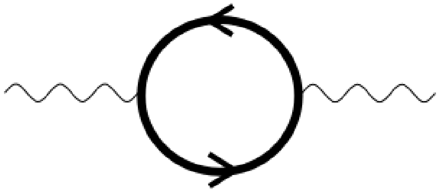

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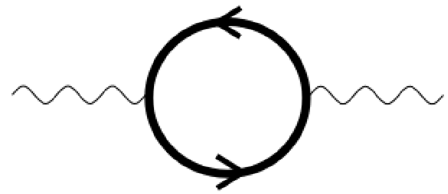

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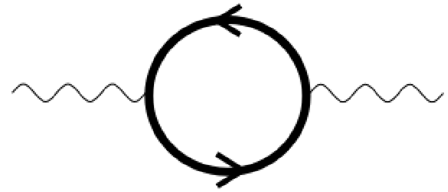

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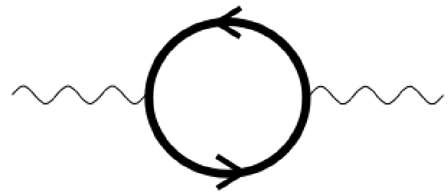

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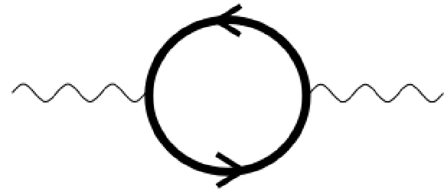

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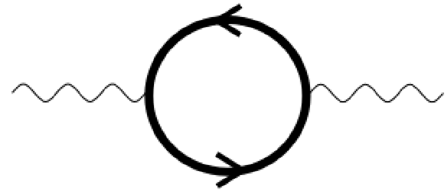

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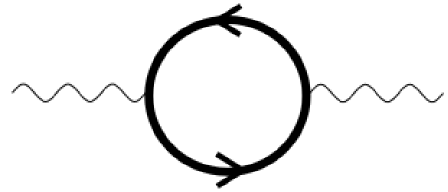

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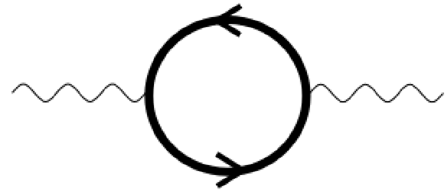

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Vacuum birefringence

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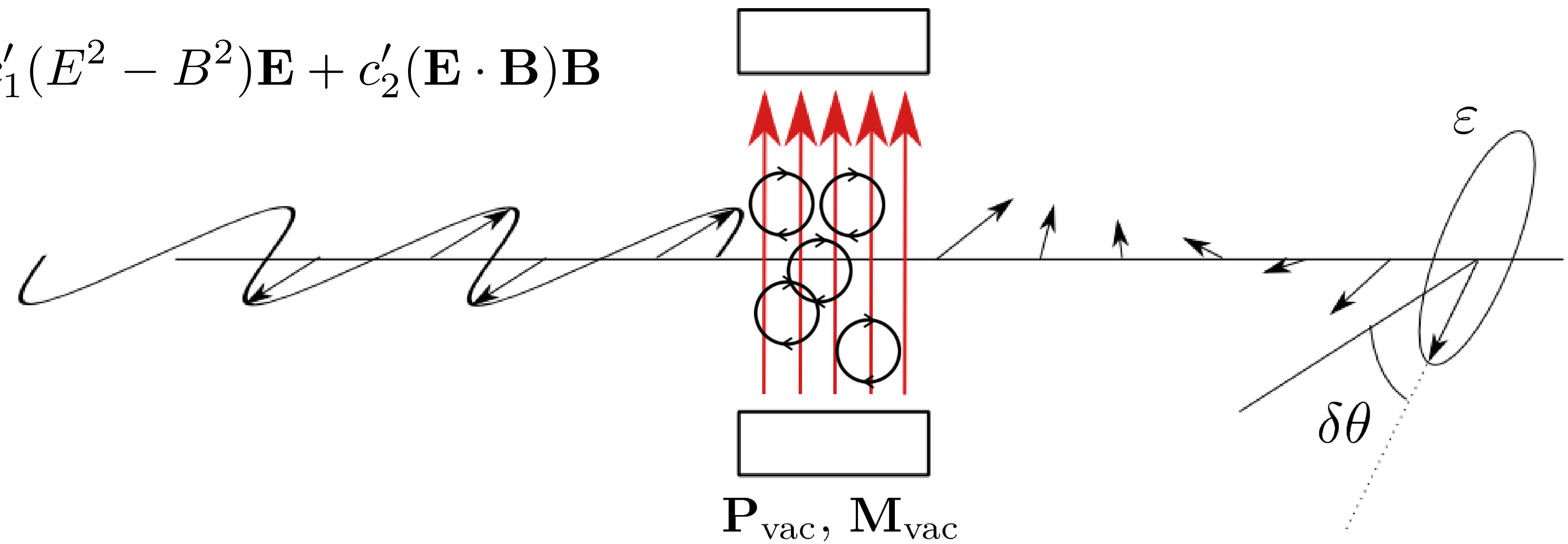

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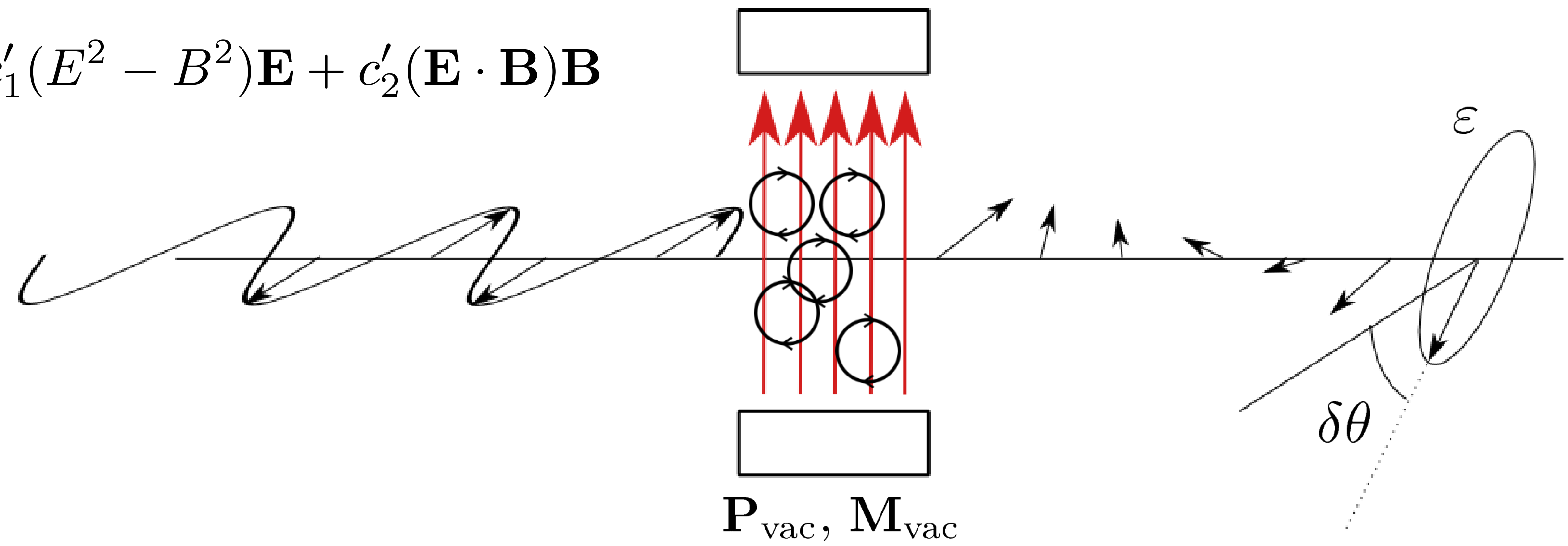

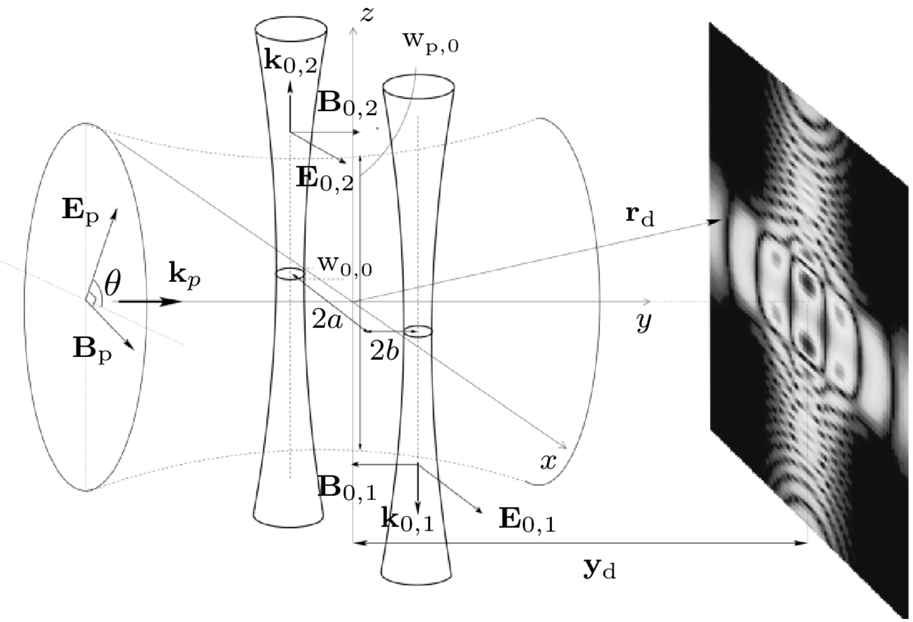

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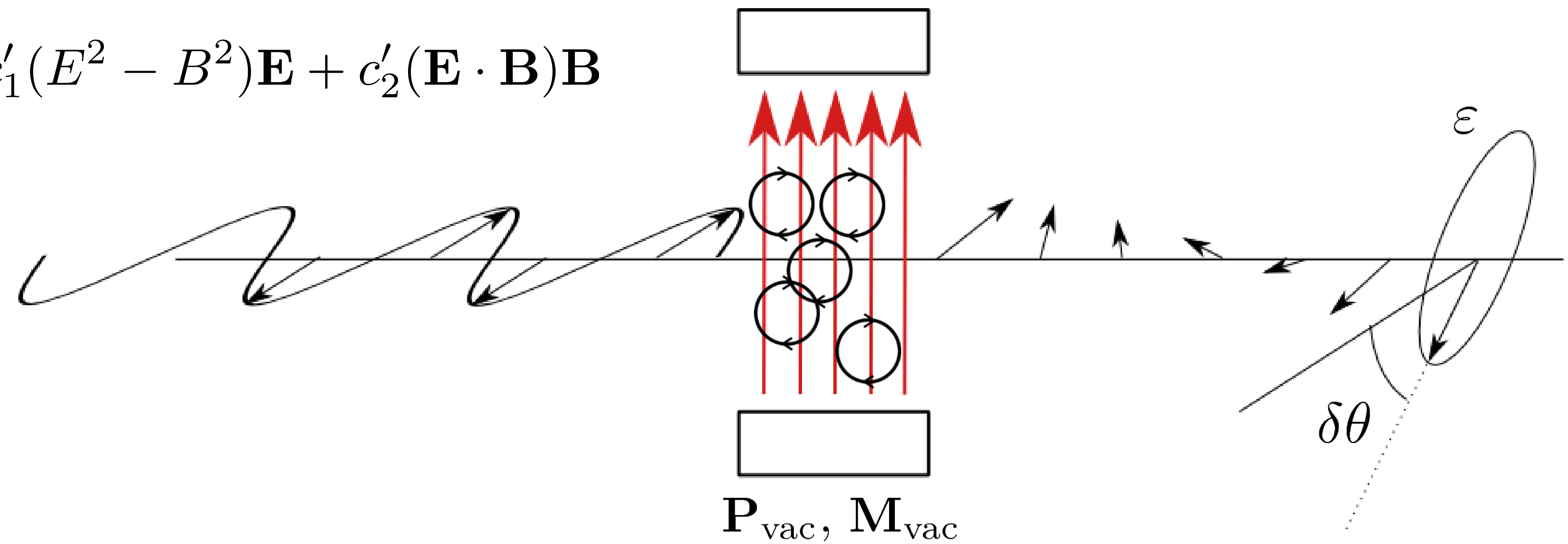

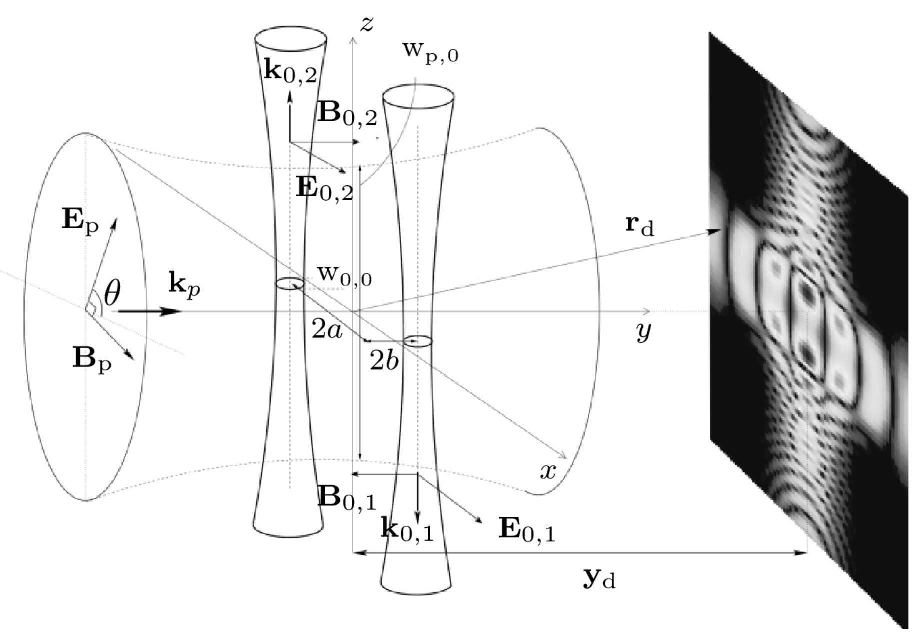

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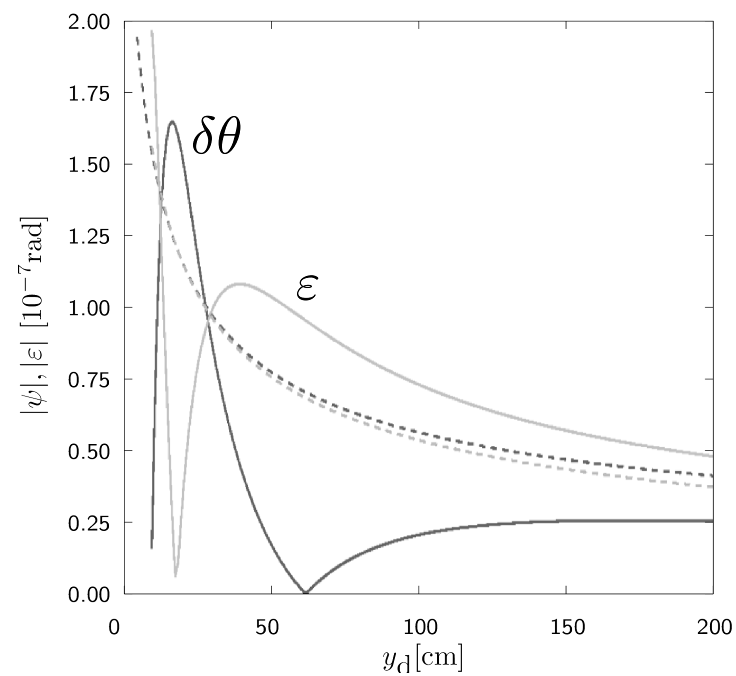
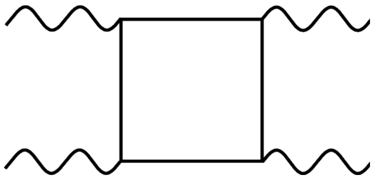


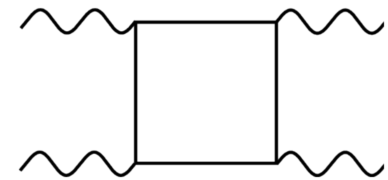
BK, A. Di Piazza and C. H. Keitel, PRA **82**, 032114 (2010)

Photon-photon scattering



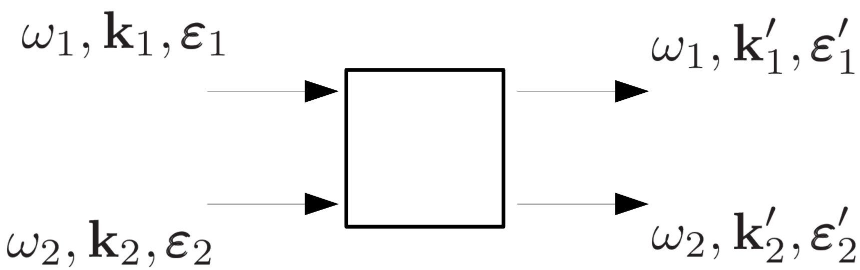
R. Karplus and M. Neuman
Phys. Rev. **80** 380-385 (1950)

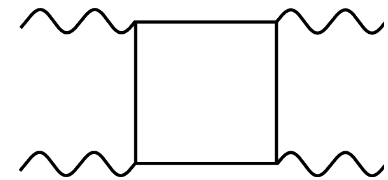
Photon-photon scattering



R. Karplus and M. Neuman
Phys. Rev. **80** 380-385 (1950)

Elastic photon-photon scattering





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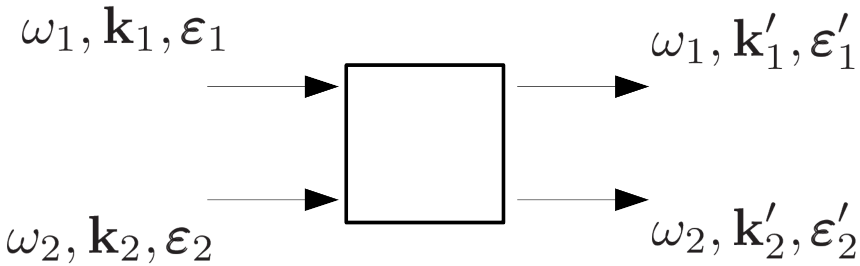
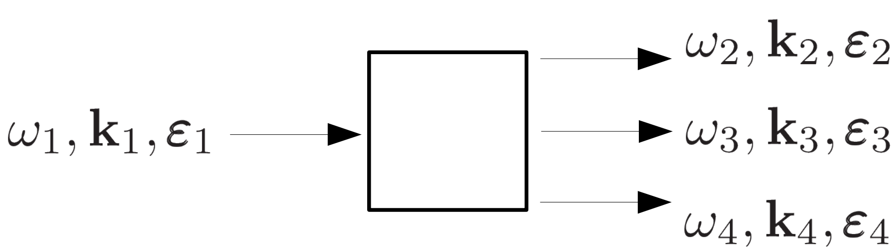
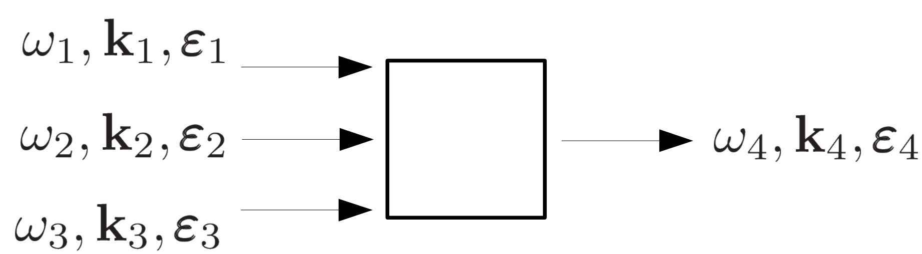
Elastic photon-photon scattering



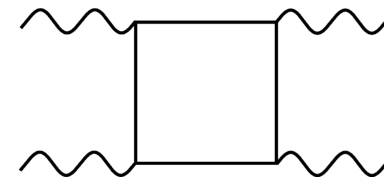
Inelastic photon-photon scattering

(four-wave mixing)





Photon-photon scattering



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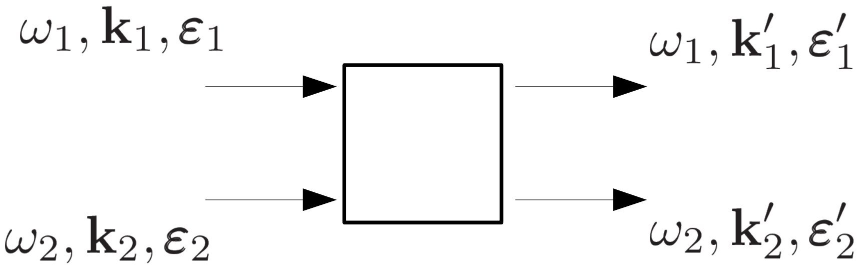
Elastic photon-photon scattering



Inelastic photon-photon scattering

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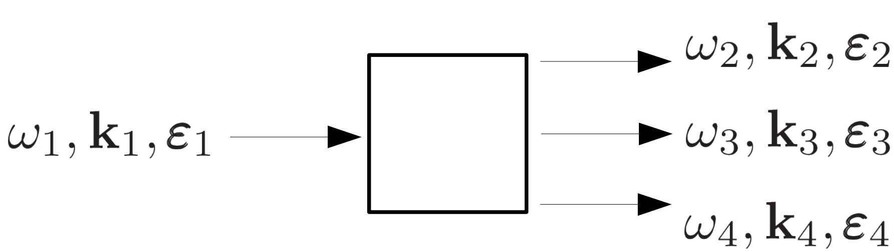
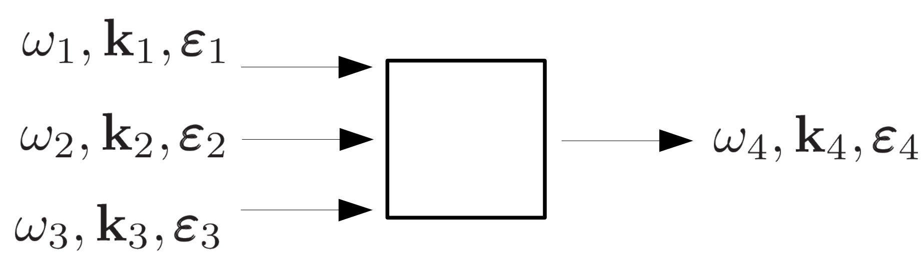
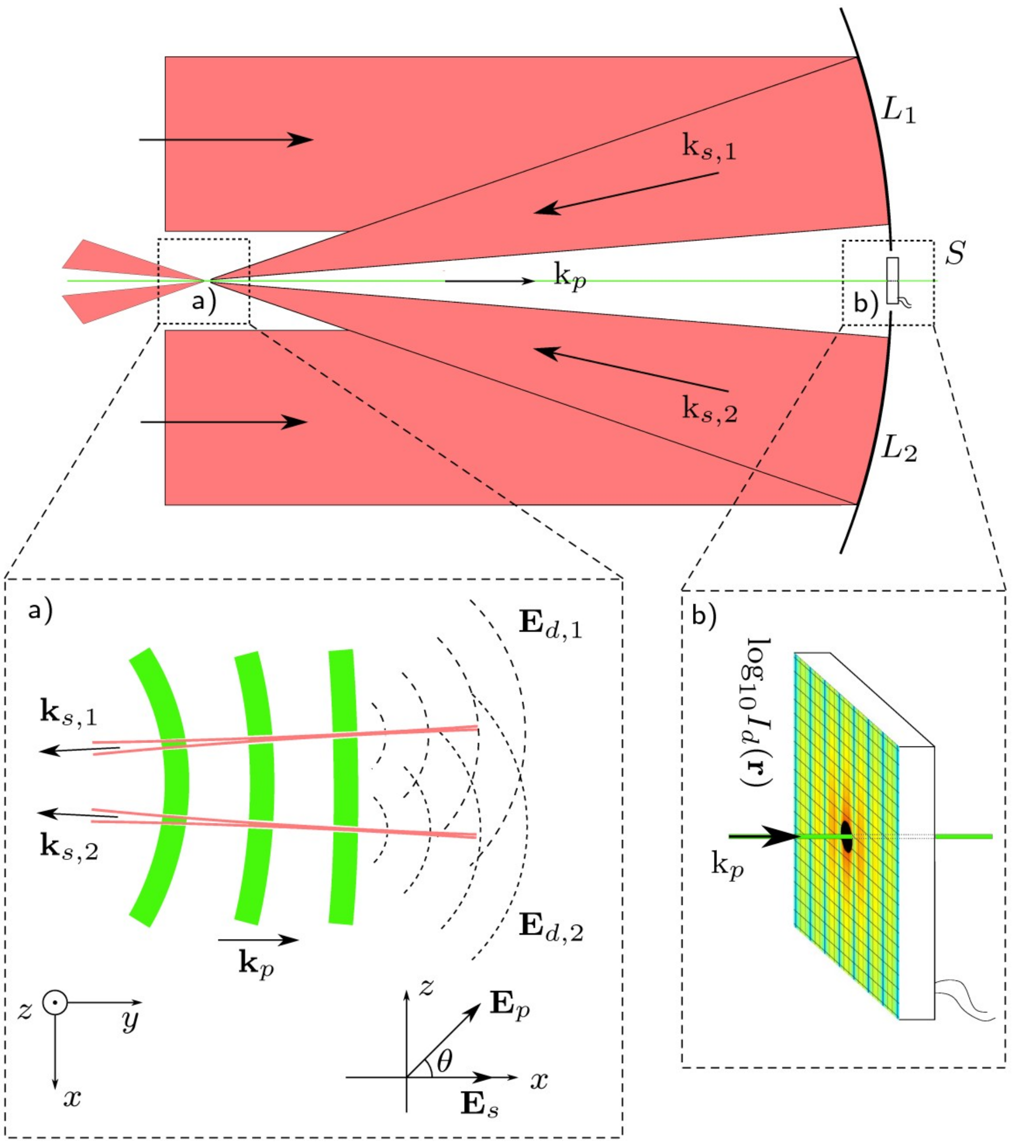
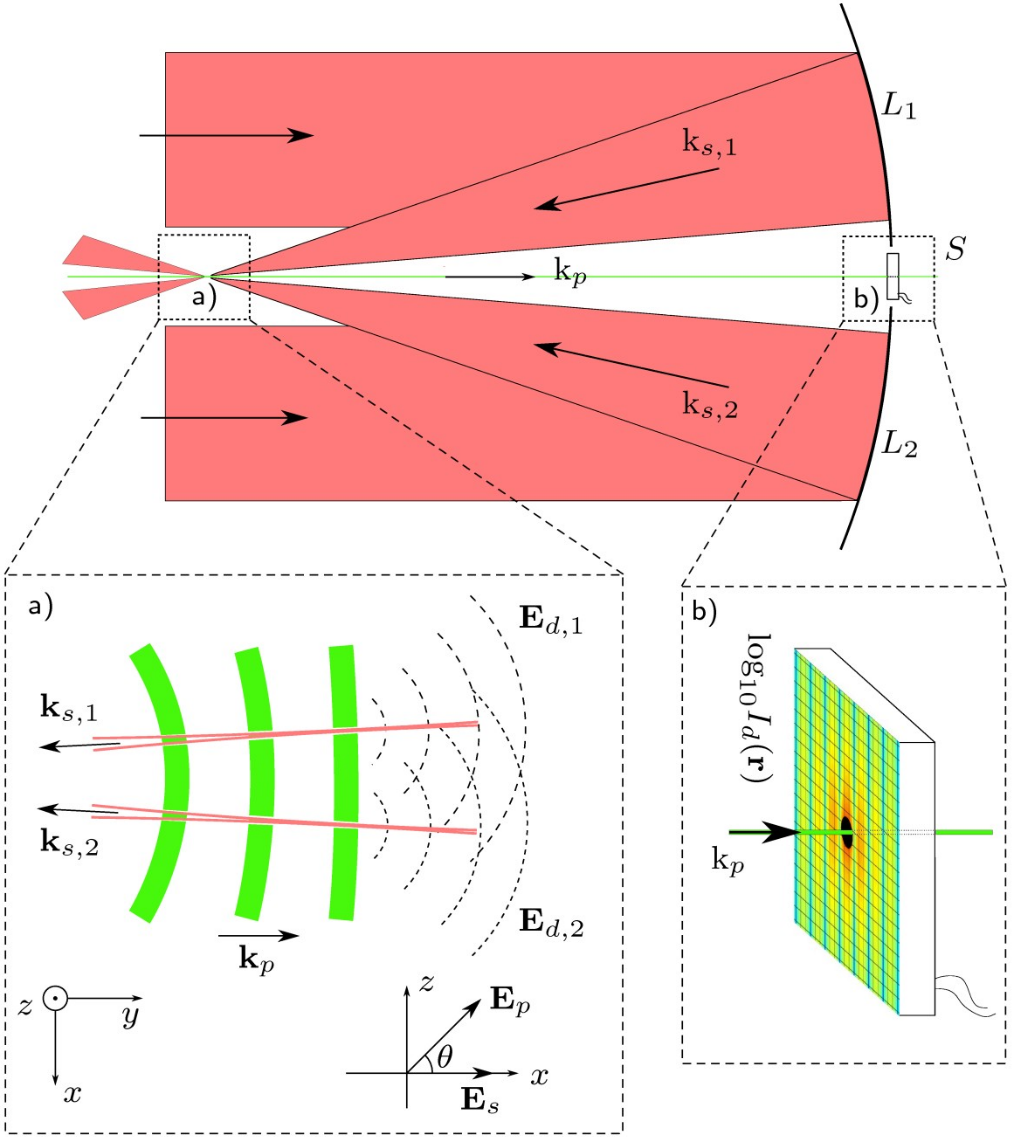




$$k_1^\mu + k_2^\mu + k_3^\mu + k_4^\mu = 0$$

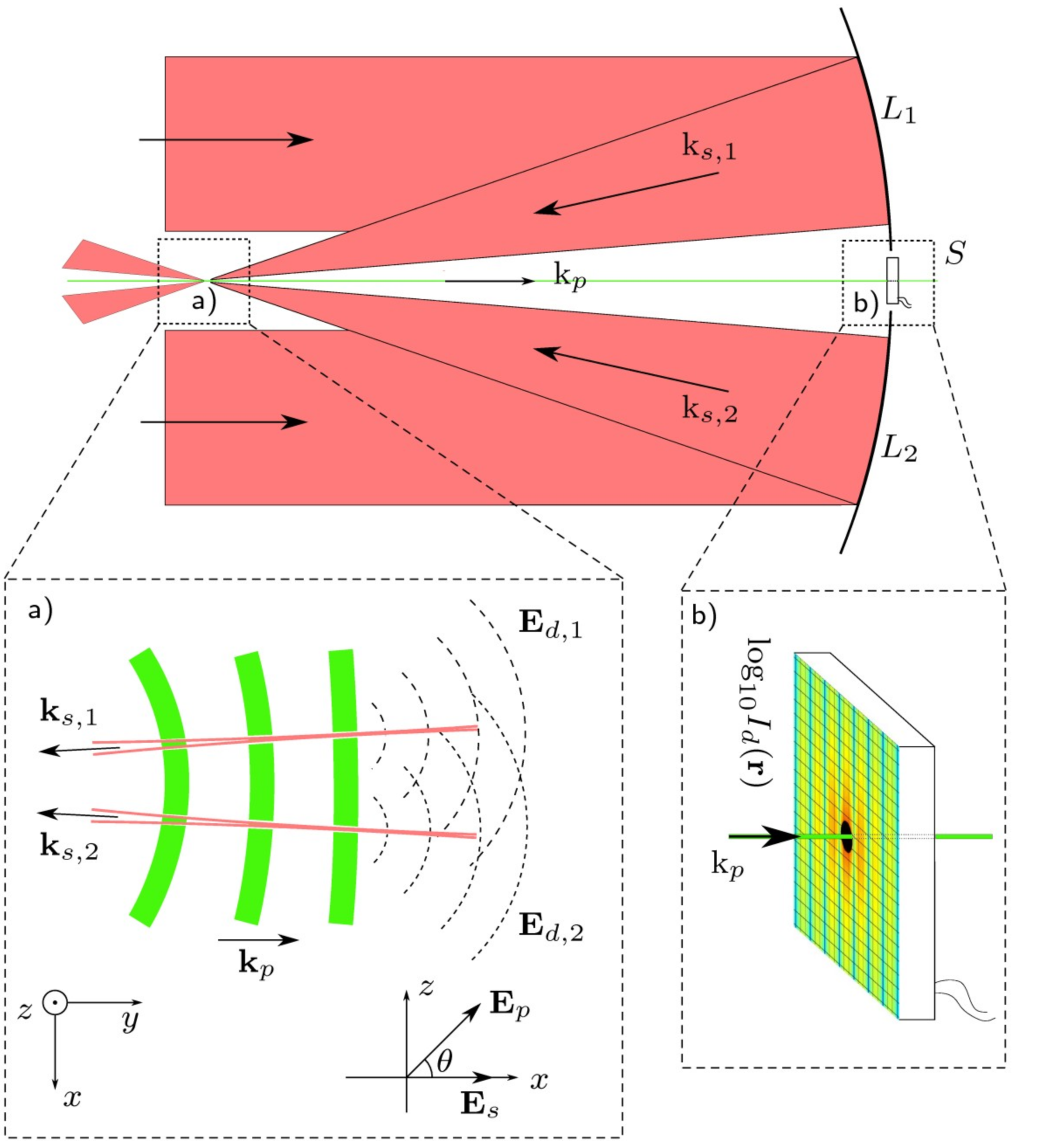

L_1
k_{s,1}
S
k_p
a)
b)
k_{s,2}
L_2
a)
E_{d,1}
k_{s,1}
k_{s,2}
E_{d,2}
k_p
z
y
x
z
E_p
θ
x
E_s
b)
log_{10} I_d(r)
k_p

- Strong laser: $150\,\mathrm{PW}, 800\,\mathrm{nm}, 30\,\mathrm{fs}$
  diffraction limited



Elastic photon-photon scattering

- Strong laser: $150\,\mathrm{PW}, 800\,\mathrm{nm}, 30\,\mathrm{fs}$
  diffraction limited
- Probe laser: $200\,\mathrm{TW}, 527\,\mathrm{nm}, 100\,\mathrm{fs}$
  focused to $300\,\mu\mathrm{m}$



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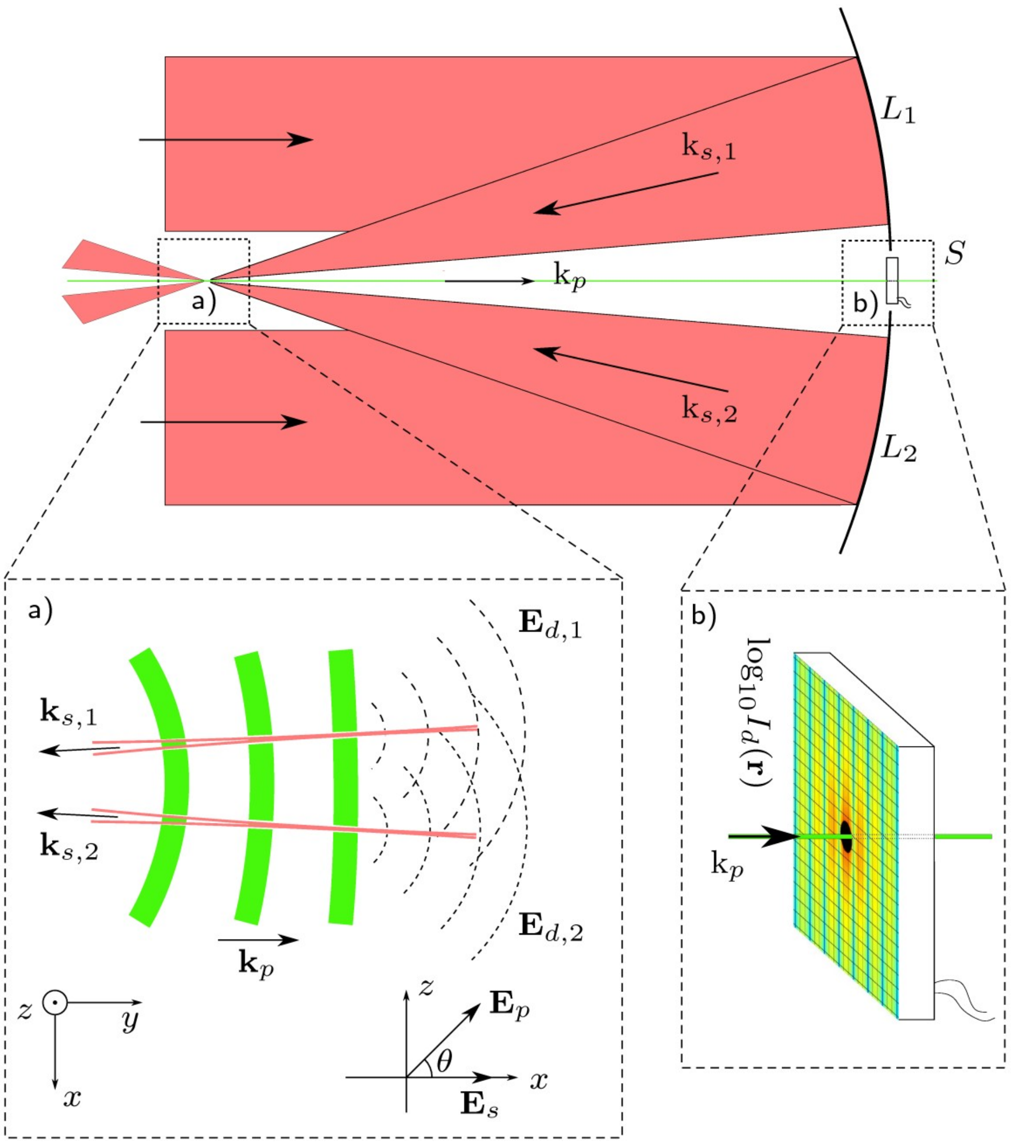
- Gaussian beams: 1st-order space, monochromatic



Elastic photon-photon scattering

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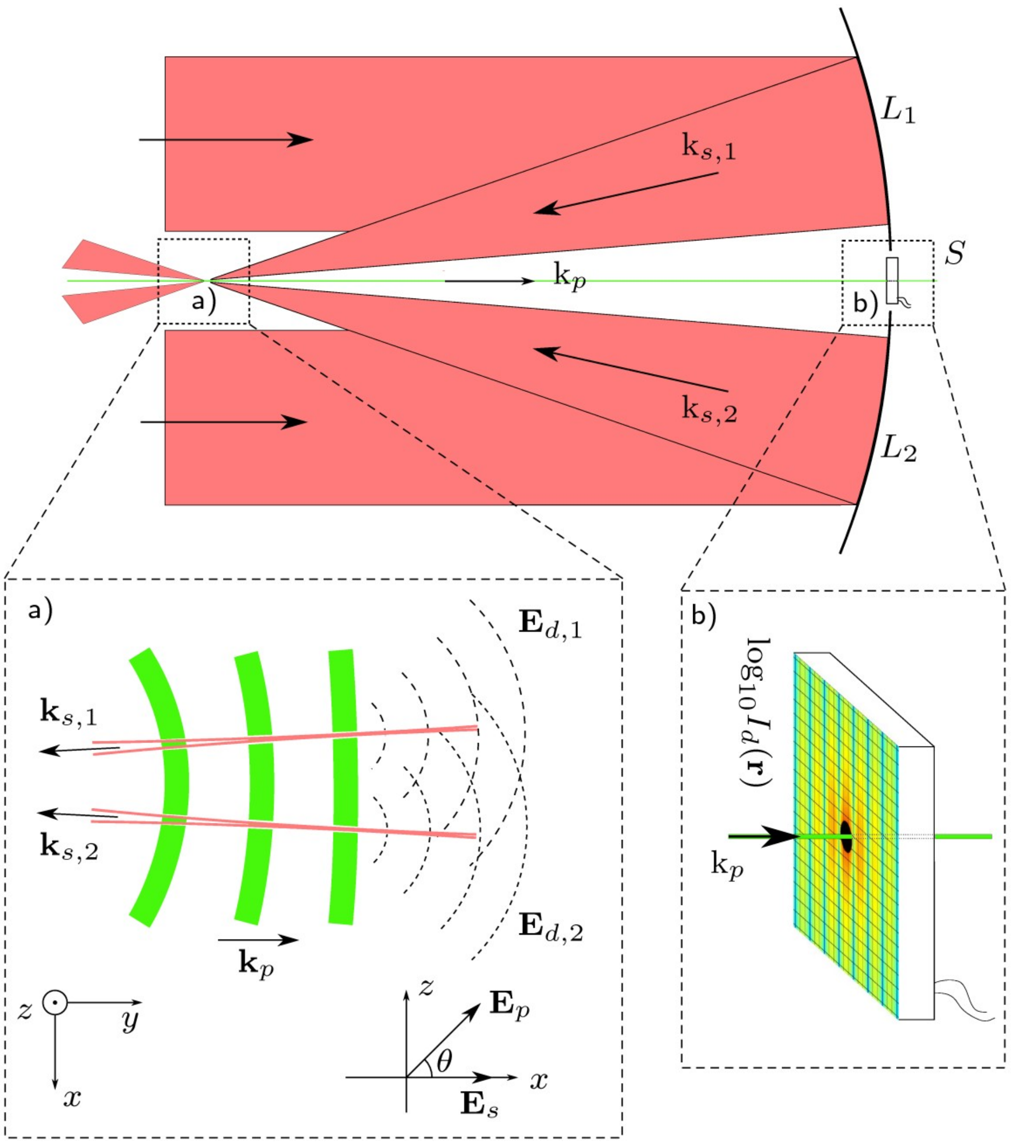

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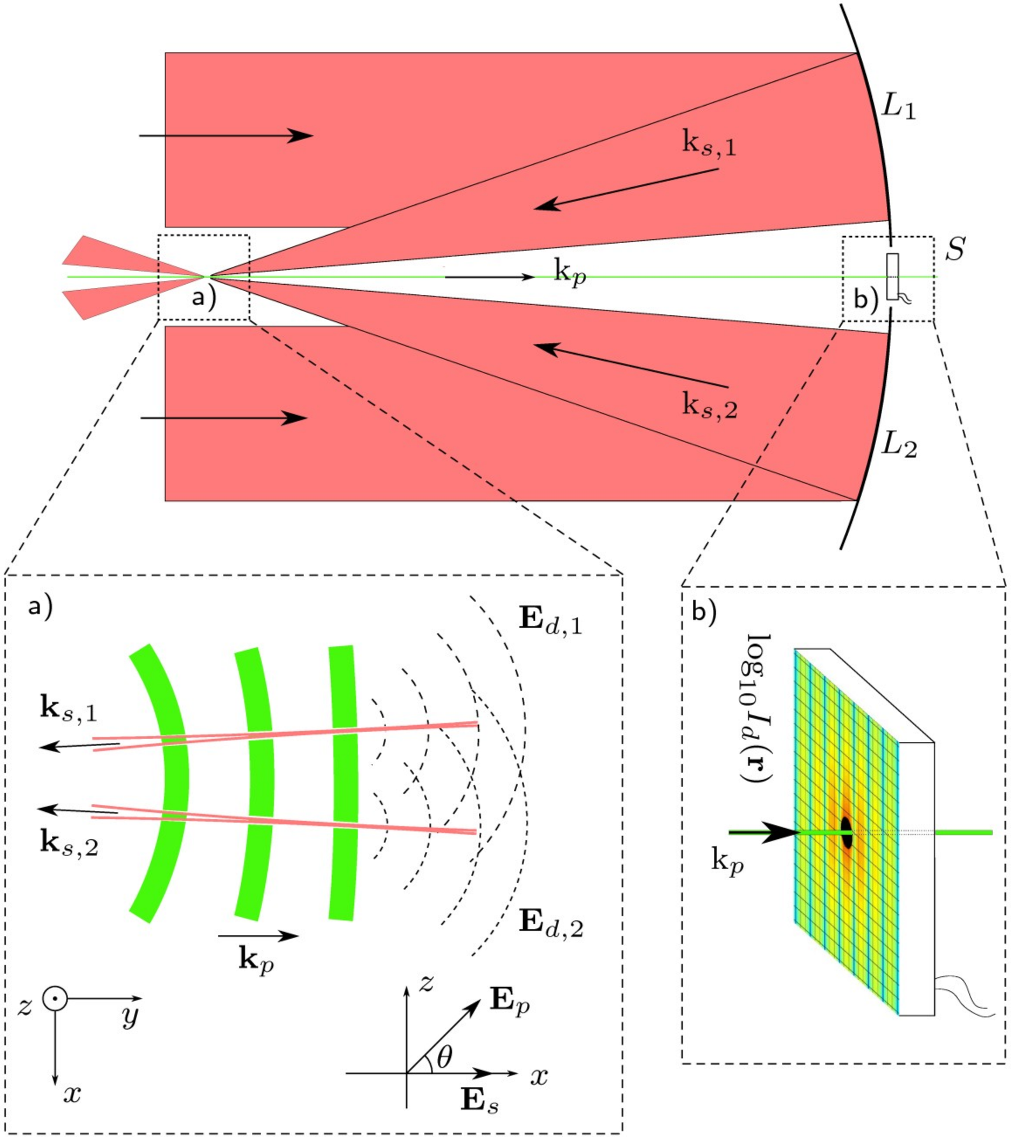
- Probe laser: $200\,\mathrm{TW}, 527\,\mathrm{nm}, 100\,\mathrm{fs}$
  focused to $300\,\mu\mathrm{m}$
- Gaussian beams: 1st-order space,
  monochromatic
- Parallel geometry
- Required vacuum pressure
  at room temperature: $P \leq 10^{-6}\,\mathrm{torr}$



$$\frac{1}{2}\langle|\mathbf{E}_p + \mathbf{E}_d|^2\rangle = I_p + I_{pd} + I_d$$

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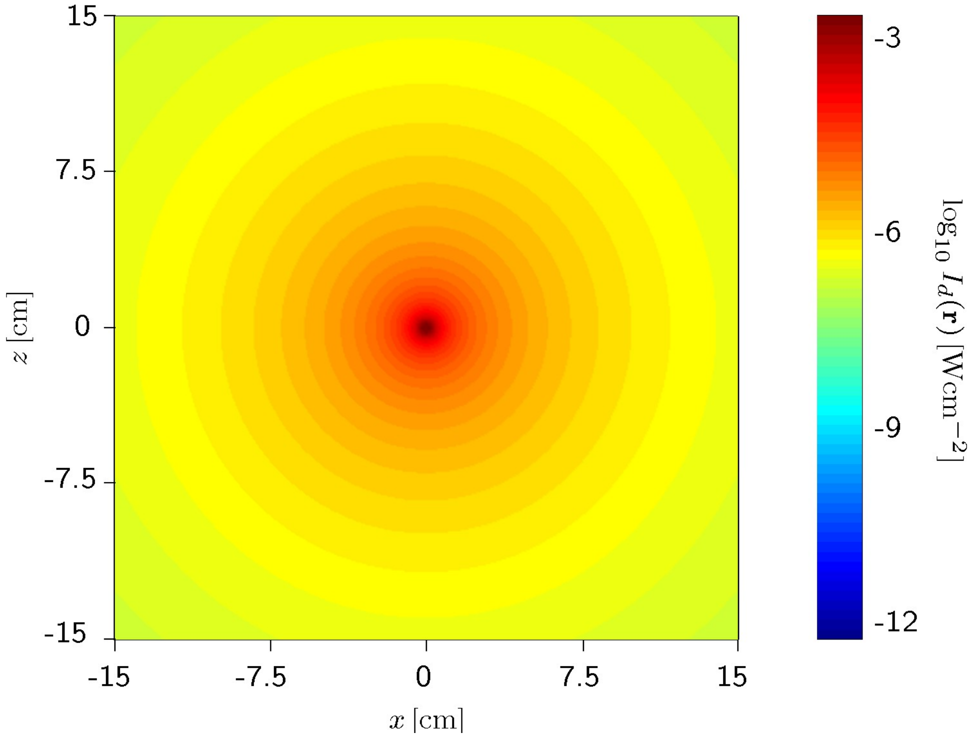

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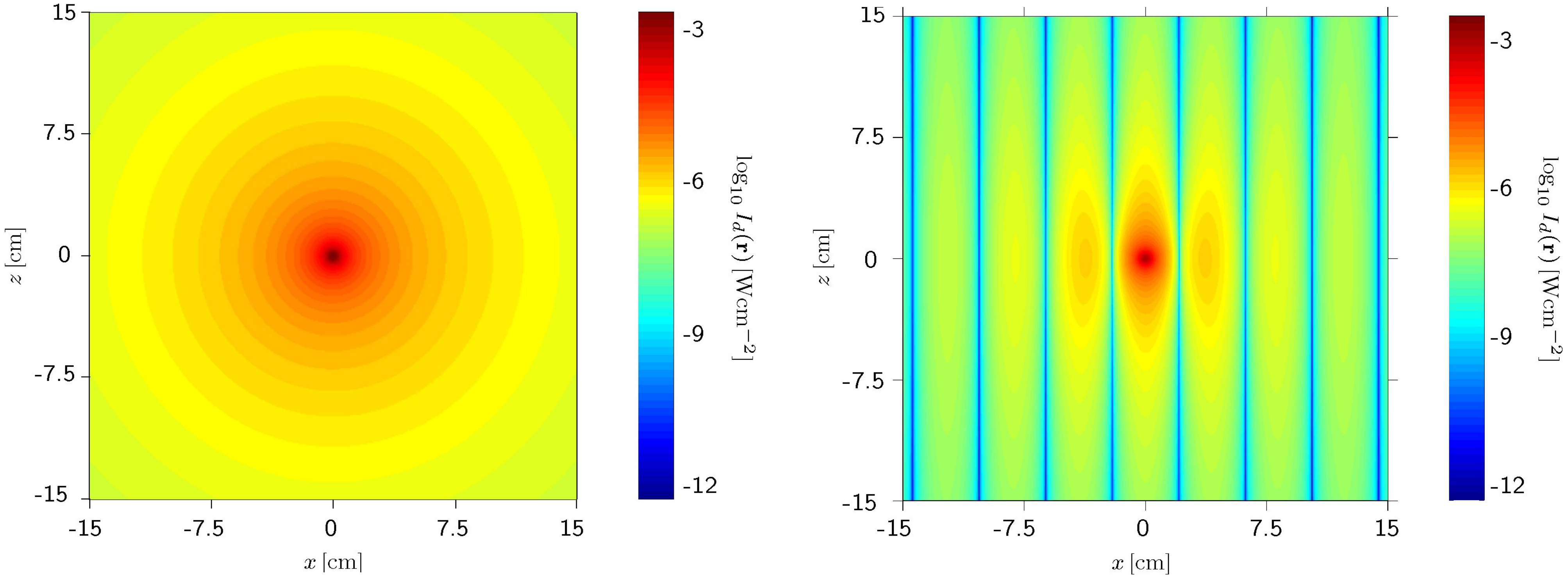
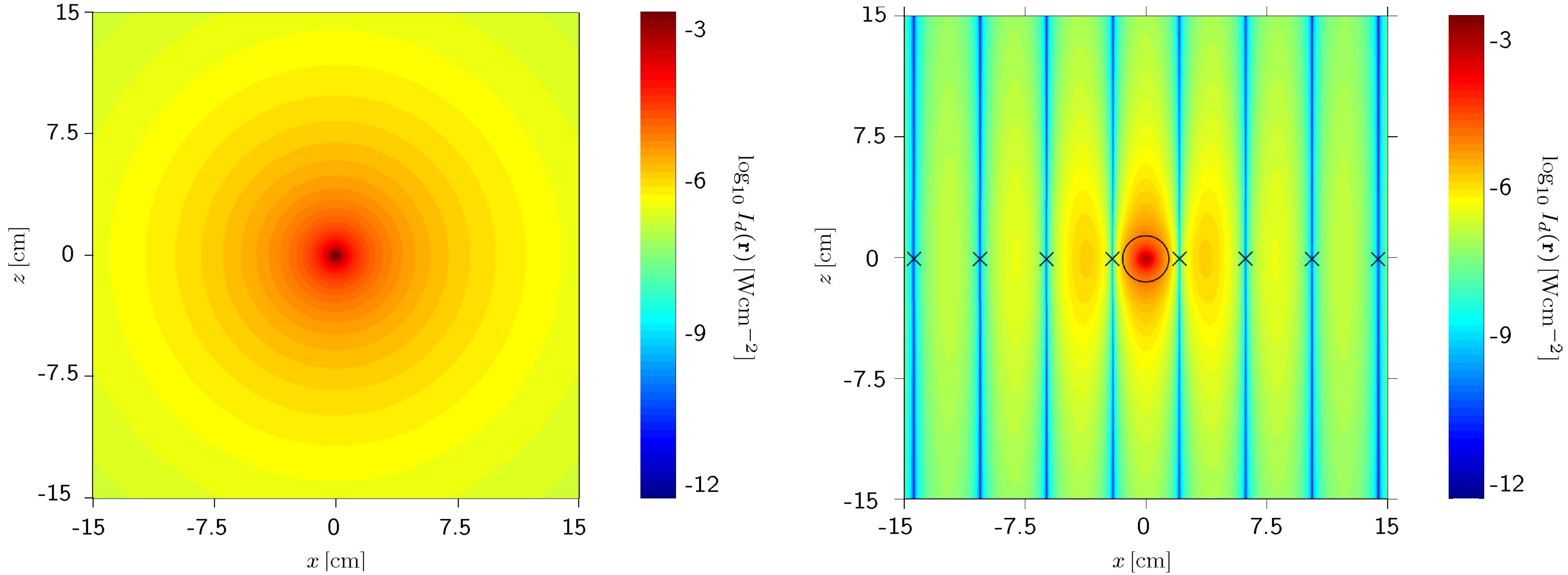
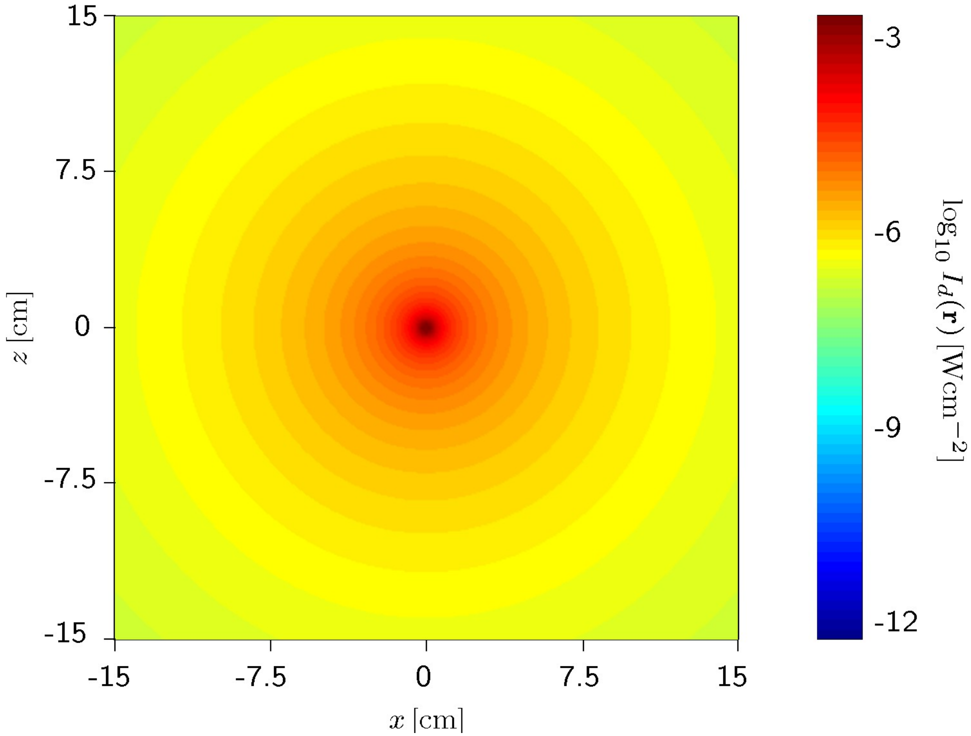


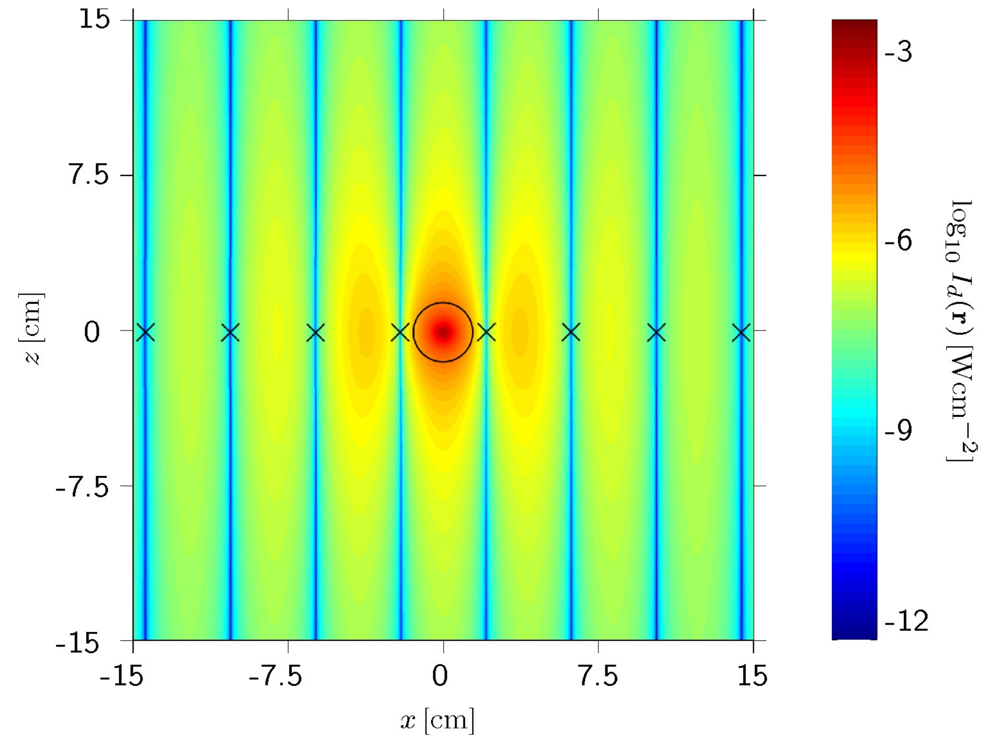
$$\frac{1}{2}\langle|\mathbf{E}_p + \mathbf{E}_d|^2\rangle = I_p + I_{pd} + I_d$$



- Double-slit minima: $(m + 1/2)\lambda_p = D \sin\theta$

$$\frac{1}{2}\langle|\mathbf{E}_p + \mathbf{E}_d|^2\rangle = I_p + I_{pd} + I_d$$





- Double-slit minima: $(m + 1/2)\lambda_p = D \sin\theta$
- "Detectable" vacuum signal: $I_d > 100(I_p + I_{pd})$

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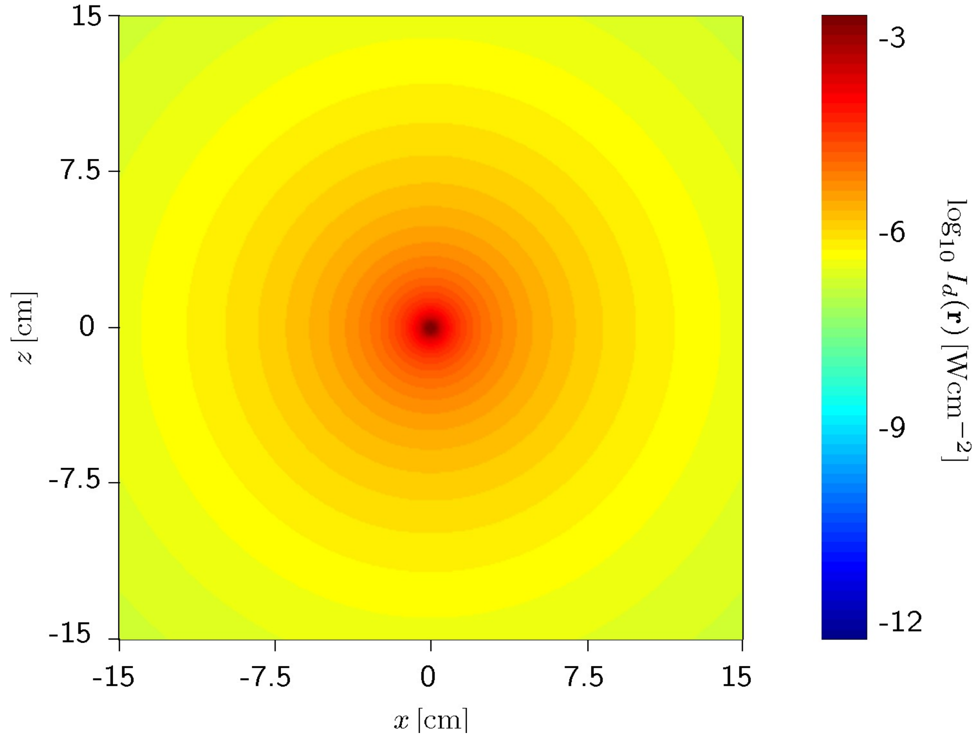
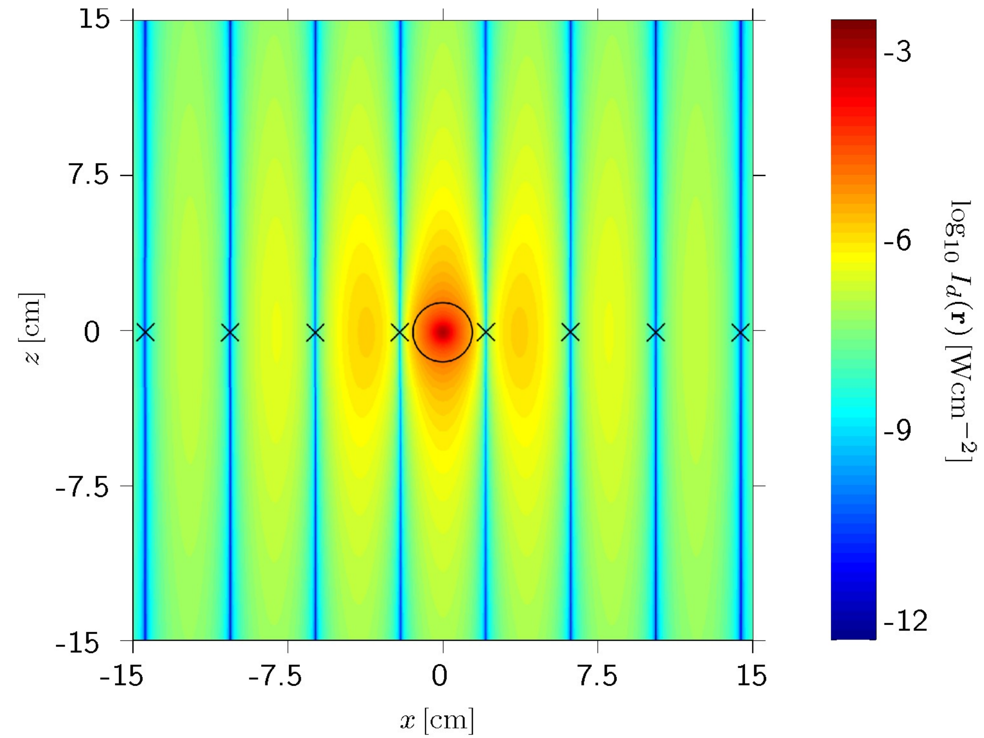


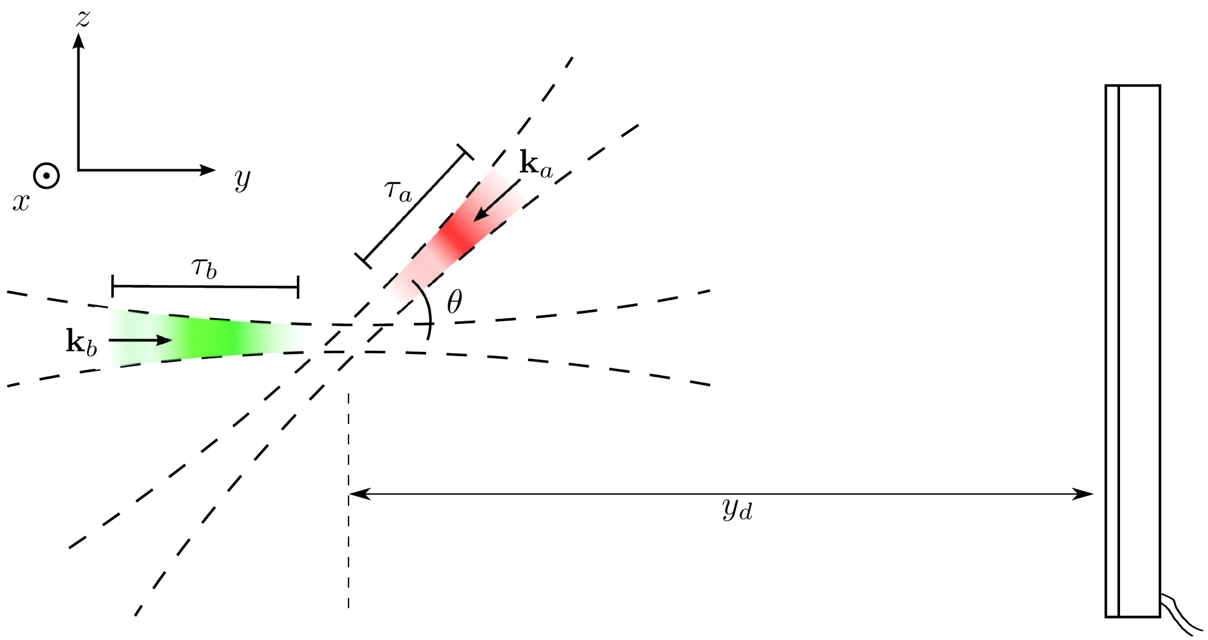


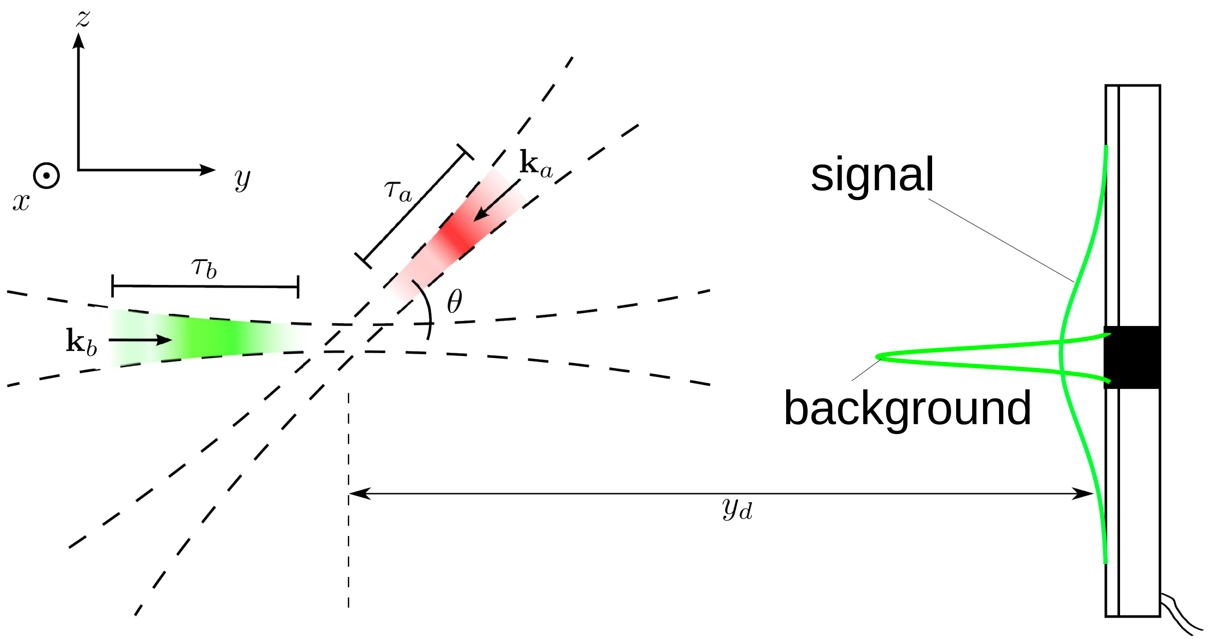
- Double-slit minima: $(m + 1/2)\lambda_p = D \sin\theta$
- “Detectable” vacuum signal: $I_d > 100(I_p + I_{pd})$
- ~ 40 / 4 diffracted photons per shot

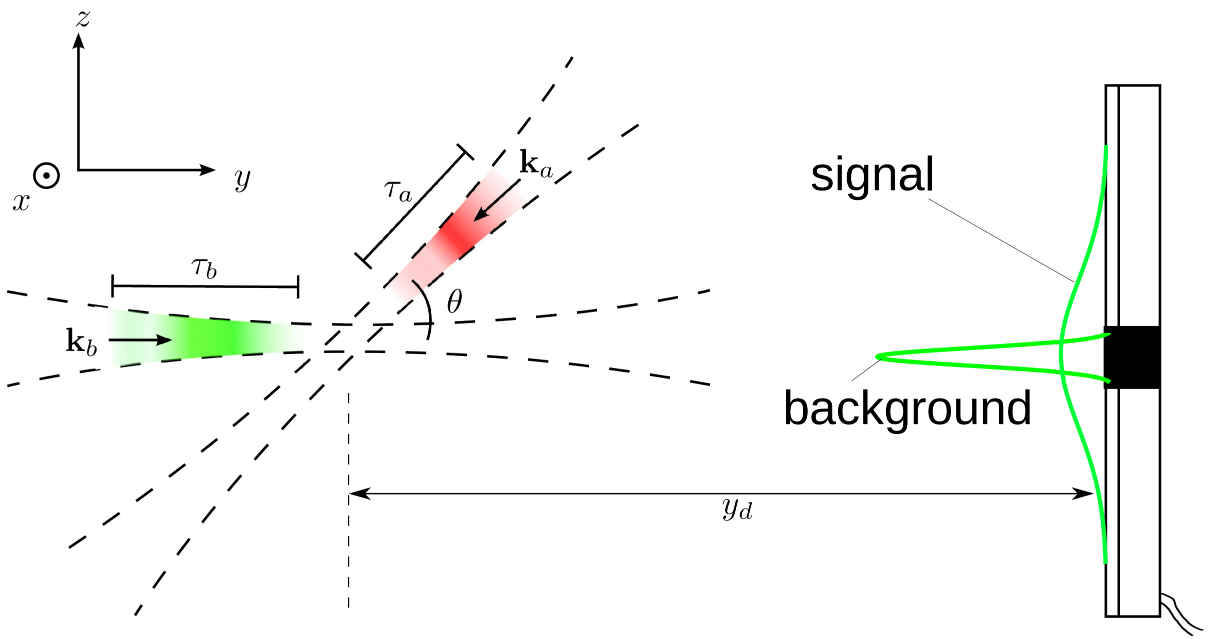
BK, A. Di Piazza and C. H. Keitel, Nature Photon. **4**, 92 (2010)

Photon-photon scattering scenario

Photon-photon scattering scenario




z
y
x
τ_a
$\mathbf{k}_a$
τ_b
$\mathbf{k}_b$
θ
y_d
signal
background



$$\mathbf{E}_b = \boldsymbol{\varepsilon}_b E_b f(x, y, z, t, \mathrm{w}_b, \omega_b) g(t - y)$$

$$\mathbf{E}_a = \boldsymbol{\varepsilon}_a E_a f(\tilde{x} - \tilde{x}_0, \tilde{y}, \tilde{z} - \tilde{z}_0, t - \Delta t, \mathrm{w}_a, \omega_a) g(t - \Delta t + \tilde{y})$$

Elastic scattering

Vulcan laser parameters:

$$\lambda_a = \lambda_b = 0.91\,\mu\mathrm{m}$$

$$\tau_a = \tau_b = 30\,\mathrm{fs}$$

$$P_a = P_b = 5\,\mathrm{PW}$$

$$w_a = 0.91\,\mu\mathrm{m}$$

$$w_b = 100\,\mu\mathrm{m}$$

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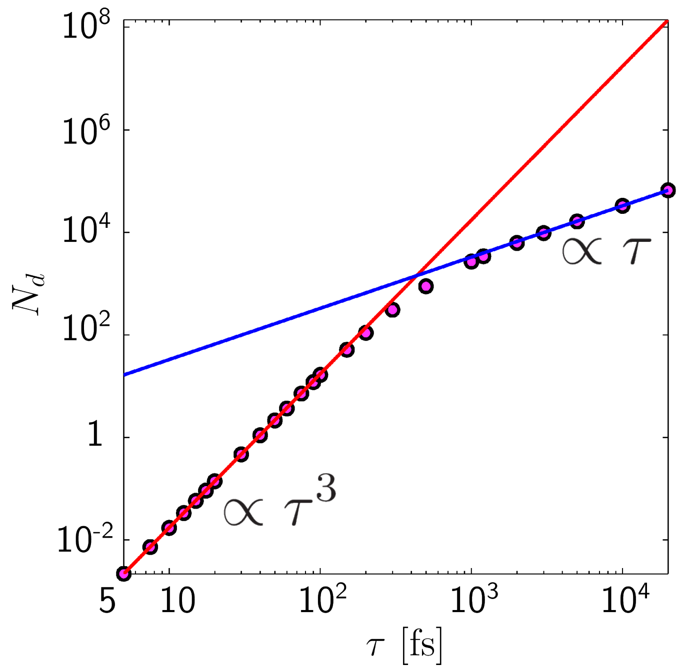

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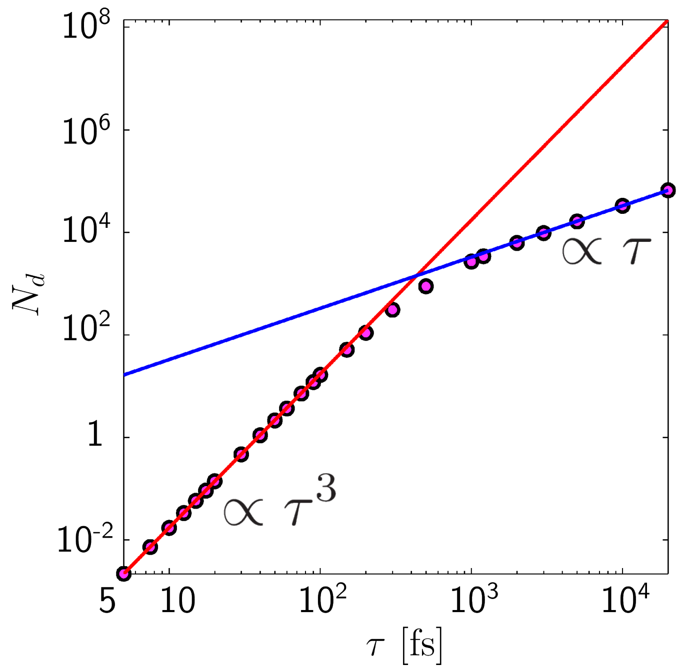

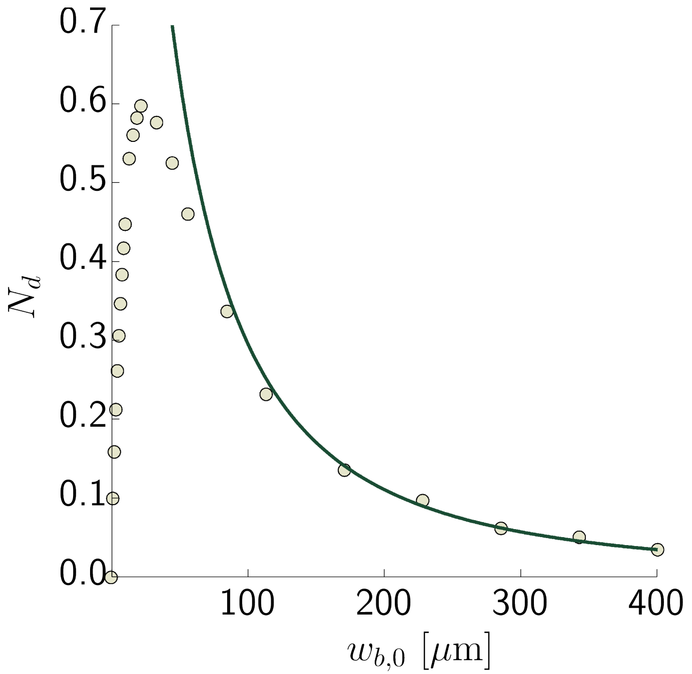

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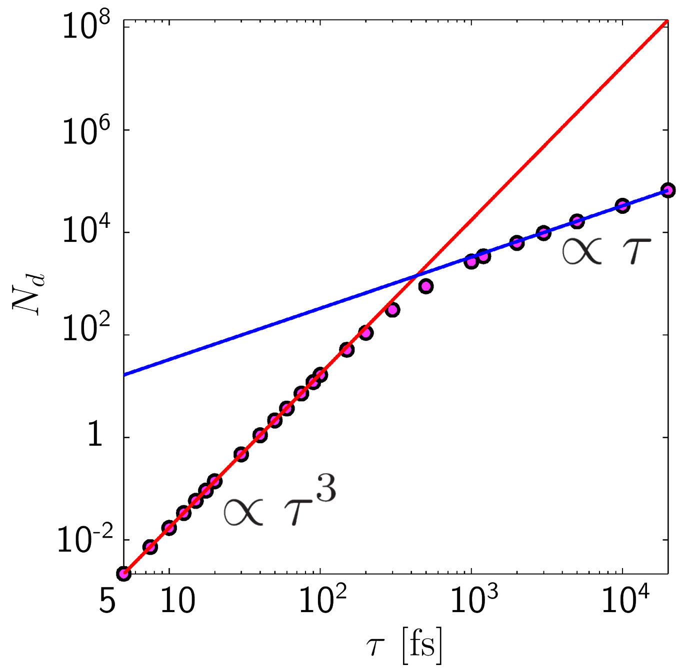

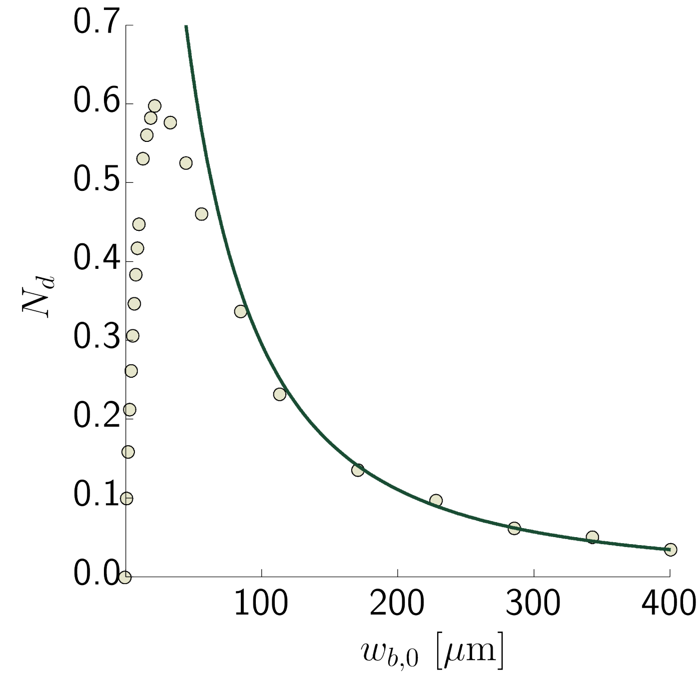

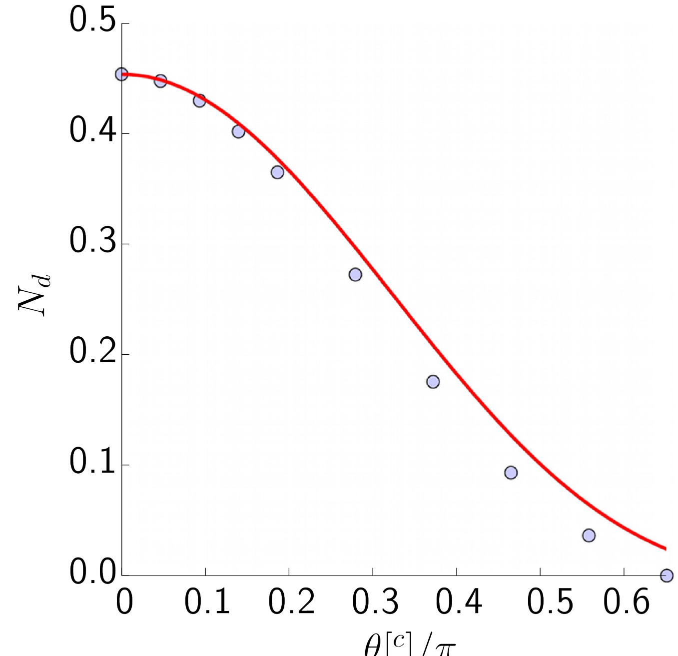

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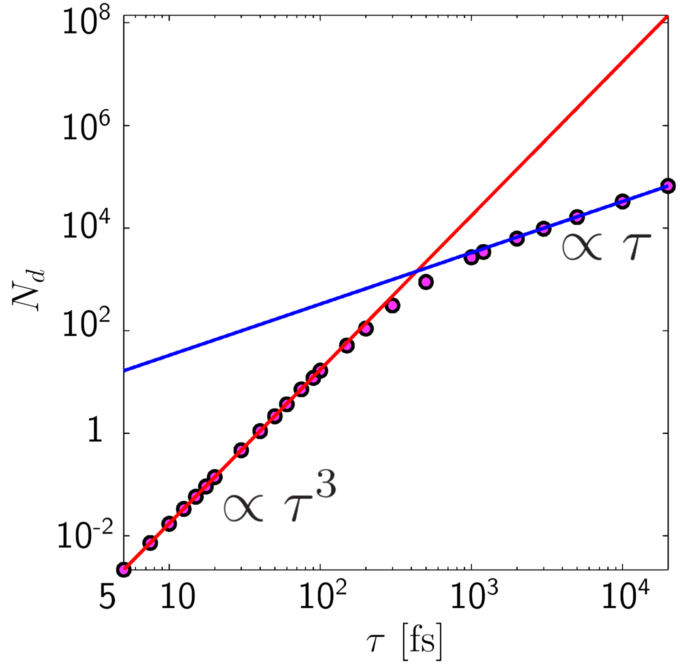

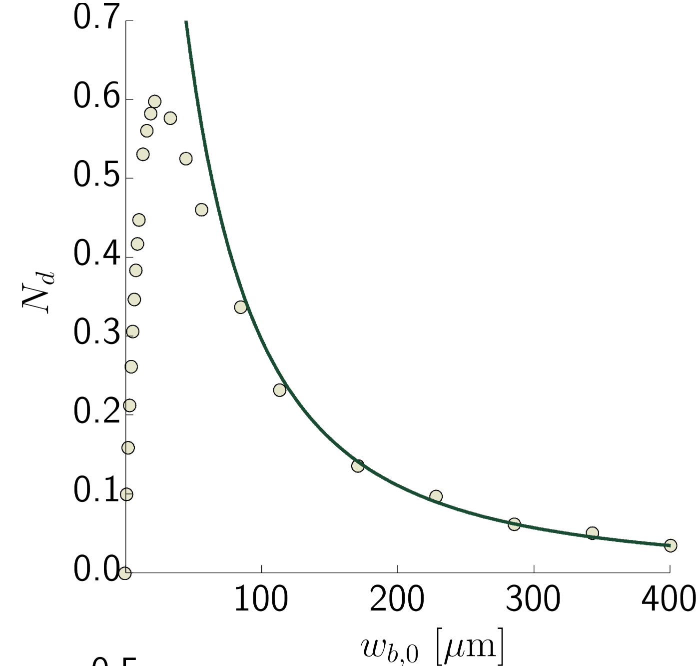

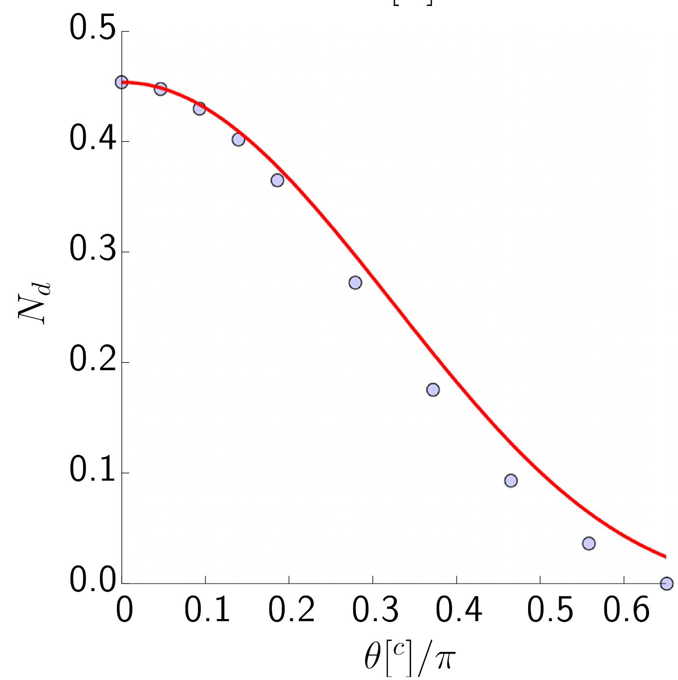

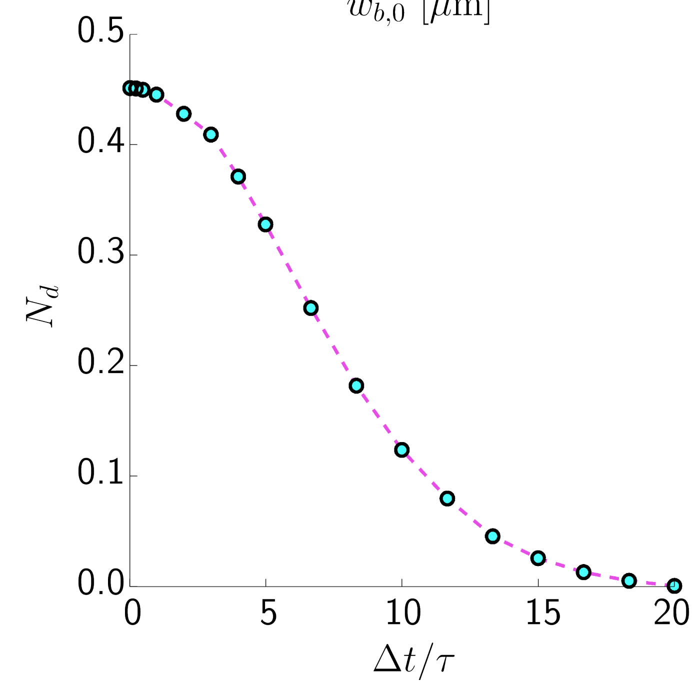

Elastic scattering

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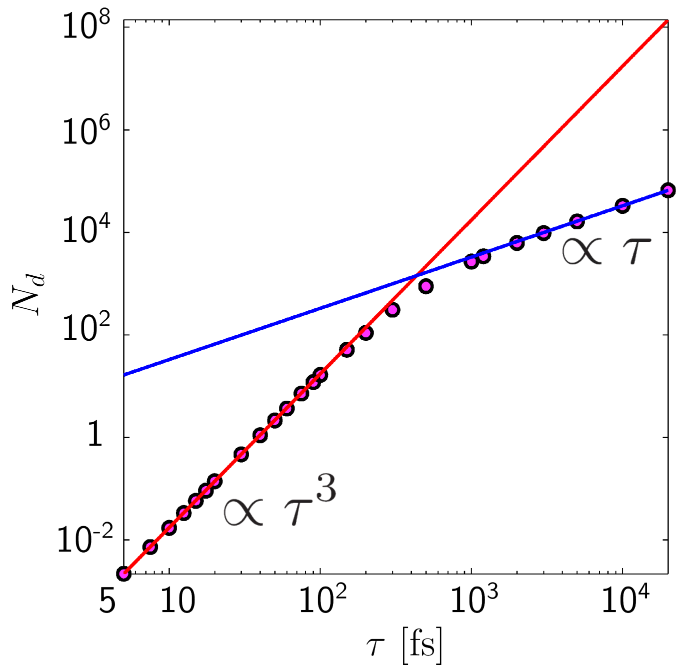
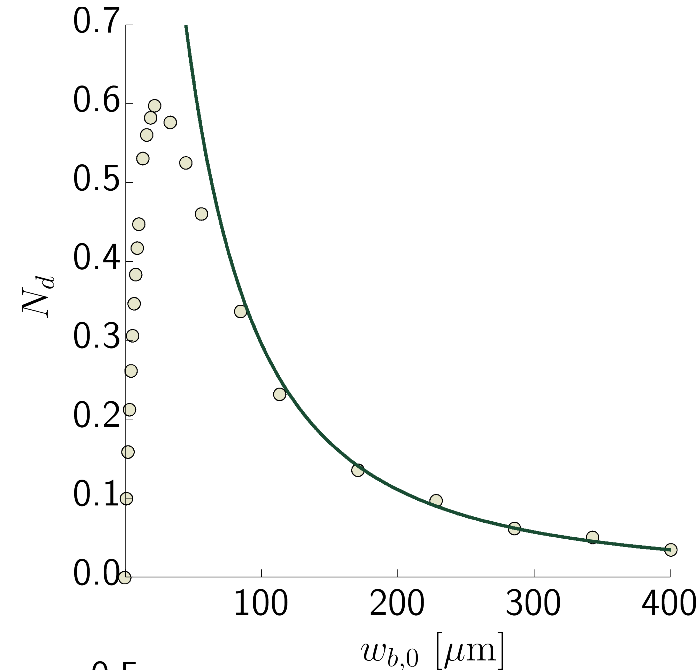


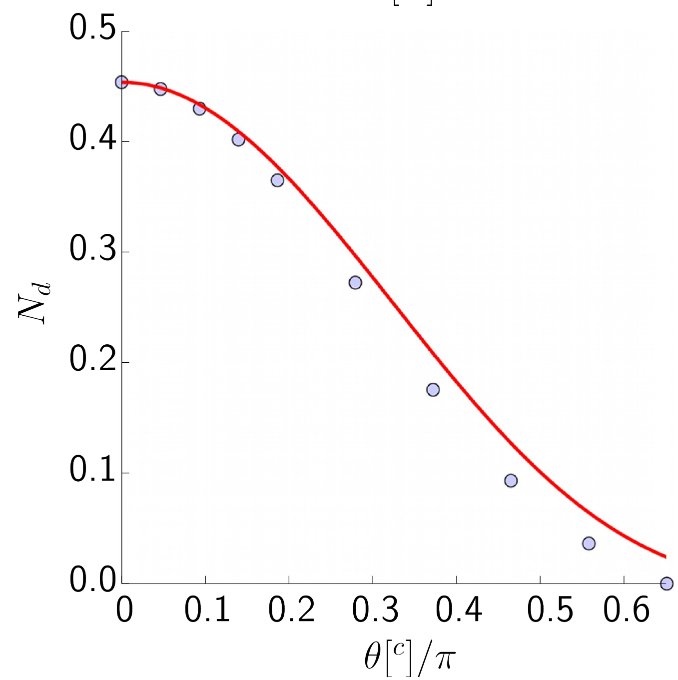


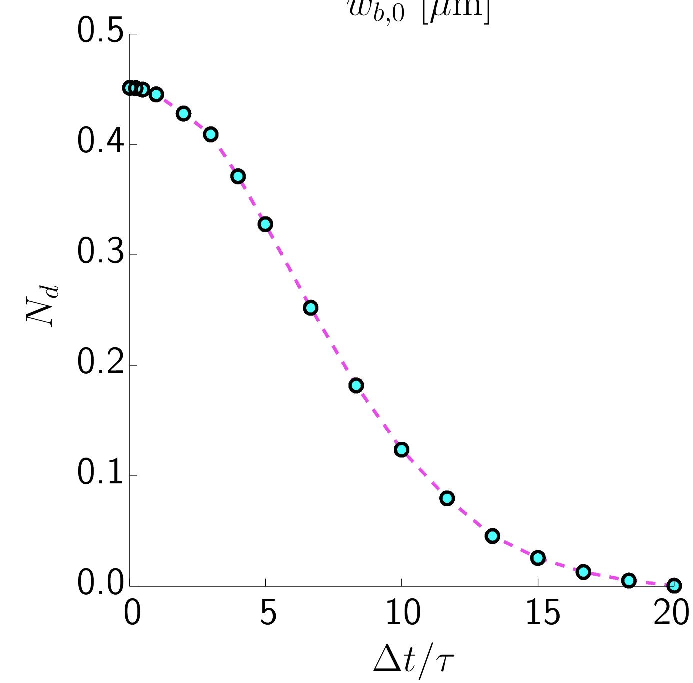
$$\theta = 0.1$$

$$P_a = 2P_{\mathrm{tot}}/3$$

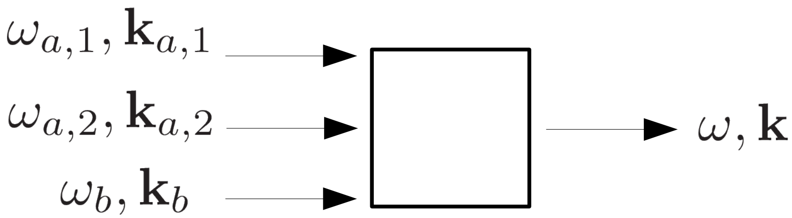
$$N_d(\lambda_b = 0.46\,\mu\mathrm{m}) \approx 4$$

$$N_d(\lambda_b = 0.23\,\mu\mathrm{m}) \approx 16$$





Inelastic scattering

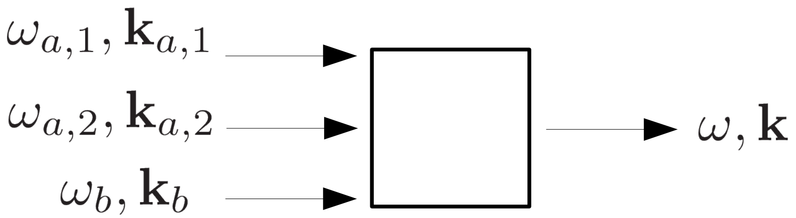


$$\omega = \omega_{a,1} + \omega_{a,2} + \omega_b$$

$$\omega \frac{y}{r} = \omega_{a,1} \cos\theta_{a,1} + \omega_{a,2} \cos\theta_{a,2} + \omega_b \cos\theta_b$$

$$\omega \frac{\rho}{r} = \omega_{a,1} \sin\theta_{a,1} + \omega_{a,2} \sin\theta_{a,2} + \omega_b \sin\theta_b$$

Inelastic scattering



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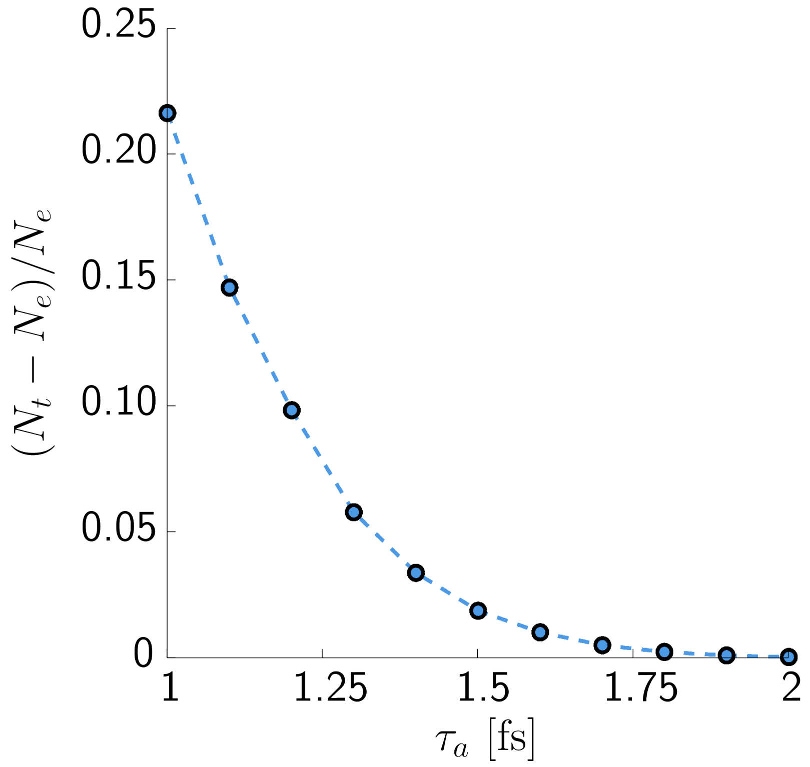
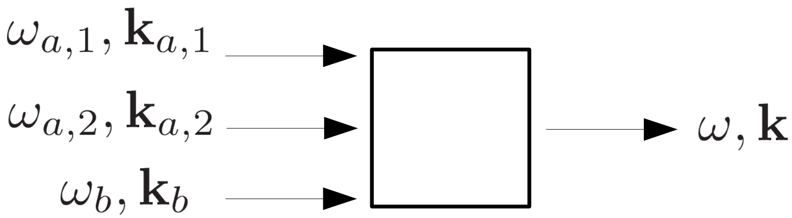


Inelastic scattering



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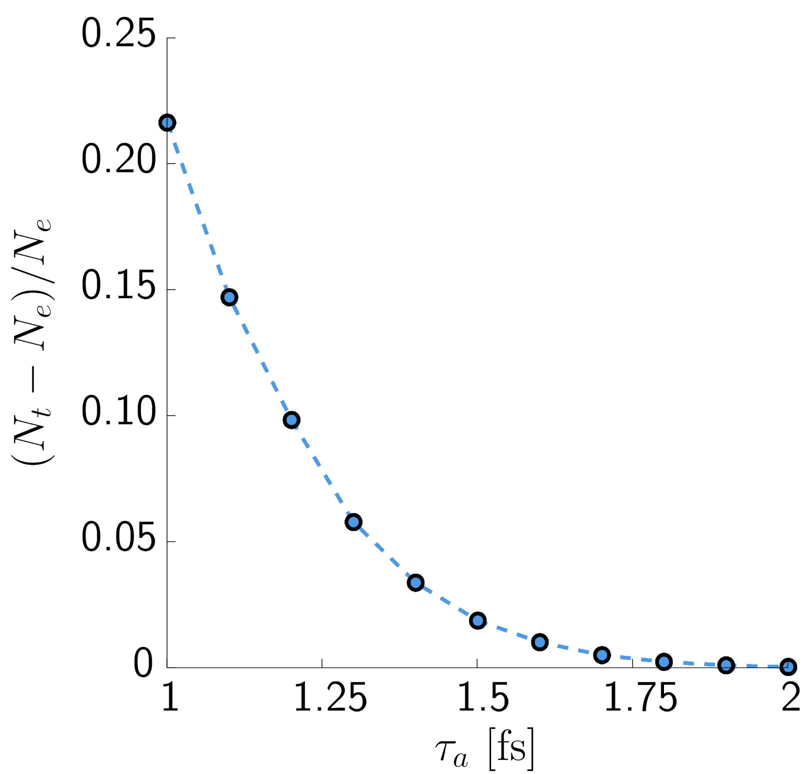

$\tau_a = 1\,\mathrm{fs} \qquad \tau_b = 30\,\mathrm{fs}$

$N_d(\lambda_b = 0.46\,\mu\mathrm{m}) \approx 1$

$N_d(\lambda_b = 0.23\,\mu\mathrm{m}) \approx 4$

Inelastic scattering

Inelastic scattering

$$\mathbf{E}_a(y+t) = \boldsymbol{\varepsilon}_a E_a \cos[\omega_a(y+t)]\,\mathrm{sech}[(y+t)/\tau_a]$$

$$\mathbf{E}_b(y-t) = \boldsymbol{\varepsilon}_b E_b \cos[\omega_b(y-t)]\,\mathrm{sech}[(y-t)/\tau_b]$$

Inelastic scattering

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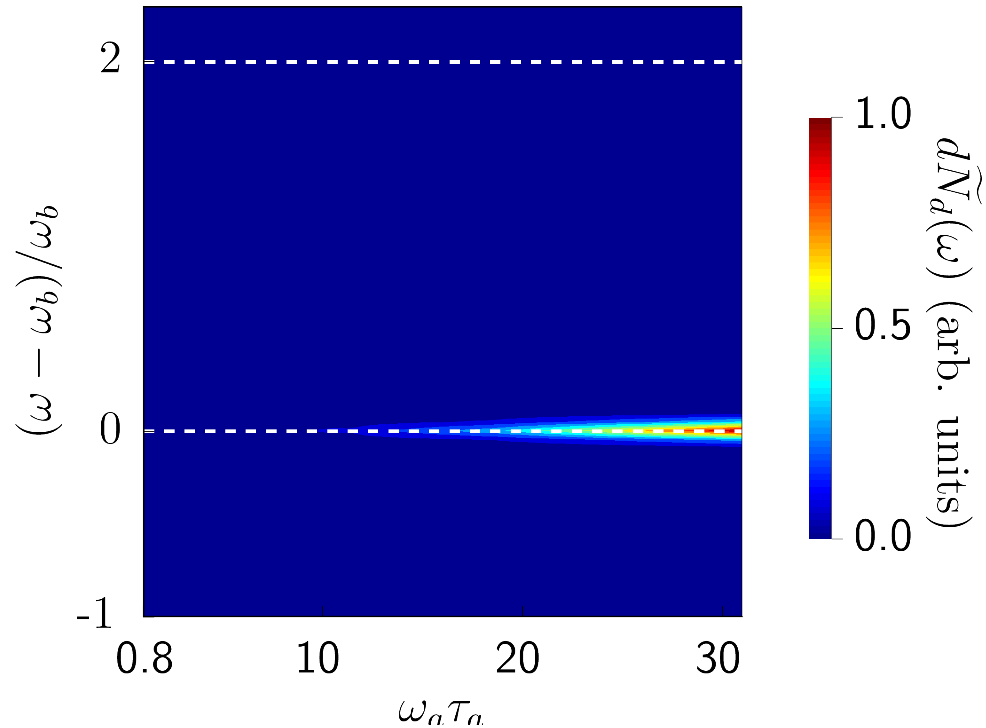
$$\mathbf{E}_b(y-t) = \boldsymbol{\varepsilon}_b E_b \cos[\omega_b(y-t)]\,\mathrm{sech}[(y-t)/\tau_b]$$



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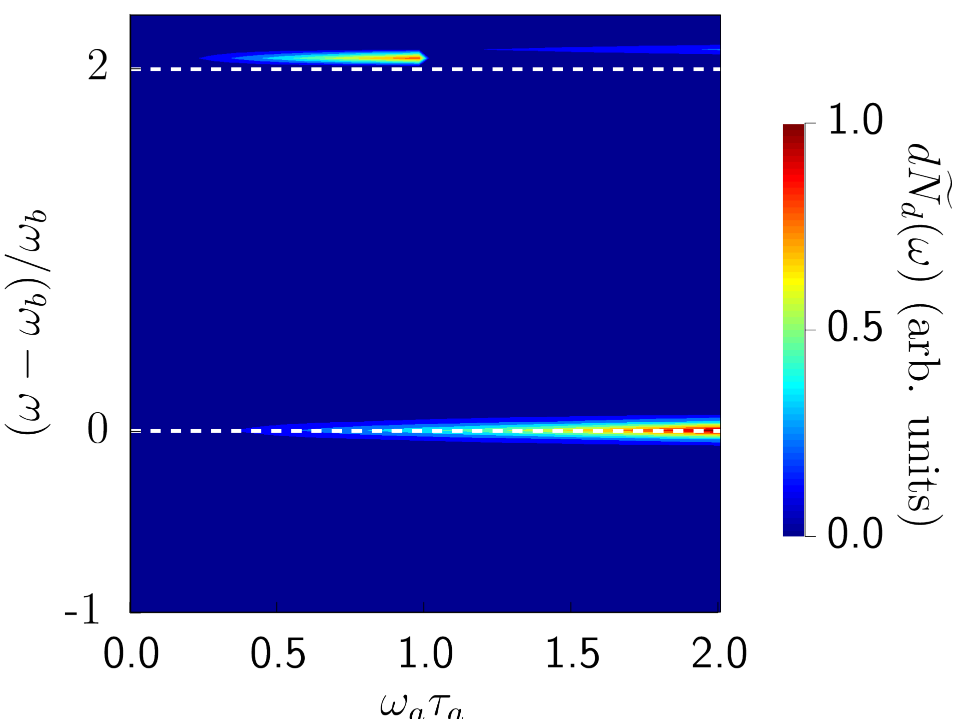

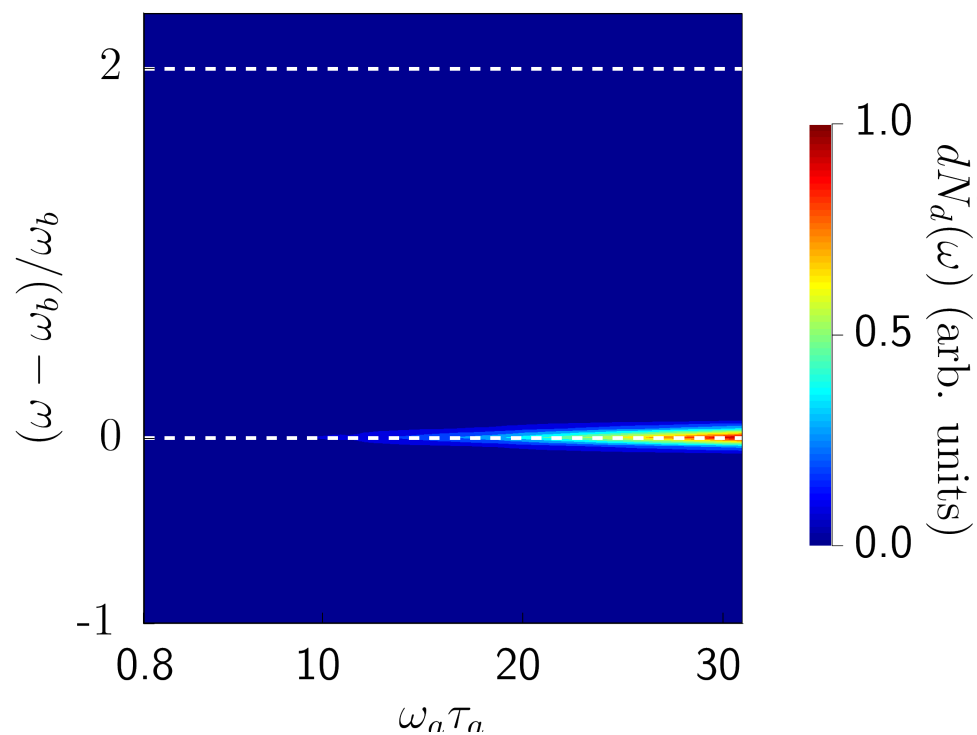

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Inelastic scattering

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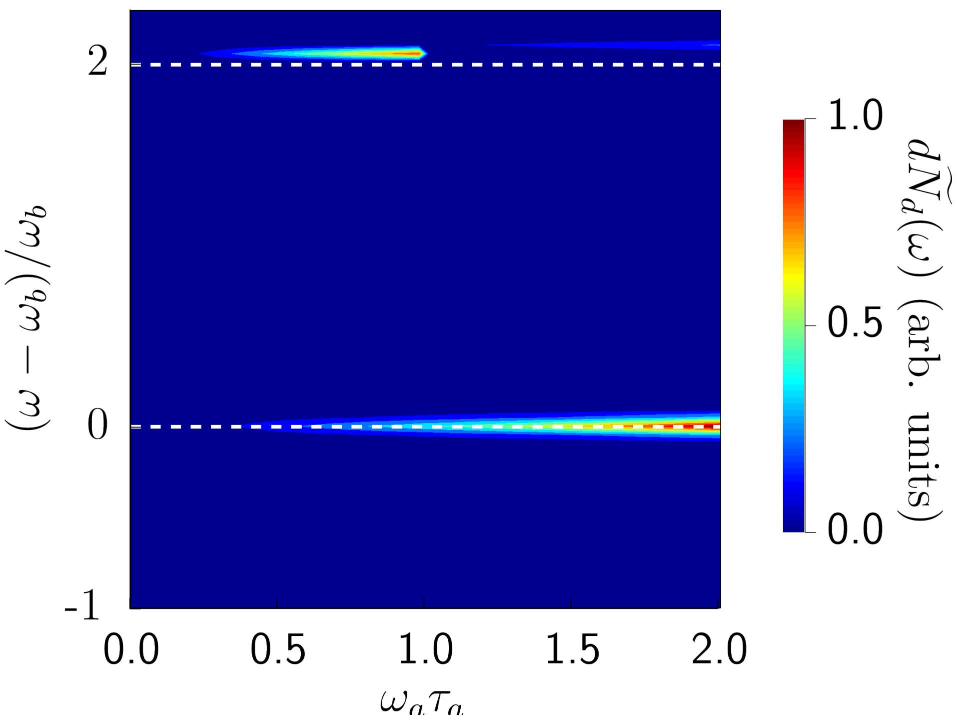

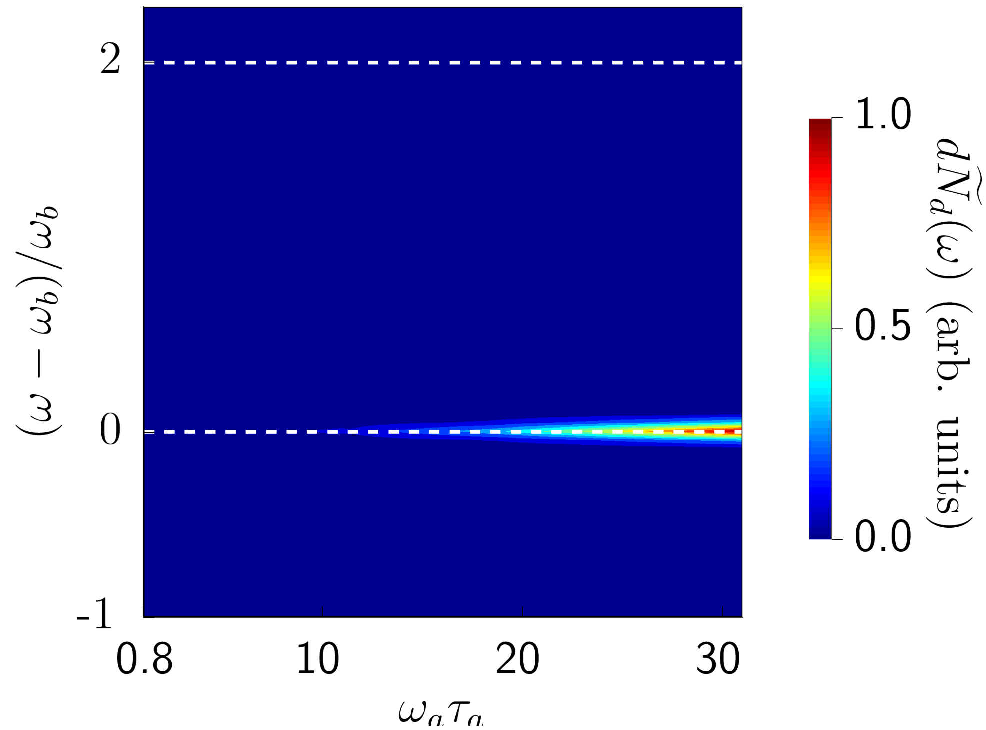

$$\mathbf{E}_a^2 |\mathbf{E}_b| \sim \cos^2(\varphi_a)\cos(\varphi_b) = \frac{1}{2}\left[\cos(\varphi_b) + \cos(2\varphi_a)\cos(\varphi_b)\right]$$

BK and C. H. Keitel, NJP **14** 103002 (2012)

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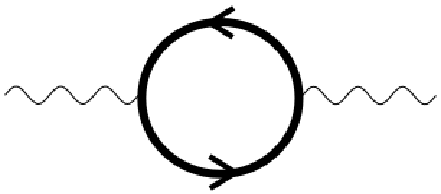
BK and C. H. Keitel, NJP **14** 103002 (2012) (see also NJP Highlights 2012)

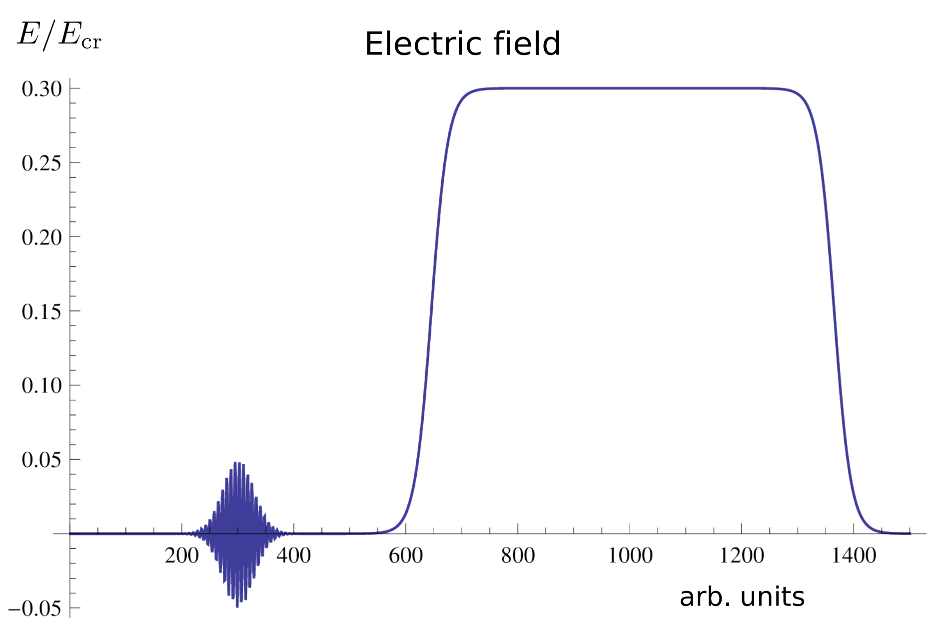
BK, A. Di Piazza and C. H. Keitel, Nature Photon. **4**, 92 (2010)

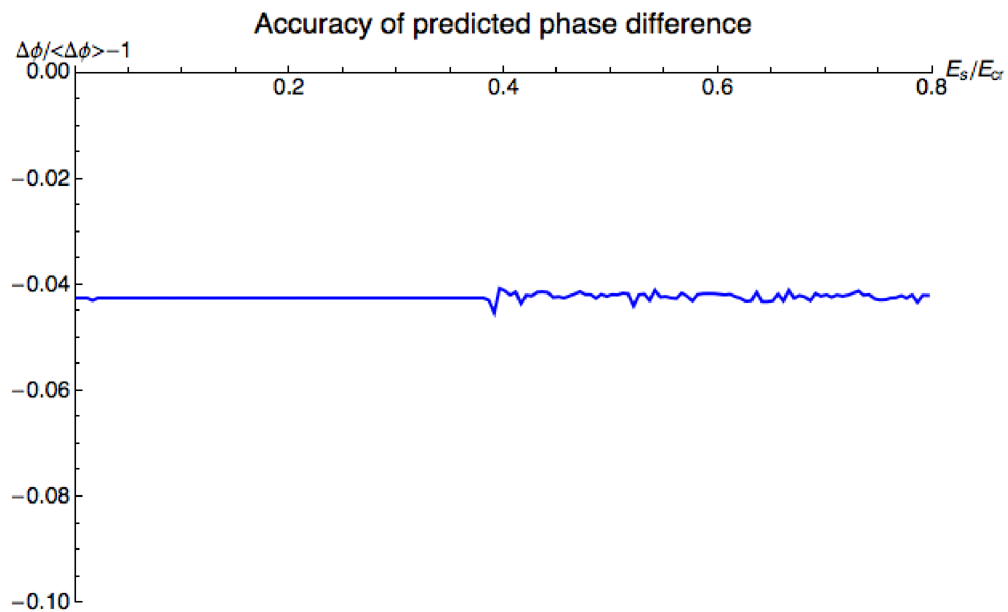
BK, A. Di Piazza and C. H. Keitel, PRA **82**, 032114 (2010)

$$\nabla^2 \mathbf{E} - \partial_t^2 \mathbf{E} = \mathbf{J}_{\rm vac}(\mathbf{E})$$



$$\Delta\phi = \frac{11 \pm 3}{45\pi} \frac{\alpha I_{\rm s}}{I_{\rm cr}} \omega_p T$$



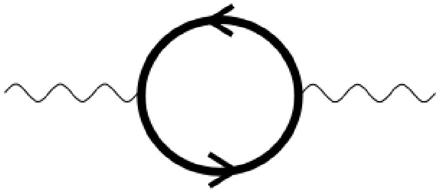


P. Boehl, BK and H. Ruhl (in preparation)

Envisaged scenario

$$-\frac{\alpha}{(2\pi)^4}\int d^4x\,\mathrm{Tr}\,\langle x|\frac{1}{\gamma(p+eA)-m}\mathrm{e}^{-ikx}\gamma^\mu\frac{1}{\gamma(p+eA)-m}\mathrm{e}^{ik'x}\gamma^\nu|x\rangle$$

$$a_0=\frac{eE\lambda_{\mathrm{C}}}{\hbar\omega},$$



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