All-optical probes of quantum vacuum nonlinearity

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(i) Abstract

In this talk,

- I will exemplarily focus on **vacuum birefringence** in strong **inhomogeneous** (laser) **fields**.

- I will present new key ideas that can make the experimental verification of vacuum birefringence with high-intensity lasers feasible

  → with **state of the art** technology,

  → e.g. at the **H**elmholtz **I**nternational **B**eamline for **E**xtreme **F**ields at the European XFEL.

(ii) Our approach

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Effective theory for probe photon (A^μ) propagation in inhomogeneous electromagnetic background ($\mathcal{A}^\mu$):

$$S_{\text{eff}}[A, \mathcal{A}] = -\frac{1}{4}\int_x \mathbb{F}_{\mu\nu}(x)\mathbb{F}^{\mu\nu}(x) \qquad \text{where} \quad \mathbb{A}^\mu = \mathcal{A}^\mu + A^\mu$$

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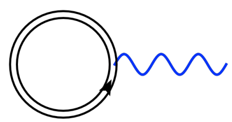
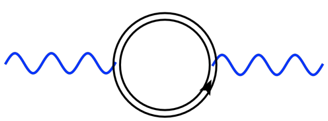
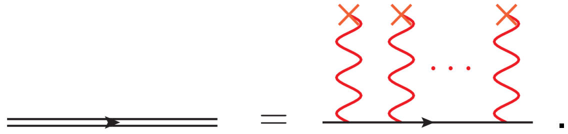
$$+ \int_x j^\mu(x|\mathcal{A})A_\mu(x) - \frac{1}{2}\int_x\int_{x'} A_\mu(x)\Pi^{\mu\nu}(x,x'|\mathcal{A})A_\nu(x') + \ \ldots$$





with dressed $\mathrm{e}^-/\mathrm{e}^+$ propagator



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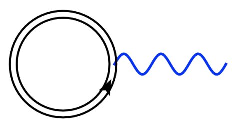

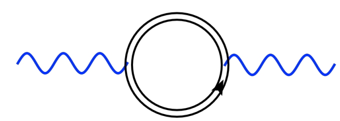

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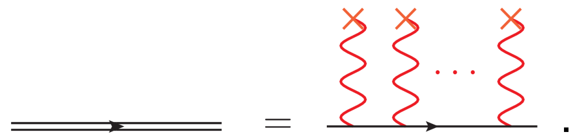

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Problem: Most analytical calculations have been performed either for uniform, constant or planewave (null-field) backgrounds.

- e.g. photon polarization tensor

[Batalin, Shabad: Sov. Phys. JETP **33** 483 (1971)]
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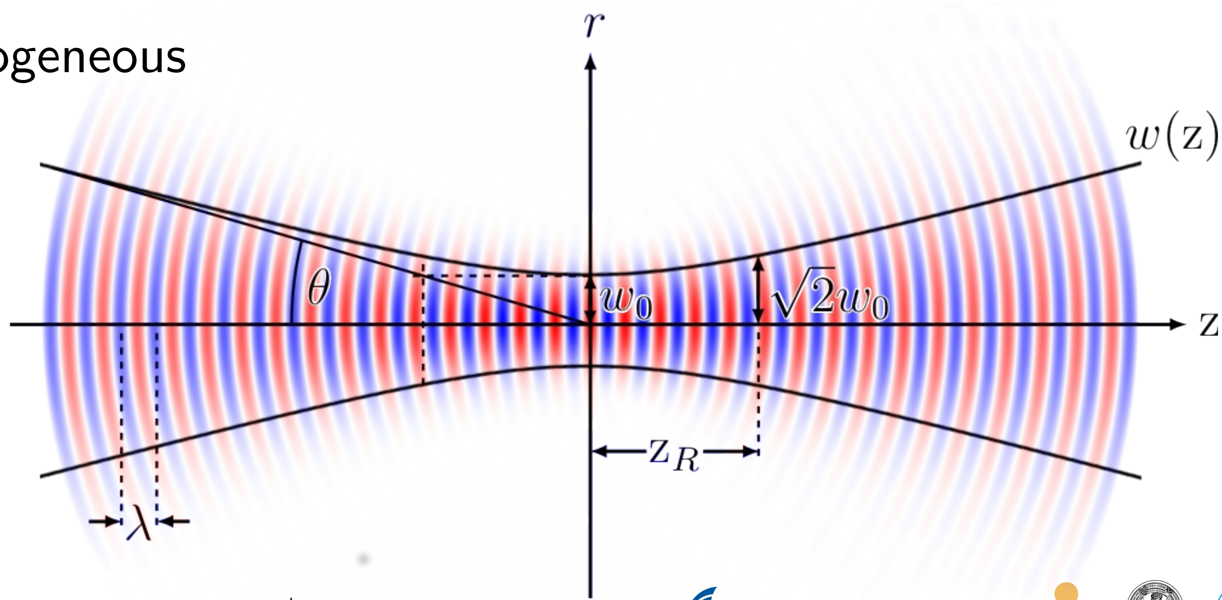

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$$I(x) = I_0\Big[\mathrm{e}^{-\frac{(\mathrm{z}-t)^2}{(\tau/2)^2}}\,\frac{w_0}{w(\mathrm{z})}\,\mathrm{e}^{-\frac{\mathrm{x}^2+\mathrm{y}^2}{w^2(\mathrm{z})}} \times \cos\Big(\Omega(\mathrm{z}-t) + \frac{\mathrm{x}^2+\mathrm{y}^2}{w^2(\mathrm{z})}\frac{\mathrm{z}}{\mathrm{z}_R} - \arctan\big(\tfrac{\mathrm{z}}{\mathrm{z}_R}\big) + \varphi_0\Big)\Big]^2$$

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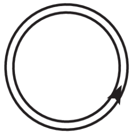
But: On the other hand, we have the Heisenberg-Euler Lagrangian:

[Heisenberg, Euler: Z. Phys. **98** 714 (1936)]

$\mathcal{L}(\mathcal{F},\mathcal{G}) =$  $+ \ \ldots$

$$\mathcal{F} = \frac{1}{4}F_{\mu\nu}F^{\mu\nu} = \frac{1}{2}(\vec{B}^2 - \vec{E}^2)\,,$$

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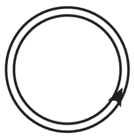
$\mathcal{L}(\mathcal{F},\mathcal{G}) =$  $+ \ \ldots$

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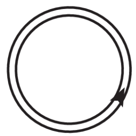
$$\mathcal{L}(\mathcal{F},\mathcal{G}) =$$  $$+ \ \ldots$$

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$\rightarrow$ photon polarization tensor, current, etc. for slowly varying fields can be derived therefrom (decomposition $\mathcal{A}^\mu(x) \rightarrow \mathcal{A}^\mu \quad + A^\mu(x)$)

[Bialynicka-Birula, Bialynicka-Birula: Phys. Rev. D **2** 2341 (1970)]

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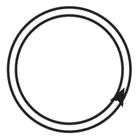
$\mathcal{L}(\mathcal{F},\mathcal{G}) =$  $+ \ \dots$

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[FK, Shaisultanov: Phys. Rev. D **91** 085027 (2015)]

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Our approach: The locally constant field approximation constitutes a good approximation, for

```
[…] den speziellen Fall [...], in dem keine wirklichen
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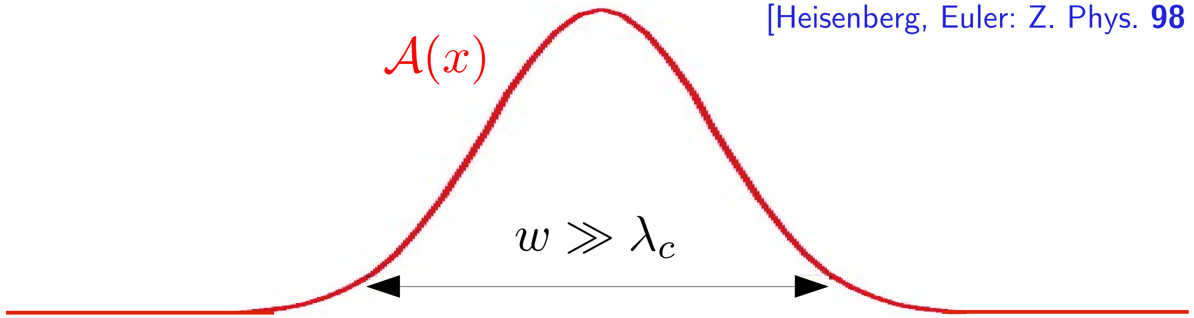

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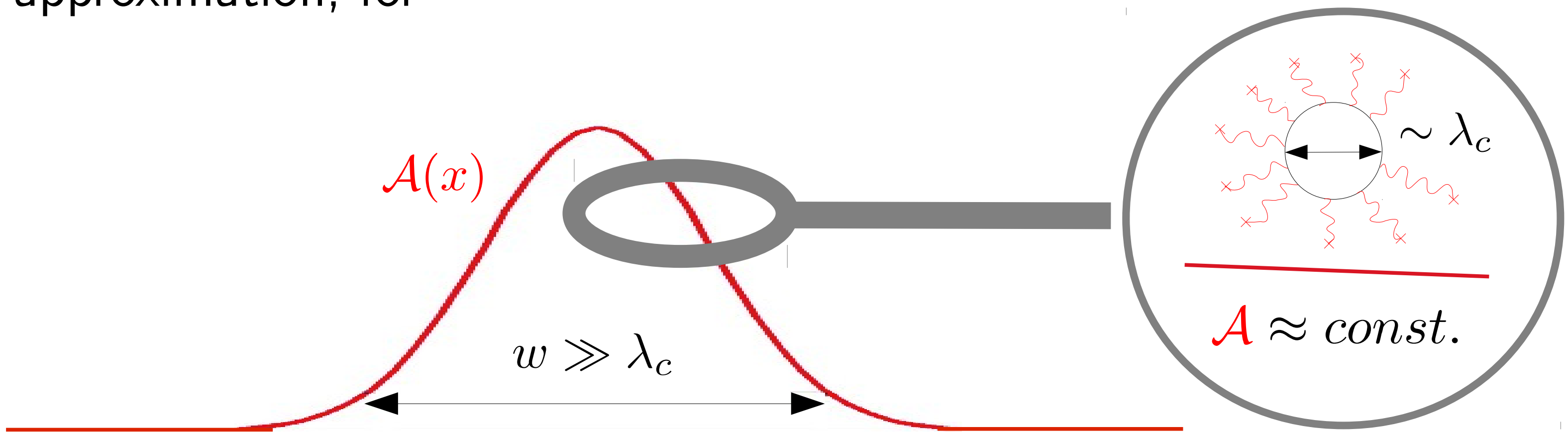

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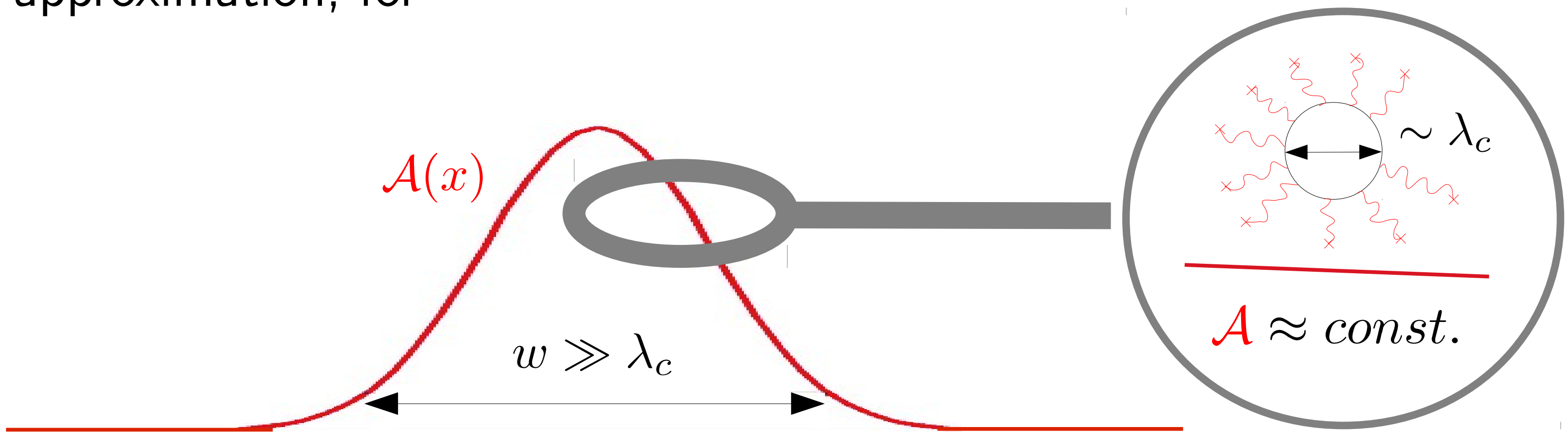

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$\rightarrow$ Polarization tensor in inhomogeneous, slowly varying backgrounds

$$\Pi^{\rho\sigma}(k', k|\mathcal{A}) = \left(g^{\rho\beta}k'^{\alpha} - g^{\rho\alpha}k'^{\beta}\right)\left[\int_x \mathrm{e}^{i(k'+k)x} \frac{\partial^2 \mathcal{L}}{\partial F^{\alpha\beta}\partial F^{\mu\nu}}(x)\right]\left(k^{\mu}g^{\nu\sigma} - k^{\nu}g^{\mu\sigma}\right)$$

[FK, Shaisultanov: Phys. Rev. D **91** 085027 (2015)]

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Our result for the photon polarization tensor:

[FK, Shaisultanov: Phys. Rev. D **91** 085027 (2015)]

$$\Pi^{\rho\sigma}(k',k|\mathcal{A}) = \int_x \mathrm{e}^{i(k'+k)x}\Big[\big((k'k)g^{\rho\sigma} - k^\rho k'^\sigma\big)\frac{\partial\mathcal{L}}{\partial\mathcal{F}} + k_\mu k'_\alpha \epsilon^{\rho\sigma\mu\alpha}\frac{\partial\mathcal{L}}{\partial\mathcal{G}}$$
$$+ (k'F)^\rho(kF)^\sigma\frac{\partial^2\mathcal{L}}{\partial\mathcal{F}^2} + (k'^*F)^\rho(k^*F)^\sigma\frac{\partial^2\mathcal{L}}{\partial\mathcal{G}^2}$$
$$+ \left[(k'^*F)^\rho(kF)^\sigma + (k'F)^\rho(k^*F)^\sigma\right]\frac{\partial^2\mathcal{L}}{\partial\mathcal{F}\partial\mathcal{G}}\Big]$$

- mediates between two distinct photon momenta k'^μ, k^μ

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$\rightarrow$ for orthogonal electric and magnetic fields of same amplitude we have $\mathcal{F}(x) = \mathcal{G}(x) = 0$, such that

$$\Pi^{\rho\sigma}(k',k|\mathcal{A}) = \frac{\alpha}{\pi}\frac{1}{45}\Big(\frac{e}{m^2}\Big)^2 \int_x \mathrm{e}^{i(k'+k)x}\Big[4\,(k'F)^\rho (kF)^\sigma + 7\,(k'^*F)^\rho (k^*F)^\sigma\Big]$$

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(iii) Vacuum birefringence

[Toll: PhD thesis, Princeton Universiy, unpublished (1952)]

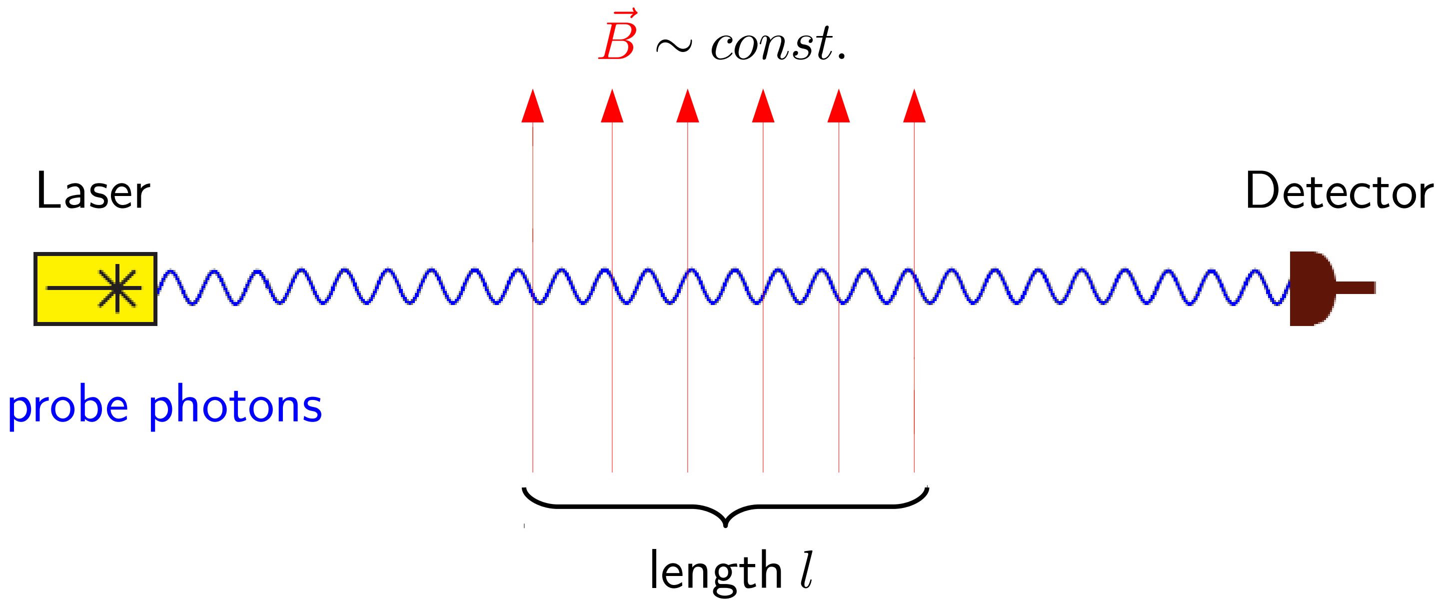
[Baier, Breitenlohner: Act. Phys. Austriaca **25** 212 (1967) & Nuov. Cim. B **47** 117 (1967)]

(iii) Vacuum birefringence

Conventional scenario:

[BMV (Biréfringence Magnétique du Vide) experiment, Toulouse]

[PVLAS (Polarizzazione del Vuoto con Laser) experiment, Padova/Ferrara]



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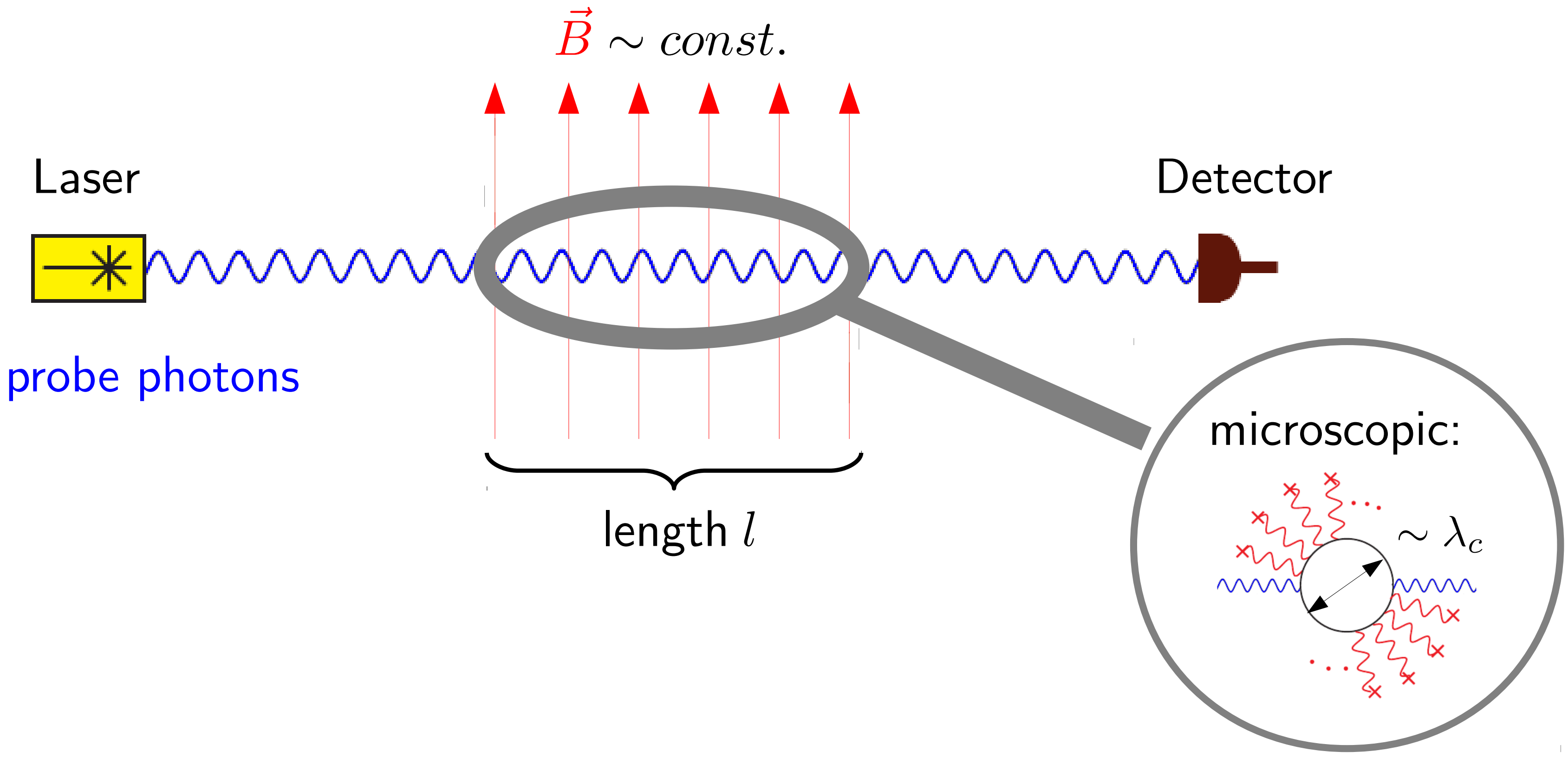

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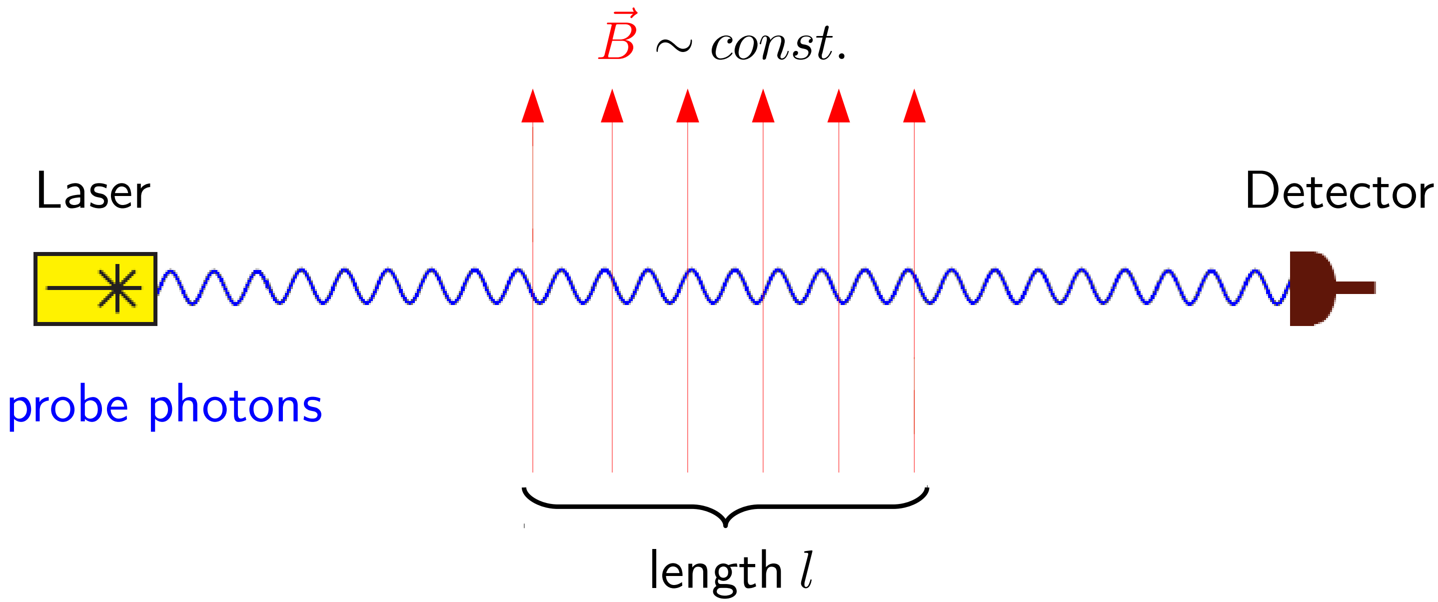

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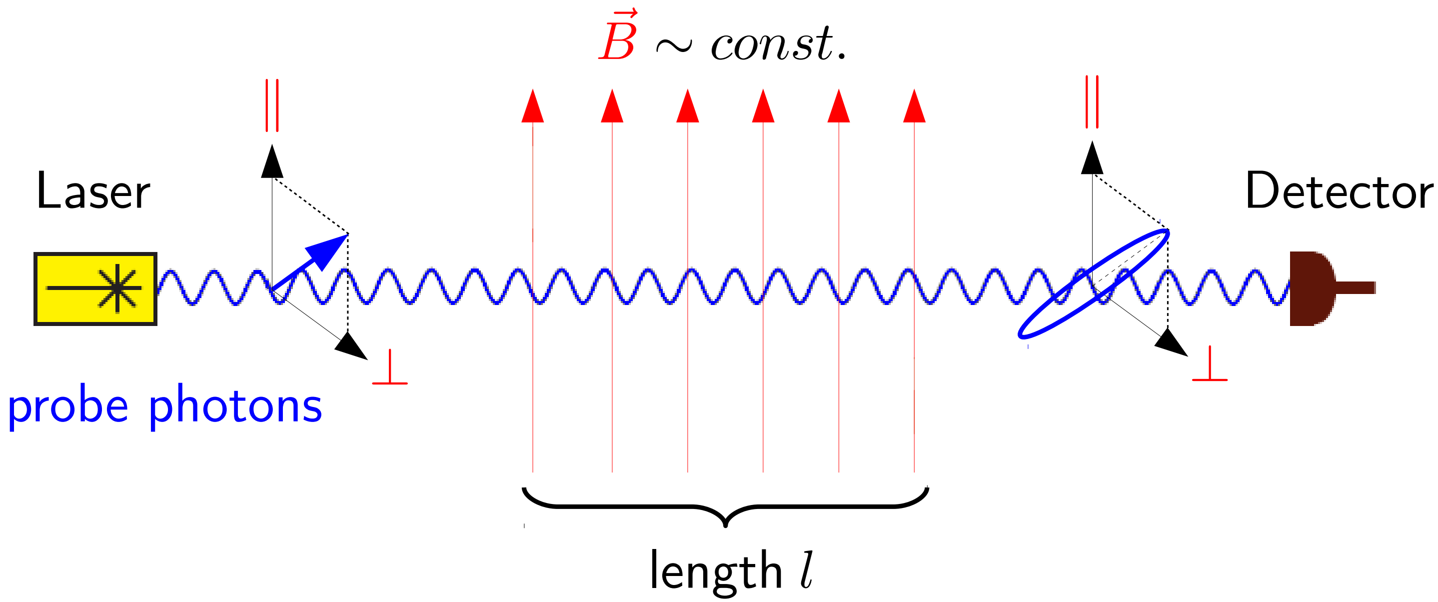

- vacuum birefringence $\rightarrow$ ellipticity: $\Delta\phi \sim \alpha \frac{l}{\lambda} \left(\frac{eB}{m_e^2} \right)^2$ $\leftarrow$ relative phase shift between $\parallel$ and $\perp$ modes

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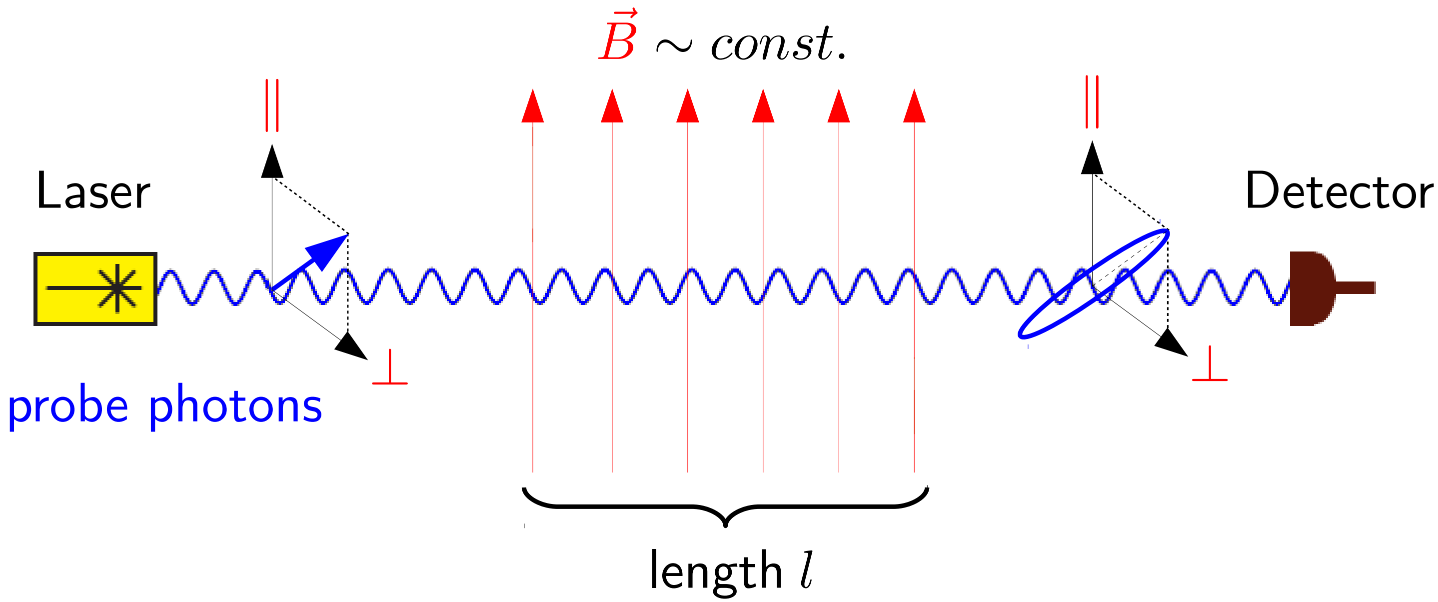

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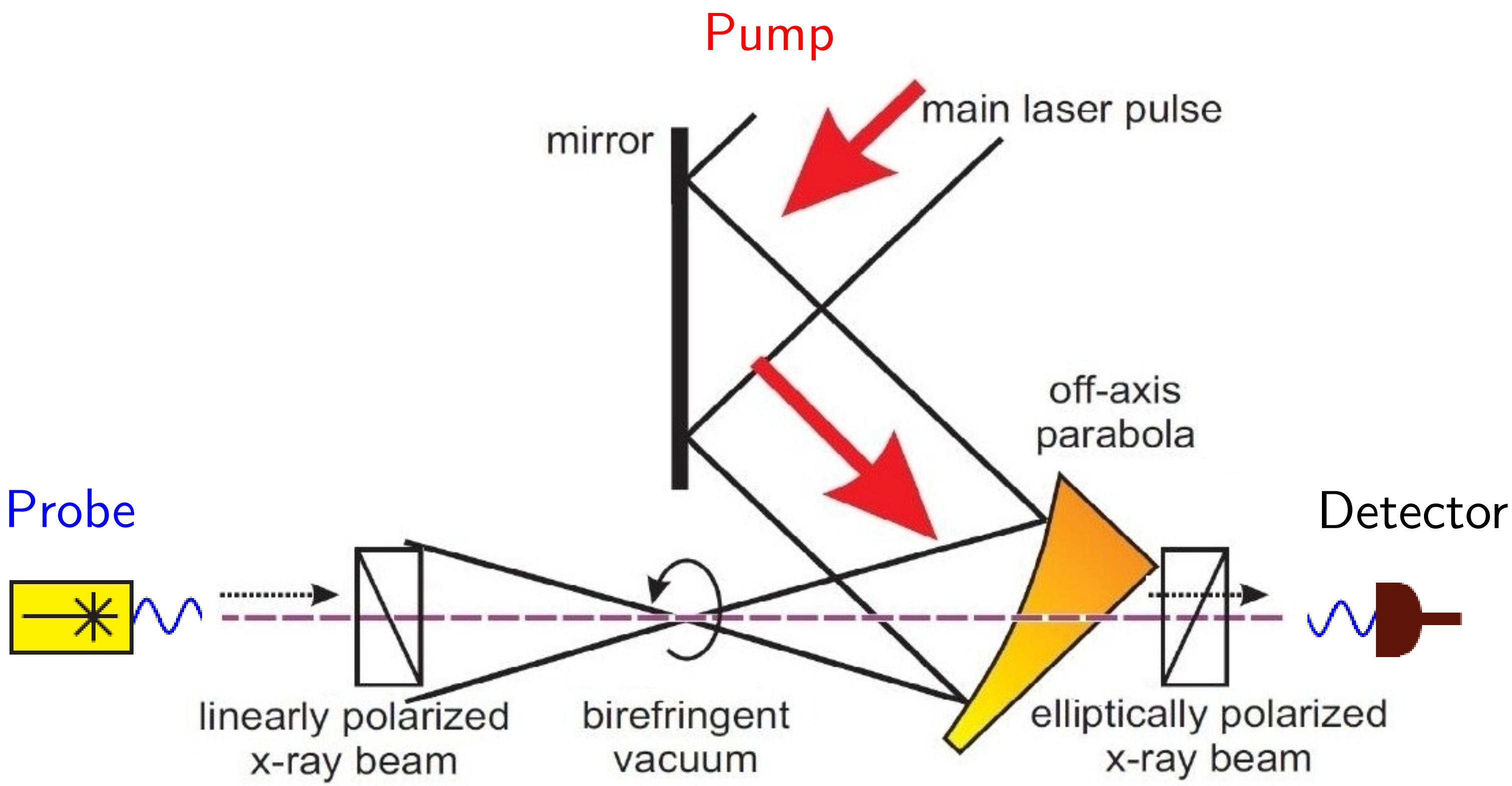
↔ photons in $\perp$ polarization mode induced: $N_\perp \simeq \left(\frac{\Delta\phi}{2} \right)^2 N_{\text{in}}$

(iii) Vacuum birefringence

Analogous scenario with pump = high-intensity laser:

[Heinzl, Liesfeld, Amthor, Schwoerer, Sauerbrey, Wipf: Opt. Comm. **267** 318 (2006)]



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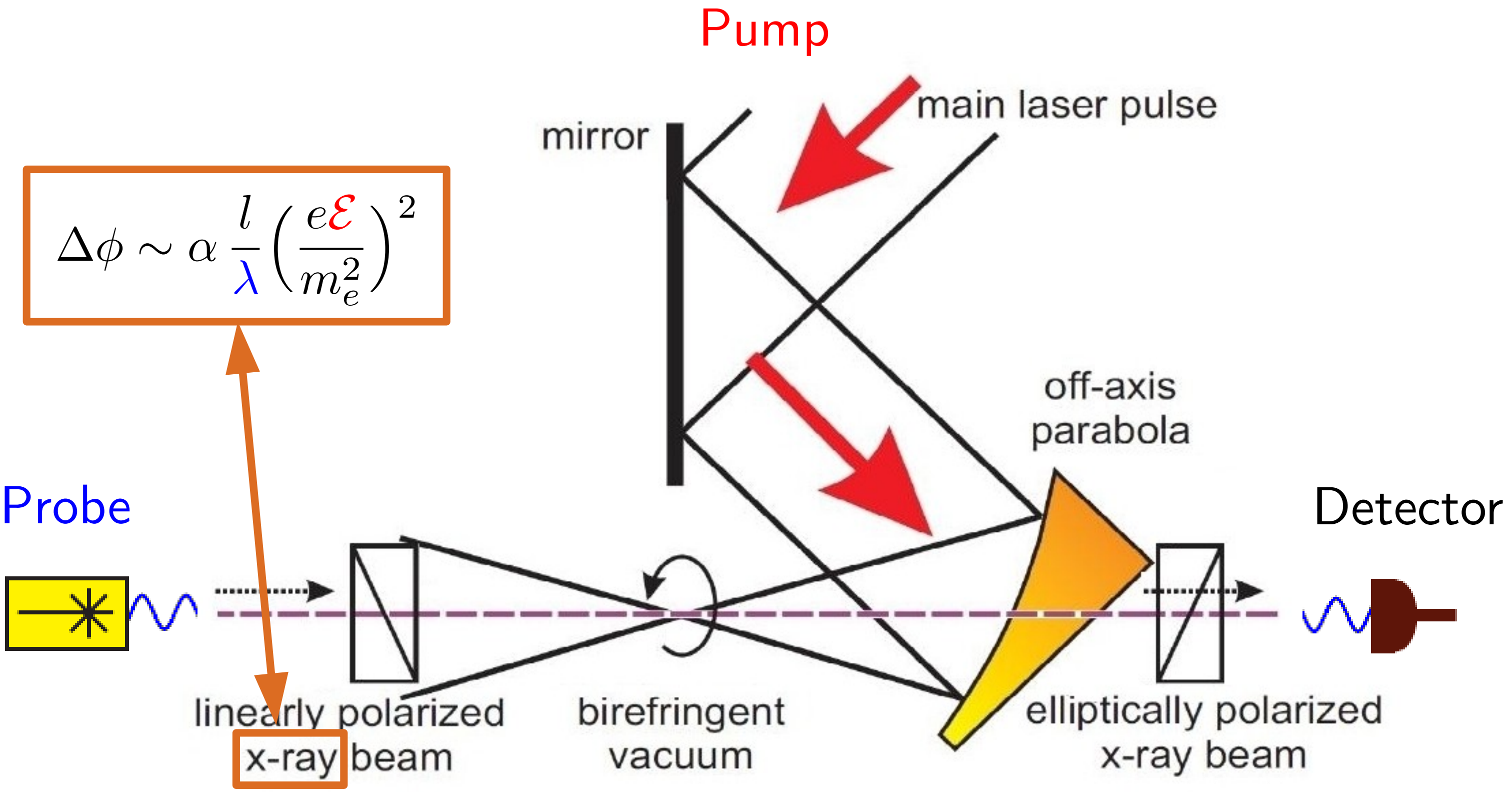
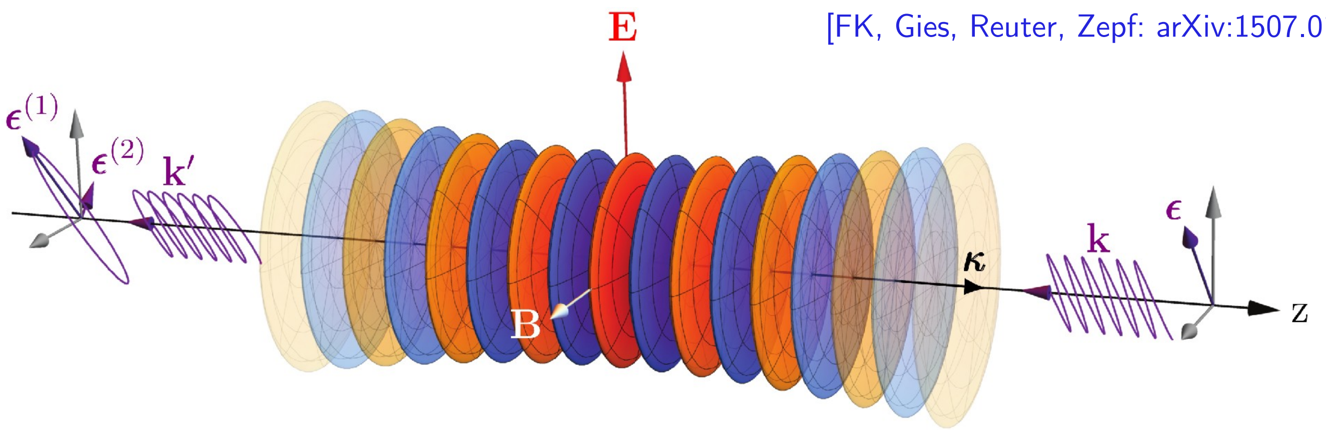


(iii) Vacuum birefringence

Analogous scenario with pump = high-intensity laser:

- in a recent study we account for the full inhomogeneous field profile of a linearly polarized, pulsed Gaussian laser beam

[FK, Gies, Reuter, Zepf: arXiv:1507.01084]



- pump: $1\mathrm{PW}$ class laser $(W = 30\mathrm{J},\ \tau = 30\mathrm{fs},\ \lambda = 800\mathrm{nm}, w_0 = 1\mu\mathrm{m})$

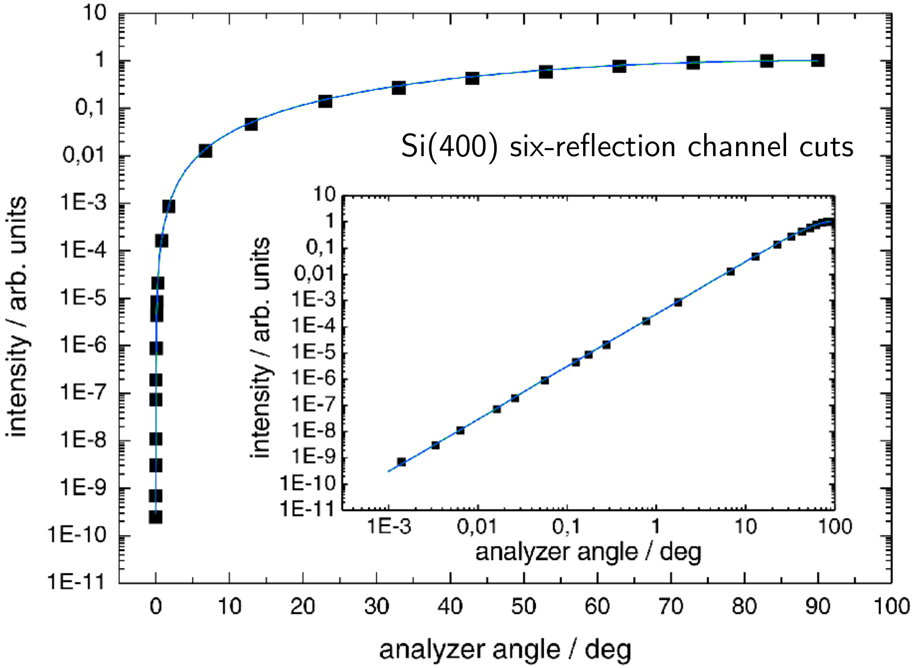
- probe: x-ray beam from FEL $(\omega = 12914\mathrm{eV},\ N_{\mathrm{in}} \simeq 10^{12})$

cf. also [Dinu, Heinzl, Ilderton, Marklund, Torgrimsson: Phys. Rev. D **89**, 125003 & **90** 045025 (2014)]

(iii) Vacuum birefringence

Analogous scenario with pump = high-intensity laser:

$\rightarrow$ demand for high-purity x-ray polarimetry



[Marx, Schulze, Uschmann, Kämpfer, Lötzsch, Wehrhan, Wagner, Detlefs, Roth, Härtwig, Förster, Stöhlker, Paulus: Phys. Rev. Lett. **110** 254801 (2013)]

Polarization purity record @ $\omega = 12914\mathrm{eV}$:

$$\mathcal{P} = 5.7 \cdot 10^{-10}$$

$\leftrightarrow$ experimental confirmation of vacuum birefringence requires $\dfrac{N_\perp}{N_{\mathrm{in}}} > \mathcal{P}$.

(iii) Vacuum birefringence

Our theoretical approach:

Idea: Interpret vacuum birefringence as **vacuum emission process**:

[FK, Shaisultanov: Phys. Rev. D **91** 113002 (2015)]

- laser fields correspond to macroscopic electromagnetic fields
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↔ vacuum in the presence of pump and probe beams $= |0\rangle$

- the signal of quantum vacuum nonlinearity is encoded in (single) photons $= |\gamma_{(p)}(\vec{k}')\rangle$ emitted from the strong field region

→ amplitude: $\mathcal{S}_{(p)}(k') = \langle\gamma_p(\vec{k}')| \int_x a_\mu(x) j^\mu(x)|0\rangle.$

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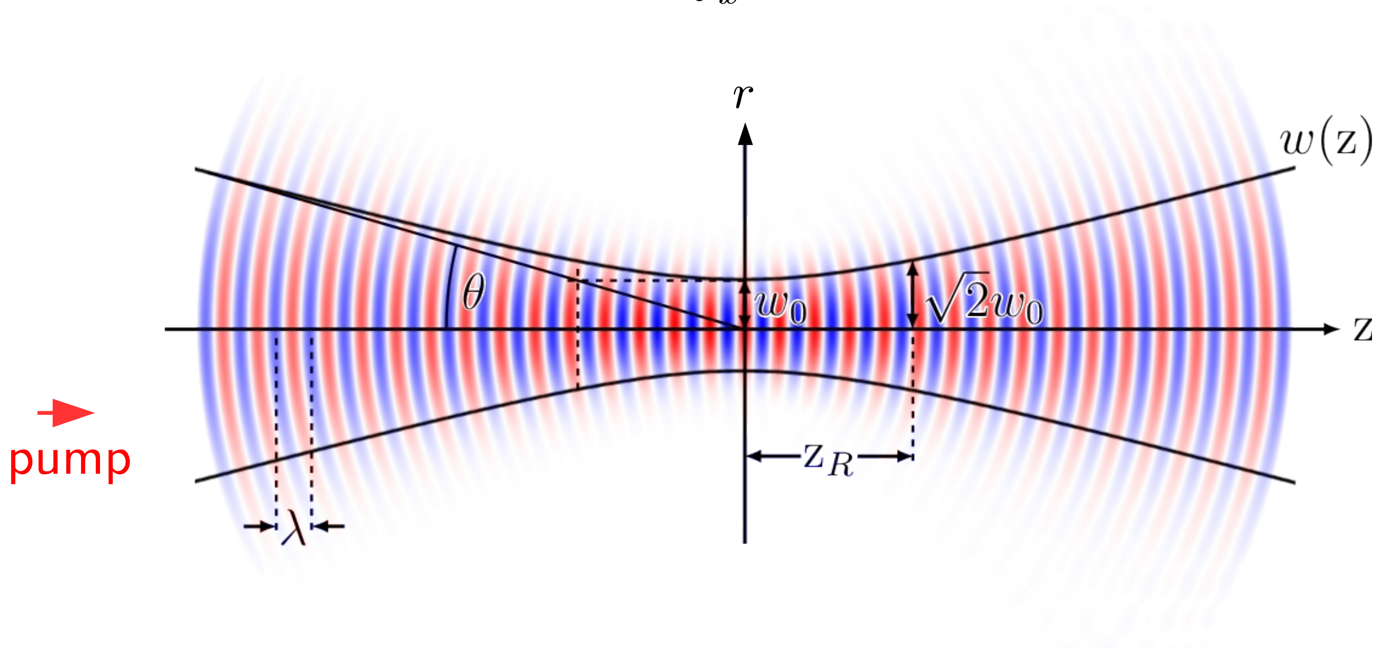

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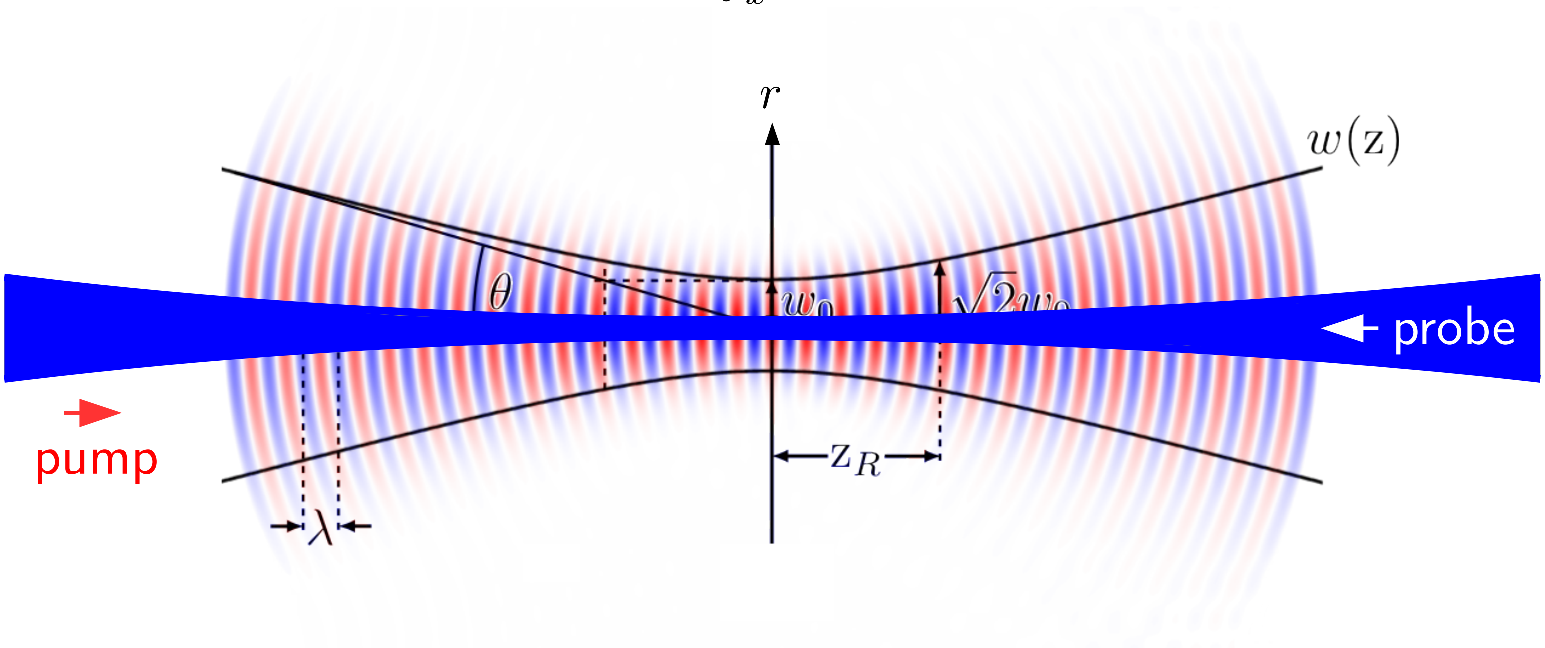

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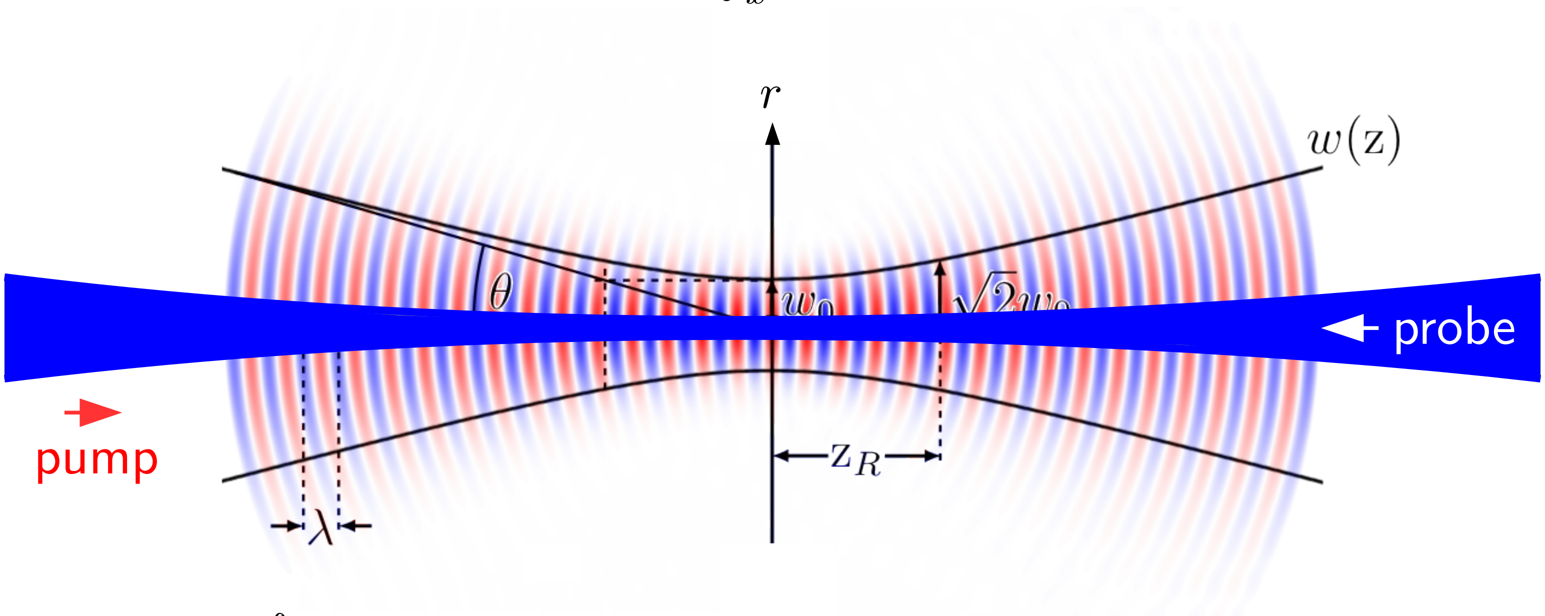

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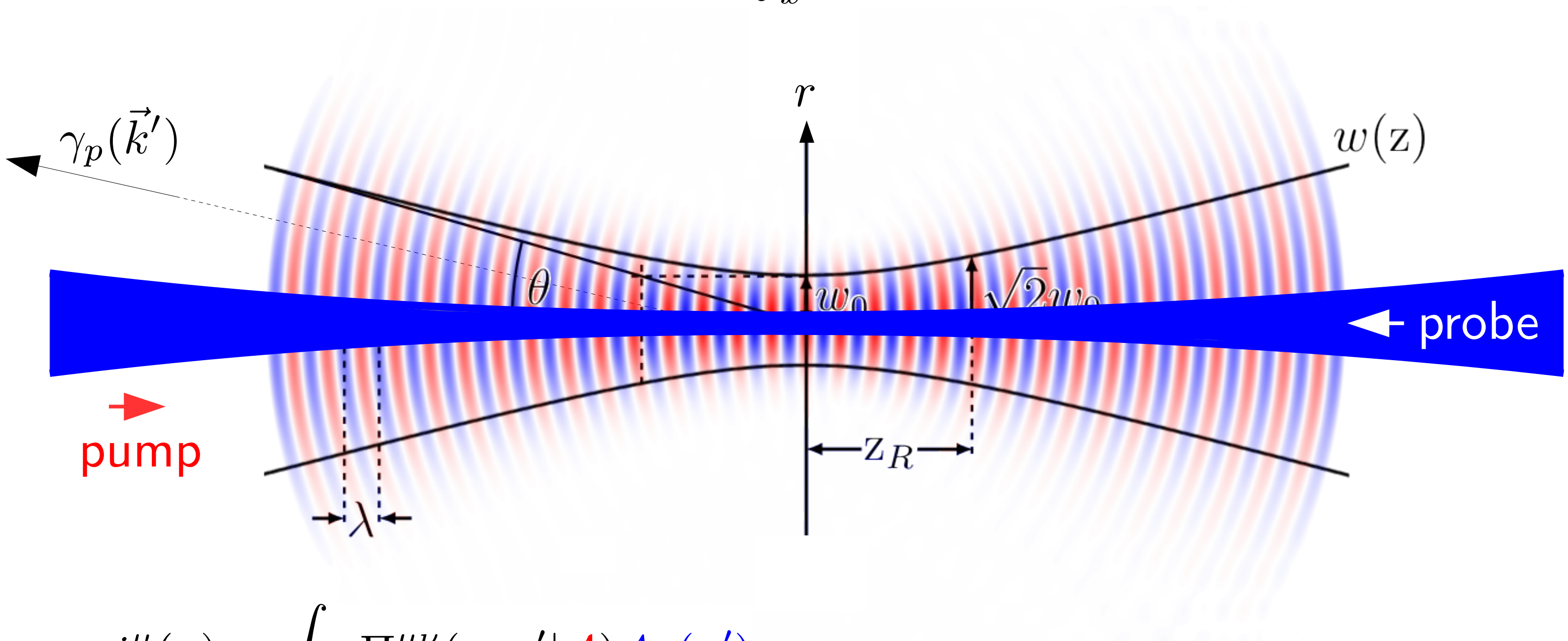

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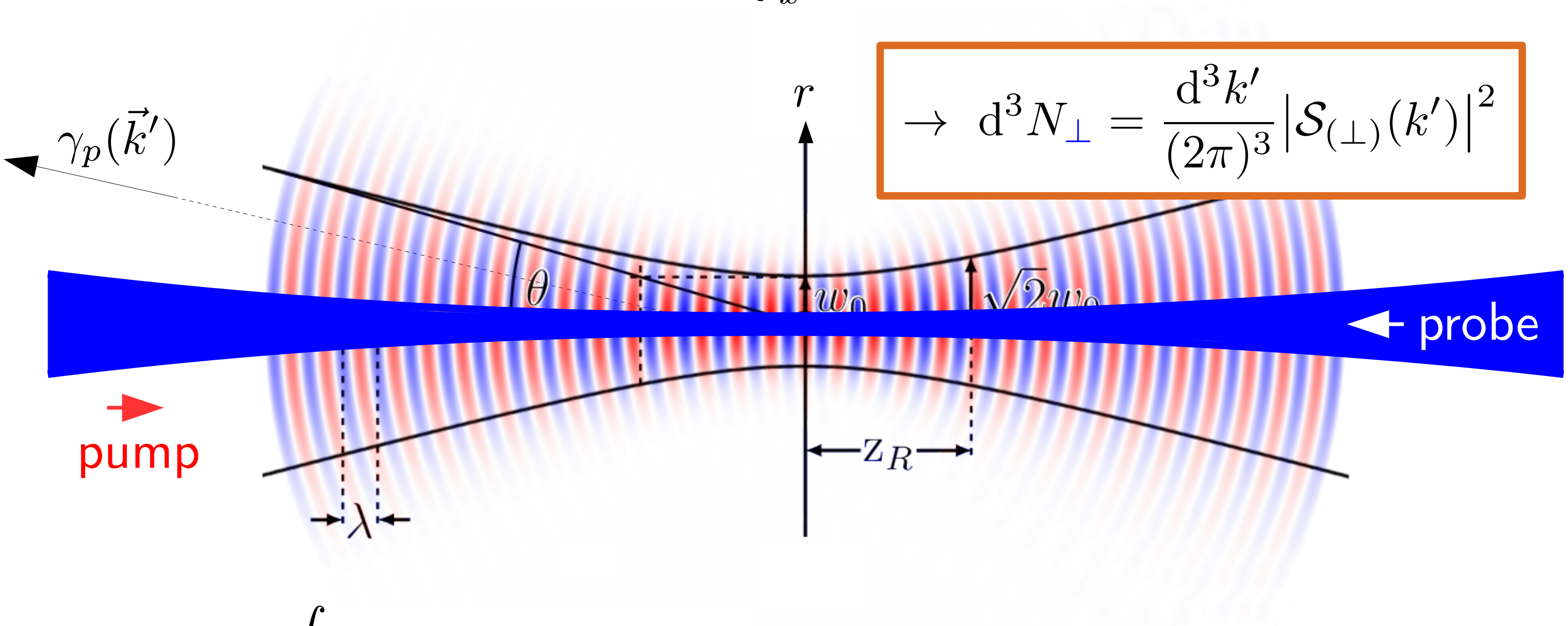


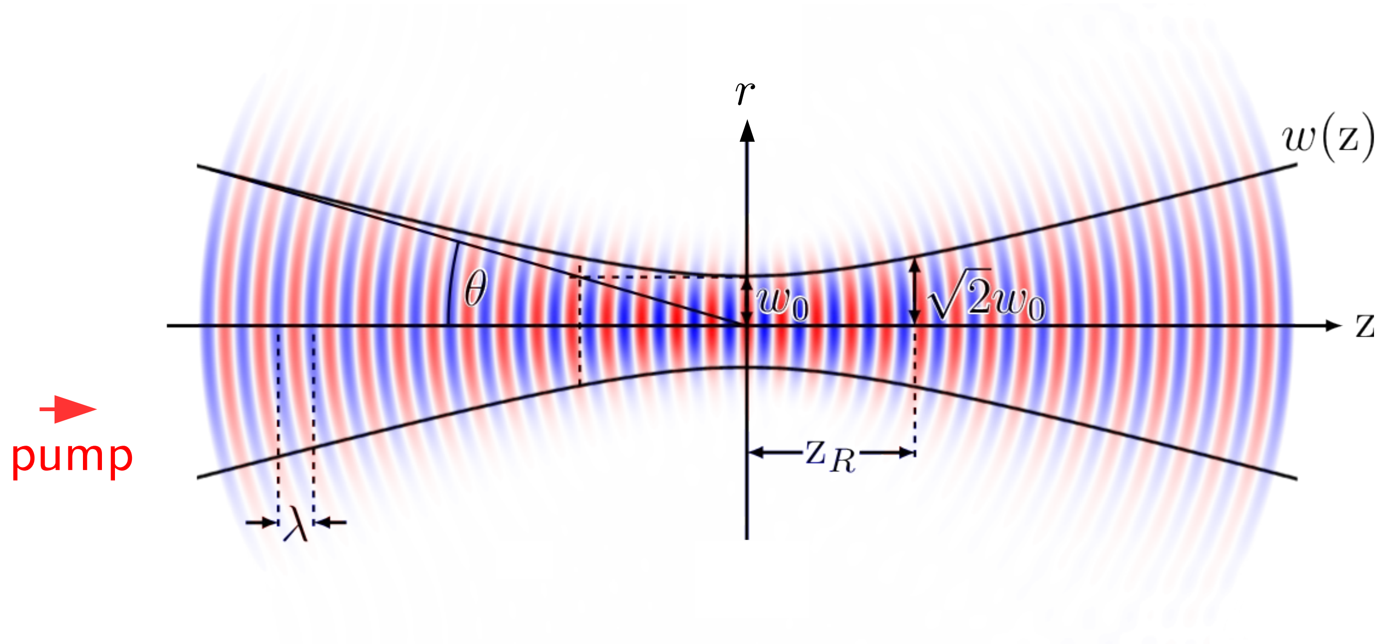
$$\rightarrow \; \mathrm{d}^3 N_\perp = \frac{\mathrm{d}^3 k'}{(2\pi)^3} \left| \mathcal{S}_{(\perp)}(k') \right|^2$$

$$j^\mu(x) = \int_{x'} \Pi^{\mu\nu}(x, x' | \mathcal{A}) A_\nu(x')$$

(iii) Vacuum birefringence

Our **results**: [FK, Gies, Reuter, Zepf: arXiv:1507.01084]

- we consider three different cases



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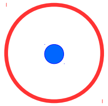
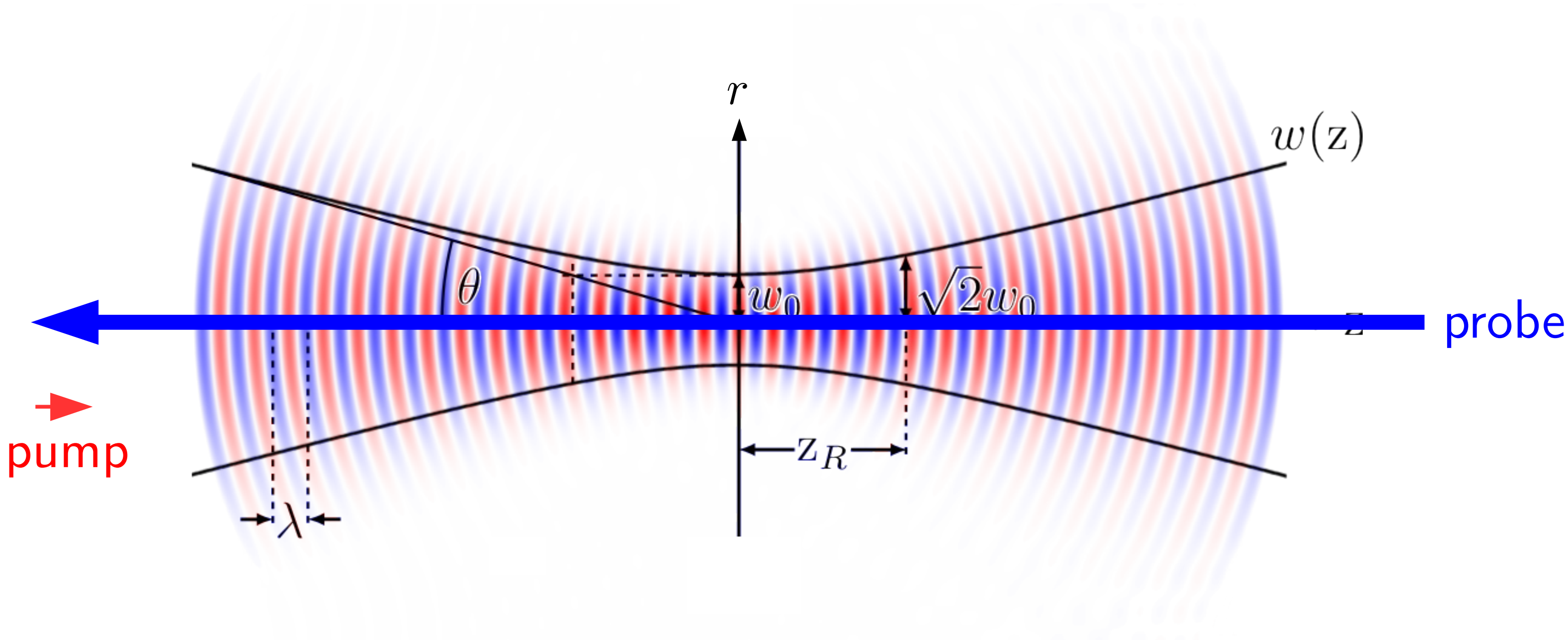
→ case (a): 



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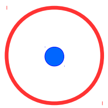
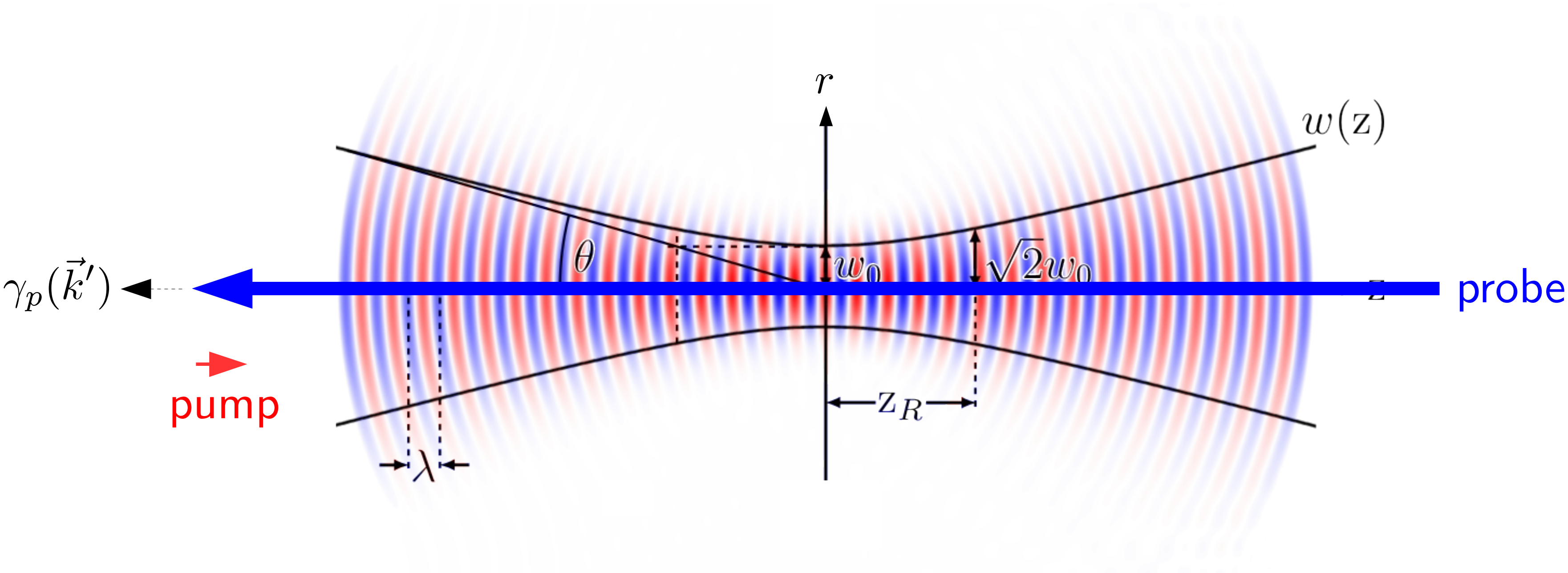
→ case (a): 



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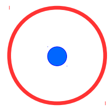
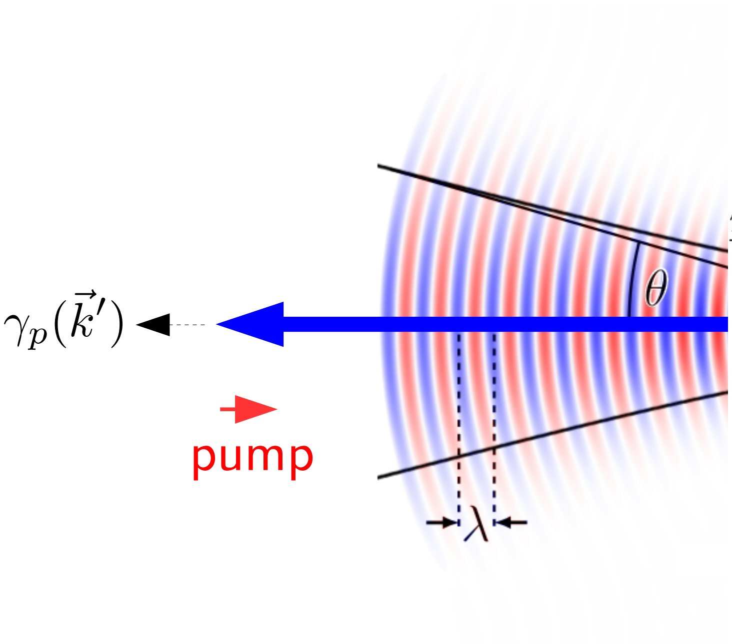
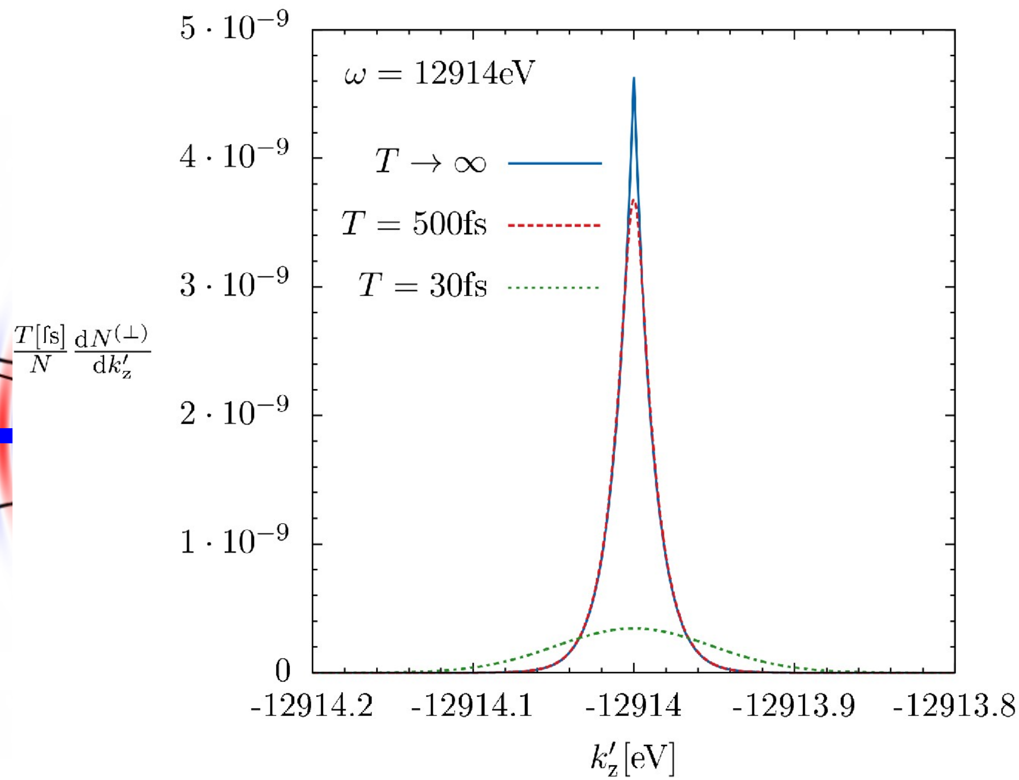
→ case (a): 





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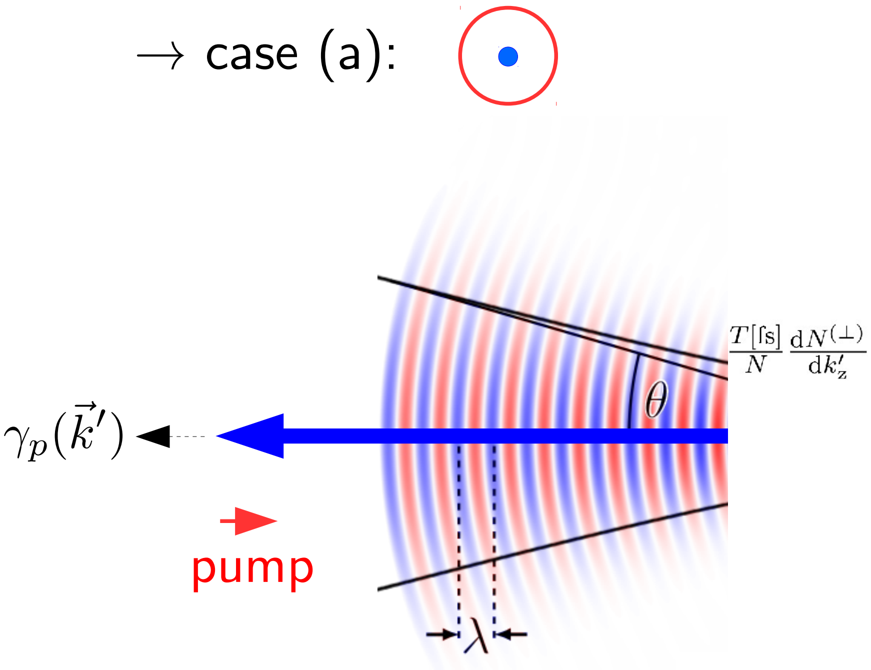

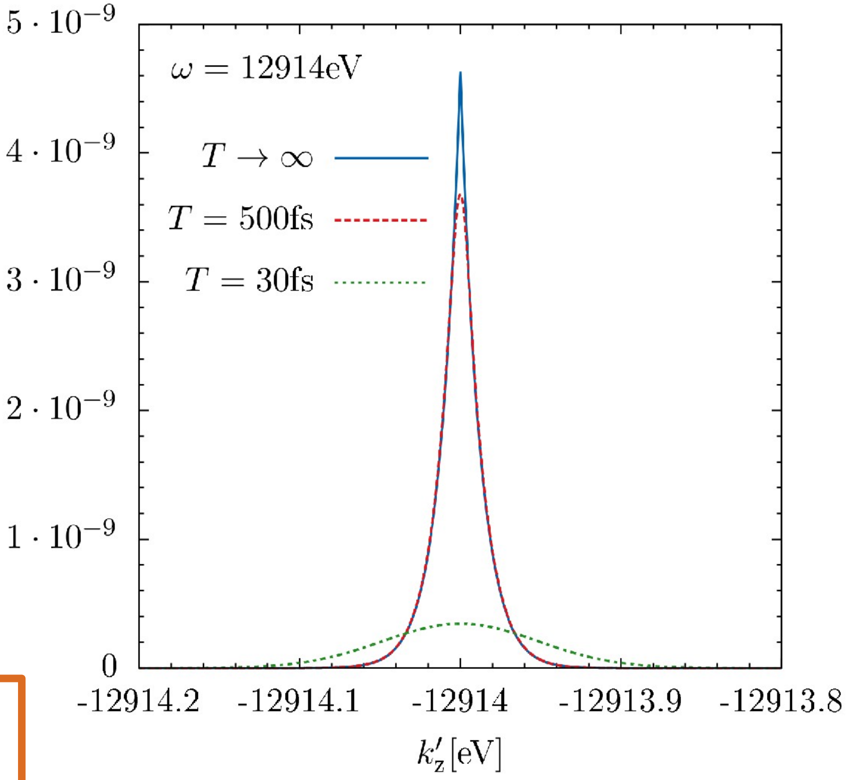

$$\left.\frac{N_\perp}{N_{\rm in}}\right|_{T=30\text{fs}} = 1.39 \cdot 10^{-12} \approx \frac{\mathcal{P}}{410}$$

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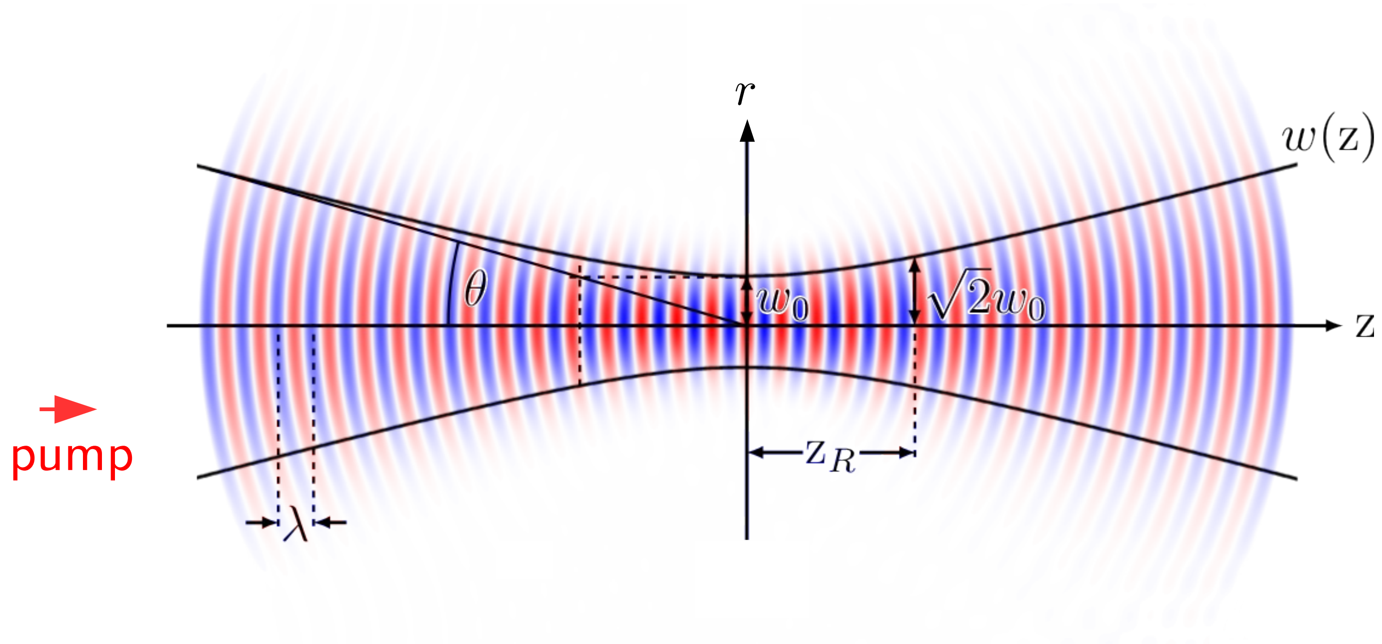

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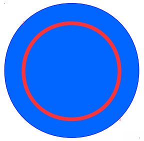
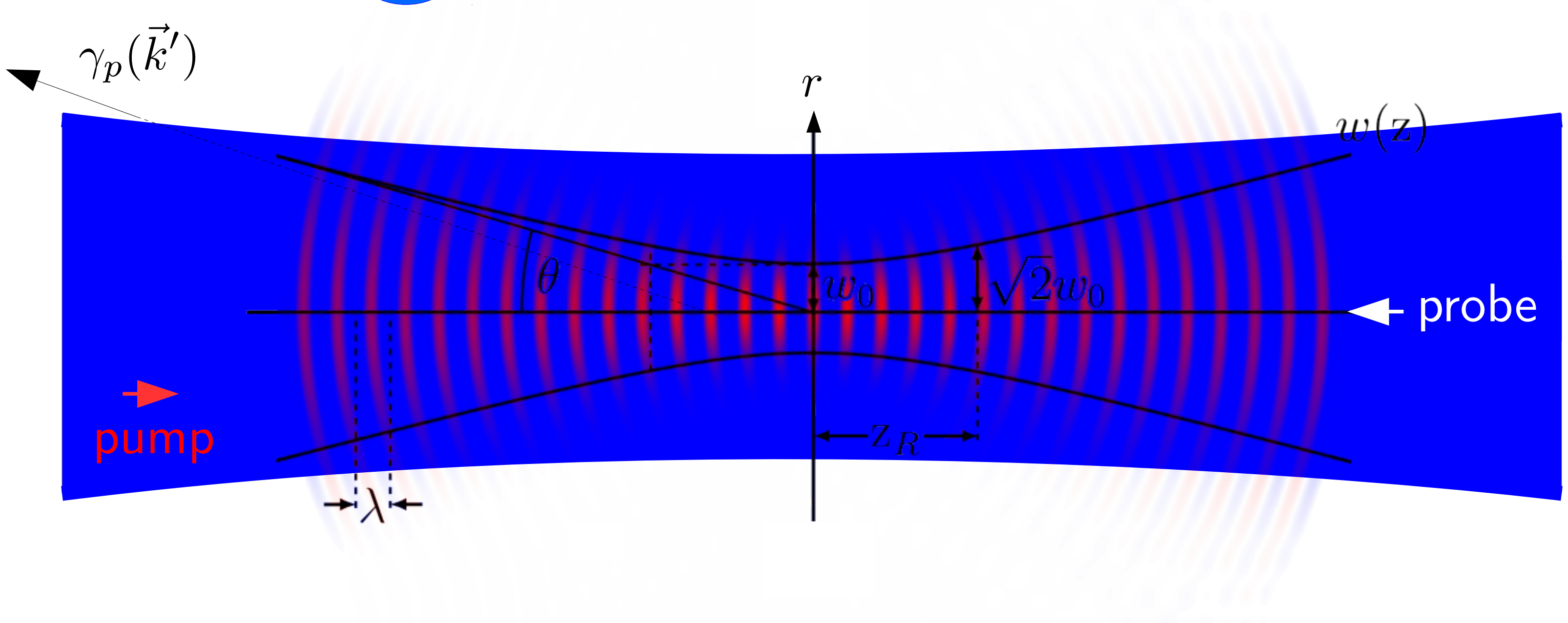
$\rightarrow$ case (b): 



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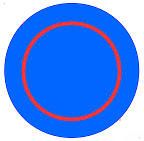
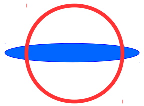
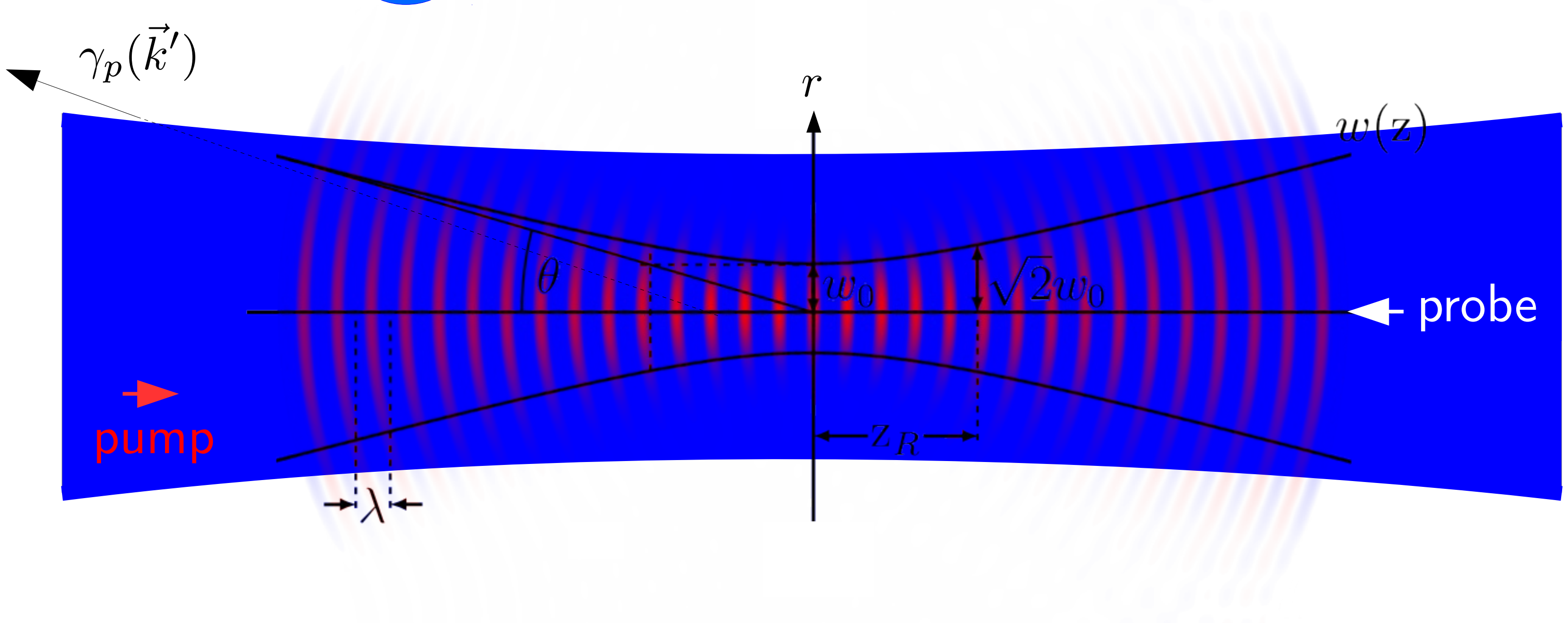
$\rightarrow$ case (b):  and case (c): 



ExHILP Conference, MPI Heidelberg, July 22th 2015

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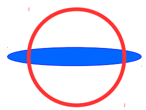
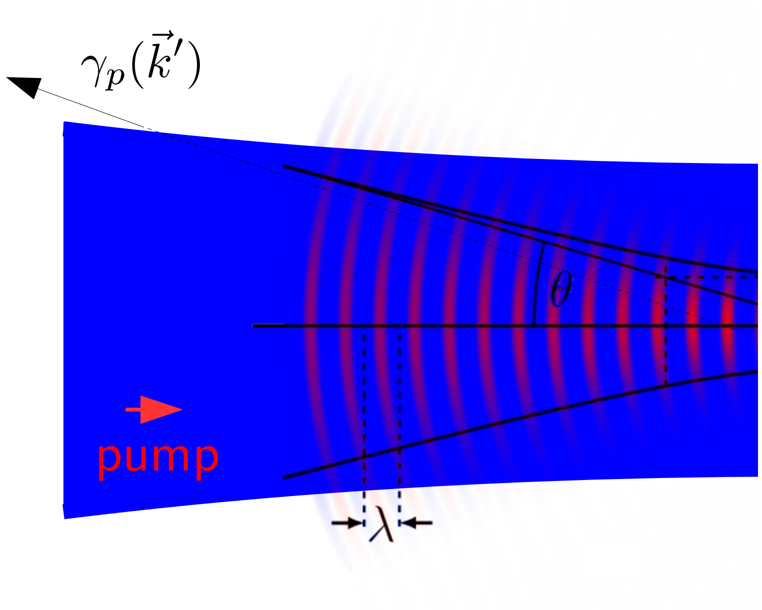
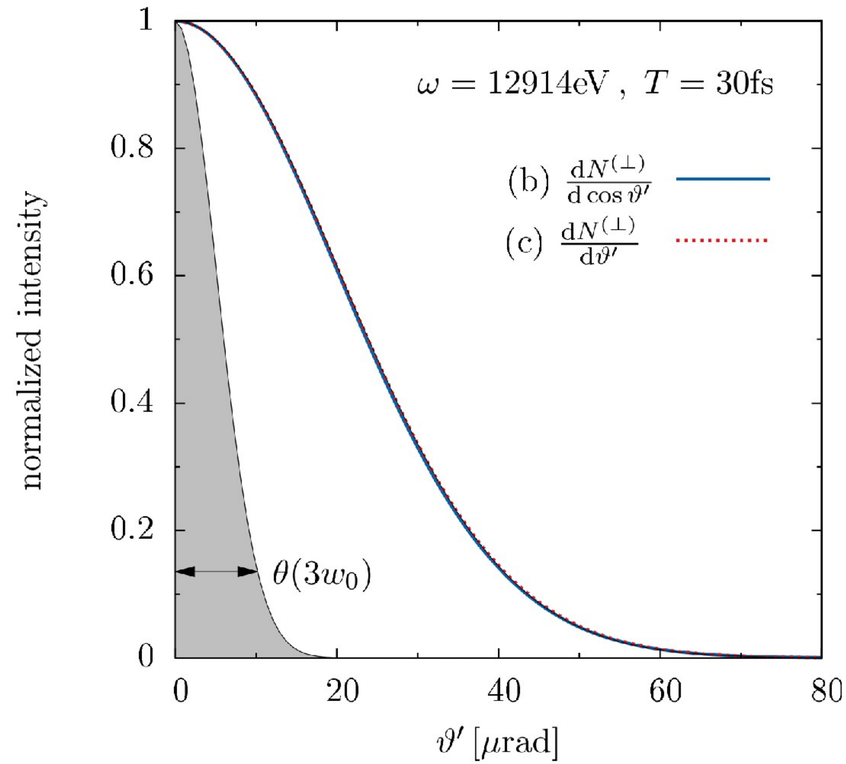
→ case (c): 





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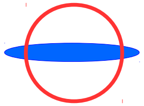
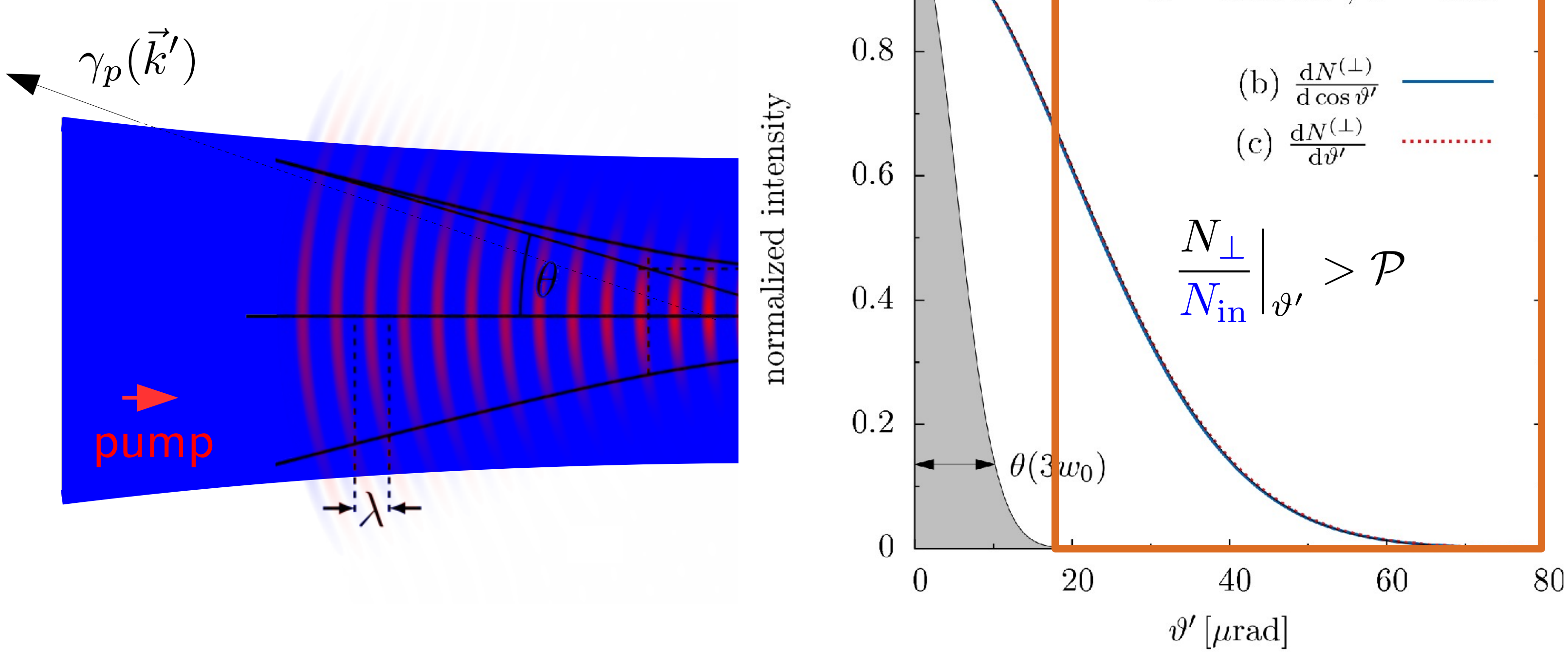
→ case (c): 



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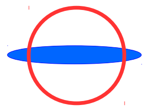
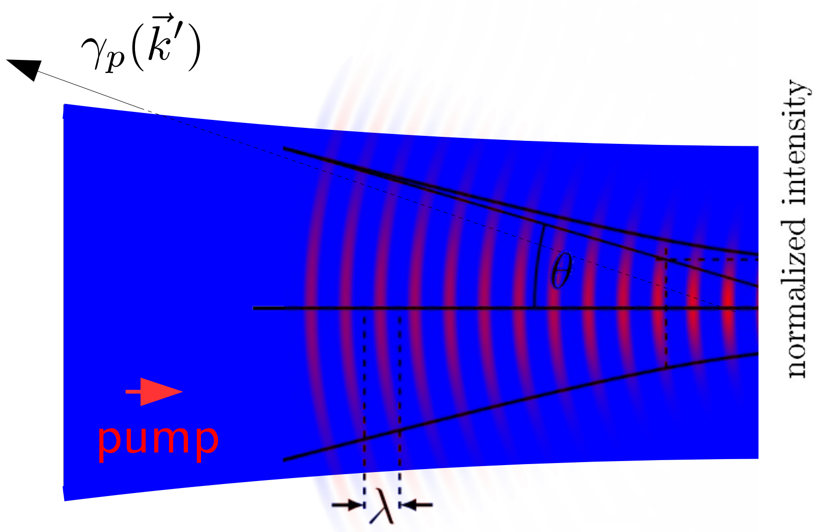
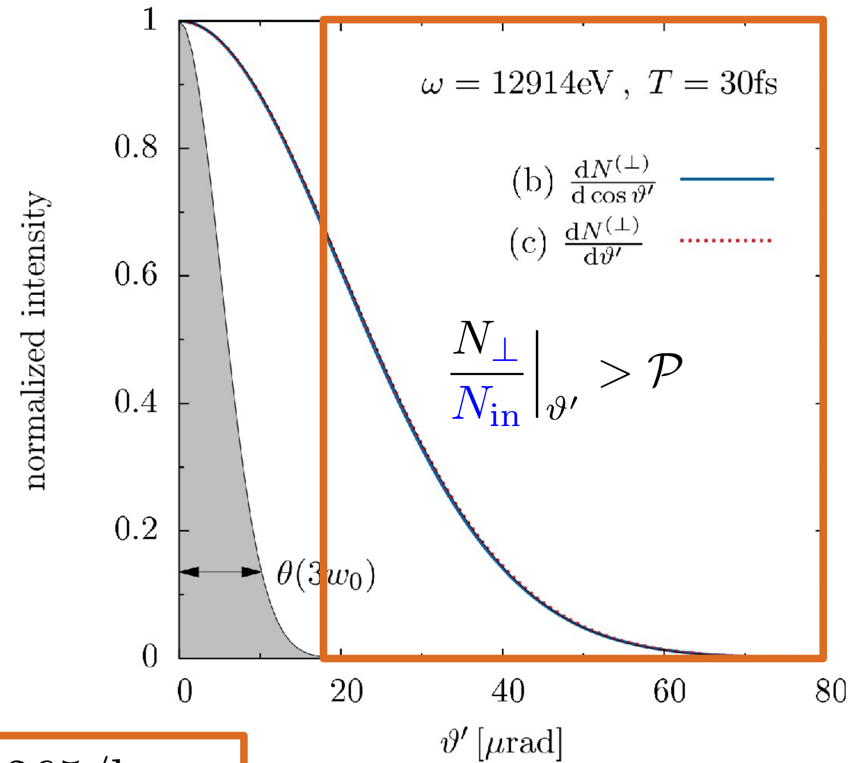
→ case (c): 





→ repetition rate 1Hz : $N_\perp \approx 265/\text{hour}$

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Thank you for your attention!