All-optical probes of quantum vacuum nonlinearity

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Helmholtz-Institut Jena & Friedrich-Schiller-Universität Jena

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Probing quantum vacuum nonlinearity with high-intensity lasers

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HELMHOLTZ GEMEINSCHAFT

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Outline

(i) Introduction

(ii) Our approach

(iii) Vacuum birefringence

(iv) Conclusions & Outlook

(i) Introduction

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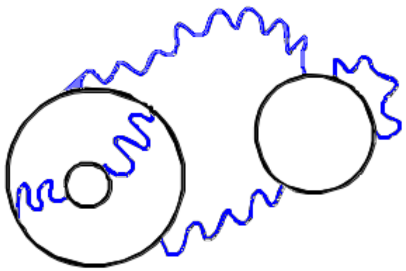
The **quantum** vacuum is not empty and boring, but rather a highly nontrivial interacting medium.



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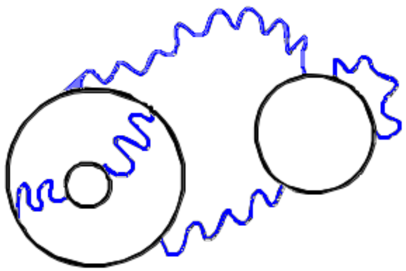
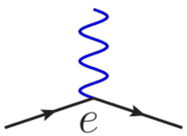


- knows about particle content and interactions of the theory,
  in QED: $\mathrm{e}^-, \mathrm{e}^+, \gamma$ interacting via



e: electron charge

- particle-antiparticle fluctuations, virtual (= off-shell) particles

- happens everywhere/all the time

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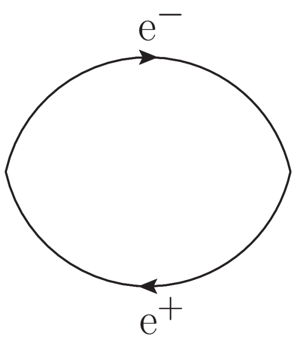

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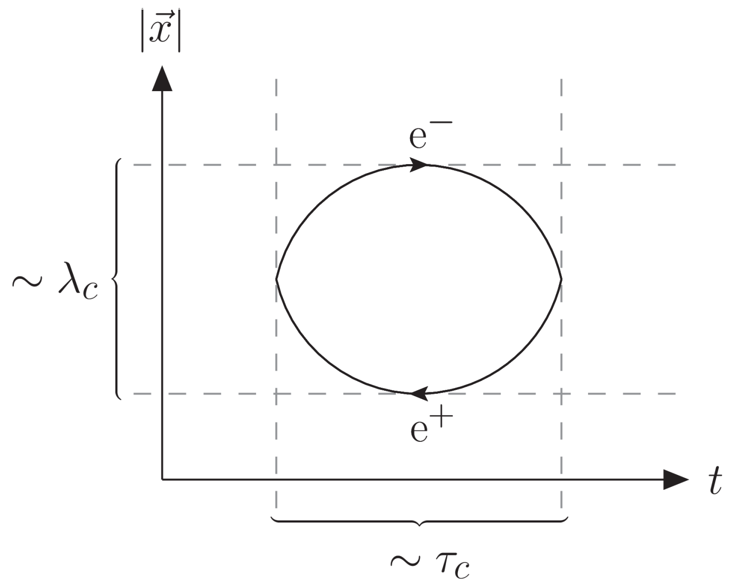

$$\lambda_c \sim \tau_c \sim \frac{1}{m_e}$$

$$\lambda_c = 3.9 \cdot 10^{-13}\mathrm{m}$$

$$\tau_c = 1.3 \cdot 10^{-21}\mathrm{s}$$

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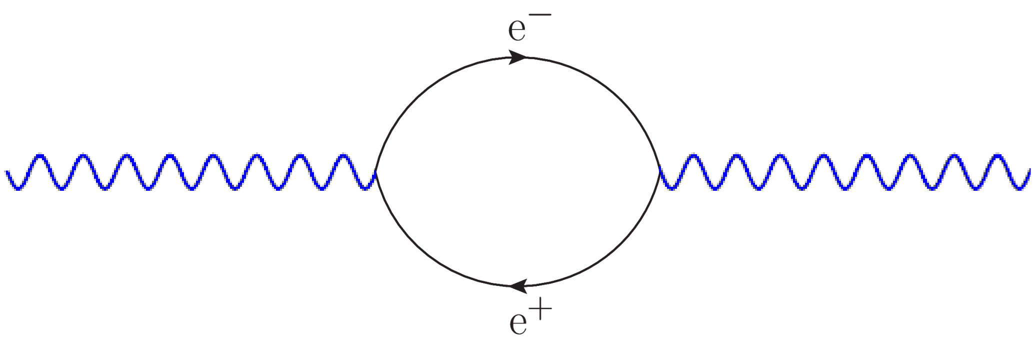

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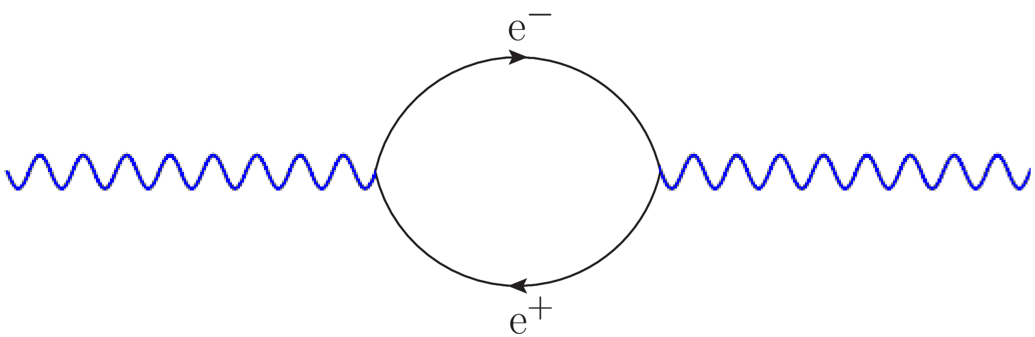

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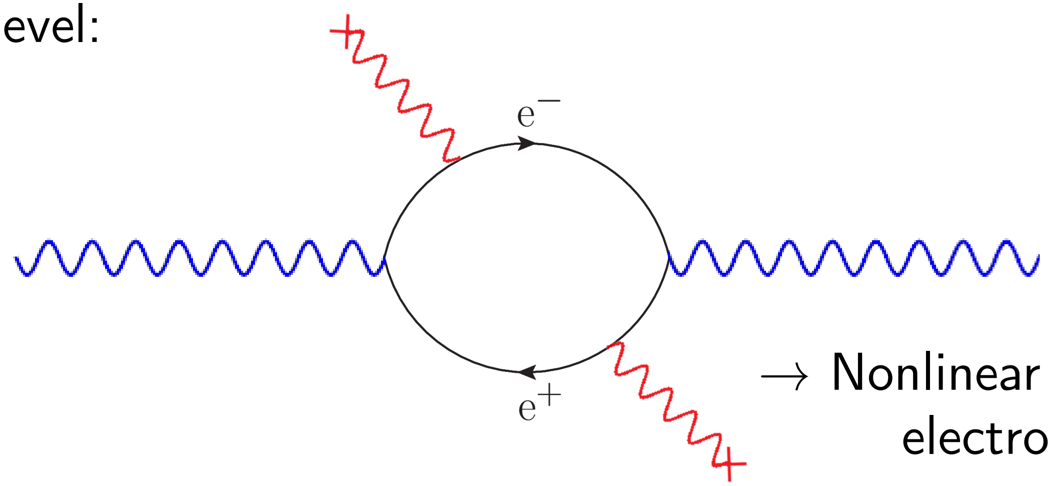

→ Nonlinear couplings between electromagnetic fields.

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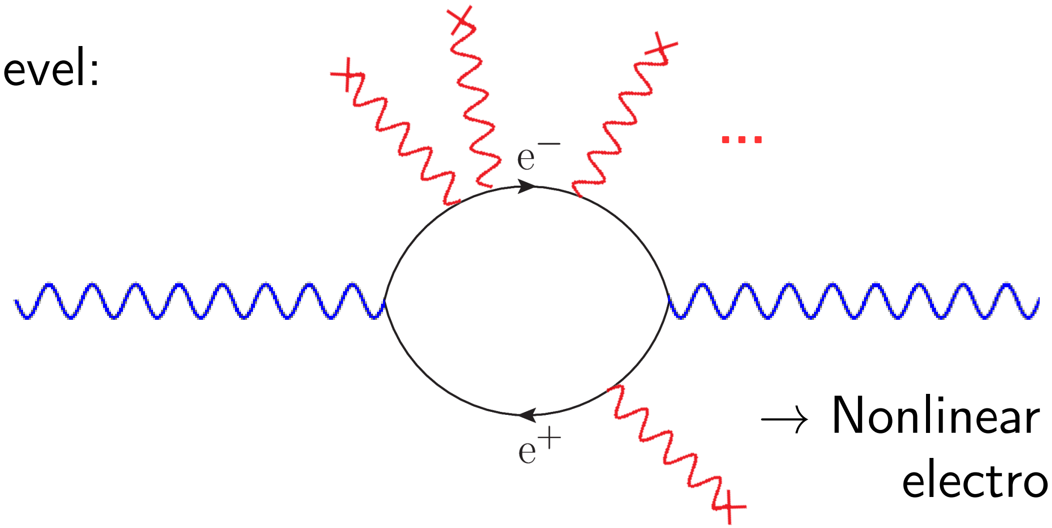

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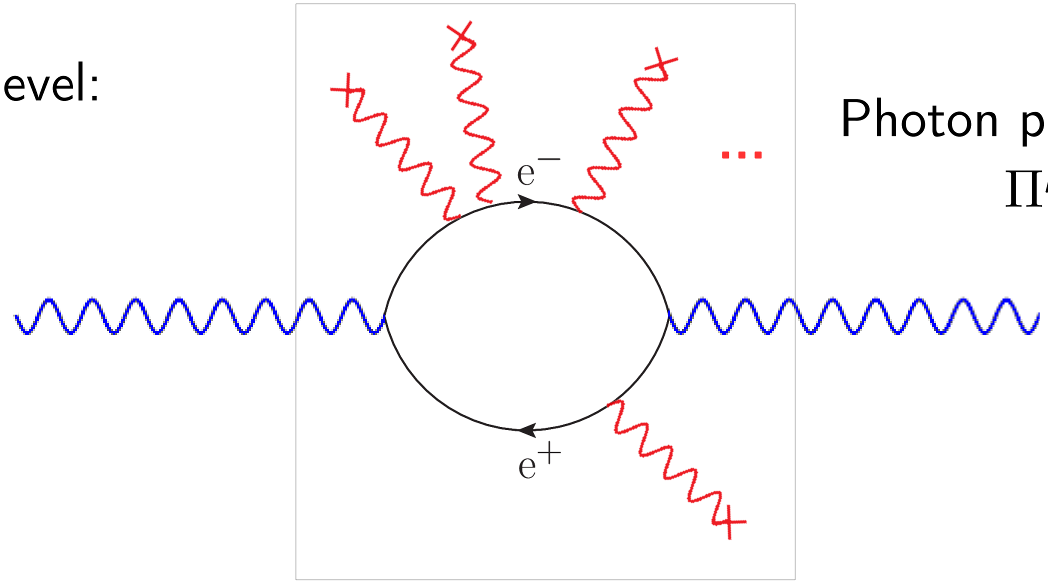

Photon polarization tensor:
$\Pi^{\mu\nu}(x, x'|\mathcal{A})$

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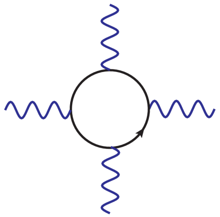
Quantum vacuum nonlinearity manifests itself in various effects, e.g.,

- direct light-by-light scattering



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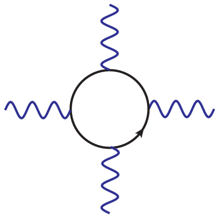

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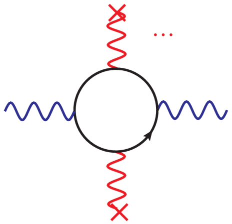
- vacuum birefringence



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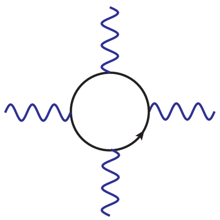

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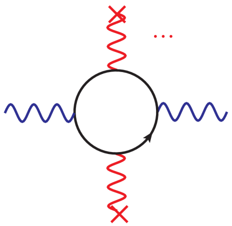

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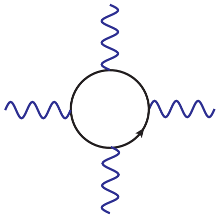

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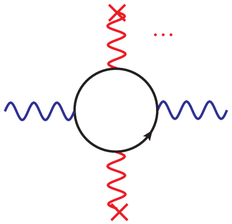

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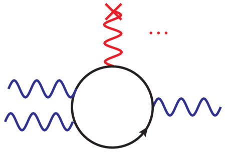

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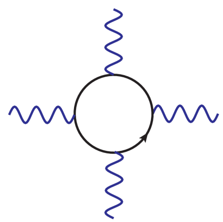

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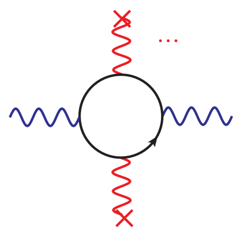

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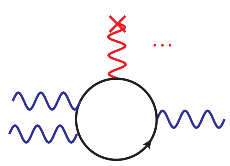

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[Gies, FK, Shaisultanov: Phys. Rev. D 2014]

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

- Photon polarization tensor [Batalin, Shabad: JETP 1971] [Baier, Milshtein, Strakhovenko: JETP 1975] [Becker, Mitter: J. Phys. A 1975]

↔ the electromagnetic fields delivered by focused high-intensity lasers are highly inhomogeneous

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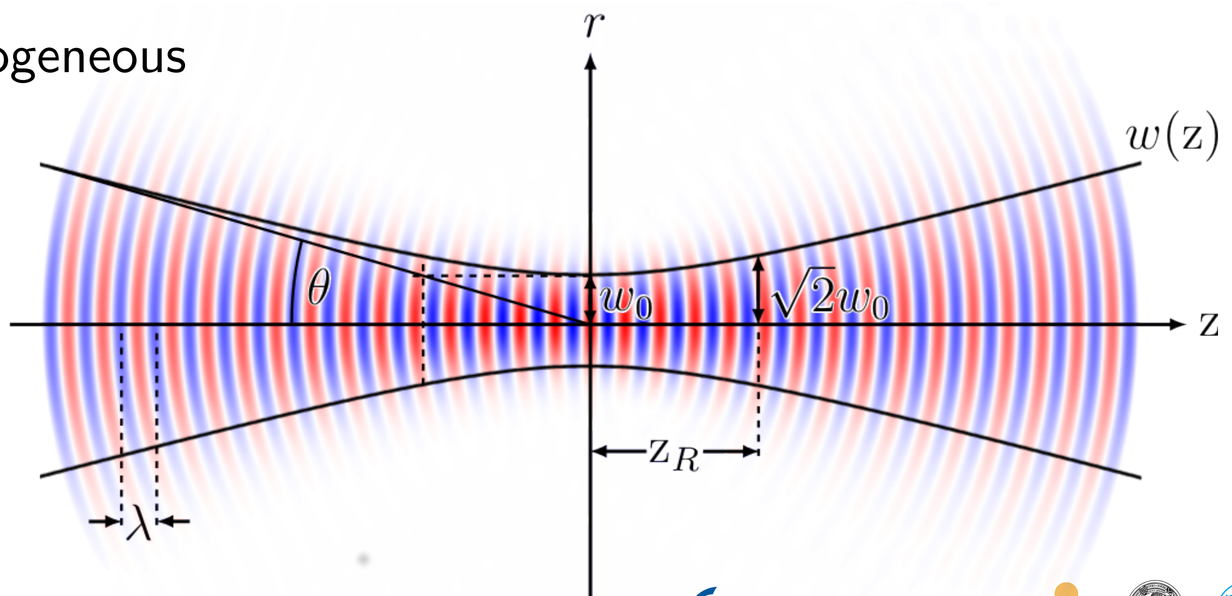
- Pulsed, focused Gaussian beams



(ii) Our approach

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

```
[…] den speziellen Fall […], in dem keine wirklichen
Elektronen und Positronen vorhanden sind, und in dem sich
das Feld auf Strecken der Compton-Wellenlänge nur wenig ändert.
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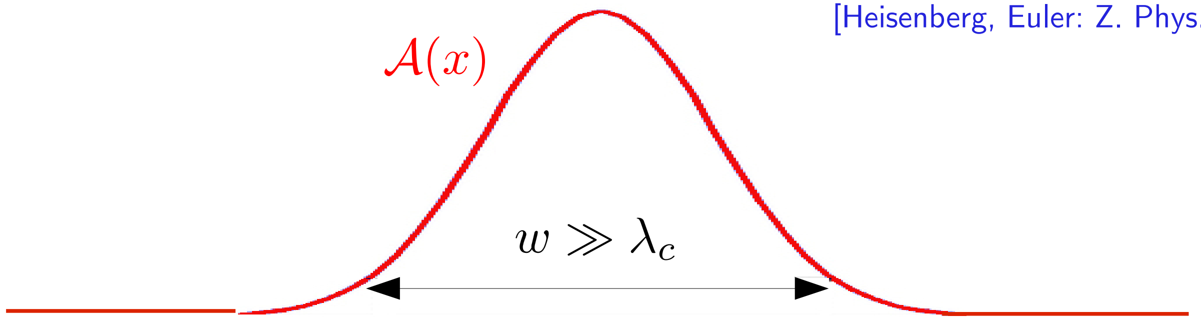
[Heisenberg, Euler: Z. Phys. 1936]



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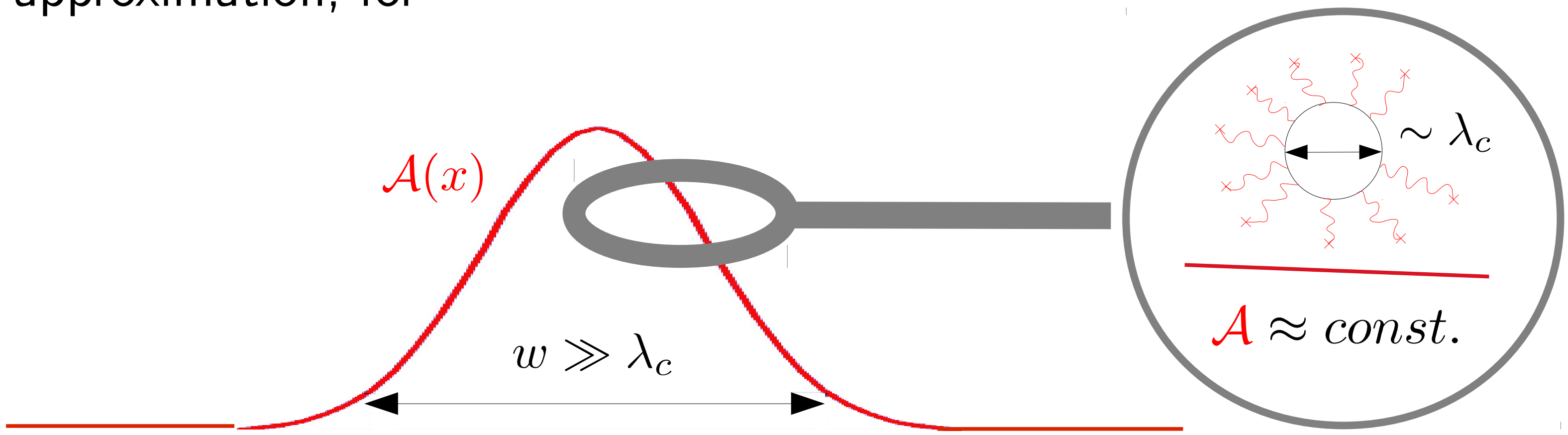

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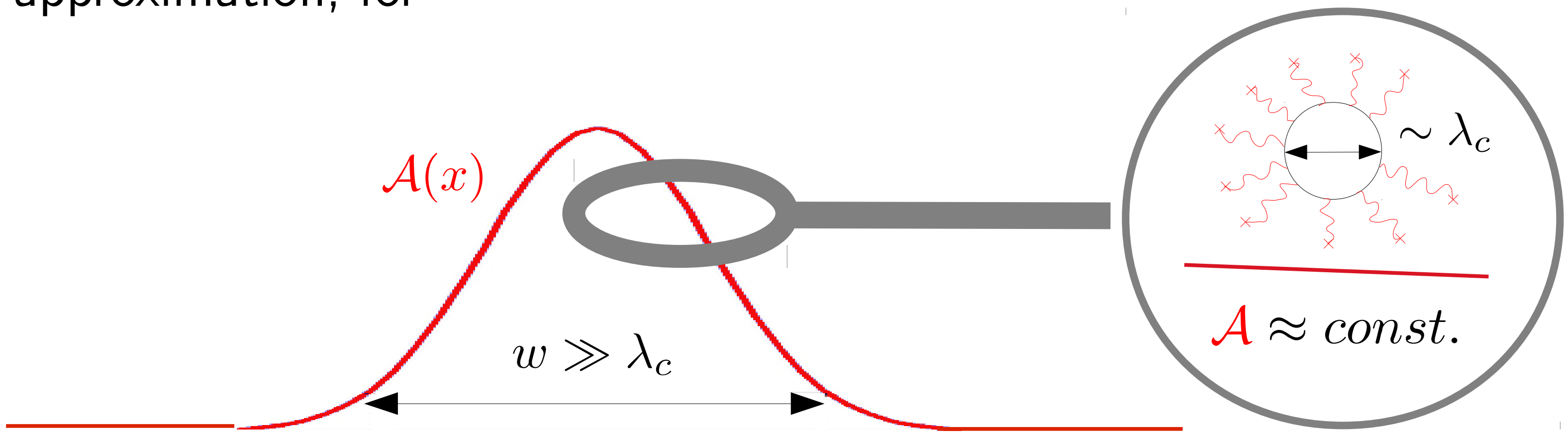

- analytical insights possible without having to solve the problem for the exact, inhomogeneous background field configuration.

$\rightarrow$ Polarization tensor in pulsed, focused Gaussian beams

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

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

(iii) Vacuum birefringence

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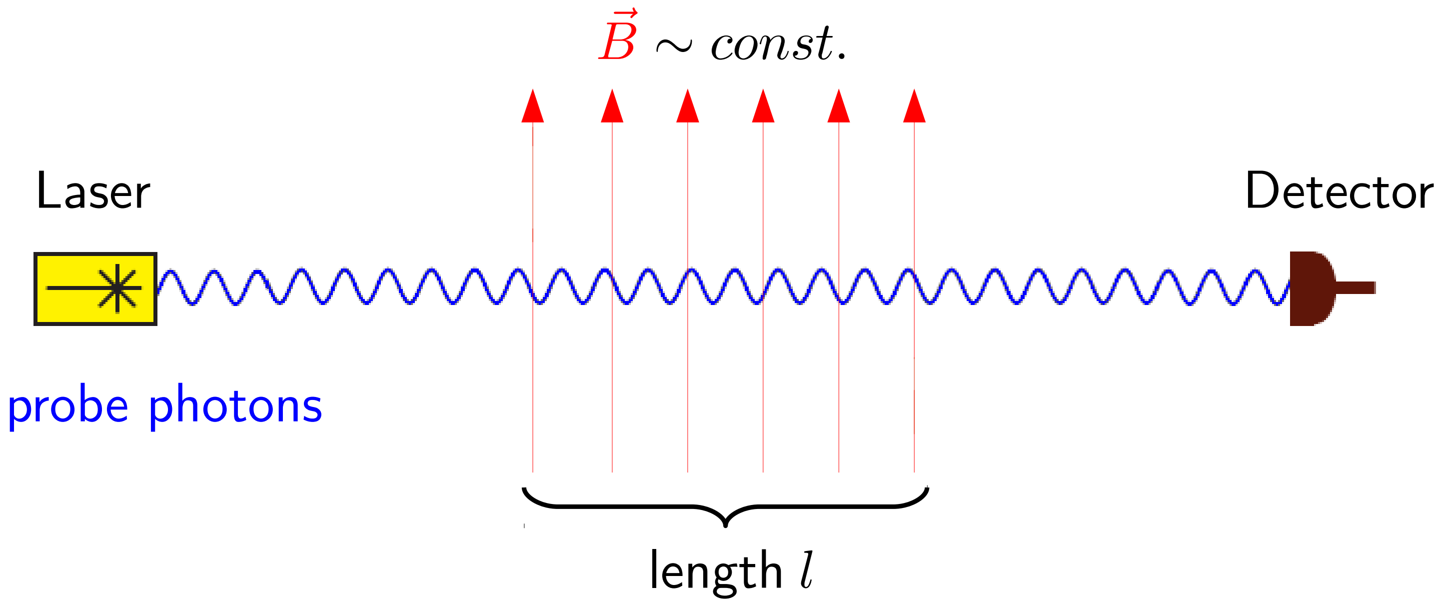
Conventional scenario:

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

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



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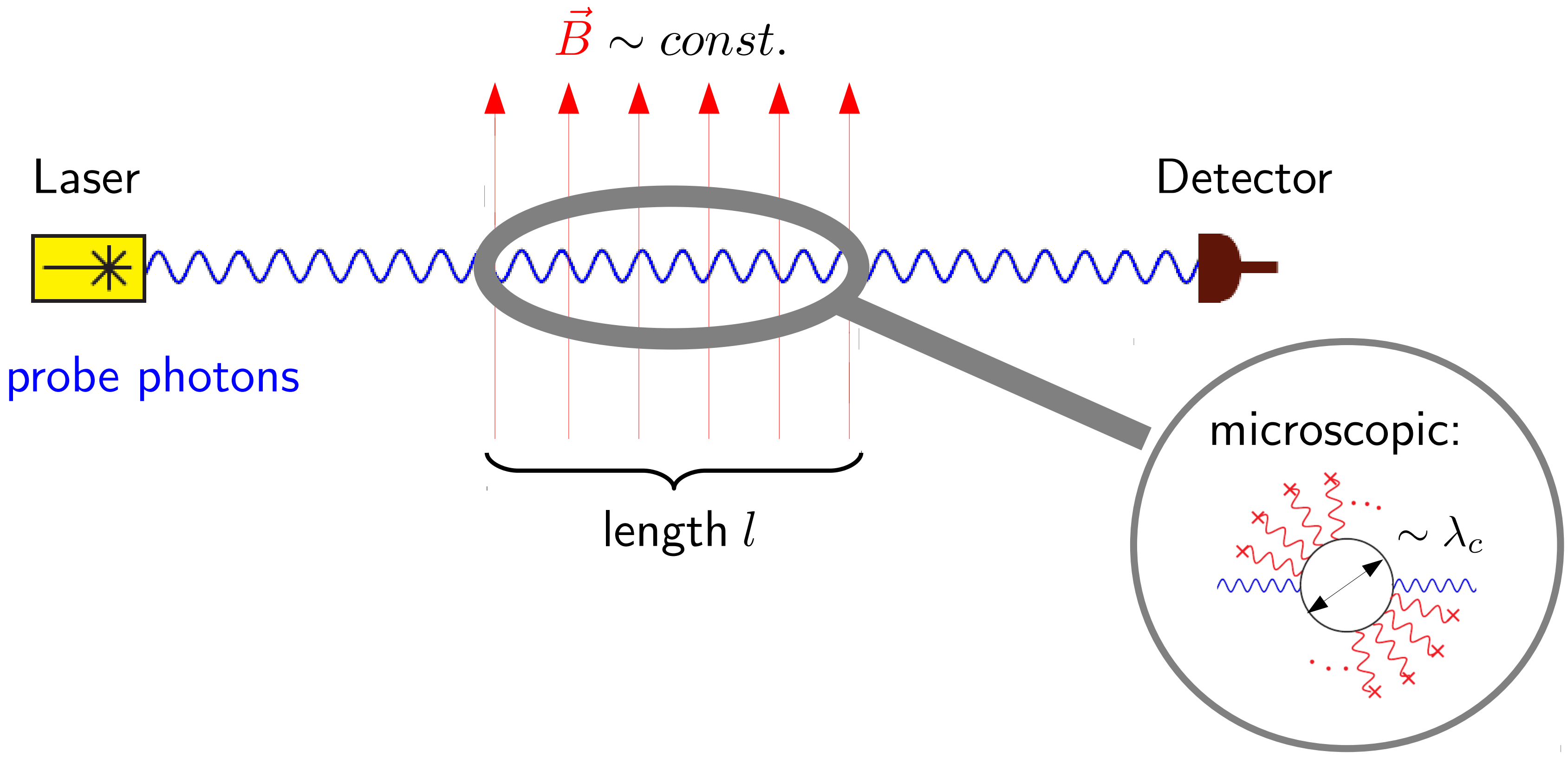

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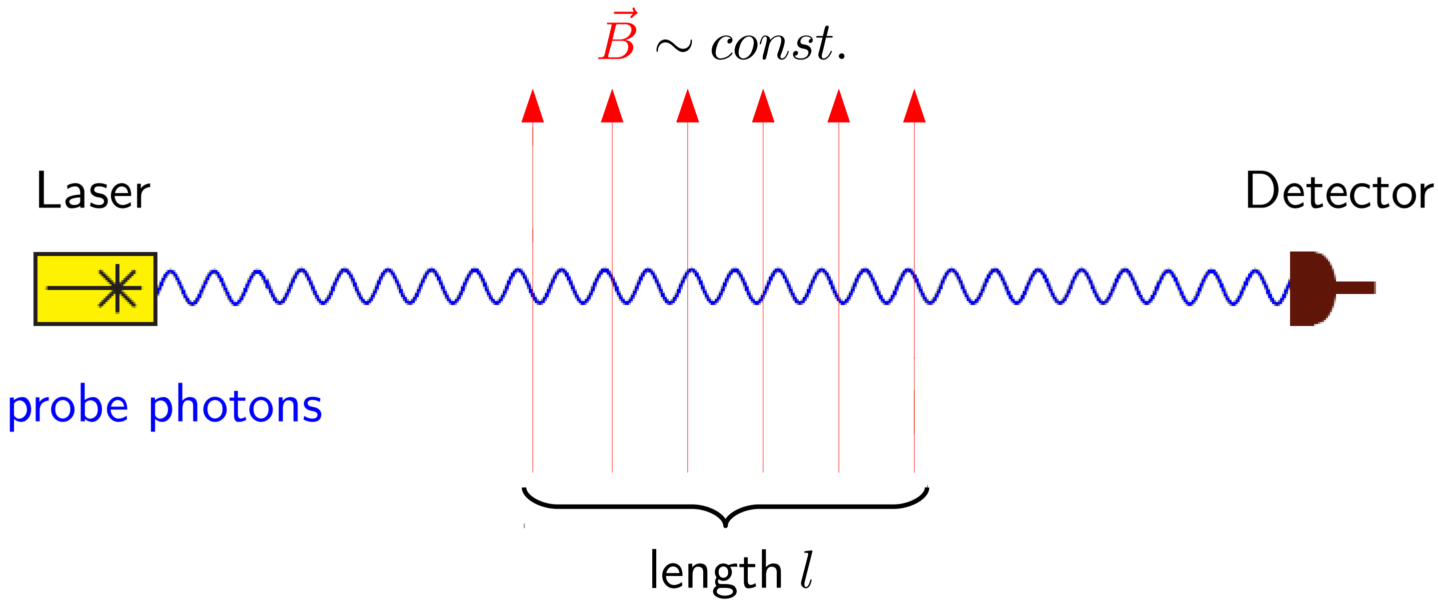

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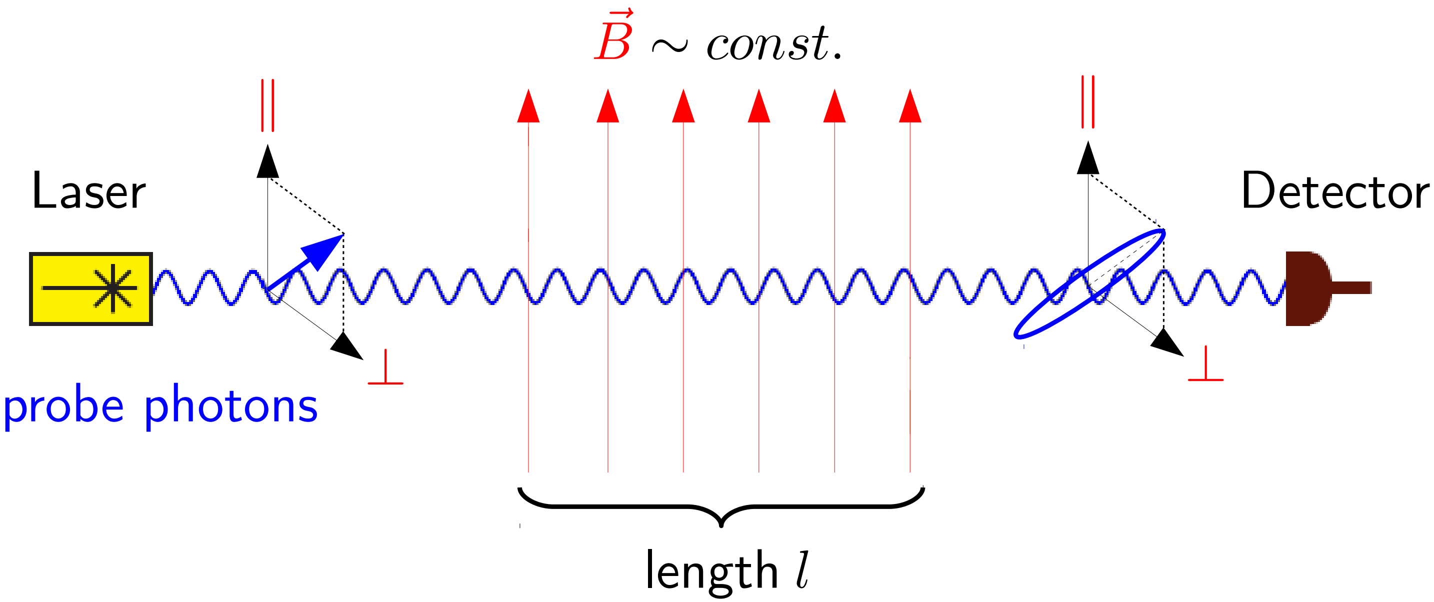

- vacuum birefringence $\rightarrow$ ellipticity: $\Delta\phi \sim \alpha \, \frac{l}{\lambda} \left(\frac{eB}{m_e^2} \right)^2$ $\leftarrow$ relative phase shift between $\parallel$ and $\perp$ modes

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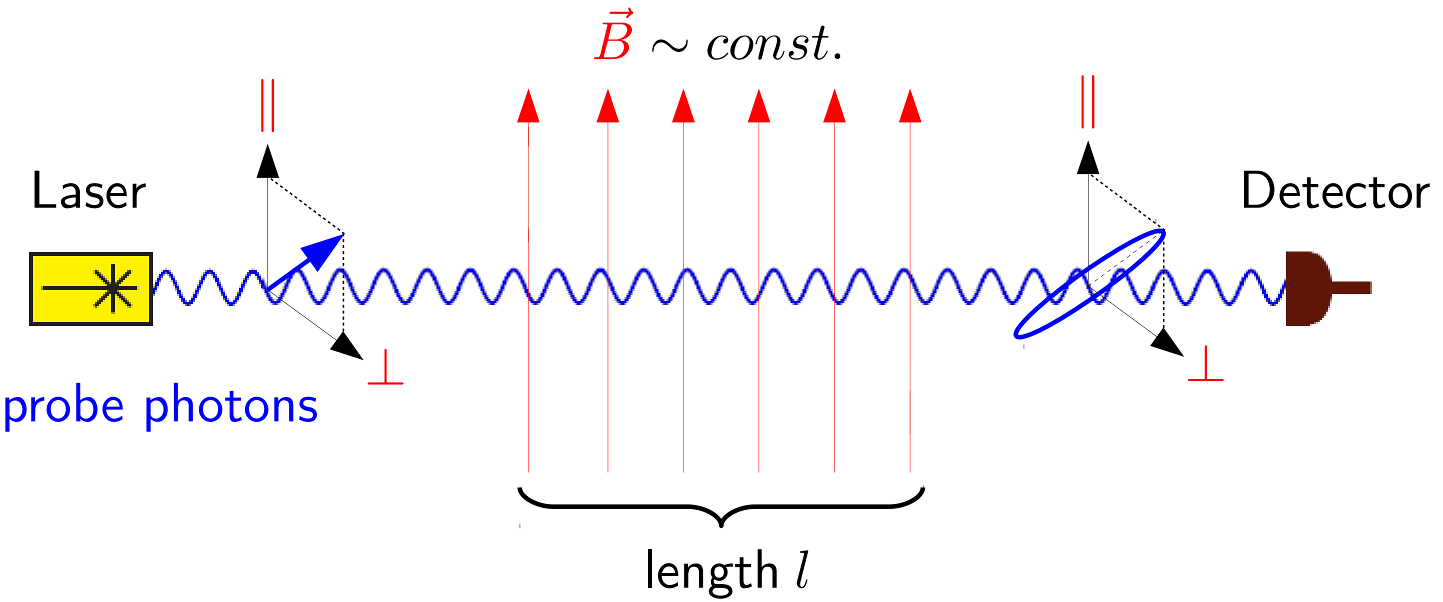

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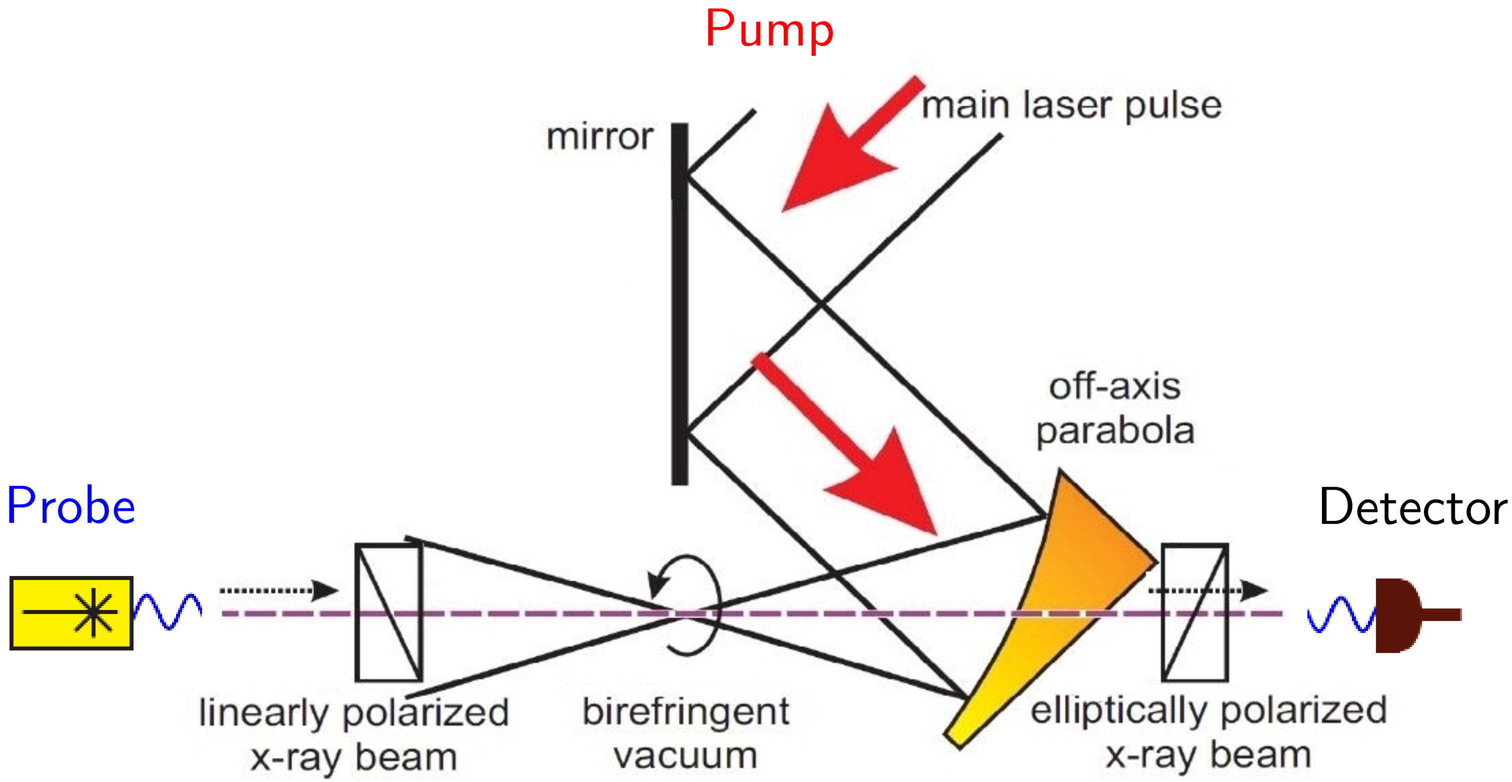
$\leftrightarrow$ photons in $\perp$ polarization mode induced: $N_\perp \simeq \left(\frac{\Delta\phi}{2} \right)^2 N_{\text{in}}$

(iii) Vacuum birefringence

Analogous scenario with pump = high-intensity laser:

[Heinzl, Liesfeld, Amthor, Schwoerer, Sauerbrey, Wipf: Opt. Comm. 2006]



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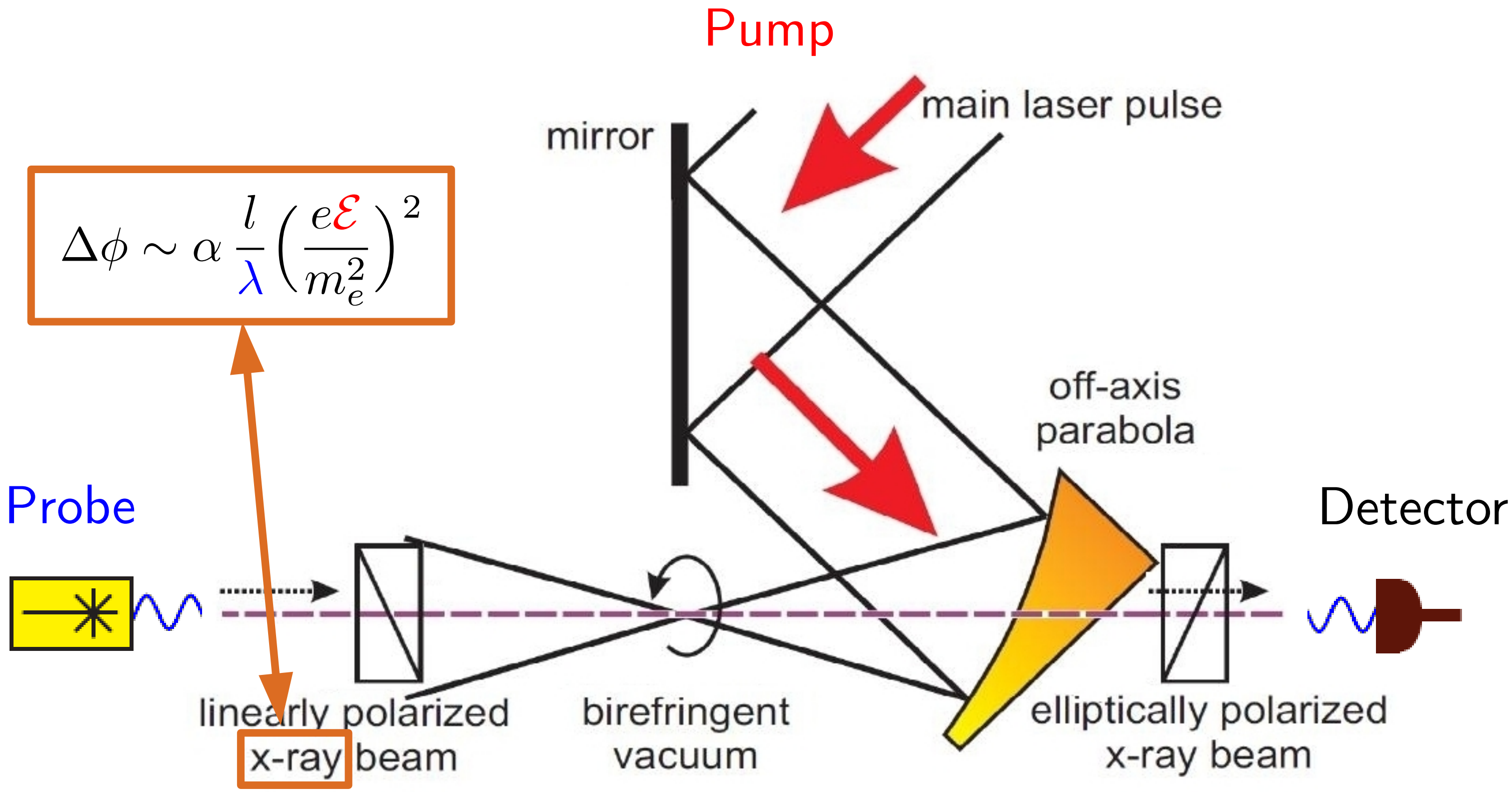
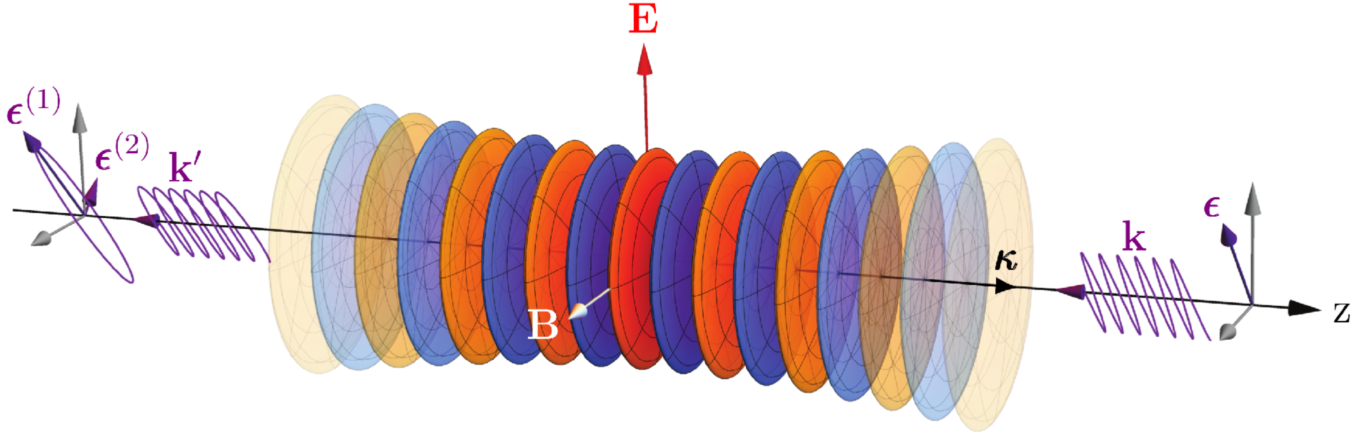


(iii) Vacuum birefringence

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, et al.: in preparation 2015]



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

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

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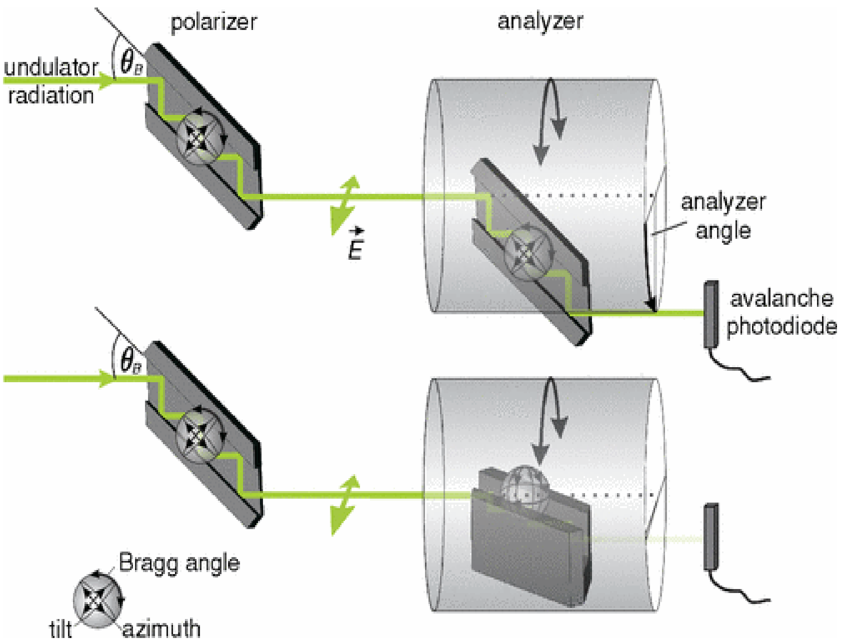
Analogous scenario with pump = high-intensity laser:

→ demand for high-purity x-ray polarimetry [Marx et al.: Phys. Rev. Lett. 2013]



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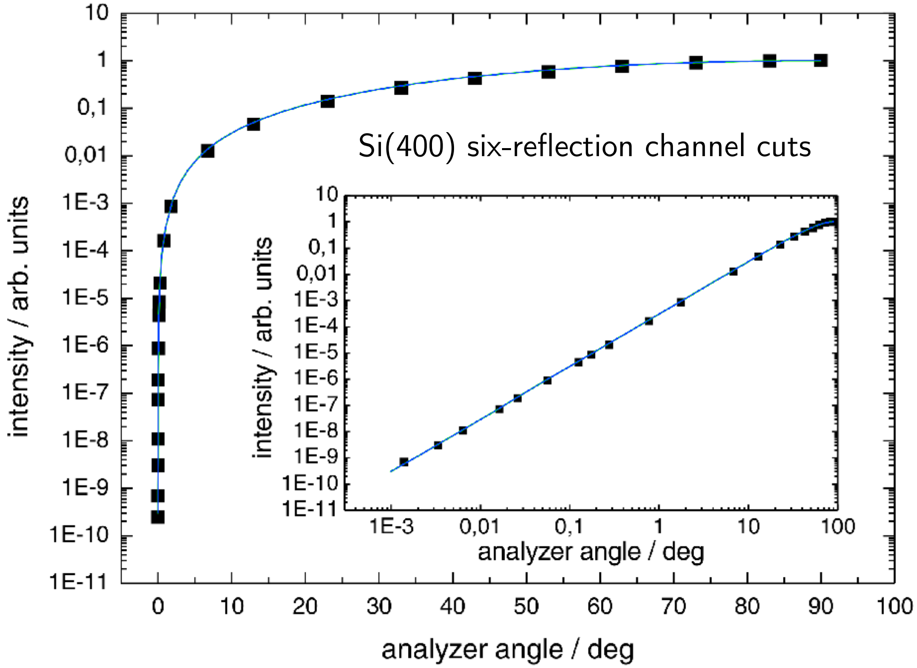

Polarization purity record @ $\omega = 12914\text{eV}$:

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

- experimental confirmation of vacuum birefringence requires $\frac{N_\perp}{N_{\rm in}} > \mathcal{P}$.

(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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$\leftrightarrow$ 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

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

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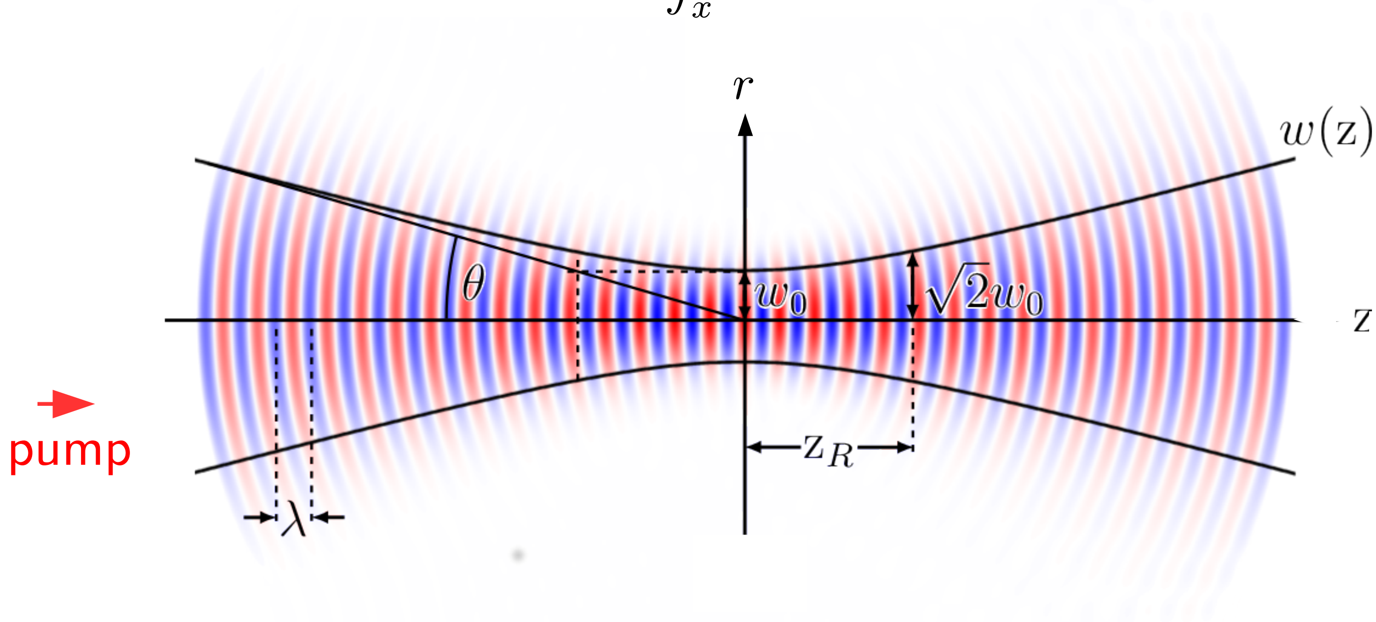

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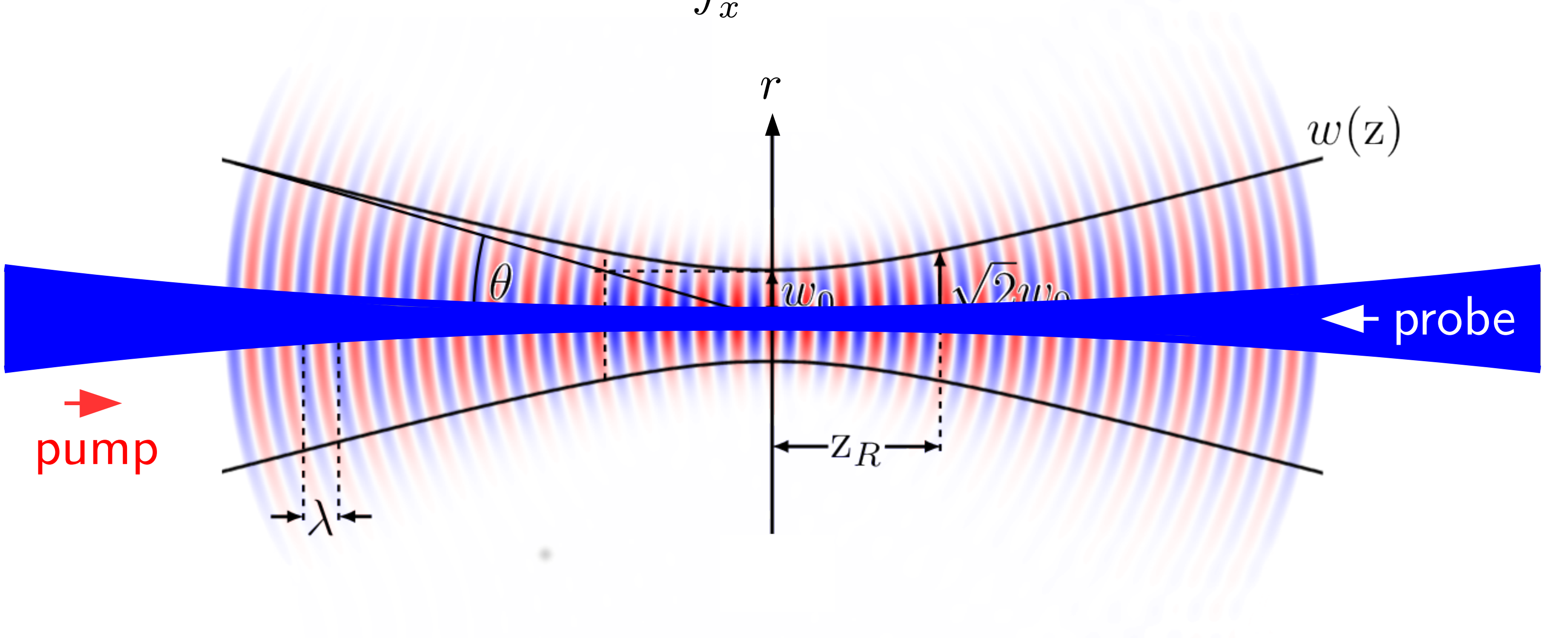

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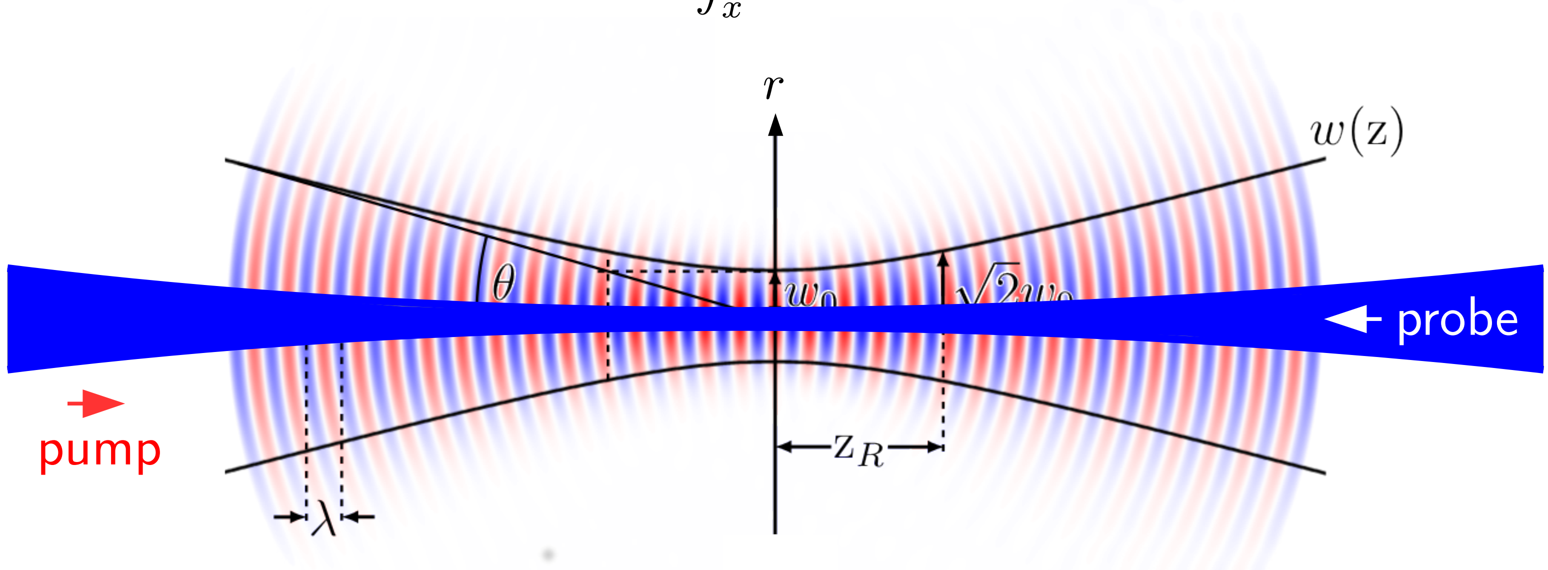

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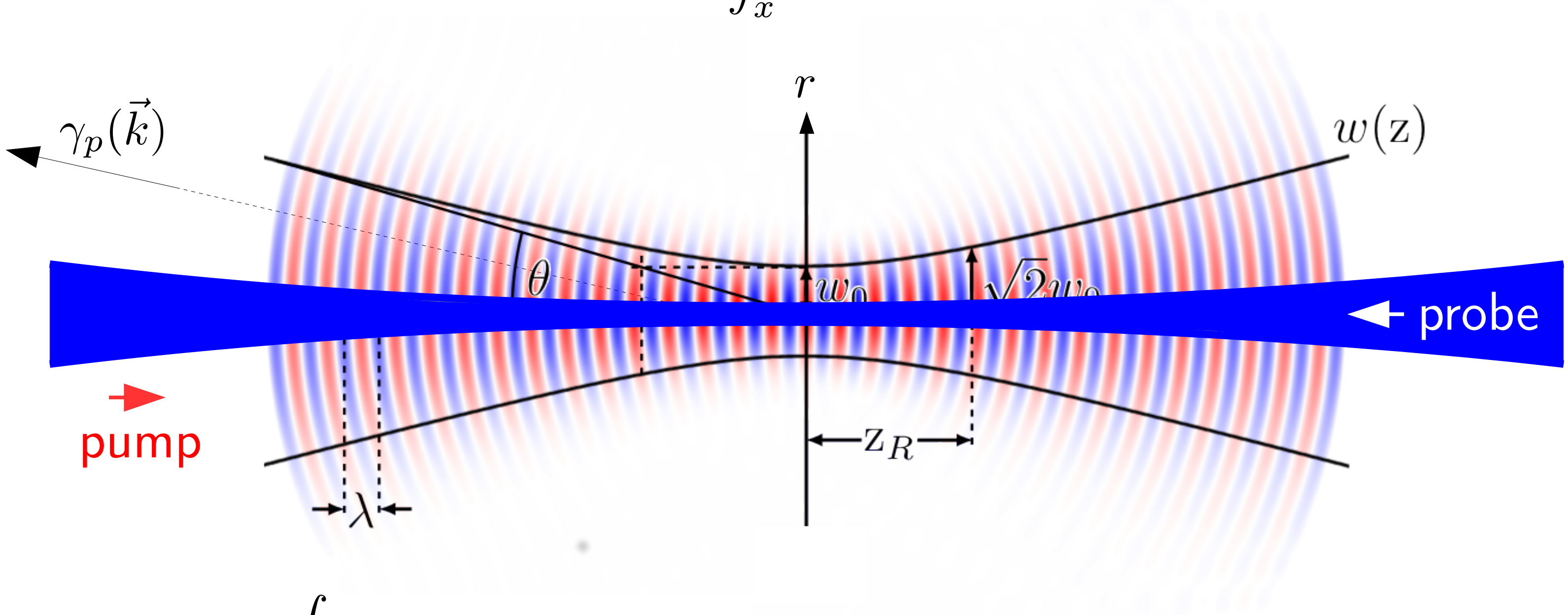

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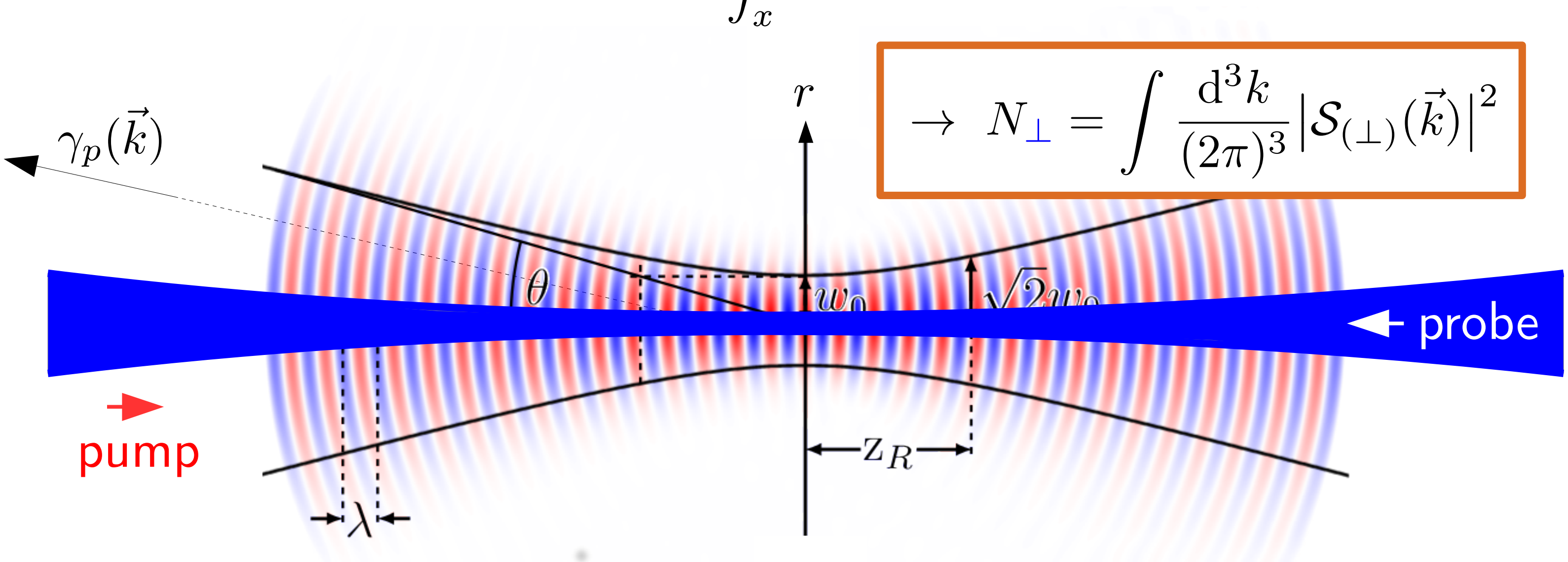
$$\boxed{\rightarrow \quad N_\perp = \int \frac{\mathrm{d}^3 k}{(2\pi)^3} \left| \mathcal{S}_{(\perp)}(\vec{k}) \right|^2}$$

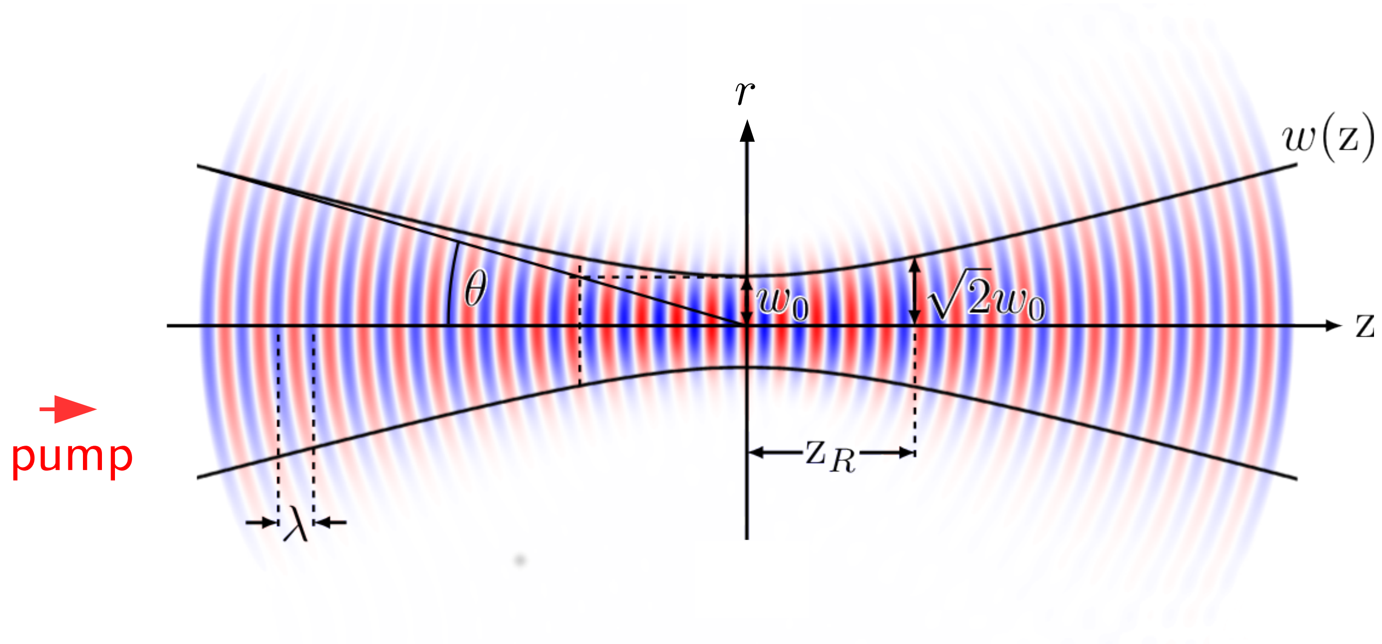


$$j^\mu(x) = \int_{x'} \Pi^{\mu\nu}(x, x' | \mathcal{A}) A_\nu(x')$$

(iii) Vacuum birefringence

Our **results**: [FK, et al.: in preparation 2015]

- we consider three different cases



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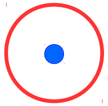
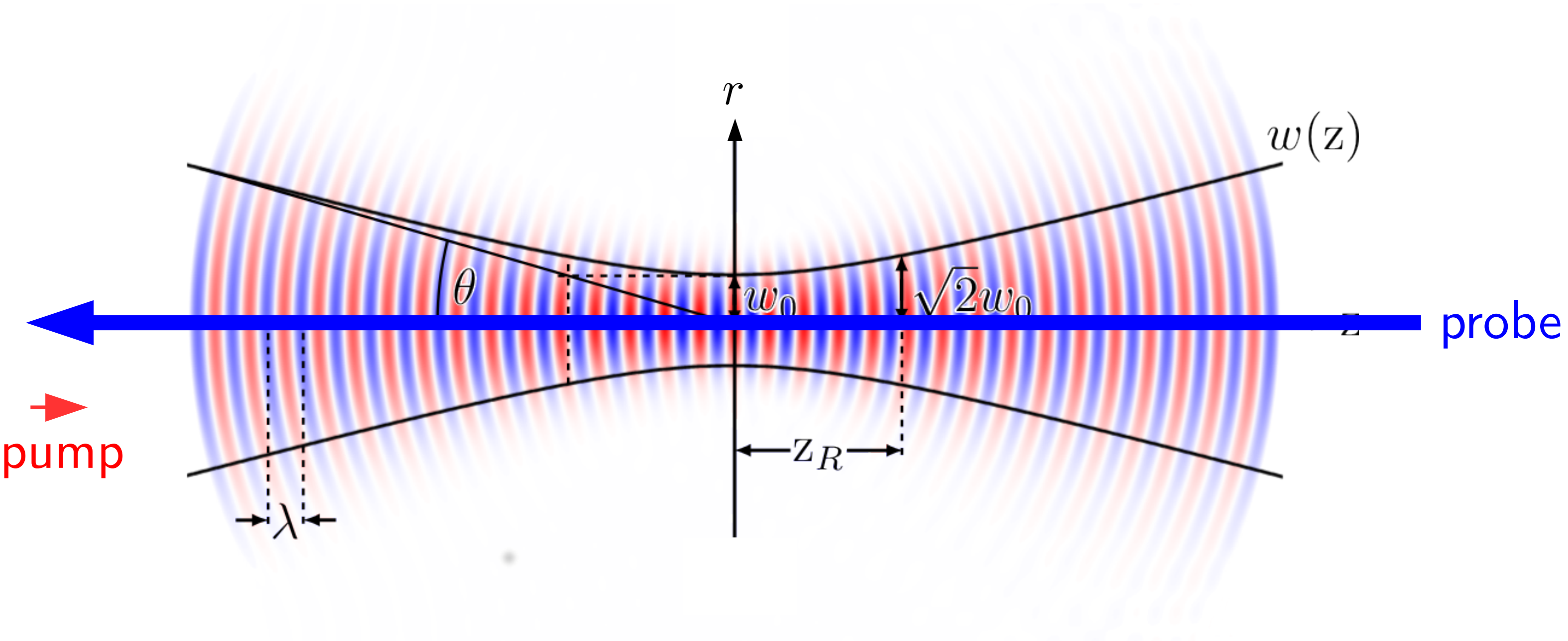
→ case (a):





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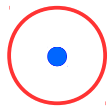
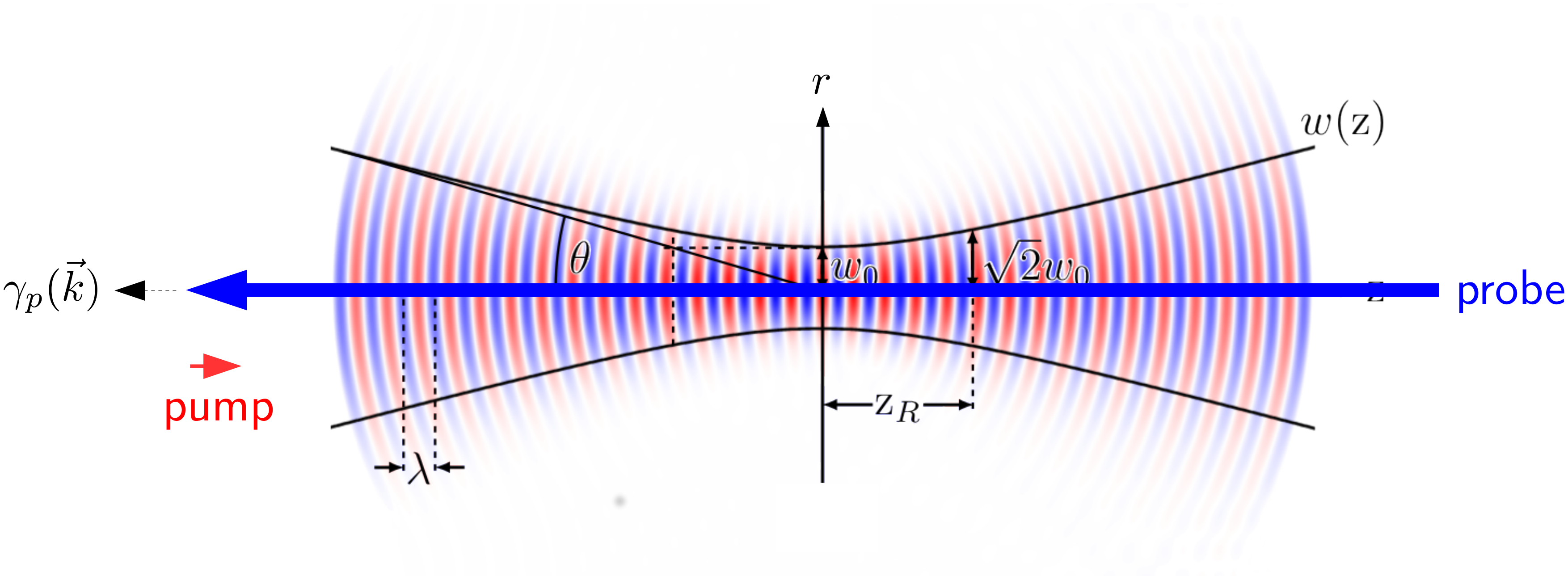
$\rightarrow$ case (a): 



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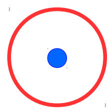
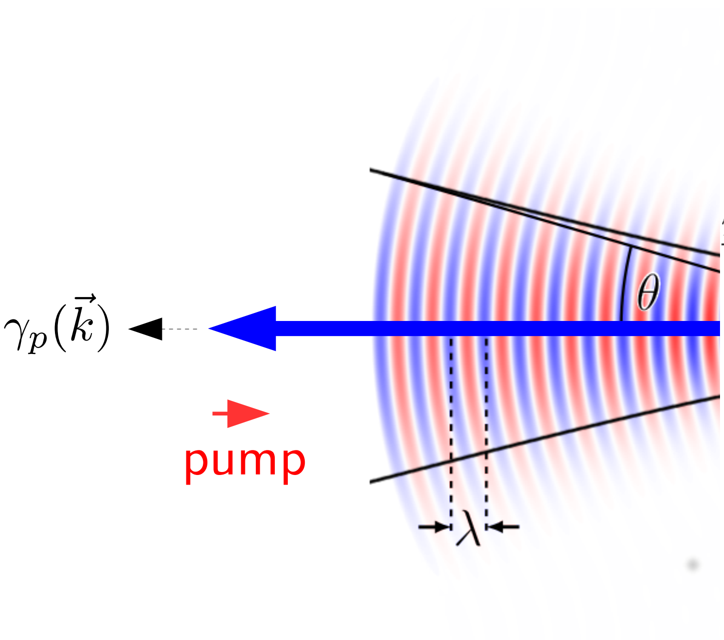
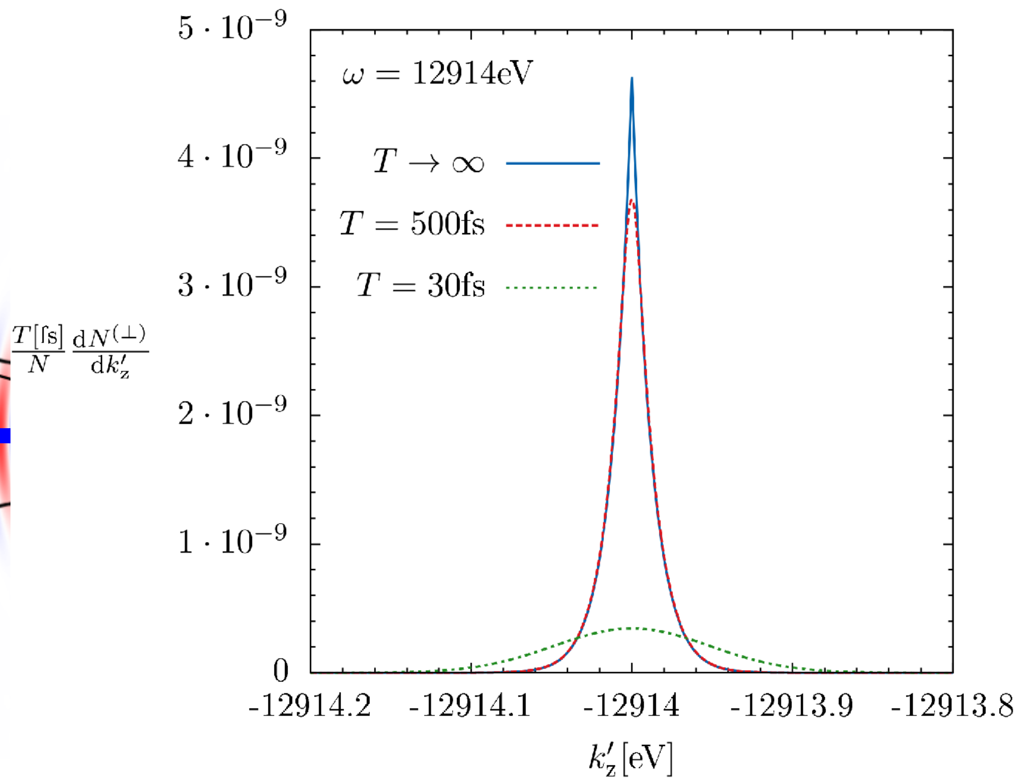
$\rightarrow$ case (a): 





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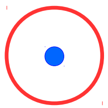
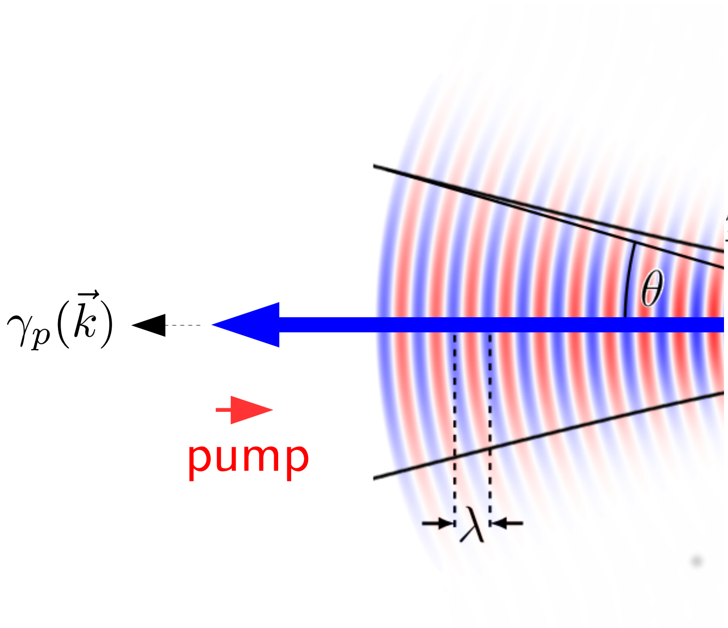
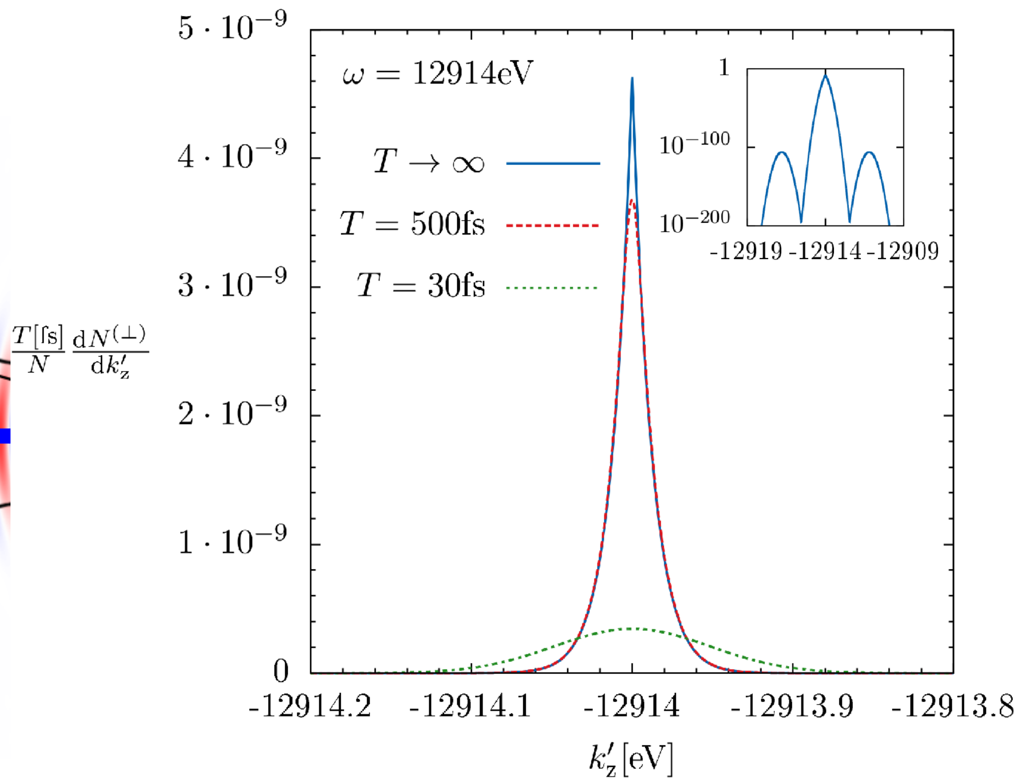
$\rightarrow$ case (a): 





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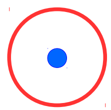
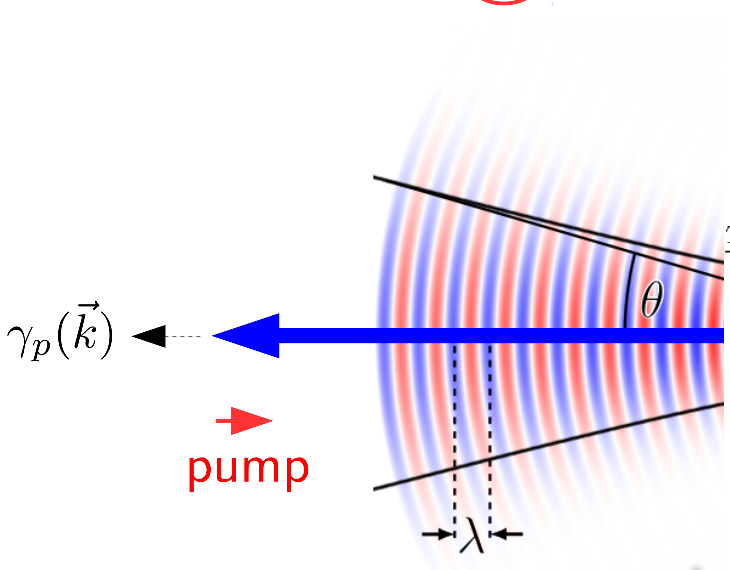
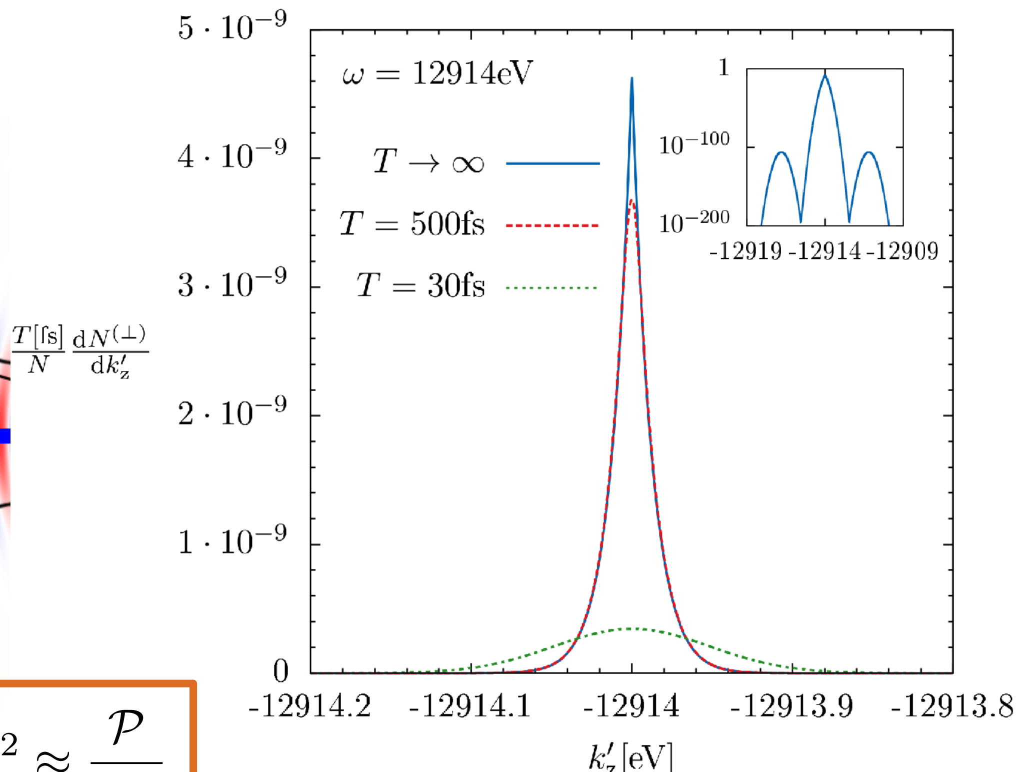
$\rightarrow$ case (a): 





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

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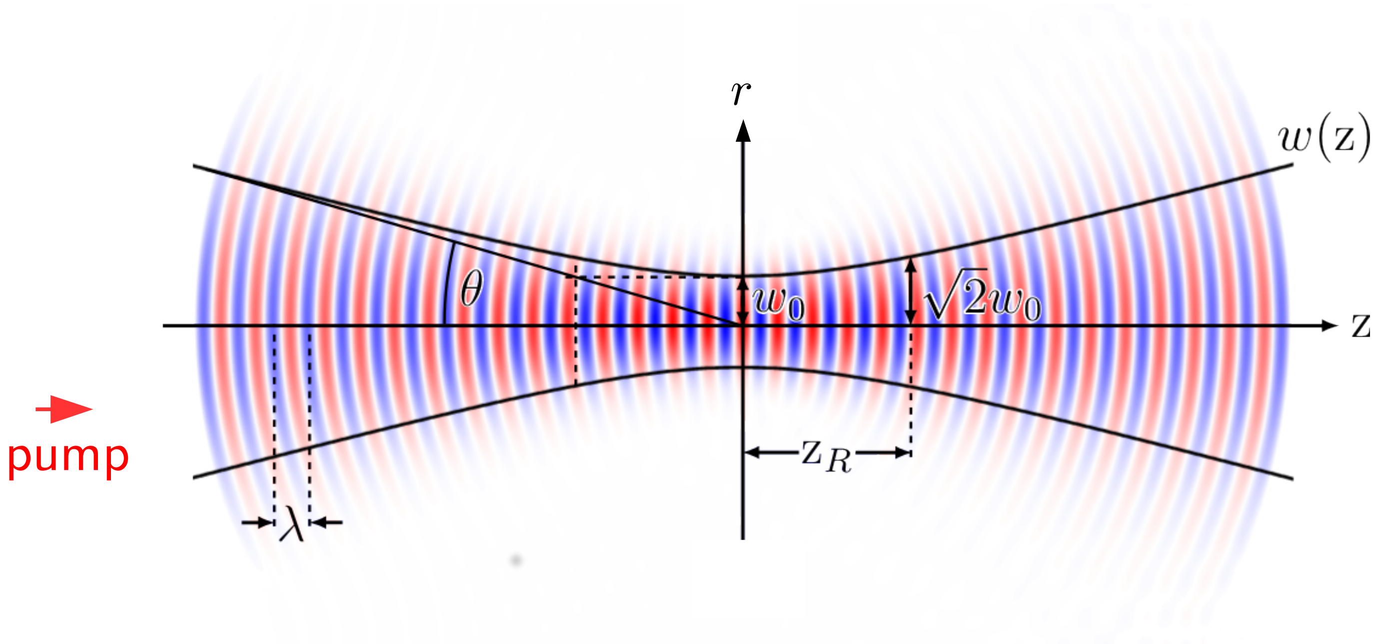

(iii) Vacuum birefringence

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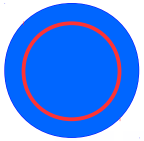
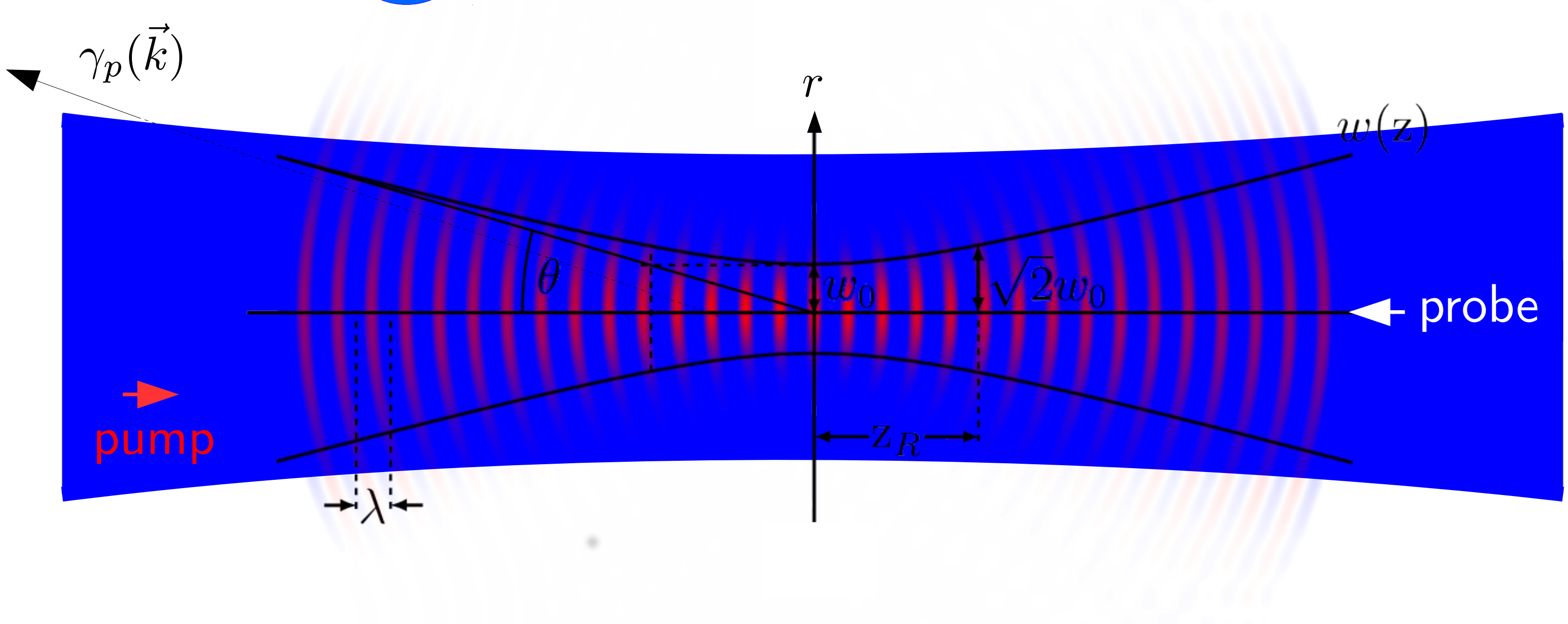
$\rightarrow$ case (b): 



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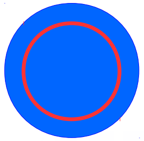
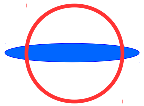
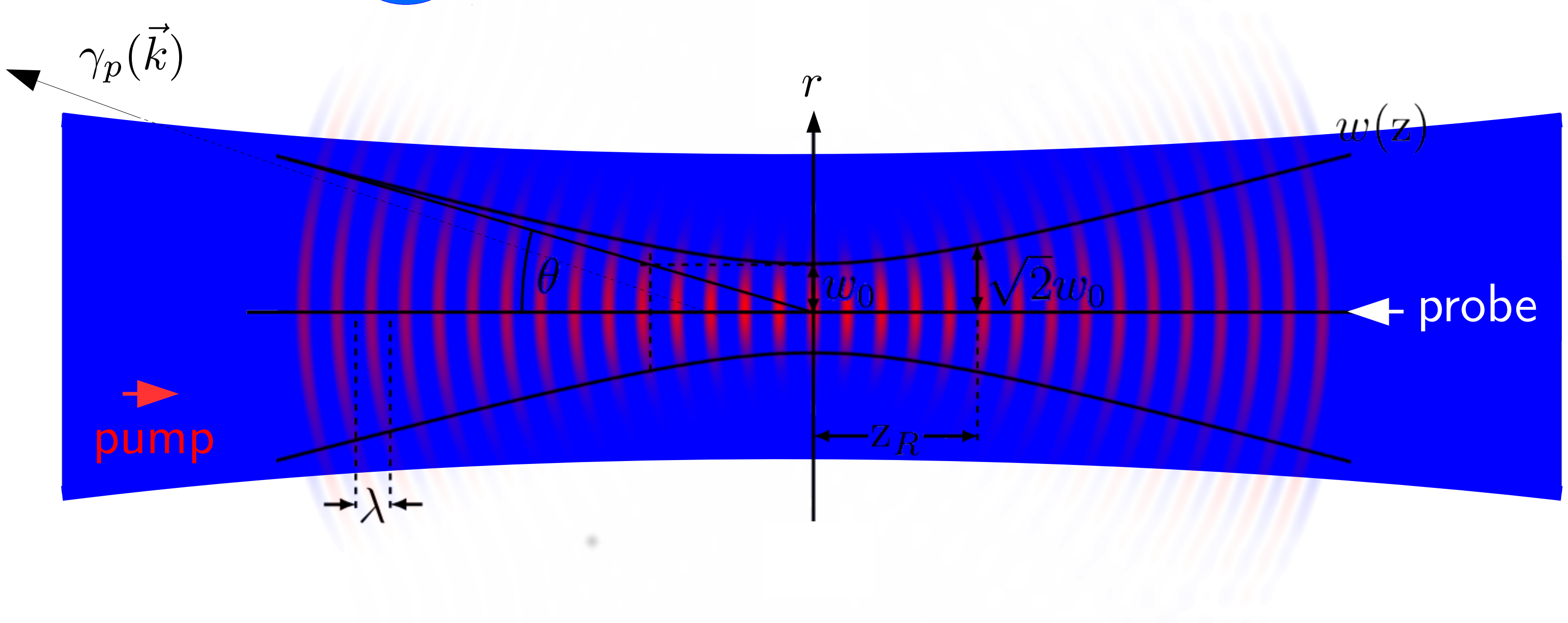
$\rightarrow$ case (b):  and case (c): 



Our **results**: [FK, et al.: in preparation 2015]

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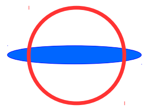
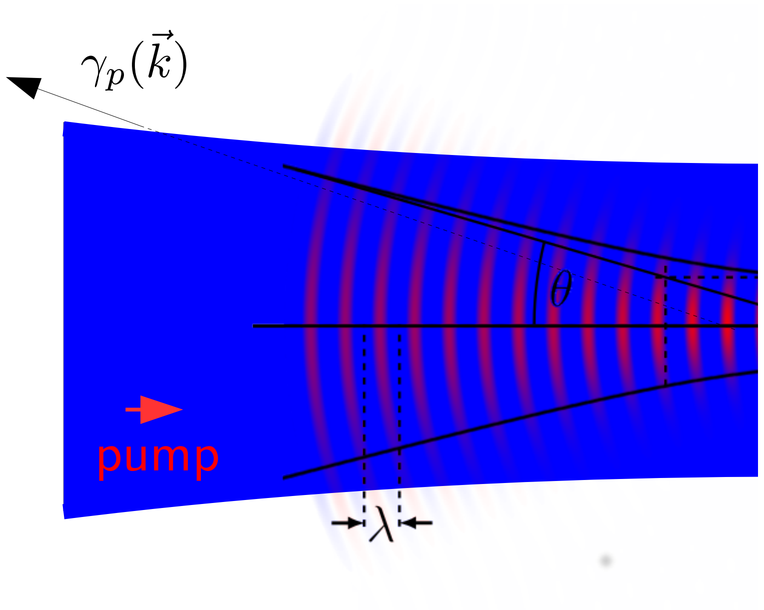
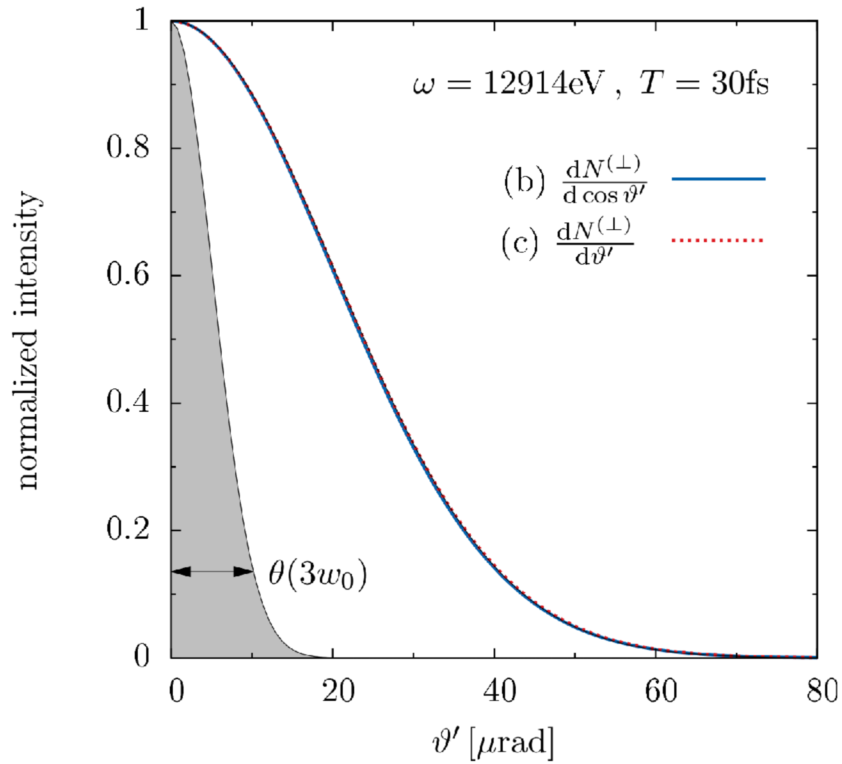
→ case (c): 





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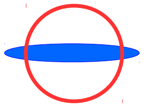
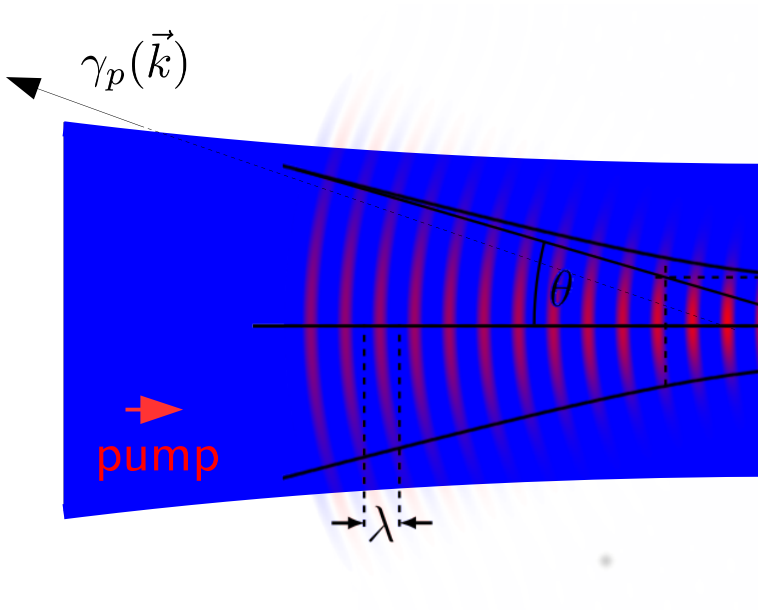
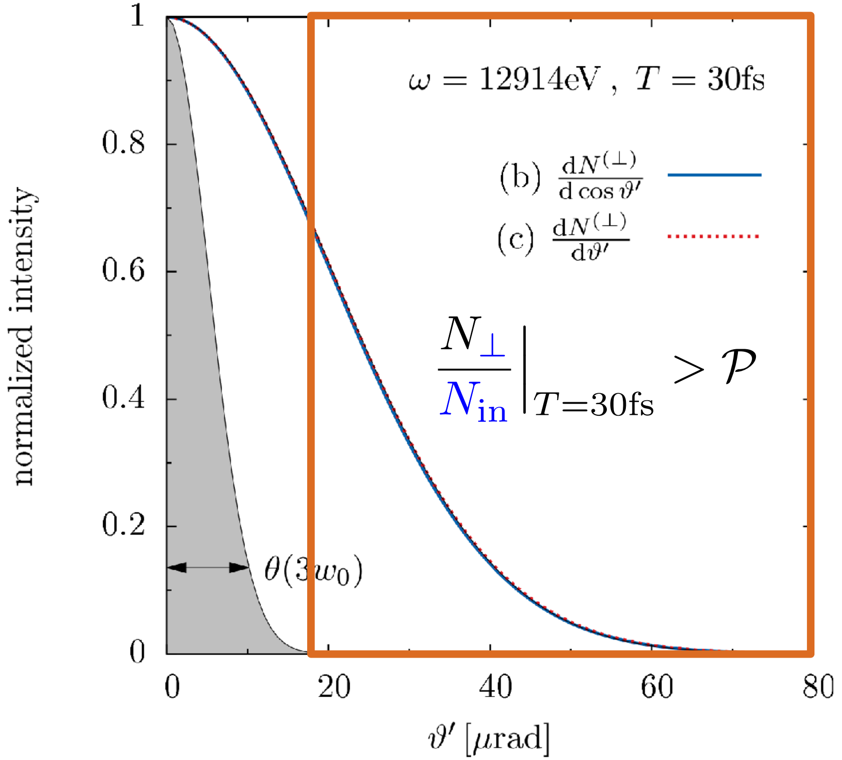
$\rightarrow$ case (c): 





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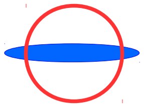
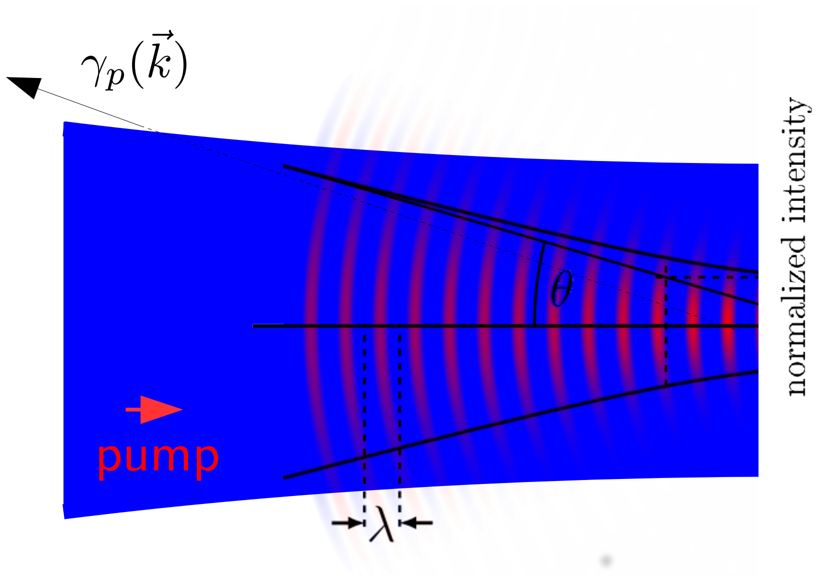
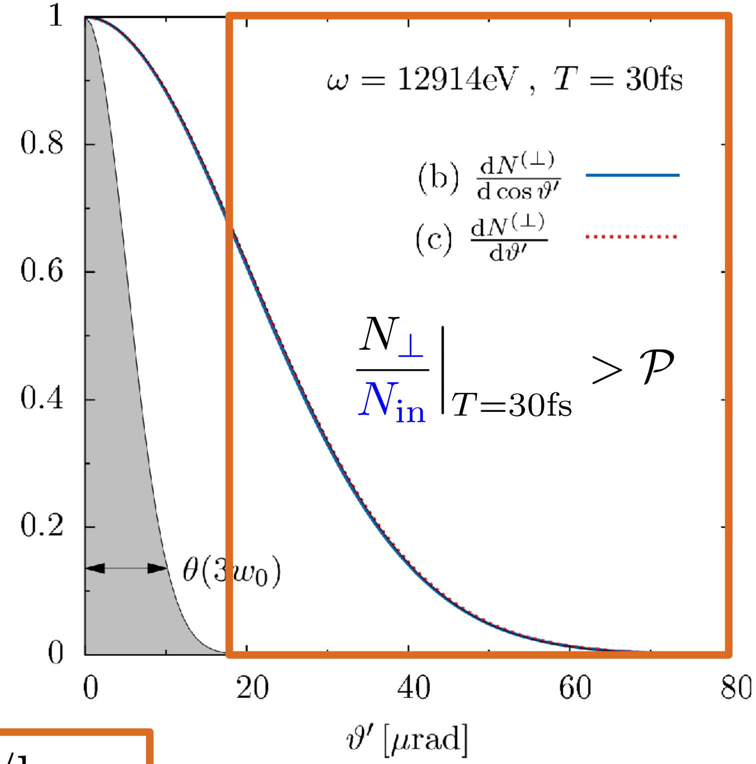
→ case (c): 





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

(iv) Conclusions and Outlook

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- I focused on **all-optical probes** of quantum vacuum nonlinearity.
- I presented and advocated a different perspective to analyze optical signatures of **quantum vacuum nonlinearities**.
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Thank you for your attention!