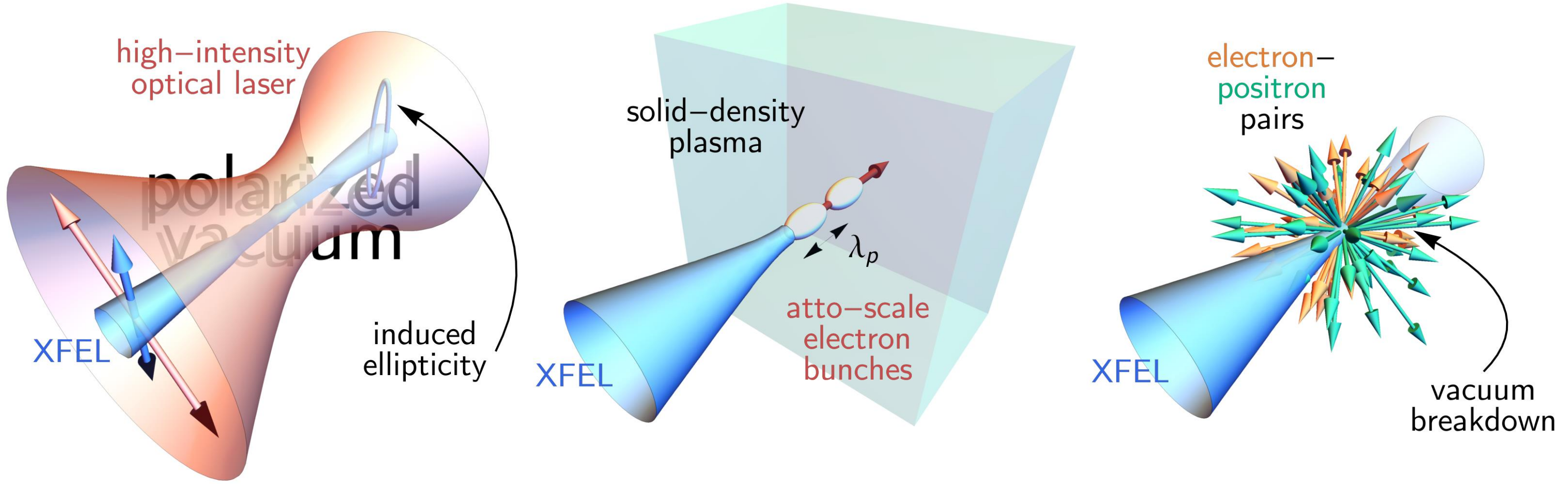
Opportunities in nonlinear classical and quantum physics with intense XFELs



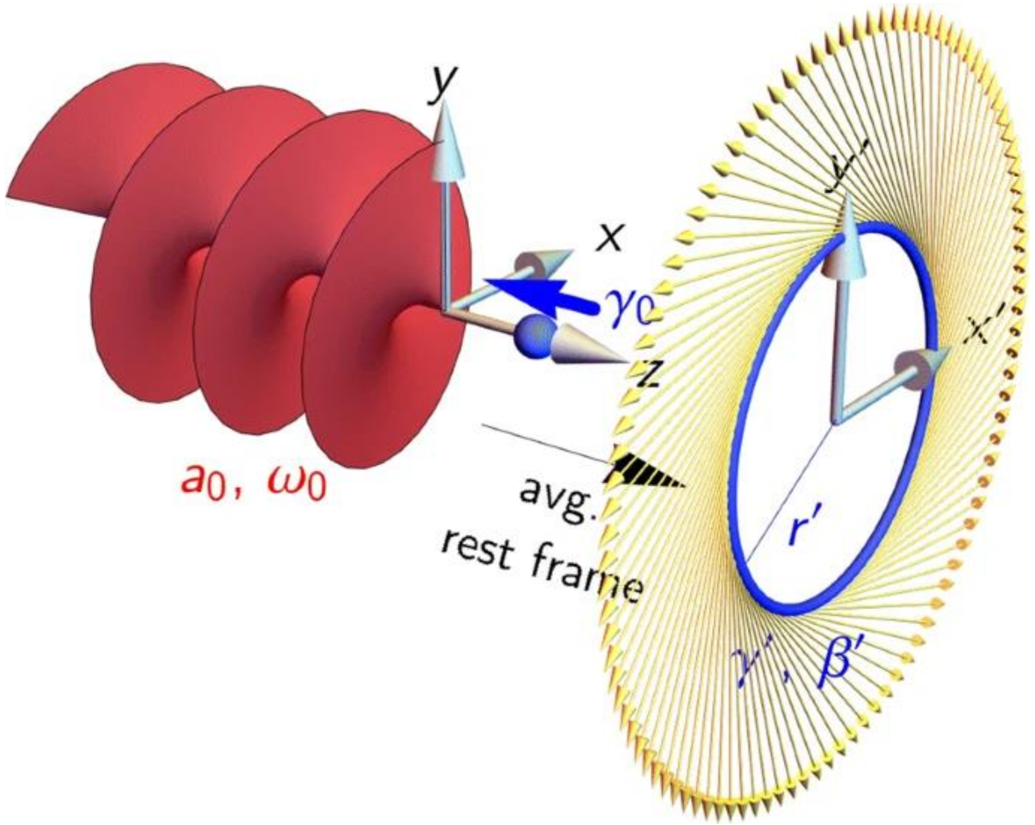
Tom Blackburn
Department of Physics, University of Gothenburg
www.gu.se/en/research/plasma-physics

19th January 2023
UK XFEL Townhall – Fundamental Physics, Quantum Computing and AI

Summary

- Introduction: key parameters, the nonlinear regimes
- XFELs as probes: vacuum birefringence
- XFELs as backgrounds: gamma-ray sources for nuclear photonics
- XFELs as drivers: wakefields in solid-density plasmas...
- ... and Schwinger pair creation in vacuum

Classical nonlinearity parameter, a_0



Blackburn, RMPP 2020

- Compare the characteristic frequency of the emitted radiation to the orbital (cyclotron) frequency:

$$\frac{\omega'}{\omega_c} \simeq a_0^3$$

- Harmonic order of the emitted radiation, or number of participating photons.

Classical nonlinearity parameter, a_0

force exerted by electric field

Compton length

$$a_0 = \frac{eE \frac{\hbar}{mc}}{\hbar\omega}$$

photon energy

- Alternatively...
- Electron does not interact with one photon of the radiation field, but many.
- Determines the importance of higher order terms in a perturbative expansion, which only works if a_0 is much smaller than one.

Classical nonlinearity parameter, a_0

force exerted by electric field

Compton length

$$? = \frac{eE \frac{\hbar}{mc}}{mc^2}$$

electron rest energy

- Alternatively...
- Electron does not interact with one photon of the radiation field, but many.
- Determines the importance of higher order terms in a perturbative expansion, which only works if a_0 is much smaller than one.
- If we swap out the photon energy...

Quantum nonlinearity parameter $\chi_{e,\gamma}$

force exerted by electric field

Compton length

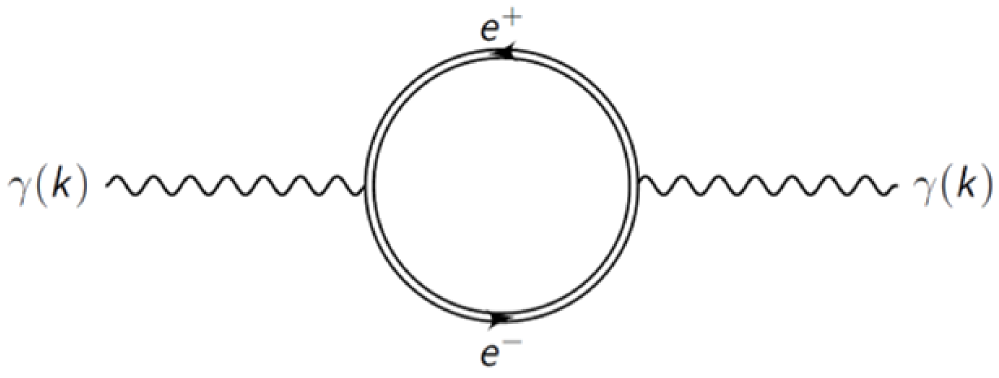
$$\chi = \frac{eE\,\frac{\hbar}{mc}}{mc^2}$$

electron rest energy

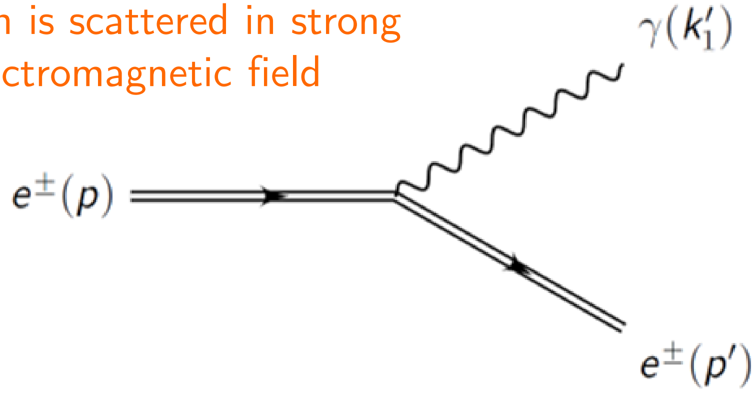
- … we see if the field does enough work over a Compton length to create an electron,
- or the field strength in the particle rest frame, in units of the critical (Schwinger) field.
- Then quantum effects must be important – even if the field amplitude in the lab frame is far below critical.

Quantum nonlinearity parameter $\chi_{e,\gamma}$

photon interacts with virtual electron-positron pair of polarized vacuum



electron is scattered in strong electromagnetic field



- For a photon, vacuum polarization and electron-positron pair creation are controlled by

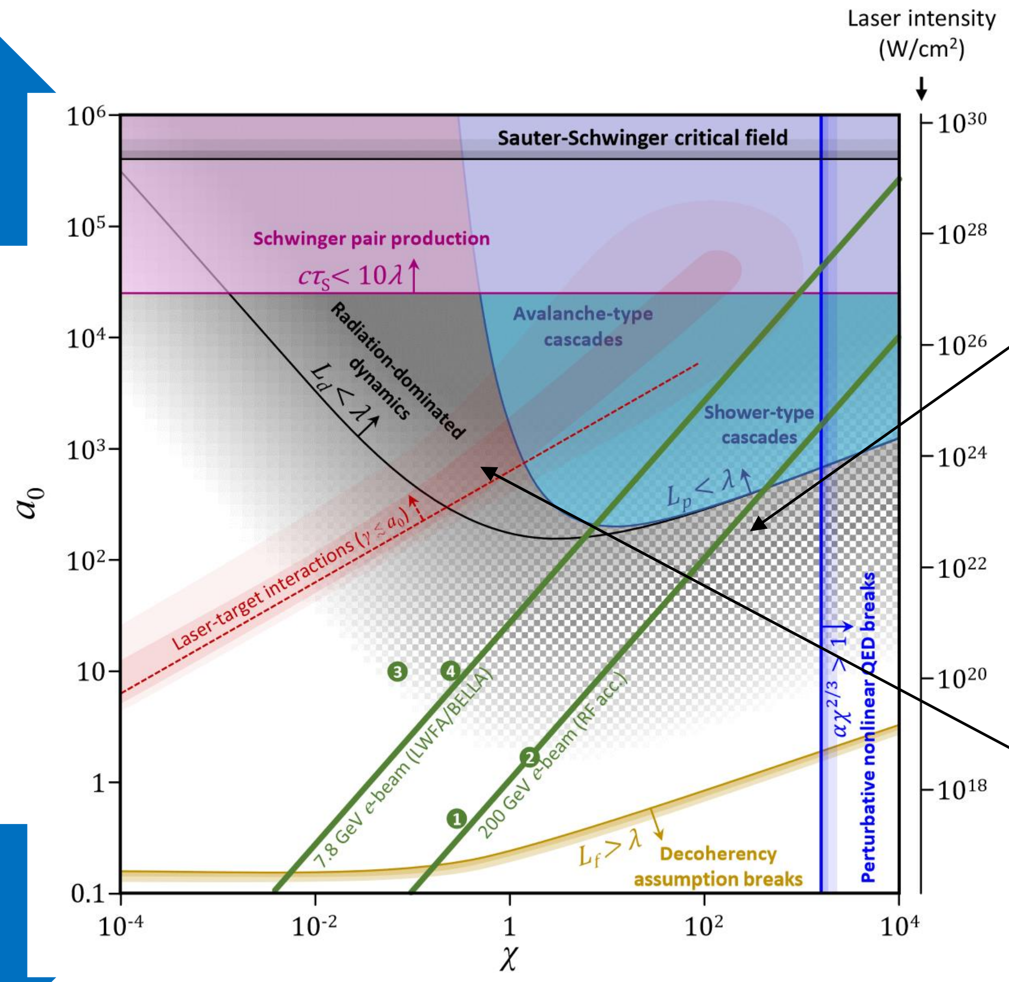
$$\chi_\gamma = \frac{e\sqrt{-(F_{\mu\nu}k^\nu)^2}}{m^3} = \frac{\omega|\vec{E}_\perp + \vec{n} \times \vec{B}|}{mE_{\text{crit}}}$$

- For an electron, photon emission (and recoil effects) are controlled by

$$\chi_e = \frac{e\sqrt{-(F_{\mu\nu}p^\nu)^2}}{m^3} \simeq \frac{\gamma|\vec{E}_\perp + \vec{v} \times \vec{B}|}{E_{\text{crit}}}$$

Parameter space

high intensity,
quasistatic,
tunnelling,
field can be treated as
being locally constant



Gonoskov et al, RMP 2022

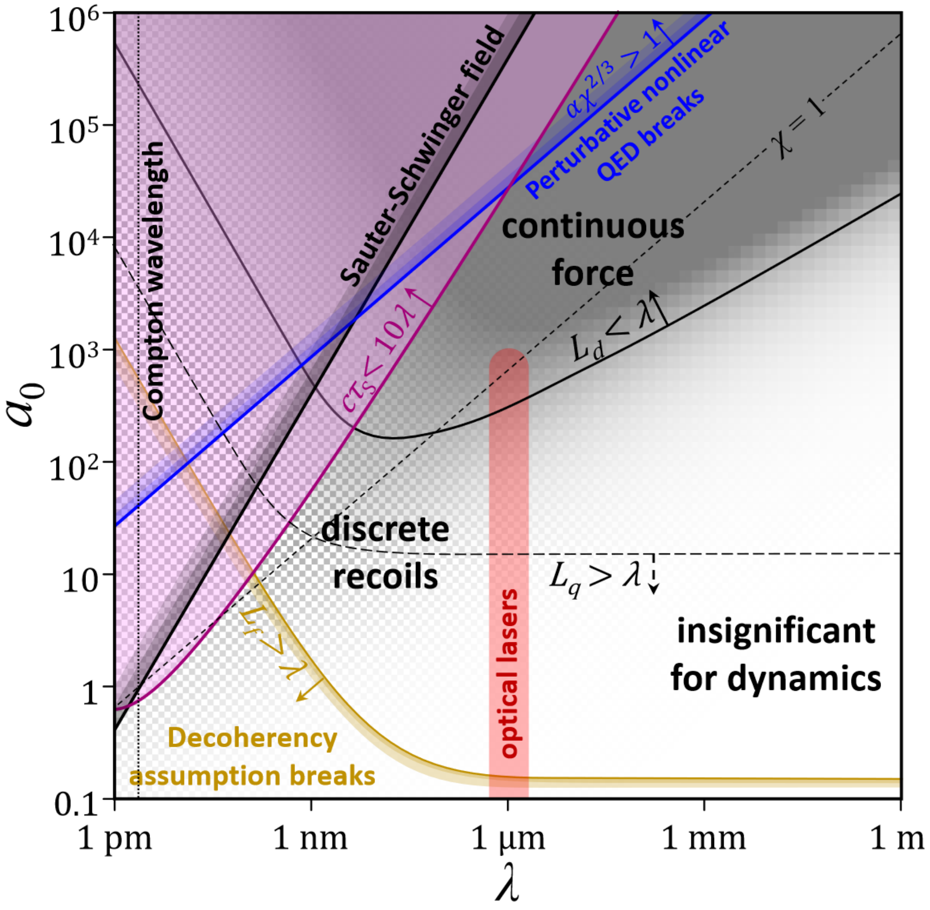
optical laser +
high-energy
electron beam

optical laser +
matter

low intensity,
weakly multiphoton,
use perturbation
theory

Introduction

Wavelength matters



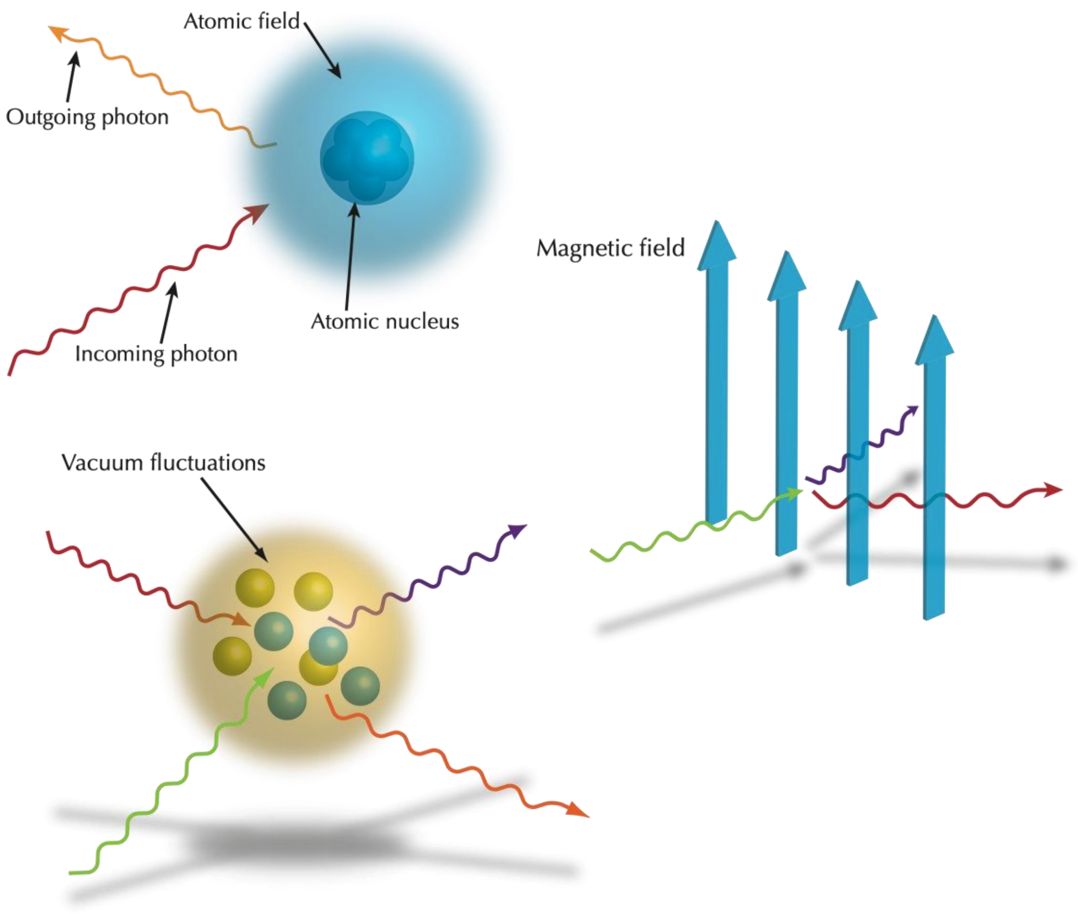
Gonoskov et al, RMP 2022

- Which of nonlinear classical or quantum effects kicks in first depends on the wavelength of the strong field (among other things).
- Most research has focused on high-power optical lasers.
- In this talk I will present some ideas, all of which rely upon the co-location of intense XFELs with other particle and radiation sources.

Summary

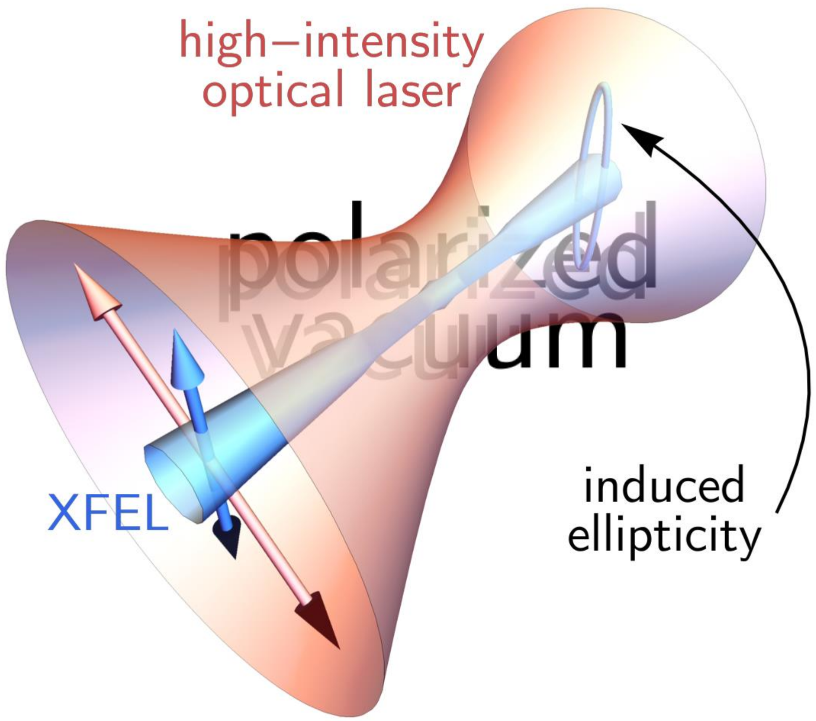
- Introduction: key parameters, the nonlinear regimes
- XFELs as probes: vacuum birefringence
- XFELs as backgrounds: gamma-ray sources for nuclear photonics
- XFELs as drivers: wakefields in solid-density plasmas...
- ... and Schwinger pair creation in vacuum

The quantum vacuum



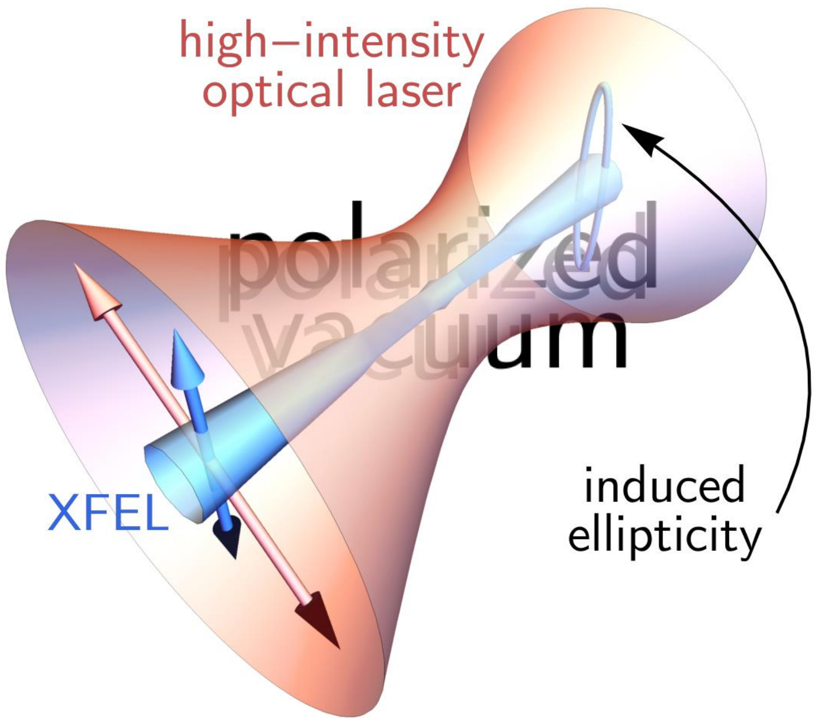
- Photons can interact with each other via fluctuating electron-positron pairs.
- Astrophysical applications; laboratory tests of strong-field QED.
- Many of these cross sections scale positively with increased frequency.
- Top to bottom: Delbruck scattering, photon splitting, four-wave mixing.

Vacuum birefringence



- Cross section for four-photon scattering σ [cm^{-2}] $= 10^{-31}$ $(\omega/m)^6$ ($\omega =$ photon energy in ZMF, natural units hereon).
- 11 orders of magnitude larger for XFEl-laser than laser-laser (33 for XFEL-XFEL vs laser-laser).
- Use optical laser as "vacuum polarizer" (coherence!) and XFEL as probe [HIBEF, SEL etc].

Vacuum birefringence

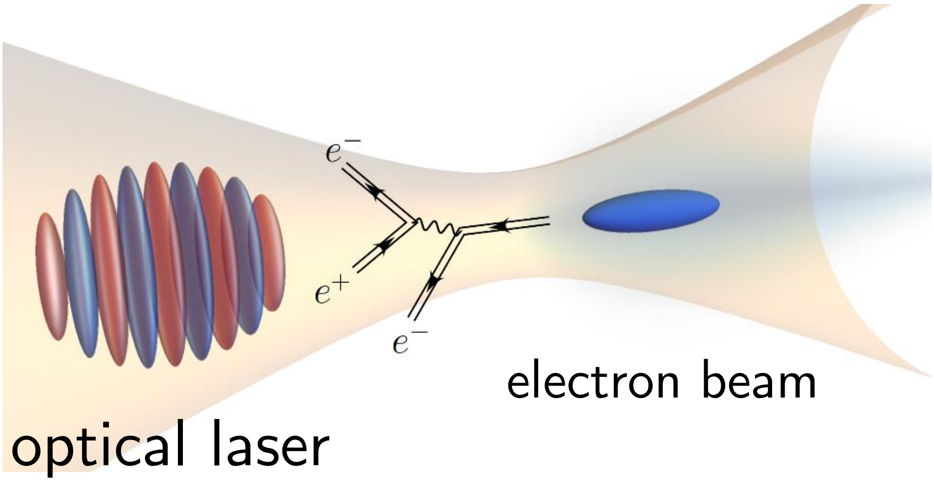


- Scattering visible in helicity change of the probe X rays, as if the vacuum refractive index were polarization dependent.
- Initially linearly polarized probe acquires a small ellipticity $\delta = \omega_X L \Delta n/2$, where $\Delta n = 2\alpha I_{\text{laser}}/I_{\text{cr}}$.
- Why X rays? High polarization purity and precision of measurement.

Summary

- Introduction: key parameters, the nonlinear regimes
- XFELs as probes: vacuum birefringence
- XFELs as backgrounds: gamma-ray sources for nuclear photonics
- XFELs as drivers: wakefields in solid-density plasmas...
- ... and Schwinger pair creation in vacuum

Gamma-ray source

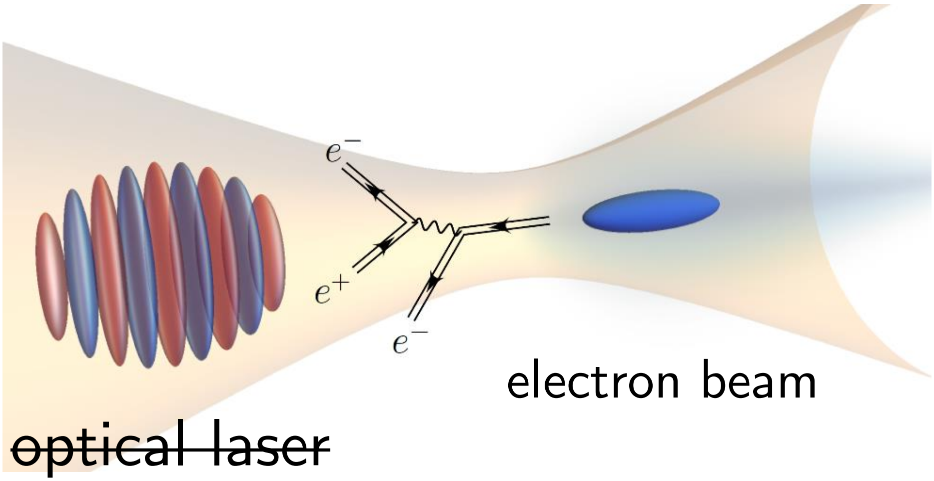


$$R = f\,\frac{\sigma_T N_L N_e}{\pi(r_L^2 + r_e^2)}$$

BX/s; no. laser photons; no. electrons; photons/s; transverse sizes

- Compton scattering of electrons is a source of polarized, monochromatic photons.
- The 10 to 100 MeV range useful for nuclear photonics: excitation of resonances, transitions etc
- e.g. 720 MeV electrons + 1 eV optical laser (ELI-NP)
- or 1 GeV + 1 to 5 eV FEL (HIGS)

Gamma-ray source



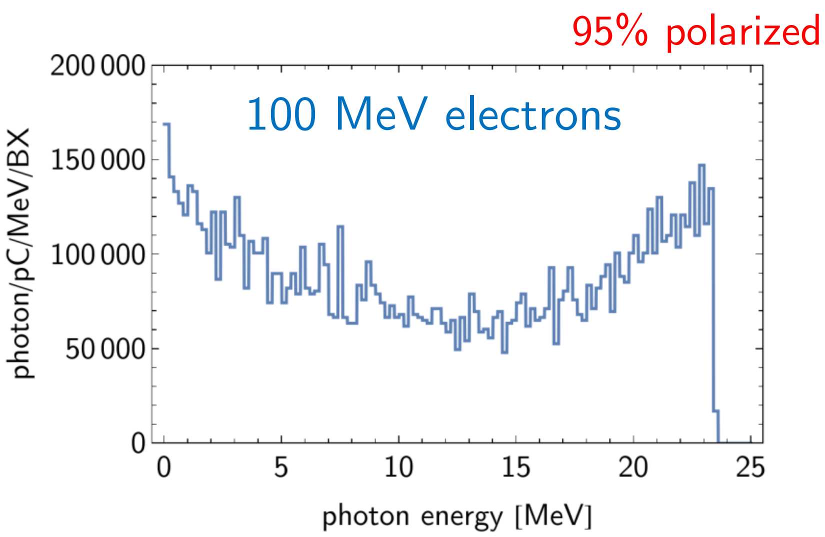
XFEL?

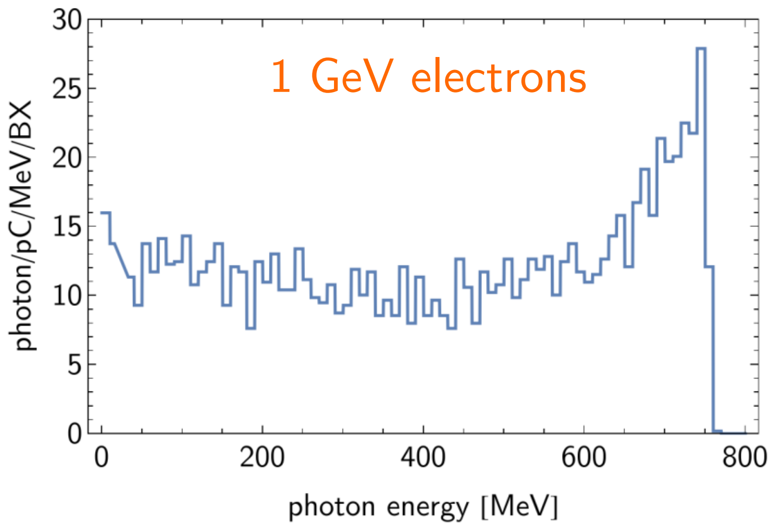
$$R = f\,\frac{\sigma_T N_L N_e}{\pi(r_L^2 + r_e^2)}$$

- BX/s → f
- no. laser photons → N_L
- no. electrons → N_e
- photons/s → R
- transverse sizes → r_L, r_e

- Compton scattering of electrons is a source of polarized, monochromatic photons.
- The 10 to 100 MeV range useful for nuclear photonics: excitation of resonances, transitions etc
- e.g. 720 MeV electrons + 1 eV optical laser (ELI-NP)
- or 1 GeV + 1 to 5 eV FEL (HIGS)

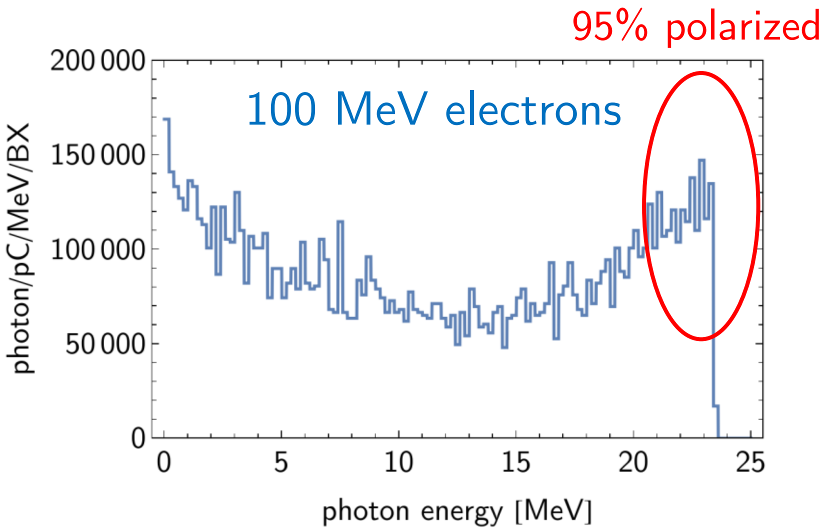
Gamma-ray source

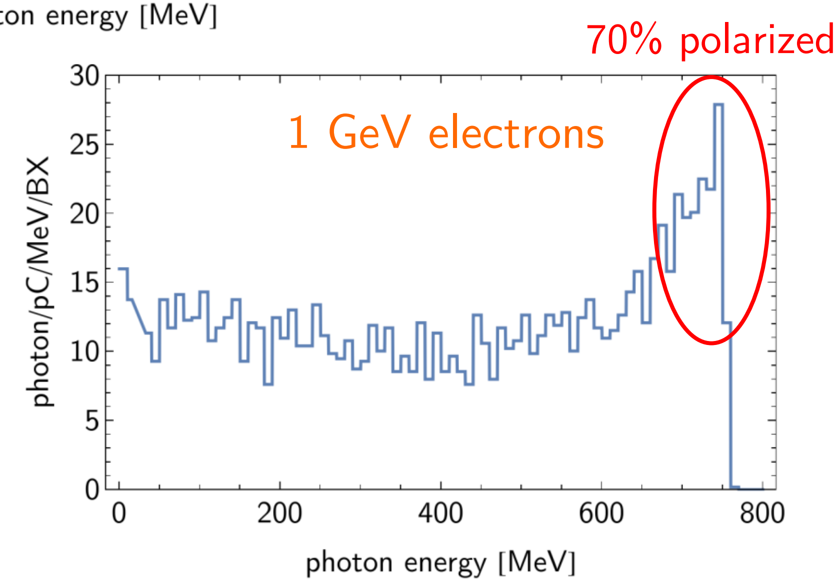




- To achieve the same photon energies by scattering XFEL light requires lower electron energies.
- Example: 100 MeV or 1 GeV electrons + 200 eV light @ 10^{19} W/cm^2 (300 cycles in duration)

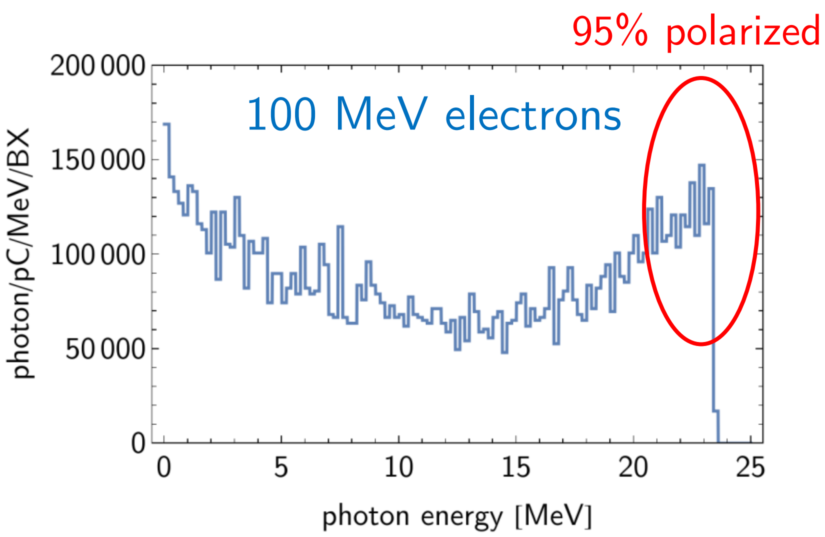
XFELs as backgrounds
Gamma-ray source

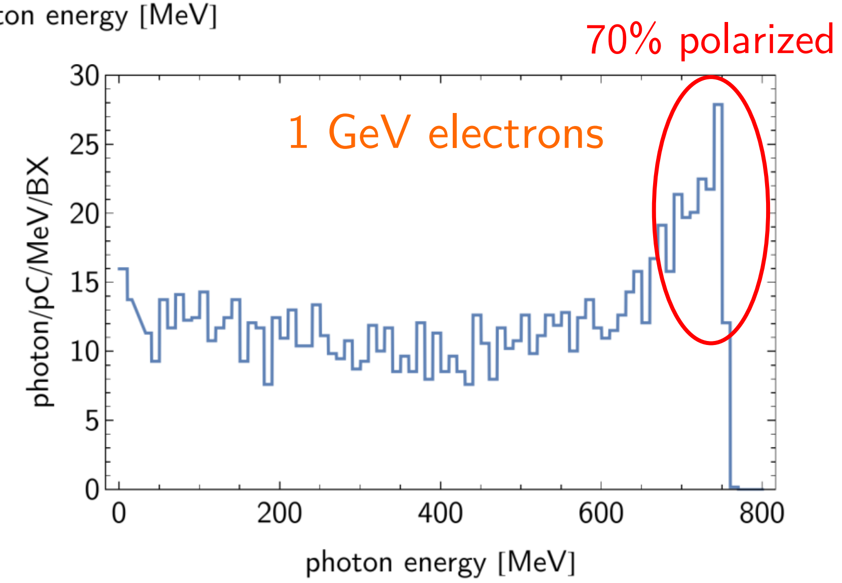




- To achieve the same photon energies by scattering XFEL light requires lower electron energies.
- Example: 100 MeV or 1 GeV electrons + 200 eV light @ 10^{19} W/cm^2 (300 cycles in duration)
- Gammas inherit polarization properties of the XFEL light: linear, circular etc
- Monochromatise by angle selection

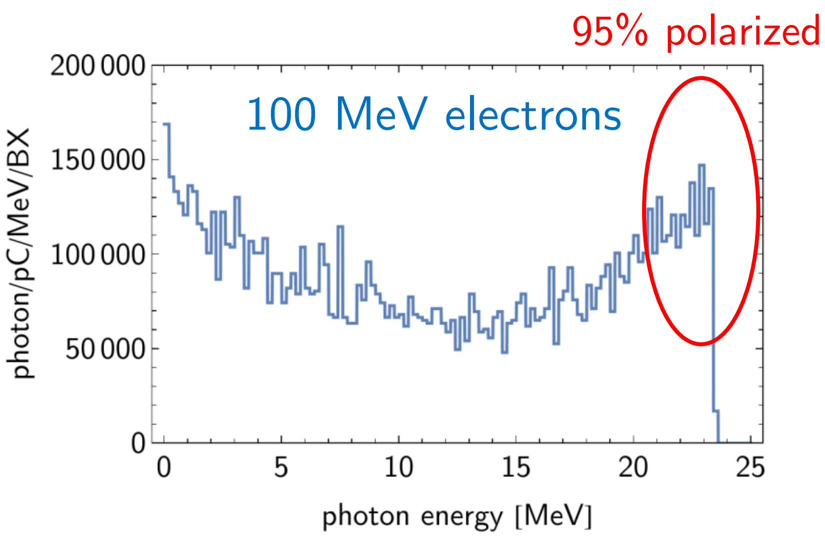
Gamma-ray source

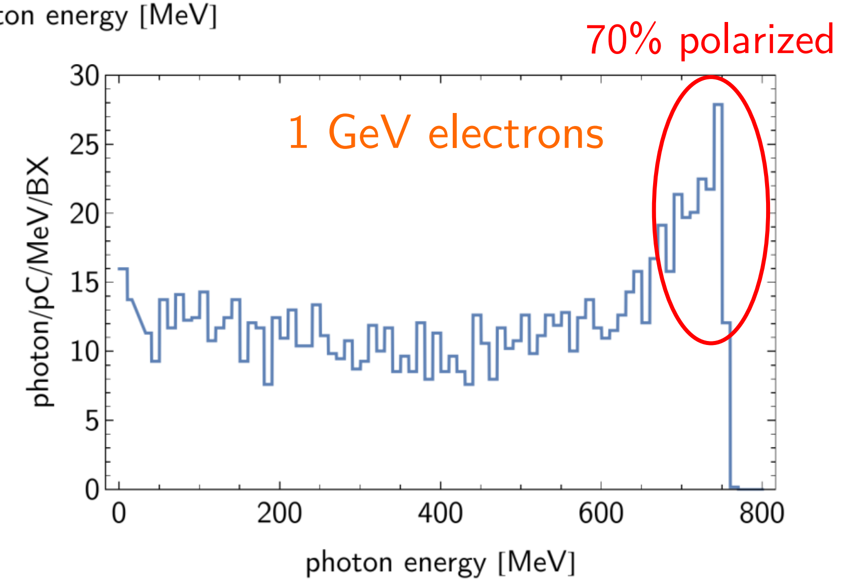




- How far can one go?
- Multi-GeV polarized gammas needed for hadron studies in strange sector / photoproduction of QCD exotics
- LEPS2 @ Spring-8 (ICS with 8-GeV electrons + VUV), GlueX (coherent bremstrahlung)
- At 10 GeV, Compton edge at 9.7 GeV.

Radiation reaction in the deep quantum regime





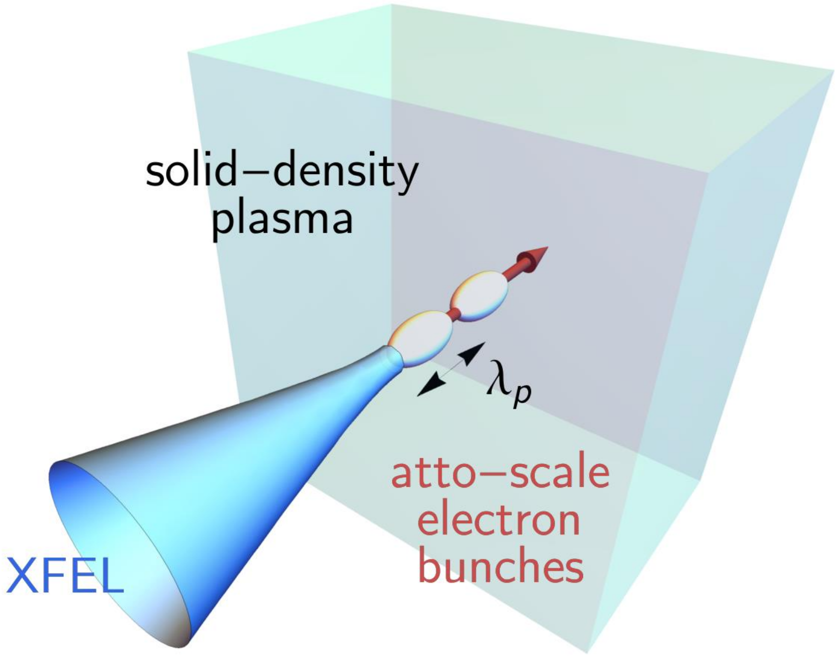
- Recoil effects on the electron beam are significant!
- Investigation of radiation reaction with optical lasers usually in the regime where single-photon recoil is much less important than the accumulated recoil from many emissions.
- Importance of “spin light” increased.

Summary

- Introduction: key parameters, the nonlinear regimes
- XFELs as probes: vacuum birefringence
- XFELs as backgrounds: gamma-ray sources for nuclear photonics
- XFELs as drivers: wakefields in solid-density plasmas...
- ... and Schwinger pair creation in vacuum

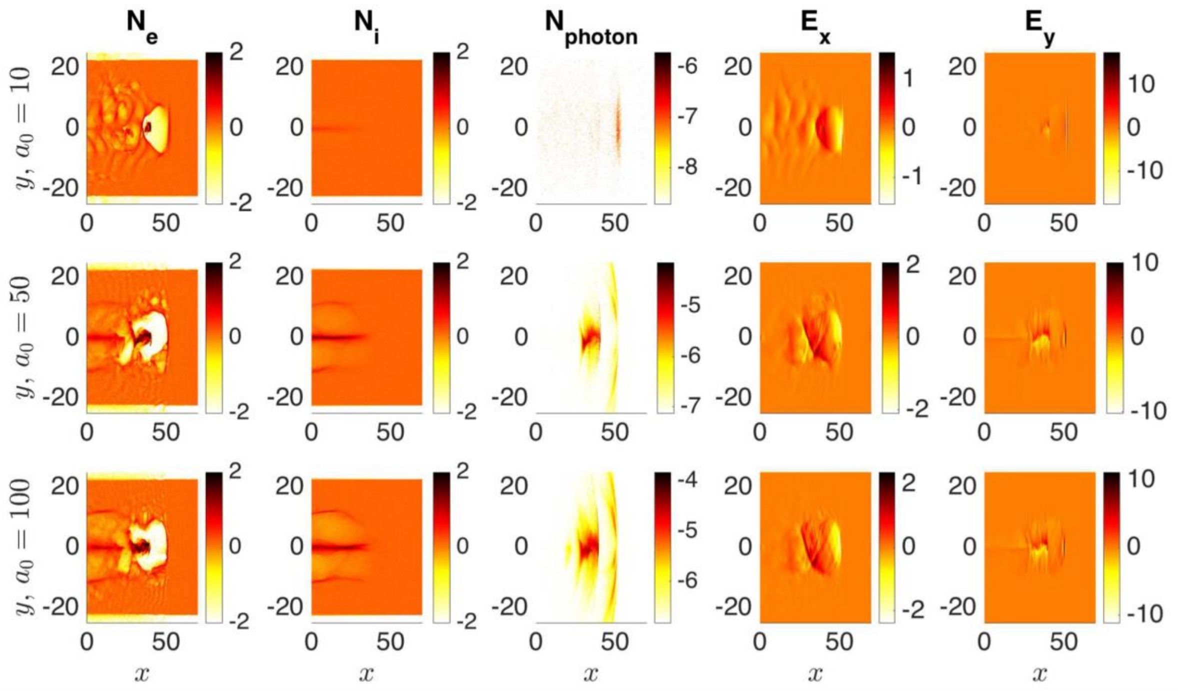
XFELs as drivers

XWFA



- Solid-density plasmas become underdense at XUV/X-ray wavelengths: λ_p [µm] $= n^{-1/2}$ [10^{21} cm^{-3}]
- As an example, a relativistically intense XUV pulse could drive wakefield acceleration of electrons [Tajima EPJST 2014].
- $a_0 > 1 \Rightarrow I > 10^{24}\ (\lambda_X\ [\text{nm}])^{-2}\ \text{W/cm}^2$

XWFA



Wettervik, PoP 2018

- Scaling wakefield acceleration to XUV wavelengths relies on similarity theory ($S = n_e/a_0 n_{cr}$).
- But not all physics scales with this parameter, e.g. radiation generation (betatron or nonlinear Compton) [Zhang PRAB 2016].
- PIC simulations show it holds to a wavelength of 1 nm.

XWFA

Quantity	Scaling
Timescale	λ
Spatial dimensions of cavity	λ
Density	a_0/λ^2
Current density	a_0/λ^2
Current	a_0
Trapped charge	λa_0
Electron energy	a_0
Electromagnetic fields	a_0/λ
Pulse energy	λa_0^2
Ion motion	a_0
Quantum parameter, χ	a_0^2/λ
Radiated energy fraction	$\lambda^{1-\alpha} a_0^{2\alpha-1}$
Photon energy ($\chi \ll 1$)	a_0^3/λ
Photon energy ($\chi \sim 1$)	a_0
Time between emissions ($\chi \ll 1$)	T/a_0
Time between emissions ($\chi \sim 1$)	$T/(\lambda a_0)^{1/3}$

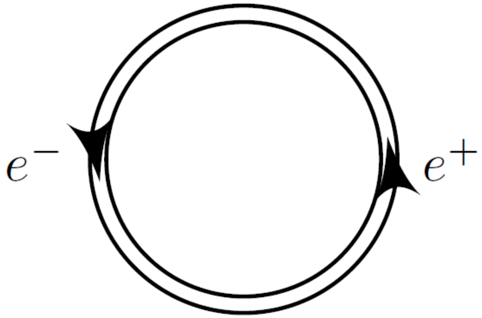
Wettervik, PoP 2018

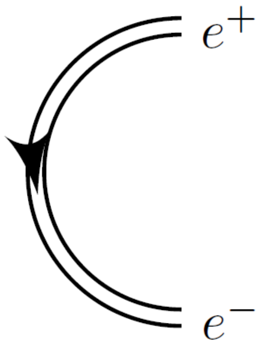
- Motivation might be accelerating gradient (TeV/cm)...
- or perhaps the current density or electron bunch duration.
- For densities of 10^{23} to 10^{25} cm^{-3}, cavity size implies an equivalent duration of 10^{-17} to 10^{-15} seconds.

Summary

- Introduction: key parameters, the nonlinear regimes
- XFELs as probes: vacuum birefringence
- XFELs as backgrounds: gamma-ray sources for nuclear photonics
- XFELs as drivers: wakefields in solid-density plasmas...
- ... and Schwinger pair creation in vacuum

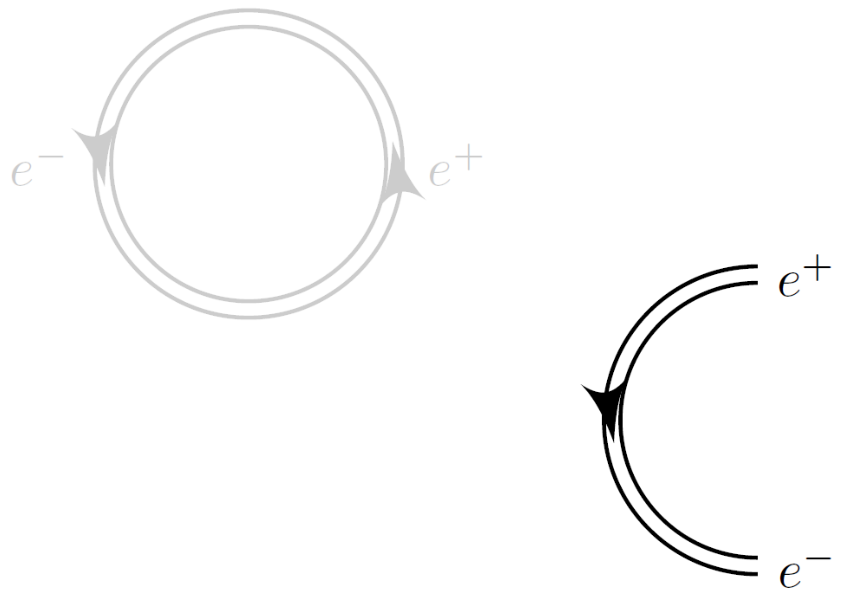
How do fields interact?





- Maxwell's equations are linear, at but ultrahigh field strengths this is not an adequate description anymore.
- Vacuum polarisation (photon-photon scattering, birefringence, dichroism)
- Schwinger pair creation/vacuum pair creation

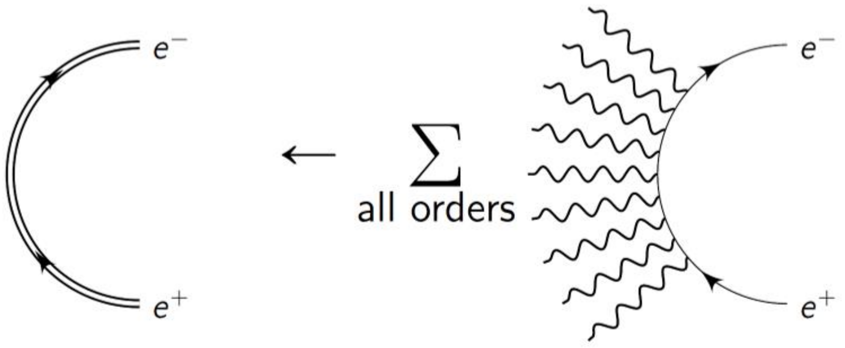
How do fields interact?



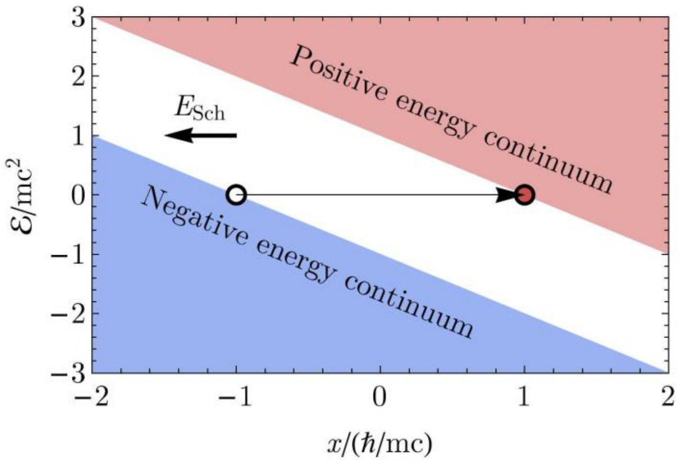
- Maxwell's equations are linear, at but ultrahigh field strengths this is not an adequate description anymore.
- Vacuum polarisation (photon-photon scattering, birefringence, dichroism)
- Schwinger pair creation/vacuum pair creation

XFELs as drivers

Schwinger effect



not to be taken too literally…

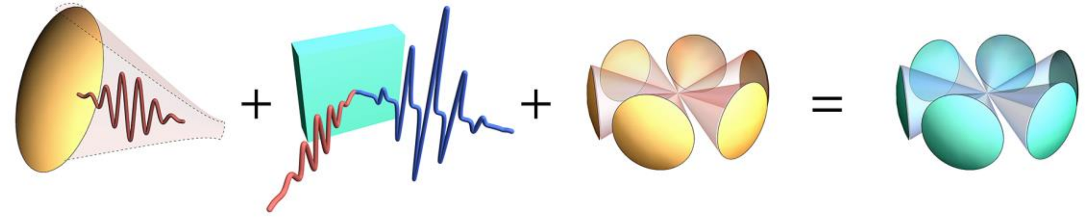


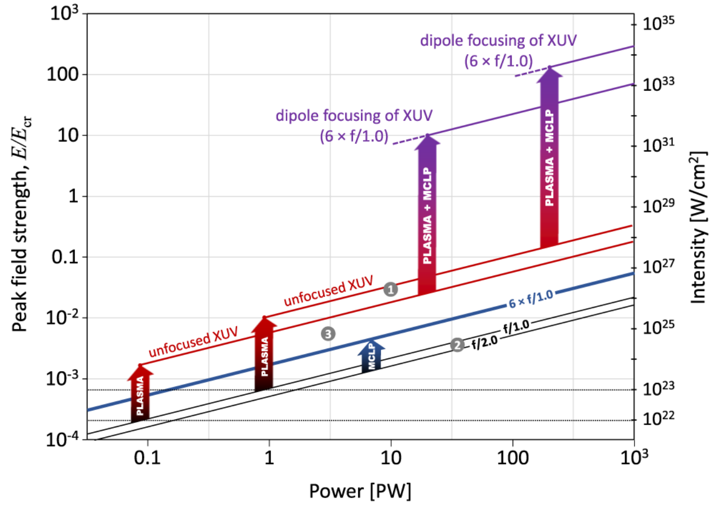
- The action for a static electric field acquires an imaginary part that is non-perturbative in the electric field strength.
- The characteristic field strength required is $E_{\text{crit}} = 1.3\times10^{18}$ V/m…
- … which corresponds to an intensity of 2×10^{29} W/cm^2

XFELs as drivers

Reaching critical/supercritical field strengths

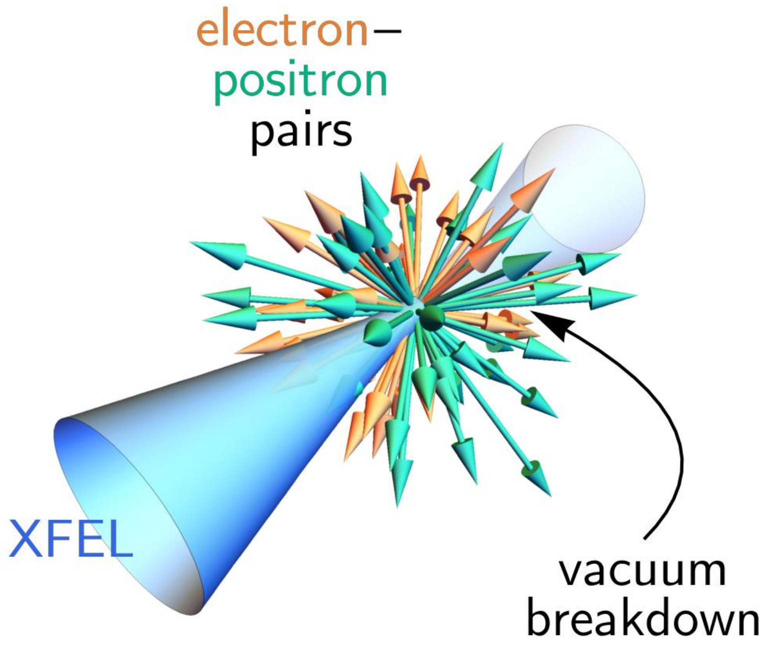
conversion of optical laser to XUV via plasma interaction [Gonoskov et al, HPLSE 2023]





- $2{\times}10^{29}$ W/cm^2 ?
- Aside from the technological challenges(!), it's likely impossible to reach an intensity anywhere near this with optical lasers because of pair avalanches [Bulanov et al, PRL 2010; Fedotov et al, PRL 2010].
- Routes toward "extremer" extreme field science rely on some means of conversion to higher frequencies.

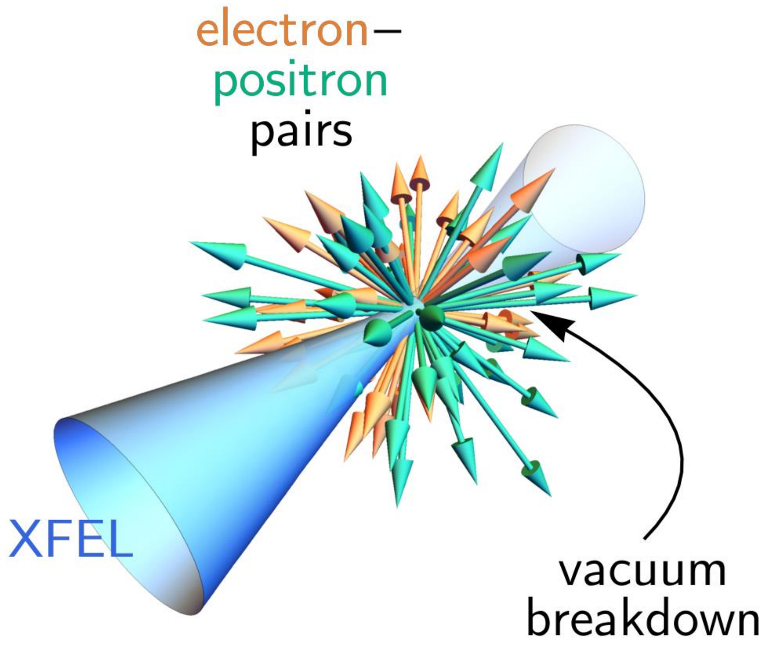
Reaching critical/supercritical field strengths



- Takes advantage of smaller focal spot sizes at shorter wavelength
- ... and suppression of pair avalanche growth due to volume factors.
- In principle, Schwinger pair creation observable with a terawatt XFEL... focused to nm focal spot sizes [Ringwald, PLB 2001]

XFELs as drivers

Reaching critical/supercritical field strengths



- Rate depends on invariants $E^2 - B^2$ and $\boldsymbol{E.B}$, not the electric field strength alone.
- Theory question: does a quasistatic model of pair creation work at high frequency/field gradient?
- "Assisted" Schwinger pair creation: reduce field strength required by combining the driver with other high-frequency EM waves.

Summary

- Introduction: key parameters, the nonlinear regimes
- XFELs as probes: vacuum birefringence
- XFELs as backgrounds: gamma-ray sources for nuclear photonics
- XFELs as drivers: wakefields in solid-density plasmas...
- ... and Schwinger pair creation in vacuum