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Modern Tests of Vacuum-Polarization Effects in Strong Laser Fields

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Outline

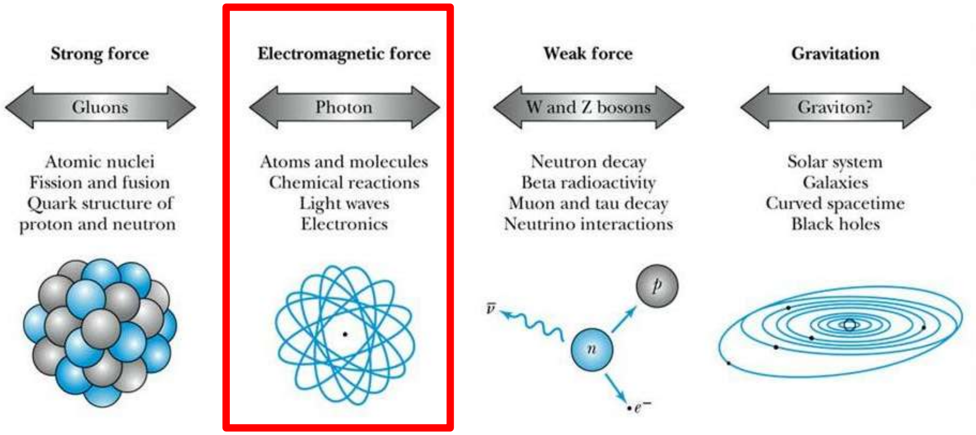
- Introduction to strong-field QED
- Quantum vacuum and strong-field QED
  - Low-energy vacuum-polarization effects
  - High-energy vacuum-polarization effects
- Conclusions

- For more information see the recent books/reviews:

1. W. Dittrich and M. Reuter, Effective Lagrangians in Quantum Electrodynamics (Springer, Heidelberg, 1985)
2. A. Di Piazza et al., Rev. Mod. Phys. **84**, 1177 (2012)
3. B. King and T. Heinzl, High Power Laser Sci. Eng. **4**, e5 (2016)

Electromagnetic interaction

- The electromagnetic interaction is one of the four fundamental interactions in Nature
- By accounting only for the lightest charged particles (electrons and positrons), the Lagrangian of the theory depends on two parameters:



  - Electron mass m=9.1×10^{-28} g
  - Electron charge e, with $|e|$=4.8×10^{-10} statcoulomb
- The typical scales of classical electrodynamics (CED) are determined by combining m and e with another fundamental constant:
  - Speed of light c=3.0×10^{10} cm/s
- In quantum electrodynamics (QED) the dynamics is richer:
  - Reduced Planck constant $\hbar$ =1.1×10^{-27} erg s

Typical scales of QED

Strength: $\alpha = e^2/\hbar c = 7.3\times10^{-3}$ (Fine-structure constant)	Energy: $mc^2 = 0.511$ MeV (Electron rest energy)
Length: $\lambda_C = \hbar/mc = 3.9\times10^{-11}$ cm (Compton wavelength)	Field: $E_{cr} = m^2c^3/\hbar\|e\| = 1.3\times10^{16}$ V/cm $B_{cr} = m^2c^3/\hbar\|e\| = 4.4\times10^{13}$ G (Critical fields of QED)

Intensity scale

$$E_{cr} = \frac{m^2c^3}{\hbar|e|} = 1.3\times10^{16}\ \mathrm{V/cm}$$

$$B_{cr} = \frac{m^2c^3}{\hbar|e|} = 4.4\times10^{13}\ \mathrm{G}$$

$$\Rightarrow \quad I_{cr} = \frac{cE_{cr}^2}{4\pi} = 4.6\times10^{29}\ \mathrm{W/cm^2}$$

Critical fields of QED and vacuum physics

- The vacuum state is the lowest-energy state of the theory where no particles are present
- In quantum field theory
  - "Fluctuations" of particles-antiparticles are present in the vacuum
  - They cover a very short distance and annihilate again after a very short time (for electrons and positrons $\lambda_C = \hbar / mc \sim 10^{-11}$ cm and $\tau = \lambda_C / c \sim 10^{-21}$ s, respectively)

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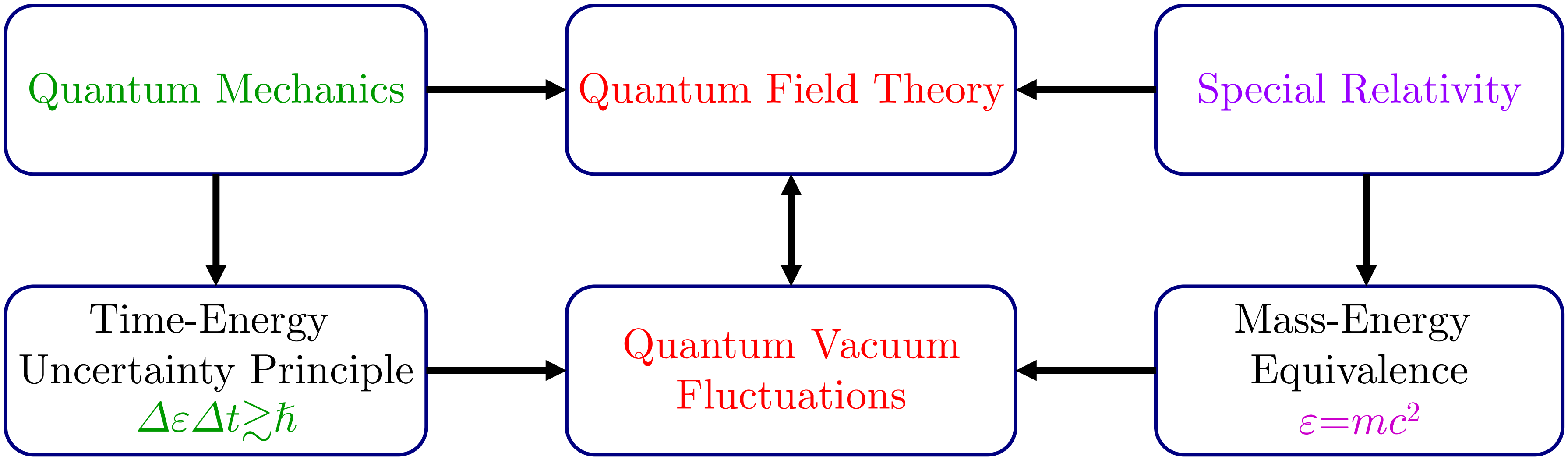


Quantum Mechanics

Quantum Field Theory

Special Relativity

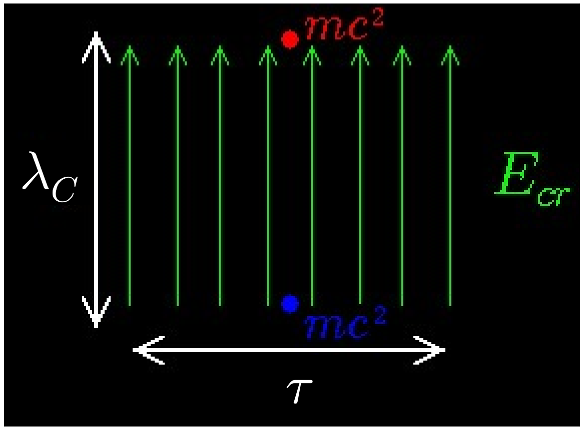
Time-Energy Uncertainty Principle $\Delta\varepsilon \Delta t \gtrsim \hbar$

Quantum Vacuum Fluctuations

Mass-Energy Equivalence $\varepsilon = mc^2$

- Physical meaning of the critical fields:

$$|e|E_{cr} \times \frac{\hbar}{mc} = mc^2$$

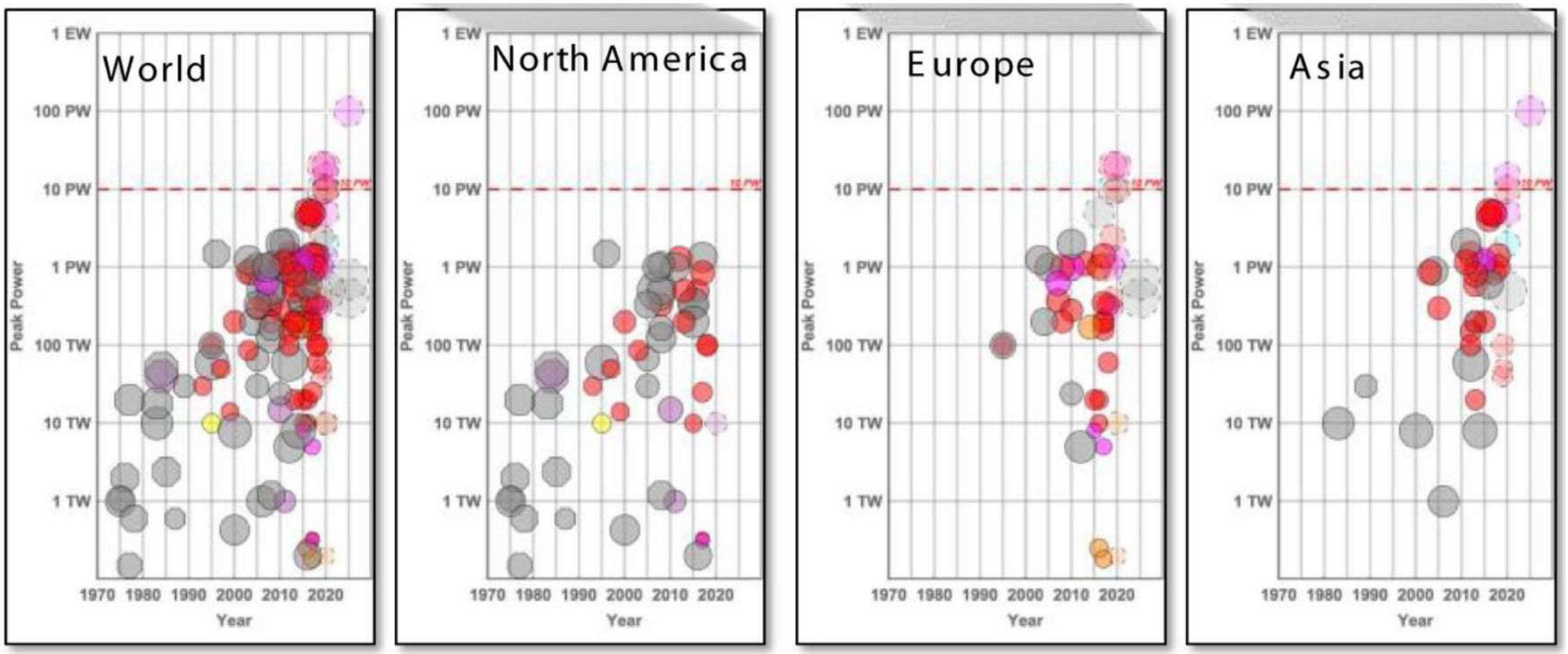


- Vacuum instability and electromagnetic cascades (Bell et al., PRL 2008, Bulanov et al., PRL 2010, Fedotov et al., PRL 2010)
- The interaction energy of a Bohr magneton with a magnetic field of the order of B_{cr} is of the order of the electron rest energy
- In the presence of background electromagnetic fields of the order of the critical ones a new regime of QED, the strong-field QED regime, opens:

1. where the properties of the vacuum are substantially altered by the fields
2. where a tight interplay unavoidably exists between collective (plasma-like) and quantum effects
3. which is unaccessible to conventional accelerators because it requires coherent fields

Intense optical lasers

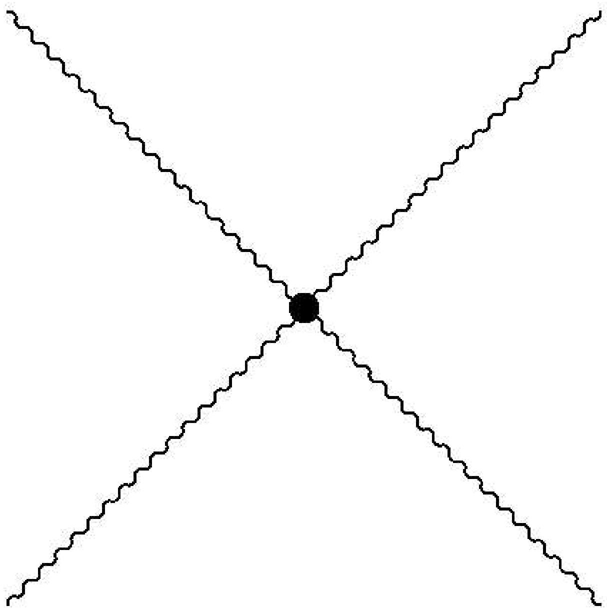
Optical laser technology ($\hbar\omega_L$=1 eV, λ_L=1 μm)	Energy (J)	Pulse duration (fs)	Spot radius (μm)	Intensity (W/cm^2)
State-of-art (Yoon et al., Opt. Express 2019)	83	20	1.5	5.5×10^{22}
Soon (APOLLON, CoReLS, ELI etc...)	$10\div100$	10	1	$10^{23}\div10^{24}$
Near future (ELI 4th pillar, XCELS)	10^4	10	1	$10^{25}\div10^{26}$



Danson et al., High Power Laser Sci. Eng. **7**, e54 (2019)

Probing the quantum vacuum: effective Lagrangian approach

- At a quantum level photons interact with each other and with external electromagnetic fields also in vacuum:
    - The interaction occurs through the virtual electrons and positrons
    - The interaction is non-local, with the typical interaction distance being the Compton wavelength $\lambda_C = \hbar/mc$
    - If the interacting photons and the external fields do not vary much on a Compton wavelength, the local approximation can be used (effective Lagrangian approach)



- Approach valid if $\hbar\omega \ll mc^2$, with ω being the typical angular frequency of the photons and the external fields

- Euler and Heisenberg in 1936 obtained the effective Lagrangian density for an arbitrary constant and uniform electromagnetic field (E,B) only in terms of the two Lorentz-invariant quantities $\mathcal{F} = (B^2 - E^2)/2$, $\mathcal{G} = \boldsymbol{E} \cdot \boldsymbol{B}$

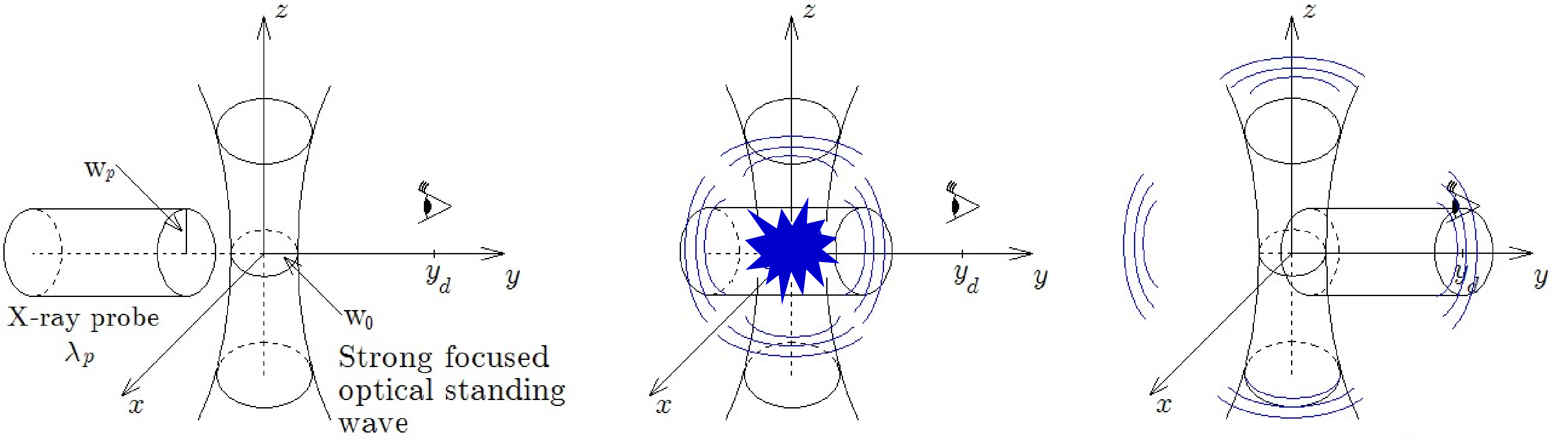
Units with $\hbar = c = 1$

$$\mathcal{L}_{\text{eff}} = -\frac{1}{4\pi}\mathcal{F} - \frac{\alpha}{8\pi^2}F_{cr}^2 \int_0^\infty \frac{ds}{s} e^{-s} \left\{ \frac{\mathcal{G}}{F_{cr}^2} \frac{\operatorname{Re}\cosh\left[s\sqrt{2(\mathcal{F} + i\mathcal{G})/F_{cr}^2}\right]}{\operatorname{Im}\cosh\left[s\sqrt{2(\mathcal{F} + i\mathcal{G})/F_{cr}^2}\right]} - \frac{1}{s^2} - \frac{2}{3}\frac{\mathcal{F}}{F_{cr}^2} \right\}$$

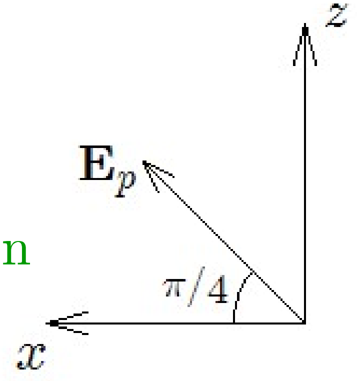
- The quantum part of the Lagrangian density depends on the ratios $\mathcal{F}/F_{cr}^2$ and $|\mathcal{G}|/F_{cr}^2$, where $F_{cr} = E_{cr} = B_{cr} = m^2/|e|$
- The imaginary part of $\mathcal{L}_{\text{eff}}$ is connected with the pair production probability per unit volume and unit time
- If the external field is purely magnetic $\mathcal{L}_{\text{eff}}$ is real then no pair production, while for purely electric fields $\mathcal{L}_{\text{eff}}$ contains an imaginary part (Dittrich et al. 1985)
- A single plane-wave field with $\mathcal{F} = \mathcal{G} = 0$ cannot give rise to any nonlinear vacuum-polarization effects
- For small field $|\mathcal{F}|/F_{cr}^2$, $|\mathcal{G}|/F_{cr}^2 \ll 1$, $\mathcal{L}_{\text{eff}}$ can be expanded as

$$\mathcal{L}_{\text{eff}} = \frac{1}{8\pi}(E^2 - B^2) + \frac{\alpha}{360\pi^2}\frac{(E^2 - B^2)^2 + 7(\mathbf{E} \cdot \mathbf{B})^2}{F_{cr}^2}$$

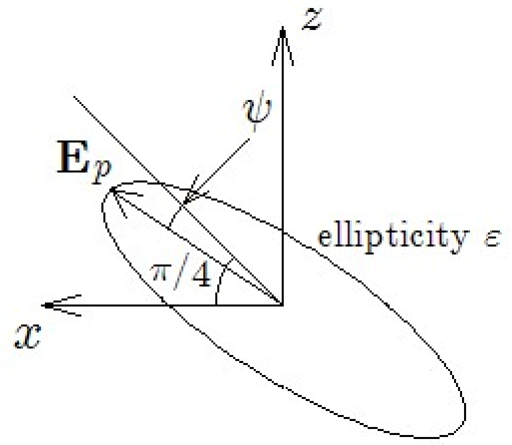
Light-by-light diffraction



Probe polarization
before the interaction



Probe polarization
after the interaction



The scheme also works with a single strong traveling wave (electromagnetic cascade generation in a standing wave of intensity $\gtrsim 10^{24}$ W/cm^2 in the presence of residual electrons: A. Bell and J. Kirk, Phys. Rev. Lett. **101**, 200403 (2008))

Effects of diffraction on the probe polarization

- It is as if the vacuum in the presence of a background electromagnetic field behaves as a birefringent medium

$$n_E = 1 + \frac{4\alpha}{90\pi}\frac{(\boldsymbol{n}\times\boldsymbol{E})^2 + (\boldsymbol{n}\times\boldsymbol{B})^2 - 2\boldsymbol{n}\cdot(\boldsymbol{E}\times\boldsymbol{B})}{F_{cr}^2}$$

$$n_B = 1 + \frac{7\alpha}{90\pi}\frac{(\boldsymbol{n}\times\boldsymbol{E})^2 + (\boldsymbol{n}\times\boldsymbol{B})^2 - 2\boldsymbol{n}\cdot(\boldsymbol{E}\times\boldsymbol{B})}{F_{cr}^2}$$

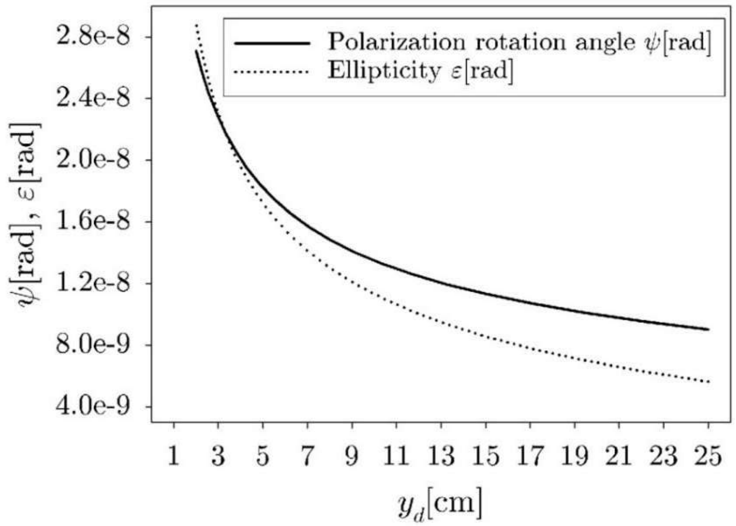
- Diffraction effects play a role for a tightly-focused strong beam
- Numerical example

  Strong optical laser beam:

  I_L=10^{23} W/cm^2, w$_L$=λ_L=0.745 μm

  Probe beam:

  λ_p=0.4 nm, w$_p$=8 μm



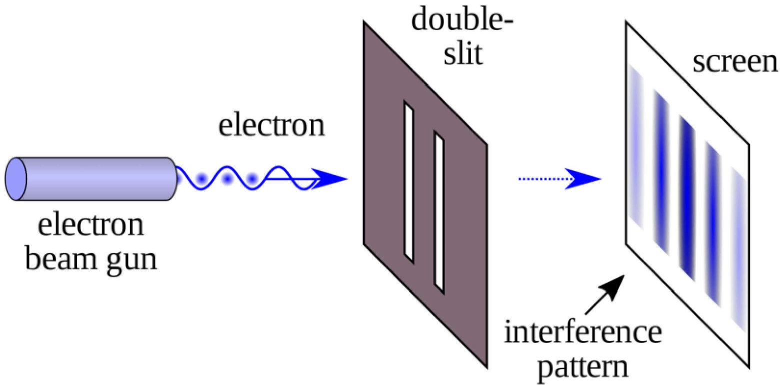
- Results

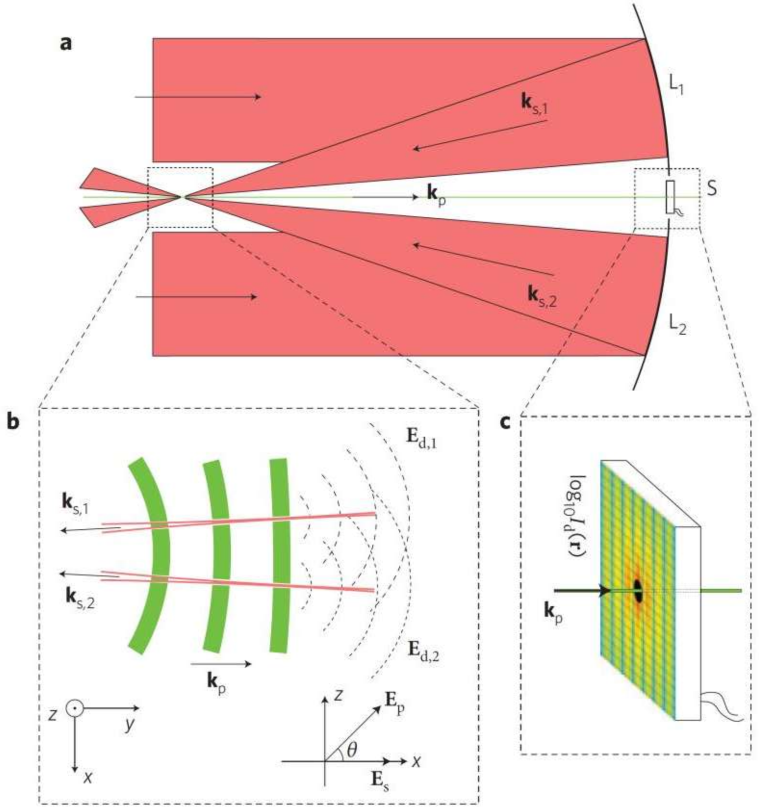
1. The observables ψ and ε are inversely proportional to λ_p
2. The quantities ψ and ε converge at large distances to values of the order of 10^{-9} rad, which are envisaged to be soon measurable in the soft x-ray regime (Schmitt et al. 2020)

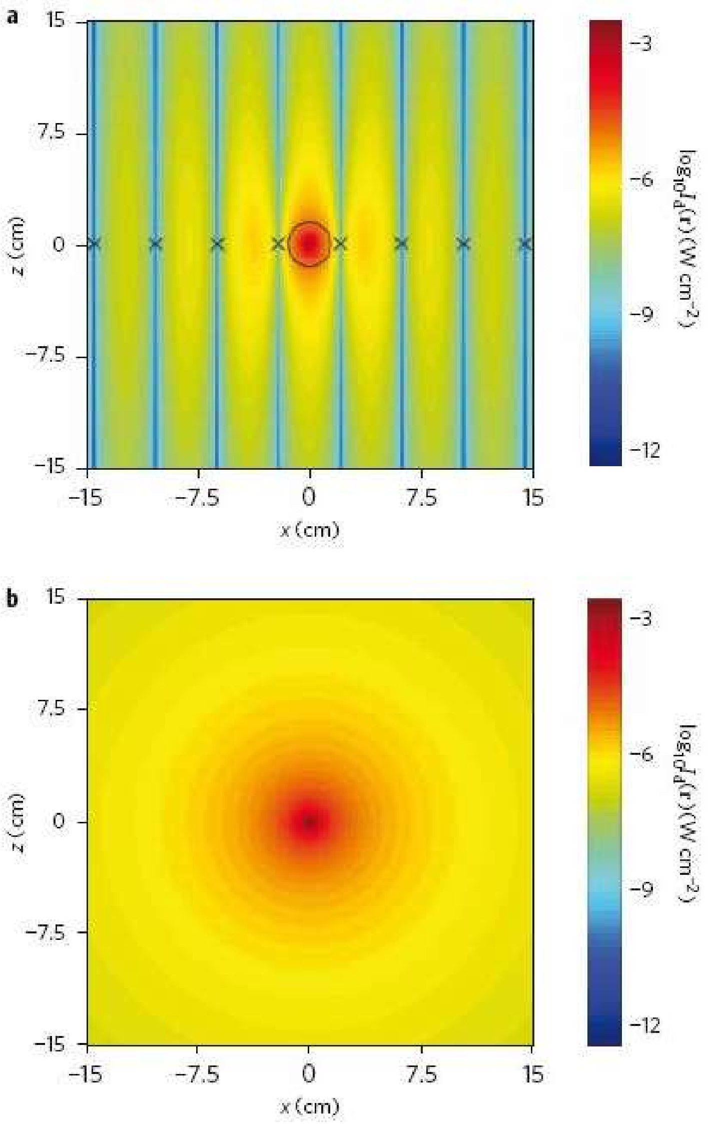
Di Piazza et al. Phys. Rev. Lett. **97**, 083603 (2006)

A matterless double-slit

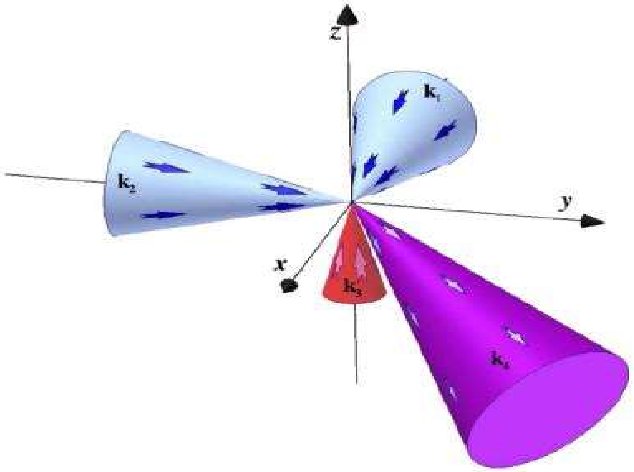
- The double slit experiment has played a fundamental role in our understanding of quantum mechanics, in particular the so-called wave-particle duality of particles
- All double-slit schemes proposed so far have always involved matter (either the particles employed like electrons, neutrons and so on or the wall where the double slit is)
- By exploiting the quantum interaction among laser beams in the vacuum, we have put forward a matterless double slit setup (King et al. 2010, ibid. 2012)







- Strong field: 150 PW (ELI), 800 nm, 30 fs, focused to one wavelength
- Weak field: 200 TW, 527 nm, 100 fs focused to 290 μm
- The × are at: $(n+1/2)\lambda_p = D\sin(\vartheta_n)$
- With the above parameters one obtains about 4 diffracted photons per shot
- Photon-photon scattering

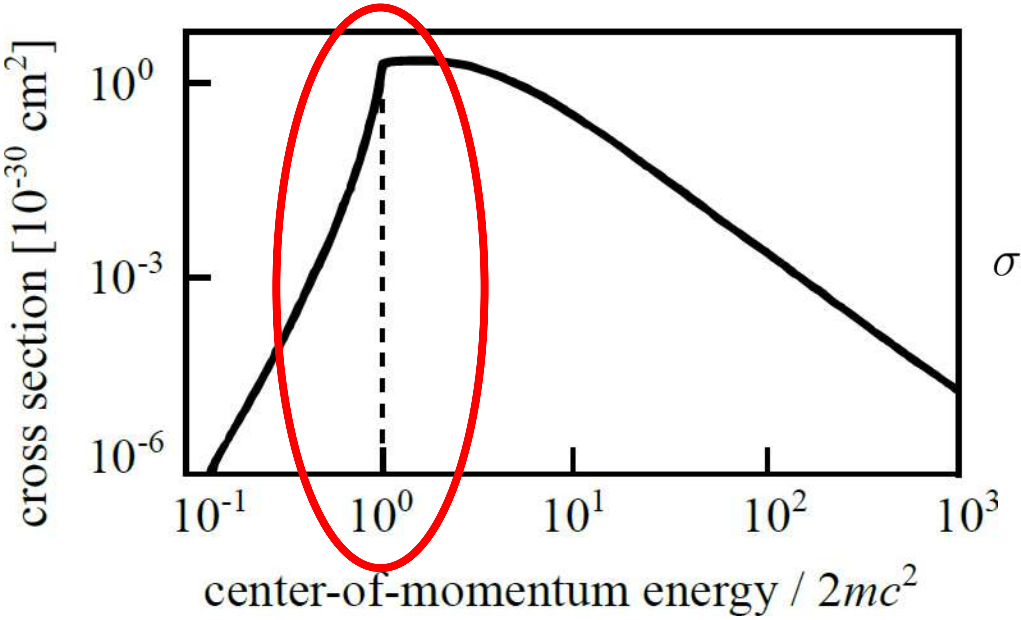


- Multi PW-class laser systems may open the possibility of observing for the first time either direct photon-photon scattering in vacuum (Lundstroem et al. Phys. Rev. Lett. 2006)

High-energy vacuum-polarization effects

Units with $\hbar$=c=1

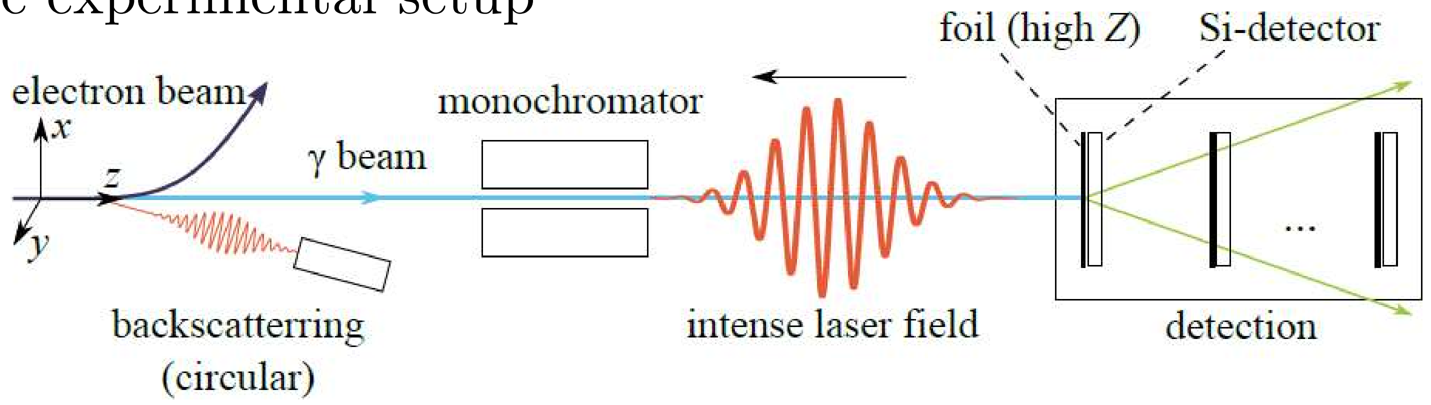
- At photon energies much lower than the electron rest energy the effective-Lagrangian approach can be successfully applied
- If two photons with four-momenta ${k_1}^\mu$ and ${k_2}^\mu$ collide the Lorentz-invariant condition to apply the effective-Lagrangian approach reads: $(k_1 k_2) \ll m^2$
- However, the cross-section of photon-photon scattering scales as $[(k_1 k_2)/m^2]^6$ for $(k_1 k_2) \ll m^2$ (Berestetskii et al. 1982)



$$\sigma_T = \frac{8\pi}{3}\alpha^2\lambda_C^2 \approx 6.8 \times 10^{-25}\ \mathrm{cm}^2$$

- It is more convenient to work at $(k_1 k_2) \sim m^2$

- In the regime $(k_1k_2)\sim m^2$ the interaction between two photons is non-local and the effective-Lagrangian approach is not applicable
- The experimental setup



- In the laser-photon head-on collision, the photon state can be expanded into two polarization states $\Lambda_1^{\mu}=(0, \mathbf{\Lambda}_1)$ and $\Lambda_2^{\mu}=(0, \mathbf{\Lambda}_2)$, with $\mathbf{\Lambda}_1 \| \boldsymbol{E}_L$ and $\mathbf{\Lambda}_2 \| \boldsymbol{B}_L$
- By solving the nonlocal equation for $\Phi^{\mu}(x)$, one finds

$$\Phi_i^{\mu}(x) = e_i^{\mu} e^{-i(kx)} = \sum_{l=1,2} c_l \Lambda_l^{\mu} e^{-i(kx)} \longrightarrow \Phi_f^{\mu}(x) = e_f^{\mu} e^{-i(kx)} = \sum_{l=1,2} c_l \Lambda_l^{\mu} e^{-i(kx)} e^{-i\phi_l} e^{-\lambda_l}$$

- The two additional phases ϕ_l (real exponents λ_l) indicate that the vacuum is a birefringent (dichroic) medium (the physical origin of dichroism is the possibility of pair production)

S. Bragin et al., Phys. Rev. Lett. **119**, 250403 (2017)

Conclusions

- According to Quantum Electrodynamics the vacuum is not simply ‘nothing’ but it is an interesting and fascinating object to investigate
- Its properties can be studied with the help of ultra-intense lasers
- The vacuum behaves as a ‘medium’, allowing for exotic effects like
  - light-by-light diffraction
  - matterless double-slit interference
  - field-dependent vacuum refractive indexes
  - vacuum birefringence and dichroism