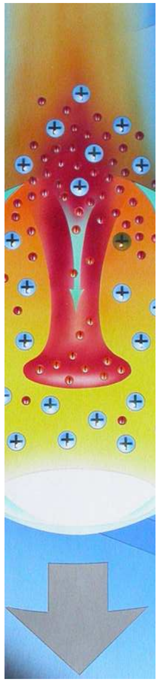
DYNAMICAL SCHWINGER EFFECT AT LASER FACILITIES

David Blaschke (Univ. Wroclaw, Poland & JINR Dubna, Russia)



- Introduction: Schwinger Effect
- Kinetic formulation of pair production
- Discussion of the landscape: E_0- and λ- dependence
- Experimental verification of $\mathrm{e}^+\mathrm{e}^-$ pair density
- Astra-Gemini Laser experiment: below the Schwinger limit
- ELI: towards the Schwinger limit and beyond QED

Recent paper: Phys. Rev. D 84, 085028 (2011)

Collaboration:
Burkhard Kämpfer (Dresden University & HZ Dresden-Rossendorf, Germany)
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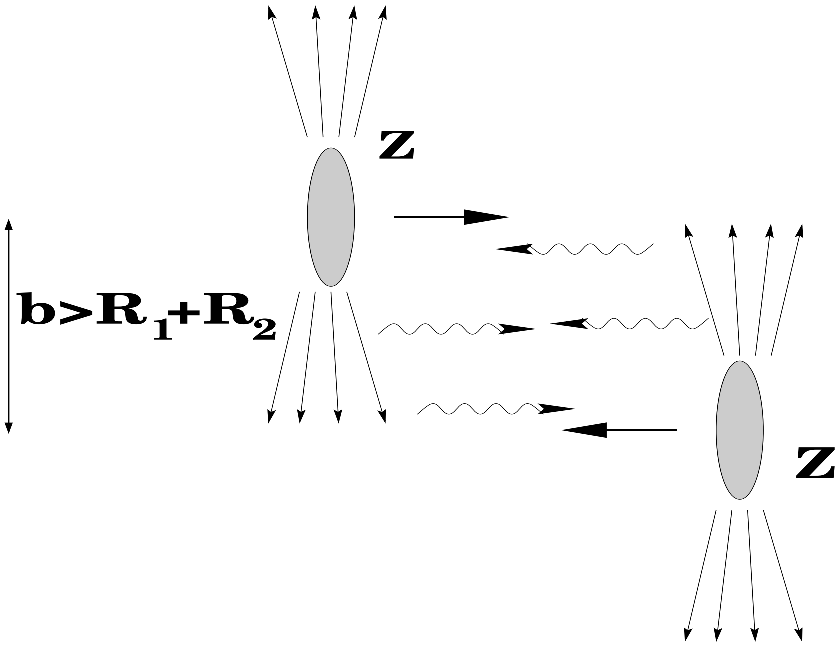
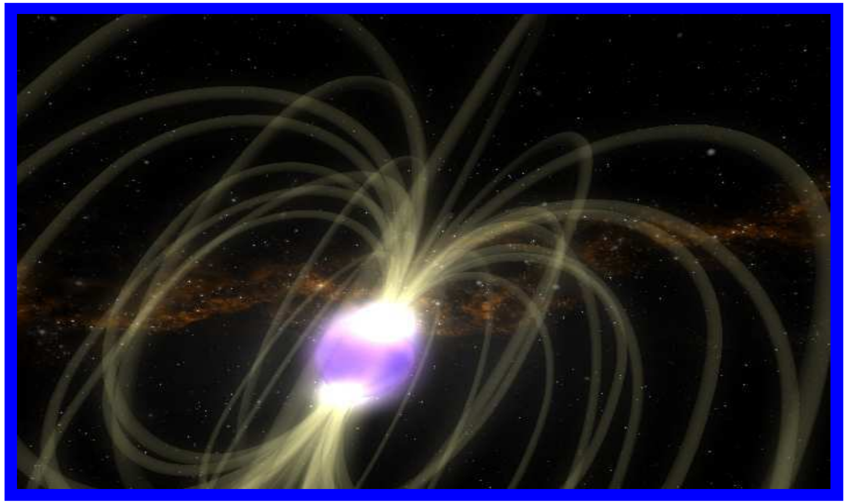
Gianluca Gregori (Univ. Oxford & Rutherford Appleton Lab, UK)
Craig Roberts (Argonne National Laboratory, USA)
Sebastian Schmidt (Forschungszentrum Jülich, Germany)
Alexander Prozorkevich, Stanislav Smolyansky, Alexander Panferov (Saratov Univ., Russia)

PAIR CREATION IN STRONG ELECTROMAGNETIC FIELDS

- Magnetars: B$\sim 10^{15}$G $\Longrightarrow$
  Problem: unclear conditions!
- Ultra-Peripheral Heavy Ion Coll.



Problem: extremely short $\sim 10^{-29}$ s



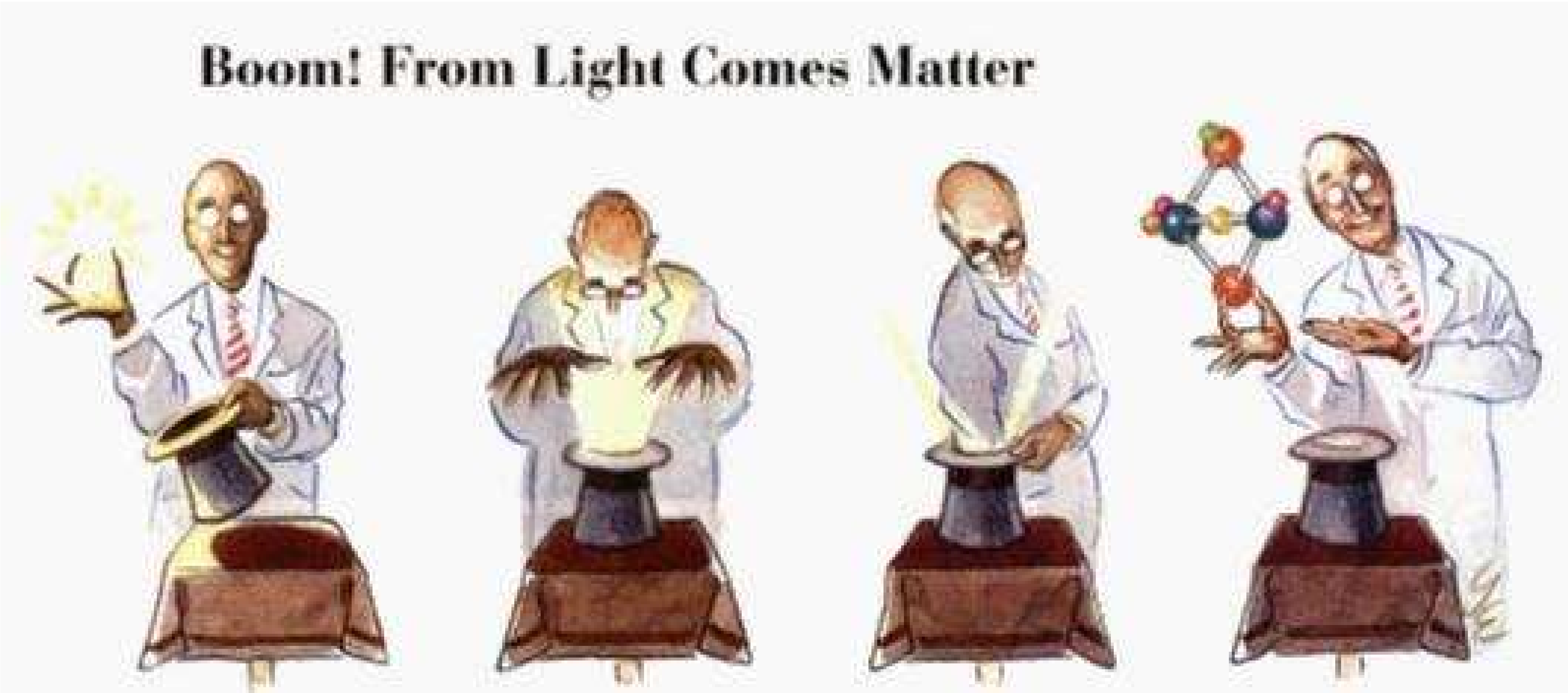
ARTIST VIEW OF A MAGNETAR (NASA)

- ELI: Optical $\rightarrow$ X-Ray @ 1 EW:
  $I_0 \sim\ 10^{25}$ W/cm^2 $\rightarrow I_{CHF} \sim\ 10^{36}$ W/cm^2

  \+ Long lifetime:
  $\tau \sim 10^{-15} \ldots 10^{-18}$ s $\gg\ 10^{-22}$ s

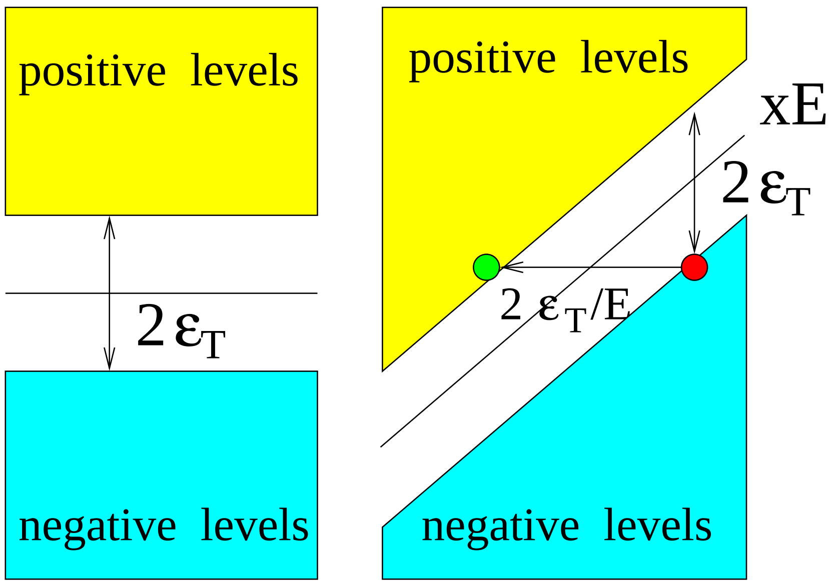
  \+ Condition for pair creation:
  $E^2 - B^2 \neq 0$, (crossed lasers)

SCHWINGER EFFECT: PAIR CREATION IN STRONG FIELDS



Schwinger Effect: Pair Creation in Strong Fields

Pair creation as barrier penetration
in a strong constant field



Schwinger result (rate for pair production)

$$\frac{dN}{d^3x\,dt} = \frac{(eE)^2}{4\pi^3} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(-n\pi \frac{E_{\rm crit}}{E}\right)$$

- To "materialize" a virtual e^+e^- pair in a constant electric field E the separation d must be sufficiently large

$$eEd = 2mc^2$$

- Probability for separation d as quantum fluctuation

$$P \propto \exp\left(-\frac{d}{\lambda_c}\right) = \exp\left(-\frac{2m^2c^3}{e\hbar E}\right) = \exp\left(-\frac{2E_{\rm crit}}{E}\right)$$

- Emission sufficient for observation when $E \sim E_{\rm crit}$

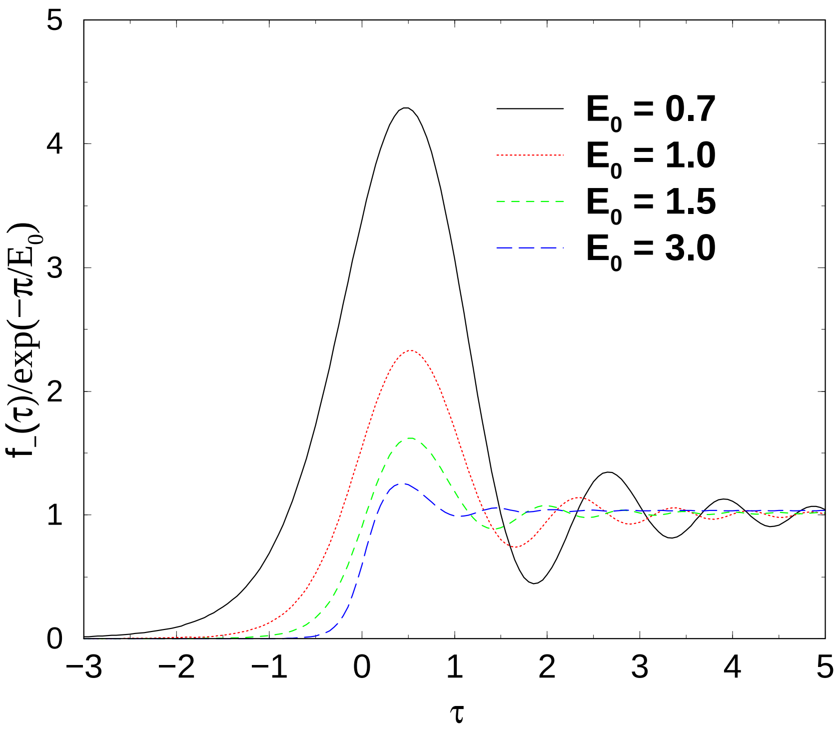
$$E_{\rm crit} \equiv \frac{m^2c^3}{e\hbar} \simeq 1.3 \times 10^{18}\,{\rm V/m}$$

- For time-dependent fields: Kinetic Equation approach from Quantum Field Theory

J. Schwinger: "On Gauge Invariance and Vacuum Polarization", Phys. Rev. 82 (1951) 664

KINETIC FORMULATION OF PAIR PRODUCTION

Kinetic equation for the single particle distribution function $f(\bar{P},t) =< 0|a^\dagger_{\bar{P}}(t)a_{\bar{P}}(t)|0>$



$$\frac{df_\pm(\bar{P},t)}{dt} = \frac{\partial f_\pm(\bar{P},t)}{\partial t} + eE(t)\frac{\partial f_\pm(\bar{P},t)}{\partial P_\parallel(t)}$$

$$= \frac{1}{2}\mathcal{W}_\pm(t)\int_{-\infty}^{t} dt'\mathcal{W}_\pm(t')[1 \pm 2f_\pm(\bar{P},t')]\cos[x(t',t)]$$

Kinematic momentum $\bar{P} = (p_1, p_2, p_3 - eA(t))$,

$$\mathcal{W}_-(t) = \frac{eE(t)\varepsilon_\perp}{\omega^2(t)} ,$$

where $\omega(t) = \sqrt{\varepsilon_\perp^2 + P_\parallel^2(t)}$, with $\varepsilon_\perp = \sqrt{m^2 + \bar{p}_\perp^2}$
and $x(t',t) = 2[\Theta(t) - \Theta(t')]$.

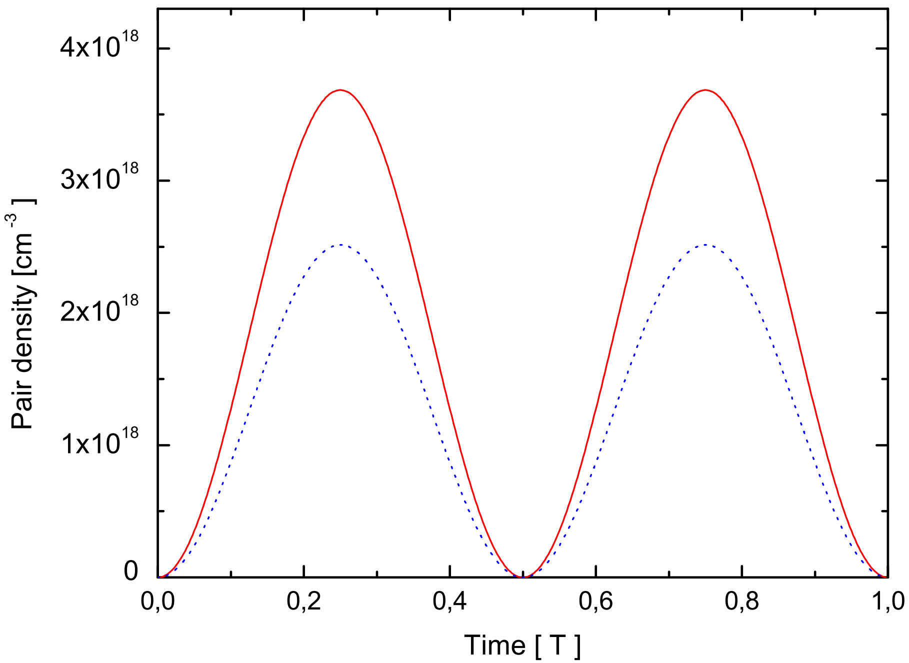
$$\Theta(t) = \int_{-\infty}^{t} dt'\omega(t')$$

Constant field: Schwinger limit reproduced

$$f(\tau \to \infty) = \exp\left(\frac{-\pi}{E_0}\right)$$

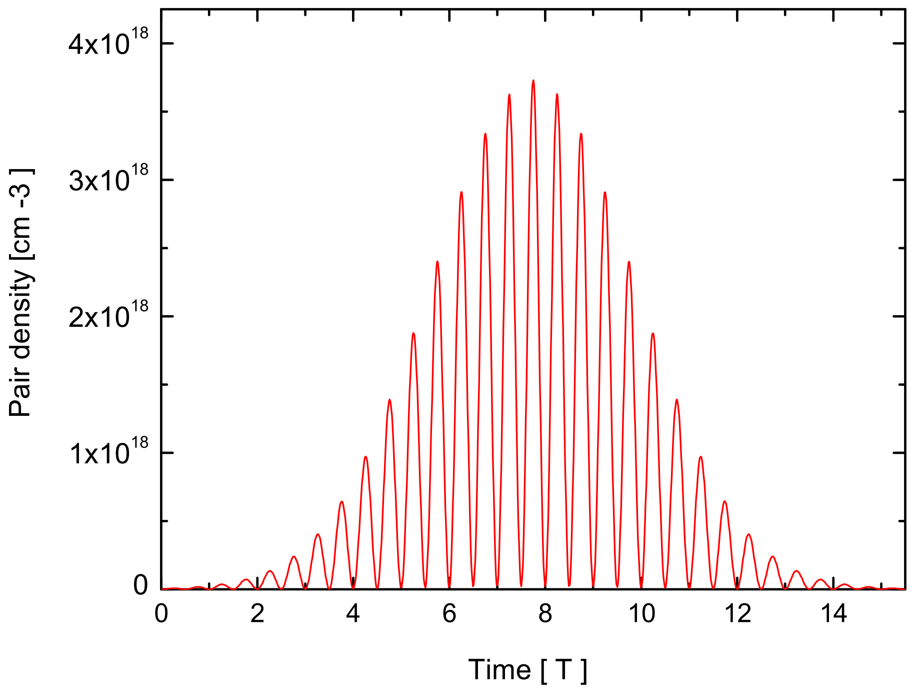
Schmidt, Blaschke, Röpke, et al:
Non-Markovian effects in strong-field pair creation
Phys. Rev. D 59 (1999) 094005

e^+e^- PAIR PRODUCTION IN SUBCRITICAL LASER FIELDS (II)



Time dependence of the density $n(t)$ for a monochromatic field

$$E(t) = E_m \sin \omega t, \quad 0 \leq t \leq NT, \quad T = \frac{2\pi}{\omega}$$



Time dependence of the density $n(t)$ for a Gaussian wave packet

$$E(t) = E_m e^{-(t/\tau_L)^2} \sin \omega t.$$

Pair production in subcritical fields (I)

Kinetic formulation for $E(t) = -\dot{A}(t)$ in the Hamiltonian gauge $A^\mu = (0,0,0,A(t))$

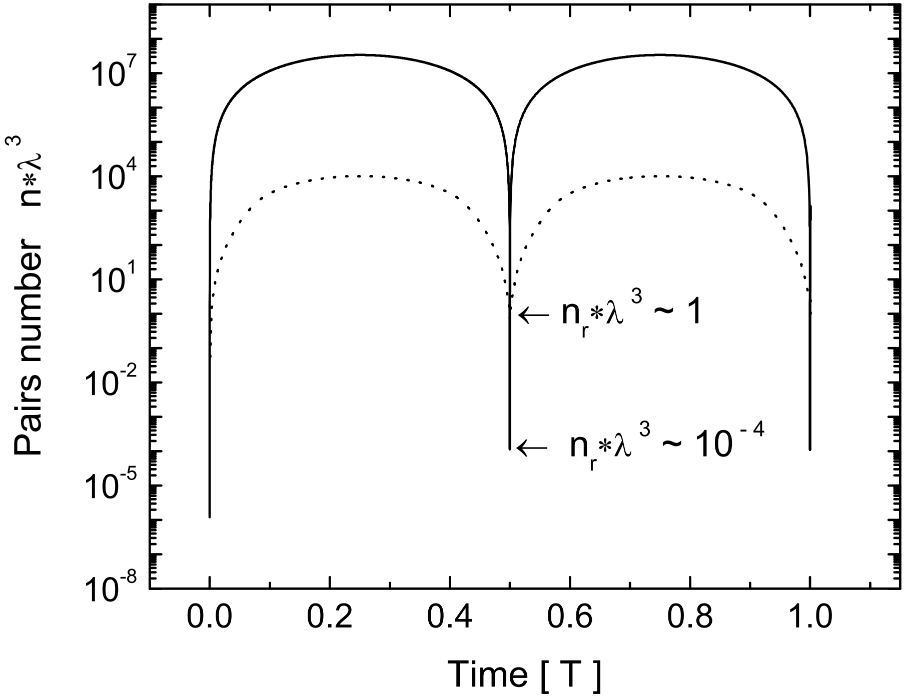
$$\frac{df(\mathbf{p},t)}{dt} = \frac{1}{2}\Delta(\mathbf{p},t)\int_{t_0}^{t} dt'\,\Delta(\mathbf{p},t')\,[1-2f(\mathbf{p},t')] \times \cos\left[2\int_{t'}^{t} dt_1\,\varepsilon(\mathbf{p},t_1)\right],$$

where

$$\Delta(\mathbf{p},t) = eE(t)\frac{\sqrt{m^2+p_\perp^2}}{\varepsilon^2(\mathbf{p},t)},$$
$$\varepsilon(\mathbf{p},t) = \sqrt{m^2+p_\perp^2+[p_3-eA(t)]^2}$$

The particle number density

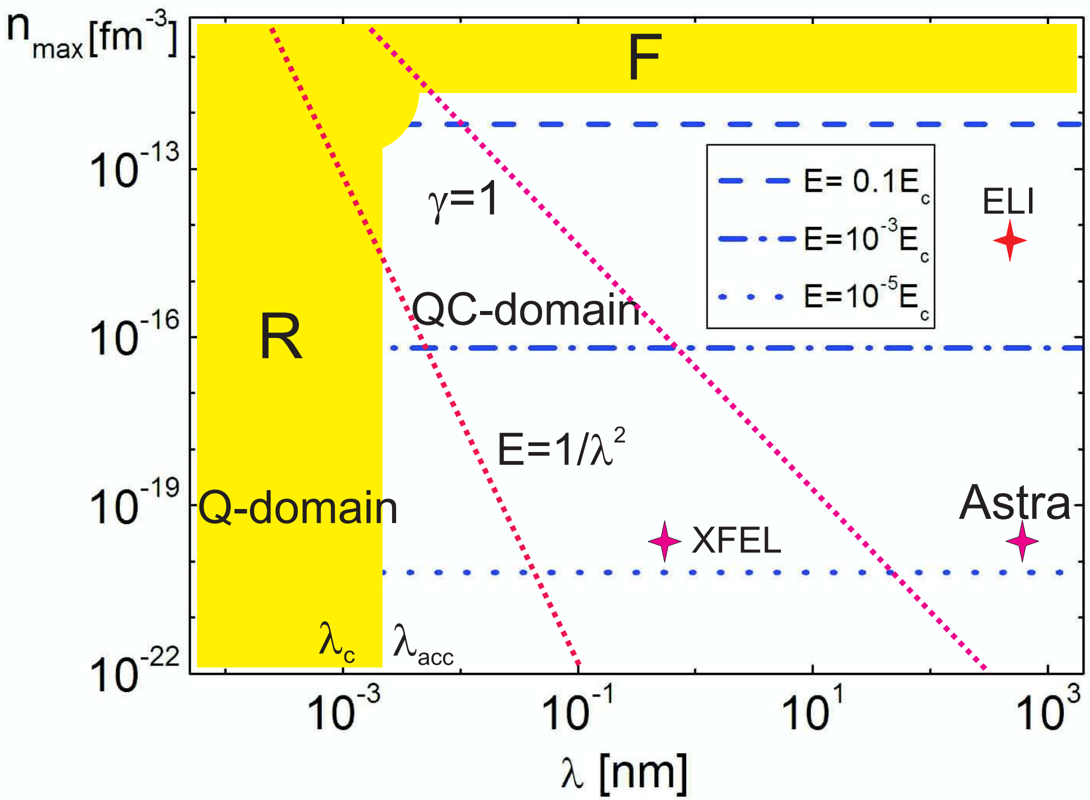
$$n(t) = 2\int \frac{d\mathbf{p}}{(2\pi)^3} f(\mathbf{p},t)$$



Number of e^+e^- pairs in the volume λ^3 for a weak field (Jena Ti:AlO$_3$ laser, solid line) and for near-critical field $E_m/E_{\rm crit} = 0.24$, $\lambda = 0.15$ nm (X-FEL, dashed line).

D.B. et al., PRL 96 (2006) 140402

THE LANDSCAPE: FIELD STRENGTHS AND WAVELENGTHS



Adiabaticity parameter

$$\gamma = \frac{E_c}{E_0}\frac{\lambda_c}{\lambda}$$

,

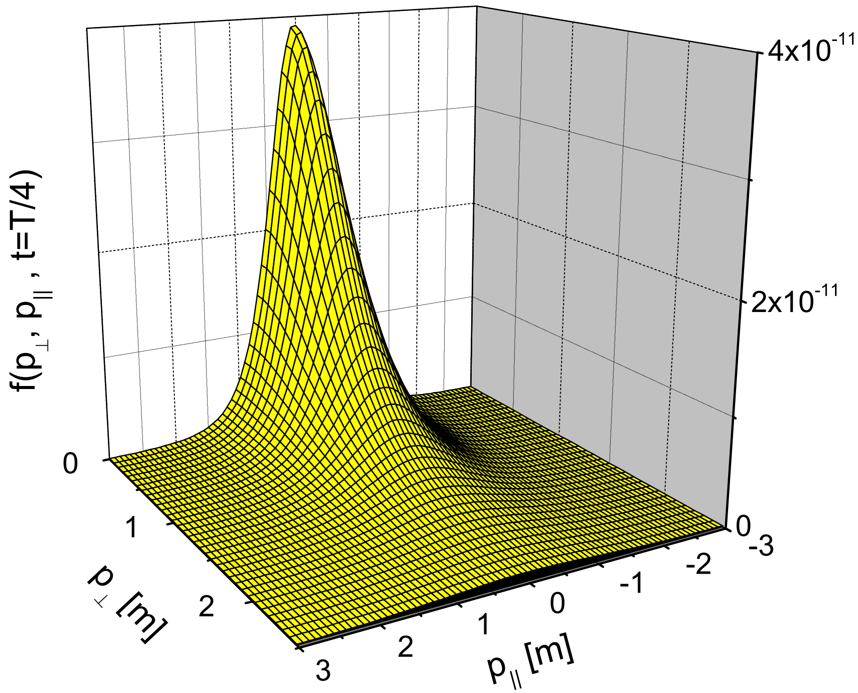
- $\gamma > 1 \rightarrow$ tunneling
- $\gamma < 1 \rightarrow$ multiphoton **Two**

1 Attometer (am) $= 10^{-18}$ m
$= 10^{-3}$ fm

1 fm^{-3} = 10^{18} nm^{-3}

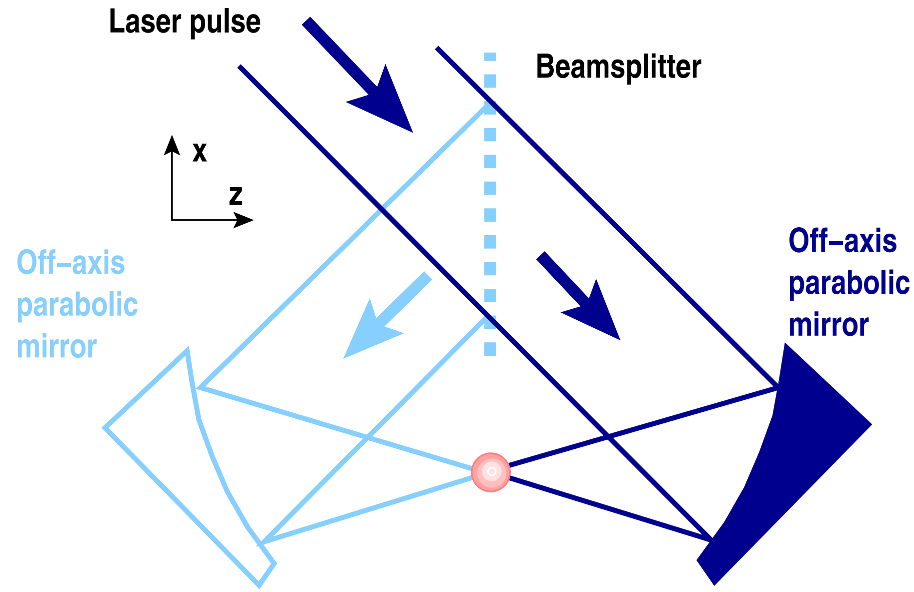
accumulation domains (R and F) and the "calm valley"

Application to subcritical laser fields



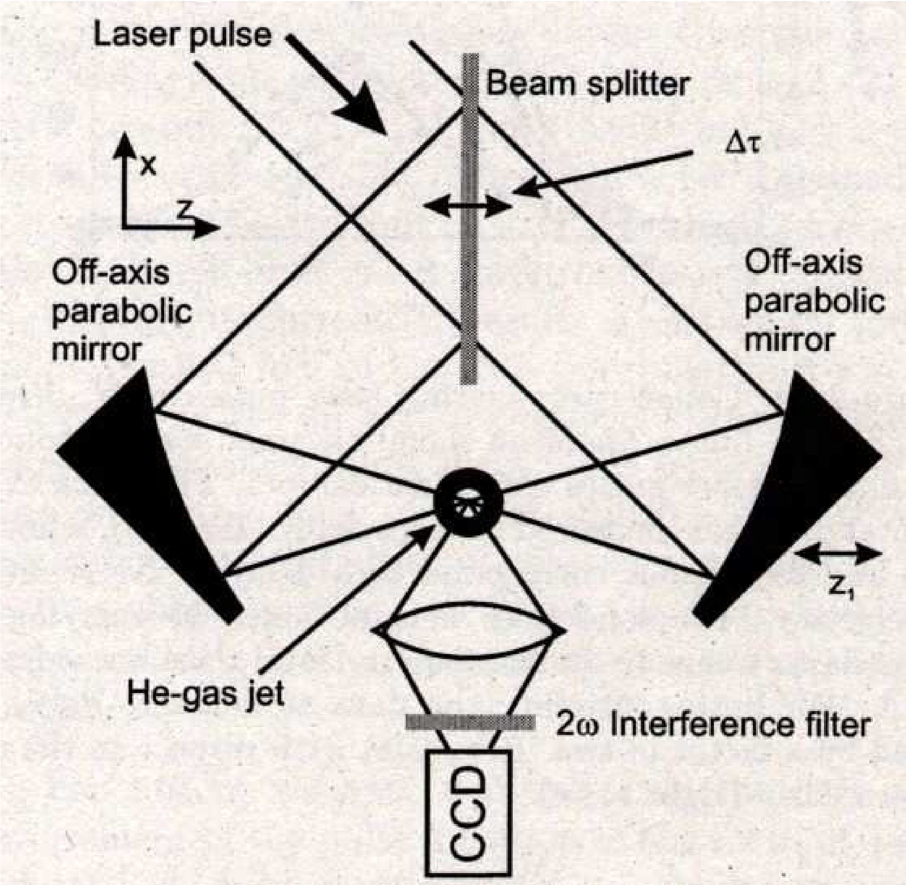
Equilibrium-like momentum distribution at the time of maximal field amplitude $t = T/4$.

Setup of the Jena Laser Exp. (2005)

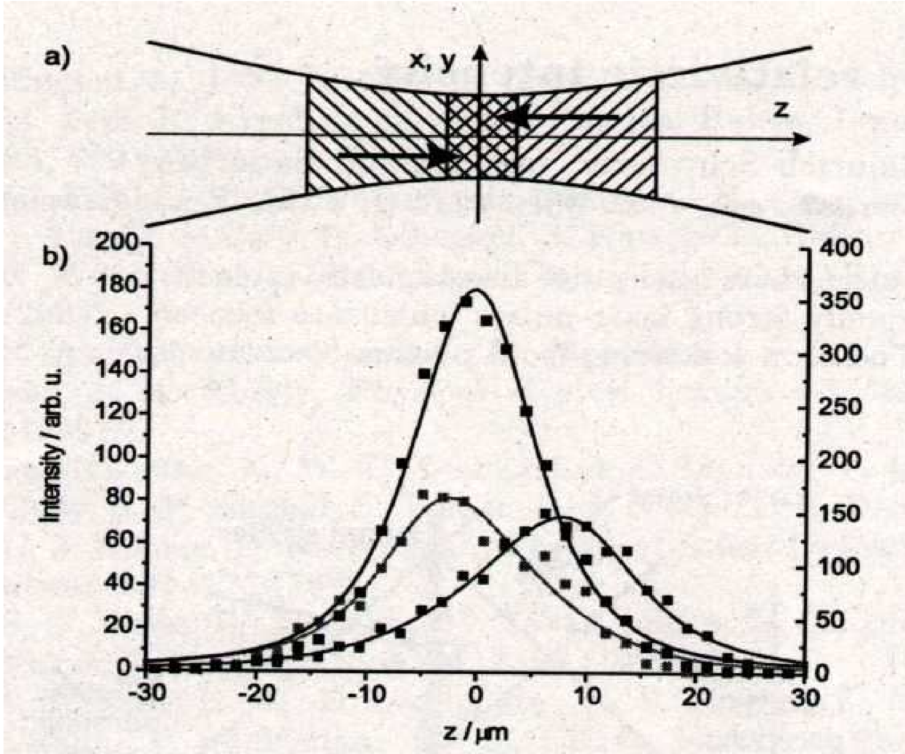


Heinzl, et al., Opt. Commun. 267, 318 (2006)

APPLICATION TO JENA MULTI-TW LASER



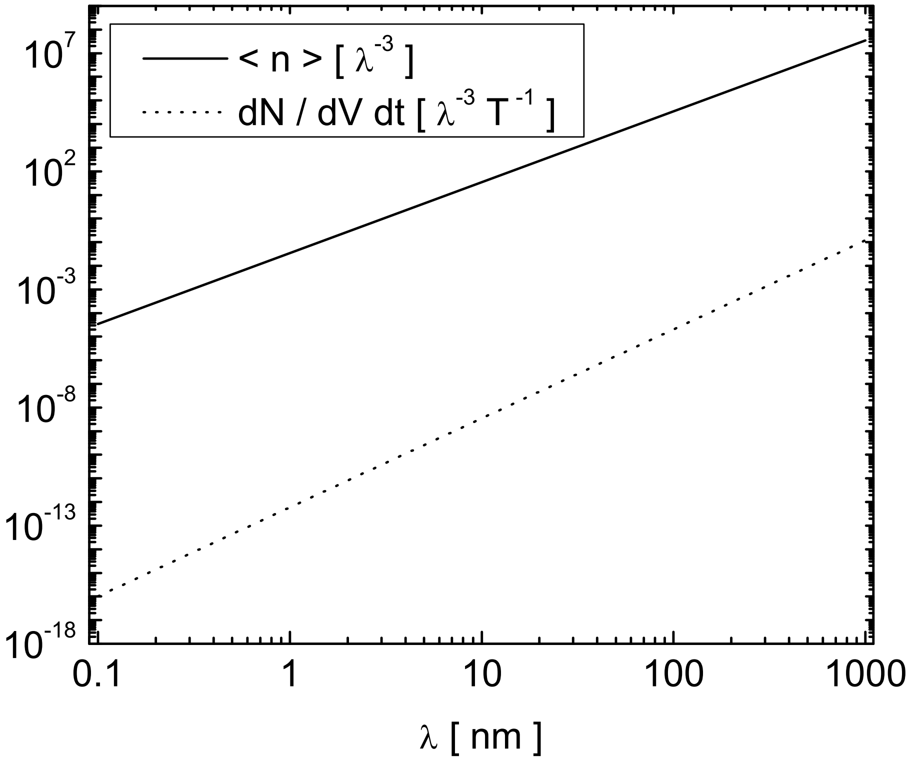
Colliding laser pulses of a Ti:sapphire laser with $E_m/E_{\rm crit} \approx 3 \cdot 10^{-5}$ and $\omega/m = 2.84 \cdot 10^{-6}$



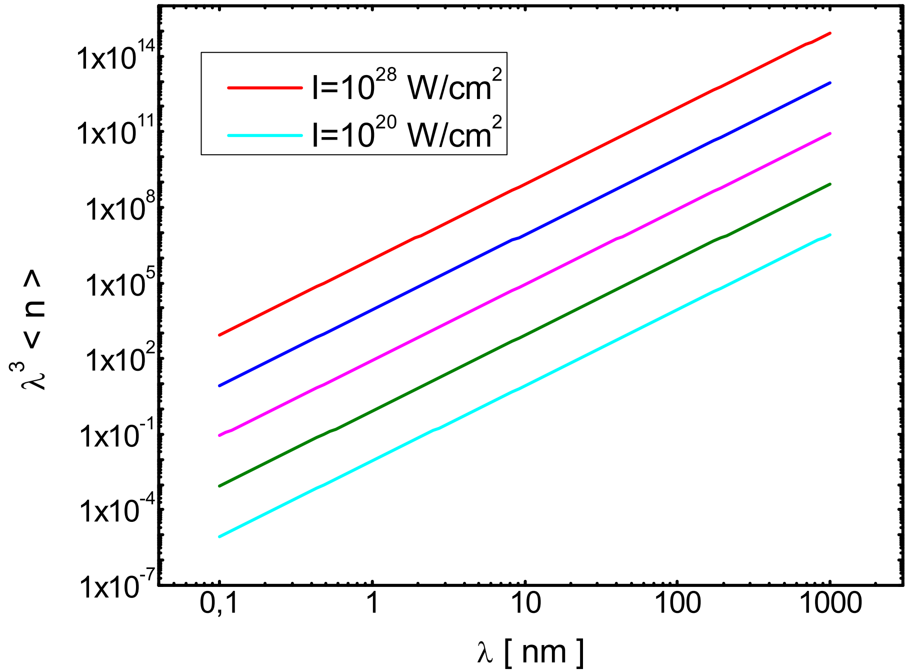
Laser diagnostic by nonlinear Thomson scattering off e$^-$ in a He-gas jet
Pulse intensity: $I = 10^{18}$ W/cm^2, duration: $\tau_L \sim 80fs$, wavelength: $\lambda = 795$ nm, cross-size: $z_0 = 9\mu$m

B. Liesfeld et al: "Single-shot autocorrelation at relativistic intensity", Jena Preprint (2004)

Application to subcritical laser fields (III)



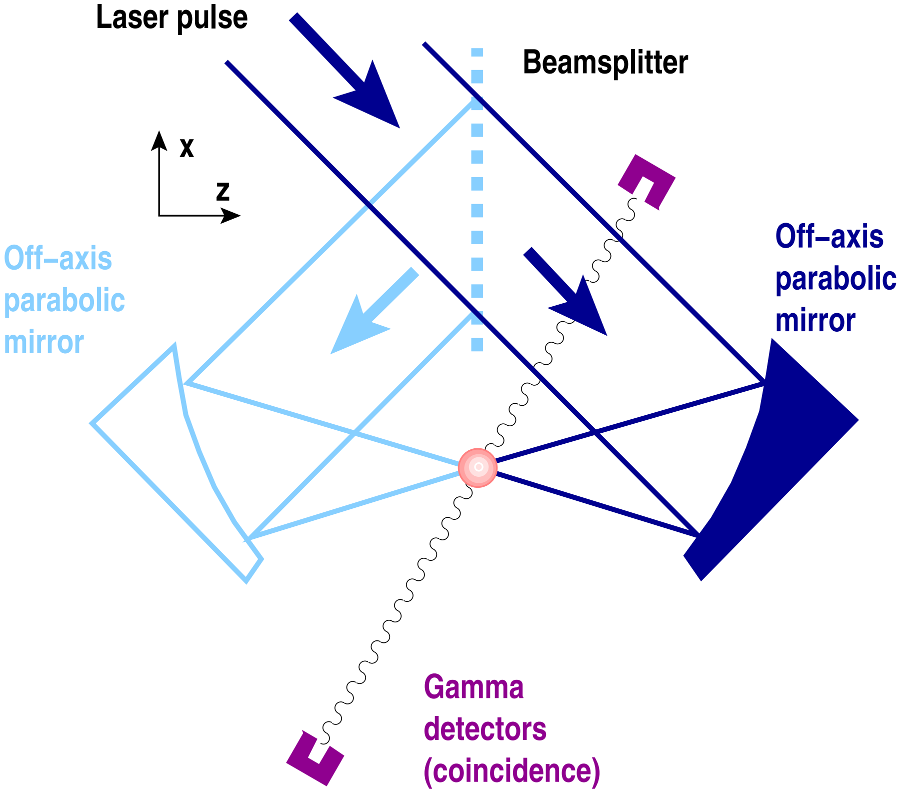
Wavelength dependence of the mean density of e^+e^- pairs (solid line) and their annihilation rate (dotted line). $E = 3 \times 10^{-5} E_{cr}$.

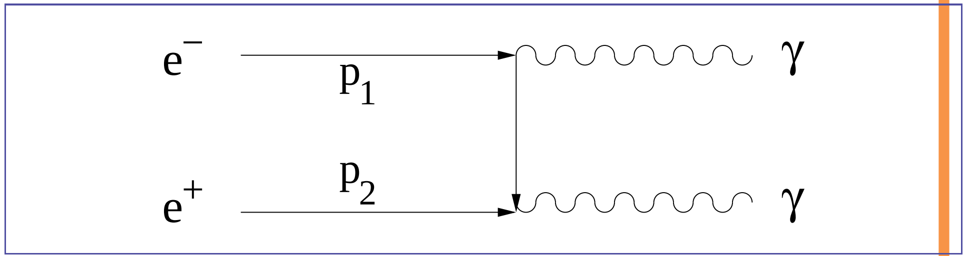


Wavelength dependence of the mean density of e^+e^- pairs for different E/E_{cr}

PERSPECTIVES FOR e^+e^- PAIRS @ OPTICAL LASERS (I)

Observable: photon pair $(e^+ + e^- \to 2\ \gamma)$





$$\frac{d\nu}{dV\,dt} = \int d\mathbf{p}_1 d\mathbf{p_2}\, \sigma(\mathbf{p}_1, \mathbf{p}_2) f(\mathbf{p}_1, t) f(\mathbf{p}_2, t) \times \sqrt{(\mathbf{v}_1 - \mathbf{v}_2)^2 - |\mathbf{v}_1 \times \mathbf{v}_2|^2},$$

cross-section σ of two-photon annihilation

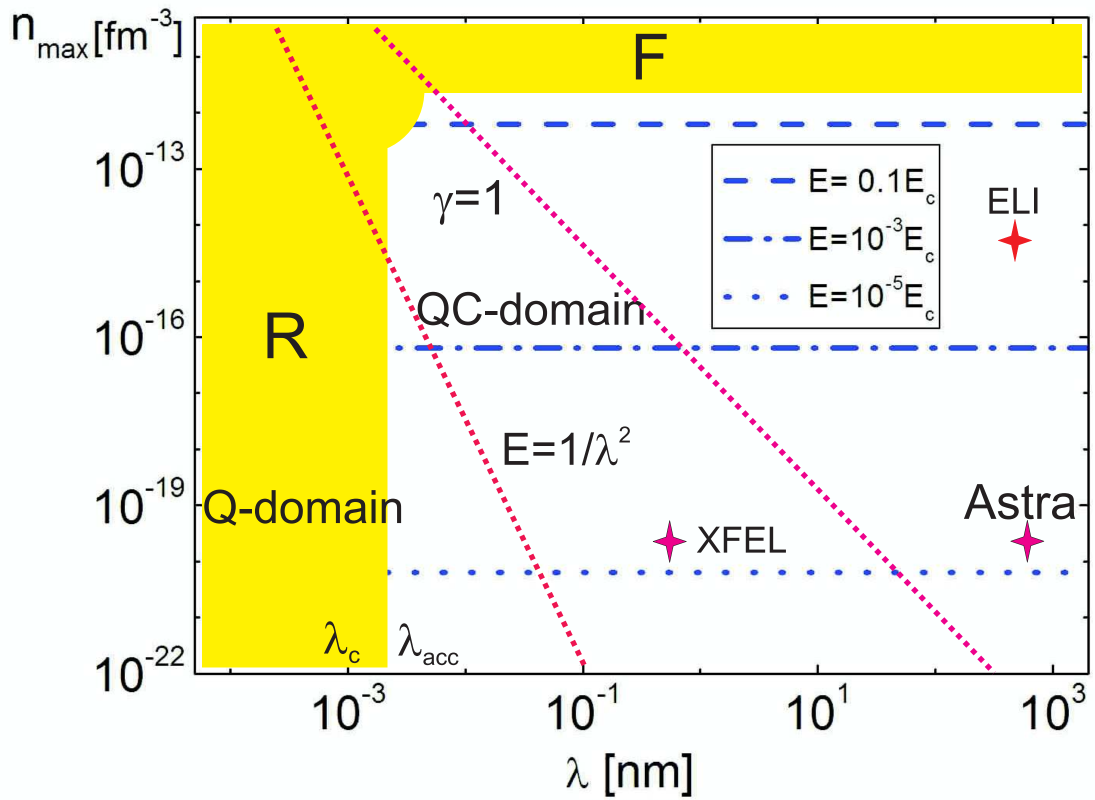
$$\sigma(\mathbf{p}_1, \mathbf{p}_2) = \frac{\pi e^4}{2m^2\tau^2(\tau - 1)} \Big[(\tau^2 + \tau - 1/2) \times \ln\left\{\frac{\sqrt{\tau} + \sqrt{\tau - 1}}{\sqrt{\tau} - \sqrt{\tau - 1}}\right\} - (\tau + 1)\sqrt{\tau(\tau - 1)}\Big],$$

t-channel kinematic invariant

$$\tau = \frac{(p_1 + p_2)^2}{4m^2} = \frac{1}{4m^2}[(\varepsilon_1 + \varepsilon_2)^2 - (\mathbf{p}_1 + \mathbf{p}_2)^2].$$

Project: G. Gregori et al. (2008) at RAL Astra-Gemini Laser

THE LANDSCAPE: FIELD STRENGTHS AND WAVELENGTHS



Adiabaticity parameter

$$\gamma = \frac{E_c}{E_0}\frac{\lambda_c}{\lambda}$$

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Two

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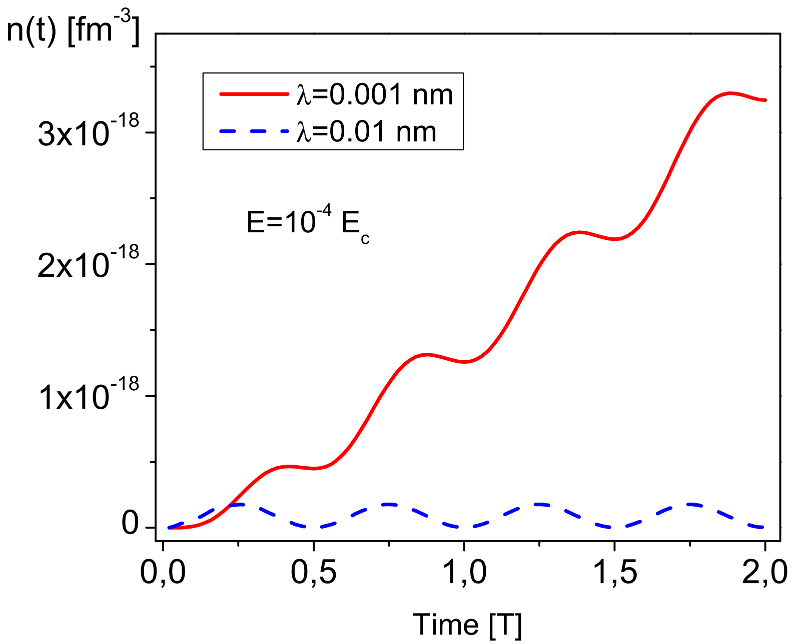
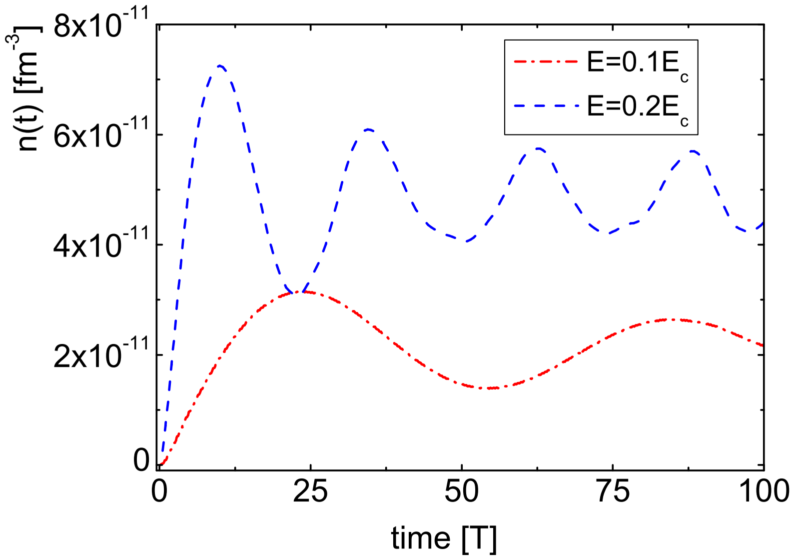
= 10^{-3} fm

1 fm^{-3} = 10^{18} nm^{-3}

accumulation domains (R and F) and the "calm valley"

ACCUMULATION IN WEAK-FIELD CASE (R-DOMAIN)

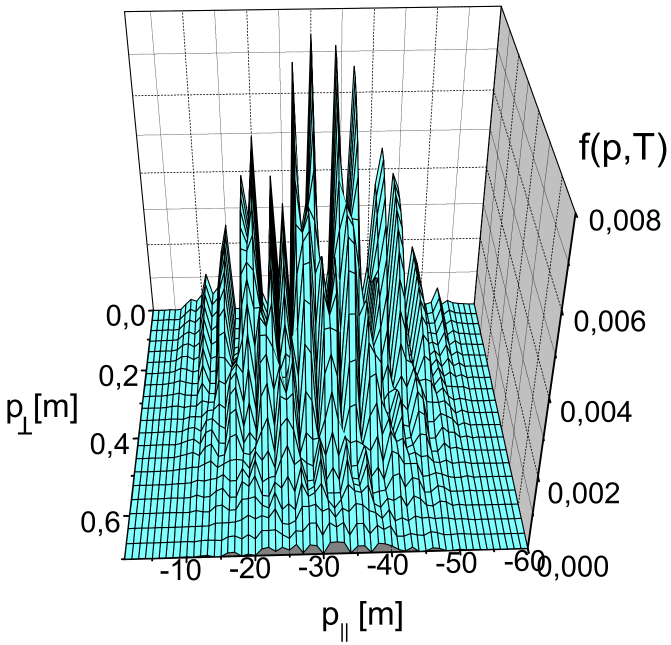


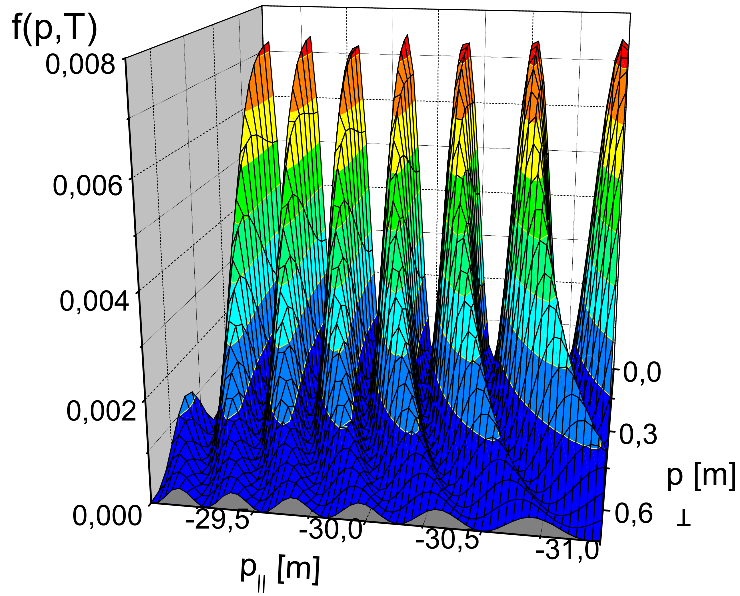


Accumulation in weak-field regime: transition from oscillating mode ($\lambda = 0.01$ nm) to the linearly (in the mean) growing mode ($\lambda = 0.001$ nm).

Limitation of accumulation due to saturation of $f(p)$ at large times for $\lambda = 0.001$ nm. Saturation is faster for stronger fields.

ACCUMULATION IN STRONG-FIELD CASE (F-DOMAIN)

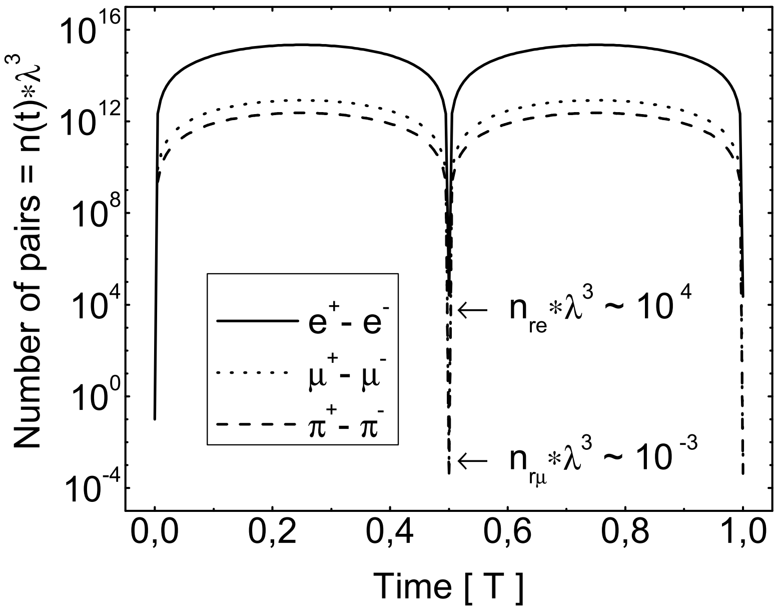


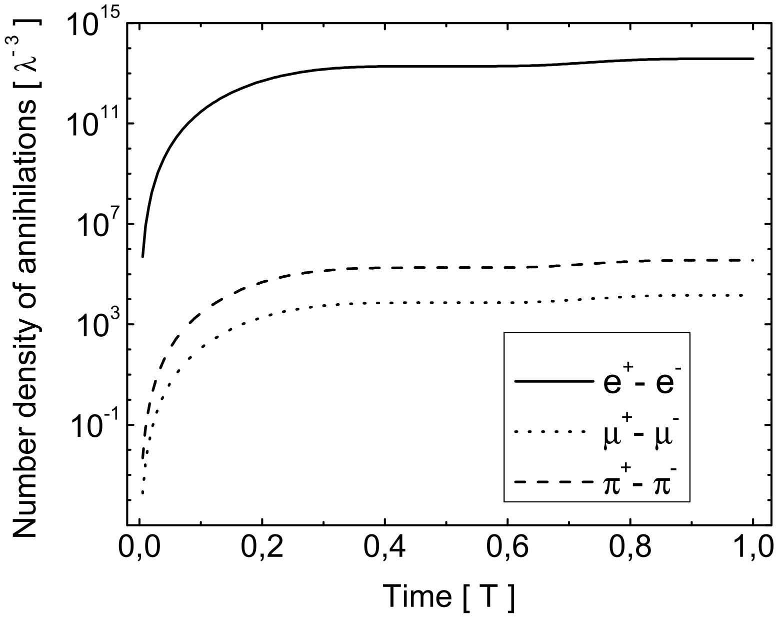


The distribution function in the strong-field accumulation case (F-domain) at $t = T$,

for $E_0 = 0.5\ E_c$, $\lambda = 0.15$ nm.
Multi-photon mechanism, simultaneous absorption from photon reservoir.
Left: General view; Right: Closeup of the region $29 < p_{||}[m] < 31$

$\pi^+\pi^-$ PAIR PRODUCTION IN SUBCRITICAL LASER FIELDS (I)





Time dependence of the pair density (left) and the number of annihilations (right) in the volume λ^3 for a periodic field (T - period) with $E_m = 10^{15}$ V/cm and $\lambda = 800$ nm for the different particle species. Laser intensity $3 \cdot 10^{27}$ W/cm^2.

$\pi^+\pi^-$ PAIR PRODUCTION IN SUBCRITICAL LASER FIELDS (II)

Pion pair creation kinetics, including decay into muons:

$$\frac{\partial f_\pi(\mathbf{p},t)}{\partial t} = \frac{1}{2}\Delta_\pi(\mathbf{p},t)\int_{t_0}^{t} dt'\Delta_\pi(\mathbf{p},t')\cos\theta_\pi(\mathbf{p},t',t) - f_\pi(\mathbf{p},t)\int d\mathbf{q}d\mathbf{k}w(\mathbf{p},\mathbf{q},\mathbf{k},t),$$

$$\frac{\partial f_\mu(\mathbf{p},t)}{\partial t} = \frac{1}{2}\Delta_\mu(\mathbf{p},t)\int_{t_0}^{t} dt'\Delta_\mu(\mathbf{p},t')\cos\theta_\mu(\mathbf{p},t',t) + \int d\mathbf{q}d\mathbf{k}w(\mathbf{q},\mathbf{p},\mathbf{k},t)f_\pi(\mathbf{q},t),$$

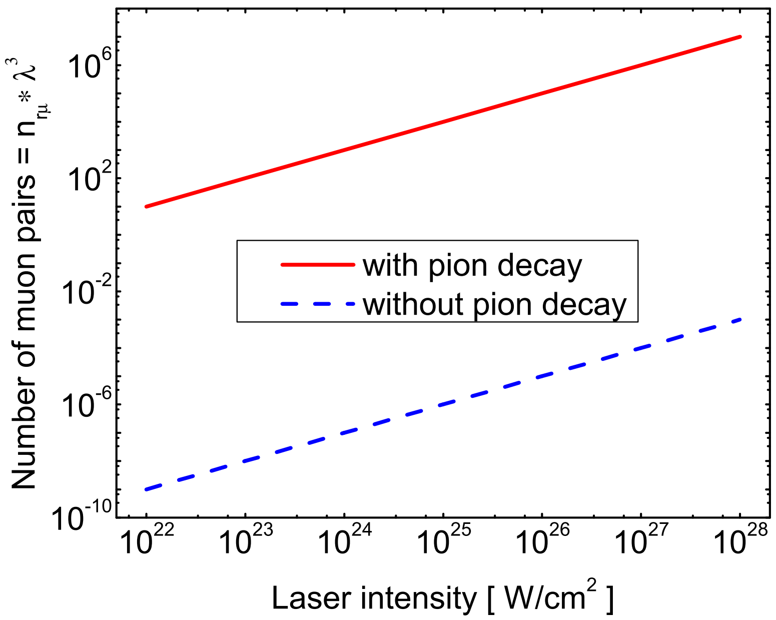
Stochastic pion decay with rate $w(\mathbf{p},\mathbf{q},\mathbf{k},t)$.

$$w(\mathbf{p},\mathbf{q},\mathbf{k},t) \approx w(\mathbf{p},\mathbf{q},\mathbf{k}) = \frac{1}{2}\left(\frac{Gm_\mu F_\pi}{2\pi}\right)^2 \frac{q\cdot k}{\varepsilon_p\varepsilon_q\varepsilon_k}\delta^{(4)}(p-q-k),$$

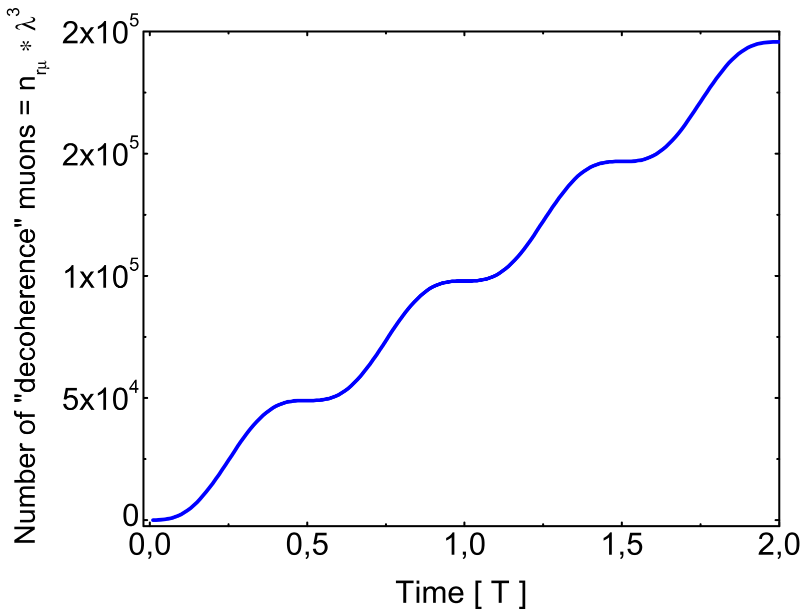
Muons seen by a detector with the time resolution δt

$$\delta n_\mu(t) \approx \frac{\delta t}{\tau_\pi}n_\pi(t) = \frac{\delta t}{\tau_\pi}\int_{t_0}^{t} dt' e^{(t'-t)/\tau_\pi}s_\pi(t')$$

$\pi^+\pi^-$ PAIR PRODUCTION IN SUBCRITICAL LASER FIELDS (III)



Number of muons as a function of the laser intensity at an optical wavelength $\lambda \sim 800$ nm.

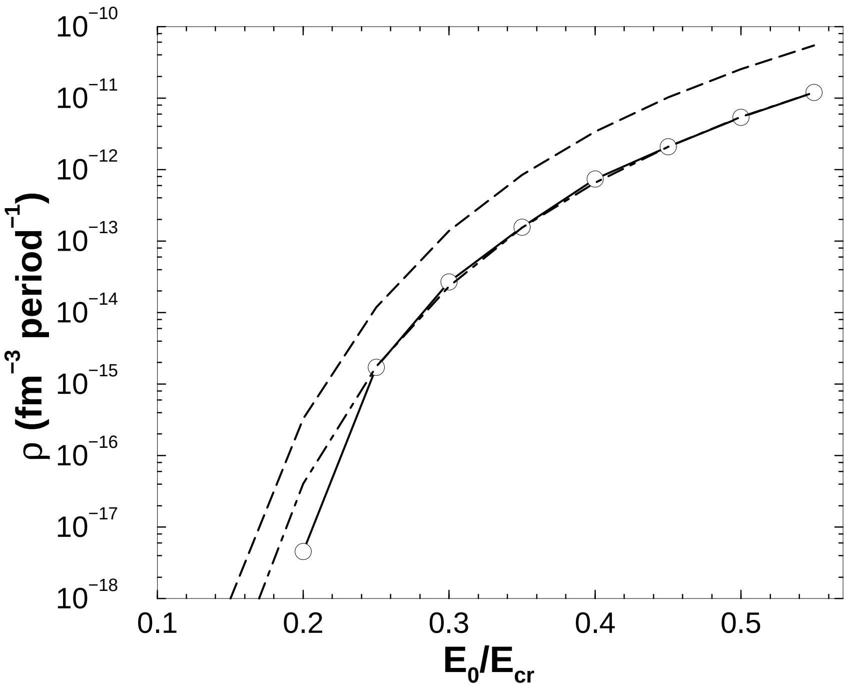


Time dependence of the number of decay muons produced in a volume λ^3, seen in a muon detector with time resolution $\delta t \sim 0.1$ fs

Blaschke, Prozorkevich, Roberts, Röpke, Schmidt, Smolyansky; in preparation (2010)

Accumulation effect in near-critical fields

Particle number density $n(T; E_0) = a_0(E_0)\sin^2(2\pi T) + \rho(T, E_0)T \quad , \quad T = t/\lambda$



Accumulation rate $\rho(0, E_0)$ (solid), Schwinger rate $a = 1,\ b = 1$ (dashed), $a = 0.305,\ b = 1.06$ (dot-dashed)

Results are nicely fitted with

$$\rho(T, E_0) = \rho(E_0) + \rho'(E_0)T \ .$$

For $E = 0.5\ E_0$, $a_0 = 1.2 \times 10^{-11}$ fm^{-3}, $\rho = 5.4 \times 10^{-12}$ fm^{-3}/period, $\rho'/\rho = 0.0033$/period.

Comparison with Schwinger rate

$$\rho = a\frac{m^4\lambda}{4\pi^3}\left[\frac{E_0}{E_{cr}}\right]^2 e^{-b\pi E_{cr}/E_0}$$

Attention:
$E_0 \sim 0.35\ E_{cr}$ backreactions become important!

Roberts, Schmidt, Vinnik: "Quantum effects with an X-Ray Free-Electron Laser", Phys. Rev. Lett (2002) 153901

EXPERIMENT FOR SUBCRITICAL VACUUM PAIR PRODUCTION

Project: G. Gregori et al. at the RAL Astra-Gemini laser facility → Summer 2010

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A proposal for testing subcritical vacuum pair production with high power lasers

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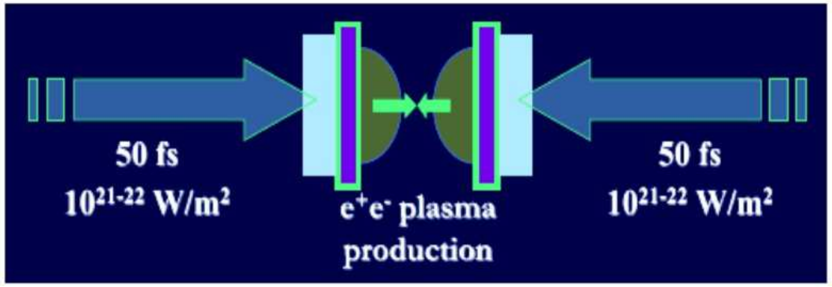
doi:10.1016/j.hedp.2009.11.001

Pair Production at RAL: Astra Gemini Laser

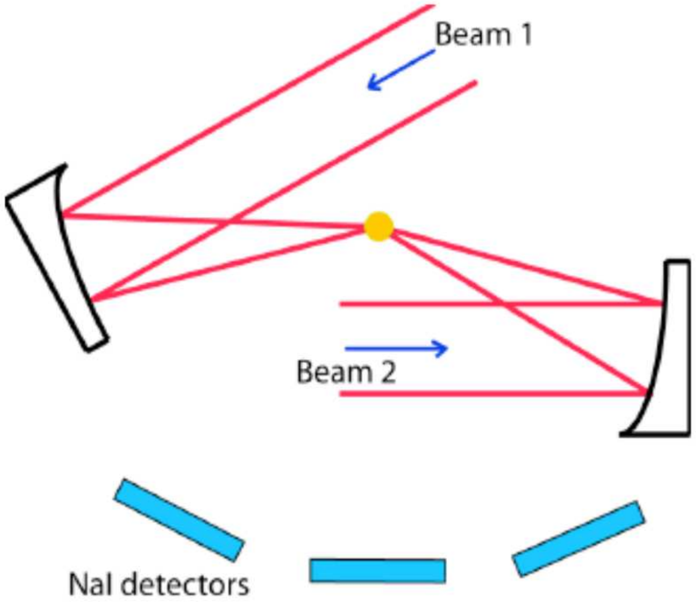
Part of an experimental campaign to explore nonperturbative and nonequilibrium QFT regimes: (1) Pair production, (2) Nonlinear mixing, (3) Unruh effect

(1-A) Pair production in high-Z foils



(1-B) Vacuum pair production
with different schemes:

- vacuum polarization
- refraction index
- $\gamma - \gamma$ coincidence
- ...



KINETICS OF THE $e^+e^-\gamma$ PLASMA IN A STRONG LASER FIELD

The photon correlation function is defined as

$$F_{rr'}(\mathbf{k},\mathbf{k}',t) = \langle A_r^+(\mathbf{k},t)A_{r'}^-(\mathbf{k}',t)\rangle \ ; \quad A_\mu(\mathbf{k},t) = A_\mu^{(+)}(\mathbf{k},t) + A_\mu^{(-)}(-\mathbf{k},t).$$

Lowest truncation of BBGKY hierarchy $\rightarrow$ photon KE for zero initial condition

$$\begin{aligned}\dot{F}(\mathbf{k},t) &= -\frac{e^2}{2(2\pi)^3 k}\int d^3p \int_{t_0}^{t} dt' K(\mathbf{p},\mathbf{p}-\mathbf{k};t,t')[1+F(\mathbf{k},t')] \\ &\quad [f(\mathbf{p},t') + f(\mathbf{p}-\mathbf{k},t') - 1]\cos\{\int_{t'}^{t} d\tau[\omega(\mathbf{p},\tau)+\omega(\mathbf{p}-\mathbf{k},\tau) - k]\},\end{aligned}$$

Markovian approximation; averaging the kernel: $K(\mathbf{p},\mathbf{p}-\mathbf{k};t,t') \rightarrow K_0 = -5$
Subcritical field case: $E \ll E_c$, lead to $(\delta = 2m - k$, frequency mismatch)

$$F(\mathbf{k},t) = \frac{5e^2 n(t)}{2k\delta^2} \ , \quad n(t) = 2\int d^3p f(\mathbf{p},t)/(2\pi)^3$$

Photon distribution in the optical region $k \ll m$ is characteristic for the flicker noise

$$\boxed{F(k) \sim 1/k}$$

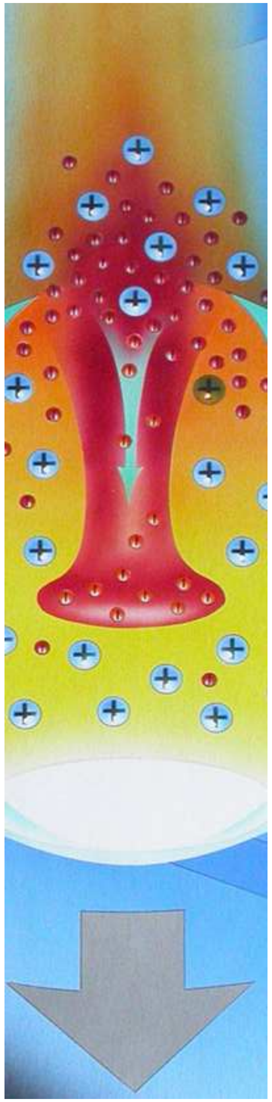
D.B. Blaschke et al., Contr. Plasma Phys. 49, 602 (2009); Phys. Rev. D 84, 085028 (2012).

Challenges of future Lasers for the Schwinger effect

- First experimental tests to theories of pair production, e.g. kinetic approach
- Simplest laser field model predicts production of dense electron-positron plasma in the focus of counter-propagating laser fields
- Observable manifestations testable, e.g., at ASTRA-Gemini:
  - several gamma-pairs per laser pulse
  - refraction index measurable by intereference with test beam
  - higher harmonics generation, in particular 3rd
- Towards/Beyond Schwinger limit, e.g., at ELI:
  - Quantum statistics: Pauli-Blocking/ Bose Condensation; Backreactions
  - Pion production limit: signalled by muons
  - Pion condensation (?) and quark-gluon-plasma formation ...
- Laser acceleration of ion beams (see arxiv:0811.3570 [physics.plasm-ph])

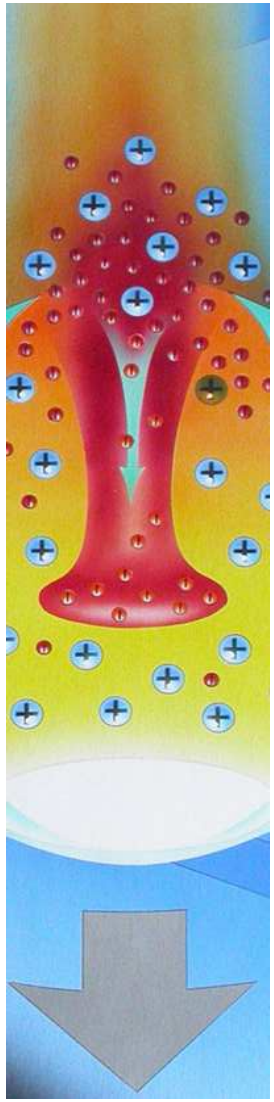
Thanks to: D. Habs (Munich), G. Mourou (Paris), R. Sauerbrey (Rossendorf)

INTENSE THEORY-EXPERIMENT INTERACTION ...



Astra Collaboration Meeting, Juelich 2009

INTENSE THEORY-EXPERIMENT INTERACTION ...



MORE BRAINSTORMING WORKSHOPS NEEDED ...

D.B., Smolyansky, Nikishov in ITEP Moscow (2009)