Subcritical Pair Production by High-Intensity Lasers

David Blaschke (Univ. Wroclaw & JINR Dubna)

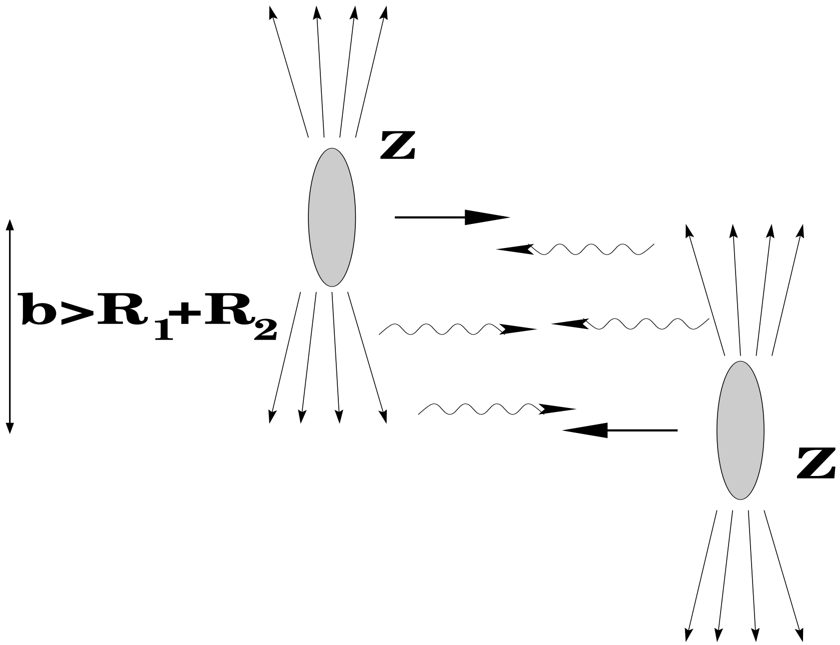
- Introduction: Schwinger Effect
- Kinetic formulation of pair production
- Application to pair production in subcritical laser fields
- Experimental verification of e^+e^- pair density
- Astra-Gemini Laser experiment: below the Schwinger limit
- ELI: towards the Schwinger limit and beyond QED

Collaboration:
R. Bingham, R.J. Clarke, R. Pattathil (Rutherford Appleton Laboratory, Didcot, UK)
Gianluca Gregori, T. Huffman (University of Oxford, UK)
Alexander Prozorkevich, Stanislav Smolyansky (Saratov State University, Russia)
Craig Roberts (Argonne National Laboratory, USA)
Gerd Röpke (Rostock University, Germany)
Sebastian Schmidt (Forschungszentrum Jülich & Dortmund University, Germany)

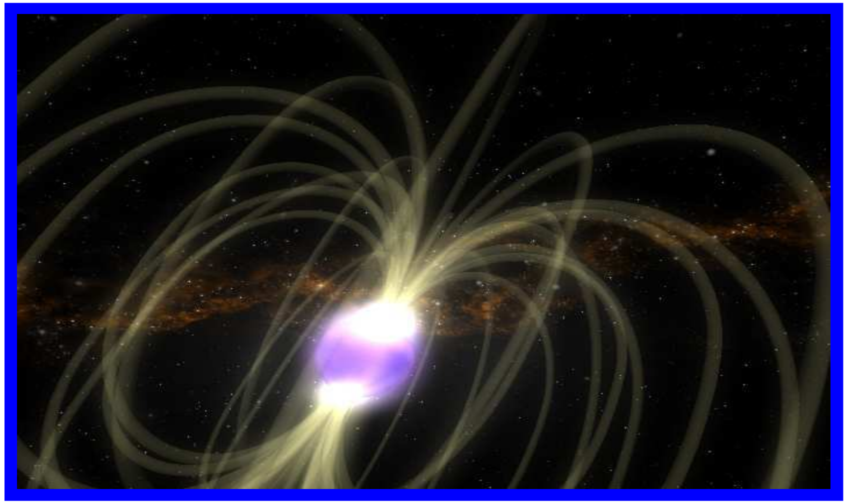
Recent review: arXiv:0811.3570 [physics.plasm-ph] (Eur. Phys. J. D., to appear)

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)

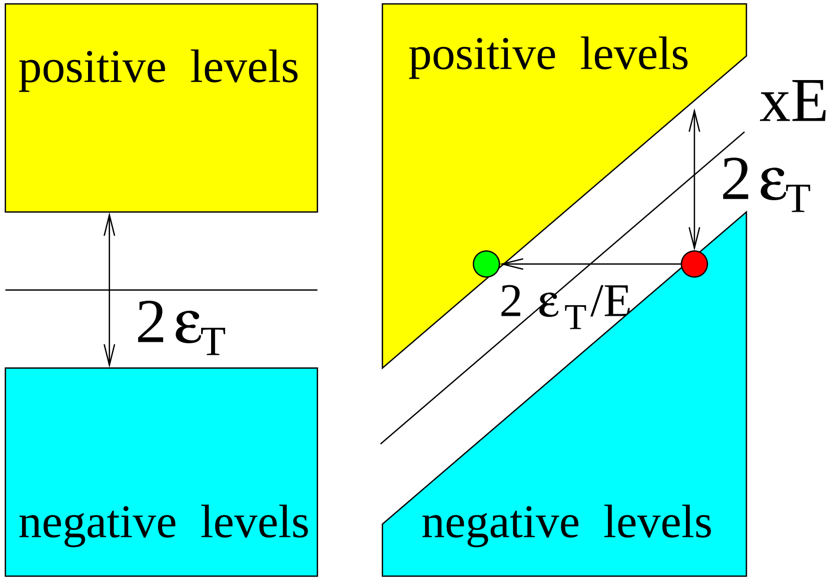
- ELI: Optical $\rightarrow$ X-Ray @ 1 EW:
  $I_0 \sim 10^{25}$ W/cm$^2 \rightarrow I_{CHF} \sim 10^{36}$ W/cm^2

  + 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

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 $E \sim E_{\rm crit}$

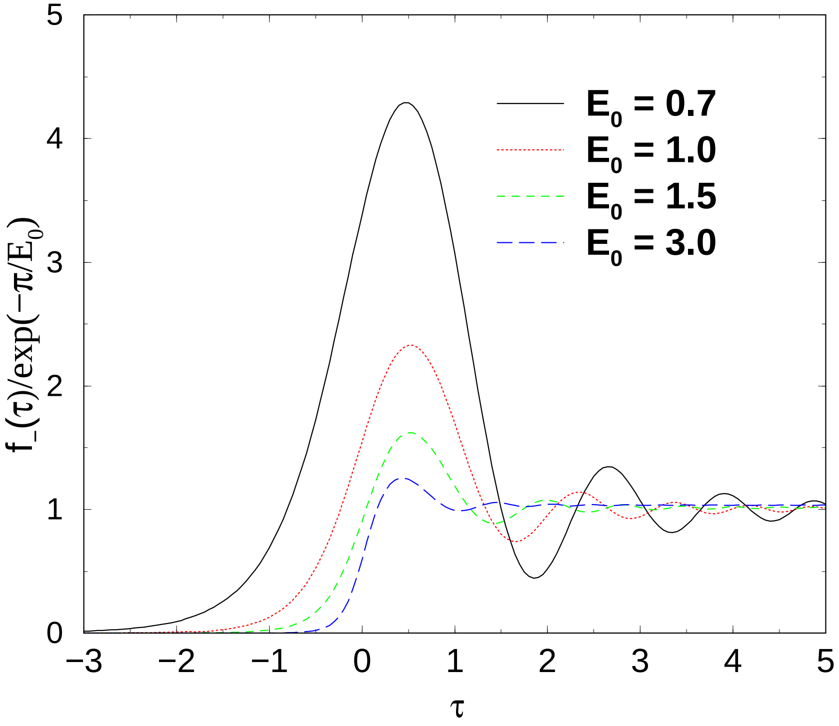
$$E_{\rm crit} \equiv \frac{m^2c^3}{e\hbar} \simeq 1.3 \times 10^{18} {\rm V/m}$$

- 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 $f(\bar{P},t) =< 0|a^\dagger_{\bar{P}}(t)a_{\bar{P}}(t)|0 >$



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

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

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

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

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

where $\omega(t) = \sqrt{\varepsilon_\perp^2 + P_\|^2(t)}$, 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

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

Pair production in subcritical fields (I)

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

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

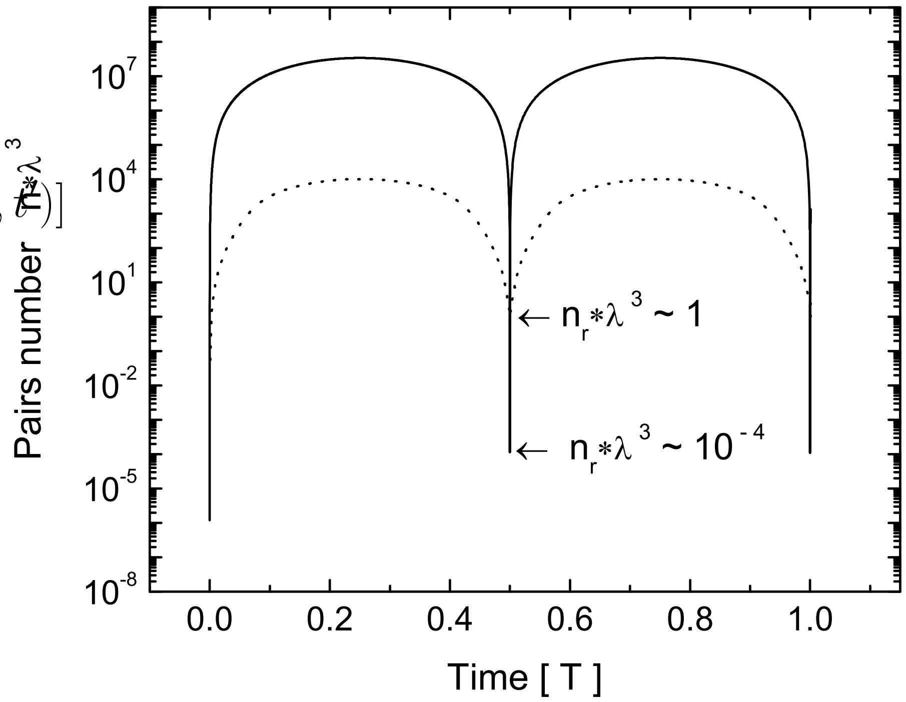
where

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

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

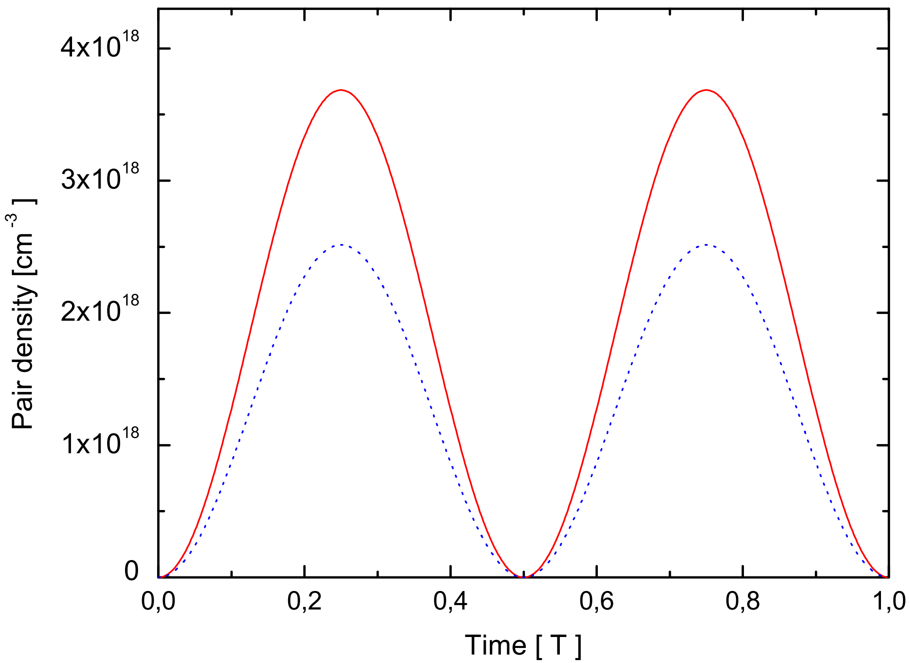
The particle number density

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



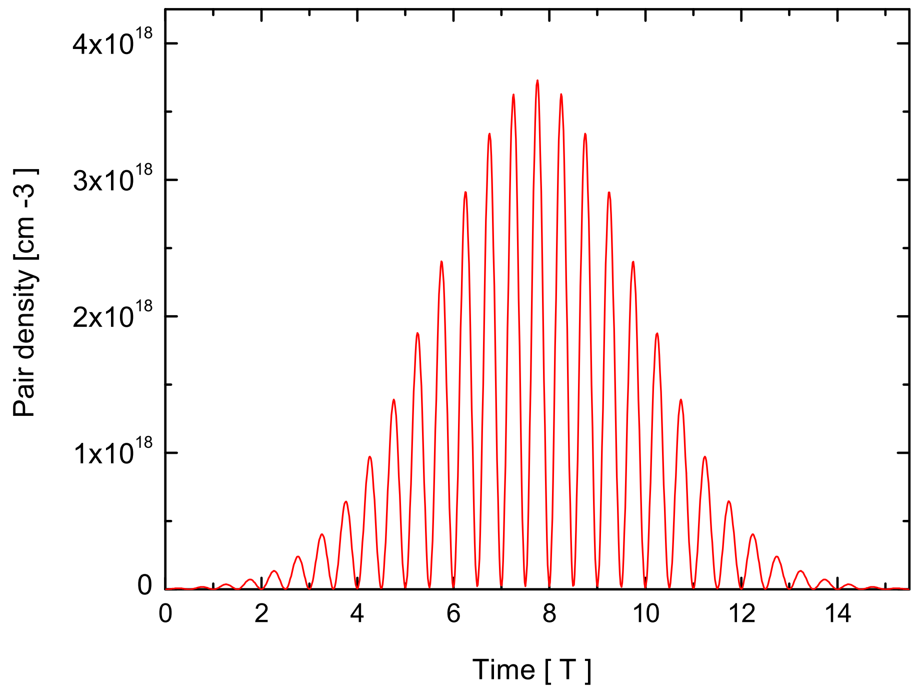
Number of e^+e^- pairs in the volume λ^3 for a weak field (Jena Ti:AlO$_3$ laser, solid line) and for near-critical field $E_m/E_{\rm crit} = 0.24$, $\lambda = 0.15$ nm (X-FEL, dashed line).

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



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

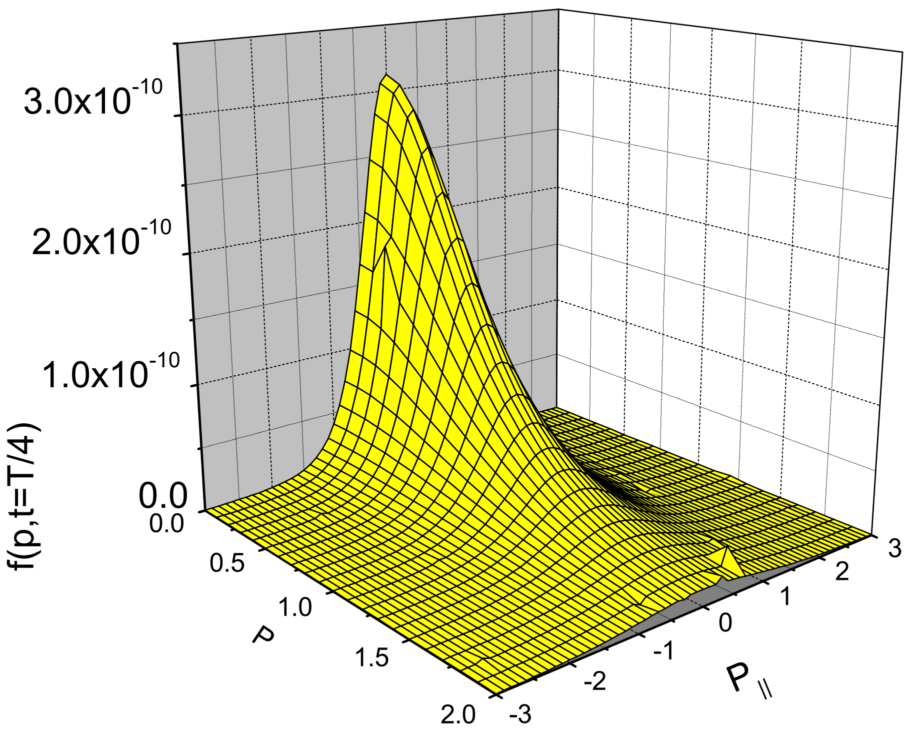
$$E(t) = E_m \sin \omega t, \quad 0 \leq t \leq NT, \quad T = \frac{2\pi}{\omega}$$



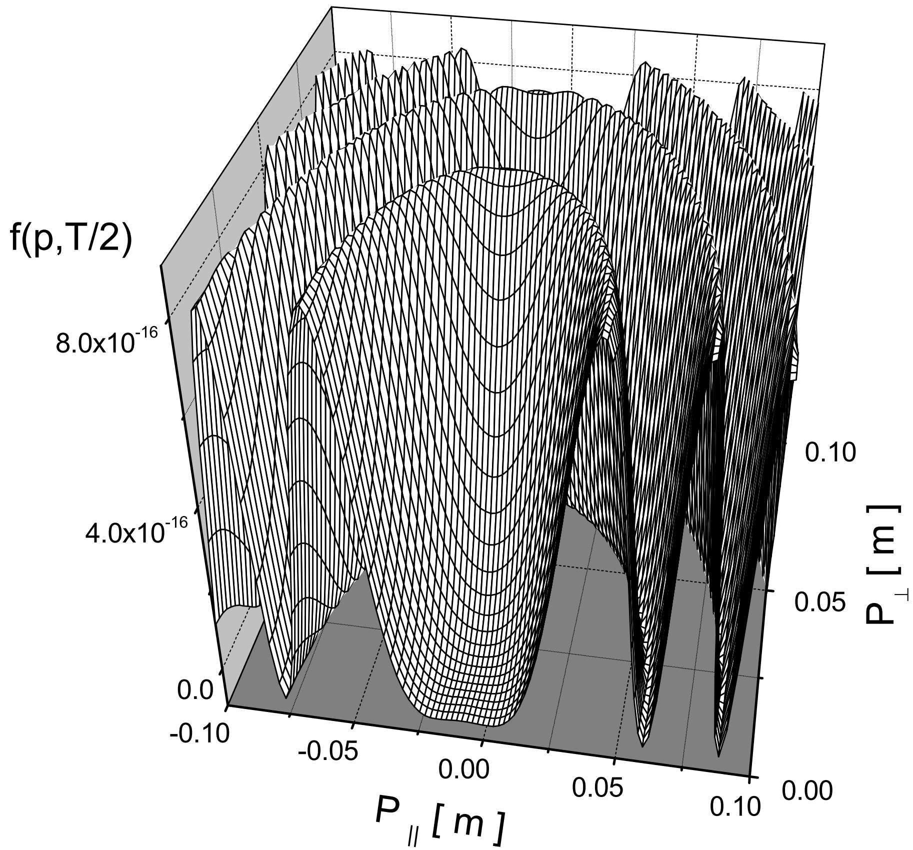
Time dependence of the density $n(t)$ for a Gaussian wave packet

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

APPLICATION TO SUBCRITICAL LASER FIELDS

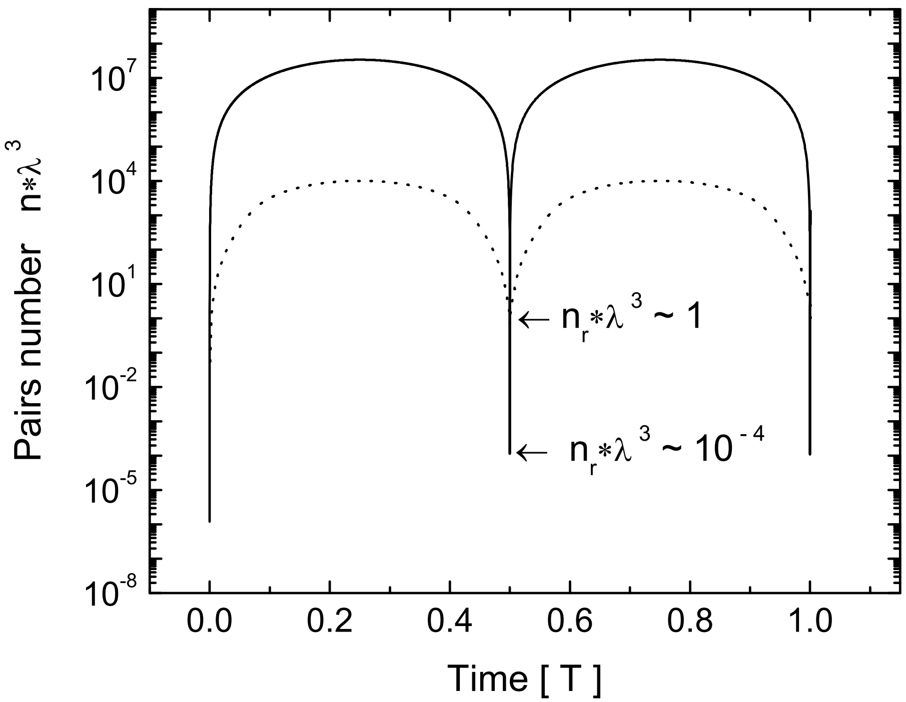


Equilibrium-like momentum distribution at the time of maximal field amplitude $t = T/4$.

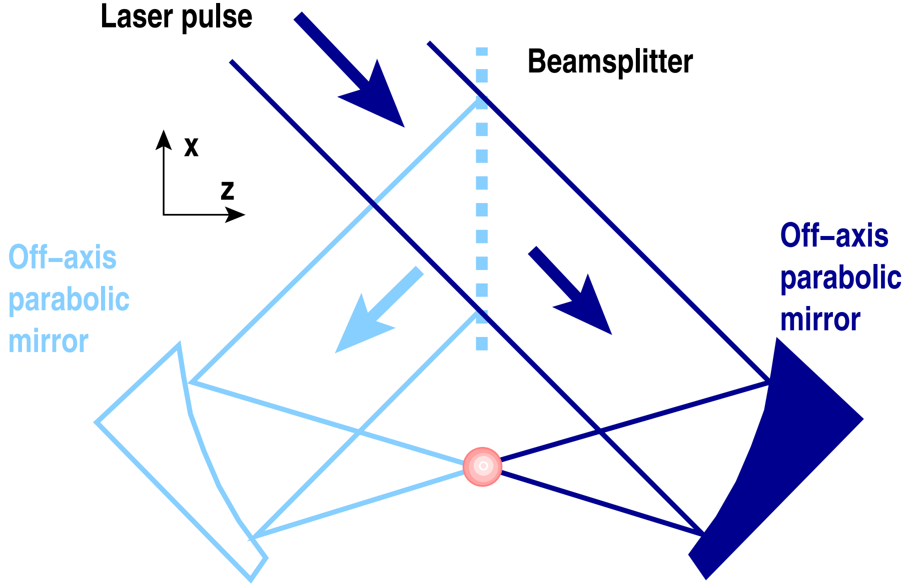


Stratum-like structure of the momentum distribution at the time of zero field amplitude $t = T/2$, determining the residual density.

Application to subcritical laser fields (II)

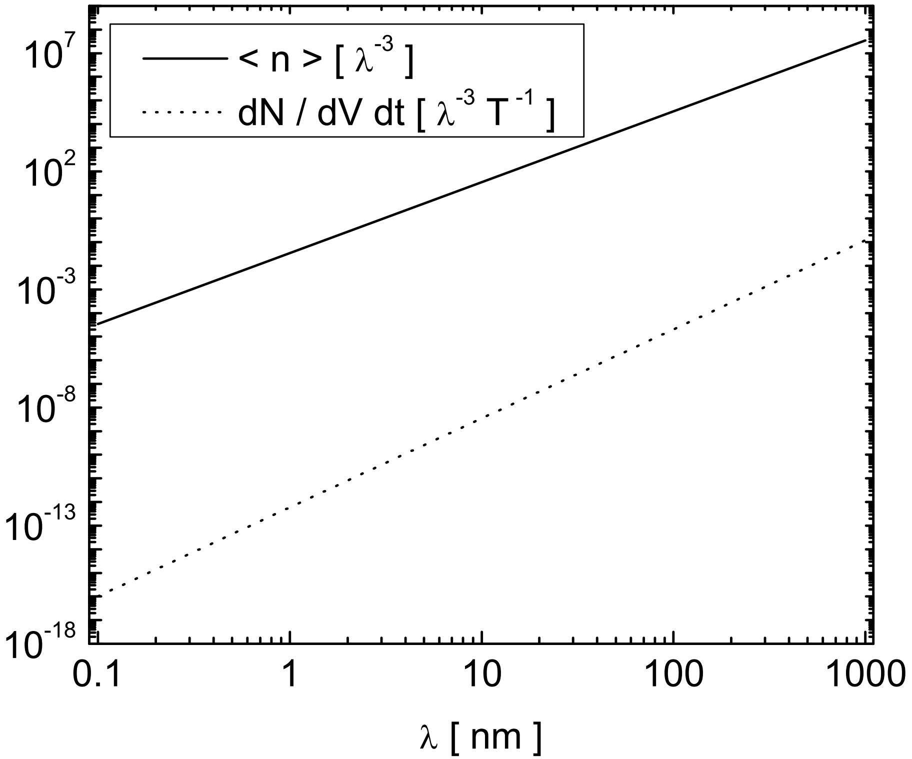


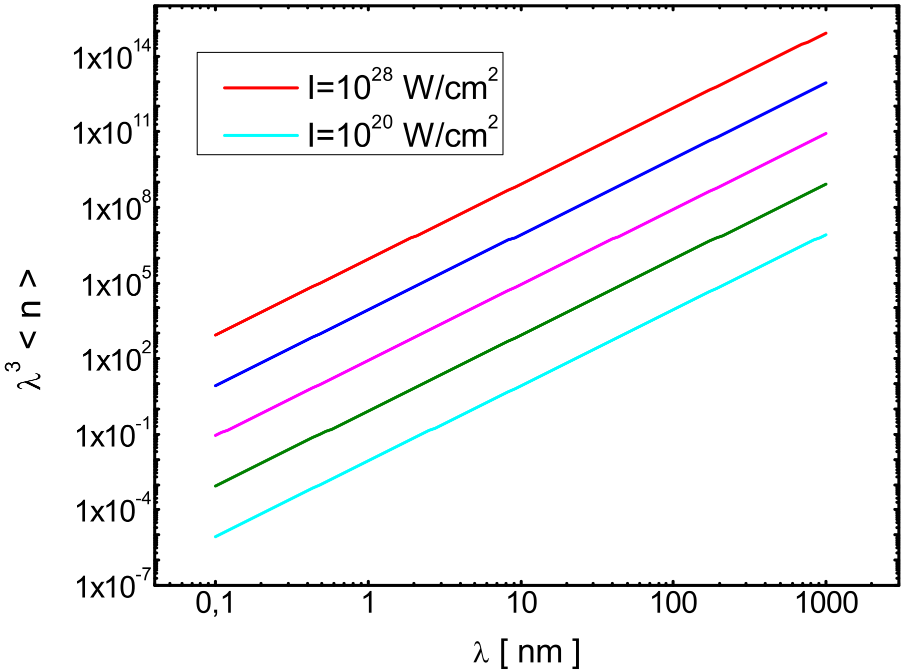
Number of e^+e^- pairs in the volume λ^3 for a weak field (Jena Ti:AlO_3 laser, solid line) and for near-critical field $E_m/E_{\rm crit} = 0.24$, $\lambda = 0.15$ nm (X-FEL, dashed line).



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

Application to subcritical laser fields (III)



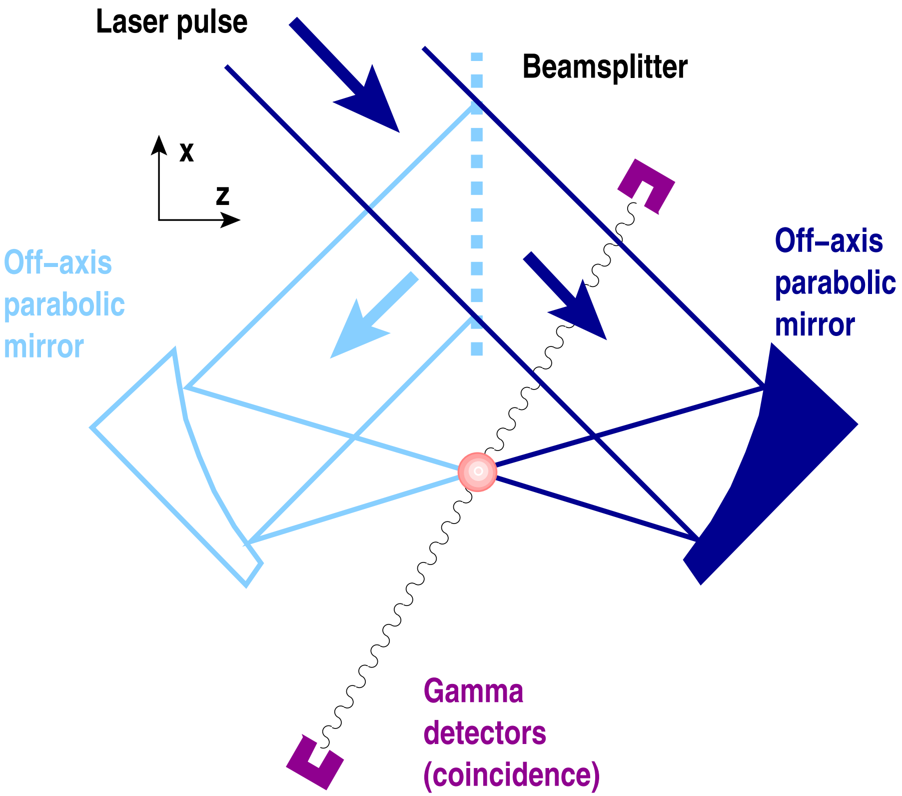


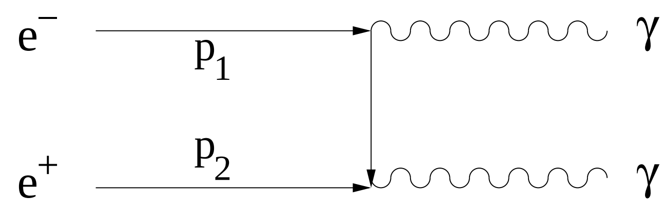
Wavelength dependence of the mean density of e^+e^- pairs (solid line) and their annihilation rate (dotted line). $E = 3 \times 10^{-5} E_{cr}$.

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

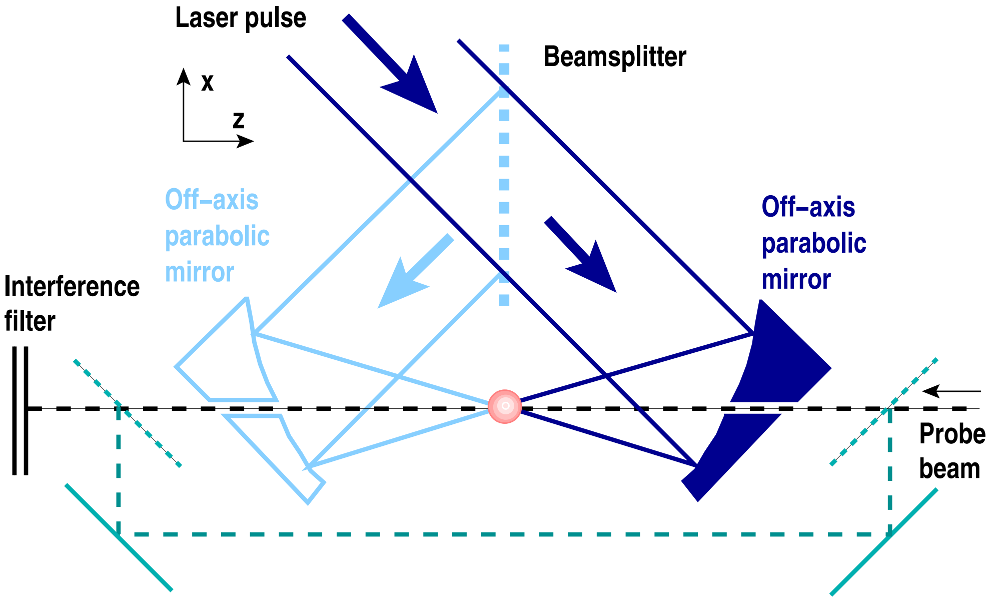
$$\sigma(\mathbf{p}_1,\mathbf{p}_2) = \frac{\pi e^4}{2m^2\tau^2(\tau-1)}\Big[(\tau^2+\tau-1/2) \times \ln\left\{\frac{\sqrt{\tau}+\sqrt{\tau-1}}{\sqrt{\tau}-\sqrt{\tau-1}}\right\} - (\tau+1)\sqrt{\tau(\tau-1)}\Big],$$

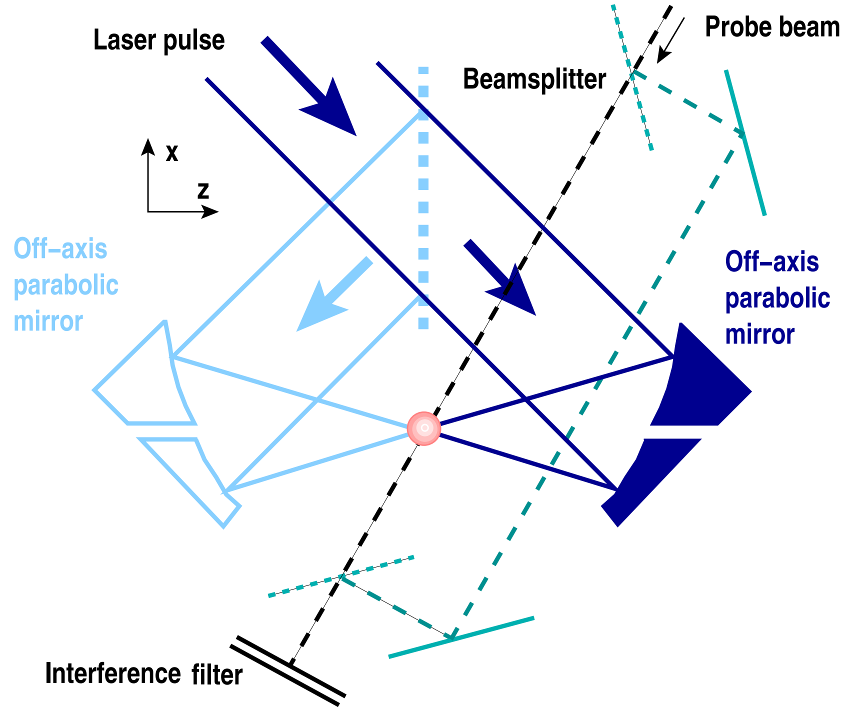
t-channel kinematic invariant

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

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

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

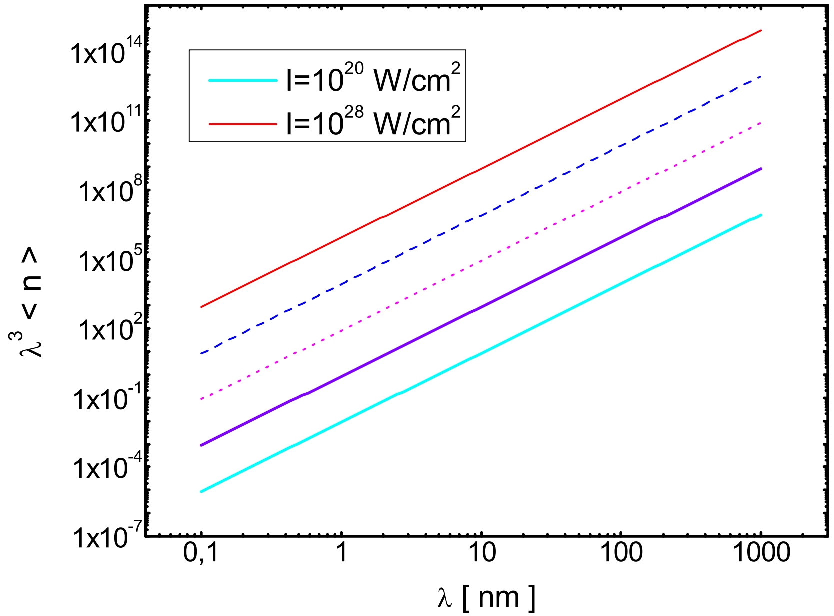


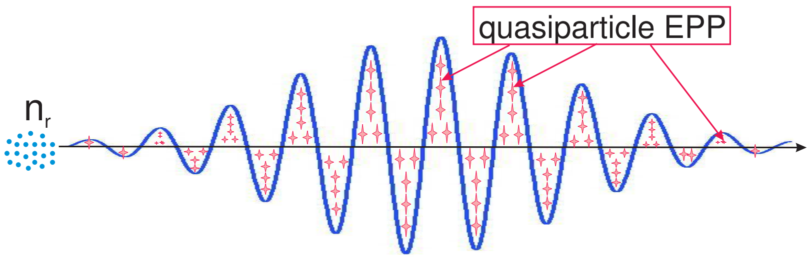


Measurement of refraction index by interference with probe beam.

Suggestion by R. Sauerbrey; **Blaschke, Prozorkevich, Smolyansky, in preparation**

HOW TO 'SEE' e^+e^- PAIRS @ OPTICAL LASERS (III)





Measurement of refraction index

Interference condition: $D = \lambda_p/2$

Refraction index:

$n = 1/\sqrt{1 + \eta^2[(2+\eta^2)/(1+\eta^2)]}$

Langmuir frequency ω_L:

$\eta = \omega_L/\omega_p = 10^4\sqrt{\rho_{e+e-}[cm^{-3}]}$

Probe frequency: $\omega_p = 10\ \omega_0$

Condition fulfilled for:

$\rho_{e+e-} = 10^{23}$ cm^{-3}, i.e. $I \approx 10^{23}$ W/cm^2

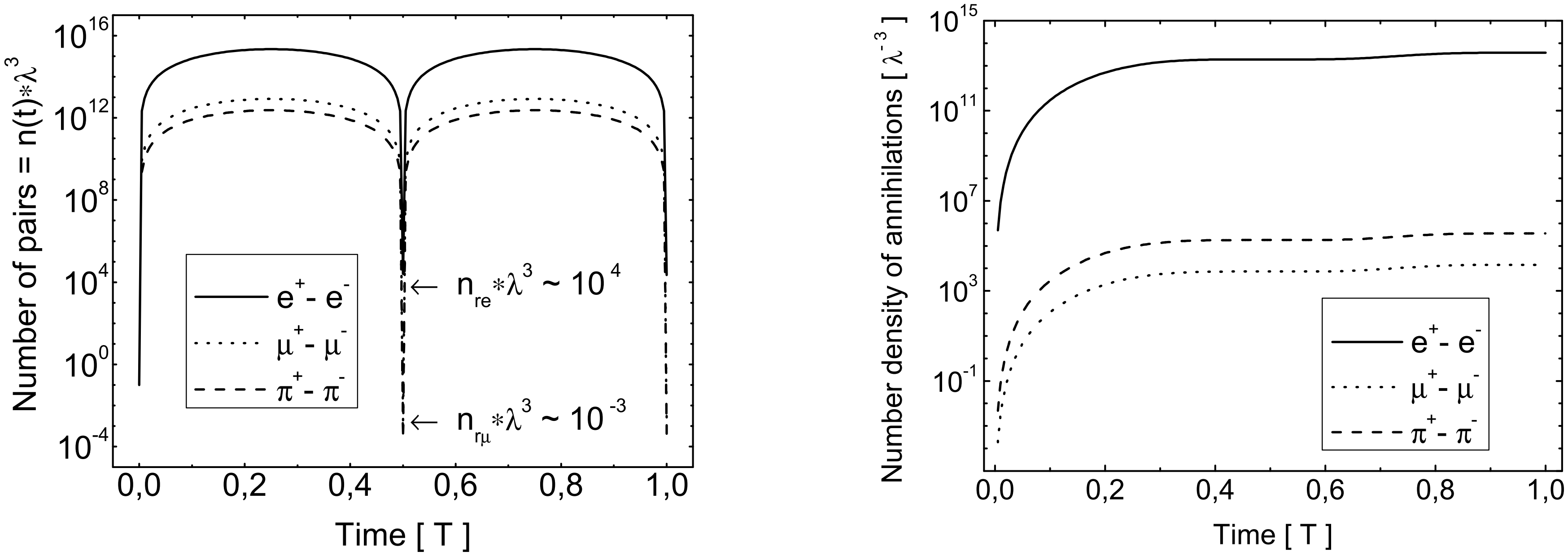
Angular dependence testable:

number of 'pancakes' crossed varies

with incidence angle: from 3-4 to 20-30

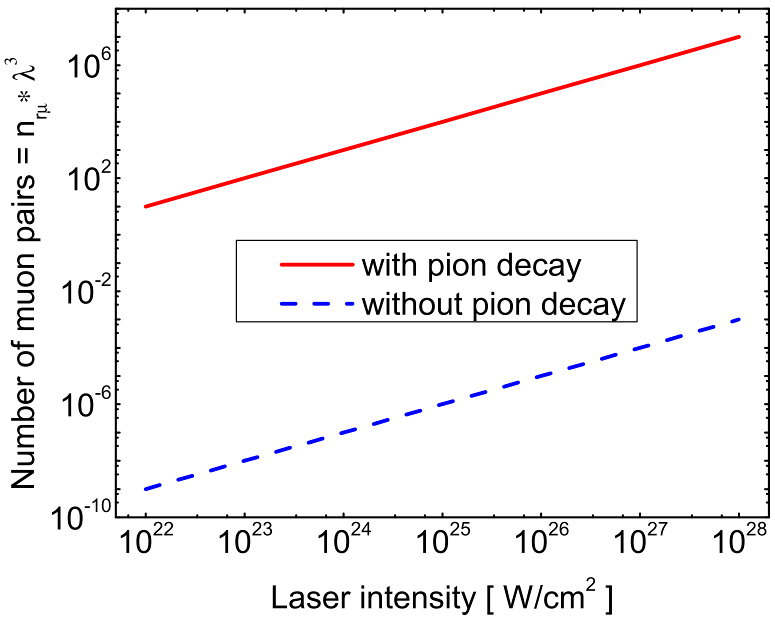
Suggestion: R. Sauerbrey; Estimate: **Blaschke, Prozorkevich, Smolyansky, in prep.**

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

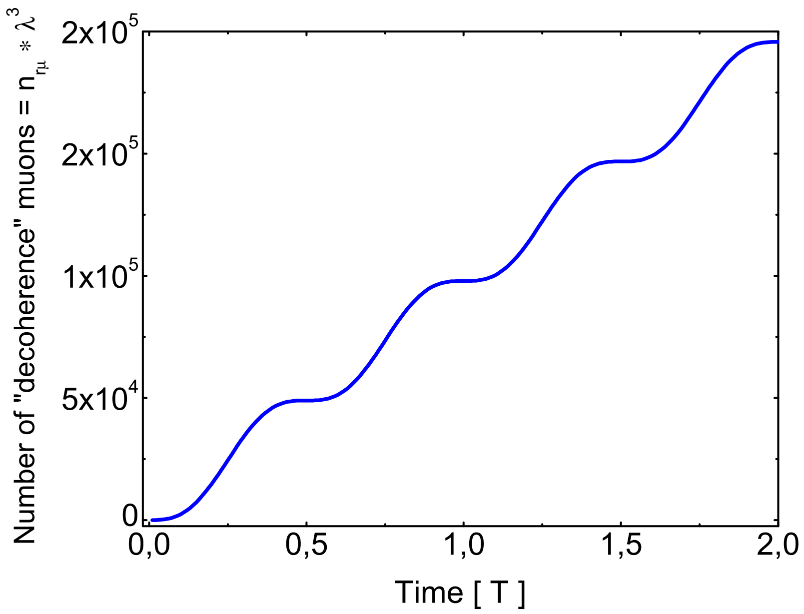


Time dependence of the pair density (left) and the number of annihilations (right) in the volume λ^3 for a periodic field (T - period) with $E_m = 10^{15}$ V/cm and $\lambda = 800$ nm for the different particle species. Laser intensity $3 \cdot 10^{27}$ W/cm^2.

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



Number of residual 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 to be seen in a muon detector with time resolution $\delta t \sim 0.1$ fs

Blaschke, Prozorkevich, Roberts, Schmidt, Smolyansky; in prep. (2008)

Comparison with imaginary time method

V.S. Popov, Phys. Lett. **A 298** (2002) 83

- imaginary time method (time indep.)
- number of pairs only after full period T
- no distribution function

$\gamma \ll 1, \quad \gamma = \frac{\hbar\omega}{mc^2}\frac{E_{cr}}{E}$

$$N(\lambda^3 T) \sim \left(\frac{m}{\nu}\right)^4 \left(\frac{E}{E_{cr}}\right)^{5/2} \exp\left[-\frac{\pi E_{cr}}{E}\right]$$

$\gamma \gg 1$

$$N(\lambda^3 T) \approx 2\pi \left(\frac{m}{\nu}\right)^{3/2} \left(\frac{e}{4\gamma}\right)^{2m/\nu}$$

Very large differences for $E \ll E_{cr}$

Here: Grib, Mamaev, Mostepanenko (1988)

- Bogoliubov transformation (time dep.)
- pair number during field evolution
- distribution function

$\gamma \ll 1$

$$\lambda^3 n_r \sim \left(\frac{m}{\nu}\right)^4 \left(\frac{E}{E_{cr}}\right)^2 \exp\left[-1.05\frac{\pi E_{cr}}{E}\right]$$

$\gamma \gg 1$ (mean)

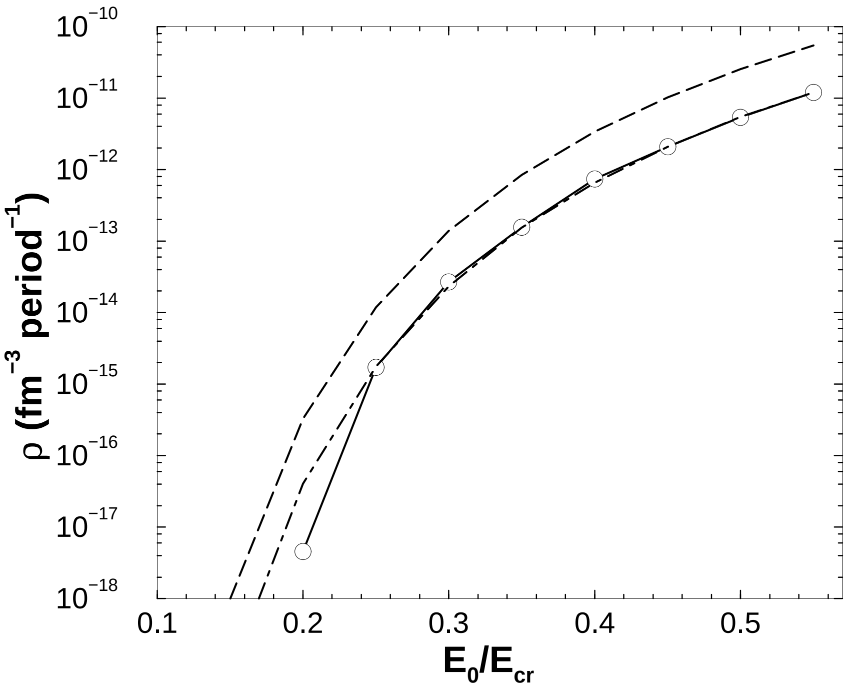
$$\lambda^3 \langle n \rangle \sim \left[\frac{(eE_m)}{m^2}\right]^2 \left[\frac{m\lambda}{2\pi}\right]^3, \qquad \frac{n_r}{\langle n \rangle} \sim \frac{\omega^2}{m^2}$$

$\gamma \gg 1$ (residual)

$$n_r \sim \left(\frac{m}{\nu}\right)$$

ACCUMULATION EFFECT IN NEAR-CRITICAL FIELDS

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



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

More brainstorming workshops needed ...

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

More brainstorming ELI workshops needed …

More brainstorming workshops needed ...

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QED with High Power Lasers

Pair production experiment

Dr Gianluca Gregori

Oxford University and
Rutherford Appleton Laboratory

List of collaborators (more to add…)

- ➔ This is the first attempt to observe measurable QED effects with high power lasers – need to include all interested organizations
- ➔ If you are not in the proposal, just let me know and you'll be included!

G Gregori[1,2], P. P. Rajeev[2], D Neely[2], P Norreys[2], R Bingham[2,3], DB Blaschke[4], G Brodin[5], RJ Clarke[2], RG Evans[2,6], SH Glenzer[7], T Heinzl[8], T Huffman[1], C Joshi[9], J Lundin[5], M Marklund[5], AV Prozorkevich[10], G Roepke[11], SJ Rose[6], CD Roberts[12], R Sauerbrey[13], SA Smolyansky[9], G Tynan[14], JL Collier[2,15]

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[3] Department of Physics, University of Strathclyde, Glasgow, UK; [4] Institute for Theoretical Physics, University of Wroclaw, 50-204 Wroclaw, Poland; [5] Department of Physics, Umea University, Sweden; [6] Department of Physics, Imperial College, London SW7 2BW, UK; [7] Lawrence Livermore National Laboratory, Livermore CA 94551, USA; [8] School of Mathematics & Statistics, University of Plymouth, Plymouth PL4 8AA, UK; [9]University of California, Los Angeles CA 90095, USA; [10]Saratov State University, RU-410026, Saratov, Russia; [11] Institute of Physics, University of Rostock, D-18051 Rostock, Germany; [12]Physics Division, Argonne National Laboratory, Argonne IL 60439, USA, [13]Technische Universität Dresden, D-01328, Germany, [14]Department of Mechanical Engineering, University of California, San Diego CA 92093, USA [15]Department of Physics, University of Swansea, SA2 8PP Swansea, UK

QED with high power lasers

- The proposed work is part of a large experimental campaign aimed at the exploitation of high power lasers to explore non-perturbative and non-equilibrium QFT regimes

  - **Pair production**: 1st experiment scheduled for winter 2010. Simplest beam arrangement and feasible on the current Gemini system.

  - **Nonlinear mixing**: vacuum polarization via four-wave mixing using a nonlinear stimulated process. It is possible to show that by interacting three beams into a high vacuum region, a fourth beam of photons with unique wavelength will be generated.

  - **Unruh radiation**: interaction of a high intensity laser with relativistic electrons (> 1 GeV) can access regimes where the electrons, in their rest frame, experience a ultra-high intensity field such as the one found at the event horizon of a black hole.

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QED with high power lasers

➔ High risk experiments (!) but high payoff from their success

➔ Pair production experiment: de-risking strategy

- Measure vacuum pair production with a variety of schemes (vacuum polarization / γ-γ co-incidence detection)
- Pair production is high-Z foils (already demonstrated)

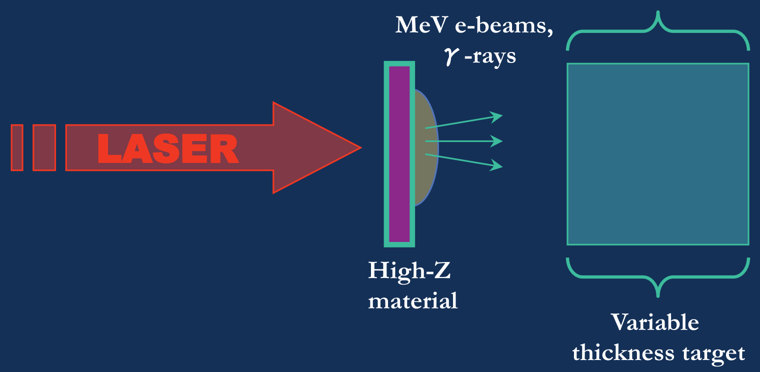
Pair production in high-Z foils

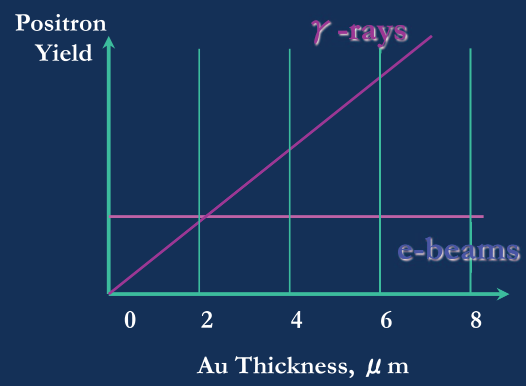
a) electron-beam ⇨ positrons

$$e^- + Z \rightarrow 2\,e^+ e^- + Z$$

b) γ-ray ⇨ positrons

$$\gamma + Z \rightarrow e^+ e^- + Z$$





Pair production in high-Z foils

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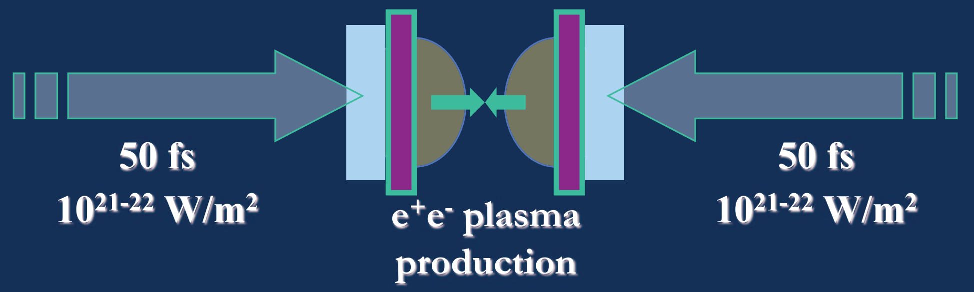
- Proposed two-foil experiment



- Detailed modelling of the experiment is required:
  - Numerical calculations of pair number vs foil thickness
  - Optimization w.r.t. pulse length and laser intensity
  - Polarization dependence?

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Pair production in vacuum

- ➔ Need to estimate the quality of vacuum (!) – Can we produce ultrahigh vacuum?
  - Detailed calculations are required in order to determine residual effect of residual atoms
  - Can we use the laser pre-pulse (nanosecond pedestal) to expel the ions from the laser focal spot?

Simple estimate: assuming 100 residual atoms in the focal spot (p~1 mTorr), we expect 0.01 pairs per laser shot (Heitler, 1954)

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Pair production in vacuum – simple theory

- The basic of this process is multi-body interaction of a large number of optical photons – non-perturbative process
- Described within the non-equilibrium quantum field theory framework: quantum Vlasov equation

$$\frac{df_k(t)}{dt} = \frac{\dot{\Omega}_k}{2\Omega_k} \int_{-\infty}^{t} dt' \frac{\dot{\Omega}_k}{2\Omega_k}(t') \left[1 - f_k(t')\right] \cos\left[2 \int_{t'}^{t} d\tau \Omega_k(\tau)\right]$$

$$\Omega_k^2 = (\mathbf{k} - e\mathbf{A})^2 + m^2$$

$$N_{ep}(t) = 2V \int \frac{d^3k}{(2\pi)^3} f_k(t)$$

- Which is the physical meaning of the time-dependent particle number?

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Pair production in vacuum – simple theory

- The particle number does not commute with the Hamiltonian – it is not a well defined quantity!

$$\Delta E \Delta t = \Delta(N_{ep} m)\Delta t \sim 1$$
$$\rightarrow \Delta N_{ep} \sim 1/(m\Delta t)$$

- Hence, the particle number is well defined at asymptotic times (*t* very large) or for classical particles (large mass)
- In our case, we need to account for the change of particle number during the time the laser is on…

$$\Delta N_{ep} \sim \frac{1}{m\Delta t} + \left|\frac{dN_{ep}}{dt}\right| \Delta t$$
$$\rightarrow \Delta t \sim \frac{1}{\left(m\left|\frac{dN_{ep}}{dt}\right|\right)^{1/2}} \sim \frac{m}{eE}$$

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Pair production in vacuum – simple theory

- Similarly, particles are produced in pairs (i.e., they are initially entangled) – this is elucidated by the cosine term in the quantum Vlasov equation
- In the case of spatially homogeneous weak fields the disentanglement time is

$$\Delta t \sim \frac{1}{\Omega_k} \sim \frac{1}{m}$$

For the proposed Gemini experiment

$$\begin{cases} (\Delta t)_{Heisenberg} = \dfrac{m}{eE} \approx 8.9 \times 10^{-18} s \\ (\Delta t)_{Entanglement} = \dfrac{1}{m} \approx 1.3 \times 10^{-21} s \end{cases}$$

- Hence, the particle number is well defined during the laser period !
- However, are this particles on the mass shell? Experiment is the only way to test the validity of NeqQFT approach

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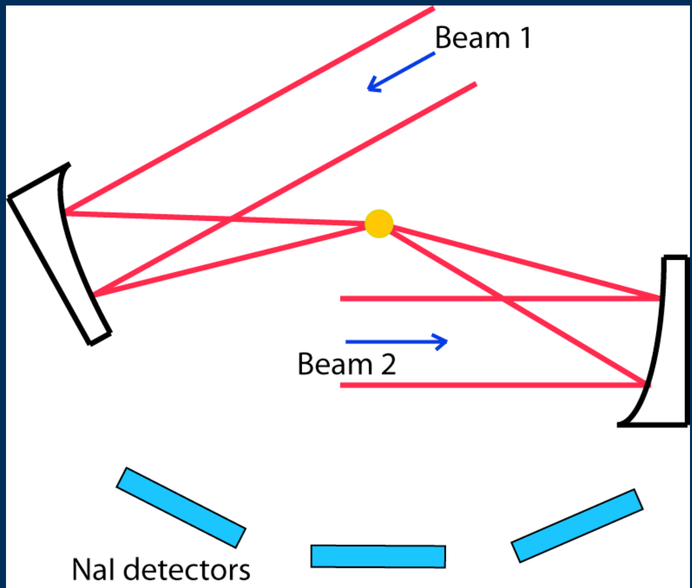
Proposed experiment (ϒϒ co-incidence)



- Solution of the quantum Vlasov equation for idealized (spatially homogeneous and sinusoidal field) gives N_{ep}~6×10^8 at the peak of the laser pulse and then ~0 after the pulse
- Those pairs can annihilate due to collisions in the laser spot volume, giving $N\gamma\gamma$~7-20 per laser shot
- More precise calculations are needed for the actual laser configuration (beam profile, spatial and temporal overlap…)

- Background level of γγ event is ~0.4 per laser shot (measured in-situ)
- Predicted signal is significantly above background level

Proposed experiment (vacuum polarization)

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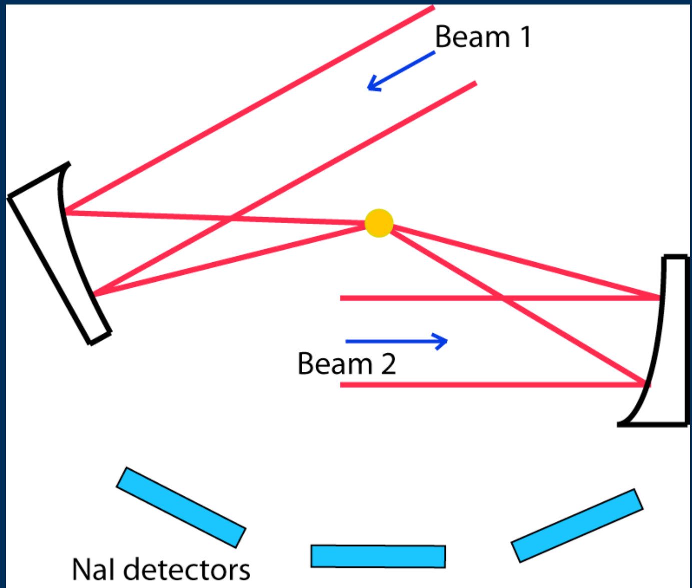


- The presence of electron-positron pairs changes the index of refraction

$$n = \left(1 + \eta^2 + \frac{\eta^2}{1+\eta^2}\right)^{-1/2}$$

$$\eta^2 = \frac{e^2 N_{ep}/\lambda^3}{\epsilon_0 m \omega^2}$$

- The corresponding reflectivity of the vacuum is

$$R = \left(\frac{1-n}{1+n}\right)^{1/2} \left(\frac{2\pi\lambda_c}{\lambda}\right)^3$$

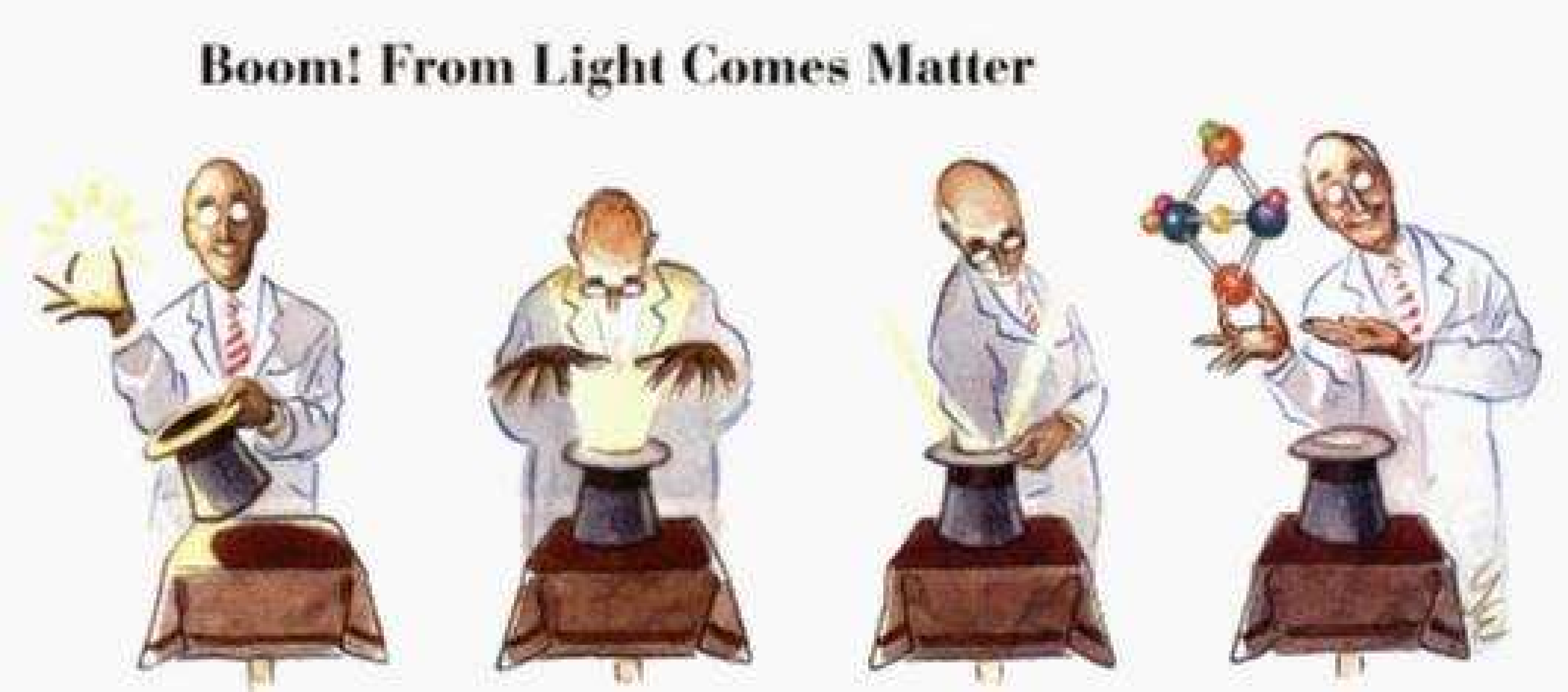
- Expect ~5 backscattered photons per laser shot
- Difficult to distinguish from the noise background but worth to try!

Challenges of future Lasers for the Schwinger effect

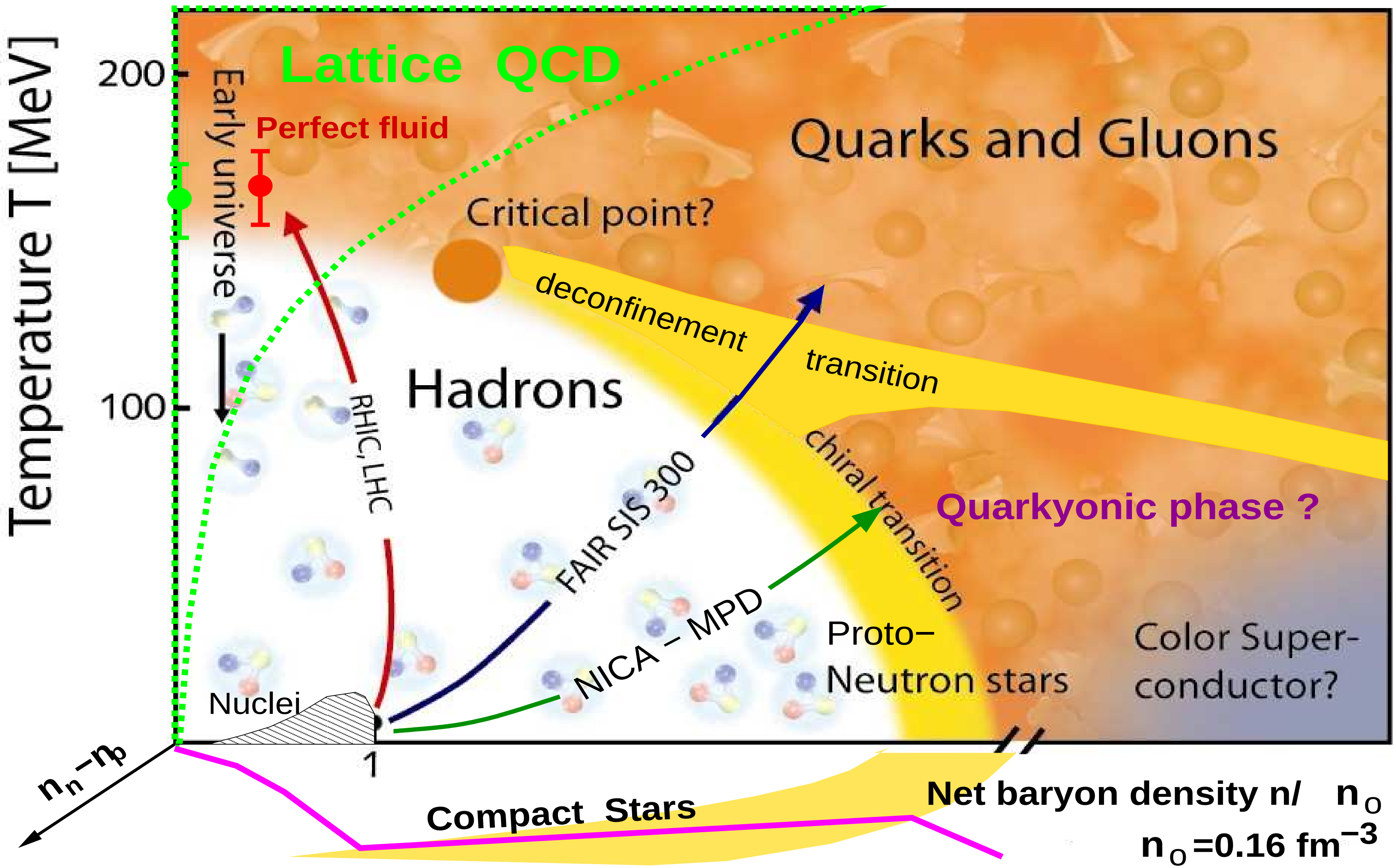
- First experimental tests to theories of pair production, e.g. kinetic approach
- Simplest laser field model predicts production of dense electron-positron plasma in the focus of counter-propagating laser fields
- Observable manifestations testable, e.g., at ASTRA-Gemini:
  - several gamma-pairs per laser pulse
  - refraction index measurable by intereference with test beam
  - higher harmonics generation, in particular 3^{rd}
- 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)

Schwinger Effect: Pair Creation in Strong Fields

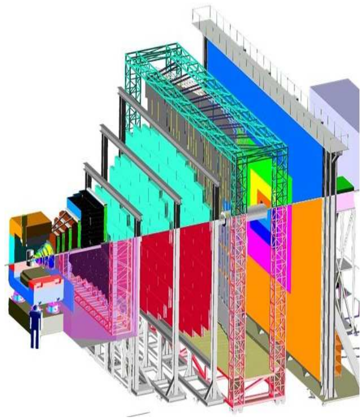


Modern QCD Phase Diagram: Quarkyonic Matter

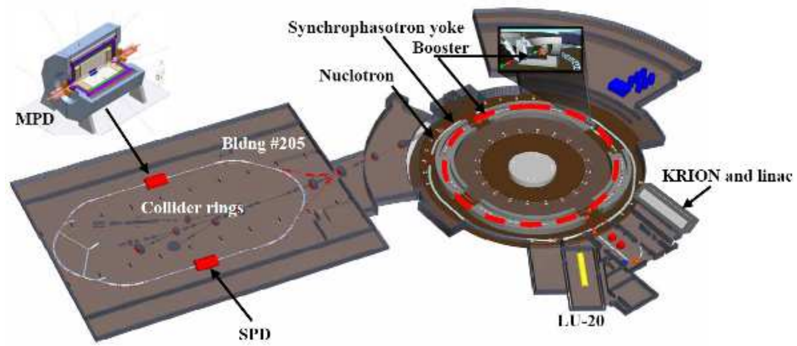


DEDICATED HEAVY-ION EXPERIMENTS FOR DENSE QCD

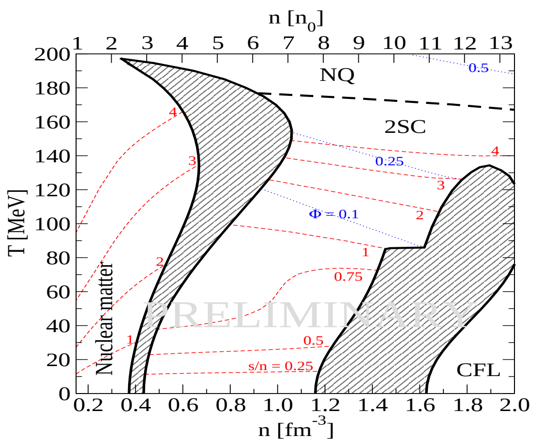
CBM experiment @ FAIR Darmstadt



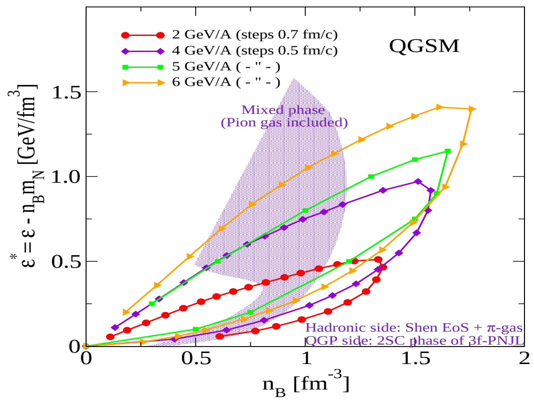
NICA-MPD experiment @ JINR Dubna



Phase Diagram: D.B., Sandin, Typel (2009)



HIC Trajectories: Skokov (2009)

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