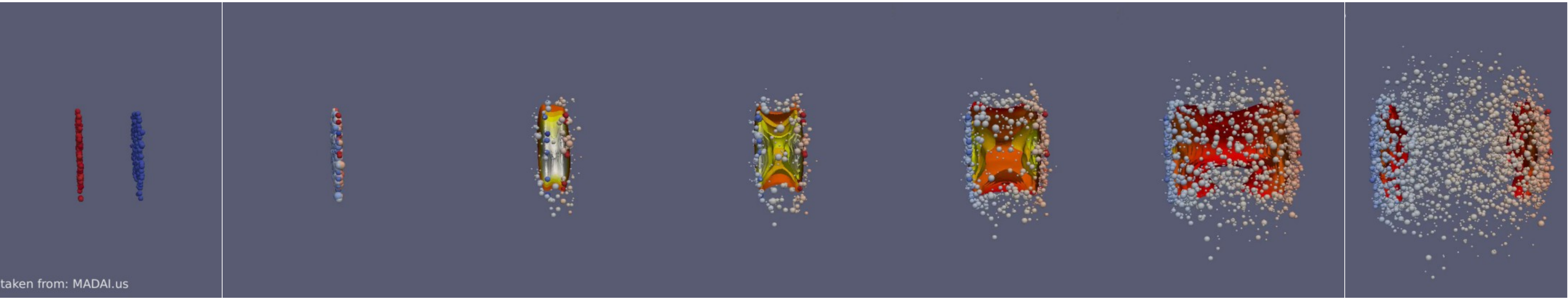
Quantum Kinetics of Particle Production in Strong Fields

David Blaschke (University of Wroclaw, Poland & JINR Dubna, Russia)



4th International HIC for FAIR Symposium on "Non-equilibrium Dynamics (NeD-2015)

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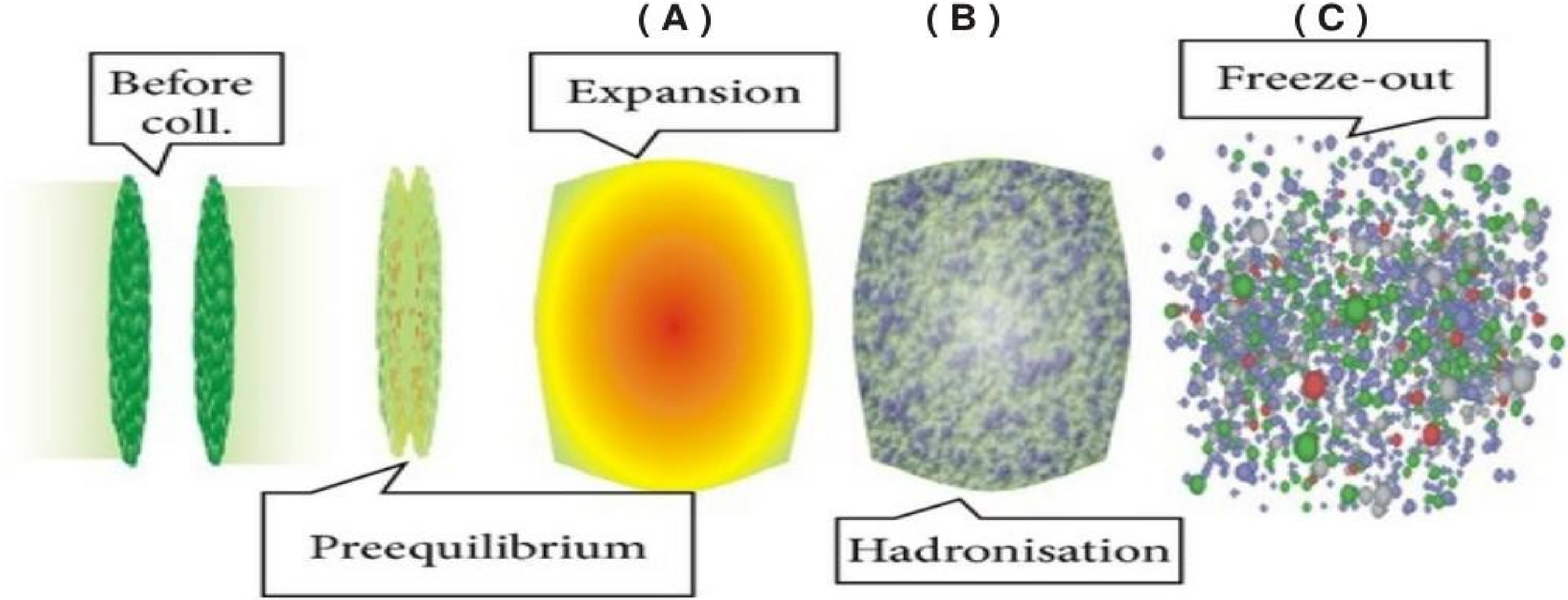

Generic kinetic equation with scalar (mass) and color meanfields, Schwinger source terms and collision integrals for hadronization and rescattering

$$\left[\partial_t + \frac{1}{E_X}\vec{p}\cdot\vec{\nabla} - \frac{m_X(\vec{x},t)}{E_X}\vec{\nabla} m_X(\vec{x},t)\cdot\vec{\nabla}_p + \vec{F}(\vec{x},t)\cdot\vec{\nabla}_p\right] f_X(\vec{p},\vec{x};t)$$
$$= S_X^{\rm Schwinger}\{f_q, f_{\bar{q}}, f_\pi, \ldots\} + C_X^{\rm gain}\{f_q, f_{\bar{q}}, f_\pi, \ldots\} - C_X^{\rm loss}\{f_q, f_{\bar{q}}, f_\pi, \ldots\}$$

(A) quark-antiquark pair creation in time-dependent color electric background field
(B) quantum kinetics of pre-hadron inelastic rescattering in the dense quark plasma
(C) chemical freeze-out by Mott-Anderson localization of bound states

Quantum Kinetics of Particle Production in Strong Fields

Topics considered in preparatory works:

- aspects of the relation between thermal hadron spectra and the Schwinger tunneling mechansim [Bialas 1999, Florkowski 2004, Ryblewski & Florkowski 2013]
- kinetic equations for Wigner functions of particles with internal degrees of freedom [Smolyansky et al. 1998] and chiral invariant transport equations for quark matter [Florkowski et al. 1996]
- kinetic equations for dynamical Schwinger effect in laser colliders [Blaschke at al. 2013] and BBGKY hierarchy for the electron-positron-gamma system in this case [Blaschke at al. 2011]
- coupled transport equations for quarks and confining meanfield [Bozek et al. 1998] and for quarks and mesons [Dolejsi et al. 1995, He et al. 1999]
- quantum statistical description of multiquark systems and heavy-flavor kinetics with color-saturated confining interactions within the string-flip model [Röpke et al. 1986, 1988; Martins et al. 1995]
- indications for chemical nonequilibrium in the statistical hadronization model fit to transverse-momentum spectra at LHC [Begun et al. 2014]
- generalized Beth-Uhlenbeck approach to mesons in quark matter in NJL [Hüfner et al. 1994] and PNJL model [Blaschke et al. 2014]
- description of lattice QCD thermodynamics in a PNJL-resonance gas model with Mott effect [Turko et al. 2012, 2014]
- pion-pion scattering in the NJL model [Quack et al. 1995, He et al. 1998]
- chemical freeze-out based on Mott-Anderson localization [Blaschke et al. 2011, 2012]

To be integrated into the unifying quantum kinetic approach ...

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Lukasz Juchnowski, Ludwik Turko (University of Wroclaw)
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Gerd Roepke (University of Rostock)
Craig Roberts (Argonne National Laboratory)
Sebastian Schmidt (Forschungszentrum Juelich)

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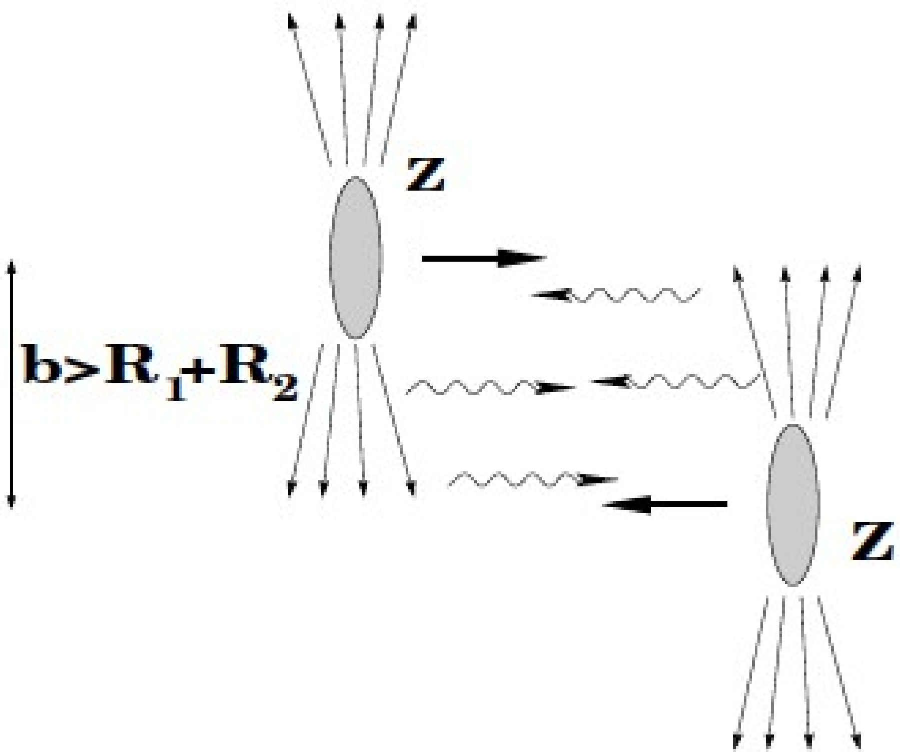
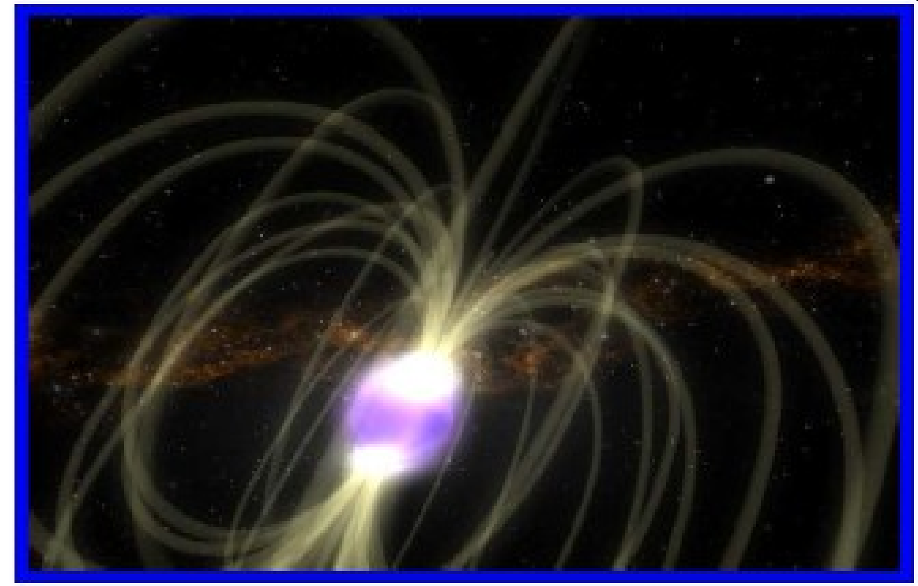
Pair Creation in Strong Electromagnetic Fields

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



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



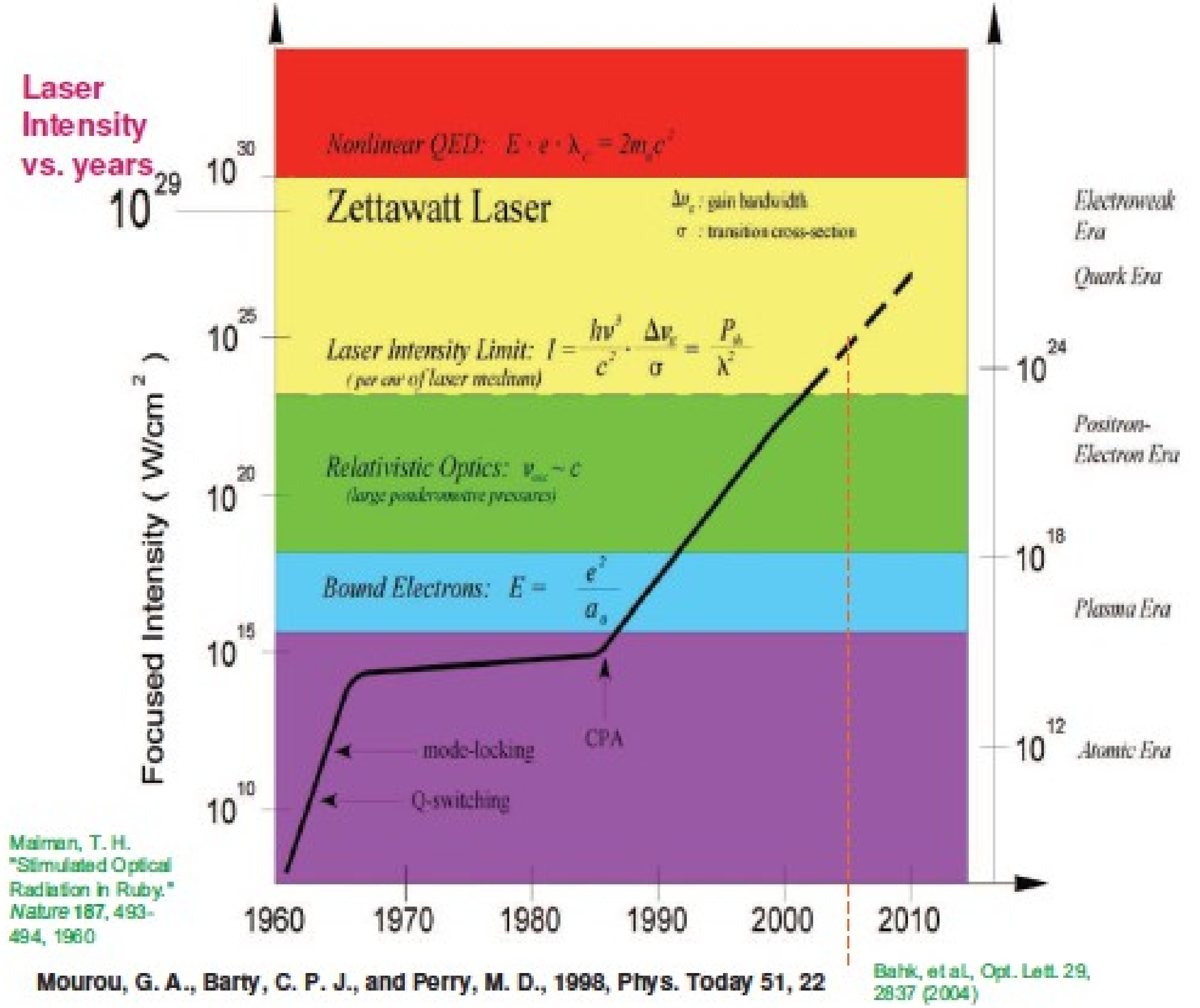
Artist view of a Magnetar (NASA)

- 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)

Frontiers of Laser Intensities



Mourou, G. A., Barty, C. P. J., and Perry, M. D., 1998, Phys. Today 51, 22

ELI - The Extreme Light Infrastructure

- ELI-Beamlines Facility (Czech Republic)
- ELI-Attosecond Facility (Hungary)
- ELI-Nuclear Physics Facility (Romania)
- ELI-Ultra High Field Facitity (location to be fixed)
  Power = 200 PW (100.000 times power of world electric grid)
  particle physics, nuclear physics, gravitational physics, nonlinear field theory, ultrahigh-pressure physics, astrophysics and cosmology (generating intensities exceeding $10^{23}\mathrm{W/cm^2}$). It will offer a new paradigm in High Energy Physics.

HAWKING-UNRUH RADIATION AT LASERS

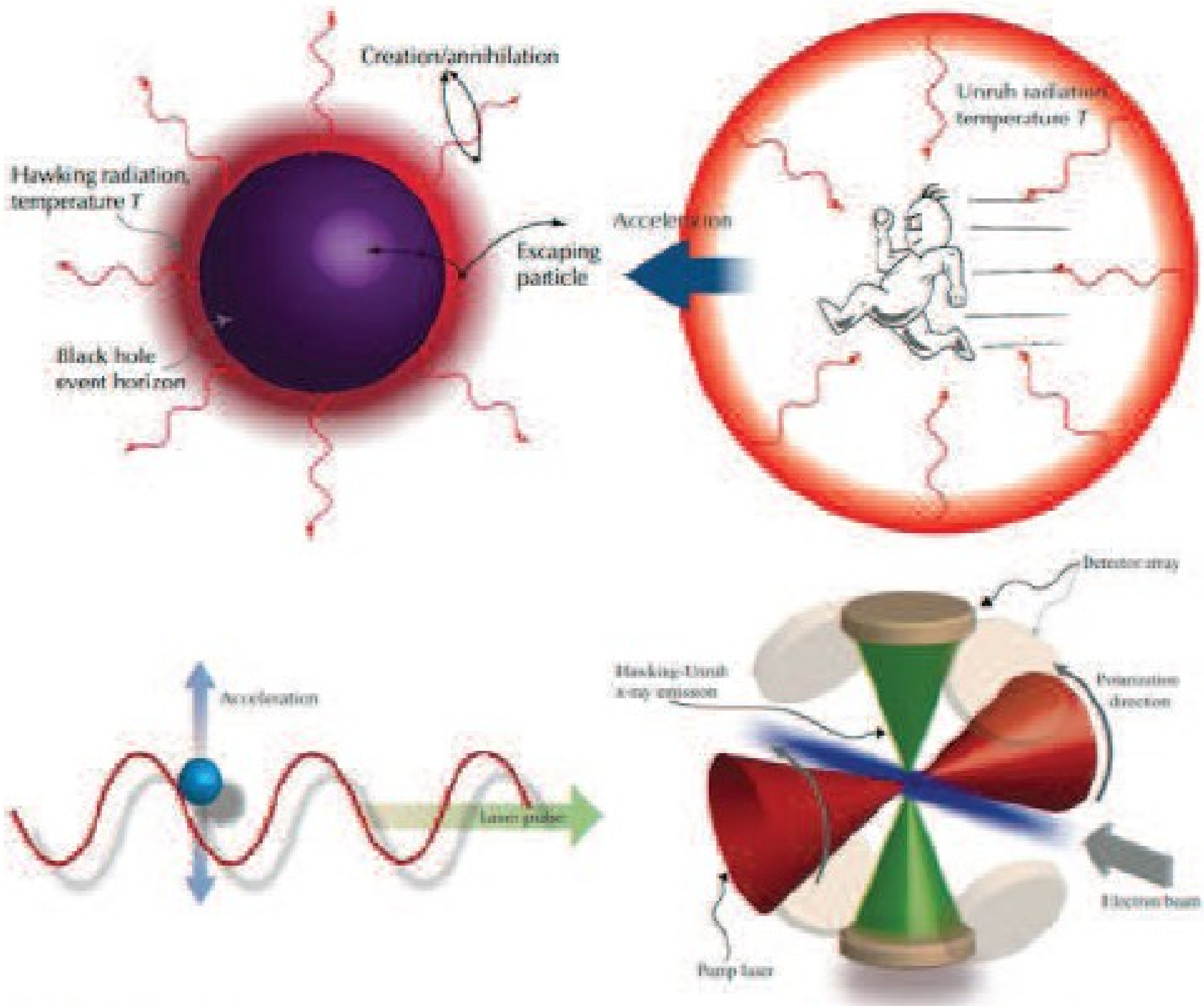
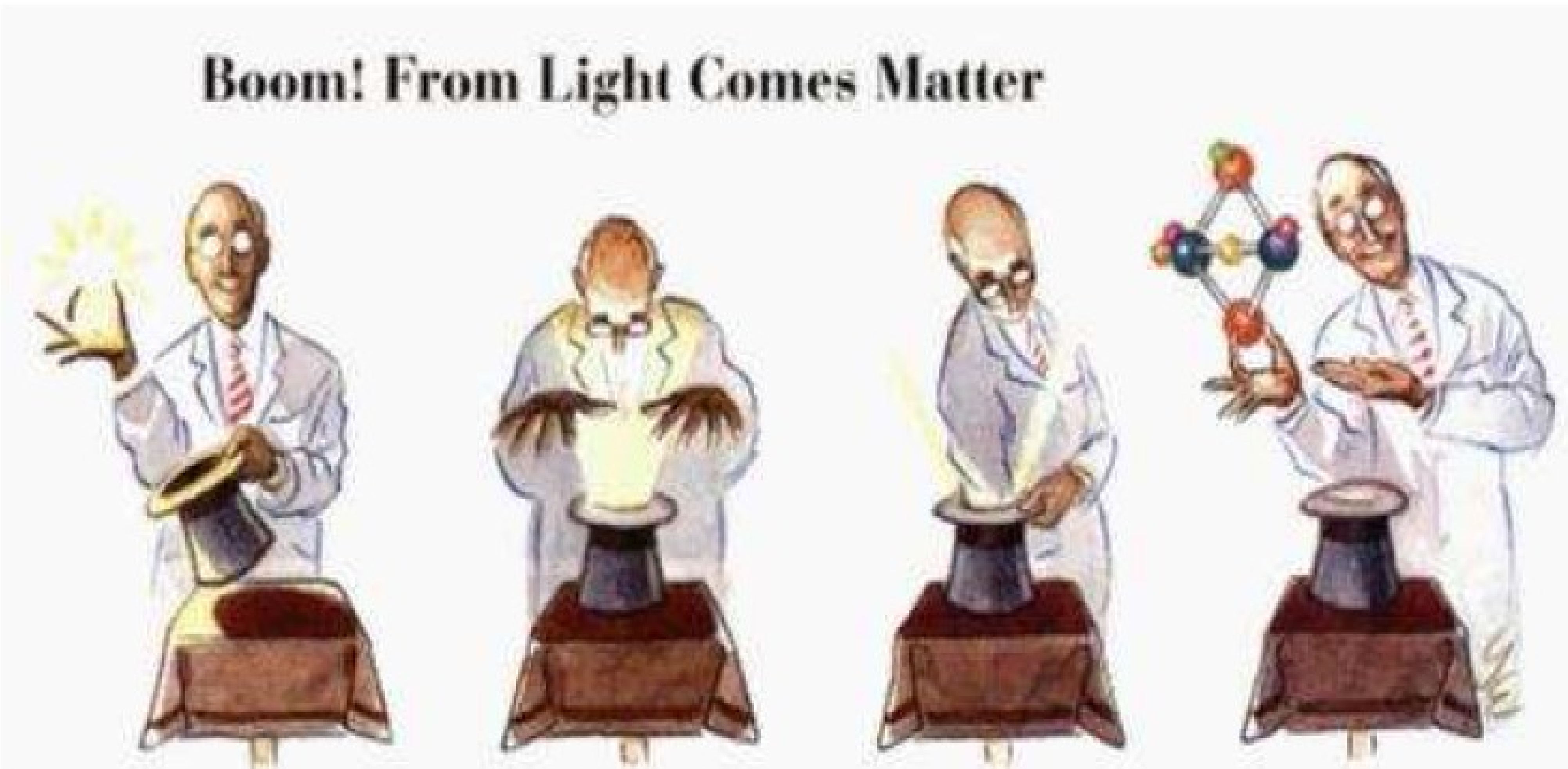


FIG. 7: The schematics of the experimental setup for Unruh radiation detection. Note than the radiation is emitted in a very particular direction as well as frequency, thus being detectable even if the background "noise" is high.

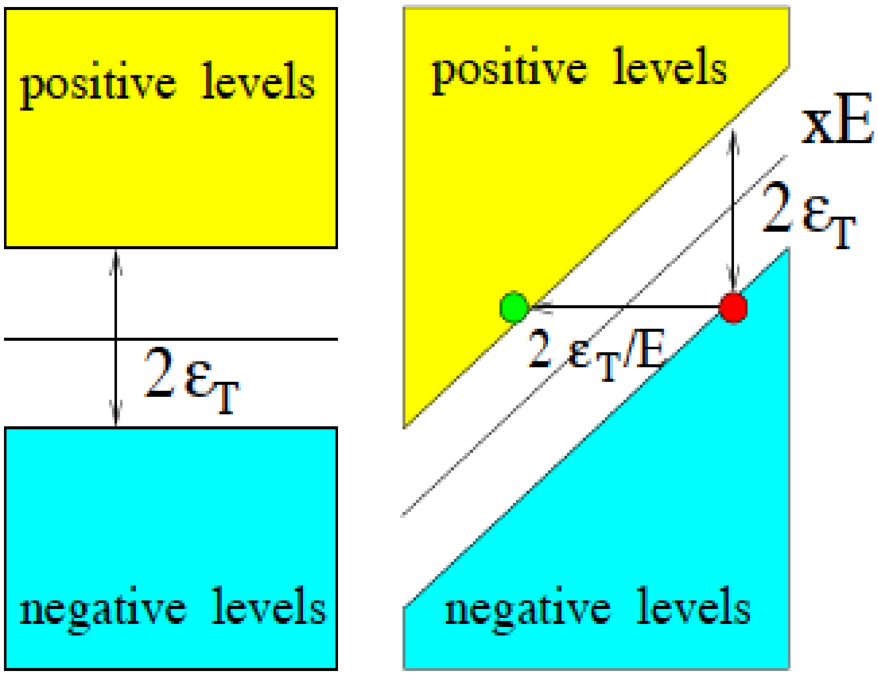
R. Schutzhold, G. Schaller, D. Habs,
"Signatures of the Unruh Effect from Electrons Accelerated by Ultrastrong Laser Fields"
Phys. Rev. Lett. 97 (2006) 121302

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 $E \sim E_{\rm crit}$

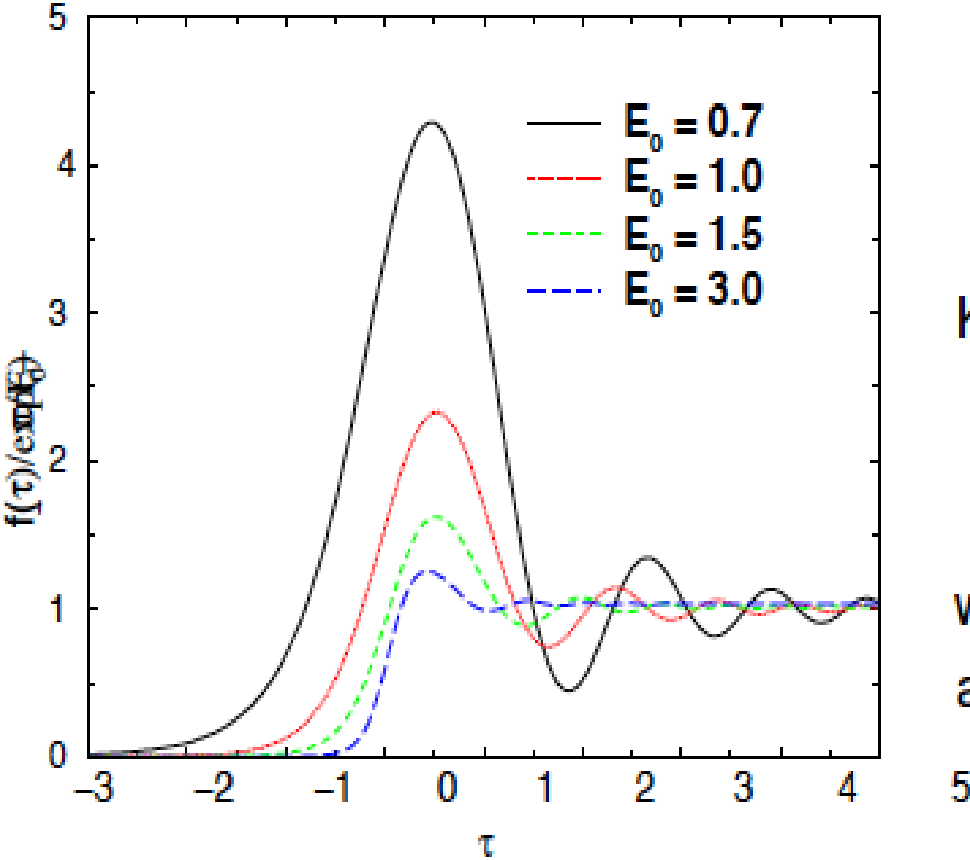
$$E_{\rm crit} \equiv \frac{m^2c^3}{e\hbar} \simeq 1.3 \times 10^{18}\,{\rm V/m}$$

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



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

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

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 $\varepsilon_{\perp} = \sqrt{m^2 + \vec{p}_{\perp}^2}$ 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

Kinetic Approach – sketch of the derivation

- Classical external time-dependant vector potential A^μ
- $A^\mu = (0, 0, 0, A(t))$

$\Downarrow$
spatially-uniform electric field

$\vec{\mathbf{E}}(t) = (0, 0, E(t))$
$E(t) = -\frac{d}{dt}A(t)$

Ansatz[1] for fermionic wavefunction

$$\psi^{(\pm)}_{\mathbf{q}r}(x) = \left[i\gamma^0\partial_0 + \gamma^k p_k - e\gamma^3 A(t) + m\right]\chi^{(\pm)}(\mathbf{q}, t)\ R_r\ e^{i\mathbf{q}\bar{x}}$$

Herein R_r $(r = 1, 2)$ is an eigenvector of the matrix $\gamma^0\gamma^3$

$$R_1 = \begin{pmatrix} 0 \\ 1 \\ 0 \\ -1 \end{pmatrix}, \qquad R_2 = \begin{pmatrix} 1 \\ 0 \\ -1 \\ 0 \end{pmatrix}, \qquad R_r^+ R_s = 2\delta_{rs}$$

- If we put $\psi^{(\pm)}_{\mathbf{q}r}$ to Dirac $(i\gamma^\mu\partial_\mu - e\gamma^\mu A_\mu - m)\psi(x) = 0$ we get

$$\ddot{\chi}^{(\pm)}(\mathbf{q}, t) + \left[\varepsilon^2(\mathbf{q}, t) + ie\dot{A}(t)\right]\chi^{(\pm)}(\mathbf{q}, t) = 0 \qquad \varepsilon^2(\mathbf{q}, t) = m^2 + (\mathbf{q} + e\mathbf{A}(\mathbf{t}))^2$$

- At $t_0 = t \to \infty$ vector potential A(t) $\to 0$ so

$$\chi^{(\pm)}(\mathbf{p}, t) \sim \exp\left(\pm i\varepsilon_0(\mathbf{p})\, t\right), \qquad \varepsilon_0(\mathbf{q}, t) = \sqrt{m^2 + \mathbf{q}^2}$$

Canonical quantization :

- Field operator :

$$\psi(x) = \sum_{r,\mathbf{q}} \left[\psi^{(-)}_{\mathbf{q}r}(x)\; b_{\mathbf{q}r} + \psi^{(+)}_{\mathbf{q}r}(x)\; d^{+}_{-\mathbf{q}r} \right]$$

- electron operators at t_0 : $b_{\mathbf{q},r}, b^{+}_{\mathbf{q}'r'}$
- positron operators : $d_{\mathbf{q}r}, d^{+}_{\mathbf{q}'r'}$
- anti-commutator

$$\left\{ b_{\mathbf{q}r}, b^{+}_{\mathbf{q}'r'} \right\} = \left\{ d_{\mathbf{q}r}, d^{+}_{\mathbf{q}'r'} \right\} = \delta_{rr'}\delta_{\mathbf{q}\mathbf{q}'}$$

- Operators describe annihilation /creation in the in-state $|0_{\mathrm{in}}\rangle$

Time-dependent Bogoliubov transformation

- Transformation

$$\begin{aligned} b_{\mathbf{q}r}(t) &= \alpha_{\mathbf{q}}(t)\; b_{\mathbf{q}r}(t_0) &+& \beta_{\mathbf{q}}(t)\; d^{+}_{-\mathbf{q}r}(t_0)\;, \\ d_{\mathbf{q}r}(t) &= \alpha_{-\mathbf{q}}(t)\; d_{\mathbf{q}r}(t_0) &-& \beta_{-\mathbf{q}}(t)\; b^{+}_{-\mathbf{q}r}(t_0) \end{aligned}$$

- with the condition

$$|\alpha_{\mathbf{q}}(t)|^2 + |\beta_{\mathbf{q}}(t)|^2 = 1\;.$$

Kinetic approach - sketch of derivation

- Time-dependent Bogoliubov transformation

$$\{B_{\mathbf{q}r}(t), B^{+}_{\mathbf{q}'r'}(t)\} = \{D_{\mathbf{q}r}(t), D^{+}_{\mathbf{q}'r'}(t)\} = \delta_{rr'}\ \delta_{\mathbf{q}\mathbf{q}'}$$

- Heisenberg-type equations of motion

$$\frac{dB_{\mathbf{q}r}(t)}{dt} = -\frac{eE(t)\varepsilon_{\perp}}{2\varepsilon^2(\mathbf{q},t)}\ D^{+}_{-\mathbf{q}r}(t) + i\ [H(t),\ B_{\mathbf{q}r}(t)]\ ,$$

$$\frac{dD_{\mathbf{q}r}(t)}{dt} = \frac{eE(t)\varepsilon_{\perp}}{2\varepsilon^2(\mathbf{q},t)}\ B^{+}_{-\mathbf{q}r}(t) + i\ [H(t),\ D_{\mathbf{q}r}(t)]\ ,$$

- New Hamiltonian

$$H(t) = \sum_{r,\mathbf{q}} \varepsilon(\mathbf{q},t)\left[B^{+}_{\mathbf{q}r}(t)B_{\mathbf{q}r}(t) - D_{-\mathbf{q}r}(t)\ D^{+}_{-\mathbf{q}r}(t)\right]$$

- Kinetic equation

$$\frac{df_r(\mathbf{q},t)}{dt} = -\frac{eE(t)\varepsilon_{\perp}}{\varepsilon^2(\mathbf{q},t)}\mathrm{Re}\langle 0|D_{-\mathbf{q}r}(t)B_{\mathbf{q}r}(t)|0\rangle$$

Kinetic equation (without back reaction)

$$\frac{df_r(\mathbf{q},t)}{dt} = \frac{eE(t)\varepsilon_{\perp}}{2\varepsilon^2(\mathbf{q},t)}\int_{t_0}^{t} dt'\,\frac{eE(t')\varepsilon_{\perp}}{\varepsilon^2(\mathbf{q},t')}\left[1-2f_r(\mathbf{q},t')\right]\cos\left[2\,\theta(\mathbf{q},t',t)\right]$$

$$\varepsilon^2(\mathbf{q},t) = m^2 + \mathbf{P}^2(t) = m^2 + (\mathbf{q} + e\mathbf{A}(\mathbf{t}))^2$$

Non-Markovian kinetic equation

$$\frac{df_r(\mathbf{q},t)}{dt} = \overbrace{\frac{1}{2}\lambda_\pm(\mathbf{q},t)\int_{t_0}^{t} dt'\lambda_\pm(\mathbf{q},t')\underbrace{[1\pm 2f(\mathbf{q},t')]}_{\text{Non-Markovian factor}}\cos\theta(t,t')}^{\mathcal{S}(\mathbf{q},t)-\text{source term}}$$

$$\lambda_-(\mathbf{q},t) = eE(t)\varepsilon_\perp/\varepsilon^2(\mathbf{q},t) \qquad \lambda_+(\mathbf{p},t) = eE(t)\mathrm{p}/\varepsilon^2(\mathbf{q},t)$$

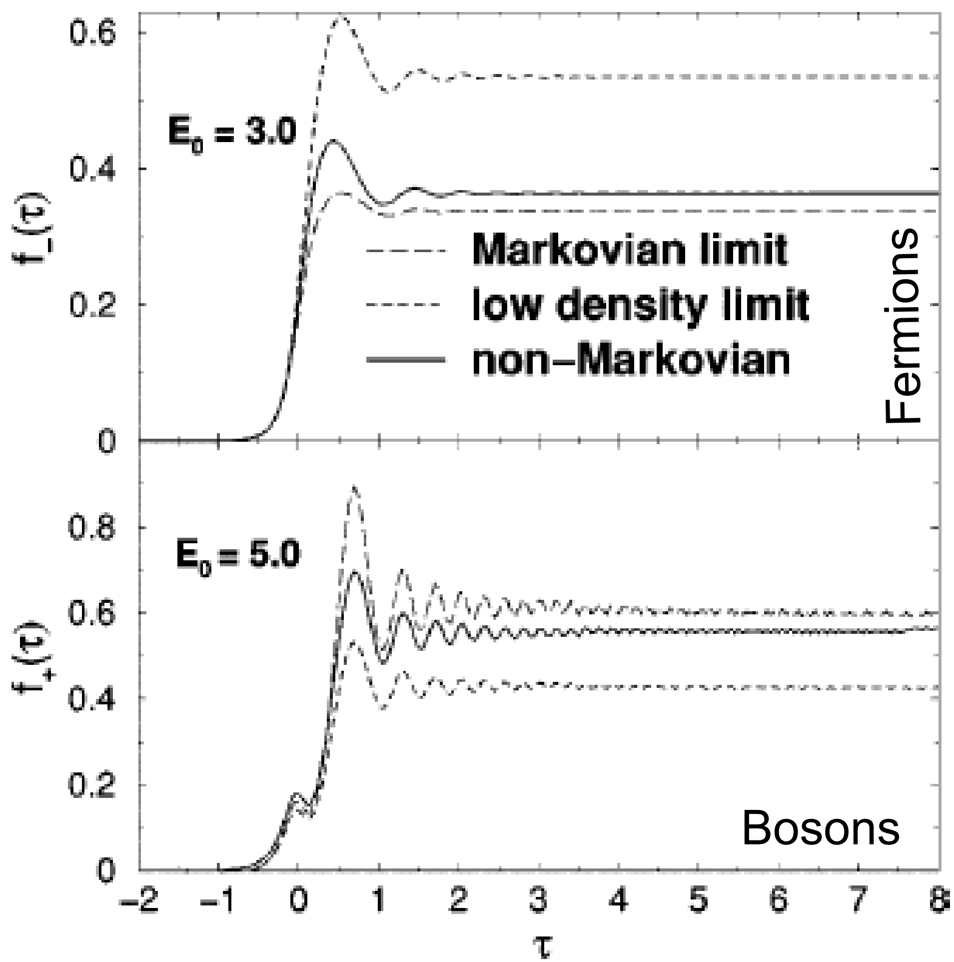
$$\varepsilon_\perp = \sqrt{m^2+q_\perp^2}$$

$$\theta(t,t') = 2\int_{t'}^{t} d\tau\,\varepsilon(\mathbf{q},\tau)$$

KE is equivalent to a system of ordinary differential equations

$$\dot f = \frac{1}{2}\lambda u, \qquad \dot u = \lambda(1\pm 2f) - 2\varepsilon v, \qquad \dot v \;=\; 2\varepsilon u,$$

Markovian and Low-Density Limits for the Dynamical Schwinger Process in Strong External Fields



Markovian limit :

$$\frac{d f^M_\pm(\tau)}{d\tau} = [1 \pm 2 f^M_\pm(\tau)] S^0_\pm(\tau) = S^M_\pm(\tau),$$

$$f^M_\pm(\tau) = \mp\frac{1}{2}\left(1 - \exp\left[\pm 2\int_{-\infty}^{\tau} d\tau' S^0_\pm(\tau')\right]\right).$$

Low-density limit :

$$f^0_\pm(\tau) = \int_{-\infty}^{\tau} d\tau' S^0_\pm(\tau').$$

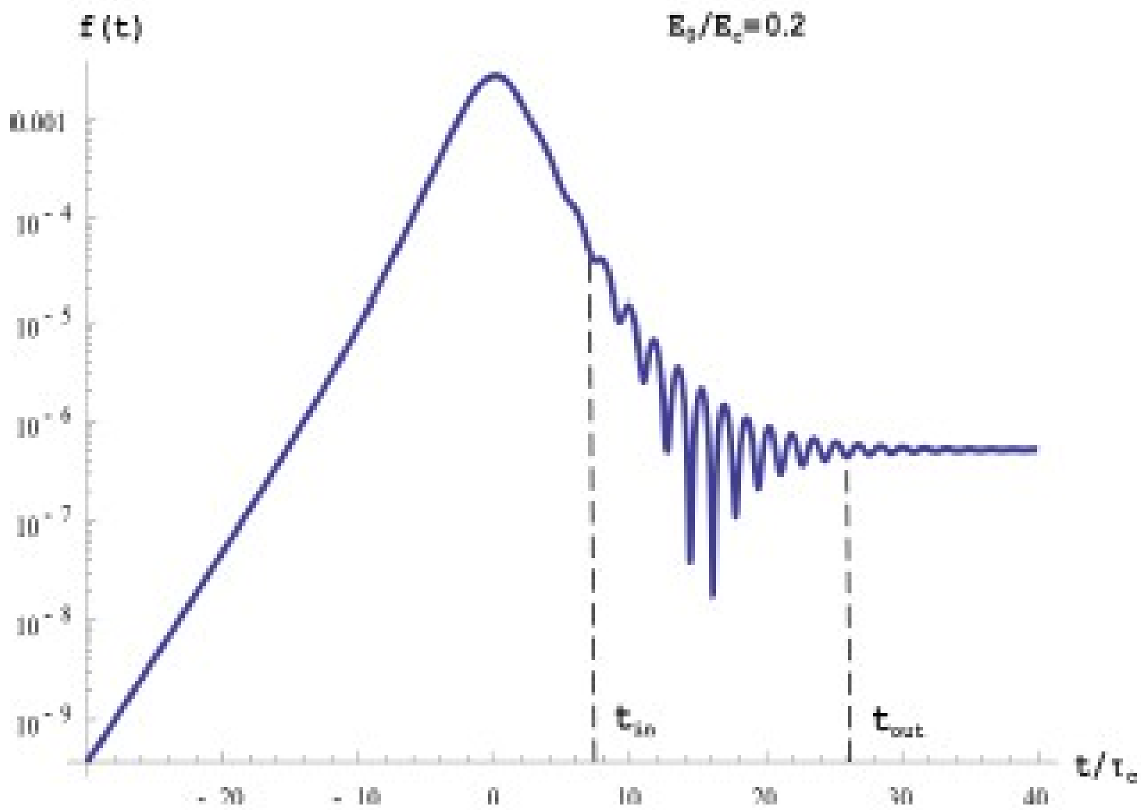
$$f^0_\pm(\tau) = \frac{1}{2}\int_{-\infty}^{\tau} d\tau' g^1_\pm(\tau') \int_{-\infty}^{\tau'} d\tau'' g^1_\pm(\tau'') + \frac{1}{2}\int_{-\infty}^{t} d\tau' g^2_\pm(\tau') \int_{-\infty}^{\tau'} d\tau'' g^2_\pm(\tau''),$$

$$g^{1,2}_\pm(\tau) = W_\pm(\tau)\begin{Bmatrix}\cos[2\Theta(\tau)] \\ \sin[2\Theta(\tau)]\end{Bmatrix}.$$

$$f^0_\pm(\tau) = \frac{1}{4}\left(\int_{-\infty}^{\tau} d\tau' g^1_\pm(\tau')\right)^2 + \frac{1}{4}\left(\int_{-\infty}^{\tau} d\tau' g^2_\pm(\tau')\right)^2.$$

PHYSICAL REVIEW D, VOLUME 59, 094005

Examples (quasi-particle and mass-shell stage)



- Sauter pulse

$$E(t) = E_0 \cosh^{-2}(t/T)$$

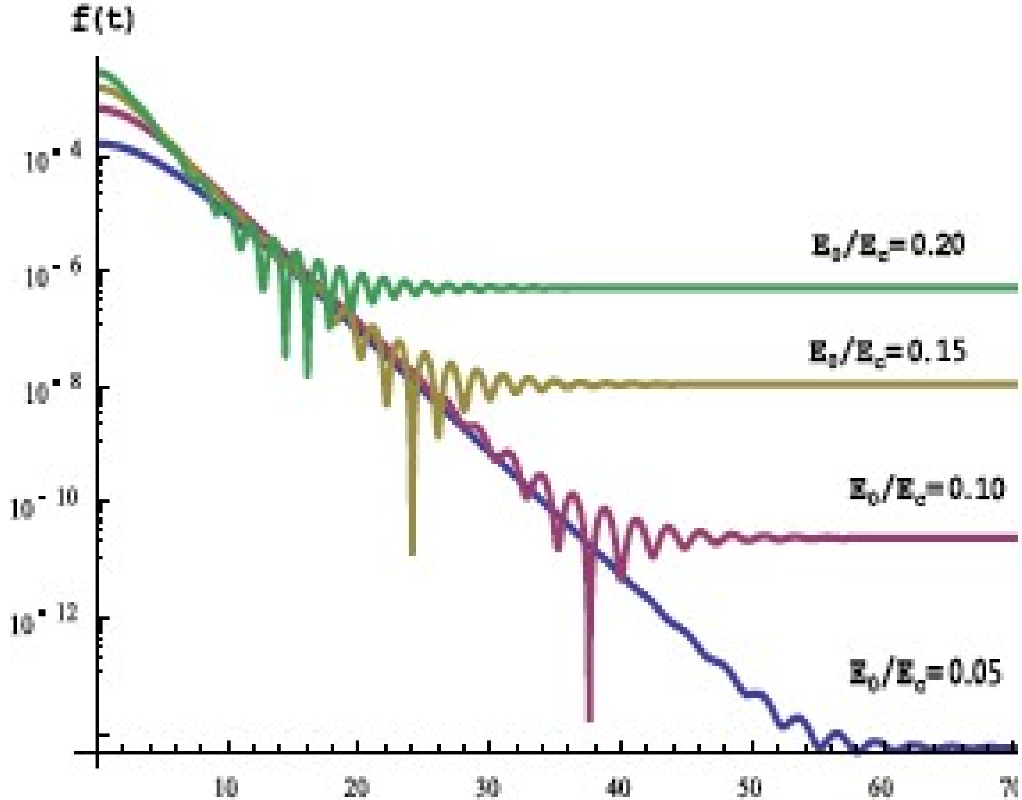
- $T = 0.02$nm
- $p_\perp = p_\parallel = 0$
- $[t_{\text{in}}, t_{\text{out}}]$ - transient region between quasi-particle and mass-shell stage

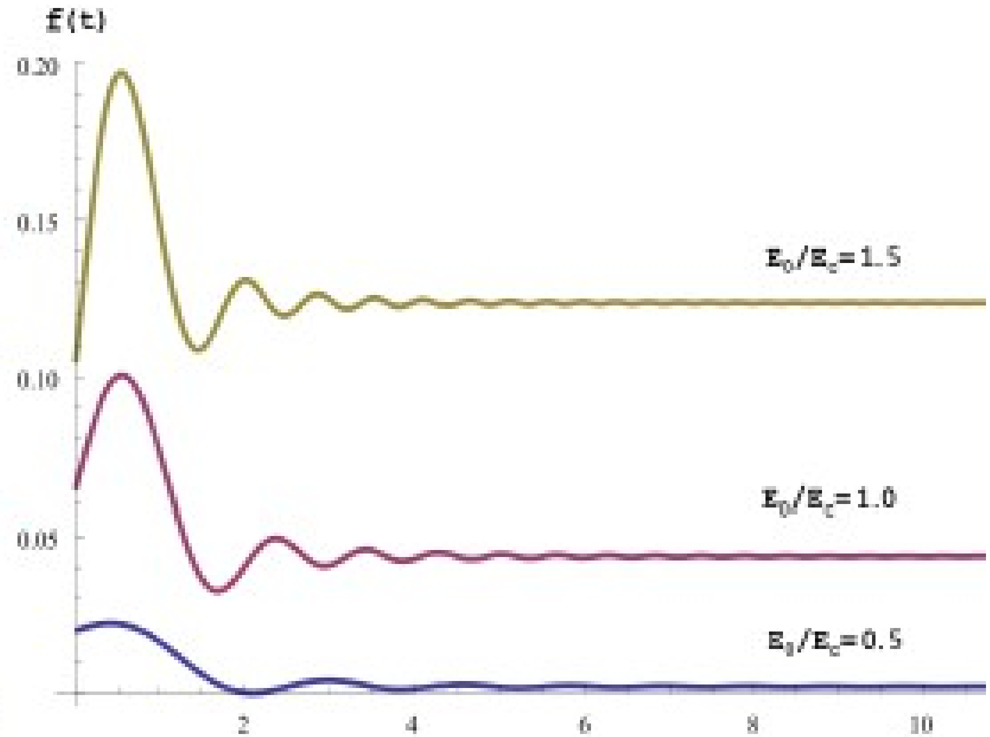
Dynamical Schwinger effect: Properties of the e^+e^- plasma created from vacuum in strong laser fields

Blaschke, Juchnowski , Panferov et al. arXiv:1412.6372

Examples (quasi-particle and mass-shell stage)

$$E(t) = E_0 \cosh^{-2}(t/T), \quad T = 8.24\tau_c, \quad p_\perp = p_{||} = 0$$





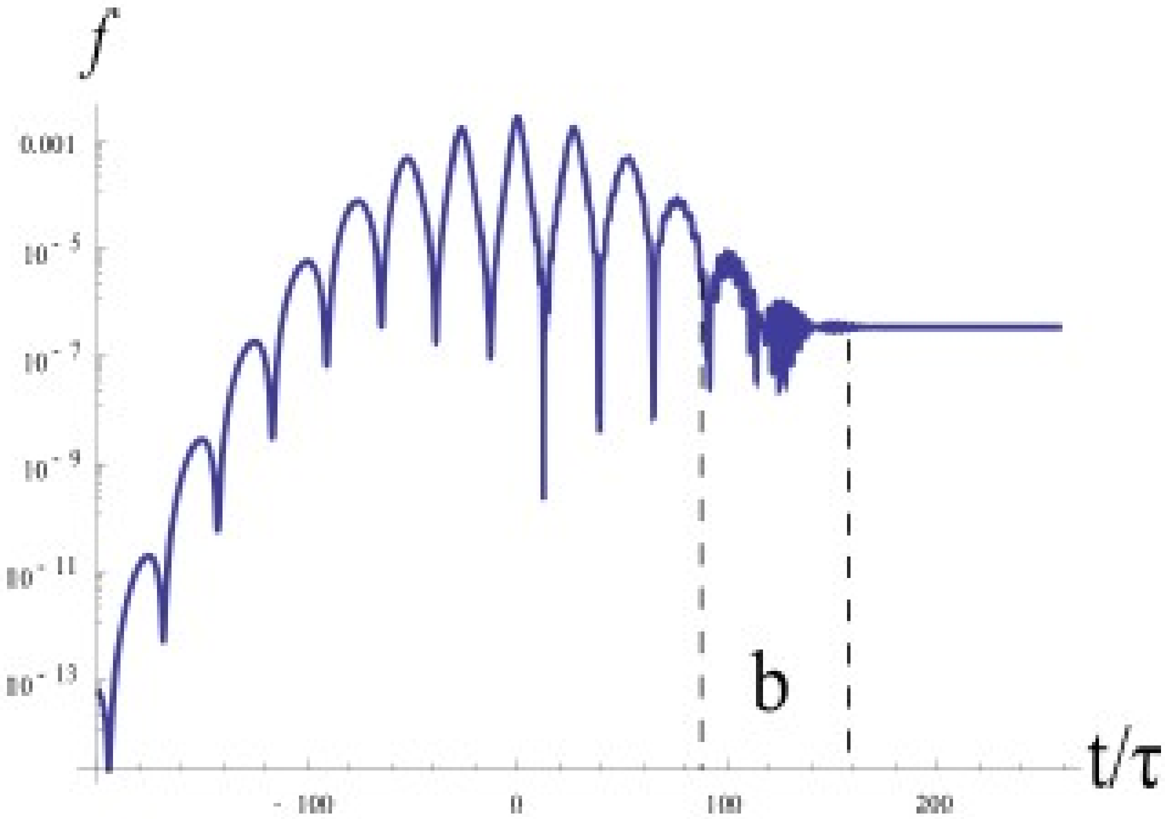
t/τ_c $\qquad$ t/τ_c

Dynamical Schwinger effect: Properties of the e^+e^- plasma created from vacuum in strong laser fields

Blaschke, Juchnowski , Panferov et al. arXiv:1412.6372

Examples (quasi-particle and mass-shell stage)

$$E(t) = E_0 \cos(\omega t + \phi)\, e^{-t^2/2\tau^2}, \quad \phi = 0, \quad \sigma = \omega\tau = 0.5 \quad p_\perp = p_\| = 0$$



t/τ_c

$E_0 = 0.2E_c$

the region "b" corresponds to the transient process

Dynamical Schwinger effect: Properties of the e^+e^- plasma created from vacuum in strong laser fields

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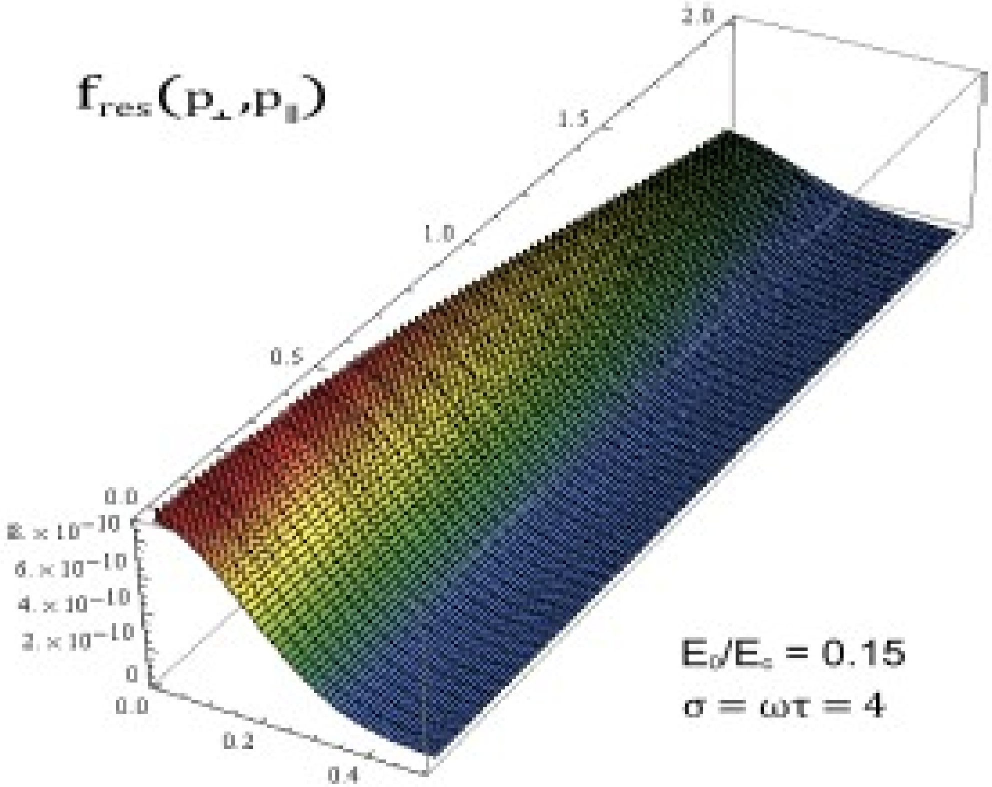
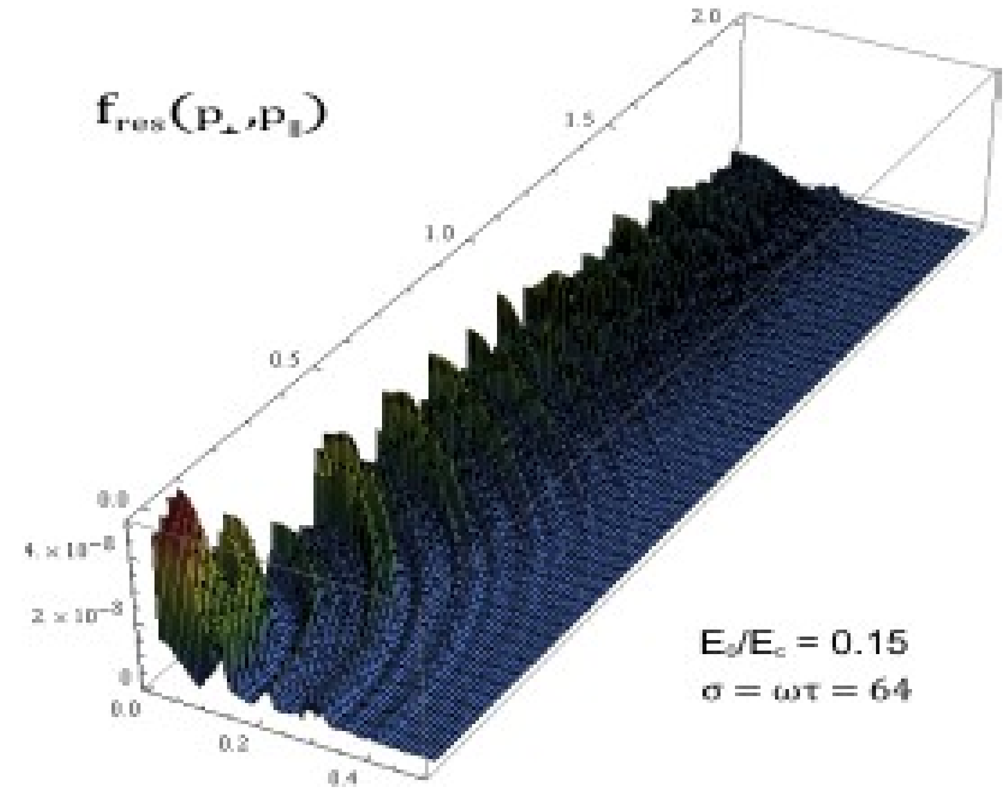
Mass-shell stage : $f_{res}(p_\perp, p_\parallel) = f(p_\perp, p_\parallel, t \to \infty)$

$$E(t) = E_0 \cos(\omega t + \phi)\, e^{-t^2/2\tau^2}, \quad \phi = 0, \quad \lambda_\omega = 0.1\text{nm}$$



Short pulse



Long pulse

Dynamical Schwinger effect: Properties of the e^+e^- plasma created from vacuum in strong laser fields

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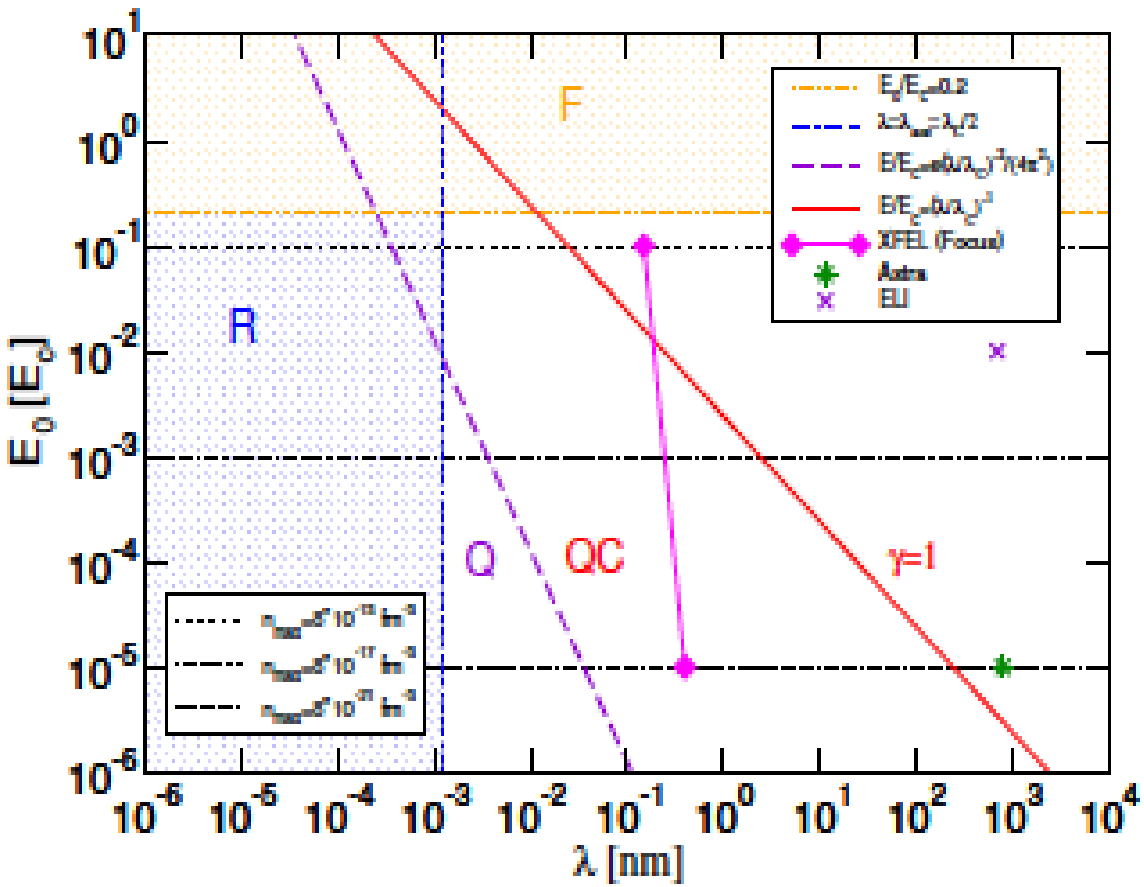
Landscape



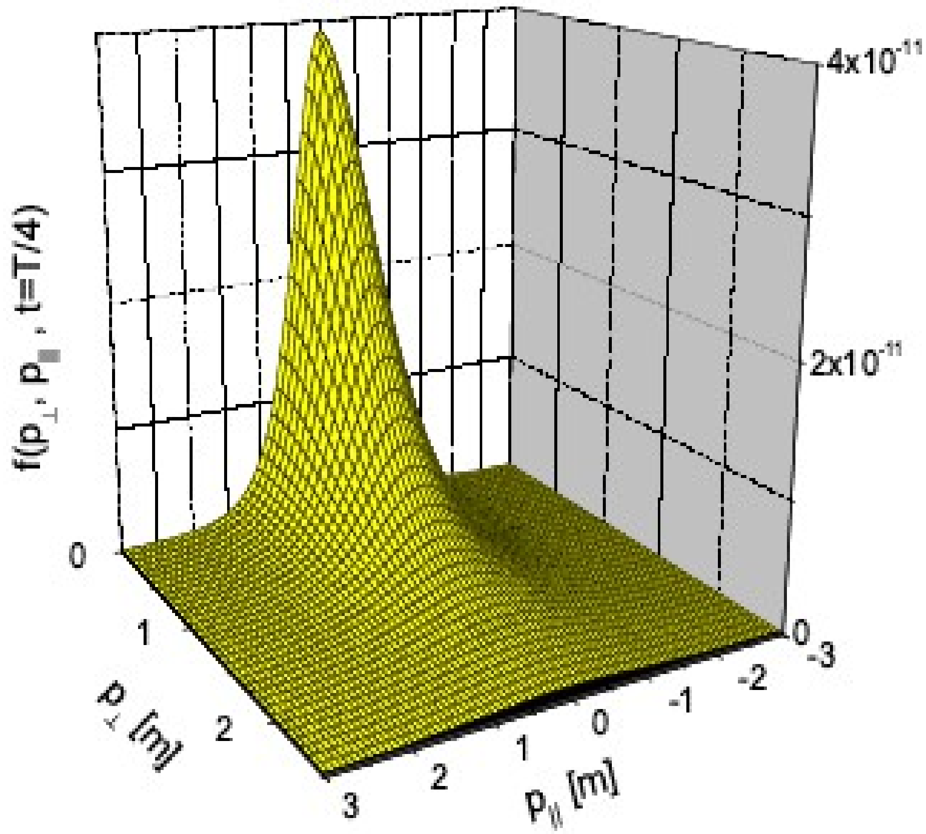
- Change of variables $(\omega, E) \to (\gamma, E)$
- Adiabaticity parameter

$$\gamma = \frac{E_c}{E}\frac{\omega}{m} = \frac{E_c}{E}\frac{\lambda_c}{\lambda}$$

- Red line $\gamma = 1$ separates two regimes
- Tunneling limit $\gamma \ll 1$
- Multiphoton limit $\gamma \gg 1$

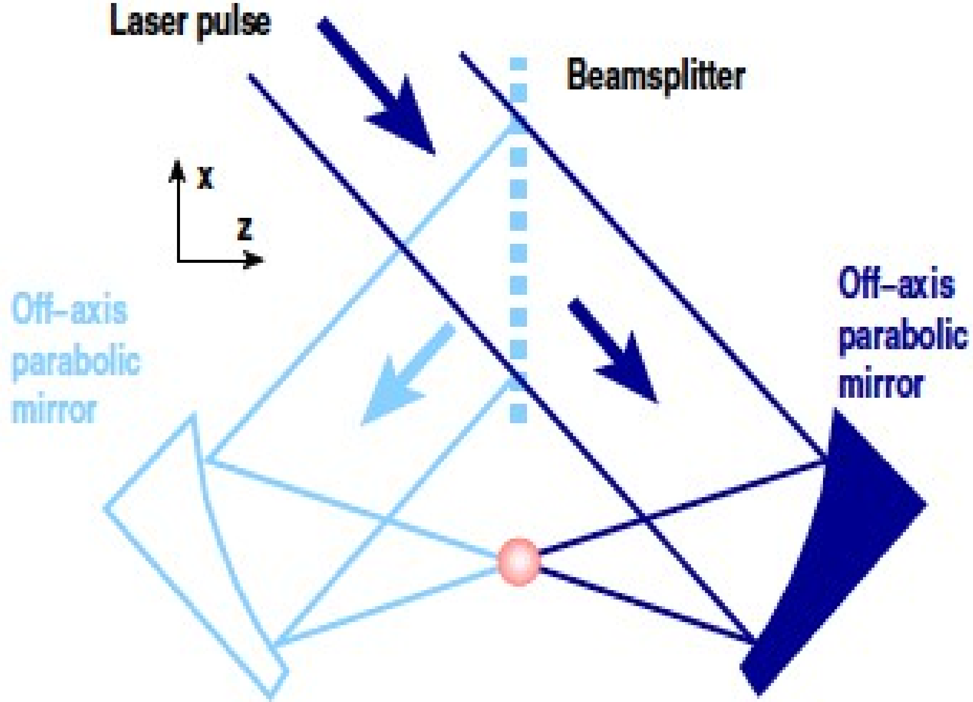
D. B. Blaschke, B. Kampfer, *et al.* , Phys. Rev. D 88 045017 (2013)

APPLICATION TO SUBCRITICAL LASER FIELDS



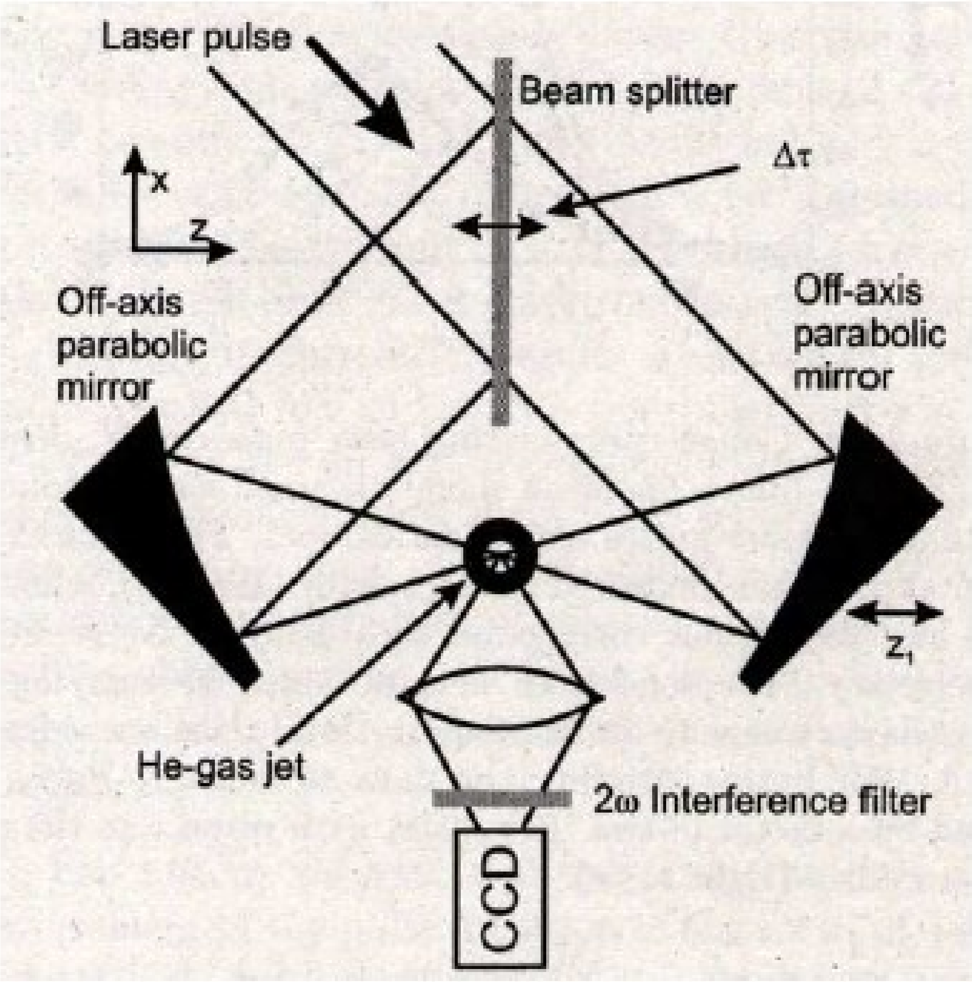
Equilibrium-like momentum distribution at the time of maximal field amplitude $t = T/4$.

Setup of the Jena Laser Exp. (2005)

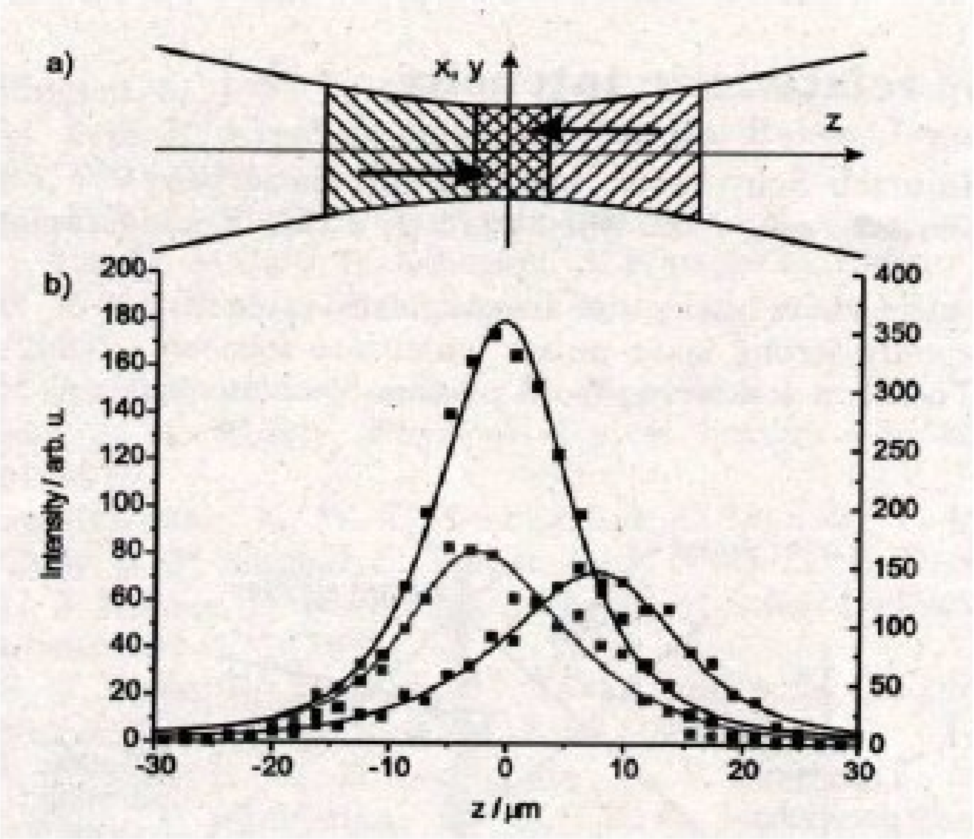


Heinzl, et al., Opt. Commun. 267, 318 (2006)

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 $\omega/m = 2.84 \cdot 10^{-6}$

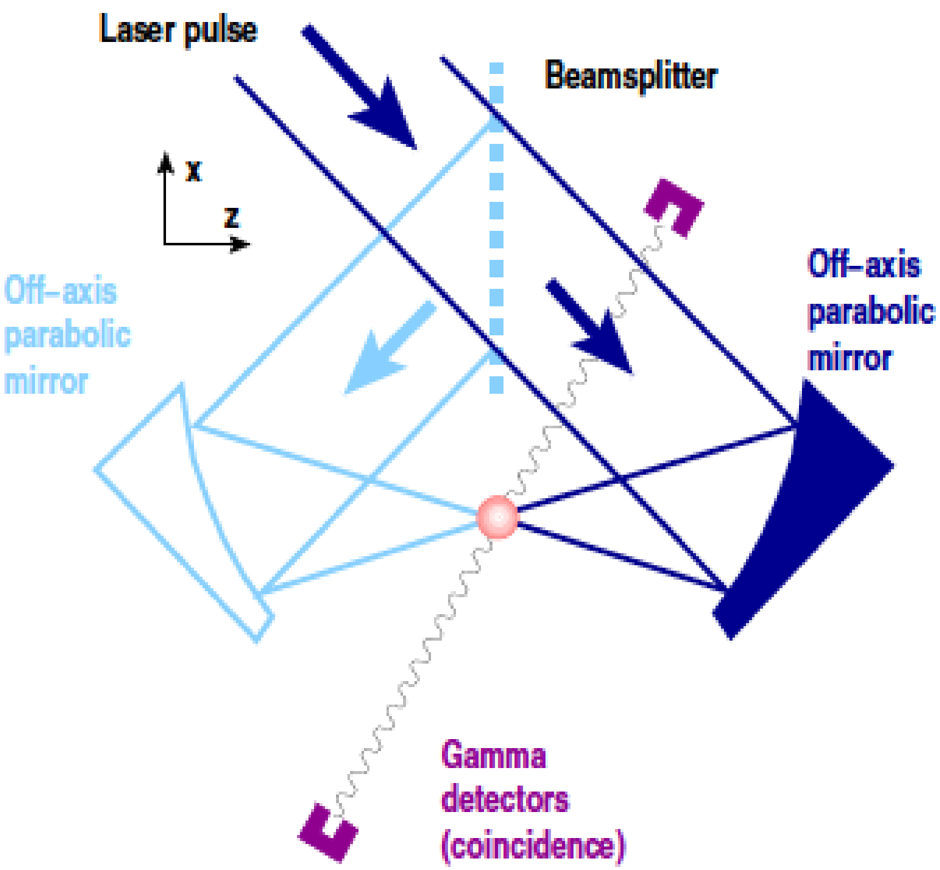


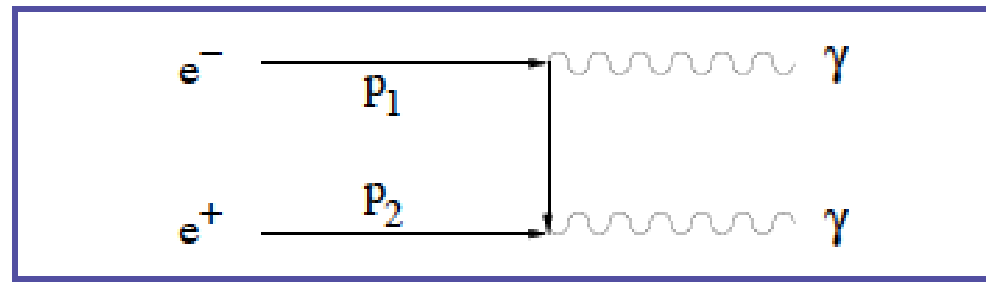
Laser diagnostic by nonlinear Thomson scattering off e⁻ in a He-gas jet
Pulse intensity: $I = 10^{18}$ W/cm², duration: $\tau_L \sim 80 fs$, wavelength: $\lambda = 795$ nm, cross-size: $z_0 = 9\mu$m

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

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

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 $\to$ photon KE for zero initial condition

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

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

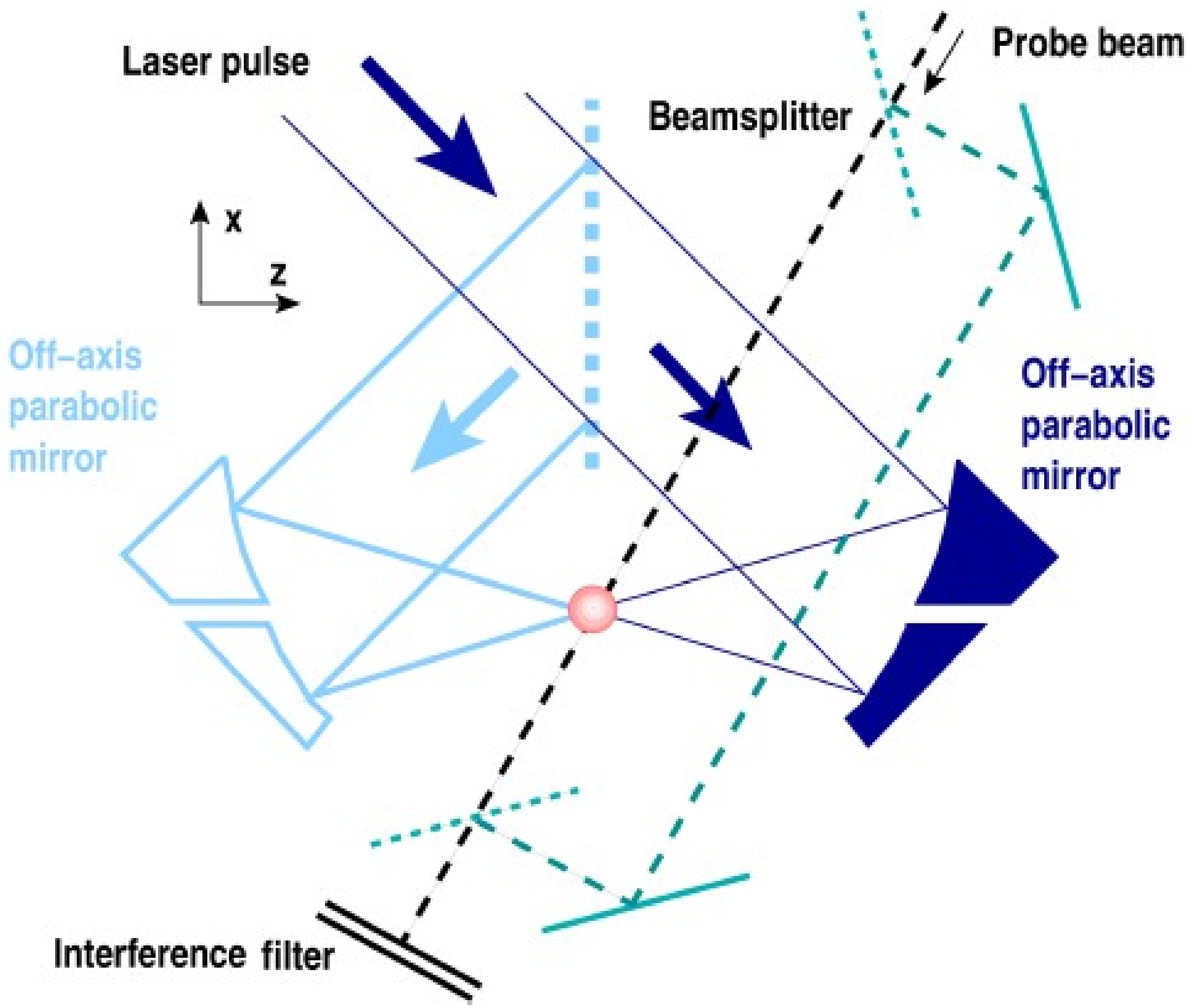
$$F(\mathbf{k},t) = \frac{5e^2 n(t)}{2k\delta^2}\ ,\quad n(t) = 2\int d^3p f(\mathbf{p},t)/(2\pi)^3$$

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).

Two Laser Beams: XFEL & High Intensity Optical Laser (HIBEF)



Why is it interesting?

- pump (HI optical laser) & Probe (XFEL) experiment exploring modification of QED vacuum structure

- refraction & birefringence

- “assisted” dynamical Schwinger effect

A. Otto, D. Seipt, D. Blaschke, B. Kaempfer, S.A. Smolyansky, PLB 740, 335 (2015)
D. Blaschke, L. Juchnowski, HIBEF kickoff meeting, DESY (2013)

Dynamical Schwinger process in a bifrequent electric field

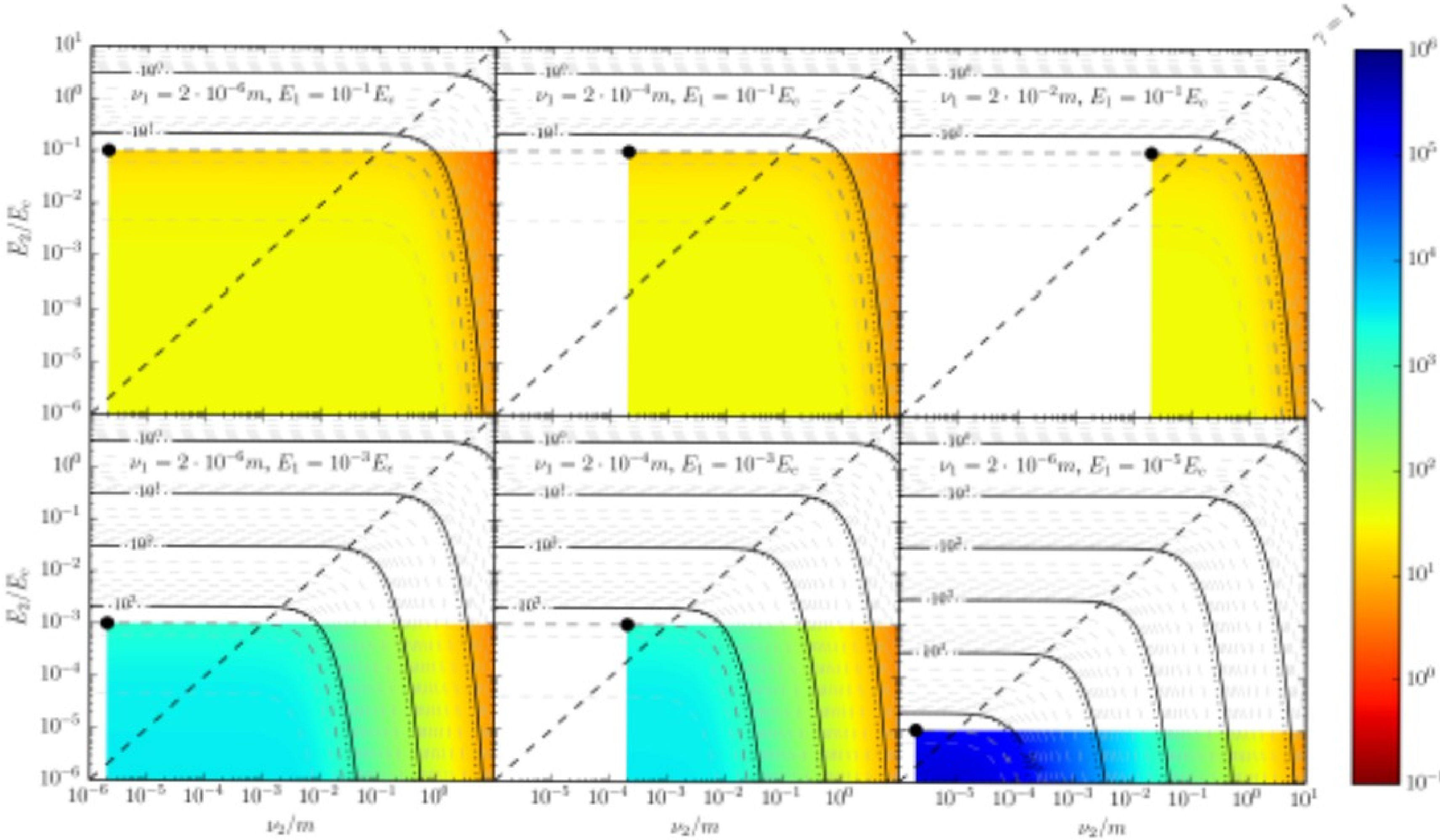


Figure 3: Contour plots of the exponential $4\frac{m}{\nu_1}G(p_\perp \ll m, \gamma_1, \gamma_2, N)$ for six given fields ν_1, E_1 in the adiabatic region (positions depicted by the bullets, which are the loci of field doubling) over the field-frequency (E_1/E_c vs. ν_1/m) plane, i.e. actually $4\frac{m}{\nu_1}G(p_\perp \ll m, \nu_1, E_1, \nu_2, E_2)$. Despite of the displayed smooth distribution, our results are strictly valid only for $E_2 < E_1$ and $\nu_2 = (4n+1)\nu_1$, $n = 0, 1, 2\cdots$. Light grey dashed contour curves are for $2, \cdots, 9$ between the solid decade contour curves. The heavy grey dashed curves are constructed to go through the bullets. An amplification beyond the field doubling occurs right and below the bullets and right to the heavy grey dashed curves, in the colored regions.

A. Otto, D. Seipt, D. Blaschke, S.A. Smolyansky, B. Kaempfer, Phys. Rev. D 91, 105018 (2015); arxiv:1503.08675 [hep-ph]

Lessons for Nonequilibrium Dynamics in Heavy-Ion Collisions ?

4 November 1999

PHYSICS LETTERS B

Physics Letters B 466 (1999) 301–304

Fluctuations of the string tension and transverse mass distribution

A. Bialas [a,b]

"Schwinger" "Thermal"

$$\frac{dn_\kappa}{d^2p_\perp} \sim e^{-\pi m_\perp^2/\kappa^2}, \quad m_\perp = \sqrt{p_\perp^2 + m^2}\,. \quad \longrightarrow \quad \frac{dn}{d^2p_\perp} \sim \exp\left(-m_\perp\sqrt{\frac{2\pi}{\langle\kappa^2\rangle}}\right), \quad T = \sqrt{\frac{\langle\kappa^2\rangle}{2\pi}}\,.$$

$$P(\kappa)\,d\kappa = \sqrt{\frac{2}{\pi\langle\kappa^2\rangle}}\exp\left(-\frac{\kappa^2}{2\langle\kappa^2\rangle}\right)d\kappa\,, \qquad \langle\kappa^2\rangle = \int_0^\infty P(\kappa)\,\kappa^2\,d\kappa\,.$$

$$\frac{dn}{d^2p_\perp} \sim \int_0^\infty d\kappa\, P(\kappa)\, e^{-\pi m_\perp^2/\kappa^2} = \frac{\sqrt{2}}{\sqrt{\pi\langle\kappa^2\rangle}}\int_0^\infty d\kappa\, e^{-\kappa^2/2\langle\kappa^2\rangle} e^{-\pi m_\perp^2/\kappa^2} \sim \exp\left(-m_\perp\sqrt{\frac{2\pi}{\langle\kappa^2\rangle}}\right)$$

$$\int_0^\infty dt\, e^{-st}\frac{u}{2\sqrt{\pi t^3}}e^{-u^2/4t} = e^{-u\sqrt{s}}\,.$$

Vol. 35 (2004) ACTA PHYSICA POLONICA B No 2

SCHWINGER TUNNELING AND THERMAL CHARACTER OF HADRON SPECTRA

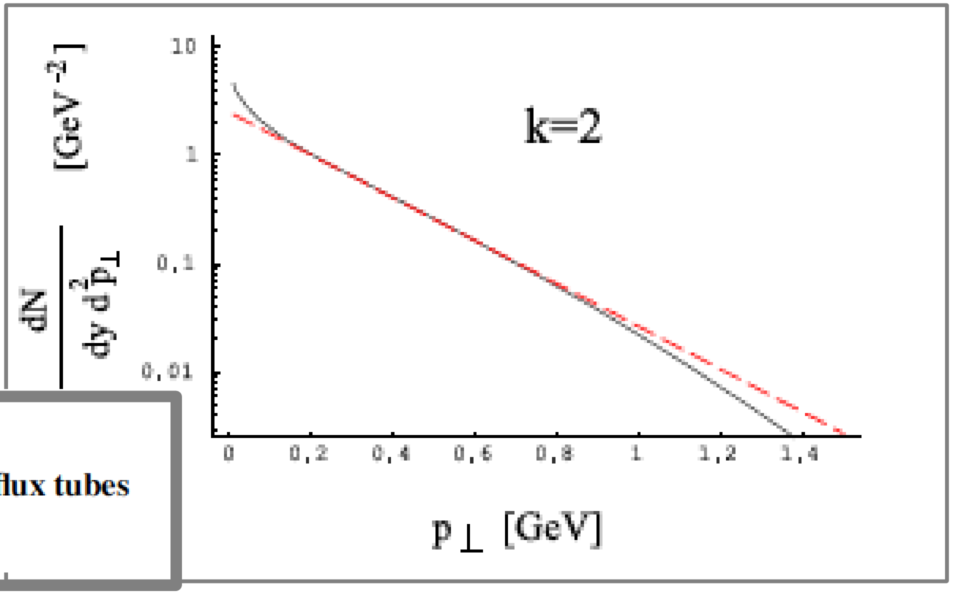
WOJCIECH FLORKOWSKI

$$\left(p^\mu \partial_\mu \pm g\epsilon_i \cdot F^{\mu\nu} p_\nu \partial^p_\mu\right) G^\pm_i(x,p) = \frac{dN^\pm_i}{d\Gamma},$$

$$\frac{dN}{d\Gamma} = p^0 \frac{dN}{d^4x\, d^3p} = \frac{F}{4\pi^3}\left|\ln\left(1\mp\exp\left(-\frac{\pi p_\perp^2}{F}\right)\right)\right|\delta\left(w-w_0\right)v\,, \qquad w_0 = -\frac{p_\perp^2}{2F}\,,$$

$$\frac{dN}{dy\,d^2p_\perp} = \int d^4x \frac{dN}{d\Gamma} = \pi R^2 \int\limits_0^\infty d\tau'\,\tau' \int\limits_{-\infty}^{+\infty} d\eta\, \mathcal{R}(\tau',p_\perp)\delta\left(w\mp w_0\right)v = \pi R^2 \int\limits_0^\infty d\tau'\,\tau'\,\mathcal{R}(\tau',p_\perp)\,,$$

$$\frac{dN}{dy\,d^2p_\perp} = \frac{R^2}{4\pi^2} \sum_{\text{all partons}} \int\limits_0^\infty d\tau'\,\tau'\,F(\tau')\left|\ln\left(1\mp\exp\left(-\frac{\pi p_\perp^2}{F(\tau')}\right)\right)\right|.$$



PHYSICAL REVIEW D 88, 034028 (2013)

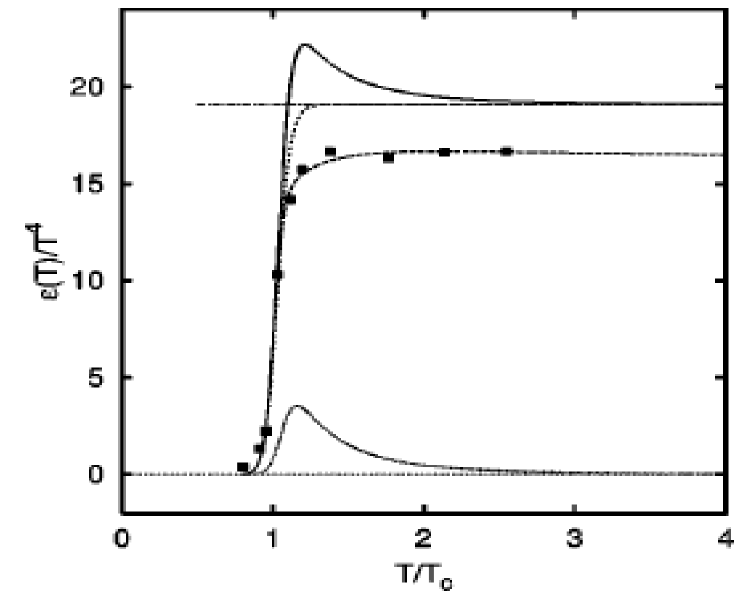
Equilibration of anisotropic quark-gluon plasma produced by decays of color flux tubes

Radoslaw Ryblewski[1,*] and Wojciech Florkowski[1,2,†]

PHYSICAL REVIEW C VOLUME 57, NUMBER 6 JUNE 1998

Transport theory with self-consistent confinement related to the lattice data

P. Bożek,* Y. B. He, and J. Hüfner

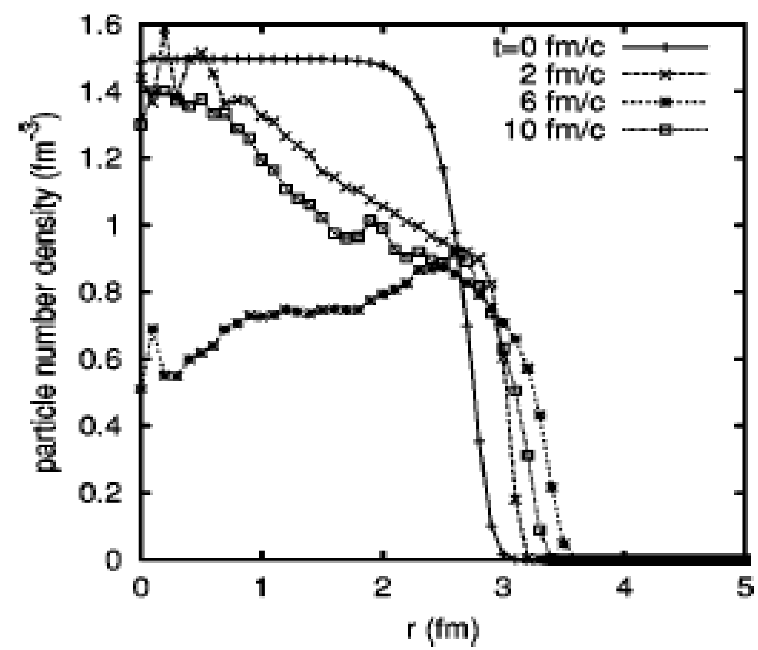


Define mean field V[{m(T)}] so that $\epsilon_{qp}(T)=\epsilon_{lat}(T)$.

$$\epsilon_{qp}(T)=\sum_i g_i\int\frac{d^3p}{(2\pi)^3}E_i f_i(E_i)+V(T)$$
$$=\epsilon_{kin}(m,T)+V(T),$$

Vlasov Equation for phase space distribution function:

$$\partial_t f(x,t,p)+\frac{p}{E(p,x,t)}\nabla_x f(x,t,p)$$
$$-\frac{m(x,t)}{E(p,x,t)}\nabla_x m(x,t)\nabla_p f(x,t,p)=0.$$



Gap equation for space-time dependent mass m(x,t)

$$\frac{dV}{dm}=-g\int\frac{d^3p}{(2\pi)^3}\frac{m(x,t)}{E(p,x,t)}f(x,t,p)=-\rho(x,t).$$

Physics of Particles and Nuclei, 2008, Vol. 39, No. 7, pp. 1116–1118.

Low Momentum π-Meson Production from Evolvable Quark Condensate¶

A. V. Filatov[a], A. V. Prozorkevich[a], S. A. Smolyansky[a], and D. B. Blaschke[b]

Time-dependent mass at chiral transition

$$\omega_\sigma(\mathbf{p}, t) = \sqrt{m_\sigma^2(T(t)) + \mathbf{p}^2}$$

Generates a source term

$$I_\sigma^{\rm vac}(\mathbf{p}, t) = \frac{1}{2}\Delta_\sigma(\mathbf{p}, t)\int_{t_0}^{t} dt'\Delta_\sigma(\mathbf{p}, t') \times[1 + 2f_\sigma(\mathbf{p}, t')]\cos[2\theta_\sigma(\mathbf{p}; t, t')],$$

where

$$\Delta_\sigma(\mathbf{p}, t) = \frac{\dot\omega_\sigma(\mathbf{p}, t)}{\omega_\sigma(\mathbf{p}, t)} = \frac{m_\sigma(t)\dot m_\sigma(t)}{\omega_\sigma^2(\mathbf{p}, t)},$$

$$\theta_\sigma(\mathbf{p}; t, t') = \int_{t'}^{t} dt''\omega_\sigma(\mathbf{p}, t''),$$

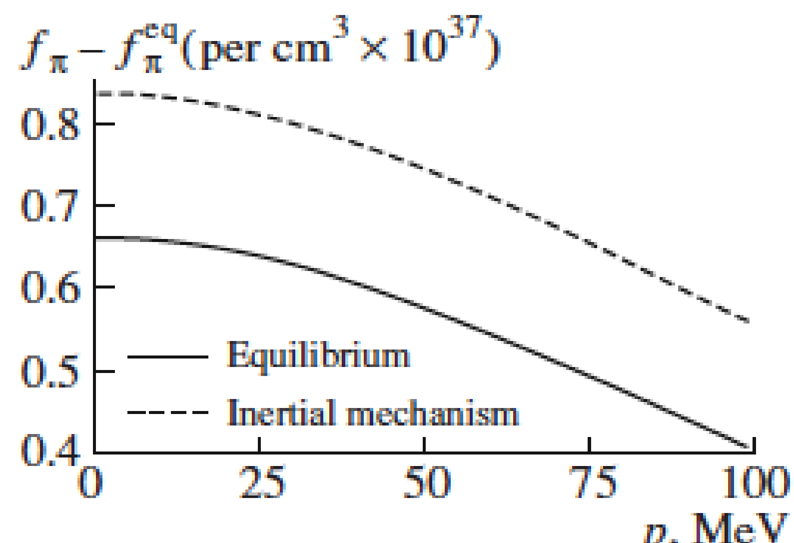
in Kinetic equation for the pion-sigma system

$$\dot f_\alpha = I_\alpha^{\rm vac} + I_\alpha^{\sigma\to\pi\pi} + I_\alpha^{\rm ex}$$

Detailed balance: Loss <--> Gain ...
Bose enhancement for pion distribution!

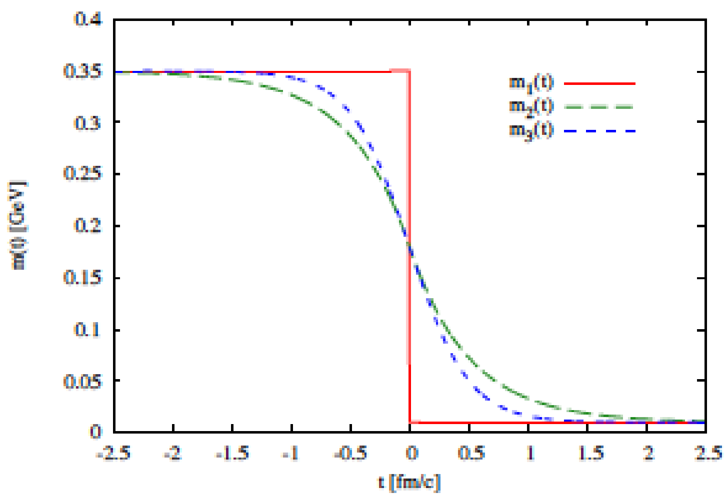
$$I_\sigma^{\rm loss}(\mathbf{p}, t) = -\int\frac{d\mathbf{p}_1 d\mathbf{p}_2}{\omega_\pi(\mathbf{p}_1, t)\omega_\pi(\mathbf{p}_2, t)}\Gamma_{\sigma\to\pi\pi}(\mathbf{p}, \mathbf{p}_1, \mathbf{p}_2; t) \times f_\sigma(\mathbf{p}, t)[1 + f_\pi(\mathbf{p}_1, t)][1 + f_\pi(\mathbf{p}_2, t)] \times\delta\{\omega_\sigma(\mathbf{p}, t) - \omega_\pi(\mathbf{p}_1, t) - \omega_\pi(\mathbf{p}_2, t)\} \times\delta(\mathbf{p} - \mathbf{p}_1 - \mathbf{p}_2), \quad (4)$$

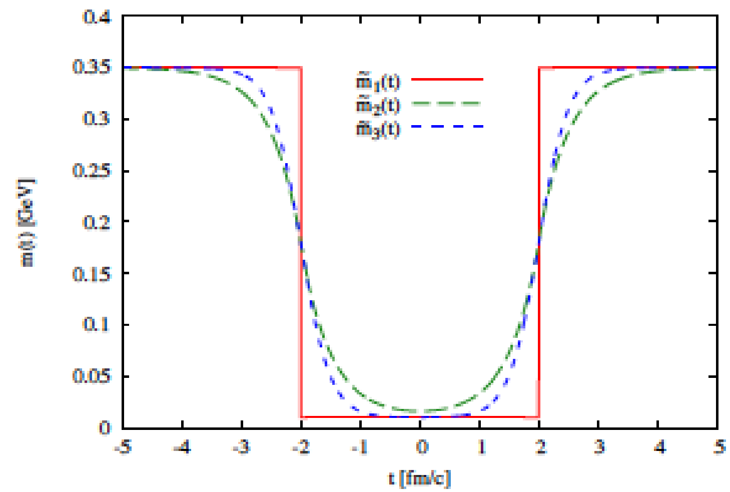
$$I_\sigma^{\rm loss}(t) = \pi\left[\frac{4p_{\rm tr}(t)}{m_\sigma(t)}\right]^3\Gamma_{\sigma\to\pi\pi}(p_{\rm tr}, t)[1 + f_\pi(p_{\rm tr}, t)]^2$$



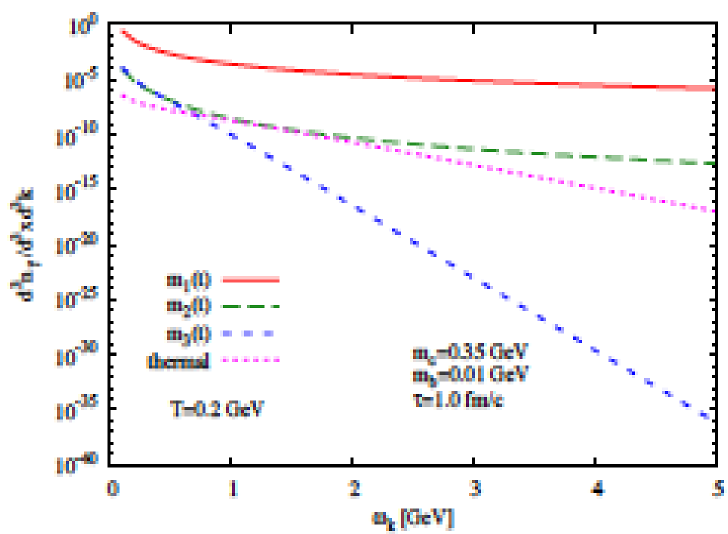
Off-equilibrium photon production during the chiral phase transition

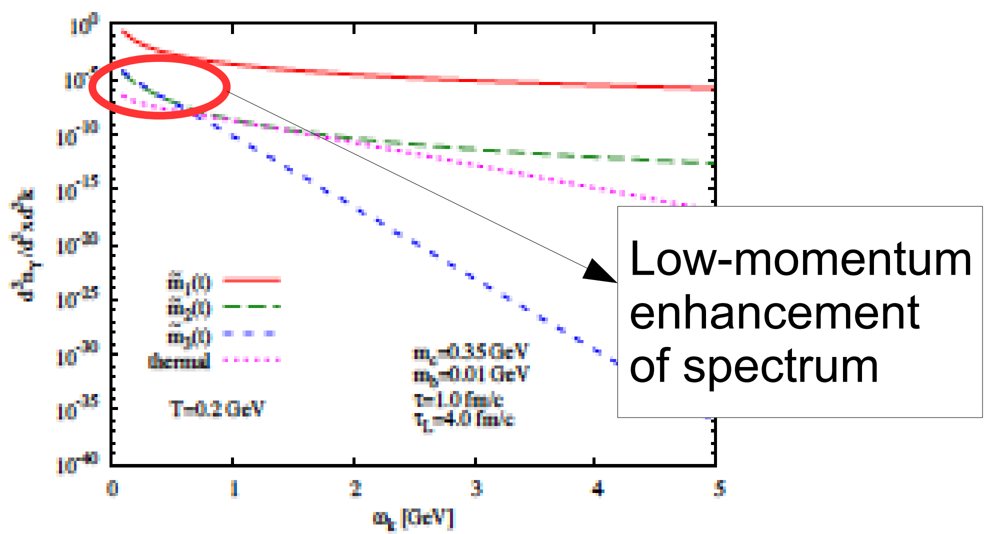
Time dependence of quark mass during chiral transition $E_{\vec{p}}(t) = \sqrt{p^2 + m^2(t)}$





Nonequilibrium photon production by chiral transition vs. Thermal one

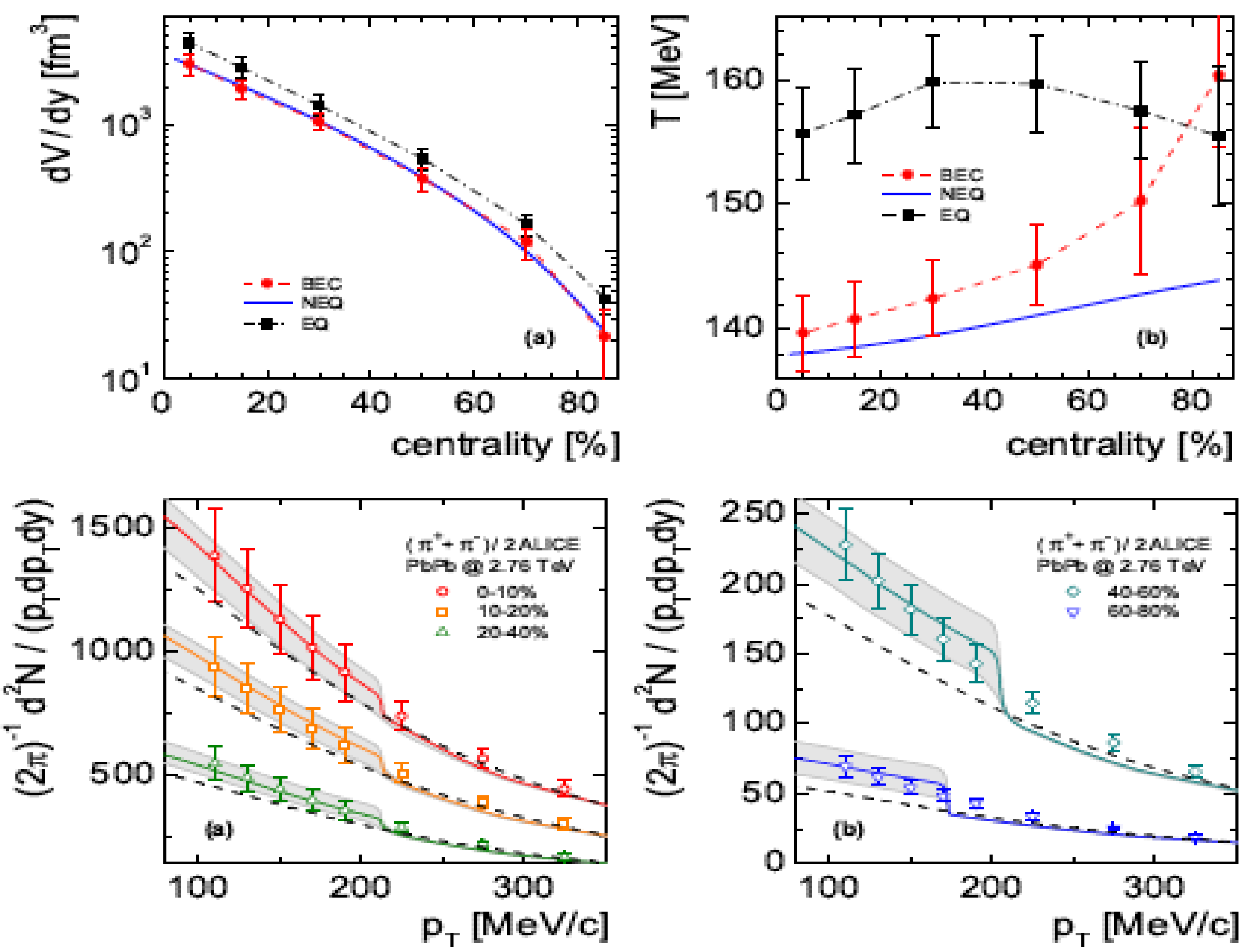




F. Michler, H. Van Hees, D.D. Dietrich, S. Leupold, C. Greiner, Ann. Phys. (2014) ; arxiv:1208.6565

Low-momentum pion enhancement at LHC - Onset of Bose-Einstein Condensation of pions ?

$$n = \int d^3p \, \frac{1}{(2\pi)^3} \frac{g}{\exp\left(\frac{\sqrt{p^2+m^2}-\mu}{T}\right) - 1} \left[1 + \frac{(2\pi)^3}{V} \delta(p_x)\, \delta(p_y)\, \delta(p_z) \right]$$



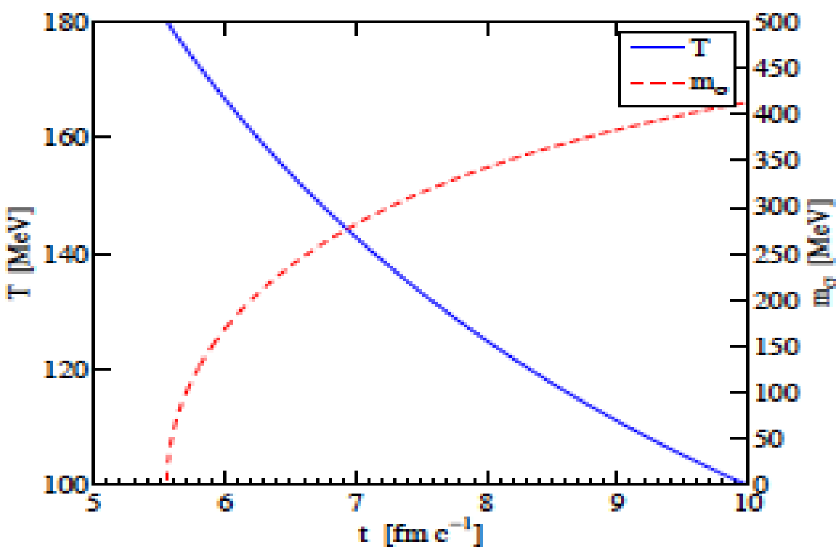
V. Begun, W. Florkowski, PRD (2015); arxiv:1503.04040

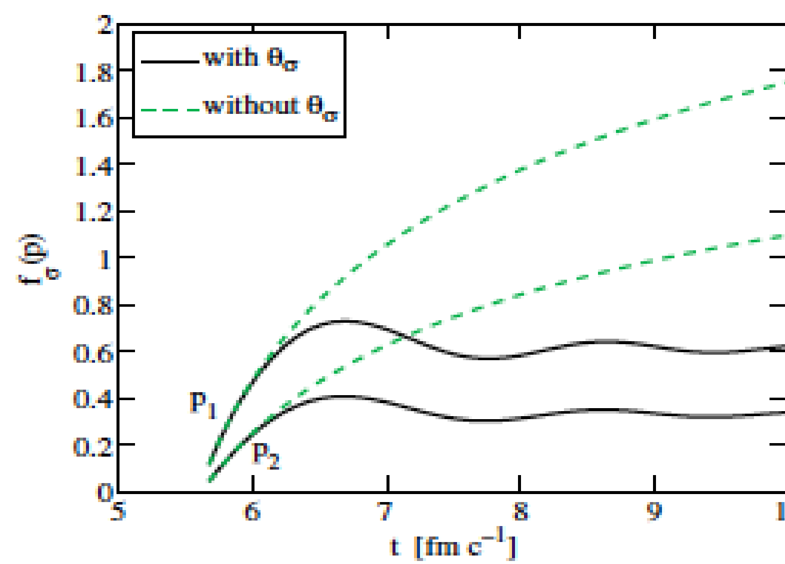
Low-momentum pion enhancement from quantum kinetics of chiral symmetry breaking

$$\frac{\partial f_\sigma}{\partial t}(t,\vec{p}_\sigma) = \left.\frac{df_\sigma}{dt}\right|_{\text{collisions}}$$
$$= \frac{\Delta_\sigma(t,\vec{p}_\sigma)}{2}\int_{t_0}^{t} dt'\,\Delta_\sigma(t',\vec{p}_\sigma)\,(1+f_\sigma(t',\vec{x},\vec{p}_\sigma))\cos\left(2\theta_\sigma(t,t',\vec{p}_\sigma)\right)$$
$$+ (1+f_\sigma(t,\vec{p}_\sigma))\left(\int\frac{d^3p_1}{(2\pi)^3 2w_1}\frac{d^3p_2}{(2\pi)^3 2w_2}\Gamma_{\pi\pi\to\sigma}(\vec{p}_\sigma,\vec{p}_1,\vec{p}_2)f_\pi(t,\vec{p}_1)f_\pi(t,\vec{p}_2)\right)$$
$$- f_\sigma(t,\vec{p}_\sigma)\left(\int\frac{d^3p_1}{(2\pi)^3 2w_1}\frac{d^3p_2}{(2\pi)^3 2w_2}\Gamma_{\sigma\to\pi\pi}(\vec{p}_\sigma,\vec{p}_1,\vec{p}_2)\,(1+f_\pi(t,\vec{p}_1))\,(1+f_\pi(t,\vec{p}_2))\right)$$

$$\frac{\partial f_\pi}{\partial t}(t,\vec{p}_1) = \left.\frac{df_\pi}{dt}\right|_{\text{collisions}}$$
$$= (1+f_\pi(t,\vec{p}_1))\left(\int\frac{d^3p_\sigma}{(2\pi)^3 2w_\sigma}\frac{d^3p_2}{(2\pi)^3 2w_2}\Gamma_{\sigma\to\pi\pi}(\vec{p}_\sigma,\vec{p}_1,\vec{p}_2)\,(1+f_\pi(t,\vec{p}_2))\,f_\sigma(t,\vec{p}_\sigma)\right)$$
$$- f_\pi(t,\vec{p}_1)\left(\int\frac{d^3p_\sigma}{(2\pi)^3 2w_\sigma}\frac{d^3p_2}{(2\pi)^3 2w_2}\Gamma_{\pi\pi\to\sigma}(\vec{p}_\sigma,\vec{p}_1,\vec{p}_2)f_\pi(t,\vec{p}_2)\,(1+f_\sigma(t,\vec{p}_\sigma))\right).$$

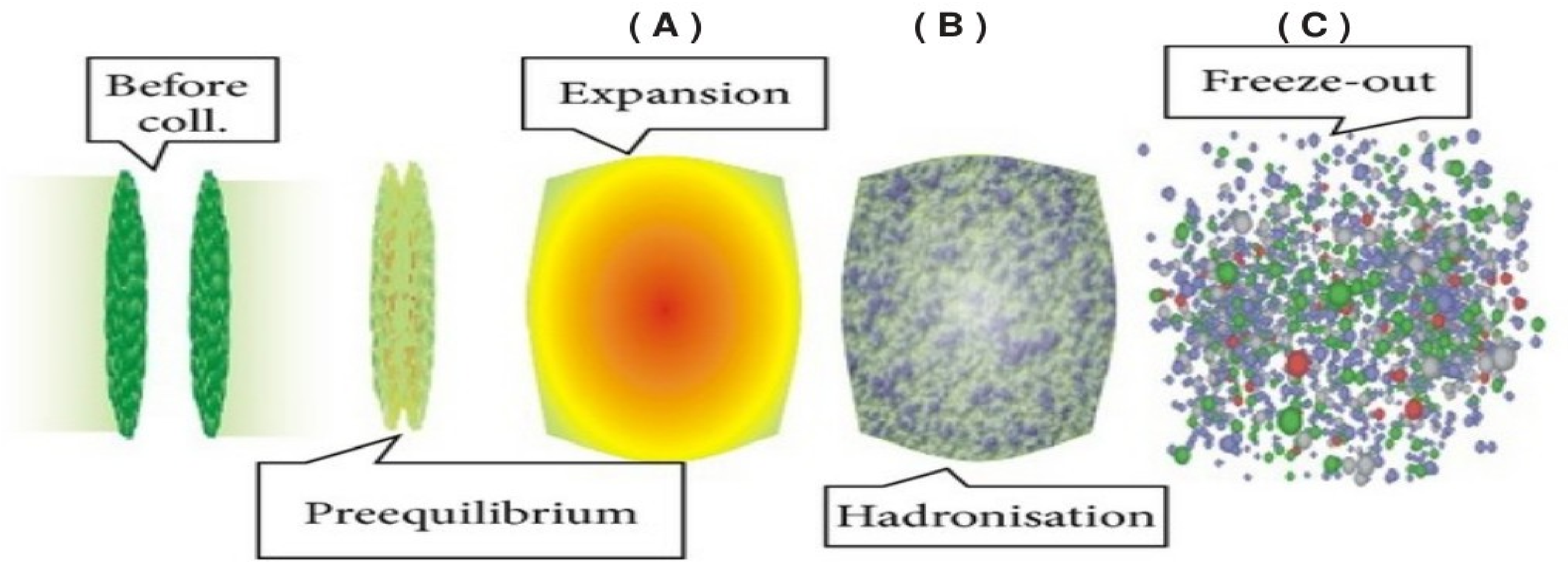
$$\Delta_\sigma(t,\vec{p}_\sigma) = \frac{m_\sigma}{w_\sigma^2}\frac{\partial m_\sigma}{\partial t},$$
$$\theta_\sigma(t,t',\vec{p}_\sigma) = \int_{t'}^{t} dt''\,w_\sigma(t'',\vec{p}_\sigma)$$





L. Juchnowski, D. Blaschke, T. Fischer,
in preparation (2015)

Quantum Kinetics of Particle Production in Strong Fields

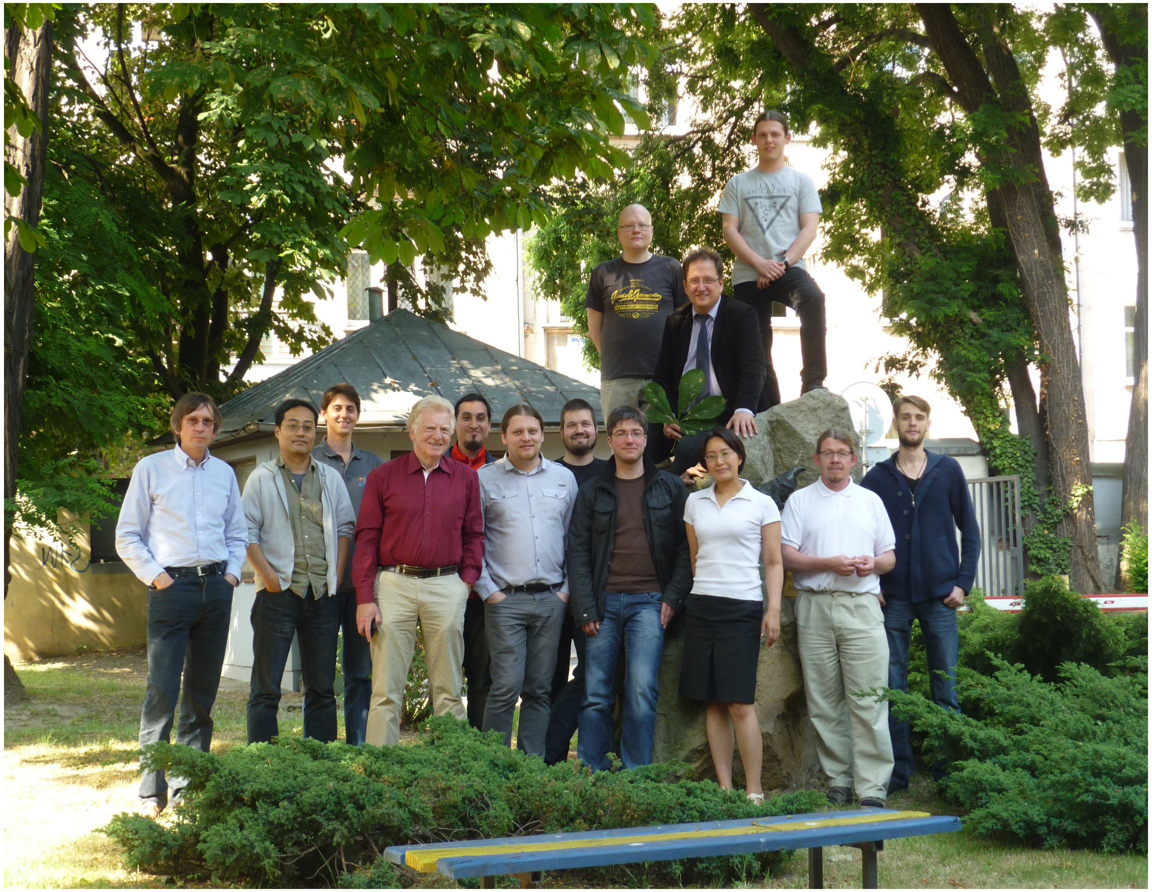


Generic kinetic equation with scalar (mass) and color meanfields, Schwinger source terms and collision integrals for hadronization and rescattering

$$\left[\partial_t + \frac{1}{E_X}\vec{p}\cdot\vec{\nabla} - \frac{m_X(\vec{x},t)}{E_X}\vec{\nabla}m_X(\vec{x},t)\cdot\vec{\nabla}_p + \vec{F}(\vec{x},t)\cdot\vec{\nabla}_p\right] f_X(\vec{p},\vec{x};t)$$
$$= S_X^{\rm Schwinger}\{f_q, f_{\bar{q}}, f_\pi, \ldots\} + C_X^{\rm gain}\{f_q, f_{\bar{q}}, f_\pi, \ldots\} - C_X^{\rm loss}\{f_q, f_{\bar{q}}, f_\pi, \ldots\}$$

(A) quark-antiquark pair creation in time-dependent color electric background field
(B) quantum kinetics of pre-hadron inelastic rescattering in the dense quark plasma
(C) chemical freeze-out by Mott-Anderson localization of bound states

Division: Theory of Elementary Particles



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Mark Kaltenborn
Maciej Lewicki
Michał Naskręt
Michał Szymański

+many visitors from 4 continents

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Maestro (2), Opus (4), Sonata (1)

Main research topics:

- Quantum field theory under extreme conditions
- Physics of ultra-relativistic heavy-ion collisions
- Physics of compact stars and supernovae

Publications in 2010-2015: 241 (98 with ALICE Collab.)

Division: Theory of Elementary Particles - Collaborations