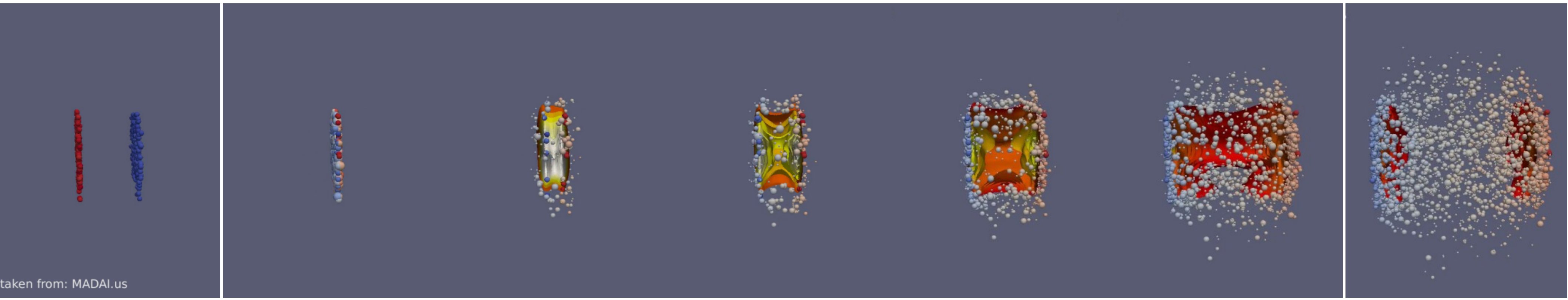
Particle Production in Strong Time-dependent Fields

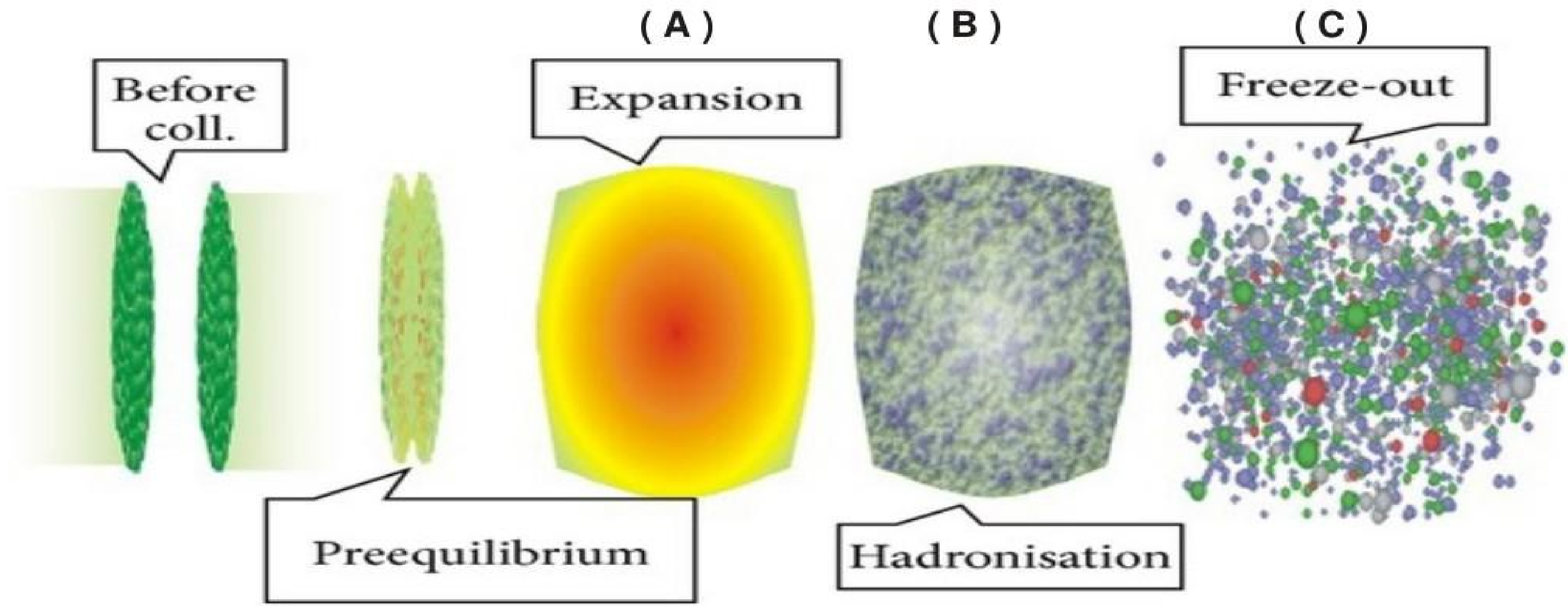
David Blaschke (Uni Wroclaw, Poland & JINR Dubna & MEPhI, Russia)



Winter College on
"Extreme Non-linear Optics, Attosecond Science and High-field Physics"

ICTP Trieste (Italy), February 5-16, 2018

Particle Production in Strong, Time-dependent 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

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Particle Production in Strong, Time-dependent Fields

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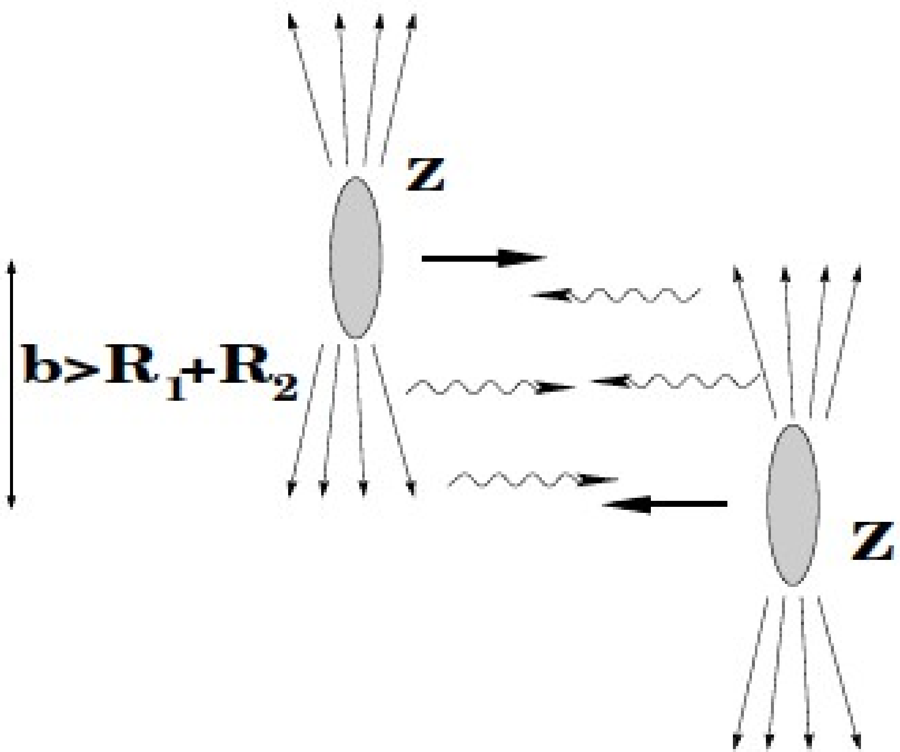
Contents of this Lecture:

1. Introduction to Schwinger formula: Elementary; WKB; Kinetic equation
2. Derivation of kinetic equation
3. Applications for time-dependent (laser) fields
   - Sauter pulse
   - Gaussian envelope harmonic pulse
   - E^2 rule for weak fields
4. “Pump&Probe” the vacuum: Bifrequent fields
5. Schwinger effect & Hawking-Unruh radiation in heavy-ion collisions

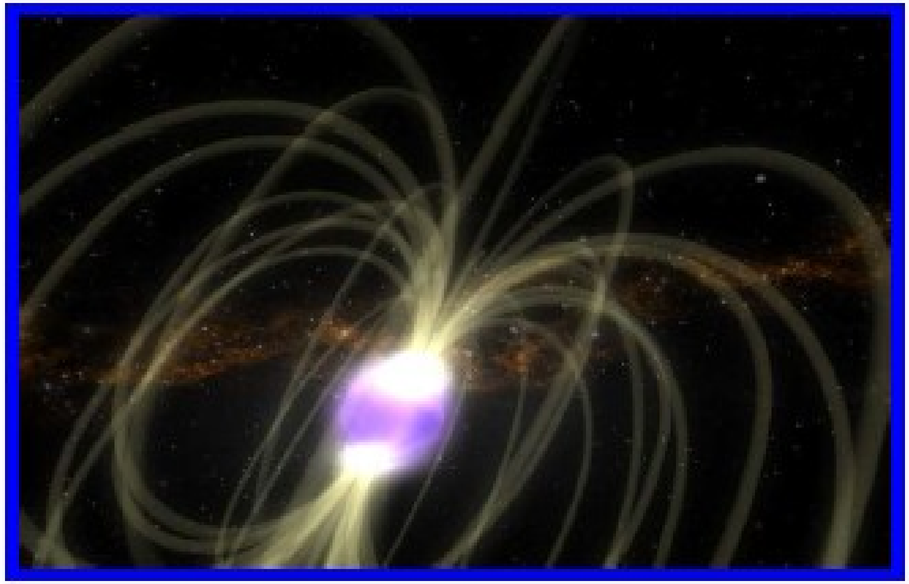
DUBNA JINR Joint Institute for Nuclear Research
HELMHOLTZ ASSOCIATION
cost EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY
comp star
MEPhI National Research Nuclear University • Moscow Engineering Physics Institute • MEPhI
HIC for FAIR Helmholtz International Center
NARODOWE CENTRUM NAUKI
Uniwersytet Wrocławski

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



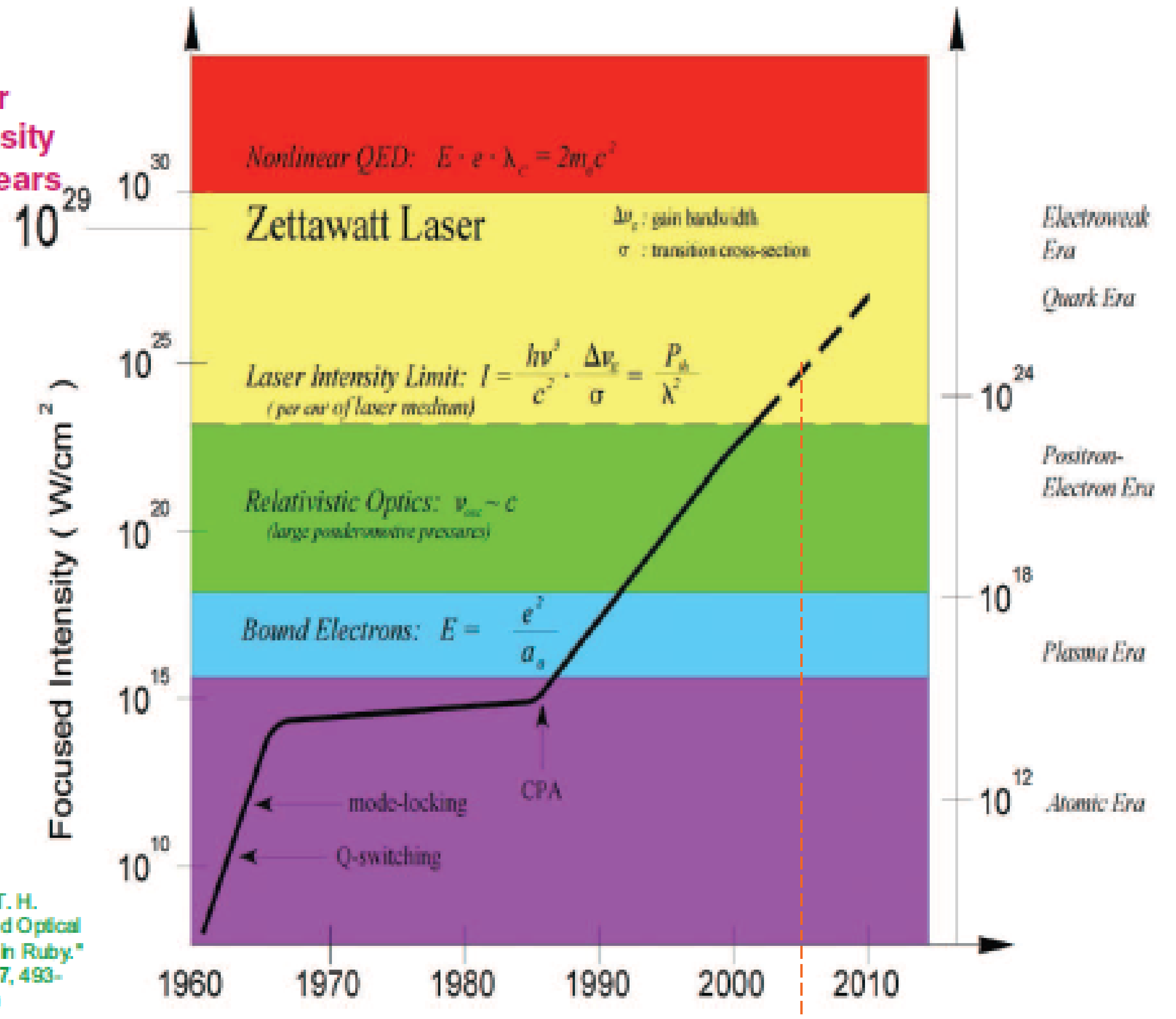
Artist view of a Magnetar (NASA)

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



Maiman, T. H. "Stimulated Optical Radiation in Ruby." *Nature* 187, 493-494, 1960

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

Bahk, et al., Opt. Lett. 29, 2837 (2004)

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

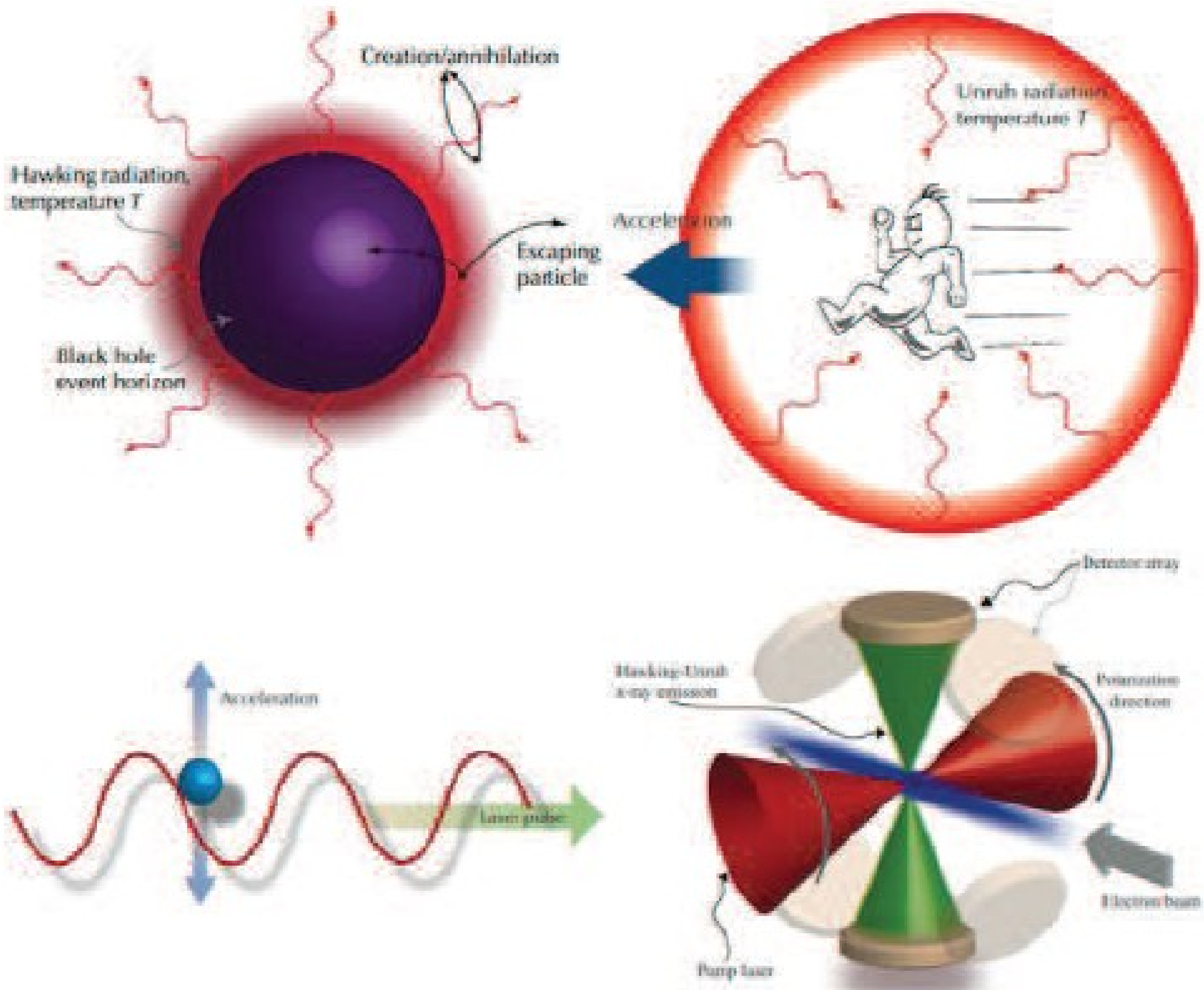
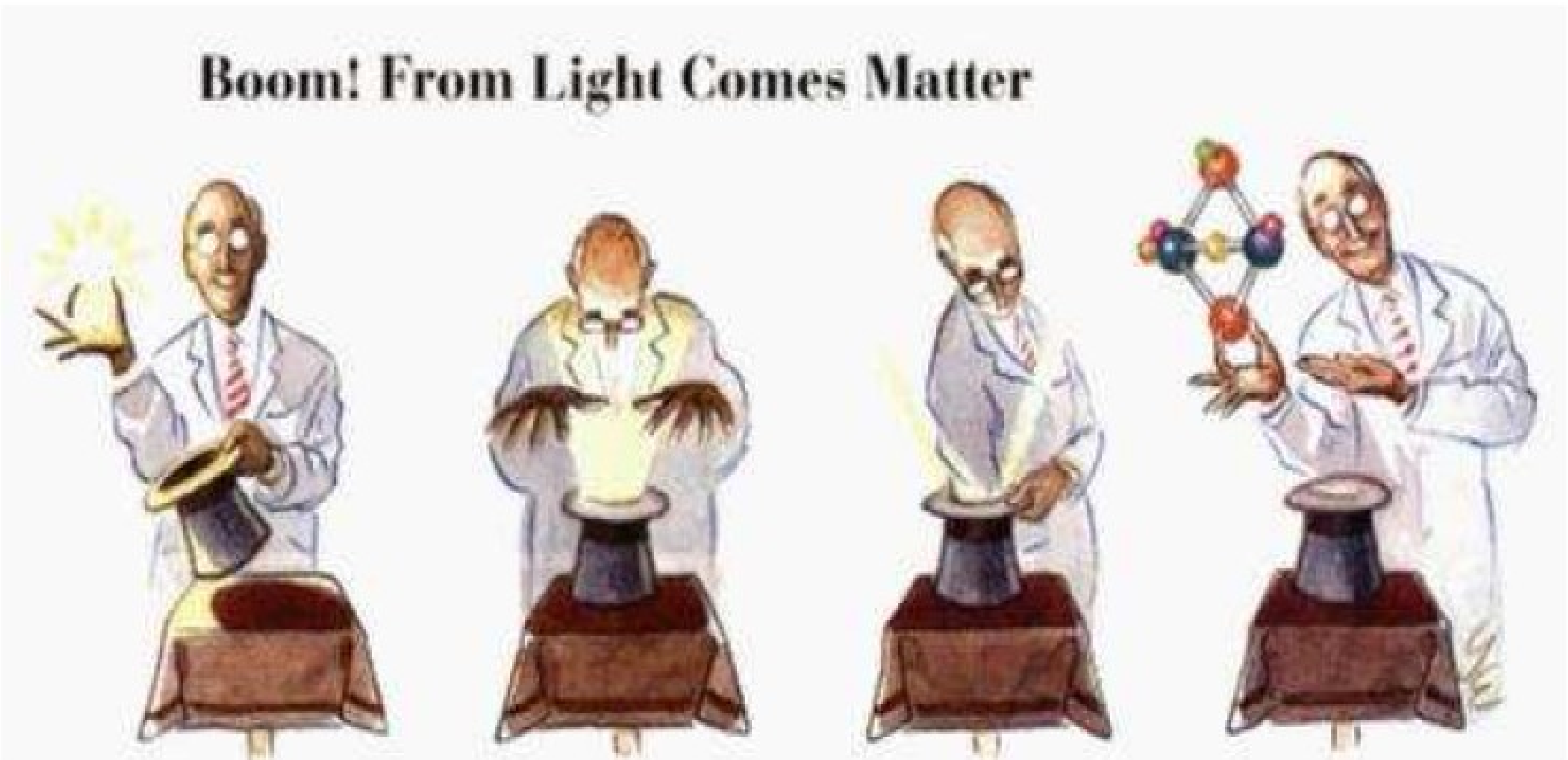


FIG. 7: The schematics of the experimental setup for Unruh radiation detection. Note than the radiation is emitted in a very particular direction as well as frequency, thus being detectable even if the background "noise" is high.

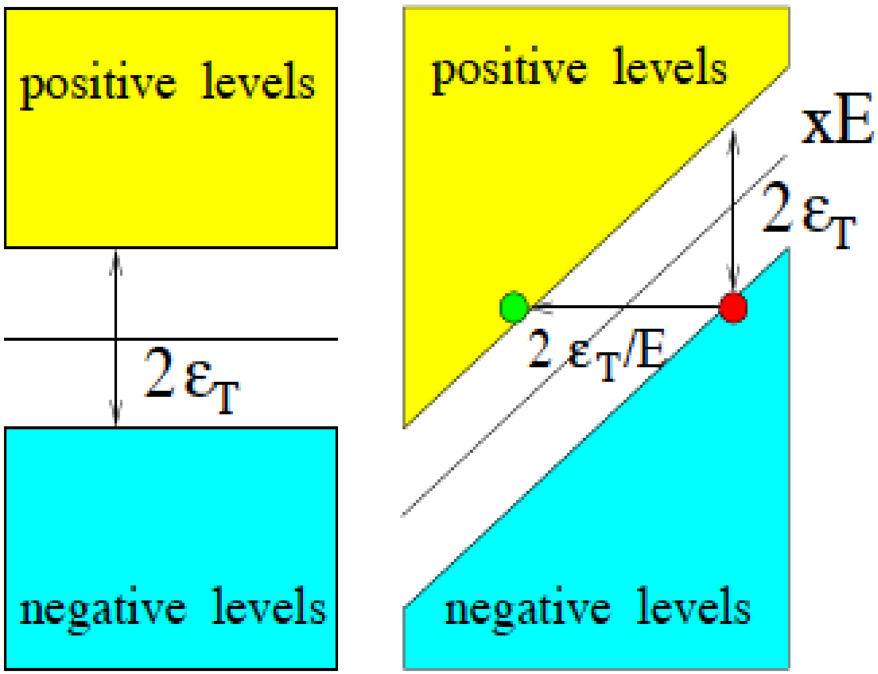
R. Schutzhold, G. Schaller, D. Habs,
"Signatures of the Unruh Effect from Electrons Accelerated by Ultrastrong Laser Fields"
Phys. Rev. Lett. 97 (2006) 121302

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

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

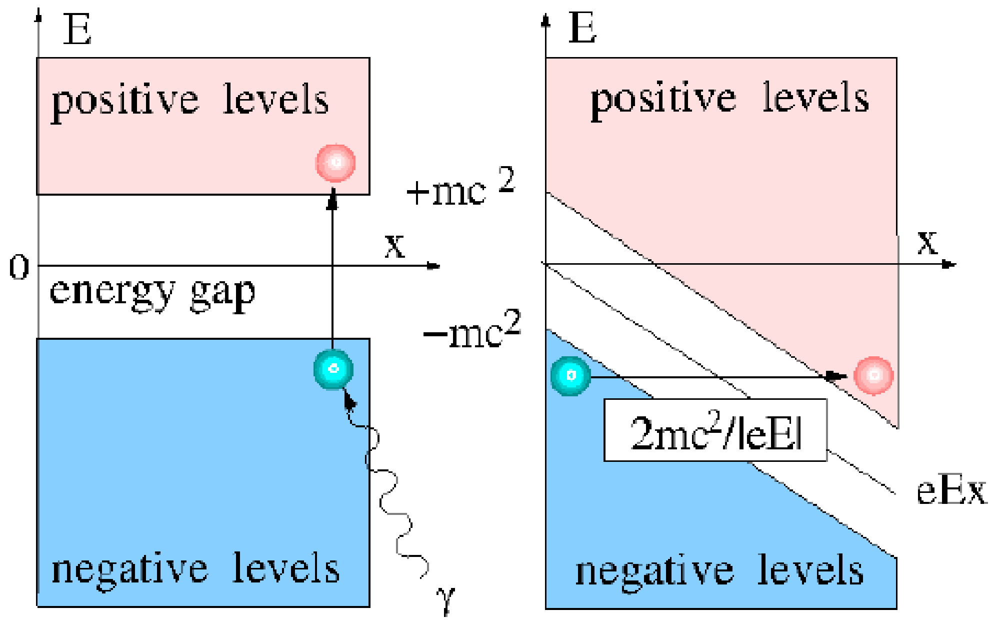
- Emission sufficient for observation when $E \sim E_{\rm crit}$

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

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

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

Schwinger effect in WKB approximation



Relativistic dispersion $\varepsilon = c\sqrt{m^2c^2 + \bar{p}^2}$

In an external field

$$\left(\varepsilon - |e|E_0 x\right)^2 = c^2\left(m^2c^2 + p^2(x)\right)$$

Probability for tunneling (Gamov)

$$w \sim \exp\left\{-\frac{2}{\hbar} i \int_{x_2}^{x_1} dx p(d)\right\}$$

Turning points in p(x) for given E_0:

$$x_1 = \left(\varepsilon - mc^2\right)/\left(|e|E_0\right), \quad x_2 = \left(\varepsilon + mc^2\right)/\left(|e|E_0\right)$$

Probability for tunneling process (without prefactor)

$$w \sim \exp\left\{-\frac{4m^2c^3}{|e|\hbar E_0}\int_0^1 ds\sqrt{1-s^2}\right\} = \exp\left\{-\frac{\pi m^2c^3}{|e\hbar E_0|}\right\}$$

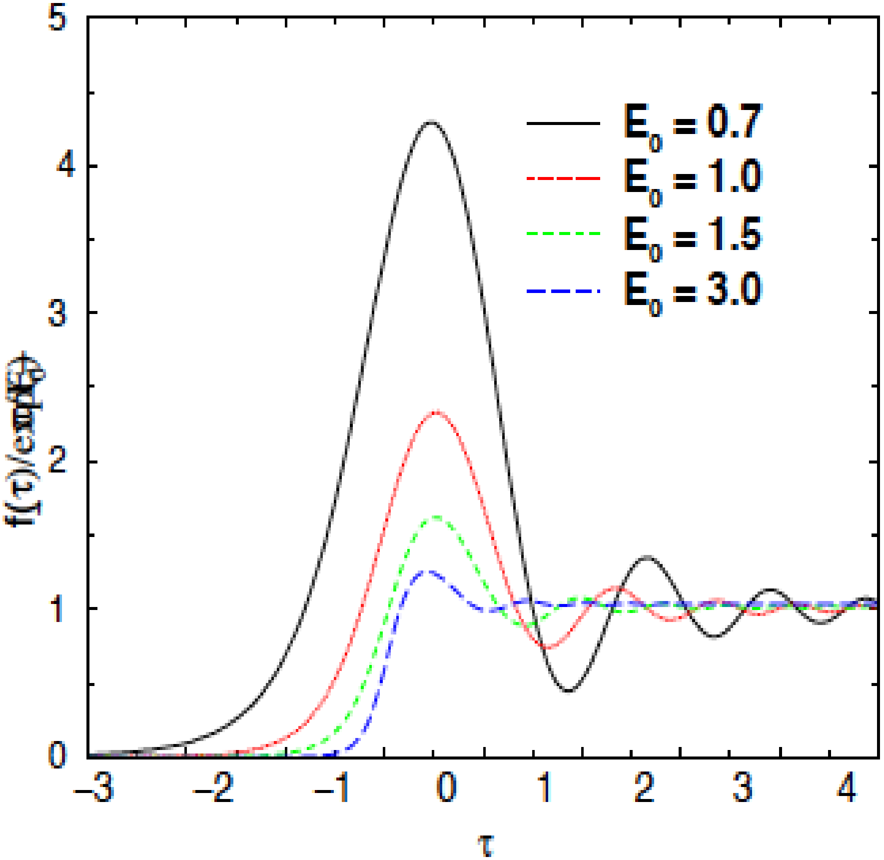
Schwinger formula (basic mode, n=0)

$$w = \frac{ce^2E_0^2}{4\pi^3\hbar^2}\exp\left\{\frac{\pi m^2c^3}{|e|\hbar E_0}\right\} = \frac{ce^2E_0^2}{4\pi^3\hbar^2}\exp\left\{-\pi\frac{E_c}{E_0}\right\}$$

$E_c = m^2c^3/\hbar|e|$ … critical field strength (=1.3 10^18 V/m)

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 $\varepsilon_\perp = \sqrt{m^2 + \vec{p}_\perp^2}$ and $x(t',t) = 2[\Theta(t) - \Theta(t')]$.

5

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

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 $|0_{\text{in}}\rangle$

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

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

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

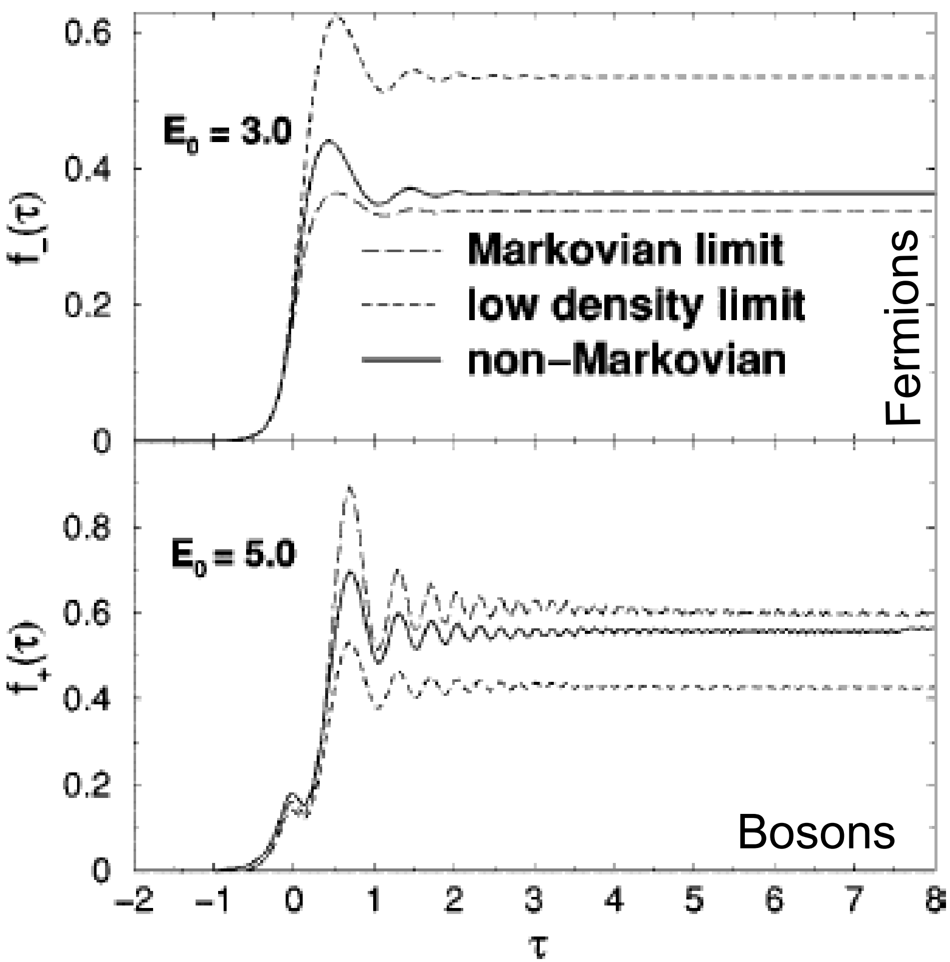
$$\varepsilon_\perp = \sqrt{m^2+q_\perp^2}$$

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

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



PHYSICAL REVIEW D, VOLUME 59, 094005

Markovian limit :

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

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

Low-density limit :

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

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

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

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

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

Understanding the Dynamical Schwinger Process: E^2 - rule

Low-density limit, p=0, low external field eA(t) << m:

$W_-(t) = e\,E(t)\,\varepsilon_T / \varepsilon^2(p,t) \rightarrow e\,E(t) / m$

$\Theta(t) = \int_{t'}^{t} d\tau\, \varepsilon(\mathbf{p},\tau) \rightarrow m\,t$

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

$\rightarrow g^1_-(t) = [\,e\,E(t) / m\,]\ \cos(2mt)$

$\rightarrow g^2_-(t) = [\,e\,E(t) / m\,]\ \sin(2mt)$

Approximation that E(t) is suffciently slowly varying, then:

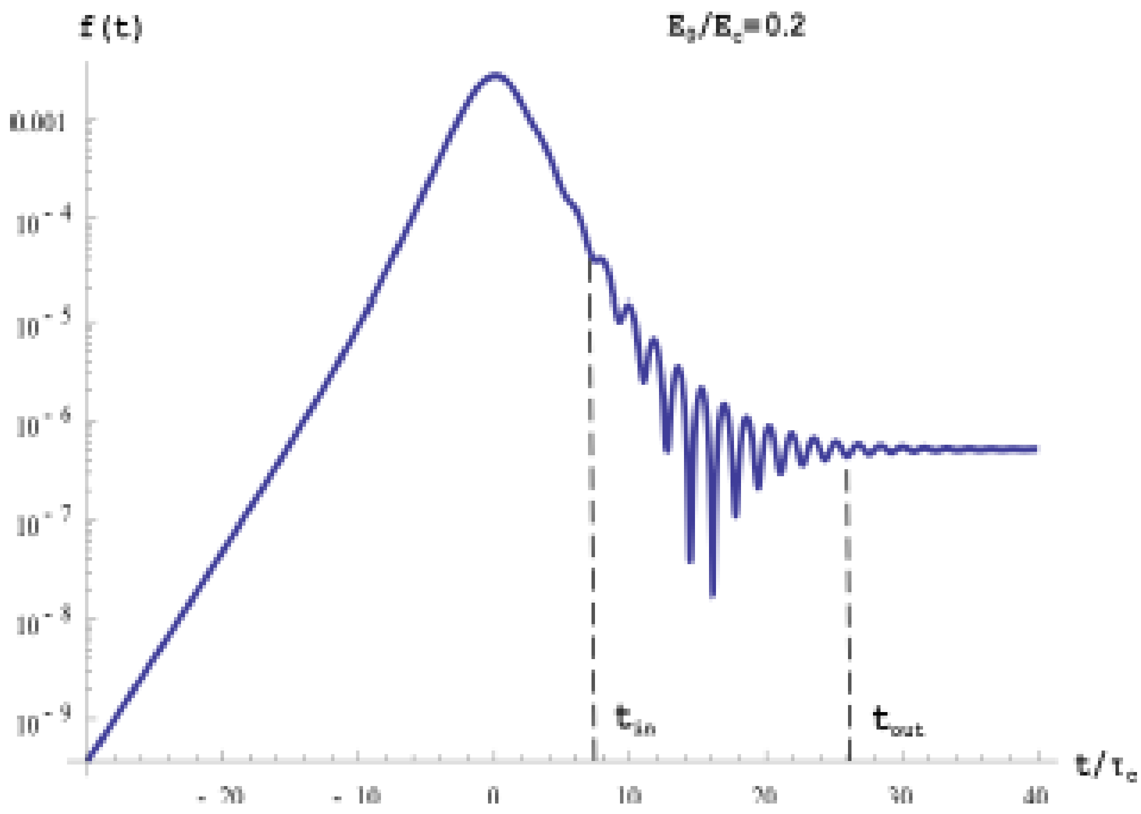
$$f_{\pm}^{0}(\tau) = \frac{1}{4}\left(\int_{-\infty}^{\tau} d\tau' g_{\pm}^{1}(\tau')\right)^2 + \frac{1}{4}\left(\int_{-\infty}^{\tau} d\tau' g_{\pm}^{2}(\tau')\right)^2.$$

$$= \tfrac{1}{4}\,[e\,E(t)/(2\,m^2)]^2\,[\sin^2(2mt) + \cos^2(2mt)]$$

$f_-(t) \rightarrow 1/16\,[e\,E(t)]^2 / m^4$

This rule holds when interference effects due to the dynamical phase can be neglected.
It is obviously violated at large times when the limit of the Schwinger formula is approached asymptotically
While the external field vanishes $E(t) \rightarrow 0$

Examples (quasi-particle and mass-shell stage)



- Sauter pulse

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

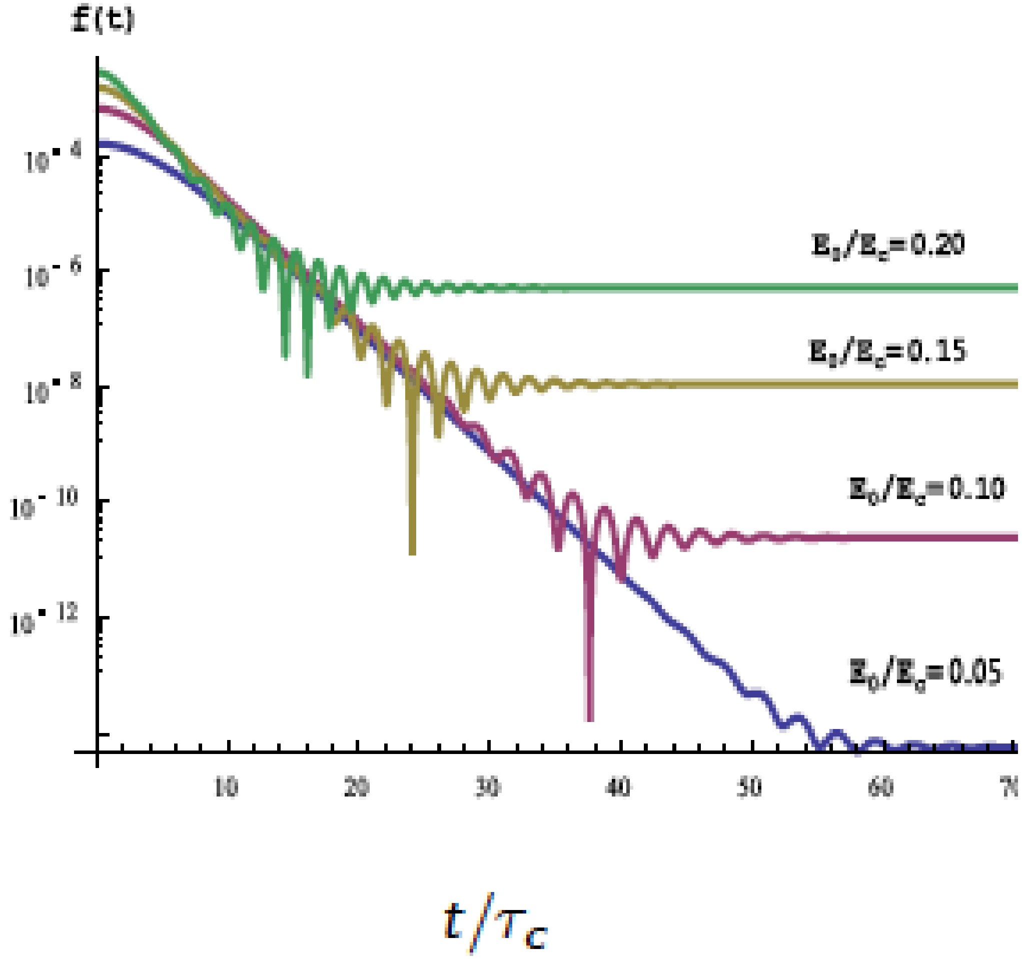
- $T = 0.02$nm
- $p_\perp = p_\parallel = 0$
- $[t_{in}, t_{out}]$ - transient region between quasi-particle and mass-shell stage

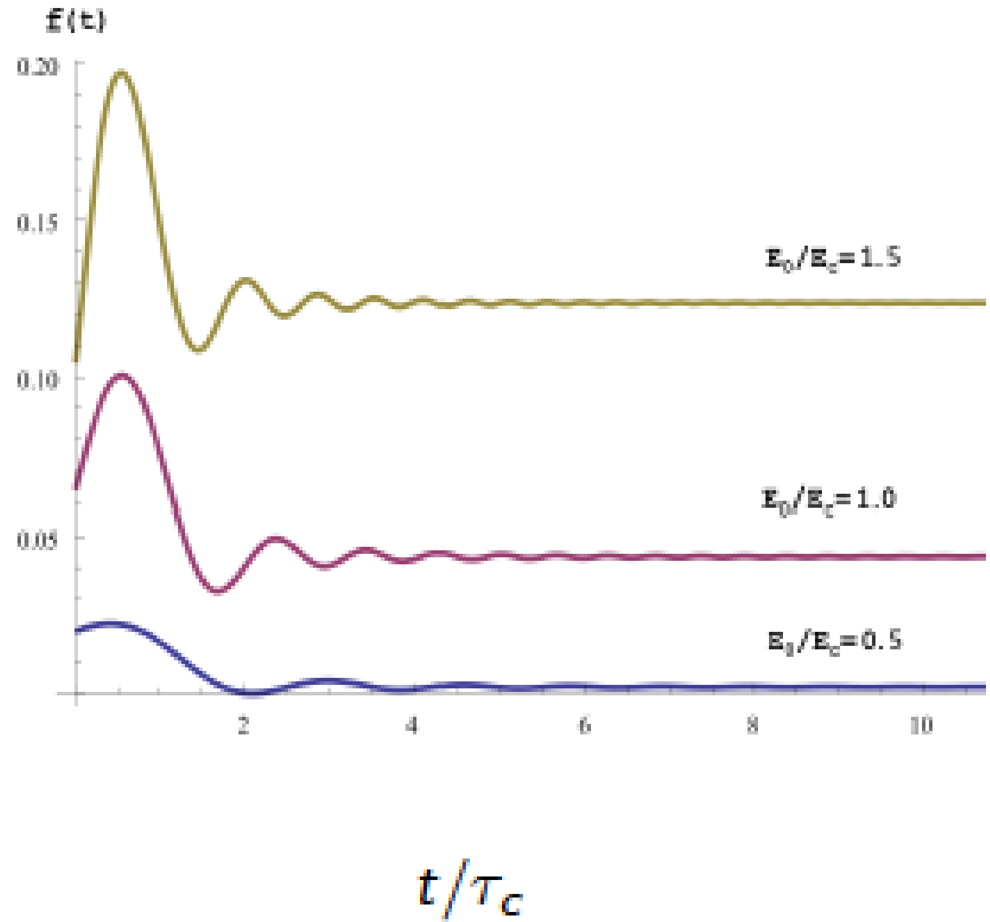
Dynamical Schwinger effect: Properties of the e^+e^- plasma created from vacuum in strong laser fields

Blaschke, Juchnowski , Panferov et al. arXiv:1412.6372

Examples (quasi-particle and mass-shell stage)

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



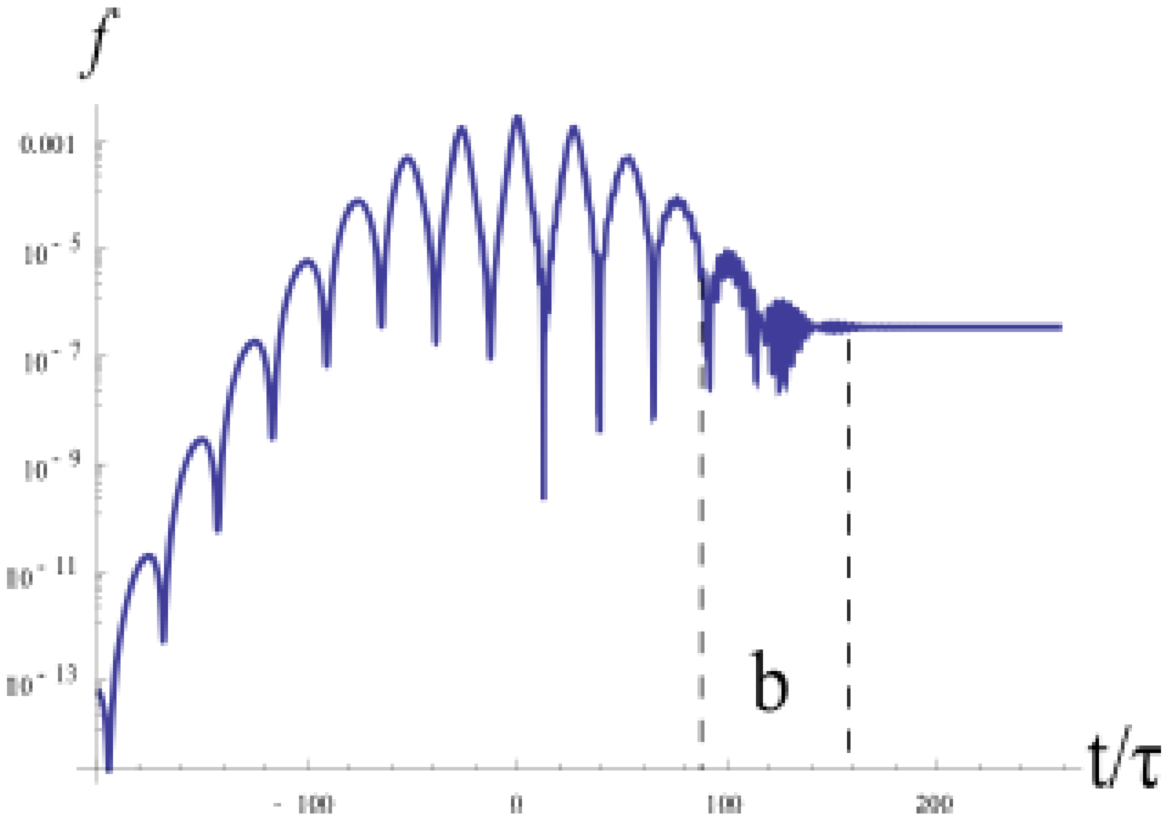


Dynamical Schwinger effect: Properties of the e^+e^- plasma created from vacuum in strong laser fields

Blaschke, Juchnowski , Panferov et al. arXiv:1412.6372

Examples (quasi-particle and mass-shell stage)

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



t/τ_c

$E_0 = 0.2 E_c$

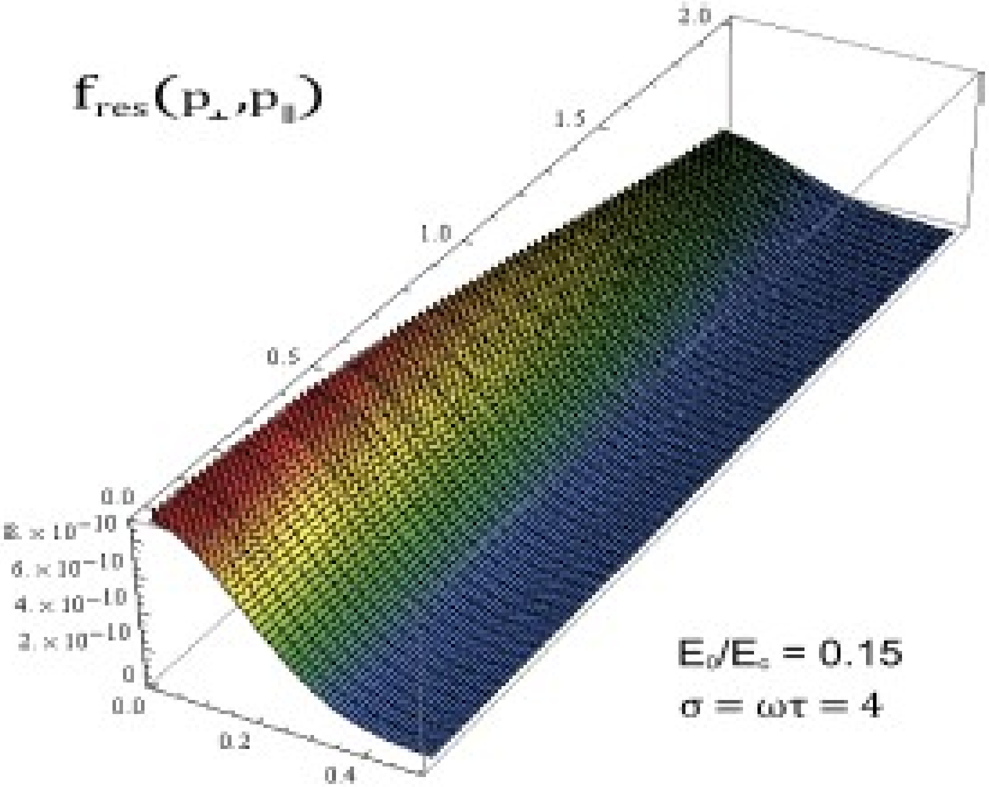
the region "b" corresponds to the transient process

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

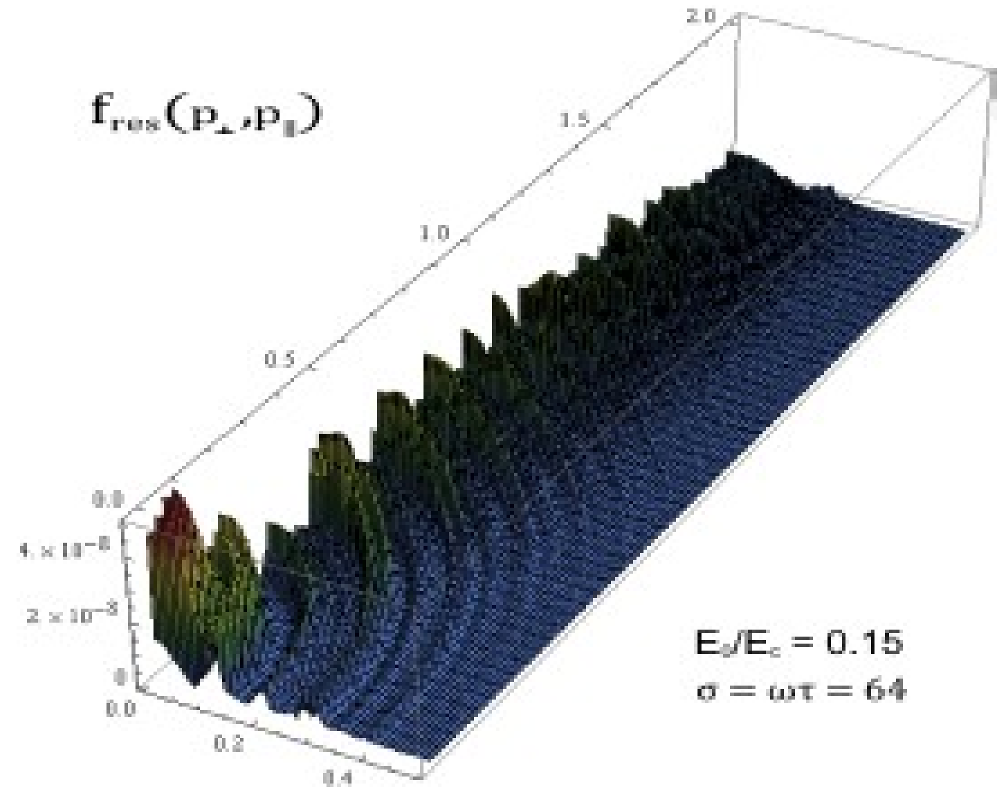
Blaschke, Juchnowski , Panferov et al. arXiv:1412.6372

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

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



Short pulse

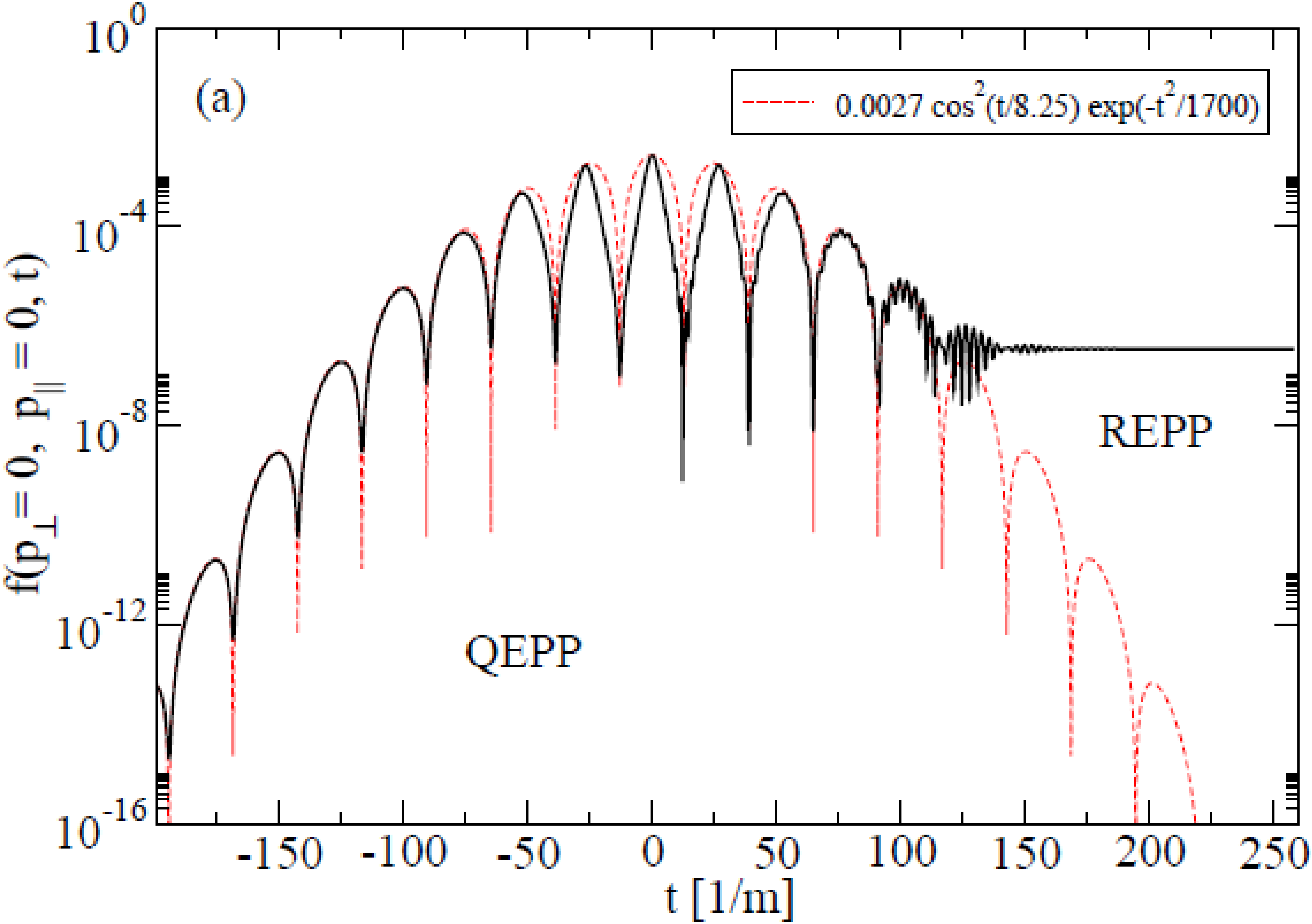


Long pulse

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

Blaschke, Juchnowski , Panferov et al. arXiv:1412.6372

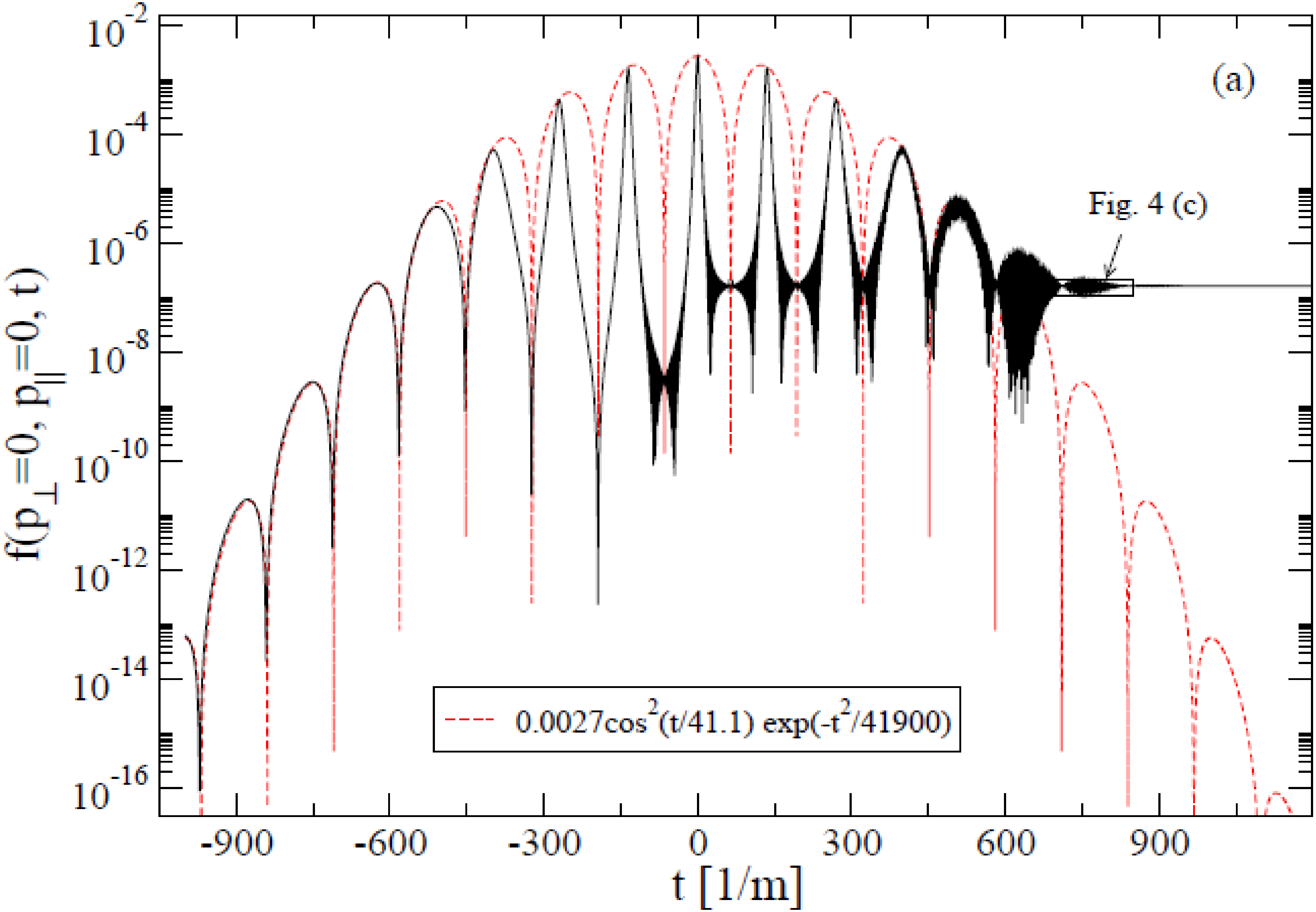
Gaussian envelope harmonic pulse vs. E^2 rule



$E_0 = 0.2E_c$, $\sigma = 5.0$ and wavelength 0.2 nm

S.A. Smolyansky et al., arxiv:1607.08775

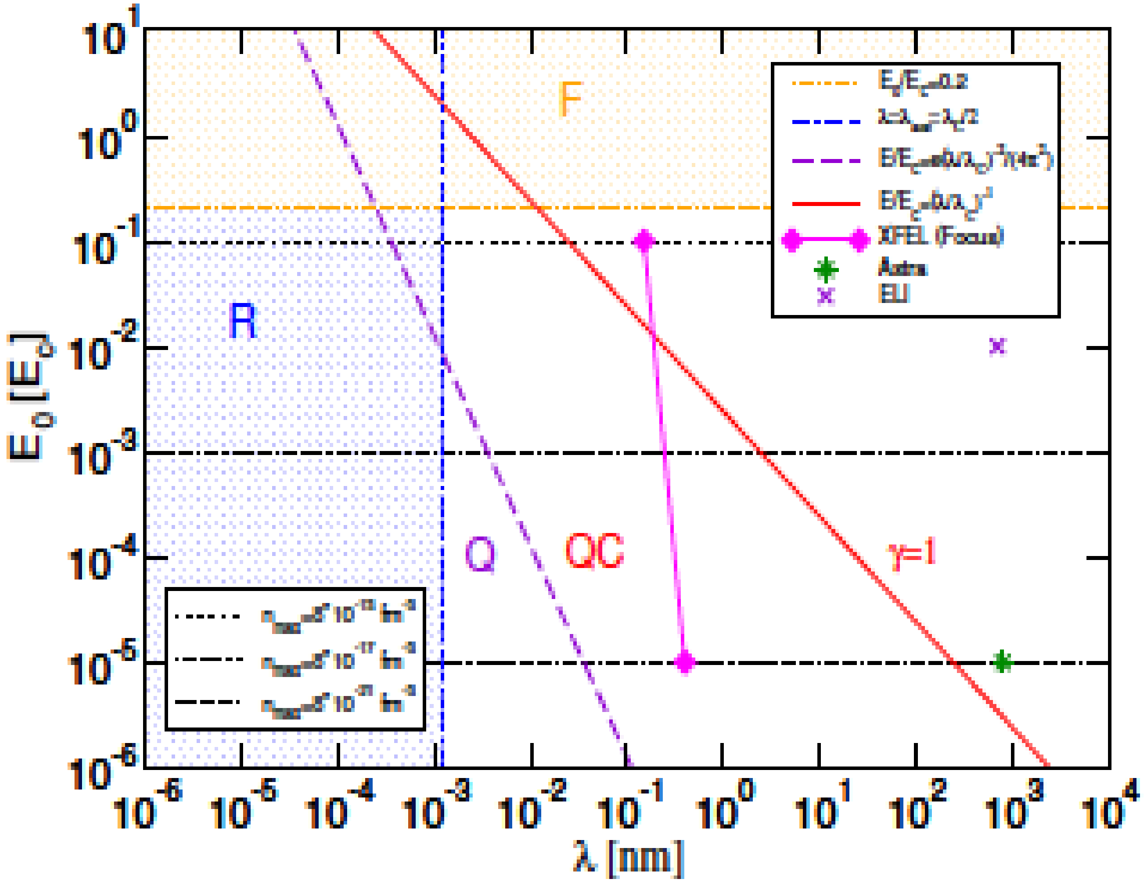
Gaussian envelope harmonic pulse vs. E^2 rule



$E_0 = 0.2E_c$, $\sigma = 5.0$ and wavelength 0.1 nm

S.A. Smolyansky et al., arxiv:1607.08775

Landscape



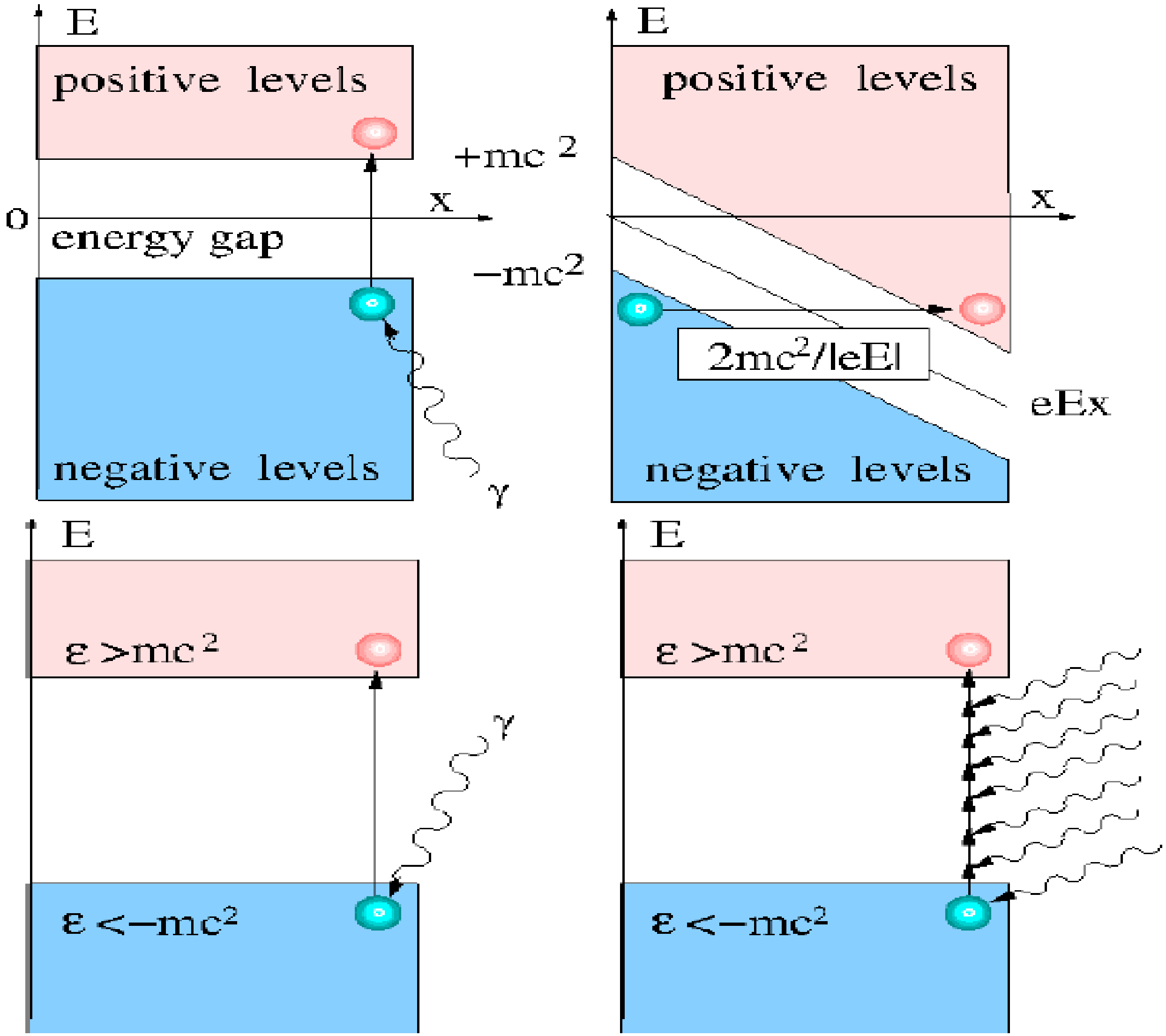
- Change of variables $(\omega, E) \to (\gamma, E)$
- Adiabaticity parameter

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

- 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)

Landscape



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

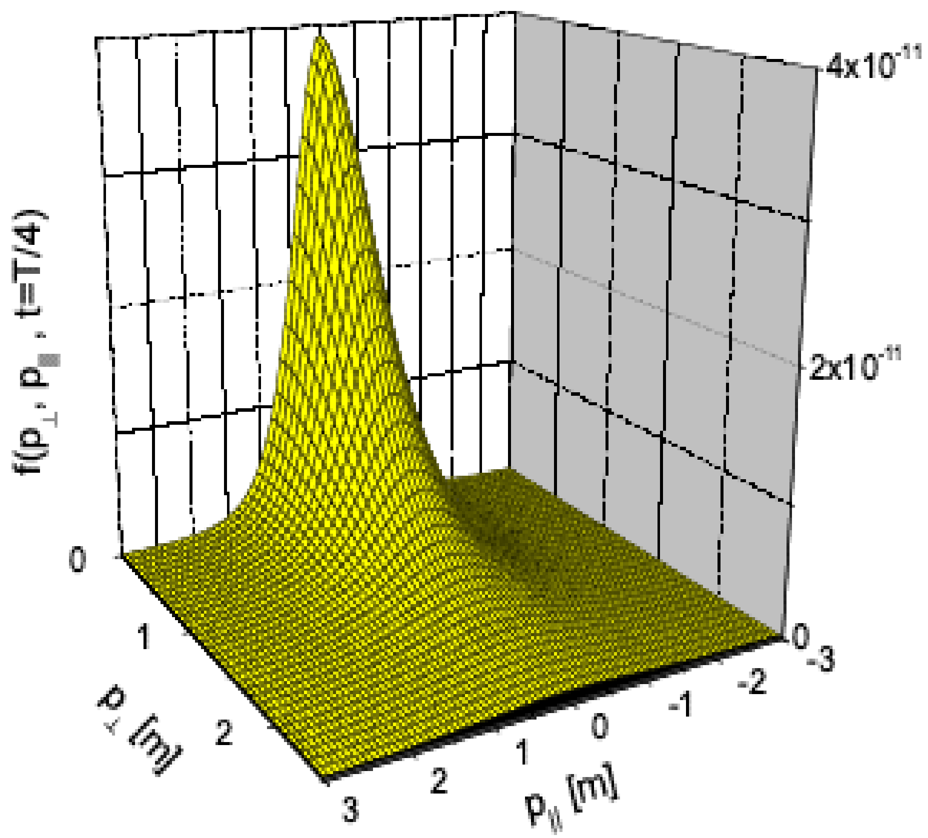
$$\gamma = \frac{E_c}{E}\frac{\omega}{m} = \frac{E_c}{E}\frac{\lambda_c}{\lambda}$$

- 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)

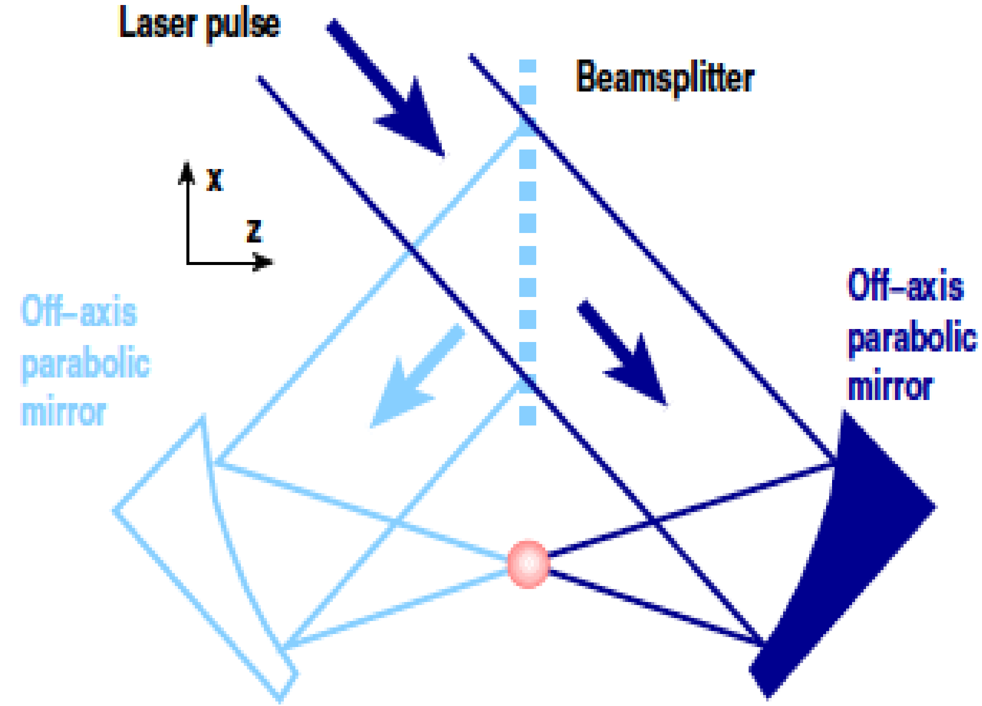
D. Blaschke, N.T. Gevorgyan, A.D. Panferov, S.A. Smolyansky, JPCS 672, 012020 (2016)

Application to subcritical laser fields



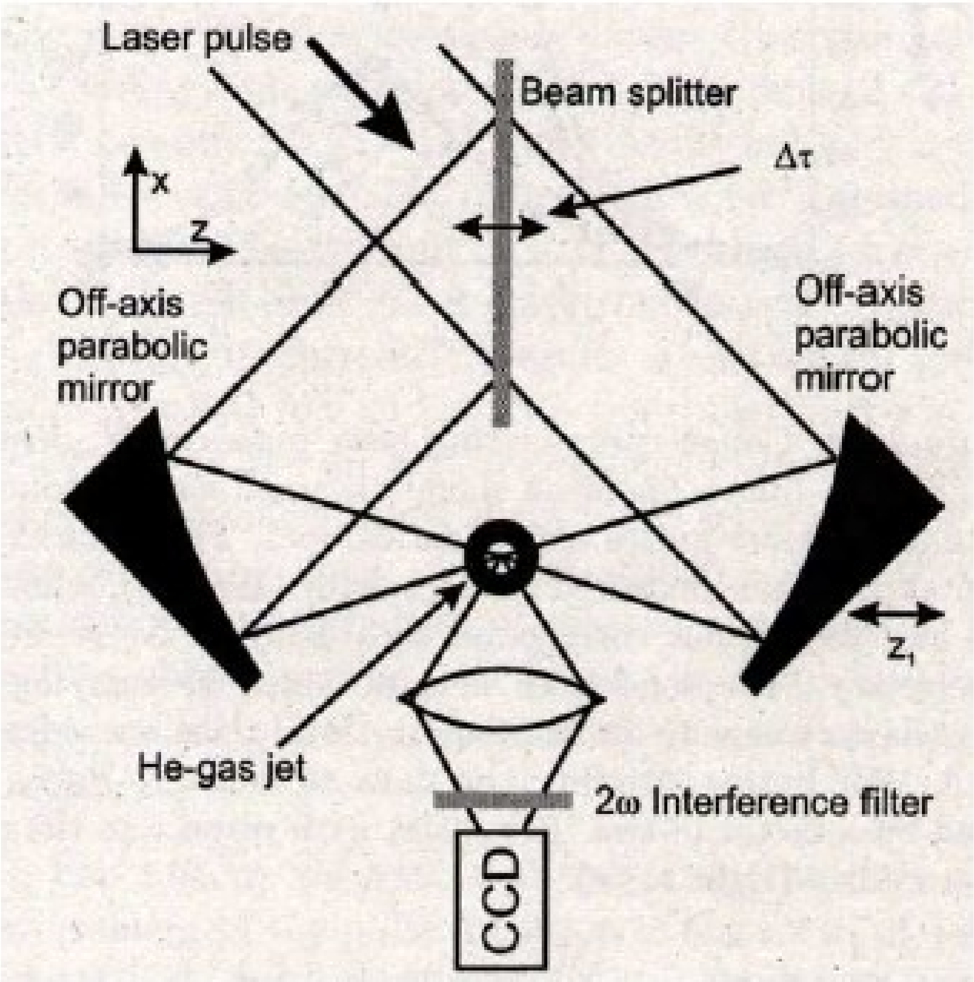
Equilibrium-like momentum distribution at the time of maximal field amplitude $t = T/4$.

Setup of the Jena Laser Exp. (2005)

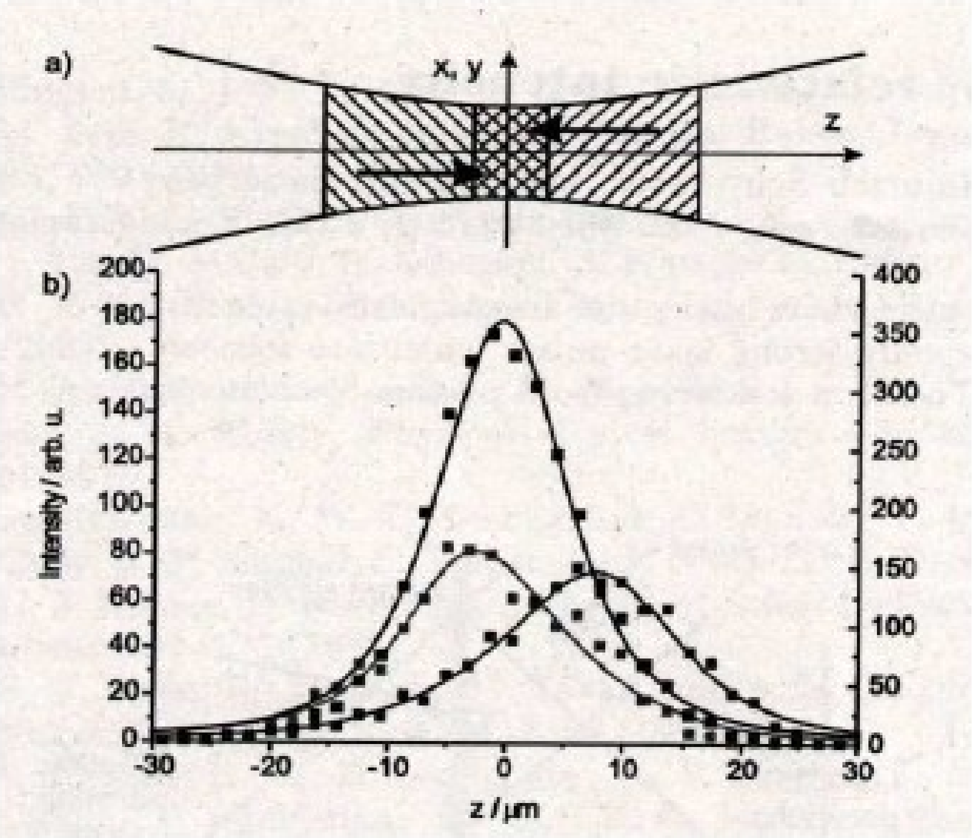


Heinzl, et al., Opt. Commun. 267, 318 (2006)

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



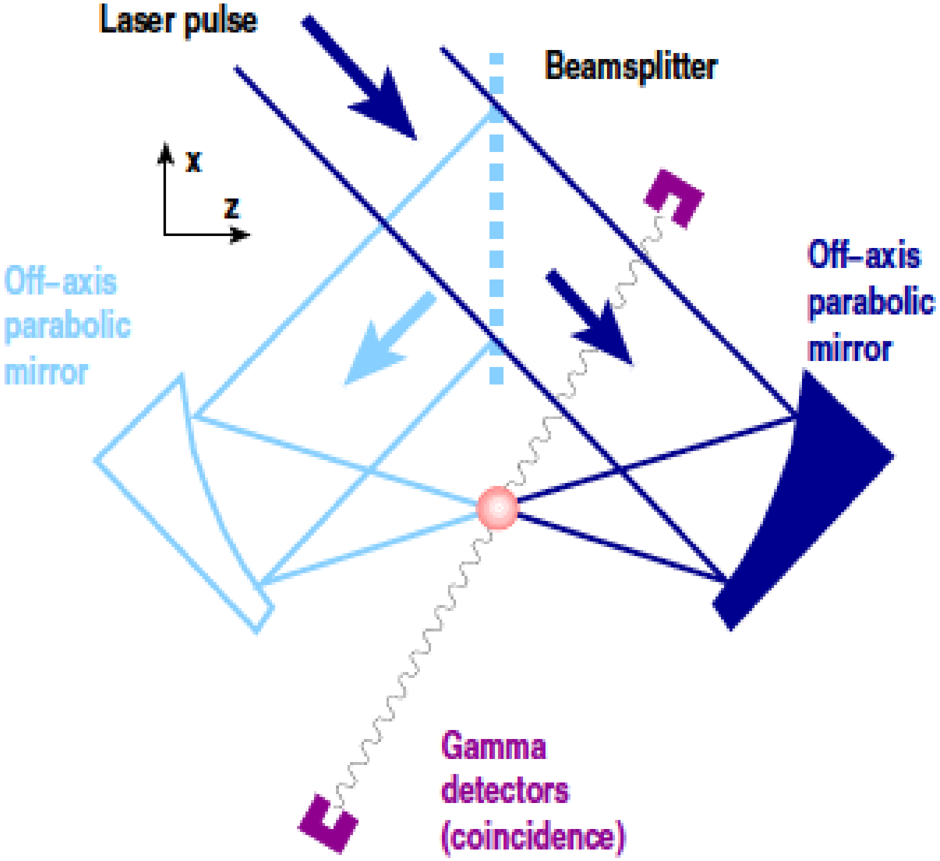
Laser diagnostic by nonlinear Thomson scattering off e$^-$ in a He-gas jet

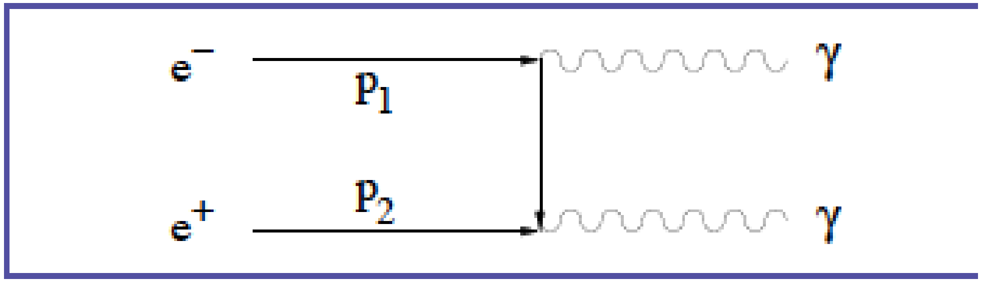
Pulse intensity: $I = 10^{18}$ W/cm^2, duration: $\tau_L \sim 80 fs$, wavelength: $\lambda = 795$ nm, cross-size: $z_0 = 9\mu$m

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

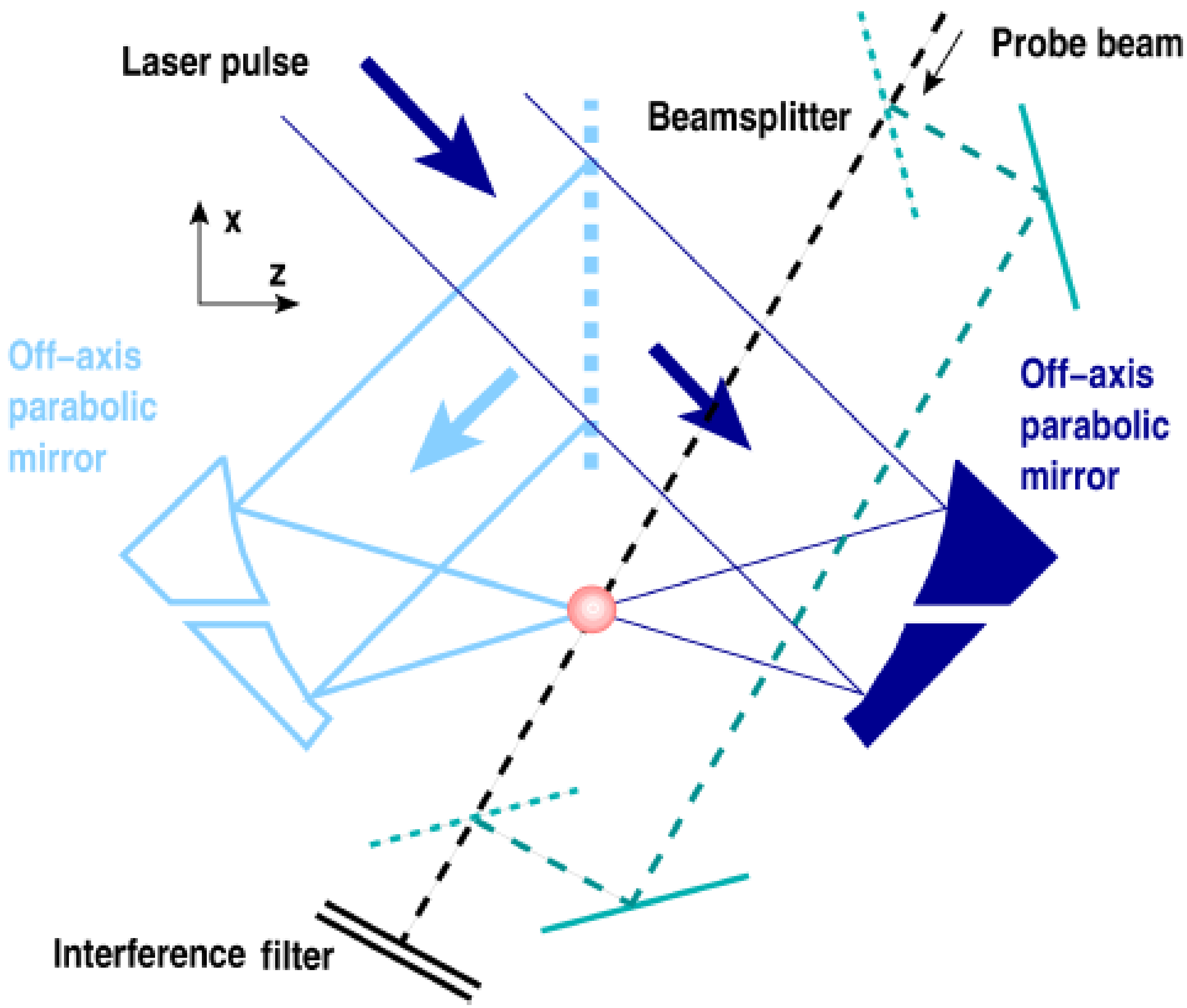
$$F(\mathbf{k},t) = \frac{5e^2 n(t)}{2k\delta^2} \; , \quad n(t) = 2\int d^3p f(\mathbf{p},t)/(2\pi)^3$$

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).

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

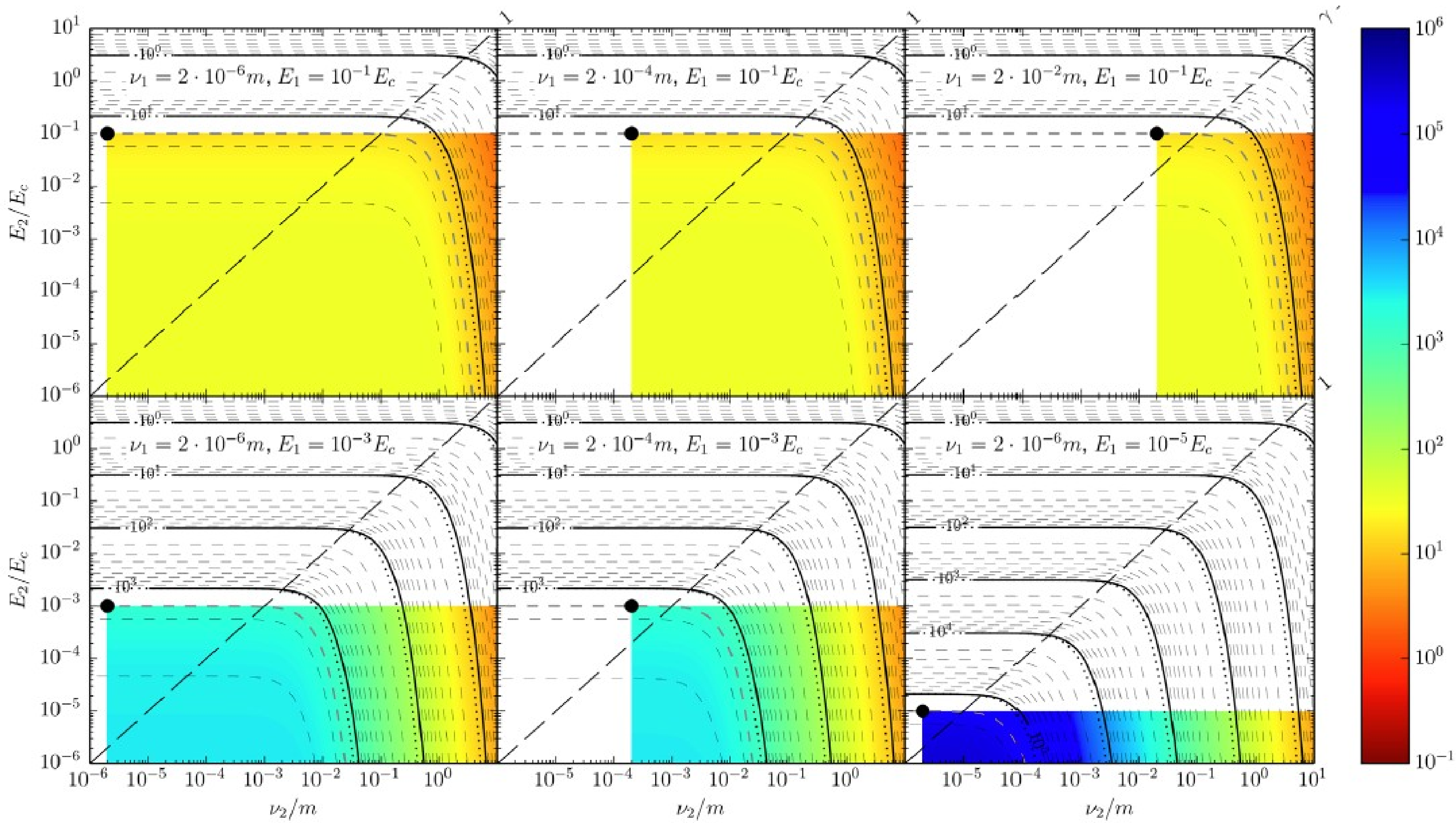


FIG. 3 (color online). Contour plots of the exponential $4\frac{m}{\nu_1}G(p_\perp \ll m, \gamma_1, \gamma_2, N)$ for six given fields ν_1, E_1 in the adiabatic region (positions depicted by the bullets, which are the loci of field doubling) over the field-frequency (E_2/E_c vs ν_2/m) plane, i.e. actually $4\frac{m}{\nu_1}G(p_\perp \ll m, \nu_1, E_1, \nu_2, E_2)$. Despite the displayed smooth distribution, our results are strictly valid only for $E_2 < E_1$ and $\nu_2 = (4n+1)\nu_1$, $n = 0, 1, 2\ldots$ [solid curves: using (6) for G, dotted curves: the approximation (9)]. The heavy grey dashed contour curves are constructed to go through the bullets. An amplification beyond the field doubling occurs in the colored [grey] rectangular regions right to these curves.

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 ?

<u>The big question is:</u>

How can one explain that spectra of particles produced in an ultrarelativistic heavy-ion collisions appear perfectly thermal if they are created by the Schwinger mechanism (thus with a nonthermal spectrum) in the strong gluon field of color-electric ropes which receeding heavy ions stretch between them after passing through each other in the collision and there Is not enough time before freeze-out for their thermalization due to 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

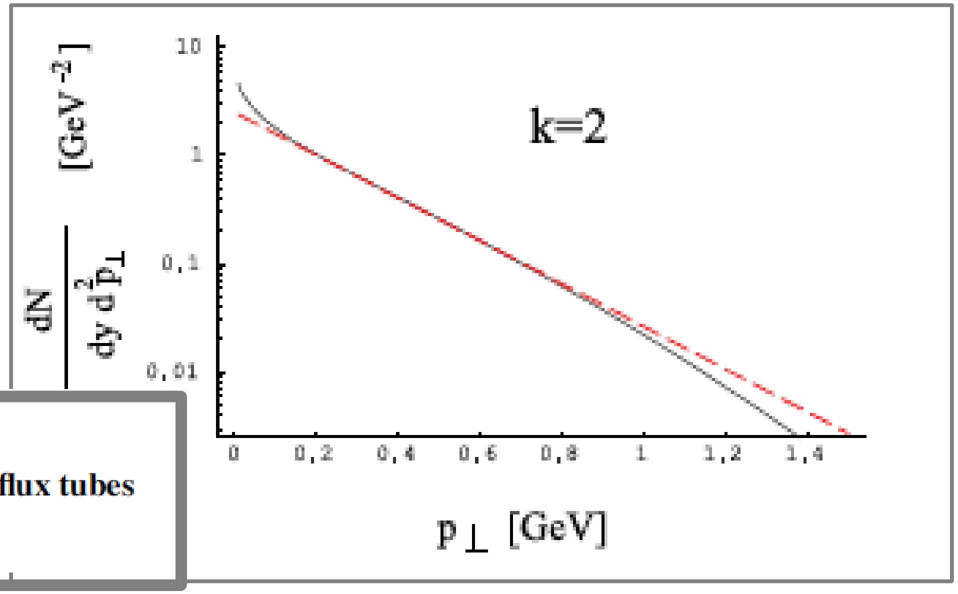
Wojciech Florkowski

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

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

$$\frac{dN}{dy\, d^2p_\perp} = \int d^4x \frac{dN}{d\Gamma} = \pi R^2 \int_0^\infty d\tau'\, \tau' \int_{-\infty}^{+\infty} d\eta\, \mathcal{R}(\tau', p_\perp) \delta\left(w \mp w_0\right) v = \pi R^2 \int_0^\infty d\tau'\, \tau'\, \mathcal{R}(\tau', p_\perp),$$

$$\frac{dN}{dy\, d^2p_\perp} = \frac{R^2}{4\pi^2} \sum_{\text{all partons}} \int_0^\infty d\tau'\, \tau' F(\tau') \left|\ln\left(1 \mp \exp\left(-\frac{\pi p_\perp^2}{F(\tau')}\right)\right)\right|.$$



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,†]

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

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

where

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

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

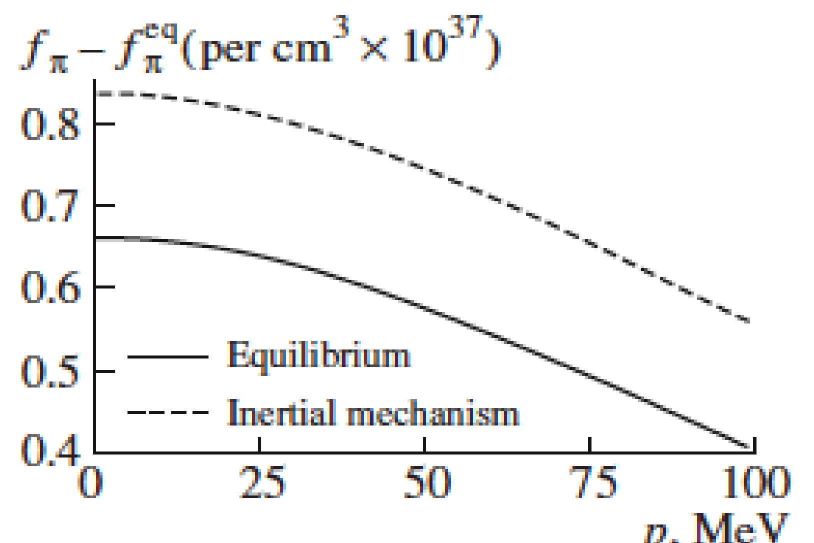
in Kinetic equation for the pion-sigma system

$$\dot{f}_\alpha = I_\alpha^{\mathrm{vac}} + I_\alpha^{\sigma\to\pi\pi} + I_\alpha^{\mathrm{ex}}$$

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

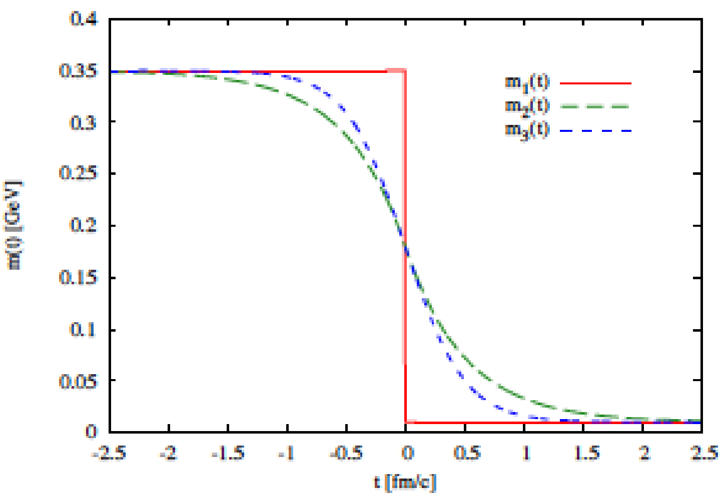
$$I_\sigma^{\mathrm{loss}}(\mathbf{p}, t) = -\int\frac{d\mathbf{p}_1 d\mathbf{p}_2}{\omega_\pi(\mathbf{p}_1, t)\omega_\pi(\mathbf{p}_2, t)}\Gamma_{\sigma\to\pi\pi}(\mathbf{p}, \mathbf{p}_1, \mathbf{p}_2; t) \times f_\sigma(\mathbf{p}, t)[1 + f_\pi(\mathbf{p}_1, t)][1 + f_\pi(\mathbf{p}_2, t)] \times\delta\{\omega_\sigma(\mathbf{p},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

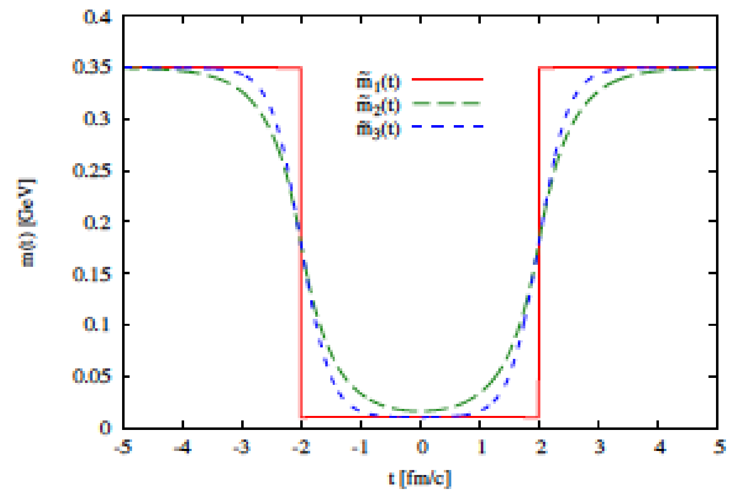
$$I_\sigma^{\mathrm{loss}}(t) = \pi\left[\frac{4p_{\mathrm{tr}}(t)}{m_\sigma(t)}\right]^3\Gamma_{\sigma\to\pi\pi}(p_{\mathrm{tr}}, t)[1 + f_\pi(p_{\mathrm{tr}}, t)]^2$$



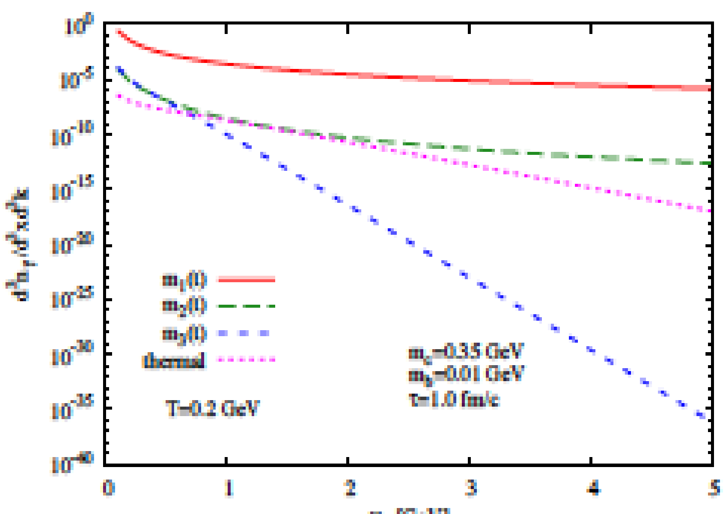
Off-equilibrium photon production during the chiral phase transition

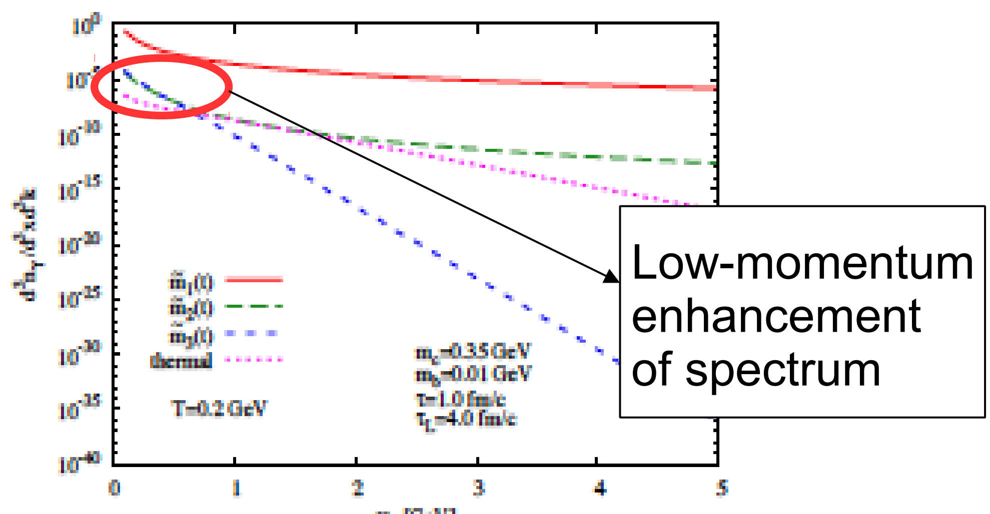
Time dependence of quark mass during chiral transition $E_{\vec{p}}(t) = \sqrt{p^2 + m^2(t)}$





Nonequilibrium photon production by chiral transition vs. Thermal one

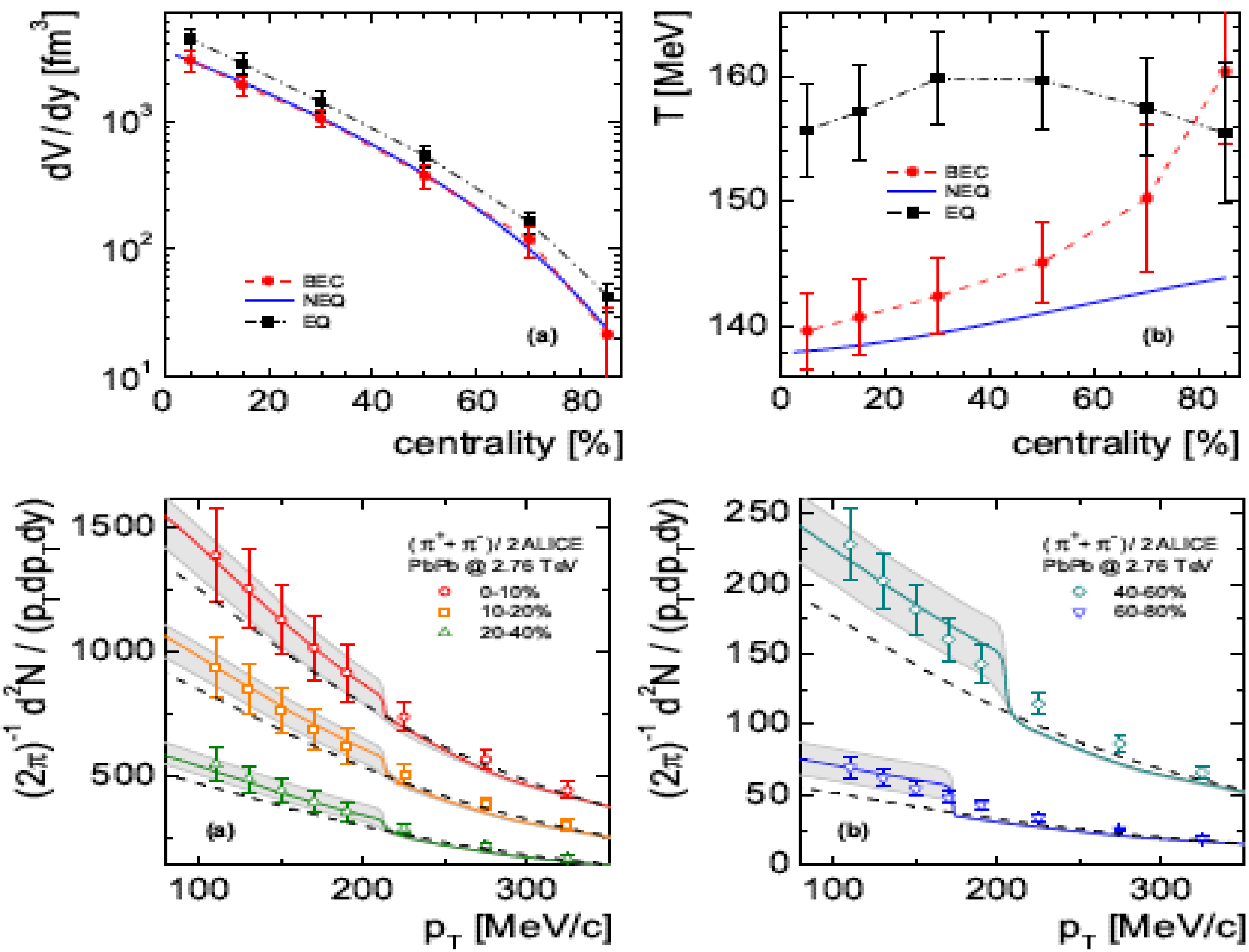




F. Michler, H. Van Hees, D.D. Dietrich, S. Leupold, C. Greiner, Ann. Phys. (2014) ; arxiv:1208.6565

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

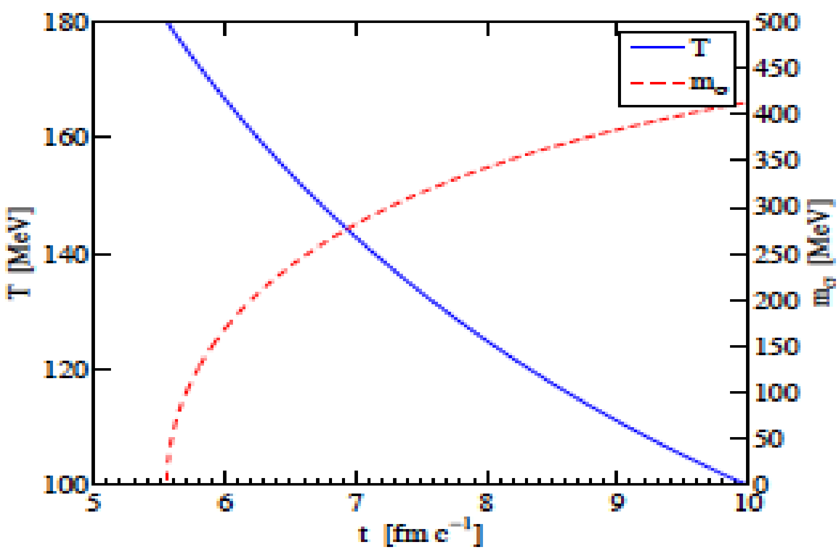
Low-momentum pion enhancement from quantum kinetics of chiral symmetry breaking

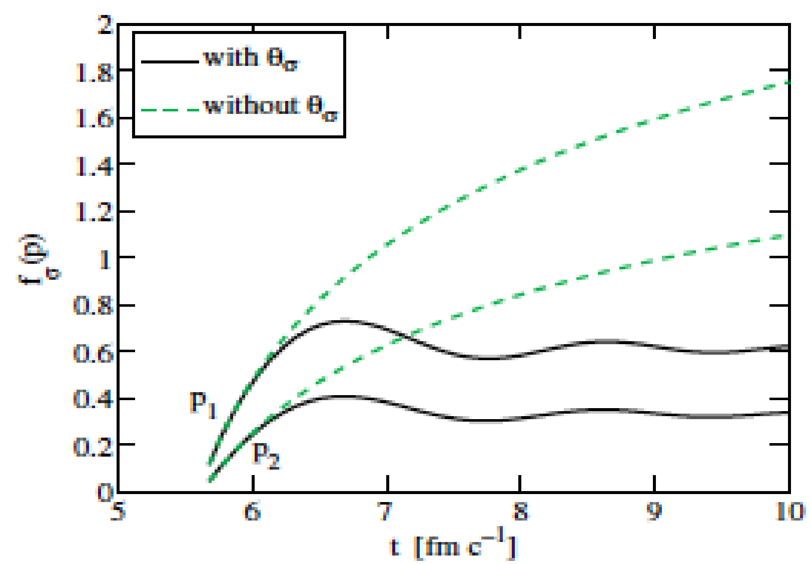
$$\Delta_\sigma(t,\vec{p}_\sigma) = \frac{m_\sigma}{w_\sigma^2}\frac{\partial m_\sigma}{\partial t}\,,$$

$$\theta_\sigma(t,t',\vec{p}_\sigma) = \int_{t'}^{t} dt'' w_\sigma(t'',\vec{p}_\sigma)$$

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

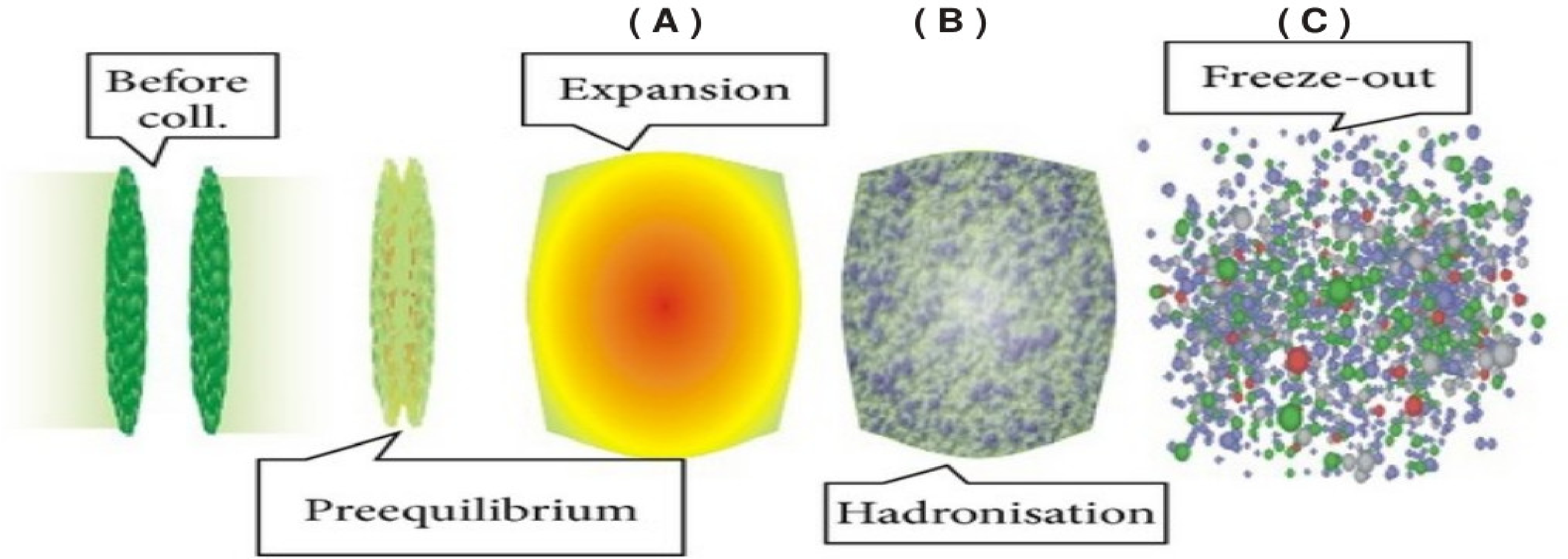
$$\begin{aligned}
\frac{\partial f_\pi}{\partial t}(t,\vec{p}_1) &= \left.\frac{df_\pi}{dt}\right|_{\text{collisions}} \\
&= (1+f_\pi(t,\vec{p}_1))\left(\int \frac{d^3p_\sigma}{(2\pi)^3 2w_\sigma}\frac{d^3p_2}{(2\pi)^3 2w_2}\Gamma_{\sigma\to\pi\pi}(\vec{p}_\sigma,\vec{p}_1,\vec{p}_2)\,(1+f_\pi(t,\vec{p}_2))\,f_\sigma(t,\vec{p}_\sigma)\right)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





L. Juchnowski, D. Blaschke, T. Fischer,
J. Phys. Conf. Ser. 673 (2016) 012009

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

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

(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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mgr Michał Marczenko

Master students:
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+many visitors from 4 continents

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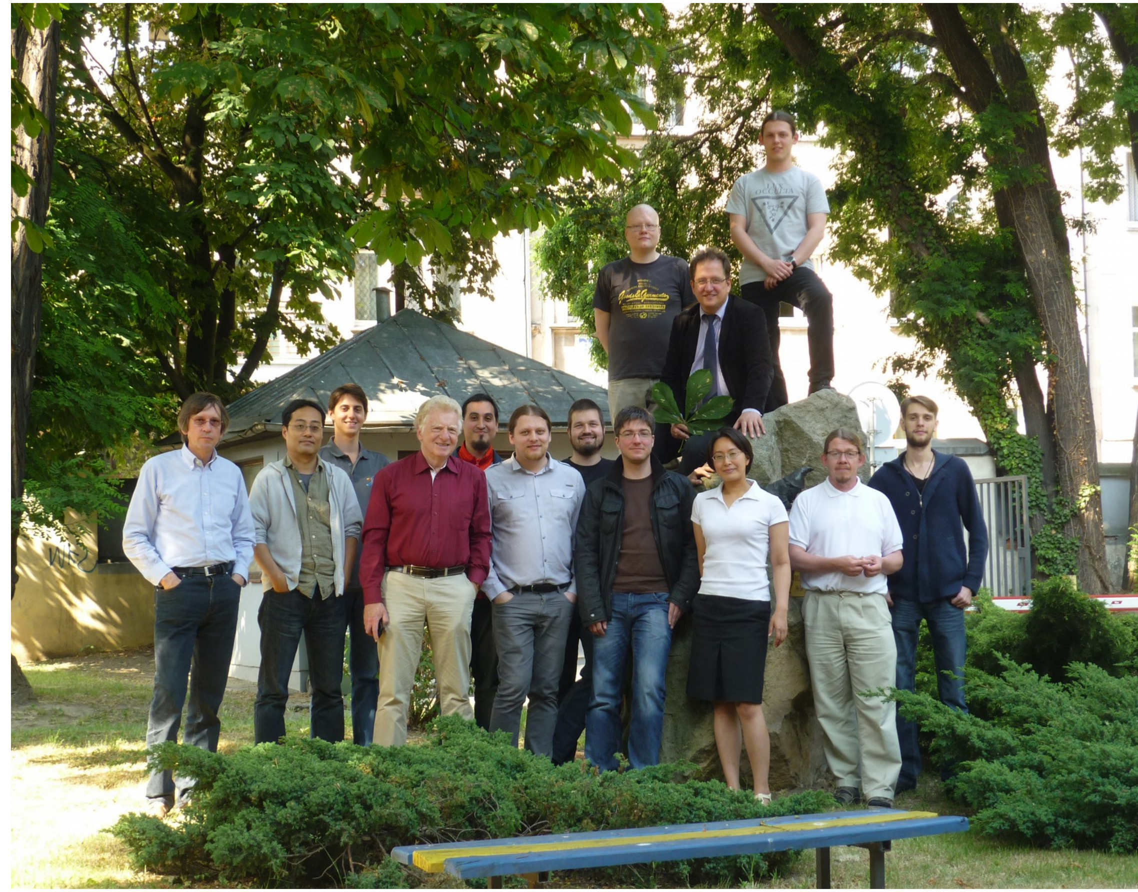
Maestro (2), Opus (4), Sonata (1)

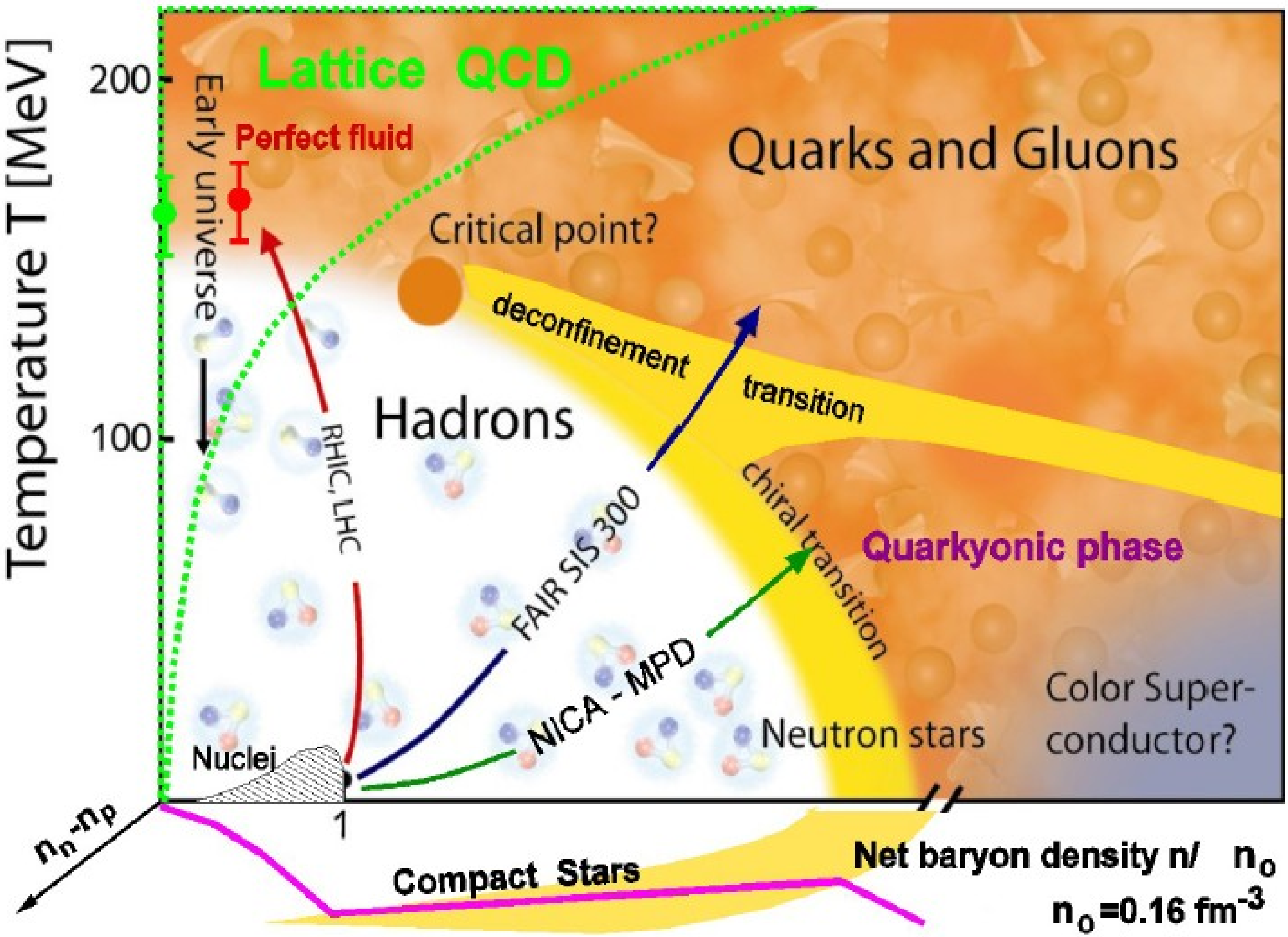


Main research topics:

- 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



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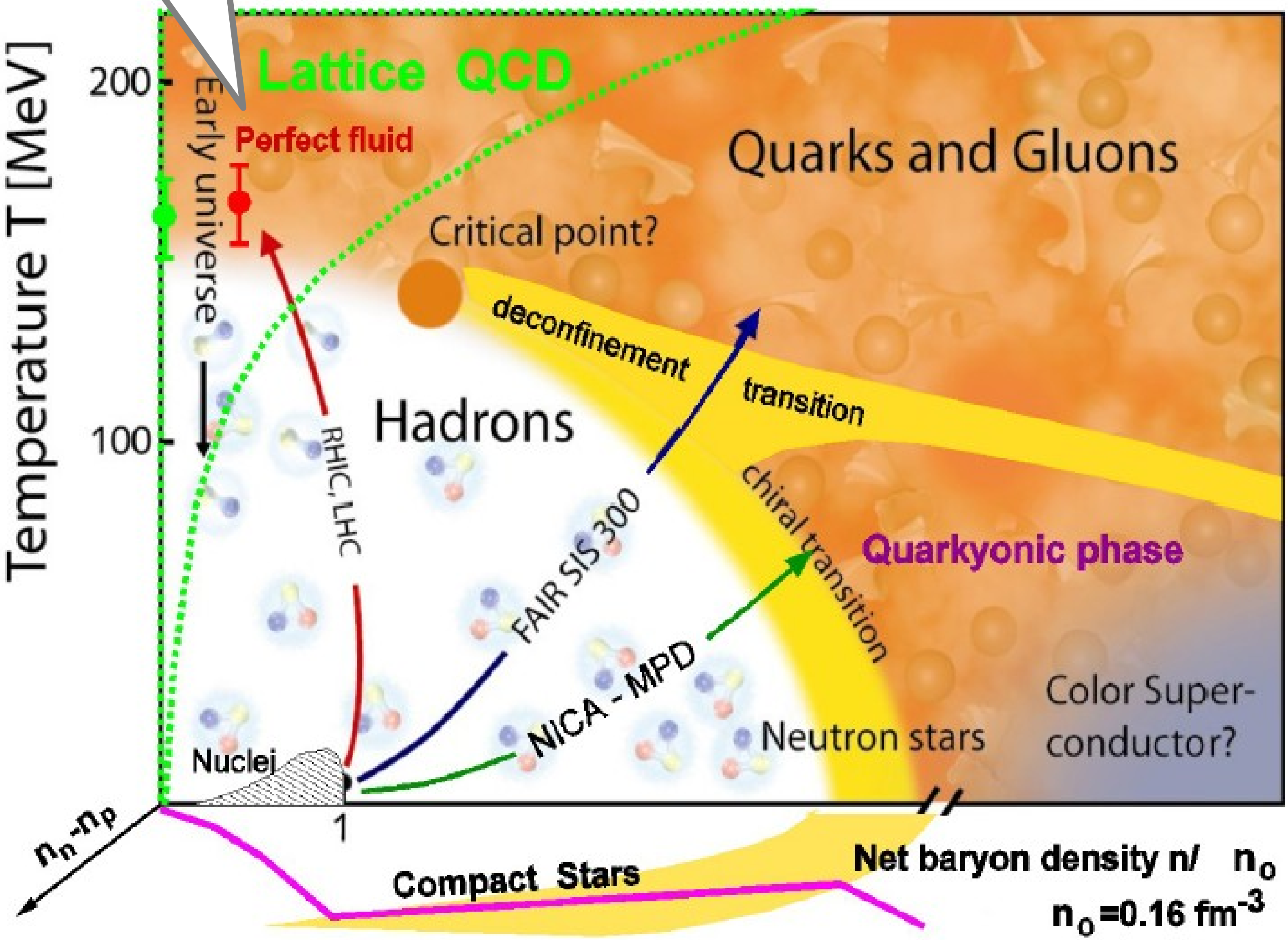

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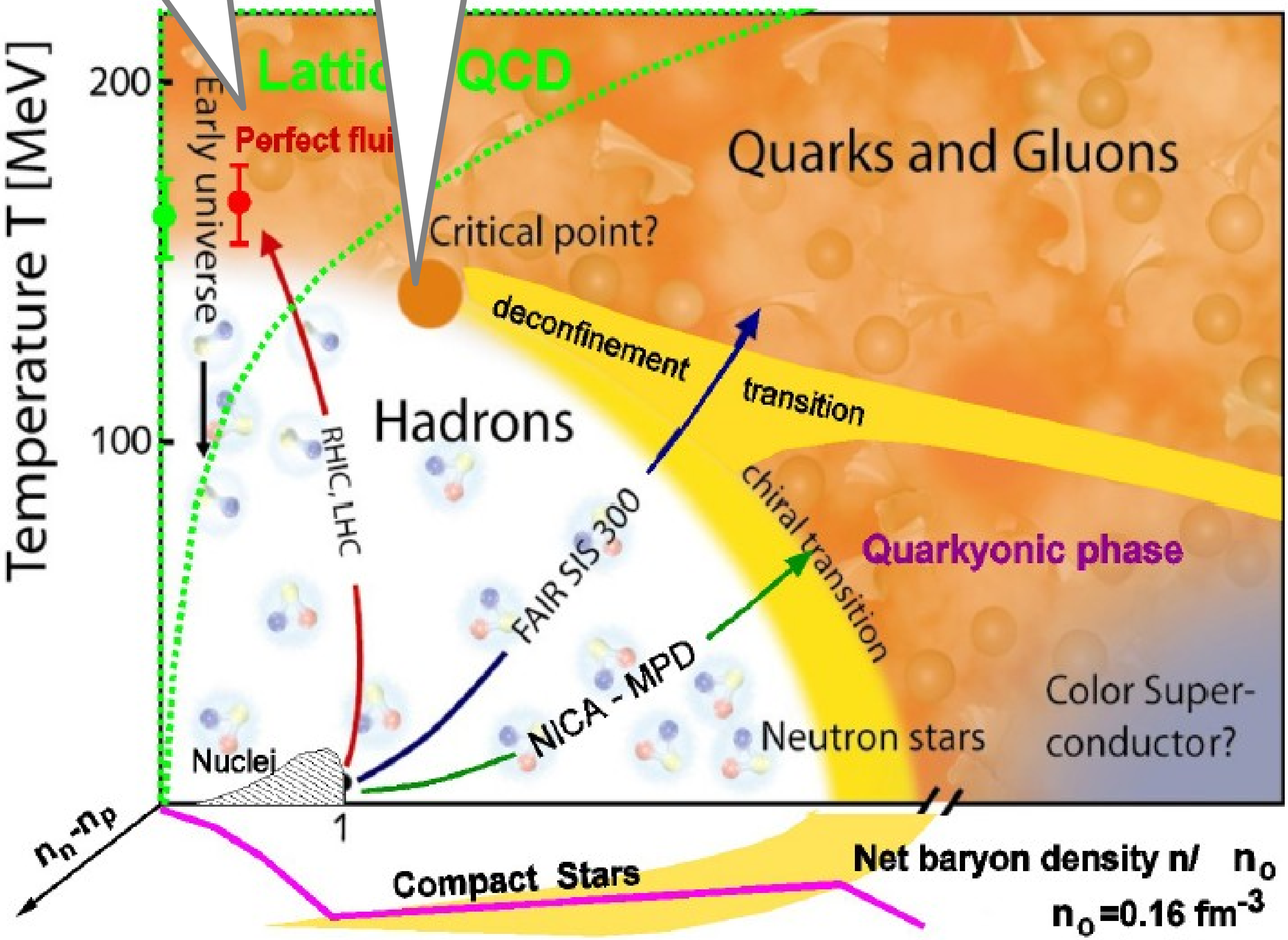

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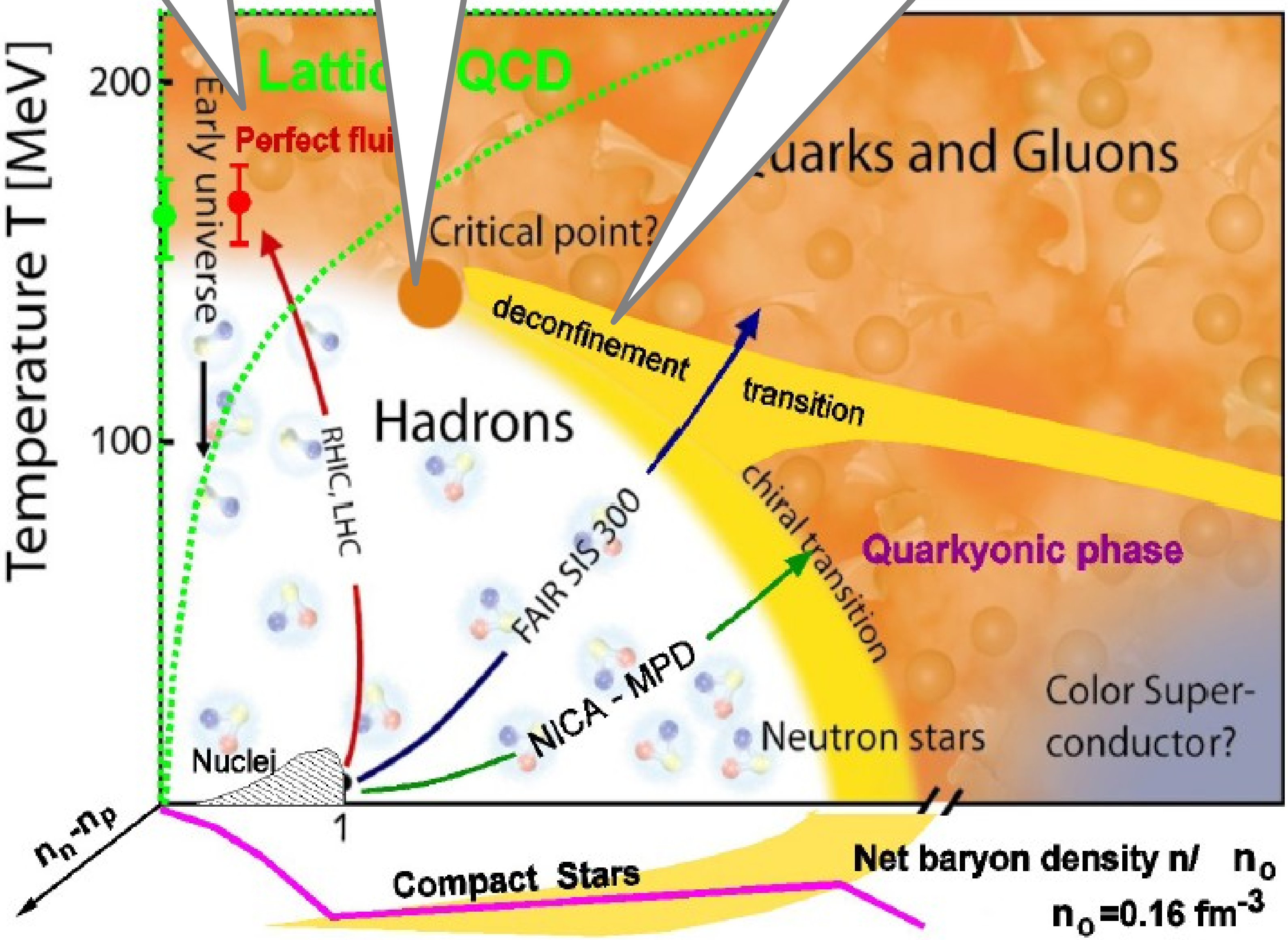
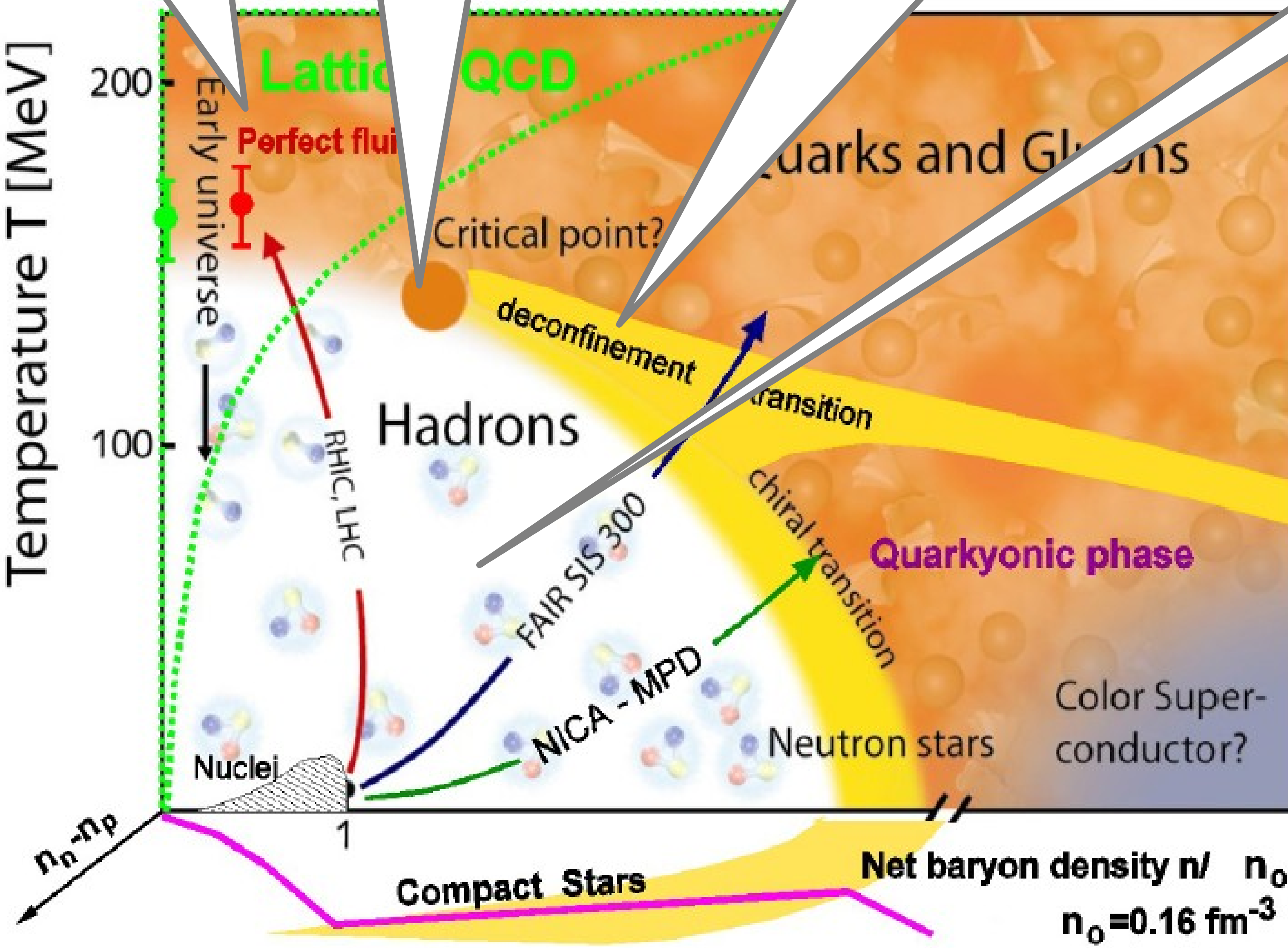


Division: Theory of Elementary Particles - Collaborations

CERN
ALICE
CERN
SHINE NA61
FAIR
HIC for FAIR
Helmholtz International Center
NAVI



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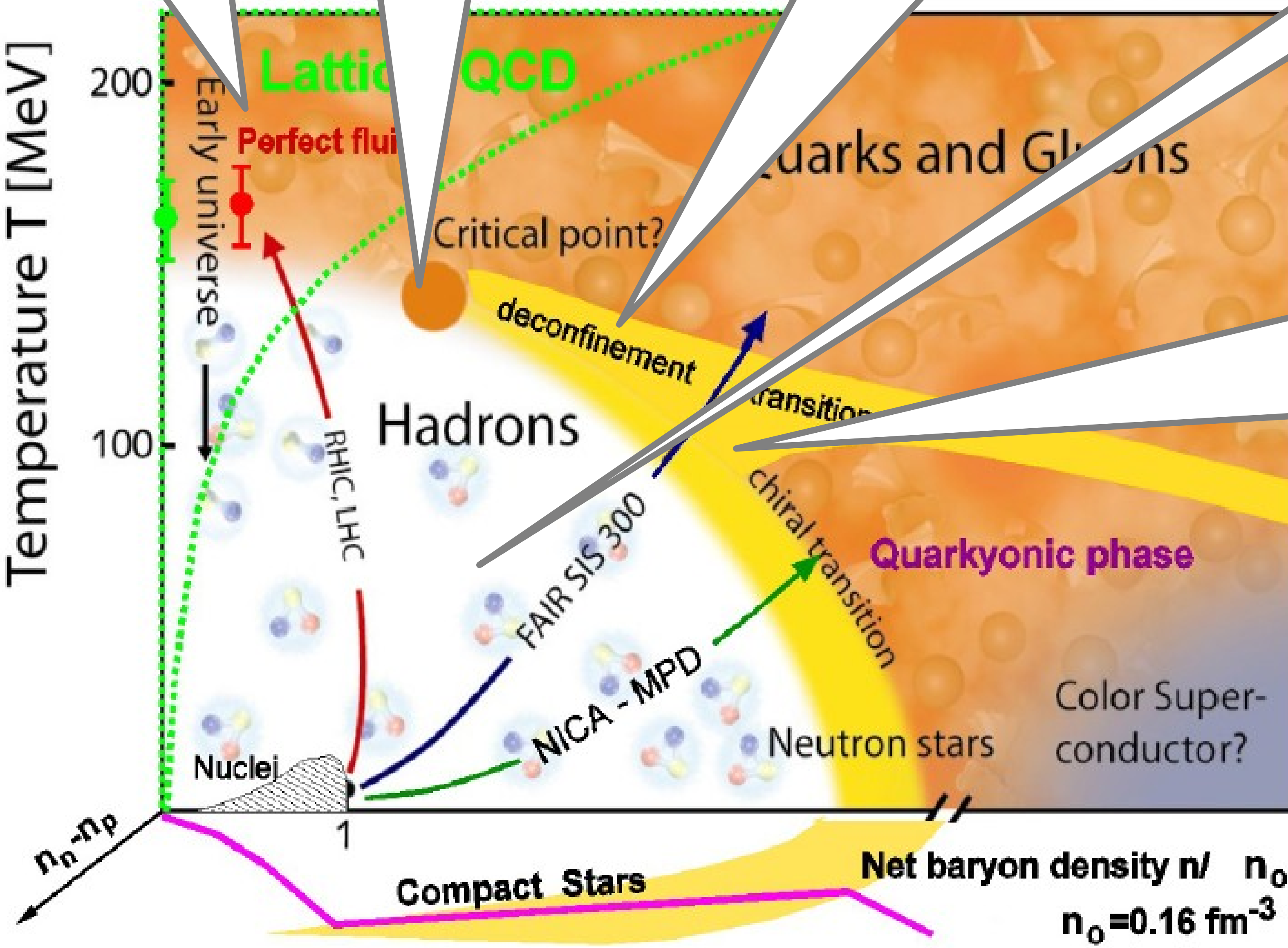
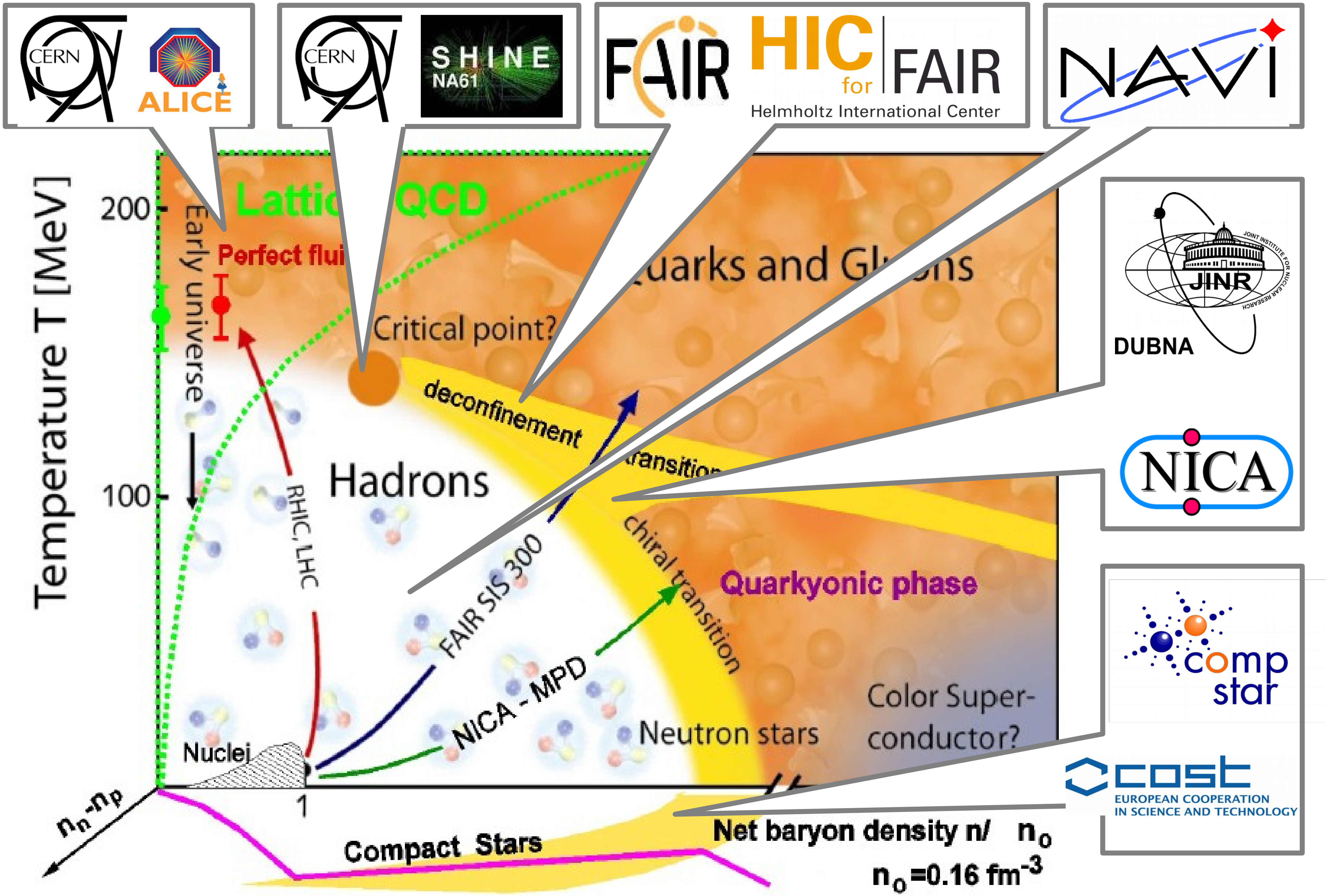
Division: Theory of Elementary Particles - Collaborations



Division: Theory of Elementary Particles - Collaborations

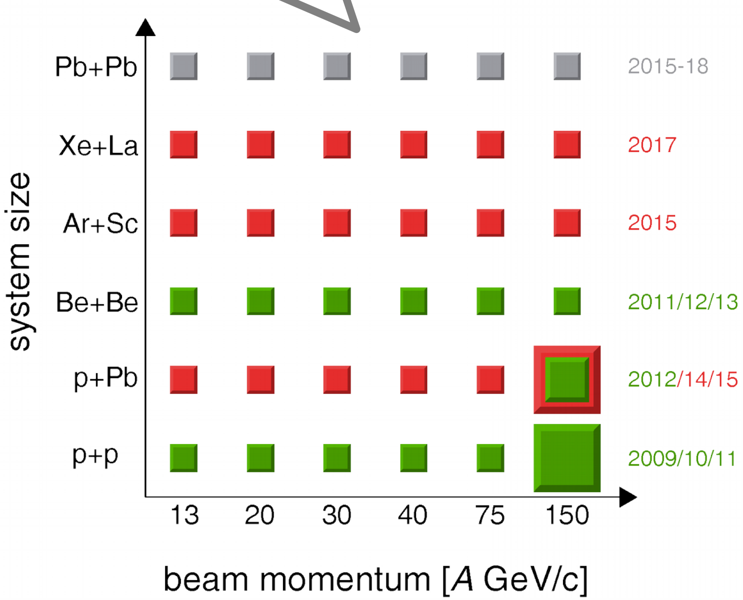


Division: Theory of Elementary Particles

Collaboration with CERN Experiment NA61/SHINE since 2011

Goals of the experiment:
- study of the properties of the onset of deconfinement and the search for the critical point of strongly interacting matter with nucleus-nucleus, proton-proton and proton-lead collisions at six collision momenta
- Precise hadron production measurements for calibrating neutrino beams at J-PARC, Japan and Fermilab, US. Proton/pion-carbon and proton/pion-(replica target) interactions recorded
- Precise hadron production measurements for reliable simulations of cosmic-ray air showers in the Pierre Auger Observatory and KASCADE experiments

Energy and system size scan for Finding the QCD critical endpoint



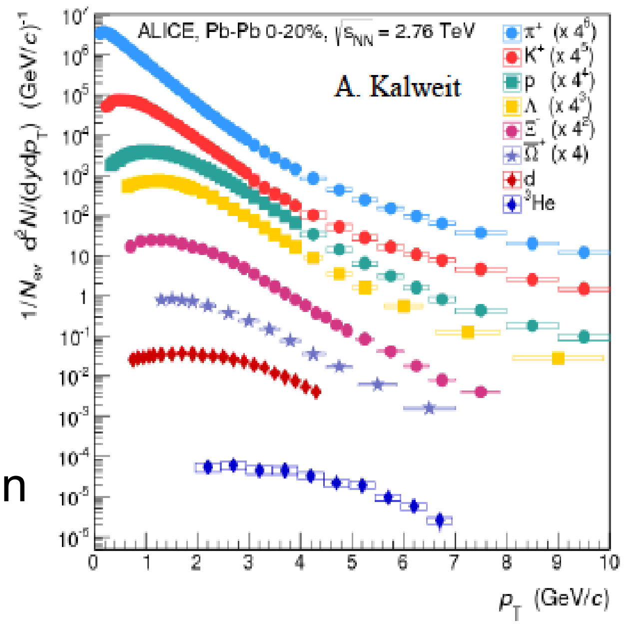
NA61/SHINE Collaboration

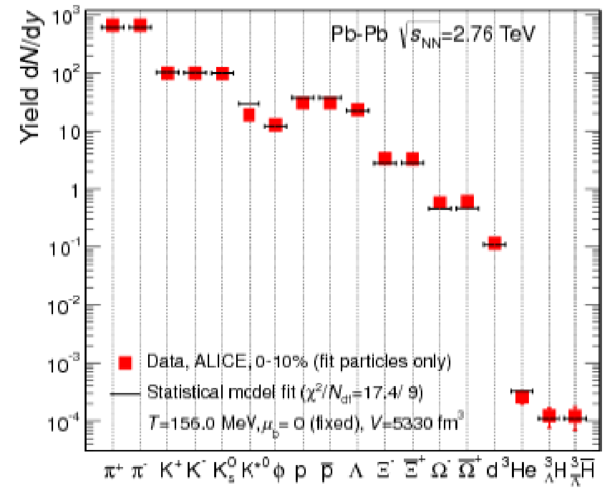
- SPS Heavy Ion and Neutrino Experiment (SHINE)
- Located at the Super Proton Synchrotron (SPS)
- 140 Physicists from 14 countries and 28 institutions

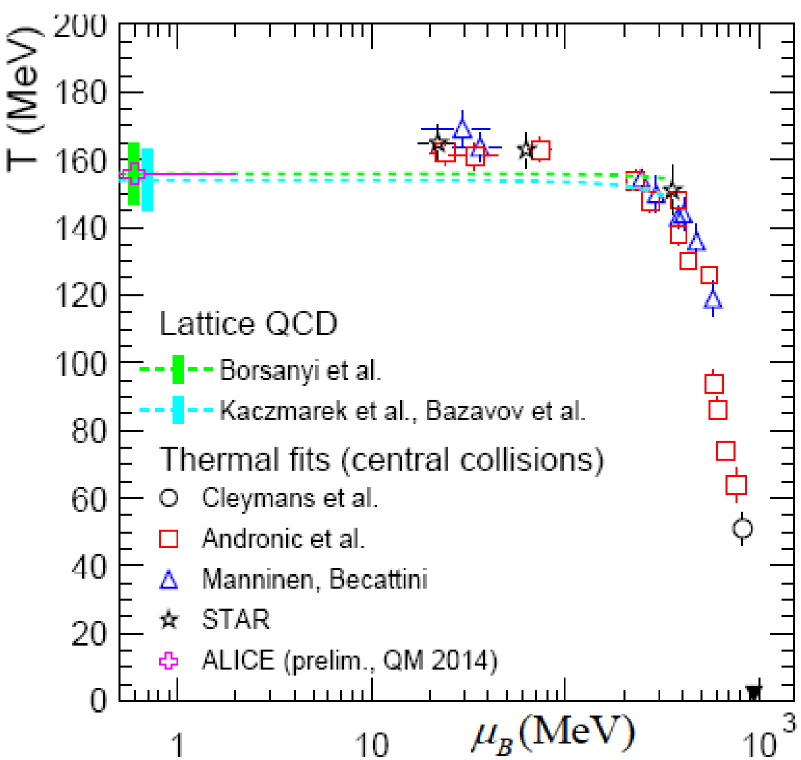
Division: Theory of Elementary Particles

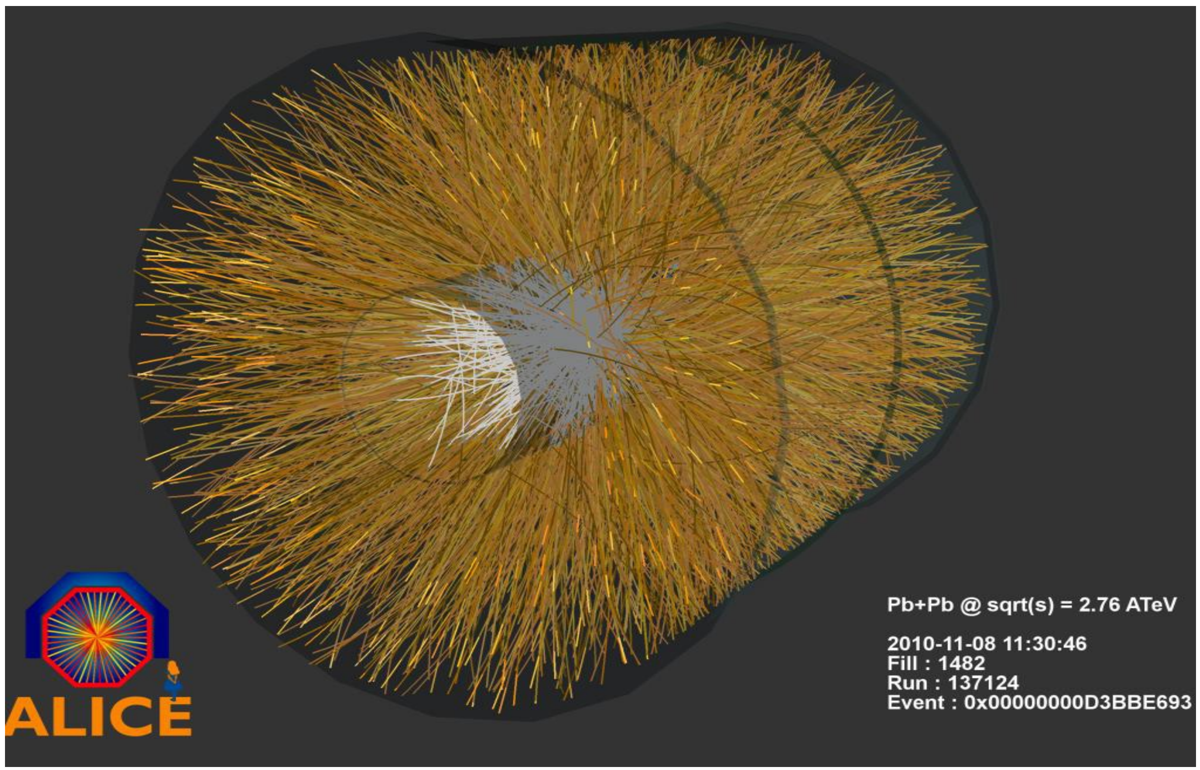
Collaboration with ALICE @ CERN

- excellent particle identification
- high statistics data allow new level unprecendented accuracy
- multihadron production near the QCD phase boundary challenges our understanding of the process of nonequilibrium QGP hadronization
- confirmation of lattice QCD theory





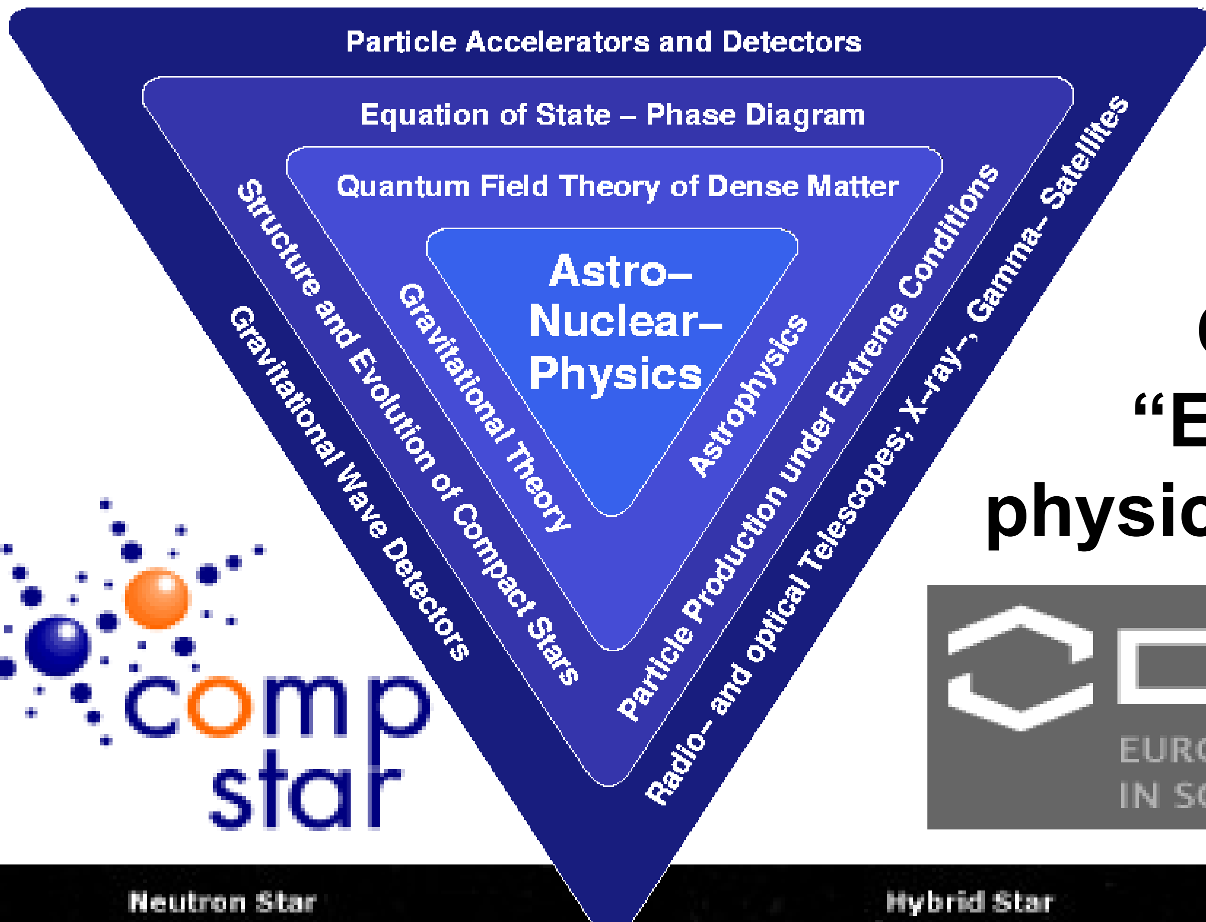




Division: Theory of Elementary Particles

NICA

JINR DUBNA



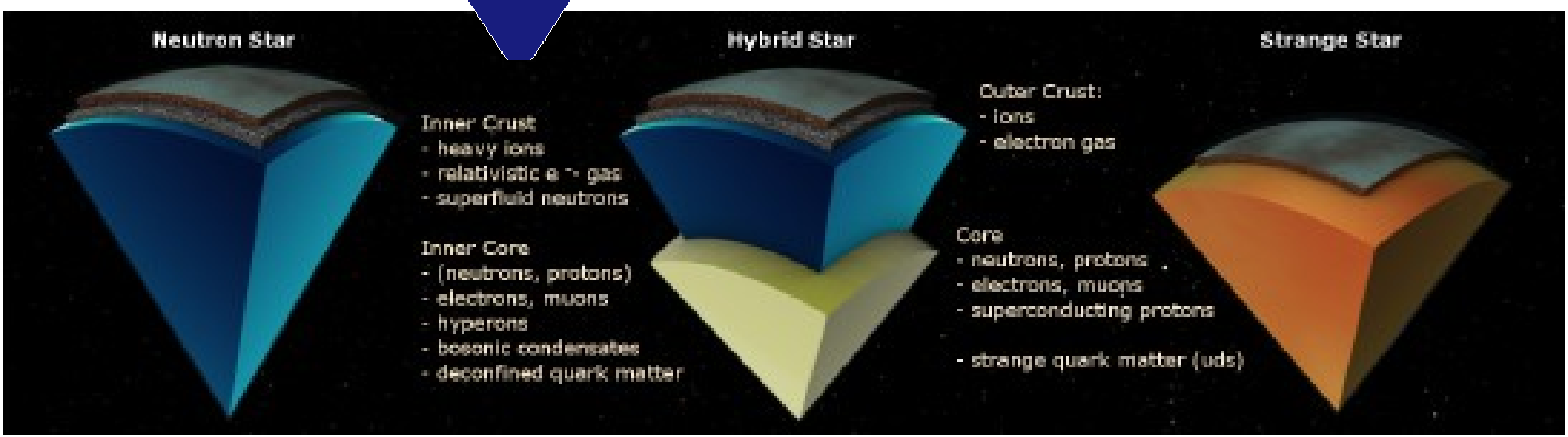
NewCompStar

COST Action MP1304: “Exploring fundamental physics with compact stars”

compstar

cost

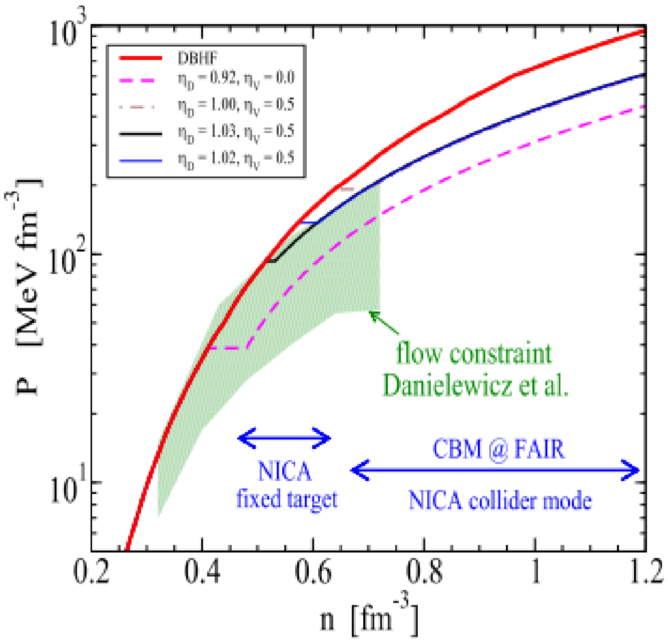
EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY



Division: Theory of Elementary Particles

Collaboration with NICA – MPD Collaboration at JINR Dubna
and COST Action MP1304 “NewCompStar”

Heavy-Ion Collisions



- stiff EoS
(at flow limit)

- low ncrit
(at NICA fixT)

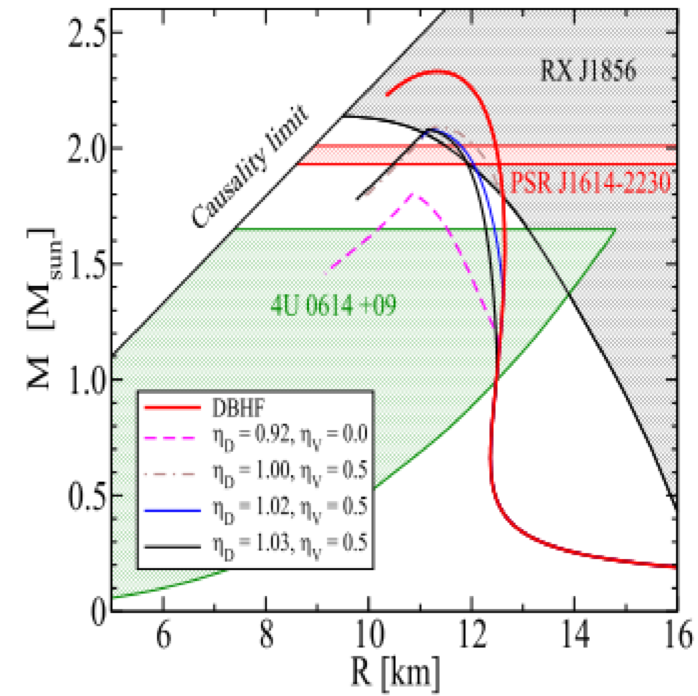
- soft EoS
(dashed line)

- high Mmax
(J1614-2230)

- low Monset
(all NS hybrid)

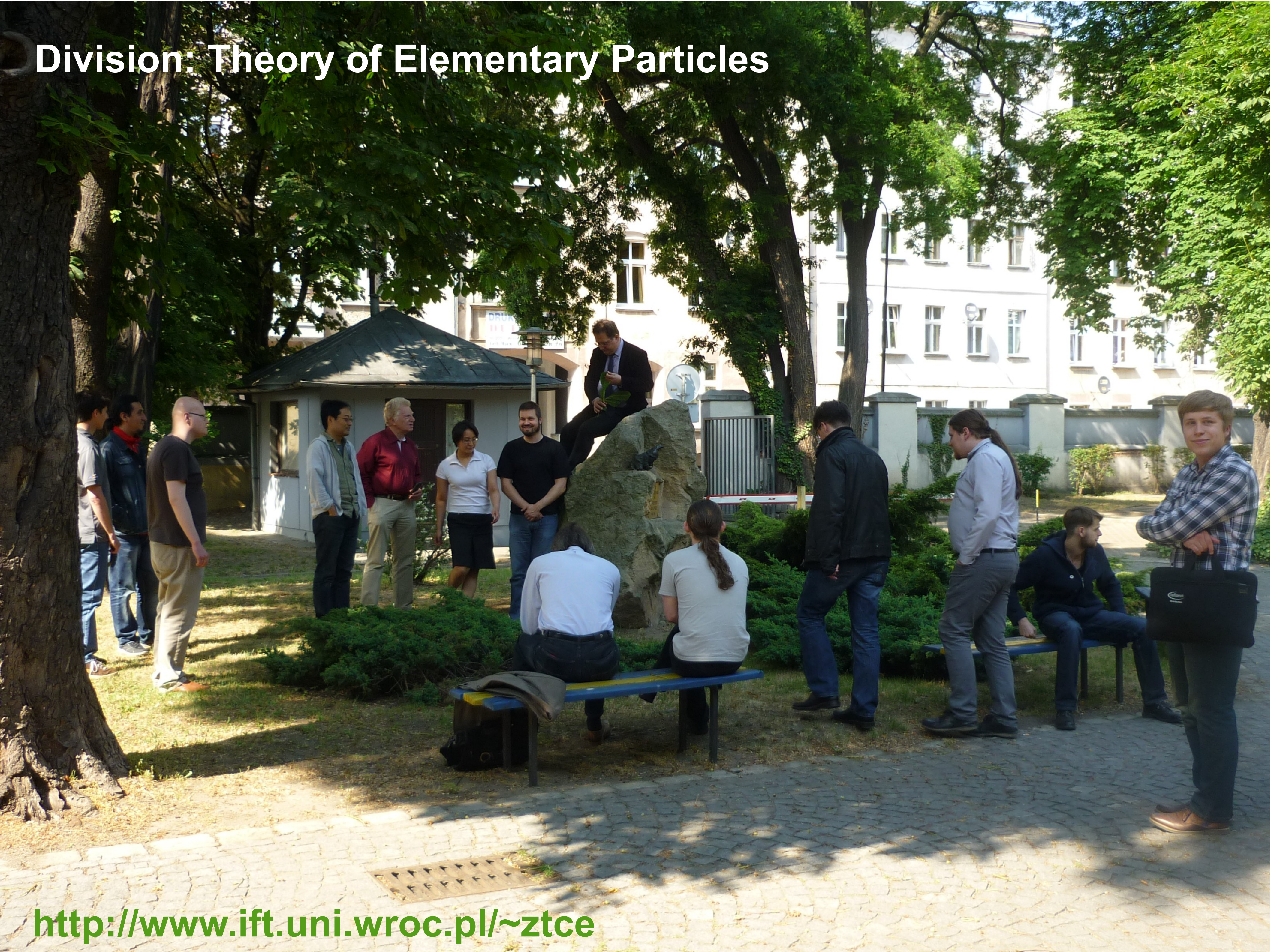
- excluded
(J1614-2230)

Compact Stars



29 member countries

Division: Theory of Elementary Particles



http://www.ift.uni.wroc.pl/~ztce