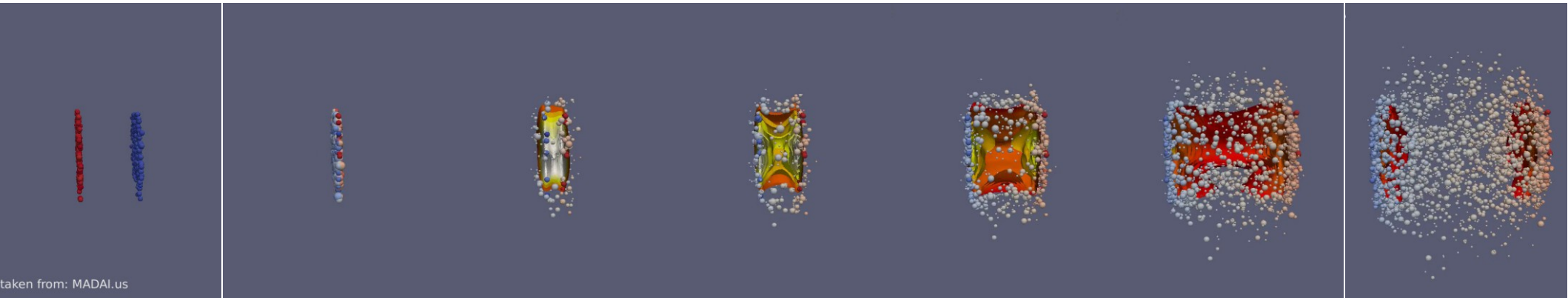


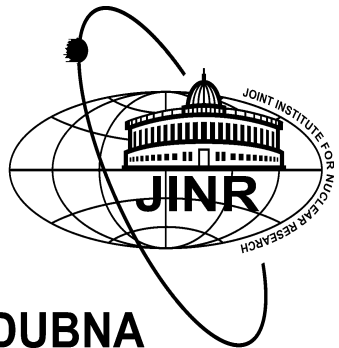
Particle Production in Strong Time-dependent Fields

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

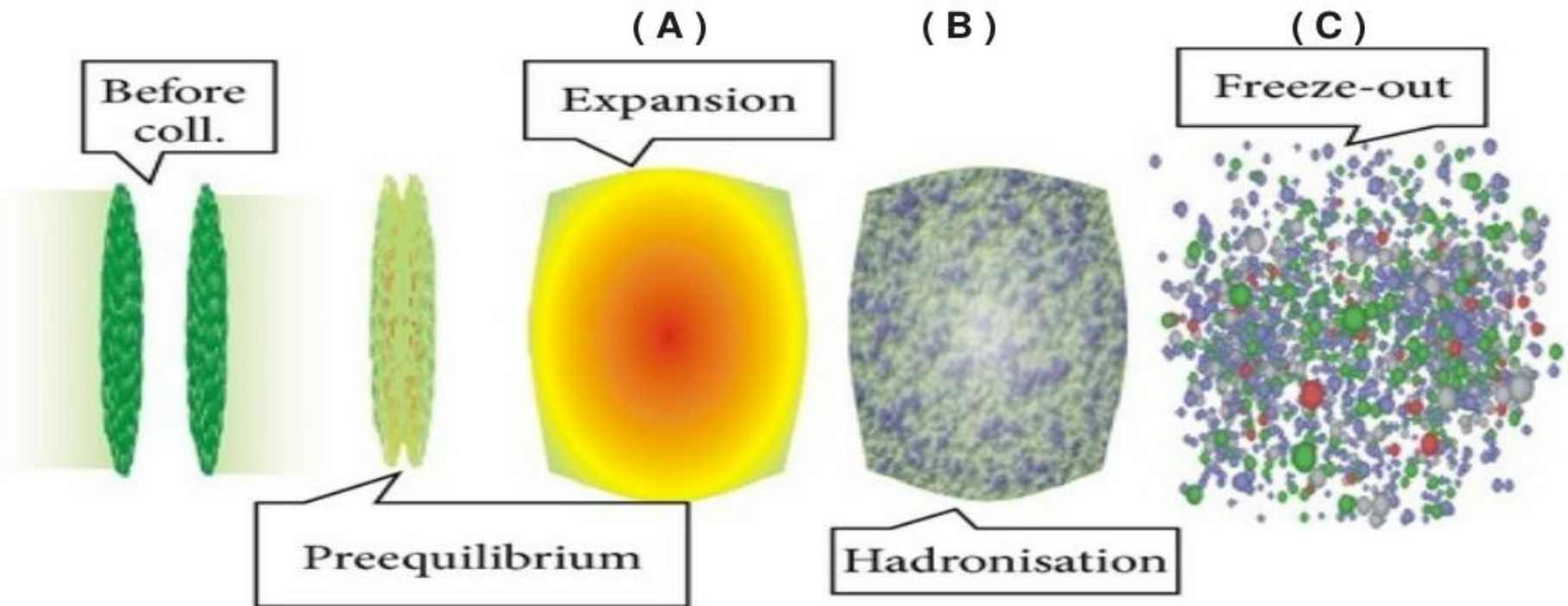


Helmholtz International Summer School “From Strong Fields to Heavy Quarks”

JINR Dubna (Russia), July 18-30, 2016



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

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

- (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 mechanism [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 et al. 2013] and BBGKY hierarchy for the electron-positron-gamma system in this case [Blaschke et 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 multi-quark 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]
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- 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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Quantum Kinetics of Particle Production in Strong Fields

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

Thanks for collaboration go to:

Lukasz Juchnowski, Ludwik Turko (University of Wroclaw)

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Burkhard Kaempfer, Andreas Otto (University of Dresden & HZ Dresden-Rossendorf)

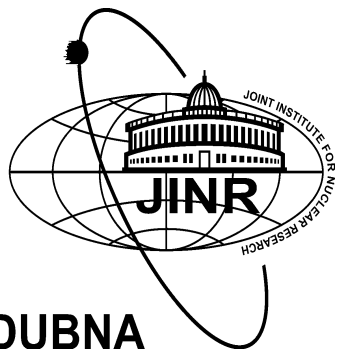
Anatoly Panferov, Alexander Prozorkevich, Stanislav Smolyanksy (Saratov State University)

Gianluca Gregory, Chris Murphy (University Oxford & Rutherford Appleton Laboratory)

Gerd Roepke (University of Rostock)

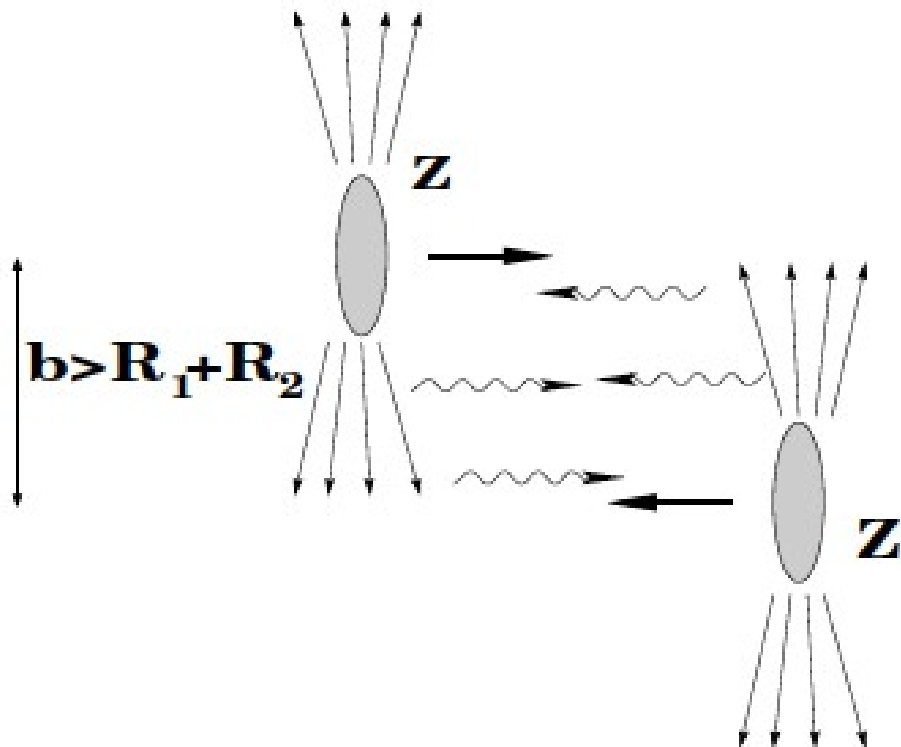
Craig Roberts (Argonne National Laboratory)

Sebastian Schmidt (Forschungszentrum Juelich)

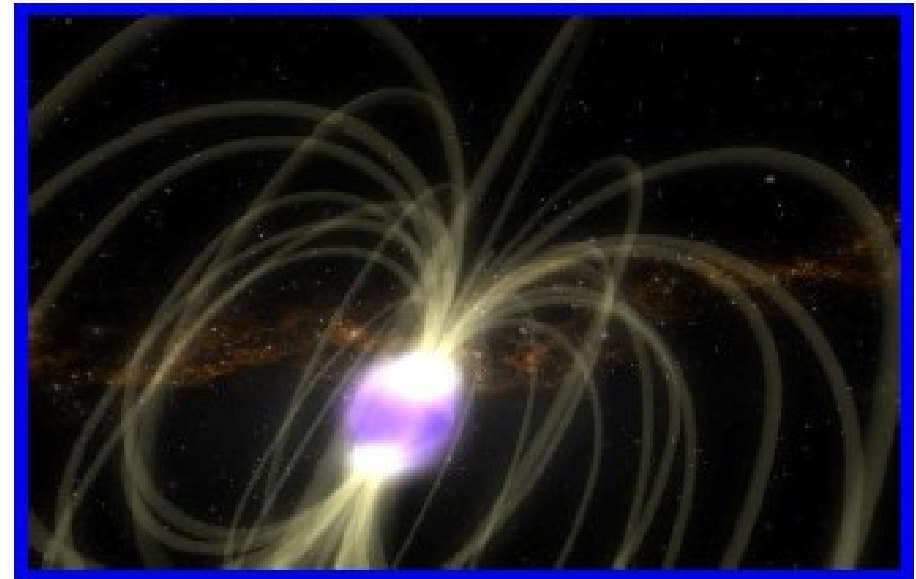


PAIR CREATION IN STRONG ELECTROMAGNETIC FIELDS

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



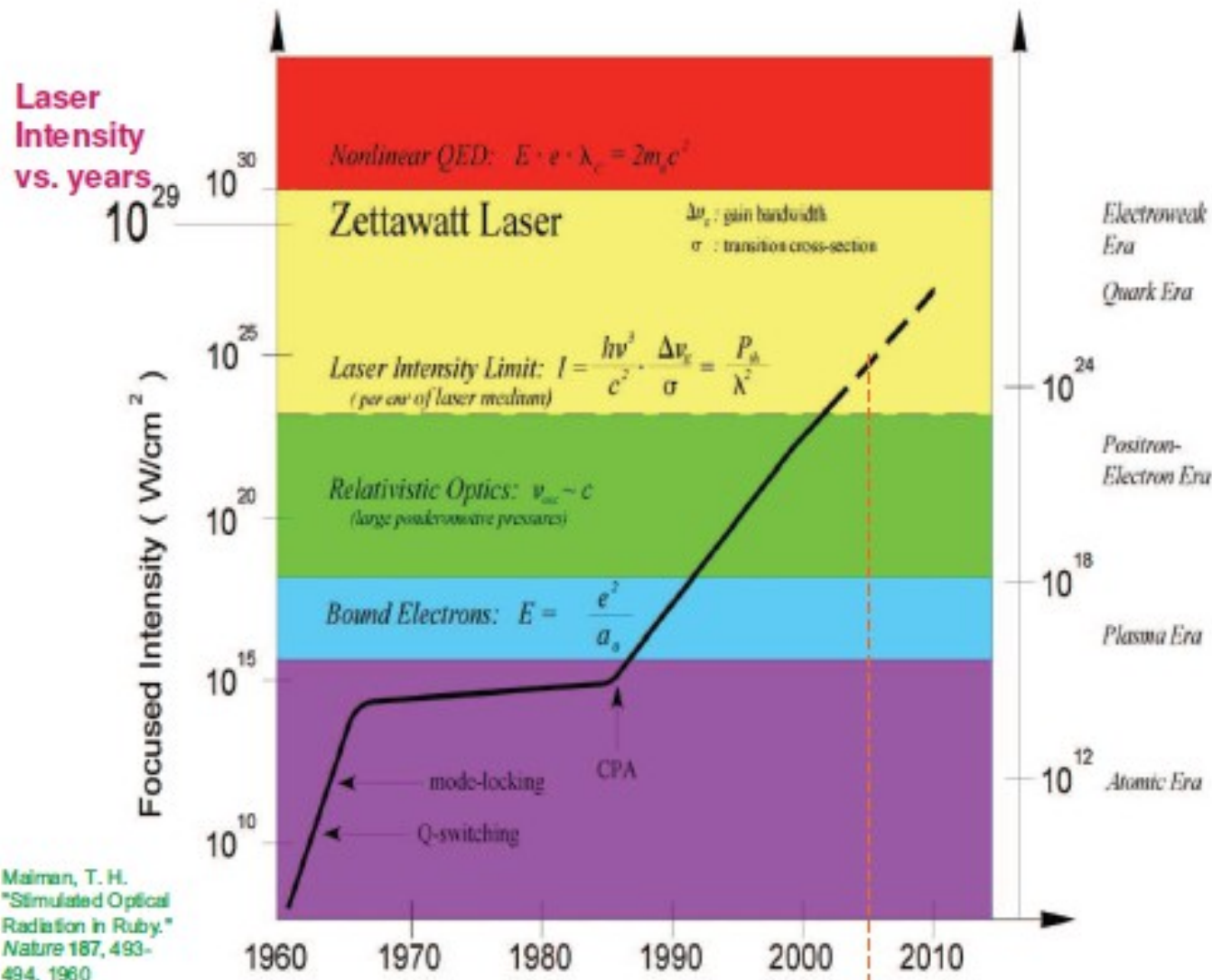
Problem: extremely short $\sim 10^{-29} \text{ s}$



ARTIST VIEW OF A MAGNETAR (NASA)

- **ELI:** Optical \rightarrow X-Ray @ 1 EW:
 $I_0 \sim 10^{25} \text{ W/cm}^2 \rightarrow I_{CHF} \sim 10^{36} \text{ W/cm}^2$
- + Long lifetime:
 $\tau \sim 10^{-15} \dots 10^{-18} \text{ s} \gg 10^{-22} \text{ s}$
- + 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

Baňk, 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 Facility (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}W/cm^2). It will offer a new paradigm in High Energy Physics.

HAWKING-UNRUH RADIATION AT LASERS

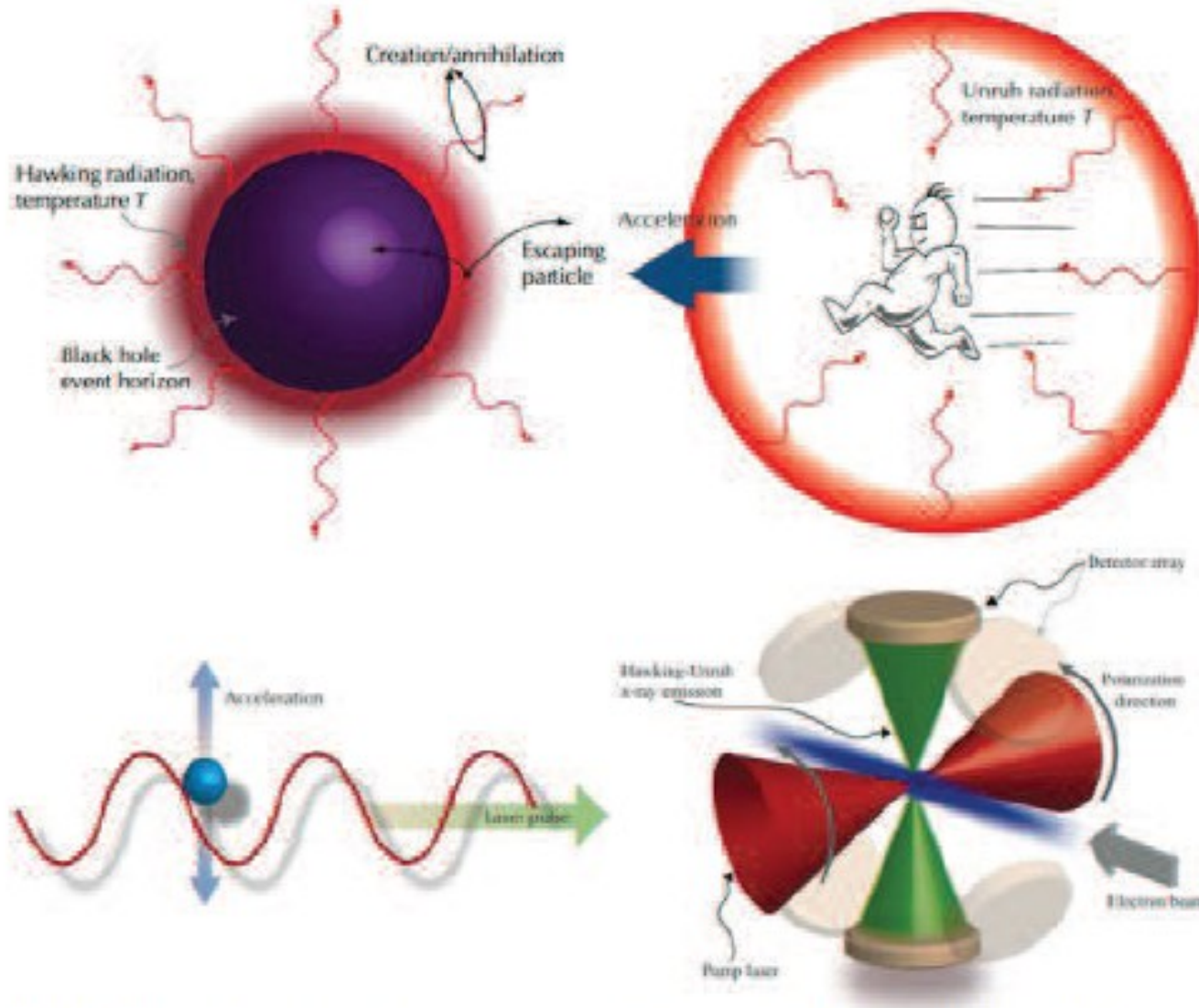


FIG. 7: The schematics of the experimental setup for Unruh radiation detection. Note that the radiation is emitted in a very particular direction as well as frequency, thus being detectable even if the background "noise" is high.

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

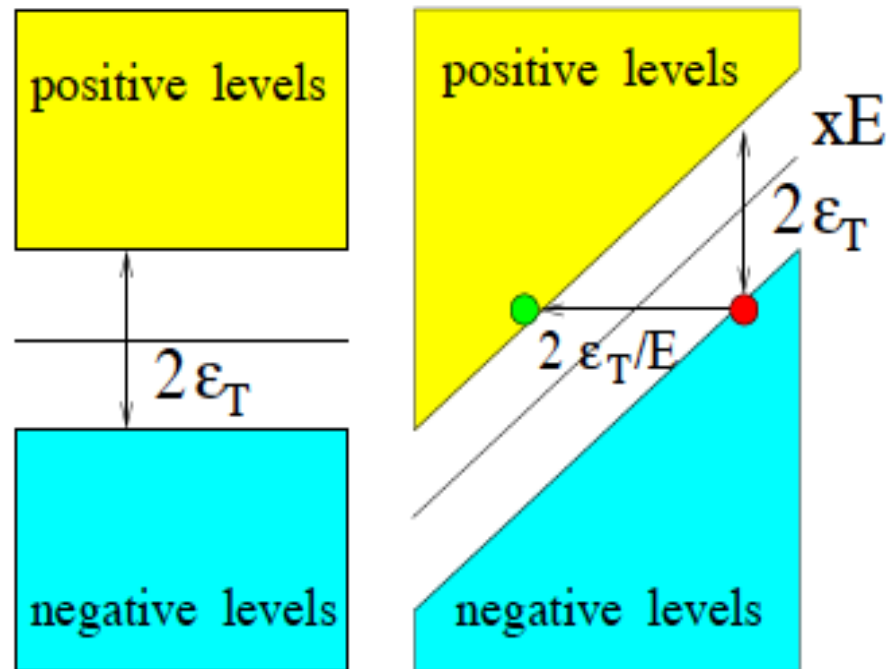
SCHWINGER EFFECT: PAIR CREATION IN STRONG FIELDS

Boom! From Light Comes Matter



SCHWINGER EFFECT: PAIR CREATION IN STRONG FIELDS

Pair creation as barrier penetration in a strong constant field



Schwinger result (rate for pair production)

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

- 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

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

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

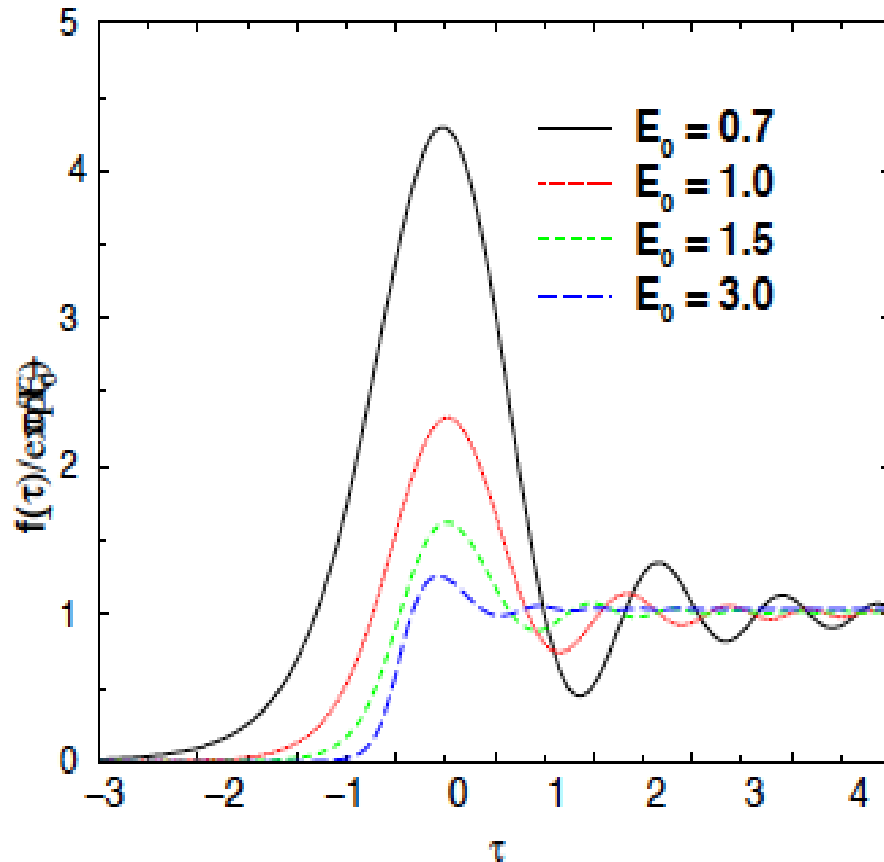
$$E_{\text{crit}} \equiv \frac{m^2c^3}{e\hbar} \simeq 1.3 \times 10^{18} \text{V/m}$$

- 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 $f(\bar{P}, t) = \langle 0 | a_{\bar{P}}^\dagger(t) a_{\bar{P}}(t) | 0 \rangle$



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

$$\begin{aligned} \frac{df_{\pm}(\bar{P}, t)}{dt} &= \frac{\partial f_{\pm}(\bar{P}, t)}{\partial t} + eE(t) \frac{\partial f_{\pm}(\bar{P}, t)}{\partial P_{\parallel}(t)} \\ &= \frac{1}{2} \mathcal{W}_{\pm}(t) \int_{-\infty}^t dt' \mathcal{W}_{\pm}(t') [1 \pm 2f_{\pm}(\bar{P}, t')] \cos[x(t', t)] \end{aligned}$$

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 $x(t', t) = 2[\Theta(t) - \Theta(t')]$.

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

Constant field: Schwinger limit reproduced

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

Kinetic Approach – sketch of the derivation

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

↓

spatially-uniform electric field

$$\vec{E}(t) = (0, 0, E(t))$$

$$E(t) = -\frac{d}{dt}A(t)$$

Ansatz¹ for fermionic wavefunction

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

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

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

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

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

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

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

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

$$\{ b_{\mathbf{q}r}, b_{\mathbf{q}'r'}^+ \} = \{ d_{\mathbf{q}r}, d_{\mathbf{q}'r'}^+ \} = \delta_{rr'} \delta_{\mathbf{q}\mathbf{q}'}$$

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

Time-dependent Bogoliubov transformation

- Transformation

$$b_{\mathbf{q}r}(t) = \alpha_{\mathbf{q}}(t) b_{\mathbf{q}r}(t_0) + \beta_{\mathbf{q}}(t) d_{-\mathbf{q}r}^+(t_0) ,$$

$$d_{\mathbf{q}r}(t) = \alpha_{-\mathbf{q}}(t) d_{\mathbf{q}r}(t_0) - \beta_{-\mathbf{q}}(t) b_{-\mathbf{q}r}^+(t_0)$$

- 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

$$\begin{aligned}\frac{dB_{\mathbf{q}r}(t)}{dt} &= -\frac{eE(t)\varepsilon_{\perp}}{2\varepsilon^2(\mathbf{q}, t)} D_{-\mathbf{q}r}^+(t) + i [H(t), B_{\mathbf{q}r}(t)] , \\ \frac{dD_{\mathbf{q}r}(t)}{dt} &= \frac{eE(t)\varepsilon_{\perp}}{2\varepsilon^2(\mathbf{q}, t)} B_{-\mathbf{q}r}^+(t) + i [H(t), D_{\mathbf{q}r}(t)] ,\end{aligned}$$

- New Hamiltonian

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

- Kinetic equation

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

Kinetic equation (without back reaction)

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

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

Non-Markovian kinetic equation

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

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

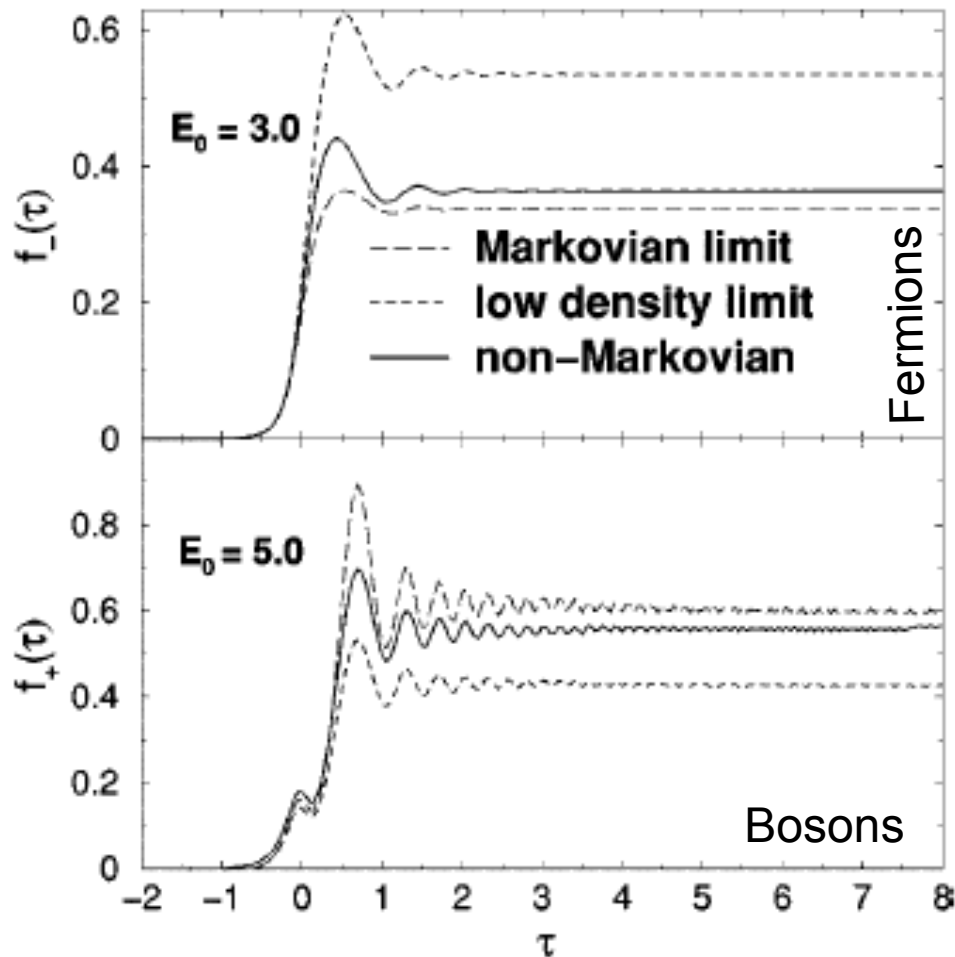
$$\varepsilon_{\perp} = \sqrt{m^2 + q_{\perp}^2}$$

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

KE is equivalent to a system of ordinary differential equations

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

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



Markovian limit :

$$\frac{d f_{\pm}^M(\tau)}{d\tau} = [1 \pm 2f_{\pm}^M(\tau)] S_{\pm}^0(\tau) = S_{\pm}^M(\tau),$$

$$f_{\pm}^M(\tau) = \mp \frac{1}{2} \left(1 - \exp \left[\pm 2 \int_{-\infty}^{\tau} d\tau' S_{\pm}^0(\tau') \right] \right).$$

Low-density limit :

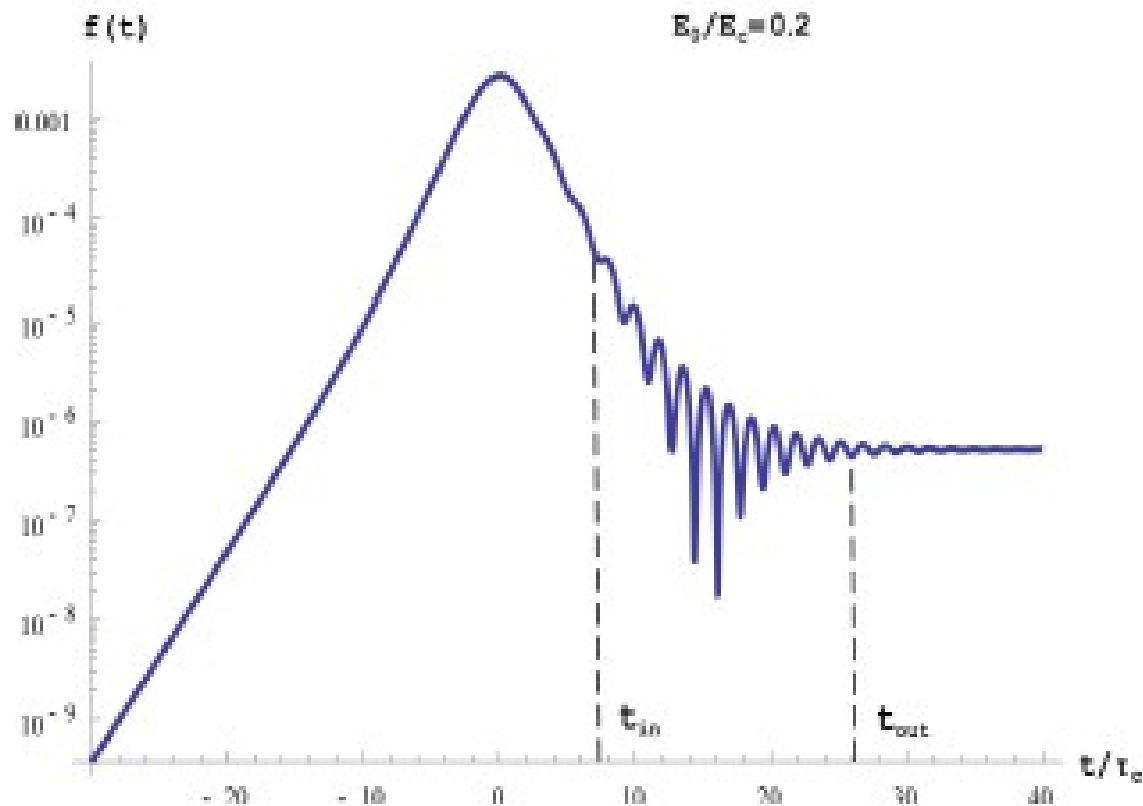
$$f_{\pm}^0(\tau) = \int_{-\infty}^{\tau} d\tau' S_{\pm}^0(\tau').$$

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

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

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

Examples (quasi-particle and mass-shell stage)



- Sauter pulse

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

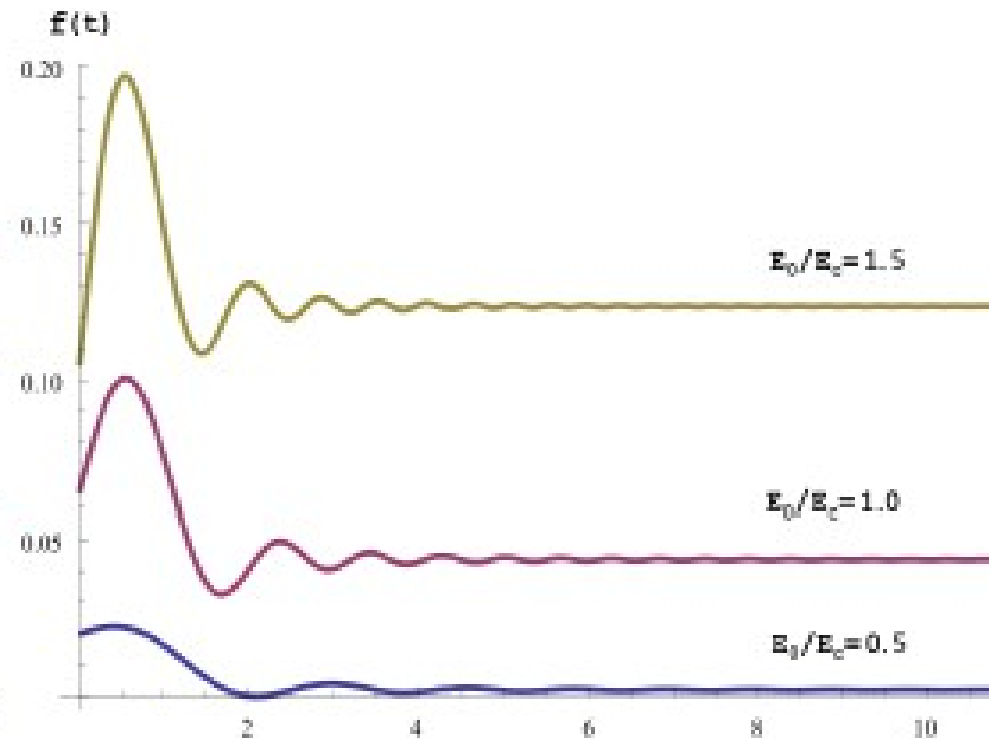
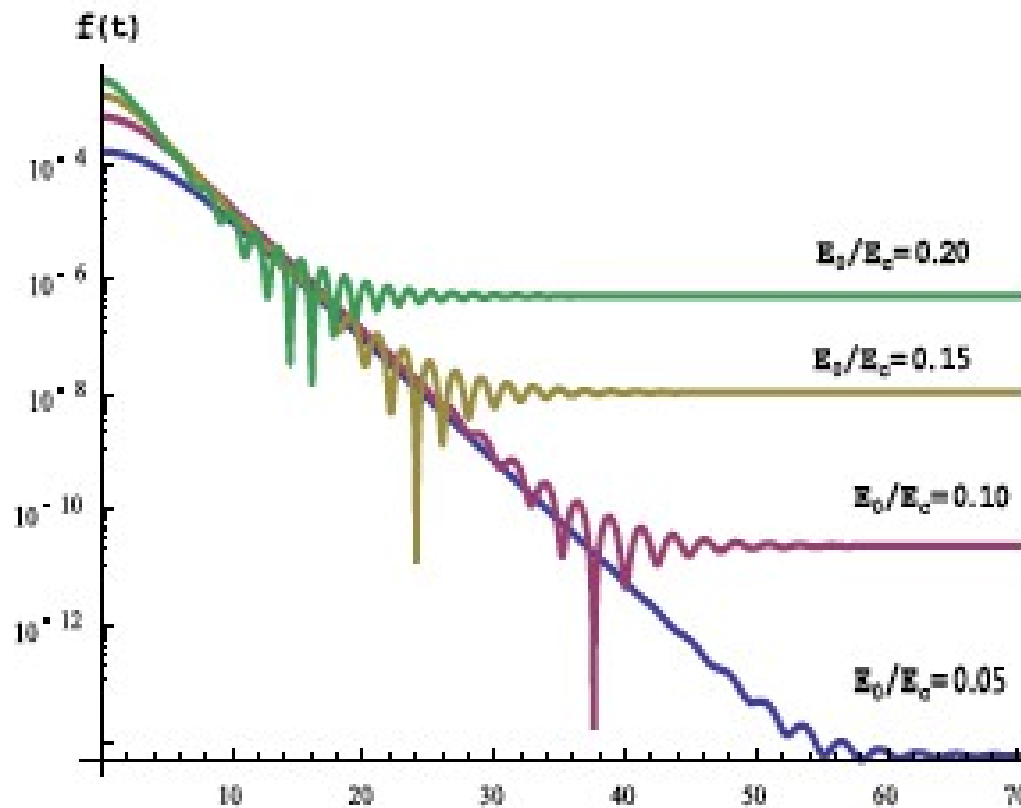
- $T = 0.02\text{nm}$
- $p_{\perp} = p_{\parallel} = 0$
- $[t_{in}, t_{out}]$ - transient region between quasi-particle and mass-shell stage

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)

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



t/τ_c

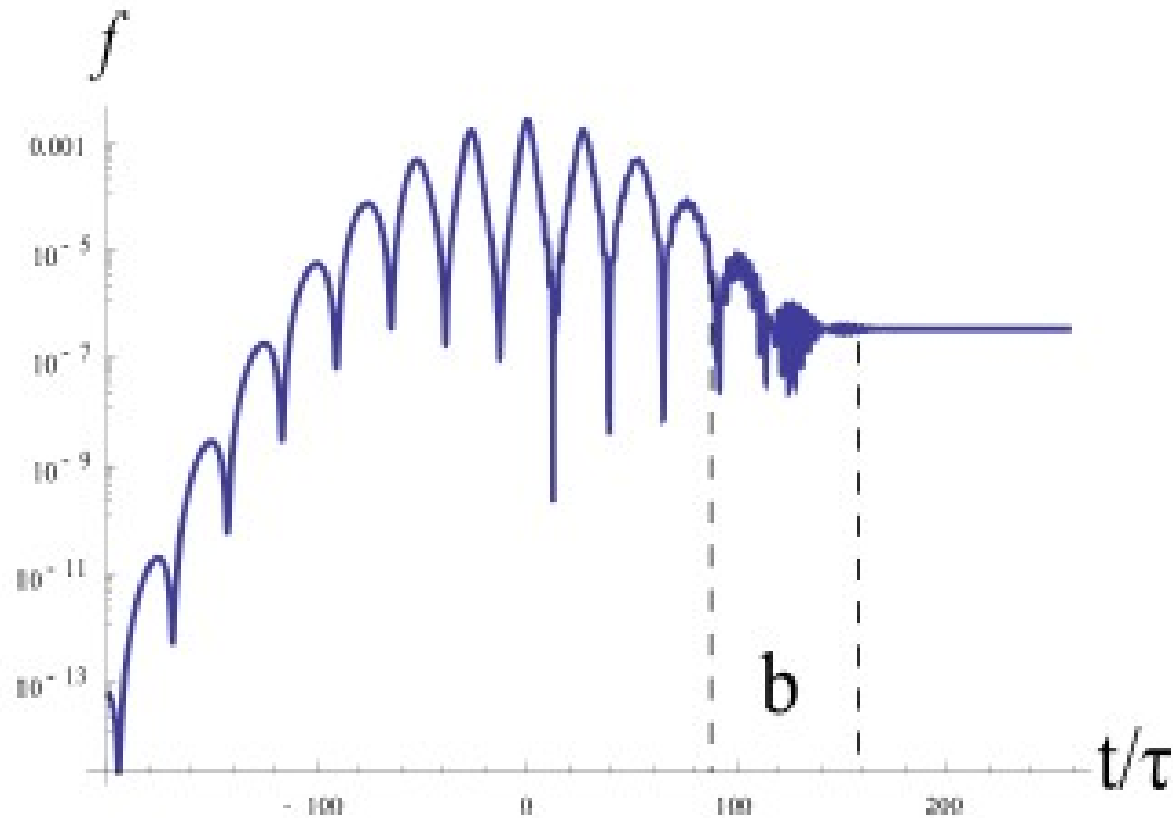
Dynamical Schwinger effect: Properties of the e^+e^- plasma created from vacuum in strong laser fields

t/τ_c

Blaschke, Juchnowski, Panferov et al. arXiv:1412.6372

Examples (quasi-particle and mass-shell stage)

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



$$E_0 = 0.2E_c$$

the region "b" corresponds to the transient process

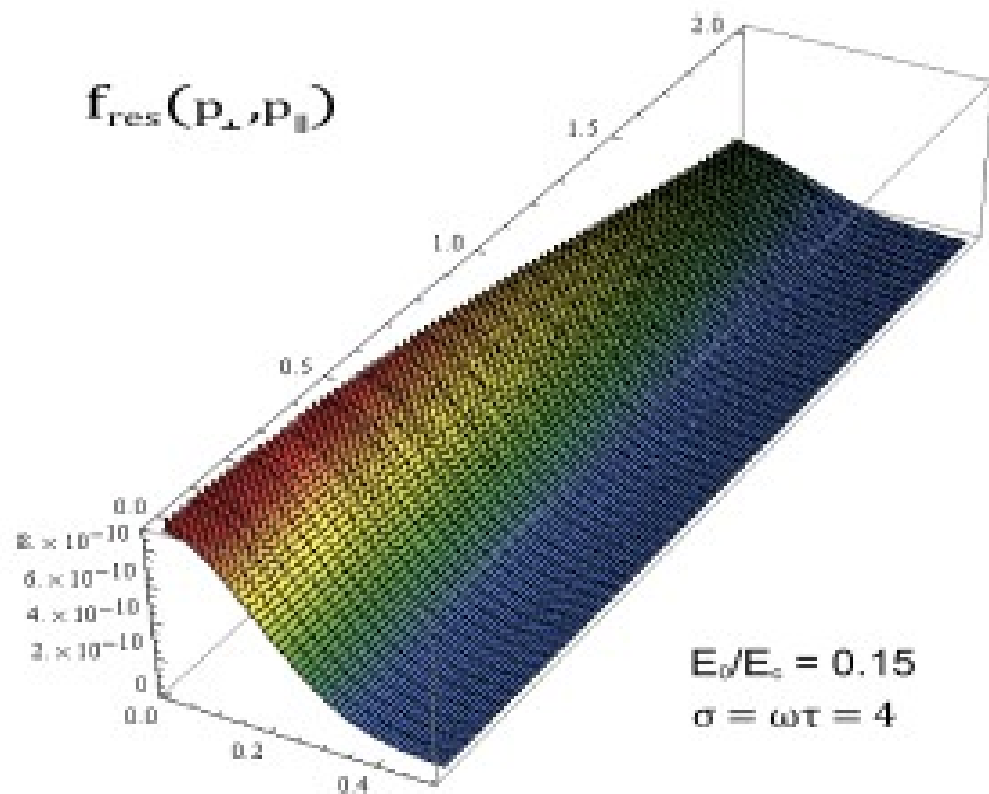
$$t/\tau_c$$

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

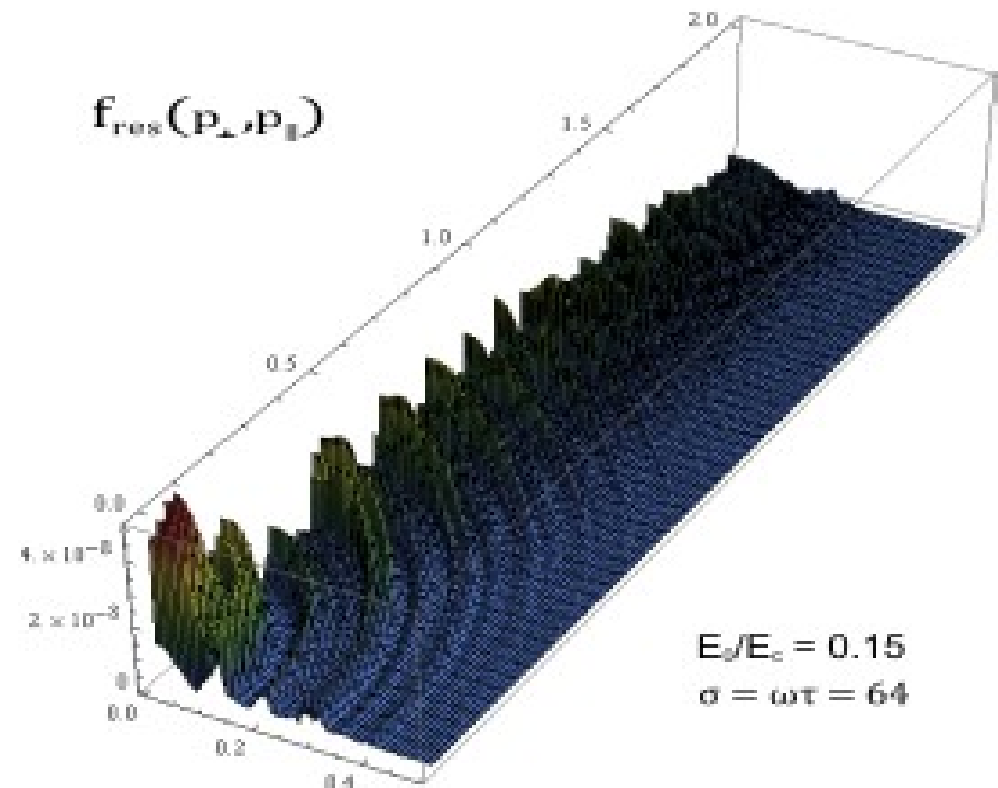
Blaschke, Juchnowski, Panferov et al. arXiv:1412.6372

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

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



Short pulse

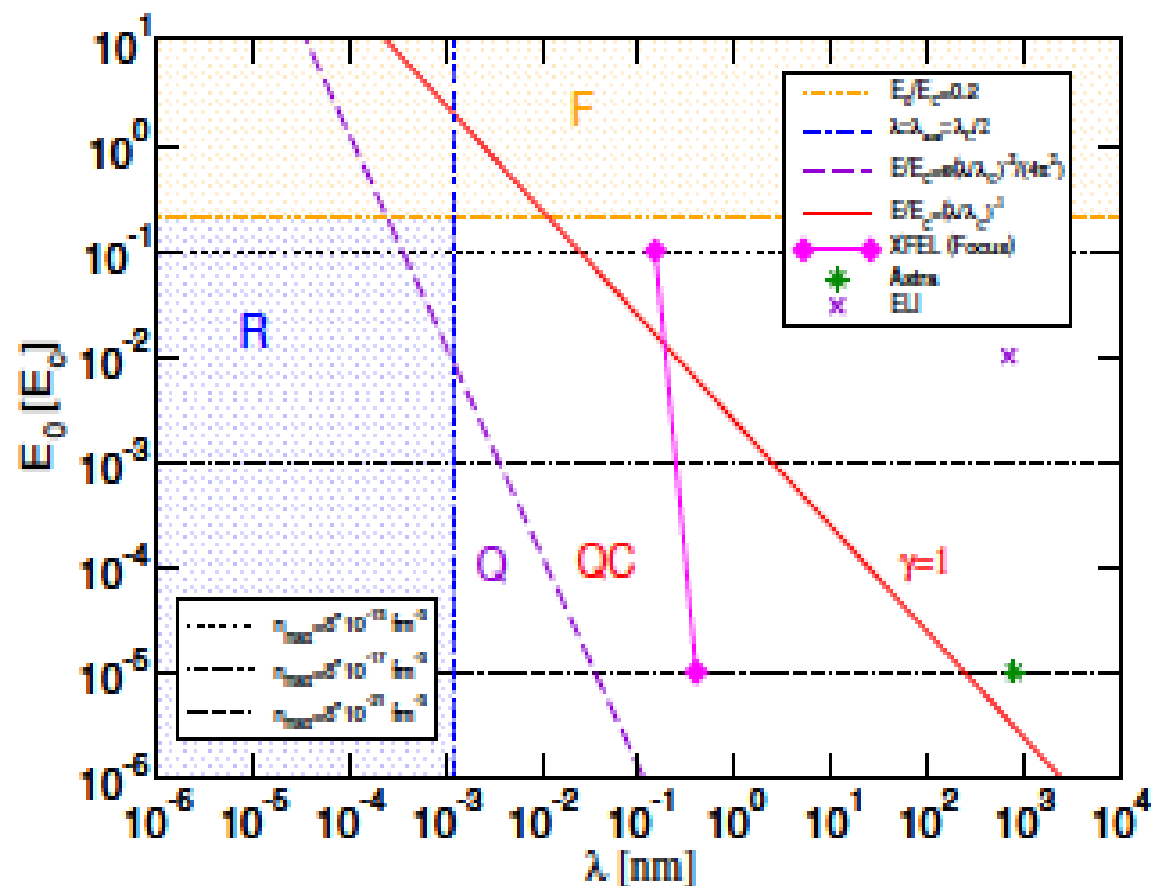


Long pulse

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

Blaschke, Juchnowski, Panferov et al. arXiv:1412.6372

Landscape

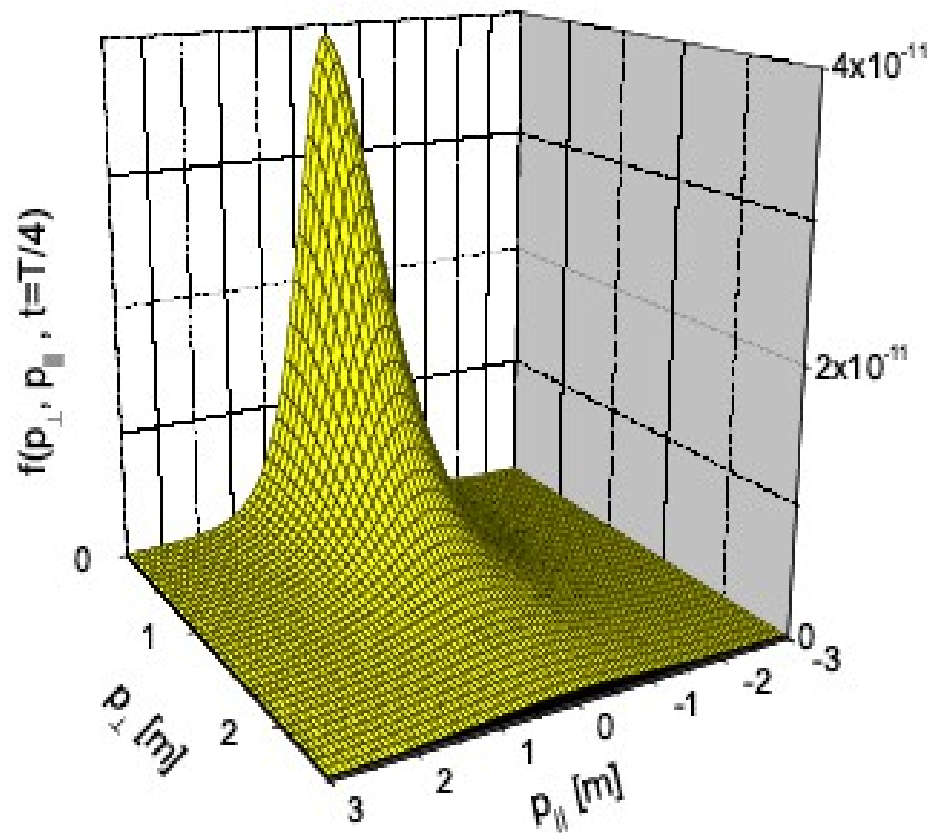


- Change of variables
 $(\omega, E) \rightarrow (\gamma, E)$
- Adiabaticity parameter

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

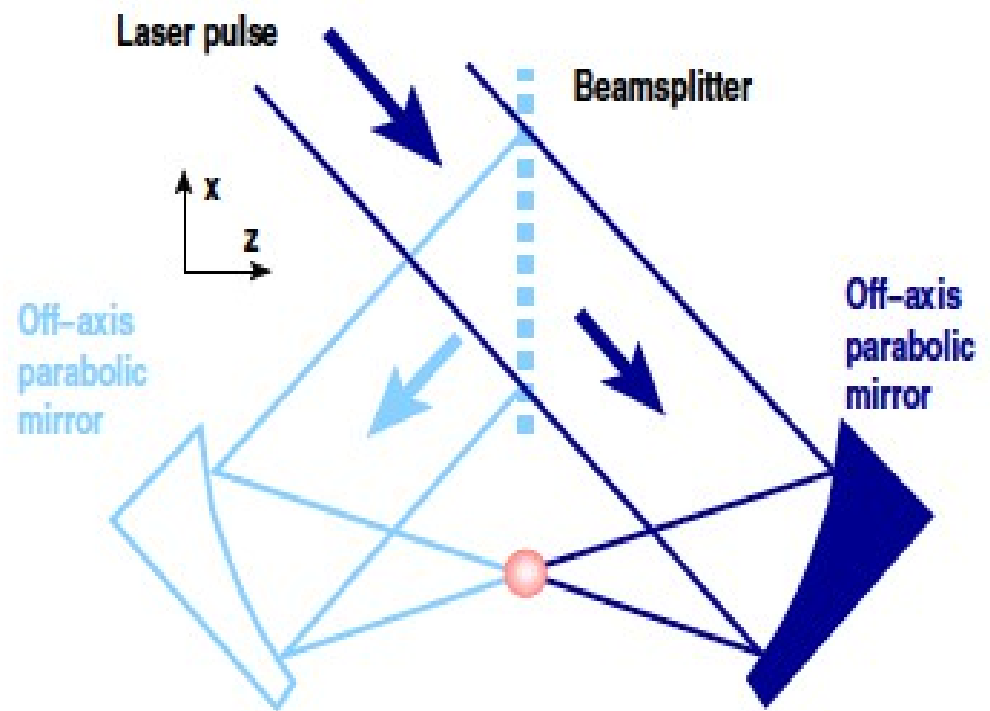
- Red line $\gamma = 1$ separates two regimes
- Tunneling limit $\gamma \ll 1$
- Multiphoton limit $\gamma \gg 1$

APPLICATION TO SUBCRITICAL LASER FIELDS



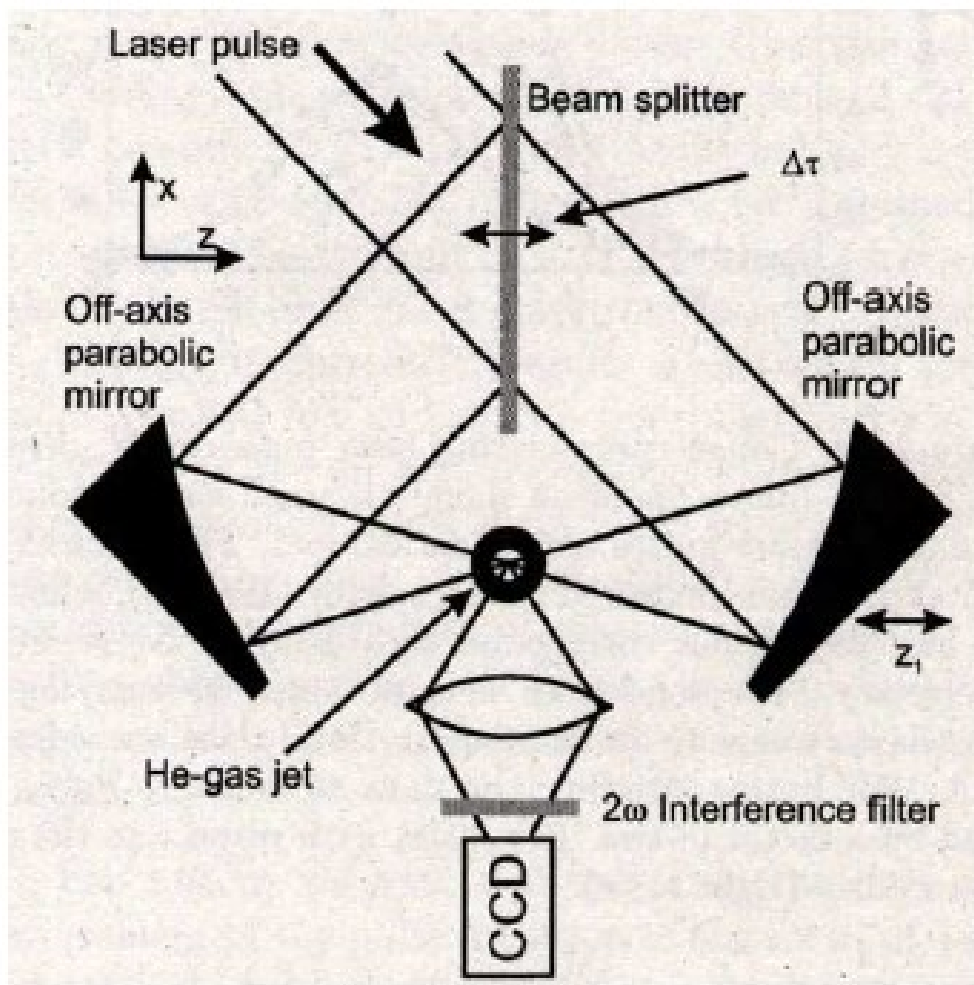
Equilibrium-like momentum distribution at the time of maximal field amplitude $t = T/4$.

Setup of the Jena Laser Exp. (2005)

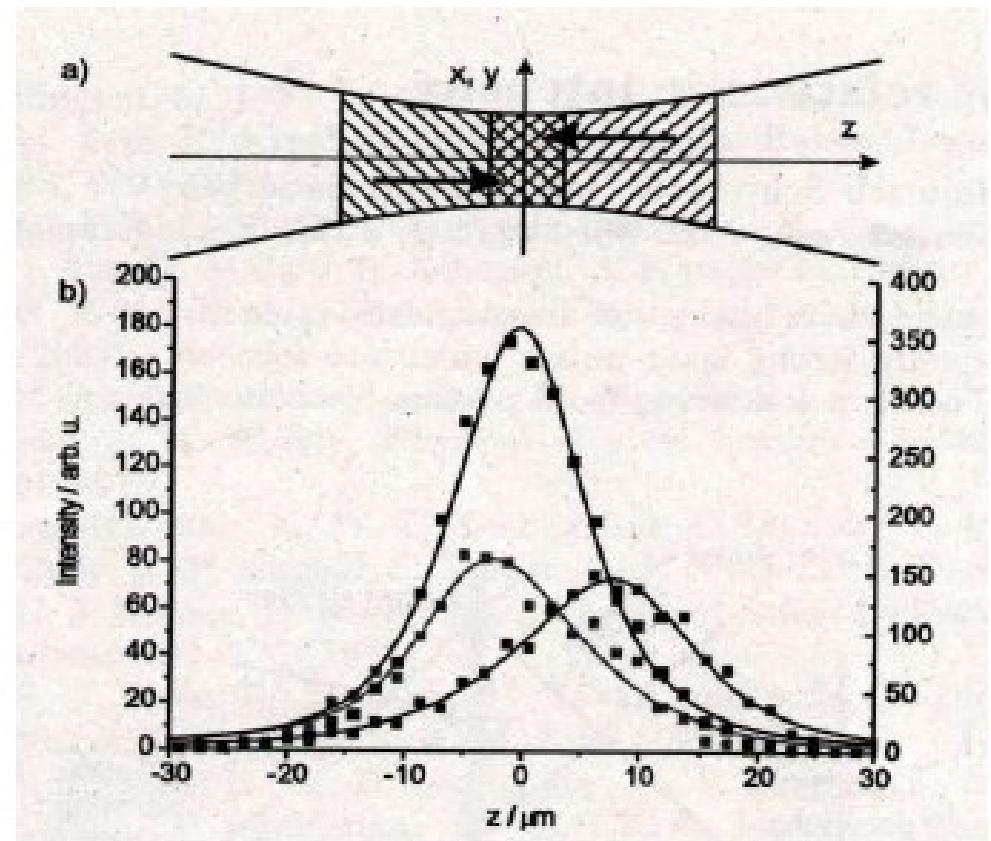


Heinzl, et al., *Opt. Commun.* 267, 318 (2006)

APPLICATION TO JENA MULTI-TW LASER



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



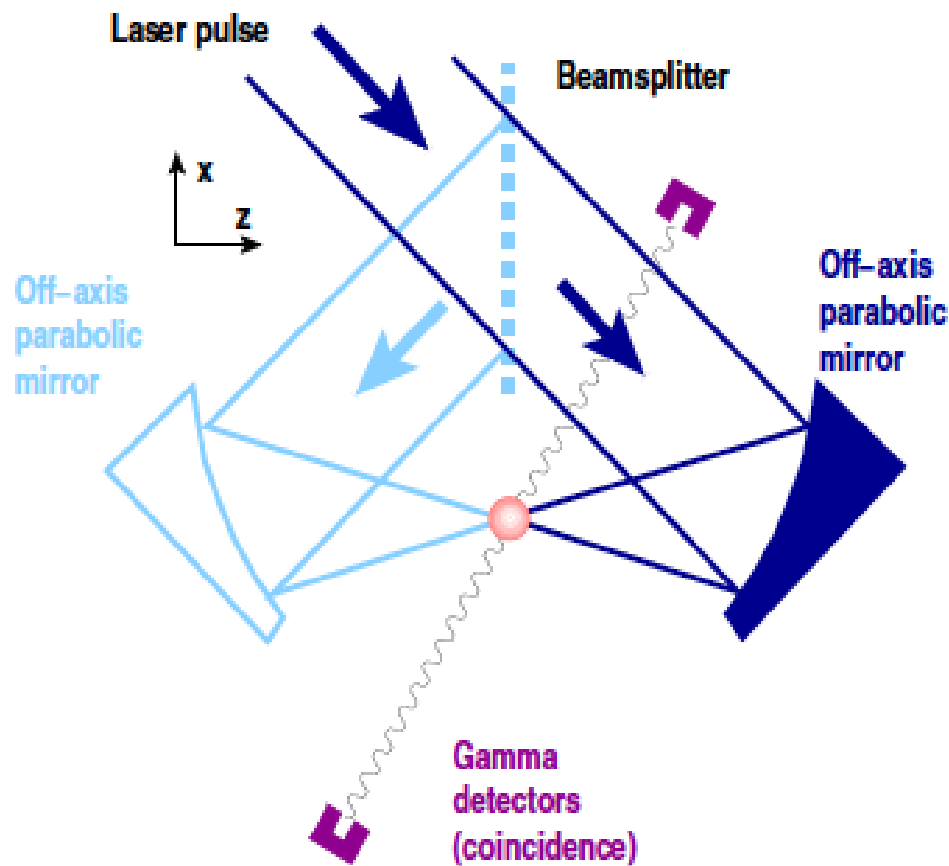
Laser diagnostic by nonlinear Thomson scattering off e^- in a He-gas jet

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

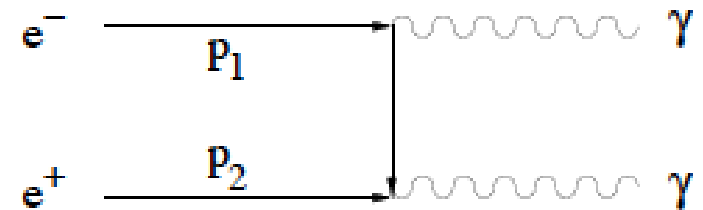
B. Liesfeld et al: "Single-shot autocorrelation at relativistic intensity", Jena Preprint (2004)

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

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



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



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

cross-section σ of two-photon annihilation

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

t-channel kinematic invariant

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

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

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

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 $(\delta = 2m - k, \text{ frequency mismatch})$

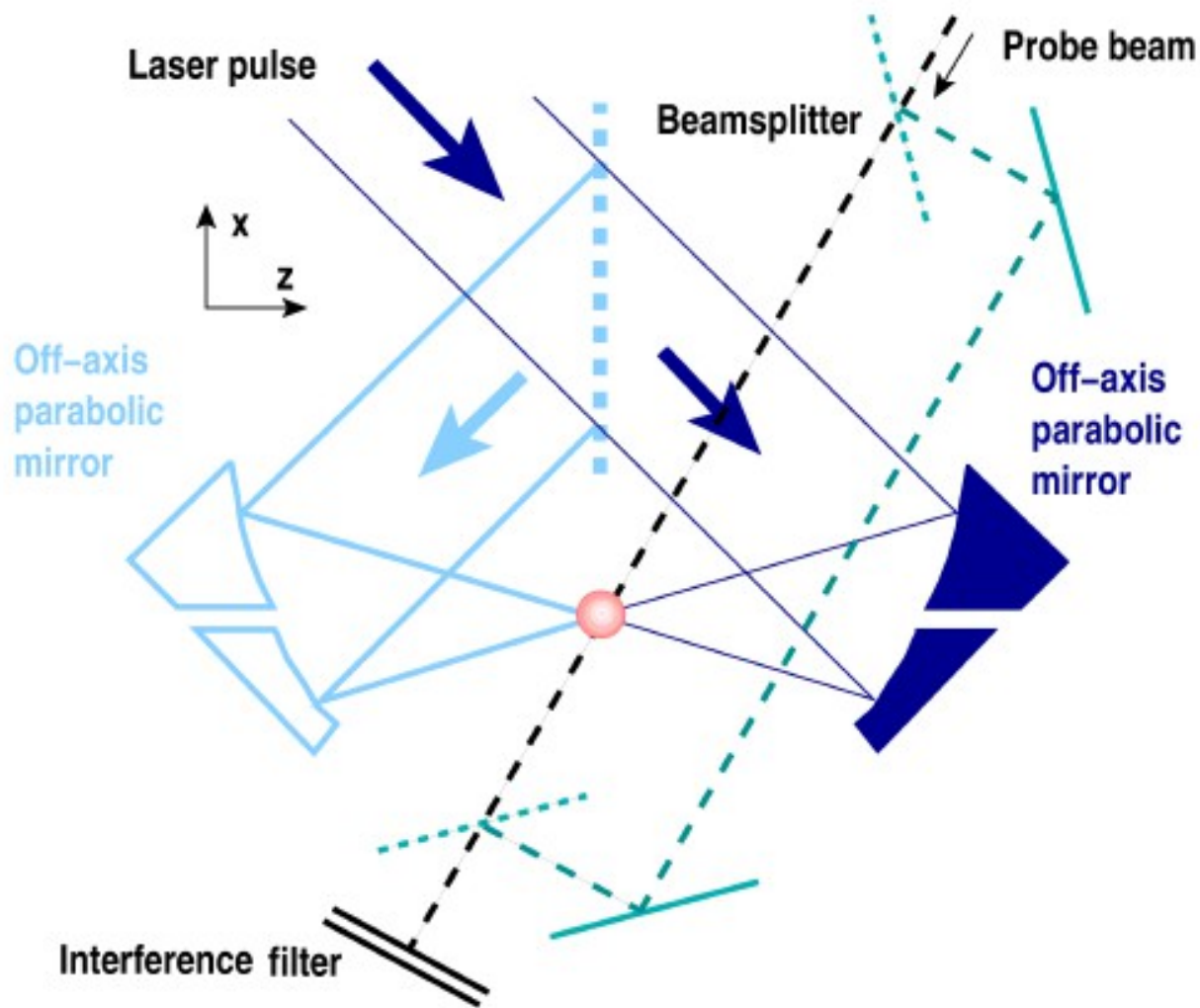
$$F(\mathbf{k}, t) = \frac{5e^2 n(t)}{2k\delta^2}, \quad n(t) = 2 \int d^3p f(\mathbf{p}, t) / (2\pi)^3$$

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

$$F(k) \sim 1/k$$

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

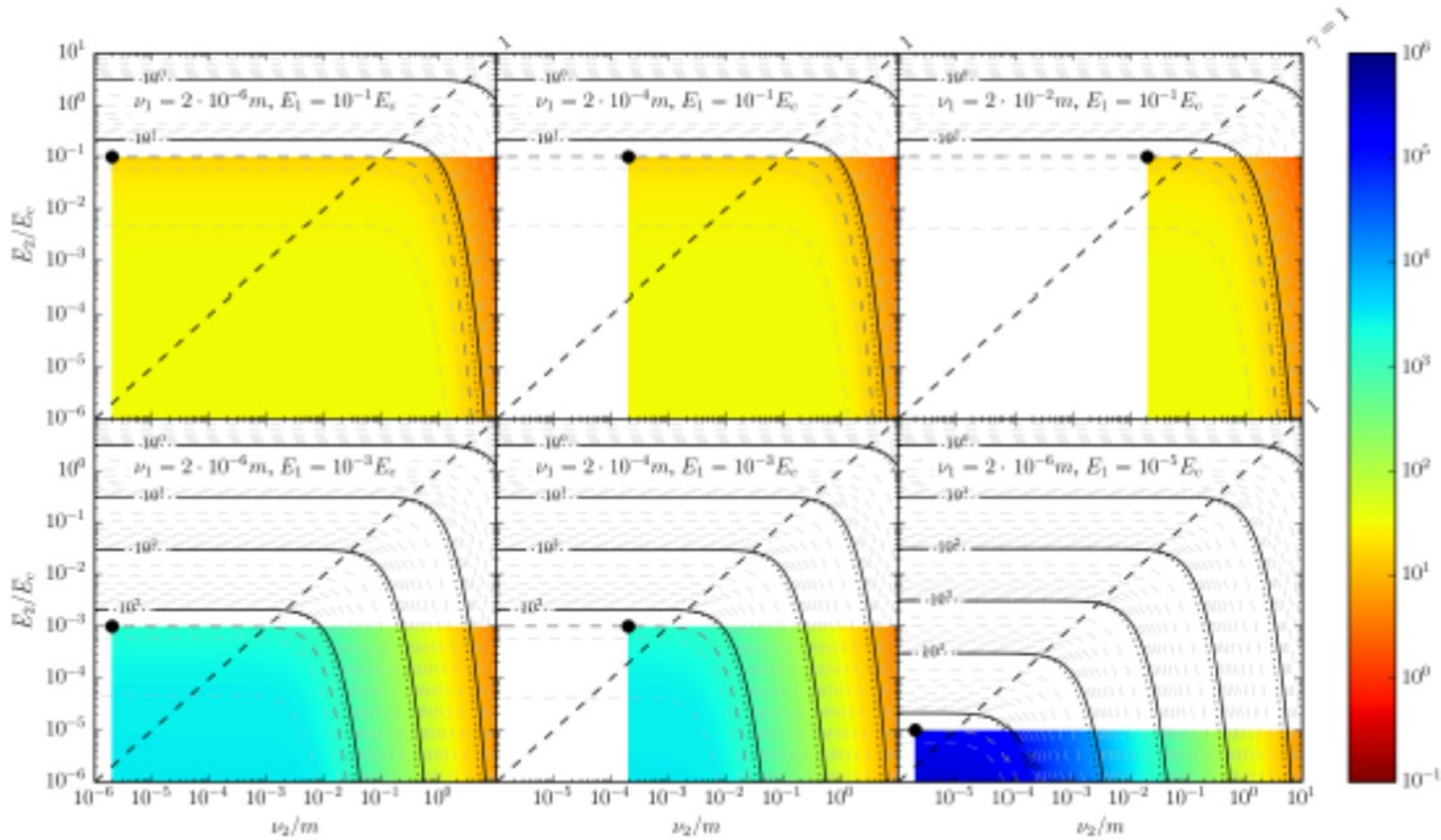


Figure 3: Contour plots of the exponential $4 \frac{m}{\nu_1} G(p_{\perp} \ll m, \gamma_1, \gamma_2, N)$ for six given fields ν_1, E_1 in the adiabatic region (positions depicted by the bullets, which are the loci of field doubling) over the field-frequency (E_2/E_c vs. ν_2/m) plane, i.e. actually $4 \frac{m}{\nu_1} G(p_{\perp} \ll m, \nu_1, E_1, \nu_2, E_2)$. Despite of the displayed smooth distribution, our results are strictly valid only for $E_2 < E_1$ and $\nu_2 = (4n + 1)\nu_1$, $n = 0, 1, 2, \dots$. Light grey dashed contour curves are for $2, \dots, 9$ 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.

Lessons for Nonequilibrium Dynamics in Heavy-Ion Collisions ?



Fluctuations of the string tension and transverse mass distribution

A. Bialas^{a,b}

“Schwinger”

“Thermal”

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

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

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

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

SCHWINGER TUNNELING AND THERMAL CHARACTER OF HADRON SPECTRA

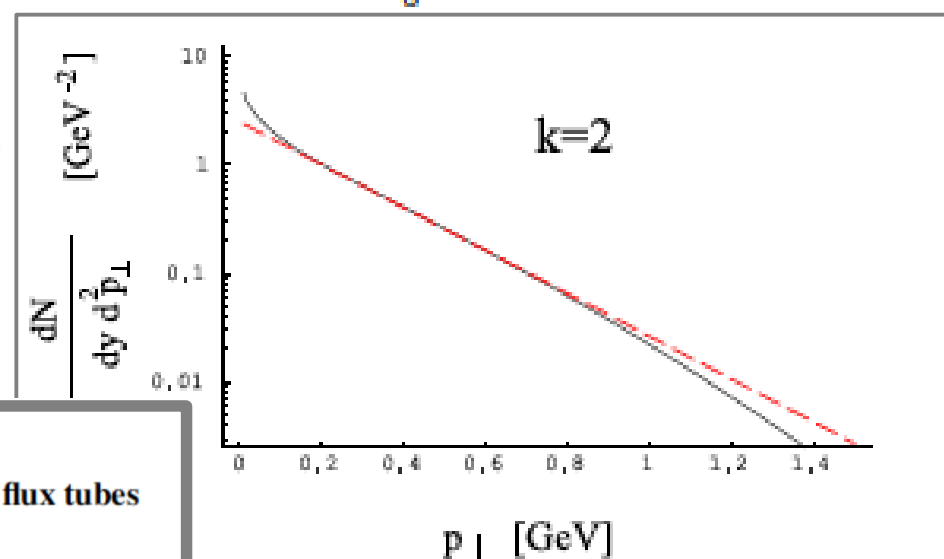
WOJCIECH FLORKOWSKI

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

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

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

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



PHYSICAL REVIEW D 88, 034028 (2013)

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

Radosław Ryblewski^{1,*} and Wojciech Florkowski^{1,2,†}

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 $\epsilon_{qp}(T) = \epsilon_{lat}(T)$.

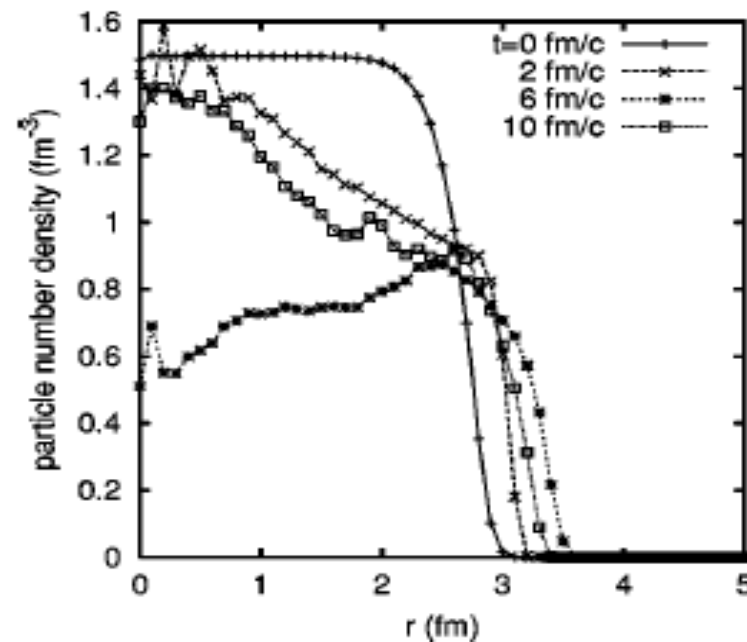
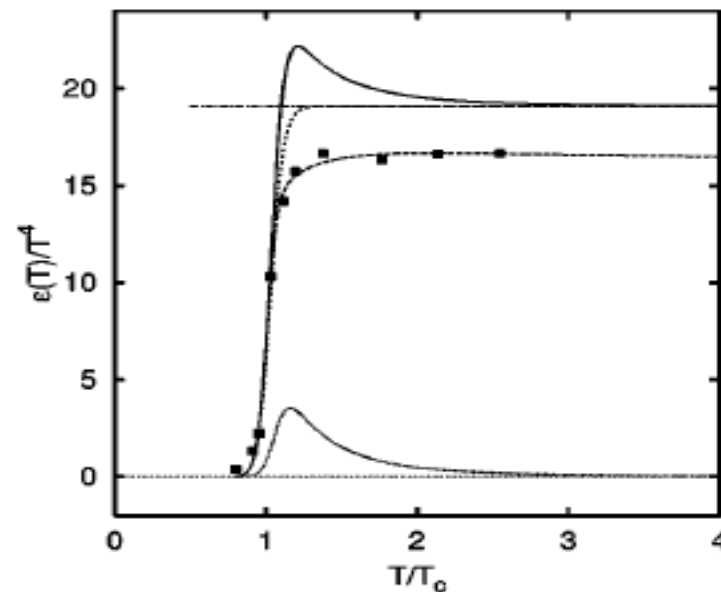
$$\begin{aligned} \epsilon_{qp}(T) &= \sum_i g_i \int \frac{d^3p}{(2\pi)^3} E_i f_i(E_i) + V(T) \\ &= \epsilon_{kin}(m, T) + V(T), \end{aligned}$$

Vlasov Equation for phase space distribution function:

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

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

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



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

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

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

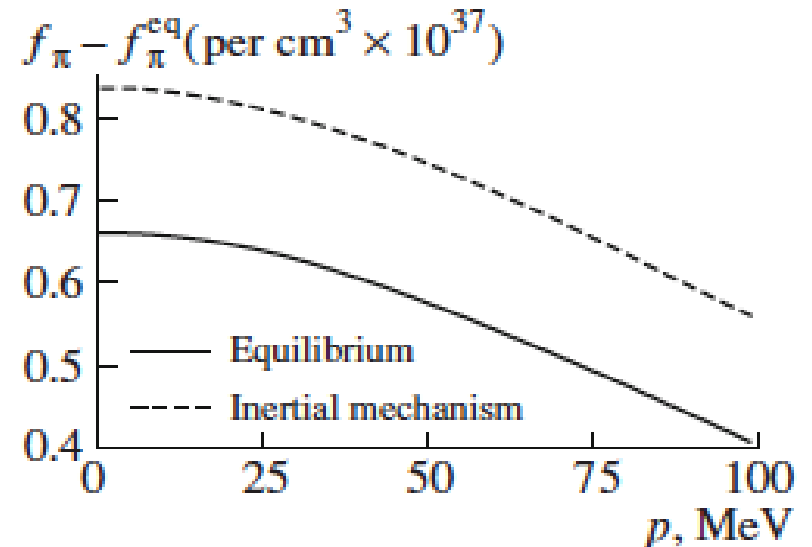
$$\dot{f}_\alpha = I_\alpha^{\text{vac}} + I_\alpha^{\sigma \rightarrow \pi\pi} + I_\alpha^{\text{ex}}.$$

Detailed balance: Loss \leftrightarrow Gain ...

Bose enhancement for pion distribution!

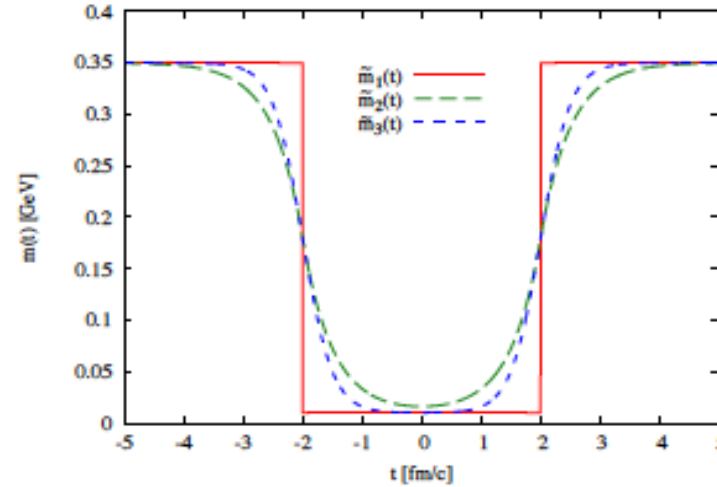
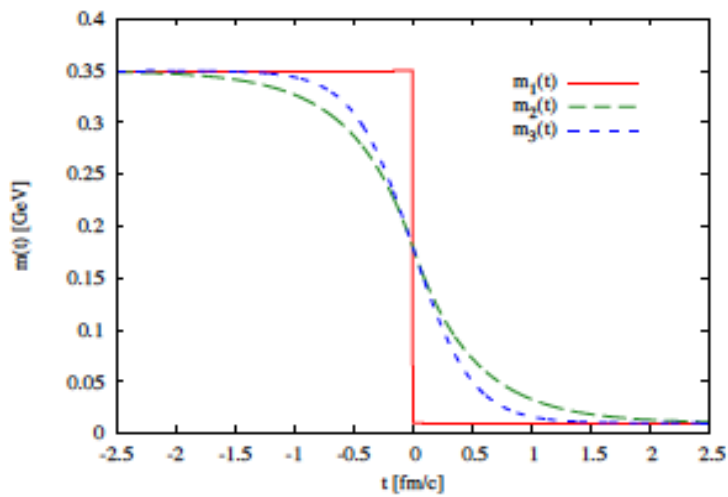
$$I_\sigma^{\text{loss}}(\mathbf{p}, t) = - \int \frac{d\mathbf{p}_1 d\mathbf{p}_2}{\omega_\pi(\mathbf{p}_1, t) \omega_\pi(\mathbf{p}_2, t)} \Gamma_{\sigma \rightarrow \pi\pi}(\mathbf{p}, \mathbf{p}_1, \mathbf{p}_2; t) \times f_\sigma(\mathbf{p}, t) [1 + f_\pi(\mathbf{p}_1, t)] [1 + f_\pi(\mathbf{p}_2,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

$$I_\sigma^{\text{loss}}(t) = \pi \left[\frac{4p_u(t)}{m_\sigma(t)} \right]^3 \Gamma_{\sigma \rightarrow \pi\pi}(p_u, t) [1 + f_\pi(p_u, t)]^2.$$

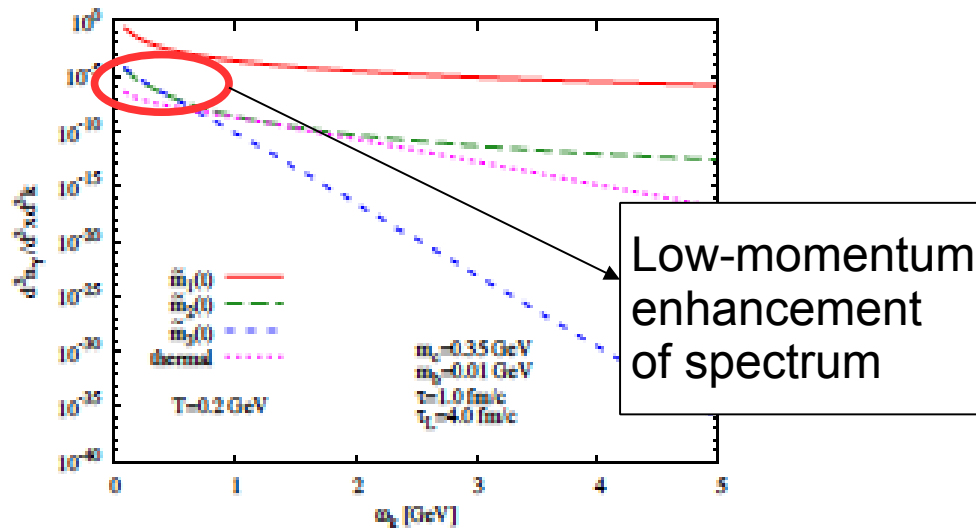
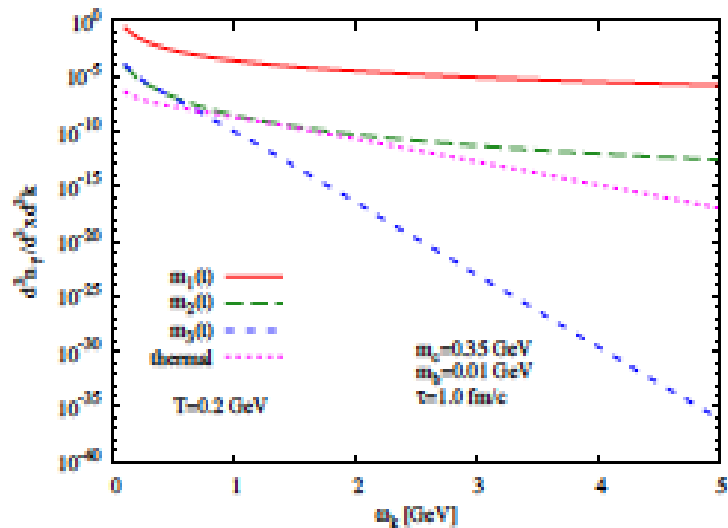


Off-equilibrium photon production during the chiral phase transition

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

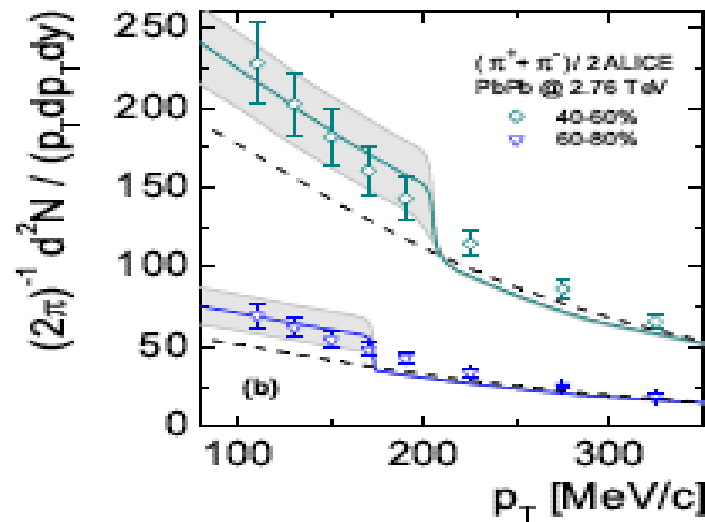
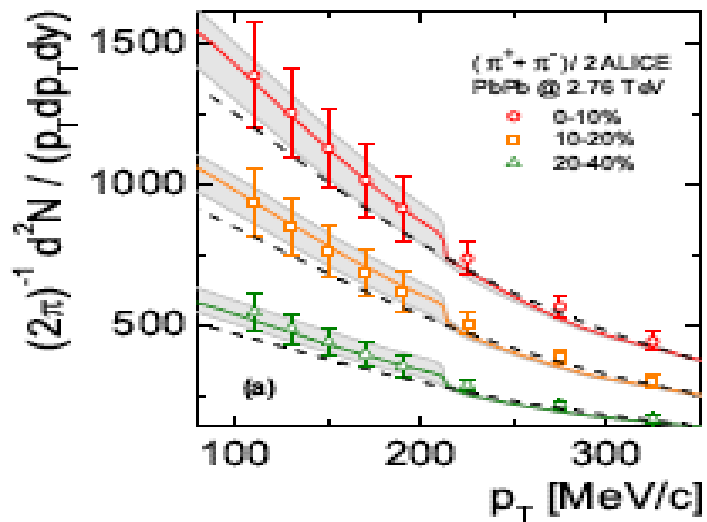
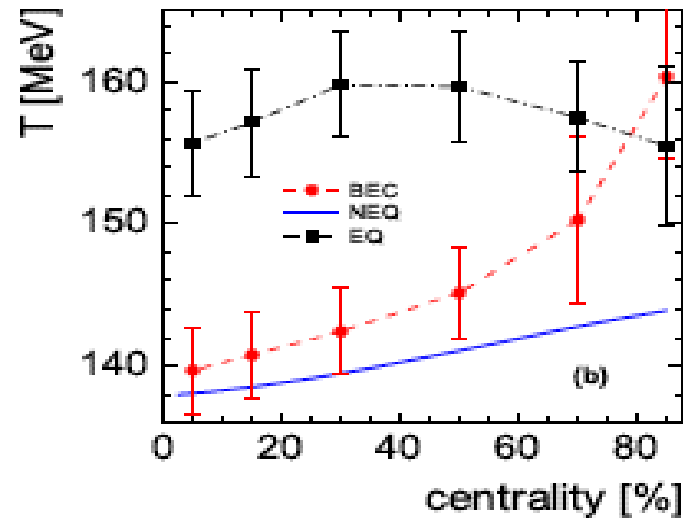
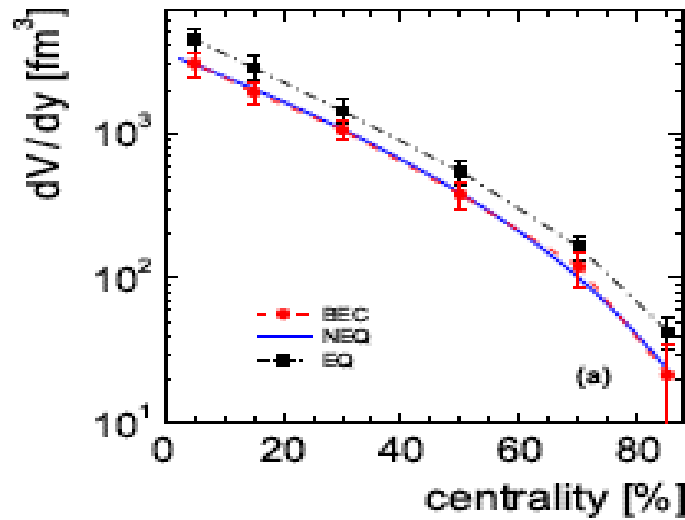


Low-momentum enhancement of spectrum

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 ?

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

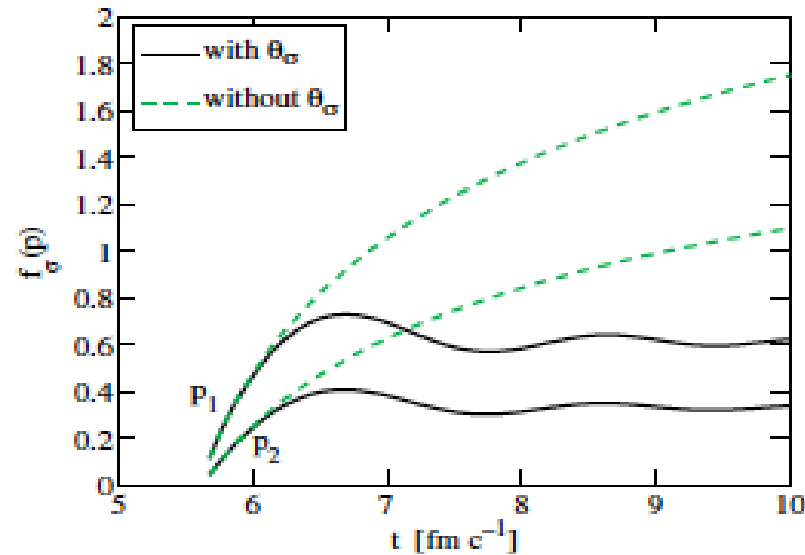
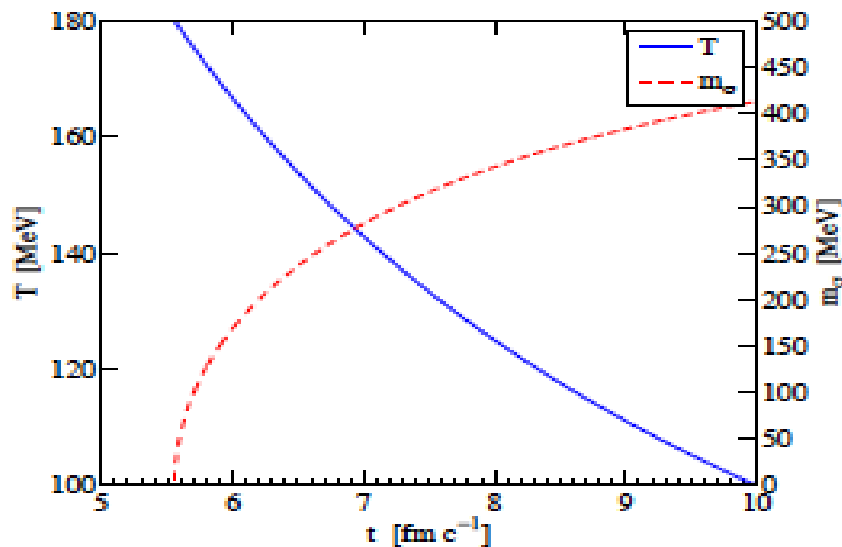


Low-momentum pion enhancement from quantum kinetics of chiral symmetry breaking

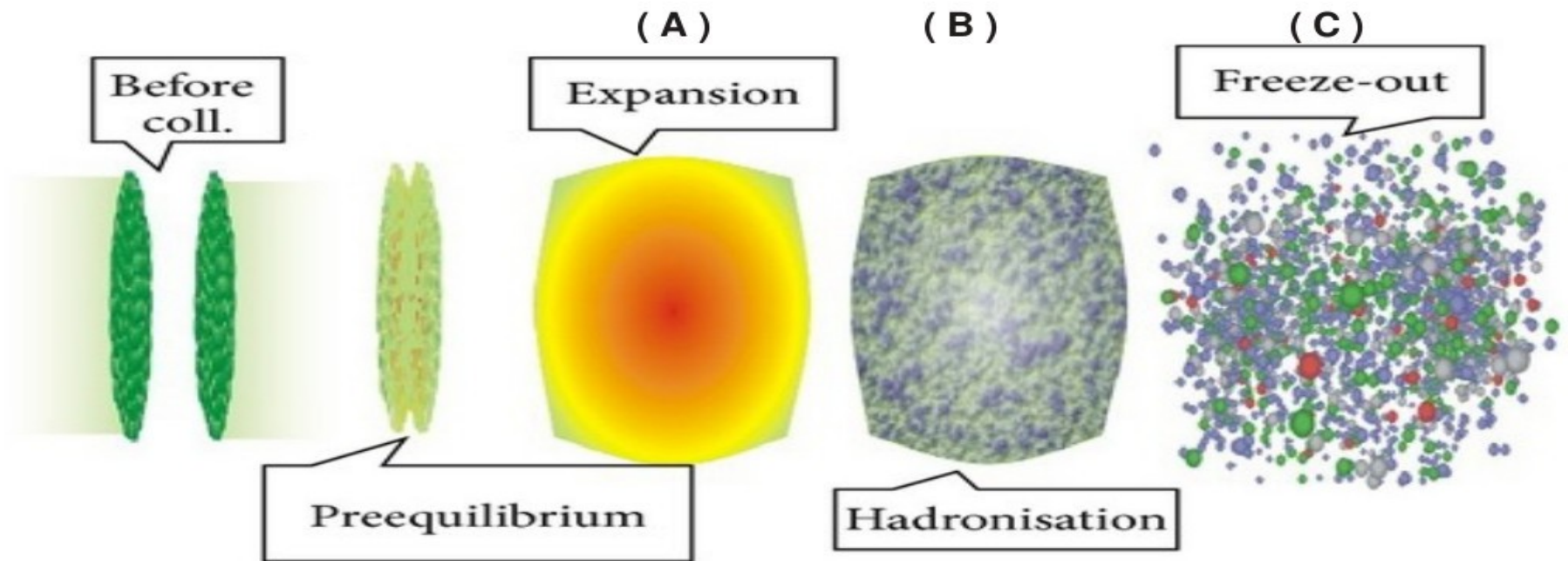
$$\begin{aligned} \frac{\partial f_\sigma}{\partial t}(t, \vec{p}_\sigma) &= \left. \frac{df_\sigma}{dt} \right|_{\text{collisions}} \\ &= \frac{\Delta_\sigma(t, \vec{p}_\sigma)}{2} \int_{t_0}^t dt' \Delta_\sigma(t', \vec{p}_\sigma) (1 + f_\sigma(t', \vec{x}, \vec{p}_\sigma)) \cos(2\theta_\sigma(t, t',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

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

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



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

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

- (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

Staff:

prof. dr hab. Krzysztof Redlich (head)
prof. dr hab. David Blaschke
prof. dr hab. Ludwik Turko
dr Chihiro Sasaki, prof. Uwr
dr Tobias Fischer
dr Thomas Klähn
dr Pok Man Lo

PhD students:

Dipl.-phys. Niels-Uwe Bastian
Dipl.-phys. Aleksandr Dubinin
mgr Łukasz Juchnowski
mgr Michał Marczenko

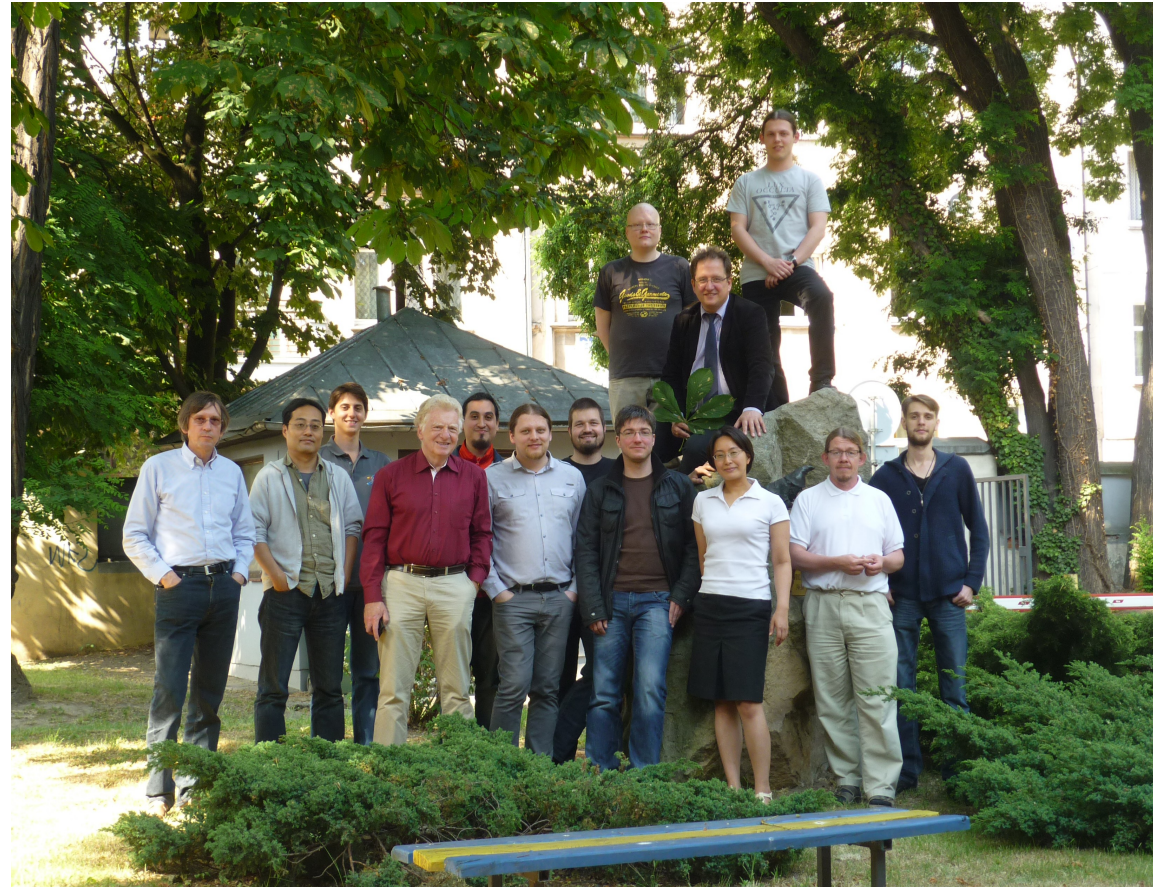
Master students:

Alaksiej Kachanovich
Mark Kaltenborn
Maciej Lewicki
Michał Naskręt
Michał Szymański

+many visitors from 4 continents

Current NCN research projects:

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

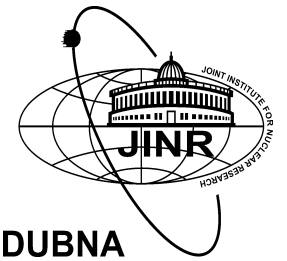
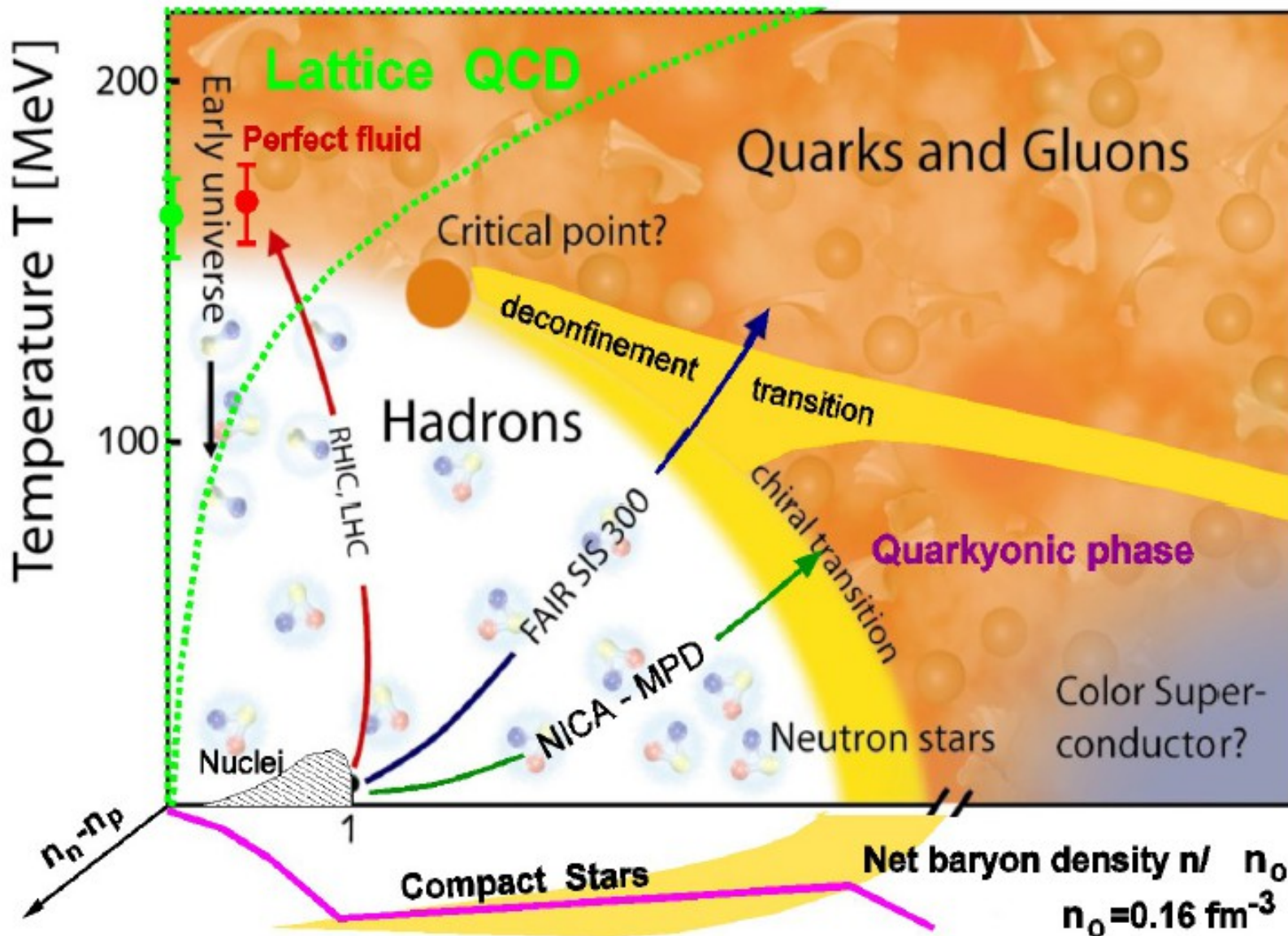


Main research topics:

- 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

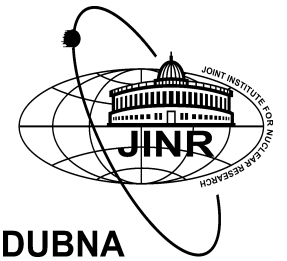
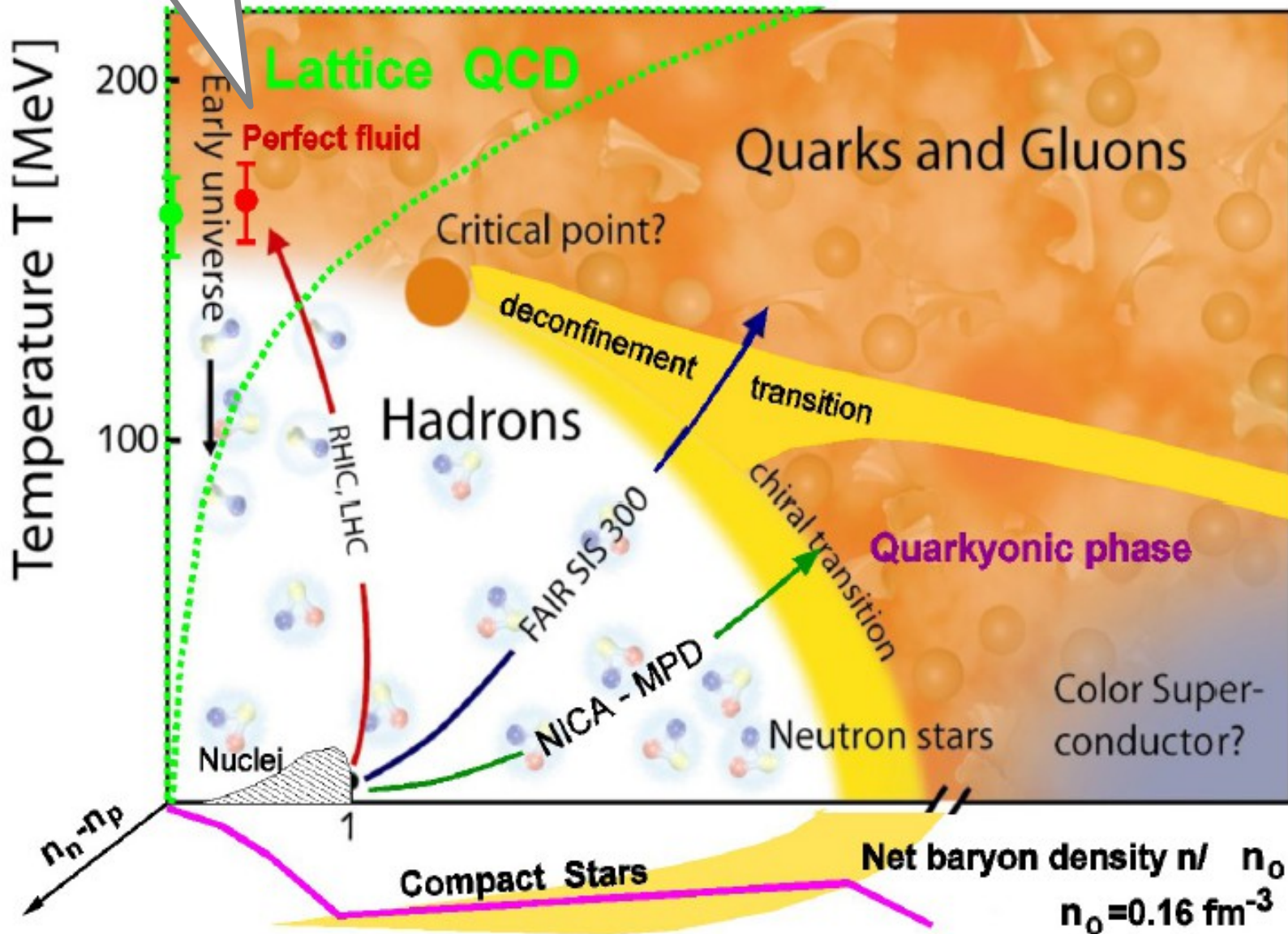


DUBNA



EUROPEAN COOPERATION
IN SCIENCE AND TECHNOLOGY

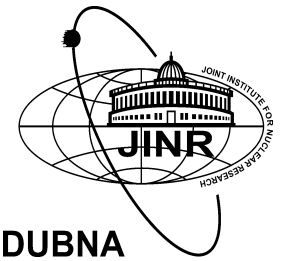
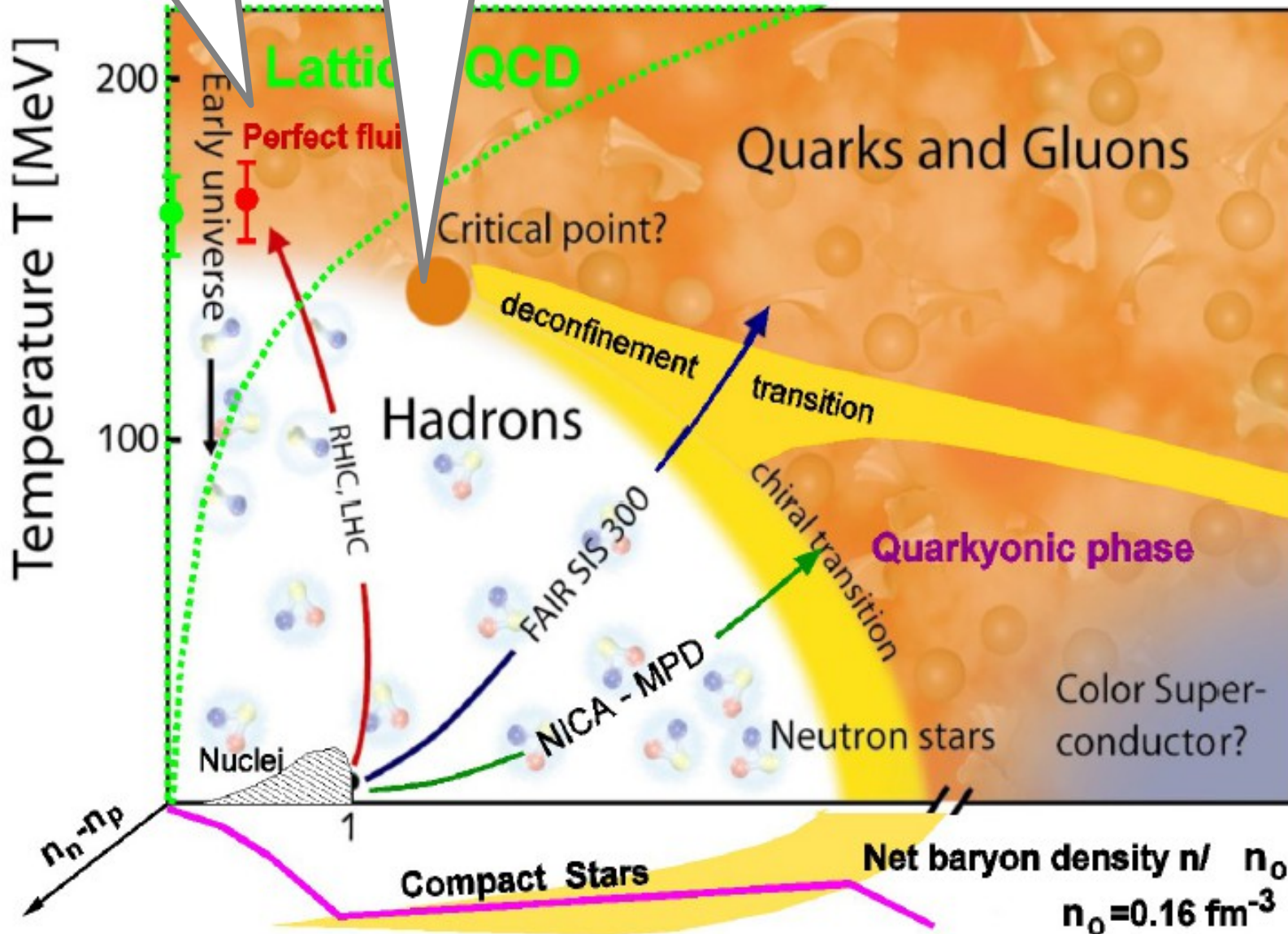
Division: Theory of Elementary Particles - Collaborations



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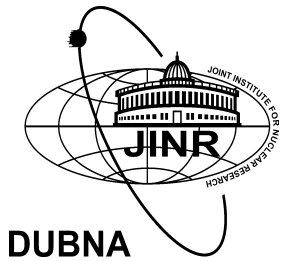
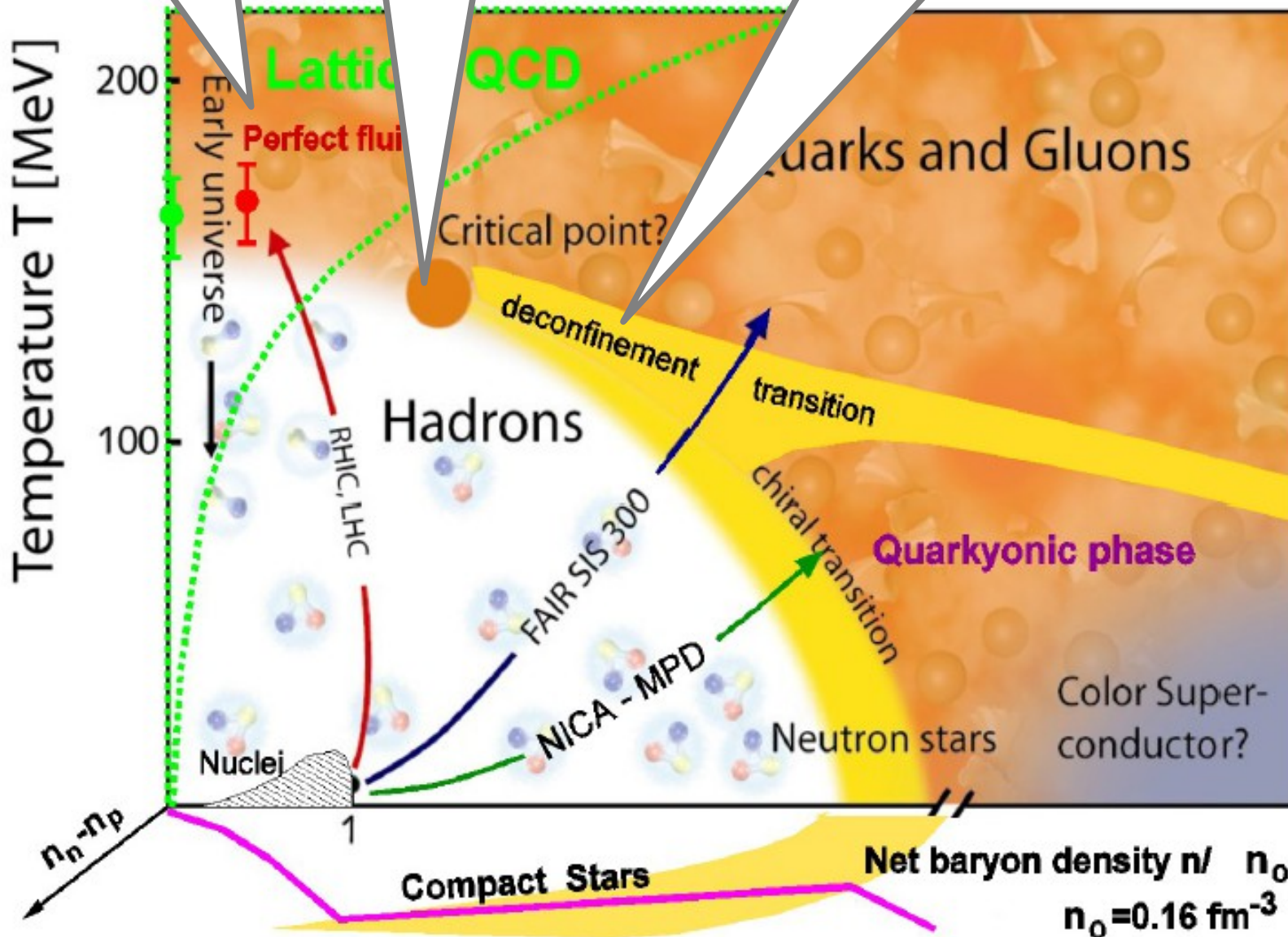
Division: Theory of Elementary Particles - Collaborations



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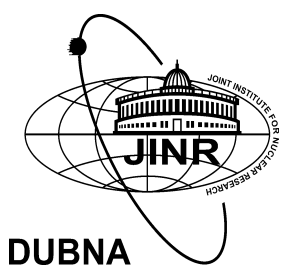
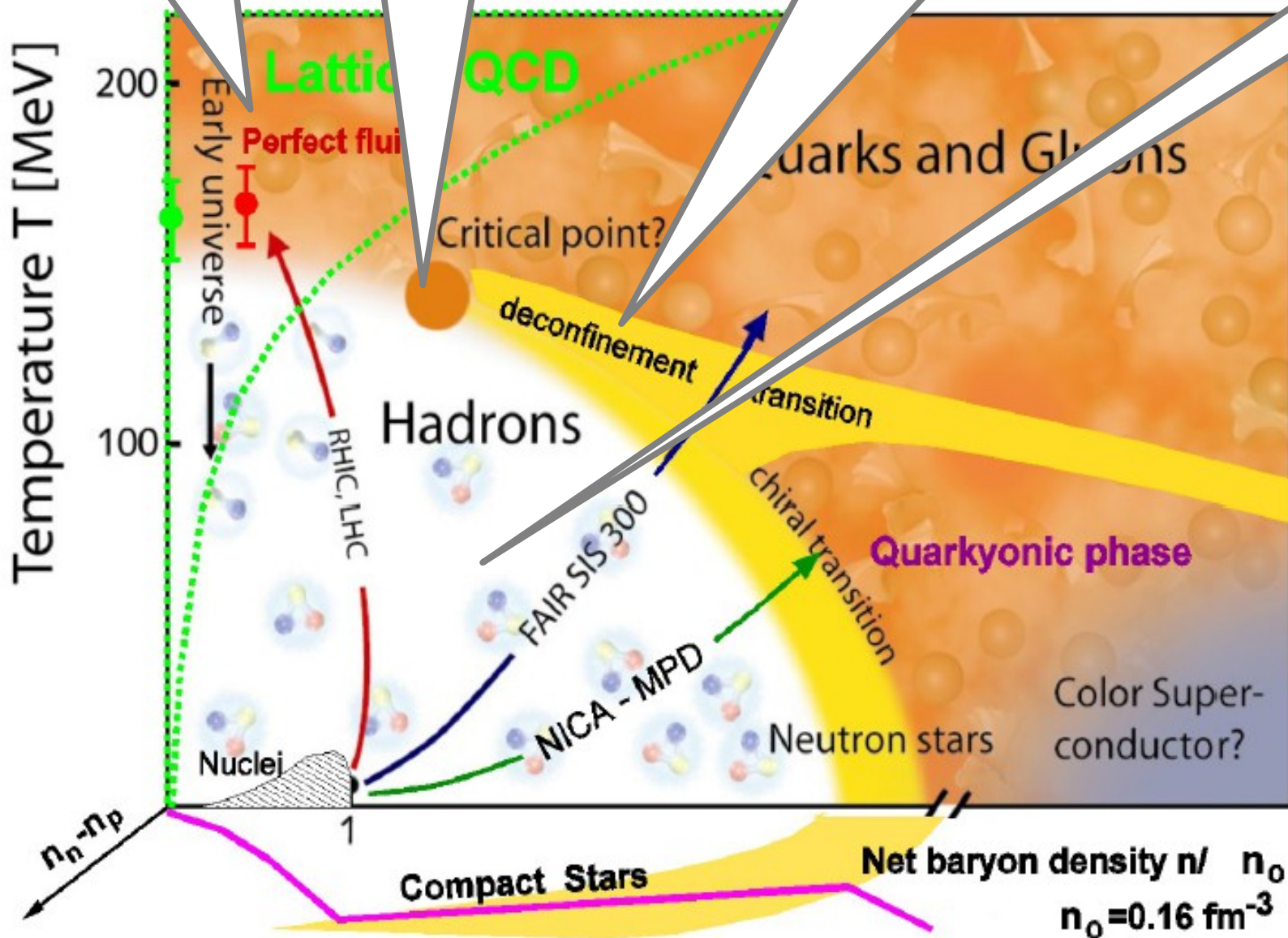
Division: Theory of Elementary Particles - Collaborations



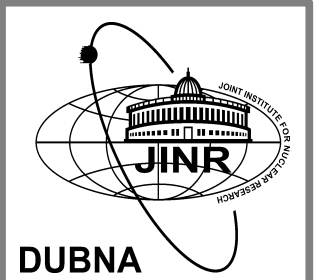
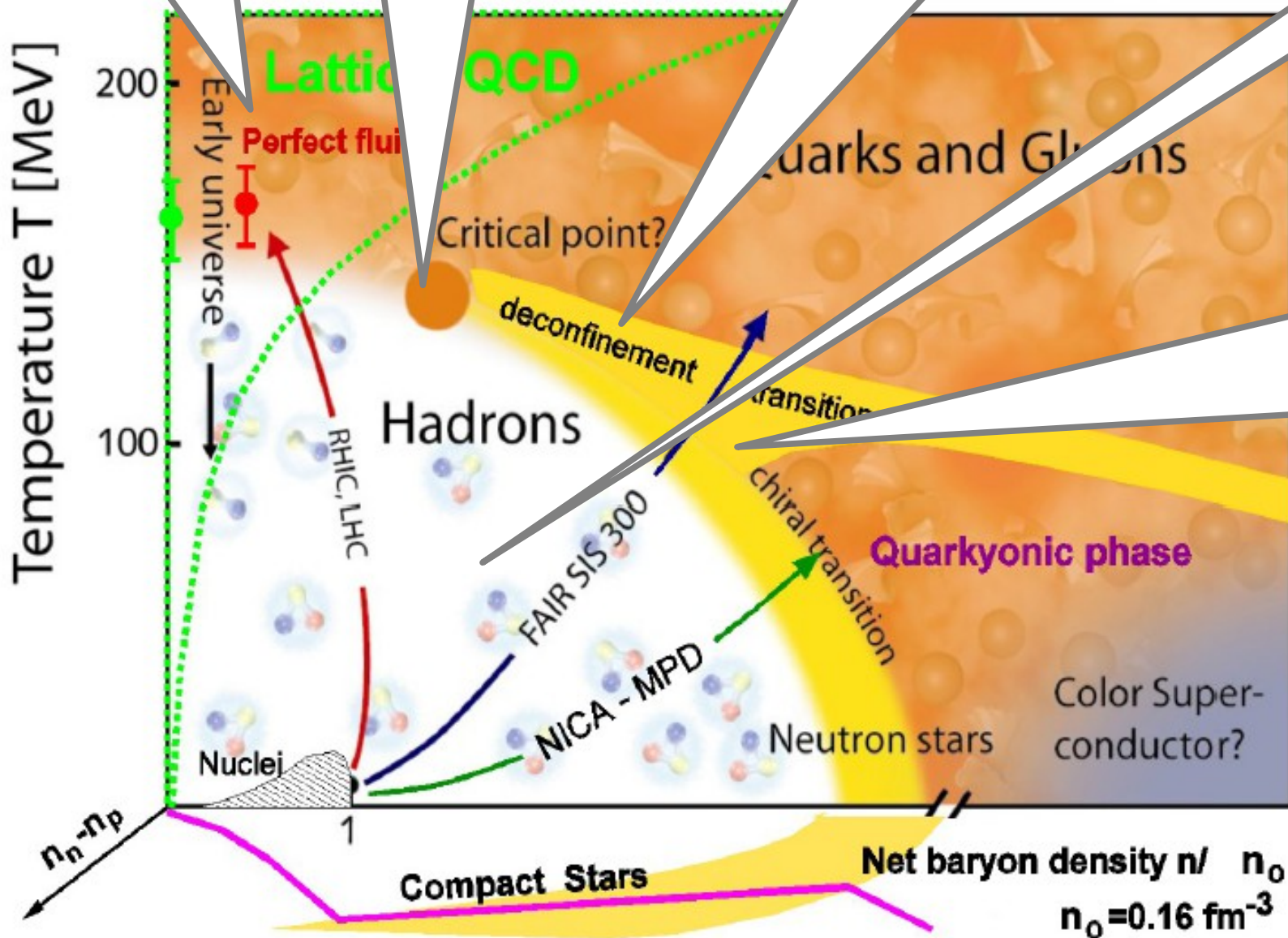
DUBNA



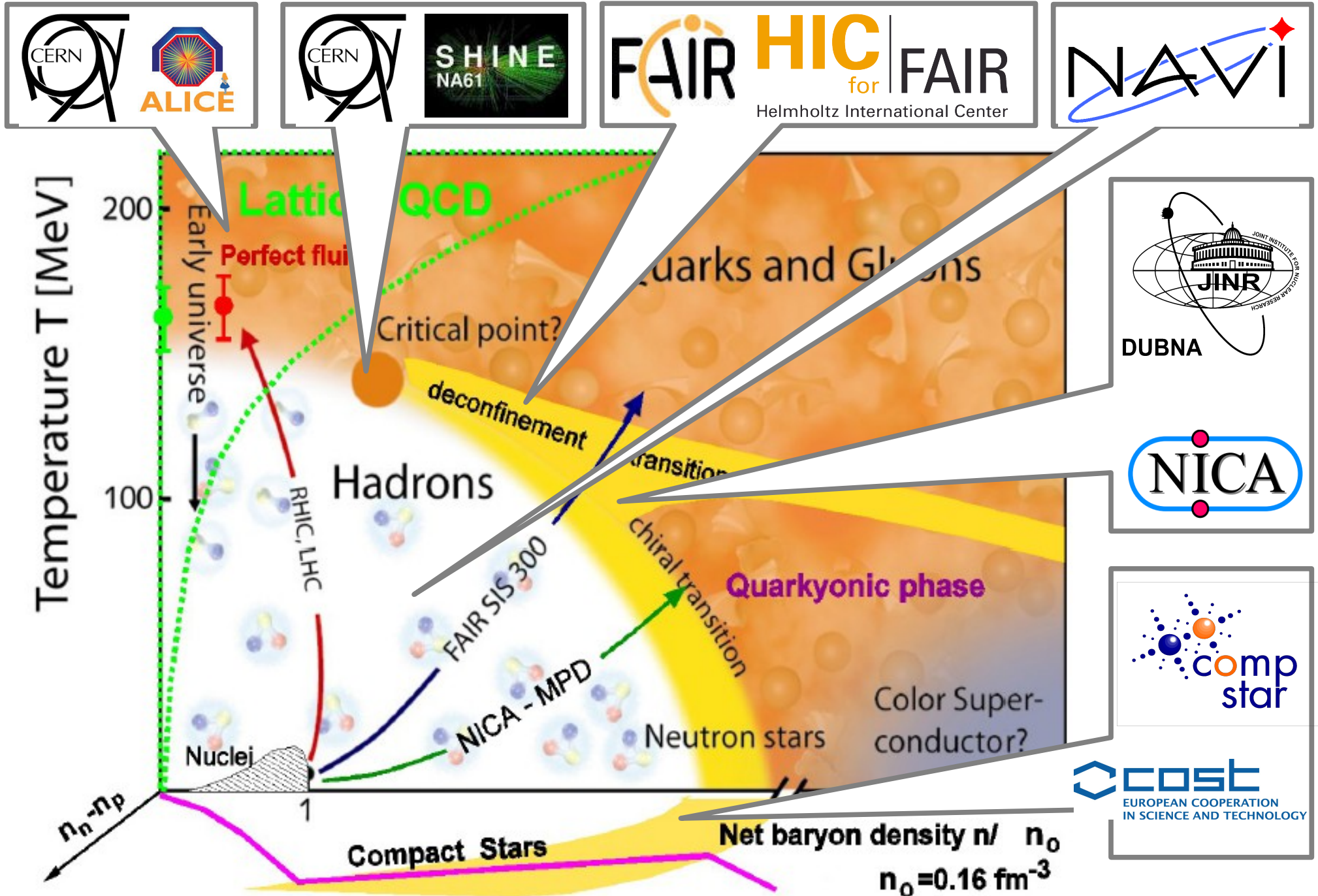
Division: Theory of Elementary Particles - Collaborations



Division: Theory of Elementary Particles - Collaborations



Division: Theory of Elementary Particles - Collaborations



Division: Theory of Elementary Particles

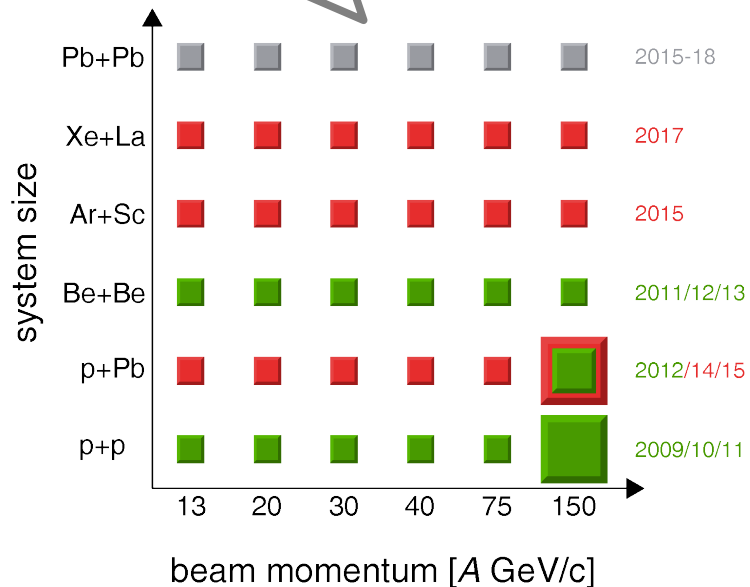
Collaboration with CERN Experiment NA61/SHINE since 2011



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



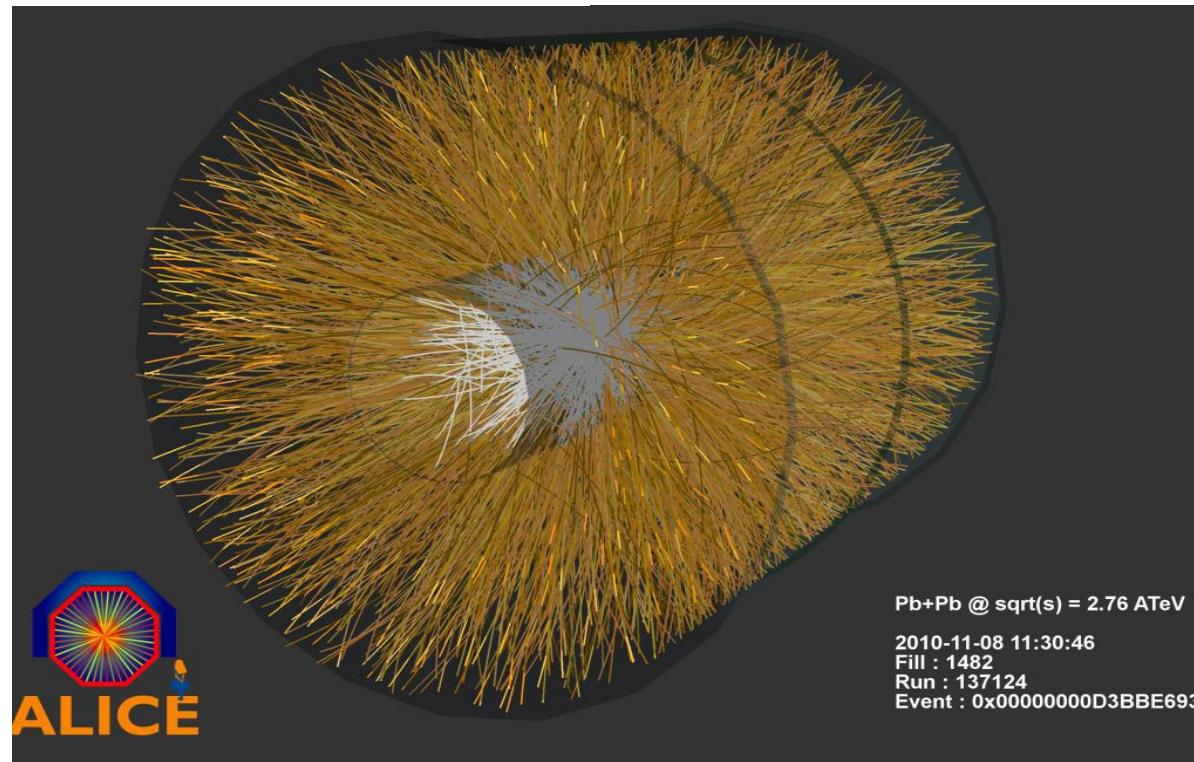
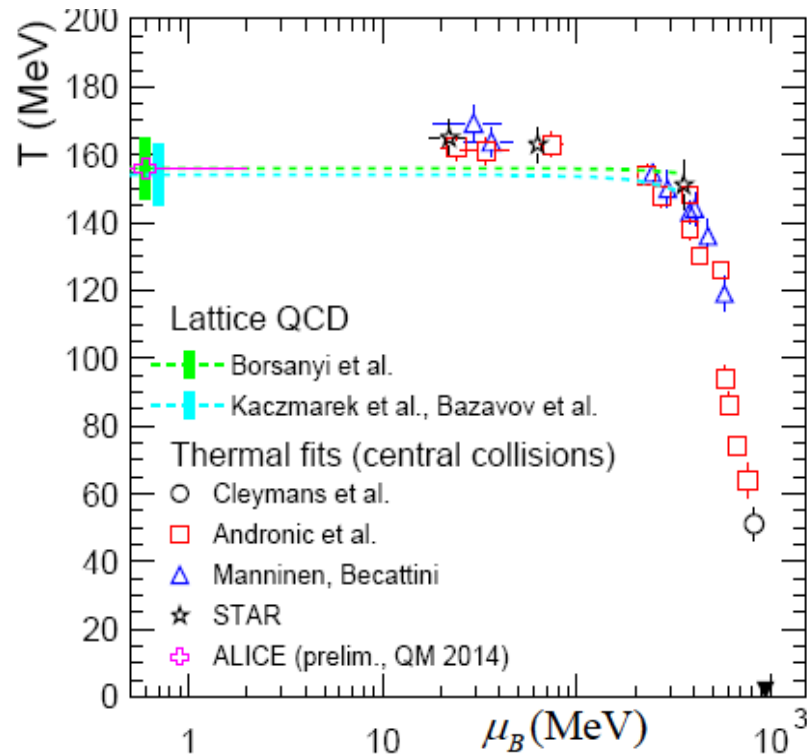
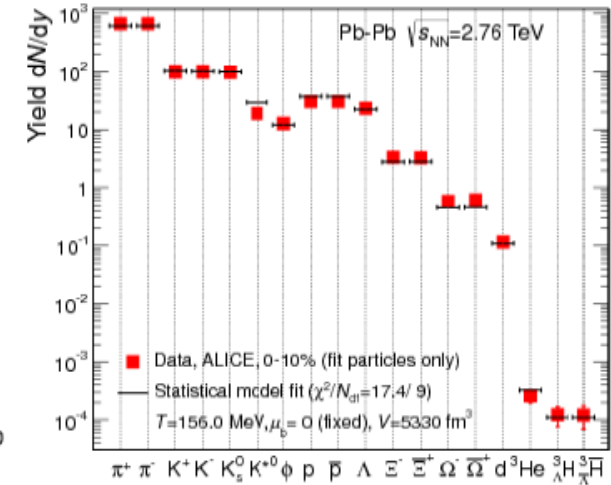
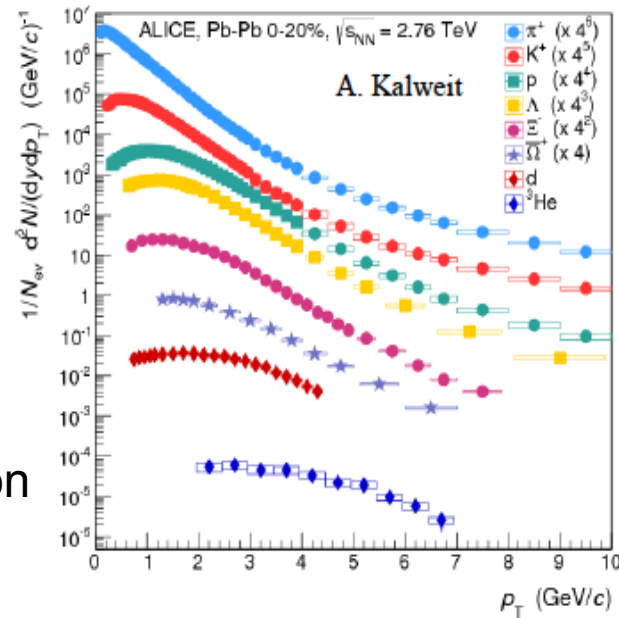
- SPS Heavy Ion and Neutrino Experiment (SHINE)
- Located at the Super Proton Synchrotron (SPS)
- 140 Physicists from 14 countries and 28 institutions



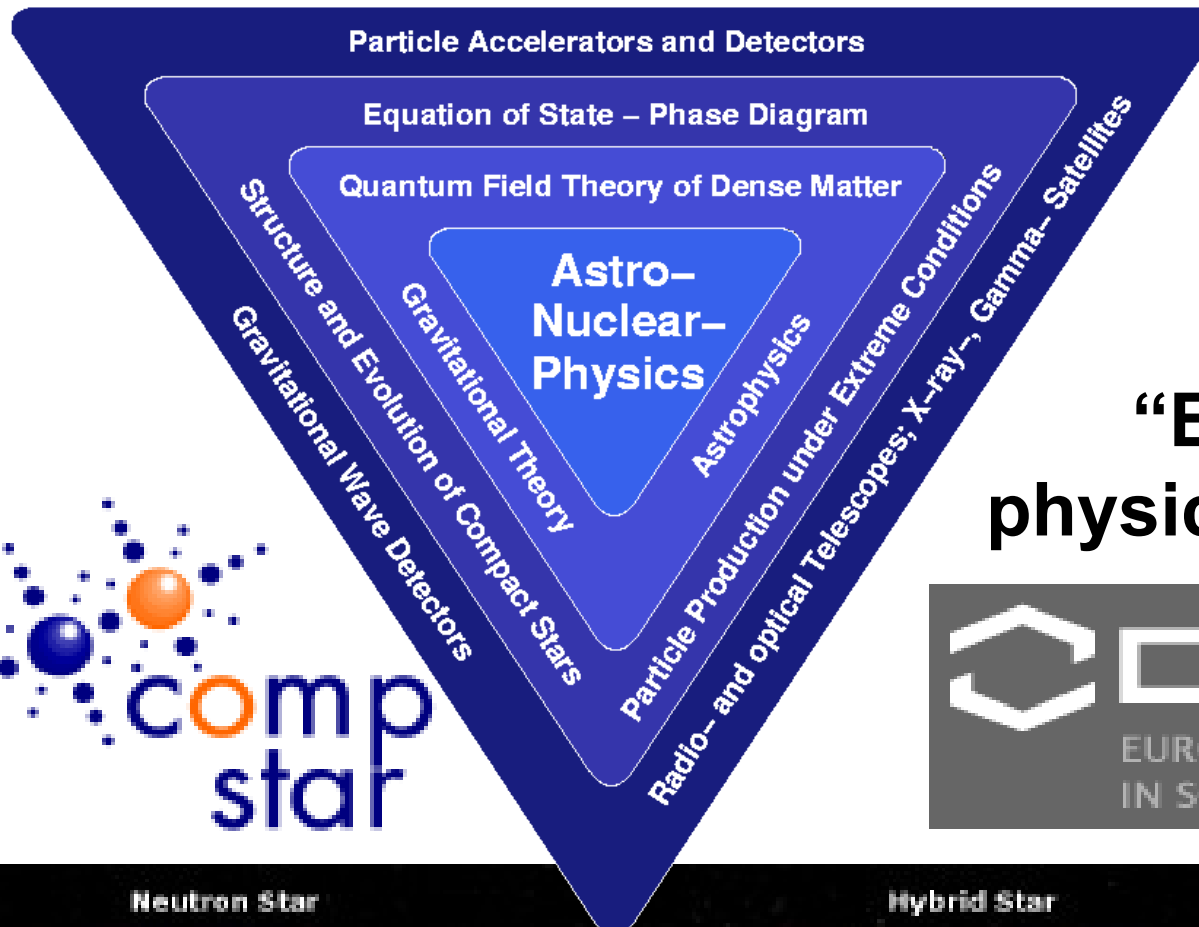
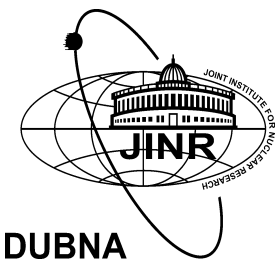
Division: Theory of Elementary Particles

Collaboration with ALICE @ CERN

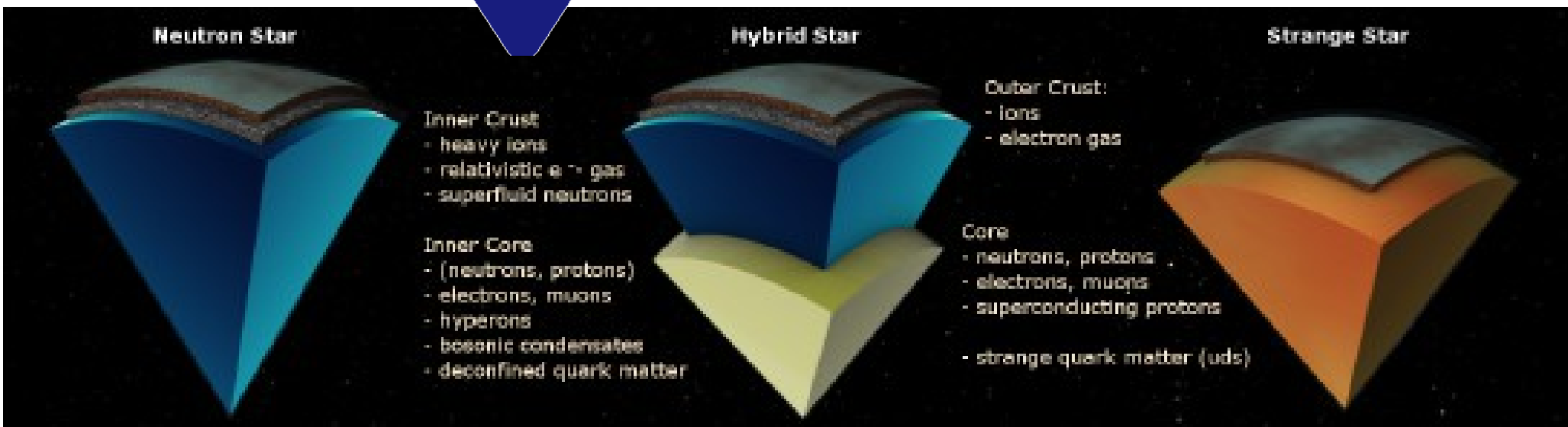
- excellent particle identification
- high statistics data allow new level unprecedented accuracy
- multihadron production near the QCD phase boundary challenges our understanding of the process of nonequilibrium QGP hadronization
- confirmation of lattice QCD theory



Division: Theory of Elementary Particles

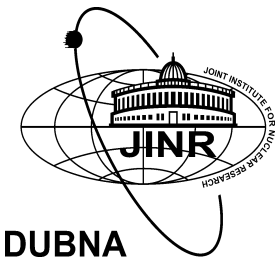


NewCompStar
COST Action MP1304:
“Exploring fundamental physics with compact stars”



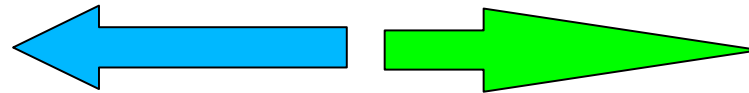
Division: Theory of Elementary Particles

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

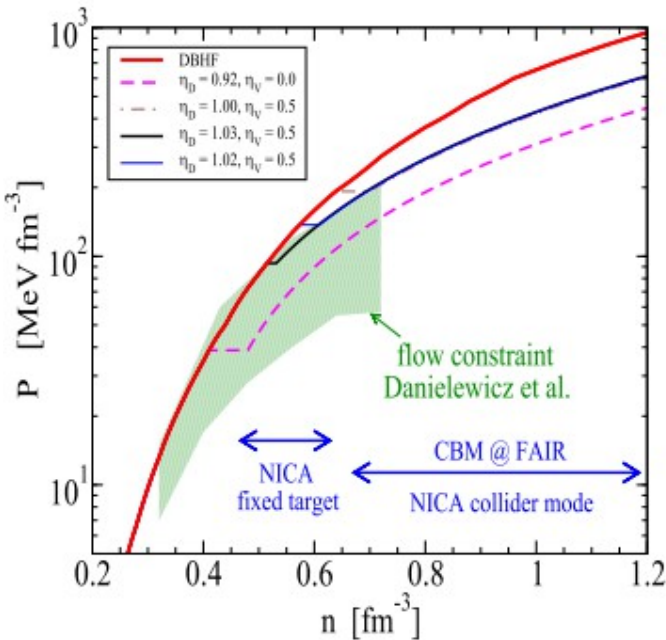


DUBNA

Heavy-Ion Collisions

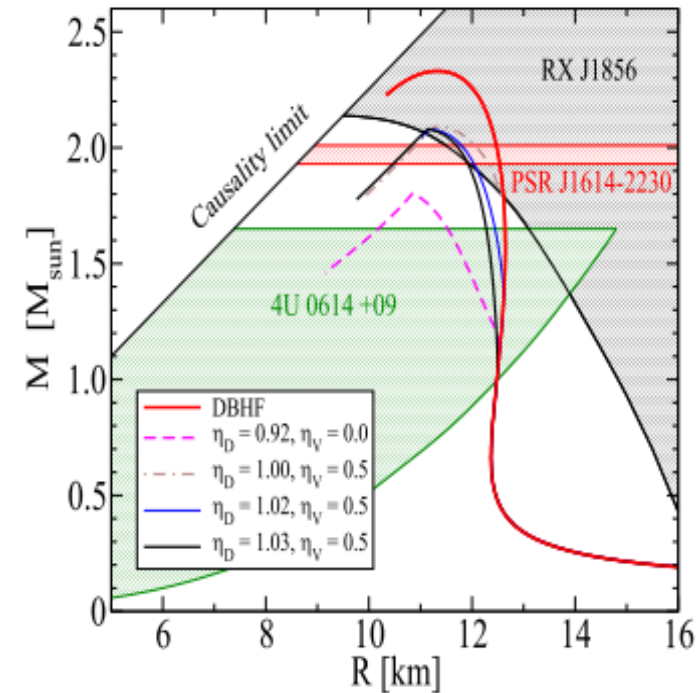


Compact Stars



- stiff EoS (at flow limit)
- low n_{crit} (at NICA fixT)
- soft EoS (dashed line)

- high M_{max} (J1614-2230)
- low M_{onset} (all NS hybrid)
- excluded (J1614-2230)



29 member countries



Division: Theory of Elementary Particles

