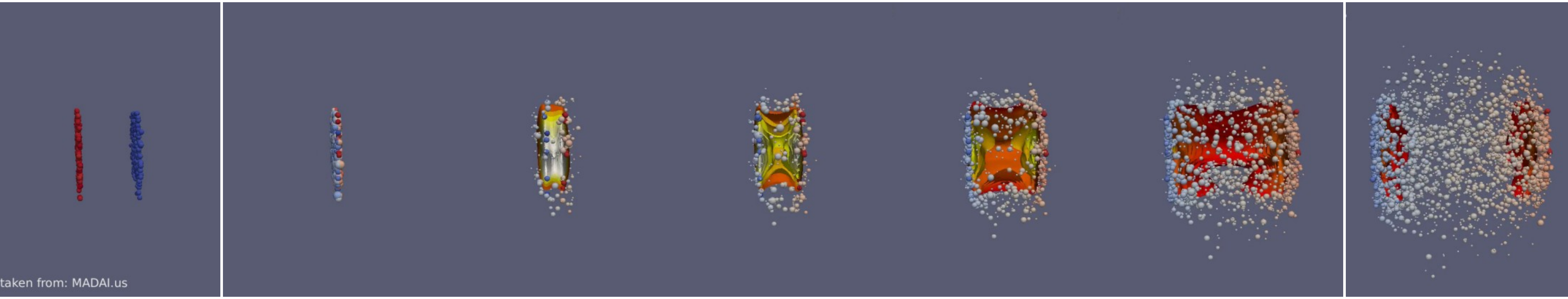
Particle Production in Strong Time-dependent Fields

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



taken from: MADAI.us

Helmholtz International Summer School on
"Quantum Field Theory at the Limits: From Strong Fields to Heavy Quarks"

JINR Dubna (Russia), July 22 – August 2, 2019

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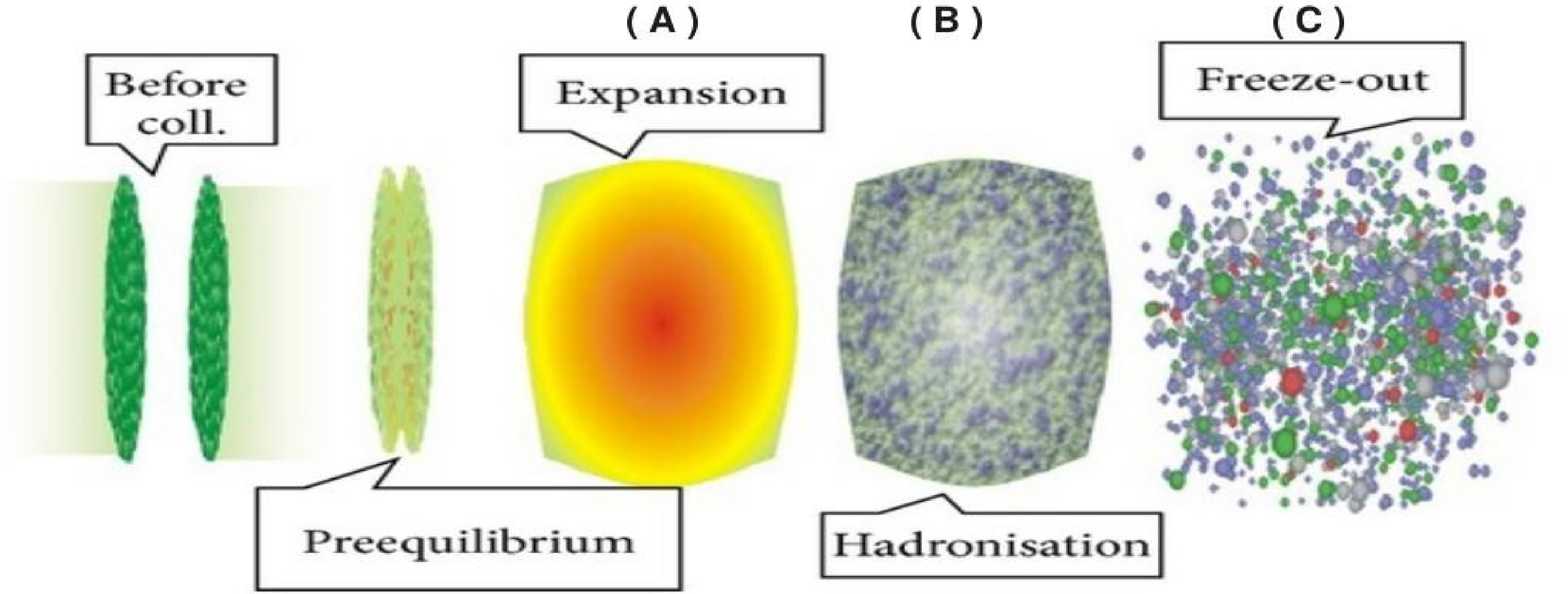
Particle Production in Strong, Time-dependent Fields



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

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

(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

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
    - “Pump&Probe” the vacuum: Bifrequent fields
4. Applications to heavy-ion collisions
    - Schwinger effect & Hawking-Unruh radiation
    - Equilibration: Thermalization & Isotropization (Ruggieri)
    - Cathode tube effect (Ruggieri)

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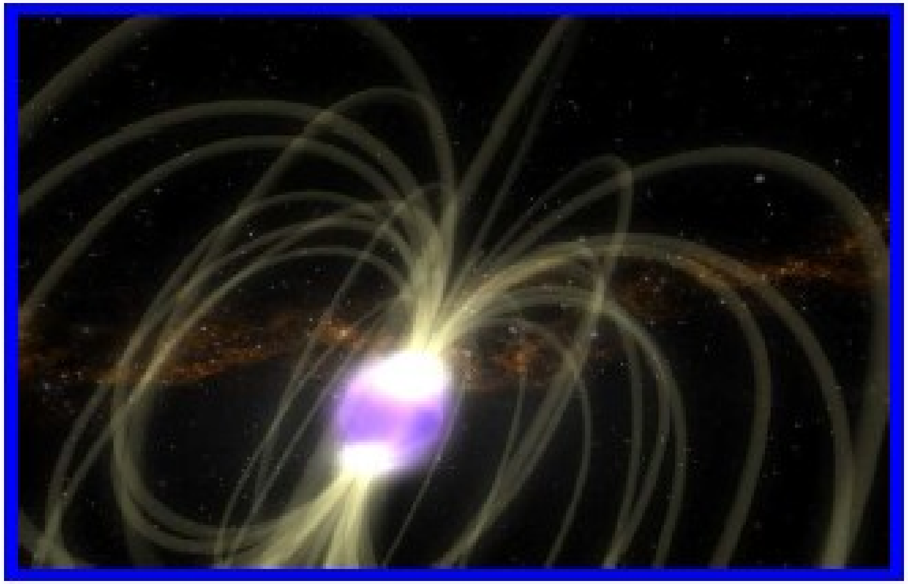
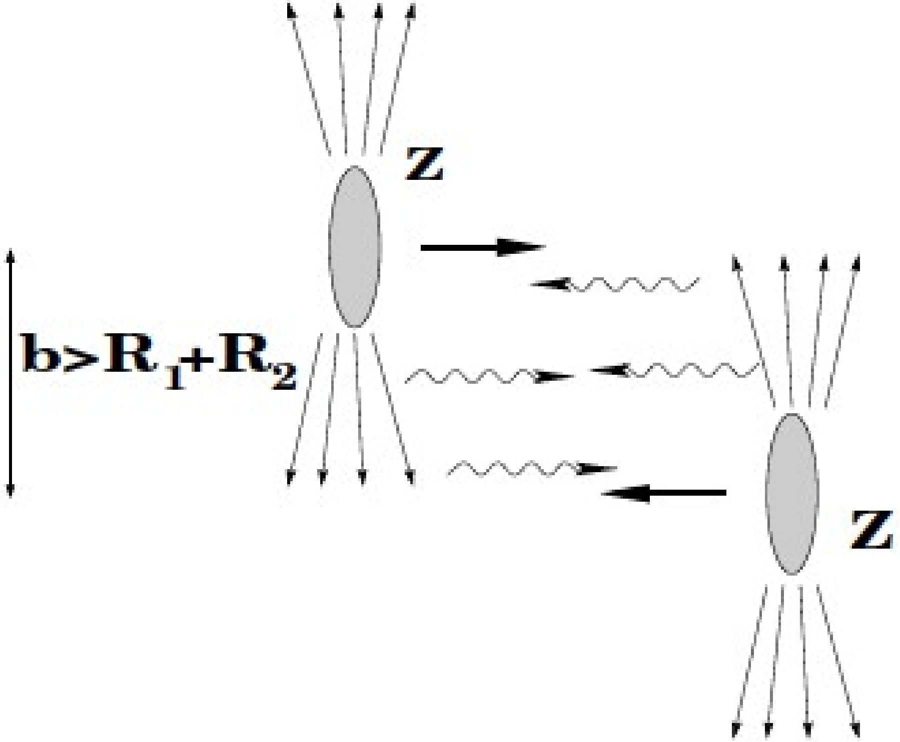
PAIR CREATION IN STRONG ELECTROMAGNETIC FIELDS

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



ARTIST VIEW OF A MAGNETAR (NASA)



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

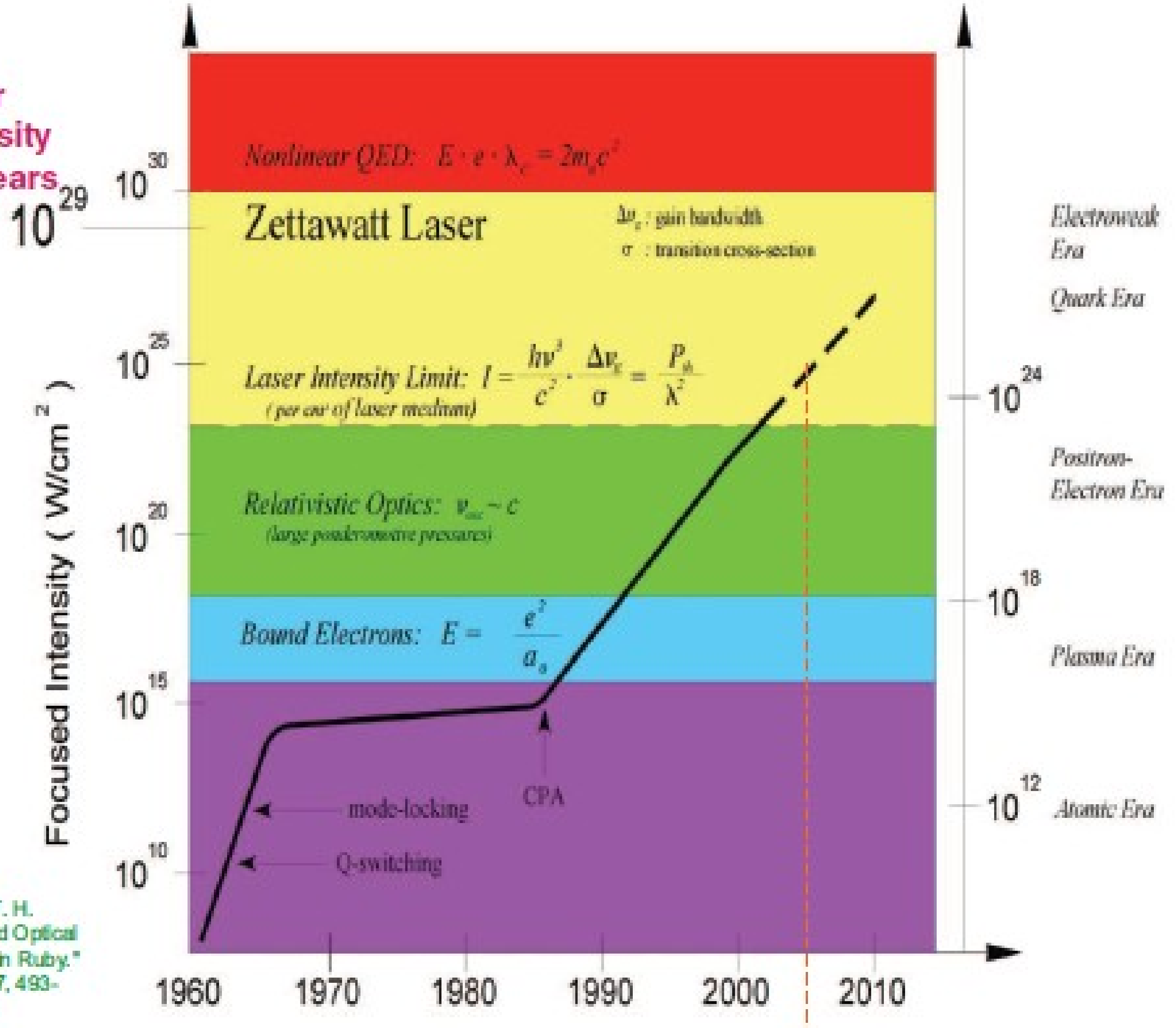
- ELI: Optical → X-Ray @ 1 EW:
  $I_0 \sim\ 10^{25}$ W/cm^2 $\to I_{CHF} \sim\ 10^{36}$ W/cm^2

  \+ 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

Laser Intensity vs. years



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

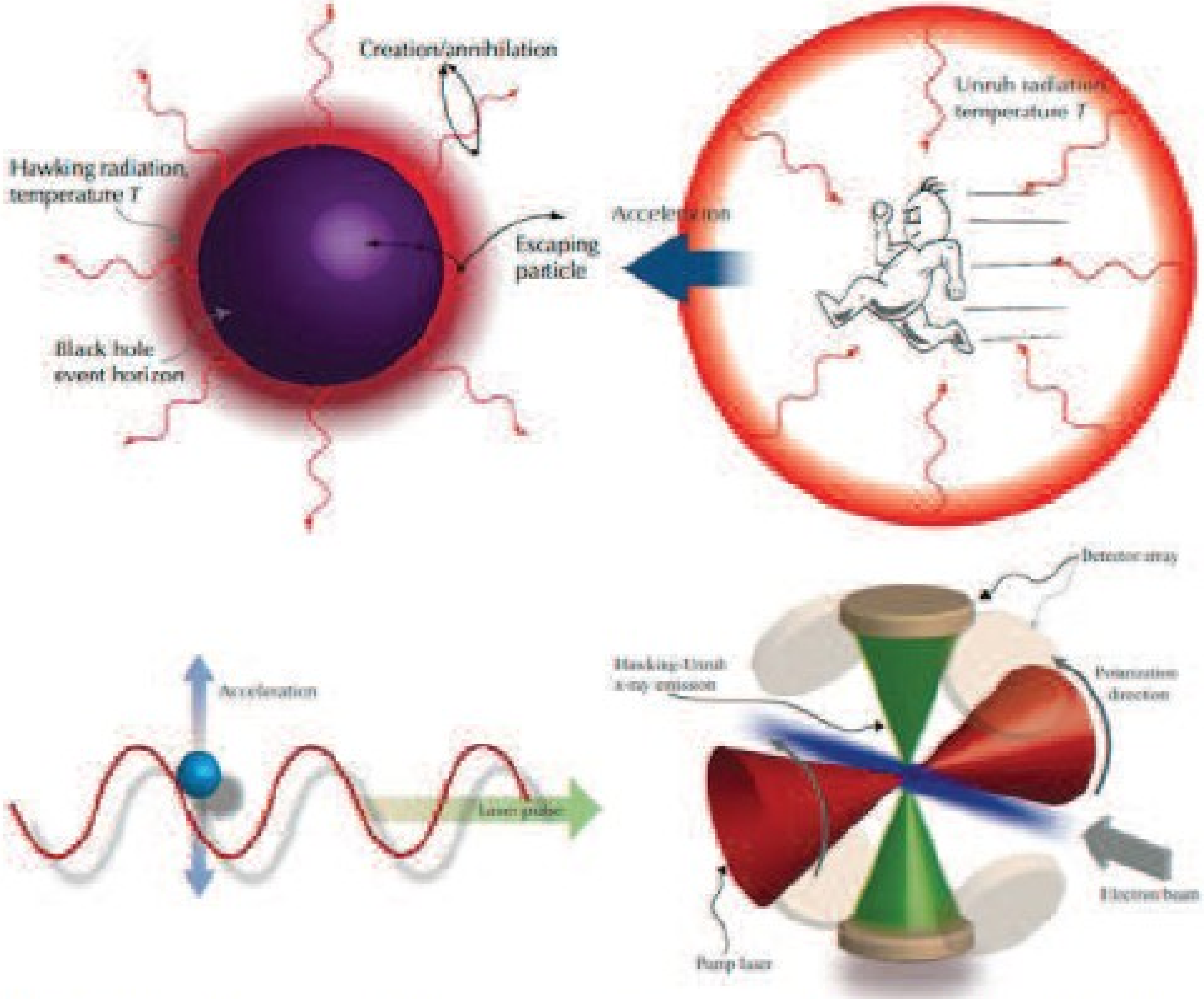
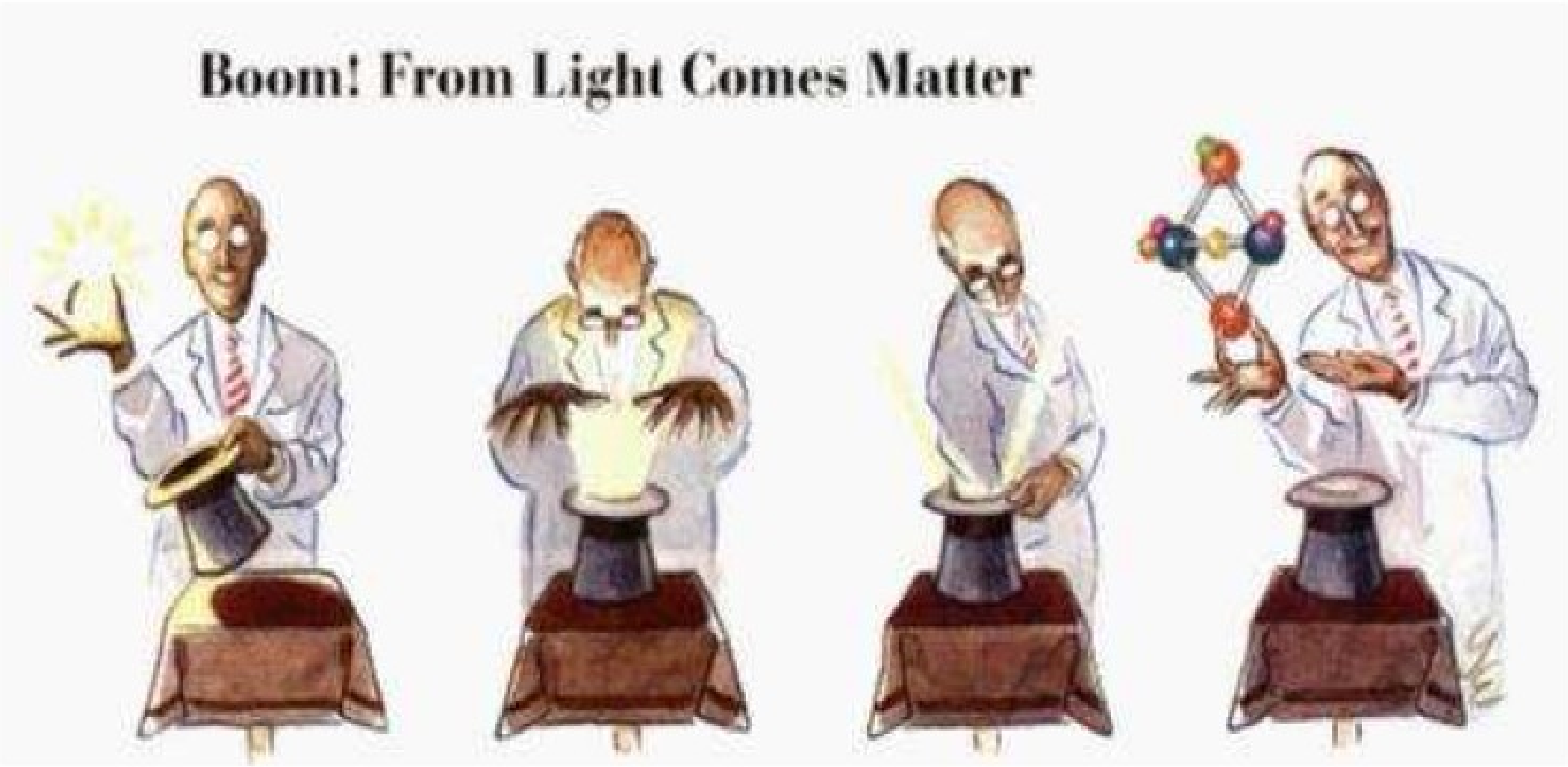


FIG. 7: The schematics of the experimental setup for Unruh radiation detection. Note than the radiation is emitted in a very particular direction as well as frequency, thus being detectable even if the background "noise" is high.

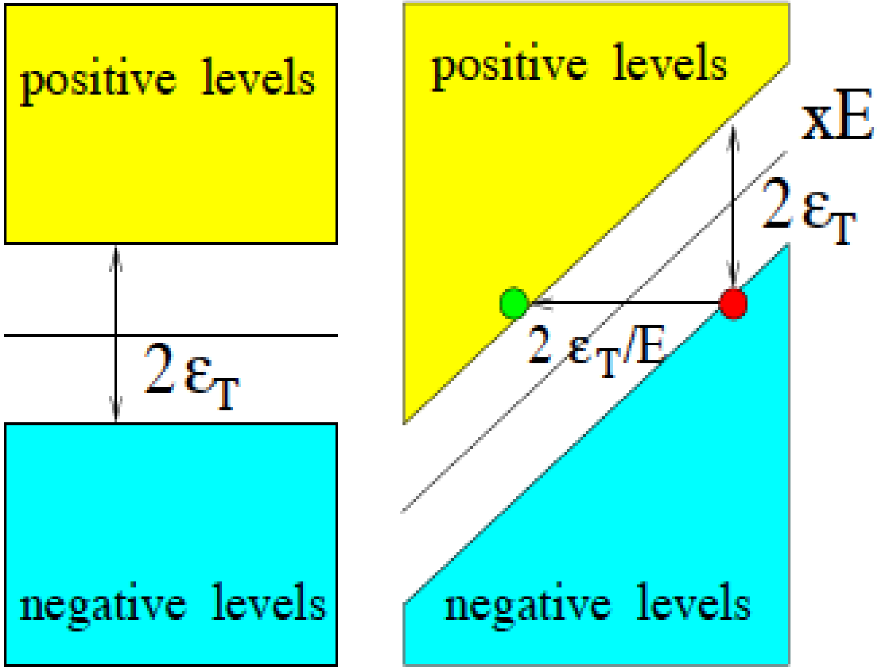
R. Schutzhold, G. Schaller, D. Habs,
"Signatures of the Unruh Effect from Electrons Accelerated by Ultrastrong Laser Fields"
Phys. Rev. Lett. 97 (2006) 121302

SCHWINGER EFFECT: PAIR CREATION IN STRONG FIELDS



SCHWINGER EFFECT: PAIR CREATION IN STRONG FIELDS

Pair creation as barrier penetration in a strong constant field



- 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 $E \sim E_{\text{crit}}$

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

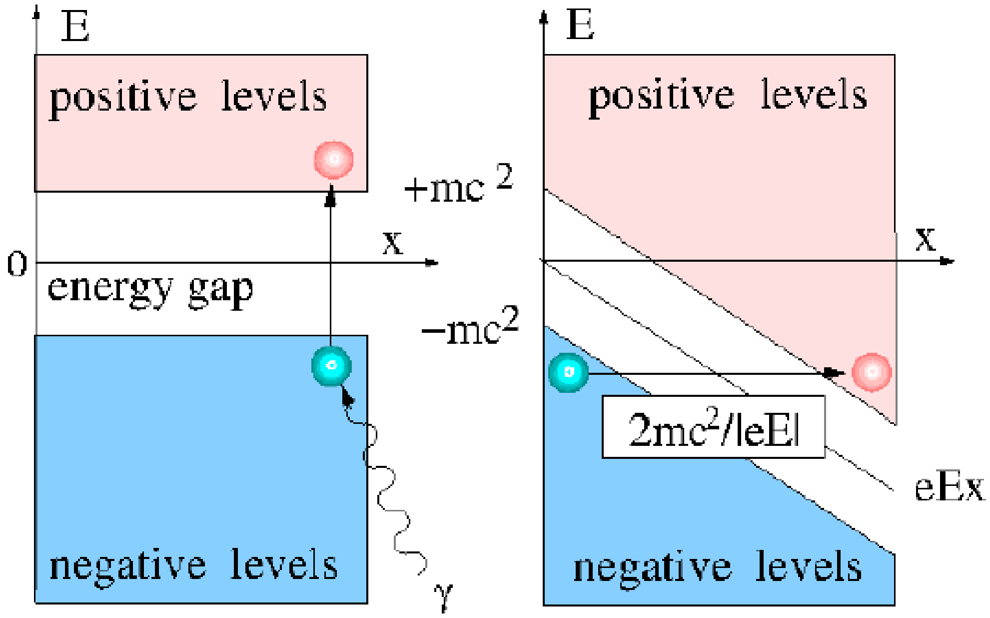
- For time-dependent fields: Kinetic Equation approach from Quantum Field Theory

Schwinger result (rate for pair production)

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

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)

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

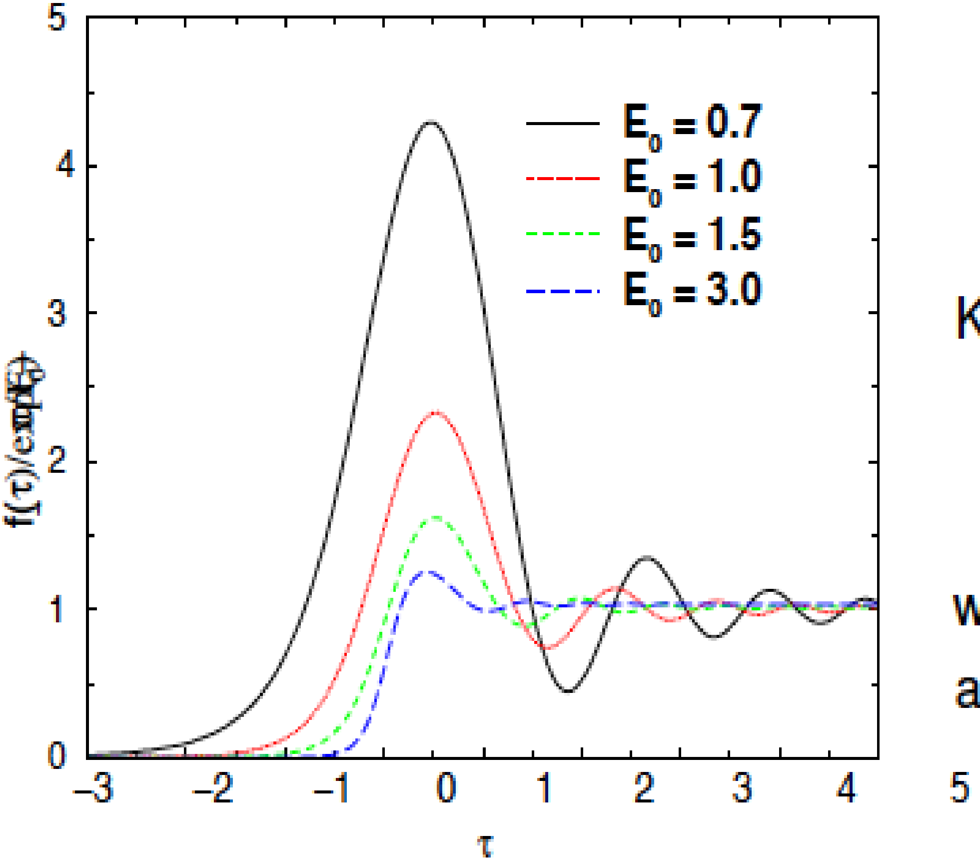
Schwinger formula (basic mode, n=0)

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

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

KINETIC FORMULATION OF PAIR PRODUCTION

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



Schmidt, Blaschke, Röpke, et al:

Non-Markovian effects in strong-field pair creation

Phys. Rev. D 59 (1999) 094005

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

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

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

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

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

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

Constant field: Schwinger limit reproduced

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

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) → 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 $|0_{\rm in}\rangle$

Time-dependent Bogoliubov transformation

- Transformation

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

- 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)

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

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

Non-Markovian kinetic equation

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

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

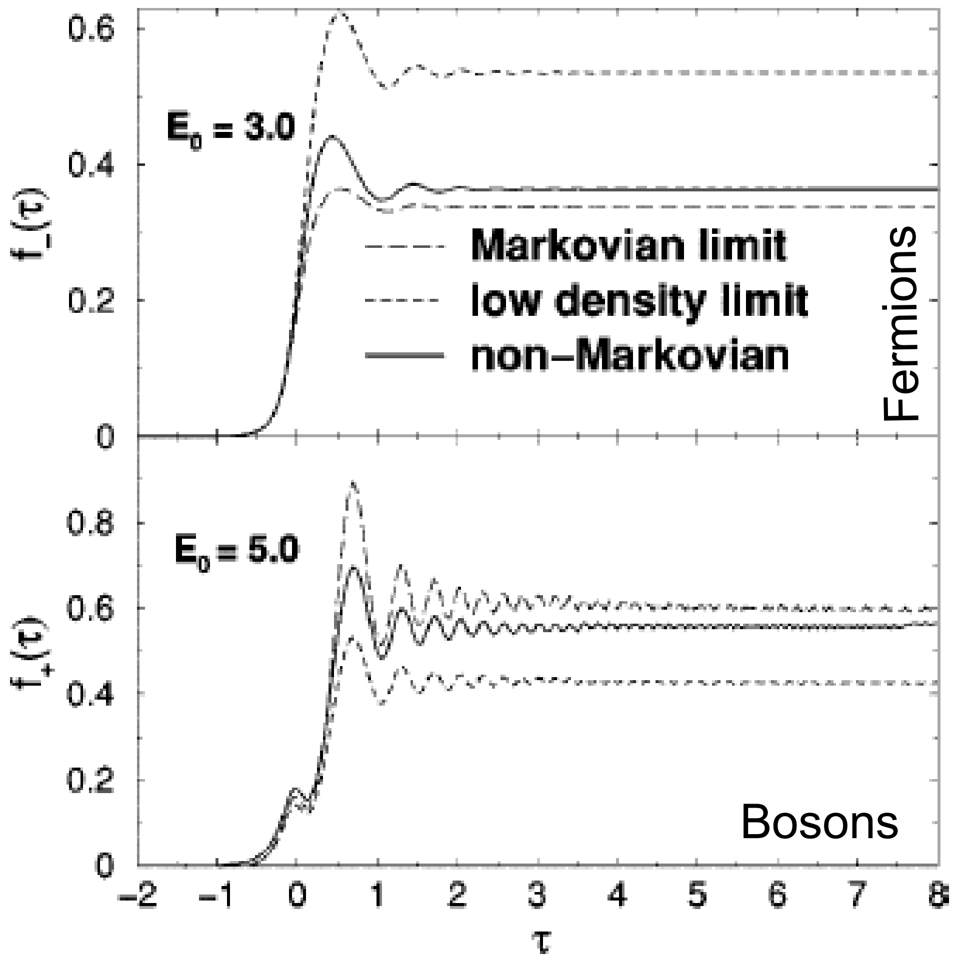
$$\varepsilon_\perp = \sqrt{m^2 + q_\perp^2}$$

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

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 :

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

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

Low-density limit :

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

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

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

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

PHYSICAL REVIEW D, VOLUME 59, 094005

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

Understanding the Dynamical Schwinger Process: E^2 - rule

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

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

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

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

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

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

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

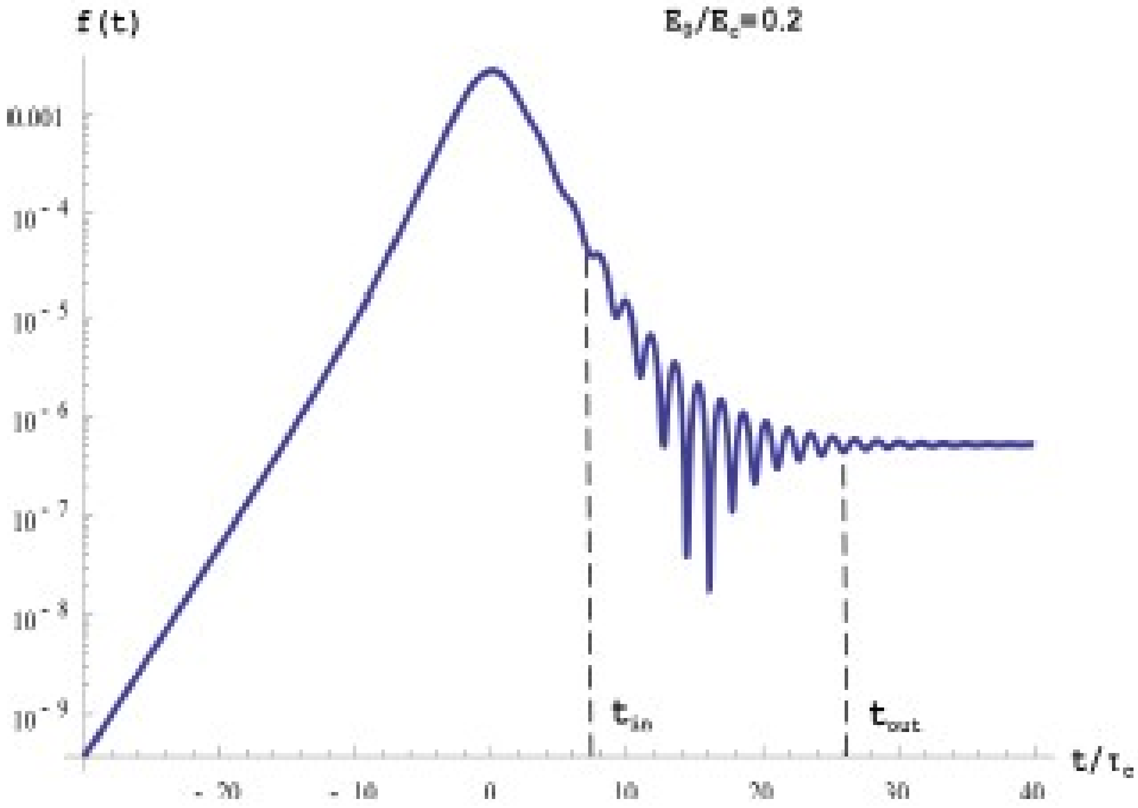
$$f^0_{\pm}(\tau) = \frac{1}{4}\left(\int_{-\infty}^{\tau} d\tau' g^1_{\pm}(\tau') \right)^2 + \frac{1}{4}\left(\int_{-\infty}^{\tau} d\tau' g^2_{\pm}(\tau') \right)^2 .$$

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

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

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) → 0

Examples (quasi-particle and mass-shell stage)



- Sauter pulse

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

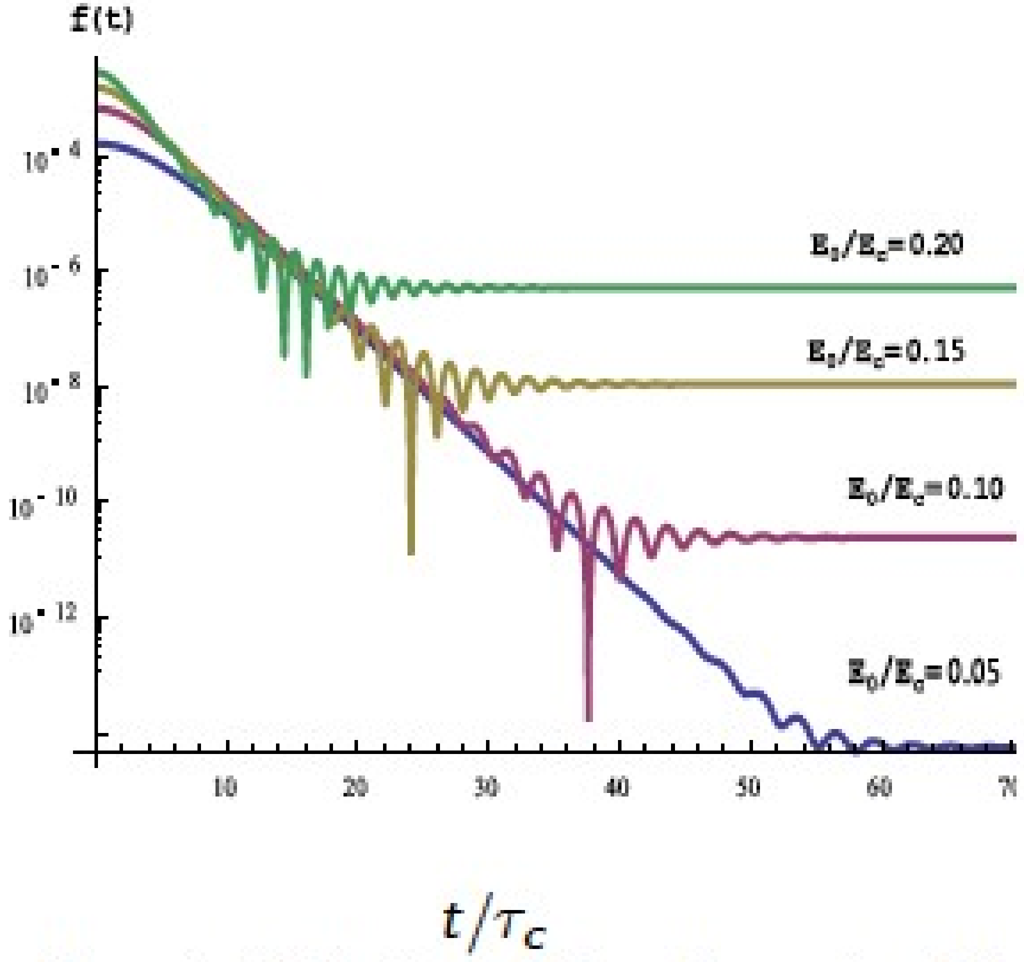
- $T = 0.02\text{nm}$
- $p_\perp = p_\parallel = 0$
- $[t_{\rm in}, t_{\rm out}]$ - transient region between quasi-particle and mass-shell stage

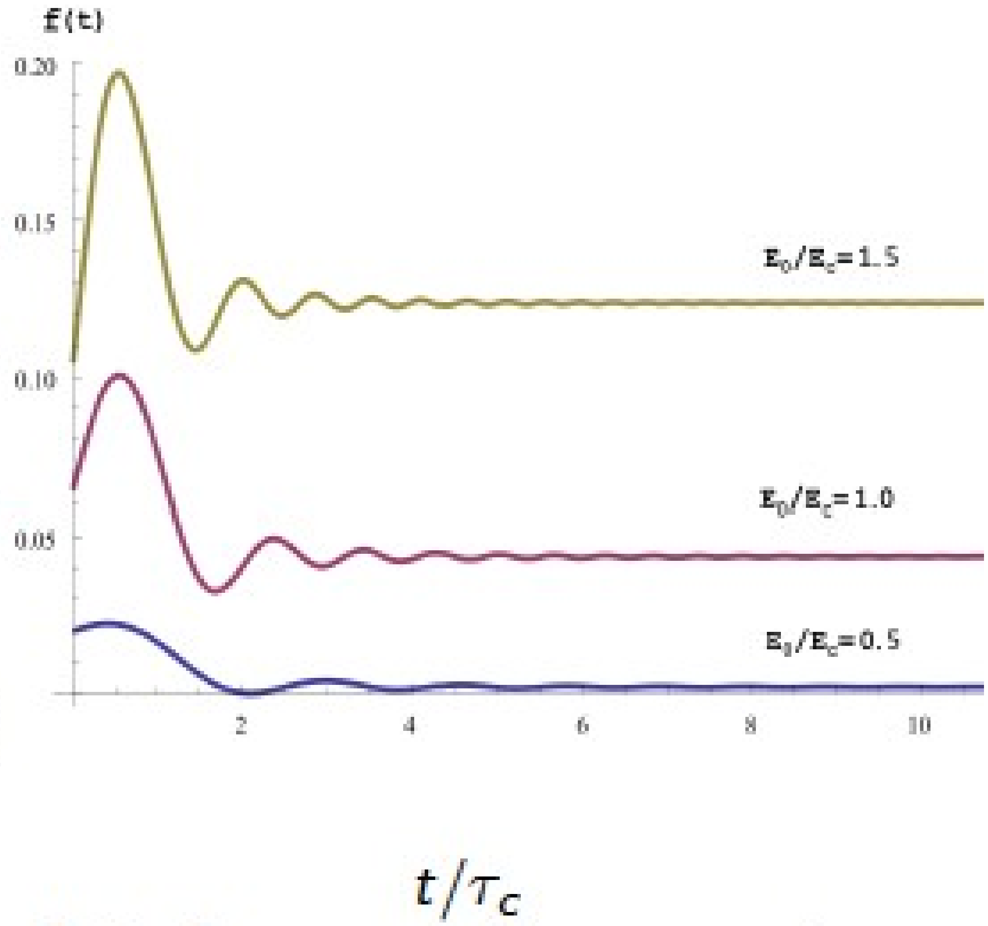
Dynamical Schwinger effect: Properties of the e^+e^- plasma created from vacuum in strong laser fields

Blaschke, Juchnowski , Panferov et al. arXiv:1412.6372

Examples (quasi-particle and mass-shell stage)

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



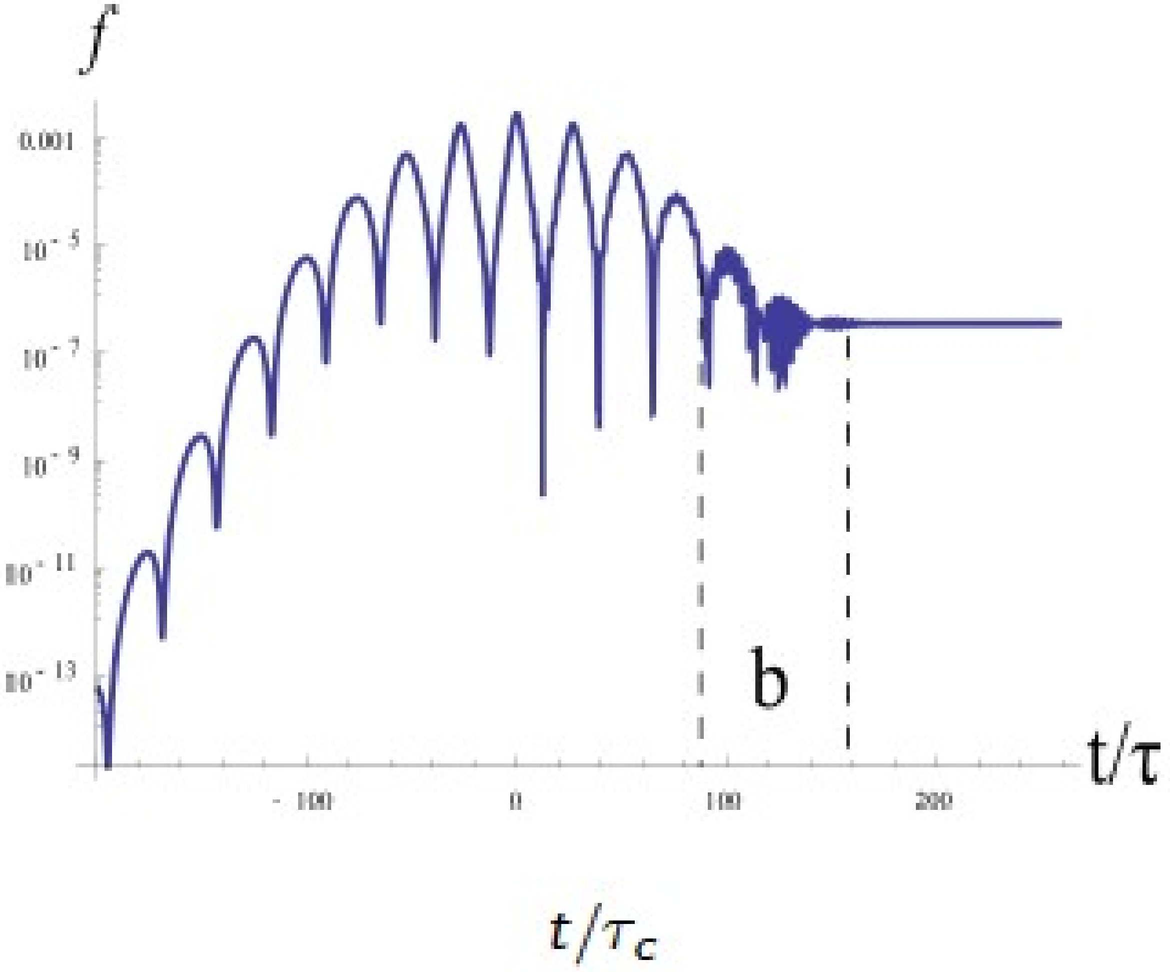


Dynamical Schwinger effect: Properties of the e^+e^- plasma created from vacuum in strong laser fields

Blaschke, Juchnowski , Panferov et al. arXiv:1412.6372

Examples (quasi-particle and mass-shell stage)

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



$E_0 = 0.2E_c$

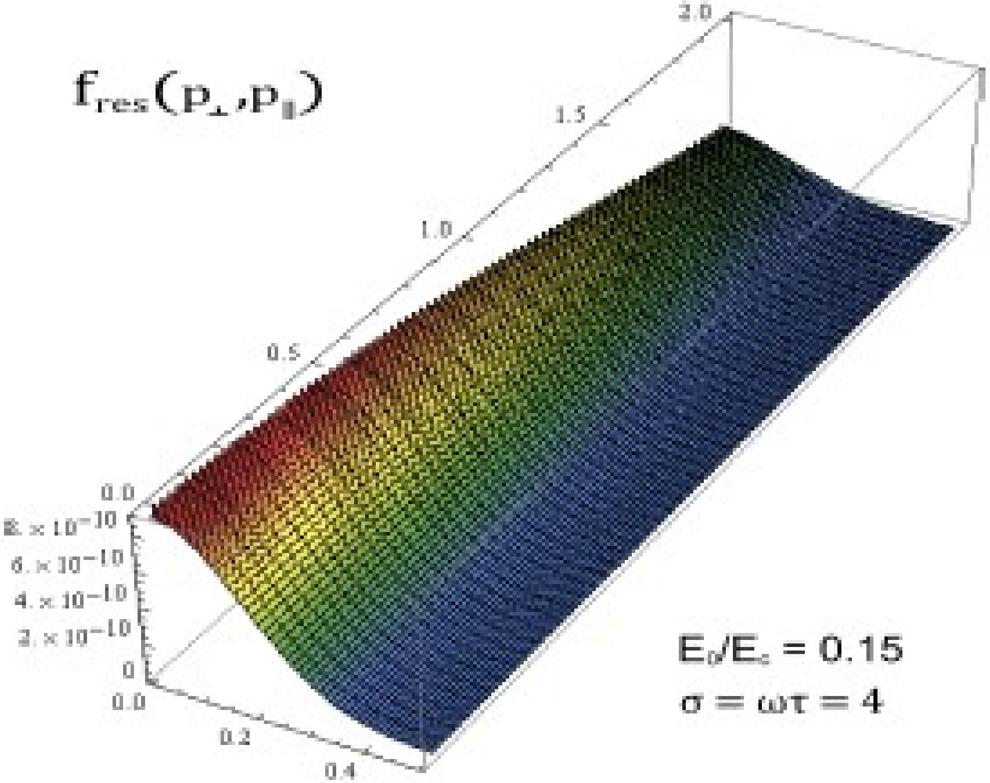
the region "b" corresponds to the transient process

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

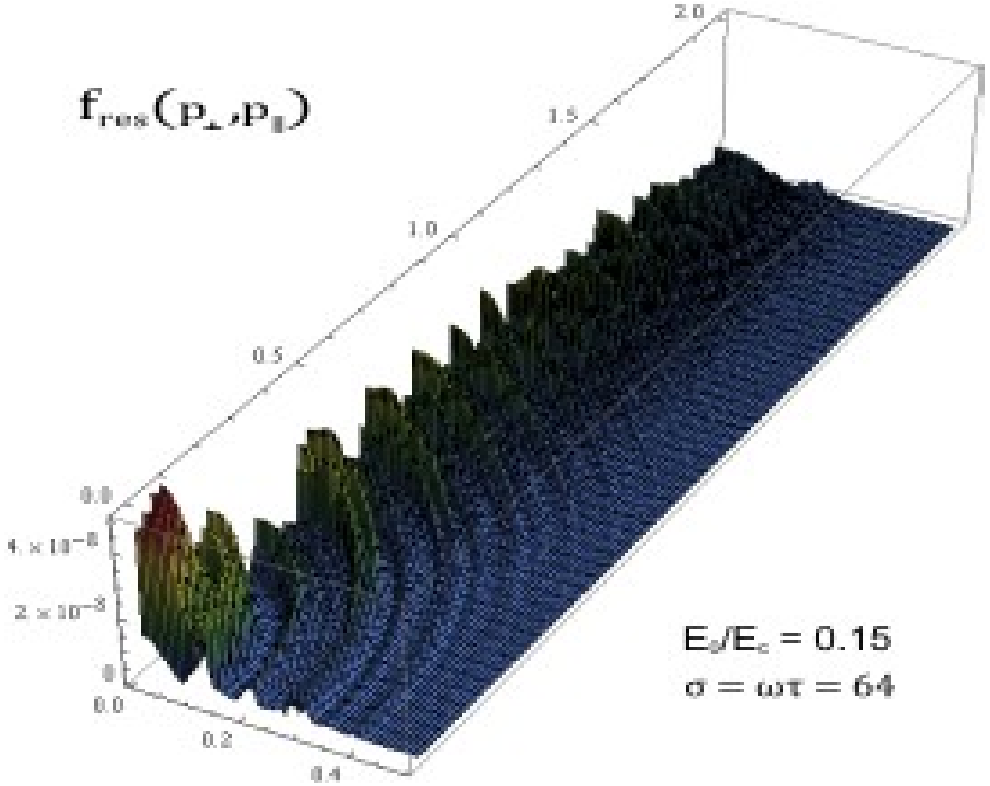
Blaschke, Juchnowski , Panferov et al. arXiv:1412.6372

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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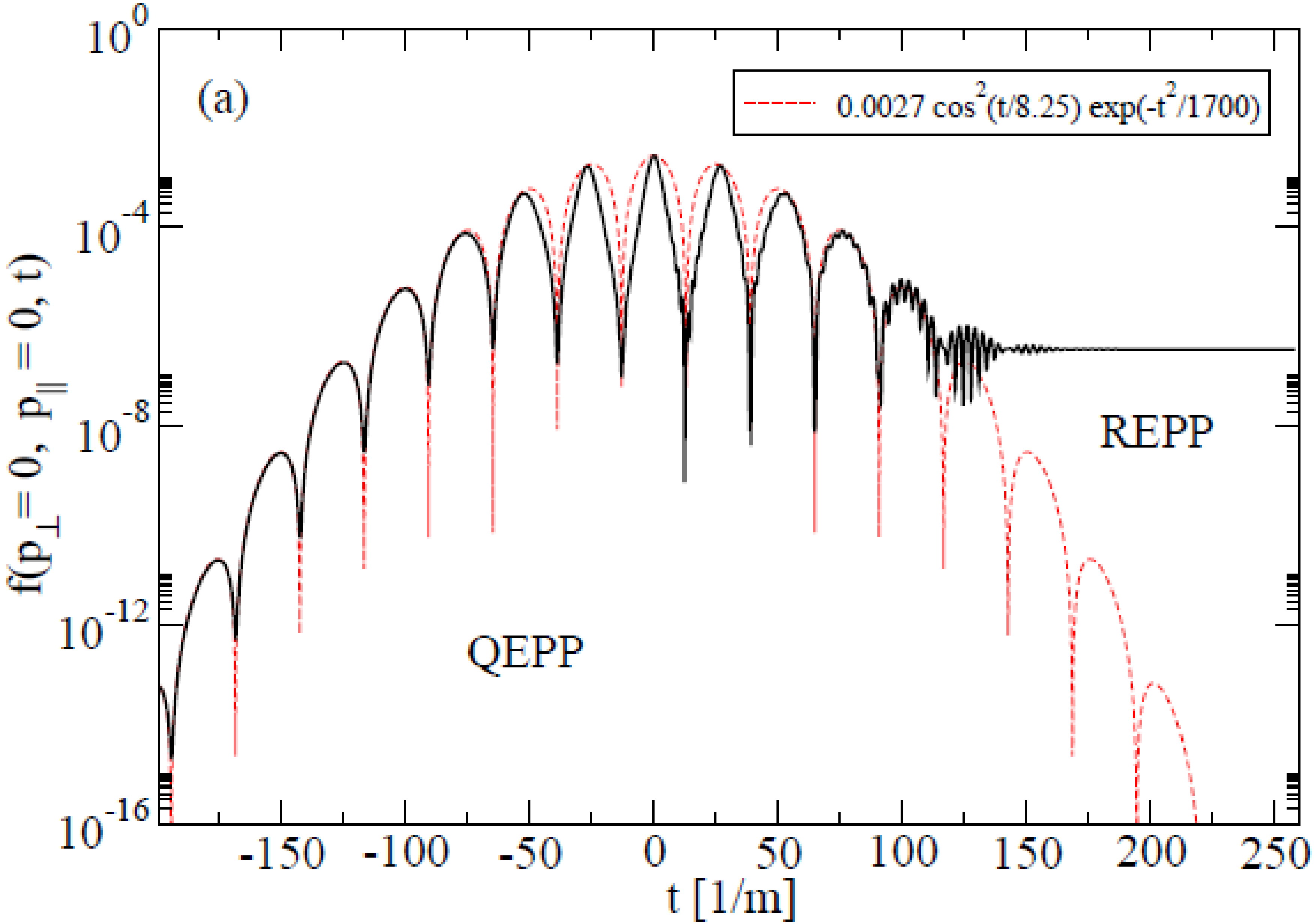
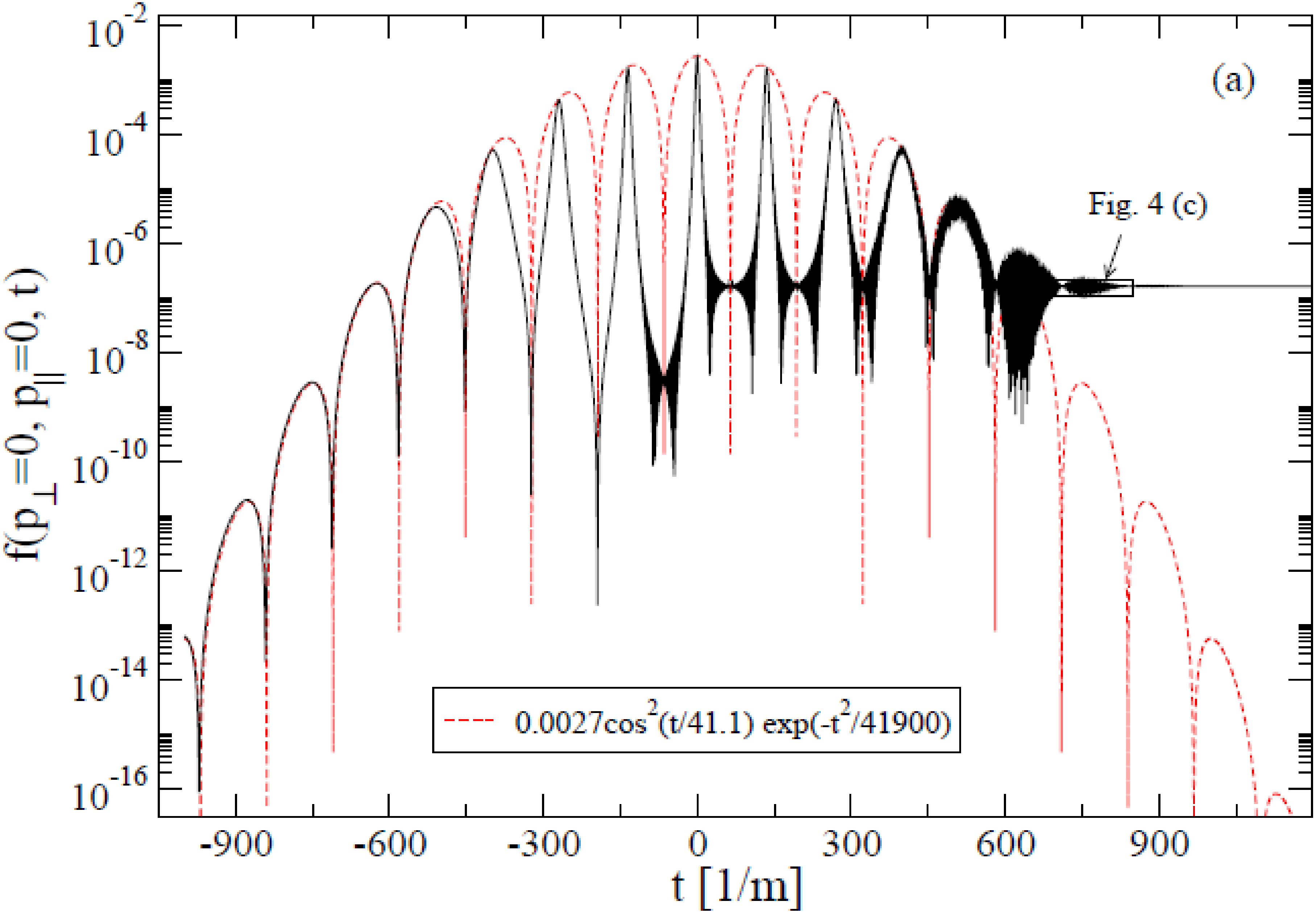
Gaussian envelope harmonic pulse vs. E^2 rule



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

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

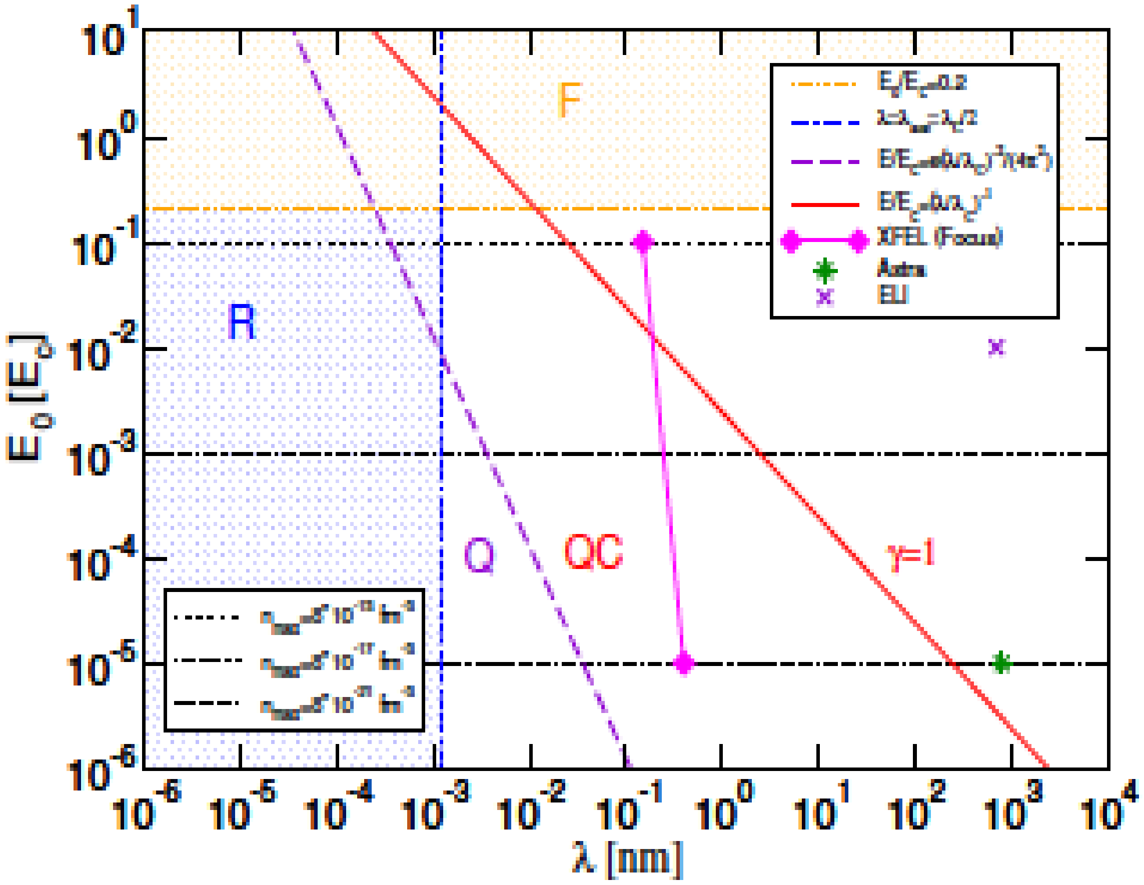
Gaussian envelope harmonic pulse vs. E^2 rule



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

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

Landscape



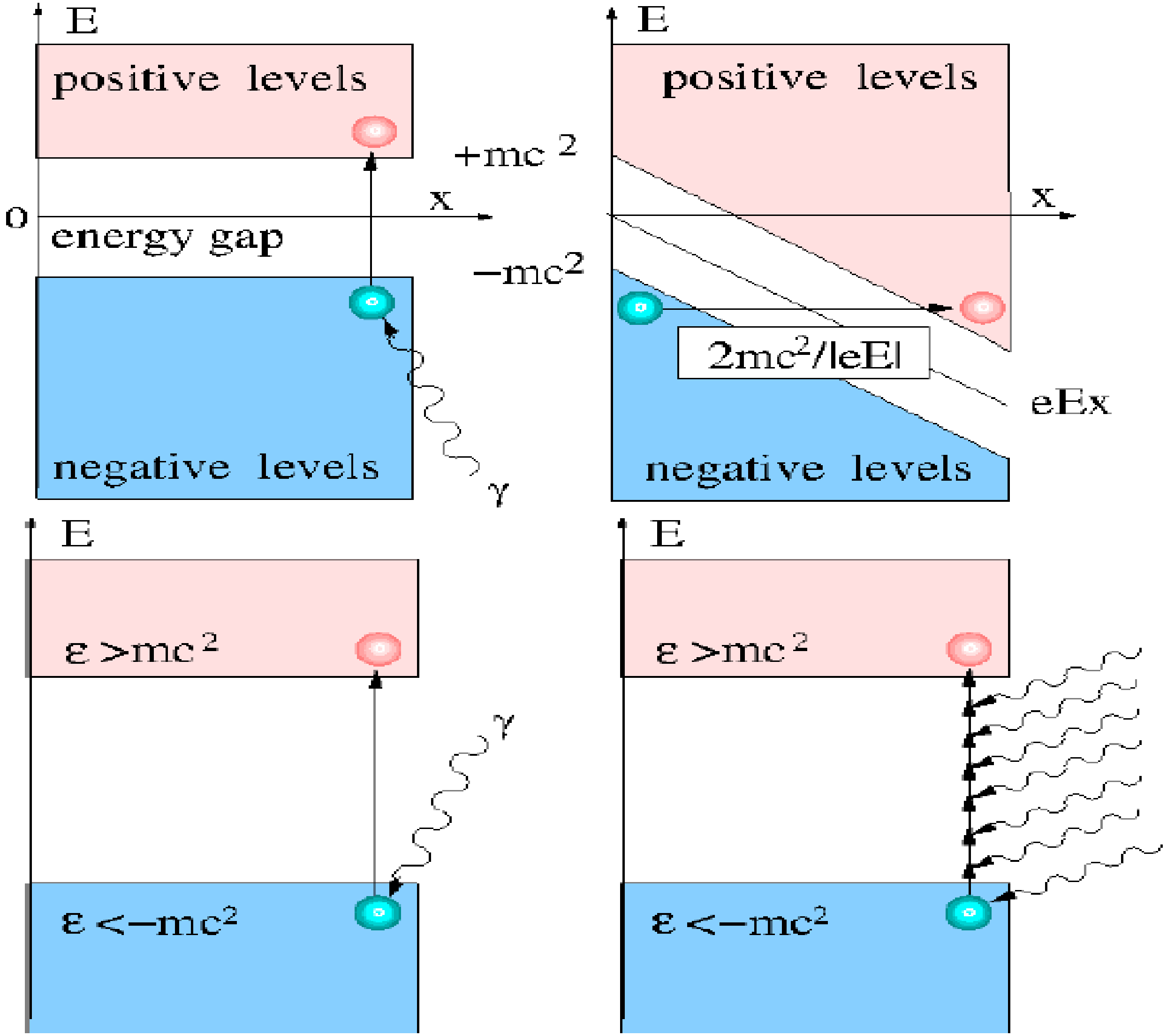
- Change of variables $(\omega, E) \to (\gamma, E)$
- Adiabaticity parameter

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

- 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



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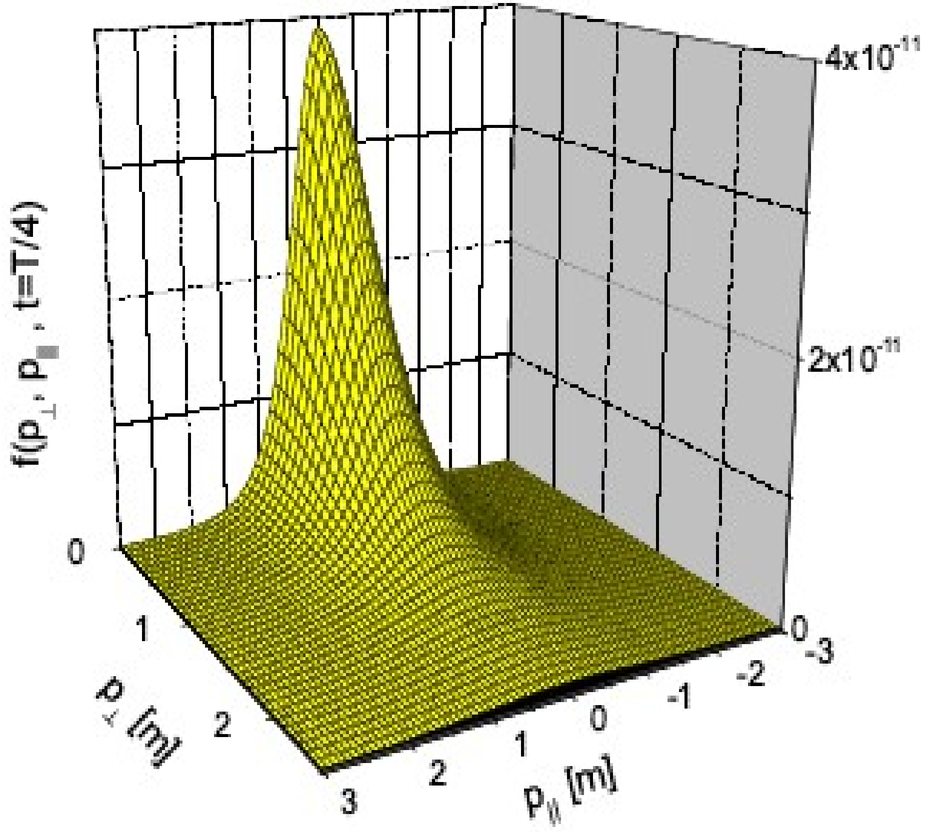
D. B. Blaschke, B. Kampfer, *et al.* , Phys. Rev. D 88 045017 (2013)

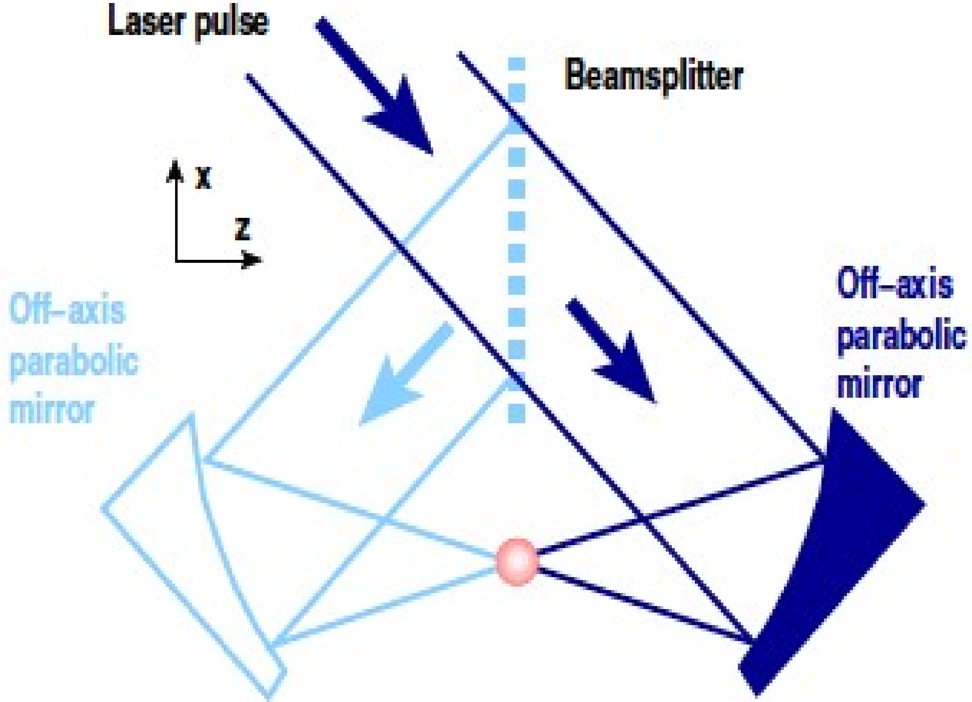
D. Blaschke, N.T. Gevorgyan, A.D. Panferov, S.A. Smolyansky, JPCS 672, 012020 (2016)

APPLICATION TO SUBCRITICAL LASER FIELDS



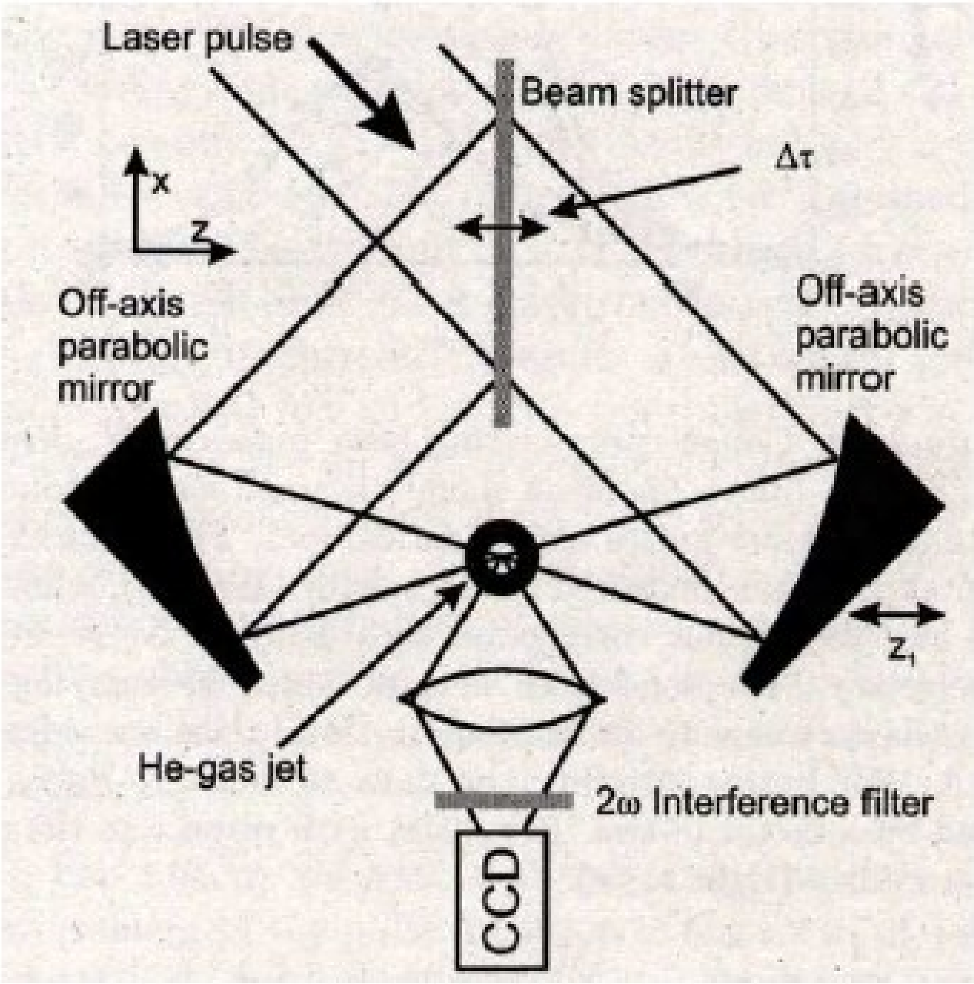
Equilibrium-like momentum distribution at the time of maximal field amplitude $t = T/4$.

Setup of the Jena Laser Exp. (2005)

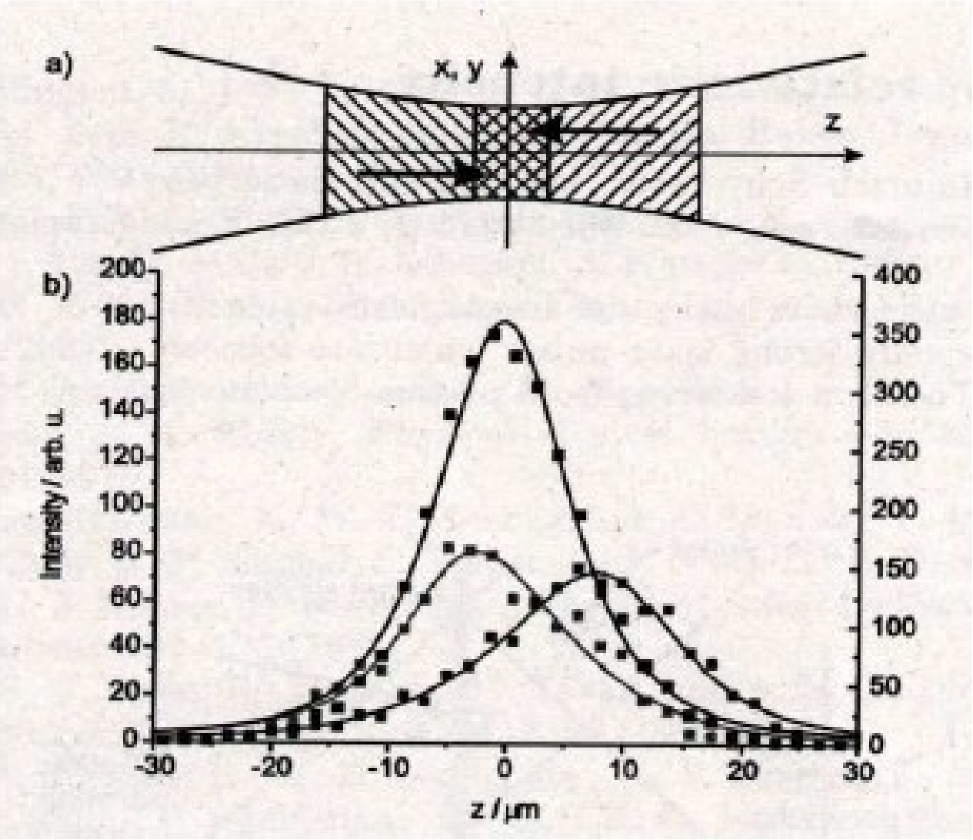


Heinzl, et al., Opt. Commun. 267, 318 (2006)

APPLICATION TO JENA MULTI-TW LASER



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



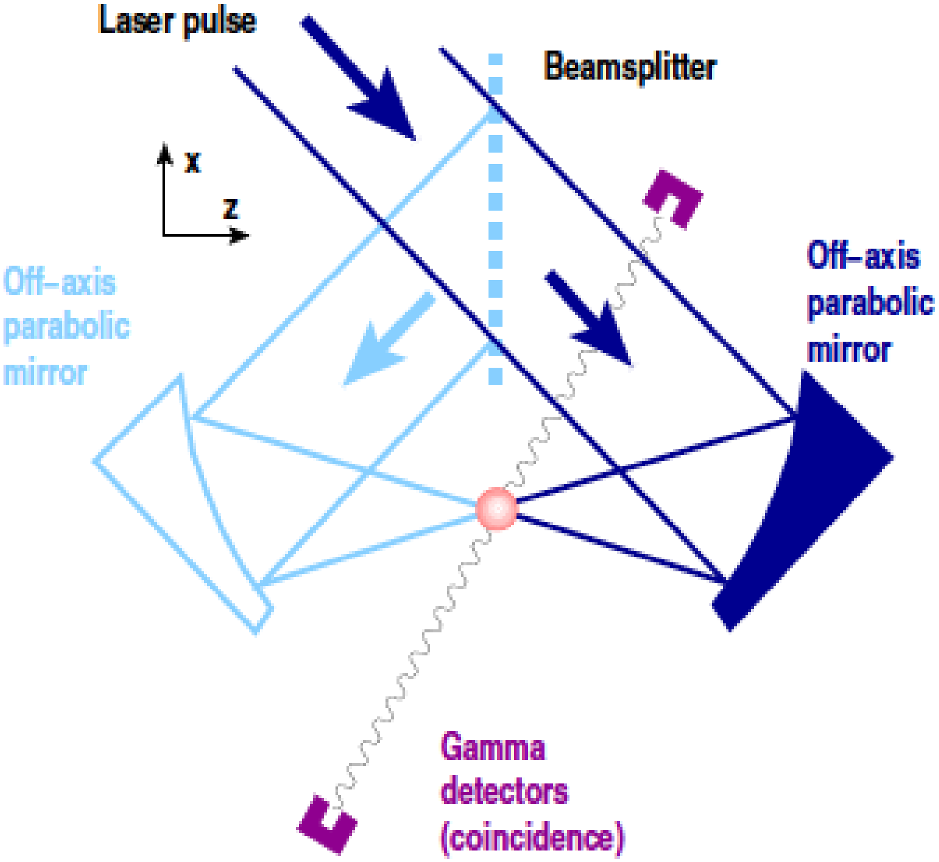
Laser diagnostic by nonlinear Thomson scattering off e^- in a He-gas jet

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

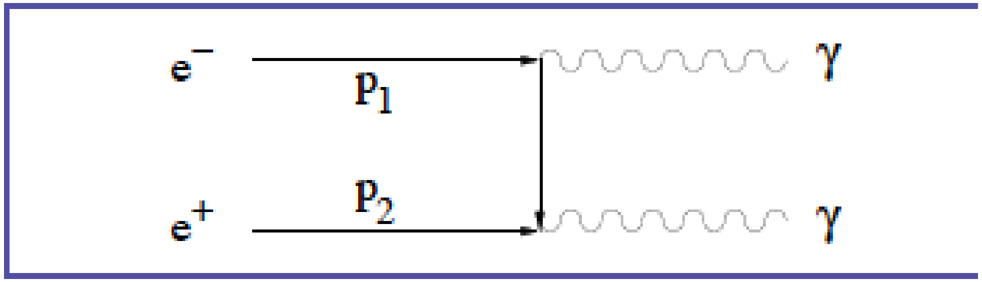
B. Liesfeld et al: "Single-shot autocorrelation at relativistic intensity", Jena Preprint (2004)

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

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



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

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

t-channel kinematic invariant

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

KINETICS OF THE E^{+}E$^{-}\gamma$ PLASMA IN A STRONG LASER FIELD

The photon correlation function is defined as

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

Lowest truncation of BBGKY hierarchy → photon KE for zero initial condition

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

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

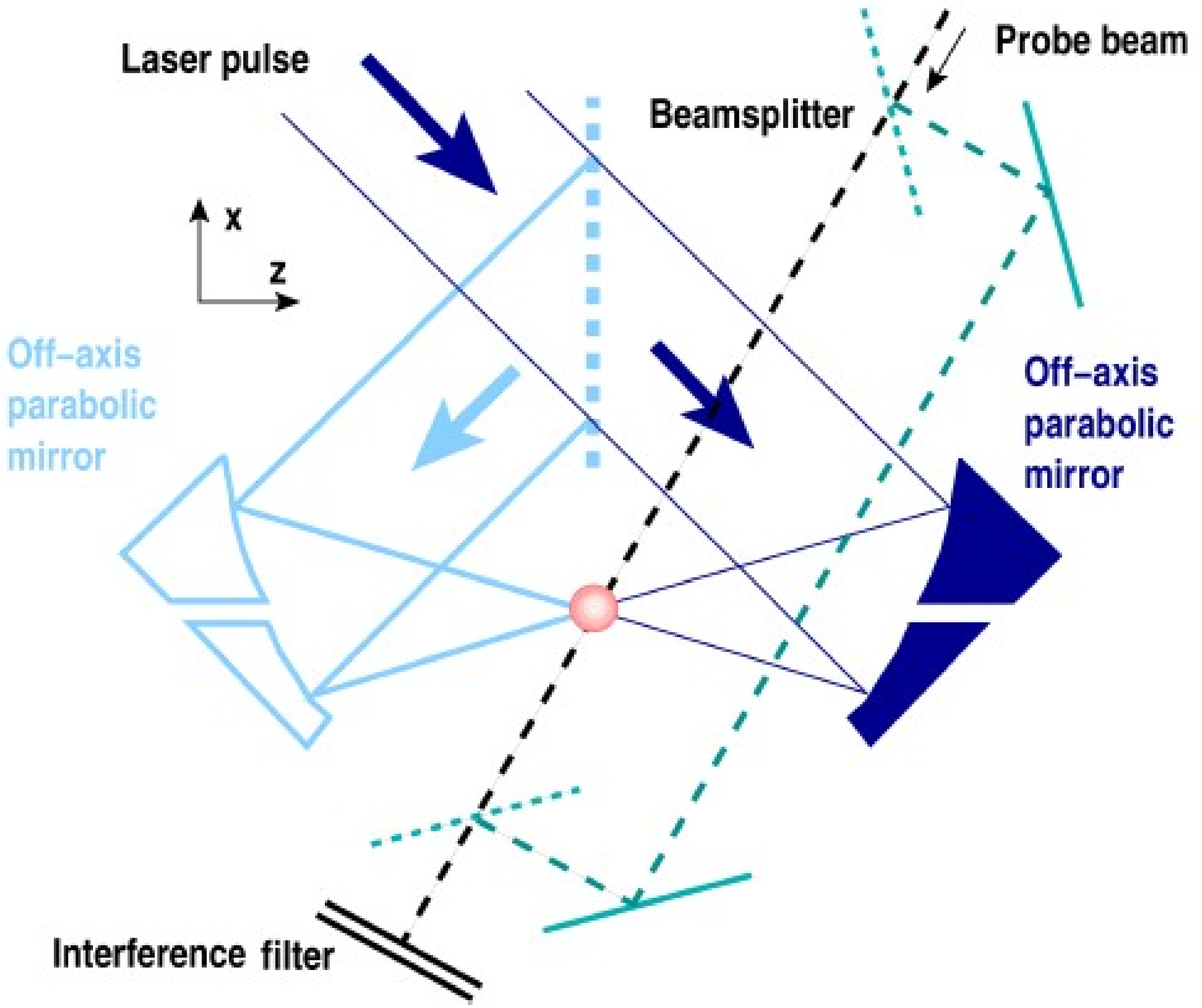
$$F(\mathbf{k},t) = \frac{5e^2 n(t)}{2k\delta^2}\ \ ,\ \ n(t) = 2\int d^3p f(\mathbf{p},t)/(2\pi)^3$$

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 (2011).

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

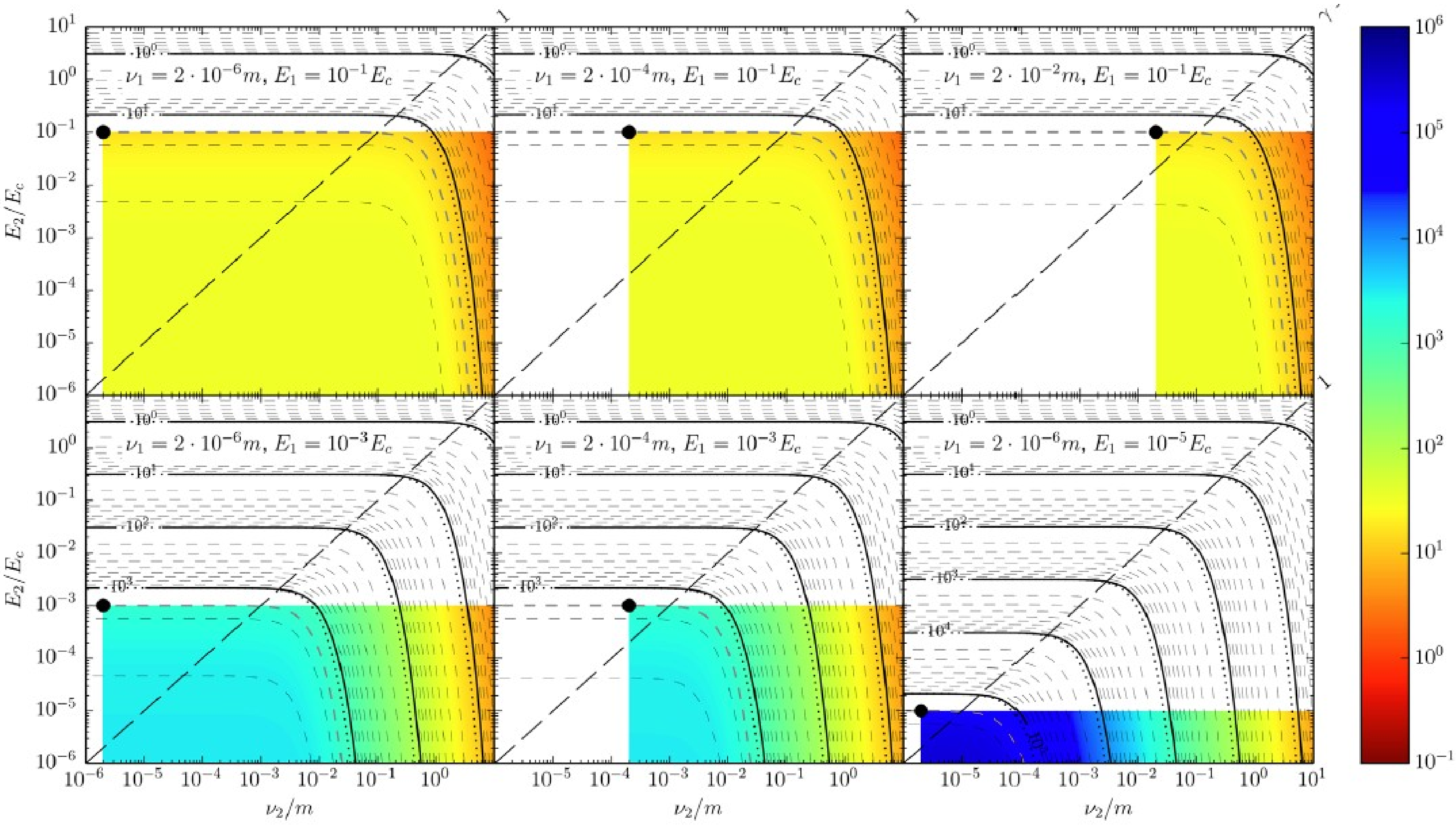
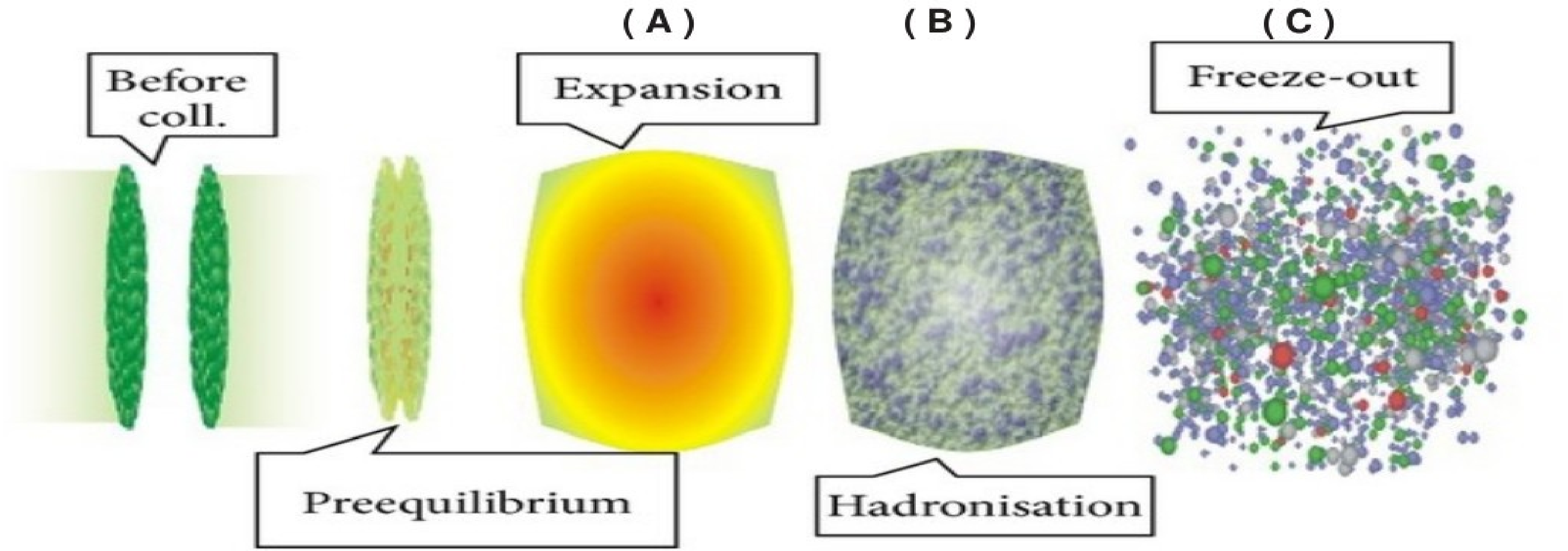


FIG. 3 (color online). Contour plots of the exponential $4\frac{m}{\nu_1}G(p_\perp \ll m, \gamma_1, \gamma_2, N)$ for six given fields ν_1, E_1 in the adiabatic region (positions depicted by the bullets, which are the loci of field doubling) over the field-frequency (E_2/E_c vs ν_2/m) plane, i.e. actually $4\frac{m}{\nu_1}G(p_\perp \ll m, \nu_1, E_1, \nu_2, E_2)$. 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]

Quantum Kinetics of Particle Production in Strong Fields

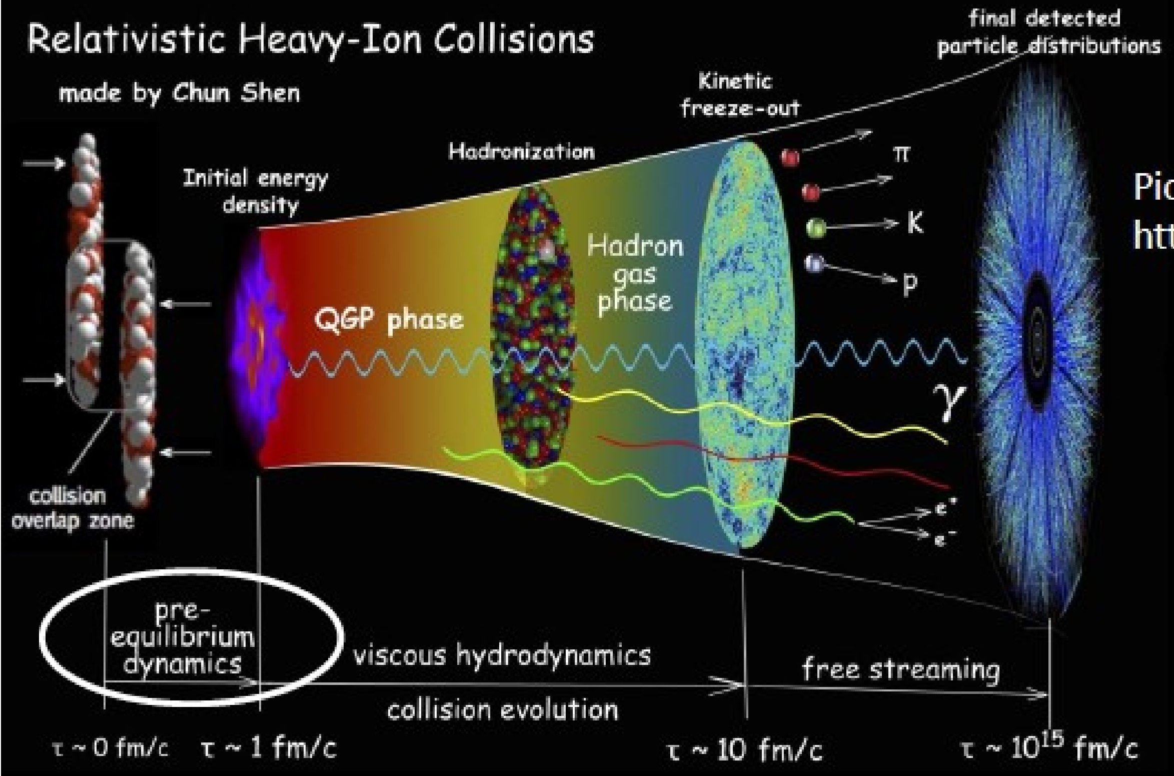


Generic kinetic equation with scalar (mass) and color meanfields, Schwinger source terms and collision integrals for hadronization and rescattering

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

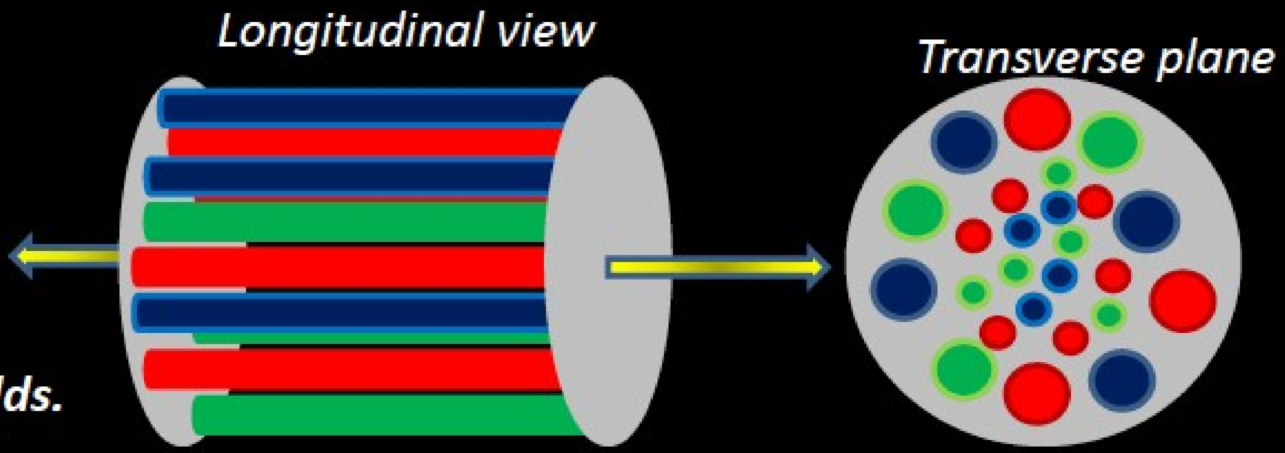
(A) quark-antiquark pair creation in time-dependent color electric background field
(B) quantum kinetics of pre-hadron inelastic rescattering in the dense quark plasma
(C) chemical freeze-out by Mott-Anderson localization of bound states

Sketchy evolution of a RHIC



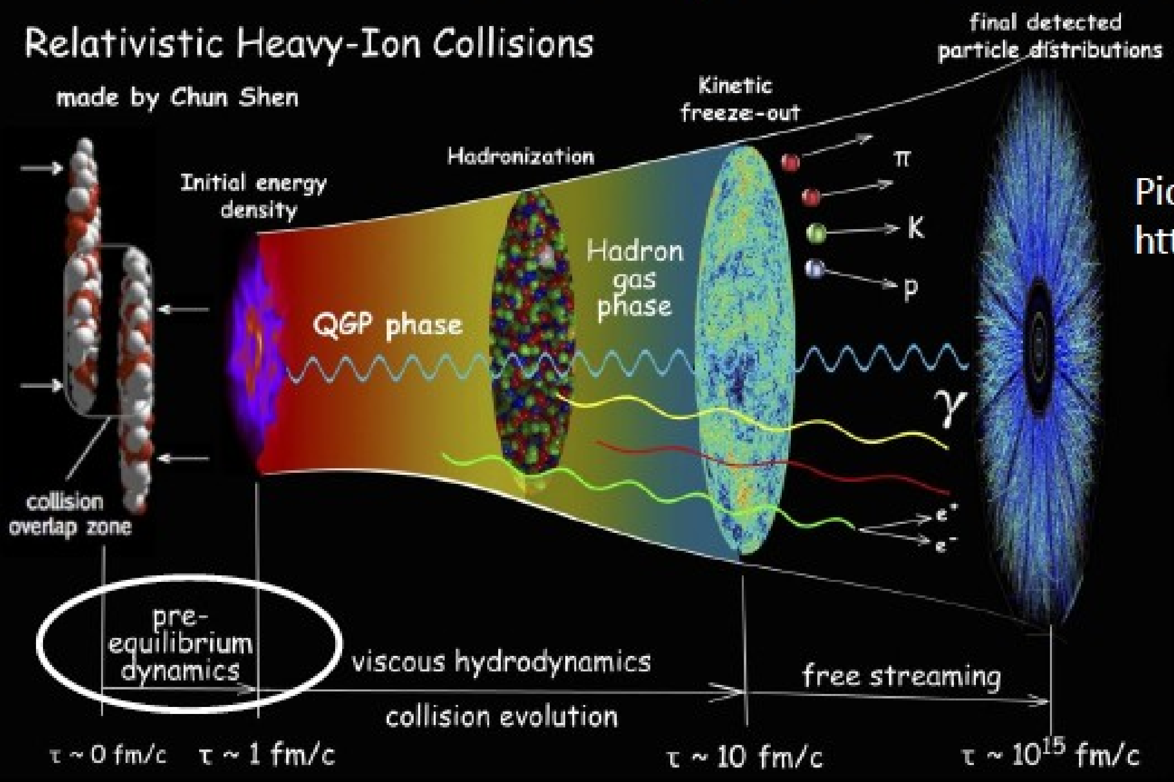
Picture taken from:
http://snelling.web.cern.ch/snelling/img/little_bang.jpg

Initial out-of-equilibrium state:
Glasma
namely, ***a peculiar configuration of longitudinal color–electric and color-magnetic fields.***



Courtesy: Marco Ruggieri, Kyoto 2018

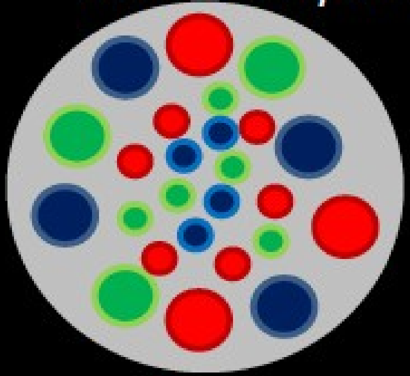
Sketchy evolution of a RHIC



Picture taken from:
http://snelling.web.cern.ch/snelling/img/little_bang.jpg

Longitudinal view

Transverse plane



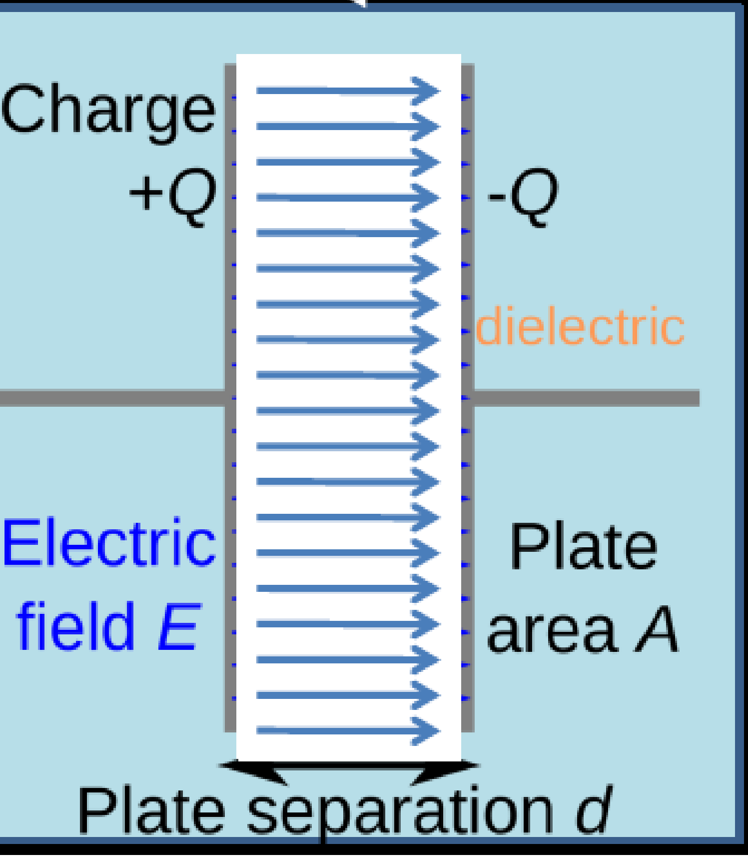
Problem:
how does the QCD dynamics leads to a thermalized and isotropic QGP,
starting from a configuration of classical color fields?

Here we describe *one possible approach* to the problem,
based on the assumption that classical color fields decay to a QGP
via vacuum tunneling, namely via the ***Schwinger effect*** (Schwinger, 1951).

Courtesy: Marco Ruggieri, Kyoto 2018

Schwinger effect in Electrodynamics

Vacuum with an electric field → ***Unstable towards pair creation***



In fact, *quantum effective action* of a pure electric field has *imaginary part* which is responsible for field instability

Euler-Heisenberg (1936)
J. Schwinger (1951)

Vacuum Decay Probability

Probability per unit of spacetime to create an electron-positron pair from the vacuum:

$$\mathcal{W}(x) = \frac{e^2E^2}{4\pi^3}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(-\frac{n\pi m^2}{|eE|}\right)$$

J. Schwinger (1951)

Electric field decay by Schwinger effect can be described as a *quantum tunneling process*

Casher et al., PRD 20 (1979)

Courtesy: Marco Ruggieri, Kyoto 2018

Schwinger effect in Electrodynamics

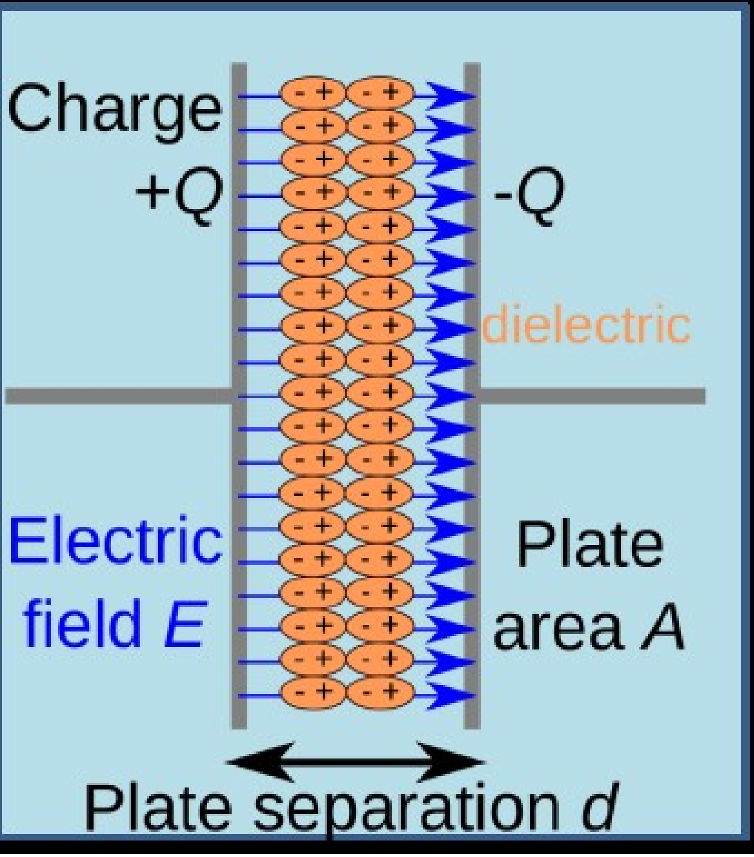
$$\mathcal{W}(x) = -\frac{|g\boldsymbol{E}|}{4\pi^3}\int d^2p_T \log\left(1-e^{-\frac{\pi^2 E_T^2}{|g\boldsymbol{E}|}}\right)$$
$$= \frac{g^2E^2}{4\pi^3}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(-\frac{n\pi m^2}{|g\boldsymbol{E}|}\right)$$

Quantum tunneling interpretation:

(.) Gives the p_z and p_T spectrum of the produced pair

(.) Describes the Schwinger effect as a dipole formation in the vacuum; each dipole has moment

$$p = g \times 2 \times \frac{d}{2} = g\frac{2E_T}{|g\boldsymbol{E}|}$$



Courtesy: Marco Ruggieri, Kyoto 2018

Schwinger effect in Electrodynamics

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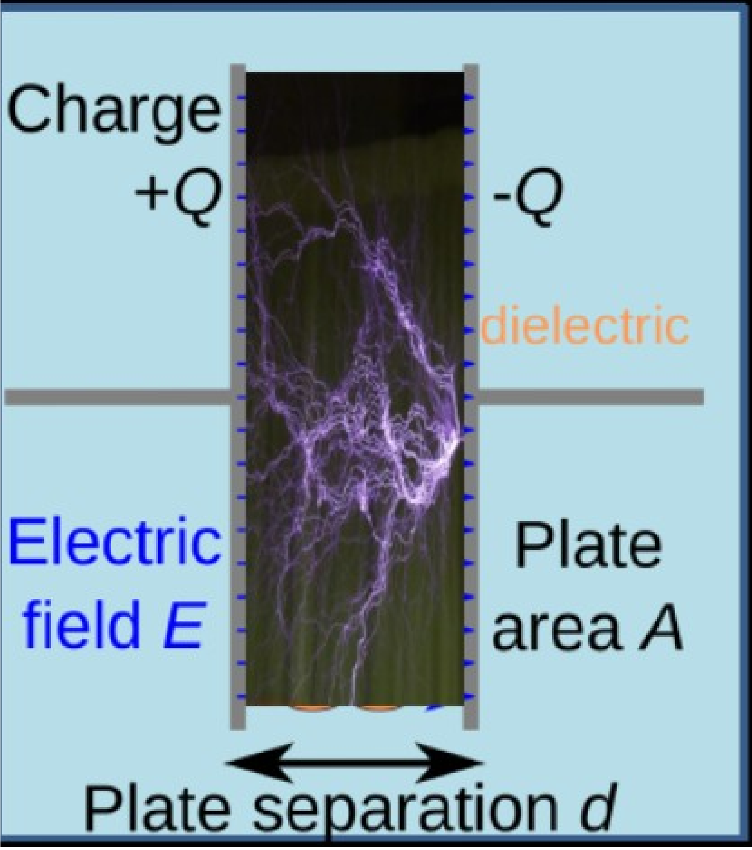


Once pairs pop up from the vacuum, charged particles propagate in real time producing electric currents:

$$\boxed{J = \sigma E}$$

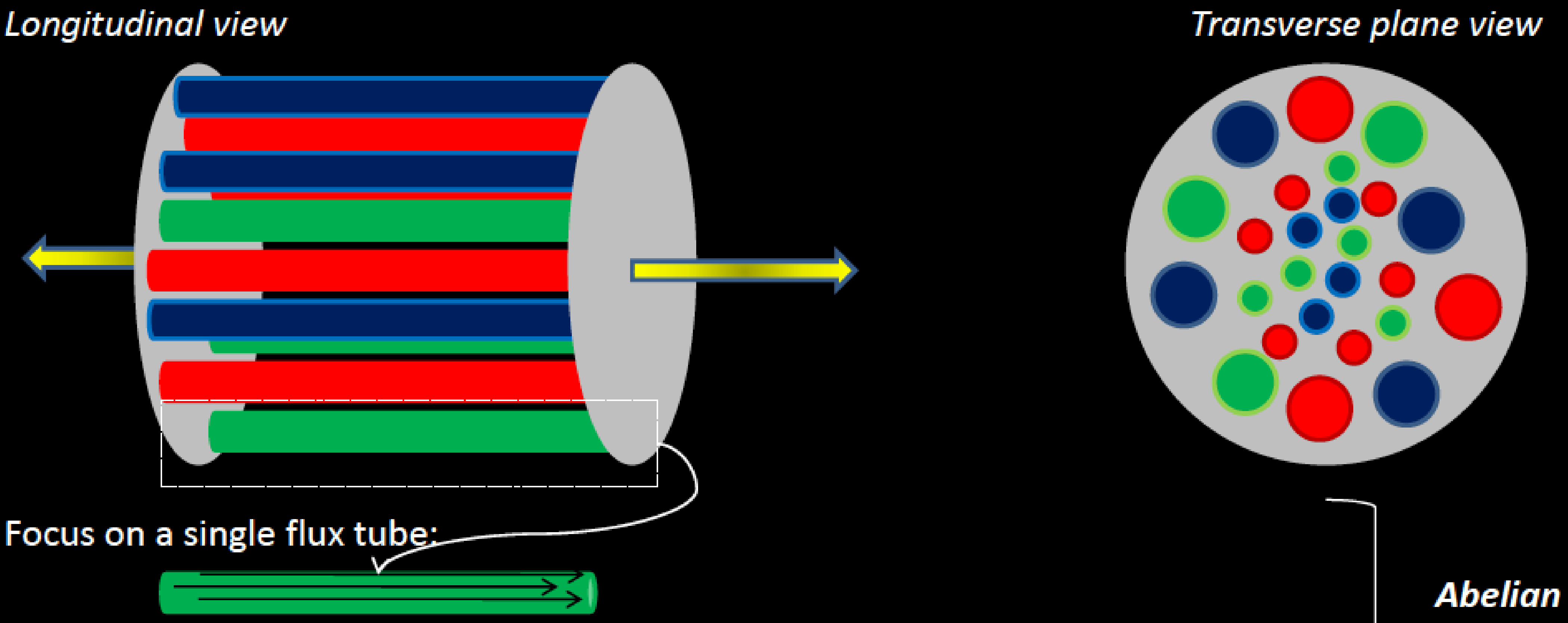
in linear response theory

Vacuum polarization
Electric current
→ ***Dielectric breakdown***

Courtesy: Marco Ruggieri, Kyoto 2018

Schwinger effect in Chromodynamics

Abelian Flux Tube Model



Focus on a single flux tube:

- (.) neglect color-magnetic fields;
- (.) assume abelian dynamics for ***color-electric fields***;
- (.) initial field is ***longitudinal;***
- (.) assume ***Schwinger effect*** takes place:

  Color-eletric color field decays into quark-antiquark as well as gluon pairs

Abelian Flux Tube Model

Courtesy: Marco Ruggieri, Kyoto 2018

Boltzmann equation and QGP

In order to *simulate* the temporal evolution of the fireball we solve the ***Boltzmann equation*** for the parton distribution function ***f***:

$$\left(p_\mu \partial^\mu + gQF^{\mu\nu} p_\mu \partial_\nu^p\right) f = \mathcal{C}[f]$$

Field interaction (EoS)

Collision integral

Collision integral: change of ***f*** due to collision processes in the phase space volume centered at (***x***,***p***).
Responsible for deviations from ideal hydro (non vanishing η/s).

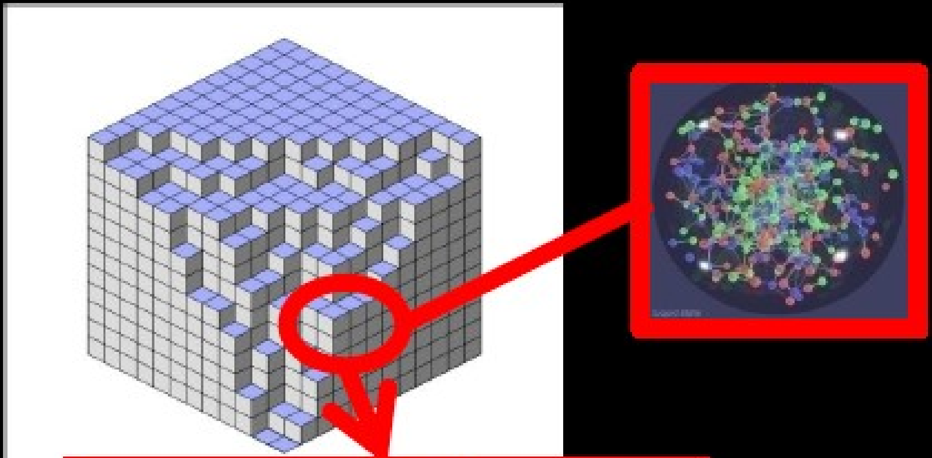
We map by C[f] the phase space evolution of a fluid which dissipates with a given value of η/s.

One can expand C[f] over microscopic details (2<->2,2<->3…), but in a hydro language this is irrelevant: ***only the global dissipative effect of C[f] is important.***

Courtesy: Marco Ruggieri, Kyoto 2018

Transport *gauged* to hydro

Total Cross section is ***computed*** in ***each configuration space cell*** according to ***Chapman-Enskog equation*** to give the ***wished value of eta/s***.



$$\frac{\eta}{s} = \frac{\langle p \rangle}{g(m_D)\rho}\frac{1}{\sigma}$$

(.) Collision integral is gauged in each cell to assure that the fluid dissipates according to the desired value of η/s.

(.) Microscopic details are not important: the specific microscopic process producing η/s is not relevant, only macroscopic quantities are, in analogy with hydrodynamics.

Transport

Description in terms of parton distribution function

←

→

Hydro

Dynamical evolution governed by macroscopic quantities

Courtesy: Marco Ruggieri, Kyoto 2018

Boltzmann equation and QGP

In order to permit ***particle creation*** from the vacuum we need to add a ***source term*** to the rhs of the Boltzmann equation:

$$\left(p_\mu \partial^\mu + g Q_{jc} F^{\mu\nu} p_\mu \partial_\nu^p\right) f_{jc} = p_0 \frac{\partial}{\partial t} \frac{dN_{jc}}{d^3x d^3p} + \mathcal{C}[f]$$

Florkowski and Ryblewski, PRD 88 (2013)

Invariant source term

Invariant source term: change of ***f*** due to particle creation in the volume at ***(x,p).***

In our model, particles are created by means of the Schwinger effect, hence

$$\frac{dN_{jc}}{d\Gamma} \equiv p_0 \frac{dN_{jc}}{d^4x d^2p_T dp_z} = \mathcal{R}_{jc}(p_T)\delta(p_z)p_0$$

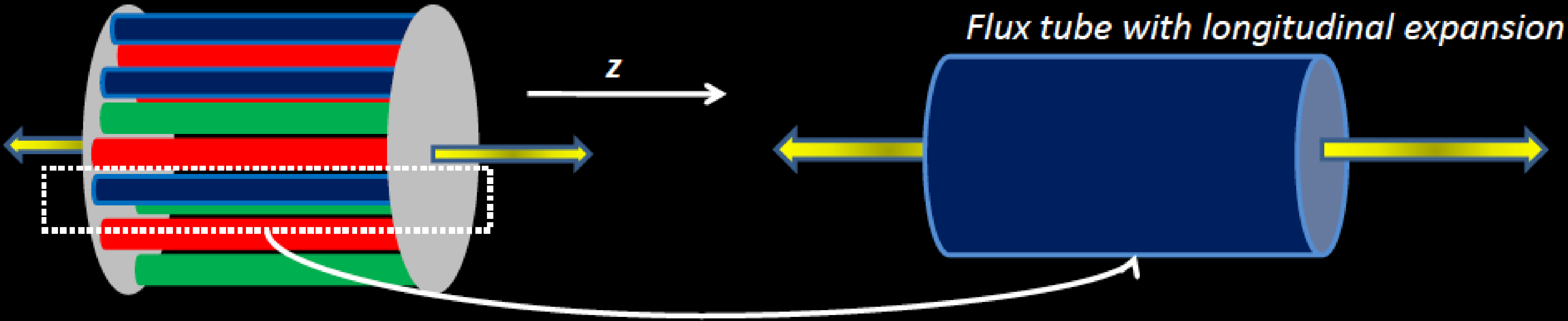
$$\mathcal{R}_{jc}(p_T) = \frac{\mathcal{E}_{jc}}{4\pi^3}\left|\ln\left(1 \pm e^{-\pi p_T^2/\mathcal{E}_{jc}}\right)\right|$$

$$\mathcal{E}_{jc} = \left(g|Q_{jc}E| - \sigma_j\right)\theta\left(g|Q_{jc}E| - \sigma_j\right)$$

See also:
Gelis and Tanji, PRD 87 (2013)

Courtesy: Marco Ruggieri, Kyoto 2018

Boost invariant 1+1D expansion



$$(p_\mu \partial^\mu + g Q_{jc} F^{\mu\nu} p_\mu \partial^p_\nu) f_{jc} = p_0 \frac{\partial}{\partial t} \frac{dN_{jc}}{d^3x\, d^3p} + \mathcal{C}[f]$$

We assume

(.) initial field is ***longitudinal***, and field dynamics is ***boost invariant.***

(.) ***ignore transverse expansion*** (via proper boundary conditions).

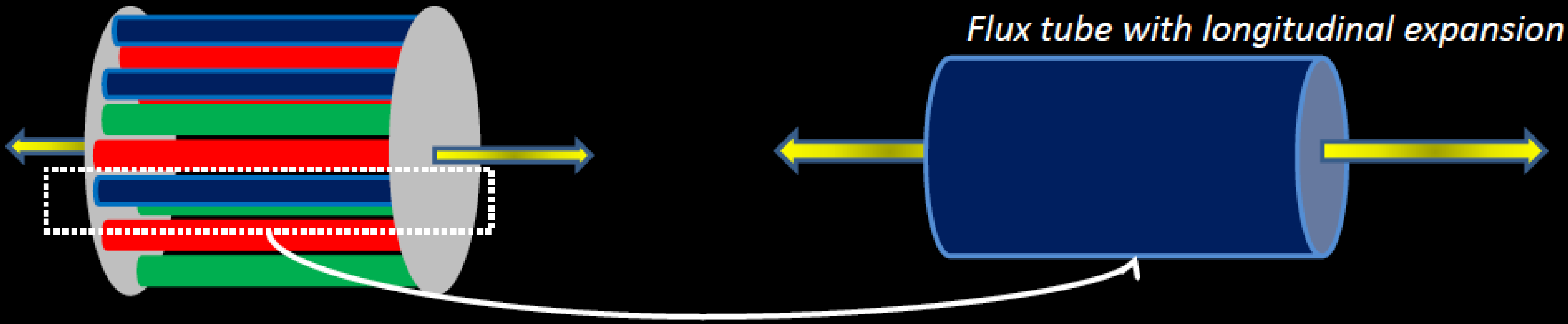
Hence *field dynamics is effectively 1+1 (long.+time) dimensional*

$$\left.\begin{aligned}\frac{\partial E}{\partial z} &= \rho \\ \frac{\partial E}{\partial t} &= -j\end{aligned}\right\}$$

$$\frac{dE}{dt} = \rho \tanh\eta - j_M - \frac{j_D}{\cosh\eta}$$

Courtesy: Marco Ruggieri, Kyoto 2018

Boost invariant 1+1D expansion



$$(p_\mu \partial^\mu + gQ_{jc}F^{\mu\nu}p_\mu\partial^p_\nu) f_{jc} = p_0 \frac{\partial}{\partial t}\frac{dN_{jc}}{d^3x d^3p} + \mathcal{C}[f]$$

We assume field dynamics is ***boost invariant.*** This means E=E(τ), hence independent on η:

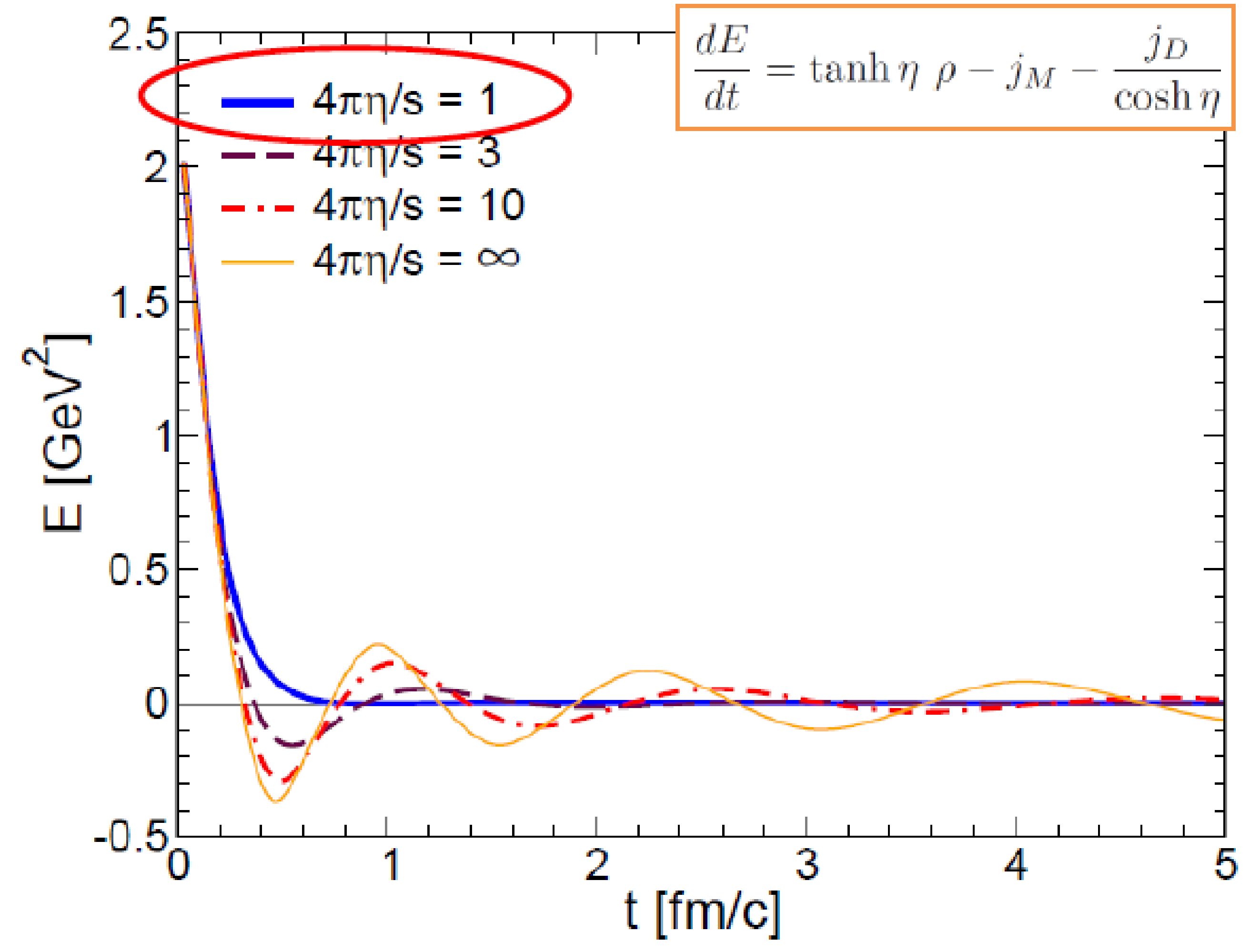
$$\left.\begin{aligned}\frac{\partial E}{\partial z} &= \rho\\ \frac{\partial E}{\partial t} &= -j\end{aligned}\right\} \qquad \frac{dE}{dt} = \rho\tanh\eta - j_M - \frac{j_D}{\cosh\eta}$$

depend on distribution functions

Link Maxwell equation to kinetic equation

Courtesy: Marco Ruggieri, Kyoto 2018

Field decay in 1+1D expansion



$$\frac{dE}{dt} = \tanh\eta\ \rho - j_M - \frac{j_D}{\cosh\eta}$$

ρ	*electric charge density*
j_M	*electric current*
j_D	*polarization current*

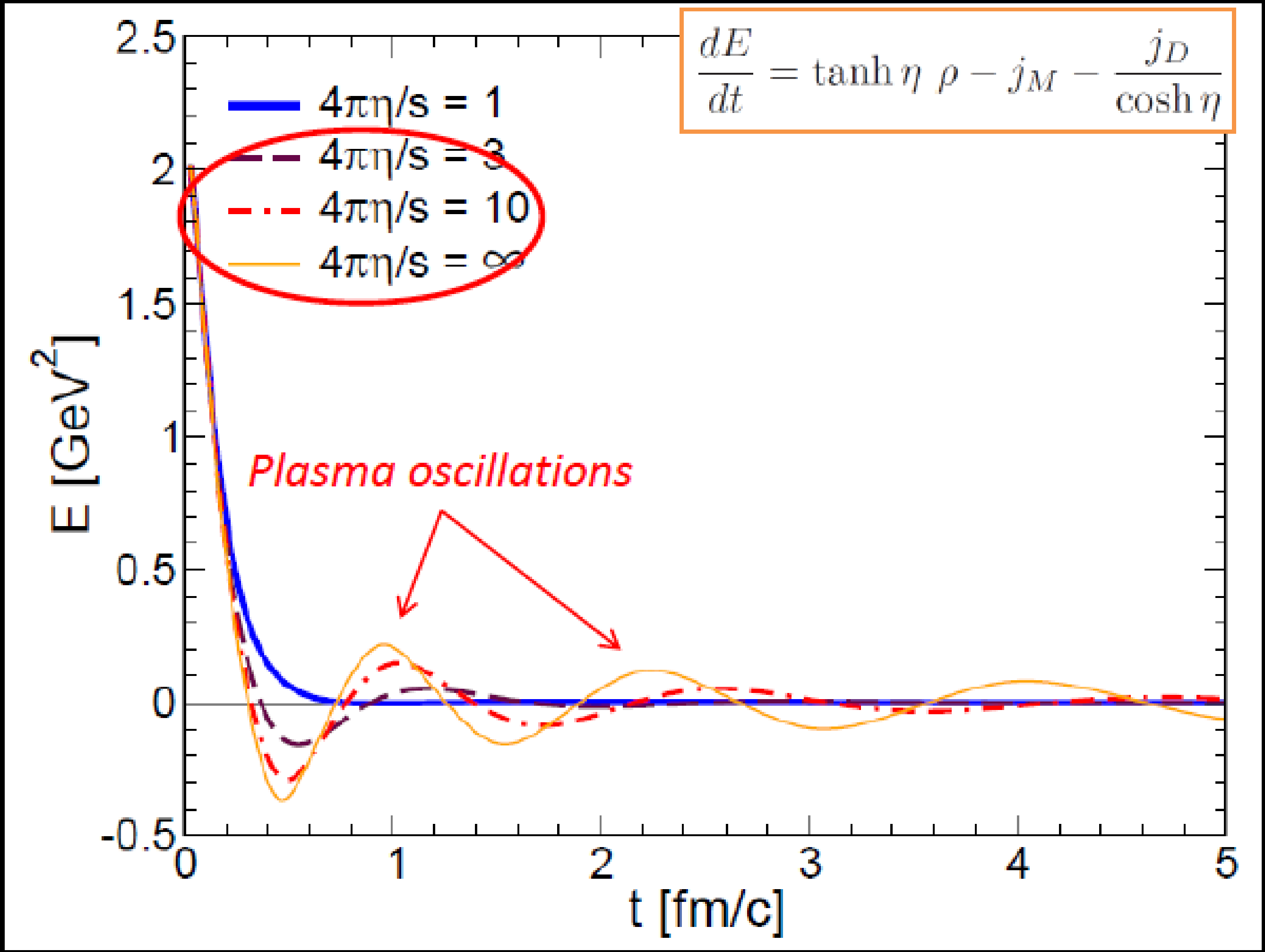
Small η/s
(.) Field decays quickly (power law)

Small η/s implies *large scattering rate*, meaning *efficient randomization* of particles momenta in each cell, thus damping ordered particle flow along the field direction (electric current).

Decay controlled by Schwinger effect

Courtesy: Marco Ruggieri, Kyoto 2018; arxiv:1505.08081

Field decay in 1+1D expansion



$$\frac{dE}{dt} = \tanh\eta\ \rho - j_M - \frac{j_D}{\cosh\eta}$$

ρ	*electric charge density*
j_M	*electric current*
j_D	*polarization current*

Large η/s
(.) Initial times dynamics faster,
due to electric current:

$$\frac{d}{dt}\left(\frac{\boldsymbol{E}^2}{2}\right) = -\boldsymbol{j}\cdot\boldsymbol{E}$$

Smaller coupling (i.e. smaller isotropization efficiency) favors development of conductive electric currents: the net effect is a continuous energy exchange between particles and field.

Plasma oscillations controlled by electric current

Courtesy: Marco Ruggieri, Kyoto 2018; arxiv:1505.08081

Pressure isotropization

$$T^{\mu\nu}_{field} = \mathrm{diag}\left(\varepsilon, P_T, P_T, P_L\right)$$
$$\propto \mathrm{diag}\left(\mathcal{E}^2, \mathcal{E}^2, \mathcal{E}^2, -\mathcal{E}^2\right)$$

$$T^{\mu\nu}_{particles} = \int \frac{d^3\boldsymbol{p}}{(2\pi)^3}\frac{p^\mu p^\nu}{E} f(\boldsymbol{x}, \boldsymbol{p})$$

$$T^{\mu\nu} = T^{\mu\nu}_{particles} + T^{\mu\nu}_{field}$$

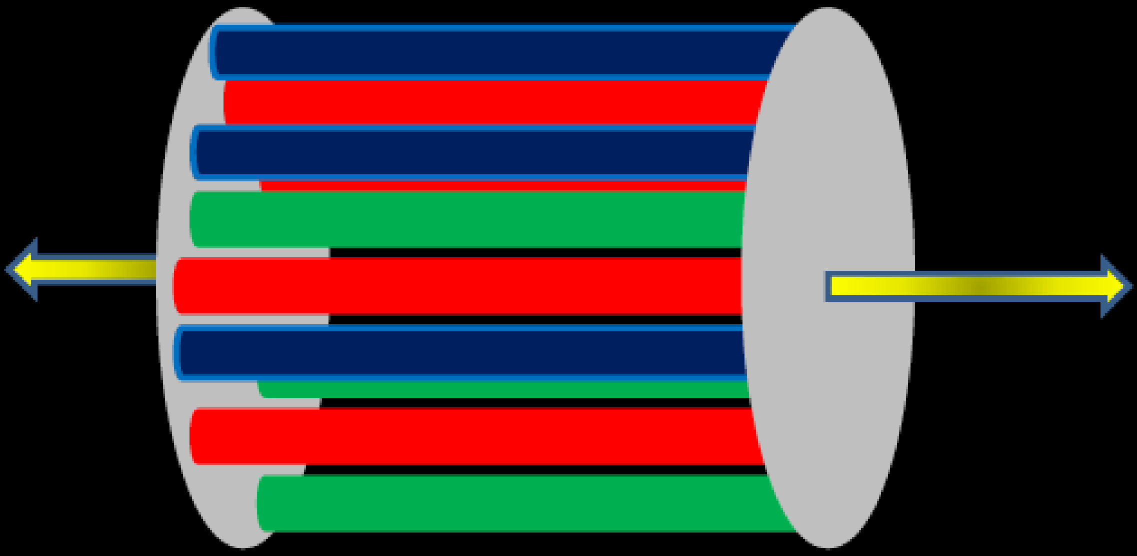
$$P_L = T_{zz}$$

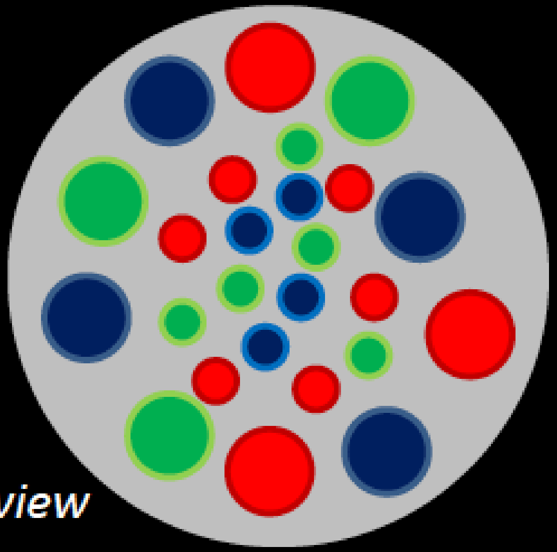
Along flight direction

$$P_T = \frac{T_{xx} + T_{yy}}{2}$$

On transverse plane

Longitudinal view



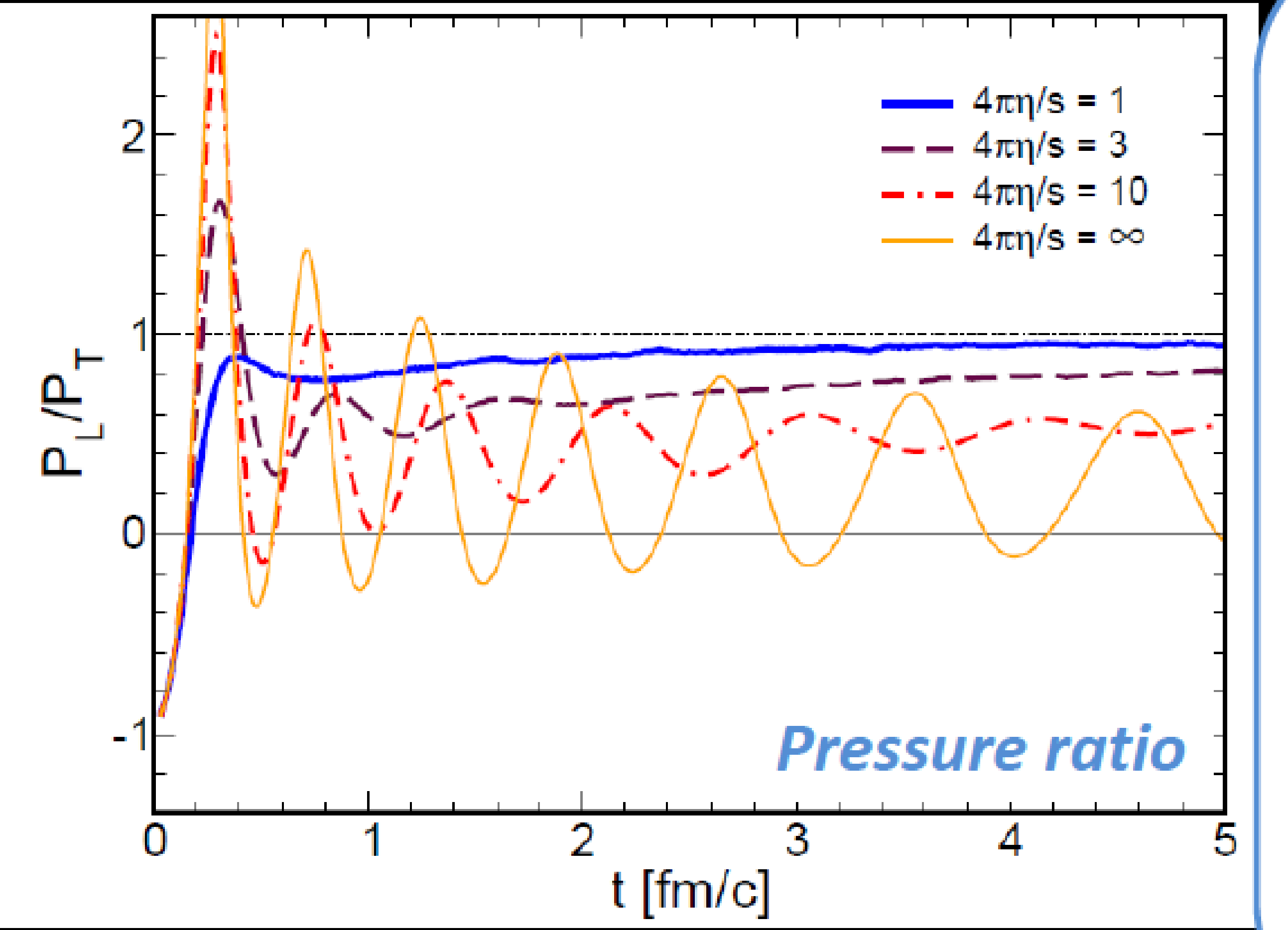


Transverse plane view

Isotropy is achieved if PL = PT

Courtesy: Marco Ruggieri, Kyoto 2018; arxiv:1505.08081

Pressure isotropization



$$T^{\mu\nu}_{field} = \mathrm{diag}\,(\varepsilon, P_T, P_T, P_L)$$

$$\propto \mathrm{diag}\,(\mathcal{E}^2, \mathcal{E}^2, \mathcal{E}^2, -\mathcal{E}^2)$$

$$T^{\mu\nu}_{particles} = \int \frac{d^3\boldsymbol{p}}{(2\pi)^3}\frac{p^\mu p^\nu}{E} f(\boldsymbol{x}, \boldsymbol{p})$$

$$T^{\mu\nu} = T^{\mu\nu}_{particles} + T^{\mu\nu}_{field}$$

$$P_L = T_{zz}$$

$$P_T = \frac{T_{xx} + T_{yy}}{2}$$

Courtesy: Marco Ruggieri, Kyoto 2018; arxiv:1505.08081

Lessons for Nonequilibrium Dynamics in Heavy-Ion Collisions ?

One big question is:

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?

ELSEVIER

4 November 1999

Physics Letters B 466 (1999) 301–304

PHYSICS LETTERS B

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

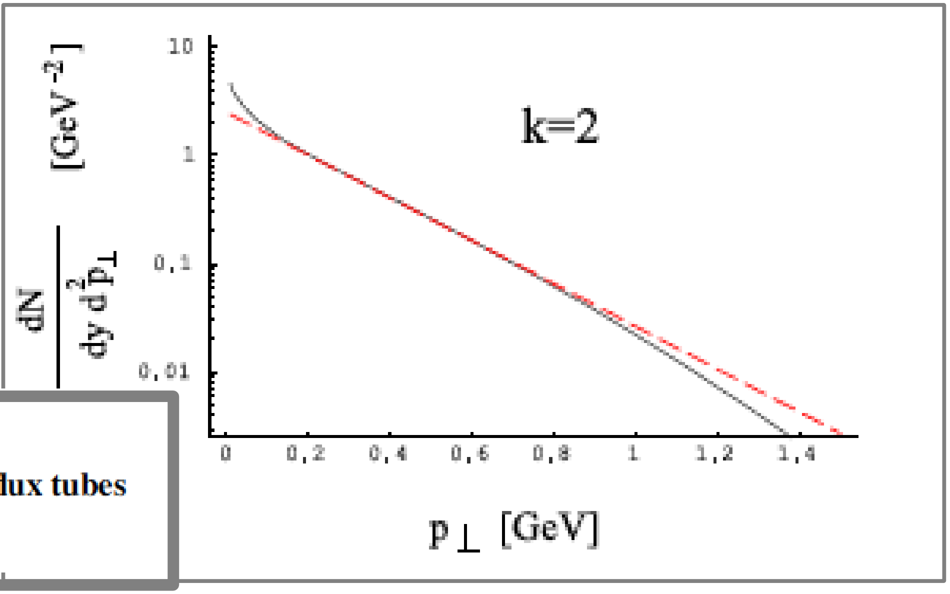
WOJCIECH FLORKOWSKI

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

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

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

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



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,†]

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

$$I_\sigma^{\text{vac}}(\mathbf{p}, t) = \frac{1}{2}\Delta_\sigma(\mathbf{p}, t)\int_{t_0}^{t} dt'\Delta_\sigma(\mathbf{p}, t')$$

$$\times[1 + 2f_\sigma(\mathbf{p}, t')]\cos[2\theta_\sigma(\mathbf{p}; t, t')],$$

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

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

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

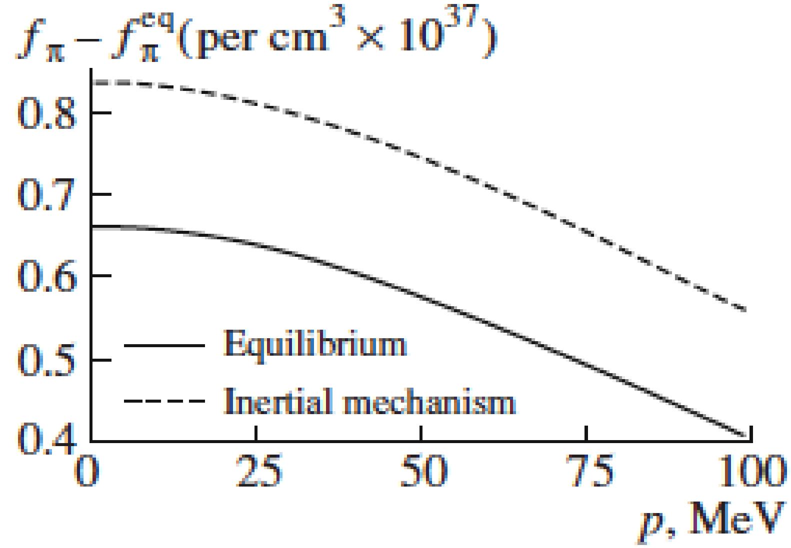
$$I_\sigma^{\text{loss}}(\mathbf{p}, t) = -\int\frac{d\mathbf{p}_1 d\mathbf{p}_2}{\omega_\pi(\mathbf{p}_1, t)\omega_\pi(\mathbf{p}_2, t)}\Gamma_{\sigma\to\pi\pi}(\mathbf{p}, \mathbf{p}_1, \mathbf{p}_2; t)$$

$$\times f_\sigma(\mathbf{p}, t)[1 + f_\pi(\mathbf{p}_1, t)][1 + f_\pi(\mathbf{p}_2, t)] \qquad (4)$$

$$\times\delta\{\omega_\sigma(\mathbf{p}, t) - \omega_\pi(\mathbf{p}_1, t) - \omega_\pi(\mathbf{p}_2, t)\}$$

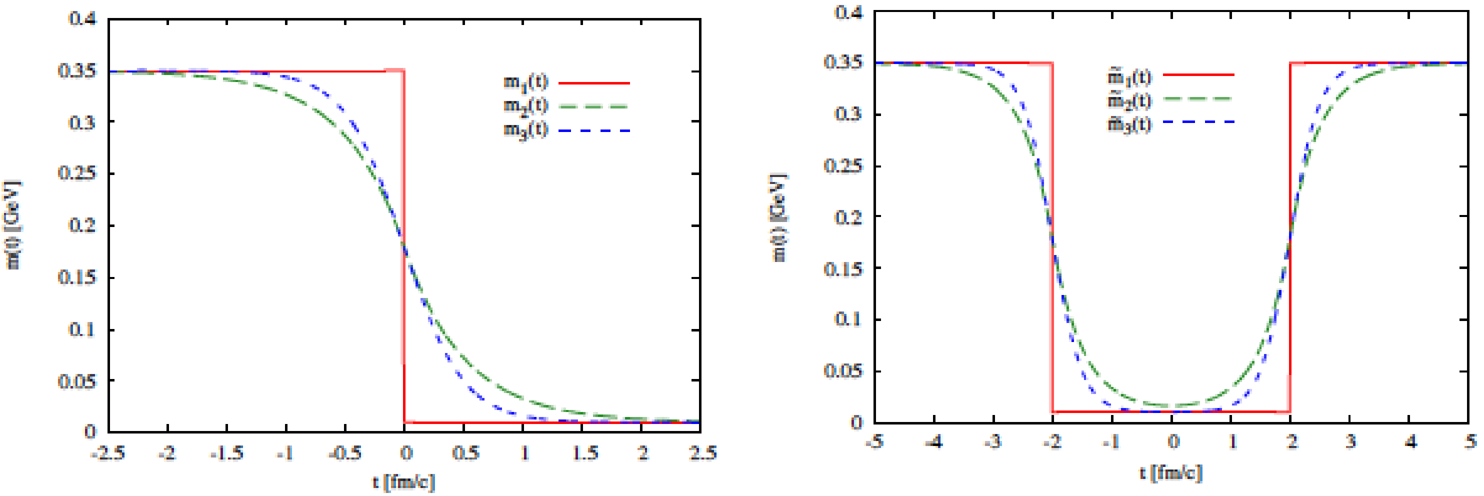
$$\times\delta(\mathbf{p} - \mathbf{p}_1 - \mathbf{p}_2),$$

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

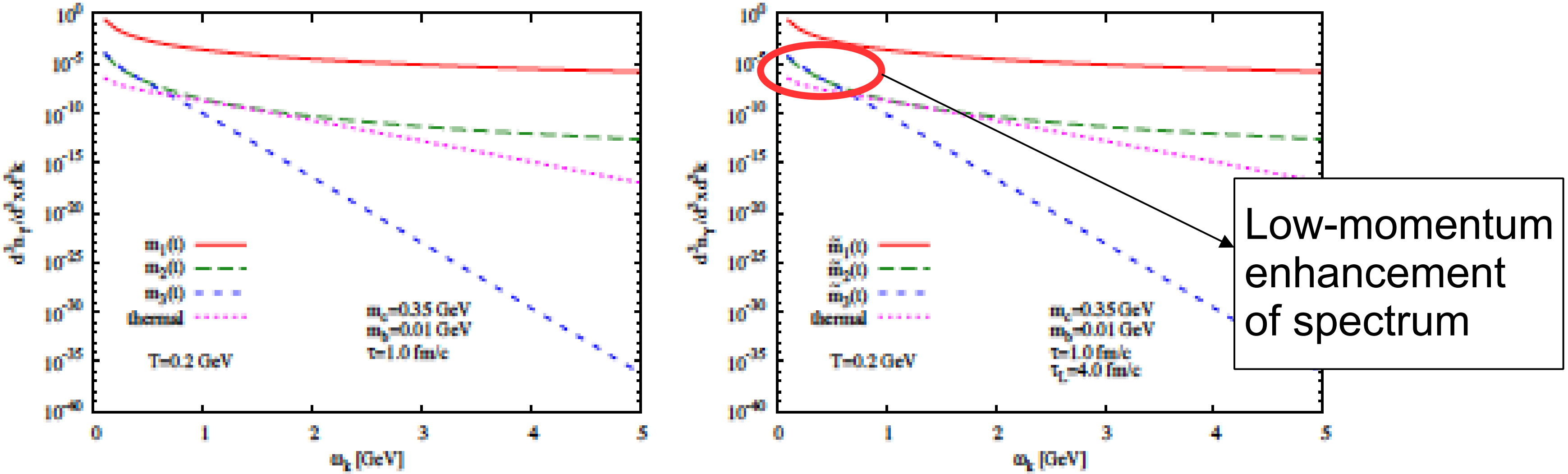


Off-equilibrium photon production during the chiral phase transition

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

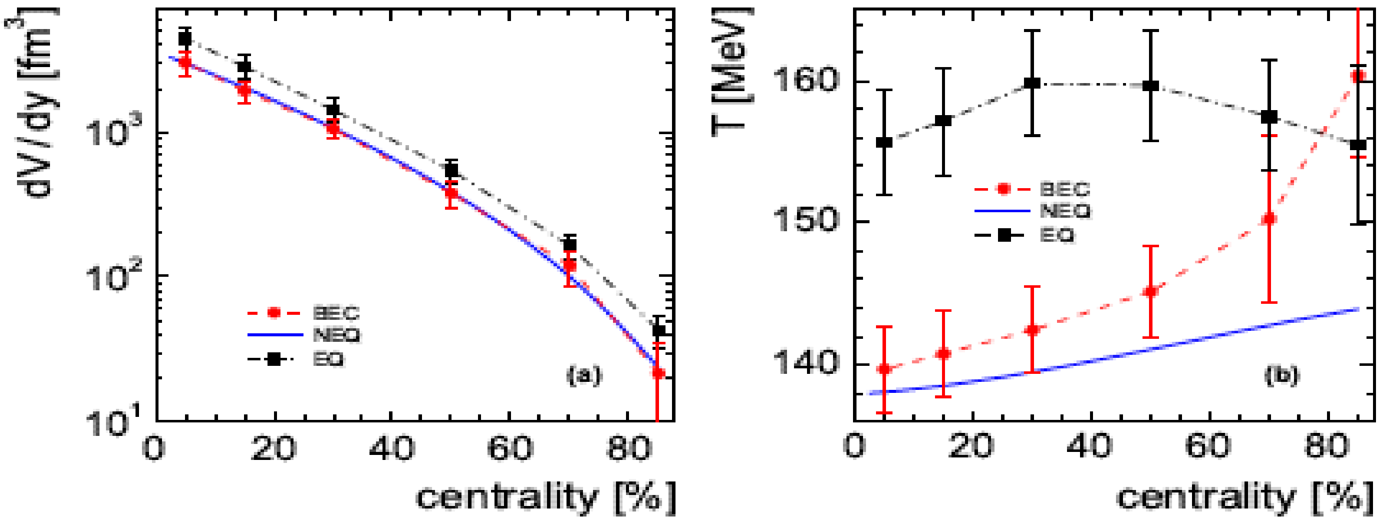


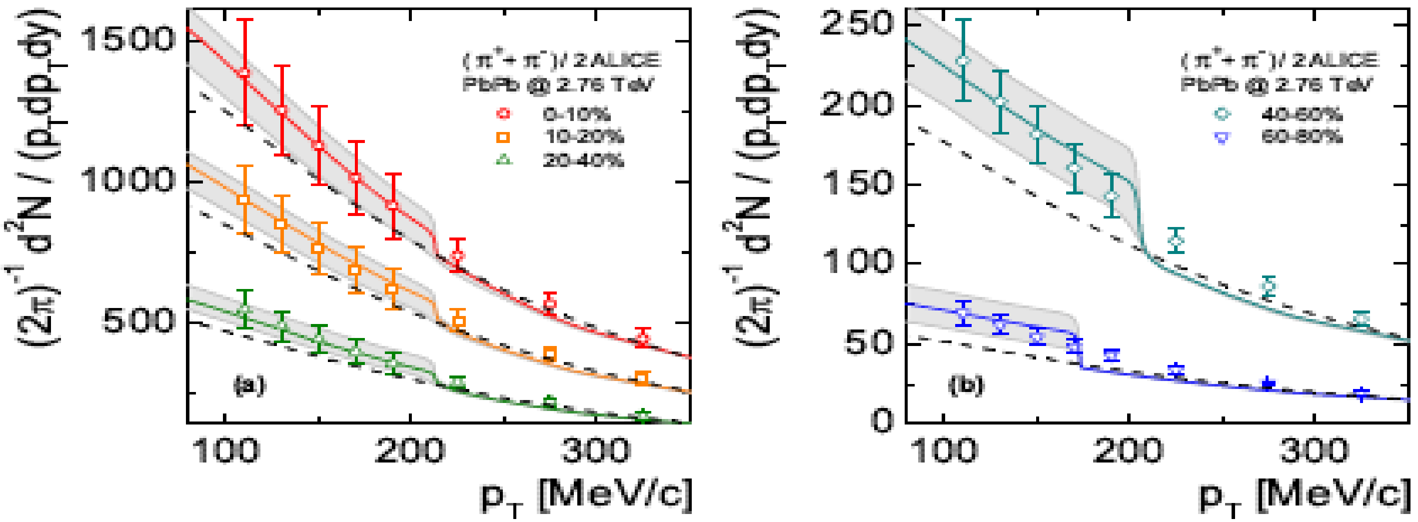
Low-momentum enhancement of spectrum

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 ?

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





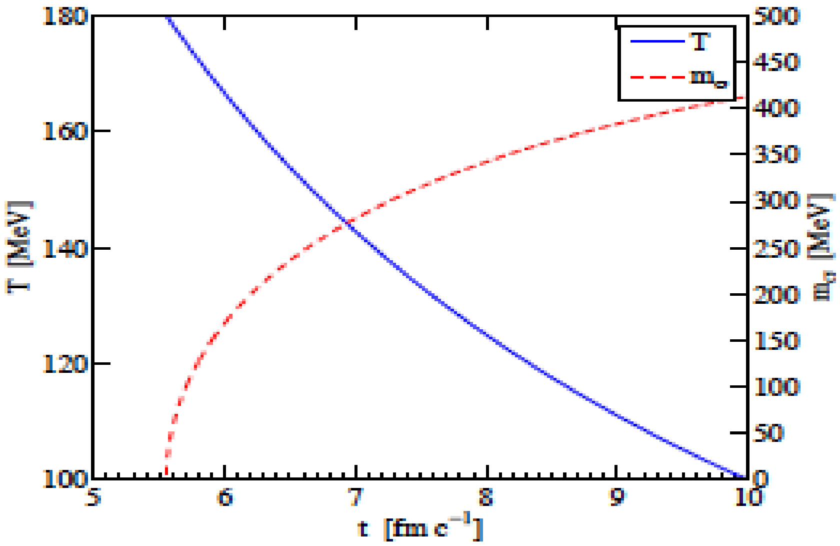
V. Begun, W. Florkowski, PRD (2015); arxiv:1503.04040

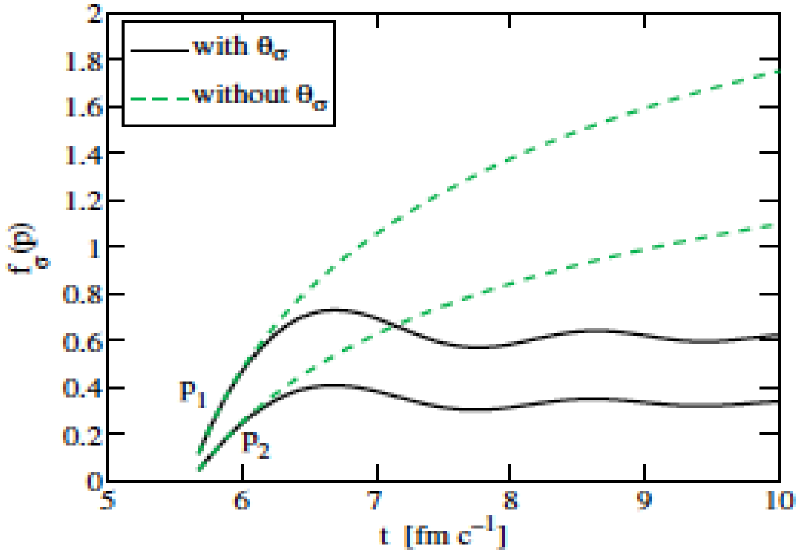
Low-momentum pion enhancement from quantum kinetics of chiral symmetry breaking

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

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

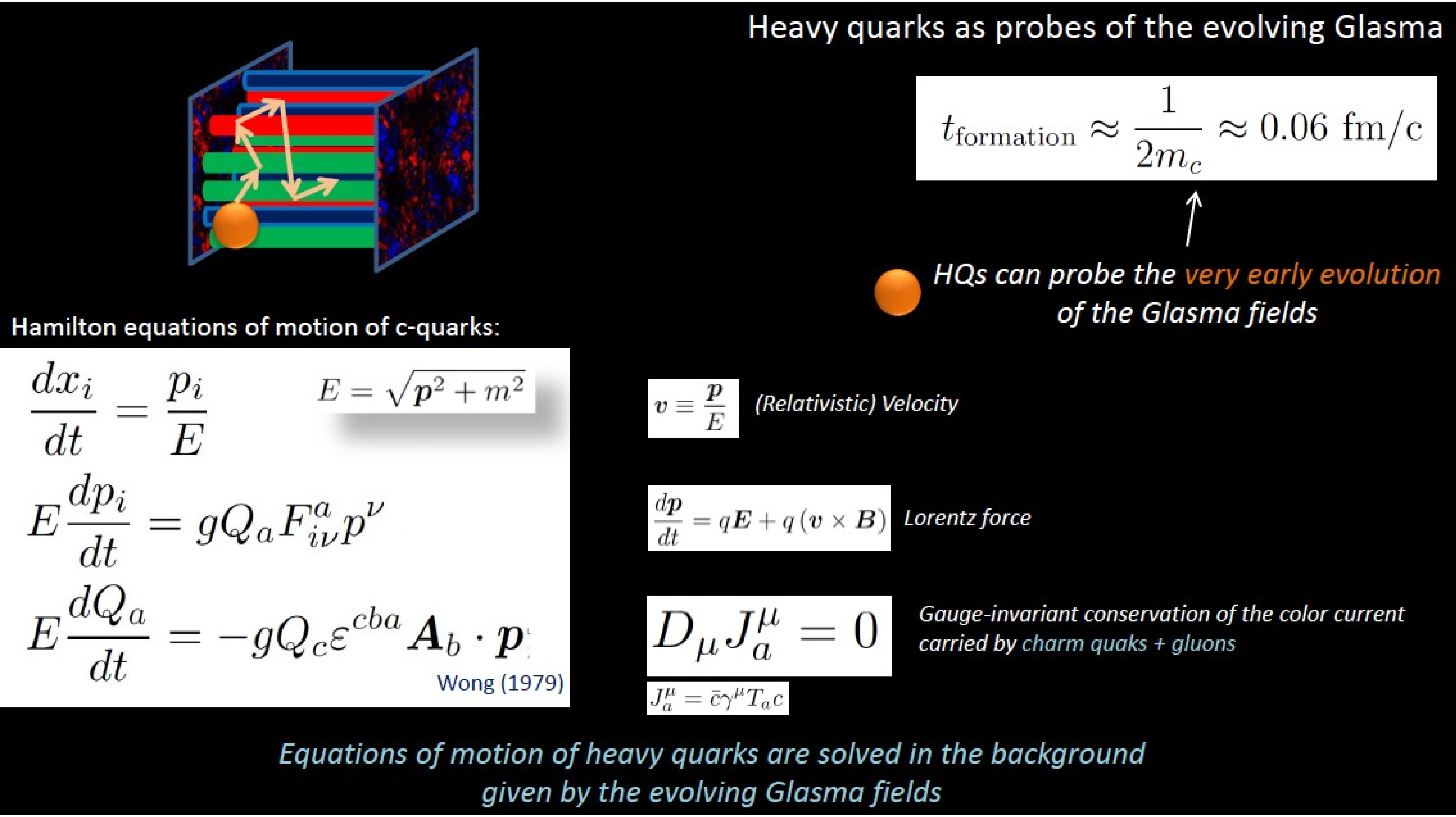
$$
\begin{aligned}
\Delta_\sigma(t,\vec{p}_\sigma) &= \frac{m_\sigma}{w_\sigma^2}\frac{\partial m_\sigma}{\partial t} , \\
\theta_\sigma(t,t',\vec{p}_\sigma) &= \int_{t'}^{t} dt''\,w_\sigma(t'',\vec{p}_\sigma)
\end{aligned}
$$





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

Heavy quarks as probes of the evolving Glasma



Heavy quarks as probes of the evolving Glasma

$$t_{\text{formation}} \approx \frac{1}{2m_c} \approx 0.06\ \text{fm/c}$$

↑

HQs can probe the very early evolution of the Glasma fields

Hamilton equations of motion of c-quarks:

$$\frac{dx_i}{dt} = \frac{p_i}{E} \qquad E = \sqrt{\boldsymbol{p}^2 + m^2}$$

$$E\frac{dp_i}{dt} = gQ_a F^a_{i\nu} p^\nu$$

$$E\frac{dQ_a}{dt} = -gQ_c \varepsilon^{cba} \boldsymbol{A}_b \cdot \boldsymbol{p}$$

Wong (1979)

$$\boldsymbol{v} \equiv \frac{\boldsymbol{p}}{E}$$ *(Relativistic) Velocity*

$$\frac{d\boldsymbol{p}}{dt} = q\boldsymbol{E} + q(\boldsymbol{v} \times \boldsymbol{B})$$ *Lorentz force*

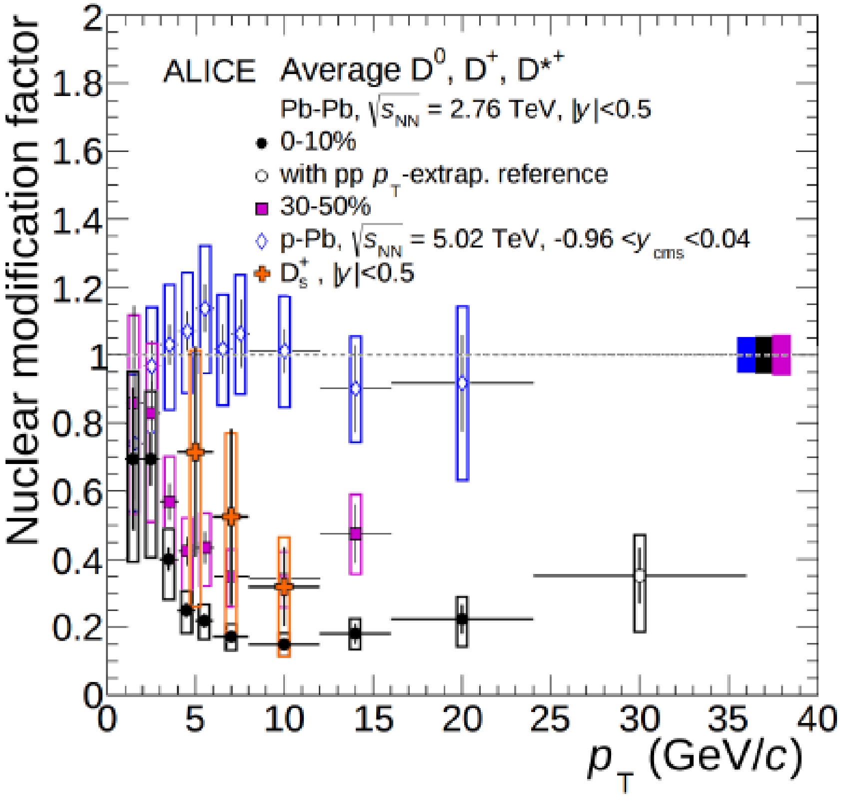
$$D_\mu J^\mu_a = 0$$ *Gauge-invariant conservation of the color current carried by charm quaks + gluons*

$$J^\mu_a = \bar{c}\gamma^\mu T_a c$$

Equations of motion of heavy quarks are solved in the background given by the evolving Glasma fields

Courtesy: Marco Ruggieri, Kyoto 2018

Heavy quarks as probes of the evolving Glasma



Heavy quarks as probes of the evolving Glasma

Measured R_{pPb} suggest that a hot QGP might not form in p-Pb collisions

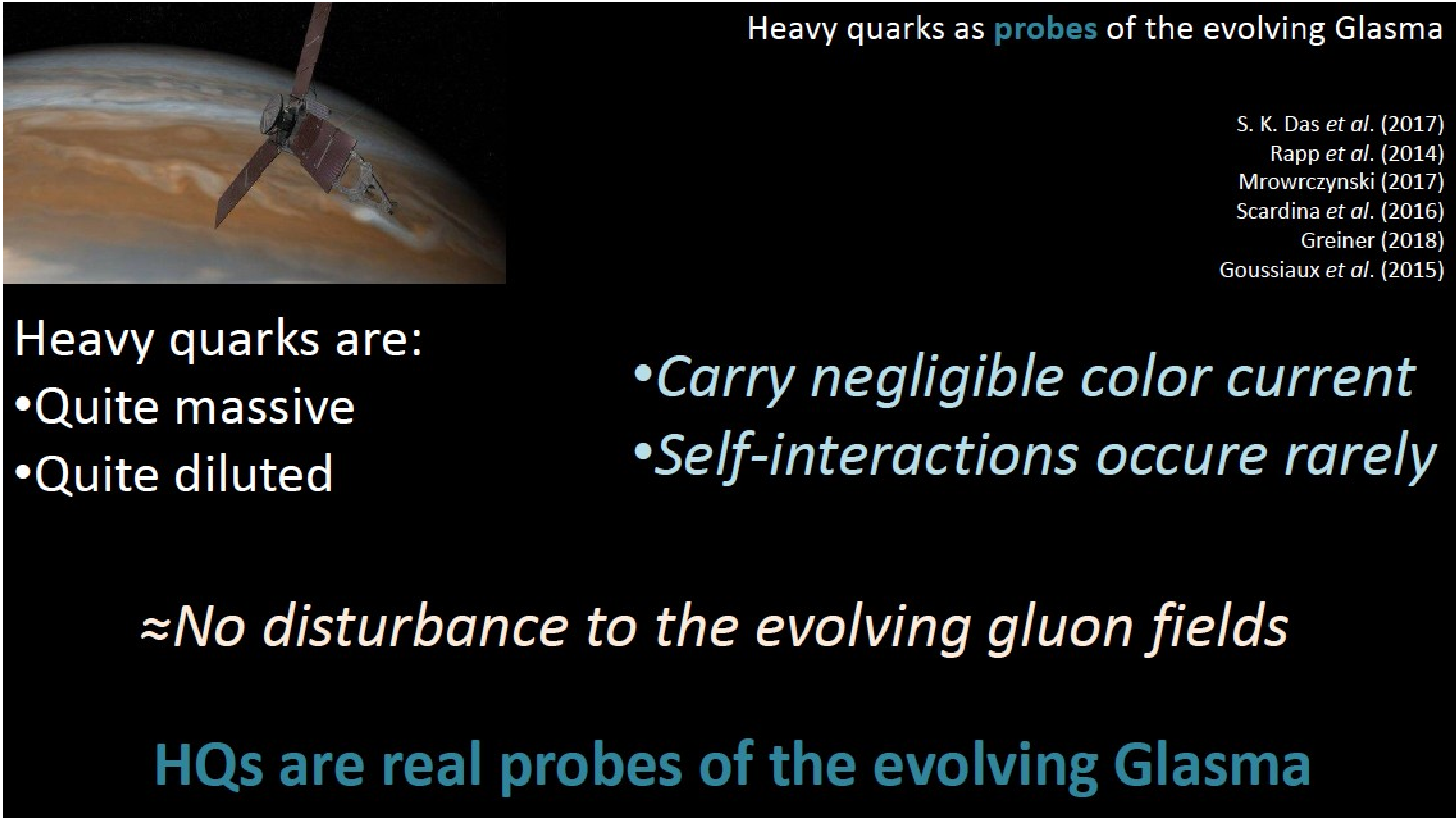
Assumption

Bulk consists of gluons from the evolving Glasma.

This assumption will be relaxed in a forthcoming study.

Courtesy: Marco Ruggieri, Kyoto 2018

Heavy quarks as probes of the evolving Glasma



Heavy quarks as **probes** of the evolving Glasma

S. K. Das *et al*. (2017)
Rapp *et al*. (2014)
Mrowrczynski (2017)
Scardina *et al*. (2016)
Greiner (2018)
Goussiaux *et al*. (2015)

Heavy quarks are:

- Quite massive
- Quite diluted

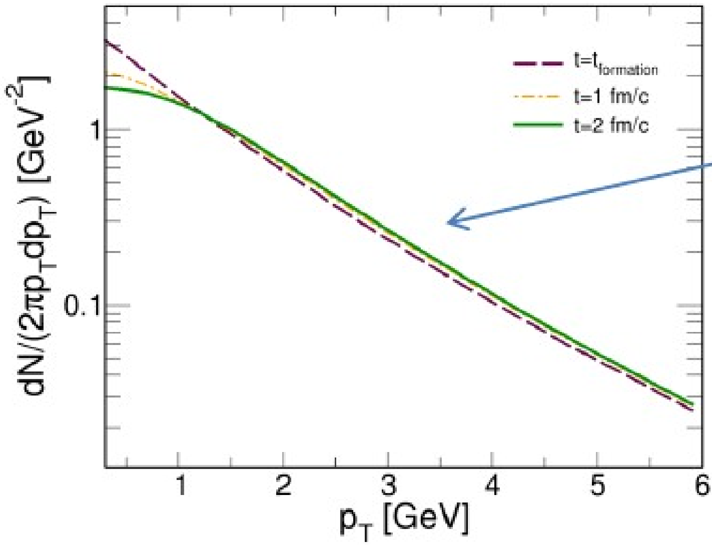
- *Carry negligible color current*
- *Self-interactions occure rarely*

≈No disturbance to the evolving gluon fields

HQs are real probes of the evolving Glasma

Courtesy: Marco Ruggieri, Kyoto 2018

Heavy quarks as probes of the evolving Glasma


p-Pb @ 5.02 TeV

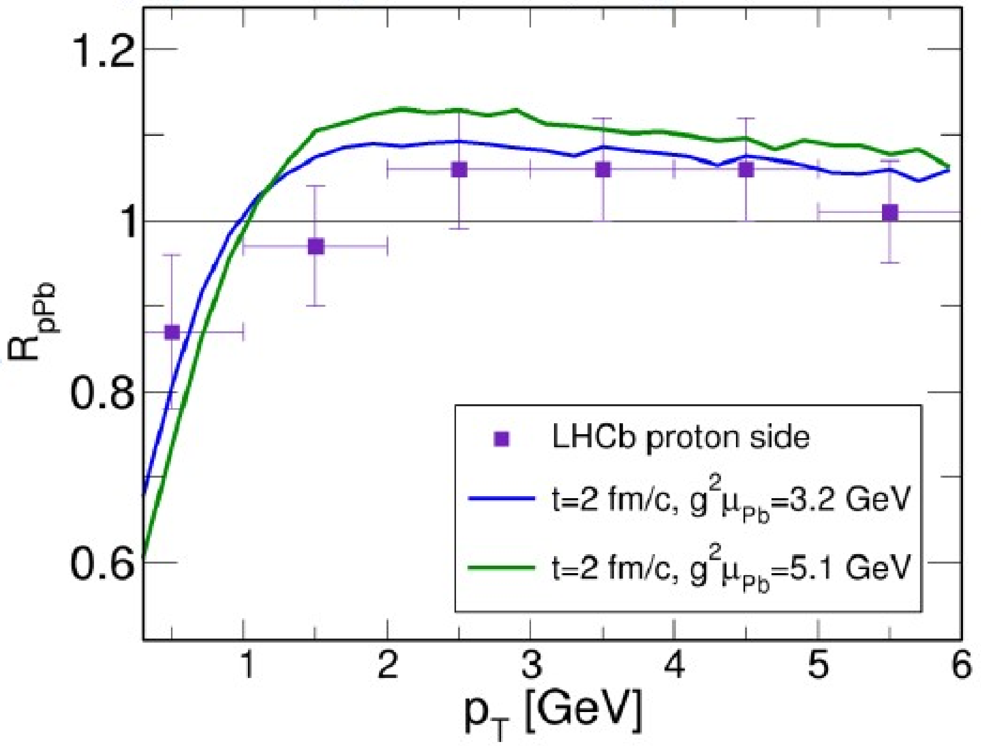
Nuclear modification factor (R_{pPb}) for p-Pb collisions

*Initial distribution: from perturbative QCD, aka **prompt***
Evolution: interaction with the Glasma

D-mesons R_{pPb}

M. Ruggieri and S. K. Das, 1805.09617

Standard fragmentation [Peterson *et al.*(1983)]



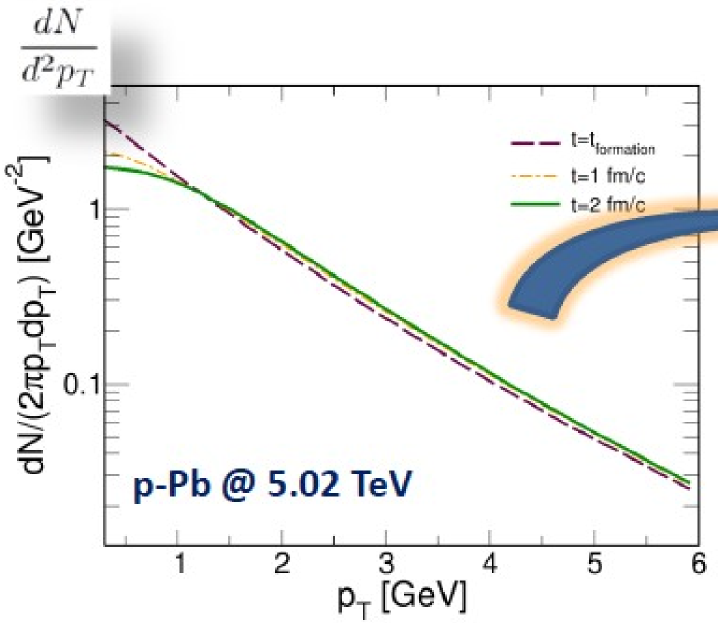
$$R_{\mathrm{pPb}} = \frac{(dN/d^2p_T)_{\mathrm{final}}}{(dN/d^2p_T)_{\mathrm{pQCD}}}$$

$R_{pPb} \neq 1$
Interaction with the fields created by the collision

Courtesy: Marco Ruggieri, Kyoto 2018

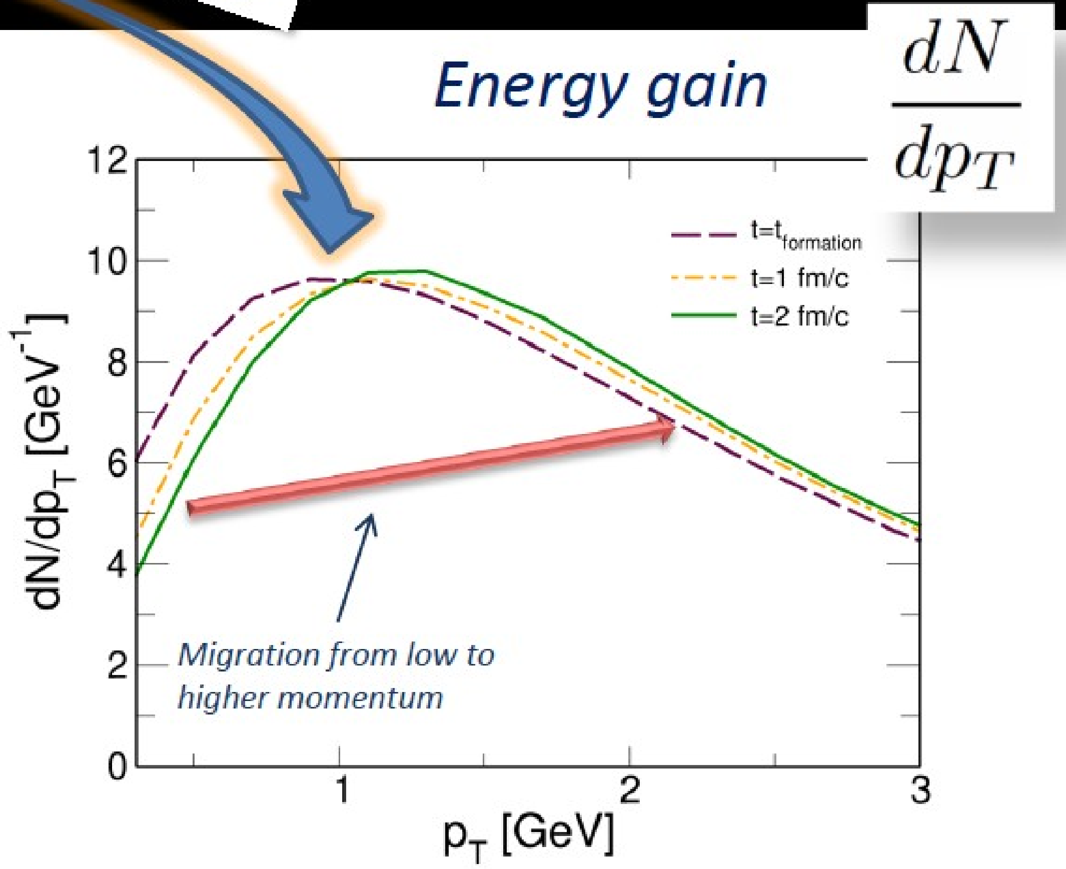
Heavy quarks as probes of the evolving Glasma

The cathode tube effect

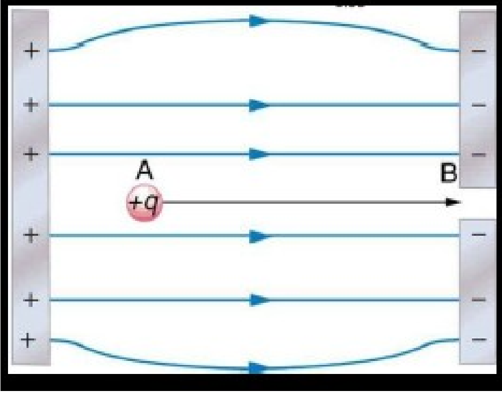


$\times p_T(\times 2\pi)$

Energy gain



Heavy quarks are accelerated by the (color-)electric field

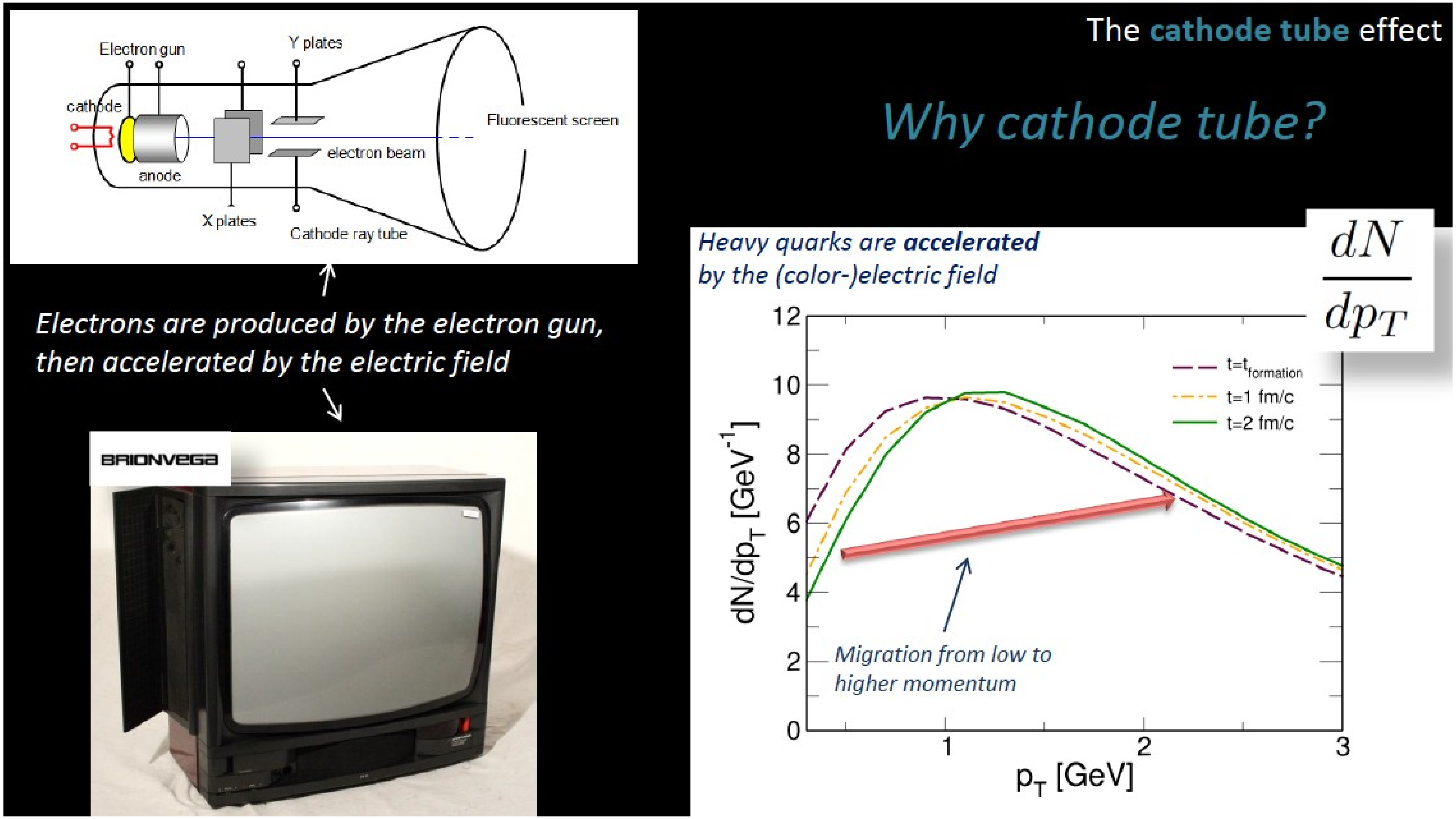


$$\frac{\Delta \boldsymbol{p}}{\Delta t} = q\boldsymbol{E}$$

“Cathode tube effect”

Courtesy: Marco Ruggieri, Kyoto 2018

Heavy quarks as probes of the evolving Glasma



The **cathode tube** effect

Why cathode tube?

Electrons are produced by the electron gun, then accelerated by the electric field

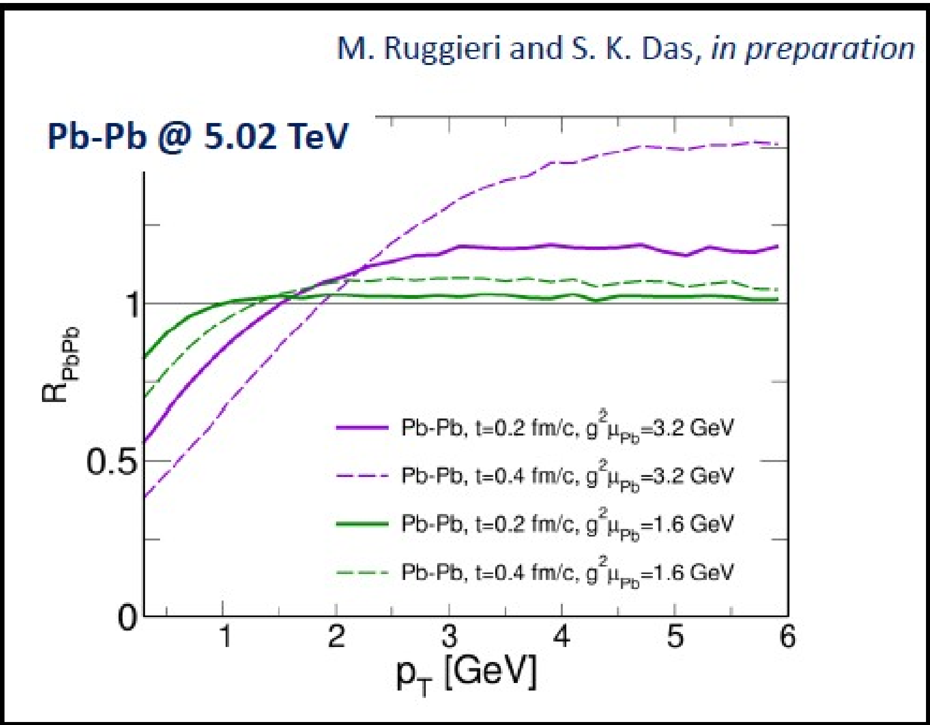
*Heavy quarks are **accelerated** by the (color-)electric field*

$$\frac{dN}{dp_T}$$

Migration from low to higher momentum

Courtesy: Marco Ruggieri, Kyoto 2018

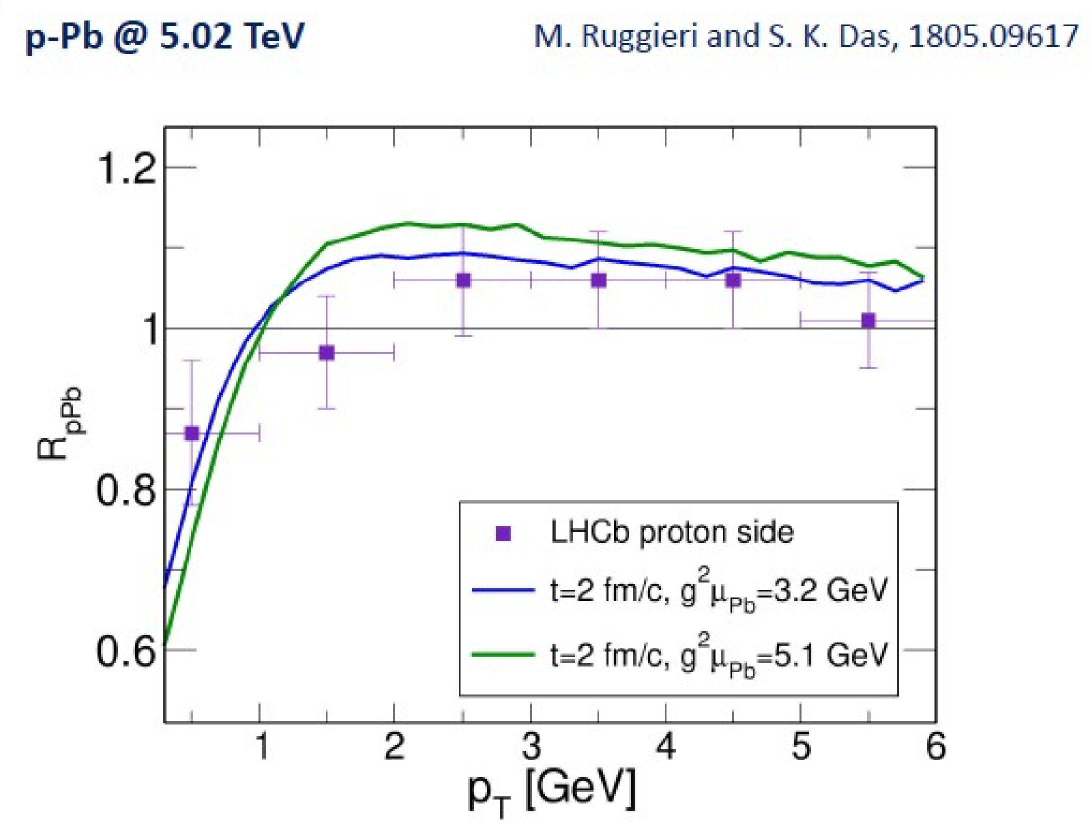
Heavy quarks as probes of the evolving Glasma


M. Ruggieri and S. K. Das, *in preparation*

Pb-Pb @ 5.02 TeV

p-Pb versus Pb-Pb

Interaction with Glasma affects the spectrum of c in Pb-Pb


p-Pb @ 5.02 TeV

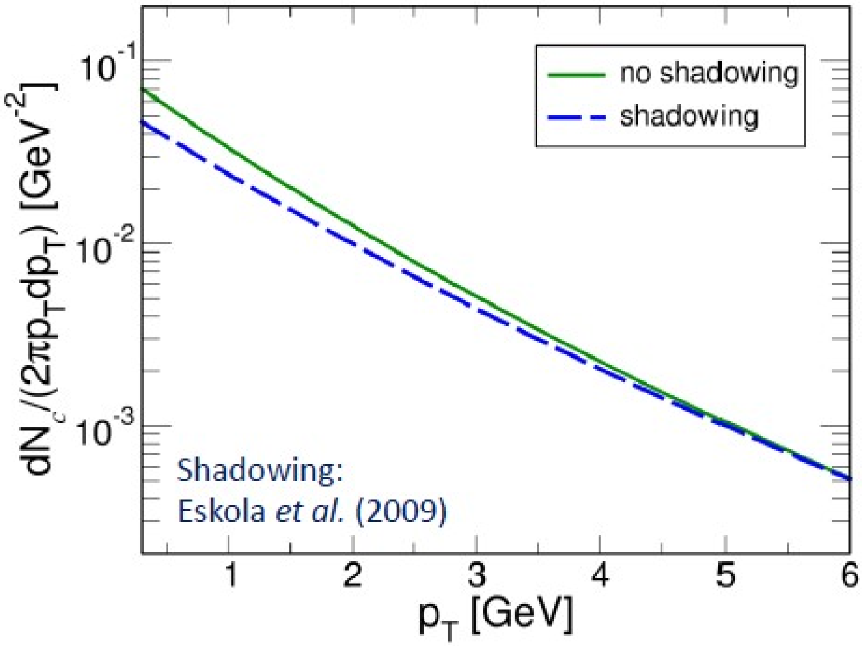
M. Ruggieri and S. K. Das, 1805.09617

$$R_{\mathrm{pPb}} = \frac{(dN/d^2p_T)_{\mathrm{final}}}{(dN/d^2p_T)_{\mathrm{pQCD}}}$$

“Cathode tube effect”

Courtesy: Marco Ruggieri, Kyoto 2018

Heavy quarks as probes of the evolving Glasma



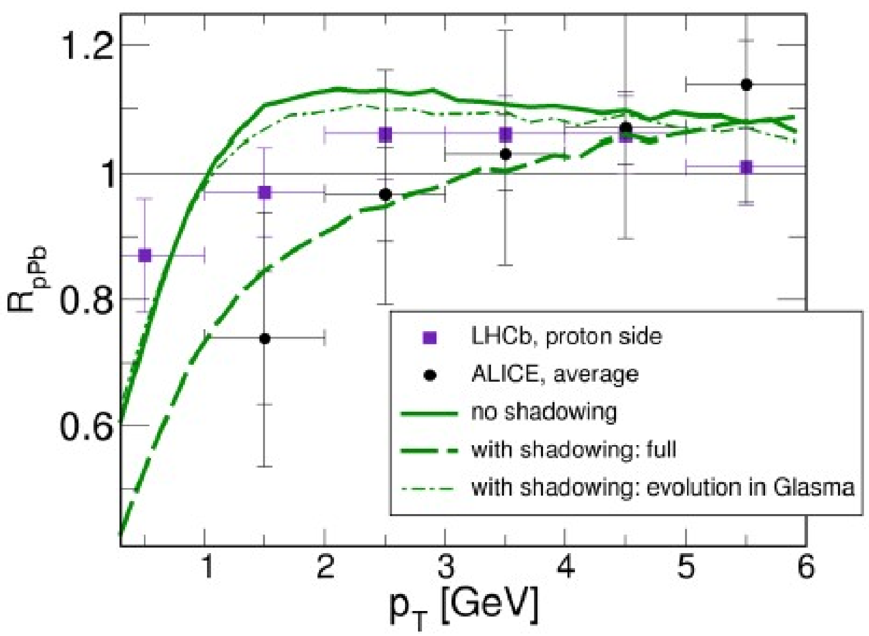
Shadowing:
Eskola *et al.* (2009)

Including shadowing in p-Pb

Nuclear shadowing does not affect the cathode tube

$$R_{\mathrm{pPb}} = \frac{(dN/d^2p_T)_{\mathrm{final}}}{(dN/d^2p_T)_{\mathrm{pQCD}}}$$

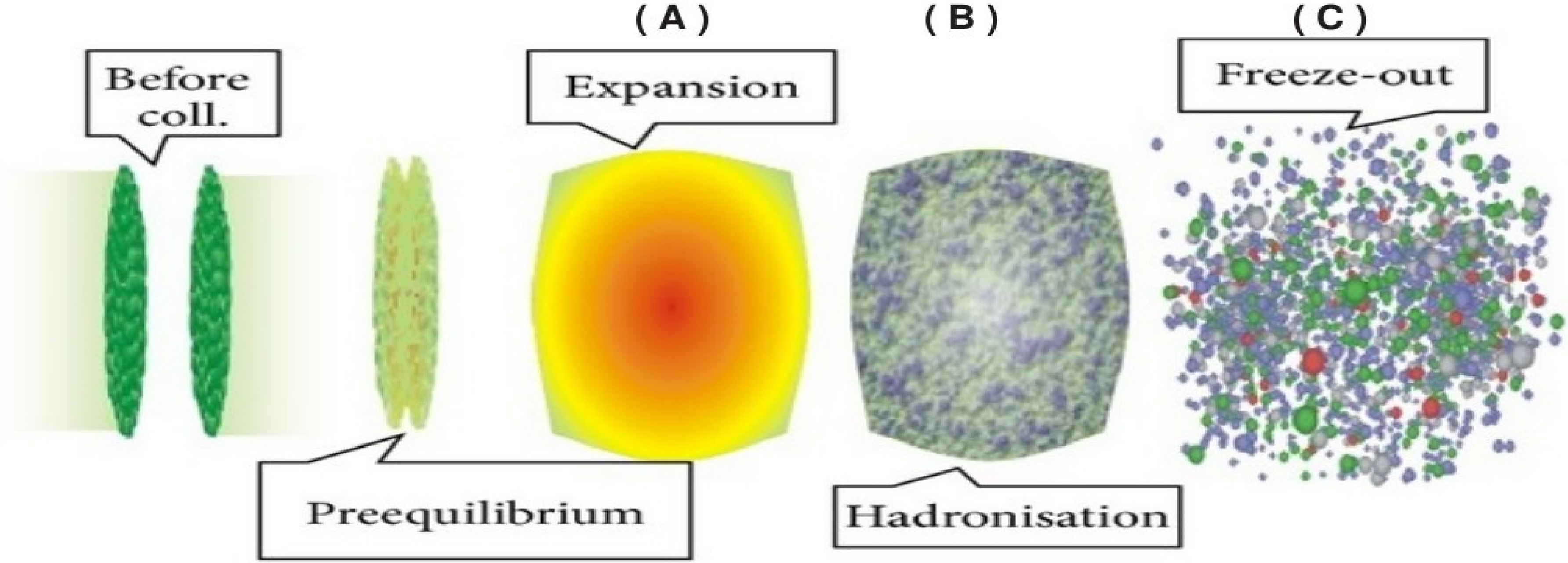
p-Pb @ 5.02 TeV M. Ruggieri and S. K. Das, *in preparation*



"Cathode tube effect"

Courtesy: Marco Ruggieri, Kyoto 2018

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

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

(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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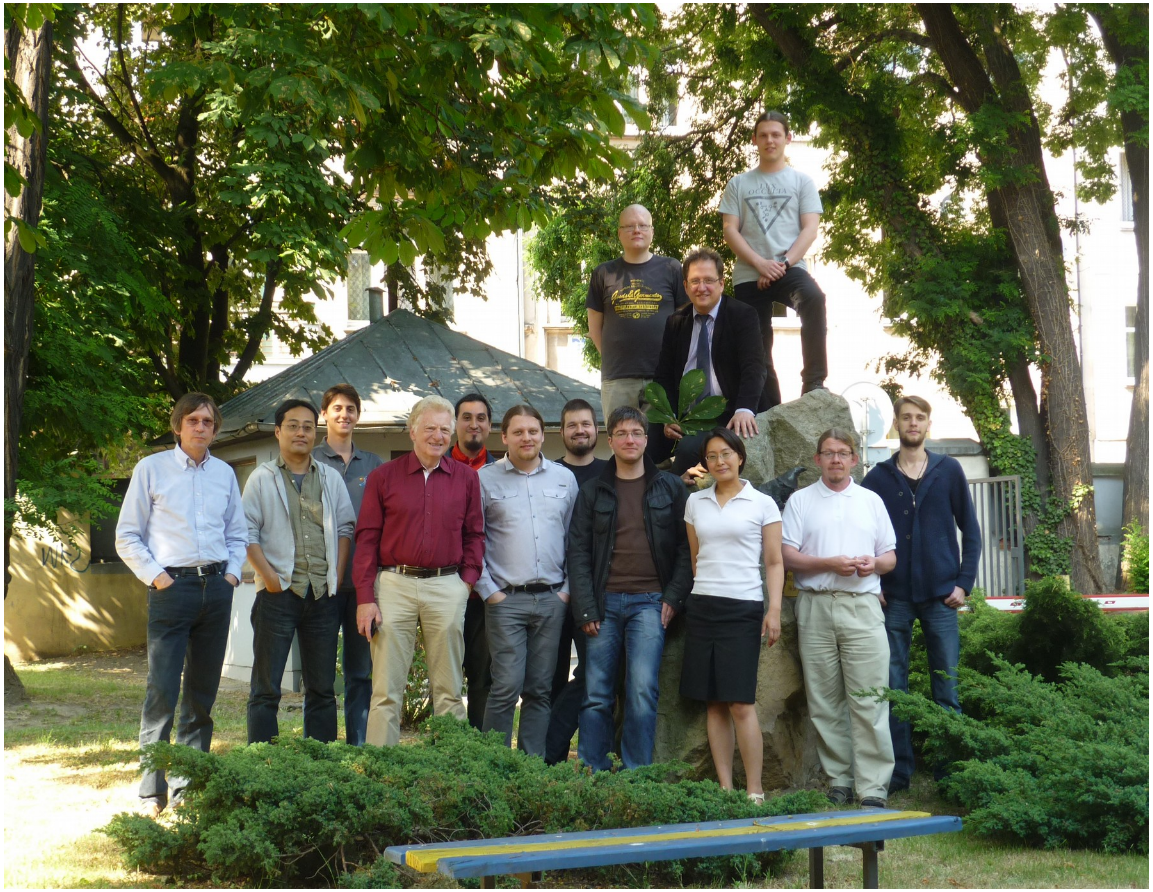

Main research topics:

- 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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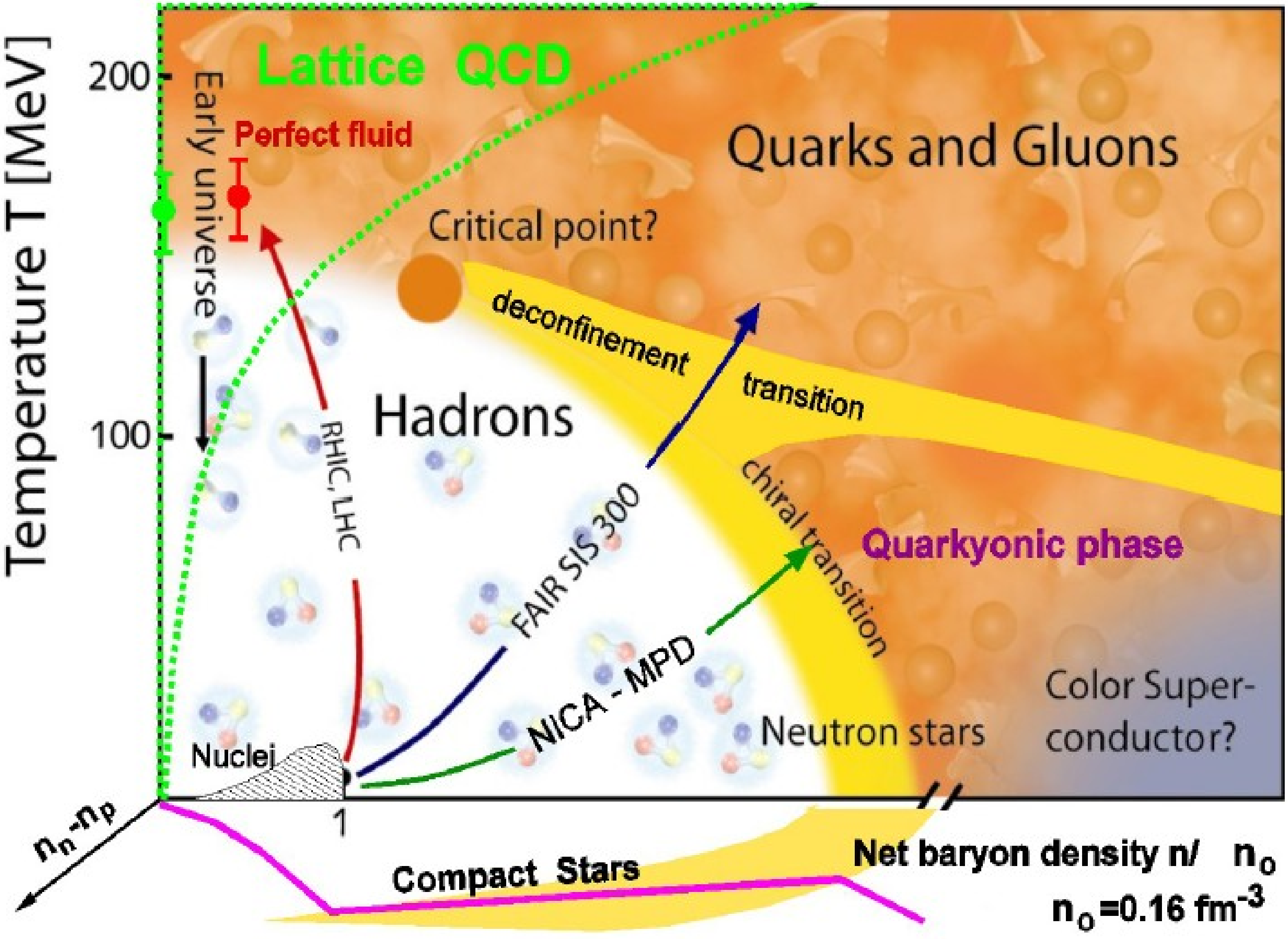

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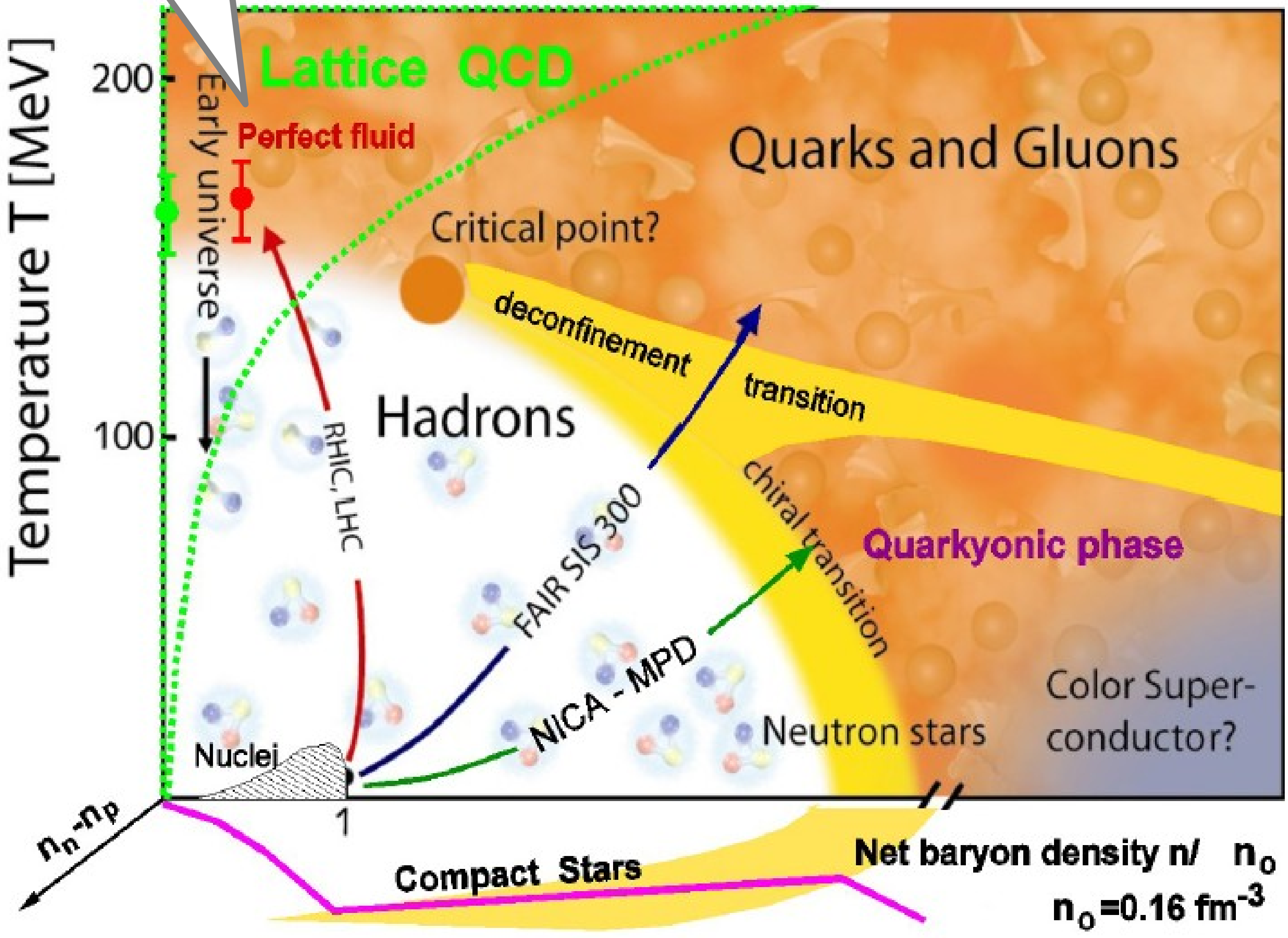

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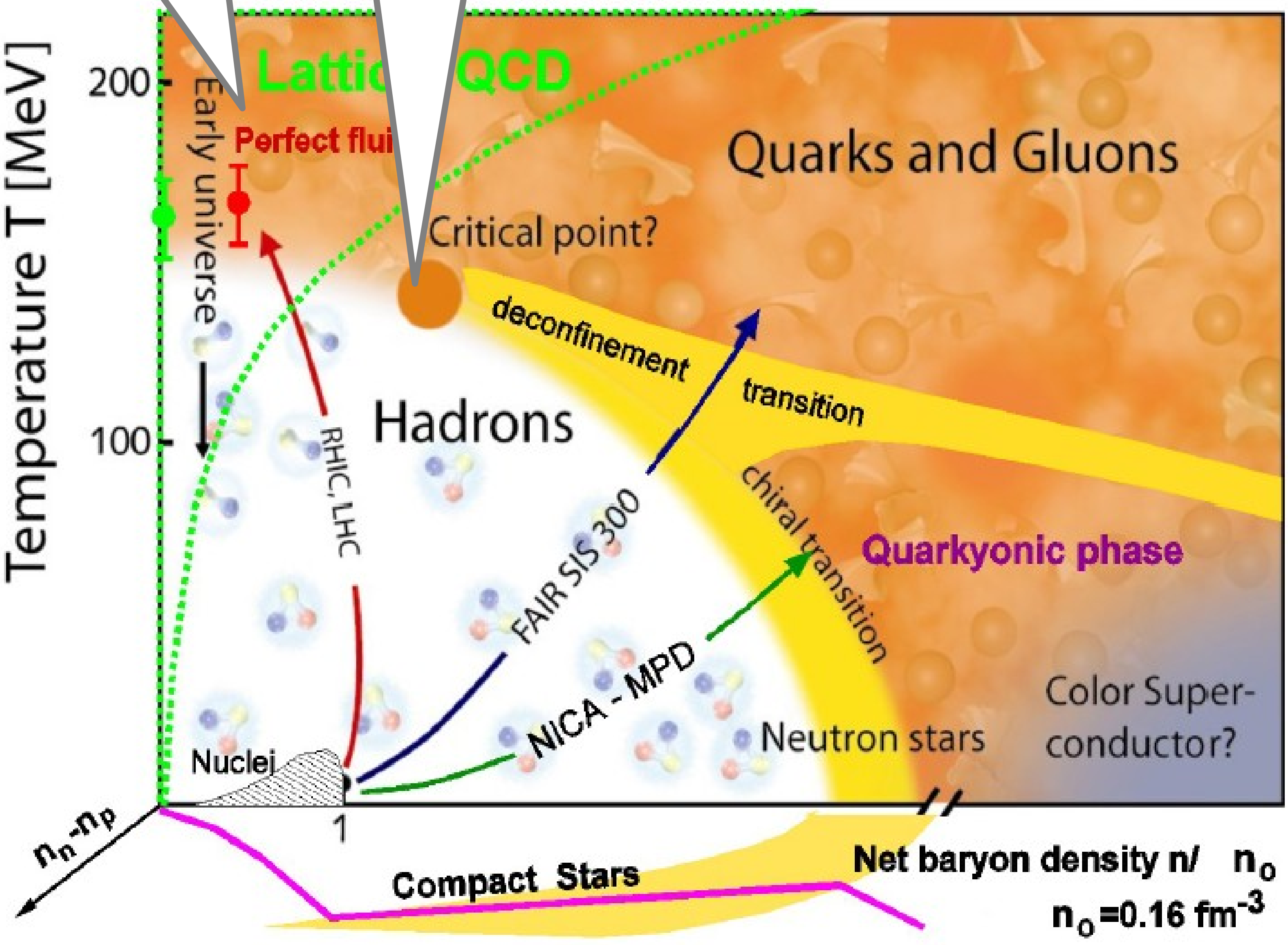

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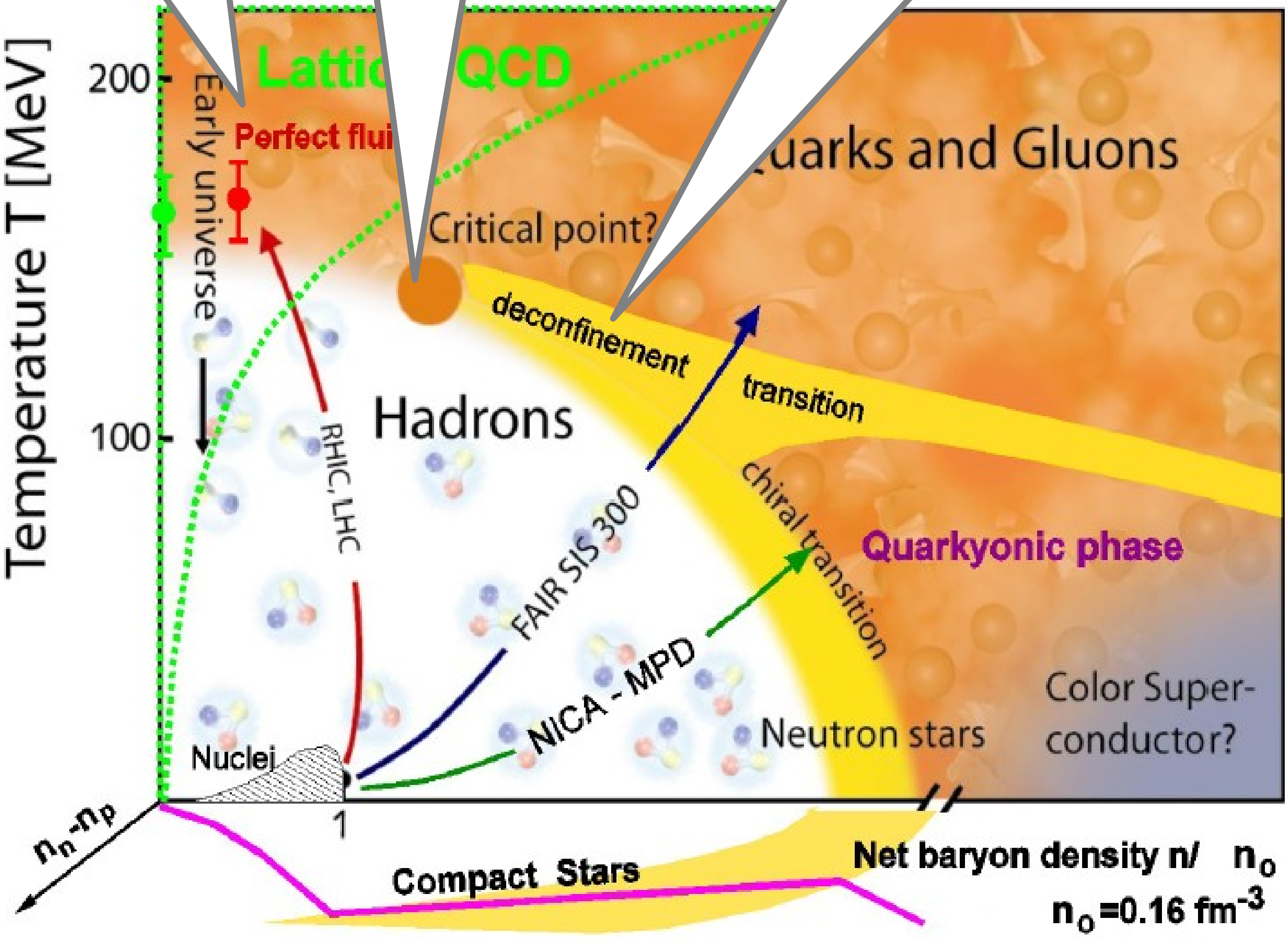


Division: Theory of Elementary Particles - Collaborations

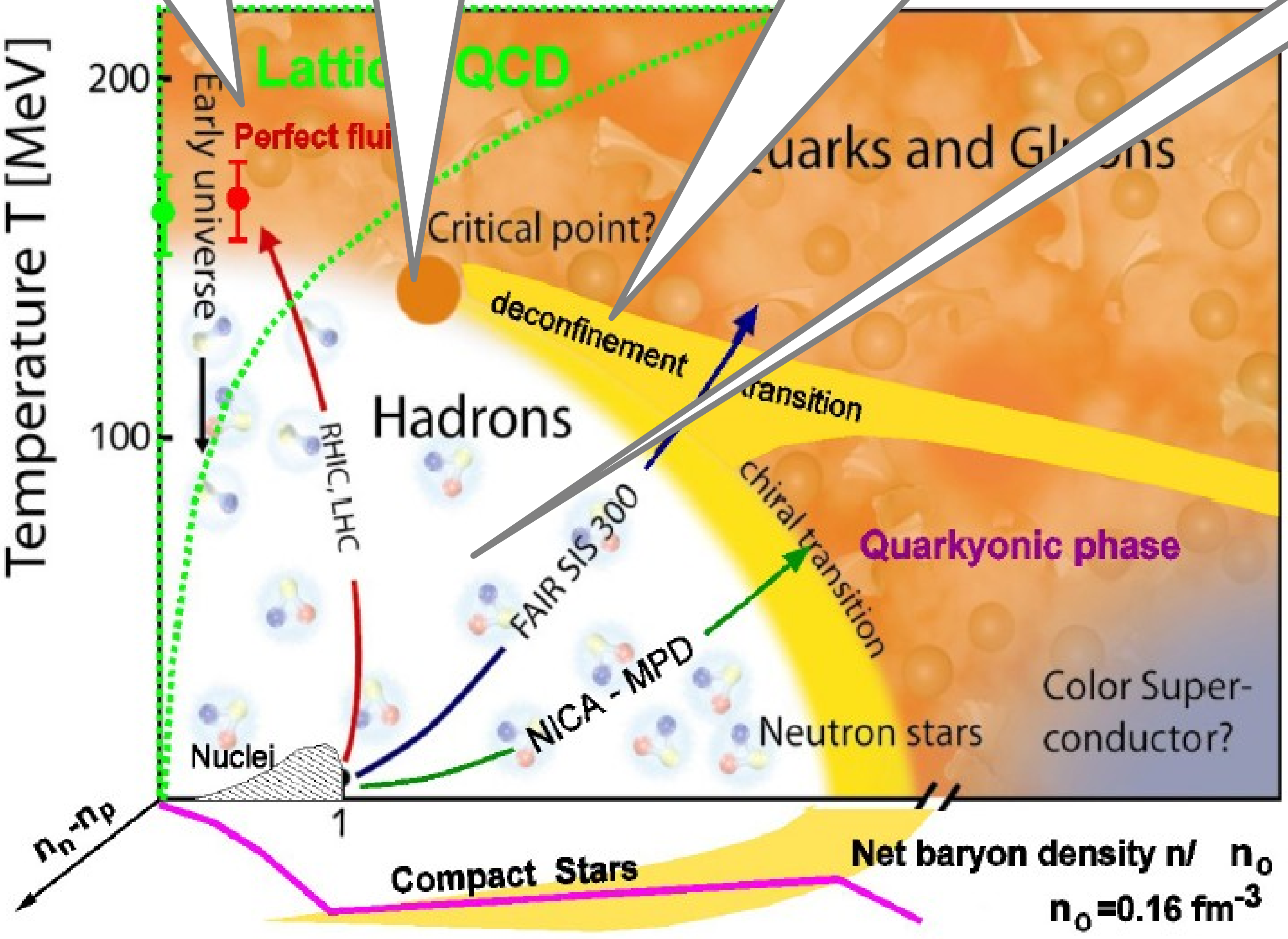
CERN ALICE

CERN SHINE NA61

FAIR

HIC for FAIR
Helmholtz International Center

NAVI



JOINT INSTITUTE FOR NUCLEAR RESEARCH
JINR
DUBNA

NICA

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Division: Theory of Elementary Particles - Collaborations

CERN ALICE

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JINR DUBNA

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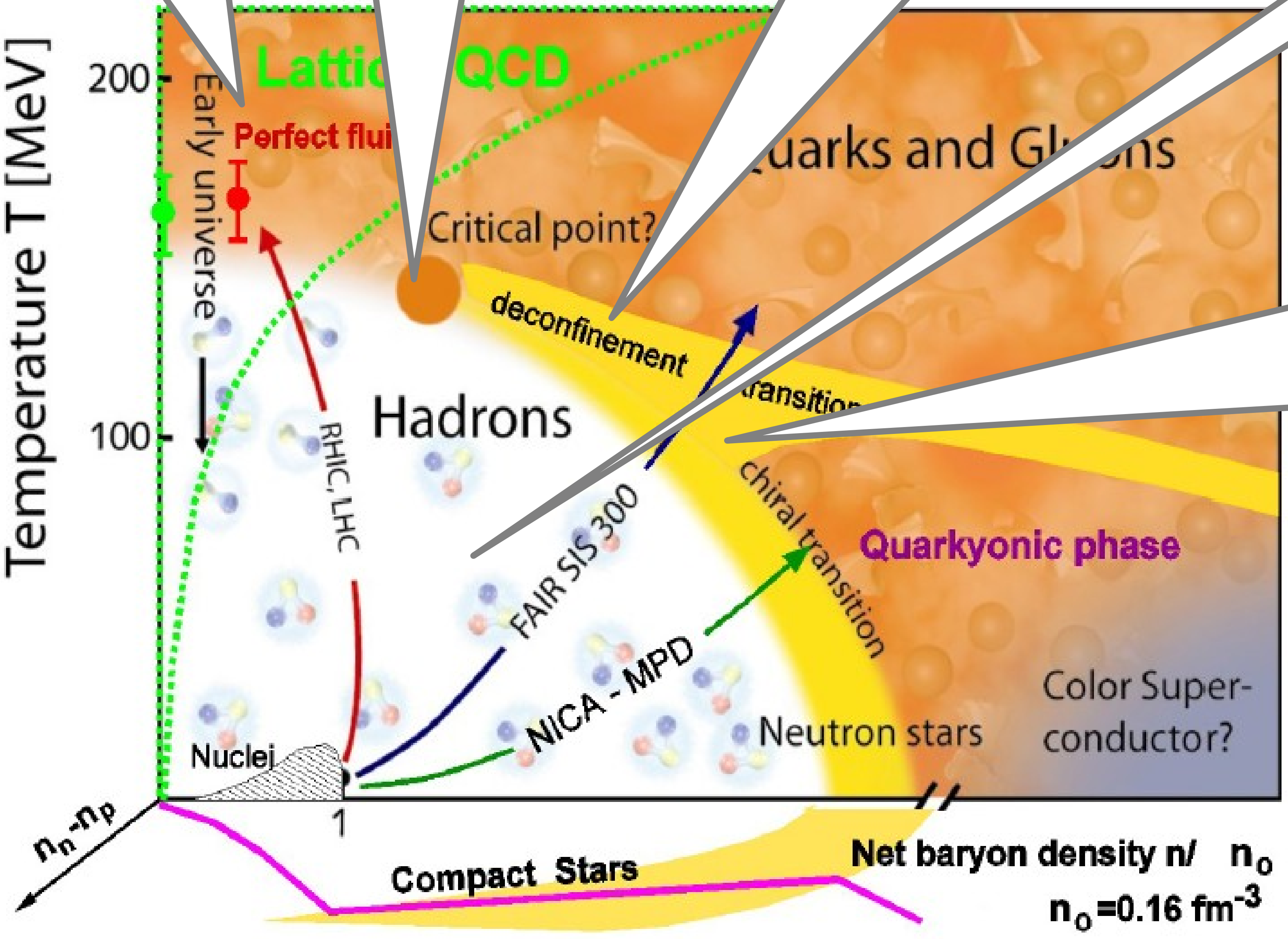

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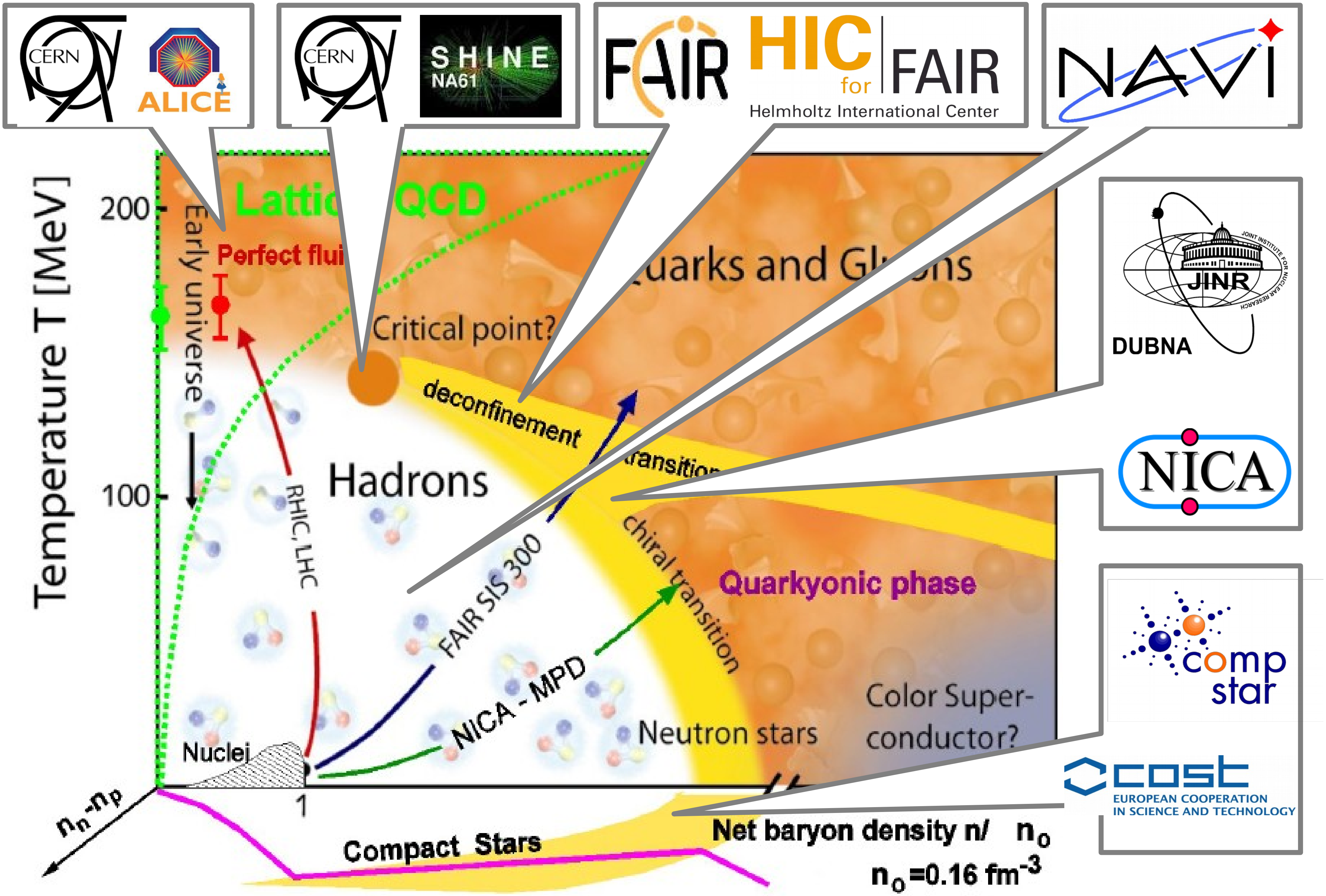
COST EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

Division: Theory of Elementary Particles - Collaborations

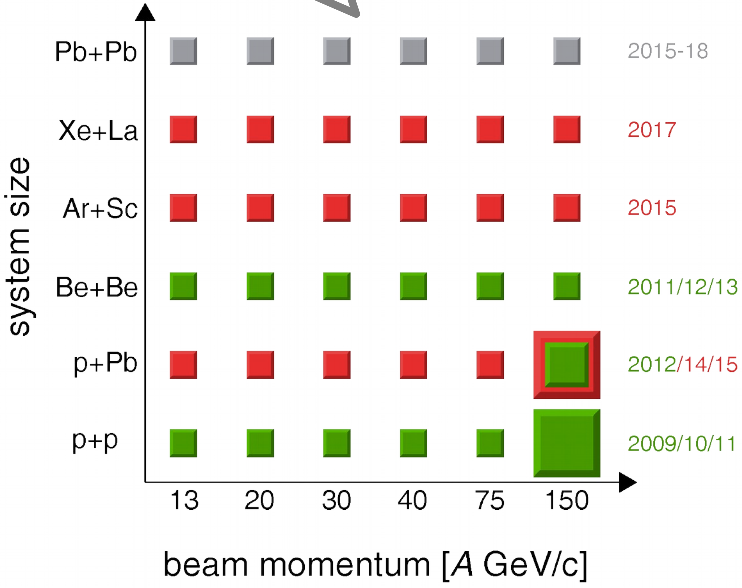


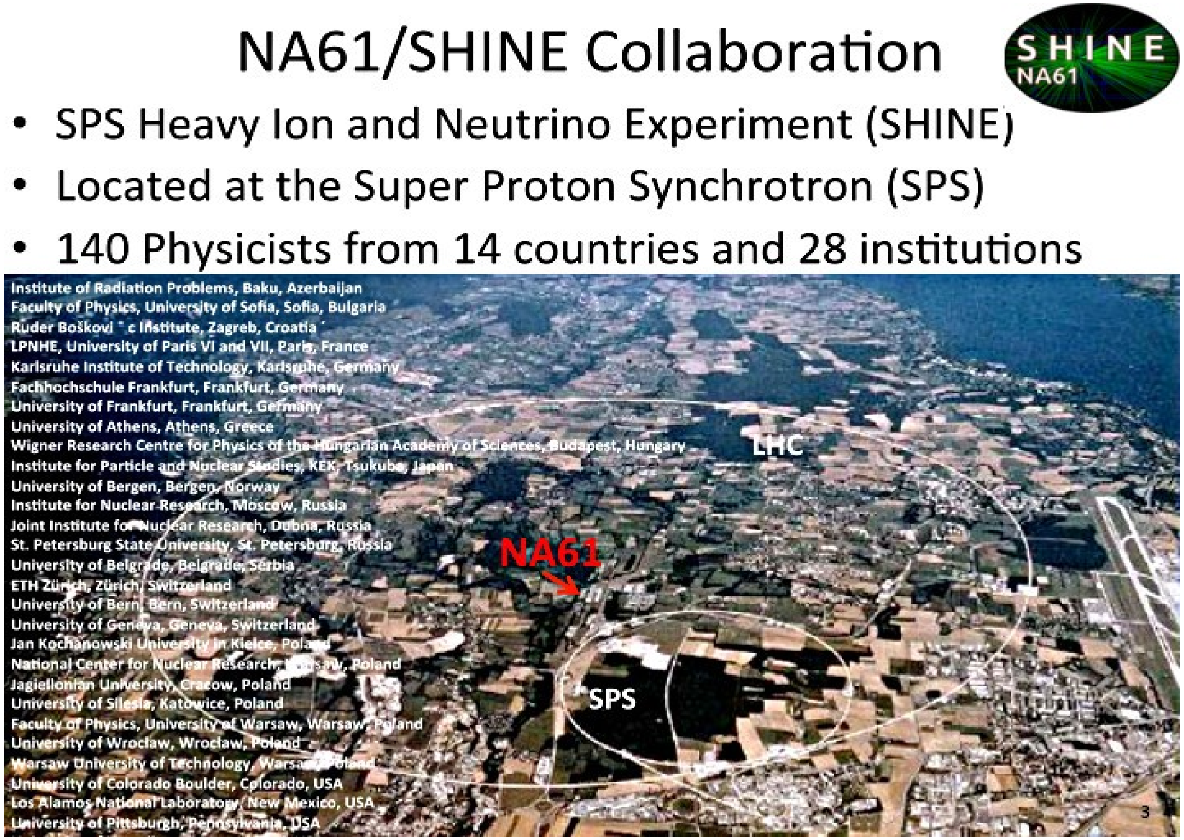
Division: Theory of Elementary Particles

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

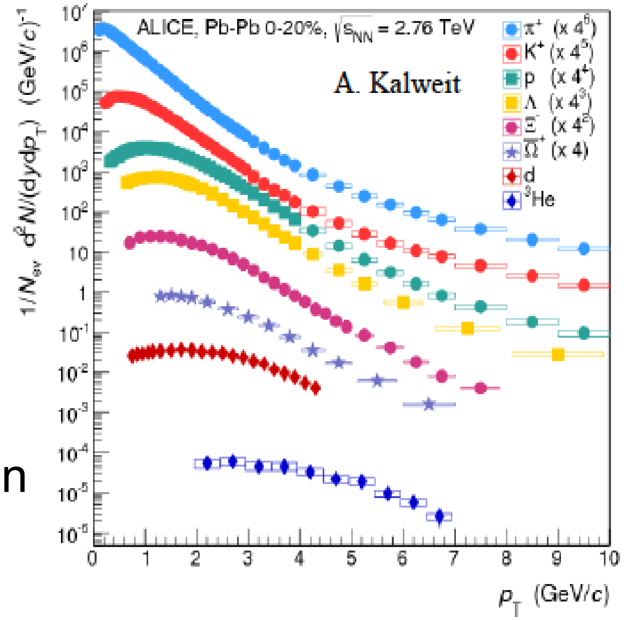
- SPS Heavy Ion and Neutrino Experiment (SHINE)
- Located at the Super Proton Synchrotron (SPS)
- 140 Physicists from 14 countries and 28 institutions

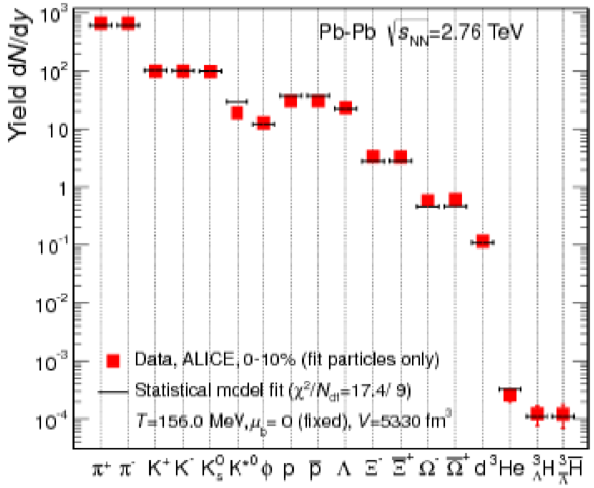
Institute of Radiation Problems, Baku, Azerbaijan
Faculty of Physics, University of Sofia, Sofia, Bulgaria
Ruder Boškovi ˇ c Institute, Zagreb, Croatia ´
LPNHE, University of Paris VI and VII, Paris, France
Karlsruhe Institute of Technology, Karlsruhe, Germany
Fachhochschule Frankfurt, Frankfurt, Germany
University of Frankfurt, Frankfurt, Germany
University of Athens, Athens, Greece
Wigner Research Centre for Physics of the Hungarian Academy of Sciences, Budapest, Hungary
Institute for Particle and Nuclear Studies, KEK, Tsukuba, Japan
University of Bergen, Bergen, Norway
Institute for Nuclear Research, Moscow, Russia
Joint Institute for Nuclear Research, Dubna, Russia
St. Petersburg State University, St. Petersburg, Russia
University of Belgrade, Belgrade, Serbia
ETH Zürich, Zürich, Switzerland
University of Bern, Bern, Switzerland
University of Geneva, Geneva, Switzerland
Jan Kochanowski University in Kielce, Poland
National Center for Nuclear Research, Warsaw, Poland
Jagiellonian University, Cracow, Poland
University of Silesia, Katowice, Poland
Faculty of Physics, University of Warsaw, Warsaw, Poland
University of Wroclaw, Wroclaw, Poland
Warsaw University of Technology, Warsaw, Poland
University of Colorado Boulder, Colorado, USA
Los Alamos National Laboratory, New Mexico, USA
University of Pittsburgh, Pennsylvania, USA

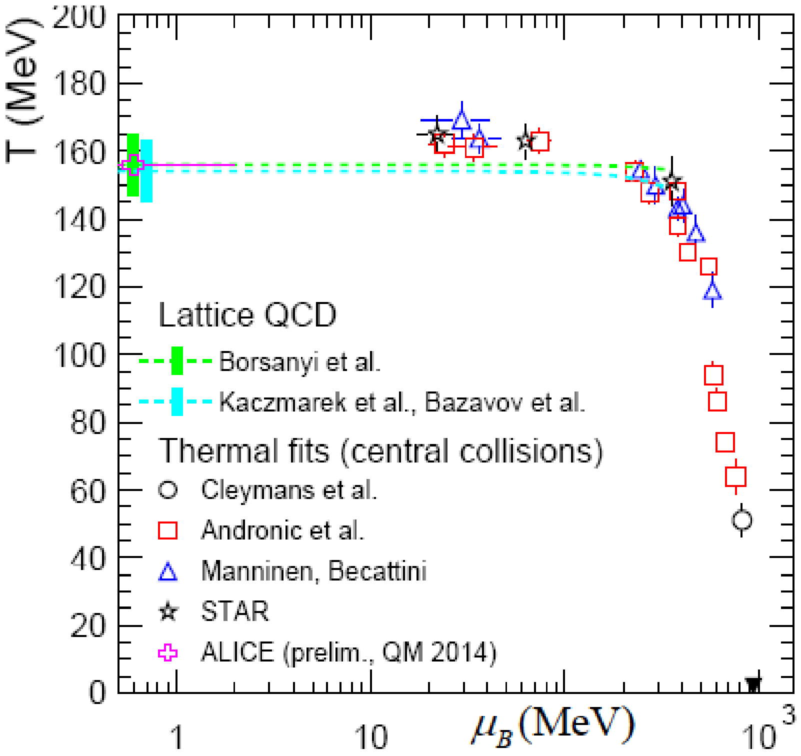
Division: Theory of Elementary Particles

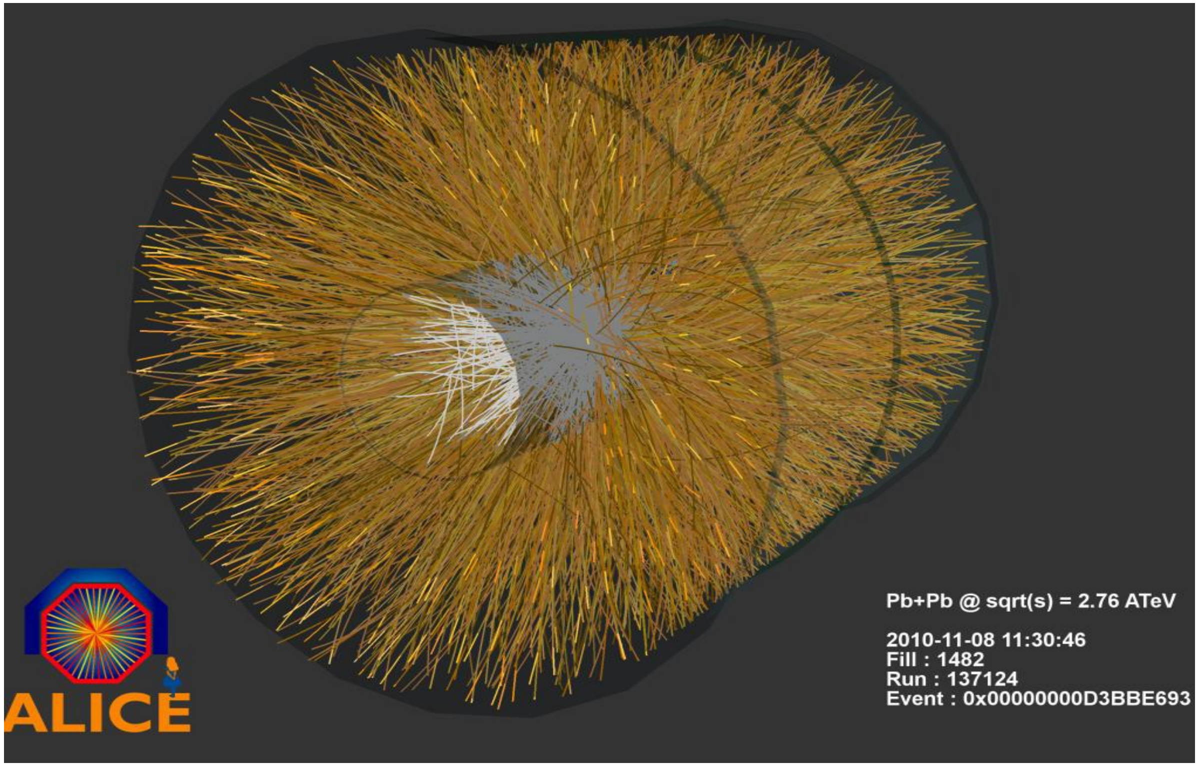
Collaboration with ALICE @ CERN

- 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









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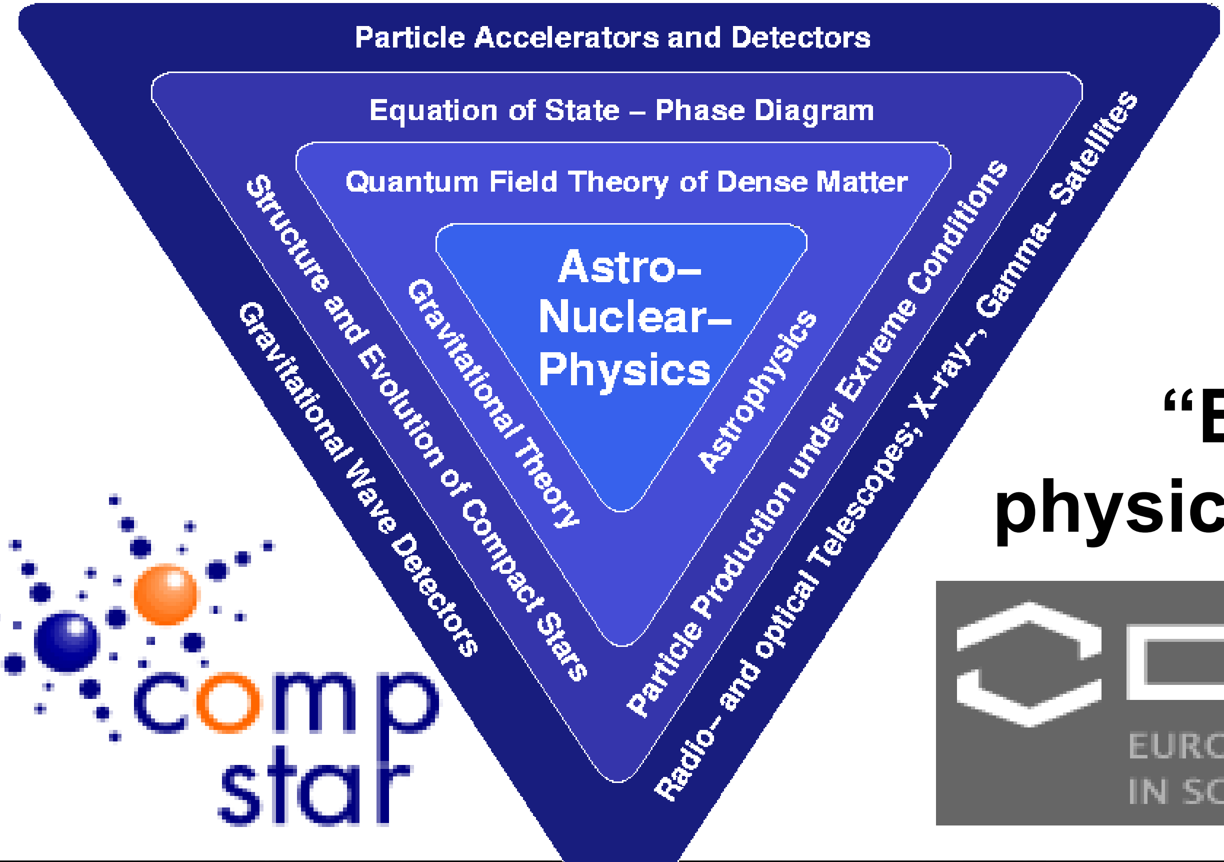

Particle Accelerators and Detectors

Equation of State – Phase Diagram

Quantum Field Theory of Dense Matter

Astro–Nuclear–Physics

Gravitational Theory

Astrophysics

Structure and Evolution of Compact Stars

Particle Production under Extreme Conditions

Gravitational Wave Detectors

Radio– and optical Telescopes; X–ray–, Gamma– Satellites

NewCompStar

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

EUROPEAN COOPERATION
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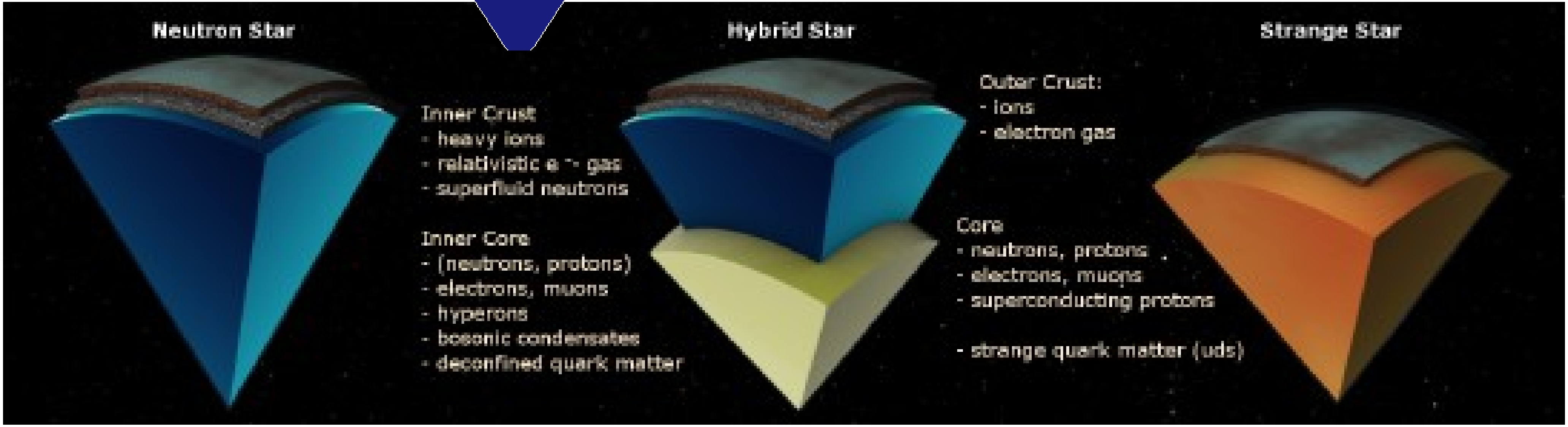
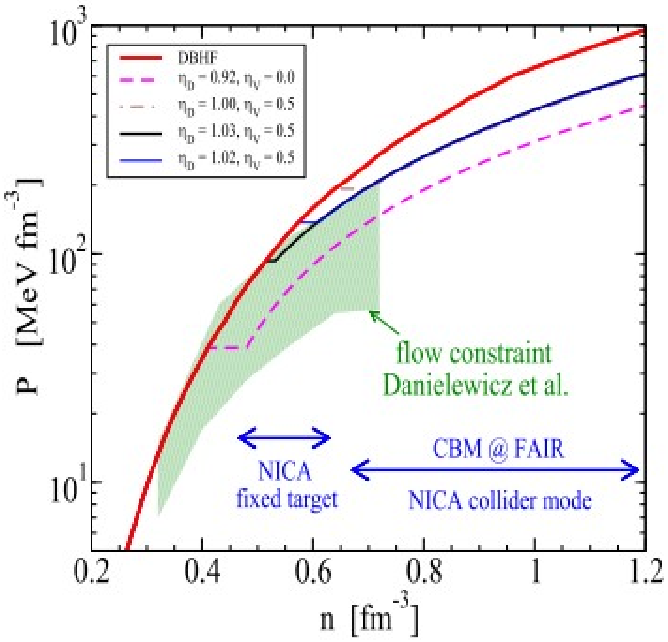


Division: Theory of Elementary Particles

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

Heavy-Ion Collisions

Compact Stars



- stiff EoS
(at flow limit)

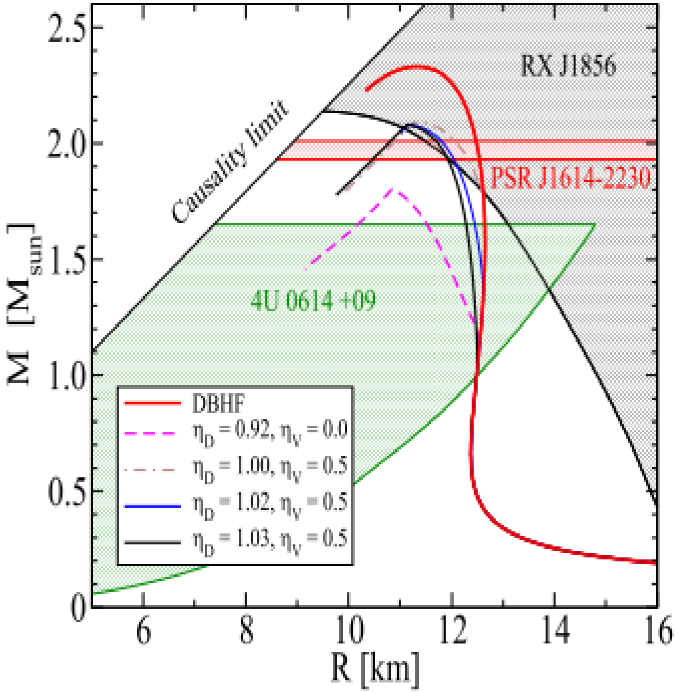
- low ncrit
(at NICA fixT)

- soft EoS
(dashed line)

- high Mmax
(J1614-2230)

- low Monset
(all NS hybrid)

- excluded
(J1614-2230)



29 member countries

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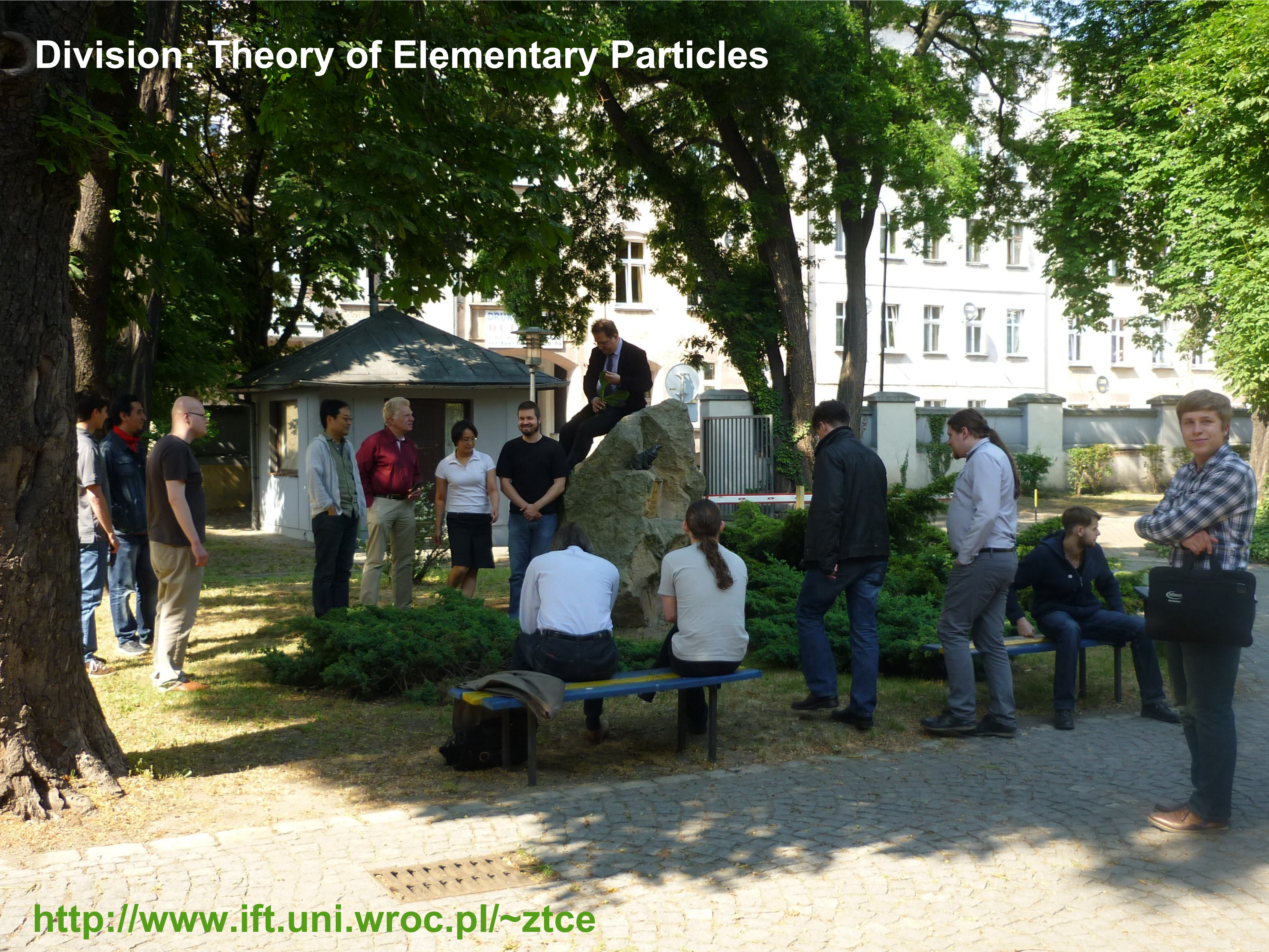
Division: Theory of Elementary Particles



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