Color Instabilities in Quark-Gluon Plasma

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over 30 years

1) St. Mrówczyński,
Stream instabilities of the quark-gluon plasma,
Physica Letters B **214**, 587 (1988), Erratum B **656**, 273 (2007)

2) St. Mrówczyński,
Plasma Instability at the initial stage of ultrarelativistic heavy-ion collisions,
Physics Letters B **314**, 118 (1993)

⋮

5) St. Mrówczyński and M. Thoma,
Hard loop approach to anisotropic systems,
Physical Review D **62**, 036011 (2000)

⋮

17) St. Mrówczyński, B. Schenke and M. Strickland,
Color instabilities in the quark-gluon plasma,
Physics Reports **682**, 1 (2017)

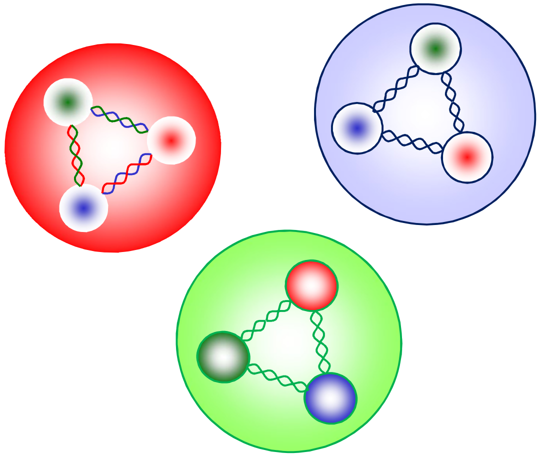
⋮

Elementary Physics Story on Color Instabilities in Quark-Gluon Plasma

Hadrons, Quarks & Gluons

baryons

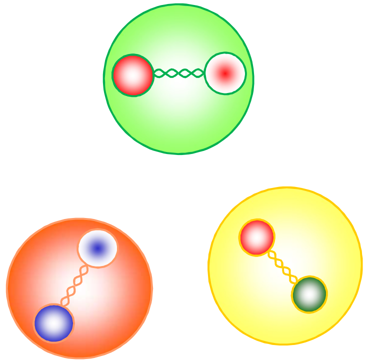
$n, p, \Delta, N^*, \Lambda, \Sigma, \Xi, \Omega, \ldots$



(q, q, q)

mesons

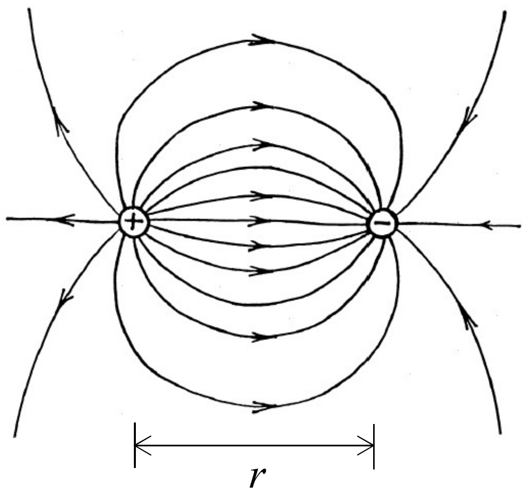
$\pi, K, \rho, \eta, \ldots$



$(q, \bar{q})$

Confinement

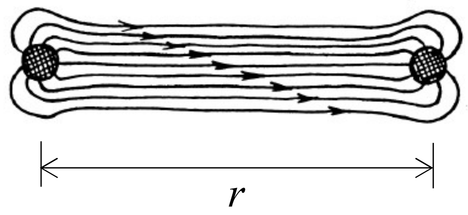
Electrodynamics



$$E(r) = \frac{e}{r^2} \quad \Rightarrow \quad V(r) = -\frac{e^2}{r}$$

K. Kogut & L. Susskind, Phys. Rev, D **9**, 3501 (1974)
H.B. Nielsen & P. Olesen, Nucl. Phys. B **61**, 45 (1973)

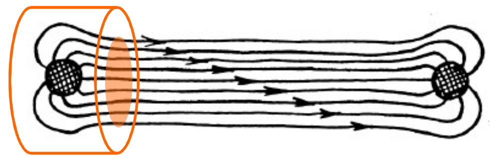
Chromodynamics



energy density

$$\vec{D} = \varepsilon \vec{E}, \qquad \varepsilon = 0, \qquad u = \frac{1}{8\pi} \vec{E}\vec{D} = \frac{1}{8\pi\varepsilon} E^2$$

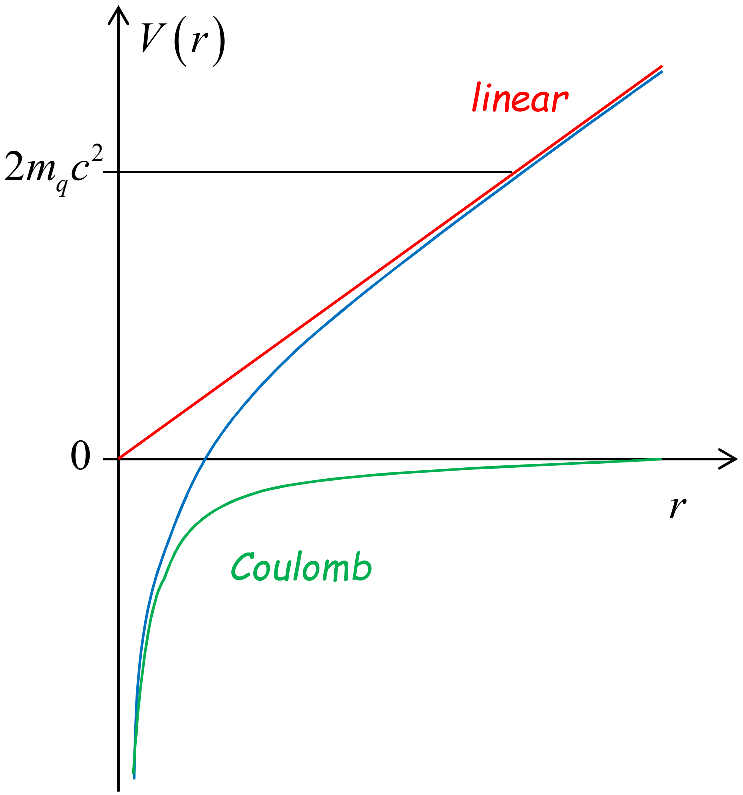
Gauss law



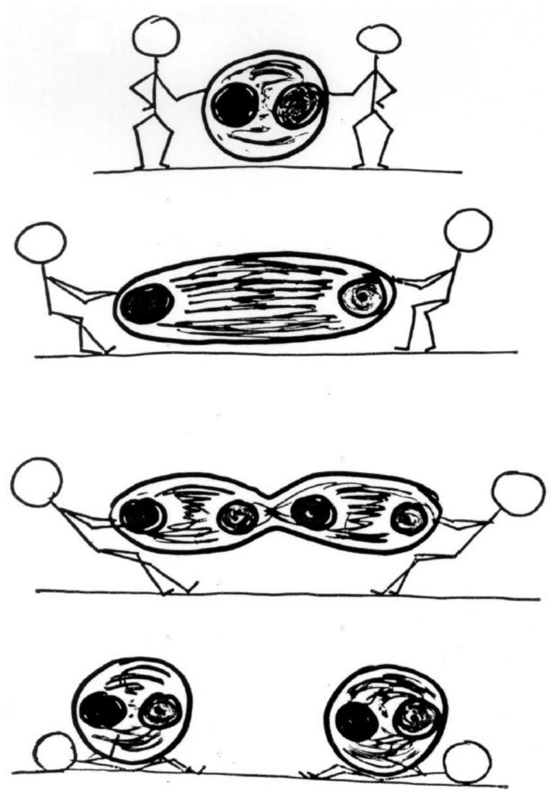
$$\Phi = \sigma E = 4\pi g \qquad \sigma = \text{const}$$

$$E(r) = \frac{4\pi g}{\sigma} \quad \Rightarrow \quad V(r) = \frac{4\pi g}{\sigma} r$$

Confinement cont.



The potential is studied
in spectroscopy of heavy quarkonia.



Asymptotic Freedom

Color charge vanishes at small distances

$$\alpha_s(Q^2) = \frac{12\pi}{(33-2N_f)\ln\left(\frac{Q^2}{\Lambda^2_{\mathrm{QCD}}}\right)}$$

Sourceless Maxwell equations in a medium

$$\left\{\begin{aligned} &\nabla\cdot\mathbf{D} = 0 \\ &\nabla\cdot\mathbf{B} = 0 \\ &\nabla\times\mathbf{E} = -\frac{1}{c}\frac{\partial\mathbf{B}}{\partial t} \\ &\nabla\times\mathbf{H} = \frac{1}{c}\frac{\partial\mathbf{D}}{\partial t} \end{aligned}\right. \quad\Rightarrow\quad \left\{\begin{aligned} &\mathbf{D} = \varepsilon\mathbf{E} \qquad \mathbf{B} = \mu\mathbf{H} \\ &\left(\Delta - \frac{\varepsilon\mu}{c^2}\frac{\partial^2}{\partial t^2}\right)\mathbf{E} = 0 \\ &\left(\Delta - \frac{\varepsilon\mu}{c^2}\frac{\partial^2}{\partial t^2}\right)\mathbf{B} = 0 \end{aligned}\right.$$

$\frac{c}{\sqrt{\varepsilon\mu}}$ *phase velocity of EM wave*

in vacuum $\varepsilon\mu = 1$

Asymptotic Freedom cont.

$$\varepsilon\mu = 1 \quad \begin{cases} \textit{diamagnetic} \quad \mu < 1 \quad \Rightarrow \quad \textit{dielectric} \quad \varepsilon > 1 \quad \textit{charges are screened} \\ \textit{paramagnetic} \quad \mu > 1 \quad \Rightarrow \quad \textit{paraelectric} \quad \varepsilon < 1 \quad \textit{charges are antiscreened!} \end{cases}$$

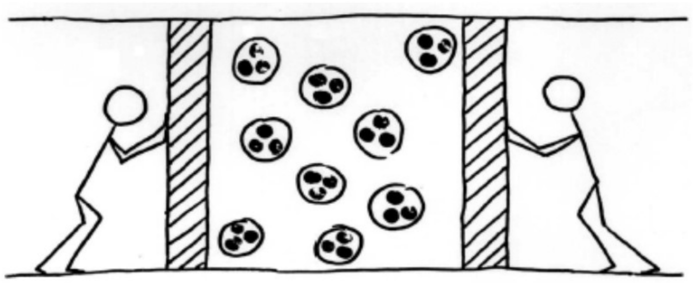
Quarks of spin ½ produce diamagnetic effect

Gluons of spin 1 produce paramagnetic effect

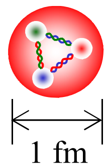
Gluons win!

G. 't Hooft, unpublished
N. K. Nielsen, Am. J. Phys. **49**, 1171 (1981)

Creation of Quark-Gluon Plasma



compression of nuclear matter



$$\rho_0 = 0.12 \text{ fm}^{-3}$$

normal nuclear density

heating up hadron gas

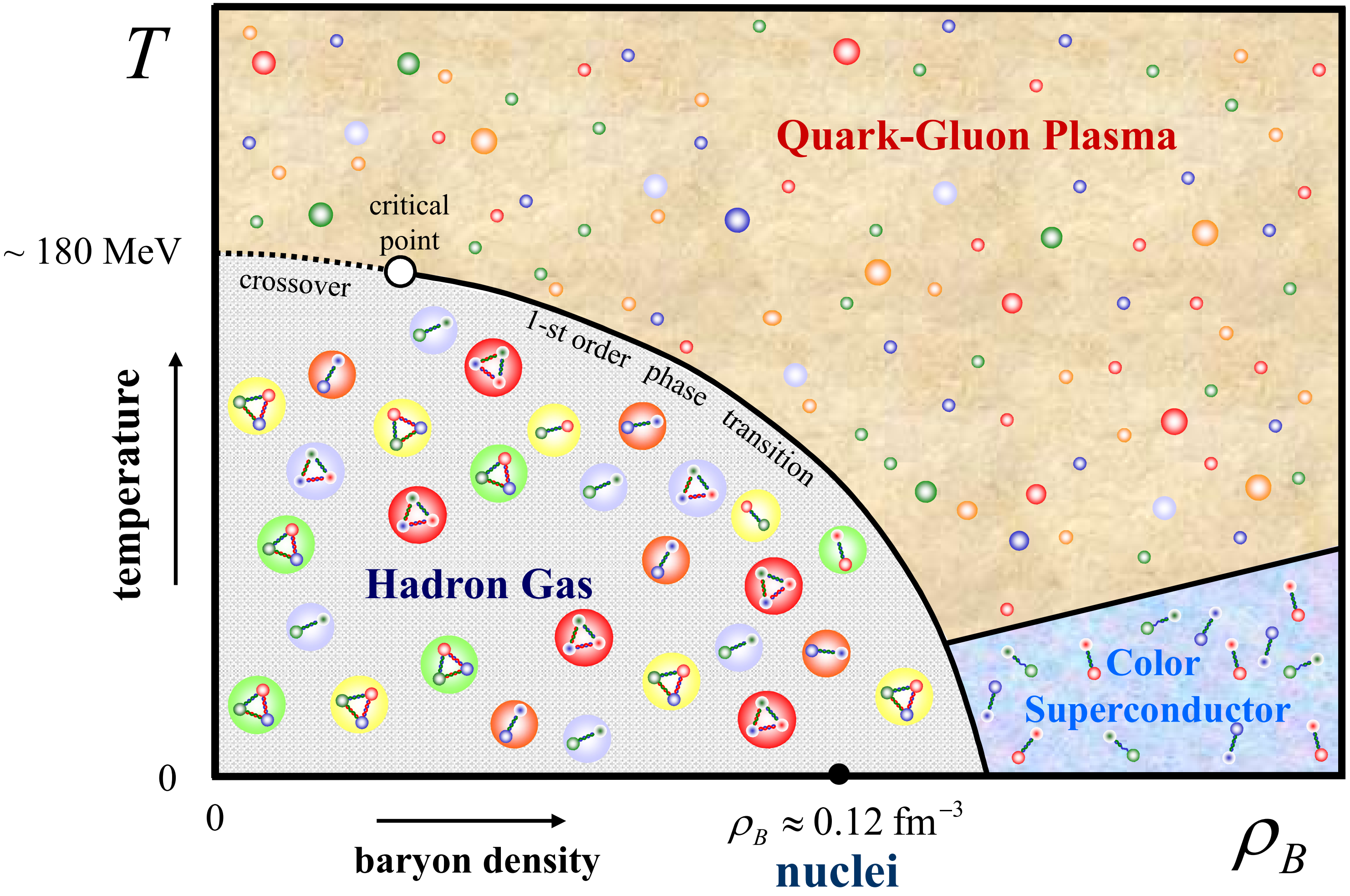
hadron density

$$\rho \sim T^3$$

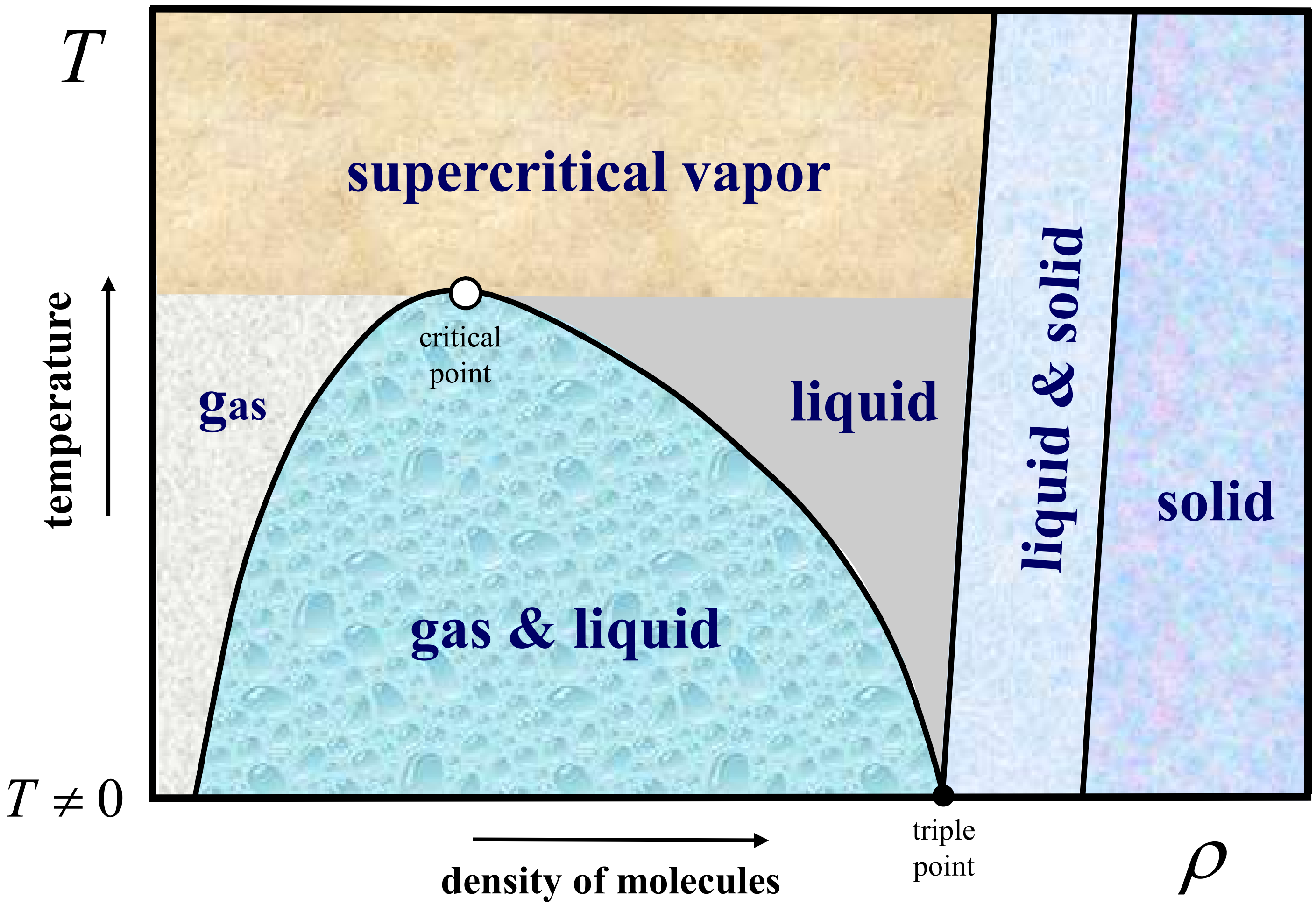
$$m_\pi << T$$

natural system of units: $\hbar = c = k_B$

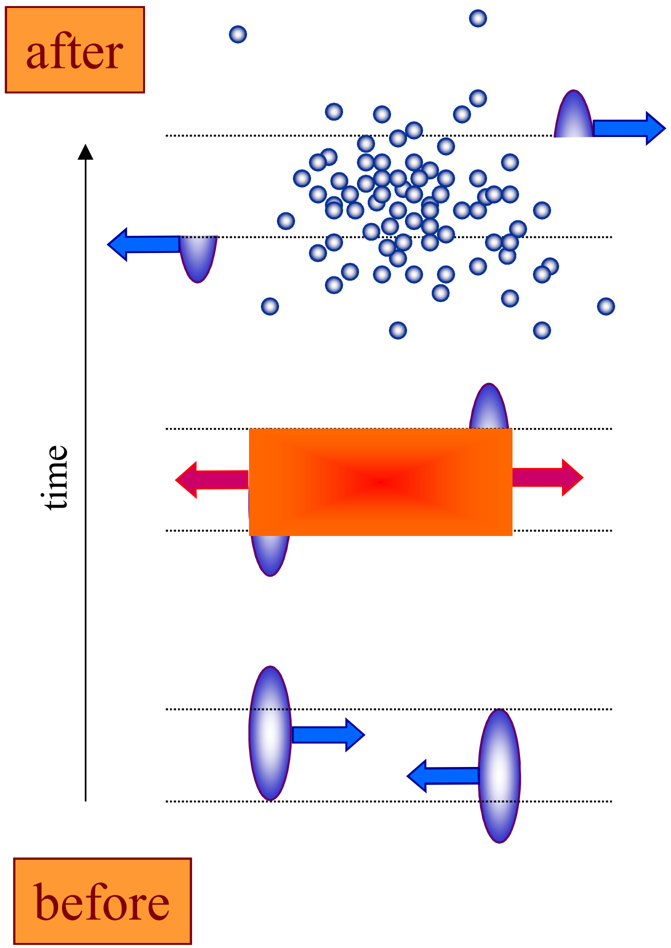
Phase diagram of strongly interacting matter

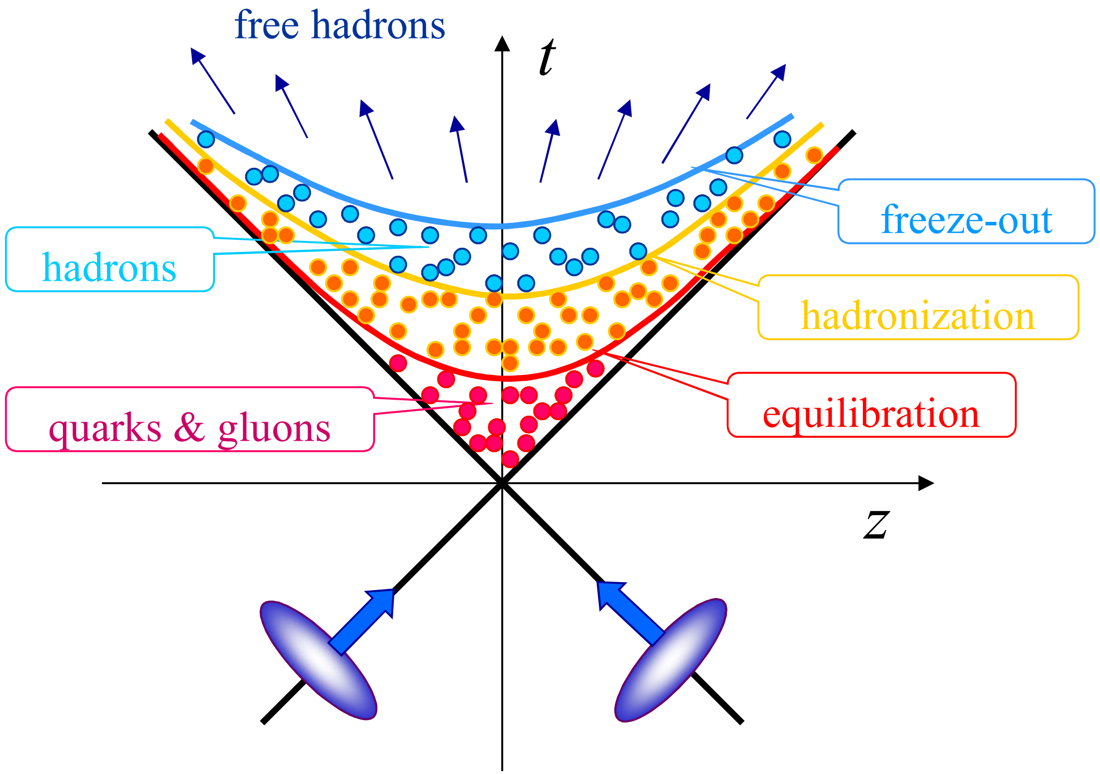


Schematic phase diagram of water



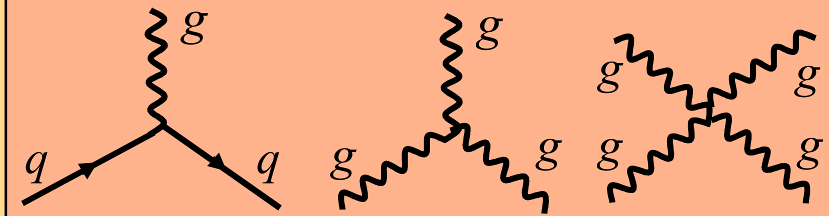
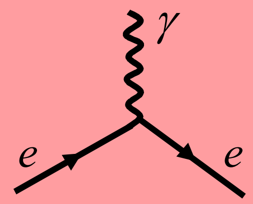
Relativistic heavy-ion collisions





An important role of boost invariance $\tau = \sqrt{t^2 - z^2}$

Quark-Gluon Plasma vs. EM Plasma

		Quark-Gluon Plasma	**Electromagnetic Plasma**
Underlying Microscopic Theory		**QCD**	**QED**
Elementarny Interactions			
Constituents	**Fermions**	quarks, antiquarks	electrons, positrons
	Massless Gauge Bosons	gluons	photons
		-	massive ions
Coupling		$\alpha(Q^2) = \frac{g^2}{4\pi} \approx 0.1-1$	$\alpha = \frac{e^2}{4\pi} \approx \frac{1}{137}$

Ultrarelativistic Quark-Gluon Plasma

Plasma constituents – quarks & gluons – are massless!

$$m_q << T$$

Temperature T is often the only dimensional parameter.

density: $\rho \sim T^3$

inter-particle spacing: $l \sim T^{-1}$

energy density: $\varepsilon \sim T^4$

pressure: $p \sim T^4$

Weakly Coupled Quark-Gluon Plasma

Plasma from the earliest stage of relativistic heavy-ion collisions is assumed to be weakly coupled.

Asymptotic freedom formula:

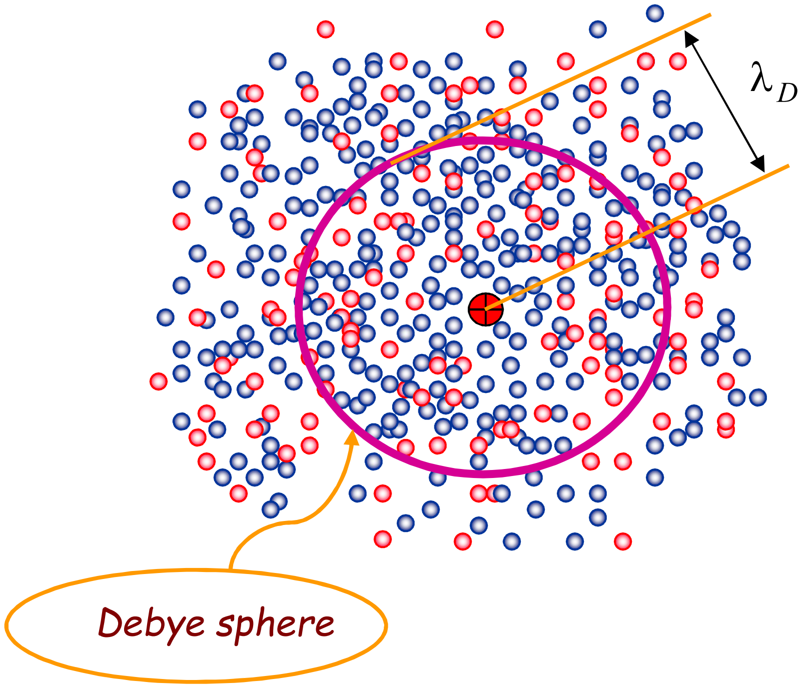
$$\alpha_S(Q^2) = \frac{12\pi}{\left(33 - 2N_f\right)\ln\left(\frac{Q^2}{\Lambda^2_{\mathrm{QCD}}}\right)}$$

Dimensional argument:

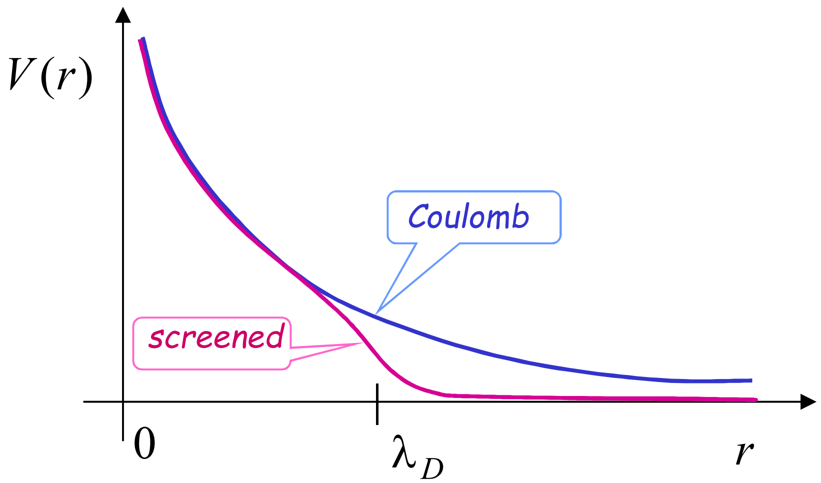
$$Q \rightarrow \varepsilon^{1/4}$$

ε *- energy density*

Plasma manifests collective behavior



$$\lambda_D = \frac{1}{m_D} \sim \frac{1}{gT}$$ *screening length* $$V(r) \sim \frac{e^{-\frac{r}{\lambda_D}}}{r}$$



$$V_D = \frac{4}{3}\pi\lambda_D^3 \sim \frac{1}{g^3T^3}, \qquad n \sim T^3, \qquad \boxed{n\,V_D \sim \frac{1}{g^3} >> 1} \text{ if } \quad g << 1$$

In a weakly coupled plasma, there are many particles in a Debye sphere!

Screening length

Poisson equation

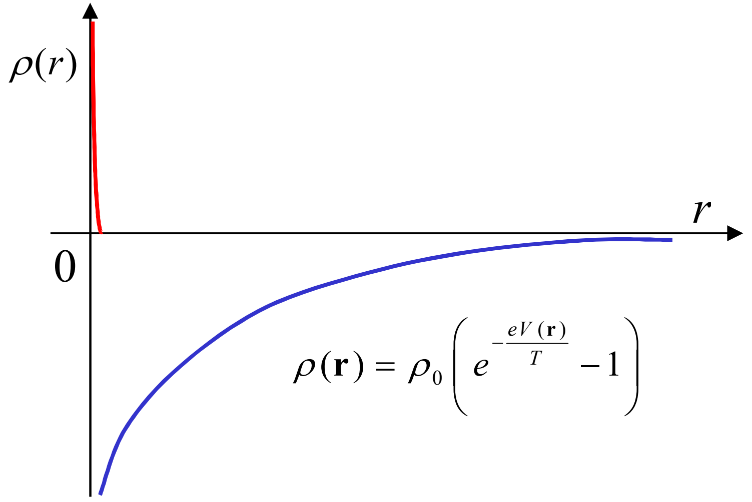
$$\boxed{\Delta V(\mathbf{r}) = -e\rho(\mathbf{r})}$$

$e|V(\mathbf{r})| << T$

$$e^{-\frac{eV(\mathbf{r})}{T}} - 1 \approx 1 - \frac{eV(\mathbf{r})}{T} \ldots - 1 = -\frac{eV(\mathbf{r})}{T}$$

$$\Delta V(\mathbf{r}) = -e\rho(\mathbf{r}) \approx \frac{e^2\rho_0}{T} V(\mathbf{r})$$

charge density



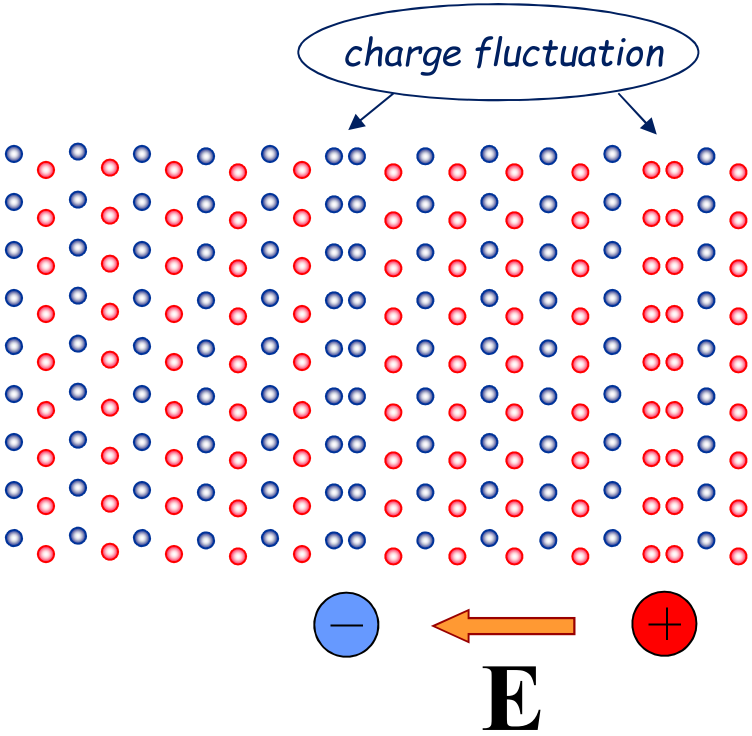
$$\boxed{\frac{d^2}{dx^2} V(x) = m_D^2 V(x) \quad \Rightarrow \quad V(x) \sim e^{-m_D|x|}}$$

Debye mass

$$m_D \equiv e\sqrt{\frac{\rho_0}{T}} = \frac{1}{\lambda_D} \sim eT$$

$$\rho_0 \sim T^3$$

Plasma oscillations

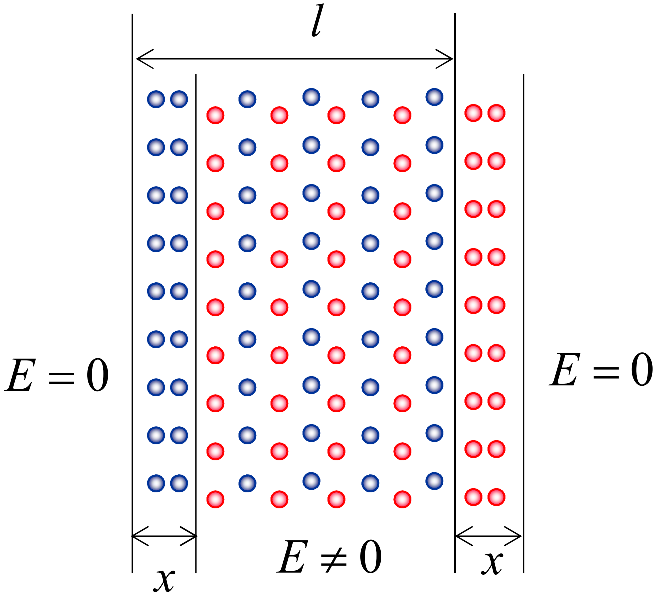


$$\mathbf{E}(t,\mathbf{r}) = \mathbf{E_0}\cos(\omega(\mathbf{k})t - \mathbf{k}\cdot\mathbf{r} + \varphi)$$

$$\omega(\mathbf{k}) \underset{\mathbf{k}\to 0}{\approx} \omega_p \sim gT$$

plasma or Langmuir frequency

Plasma frequency



Gauss theorem

$$\boxed{\Phi = Q_s}$$

flux $\Phi = ES$

charge $Q_s = e\rho Sx$

electric field $E = e\rho x$

Equation of motion

$$\boxed{M\ddot{x} = F}$$

mass $M = \rho m S l$

force $F = QE$

charge $Q = e\rho S l$

Harmonic oscillator

$$\boxed{\ddot{x} = -\omega_p^2 x}$$

plasma frequency

$$\omega_p \equiv e\sqrt{\frac{\rho}{m}}$$

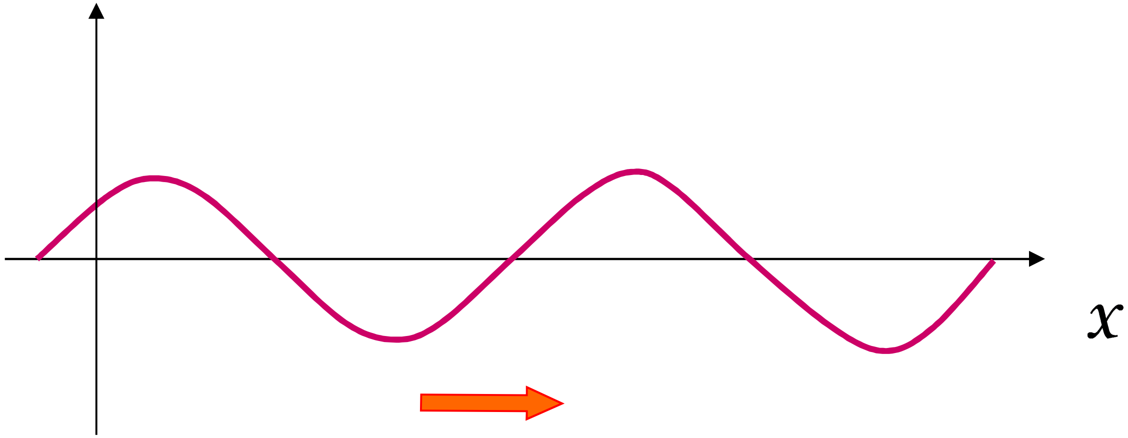
$$\lambda \to \infty$$

Quark-gluon plasma

$$e \to g$$
$$\rho \sim T^3$$
$$m \sim T$$
$$\omega_p \sim gT$$

Landau damping

$$E^x(t,x) = E_0 \cos(\omega_0 t - kx)$$



$$v_\varphi = \frac{\omega_0}{k}$$

Resonance energy transfer from electric field to particles with $v = v_\varphi$

Instabilities

stationary state

$$A(t) = A_0 + \delta A(t)$$

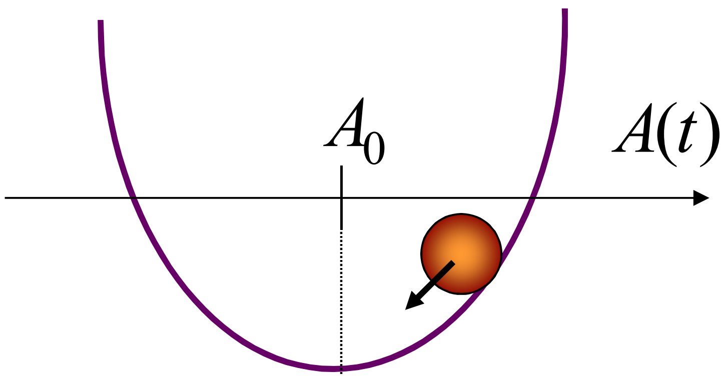
fluctuation

Instability

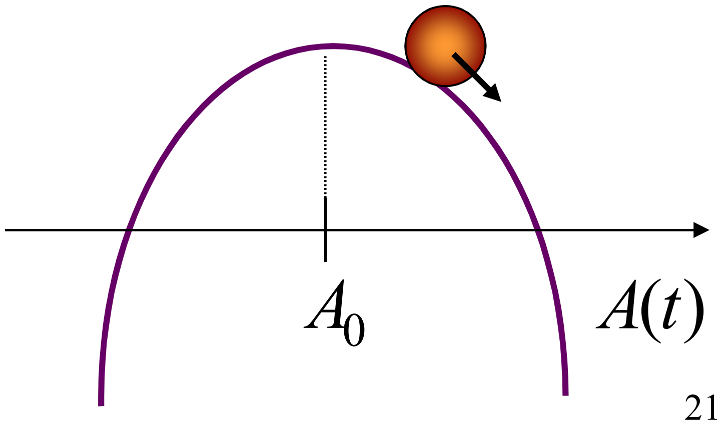
$$\delta A(t) \propto e^{\gamma t}$$

$$\gamma > 0$$

stable configuration



unstable configuration



Plasma instabilities

- *instabilities in configuration space – hydrodynamic instabilities*

- *instabilities in momentum space – kinetic instabilities*

instabilities due to non-equilibrium momentum distribution

$$f(\mathbf{p}) \ \text{ is not } \sim \exp\left(-\frac{E}{T}\right)$$

Kinetic instabilities

- *longitudinal modes* – $\mathbf{k} \parallel \mathbf{E}\,,\ \ \delta\rho \sim e^{-i(\omega t - \mathbf{kr})}$

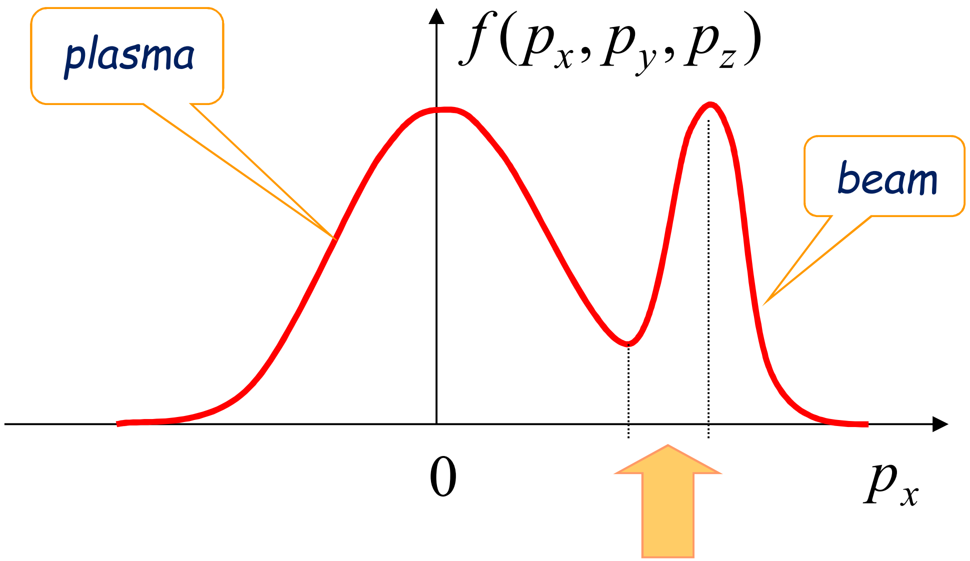
- *transverse modes* – $\mathbf{k} \perp \mathbf{E}\,,\ \ \delta\mathbf{j} \sim e^{-i(\omega t - \mathbf{kr})}$

$\mathbf{E}$ – *electric field*, $\mathbf{k}$ – *wave vector*, ρ – *charge density*, $\mathbf{j}$ – *current*

Which modes are relevant for QGP from relativistic heavy-ion collisions?

Logitudinal modes

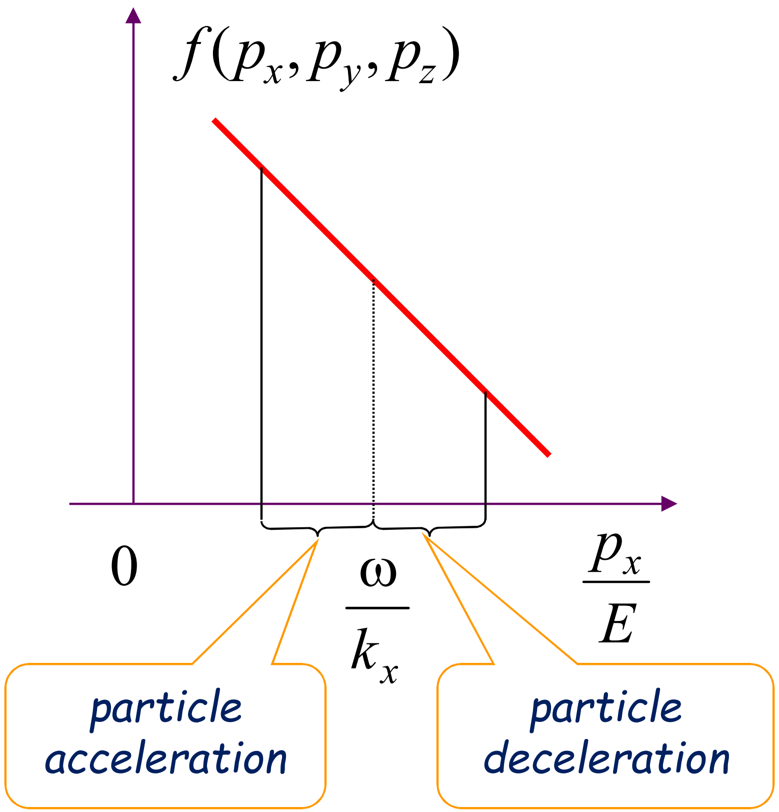
unstable configuration



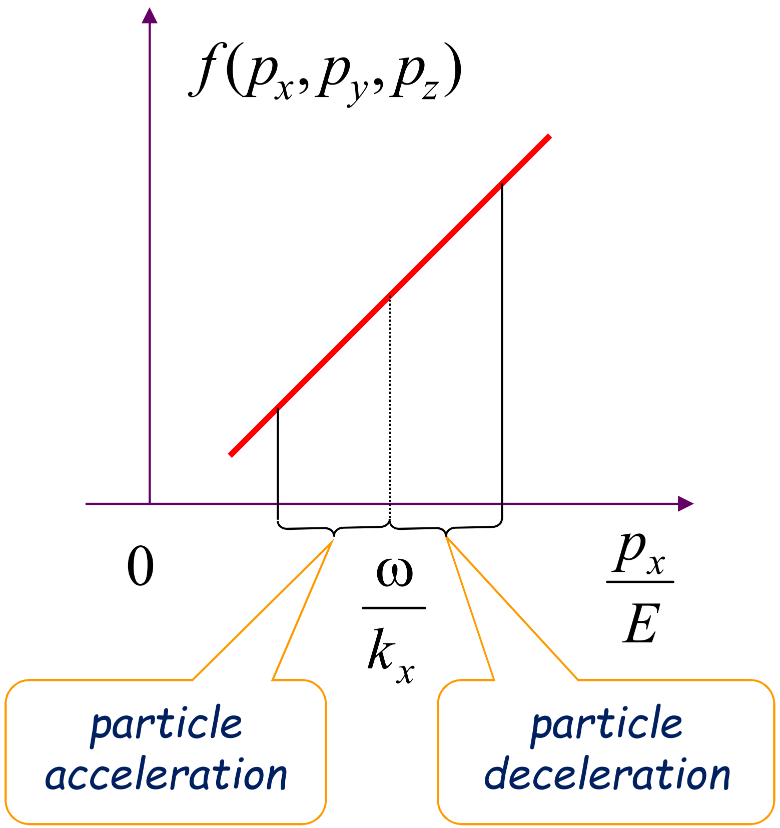
Energy is transferred from particles to fields.

Logitudinal modes

Electric field decays - damping

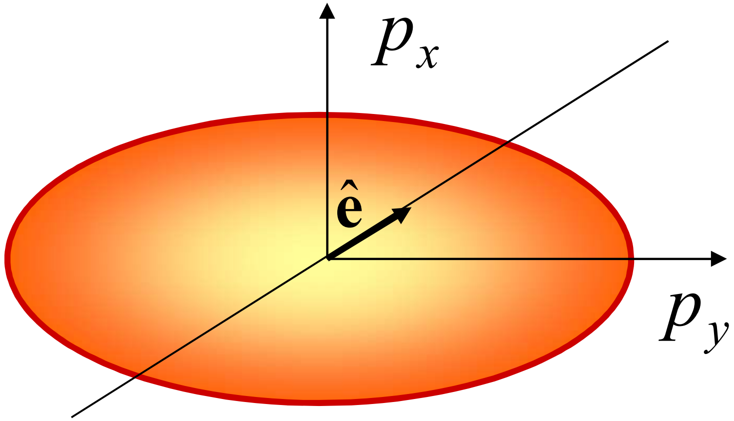


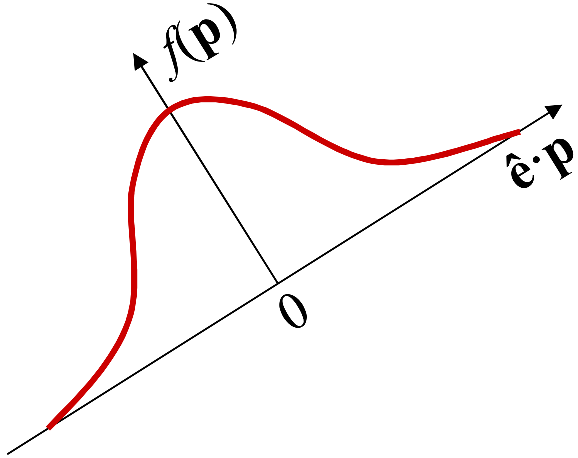
Electric field grows - instability



$\frac{\omega}{k_x}$ - *phase velocity of the electric field wave,* $\frac{p_x}{E}$ - *particle's velocity*

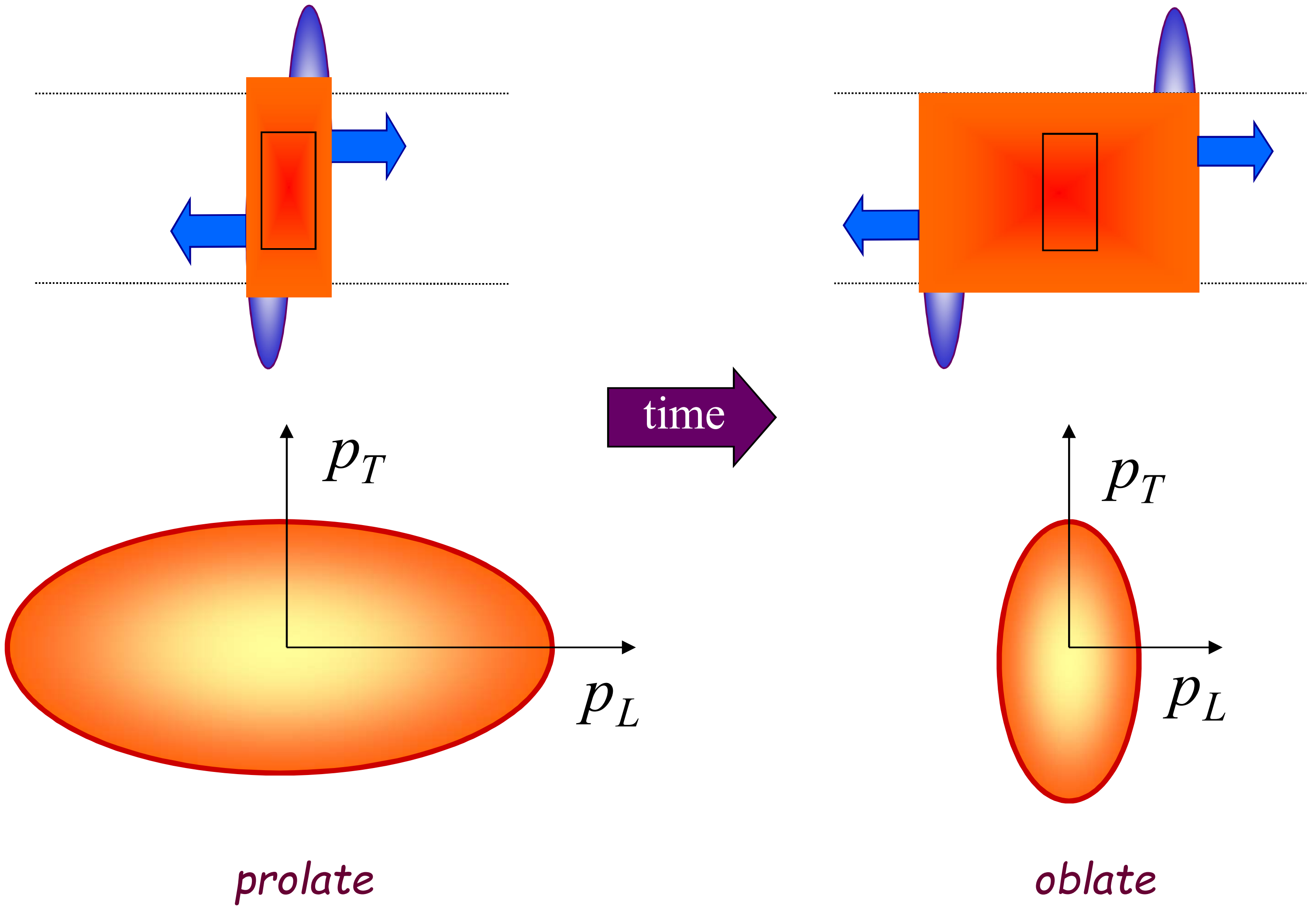
Parton momentum distribution in AA collisions





- Momentum distribution has a single maximum and monotonously decreases in every direction.
- Longitudinal unstable modes are irrelevant for relativistic heavy-ion collisions.
- There are unstable transverse modes.

Evolution of Parton Momentum Distribution



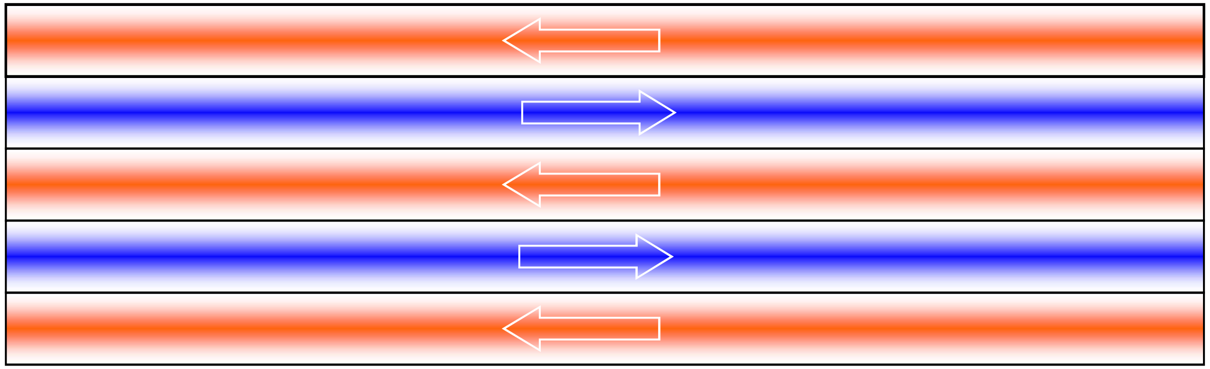
Seeds of instability

$\left\langle j_a^{\mu}(x)\right\rangle = 0$ *but current fluctuations are finite*

$$\left\langle j_a^{\mu}(x_1)\, j_b^{\nu}(x_2)\right\rangle = \frac{1}{2}\delta^{ab}\int \frac{d^3p}{(2\pi)^3}\frac{p^{\mu}p^{\nu}}{E_p^2} f(\mathbf{p})\delta^{(3)}(\mathbf{x}-\mathbf{v}t) \neq 0$$

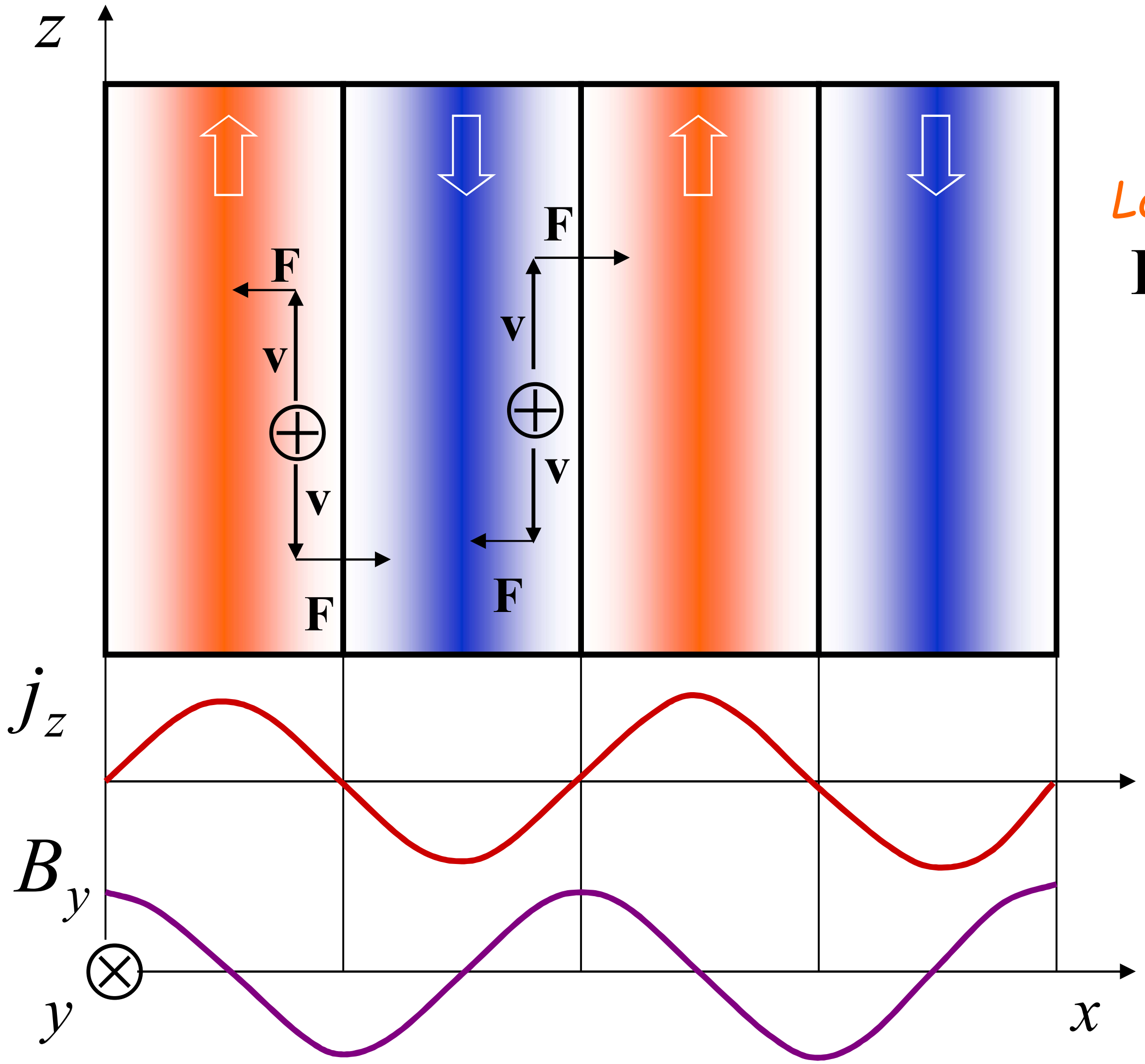
$x_2 = (t_2, \mathbf{x}_2)$

$x_1 = (t_1, \mathbf{x}_1)$ $\qquad$ $x \equiv (t_1 - t_2, \mathbf{x}_1 - \mathbf{x}_2)$



Direction of the momentum surplus

Mechanism of filamentation



Lorentz force

$$\mathbf{F} = q\,\mathbf{v}\times\mathbf{B}$$

Ampere's law

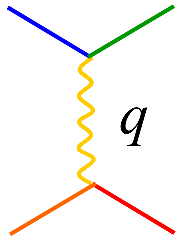
$$\nabla\times\mathbf{B} = \mathbf{j}$$

Time scale & collisional damping

Time scale of collective phenomena

$$\boxed{t_{\text{collec}} \sim \frac{1}{gT} \quad \Rightarrow \quad \nu_{\text{collec}} \sim \frac{1}{t_{\text{collec}}} \sim gT}$$

Parton-parton scattering



hard scattering: $q \sim T$

soft scattering: $q \sim gT$

Frequency of collisions

$$\nu_{\text{hard}} \sim g^4 \ln(1/g)\, T$$

$$\nu_{\text{soft}} \sim g^2 \ln(1/g)\, T$$

$$g^2 << 1 \quad \Rightarrow \quad \nu_{\text{hard}} << \nu_{\text{soft}} << \nu_{\text{collec}}$$

The instabilities are fast!

Growth of instabilities – 1+1 numerical simulations

SU(2) Hard Loop Dynamics

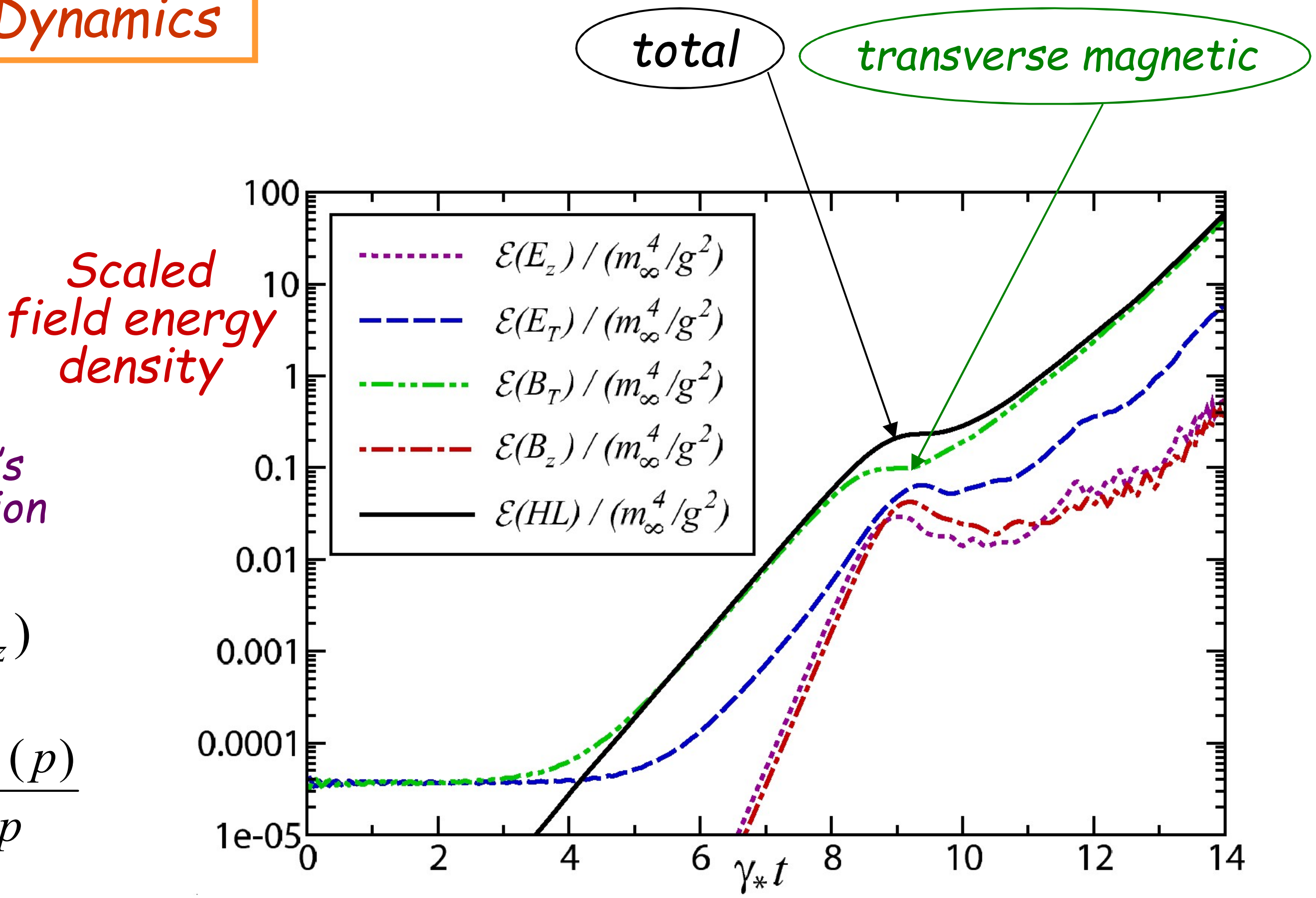
1+1 dimensions

$$A_a^\mu = A_a^\mu(t,z)$$

Anisotropic particle's momentum distribution

$$f(\mathbf{p}) = f_{\text{iso}}(|\mathbf{p}| + \zeta p_z)$$

$$m_D^2 = -\frac{\alpha_s}{\pi}\int_0^\infty dp\,p^2 \frac{df_{\text{iso}}(p)}{dp}$$



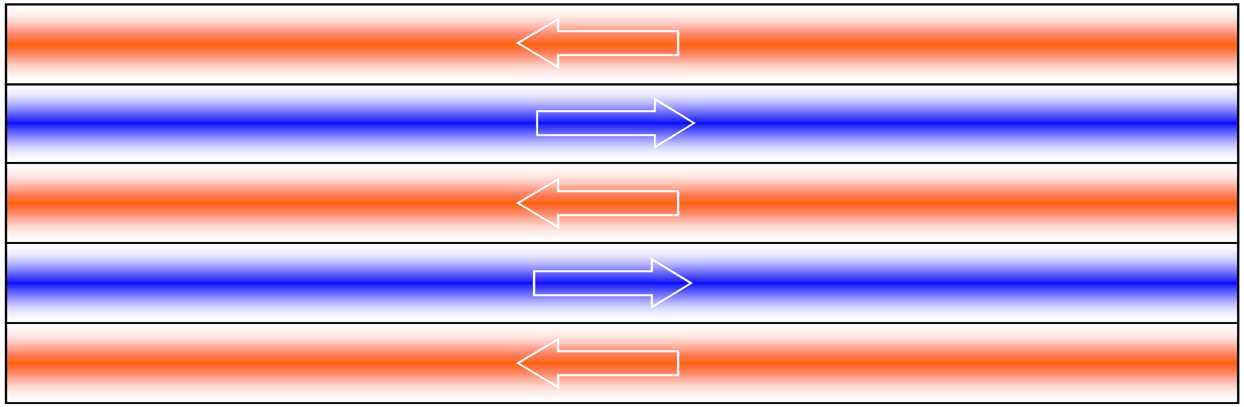
Strong anisotropy $\zeta = 10$ γ_* *- maximal growth rate*

A. Rebhan, P. Romatschke & M. Strickland, Phys. Rev. Lett. **94**, 102303 (2005)

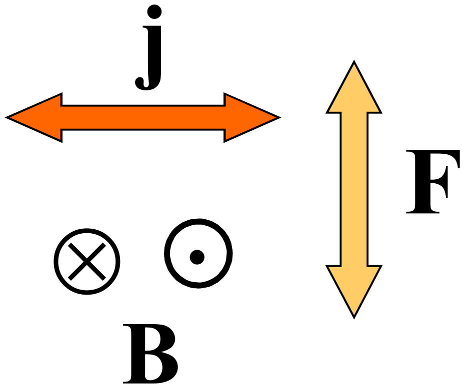
What is the role of instabilities in nuclear collisions?

Instabilities speed up equilibration of quark-gluon plasma

Isotropization - particles



Direction of the momentum surplus



$$\Delta \mathbf{p} = \int dt\, \mathbf{F}$$

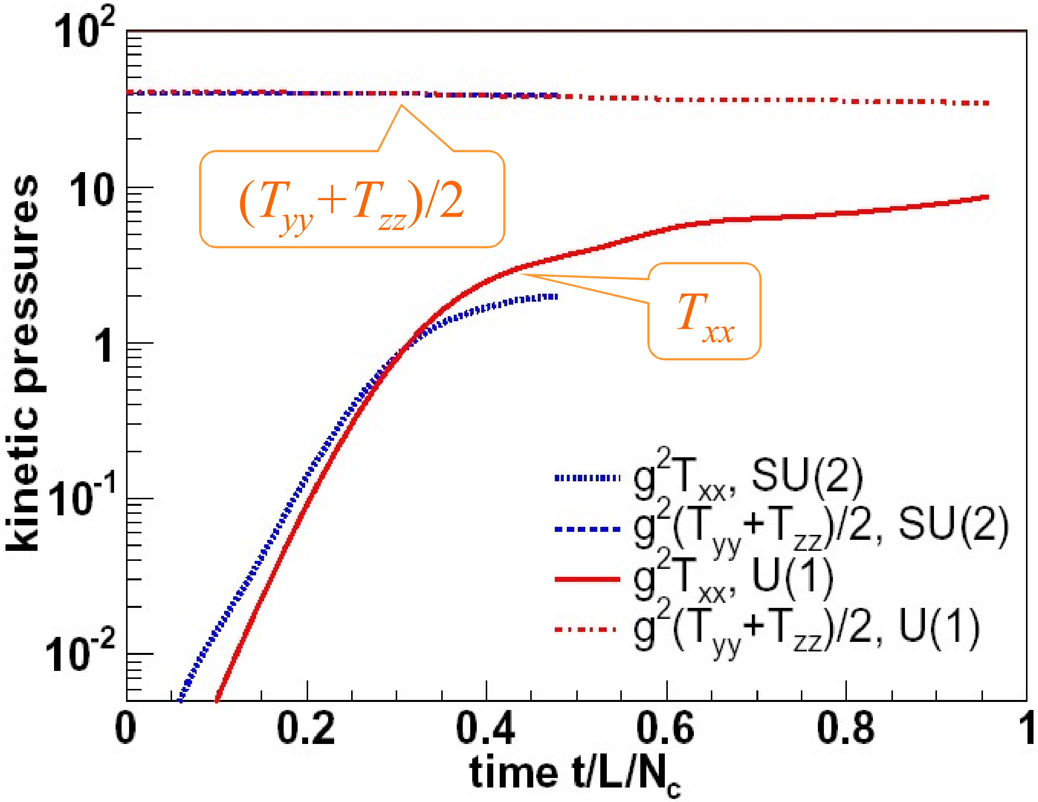
Isotropization – numerical simulation

Classical system of colored particles & fields

$$T_{ij} = \int \frac{d^3 p}{(2\pi)^3} \frac{p_i p_j}{E} f(\mathbf{p})$$

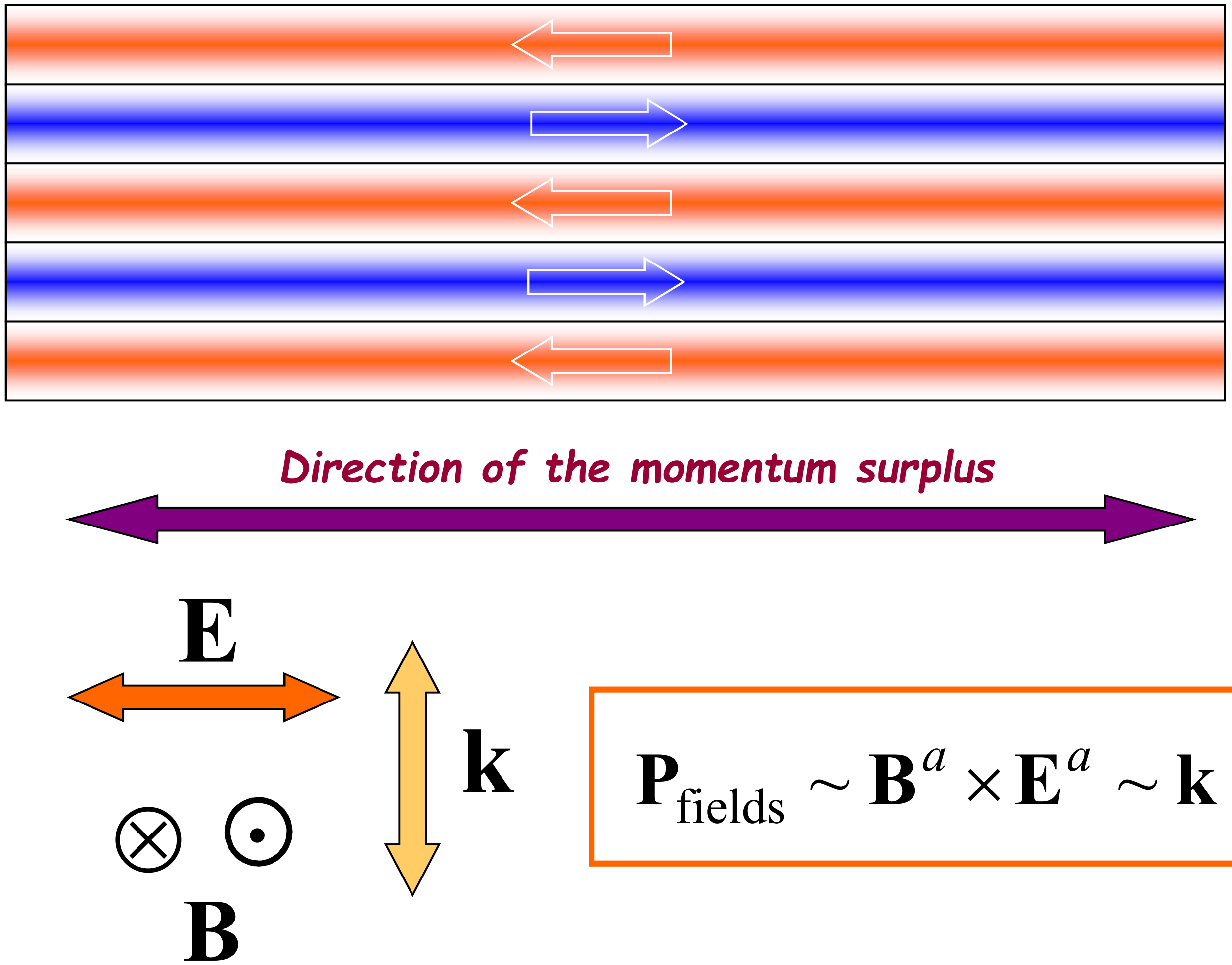
Isotropy:

$$T_{xx} = (T_{yy} + T_{zz})/2$$



A. Dumitru & Y. Nara, Phys. Lett. B **621**, 89 (2005).

Isotropization - fields

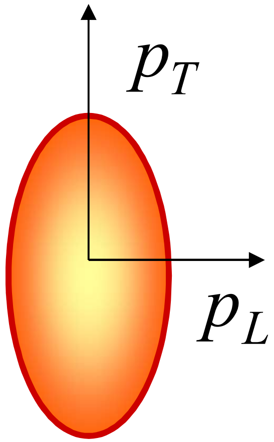


$$\boxed{\mathbf{P}_{\text{fields}} \sim \mathbf{B}^a \times \mathbf{E}^a \sim \mathbf{k}}$$

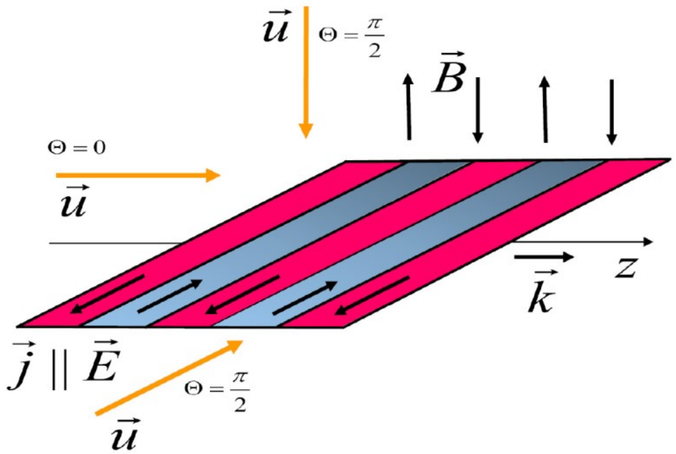
Transport in unstable plasma

Test particle in unstable plasma

oblate

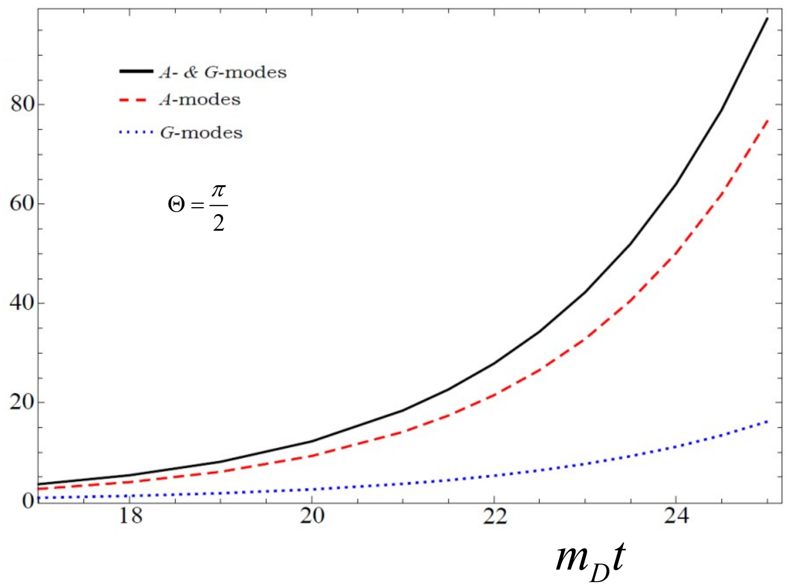


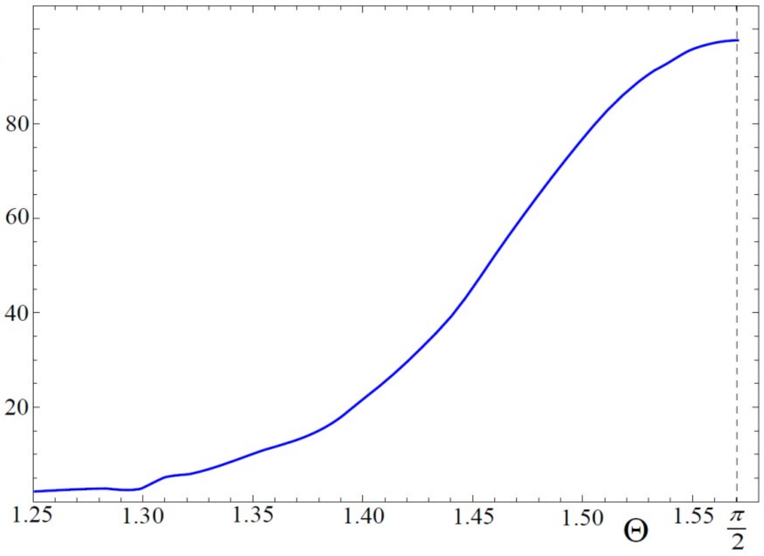
fastest unstable mode



Collisional energy loss or gain

$$\pm \frac{1}{g^2 m_D^2} \frac{dE}{dx}$$





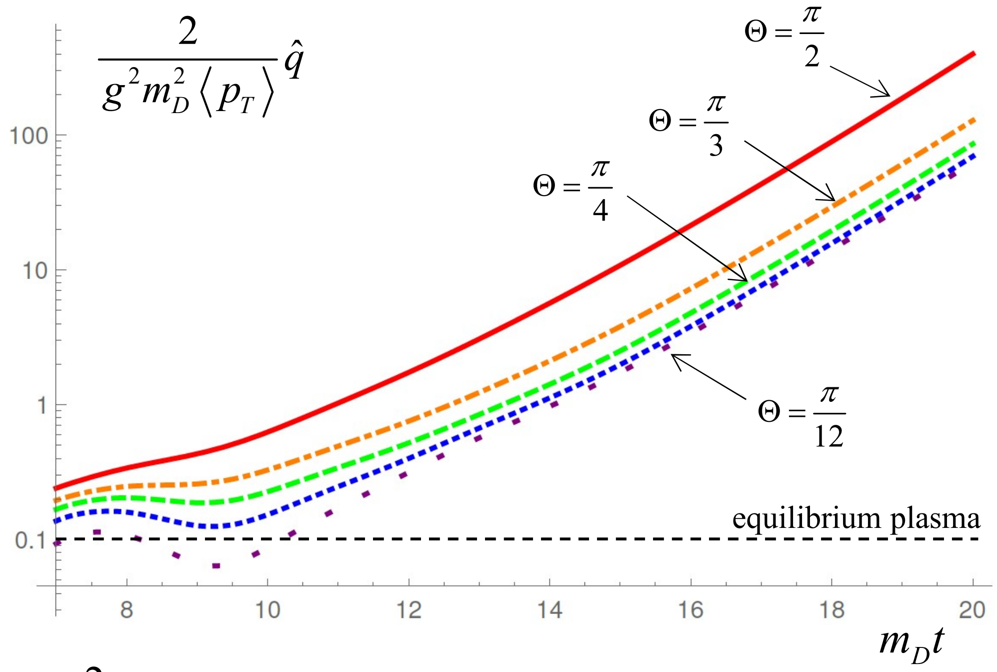
equilibrium value: $-\frac{1}{g^2 m_D^2} \frac{dE}{dx} \approx 0.1$

Initial conditions are crucially important!

M. Carrington, K. Deja and St. Mrówczyński, Phys. Rev. C **92**, 044914 (2015)

Raditive energy loss

Radiative energy loss: $-\dfrac{dE}{dx} = \alpha_s \hat{q} L$ $\hat{q}$ *- momentum broadening*



equilibrium value: $\dfrac{2}{g^2 m_D^2 \langle p_T \rangle}\hat{q} \approx 0.1$

M. Carrington, St. Mrówczyński and B. Schenke, Phys. Rev. C **95**, 024906 (2017),
A. Dumitru, Y. Nara, B. Schenke and M. Strickland, Phys. Rev. C **78**, 024909 (2008)

Conclusions

- *Non-equilibrium QGP can be unstable*
- *Unstable transverse modes are relevant for AA collisions*
- *Instabilities drive equilibration*
- *Unstable QGP is highly opaque and anisotropic medium*