Title: Topical Currents in Dense Matter. Applications: From RHIC Physics to Cosmology

Date: May 25, 2007 11:40 AM

URL: http://pirsa.org/07050076

Abstract:

Charge Separation Effect: From RHIC Physics to Cosmology

Ariel Zhitnitsky
University of British Columbia
Vancouver

(Based on work done with Dima Kharzeev, BNL)

Little Bang vs Big Bang

a) Goal of this workshop is to study " ... extreme conditions as found in the **early Universe**, the interior of compact stars, and quark-gluon plasma produced in the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory. "
(from the workshop Web page)

b) One of the motivations to build the RHIC was to produce and study the **state** which existed few moments after the **Big Bang** .
(from the proposal suggesting to build RHIC. Exact wording is not known.)

c) Almost every talk in this workshop has words " Black Holes". However, these black holes have no relation to cosmology.

d) We want to fill the gap: We want to formulate some questions which may have some astrophysical implications (for QCD- people working in RHIC -related physics)

therefore, I start from cosmology...

I. Motivation

Observational Cosmological Puzzles (Big Bang):

• The relation $\Omega_B \sim \Omega_{DM}$ between the two very different contributions to Ω is extremely difficult to explain in models that invoke a **DM** candidates not related to the ordinary baryon degrees of freedom: the baryon masses $m_N \sim \Lambda_{QCD}$.

• Several independent observations of the galactic core suggest **unexplained sources of energy.**

1. The most known case is the 511 keV line (INTEGRAL) which has proven **very difficult to explain** with conventional astrophysical positron sources.
a) It must come from the positronium decays, but number of positrons in the bulge of the galaxy 10 times smaller than needed to explain the flux.
b) Flux comes from the bulge rather than from the disk while the known positrons mostly concentrated in the disk.
c) Extra positrons must come from somewhere...

2. A similar, but less known mystery is the excess of gamma-ray photons detected by COMPTEL across a broad energy range $\sim 1 - 20$ MeV. Such photons have been found to be **very difficult to produce** via known astrophysical sources.

3. Detection by the CHANDRA satellite of diffuse X-ray emission from across the galactic bulge provides a **puzzling picture**: after subtracting known X-ray sources one finds a residual diffuse thermal X-ray emission consistent with very hot plasma ($T \simeq 10$ keV).

a) Such a plasma would be **too hot to be bound** to the galactic center (speed of sound is larger than the escape velocity).

b) The energy required to sustain a plasma of this temperature corresponds to the **entire** kinetic energy of one supernova every 3000 yr, which is unreasonably high.

c) **Source of energy** fueling this plasma is a mystery.

II. Charge separation in QCD at $\theta \neq 0$ (Big Bang)

1. We proposed that on the global level the Universe is symmetric. The **separation of charges** is originated during the QCD phase transition if $\theta \neq 0$.

2. Such a scenario **does not** contradict to the observations on antimatter abundance.

3. The **visible** content consists of **"normal" baryons** which are in the hadronic phase, while the **dark** content is in the form of matter B_{DM} and antimatter $\bar{B}_{DM}$nuggets in **color super -conducting** phase (similar to the Witten's nuggets 1984).

4. The first cosmological puzzle mentioned above is resolved in such a scenario: If **DM** is originated from the **QCD scale** $\Longrightarrow \Omega_{DM} \sim \Omega_B$ **comes naturally.**

5. Few mysteries with unexplained sources of energy (mentioned above) also find their natural explanation: **additional source of energy** is due to the rare events of **annihilation of antimatter nuggets** with visible matter (electrons and protons). Intensities, spectrum, angular distributions measured by CHANDRA, INTEGRAL, COMPTEL in vastly different energy bands can be naturally explained within the same framework.

Can the charge separation phenomenon be tested at RHIC?

Little Bang $\Longleftrightarrow$ Big Bang

(subject of the present talk)

1. We assume that the "induced" -θ vacuum state (CP odd bubles) can be produced at RHIC for a short period of time (similar to disoriented chiral condensates): D.Kharzeev and R.Pisarski, 1998; AZ et al, 1999; R.Baier et al, 2000; E.Shuryak and AZ, 2001.

2. We demonstrate that the charge separation phenomenon indeed takes place when angular momentum $\vec{L}$ and θ are nonzero. The basic technique is anomalous effective lagrangian in dense matter developed by D. Son and AZ, 2004; M.Metlitski and AZ, 2005.

3. Preliminary STAR results support our findings: I. V. Selyuzhenkov [STAR Collaboration]

II. Charge separation in QCD at $\theta \neq 0$ (Big Bang)

1. We proposed that on the global level the Universe is symmetric. The **separation of charges** is originated during the QCD phase transition if $\theta \neq 0$.

2. Such a scenario **does not** contradict to the observations on antimatter abundance.

3. The **visible** content consists of **"normal" baryons** which are in the hadronic phase, while the **dark** content is in the form of matter B_{DM} and antimatter $\bar{B}_{DM}$nuggets in **color super -conducting** phase (similar to the Witten's nuggets 1984).

4. The first cosmological puzzle mentioned above is resolved in such a scenario: If **DM** is originated from the **QCD scale** $\Longrightarrow \Omega_{DM} \sim \Omega_B$ **comes naturally.**

5. Few mysteries with unexplained sources of energy (mentioned above) also find their natural explanation: **additional source of energy** is due to the rare events of **annihilation of antimatter nuggets** with visible matter (electrons and protons). Intensities, spectrum, angular distributions measured by CHANDRA, INTEGRAL, COMPTEL in vastly different energy bands can be naturally explained within the same framework.

Can the charge separation phenomenon be tested at RHIC?

Little Bang $\Longleftrightarrow$ Big Bang

(subject of the present talk)

1. We assume that the "induced" -θ vacuum state (CP odd bubles) can be produced at RHIC for a short period of time (similar to disoriented chiral condensates): D.Kharzeev and R.Pisarski, 1998; AZ et al, 1999; R.Baier et al, 2000; E.Shuryak and AZ, 2001.

2. We demonstrate that the charge separation phenomenon indeed takes place when angular momentum $\vec{L}$ and θ are nonzero. The basic technique is anomalous effective lagrangian in dense matter developed by D. Son and AZ, 2004; M.Metlitski and AZ, 2005.

3. Preliminary STAR results support our findings: I. V. Selyuzhenkov [STAR Collaboration]

III. Similarities between systems with $\vec{B} \neq 0$ and $\vec{\Omega} \neq 0$

1. We start with nonzero magnetic field $\vec{B} \neq 0$ when the anomalous effective lagrangian is well known, and the corresponding phenomenon is well understood.

2. After that we shall discuss the systems with rotation $\vec{\Omega}$ which replaces the magnetic field,

$$\vec{B} \Longrightarrow \frac{2m}{e}\,\vec{\Omega}. \tag{1}$$

3. We shall see that the crucial ingredient in what follows is the following similarity between the two systems (external magnetic field $\vec{B}$ vs rotating system, $\vec{\Omega}$),

$$\Delta\Phi_{rot} = 2m \int \vec{\Omega}\, d\vec{\Sigma}, \qquad \Delta\Phi_B = e \int \vec{B}\, d\vec{\Sigma}. \tag{2}$$

4. All nontrivial topological phenomena such as induced electric field, charge separation effect, induced currents etc in the presence of the external magnetic field $\vec{B}$ will have their analogies for the rotating systems, $\vec{\Omega}$.

IV. Charge separation in QCD at $\theta \neq 0$. Heuristic arguments.

1. Anomalous effective lagrangian at $\theta \neq 0$,

$$L = \frac{1}{2}\vec{E}^2 - \frac{1}{2}\vec{B}^2 + N_c \sum_f \frac{e_f^2}{4\pi^2} \cdot \left(\frac{\theta}{N_f}\right)\left(\vec{E}\cdot\vec{B}\right), \tag{3}$$

2. We minimize the action density (3) with respect to the electric field E assuming $\vec{B}^{ext} \neq 0, \theta \neq 0$. Electric field is generated: $E^{ind} \sim \theta \cdot B^{ext}$,

$$\frac{\delta L}{\delta E} = \vec{E} + N_c \sum_f \frac{e_f^2}{4\pi^2} \cdot \left(\frac{\theta}{N_f}\right)\vec{B} = 0; \tag{4}$$

3. For magnetic monopole $\vec{B}^{ext} = (g/r^2)\,\vec{n}$, $N_c = N_f = 1$

$$\vec{E}^{ind} = -\vec{n}\cdot\frac{1}{r^2}\cdot\left(\frac{e\cdot g}{2\pi}\right)\cdot\left(\frac{e\theta}{2\pi}\right), \quad \vec{n} \equiv \frac{\vec{r}}{r},$$

i.e. the magnetic monopole in the presence of θ becomes a "dyon", Witten 1979.

4. Consider uniform magnetic field, B_z pointing in the z direction which does not depend on x and y coordinates (effectively a 2-dimensional theory). Electric field will be induced along z,

$$L^2 E_z^{ind} = -\left(\frac{e\,\theta}{2\pi}\right) l, \quad \text{where} \quad l = \frac{e}{2\pi}\int d^2x_\perp B_z{}^{ext} \tag{5}$$

The situation here resembles the $2d$ Schwinger model when $\theta \neq 0$ indeed can be thought as electric field.

5. It is clear that the induced electric field will lead to the induced currents and to the separation of charges along z, $[Q(z=+L) - Q(z=-L)] \sim \left(\frac{e\,\theta}{2\pi}\right) l$ in the presence of $B_z \neq 0, \theta \neq 0$.

6. Now we want to use analogy $\vec{B} \Longrightarrow \frac{2m}{e}\,\vec{\Omega}$ to argue that one should anticipate that the electric field will be induced (and the charges will be separated, $\Delta Q \neq 0$) even when the magnetic field is zero $\vec{B} \equiv 0$, but the system is rotating with angular velocity $\vec{\Omega}$.

7. We anticipate a relation $\vec{E} \sim \left(\frac{e\,\theta}{2\pi}\right)\vec{\Omega}$ when the magnetic field is replaced by $\vec{\Omega}$. Amazingly, the corresponding relation indeed can be derived using the anomalous effective lagrangian approach.

IV. Charge separation in QCD at $\theta \neq 0$. Heuristic arguments.

1. Anomalous effective lagrangian at $\theta \neq 0$,

$$L = \frac{1}{2}\vec{E}^2 - \frac{1}{2}\vec{B}^2 + N_c \sum_f \frac{e_f^2}{4\pi^2} \cdot \left(\frac{\theta}{N_f}\right)\left(\vec{E}\cdot\vec{B}\right), \tag{3}$$

2. We minimize the action density (3) with respect to the electric field E assuming $\vec{B}^{ext} \neq 0, \theta \neq 0$. Electric field is generated: $E^{ind} \sim \theta \cdot B^{ext}$,

$$\frac{\delta L}{\delta E} = \vec{E} + N_c \sum_f \frac{e_f^2}{4\pi^2} \cdot \left(\frac{\theta}{N_f}\right)\vec{B} = 0; \tag{4}$$

3. For magnetic monopole $\vec{B}^{ext} = (g/r^2)\,\vec{n}, N_c = N_f = 1$

$$\vec{E}^{ind} = -\vec{n}\cdot\frac{1}{r^2}\cdot\left(\frac{e\cdot g}{2\pi}\right)\cdot\left(\frac{e\theta}{2\pi}\right), \quad \vec{n} \equiv \frac{\vec{r}}{r},$$

i.e. the magnetic monopole in the presence of θ becomes a "dyon", Witten 1979.

4. Consider uniform magnetic field, B_z pointing in the z direction which does not depend on x and y coordinates (effectively a 2-dimensional theory). Electric field will be induced along z,

$$L^2 E_z^{ind} = -\left(\frac{e\,\theta}{2\pi}\right) l, \quad \text{where} \quad l = \frac{e}{2\pi}\int d^2x_\perp B_z^{ext} \tag{5}$$

The situation here resembles the $2d$ Schwinger model when $\theta \neq 0$ indeed can be thought as electric field.

5. It is clear that the induced electric field will lead to the induced currents and to the separation of charges along z, $[Q(z=+L) - Q(z=-L)] \sim \left(\frac{e\,\theta}{2\pi}\right) l$ in the presence of $B_z \neq 0, \theta \neq 0$.

6. Now we want to use analogy $\vec{B} \Longrightarrow \frac{2m}{e}\,\vec{\Omega}$ to argue that one should anticipate that the electric field will be induced (and the charges will be separated, $\Delta Q \neq 0$) even when the magnetic field is zero $\vec{B} \equiv 0$, but the system is rotating with angular velocity $\vec{\Omega}$.

7. We anticipate a relation $\vec{E} \sim \left(\frac{e\,\theta}{2\pi}\right)\vec{\Omega}$ when the magnetic field is replaced by $\vec{\Omega}$. Amazingly, the corresponding relation indeed can be derived using the anomalous effective lagrangian approach.

IV. Charge separation in QCD at $\theta \neq 0$. Heuristic arguments.

1. Anomalous effective lagrangian at $\theta \neq 0$,

$$L = \frac{1}{2}\vec{E}^2 - \frac{1}{2}\vec{B}^2 + N_c \sum_f \frac{e_f^2}{4\pi^2} \cdot \left(\frac{\theta}{N_f}\right)\left(\vec{E}\cdot\vec{B}\right), \tag{3}$$

2. We minimize the action density (3) with respect to the electric field E assuming $\vec{B}^{ext} \neq 0, \theta \neq 0$. Electric field is generated: $E^{ind} \sim \theta \cdot B^{ext}$,

$$\frac{\delta L}{\delta E} = \vec{E} + N_c \sum_f \frac{e_f^2}{4\pi^2} \cdot \left(\frac{\theta}{N_f}\right)\vec{B} = 0; \tag{4}$$

3. For magnetic monopole $\vec{B}^{ext} = (g/r^2)\,\vec{n}, N_c = N_f = 1$

$$\vec{E}^{ind} = -\vec{n} \cdot \frac{1}{r^2} \cdot \left(\frac{e \cdot g}{2\pi}\right) \cdot \left(\frac{e\theta}{2\pi}\right), \quad \vec{n} \equiv \frac{\vec{r}}{r},$$

i.e. the magnetic monopole in the presence of θ becomes a "dyon", Witten 1979.

4. Consider uniform magnetic field, B_z pointing in the z direction which does not depend on x and y coordinates (effectively a 2-dimensional theory). Electric field will be induced along z,

$$L^2 E_z^{ind} = -\left(\frac{e\,\theta}{2\pi}\right) l, \quad \text{where} \quad l = \frac{e}{2\pi}\int d^2x_\perp B_z{}^{ext} \tag{5}$$

The situation here resembles the $2d$ Schwinger model when $\theta \neq 0$ indeed can be thought as electric field.

5. It is clear that the induced electric field will lead to the induced currents and to the separation of charges along z, $[Q(z=+L) - Q(z=-L)] \sim \left(\frac{e\,\theta}{2\pi}\right) l$ in the presence of $B_z \neq 0, \theta \neq 0$.

6. Now we want to use analogy $\vec{B} \Longrightarrow \frac{2m}{e}\,\vec{\Omega}$ to argue that one should anticipate that the electric field will be induced (and the charges will be separated, $\Delta Q \neq 0$) even when the magnetic field is zero $\vec{B} \equiv 0$, but the system is rotating with angular velocity $\vec{\Omega}$.

7. We anticipate a relation $\vec{E} \sim \left(\frac{e\,\theta}{2\pi}\right)\vec{\Omega}$ when the magnetic field is replaced by $\vec{\Omega}$. Amazingly, the corresponding relation indeed can be derived using the anomalous effective lagrangian approach.

V. Quantum Anomalies: $\vec{\Omega} \neq 0,\ \mu \neq 0,\ \theta \neq 0.$

1. Anomalous effective lagrangian

a) Our goal is to derive a **new** **anomalous effective lagrangian** describing the interaction of light fields: the electromagnetic photons A_μ, neutral light Nambu-Goldstone bosons $(\pi,\ \eta,\ \eta')$, the **superfluid phonon** and **axion** θ in dense matter.

b) We do not assume that the axion exists at this point. We treat $\theta(x)$ as external induced background field which depends on time and coordinates.

c) Anticipating the event– the main result of the calculations– **new** **anomalous** terms which include superfluid phonon field identically **vanish** unless background contains topological defects, external magnetic field or $\vec{\Omega} \neq 0$.

d) If the anomaly induced interactions do not vanish (in case of nontrivial backgrounds) they lead to a number of interesting phenomena.

2. Main Idea

a) Consider QCD in the background of two U(1) fields: the electromagnetic field A_μ and a fictitious (spurion) V_μ field which couples to the baryon current.

b) The fundamental Lagrangian describing the coupling of quarks with V_ν is

$$\mathcal{L} = \sum_f (\mu_f V_\nu - e_f A_\nu)\bar{\psi}_f \gamma_\nu \psi_f$$

It is invariant under $U(1)_V$ local gauge transformations $q \to e^{i\beta(x)} q$, $V_\mu(x) \to V_\nu(x) + \partial_\mu \beta(x)$ similar to the conventional electrodynamics, $U(1)_{EM}$.

c) The effective low-energy description must respect the $U(1)_V$ gauge symmetry. Therefore, in the effective Lagrangian the covariant derivative $D_\mu \varphi_V = \partial_\mu \varphi_V - \mu V_\mu$ (similar to the conventional $E\&M$) must appear.

d) Consider the transformation properties of the path integral under the $U(1)_A$ chiral transformation. As is known, the measure is not invariant under these transformations due to the chiral anomaly: it receives an additional contribution $\delta S = -\int d^4x\, \partial^\mu \alpha\, j^{\rm A}_\mu = \int d^4x\, \alpha\, \partial^\mu j^{\rm A}_\mu$.

e) The problem is reduced to the calculation of the divergenece of the axial current in the presence of the electromagnetic A_μ background field as well as in the presence of fictitious V_μ background field and $\theta(x) \neq 0$.

3. Rotating System, $\vec{\Omega} \neq 0$.

The relevant term is

$$L_{\theta\gamma V} = -N_c \sum_f \frac{e_f \mu_f}{4\pi^2 N_f} \cdot \epsilon^{\mu\nu\lambda\sigma} \partial_\mu \theta (\partial_\lambda V_\nu) A_\sigma, \tag{6}$$

where $\vec{\Omega}$ is defined as $2\epsilon_{ijk}\Omega_k = (\partial_i V_j - \partial_j V_i)$ is the angular velocity of the rotating system.

$$L = \frac{1}{2}\vec{E}^2 - \frac{1}{2}\vec{B}^2 + N_c \sum_f \frac{e_f \mu_f}{2N_f \pi^2} \cdot \theta \left(\vec{E} \cdot \vec{\Omega}\right), \tag{7}$$

VI. Induced E and separation of charges in the background $\vec{\Omega} \neq 0$

1. Induced electric field E

Minimization of the anomalous effective lagrangian with respect to $\vec{E}$ gives,

$$\frac{\delta L}{\delta E} = \vec{E} + N_c \sum_f \frac{e_f \mu_f}{2\pi^2} \cdot \left(\frac{\theta}{N_f}\right) \cdot \vec{\Omega} = 0,$$

which is analogous to a similar result with nonzero magnetic field, $\vec{B} \to \vec{\Omega}$ as anticipated.

$$\vec{E} = -N_c \sum_f \frac{e_f \mu_f}{2\pi^2} \cdot \left(\frac{\theta}{N_f}\right) \cdot \vec{\Omega}$$

2. Charge separation

a) The local charge density is defined as

$$J_0^{ind} = \frac{\delta L_{\theta\gamma V}}{\delta A_0} = N_c \sum_f \frac{e_f \mu_f}{2N_f \pi^2} \cdot \left(\vec{\nabla}\theta \cdot \vec{\Omega}\right),$$

b) Assume that θ is a value of $\theta(x=0)$ inside the CP odd bubble for a given event while $\theta = 0$ in the vacuum, outside the region of interest, we have

$$\sigma_{xy} \equiv \frac{Q}{\Sigma_{xy}} = \int_0^{L/2} dz\, J_0^{ind} = -N_c \sum_f \frac{e_f \mu_f}{2\pi^2} \cdot \Omega_z \frac{\theta}{N_f},$$

c) As expected, for an infinitely large capacitor, the electric E_z field between the plates equal to the charge density $\sigma_{xy} \equiv \frac{Q}{\Sigma_{xy}}$ on the plates. Our formulae satisfy this condition,

$$\sigma_{xy} \equiv \frac{Q}{\Sigma_{xy}} = E_z = -N_c \sum_f \frac{e_f \mu_f}{2\pi^2} \cdot \left(\frac{\theta}{N_f}\right) \cdot \Omega_z$$

VI. Induced E and separation of charges in the background $\vec{\Omega} \neq 0$

1. Induced electric field E

Minimization of the anomalous effective lagrangian with respect to $\vec{E}$ gives,

$$\frac{\delta L}{\delta E} = \vec{E} + N_c \sum_f \frac{e_f \mu_f}{2\pi^2} \cdot \left(\frac{\theta}{N_f}\right) \cdot \vec{\Omega} = 0,$$

which is analogous to a similar result with nonzero magnetic field, $\vec{B} \to \vec{\Omega}$ as anticipated.

$$\vec{E} = -N_c \sum_f \frac{e_f \mu_f}{2\pi^2} \cdot \left(\frac{\theta}{N_f}\right) \cdot \vec{\Omega}$$

d) Consider the transformation properties of the path integral under the $U(1)_A$ chiral transformation. As is known, the measure is not invariant under these transformations due to the chiral anomaly: it receives an additional contribution $\delta S = -\int d^4x\, \partial^\mu \alpha\, j^{\rm A}_\mu = \int d^4x\, \alpha\, \partial^\mu j^{\rm A}_\mu$.

e) The problem is reduced to the calculation of the divergenece of the axial current in the presence of the electromagnetic A_μ background field as well as in the presence of fictitious V_μ background field and $\theta(x) \neq 0$.

3. Rotating System, $\vec{\Omega} \neq 0$.

The relevant term is

$$L_{\theta\gamma V} = -N_c \sum_f \frac{e_f \mu_f}{4\pi^2 N_f} \cdot \epsilon^{\mu\nu\lambda\sigma} \partial_\mu \theta (\partial_\lambda V_\nu) A_\sigma, \tag{6}$$

where $\vec{\Omega}$ is defined as $2\epsilon_{ijk}\Omega_k = (\partial_i V_j - \partial_j V_i)$ is the angular velocity of the rotating system.

$$L = \frac{1}{2}\vec{E}^2 - \frac{1}{2}\vec{B}^2 + N_c \sum_f \frac{e_f \mu_f}{2N_f \pi^2} \cdot \theta\left(\vec{E}\cdot\vec{\Omega}\right), \tag{7}$$

VI. Induced E and separation of charges in the background $\vec{\Omega} \neq 0$

1. Induced electric field E

Minimization of the anomalous effective lagrangian with respect to $\vec{E}$ gives,

$$\frac{\delta L}{\delta E} = \vec{E} + N_c \sum_f \frac{e_f \mu_f}{2\pi^2} \cdot \left(\frac{\theta}{N_f}\right) \cdot \vec{\Omega} = 0,$$

which is analogous to a similar result with nonzero magnetic field, $\vec{B} \to \vec{\Omega}$ as anticipated.

$$\vec{E} = -N_c \sum_f \frac{e_f \mu_f}{2\pi^2} \cdot \left(\frac{\theta}{N_f}\right) \cdot \vec{\Omega}$$

2. Charge separation

a) The local charge density is defined as

$$J_0^{ind} = \frac{\delta L_{\theta\gamma V}}{\delta A_0} = N_c \sum_f \frac{e_f \mu_f}{2N_f \pi^2} \cdot \left(\vec{\nabla}\theta \cdot \vec{\Omega}\right),$$

b) Assume that θ is a value of $\theta(x=0)$ inside the CP odd bubble for a given event while $\theta = 0$ in the vacuum, outside the region of interest, we have

$$\sigma_{xy} \equiv \frac{Q}{\Sigma_{xy}} = \int_0^{L/2} dz\, J_0^{ind} = -N_c \sum_f \frac{e_f \mu_f}{2\pi^2} \cdot \Omega_z \frac{\theta}{N_f},$$

c) As expected, for an infinitely large capacitor, the electric E_z field between the plates equal to the charge density $\sigma_{xy} \equiv \frac{Q}{\Sigma_{xy}}$ on the plates. Our formulae satisfy this condition,

$$\sigma_{xy} \equiv \frac{Q}{\Sigma_{xy}} = E_z = -N_c \sum_f \frac{e_f \mu_f}{2\pi^2} \cdot \left(\frac{\theta}{N_f}\right) \cdot \Omega_z$$

d) Consider the transformation properties of the path integral under the $U(1)_A$ chiral transformation. As is known, the measure is not invariant under these transformations due to the chiral anomaly: it receives an additional contribution $\delta S = -\int d^4x\, \partial^\mu \alpha\, j^{\rm A}_\mu = \int d^4x\, \alpha\, \partial^\mu j^{\rm A}_\mu$.

e) The problem is reduced to the calculation of the divergenece of the axial current in the presence of the electromagnetic A_μ background field as well as in the presence of fictitious V_μ background field and $\theta(x) \neq 0$.

3. Rotating System, $\vec{\Omega} \neq 0$.

The relevant term is

$$L_{\theta\gamma V} = -N_c \sum_f \frac{e_f \mu_f}{4\pi^2 N_f} \cdot \epsilon^{\mu\nu\lambda\sigma} \partial_\mu \theta (\partial_\lambda V_\nu) A_\sigma, \tag{6}$$

where $\vec{\Omega}$ is defined as $2\epsilon_{ijk}\Omega_k = (\partial_i V_j - \partial_j V_i)$ is the angular velocity of the rotating system.

$$L = \frac{1}{2}\vec{E}^2 - \frac{1}{2}\vec{B}^2 + N_c \sum_f \frac{e_f \mu_f}{2N_f \pi^2} \cdot \theta \left(\vec{E} \cdot \vec{\Omega}\right), \tag{7}$$

2. Charge separation

a) The local charge density is defined as

$$J_0^{ind} = \frac{\delta L_{\theta\gamma V}}{\delta A_0} = N_c \sum_f \frac{e_f \mu_f}{2N_f \pi^2} \cdot \left(\vec{\nabla}\theta \cdot \vec{\Omega}\right),$$

b) Assume that θ is a value of $\theta(x=0)$ inside the CP odd bubble for a given event while $\theta = 0$ in the vacuum, outside the region of interest, we have

$$\sigma_{xy} \equiv \frac{Q}{\Sigma_{xy}} = \int_{-L/2}^{L/2} dz\, J_0^{ind} = -N_c \sum_f \frac{e_f \mu_f}{2\pi^2} \cdot \Omega_z \frac{\theta}{N_f},$$

c) As expected, for an infinitely large capacitor, the electric E_z field between the plates equal to the charge density $\sigma_{xy} \equiv \frac{Q}{\Sigma_{xy}}$ on the plates. Our formulae satisfy this condition,

$$\sigma_{xy} \equiv \frac{Q}{\Sigma_{xy}} = E_z = -N_c \sum_f \frac{e_f \mu_f}{2\pi^2} \cdot \left(\frac{\theta}{N_f}\right) \cdot \Omega_z$$

VII. Numerical estimates

1. Quantization

Quantization for the rotating system is very similar to magnetic flux quantization

$$\int e\vec{B}\cdot\ d\vec{\Sigma} = 2\pi l, \qquad \int \mu\vec{\Omega}\cdot\ d\vec{\Sigma} = 2\pi l$$

2. Charge separation: numerical estimate

θ fluctuates on the event-by-event basis. Therefore: an upper hemisphere can thus have either excess of quarks over anti-quarks or vice-versa,

$$Q(L) - Q(-L) \simeq 2e\left(\frac{\theta}{\pi}\right) l,$$

3. Numerics:

a) Take $\frac{\theta}{\pi} \sim 1$

b) Use $l = 4$ for a semi-central $Au - Au$ event as identified at RHIC

c) Assume that the multiplicity of quarks and antiquarks at hadronization is approximately equal to the multiplicity of produced hadrons

d) Assume that the produced gluons split into quark–antiquark pairs before they hadronize

e) Take $N_{q+\bar{q}}$ for semi-central collisions at RHIC to be $\sim (200 - 500)$

f) A typical event at RHIC would have 3-5 more quarks than antiquarks in the upper hemisphere and an equal excess of antiquarks over quarks in the lower hemisphere.

$$A \equiv \frac{N_{q-\bar{q}}}{N_{q+\bar{q}}} \sim \mathcal{O}(3\%), \quad a_+ = \frac{4}{\pi}A, \quad a_- = -\frac{4}{\pi}A$$

g) If asymmetry is present in Fig1: $a_+^2 \simeq a_-^2 \simeq (-)a_+ \cdot a_- \sim 10^{-3}$

h) The asymmetry between quarks and anti-quarks $\longrightarrow$ translates to electric charge separation $\longrightarrow$ translates into the corresponding asymmetry for charged pions (depends on the dynamics of hadronization)

i) More direct way of observing the quark–antiquark asymmetry would be provided by the studies of baryon–antibaryon production.

VII. Numerical estimates

1. Quantization

Quantization for the rotating system is very similar to magnetic flux quantization

$$\int e\vec{B}\cdot\ d\vec{\Sigma} = 2\pi l, \qquad \int \mu\vec{\Omega}\cdot\ d\vec{\Sigma} = 2\pi l$$

2. Charge separation: numerical estimate

θ fluctuates on the event-by-event basis. Therefore: an upper hemisphere can thus have either excess of quarks over anti-quarks or vice-versa,

$$Q(L) - Q(-L) \simeq 2e\left(\frac{\theta}{\pi}\right) l,$$

3. Numerics:

a) Take $\frac{\theta}{\pi} \sim 1$

b) Use $l = 4$ for a semi-central $Au - Au$ event as identified at RHIC

c) Assume that the multiplicity of quarks and antiquarks at hadronization is approximately equal to the multiplicity of produced hadrons

d) Assume that the produced gluons split into quark–antiquark pairs before they hadronize

e) Take $N_{q+\bar{q}}$ for semi-central collisions at RHIC to be $\sim (200 - 500)$

f) A typical event at RHIC would have 3-5 more quarks than antiquarks in the upper hemisphere and an equal excess of antiquarks over quarks in the lower hemisphere.

$$A \equiv \frac{N_{q-\bar{q}}}{N_{q+\bar{q}}} \sim \mathcal{O}(3\%), \quad a_+ = \frac{4}{\pi}A, \quad a_- = -\frac{4}{\pi}A$$

g) If asymmetry is present in Fig1: $a_+^2 \simeq a_-^2 \simeq (-)a_+ \cdot a_- \sim 10^{-3}$

h) The asymmetry between quarks and anti-quarks $\longrightarrow$ translates to electric charge separation $\longrightarrow$ translates into the corresponding asymmetry for charged pions (depends on the dynamics of hadronization)

i) More direct way of observing the quark–antiquark asymmetry would be provided by the studies of baryon–antibaryon production.

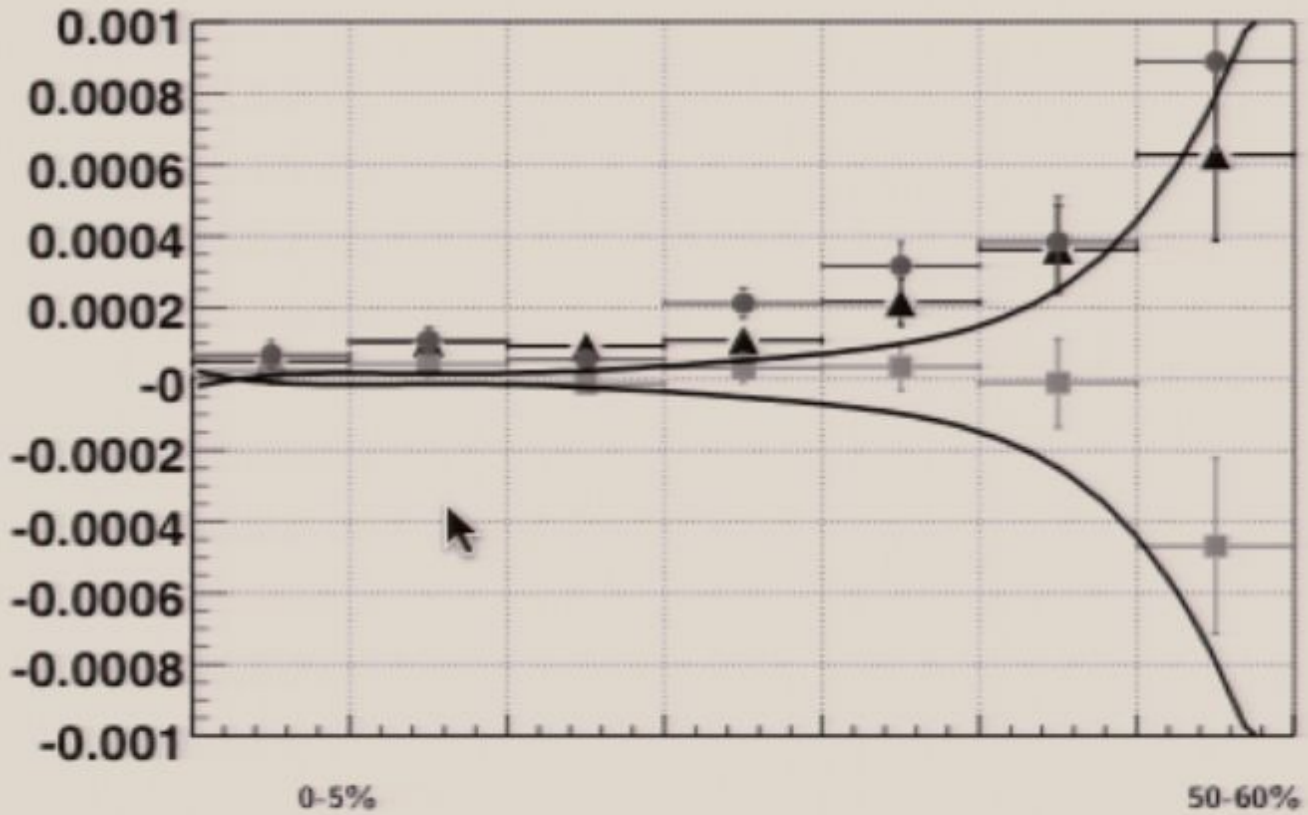

Figure 1: Preliminary data from I. V. Selyuzhenkov [STAR Collaboration], "Global polarization and parity violation study in Au + Au collisions," Rom. Rep. Phys. **58**, 049 (2006) [arXiv:nucl-ex/0510069]. Charged particle asymmetry parameters as a function of standard STAR centrality bins. Points are STAR preliminary data for Au+Au at $\sqrt{s_{NN}} = 62$ GeV: circles are a_+^2, triangles are a_-^2 and squares are $a_+ a_-$.

3. Numerics:

a) Take $\frac{\theta}{\pi} \sim 1$

b) Use $l = 4$ for a semi-central $Au - Au$ event as identified at RHIC

c) Assume that the multiplicity of quarks and antiquarks at hadronization is approximately equal to the multiplicity of produced hadrons

d) Assume that the produced gluons split into quark–antiquark pairs before they hadronize

e) Take $N_{q+\bar{q}}$ for semi-central collisions at RHIC to be $\sim (200 - 500)$

f) A typical event at RHIC would have 3-5 more quarks than antiquarks in the upper hemisphere and an equal excess of antiquarks over quarks in the lower hemisphere.

$$A \equiv \frac{N_{q-\bar{q}}}{N_{q+\bar{q}}} \sim \mathcal{O}(3\%), \quad a_+ = \frac{4}{\pi}A, \quad a_- = -\frac{4}{\pi}A$$

g) If asymmetry is present in Fig1: $a_+^2 \simeq a_-^2 \simeq (-)a_+ \cdot a_- \sim 10^{-3}$

h) The asymmetry between quarks and anti-quarks $\longrightarrow$ translates to electric charge separation $\longrightarrow$ translates into the corresponding asymmetry for charged pions (depends on the dynamics of hadronization)

i) More direct way of observing the quark–antiquark asymmetry would be provided by the studies of baryon–antibaryon production.

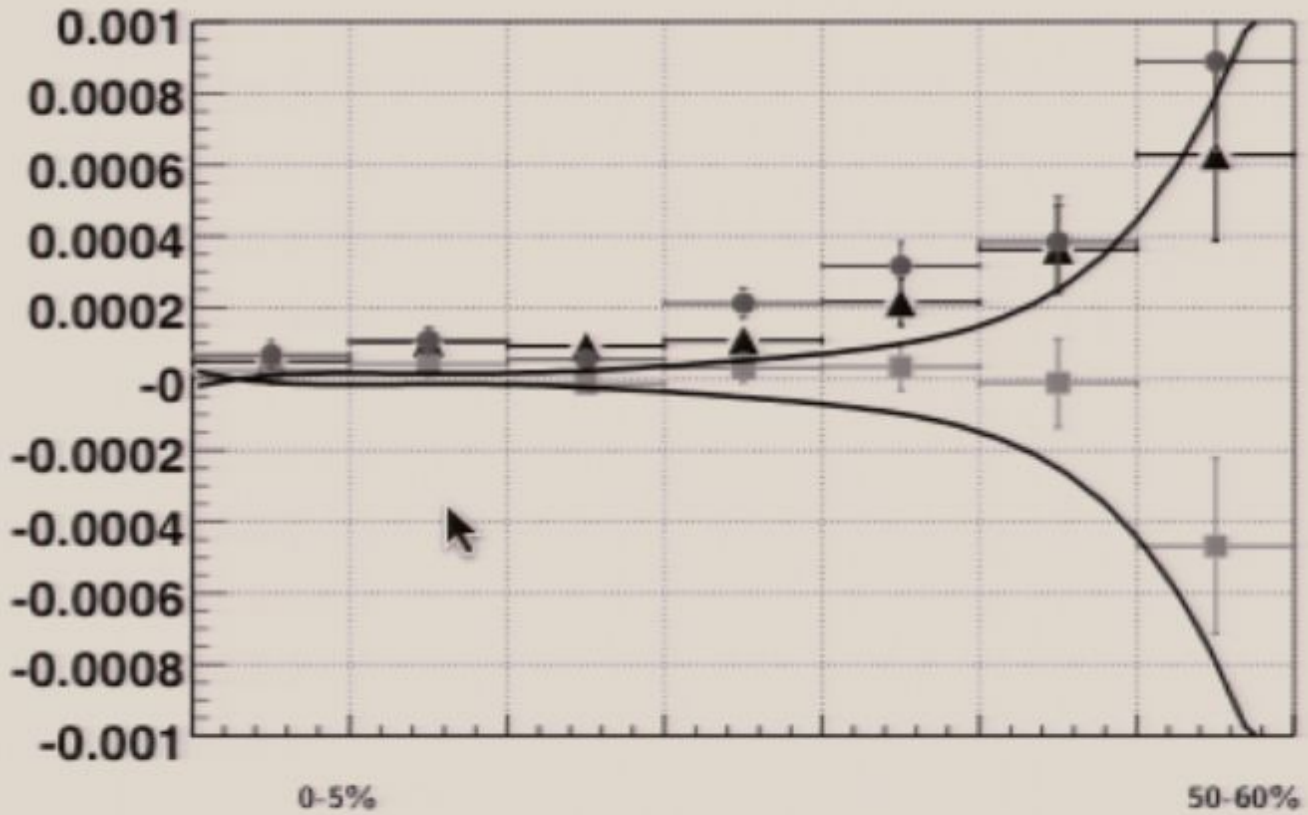

Figure 1: Preliminary data from I. V. Selyuzhenkov [STAR Collaboration], "Global polarization and parity violation study in Au + Au collisions," Rom. Rep. Phys. **58**, 049 (2006) [arXiv:nucl-ex/0510069]. Charged particle asymmetry parameters as a function of standard STAR centrality bins. Points are STAR preliminary data for Au+Au at $\sqrt{s_{NN}} = 62$ GeV: circles are a_+^2, triangles are a_-^2 and squares are $a_+ a_-$.

3. Numerics:

a) Take $\frac{\theta}{\pi} \sim 1$

b) Use $l = 4$ for a semi-central $Au - Au$ event as identified at RHIC

c) Assume that the multiplicity of quarks and antiquarks at hadronization is approximately equal to the multiplicity of produced hadrons

d) Assume that the produced gluons split into quark–antiquark pairs before they hadronize

e) Take $N_{q+\bar{q}}$ for semi-central collisions at RHIC to be $\sim (200 - 500)$

f) A typical event at RHIC would have 3-5 more quarks than antiquarks in the upper hemisphere and an equal excess of antiquarks over quarks in the lower hemisphere.

$$A \equiv \frac{N_{q-\bar{q}}}{N_{q+\bar{q}}} \sim \mathcal{O}(3\%), \quad a_+ = \frac{4}{\pi}A, \quad a_- = -\frac{4}{\pi}A$$

g) If asymmetry is present in Fig1: $a_+^2 \simeq a_-^2 \simeq (-)a_+ \cdot a_- \sim 10^{-3}$

h) The asymmetry between quarks and anti-quarks $\longrightarrow$ translates to electric charge separation $\longrightarrow$ translates into the corresponding asymmetry for charged pions (depends on the dynamics of hadronization)

i) More direct way of observing the quark–antiquark asymmetry would be provided by the studies of baryon–antibaryon production.

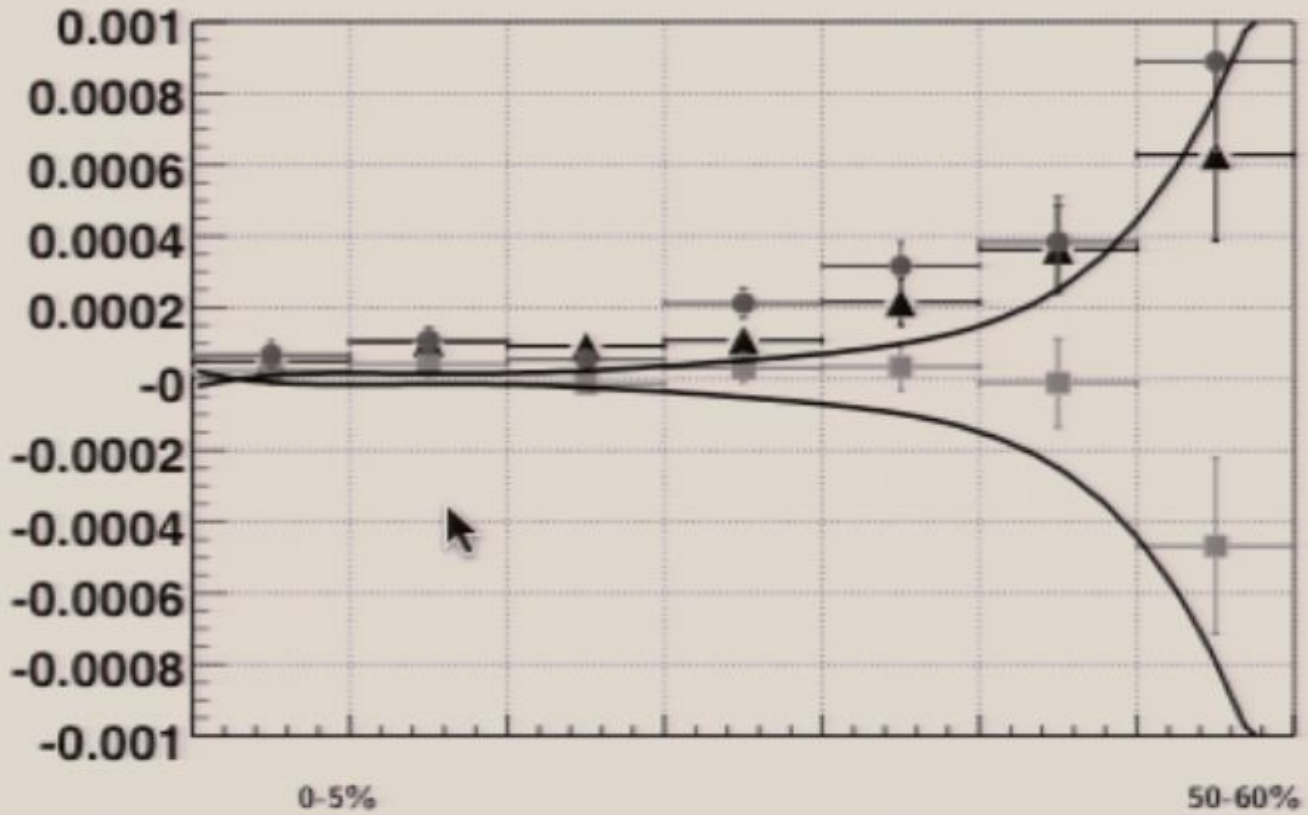

Figure 1: Preliminary data from I. V. Selyuzhenkov [STAR Collaboration], "Global polarization and parity violation study in Au + Au collisions," Rom. Rep. Phys. **58**, 049 (2006) [arXiv:nucl-ex/0510069]. Charged particle asymmetry parameters as a function of standard STAR centrality bins. Points are STAR preliminary data for Au+Au at $\sqrt{s_{NN}} = 62$ GeV: circles are a_+^2, triangles are a_-^2 and squares are $a_+ a_-$.

VII. Numerical estimates

1. Quantization

Quantization for the rotating system is very similar to magnetic flux quantization

$$\int e\vec{B}\cdot\ d\vec{\Sigma} = 2\pi l, \qquad \int \mu\vec{\Omega}\cdot\ d\vec{\Sigma} = 2\pi l$$

2. Charge separation: numerical estimate

θ fluctuates on the event-by-event basis. Therefore: an upper hemisphere can thus have either excess of quarks over anti-quarks or vice-versa,

$$Q(L) - Q(-L) \simeq 2e\left(\frac{\theta}{\pi}\right) l,$$

3. Numerics:

a) Take $\frac{\theta}{\pi} \sim 1$

b) Use $l = 4$ for a semi-central $Au - Au$ event as identified at RHIC

c) Assume that the multiplicity of quarks and antiquarks at hadronization is approximately equal to the multiplicity of produced hadrons

d) Assume that the produced gluons split into quark–antiquark pairs before they hadronize

e) Take $N_{q+\bar{q}}$ for semi-central collisions at RHIC to be $\sim (200 - 500)$

f) A typical event at RHIC would have 3-5 more quarks than antiquarks in the upper hemisphere and an equal excess of antiquarks over quarks in the lower hemisphere.

$$A \equiv \frac{N_{q-\bar{q}}}{N_{q+\bar{q}}} \sim \mathcal{O}(3\%), \quad a_+ = \frac{4}{\pi}A, \quad a_- = -\frac{4}{\pi}A$$

g) If asymmetry is present in Fig1: $a_+^2 \simeq a_-^2 \simeq (-)a_+ \cdot a_- \sim 10^{-3}$

h) The asymmetry between quarks and anti-quarks $\longrightarrow$ translates to electric charge separation $\longrightarrow$ translates into the corresponding asymmetry for charged pions (depends on the dynamics of hadronization)

i) More direct way of observing the quark–antiquark asymmetry would be provided by the studies of baryon–antibaryon production.

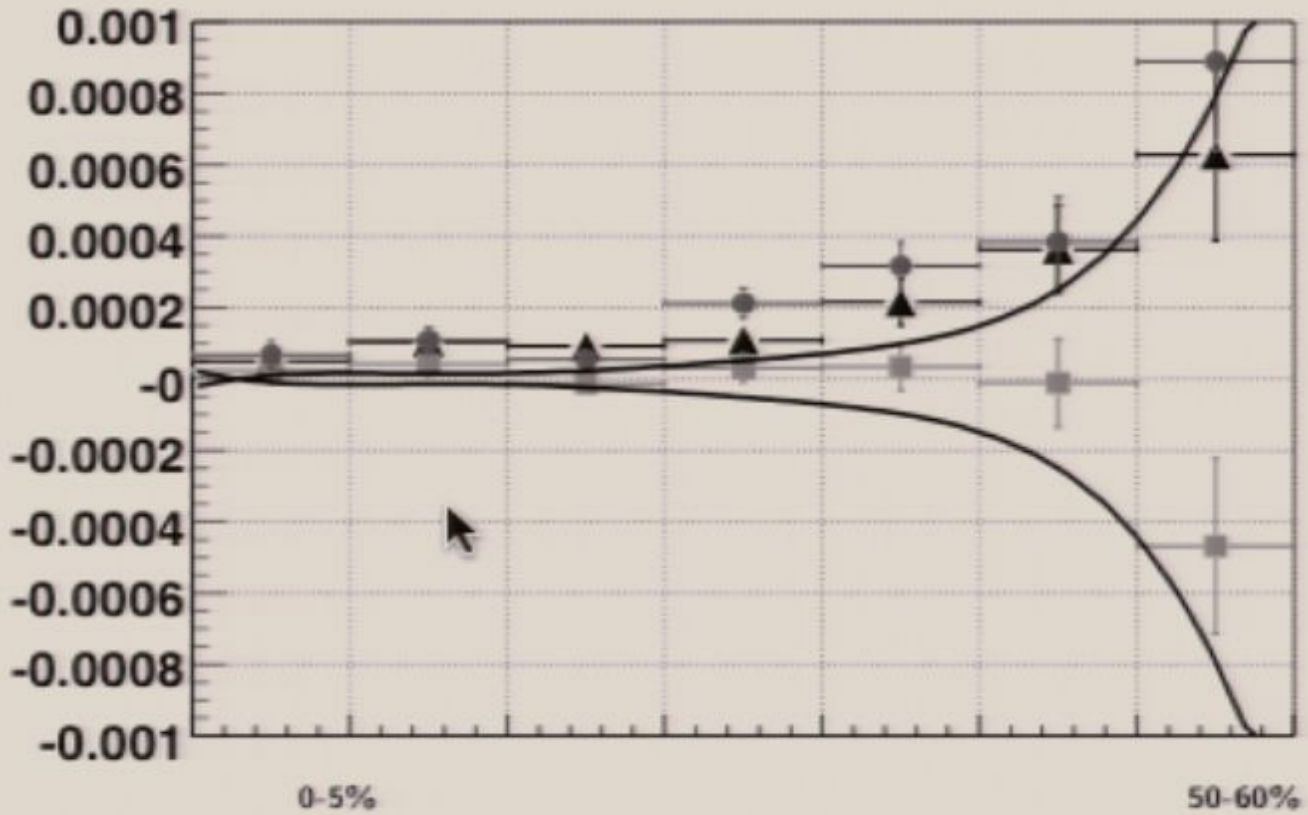

Figure 1: Preliminary data from I. V. Selyuzhenkov [STAR Collaboration], "Global polarization and parity violation study in Au + Au collisions," Rom. Rep. Phys. **58**, 049 (2006) [arXiv:nucl-ex/0510069]. Charged particle asymmetry parameters as a function of standard STAR centrality bins. Points are STAR preliminary data for Au+Au at $\sqrt{s_{NN}} = 62$ GeV: circles are a_+^2, triangles are a_-^2 and squares are $a_+ a_-$.

VIII. Conclusion

1. Terrestrial physics

An observation of such an asymmetry at RHIC (**Little Bang**) would signal for the first time the possibility of P, CP odd effects in strong interactions. Such an observation would establish unambiguously the formation of a new phase of quark-gluon matter (whatever it is).

2. Cosmological applications

An observation of such an asymmetry at RHIC would give a hint on how separation of charges could occur during the QCD phase transition few moments after the **Big Bang**.

Some astrophysical observations apparently do support an idea that a separation of charges indeed took place. Rare events of annihilation of the visible matter with antimatter nuggets apparently pointing into such a "crazy" scenario on resolution of dark matter, baryogenesis and many other (seemingly unrelated) problems...

3. Numerics:

a) Take $\frac{\theta}{\pi} \sim 1$

b) Use $l = 4$ for a semi-central $Au - Au$ event as identified at RHIC

c) Assume that the multiplicity of quarks and antiquarks at hadronization is approximately equal to the multiplicity of produced hadrons

d) Assume that the produced gluons split into quark–antiquark pairs before they hadronize

e) Take $N_{q+\bar{q}}$ for semi-central collisions at RHIC to be $\sim (200 - 500)$

f) A typical event at RHIC would have 3-5 more quarks than antiquarks in the upper hemisphere and an equal excess of antiquarks over quarks in the lower hemisphere.

$$A \equiv \frac{N_{q-\bar{q}}}{N_{q+\bar{q}}} \sim \mathcal{O}(3\%), \quad a_+ = \frac{4}{\pi}A, \quad a_- = -\frac{4}{\pi}A$$

g) If asymmetry is present in Fig1: $a_+^2 \simeq a_-^2 \simeq (-)a_+ \cdot a_- \sim 10^{-3}$

h) The asymmetry between quarks and anti-quarks $\longrightarrow$ translates to electric charge separation $\longrightarrow$ translates into the corresponding asymmetry for charged pions (depends on the dynamics of hadronization)

i) More direct way of observing the quark–antiquark asymmetry would be provided by the studies of baryon–antibaryon production.

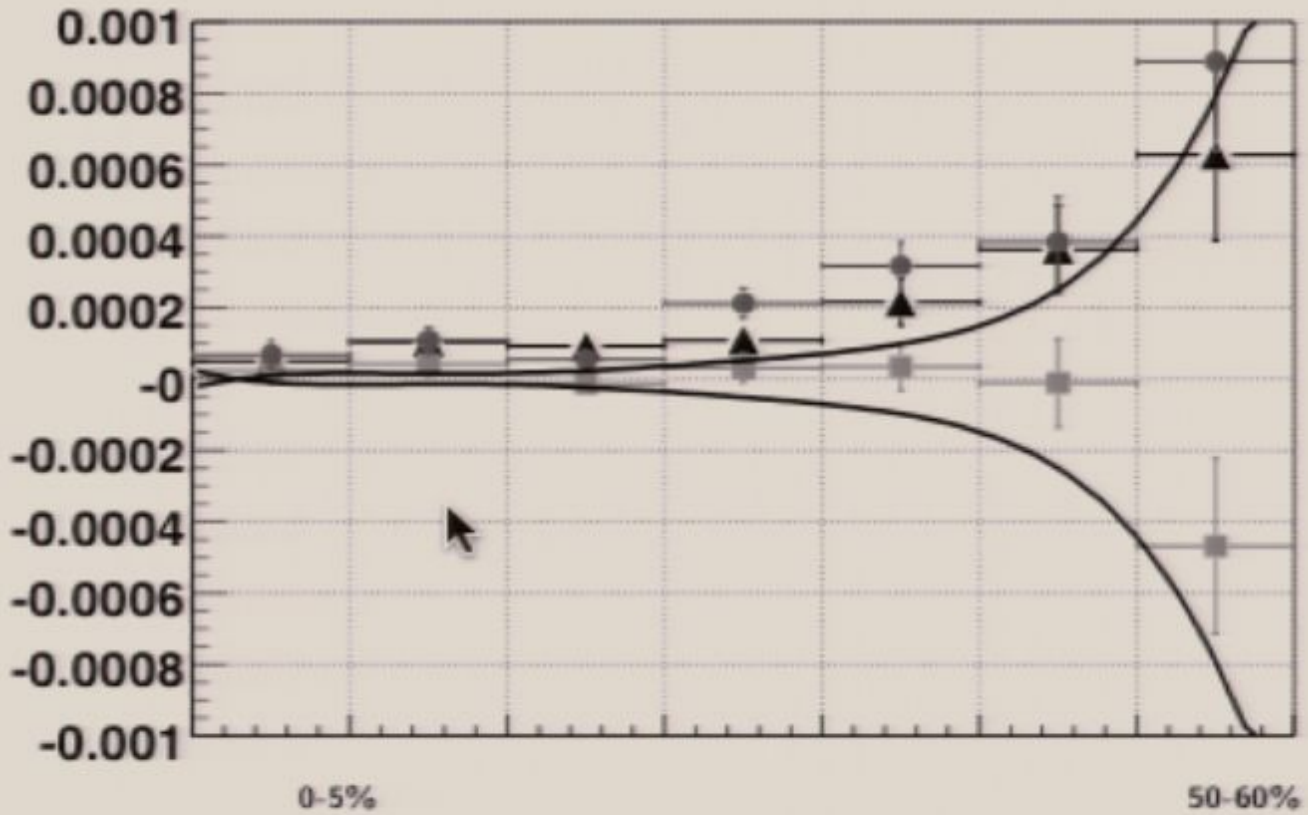

Figure 1: Preliminary data from I. V. Selyuzhenkov [STAR Collaboration], "Global polarization and parity violation study in Au + Au collisions," Rom. Rep. Phys. **58**, 049 (2006) [arXiv:nucl-ex/0510069]. Charged particle asymmetry parameters as a function of standard STAR centrality bins. Points are STAR preliminary data for Au+Au at $\sqrt{s_{NN}} = 62$ GeV: circles are a_+^2, triangles are a_-^2 and squares are $a_+ a_-$.

VIII. Conclusion

1. Terrestrial physics

An observation of such an asymmetry at RHIC (**Little Bang**) would signal for the first time the possibility of P, CP odd effects in strong interactions. Such an observation would establish unambiguously the formation of a new phase of quark-gluon matter (whatever it is).

2. Cosmological applications

An observation of such an asymmetry at RHIC would give a hint on how separation of charges could occur during the QCD phase transition few moments after the **Big Bang**.

Some astrophysical observations apparently do support an idea that a separation of charges indeed took place. Rare events of annihilation of the visible matter with antimatter nuggets apparently pointing into such a "crazy" scenario on resolution of dark matter, baryogenesis and many other (seemingly unrelated) problems...

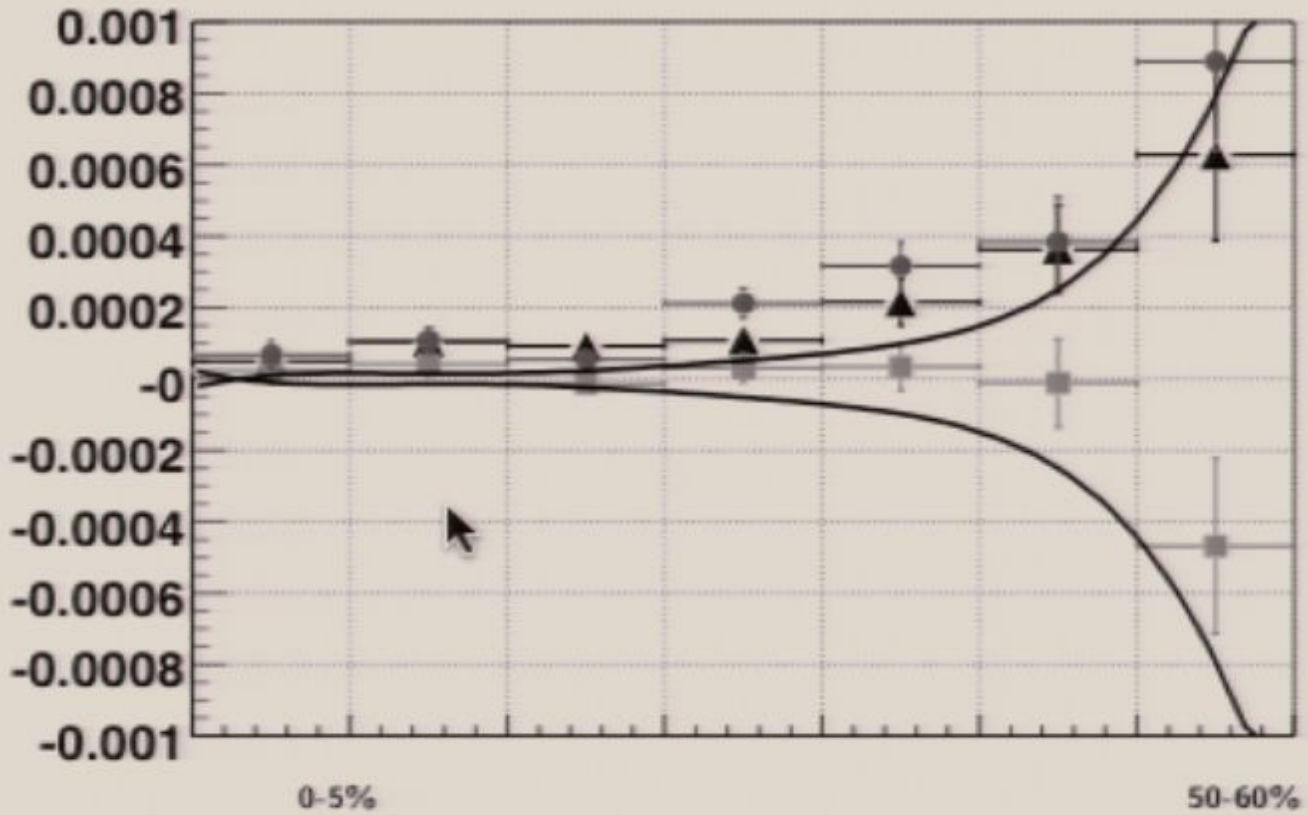

Figure 1: Preliminary data from I. V. Selyuzhenkov [STAR Collaboration], "Global polarization and parity violation study in Au + Au collisions," Rom. Rep. Phys. **58**, 049 (2006) [arXiv:nucl-ex/0510069]. Charged particle asymmetry parameters as a function of standard STAR centrality bins. Points are STAR preliminary data for Au+Au at $\sqrt{s_{NN}} = 62$ GeV: circles are a_+^2, triangles are a_-^2 and squares are $a_+ a_-$.

VIII. Conclusion

1. Terrestrial physics

An observation of such an asymmetry at RHIC (**Little Bang**) would signal for the first time the possibility of P, CP odd effects in strong interactions. Such an observation would establish unambiguously the formation of a new phase of quark-gluon matter (whatever it is).

2. Cosmological applications

An observation of such an asymmetry at RHIC would give a hint on how separation of charges could occur during the QCD phase transition few moments after the **Big Bang**.

Some astrophysical observations apparently do support an idea that a separation of charges indeed took place. Rare events of annihilation of the visible matter with antimatter nuggets apparently pointing into such a "crazy" scenario on resolution of dark matter, baryogenesis and many other (seemingly unrelated) problems...

$$\frac{11}{3}N_c - \frac{2}{3}N_f$$

$$\vec{B} = \vec{R} \times \vec{A}$$

$$\vec{\Omega} = \vec{B} \times \vec{V}$$