From RHIC Physics to Cosmology: 511 KeV Line and Other Diffuse Emissions as a Trace of the Dark Matter

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Nonequilibrium Phenomena in Cosmology and Particle Physics,
KITP, February, 25-29, 2008

Plan of this talk

a) This talk deals with two (naively unrelated) subjects:
I. RHIC physics (Little Bang)
II. Cosmology at the QCD phase transition (Big Bang)

b) The crucial element which links these two subjects is **Charge Separation Effect** which is a result of anomaly (and which is leitmotiv of the entire talk).

c) First, I argue that **we are observing presently traces** of the **Charge Separation Effect** which took place during the QCD phase transition in early universe (analysis of a number of cosmological/astrophysical puzzles).

d) Second, I present some **recent preliminary results** from RHIC which apparently suggest that **Charge Separation Effect** on macroscopically large scales (much larger than $\gg \Lambda_{QCD}^{-1}$) indeed takes place at RHIC.

e) Similar phenomena (which can be interpreted as a result of anomaly) have been extensively studied in CM literature, e.g.: spin segregation effect in the background of electric field or charge separation effect in the background of magnetic field etc.

I. Observational Cosmological Puzzles:

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

4. The WMAP experiment has revealed an excess of microwave emission, $23 < \nu < 61$ GHz (which corresponds to the energy $\sim 10^{-4}$eV), from the center of our Galaxy. This excess, which is uncorrelated to the known foregrounds, is known as the "WMAP haze". Origin of this excess remains a mystery as all conventional sources for this emission have been ruled out.

- **Typically, all these puzzles** (such as DM, Baryogenesis, excess of the diffuse emissions in X ray band, γ band, microwave bands, etc) are discussed separately because of the very different technique to study them.

(e.g. different Sessions on COSMO, DM, etc meetings)

" Naive" Moral:

$$\Downarrow$$

Dark matter requires **New (unknown) Fields**

$$\Downarrow$$

New Fields *must be* **Nonbaryonic**

(Arguments come from structure formation requirements, BBN, decoupling DM from radiation, etc...)

II. This Proposal

Instead of "New Fields"

$\Downarrow$

New phases of "Old (known) Fields"

• We propose that on the global level the Universe is **symmetric.** The **separation of baryon charges** (rather than **baryogenesis**) is originated at the QCD scale.

• 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 (few times nuclear density).

• Excess **of antimatter is locked away** in antimatter nuggets requiring **no fundamental baryon asymmetry** to explain the observed matter/antimatter asymmetry.

• The nuggets have a large binding energy (gap $\Delta \approx 100$ MeV) such that baryon charge in the nuggets is **not available** to participate in BBN at $T \approx 1$ MeV

Few Remarks on this Proposal:

1. As me ntioned: The relation $\Omega_B \sim \Omega_{DM}$ between the two very different contributions to Ω is extremely difficult to explain as the baryon masses $m_N \sim \Lambda_{QCD}$ (and Ω_B correspondingly) appear as a result of dimensional transmutation at the QCD. If **DM** is originated from the **QCD scale** $\Longrightarrow \Omega_{DM} \sim \Omega_B$ comes naturally.
2. The idea to replace "New Fields" by New Phases of "Old (known) Fields" is not new, and it was advocated long ago by Witten, 1984 (nuggets, strangelets...).
3. The **DM** nuggets made of quarks/antiquarks **do** interact with **visible matter**. However, the interaction is *strongly suppressed because matter/ antimatter nuggets occupy only a small volume of space.* A **small** geometrical factor $\epsilon \sim S/V \sim B^{-1/3} << 1$ replaces the standard requirement for the coupling constant to be weak. **Standard tight constraint on antimatter presence in our universe does not apply here.**
4. Rare events of annihilation of the visible matter with antimatter nuggets (which is the result of **charge separation phenomenon during the QCD phase transition**) provide an excess of radiation which apparently have been observed in different frequency bands: 511 keV, 1-20 MeV, X -rays, microwaves (WMAP haze),....

III. 511 KeV line from annihilation with dark antimatter

1. SPI/INTEGRAL observes 511 keV photons from positronium decay from the galactic center which is difficult to explain with conventional astrophysical positron sources.

2. We propose that the 511 keV γ line can be naturally explained as a result of annihilation of visible matter with the dark antimatter nuggets (observing effects which are direct consequence of a charge separation effect)

3. The positronium form due to the collisions of electrons from the visible matter with positrons from dark antimatter droplets which result in the bright 511 KeV narrow $(\Gamma \simeq 3KeV)$ γ-ray line from the bulge of the Galaxy.

4. All ingredients are present in this scenario:
a) the DM droplets carry positrons in the bulk or/and on the surface;
b) if electron (from the visible matter) reaches the surface, the formation of positronium and/or annihilation is unavoidable;
c) the relevant cross section for the electron falling to the DM droplet is given by the geometrical size of the object, $4\pi R^2$.
d)About a quarter of the positronium annihilations release back-to-back 511 keV photons.

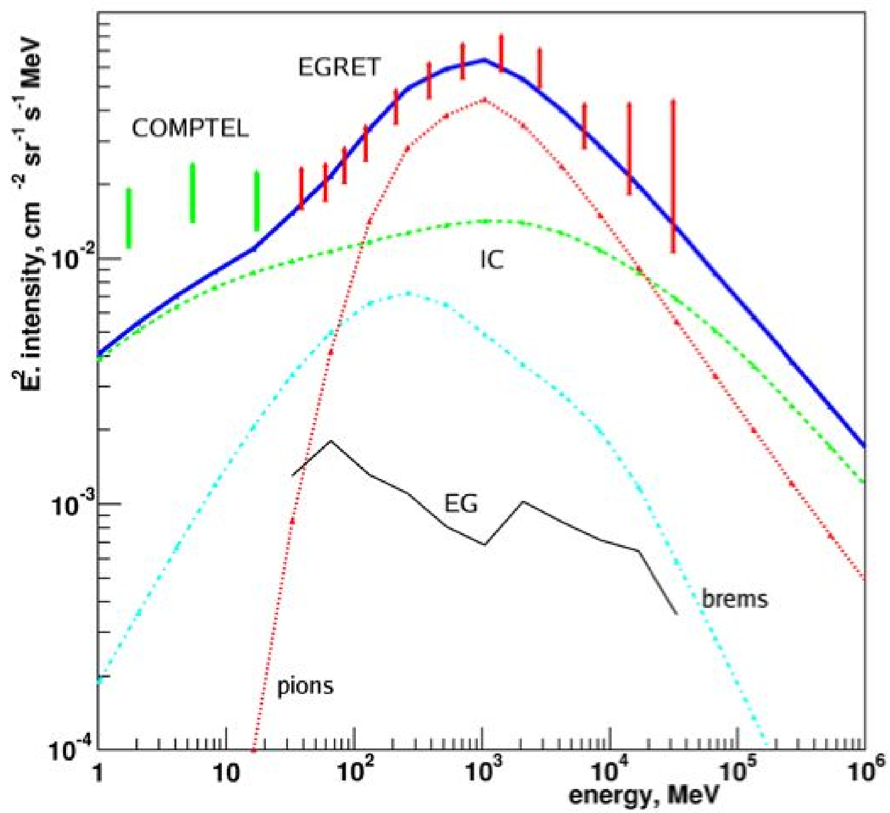
IV. Puzzle: Excess of the soft gamma-ray in $1-20$ MeV band. Observations.

1. The flux of gamma rays in the 1-20 MeV range measured by COMPTEL represents yet **another mystery.**

2. The models (based on study of cosmic rays) for diffuse galactic γ rays fit the observed spectrum well for a very broad range of energies, 20 MeV- 100 GeV. The models typically also give a good representation of the latitude distribution of the emission from the plane to the poles, and of the longitudinal distribution. However, the models **fail to explain** the excess in the 1-20 MeV range observed by COMPTEL (see Fig. below).

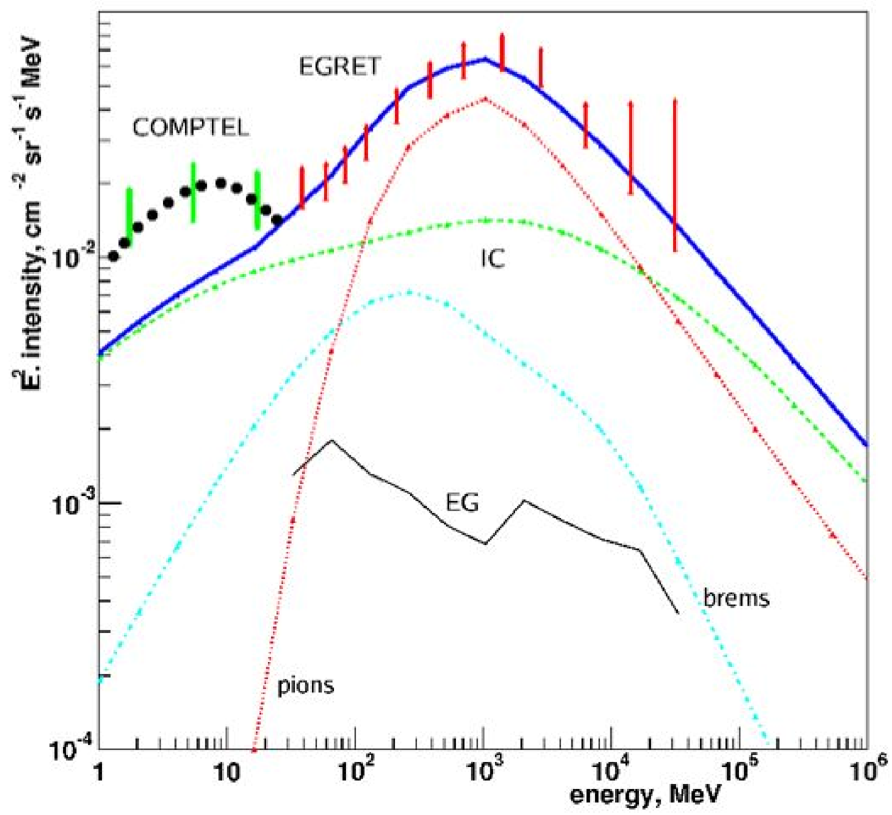
3. Some additional γ ray sources are required to explain this excess in the 1-20 MeV range (Strong et al, 2004). These data suggest the existence of an energy source beyond currently established astrophysical phenomenon.

4. The observed spectrum is extremely difficult to explain by known astrophysical mechanisms.


EGRET
COMPTEL
IC
EG
brems
pions
E^2. intensity, cm^{-2} sr^{-1} s^{-1} MeV
energy, MeV
10^{-2}
10^{-3}
10^{-4}
1
10
10^2
10^3
10^4
10^5
10^6

V. Excess of the soft gamma-ray spectrum in $1-20$ MeV band. Proposal for a possible resolution

1. As discussed previously: The resonance formation of positronium between impinging galactic electrons (e^-) and positrons (e^+) from the DM nuggets, and their subsequent decay, lead to the 511 keV line.
2. Non-resonance direct $e^+e^- \rightarrow 2\gamma$ annihilation would produce a broad spectrum at 1 MeV $\leq \omega \leq$ 20 MeV which we identify with the excess observed by COMPTEL. This continuum emission must always accompany the 511 keV line and the two must be spatially correlated (**prediction!**).
3. The typical energy scale is not introduced as a free parameter but **fixed** by the value of the lepton chemical potential $\mu \sim 20$ MeV (was calculated long ago for the quark matter). It is **precisely where an excess** of diffuse γ-rays is observed by COMPTEL.
4. No new parameters are required to explain the excess in the 1-20 MeV range – the normalization and spectrum are fixed by 511 keV flux and known QED physics.
5. If spatial correlations between 511 keV line and excess of the diffuse γ -ray emission in 1-20 MeV range is confirmed, this would unambiguously imply that the positrons are hidden in some form of antimatter nuggets as both emissions are originated from e^+e^- annihilation but there is very tight constraints on free energetic ~ 20 MeV positrons.


EGRET
COMPTEL
IC
EG
brems
pions
E². intensity, cm⁻² sr⁻¹ s⁻¹ MeV
energy, MeV

VI. Puzzle: Excess in X rays and microwave bands (WMAP haze)

1. 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.

2. The WMAP experiment has revealed an excess of microwave emission, $23 < \omega < 61$ GHz from the center of our Galaxy. This excess, which is uncorrelated to the known foregrounds, is known as the "WMAP haze". Origin of this excess remains a mystery as all conventional sources for this emission have been ruled out.

VII. Proposal for a possible resolution.

1. The antimatter nuggets provide a significant source of anti-baryonic matter such that impinging protons will annihilate. We assume that the proton annihilation rate is directly related to that of electrons

2. Proton annihilation events will release about $2m_p \approx 2$ GeV of energy per event and will occur close to the surface of the nugget creating a hot spot that will mainly radiate X-ray photons with keV energies rather than GeV gamma-rays.

3. Considerable portion of this energy will be thermalized inside the bulk of the nuggets and will be emitted as bremsstrahlung radiation from the entire surface of the nugget with long tail at small $\omega \sim 10^{-4}$ eV, $\frac{dQ}{dt} \sim \frac{T^3\alpha^{5/2}}{\pi}\sqrt[4]{\frac{T}{m}}(1+\frac{\omega}{T})\exp(-\frac{\omega}{T})\ln\frac{T}{\omega}$, which provides a natural explanation for "WMAP haze" intensity.

4. I emphasize: there are no free parameters in this calculation (intensities and spectrum) as all of the scales are set by well-established nuclear and electromagnetic physics. The only unknown parameter that enters is the overall normalization factor.

Can the charge separation phenomenon be tested at RHIC?

Little Bang $\Longleftrightarrow$ Big Bang

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 (with D.Kharzeev, 2007) 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]

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

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

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

2. We minimize the action density (1) with respect to the electric field E assuming $\vec{B}^{ext} \neq 0, \theta \neq 0$. Electric field is generated: $E^{ind} \sim \theta \cdot B^{ext}$,

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

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,

$$L^2 E_z^{ind} = -\left(\frac{e\ \theta}{2\pi}\right) l, \quad \text{where} \quad l = \frac{e}{2\pi}\int d^2x_\perp {B_z}^{ext} \tag{3}$$

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.

IX. 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 (π, η, η'), 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 $q \rightarrow e^{i\beta(x)} q, \quad V_\mu(x) \rightarrow V_\nu(x) + \partial_\mu \beta(x)$ 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 $\delta S = -\int d^4x\, \partial^\mu \alpha\, j_\mu^{\mathrm{A}} = \int d^4x\, \alpha\, \partial^\mu j_\mu^{\mathrm{A}}$.

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

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

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.

$$L = \frac{1}{2}\vec{E}^2 - \frac{1}{2}\vec{B}^2 + N_c \sum_f \frac{e_f \mu_f}{2N_f \pi^2} \cdot \theta \left(\vec{E} \cdot \vec{\Omega} \right), \tag{5}$$

X. 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, $\vec{B} \longrightarrow \vec{\Omega}$ 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,

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

XI. 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.

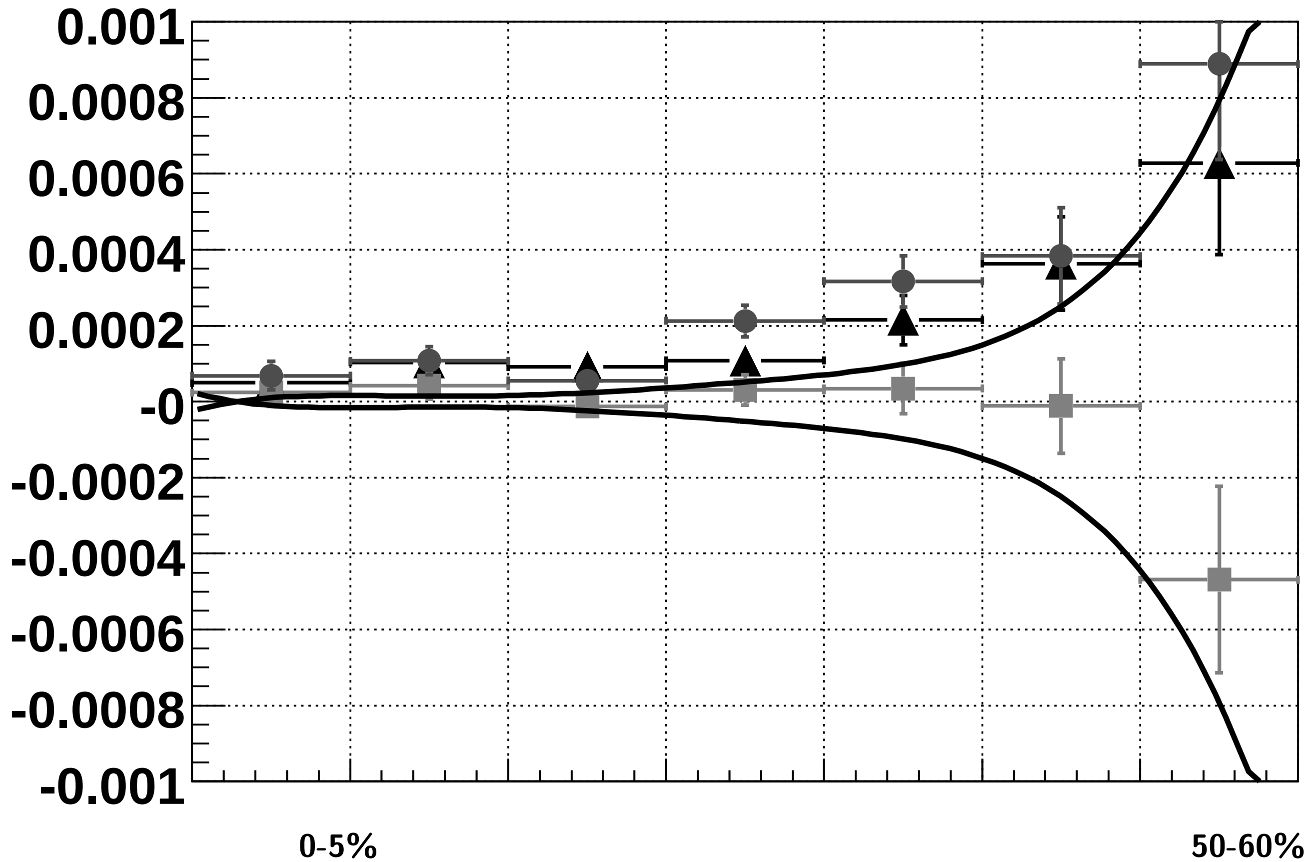


Figure 3: Preliminary data from I. V. Selyuzhenkov [STAR Collaboration], "Global polarization and parity violation study in Au + Au collisions," Rom. Rep. Phys. **58**, 049 (2006) [arXiv:nucl-ex/0510069]. Charged particle asymmetry parameters as a a function of standard STAR centrality bins. Points are STAR preliminary data for Au+Au at $\sqrt{s_{NN}} = 62$ GeV: circles are a_+^2, triangles are a_-^2 and squares are $a_+ a_-$.

XII. 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) puzzles ...