511 KeV line and diffuse γ -rays at 1-20 MeV from the Bulge: a trace of the dark matter?

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I. Motivation

Observational Cosmological Puzzles:

Dark Matter, Baryogenesis, n_B/n_γ, Structure Formation, Diffuse Galactic Radiation....

Could these be linked?

1. Dark Matter Candidates: WIMPs:neutralino, axino,gravitino, axion, Sterile neutrinos, Q-Balls, Mirror particles, Wimpzillas *(to name just a few...)*

2. Mechanisms for Baryogenesis: GUT, Affleck-Dine, Electroweak, SUSY-based, Leptogenesis *(to name just a few...)*

3. Puzzles with Structure Formation. Suggestions: Self-Interacting dark matter, Self-Annihilating DM, Warm DM, Decaying DM *(to name just a few...)*

4. Puzzles with Diffuse Galactic Radiation: 511 KeV line (INTEGRAL); Diffuse X-rays, 10 KeV (CHANDRA); Soft γ-rays, $1-20$ MeV (COMPTEL), *(to name just a few...)*

• **Typically, DM and Baryogenesis problems are discussed/considered separately because of the very different requirements for 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"

(Old Fields: quarks, antiquarks and gluons;
New Phases: Color Superconductors)

Few Remarks:

1. The requirements for two very distinct phenomena (DM $\Leftrightarrow$Baryogenesis) are very different. However, these phenomena must be related somehow...
2. 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 $m_N \sim \Lambda_{QCD}$ (and Ω_B correspondingly) appear as a result of dimensional transmutation at the QCD.
3. 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...).

Immediate Consequences of the Proposal :

1. If **DM** is originated from the **QCD scale** $\Longrightarrow \Omega_{DM} \sim \Omega_B$ comes naturally.
2. The **DM** nuggets made of quarks/antiquarks **do** interact with **visible matter**. However, the interaction is *strongly suppressed due to the dynamical reasons* (not due to the small coupling constant). Interaction becomes essential at large densities (galaxy scale $\sim$kpc), remains irrelevant at small densities ($\sim$ mpc scale). A universal behavior is not expected.

III Baryogenesis and Dark Matter

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

2. Such a scenario **does not** contradict to the observations because matter/ antimatter nuggets occupy only a small volume of space such that number of annihilation events is suppressed. A **small** geometrical factor $\epsilon \sim S/V \sim B^{-1/3} << 1$ replaces the standard requirement for the coupling constant to be weak. The baryon charge of each nugget is very large, $B \sim 10^{20} - 10^{33}$, so they have a tiny number density. Standard tight constraint on antimatter presence in our universe does not apply here.

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 (few times nuclear density).

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

- $B_{Univ} = B_{DM} + B_{Visible} - \bar{B}_{DM} = 0$,
- $\bar{B}_{DM}$:B_{DM}:$B_{Visible}$ = 3:2:1 *(In QCD everything is the same order of magnitude)*.

5. Inequality $\bar{B}_{DM} > B_{DM}$ is a result of the strong CP violation, $\theta \neq 0$ during the QCD phase transition. **DM and visible** components are formed and originated from the same QCD related physics at the same instant. Such a scenario offers a simple explanation of the ratio

$$\frac{\Omega_{DM}}{\Omega_B} \simeq \frac{(B_{DM} + \bar{B}_{DM})m_N}{(B_{Visible})m_N} \simeq \frac{(2+3)}{(1)} \simeq 5.$$

6. 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
7. The fundamental ratio in our framework $n_B/n_\gamma \sim 6 \cdot 10^{-10}$ is fixed by the formation temperature of the QCD nuggets $T_{formation} \sim \Delta \sim 40 MeV$, which is a typical QCD scale *(no fine tuning is required)*.
8. On large scales (small densities), the nuggets are sufficiently dilute that they behave as standard **collisionless cold dark matter, CCDM**.
9. On small scales (large densities): A universal " density profile" $\rho(r) \sim r^{-\gamma}$ is **not** expected– **Chameleon -like behavior**. Question on separation of DM from visible matter is not well defined when the density is large and interaction becomes crucial. Also: collisions may release significant radiation and energy which may be directly observed **(subject of this talk)**. It may also modify the standard CCDM behavior.

IV. 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 by the supermassive very dense droplets (nuggets) of dark antimatter.

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.

V. 511-KeV- Estimations

1. The probability per unit time that collision happens in the presence of a single QCD ball is given by $\frac{dW}{dt} = 4\pi R^2 n_{e^-} v$ where $v/c \sim 10^{-3}$ and the number of electrons is roughly determined by the number density of protons, $n_{e^-} \simeq n_B$.
2. The probability of such events per unit volume per unit time is given by,

$$\frac{dW}{dV\,dt} \simeq 4\pi R^2 n_{e^-}(r) \cdot v \cdot \overline{n}_{DM}(r) \simeq \frac{4\pi R^2}{B} \cdot v \cdot (\frac{\rho_{visible}}{1GeV}) \cdot (\frac{3/5\rho_{DM}}{1GeV})$$

3. The total flux of photons resulting from annihilation is obtained by integrating over the line of sight and over the whole solid angle of observation,

$$\Phi = \int dr \int_{\Delta\Omega} d\Omega \frac{dW}{dV\,dt} \sim B^{-1/3} \int dr \rho_{visible}(r) \cdot \rho_{DM}(r)$$

4. The prediction is sensitive to the product dark $\rho_{DM}(r)$ visible $\rho_{visible}(r)$ matter distributions in the galaxy, $\int dr \rho_{visible}(r) \cdot \rho_{DM}(r)$.
5. The observed width, $\Gamma \sim m_e \alpha \simeq 3KeV$ is determined by known atomic physics (resonance positronium formation when velocities of e^+e^- have typical values $v/c \sim \alpha$).

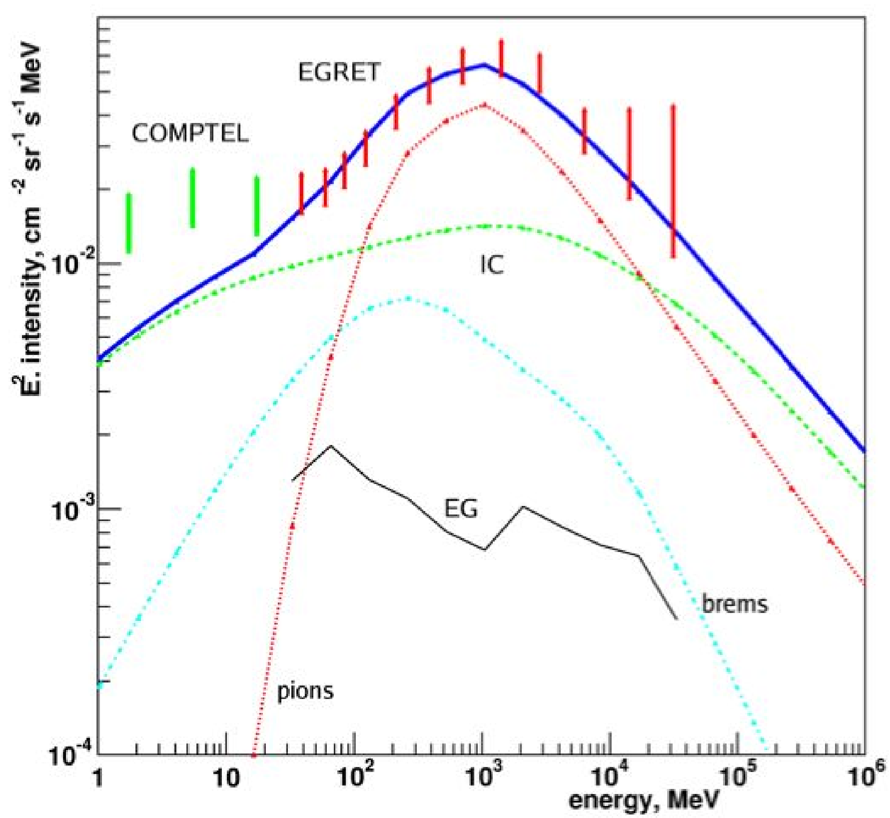
VI. Excess of the soft gamma-ray spectrum in $1-20$ MeV band. Observations.

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.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VII. Excess of the soft gamma-ray spectrum in $1-20$ MeV band. Proposal.

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.

VIII. Excess in $1-20$ MeV band. Calculation of the spectrum

1. We treat the positrons at the nugget's surface as a non-interacting Fermi gas of chemical potential μ. The density of states in the momentum range p to $p+dp$ is then given by, $dn(p)=\frac{2d^3p}{(2\pi)^3}$

2. The net production rate of photons of momentum k is then given by integrating of the corresponding cross section $\sigma(e^+e^-\rightarrow 2\gamma)$ over all allowed momentum states of the Fermi gas. For large $\mu\gg m$ the total emission (integrated over frequencies) is given by

$$\frac{dI(\mu)}{dt}=\int\frac{dI(k,\mu)}{dkdt}dk\simeq\frac{\alpha^2 m}{2\pi}\left(\frac{\mu}{m}\right)^2\ln\left(\frac{\mu}{m}\right)$$

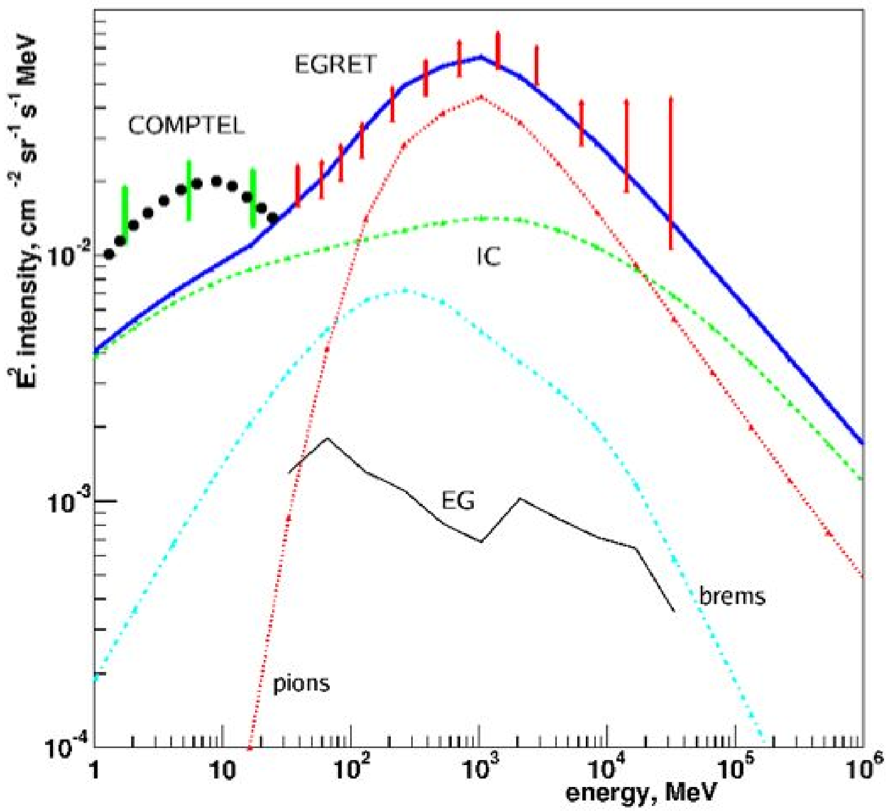
3. Mean field calculations similar to the Thomas-Fermi approximation in atomic physics leads to the following expression for the local positron chemical potential as a function distance z from the surface (Alcock et al, 1986).

$$\mu_{e^+}(z)=\sqrt{\frac{3\pi}{2\alpha}}\frac{1}{(z+z_0)},\quad z_0=\sqrt{\frac{3\pi}{2\alpha}}\frac{1}{\mu_0},\quad n_{e^+}(z)\simeq\frac{\mu^3_{e^+}(z)}{3\pi^2}$$

4. The number of incoming electrons which survive (avoid annihilation) at height z from the surface of the nugget satisfies,

$$\left(\frac{dN_{e-}(z)}{dt}\right) = N_{e-}(z)\left(\frac{dI(\mu(z))}{dt}\right), \qquad N_{e-}(z) \sim e^{-\frac{3\alpha \ln(\mu_0/m)}{4mv_e(z+z_0)}},$$

5. All the ingredients presented above lead to a very nontrivial calculation of the spectrum. The total normalization is fixed by 511 keV intensity $\sim \int dr \rho_{visible}(r) \cdot \rho_{DM}(r)$. We assume that 511 keV line is originated from the same physics. The combined result (background due to Strong et al, 2004+ our mechanism) is presented on Fig. below.
6. 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 by known QED physics.
7. We predict the spatial correlations between 511 keV line and excess of the diffuse γ -ray emission in 1-20 MeV range.
8. The observed excess in $1-20$ MeV band is extremely difficult to explain by known astrophysical mechanisms.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IX. Charge separation phenomenon at RHIC Little Bang $\Longleftrightarrow$ Big Bang

1. The crucial element for previous discussions (DM in form of dense nuggets) requires **charge separation** at $\theta \neq 0$ during the QCD phase transition when the same quarks can form visible matter as well as DM in form of dense nuggets.

2. We can mimic the effect of charge separation at RHIC. Instead of real $\theta \neq 0$ at Big Bang one can argue that the**"induced"**-θ vacuum state can be produced at Little Bang 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.

3. We demonstrate that the charge separation phenomenon takes place when "induced"-θ and angular momentum $\vec{L}$ (which place the role of the magnetic field $\vec{B}$ in early universe) are present, D. Kharzeev+AZ, NPA, 2007.

4. Preliminary STAR results support our findings for little Bang: I. V. Selyuzhenkov [STAR Collaboration, 2006] which is the subject of this section.

5. Applications to cosmology. Did charge separation effect occur during the QCD phase transition in early universe when $\theta \neq 0$? Some observations suggest that the answer might be "YES" (see previous sections on baryogenesis, $\Omega_{DM} \sim \Omega_B$, 511 keV line, 1-20 MeV excess etc when DM in form of dense nuggets resolves a number of puzzles simultaneously).

X. Charge separation phenomenon in Little Bang. Numerics.

1.The local charge density is nonzero due to the anomaly,

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

This result implies that there is a charge separation phenomenon in the presence of θ in the rotating system along the vector of the rotation $\vec{\Omega}$ on macroscopically large scales, much larger than Λ_{QCD}^{-1}.

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

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

3. Charge separation: 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,

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

4. 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.

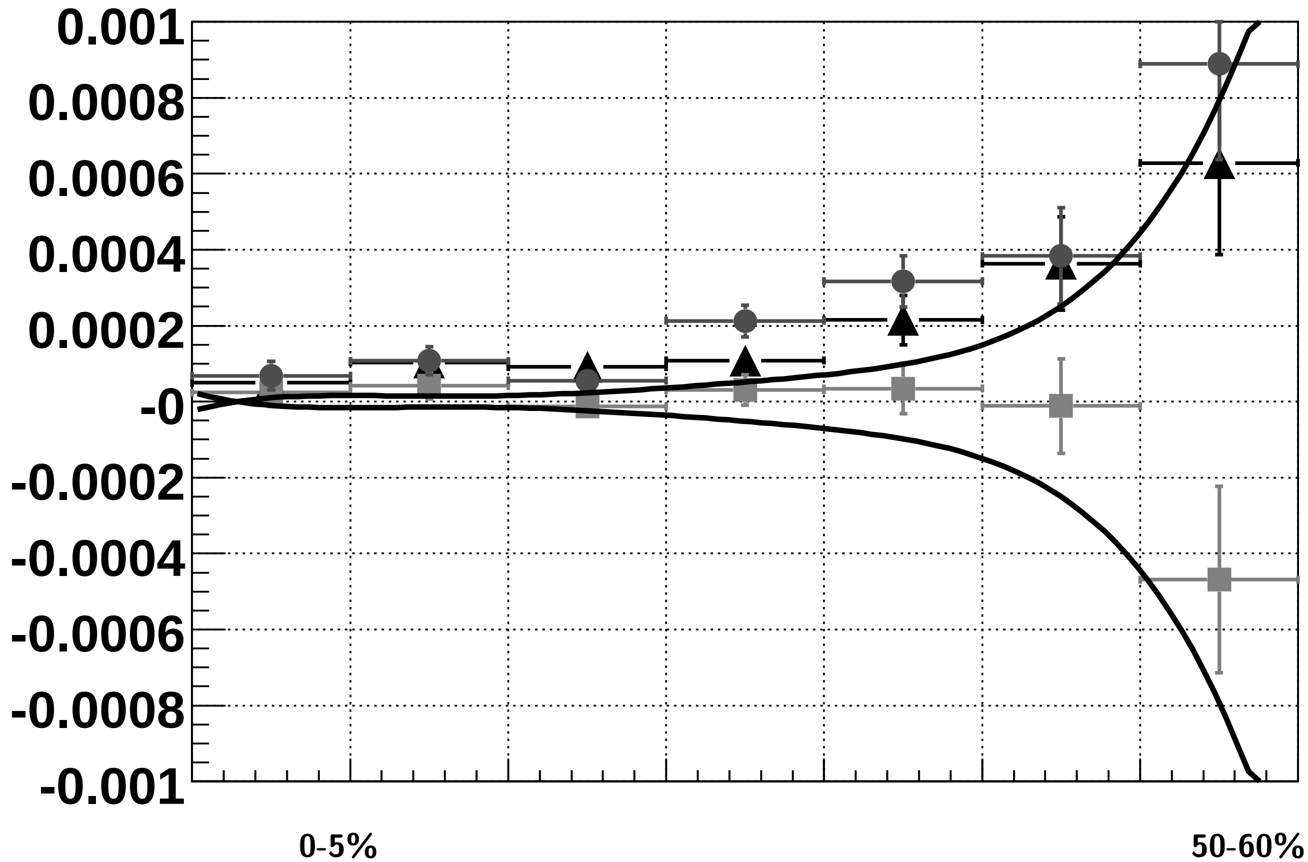

Figure 3: Preliminary data from I. V. Selyuzhenkov [STAR Collaboration], "Global polarization and parity violation study in Au + Au collisions," Rom. Rep. Phys. **58**, 049 (2006) [arXiv:nucl-ex/0510069]. Charged particle asymmetry parameters as a a function of standard STAR centrality bins. Points are 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_-.

XI. Main Results. Future Directions.

1. " Non- baryonic Dark matter" could be ordinary quarks/antiquarks which are not in the "normal hadronic phase", but rather, in the exotic color superconducting phase.
2. In this phase the baryon charge is not available for BB Nucleosynthesis.
3. A **small** geometrical factor $\epsilon \sim S/V \sim B^{-1/3} << 1$ replaces a weak coupling const.
4. Natural predictions: $\Omega_{DM}/\Omega_B \simeq 5$ and $n_B/n_\gamma \sim 6 \cdot 10^{-10}$ without fitting any parameters
5. A number of different puzzles may have the same nature: 511 KeV line and excess of the soft gamma-ray spectrum in $1-20$ MeV region may have been originated from the same source.
6. On large scales, the nuggets behave as standard **collisionless cold dark matter**. However: some **modifications are expected** in dense regions (galaxies), where **DM does interact strongly with visible matter.**
7. The idea of the **charge separation** during QCD phase transition (the key element of the proposal) **can be tested at RHIC** , Brookhaven (work done in collaboration with D. Kharzeev). Preliminary analysis of data apparently supports the idea of charge separation (experimental work/ analysis is in progress).

XII. X-rays from the Core of our Galaxy

1. A recent analysis of the CHANDRA image of the galactic center finds that the intensity of the diffuse X ray emission (after subtracting known X-ray sources) well described by a hot 8 keV plasma with surface brightness $\Phi_T = (1.8 - 3.1) \times 10^{-6}$ erg/cm^2/s/sr [Muno et al 2004].
2. The energy required to sustain such plasma corresponds to the entire kinetic energy of one supernova every 3000 yr, which is unreasonably high. Also: it would be too hot to be bound to the Galactic center.
3. Source of energy fueling this plasma is a mystery.

- Could the Missing Energy be " Dark Antimatter"?

4.Proposal: antimatter nuggets provide a single annihilation target for both electrons and protons/neutrons. As a result, both the 511 keV emission from electron annihilation and the thermal X-ray emission from proton annihilation should originate from the same regions of space with the same normalization factor $B^{-1/3} \int dr \rho_{visible}(r) \cdot \rho_{DM}(r)$ *(testable predictions)*

XIII. X-rays . Proposal. Details.

1. The nuggets provide a significant source of anti-baryonic matter such that surrounding protons and ions (from visible matter) can annihilate.
2. Proton annihilation rate is directly related to that of electrons (which, according to this scenario, explains 511 KeV line). It gives a testable prediction between 511 KeV line and diffuse hot 8 KeV X ray emission. The prediction does not depend on visible and DM distributions, nor on nugget's size B as both processes are proportional to the same factor, $\sim B^{-1/3}\int dr \rho_{visible}(r) \cdot \rho_{DM}(r)$.
3. Our proposal can easily accommodate the observed flux, $\Phi_T = (1.8 - 3.1) \times 10^{-6}$ erg/cm^2/s/sr when normalization to 511 KeV line is used.
4. Proton annihilation events $\bar{q}q \rightarrow gluons$ will release about 2 GeV of energy per event. This occurs inside the nuggets, and the energy will be quickly thermalized. This is in contrast with e^+e^- annihilation to photons which can escape the nuggets.
5. The nuggets will act as heaters for the surrounding plasma, which will subsequently radiate the energy as thermal X-rays.
6. Occasionally the proton annihilation leads to the emission of an energetic photon (α/α_s suppression). The corresponding rate is constrained by EGRET in GeV region.