Anomaly and Polarisation in Heavy-Ion Collsions

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ArXiv 1805.12029, 1807.03584 and work in progress

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Main Topics

- Anomalous mechanism: 4-velocity as gauge field+quark-hadron duality
- Pre(post)dictions:
- Chemical potential and Energy dependence – growth for low energies –now also in other approaches
- Polarization of antibaryons: same sign (and larger magnitude)
- Comparison of approaches: “hidden anomaly” for average TD (“Firenze”) polarization at m ->
- Comparison with the data
- Conclusions

Global polarization

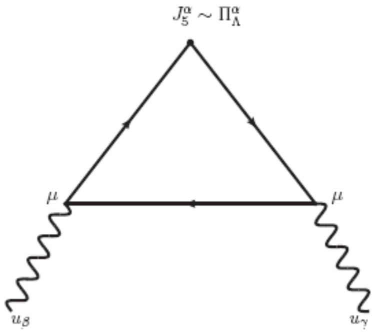
- Global polarization normal to REACTION plane
- Predictions (Z.-T.Liang et al.): large orbital angular momentum -> large polarization
- Search by STAR (Selyuzhenkov et al.'07) : polarization NOT found at % level!
- Maybe due to locality of LS coupling while large orbital angular momentum is distributed
- How to transform rotation to spin?

Anomalous mechanism – polarization –kind of anomalous transport similar to CM(V)E

- 4-Velocity is also a GAUGE FIELD (V.I. Zakharov et al)

$$e_j A_\alpha J^\alpha \Rightarrow \mu_j V_\alpha J^\alpha$$

- Triangle anomaly (Vilenkin, Son&Surowka, Landsteiner) leads to polarization of quarks and hyperons (Rogachevsky, Sorin. OT '10)
- Analogous to anomalous gluon contribution to nucleon spin (Efremov,OT'88)
- 4-velocity instead of gluon field!



O. Rogachevsky, A. Sorin, O. Teryaev
Chiral vortaic effect and neutron asymmetries in heavy-ion collisions
PHYSICAL REVIEW C 82, 054910 (2010)

One would expect that polarization is proportional to the anomalously induced axial current [7]

$$j_A^\mu \sim \mu^2 \left(1 - \frac{2\mu n}{3(\epsilon + P)}\right) \epsilon^{\mu\nu\lambda\rho} V_\nu \partial_\lambda V_\rho, \qquad (6)$$

where n and ϵ are the corresponding charge and energy densities and P is the pressure. Therefore, the μ dependence of polarization must be stronger than that of the CVE, leading to the effect's increasing rapidly with decreasing energy.

This option may be explored in the framework of the program of polarization studies at the NICA [17] performed at collision points as well as within the low-energy scan program at the RHIC.

From (chiral) quarks to hadrons: quark-hadron duality via axial charge

- Induced axial charge

$$c_V = \frac{\mu_s^2 + \mu_A^2}{2\pi^2} + \frac{T^2}{6}, \quad Q_5^s = N_c \int d^3x \, c_V \gamma^2 \epsilon^{ijk} v_i \partial_j v_k$$

- Neglect axial chemical potential
- T-dependent term (Landsteiner's gravity anomaly)
- Lattice simulations: suppressed due to collective effects

Energy dependence

- Coupling -> chemical potential

$$Q_5^s = \frac{N_c}{2\pi^2}\int d^3x\, \mu_s^2(x)\gamma^2\epsilon^{ijk}v_i\partial_j v_k$$

- Field -> velocity; (Color) magnetic field strength -> vorticity;
- Topological current -> hydrodynamical helicity
- Rapid decrease with energy
- Large chemical potential: appropriate for NICA/FAIR energies

From axial charge to polarization (and from quarks to confined hadrons) – analog of Cooper-Frye

- Analogy of matrix elements and classical averages

$$< p_n | j^0(0) | p_n >= 2p_n^0 Q_n \qquad < Q >\equiv \frac{\sum_{n=1}^N Q_n}{N} = \frac{\int d^3x\, j^0_{class}(x)}{N}$$

- Axial current: charge -> polarization vector
- Lorentz boost: requires the sign change of helicity "below" and "above" the RP

$$\Pi^{\Lambda,lab} = (\Pi_0^{\Lambda,lab}, \Pi_x^{\Lambda,lab}, \Pi_y^{\Lambda,lab}, \Pi_z^{\Lambda,lab}) = \frac{\Pi_0^{\Lambda}}{m_\Lambda}(p_y, 0, p_0, 0)$$

$$< \Pi_0^{\Lambda} >= \frac{m_\Lambda \Pi_0^{\Lambda,lab}}{p_y} = < \frac{m_\Lambda}{N_\Lambda\, p_y} > Q_5^s \equiv < \frac{m_\Lambda}{N_\Lambda\, p_y} > \frac{N_c}{2\pi^2}\int d^3x\, \mu_s^2(x)\gamma^2\epsilon^{ijk}v_i\partial_j v_k$$

Axial charge and properties of polarization

- Polarization is enhanced for particles with small transverse momenta – azimuthal dependence naturally emerges

- Antihyperons : same sign (C-even axial charge) and larger value (smaller N)

- More pronounced at lower energy. Baryon/antibaryon splitting due to magnetic field – increase (?!) with energy. Non-linear effects in H may be essential, cf vector mesons on the lattice: Luschevskaya, Solovjeva, OT: **JHEP 1709 (2017) 142**

Lambda vs Antilambda and role of vector mesons

- Difference at low energies too large – same axial charge carried by much smaller number
- Strange axial charge may be also carried by K* mesons
- Λ - accompanied by (+,anti 0) K* mesons with two sea quarks – small corrections
- Anti Λ – more numerous (-,0) K* mesons with single (sea) strange antiquark
- Dominance of one component of spin results also in tensor polarization (P-even source) –revealed in dilepton anisotropies (Bratkovskaya, Toneev,OT'95)

Chemical potential and flavour dependence

- Way via axial current/charge differs from “direct” TD
- TD-Universal, “flavor-blind” (only mass-dependent) polarization
- Axial current: polarization depends on baryon structure
- Most pronounced at low energies
- Comparison of hyperons polarization (c.f. hadronic collisions)

Other approach to baryons in confined phase: vortices in pionic superfluid (V.I. Zakharov,OT: 1705.01650;PRD96,09623)

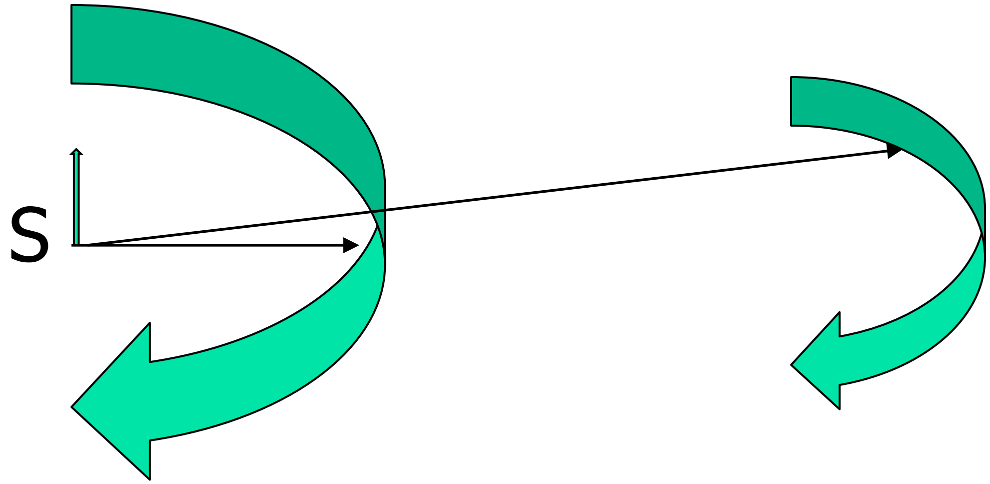
- Pions may carry the axial current due to quantized vortices in pionic superfluid (Kirilin,Sadofyev,Zakharov'12)

$$j_5^\mu = \frac{1}{4\pi^2 f_\pi^2}\epsilon^{\mu\nu\rho\sigma}(\partial_\nu \pi^0)(\partial_\rho \partial_\sigma \pi^0) \qquad \frac{\pi_0}{f_\pi} = \mu \cdot t + \varphi(x_i) \qquad \oint \partial_i \varphi dx_i = 2\pi n$$

$$\partial_i \varphi = \mu v_i$$

- Suggestion: core of the vortex- baryonic degrees of freedom- polarization

Core of quantized vortex

- Constant circulation – velocity increases when core is approached
- 

- Helium ($v < v_{sound}$) bounded by intermolecular distances
- Pions ($v<c$) –> (baryon) spin in the center

Comparison of methods

Wigner function for Dirac fields

$$W(x,k)_{AB} = -\frac{1}{(2\pi)^4}\int d^4y\, e^{-ik\cdot y}\langle : \Psi_A(x-y/2)\overline{\Psi}_B(x+y/2) : \rangle$$

$$W(x,k) = \frac{1}{2}\int \frac{d^3p}{\varepsilon}\Big(\delta^4(k-p)U(p)f(x,p)\bar{U}(p) - \delta^4(k+p)V(p)\bar{f}^T(x,p)\bar{V}(p)\Big)$$

$$\frac{1}{2m}\bar{U}(p)X(x,p)U(p) = f(x,p) \qquad X(x,p) = \Big(\exp[\beta_\mu p^\mu - \zeta]\exp\Big[-\frac{1}{2}\varpi_{\mu\nu}\Sigma^{\mu\nu}\Big] + I\Big)^{-1}$$

- Wigner function – induced axial current (triangle diagram– V.I. Zakharov)

$$\langle : j^5_\mu : \rangle = -\frac{1}{16\pi^3}\epsilon_{\mu\alpha\nu\beta}\int \frac{d^3p}{\varepsilon}p^\alpha\Big\{\mathrm{tr}\big(X\Sigma^{\nu\beta}\big) - \mathrm{tr}\big(\bar{X}\Sigma^{\nu\beta}\big)\Big\}$$

$$\alpha_\mu = \frac{1}{T}u^\nu\partial_\nu u_\mu = \frac{a_\mu}{T}, \quad w_\mu = \frac{1}{2T}\epsilon_{\mu\nu\alpha\beta}u^\nu\partial^\alpha u^\beta = \frac{\omega_\mu}{T}$$

$$\langle : j^5_\mu : \rangle = \Big(\frac{1}{6}\Big[T^2 + \frac{a^2-\omega^2}{4\pi^2}\Big] + \frac{\mu^2}{2\pi^2}\Big)\omega_\mu + \frac{1}{12\pi^2}(\omega\cdot a)\,a_\mu$$

$$\langle : j^5_\mu : \rangle = 2\pi\,\mathrm{Im}\Big[\Big(\frac{1}{6}(T^2+\varphi^2) + \frac{\mu^2}{2\pi^2}\Big)\varphi_\mu\Big] \qquad \varphi_\mu = \frac{a_\mu}{2\pi} + \frac{i\omega_\mu}{2\pi}$$

- New terms of higher order in vorticity

Complex angular velocity

$$\langle j^5_\mu \rangle = \frac{\omega_\mu + i\,\mathrm{sgn}(\omega a) a_\mu}{2(g_\omega - i g_a)} \int \frac{d^3p}{(2\pi)^3} \Big\{ n_F(E_p - \mu - g_\omega/2 + i g_a/2) - n_F(E_p - \mu + g_\omega/2 - i g_a/2) + n_F(E_p + \mu - g_\omega/2 + i g_a/2) - n_F(E_p + \mu + g_\omega/2 - i g_a/2) \Big\} + c.c.\,,$$

Fermi-Dirac distribution

$$g_\omega = \frac{1}{\sqrt{2}} \Big(\sqrt{(a^2 - \omega^2)^2 + 4(\omega a)^2} + a^2 - \omega^2 \Big)^{1/2}$$

$$g_a = \frac{1}{\sqrt{2}} \Big(\sqrt{(a^2 - \omega^2)^2 + 4(\omega a)^2} - a^2 + \omega^2 \Big)^{1/2}$$

$$\boldsymbol{\Omega} \,||\, \boldsymbol{a}$$

$$\langle \boldsymbol{j}^5 \rangle = \frac{1}{2} \int \frac{d^3p}{(2\pi)^3} \Big\{ n_F(E_p - \mu - \frac{\Omega}{2} + i\frac{|\boldsymbol{a}|}{2}) - n_F(E_p - \mu + \frac{\Omega}{2} + i\frac{|\boldsymbol{a}|}{2}) + n_F(E_p + \mu - \frac{\Omega}{2} + i\frac{|\boldsymbol{a}|}{2}) - n_F(E_p + \mu + \frac{\Omega}{2} + i\frac{|\boldsymbol{a}|}{2}) + c.c. \Big\} \boldsymbol{e}_\Omega\,,$$

Fermi-Dirac distribution

unit vector in the direction of the angular velocity

Angular velocity and acceleration appear in combination with chemical potential $\mu \pm (\Omega \pm i|\boldsymbol{a}|)/2$

- Angular velocity $\frac{\Omega}{2}$ as a real chemical potential.
- Acceleration $i\frac{|\boldsymbol{a}|}{2}$ as an **imaginary** chemical potential.

Unruh temperature in massless limit

$$\langle j^5_\mu\rangle = \left(\frac{1}{6}\left[T^2 + \frac{a^2-\omega^2}{4\pi^2}\right] + \frac{\mu^2}{2\pi^2}\right)\omega_\mu + \frac{1}{12\pi^2}(\omega a)\, a_\mu + \omega_\mu\Big[-\frac{4\pi T g_a}{g_a^2+g_\omega^2}\Big(\frac{T^2}{6} + \frac{\mu^2}{2\pi^2} - \frac{g_a^2}{8\pi^2} - \frac{g_\omega^2}{8\pi^2}\Big)\Big\lfloor\frac{g_a}{4\pi T}+\frac{1}{2}\Big\rfloor - 2T^2\Big\lfloor\frac{g_a}{4\pi T}+\frac{1}{2}\Big\rfloor^2 + \frac{8\pi T^3 g_a}{3(g_a^2+g_\omega^2)}\Big\lfloor\frac{g_a}{4\pi T}+\frac{1}{2}\Big\rfloor^3\Big] +$$
$$a_\mu \mathrm{sgn}(\omega a)\Big[-\frac{4\pi T g_\omega}{g_a^2+g_\omega^2}\Big(\frac{T^2}{6} + \frac{\mu^2}{2\pi^2} + \frac{g_a^2}{8\pi^2} + \frac{g_\omega^2}{8\pi^2}\Big)\Big\lfloor\frac{g_a}{4\pi T}+\frac{1}{2}\Big\rfloor + \frac{8\pi T^3 g_\omega}{3(g_a^2+g_\omega^2)}\Big\lfloor\frac{g_a}{4\pi T}+\frac{1}{2}\Big\rfloor^3\Big]$$

Instabilities due to the terms with integer part below $\widetilde{T}_U = \frac{g_a}{2\pi}$

$$\Big\lfloor\frac{g_a}{4\pi T}+\frac{1}{2}\Big\rfloor$$

In particular case $\boldsymbol{\Omega} = 0$ or $\boldsymbol{\Omega} \,||\, \boldsymbol{a}$

$$\widetilde{T}_U \to T_U = \frac{|\boldsymbol{a}|}{2\pi}$$

Unruh temperature

- **Instabilities below the temperature $\widetilde{T}_U$ are a manifestation of the Unruh-Hawking radiation.**
- **From this point of view, the temperature $\widetilde{T}_U(\Omega, |\boldsymbol{a}|, \theta)$ should be considered as a generalization of the Unruh-Hawking temperature to the case of systems having simultaneously non-zero acceleration and angular velocity.**

- Unruh temperature as a minimal one

Role of mass effects

- Threshold effects in chemical potential and angular velocity

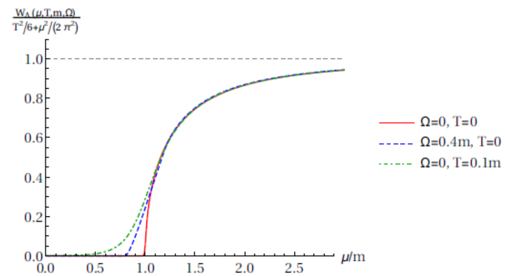


FIG. 1: Axial current coefficient $j_5 = W_A(\mu, T, m, \Omega)\Omega$ normalised to $T^2/6+\mu^2/(2\pi^2)$ as a function of chemical potential μ/m. Acceleration $a = 0$. There is a step at $\mu = m$ for $T = 0$ and $\Omega = 0$ (red solid line), which is smoothed for nonzero T (green dashed-dot line) and nonzero rotational velocity Ω (blue dashed line). For high chemical potential axial current asymptotically tends to its value $T^2/6 + \mu^2/(2\pi^2)$, corresponding to $a = \Omega = m = 0$.

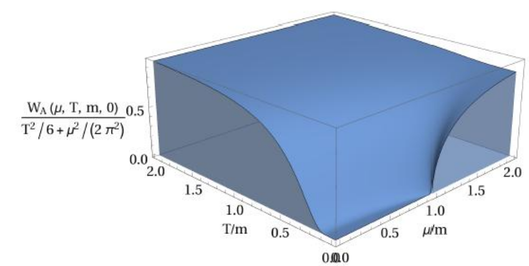


FIG. 3: Coefficient $W_A(\mu, T, m, 0)$ as a function of μ and T for zero rotational velocity $\Omega = 0$, normalised to zero mass value. For zero temperature $T = 0$ it vanishes below $\mu < m$.

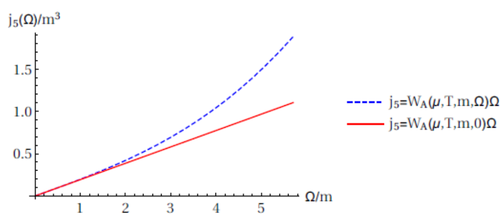


FIG. 2: Typical behaviour of axial current as a function of rotational velocity Ω (blue dashed line) in comparison with its value in linear approximation over Ω (red line). Chemical potential $\mu = m$, temperature $T = m$. One can see, that rotational velocity dependence in the coefficient W_A increases axial current value. Acceleration $a = 0$.

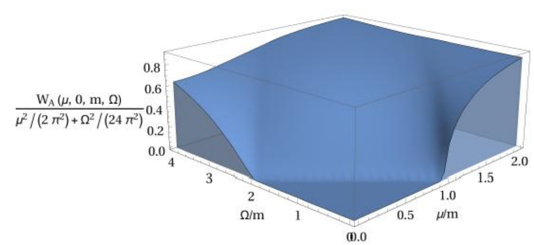


FIG. 4: Coefficient $W_A(\mu, 0, m, \Omega)$ as a function of μ and Ω for zero temperature $T = 0$, normalised to zero mass limit value. There is an area with vanishing $W_A(\mu, 0, m, \Omega) = 0$ for low μ and Ω, border is $\Omega = 2(m - \mu)$. In particular $W_A(m, 0, m, 0) = W_A(0, 0, m, 2m) = 0$. For high rotational velocity and chemical potential W_A tends to zero mass limit value.

“Hidden anomaly”

- Chemical potential (follows already from M. Buzzegoli, E. Grossi and F. Becattini, JHEP 1710 (2017) 091) and angular velocity – “phase structure”

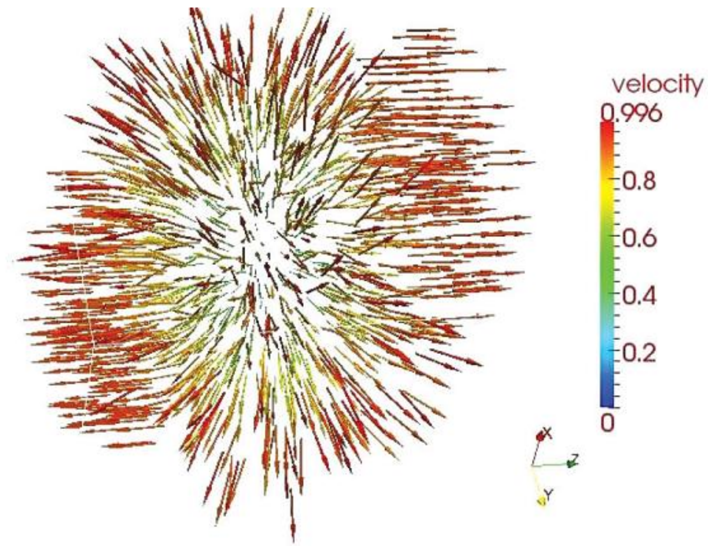
- Anomalous current recovered in chiral limit and integration over all momenta

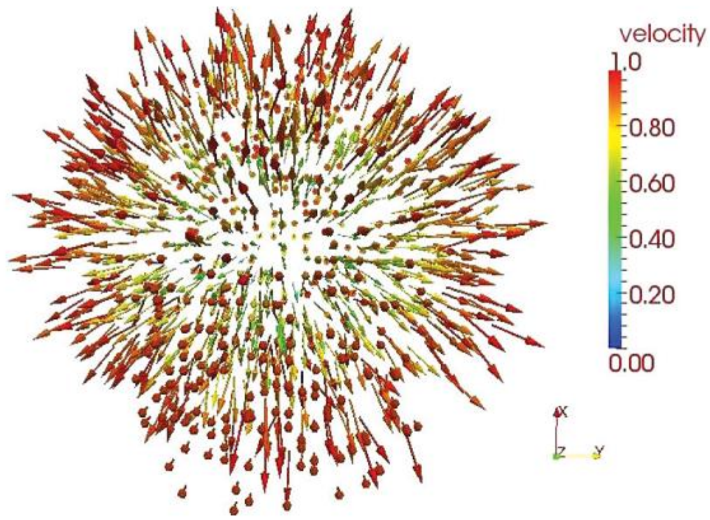
Microworld: where is the fastest possible rotation?

- Non-central heavy ion collisions (Angular velocity ~ c/Compton wavelength)
- ~25 orders of magnitude faster than Earth's rotation
- Calculation in kinetic quark - gluon string model (DCM/QGSM) – Boltzmann type eqns + phenomenological string amplitudes): Baznat, Gudima, Sorin, OT:
- PRC'13 (helicity separation+P@NICA~1%), 16 (femto-vortex sheets, NICA), 17 (antihyperons, gravitational anomaly, STAR)

Distribution of velocity ("Little Bang")

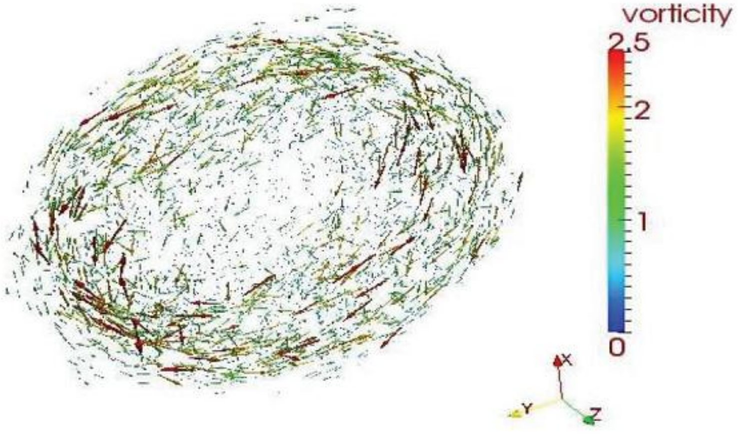
- 3D/2D projection
- z-beams direction
- x-impact paramater

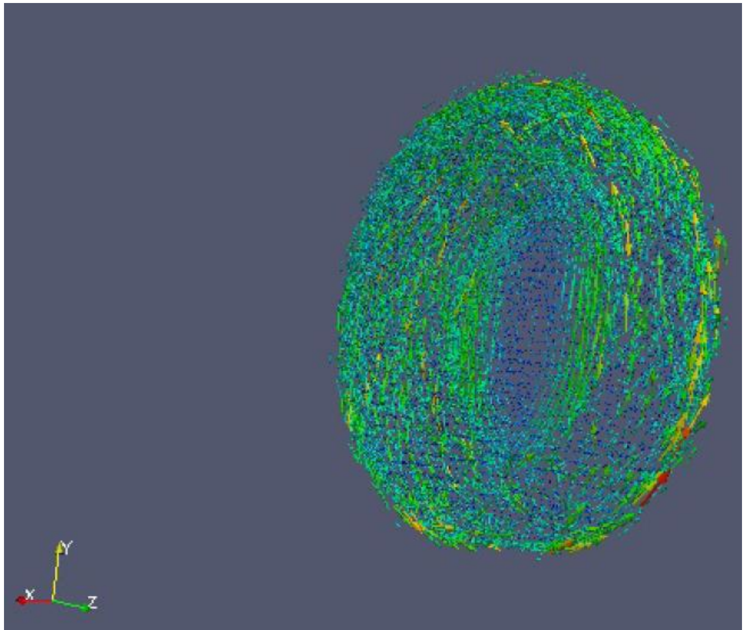


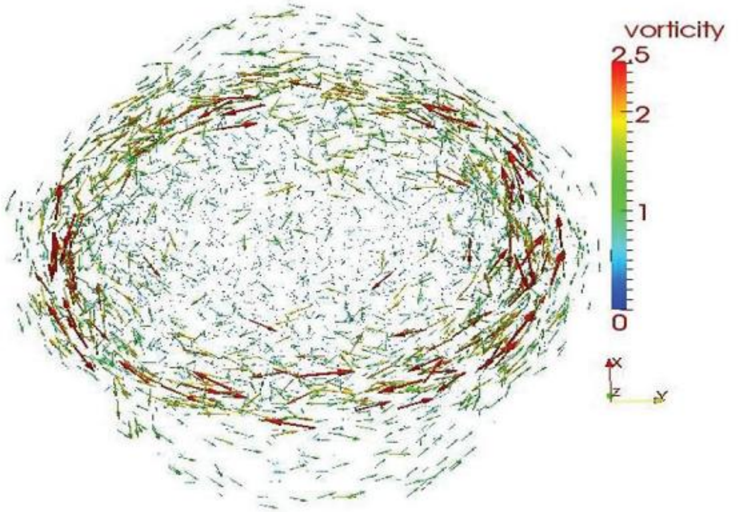


Distribution of vorticity ("Little galaxies")

- Layer (on core - corona borderline) patterns

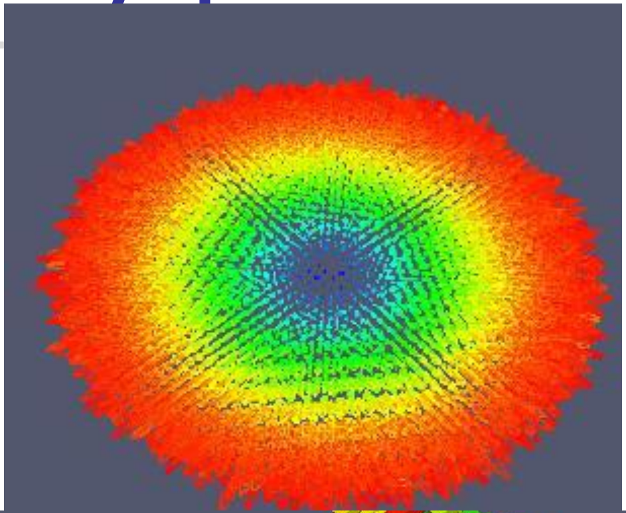




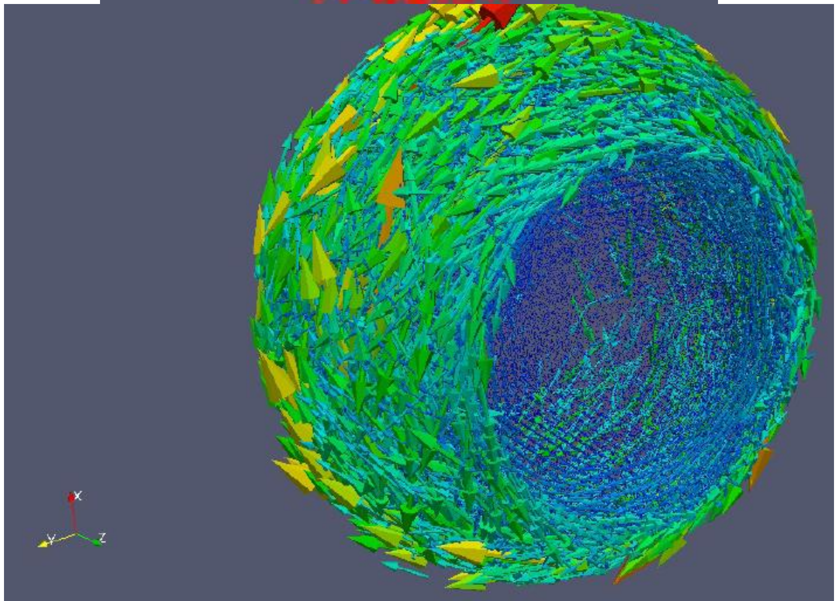


Velocity and vorticity patterns

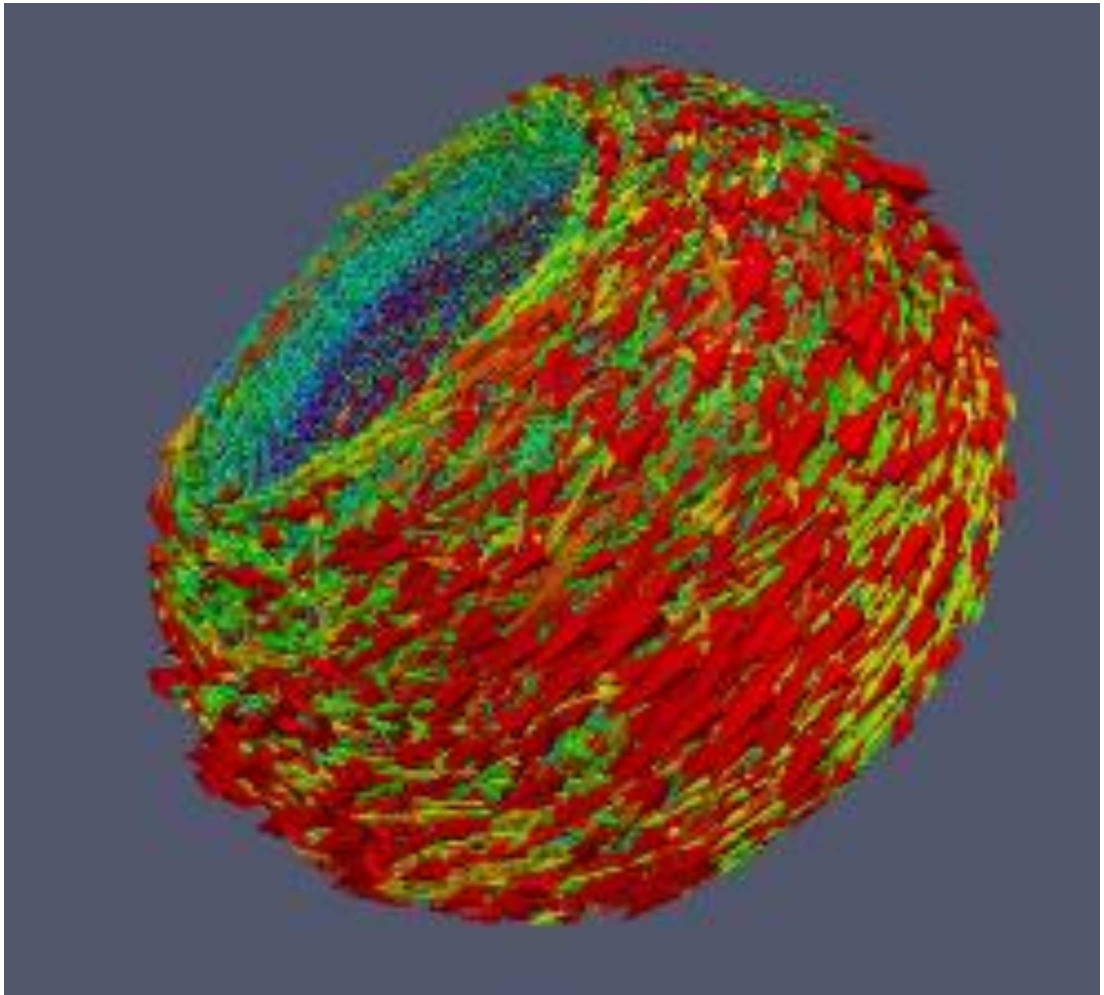
- Velocity



- Vorticity pattern – vortex sheets

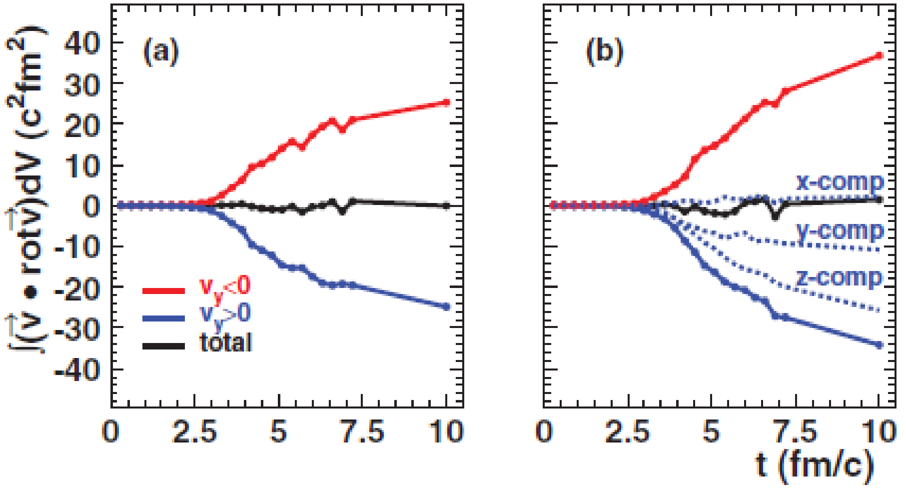


Vortex sheet



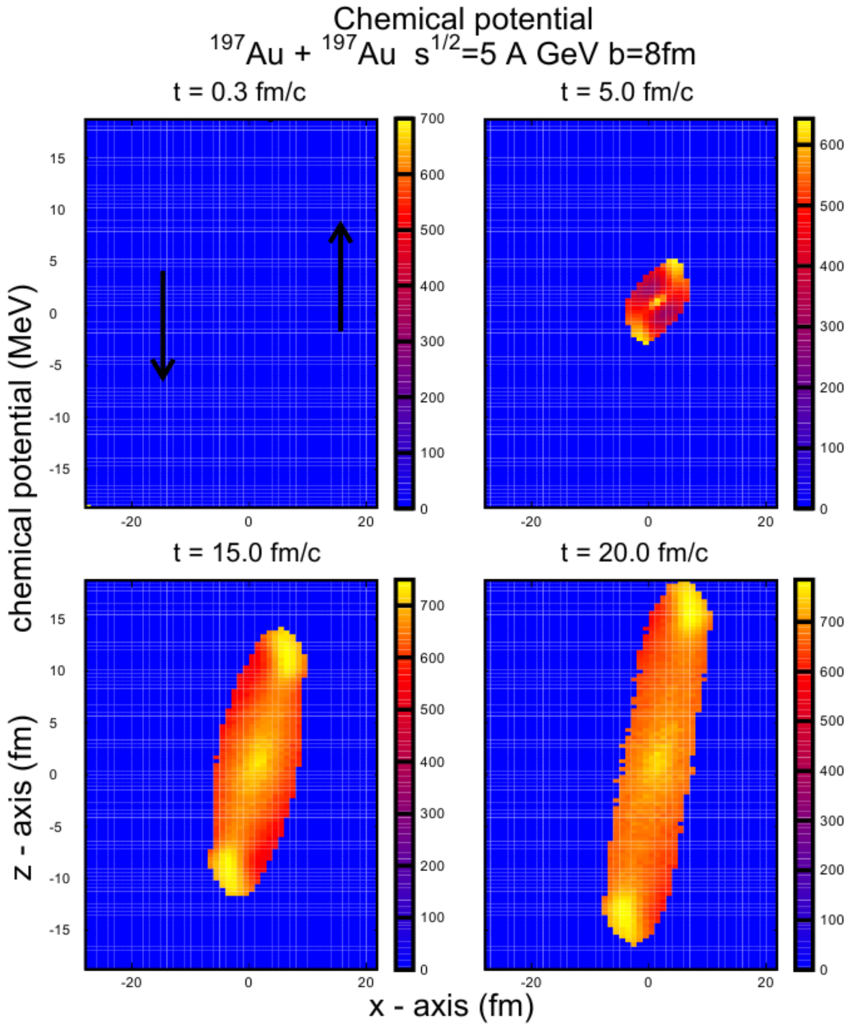
Helicity separation in QGSM **PRC88 (2013) 061901**

- Total helicity integrates to zero BUT
- Mirror helicities below and above the reaction plane – required by boost!
- Confirmed in HSD (OT, Usubov, PR**C92 (2015) 014906**
- **zz-> quadrupole structure**

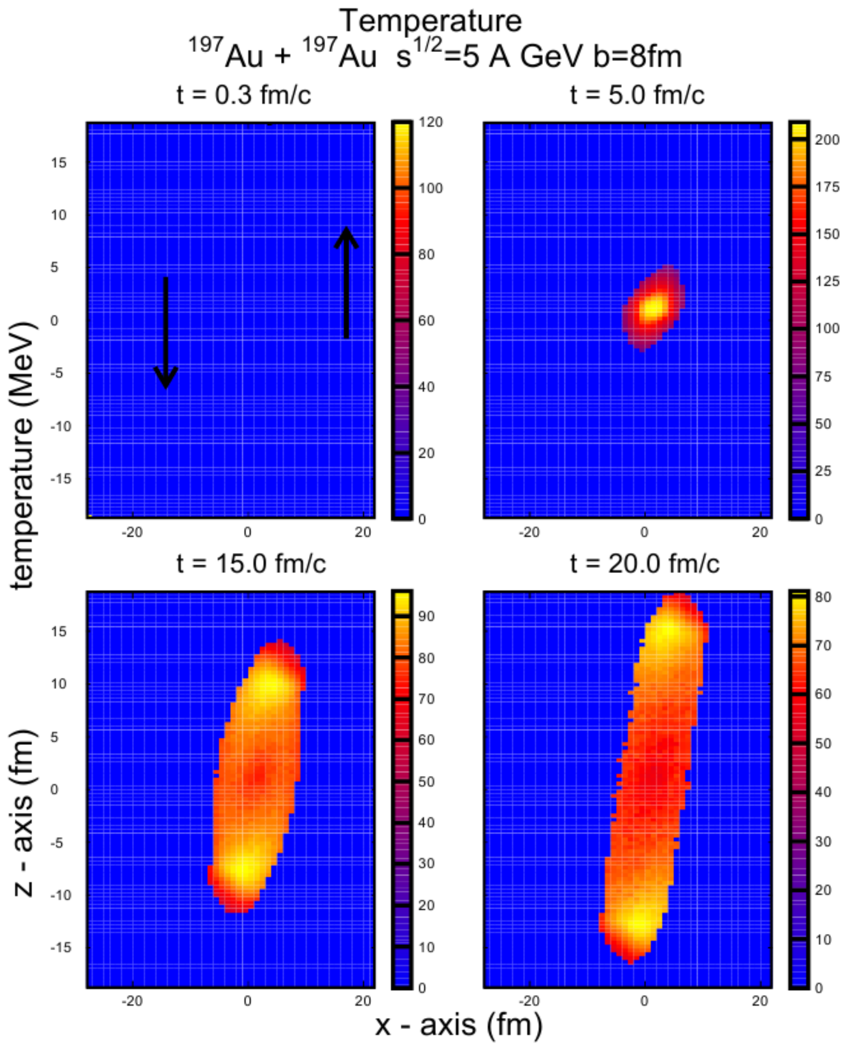


Chemical potential : Kinetics -> TD

- TD and chemical equilibrium
- Conservation laws
- Chemical potential from equilibrium distribution functions
- 2d section: y=0

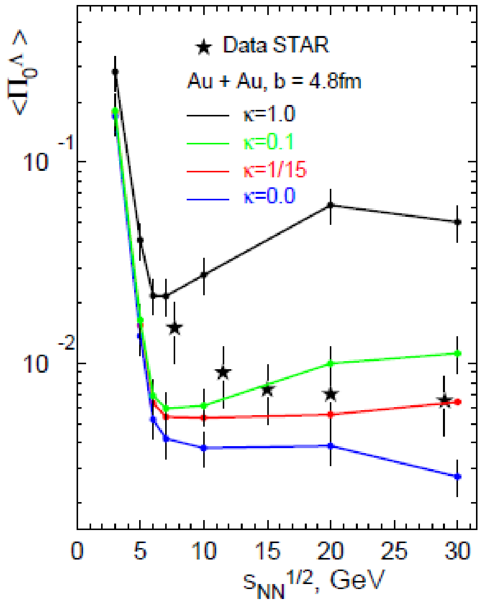


Temperature



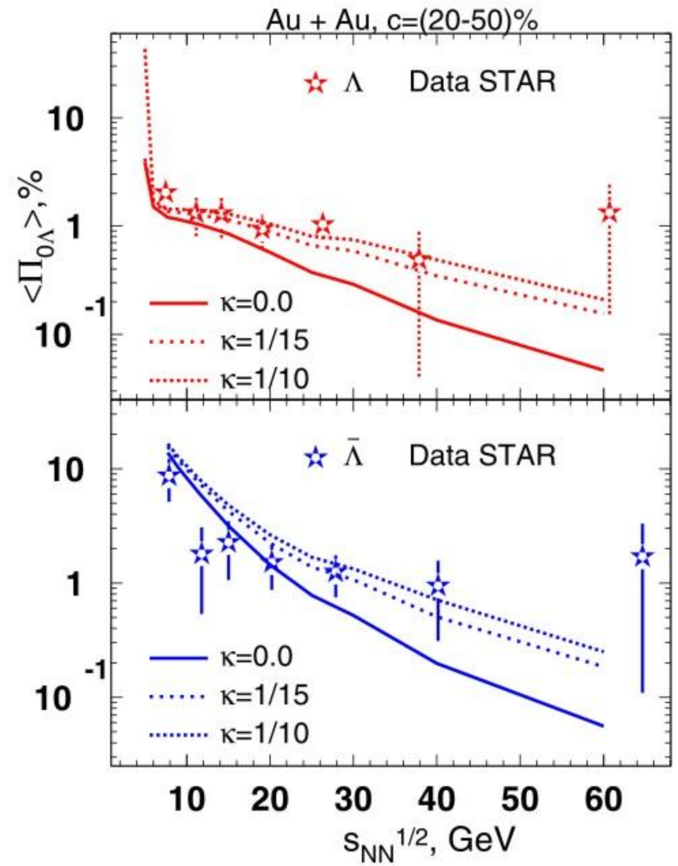
The role of (gravitational anomaly related) T^2 term

- Different values of coefficient probed



- LQCD suppression by collective effects supported

Λ vs Anti Λ



Au + Au, c=(20-50)%
Λ Data STAR
$\bar{\Lambda}$ Data STAR
κ=0.0
κ=1/15
κ=1/10
κ=0.0
κ=1/15
κ=1/10
$<\Pi_{0\Lambda}>$,%
10
1
10^{-1}
10
1
10^{-1}
10 20 30 40 50 60
$s_{NN}^{1/2}$, GeV

Conclusions/Outlook

- Polarization may provide the new probe of anomaly in quark-gluon matter (to be studied at NICA!?)
- Quark-hadron duality via axial charge/pionic superfluid

- Predictions
- Energy dependence: confirmed, reproduced
- Same sign and larger magnitude of antihyperon polarization: splitting decreases with energy
- Flavor dependence of size and sign of polarization as a probe of anomaly
- Induced extra current from Wigner functions – "hidden anomaly" in averaged TD (Firenze) polarization at m ->0

- Femto-vortex sheets

BACKUP

Properties of SSA

The same for the case of initial or final state polarization.

Various possibilities to measure the effects: change sign of $\vec{n}$ or $\vec{P}$: left-right or up-down asymmetry.

Qualitative features of the asymmetry

Transverse momentum required (to have $\vec{n}$)

Transverse polarization (to maximize $(\vec{P}\vec{n})$)

Interference of amplitudes

IMAGINARY phase between amplitudes - absent in Born approximation

Phases and T-oddness

Clearly seen in relativistic approach:

$\rho = \frac{1}{2}(\hat{p} + m)(1 + \hat{s}\gamma_5)$

Than: $d\sigma \sim Tr[\gamma_5 ....] \sim im\varepsilon_{sp_1p_2p_3}...$

Imaginary parts (loop amplitudes) are required to produce real observable.

$\varepsilon_{abcd} \equiv \varepsilon^{\alpha\beta\gamma\delta} a_\alpha b_\beta c_\gamma d_\delta$ each index appears once: $P-$ (compensate S) and $T-$ odd.

However: no real $T-$violation: interchange $|i\ > \leftrightarrow\ |f\ >$ is the nontrivial operation in the case of nonzero phases of $< f|S|i >^* = < i|S|f >$.

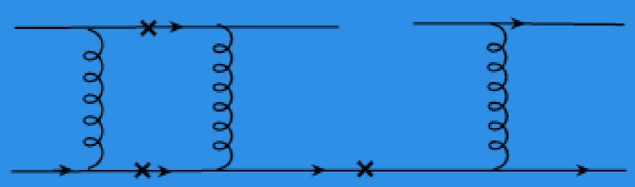
SSA - either T-violation or the phases.

DIS - no phases ($Q^2 < 0$)- real T-violation.

Perturbative PHASES IN QCD

QCD factorization: where to borrow imaginary parts?

Simplest way: from short distances - loops in partonic subprocess. Quarks elastic scattering (like $q-e$ scattering in DIS):

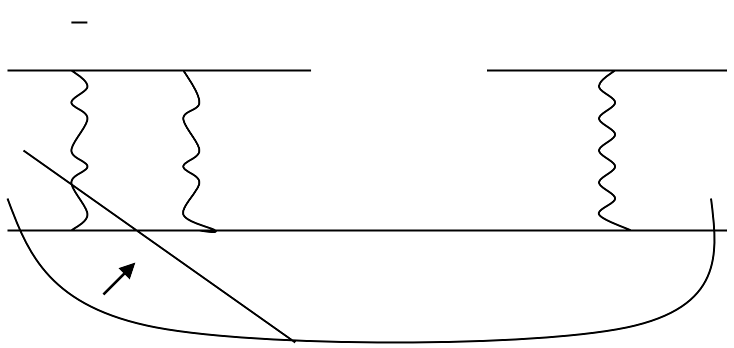


$$A \sim \frac{\alpha_S m p_T}{p_T^2 + m^2}$$

Large SSA "...contradict QCD or its applicability"

Short+ large overlap– twist 3

- Quarks – only from hadrons
- Various options for factorization – shift of SH separation



- New option for SSA: Instead of 1-loop twist 2 – Born twist 3 (quark-gluon correlator): Efremov, OT (85, Fermionic poles); Qiu, Sterman (91, GLUONIC poles)
- Further shift to large distances – T-odd fragmentation functions (Collins, dihadron, handedness)

Polarization at NICA/MPD (A. Kechechyan)

- QGSM Simulations and recovery accounting for MPD acceptance effects