Vorticity and Lambda polarization in baryon-rich matter

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Critical Point and Onset of Deconfinement

Stony Brook University, USA, 9 August 2017

Main Topics

- Λ Polarization for heavy ions
- Anomalous mechanism: 4-velocity as gauge field
- Chemical potential and Energy dependence
- Rotation in heavy-ion collisions: Vortex sheets, helicity separation and quadrupole structure
- Baryons vs antibaryons
- Conclusions

Global Λ polarization

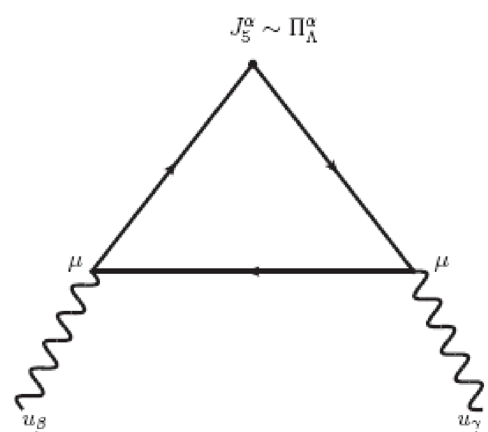
- Global polarization normal to REACTION plane
- Predictions (Z.-T.Liang et al.): large orbital angular momentum -> large polarization
- Search by STAR (Selyuzhenkov et al.'07) : polarization NOT found at % level!
- Maybe due to locality of LS coupling while large orbital angular momentum is distributed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

Anomalous mechanism – polarization similar to CM(V)E (Kharzeev, McLerran,Warringa; Fukushima; Vilenkin;…)

- 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 leads to polarization of quarks and hyperons (Rogachevsky, Sorin, Teryaev, 2010)
- Analogous to anomalous gluon contribution to nucleon spin
  (Efremov, Teryaev 88)
- 4-velocity instead of gluon field!



Anomaly for polarization

- 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 - related to gravitational anomaly
- Lattice simulation: suppressed due to collective effects

Quark mass effects

- Heavy quarks

$$\langle p|\bar{Q}\gamma_\mu\gamma_5 Q|p\rangle = i\frac{N_c\alpha_s}{2\pi}\varepsilon_{\mu\nu\lambda\rho}e^\nu e^{*\rho}p^\lambda\left\{1-\int_0^1 dx \times \frac{2m_Q^2(1-x)}{m_Q^2-p^2x(1-x)}\right\}$$

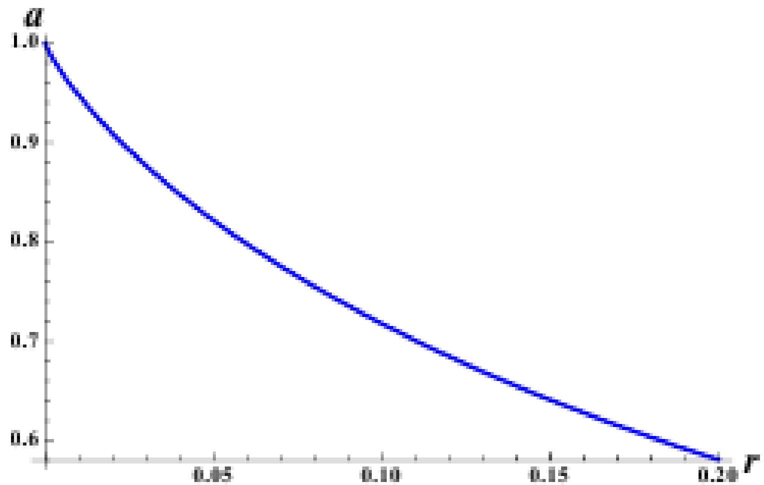


FIG. 2. Dependence of the anomaly coefficient on $r = 2m^2/k^2$

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

One might compare the prediction below with the right panel figures

M. Lisa, for the STAR collaboration , QCD Chirality Workshop, UCLA, February 2016; SQM2016, Berkeley, June 2016

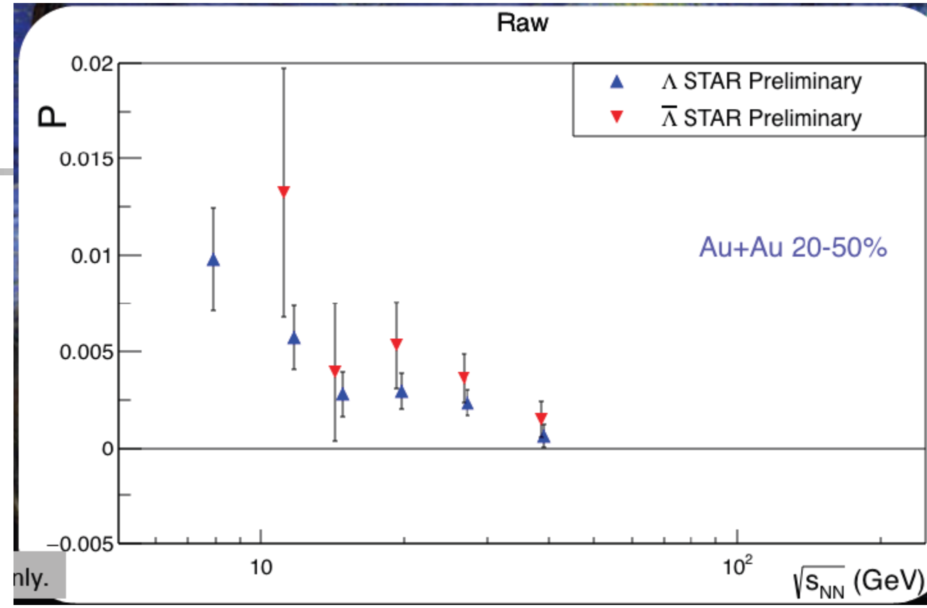
O. Rogachevsky, A. Sorin, O. Teryaev
Chiral vortaic effect and neutron asymmetries in heavy-ion collisions
PHYSICAL REVIEW C 82, 054910 (2010)

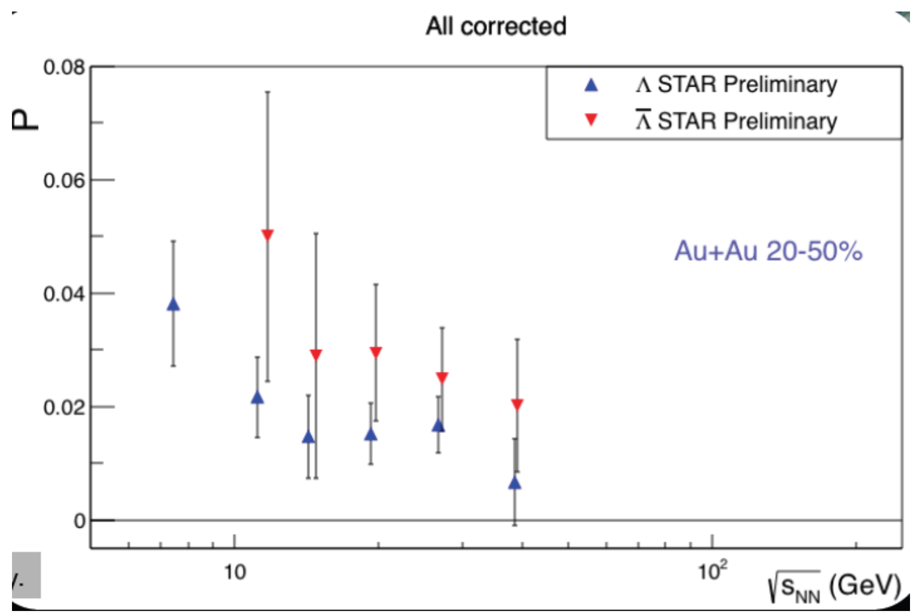
One would expect that polarization is proportional to the anomalously induced axial current [7]

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

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.





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
- Differential rotation – vorticity
- P-odd :May lead to various P-odd effects
- Calculation in kinetic quark - gluon string model (DCM/QGSM) – Boltzmann type eqns + phenomenological string amplitudes): Baznat,Gudima,Sorin,Teryaev, PRC'13,16

Rotation in HIC and related quantities

- Non-central collisions – orbital angular momentum
- $L = \Sigma\, r \times p$
- Differential pseudovector characteristics – vorticity
  $\varpi = \mathrm{curl}\, v$
- Pseudoscalar – helicity
- $H \sim \langle (v\ \mathrm{curl}\ v) \rangle$
- Maximal helicity – Beltrami chaotic flows
  $v \parallel \mathrm{curl}\, v$

Simulation in QGSM (Kinetics -> HD)

50 x 50 x 100 cells $dx = dy = 0.6\ \mathrm{fm},\ dz = 0.6/\gamma\ \mathrm{fm}$

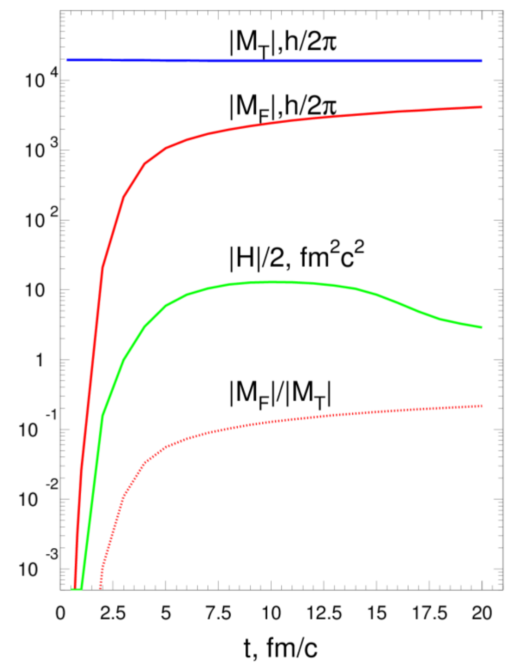
- Velocity

$$\vec{v}(x, y, z, t) = \frac{\sum_i \sum_j \vec{P}_{ij}}{\sum_i \sum_j E_{ij}}$$

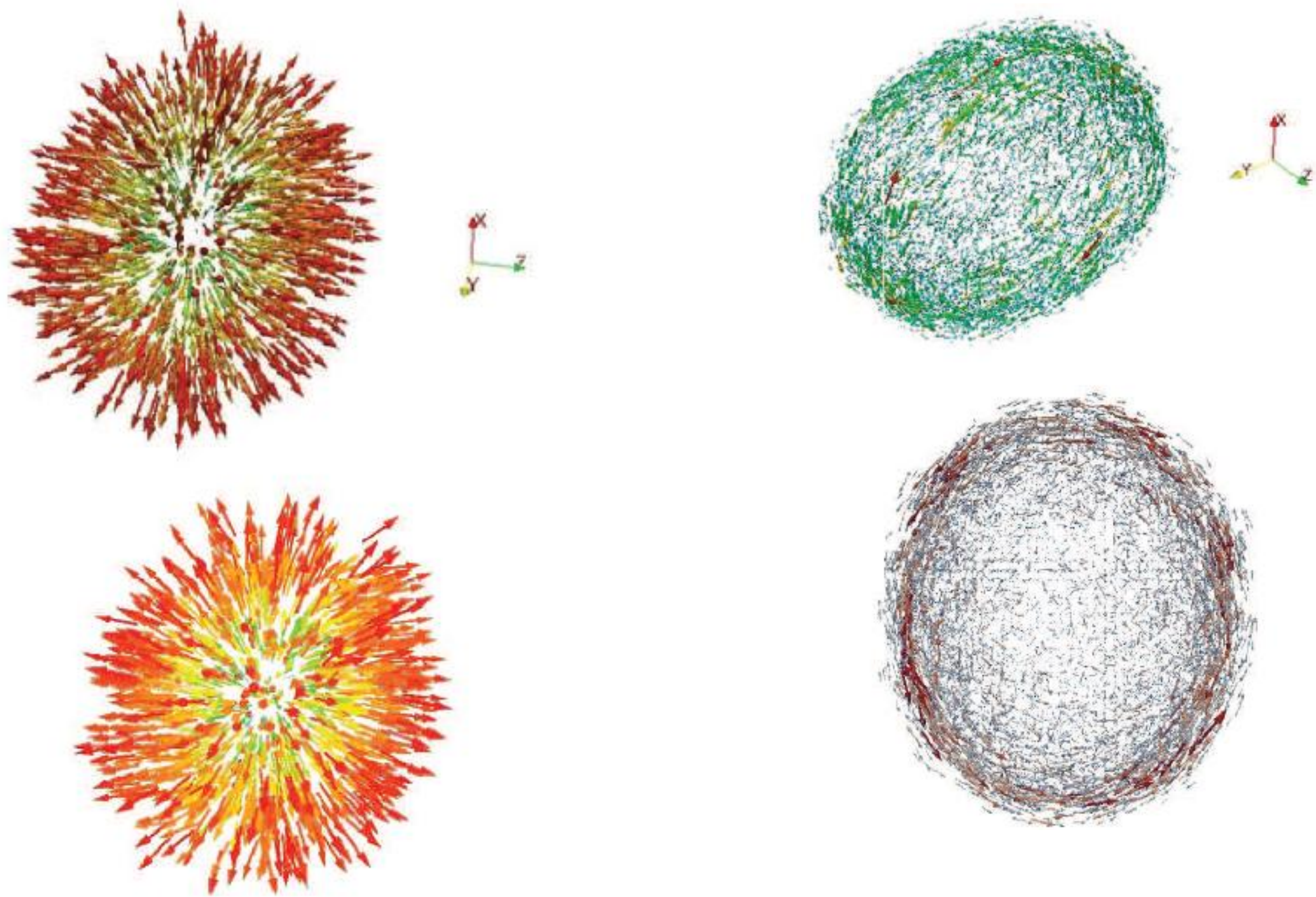
- Vorticity – from discrete partial derivatives

Angular momentum conservation and helicity

- Helicity vs orbital angular momentum (OAM) of fireball
- (~10% of total)
- Conservation of OAM with a good accuracy!

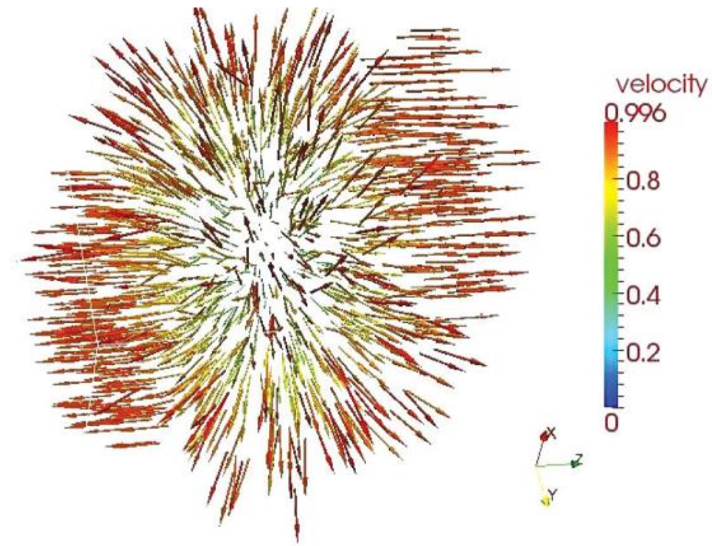


Structure of velocity and vorticity fields (NICA@JINR-5 GeV/c)



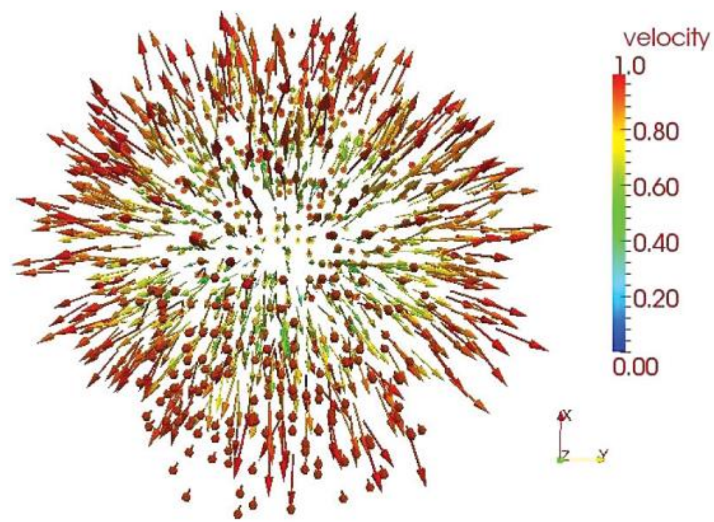
Distribution of velocity ("Little Bang")

- 3D/2D projection



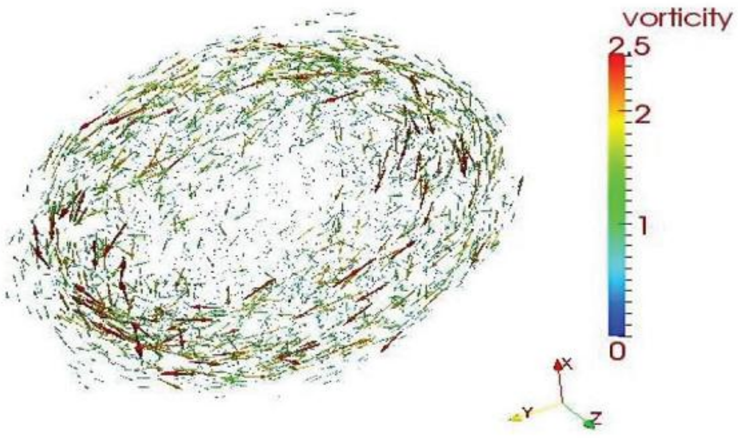
- z-beams direction
- x-impact paramater
- Little Hubble law

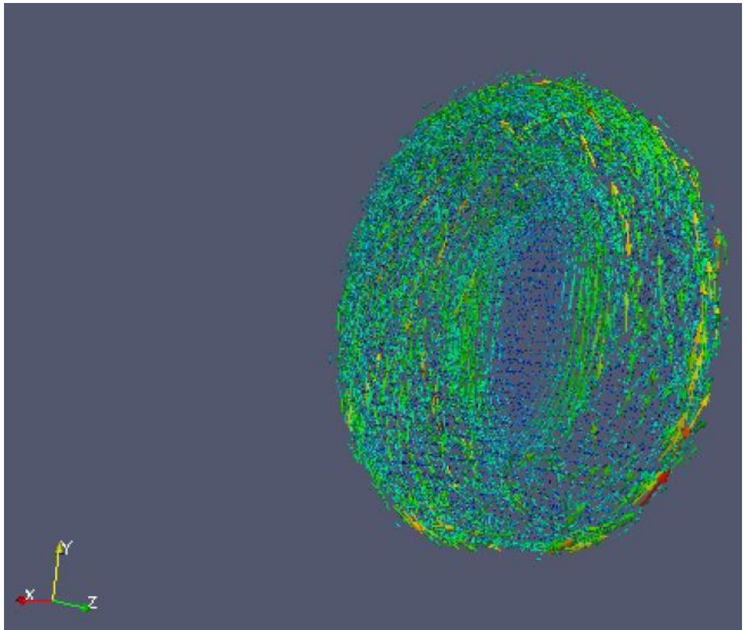
$$H = 0.024 \div 0.028\,(\mathrm{fm}/c)^{-1}$$

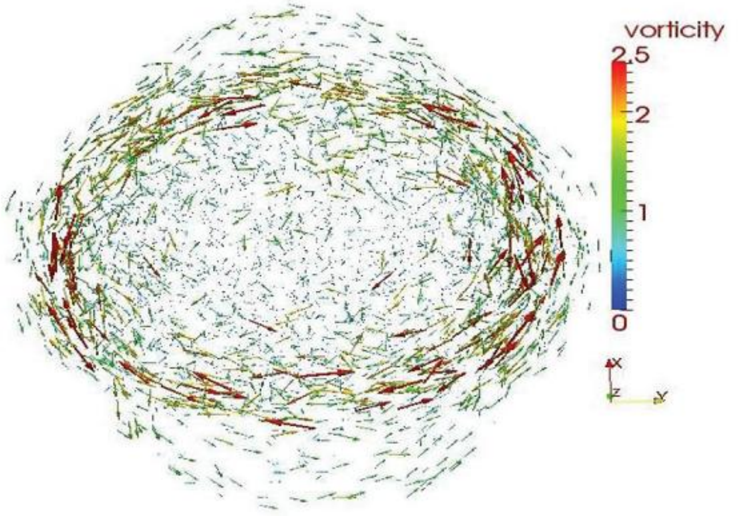


Distribution of vorticity ("Little galaxies")

- Layer (on core - corona borderline) patterns

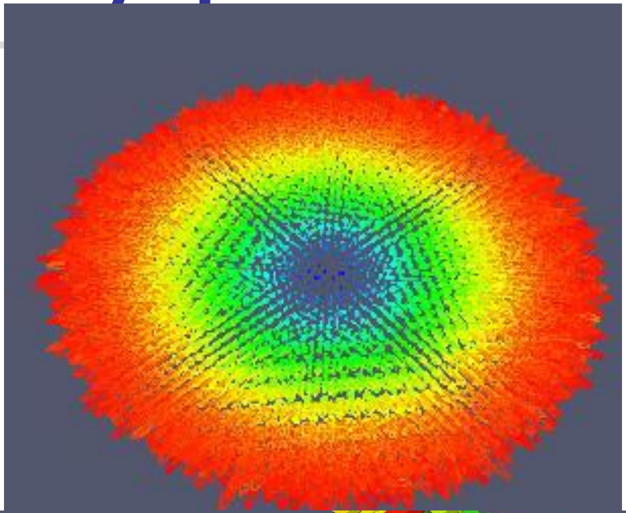




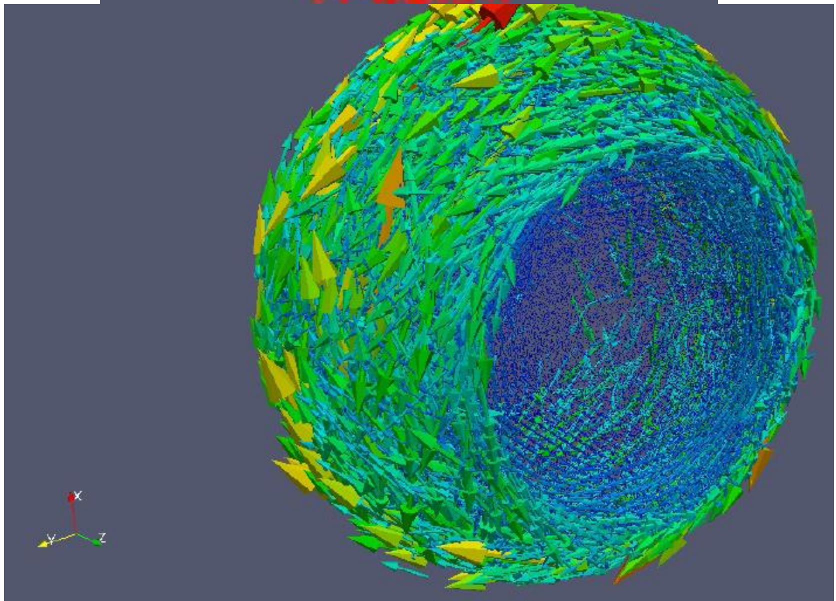


Velocity and vorticity patterns

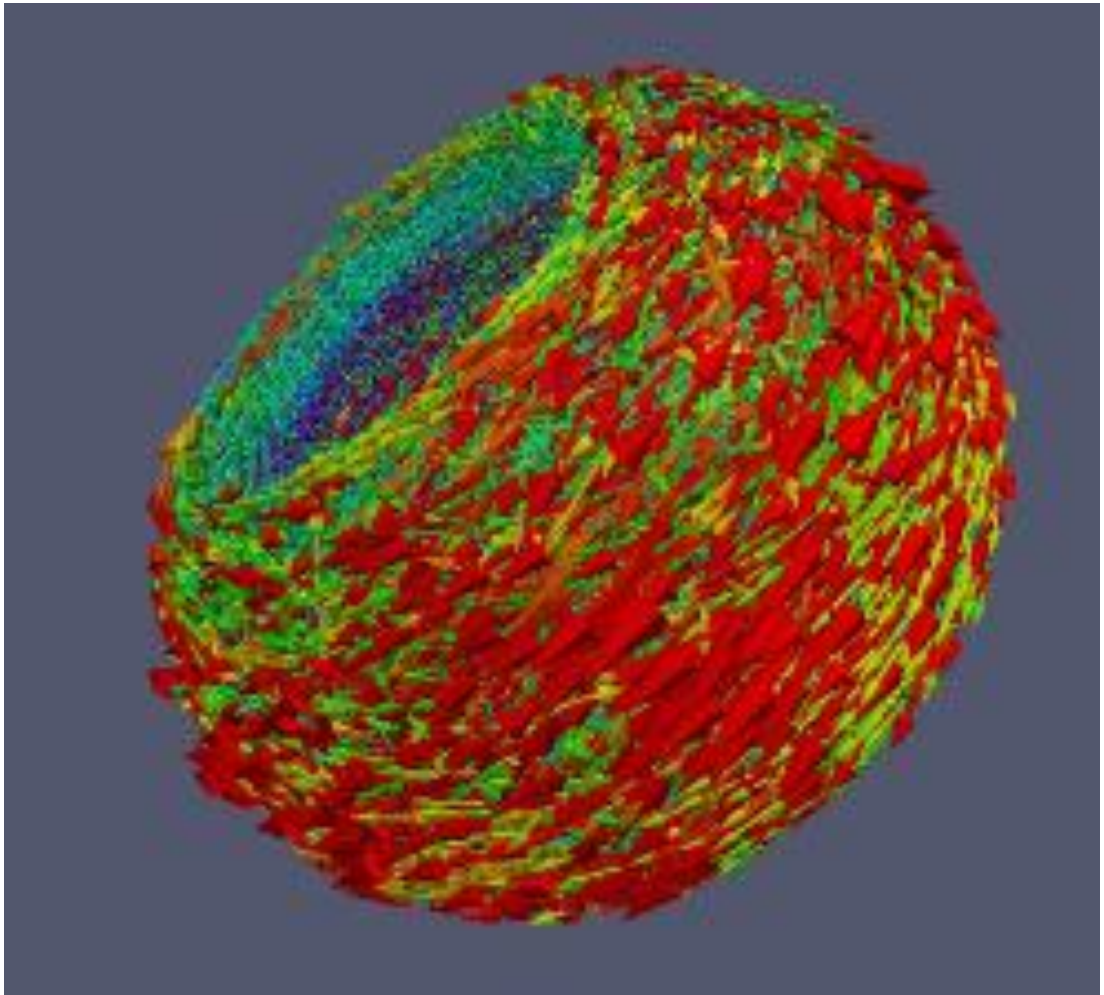
- Velocity



- Vorticity pattern – vortex sheets

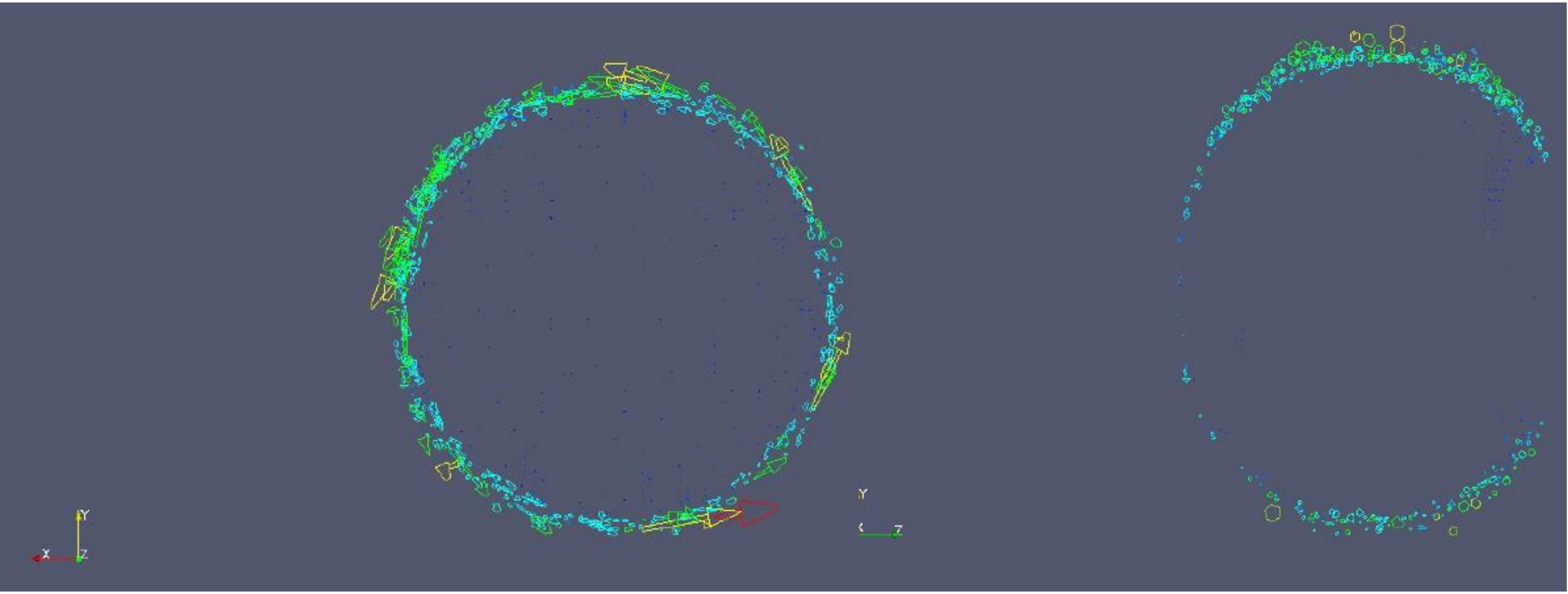


Vortex sheet



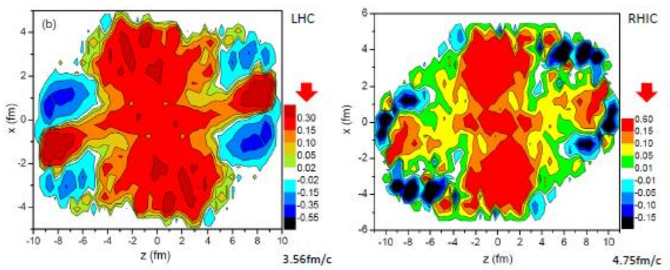
Sections of vorticity patterns

- Front and side views



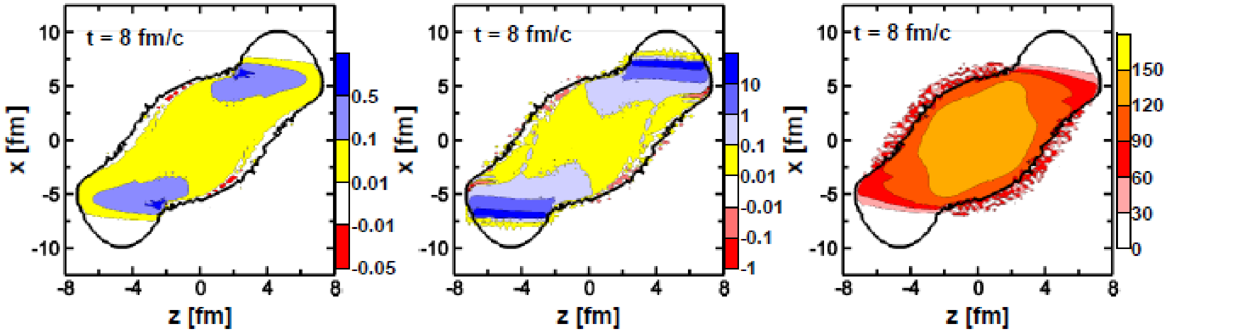
Vortex sheets

- Naturally appears in kinetic models
- Absent in viscous HD (L. Csernai et al)



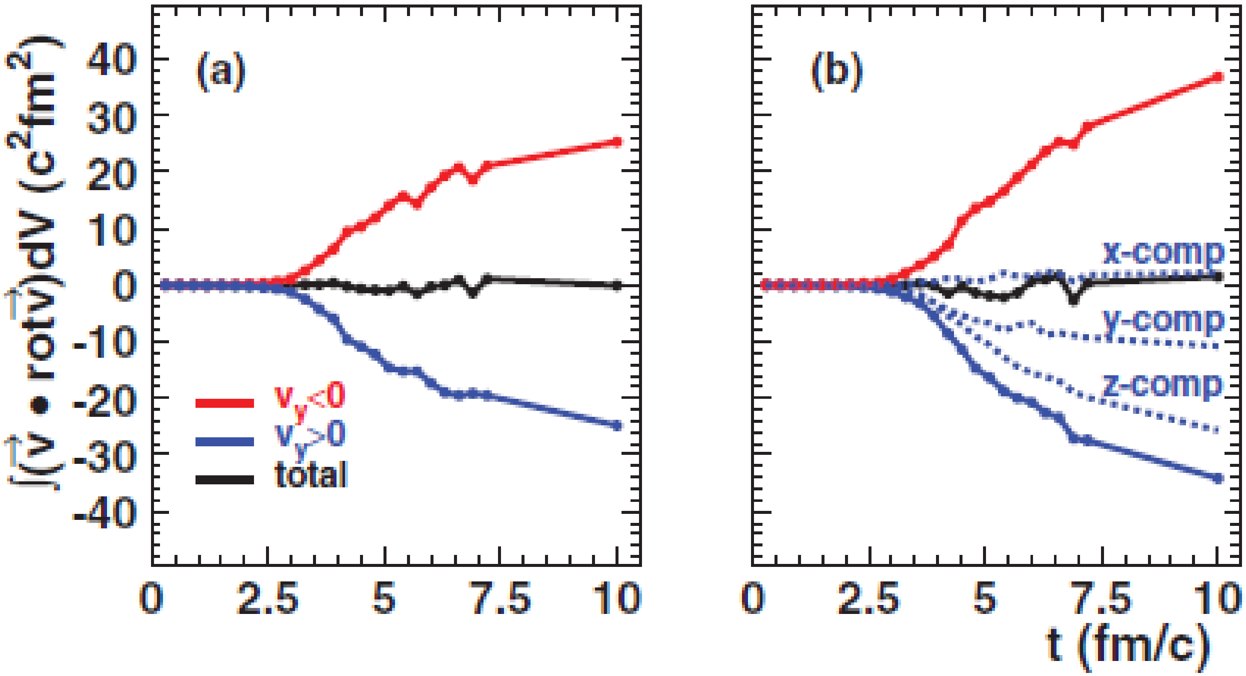
- Appears in 3 fluid dynamics model

  (Yu. Ivanov, A. Soldatov, **arXiv:1701.01319**)



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

- Total helicity integrates to zero BUT
- Mirror helicities below and above the reaction plane
- Confirmed in HSD (Teryaev, Usubov, PRC92 (2015) 014906



Transverse and longitudinal vorticity

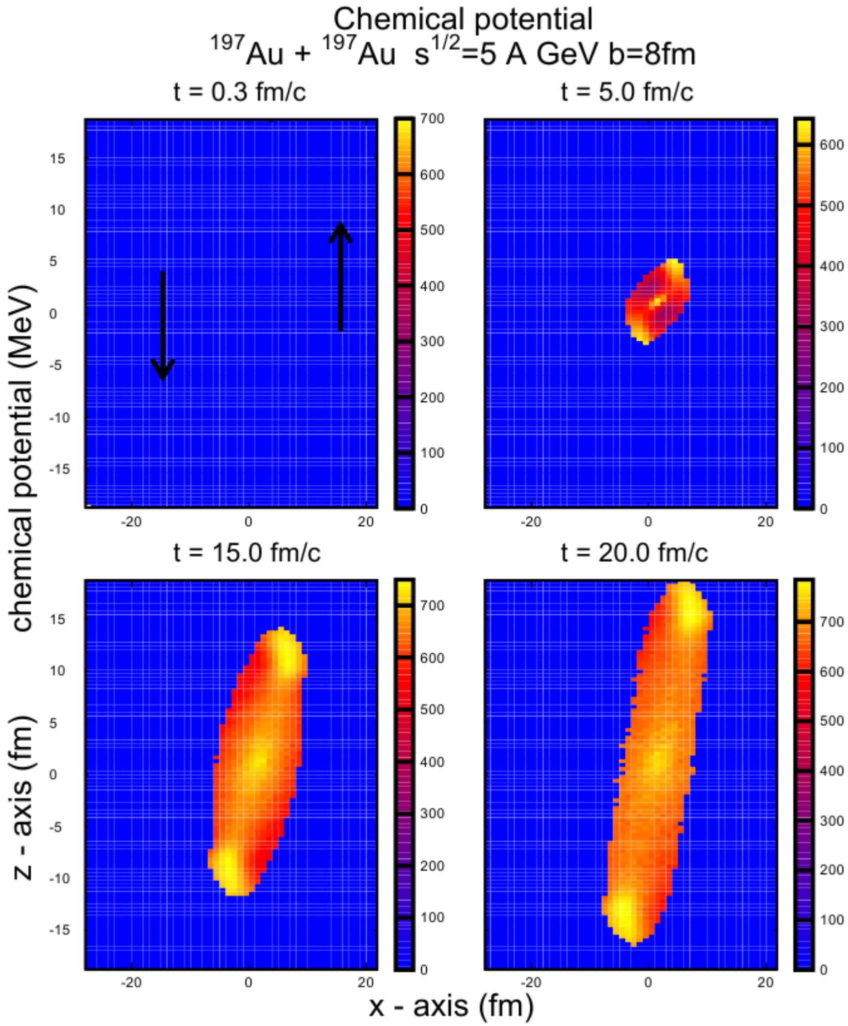
- Transverse vorticity – the same sign on the two sides of reaction plane
- Change of velocity sign   ($v_y \sim sign(y)$) leads to helicity separation $h_y \sim sign(y)$
- Longitudinal vorticity – must have quadrupole structure to provide mirror structure of helicity

$$h = h_x + h_y + h_z \sim sign(y); v_z \sim sign(x); \omega_z \sim sign(x) sign(y)$$

$$h_z = \omega_z v_z = (sign(x))^2 sign(y) = sign(y)$$

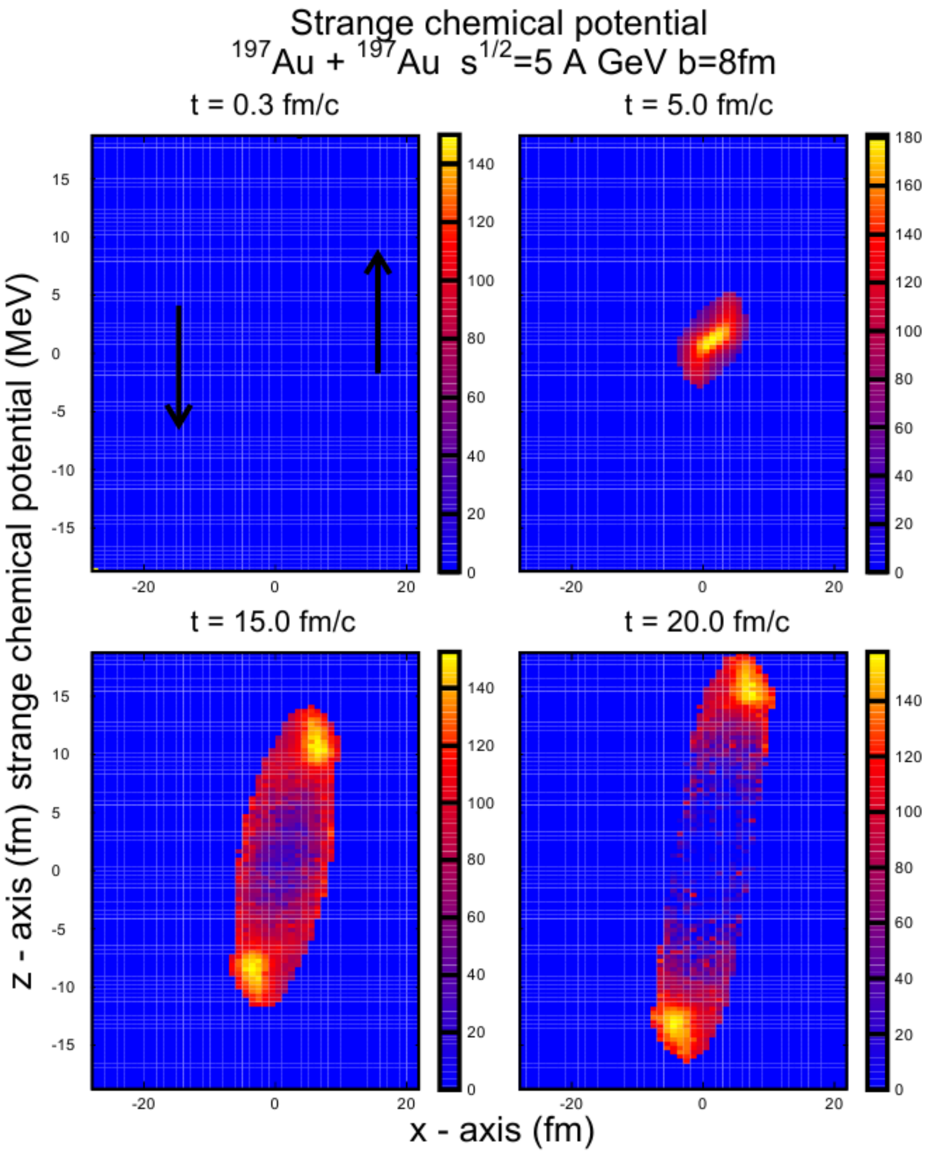
Chemical potential : Kinetics -> TD

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

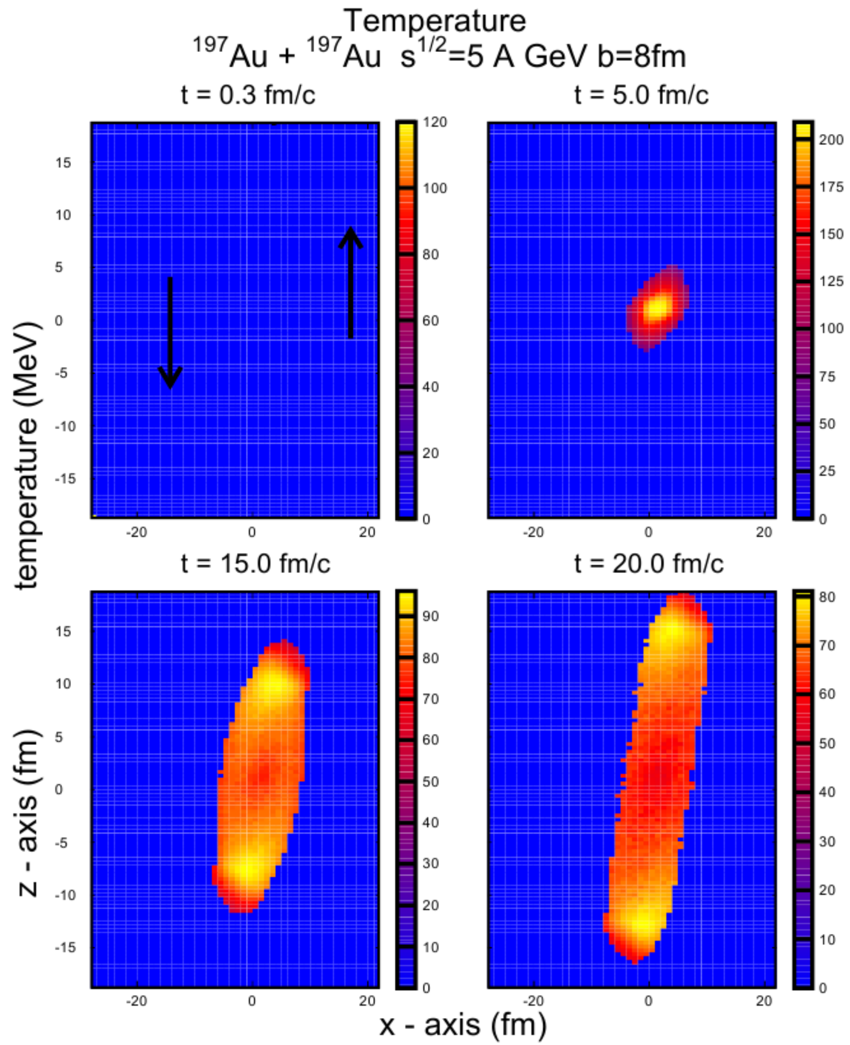


Strange chemical potential (polarization of Lambda is carried by strange quark!)

- Non-uniform in space and time



Temperature



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

- Analogy of matrix elements and classical averages (account for other charges!)

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

- Lorentz boost: compensate the sign of helicity

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

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

Axial charge and properties of polarization

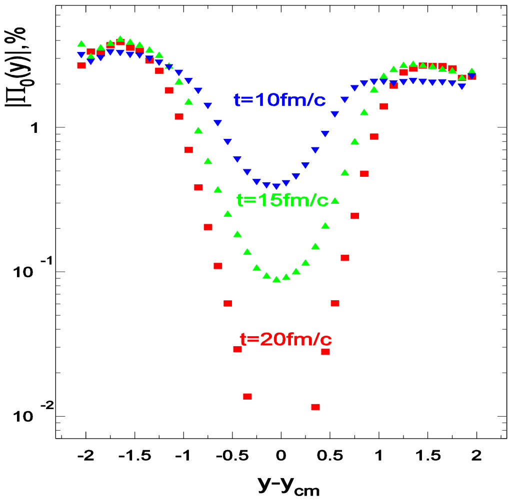
- Polarizationis enhanced for particles with small transverse momenta – azimuthal dependence naturally emerges
- Antihyperons: same sign (C-even axial charge) and larger value (smaller N)
- More pronounced at lower energy BUT
- Baryon/antibaryon splitting due to magnetic field – increase with energy
- Recent STAR data support polarization for particles with angles close to reaction plane and closeness of baryons and antibaryons polarization at 200 GeV

QGSM numerics for polarization

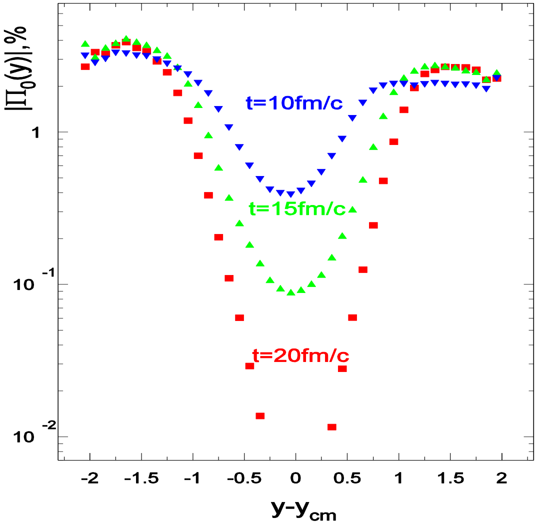
- Helicity ~ 0th component of polarization in lab. frame + effect of boost to Lambda rest frame

$$\Pi_0(y)=1/(4\pi^2)\int \gamma^2(x)\mu_s^2(x)|v\cdot rot(v)|n_\Lambda(y,x)w_1d^3x \Big/ \int n_\Lambda(y,x)w_2d^3x$$

$w_1=1$, $w2=1$

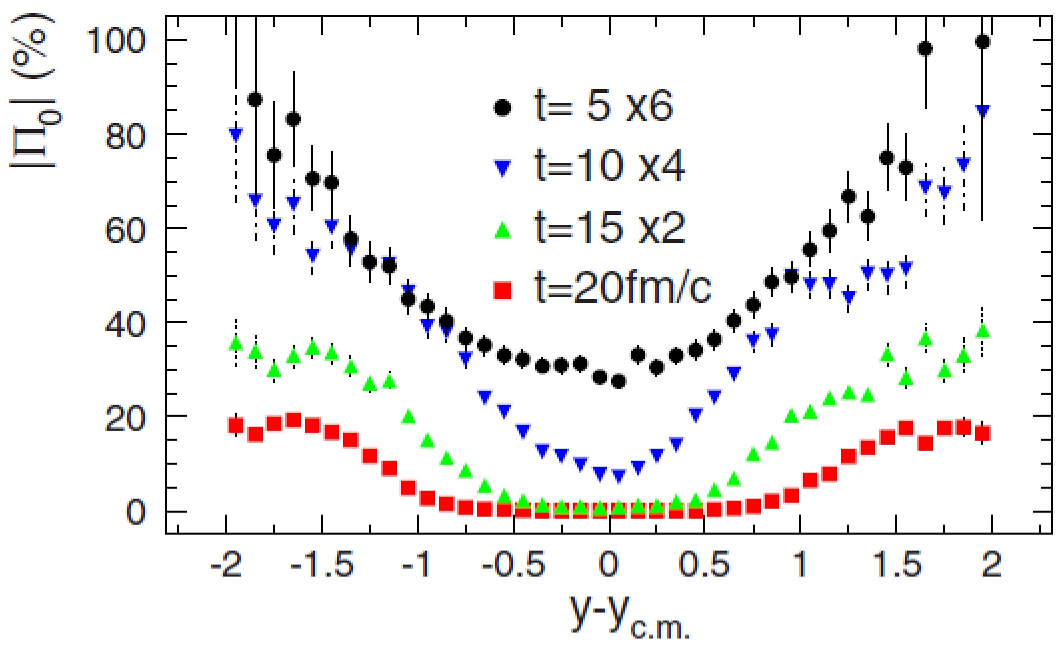


$w_1=1$, $w_2=p_y/m$



Combining QGSM (thermal)vorticity with TD mechanism

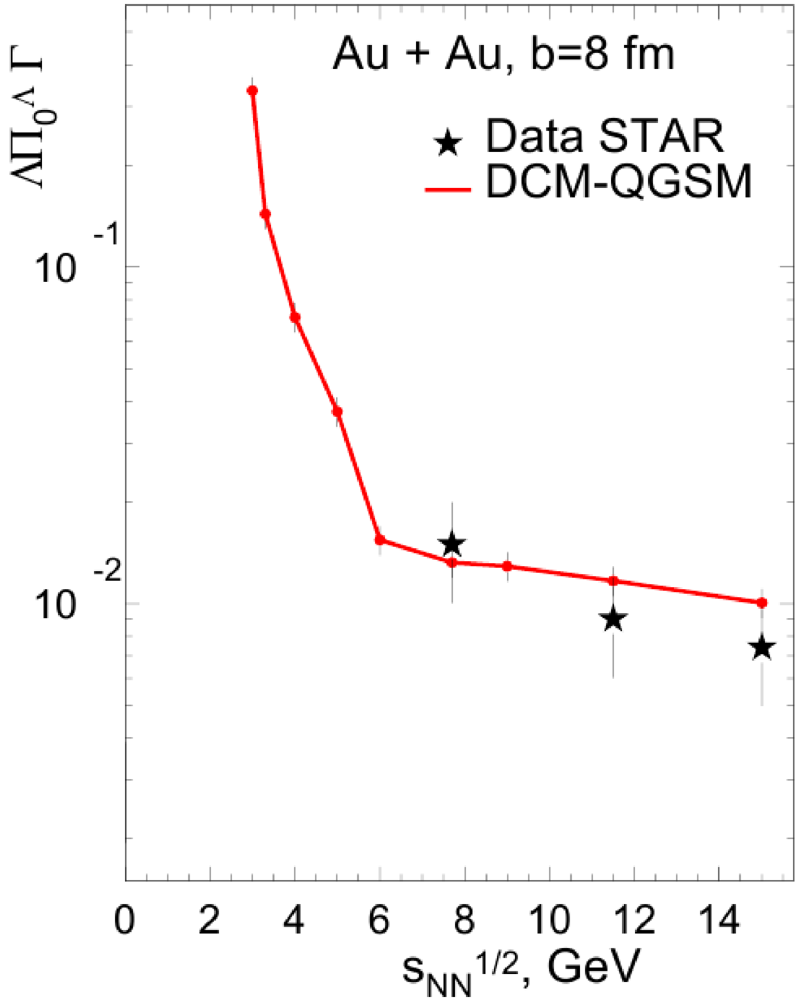
- Thermal vorticity + axial charge



- Similar polarization pattern

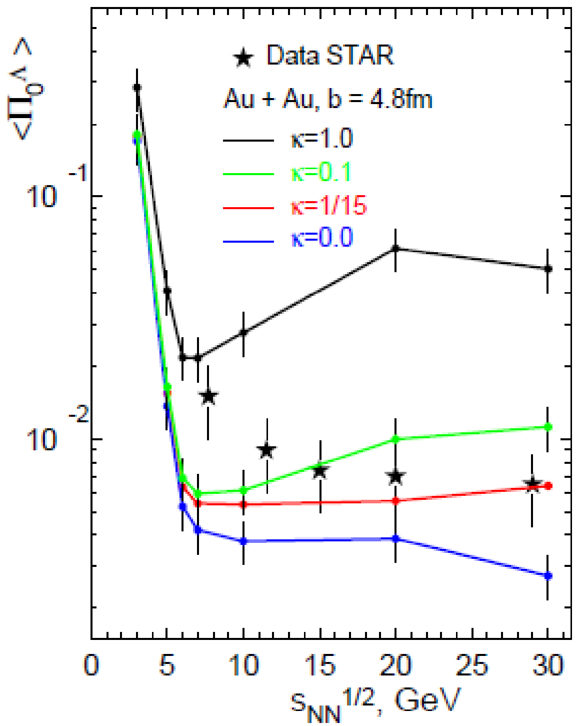
Energy dependence

- Growth at low energy
- Close to STAR data
- Structure – due to low number of Lambdas



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

- Different values of coefficient probed



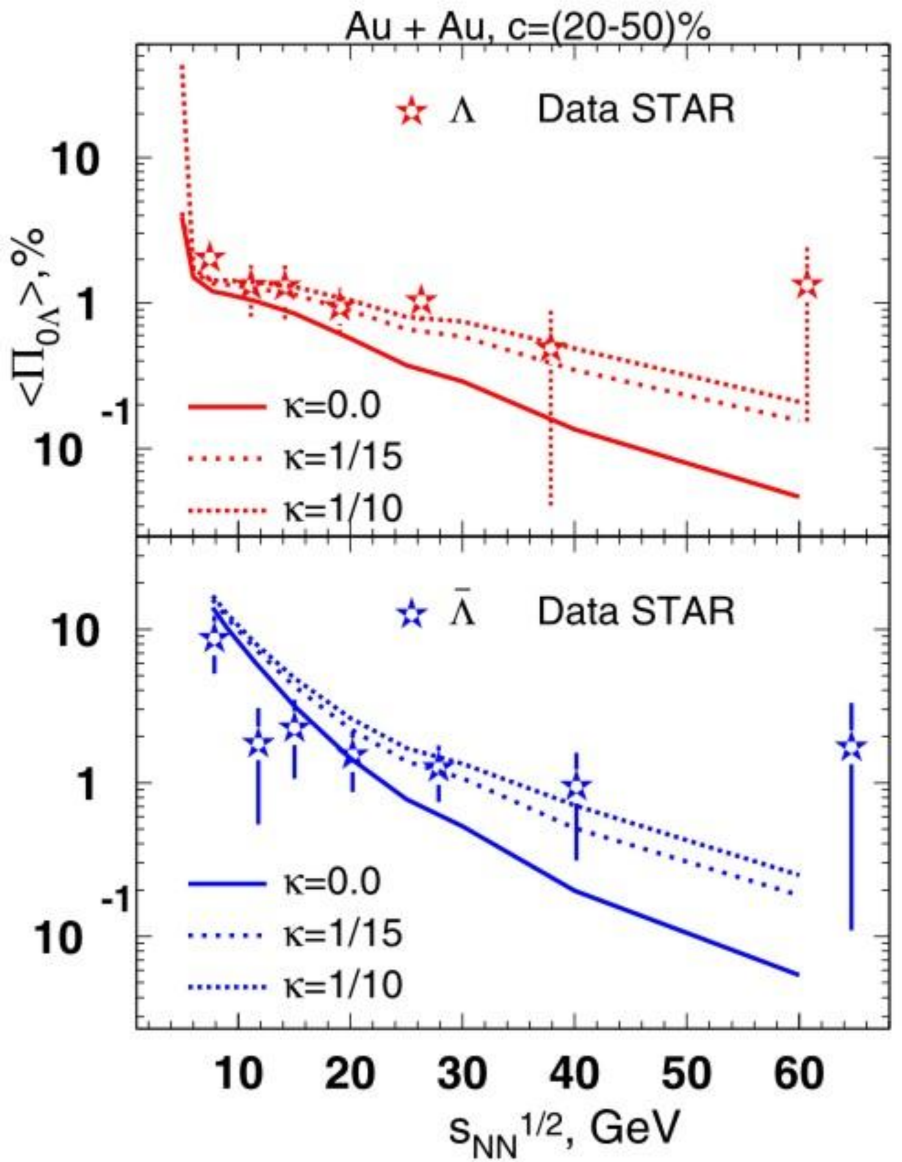
$$c_V = \frac{\mu_s^2 + \mu_A^2}{2\pi^2} + k\frac{T^2}{6}, \quad Q_5^s = N_c \int d^3x\, c_V \gamma^2 \epsilon^{ijk} v_i \partial_j v_k$$

- LQCD suppression by collective effects supported

Lambda vs Antilambda and role of vector mesons

- Difference at low energies too large – same axial charge carried by much smaller number of hadrons
- 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 – accompanied by more numerous (+,0) K* mesons with single (sea) strange antiquark

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
<Π0Λ>,%
10
1
10-1
10 20 30 40 50 60
sNN1/2, GeV

Conclusions/Outlook

- Polarization – new probe of anomaly in quark-gluon matter (to be studied at NICA
- Generated by femto-vortex sheets
- Energy dependence predicted and confirmed
- Same sign and larger magnitude of antihyperon polarization: splitting decreases with energy (contradicts to explanation due to magnetic moment/field ; supported by the data)
- T-dependent term due to gravitational anomaly may be extracted from the data
- All known tests seem to be passed – but further studies required

THANK YOU FOR ATTENTION! WELCOME TO DUBNA!

Polarization at NICA/MPD (A. Kechechyan)

- QGSM Simulations and recovery accounting for MPD acceptance effects