Axial vortical effect and hyperon polarization

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Global Λ hyperon polarization in nuclear collisions: evidence for the most vortical fluid

The extreme temperatures and energy densities generated by ultra-relativistic collisions between heavy nuclei produce a state of matter with surprising fluid properties[1]. Non-central collisions have angular momentum on the order of $1000\hbar$, and the resulting fluid may have a strong vortical structure[2–4] that must be understood to properly describe the fluid. It is also of particular interest because the restoration of fundamental symmetries of quantum chromodynamics is expected to produce novel physical effects in the presence of strong vorticity[15]. However, no experimental indications of fluid vorticity in heavy ion collisions have so far been found. Here we present the first measurement of an alignment between the angular momentum of a non-central collision and the spin of emitted particles, revealing that the fluid produced in heavy ion collisions is by far the most vortical system ever observed. We find that Λ and $\overline{\Lambda}$ hyperons show a positive polarization of the order of a few percent, consistent with some hydrodynamic predictions[5]. A previous measurement[6] that reported a null result at higher collision energies is seen to be consistent with the trend of our new observations, though with larger statistical uncertainties. These data provide the first experimental access to the vortical str hydrodynamic spin alignment to the subatomic realm. prove valuable in the development of hydrodynamic models that quantitatively connect observations to the theory of the Strong Force. Our results extend the recent discovery[8] of

Polarization data has often been the graveyard of fashionable theories.
If theorists had their way, they might just ban such measurements altogether out of self-protection.
J.D. Bjorken
St. Croix, 1987

Outline

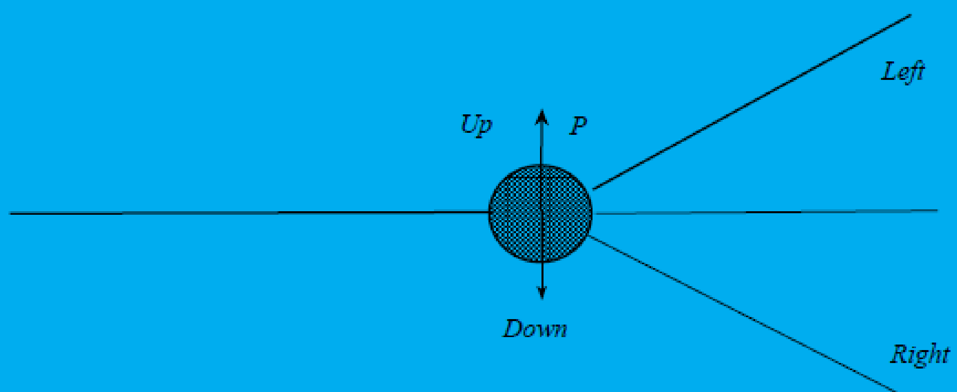
- QCD factorization and hadronic polarization (Lecture 1)
- Axial anomaly and transport in hadronic media (Lecture 2)
- Vorticity and hyperon polarization (Lecture 3)

Main Topics

- Polarization: from nucleons to ions
- Anomalous mechanism: 4-velocity as gauge field
- Chemical potential and Energy dependence
- Rotation in heavy-ion collisions: Vortical structures
- Vortices in pionic superfluid
- Conclusions

Single Spin Asymmetries (recall lecture 1)

Simplest example - (non-relativistic) elastic pion-nucleon scattering $\pi \vec{N} \to \pi N$



$M = a + ib(\vec{\sigma}\vec{n})$ $\vec{n}$ is the normal to the scattering plane.
Density matrix: $\rho = \frac{1}{2}(1 + \vec{\sigma}\vec{P})$,
Differential cross-section: $d\sigma \sim 1 + A(\vec{P}\vec{n})$, $A = \frac{2Im(ab^*)}{|a|^2+|b|^2}$

SSA (recall lecture 1)

- Parity conservation – normal to scattering plane

- Interference – LS coupling

Λ-polarisation

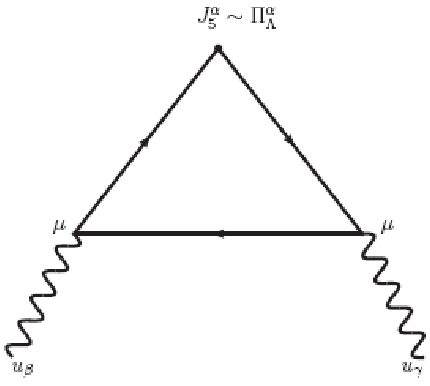
- Self-analyzing in weak decay
- Directly related to s-quarks polarization: complementary probe of strangeness
- Widely explored in hadronic processes
- Disappearance-probe of QCD matter formation (Hoyer; Jacob, Rafelsky: '87): Randomization – smearing – no direction normal to the scattering plane
- But is it complete (smoothly from hadrons to ions)? !

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 similar to CM(V)E

- 4-Velocity is also a GAUGE FIELD (V.I. Zakharov et al). Magnetic field -> VORTICITY
- $e_j A_\alpha J^\alpha \Rightarrow \mu_j V_\alpha J^\alpha$ rot A -> rot V
- Triangle anomaly (Axial Vortical Effect) 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!



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 (Braguta et al.) using similarity to Axial Magnetic Effect: suppressed due to collective effects

Energy dependence

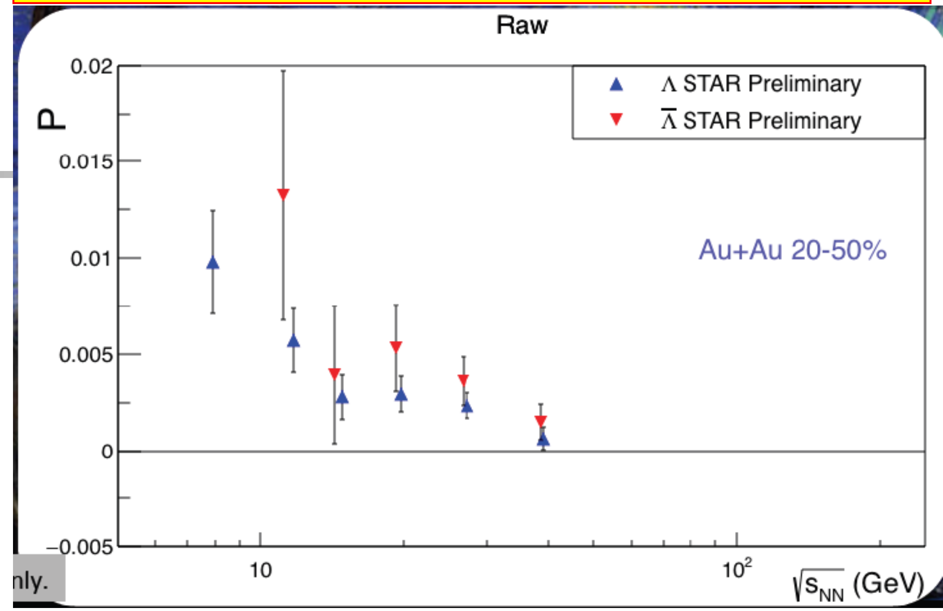
- Coupling -> chemical potential

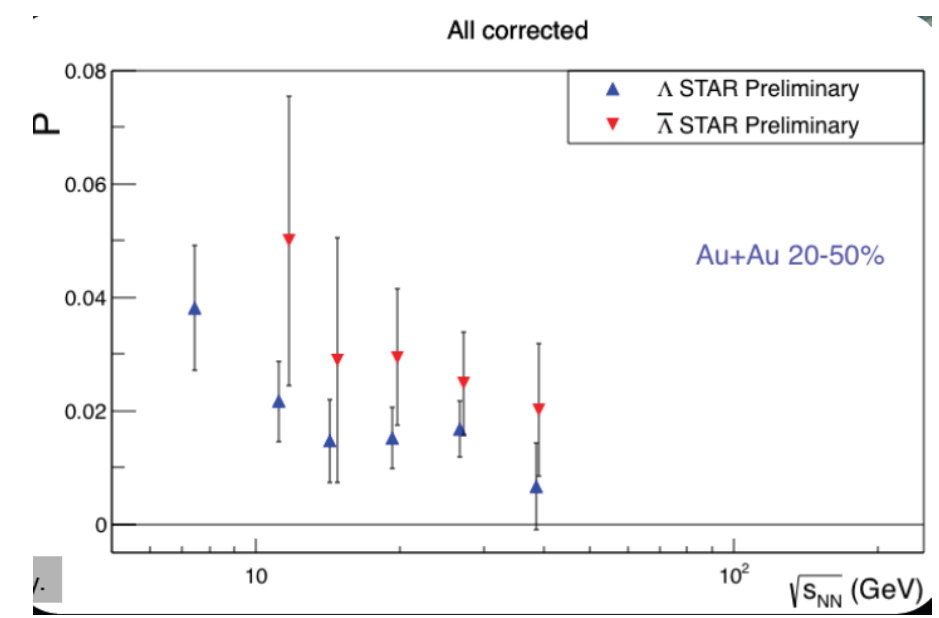
$$Q_5^s = \frac{N_c}{2\pi^2}\int d^3x\, \mu_s^2(x)\gamma^2\epsilon^{ijk}v_i\partial_j v_k$$

- Field -> velocity; (Color) magnetic field strength -> vorticity;
- Topological current -> hydrodynamical helicity
- 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,OT, PRC’13,16

Rotation in HIC and related quantities

- Non-central collisions – orbital angular momentum
- $L = \Sigma\ r \times p$
- Differential pseudovector characteristics – vorticity
- $\omega = \mathrm{curl}\ v$
- 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)

$50 \times 50 \times 100$ cells $\quad dx = dy = 0.6$ fm, $dz = 0.6/\gamma$ fm

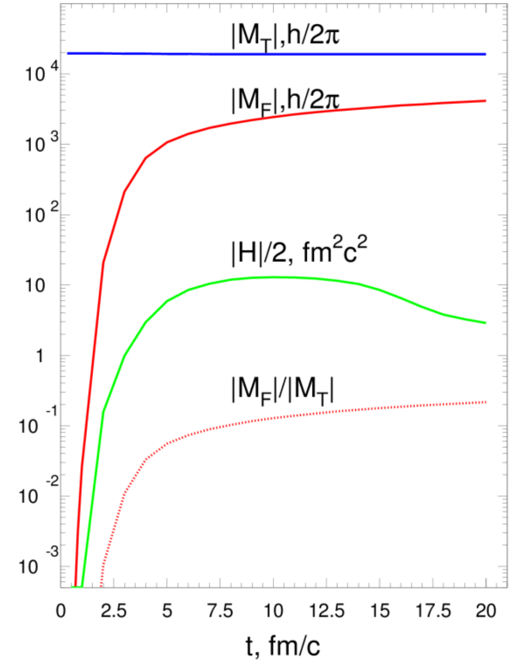
- Velocity

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

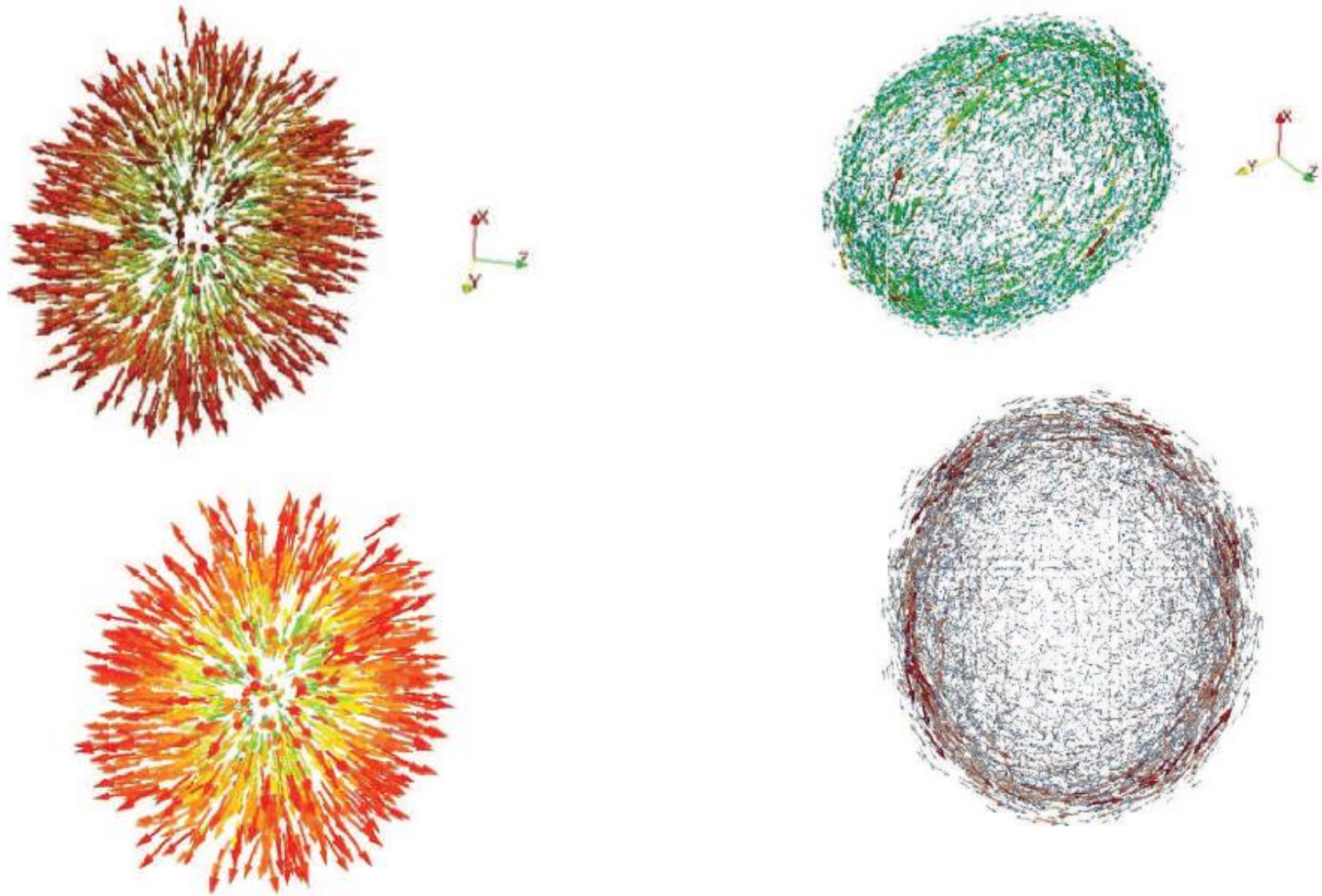
- Vorticity – from discrete partial derivatives

Angular momentum conservation and helicity

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

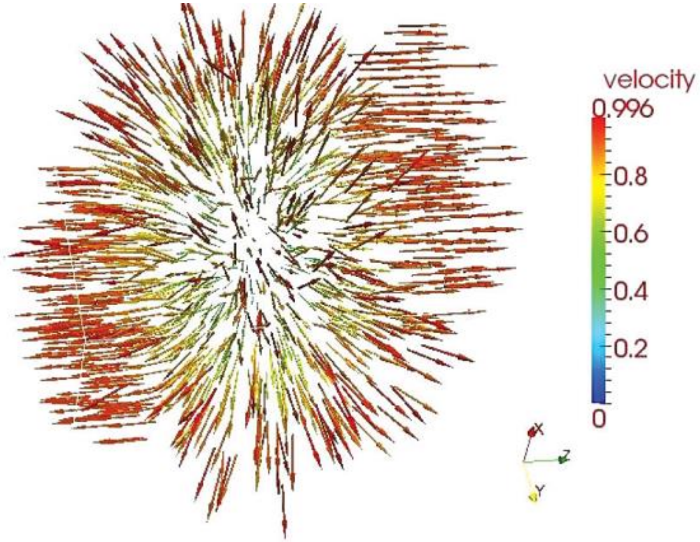


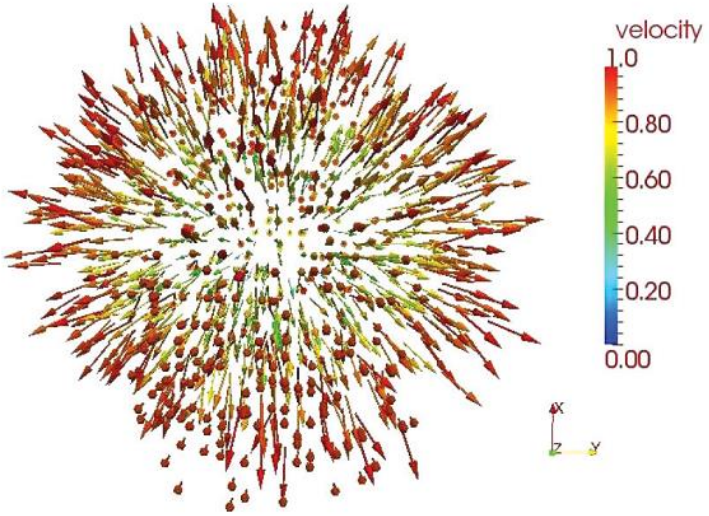
Structure of velocity and vorticity fields (NICA@JINR-5 GeV/c)



Distribution of velocity ("Little Bang")

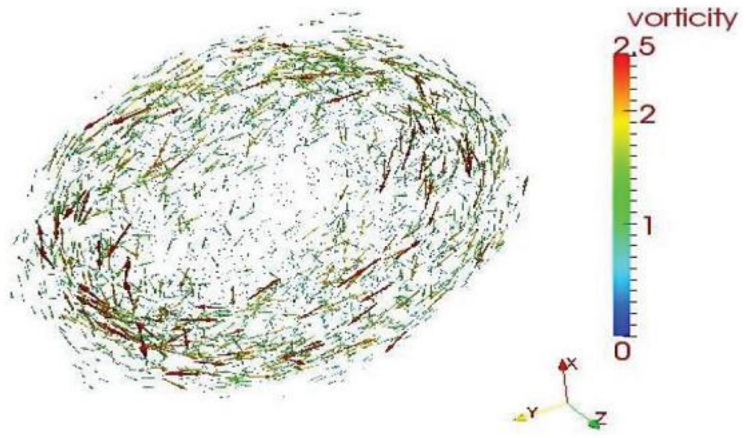
- 3D/2D projection
- z-beams direction
- x-impact paramater

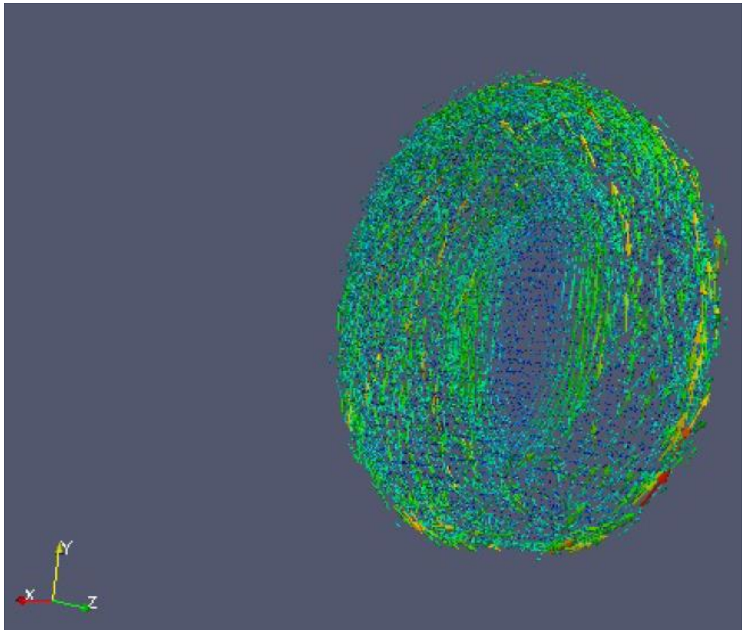


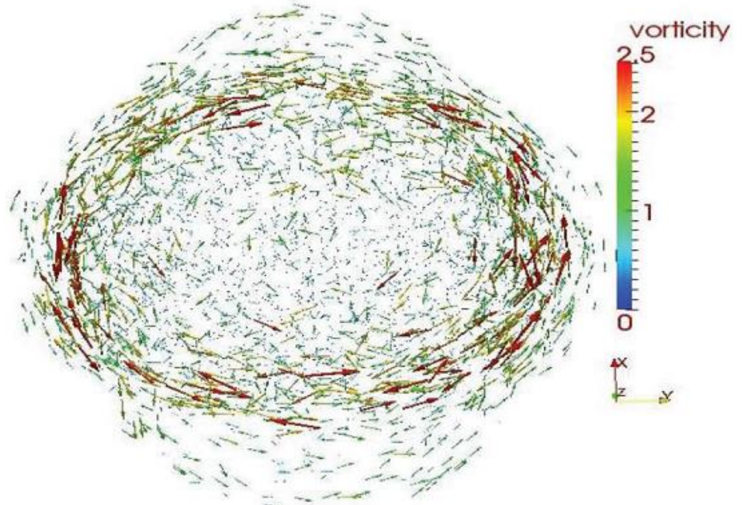


Distribution of vorticity ("Little galaxies")

- Layer (on core - corona borderline) patterns

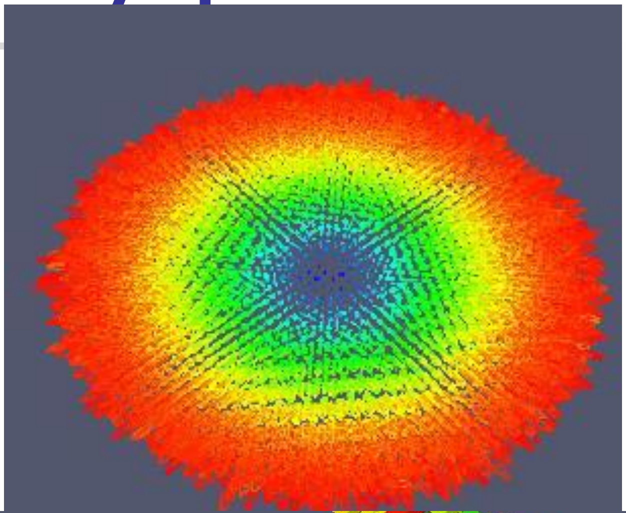




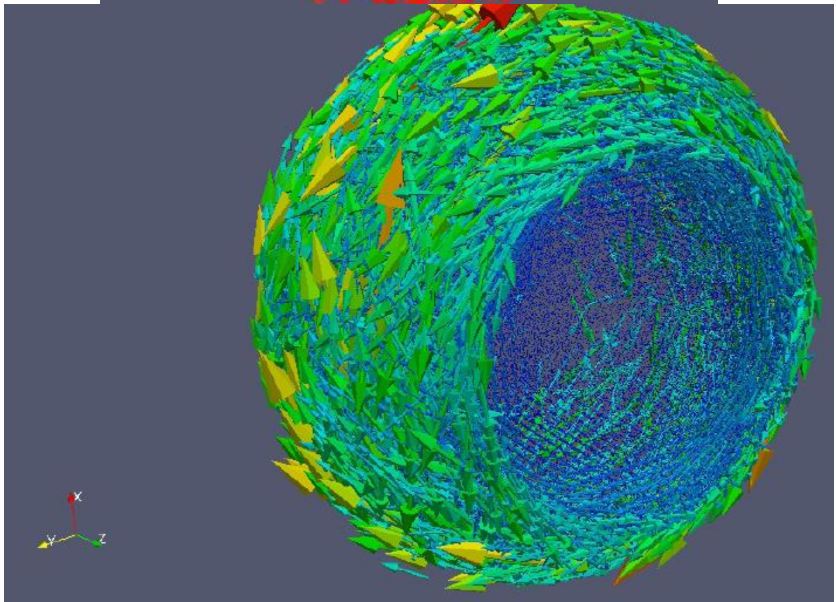


Velocity and vorticity patterns

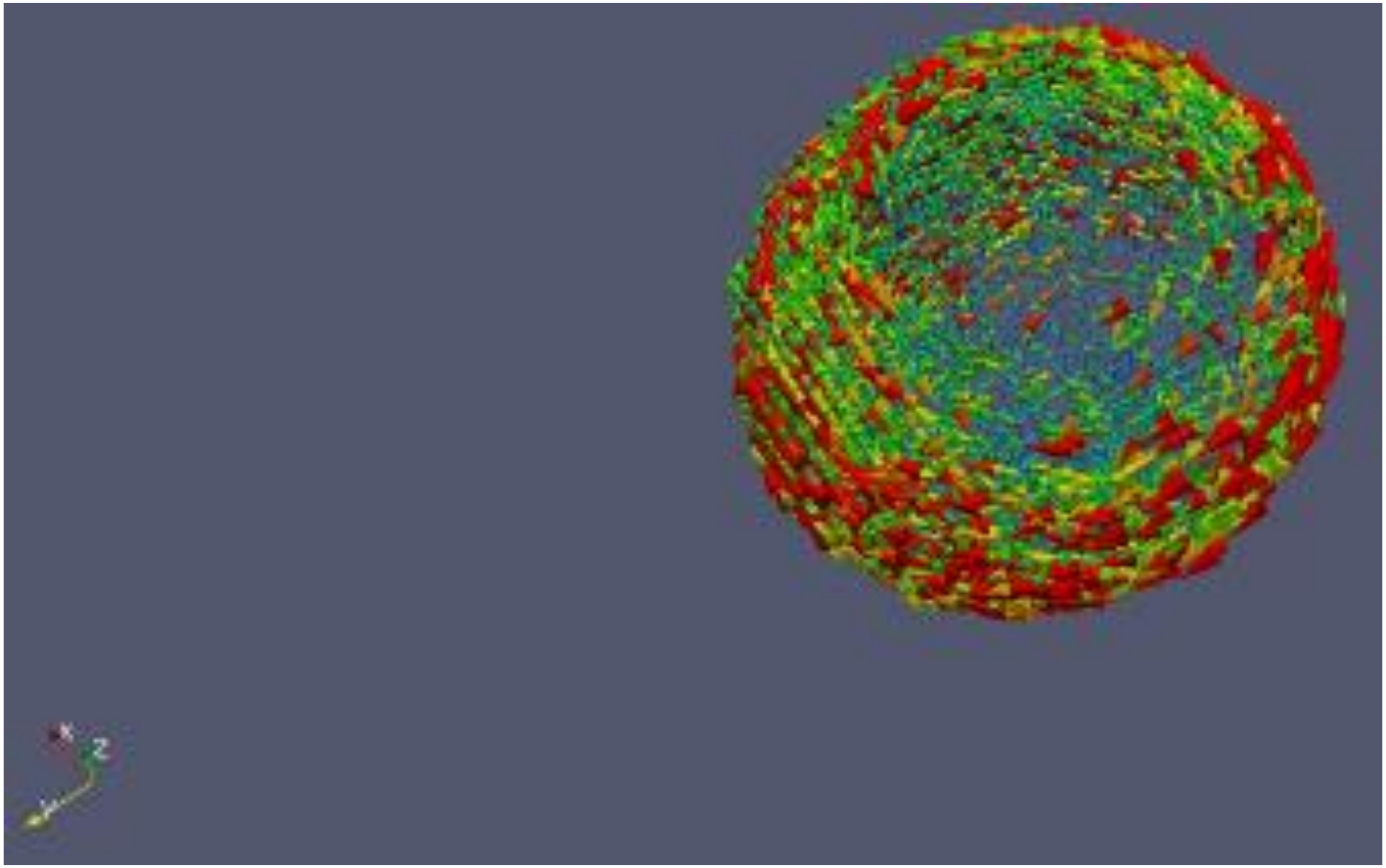
- Velocity



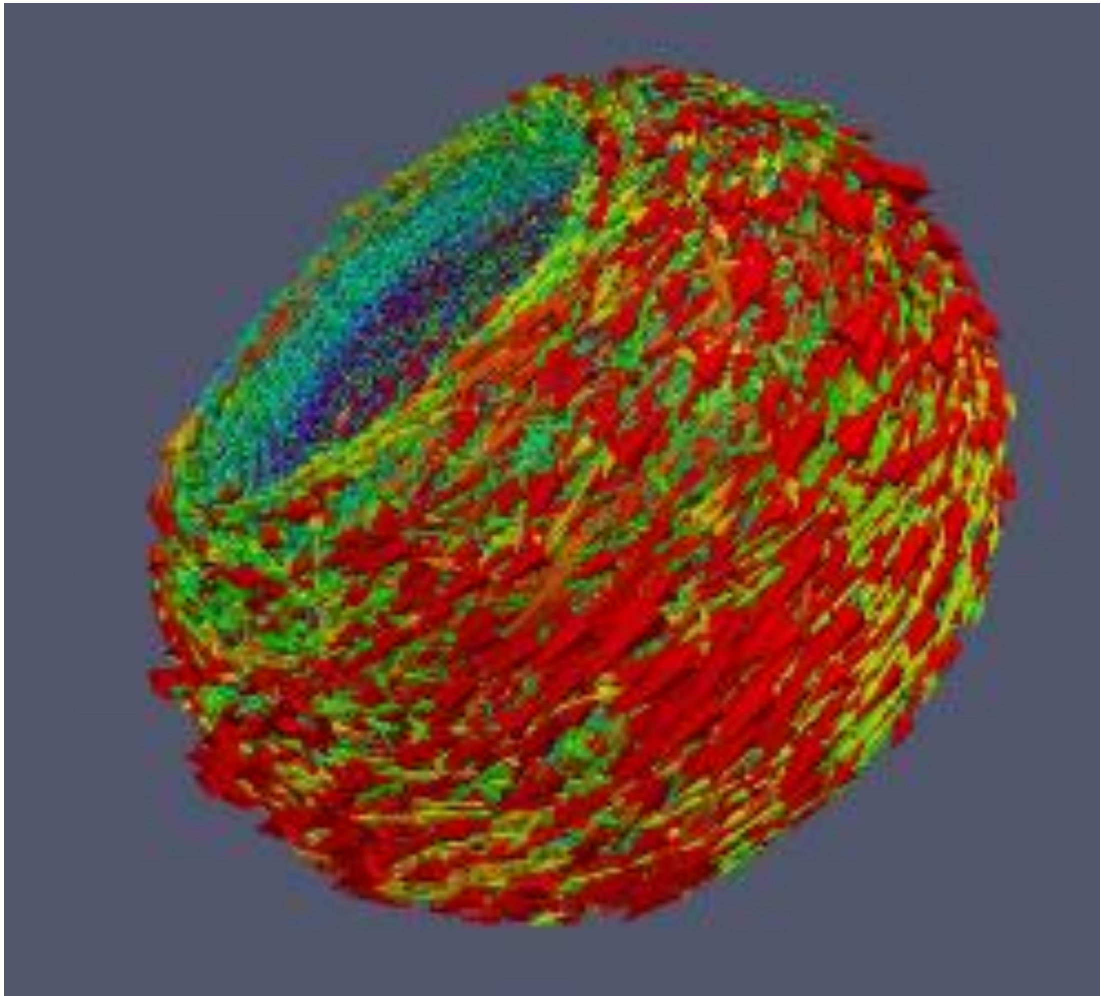
- Vorticity pattern – vortex sheets - due to L BUT cylinder symmetry!



Vortex sheet (fixed direction of L)

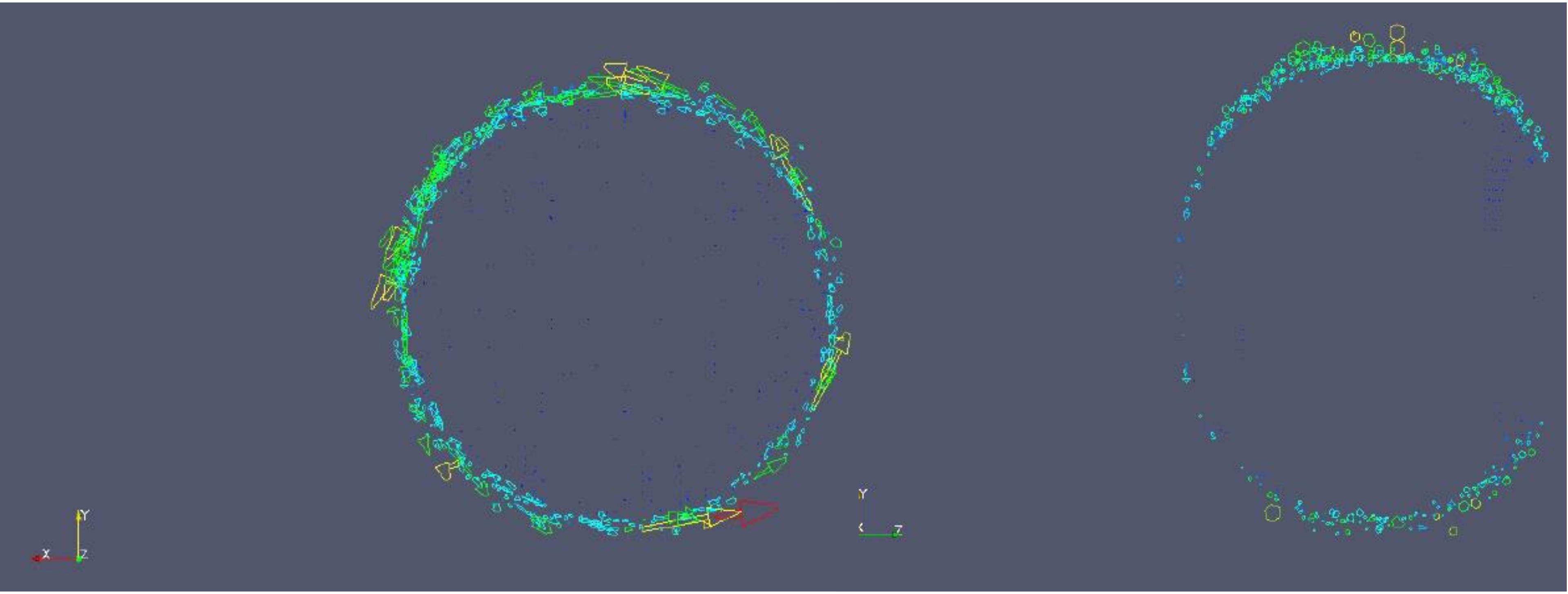


Vortex sheet （ Average over L directions ）



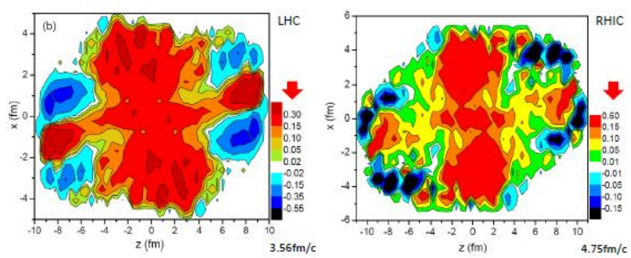
Sections of vorticity patterns

- Front and side views

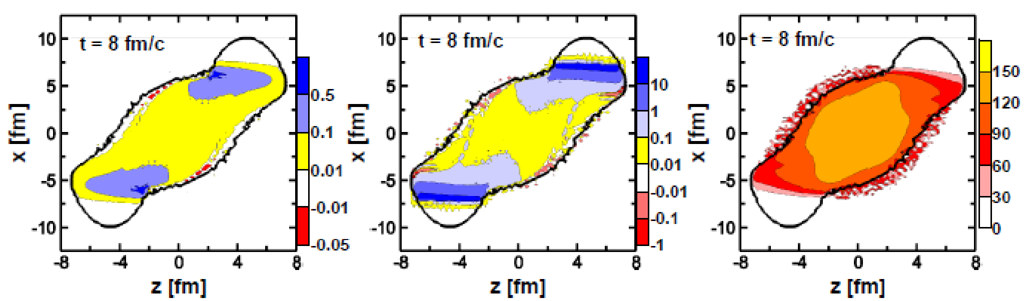


Vortex sheets

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

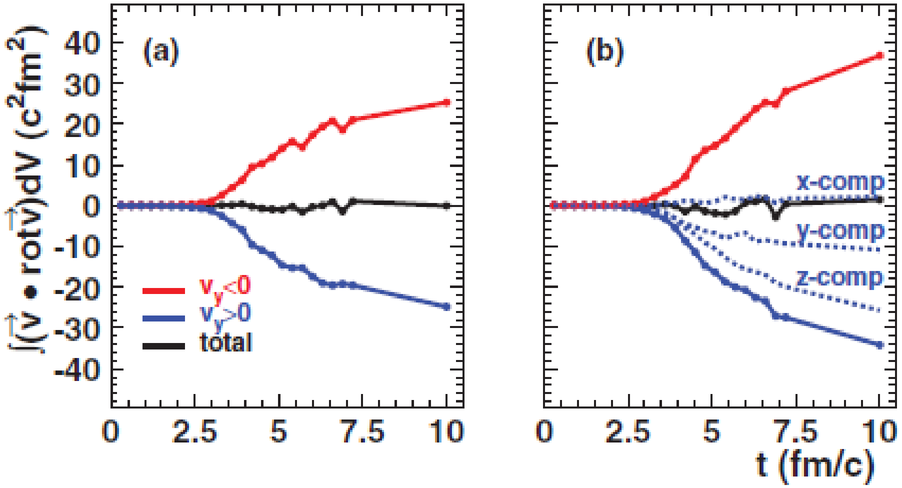


- Appears in 3 fluid dynamics model (Yu. Ivanov, A. Soldatov, arXiv:1701.01319)



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

- Total helicity integrates to zero BUT
- Mirror helicities below and above the reaction plane
- Confirmed in HSD (OT, Usubov, PR**C92 (2015) 014906**

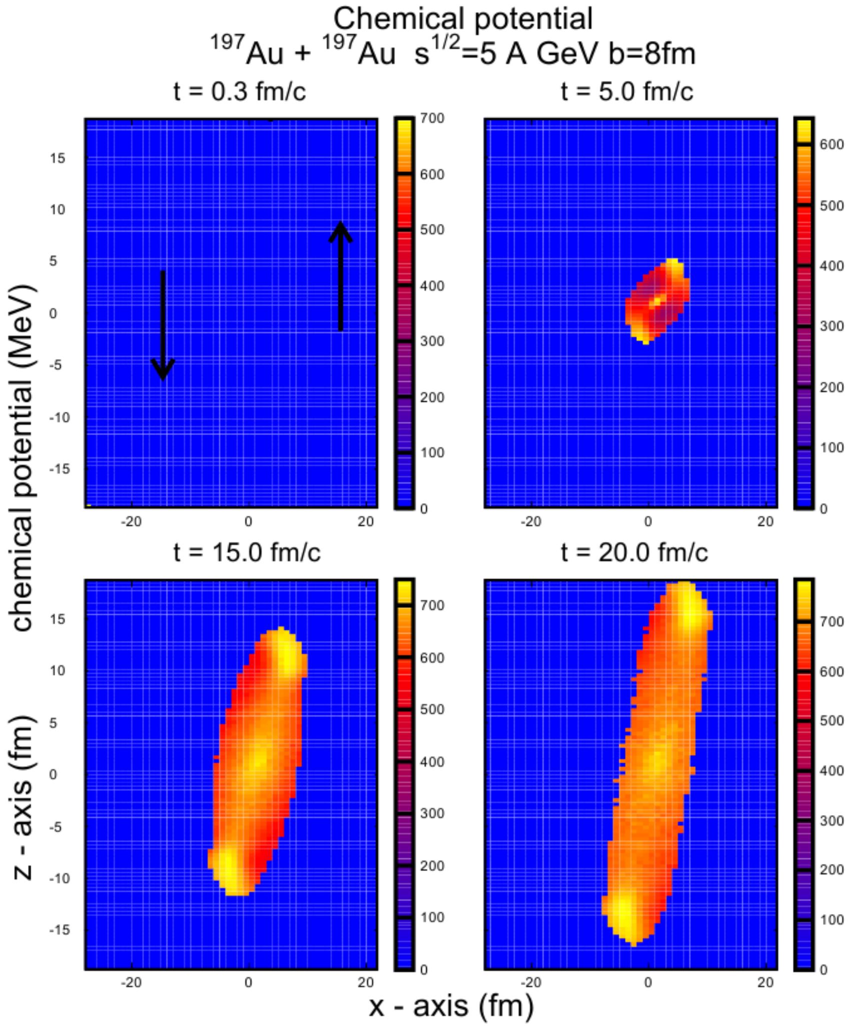


Structure of vorticity

- y-component: constant vorticity, velocity changes sign
- z-component: quadrupole structure of vorticity

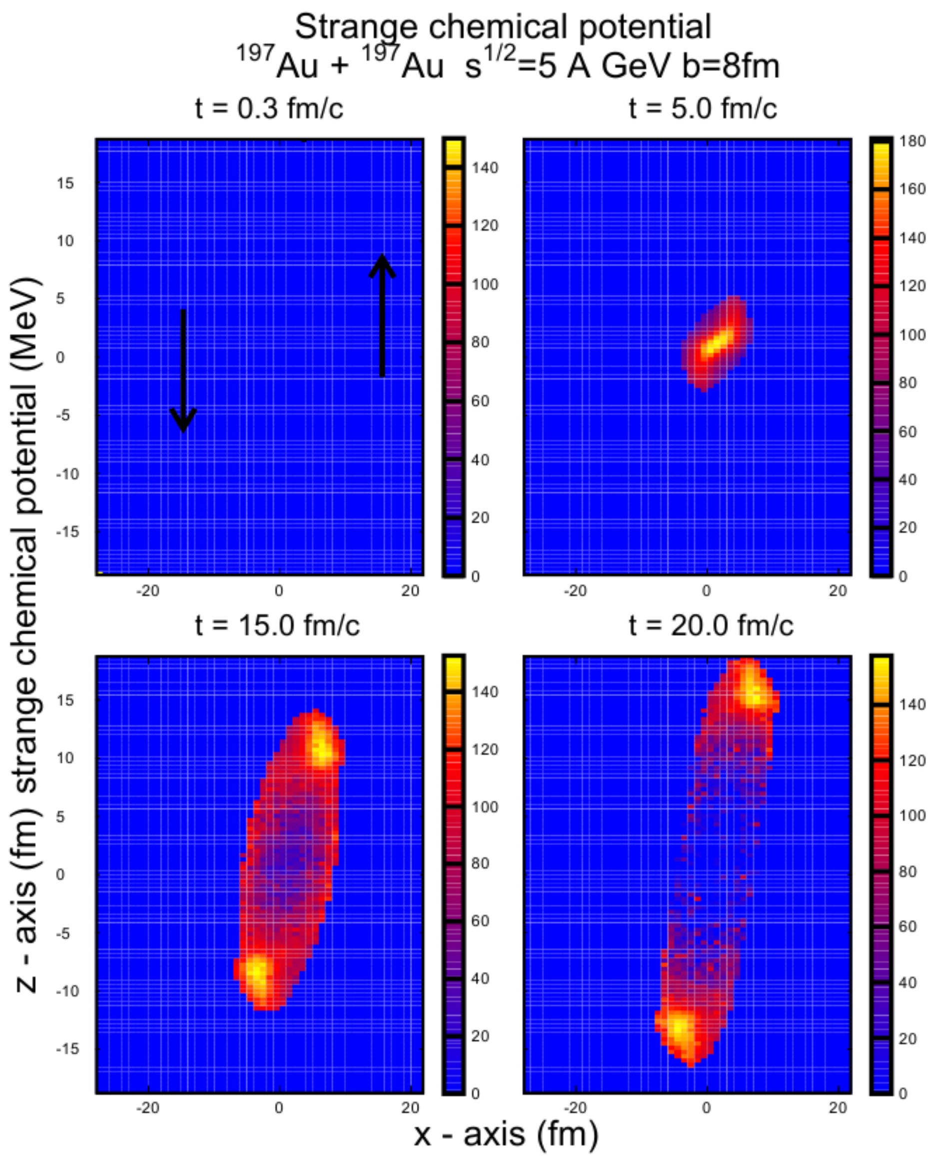
Chemical potential : Kinetics -> TD

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

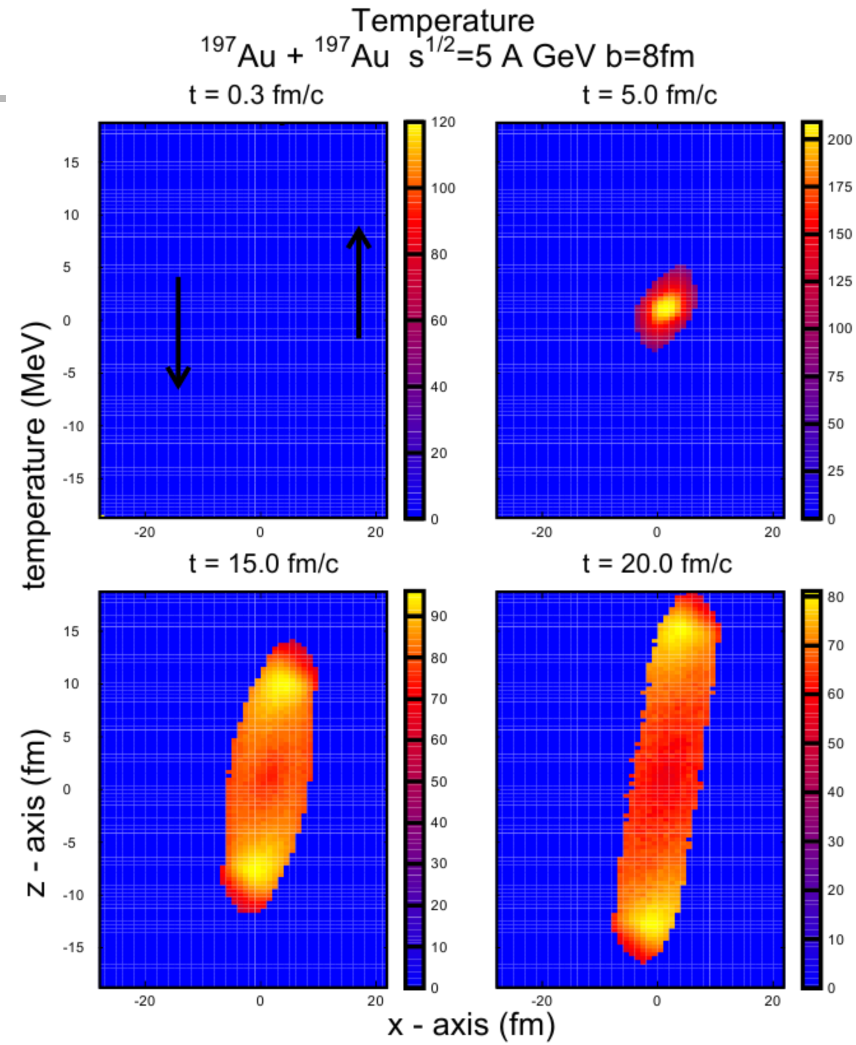


Strange chemical potential (polarization of Lambda is carried by strange quark!)

- Non-uniform in space and time



Temperature



From axial charge to polarization (and from quarks to confined hadrons)

- Analogy of matrix elements and classical averages

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

- Lorentz boost: compensate the sign of helicity $\Pi^{\Lambda,lab} = (\Pi_0^{\Lambda,lab}, \Pi_x^{\Lambda,lab}, \Pi_y^{\Lambda,lab}, \Pi_z^{\Lambda,lab}) = \frac{\Pi_0^\Lambda}{m_\Lambda}(p_y, 0, p_0, 0)$

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

- Antihyperons (smaller N) : same sign and larger value (more pronounced at lower energy; EM difference-decrease)

Other approach to confinement: vortices in pionic superfluid (V.I. Zakharov, OT:1705.01650)

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

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

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

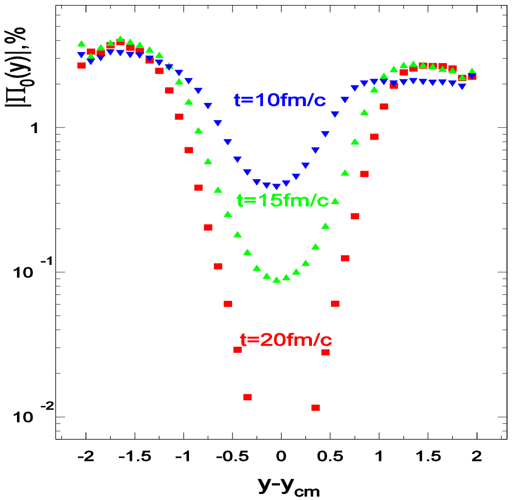
- Suggestion: core of the vortex- baryonic degrees of freedom- polarization

Helicity -> rest frame polarization

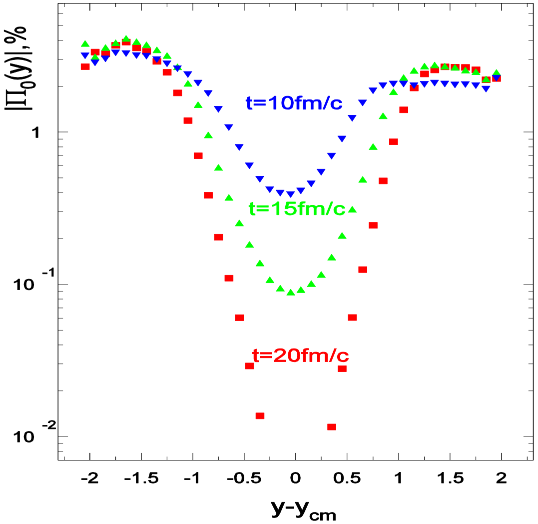
- Helicity ~ 0th component of polarization in lab. frame – effect of boost to Lambda rest frame – various options

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

$w_1=1$, $w2= 1$



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



Comparison of methods

- Wigner function – induced axial current (triangle diagram– V.I. Zakharov) – Prokhorov (poster), OT,1707.02491

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

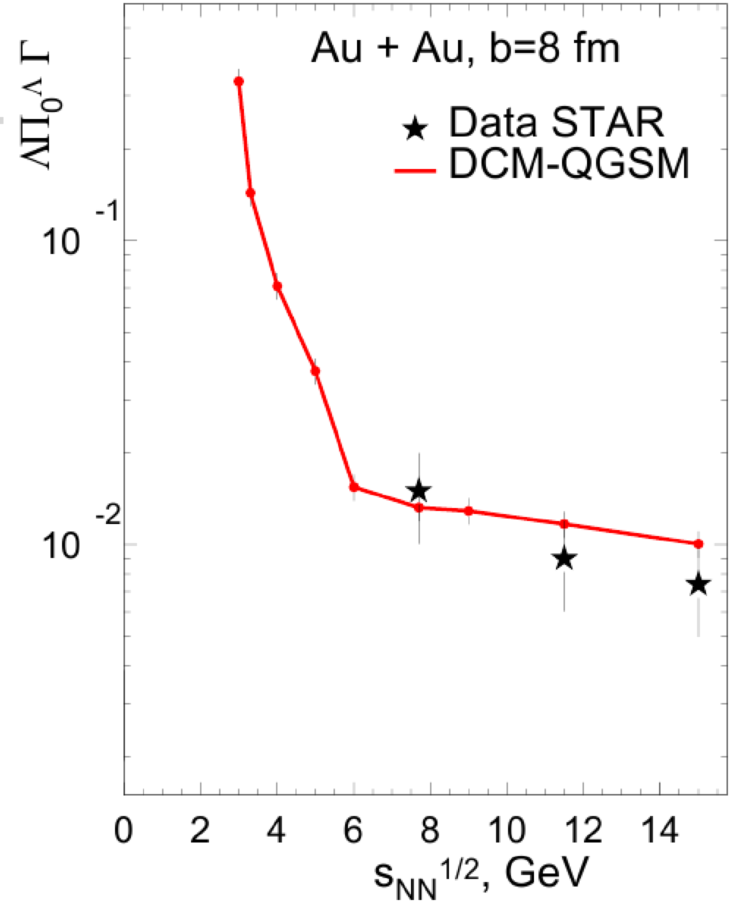
$$\langle : j^5_\mu : \rangle = \Big(\frac{1}{6} \big[T^2 + \frac{a^2 - \omega^2}{4\pi^2} \big] + \frac{\mu^2}{2\pi^2} \Big) \omega_\mu + \frac{1}{12\pi^2} (\omega \cdot a)\, a_\mu$$

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

- New terms of higher order in vorticity
- Topological universal acceleration-directed term

Energy dependence

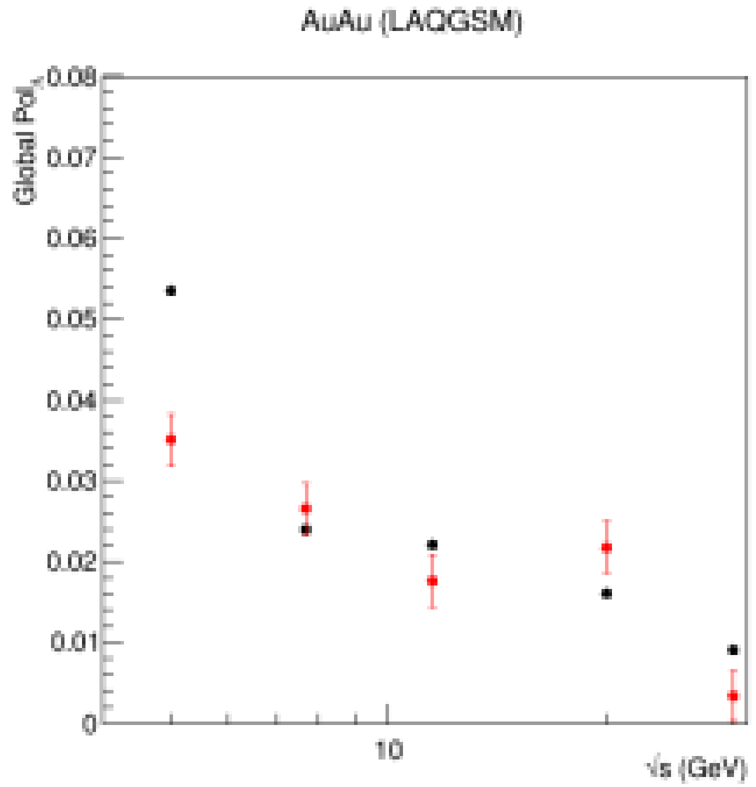
- Growth at low energy
- Surprisingly close to STAR data!



- Structure – may be due to fluctuation for low particles number

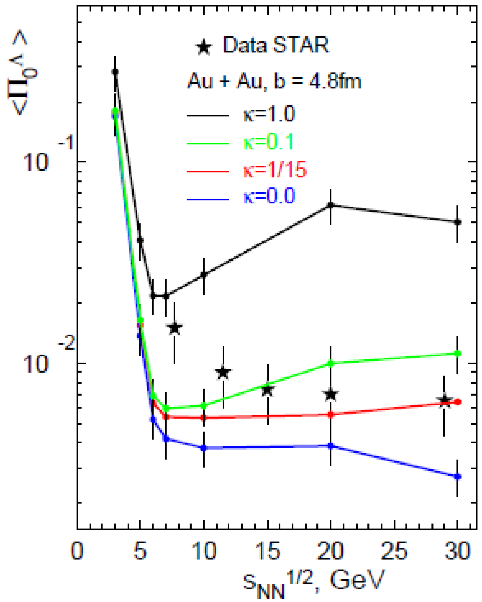
Polarization at NICA/MPD (A. Kechechyan)

- QGSM Simulations and recovery accounting for MPD acceptance effects



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

- Different values of coefficient probed

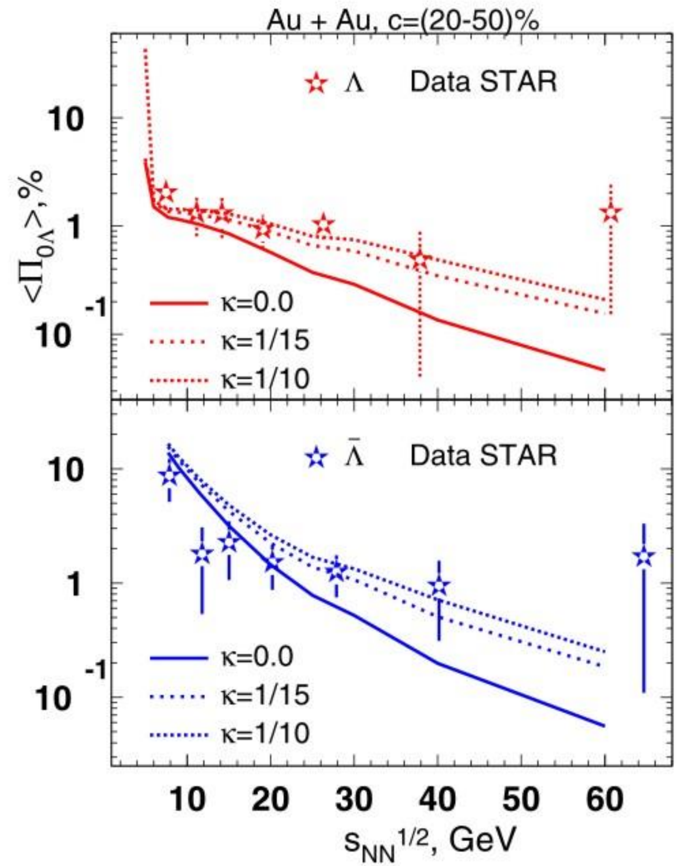


- LQCD suppression by collective effects supported

Lambda vs Antilambda and role of vector mesons

- Difference at low energies too large – same axial charge carried by much smaller number
- 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
- Differ with magnetic field effects in energy dependence

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

Summary of lecture 3

- Polarization – new probe of anomaly in quark-gluon matter (to be studied at NICA)
- Generated by femto-vortex sheets
- Same sign and larger magnitude of antihyperon polarization
- T-dependent term due to gravitational anomaly may be extracted from the data
- Polarization - from core of vortices in pionic superfluid

General Summary

- Polarization observables – sensitive tests of the theory
- Anomalies – generic quantum effects with various manifestations
- Polarization of heavy ions – new common manifestation of anomalies and relativistic hydrodynamics – probe of fastest ever rotation?

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: $d\sigma \sim Tr[\gamma_5 ....] \sim i m \varepsilon_{s p_1 p_2 p_3} ...$

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 $<f|S|i>^* = <i|S|f>$.

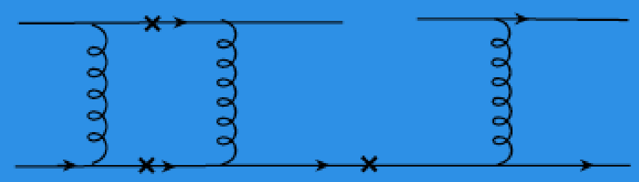
SSA - either T-violation or the phases.

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):

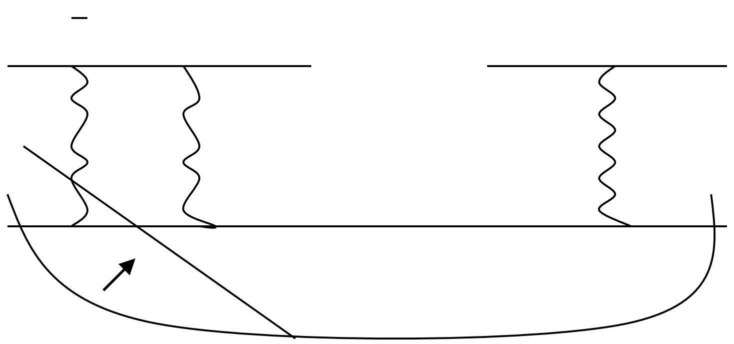


$$A \sim \frac{\alpha_S m p_T}{p_T^2 + m^2}$$

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)