Spin effects in hadronic and heavy ion collisions: superstrong gravity probe?

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How strongest (QCD) and weakest (gravity) interactions are related?

- Hadronic matrix elements of energy-momentum tensor operator describe the interaction with classical gravity, and QCD hard exclusive processes

- The medium emergng in heavy-ion collisions manifests the highest ever acceleration and vorticity corresponding according to the Equivalence Principle   to the superstrong "Equivalent" Gravity

Main Topics

- Equivalence Principle: way to merge strongest and weakest interactions
- Gravitational Formfactors ("old" and "new"): EP for spin and its Extension
- Spin-1 in exclusive and inclusive processes: shear and viscosity
- Heavy ion collisions : highest vorticity and acceleration (="equivalent" gravity)
- Anomalous current and polarization
- Unruh effect and temperature in medium

Electromagnetism vs Gravity (OT'99)

- Interaction – field vs metric deviation

$$M = \langle P' | J_q^\mu | P \rangle A_\mu(q) \qquad M = \frac{1}{2} \sum_{q,G} \langle P' | T_{q,G}^{\mu\nu} | P \rangle h_{\mu\nu}(q)$$

- Static limit

$$\langle P | J_q^\mu | P \rangle = 2 e_q P^\mu \qquad \sum_{q,G} \langle P | T_i^{\mu\nu} | P \rangle = 2 P^\mu P^\nu$$

$$h_{00} = 2\phi(x)$$

$$M_0 = \langle P | J_q^\mu | P \rangle A_\mu = 2 e_q M \phi(q) \qquad M_0 = \frac{1}{2} \sum_{q,G} \langle P | T_i^{\mu\nu} | P \rangle h_{\mu\nu} = 2M \cdot M \phi(q)$$

- Mass as charge – equivalence principle
- Low-energy theorem

EP and hadron structure

- "Microscopic" EP (coupling of gravity to EMT)
- +
- Conservation law
  (Momentum SR to get local from LC pdf's):
  $\int dx\, x\, (\Sigma\, q(x) + G(x))=1)$
- =
- "Macroscopic" EP (universal falling) :
- Tested VERY precisely

Gravitational Formfactors (Pagels'66, Ji'97, talks of K. Semenov-Tyan-Shanskiy, O. Selyugin): O (Δ)

$$\langle p'|T^{\mu\nu}_{q,g}|p\rangle = \bar{u}(p')\Big[A_{q,g}(\Delta^2)\gamma^{(\mu}p^{\nu)} + B_{q,g}(\Delta^2)P^{(\mu}i\sigma^{\nu)\alpha}\Delta_\alpha/2M\Big]u(p)$$

- Conservation laws - zero Anomalous Gravitomagnetic Moment : $\mu_G = J$ (g=2)

$$P_{q,g} = A_{q,g}(0) \qquad A_q(0) + A_g(0) = 1$$

$$J_{q,g} = \frac{1}{2}\left[A_{q,g}(0) + B_{q,g}(0)\right] \qquad A_q(0) + B_q(0) + A_g(0) + B_g(0) = 1$$

- No M_{Pl}! May be extracted from high-energy experiments/NPQCD calculations
- Describe the partition of angular momentum between quarks and gluons Ji's SRs
- Describe interaction with both classical and "equivalent" gravity

Gravitomagnetism

- Gravitomagnetic field (weak, except in gravity waves) – action on spin from $M = \frac{1}{2}\sum_{q,G}\langle P'|T^{\mu\nu}_{q,G}|P\rangle h_{\mu\nu}(q)$

$$\vec{H}_J = \frac{1}{2}rot\vec{g};\ \vec{g}_i \equiv g_{0i}$$

spin dragging twice smaller than EM

- Lorentz force – similar to EM case: factor ½ cancelled with 2 from $h_{00} = 2\phi(x)$ Larmor frequency same as EM

$$\omega_J = \frac{\mu_G}{J}H_J = \frac{H_L}{2} = \omega_L\ \vec{H}_L = rot\vec{g}$$

- Orbital and Spin momenta dragging – the same - Equivalence principle
- Generalized for arbitrary strong fields Obukhov,Silenko,OT, 1308.4552 and PRD

Equivalence principle

- Newtonian – “Falling elevator” – well known and checked (also for elementary particles)
- Post-Newtonian – gravity action on (quantum!) SPIN – known since 1962 (Kobzarev and Okun’; ZhETF paper contains acknowledgment to Landau: probably his last contribution to theoretical physics before car accident); rederived from conservarion laws - Kobzarev and V.I. Zakharov
- Anomalous gravitomagnetic (and electric-CP-odd) moment iz ZERO or
- Classical and QUANTUM rotators behave in the SAME way

Experimental test of PNEP

- Reinterpretation of the data on G(EDM) search

PHYSICAL REVIEW LETTERS

VOLUME 68 | 13 JANUARY 1992 | NUMBER 2

Search for a Coupling of the Earth's Gravitational Field to Nuclear Spins in Atomic Mercury

B. J. Venema, P. K. Majumder, S. K. Lamoreaux, B. R. Heckel, and E. N. Fortson
Physics Department, FM-15, University of Washington, Seattle, Washington 98195
(Received 25 September 1991)

- If (CP-odd!) GEDM (new EMT FF, also forbidden by EP: extra γ_5 in B) =0 -> constraint for AGM (Silenko, OT'07) from Earth rotation – was considered as obvious (but it is just EP!) background

$$\mathcal{H} = -g\mu_N \boldsymbol{B}\cdot\boldsymbol{S} - \zeta\hbar\boldsymbol{\omega}\cdot\boldsymbol{S}, \quad \zeta = 1+\chi$$

$$|\chi(^{201}\mathrm{Hg}) + 0.369\chi(^{199}\mathrm{Hg})| < 0.042 \quad (95\%\mathrm{C.L.})$$

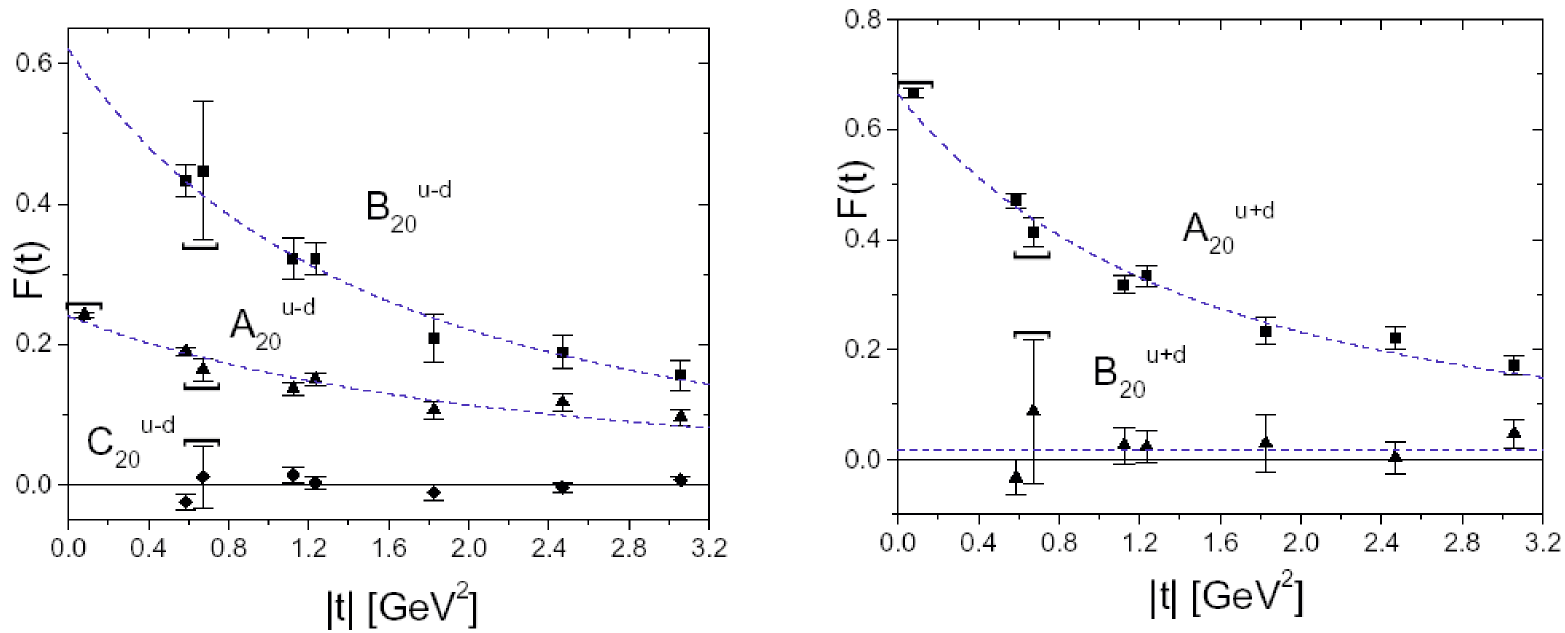
- Gravitational test of Ji's SR (for Hg)!
- New high precision EDM experiments: gravity is essential (NN Nikolaev,Vergeles,Obukhov, Silenko,OT, 2204.00427 and UFN)

EP and quantum measurement

- If spin is just a geometric vector, EP for Earth’s rotation is “trivial”: looking from stars, spin rotates with Earth’s angular velocity like Foucault pendulum
- Non-trivial if quantum measurement (quite practical here) is performed in the rotating frame
- Cf with Unruh effect (measurement in accelerated frame is crucial)

Extension of Equivalence principle

- Various arguments: AGM ≈ 0 separately for quarks and gluons – most clear from the lattice (LHPC/SESAM)



Extended Equivalence Principle=Exact EquiPartition

- In NLO pQCD – violated (LF:S.Brodsky et al.)
- Reason – in the case of ExEP- no smooth transition for zero fermion mass limit (Milton, 71)
- Conjecture (O.T., 2001 – prior to lattice data) – valid in NP QCD – zero quark mass limit is safe due to chiral symmetry breaking
- Smallness of singlet AMM (proton (1.79) and neutron (-1.91)) is related to ExEP (OT'99): 1st and 2nd moments (with different parity: antiquarks subtracted for AMM and added for AGMM) of GPD $E(x,\xi)_{u+d}$
- Gravityproof confinement?! Nucleons are not broken even by black holes?!
- Equivalent gravity effect is absent (limited)?

Exact Equipartition and Pivot

- Important notion introduced by C. Lorce to relate transverse spin SR's of Ji&Yuan and Leader et al.
- Naïve interpretation of ExEP: common (approximately, averagely) pivot for quarks and gluons:
- $\langle J_{T(q,G)} \rangle = \langle x_0 \rangle \langle P_{L(q,G)} \rangle$
- Can this be satisfied for some of pivot choices?

Conformality (talk of A. Kataev) and ExEP

- Closeness of AMMs of proton (1.79) and neutron (-1.91) squared

$$\frac{d\alpha_{g_1}(Q^2)}{dQ^2}|_{Q^2=0} = \frac{3\pi}{4g_A}\left(\frac{\kappa_n^2}{M_n^2} - \frac{\kappa_p^2}{M_p^2}\right)$$

- Relation between higher dimensional (in AdS QCD) and real gravity

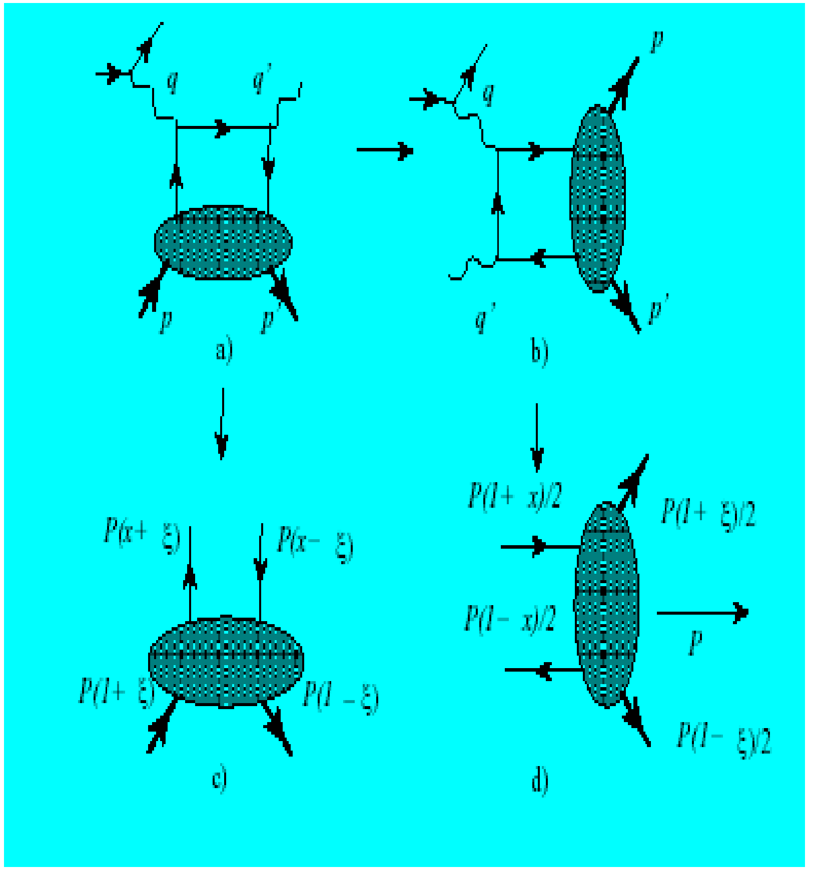
Also seen for J=1 if density matrix instead of wave functions is used for definitions of GPDs at O(Δ): g=2 is selected for EMT by conservation laws (OT'99)

SB Gerasimov was pointing out that in GDHSR for arbitrary spin AMM is counted as g-2

- J=1/2 -> J=1. QCD SR/model/lattice (1608.03472; also K*:2405.02600) calculations of ρ-meson MM gives g close to 2 (g=2 exactly in AdS QCD). Why?
- Maybe because of similarity of moments and ExEP
- $g-2 = \langle E_u(x)\rangle$; $B=\langle x\, E_u(x)\rangle$
- Directly for ρ (because of isospin invariance combinations like p+n for nucleons unnecessary!). Not reduced to non-extended EP: Gluons momentum fraction sizable
- Deutrons: also g=2 with good accuracy. Qualitative reason for ExEP. Quantitative – also may be done in AdS QCD containing already all necessary ingredients (talk of M. Allahverdiyeva)

Crossing for DVCS and GPD

- DVCS -> hadron pair production in the collisions of real and virtual photons
- GPD -> Generalized Distribution Amplitudes
- Duality between s and t channels (Polyakov,Shuvaev, Guzey, Vanderhaeghen)



Gravitational FFs from Belle data on GDAs

S. Kumano, Qin-Tao Song and O. Teryaev, PRD **97** (2018) 014020.

- Gravitational FFs are related to twist-2 GDAs

$$A_{\lambda_1\lambda_2} = T_{\mu\nu}\,\varepsilon^{\mu}(\lambda_1)\,\varepsilon^{\nu}(\lambda_2)/e^2$$

$$A_{++} = \sum_q \frac{e_q^2}{2}\int_0^1 dz\,\frac{2z-1}{z(1-z)}\,\Phi^q(z,\xi,W^2)$$

$$\int dz(2z-1)\,\Phi_q^{+}(z,\xi,W^2) = \frac{2}{(P^+)^2}\left\langle \pi^+(p_1)\pi^-(p_2)\right|T_q^{++}(0)\left|0\right\rangle$$

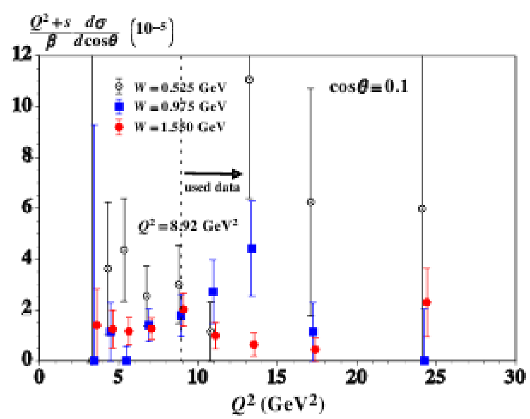
$$\left\langle \pi^0(p_1)\pi^0(p_2)\right|T^{\mu\nu}(0)\left|0\right\rangle = \frac{1}{2}\left[\left(sg^{\mu\nu}-P^{\mu}P^{\nu}\right)\Theta_1 + \Delta^{\mu}\Delta^{\nu}\Theta_2\right]$$

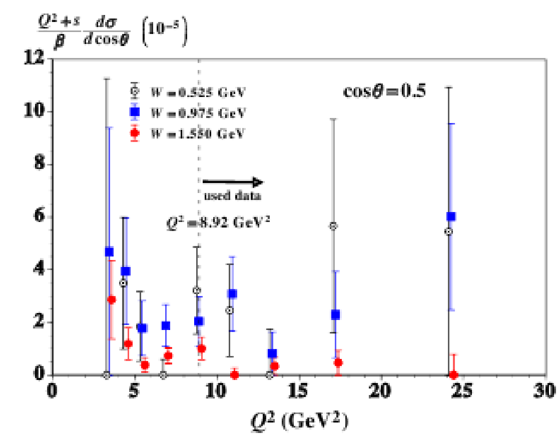
$$P = p_1 + p_2\ ,\ \Delta = p_1 - p_2$$

M. Masuda et al. [Belle Collaboration], PRD 93 (2016), 032003

- Belle data and scaling : W=0.525,0.975, 1.55 GeV

$$\frac{(Q^2+s)d\sigma}{\beta d|\cos\theta|} \propto \left|\Phi^{\pi^0\pi^0}(z,\cos\theta,W,Q)\right|^2$$





New EMT formfactor : Shear viscosity

- From spherically symmetric object to fluid (EoS!)
- $T^{\mu\lambda} = (e+p)\, v^\mu v^\lambda - p\, g^{\mu\lambda}$
- $V^\mu = P^\mu/M$: correct normalization but no coordinate dependence
- Another suggestion (OT'19):
- $V^\mu = (P^\mu + a(t)\, k_T^{\ \mu}) / (M^2 + a^2(t)\, k_T^{\ 2})^{1/2}$
- Viscosity: $\eta\, dv^\mu / d\, x_T^{\ \lambda} \sim E_\eta\, p^{[\mu} \Delta^{\lambda]}$
- NO such term in total EMT (but can be for quarks separately)
- Naïve T-oddness: phases in GPD channel from decays in TGPDs (talk of K. Semenov-Tyan-Shanskiy)
- Phases <-> dissipation: polarization in pionic superfluidity model (V. I. Zakharov, OT' 17)

Viscosity in GDA channel

- Viscosity:will correspond to Exotic $J^{PC}=1^{-+}$ meson (studied long ago without mentioning gravity: Anikin, Pire, Szymanowski,OT, Wallon'06)
- Spin: related to structure of matrix element: One index of EMT (0^{th} in rest frame) is carried by momentum and other by polarization vector - just what we need for viscosity
- NO for conserved EM: zero coupling for (G)DA!
- $\pi\eta$ pairs observation instead of $\pi\pi$ required : related y by crossing to transition GPDs(talk of K. Semenov-Tyan-Shanskiy)
- Smallness of viscosity: related to smallness of exotic GDAs and ExEP violation?!
- Calculation in perturbative limit: Song, OT,Yoshida (2503.11316 and PLB): relation to meson's DA

Viscosity for GDAs and holography

- Terms in EMT:
- $(e+p)\, v^\mu v^\lambda \sim A\, P^\mu P^\lambda$
- $\eta\, dv^\mu / d\, x_T^{\ \lambda} \sim E_\eta\, p^{[\mu} \Delta^{\lambda]}$
- TD: e+p -> Ts
- $\eta/s\ (> 1/(4\pi)) \sim E_\eta T / AM$
- Correct dependence on Planck constant recovered via $\Delta^\lambda \to -i\hbar\, d / d\, x_T^{\ \lambda}$

Spin 1 EMT and inclusive processes

- Forward matrix element -> density matrix
- Contains P-even term: tensor polarization $S^{\alpha\beta}$ New EMT FF
- $< P|T^{\alpha\beta}|P>= A\, P^{\alpha}\, P^{\beta} + T\, S^{\alpha\beta}$
- Symmetric and traceless: correspond to (average) shear forces
- Cf with spin ½ and spin 1 vector polarization : P-odd vector polarization requires another vector (q) to form vector product

SUM RULEs

- Efremov,OT'82 : zero sum rules:
- Current conservation: 1st moment: also in parton model by Close and Kumano (90)
- EMT conservation: 2nd moment (forward analog of Ji's SR: ∑ B=0 <=> ∑ T=0)
- Average shear force (compensated between quarks and gluons)
- Gravity and (Ex)EP (zero average shear separately for quarks and gluons) – OT'09
- EP: No monopole spin-gravity coupling!
- Deutrons in |0> and (|1>+|-1>)/√2 states fall in the same way
- C.f. with Protons and electrons: |1/2> and |-1/2> ------//-------

Manifestation of post-Newtonian (Ex)EP for spin 1 hadrons

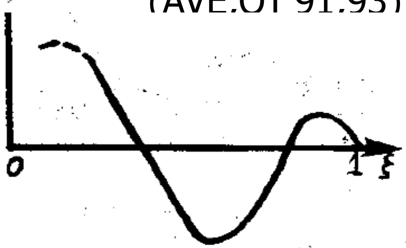
- Tensor polarization - coupling of EMT to spin in forward matrix elements - inclusive processes
- Second moments of tensor distributions should sum to zero

$$A_T = \frac{\sigma_+ + \sigma_- - 2\sigma_0}{3\bar{\sigma}}.$$

$$\int_0^1 C_i^T(x)dx = 0$$

$$\langle P,S|\bar{\psi}(0)\gamma^\nu D^{\nu_1}...D^{\nu_n}\psi(0)|P,S\rangle_{\mu^2} = i^{-n}M^2 S^{\nu\nu_1}P^{\nu_2}...P\nu_n \int_0^1 C_q^T(x)x^n dx$$

(AVE,OT'91,93)



$$\sum_q \langle P,S|T_i^{\mu\nu}|P,S\rangle_{\mu^2} = 2P^\mu P^\nu(1-\delta(\mu^2)) + 2M^2 S^{\mu\nu}\delta_1(\mu^2)$$

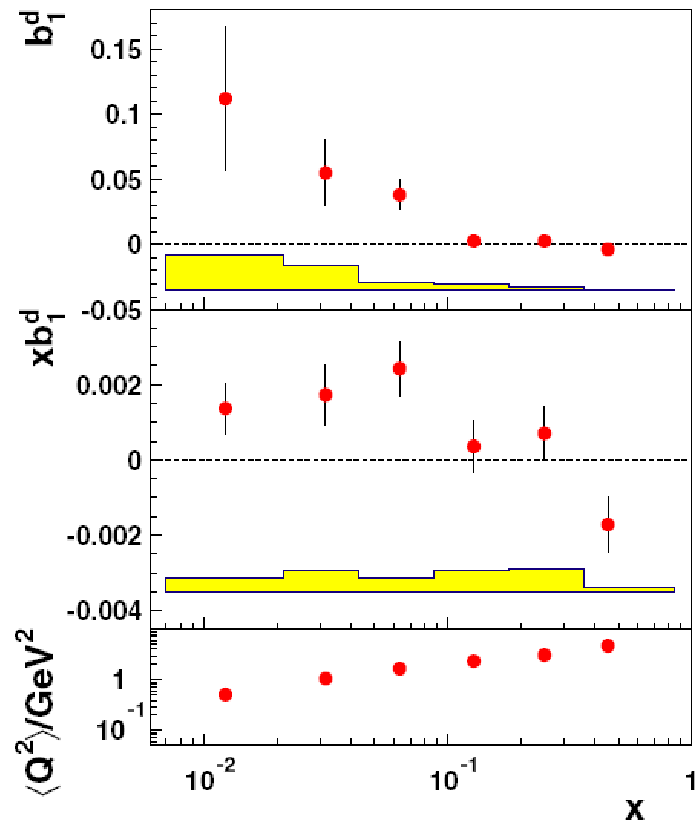
$$\langle P,S|T_g^{\mu\nu}|P,S\rangle_{\mu^2} = 2P^\mu P^\nu \delta(\mu^2) - 2M^2 S^{\mu\nu}\delta_1(\mu^2)$$

$$\sum_q \int_0^1 C_i^T(x)xdx = \delta_1(\mu^2) = 0$$ for ExEP

HERMES – data on tensor spin structure function

PRL 95, 242001 (2005)

- Isoscalar target – proportional to the sum of u and d quarks – combination required by (Ex)EP
- Second moments – compatible to zero better than the first one (collective tensor polarized glue << sea)



Where else to test?

- EIC?
- DY@J-PARC: (Song,Kumano:1902.04712)
- ET'82-any hard process
- $f_{AI}\sim b_1$

$$P_{zz}=-2P_{yy}=-2P_{xx}=\frac{2\int_0^1 d\xi\, f_{AI}(\xi)\, Sp[\hat{P}E(\xi,P)]}{3\int_0^1 d\xi\, f(\xi)\, Sp[\hat{P}E(\xi,P)]}=\frac{2F_{AI}(x_1,x_2)}{3F(x_1,x_2)},$$

- Suggestion: hadronic (pion) inclusive tensor SSA(OT'19)
- A = (dσ(1)+dσ(-1)-2 dσ(0))/(dσ(1)+dσ(-1)+dσ(0))
- Complementary to other deutrons studies at SPD (talk of N. Nikolaev)

EP: Where is the fastest possible rotation and acceleration?

- Non-central heavy ion collisions (Angular velocity ~ c/Compton wavelength) $\Omega \sim \frac{c}{\lambda_p} = \frac{m_p c^2}{\hbar}$
- ~25 orders of magnitude faster than Earth's rotation $\eta_{\rm rot} = \frac{\Omega}{\omega_\oplus} = \frac{c}{R_A} \cdot \frac{T_\oplus}{2\pi} = \frac{1}{2\pi} \cdot \frac{c T_\oplus}{R_A} \approx 10^{27}$
- Differential rotation – vorticity
- P-odd :May lead to various P-odd effects (Chiral magnetic/vortical effects)
- Acceleration: even larger ratio with the gravity of Earth

$$\eta_{\rm acc} = \frac{c}{R_A} \cdot \frac{c}{g_\oplus} = \eta_{\rm rot} \frac{2\pi c}{T_\oplus g_\oplus} \approx 10^{30} \qquad \eta_{\rm acc} = \frac{c}{R_A} \cdot \frac{c}{g_\oplus} = \frac{c^2}{v_\oplus^2} \cdot \frac{R_\oplus}{R_A}$$

HIC: Strong interactions and superstrong "EP-gravity" (explored in lattice simulations: talks of V. Zakharov, Yu. Obukhov, V. Braguta, A. Roenko, J. Day, V. Voronyuk, N. Tsegelnik, E. Dlin)

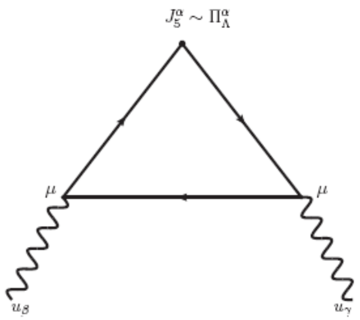
- $E_{EM}/E_G \sim e^2/(m/M_{Pl})^2$ $\qquad$ $M_{Pl} \sim 10^{18}$ GeV
- For 2 particles with M_{Pl} mass at Compton wavelength distance ($1/M_{Pl}$): $E_G \sim (G = 1/M_{Pl}^2)\, M_{Pl}^2 / (1/M_{Pl}) = M_{Pl}$
  $g \sim (G = 1/M_{Pl}^2)\, M_{Pl} / (1/M_{Pl})^2 = M_{Pl}$
- Gravitational interaction is strongly suppressed wrt strong one $\sim (\Lambda/M_{Pl})^2$
- Equivalence Principle
- I: Acceleration <-> Gravity
- HIC: $a \sim \Lambda$, $a/g \sim \frac{c^2}{v_\oplus^2} \cdot \frac{R_\oplus}{R_A} \sim 10^{30}$
- $M_{Pl} \to \Lambda$ ("GeV Gravity" to be compared with 'TeV gravity" from extra dimensions)

Effective field theory: Anomalies

- 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, OT ’10)
- Analogous to anomalous gluon contribution to nucleon spin
(Efremov,OT’88)
- 4-velocity instead of gluon field potential and vorticity ------//-------
(chromo)magnetic field strength!



***STAR*, Nature 548 (2017) 62-65**

Observable for AVE: polarization (talks of A. Taranenko, A. Jaiswal, A. Ayala, E. Alpatov, V. Troshin, S. Rode, V/ Voronyuk, N. Tsegelnik, J.J. Medina Serna)

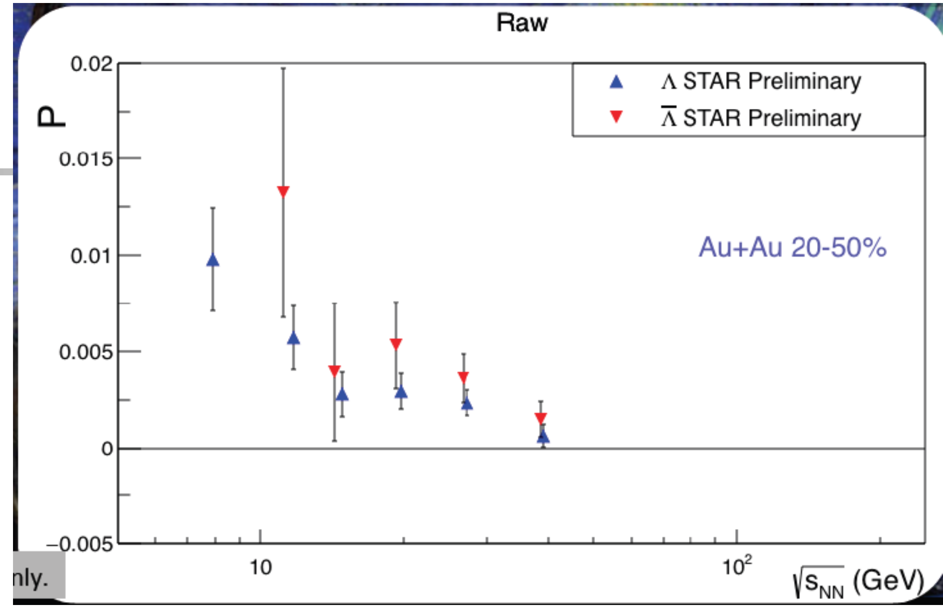
O. Rogachevsky, A. Sorin, O. Teryaev
Chiral vortaic effect and neutron asymmetries in heavy-ion collisions
PHYSICAL REVIEW C 82, 054910 (2010)

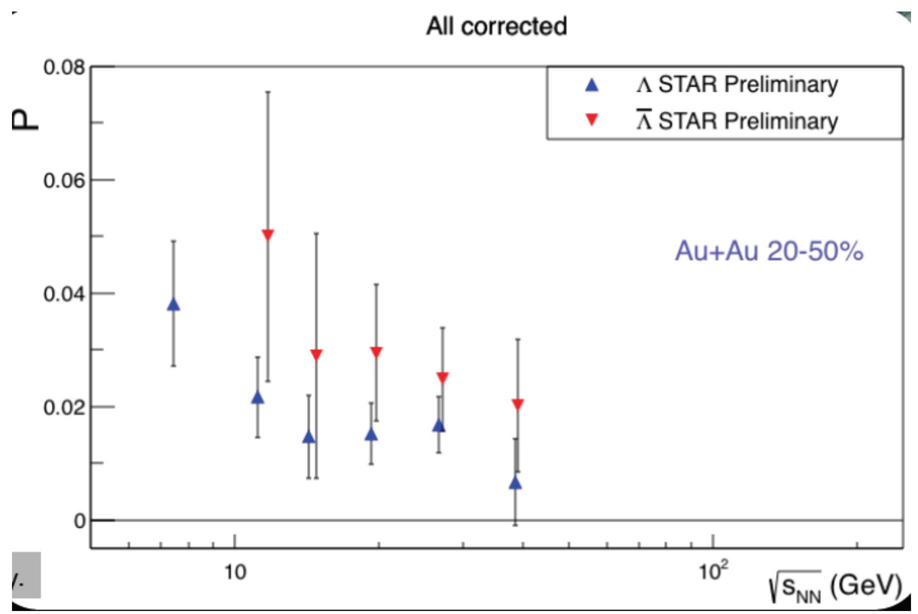
One would expect that polarization is proportional to the anomalously induced axial current [7]

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

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.





“Anomalous” mechanism

- Prediction of decrease with energy (due to chemical potential)
- Prediction of P~1%

BAZNAT, GUDIMA, SORIN, AND TERYAEV

PHYSICAL REVIEW C **88**, 061901(R) (2013)

$$\langle P_\Lambda \rangle \sim \frac{\langle \mu^2 \rangle N_c H}{2\pi^2 \langle N_\Lambda \rangle}.$$

For numerical estimate at NICA energies, we take (see Fig. 3) $H = 30\ \mathrm{fm}^2 (c = 1)$ and, as typical values, $\langle \mu^2 \rangle = 900\ \mathrm{MeV}^2$, $\langle N_\Lambda \rangle = 15$ to get $\langle P_\Lambda \rangle \sim 0.8\%$. This value is

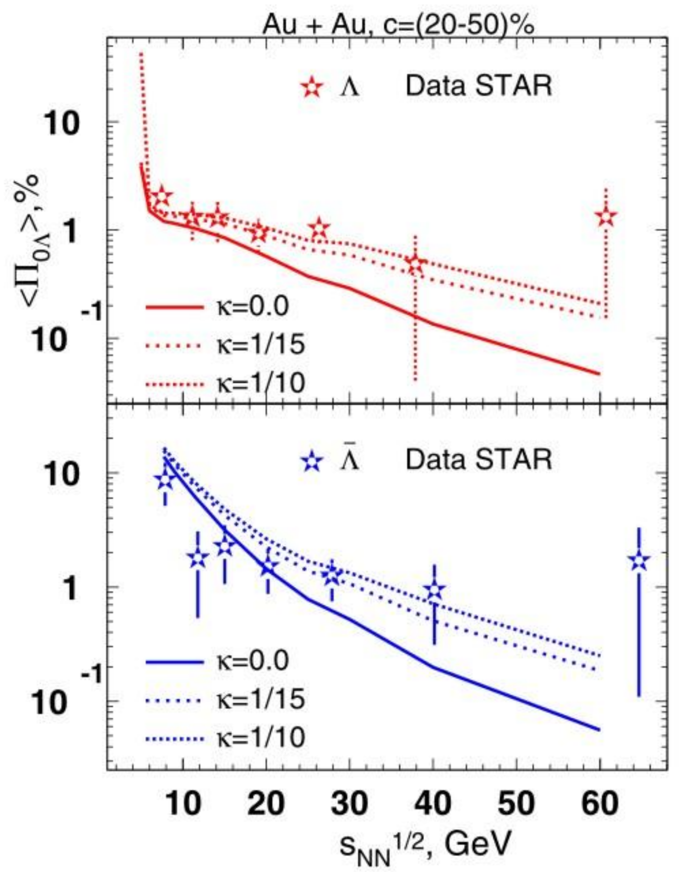
- Postdiction of larger polarization of antilambdas

ALEXANDER SORIN AND OLEG TERYAEV

PHYSICAL REVIEW C **95**, 011902(R) (2017)

The proportionality of the polarization to the square of the chemical potential related to C-even parity of axial current leads to the same sign of polarization of Λ and $\bar{\Lambda}$ hyperons. The smaller number of the latter should result in a larger fraction of the axial charge, corresponding to each antihyperon and to a larger absolute value of polarization. Detailed numerical sim-

Λ vs Anti Λ: same axial charge is distributed between lower number of hadrons (also for Ω⁻ ?!)



TD approach to gauge anomaly (D.T. Son and P. Surowka; S.-Z. Yang, J.-H. Gao and Z.-T. Liang) -> gravitational anomaly

Gravitational chiral anomaly in hydrodynamics

*G. Yu. Prokhorov, O.V. Teryaev, V.I. Zakharov, **Phys. Rev. Lett.** 129, 151601 (2022)*

- In heavy ion collisions (in particular, at **NICA**) a relativistic quantum liquid is formed with **extremely high vorticity** ω^{μ} and **acceleration** a^{ν}. The axial current is related to the hyperon **polarization**. **New** contributions to current and **polarization**:

KVE:
$$\boxed{j_A^{\mu} \;=\; \lambda_1(\omega_{\nu}\omega^{\nu})\omega^{\mu} + \lambda_2(a_{\nu}a^{\nu})\omega^{\mu}}$$

Transport coefficients

Connection with anomaly and gravity:

$$\boxed{\lambda_1 - \lambda_2 = 32\mathcal{N}}$$

$$\nabla_{\mu} j_A^{\mu} = \mathcal{N}\epsilon^{\mu\nu\alpha\beta}R_{\mu\nu\lambda\rho}R_{\alpha\beta}{}^{\lambda\rho}$$

- **The novel kinematical vortical effect (KVE)** depends only on vorticity and acceleration, but is independent of **temperature** and **chemical potential**, and is determined by a **quantum anomaly** in **curved** space.
- The effect exists even when there are **no gravitational** fields ('Cheshire cat" or "Structural stability of hydrodynamics")
- Derivation is essentially making use of the method developed (for the case of electromagnetic fields) In the paper
- Besides further exploration of the anomalous transport the collaboration in investigations of various polarization effects in hadronic and heavyi-ion collisions iwould be of great importance for us. Both the theoretical studies and modeling for experiments (in particular, at NICA and HIAF) are of interest

[27] Shi-Zheng Yang, Jian-Hua Gao, and Zuo-Tang Liang, Constraining non-dissipative transport coefficients in global equilibrium, Symmetry **14**, 948 (2022).

Statistics vs geometry: Unruh effect (Becattini'18; Prokhorov, OT, Zakharov'19)

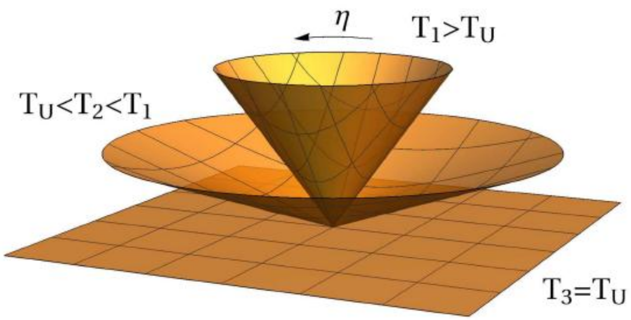
- Results for energy density of thermal system in Minkowski space coincide with the early known for the space with conical singularity (e.g. cosmic strings)

$$\rho_{s=0} = \frac{\pi^2 T^4}{30} + \frac{T^2|a|^2}{12} - \frac{11|a|^4}{480\pi^2},$$
$$\rho_{s=1/2} = \frac{7\pi^2 T^4}{60} + \frac{T^2|a|^2}{24} - \frac{17|a|^4}{960\pi^2}$$

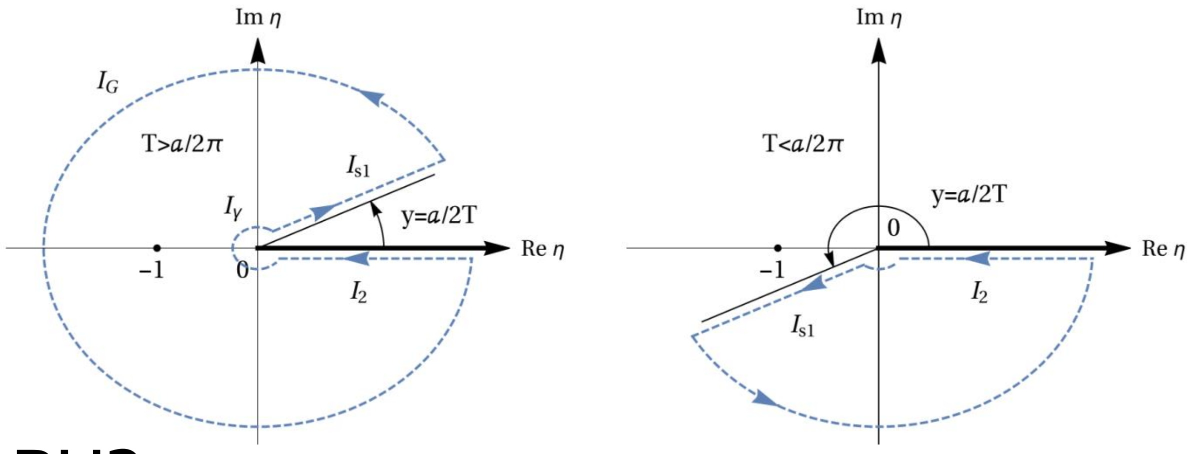
$$c_V = \frac{\mu_s^2 + \mu_A^2}{2\pi^2} + \frac{T^2}{6}, \quad Q_5^s = N_c \int d^3x\, c_V \gamma^2 \epsilon^{ijk} v_i \partial_j v_k$$

- Energy density turns to zero for $T=T_U=a/(2\pi)$ (~"physical conditions of renormalization". also simple explanation of coefficient)
- Unruh effect explains fast HIC thermalization

Instability for high accelerations



- Normally $T>T_U$
- Fast accelration without thermalization: instability (leads to hadronization)



- EP ~ fall to BH?

Hawking vs Unruh effects

- Pair creation in gravity field or accelerated frame
- EP: g=a: => $T_H = T_U$
- One particle goes to observer outside BH or accelerating detector
- Second particle falls to the BH or goes to inertial observer
- Observation of thermal spectra in HIC ~ looking from BH interior

NICA (Nuclotron based Ion Colider fAcility)

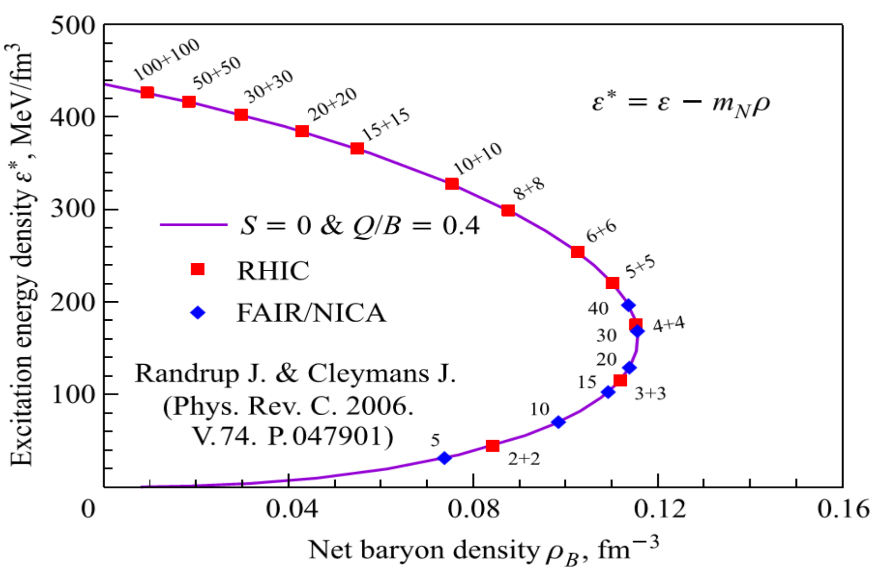
– the flagship project in HEP of Joint Institute for Nuclear Research (JINR)

Main targets of "NICA Complex":

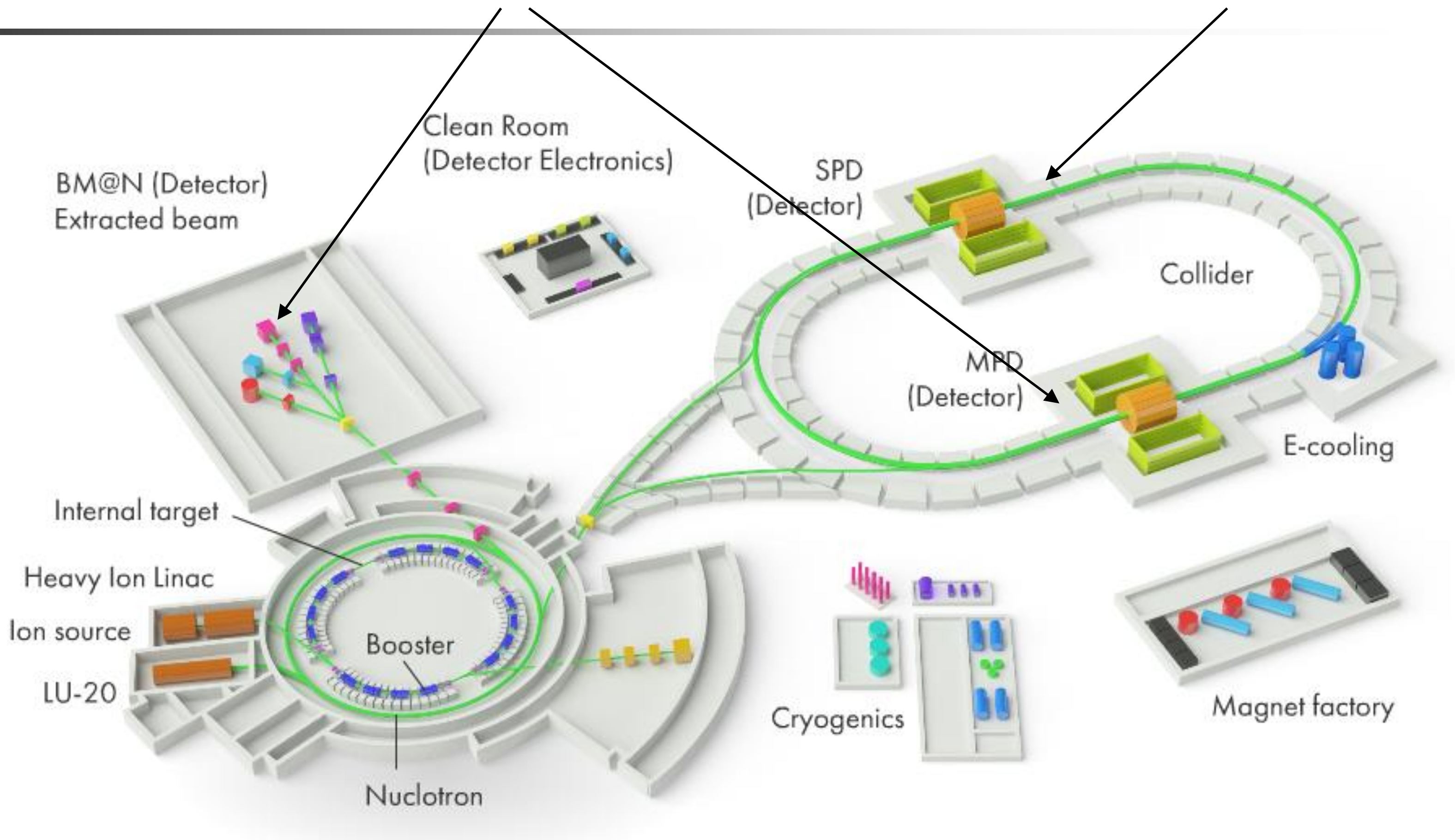
- ***study of hot and dense baryonic matter***
- *investigation of hadronic spin structure through various polarization phenomena*
- *development of accelerator facility for HEP @ JINR providing intensive beams of relativistic ions from p to Au polarized protons and deuterons with energy up to*

*$\sqrt{S_{NN}}$ = 11 GeV (Au^{79+}, **L ~ 10^{32}** $cm^{-2}\ c^{-1}$)*

*$\sqrt{S}$ =27 GeV (p, L ~ **10^{32}** $cm^{-2}\ c^{-1}$)*



NICA: heavy ions and hadrons



CONCLUSIONS

- Interplay of QCD and gravity in hadronic and heavy-ion collisions
- Special role of fundamental notions of Equivalence Principle and Quantum Measurement
- Special role of tensor and global polarization
- Modern accelerators (LHC, RHIC, CEBAF EIC, EIcC, FAIR,NICA, HIAF… also “equivalent gravity” labs (with “access” to BH interior☺)

Outloook: hadronic and HIC interlay in both directions

- Hadronic medium properties (viscosity) from GrFFs
- Coupling of in-medium hadrons tp acceleration and vorticity via GrFFs
- ?

BACKUP

Equivalence principle for moving particles EPII vs EPI

- Compare gravity and acceleration: gravity provides EXTRA space components of metrics
- Matrix elements DIFFER $h_{zz} = h_{xx} = h_{yy} = h_{00}$

$$\mathcal{M}_g = (\epsilon^2 + p^2) h_{00}(q), \qquad \mathcal{M}_a = \epsilon^2 h_{00}(q)$$

- Ratio of accelerations: $R = \frac{\epsilon^2 + p^2}{\epsilon^2}$ - confirmed by explicit solution of Dirac equation (Silenko, OT, '05)
- Arbitrary fields – Obukhov, Silenko, OT '09,'11,'13,16,17: also the same dynamics for classical and quantum rotators ("EP for strong fields")

Gravity vs accelerated frame for spin and helicity

- Spin precession – well known factor 3 (Probe B; spin at satellite – probe of PNEP!) – smallness of relativistic correction ($\sim\mathbf{P}^2$) is compensated by $1/\mathbf{P}^2$ in the momentum direction precession frequency
- Helicity flip – the same!
- No helicity flip in gravitomagnetic field – another formulation of PNEP (OT'99) and
- Flip by "gravitoelectric" field: relic neutrino (Anisotropic Universe: Kamenshchik,OT'15)? Black hole?

$$\frac{d\sigma_{+-}}{d\sigma_{++}} = \frac{tg^2(\frac{\phi}{2})}{(2\gamma-\gamma^{-1})^2}$$

Cosmological implications of PNEP

- Necessary condition for Mach's Principle (in the spirit of **S.Weinberg's** textbook-Section 9.7)
- Lense-Thirring inside massive rotating empty shell (=model of Universe)
- For flat "Universe" - precession frequency equal to that of shell rotation
- Simple observation-Must be the same for classical and quantum rotators – PNEP!
- More elaborate models - Tests for cosmology ?!