# Актуальные проблемы физики тяжелых ионов и адронов

***Школа по физике кварк-глюонной материи***

УНЦ ОИЯИ
3.04.2023

Теряев О.В.
ОИЯИ
teryaev@jinr.ru

# Некоторые актуальные проблемы и их отдельные интересные (по крайней мере, для лектора) аспекты

# “Эффективная” (в соответствии с принципом эквивалентности) гравитация в столкновениях тяжелых ионов *УФН* 193 (2023) 2, 113-154

- e-Print: 2204.00427 [hep-th]

**Эффекты общей теории относительности в прецизионных спиновых экспериментах по проверке фундаментальных симметрий**


Сергей Н. Вергелес* и Николай Н. Николаев†
*Институт теоретической физики им. Л. Д. Ландау Российской академии наук, 142432 Черноголовка, Московская обл., Россия*
*Московский физико-технический институт, 141707 Долгопрудный, Московская обл., Россия*

Юрий Н. Обухов‡
*Институт проблем безопасного развития атомной энергетики Российской академии наук, Б. Тульская 52, 115191 Москва, Россия*

Александр Я. Силенко§
*Лаборатория теоретической физики им. Н. Н. Боголюбова, Объединенный институт ядерных исследований, 141980 Дубна, Россия*
*Институт современной физики, Китайская академия наук, 730000 Ланьчжоу, КНР*
*Научно-исследовательский институт ядерных проблем, Белорусский государственный университет, 220030 Минск, Беларусь*

Олег В. Теряев¶
*Лаборатория теоретической физики им. Н. Н. Боголюбова, Лаборатория физики высоких энергий им. В. И. Векслера и А. М. Балдина, Объединенный институт ядерных исследований, 141980 Дубна, Россия*
*Национальный исследовательский ядерный университет “МИФИ”, Каширское ш. 31, 115409 Москва, Россия*
*Государственный университет “Дубна”, 141980 Дубна, Россия*


Действительно, локальную угловую скорость $\Omega$, можно оценить, полагая, что скорость меняется на величину порядка скорости света $c$ на масштабах, соответствующих размеру ядра $R_A$. Ее отношение к угловой скорости вращения Земли (6.8) удобно представить в виде

$$\eta_{\rm rot} = \frac{\Omega}{\omega_\oplus} = \frac{c}{R_A}\cdot\frac{T_\oplus}{2\pi} = \frac{1}{2\pi}\cdot\frac{cT_\oplus}{R_A} \approx 10^{27} \qquad (10.1)$$

отношения световых суток (расстояния, проходимого светом за время оборота Земли вокруг своей оси $T_\oplus$, и примерно в 150 раз превышающего ее расстояние до Солнца) и размера ядра.

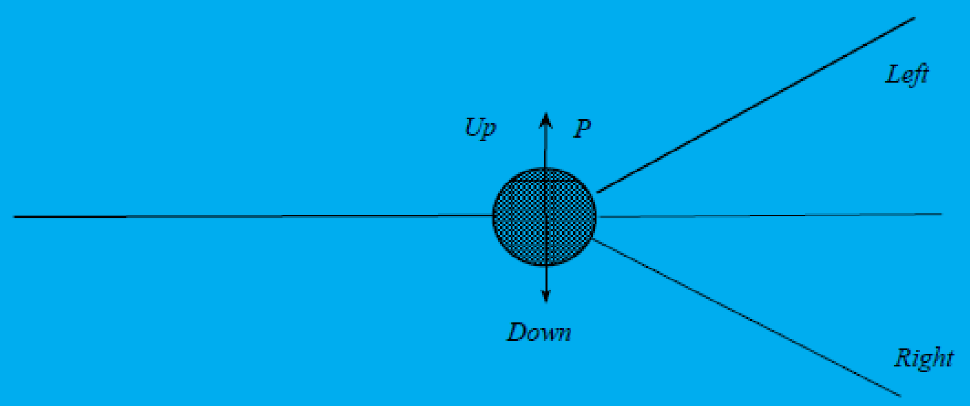
Оценку для ускорения можно связать с оценкой для угловой скорости, помножив и разделив очевидное выражение для нее на $T_\oplus/2\pi$:

$$\eta_{\rm acc} = \frac{c}{R_A}\cdot\frac{c}{g_\oplus} = \eta_{\rm rot}\,\frac{2\pi c}{T_\oplus g_\oplus} \approx 10^{30}. \qquad (10.2)$$

Дополнительный фактор $\sim 2000$ пропорционален отношению скорости света к скорости, приобретаемой в течение суток при движении с ускорением $g_\oplus$.

# Single Spin Asymmetries (vector polarization)

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: $\rho = \frac{1}{2}(1 + \vec{\sigma}\vec{P})$,

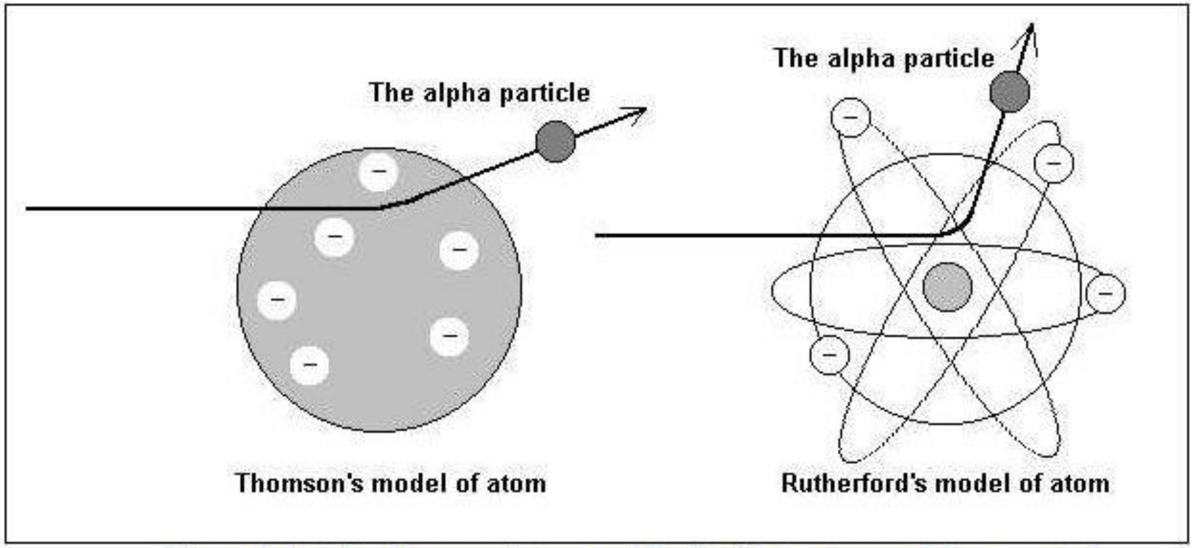
Differential cross-section: $d\sigma \sim 1 + A(\vec{P}\vec{n})$, $A = \frac{2Im(ab^*)}{|a|^2+|b|^2}$

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

# Вероятность рассеяния на определенном прицельном расстоянии пропорциональна сечению




The models of the Thomson's atom and Rurtherford's atom; and the expected aberrations of alpha particle in both cases.

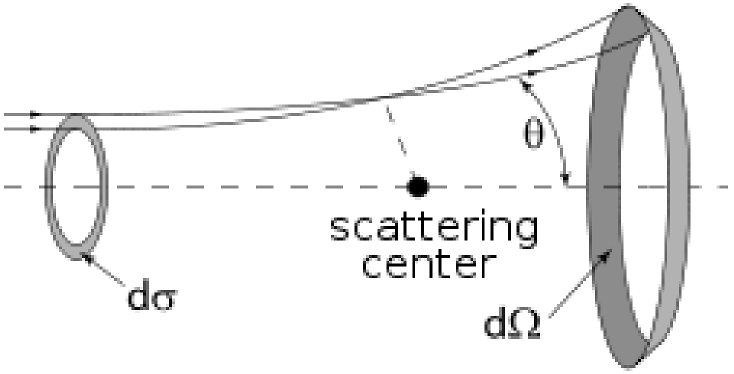
$$\sigma(\Omega)d\Omega = \frac{\text{number of particles scattered into solid angle d}\Omega\text{ per unit time}}{\text{incident intensity}}$$

$$b = \frac{Z_1 Z_2 e^2}{4\pi\epsilon_0 m v_0^2}\cot\frac{\Theta}{2}.$$

$$2\pi I b\,|db| = I\sigma d\Omega$$

$$\sigma = \frac{b}{\sin\Theta}\left|\frac{db}{d\Theta}\right|$$

$$\sigma = \left(\frac{Z_1 Z_2 e^2}{8\pi\epsilon_0 m v_0^2}\right)^2 \csc^4\left(\frac{\Theta}{2}\right).$$



# SSA

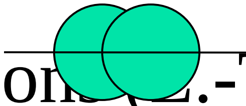
- Parity conservation – normal to (elastic or inclusive) scattering plane  (HIC – angular momentum)
- Interference – LS coupling (HIC-hydrodynamical axial anomaly)
- T conservation – absorptive phases (HIC : dissipation)

# $\Lambda$-polarisation

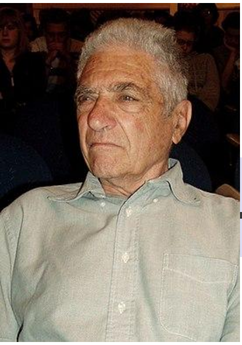
- Self-analyzing (spin-momentum couplins) in weak decay
- Directly related to s-quarks polarization: complementary probe of strangeness
- Widely explored in hadronic processes
- Disappearance-probe of QCD matter formation (Hoyer; Jacob, Rafelsky: ’87): Randomization – smearing – of the scattering plane

# 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!
- Due to locality of LS coupling while large orbital angular momentum is distributed
- How to transform rotation to spin?



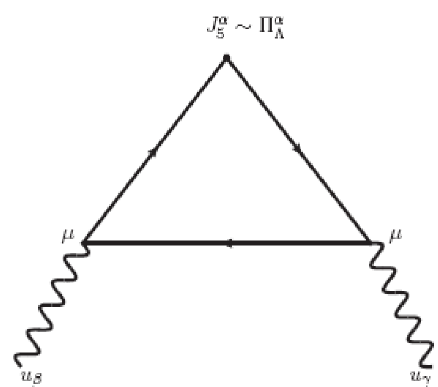
# Anomalous mechanism

Аномалии – нарушение законов сохранения квантовыми эффектами (впервые –Дж. Стейнбергер (1921-2020) в 1949 г. (в 1988 г. как экспериментатор стал лауреатом Нобелевской премии за открытие 2 типов нейтрино)

- 4-Velocity is also a GAUGE FIELD (V.I. Zakharov et al): $\mu\,\varrho = \mu\, J_0 V^0 \rightarrow \mu\, J_\gamma V^\gamma$

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

- 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!



# “Anomalous” mechanism

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

- Prediction of decrease with energy (due to chemical potential)

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 $\epsilon$ are the corresponding charge and energy densities and $P$ is the pressure. Therefore, the $\mu$ 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.

- 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 $\Lambda$ 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-

# 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=Σ r x p
- Differential pseudovector characteristics – vorticity
- ϖ = curl v
- Pseudoscalar – helicity
- H ~ <(v curl v)>
- Maximal helicity – Beltrami chaotic flows v || curl v

# Simulation in QGSM
(First calculation of vorticity in kinetic model; Baznat, Gudima, Sorin, OT, PRC'13)

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

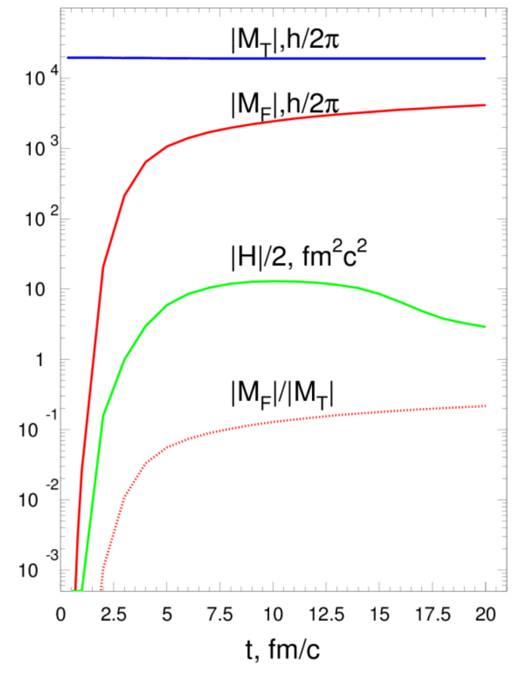
- Velocity

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

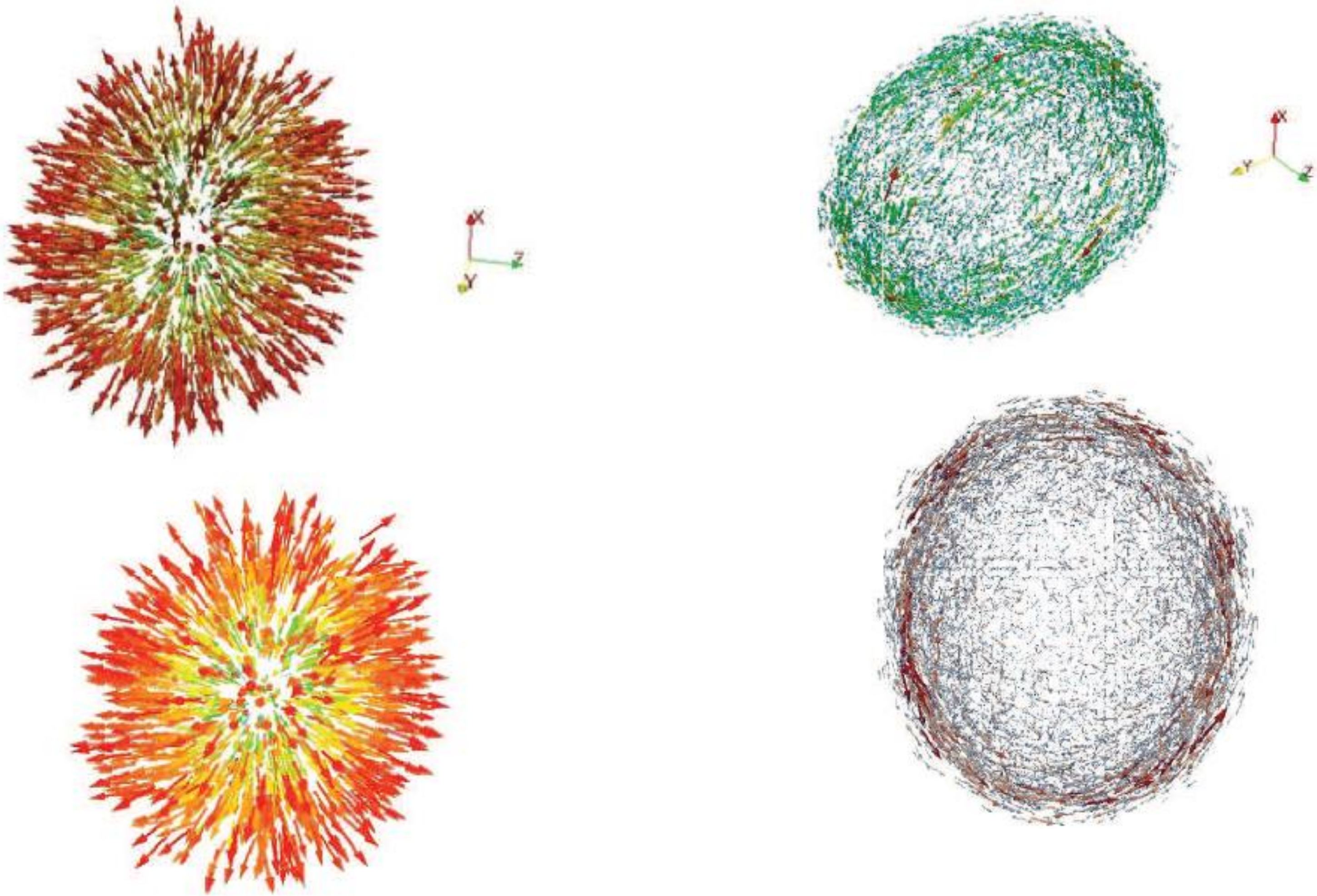
- Vorticity – from discrete partial derivatives

# Angular momentum conservation and helicity

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

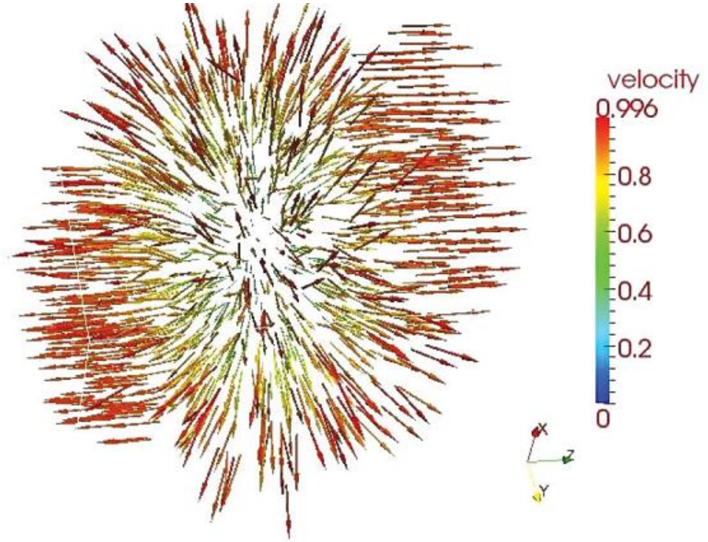


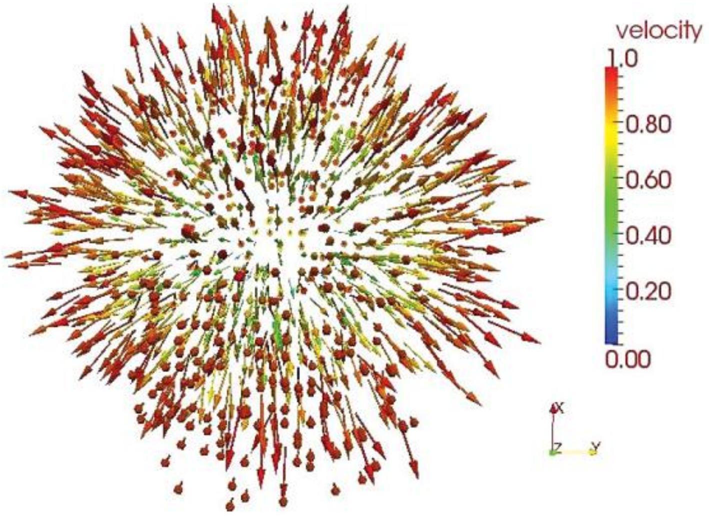
# Structure of velocity and vorticity fields (NICA@JINR-5 GeV/c)



# Distribution of velocity ("Little Bang")

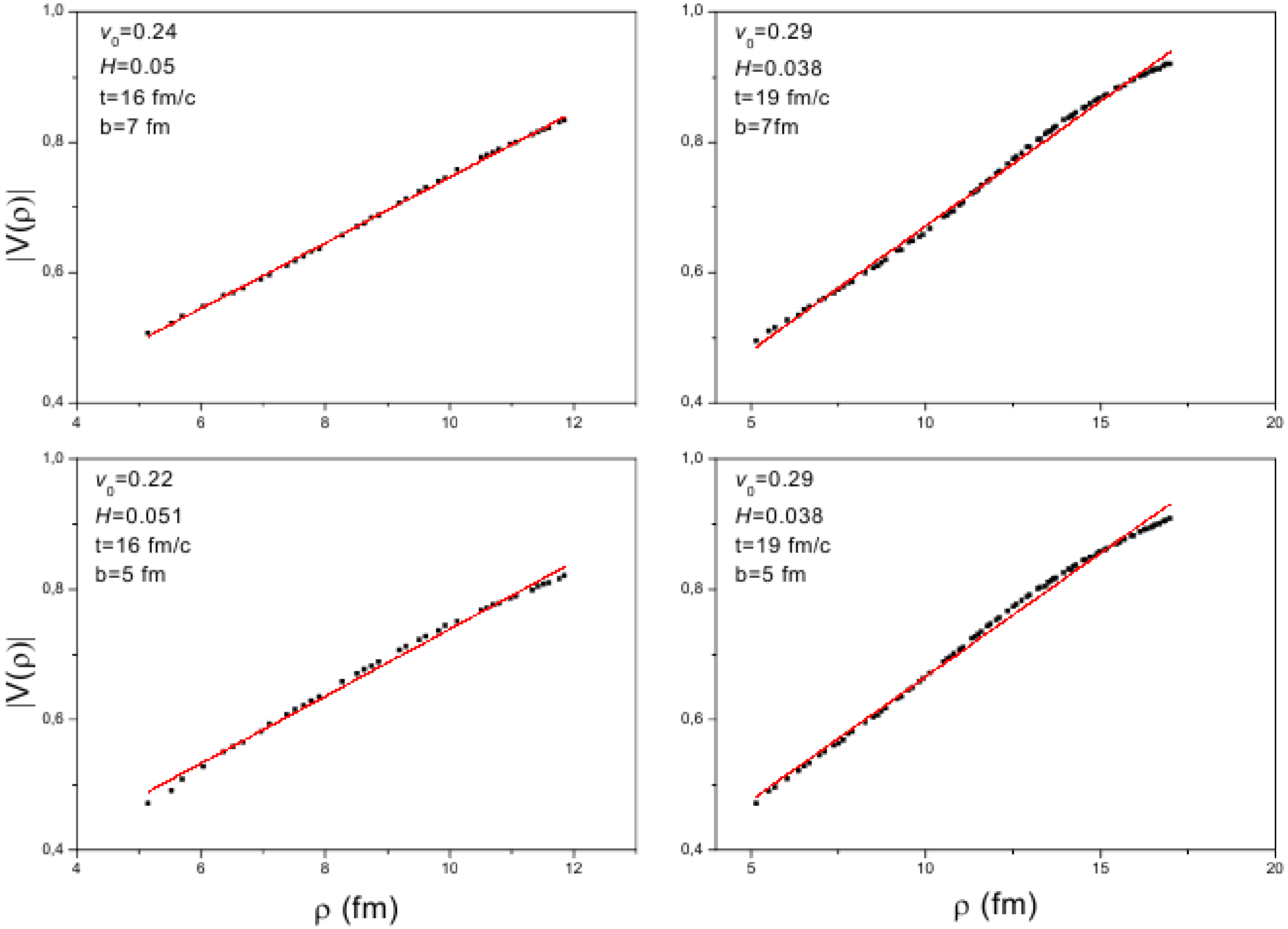
- 3D/2D projection
- z-beams direction
- x-impact paramater



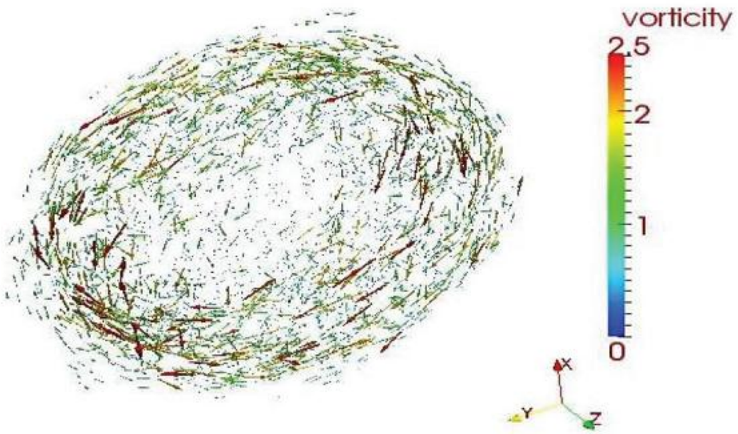
# “Little Hubble” in PHSD

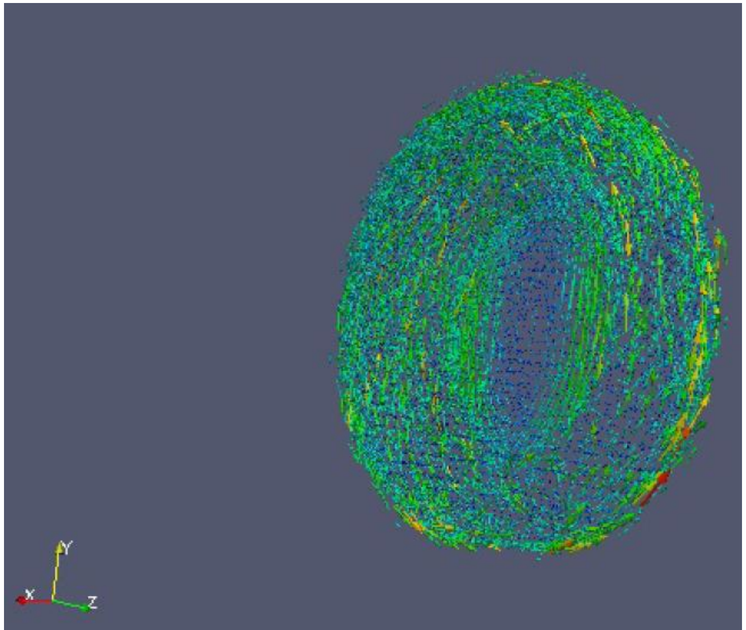
$$v = v_0 + H\rho$$

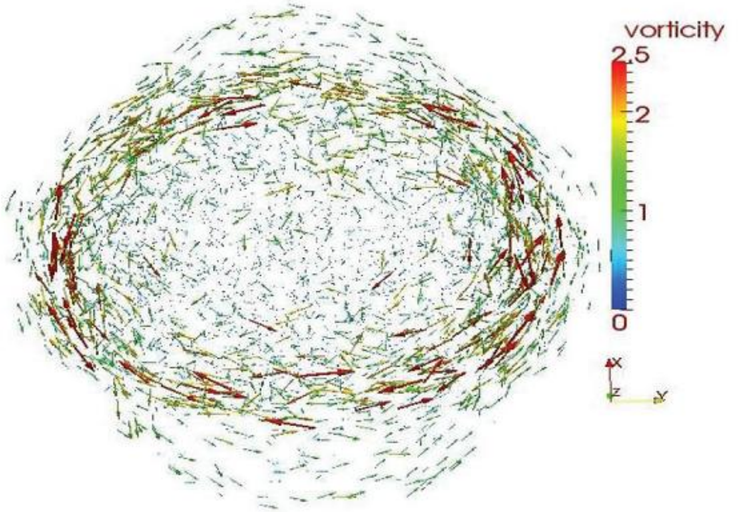


# Distribution of vorticity ("Femto-cyclones", "Little galaxies")

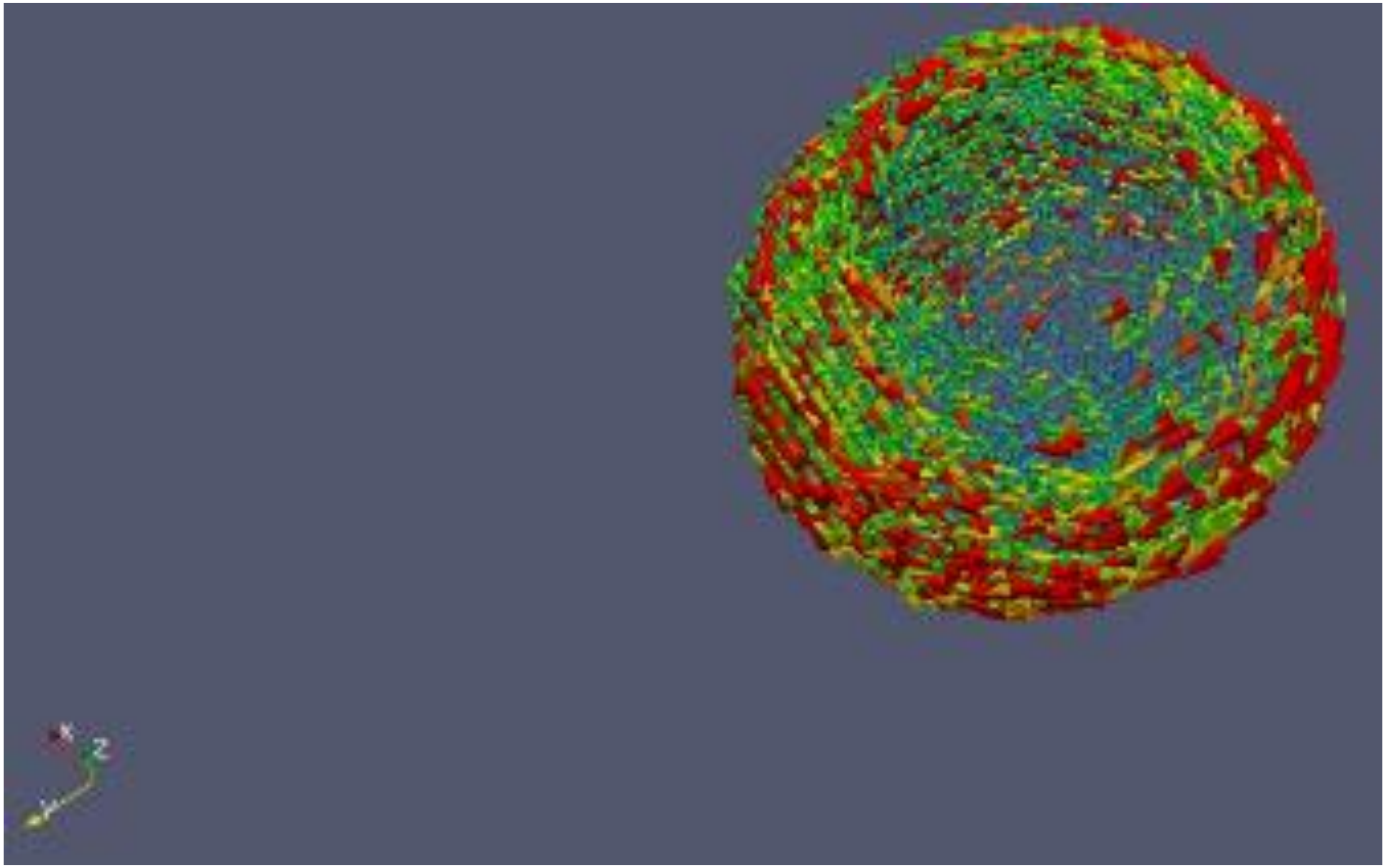
- Layer (on core - corona borderline) patterns



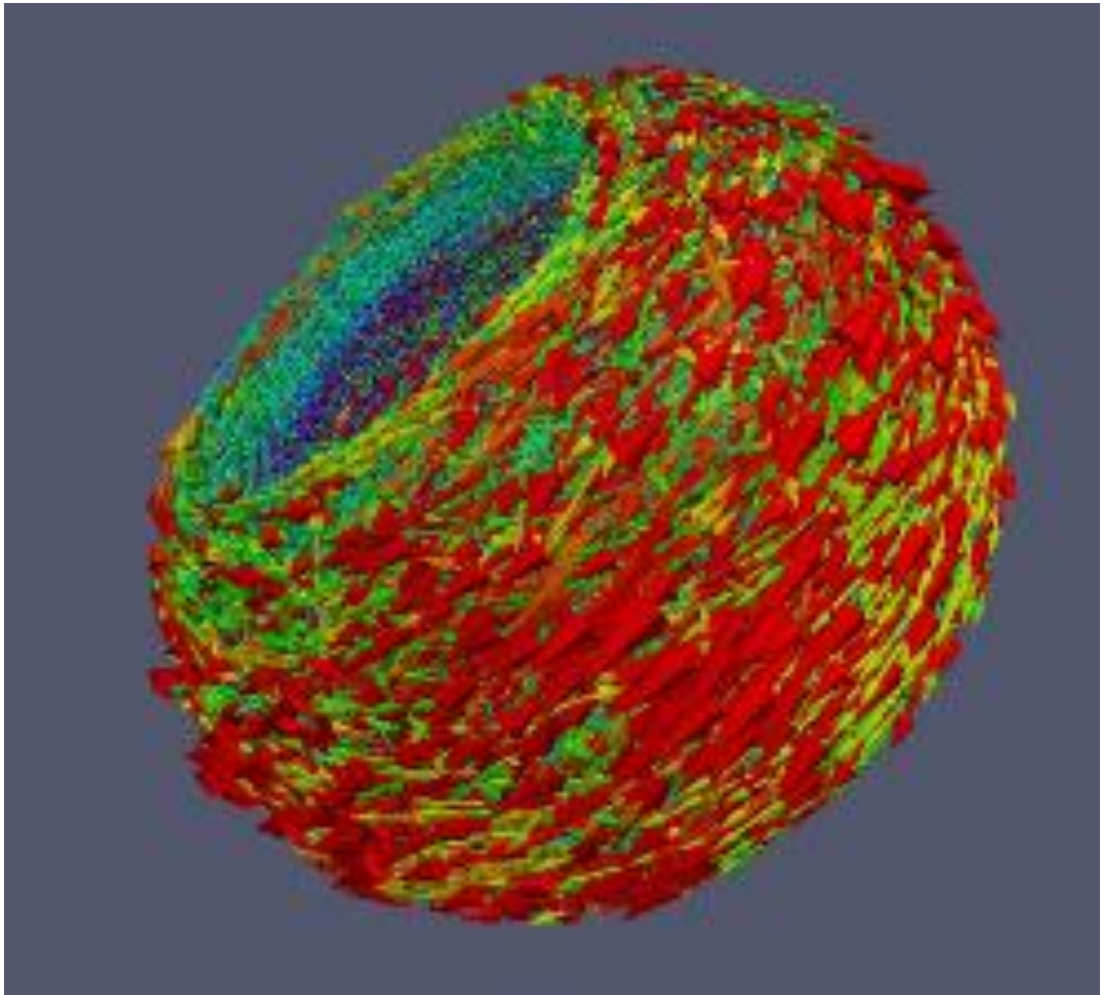



# Vortex sheet (Femto-cyclone) with fixed direction of L

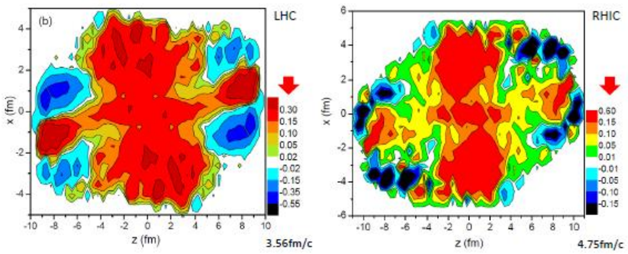


# Vortex sheet ( Average over L directions )

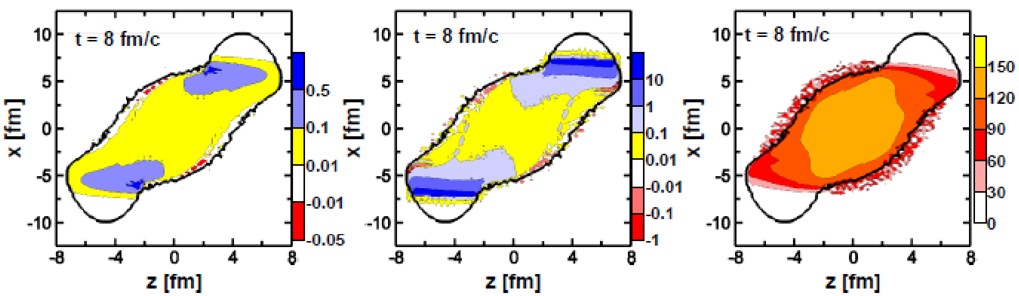


# Vortex sheets

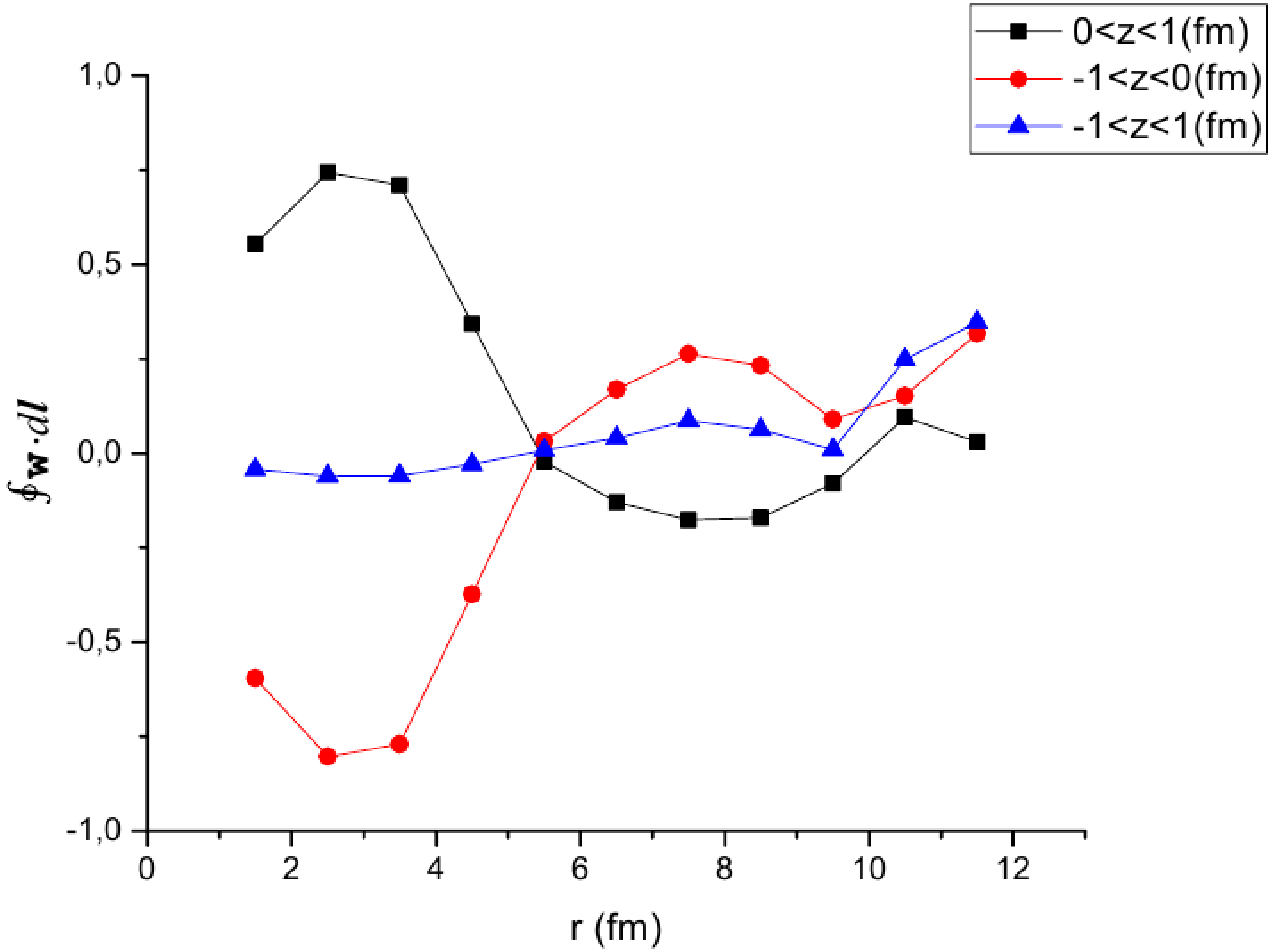
- Naturally appears in kinetic models
- Absent in viscous HD (L. Csernai et al)




- Appears in 3 fluid dynamics model (Yu. Ivanov, A. Soldatov,PRC’17)

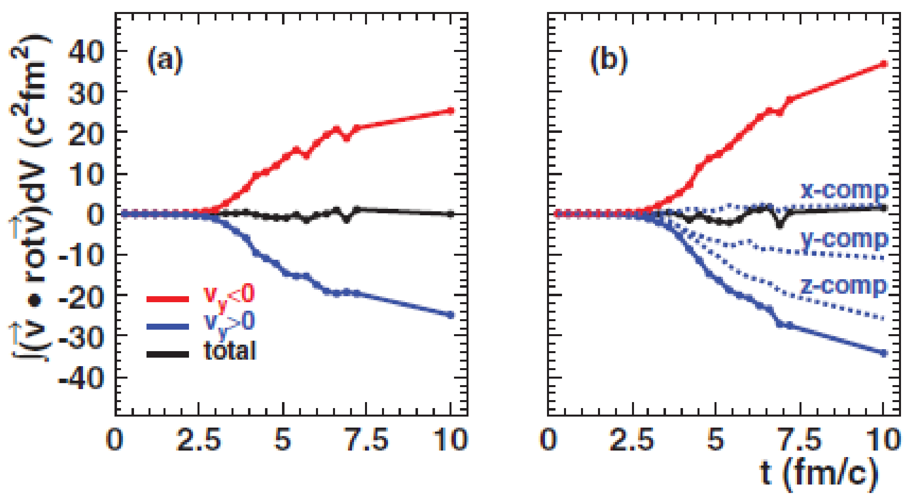


# Mirror vortex rings in PHSD

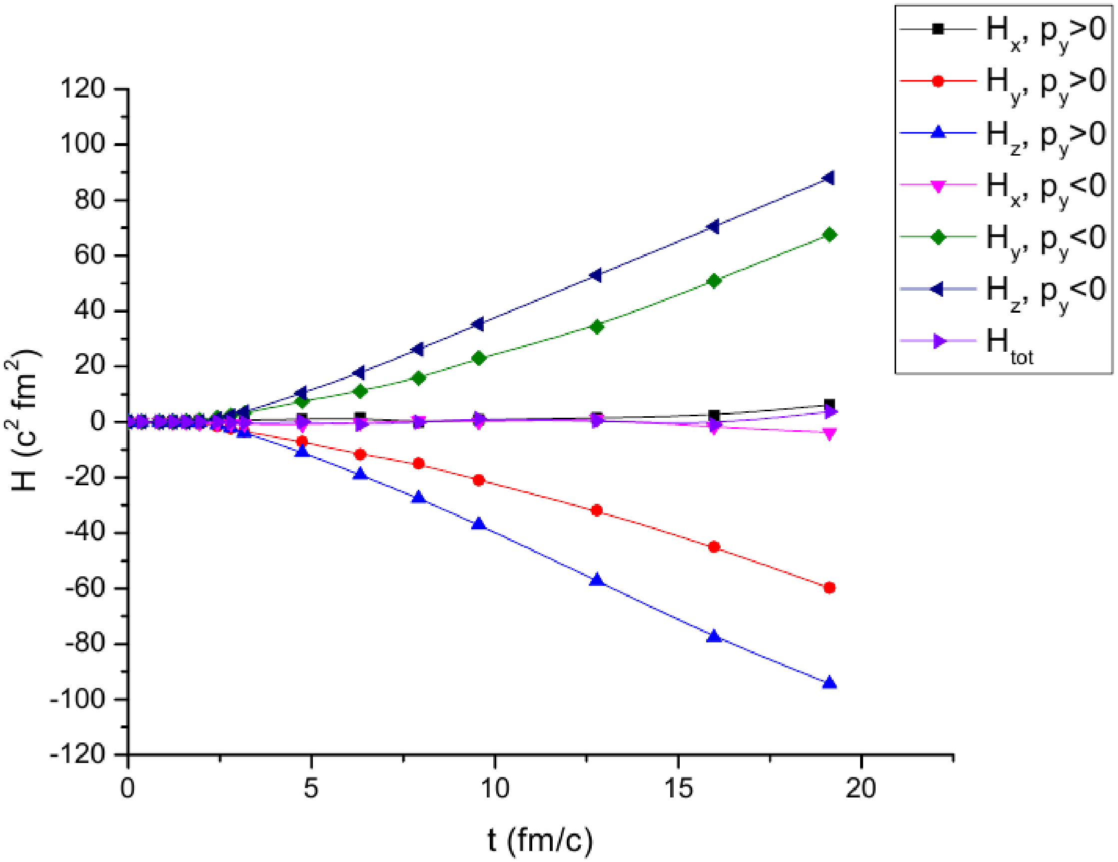


# Helicity separation in QGSM
# **PRC88 (2013) 061901**

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

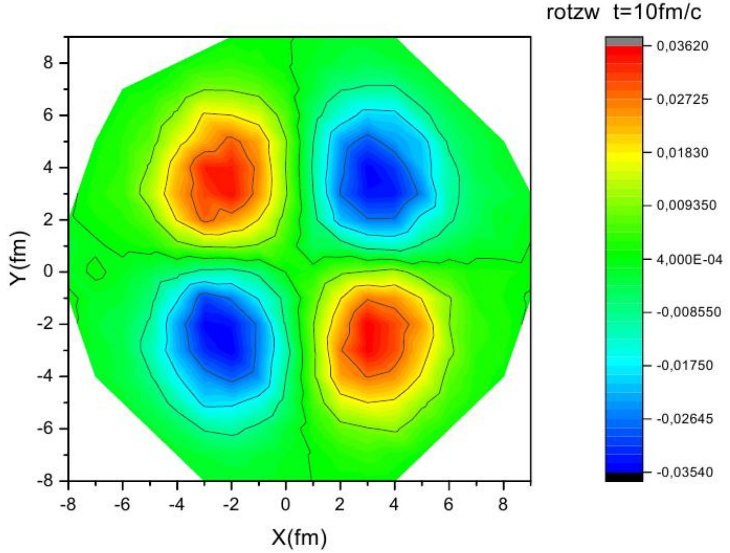


# Helicity@PHSD

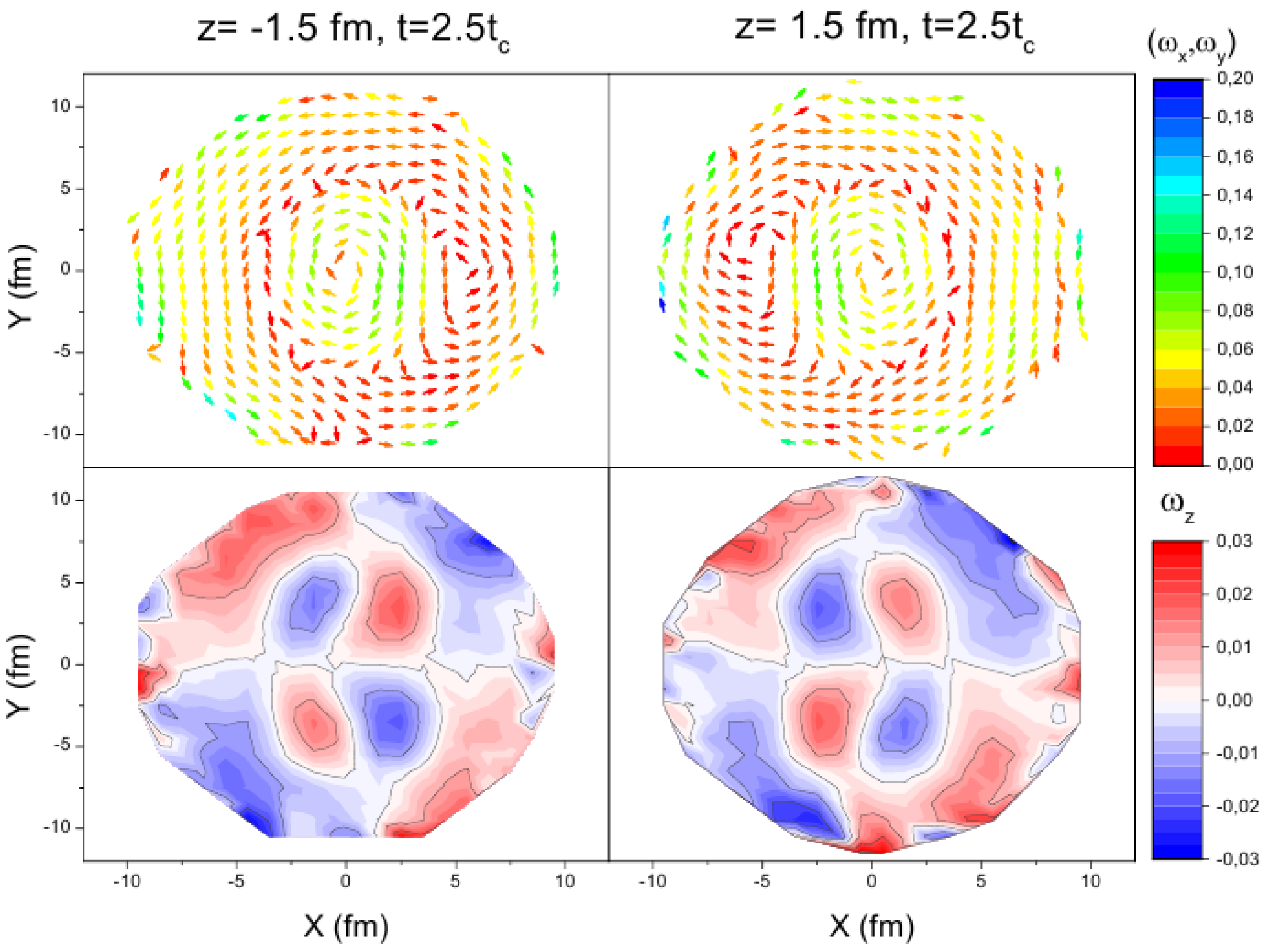


# Structure of vorticity (Baznat, Gudima, Sorin, OT'17)

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



# PHSD: 2nd Quadrupole Structure



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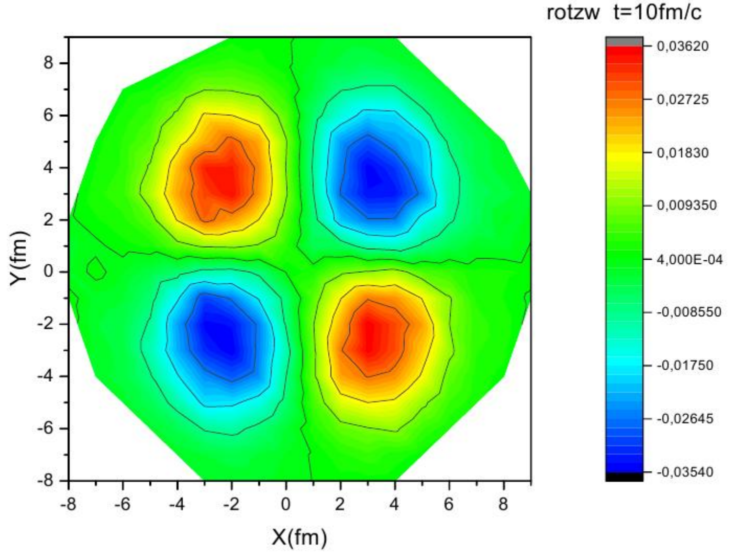
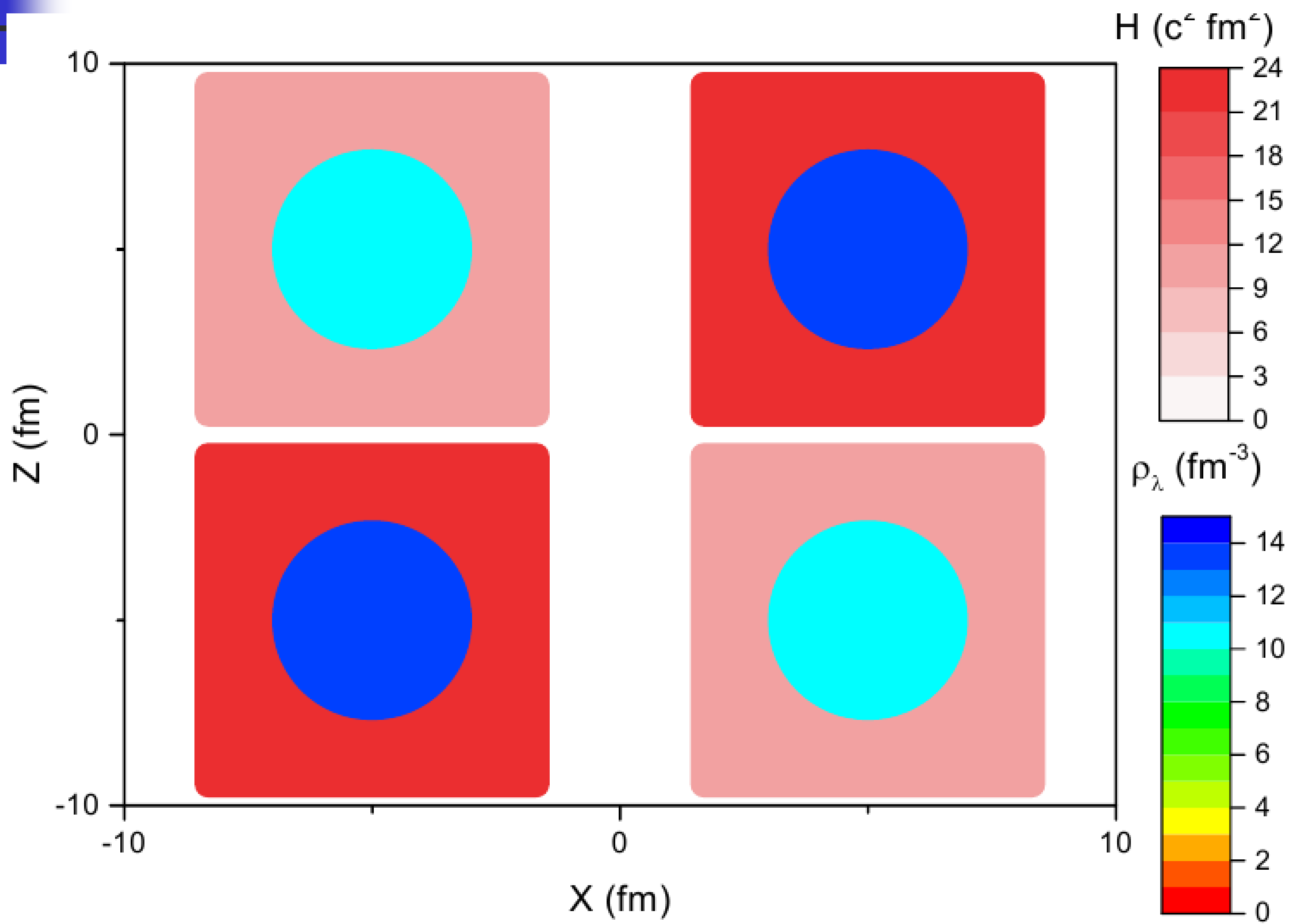
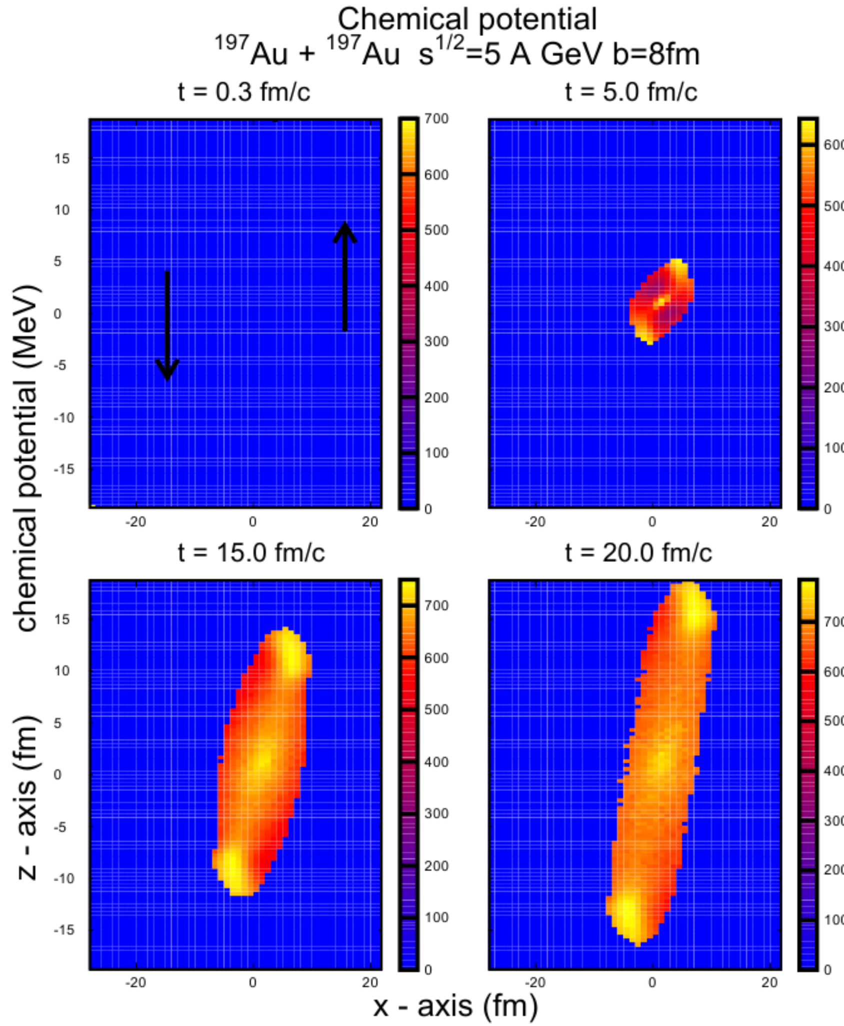


# XZ- structure of helicity and polarization

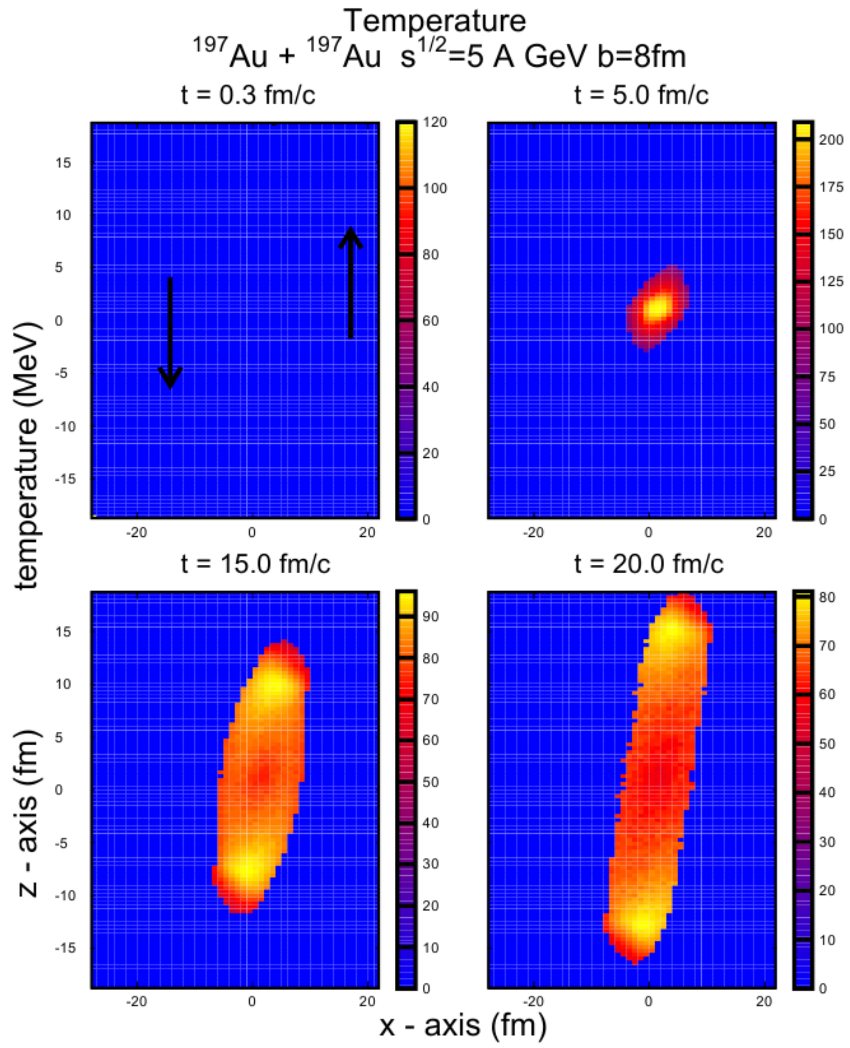


# Chemical potential : Kinetics -> TD

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

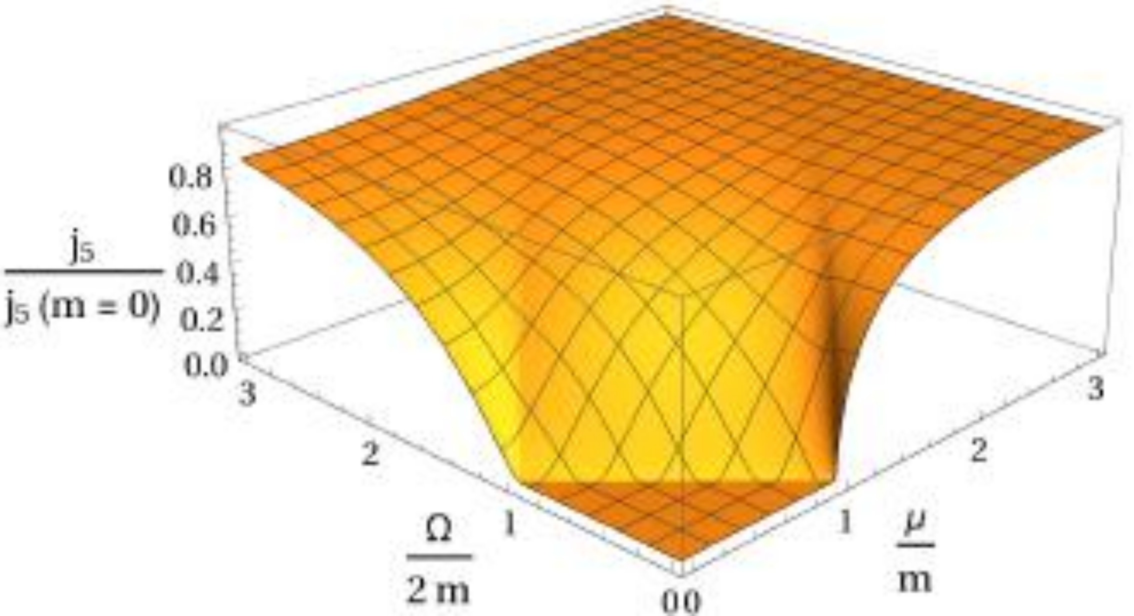


# Temperature



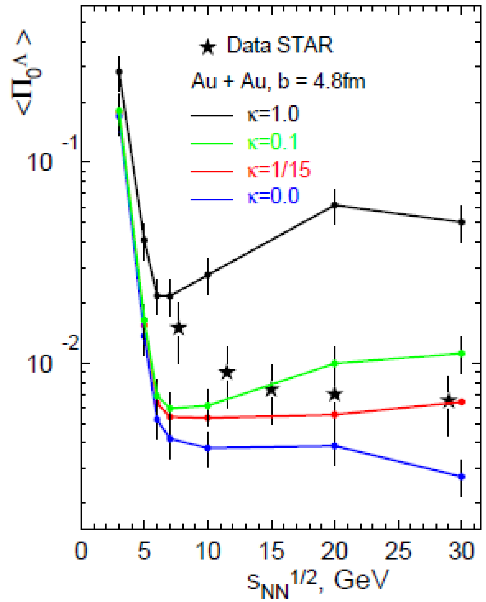
# Axial current in TD approach: Role of mass effects (Prokhorov, OT, Zakharov, PRD98 (2018), 071901)

- Threshold effects in chemical potential and angular velocity; 1906.03529: acceleration (important for longitudinal polarization)



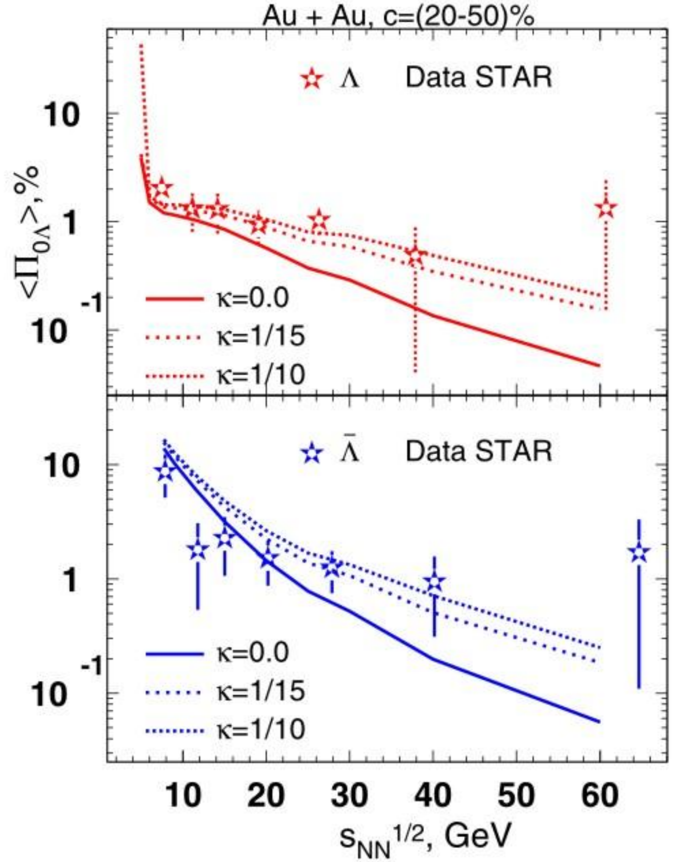
# The role of (gravitational anomaly related) $T^2$ term

- 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
<Π$_{0Λ}$>, %
κ=0.0
κ=1/15
κ=1/10
10
1
$10^{-1}$
10 20 30 40 50 60
$s_{NN}^{1/2}$, GeV

## 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** $\omega^\mu$ and **acceleration** $a^\nu$. The axial current is related to the hyperon **polarization**. **New** contributions to current and **polarization**:

**KVE:**

$$j_A^\mu = \lambda_1(\omega_\nu\omega^\nu)\omega^\mu + \lambda_2(a_\nu a^\nu)\omega^\mu$$

Transport coefficients

***Connection with anomaly and gravity:***

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

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

- **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")

# Gravitational Formfactors

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

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

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

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

- May be extracted from high-energy experiments/NPQCD calculations
- Describe the partition of angular momentum between quarks and gluons
- Describe interaction with both classical and TeV gravity

# Generalized Parton Diistributions (related to matrix elements of non local operators ) – models for both EM and Gravitational Formfactors (Selyugin,OT ’09)

- Smaller mass square radius (attraction vs repulsion!?)

$$\rho(b) = \sum_q e_q \int dx q(x,b) \qquad = \int d^2 q F_1(Q^2 = q^2) e^{i\vec{q}\,\vec{b}}$$

$$= \int_0^\infty \frac{q dq}{2\pi} J_0(qb) \frac{G_E(q^2) + \tau G_M(q^2)}{1+\tau}$$

$$\rho_0^{\rm Gr}(b) = \frac{1}{2\pi} \int_\infty^0 dq q J_0(qb) A(q^2)$$

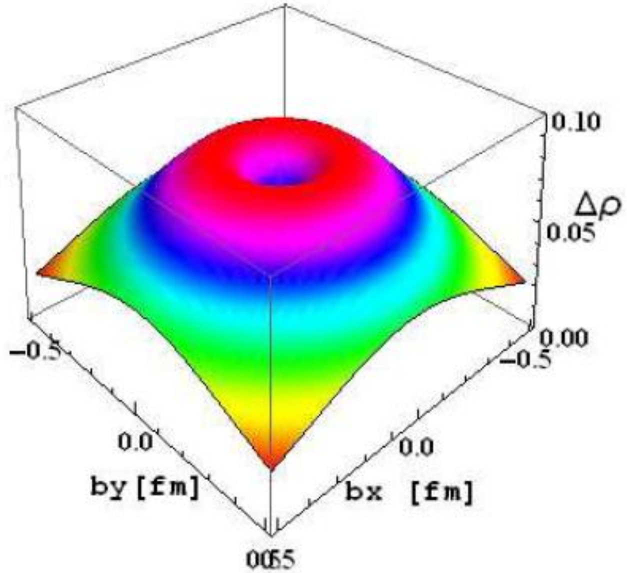



FIG. 17: Difference in the forms of charge density $F_1^P$ and "matter" density $(A)$

# Electromagnetism vs Gravity

- 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

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

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

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

- Mass as charge – equivalence principle (Einstein ’10-11, Praha)

# Equivalence principle

- Newtonian – “Falling elevator” – well known and checked with high accuracy (also for elementary particles)
- Post-Newtonian – gravity action on 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 Zakharov
- Anomalous gravitomagnetic (and electric-CP-odd) moment iz ZERO or
- Classical and QUANTUM rotators behave in the SAME way

- For GEDM –checked with sometimes controversial results
- For AGM not checked on purpose but in fact checked in the same atomic spins experiments at % level (Silenko,OT’07)

# 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

# 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=0 -> constraint for AGM (Silenko, OT'07) from Earth rotation – was considered as obvious (but it is just EP!) background

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

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

# Gyromagnetic and Gravigyromagnetic ratios

- Free particles – coincide
- $<P+q|T^{mn}|P-q> = P^{\{m}<P+q|J^{n\}}|P-q>/e$ up to the terms linear in q
- Special role of g=2 for any spin (asymptotic freedom for vector bosons)

- Should Einstein know about PNEP, the outcome of his and de Haas experiment would not be so surprising
- Recall also g=2 for Black Holes. Indication of "quantum" nature?!

# Cosmological implications of PNEP

- Necessary condition for Mach's Principle (in the spirit of Weinberg's&MTW textbooks) -
- Lense-Thirring inside massive rotating

empty shell (=model of Universe)

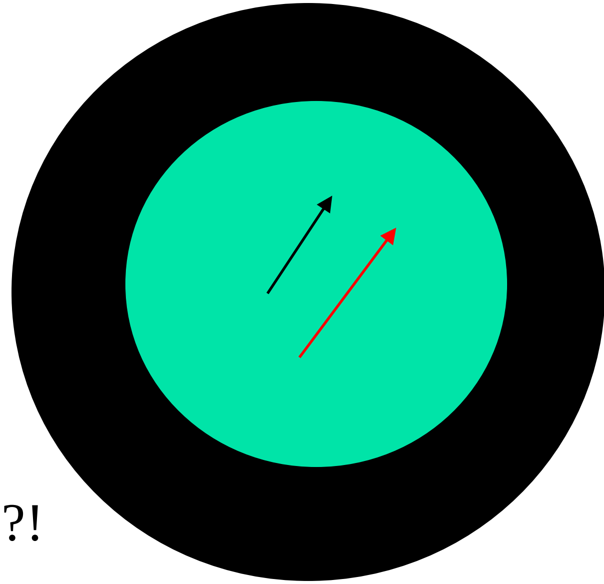
- For $E_G=E_M$ (inflated, produced from

vacuum, flat?) "Universe" -
equal to that of shell rotation

- Simple observation-Must be the
and quantum rotators –

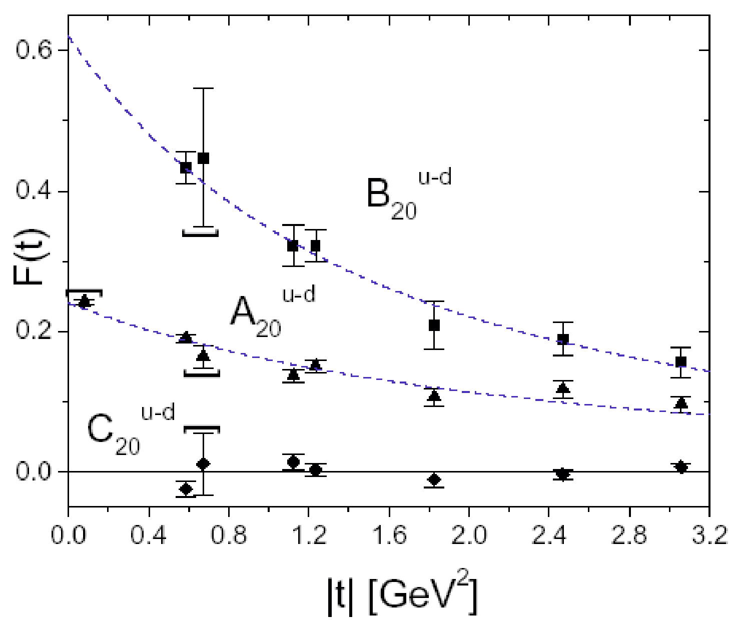
PNEP!

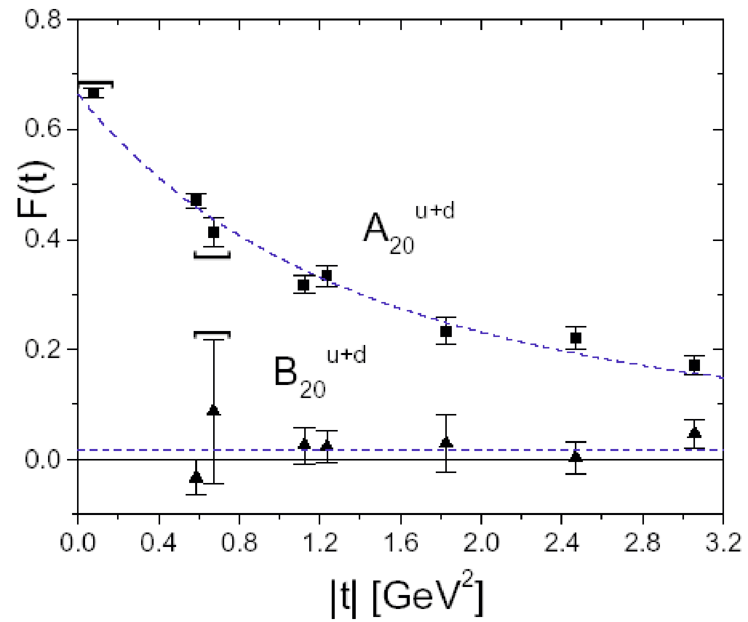
- More elaborate models - Tests for cosmology ?!



# Generalization of Equivalence principle

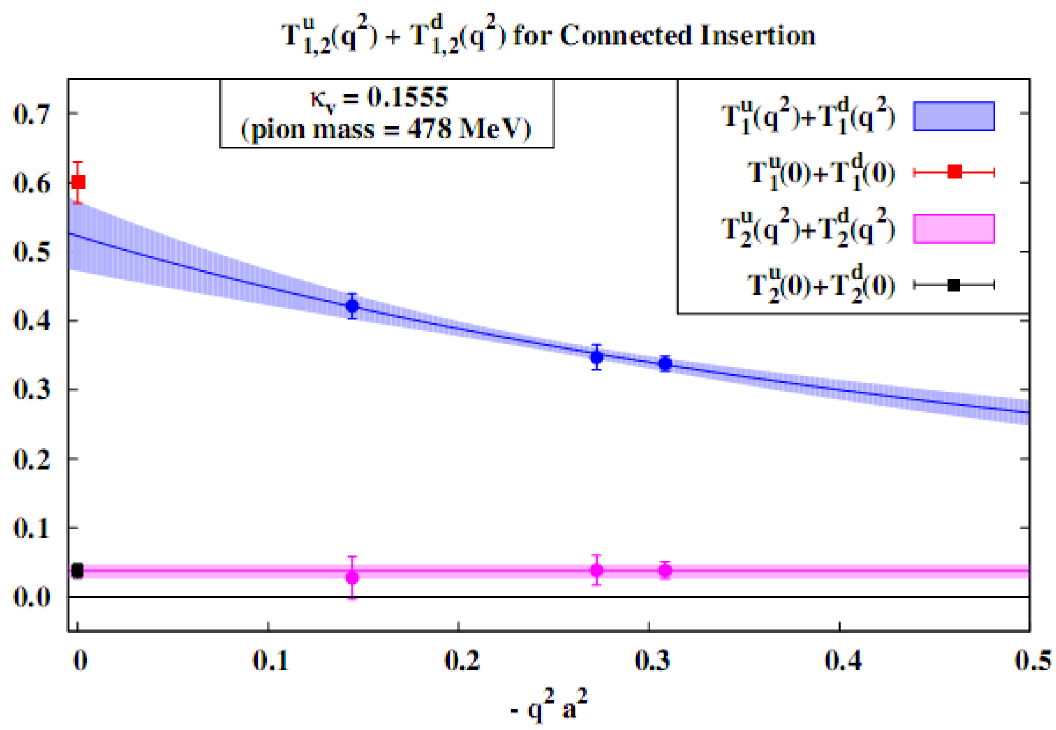
- Various arguments: AGM ≈0 separately for quarks and gluons – most clear from the lattice (LHPC/SESAM)



# Recent lattice study (M. Deka et al. arXiv:1312.4816)

- Sum of u and d for Dirac (T1) and Pauli (T2) FFs

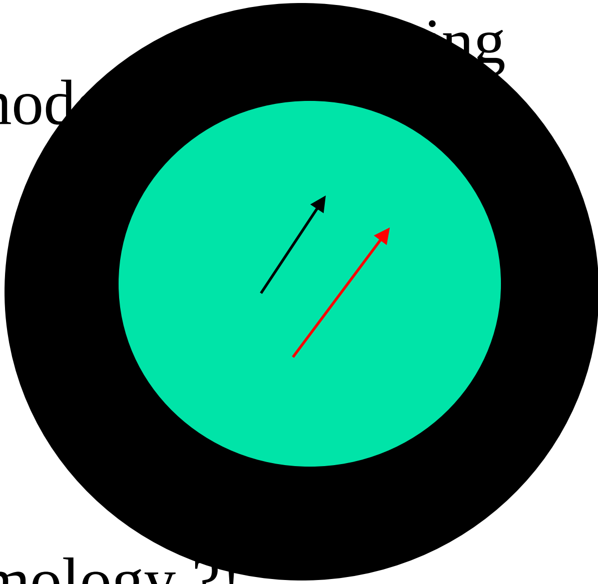


# Extended Equivalence Principle=Exact EquiPartition

- In pQCD – violated
- Reason – in the case of ExEP- no smooth transition for zero fermion mass limit (Milton, 73)
- Conjecture (O.T., 2001 – prior to lattice data) – valid in NP QCD – zero quark mass limit is safe due to chiral symmetry breaking
- Gravity-proof confinement (should the hadrons survive eneteering Black Hole?)?!

# Cosmological implications of PNEP

- Necessary condition for Mach's Principle (in the spirit of Weinberg's textbook) -
- Lense-Thirring inside massive ing empty shell (=mod
- For flat "Universe" - frequency rotation
- Simple observation-Must be the for classical and quantum PNEP!
- More elaborate models - Tests for cosmology ?!

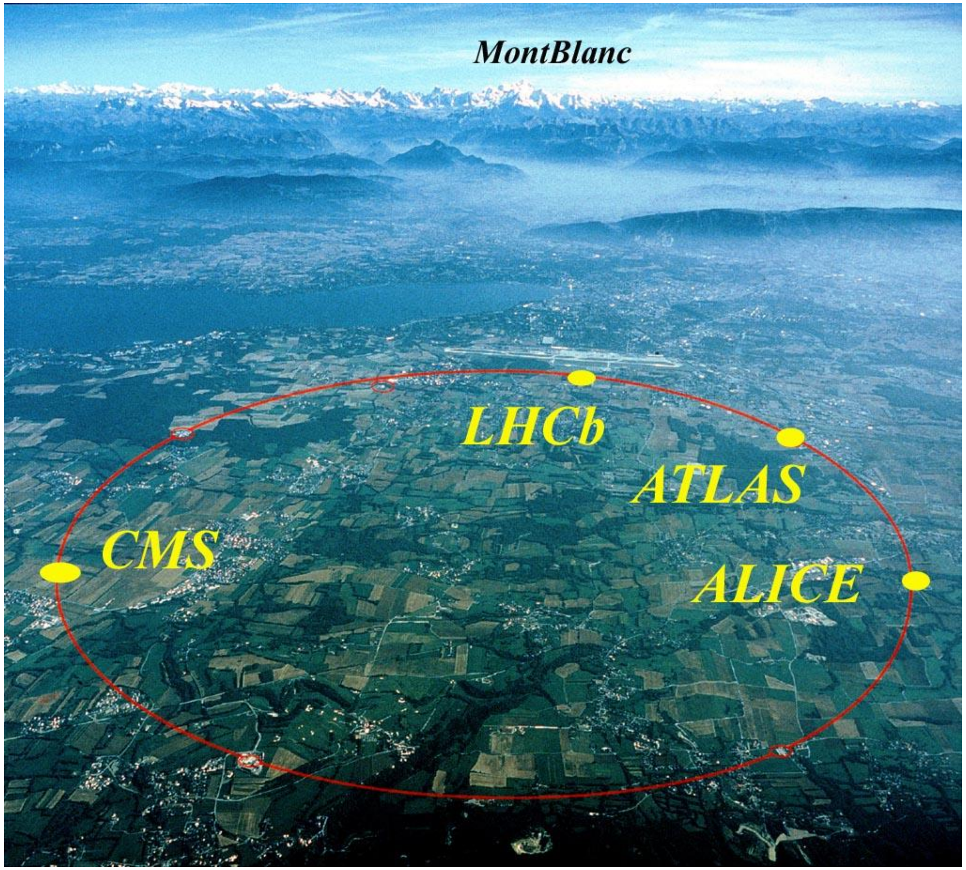


# Заключение

- Аномалии и гравитация – проявляются в спиновой структуре адронов и поляризации в столкновениях тяжелых ионов
- NICA – поляризация в соударениях тяжелых ионов и адронов - зависящие от поперечного импульса (косвенно связаны с гравитационными формфакторами) глюонные распределения
- Множество нерешенных вопросов

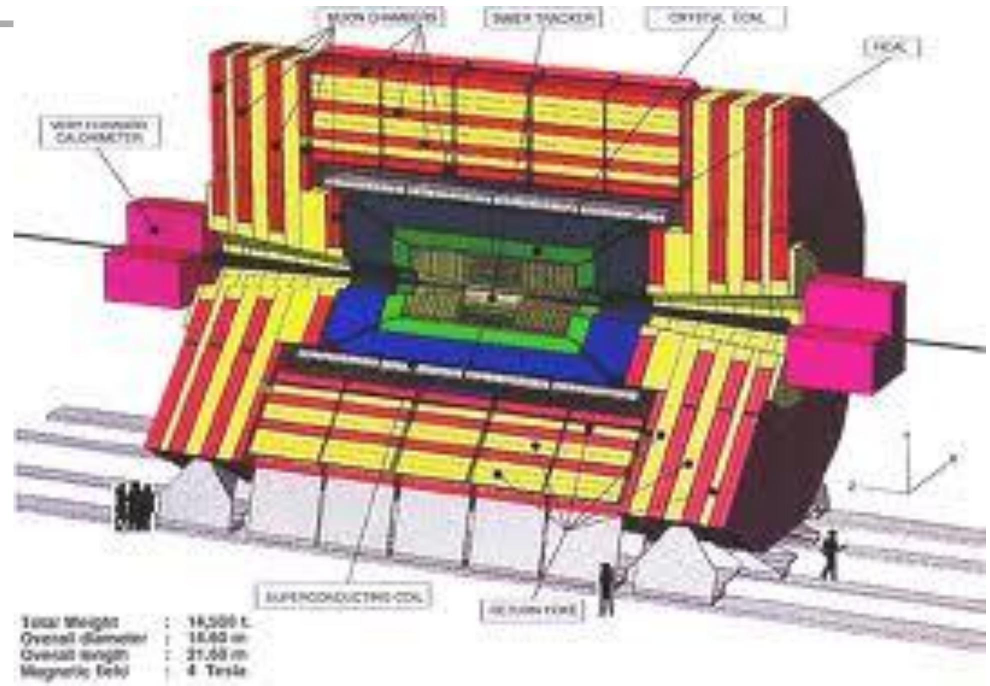
и в теории, и в эксперименте ждут вас!

# Большой Адронный Коллайдер



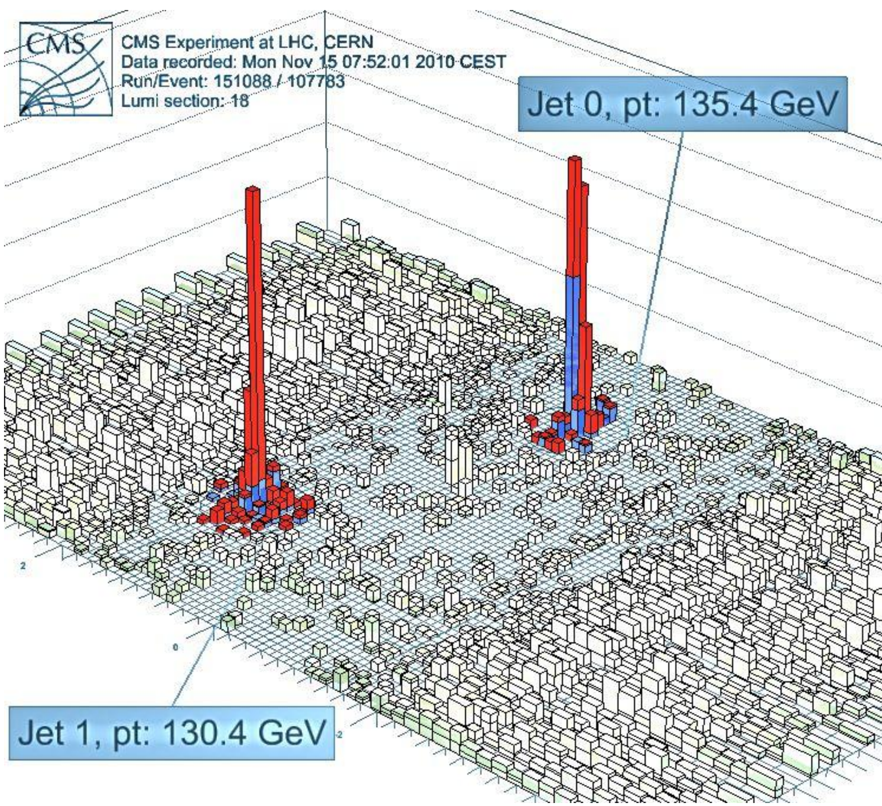
# Ускоритель

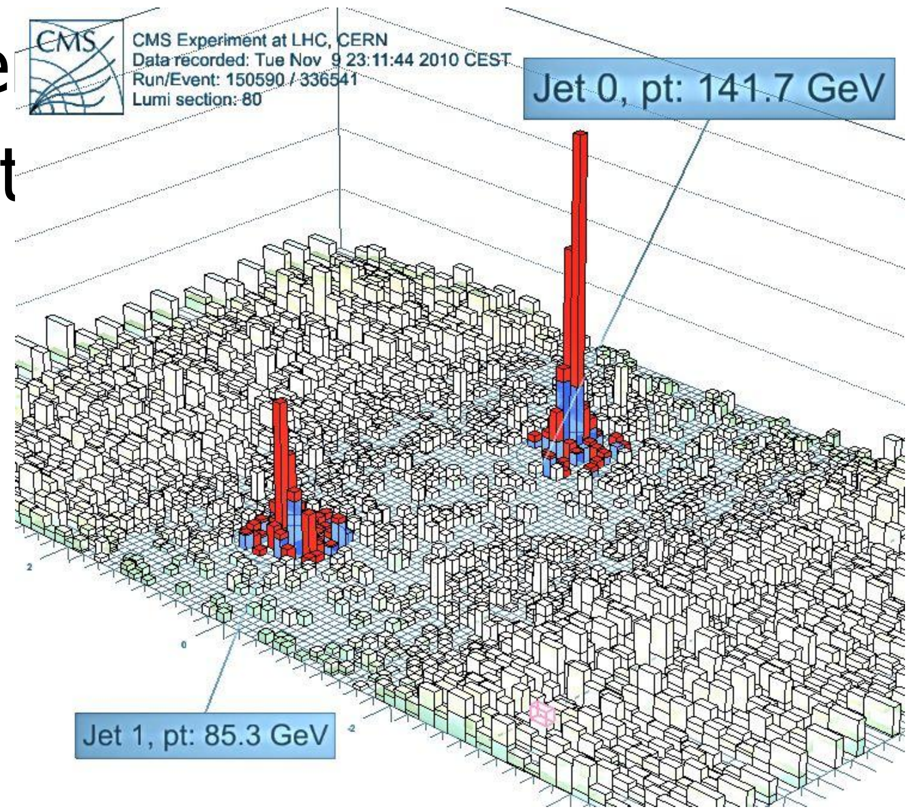
# Детектор (CMS)



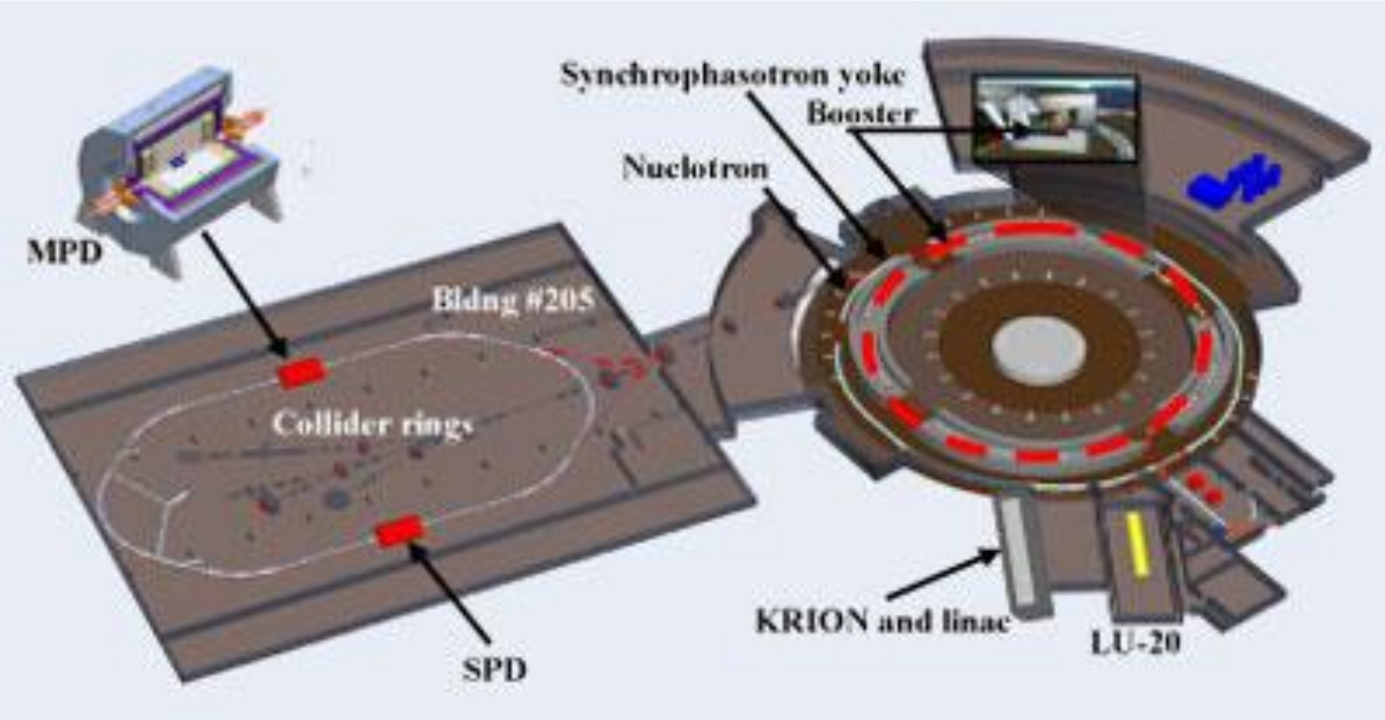

# Dijet event candidates in CMS

- First hours of LHC running

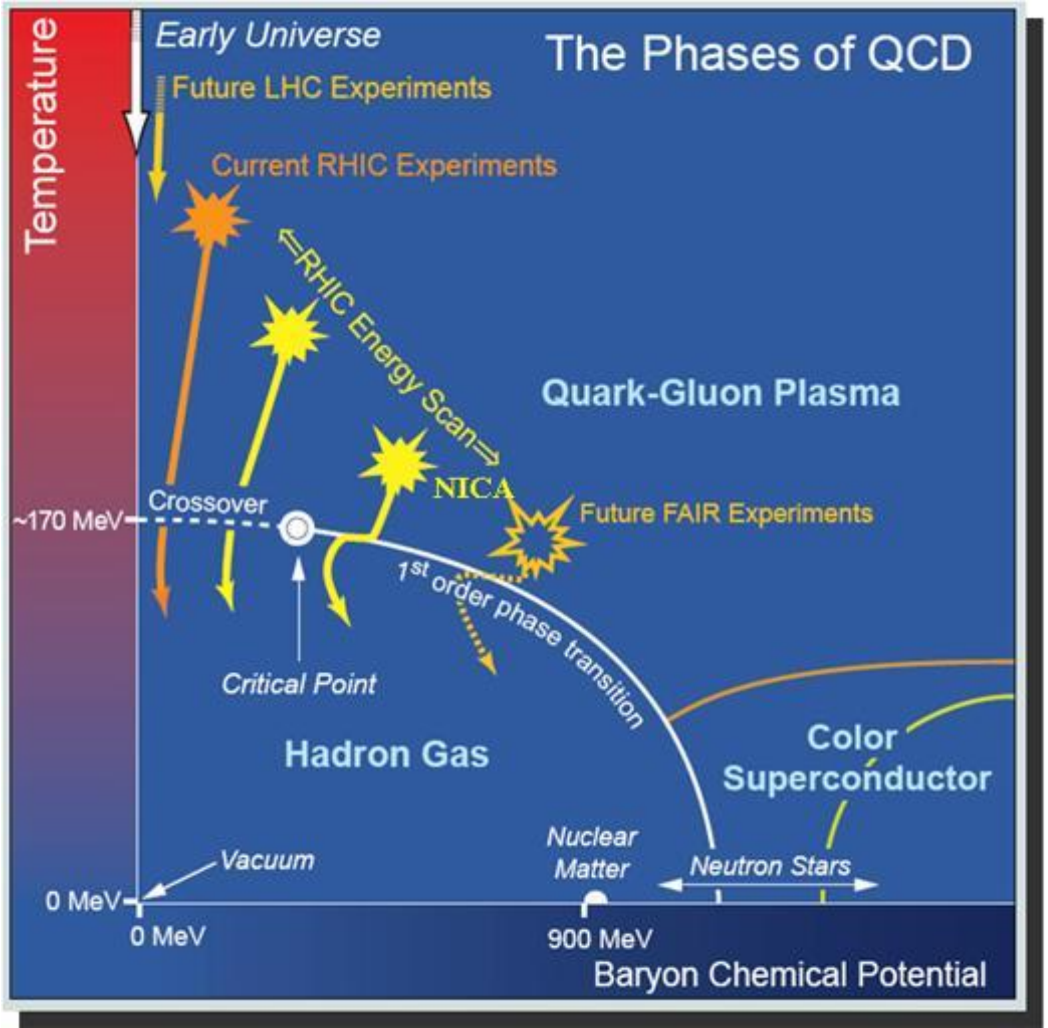


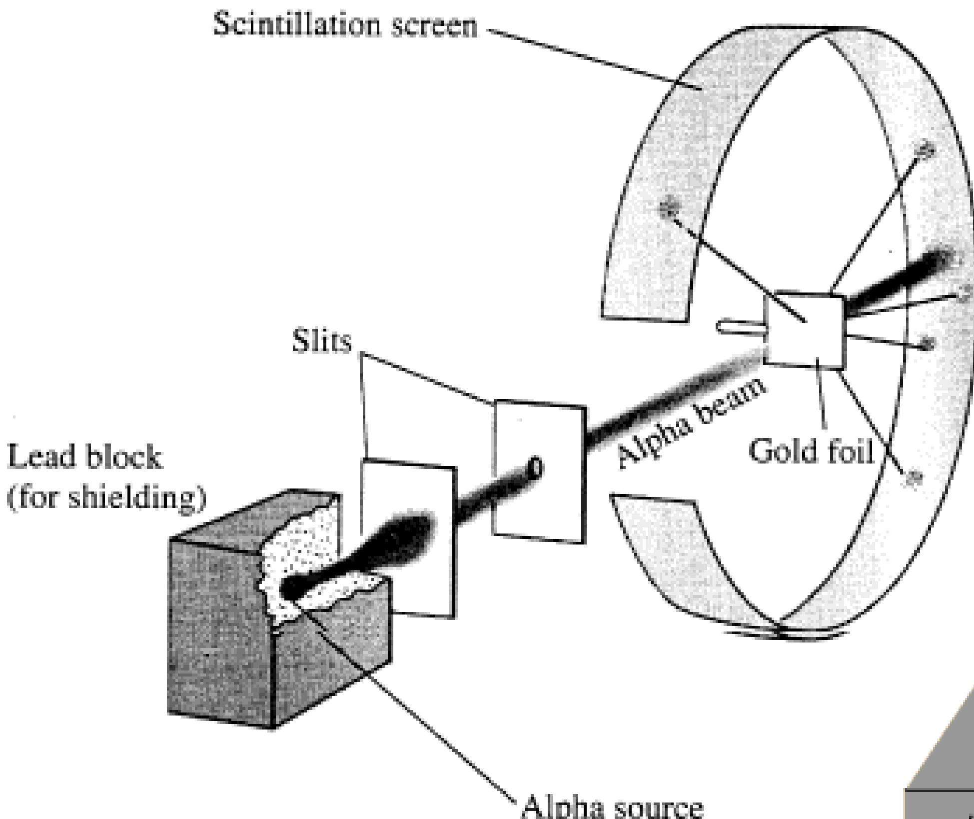
# ОИЯИ – NICA=Nuclotron-based Ion Collider fAcility

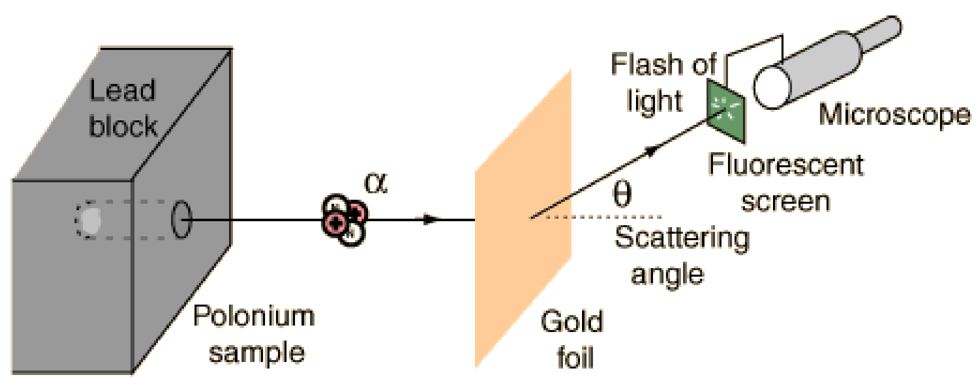


# Фазы кварк-адронной материи

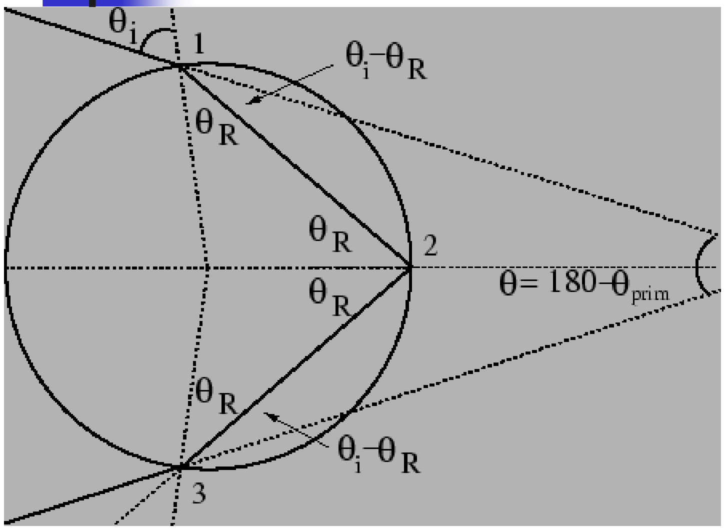


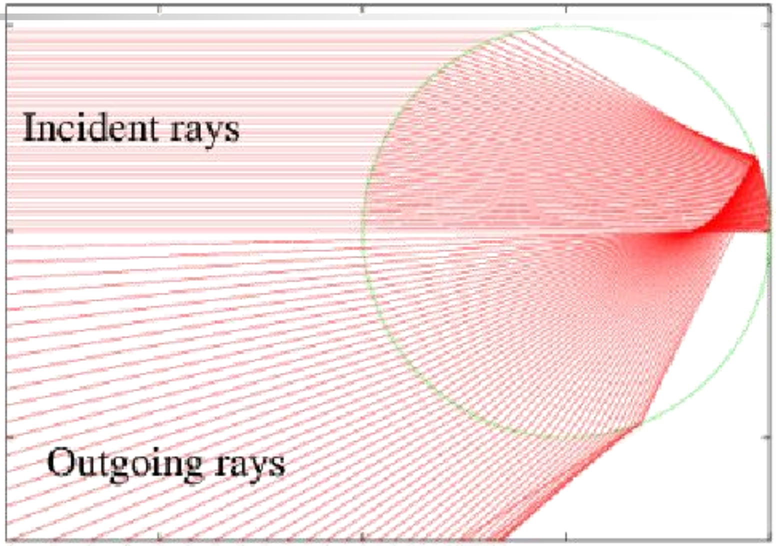
# Начало: Резерфорд (1911)
# Протоны <-> альфа-частицы
# Ускоритель <-> их источник
# Детектор <-> флюоресцентный экран



# Радуга как бесконечное сечение




$$\theta = (\theta_i - \theta_r) + (180 - 2\theta_r) + (\theta_i - \theta_r) = 180 + 2\theta_i - 4\theta_r$$

$$0 = \frac{d\theta}{d\theta_i} = 2 - \frac{4cos\theta_i}{n_{water}\sqrt{1 - \frac{sin^2\theta_i}{n^2_{water}}}}$$

$$\theta_i = cos^{-1}\left[\frac{1}{3}\left(n^2_{water} - 1\right)\right]^{\frac{1}{2}}$$

$$\theta_{primary} = 180 + 2cos^{-1}\left[\frac{1}{3}\left(n^2_{water} - 1\right)\right]^{\frac{1}{2}} - 4sin^{-1}\left[\frac{sin\left[cos^{-1}\left[\frac{1}{3}\left(n^2_{water} - 1\right)\right]^{\frac{1}{2}}\right]}{n_{water}}\right]$$

# Видимость в тумане и вероятность столкновения с айсбергом при ясной погоде – сечение при разном числе измерений

- Видимость в тумане (задача П.Л. Капицы):
- $L\, s/d^3 \sim 1$
- s – (2-мерное) сечение капли
- d – среднее расстояние между каплями
- L – видимость = длина свободного пробега

- "Титаник" и айсберги:
- $L\, s/d^2 \sim 1$
- …
- s (1-мерный) размер льдины
- s=100m, d=100km -> L= 100.000км (~ 100 рейсов)

# Hard exotics: Theoretical Interpretation of L3 data on neutral and charged rho's production in collisions of virtual and real photons

Observation: Q dependence of charged/ neutral ratio

Large Q

$$\frac{d\sigma}{dQ^2}(\rho^+\rho^-) : \frac{d\sigma}{dQ^2}(\rho^0\rho^0) = 2 : 1$$

Small Q

$$\frac{d\sigma}{dQ^2}(\rho^0\rho^0) > \frac{d\sigma}{dQ^2}(\rho^+\rho^-)$$

The L3 data can be described by exotical 4 – quarks isotensor resonance – higher twist 4 – explains Q suppression

*I.V. Anikin, B.Pire, O.V. Teryaev PLB 626 (2005) 86; PRD 69 (2004) 014018*

# Exloring hard exotics in QCD

- The QCD fit of L3 data is compatible with the existence of isotensor (I=2) four quark exotic meson with
  mass: 1.5 GeV
  width: 0.4 GeV

neutral – red

charged - blue