Vortex rings and global hyperon polarization in heavy-ion collisions at NICA energies

based on *Phys.Rev.C 107 (2023) 3*, *Particles 6 (2023) 1*, *arXiv:2305.10792*

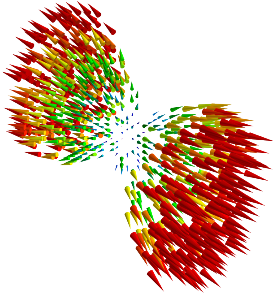
Nikita Tsegelnik[1,*] Evgeni Kolomeitsev[1,2] Vadim Voronyuk[3,4]

[1]*Bogoliubov Laboratory of Theoretical Physics, JINR, Dubna, Russia*
[2]*Matej Bel University, Banska Bystrica, Slovakia*
[3]*Laboratory of High Energy Physics, JINR, Dubna, Russia*
[4]*Bogolyubov Institute for Theoretical Physics, Kiev, Ukraine*

[*]tsegelnik@theor.jinr.ru

Alushta-2023, 08.06.23

Heavy-ion collisions



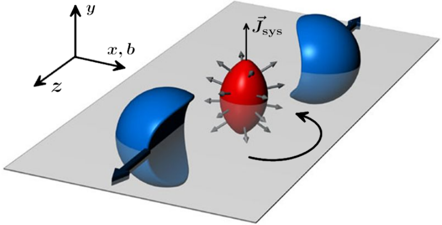
- Hot and dense created matter undergoes explosive expansion — **the Little Bang**
- Large initial orbital angular momentum is partially transferred to the medium, what leads to the non-vanishing averaged *vorticity*:

$$\boldsymbol{L} \quad \longrightarrow \quad \langle \boldsymbol{\omega} \rangle = \langle \mathrm{rot}\, \boldsymbol{v} \rangle$$

- The vorticity is a source of the *global particle polarization*

  F. Becattini, V. Chandra, L. Del Zanna, and E. Grossi, Annals Phys. **338** (2013)
  F. Becattini, M.A. Lisa, Annu. Rev. Nucl. Part. Sci. **70** (2020)

- The vorticity field may have *intricate space structure*
  - **Femto-vortex sheets**: *M.I. Baznat, K.K. Gudima, A.S. Sorin, and O.V. Teryaev*, Phys. Rev. C **93** (2016)
  - **Vortex rings**: *Yu.B. Ivanov, A.A. Soldatov*, Phys. Rev. C **97** (2018)



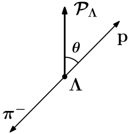
Global Λ and $\bar{\Lambda}$ polarization and vorticity

- The Λ and $\bar{\Lambda}$ are the *self-analyzing particles*: due to **P**-violation in weak decays, the angular distribution of final protons depends on the orientation of the Λ-hyperon spin

- In the hyperon *rest frame*, the decay product distribution is

$$\frac{dN}{d\cos\theta} = \frac{1}{2}\left(1 + \alpha_{\rm H}|\mathcal{P}_{\rm H}|\cos\theta\right)$$

$$\alpha_\Lambda = -\alpha_{\bar{\Lambda}} = 0.732 \pm 0.014$$



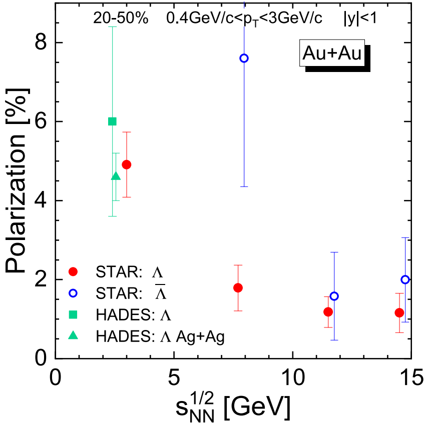
- The *rough estimate* of vorticity (**STAR**):

$$\omega_{\rm STAR} \approx \left\langle \frac{k_B T}{\hbar}(\overline{\mathcal{P}}_\Lambda + \overline{\mathcal{P}}_{\bar{\Lambda}}) \right\rangle_{\sqrt{s_{NN}}} \approx 10^{22}\ {\rm s}^{-1}$$

The fastest-rotating fluid?

pulsar PSR J1748–2446ad	$\omega \sim 5 \times 10^3\ {\rm s}^{-1}$
superfluid He II nanodroplets	$\omega \sim 10^7\ {\rm s}^{-1}$

- The experimental data of global Λ and $\bar{\Lambda}$ polarization



L. Adamczyk et al., Nature **548** (2017)
R.A.Yassine et al. (HADES Coll.), Phys.Lett.B **835** (2022)

The setup

- The **PHSD transport model** as a heavy-ion collisions framework: *Kadanoff-Baym equations, DQPM, FRITIOF Lund, Chiral Symmetry Restoration, ...*

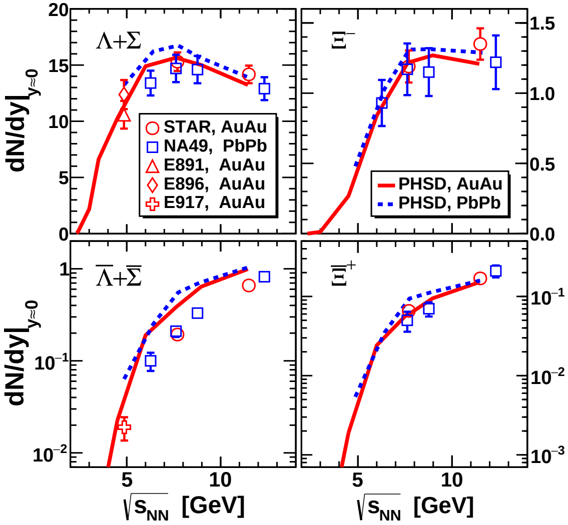
  W. Cassing, E.L. Bratkovskaya,
  Phys. Rev. C **78** (2008)
  Nucl. Phys. A **831** (2009)

- Good description of a large number of experimental observables

  O. Linnyk, E.L. Bratkovskaya, W .Cassing,
  Prog. Part. Nucl. Phys. **87** (2016)

- The simulations are performed on the **Govorun** supercomputer at **JINR**

- The **PHSD** performance



The fluidization procedure

- Transition from kinetic to hydrodynamic description via *fluidization* procedure:

$$T^{\mu\nu}(\boldsymbol{x},t) = \frac{1}{\mathcal{N}} \sum_{a,i_a} \frac{p^{\mu}_{i_a}(t)\, p^{\nu}_{i_a}(t)}{p^{0}_{i_a}(t)} \Phi\left(\boldsymbol{x}, \boldsymbol{x}_{i_a}(t)\right), \qquad \mathcal{N} = \int \Phi\left(\boldsymbol{x}, \boldsymbol{x}_i(t)\right)\, d^3x,$$

$$J^{\mu}_{B}(\boldsymbol{x},t) = \frac{1}{\mathcal{N}} \sum_{a,i_a} B_{i_a} \frac{p^{\mu}_{i_a}(t)}{p^{0}_{i_a}(t)} \Phi\left(\boldsymbol{x}, \boldsymbol{x}_{i_a}(t)\right), \qquad \Phi\left(\boldsymbol{x}, \boldsymbol{x}_i(t)\right) - \text{smearing function},$$

$$u_\mu T^{\mu\nu} = \varepsilon\, u^{\nu}, \qquad n_B = u_\mu J^{\mu}_{B}, \qquad \longrightarrow \qquad \text{EoS} \qquad \longrightarrow \qquad \text{Temperature}(\varepsilon, n_B)$$

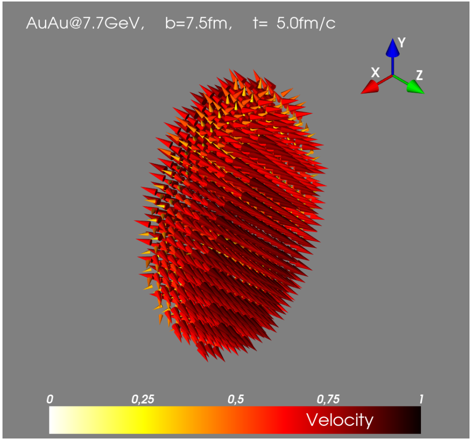
- Equation of State: **Hadron resonance gas**
  L.M. Satarov, M.N. Dmitriev, and I.N. Mishustin, Phys. Atom. Nucl. **72** (2009)

- *The fluidization criterion*: *fluidize only cells with* $\varepsilon > 0.05\,\mathrm{GeV/fm^3}$!

- *Spectators separation*: spectators move with approximately beam rapidity $||y| - y_{\mathrm{b}}| \le 0.27$
  Spectators do not form fluid!

Velocity and vorticity fields

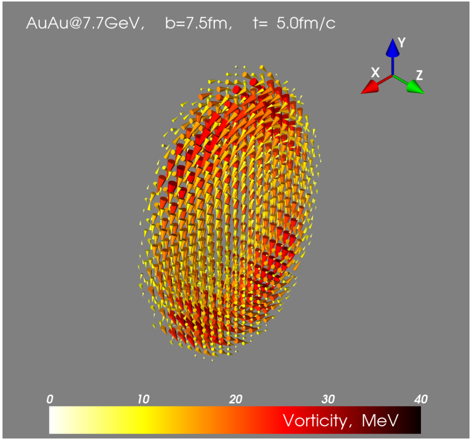
$\omega_{\text{STAR}} \approx 10^{22}\,\text{s}^{-1} \approx 6.6\,\text{MeV}/\hbar$



Hydrodynamic velocity field

$\varepsilon > 0.05\,\text{GeV}/\text{fm}^3$

$\boldsymbol{v} \approx \boldsymbol{v}_{\text{Hubble}} = (\alpha_T\, x, \alpha_T\, y, \alpha_z\, z)$



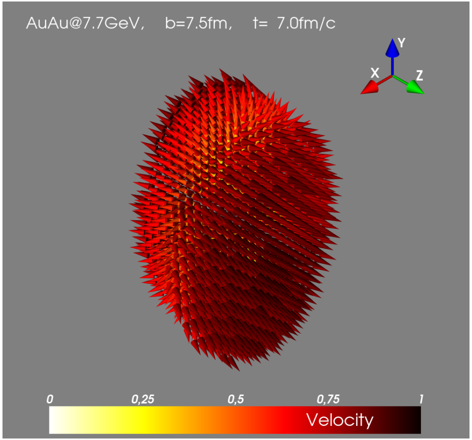
Hydrodynamic vorticity field

$\boldsymbol{\omega} = \text{rot}\,\boldsymbol{v}$

for clarity draw only $|\boldsymbol{\omega}| > 5\,\text{MeV}/\hbar$

Velocity and vorticity fields

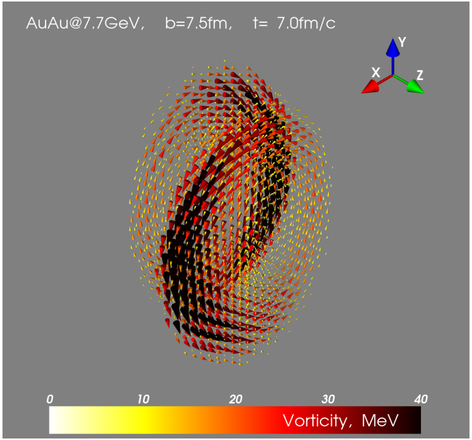
$\omega_{\mathrm{STAR}} \approx 10^{22}\,\mathrm{s}^{-1} \approx 6.6\,\mathrm{MeV}/\hbar$



Hydrodynamic velocity field

$\varepsilon > 0.05\,\mathrm{GeV}/\mathrm{fm}^3$

$\boldsymbol{v} \approx \boldsymbol{v}_{\mathrm{Hubble}} = (\alpha_T\, x, \alpha_T\, y, \alpha_z\, z)$



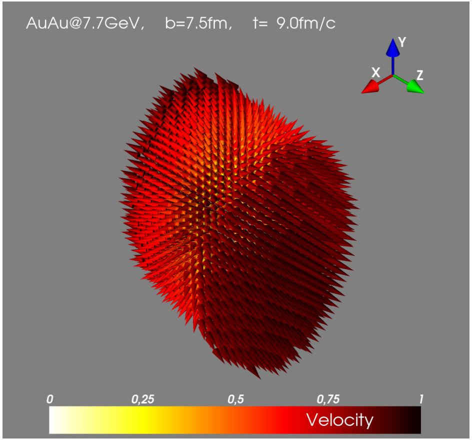
Hydrodynamic vorticity field

$\boldsymbol{\omega} = \mathrm{rot}\, \boldsymbol{v}$

$|\boldsymbol{\omega}|_{\max} \approx 67.1\, MeV/\hbar!$

Velocity and vorticity fields

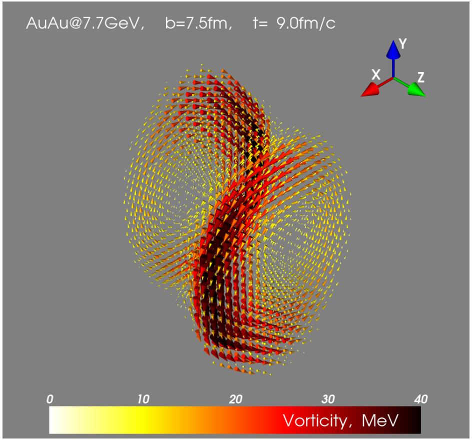
$\omega_{\text{STAR}} \approx 10^{22}\,\text{s}^{-1} \approx 6.6\,\text{MeV}/\hbar$



Hydrodynamic velocity field

$\varepsilon > 0.05\,\text{GeV}/\text{fm}^3$

$\boldsymbol{v} \approx \boldsymbol{v}_{\text{Hubble}} = (\alpha_T\, x, \alpha_T\, y, \alpha_z\, z)$



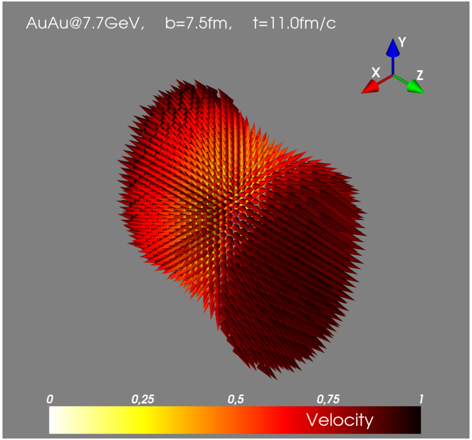
Hydrodynamic vorticity field

$\boldsymbol{\omega} = \text{rot}\,\boldsymbol{v}$

$|\boldsymbol{\omega}|_{\text{max}} \approx 67.1\,MeV/\hbar!$

Velocity and vorticity fields

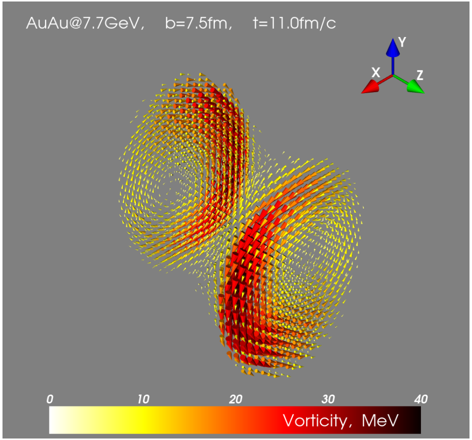
$\omega_{\mathrm{STAR}} \approx 10^{22}\,\mathrm{s}^{-1} \approx 6.6\,\mathrm{MeV}/\hbar$



Hydrodynamic velocity field

$\varepsilon > 0.05\,\mathrm{GeV}/\mathrm{fm}^3$

$\boldsymbol{v} \approx \boldsymbol{v}_{\mathrm{Hubble}} = (\alpha_T\, x, \alpha_T\, y, \alpha_z\, z)$



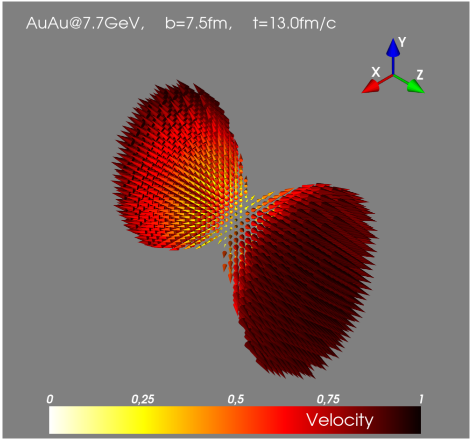
Hydrodynamic vorticity field

$\boldsymbol{\omega} = \mathrm{rot}\,\boldsymbol{v}$

for clarity draw only $|\boldsymbol{\omega}| > 5\,\mathrm{MeV}/\hbar$

Velocity and vorticity fields

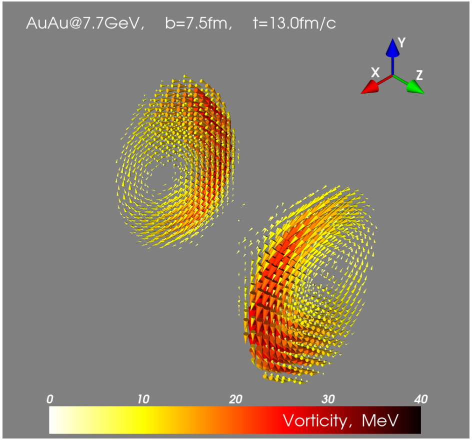
$\omega_{\text{STAR}} \approx 10^{22}\,\text{s}^{-1} \approx 6.6\,\text{MeV}/\hbar$



Hydrodynamic velocity field

$\varepsilon > 0.05\,\text{GeV}/\text{fm}^3$

$\boldsymbol{v} \approx \boldsymbol{v}_{\text{Hubble}} = (\alpha_T\, x, \alpha_T\, y, \alpha_z\, z)$

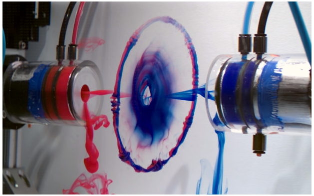


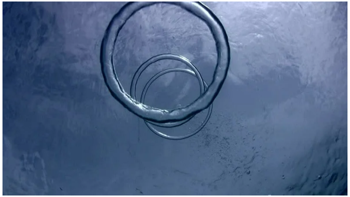
Hydrodynamic vorticity field

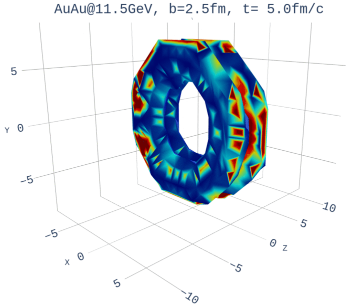
$\boldsymbol{\omega} = \text{rot}\,\boldsymbol{v}$

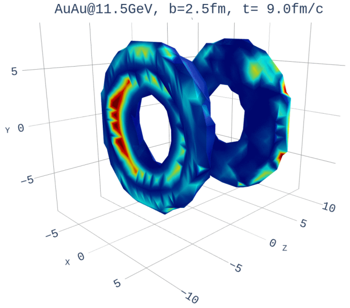
for clarity draw only $|\boldsymbol{\omega}| > 5\,\text{MeV}/\hbar$

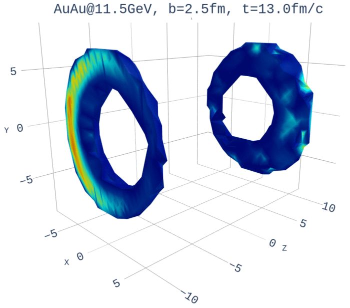
Vortex rings in nature and PHSD











Polarization of particles with spin in vorticity field

- **The thermodynamic approach**

  F. Becattini, V. Chandra, L. Del Zanna, E. Grossi, Annals Phys. **338** (2013)

  Relativistic thermal vorticity:

  $$\varpi_{\mu\nu} = \frac{1}{2}(\partial_\nu \beta_\mu - \partial_\mu \beta_\nu), \quad \beta_\nu = \frac{u_\nu}{T}$$

  Spin vector:

  $$S^\mu(x,p) = -\frac{s(s+1)}{6m}(1 \pm n(x,p))\varepsilon^{\mu\nu\lambda\delta}\varpi_{\nu\lambda}p_\delta$$

  s – spin, p_δ – 4 momentum of particle

  Polarization: $\mathbf{P} = \mathbf{S}^*/s$
  $\mathbf{S}^*$ spin vector in rest frame

- **Our statements**

  • *Hydro velocity* • *No spectators*

- **Interaction/production point**

  • *No "Medium":* $\varepsilon < 0.05\mathrm{GeV/fm}^3$
  $\Rightarrow$ *No thermal vorticity* $\varpi_{\mu\nu} = 0$

  Elastic or inelastic process:
  "Medium": particle is polarized
  No "Medium": zero polarization

  Strong decays:
  $\Sigma^* \to \Lambda + \pi, \quad \Xi^* \to \Xi + \pi$
  spin transfer $C_{\Lambda\,\Sigma^*} = C_{\Xi\,\Xi^*} = 1/3$

  $$S_{Daughter} = C_{D\,P}\, S_{Parent}$$

- **Λ, Σ^0, Ξ, Ω are stable in PHSD**

The Λ and $\bar{\Lambda}$ polarization

- *The feed-down effects*

  strong: *is already included*

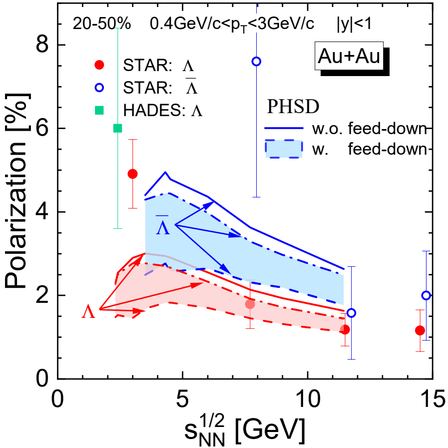
  weak: $\Xi \to \Lambda + \pi$

  EM: $\Sigma^0 \to \Lambda + \gamma$

Spin transfer coefficients:

$C_{\Lambda\,\Xi^-} = 0.927$, $C_{\Lambda\,\Xi^0} = 0.900$,

$C_{\Lambda\,\Sigma^0} = -1/3$

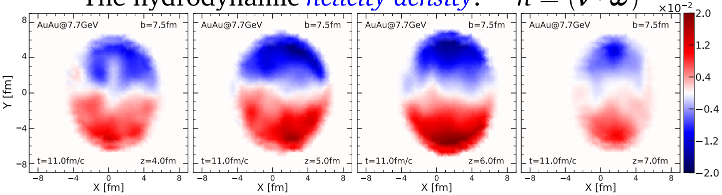


- The polarization of $\mathbf{\Lambda}$ hyperons *agrees* with experimental data, *except low energies* $\sqrt{s_{NN}} \leq 3$ GeV. The *maximum* of the $\mathbf{\Lambda}$ polarization at $\sqrt{s_{NN}} \approx 4$ GeV
- The polarization of $\bar{\mathbf{\Lambda}}$ *larger in 1.5 – 2 times* than $\mathbf{\Lambda}$.
  At $\sqrt{s_{NN}} \geq 11.5$ GeV *agrees* with experimental data, but at $\sqrt{s_{NN}} \leq 7.7$ GeV *less*

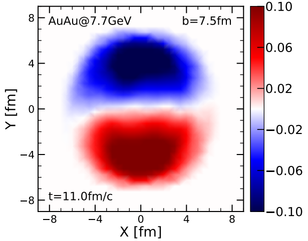
Hydrodynamic helicity

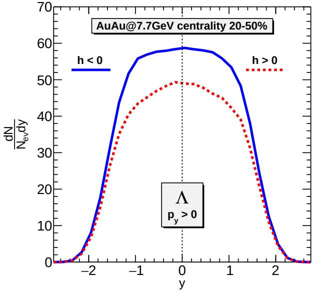
- **The axial vortex effect:** polarization due to the *helicity* [*A. Sorin, O. Teryaev*, Phys. Rev. C **95** (2017)]
- **The helicity separation effect** [*M. Baznat, O. Teryaev, A. Sorin, K. Gudima*, Phys. Rev. C **88** (2013)]

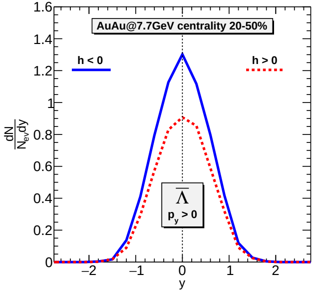
The hydrodynamic *helicity density*: $h = (\boldsymbol{v} \cdot \boldsymbol{\omega})$



$$\widetilde{h}(x,y) = \int h(x,y,z)\, dz$$







- In the upper semi-plane *with* $h < 0$ there are *more particles with* $p_y > 0$ than with $p_y < 0$!
- Zones with *negative and positive helicities* can be probed by selection of $\boldsymbol{\Lambda}$'s and $\bar{\boldsymbol{\Lambda}}$'s with positive and negative p_y

Conclusions

- The fireball velocity consists of the irrotational a *(2+1)D Hubble-like* part and *rotational part* with maximum vorticity at the edges of the system.
- We observe a formation and decay of the *two deformed elliptical vortex rings*, moving and rotating in opposite directions along z-axis. The ring deformation depends on the impact parameter of the collision.
- We observe the hydrodynamic *helicity separation effect*. Zones with *negative and positive helicities* can be probed by selection of $\mathbf{\Lambda}$'s and $\bar{\mathbf{\Lambda}}$'s with positive and negative p_y.
- The polarization of the $\mathbf{\Lambda}$ hyperons *agrees* with experimental data, *except low energies* $\sqrt{s_{NN}} \leq 3$ GeV. The *maximum* of the $\mathbf{\Lambda}$ polarization at $\sqrt{s_{NN}} \approx 4$ GeV. The polarization of $\bar{\mathbf{\Lambda}}$ *larger in* $1.5 - 2$ *times* than $\mathbf{\Lambda}$. It *agrees* with experimental data at $\sqrt{s_{NN}} = 11.5$ GeV, but is *less* at $\sqrt{s_{NN}} = 7.7$ GeV. Strong polarization suppression is caused by the *feed-down from* $\mathbf{\Sigma^0}$ *and* $\bar{\mathbf{\Sigma}}^{\mathbf{0}}$ hyperons.

Vortex rings and global hyperon polarization in heavy-ion collisions at NICA energies

based on *Phys.Rev.C 107 (2023) 3*, *Particles 6 (2023) 1*, *arXiv:2305.10792*

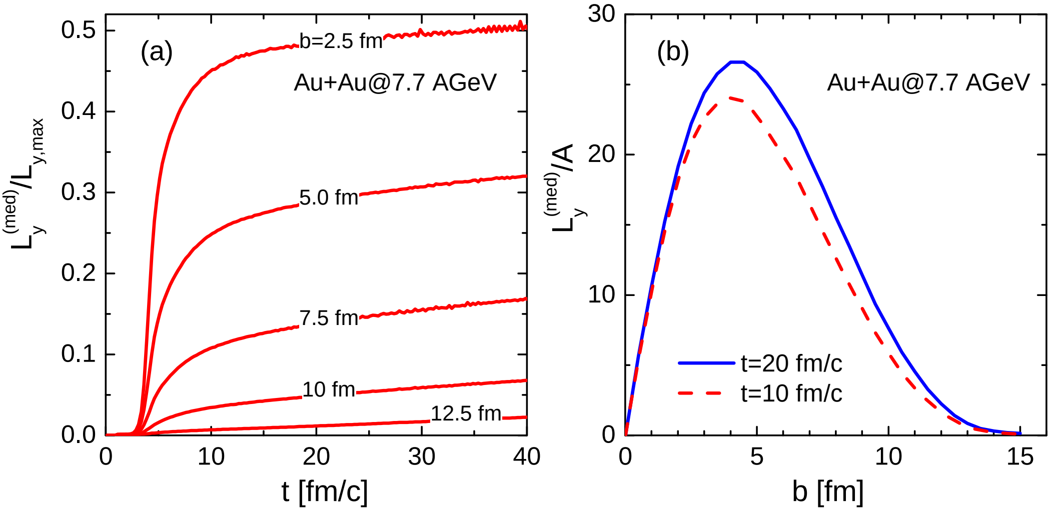
Nikita Tsegelnik[1,*] Evgeni Kolomeitsev[1,2] Vadim Voronyuk[3,4]

[1]*Bogoliubov Laboratory of Theoretical Physics, JINR, Dubna, Russia*
[2]*Matej Bel University, Banska Bystrica, Slovakia*
[3]*Laboratory of High Energy Physics, JINR, Dubna, Russia*
[4]*Bogolyubov Institute for Theoretical Physics, Kiev, Ukraine*

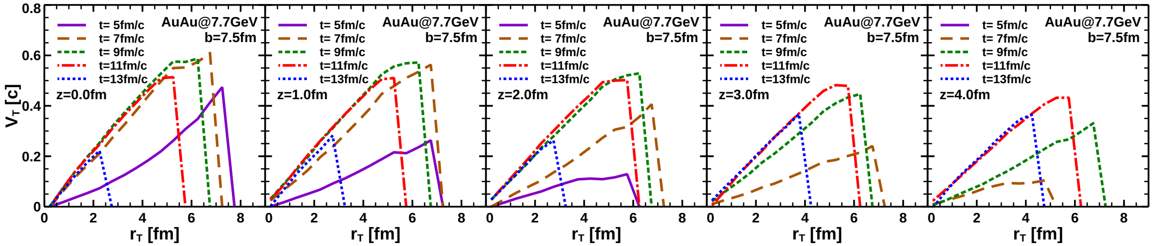
[*]tsegelnik@theor.jinr.ru

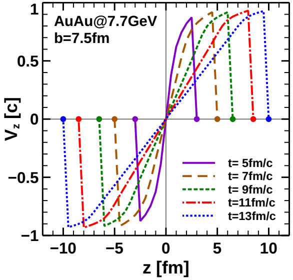
Alushta-2023, 08.06.23

Angular momentum transfer



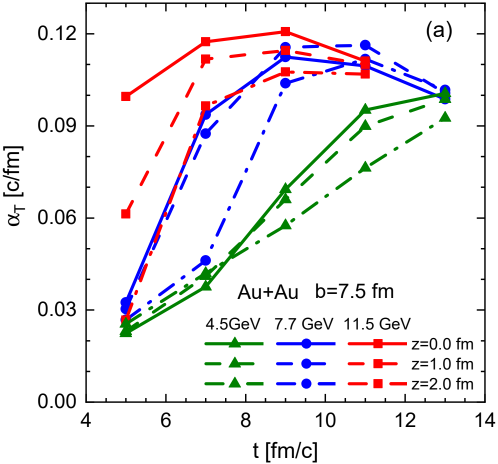
Velocity profiles

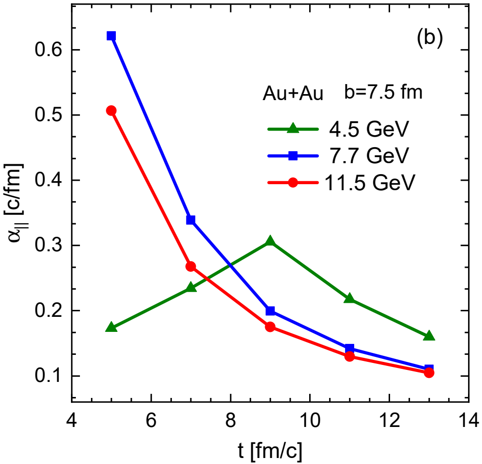




$r_T = 0$

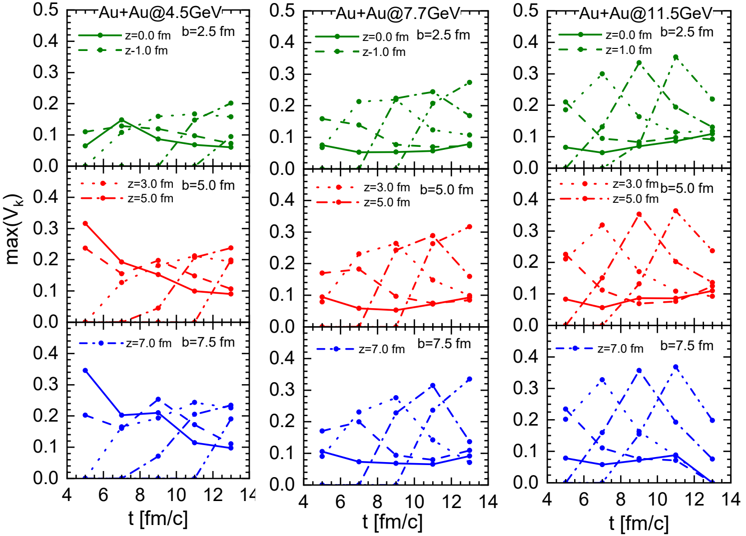
Hubble parameters





$$\alpha_{T,\perp} \gg H \approx 70(\mathrm{km/s})/\mathrm{Mpc} \approx 22.65 \times 10^{-19}\mathrm{s}^{-1} \approx 7.57 \times 10^{-27} c/\mathrm{fm}$$

Kinematic vorticity number



$$\partial_i v_j = \xi_{ij,+} + \xi_{ij,-}$$

$$\mathfrak{W}_\mathrm{k} = \sqrt{\frac{\xi_-^{ij}\xi_{ij,-}}{\xi_+^{kl}\xi_{kl,+}}} = \frac{|\boldsymbol{\omega}|}{\sqrt{2}\xi_+}$$

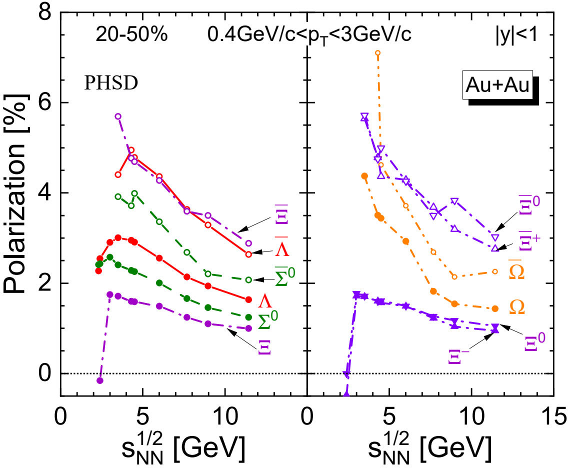
$$\xi_+^2 = \xi_+^{ij}\xi_{ij,+}$$

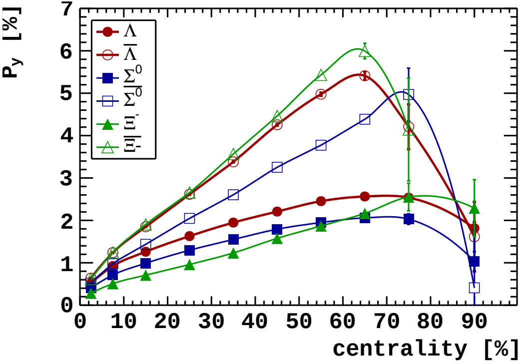
$$\xi_-^{ij}\xi_{ij,-} = \boldsymbol{\omega}^2/2$$

$$V_\mathrm{k} = \frac{2}{\pi}\arctan\mathfrak{W}_\mathrm{k}$$

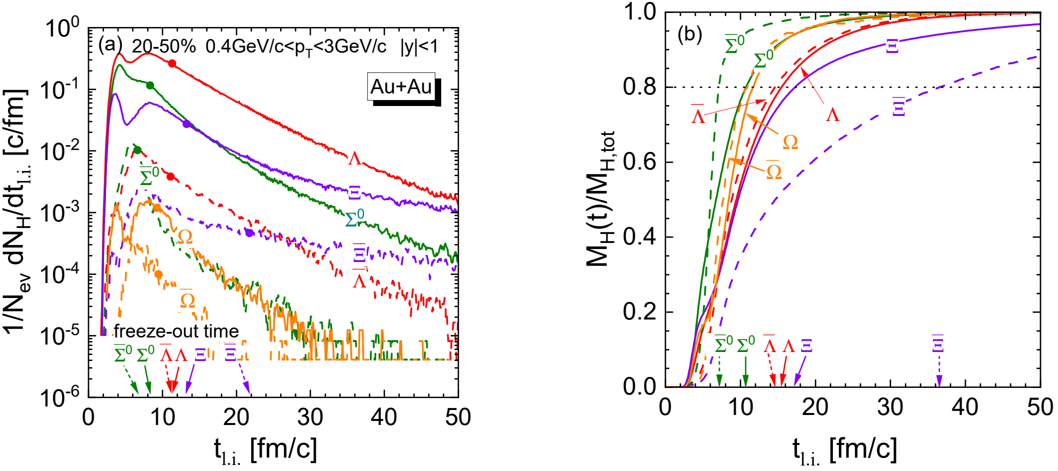
$\max(V)_\mathrm{k} < 1/2 =$ *Poiseuille flow* $\longrightarrow$ shear motion, *almost irrotational!*

Polarization of different hyperon species

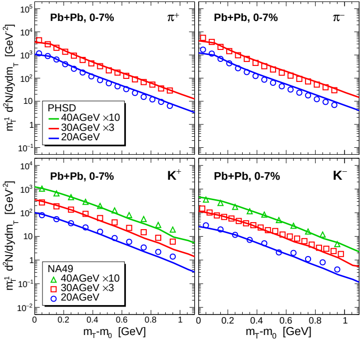


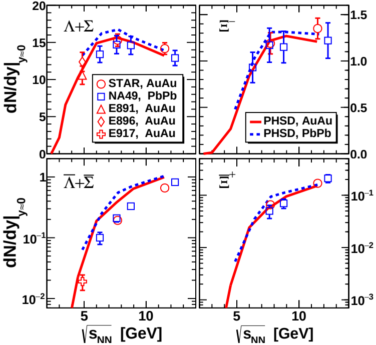


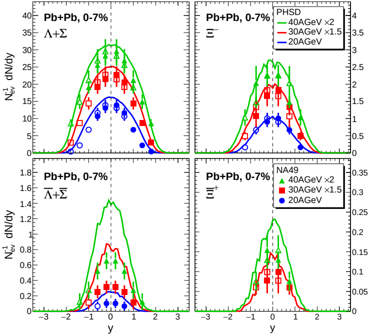
Rates of hyperon production



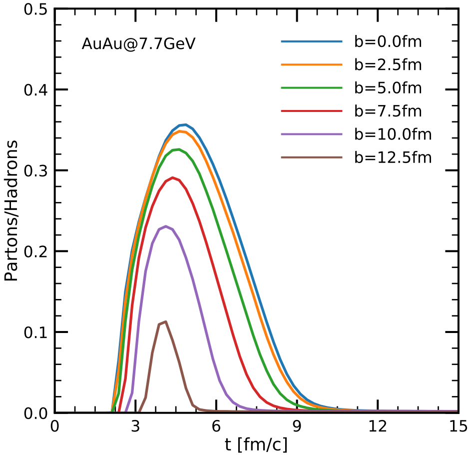
Spectra and yields

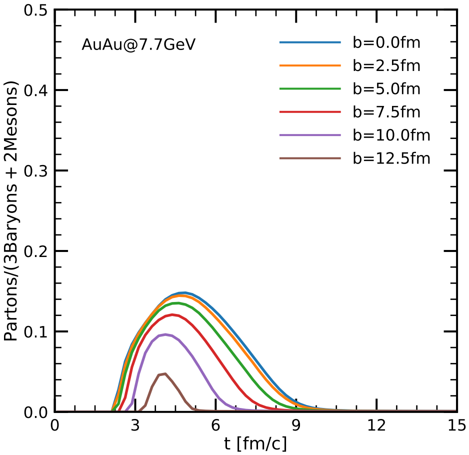






Parton phase





Only for participants!