Vorticity, freeze-out conditions and global polarization in heavy-ion collisions at the NICA energies

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

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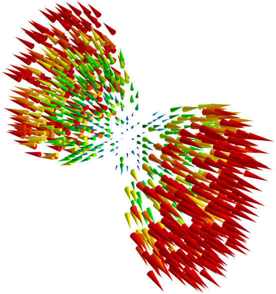
Heavy-ion collisions



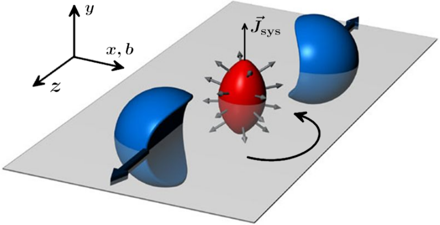
- Hot and dense created matter undergoes explosive expansion — **the Little Bang**
- Large initial orbital angular momentum is partially transferred to the medium, what leads to the non-vanishing averaged *vorticity*:

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

- 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)



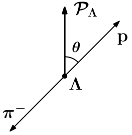
Global Λ and $\bar{\Lambda}$ polarization and vorticity

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

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

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

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



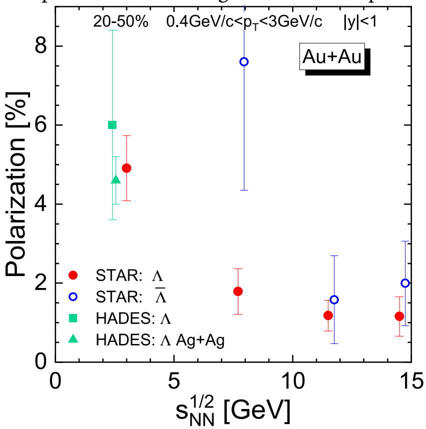
- The *rough estimate* of vorticity (**STAR**):

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

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 $\mathbf{\Lambda}$ and $\bar{\mathbf{\Lambda}}$ 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:
  the generalized off-shell transport equations, *Dynamical Quasi-Particle Model* (for partons), *FRITIOF Lund* (strings breaking) *PYTHIA* and *JETSET* (jet production and fragmentation), *Chiral Symmetry Restoration*, ...

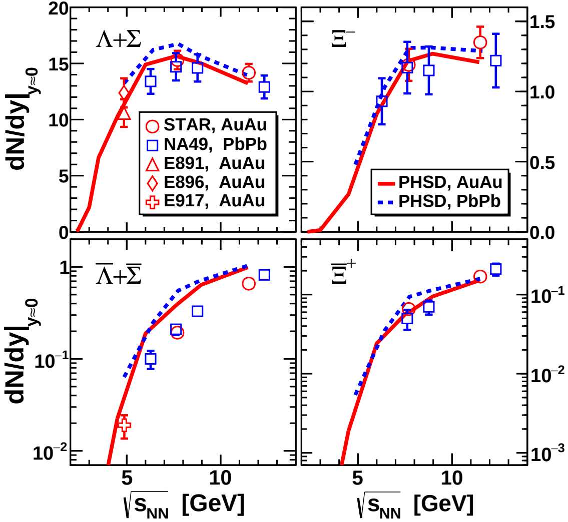
  W. Cassing, E.L. Bratkovskaya,
  Phys. Rev. C **78** (2008)
  Nucl. Phys. A **831** (2009)

- Good description of a large number of experimental observables

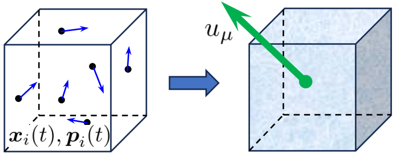
  O. Linnyk, E.L. Bratkovskaya, W .Cassing,
  Prog. Part. Nucl. Phys. **87** (2016) s

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

- The **PHSD** performance



The fluidization procedure



- Transition from kinetic to hydrodynamic description:

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

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

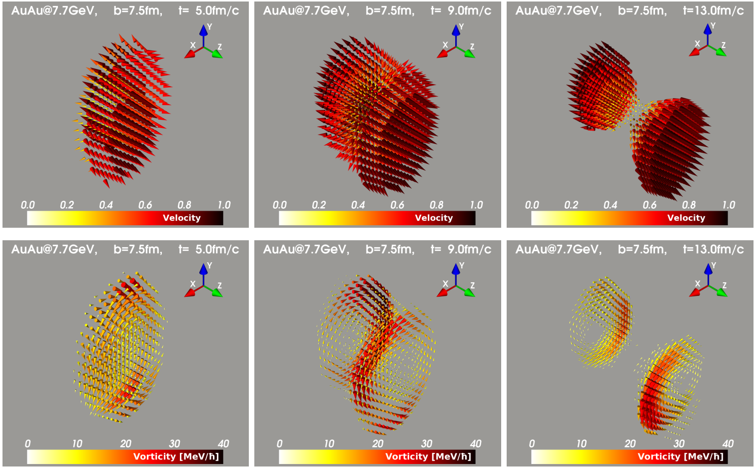
$$u_\mu T^{\mu\nu} = \varepsilon\, u^\nu, \qquad n_B = u_\mu J^\mu_B, \qquad \longrightarrow \qquad \text{EoS} \qquad \longrightarrow \qquad \text{Temperature}(\varepsilon, n_B)$$

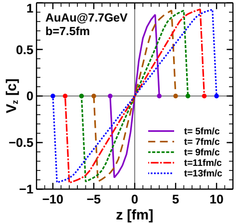
- Equation of State: **Hadron resonance gas**
  L.M. Satarov, M.N. Dmitriev, and I.N. Mishustin, Phys. Atom. Nucl. **72** (2009)

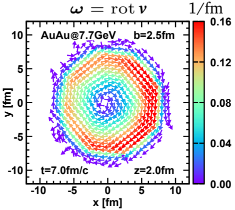
- *The fluidization criterion*: *fluidize only cells with* $\varepsilon > 0.05\,\mathrm{GeV/fm^3}$!

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

Velocity and vorticity fields



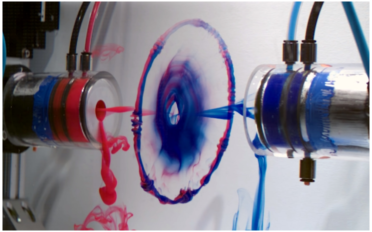


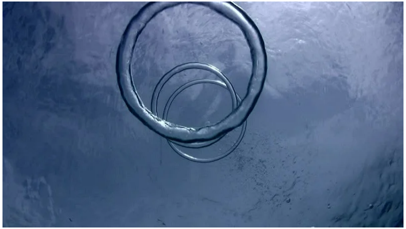


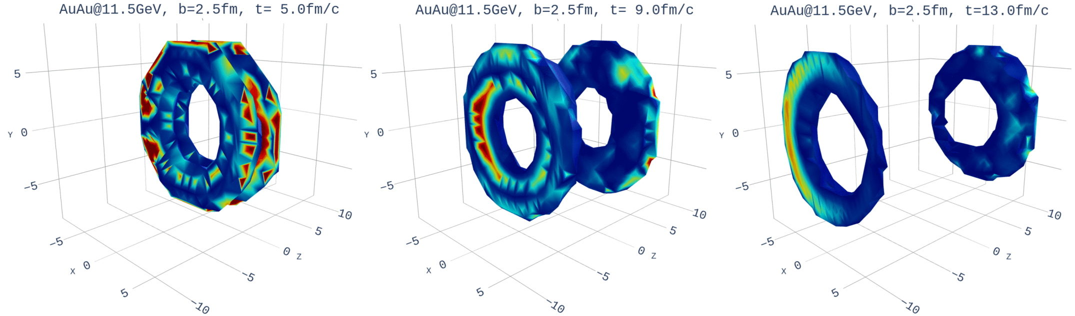
▶ The fireball velocity approximately consists of the *irrotational* **(2+1)D Hubble-like** and *rotational* terms.

▶ Maximum of the vorticity ω is located *at the edges of the system*. Two deformed **elliptical vortex rings** move and rotate in opposite directions along the collision axis. The ring deformation depends on the impact parameter b.

Vortex rings in nature and in the PHSD model







Vorticity surfaces in the PHSD model

Polarization of particles with spin in the vorticity field

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

  Thermal vorticity tensor:

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

  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: $\mathbf{P} = \mathbf{S}^*/s$

  $\mathbf{S}^*$ is a spin vector in the rest frame

- ***Our statements:***
  - *kinetic* $\longrightarrow$ *hydro*
  - *no spectators*

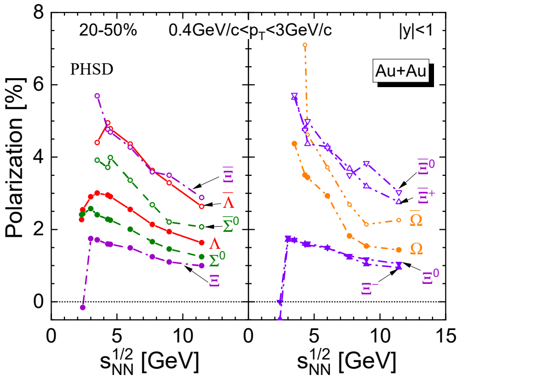
- ***Interaction/production point:***
  - $\varepsilon < 0.05 \mathrm{GeV/fm}^3 \Rightarrow$ *no "medium"*
    $\Rightarrow$ *no thermal vorticity* $\varpi_{\mu\nu} = 0$
  - ***Elastic or inelastic process:***
    "medium": particle is polarized
    no "medium": zero polarization
  - ***Strong decays:***
    $\Sigma^* \to \Lambda + \pi, \quad \Xi^* \to \Xi + \pi$
    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

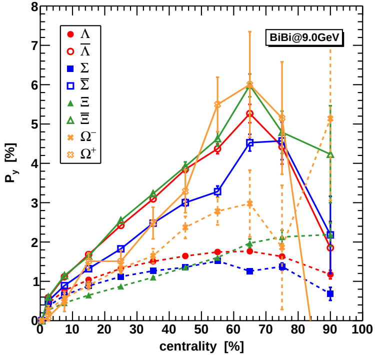
Global polarization of different hyperon species

▶ There is a *different polarization* of particles and antiparticles for all the hyperon kinds.



▶ Polarization of all the hyperon species *decreases with an energy increase* for $\sqrt{s_{NN}} > 3 - 5$ GeV.

▶ The *strongest decrease* and *smallest difference* is for **Ω** and $\bar{\mathbf{\Omega}}$. The *biggest difference* is for **Ξ** and $\bar{\mathbf{\Xi}}$.



▶ Polarization *increases with centrality* up to the 50 – 80% class and then *decreases*.

▶ The *maximum magnitude* of the polarization and *the biggest difference* for the particles/antiparticles belong to the 50 – 80% centrality class.

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

▶ ***The feed-down effects***

strong: *is already included*

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

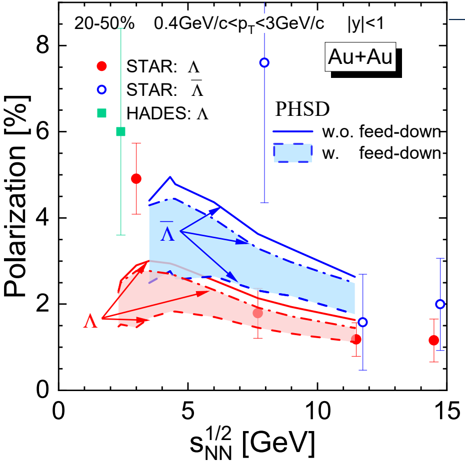
EM: $\Sigma^0 \to \Lambda + \gamma$

Spin transfer coefficients:

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

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

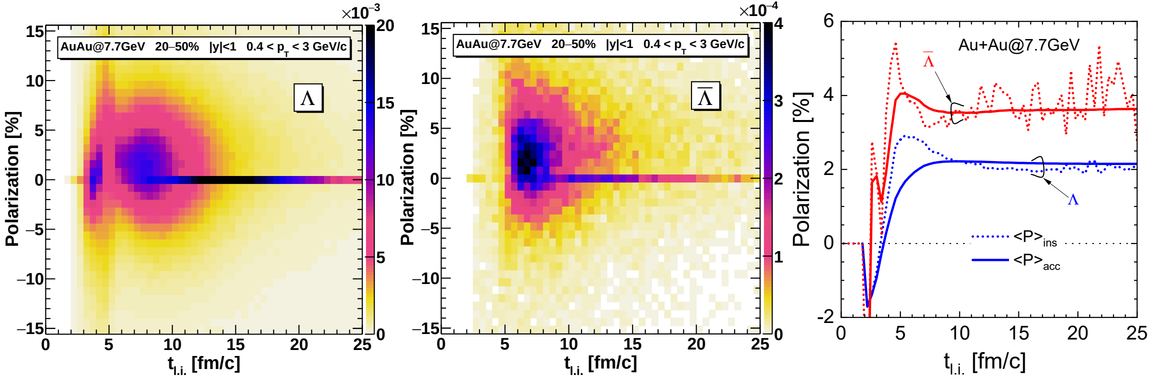
▶ *The strong suppression of the polarization due to the* $\boldsymbol{\Sigma^0}$ *and* $\boldsymbol{\bar{\Sigma}^0}$ *hyperons!*



▶ The polarization of $\boldsymbol{\Lambda}$ hyperons *agrees* with experimental data, *except low energies* $\sqrt{s_{NN}} \leq 3\,\mathrm{GeV}$. The *maximum* of the $\boldsymbol{\Lambda}$ polarization at $\sqrt{s_{NN}} \approx 4\,\mathrm{GeV}$.

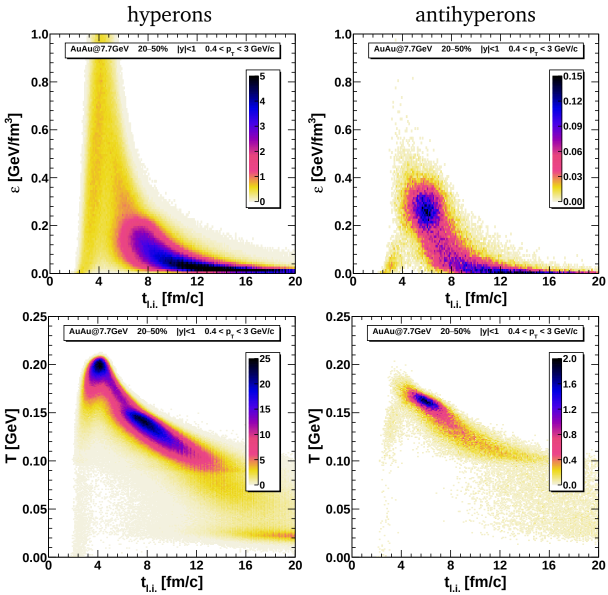
▶ The polarization of $\boldsymbol{\bar{\Lambda}}$ is *larger in 1.5 – 2 times* than $\boldsymbol{\Lambda}$. At $\sqrt{s_{NN}} \geq 11.5\,\mathrm{GeV}$ *agrees* with experimental data, but at $\sqrt{s_{NN}} \leq 7.7\,\mathrm{GeV}$ is *less*.

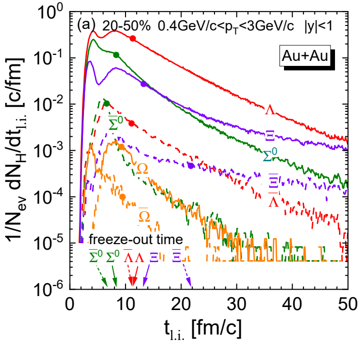
Polarization source



- There are *two* main sources for $\boldsymbol{\Lambda}$ and only *one* for $\boldsymbol{\overline{\Lambda}}$.
- $P_y(\overline{\Lambda}) > P_y(\Lambda)$ at $t_{\text{l.i.}} \gtrsim 3\,\text{fm}/c$ for both instantaneous and accumulated polarizations.
- *Change in the polarization sign* at the moment of the ions overlap.
- For $t \gtrsim 10\,\text{fm}/c$ the accumulated polarization stays *approximately constant*.

Freeze-out conditions



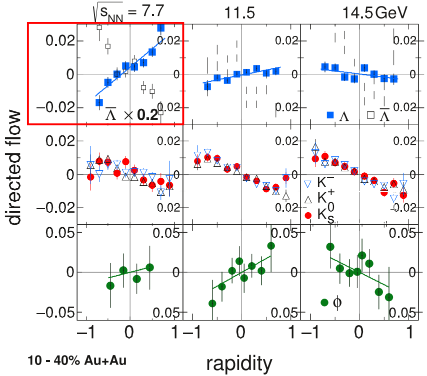


- $t_{\Lambda}^{(\mathrm{f.o.})} \approx t_{\bar{\Lambda}}^{(\mathrm{f.o.})}$
- $t_{\Omega}^{(\mathrm{f.o.})} \approx t_{\bar{\Omega}}^{(\mathrm{f.o.})}$
- $t_{\Sigma}^{(\mathrm{f.o.})} > t_{\bar{\Sigma}}^{(\mathrm{f.o.})}$
- $t_{\Xi}^{(\mathrm{f.o.})} < t_{\bar{\Xi}}^{(\mathrm{f.o.})}$

- There is *no direct connection* of the global polarization with the freeze-out time.
- *Two* main sources for *hyperons* and only *one* for *antihyperons*.
- *Different thermodynamic conditions* for particles and antiparticles $\longrightarrow$ *different polarization!*

The reason of the different polarization

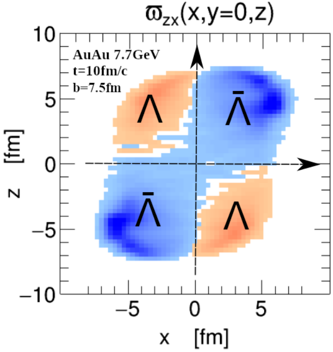
- The directed flow (STAR):



$$\varpi_{\mu\nu} = \partial_\nu \left(\frac{u_\mu}{T}\right) - \partial_\mu \left(\frac{u_\nu}{T}\right)$$

$$\varpi_{\mu\nu} \sim \frac{\omega_{\mu\nu}}{T}$$

$$\varpi_{zx} \to P_y$$



blue: $\varpi_{zx} < 0$
orange: $\varpi_{zx} > 0$

- The most part of $\bar{\Lambda}$ comes from the blue zones (in average high vorticity), while the most of Λ comes the from orange area (in average small vorticity).

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*. *Two deformed elliptical vortex rings* move and rotate in opposite directions along the collision axis.
- Global polarization *increases with centrality* up to the $50-80\%$ class and then *decreases*. The *maximum magnitude* of the polarization and *the biggest difference* for the particles/antiparticles belong to the $50-80\%$ centrality class.
- Polarization of all the hyperon species *decreases with an energy increase* for $\sqrt{s_{NN}} > 3-5$ GeV. The *strongest decrease* and *smallest difference* is for $\boldsymbol{\Omega}$ and $\bar{\boldsymbol{\Omega}}$. The *biggest difference* is for $\boldsymbol{\Xi}$ and $\bar{\boldsymbol{\Xi}}$.
- The global polarization of the $\boldsymbol{\Lambda}$ hyperons *agrees* with experimental data, *except low energies* $\sqrt{s_{NN}} \leq 3$ GeV. The *maximum* of the $\boldsymbol{\Lambda}$ polarization at $\sqrt{s_{NN}} \approx 4$ GeV. The global polarization of $\bar{\boldsymbol{\Lambda}}$ is *larger in* $1.5-2$ *times* than $\boldsymbol{\Lambda}$. 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* $\boldsymbol{\Sigma^0}$ *and* $\bar{\boldsymbol{\Sigma}}^{\mathbf{0}}$ hyperons.
- There are *two* main sources for $\boldsymbol{\Lambda}$ and only *one* for $\bar{\boldsymbol{\Lambda}}$. $P_y(\bar{\Lambda}) > P_y(\Lambda)$ at $t_{\mathrm{l.i.}} \gtrsim 3\,\mathrm{fm}/c$ for both instantaneous and accumulated polarizations.
- There is *no direct connection* of the global polarization with the freeze-out time. There are *two* main sources for *hyperons* and only *one* for *antihyperons*. *Different thermodynamic conditions* for particles and antiparticles $\longrightarrow$ *different polarization!*

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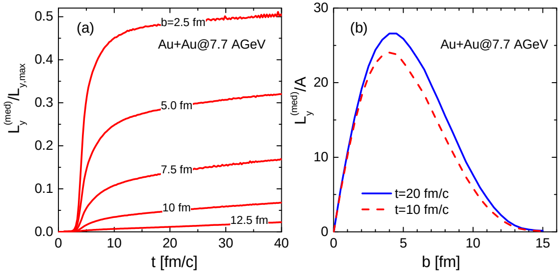
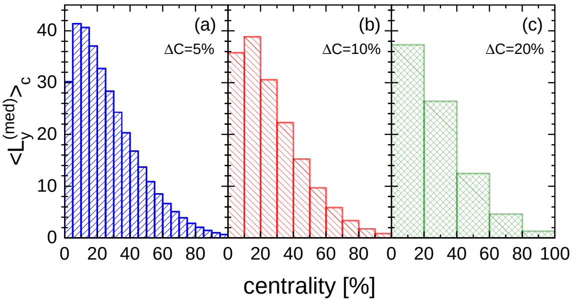
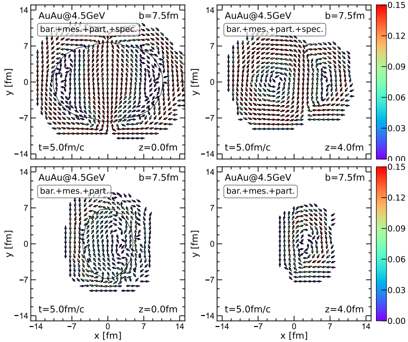
Angular momentum transfer



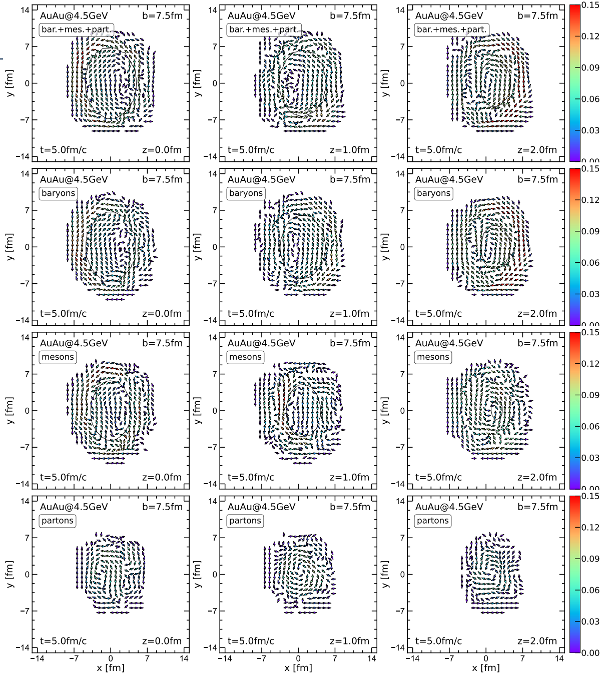


Different components

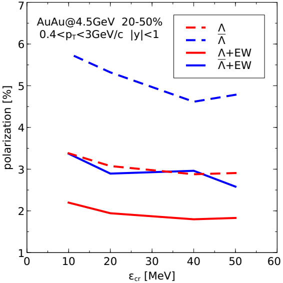
▶ *There are differences in the rotation of the different phases!*

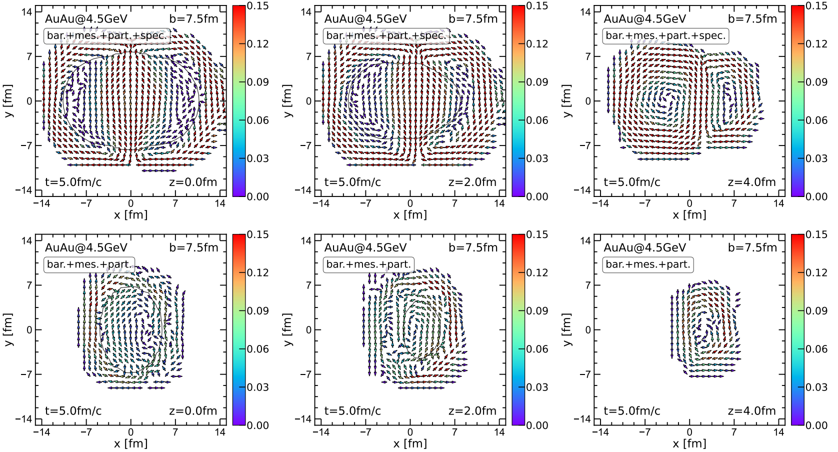


▶ *Spectators change the picture!*



Fluidization criterion and spectators



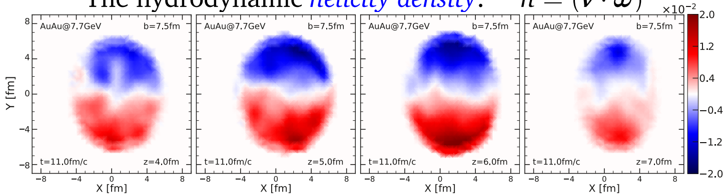


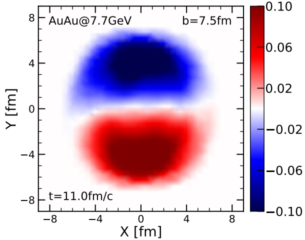
Hydrodynamic helicity

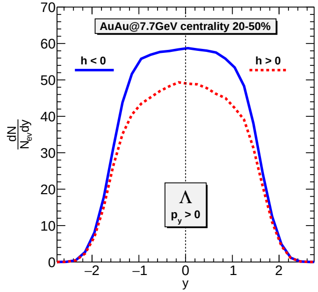
- **The axial vortex effect:** polarization due to the *helicity* [*A. Sorin, O. Teryaev*, Phys. Rev. C **95** (2017)]
- **The helicity separation effect** [*M. Baznat, O. Teryaev, A. Sorin, K. Gudima*, Phys. Rev. C **88** (2013)]

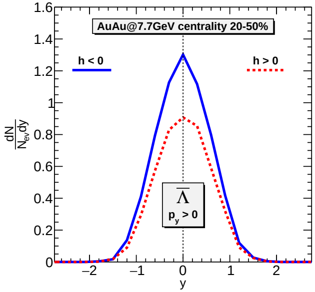
The hydrodynamic *helicity density*: $h = (\boldsymbol{v} \cdot \boldsymbol{\omega})$

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



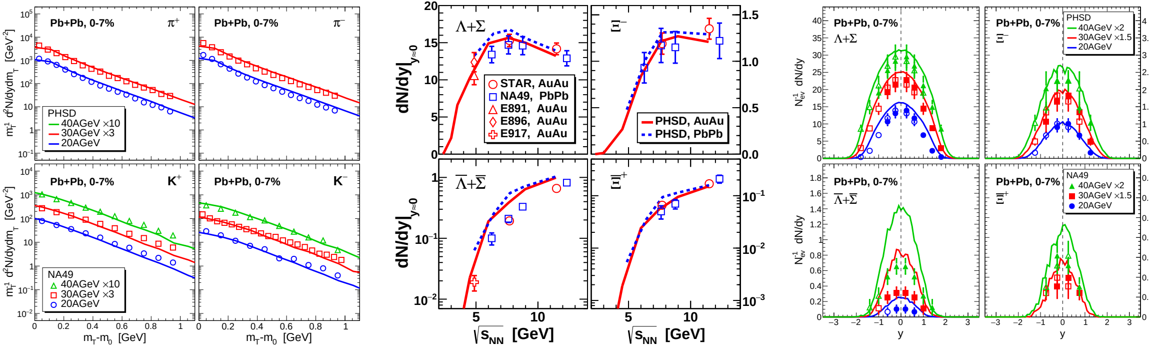




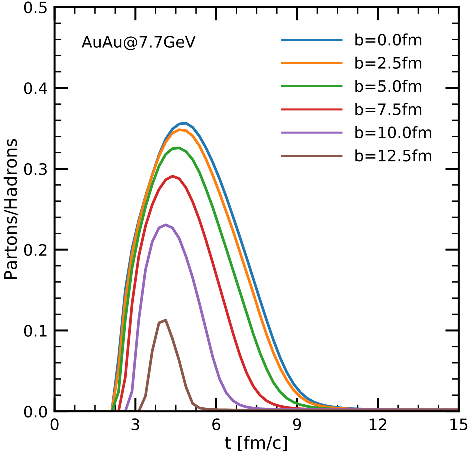


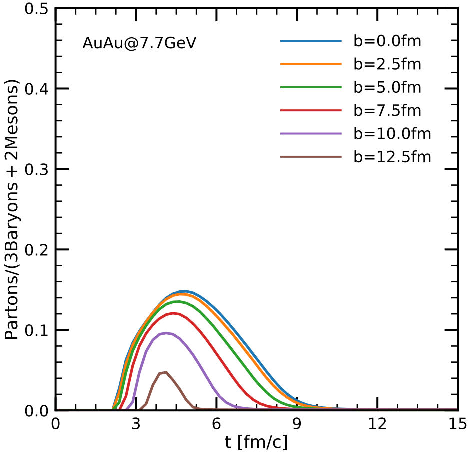
- In the upper semi-plane *with* $h < 0$ there are *more particles with* $p_y > 0$ than with $p_y < 0$!
- Zones with *negative and positive helicities* can be probed by selection of Λ's and $\bar{\Lambda}$'s with positive and negative p_y

Spectra and yields



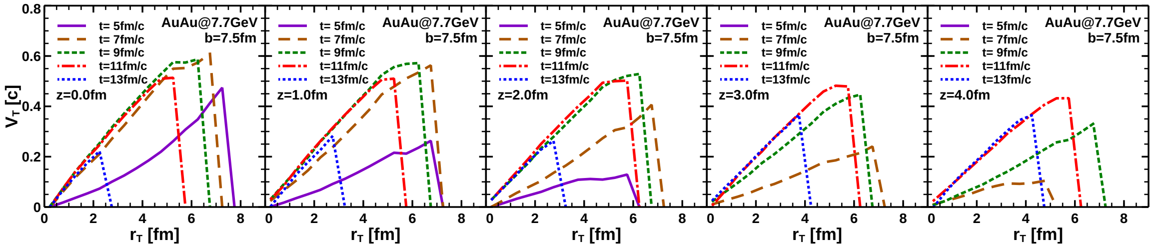
Parton phase

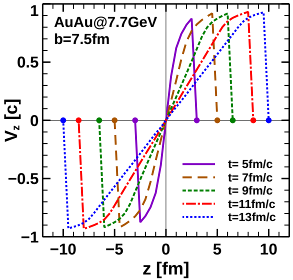




Only for participants!

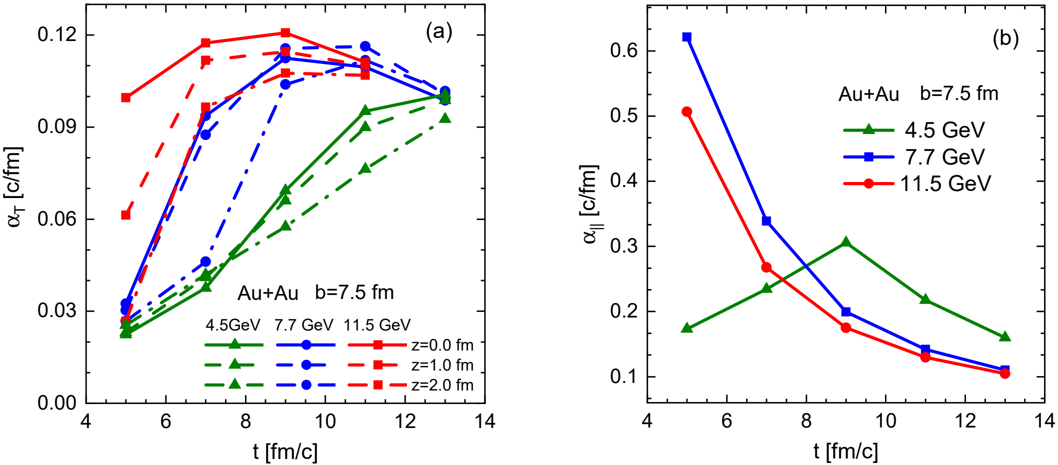
Velocity profiles





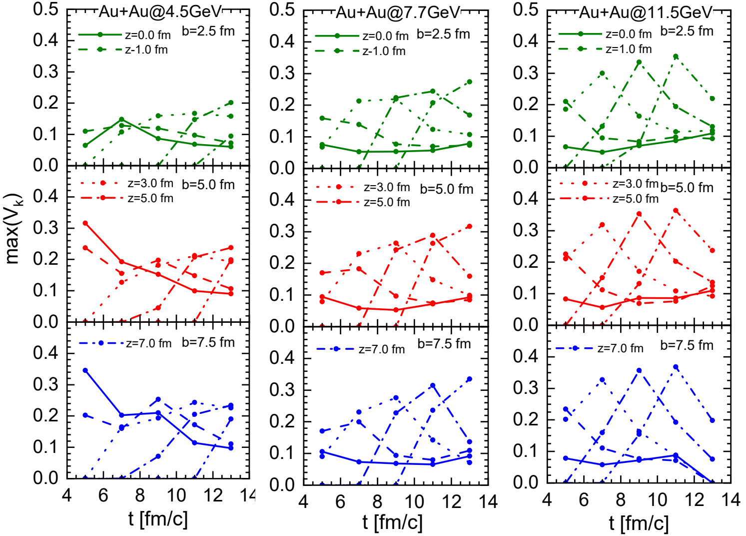
$r_T = 0$

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!*