Momentum anisotropies in the initial stages of heavy-ion collisions: the hunt is on

by

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Anisotropic flow is all over the place!

What is its origin?

[ALICE Collaboration, 1903.01790]
[Schenke, Shen, Tribedy, 2005.14682]
Anisotropic flow from spatial anisotropies: \[ F = -\nabla P \]

Profile has non-vanishing multipole moments. They source anisotropic flow:

\[ \mathcal{E}_n \propto \int r^n e^{in\phi} \epsilon(r, \phi) \]

\[ V_n \propto \mathcal{E}_n \]
Relation is simple: $V_n \propto \mathcal{E}_n$

Verified in full hydrodynamic simulations ($\varepsilon_n = |\mathcal{E}_n|$, $v_n = |V_n|$)

Expects experimental data in both large and small systems.

**The importance of initial conditions.**

[Giacalone, Noronha-Hostler, Ollitrault, 1702.01730]
Going beyond $F = - \nabla P$.
The **primordial** energy-momentum tensor contains more structures.

**“MOMENTUM” ANISOTROPIES**

\[
E_{2p} \propto \langle T^{xx} - T^{yy} + 2iT^{xy} \rangle
\]

\[
E_{3p} \propto \langle re^{i\phi} (T^{xx} - T^{yy} + 2iT^{xy}) \rangle
\]

Off-diagonal terms are filled by pre-equilibrium phase over the first fm/c.

[Kurkela, Mazeliauskas, Paquet, Schlichting, Teaney, *1805.00961, 1805.01604*]

[Schlichting, Teaney, *1908.02113*]

Only known theory that predicts these terms is the color glass condensate (CGC). Longstanding question in the field: **do we see initial-state CGC anisotropy in the data?**

Evaluations in the IP-GLASMA+MUSIC+urQMD framework. 

System is anisotropic (n=2) shortly after the collision.

\[ \mathcal{E}_p \equiv \mathcal{E}_p e^{i2\Psi_2} \equiv \frac{\langle T^{xx} - T^{yy} \rangle + i\langle 2T^{xy} \rangle}{\langle T^{xx} + T^{yy} \rangle} \]

[Schenke, Shen, Tribedy, 1908.06212]

Salient property: system-size dependence.
Does the primordial anisotropy play a role?

\[ Q_{\varepsilon} = \frac{\text{Re}\langle \mathcal{E} V_2^* \rangle}{\sqrt{\langle |\mathcal{E}|^2 \rangle \langle |V_2|^2 \rangle}} \]

- Q coefficient of linear correlation.
- \( E_2 \) is the dominant contribution to \( V_2 \) for \( dN/d\eta \geq 20 \).
- At low multiplicity, \( V_2 \) is instead in a stronger correlation with \( E_p \).

[Schenke, Shen, Tribedy, 1908.06212]

What **observables** can reveal this transition and probe \( E_p \)?
I use two observables in small systems.

– Bożek’s correlation between $\langle p_t \rangle$ and $v_n^2$:

$$
\rho(v_n^2, [p_t]) = \frac{\langle \delta v_n^2 \delta [p_t] \rangle}{\sqrt{\langle (\delta v_n^2)^2 \rangle \langle (\delta [p_t])^2 \rangle}}
$$

[Bożek, 1601.04513]

– ALICE’s correlation between $v_2^2$ and $v_3^2$:

$$
N_{sc}(3,2) = \frac{\langle \delta v_2^2 \delta v_3^2 \rangle}{\sqrt{\langle (\delta v_2^2)^2 \rangle \langle (\delta v_3^2)^2 \rangle}}
$$

[ALICE collaboration, 1604.07663]

With $\delta o = o - \langle o \rangle$ at fixed multiplicity (entropy).

These are natural probes of the primordial momentum anisotropies.
Select two peripheral events (69-70%) at the same multiplicity but very different [pt]. It is an “isentropic” transformation of the QGP which increases T and reduces R.

@large [pt]: hot spots clustered around one transverse point. Very round system.

**Prediction.** In small systems: \( \rho(v_2^2, [p_t]) < 0 \)  
[Bożek, Mehrabpour, 2002.08832]  
[Schenke, Shen, Teaney, 2004.00690]
Verified at LHC. Correlation is negative. Captured by hydrodynamic models.

\[ \rho_2(\langle p_t \rangle) \]

\[ \sqrt{s_{NN}} = 5.02 \text{ TeV} \]

\[ N_{\text{part}} \]

\[ 0.5 < p_t < 2 \text{ GeV} \]

\[ |\eta| < 2.5 \]

\[ \text{Pb+Pb} \]

\[ \text{p+Pb} \]

\[ \text{p+Pb 5020 GeV} \]

\[ 0.5 < p_T < 2 \text{ GeV} \]

\[ N_{\text{ch}} \]

\[ [\text{Schenke, Shen, Teaney, 2004.00690}] \]
What about the initial momentum anisotropy? Intuitive picture.

@large $[pt]$: hot spots clustered around one transverse point. Smaller size, more $\varepsilon_p$.

**Prediction.** In small systems: $\rho(\varepsilon_p^2, \langle p_t \rangle) > 0$
Consider $V_2 = \kappa_2 \mathcal{E}_2 + \kappa_p \mathcal{E}_p$, we expect:

\[
\rho(v^2_2, [p_t]) = \kappa_2^2 \rho(\varepsilon^2_2, [p_t]) + \kappa_p^2 \rho(\varepsilon^2_p, [p_t])
\]

Analyze the contributions separately:

Positive! Confirms the intuitive picture. A new feature of high-energy QCD.

Negative. As expected.

The contributions are qualitatively different. [Giacalone, Schenke, Shen, 2006.15721]
IP-Glasma+Hydro: full prediction.

- Sign change occurring as expected around $dN/d\eta=10$.
- A neat prediction (both AA and pA).
- No sign change if we set $E_p=0$.
- Non-flow has to be addressed carefully in future measurements.

[Behera, Bhatta, Jia, Zhang, 2102.05200]
[Lim, Nagle, 2103.01348]

[Giacalone, Schenke, Shen, 2006.15721]
Select two peripheral events (69-70%) at the same multiplicity but very different \([p_t]\).

@large \([p_t]\): hot spots clustered around one transverse point. **Both** \(\varepsilon_2\) **and** \(\varepsilon_3\) **decrease!**

**Prediction.** In small systems: \(\rho(v_2^2, v_3^2) > 0\)
Confirmed in hydro...

...but data?

[Noronha-Hostler, Sievert 1901.01319]

Include full $T_{\mu\nu}$?

[CMS Collaboration, 1709.09189, 1905.09935]
[ATLAS Collaboration, 1807.02012]
Consider now the correlation between $V_2$ and $V_3$. Very simple model:

\[
V_2 = \kappa_2 \mathcal{E}_2 + \kappa_{2p} \mathcal{E}_{2p}
\]
\[
V_3 = \kappa_3 \mathcal{E}_3 + \kappa_{3p} \mathcal{E}_{3p}
\]

Evaluate the symmetric cumulant. **Expectations from system size dependence:**

\[
\langle V_2 V_2^* V_3 V_3^* \rangle - \langle V_2 V_2^* \rangle \langle V_3 V_3^* \rangle =
\]

\[
\begin{align*}
\kappa_2^2 \kappa_3^2 \left( \langle \varepsilon_2^2 \varepsilon_3^2 \rangle - \langle \varepsilon_2^2 \rangle \langle \varepsilon_3^2 \rangle \right) + \\
\kappa_2^2 \kappa_{3p}^2 \left( \langle \varepsilon_2^2 \varepsilon_{3p}^2 \rangle - \langle \varepsilon_2^2 \rangle \langle \varepsilon_{3p}^2 \rangle \right) + \\
\kappa_{2p}^2 \kappa_3^2 \left( \langle \varepsilon_{2p}^2 \varepsilon_3^2 \rangle - \langle \varepsilon_{2p}^2 \rangle \langle \varepsilon_3^2 \rangle \right) + \\
\kappa_{2p}^2 \kappa_{3p}^2 \left( \langle \varepsilon_{2p}^2 \varepsilon_{3p}^2 \rangle - \langle \varepsilon_{2p}^2 \rangle \langle \varepsilon_{3p}^2 \rangle \right)
\end{align*}
\]

**Prediction:** initial momentum anisotropies yield a **negative** contribution to $\text{sc}(3,2)$. 
**Prediction:** initial momentum anisotropies yield a negative contribution to sc(3,2).
Ultra-recent developments. Cumulant of three variables (with $<p_t>$):

$$\langle \delta v_2^2 \delta v_3^2 \delta \langle p_t \rangle \rangle$$

Involves the correlators:

$$\langle v_2^2 \langle p_t \rangle \rangle - \langle v_2^2 \rangle \langle p_t \rangle \rangle$$

$$\langle v_3^2 \langle p_t \rangle \rangle - \langle v_3^2 \rangle \langle p_t \rangle \rangle$$

$$\langle v_2^2 v_3^2 \langle p_t \rangle \rangle - \langle v_2^2 v_3^2 \rangle \langle p_t \rangle \rangle$$

Naturally sensitive to initial anisotropies.

Funny prospects for future high-stat data.
• “Geometry” paradigm explains anisotropic flow at large multiplicities.

• Beyond $F = -\nabla P$: initial momentum anisotropies at small multiplicity.

• Predicted by high-energy QCD.

• Natural handle: vary system size with $<p_t>$.

• Natural handle: correlation between $v_2$ and $v_3$.

• **Hunt is ON**: more and more observables for a consistent picture that will lead to an unambiguous discovery.
THANK YOU!