The origin of anisotropy from pp to AA collisions

by

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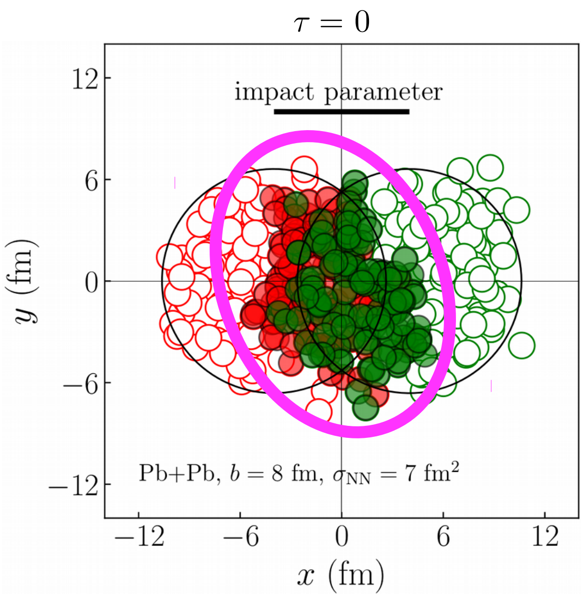
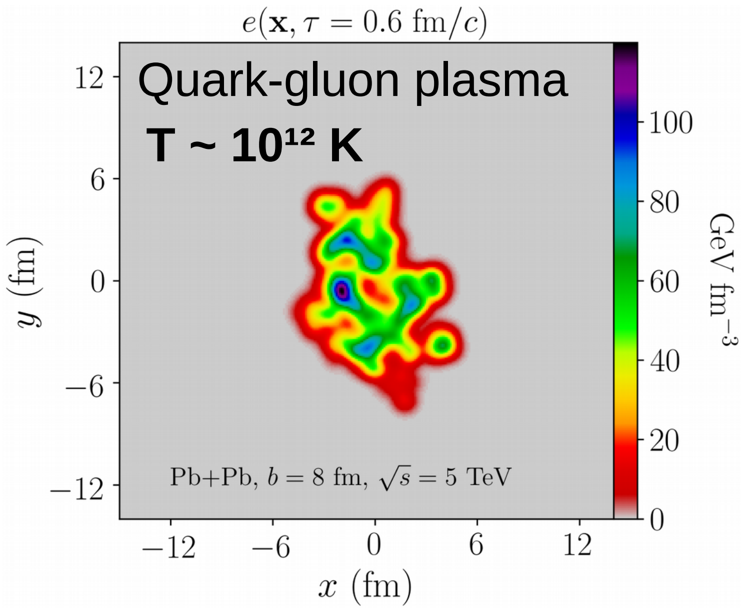
HEAVY-ION COLLISIONS = THE EARLY UNIVERSE IN THE LAB





$\Longrightarrow$ **Effective description: <u>relativistic fluid</u>.** [Romatschke & Romatschke, 1712.05815]

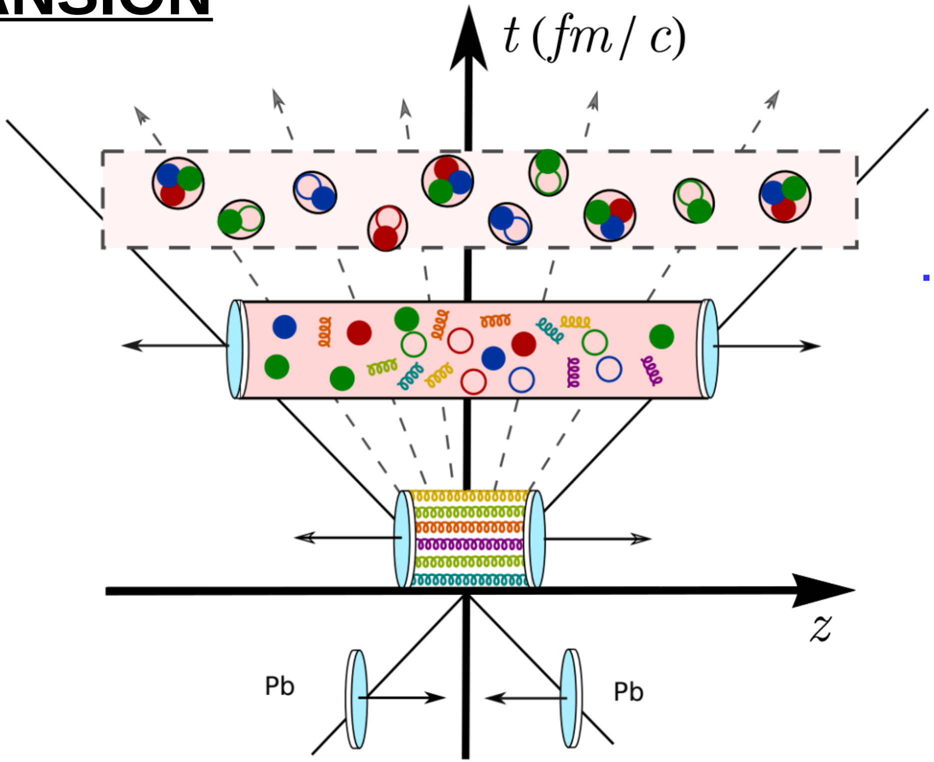
$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - P g^{\mu\nu}$ + small viscous corrections ($\eta/s, \zeta/s$, ...) **+** $\partial_\mu T^{\mu\nu} = 0$

Equation of state from lattice QCD (T > 156 MeV). Large number of DOF (~40): QGP.

[HotQCD collaboration, 1407.6387]

THE EXPANSION

(courtesy A. Mazeliauskas)



$10 < t < \infty$ *hadronic gas*

· · · · FREEZE-OUT · · · ·

$1 < t \lesssim 10$ *fluid expansion*
(QGP phase)

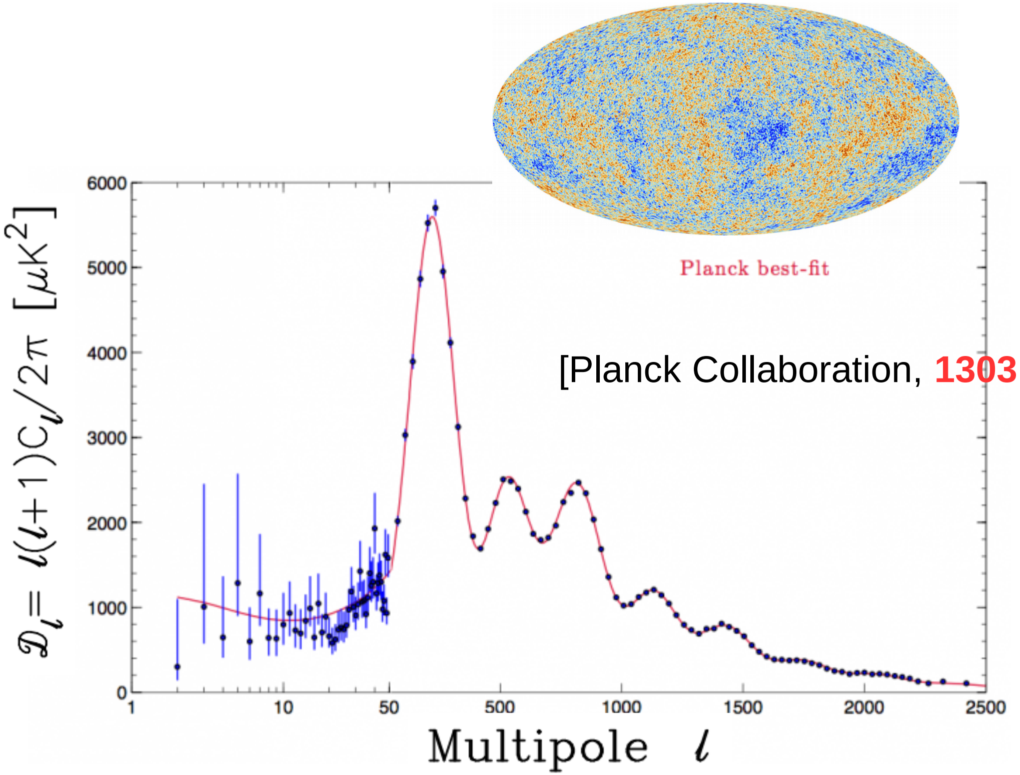
$0 < t \lesssim 1$ *equilibration*

$-\infty < t < 0$

$t = \infty$ → $\dfrac{dN}{d^3\mathbf{p}}$ **or** $\dfrac{dN}{dy\,d^2\mathbf{p}_t}$ **Hadron spectrum in momentum space.**

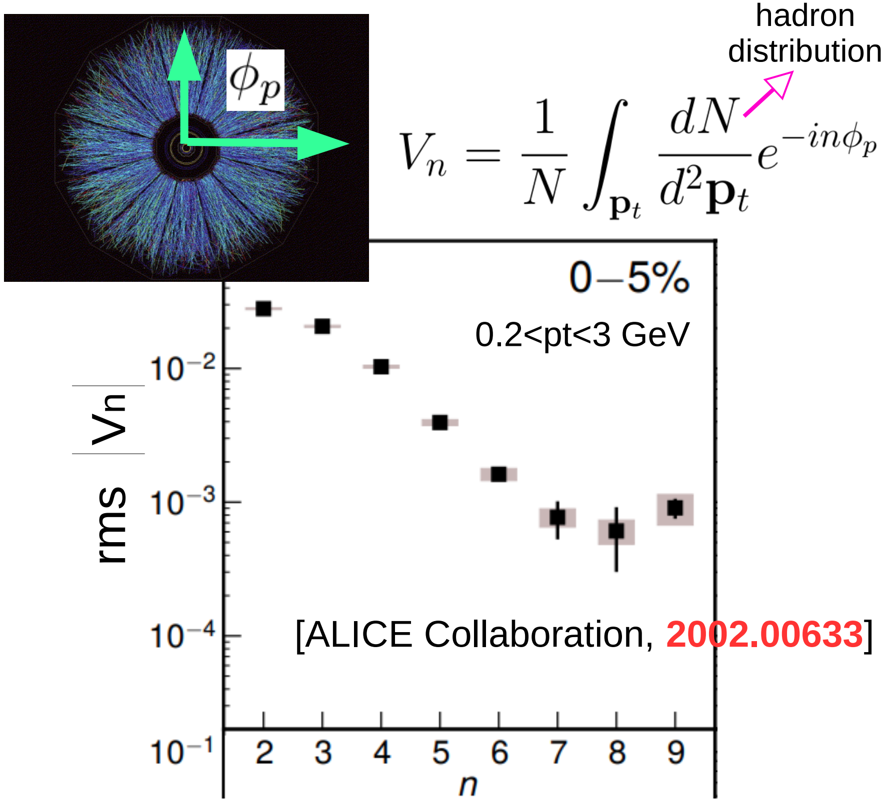
The final state presents anisotropy in azimuthal angle.

A great Big Bang.



[Planck Collaboration, 1303.5076]

A billion Little Bangs.



hadron distribution

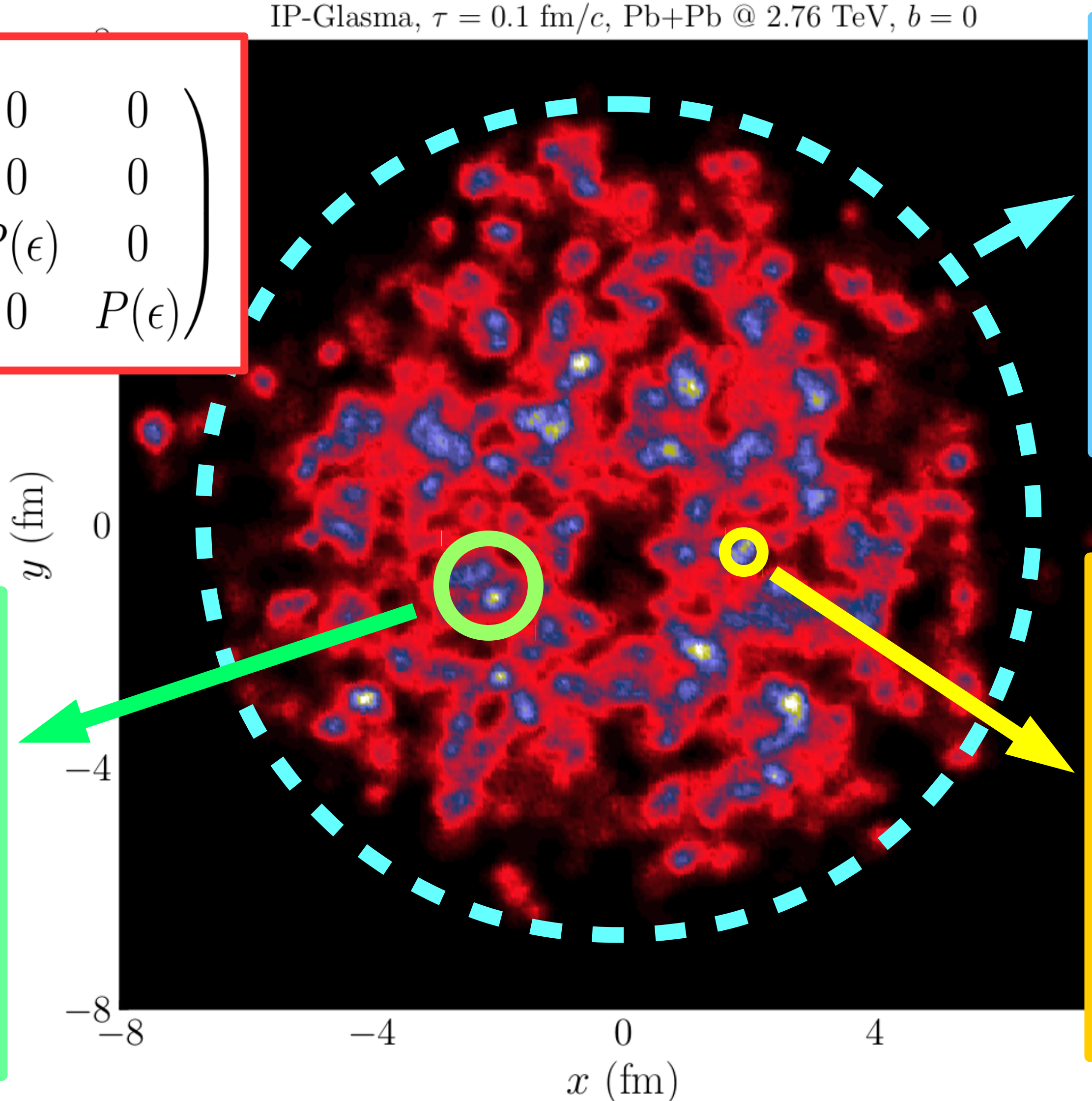
$$V_n = \frac{1}{N}\int_{\mathbf{p}_t} \frac{dN}{d^2\mathbf{p}_t} e^{-in\phi_p}$$

[ALICE Collaboration, 2002.00633]

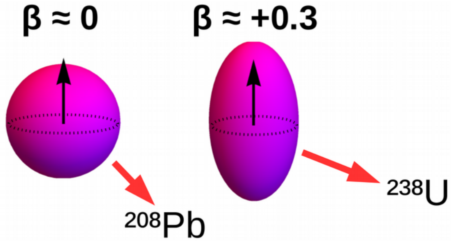
What is the origin of anisotropy?

Structure of nuclei across length scales → primordial anisotropy → observed anisotropy

$$T^{\mu\nu}(\tau_0) \approx \begin{pmatrix} \epsilon & 0 & 0 & 0 \\ 0 & P(\epsilon) & 0 & 0 \\ 0 & 0 & P(\epsilon) & 0 \\ 0 & 0 & 0 & P(\epsilon) \end{pmatrix}$$

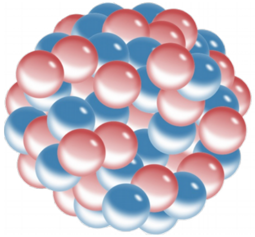


Collective features



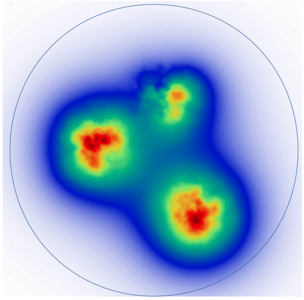
Scale ~ RA

Individual nucleons



Scale ~ 1fm - RA

Subnucleonic structure ?

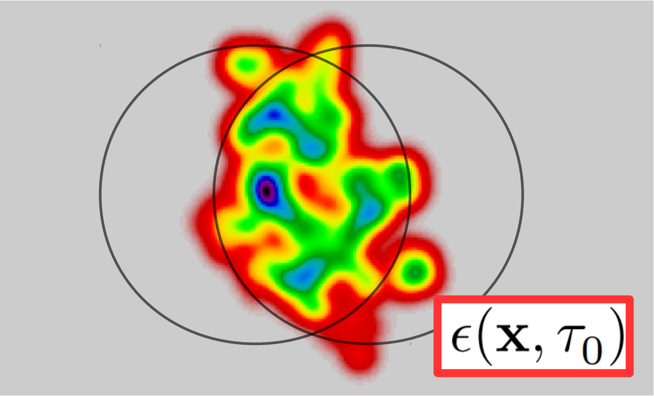


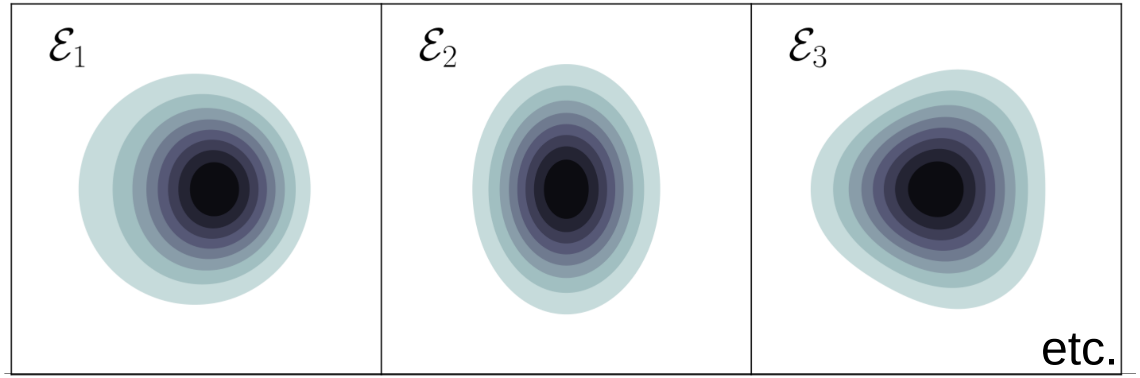
Scale < 1fm

Anisotropic flow from spatial anisotropy.

$$F = -\nabla P$$

[Ollitrault, **1992**]





[Alver, Roland, **1003.0194**]

In the QGP, all multi-pole moments are nonzero:

$$\mathcal{E}_n = -\frac{\int r dr d\phi \; r^n e^{in\phi} \epsilon(r, \phi)}{\int r dr d\phi \; r^n \epsilon(r, \phi)}$$

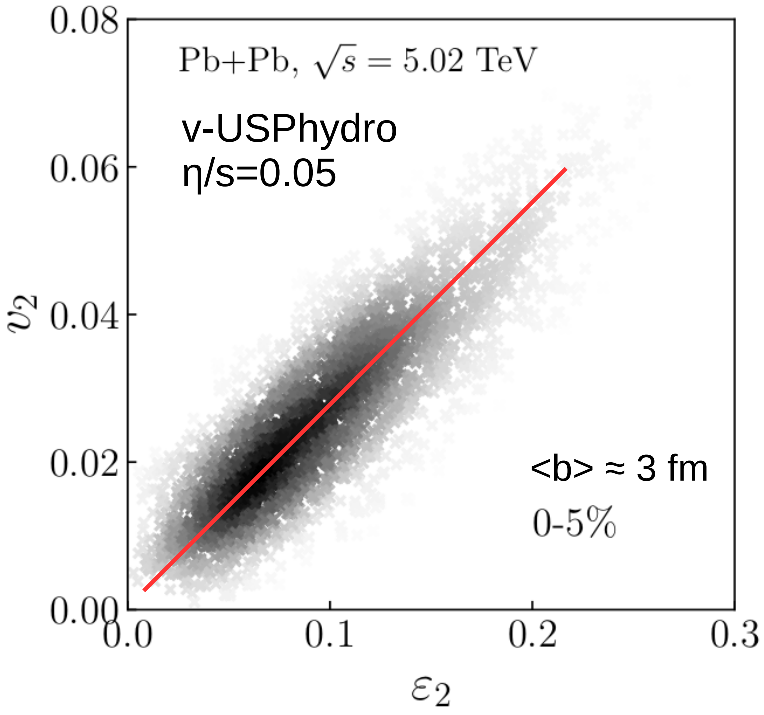
$$V_n \propto \mathcal{E}_n$$

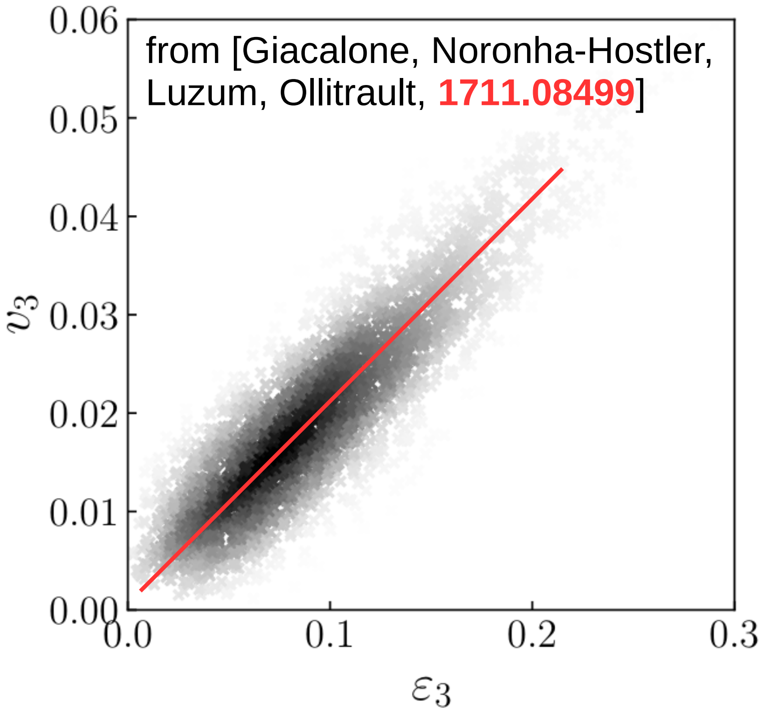
[Teaney, Yan, **1010.1876**]

Each En in the initial state leads to Vn in the final state.

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

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





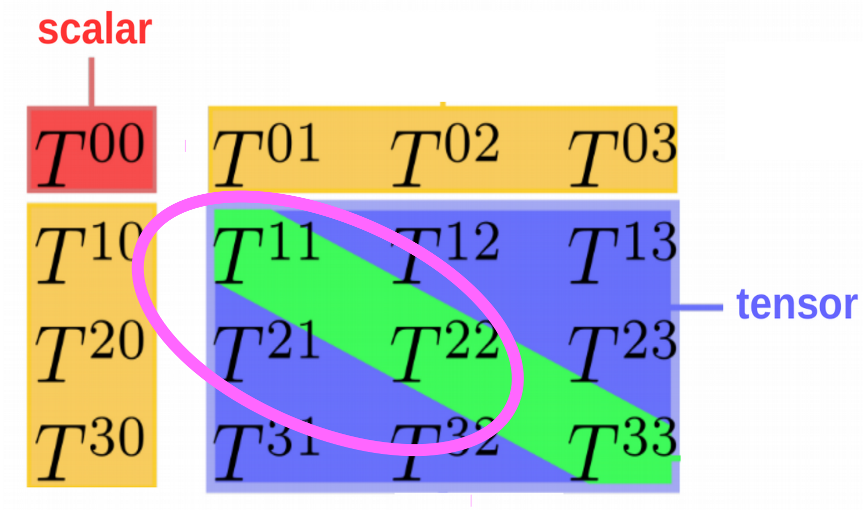
from [Giacalone, Noronha-Hostler, Luzum, Ollitrault, 1711.08499]

Explains experimental data in both large and small systems.
The importance of initial conditions.

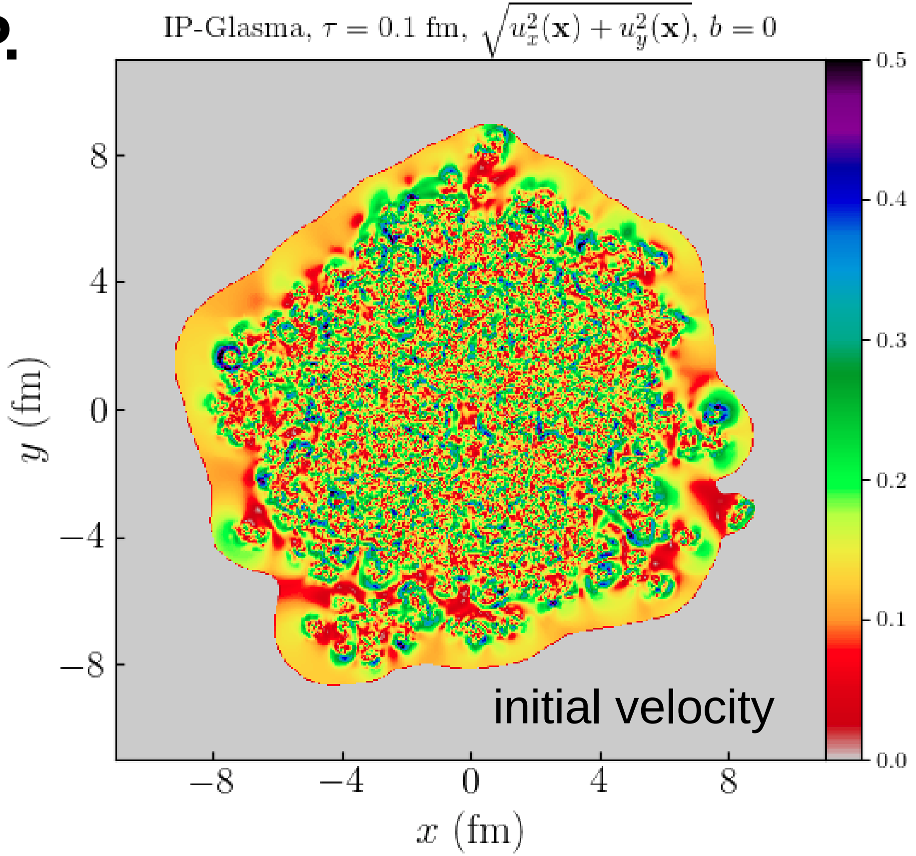
[Giacalone, Noronha-Hostler, Ollitrault, 1702.01730]

New frontier: Going beyond F = - ∇P.

Including the full stress-energy tensor.



$$\begin{matrix} T^{00} & T^{01} & T^{02} & T^{03} \\ T^{10} & T^{11} & T^{12} & T^{13} \\ T^{20} & T^{21} & T^{22} & T^{23} \\ T^{30} & T^{31} & T^{32} & T^{33} \end{matrix}$$



PRIMORDIAL “MOMENTUM” ANISOTROPIES

$$\mathcal{E}_{2p} \propto \langle T^{xx} - T^{yy} + 2iT^{xy} \rangle$$

$$\mathcal{E}_{3p} \propto \left\langle r e^{i\phi} \left(T^{xx} - T^{yy} + 2iT^{xy} \right) \right\rangle$$

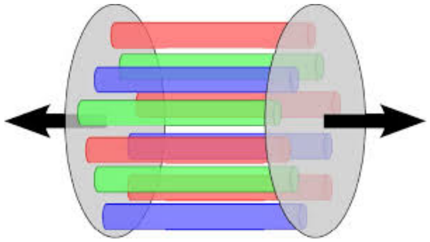
Evidence in data?

[Sousa, Luzum, Noronha, 2002.12735]

… evidence in theoretical calculations? **Natural framework: CGC**

$$T^{00}_{\mathrm{LO}} = \frac{1}{2}\Big[\underbrace{\boldsymbol{E}^2 + \boldsymbol{B}^2}_{\text{class. fields}}\Big], \qquad T^{0i}_{\mathrm{LO}} = \big[\boldsymbol{E}\times\boldsymbol{B}\big]^i$$

$$T^{ij}_{\mathrm{LO}} = \frac{\delta^{ij}}{2}\big[\boldsymbol{E}^2 + \boldsymbol{B}^2\big] - \big[\boldsymbol{E}^i\boldsymbol{E}^j + \boldsymbol{B}^i\boldsymbol{B}^j\big],$$

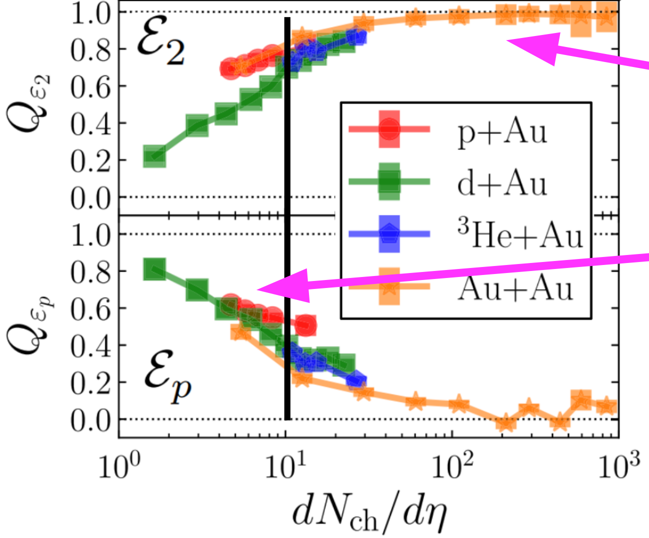


[Gelis, **2102.07604**]

[upcoming talk by
A. Czajka]

Hybrid CGC+Hydro framework: IP-Glasma+MUSIC.

$$\boxed{Q_{\mathcal{E}} = \frac{\mathrm{Re}\langle \mathcal{E} V_2^* \rangle}{\sqrt{\langle|\mathcal{E}|^2\rangle\langle|V_2|^2\rangle}}}$$



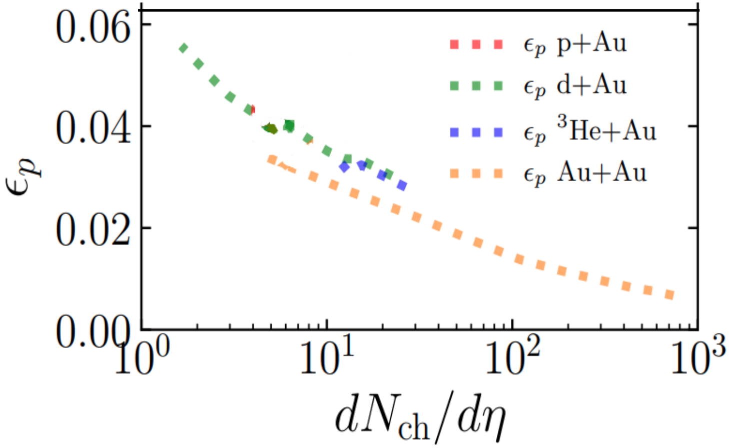
[Schenke, Shen, Tribedy, **1908.06212**]

E_2 dominant contribution to V_2 for $dN/d\eta \geq 20$.

V_2 in a stronger correlation with E_p at low $dN/d\eta$.

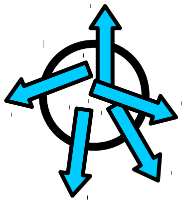
Can we reveal this transition in experiments?

Highly nontrivial… idea: exploit the dependence on system size.

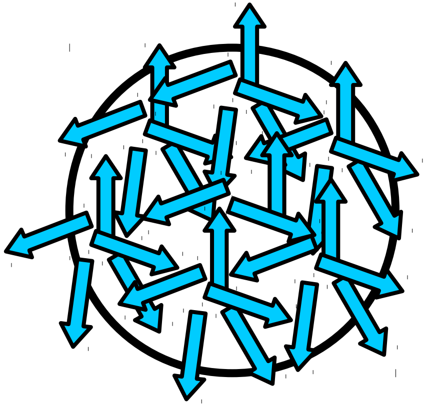


[Schenke, Shen, Tribedy, 1908.06212]

Net velocity field is naturally larger if the system has a smaller size.



larger Ep



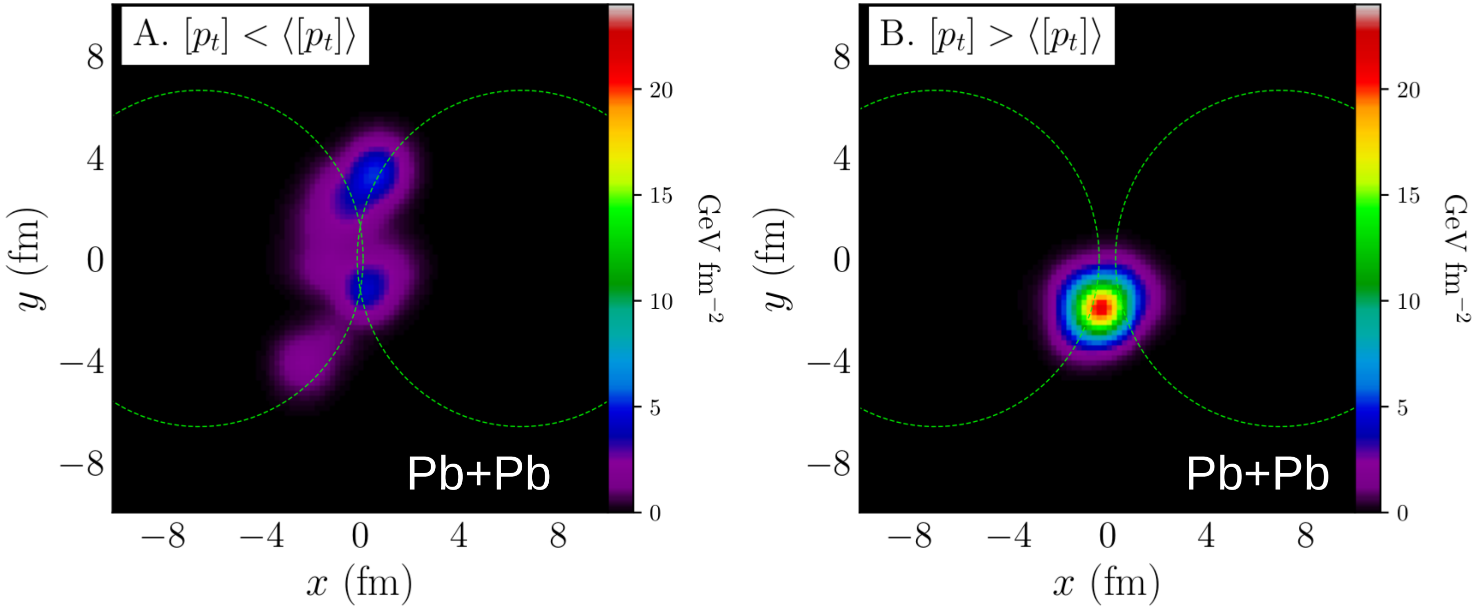
smaller Ep

Can we change the system size in experiments?

The mean transverse momentum of the hadrons gives a handle on the system size.

[Gardim, Giacalone, Noronha-Hostler, Ollitrault **2004.01765**] [Schenke, Shen, Teaney, **2004.00690**]

[Bożek, Mehrabpour, **2002.08832**]



event	A	B
$N_{\rm ch}$	134	134
b (fm)	13.0	13.9
$[p_t]/\langle [p_t] \rangle$	0.907	1.143
R (fm)	2.97	1.34
ε_2	0.675	0.133
ε_3	0.229	0.067

Small systems: at large <pt> hot spots clustered around one transverse point.

The mean transverse momentum of the hadrons gives a handle on the system size.

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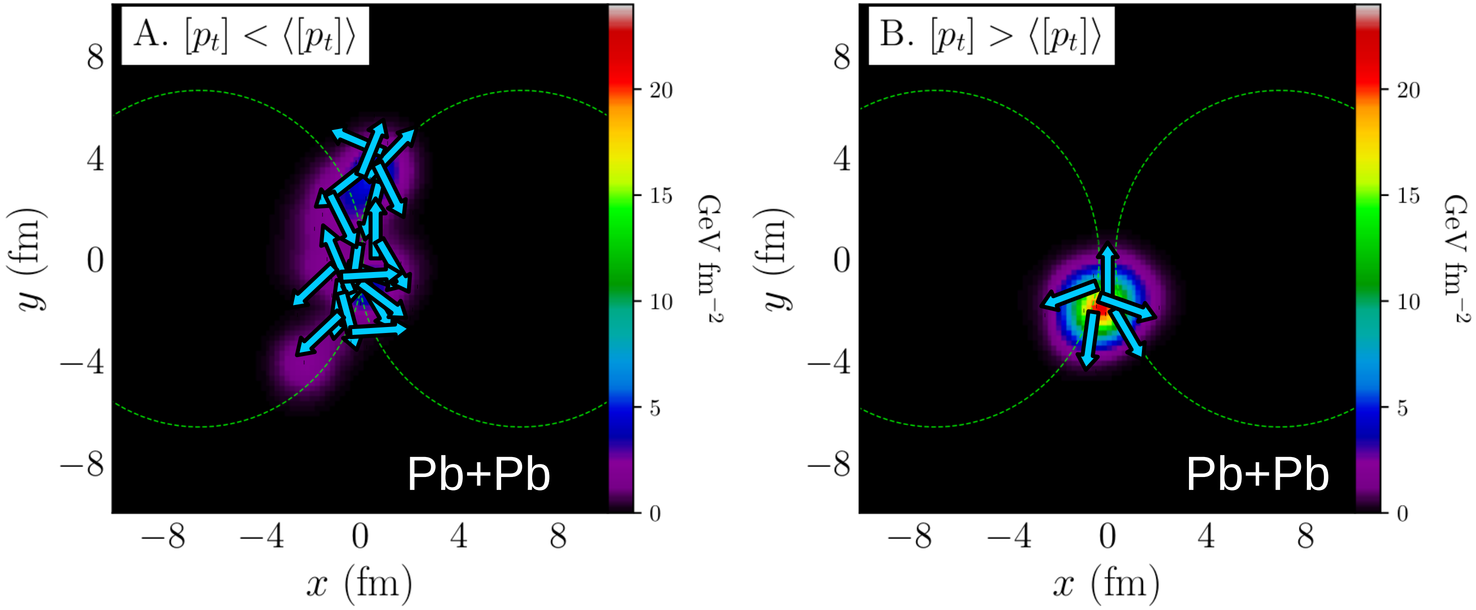

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$\langle \varepsilon_p \rangle_A \approx 0.5 \langle \varepsilon_p \rangle_B$

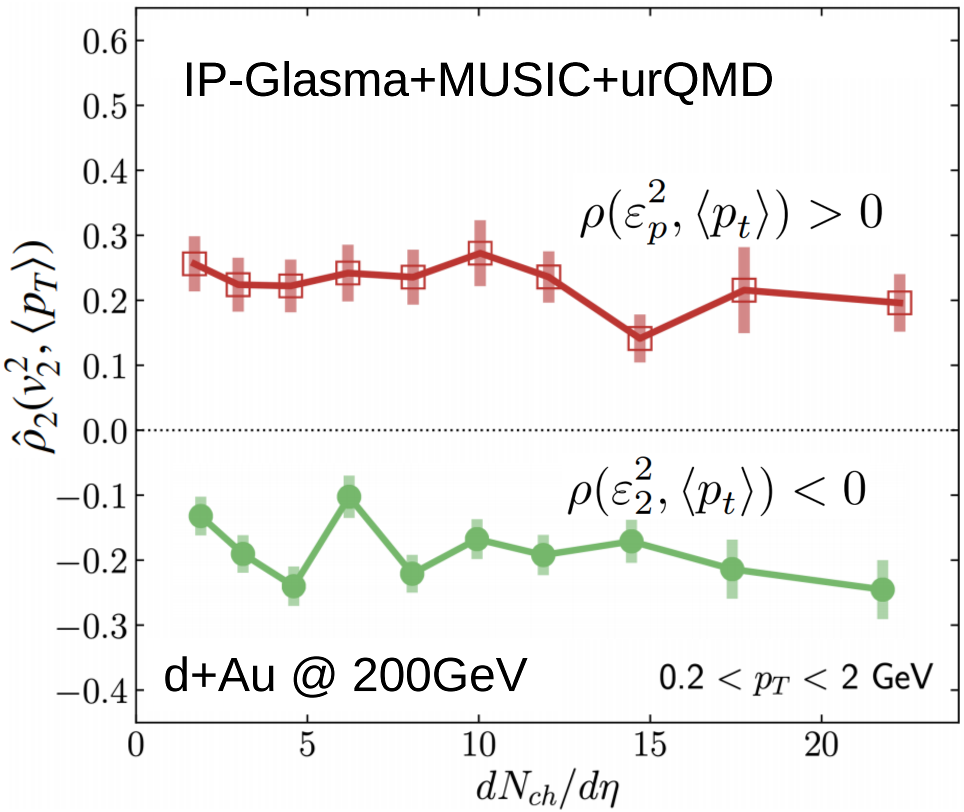
Small systems: at large <pt> hot spots clustered around one point (at fixed centrality).

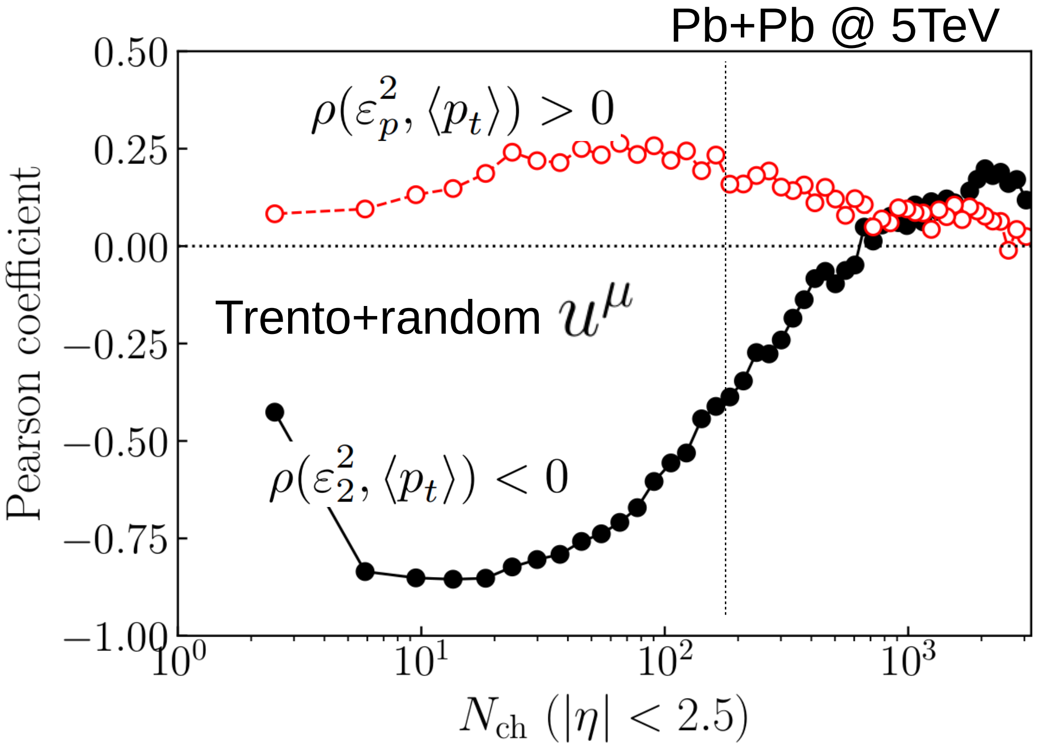
Prediction:

$$\boxed{\rho(\varepsilon_2^2, \langle p_t \rangle) < 0} \qquad \boxed{\rho(\varepsilon_p^2, \langle p_t \rangle) > 0}$$

statistical correlation
(Pearson coefficient)

Validation in models. Generic feature of small systems (pp, pA, peripheral AA).



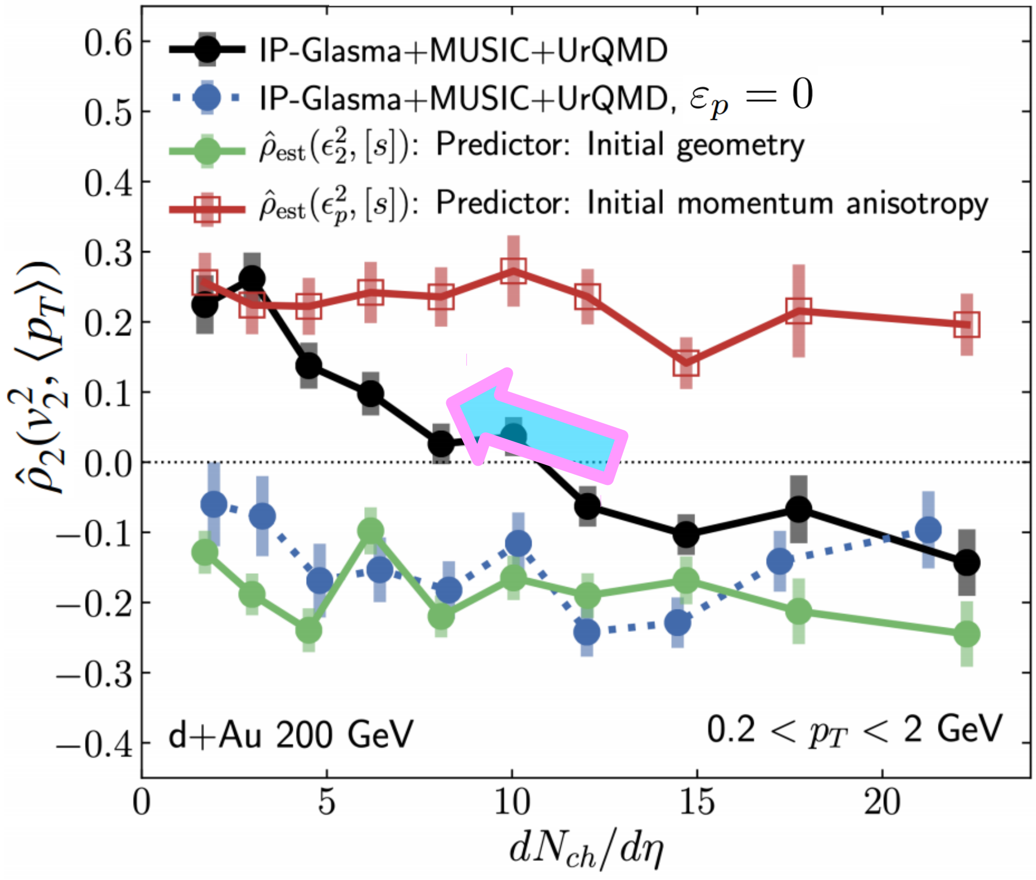


The contributions are qualitatively different.

[Giacalone, Schenke, Shen, 2006.15721]

Turning to elliptic flow. Momentum anisotropy is dominant for dN/dη < 10.

[Giacalone, Schenke, Shen, 2006.15721]



– **Sign change around dN/dη=10.**
A neat prediction for experiments.

– **No sign change if we set Ep=0.**

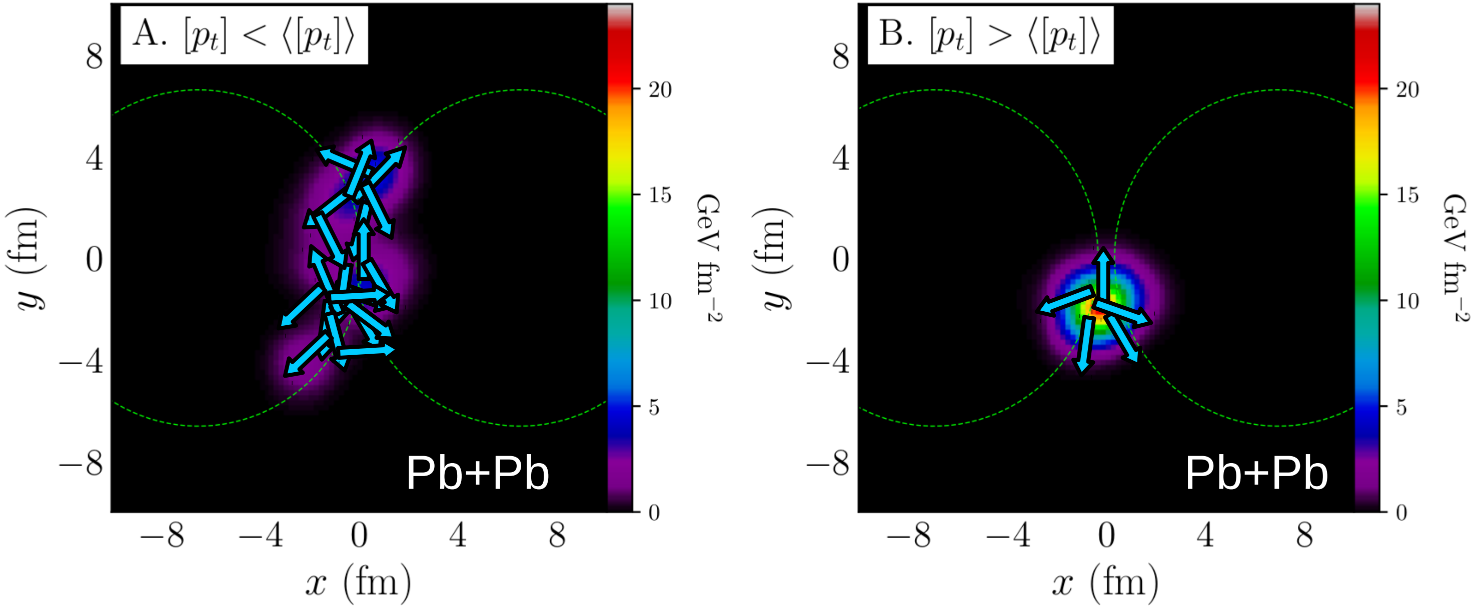
– **Measurement is however difficult.**
Non-flow (PYTHIA) mimics the signal.

[Zhang, Behera, Bhatta, Jia, 2102.05200]

[Lim, Nagle, 2103.01348]

SOMETHING NEW FOR THIS CONFERENCE

In small systems, e2 and e3 have the same geometric origin.



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$$\langle \varepsilon_p \rangle_A \approx 0.5 \langle \varepsilon_p \rangle_B$$

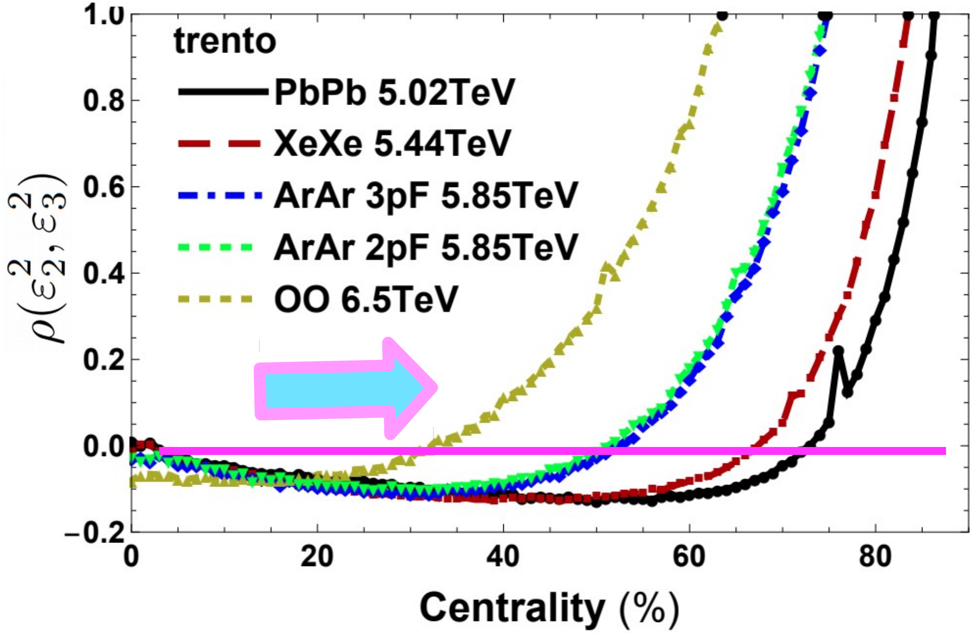
Remarkable prediction for small systems:

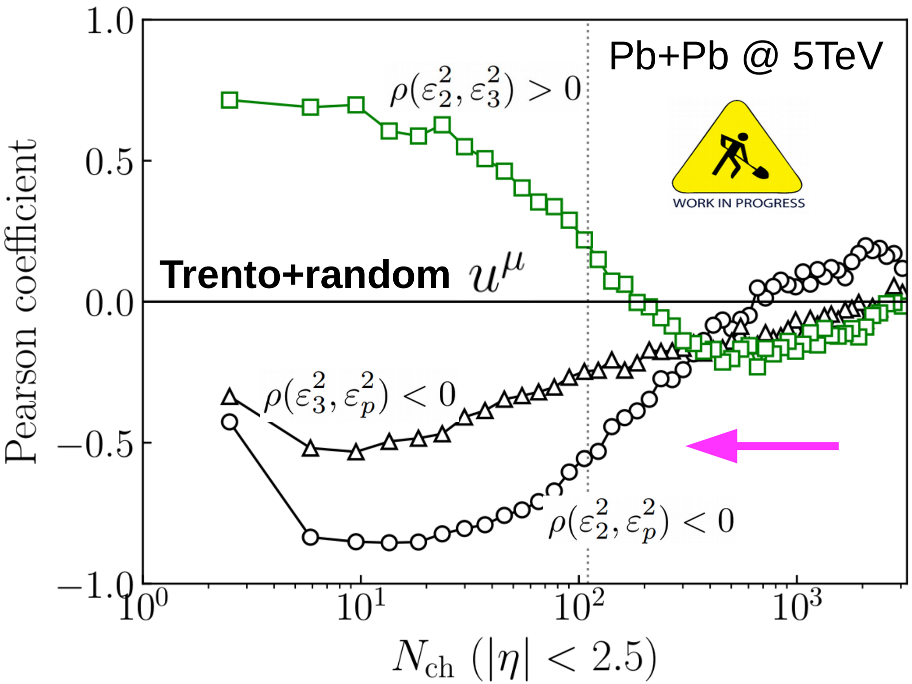
$$\boxed{\rho(\varepsilon_2^2, \varepsilon_3^2) > 0}$$

$$\boxed{\rho(\varepsilon_2^2, \varepsilon_p^2) < 0 \, , \;\; \rho(\varepsilon_3^2, \varepsilon_p^2) < 0}$$

Predictions verified in a toy calculation + geometry-only results.

[Noronha-Hostler, Sievert 1901.01319]





Negative contributions appear due to initial momentum anisotropy.

Replace eccentricities with flow coefficients. Sign of $\rho(v_2^2, v_3^2)$?

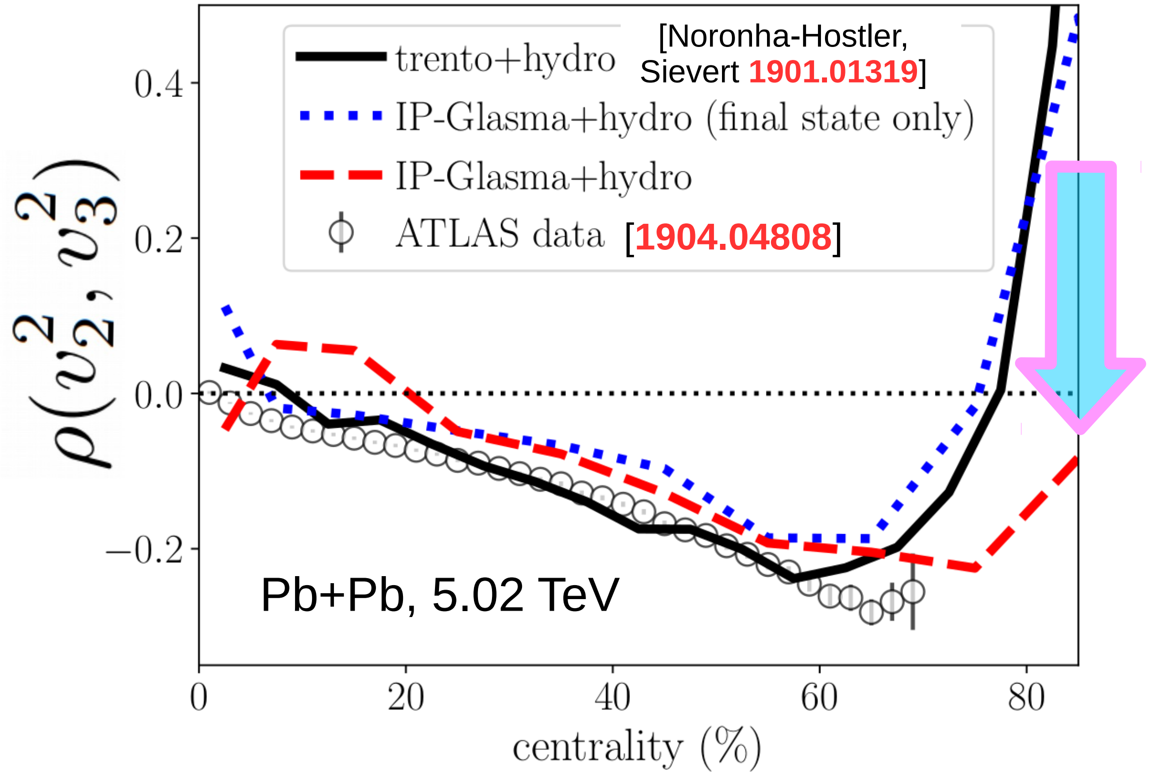
With initial momentum anisotropy:

$$\rho(v_2^2, v_3^2) \propto \langle v_2^2 v_3^2\rangle - \langle v_3^2\rangle\langle v_3^2\rangle =$$

Assume, e.g., $V_2 = \kappa_2\mathcal{E}_2 + \kappa_p\mathcal{E}_p$

$$\kappa_2^2\kappa_3^2\left(\langle\varepsilon_2^2\varepsilon_3^2\rangle - \langle\varepsilon_2^2\rangle\langle\varepsilon_3^2\rangle\right) + \kappa_2^2\kappa_{3p}^2\left(\langle\varepsilon_2^2\varepsilon_{3p}^2\rangle - \langle\varepsilon_2^2\rangle\langle\varepsilon_{3p}^2\rangle\right) + \kappa_{2p}^2\kappa_3^2\left(\langle\varepsilon_{2p}^2\varepsilon_3^2\rangle - \langle\varepsilon_{2p}^2\rangle\langle\varepsilon_3^2\rangle\right) + \kappa_{2p}^2\kappa_{3p}^2\left(\langle\varepsilon_{2p}^2\varepsilon_{3p}^2\rangle - \langle\varepsilon_{2p}^2\rangle\langle\varepsilon_{3p}^2\rangle\right)$$

POSITIVE **NEGATIVE** **NEGATIVE** **?**



[Noronha-Hostler, Sievert 1901.01319]

[1904.04808]

Pb+Pb, 5.02 TeV

WORK IN PROGRESS

Initial Ep keeps the correlation negative.

Effect at dN/dη~30, very promising.

Prediction for experiments.

- Conclusion.
- Cosmological model for pp, pA, AA collisions at high energy.
- Origin of anisotropy: mostly $F = -\nabla P$.
- Beyond response to geometry: primordial momentum anisotropy.
- Effects visible in theory results: Phenomenology is possible!
- **Natural handle: vary system size with $\langle p_t \rangle$.**
- **Natural handle: correlation between v_2 and v_3.**
- **Hunt is ON**: more observables for unambiguous discovery.

THANK YOU!