# VORTEX RINGS IN HEAVY-ION COLLISIONS

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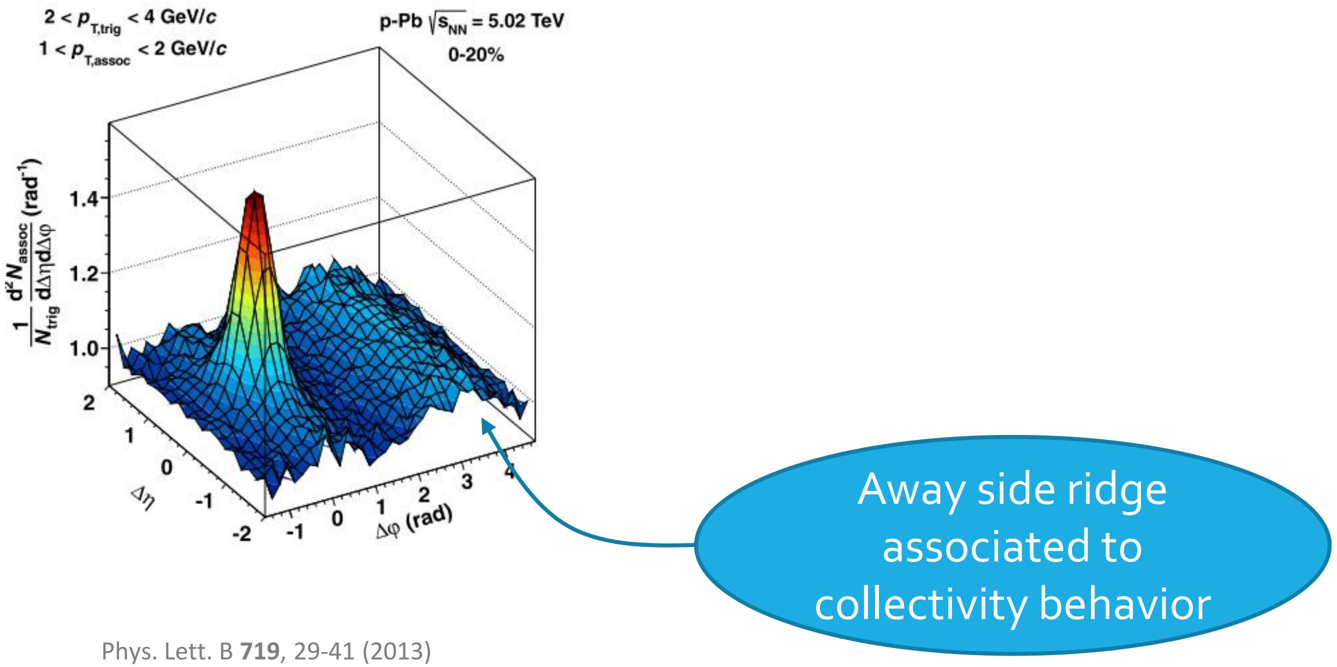
# Small systems: pA collisions

- It was not expected hydro-like signals at smaller system
  - Shorter lived:
    - It was not expected it would have time for thermalization
    - It was not expected it would have time to develop collectivity behavior
  - They also have less degrees of freedom, leading many to think a thermodynamics would have limited applicability

# pA collisions: The smallest fluid droplet?

- Presence of away side in 2-particle correlation at LHC




Phys. Lett. B **719**, 29-41 (2013)

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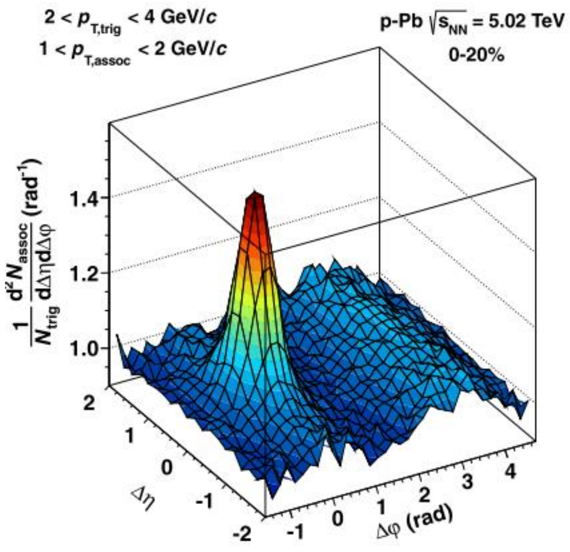
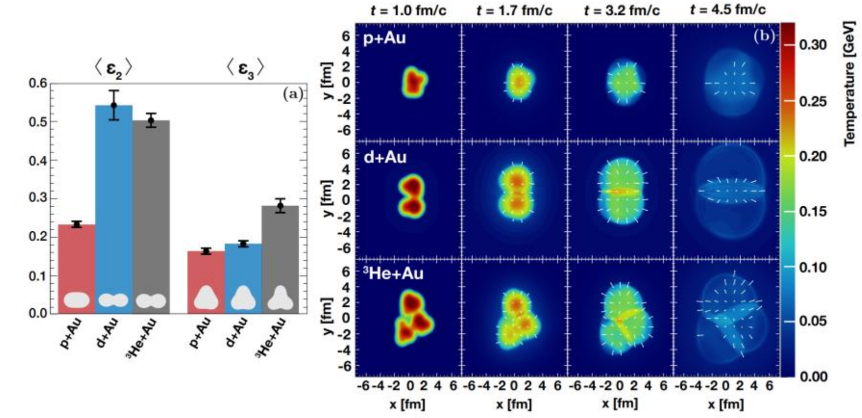
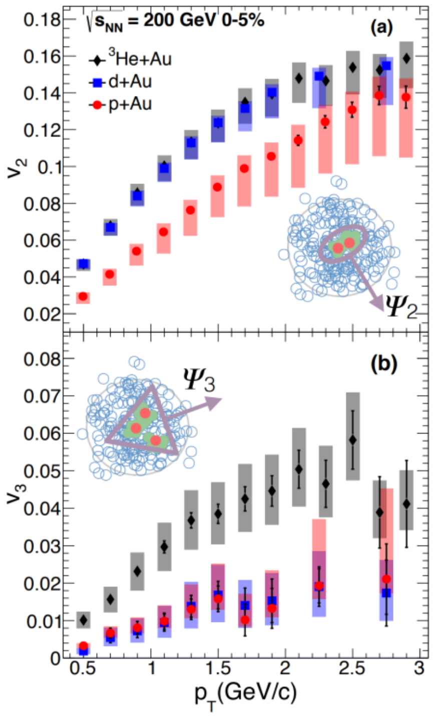



Phys. Lett. B **719**, 29-41 (2013)

- Elliptic flow also observed in p+Au, d+Au and $^3$He+Au




*Nat. Phys.* **15,** 214–220 (2019)




*Nat. Phys.* **15,** 214–220 (2019)

# ARE THERE OTHER PHENOMENA HYDRODYNAMICS PREDICTS?

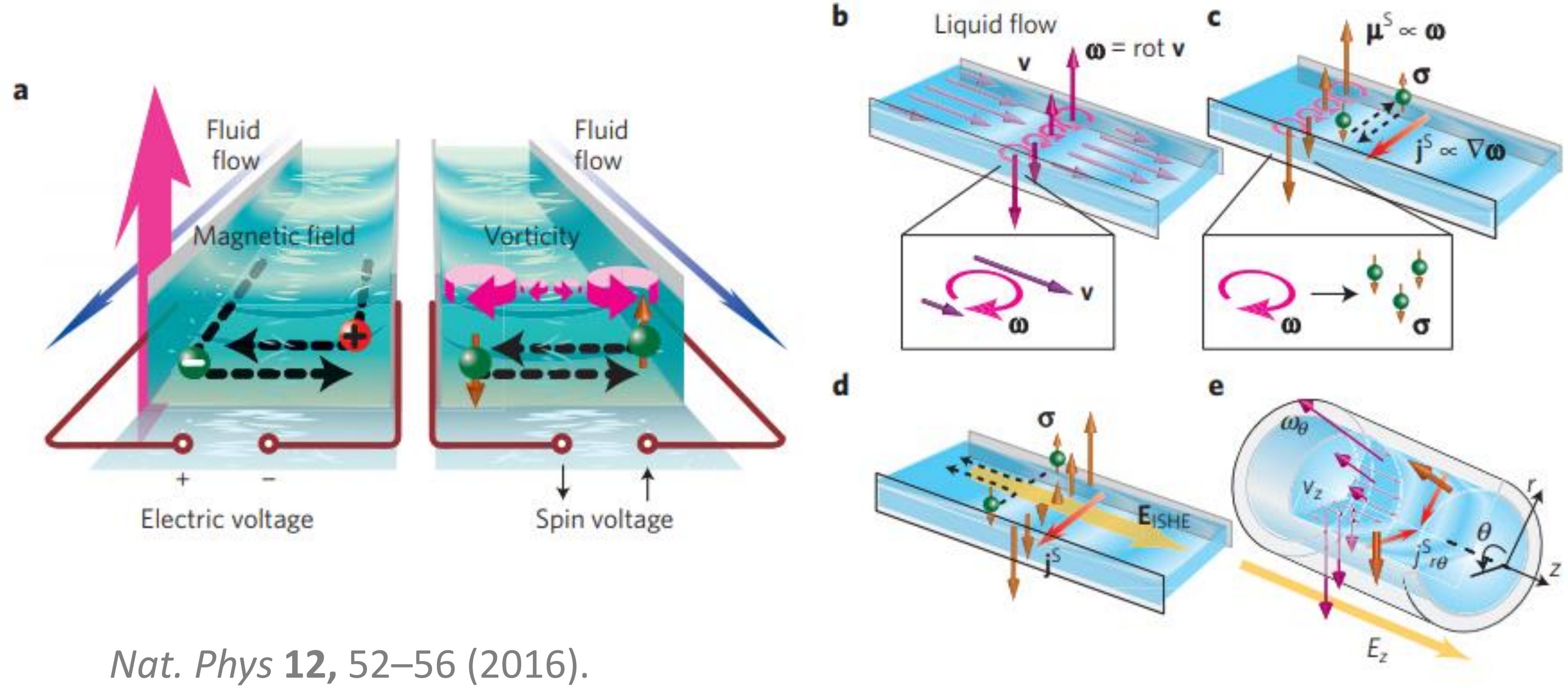
And does it happen in the QGP?

# From galaxies…

- Hydrodynamic simulation of two colliding galaxies

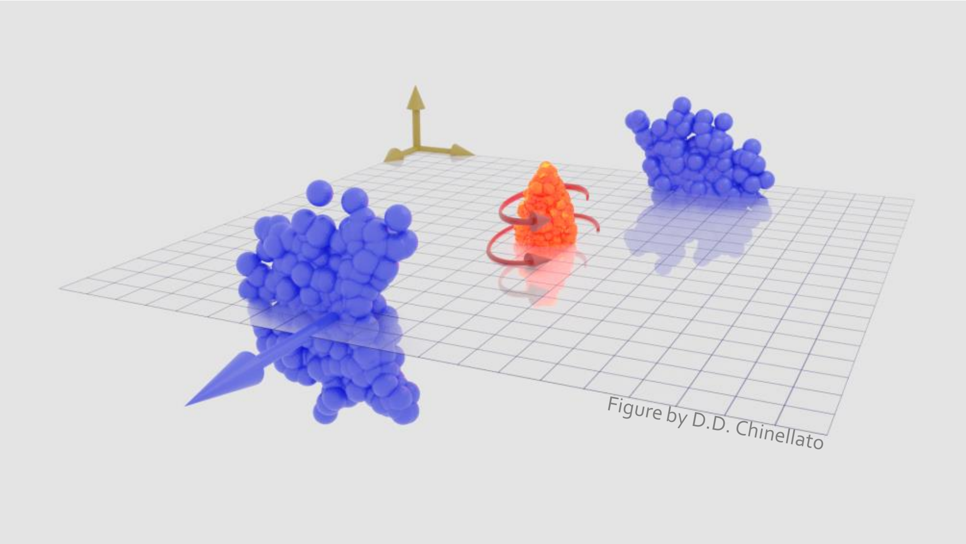
https://www.cct.lsu.edu/~werner/SphGal/

# From galaxies… to the lab…




*Nat. Phys* **12,** 52–56 (2016).

# … to the QGP



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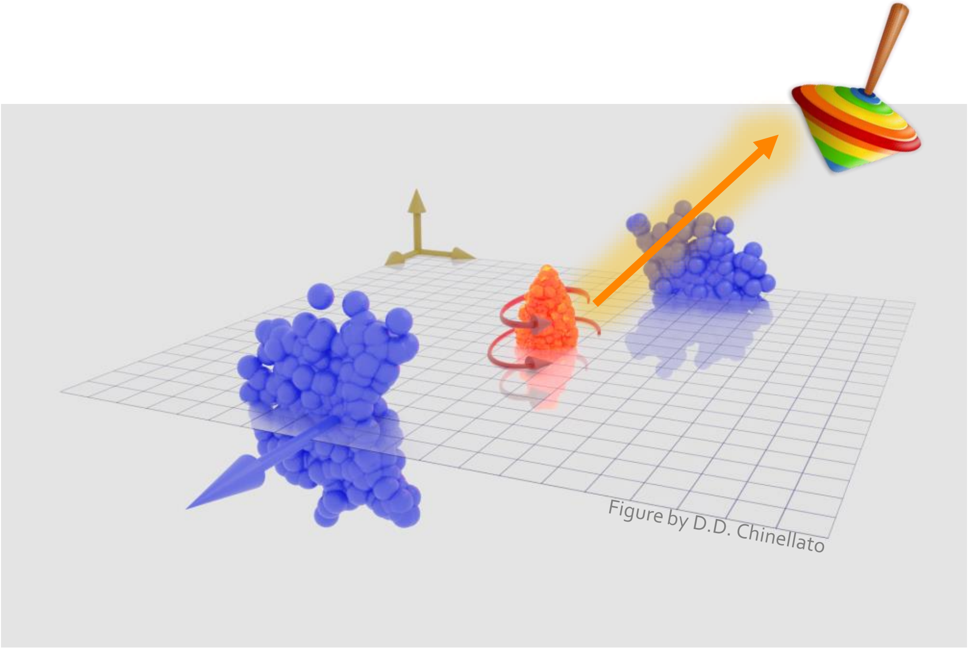

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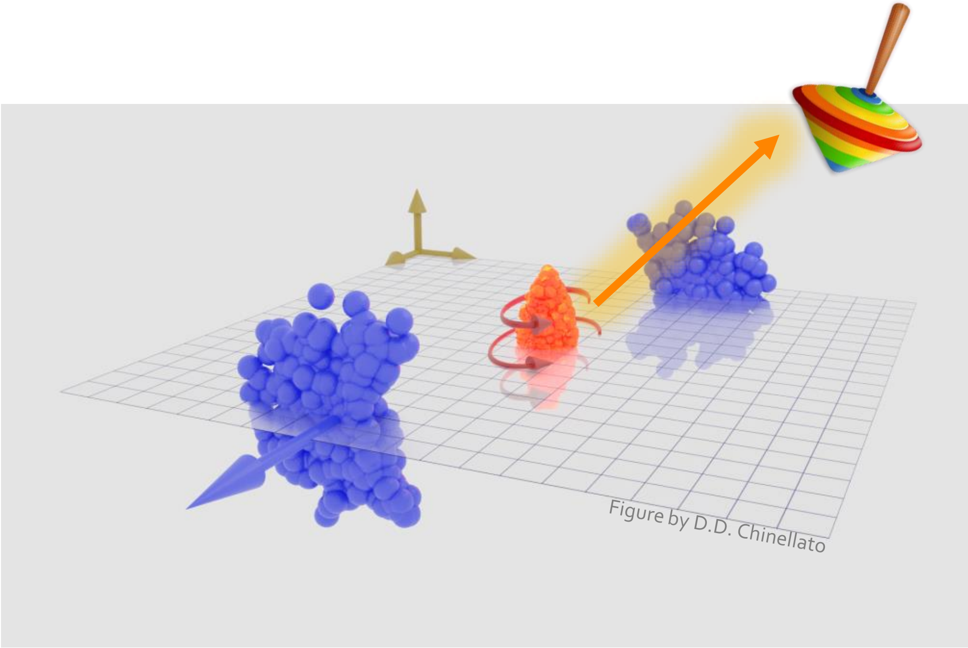
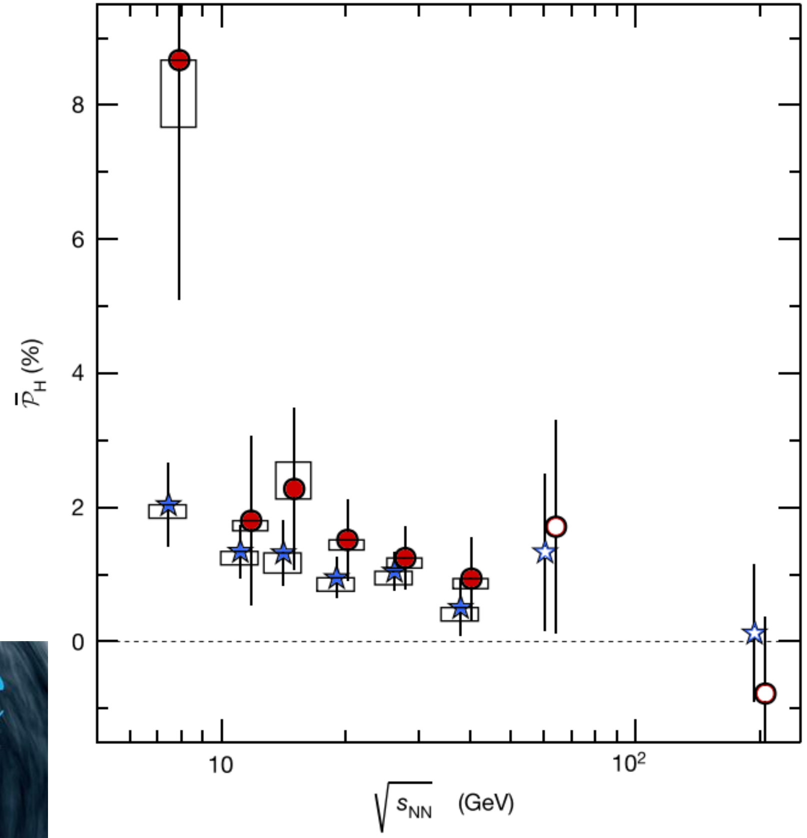


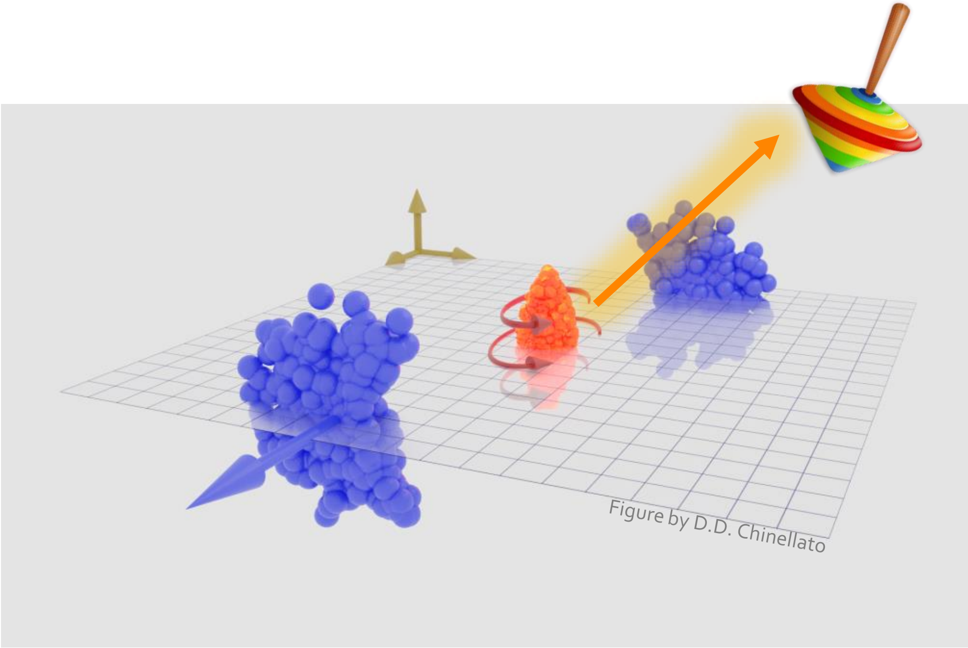

$$S^\mu = -\frac{1}{8m}\varepsilon^{\mu\rho\sigma\tau}p_\tau \frac{\int d\Sigma_\lambda p^\lambda (1-n_F)\omega_{\rho\sigma}}{\int d\Sigma_\lambda p^\lambda n_F}$$

$$n_f = \frac{1}{e^{\beta^\mu(x)p_\mu - \xi(x)}}$$


*Nature* **548,** 62–65 (2017)

# … to the QGP

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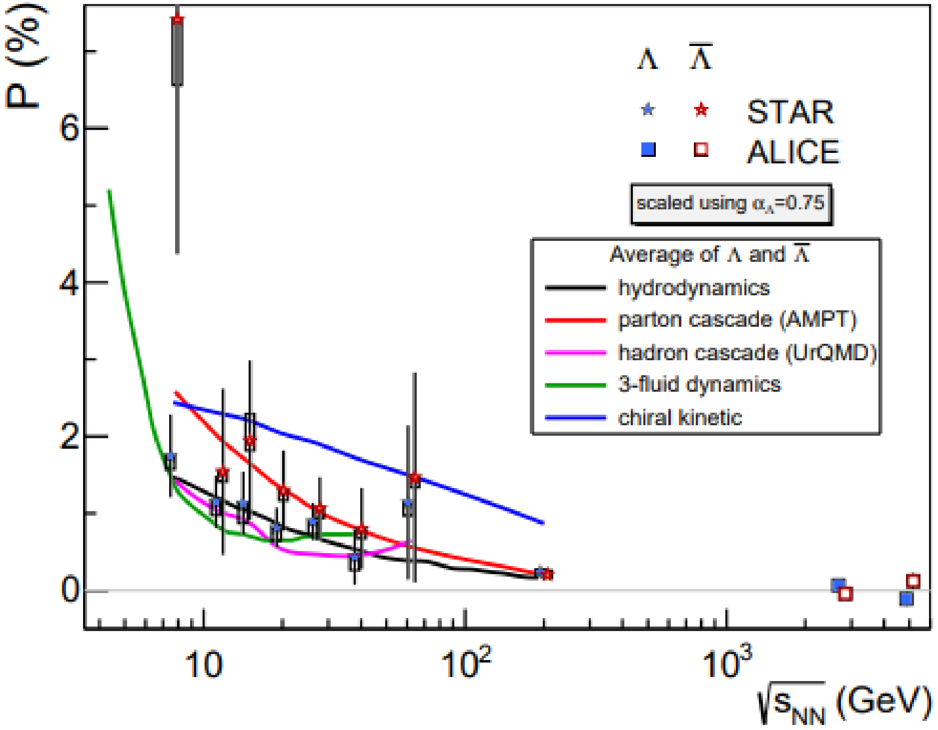
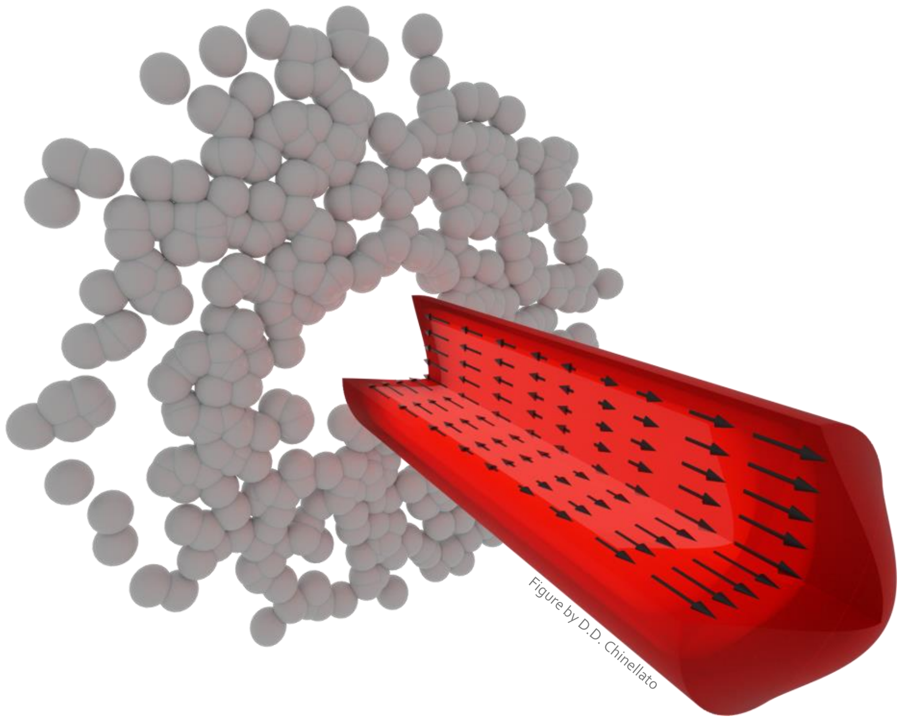



*Ann. Rev. Nucl. Part. Sci.* 70, 395-423 (2020)

# Could we generate the “smallest swirls” in pA collisions?

**Bjorken Flow**



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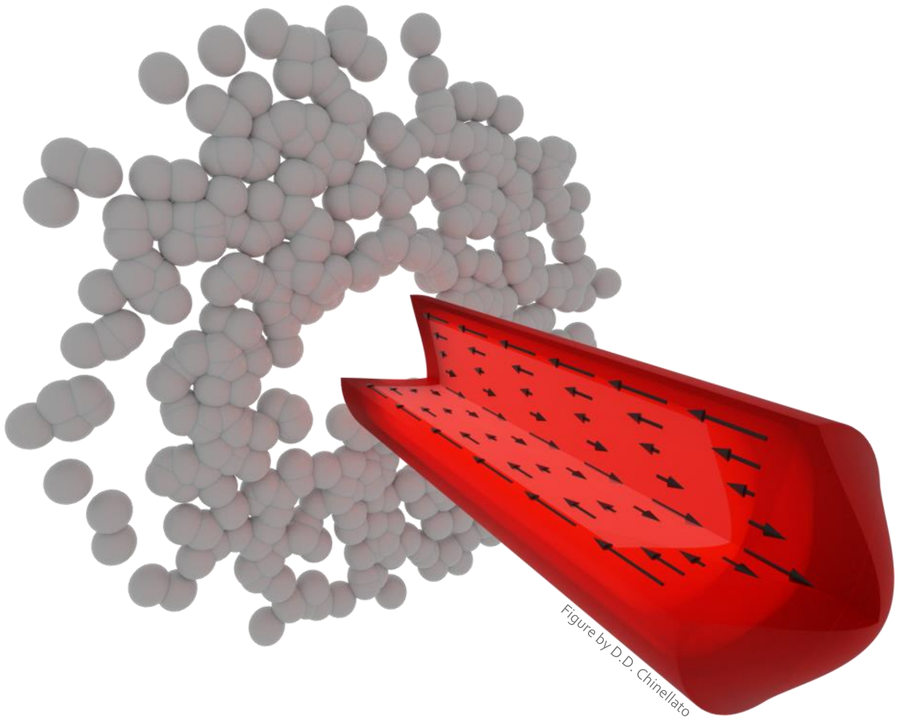
**Geometric-based 3D IC**



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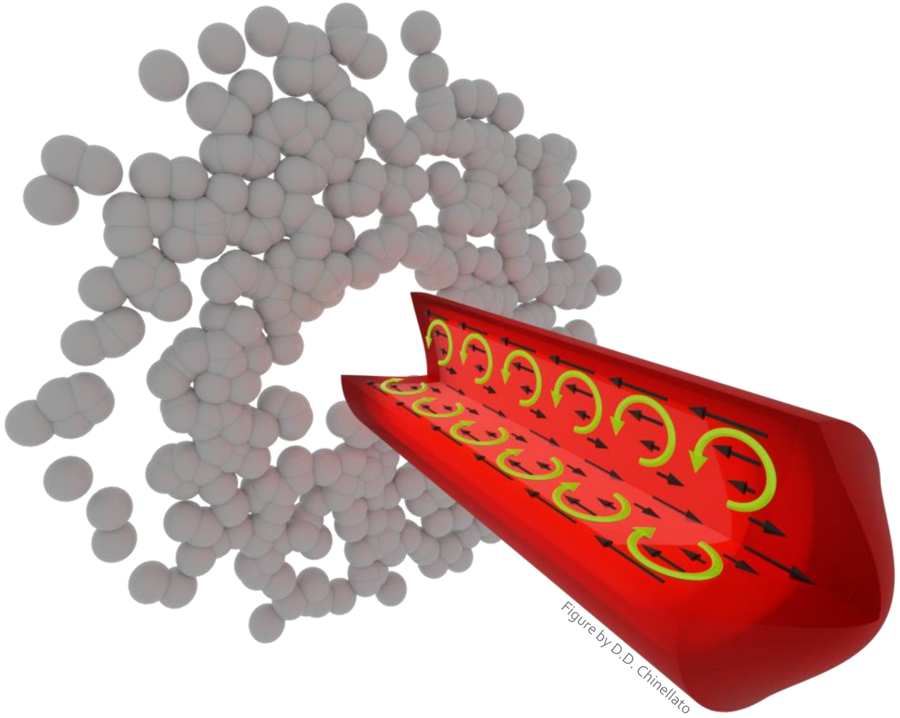

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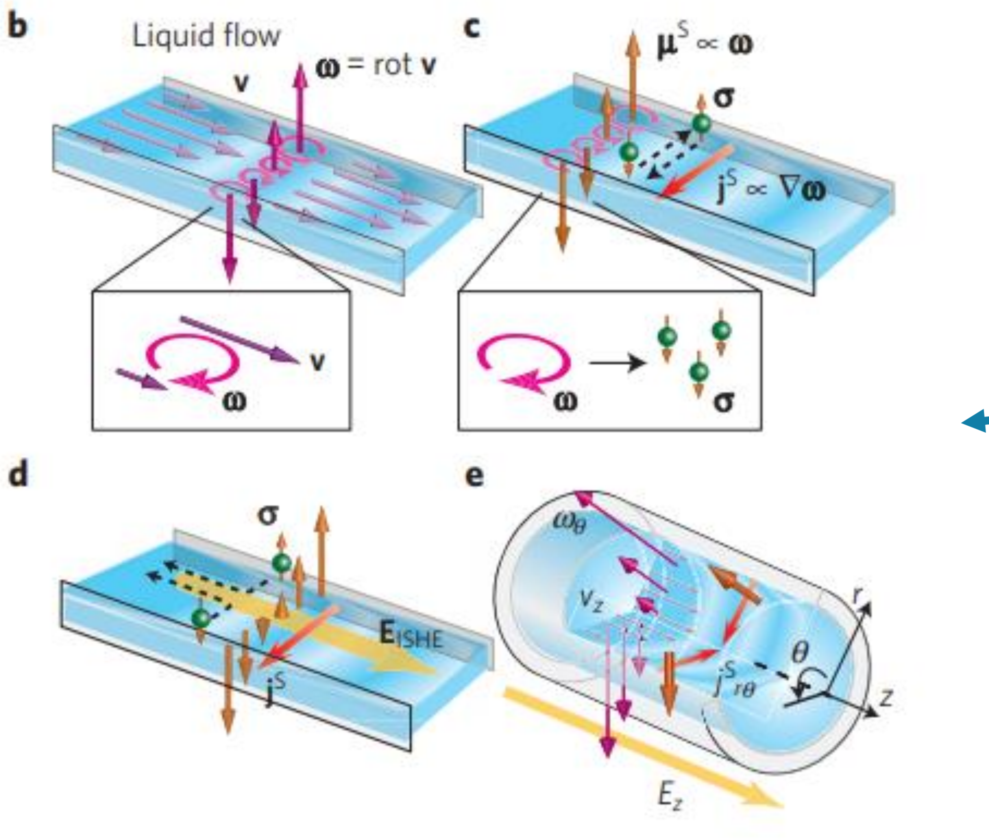


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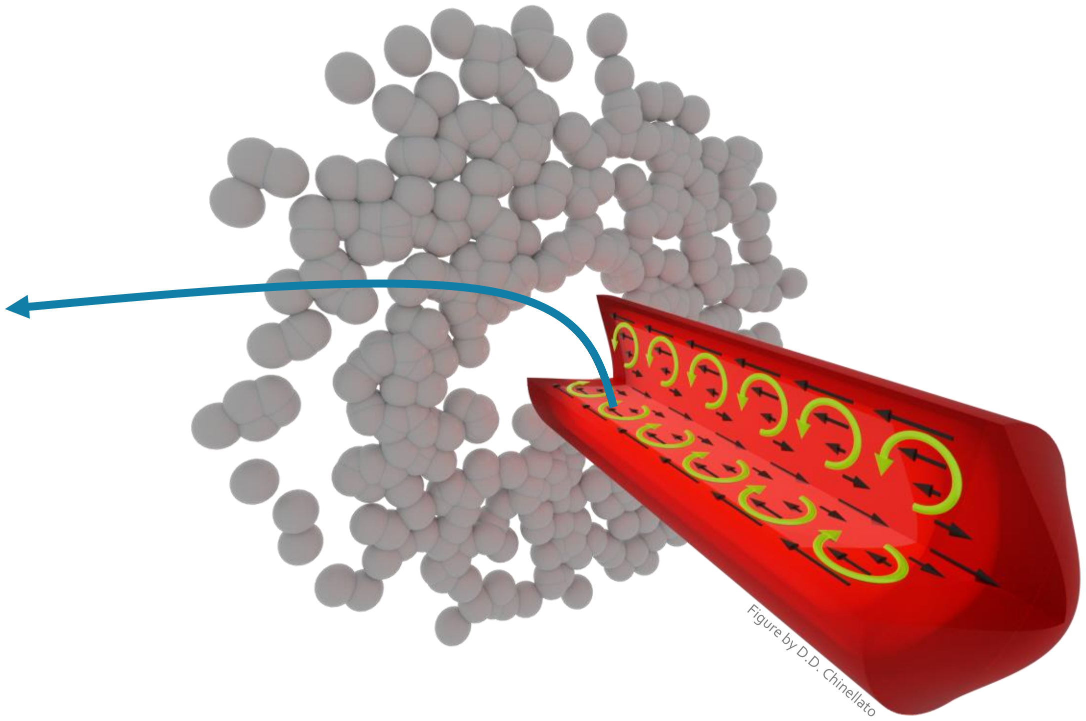
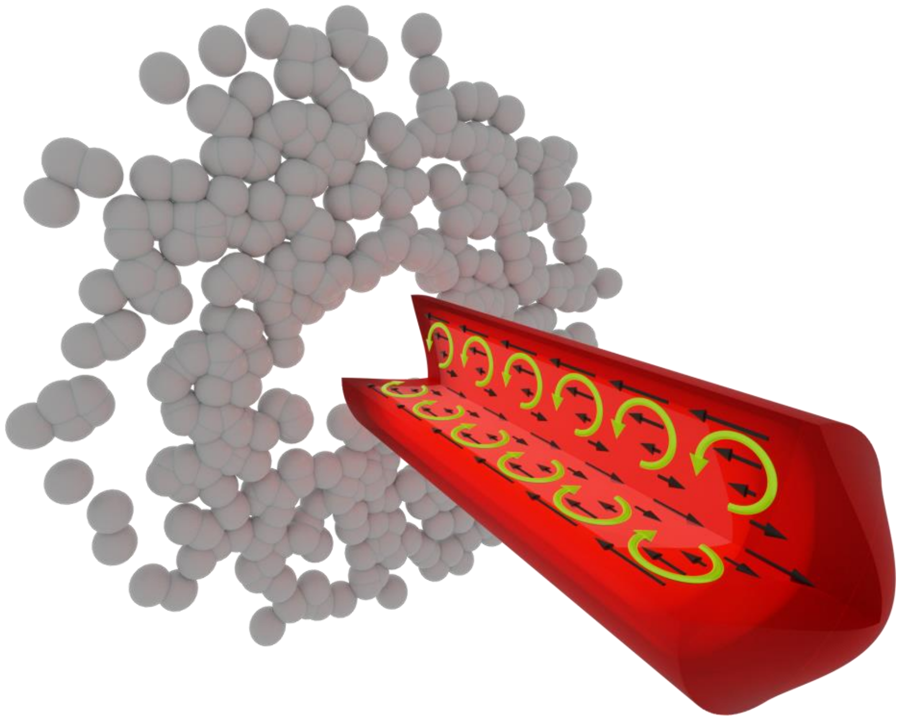


# Geometric-based 3D IC

arXiv:2203.15718

- $T^{\tau\tau} = e(\vec{x}_\perp, \eta_s)\cosh y_L(\vec{x}_\perp)$
- $T^{\tau\eta} = \frac{1}{\tau_0} e(\vec{x}_\perp, \eta_s)\sinh y_L(\vec{x}_\perp)$
- $y_L(\vec{x}_\perp) = f y_{CM}(\vec{x}_\perp)$
- $y_{CM}(\vec{x}_\perp) = \text{arctanh}\left[\frac{T_A(\vec{x}_\perp)-T_B(\vec{x}_\perp)}{T_A(\vec{x}_\perp)+T_B(\vec{x}_\perp)}\tanh(y_{\text{beam}})\right]$
- $e\,(\vec{x}_\perp, \eta_s; y_{\text{CM}} - y_L) = N_e(x,y)\exp\left[-\frac{(|\eta_s-(y_{CM}-y_L)|-\eta_0)^2}{2\sigma_\eta^2}\theta(|\eta_s - (y_{CM} - y_L)| - \eta_0)\right]$



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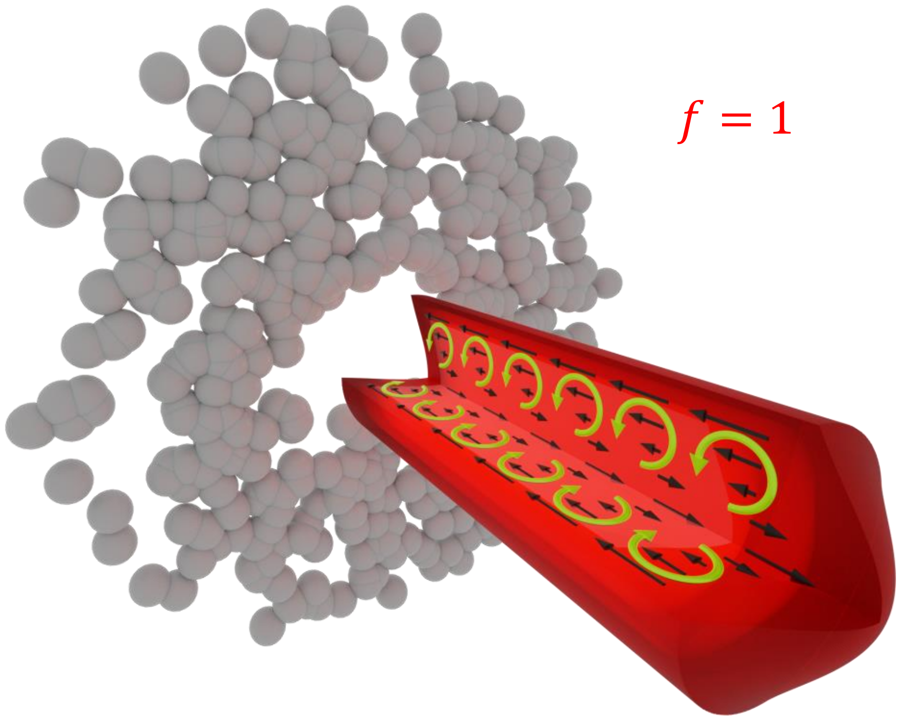
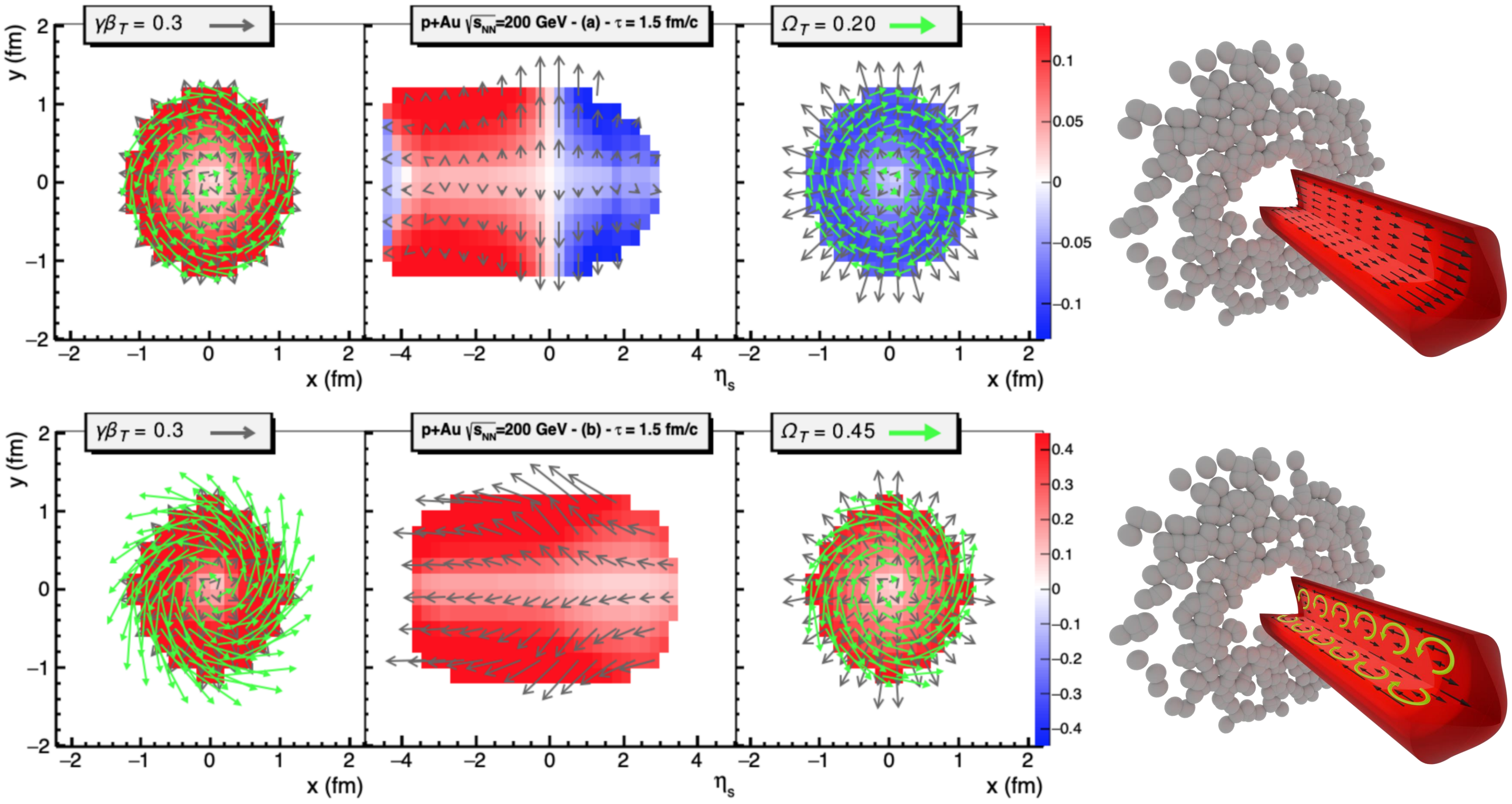


# Hydrodynamic evolution



# Spin Cooper-Frye

- $S^\mu = -\frac{1}{8m}\varepsilon^{\mu\rho\sigma\tau}p_\tau \frac{\int d\Sigma_\lambda p^\lambda (1-n_F)\omega_{\rho\sigma}}{\int d\Sigma_\lambda p^\lambda n_F}$
- Three different kinds of vorticity
  - Thermal: $\omega^{\mu\nu} = \frac{1}{2}\left[\partial^\mu\left(\frac{u^\nu}{T}\right) - \partial^\nu\left(\frac{u^\mu}{T}\right)\right]$
  - Kinetic: $\omega^{\mu\nu} = \frac{1}{2T}[\partial^\mu u^\nu - \partial^\nu u^\mu]$
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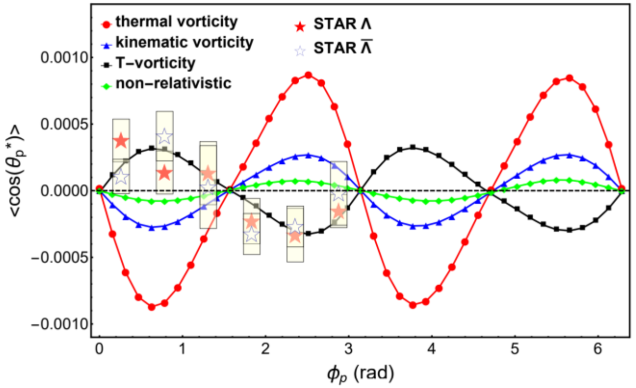


Favored by longitudinal polarization data

Phys. Rev. Research. 1, 033058 (2019). arXiv:1906.09385.
I. Karpenko. arXiv:2101.04963

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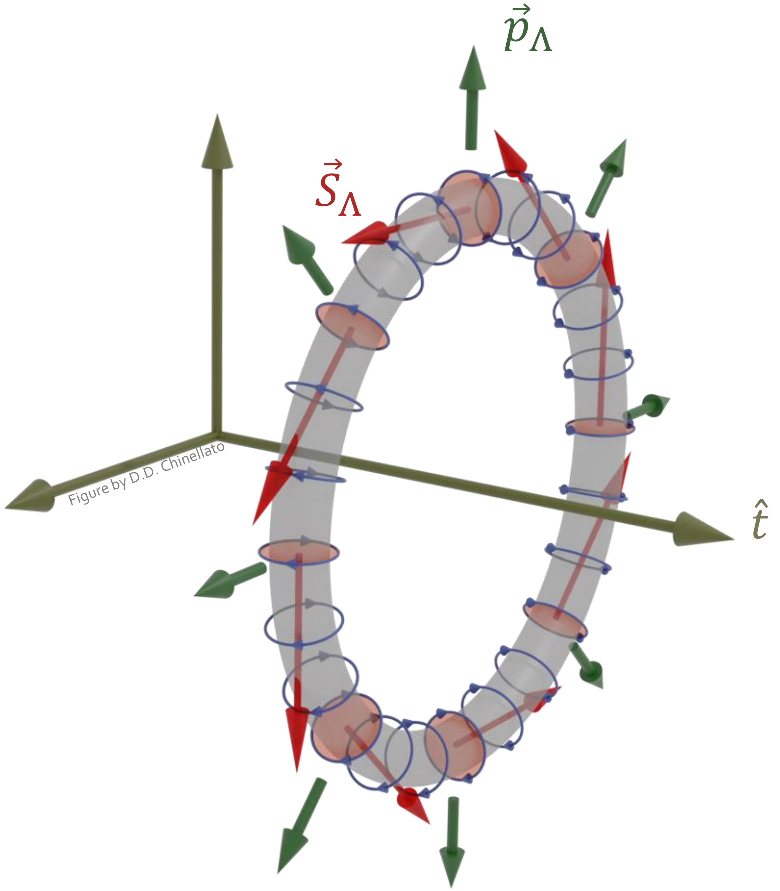
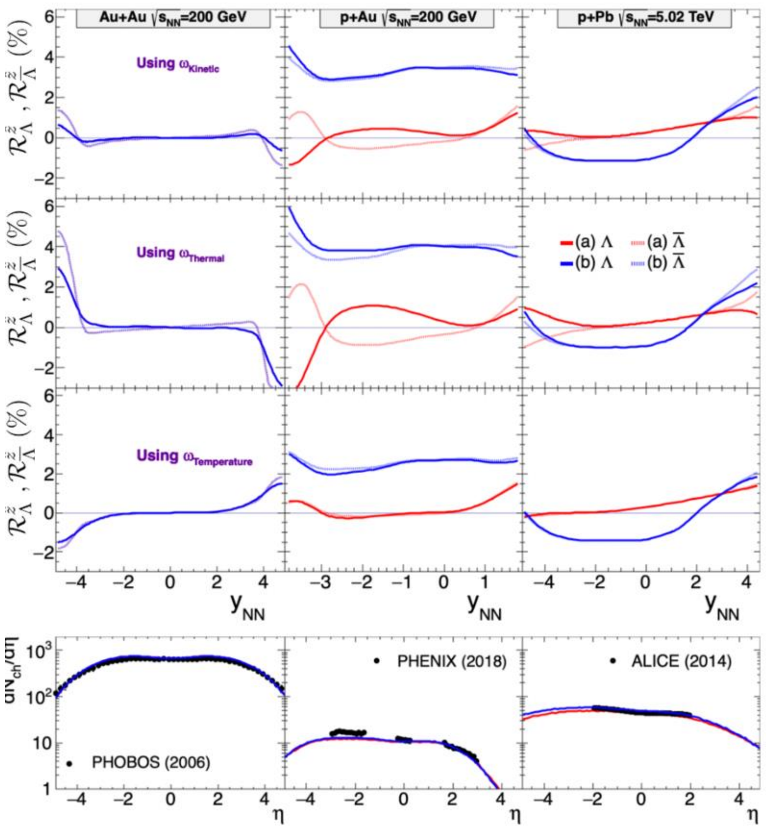
- Vorticity generated by smoke rings tends to cancel each other when averaged
  - Ring observable: $R_\Lambda^{\hat{t}} = 2\left\langle\frac{\vec{S}_\Lambda\cdot(\hat{t}\times\vec{p}_\Lambda)}{|\hat{t}\times\vec{p}_\Lambda|}\right\rangle_\phi$



# Results for Smooth Initial conditions

See *Phys. Rev. C* **104** (2021) 1, 011901




- Negligible effects on $dN/d\eta$ of charged particles

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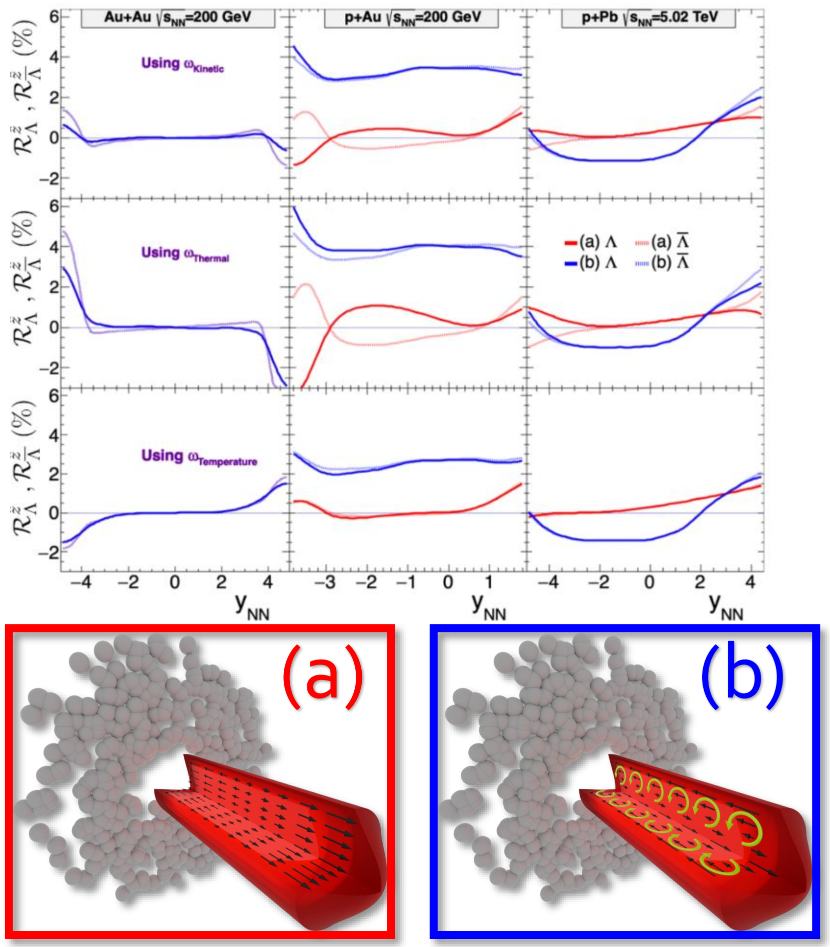
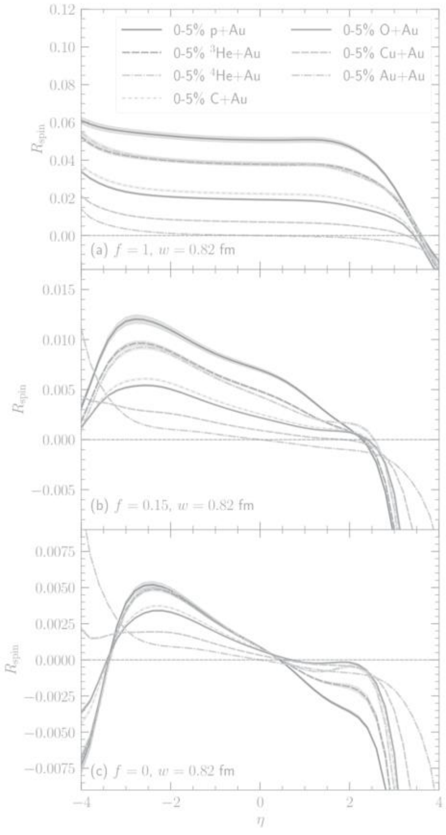
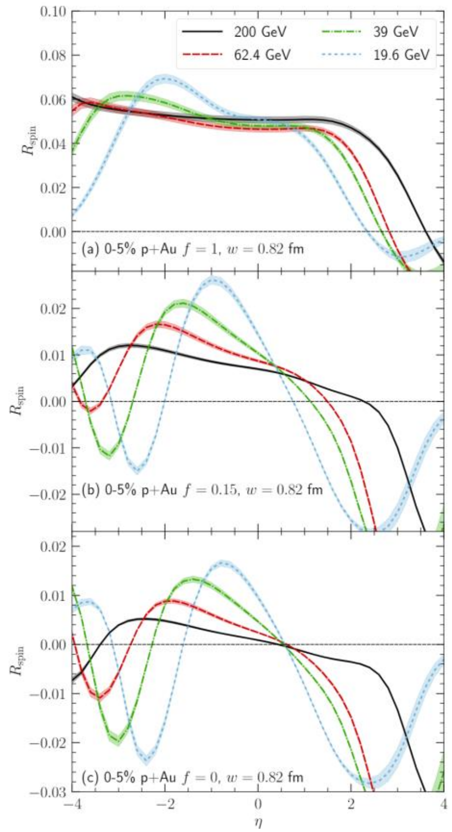



- Negligible effects on $dN/d\eta$ of charged particles
- Large ring polarization present in pA collisions at all centralities for geometric based IC
  - Effect more pronounced at RHIC than LHC
- For Bjorken-like IC:
  - Bigger signal at large rapidity

# Fluctuating initial condition

In preparation




- Collision energy (p+Au)
  - Full 3D geometric based IC
    - Signal is ~50% bigger than smooth
    - More sensitive to change of collision energy at forward rapidity
  - Bjorken based IC is sensitive to changes in energy collision at all energies

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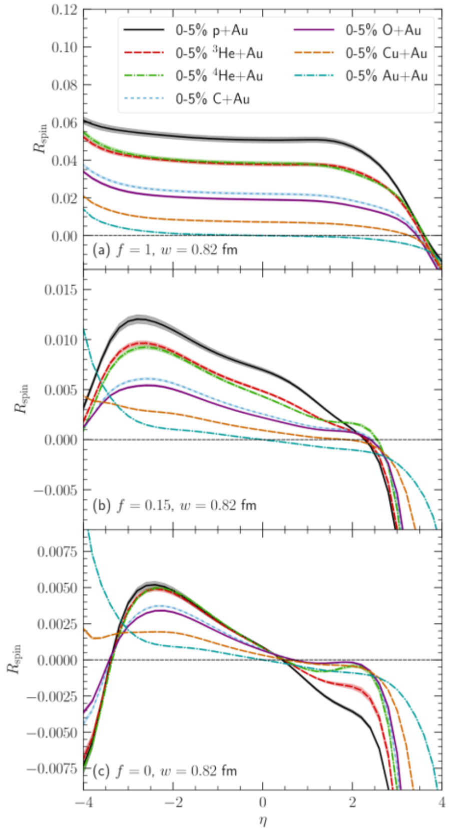


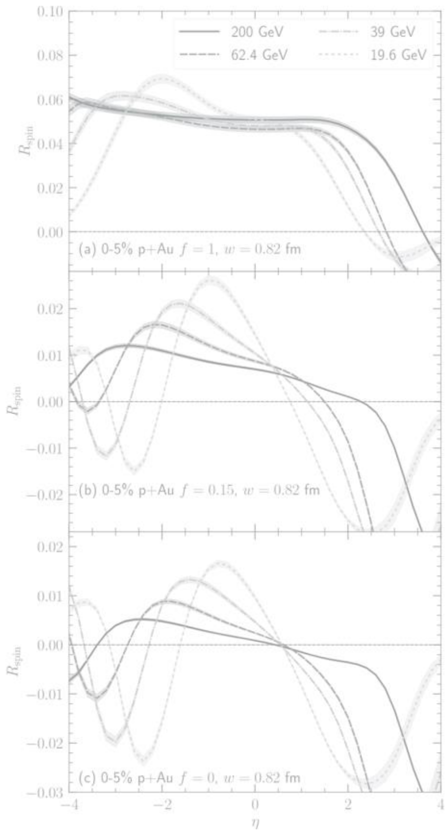


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  - Full 3D geometric based IC
    - Signal is ~50% bigger than smooth
    - More sensitive to change of collision energy at forward rapidity
  - Bjorken based IC is sensitive to changes in energy collision at all energies
- System size ($\sqrt{s_{NN}} = 200$ GeV)
  - The way $R_{spin}$ changes with energy can act as a probe to the parameter $f$

# Corrections to thermal vorticity

### Symmetric shear induced polarization

- $S^\mu \to S^\mu + \langle A^\mu \rangle$
- $A^\mu = \frac{\epsilon^{\mu\rho\tau\sigma}}{E} p_\tau \xi_{\rho\lambda} \times \begin{cases} \hat{t}_\rho p^\lambda \\ \hat{u}_\rho p_\perp^\lambda \end{cases}$
- $\xi_{\rho\lambda} = \frac{1}{2}\left[\partial_\rho \left(\frac{u_\lambda}{T}\right) + \partial_\lambda \left(\frac{u_\rho}{T}\right)\right]$
- $\hat{t} = (1, 0, 0, 0)$
- $p_\perp^\lambda = (\eta^{\sigma\lambda} - u^\sigma u^\lambda) p_\lambda$

Phys. Lett. B **820**, 136519 (2021)
JHEP **07**, 188 (2021)

### Spin Hall effect induced polarization

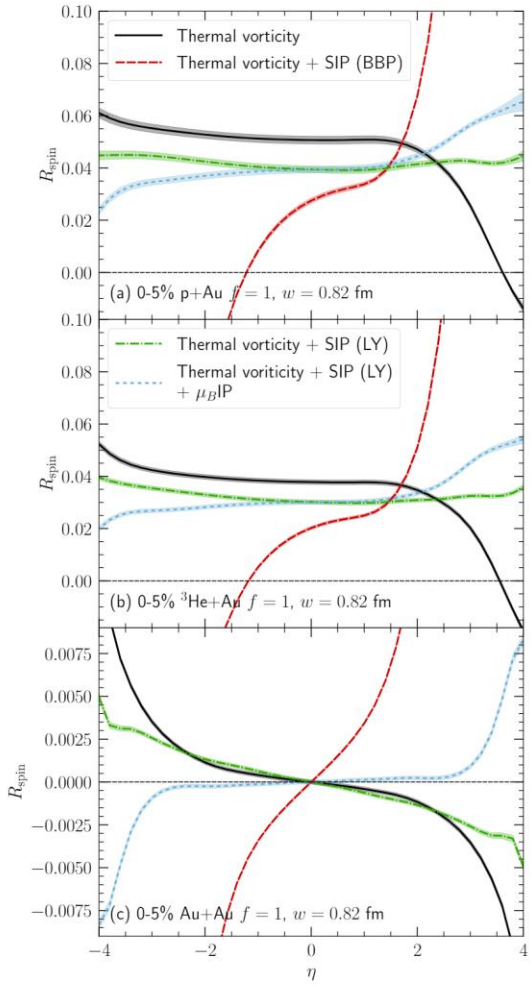
- $S^\mu \to S^\mu + \left\langle T \epsilon^{\mu\nu\alpha\beta} u_\nu p_\alpha \partial_\beta \left(\frac{\mu_B}{T}\right) \right\rangle$

Phys. Rev. D 104, 054043 (2021)

# Corrections to thermal vorticity

- $A^{\mu} = \frac{\varepsilon^{\mu\rho\tau\sigma}}{E} p_{\tau} \xi_{\rho\lambda} \times \begin{cases} \hat{t}_{\rho} p^{\lambda} \\ \hat{u}_{\rho} p_{\perp}^{\lambda} \end{cases}$ BBP / LY
- $\left\langle T \varepsilon^{\mu\nu\alpha\beta} u_{\nu} p_{\alpha} \partial_{\beta} \left( \frac{\mu_B}{T} \right) \right\rangle$ $\mu_B$IP

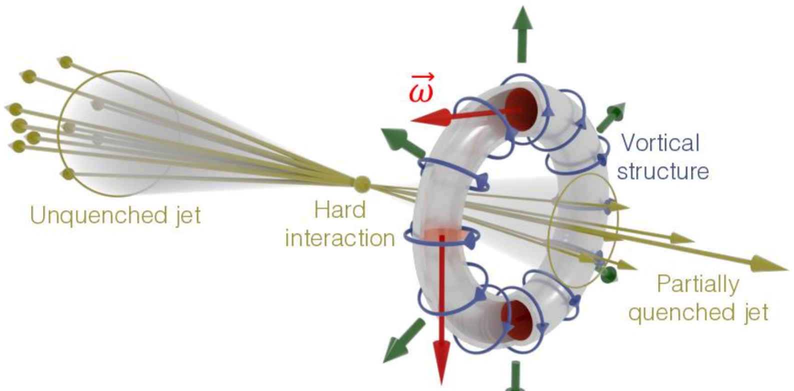
- Very sensitive to symmetric shear model
- Behavior is not intuitive
- Role of $\mu_B$ is noticeable



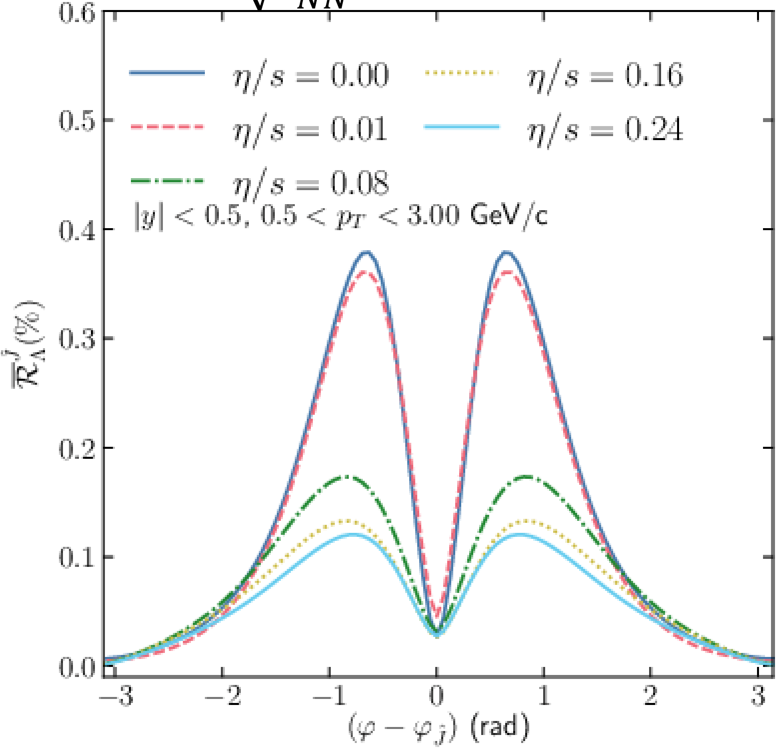
# Applicability on jets

Phys. Lett. B **820**, 136500 (2021)

- One can change the trigger direction from beam axis to jet direction
- A simple model (a hot spot with an initial velocity) has shown promising results
- A more difficult problem:
  - Predictions are very sensitive to parton-medium interaction model




PbPb - $\sqrt{s_{NN}} = 2.76$ TeV



# Summary

- Ring observable can be used as a probe for different models in heavy-ion collisions
- **Experiments should measure this now—discovery potential!**
  - It is sensitive to longitudinal velocity patterns in IC
  - An energy scan can confirm a value for $f \sim 1$ if one looks at forward rapidity.
  - Similarly, a system size scan can also probe values for $f$
  - When considering symmetric shear induced polarization, one can see large differences between the two competing models
- It may also be used to constraint parton-medium interaction models

# Thanks

FAPESP 60 — CIÊNCIA, CULTURA E DESENVOLVIMENTO — 1962 - 2022

Grant # 2017/05685-2
Grant # 2018/24720-6

Grant # 2021/01670-6
Grant # 2021/01700-2

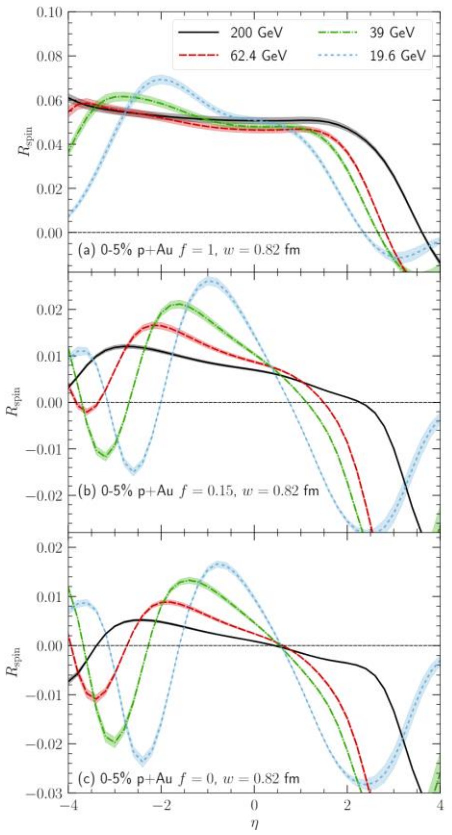
CNPq — Conselho Nacional de Desenvolvimento Científico e Tecnológico

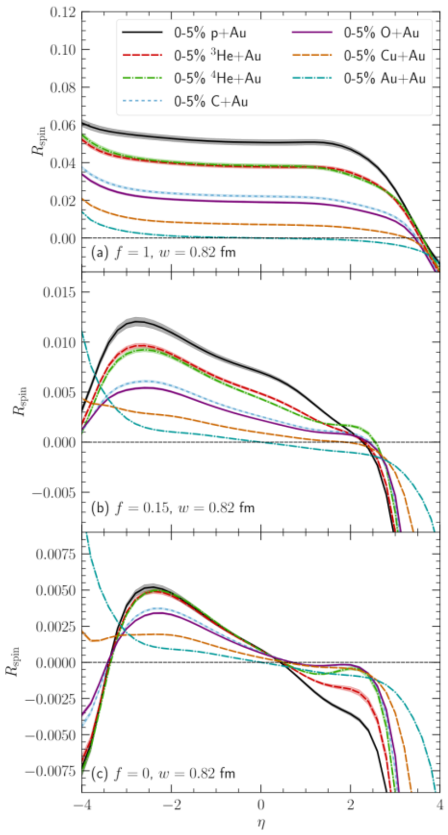
Grant # 306152/2020-7

U.S. DEPARTMENT OF ENERGY | Office of Science

# Backup

# Fluctuating initial condition



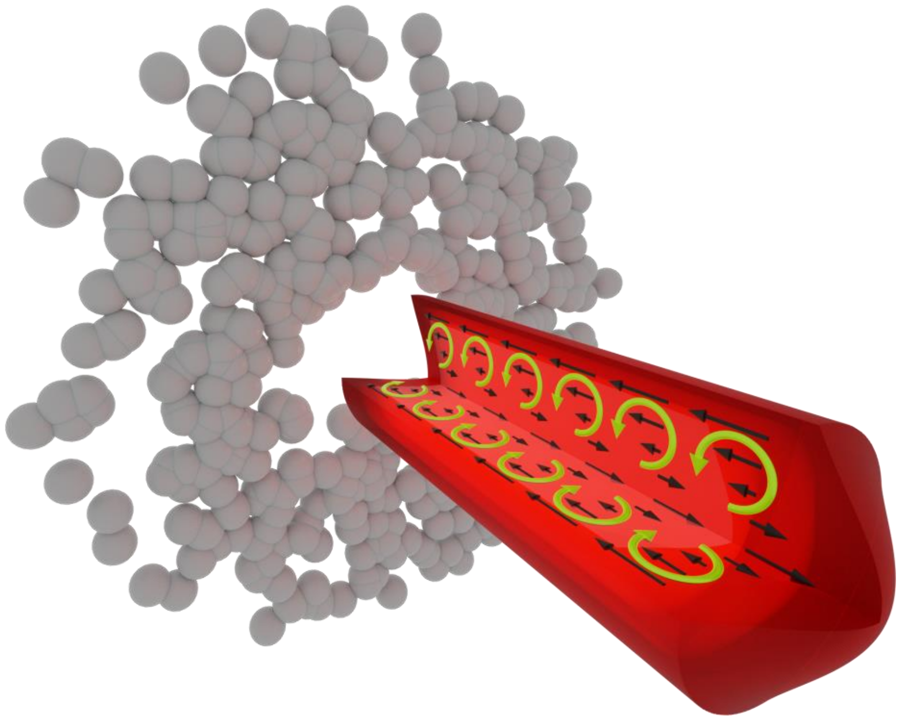




- Signal is bigger by a factor ~2
- Full 3D geometric based IC
  - Reduced sensitive to energy

# Ring fluid strength

$$\bar{R}^{\hat{t}}_{\text{fluid}} = \frac{\varepsilon^{\mu\nu\rho\sigma}\Omega_\mu n_\nu \hat{t}_\rho u_\sigma}{\left|\varepsilon^{\mu\nu\rho\sigma}\Omega_\mu n_\nu \hat{t}_\rho u_\sigma\right|} \qquad \Omega_\mu = -\varepsilon^{\mu\nu\rho\sigma}\omega_{\rho\sigma}(u_\nu u^\alpha + C\Delta_\nu{}^\alpha)n_\alpha$$

# Geometric-based 3D IC



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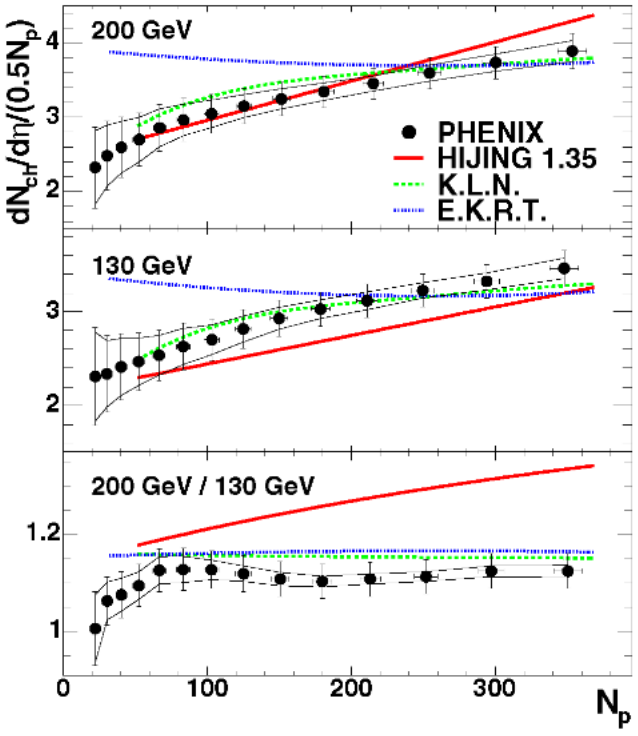
# Some QGP properties




Nucl. Phys. A 757, 184-283 (2005)

- A dense system

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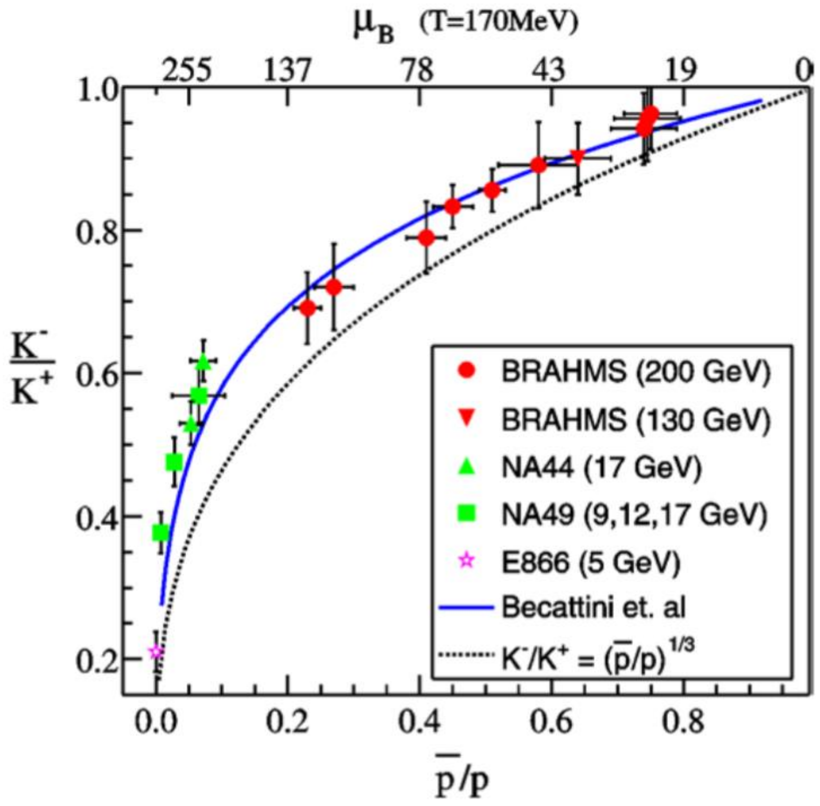
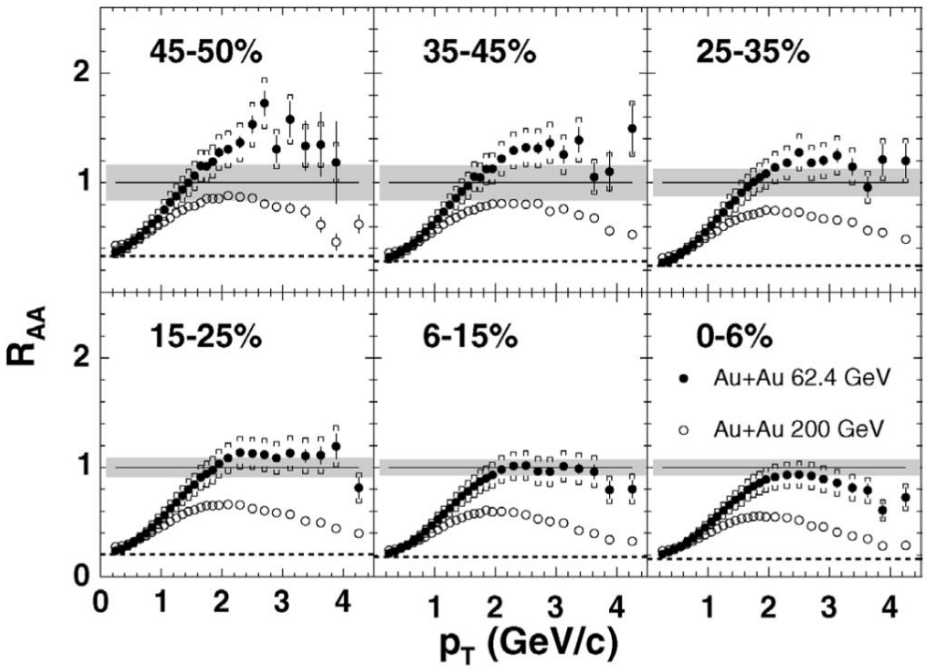



Nucl. Phys. A 757, 1-27 (2005)

- A dense system
- Hints of a thermalized system

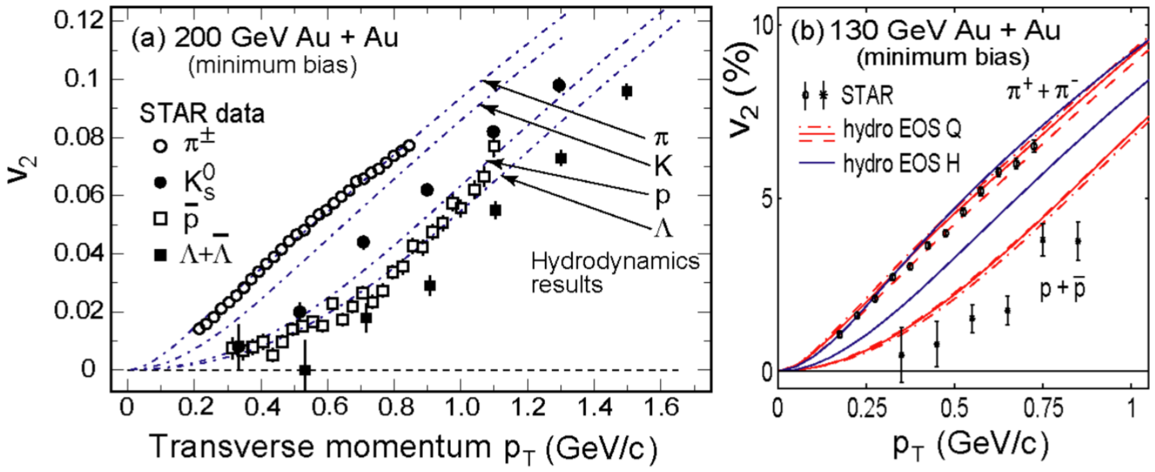
# Some QGP properties




Nucl. Phys. A 757, 28-101 (2005)

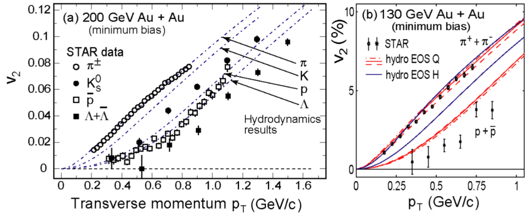
- A dense system
- Hints of a thermalized system
- A strongly interacting medium

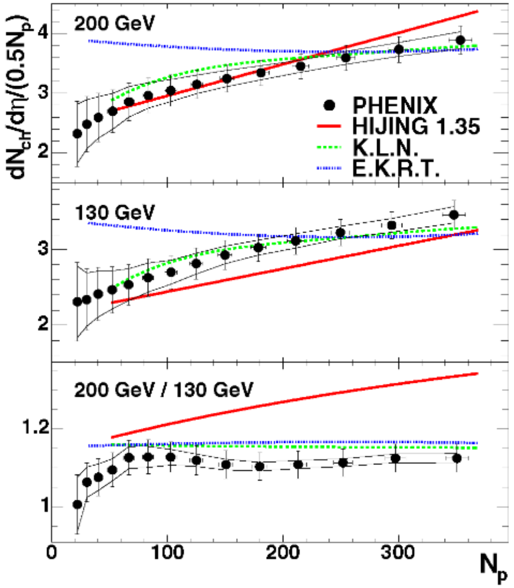
# Some QGP properties

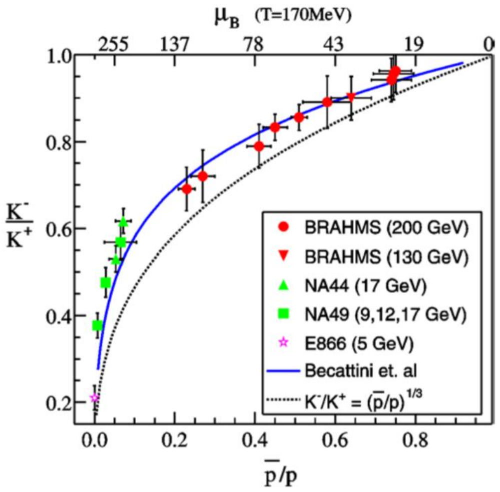


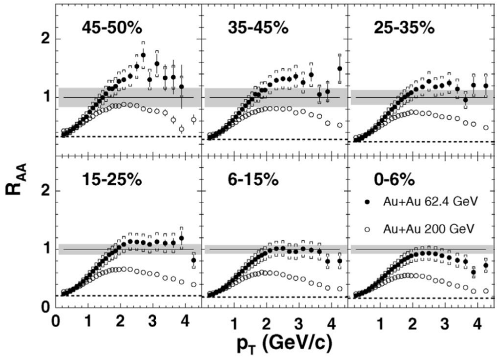

Nucl. Phys. A 757, 102-183 (2005)

- A dense system
- Hints of a thermalized system
- A strongly interacting medium
- A system which presents collectivity behavior




# LOW-VISCOSITY RELATIVISTIC HYDRODYNAMICS IS ABLE TO DESCRIBE RELATIVELY WELL MOST OF THESE SIGNALS


https://www.youtube.com/watch?v=YoLKve4kofc