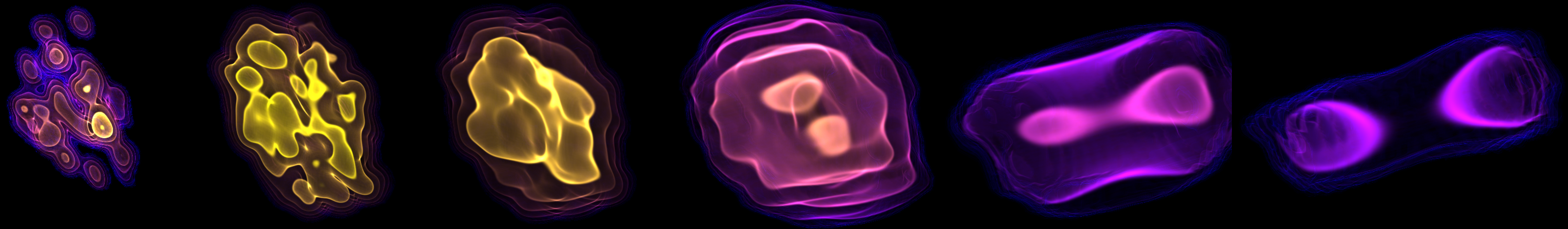
RBRC
RIKEN BNL Research Center

BEST COLLABORATION

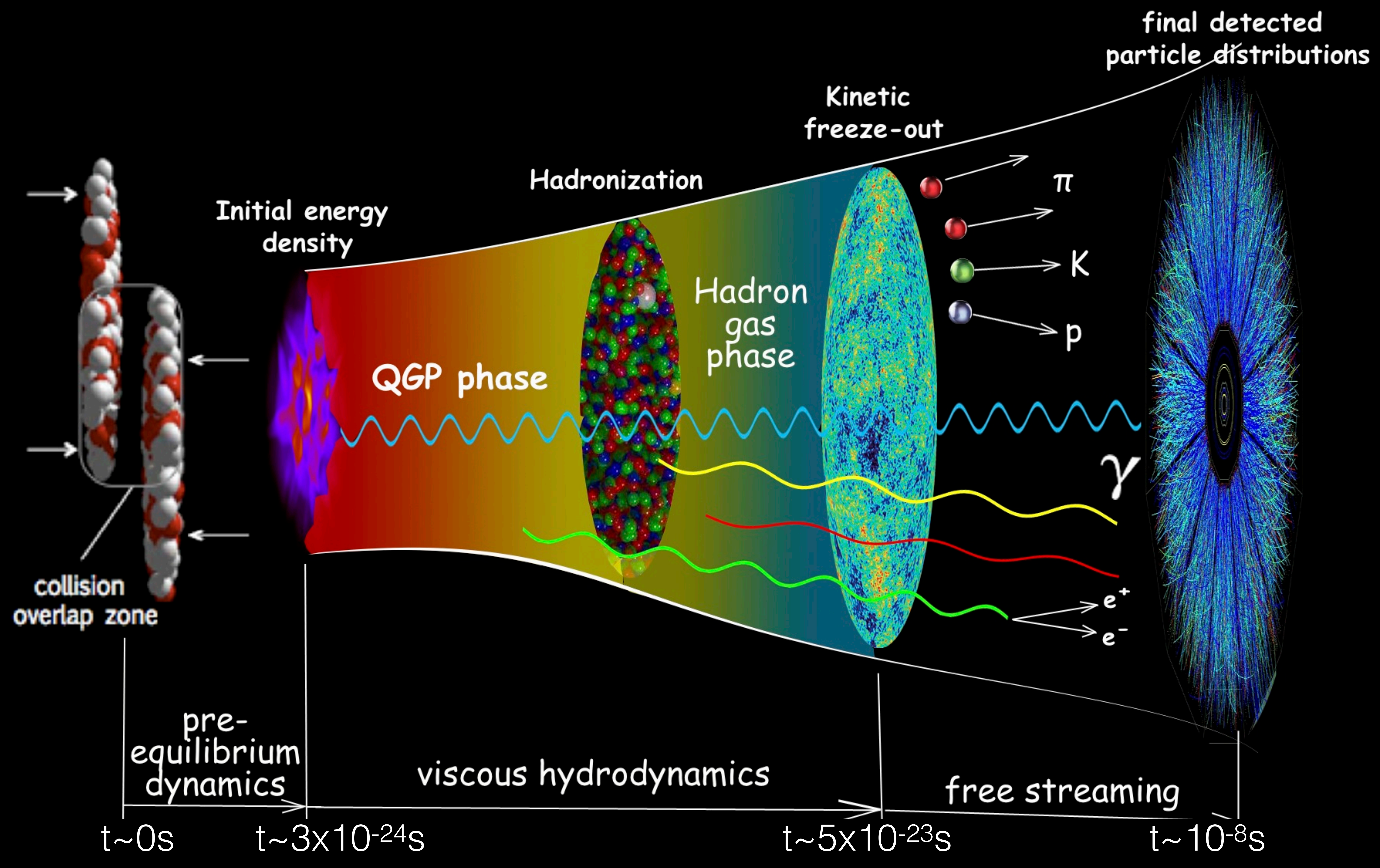
PROGRESS IN DYNAMICAL MODELING OF HEAVY-ION COLLISIONS AT HIGH ENERGY

CHUN SHEN



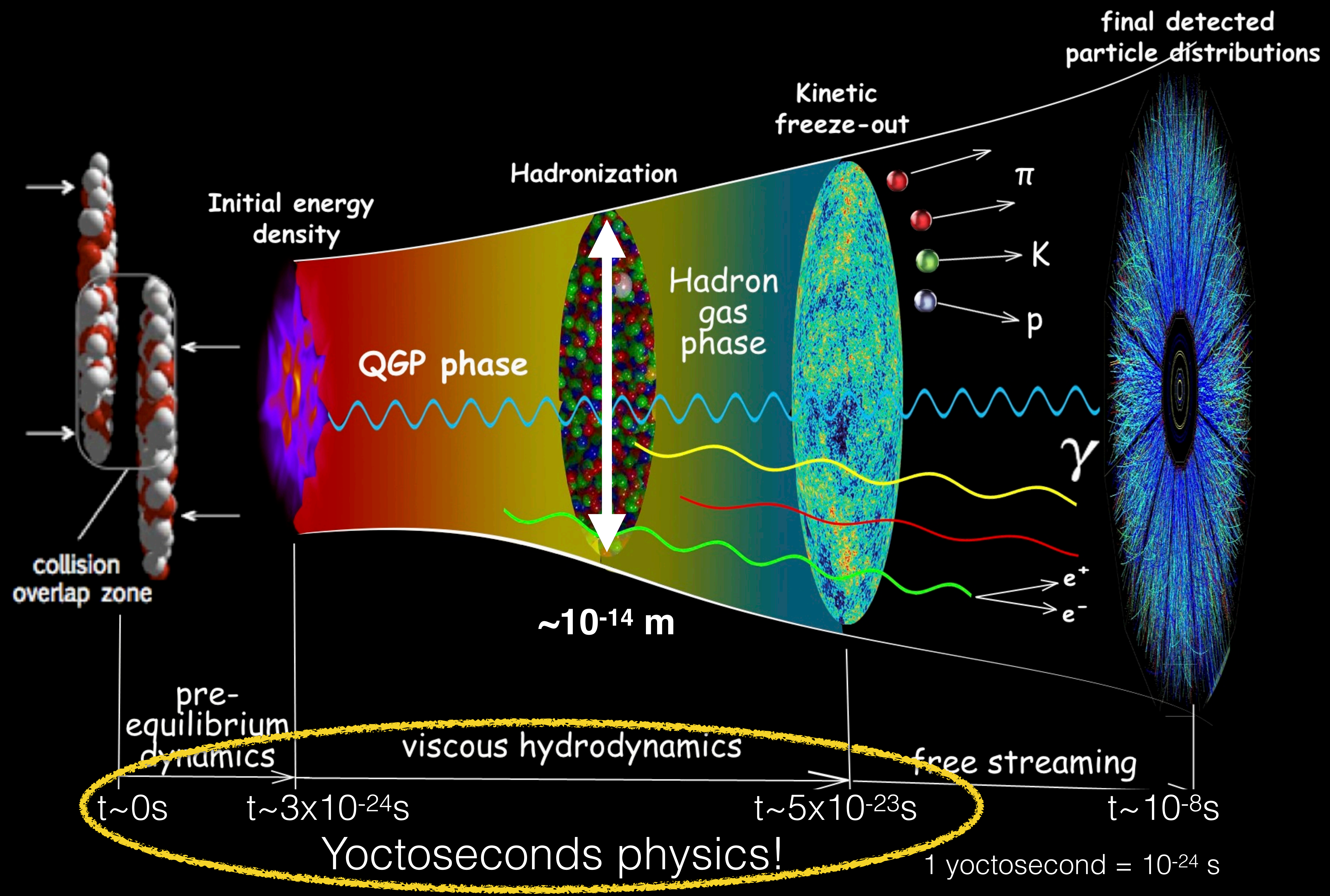
Sept. 16, 2021
NBI Heavy-ion Seminar

NUCLEAR MATTER UNDER EXTREME CONDITIONS



1 yoctosecond = 10^{-24} s

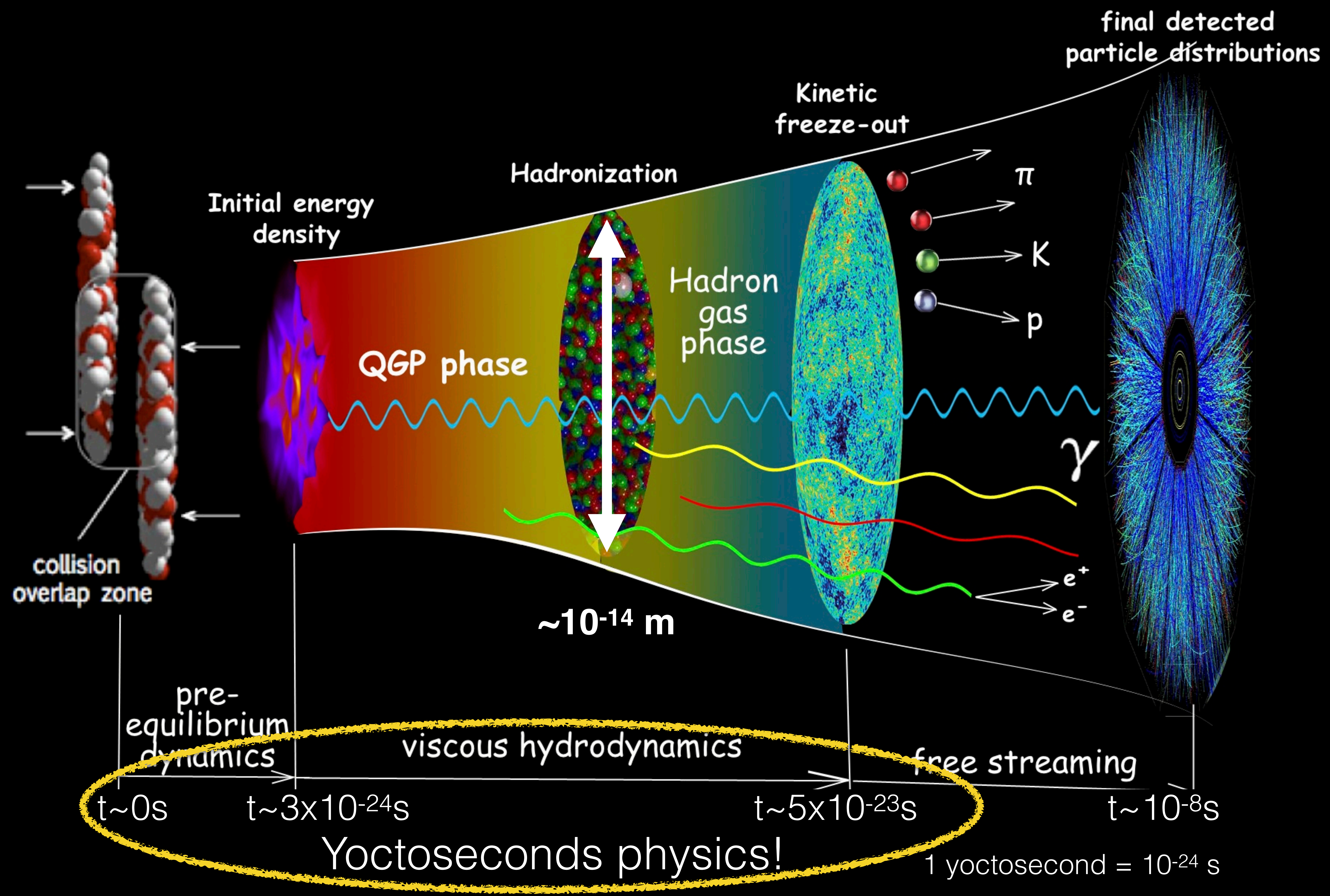
NUCLEAR MATTER UNDER EXTREME CONDITIONS



1 yoctosecond = 10^{-24} s

Heavy-ion collisions are tiny and have ultra-fast dynamics

NUCLEAR MATTER UNDER EXTREME CONDITIONS



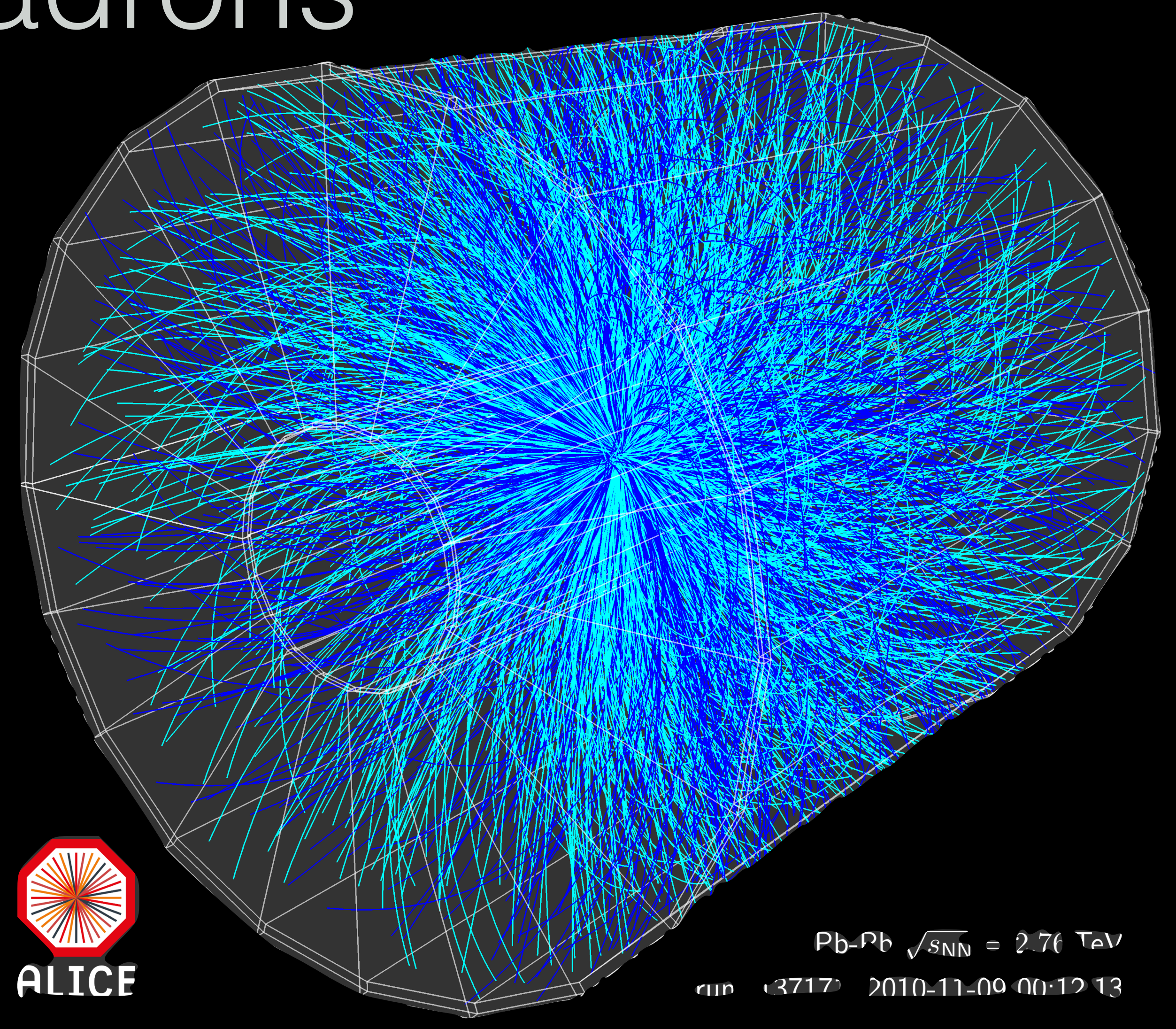
Heavy-ion collisions are tiny and have ultra-fast dynamics

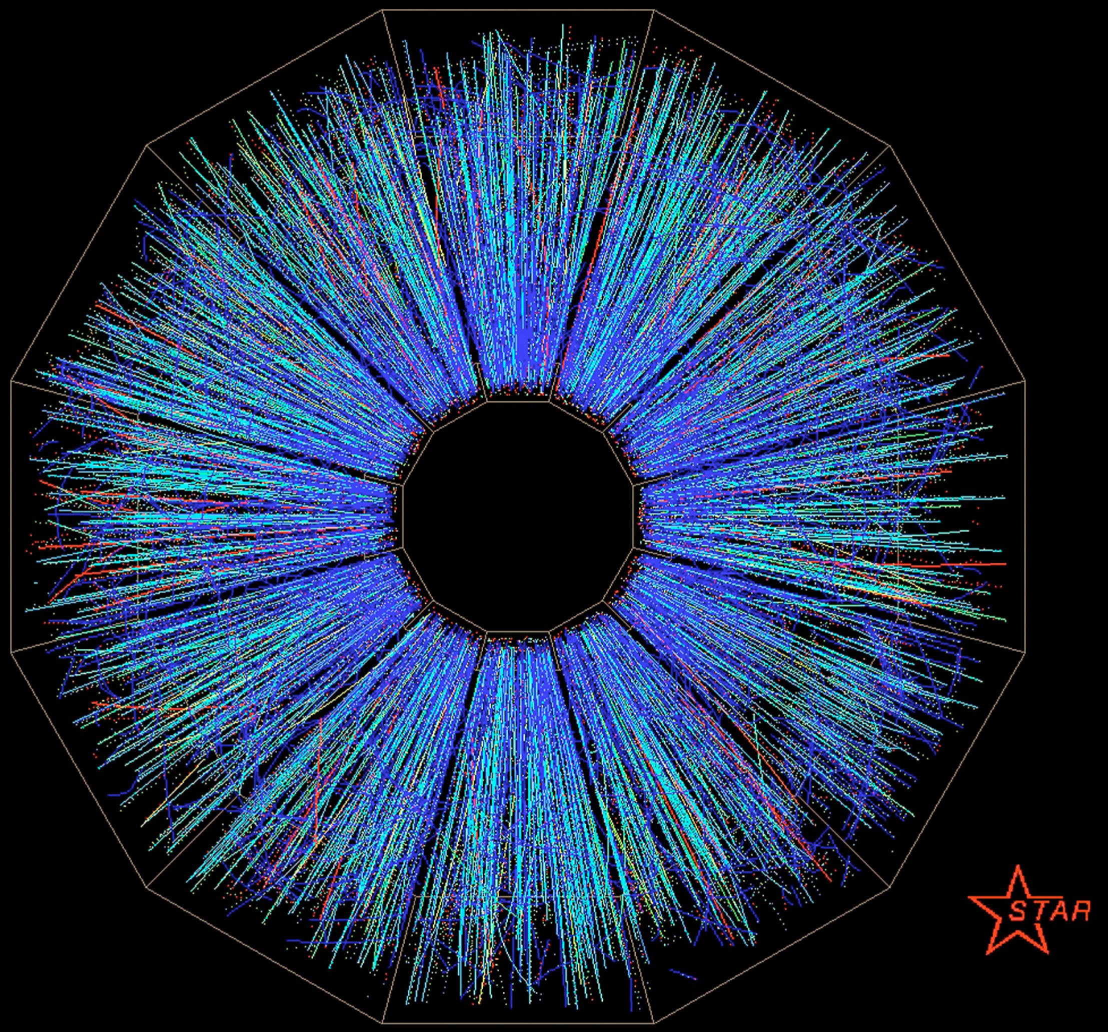
A variety of particles are emitted from the collisions

Multi-messenger nature of heavy-ion physics

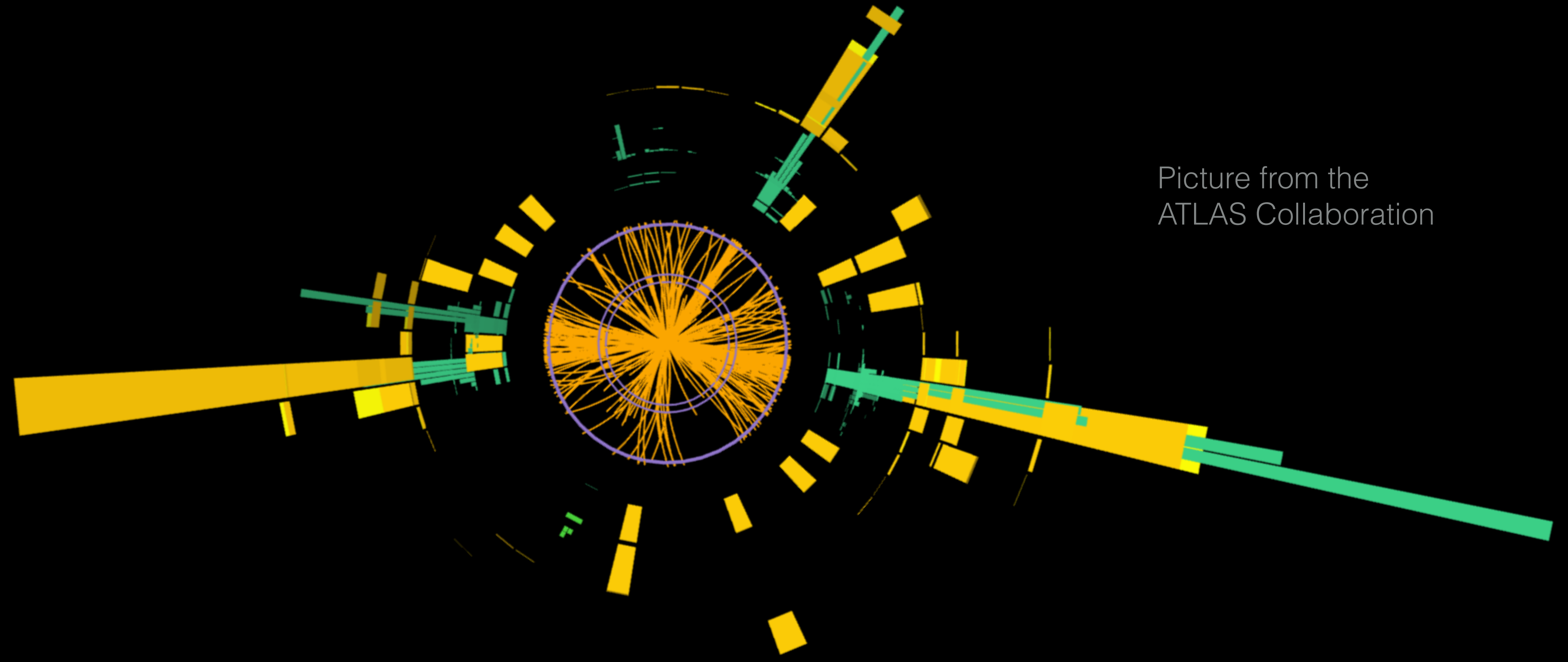
MULTI-MESSENGER HEAVY-ION PHYSICS

Hadrons



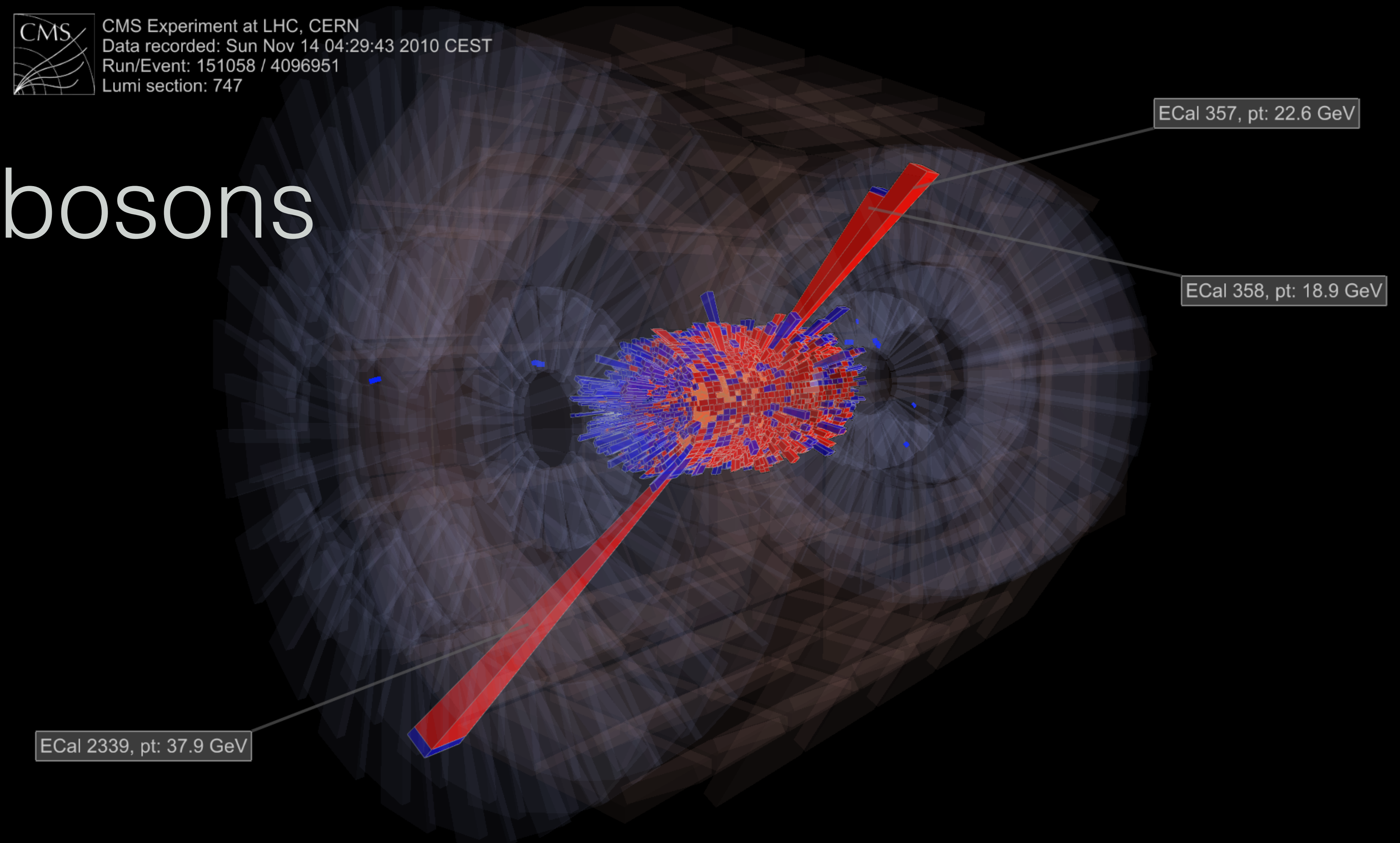


QCD jets

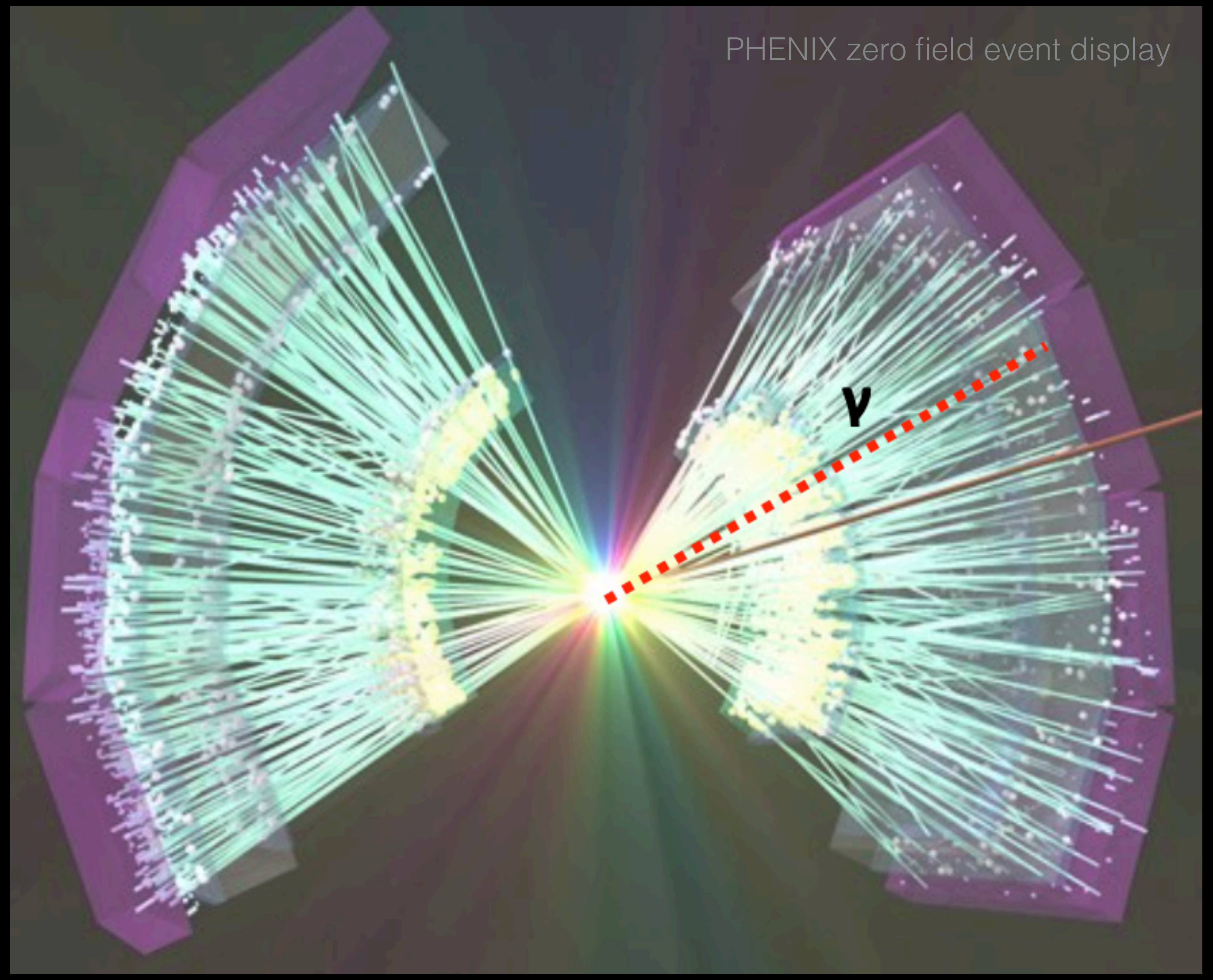


Picture from the ATLAS Collaboration

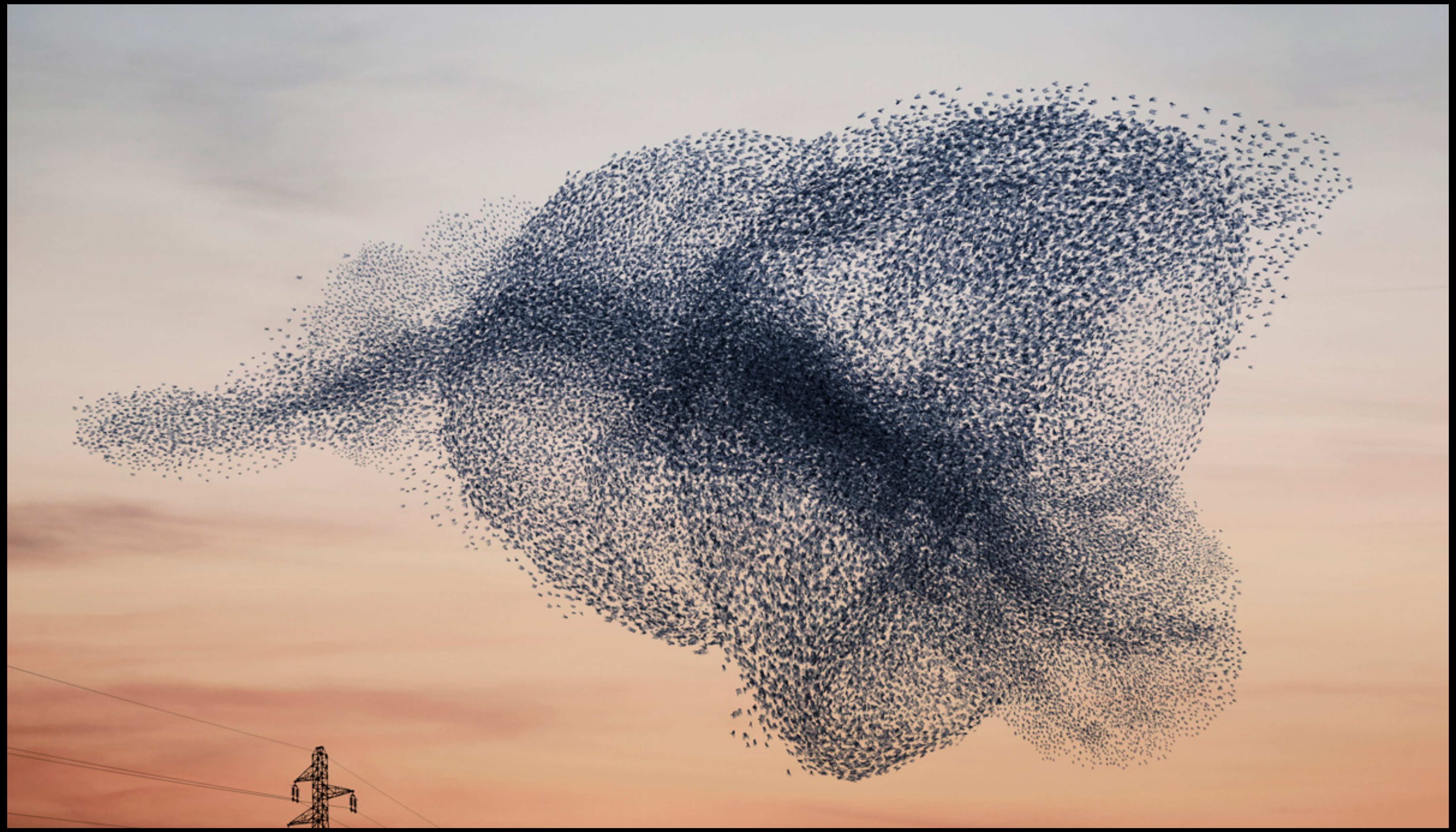
EW bosons

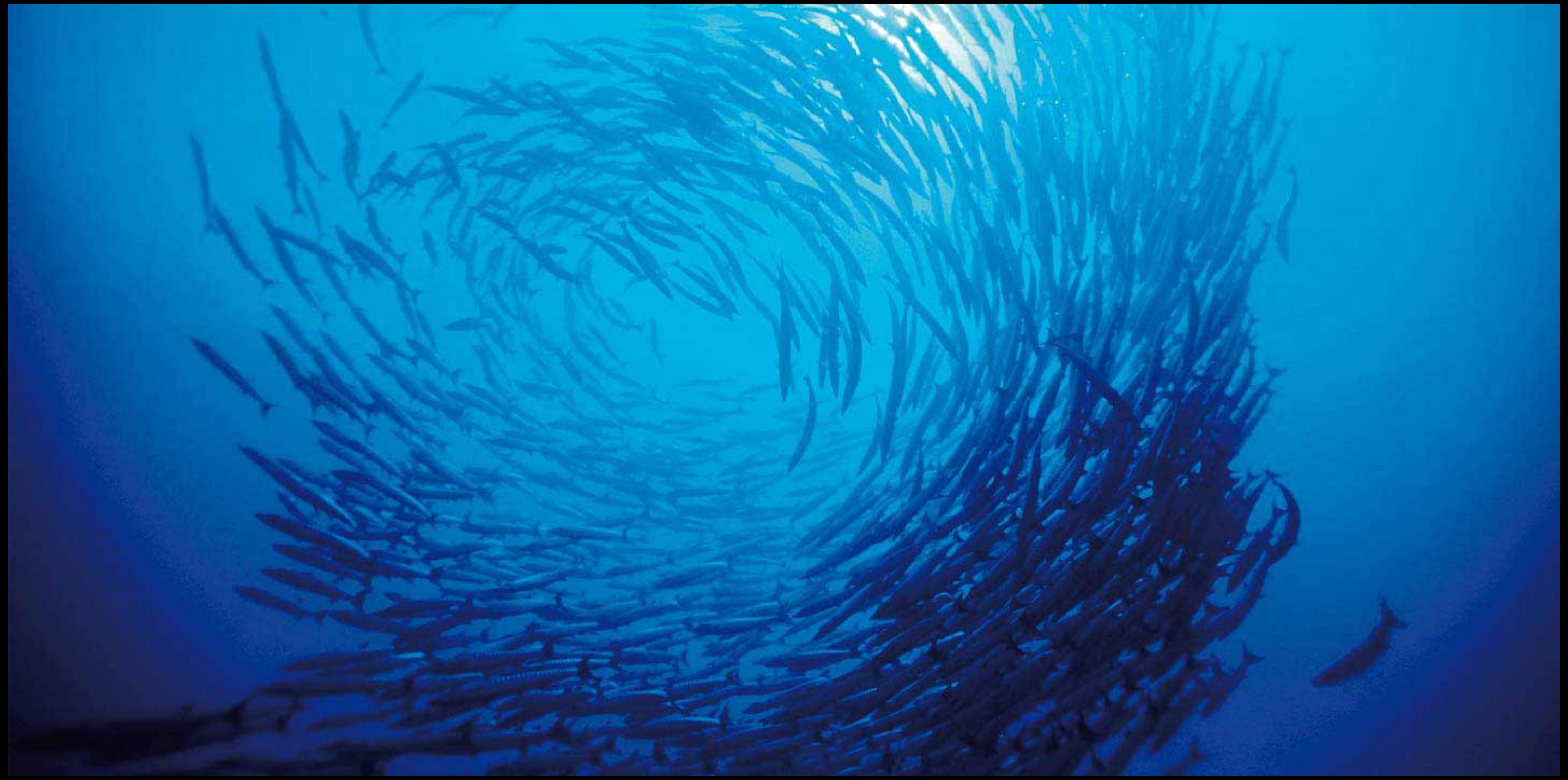


EM radiations



MORE IS DIFFERENT!

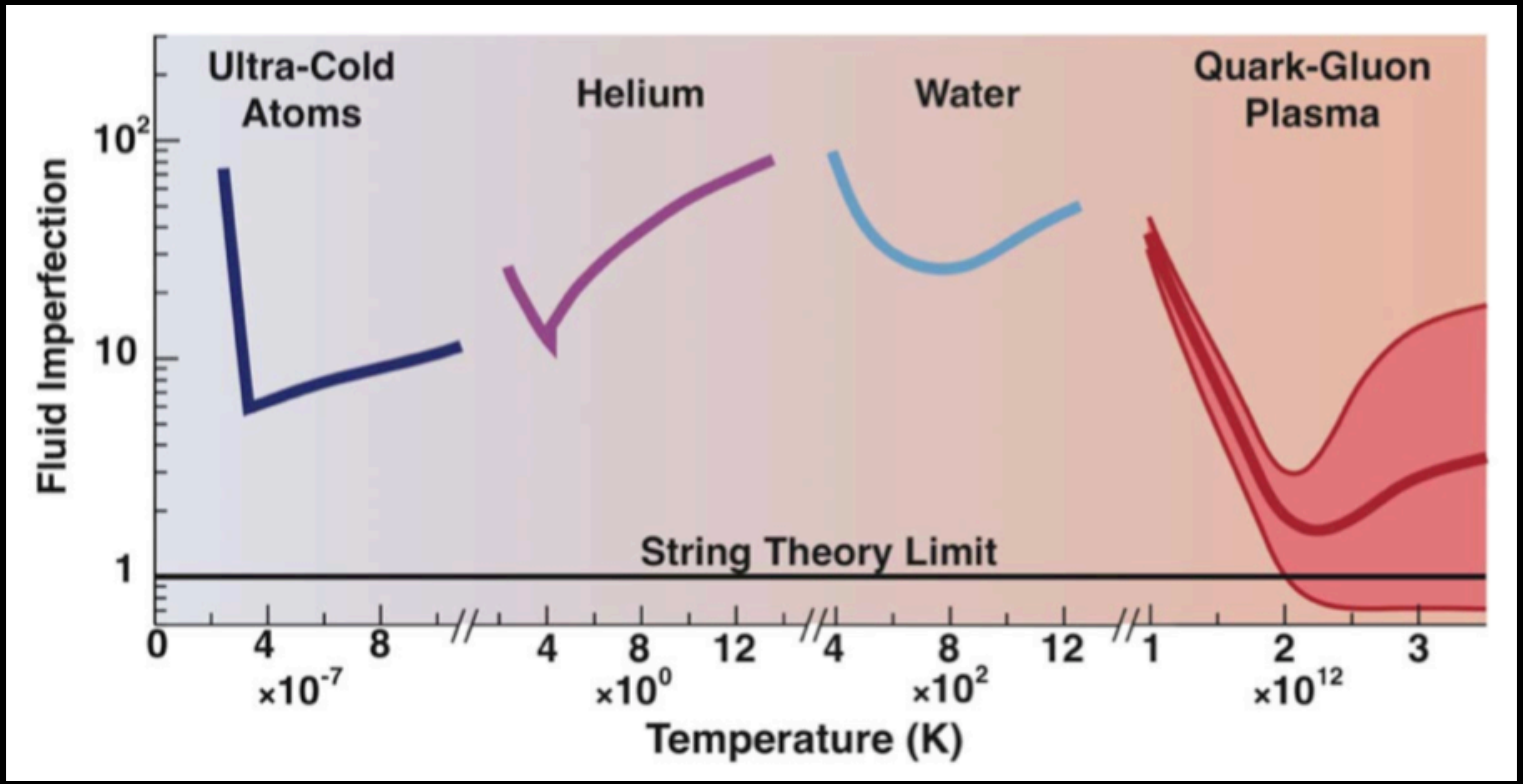


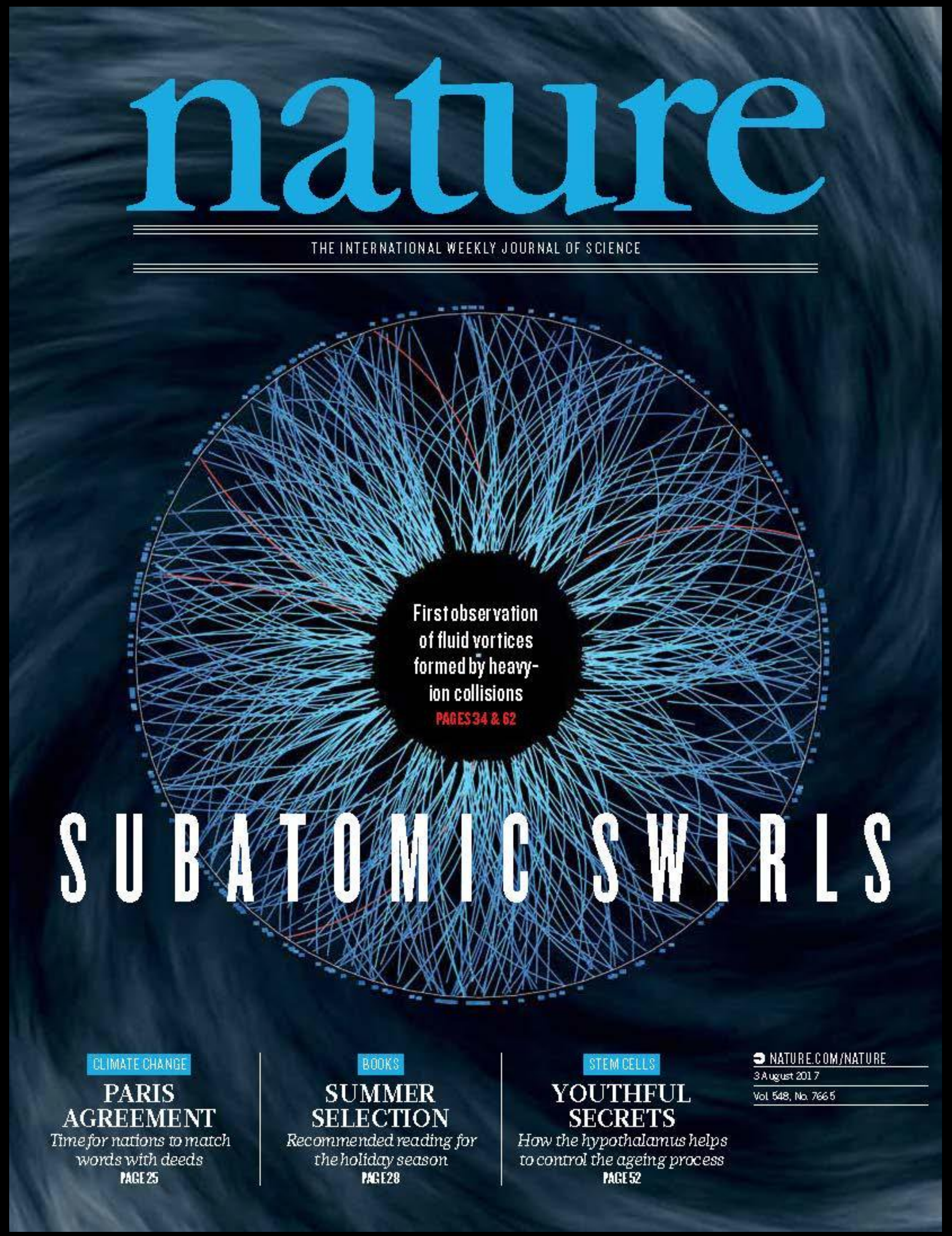


QUARK-GLUON PLASMA (QGP)

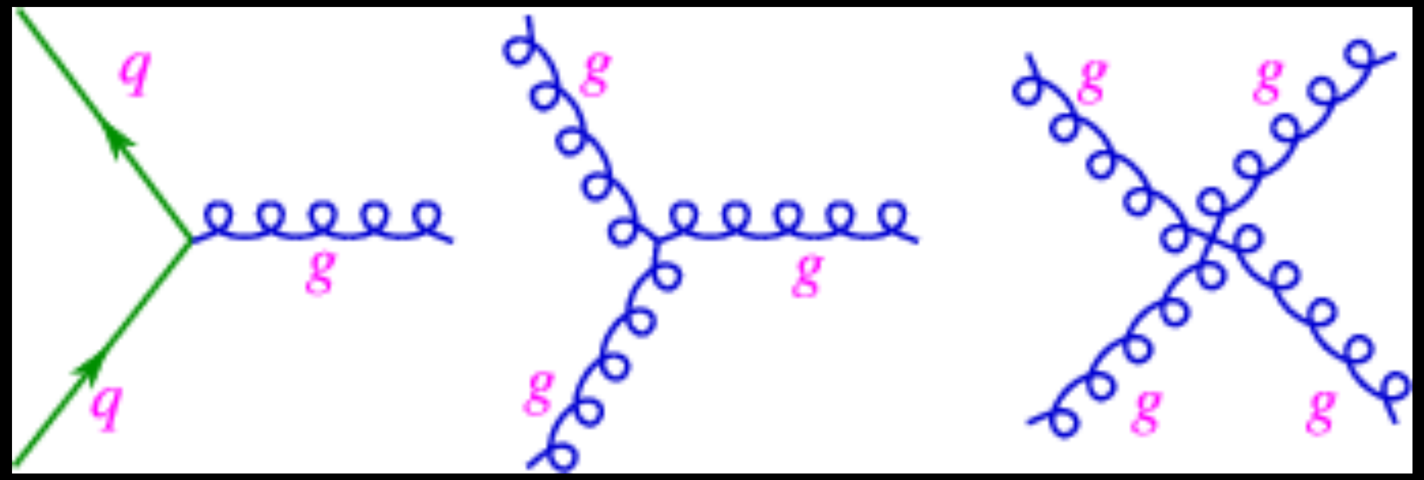
- Quark-Gluon Plasma is the hottest, smallest, and the most perfect (and vortical) fluid in nature!

Burrows A et al. 2013 Implementing the 2007 Long Range Plan

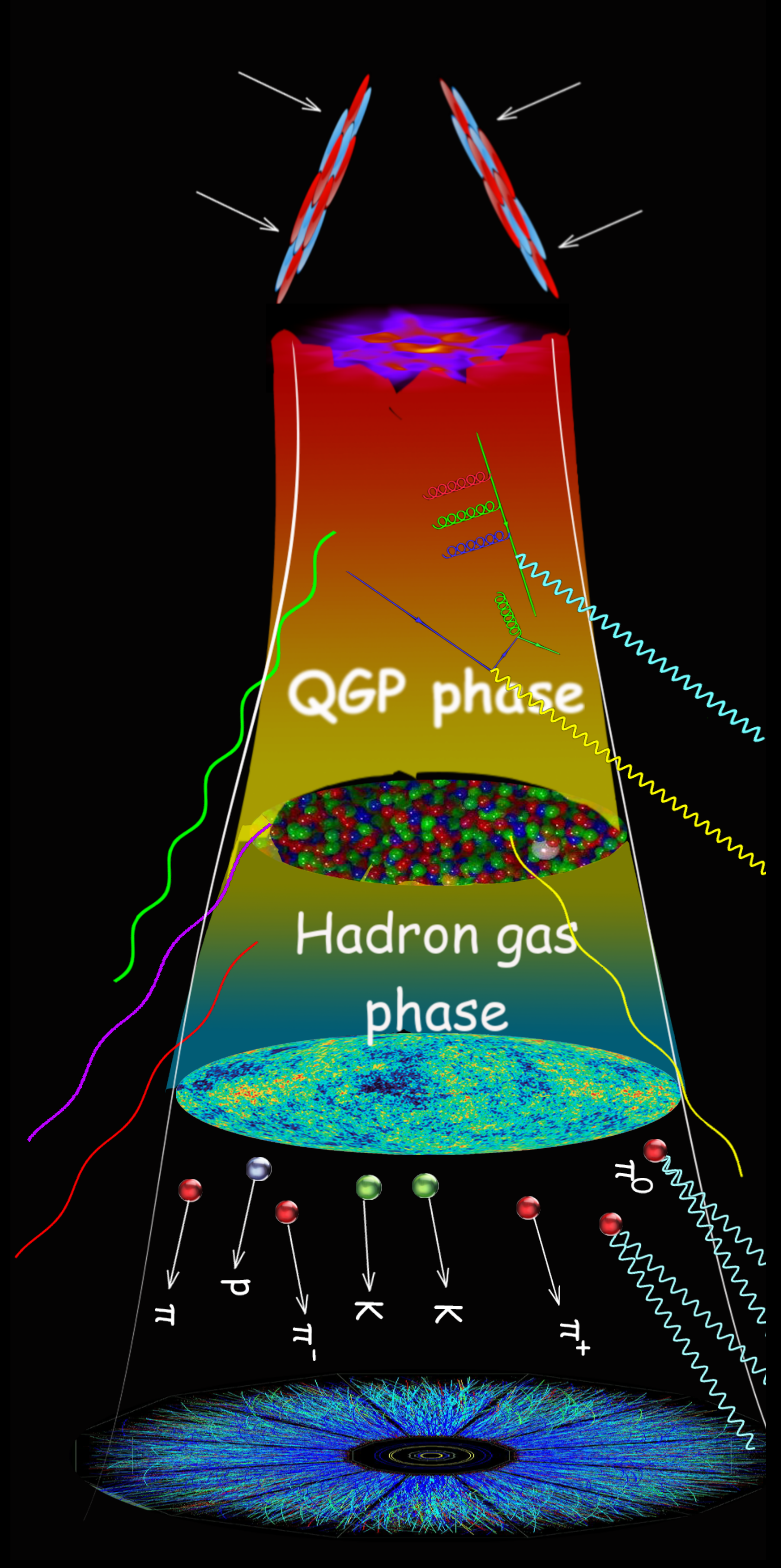




- How does this emerge from QCD?



DEFINING THE QUARK-GLUON PLASMA



Which **properties of hot QCD matter** can we determine from relativistic heavy ion data (LHC, RHIC, and future FAIR/NICA/JPAC)?

Equation of State $T^{\mu\nu} \Longleftrightarrow e, P, s$

$$c_s^2 = \partial P/\partial e|_{s/n}$$

Shear and bulk viscosities $\eta/s(T, \mu_B), \zeta/s(T, \mu_B)$

Charge diffusion D_B, D_Q, D_S

Electromagnetic emissivity

Energy-momentum transport $\hat{q}, \hat{e}, \hat{e}_2, \ldots$

Spectra, collective flow, femtoscopy

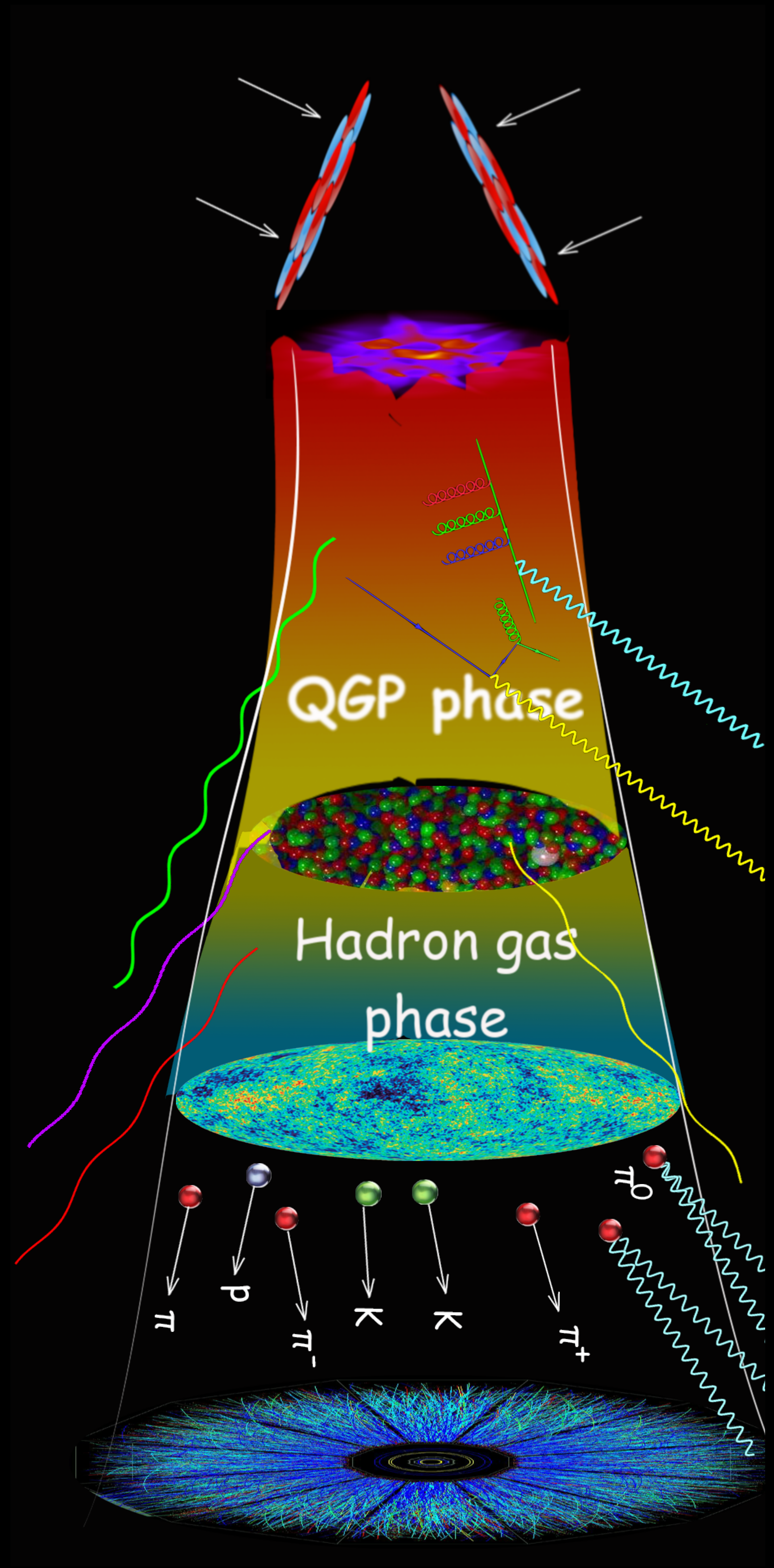
Anisotropic flow v_n
Flow correlations

Balance functions

Photons and dileptons

Jets and heavy-quarks

DEFINING THE QUARK-GLUON PLASMA



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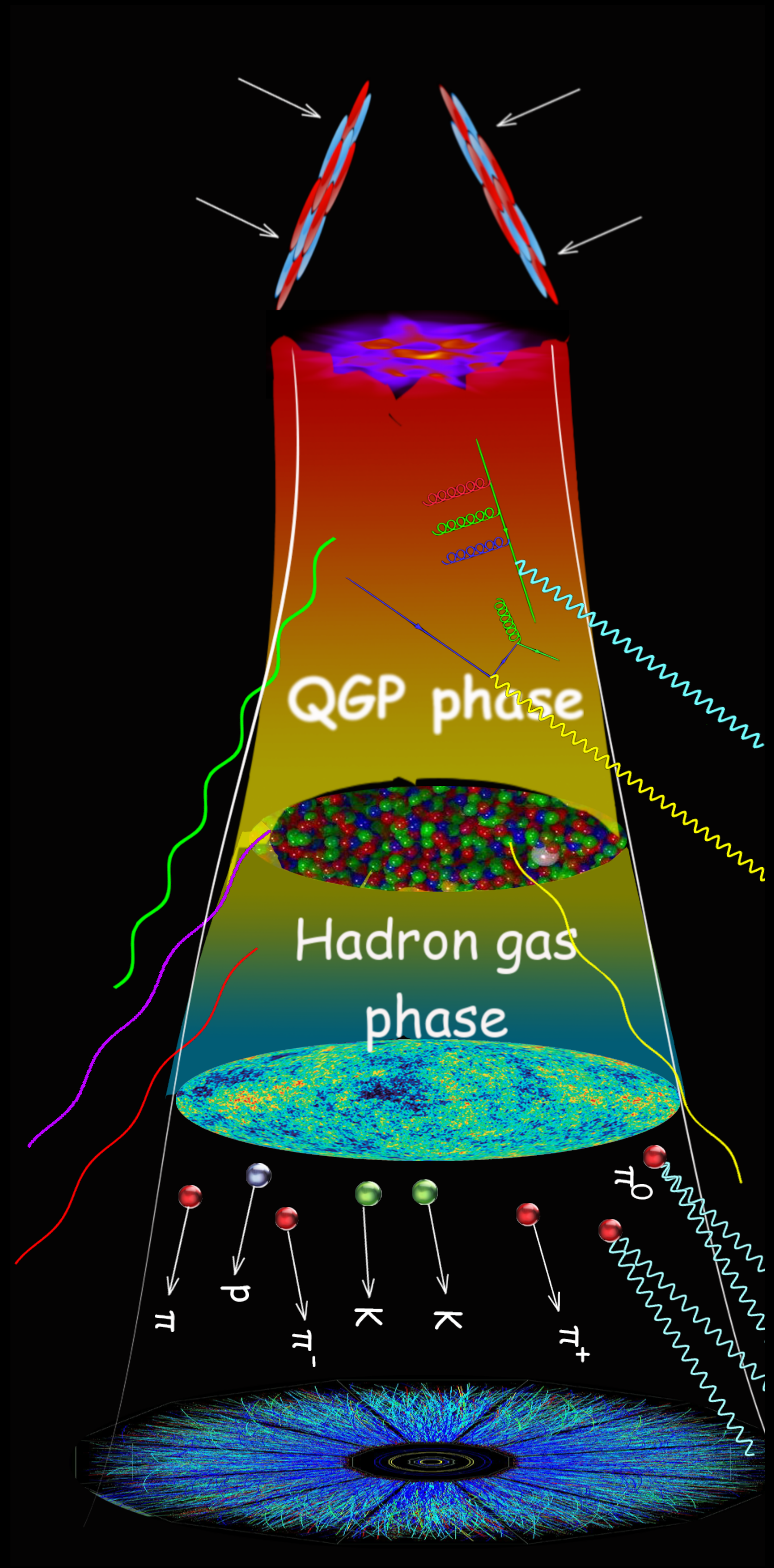
Shear and bulk viscosities $\eta/s(T, \mu_B), \zeta/s(T, \mu_B)$	Anisotropic flow v_n Flow correlations
Charge diffusion D_B, D_Q, D_S	Balance functions
Electromagnetic emissivity	Photons and dileptons
Energy-momentum transport $\hat{q}, \hat{e}, \hat{e}_2, \ldots$	Jets and heavy-quarks

DEFINING THE QUARK-GLUON PLASMA



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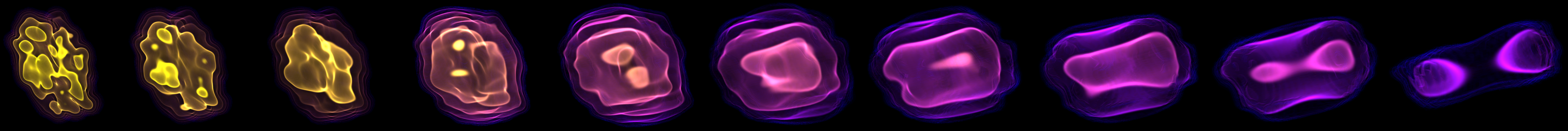
THE MULTI-STAGE THEORETICAL FRAMEWORK



$T^{\mu\nu}$ 0^+ 0.5-1 τ (fm)

Initial State +
Pre-equilibrium dynamics

Hydrodynamics

Hadronic Transport

$$T^{\mu\nu}_{\rm pre.\,eq} = T^{\mu\nu}_{\rm hydro}$$

+ Landau Matching
with lattice EoS

Cooper-Frye
particlization

- Continuously connect the system's energy-momentum tensor $T^{\mu\nu}$ between different stages

COLLECTIVITY & HYDRODYNAMICS

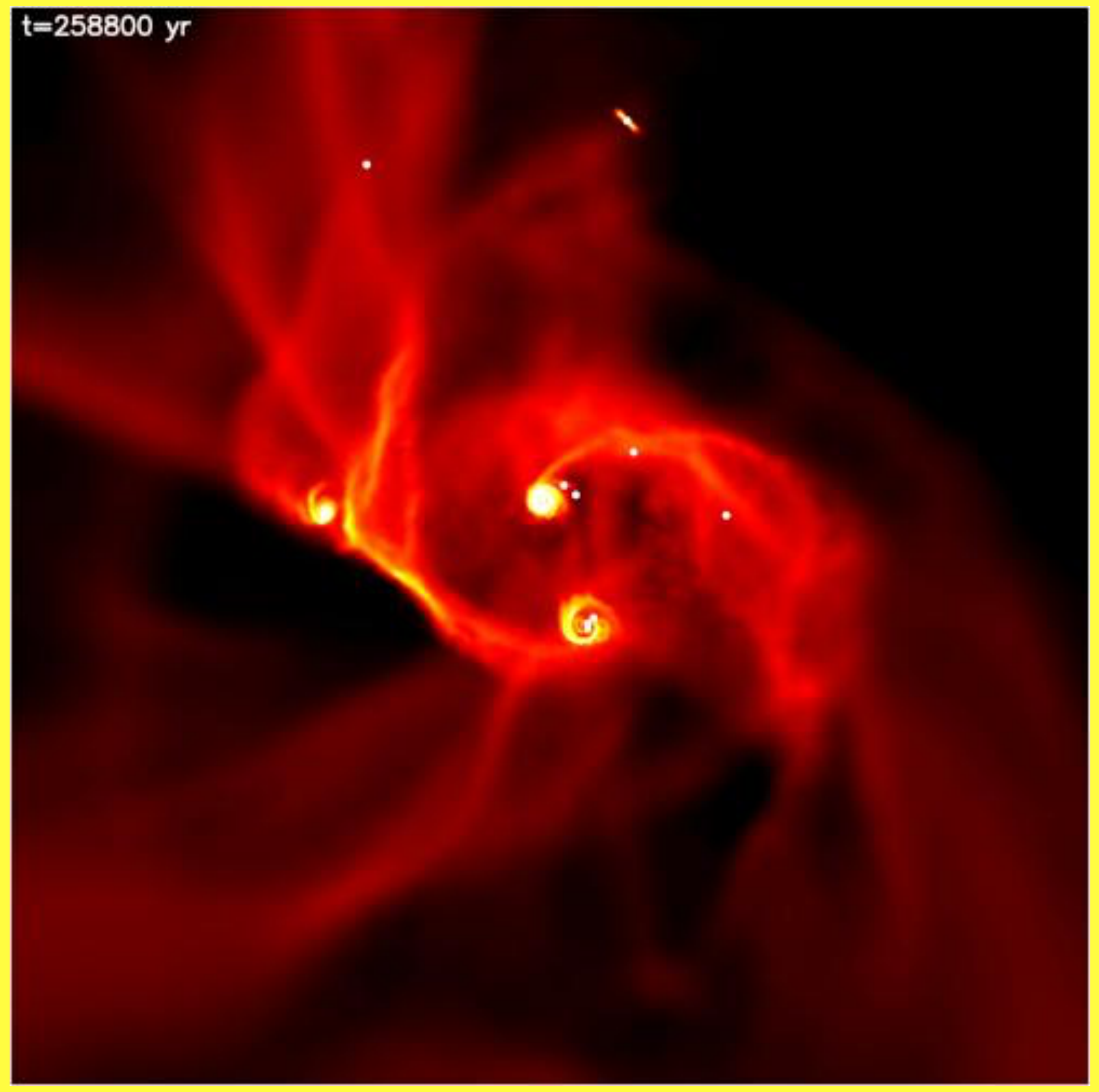
A long wavelength effective description of interacting systems

Conservation laws

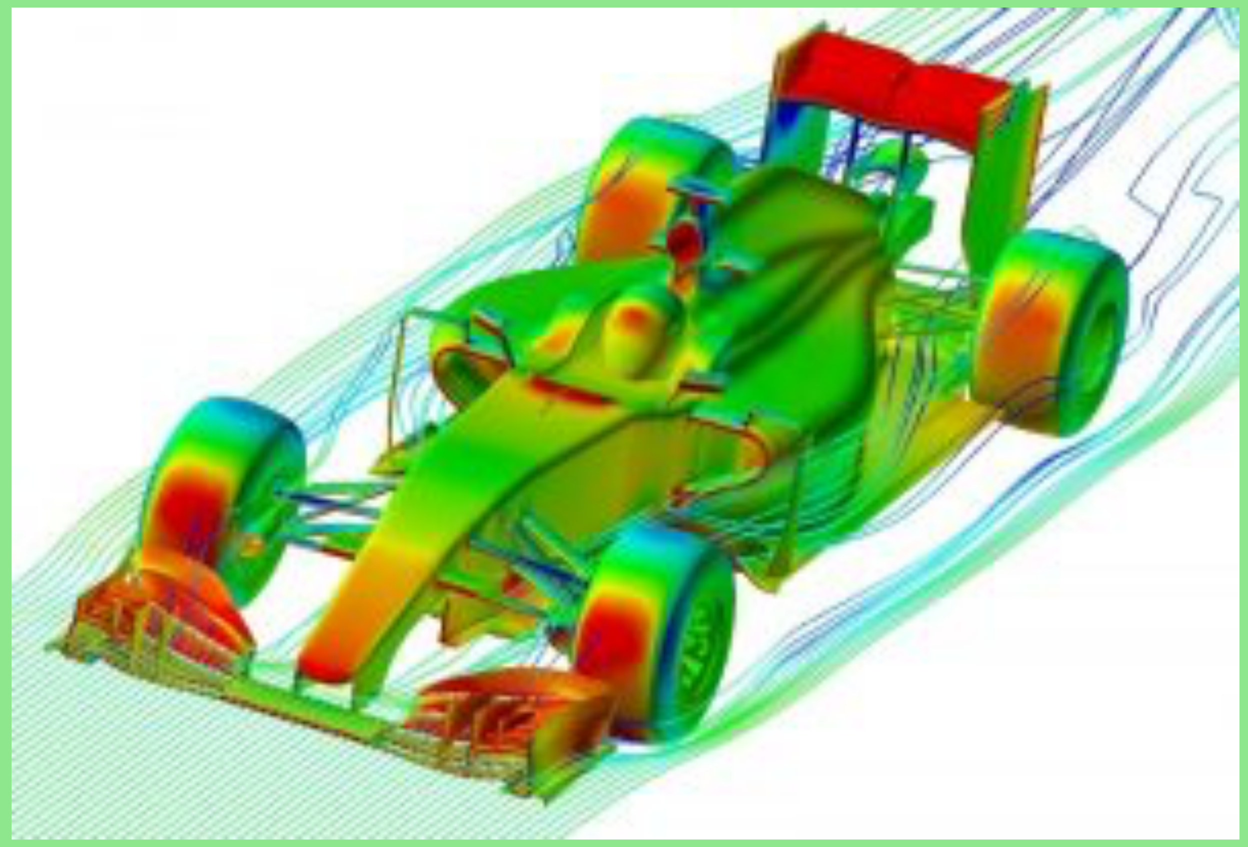
+

Equation of State

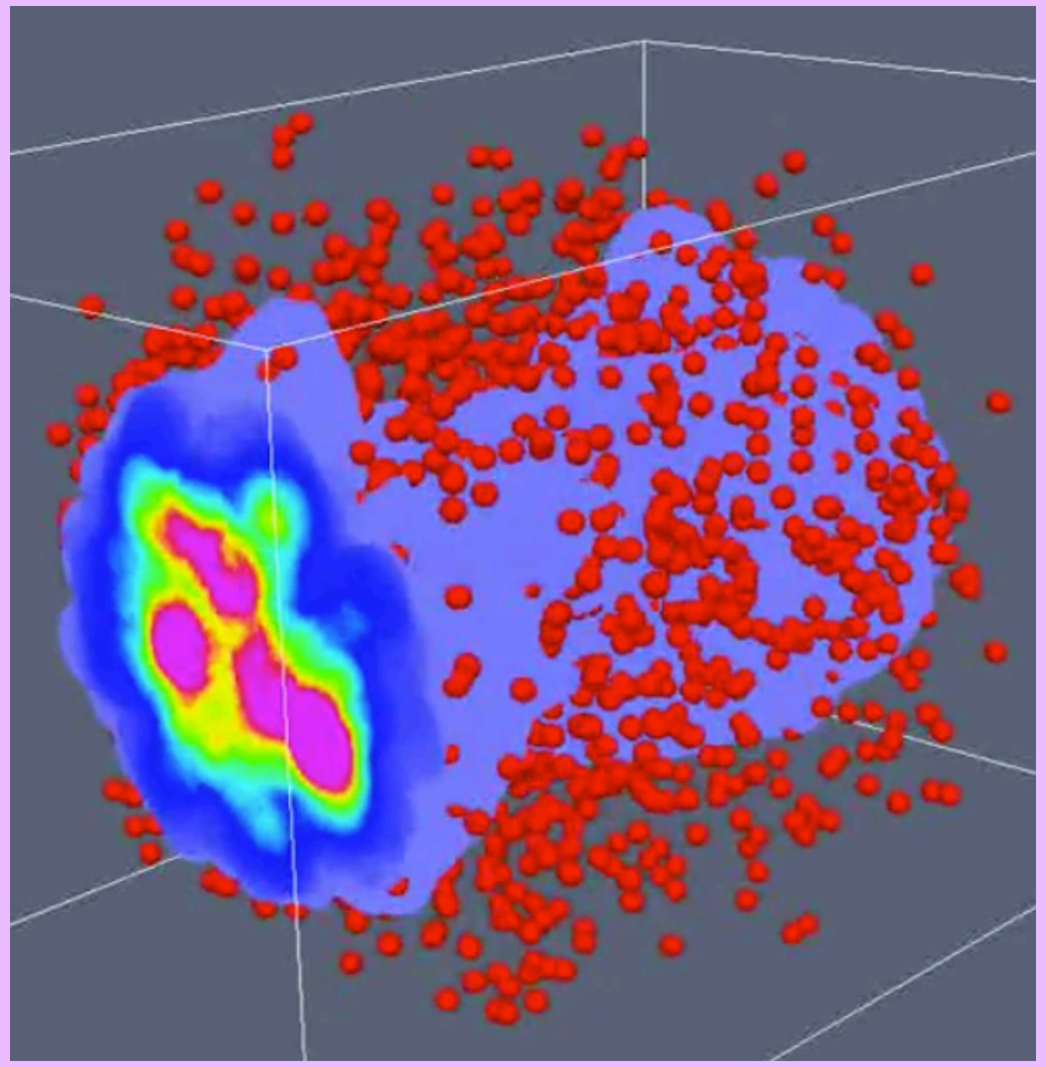
Star formation



Air dynamics of race car



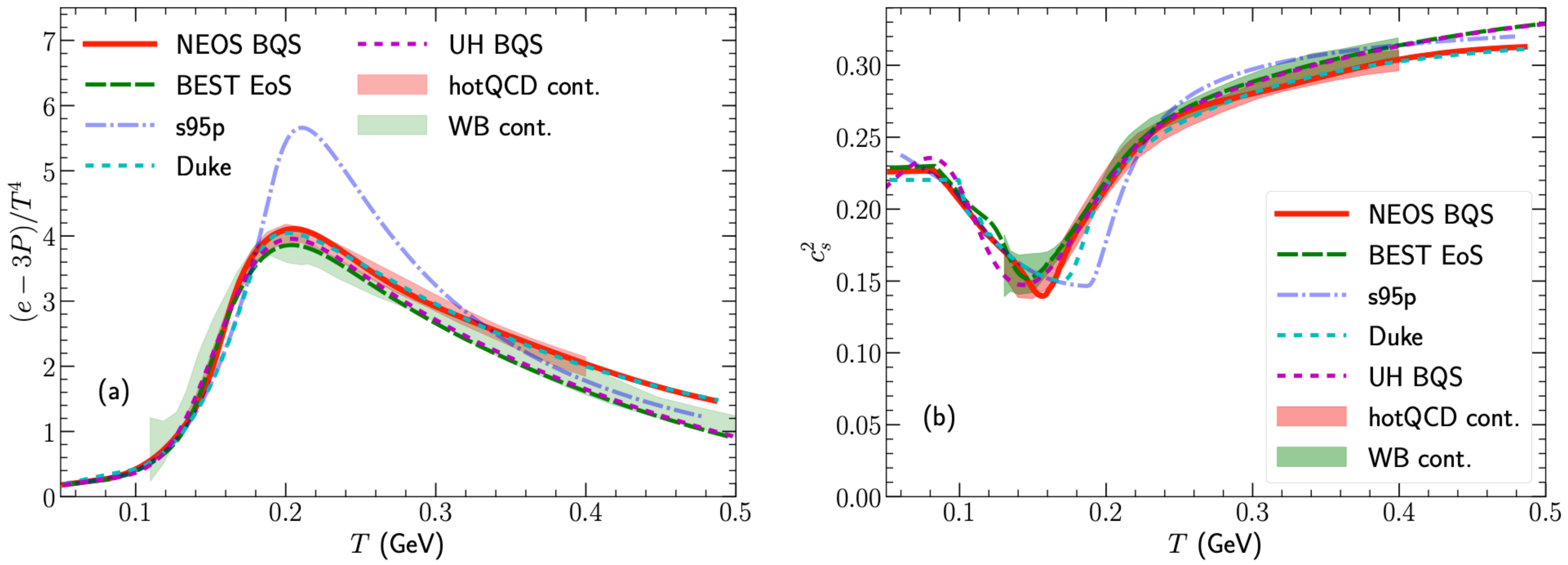
Quark-Gluon Plasma



Studying collective phenomena in heavy-ion collisions has been leading the theory frontier of developing causal viscous relativistic hydrodynamics

QCD EQUATION OF STATE

A. Monnai, B. Schenke and C. Shen, Int. J. Mod. Phys. A36, 2130007 (2021)



- QCD equation of state are constrained by Lattice QCD calculations

PRESSURE GRADIENTS DRIVEN DYNAMICS

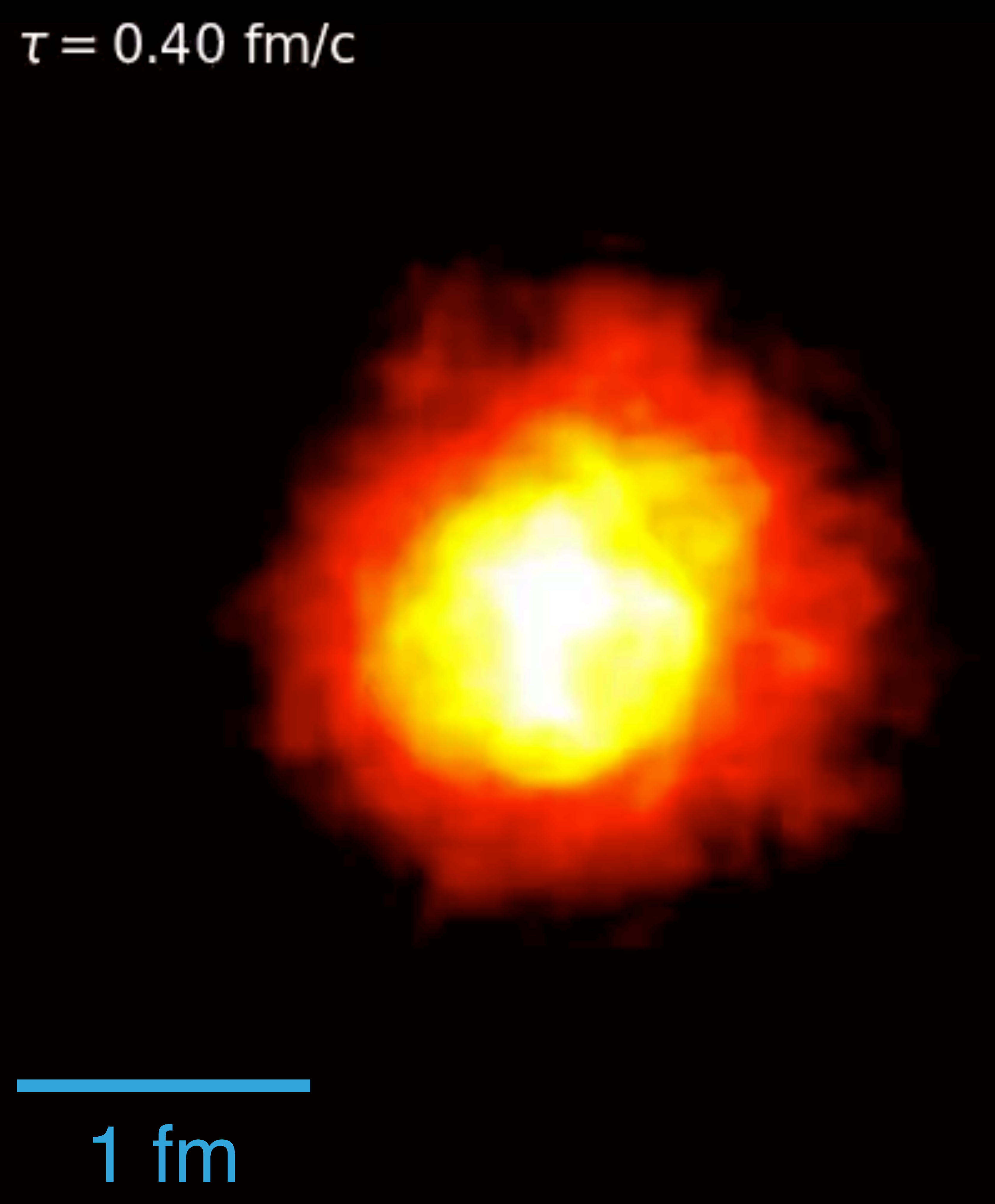
force

$$Du^\mu = \frac{\nabla^\mu P}{e + P} \sim \frac{c_s^2}{(1 + c_s^2)} \frac{\nabla^\mu e}{e}$$

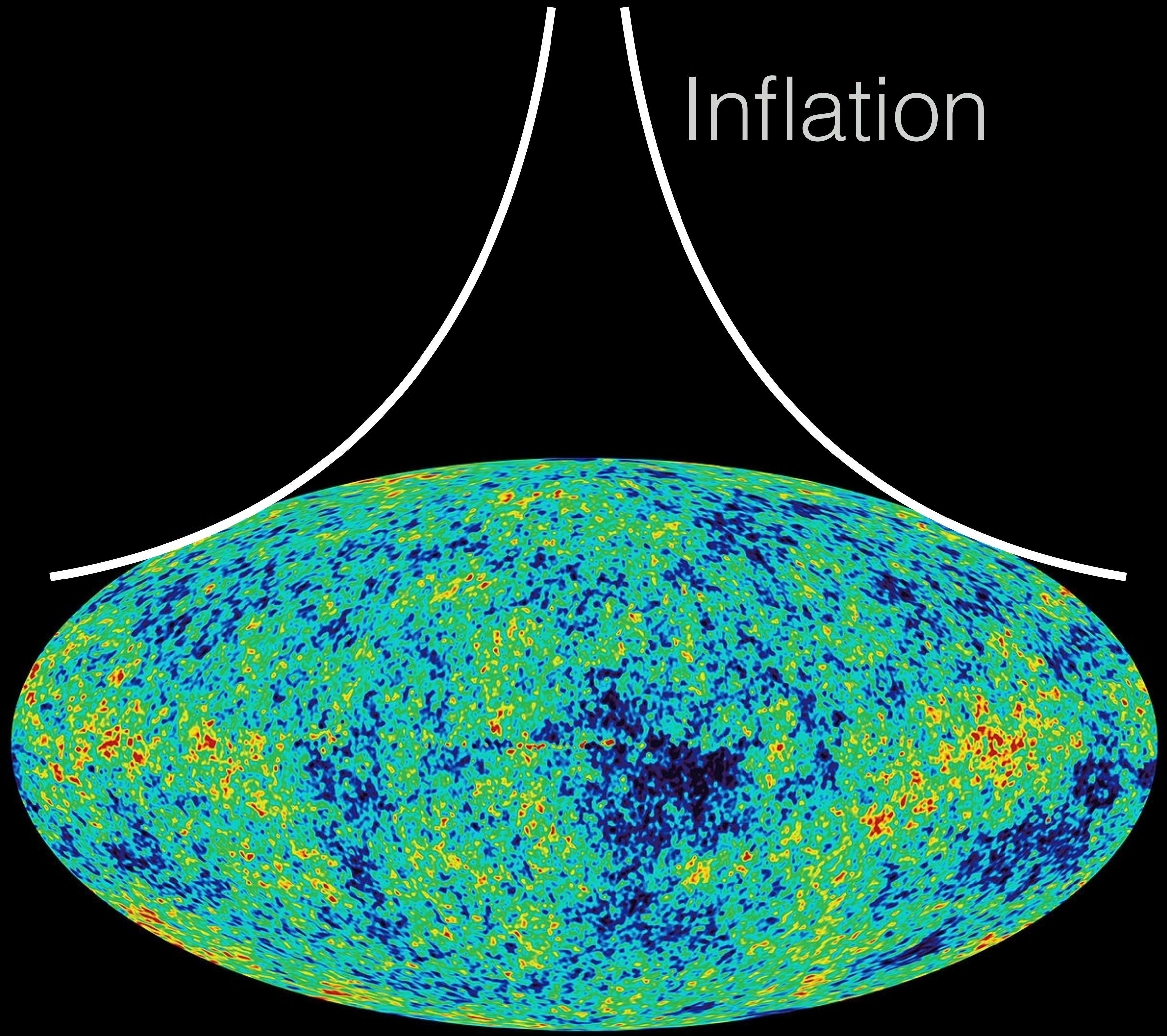
acceleration

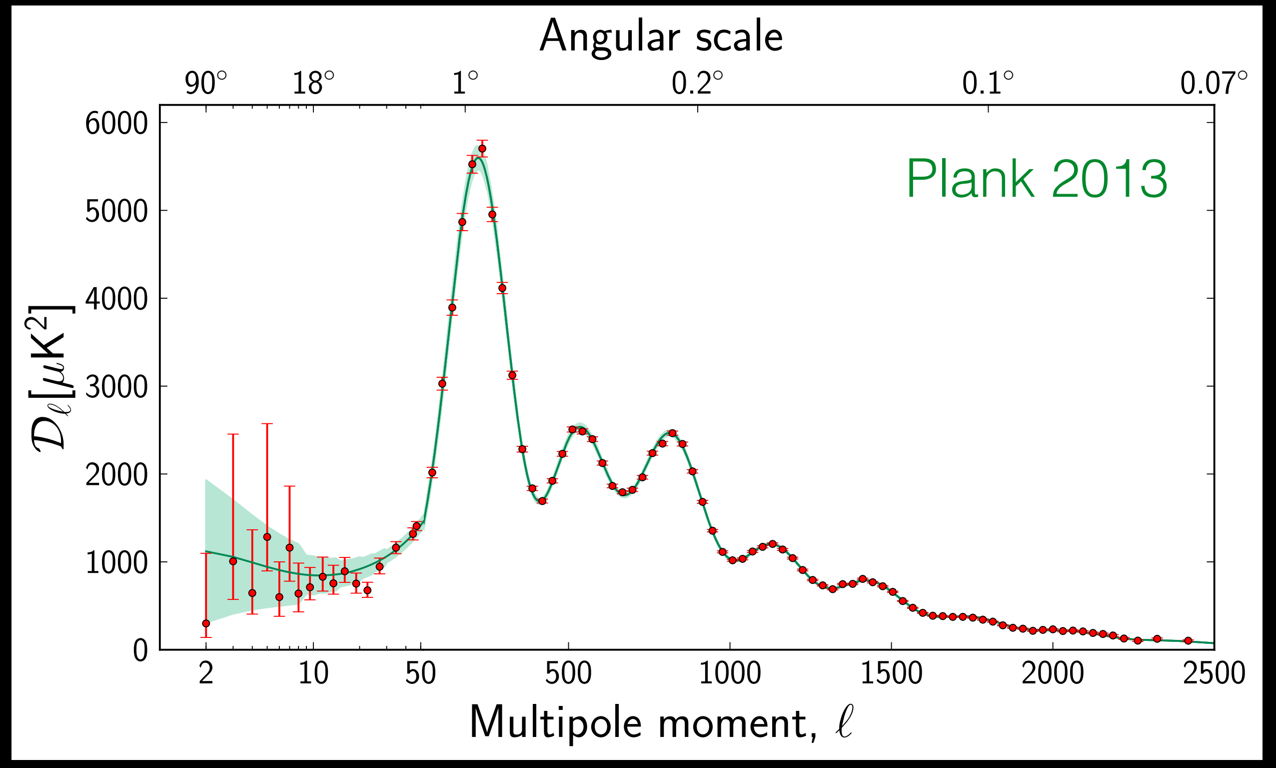
moment
of inertia

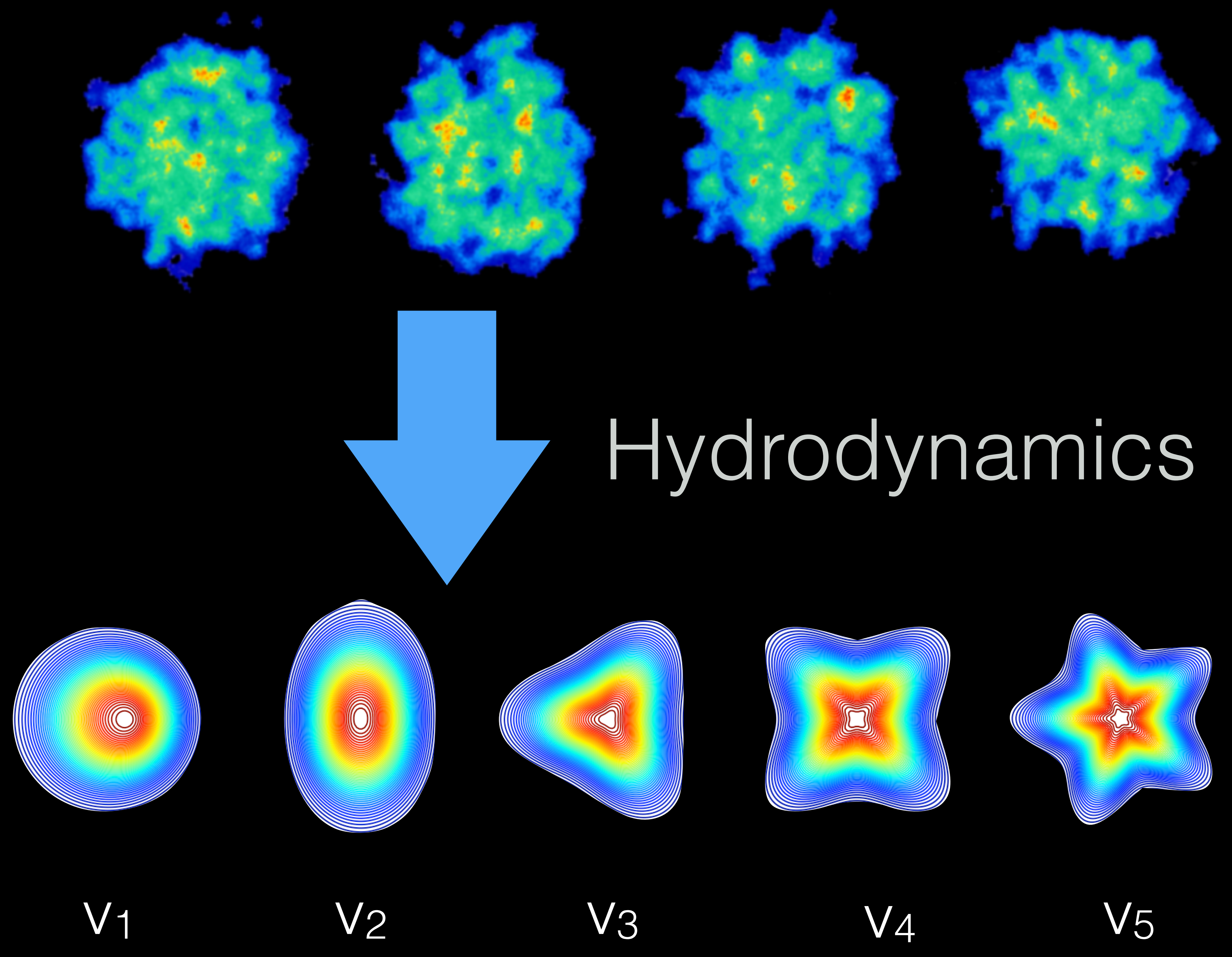
Spatial
imhomogeneity → Flow
velocity

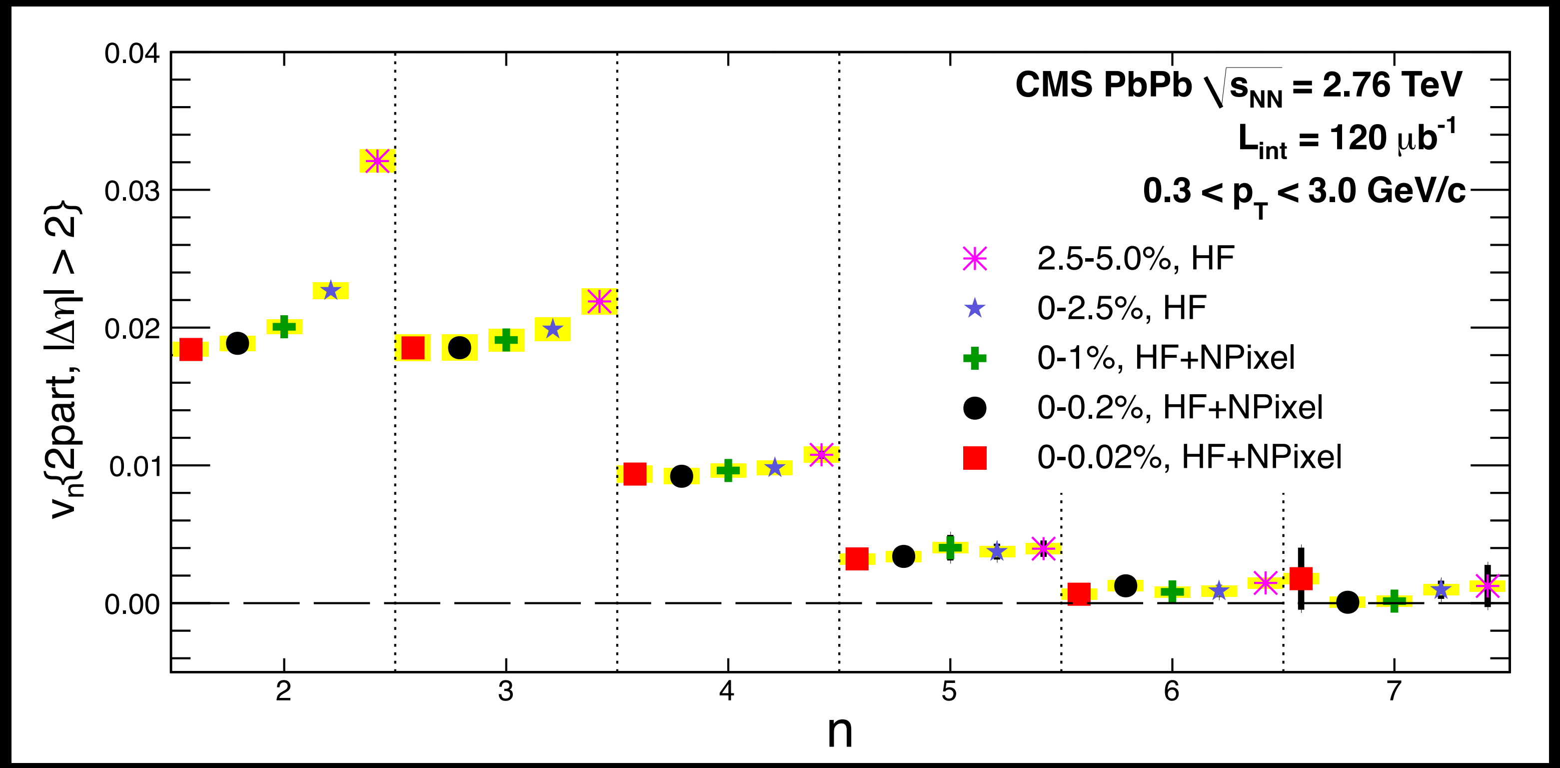


FLUCTUATION POWER SPECTRUM

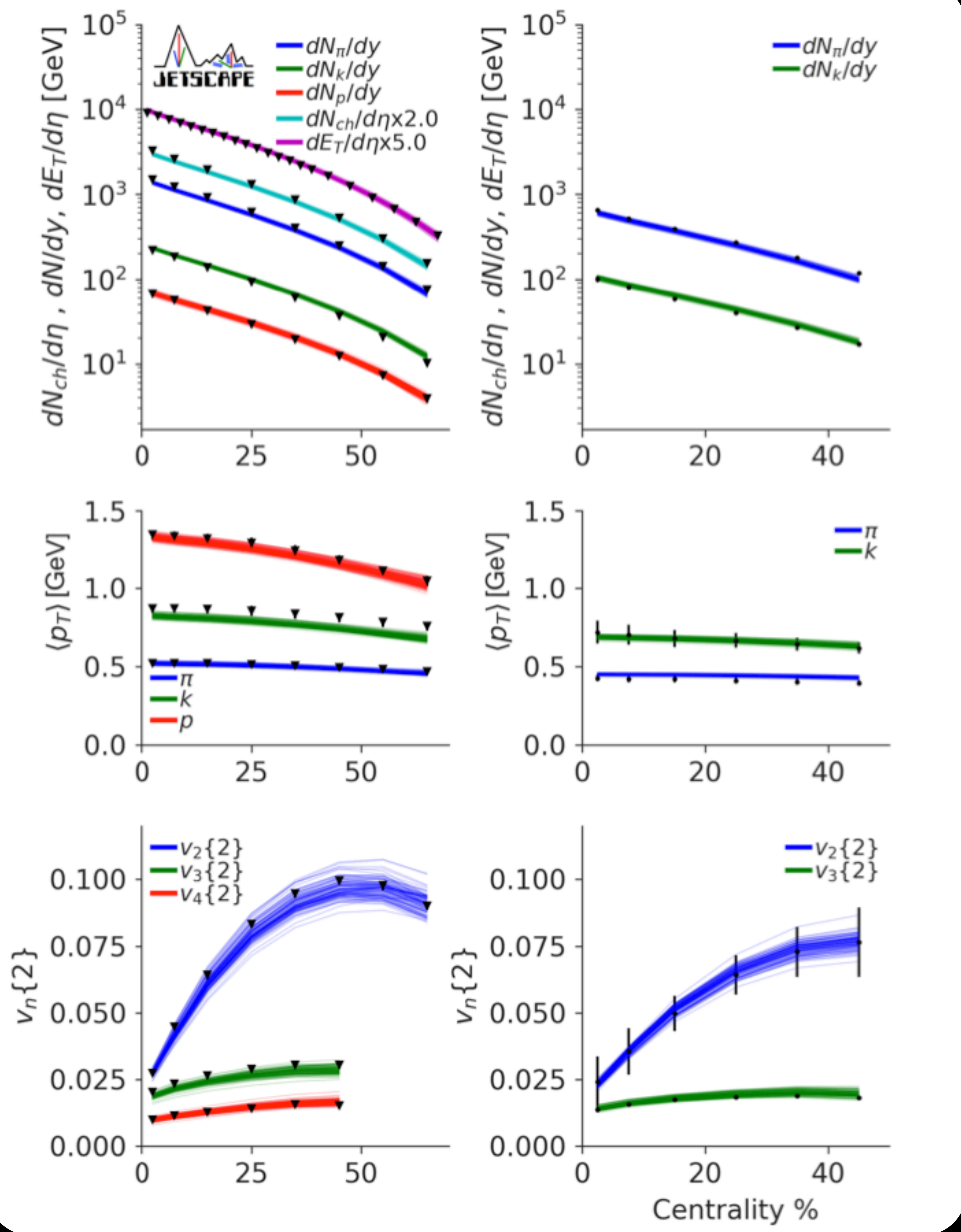








GLOBAL BAYESIAN CONSTRAINTS ON QGP VISCOSITY



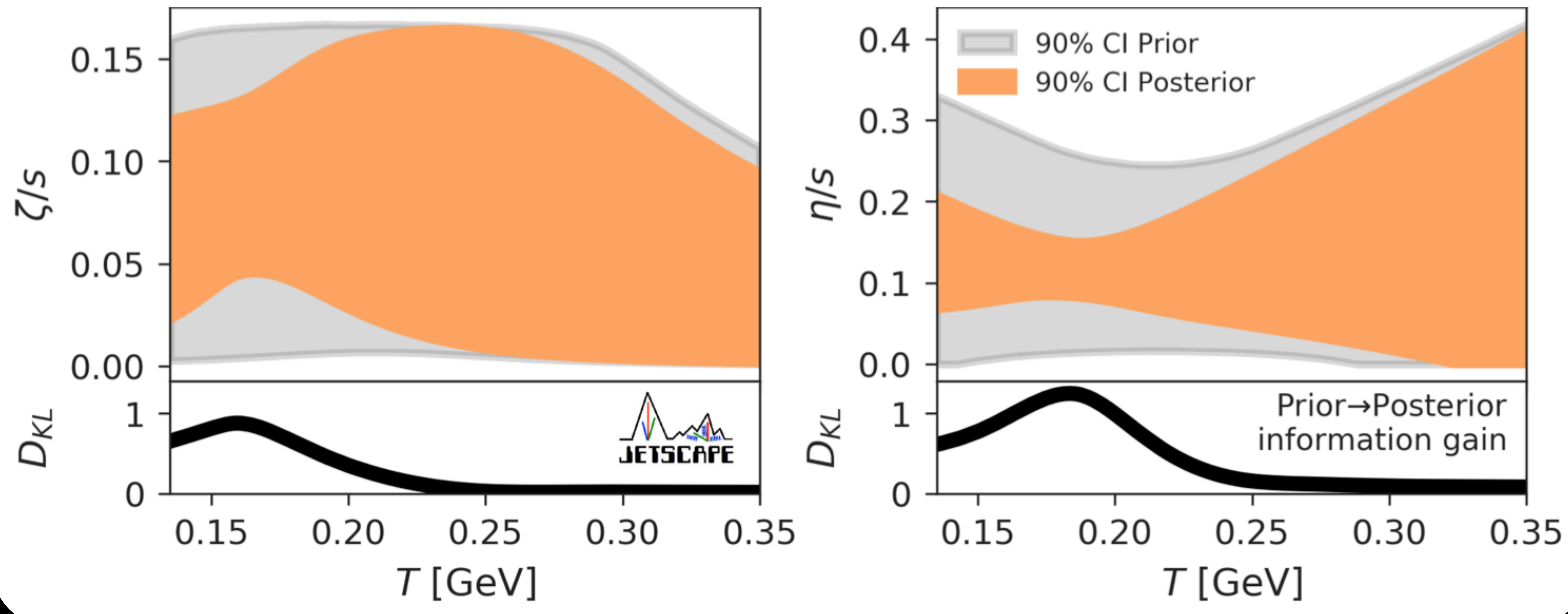
S. Pratt, E. Sangaline, P. Sorensen and H. Wang, Phys. Rev. Lett. 114, 202301 (2015)

J. E. Bernhard, J. S. Moreland, S. A. Bass, J. Liu and U. Heinz, Phys. Rev. C94, 024907 (2016)

J. E. Bernhard, J. S. Moreland and S. A. Bass, Nature Phys. 15, 1113-1117 (2019)

G. Nijs, W. Van Der Schee, U. Gursoy and R. Snellings, Phys. Rev. Lett. 126, 202301 (2021) & Phys. Rev. C103, 054909 (2021)

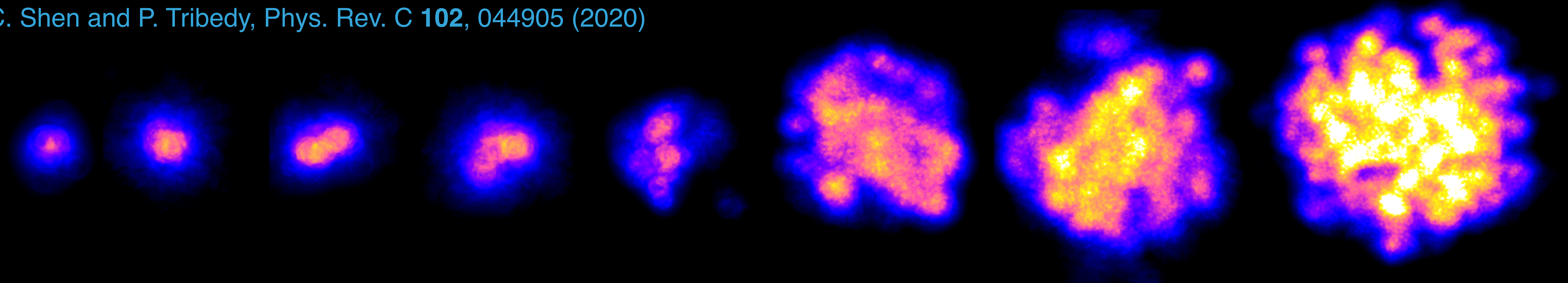
D. Everett *et al.* [JETSCAPE], arXiv:2010.03928 [hep-ph] & Phys. Rev. C103, 054904 (2021)



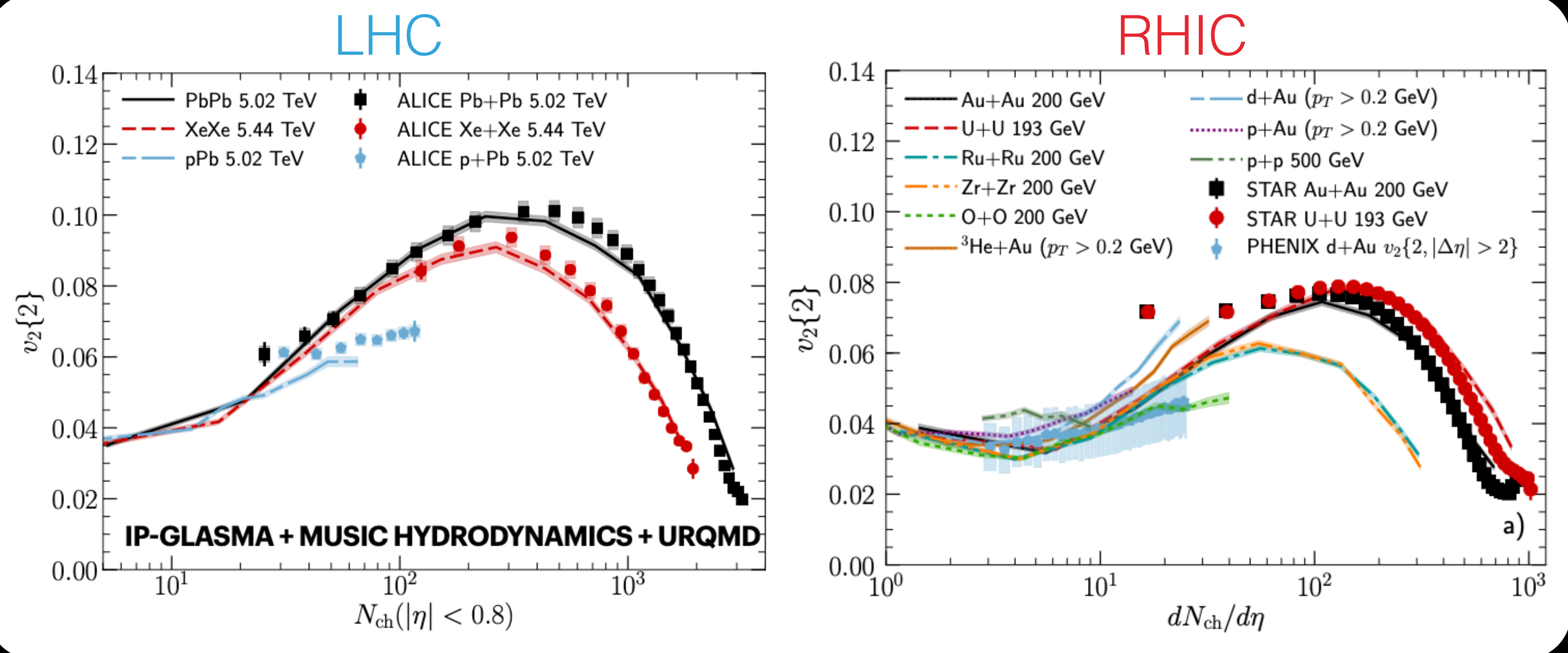
- Precision hadronic measurements can systematically constrain the QGP viscosity

RUNNING THE GAMUT OF HIGH ENERGY NUCLEAR COLLISIONS

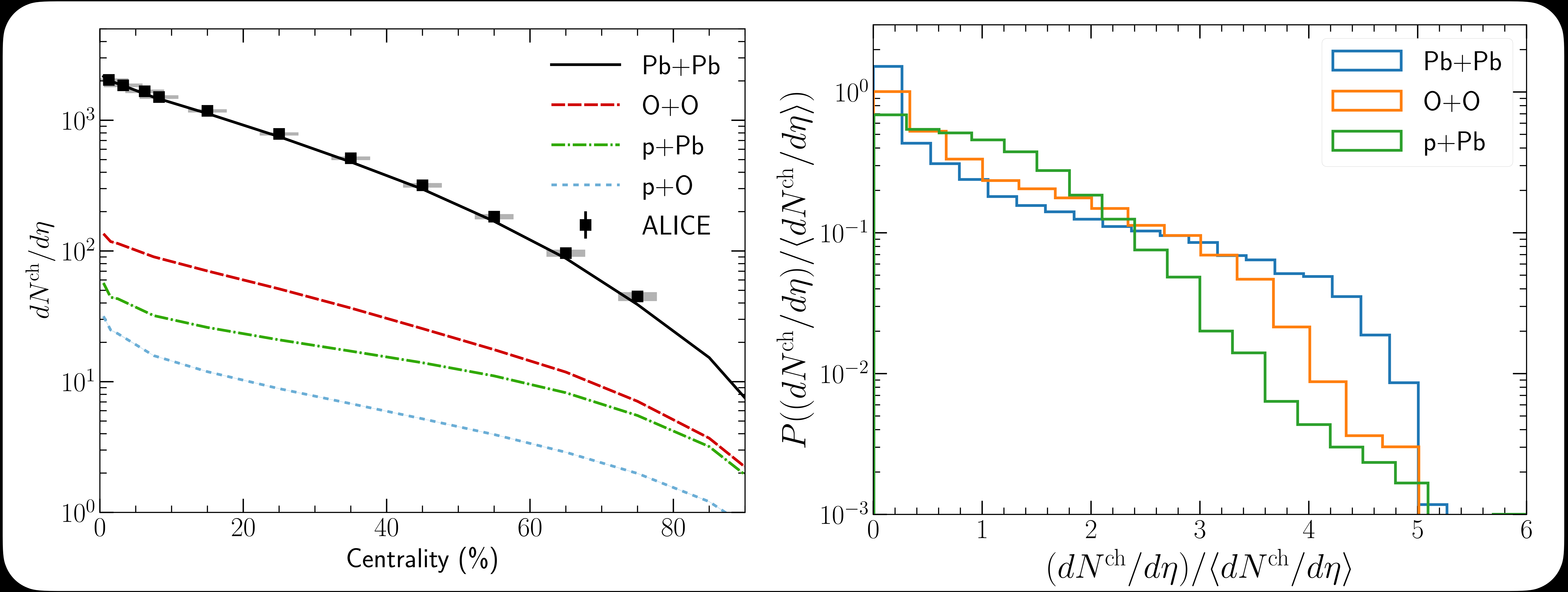
B. Schenke, C. Shen and P. Tribedy, Phys. Rev. C **102**, 044905 (2020)



- One single set of model parameters for *ALL* types of collisions at the top RHIC and LHC energies



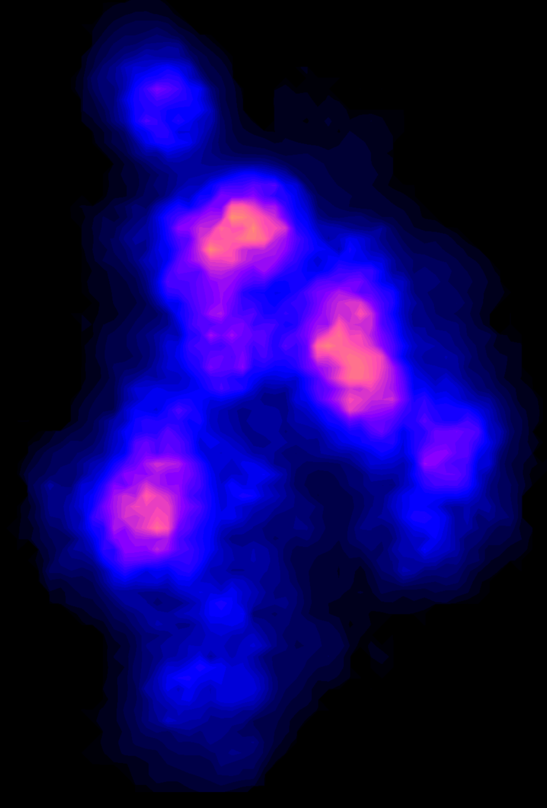
CENTRALITY AND PARTICLE MULTIPLICITY DISTRIBUTIONS



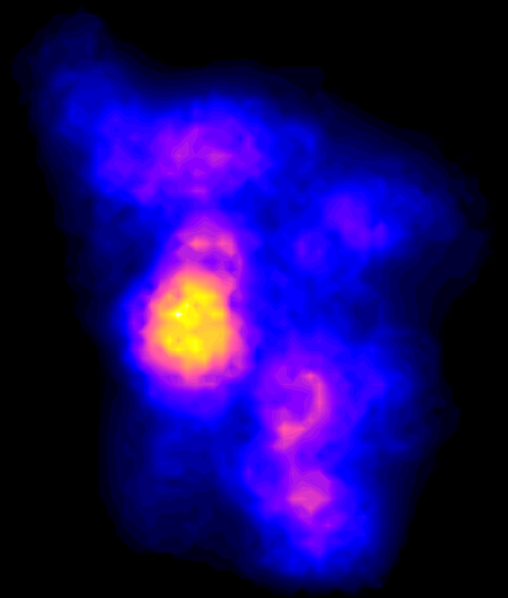
- 0-5% O+O collisions ≈ 50-70% Pb+Pb collisions
- Event activities in OO depend on both the collision geometry and event-by-event fluctuations

EVOLUTION OF PB+PB AND O+O AT SIMILAR MULTIPLICITY

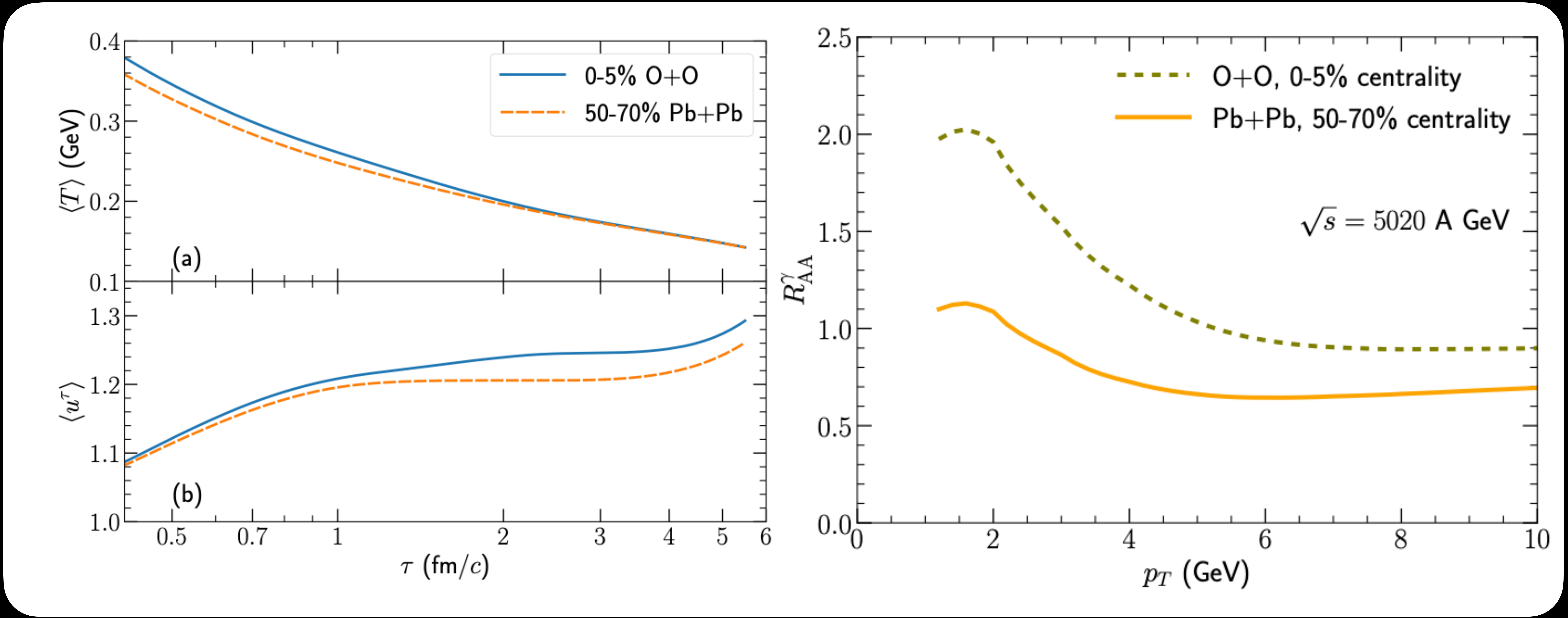
Pb+Pb



O+O

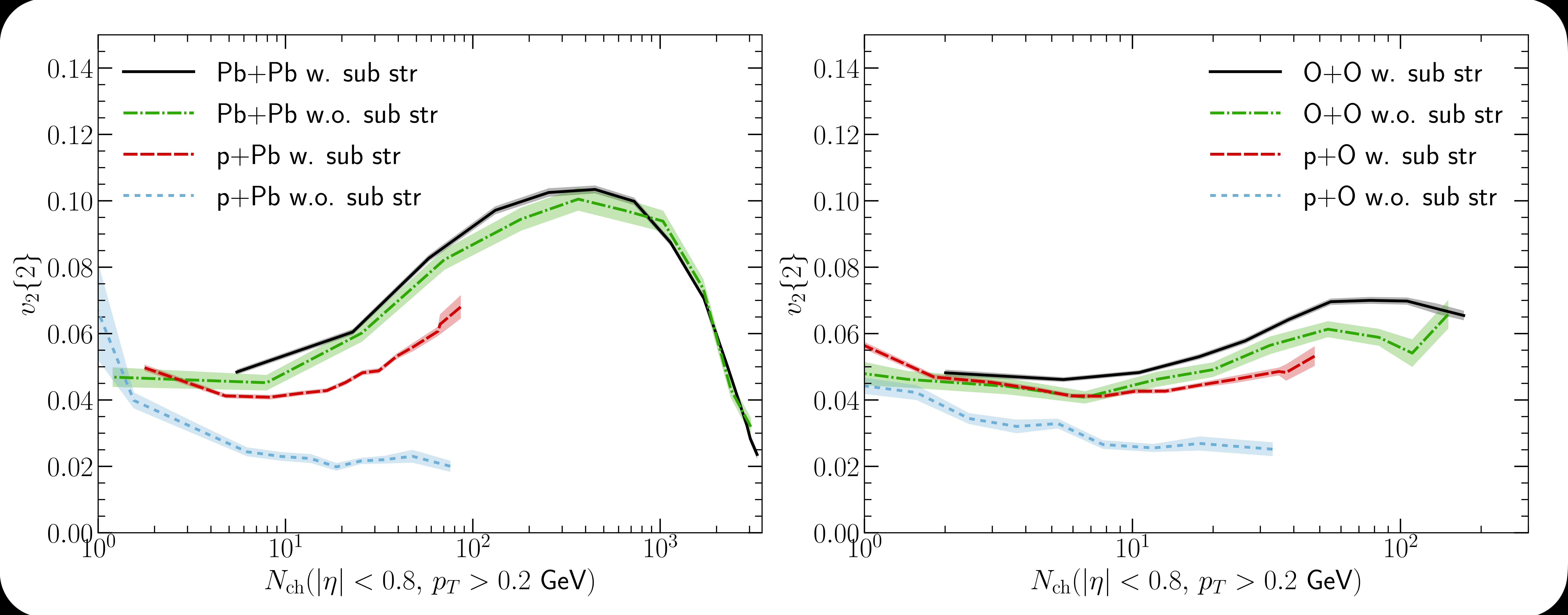


C. Gale, J. F. Paquet, B. Schenke and C. Shen, arXiv:2106.11216 [nucl-th]



- OO collisions have more compact density profiles which lead to a higher averaged temperature and faster expansion than PbPb collisions
- Enhancement of thermal photon radiation in OO

EFFECTS OF SUB-NUCLEON STRUCTURE ON V_2



- The v_2 of p+Pb and p+O show strong dependence of sub-nucleon structures; Pb+Pb collisions are mainly driven by nucleon fluctuations

CORRELATION BETWEEN V_N AND MEAN P_T AT FIXED MULTIPLICITY

$$\hat{\rho}_n(v_n^2, \langle p_T \rangle) = \frac{\langle \hat{\delta} v_n^2 \hat{\delta} \langle p_T \rangle \rangle}{\sqrt{\langle (\hat{\delta} v_n^2)^2 \rangle \langle (\hat{\delta} \langle p_T \rangle)^2 \rangle}}$$

P. Bozek, Phys. Rev. C 93, 044908 (2016)

Event-by-event correlation between v_n and $\langle p_T \rangle$
At fixed multiplicity: reduce contamination from system size fluctuations

Fluctuations from multiplicity(centrality) can be removed by binning events into unit multiplicity bins or by the following procedure

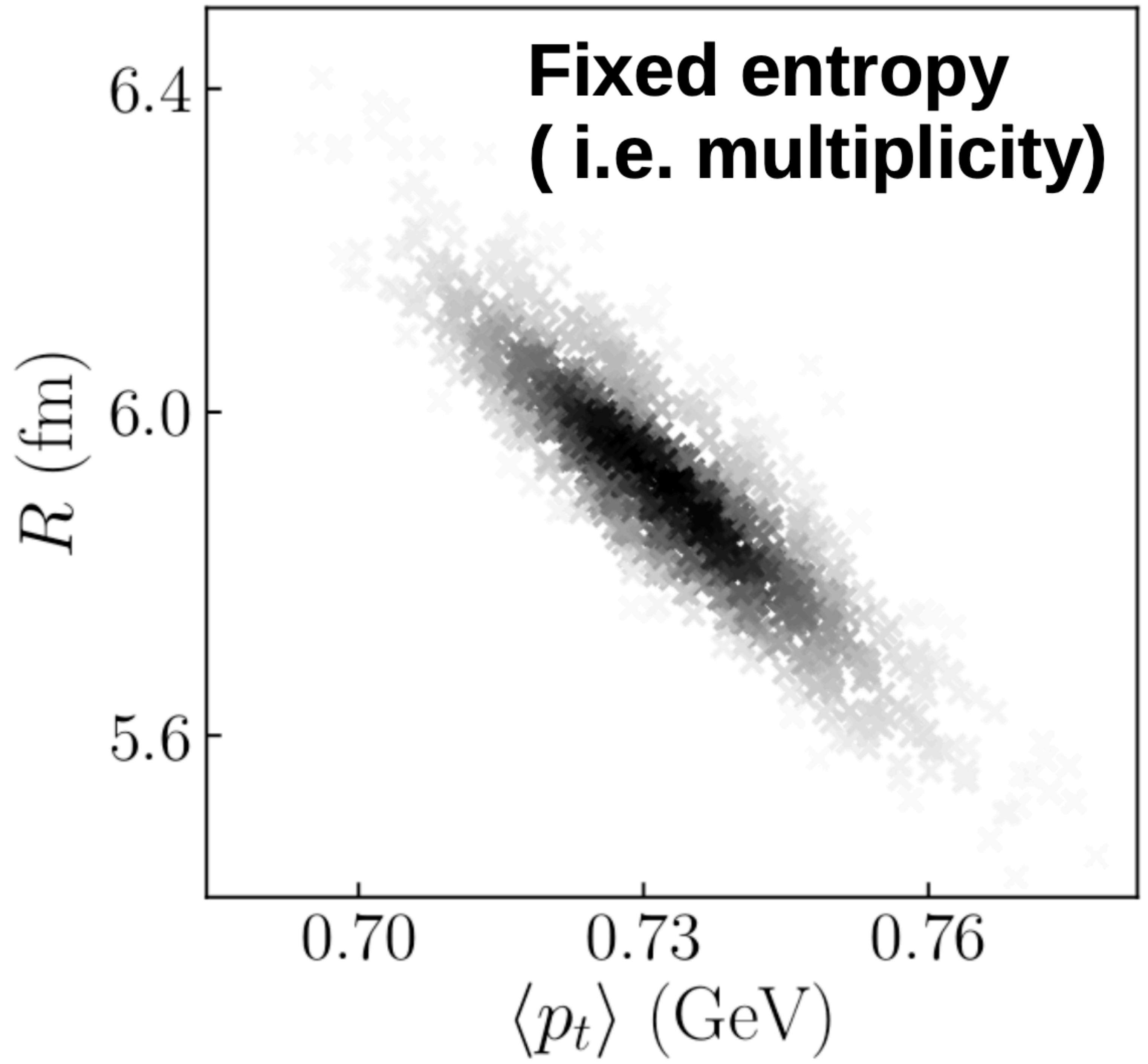
A. Olszewski and W. Broniowski, Phys. Rev. C 96, 054903 (2017)
B. Schenke, C. Shen, and D. Teaney, Phys.Rev.C 102, 034905 (2020)

$$\hat{\delta} O \equiv \delta O - \frac{\langle \delta O \delta N \rangle}{\sigma_N^2} \delta N \qquad \delta O \equiv O - \langle O \rangle$$

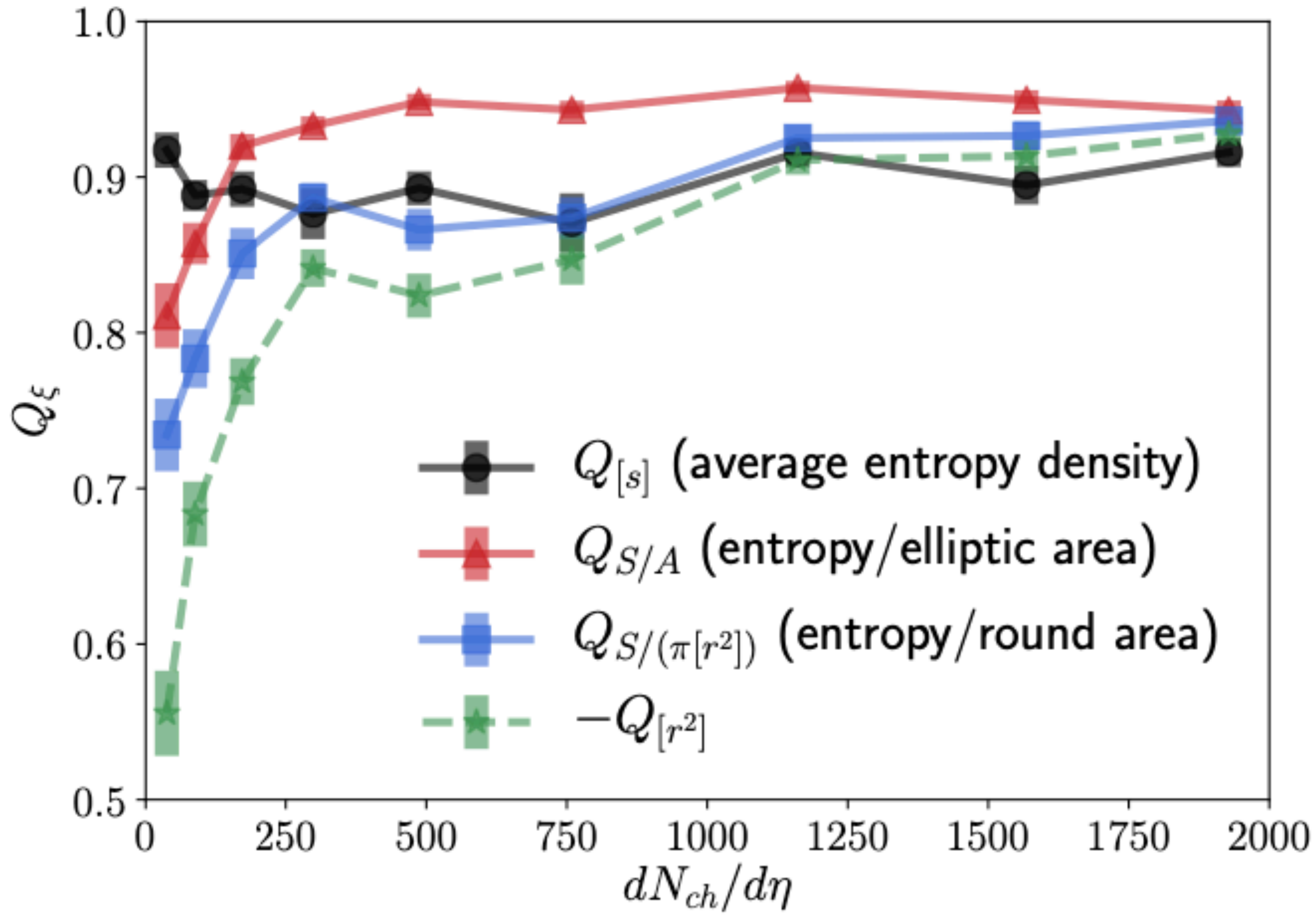
remove the linear correlation between the observable O and multiplicity

WHAT EVENTS DOES $\langle p_T \rangle$ SELECT?

Gardim, Giacalone, Luzum, Ollitrault, 1908.09728



B. Schenke, C. Shen, and D. Teaney, Phys.Rev.C 102, 034905 (2020)



$$Q_\xi = \frac{\hat{\delta} P_T \hat{\delta} \xi}{\sqrt{\langle (\hat{\delta} P_T)^2 \rangle \langle (\hat{\delta} \xi)^2 \rangle}}$$

$$P_T = N \langle p_T \rangle$$

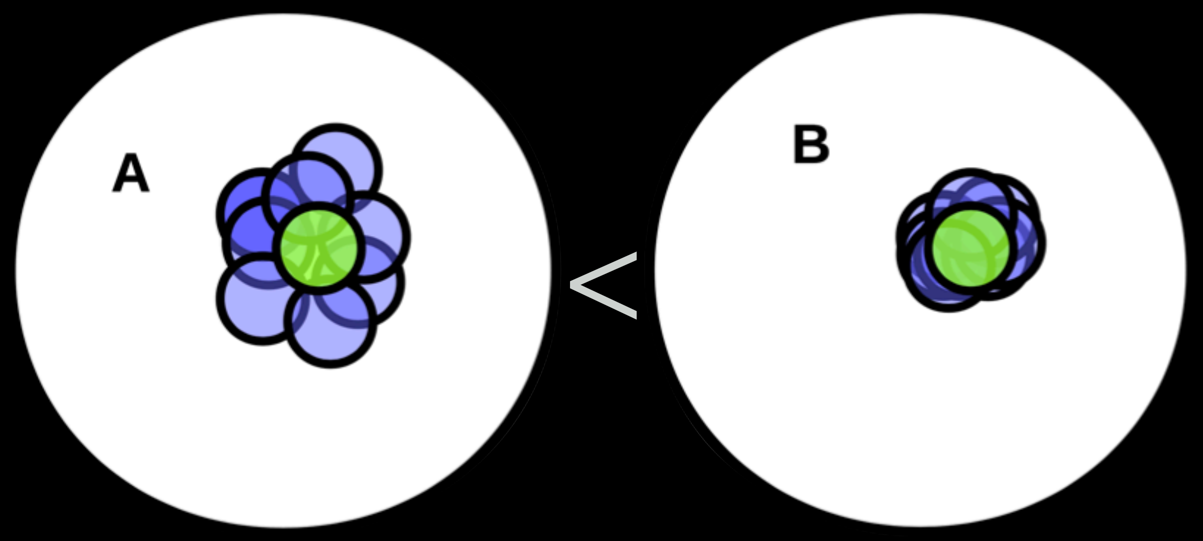
The system's $\langle p_T \rangle$ is strongly anti-correlated with the transverse area

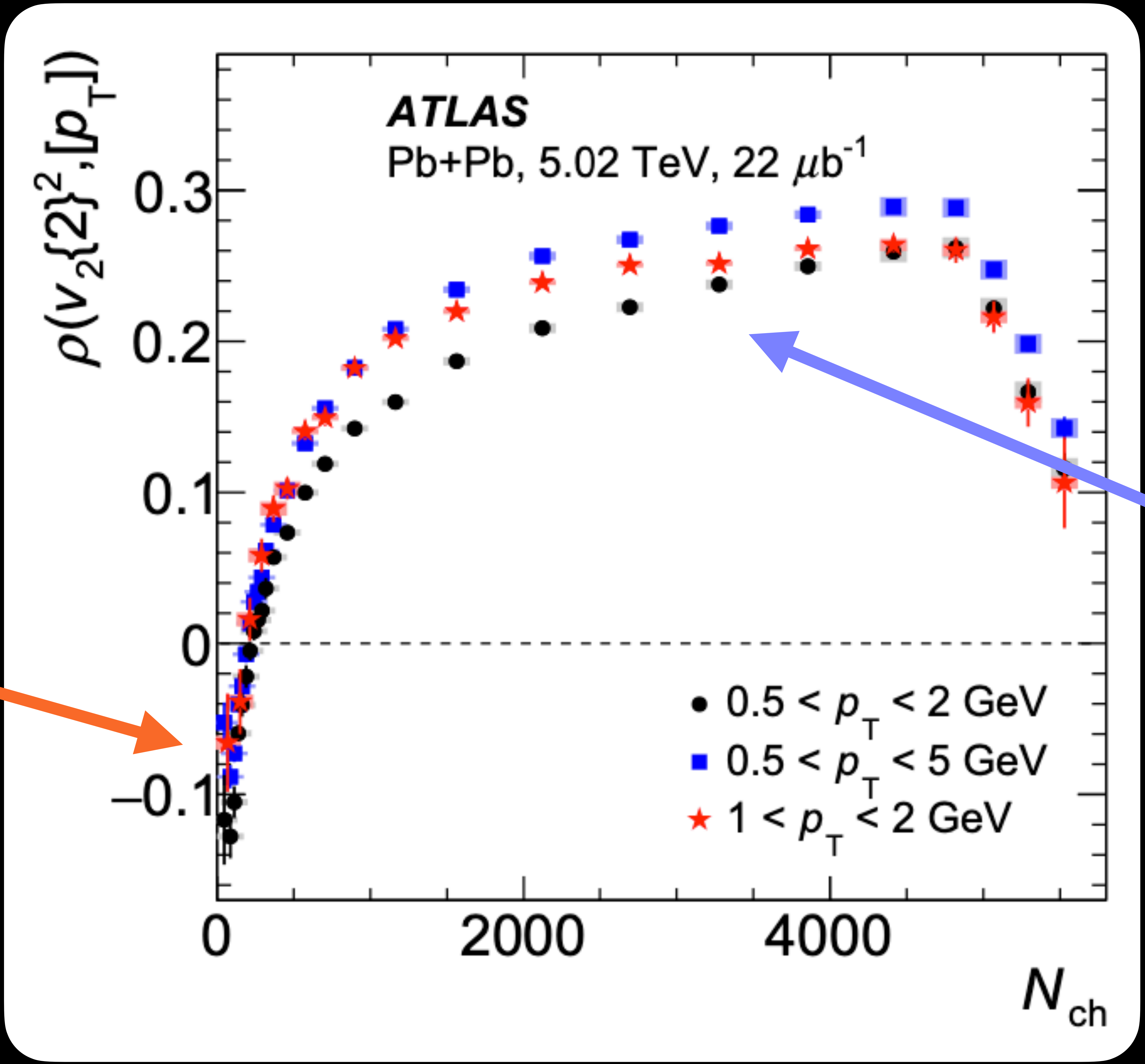
$\langle p_T \rangle > \langle \langle p_T \rangle \rangle$ → Smaller system, higher density gradients, hotter

$\langle p_T \rangle < \langle \langle p_T \rangle \rangle$ → Larger system, lower density gradients, colder

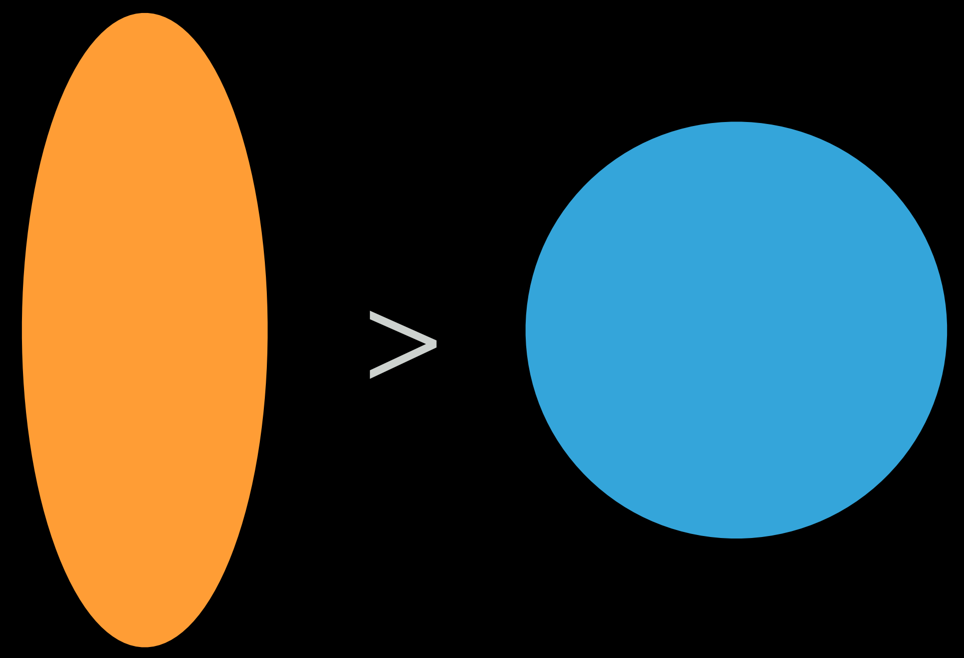
THE $\hat{\rho}_2$ IN HEAVY-ION COLLISIONS

Pressure gradients

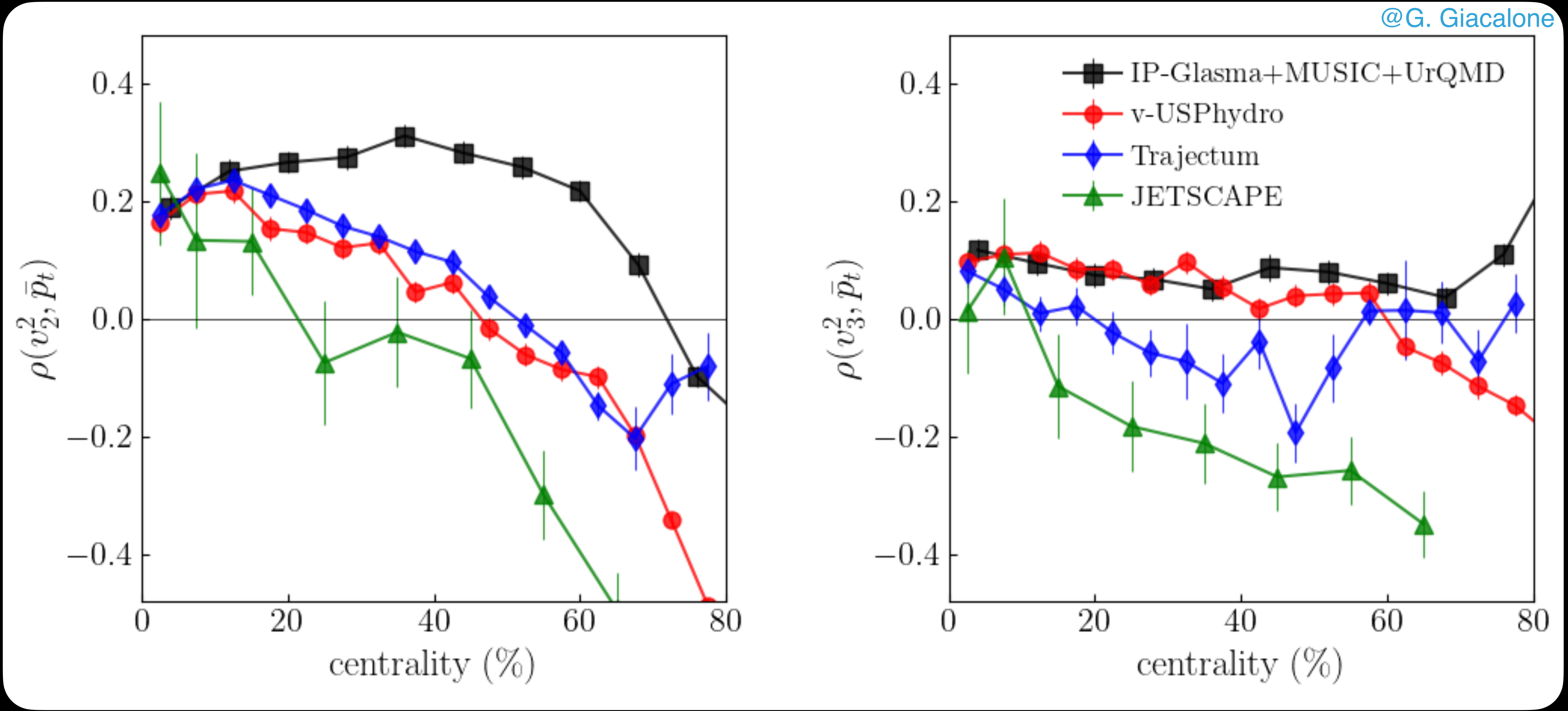




Pressure gradients

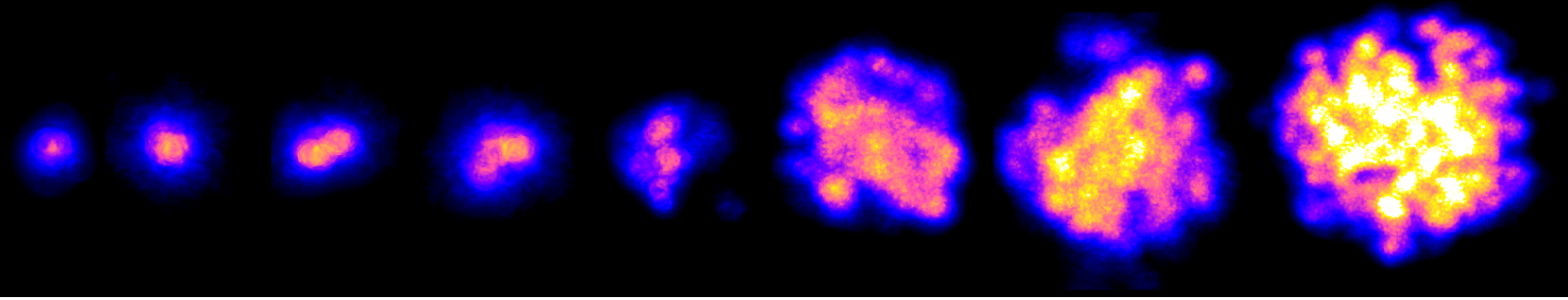


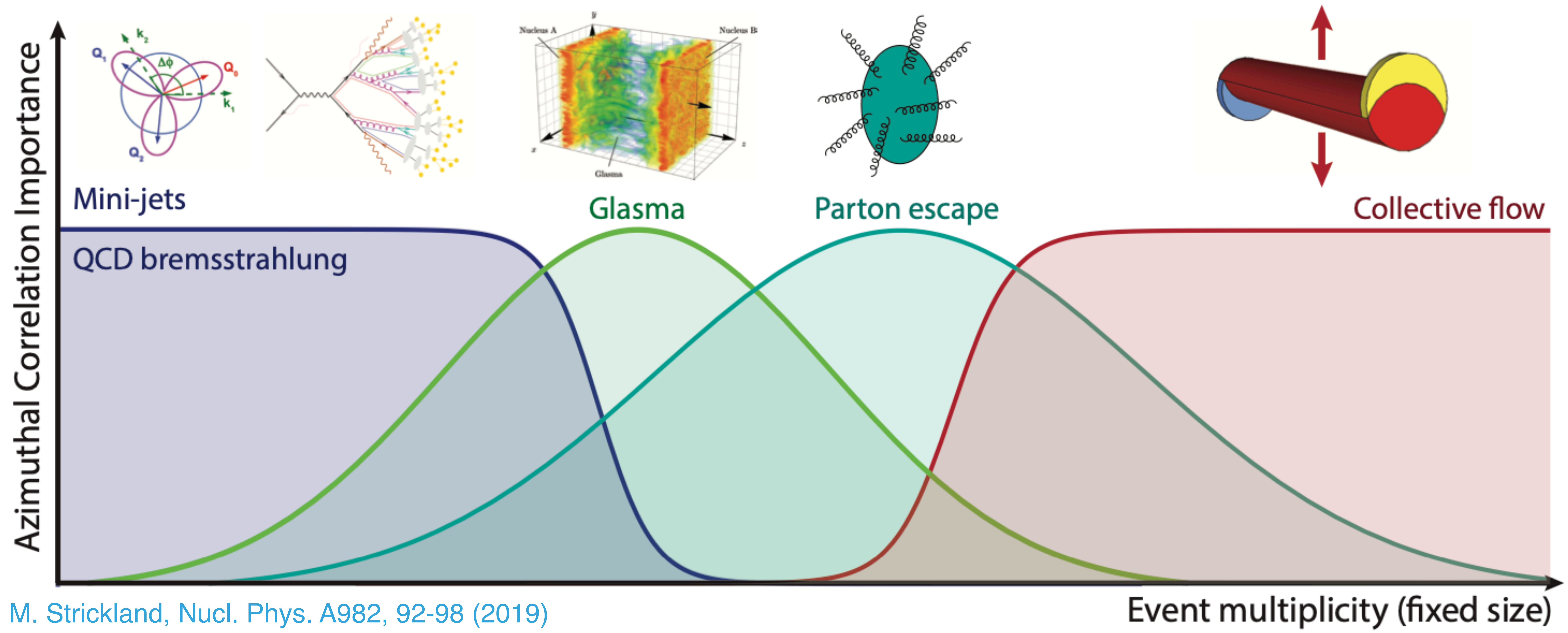
WHY IS $\hat{\rho}_n$ INTERESTING?



- All models are calibrated to dN/dy, $\langle p_T \rangle$, v_n data; But they differ significantly in the $\hat{\rho}_n$ correlators
- Measurements of $\hat{\rho}_n$ have strong power to discriminate models

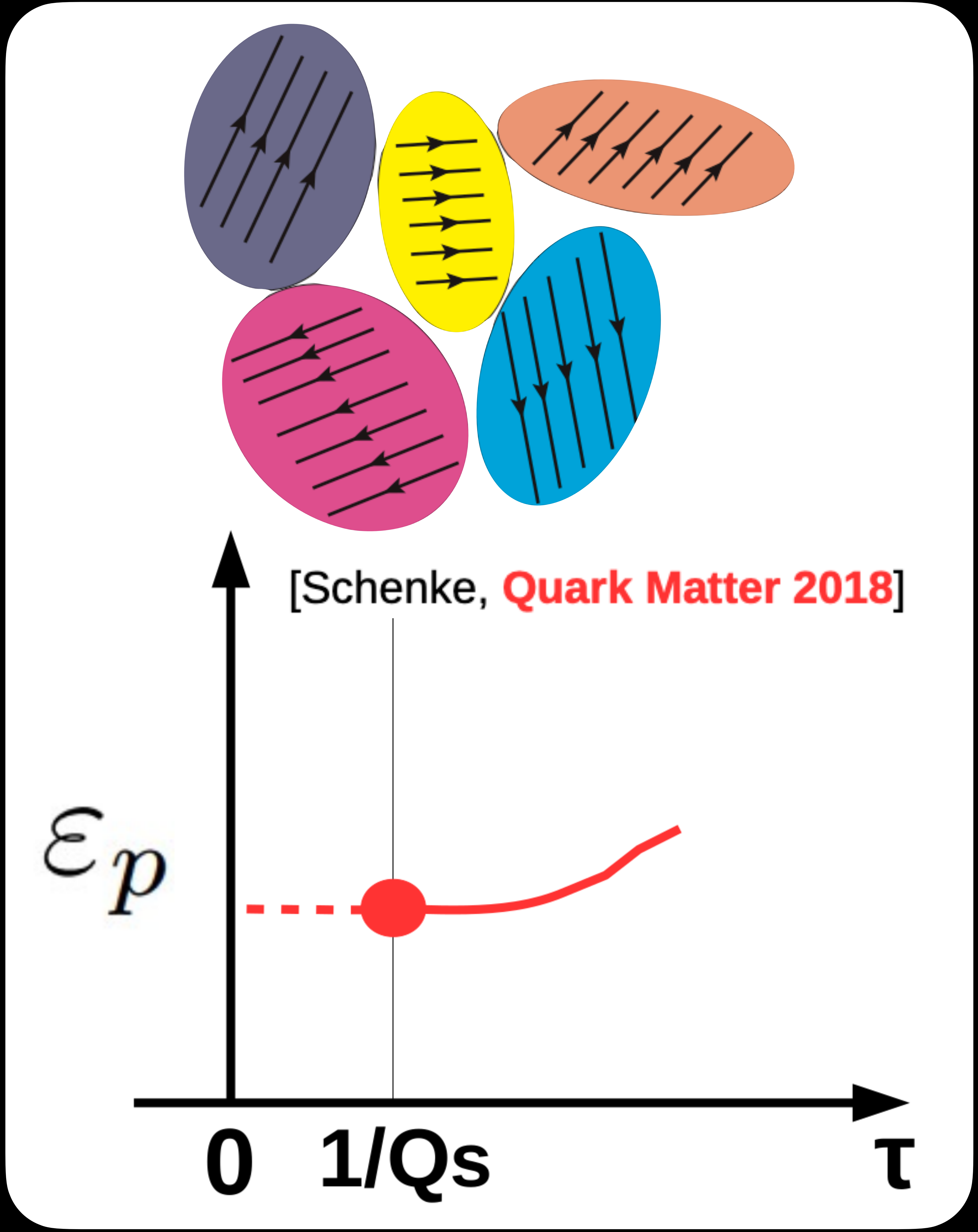
HOW TO ACCESS INITIAL-STATE CORRELATIONS





M. Strickland, Nucl. Phys. A982, 92-98 (2019)

BEYOND GEOMETRIC RESPONSE



B.Schenke, P.Tribedy, R.Venugopalan, PRL108, 252301 (2012), PRC86, 034908 (2012)

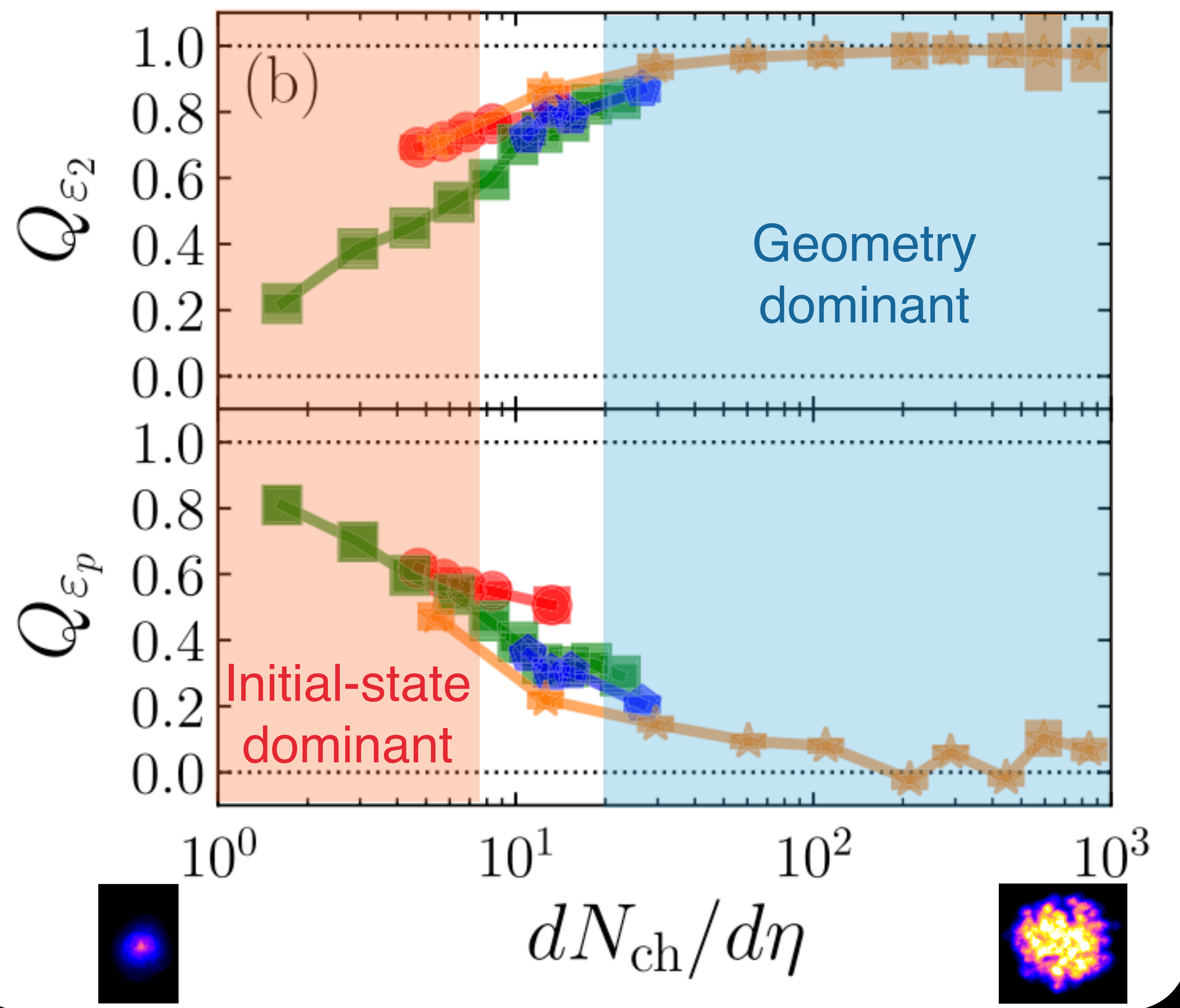
- The Color Glass Condensate (CGC) predicts anisotropic particle productions because of

  1. Local anisotropies in the color fields
  2. Local density gradients
  3. Quantum interference effects

$$\mathcal{E}_p = \varepsilon_p e^{i2\psi_2^p} = \frac{\langle T^{xx} - T^{yy}\rangle + i\langle 2T^{xy}\rangle}{\langle T^{xx} + T^{yy}\rangle}$$

INITIAL STATE ANISOTROPIES VS HYDRODYNAMIC RESPONSE

B. Schenke, C. Shen and P. Tribedy, Phys. Lett. B803, 135322 (2020)



Examine the Pearson correlation between initial state $\mathscr{E}_2$, $\mathscr{E}_p$ and final state V_2 in the model

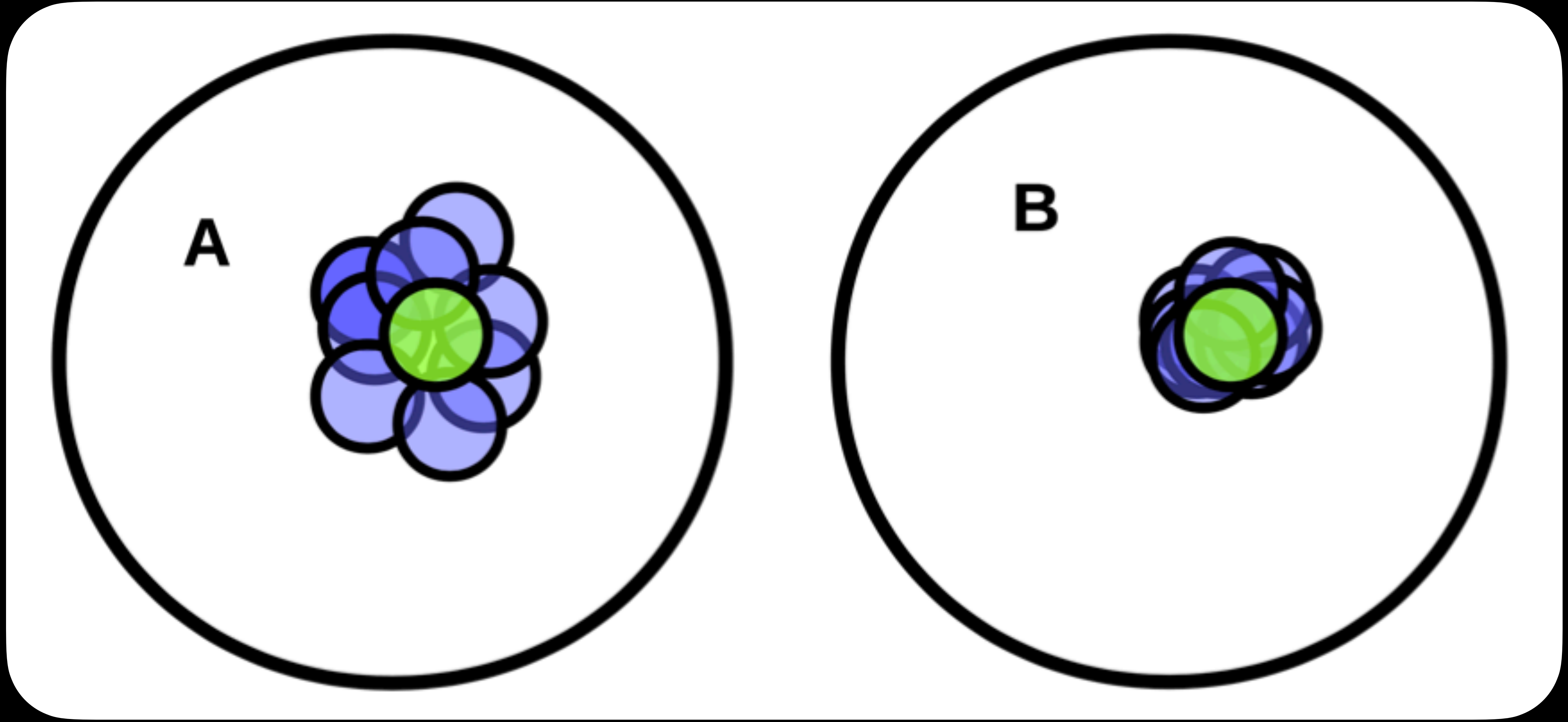
$$Q_\varepsilon = \frac{Re\{\langle \mathscr{E} V_2^* \rangle\}}{\sqrt{\langle |\mathscr{E}|^2 \rangle \langle |V_2|^2 \rangle}}$$

The elliptic flow in low multiplicity events is more strongly correlated with $\mathscr{E}_p$ than $\mathscr{E}_2$

HOW DOES V_2 CORRELATE WITH EVENT SHAPE IN SMALL SYSTEMS?

Geometric Response:

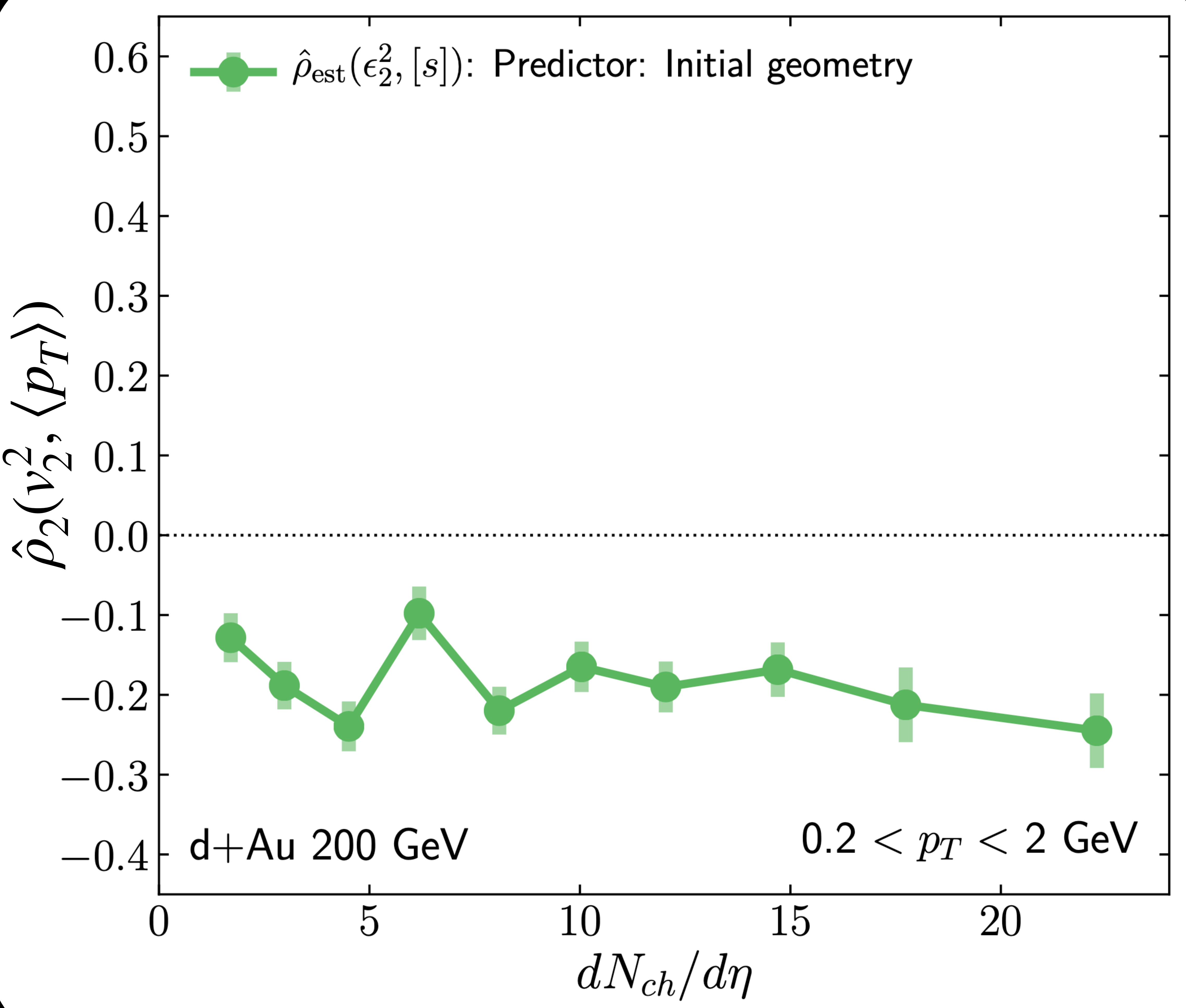
G. Giacalone, B. Schenke and C. Shen, Phys. Rev. Lett. 125, 192301 (2020)



$R(A) > R(B)$ → $\langle p_T \rangle(A) < \langle p_T \rangle(B)$

$\varepsilon_2(A) > \varepsilon_2(B)$ → $v_2(A) > v_2(B)$

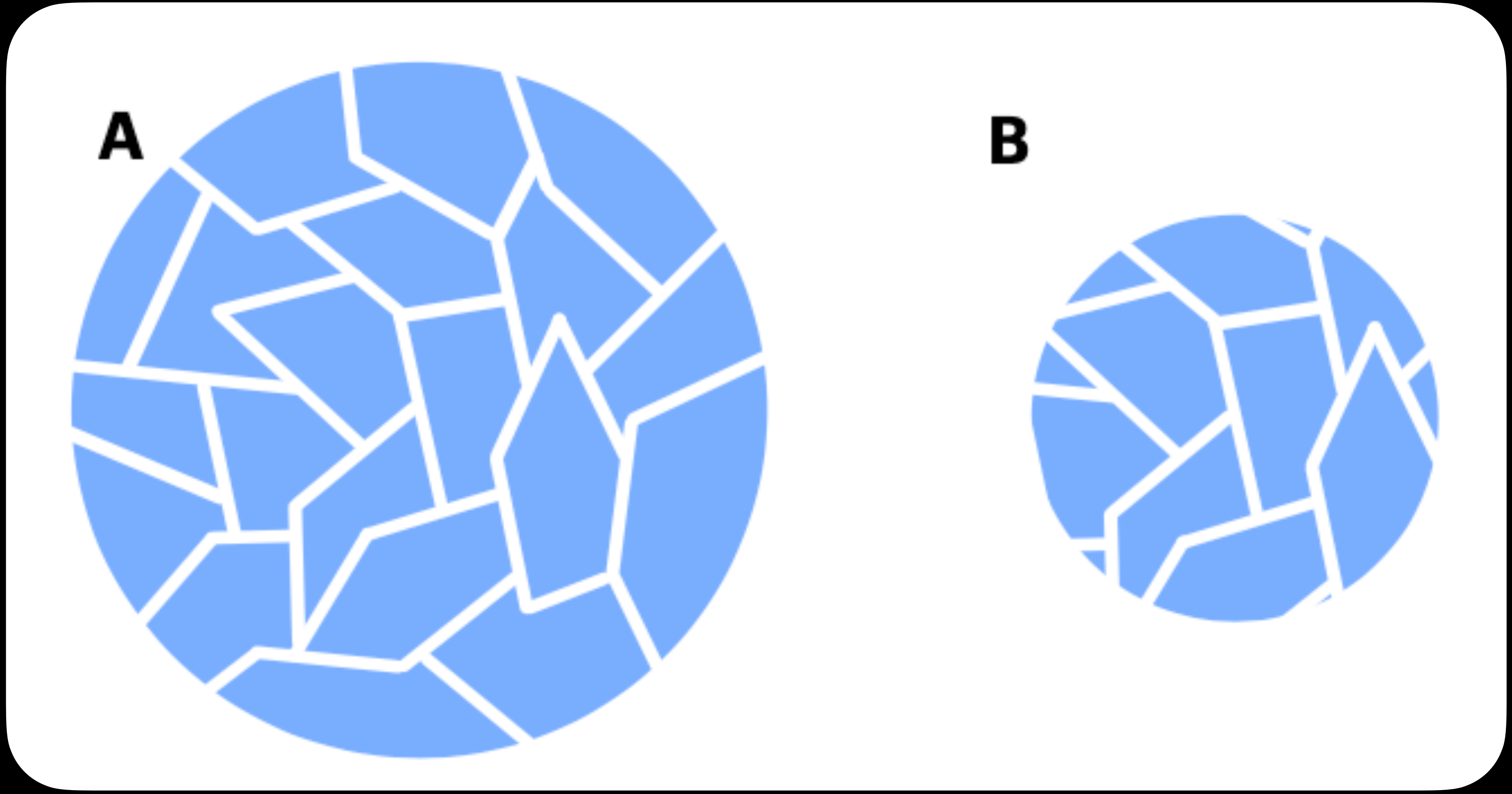
→ v_2 and $\langle p_T \rangle$ are anti-correlated

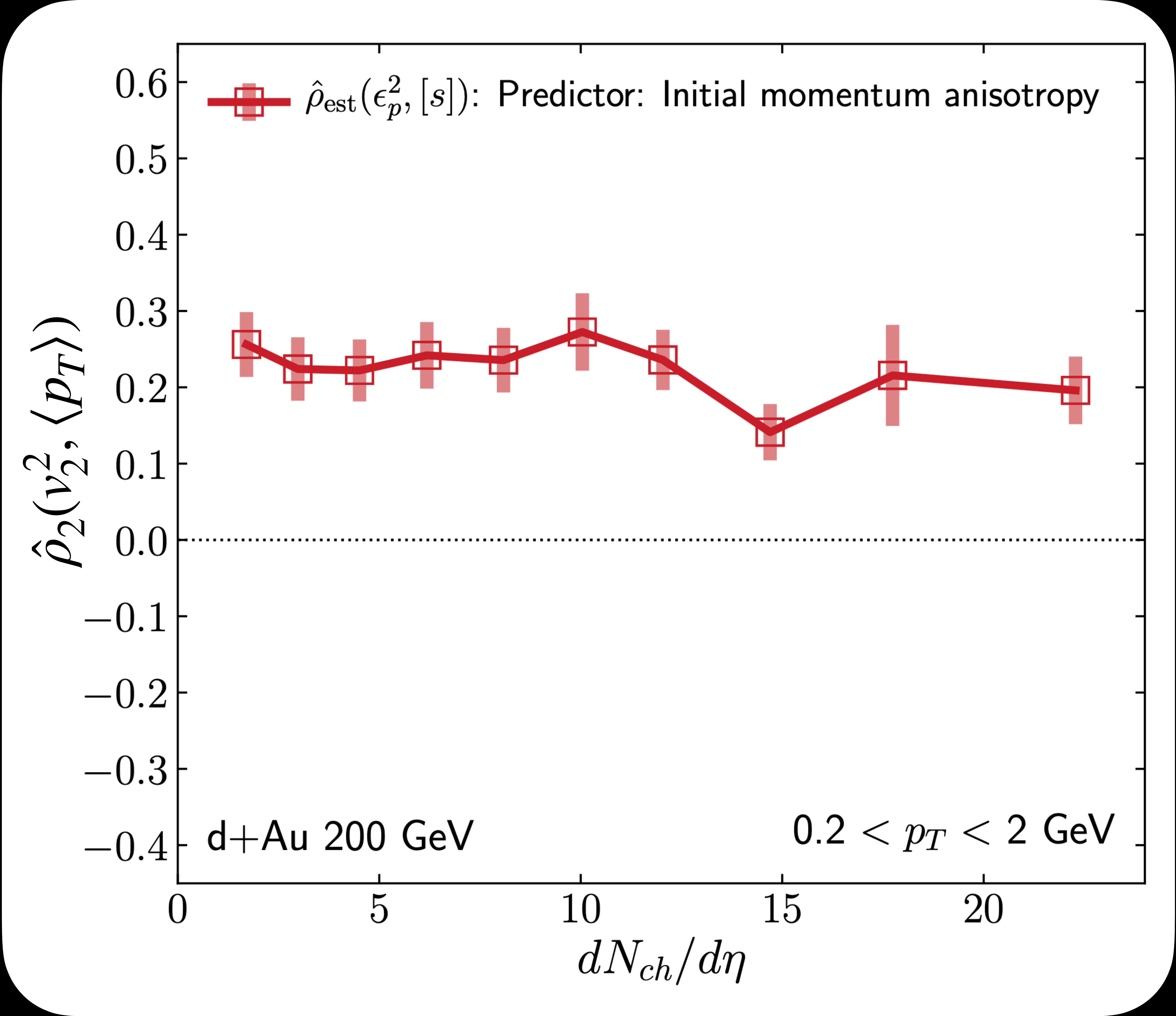


HOW DOES V_2 CORRELATE WITH EVENT SIZE IN SMALL SYSTEMS?

Color Glass Condensate:

G. Giacalone, B. Schenke and C. Shen, Phys. Rev. Lett. 125, 192301 (2020)





$R(A) > R(B)$ ➡ $\langle p_T \rangle (A) < \langle p_T \rangle (B)$

$\varepsilon_p(A) < \varepsilon_p(B)$ ➡ $v_2(A) < v_2(B)$

➡ v_2 and $\langle p_T \rangle$ are correlated

THE FULL PICTURE — WHICH ONE DOMINATES?

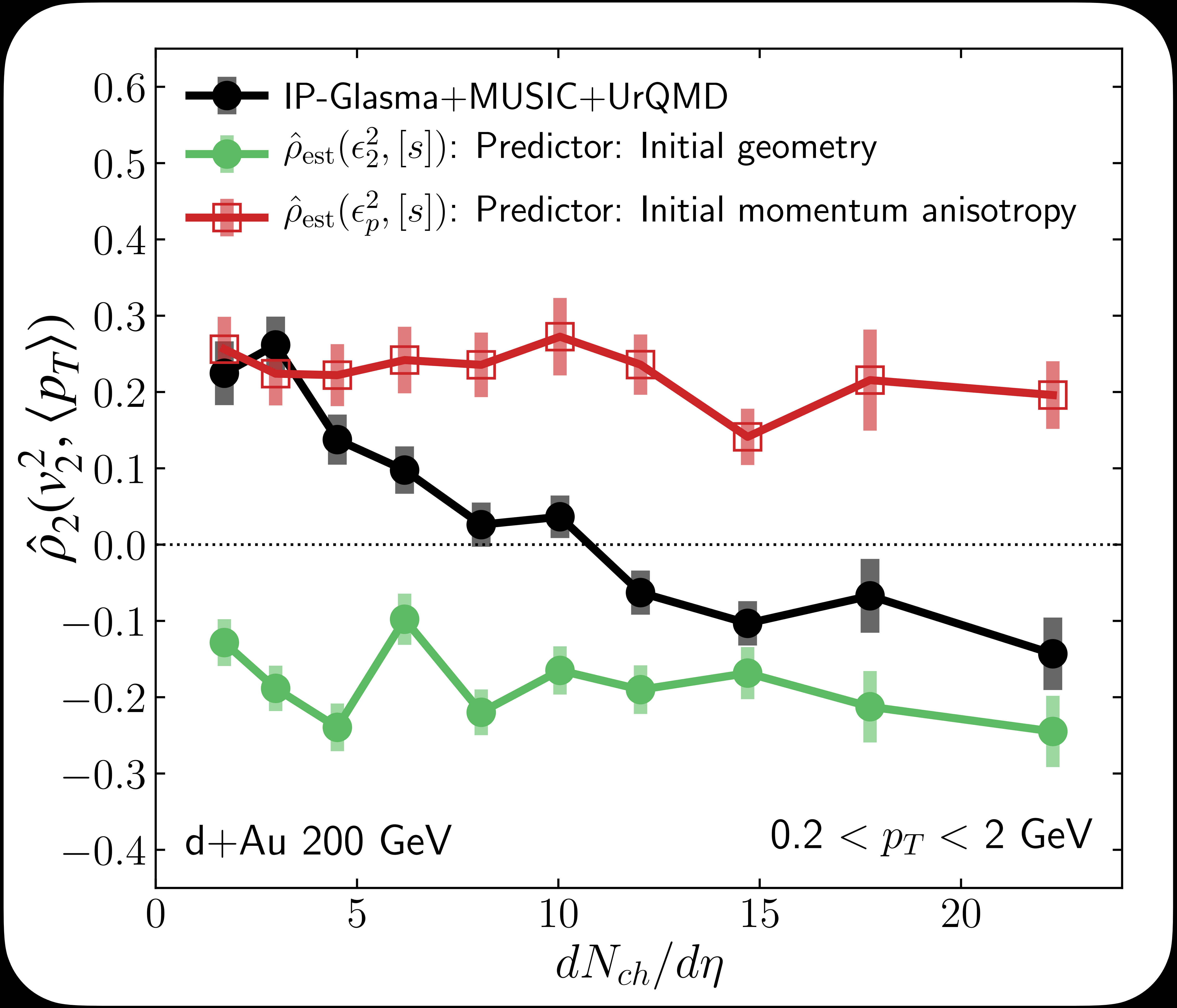
G. Giacalone, B. Schenke and C. Shen, Phys. Rev. Lett. 125, 192301 (2020)

We predict a sign change of the $\hat{\rho}_2$ correlator with multiplicity in p/d+Au collisions at RHIC and p+Pb collisions at LHC

For $dN^{ch}/d\eta \lesssim 10$, initial state correlation dominates

For $dN^{ch}/d\eta \gtrsim 10$, final state response to geometry dominates

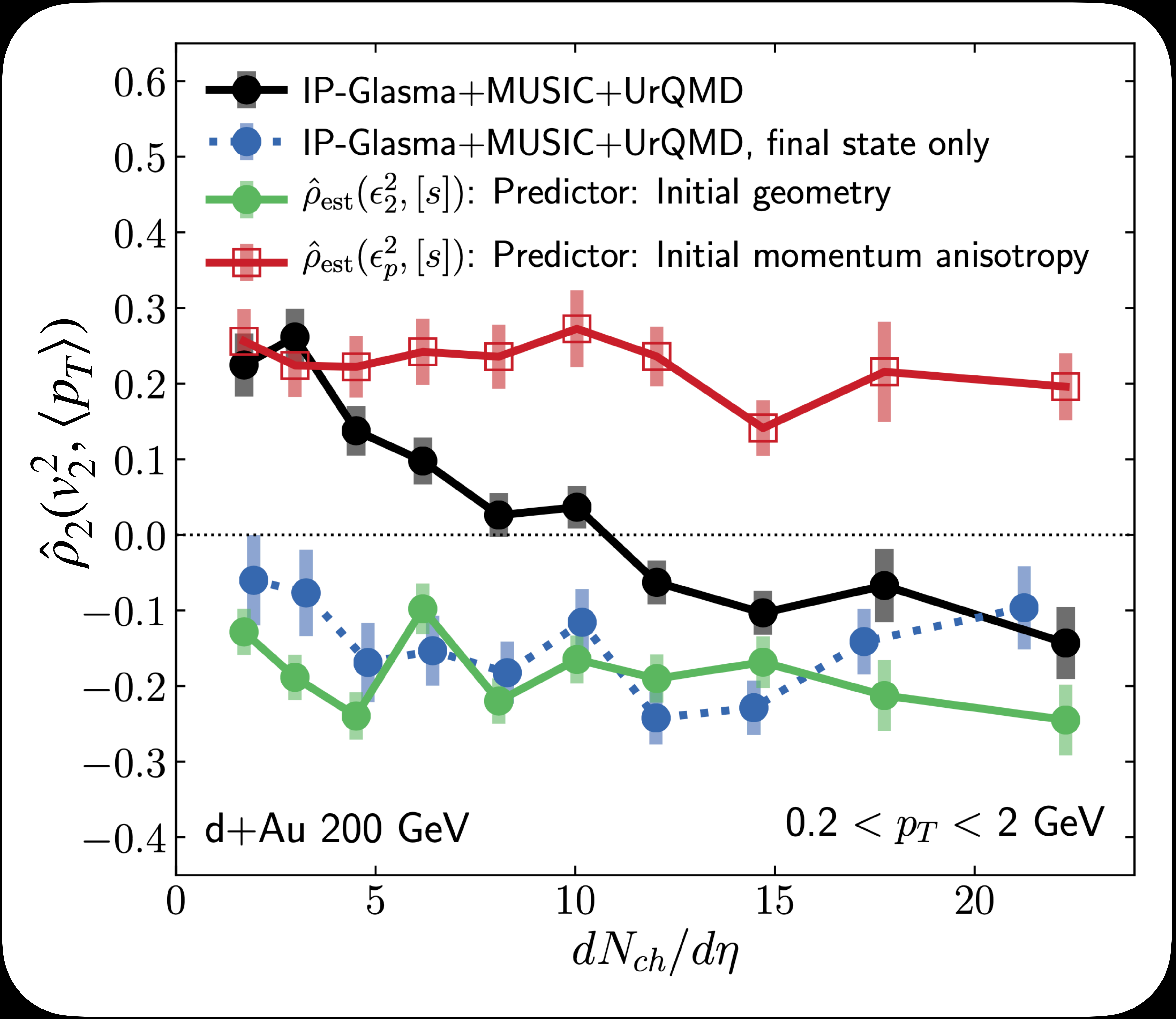
The full correlation smoothly move from one initial-state predictor to the other



THE FULL PICTURE — WHICH ONE DOMINATES?

G. Giacalone, B. Schenke and C. Shen, Phys. Rev. Lett. 125, 192301 (2020)

Setting the initial momentum anisotropy to zero, our results follow the geometric predictor for all $dN^{ch}/d\eta$ as expected (no sign change)



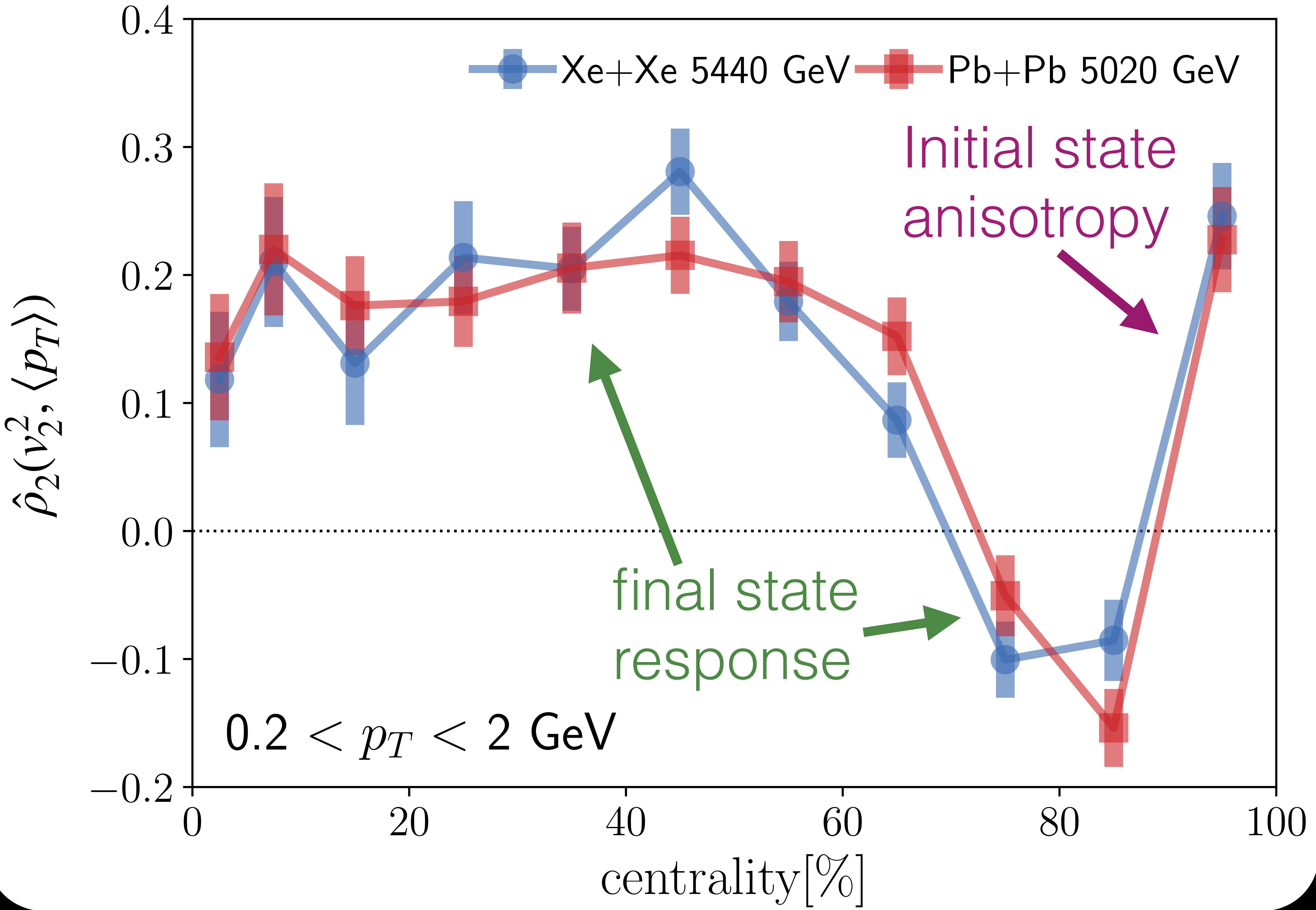
PUSHING HEAVY-ION COLLISIONS TO THE EXTREME

Final state effects are strong in heavy-ion collisions at the LHC up to 80% in centrality

Pushing $\hat{\rho}_2$ beyond 90% centrality at LHC also can reveal the initial state momentum anisotropy!

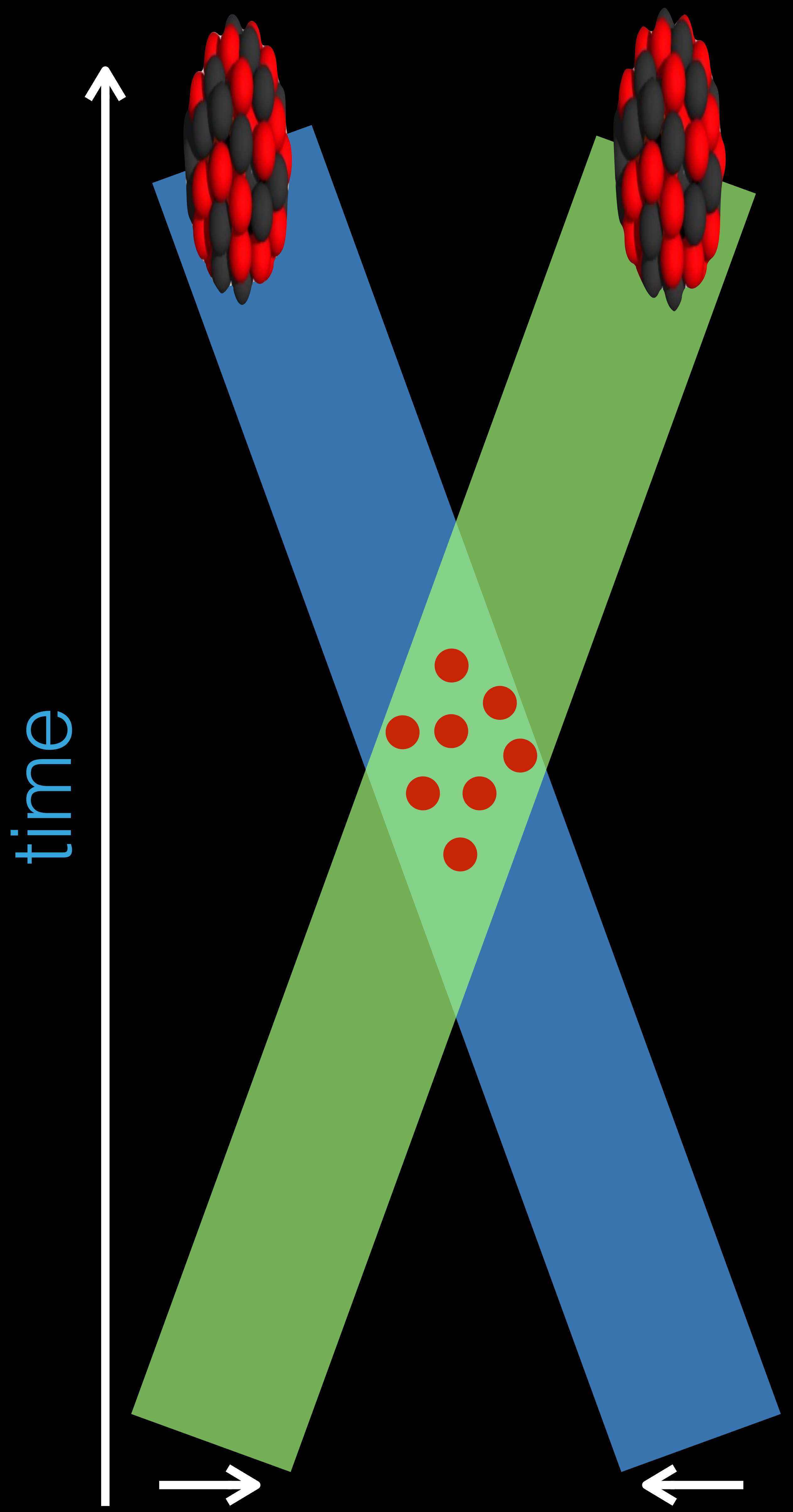
Our model predicts the sign of $\hat{\rho}_2$ changes twice in Pb+Pb and Xe+Xe collisions at the LHC

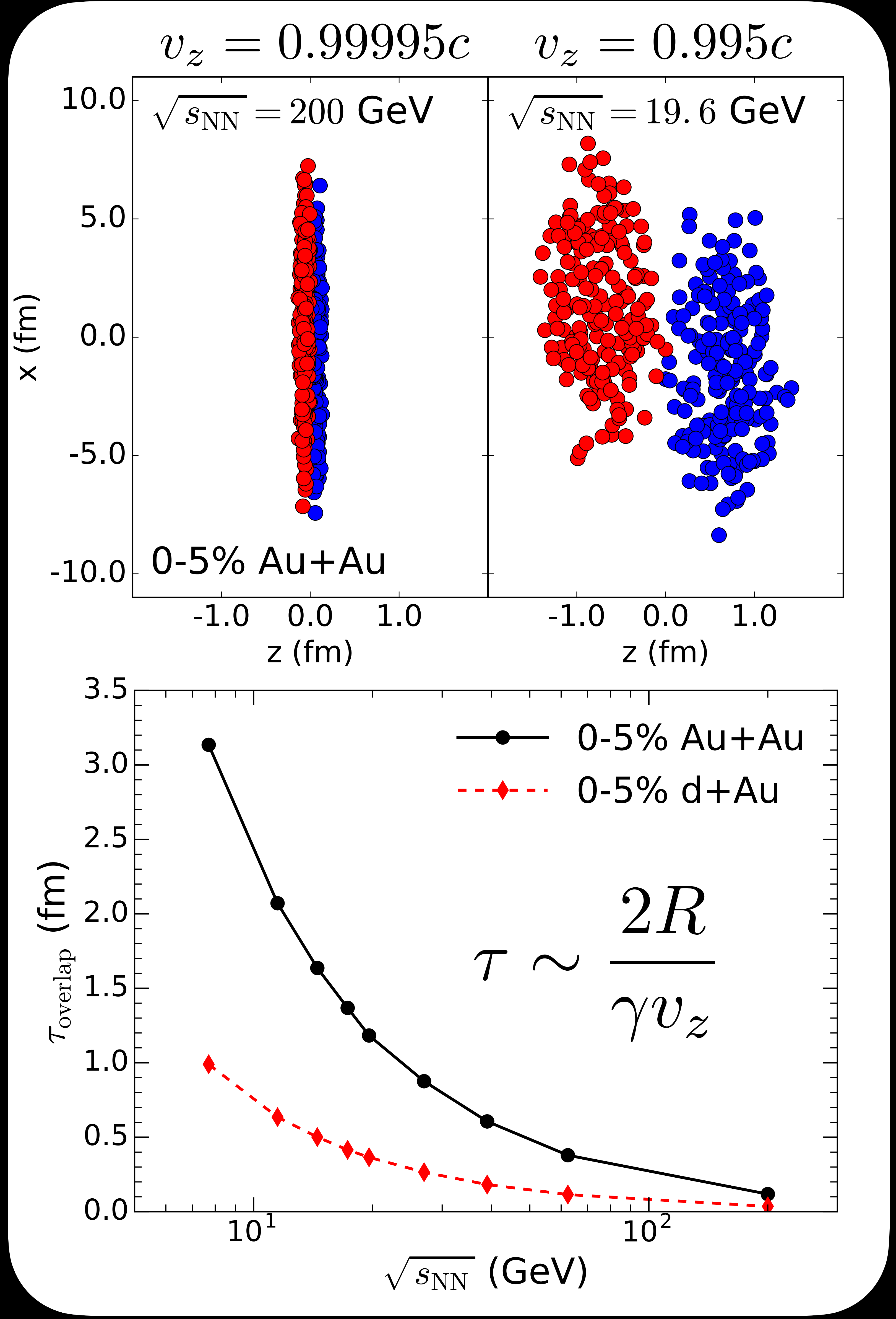
G. Giacalone, B. Schenke and C. Shen, Phys. Rev. Lett. 125, 192301 (2020)



MOVING FORWARD WITH FULL 3D DYNAMICS

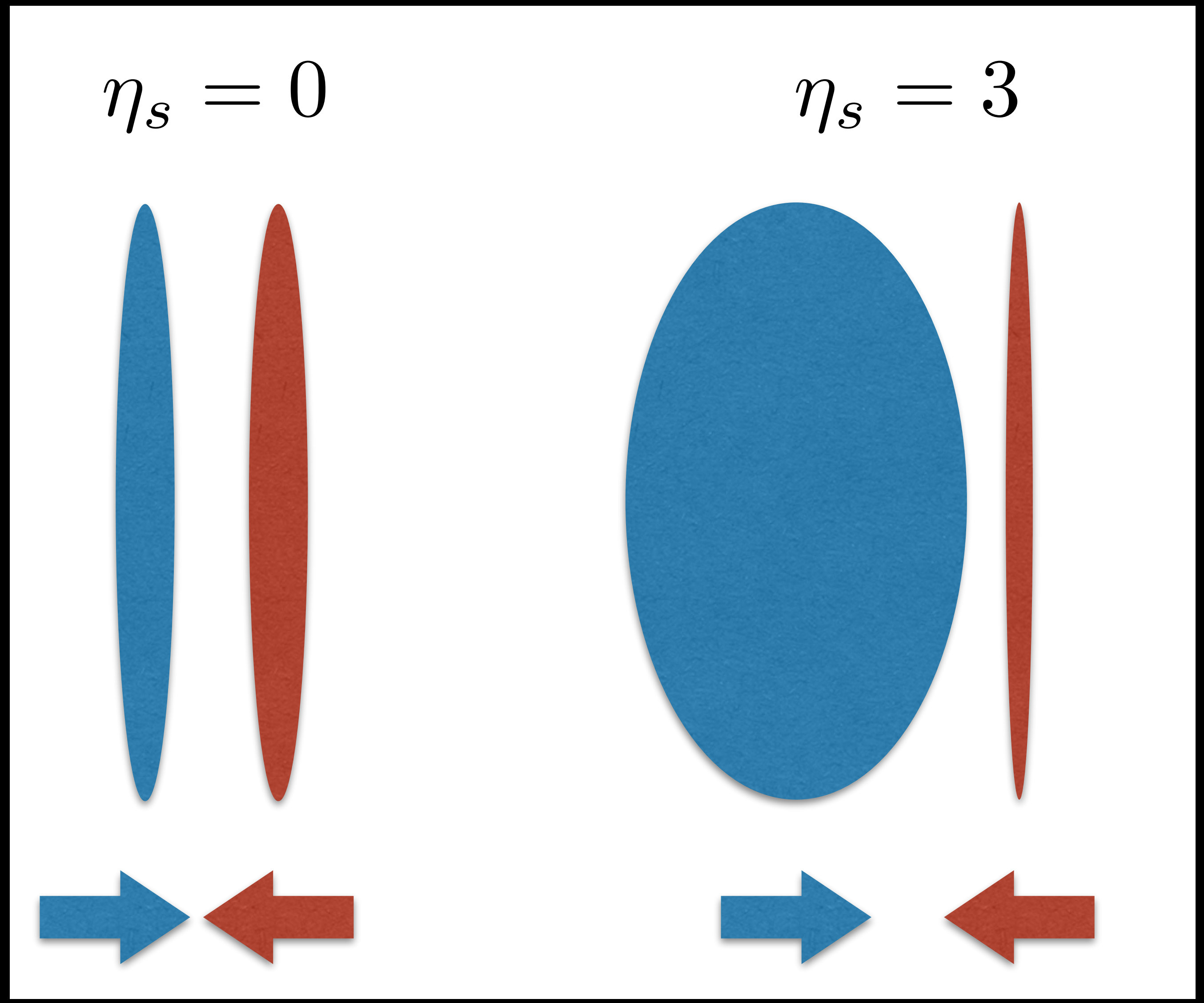
3D DYNAMICS BEYOND THE BJORKEN PARADIGM

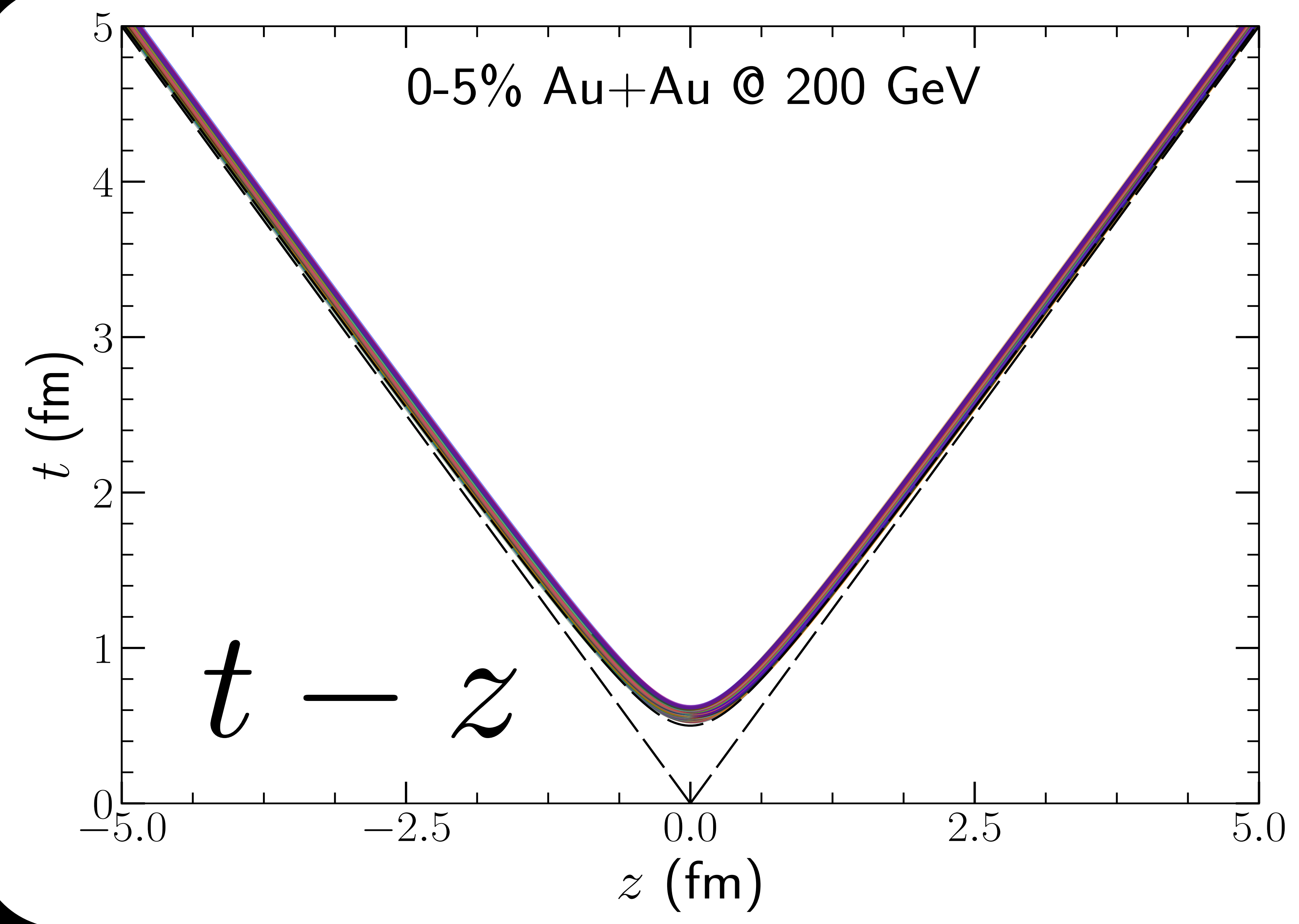


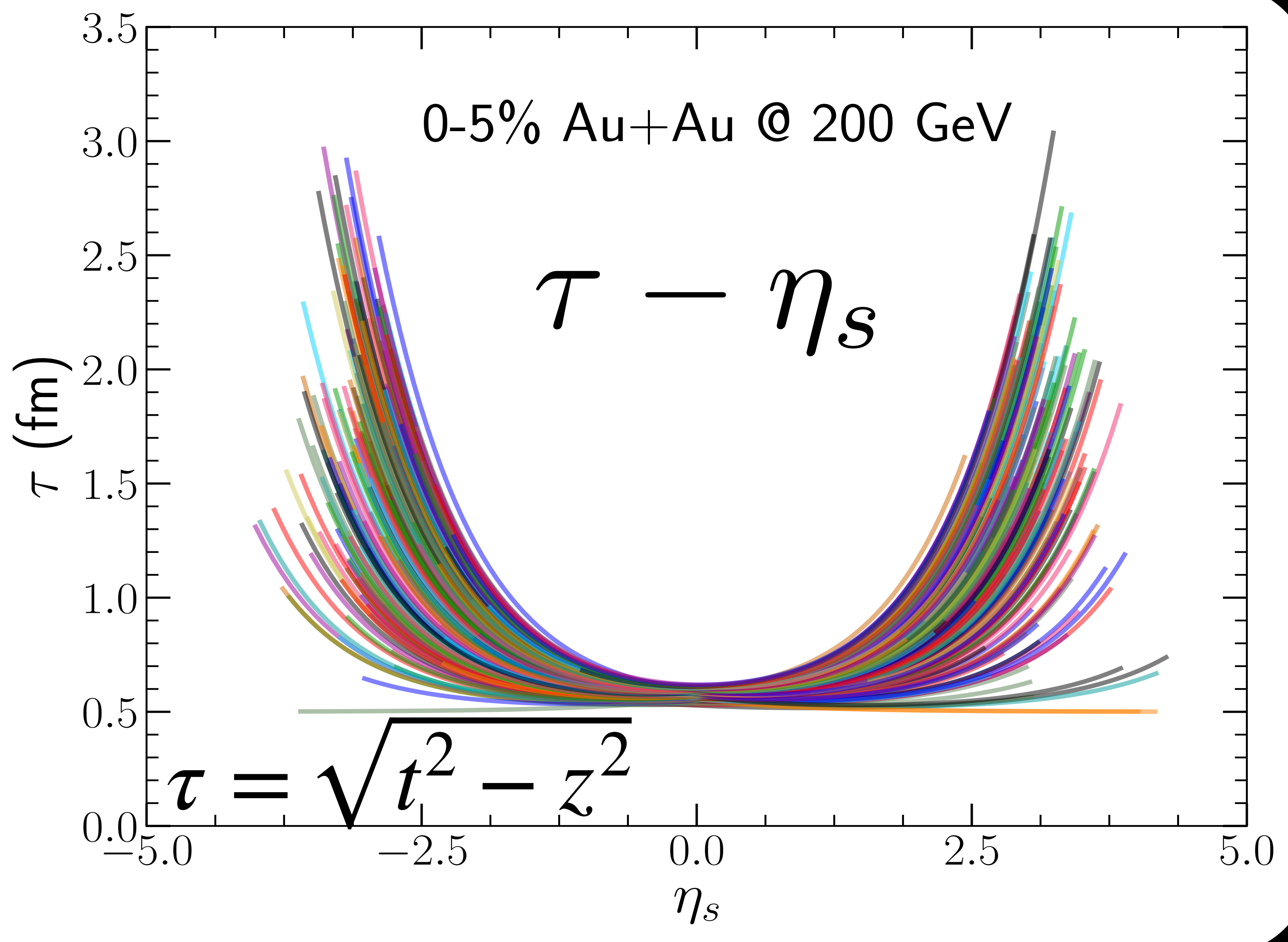


- Geometry-Based initial conditions
  - C. Shen and S. Alzhrani, Phys. Rev. C 102, 014909 (2020)
  - X. Y. Wu, G. Y. Qin, L. G. Pang and X. N. Wang, arXiv:2107.04949 [hep-ph]
- Classical string-based initial conditions
  - A. Bialas, A. Bzdak and V. Koch, Acta Phys. Polon. B49 (2018)
  - C. Shen and B. Schenke, Phys.Rev. C97 (2018) 024907
- Transport model based initial conditions
  - I. A. Karpenko, P. Huovinen, H. Petersen and M. Bleicher, Phys. Rev. C91 (2015) 064901
  - L. Du, U. Heinz and G. Vujanovic, Nucl. Phys. A982 (2019) 407-410
- Color Glass Condensate based models
  - M. Li and J. Kapusta, Phys. Rev. C 99, 014906 (2019)
  - L. D. McLerran, S. Schlichting and S. Sen, Phys. Rev. D 99, 074009 (2019)
  - M. Martinez, M. D. Sievert, D. E. Wertepny and J. Noronha-Hostler, arXiv:1911.10272 + arXiv:1911.12454 [nucl-th]
- Holographic approach at intermediate coupling
  - M. Attems, et al., Phys.Rev.Lett. 121 (2018), 261601

STRINGS' SPACE-TIME DISTRIBUTION



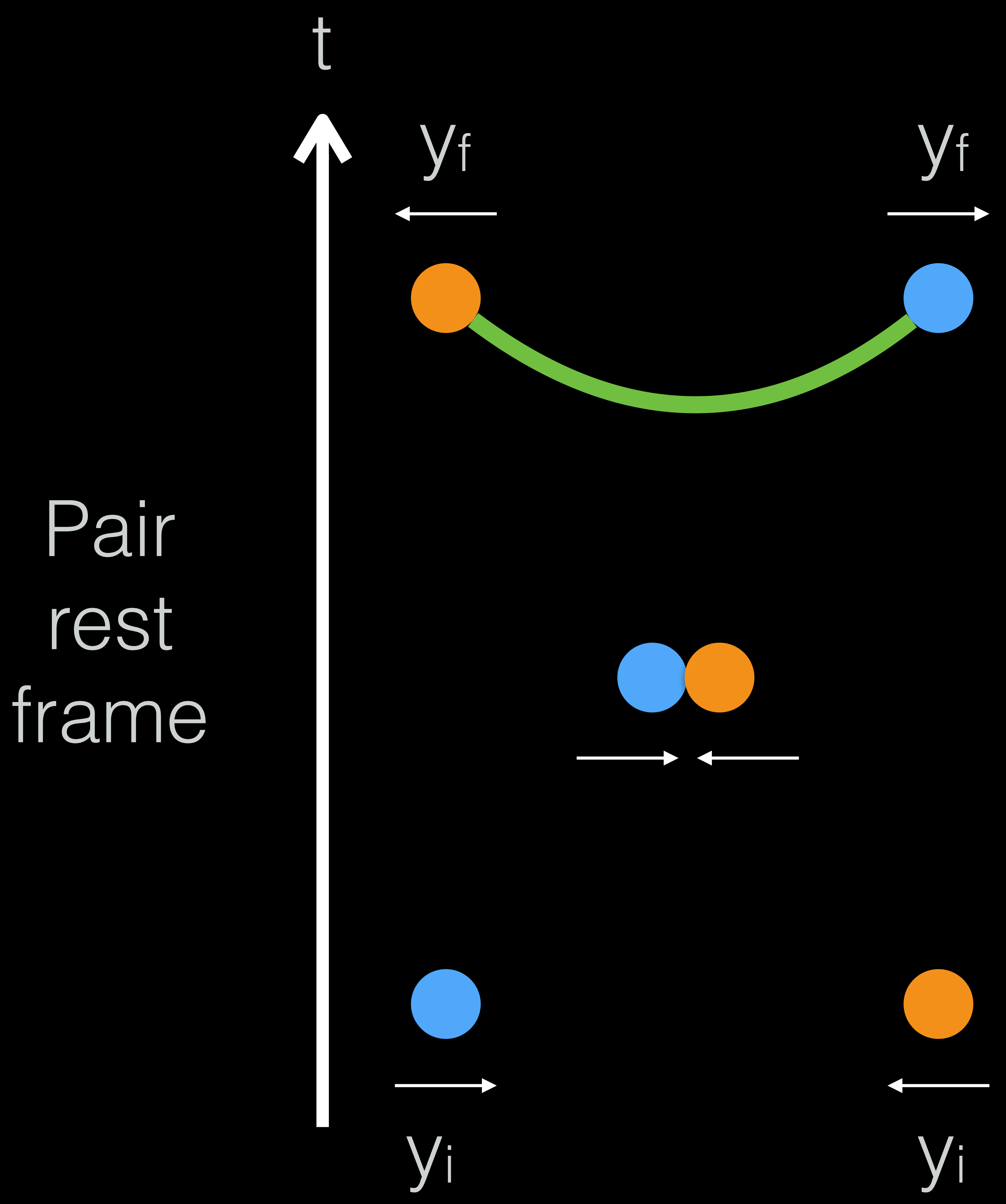




- The finite thickness of the projectile matters at forward rapidity in high energy

THE 3D MC-GLAUBER + STRING MODEL

C. Shen and B. Schenke, Phys.Rev. C97 (2018) 024907



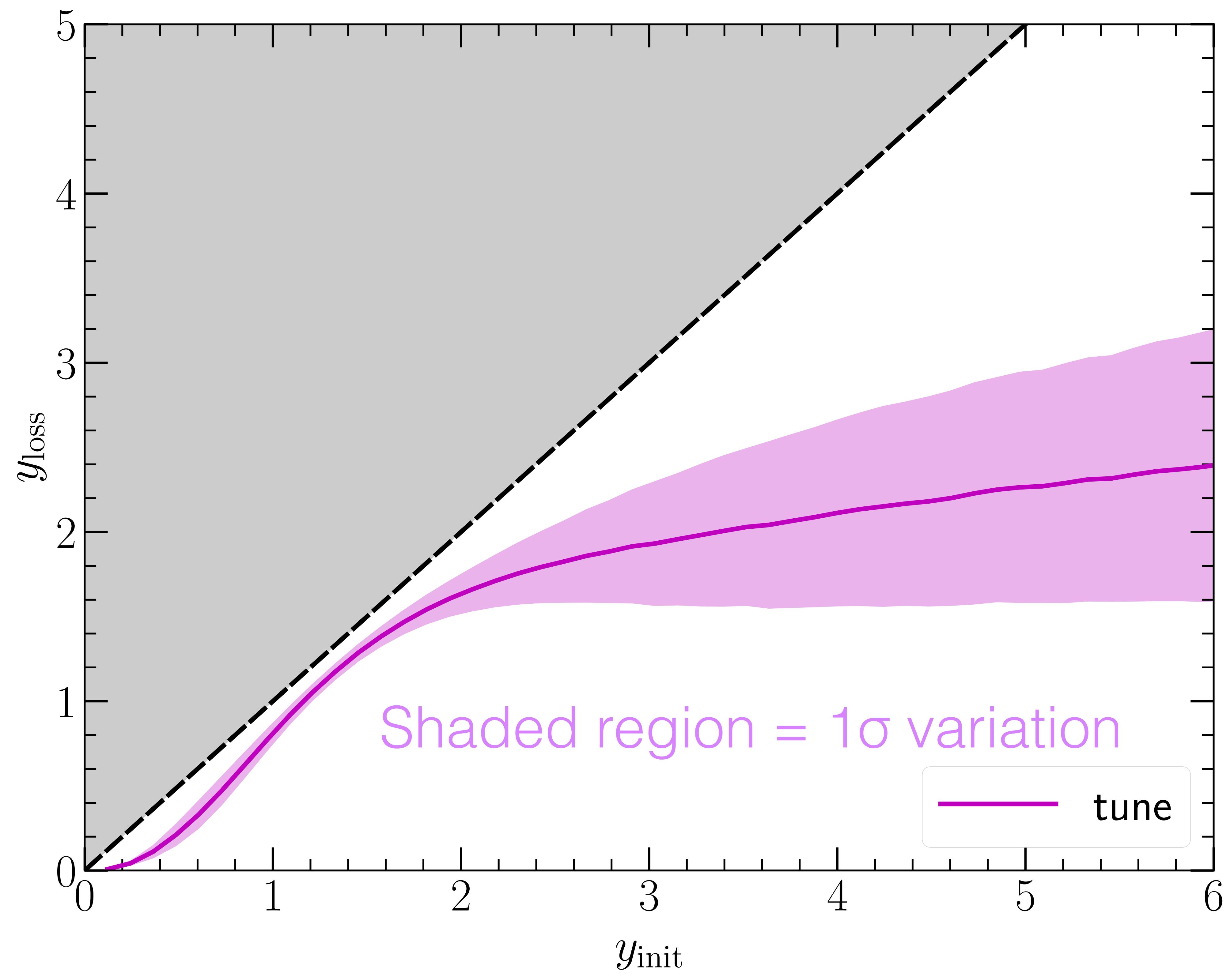
- Collision geometry is determined by MC-Glauber model
- 3 valence quarks are sampled from PDF and randomly picked to lose energy during a collision $\left(\sum_i x_i \leq 1\right)$
- Incoming quarks are decelerated with a classical string tension,

$$dp^\mu = -T^{\mu\nu} d\Sigma_\nu$$

$$T^{\mu\nu} = \begin{pmatrix} \sigma & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\sigma \end{pmatrix} \qquad d\Sigma_\nu = (dz, 0, 0, -dt)$$

PARAMETERIZE THE VALENCE QUARK ENERGY LOSS

B. Schenke and C. Shen, in preparation



$$\langle y_{\rm loss} \rangle = A y_{\rm init}^{\alpha_2} [\tanh(y_{\rm init})]^{\alpha_1 - \alpha_2}$$

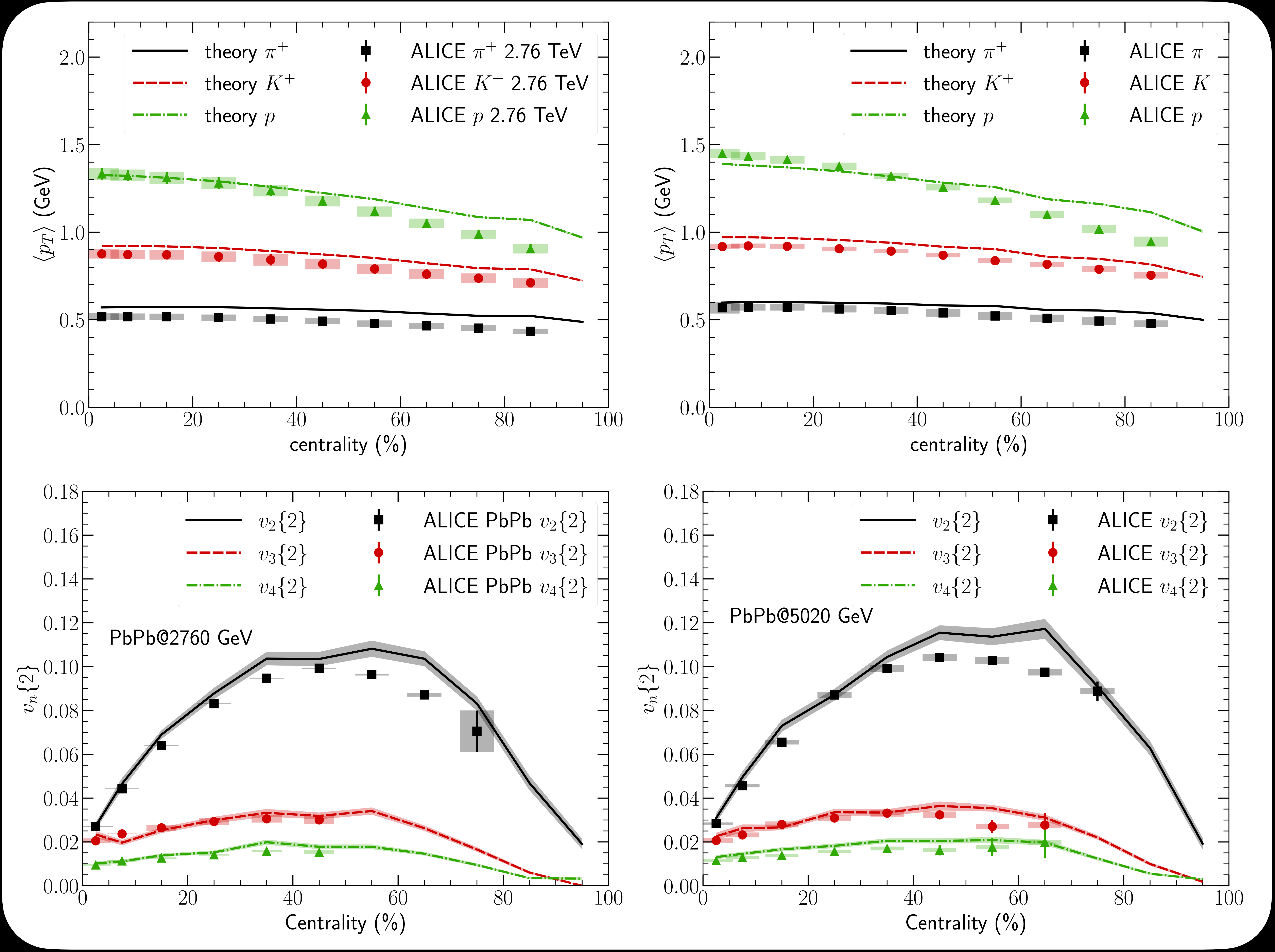
- A: the slope
- At small y: $\langle y_{\rm loss} \rangle \propto y_{\rm init}^{\alpha_1}$
- At large y: $\langle y_{\rm loss} \rangle \propto y_{\rm init}^{\alpha_2}$
- Std of $y_{\rm loss}$ fluctuations: σ_y ($y_{\rm loss} \in [0, y_{\rm init}]$)

PARTICLE PRODUCTION AT THE LHC ENERGIES

B. Schenke and C. Shen, in preparation

- The centrality and rapidity dependence of Pb+Pb collisions are reasonably reproduced; They probe initial energy loss at high rapidity regions

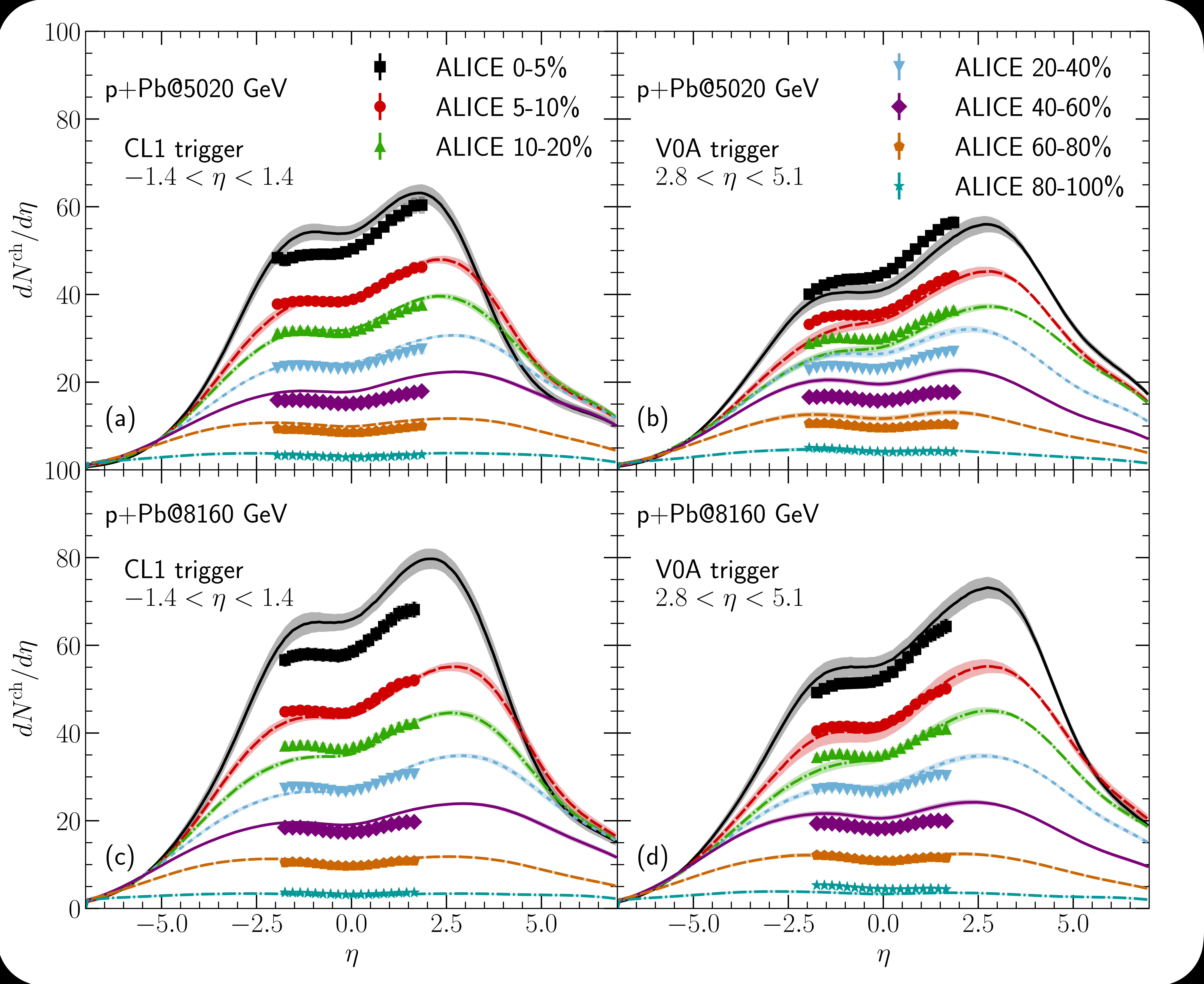
FLOW OBSERVABLES AT LHC ENERGIES



B. Schenke and C. Shen, in preparation

- Mid-rapidity radial flow is slightly larger than the identified particles' mean pT measurements suggest
- Anisotropic flow coefficients are well predicted from our 3D hybrid model
- Flow fluctuations at different rapidity is underway

P+PB COLLISIONS AT LHC

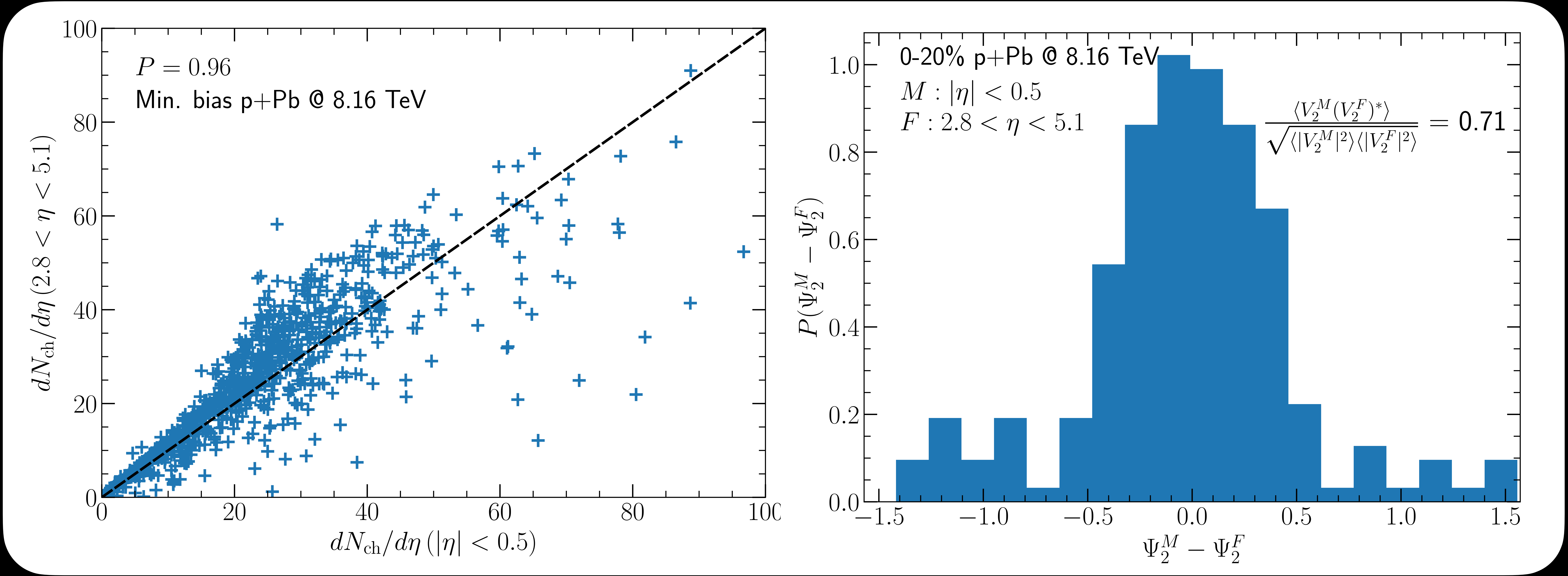


C. Shen and B. Schenke, in preparation

- Model prediction gives reasonable description of particle pseudo-rapidity distributions in p+Pb collisions at 5.02 and 8.16 TeV using two centrality triggers
- With the 3D model, we can study the different event classification with centrality triggers at different rapidity windows

UNLOCK FORWARD TO CENTRAL CORRELATION

C. Shen and B. Schenke, in preparation



- Decorrelation of particle multiplicity between the ALICE V0A and the midrapidity region is important for centrality selection
- The event-plane angle at the ALICE V0A decorrelates with the mid-rapidity elliptic flow vector

SUMMARY

- Dynamical frameworks are effective to understand particle production and flow in relativistic heavy-ion collisions

    First principles inputs from lattice QCD for EoS

    Elucidating the initial stopping and QGP transport properties

- Subnucleon scale fluctuations are essential for v_n in proton-nucleus collisions
- Peripheral AA, pA, and pp collisions can systematically study the $\hat{\rho}_2(v_2^2, \langle p_T \rangle)$ correlations to reveal initial-state momentum anisotropy
- New development of the 3D framework enables us to quantitatively study particle production and flow correlation in rapidity

    Consistent 3D dynamical description of pp, pA, and AA collisions from few GeV to TeV in collision energy