# Unique physics opportunities with the STAR forward upgrade: A heavy ion perspective

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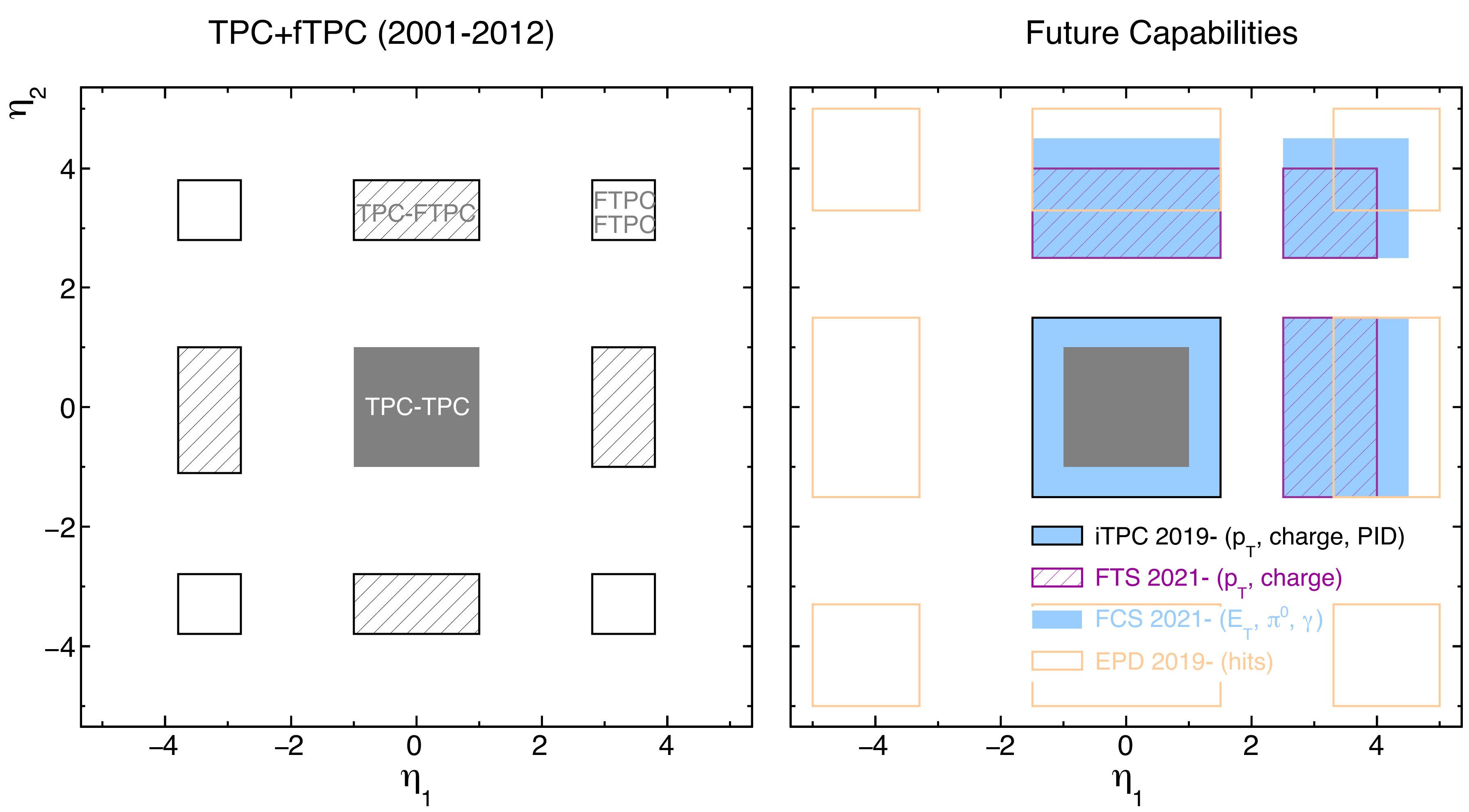
BROOKHAVEN NATIONAL LABORATORY

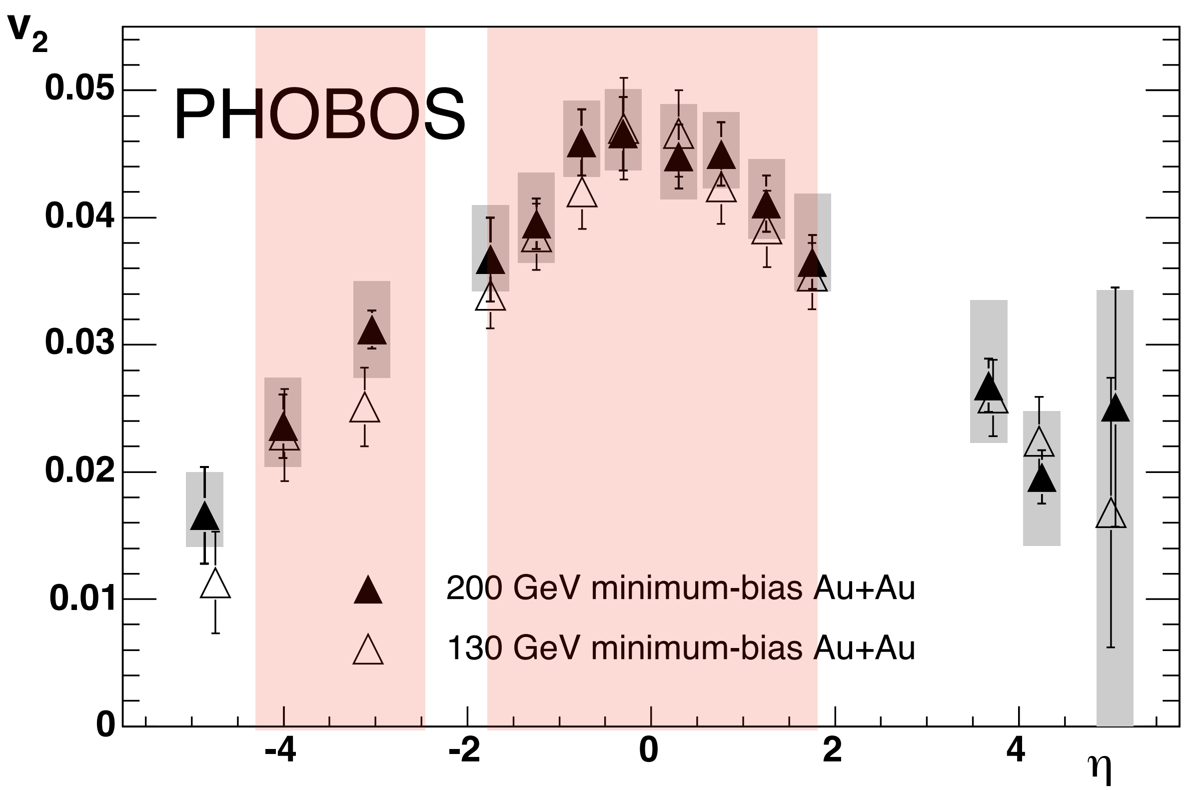
STAR Forward Upgrade Workshop, Shandong University, Qingdao, China, May 7-8, 2019



# Why forward upgrade at RHIC is unique ?

At RHIC it is possible to build detectors that can cover up to beam rapidity and study many unexplored physics

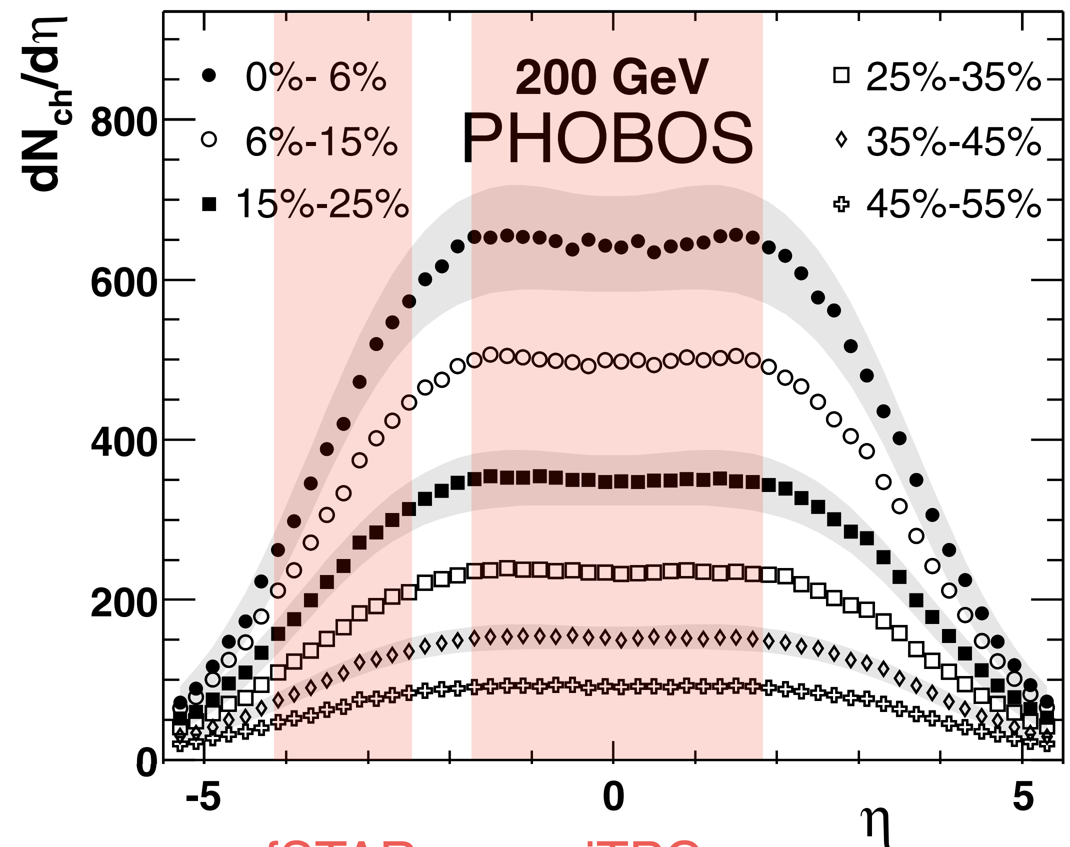
Phys Rev C 72, 051901(R) (2005)




fSTAR iTPC

Charged hadrons flow

Phys. Rev. Lett. 91, 052303 (2003)



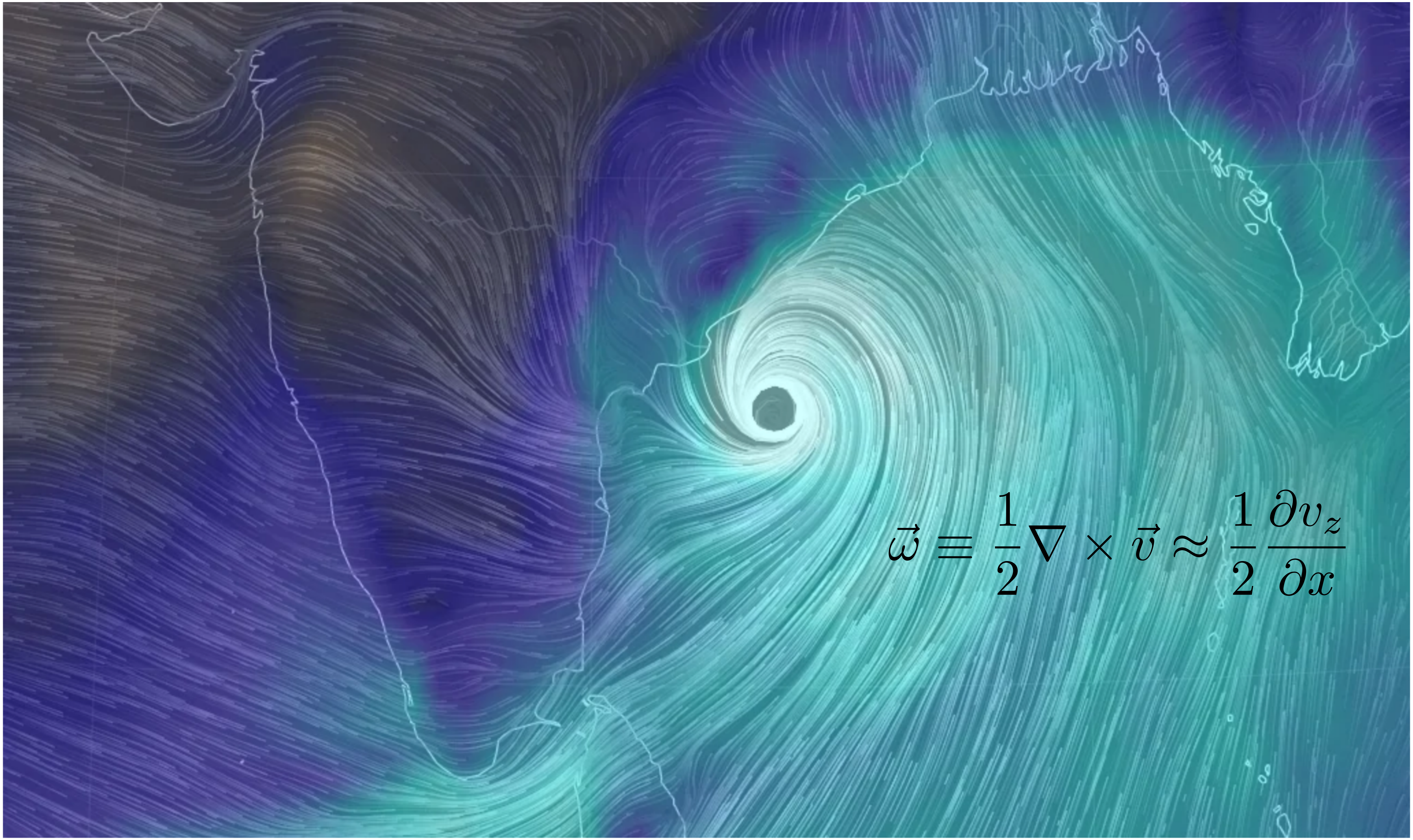

fSTAR iTPC

Charged hadrons multiplicity

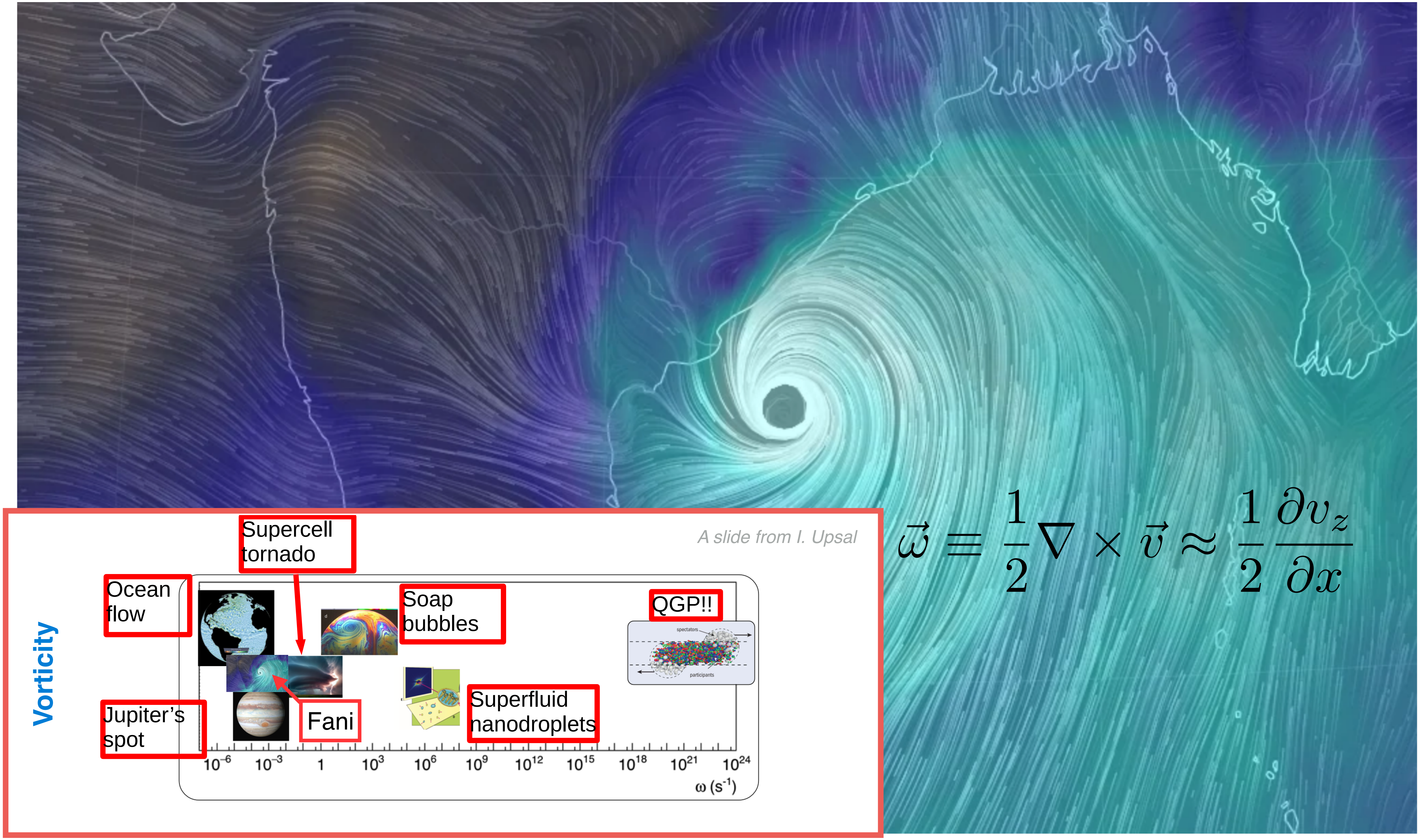
Previous measurements have large uncertainties & limited capabilities, therefore fSTAR will open many new possibilities

# Vortical and Chiral Effects

# Cyclone “Fani” : Last week in India



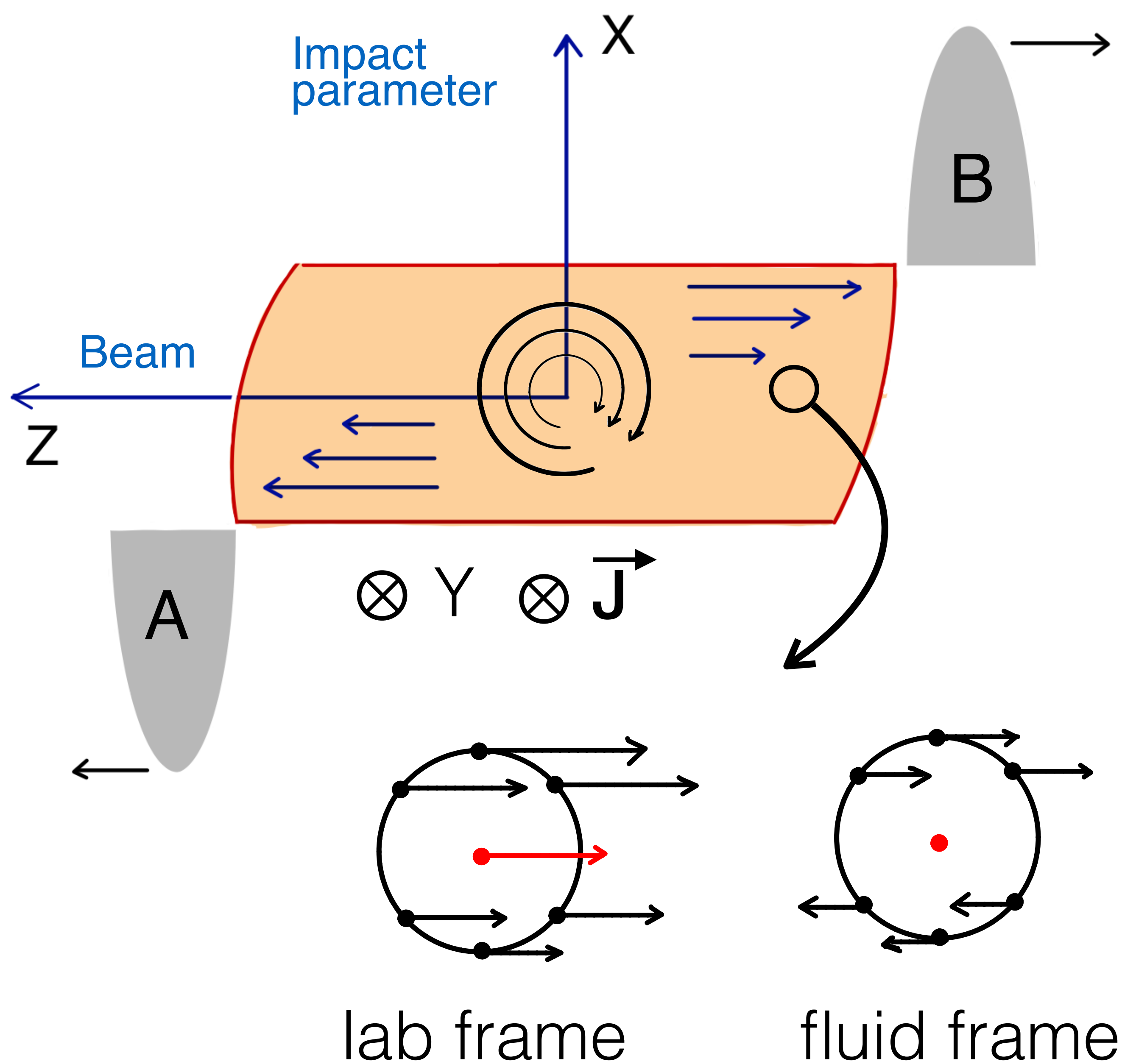
# Cyclone “Fani” : Last week in India




$$\vec{\omega} \equiv \frac{1}{2}\nabla \times \vec{v} \approx \frac{1}{2}\frac{\partial v_z}{\partial x}$$

# Angular momentum in HICs

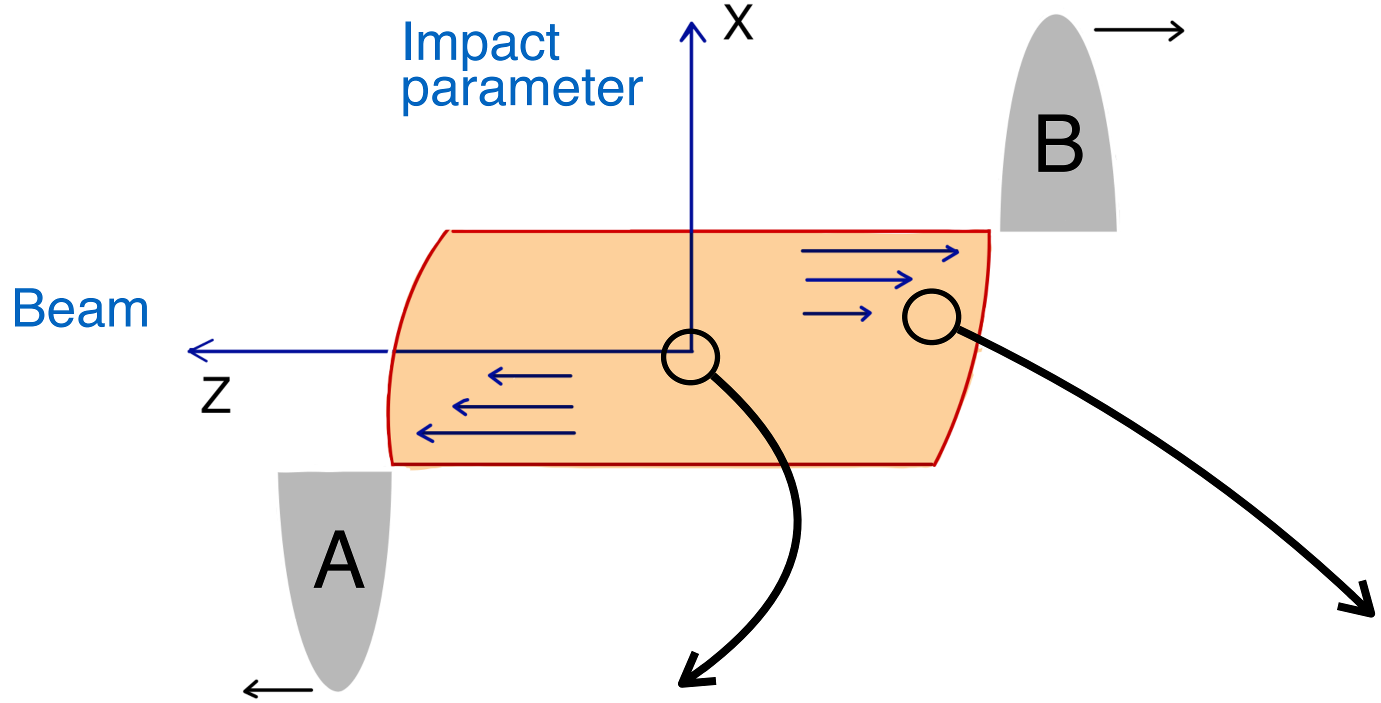
Larger gradient in forward rapidity makes it ideal to study vortical effects




Vorticity:

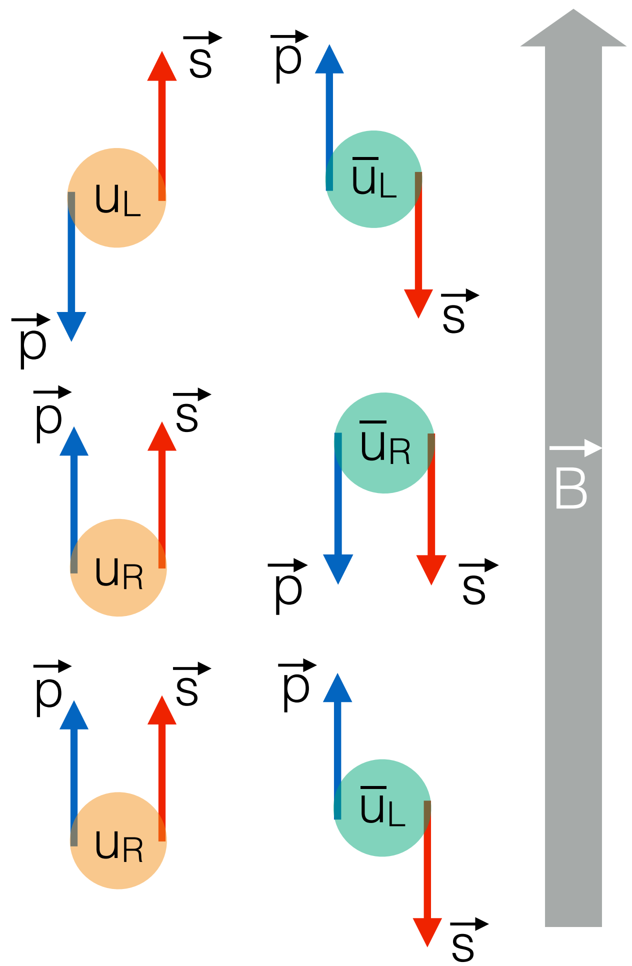
$$\vec{\omega} \equiv \frac{1}{2}\nabla \times \vec{v} \approx \frac{1}{2}\frac{\partial v_z}{\partial x}$$

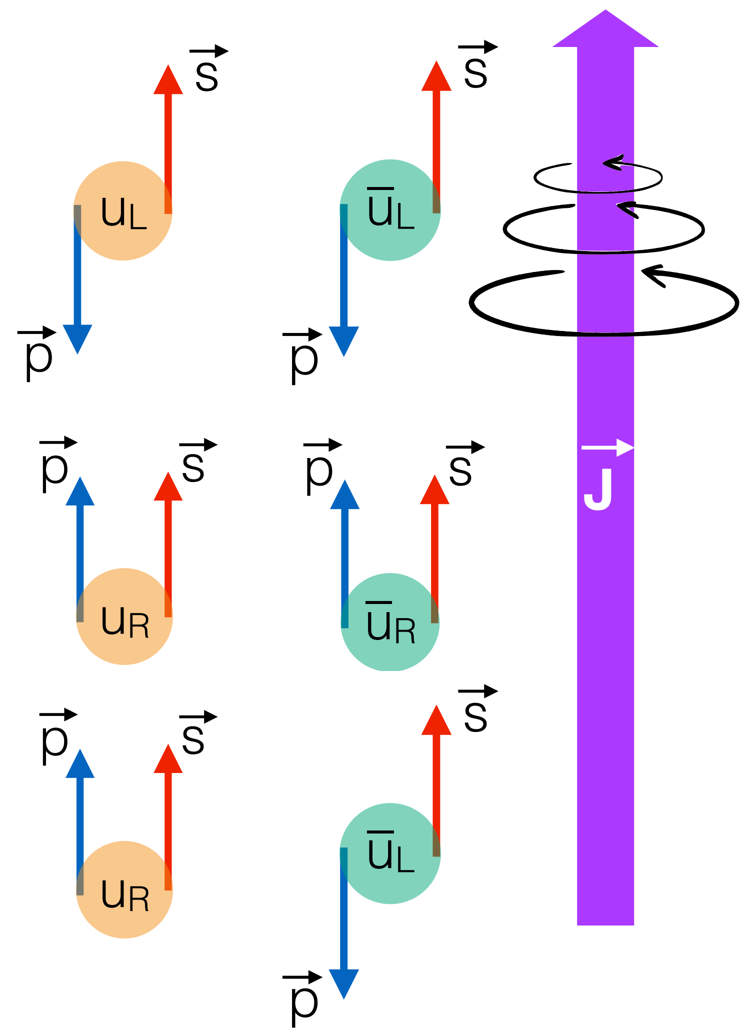
# Global Polarization & CME




Change of rapidity will affect Magnetic polarization and spin polarization differently

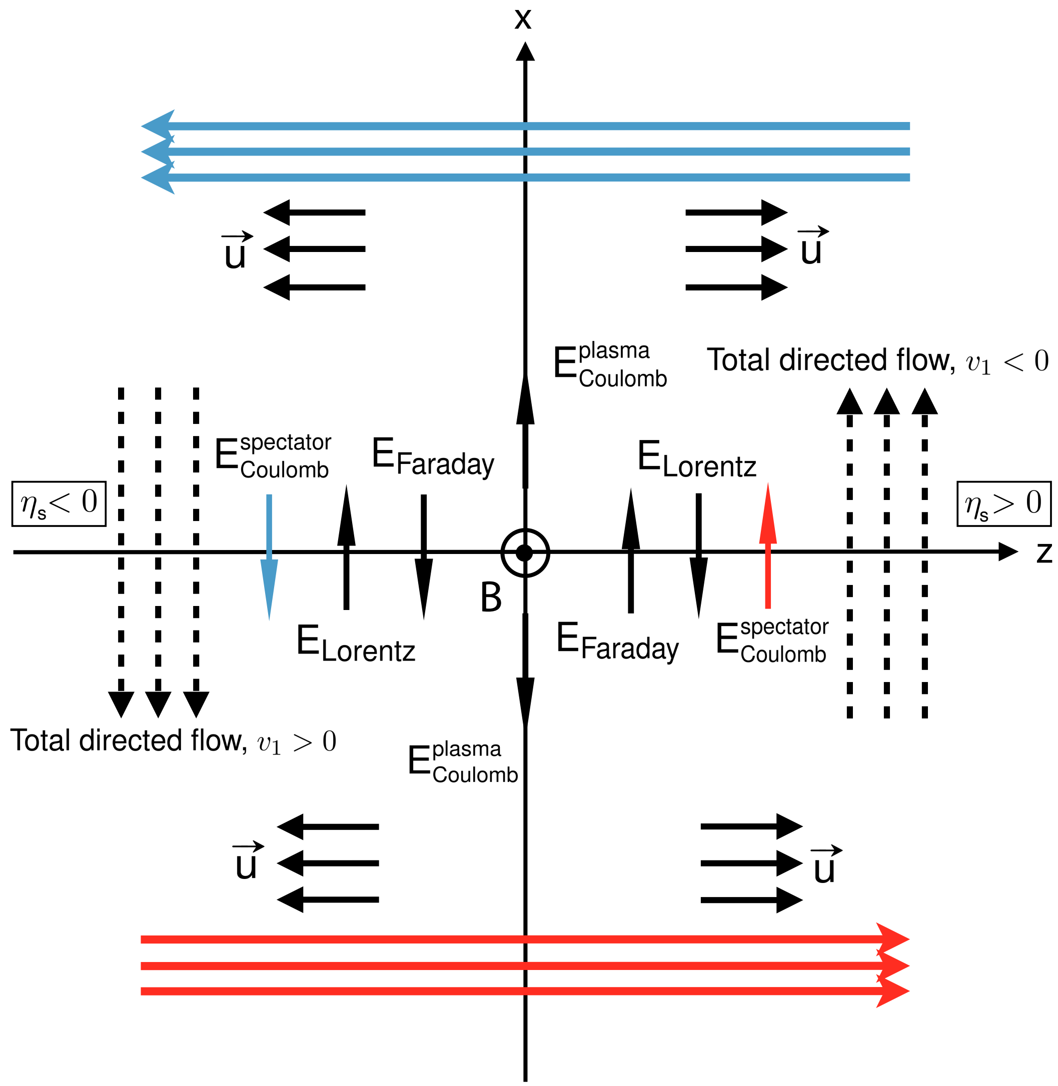
Magnetic Polarization (e.g. CME)

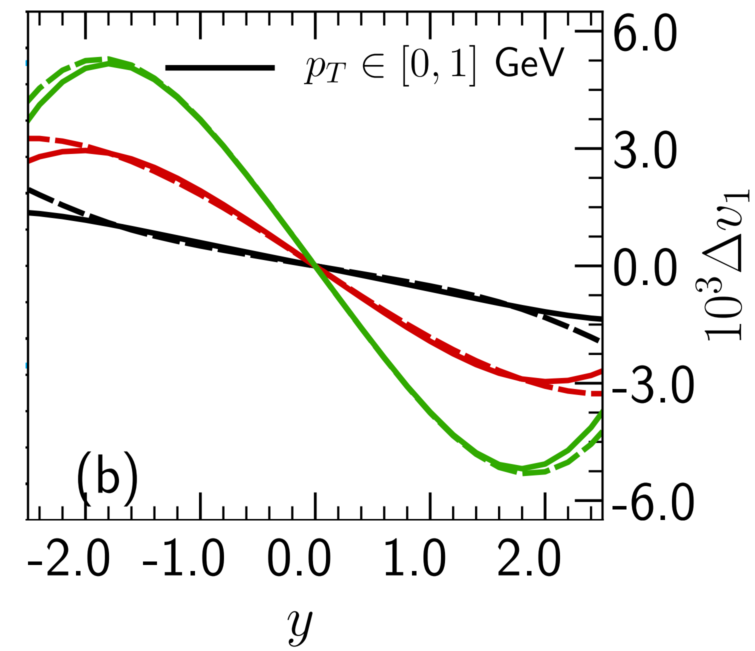


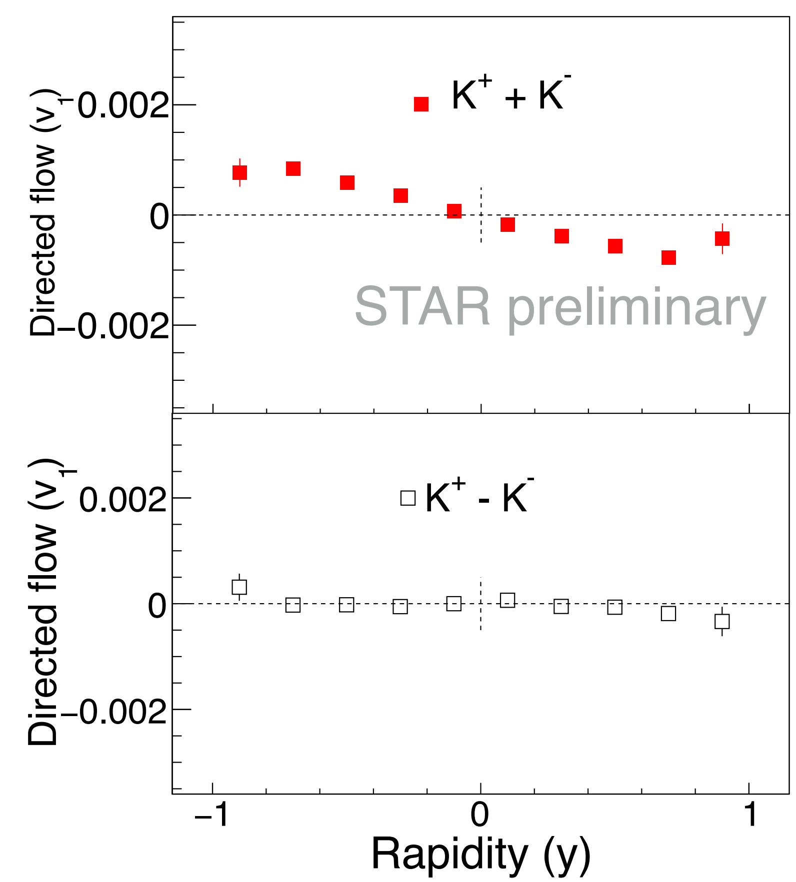




Spin Polarization

# Search for the Faraday fluid




Gursoy et al, 1806.05288

$$\Delta v_1 \equiv v_1(h^+) - v_1(h^-)$$

$$\Delta \mathcal{V}_n = \frac{\left\langle \bar{Q}_{n,TPC}\, Q^*_{n,ZDCE} \right\rangle}{\left\langle Q_{n,ZDCE}\, Q^*_{n,ZDCW} \right\rangle}$$

$$Q_{n,TPC} = \sum \mathbf{y}\,\mathbf{q}\, e^{in\phi}$$

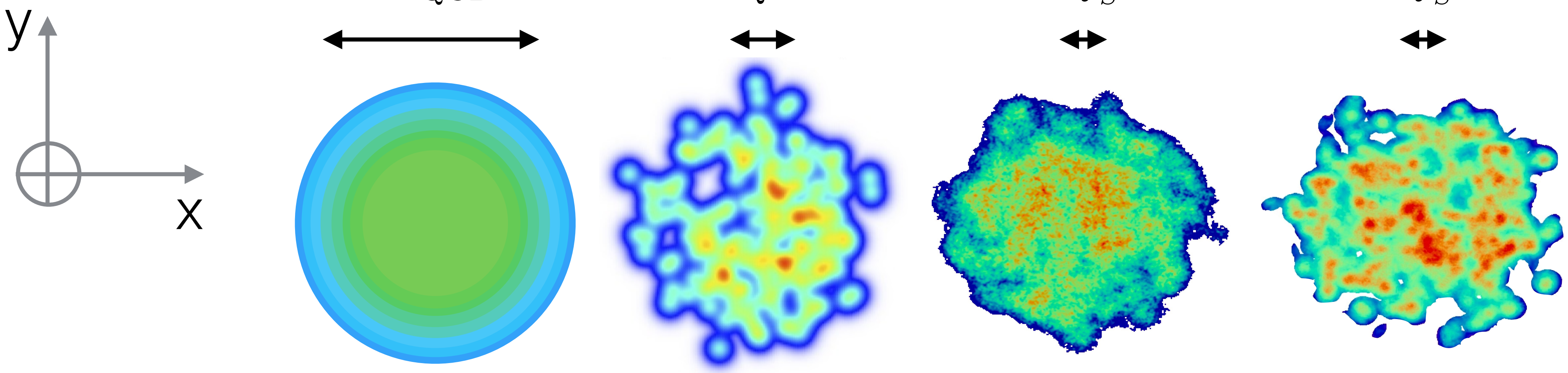
Charge and rapidity weighted cumulants is a way to probe this

# Initial conditions of heavy ion collisions

# What scale of physics dominate initial state?

Over a decade we have been proposing different transverse structures of the initial stages of the colliding nuclei

| Nucleus | Nucleon | Sub-nucleon | Quark hotspots |
|---|---|---|---|
| $\sim \frac{A^{\frac{1}{3}}}{\Lambda_{\mathrm{QCD}}}$ | $\sim \frac{1}{\Lambda_{\mathrm{QCD}}}$ | $\sim \frac{1}{Q_S}$ | $\sim \frac{1}{Q_S}$ |

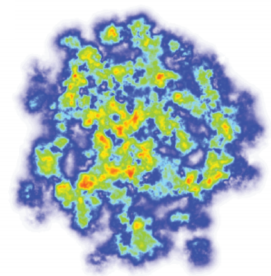



Gluon saturation predicts at higher energies the fields inside the colliding nuclei should have correlations smaller than nucleon scale

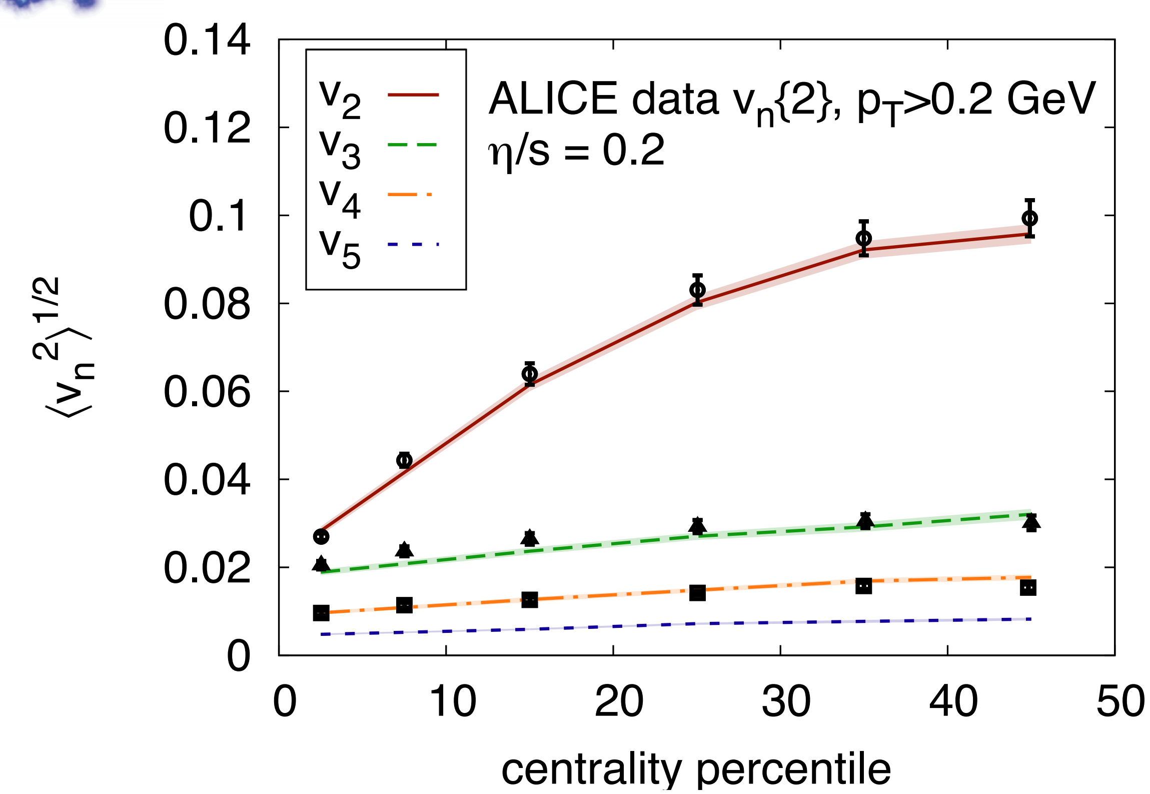
Do sub-nucleonic scale correlations manifest in observables ?

# What manifest in flow measurements

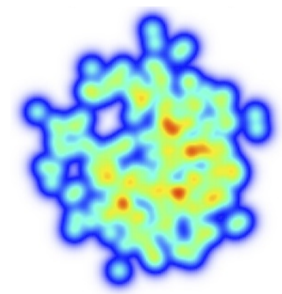
Sub-nucleonic hotspots are not needed to explain heavy ion flow harmonic data, they maybe essential to explain p+p data



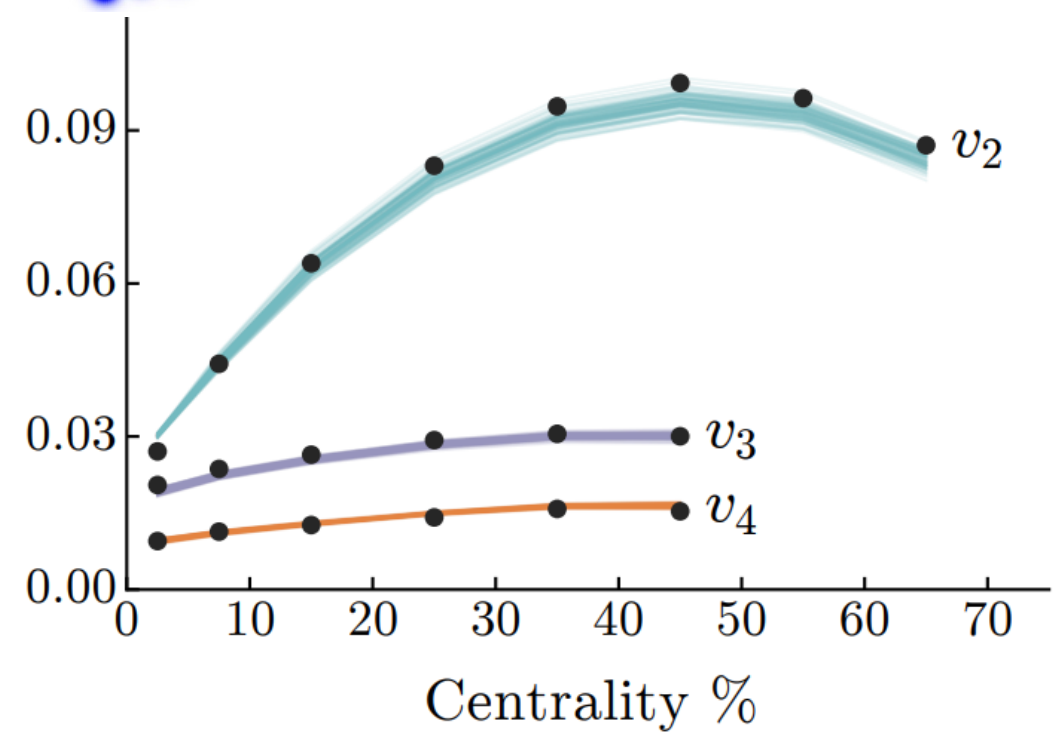
Nuclei with sub-nucleonic scale correlations




Gale, Jeon, Schenke, PT, Venugopalan 1209.6330



Nuclei with nucleonic scale correlations



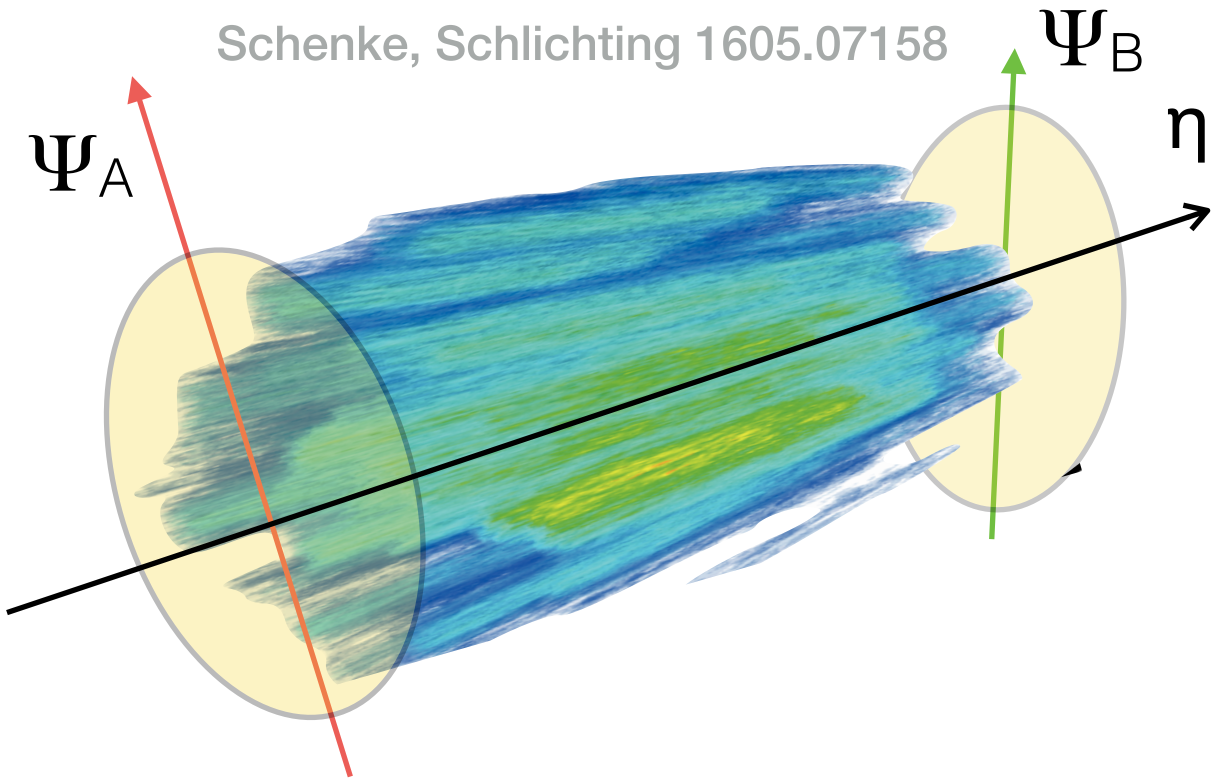

Moreland, Bernhard, Bass 1412.4708

Flow observables in A+A may be dominated by nucleon geometry ?

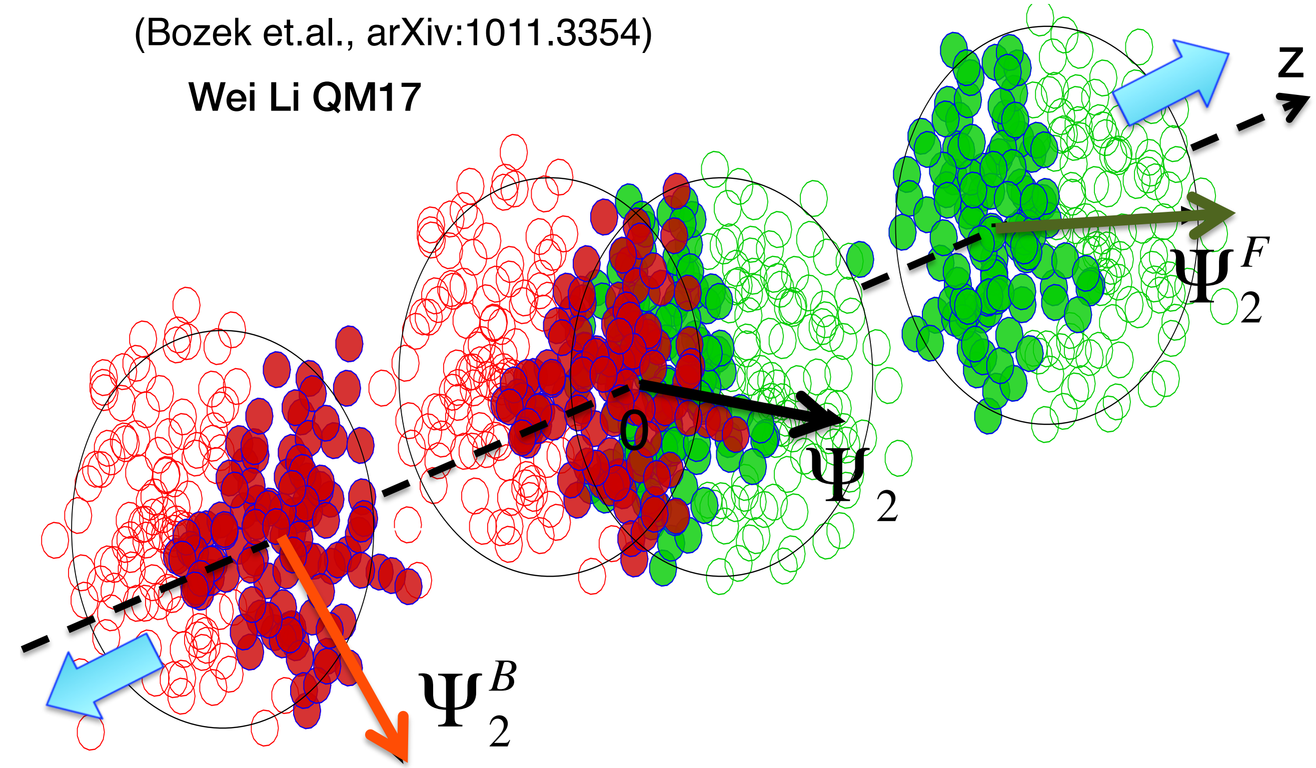
Ollitrault et al “New paradigm”, nucleons are not important: 1902.07168

# A different picture when you change rapidity

## Sub-nucleonic scale correlations (flux-tubes)




## Wounded Nucleons




Scale in the problem: $\Delta\eta \sim 1/\alpha_S$

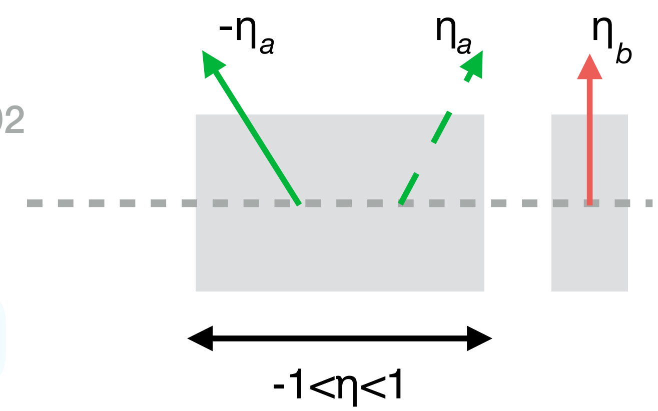
Scale in the problem: $\Delta\eta \sim Y_{beam}$

At what scale does the boost invariance break ?

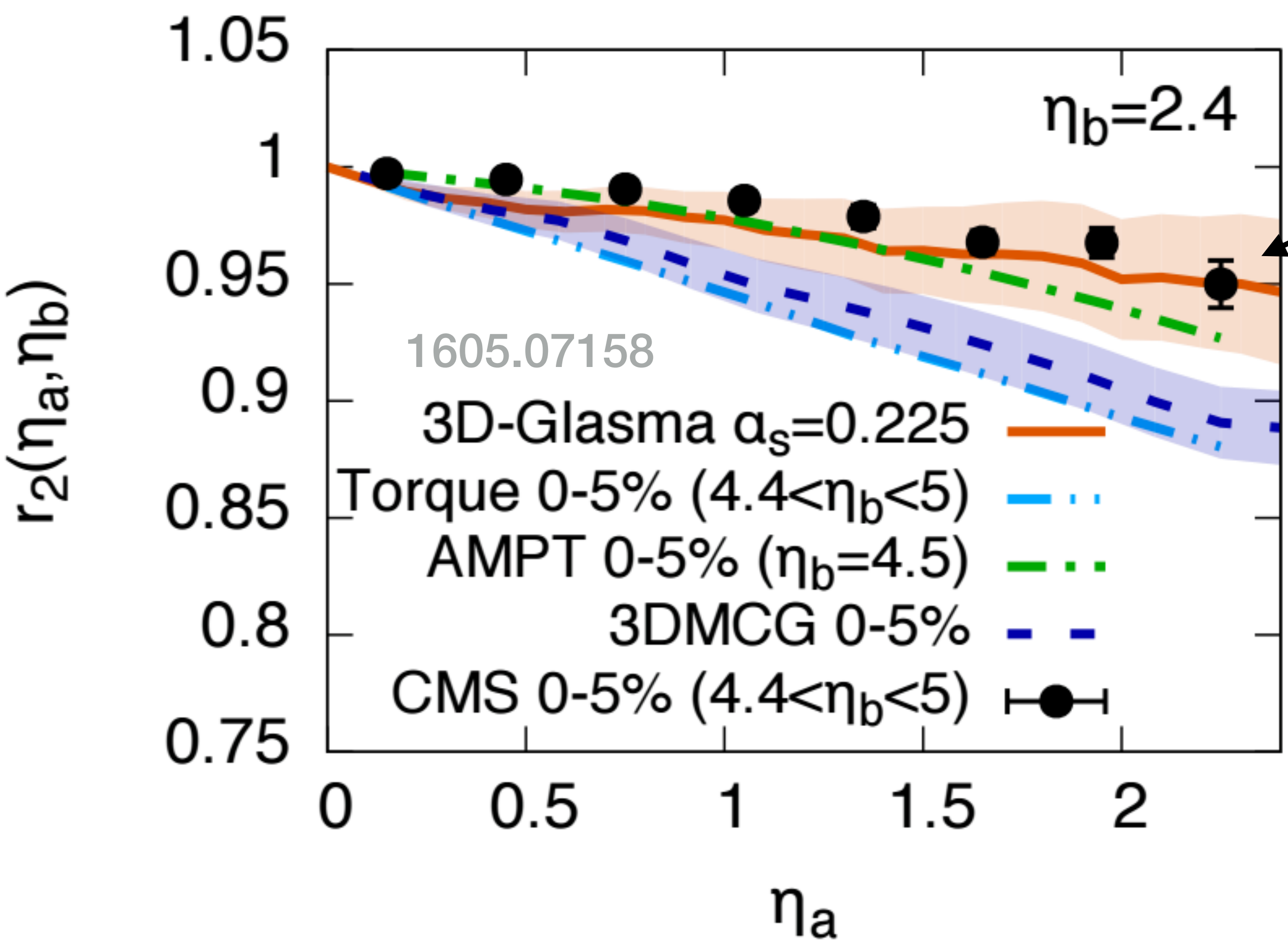
# Longitudinal de-correlation around mid-rapidity

$$r_n(\eta^a, \eta^b) \equiv \frac{V_{n\Delta}(-\eta^a, \eta^b)}{V_{n\Delta}(\eta^a, \eta^b)}$$

CMS 1503.01692




$$C_n\{2\} = V_{n\Delta} = \langle\langle \cos(n\phi_1 - n\phi_2)\rangle\rangle$$




Weak de-correlation in flux-tube initial conditions

# Longitudinal de-correlation around mid-rapidity

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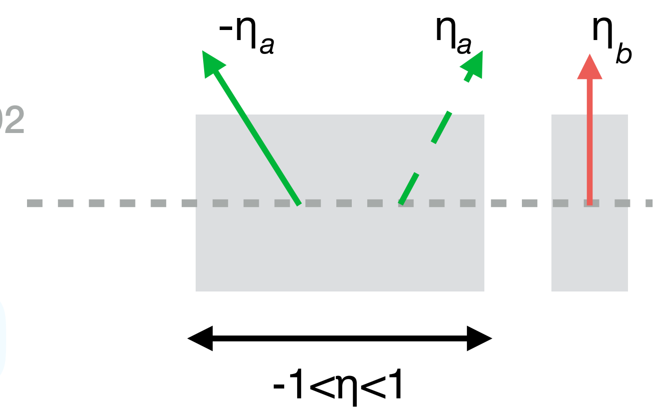
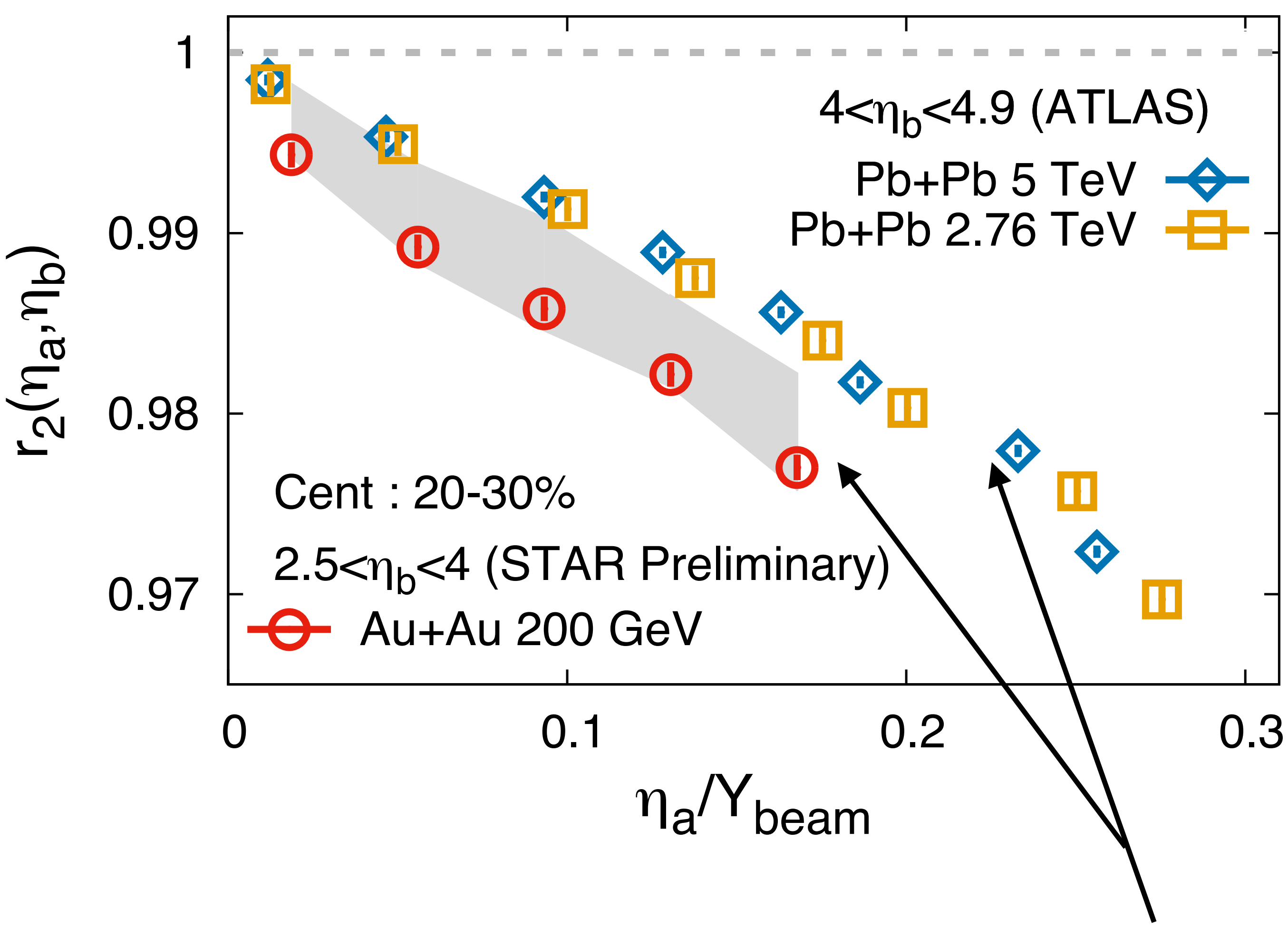


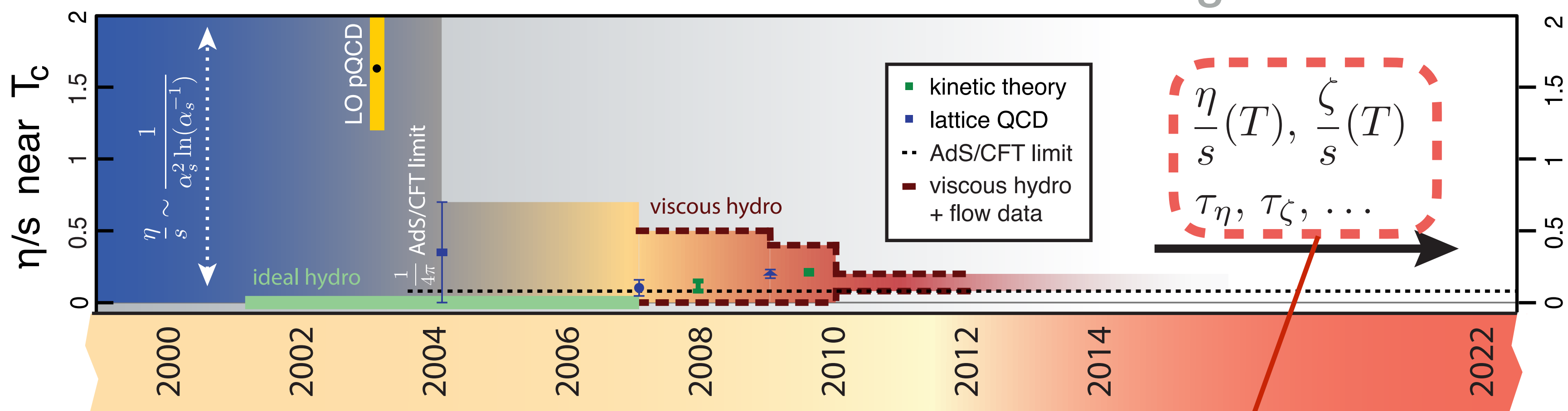

Longitudinal de-correlation scaled w.r.to beam rapidity, LHC results seems to show a scaling, do we see a breaking at RHIC ?

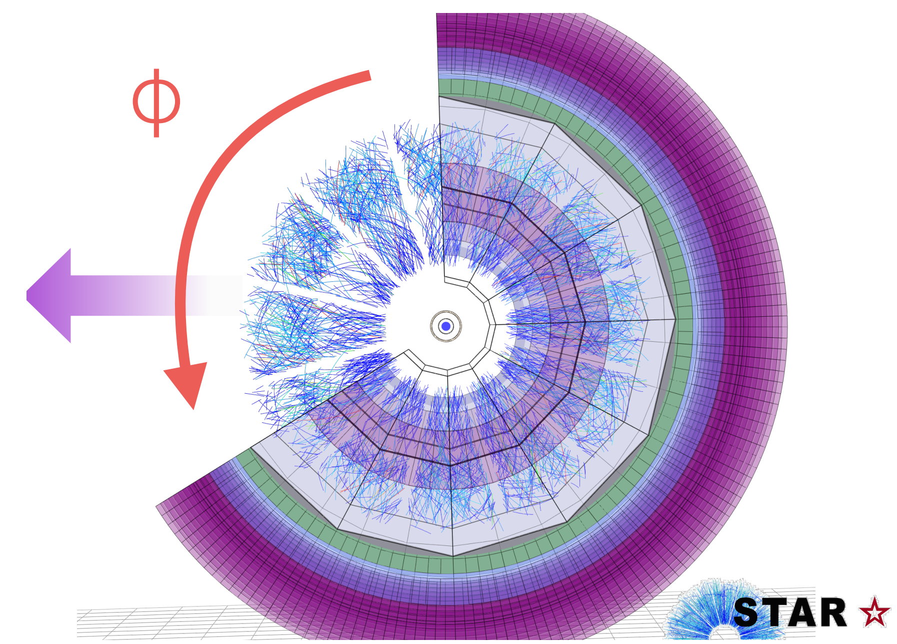
# Characterizing the perfect fluid

# Transport properties of matter formed in HICs

We have made precision measurements of the shear viscosity to entropy density ratio η/s of the matter formed in HICs

fig: B. Schenke




"…temperature dependence will be more tightly constrained by upcoming measurements…"

Page 22, The 2015 LONG RANGE PLAN for NUCLEAR SCIENCE

Can we map out the temperature dependence profile of transport parameters ?

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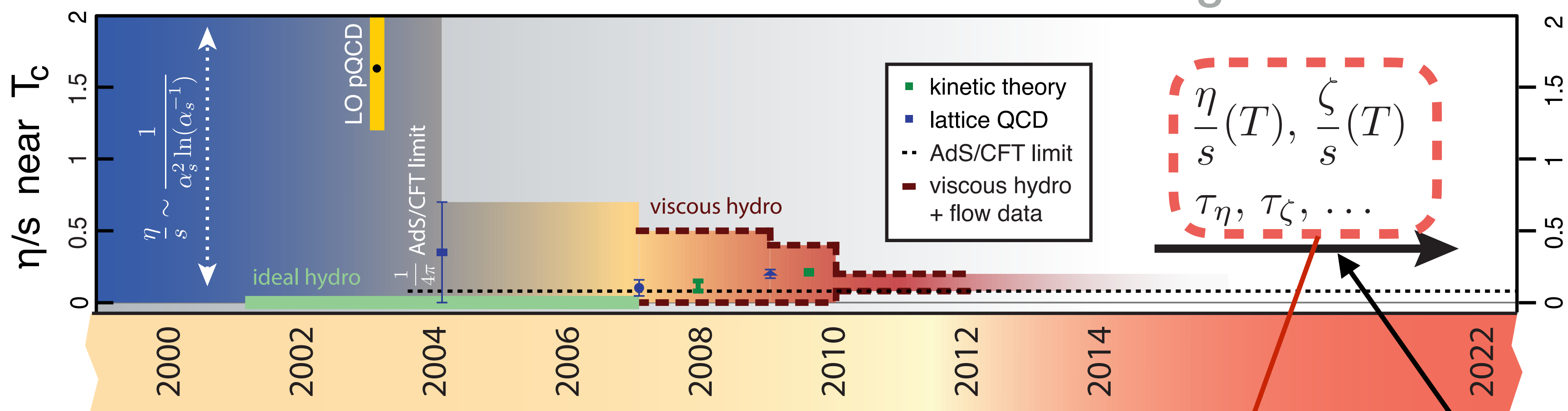


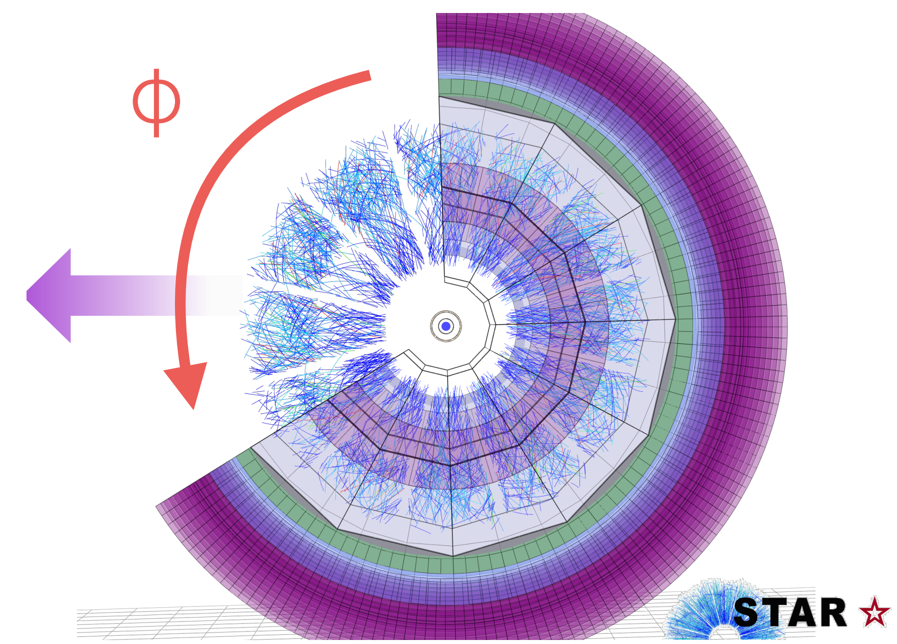


“…temperature dependence will be more tightly constrained by upcoming measurements…”

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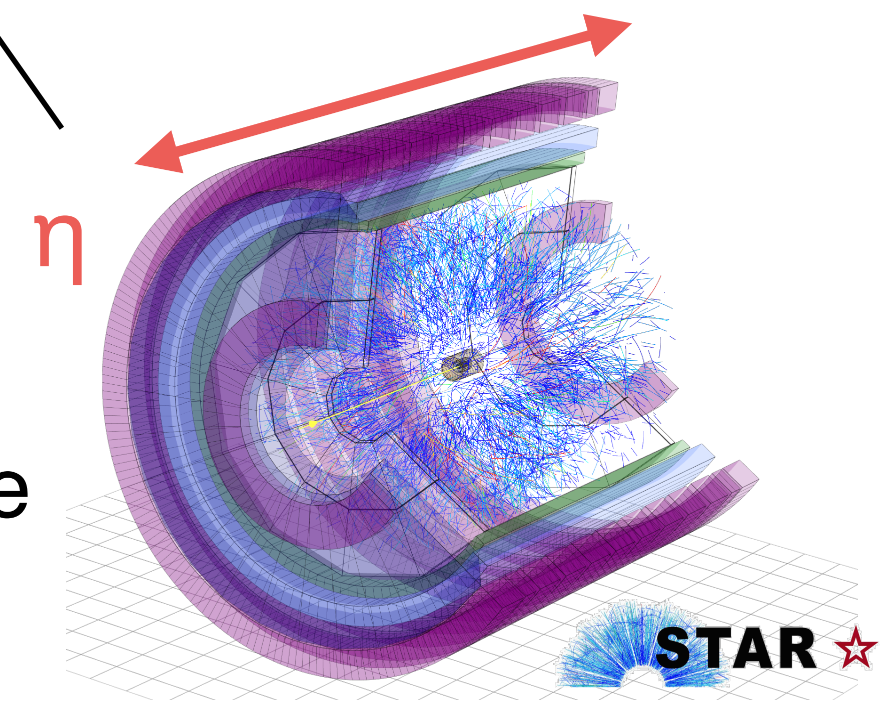
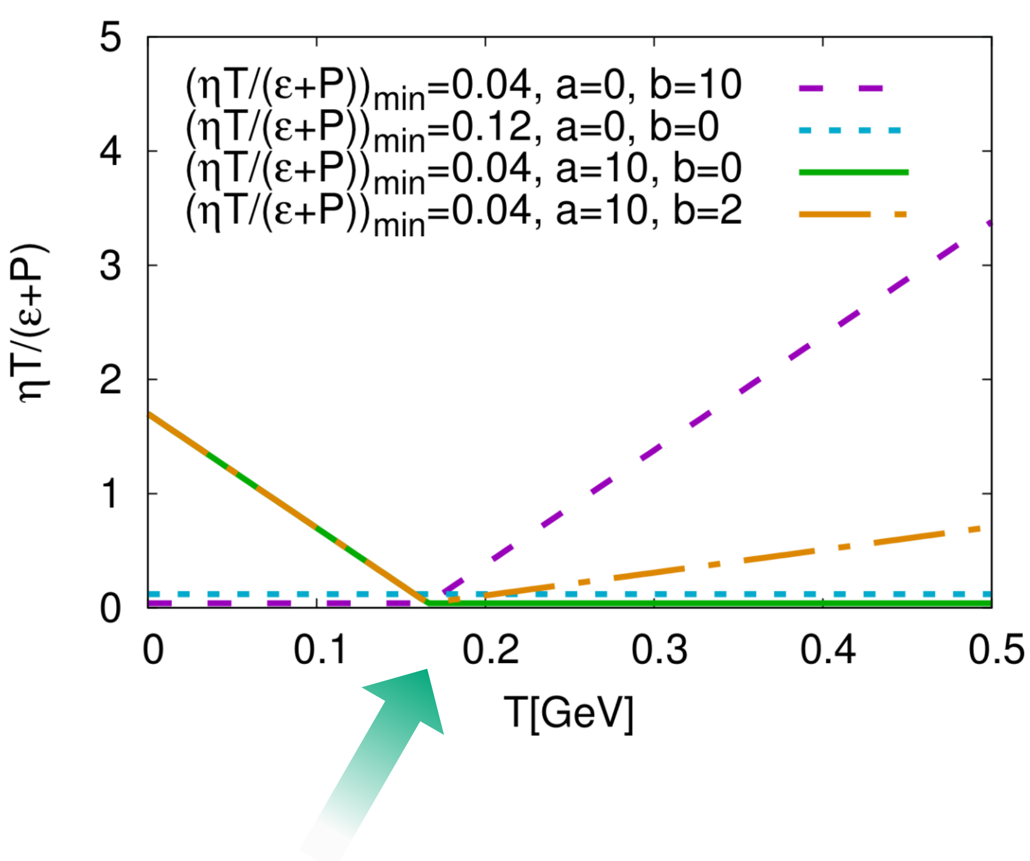



Can we map out the temperature dependence profile of transport parameters ?

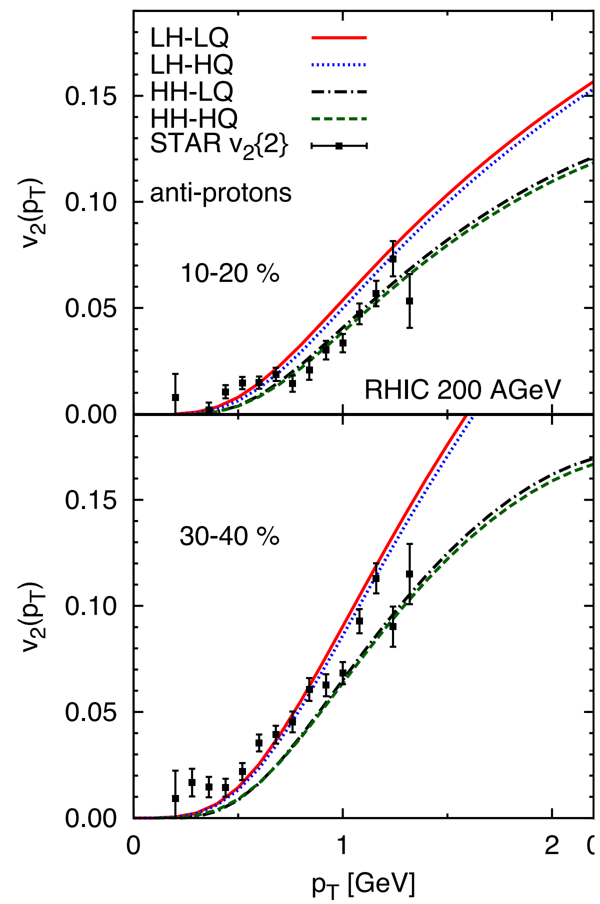
# Constraining temperature dependence of η/s(T)

## Viscosity has temperature dependence, RHIC & LHC probe different regions

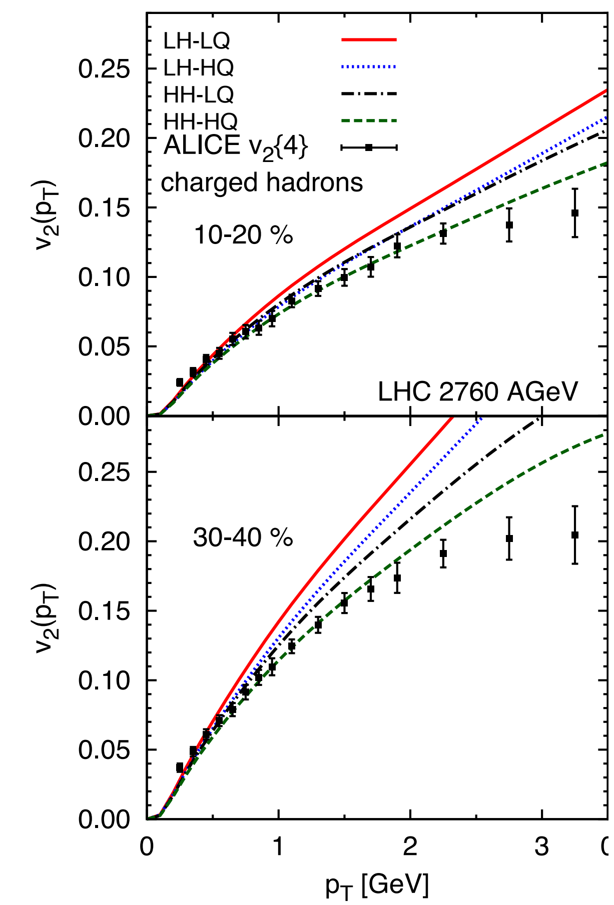
Niemi et al 1203.2452




RHIC $\eta/s(T \lesssim T_C)$




LHC $\eta/s(T > T_C)$

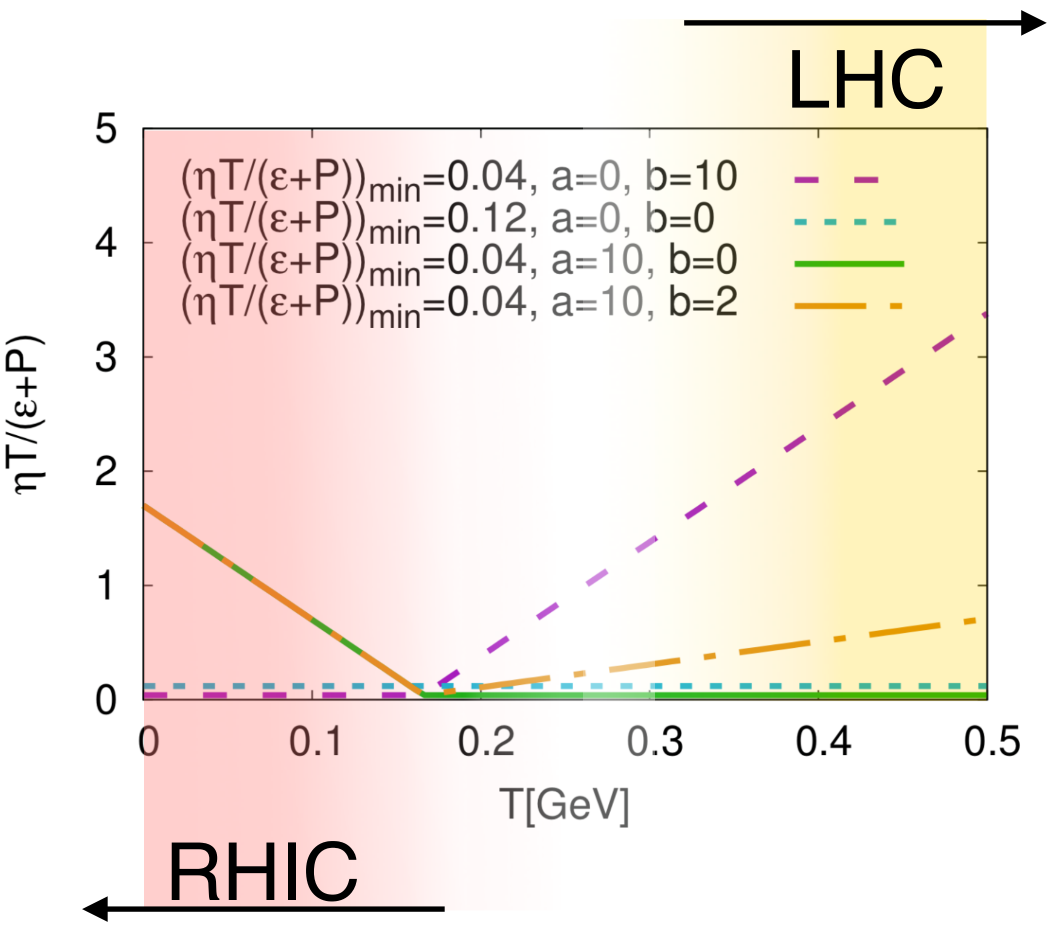



Region of nearly perfect fluidity (RHIC collisions spend a lot of time here)

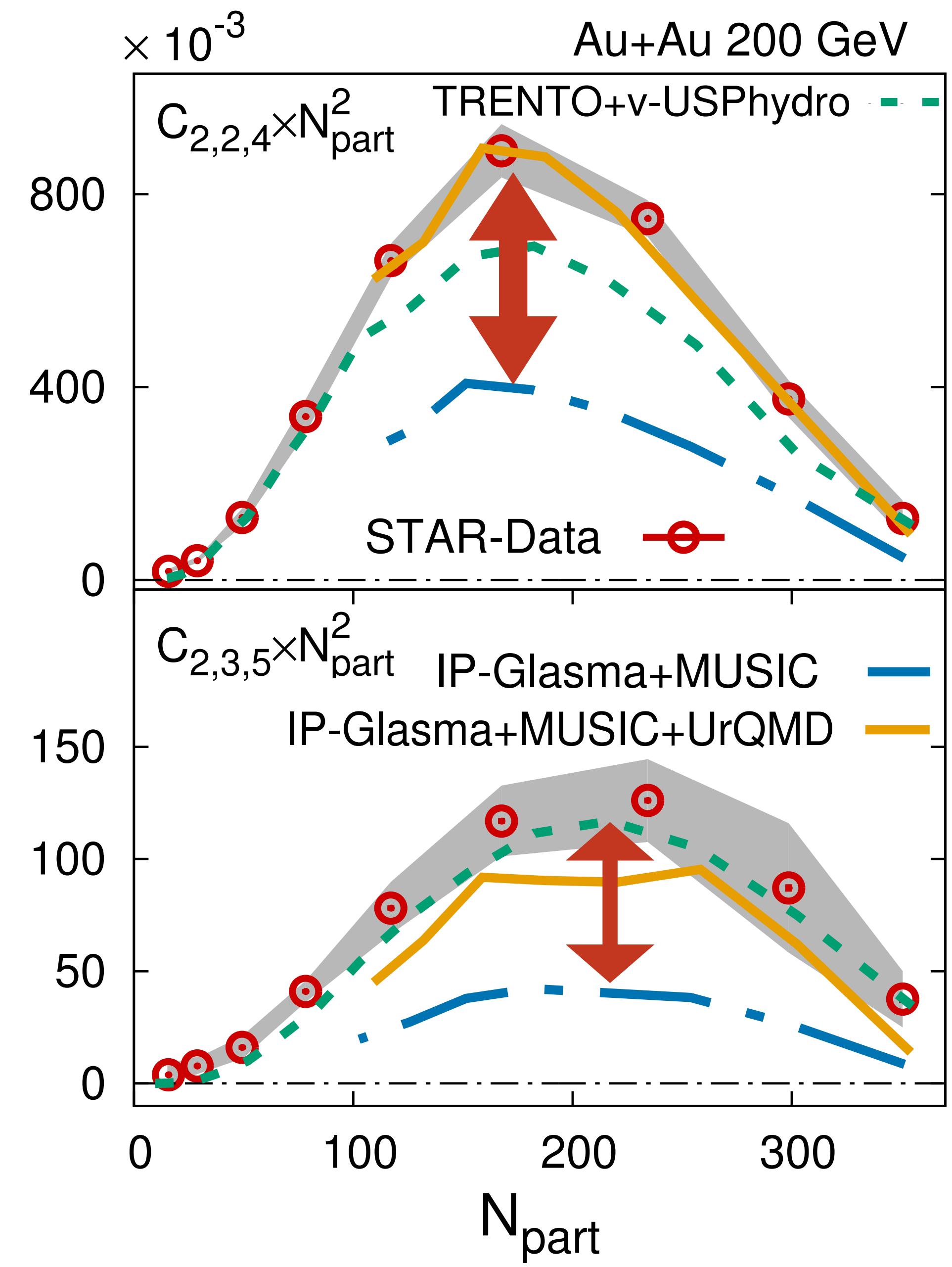
# Constraining temperature dependence of η/s(T)

Recent STAR results and comparison to model indicate a large fraction of flow correlations are developed at the hadronic stage

Niemi et al 1203.2452




STAR, L. Adamczyk et al, PLB 2019



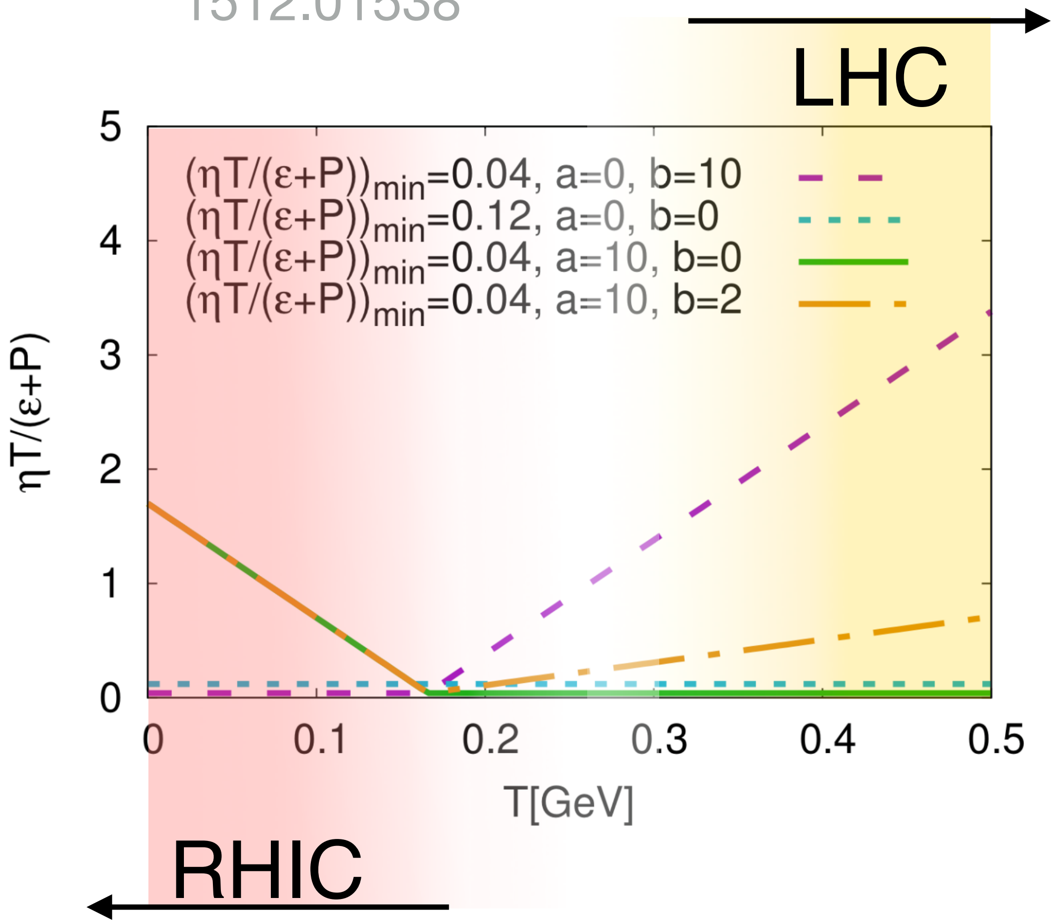

This unique feature of RHIC can be utilized

# Constraining temperature dependence of η/s(T)

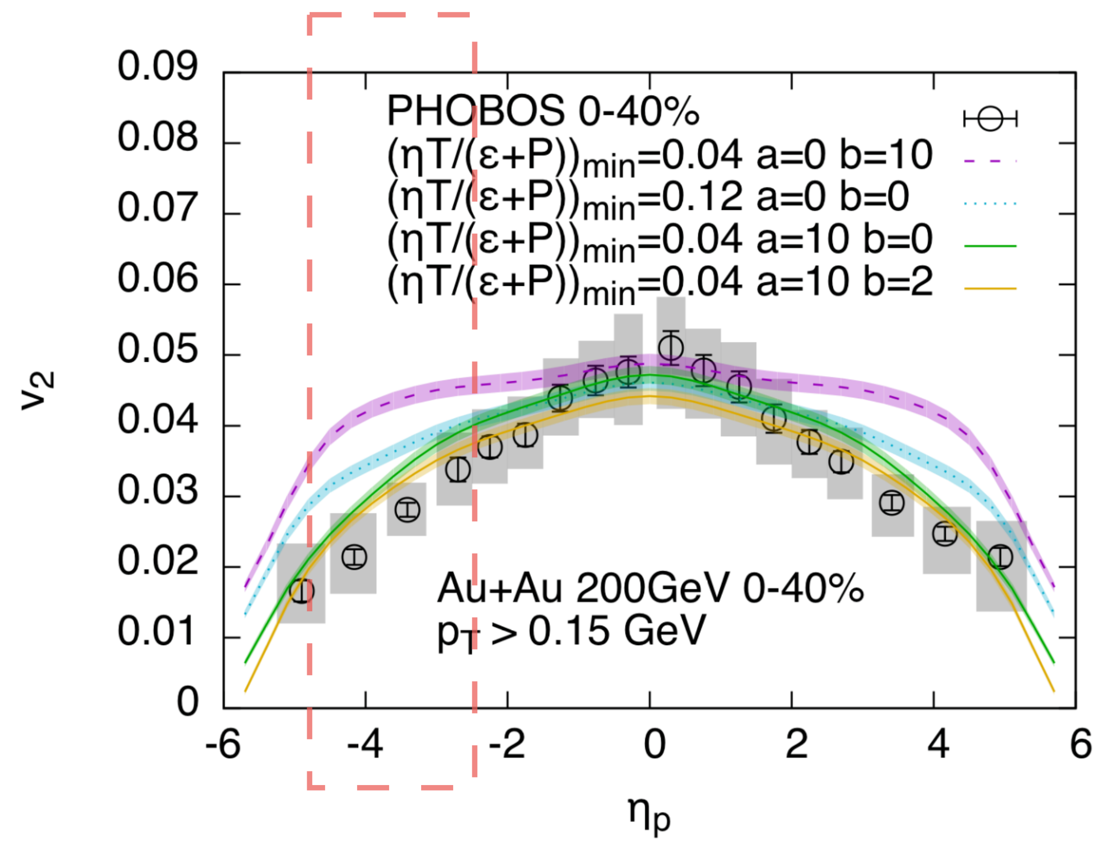
Viscosity has temperature dependence :

RHIC collisions can probe the region of perfect fluidity

Denicol *et al* 1512.01538




Denicol et al PhysRevLett.116.212301

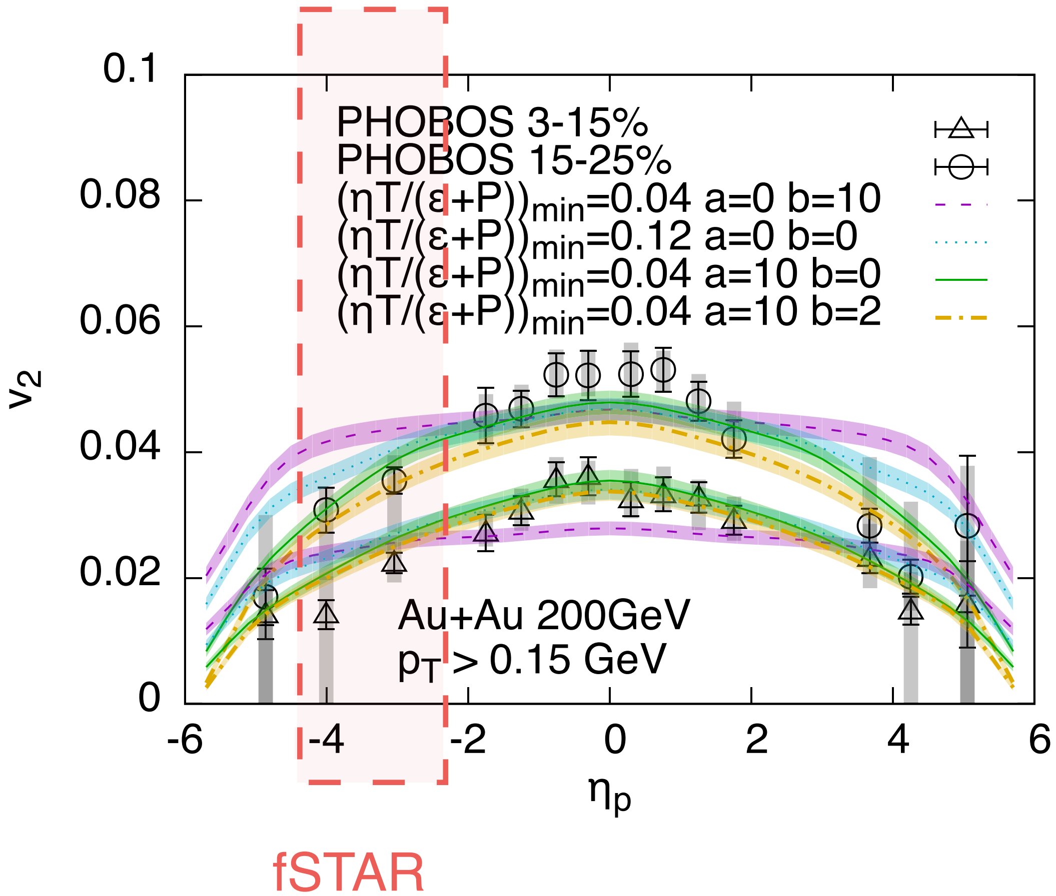


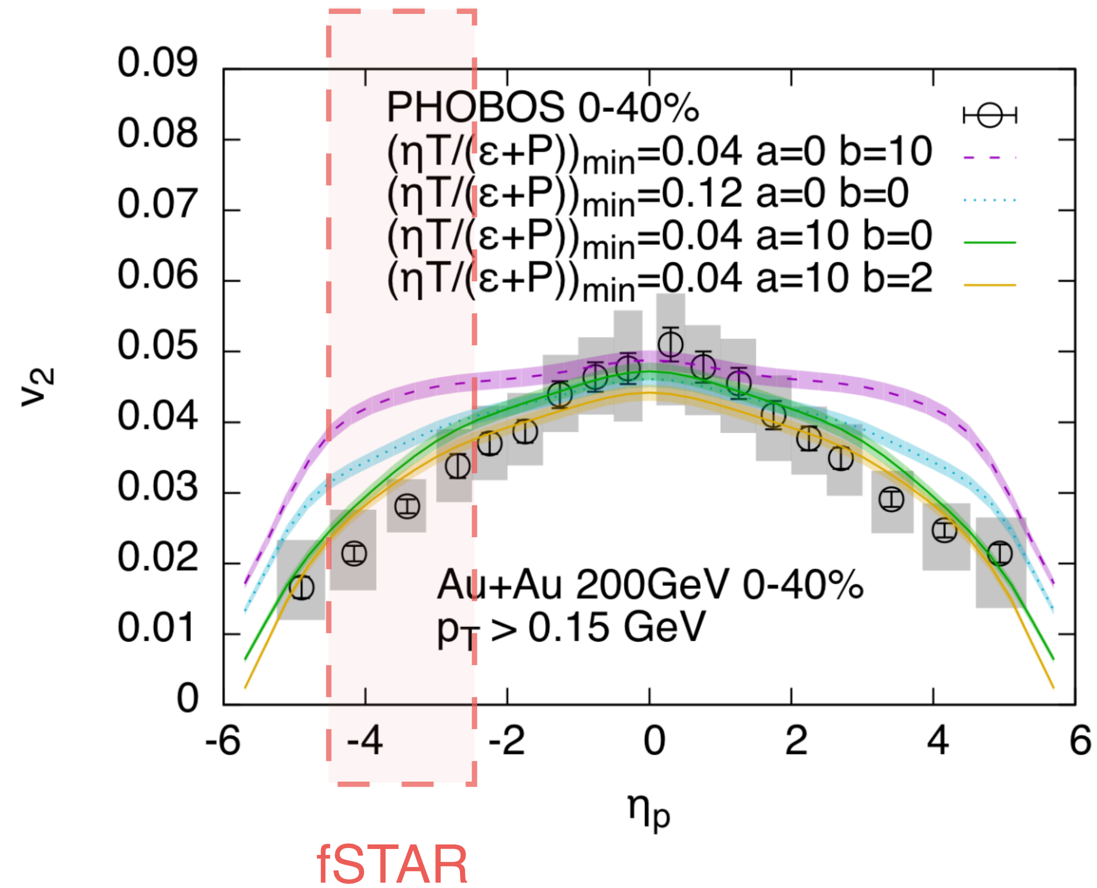

Measurements at RHIC with STAR forward upgrade can constrain η/s (T) over wide window of temperatures

# Constraining temperature dependence of η/s(T)

## Existing data has large uncertainties to constrain η/s (T)

Denicol et al PhysRevLett.116.212301



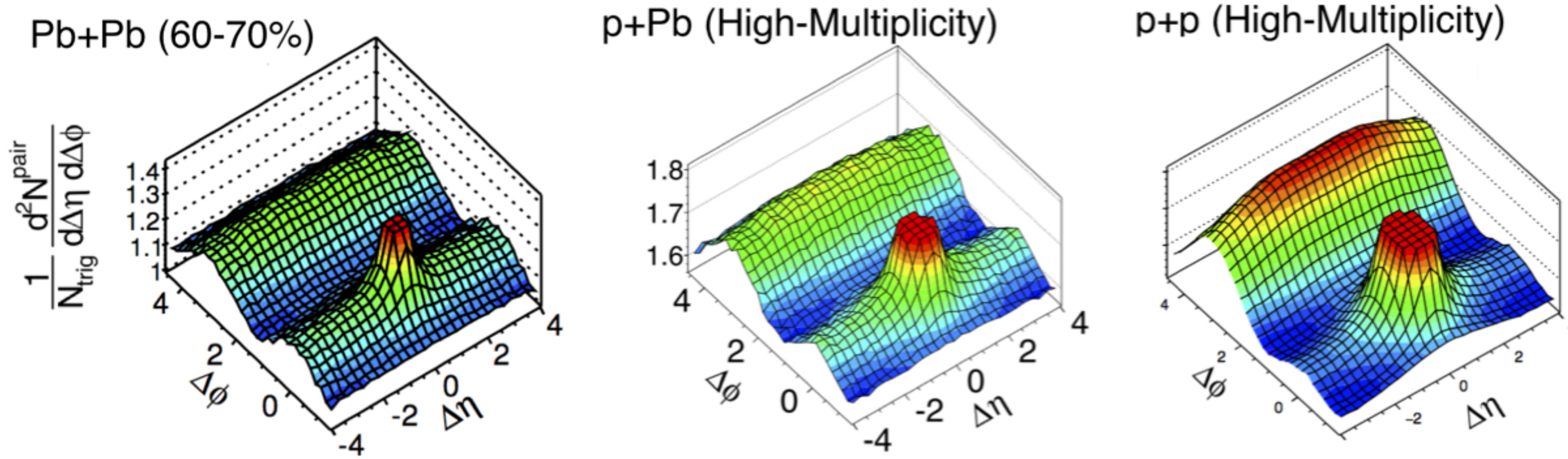




Measurements at RHIC with STAR forward upgrade can constrain η/s (T) over wide window of temperatures

# Collectivity in Small systems

# Collectivity in small collision systems

High multiplicity events in small collision systems and HICs

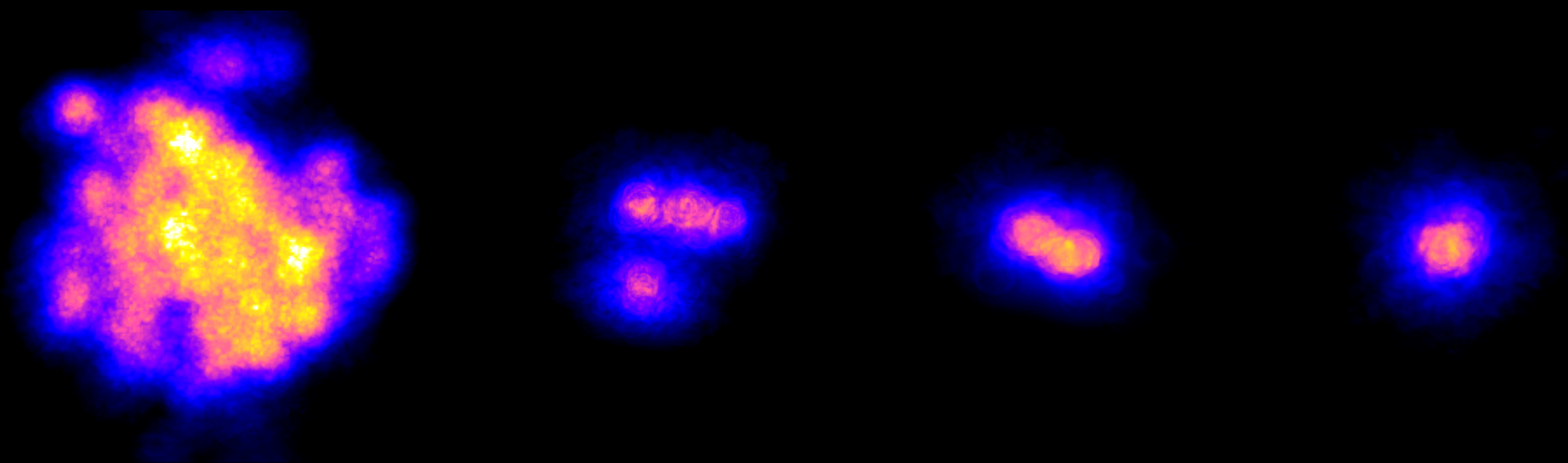



Signature of collectivity: similar pattern of particle emission over a wide range in momentum space

What kind of initial state correlations lead to such momentum space distribution of particle emission ?

Hydrodynamic evolution: one possible mechanism, but what else ?

# From Heavy Ion to small collisions



Au+Au $^{3}$He+Au d+Au p+Au

# How anisotropy is generated with time

Full stress-energy tensor from IP-Glasma

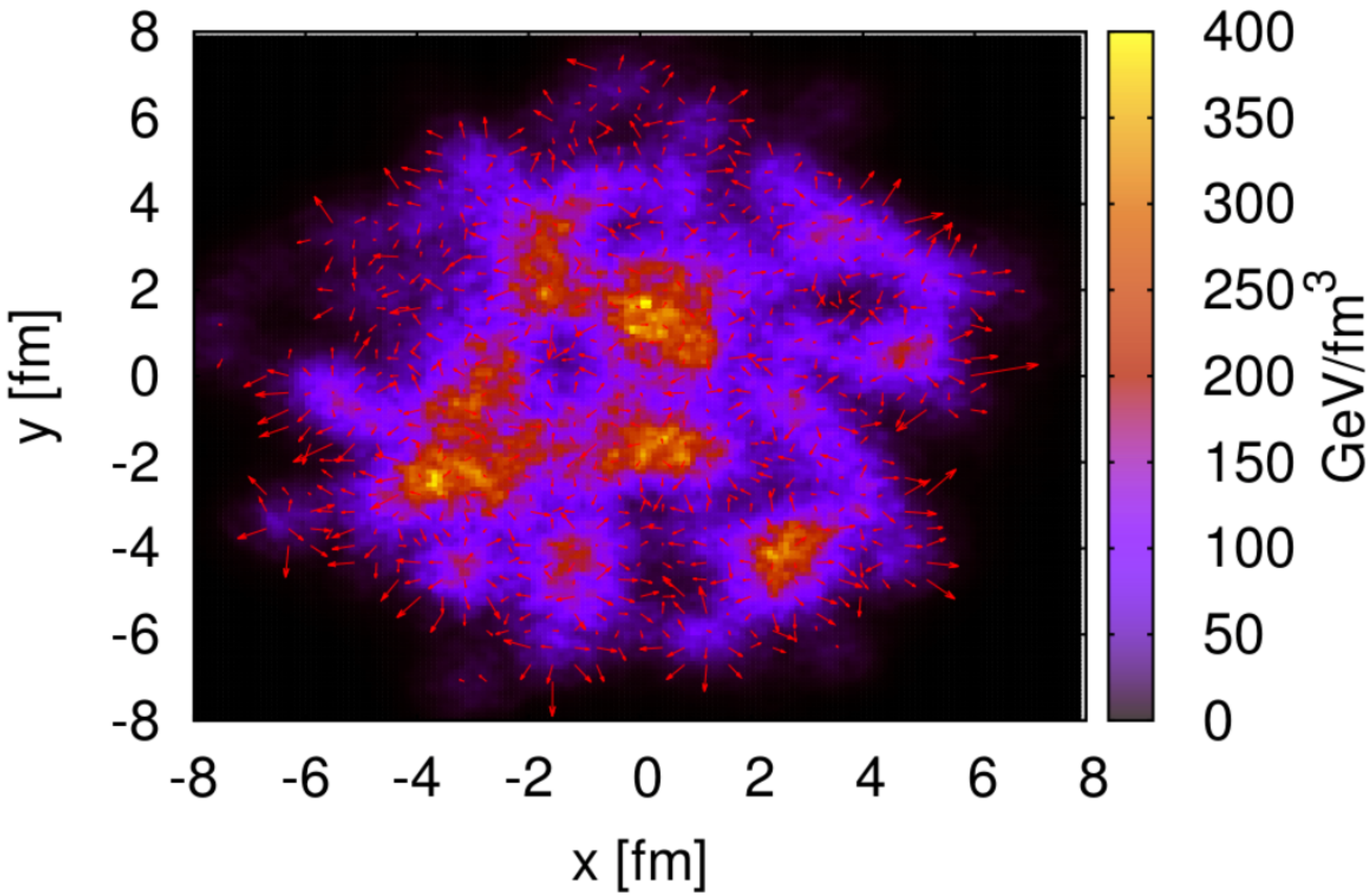



fig: McDonald et al, arXiv:1704.07680

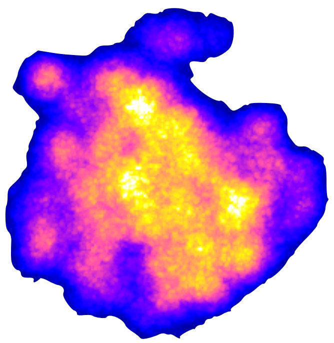
Initial conditions: position space and momentum space anisotropy

Before hydrodynamics takes over, the system already has momentum space anisotropy

# How anisotropy is generated with time

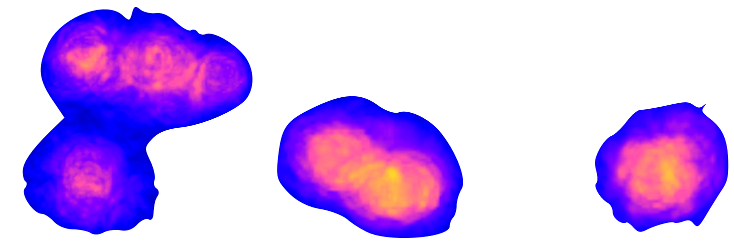
IP-Glasma + MUSIC (Hydro)

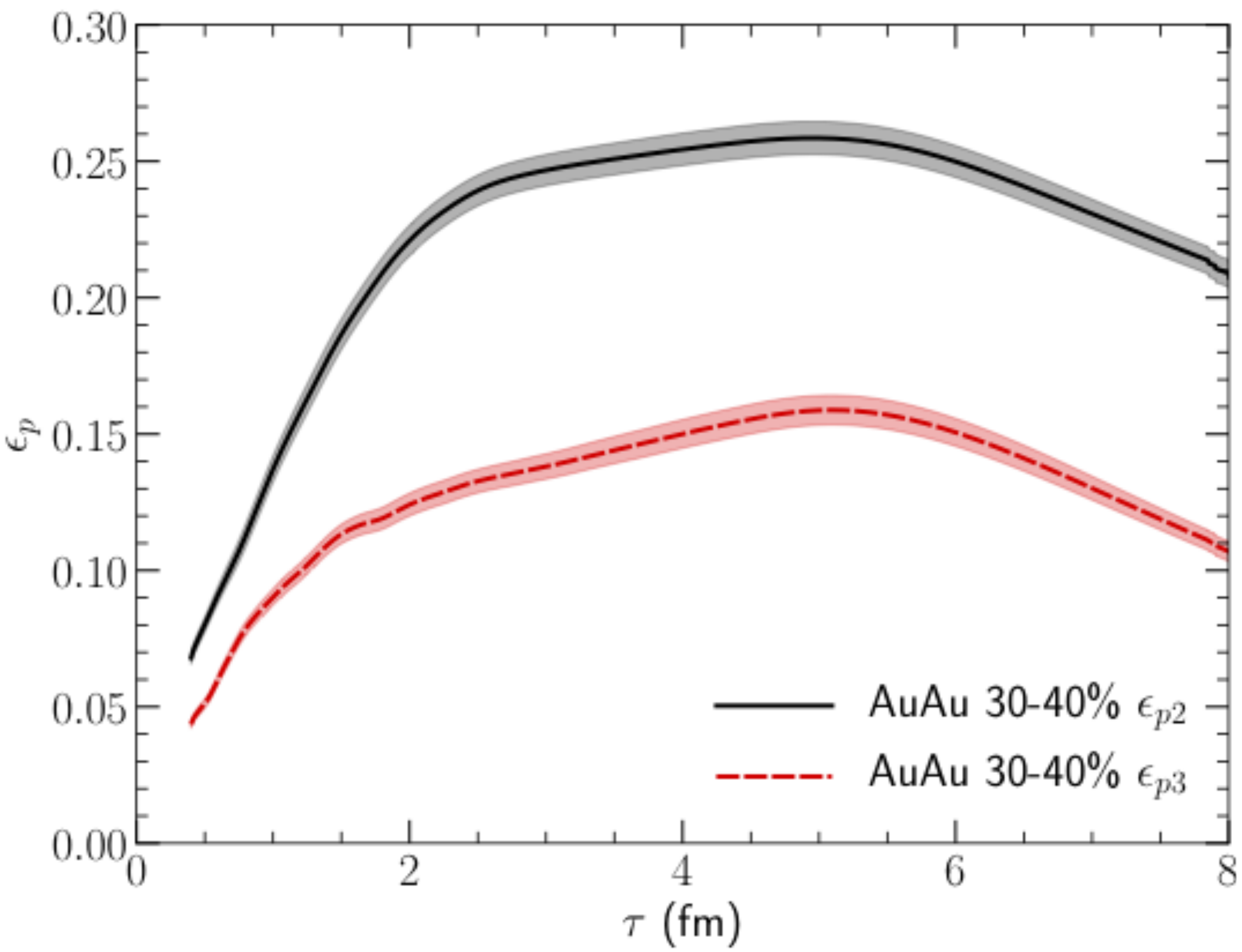
Schenke, Shen, PT in preparation

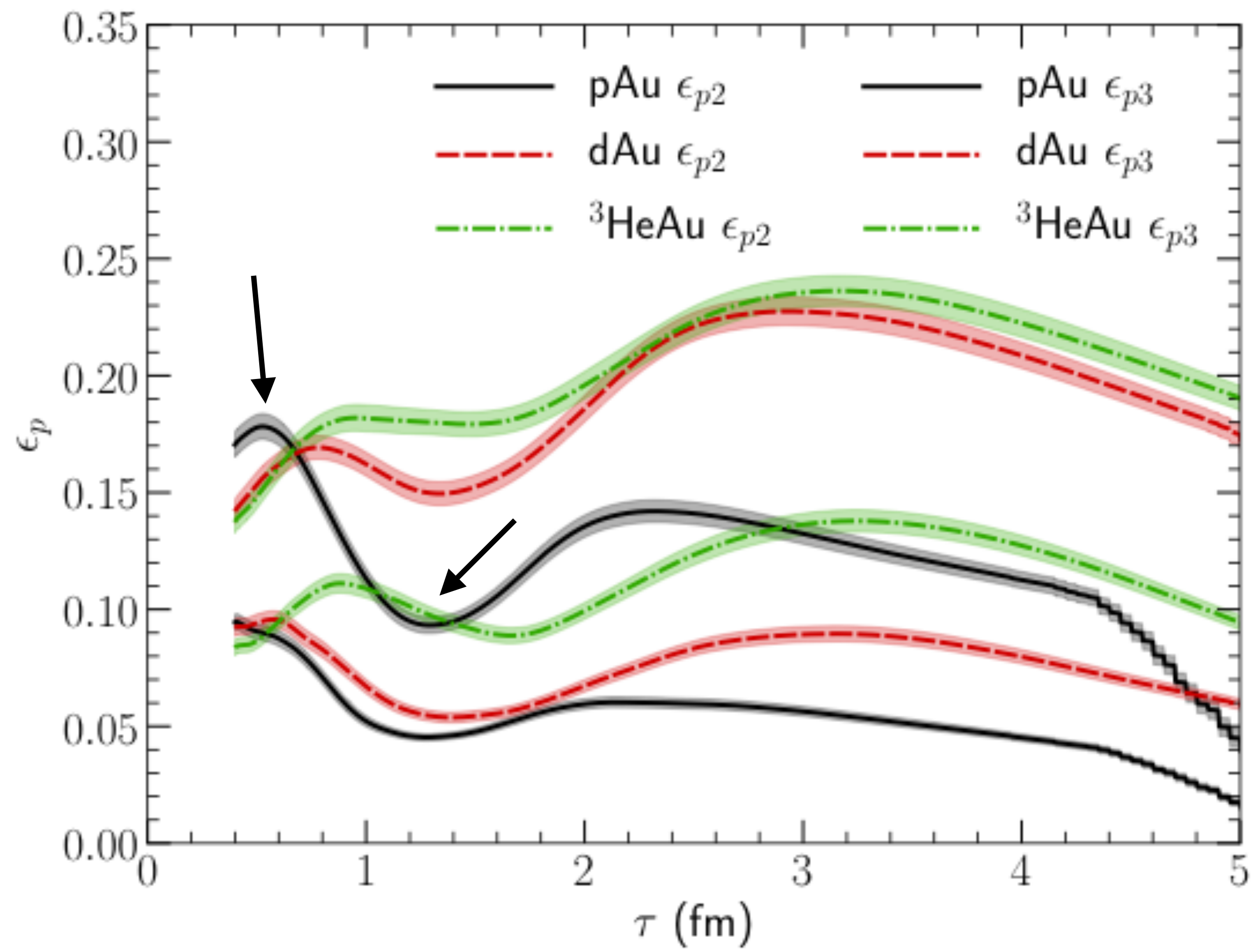


Au+Au

p/d/$^3$He+Au





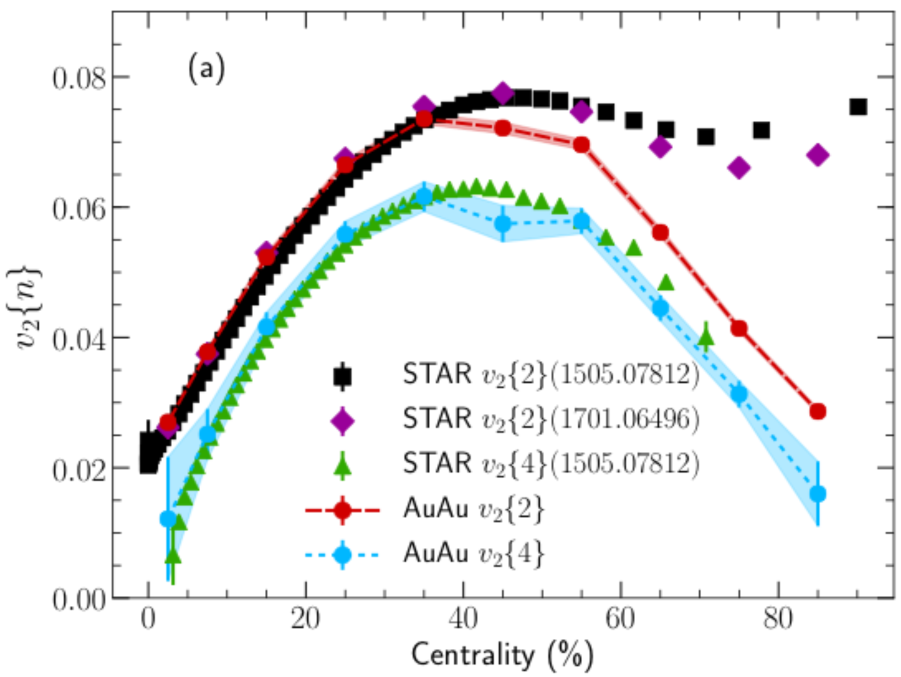

Smooth evolution in A+A

Evolution in small systems

Very different trends between large and small systems

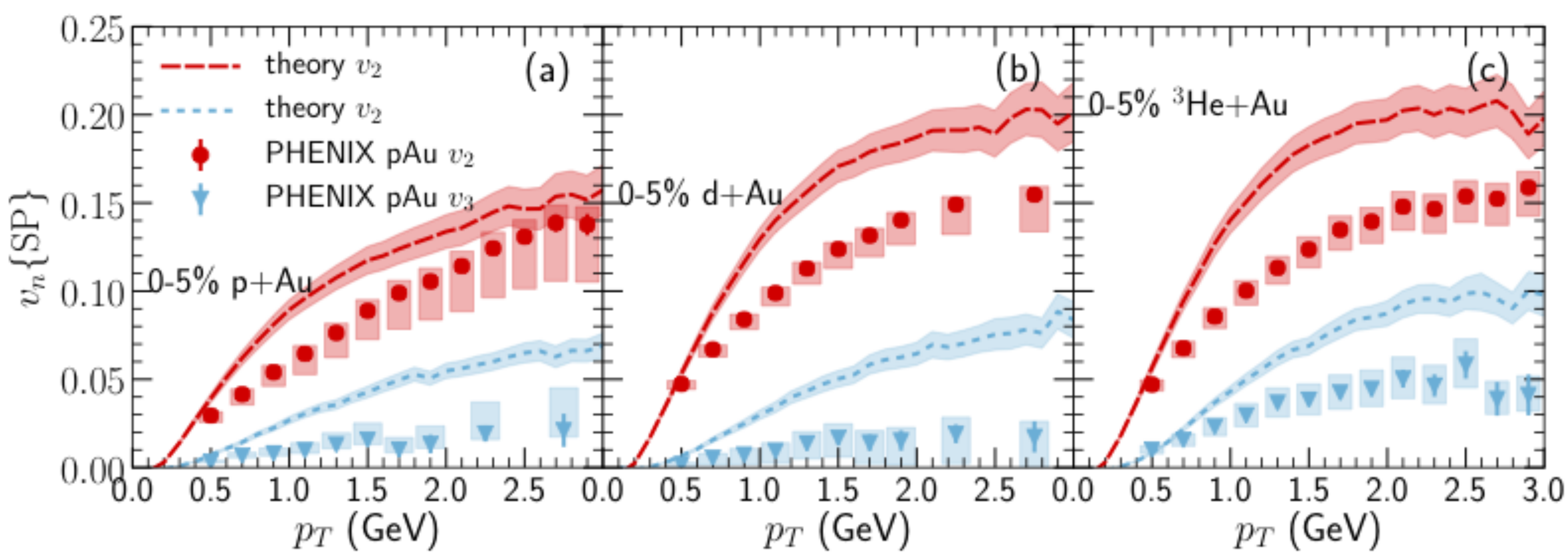
# How anisotropy is generated in small systems

Schenke, Shen, PT  in preparation




Use STAR data to constrain model

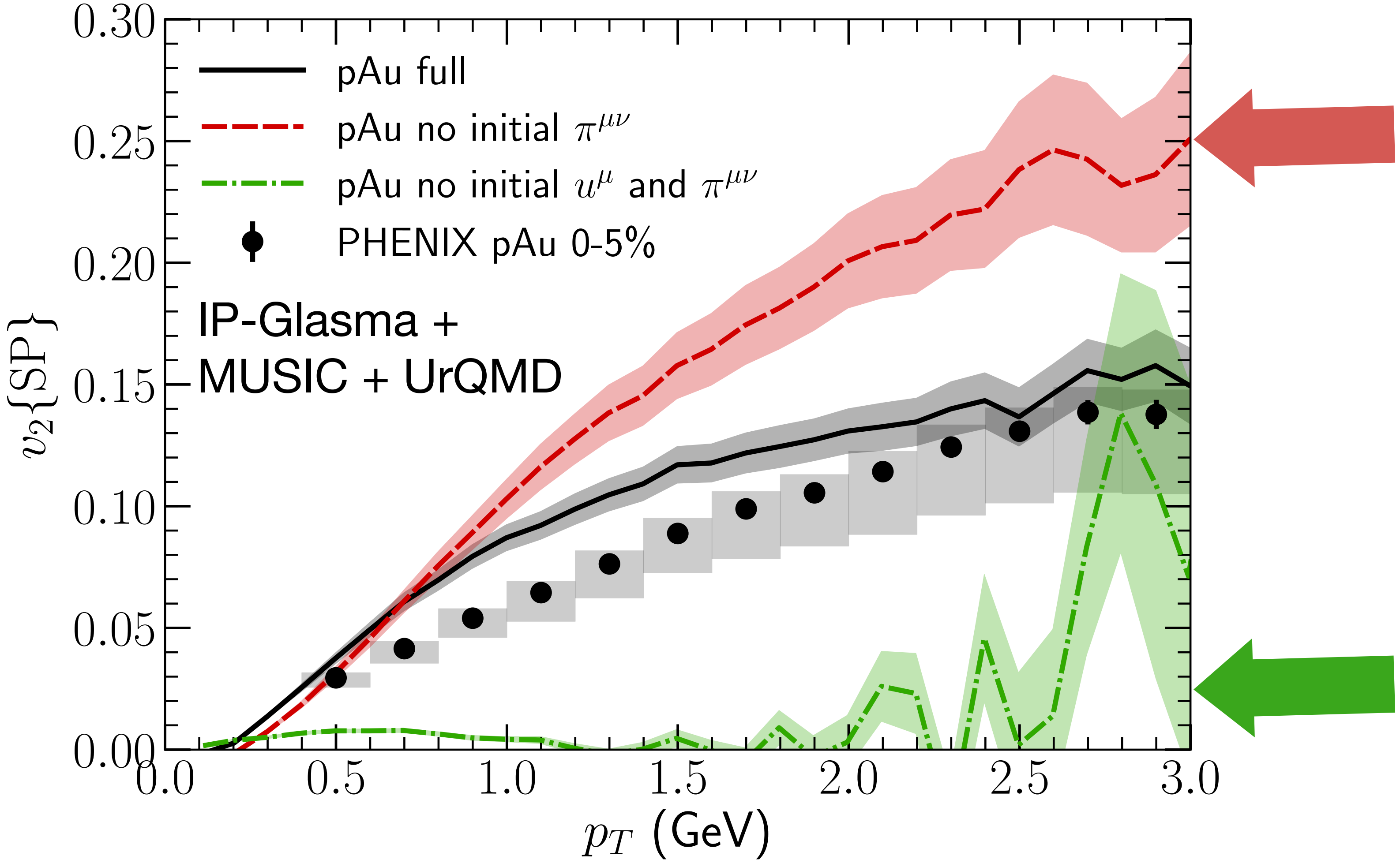
Make prediction for small systems

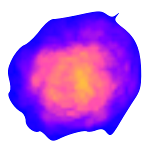


# How anisotropy is generated in small systems

Flow in d+A using a hybrid framework constrained by A+A data at RHIC

Schenke, Shen, PT in preparation



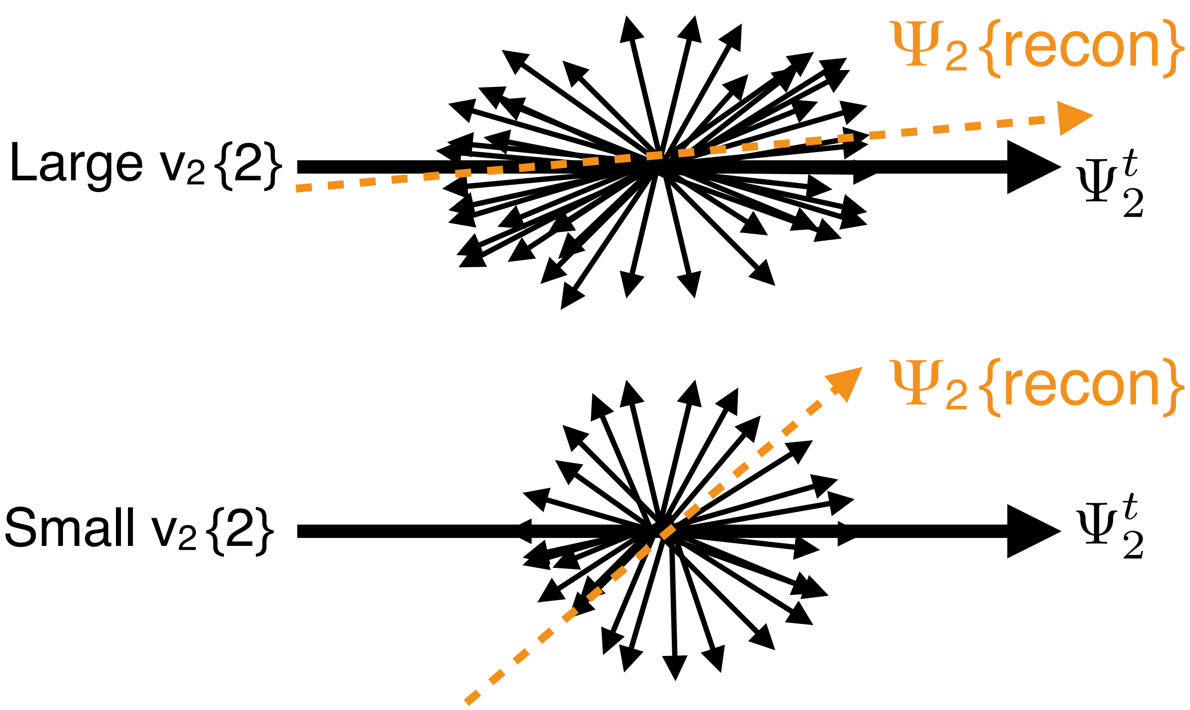



A large fraction of the anisotropy is coming from initial flow not geometry

In IP-Glasma framework this initial flow is coming from Glasma & CGC

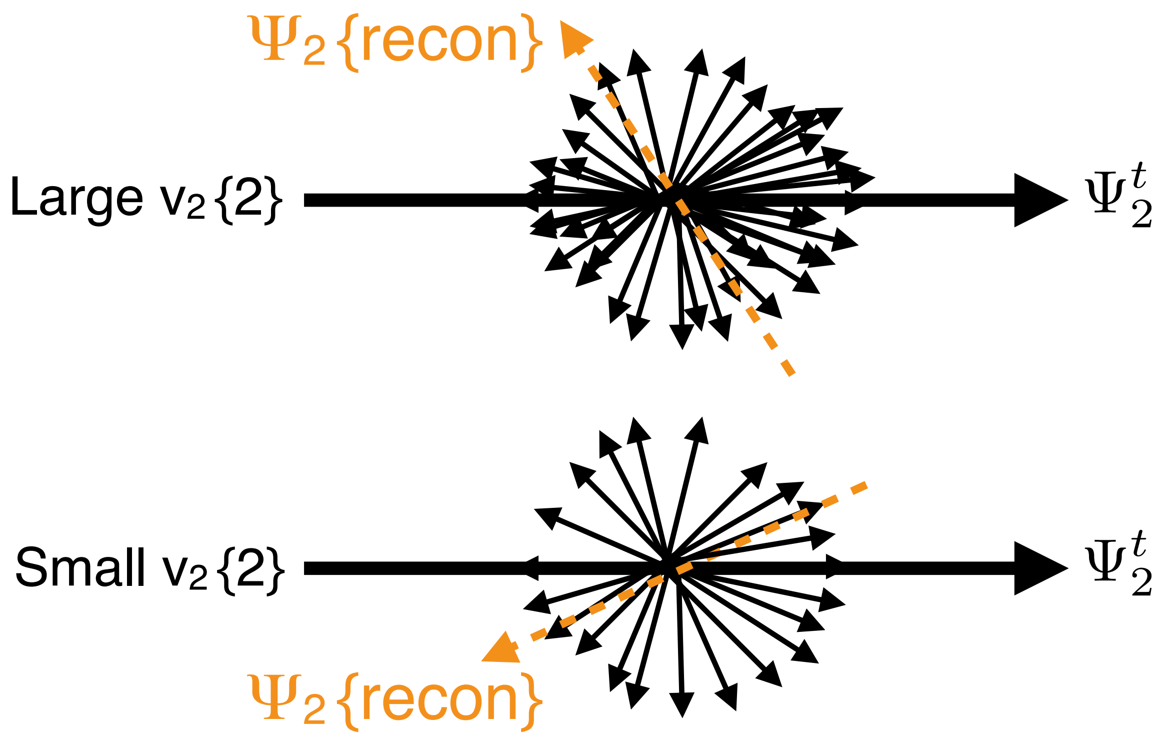
# Hydro vs other models such as CGC

## Hydrodynamics (single-particle anisotropy)

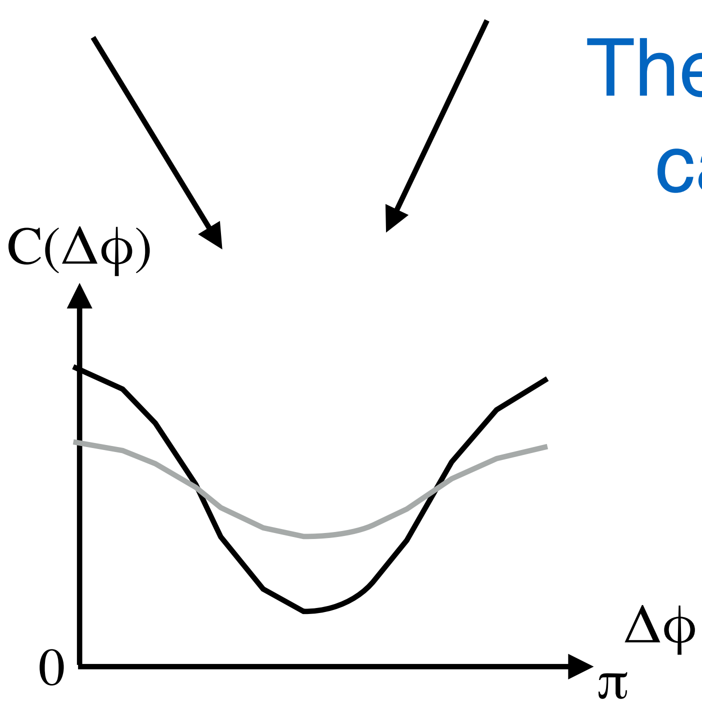



There is something called event-plane

## CGC (two-particle anisotropy)



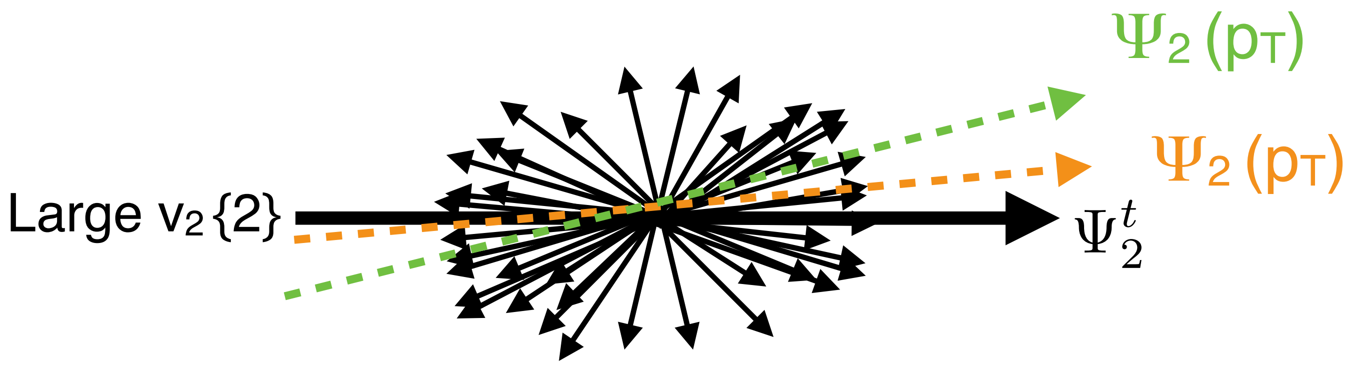

There is no such thing called event-plane



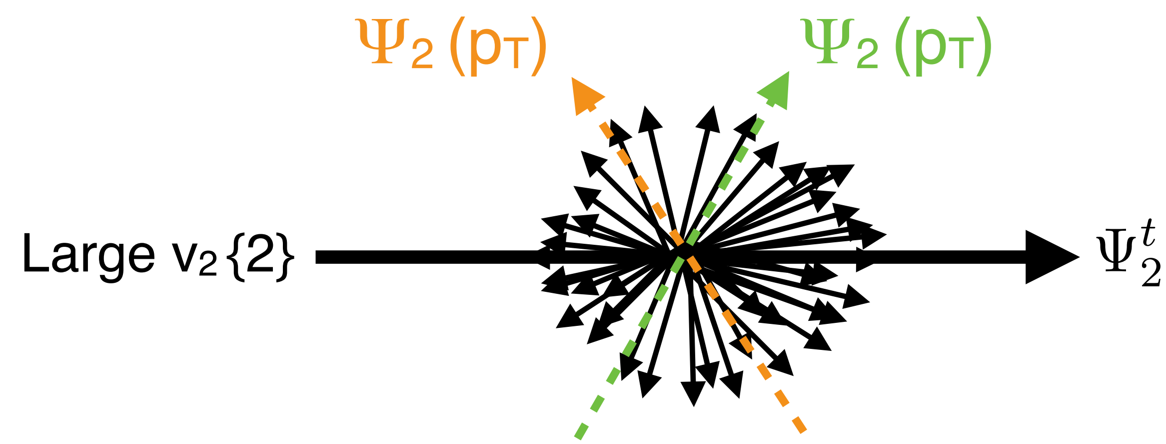
# How much anisotropy come from Hydro ?

Triggered by interesting discussions at GHP@APS 2019

Hydrodynamics (single-particle anisotropy)




CGC (two-particle anisotropy)




Goal is to test if factorization holds

$$v_2(2PC) = \frac{v_2^2\{2\}(p_{T,1}, p_{T,2})}{v_2\{2\}(p_{T,2}, p_{T,2})}$$

$$= \frac{\langle v_2(p_T, 1)v_2(p_{T,2})\cos(2\Psi_2(p_{T,1}) - 2\Psi_2(p_{T,2}))\rangle}{\sqrt{\langle v_2^2(p_{T,2})\rangle}}$$

Only STAR has the capability to measure factorization breaking of long-range azimuthal correlation, even one systems is enough

# Summary

| Physics Measurements | | Longitudinal decorrelation $C_n(\Delta\eta)$ $r_n(\eta_a,\eta_b)$ | Temperature dependent transport $\eta/s(T)$, $\zeta/s(T)$ | Mixed flow Harmonics correlation $C_{m,n,m+n}$ | Ridge $V_{n\Delta}$ | Event Shape and Jet-studies |
|---|---|---|---|---|---|---|
| **Detectors** | **Acceptance** | | | | | |
| Forward Calorimeter **(FCS)** | -2.5 > $\eta$ > - 4.2, $E_T$ (photons, hadrons) | One of these detectors necessary | | One of these detectors necessary | Good to have | One of these detectors needed |
| Forward Tracking System **(FTS)** | -2.5 > $\eta$ > - 4.2, $p_T$ (charged particles) | | Important | | Important | |

fSTAR upgrade at RHIC will provide unique opportunity to :

1) Breaking of boost invariance in heavy ion collisions
2) Transport parameters near the region of perfect fluidity
3) Breaking of flow factorization in small collision systems
4) Enhanced Spin Polarization and reduced CME like phenomena

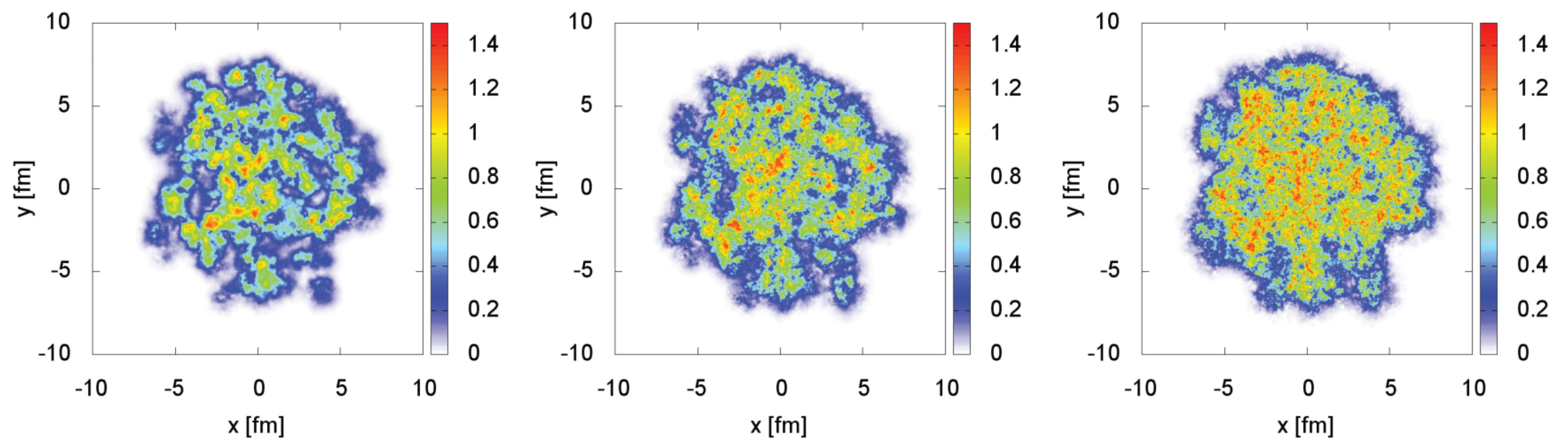
# Backup

# A different picture when you change rapidity

Schenke, Schlichting 1407.8458

How color fields inside colliding nuclei changes with x (rapidity)

$\eta = 0\,(x \approx 2 \times 10^{-3})$ $\eta = -2.3\,(x \approx 2 \times 10^{-4})$ $\eta = -4.8\,(x \approx 1.6 \times 10^{-5})$




Even for a fixed nucleon configuration the correlation length has to change as saturation scale change with rapidity

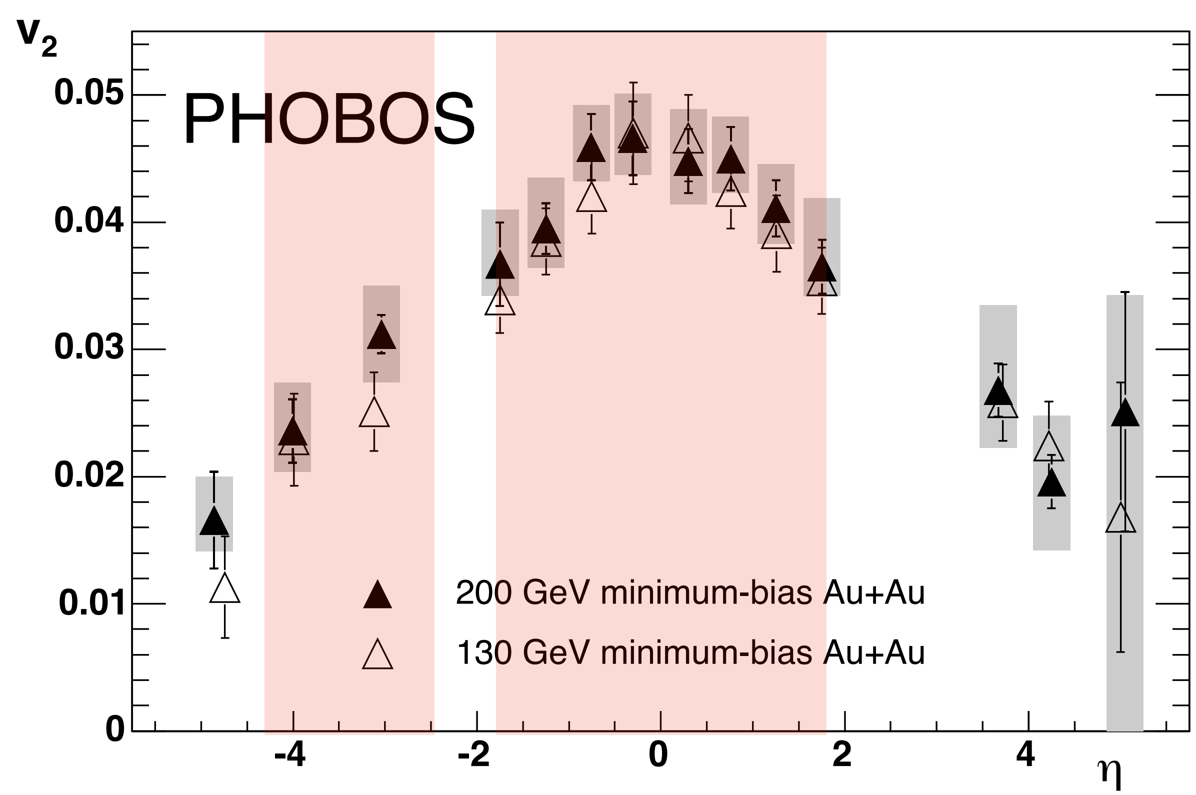
Can we study this with precision measurements at forward rapidity ?

# Many approaches to describe initial stages

# Existing measurements at forward rapidity

Limited previous measurements exist at forward rapidity at RHIC

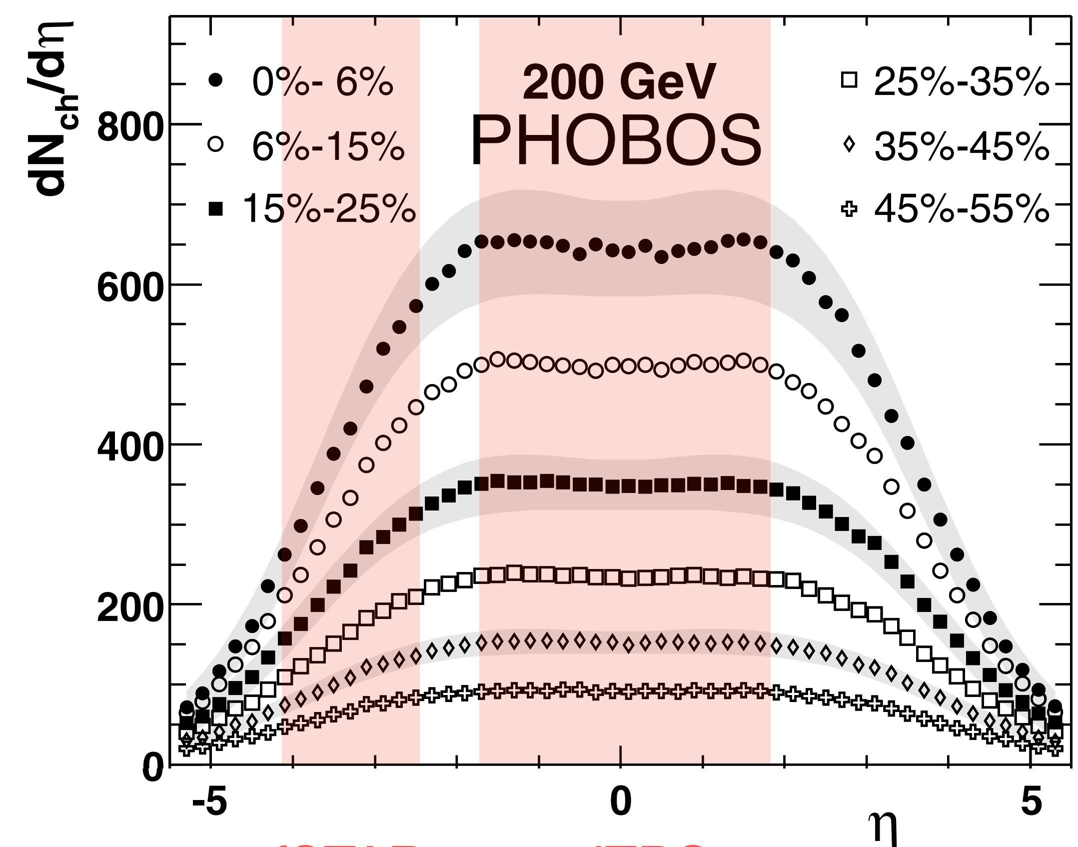
Phys Rev C 72, 051901(R) (2005)




fSTAR iTPC

Charged hadrons flow

Phys. Rev. Lett. 91, 052303 (2003)




fSTAR iTPC

Charged hadrons multiplicity

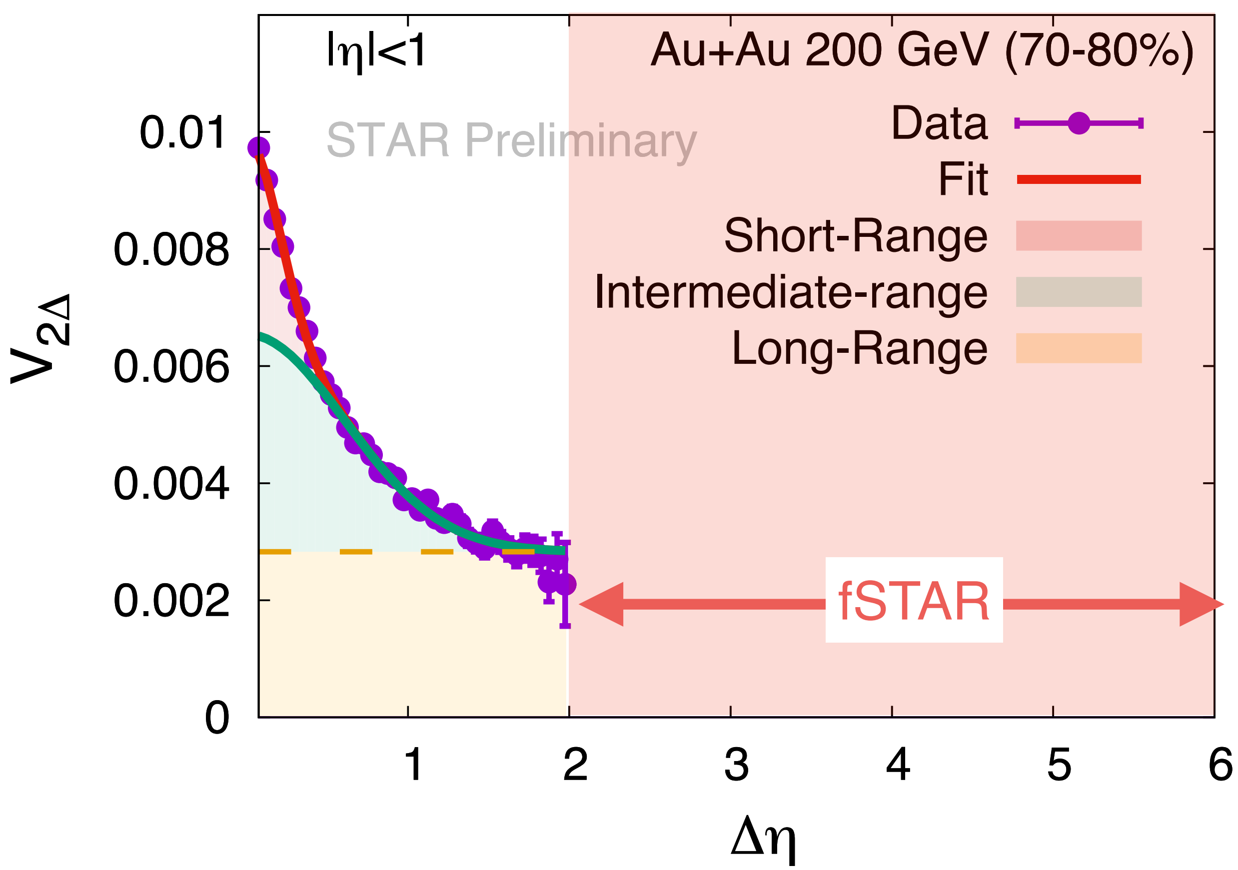
No data on higher order flow harmonics $(v_3, v_4, v_5)$& rapidity density correlations/fluctuations $\left\langle \frac{dN}{dY_1} \frac{dN}{dY_2} \right\rangle$ → fSTAR

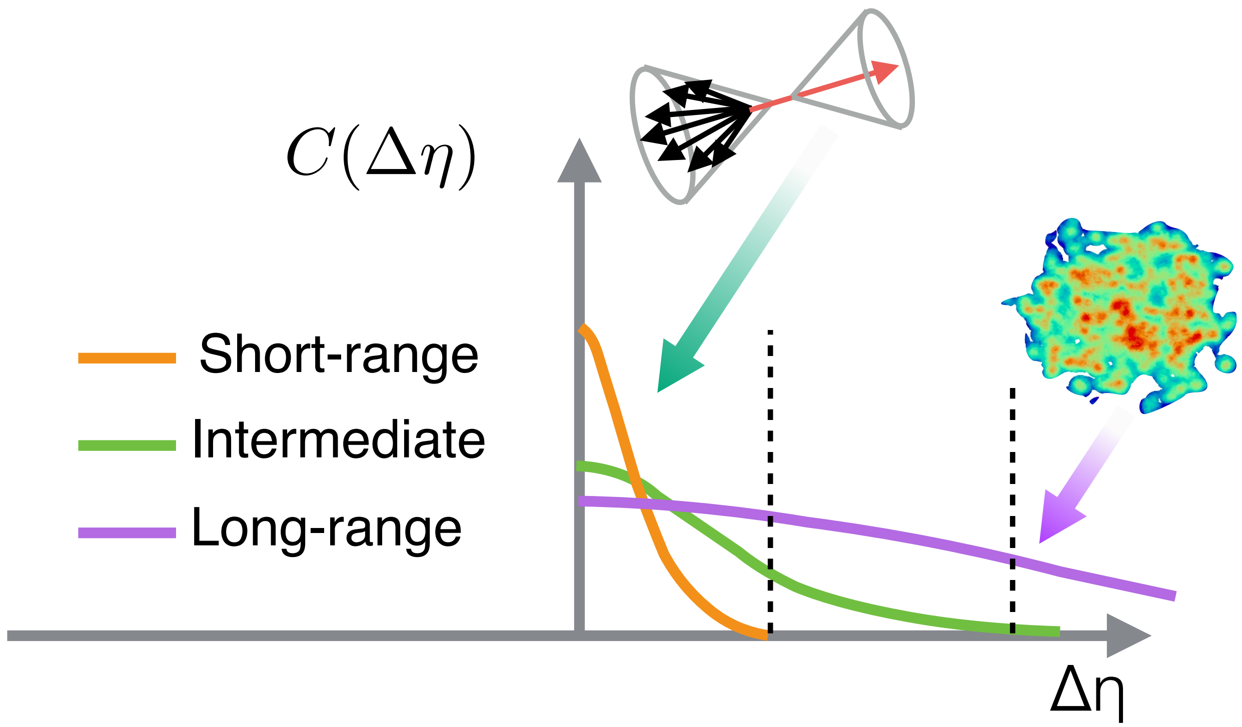
# Why do we need wider window of rapidity ?

Flow like correlations are early time long-range → large Δη

Background comes from Jets & non-flow → small Δη

$$V_{2\Delta} = \langle \cos(2(\phi_1(\eta_1) - \phi_2(\eta_2))) \rangle$$

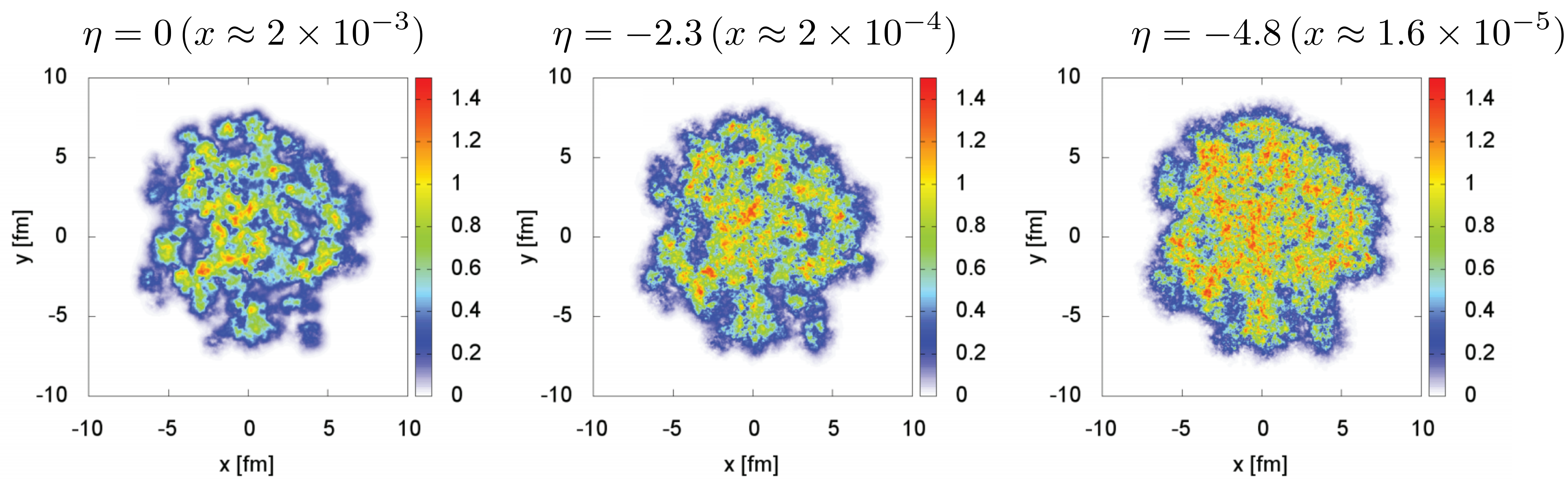


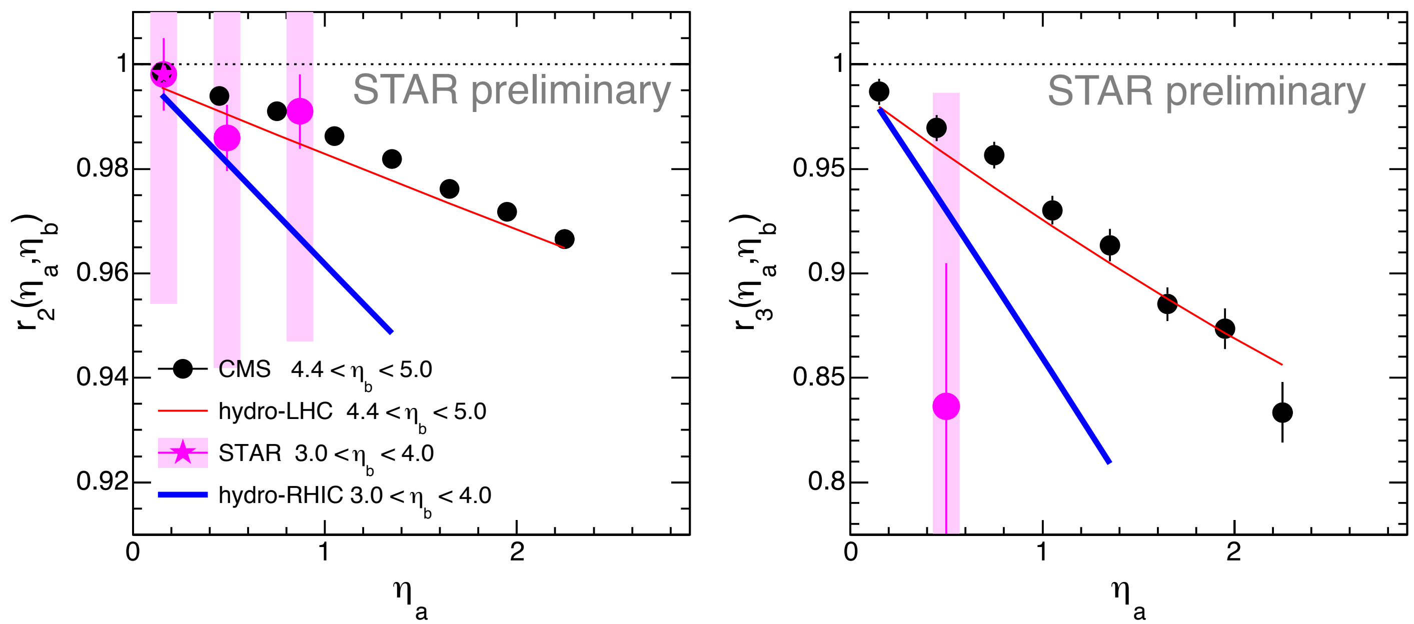

Precise extraction of flow (azimuthal correlations) requires measurements over wide window of rapidity

# Very first attempt from STAR

fig : Schenke, Schlichting 1605.07158




Observables : $r_n(\eta^a, \eta^b) \equiv \frac{V_{n\Delta}(-\eta^a, \eta^b)}{V_{n\Delta}(\eta^a, \eta^b)}$ $V_{n\Delta} = \langle \cos(n(\phi_1(\eta_1) - \phi_2(\eta_2))) \rangle$



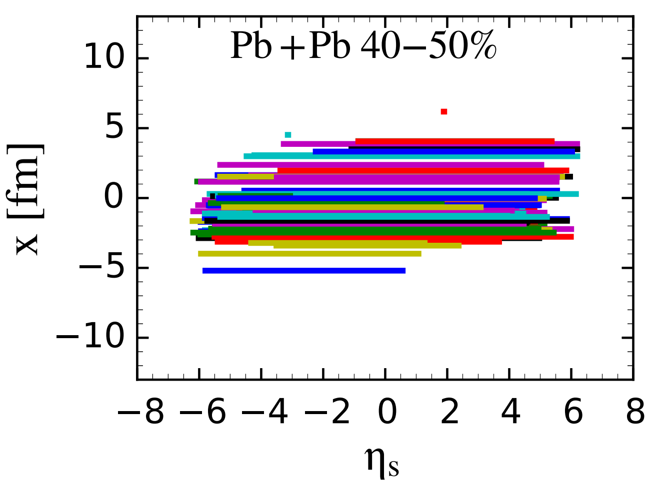

Current measurements with FTPC (3<η<4) have large uncertainties

**fSTAR will provide improved measurements**

# 3D structure of Initial state physics

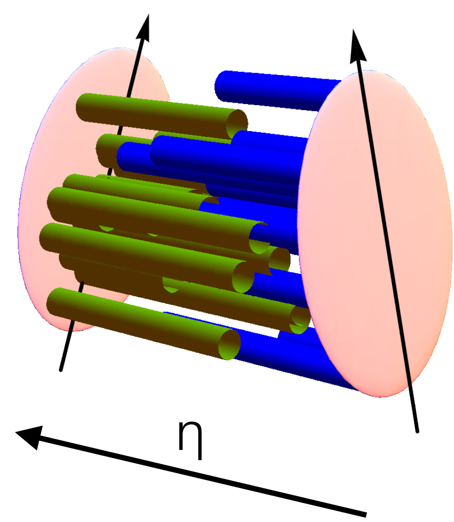
Several recent models have been proposed with different underlying dynamics for longitudinal structure of initial state of HICs

**Longitudinal strings**



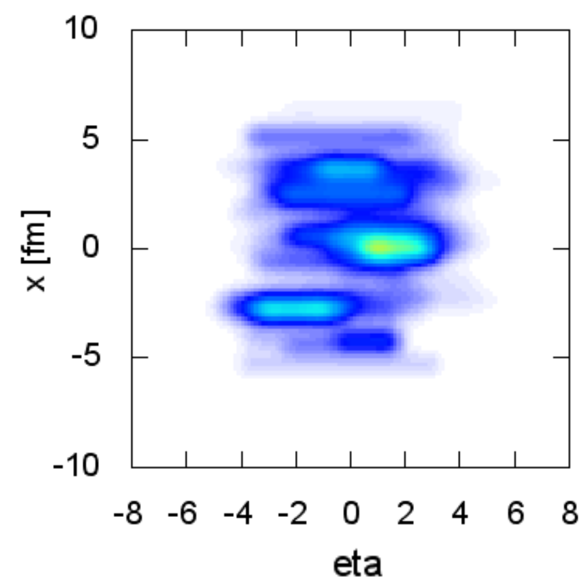

Pang, Petersen, Qin, Roy, Wang 1511.04131

**Torqued fireball**



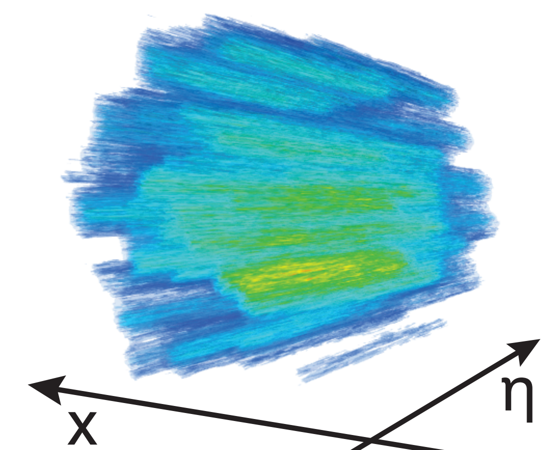

Bozek, Broniowski 1506.02817

**3D-Glauber**




Schenke, Monnai 1509.04103

**3D-Glasma**




Schenke, Schlichting 1605.07158

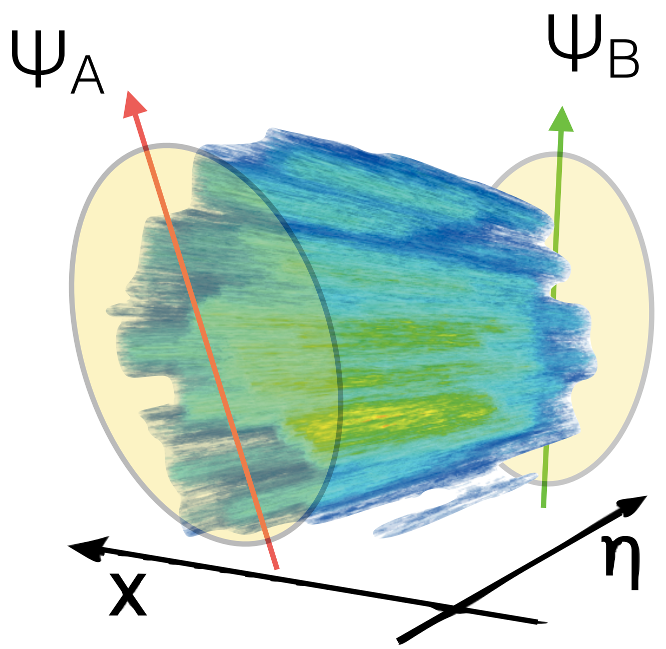
**Can future measurement discriminate these models ?**

**What is the scale at which boost invariance is broken ?**

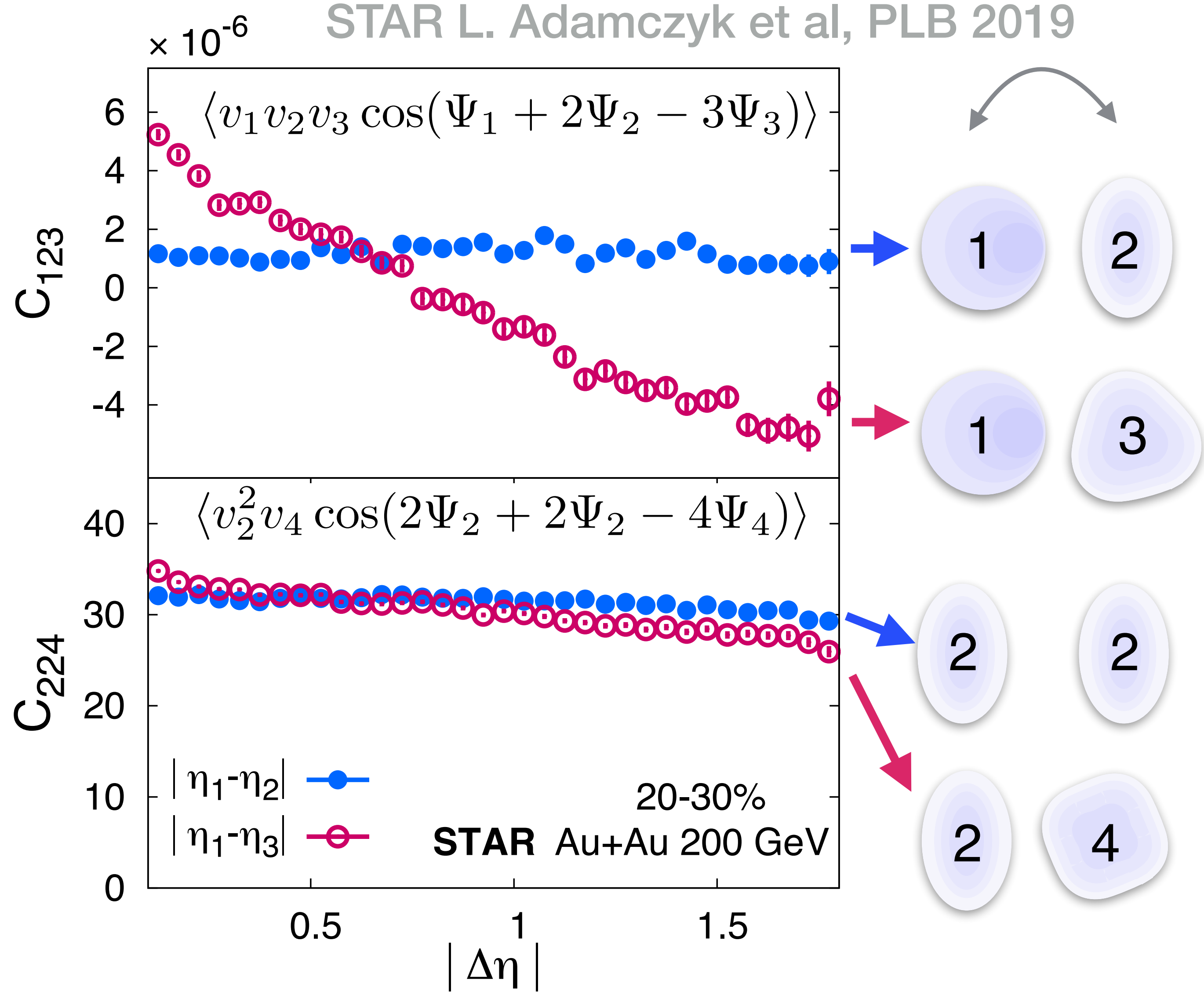
# Very first attempt from STAR

Measurement from STAR with existing detectors :
Hints of longitudinal de-correlations

fig : 1605.07158




STAR L. Adamczyk et al, PLB 2019




Measurement using 300 M event with TPC → could go up to 1.8

# Very first attempt from STAR

Measurement from STAR with existing detectors :
Hint of longitudinal de-correlations

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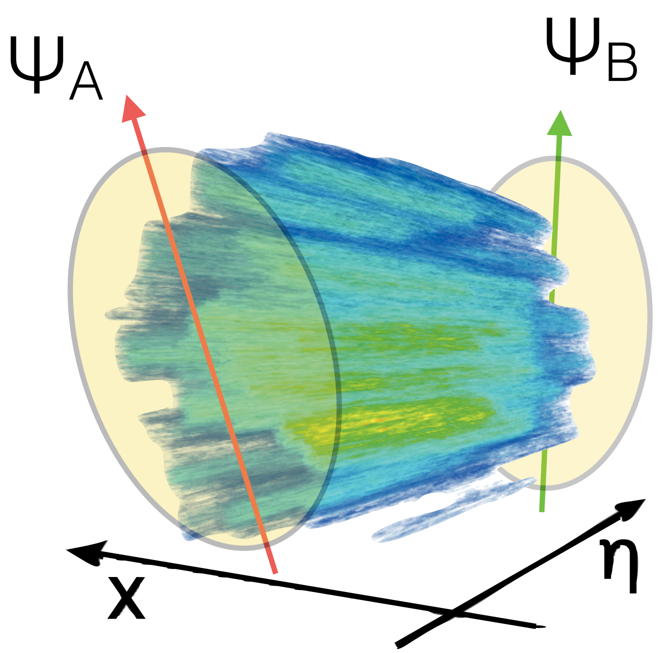
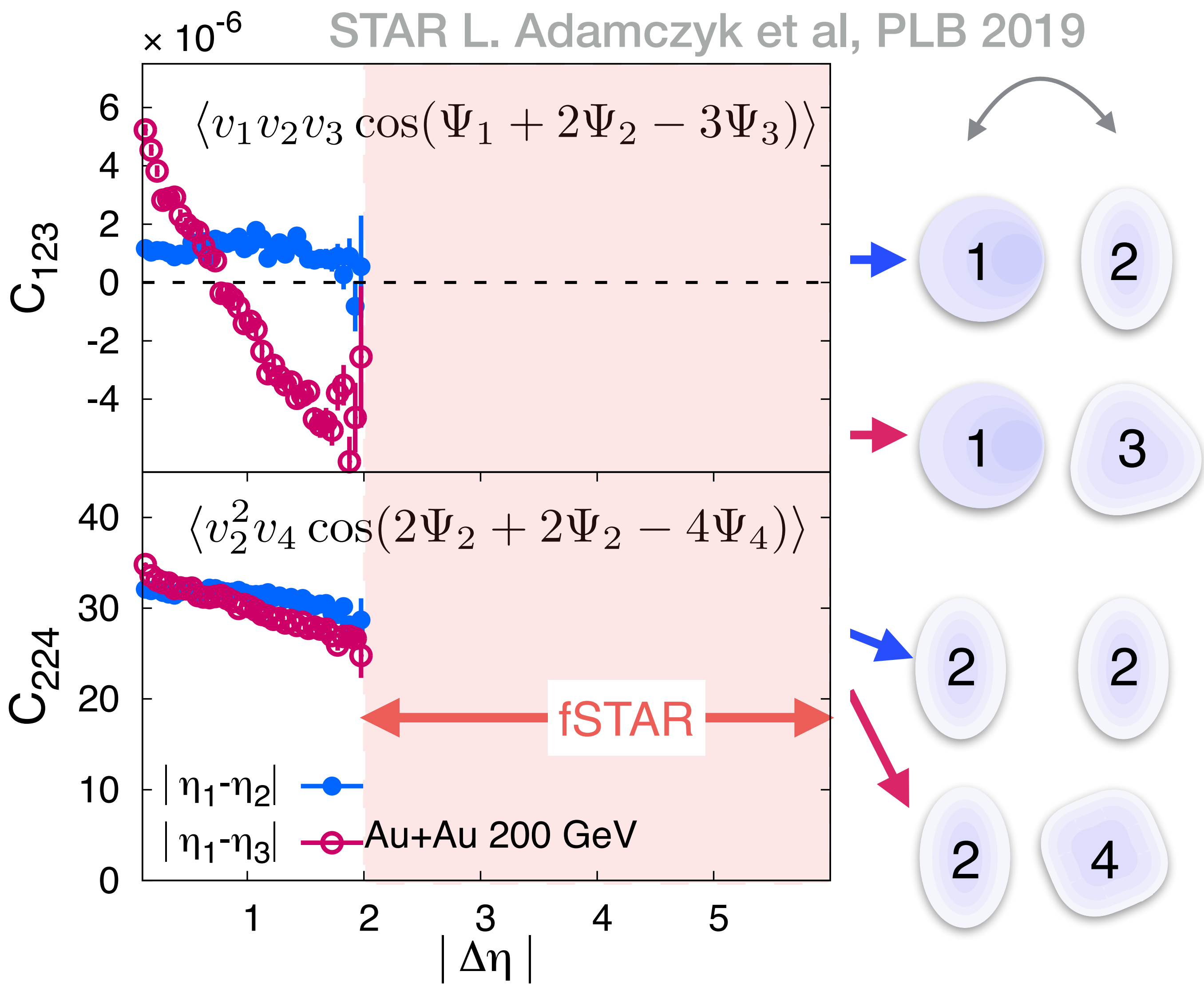



STAR L. Adamczyk et al, PLB 2019




Measurement using 300 M event with TPC → could go up to 1.8

Wider Δη can probe this in more details