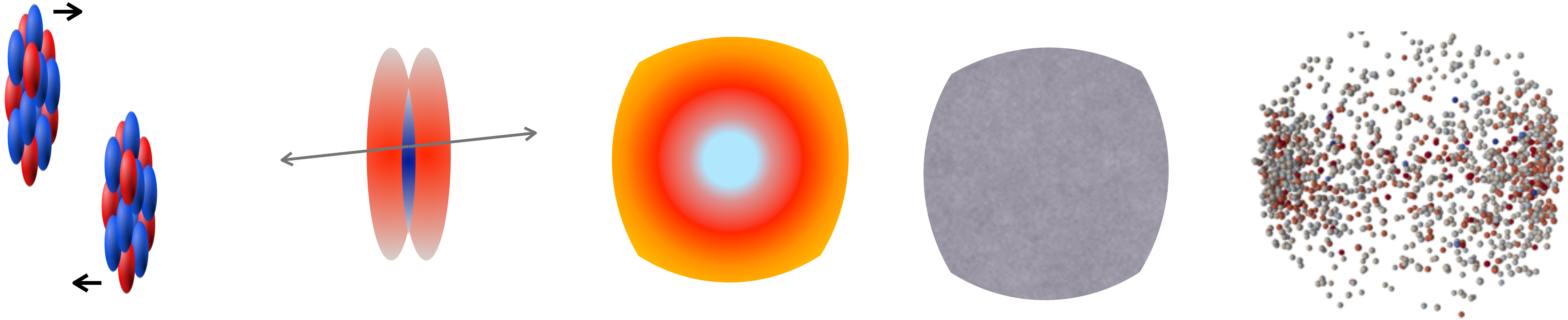
Recap: timeline of a heavy-ion collision



colliding nuclei | collision | QGP | hadronization | hadrons

- what we can constrain in e+A experiments (e.g. EIC)

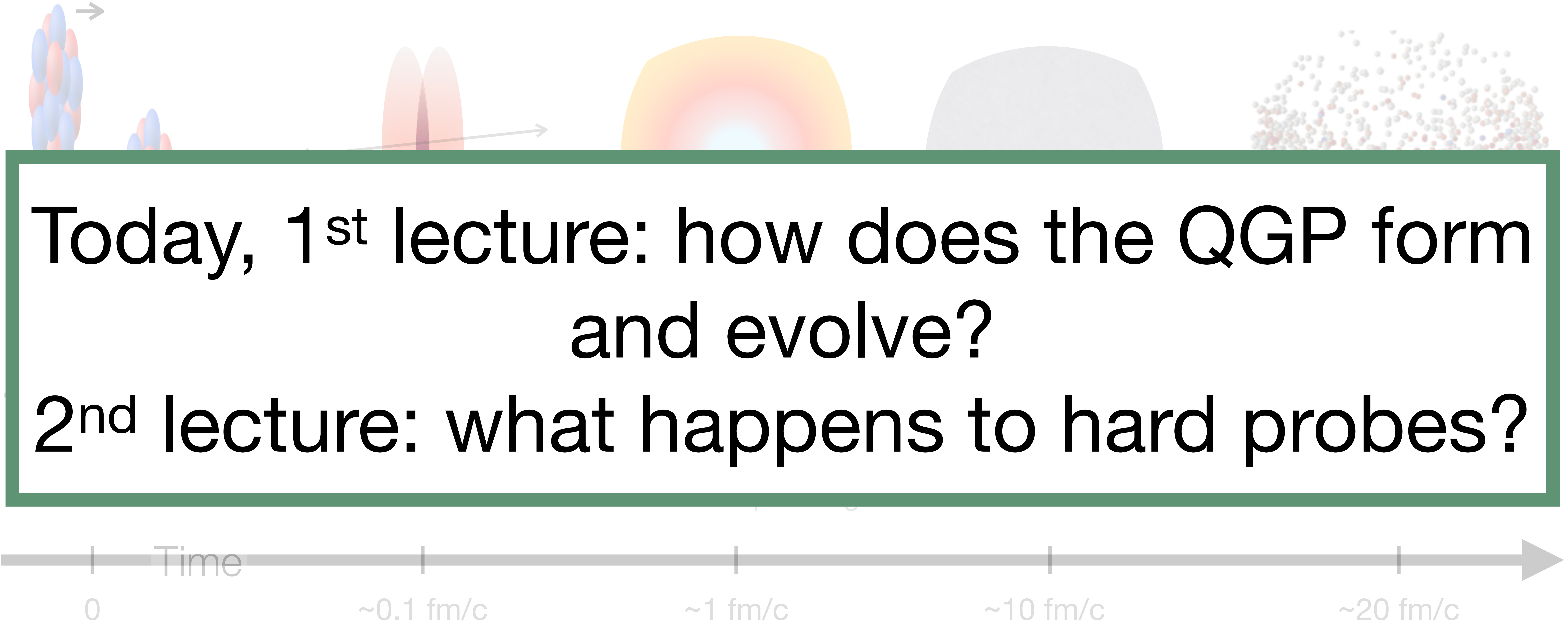
- what we want to understand:
  - how we get here?
  - what it is?
  - how it stops being?

- all we have

Time

0 | ~0.1 fm/c | ~1 fm/c | ~10 fm/c | ~20 fm/c

Recap: timeline of a heavy-ion collision

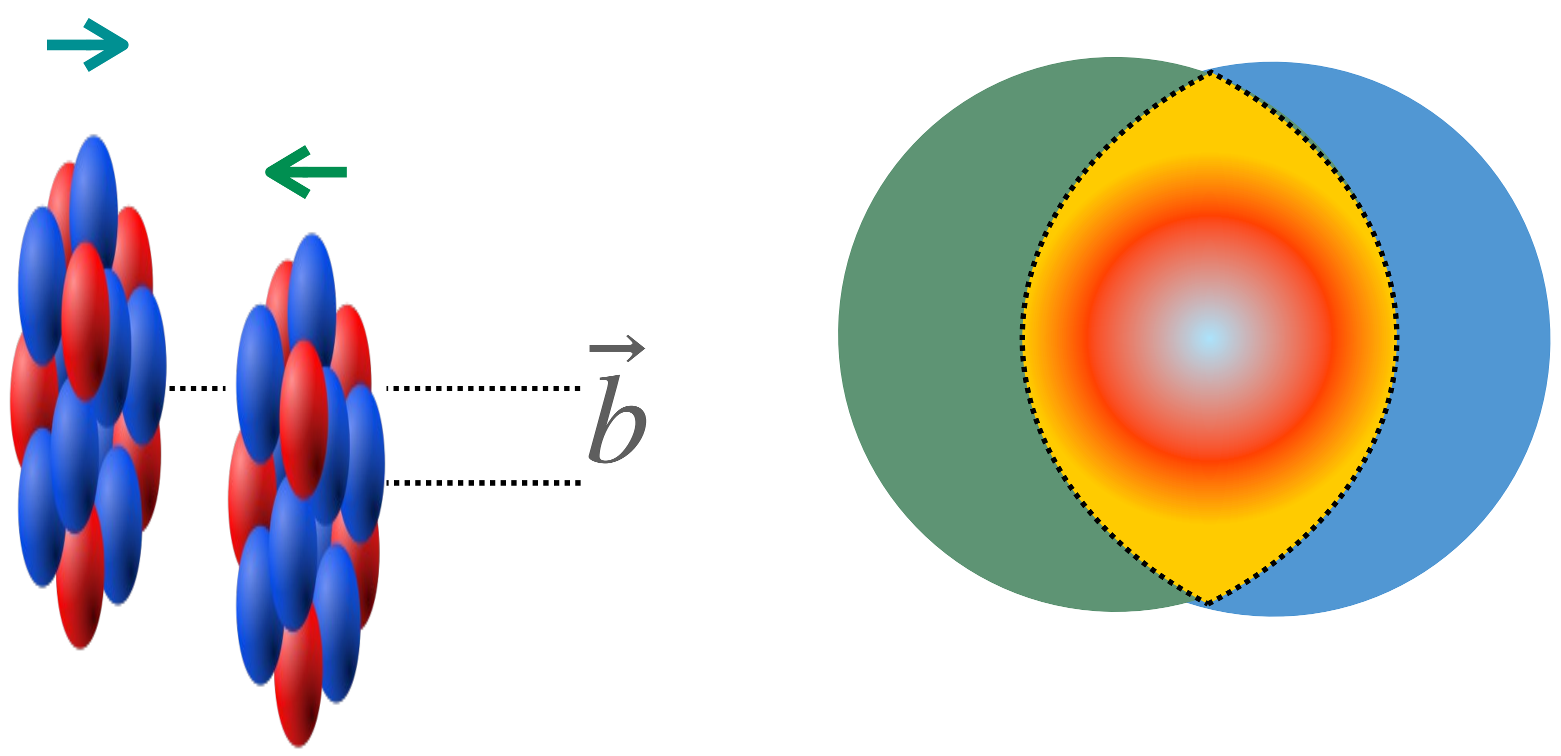


Today, 1st lecture: how does the QGP form and evolve?

2nd lecture: what happens to hard probes?

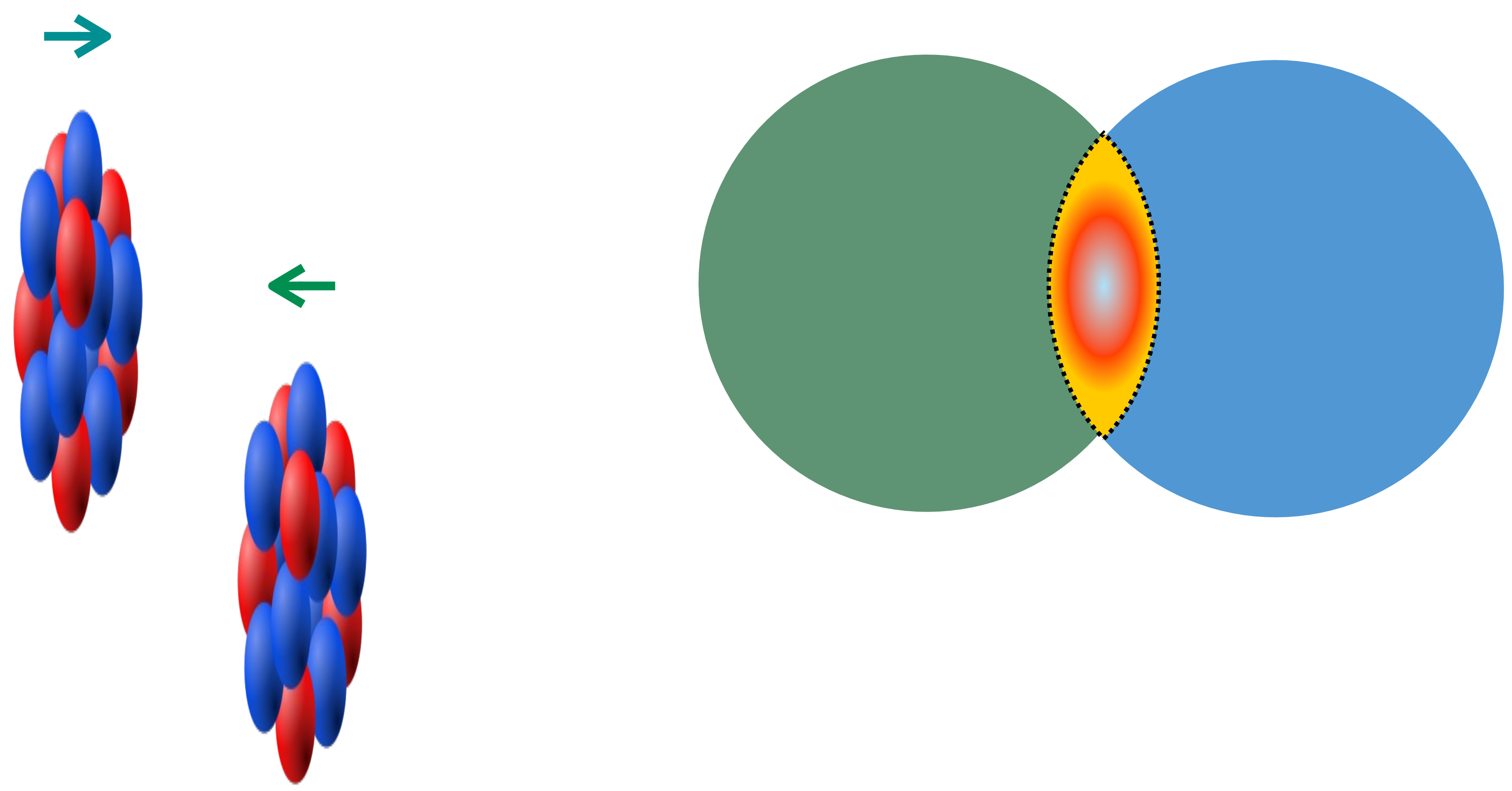
Recap from yesterday

Central collision



- Hotter medium
- Larger energy density
- More particles produced

Peripheral collision



- Cooler medium
- Smaller energy density
- Few particles produced

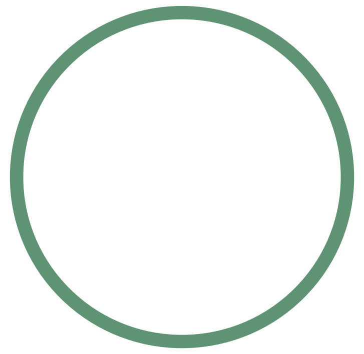
The initial geometry of the system for off-central collisions is clearly anisotropic

Spatial eccentricities

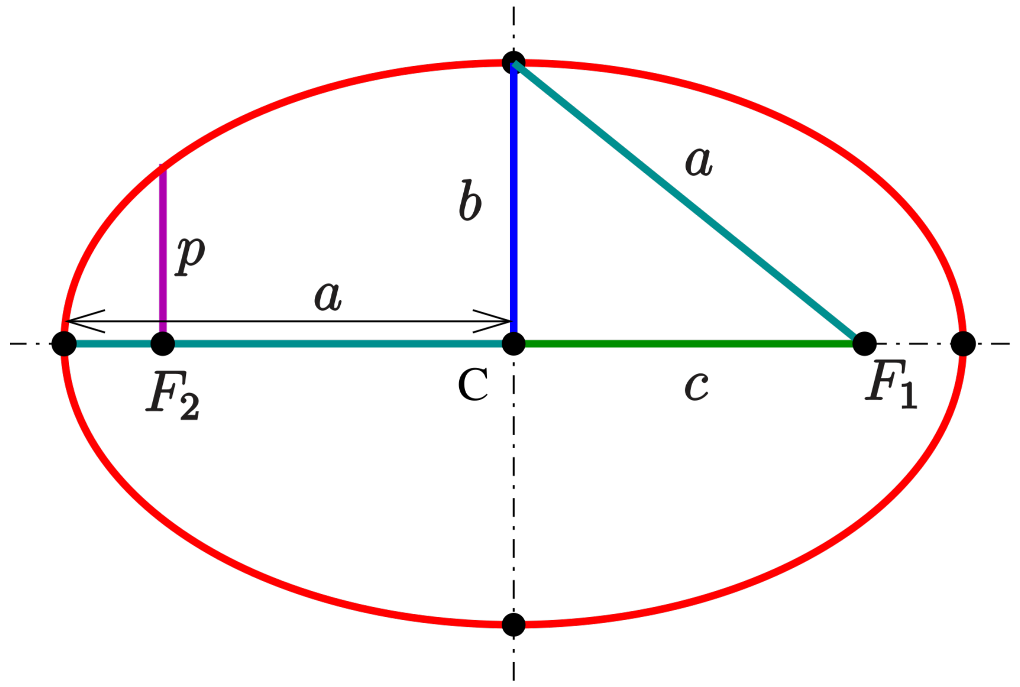
Quantitative measurement of the initial anisotropy of the geometry in a collision

$$0 \leq \varepsilon_n = \frac{\sqrt{\langle r^n \cos(n\phi) \rangle + \langle r^n \sin(n\phi) \rangle}}{\langle r^n \rangle} \leq 1$$

For $n = 2$ it reduces to standard definition of the eccentricity, i.e.



$\varepsilon_2 = 0$



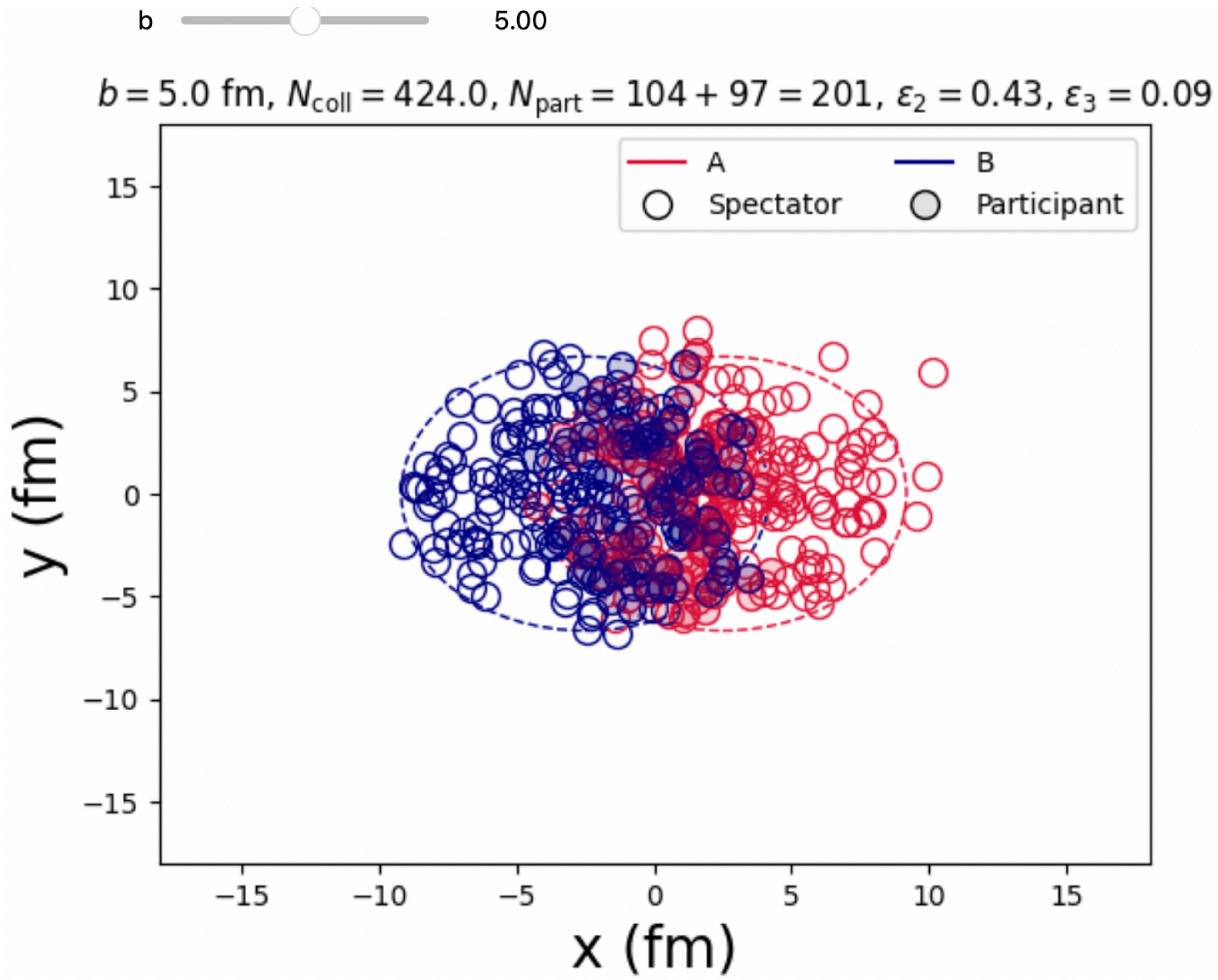
$$\varepsilon_2 = \sqrt{1 - \frac{b^2}{a^2}}$$

Higher moments characterise the triangularity, quadrupolarity etc

Note: in Glauber MC odd eccentricity moments arise through fluctuations

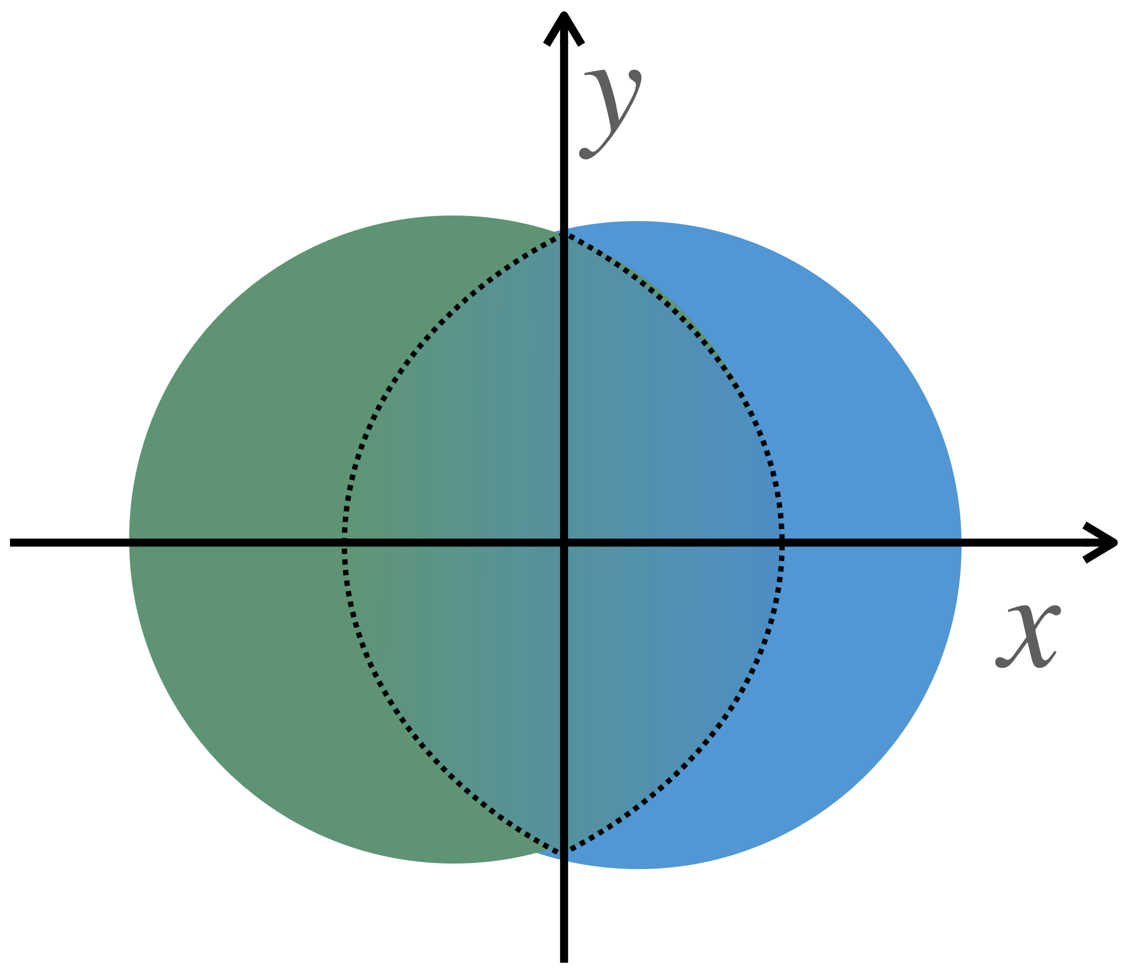
Spatial eccentricities in Glauber MC

`2024-Granada-heavyion-lectures/mc-glauber.ipynb`



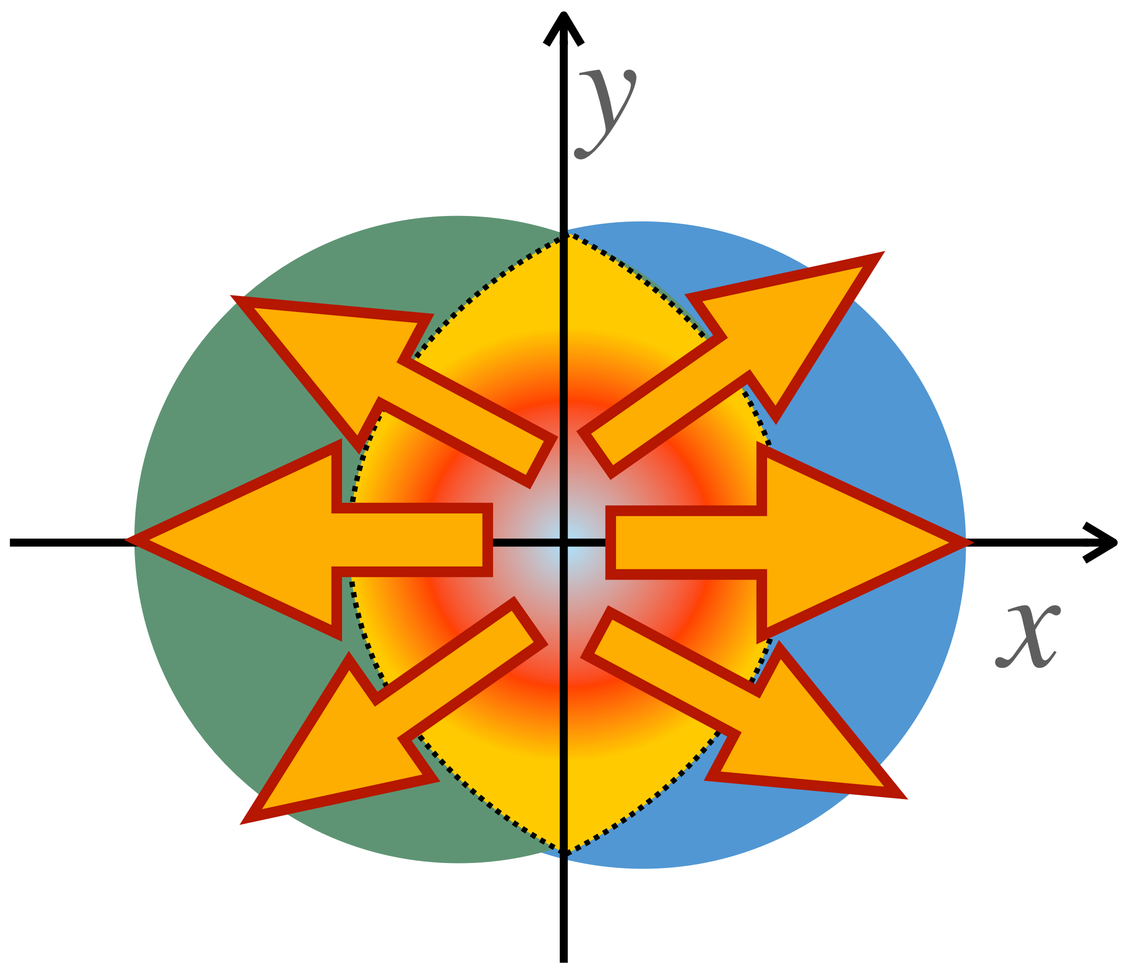
From spatial eccentricities to flow harmonics

[Ollitrault PRD 46 (1992) 229-24]

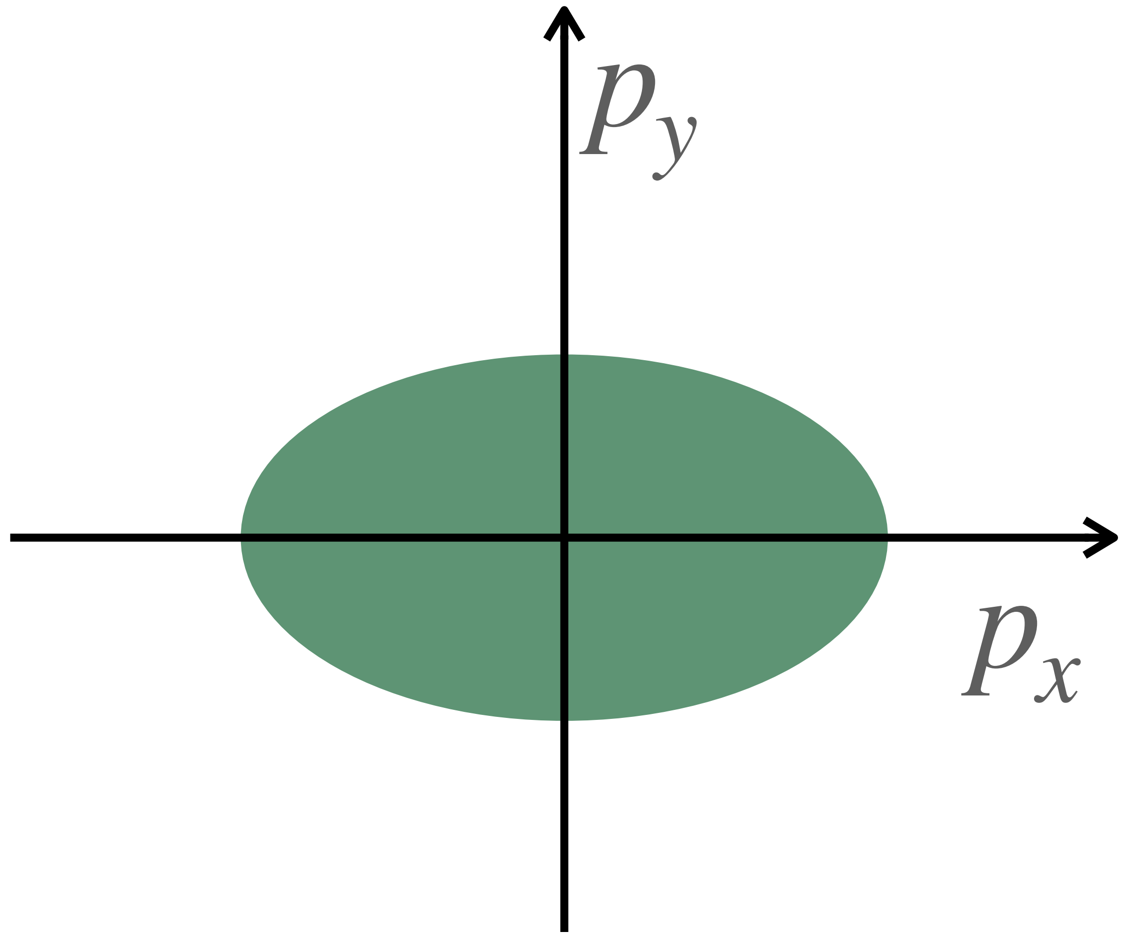


Initial geometry anisotropy

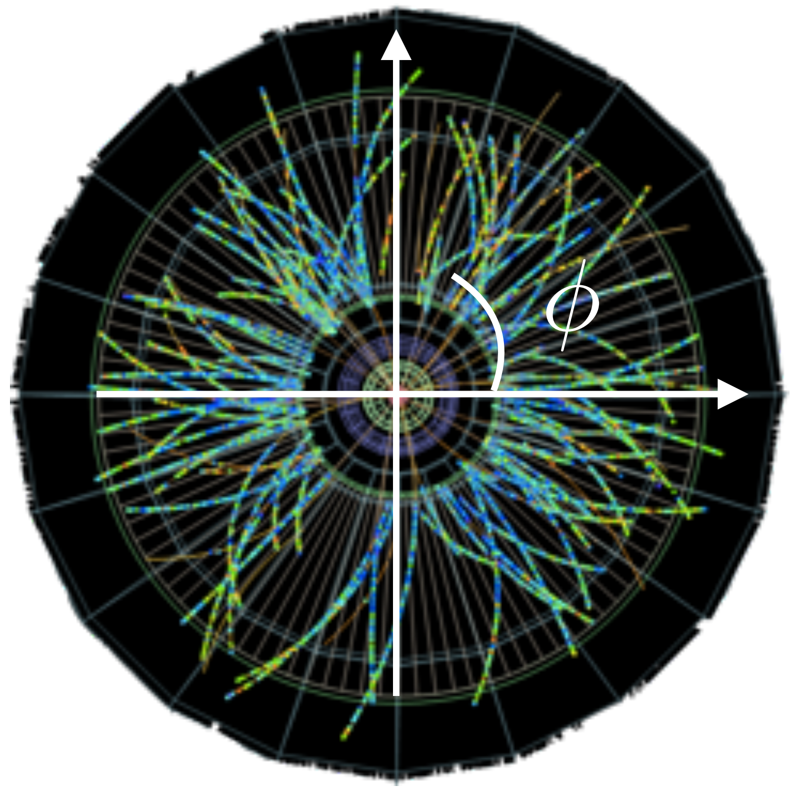
if QGP



Pressure gradients



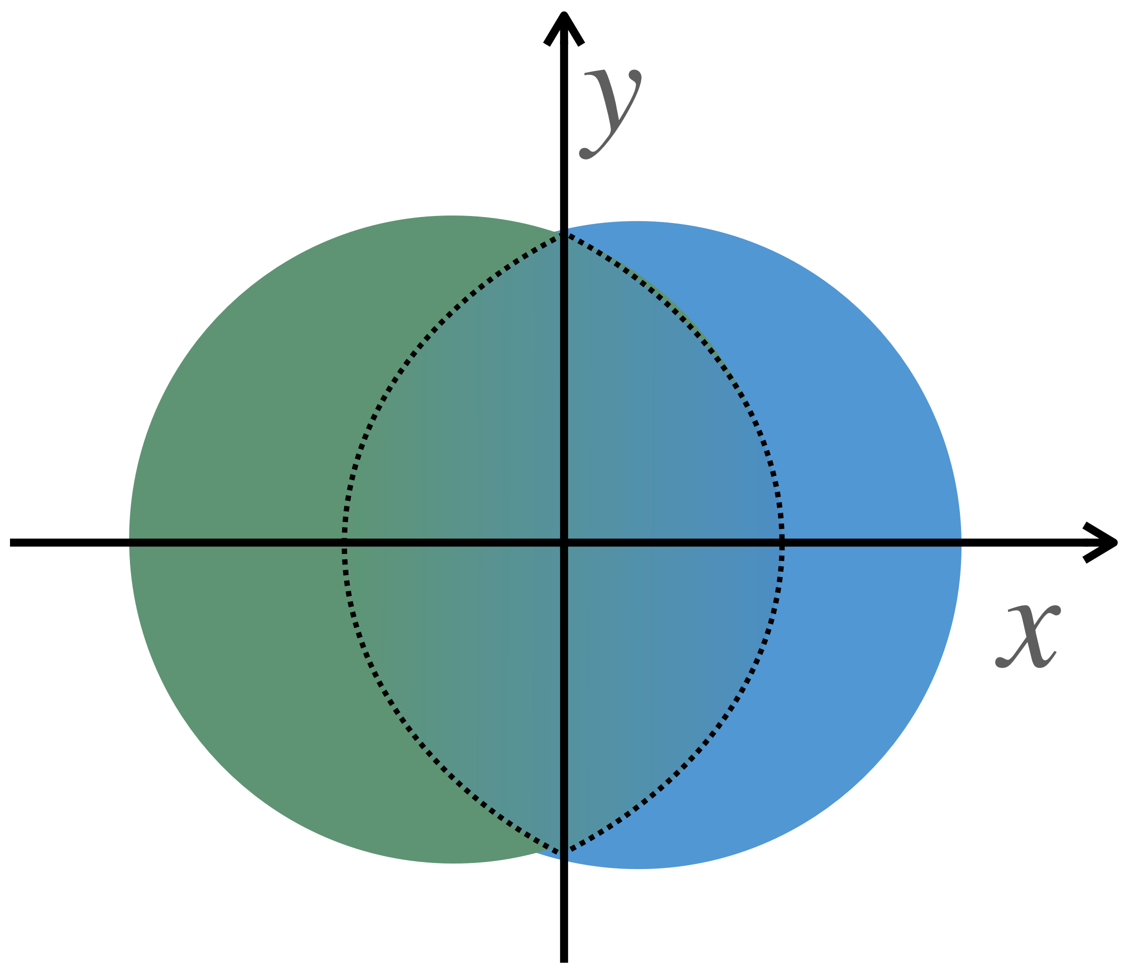
Momentum anisotropy



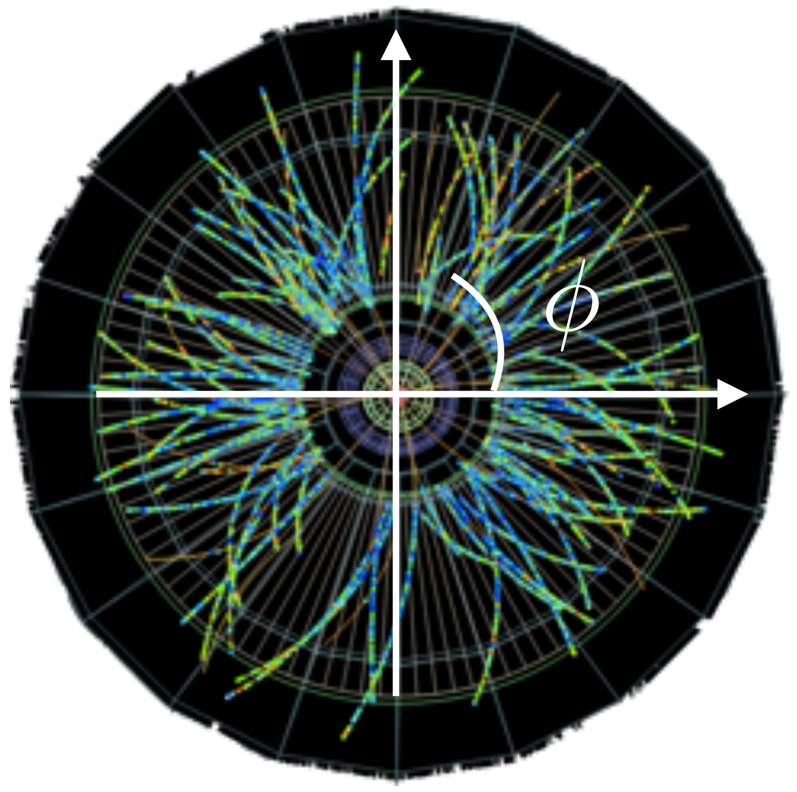
Non-flat azimuthal distribution

From spatial eccentricities to flow harmonics

[Ollitrault PRD 46 (1992) 229-24]



if QGP



Initial geometry anisotropy

Anisotropic particle distribution

reaction plane angle

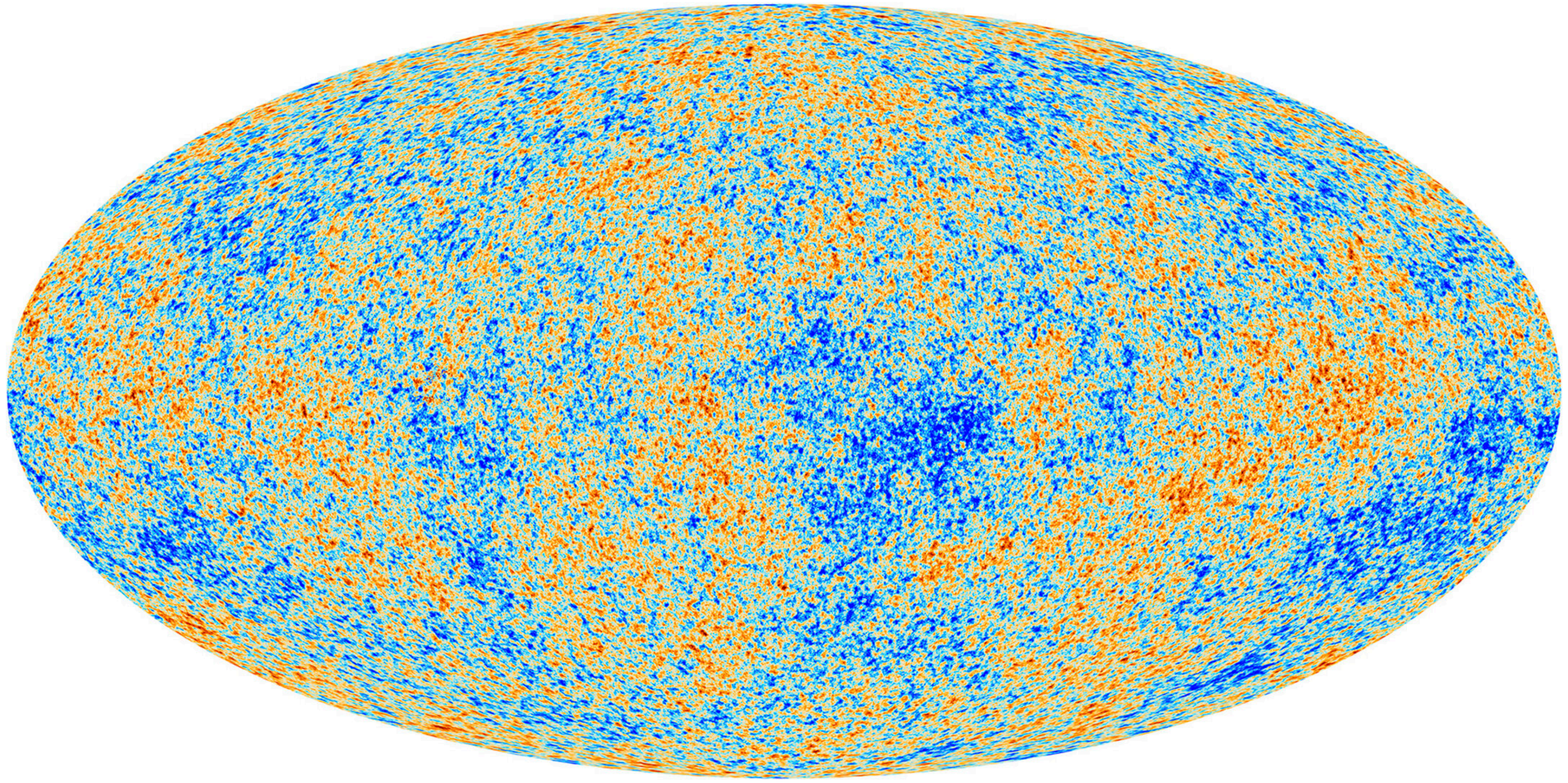
$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left[1 + 2\sum_n v_n(p_t, y)\cos(\phi - \Psi)\right]$$

- v_2: measures ellipticity of momentum distribution
- Odd coefficients: vanish by $\phi \to \phi + \pi$ symmetry (always?)

From the Big Bang to the Little Bang: flow harmonics

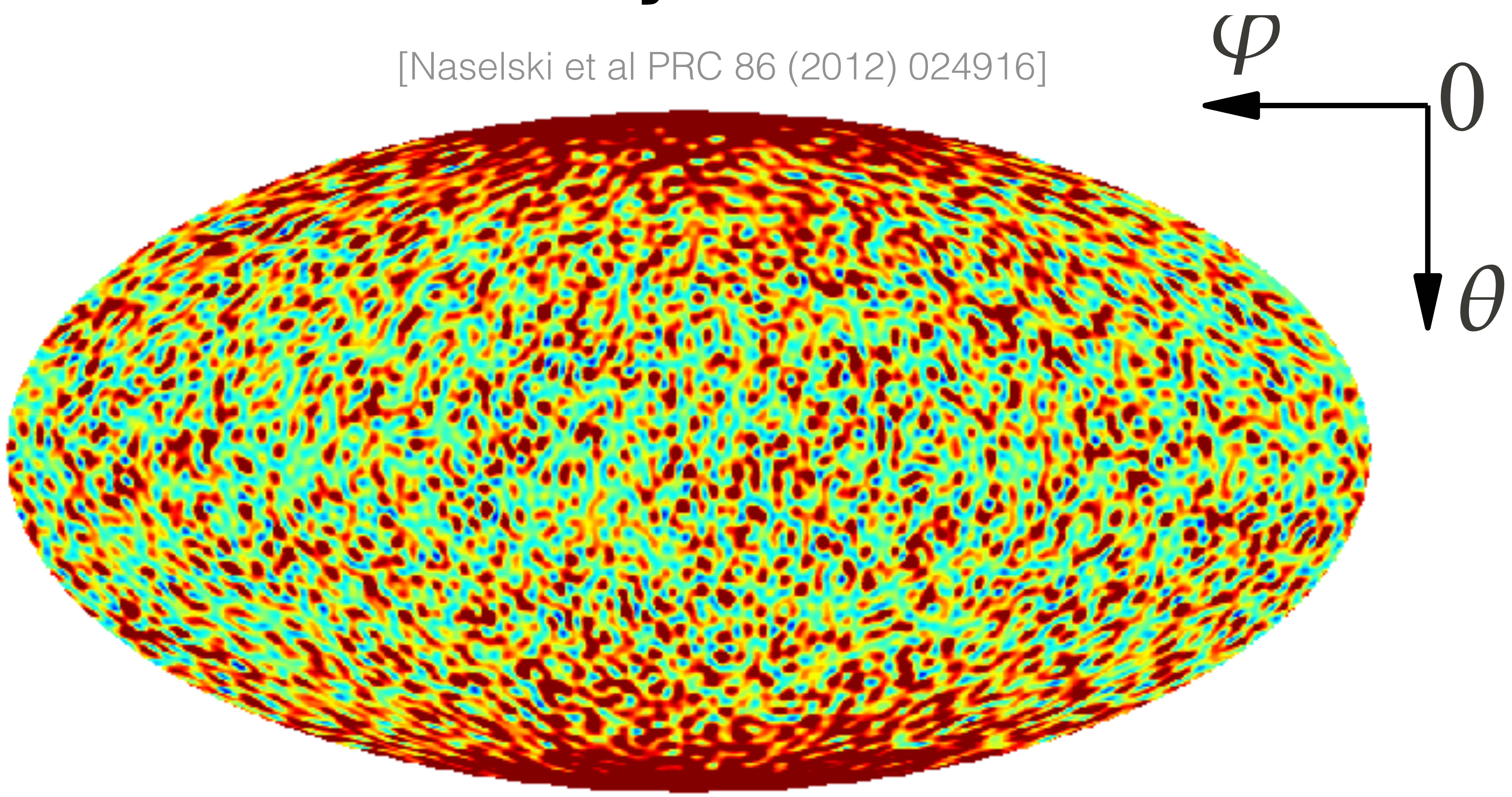
Cosmic Microwave Background

[PLANCK Collab Astron.Astrophys. 594 (2016) A13]



1 heavy-ion event

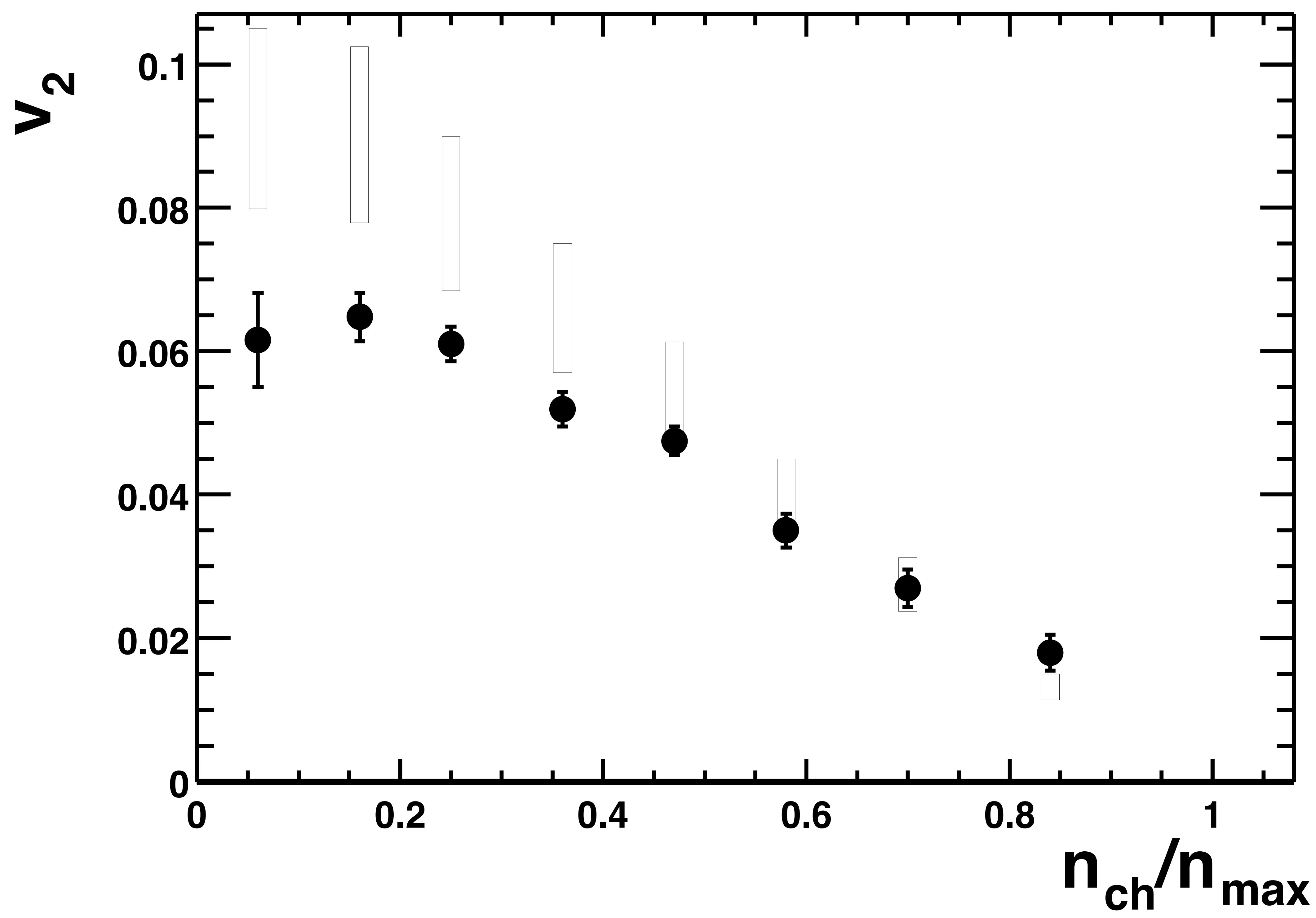
[Naselski et al PRC 86 (2012) 024916]

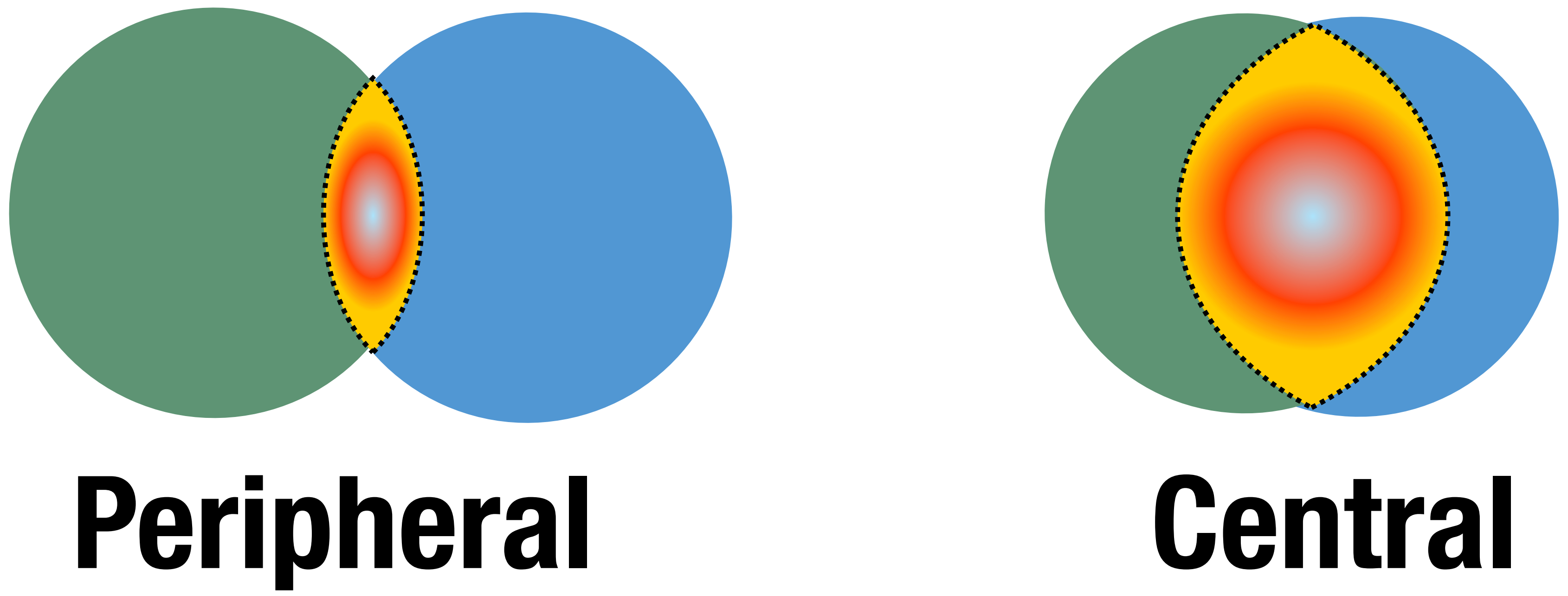


Anisotropies inform about the evolution of the Universe

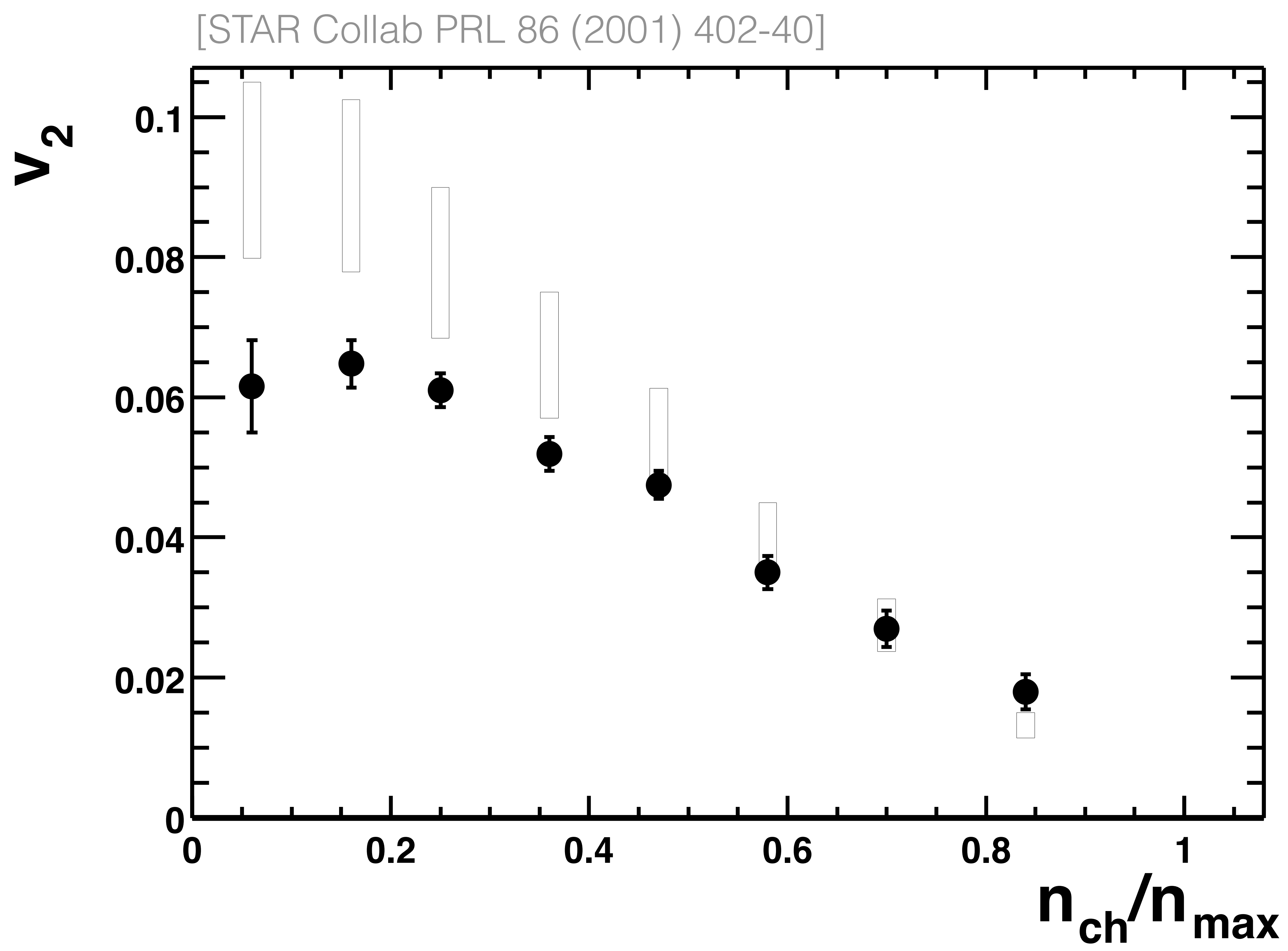
QCD matter flows: centrality dependence

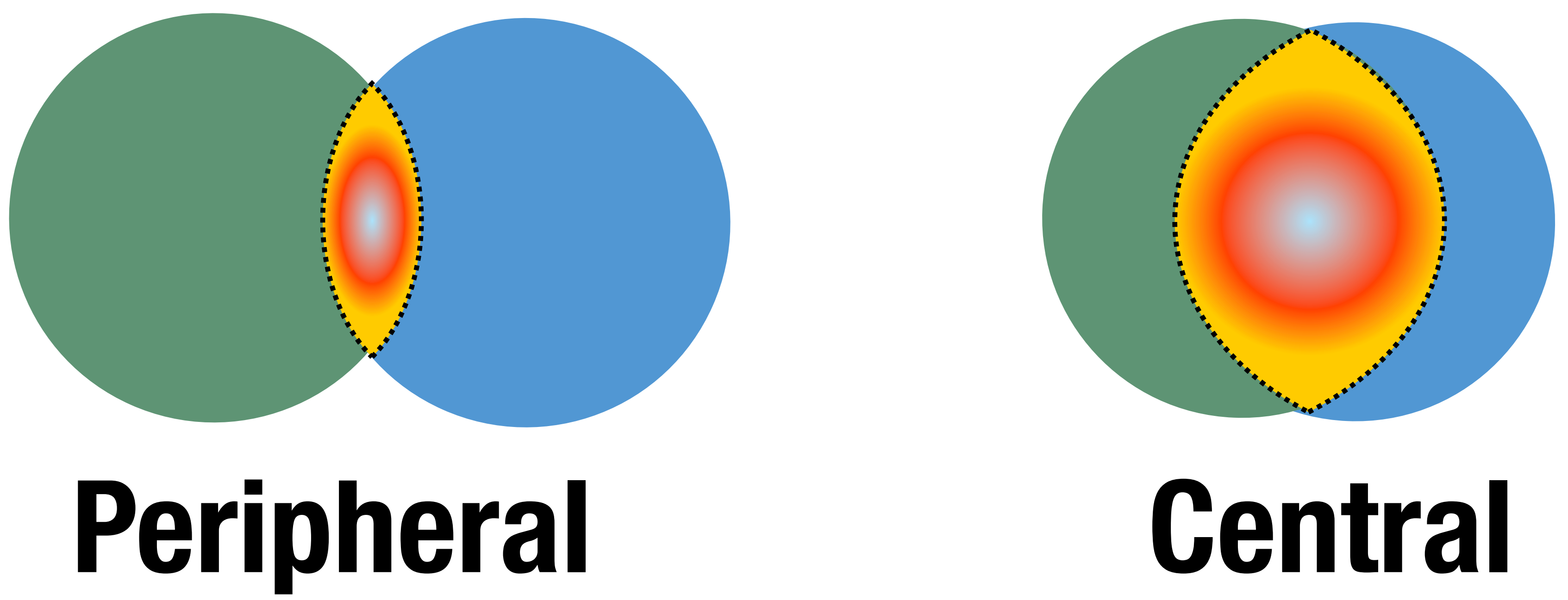
[STAR Collab PRL 86 (2001) 402-40]





QCD matter flows: centrality dependence



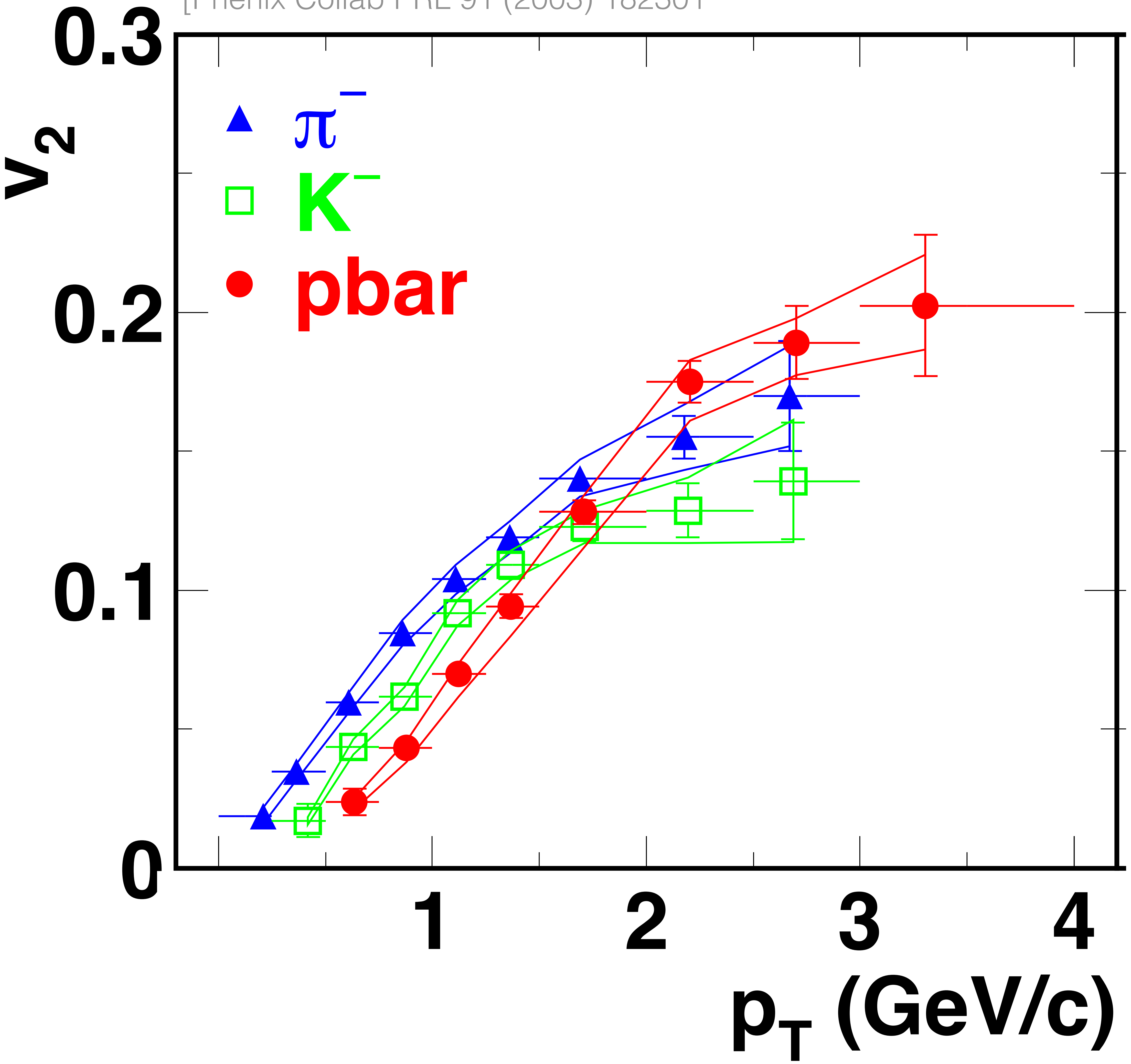


Strong centrality dependence:

- Small for central (no spatial asymmetry)
- Maximum for mid-central
- Smaller again for very peripheral (smaller QGP)

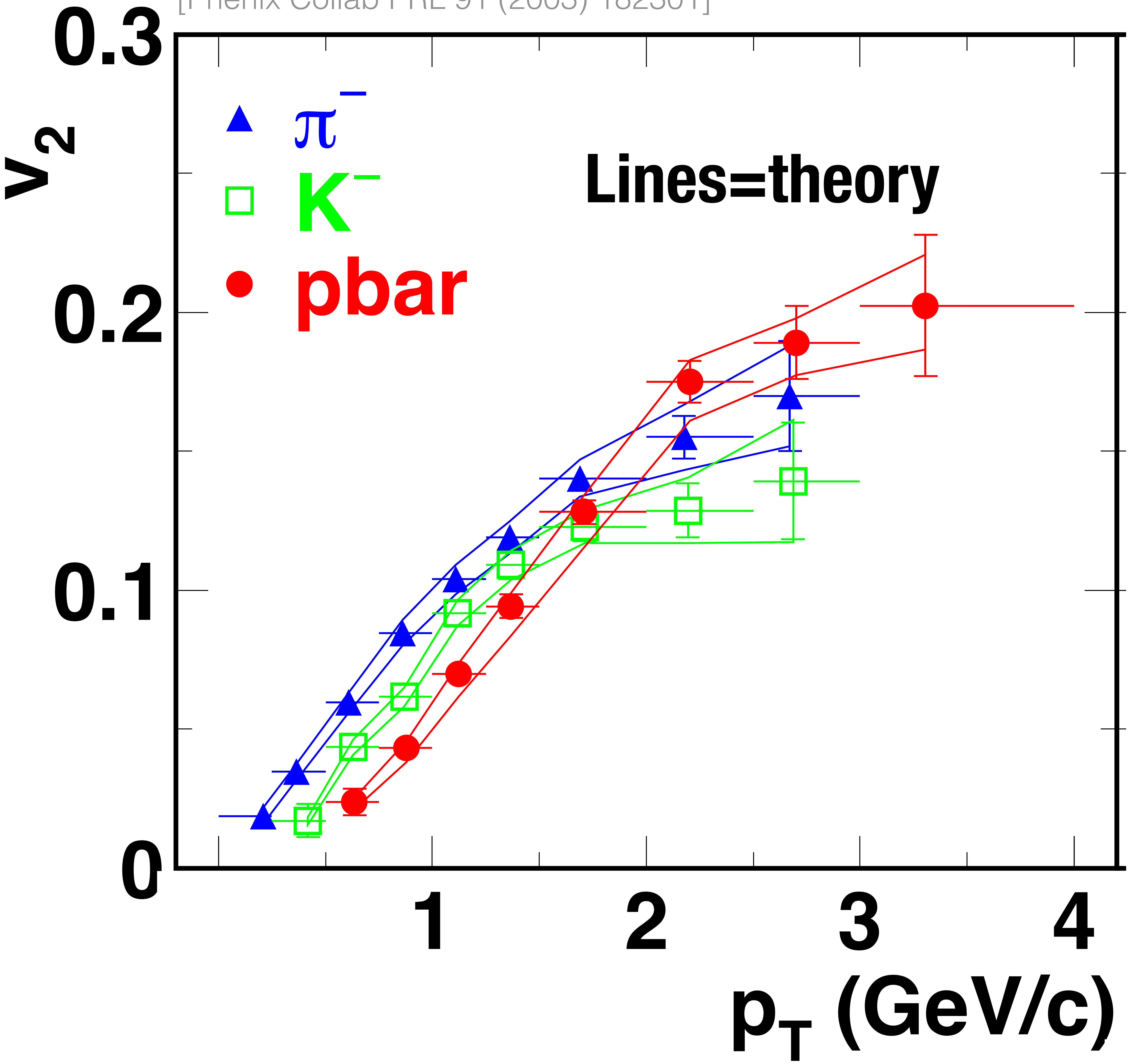
QCD matter flows: mass dependence

[Phenix Collab PRL 91 (2003) 182301



QCD matter flows: mass dependence

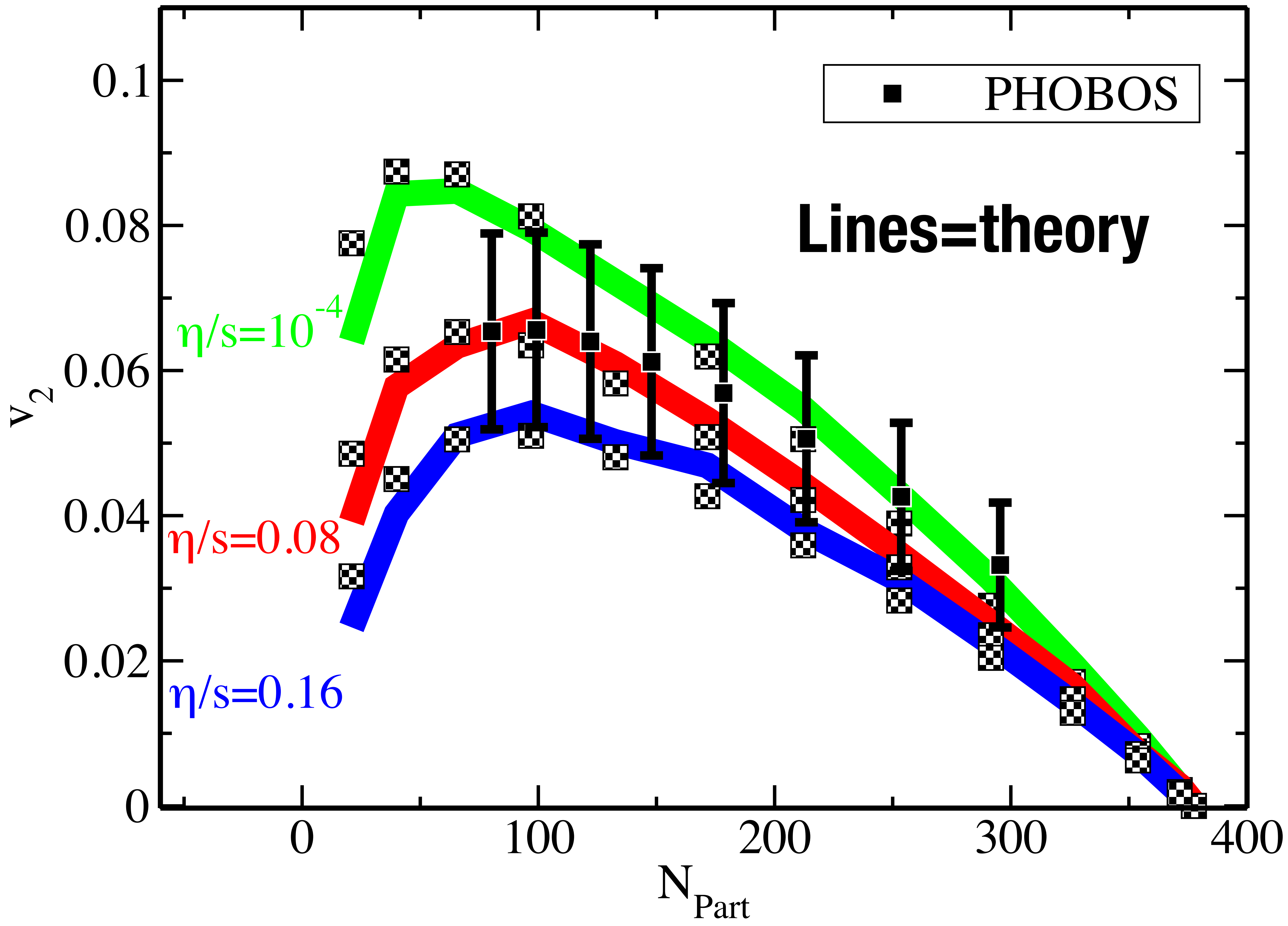
[Phenix Collab PRL 91 (2003) 182301]



Heavier particles flow less.
Theory (to be explained) does a very good job

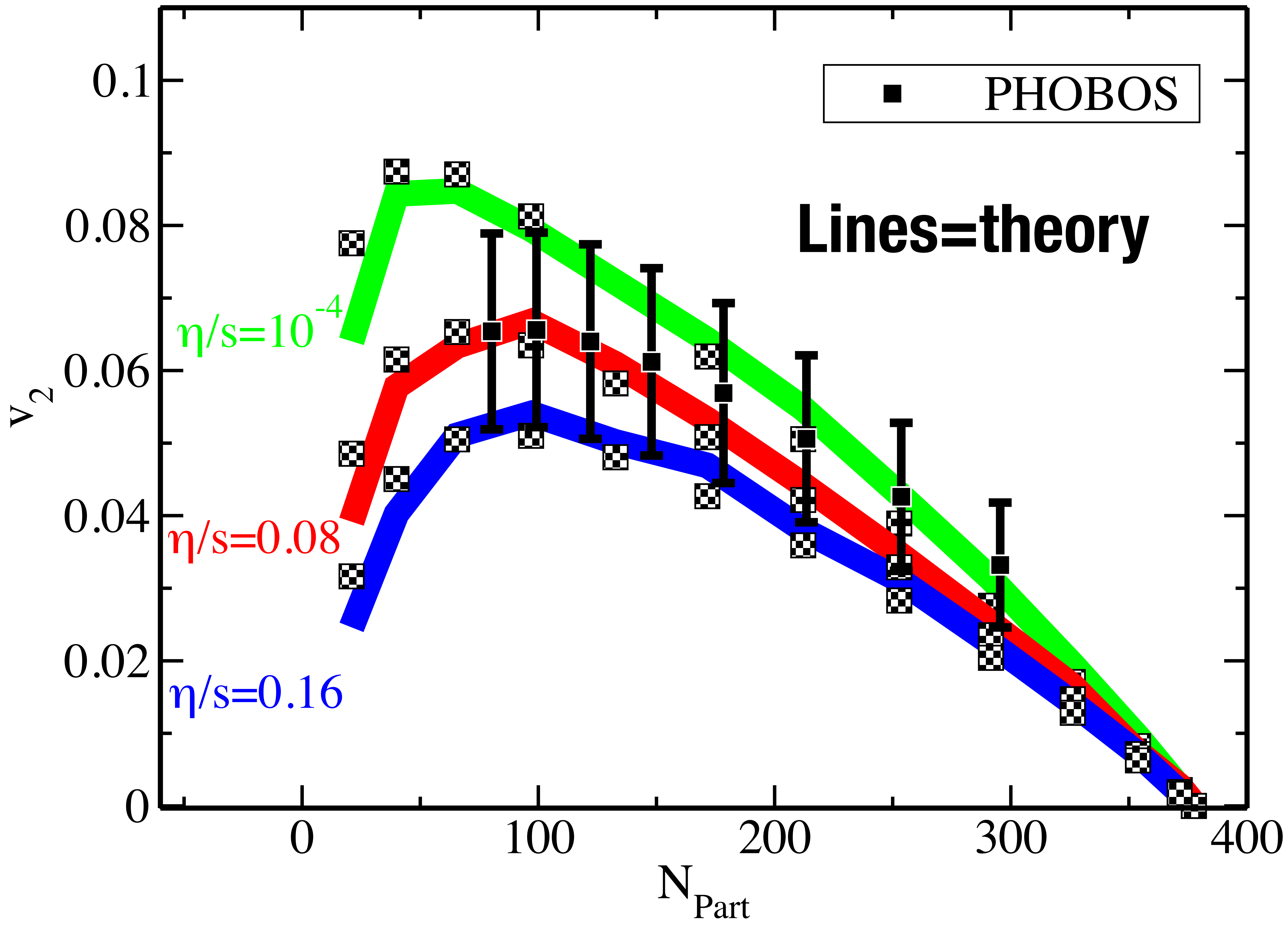
QCD matter flows: viscosity dependence

[Luzum and Romatschke PRC 78 (2008) 034915]



QCD matter flows: viscosity dependence

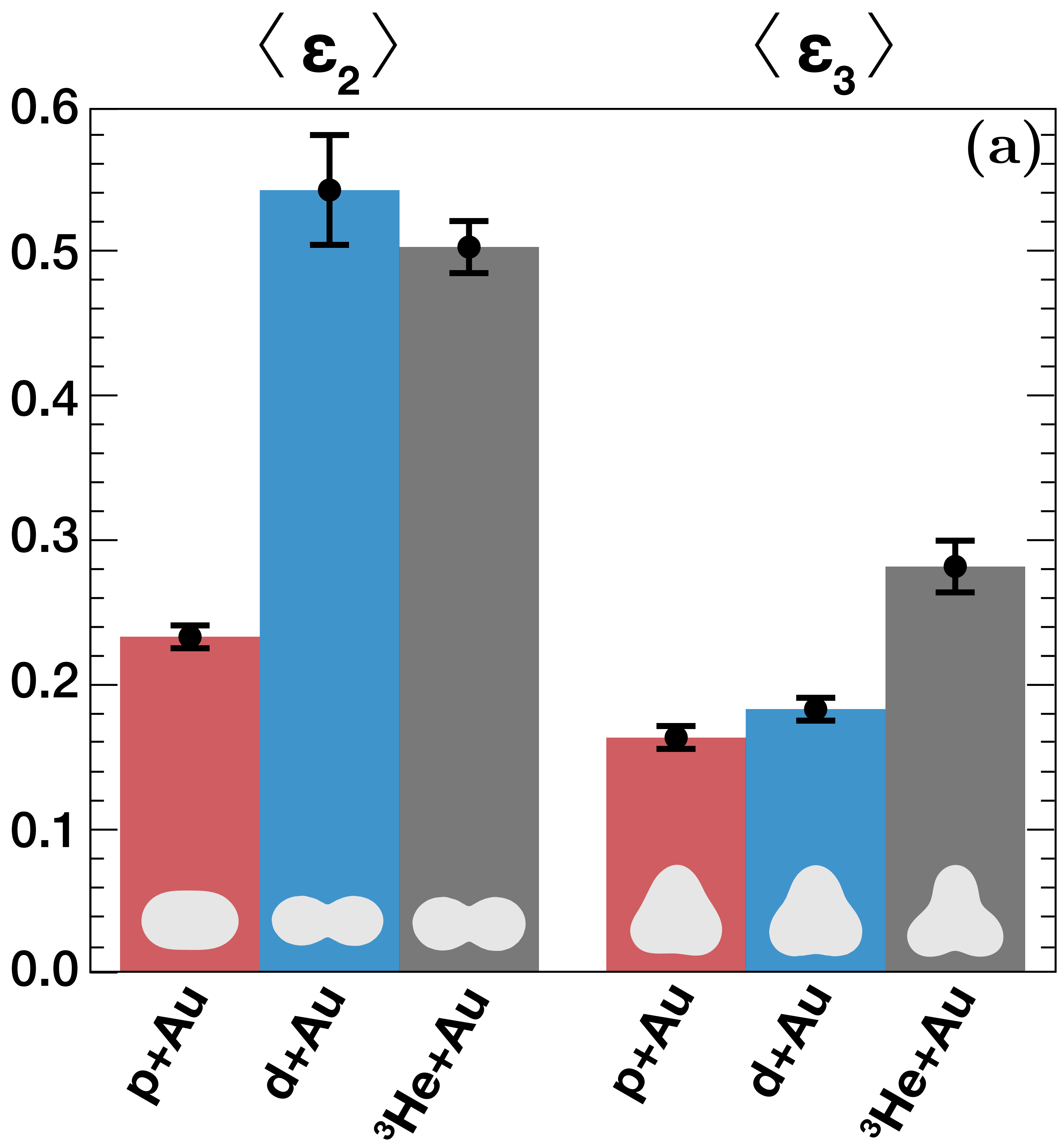
[Luzum and Romatschke PRC 78 (2008) 034915]

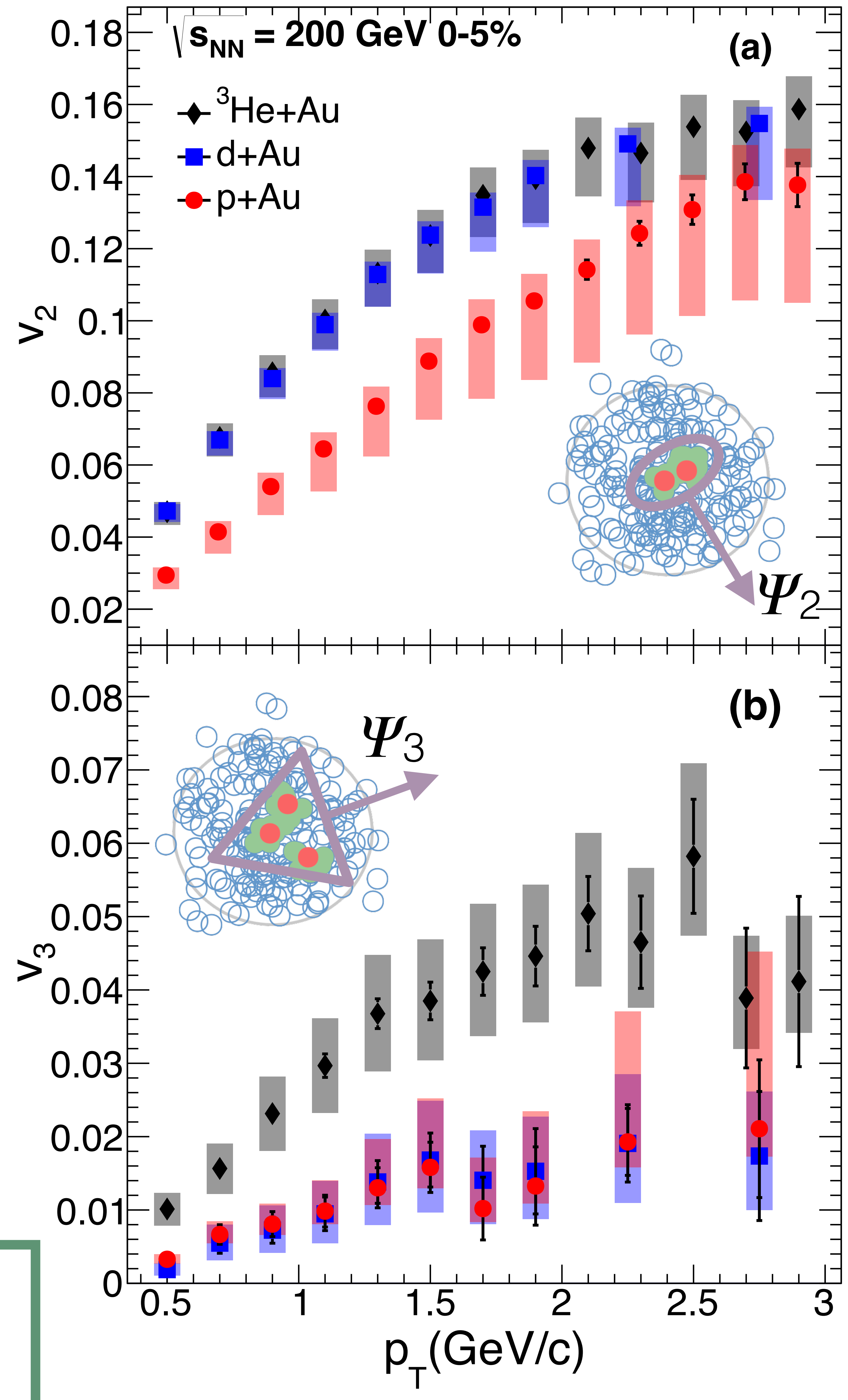


Ideal fluids flow more easily

QCD matter flows: nuclear species dependence

[Phenix Collab Nature Phys. 15 (2019) 3, 214-220]





Possible to tune the shape of the QGP droplet

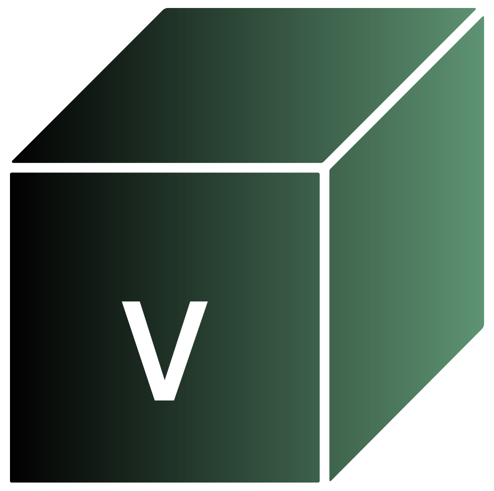
Relativistic hydrodynamics

Effective theory that describes the dynamics of a fluid (the QGP) in terms of a reduced set of macroscopic variables

Main requirement: local thermal equilibrium

$$P(V), T(V) \rightarrow \text{constant}$$

in some neighbourhood a.k.a fluid element



Equations of motion for the fluid come from conservation laws

$$\partial_\mu T^{\mu\nu} = 0 \qquad \partial_\mu j^\mu = 0$$

Note that $T^{\mu\nu}, j^\mu$ are related to microscopic quantities, i.e. $T^{\mu\nu}(x) \propto \int p^\nu p^\mu f(x, \vec{p})$

Ideal relativistic hydrodynamics

For an ideal fluid (zero mean free path), the energy momentum tensor reads

$$T^{\mu\nu} = (\epsilon + p)u^\mu u^\nu + pg^{\mu\nu}$$

velocity field

So far, 5 unknowns: $\epsilon, p, u^x, u^y, u^z$, 4 constraints: $\partial_\mu T^{\mu\nu} = 0$

Missing: equation of state that connects microscopic and macroscopic d.o.f

Ideal, massless gas: $p = \epsilon/3$

Evolution of the system reduce to a set of partial differential equations

Viscous relativistic hydrodynamics

Mean free path is no longer zero, the energy momentum tensor now reads

$$T^{\mu\nu} = (\epsilon + p)u^\mu u^\nu + pg^{\mu\nu} + \underbrace{\pi_{\text{bulk}}}_{\text{bulk viscous pressure}}(g^{\mu\nu} + u^\mu u^\nu) + \underbrace{\pi^{\mu\nu}}_{\text{shear viscous tensor}}$$

If conserved charges, n, are also present now solve $\partial_\mu T^{\mu\nu} = 0$ and $\partial_\mu j^\mu = 0$

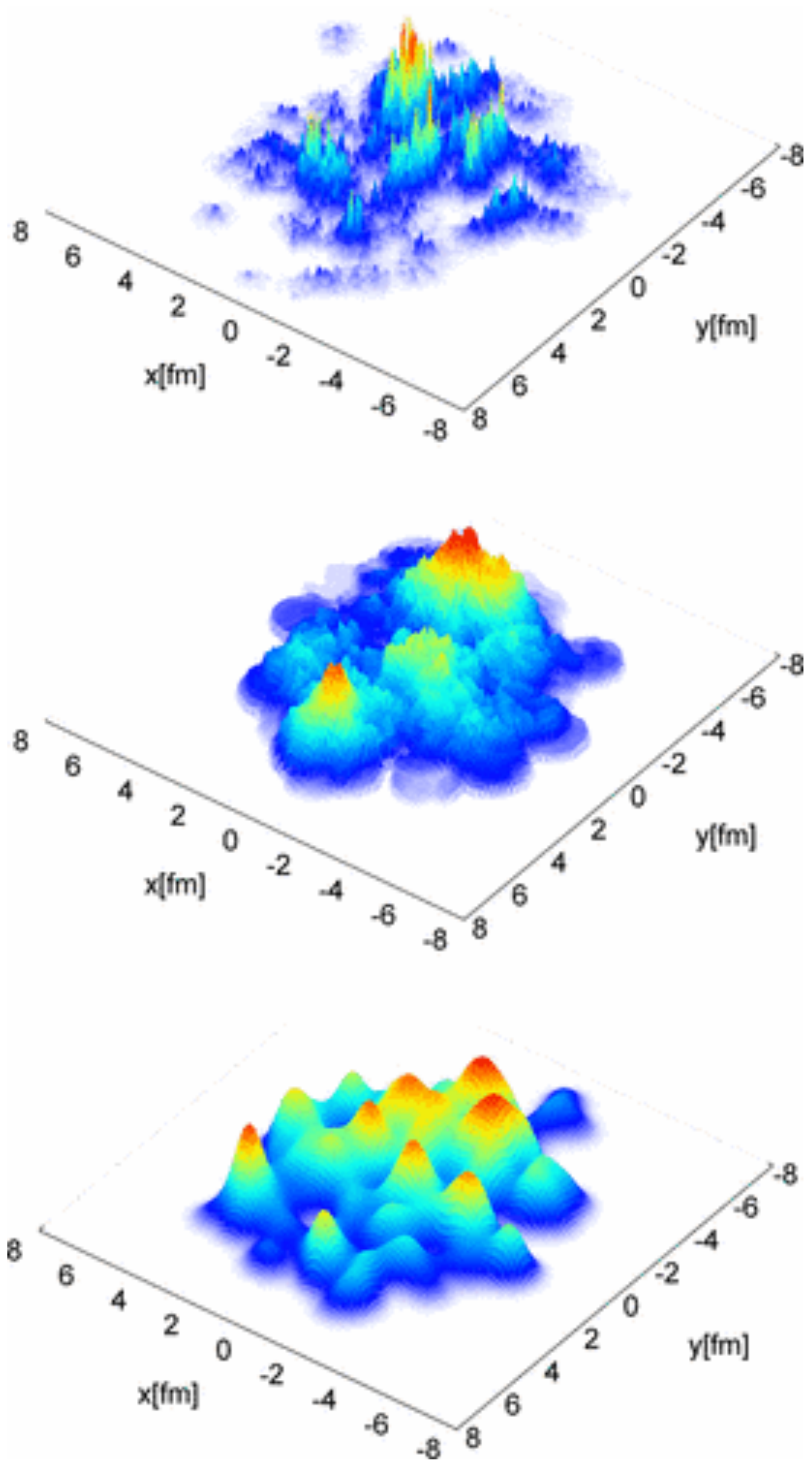
Equation of state in a more realistic scenario given by Lattice QCD: $p = p(\epsilon, n)$

Deviations from ideal hydro include so-called transport coefficients:

- Shear viscosity, η: resistance to flow
- Bulk viscosity, ζ: resistance to expansion

Workflow of hydrodynamic simulations

[Adapted from Iurii Karpenko]



Hydrodynamic equations

Initial conditions $T^{\mu\nu}(\tau_{\text{therm.}})$

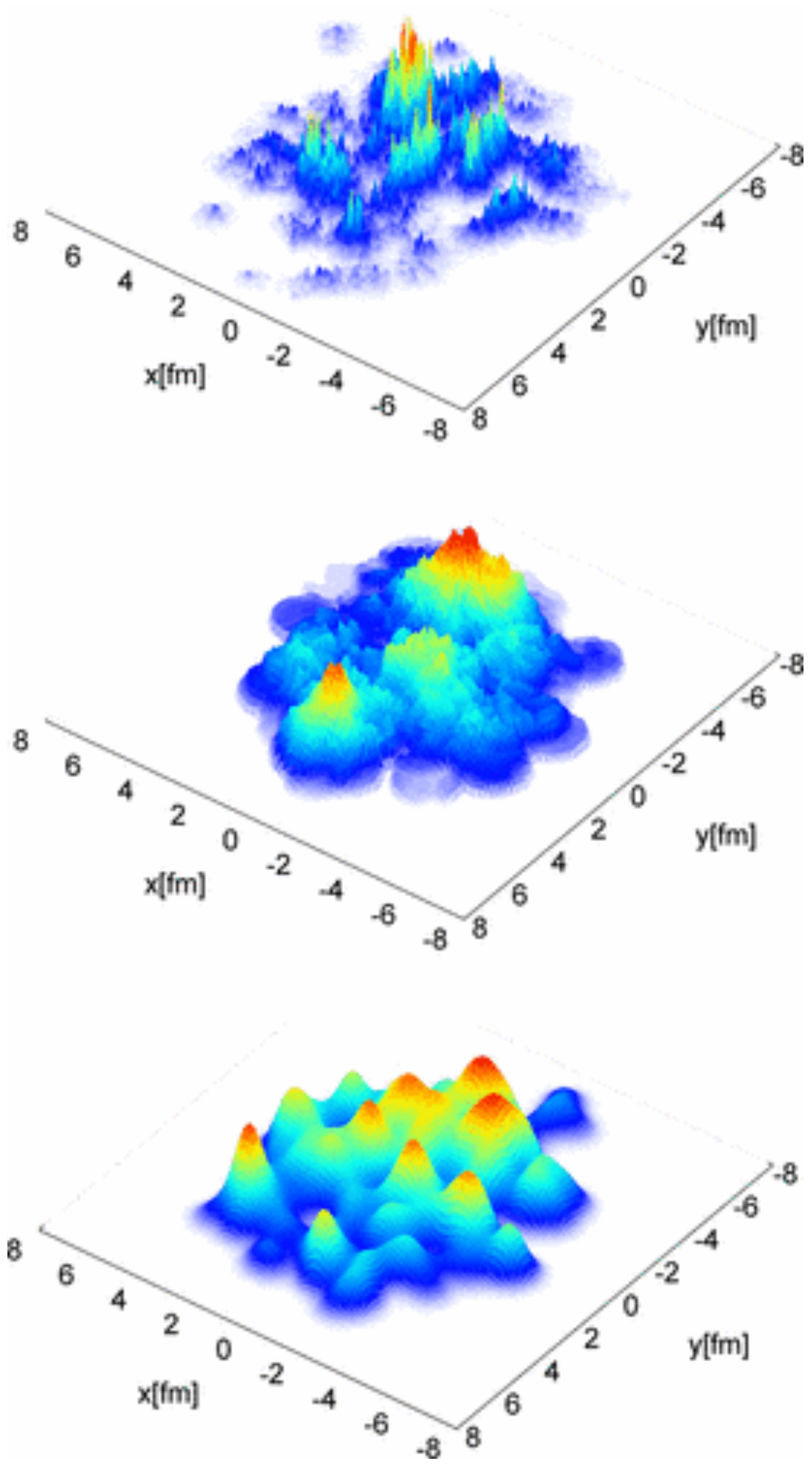
How does the QGP come into being?

How does a rapidly expanding, violently out-of-equilibrium system, reach some form of equilibrium state (fluid-like) amenable to a ‘macroscopic’ treatment?

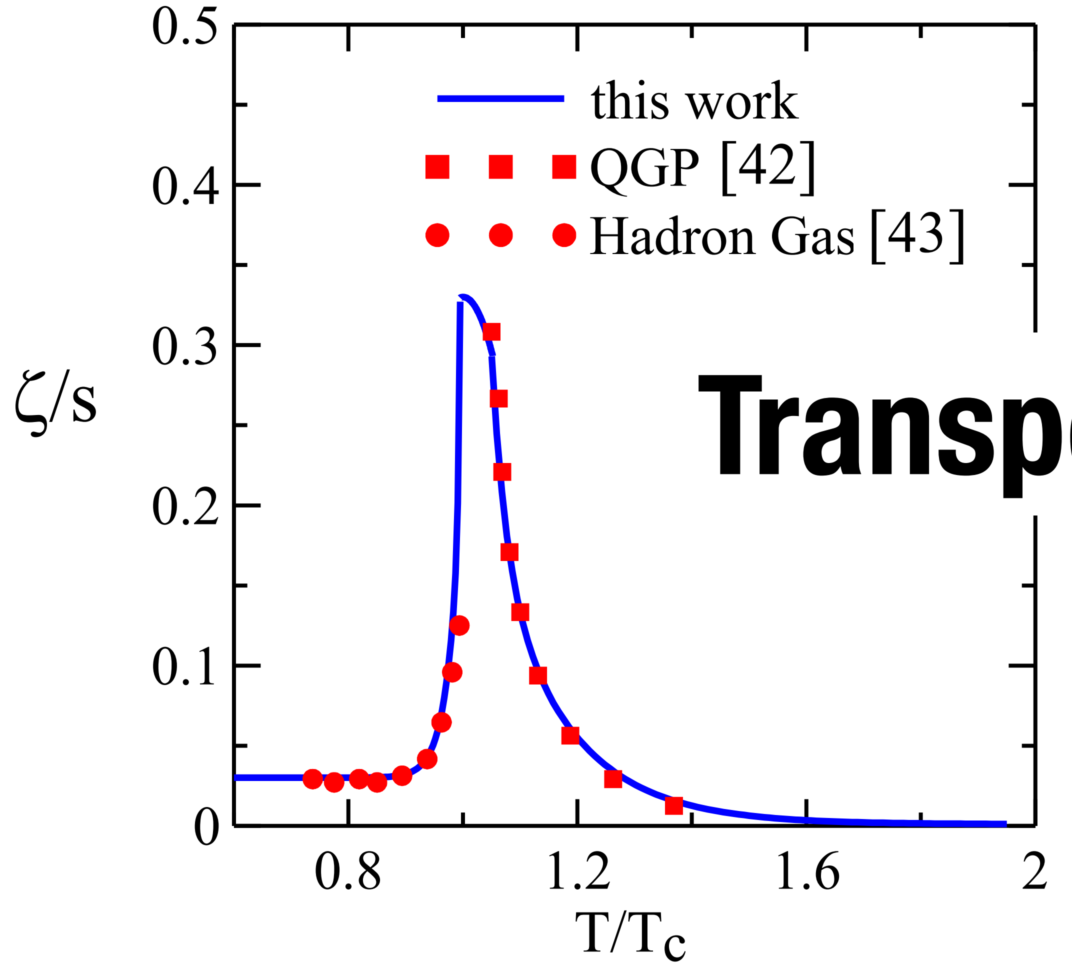
deep theoretical challenge in physics

Workflow of hydrodynamic simulations

[Adapted from Iurii Karpenko]



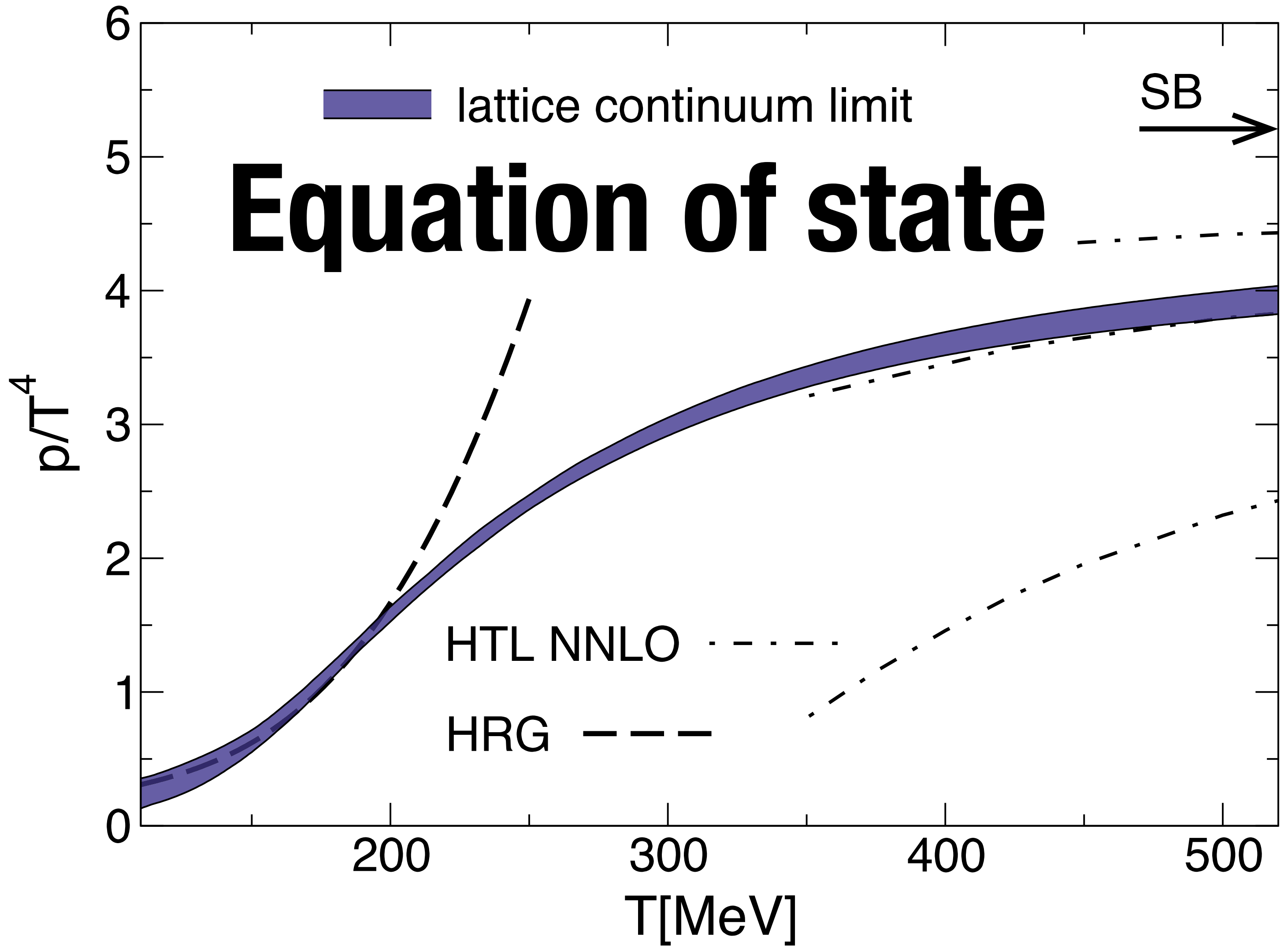
[Ryu et al PRL 115 (2015) 13, 132301]



Transport coefficients

Hydrodynamic equations

Equation of state



Workflow of hydrodynamic simulations

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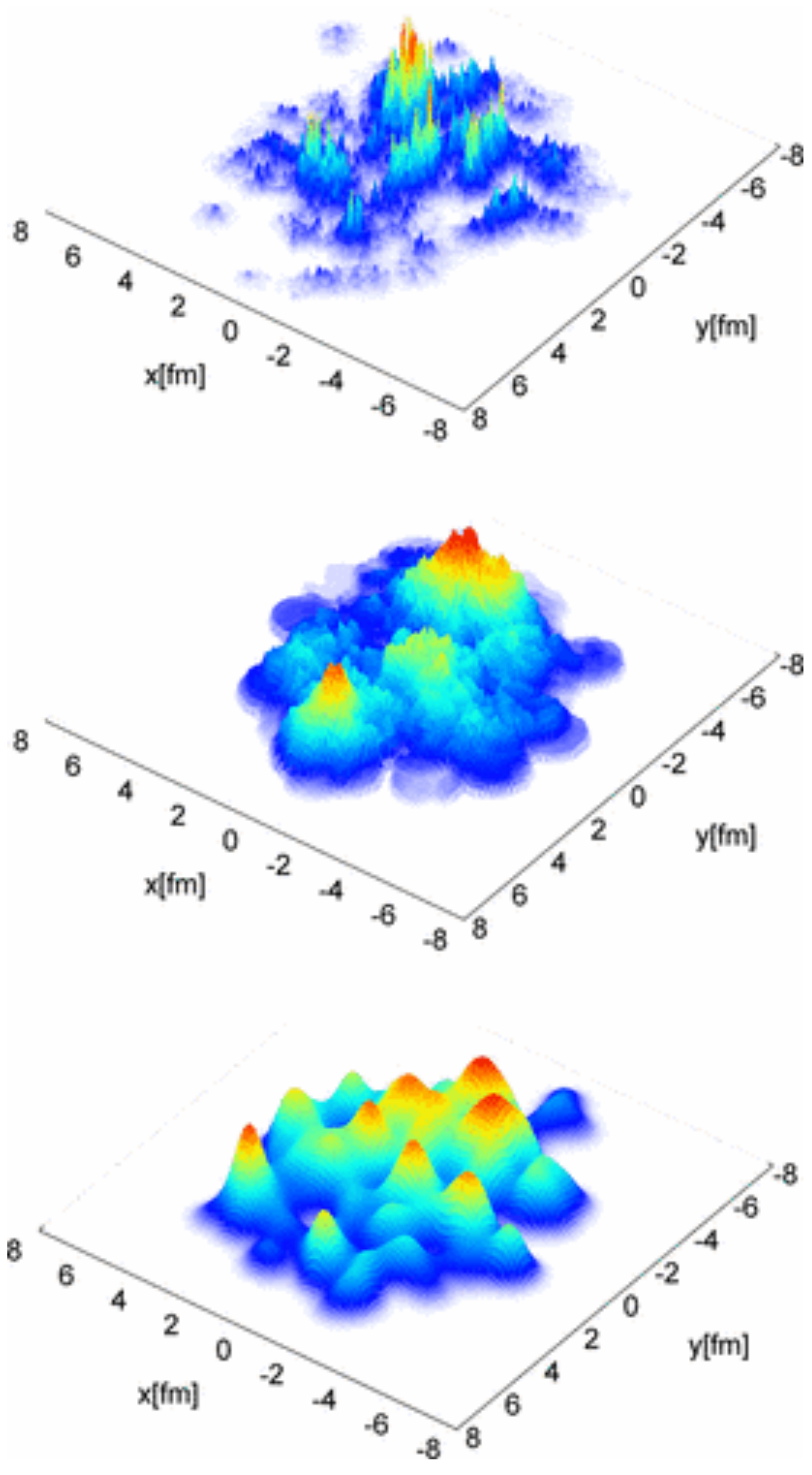

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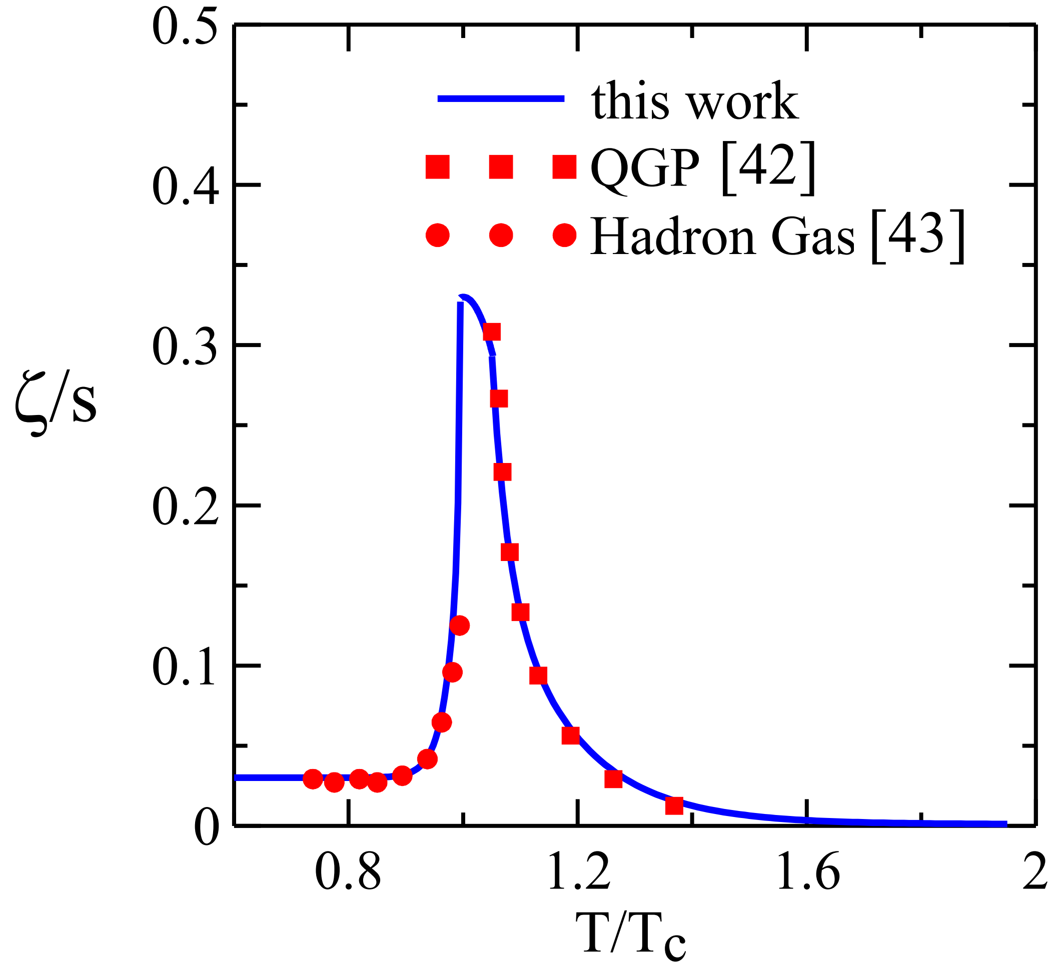
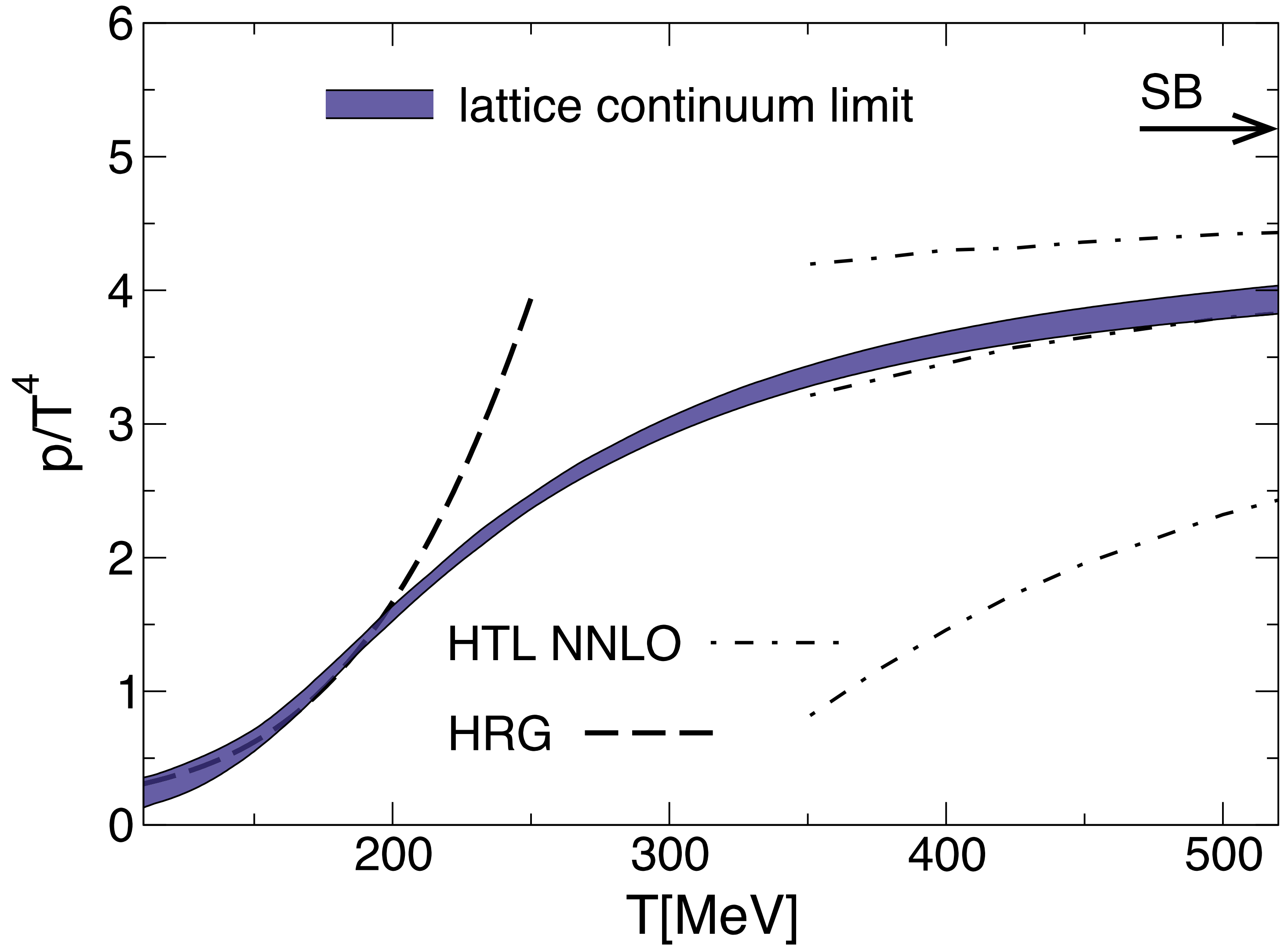


Hydrodynamic equations

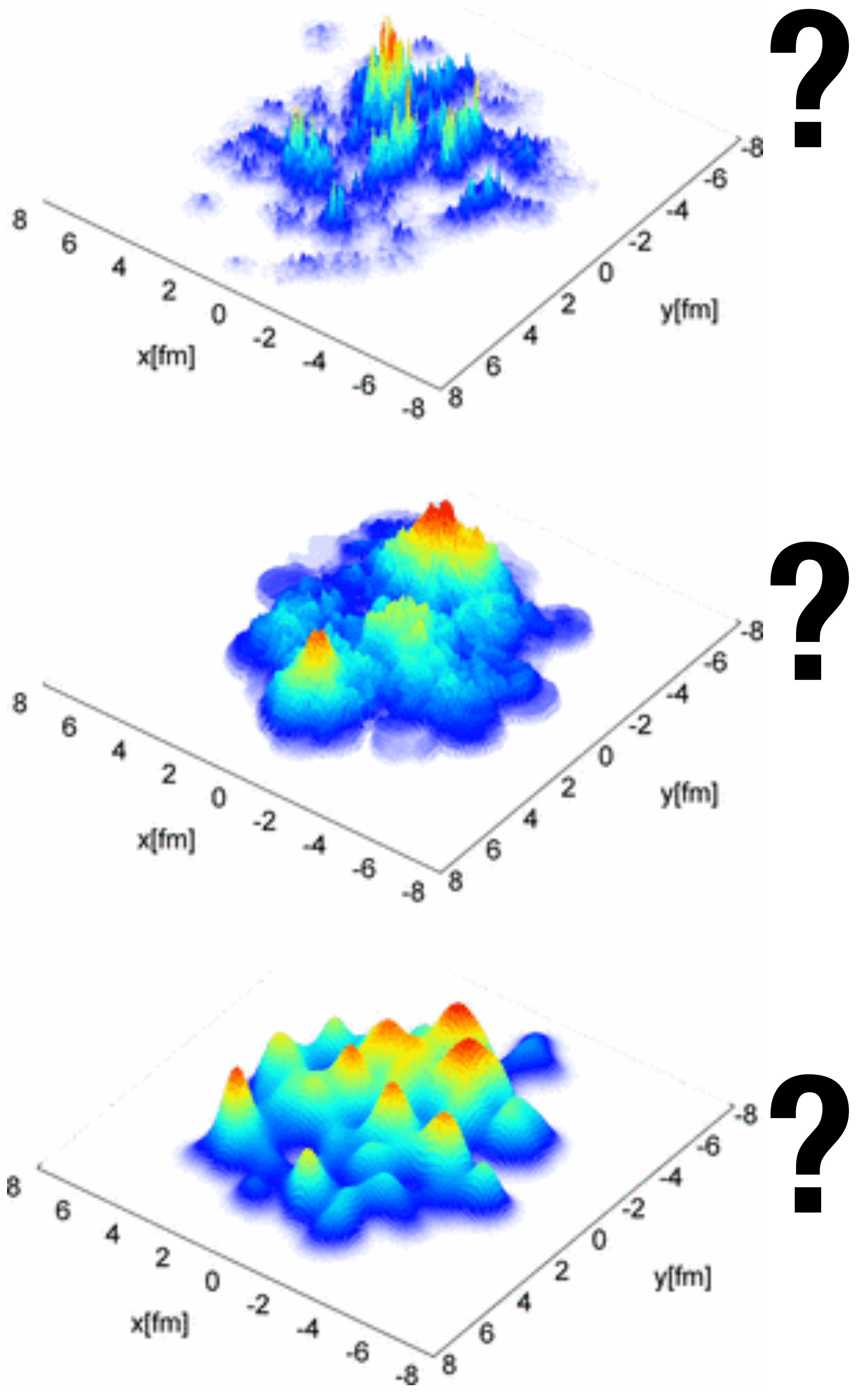
Observables

*+ some fluid to particle transition



Workflow of hydrodynamic simulations

[Adapted from Iurii Karpenko]



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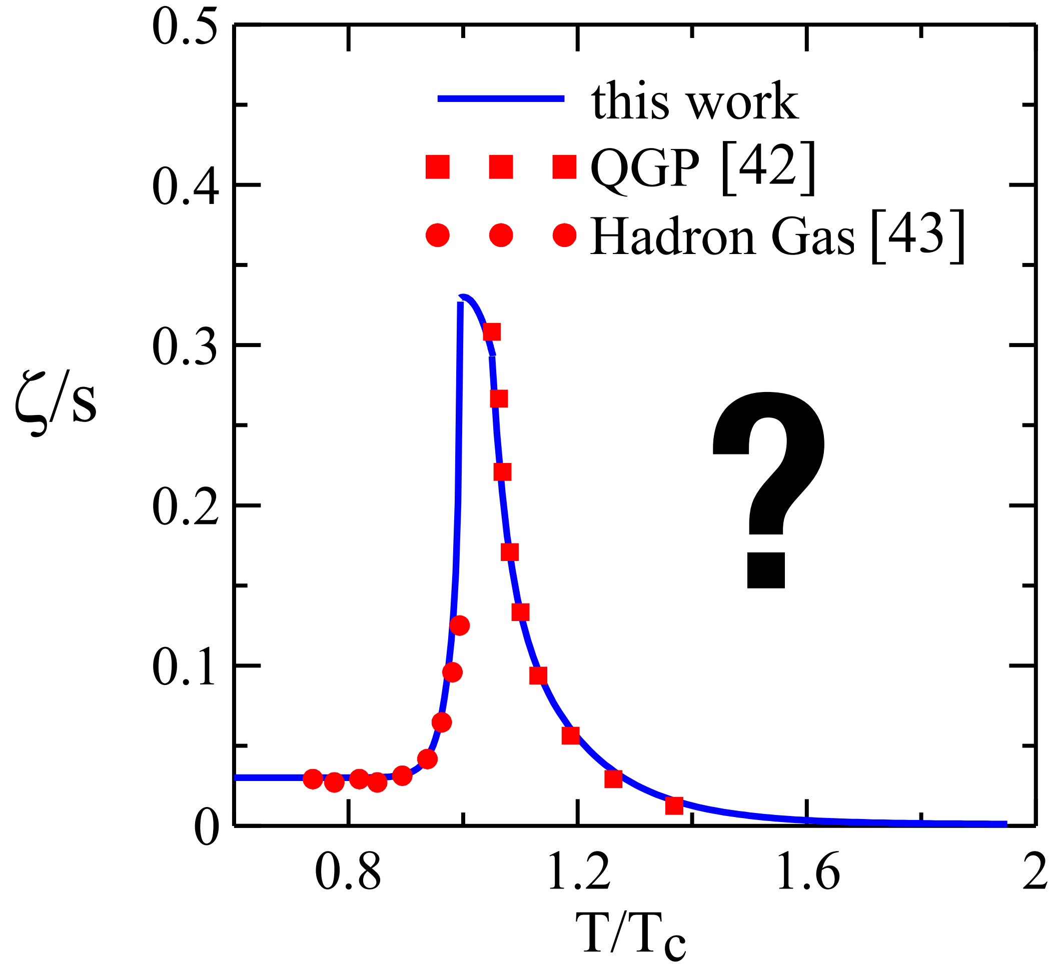
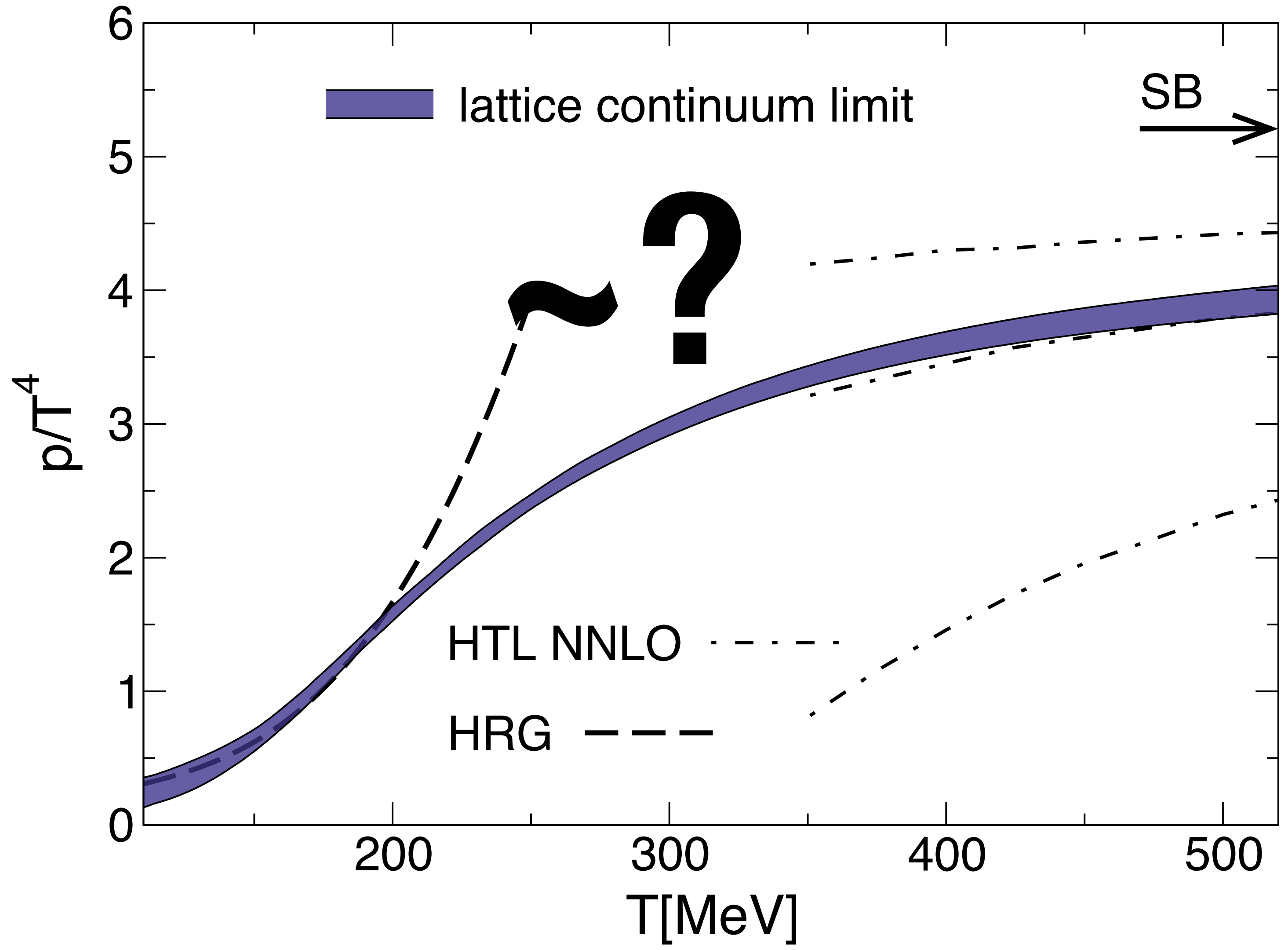


Hydrodynamic equations → **Observables**

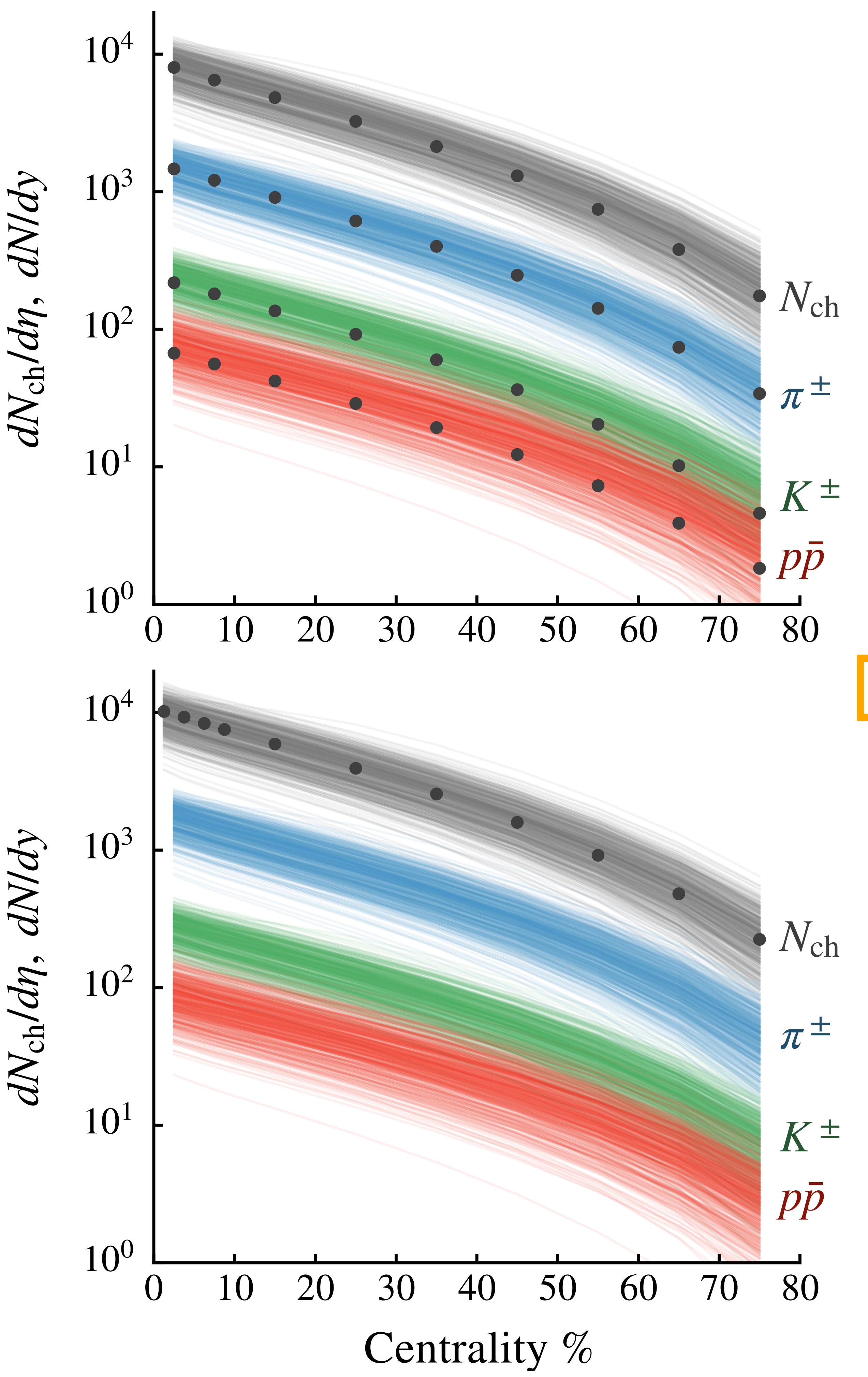
*+ some fluid to particle transition



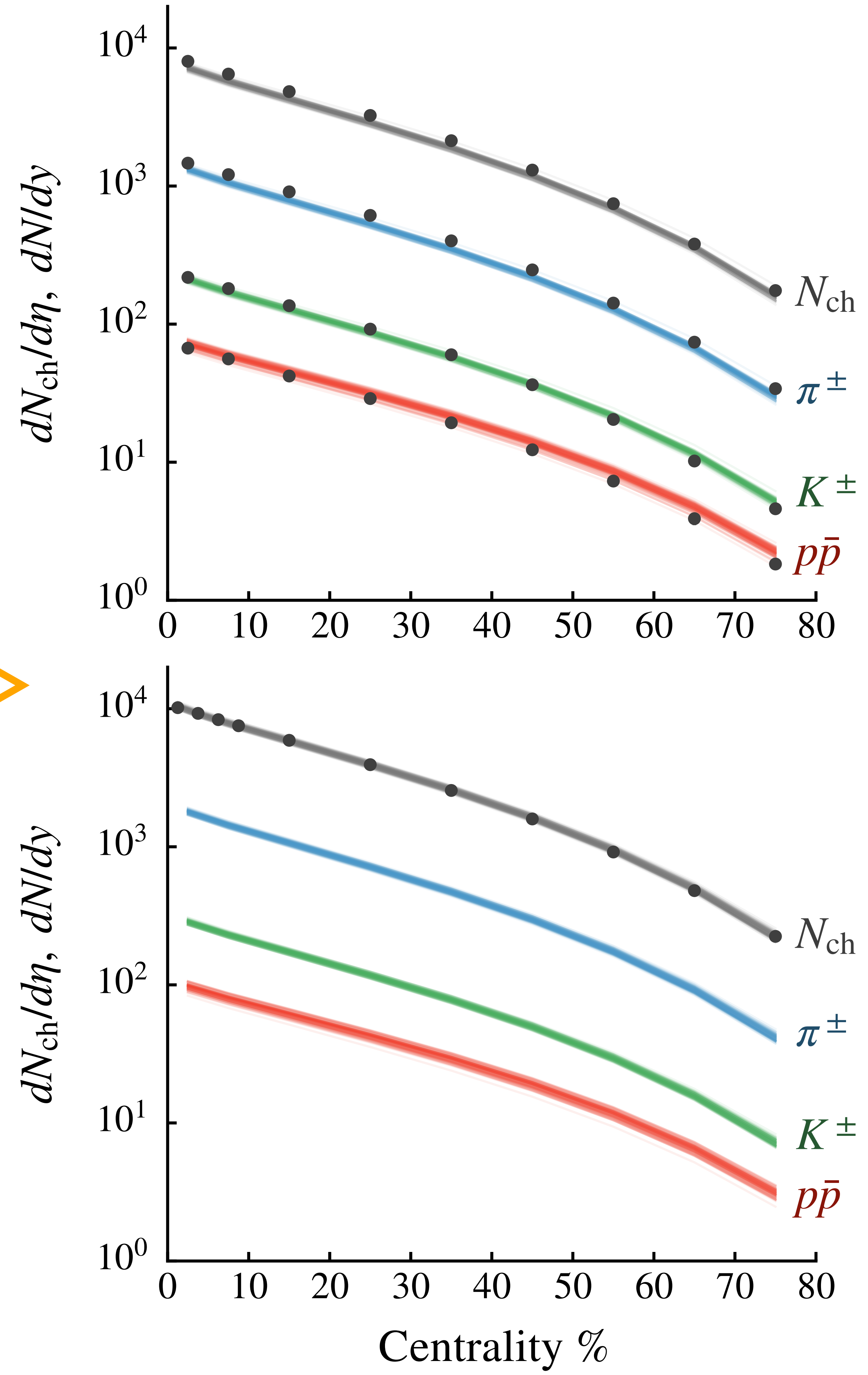
Bayesian analyses: transport coefficient results

[Bernhard et al Nature Phys. 15 (2019) 11, 1113-1117]

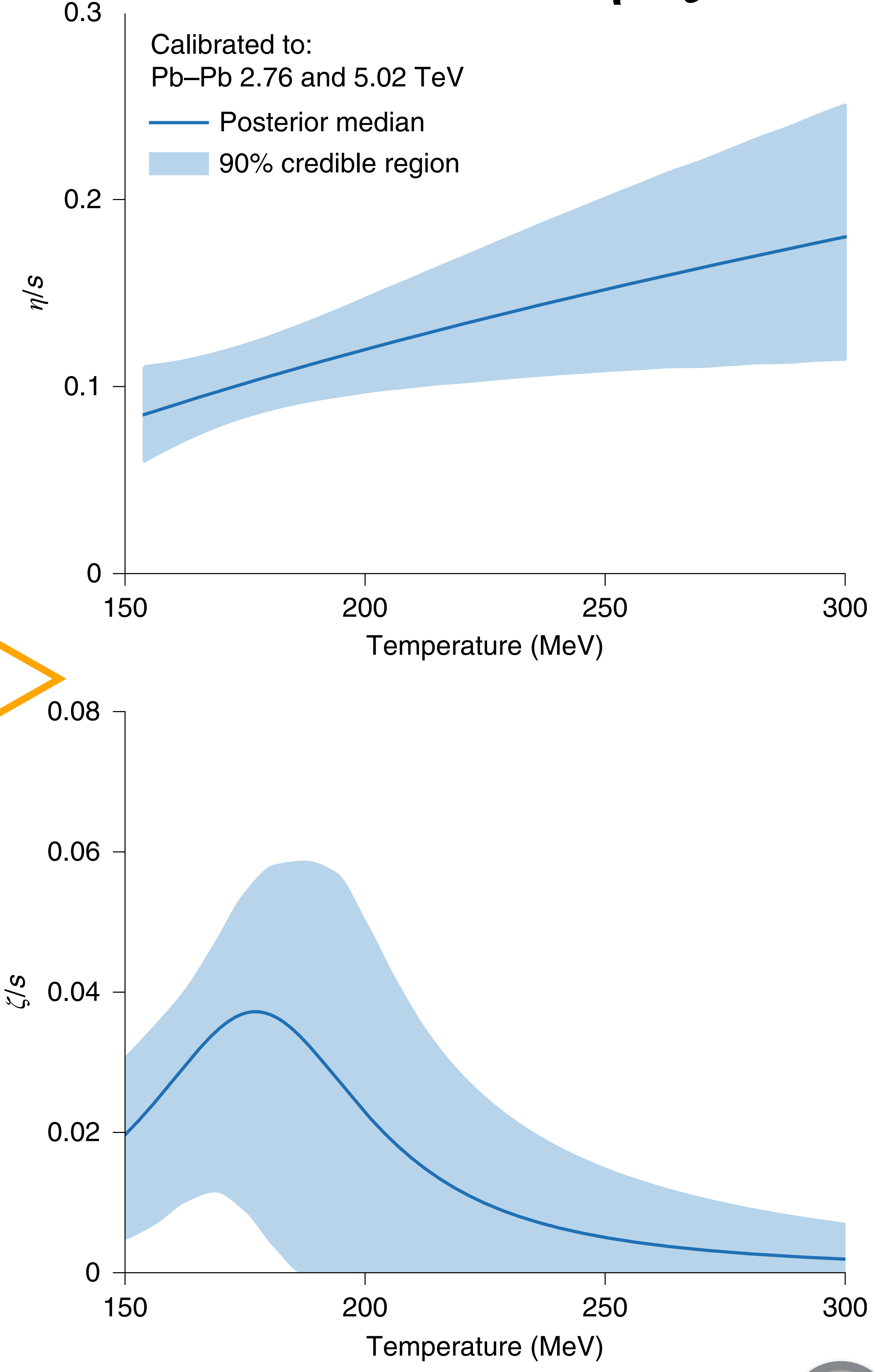
Model calculations



Best fit results

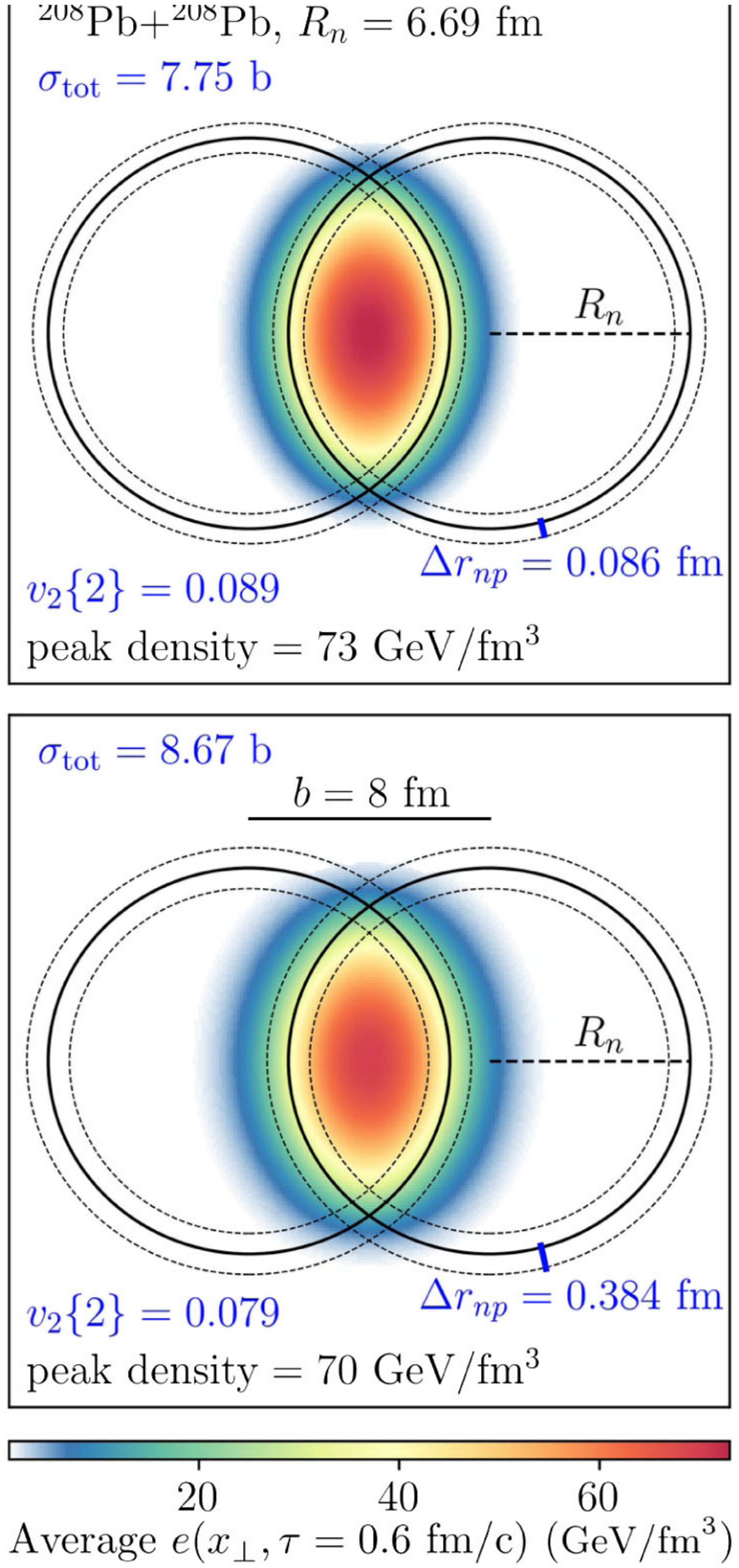


Extraction of η, ζ

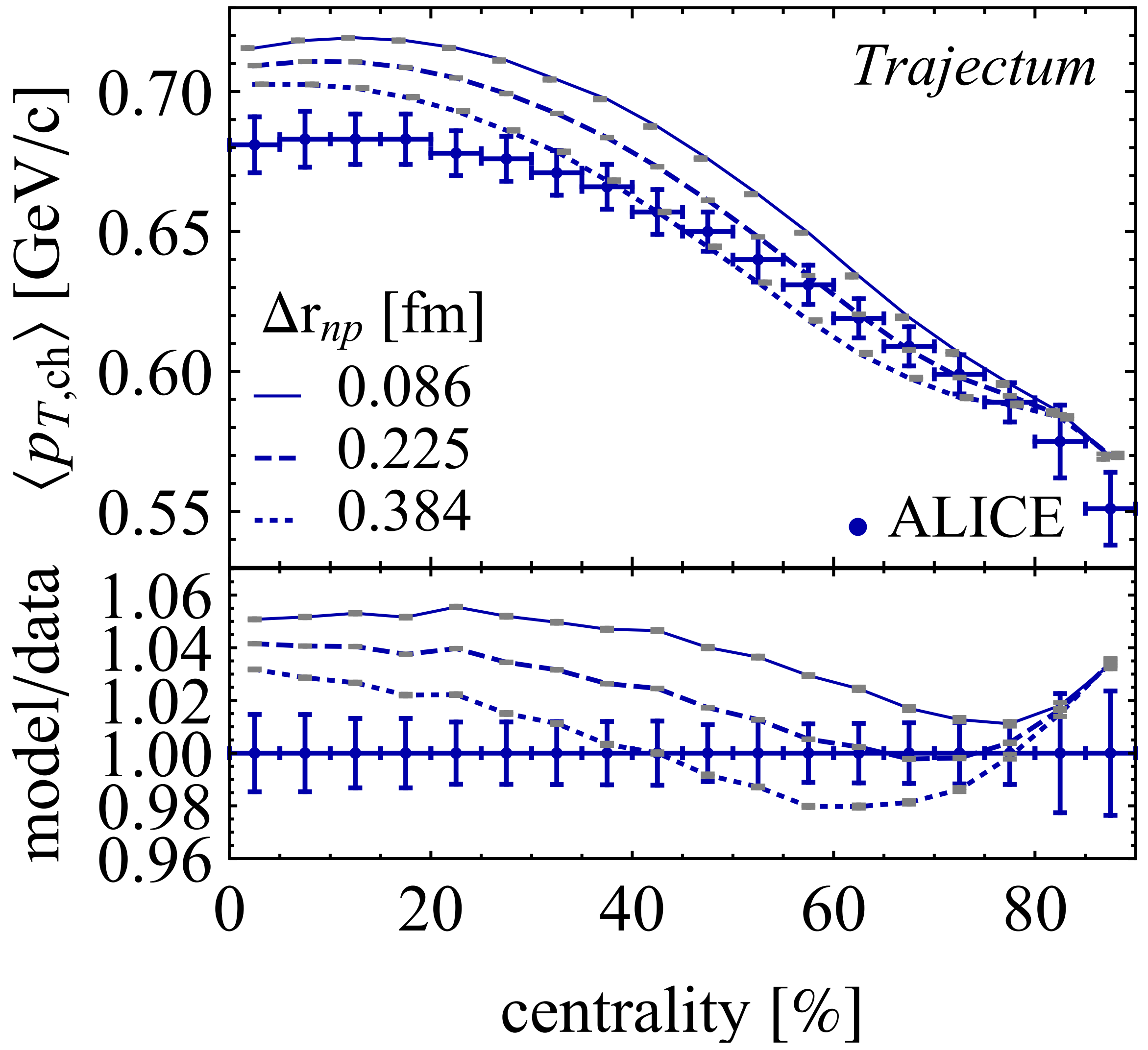


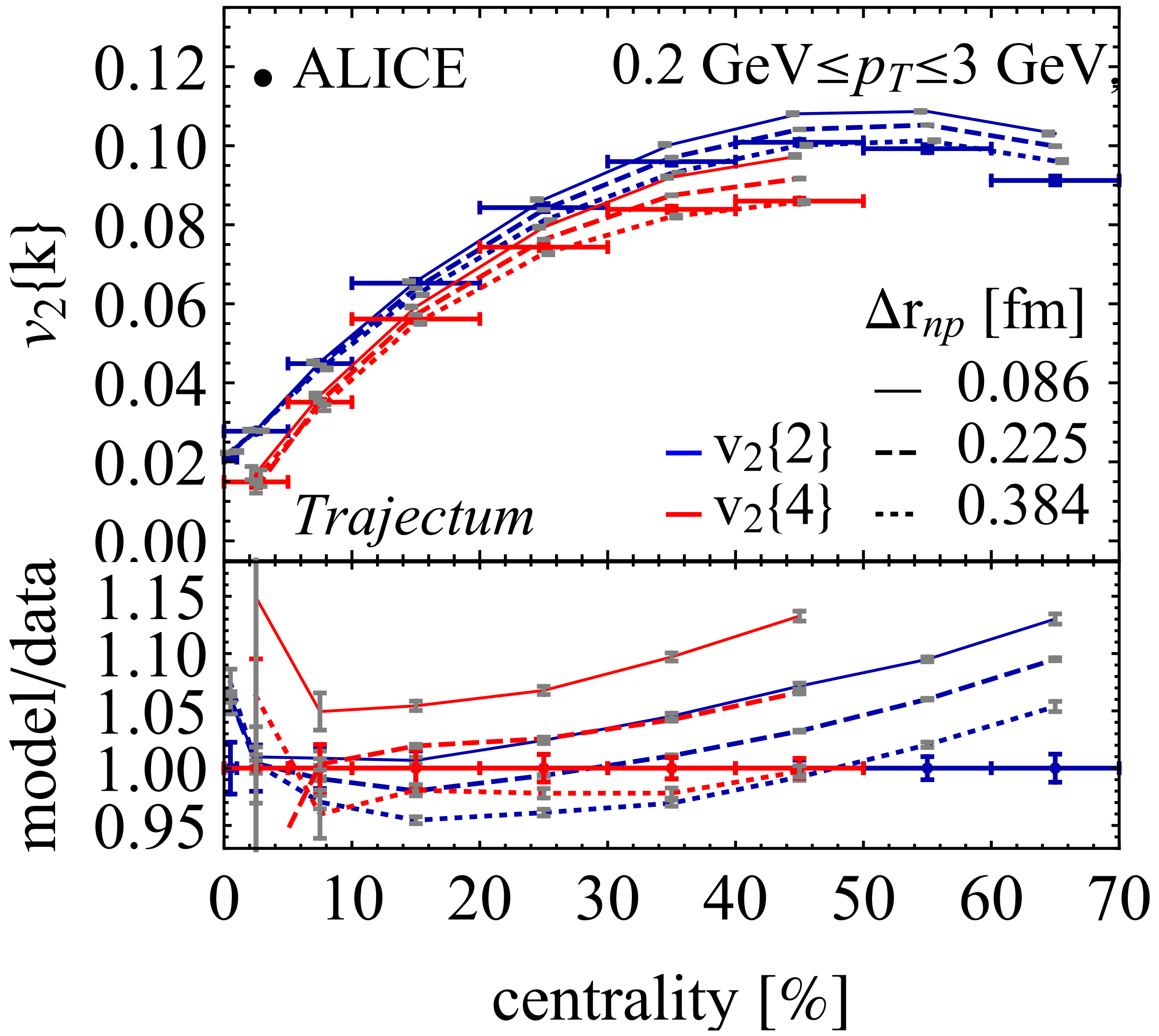
Bayesian analyses: initial geometry

Neutron skin in ^{208}Pb

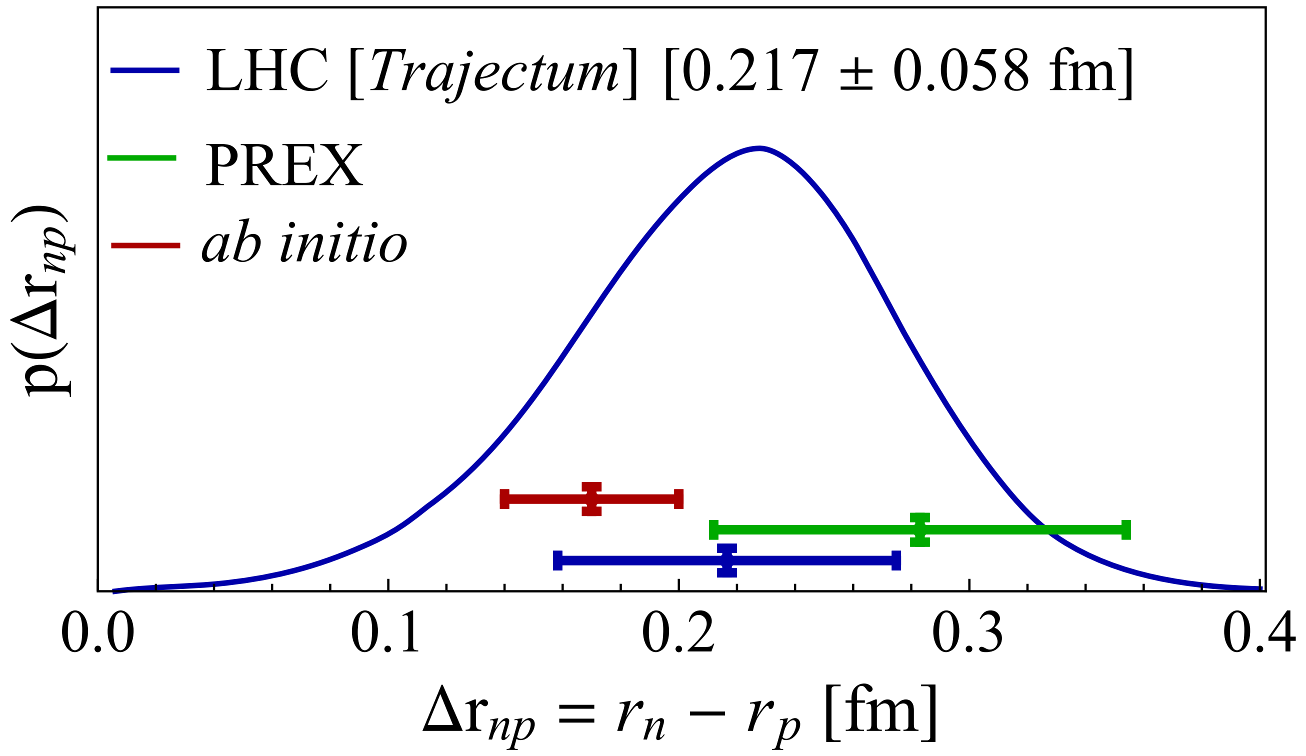


Impact on observables





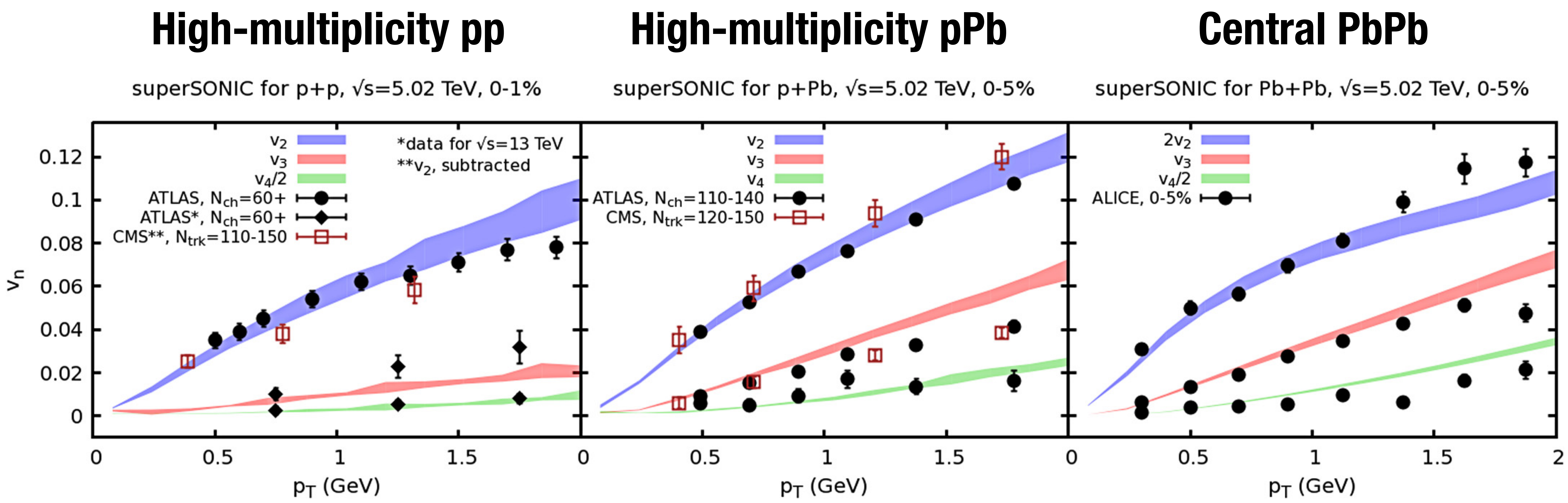
LHC as a nuclear structure experiment



[Giacalone et al PRL 131 (2023) 20, 20

Some hiccups in the hydro paradise: flow in proton-proton (?)

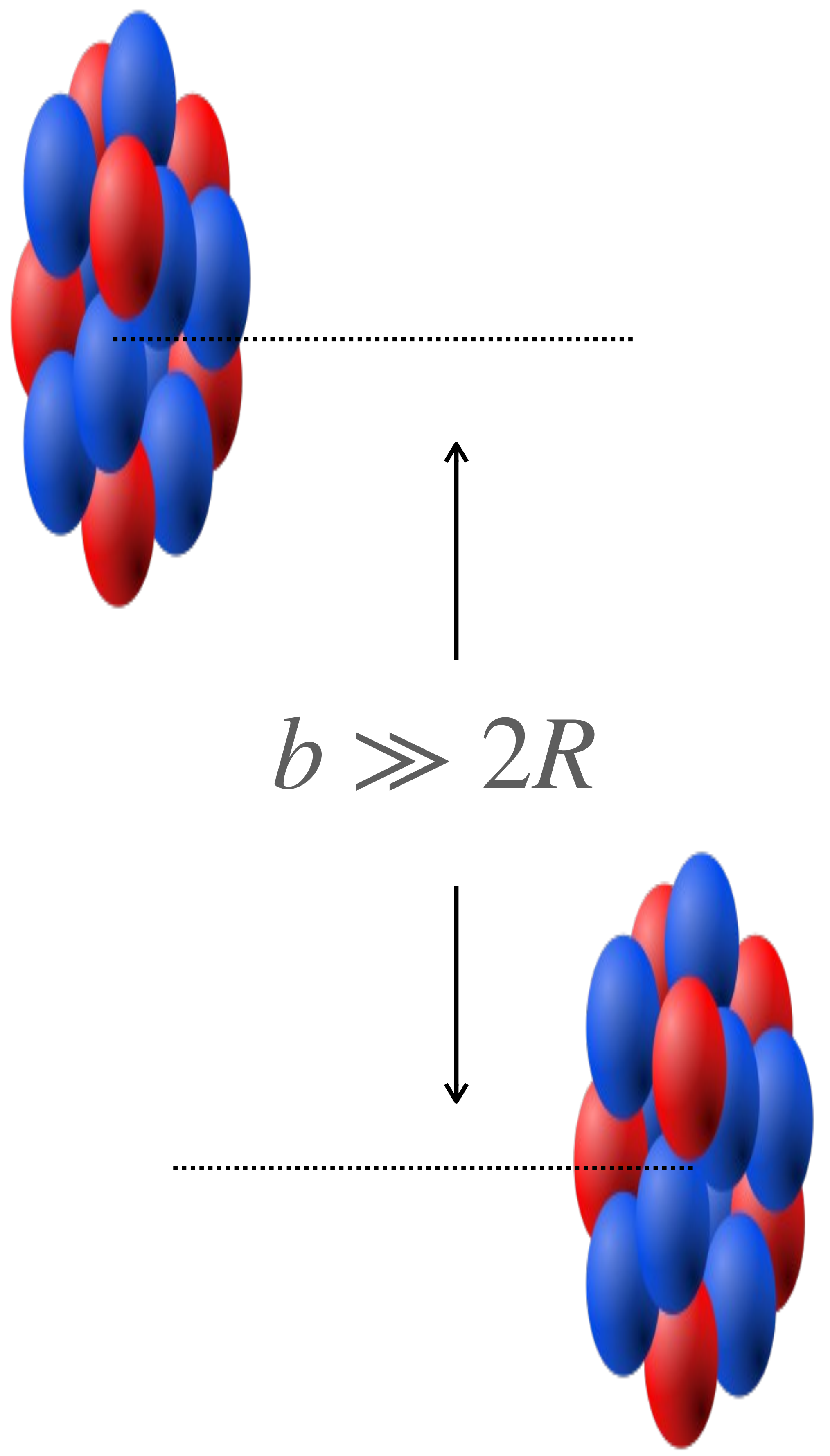
[Weller et al PLB 774 (2017) 351-356]

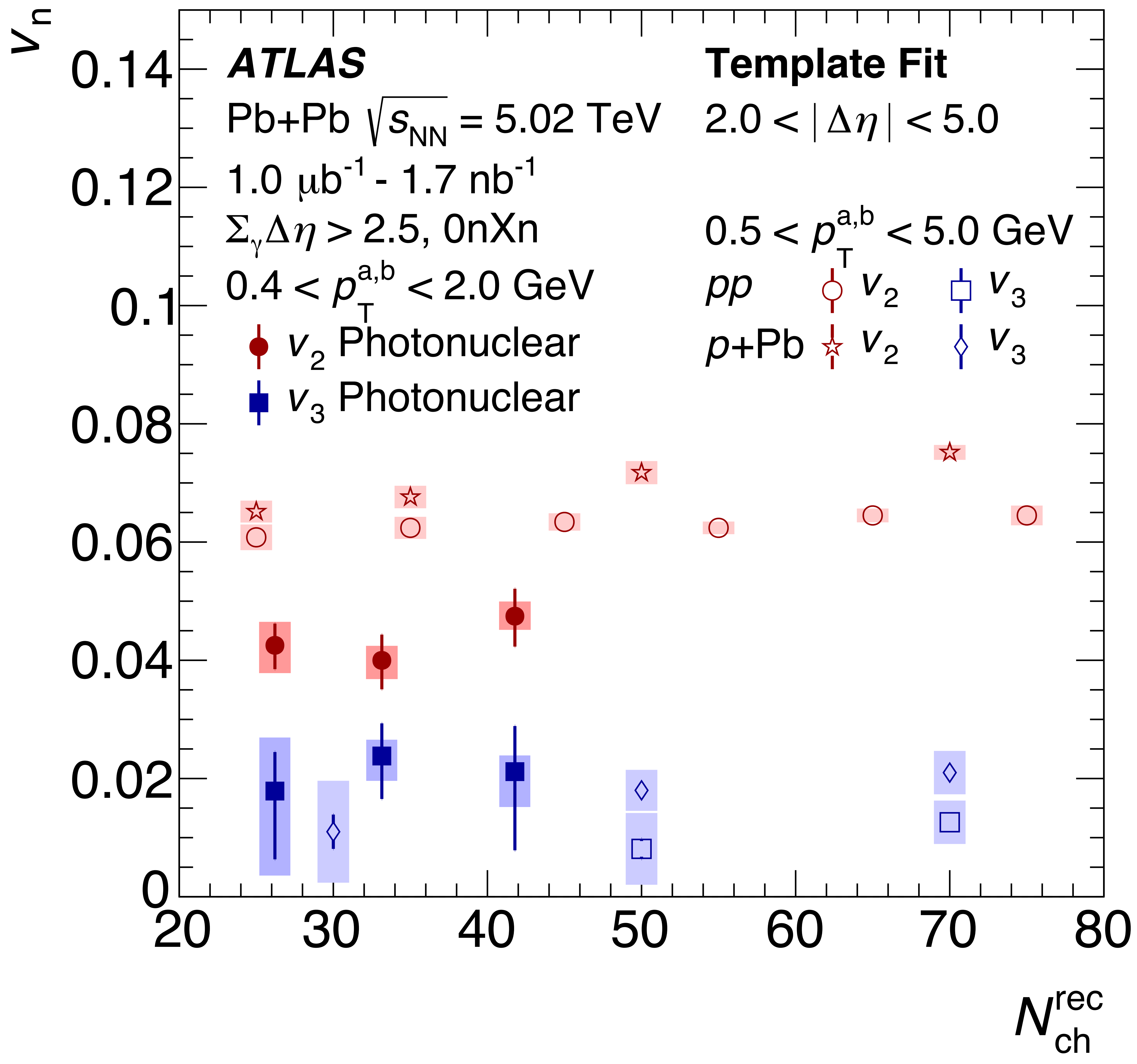


How to justify the applicability of hydro in pp? Huge gradients expected

Some hiccups in the hydro paradise: flow in γPb collisions (??)

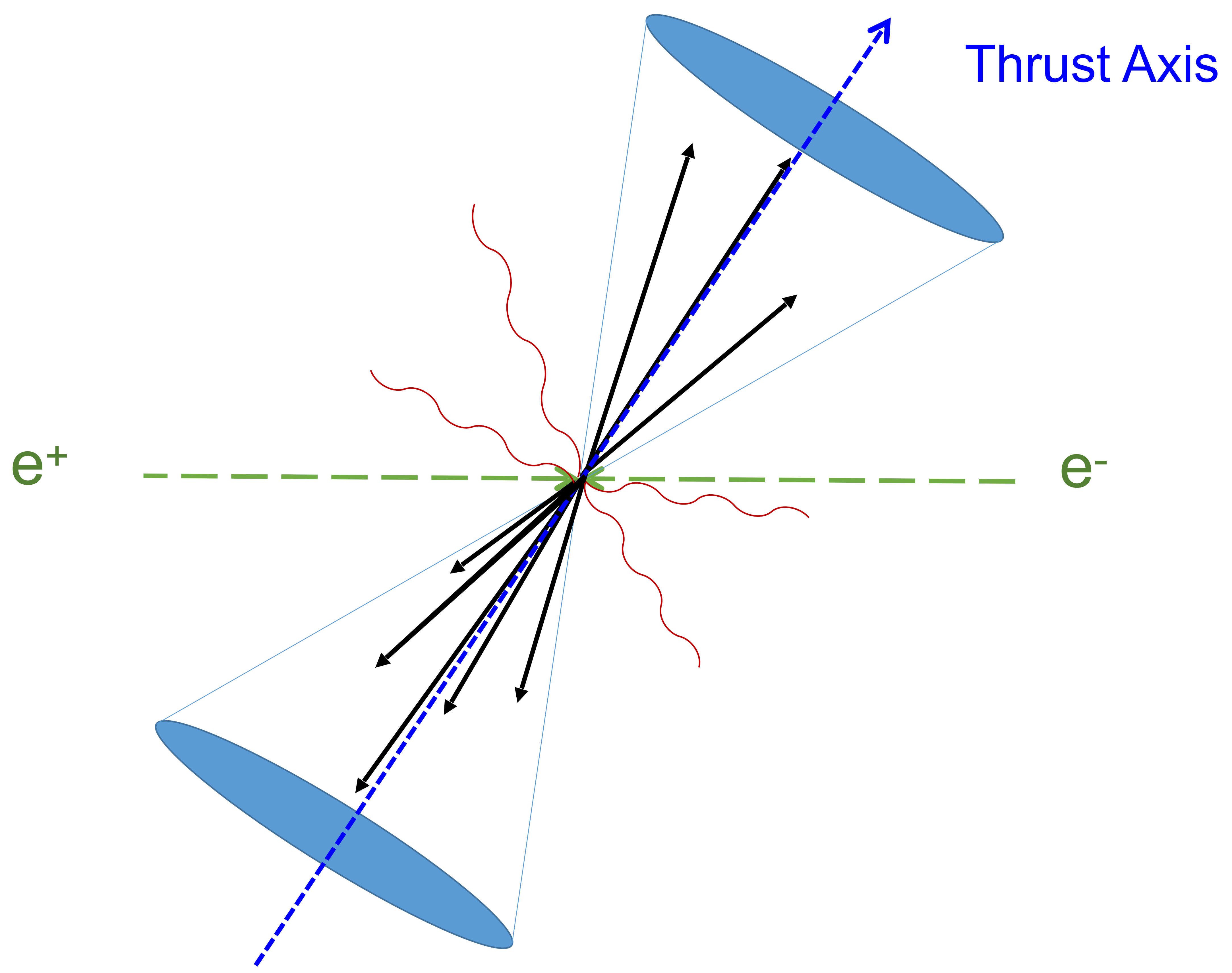
[ATLAS Collab PRC 104 (2021) 1, 014903]

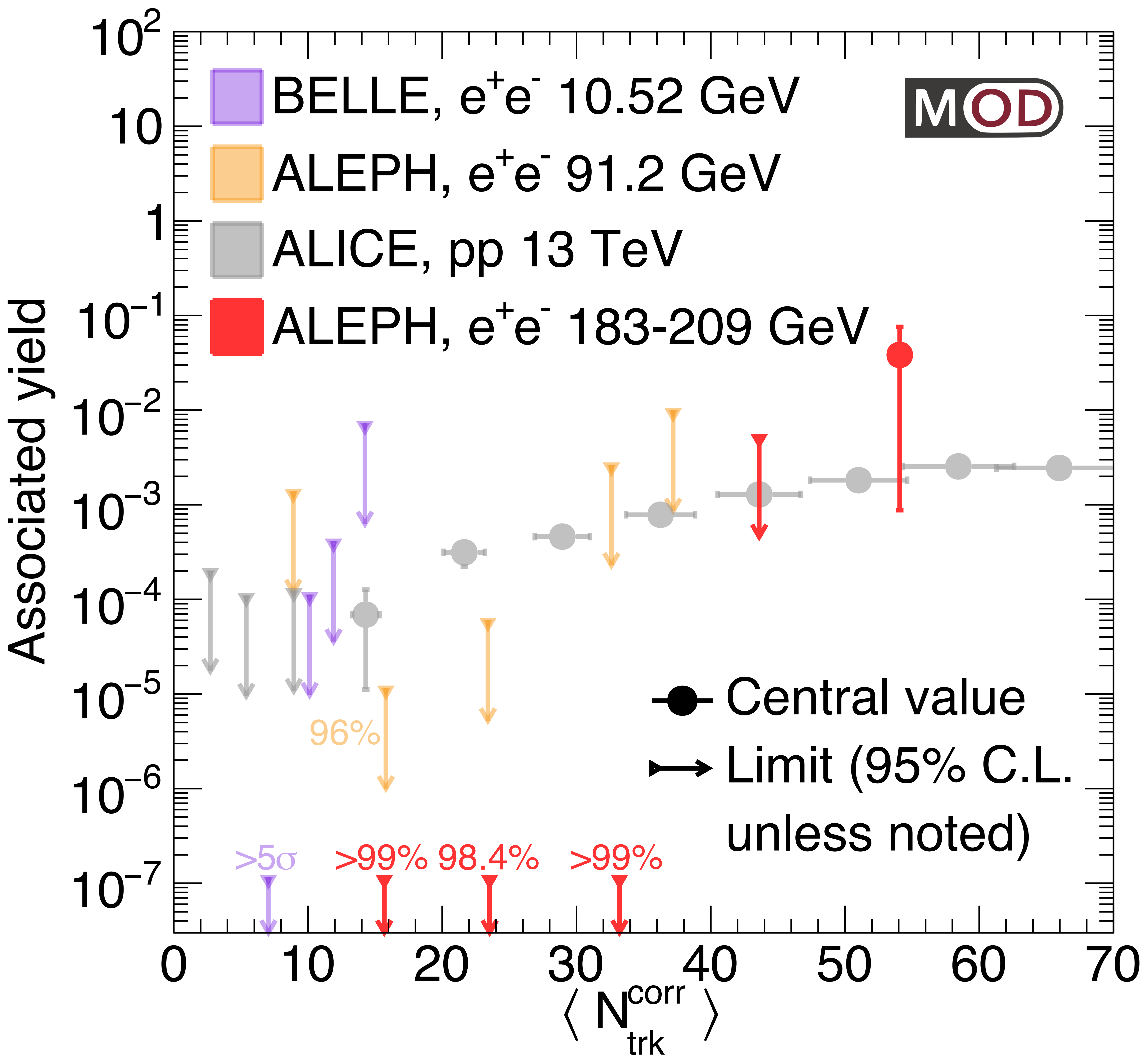




Some hiccups in the hydro paradise: flow in ee collisions (???!!?!)

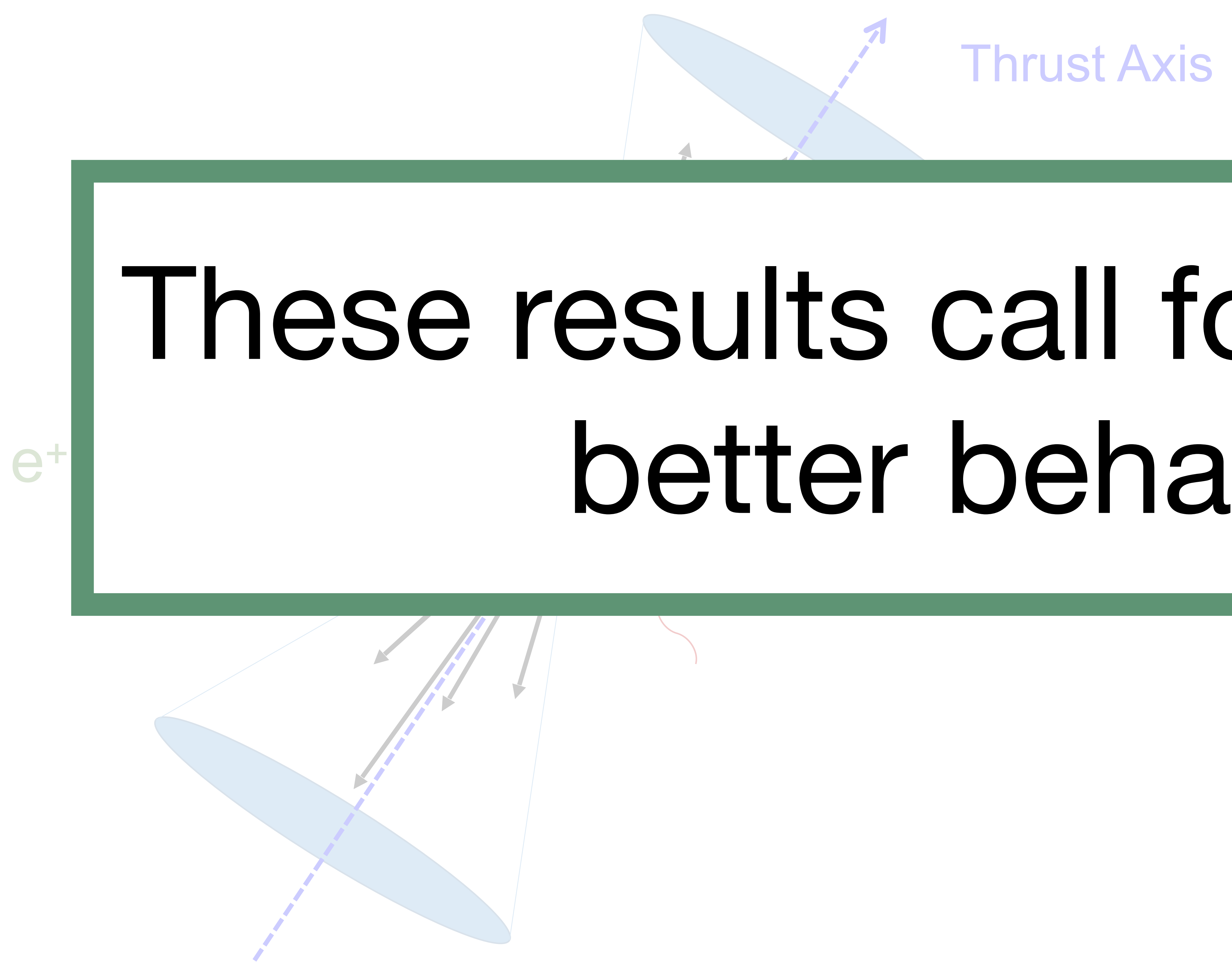
[Chen et al 2312.05084]

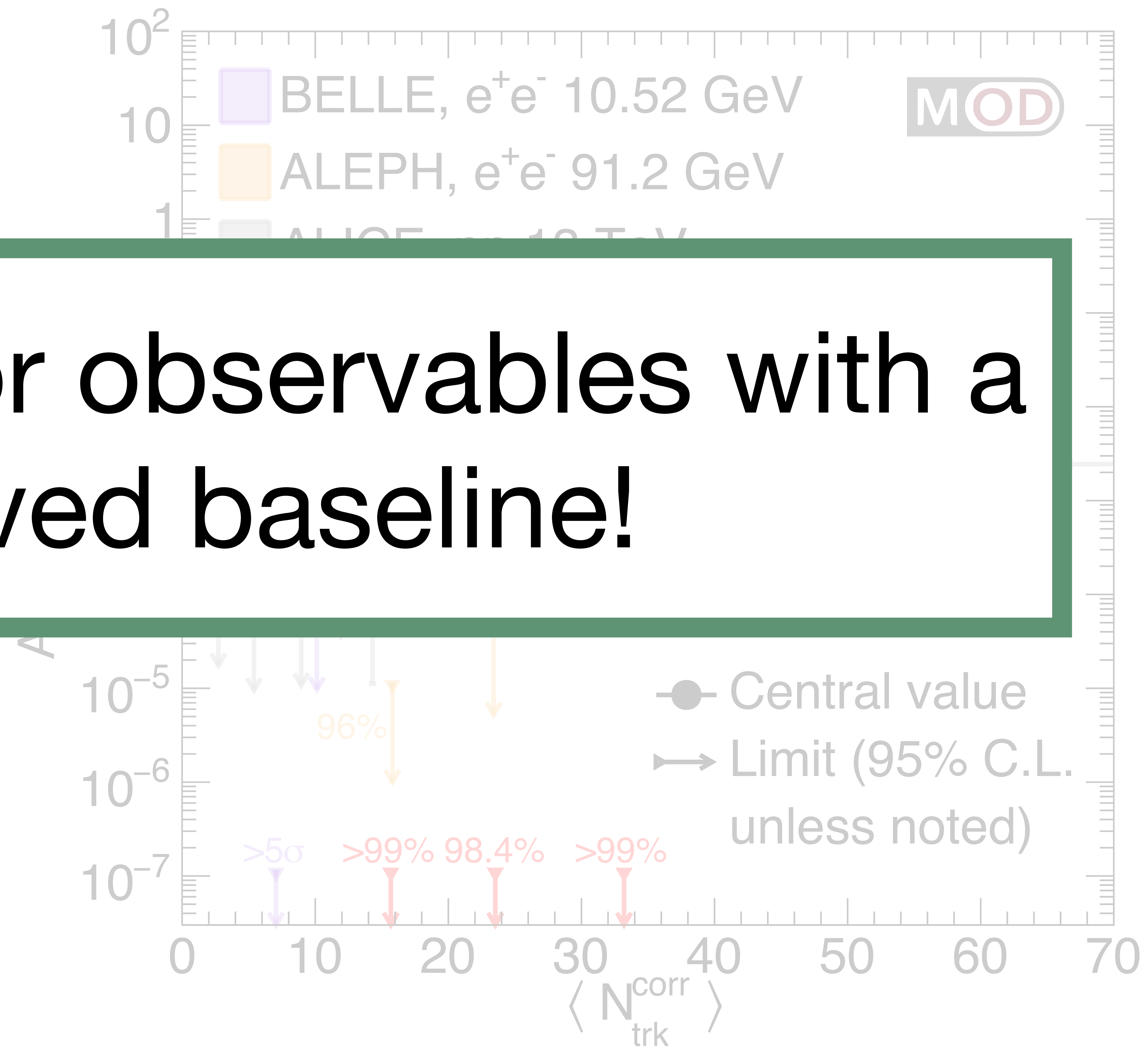




Some hiccups in the hydro paradise: flow in ee collisions (???!!?!)

[Chen et al 2312.05084]





These results call for observables with a better behaved baseline!