

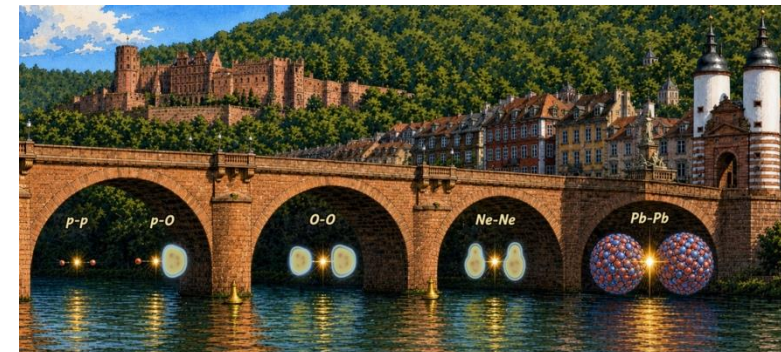
The standard model of high-energy nuclear collisions

Jean-François Paquet

September 21, 2026



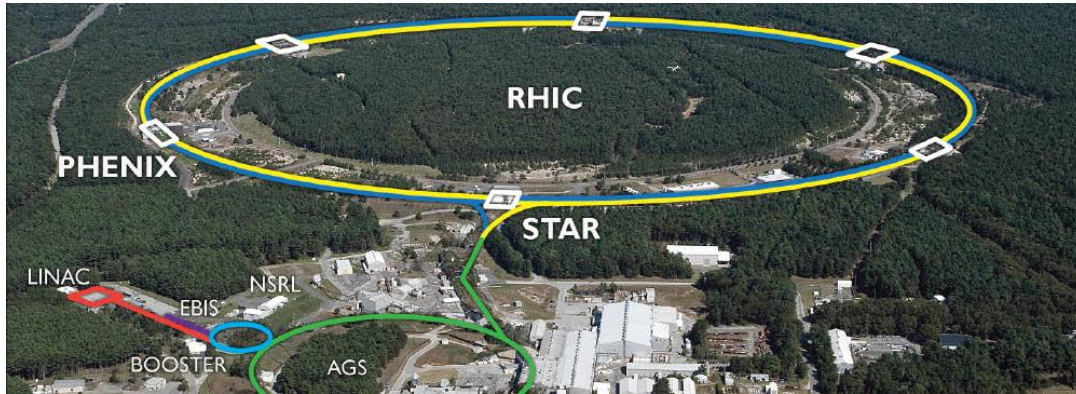
EMMI Workshop:
Light-ion collisions 2026



Relativistic ion collisions: experiments

Relativistic Heavy Ion Collider (RHIC, BNL)

Main detectors: sPHENIX, STAR, [PHENIX]



Large Hadron Collider (LHC, CERN)

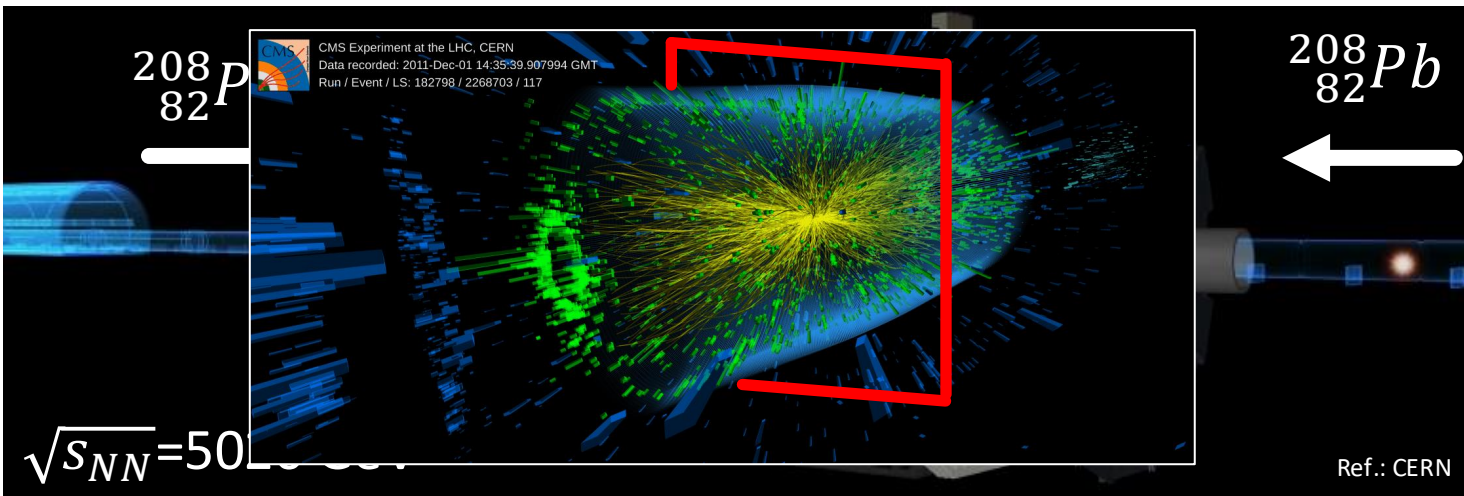
Main detectors: ALICE, ATLAS, CMS, LHCb



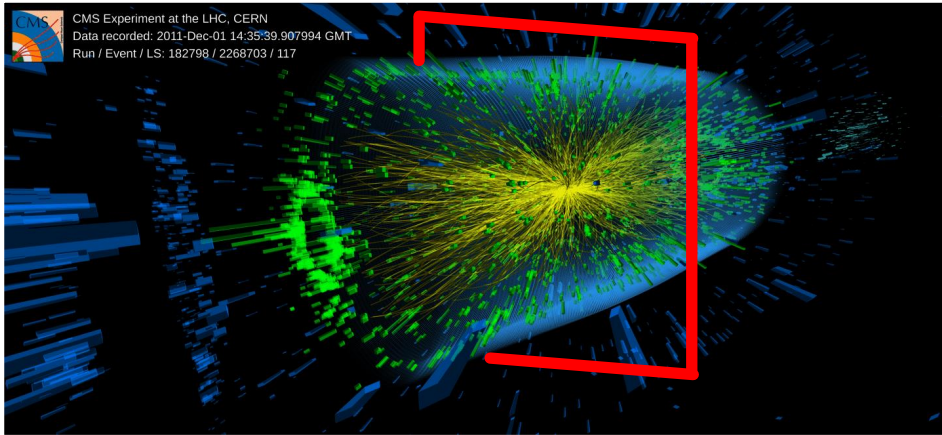
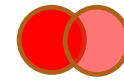
Kinetic energy of nuclei $\sim 10^2$ - 10^4 times mass of nuclei

■ In midrapidity region (LHC):

- $O(10^3)$ hadrons
- Transverse momentum: ~ 0.5 - 1 GeV
- $\pi^+ : K^+ : p$ ratio $\sim 20 : 3 : 1$
- Jets, photons, heavy quarks, ...



Relativistic nuclear collisions


 ^{208}Pb

Pb-Pb 5.02 TeV

 ^{197}Au
Au-Au 0.2 TeV

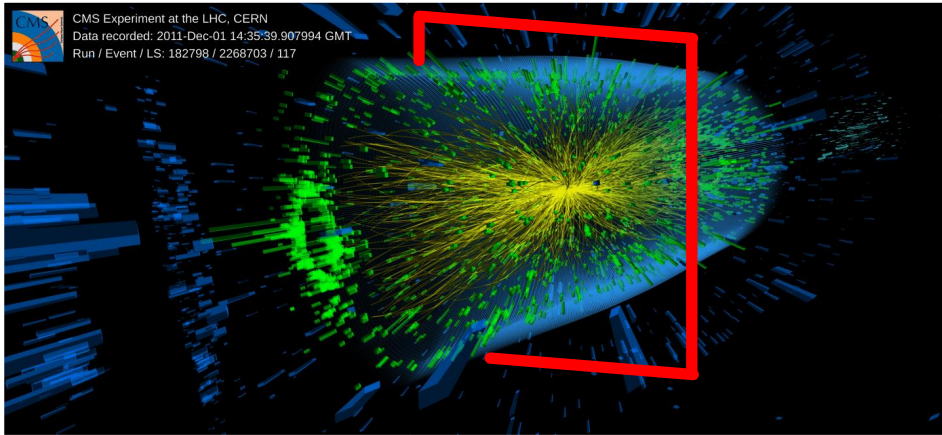
**p-p
5.02 TeV**

(note: log scale)

3 10 30 100 300 1000 3000

Number of charged hadrons per unit pseudorapidity at midrapidity $\left\langle \frac{dN_{ch}}{d\eta} \right\rangle |_{\eta \approx 0}$

Relativistic nuclear collisions

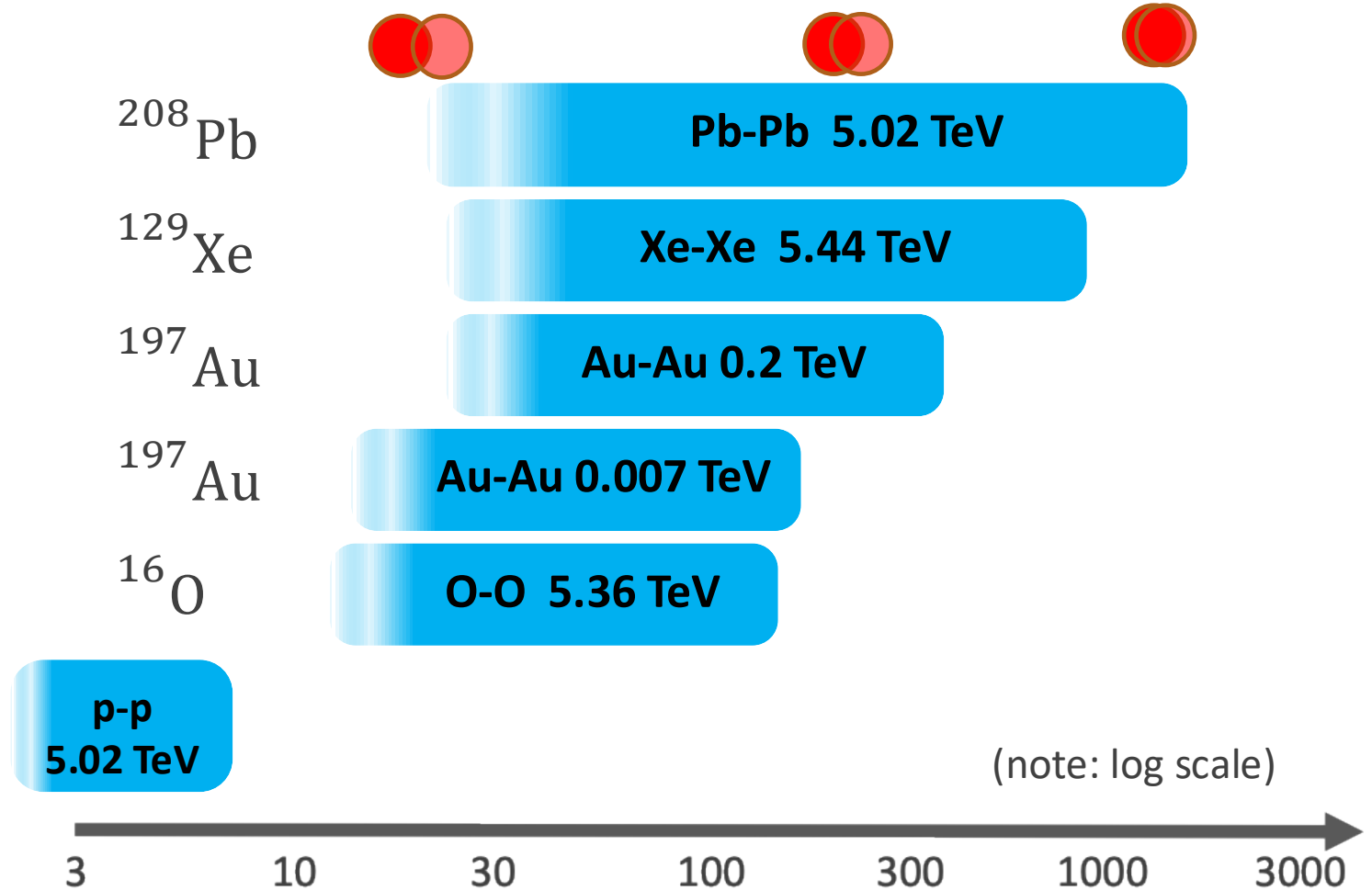
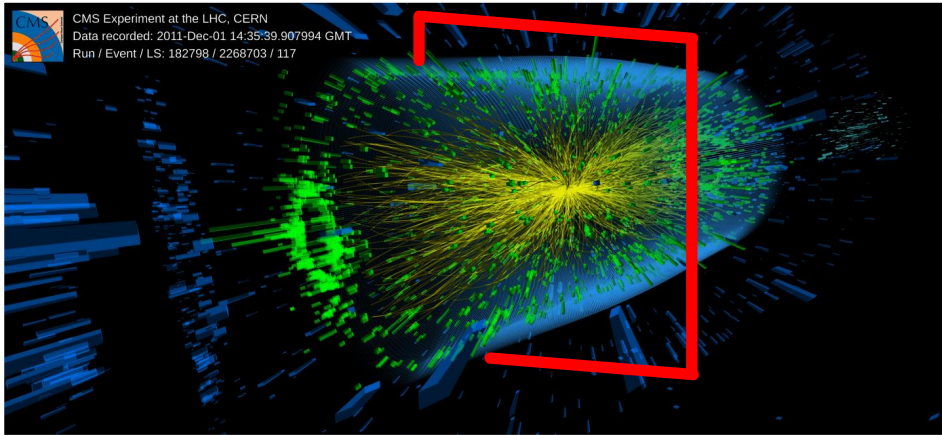

 ^{208}Pb
 ^{129}Xe
 ^{197}Au
Pb-Pb 5.02 TeV
Xe-Xe 5.44 TeV
Au-Au 0.2 TeV
**p-p
5.02 TeV**

(note: log scale)

3 10 30 100 300 1000 3000

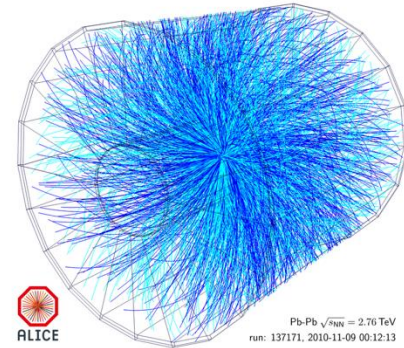
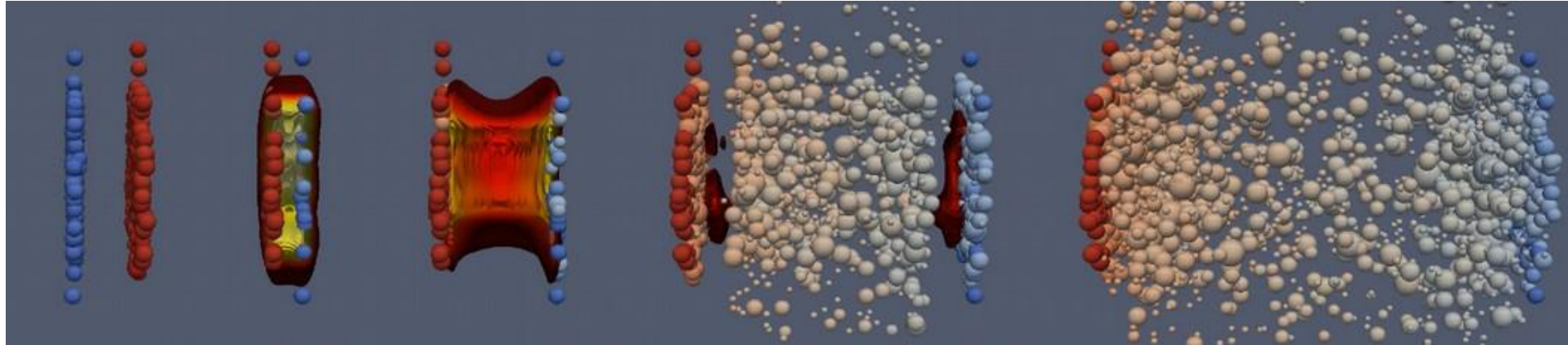
Number of charged hadrons per unit pseudorapidity at midrapidity $\left\langle \frac{dN_{ch}}{d\eta} \right\rangle |_{\eta \approx 0}$

Relativistic nuclear collisions



Number of charged hadrons per unit pseudorapidity at midrapidity $\left\langle \frac{dN_{ch}}{d\eta} \right\rangle \big|_{\eta \approx 0}$

Standard model of relativistic ion collisions



Initial conditions

- Effective QCD-based field theory
- Parametric models (e.g. Glauber)

Early dynamics

- Effective QCD kinetic theory
- Holography

Hydrodynamics

- Relativistic viscous hydrodynamics

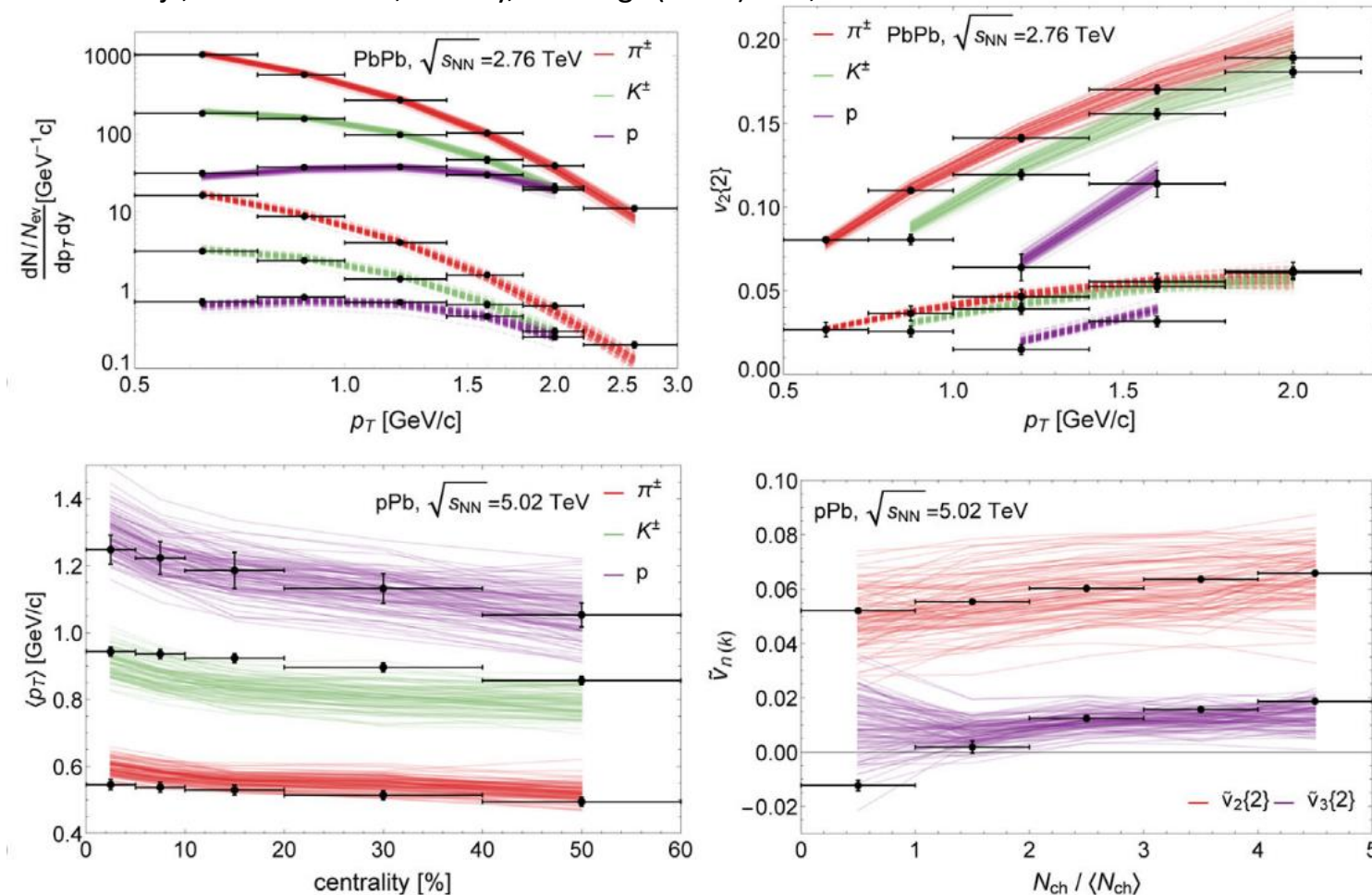
Hadronic transport

- Relativistic hadronic transport

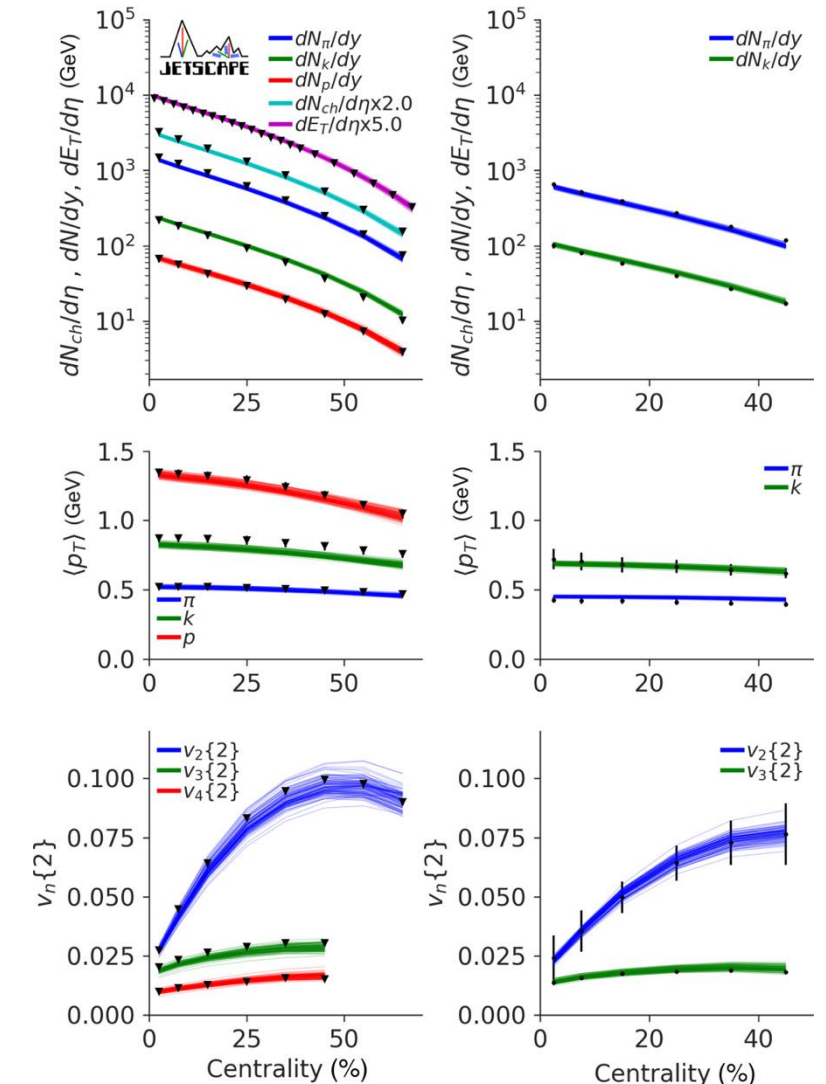
Standard model of relativistic ion collisions vs data

- Successful in describing broad sets of measurements

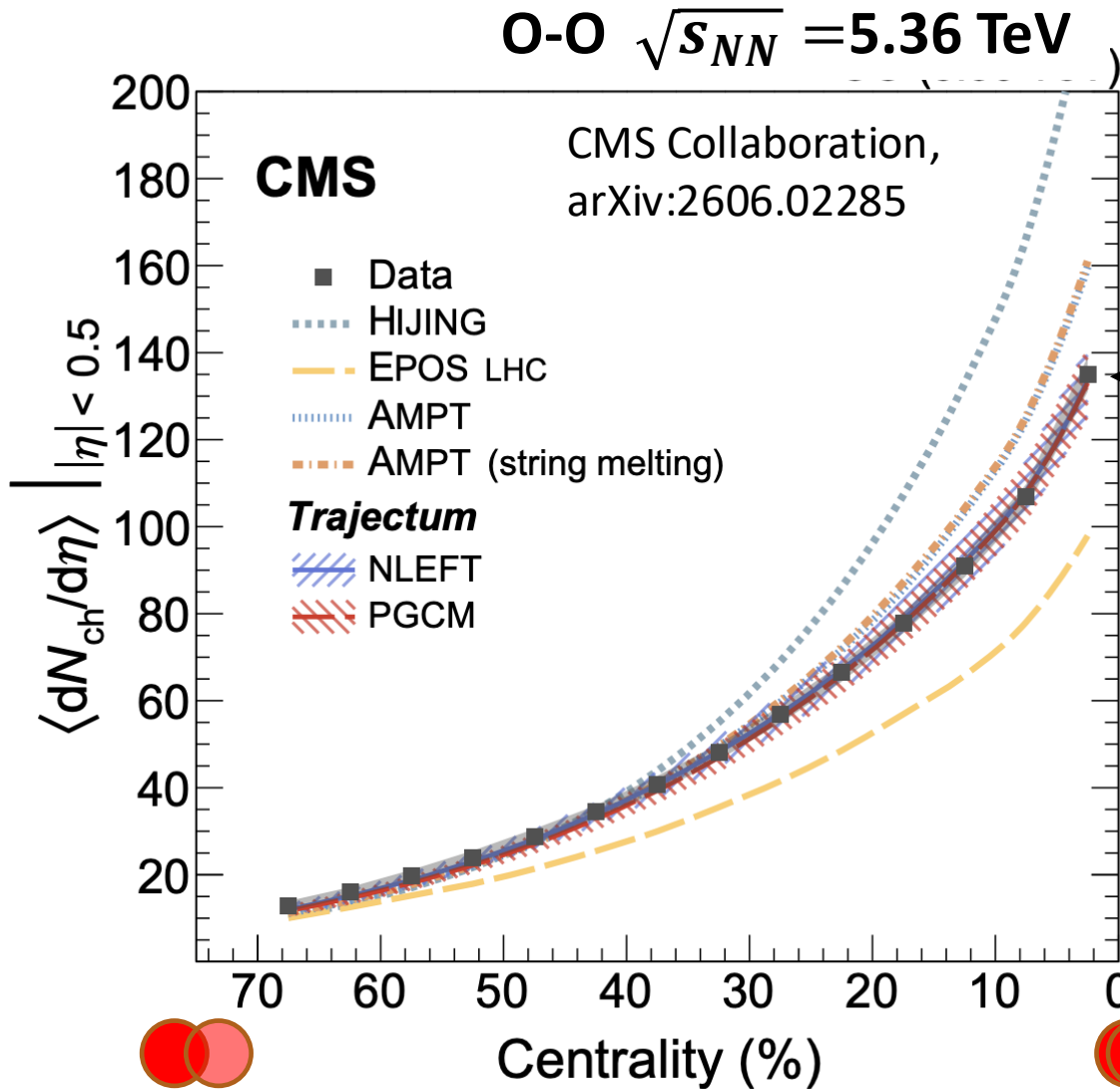
Nijs, van der Schee, Gürsoy, Snellings (2021) PRC, PRL



JETSCAPE Collaboration, (2021) PRC, PRL

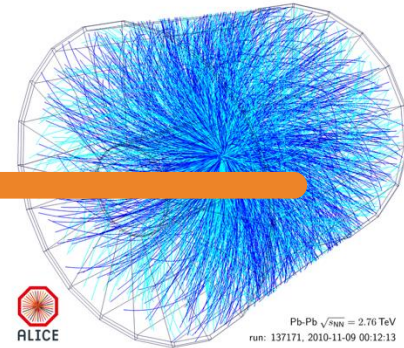
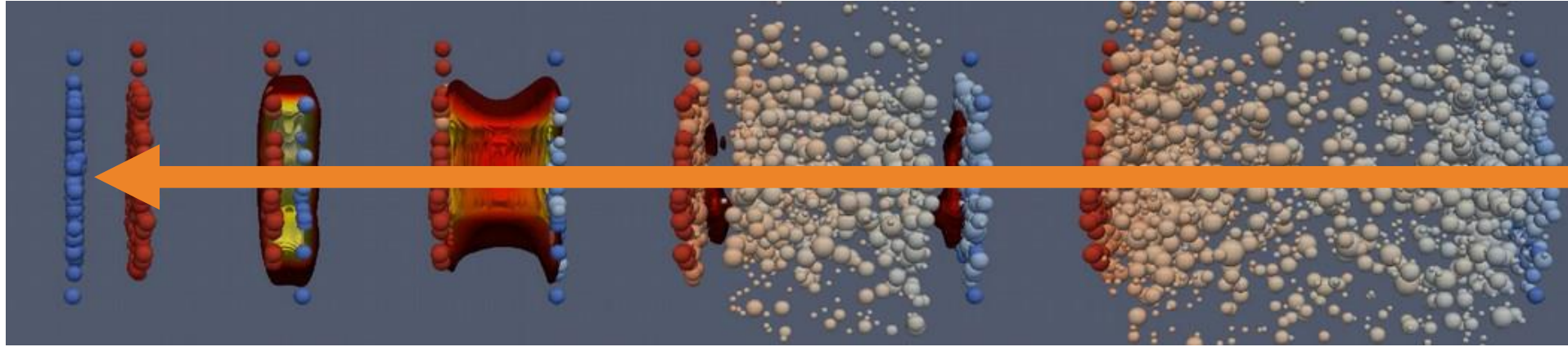


Standard model of relativistic ion collisions vs data



Prediction from “standard model of ion collisions” outperformed non-hydrodynamic models

Standard model of relativistic ion collisions



Initial conditions

- Effective QCD-based field theory
- Parametric models (e.g. Glauber)

Early dynamics

- Effective QCD kinetic theory
- Holography

Hydrodynamics

- Relativistic viscous hydrodynamics

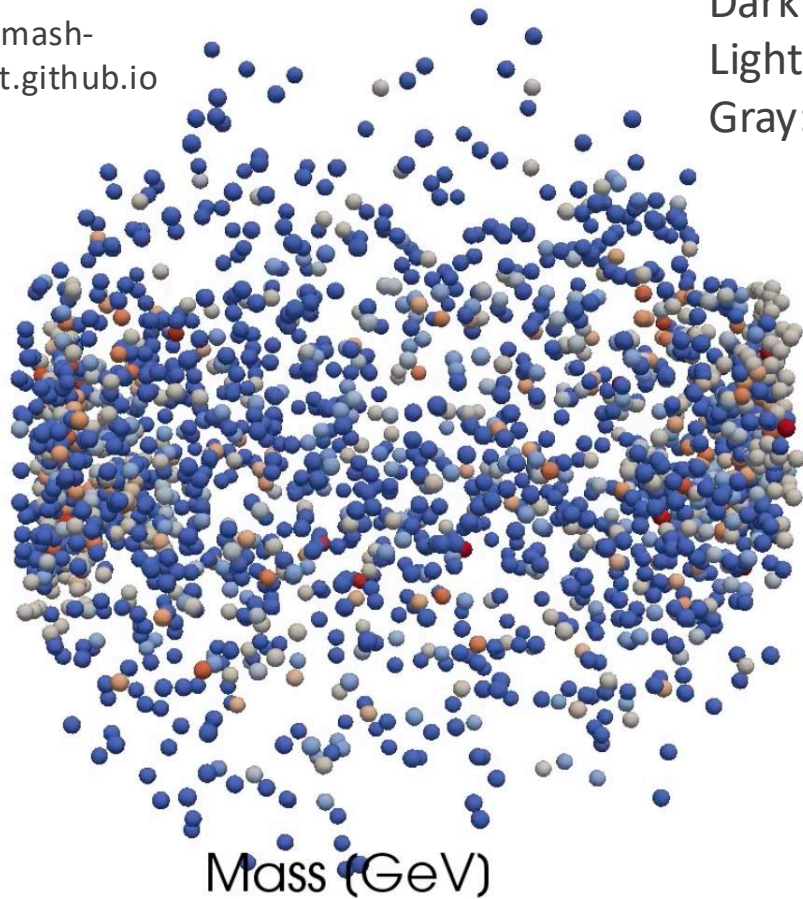
Hadronic transport

- Relativistic hadronic transport

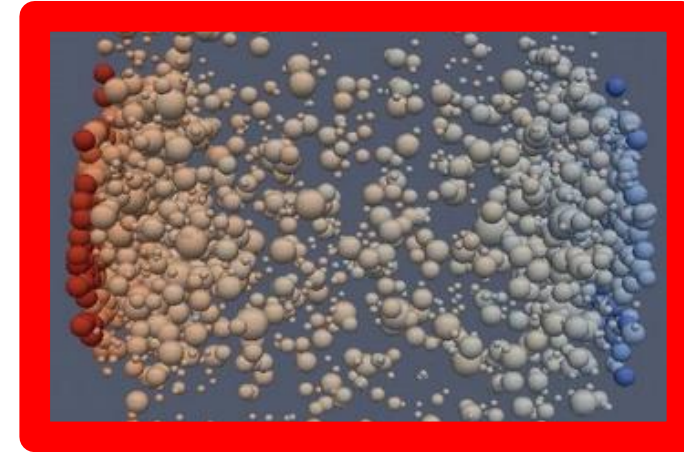
Late stage: hadronic transport

From
<https://smash-transport.github.io>

Dark blue: pions
Light blue: kaons
Gray: protons



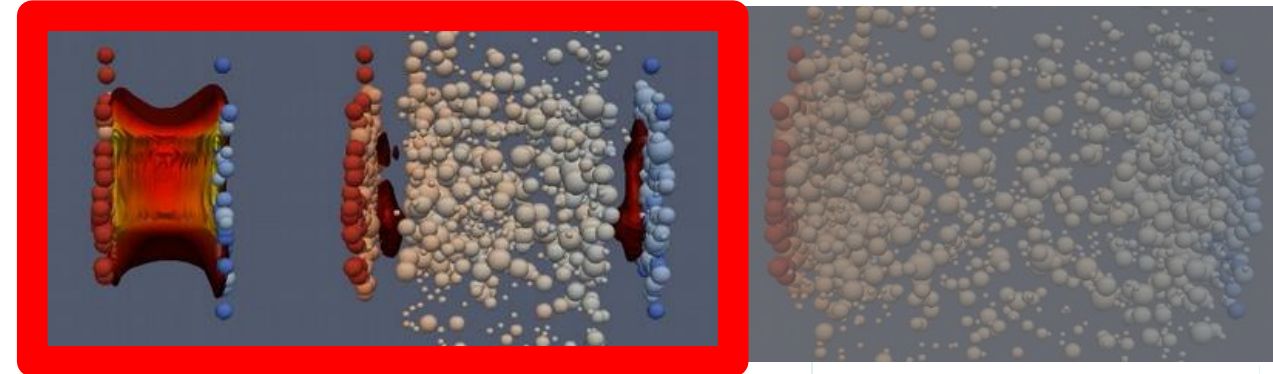
- Implementations:
SMASH, UrQMD, JAM
- Physics inputs:
 - lists of resonances
 - masses, widths, cross-sections, ...



Hadronic transport

- Relativistic hadronic transport

Intermediate stage: hydrodynamics evolution



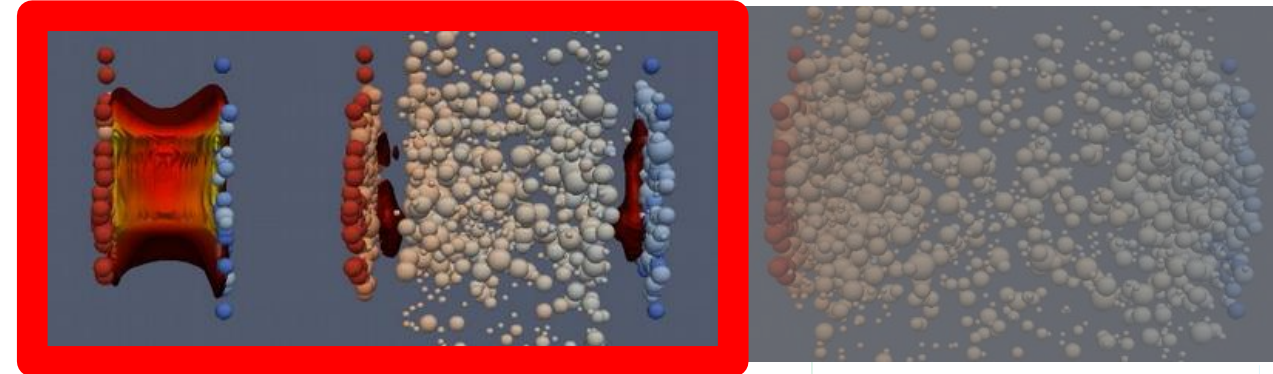
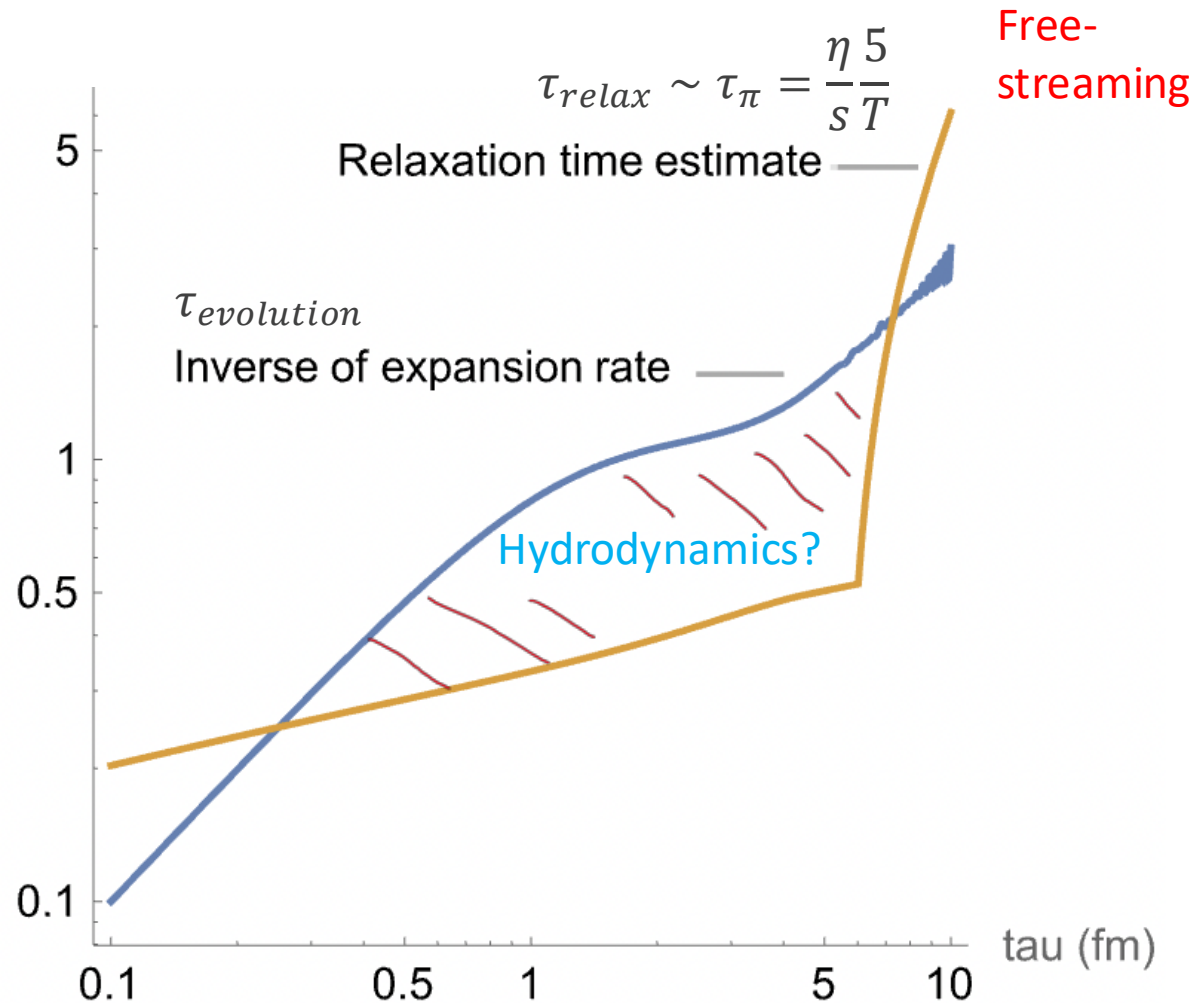
Hydrodynamics

Hadronic transport

- Relativistic viscous hydrodynamics

- Hydrodynamics description possible thanks to separation of scales:
 - relaxation time scale shorter than evolution time scale
 - $\tau_{relax} \ll \tau_{evolution} (?)$

Intermediate stage: hydrodynamics evolution



Hydrodynamics

Hadronic transport

- Relativistic viscous hydrodynamics

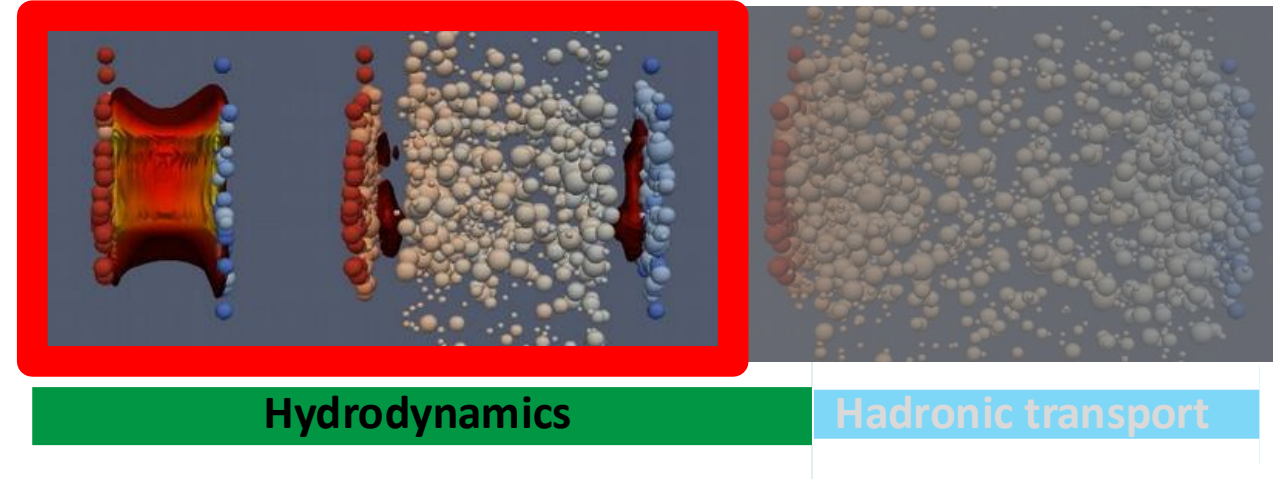
- Hydrodynamics description possible thanks to separation of scales:
 - relaxation time scale shorter than evolution time scale
 - $\tau_{relax} \ll \tau_{evolution} (?)$

Intermediate stage: hydrodynamics evolution

■ CLVisc, MUSIC, VISHNU, SONIC, Trajectum, vHLLE, CCAKE, ...:

- solve $\pm$ same fluid equations
- differences possible in transport coefficients and equation of state

■ Some exceptions: Hydro+; Anisotropic hydro



Equation of state from lattice QCD

- Energy-momentum tensor: $T^{\mu\nu} = \epsilon u^\mu u^\nu + (P(\epsilon) + \Pi)(g^{\mu\nu} + u^\mu u^\nu) + \pi^{\mu\nu}$
- Conservation of energy/momentum: $\partial_\nu T^{\mu\nu} = 0$
- DNMR transient relativistic viscous hydrodynamics

$$\tau_\pi \Delta^{\mu\nu}_{\alpha\beta} \dot{\pi}^{\alpha\beta} + \boxed{\pi^{\mu\nu} = 2 \eta(T) (\partial^\mu u^\nu + \dots)} + (2^{\text{nd}} \text{ order}); \quad \tau_\Pi \dot{\Pi} + \boxed{\Pi = -\zeta(T) \partial_\mu u^\mu} + (2^{\text{nd}} \text{ order});$$

Hydrodynamics evolution: what do we solve?

Mueller-Israel-Stewart-type hydrodynamics:

Conservation of energy and momentum: $\partial_\nu (\epsilon u^\mu u^\nu + (P(\epsilon) + \Pi)(u^\mu u^\nu + g^{\mu\nu}) + \pi^{\mu\nu}) = 0$

Evolution of bulk pressure: $\tau_\Pi \dot{\Pi} + \Pi = -\zeta \theta - \delta_{\Pi\Pi} \Pi \theta + \lambda_{\Pi\pi} \pi^{\mu\nu} \sigma_{\mu\nu}$

Evolution of shear tensor: $\tau_\pi \dot{\pi}^{\langle\mu\nu\rangle} + \pi^{\mu\nu} = 2\eta \sigma^{\mu\nu} - \delta_{\pi\pi} \pi^{\mu\nu} \theta + \phi_7 \pi_\alpha^{\langle\mu} \pi^{\nu\rangle\alpha} - \tau_{\pi\pi} \pi_\alpha^{\langle\mu} \sigma^{\nu\rangle\alpha} + \lambda_{\pi\Pi} \Pi \sigma^{\mu\nu}$

Red=1st order transport coefficient; Green=2nd order transport coefficient; Blue=Terms related to derivatives of the flow velocity

[Mueller (1967) Zeit. fur Phys; Israel&Stewart (1979) Ann. Phys.; see also Baier, Romatschke, Son, Starinets, Stephanov (2008) JHEP; Denicol, Niemi, Molnar, Rischke (2012,2015) PRD]

These equations can be coupled with:

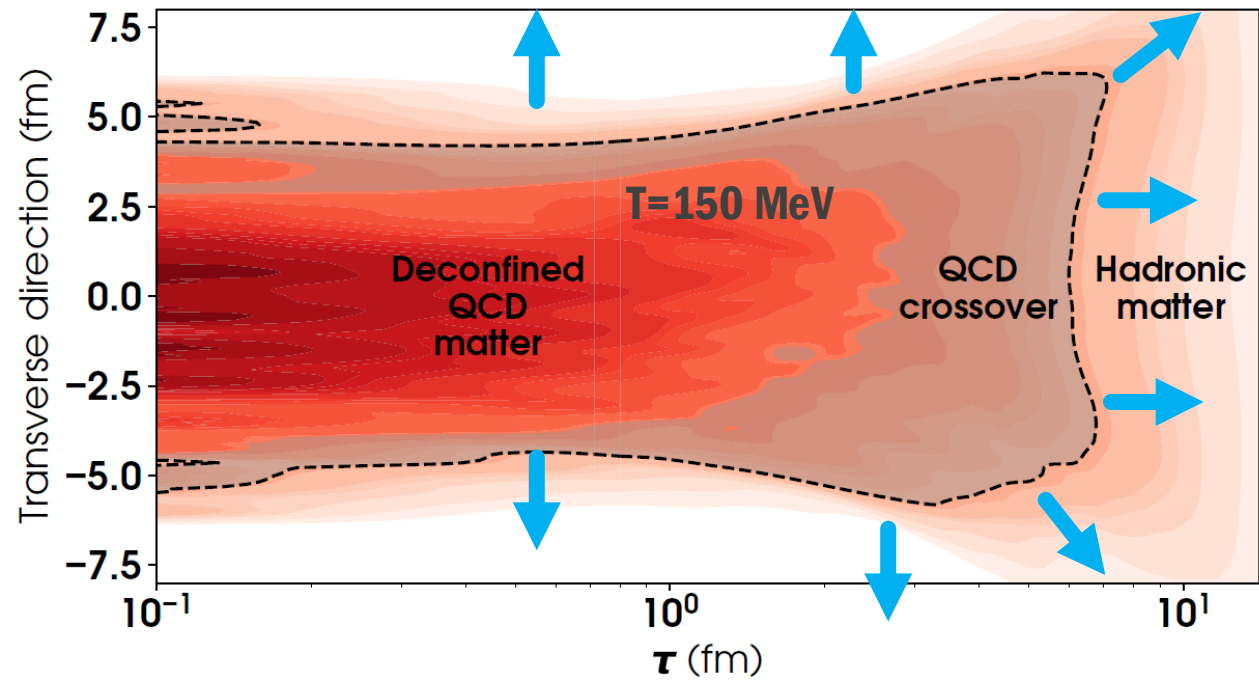
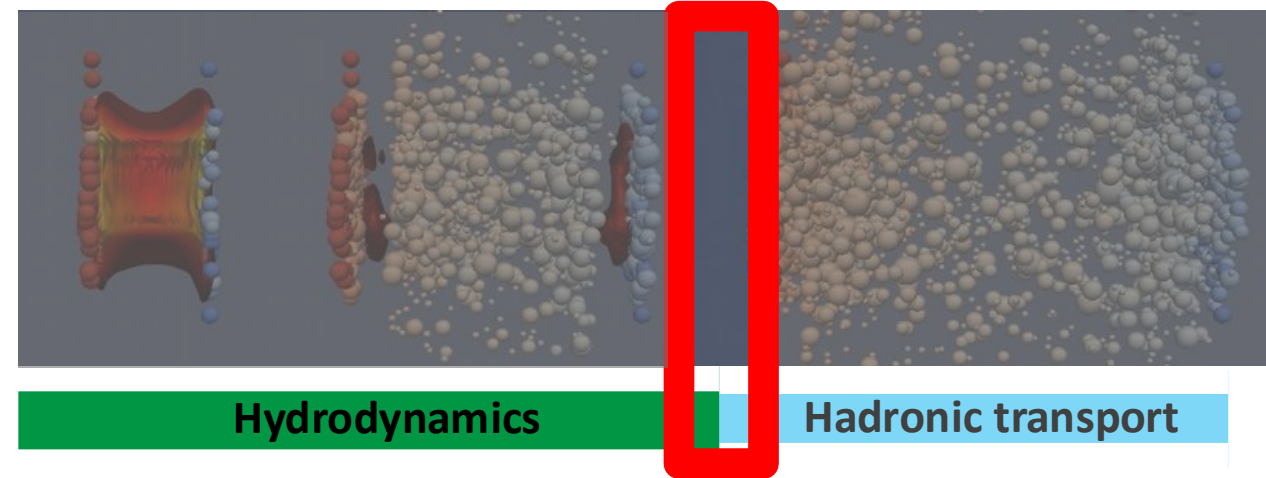
- Additional conserved currents (baryon, electric, ...) [e.g. CCAKE]
- Electromagnetic fields
- Sources, e.g. energy deposition from jets

Hydrodynamics to particles: "particlization"

- When to transition from hydrodynamics?
 - Hypersurface? Hypervolume?
 - Transition criteria?

$$T^{\mu\nu} = \sum_n g_n \int \frac{d^3k}{(2\pi)^3 K^0} K^\mu K^\nu f_n(K)$$

$$= \epsilon u^\mu u^\nu + (P + \Pi)(g^{\mu\nu} + u^\mu u^\nu) + \pi^{\mu\nu}$$



Hydrodynamics to particles: "particlization"

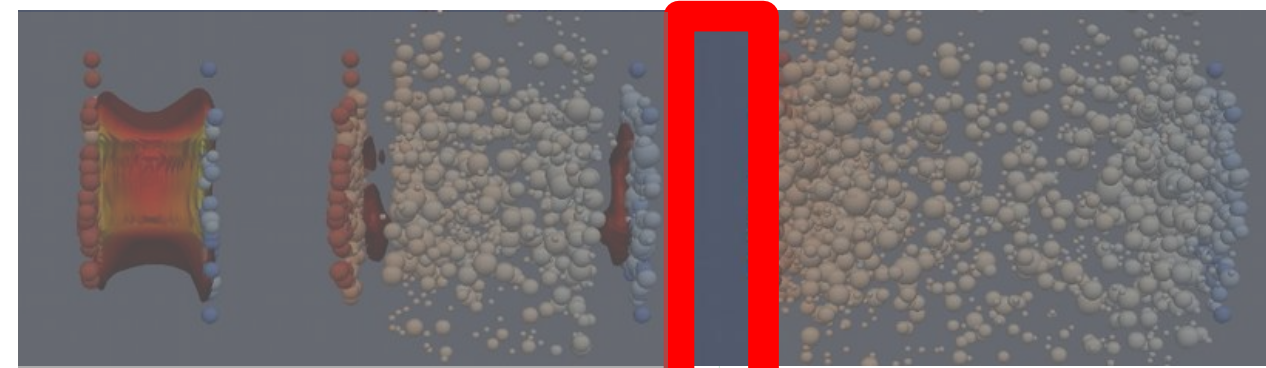
- When to transition from hydrodynamics?
 - Hypersurface? Hypervolume?
 - Transition criteria?

$$T^{\mu\nu} = \sum_n g_n \int \frac{d^3k}{(2\pi)^3 K^0} K^\mu K^\nu f_n(K)$$

$$= \epsilon u^\mu u^\nu + (P + \Pi)(g^{\mu\nu} + u^\mu u^\nu) + \pi^{\mu\nu}$$

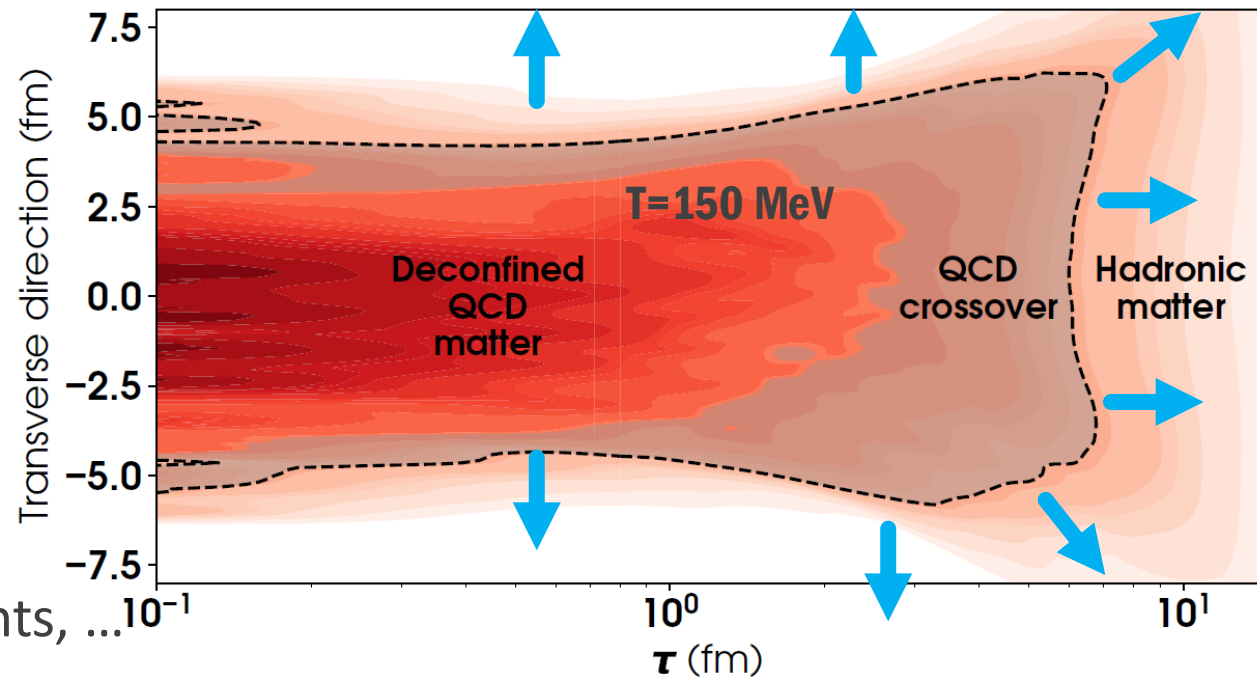
$\Rightarrow f_n(K) = \text{function}(\epsilon, u^\mu, \Pi, \pi^{\mu\nu});$
 "n" is the hadron species

- Local equilibrium:
 - Fermi-Dirac (baryons); Bose-Einstein (mesons)
- Out-of-equilibrium: not unique
 - Models like Chapman-Enskog, Grad's 14 moments, ...



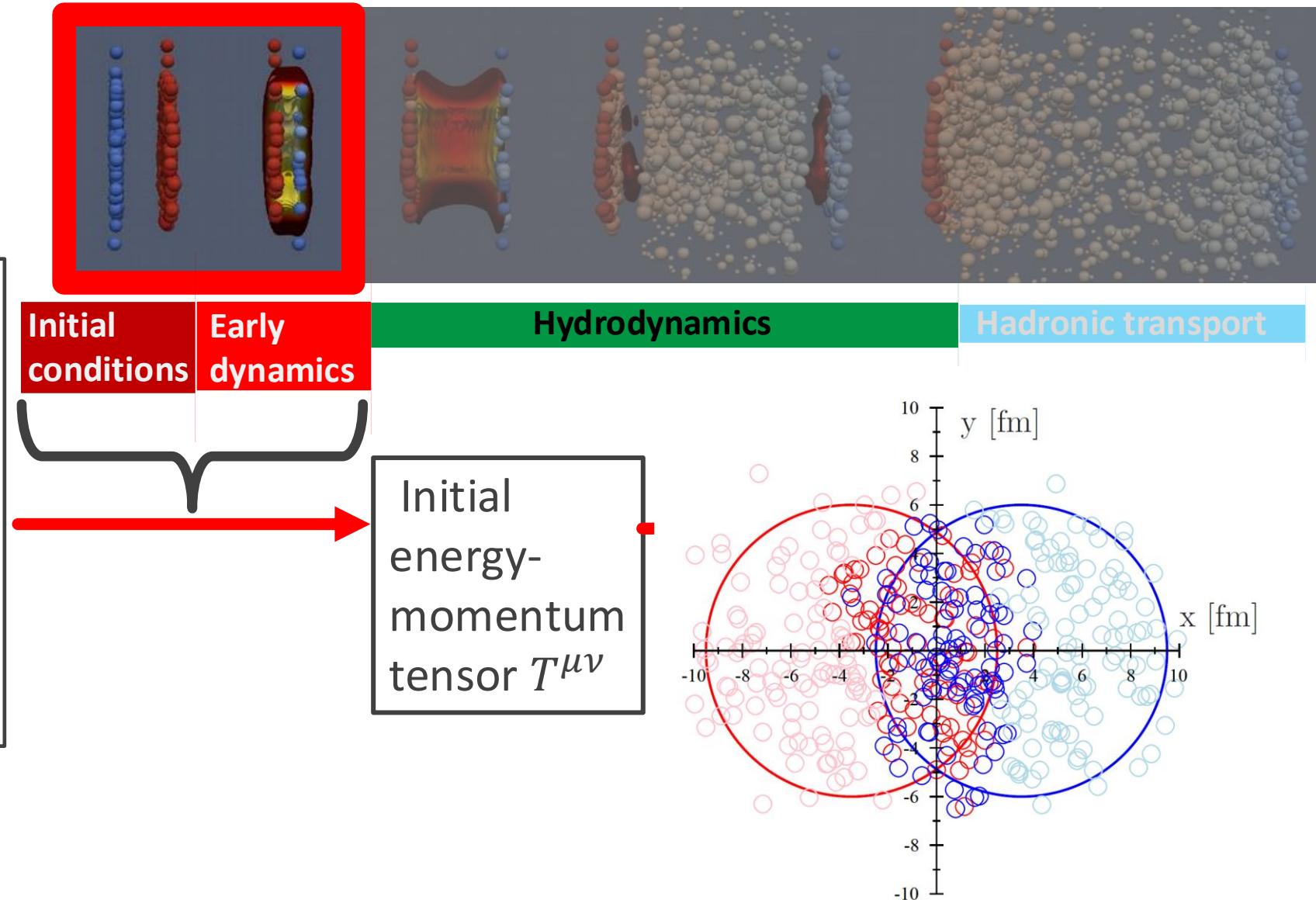
Hydrodynamics

Hadronic transport

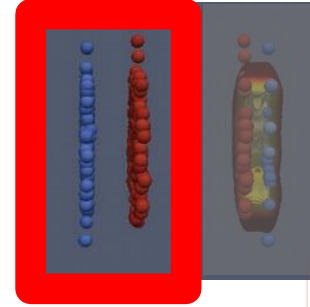


Before hydrodynamics: initial conditions and early stage

- Distribution of protons/neutrons (or color charge) in nuclei, nucleus deformation, ...
- Parton distribution functions
- Inelastic nucleon cross-section



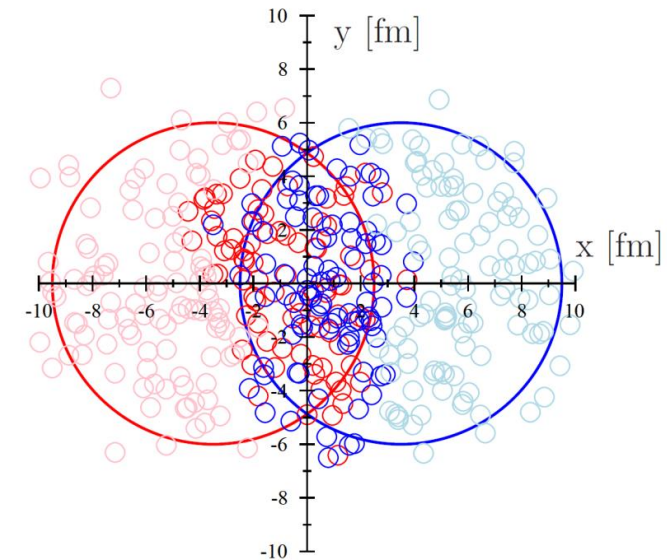
Before hydrodynamics: initial conditions and early stage



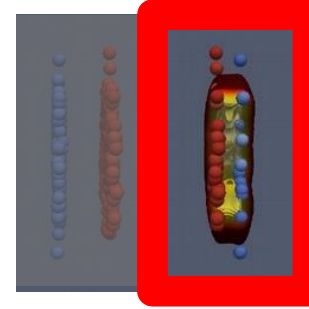
Initial conditions

- Distribution of protons/neutrons (or color charge) in nuclei, nucleus deformation, ...
- Parton distribution functions
- Inelastic nucleon cross-section

- QCD effective field theory approaches like color glass condensate
- Eikonal nucleon interactions like Glauber models (e.g. Trento) →
- Perturbative QCD (e.g. EKRT)
- Hadronic transport



Before hydrodynamics: initial conditions and early stage



Initial conditions

- Distribution of protons/neutrons (or color charge) in nuclei, nucleus deformation, ...
- Parton distribution functions
- Inelastic nucleon cross-section

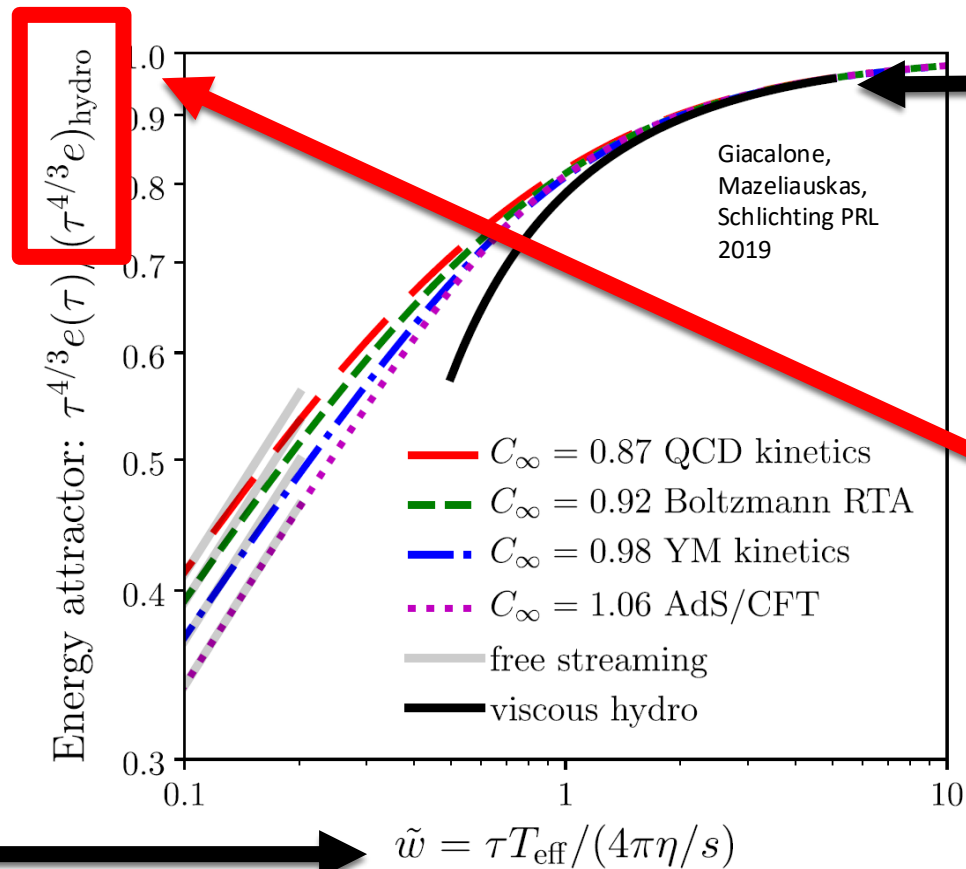
- CGC
- Glauber
- pQCD
- Hadronic

Early dynamics

- Classical Yang-Mills (IP-Glasma)
- Effective kinetic theory (attractors, KoMPoST, ...)
- Holography?

Approach to hydrodynamics in lower dimension systems

- In 0+1D hydro, we can characterize $T^{\mu\nu}$ with single component: energy density
- 0+1D dynamical models with smooth transition to hydrodynamics: Kinetic theory or AdS/CFT



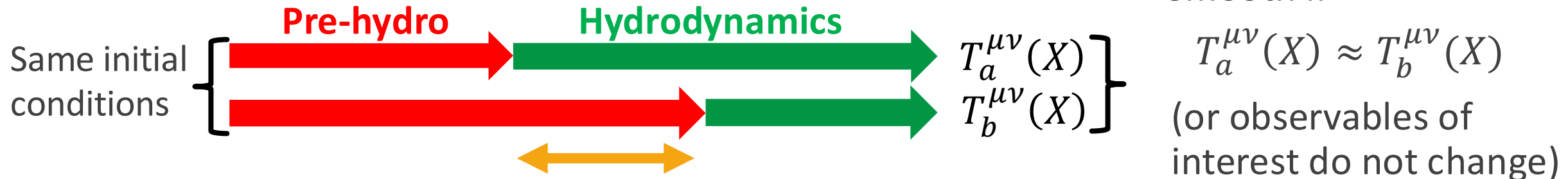
All systems converge to 0+1D viscous hydro

(note: not all systems have the same final energy density, but this can be rescaled)

Depends on relaxation time necessary to converge to hydrodynamics

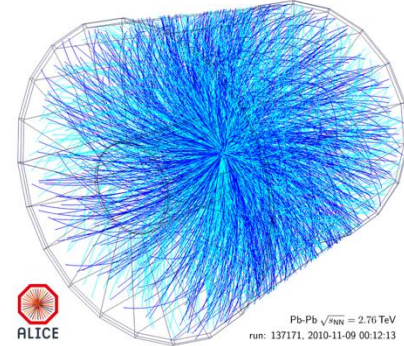
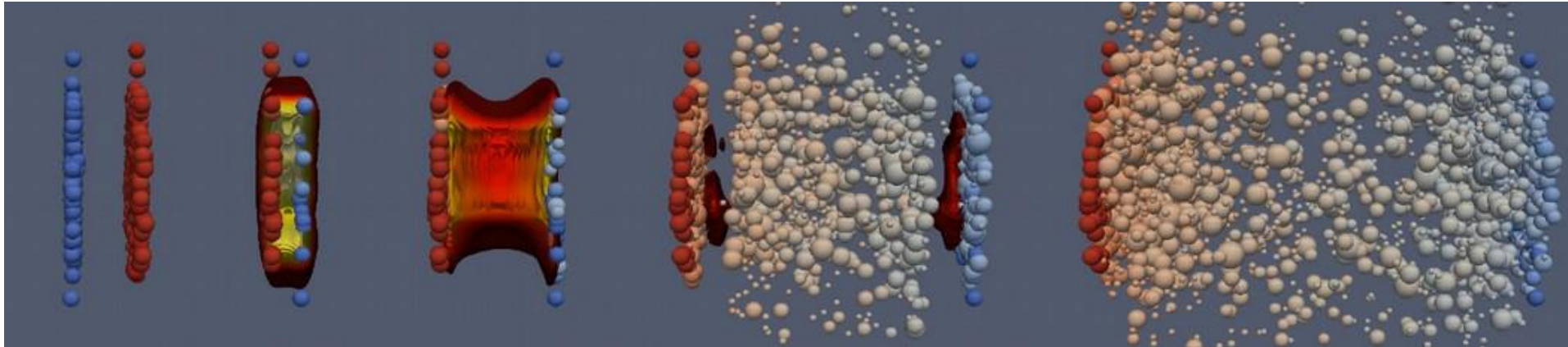
Initializing hydrodynamics vs transitioning to hydrodynamics

- Models of the pre-hydro do not generally approach hydrodynamics (or not fast enough):
 - IP-Glasma, EKRT, PYTHIA, AMPT, URQMD/SMASH, Glauber/Trento+free-streaming, ...
- Practical test of smooth transition to hydrodynamics:



- Extensive work on approach to hydrodynamics in kinetic theory and holography

Standard model of relativistic ion collisions



Initial conditions

Early dynamics

Hydrodynamics

Hadronic transport

Transition criteria
(e.g. initial time τ_0)

- Shear and bulk viscosity (functions of temperature and more)
- Other transport coefficients?

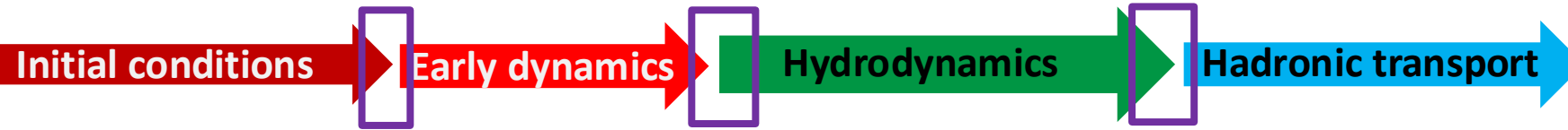
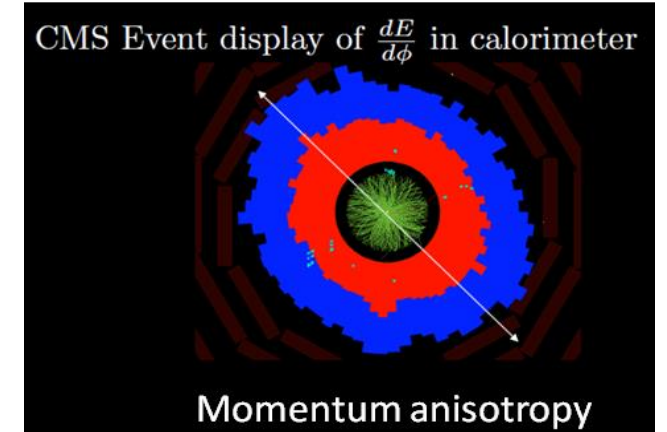
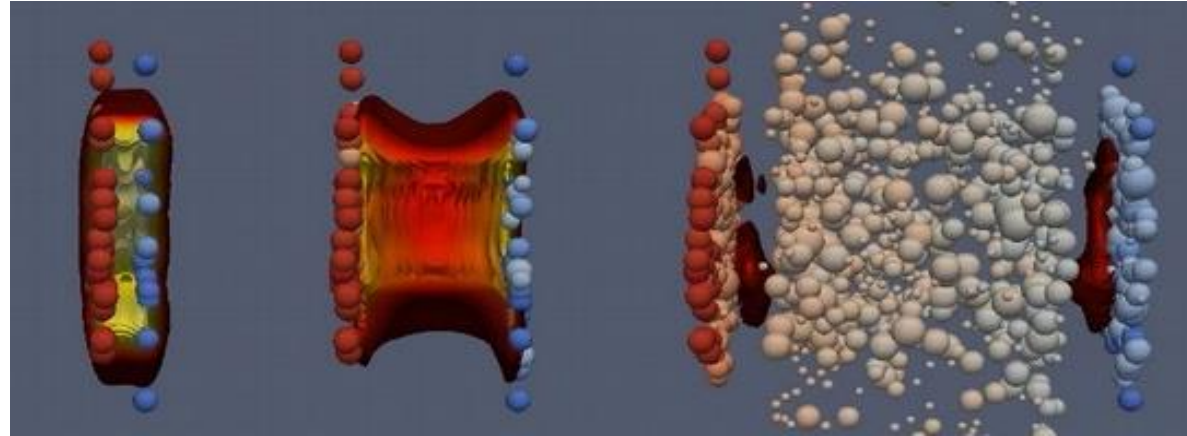
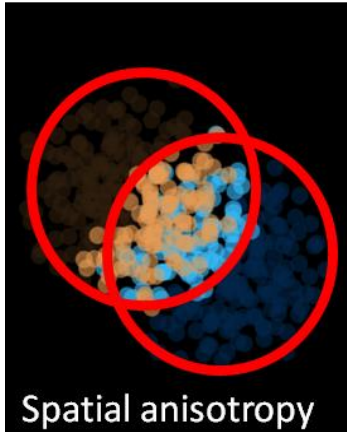
Transition criteria
(e.g. switching energy density)

Vigilance to avoid overfitting

- If parametric ansatz: normalization, nucleon width, fluctuations, ...
- Models based on effective field theory have fewer

Beyond the current standard model of collisions

Based on figures by Derek Teaney, CMS Coll., MADA1, H. Elfner and J. Bernhard

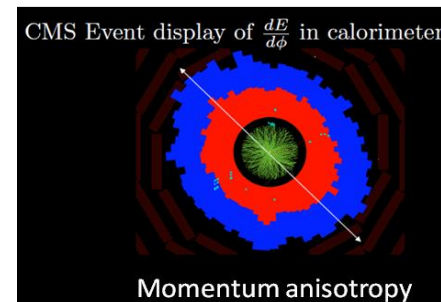
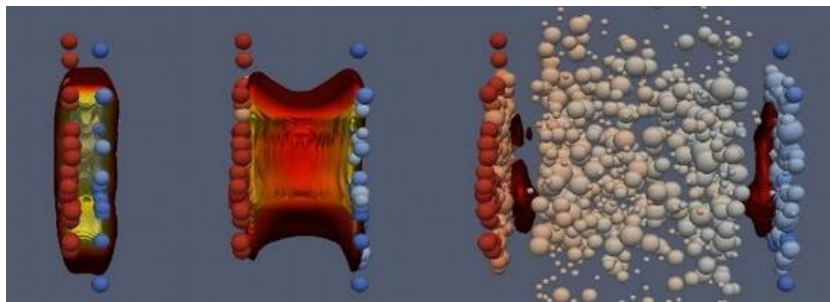
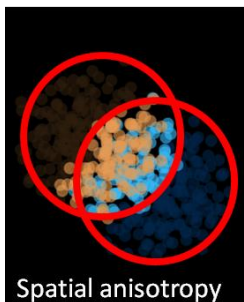


- Need (i) smooth transition between stages of collision, and
(ii) convergence between models

and/or

- Need to consider a more limited set of observables

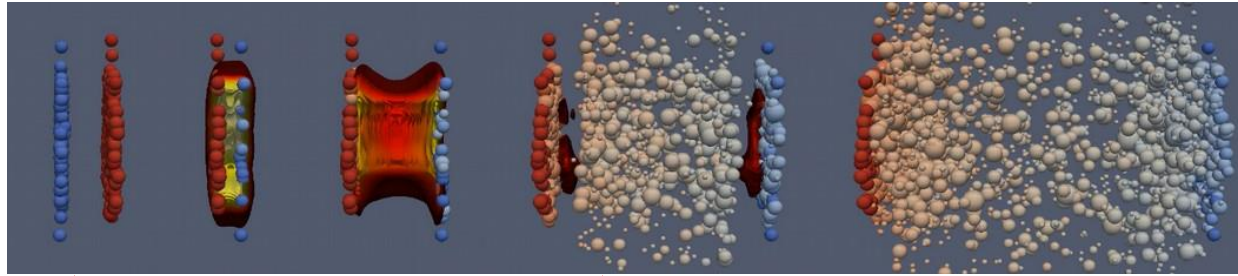
[Analogy: inclusive and exclusive observables in proton-proton collisions]



SUMMARY

Summary

- There is a phenomenologically successful standard model of ion collisions



Initial conditions

Early dynamics

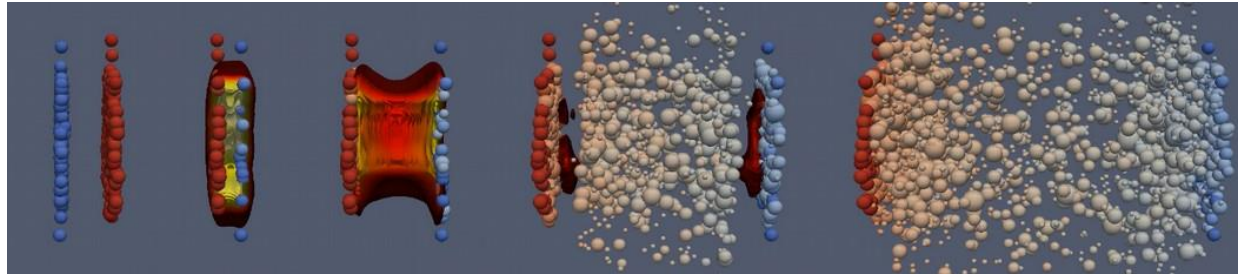
Hydrodynamics

Hadronic transport

- There has been both steady progress ...
 - Understanding of approach to hydrodynamics, attractors, ...
 - Initial conditions for rapidity direction, charges, ...
- ...and stagnation...
 - Space of initial condition models: IP-Glasma, Trento, EKRT, partonic/hadronic transport?
 - Known uncertainties (e.g. initial models, particlization) not systematically quantified

Outlook

- “Standard model of ion collisions” seem to work rather well in light ion collisions



Initial conditions

Early dynamics

Hydrodynamics

Hadronic transport

- Are model uncertainties bigger in light ion collisions?
- Perhaps we can turn a problem in an opportunity
 - Rethink/improve model
 - Rethink observables



QUESTIONS?





BACKUP

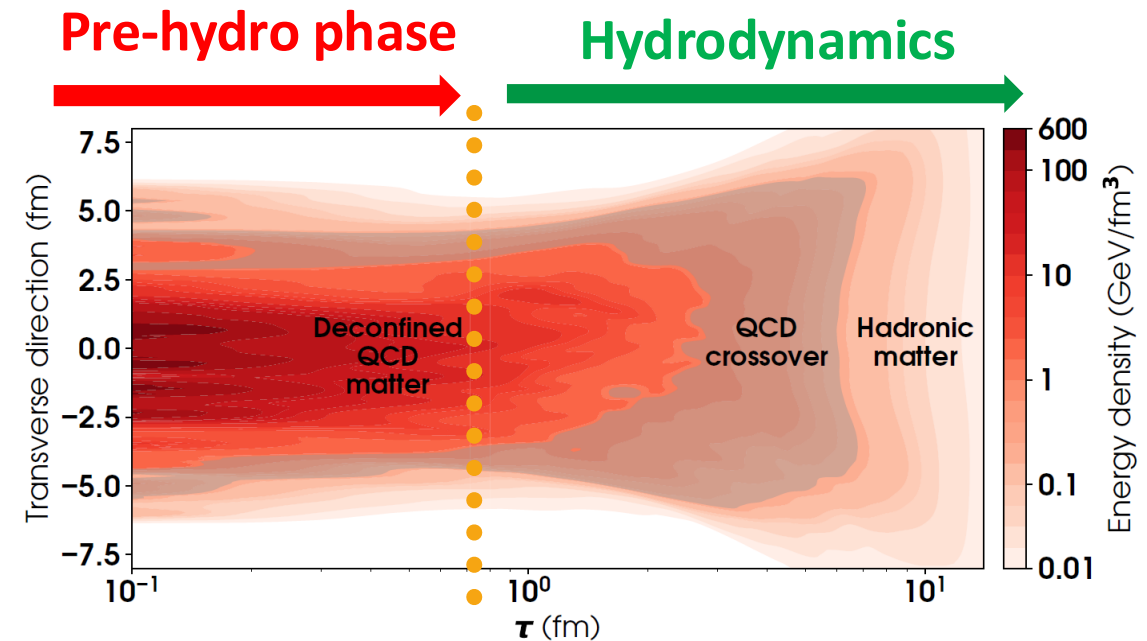


Matching to hydrodynamics: review

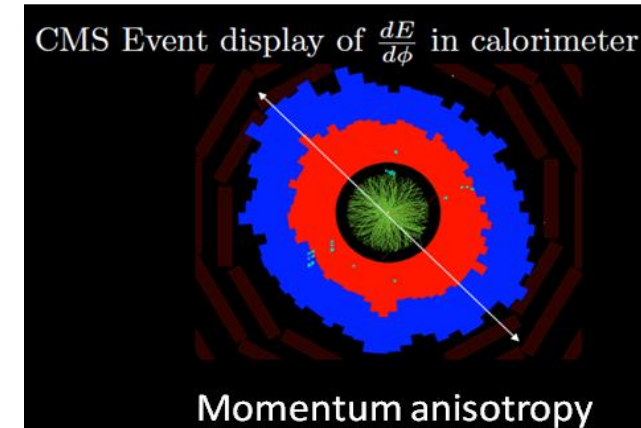
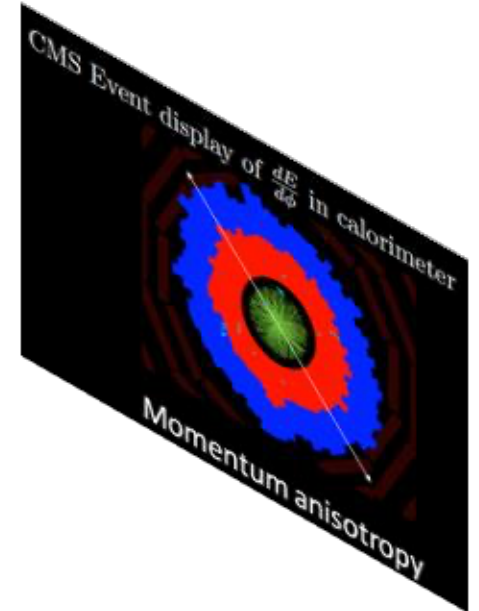
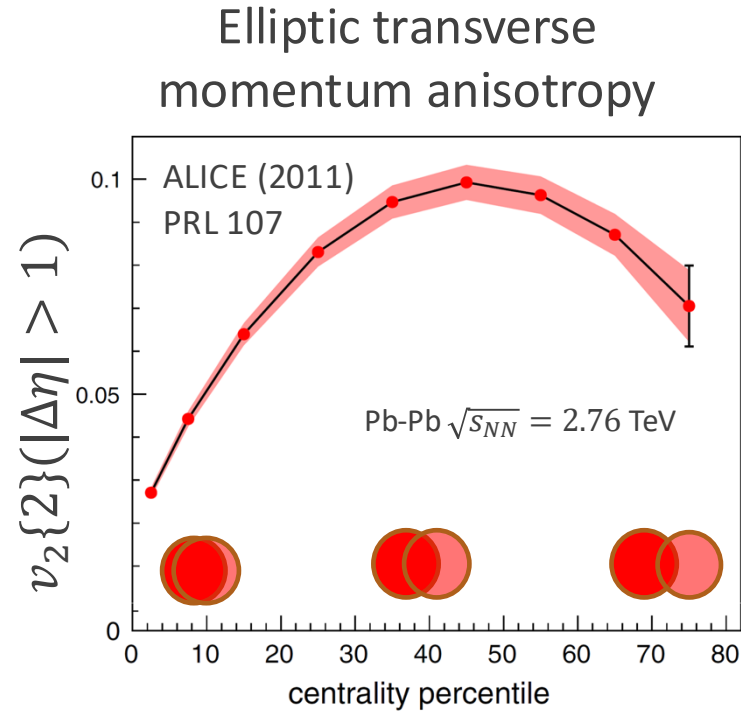
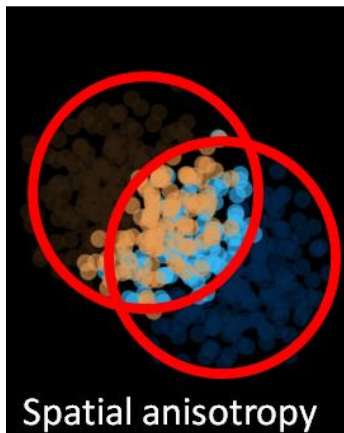
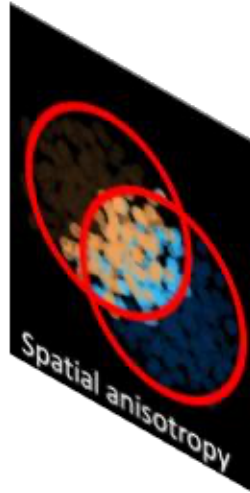
- Smooth transition to hydrodynamics is desirable
- Large amount of literature on approach to hydrodynamics
 - Mainly for 0+1D (boost invariant) systems
 - Mainly for conformal systems

For heavy ion phenomenology:

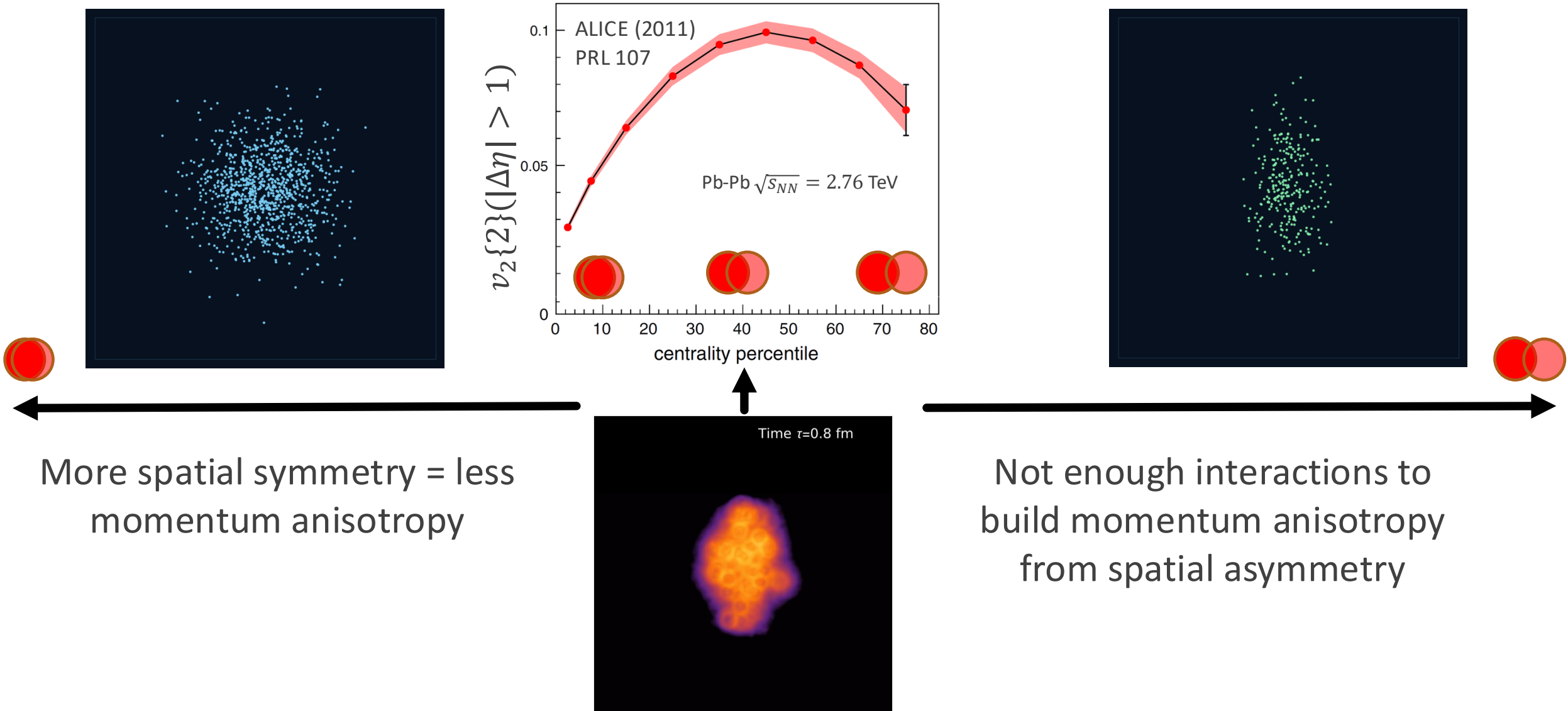
- Need non-conformal studies
- More studies of 2+1D systems
- For small system and $\sqrt{s_{NN}}$, needs:
 - 3+1D (non-boost invariant)
 - Baryon chemical potential
 - And much more



Overlap of nuclei vs anisotropy of particle production



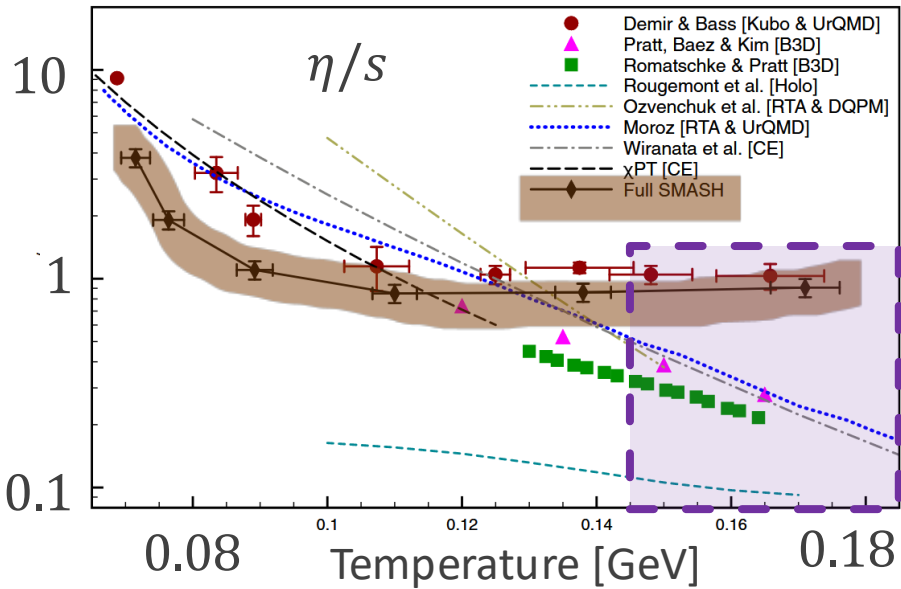
Momentum asymmetry needs interactions (and asymmetry)



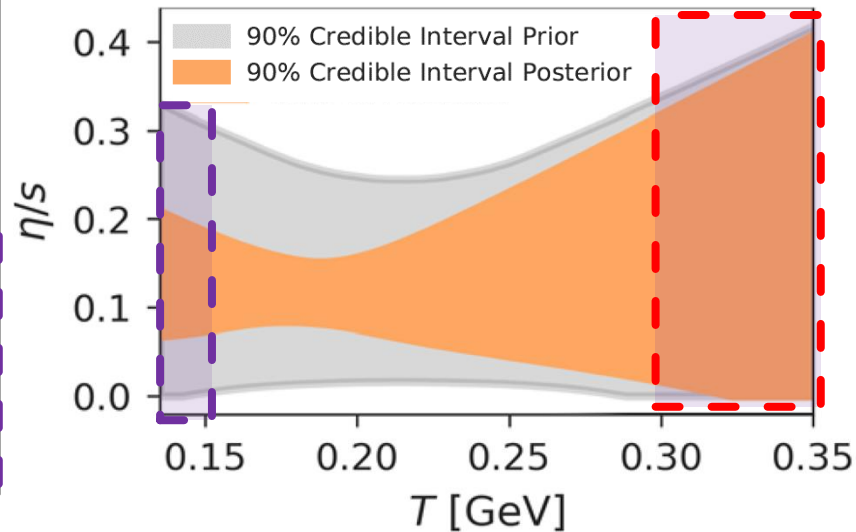
Smooth transition between models and their viscosities



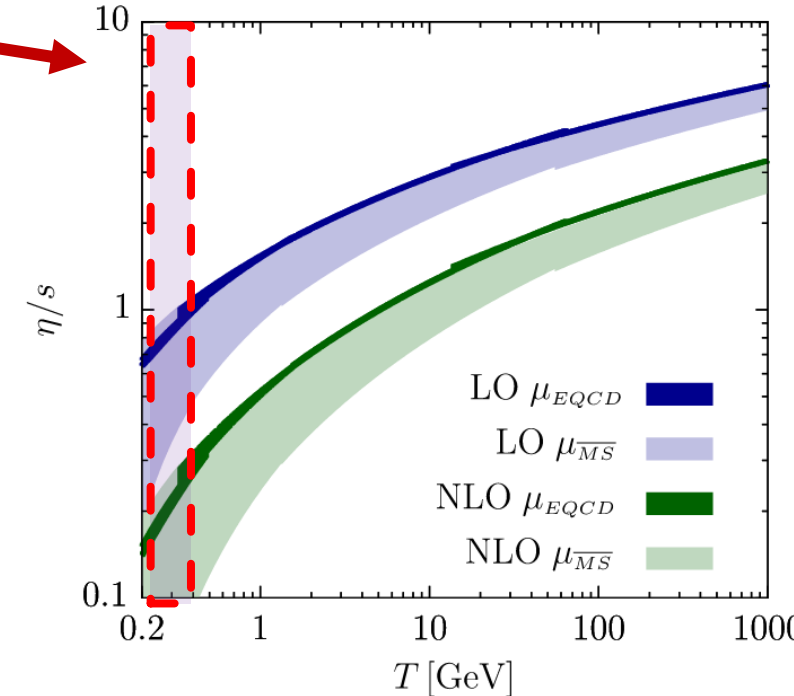
Rose, Torres-Rincon, Schäfer,
Oliinychenko, Petersen (2018) PRC



Interacting hadronic gas for
 $T < \sim 150$ MeV



Ghiglieri, Moore, Teaney (2018) JHEP



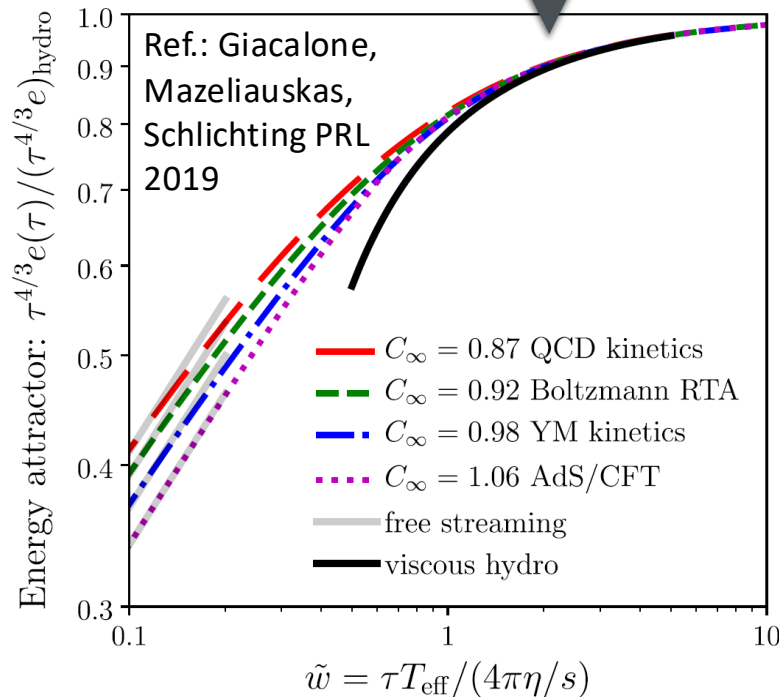
Weakly-coupled quark-gluon
plasma at high temperature

Matching to 2+1D hydrodynamics: the “KøMPøST” approach

- Take a 2+1D pre-hydro system: how does it approach hydrodynamics?
- Better approximation [KøMPøST]: decompose $T^{\mu\nu}$ in 0+1D background + **linear**

$$T^{\mu\nu}(\tau_{\text{hydro}}, \mathbf{x}) = \boxed{\bar{T}_{\mathbf{x}}^{\mu\nu}(\tau_{\text{hydro}})} + \frac{\bar{T}_{\mathbf{x}}^{\tau\tau}(\tau_{\text{hydro}})}{\bar{T}_{\mathbf{x}}^{\tau\tau}(\tau_{\text{EKT}})} \int d^2\mathbf{x}' G_{\alpha\beta}^{\mu\nu}(\mathbf{x}, \mathbf{x}', \tau_{\text{hydro}}, \tau_{\text{EKT}}) \boxed{\delta T_{\mathbf{x}}^{\alpha\beta}(\tau_{\text{EKT}}, \mathbf{x}')}$$

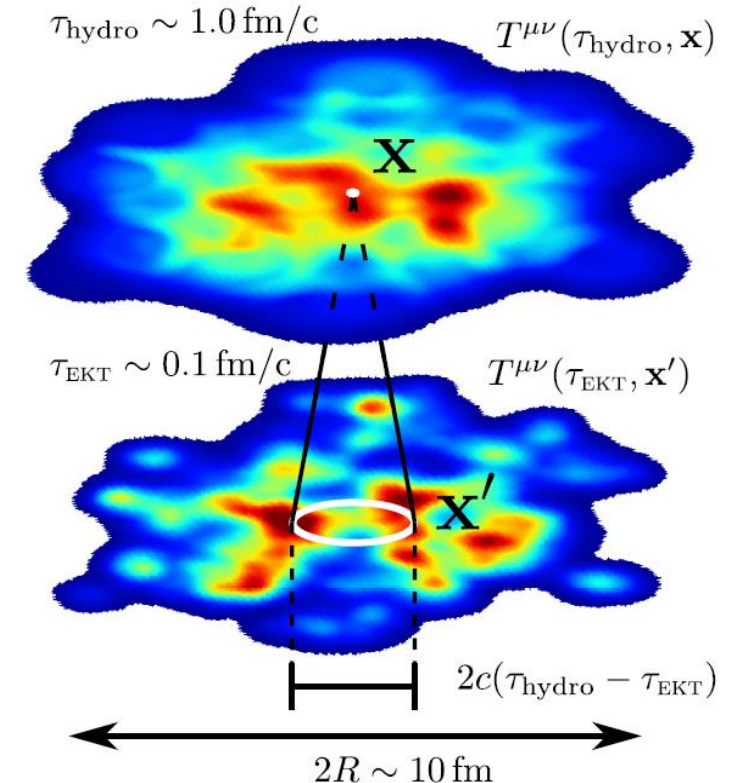
Ref.: Kurkela, Mazeliauskas, Paquet, Schlichting, Teaney PRL2019, PRC2019



Response functions describing evolution of perturbations

- Can be evaluated with QCD kinetic theory
- Also exhibits scaling with interaction strength and energy density of system

[See also Kamata, Martinez, Plaschke, Ochsenfeld, Schlichting, PRD 2020]



Models of mapping viscous hydro to momentum distributions

Fluid description	Hadronic momentum distribution
Ideal hydrodynamics & local thermal equilibrium	Equilibrium: Fermi-Dirac (baryons), Bose-Einstein (mesons)
Viscous hydrodynamics & deviation from equilibrium	?



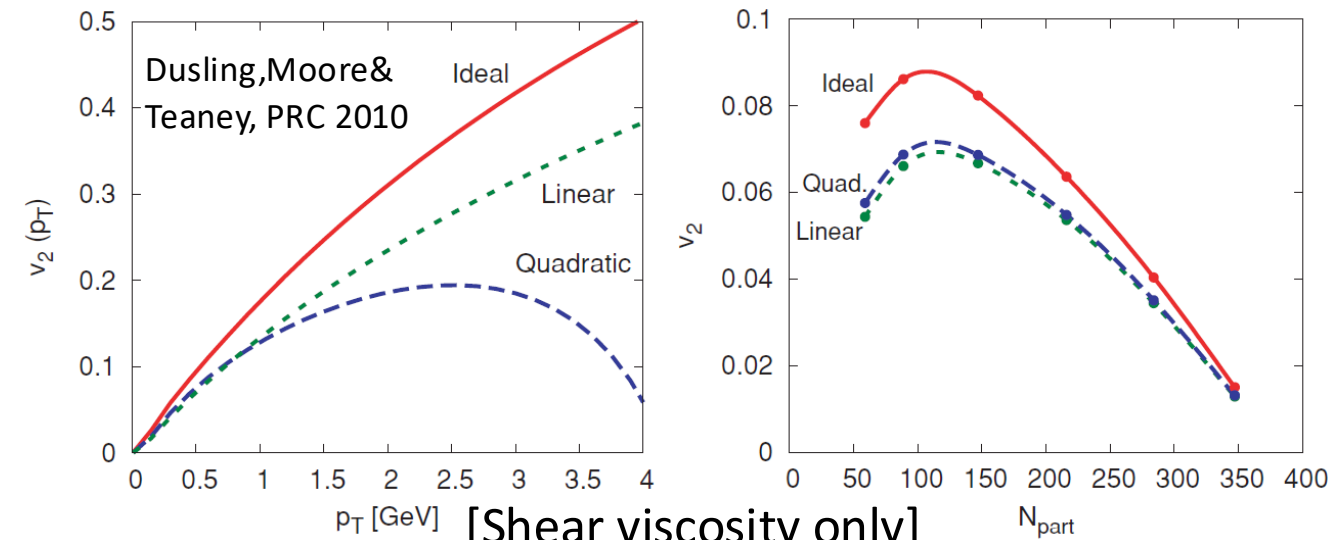
- “14 Moments (Grad)” model and related [quadratic in P for shear viscosity]:

$$f(P) = f_{eq}(P) + f_{eq}(1 \pm f_{eq})(B_{\Pi}(P) \Pi + B_{\pi} P^{\mu} P^{\nu} \pi_{\mu\nu})$$

- “Chapman-Enskog – const Relaxation Time” [linear in P for shear viscosity]:

$$f(P) = f_{eq}(P) + f_{eq}(1 \pm f_{eq}) \left(B'_{\Pi}(P) \Pi + B'_{\pi} \frac{P^{\mu} P^{\nu} \pi_{\mu\nu}}{P \cdot u} \right)$$

See e.g. McNelis, Everett & Heinz CPC 2021; Dusling, Moore & Teaney, PRC 2010 for discussion and primary references



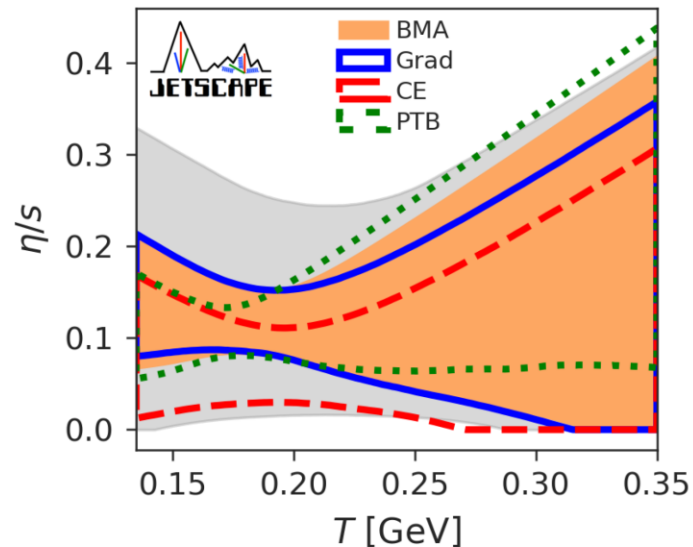
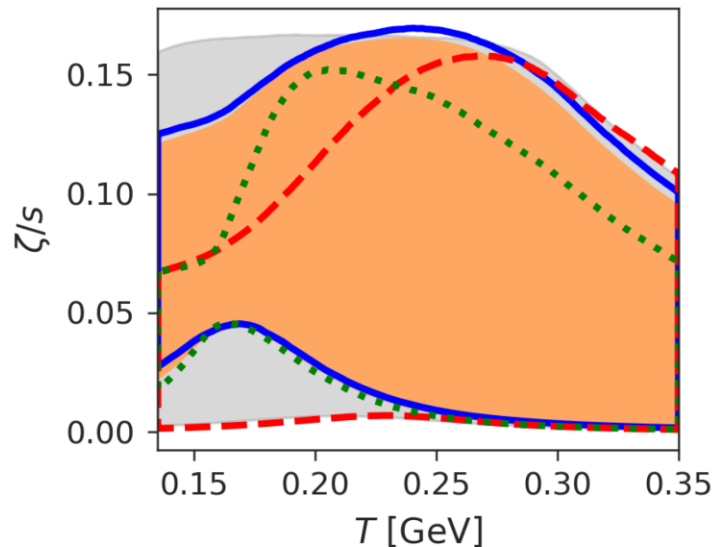
Models of mapping viscous hydro to momentum distributions

Fluid description	Hadronic momentum distribution
Ideal hydrodynamics & local thermal equilibrium	Equilibrium: Fermi-Dirac (baryons), Bose-Einstein (mesons)
Viscous hydrodynamics & deviation from equilibrium	?



Recent developments:

- Quantifying effect of uncertainty on phenomeno. constraints on shear and bulk viscosity



Major theoretical uncertainties in phenomenological studies of heavy ion collisions

JETSCAPE Collaboration, arXiv:2010.03928

Models of mapping viscous hydro to momentum distributions

Fluid description	Hadronic momentum distribution
Ideal hydrodynamics & local thermal equilibrium	Equilibrium: Fermi-Dirac (baryons), Bose-Einstein (mesons)
Viscous hydrodynamics & deviation from equilibrium	 ?

Recent developments:

- Quantifying effect of uncertainty on phenomeno. constraints on shear and bulk viscosity
- New approach: Everett, Chattopadhyay & Heinz, arXiv:2101.01130
Momentum distribution that maximizes the entropy given conditions on $T^{\mu\nu}$

$$T^{\mu\nu} = \sum_n g_n \int \frac{d^3P}{(2\pi)^3 P^0} P^\mu P^\nu f_n(P)$$

$$\text{Entropy current: } s^\mu = - \sum_n g_n \int \frac{d^3P}{(2\pi)^3 P^0} P^\mu [f_n \ln f_n \mp (1 \pm f_n) \ln(1 \pm f_n)]$$

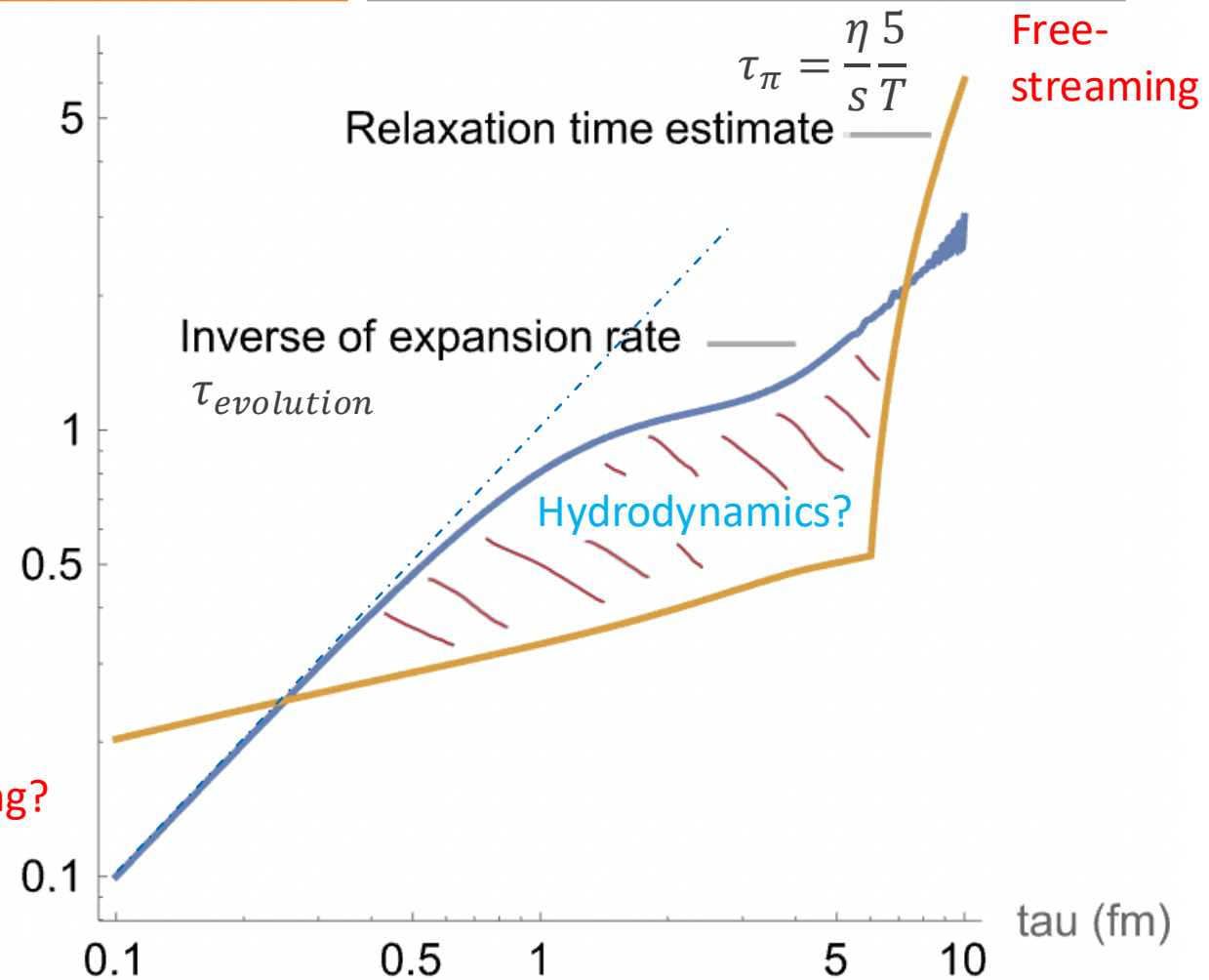
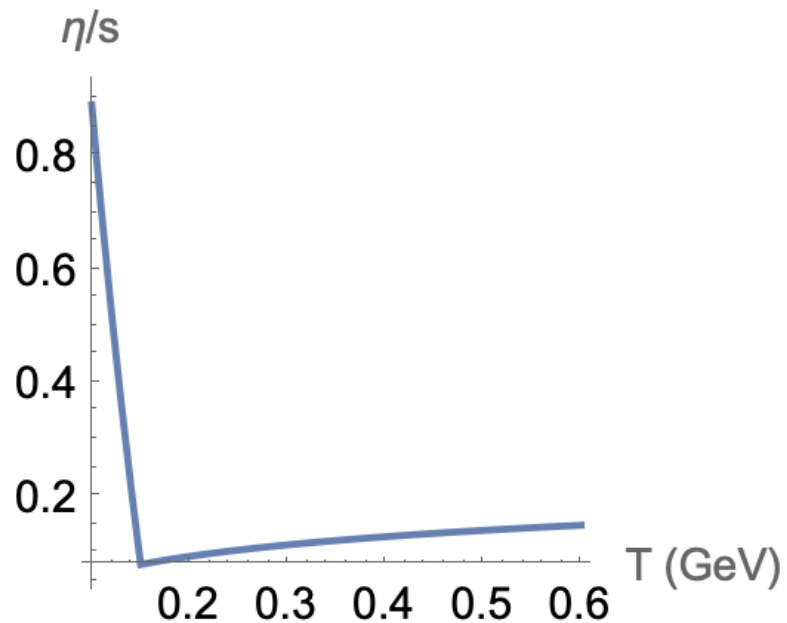
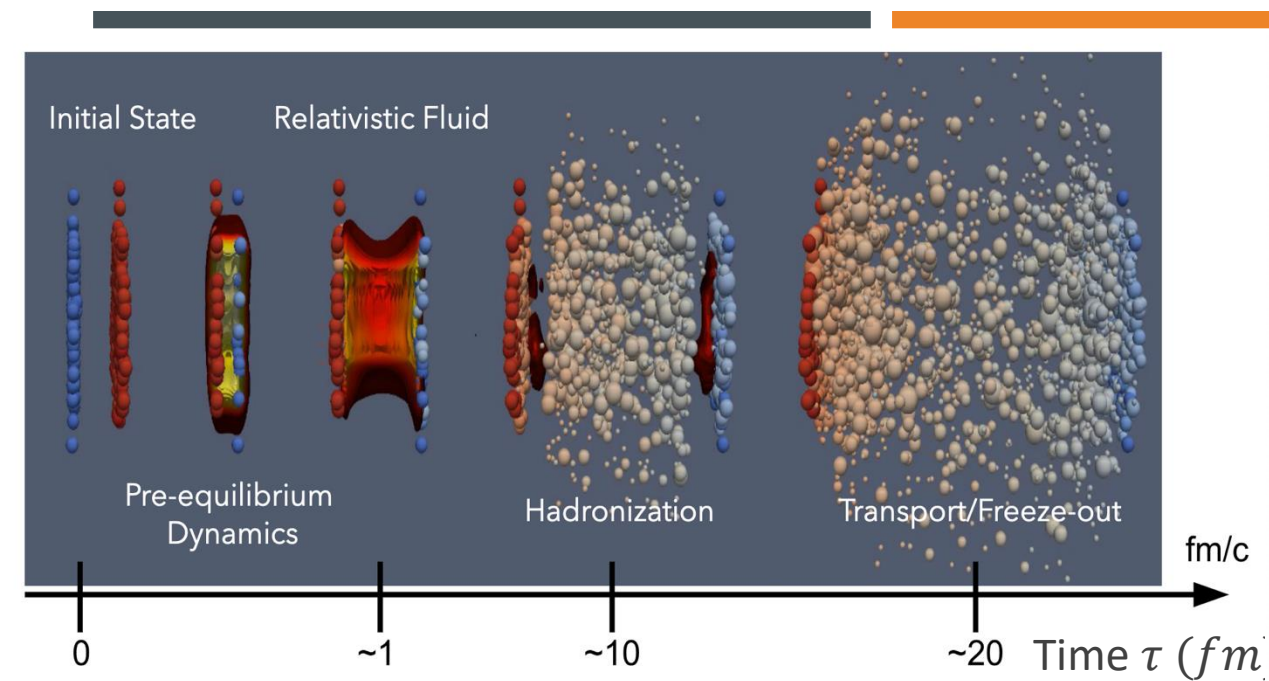
What is $f_h(P)$ that maximizes the entropy? $\delta(s_\mu u^\mu)/\delta f_h = 0$

Models of mapping viscous hydro to momentum distributions

Fluid description	Hadronic momentum distribution
Ideal hydrodynamics & local thermal equilibrium	Equilibrium: Fermi-Dirac (baryons), Bose-Einstein (mesons)
Viscous hydrodynamics & deviation from equilibrium	

Recent developments:

- Quantifying effect of uncertainty on phenomeno. constraints on shear and bulk viscosity
- New approach: $f_h(P)$ that maximizes the entropy
- Studying consistency of $f_h(P)$ ansatz with simplified transport theories
 - Molnar, arXiv:2012.1557:
effect of bulk viscosity in 1-component gas with isotropic $2 \rightarrow 2$ interactions
 - Damodaran, Molnar, Barnaföldi, Berényi, and Nagy-Egri, PRC 2020:
effect of shear viscosity in 0+1D parton cascade
 - See also
Molnar & Wolff, PRC 2017
Chakraborty & Kapusta, PRC 2017



- Free-streaming is (relatively) easy
- Hydrodynamics is doable
- Intermediate regimes are challenging

Considering theoretical uncertainties of observables

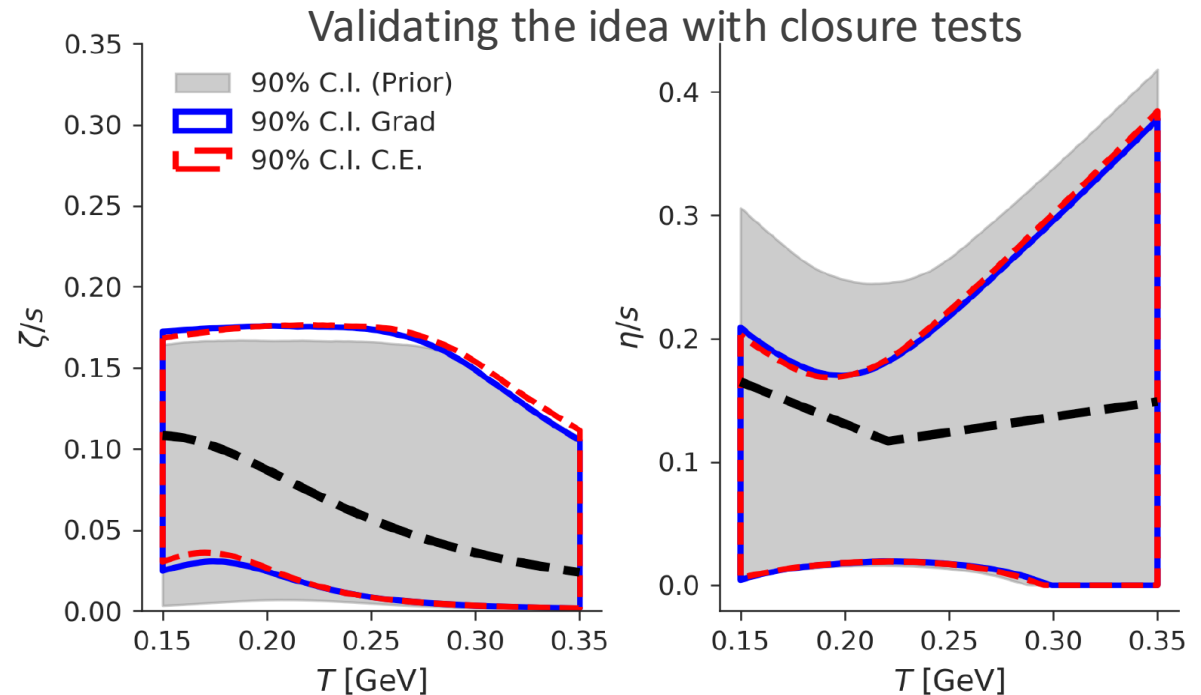
- Viscosity is probed through the hydrodynamic phase



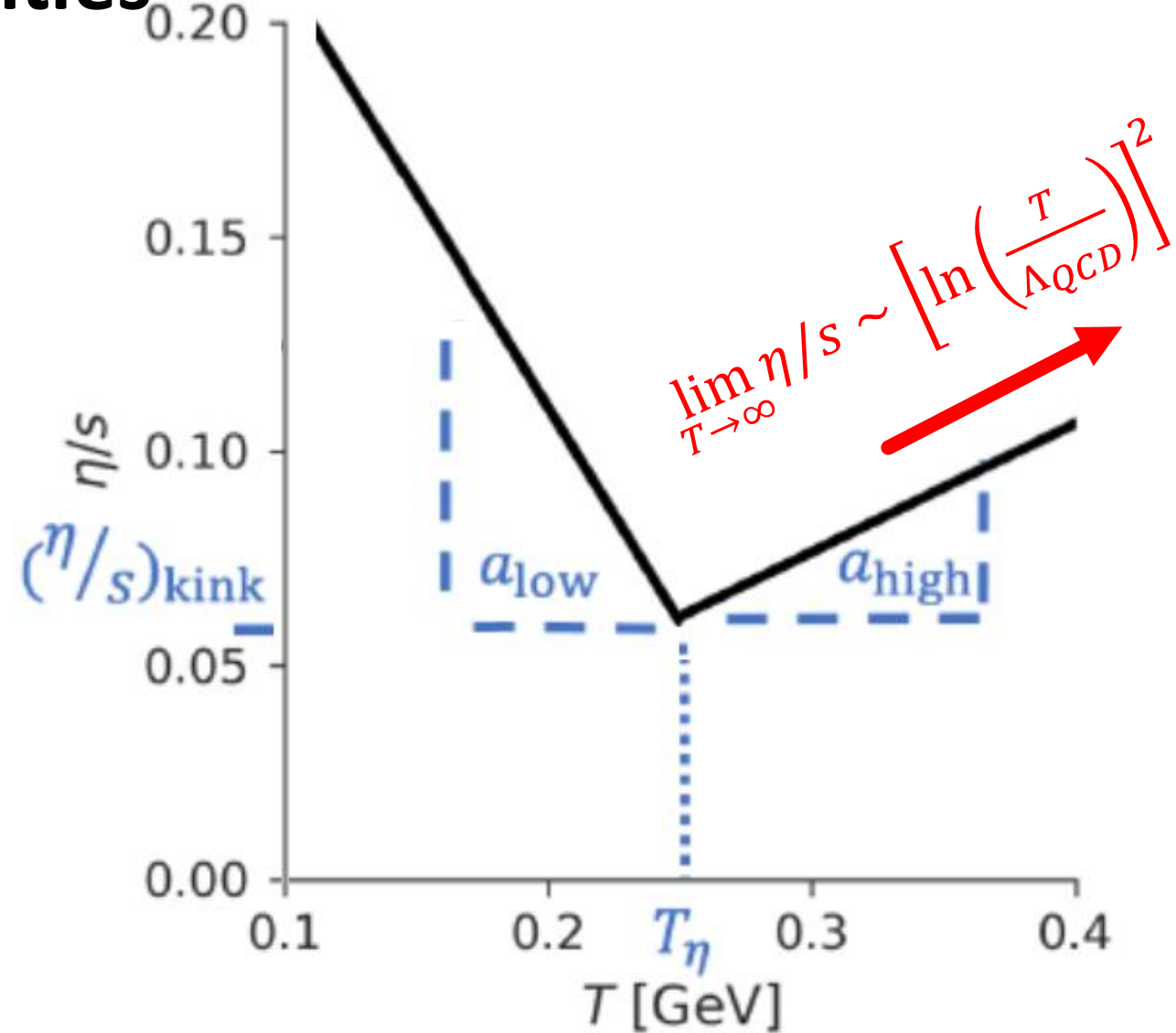
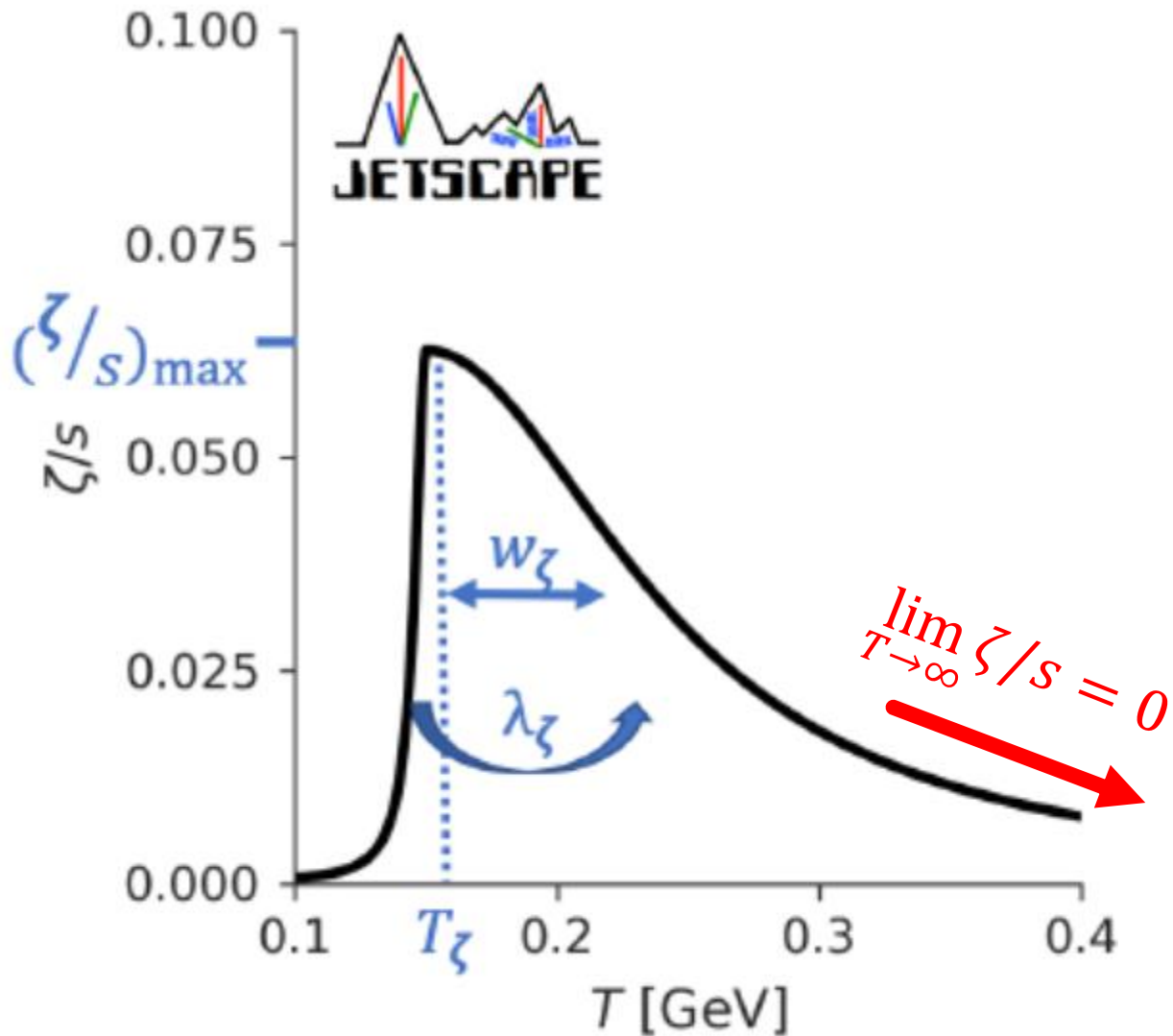
$$\partial_\nu T^{\mu\nu} = 0; \quad T^{\mu\nu} = \epsilon u^\mu u^\nu - (P(\epsilon) + \Pi)(g^{\mu\nu} - u^\mu u^\nu) + \pi^{\mu\nu}$$

$$T^{\mu\nu} = \sum_n g_n \int \frac{d^3P}{(2\pi)^3 P^0} P^\mu P^\nu f_n(P)$$

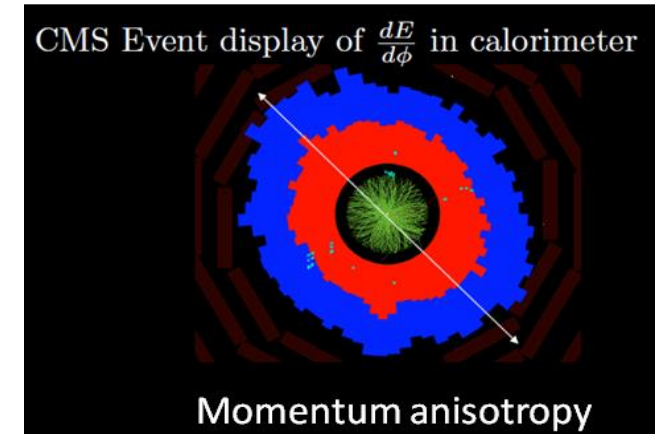
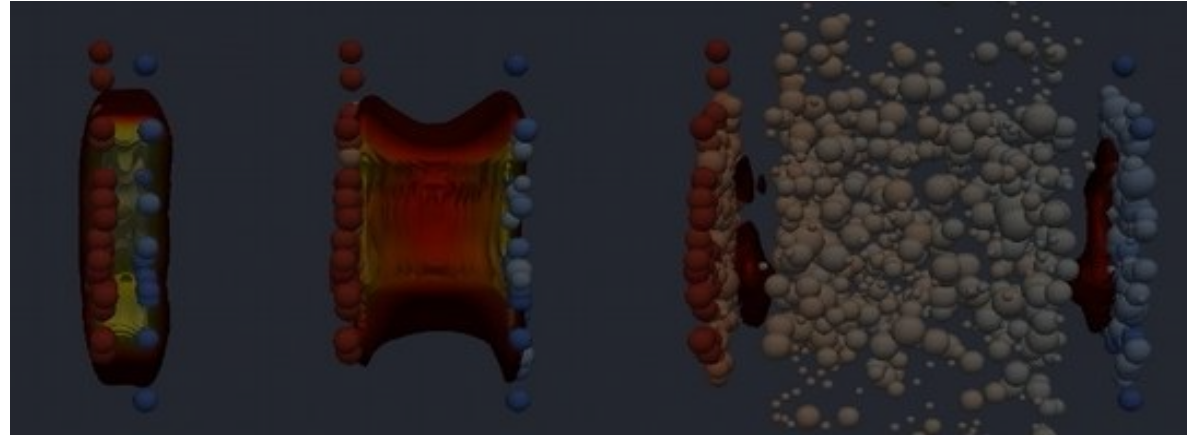
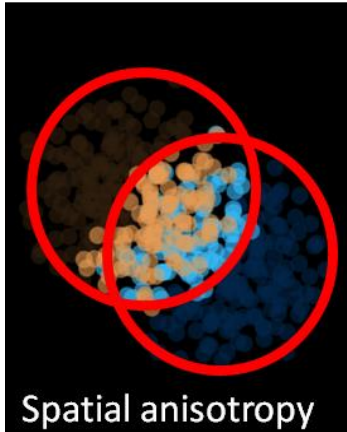
Hadron momentum distributions;
deviate from Fermi-Dirac/Bose-
Einstein distribution



Parametrization of the viscosities



Targeted observables



Energy deposition

