# QCD in heavy-ion collisions

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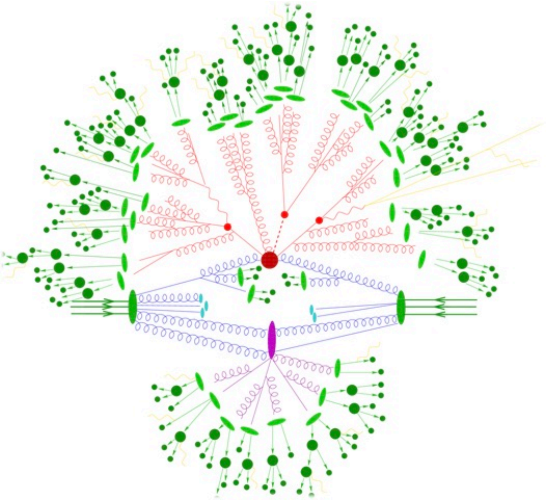
# Outline:

- Phenomenological prelude
- QCD effective kinetic theory
- Thermalization in simple examples, Bottom-up thermalization

Phenomenological prelude:

# “Standard picture” in p-p collisions:

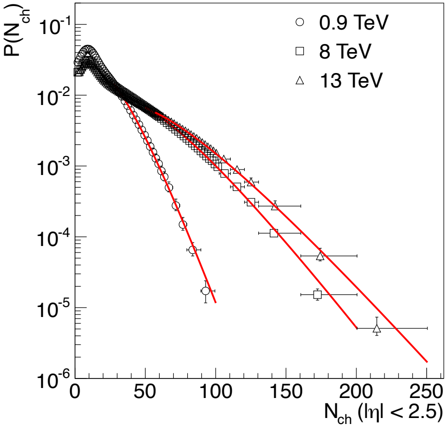


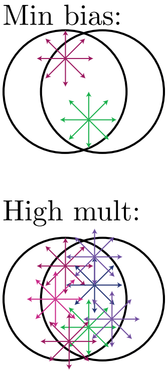
- Initial state radiation
- Hard processes
- Multi-parton interactions
- Fragmentation
- Hadronization
- . . .

PYTHIA, HERWIG,. . .

- Hadronic collisions = superposition of individual partonic collisions
- No *final state interactions:* free streaming

# High-multiplicity collisions

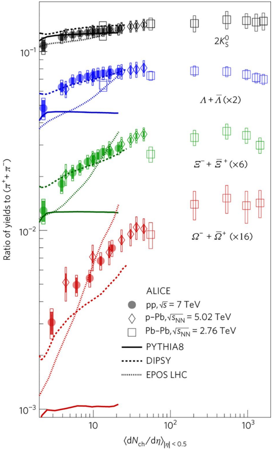



ATLAS EPJC76 (2016)

- Typical p-p collisions have $\mathcal{O}(10)$ final state hadrons
  in central rapidity region
- Very rarely a collisions results in $N_{ch} \sim \mathcal{O}(150)$

# Strangeness enhancement



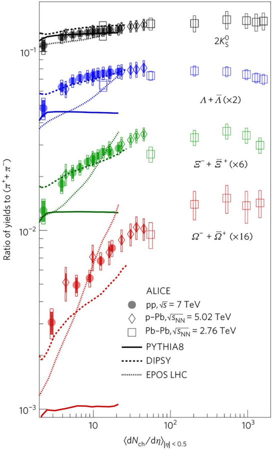

ALICE Nature Phys. 13 (2017) 535-539

- The *kind* of particles coming out changes as function of system size
- The bigger the system ($dN/d\eta$), more (multi-)strange particles

⇒ High multiplicity collisions not just more of the same

$K = us, \Lambda = uds, \Xi = uss, \Omega = sss$

# Strangeness enhancement




ALICE Nature Phys. 13 (2017) 535-539

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⇒ High multiplicity collisions not just more of the same

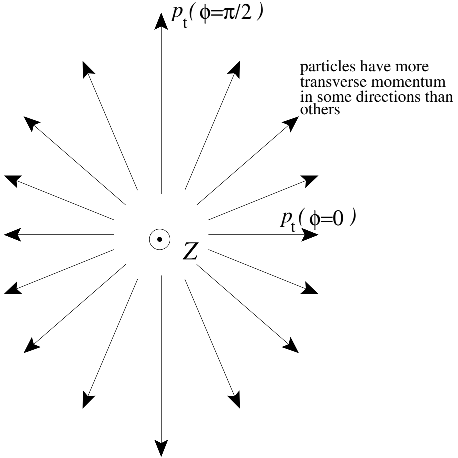
- Significant new physics needed to reproduce qualitative features

Sjöstrand, Fischer JHEP 1701 (2017)

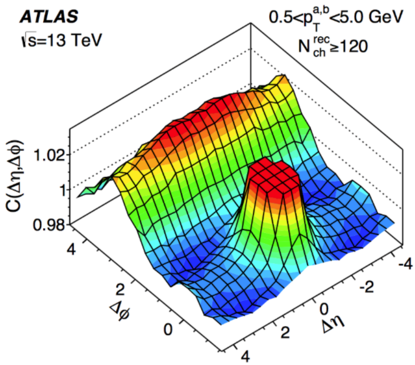
$K = us, \Lambda = uds, \Xi = uss, \Omega = sss$

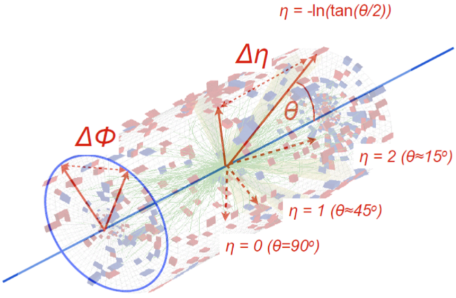
# Long-range azimuthal correlations

Individual events pick a preferred direction:



# Long-range azimuthal correlations

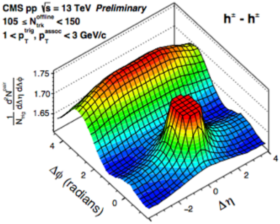


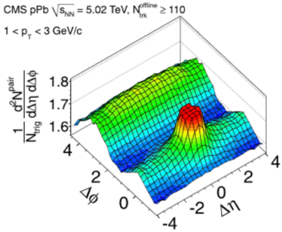

CMS cumulant analysis:PLB 765 (2017)

# Collectivity in nuclear collisions

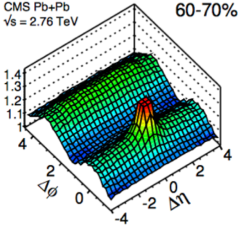
pp:




pA:

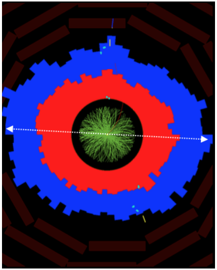


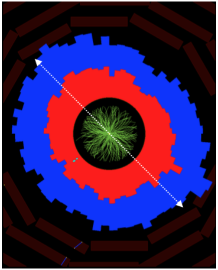

AA:

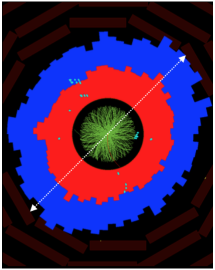



- Long range azimuthal correlations more prominent in larger systems

# Collectivity in nuclear collisions

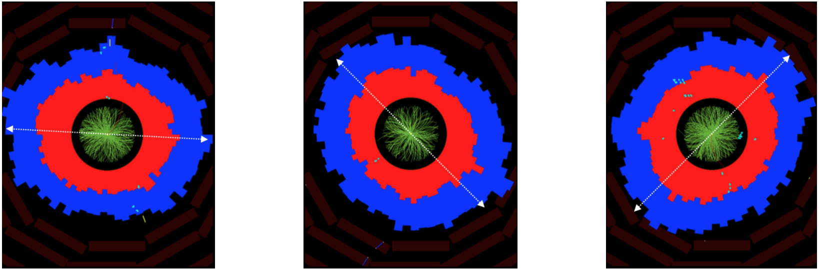




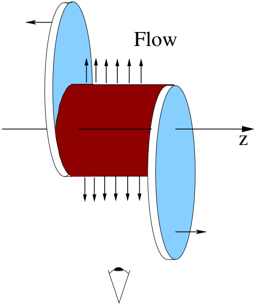


G. Roland, Trento 2017

# Collectivity in nuclear collisions



G. Roland, Trento 2017

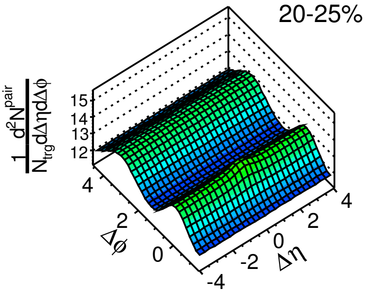


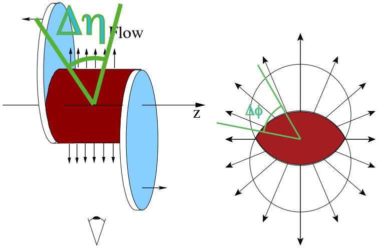

Formation of Quark-gluon plasma

- Azimuthal asymmetry from anisotropic explosion of quark-gluon plasma
- Strangeness content of plasma in chemical equilibrium

# Ridge in heavy-ion collisions:

Pb-Pb



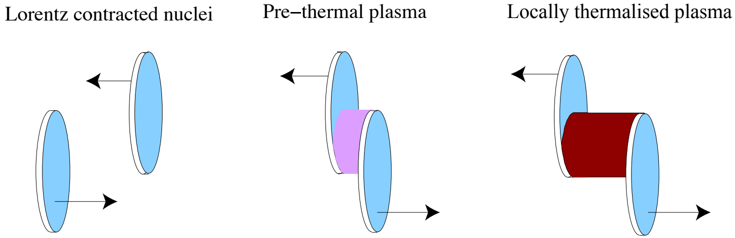




CMS 1201.3158

- Near-side ridge: particles at all longitudinal momenta, all pushed by same pressure gradient
- Away-side ridge: due to geometry, away-side correlated

Hydrodynamics

# Hydrodynamics



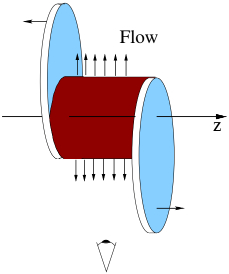

- Relativistic fluid dynamics =
  i) conservation of currents and
  ii) gradient expansion around local thermal equilibrium

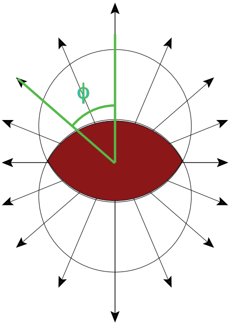
$$\partial_\mu T^{\mu\nu} = 0$$

$$T^{\mu\nu} = T^{\mu\nu}_{eq.} + \eta(T)\nabla^{<\mu}u^{\mu>} - \zeta(T)\{g^{\mu\nu} + u^\mu u^\nu\}(\nabla \cdot u) + \ldots$$

$$T^{\mu\nu}_{eq.} = \mathrm{diag}(e(T), p(T), p(T), p(T))$$

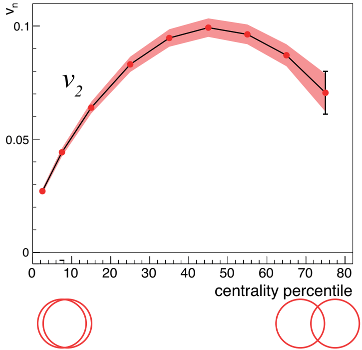
# Shear viscosity: Fluid response to initial geometry



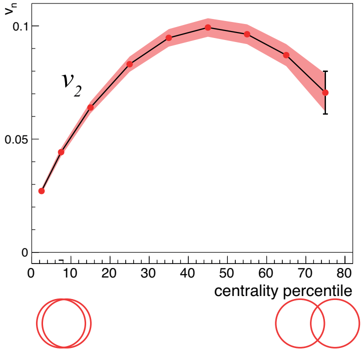

$$\frac{dN}{d\phi} \propto \left[ 1 + 2 \sum_n v_n \cos(n\phi) \right]$$

# Fluid response to initial geometry




ALICE PRL 107 (2011)

# Fluid response to initial geometry

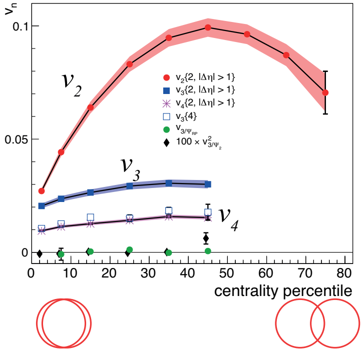



ALICE PRL 107 (2011)

- The more viscous the fluid is, the less there is flow

$$v_2 \approx v_2^{ideal} \frac{1}{1 + K/K_0}, \quad \text{Knudsen number } K \sim \frac{l_{micro}}{l_{macro}} \sim \frac{\eta}{sT} \frac{1}{R}$$

# Fluid response to initial geometry

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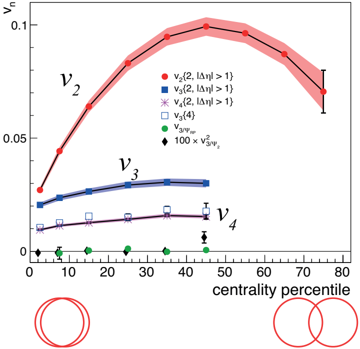
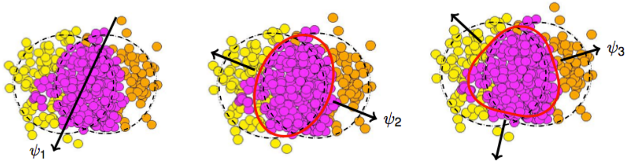
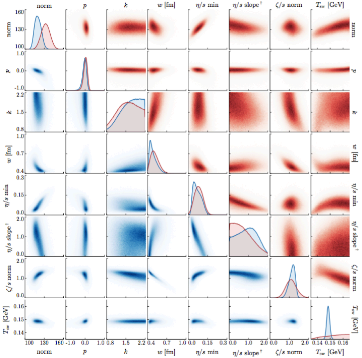



ALICE PRL 107 (2011)




- The response reflects the expected nuclear geometry
- Suite of data: Event-by-event distributions $P(v_n)$

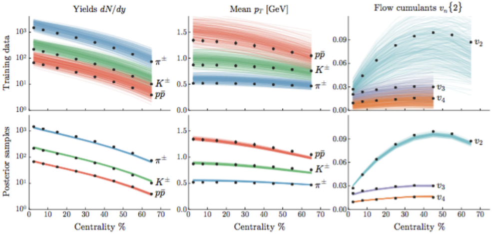
# Hydrodynamical modelling of HIC




Model must include:

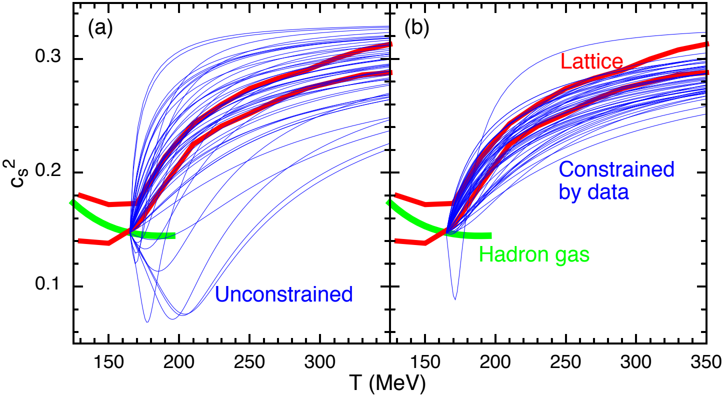
- Initial conditions — $p, k, w$
- Material properties — $e, \eta, \zeta \ldots$
- Particlization — $T_{sw}$

Many implementations: VISHNU, MUSIC, SuperSonic,Trajectum, . . .




PRC 94, 024907 (2016)

# Hydrodynamical modelling of HIC




Pratt et al. PRL 114 (2015)

- EoS typically from lattice, but one can try to extract empirically
- The empirical determination of EoS roughly agrees with the lattice

# Hydrodynamical modelling of HIC

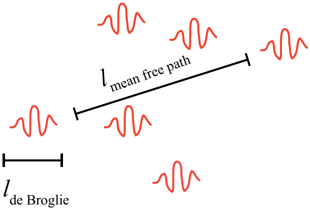
- Most likely variables indicate an almost ideal fluid

$$\frac{\eta}{s} \sim 0.1$$

- For weakly coupled systems,

$$\eta/s \sim \langle p \rangle l_{\text{mean free path}} \sim \frac{l_{\text{mean free path}}}{l_{\text{de Broglie}}} \sim \frac{4.74T}{g^4 \log(g) T} \gtrsim 1$$

Arnold et al. JHEP 0305 (2003)



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Arnold et al. JHEP 0305 (2003)

- No non-perturbative calculation in QCD, but for some strongly coupled models

$$\eta/s = \frac{1}{4\pi} \approx 0.08$$

Super Yang-Mills $\mathcal{N} = 4$, $N_c \to \infty$, $\lambda N_c \to \infty$, Starinets, Son, PRL 87 (2001)

Hydrodynamization

# Hydrodynamization

How are the two cartoons related?

- Early-time evolution:

  Hydrodynamization as function of time

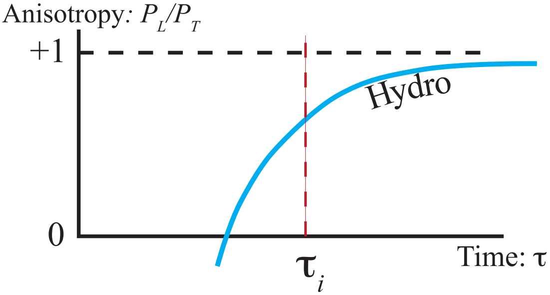
- Small systems: p-Pb, p-p

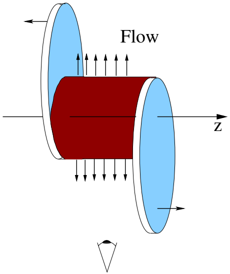
  Hydrodynamization as function of size

- Jets in dense medium:

  Hydrodynamization as function of energy scale

# Hydrodynamization

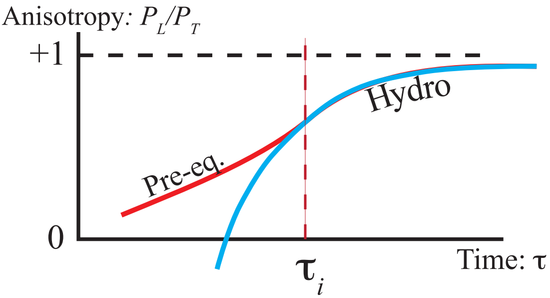


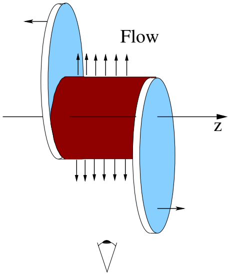




- Hydro: $T^{\mu\nu} = T^{\mu\nu}_{eq.} + \eta(T)\nabla^{<\mu}u^{\mu>} + \dots$
- Strong anisotropy $P_L/P_T \ll 1$, sign of large correction
- At early times *pre-equilibrium* evolution

Hydro: EoS, $\eta/s$, etc., Pre-equilibrium: need microscopic description

# Hydrodynamization

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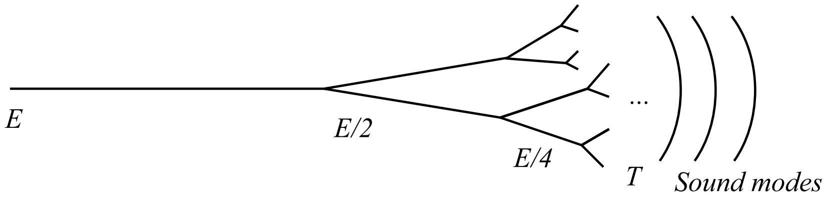
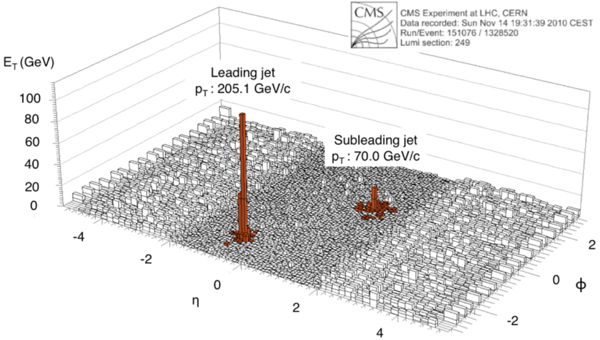
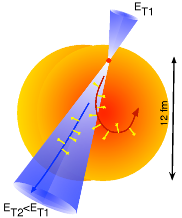
# Jet thermalization

- Hard parton propagating though plasma comes with a perturbative scale and some aspects of it must be perturbative
- If the medium is large enough, the parton will radiate and degrade its energy.
- Eventually the hard particle particle will become part of the medium, hydrodynamic modes



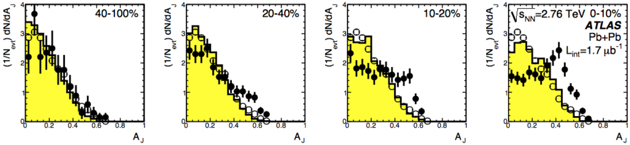
# Jet thermalization:




Dijet asymmetry:

$$A_J = \frac{E_{T,1} - E_{T,2}}{E_{T,1} + E_{T,2}}$$




ATLAS PRL 105 (2010) 252303

# Motivation:

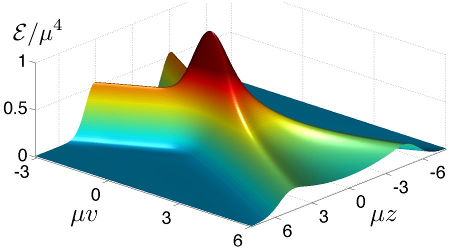
- How does collectivity arise from microscopic interactions?
- What signs of collectivity are really signs of fluid like behaviour? Which come from just final state interactions? Are there maybe other confounding effects that mimic those of final state interactions?
- How does the "perfect fluid" melt into free streaming particles in pp?

What is the microscopic structure of quark-gluon plasma?

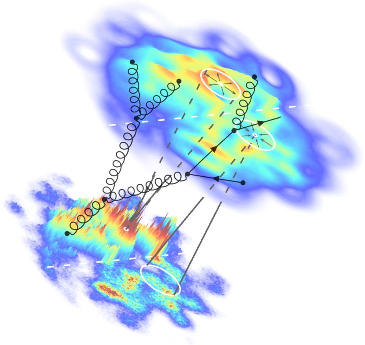
To answer these questions, must understand far-from-equilibrium physics

# Methods

- Strong coupling $\mathcal{N} = 4$ SYM, $N_c \to \infty$, $\lambda = g^2 N_c \to \infty$
- Weak coupling QCD $\alpha_s \to 0$
- Transport models mimicking QCD, ...




Chesler Yaffe, PRL. 106 (2011)



these lectures

Strong coupling, colliding shock waves

In both cases, dynamics for a classical theory

Simple transport model, example

Simple toy model:

- Kinetic transport of $f(\tau, \mathbf{x}, \mathbf{p})$ in isotropization time approximation
$$\frac{1}{p}p^{\mu}\partial_{\mu f} = -C[f] = -\frac{-v_{\mu}u^{\mu}}{\tau_{\text{iso}}}(f - f_{iso}(p^{\mu}u_{\mu}))$$

with

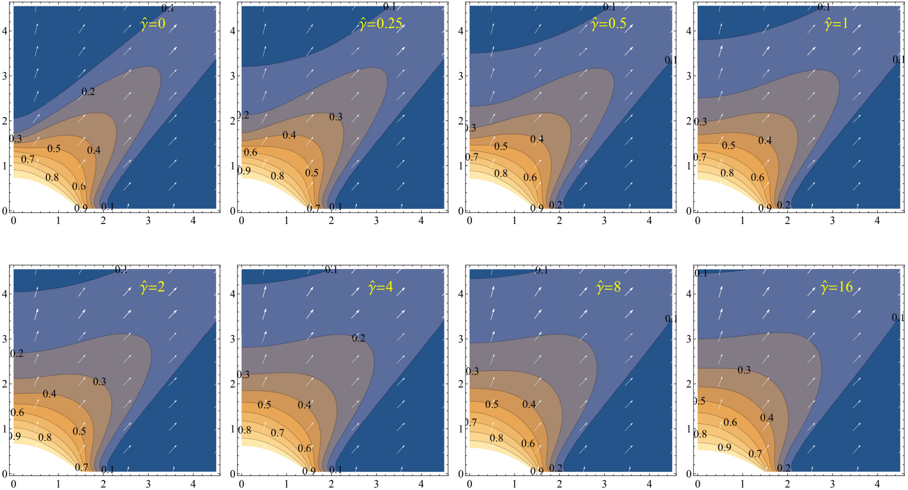
$$\tau_{\text{iso}} = \frac{1}{\gamma\epsilon^{1/4}} \tag{1}$$

Interpolates between free streaming and hydrodynamic

Solve for heavy-ionesque initial conditions $\epsilon = e^{-r^2/R^2}, P_L = 0$

Depends only on one parameter: $\hat{\gamma} = R/l_{mfp} = R^{3/4}\gamma(\epsilon_0\tau_0)^{1/4}$

# Hydrodynamization



# Fluid quality:

From a solution to kinetic theory, the hydrodynamical prediction of $T^{\mu\nu}$ can be computed

$$T^{\mu\nu} = \int \frac{d^3p}{(2\pi)^3} \frac{p^\mu p^\nu}{p^0} f$$

and the local restframe can be solved:

$$u_\mu T^{\mu\nu} = -\epsilon T^{\mu\nu}$$

With this knowledge we can ask what would hydrodynamics would have given for $T^{\mu\nu}$ for this configuration:

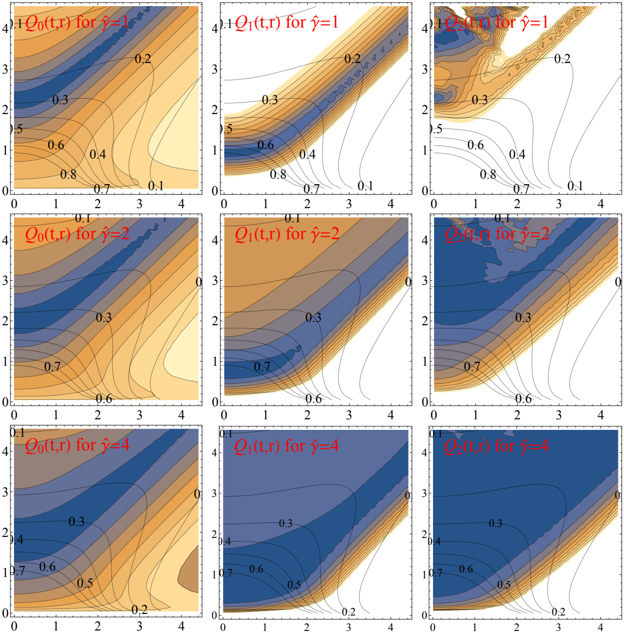
$$T^{\mu\nu}_{\rm hyd} = (\varepsilon + p)\, u^\mu\, u^\nu + p\, g^{\mu\nu} + \Pi^{\mu\nu}_{\rm hyd}$$

$$\Pi^{\mu\nu}_{\rm hyd\,2nd} = 2\tau_\Pi\, \eta_s \left[ {}^{<}D\sigma^{\mu\nu>} + \frac{1}{3}\sigma^{\mu\nu}\nabla_\alpha u^\alpha \right] + \lambda_1 \sigma^{<\mu}_{\alpha}\, \sigma^{\nu>\lambda}$$

$$\sigma^{\mu\nu} = \left\{ \frac{1}{2} \left[ \Delta^{\mu\alpha}\nabla_\alpha u^\nu + \Delta^{\nu\alpha}\nabla_\alpha u^\mu \right] - \frac{1}{3}\Delta^{\mu\nu}\nabla_\alpha u^\alpha \right\}$$

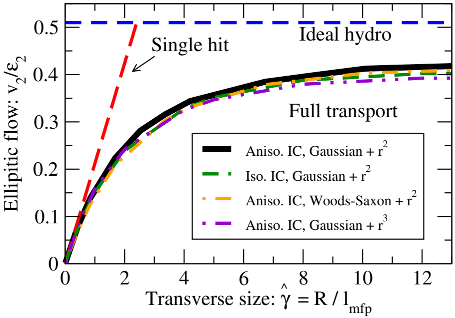
Fluid quality tells how well the constitutive equations are fulfilled:

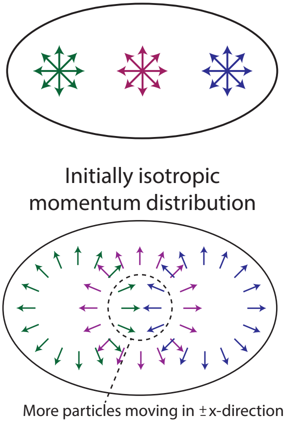
$$Q_2^n(t,r) = \sqrt{\frac{\left(T_{\text{kin}} - T_{\text{hyd}}^n\right)^{\mu\nu}\left(T_{\text{kin}} - T_{\text{hyd}}^n\right)_{\mu\nu}}{\left(T_{\text{id}}\right)^{\mu\nu}\left(T_{\text{id}}\right)_{\mu\nu}}}$$




Kinetic theory hydrodynamizes around $\hat{\gamma} = 2 - 4$

# Signs of collectivity




Signs of collectivity grow smoothly as a function of system size and arises both from fluid like and particle like regions

The way this happens is determined by the microscopic dynamics