Jet Quenching and Early-Time Dynamics

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CERN

Extreme Nonequilibrium QCD

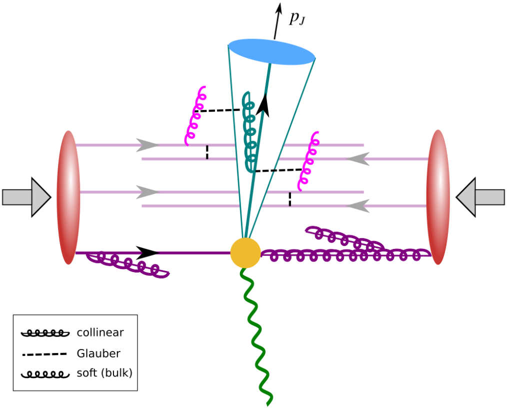
ICTS International Centre for Theoretical Sciences

TATA INSTITUTE OF FUNDAMENTAL RESEARCH

Motivations: jets & bulk

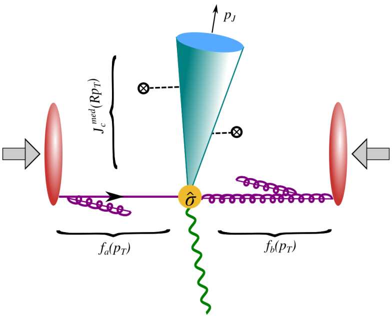
1. **Currently modelled as two different entities**
2. **Where the bulk ends and the jet starts?**

A unified framework for both jets and bulk?



- Bulk and jet constituents are partons before hadronization.
- They should be described by a unified way in QCD.

QCD factorization

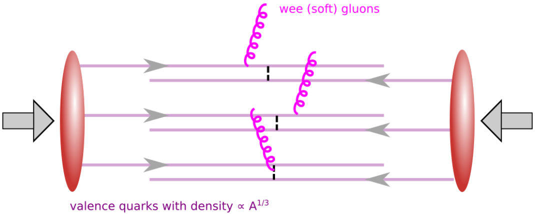


For a subclass of observables:

$$\frac{d\sigma}{dp_T d\eta} = \sum_{abc} f_a \otimes f_b \otimes \hat{\sigma}_{ab\to c} \otimes \underbrace{J_c^{med}}_{\text{Bulk enters.}}$$

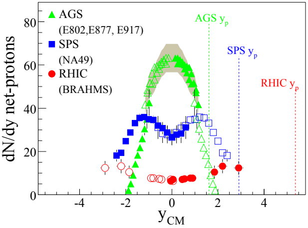
For a recent discussion: Qiu, Ringer, Sato and Zurita, Phys. Rev. Lett. **122**, no. 25, 252301 (2019) .

The Bjorken Picture for bulk matter



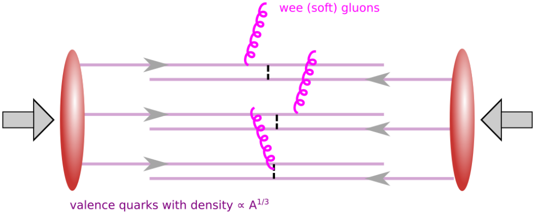
Bjorken, Lect. Notes Phys. **56**, 93 (1976).

1. The valence quarks pass through each other.



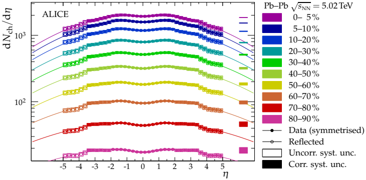
I. G. Bearden *et al.* [BRAHMS], Phys. Rev. Lett. **93**, 102301 (2004) [arXiv:nucl-ex/0312023 [nucl-ex]].

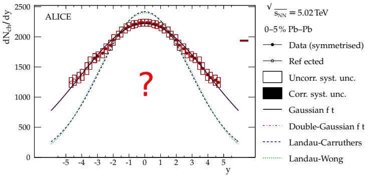
The Bjorken Picture for bulk matter



Bjorken, Lect. Notes Phys. **56**, 93 (1976).

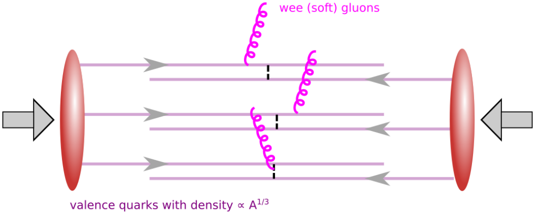
2 Longitudinal boost-invariance: "wee" partons fill a central plateau.





J. Adam *et al.* [ALICE], Phys. Lett. B **772**, 567-577 (2017) [arXiv:1612.08966 [nucl-ex]].

The Bjorken Picture for bulk matter



Bjorken, Lect. Notes Phys. **56**, 93 (1976).

1. The valence quarks pass through each other.

2. Produced "wee" partons fill a central plateau in rapidity.

3. The saturation model (CGC): $k \sim Q_s > \Lambda_{QCD}$

A comprehensive review: Kovchegov and Levin, Camb. Monogr. Part. Phys. Nucl. Phys. Cosmol. **33**, 1 (2012). .

Let us see what follows from this picture.

Bulk in AA collisions

The bottom-up thermalization

At $\tau \sim 1/Q_s$, produced wee (called "hard") partons go on mass-shell.

$$k \sim Q_s, \qquad \text{number density } n_h \sim \frac{1}{\alpha_s}$$

Then, the thermalization proceeds in kinetic theory.

Baier, Mueller, Schiff and Son, Phys. Lett. B **502**, 51 (2001) [hep-ph/0009237].

Stage I ($\alpha_s^{-\frac{3}{2}} > \tau Q_s > 1$): expansion prevails interaction.

At this stage, soft gluons play no dominant roles in any physical effects.

Jet quenching parameter

$$\hat{q} \sim \alpha_s^2 N_h f_h \sim Q_s^3/(\tau Q_s)^{5/3} \Rightarrow p_z^2 = \hat{q}\tau \sim Q_s^2/(\tau Q_s)^{2/3},$$

where $N_h \sim Q_s^2/(\alpha_s \tau)$ is the number density of hard gluons and $f_h \sim 1/(\alpha_s \tau p_z) \gg 1$ is their phase-space distribution.

The pressure anisotropy

$$P_L/P_T \sim p_z^2/p_T^2 \sim 1/(\tau Q_s)^{2/3}.$$

The bottom-up thermalization

Stage II ($\alpha_s^{-\frac{5}{2}} > \tau Q_s > \alpha_s^{-\frac{3}{2}}$): interaction countervails expansion.

At this stage, soft gluons starts to contribute dominantly to Debye screening.

Jet quenching parameter

$$\hat{q} \sim \alpha_s^2 N_h \sim \alpha_s Q_s^2/\tau \Rightarrow p_z^2 = \hat{q}\tau \sim \alpha_s Q_s^2.$$

The pressure anisotropy

$$P_L/P_T \sim p_z^2/p_T^2 \sim \alpha_s.$$

At $\tau \sim \alpha_s^{-5/2}/Q_s$,

$$\frac{\tau_{th}}{\tau} \sim \frac{1}{\alpha_s^2 \epsilon_s^{\frac{1}{4}} \tau} \sim 1.$$

Now, soft gluons are poised to form a thermal bath.

The bottom-up thermalization

Stage III ($\alpha_s^{-\frac{13}{5}} > \tau Q_s > \alpha_s^{-\frac{5}{2}}$): quenching of "hard" gluons.

Thermalization literally proceeds as jet quenching.

Jet quenching parameter

$$\hat{q} \sim \alpha_s^2 \epsilon_s^{\frac{3}{4}} \qquad \& \qquad \Delta E \sim \alpha_s^2 \hat{q} \tau^2.$$

Properties of the thermal bath

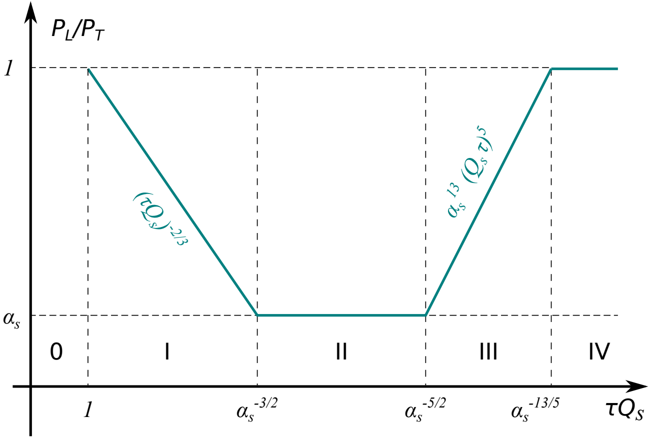
$$\epsilon_s \sim N_h \Delta E \Longleftrightarrow T \sim \epsilon^{\frac{1}{4}} \sim \alpha_s^3 Q_s^2 \tau \text{ and } \hat{q} \sim \alpha_s^{11} Q_s^3 (Q_s \tau)^3.$$

The pressure anisotropy

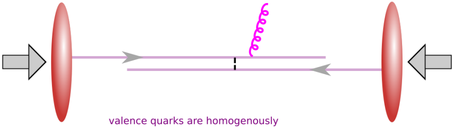
$$P_L/P_T \sim \frac{\epsilon_s}{N_h Q_s} \sim \alpha_s^{13} (\tau Q_s)^5.$$

At $\tau \sim \alpha_s^{-\frac{13}{5}}/Q_s$, $P_L/P_T \sim 1$ and $\epsilon_s \sim N_h Q_s$, signaling the establishment of thermal equilibrium.

Isotropization in the bottom-up thermalization



Stage 0: freeing wee gluon from wave functions



1. **Energy density:** $\epsilon \propto \frac{1}{\tau}$ at large τ

   Kovchegov, Nucl. Phys. A **762**, 298 (2005) [hep-ph/0503038]; Lappi, Phys. Lett. B **643**, 11 (2006) [hep-ph/0606207].

2. **Two point function in the limit $\tau \to \infty$**

$$G_{22}^{a\mu,b\nu}(X,p) \to 2\pi\delta(p^2)\delta^{ab}\sum_{\lambda=\pm}\epsilon_\lambda^\mu(p)\epsilon_\lambda^{*\nu}(p)f^{cl}(X,p)$$

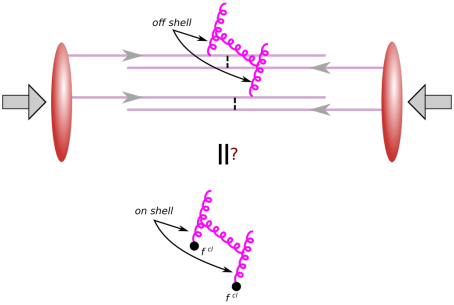
where $f^{cl}(X,p)$ a longitudinally boost-invariant distribution.

$\delta(p^2)$: classical field does go on mass-shell as $\tau \to \infty$!

BW and Kovchegov, JHEP **1803**, 158 (2018) [arXiv:1709.02866 [hep-ph]].

Does kinetic theory follows classical fields?

The question:



The answer:

No in ϕ^4 theory at this order.

Kovchegov and BW, JHEP **1803**, 157 (2018) [arXiv:1709.02868 [hep-ph]].

QFT has features that complicates the picture in kinetic theory!

Still an open question in QCD!

Modern understanding of Bottom-up thermalization

1. **Stage I: attractor in classical statistical approximation (CSA):**

   Berges, Boguslavski, Schlichting and Venugopalan, Phys. Rev. D **89**, 114007 (2014) [arXiv:1311.3005 [hep-ph]].

2. **Bottom-up in kinetic theory:**

   Kurkela and Zhu, Phys. Rev. Lett. **115**, 182301 (2015) [arXiv:1506.06647 [hep-ph]].

3. **An entire evolution by matching:**

   Kurkela, Mazeliauskas, Paquet, Schlichting and Teaney, Phys. Rev. Lett. **122**, 122302 (2019) [arXiv:1805.01604 [hep-ph]].

4. **Go beyond?**
   - Fast isotripization has been shown in CSA.

     Epelbaum and Gelis, Phys. Rev. Lett. **111**, 232301 (2013) [arXiv:1307.2214 [hep-ph]].

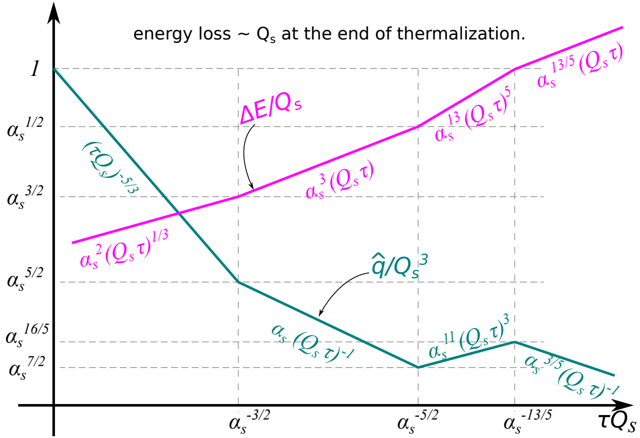
   - Technial difficulty: One has to deal with nonrenormalizablity

     Epelbaum, Gelis and BW, Phys. Rev. D **90**, no. 6, 065029 (2014) [arXiv:1402.0115 [hep-ph]].

     Berges, Boguslavski, Schlichting and Venugopalan, JHEP **1405**, 054 (2014) [arXiv:1312.5216 [hep-ph]].

Another open question!

Connection to jet quenching



BW, [arXiv:2009.04974 [hep-ph]].

Connection to jet quenching

Some detailed calculations:

1. Radiative energy spectrum can be calculated analysitcally.

$$\omega \frac{dI}{d\omega} \sim \alpha_s N_c \sqrt{\frac{\hat{q}(\tau)\tau^2}{\omega}} \qquad \text{for } t_f \ll \tau$$

Baier, Dokshitzer, Mueller and Schiff, Phys. Rev. C **58**, 1706 (1998); Arnold, Phys. Rev. D **79**, 065025 (2009).

2. Radiative correction to p_T-broadening and $\hat{q}$:

- Leading-logs and resummation

$$\hat{q}_{resum}(\tau) = \hat{q}(\tau)\, \frac{\mathrm{I}_1\left(2\sqrt{\bar{\alpha}}\, Y\right)}{\sqrt{\bar{\alpha}}\, Y} \qquad \text{with } Y = \ln(\tau/\lambda(\tau))$$

looks like a static medium with $\hat{q} = \hat{q}(\tau)$ at each time!

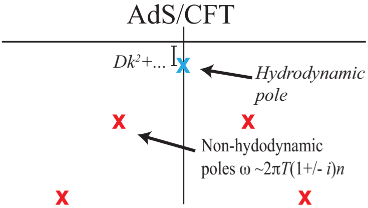
Iancu, Taels and BW, Phys. Lett. B **786**, 288 (2018) [arXiv:1806.07177 [hep-ph]].

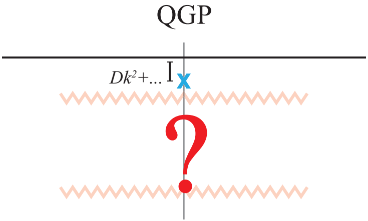
- Finite terms may also be important: Zakharov, arXiv:2003.10182 [hep-ph].

Bulk in small systems

Hydro vs non-hydro modes

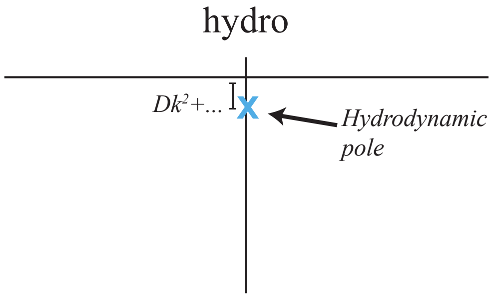
- Two statements that are generally true:
  1. QFTs contain hydrodynamics.
  2. QFTs go beyond hydrodynamics in different ways.
- Examples:





the analytic structure of $G_R^{\alpha\beta,\gamma\delta}(\omega,\vec{k}) = -i\int d^4x e^{ik\cdot x}\theta(x^0)\langle[T^{\alpha\beta}(x), T^{\gamma\delta}(0)]\rangle$

Hydro Is Hydro



Qualification of being a fluid

Criteria:

$$\boxed{\text{hydro-like} \Leftrightarrow Q < 0.1}$$

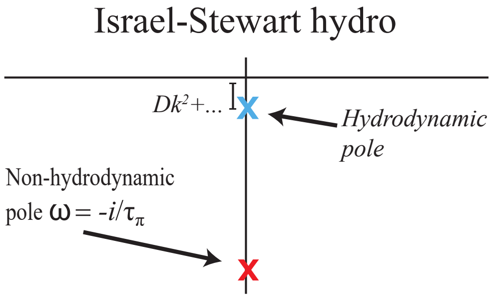
in terms of "fluid quality" for $T^{\mu\nu}$ calculated in some model

$$Q(t, r) = \sqrt{\frac{\left(T - T_{\rm hyd}\right)^{\mu\nu}\left(T - T_{\rm hyd}\right)_{\mu\nu}}{(T_{\rm id})^{\mu\nu}(T_{\rm id})_{\mu\nu}}},$$

where $T_{\rm hyd}$ is the energy-momentum tensor in hydrodynamics.

Kurkela, Wiedemann and BW, Eur. Phys. J. C **79**, no. 11, 965 (2019) [arXiv:1905.05139 [hep-ph]].

Hydrodynamic models are Not Only Hydro



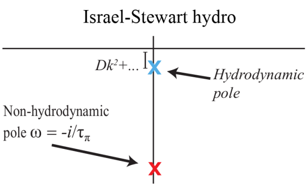
The Israel-Stewart (IS) hydro

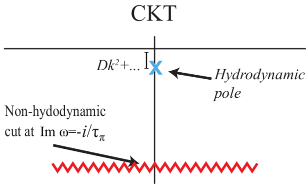
$$D\Pi^{\mu\nu} + \frac{4}{3}\Pi^{\mu\nu}\nabla_\alpha u^\alpha = \frac{1}{\tau_\pi}\left(\Pi^{\mu\nu} + 2\eta\sigma^{\mu\nu}\right).$$

Applicability of Hydrodynamic models: hydrodynamic pole dominates.

Studying the inner workings of QGP now lies beyond hydro.

A conformal kinetic transport theory (CKT)





1. Similar to kinetic theory in relaxation time approximation:

   Baym, Phys. Lett. **138B**, 18 (1984).

2. Physics depends on only one dimensionless parameter:

$$\text{Opacity: } \hat{\gamma} = \gamma R^{\frac{3}{4}} (\varepsilon_0 \tau_0)^{\frac{1}{4}} = R/l_{mfp}$$

Kurkela, Wiedemann and BW, Phys. Lett. B **783**, 274 (2018), [arXiv:1803.02072].

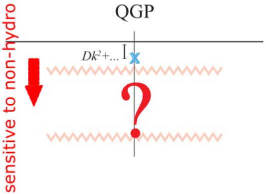
3. The transport coefficients: $\frac{\eta}{s} = \frac{1}{5} \frac{T}{\gamma \varepsilon^{\frac{1}{4}}}$.

Probes to non-hydro (particle-like) modes

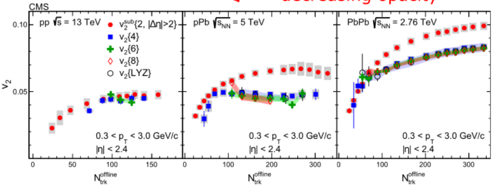
1. **Studying jet quenching**

   high p_T jets probe short wavelength

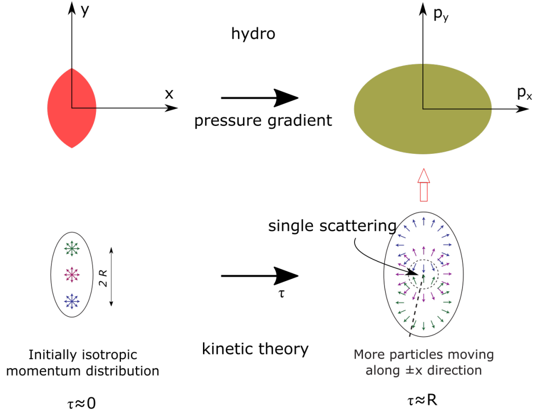
2. **Studying small systems:** $G_R(\tau, k) \sim c_{hyd}\, e^{-Dk^2\tau}$ + non-hydro terms



decreasing opacity



Flow in small and/or dilute limit



Kurkela, Wiedemann and BW, Phys. Lett. B **783**, 274 (2018), [arXiv:1803.02072].

Flow is a signature for final-state interactions

See also: Borghini & Gombeaud, Eur. Phys. J. C **71** (2011) 1612; He, Edmonds, Lin, Liu, Molnar & Wang, Phys. Lett. B **753** (2016) 506.

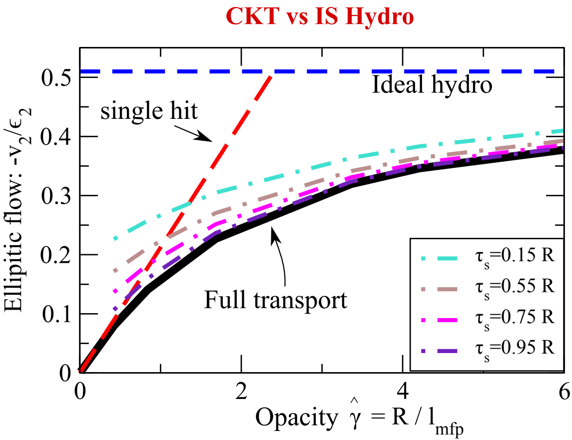
Flow PURELY from Non-hydro modes at $\hat{\gamma} \to 0$

From mode-mode coupling due to one final-state scattering

$$\frac{dE_\perp}{d\eta d\phi} = \frac{1}{2\pi}\frac{dE_\perp}{d\eta}\Big|_{\hat{\gamma}=0,\epsilon_n=0} \Bigg\{ 1 - 0.210\,\hat{\gamma} - \underbrace{0.212\,\hat{\gamma}\epsilon_2}_{v_2} 2\cos(2\phi - 2\psi_2) - \underbrace{0.140\,\hat{\gamma}\epsilon_3}_{v_3} 2\cos(3\phi - 3\psi_3) + \underbrace{0.063\,\hat{\gamma}\epsilon_2^2}_{v_4} 2\cos(4\phi - 4\psi_2) + 0.015\,\hat{\gamma}\epsilon_2^2 + \underbrace{0.112\,\hat{\gamma}\epsilon_3^2}_{v_6} 2\cos(6\phi - 6\psi_3) + 0.043\,\hat{\gamma}\epsilon_3^2 + \underbrace{0.088\,\hat{\gamma}\epsilon_2\epsilon_3}_{v_5} 2\cos(5\phi - 3\psi_3 - 2\psi_2) \Bigg\}.$$

Kurkela, Wiedemann and BW, Phys. Lett. B **783**, 274 (2018), [arXiv:1803.02072].

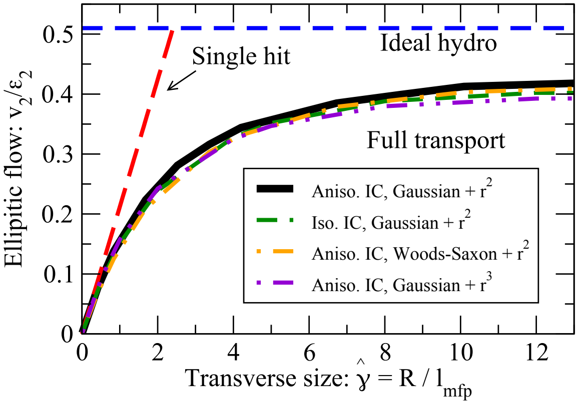
Linear Response: Single-Hit vs Ideal Hydro



Non-hydro modes are more efficient to build up v_2 in small systems!

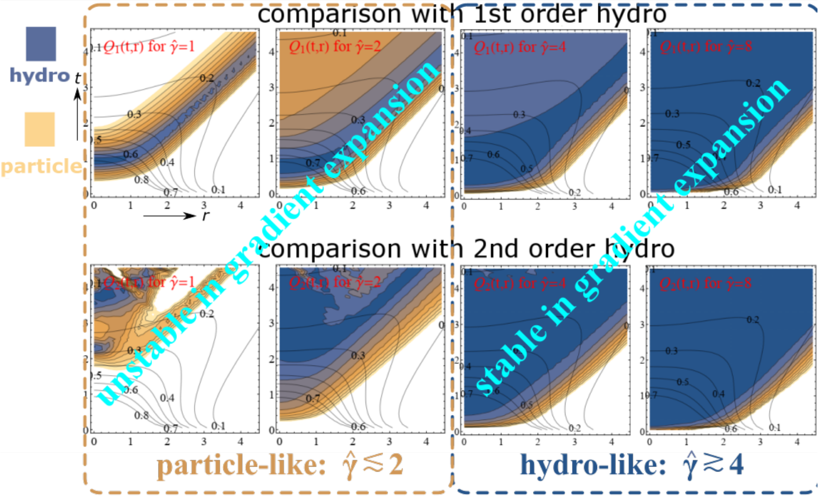
A. Kurkela, U. A. Wiedemann and BW, Eur. Phys. J. C **79**, no.9, 759 (2019) [arXiv:1805.04081 [hep-ph]].

Linear Response: insensitivity to initial profiles



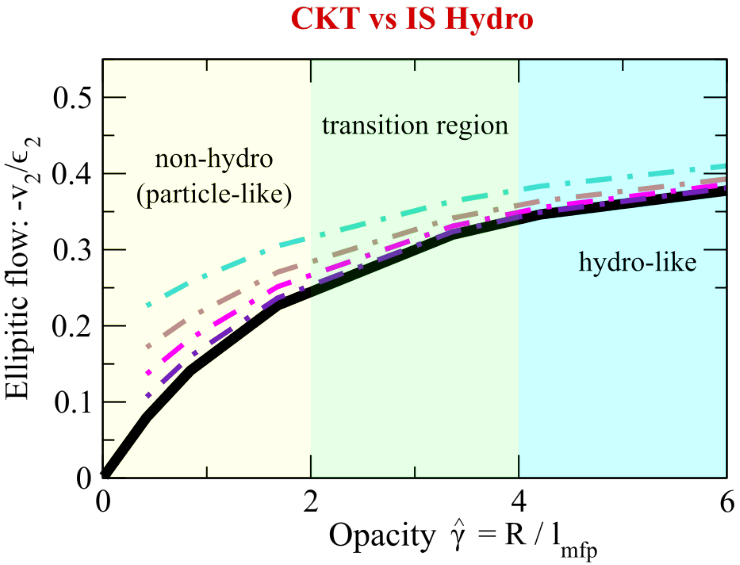
A. Kurkela, U. A. Wiedemann and BW, Eur. Phys. J. C **79**, no. 11, 965 (2019) [arXiv:1905.05139 [hep-ph]].

How much "fluid" is CKT?

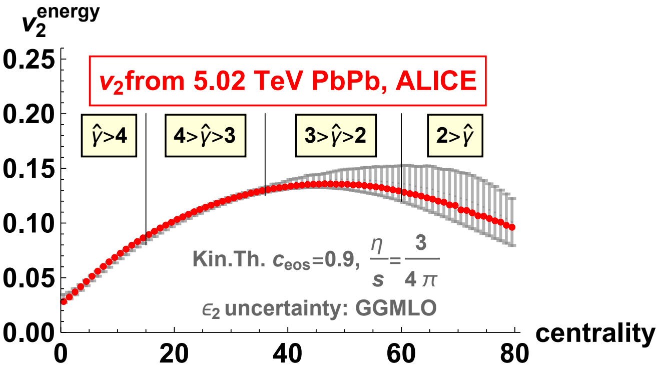


Kurkela, Wiedemann and BW, Eur. Phys. J. C **79**, no. 11, 965 (2019) [arXiv:1905.05139 [hep-ph]].

Hydrodynamic vs Non-hydrodynamic modes in flow

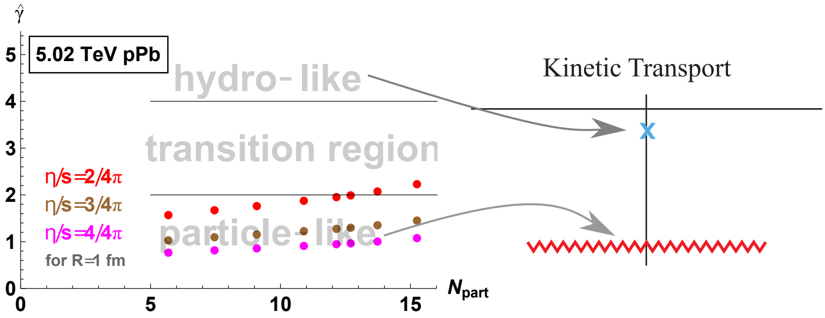


Confronting experimental Data



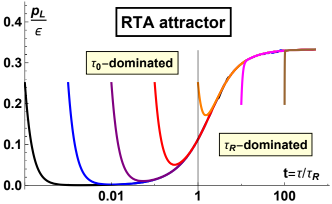
Kurkela, Wiedemann and BW, Eur. Phys. J. C **79**, no. 11, 965 (2019) [arXiv:1905.05139 [hep-ph]].

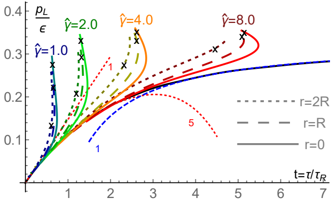
Confronting pA Data



Flow in pA collisions mostly has a non-hydro origin because bulk matter is mostly not hydro-like.

Early-time vs late-time attractors in CKT

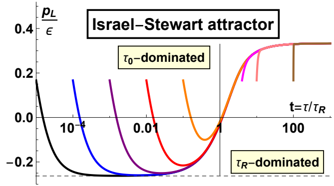


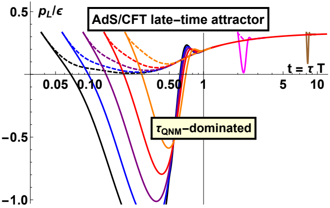


Kurkela, van der Schee, Wiedemann and BW, Phys. Rev. Lett. **124**, 102301 (2020) [arXiv:1907.08101 [hep-ph]]..

1. **Commonalities with bottom-up thermalization** (left figure).
   - Early-time attractor
   - Late-time (hydro) attractor
2. **The late-time dynamics is modified by opacity** (right figure).

Attractors in IS and AdS/CFT



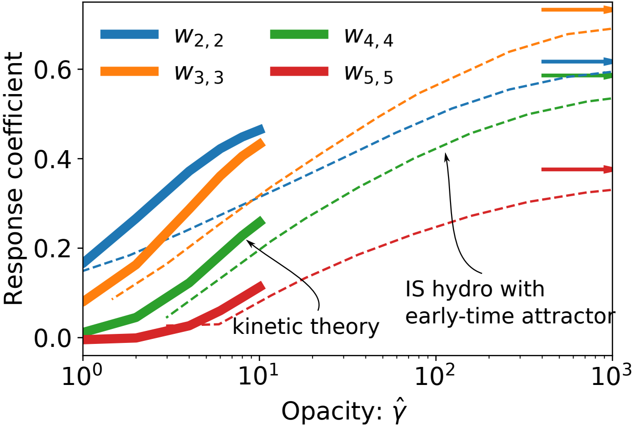


Kurkela, van der Schee, Wiedemann and BW, Phys. Rev. Lett. **124**, 102301 (2020) [arXiv:1907.08101 [hep-ph]]..

The three theories are radically different especially in early times!

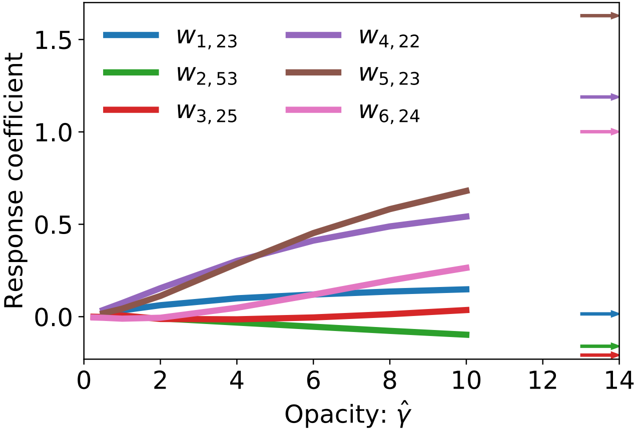
A potential probe to hydrodynamization!

Linear response with early-time attractor



A. Kurkela, S. F. Taghavi, U. A. Wiedemann and BW, [arXiv:2007.06851 [hep-ph]].

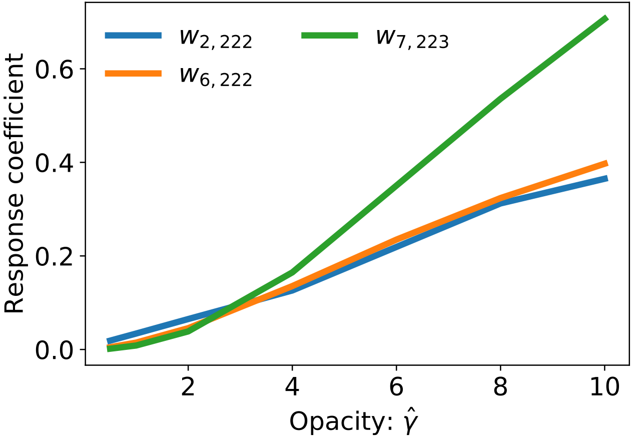
The quadratic response



$$v_{m+n} = w_{m+n,mn}\epsilon_m\epsilon_n$$

A. Kurkela, S. F. Taghavi, U. A. Wiedemann and BW, [arXiv:2007.06851 [hep-ph]].

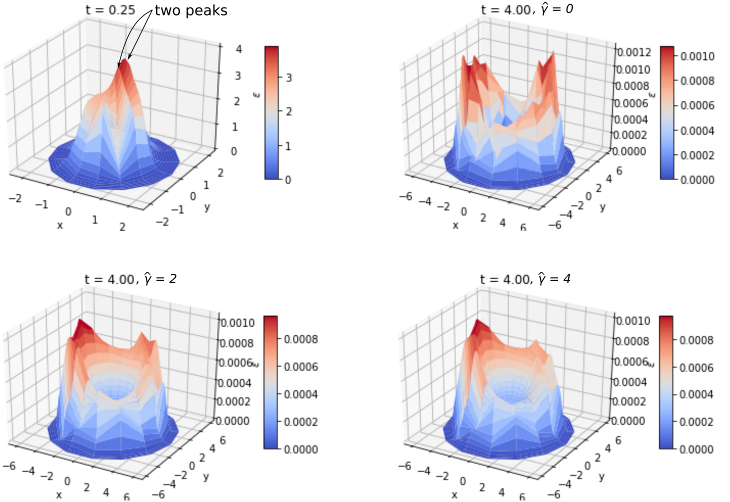
The cubic response



$$v_{l+m+n} = w_{l+m+n,lmn}\epsilon_l\epsilon_m\epsilon_n$$

A. Kurkela, S. F. Taghavi, U. A. Wiedemann and BW, [arXiv:2007.06851 [hep-ph]].

Evolution with TRENTo initial profiles



Conclusions

1. For large systems:

   ✓ The bottom-up thermalization is supported by more detailed calculations.

   ✓ The soft gluon radiation from jets with $t_f \lesssim \tau$ look like the static case.

   ✗ There are some technical questions for going beyond

2. For small systems:

   ✓ Non-hydro modes, which dominates at early time, also contribute to flow.

   ✓ Interplay between hydro and non-hydro modes can be studied (in CKT).

   ✗ potential modification of the bottom-up thermalization?

   ✗ jet quenching?

3. A unified framework for jets & bulk?