# Theory View

a theorist's view, not a theory overview

10.06.2019

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# Heavy Ion Physics - its lasting motivations ...

- Phase transitions of fundamental quantum fields have shaped our Early Universe.
  $\Longrightarrow$ broken symmetries of our vacuum, generation of mass
- **QCD** = part of standard model whose phase transition and high-$T$-phase are experimentally accessible

"... to study the question of 'vacuum', ... we should investigate some **'bulk' phenomena** by distributing high energy over a relatively large volume."

T.D. Lee, 1974

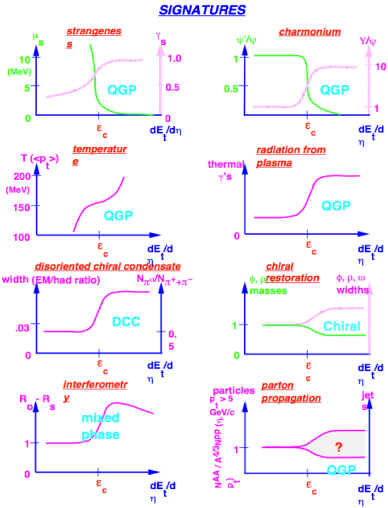
- **QCD** = conceptually richest part of standard model
  $\Longrightarrow$ pert. & non-pert. physics experimentally accessible
  $\Longrightarrow$ non-abelian, degrees of freedom change with $Q^2$

**How do collective phenomena and macroscopic properties of matter emerge from fundamental interactions in QCD?**

# … and its evolving phenomenological perspectives

J.Harris, B.Mueller,

Ann.Rev.Nucl.Part.Sci. 46 (1996) 71




Our research focus has evolved

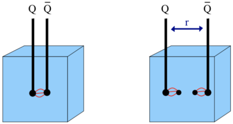
- **From** kinky signatures of the QGP equilibrium state.
- **To:** AA collisions as mesoscopic, strongly expanding systems.

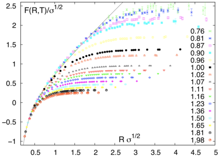
  (Not born into but evolving towards equilibrium)
- **Understanding the collective dynamics of AA collisions** is
  - unwanted complication?
  - prerequisite and portal for reliable extraction of QGP matter properties !

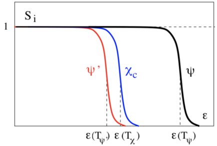
… 3 examples on following slides …

# Collective dynamics as complication and opportunity: $J/\Psi$

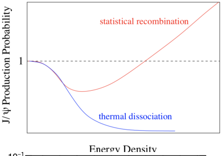
- in QCD equilibrium (Satz & Kluberg, arXiv:0901.3831)



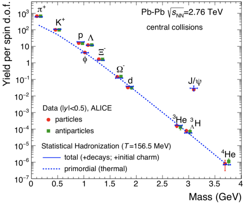



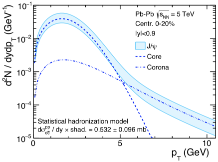




- the dynamical complications in AA Comover, CNM baseline, $J/\Psi$-production, blueshifted dissociation, complex $Q\bar{Q}$-potential, ...

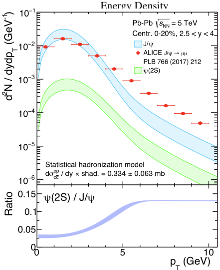



- $J/\Psi$ as test of the dynamics of hadronization?



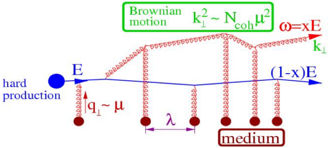

(Andronic et al. 1901.09200)



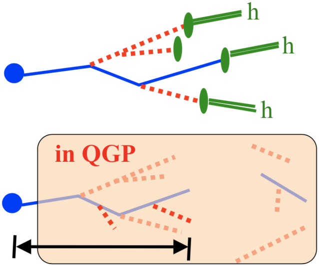
# Collective dynamics as complication and opportunity: jets

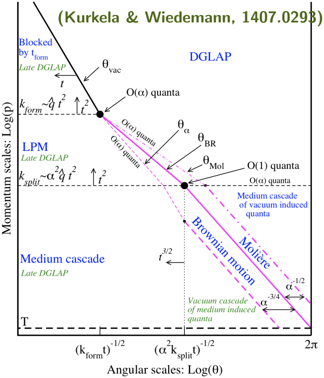
- the classical view: **jets as opacity meter**

$$\frac{1}{2}\hat{q}L^2 = \int_0^L d\xi\, \xi\, \hat{q}(\xi)$$
$$\langle W(\mathcal{C})\rangle \approx \exp\left[\frac{-1}{4\sqrt{2}}\hat{q}L^- L^2\right]$$




- Jets as **QCD lab of hadroni-, isotropi- and thermali-zation**



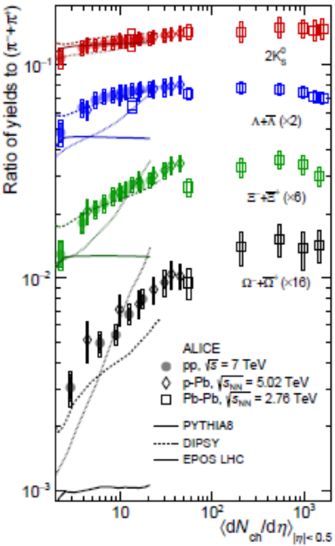



# Collectivity dynamics as opportunity: hadrochemistry

- data violate HEP working hypothesis of process-independent universal fragmentation in pp
- *"The observation of heavy-ion like behavior in pp collisions at the LHC suggests that more physics mechanisms are at play than traditionally assumed "*

  *Fisher & Sjøstrand, JHEP 01 (2017) 140*

(ALICE, Nature Physics 13 (2017) 535)



# Perspectives today


(1) Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales.
(2) Map the phase diagram of QCD with experiments planned at RHIC.

NSAC Long Range Plan 2015

European Strategy Update

HL-LHC WG5 report, arXiv:1812.06772

- Characterizing long-wavelength QGP properties
- Probing the inner workings of QGP
- System size dependence
- Exploring nuclear pdfs

$\Longrightarrow$ talk by J. Stachel

$\Longrightarrow$ emphasis on collective dynamics

# How do we probe the QGP?

- **Inject** perturbations $\delta h^{\mu\nu}$ (energy) or $\delta A^{\mu}$ (charge)
  - in form of spatial eccentricities
  - as jets
  - as electric charge, baryon number, heavy flavor
- **Measure** their propagation

$$\delta T^{\mu\nu}(t,x) = \int_{t_i,x_i} G_R^{\mu\nu,\alpha\beta}(t-t_i, x-x_i)\delta h_{\alpha\beta}(t_i,x_i)$$

- **Conclude** about matter properties. How ?

$$G_R^{\alpha\beta,\gamma\delta}(t,k) = \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} e^{-i\omega t} G_R^{\alpha\beta,\gamma\delta}(\omega,k)$$

**Inner workings of QGP encoded in $G_R(\omega,k)$.**
**How?**

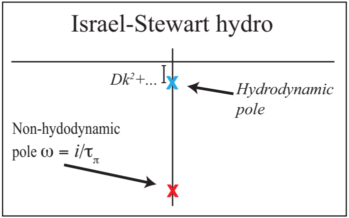
# Israel-Stewart non-hydrodynamic modes

- hydro modes are **poles** $\omega_{\rm hyd}$ **of** $G_R(\omega, k)$ (with $\lim_{k\to 0} Im[\omega_{\rm hyd}(k)] = 0$),
  $G_R^{zx,zx}(\omega,k) = \frac{-\eta\omega^2}{-i\omega + \frac{\eta k^2}{sT}}$ (shear)
- Israel-Stewart is causal due to ad hoc relaxation time

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

This introduces non-hydro mode

$$G_R^{IS}(t,k) \propto$$
$$c_{\rm hyd} \exp\left[-{\rm Im}\left[\omega_{\rm hyd}\right] t\right]$$
$$+c_{\rm non-hyd} \exp\left[-t/\tau_\pi\right]$$



# Hydro- and non-hydro modes in kinetic theory

- free-streaming $\Longrightarrow$ **branch cuts**

$$\int \frac{d\Omega}{4\pi} \frac{1}{i\omega - i\vec{v}.\vec{k}} = \frac{i}{2k} \ln\left(\frac{\omega-k}{\omega+k}\right)$$

- relaxation time approximation

$$\boxed{\frac{1}{p} p^\mu \partial_\mu f = -\frac{1}{\tau_\mathrm{R}} \left(f - f_\mathrm{eq}\right)}$$

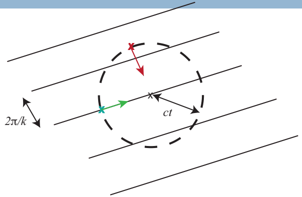
  - particle branch cut shifts

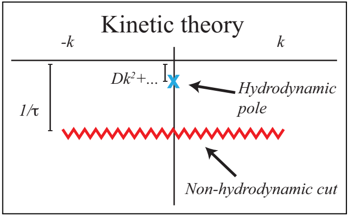
    $\mathrm{Im}\left[\omega_{non-hyd}\right] = -\frac{1}{\tau_R}$

  - hydro modes arise

    shear viscosity

    $\eta = \frac{1}{5}\tau_R \left(\varepsilon + p\right)$




Romatschke 2016,

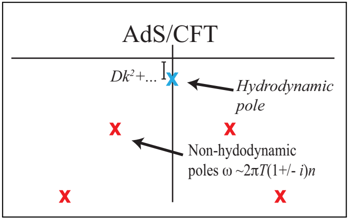
Kurkela & Wiedemann, arXiv:1712.04376

This kinetic theory ressembles Israel-Stewart with ad hoc non-hydro pole replaced by physically better motivated branch cut.

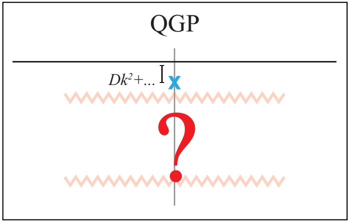
# What does Quantum Field Theory say?

No-lose theorem for "probing the inner workings of QGP":

There is no QFT without non-fluid dynamic excitations.




- hydrodynamic modes
- quasinormal modes




- hydrodynamic modes
- quasi-particle cuts ?
- Matsubara modes ?

**Probing the inner workings of QGP**
**$\Longleftrightarrow$ going beyond hydrodynamics.**

# Small systems as test of inner workings

Decreasing the transverse system size $R$

- increases the smallest wavenumber $k \propto 1/R$
- time $t \sim R$ of in-medium propagation decreases
- $\varepsilon$ decreases $\Longrightarrow \tau_R = \frac{1}{\gamma \varepsilon^{1/4}}$ increases

$$G_R(t,k) = \underbrace{c_{\mathrm{hyd}} \exp\left[-D\,k^2\,t\right]}_{\text{reduced for smaller R}} + \underbrace{c_{\mathrm{non-hyd}} \exp\left[-t/\tau_R\right]}_{\text{enhanced for smaller R}}$$

Reducing system size is one tool to enhance and characterize non-hydrodynamic modes.

$\Longrightarrow$ illustrate this strategy in a model study.

based on Kurkela, Wiedemann & Wu, arXiv:1905.05139

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based on Kurkela, Wiedemann & Wu, arXiv:1905.05139

# CKT

# Boost-invariant conformal kinetic transport (CKT)

**Isotropization time approximation** $\tau_{\rm iso} = \frac{1}{\gamma\, \epsilon^{1/4}}$

($v_\mu = \frac{p_\mu}{p}$, $p = |\vec{p}|$, invariance under boosts with $u_z = \frac{z}{t}$) (Kurkela, Wiedemann & Wu, arXiv:1905.05139)

$$\frac{1}{p} p^\mu \partial_\mu f = -C[f] = -\frac{[-v_\mu u^\mu]}{\tau_{\rm iso}} \left(f - f_{\rm iso}(p^\mu u_\mu)\right)$$

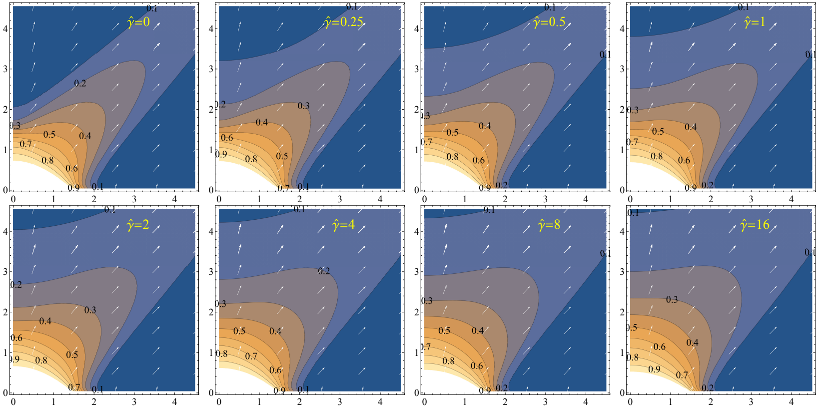
- Equations of motion close for $T^{\mu\nu}(t, r, \theta)$
- Physics depends on only one dimensionless parameter: opacity $\hat{\gamma} \equiv \gamma R^{3/4} \left(\varepsilon_0\, \tau_0\right)^{\frac{1}{4}}$
- Hydrodynamic properties known, e.g., $\frac{\eta}{s} = \frac{1}{5\gamma} \frac{T}{\varepsilon^{1/4}}\Big|_{\rm QCD} = \frac{0.11}{\gamma}$
- Hydro sector of CKT matches that of (conformal) IS theory.
- CKT interpolates between free-streaming particles ($\hat{\gamma} \to 0$) and ideal hydrodynamics ($\hat{\gamma} \to \infty$).

# Radial evolution

Initialize $F(\tau_0, r) = \varepsilon_0 \delta(v_z) P_{\mathrm{Woods-Saxon}}\left(\frac{r}{R}\right)\left(1 + \sum_m \delta_m \#\right)$

Plot $\varepsilon(r/R, t/R)$ for opacity $\hat{\gamma} \equiv \gamma R^{3/4} \left(\varepsilon_0 \tau_0\right)^{\frac{1}{4}}$

(Kurkela, Wiedemann, Wu, arXiv:1905.05139)



# How “fluid” is this kinetic theory?

Fluid dynamics is a gradient expansion, determined by **transport coefficients** (that are known as function of $\gamma$). Up to 2nd order:

$$
\begin{aligned}
T^{\mu\nu}_{\rm hyd} &= (\varepsilon + p)\, u^\mu\, u^\nu + p\, g^{\mu\nu} + \Pi^{\mu\nu}_{\rm hyd} \\
\Pi^{\mu\nu} &= -2\eta_s \sigma^{\mu\nu} + 2\tau_\Pi\, \eta_s \left[ {}^{<}D\sigma^{\mu\nu>} + \frac{4}{3}\sigma^{\mu\nu}\nabla_\alpha u^\alpha \right] + 4\lambda_1 \sigma^{<\mu}_{\alpha}\, \sigma^{\nu>\lambda} \\
\sigma^{\mu\nu} &= \left\{ \frac{1}{2}\left[\Delta^{\mu\alpha}\nabla_\alpha u^\nu + \Delta^{\nu\alpha}\nabla_\alpha u^\mu\right] - \frac{1}{3}\Delta^{\mu\nu}\nabla_\alpha u^\alpha \right\}.
\end{aligned}
$$

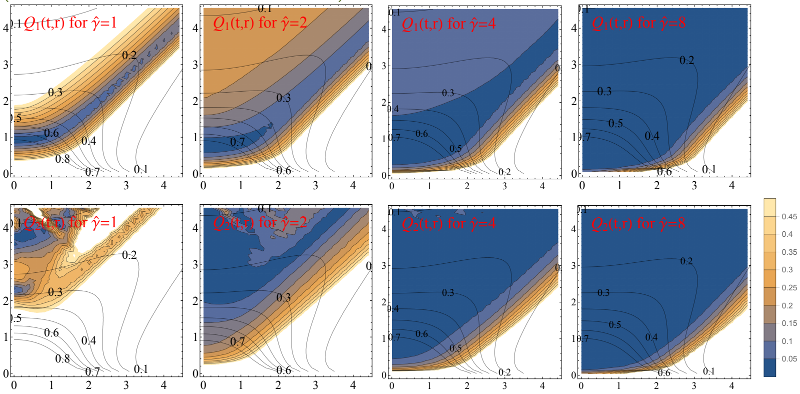
**“Fluid quality”** quantifies how “fluid” the kinetic dynamics is:

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

# How “fluid” is this kinetic theory?

particle-like: $\hat{\gamma} \lesssim 2$ | transition: $2 \lesssim \hat{\gamma} \lesssim 4$ | hydro-like: $4 \lesssim \hat{\gamma}$

(Kurkela, Wiedemann & Wu, arXiv:1905.05139)




Upper (lower) panels: $Q_1$ ($Q_2$) measured up to 1st (2nd) order.

# How "fluid" is PbPb @ LHC?

1. Work done in kinetic theory

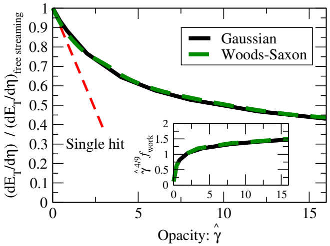
$$f_{\text{work}}(\hat{\gamma})\frac{dE_{\perp,\text{free}}}{d\eta_s} = \frac{dE_\perp(t\to\infty)}{d\eta_s}$$

2. Initial energy density

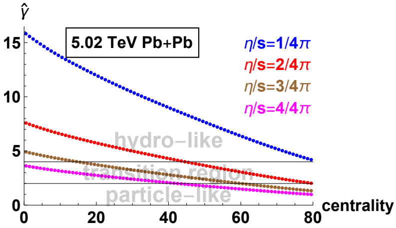
$$\varepsilon_0 = \frac{\frac{dE_{\perp,\text{free}}}{d\eta_s}}{\tau_0\,\pi\,R^2} = \frac{\frac{dE_\perp}{d\eta_s}}{f_{\text{work}}(\hat{\gamma})\tau_0\,\pi\,R^2}$$

$$\Longrightarrow \qquad \hat{\gamma} \equiv \gamma R^{\frac{3}{4}}\,(\varepsilon_0\,\tau_0)^{\frac{1}{4}}$$

$$= \frac{0.11}{\frac{\eta}{s}}\left(\frac{R\,\frac{dE_\perp}{d\eta}}{\pi f_{\text{work}}(\hat{\gamma})}\right)^{1/4}$$



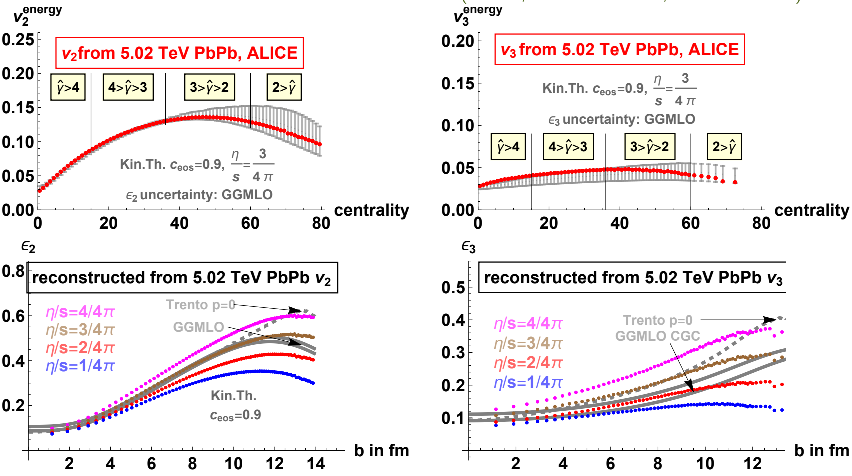

(Kurkela, Wiedemann & Wu, arXiv:1905.05139)




$$\frac{\eta}{s} = \frac{1}{5}\tau_R T = \frac{1}{5\gamma}\frac{T}{\varepsilon^{1/4}}\Big|_{\text{QCD}} = \frac{0.11}{\gamma}$$

# Compare $\frac{v_m}{\epsilon_m}(\hat{\gamma})$ to data / reconstruct $\epsilon_m$ from data

(Kurkela, Wiedemann & Wu, arXiv:1905.05139)




($c_{\rm eos}$: results corrected for non-ideal equation of state; GGMLO arXiv:1902.07168)

# Lessons from Conformal Kinetic Theory

- **CKT** accounts well for flow across system size and $\sqrt{s}_{\mathrm{NN}}$.
  - $\hat{\gamma}_{pPb} \leq 4$ and $\hat{\gamma}_{\mathrm{AuAu-RHIC}} \approx 0.83\,\hat{\gamma}_{\mathrm{PbPb-LHC}}$
  - importance of non-hydro modes demonstrated.
- Scaling of flow in non-confromal kinetic theory ($\sigma$ = fixed) small system, $\tau_R = \frac{1}{n(\tau)\sigma}$, $n(\tau) = \frac{1}{\tau A_\perp}\frac{dN}{d\eta_s}$ (Heiselberg & Levy 9812034, Voloshin & Poskanzer 9906075)

$$\frac{v_2}{\epsilon_2} \propto \frac{R}{\tau_R(\tau = R)} \sim \frac{\sigma}{A_\perp}\frac{dN}{d\eta_s}$$

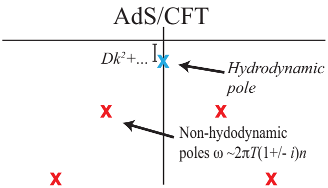
- **Conformal scaling of flow** $\hat{\gamma} = \gamma\left(\frac{R\langle p_\perp\rangle \frac{dN}{d\eta_s}}{\pi f_{\mathrm{work}}(\hat{\gamma})}\right)^{1/4}$

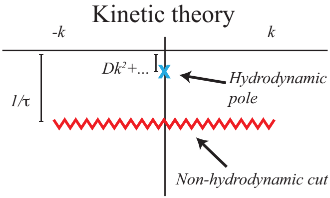
$$\left.\frac{v_2}{\epsilon_2}\right|_{\hat{\gamma}<1} \propto \left(\langle p_\perp\rangle R\frac{dN}{d\eta_s}\right)^{1/4}$$

$$\left.\hat{\gamma}\right|_{\hat{\gamma}\gg 1} \propto \left(\frac{dN}{d\eta_s}\right)^{1/3}$$

Whether flow exhibits conformal scaling could inform us about the microscopic dynamics underlying collectivity.

- Could a strongly coupled QFT be similarly successful? Definitively worth testing! But note parametric differences:
  - $\tau_{non-hyd} \propto \frac{1}{T}$ in AdS/CFT, $\tau_{\rm iso} \propto \frac{1}{\gamma \epsilon^{1/4}}$ in kinetic theory
  - and one has to explain why particles reach the detector



end CKT

# A theorist's view

- To understand the inner workings of QGP, we need to understand how microscopic QCD dynamics
  - builds up collectivity?
  - affects hadronization?
  - mediates transport? (of heavy quarks)
  - picks up recoil?
  - induces fluctuations and dissipation?
  - varies with $\sqrt{s}$ and $A$?

# LA FINE

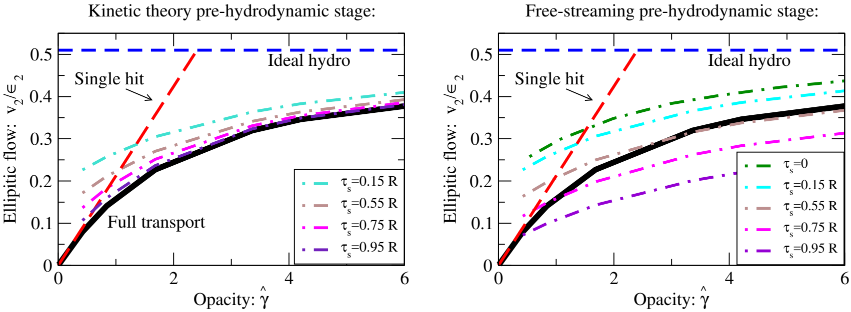

Valentino
Caffè
Sembra
sempre
impossibile
finché
non viene
realizzato

# Back-up

# Large Uncertainties in initializing Israel-Stewart

Matching kinetic theory to IS hydro at early $\tau_s$ induces large uncertainties.

(Kurkela, Wiedemann, Wu, arXiv:1805.04081)




Kinetic transport needed to reliably extract $\hat{\gamma}$ and thus $\eta/s$.

# Compare $\frac{v_m}{\epsilon_m}(\hat{\gamma})$ to data