# Transport Coefficients In QGP

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Initial Stage 2019

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# Kinetic Transport & Inner Workings of QGP

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Initial Stage 2019

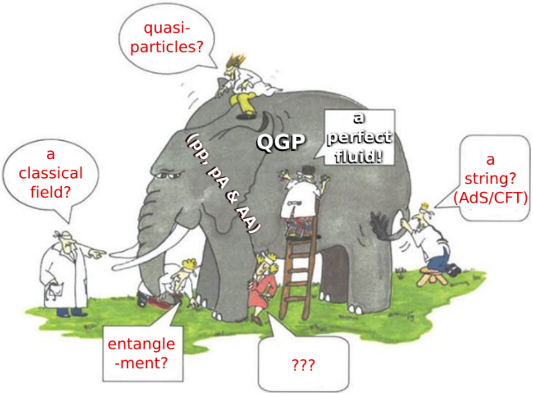
# Going Beyond Hydrodynamics

# Focus: Probing the Inner Workings of QGP


1. Hydro has been very phenomenologically successful.

2.

# Focus: Probing the Inner Workings of QGP



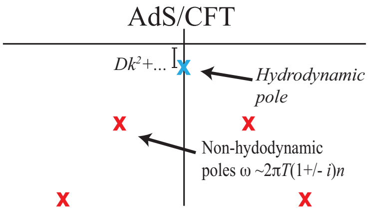

1. Hydro has been very phenomenologically successful.

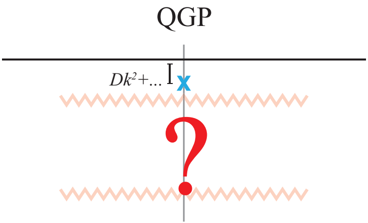
2. Studying the inner workings of QGP now lies beyond hydro.

# Hydro vs Non-hydro Modes

- Two trivial statements:
  1. QFTs contain hydrodynamics.
  2. QFTs go beyond hydrodynamics in different ways.

- Examples:

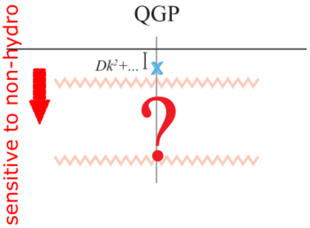


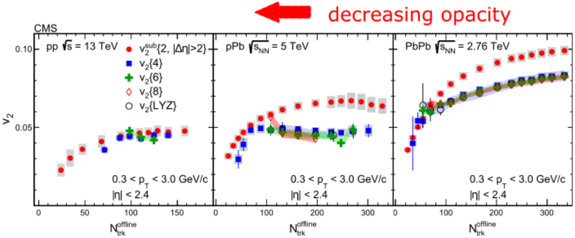




cf. Saso's talk

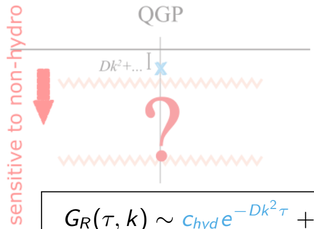
the analytic structure of $G_R^{\alpha\beta,\gamma\delta}(\omega,\vec{k}) = -i\int d^4x e^{ik\cdot x}\theta(x^0)\langle[T^{\alpha\beta}(x),T^{\gamma\delta}(0)]\rangle$

# Strategy to Probe Inner Workings of QGP



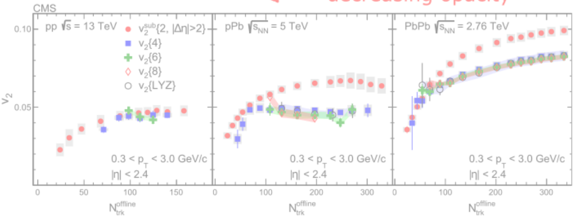



# Strategy to Probe Inner Workings of QGP




$$\boxed{G_R(\tau, k) \sim c_{hyd}\, e^{-Dk^2\tau} + \text{non-hydro terms}}$$

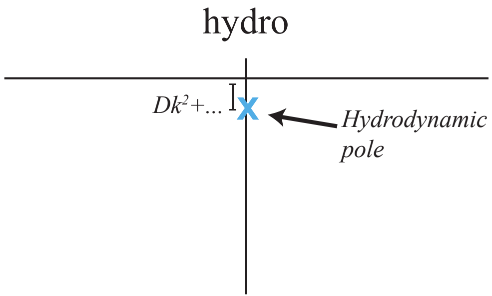
decreasing opacity



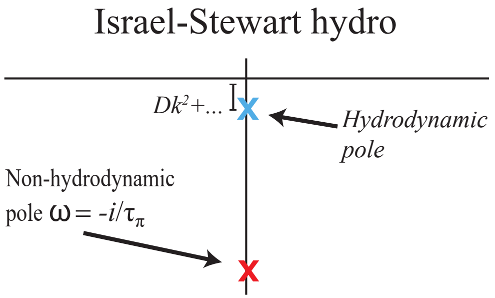

**Decreasing $R \sim 1/k$ enhances non-hydro contributions.**

# An Illustration Using A Conformal Kinetic Transport (CKT)

# Hydro Is Hydro



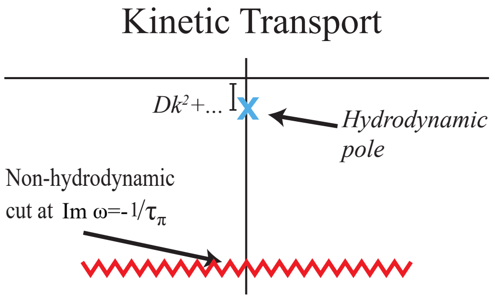
# IS Hydro Is Not Only Hydro




## The Israel-Stewart (IS) hydro

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

# Kinetic Transport in ITA Is Not Less Hydro

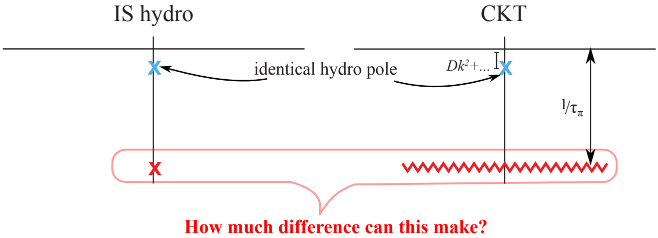



Romatschke, Eur. Phys. J. C **76**, no. 6, 352 (2016) [arXiv:1512.02641]; Kurkela and Wiedemann, arXiv:1712.04376.

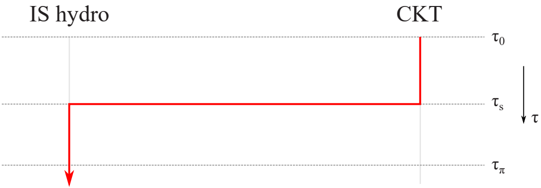
With the same transport coefficients and $\tau_\pi$ calculated in the CKT,

1. The CKT and IS hydro have the same hydro pole.
2. IS non-hydro pole is replaced by a branch cut in CKT.

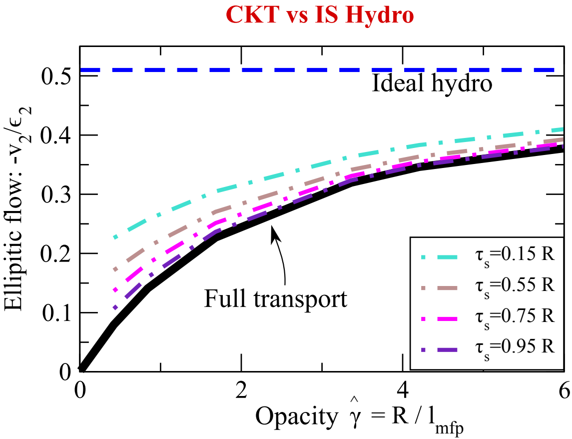
# Pin Down Sensitivity to Non-hydro Modes




The approach to answer this question:



# Proof of Sensitivity to Non-hydro Modes

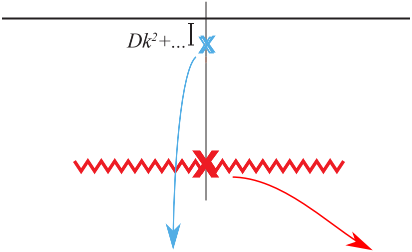



**Sensitivity to non-hydro modes is more pronounced in small systems.**

Kurkela, Wiedemann and BW, arXiv:1805.04081.

# Interpretation of Sensitivity to Non-hydro Modes

CKT or IS hydro




$$\boxed{G_R(\tau,k) \sim c_{hyd} \underbrace{e^{-Dk^2\tau}}_{\text{reduced for small } R} + c_{non-hyd} \underbrace{e^{-\frac{\tau}{\tau_\pi}}}_{\text{enhanced for small } \varepsilon}}$$

Non-hydro modes are enhanced in small or dilute systems $\Leftrightarrow$ small $\hat{\gamma} = R/l_{mfp}$ with $l_{mfp}$ mean free path.

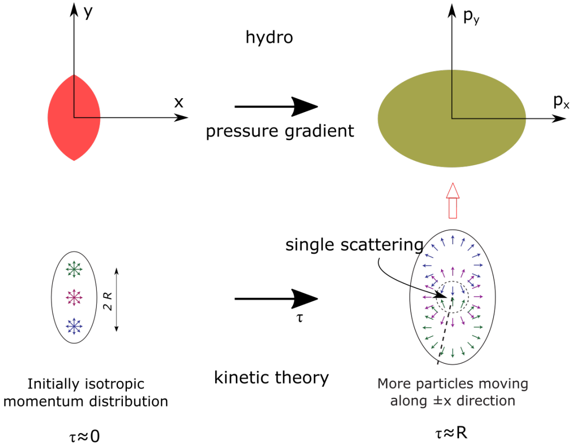
# Flow PURELY from Non-hydro modes at $\hat{\gamma} \to 0$

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].

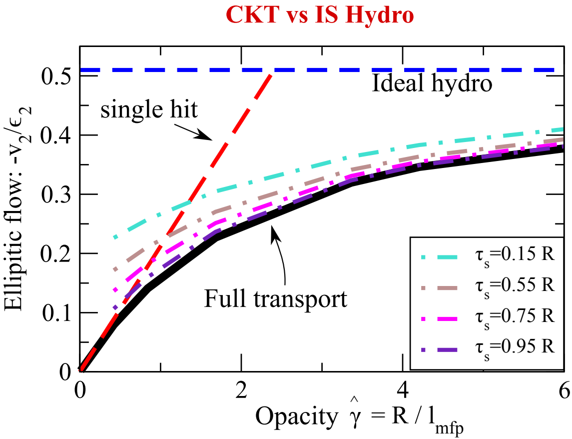
# Physical picture for flow in small systems




Flow is a signature for final-state interactions, not for hydro!

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

# From Free-streaming to Ideal Hydro




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

Kurkela, Wiedemann and BW, arXiv:1805.04081.

# Hydro vs Non-hydro

# Qualification of Being a Fluid

**Criteria:**

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

in terms of "fluid quality"

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

Kurkela, Wiedemann and BW, arXiv:1905.05139.

Up to 2nd order in gradient expansion,

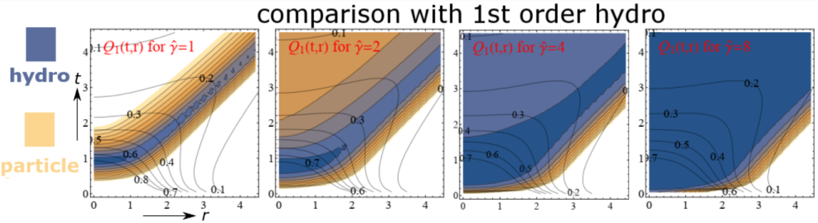
$$T^{\mu\nu}_{\rm hyd} = (\varepsilon + p)\, u^\mu\, u^\nu + p\, g^{\mu\nu} + \Pi^{\mu\nu}_{\rm hyd}$$

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

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

Baier, Romatschke, Son, Starinets and Stephanov, JHEP **0804**, 100 (2008).

# How Much "Fluid" is CKT?




Kurkela, Wiedemann and BW, arXiv:1905.05139.

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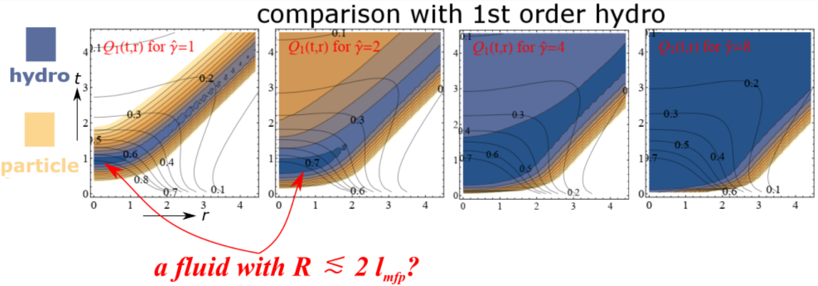


Kurkela, Wiedemann and BW, arXiv:1905.05139.

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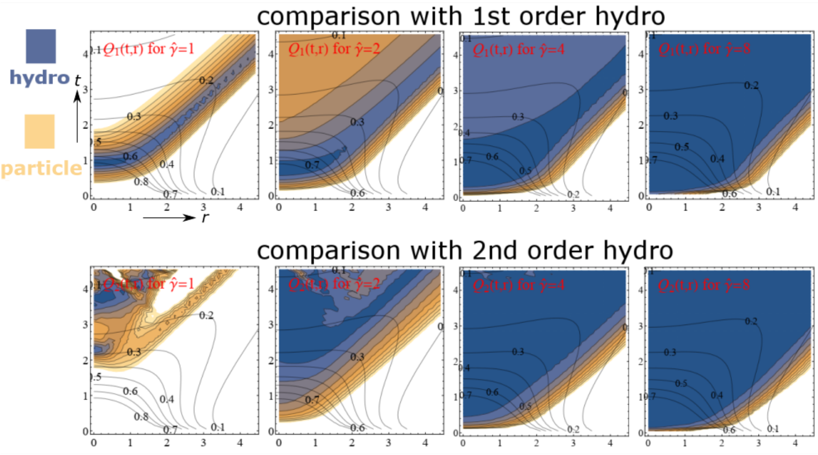


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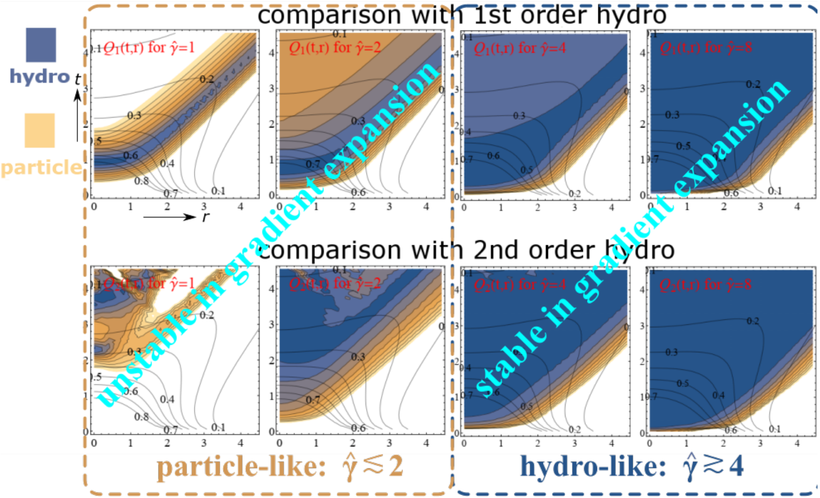
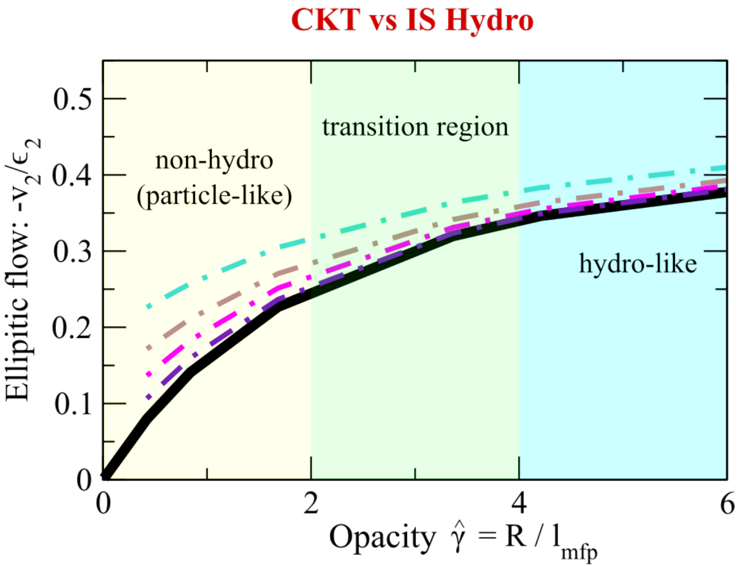


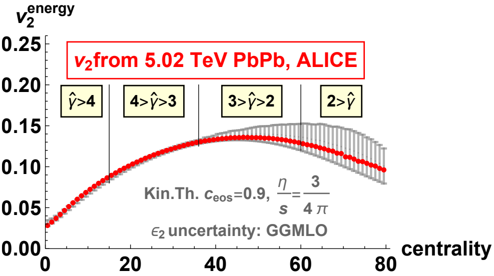

Kurkela, Wiedemann and BW, arXiv:1905.05139.

# Fluid vs Non-fluid in Our Numerical Results



# Confronting Data

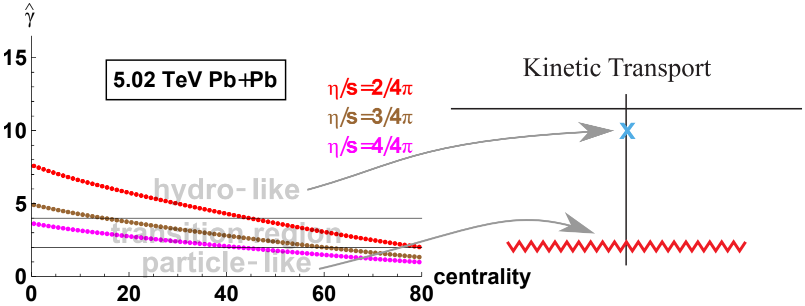
# Measurement of Opacity




GGMLO: Giacalone, Guerrero-Rodrguez, Luzum, Marquet & Ollitrault, arXiv:1902.07168.

1. Definition: $\boxed{\hat{\gamma} \equiv \gamma R(\varepsilon_0 \tau_0 / R)^{\frac{1}{4}} = \frac{0.11}{\eta/s} \left( \frac{R \frac{dE_\perp}{d\eta_s}}{\pi f_{work}(\hat{\gamma})} \right)^{\frac{1}{4}}}$
2. Conformal scaling property: $\boxed{\left.\frac{v_2}{\epsilon_2}\right|_{\hat{\gamma}<1} \propto \left( R \langle p_\perp \rangle \frac{dN}{d\eta_s} \right)^{\frac{1}{4}}}$

# Confronting AA Data

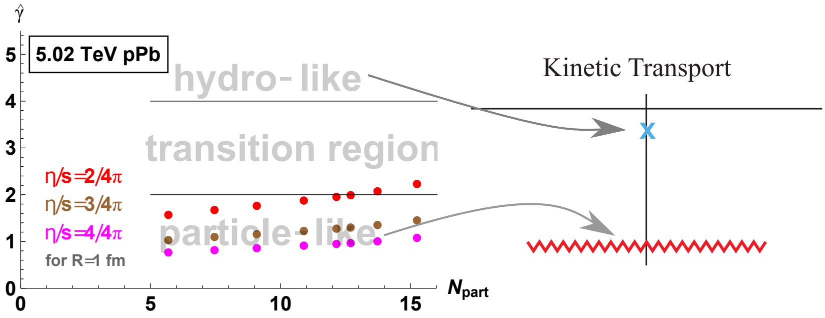



($v_2$ gives a loose constraint on $4\pi\frac{\eta}{s} \in (2, 4)$.)

**Flow in (central) AA collisions is of hydro origin.**

For details, cf. Urs' Talk

# Confronting pA Data



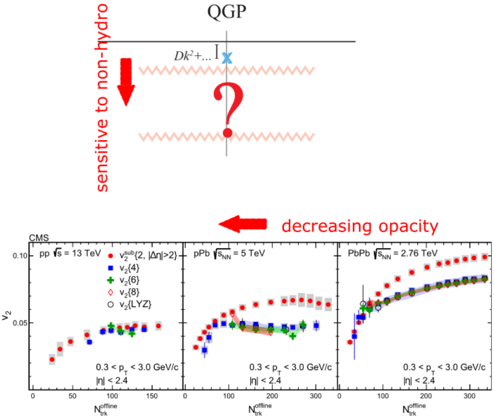

**Flow in pA collisions mostly has a non-hydro origin because bulk matter is mostly not hydro-like.**

For details, cf. Urs' Talk

# Conclusions

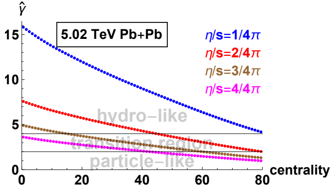
1. Probing inner workings of QGP $\Leftrightarrow$ going beyond hydrodynamics.

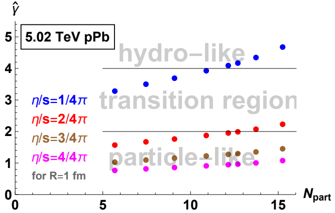
2. The strategy to do so is as follows:



# Conclusions

3. The CKT implements the same hydro as IS hydro with a physically motivated non-hydro sector. And we find



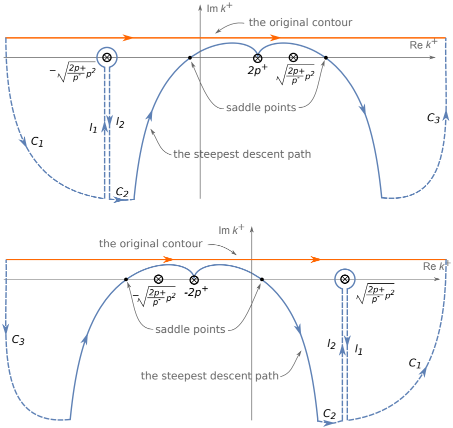

And for small systems: $\boxed{\left.\frac{v_2}{\epsilon_2}\right|_{\hat{\gamma}<1} \propto \hat{\gamma} \propto \left(R\langle p_\perp\rangle \frac{dN}{d\eta_s}\right)^{\frac{1}{4}}}$

4. The strategy provides a general approach & implementation in all theories beyond hydro is most welcome.

# Backup Slides

# Implementation in QFT

QFT has richer structures than kinetic theory. In two-point function, one has




Kovchegov & BW, JHEP **1803**, 157 & 178 (2018).

$v_2$ can be calculated using the framework in these papers (working in progress).