# Do nuclear collisions create an equilibrated QGP?

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# When is Hydro applicable?

Answer (version 2001):

System in local thermal equilibrium. For nuclear collisions, happens after

$$\tau \geq 1.5\alpha_s^{-13/5} Q_s^{-1}$$

(or $\tau > 6.9$ fm if $Q_s \sim 1$ GeV, $\alpha_s \sim 0.3$)

[Baier, Mueller, Schiff, Son, 2001]

# When is Hydro applicable?

Answer (version 2005):

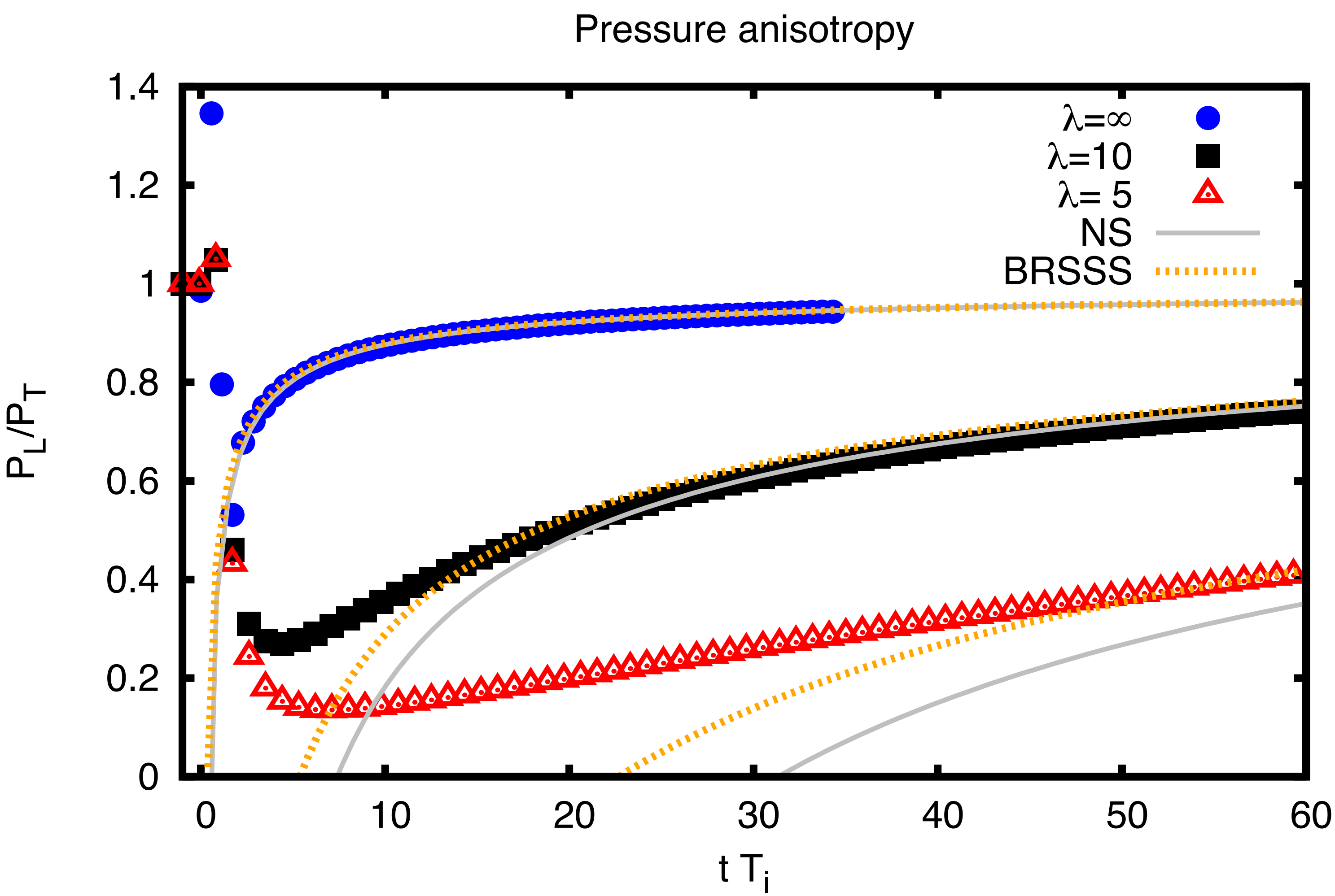
Thermal equilibrium not needed. Local isotropy will suffice, e.g.Tab=diag(ε,p,p,p)

[Arnold, Lenaghan, Moore, Yaffe, 2005]

Plasma Instabilities? [Mrowczynski & others]

Non-thermal fixed points? [Berges &others]

# When is Hydro applicable?




[adapted from Keegan et al, 1512.05347]

# When is Hydro applicable?

- Empirical Fact: Hydro works quantitatively even for anisotropic systems
- This empirical result seems solid: multiple cases, strong/weak coupling, different authors
- Onset of quantitative hydro description unrelated to thermalization or isotropization
- New type of phenomenon ("hydrodynamization") [Casalderrey-Solana, Liu, Mateos, Rajagopal, Wiedemann, 1101.0618]

# When is Hydro applicable?

# Hydro as an EFT

- Many derivations of hydro equations
- Some assume thermal equilibrium, other an underlying particle-description
- In my opinion, most general approach is Effective Field Theory (EFT)
- Hydro = EFT of long-lived, long-wavelength excitations
- EFT variables: pressure, energy density, fluid velocity

# Hydro as an EFT

- Write down quantities using EFT variables and their gradients
- E.g. Energy-Momentum Tensor for relativistic fluid

$$T^{ab} = (\epsilon + P)u^a u^b + P g^{ab} - 2\eta \nabla^{\langle a} u^{b\rangle} + \dots$$

- No thermal equilibrium or particle description needed
- Seems we need small gradients!

# Hydro as an EFT

- What if we had LARGE gradients?
- Try to improve description by including higher orders in EFT gradient series
- E.g. Bjorken flow, go to order 240 (AdS/CFT)

$$T(\tau) = T_0 \left(\frac{\tau_0}{\tau}\right)^{1/3} \left(1 + \sum_{n=1}^{240} \alpha_n \left(\frac{\tau_0}{\tau}\right)^{2n/3}\right)$$

- Find: $\alpha_n \sim n!$, gradient series diverges

[1302.0697, 1503.07514, 1603.05344, 1608.07869, 1609.04803]
see talks by Denicol, Heller, Noronha in this meeting!

# Hydro as an EFT

- Gradient series diverges
- But it is Borel-summable! [Heller et al, 1302.0697]
- Borel-resumming AdS/CFT gradient series gives

$$T(\tau) = T_{\rm hydro}(\tau) + \gamma e^{-i\int d\tau \left(\hat{\omega}_{\rm Borel}\tau^{-1/3} + \hat{\omega}_1 \tau^{-1} + \ldots\right)} + \ldots$$

- $T_{\rm hydro}$ is essentially standard Navier-Stokes
- Extra pieces non-analytic in gradient expansion; this is why grad series diverges!

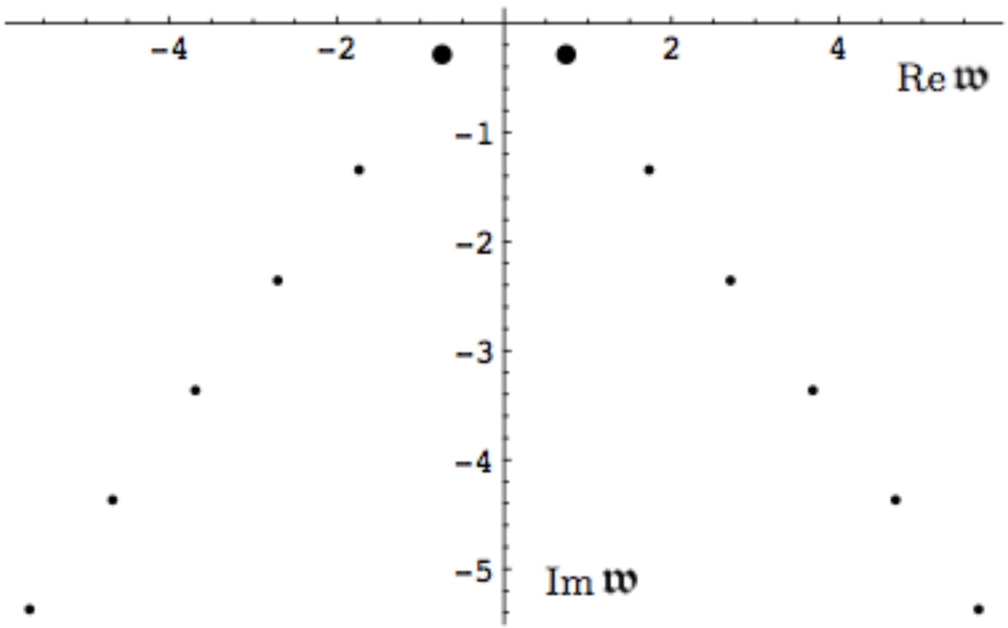
# Hydro as an EFT

- Borel resummation gives Hydro part and other ("Non-Hydro") part
- Non-hydro part:

$$\cdot\ \gamma e^{-i\int d\tau\left(\hat{\omega}_{\text{Borel}}\tau^{-1/3}+\hat{\omega}_1\tau^{-1}+\ldots\right)}+\ldots$$

- $w_{\text{Borel}}=\pm 3.1193-2.7471\, i$ [Heller et al, 1302.0697]
- $w_{\text{QNM}}=\pm 3.119-2.747i$ [Starinets, hep-th/0207133]

# Hydro as an EFT




Quasinormal spectrum of gravitational fluctuations in the sound channel,

[Kovtun&Starinets, hep-th/0506184]

# When is Hydro applicable?

# When is Hydro applicable?

Answer (version 2016):

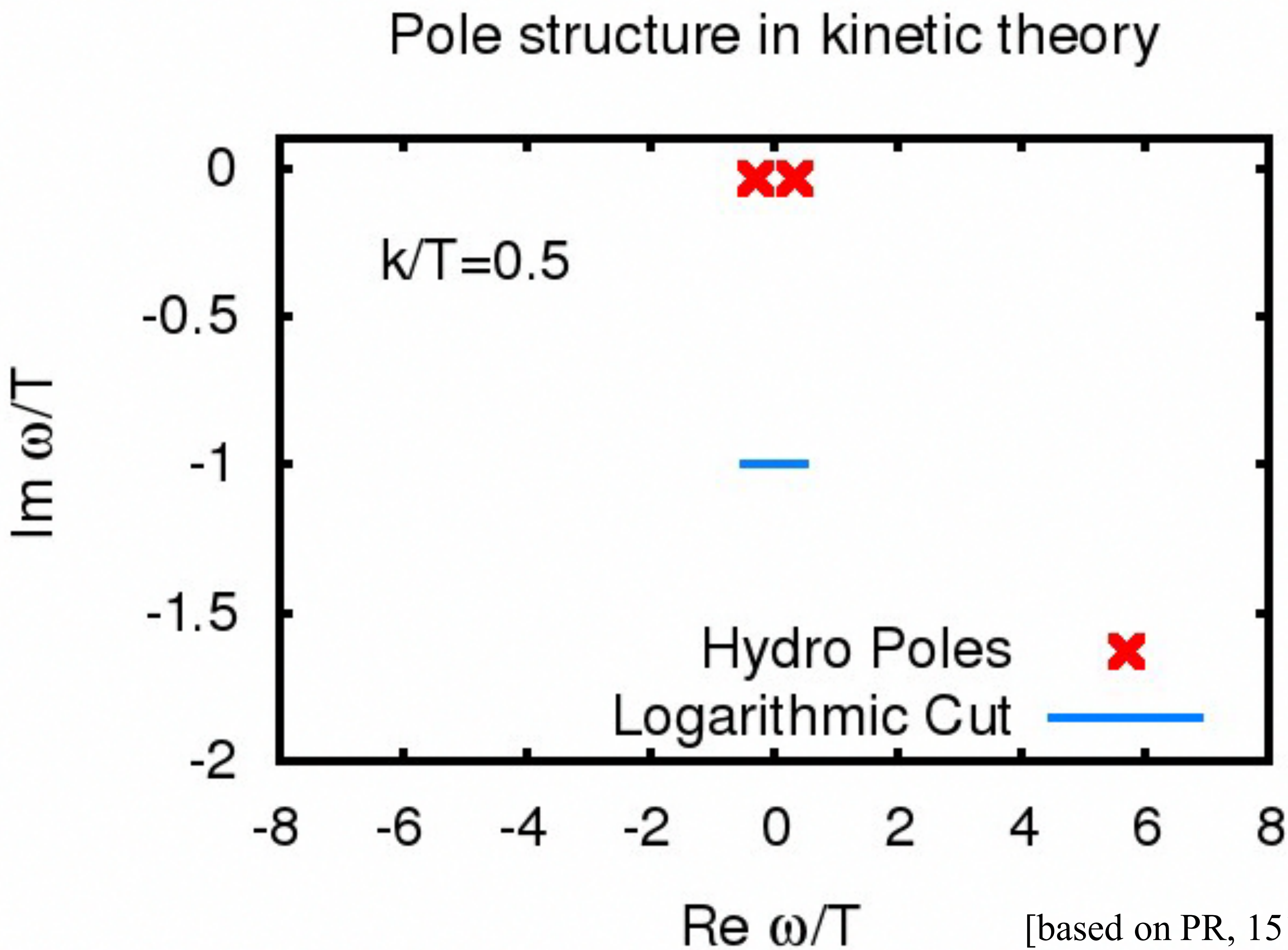
Hydrodynamics is applicable and quantitatively reliable as long as contribution from non-hydro modes can be neglected[1].

[PR, 1609.02820]

No need of thermal equilibrium!
No need of isotropy!

[1] If a local rest frame exists.

# When do non-hydro modes become important?



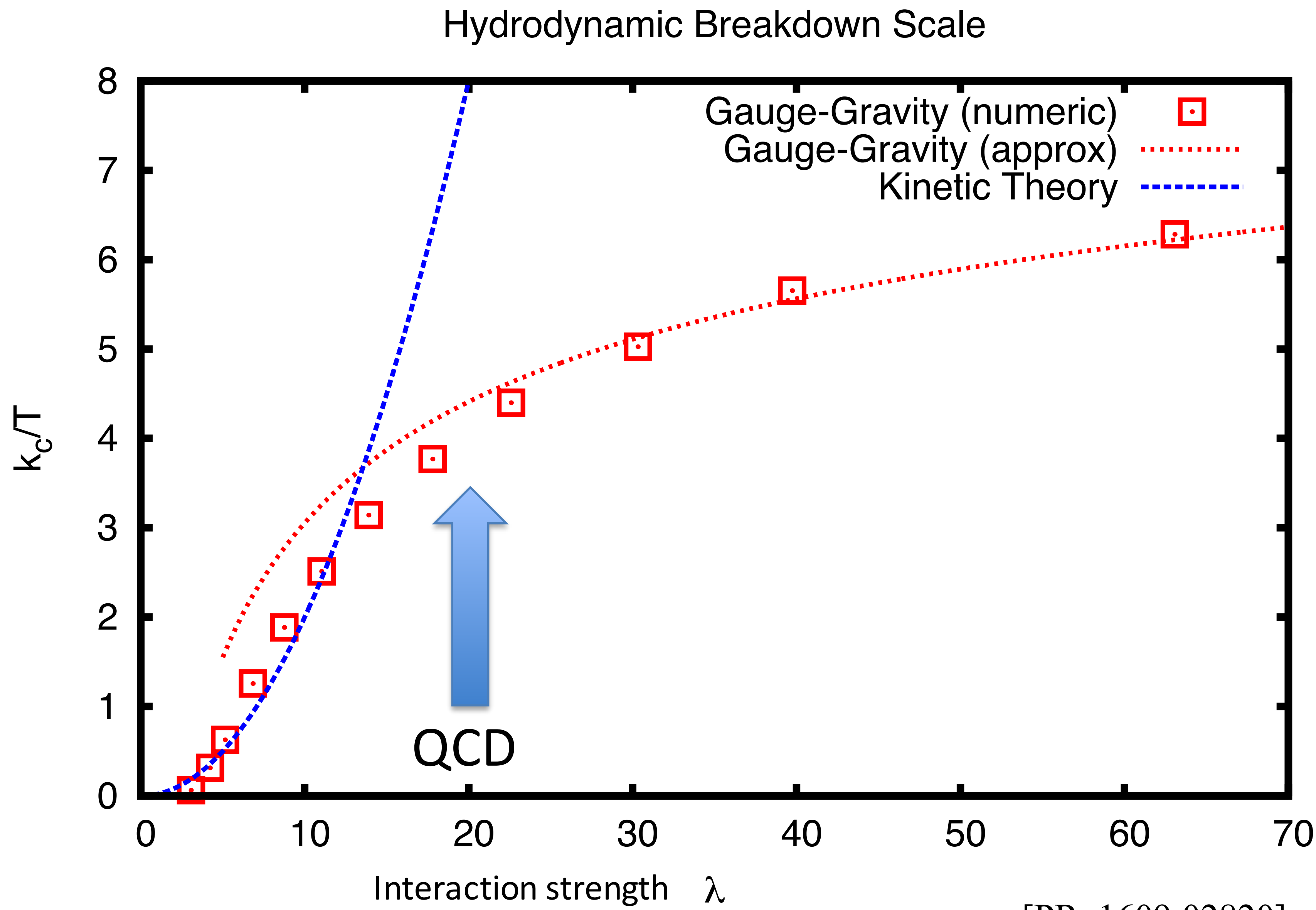

[based on PR, 1512.02641]

# Hydrodynamic Modes disappear above some critical wave number $k>k_c$

Implies: no (not even approximate) hydro description above $k_c$

# “Destruction” of Hydro Modes also in gauge gravity duality

[Grozdanov, Kaplis, Starinets, 1605.02173]




[PR, 1609.02820]

# Implications for Nuclear Collisions

- Non-hydro modes breakdown scale

$$k_c=4\text{-}7\ T$$

$$k_c^{-1}\sim L=(7\ T)^{-1}\sim 0.15\ \text{fm}$$

$$L=0.15\ \text{fm}$$

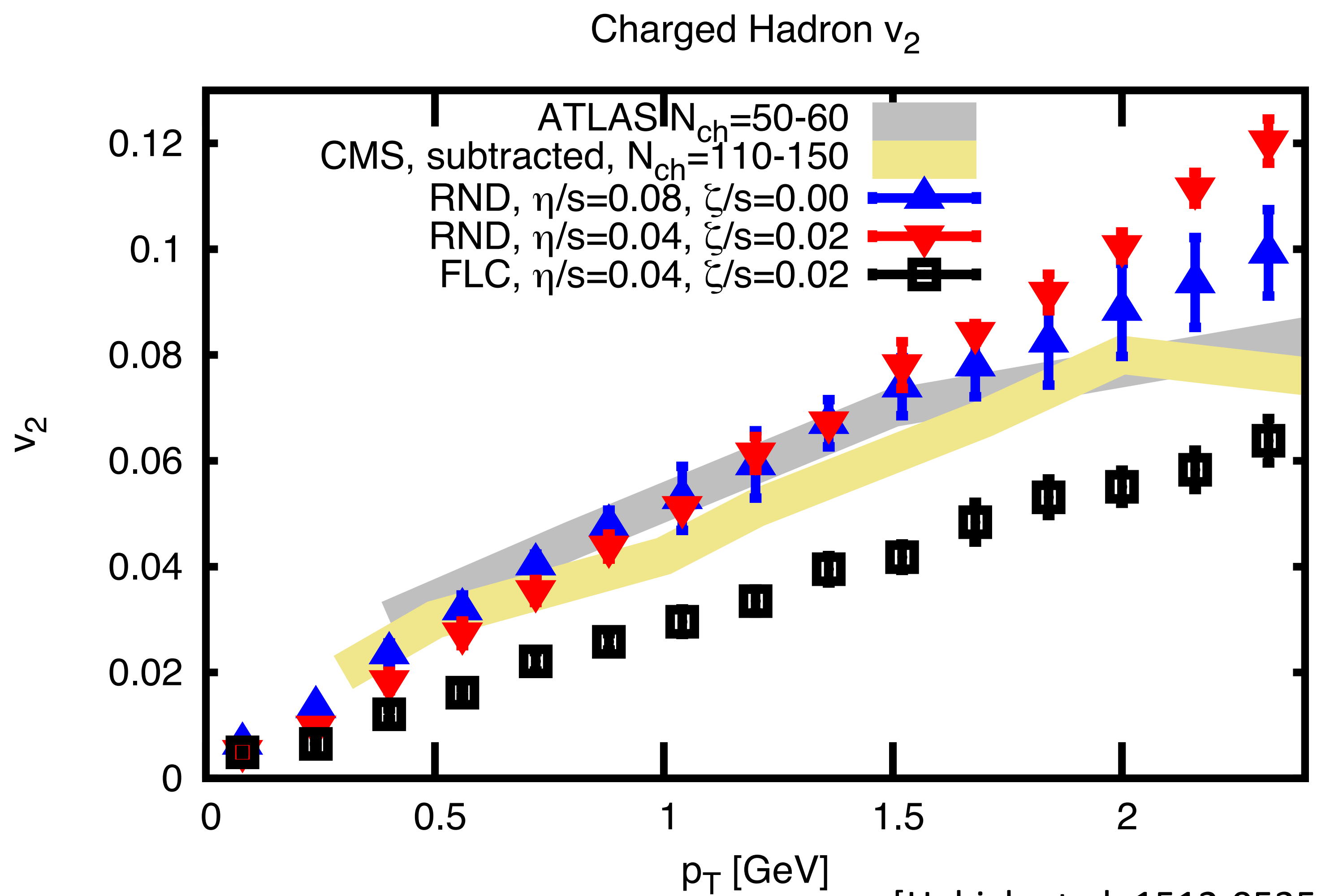
Non-hydro mode argument says hydro has to break down for $L<0.15$ fm

# Implications for Nuclear Collisions

- Smallest QCD liquid drop size L=0.15 fm
- Proton nucleus radius 0.86 fm>>L

Non-hydro mode argument says hydro can work for p+p!

# Hydro for p+p



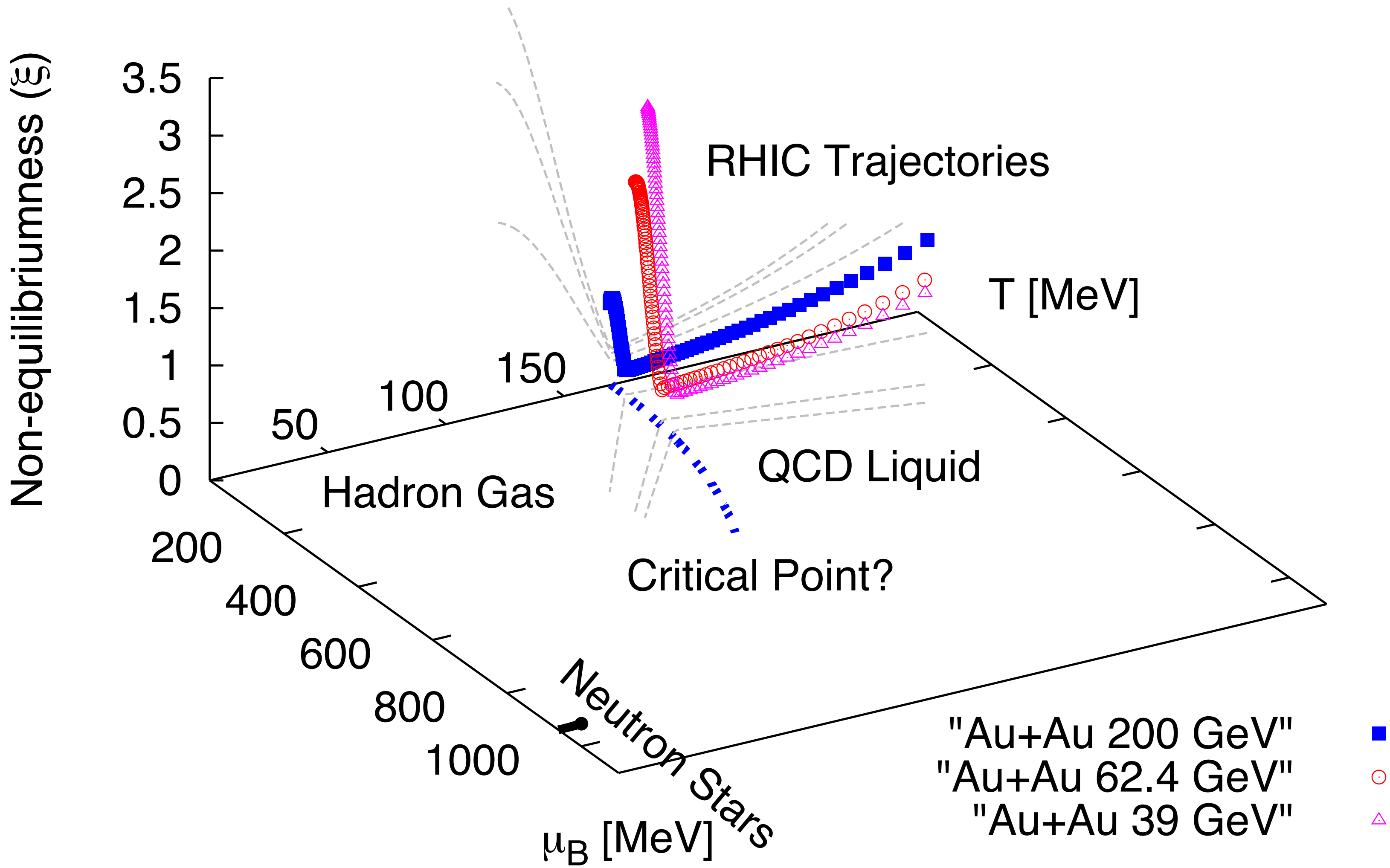

[Habich et al, 1512.05354]

# Further Implications

Hydro applies quantitatively in off-equilibrium situations

The fact that data is well described by hydrodynamics does not indicate the presence of an equilibrated QGP

# Implications for HIC




[PR, 1609.02820]

# Implications for HIC

- Also diffusion is probably working in this way
- E.g. constitutive equation such as $J=\sigma E$ out of equilibrium
- Could explain longer-than-expected lifetime of magnetic field in HICs (good news for CME?)

# Implications for Cosmology?

- Viscous cosmologies: effects from dissipation
- Once viscous effects become interesting, standard hydro picture would say theory has broken down
- New (non-hydro) picture: viscous effects may be order O(1), yet theory still applies if non-hydro modes are subdominant
- May be interesting to look at non-hydro modes in cosmology context

# Conclusions 1/3

- Hydrodynamics applies out of equilibrium for wave numbers $k<k_c$
- Good match of hydro to data is not indicative of equilibrium matter
- In nuclear collisions, we are most likely probing matter not on the QCD phase plane, but in some multi-dimensional non-equilibrium space

# Conclusions 2/3

- Hydrodynamics applies out of equilibrium for wave numbers $k<k_c$
- $k_c$ has been calculated in kinetic theory & gauge/gravity duality, finding $k_c \sim 4\text{-}7\ T$
- This implies that no hydro description is possible for QCD liquid drops smaller than $k_c^{-1}=0.15$ fm

# Conclusions 3/3

- This implies that no hydro description is possible for QCD liquid drops smaller than $k_c^{-1}$=0.15 fm
- Systems created in p+Pb, d+Au, etc have sizes on the order of 10 times $k_c^{-1}$. Hydrodynamics can reasonably be expected to describe these collision systems
- Systems created in p+p have sizes on order 6 times $k_c^{-1}$. Hydrodynamics can reasonably be expected to describe these collision systems

# Afterthought

How do we show the breakdown of hydro, if we need to probe sizes on scales of L~0.15 fm?

**Possible analysis from LEP data looking for collective effects** Inbox x

**Jamie Nagle** <jamie.nagle@colorado.edu> Aug 9

to Stefan, Peter, Dennis.Perepel., Paul, Kenneth

Hello Stefan (cc Peter, Dennis, Paul, Ken),

I was given your contact information from Bill Gary (UCR) as someone who might still have access to analyzing LEP data.

Thank you for your attention!