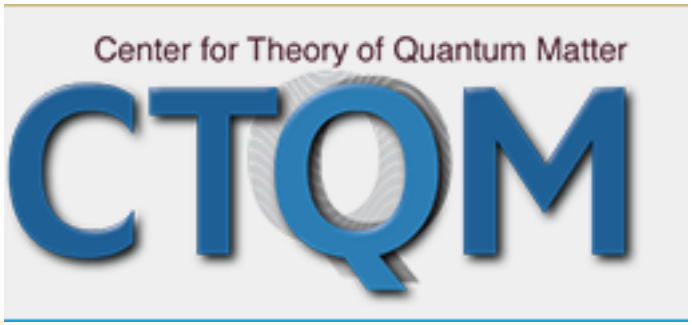
Do nuclear collisions equilibrate?

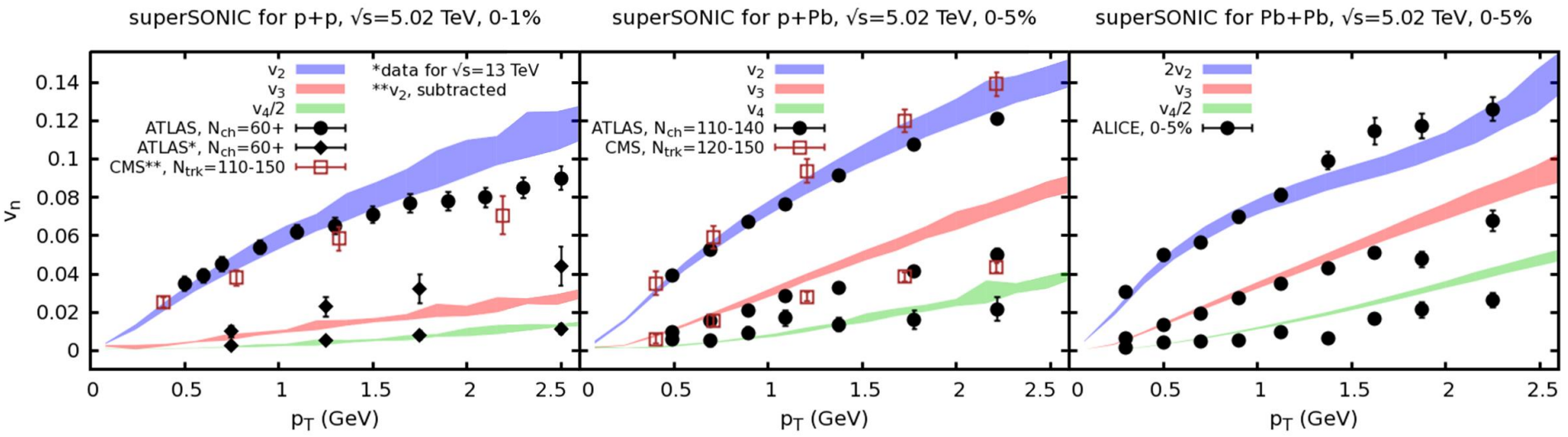
Paul Romatschke



Based on 1609.02820


TODAY'S EVENTS
2017 QUARK MATTER CONFERENCE
Registration 8:00 AM-6:30 PM REGENCY MAIN DESK
5.2 Initial State Physics and Approach to Equilibrium (III) 8:30 AM-10:10 AM REGENCY B
Parallel Session 5.1: Collective Dynamics (I) 8:30 AM-10:10 AM REGENCY A
Parallel Session 5.4: Jets and High pT Hadrons (IV) 8:30 AM-10:10 AM REGENCY D
Parallel Session 6.4: Jets and High pT Hadrons (V) 10:40 AM-12:20 PM REGENCY D
Parallel Session 6.3: New Theoretical Developments (II) 10:40 AM-12:20 PM REGENCY C
Parallel Session 6.1: QCD in small systems (III) 10:40 AM-12:20 PM REGENCY A
Parallel Session 6.2: Correlations and Fluctuations (I) 10:40 AM-12:20 PM REGENCY B
Quark Matter Conference Lunch 12:20 PM-2:00 PM CRYSTAL BALLROOM
Parallel Session 7.4: Open Heavy Flavors (II) 2:00 PM-4:00 PM REGENCY D
Parallel Session 7.1: Baryon-Rich QCD Matter and Astrophysics (II) 2:00 PM-4:00 PM REGENCY A
Parallel Session 7.3: Collective Dynamics (II) 2:00 PM-4:00 PM REGENCY C
Parallel Session 7.2: Correlations and Fluctuations (II) 2:00 PM-4:00 PM REGENCY B
Parallel Session 8.4: Open Heavy Flavors (III) 4:30 PM-6:30 PM REGENCY D
Parallel Session 8.1: Baryon-Rich QCD Matter and Astrophysics (III) 4:30 PM-6:30 PM REGENCY
8.2 Future Experimental Facilities, Upgrades, and Instrumentation 4:30 PM-6:30 PM REGENCY
Parallel Session 8.3: Collective Dynamics (III) 4:30 PM-6:30 PM REGENCY
ALCHOLOICS ANONYMOUS
ALCHOLICS ANONYMOUS 6:00 PM-7:00 PM STETSO

“Unreasonable” success of hydro



[1701.07145, see poster H8 by R. Weller]

- “Blind luck” (?)
- “Full equilibration in p+p” (?)
- something else (?)

What do we know?
versus
What do we believe?

Proof of Saturation

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 τ>6.9 fm if Q_s~1 GeV, α_s~0.3)

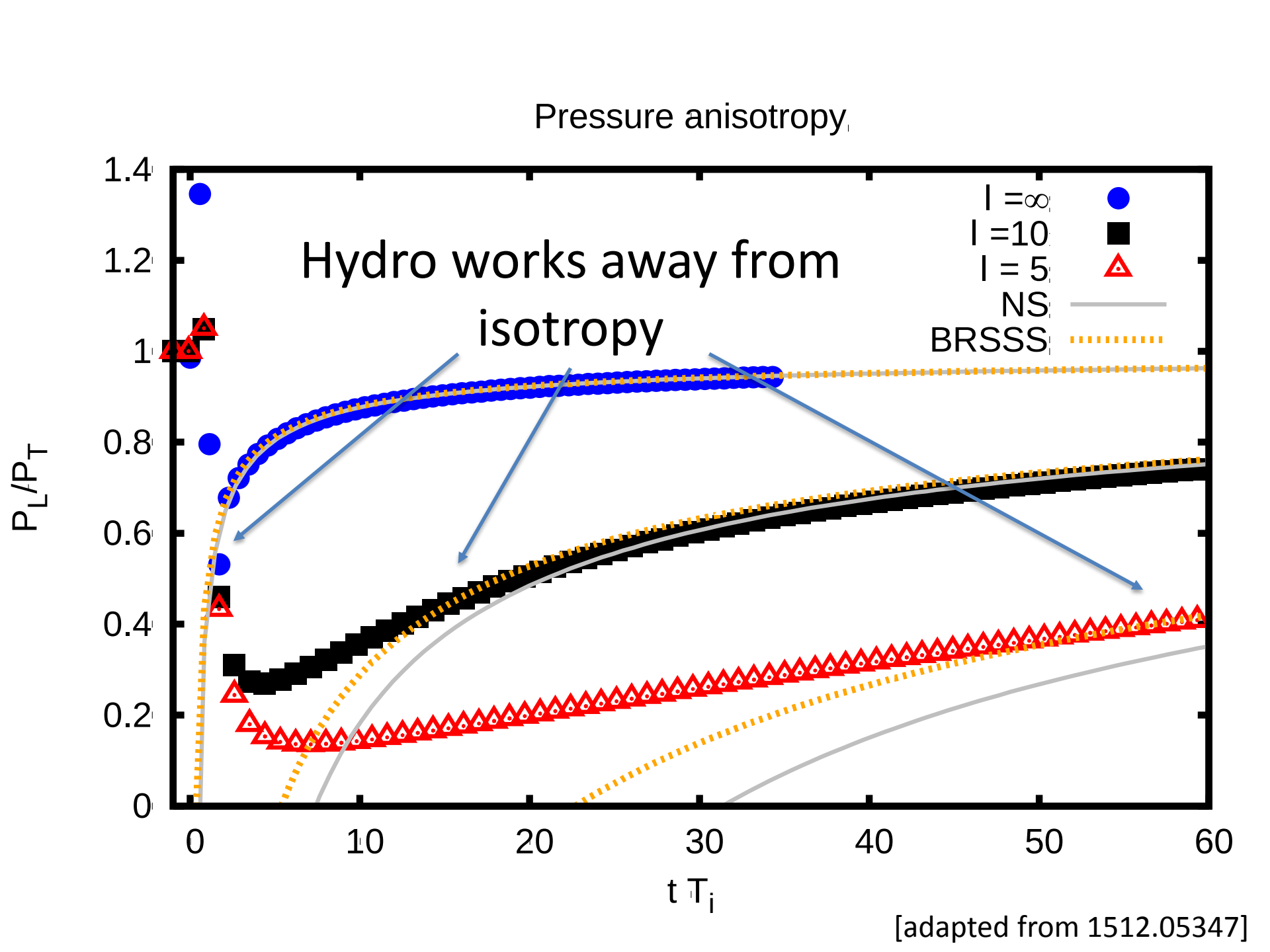
[Baier, Mueller, Schiff, Son, 2001]

When is Hydro applicable?

Answer (version 2005):

Thermal equilibrium not needed. Local isotropy will suffice, e.g. $T^{ab}=\mathrm{diag}(\varepsilon,p,p,p)$

[Arnold, Lenaghan, Moore, Yaffe, 2005]



[adapted from 1512.05347]

When is Hydro applicable?

- Empirical Fact: Hydro works quantitatively even for anisotropic systems
- Onset of quantitative hydro description unrelated to thermalization or isotropization
- New type of phenomenon ("hydrodynamization"=onset of hydro behavior)

[Casalderrey-Solana, Liu, Mateos, Rajagopal, Wiedemann, 1101.0618]

When is Hydro applicable?

Hydro as an EFT

- Many derivations of hydro equations
- Most general approach: 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
- 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)

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

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

[1302.0697, 1503.07514, 1603.05344, 1608.07869, 1609.04803]

Hydro as an EFT

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

$$T(\tau) = T_{\text{hydro}}(\tau) + \gamma \exp\left[-i \int d\hat{\tau} \left(\hat{\omega}_{\text{Borel}} \hat{\tau}^{-1/3} + \sum_{n=1} \hat{\omega}_n \hat{\tau}^{-(2n+1)/3} \right]\right) + \dots$$

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

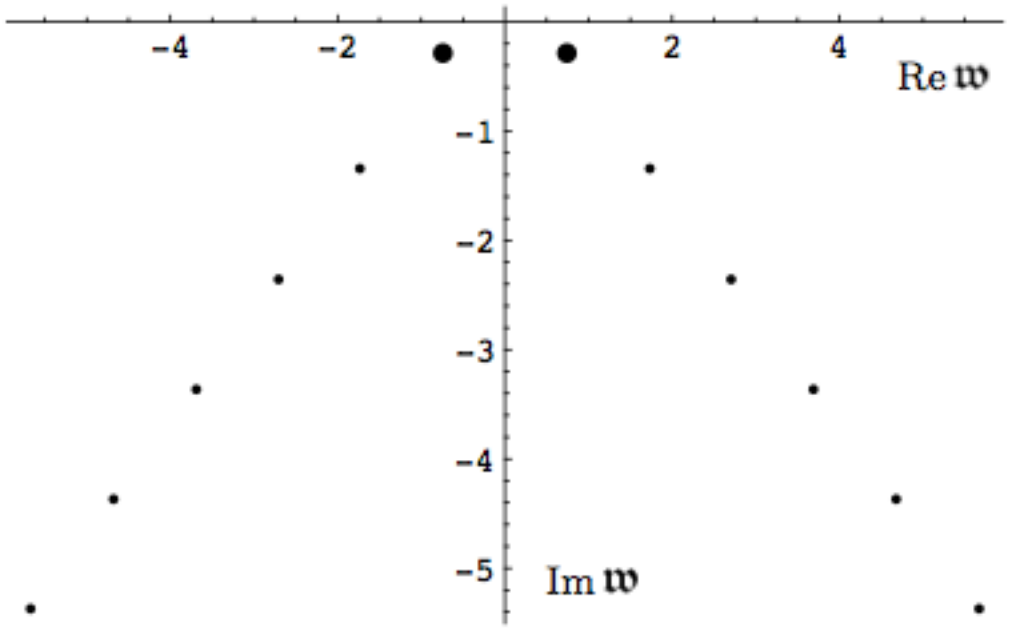
Hydro as an EFT

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

$$\gamma \exp\left[-i \int d\hat{\tau} \left(\hat{\omega}_{\text{Borel}} \hat{\tau}^{-1/3}\right)\right]$$

- $w_{\text{Borel}} = \pm 3.1193 - 2.7471\, i$ [Heller et al, 1302.0697]
- $w_{\text{QNM}} = \pm 3.119 - 2.747 i$ [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.

We know:
Hydro works even out of equilibrium

Implications

Hydro matching data does not indicate the presence of an equilibrated QGP

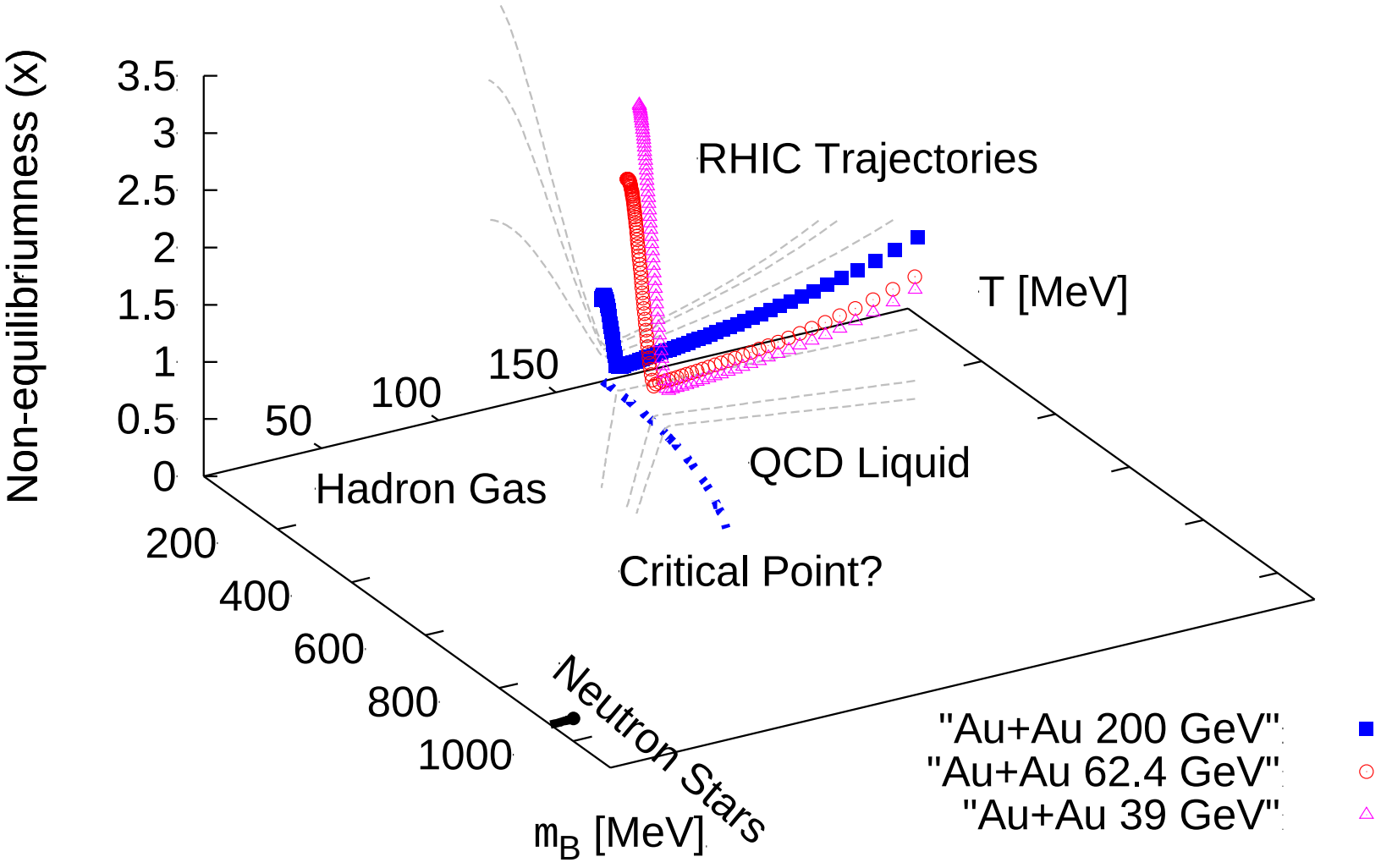
Implications

Hydro does not mean equilibrium

Do nuclear collisions equilibrate?

Let’s check: use hydro to measure “non-equilibriumness”

Implications for HIC



[PR, 1609.02820]

We know:
Nuclear collisions always out-of-equilibrium!

Not new: This has been known to all hydro practitioners for a decade

Do nuclear collisions equilibrate?

No

Reaction from Colleagues

If someone looks like crocodile and behaves like crocodile,
then it is crocodile

You can’t just say no??

This is a very destructive attitude!

Does this mean we should all go home now?

- No equilibration, no problem:
- Can probe non-equilibrium QCD
- Extreme experimental hydrodynamics: flow in small systems (did anyone check e^+ e^- yet?)
- Can study non-hydro modes in QCD

Nuclear collisions are much richer subject than expected a decade ago!

Thank you for your attention

[you may go home now]

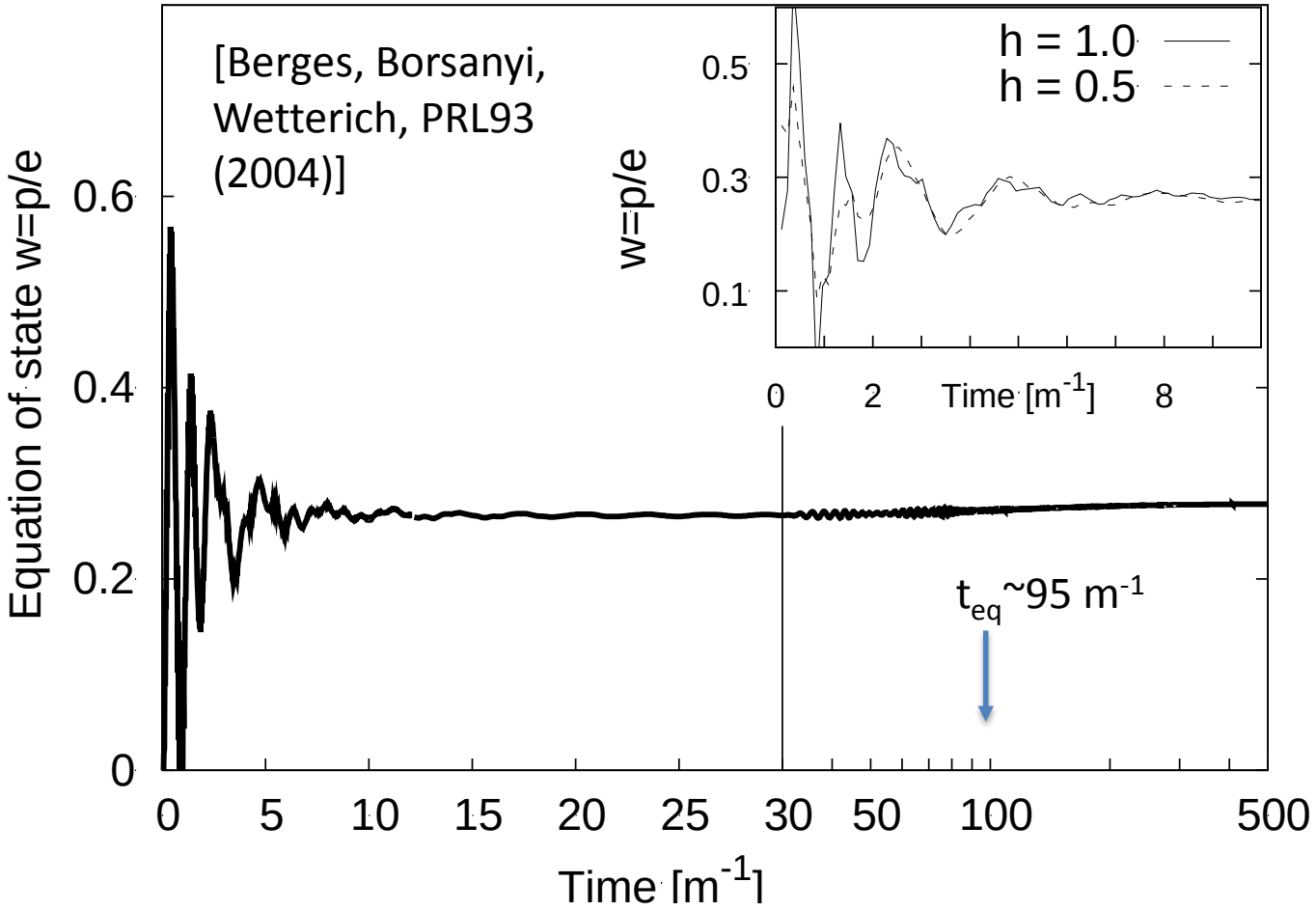
Bonus Material

What about the EoS?

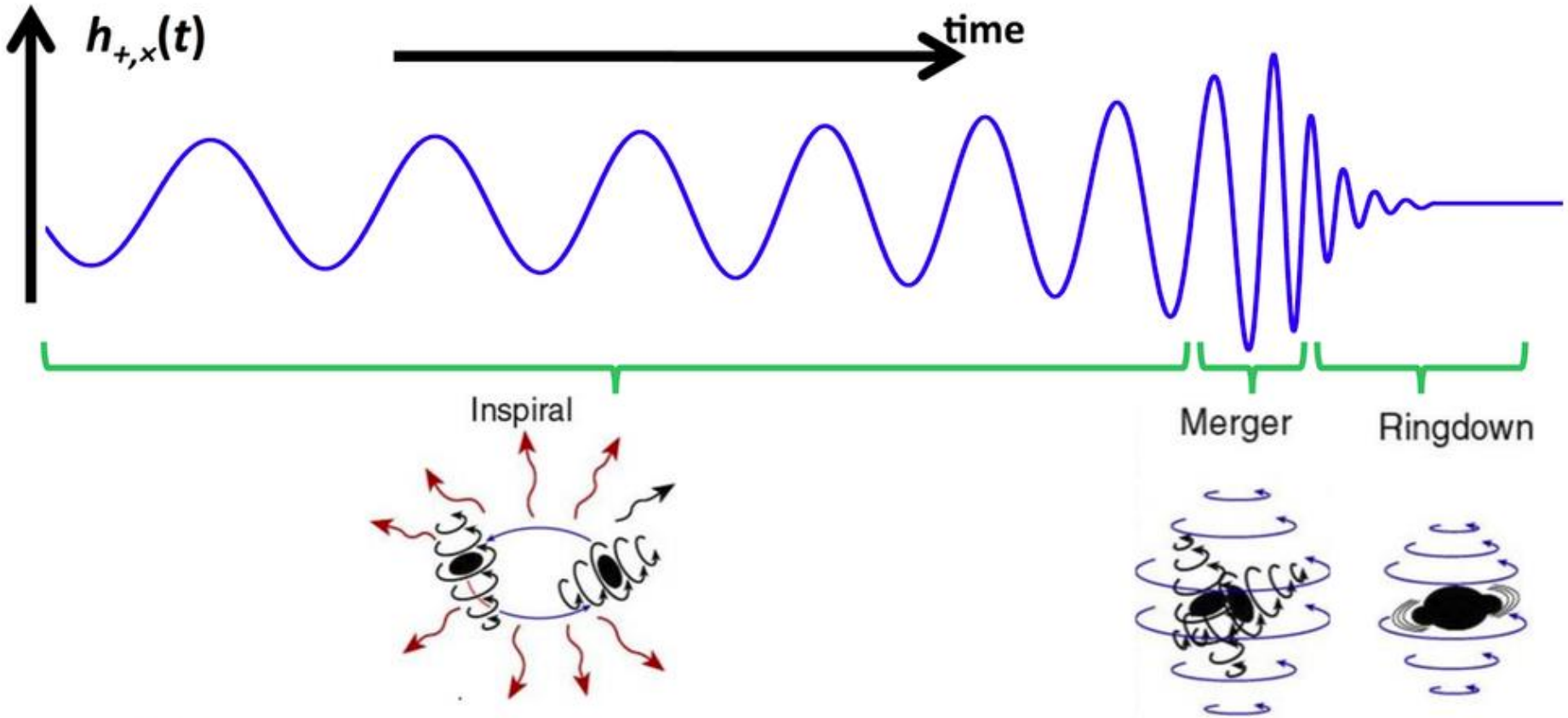
- Hydro equations need EoS to close
- In equilibrium, can take lattice QCD EoS
- Do we have an EoS out of equilibrium?

EoS out of equilibrium

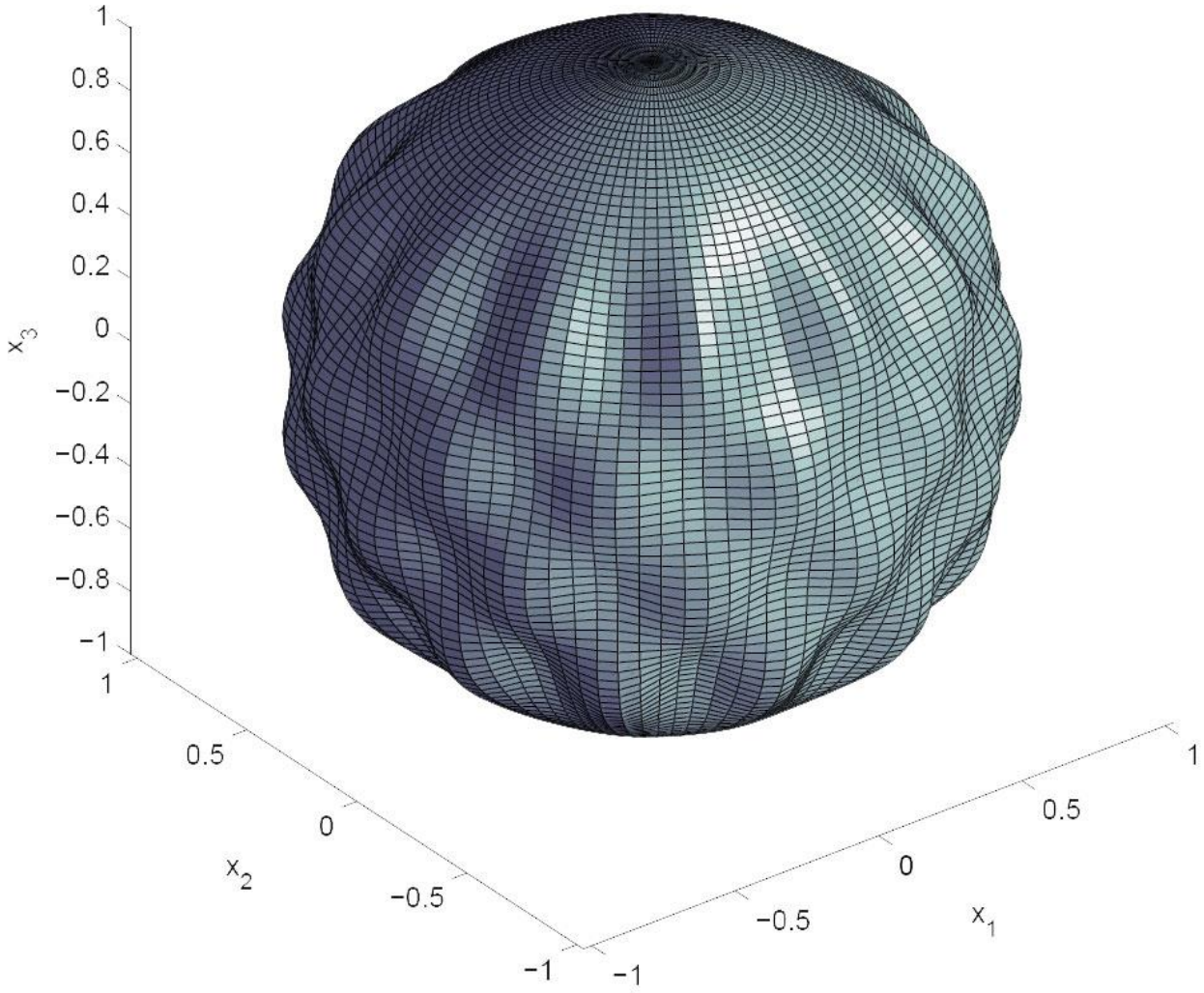
"Pre-thermalization": EoS establishes to equilibrium value on timescales dramatically shorter than equilibration time



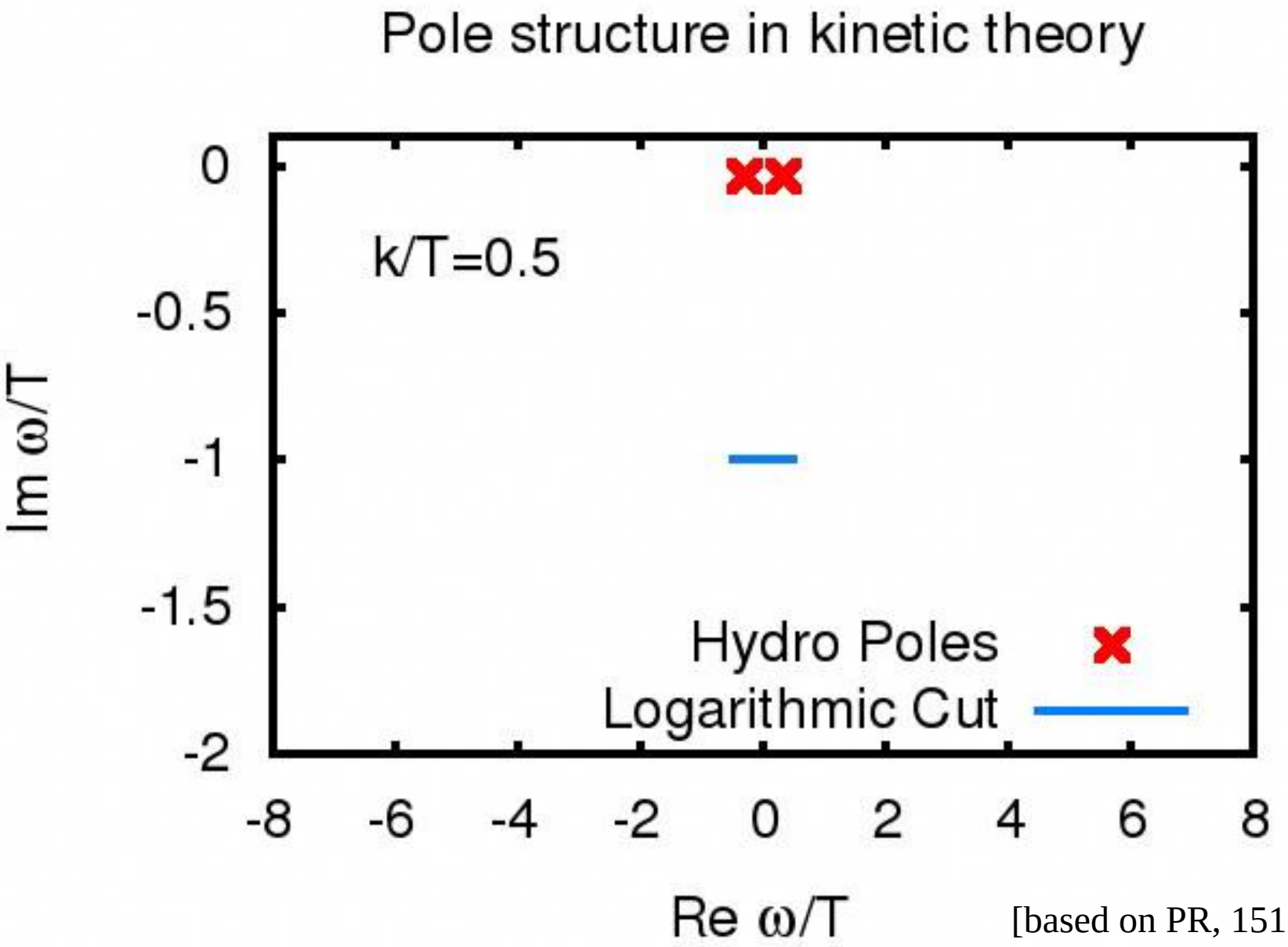
What are non-hydro modes?



Quasi-Normal Modes



When do non-hydro modes become important?



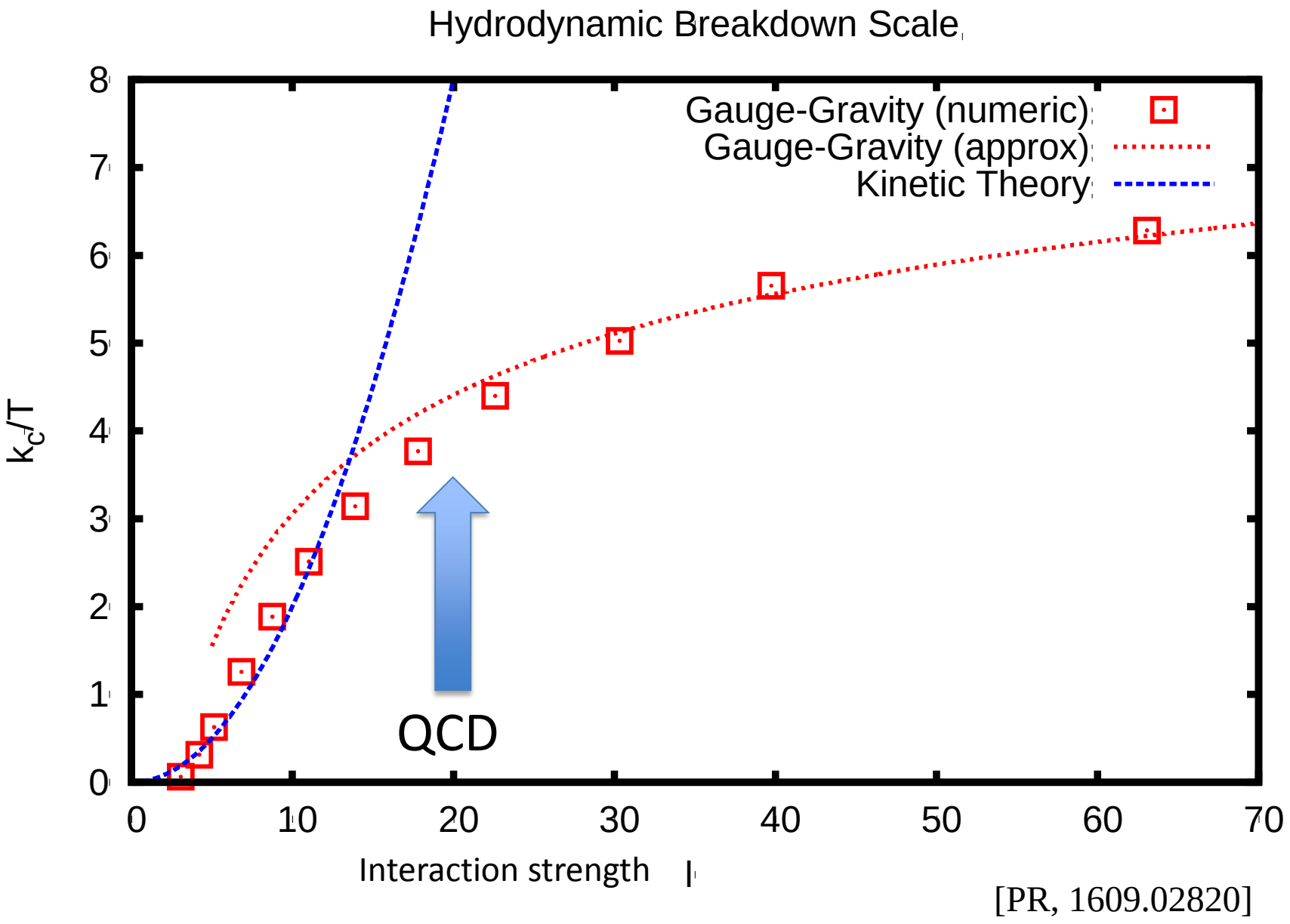
[based on PR, 1512.02641]

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!

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