Creating QCD plasma droplets in p+p collisions at the LHC

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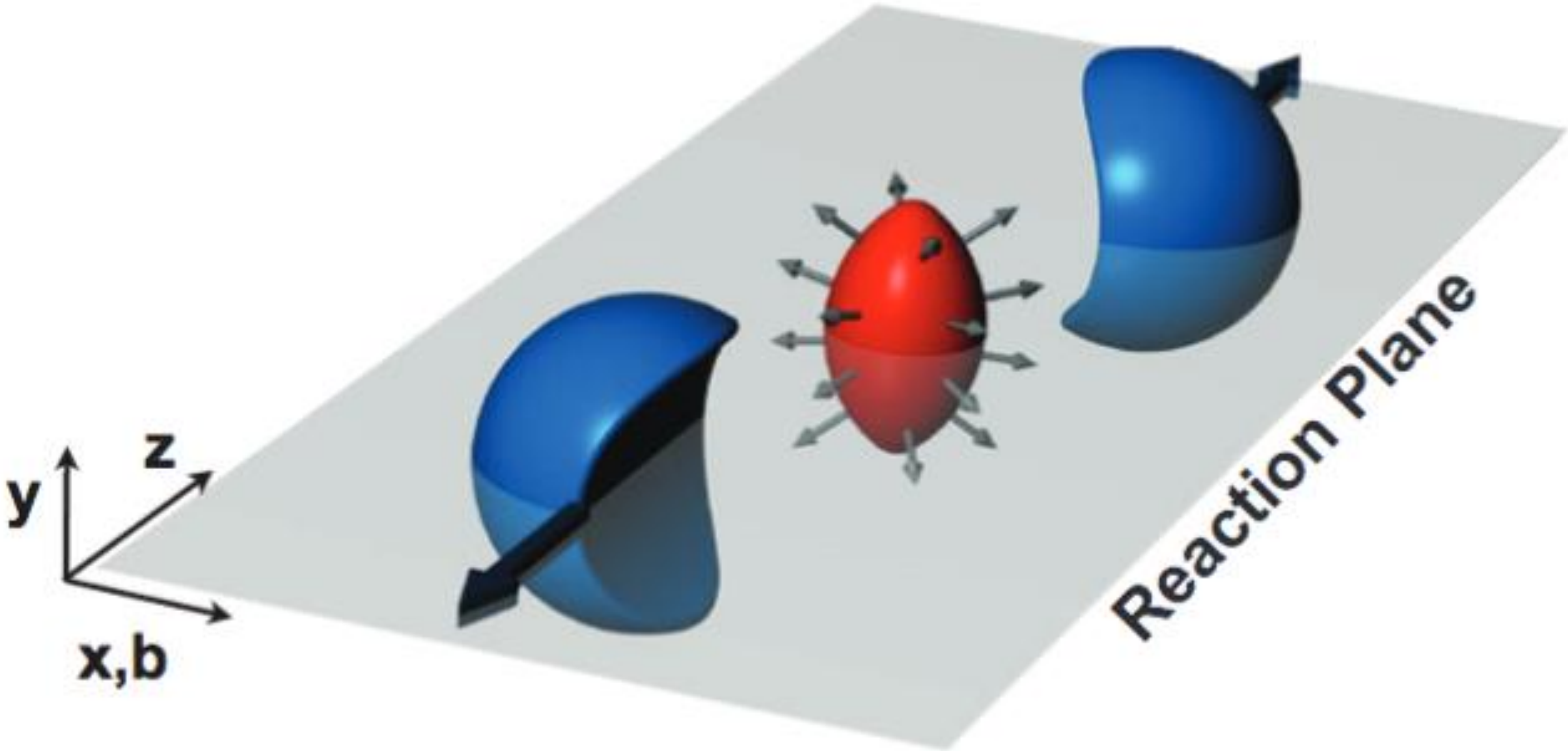
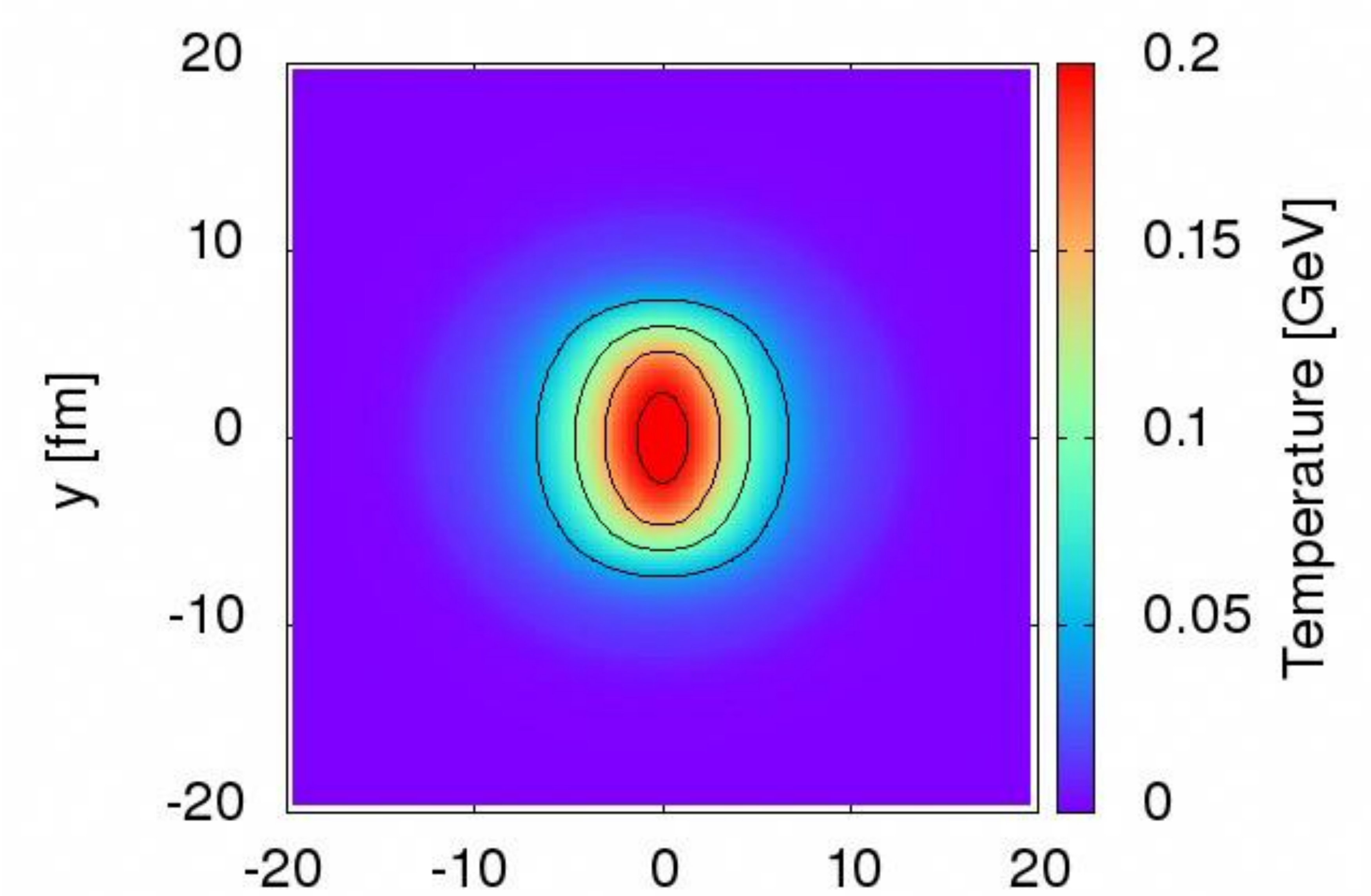
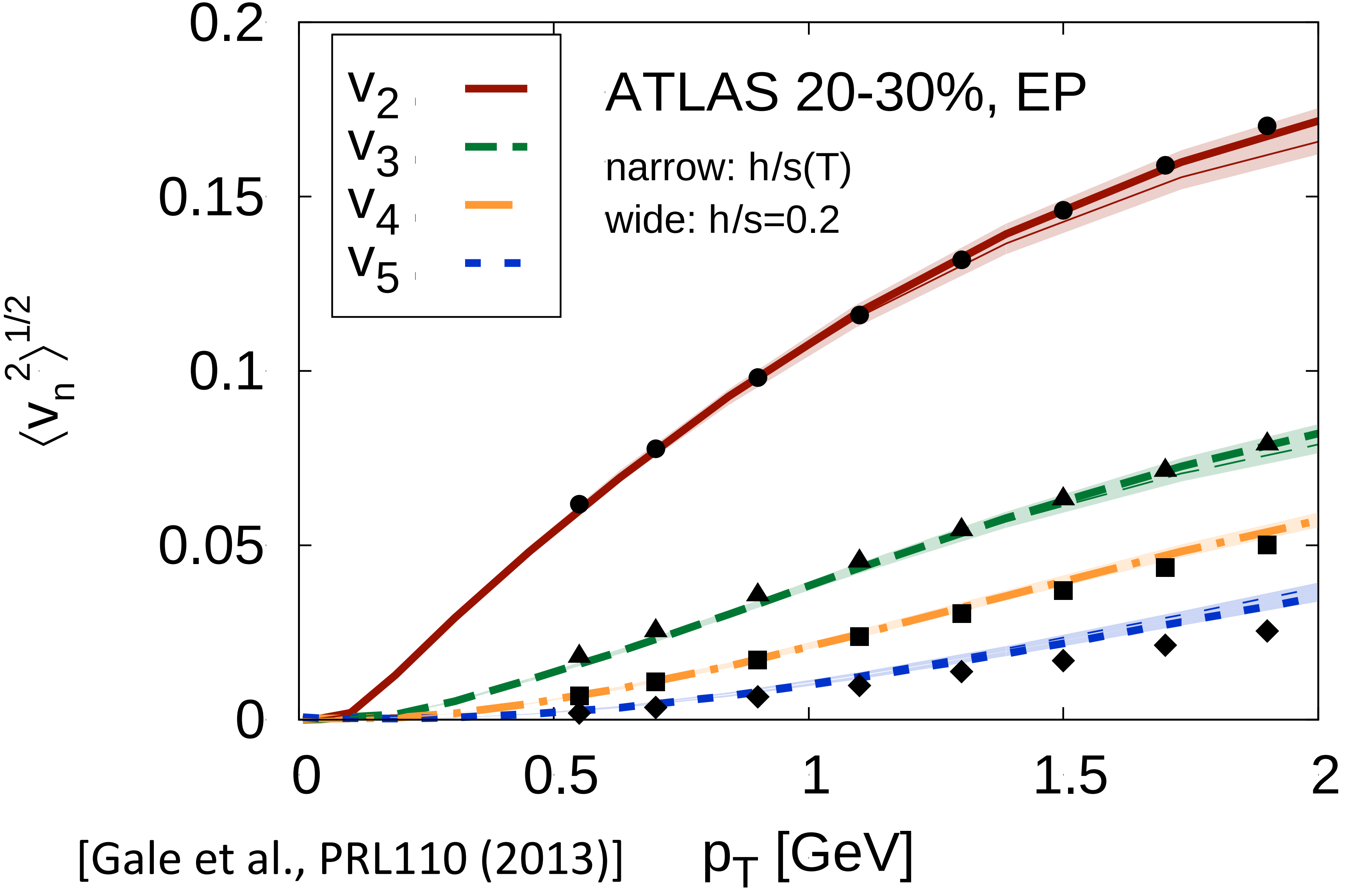
Review: Geometry & Correlations in Pb+Pb



[Snellings, 1102.3010]

Hydrodynamics converts geometry to flow





[Gale et al., PRL110 (2013)]

p_T<2 GeV:
"Soft Physics"

Main evidence for QCD matter in Pb+Pb

Selected Soft Physics Talks at EPS-HEP ‘17

- Multi-particle flow cumulants $v_n\{m\}$ (talk by Bold)
- Flow of heavy flavor (talk by Milosevic)
- Rapidity information (talk by Alam)
- Low collision energies (talks by Lipiec , Grebieszkow, Levai)
- Collisions of light ions: p+Pb and p+p (talk by Bernades, …)
- Early time-dynamics (talks by Mueller, Tanji)
- EW bosons in Pb+Pb (talk by Perepelitsa)
- ALICE highlights (plenary by Floris)

Frontiers of the field:
Going forward, going small

[Schenke, QM’17]

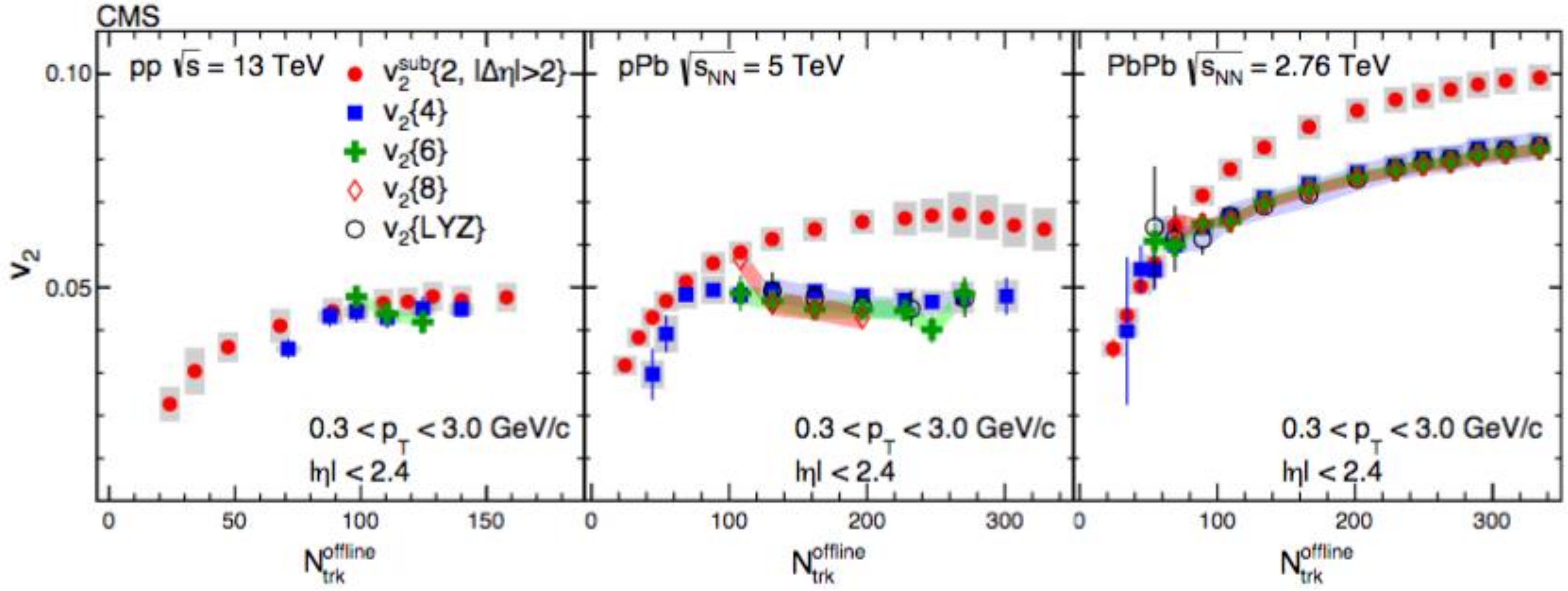
Focus of this talk: going small

Consensus: flow in Pb+Pb due to hydrodynamics

Traditional view:

- QGP in Pb+Pb
- no QGP in p+p ("baseline")

Purely Experimental Finding



Flow similar in magnitude in all systems

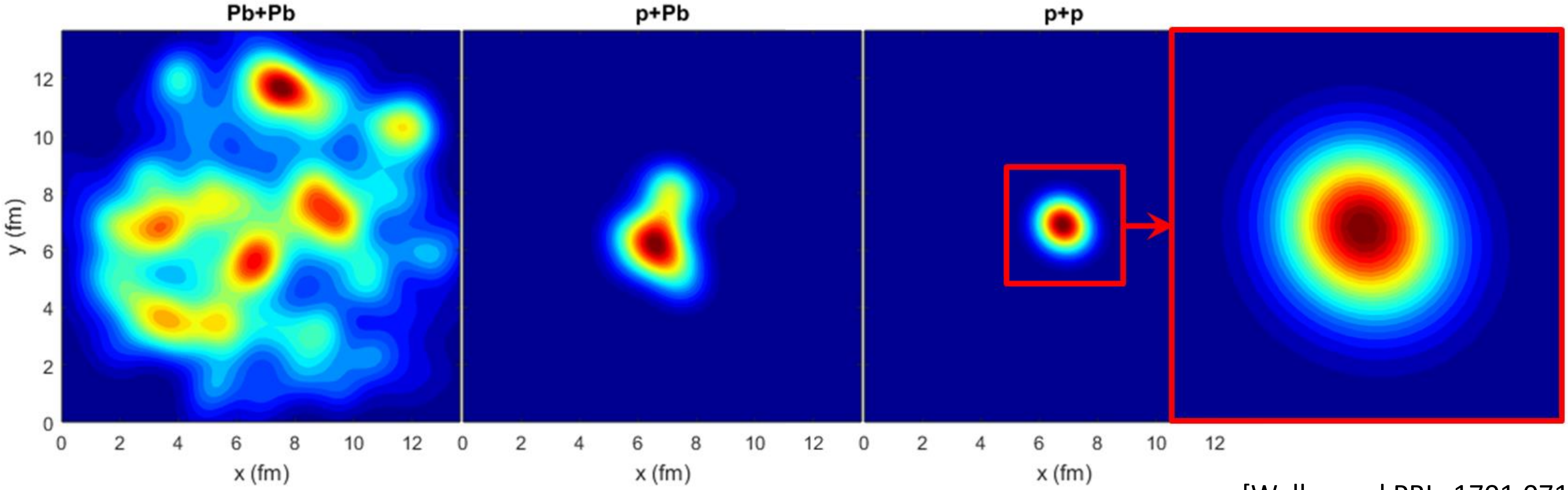
[CMS, 1606.06198]

Consensus: flow in Pb+Pb due to hydrodynamics

What if there is a fluid droplet also in (min-bias) p+p?

Assuming hydro to be applicable, how would hydro signal compare to exp' data?

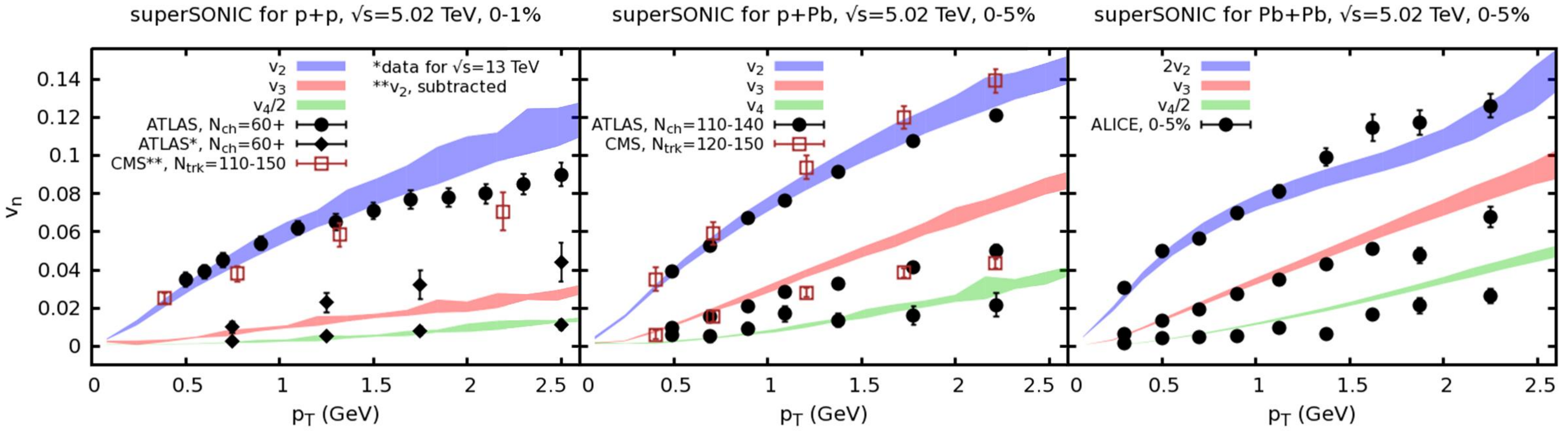
One fluid to rule them all



[Weller and PRL, 1701.07145]

Same fluid setup for Pb+Pb, p+Pb and p+p (same ICs, same viscosity, same numerics) *assuming hydro to be applicable*

One fluid to rule them all

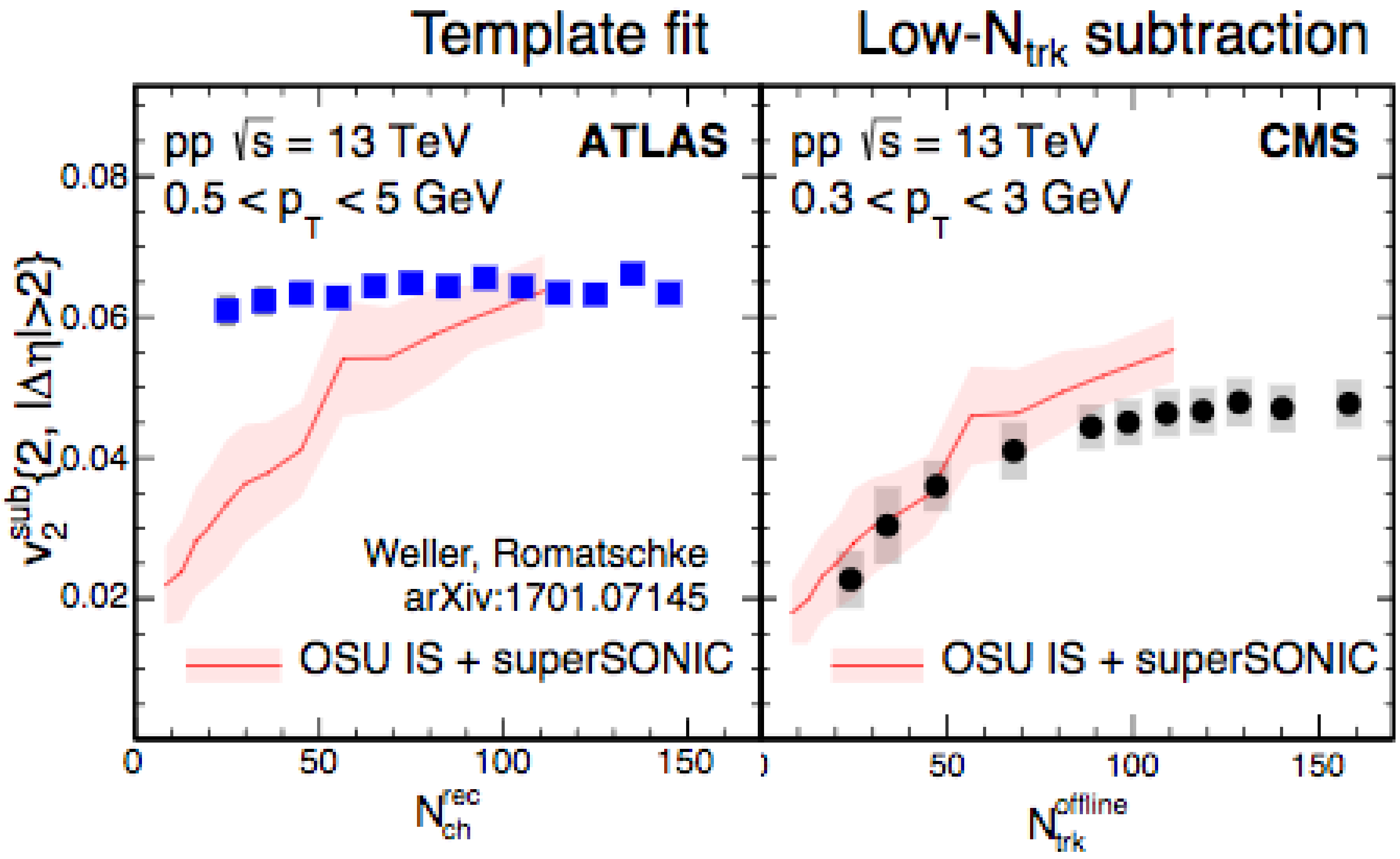


Hydro in pp empirically successful

assuming hydro to be applicable

[Weller and PRL, 1701.07145]

Hydro describes (CMS) data down to min-bias p+p



[Wei Li, **Workshop on Collectivity in Small Collision Systems**, NBI May 2017]

Finding

Hydro successfully describes min-bias p+p experimental flow data "out of the box"

Recall: Min-bias p+p used to be reference (also for HEP!)
Recall: successful hydro description main evidence of QGP in Pb+Pb

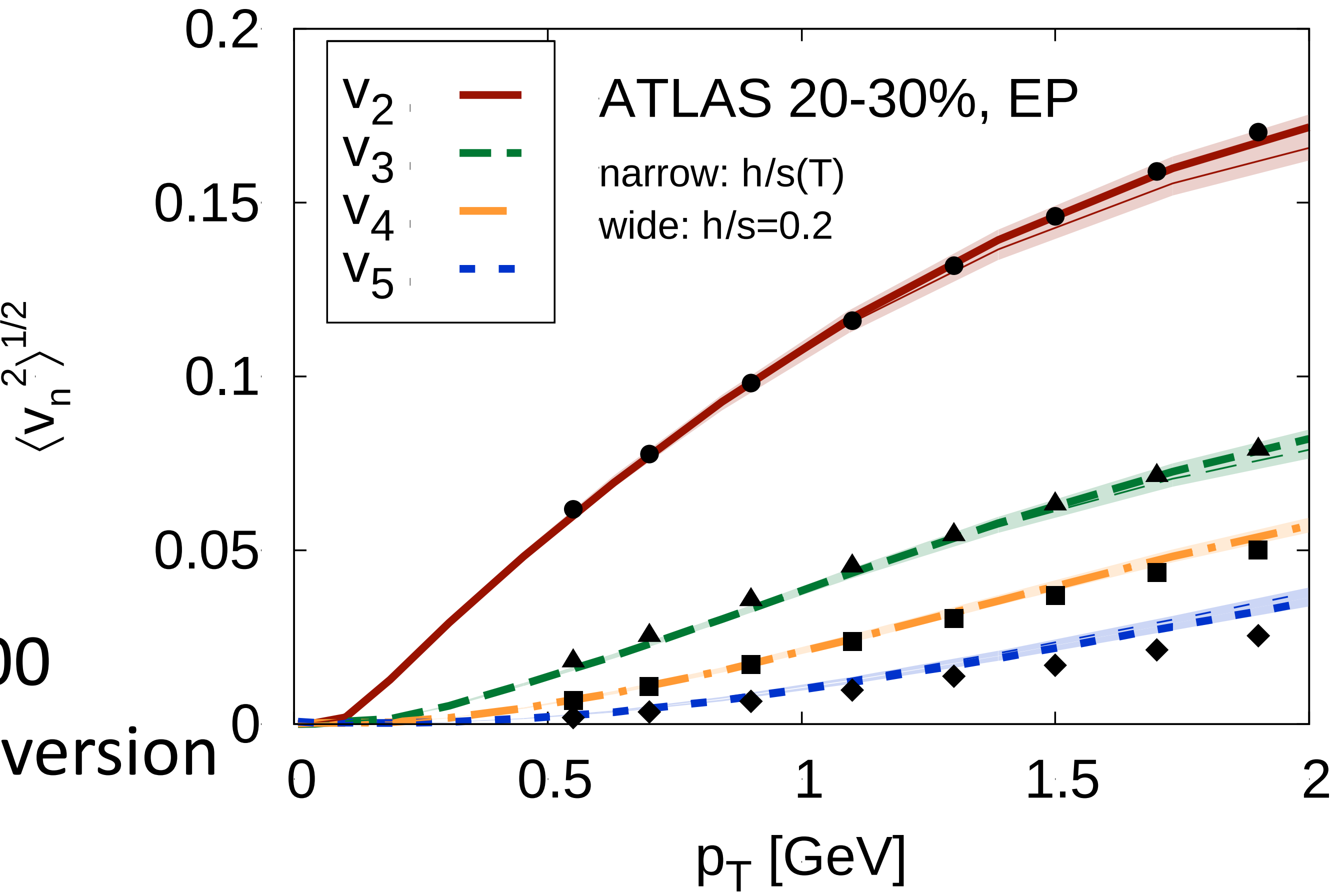
Is there a QCD fluid droplet in p+p?

Or should we revisit the hydro paradigm for ***all*** systems???

Pb+Pb: hydrodynamics describes flow

Main evidence for
QCD matter in Pb+Pb

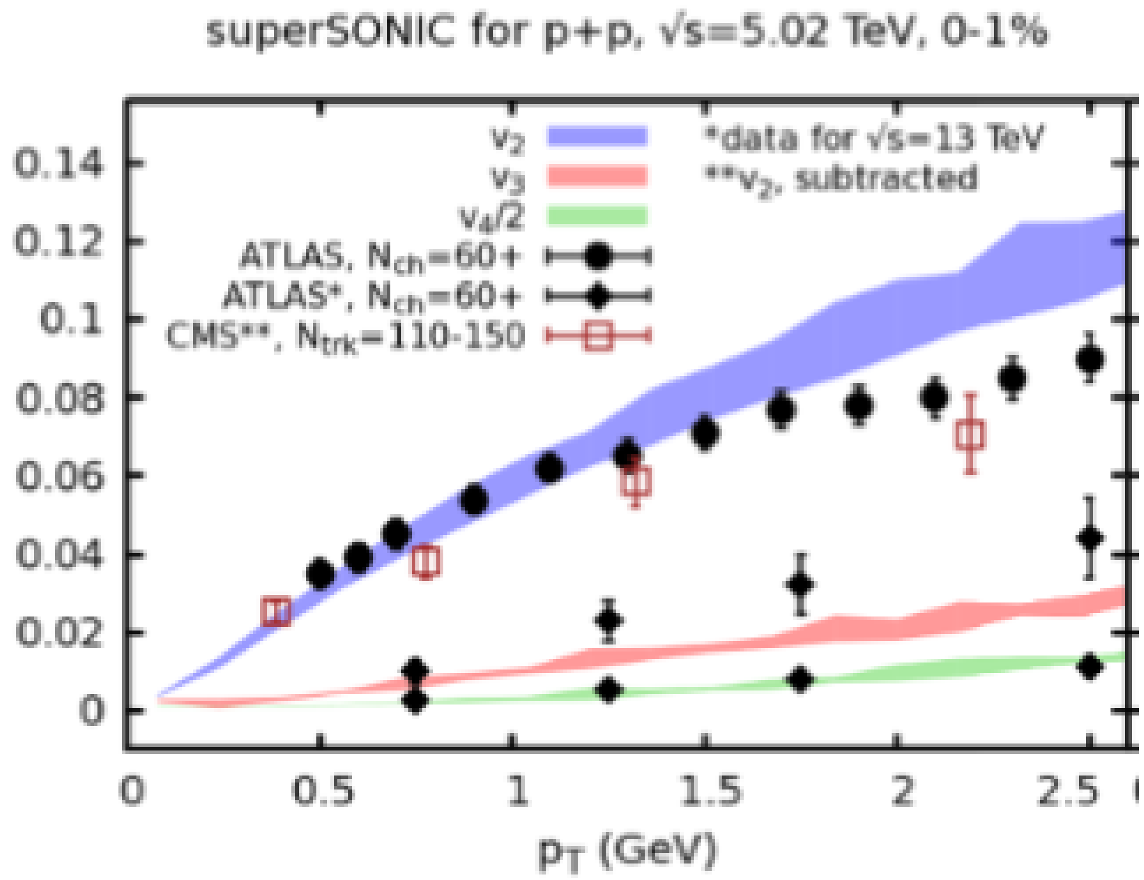
“Large” system: V~100 fm^3
Many particles: dN/dy~1000
Flow=geometry+hydro conversion



[Gale et al., PRL110 (2013)]

p+p: hydrodynamics describes flow

Small system: V~1 fm^3
Few particles: dN/dy~5
Flow=fluctuations+hydro conversion



[Weller and PR, 1701.07145]

Objections to applying hydro to (min-bias) p+p

- Too few particles, cannot be collective
- System not in equilibrium (too small)

Objections to the Objection

Hydro does not apply to 5 particles

True

Irrelevant

If QCD droplet gets created in pp, dofs are QCD fields, not hadrons.

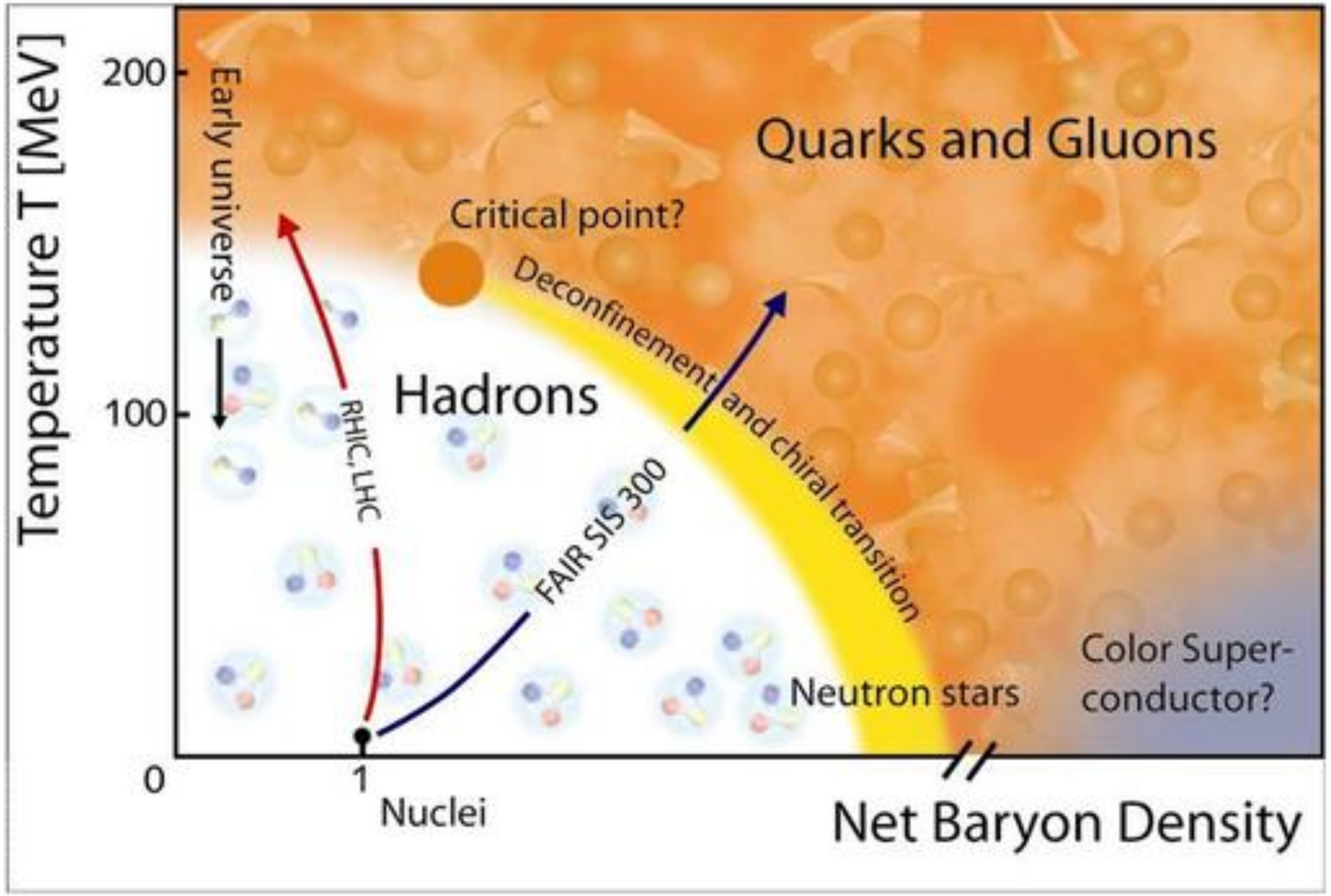
Known to have hydro behavior for strongly interacting fields without particles (e.g. AdS/CFT)

Final state particles get imprinted with hydro correlations even if 5 particles could not form correlations themselves.

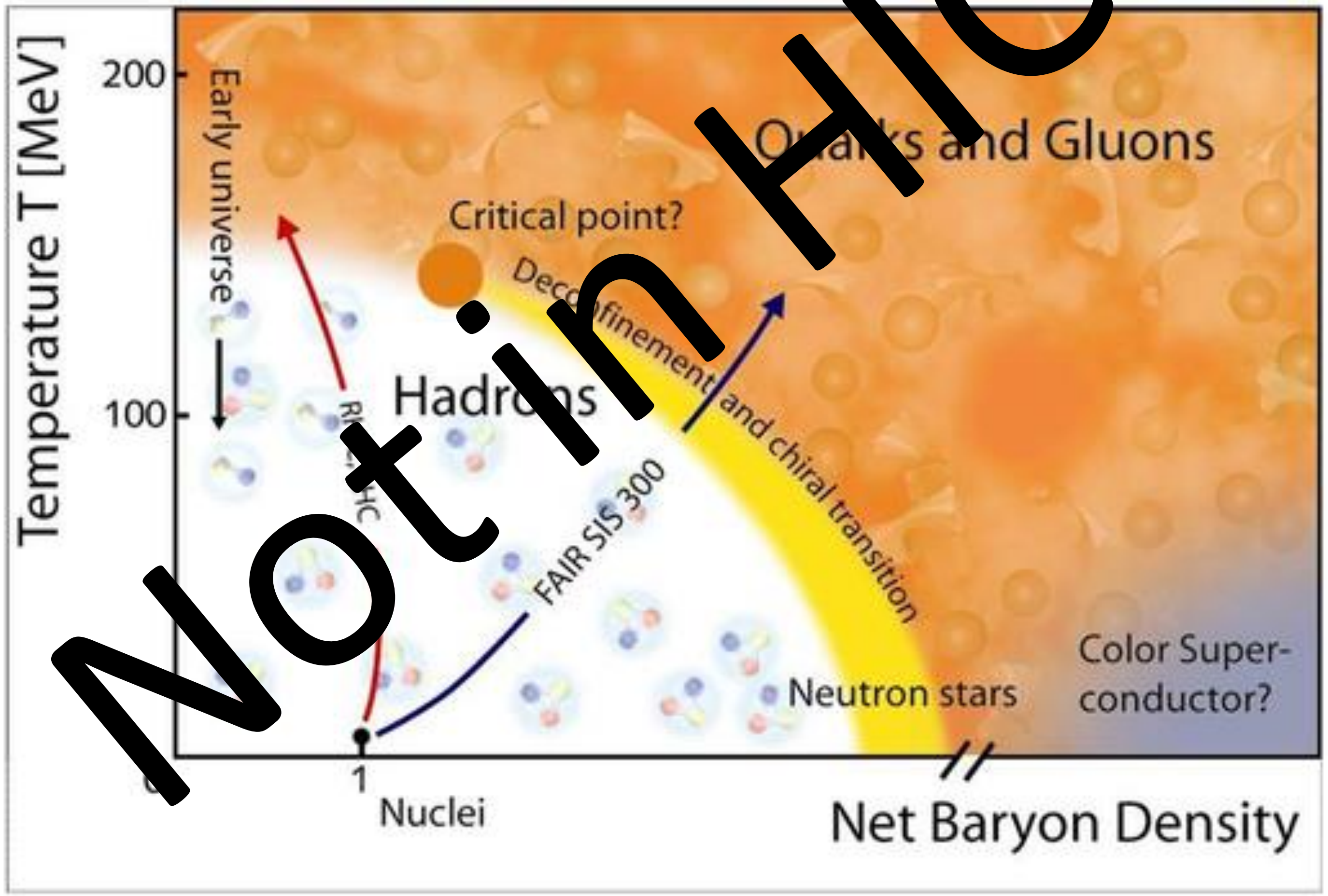
Objections to applying hydro to (min-bias) p+p

- ~~Too few particles, cannot be collective~~
- System not in equilibrium (too small)

Traditional QCD Phase Diagram

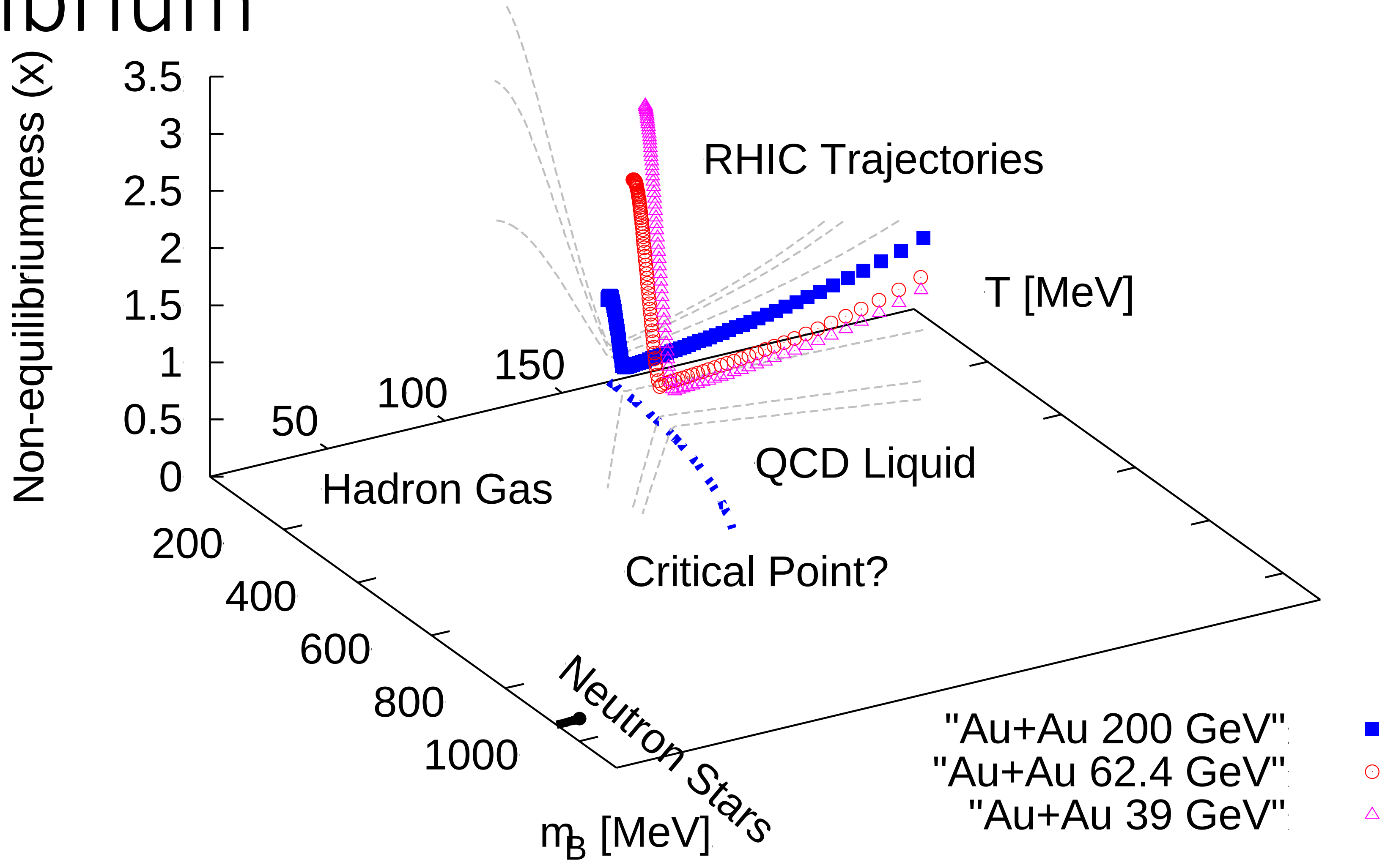


Traditional QCD Phase Diagram



Not in HIC!

Heavy-Ion Experiments are Out-of-Equilibrium



[1609.02820]

Finding

Even Heavy Ion Collisions are Out-Of-Equilibrium, but hydrodynamics is able to describe data

This trivially “solves” the “Early Thermalization Puzzle”: collisions simply do not thermalize. Ever.

Objections to applying hydro to (min-bias) p+p

- ~~Too few particles, cannot be collective~~
- ~~System not in equilibrium (too small)~~

Theory basis for applicability of hydrodynamics

Hydrodynamics requires near equilibrium ("thermalization") to be applicable

This is the textbook requirement.

Are the textbooks really correct?

Hydro as an 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

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

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

Gradient expansion example

- What if we had LARGE gradients?
- Example: $f(x)=e^x$, for $x \sim 1$
- $f(x) \sim 1+x+x^2/2+x^3/3!+x^4/4!\ldots$
- $f(1) \sim 1+1+1/2!+1/3!+1/4!=2.70833 \sim 2.71828=e^1$
- Works for any value of x because gradient expansion converges (but may need high gradient order)

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]

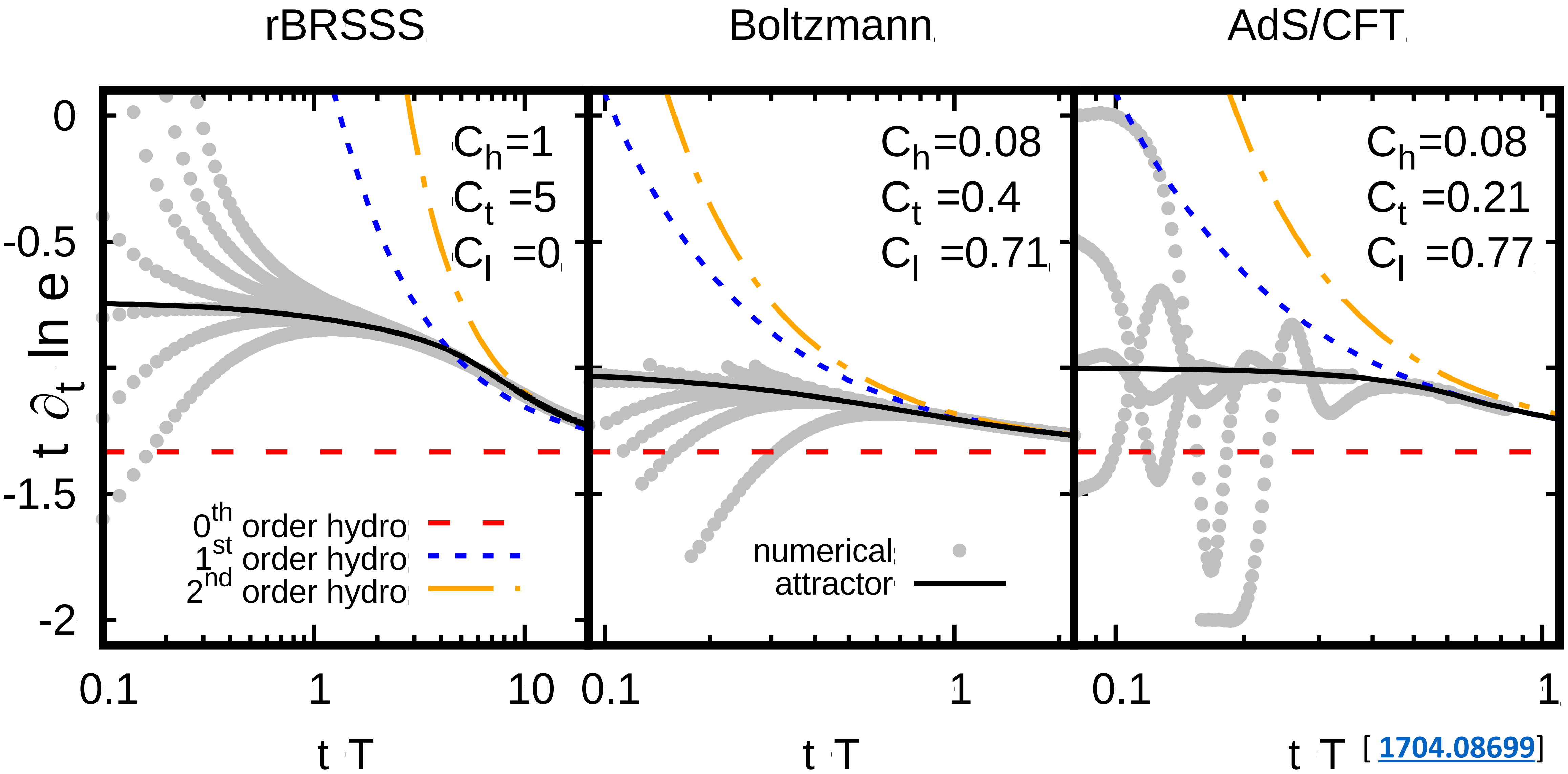
Hydro as an EFT

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

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

- T_{hydro} is "hydrodynamic attractor solution"
- Extra pieces non-analytic in gradient expansion; this is why grad series diverges!

‘Borel-resummation’ : attractor solutions far from equilibrium



[1704.08699]

Finding

Hydrodynamics applies as long as non-hydro modes can be neglected

[PR, 1609.02820]

No need of thermal equilibrium.

Truly new development "hydrodynamization" [Casalderrey-Solana, Liu, Mateos, Rajagopal, Wiedemann, 1101.0618]

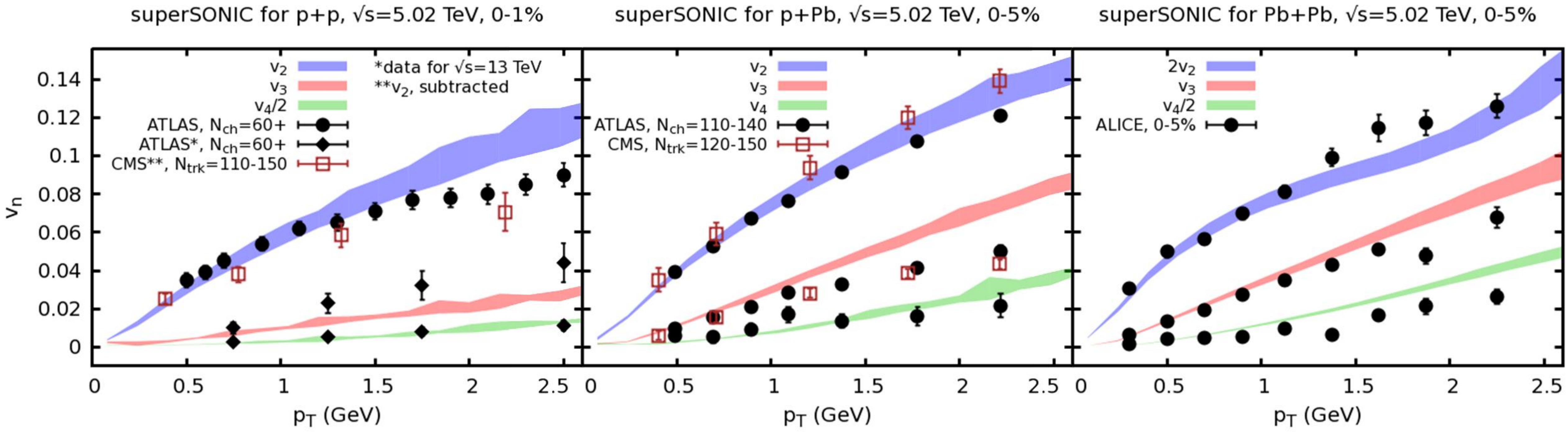
Maybe time to update textbooks???

Finding

Low Order Hydrodynamics coincides with Attractor Solutions for moderate Gradients

This explains why low-order hydrodynamics works quantitatively out-of-equilibrium!

One fluid to rule them all



[1701.07145]

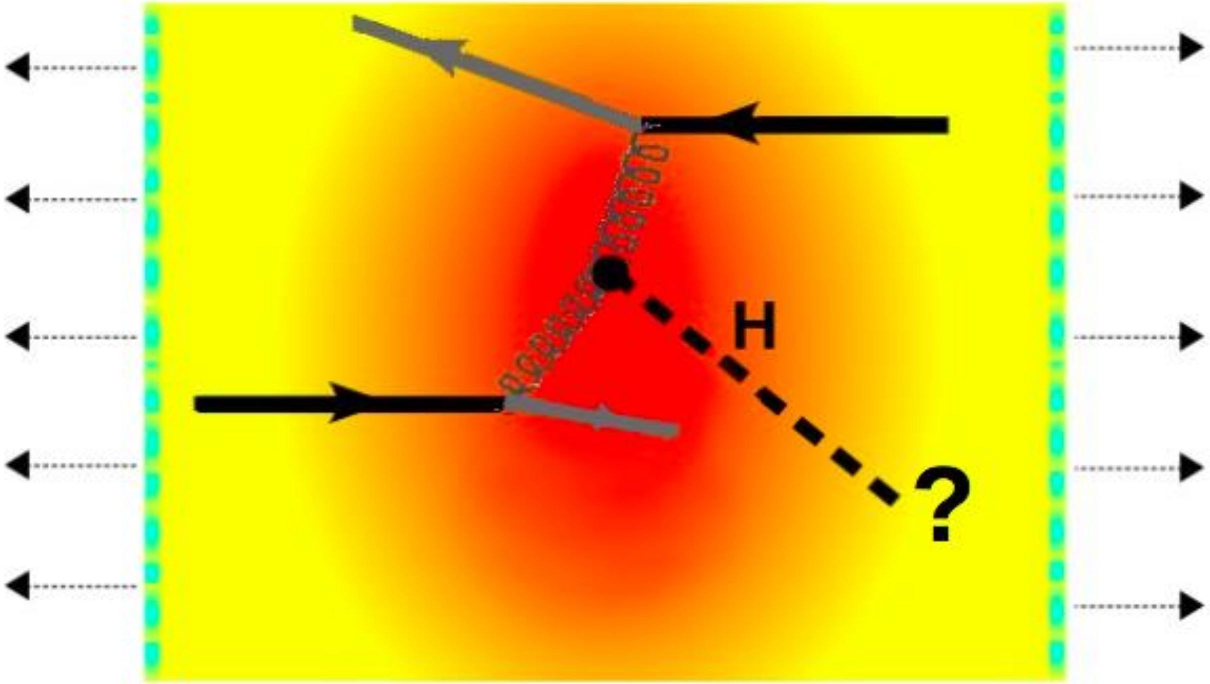
Firm theory basis for hydro in small systems

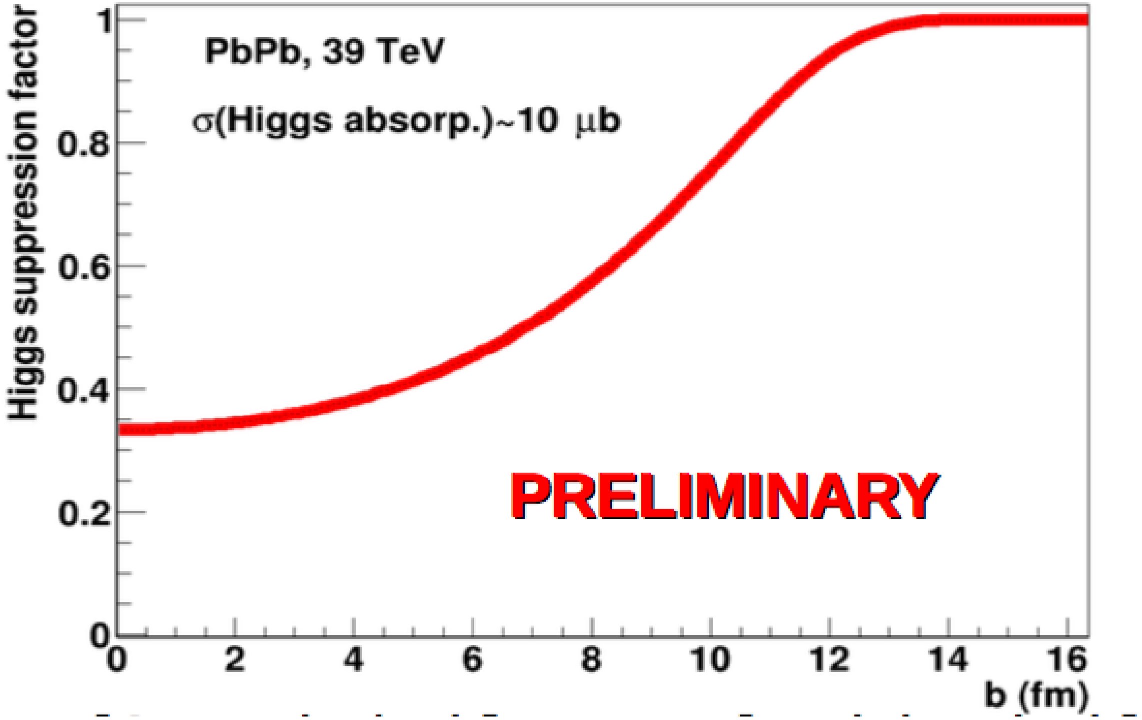
Hydro in pp empirically sucessfull

Creating tiny droplets of QCD fluids in pp

- Firm theory basis for applying hydro to pp
- Good quantitative description of exp’ pp data using hydro
- “If it walks like a duck, and it talks like a duck, …”
- Consequence: if there is a QGP in pp, need to revisit the baseline!
- Consequence: if there is a QGP in pp, need to take into account in precision standard model tests (“new” physics, just not beyond the standard model)

Example: Higgs modification in Heavy-Ion Collisions

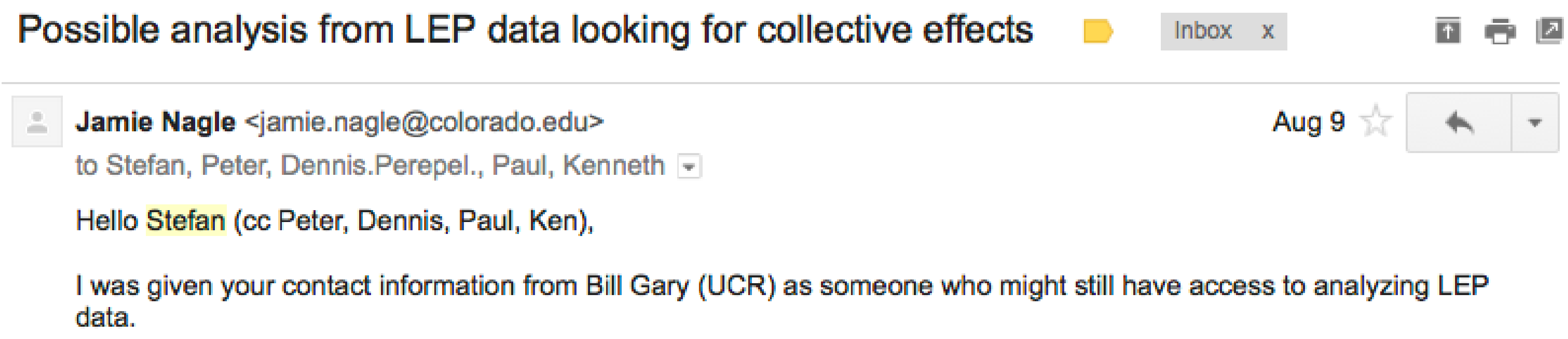




[D'Enterria, Loizides, QM 2017]

Frontier: Looking for QCD droplets in $e^+ e^-$

- "Old" CERN (LEP) data exists for $e^+ e^-$ collisions
- Idea: hunt for hydro signatures in old data using modern analysis techniques



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!

Bonus Material

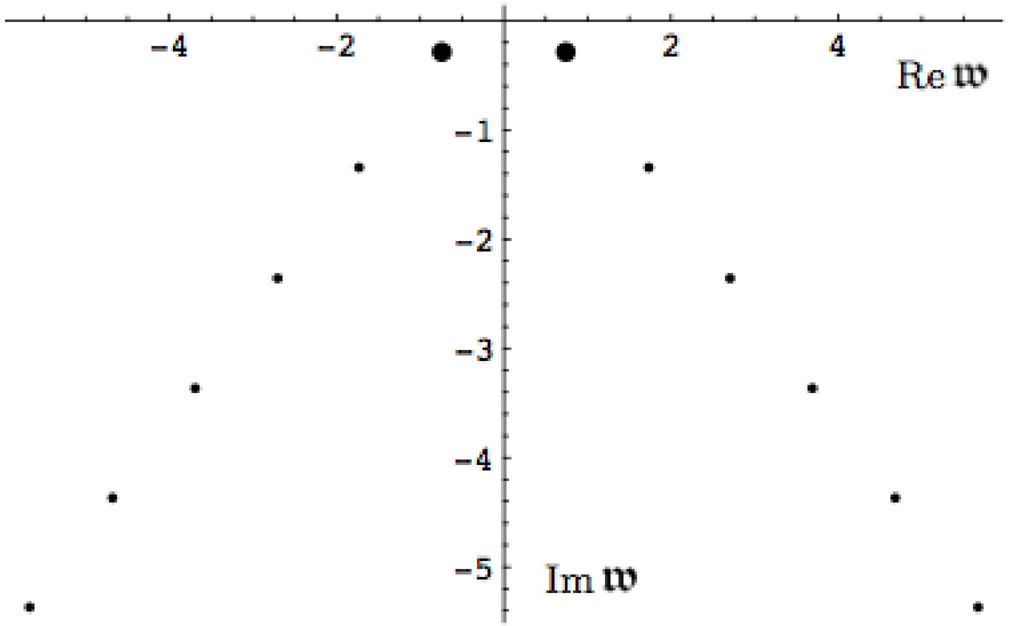
Hydro as an EFT

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

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

- w_{Borel}=±3.1193-2.7471 i [Heller et al, 1302.0697]
- w_{QNM}=±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]

Off-equilibrium hydro

- Hydrodynamic attractor solution exists even far away from equilibrium (as long as hydro modes exist)
- Arbitrary initial conditions approach attractor via non-hydro mode decay
- Near equilibrium, attractor becomes well-known hydrodynamic gradient expansion (e.g. ‘Navier-Stokes’)
- Attractor generalizes notion of hydrodynamics to very non-equilibrium situations!

Far-from-equilibrium Hydro

- Normal hydro:

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

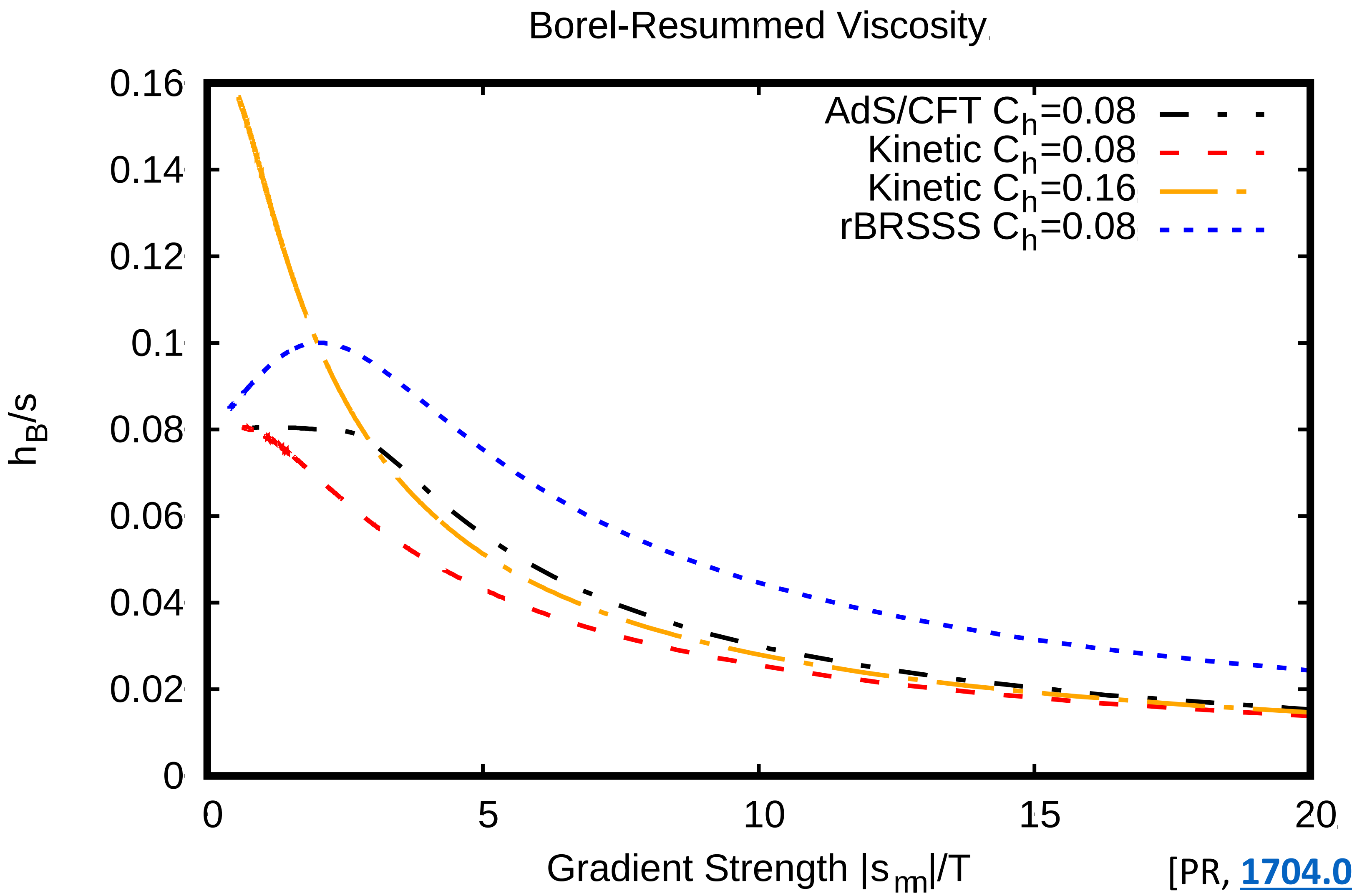
- Far-from equilibrium hydro:

$$T^{ab} = (\epsilon_B + P_B)u^a u^b + P_B g^{ab} - 2\eta_B \nabla^{\langle a} u^{b\rangle}$$

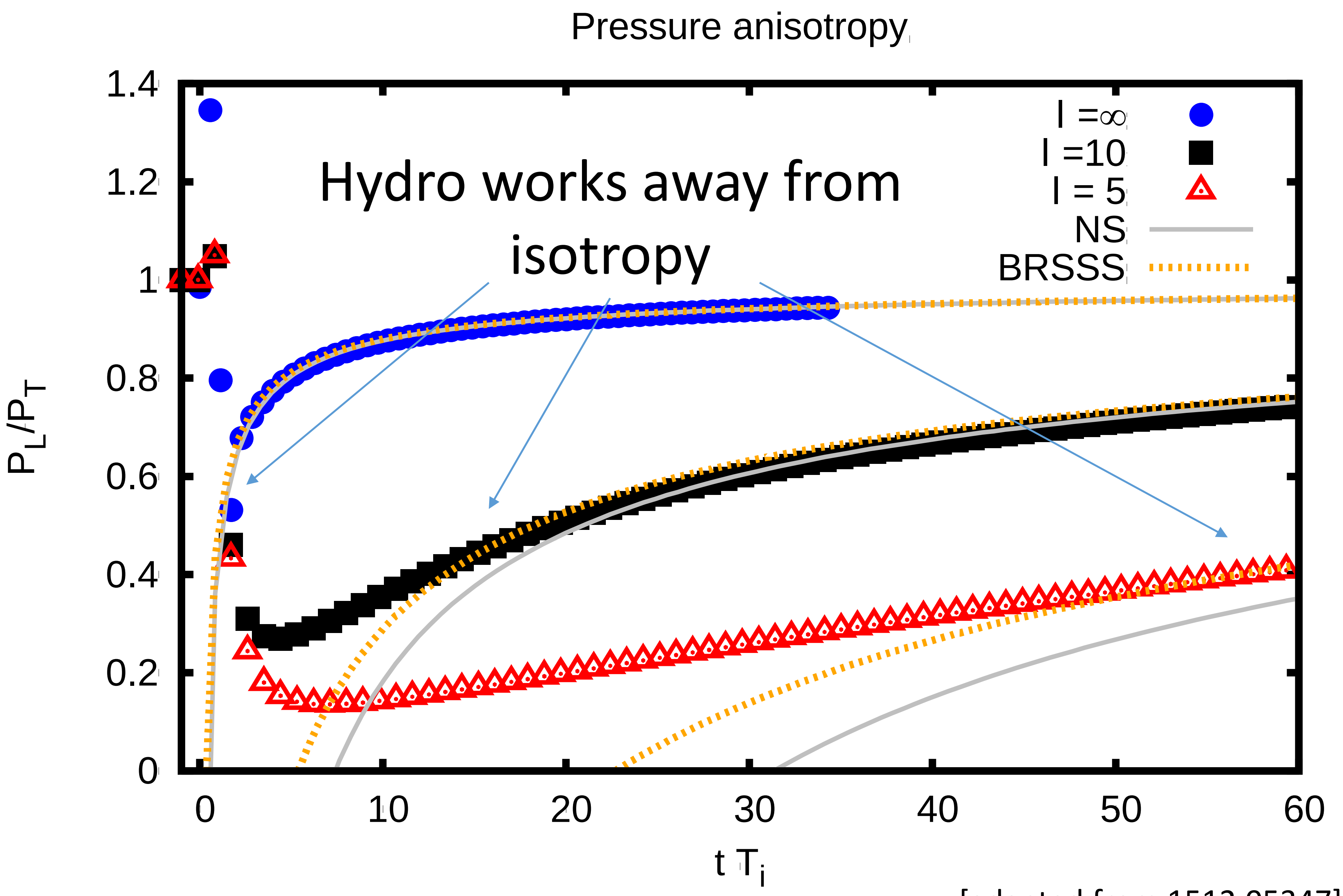
where $\eta_B = \eta_B(|\nabla^{\langle a} u^{b\rangle}|)$ depends on gradient strength

- For conformal system, $\varepsilon_B = 3 P_B$ even far from equilibrium!

Effective (Resummed) Viscosity



[PR, 1704.08699]



[adapted from 1512.05347]