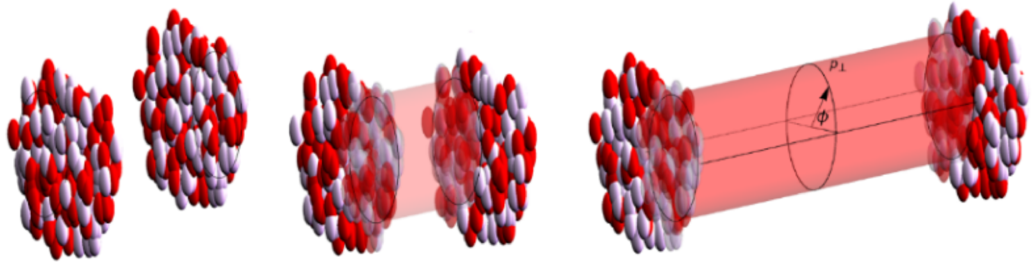
QGP Phenomenology - selected topics

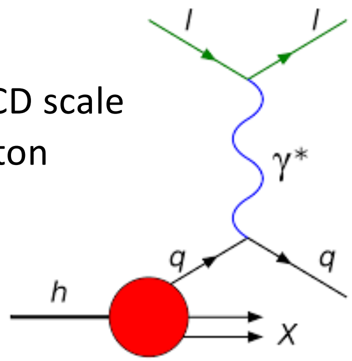


Urs Achim Wiedemann
New Vistas in Photon Physics
Online, 19 Sep 2022 Krakòw

The promise of photons as clean(est) probe of QCD

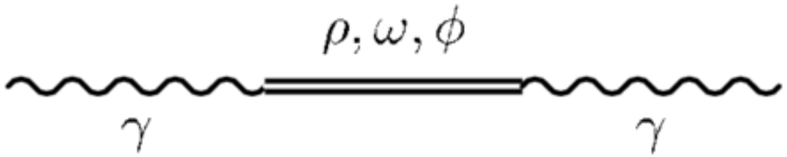
- Deep inelastic scattering

DIS established QCD scale evolution and proton structure

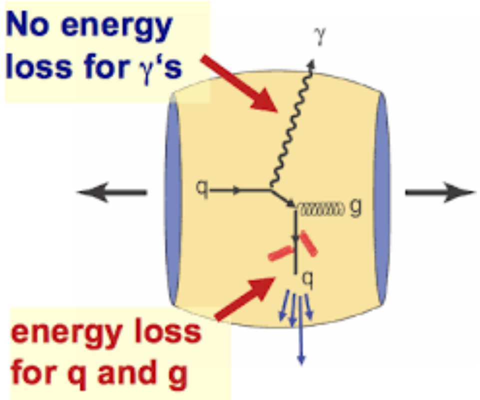


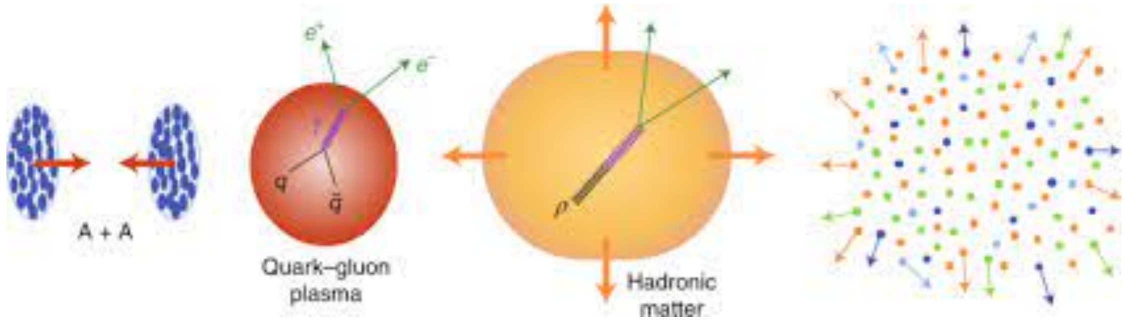
- Vector meson dominance / dileptons

Virtual photons (dileptons) reveal structure of hadronic resonances in vacuum and medium.



- DIS on the QGP is not feasible (though it would be interesting). Instead, one uses “autogenerated probes”, such as

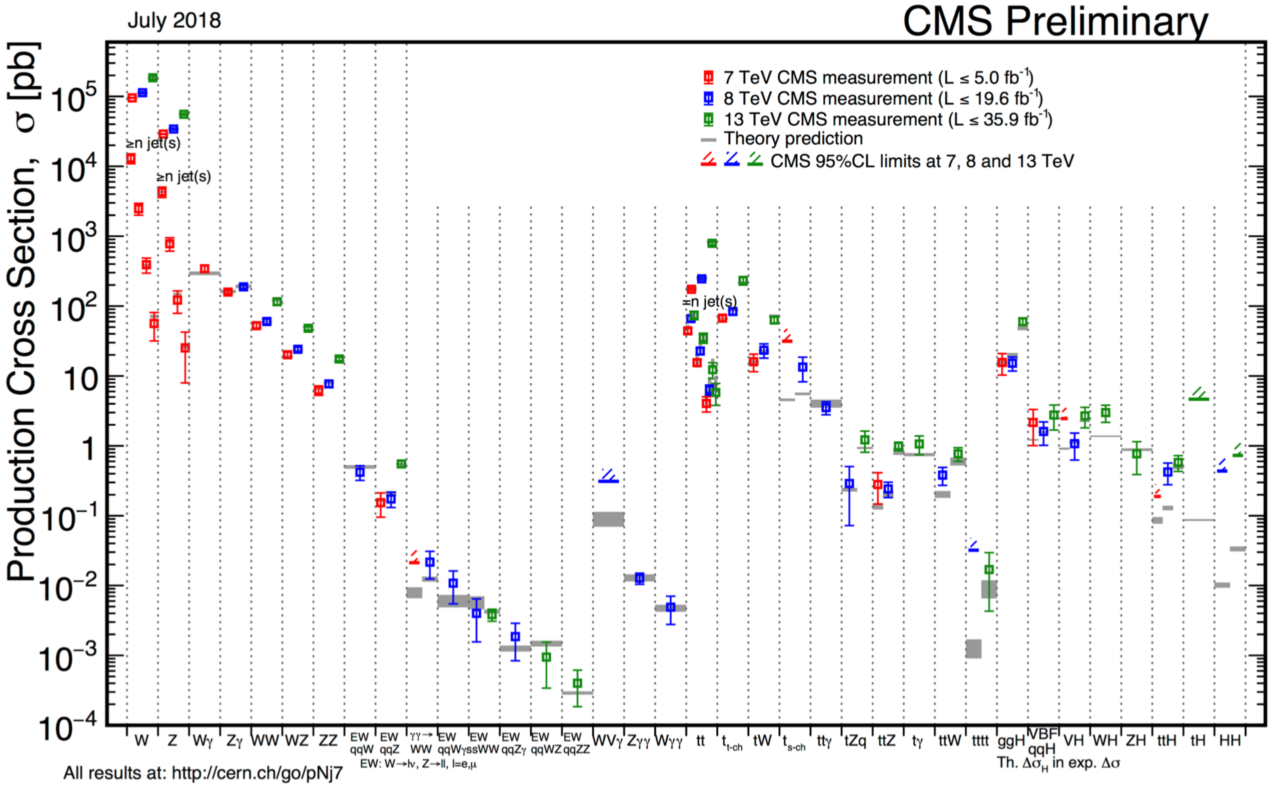


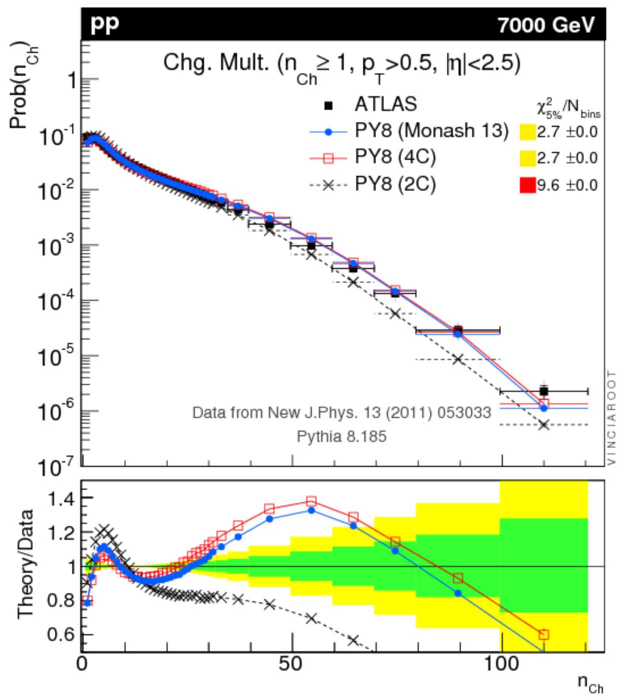


QCD in vacuum – a success story

In high energy physics (HEP), most has been learned from the rare(st) processes.

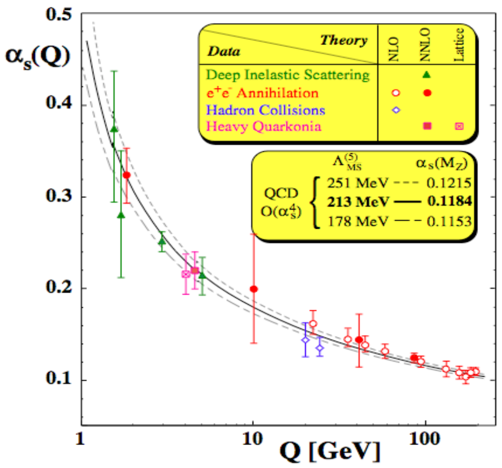
Imperfect modeling of abundant low momentum transfer processes





The success of perturbative QCD with rare processes

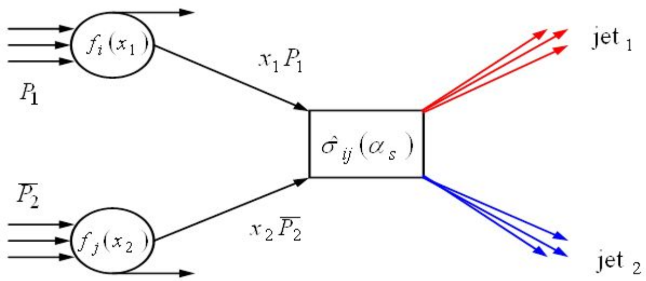
and the absence of a similar success for 'abundant' processes is a direct consequence of



- **Long distance: infrared slavery**
- **Short distance: asymptotic freedom**

For hard, rare processes, the long distance physics can be factorized, e.g.

Jet Production

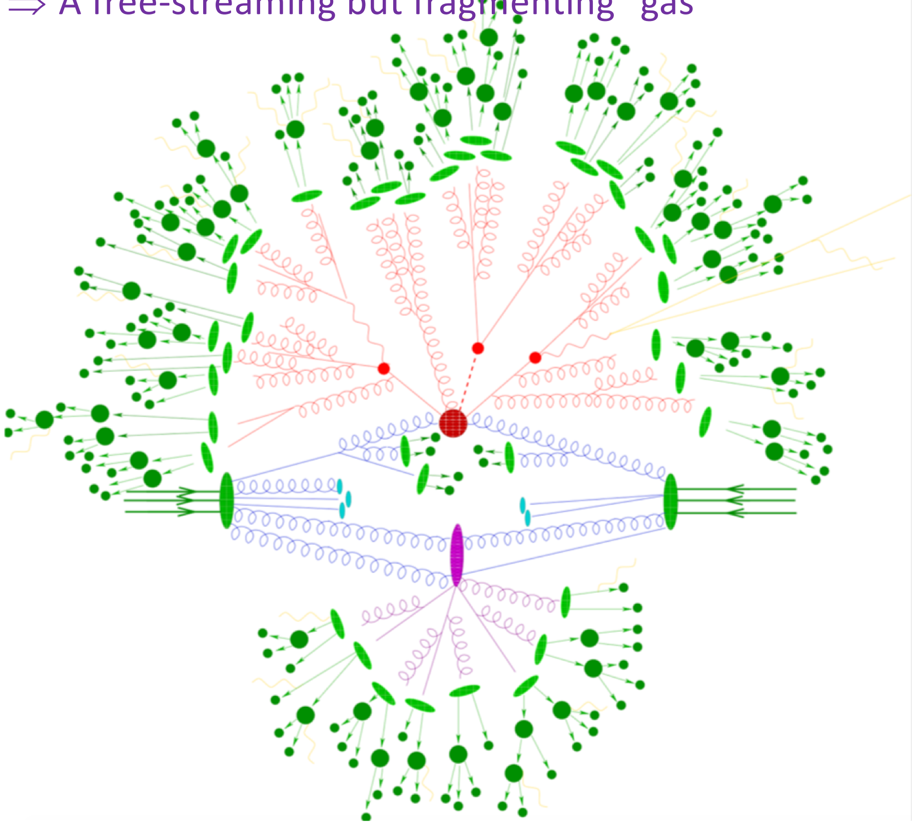


$$\sigma = \sum_{ij} \int dx_1 dx_2 f_i\left(x_1, \mu_F^2\right) f_j\left(x_2, \mu_F^2\right) \hat{\sigma}_{ij}\left(x_1 P_1, x_2 P_2, \alpha_s\left(\mu_R^2\right) \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2}\right)$$

+ parton shower + hadronization
+ jet algorithm + jet substructure
+ ...

HEP phenomenology: default picture for pp

Extrapolating perturbative picture to the soft regime
⇒ A free-streaming but fragmenting "gas"



Included:

- ❑ **Multiple Parton Interactions**
- ❑ **Hard Processes**
- ❑ Parton Showers
- ❑ **Hadronization**
- ❑ **Hadronic decays**
- ❑ **Electroweak processes**
- ❑ BSM

Not included:

- ❑ **any notion of "collectivity"**

Heavy-ion phenomenology has proceeded differently ... so far

Focus is mostly on the most abundant and most generic processes, such as:

- Hadrochemical composition of events
- Collective flow of *all* soft hadron spectra
- Quenching of *all* hard hadronic spectra
- ...

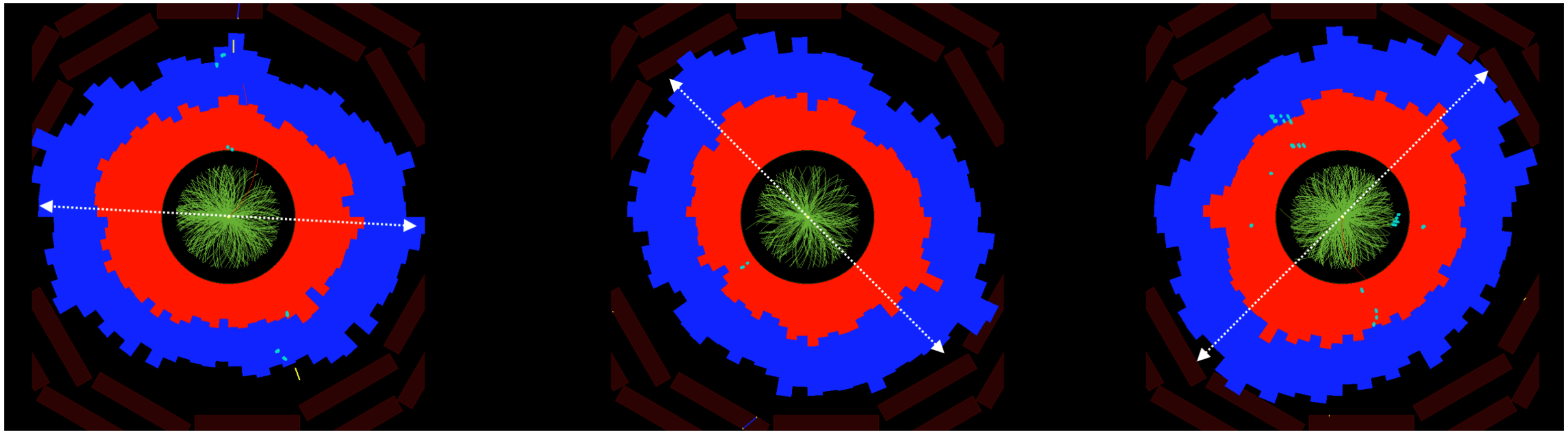
These phenomena lie outside a purely perturbative description and do not fit into the HEP default picture.

Two prominent examples:

Flow

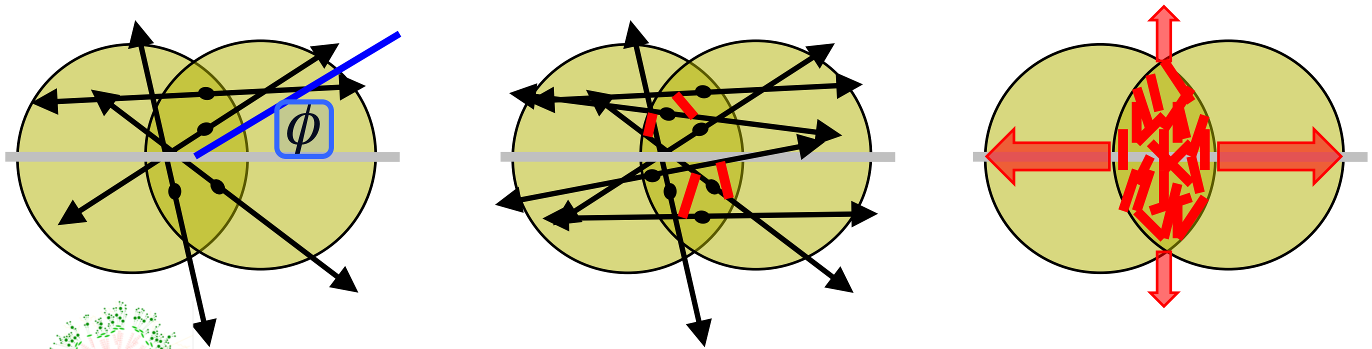
Collectivity at soft p_T

Single event calorimeter distribution of O(10’000) particles in PbPb @ LHC, CMS Coll.



Which dynamics is at play?

Free streaming → QCD transport theory → Dissipative fluid dynamics → Perfect fluid dynamics

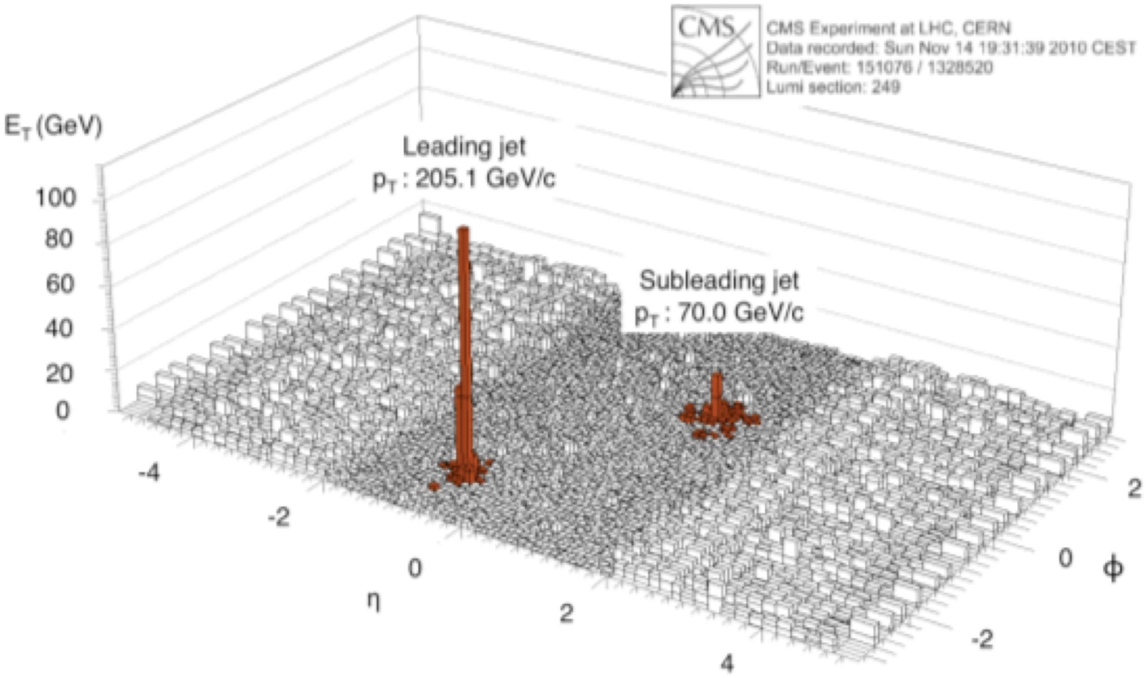


Ruled out !

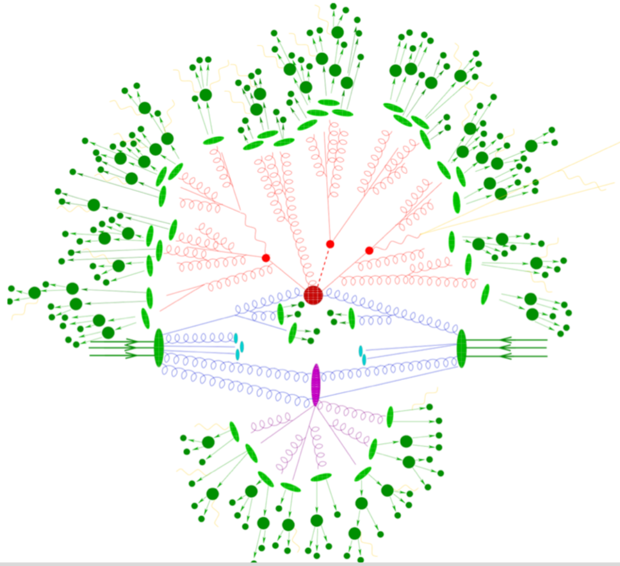
To be tested quantitatively !

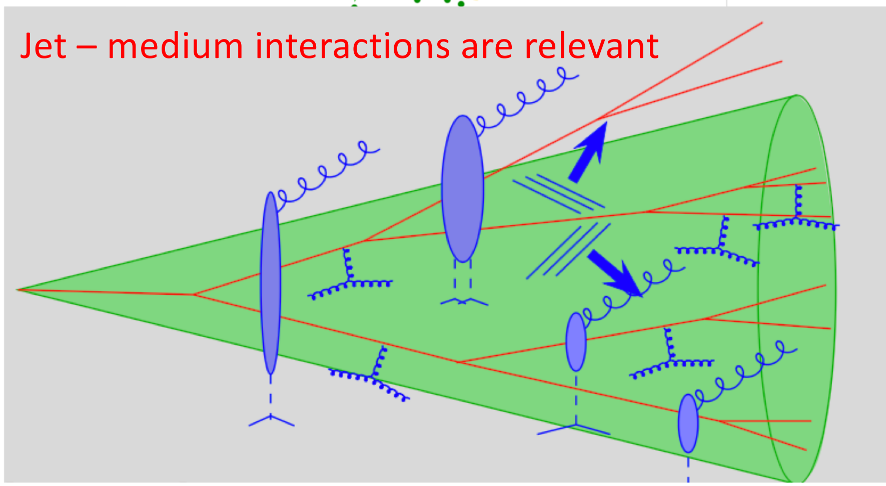
Jet quenching

Deviation form free-streaming & fragmentation at high p_T



This is not sufficient!





QCD thermo- and hydrodynamics

Assumptions and Limitations

If perturbative QCD cannot be applied and if non-perturbative QCD is not fully solved, how can one arrive at a model-independent formulation of bulk collective dynamics?

Hydrodynamics - the basics

- energy momentum tensor $T^{\mu\nu}$ .... 10 indep. components
- conserved charges N_i^{μ} .... 4n indep. components

Tensor decomposition w.r.t. flow field $u_{\mu}(x)$ projector $\Delta_{\mu\nu} = g_{\mu\nu} - u_{\mu}u_{\nu}$

$$N_i^{\mu} = n_i u^{\mu} + \overline{n}_i$$

$$T^{\mu\nu} = \varepsilon u^{\mu}u^{\nu} - p\Delta^{\mu\nu} + q^{\mu}u^{\nu} + q^{\nu}u^{\mu} + \Pi^{\mu\nu}$$

(1 comp.)	$\varepsilon \equiv u_{\mu}T^{\mu\nu}u_{\nu}$	energy density	In Local Rest Frame (LRF)
(1 comp.)	$p \equiv -T^{\mu\nu}\Delta_{\mu\nu}/3$	isotropic pressure	$u_{\mu} = (1,0,0,0)$
(3 comp.)	$q^{\mu} \equiv \Delta^{\mu\alpha}T_{\alpha\beta}u^{\beta}$	heat flow	
(5 comp.)	$\Pi^{\mu\nu} \equiv \left[\left(\Delta^{\mu}_{\alpha}\Delta^{\nu}_{\beta} + \Delta^{\mu}_{\beta}\Delta^{\nu}_{\alpha}\right)/2 - \Delta^{\mu\nu}\Delta_{\alpha\beta}/3\right]T^{\alpha\beta}$	shear viscosity	

Convenient choice of frame: Landau frame: $u = u_L \Rightarrow q^{\mu} = 0$

Eckard frame: ...

Ideal Hydrodynamics

Fluid is locally isotropic at all space-time points

$$N_i^{\mu} = n_i u^{\mu} + \bar{n}_i$$ (n comp.)

$$T^{\mu\nu} = \varepsilon u^{\mu} u^{\nu} - p\Delta^{\mu\nu} + q^{\mu} u^{\nu} + q^{\nu} u^{\mu} + \Pi^{\mu\nu}$$ (5 comp.)

Determined by conservation laws and equation of state

$$\partial_{\mu} N_i^{\mu} \equiv 0$$ (n constraints)

$$\partial_{\mu} T^{\mu\nu} \equiv 0$$ (4 constraints)

$$p = p(\varepsilon, n)$$ (1 constraint)

Region of validity? Consider conserved current:

$$\partial_{\mu} j^{\mu} = \partial_{\mu}\left(\rho\, u^{\mu}\right) = \rho \underbrace{\partial_{\mu} u^{\mu}}_{\text{expansion scalar}} + \underbrace{u^{\mu}\partial_{\mu}}_{\text{comoving } t-\text{derivative}} \rho = 0$$

Spatio-temporal variations of macroscopic fluid should be small
if compared to microscopic reaction rates

$$\Gamma \cong n\sigma >> \theta = \partial_{\mu} u^{\mu}$$

1st order viscous hydrodynamics

Now, conservation laws + eos do not close equations of motion,
additional constraints from 2nd law of thdyn.

$$S^\mu = s u^\mu + \beta q^\mu$$ Entropy to first order

Use $\varepsilon + p = \mu n + Ts$ and $u_\nu \partial_\mu T^{\mu\nu} \equiv 0$ to write:

$$T\partial_\mu S^\mu = (T\beta - 1)\partial . q + q.(\dot{u} + T\partial . \beta) + \Pi^{\mu\nu}\partial_\nu u_\mu + \Pi\theta \geq 0$$

To warrant that entropy increases, require:

Navier-Stokes
1st order hydro

$$\beta \equiv 1/T$$

bulk viscosity $\Pi \equiv \varsigma\theta$

heat conductivity $q^\mu \equiv \kappa T \Delta^{\mu\nu}(\partial_\nu \ln T - \dot{u}_\nu)$

shear viscosity $\Pi^{\mu\nu} \equiv 2\eta\left[\left(\Delta^\mu_\alpha \Delta^\nu_\beta + \Delta^\mu_\beta \Delta^\nu_\alpha\right)/2 - \Delta^{\mu\nu}\Delta_{\alpha\beta}/3\right]\partial^\alpha u^\beta$

Determines $\Pi, q^\mu, \Pi^{\mu\nu}$ in terms of flow, energy density and dissipative coeff.

$$\partial_\mu S^\mu = \frac{\Pi^2}{\varsigma T} - \frac{q q}{\kappa T^2} + \frac{\Pi^{\mu\nu}\Pi_{\mu\nu}}{2\eta T} \geq 0$$

Problem: instantaneous acausal propagation

2nd order viscous hydrodynamics

Expand entropy to 2nd order in dissipative gradients

$$S^\mu = s u^\mu + \beta q^\mu + \alpha_0 \Pi q^\mu + \alpha_1 \Pi^{\mu\nu} q_\nu + u^\mu \left(\beta_0 \Pi^2 + \beta_1 q q + \beta_2 \Pi^{\mu\nu} \Pi_{\mu\nu} \right)$$

Now, need 9 eqs. to determine $\Pi, q^\mu, \Pi^{\mu\nu}$

$\partial_\mu S^\mu \geq 0$ leads to differential equations for $\Pi, q^\mu, \Pi^{\mu\nu}$

which involve $\alpha_0, \alpha_1, \beta, \beta_0, \beta_1, \beta_2, \varsigma, \kappa, \eta$

Focus on shear viscosity only: (neglect vorticity)

$$T \partial_\mu S^\mu = \Pi_{\mu\nu} \left[-\beta_2 D \Pi^{\mu\nu} + \tfrac{1}{2} \left\langle \nabla^\mu u^\nu \right\rangle \right] \equiv \tfrac{1}{2\eta} \Pi_{\mu\nu} \Pi^{\mu\nu} \qquad \beta_2 = \tau_\Pi / 2\eta$$

Notations: covariant derivative $d_\mu u^\nu \equiv \partial_\mu u^\nu + \Gamma^\nu_{\alpha\mu} u^\alpha$

Convective derivative $D \equiv u^\mu d_\mu$

Nabla operator $\nabla^\mu \equiv \Delta^{\mu\nu} d_\nu = d^\mu - u^\mu D$

Angular bracket $\left\langle A^{\mu\nu} \right\rangle \equiv \left[\tfrac{1}{2} \left(\Delta^\mu_\alpha \Delta^\nu_\beta + \Delta^\mu_\beta \Delta^\nu_\alpha \right) - \tfrac{1}{3} \Delta^{\mu\nu} \Delta_{\alpha\beta} \right] A^{\alpha\beta}$

Hydrodynamics from relativistic transport eq.

Consider Boltzmann equation with collision term

$$p^{\mu} d_{\mu} f(x,p) = C$$

Consider momentum moments of phase space distribution

$$\int_p p^{\mu} d_{\mu} f\left(x,t,p\right) \equiv d_{\mu} N^{\mu} = 0 = \int_p C$$

$$\int_p p^{\mu} p^{\alpha} d_{\mu} f\left(x,t,p\right) \equiv d_{\mu} T^{\mu\alpha} = 0 = \int_p p^{\alpha} C$$

Energy-momentum conservation

$$\int_p p^{\mu} p^{\alpha} p^{\beta} d_{\mu} f\left(x,t,p\right) = \int_p p^{\alpha} p^{\beta} C$$

IF: - if perturbations around average stay small $f = f_0\left(1+\delta f\right)$

$$\delta f\left(x,t,p\right) = \varepsilon(x,t) + \varepsilon_{\lambda}(x,t) p^{\lambda} + \varepsilon_{\lambda\nu}(x,t) p^{\lambda} p^{\nu}$$

$$T^{\mu\nu} = T_0^{\mu\nu} + \Pi^{\mu\nu}$$

Gradient expansion

- if higher moments can be neglected

$$\Rightarrow \quad \left\langle T^{\mu\nu} - T_0^{\mu\nu} \right\rangle = \left\langle \Pi^{\mu\nu} \right\rangle = \varepsilon_{\alpha\beta}(x) \int_p p^{<\mu} p^{\nu>} p^{\alpha} p^{\beta} f_0$$

equivalent to **2nd order Israel-Stewart relativistic viscous fluid dynamics**

To sum up: 2nd order relativistic fluid dynamics

Equations of motion are involved but explicitly known

$$\left(\varepsilon + p\right) D u^{\mu} = \nabla^{\mu} p - \Delta^{\mu}_{\nu} \nabla^{\sigma} \Pi^{\nu\sigma} + \Pi^{\mu\nu} D u_{\nu}$$

$$D\varepsilon = -(\varepsilon + p)\nabla_{\mu} u^{\mu} + \tfrac{1}{2}\Pi^{\mu\nu}\left\langle \nabla_{\nu} u_{\mu}\right\rangle$$

$$\tau_{\pi}\Delta^{\mu}_{\alpha}\Delta^{\nu}_{\beta} D\Pi^{\alpha\beta} + \Pi^{\mu\nu} = \eta\left\langle \nabla^{\mu} u^{\nu}\right\rangle - 2\tau_{\pi}\Pi^{\alpha(\mu}\omega^{\nu)}_{\alpha}$$

Equations can be derived from

- **either:** E-p conservation: $\nabla_{\mu} T^{\mu\nu} = 0$

  local equilibium: $T^{\mu\nu} = \left(\varepsilon + p\right) u^{\mu} u^{\nu} + p g^{\mu\nu} + \underbrace{q^{\mu} u^{\nu} + q^{\nu} u^{\mu} + \Pi^{\mu\nu}}_{dissipative}$

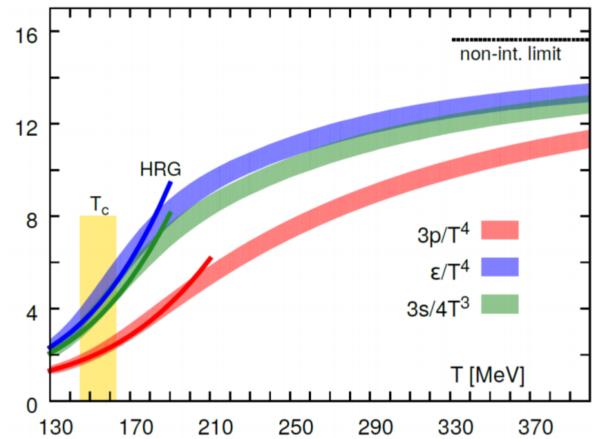
  2nd law of thermodynamics: $\nabla_{\mu} S^{\mu}(x) \geq 0$

- **or:** Boltzmann transport theory

  truncation of the hierarchy of eqs for momentum moments

What do we learn from hydro?

Testing the thermal sector of fundamental quantum fields.



- based *only* on: E-p conservation: $\partial_\mu T^{\mu\nu} = 0$

  2nd law of thermodynamics: $\partial_\mu S^\mu(x) \geq 0$

- sensitive *only* to properties of matter that are

calculable from first principles in quantum field theory

Lattice QCD =>

Finite Temp pQCD =>

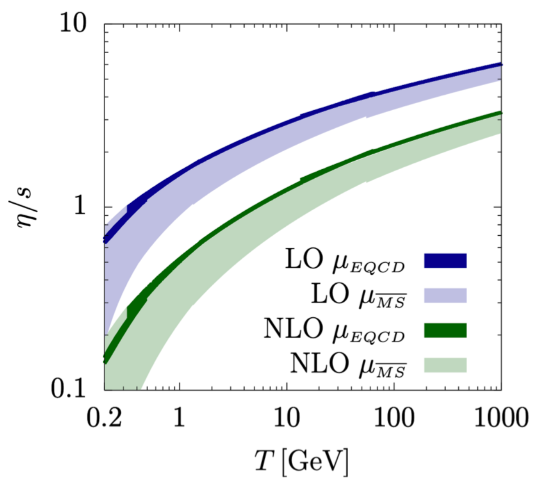
AdS/CFT =>

- **EOS**: $\varepsilon = \varepsilon(p,n)$ and **sound velocity** $c_s = \partial p / \partial \varepsilon$

- **transport coefficients**: shear η, bulk ξ viscosity, …

$$\eta = \lim_{\omega \to 0} \frac{1}{2\omega} \int dt\, dx\, e^{i\omega t} \left\langle \left[T^{xy}(x,t), T^{xy}(0,0) \right] \right\rangle_{eq}$$

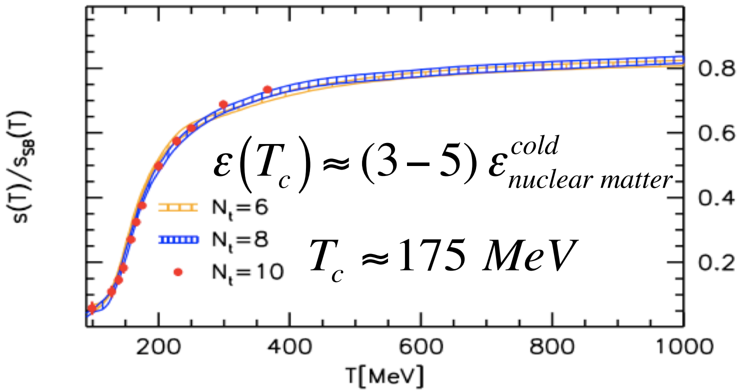
- **relaxation times**: τ_π, τ_Π, …

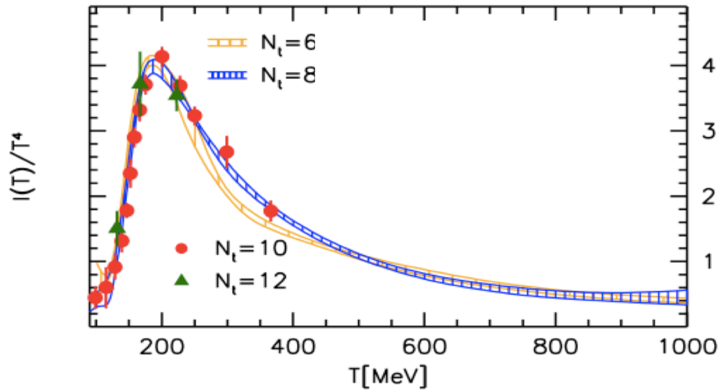


J. Ghiglieri, G. Moore, D. Teaney, QCD Shear Viscosity at (almost) NLO, JHEP 03 (2018) 179

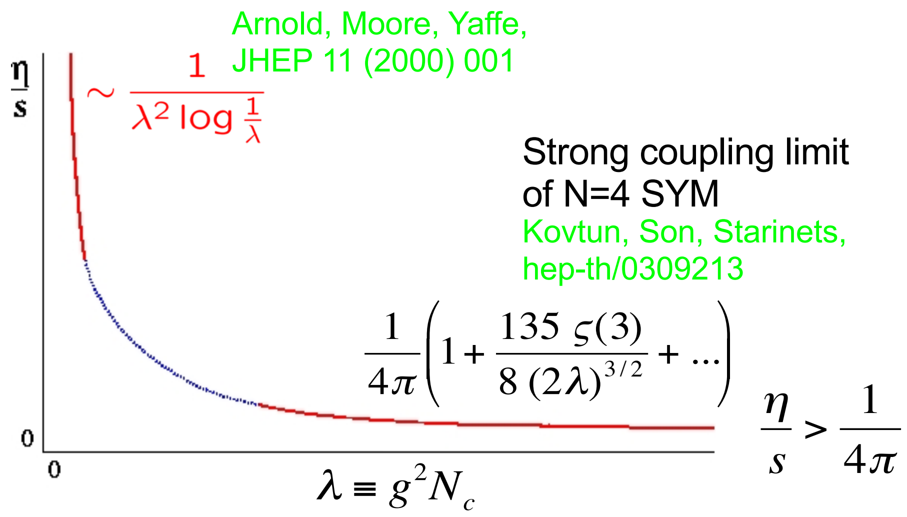
Properties of hot QCD matter (theory)

- **Equation of state** known to high precision from lattice QCD





- **Viscous transport coefficients**
  - Lattice QCD with big uncertainties
  - Gauge-gravity duality enabes strong coupling calculations
  - Also relaxation times accessible in AdS/CFT, times typically ~ 1/T



Caveat: any relativistic collective dynamics is more than hydrodynamics?

Reasoning …

How do we test medium properties?

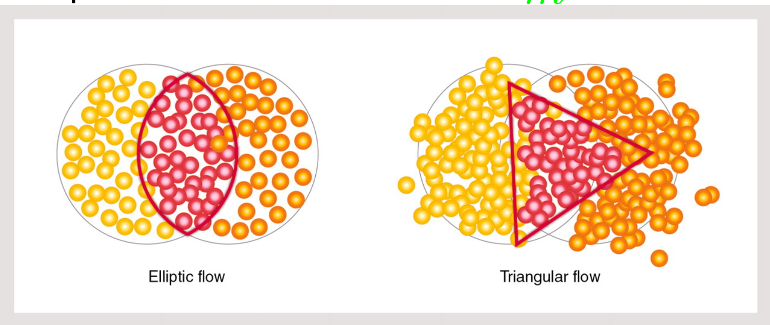
- **Excite medium**
- **Listen to response**
- Analyze

In theory:

$$G_{\mathrm{R}}^{\mu\nu,\alpha\beta} = \frac{\delta T^{\mu\nu}}{\delta h_{\alpha\beta}}$$

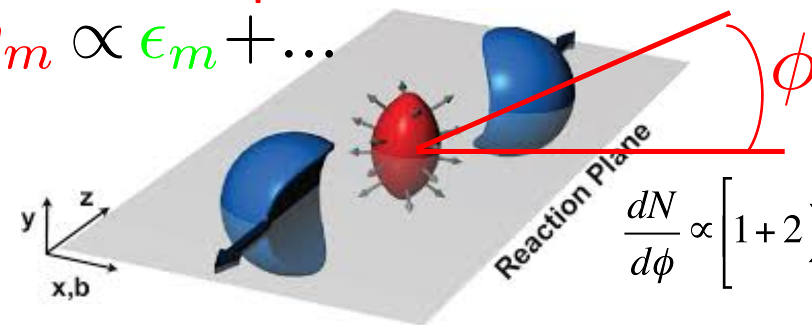
In experiment:

Prepare different **excitations** ϵ_m



measure their **response**

$$v_m \propto \epsilon_m + \ldots$$



$$\frac{dN}{d\phi} \propto \left[1 + 2\sum_m v_m \cos(m\phi)\right]$$

Analyzing medium response

$$G_R(t,k) = \int_{-\infty}^{\infty} d\omega \tilde{G}_R(\underbrace{\omega}_{\in\mathbb{C}}, k) e^{-i\omega t} = c_{\text{hyd}} \exp\left[-\Gamma_s k^2 t\right] + c_{\text{non-hyd}} \exp\left[-t/\tau_R\right]$$

- **Hydrodynamic excitations,** e.g.

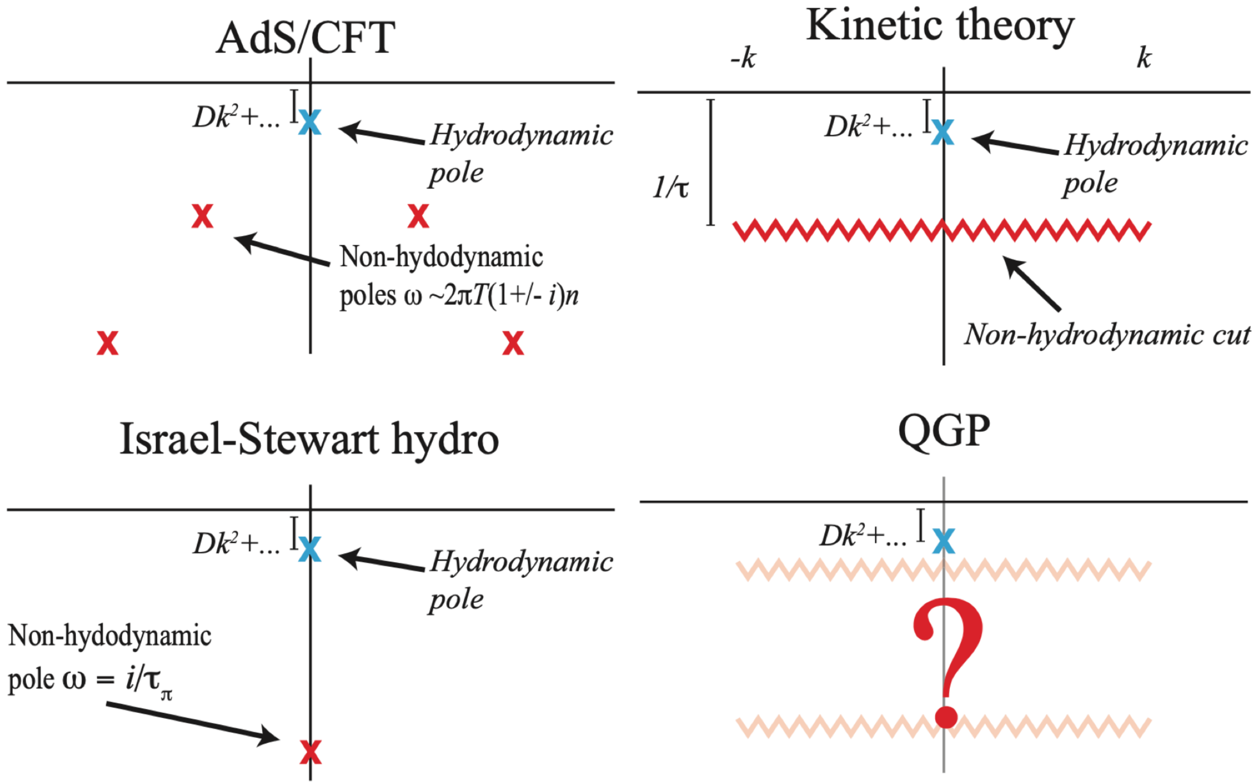
$$\omega_{\text{pole}}^{\text{hyd}}(k) = -i \underbrace{\frac{\eta}{sT}}_{\equiv \Gamma_s} k^2$$

  - Universal in QFTs
  - Consequence of conservation laws
  - Described by gradient expansion $k \leftrightarrow \nabla$

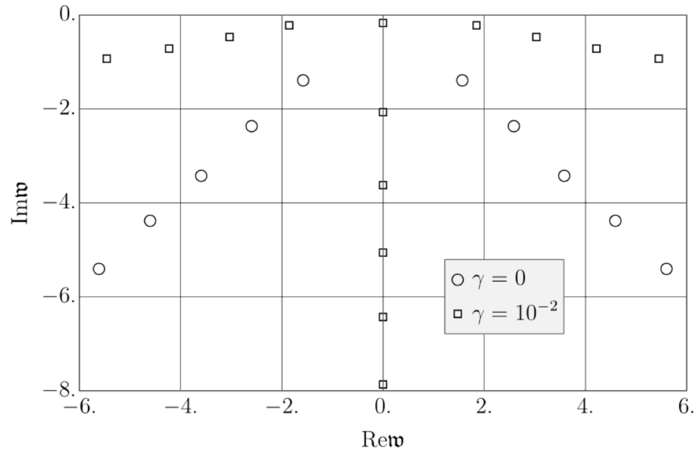
- **Non-hydro excitations,** e.g.

$$\omega_{\text{pole}}^{\text{non-hyd}}(k) = -i \frac{1}{\tau_\pi}$$

  - No QFTs without non-hydro modes
  - Consequence of causality
  - Not described by gradient expansion



The complex life of (non)-hydro modes



- **N=4 SYM at infinite coupling**
  - Xmas tree + hydro poles

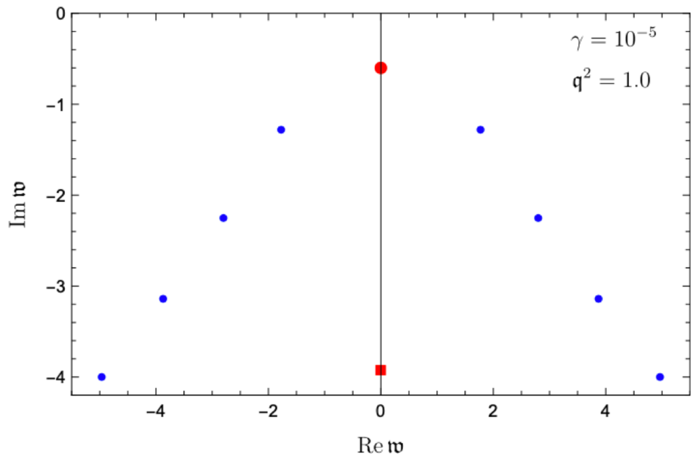
- **N=4 SYM at finite t'Hooft coupling**

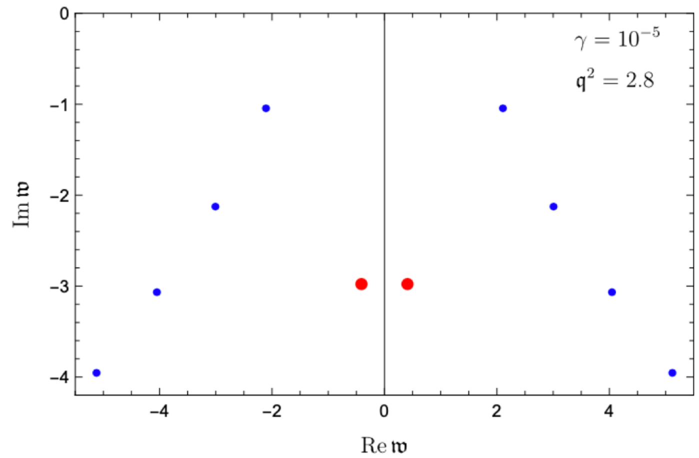
$$\gamma \propto \lambda^{-3/2}$$

  - Xmas tree flattens
  - Diffusive poles appear
  - At finite momentum,

$$\mathfrak{q} = \frac{q}{2\pi T}$$

hydro pole "disappears"

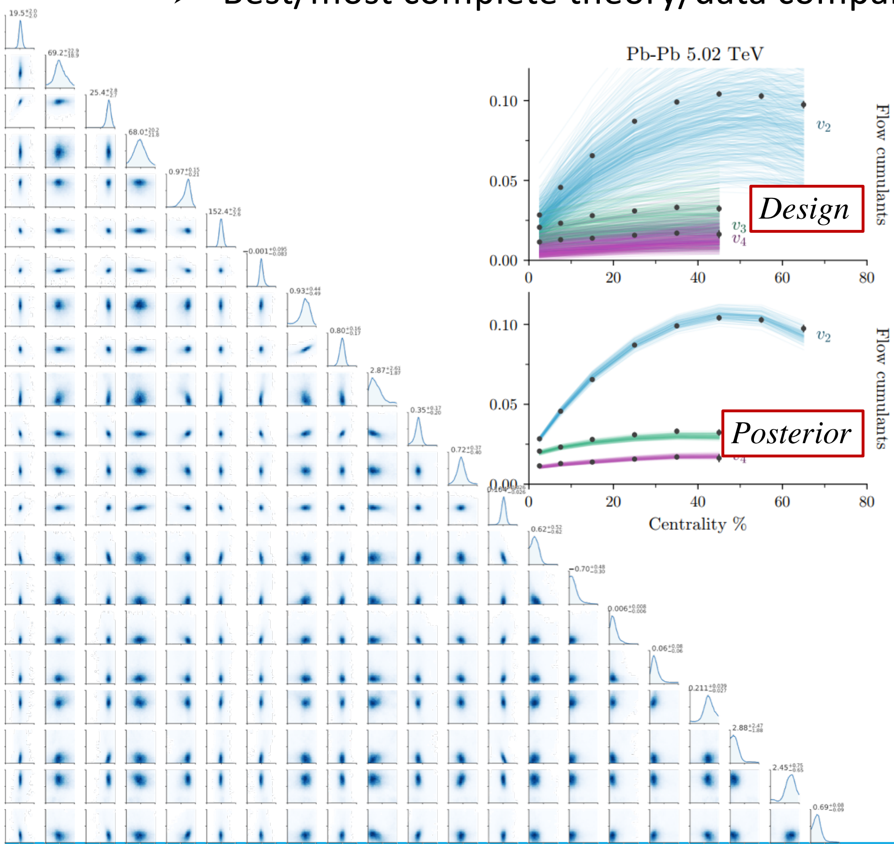




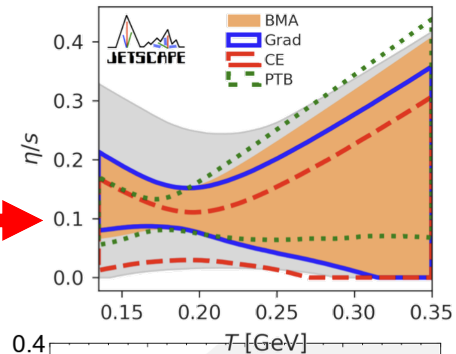
S. Grozdanov, N. Kaplis, A.O. Starinets, JHEP 09 (2016) 046; S. Grozdanov, A.O. Starinets, P. Tadic arXiv:2104.11035

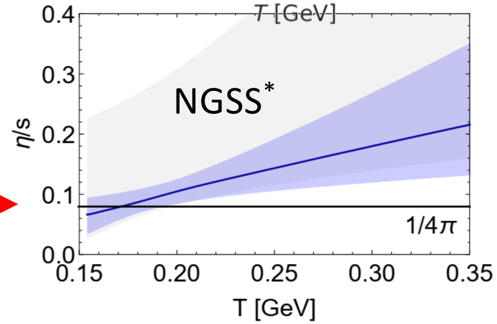
Bayesian Inference

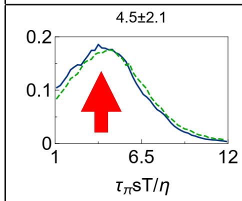
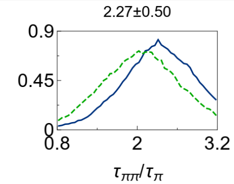
- More than fluid dynamics but constrains fluid dynamics
- Best/most complete theory/data comparison at soft p_T



State of the art: 514 data points, 20 parameters, unprecedented detail.





	NGSS*	AdS/CFT	kinetic theory
$\frac{\tau_\pi sT}{\eta}$		$4-\log(4)\approx 2.61$	5
$\frac{\tau_{\pi\pi}}{\tau_\pi}$		$\frac{88}{35(2-\log 2)}\approx 1.92$	$\frac{10}{7}\approx 1.43$

Steffen Bass, A data-driven approach to quantifying the shear viscosity of nature's most ideal liquid, https://www.youtube.com/watch?v=MGE8K8IY4cg

*G. Nijs, U. Gursoy, W. v.d. Schee, R. Snellings, arXiv:2010.15130, arXiv:2010.15134

How fluid is the fluid?

- N=4 SYM plasma has no internal structure
  "universal" lower bound $\frac{\eta}{s} = \frac{1}{4\pi}$ 2001 Policastro, Son, Starinets*
- 1-d Bjorken expansion is **isentropic** if $\frac{d(\tau s)}{d\tau} = \frac{\frac{4}{3}\eta}{\tau T} \ll s \implies \frac{\eta}{s} \ll \underbrace{\tau T}_{>1}$
- Hydro-modes dominate if

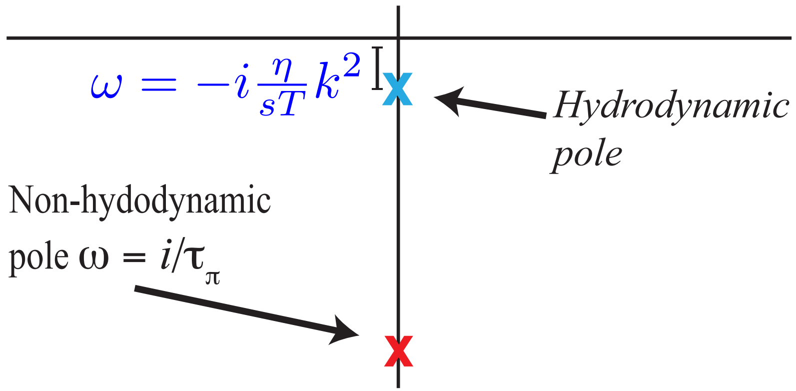
$$\frac{\eta}{sT} k^2 \ll \frac{1}{\tau_\pi} \approx \frac{1}{5} \frac{sT}{\eta}$$

- Hydro-dominated wavelengths satisfy

$$\lambda = \frac{2\pi}{k} \gg \underbrace{2\pi\sqrt{5}}_{10} \underbrace{\frac{\eta}{s}}_{0.1} \underbrace{\frac{1}{T}}_{1\,\mathrm{fm}}$$

Such wavelengths do not fit into a proton !
Experimental access of non-hydro modes seems feasible.

Israel-Stewart hydro



*G. Policastro, D.T. Son, A. Starinets, The Shear viscosity of strongly coupled N=4 supersymmetric Yang-Mills plasma, Phys.Rev.Lett. 87 (2001) 081601

How non-fluid is the fluid?

That depends on its size R:

- Smallest wavenumber

$$k \sim \frac{1}{R}$$

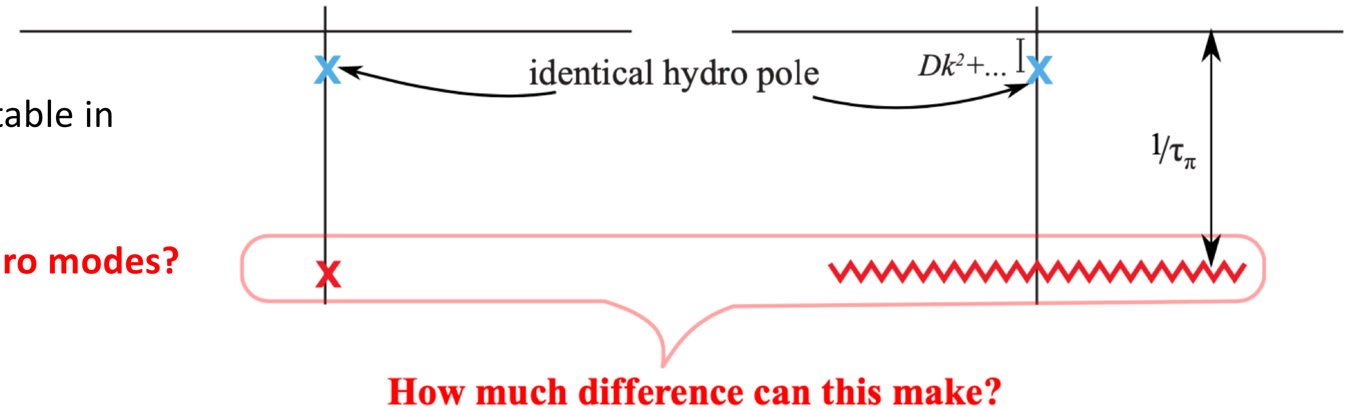
- Longest propagation time

$$t \sim R$$

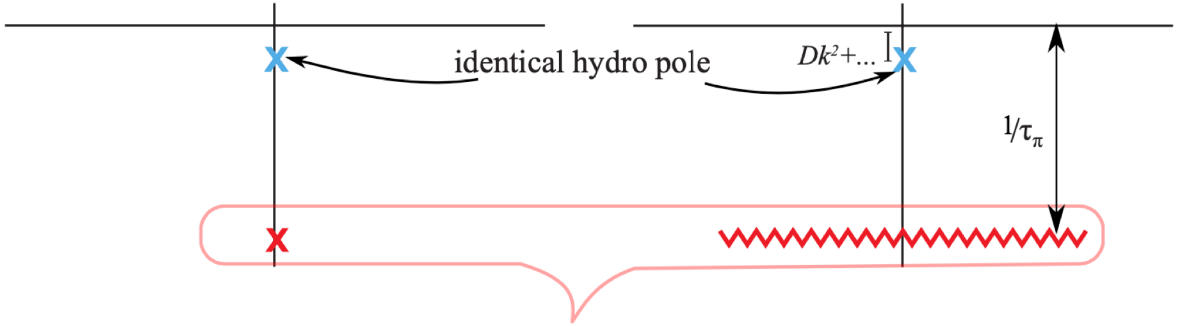
$$G_R(t,k) = \underbrace{c_{\text{hyd}}\ \exp\left[-\Gamma_s k^2 t\right]}_{\text{reduced for smaller R}} + \underbrace{c_{\text{non-hyd}}\ \exp\left[-t/\tau_R\right]}_{\text{enhanced for smaller R}}$$

Non-hydro excitations become testable in systems of sufficiently small size R:

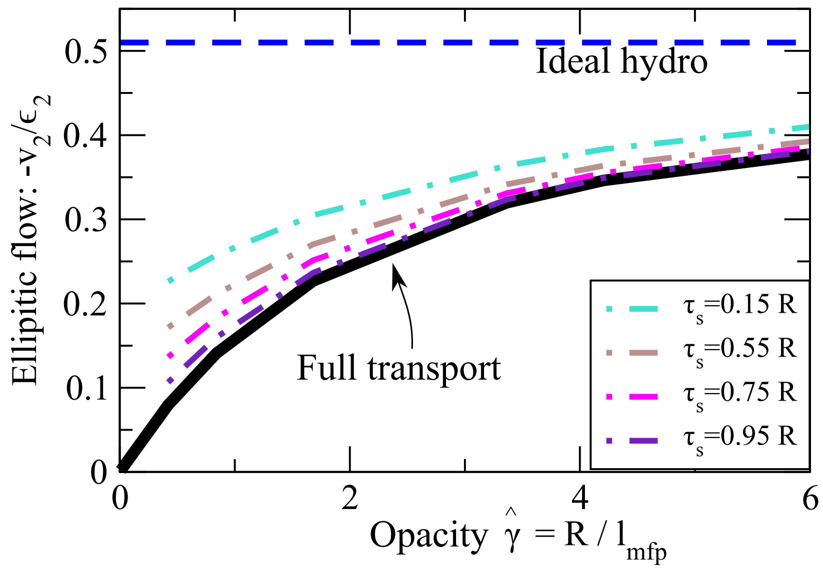
Can we test the nature of non-hydro modes?



A proof of principle (a toy model)



Construct a theory with **identical hydro poles** but **different non-hydro excitations** of the same relaxation time τ_π



Switching from one theory to the other at time τ_s leads to differences in the response v_2/ϵ_2 though the hydrodynamics did not change.

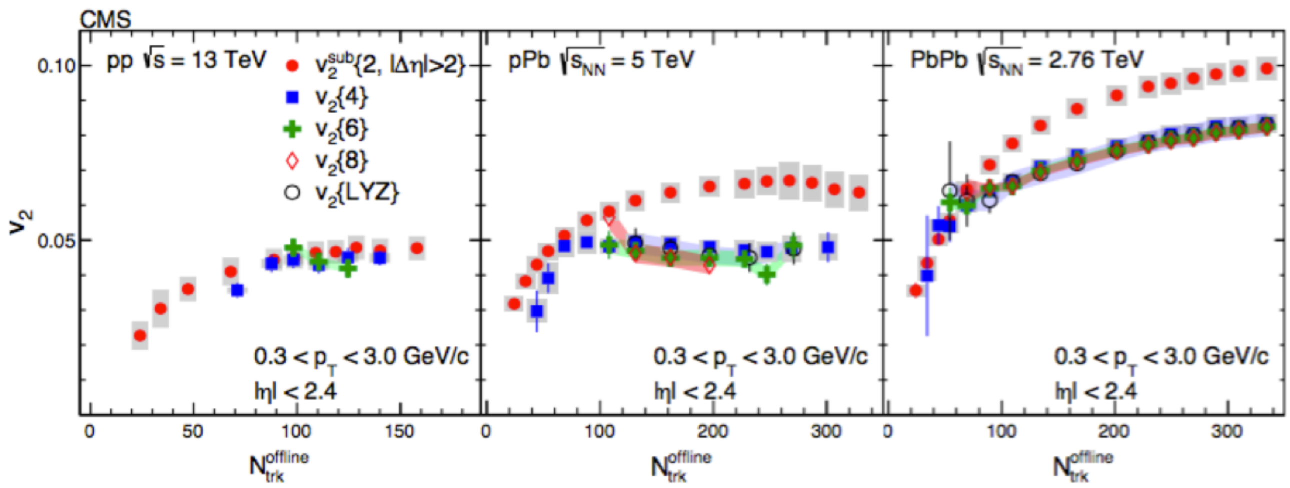
The differences increase with decreasing R.

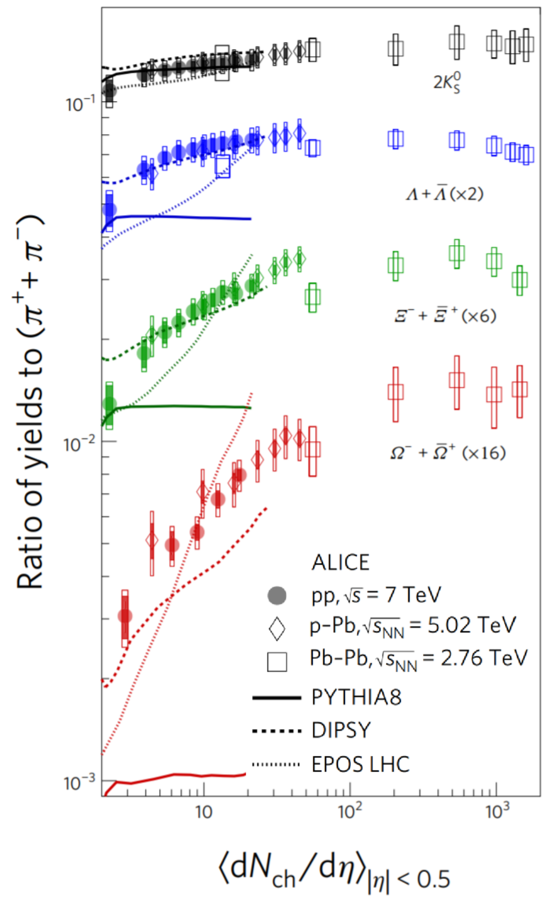
$\Rightarrow$ **Elliptic flow is sensitive to non-hydro modes.**

Discovery of collectivity in pp and pPb @ LHC

Hypothesis (consistent with what we know)

If collectivity persists to the smallest systems, it is not mediated by hydro modes alone.





CMS, Phys. Lett. B765 (2017) 193

ALICE, Enhanced production of multi-strange hadrons in high-multiplicity proton–proton collisions, Nature Physics 13 (2017) 535

QGP Phenomenology = Transport theory ?

To be phenomenologically valid, this transport theory should

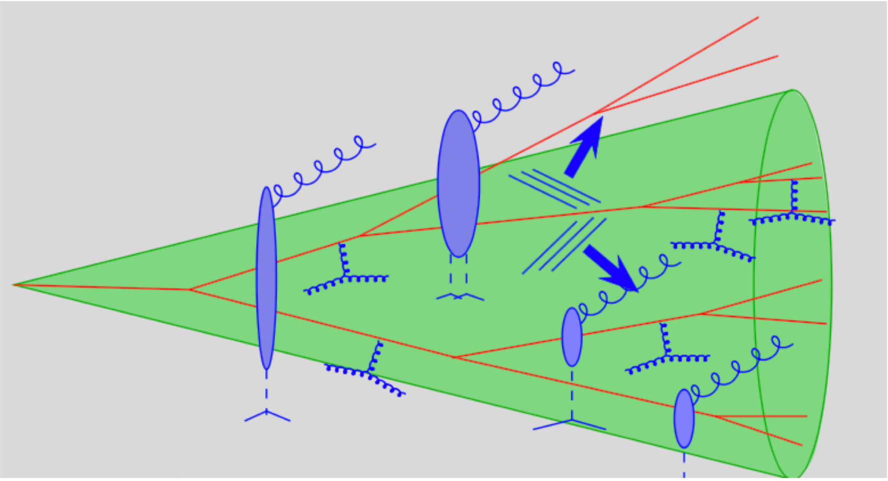
- **approximate QCD hydrodynamics** for soft momentum transfers and sufficiently large systems
- **approximate Jet quenching** dynamics for hard momentum transfers and sufficiently large systems
- **approximate free-streaming** (HEP default picture) for sufficiently small systems

Jet quenching – a *peculiar* kinetic transport

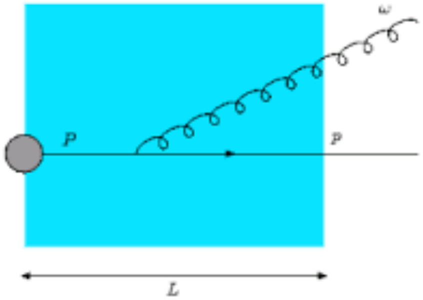
A generic quenching model implements

$$\partial_t f_g(x,p) = -C_{2\to 2}[f] - C_{1\to 2}[f]$$

- Hard partons p>> T
- Embedded in medium
- 1->2 LPM (and DGLAP)
- 2->2 elastic



What is peculiar? Soft emittees are emitted first.

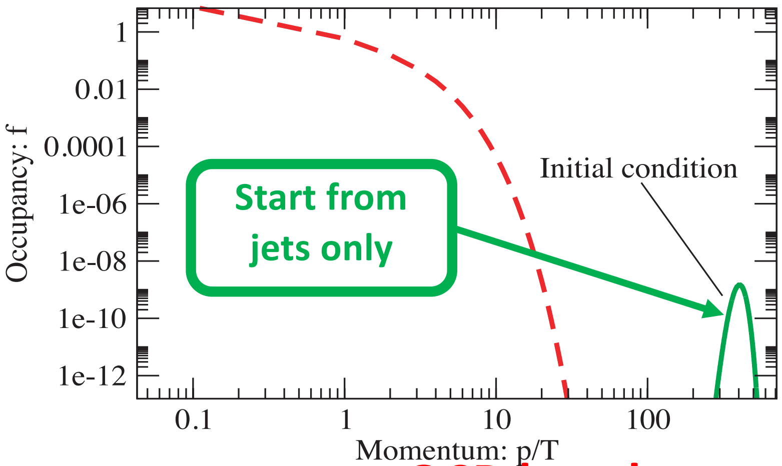


- **In vacuum**
  - Time $\tau^{\text{vac}}_{\text{form}} \simeq \frac{\omega}{k_\perp^2} = \frac{1}{\Theta^2\,\omega}$
  - Hard gluons first
  - Soft gluons late

    medium never

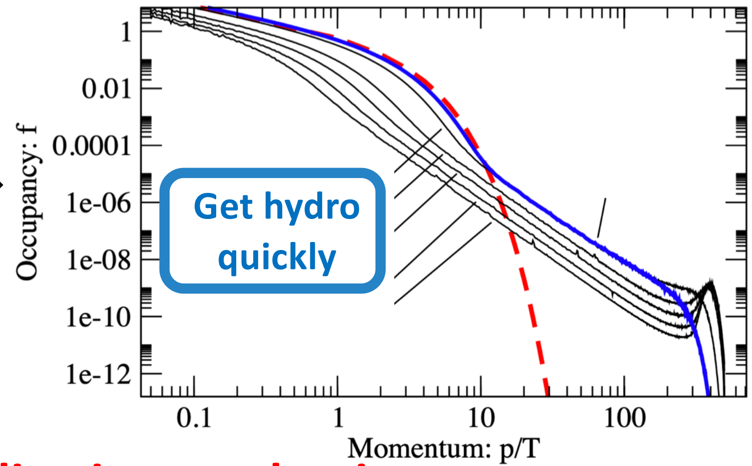
- **In medium**
  - Time $\tau^{\text{med}}_{\text{form}} \simeq \frac{\omega}{k_\perp^2} = \sqrt{\frac{\omega}{\hat{q}}}$
  - Soft gluons first
  - medium forms fast (PTO)

Jet quenching = fast perturbative hydrodynamization

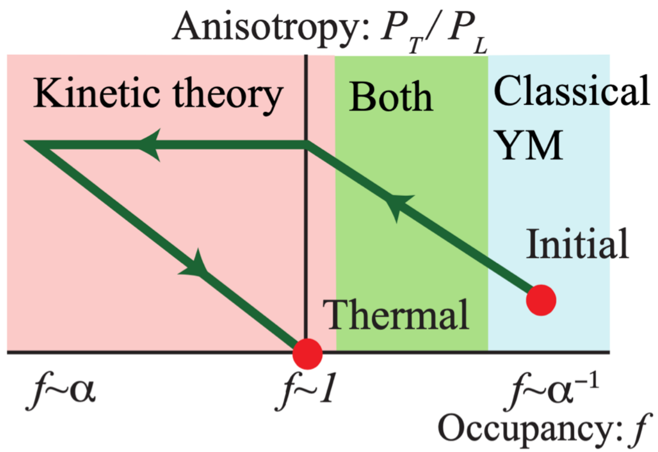


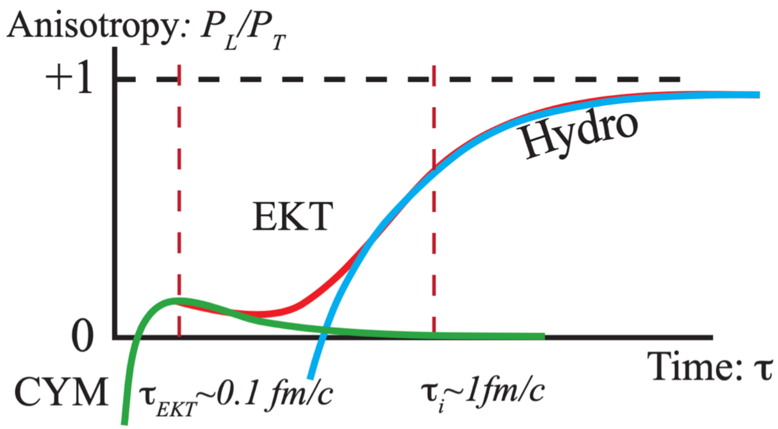
"Bottom-up"

$$\partial_t f_g(x,p) = -C_{2\to2}[f] - C_{1\to2}[f]$$



pQCD has the most remarkable thermalization mechanism





R. Baier, A.H. Mueller, D. Schiff, D.T. Son, 'Bottom up' thermalization in heavy ion collisions, Phys. Lett. B502 (2001) 51
A. Kurkela, E. Lu Phys.Rev.Lett. 113 (2014) 18; A. Kurkela, Y. Zhu Phys.Rev.Lett. 115 (2015) 18

There is a QCD transport theory that

- **approximates QCD hydrodynamics** for soft momentum transfers and sufficiently large systems
- **approximates Jet quenching** dynamics for hard momentum transfers and sufficiently large systems
- **approximates free-streaming** (HEP default picture) for sufficiently small systems

To what extent can QGP phenomenology be based on it?

END