Recent Developments in the Characterization of QGP

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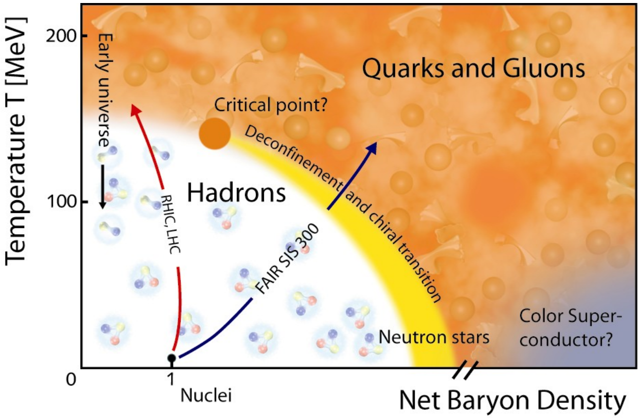
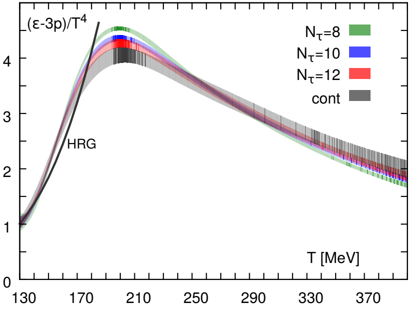
Many-body QCD

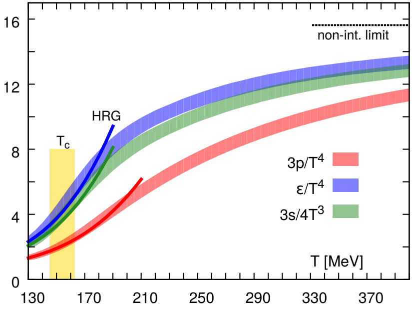


Picture credit: GSI (www.gsi.de)

QGP: WHAT do we know and HOW do we know about it?

LQCD evidence of QGP





HotQCD Collaboration arXiv:1407.6387

- QGP phase transition:
  Rapid crossover with light u, d and heavier s
- $T_c \sim 155\,\text{MeV}$

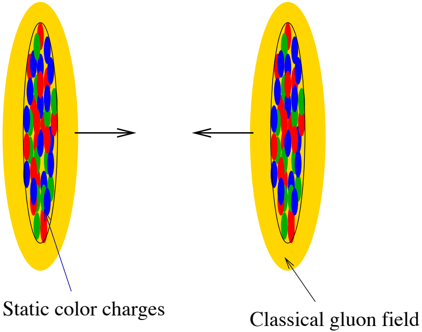
What is a QGP?

- Deconfined state of quarks and gluons
- $T \gtrsim T_c \sim \Lambda_{\rm QCD} \sim 200\,\mathrm{MeV}$
  Or about 2 trillion kelvin. Sun's interior is only about 10 million kelvin.
- $\varepsilon \gtrsim 3\,\mathrm{GeV/fm^3}$
  1 mm^3 of QGP contains about 5×10^{26} J. This can power a modern nation for about 10 million years.
- Pressure $\sim \varepsilon/3$
  This is about $10^{35} N/\mathrm{m}^2$.
  Compare: $M_{\rm Earth} g \approx 6 \times 10^{25}\,N$.

Observable Consequences

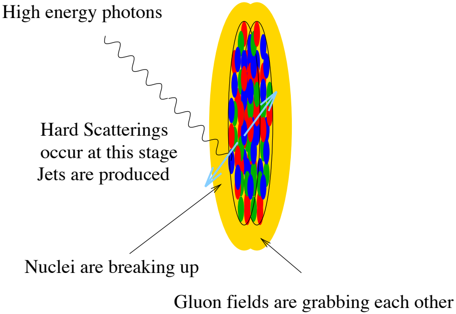
- $T \sim \Lambda_{\rm QCD} \Longrightarrow$ Multiplicity, Spectra
- High density $\Longrightarrow$ Jet quenching
- High pressure $\Longrightarrow$ Hydrodynamic flow
  - Weakly coupled: $\eta/s \gg 1$
  - Strongly coupled: $\eta/s \ll 1 \approx$ Perfect (Ideal) fluid.
- Small $\left\langle \delta Q^2 \right\rangle /s \Longrightarrow$ Tight unlike-sign correlation
- Critical point $\Longrightarrow$ Large momentum fluctuations
- Must survive during the evolution including re-equilibration in the hadronic phase

Creating QGP



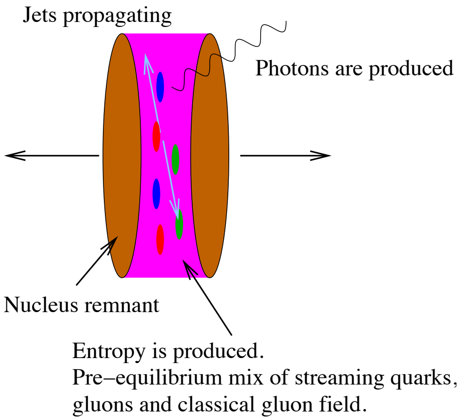
- Nuclear initial state: Static color charges (large x partons) $+$ Classical gluon field (small x gluons) $\Longrightarrow$ Color Glass Condensate.

Creating QGP



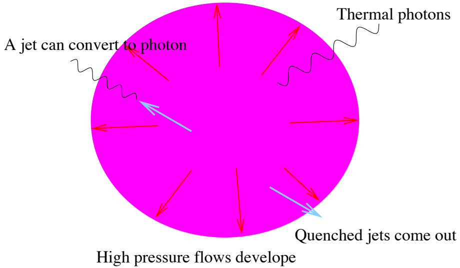
- On contact:
  - Gluon fields collide and start to evolve towards QGP $\Longrightarrow$ Glasma.
  - Jets, heavy quarks, prompt photons are produced by high p_T parton collisions

Creating QGP



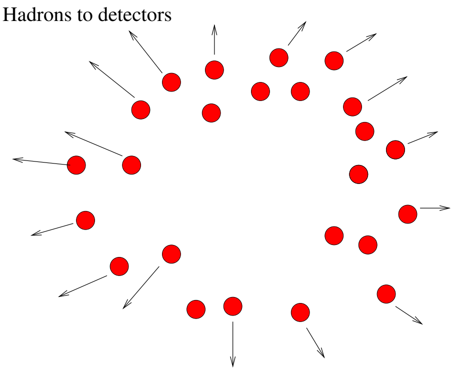
- Pre-Equilibrium
  - Glasma evolving towards QGP
  - Jets, heavy quarks, prompt photons propagating

Creating QGP



- Hydrodynamic stage - QGP is formed
  - Approximate local equilibrium achieved $\Longrightarrow$ Viscous Hydrodynamics applies
  - Jets interact with QGP, quarkonia dissolves, thermal photons and dileptons produced

Creating QGP



- After hadronization:
  - System may be too dilute for hydrodynamics
  - Chemical freeze-out first
  - Kinetic freeze-out later

Plan

- Soft (Roughly in order of increasing complexity)
  - Charge fluctuations
  - Multiplicities
  - Hydrodynamic flows and viscosities
- Hard & EM probes
  - Jet Quenching
  - Electromagnetic probes

Plan

- Soft (Roughly in order of increasing complexity)
  - ~~Charge fluctuations~~
  - ~~Multiplicities~~
  - Hydrodynamic flows and viscosities
- Hard & EM probes
  - Jet Quenching
  - ~~Electromagnetic probes~~

Plan

- Soft (Roughly in order of increasing complexity)
  - ~~Charge fluctuations~~
  - ~~Multiplicities~~
  - Hydrodynamic flows and viscosities
- Hard & EM probes
  - *Jet Quenching* $*$
  - ~~Electromagnetic probes~~

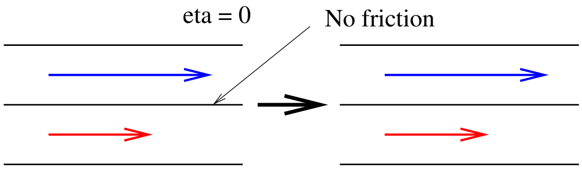
$*$: Cover if time permits

Hydrodynamic Flow and Viscosities

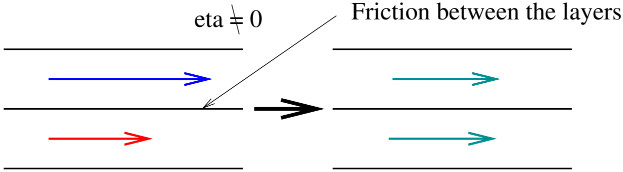
Shear Viscosity

- QGP property to learn:
  - Specific shear viscosity: η/s

Differential hydrodynamic flow

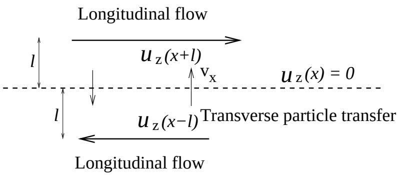


The relative velocity of the two layers does not change.



The velocities eventually become the same.

Kinetic Theory estimate (Why η/s is natural)



u_z: Flow velocity
v_x: Average speed of microscopic particles

- Rough estimate (fluid rest frame, or $u_z(x) = 0$)
  - The momentum density: $T_{0z} = (\epsilon + \mathcal{P}) u_0 u_z$ moves in the x direction with v_x

$$\langle \epsilon + \mathcal{P} \rangle \, |v_x| u_0 (u_z(x - l_{\rm mfp}) - u_z(x + l_{\rm mfp})) \sim -\eta u_0 \partial_x u_z$$

Here $l_{\rm mfp}$: Mean free path

  - Recall thermo. id.: $\langle \epsilon + \mathcal{P} \rangle = sT$

$$\eta \sim \langle \epsilon + \mathcal{P} \rangle \; l_{\rm mfp} \; \langle |v_x| \rangle \sim s\, T\, l_{\rm mfp} \; \langle |v_x| \rangle$$

Perturbative estimate

High Temperature limit: $\langle|v_x|\rangle = O(1)$

- $\eta/s \approx T l_{\rm mfp} \approx \dfrac{T}{n\sigma} \sim \dfrac{1}{T^2\sigma}$ $(\sim \Delta p \Delta x \geq \hbar/2)$
- The only energy scale: T

$$\sigma \sim \frac{(\text{coupling constant})^{\#}}{T^2}$$

Hence

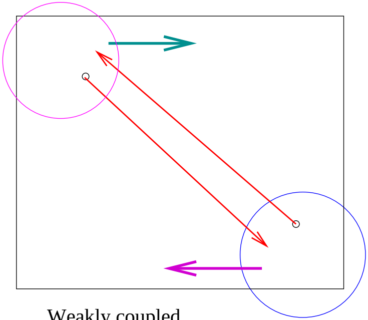
$$\frac{\eta}{s} \sim \frac{1}{(\text{coupling constant})^{\#}}$$

- In QCD, naively expect $\eta/s \sim \dfrac{1}{\alpha_s^2}$
- Coulomb enhancement (cut-off by m_D) leads to

$$\eta/s \sim \frac{1}{\alpha_s^2 \ln(1/\alpha_s)}$$

Interaction Strength and Viscosity

Weak coupling allows rapid momentum diffusion

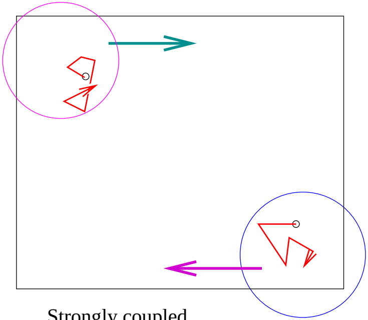


Weakly coupled
Long distance until next collision
Easy mixing

Large η/s: $u_\mu(x)$ changes due to pressure gradient and diffusion

Interaction Strength and Viscosity

Strong coupling does not allow momentum diffusion

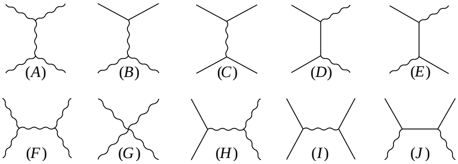


Strongly coupled
Very short distance until next collision
Mixing takes very long time

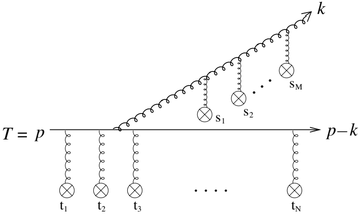
Small η/s: $u_\mu(x)$ changes due to pressure gradient only

Full leading order QCD calculation of η/s

Relevant processes



($\sim$ 80 %)

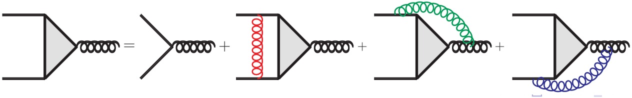


($\sim$ 20 %)

Use kinetic theory (equiv. to Kubo when linearized)

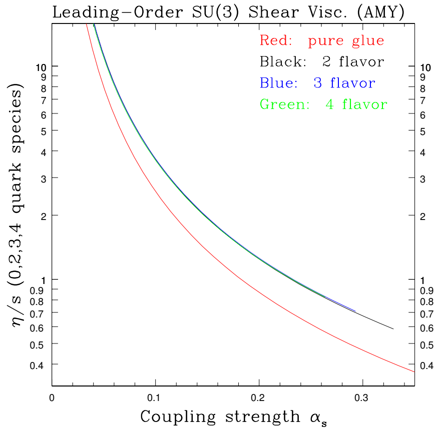
$$\frac{df}{dt} = \mathcal{C}_{2\leftrightarrow 2} + \mathcal{C}_{1\leftrightarrow 2}$$

Complication: 1 $\leftrightarrow$ 2 process needs resummation (LPM effect, AMY)
SD-Eq (Figure by G. Qin):



Full leading order QCD calculation of η/s

- Arnold-Moore-Yaffe (JHEP **0305**, 051 (2003)) [Updated figure from G.D. Moore]:



- Minimum $\eta/s \approx 0.6 \approx 7.5/4\pi$ for $\alpha_S \approx 0.3$
- Approximate formula

$$\eta/s \approx \frac{1}{15.4\alpha_S^2 \ln(0.46/\alpha_S)}$$

Shear viscosity in strongly coupled $\mathcal{N}=4$ SYM

Son, Starinets, Policastro, Kovtun, Buchel, Liu, ...

- Strong coupling limit, 4 ingredients
  - Kubo formula

$$\eta = \lim_{\omega\to 0} \frac{1}{2\omega} \int dt\, d^3x\, e^{i\omega t} \, \langle [T_{xy}(x), T_{xy}(0)] \rangle$$

  - Gauge-Gravity duality

$$\sigma_{\rm abs}(\omega) = \frac{8\pi G}{\omega} \int dt\, d^3x\, e^{i\omega t} \, \langle [T_{xy}(x), T_{xy}(0)] \rangle$$

  - $\lim_{\omega\to 0} \sigma_{\rm abs}(\omega) = A_{\rm blackhole}$
  - Entropy of the BH : $s = A_{\rm blackhole}/4G$

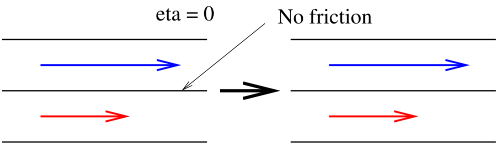
Therefore, (including the first order correction)

$$\frac{\eta}{s} = \frac{1}{4\pi}\left(1 + \frac{7.12}{(g^2 N_c)^{3/2}}\right)$$

Correction is small if $g \gg 1$ (10 % at $g = 2.4$).

To measure shear viscosity

Create this situation (Differential flow)



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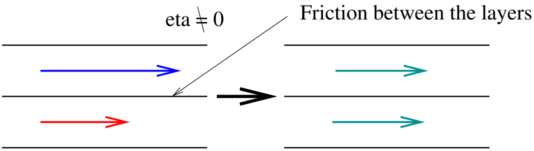
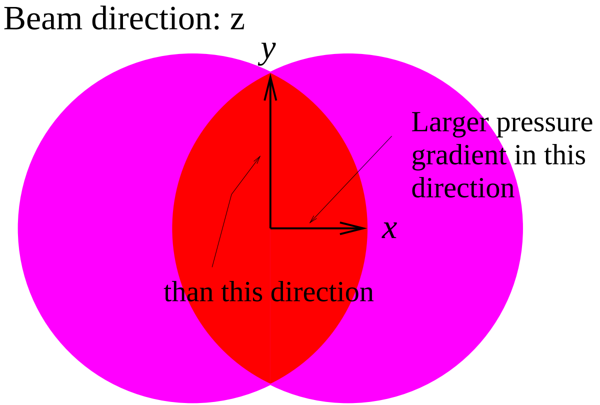


The velocities eventually become the same.

Elliptic Flow

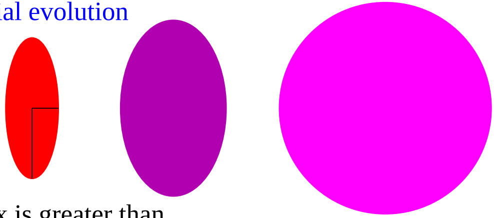
Hydrodynamic response of the system to the initial spatial anisotropy



Momentum anisotropy develops

$$\epsilon = \frac{\langle y^2 - x^2 \rangle}{\langle x^2 + y^2 \rangle}$$

Spatial evolution

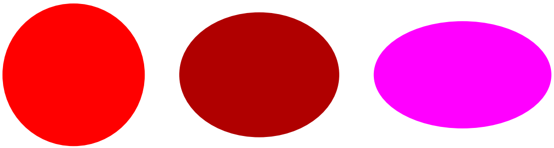


ΔP/Δ x is greater than
ΔP/Δ y

No more differential flow

Momentum space evolution

$$v_2 = \frac{\langle p_x^2 - p_y^2 \rangle}{\langle p_x^2 + p_y^2 \rangle}$$

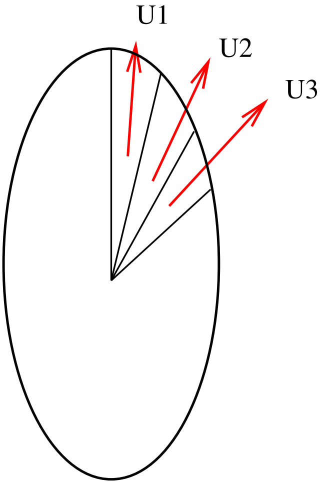


Initially spherical

Anisotropy is fixed

This happens within a few fm/c with $|v_{\mathrm{fin.}}| \sim 0.6\,c$.

Effect of viscosity



- $\eta = 0$ means $u_1 < u_2 < u_3$ is maintained for a long time
- $\eta \neq 0$ means that $u_1 \simeq u_2 \simeq u_3$ is achieved more quickly
- Shear viscosity smears out flow differences (it's a diffusion)
- Shear Viscosity reduces non-sphericity

Physics from Hydrodynamics

- Information content of single particle spectra

$$\frac{dN_i}{dy\, d^2p_T} = \frac{dN_i}{2\pi p_T dp_T dy}\left(1 + \sum_{n=1}^{\infty} 2v_{i,n}(p_T, y)\cos(n\phi)\right)$$

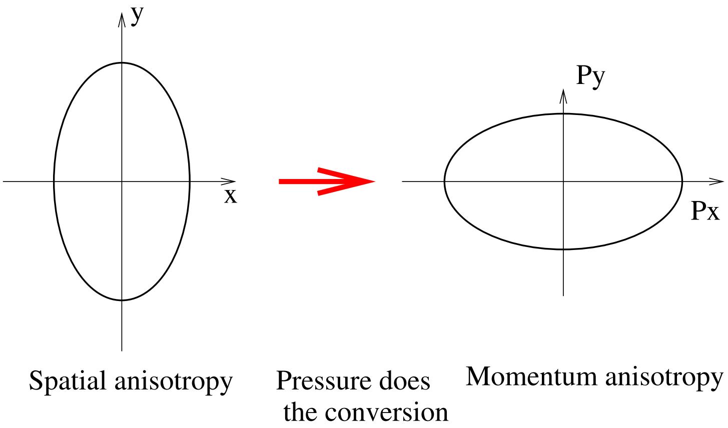
- "Flow", $v_{i,n}(p_T)$, comes from the initial state energy density distribution via pressure

$$\varepsilon(\mathbf{x}_T, \eta) = \varepsilon(r_T, \eta)\left(1 + \sum_{n=1}^{\infty} 2\epsilon_n(r_T, \eta)\cos(n\phi)\right)$$

- Efficiency of $\epsilon_n \to v_n$ depends on η/s

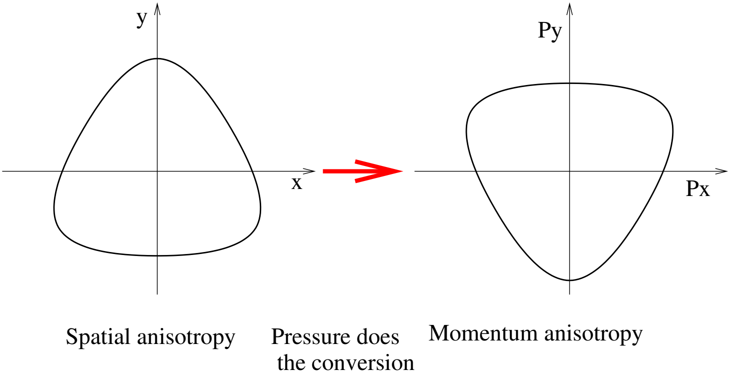
Physics from Hydrodynamics

- Elliptic Flow – $\cos(2\phi)$ component



Physics from Hydrodynamics

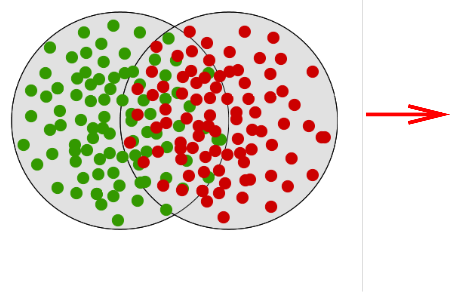
- Triangular Flow – $\cos(3\phi)$ component

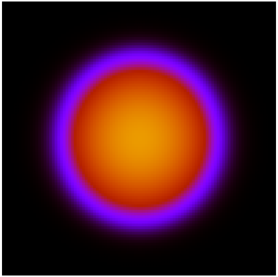


- In general: The higher n, the more sensitive to η/s

[Alver and Roland, Phys.Rev.C81:054905, 2010]

What determines the initial shape?

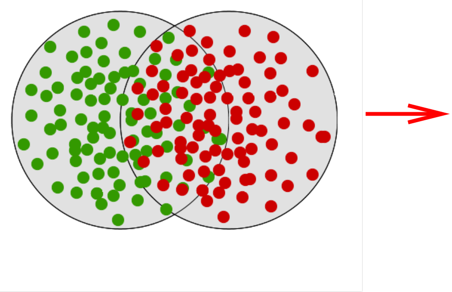


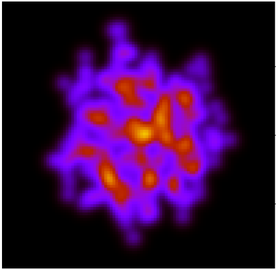


- Averaged smooth initial condition $\Longrightarrow$ Only $v_{\rm even}$'s survive.

Physics from Hydrodynamics

What determines the initial shape?





- Fluctuating initial condition $\Longrightarrow$ All v_n are non-zero.
- Local fluctuations $\Longrightarrow$ Higher v_n $\Longrightarrow$ More sensitive to dissipative smoothing

MUSIC

MUScl for Ion Collisions

MUSCL: Monotone Upstream-centered Schemes for Conservation Laws

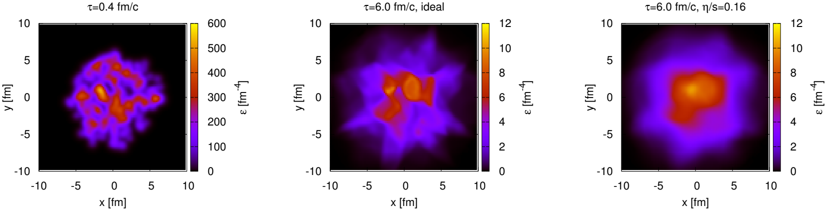
MUSIC

3+1D Event-by-Event Viscous Hydrodynamics

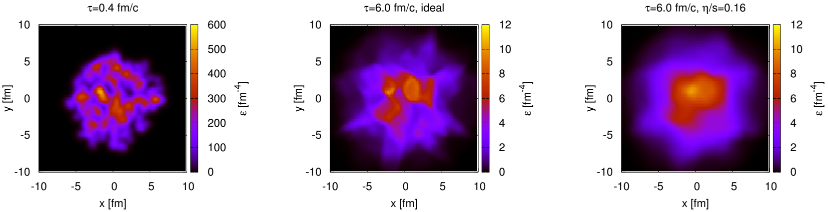
[Schenke, Jeon, Gale, Phys.Rev.Lett. 106 (2011) 042301, Phys.Rev. C82 (2010) 014903]

- 3+1D parallel implementation of Kurganov-Tadmor Scheme in (τ, η) with an additional baryon current (No need for a Riemann Solver. OK to take $\Delta t \to 0$.)
- Ideal and Viscous Hydro
- Event-by-Event fluctuating initial condition
- Sophisticated Freeze-out surface construction
- Full resonance decay (3+1D version of Kolb and Heinz)
- Many different equation of states including the newest from Huovinen and Petreczky
- New Development: UrQMD afterburner + Jet propagation (MARTINI)

Ideal vs. Viscous



Effect of viscosity

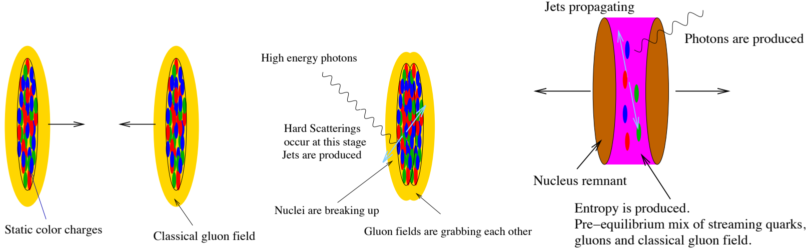


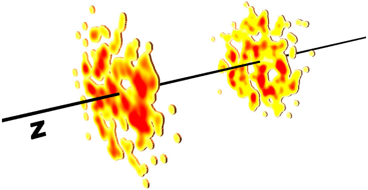
Initial condition   Ideal, $\tau = 6\,\text{fm}$ Viscous, $\tau = 6\,\text{fm}$

- Smoothing is evident
- Overall asymmetry is less affected
- The hot spots get much rounder
- v_3 is more affected than v_2

IP-Glasma

[Schenke, Tribedy and Venugopalan (STV), Phys.Rev. C86 (2012) 034908]

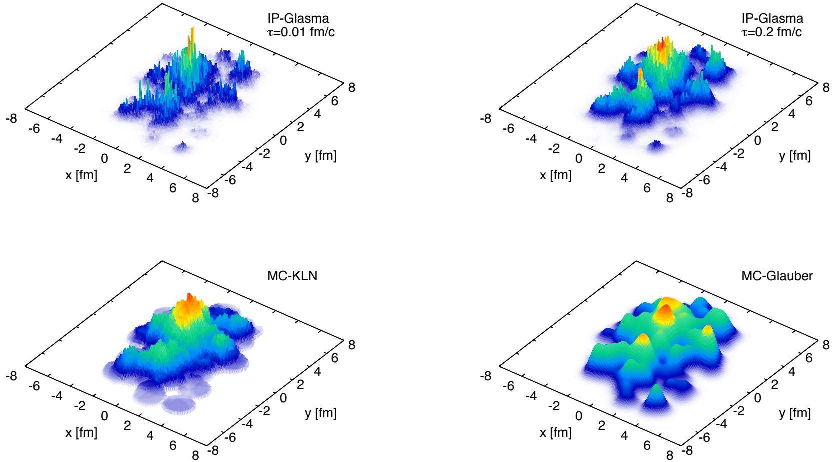




- Based on $[D_\mu, G^{\mu\nu}] = J^\nu$ with $J^\nu = \rho_A(x^-, \mathbf{x}_\perp)\delta^{+\nu} + \rho_B(x^+, \mathbf{x}_\perp)\delta^{-\nu}$
- $\rho_{A,B}(x^-, \mathbf{x}_\perp)$ distributions from IP-Sat
- Calculate the classical gluon field A^μ between the two receding disks (Glasma)

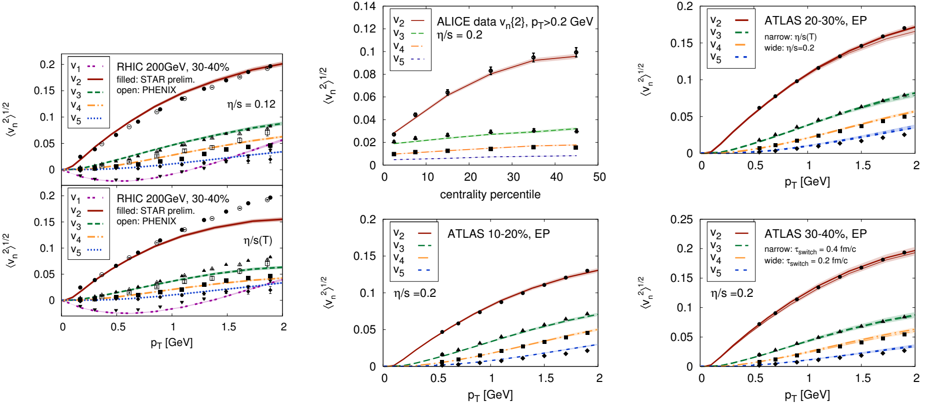
Initial Energy Density – IP-Glasma

Figures from [Schenke, Tribedy, Venugopalan, Phys.Rev.Lett.108.252301], [Gale, Jeon, Schenke, Int. J. of Mod. Phys. A, Vol. 28, 1340011 (2013)],



Not-so-ultra-central v_n

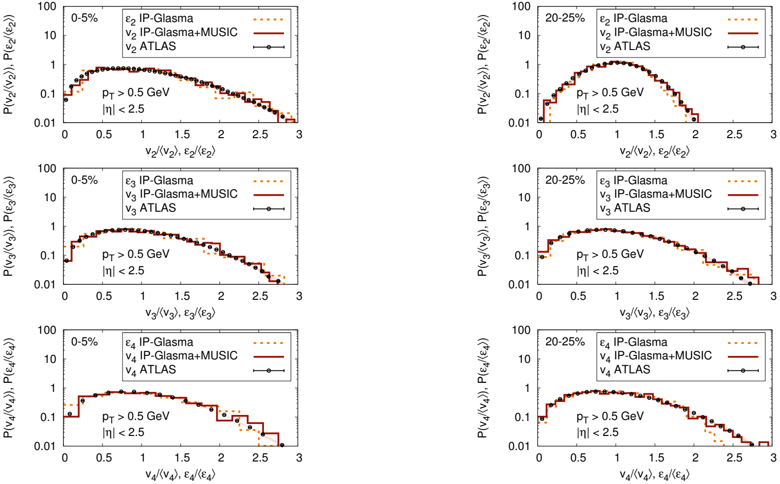
IP-Glasma RHIC and LHC:



Figures from [Gale, Jeon, Schenke, Tribedy and Venugopalan (GJSTV), Phys.Rev.Lett.110.012302]

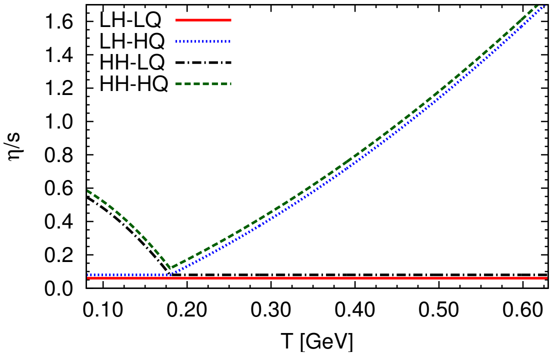
E-by-E v_n distributions

- E-by-E v_n is sensitive to E-by-E ϵ_n



Figures from [GJSTV, Nucl.Phys.A904-905 2013 (2013) 409c-412c]

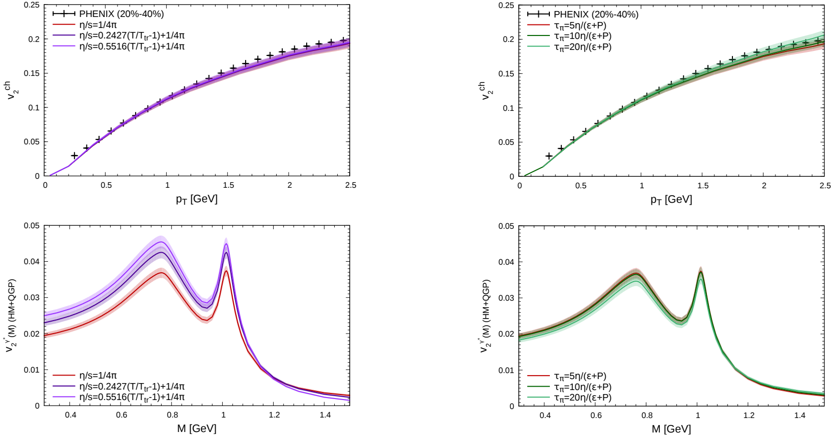
- RHIC: $\eta/s \approx 1/4\pi$
- LHC: $\eta/s \approx 2.5 \times 1/4\pi$
  or
- Temperature dependent $(\eta/s)(T)$ (We used HH-HQ)



[Niemi, Denicol, Huovinen, Molnar, Rischke, Phys.Rev. C86 (2012) 014909]

Influence of $(\eta/s)(T)$ and τ_π

[Vujanovic, Paquet, Denicol, Luzum, Schenke, Jeon, Gale, arXiv:1408.1098, Proc. of QM14]



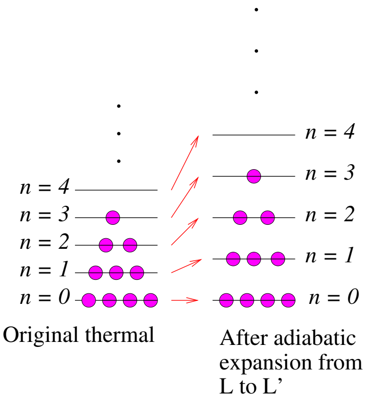
Hadronic and dilepton v_2 with differing $(\eta/s)(T)$

Hadronic and dilepton v_2 with differing τ_π

Bulk viscosity and ultra-central collisions

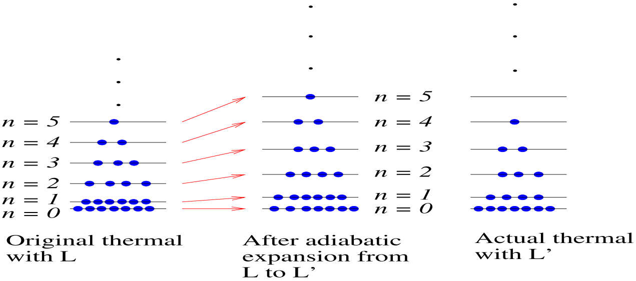
- QGP property to learn: ζ/s

Bulk viscosity in context



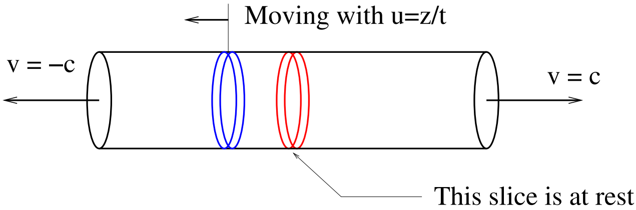
- Thermal occupation number in a box with the size L: $N_n(LT) = \exp(-2\pi n/LT)$ since $p_n = 2\pi n/L$.
- After an adiabatic expansion $L \to L'$, the original $\{N_n\}$ is still thermal with $T' = (L/L')T$
- Redistribution not necessary: $\zeta = 0$ for conformal theory

Bulk viscosity in context



- Thermal occupation number in a box with the size L:
  $N_n(m/T, LT) = \exp(-\sqrt{m^2/T^2 + (2\pi n)^2/L^2T^2})$ since $p_n = 2\pi n/L$.
- After an adiabatic expansion $L \to L'$, the original $\{N_n(m/T, LT)\}$ is no longer thermal: There is no choice of T' that will make the original $\{N_n\}$ looks like anther thermal distribution with L'
- Redistribution must occur: $\zeta \neq 0$ for non-conformal theory

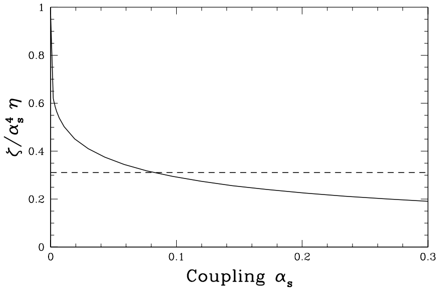
Bulk viscosity in context



- Bjorken flow – Idealized, but valid near mid-rapidity.
- Hubble-like flow in the beam direction
- Expansion disrupts local equilibrium unless conformal
- Entropy must increase $\Longrightarrow$ Multiplicity must increase
- Longitudinal expansion slows down when $\zeta \neq 0$
- Pressure degrades

Bulk viscosity calculations

- Kubo formula
  $$\zeta = \frac{1}{2}\lim_{\omega\to 0}\frac{1}{\omega}\int_{-\infty}^{\infty} dt\, e^{i\omega t}\int d^3x\,\left\langle[\hat{P}(x,t),\hat{P}(0,0)]\right\rangle$$
  Using energy conservation, can replace
  $$\hat{P} \to \frac{1}{3}\hat{T}^{\mu}_{\mu} = \hat{P} - \frac{1}{3}\hat{\varepsilon} \qquad (T^{\mu}_{\mu} = 0 \text{ if conformal})$$
- Leading order pQCD [Arnold, Dugan, Moore, Phys.Rev.D74:085021,2006]

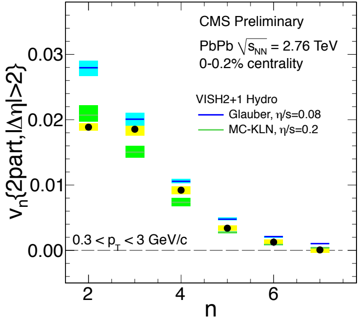


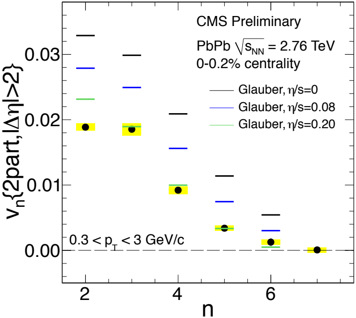
Dotted line: $\zeta = 15(1/3 - v_s^2)^2\eta$ (Weinberg)

- Pure Glue: $\zeta \approx 50(1/3 - v_s^2)^2\eta$
  [Dusling, Schaefer, Phys.Rev. C85 (2012) 044909]
- Relaxation time approx: $\zeta \approx 70(1/3 - v_s^2)^2\eta$
  [Denicol, Jeon, Gale, arXiv:1403.0962]
- $v_s^2 = \dfrac{\partial P}{\partial \varepsilon}$

Ultra-Central v_n

MC-Glauber & MC-KLN

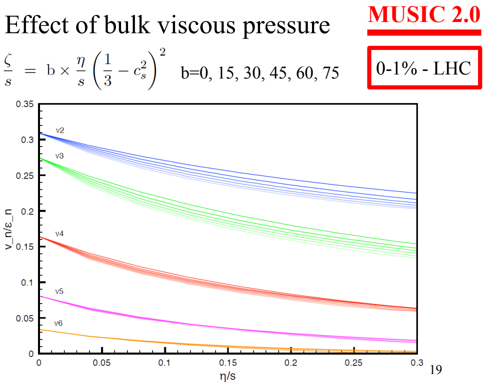




Figures from CMS-PAS HIN-12-011 and also [Harris, Kharzeev and Ullrich, 2012 CERN Courier 52 (no. 9) 17] and [Luzum and Ollitrault, Nuclear Physics A 904-905 (2013) pp. 377-380]

- Eccentricity $\epsilon_n \approx \epsilon_2$: Purely fluctuation driven
- The tension: Exp. $v_2 \approx v_3$ but Theo. $v_2 > v_3$
- Above calculations with $\zeta = 0$

Bulk viscosity and v_n/ϵ_n

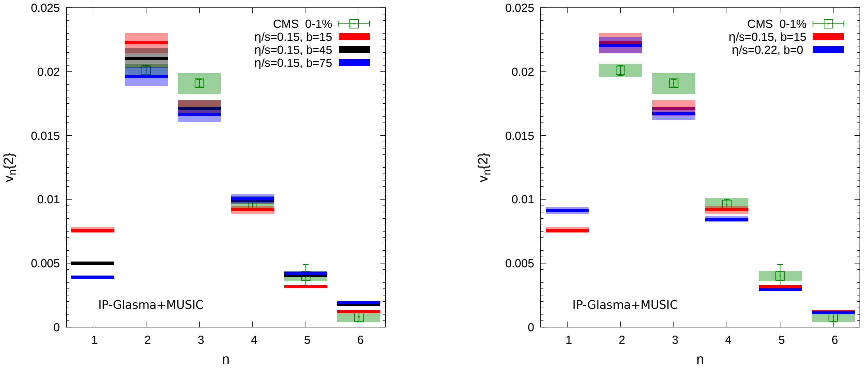


[Slide from G. Denicol's QM14 presentation]

- Higher harmonics $\Longrightarrow$ Less sensitive to ζ/s
- Ultra-central collision: $\epsilon_n \approx \epsilon_2$ – A good place for ζ/s to show up

The effect of non-zero bulk viscosity

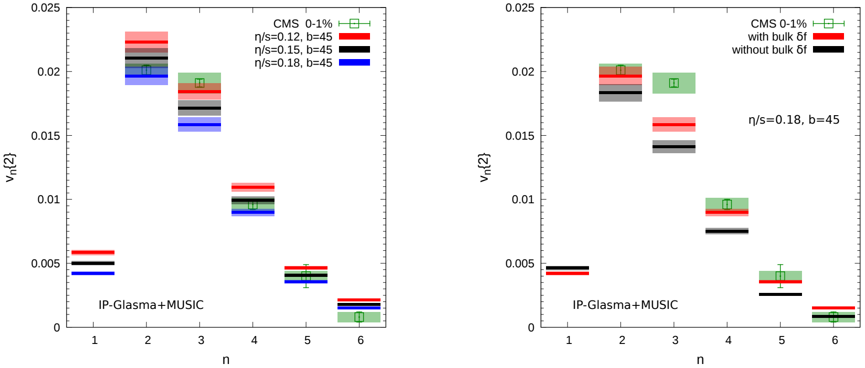
With $\zeta = b(1/3 - v_s^2)^2 \eta$



- Left: Effect of bulk viscosity with various values of b with η/s fixed
- Right: Trading bulk and shear

The effect of non-zero bulk viscosity

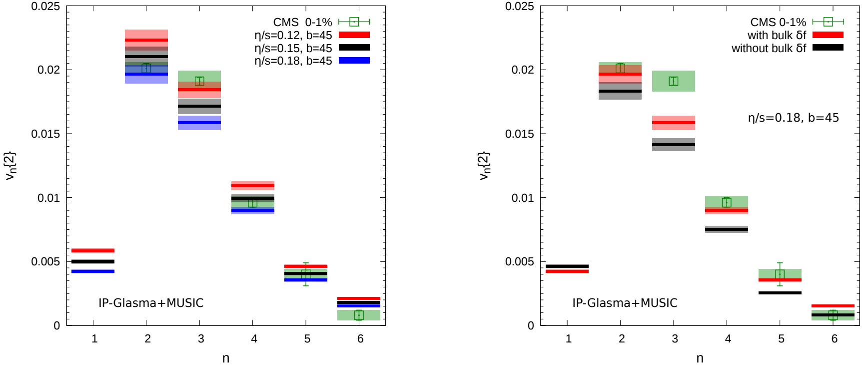
With $\zeta = b(1/3 - v_s^2)^2\eta$



- Left: Effect of bulk viscosity with various values of η/s with b fixed
- Right: Effect of bulk corrections in δf.

The effect of non-zero bulk viscosity

With $\zeta = b(1/3 - v_s^2)^2\eta$

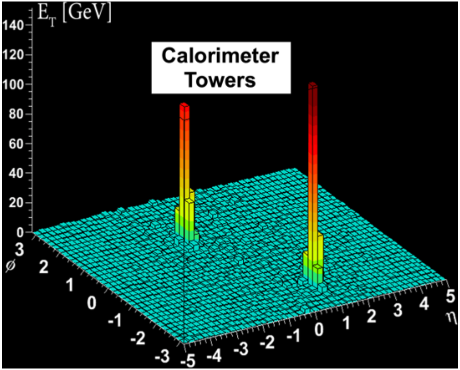


- Bulk viscosity improves the description
- Not perfect: Also need initial state nucleon-nucleon correlations
- Our best bet: $b \approx 45$

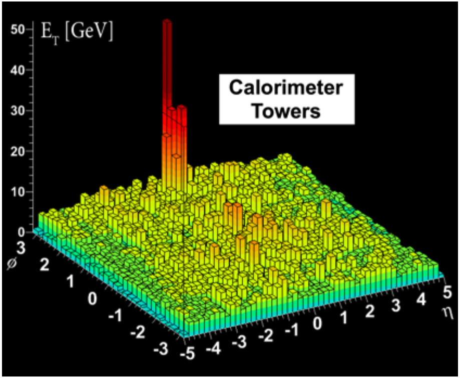
Jet Quenching
Transport Coefficient $\hat{q}$

- QGP property to learn: Jet-medium interaction

Jet Quenching

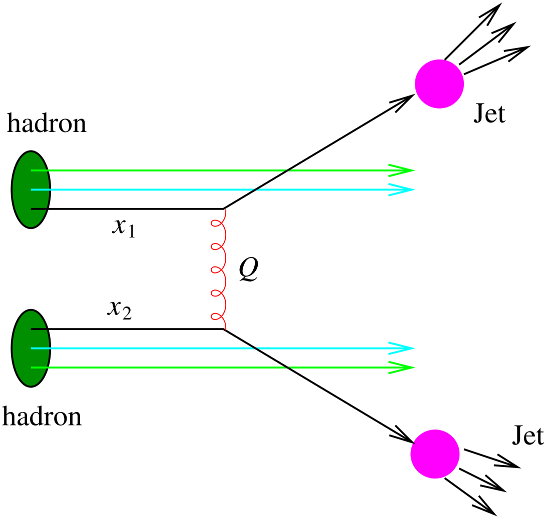


ATLAS: Two jets visible – Surface emission



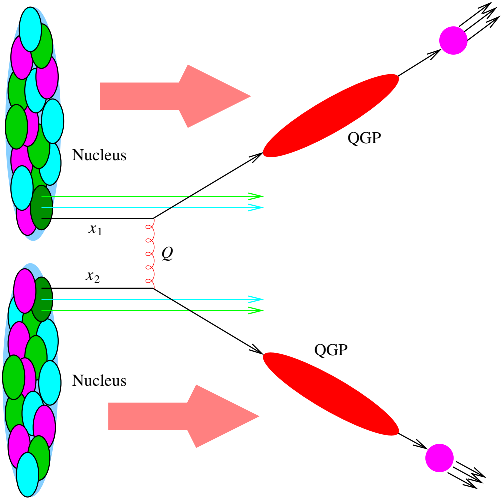
ATLAS: Mono jet. One jet escapes and its partner disappears in medium.

QCD Jets



We understand this. More or less.

Schematic Understanding

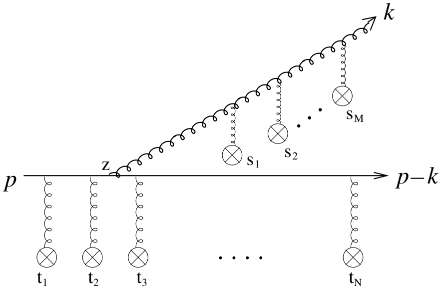


HIC Jet production scheme:

$$\frac{d\sigma_{AB}}{dt} = \int_{\text{geometry}} \int_{abcdc'} \times f_{a/A}(x_a, Q_f) f_{b/B}(x_b, Q_f) \times \frac{d\sigma_{ab\to cd}}{dt} \times \mathcal{P}(x_c \to x_c' | T, u^\mu) \times D(z_c', Q)$$

$\mathcal{P}(x_c \to x_c' | T, u^\mu)$: Medium modification of high energy parton property

Main radiative process in Energy Loss



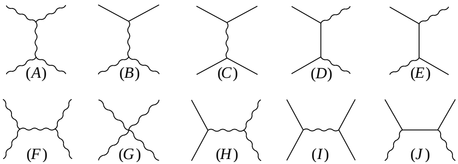
- Landau-Pomeranchuck-Migdal effect important - BDMPS-Z
- Relevant QGP property:

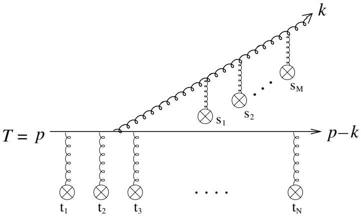
$$\hat{q} = \frac{\mu^2}{\lambda_{\rm mfp}}$$

where μ is the average (spatial) momentum exchange and $\lambda_{\rm mfp}$ is the elastic collision mean free path.

Full leading order QCD calculation of energy loss rate

Relevant processes – The same as η/s calculation





Use kinetic theory to calculate the evolution of the jet

$$\frac{df}{dt} = \mathcal{C}_{2\leftrightarrow 2} + \mathcal{C}_{1\leftrightarrow 2}$$

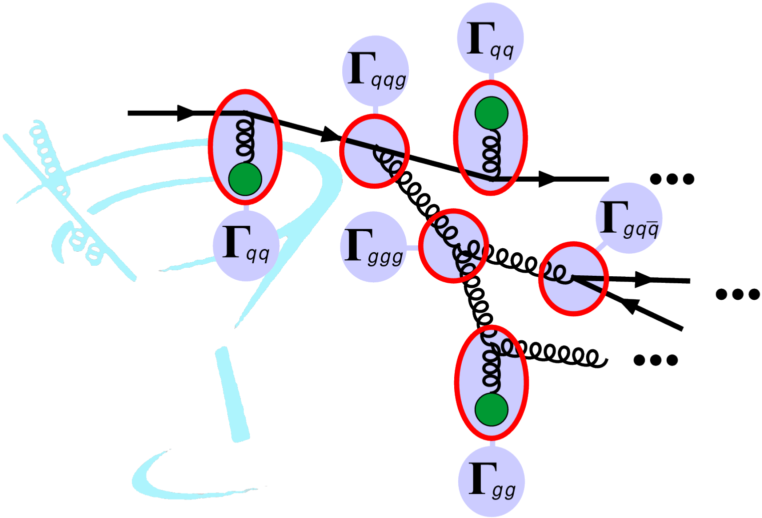
Complication 1: $1 \leftrightarrow 2$ process needs resummation (LPM effect, AMY)
Complication 2: Needs to keep track of the daughters
[c.f. E. Iancu's talk on Monday]

MARTINI

MARTINI

- Modular Alogorithm for Relativistic Treatment of Heavy IoN Interactions
- Hybrid approach
  - Calculate Hydrodynamic evolution of the soft mode
  - Propagate jets in the evolving medium according to McGill-AMY

Parton propagation



An example path in MARTINI

Example – A MARTINI Run

MARTINI movie made by B. Schenke

Determining $\hat{q}$ from Jet Quenching

JET Collaboration

- Miklos Gyulassy (Columbia University)
- Paul Romatschke (University of Colorado, Boulder)
- Steffen Bass, Berndt Mueller (Duke University)
- Michael Strickland (Kent State University)
- Xin-Nian Wang (co-spokesperson & project director) (LBNL)
- Ramona Vogt (LLNL)
- Ivan Vitev (LANL)
- Chales Gale, Sangyong Jeon (McGill University)
- Ulrich Heinz (co-spokesperson) (Ohio State University)
- Denes Molnar (Purdue University)
- Rainer Fries, Cheming Ko (Texas A & M University)
- Abhijit Majumder (Wayne State University)

Determining $\hat{q}$ from Jet Quenching

Extracting jet transport coefficient from jet quenching at RHIC and LHC,
JET Collaboration, Burke et al. Phys.Rev. C90 (2014) 014909

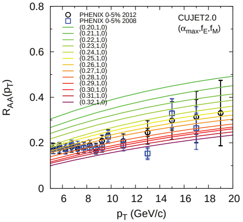
- Models
  - GLV-CUJET (Columbia)
  - HT-BW (Berkeley-Wuhan)
  - HT-M (Wayne State)
  - MARTINI (McGill)
  - McGill-AMY (McGill-Wuhan)

Determining $\hat{q}$ from Jet Quenching

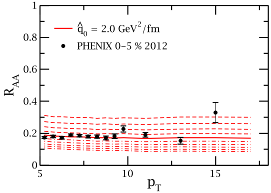
- All models based on many-body QCD
- Differences in dealing with the medium and multiple collisions
- All have adjustable parameters that can be related to $\hat{q}$

Determining $\hat{q}$ from Jet Quenching

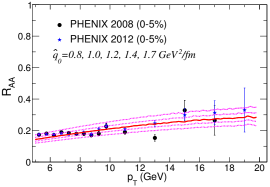
$$R_{AA} = \frac{dN_{AA}/dp_T dy}{N_{\rm coll} dN_{pp}/dp_T dy}$$ plots for RHIC



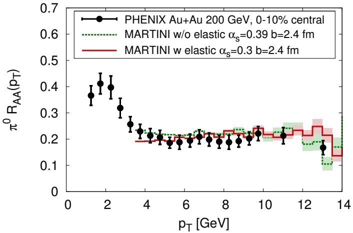
CUJET



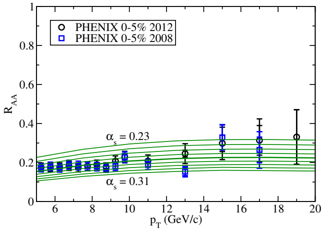
HT-M



HT-BW



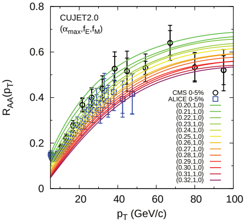
MARTINI



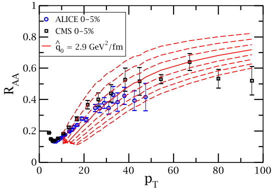
McGill-AMY

Determining $\hat{q}$ from Jet Quenching

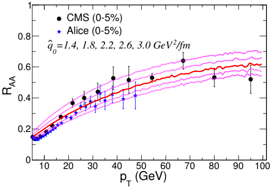
$R_{AA} = \dfrac{dN_{AA}/dp_T dy}{N_{\rm coll} dN_{pp}/dp_T dy}$ plots for the LHC



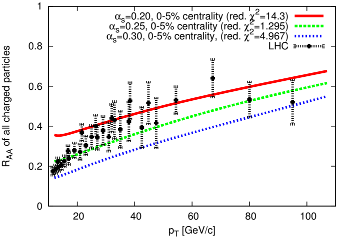
CUJET



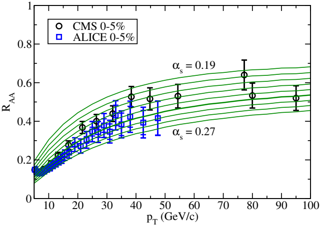
HT-M



HT-BW



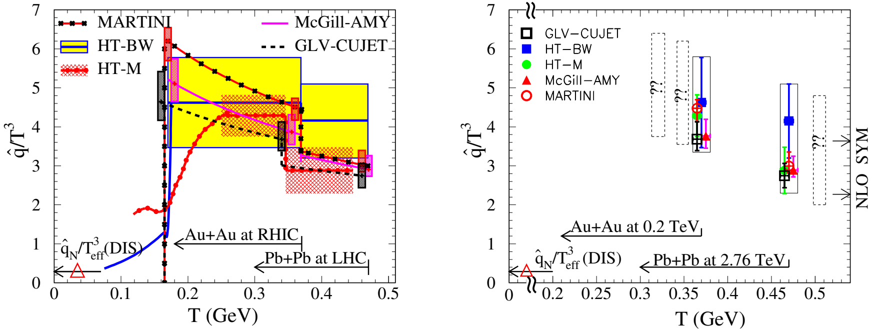
MARTINI



McGill-AMY

Determining $\hat{q}$ from Jet Quenching

JET Collaboration



- RHIC: $\hat{q}/T^3 \approx 3 - 6$
- LHC: $\hat{q}/T^3 \approx 2 - 5$

Summaries and After-thoughts

- High statistics data from RHIC and the LHC starting to permit precise evaluation of QGP properties such as $\eta/s, \zeta/s, \hat{q}$
- All parts of heavy ion collision calculations/simulations/event-generations (initial conditions, hydro evolution, hadronic afterburner, jet-medium interactions) are maturing
- Theory challenges:
  - Non-perturbative calculations of QGP properties with $\alpha_S \approx 0.3$ or $g \approx 2$
  - Thermalization mechanism ? [c.f. A. Kurkela's talk on Tuesday]
  - Hadronization mechanism ?


Hard Probes 2015
June 29 – July 03, 2015
McGill
Montréal

Backup Slides

Charge fluctuations

- QGP property to learn: Deconfined quarks and gluons?

Simple idea

$$\left\langle \delta Q^2 \right\rangle_{\rm th} = q^2 \left\langle \delta N^2 \right\rangle_{\rm th} \approx q^2 \left\langle N \right\rangle_{\rm th}$$

- QGP: $q_u = 2/3$, $q_{d,s} = -1/3$, $q_g = 0$
- Hadrons: $q = 0, 1, 2, \cdots$
- With $\langle N_{\rm parton} \rangle \approx \langle N_{\rm hadron} \rangle \sim (3/2) \langle N_{\rm ch} \rangle$,

$$\frac{\left\langle \delta Q^2 \right\rangle_{\rm free\ QGP}}{\langle N_{\rm ch} \rangle} \sim 1/4$$

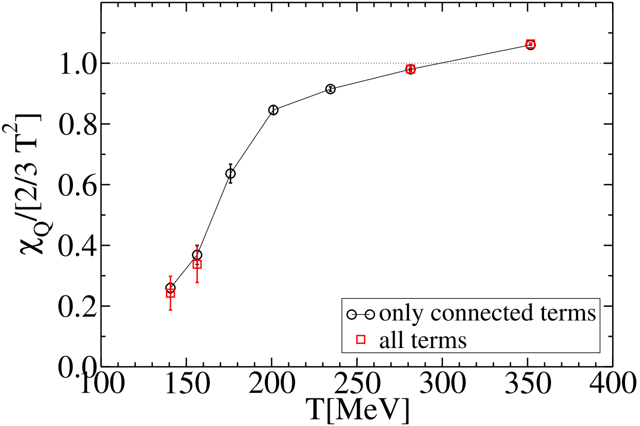
$$\frac{\left\langle \delta Q^2 \right\rangle_{\rm free\ \pi}}{\langle N_{\rm ch} \rangle} \sim 1$$

[Jeon & Koch, Phys.Rev.Lett. 85 (2000) 2076-2079,
Asakawa, Heinz & Muller, Phys.Rev.Lett. 85 (2000) 2072-2075

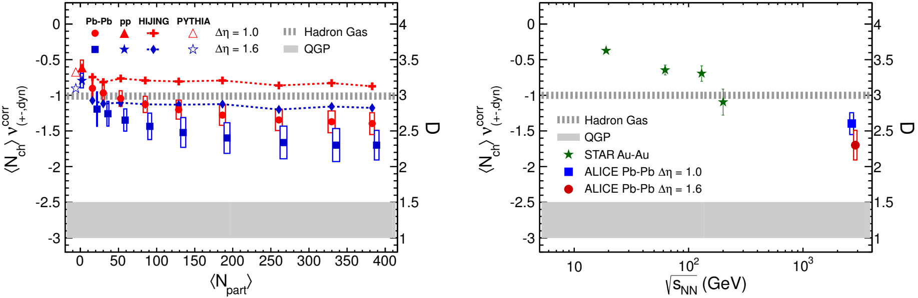
Similar conclusions from the balance function approach by S. Pratt]

Charge susceptibility from LQCD

[Giudice et al. arXiv:1309.6523]



- $\left\langle \delta Q^2 \right\rangle = \chi_Q$
- In QGP phase, χ_Q is close to the free QGP limit



[ALICE, Phys.Rev.Lett. 110 (2013) 15, 152301]

- Left: D as a function of centrality
- Right: D as a function of collision energy
- Conclusion: Smaller fluctuations seen but it seems to be contaminated by re-equilibration in the hadronic phase

Expected QGP Properties

Expected properties (3 light flavors)

- High number density

$$n \approx (36+16) \int \frac{d^3p}{(2\pi)^3} e^{-p/T} \approx 5\,T^3$$
$$= 5 \left(\frac{T}{200\,\text{MeV}} \right)^3 \text{fm}^{-3}$$

- High energy density

$$\varepsilon \approx (36+16) \int \frac{d^3p}{(2\pi)^3} p\, e^{-p/T} \approx 15\,T^4$$
$$= 3 \left(\frac{T}{200\,\text{MeV}} \right)^4 \text{GeV}/\text{fm}^3$$

- RHIC central collisions: $T \sim 390\,\text{MeV}$ or $\varepsilon \sim 40 - 45\,\text{GeV}/\text{fm}^3$
- LHC central collisions: $T \sim 470\,\text{MeV}$ or $\varepsilon \sim 90 - 95\,\text{GeV}/\text{fm}^3$

Expected properties – Cont.

- High pressure (approximately conformal if coupling is weak)

$$P \approx \frac{1}{3}\varepsilon$$

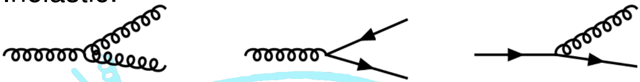
- Quarks carry fractional charges. About 30 % of entropy $(s = (\varepsilon + P)/T)$ is in the gluons. $\Longrightarrow$ Small charge/entropy ratio
- First order? Second order? Cross-over? – Critical point?

MARTINI Backups

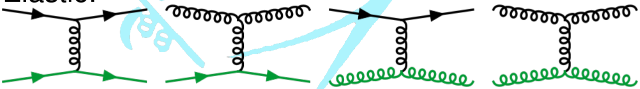
Parton propagation

Process include in MARTINI (all of them can be switched on & off):

- Inelastic:



- Elastic:

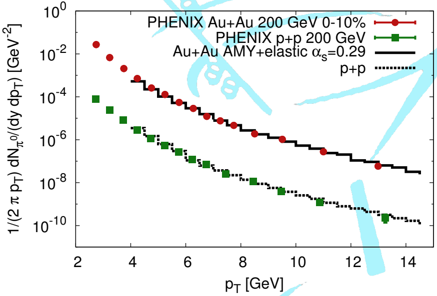


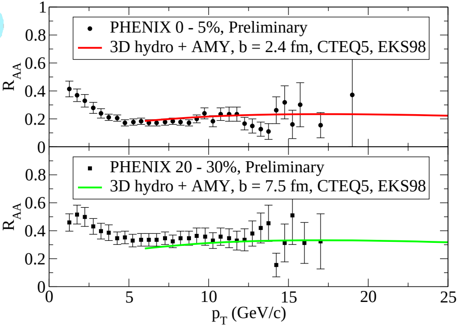
- Conversion:

- Photon: emission & conversion

[Schenke, Jeon and Gale, Phys. Rev. C 80, 054913 (2009)]

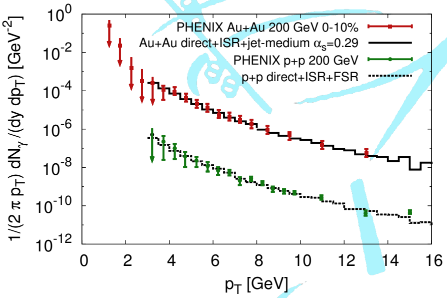
- π^0 spectra and R_{AA}

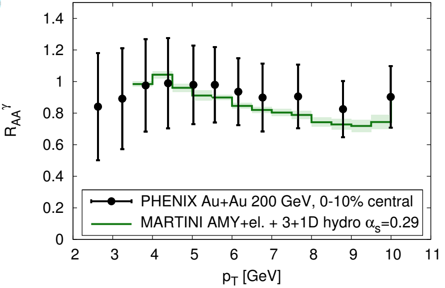




[Schenke, Jeon and Gale, Phys. Rev. C 80, 054913 (2009)]

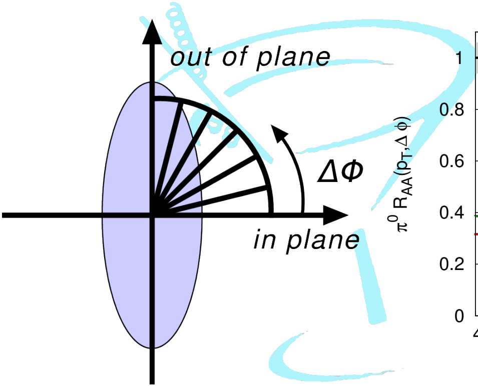
- Spectra and R_{AA}^{γ}

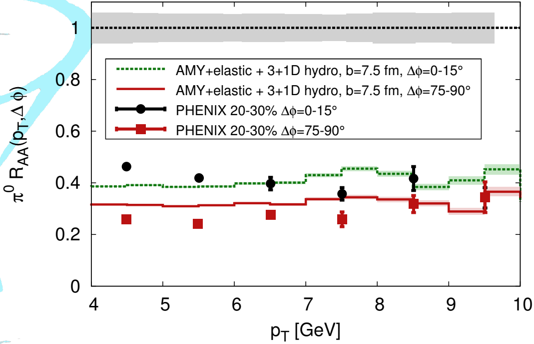




Azimuthal dependence of R_{AA}

- $R_{AA}(p_T, \Delta\phi)$

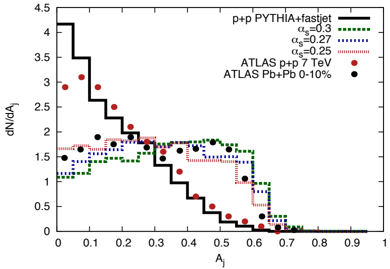


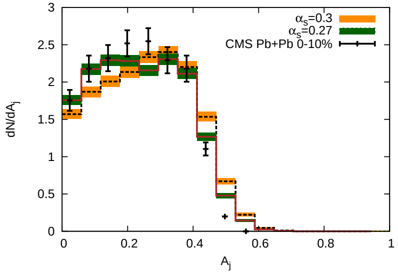


MARTINI – dN/dA

- $A = (E_t - E_a)/(E_t + E_a)$
- Right now ideal hydro with a smooth initial condition
- Full jet reconstruction with FASTJET

[Young, Schenke, Jeon, Gale, arXiv:1103.5769]





ATLAS, QM 2011

CMS, arXiv: 1102.1957 (2011)

Hydro Backups

Shear viscosity in context

- Energy-momentum conservation $\partial_\mu T^{\mu\nu} = 0$
- Local energy density and energy flow

$$T^{\mu\nu} u_\nu = -\varepsilon u^\mu$$

- Decomposition to non-dissipative and dissipative components

$$T^{\mu\nu} = \varepsilon\, u^\mu u^\nu + P(\varepsilon)(g^{\mu\nu} + u^\mu u^\nu) + \pi^{\mu\nu}$$

- Dissipative part ($\Delta^{\mu\nu} = g^{\mu\nu} + u^\mu u^\nu$, $\nabla^\mu = \Delta^{\mu\nu}\partial_\nu$)

$$\pi^{\mu\nu}_{\rm NS} = -\eta\left(\nabla^\mu u^\nu + \nabla^\nu u^\mu - \frac{2}{3}\Delta^{\mu\nu}\nabla^\alpha u_\alpha\right) - \zeta\Delta^{\mu\nu}\nabla^\alpha u_\alpha$$

Minus signs dictated by increasing entropy

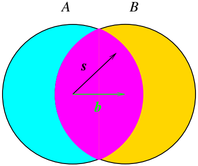
- Second order dissipative hydrodynamics

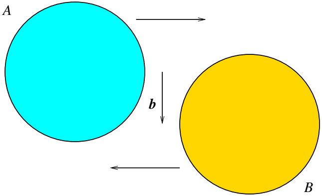
$$\Delta^{\mu\alpha}\Delta^{\nu\beta} u{\cdot}\partial\pi_{\alpha\beta} = -\frac{1}{\tau_\pi}\left(\pi^{\mu\nu} - 2\eta\nabla^{\langle\mu} u^{\mu\rangle} + \frac{4}{3}\tau_\pi\pi^{\mu\nu}(\partial_\alpha u^\alpha)\right)$$

[Baier, Romatschke, Son, Starinets, Stephanov JHEP 0804 (2008) 100]

Smooth (or Average) Initial Conditions

Optical Glauber



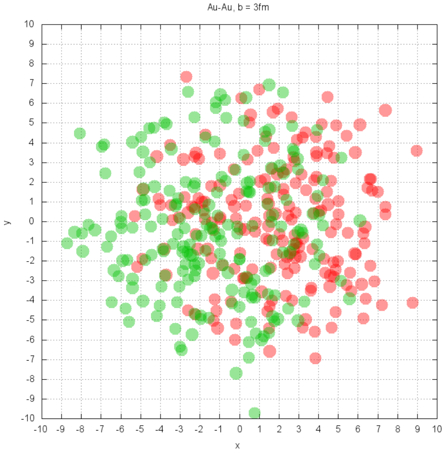


- Thickness functions: $T_{A,B}(\mathbf{s}) = \int_{-\infty}^{\infty} dz\, \rho_{A,B}(z, \mathbf{s})$
- Overlap function: $T_{AB}(\mathbf{b}) = \int d^2s\, T_A(\mathbf{s}) T_B(\mathbf{s} - \mathbf{b})$
- Number of collisions: $N_{\rm coll}(\mathbf{b}) = ABT_{AB}(\mathbf{b})\sigma_{\rm inel}^{\rm NN}$
- Number of participants:

$$
\begin{aligned}
N_{\rm part}(\mathbf{b}) = \\
& A \int d^2s\, T_A(\mathbf{s}) \left(1 - \left[1 - T_B(\mathbf{s} - \mathbf{b})\sigma_{\rm inel}^{\rm NN}\right]^B\right) \\
& + B \int d^2s\, T_B(\mathbf{s} - \mathbf{b}) \left(1 - \left[1 - T_A(\mathbf{s})\sigma_{\rm inel}^{\rm NN}\right]^A\right)
\end{aligned}
$$

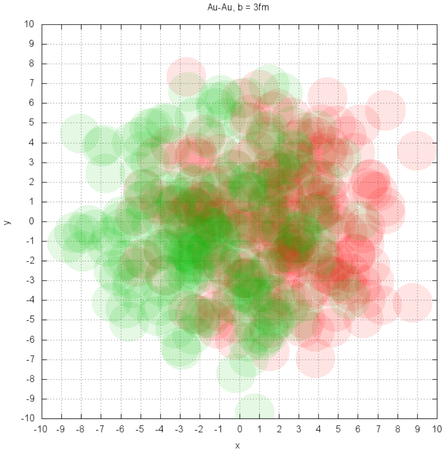
- Smooth distribution $\Longrightarrow$ No fluctuations. No $\epsilon_{\rm odd}$ nor $v_{\rm odd}$

Fluctuating Initial Conditions



1. Sample nucleon positions

Fluctuating Initial Conditions



1. Sample nucleon positions
2. Decide what collides with what
3. Decide how much energy is deposited
4. Calculate the energy density in the hydro cells

MC-Glauber

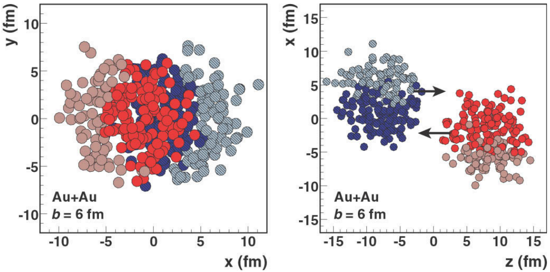
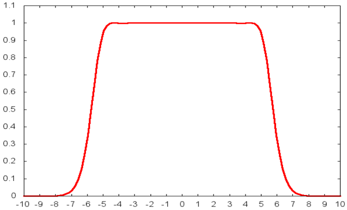


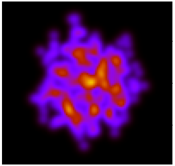
Figure from [Miller, Reygers, Sanders and Steinberg, Ann. Rev. Nucl. Part. Sci. 57 (2007) 205-243]

- Nucleon positions sampled from $T_{A,B}(\mathbf{s})$
- Collision if $d \leq \sqrt{\sigma_{\rm inel}^{NN}/\pi}$

MC-Glauber



Profile in η



Transverse profile

- Energy density in a hydro cell positioned at $\mathbf{x}_\perp^K$

$$\epsilon_\perp(\mathbf{x}_\perp^K) = \sum_{J=1}^{N_w} \frac{\epsilon_0}{2\pi\sigma^2} e^{-(\mathbf{x}_\perp^K - \mathbf{x}_\perp^J)^2/2\sigma^2}$$

- The sum is over all wounded nucleons (usually truncated) with $\sigma \sim \tau_0$.
- η profile: Smooth. An Wood-Saxon or a stretch-Gaussian

QCD Estimates of η/s

- Danielewicz and Gyulassy [PRD **31**, 53 (1985)]:
  - η/s bound from the kinetic theory:

$$\frac{\eta}{s} \gtrsim \frac{1}{12} \approx 0.08$$

  - QCD estimate in the small α_S limit with $N_f = 2$ and $2 \to 2$ only (min. at $\alpha_S = 0.6$):

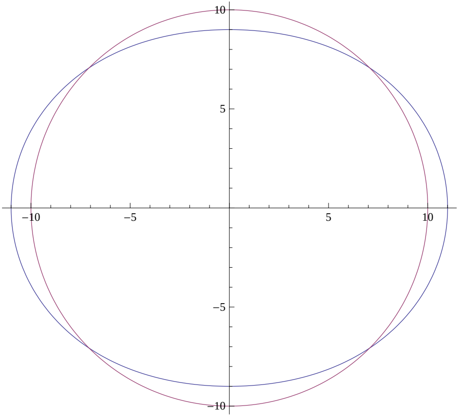
$$\eta \approx \frac{T}{\sigma_\eta} \approx \frac{0.57\,T^3}{\alpha_S^2 \ln(1/\alpha_S)} \gtrsim 0.2s$$

- Baym, Monien, Pethick and Ravenhall [PRL 64, 1867 (1990)]

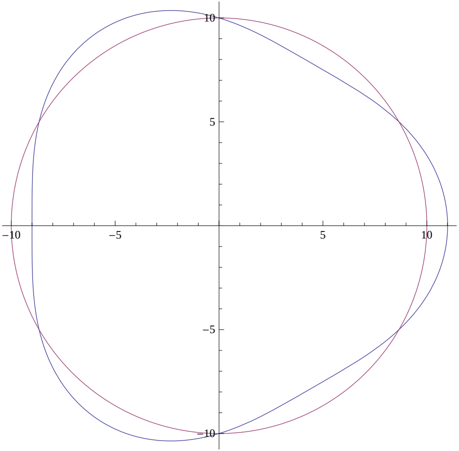
$$\eta \approx \frac{1.16\,T^3}{\alpha_S^2 \ln(1/\alpha_S)} \gtrsim 0.4s \approx (5/4\pi)s$$

- M. Thoma [PLB 269, 144 (1991)]

$$\eta \approx \frac{1.02\,T^3}{\alpha_S^2 \ln(1/\alpha_S)} \gtrsim 0.4s \approx (5/4\pi)s$$

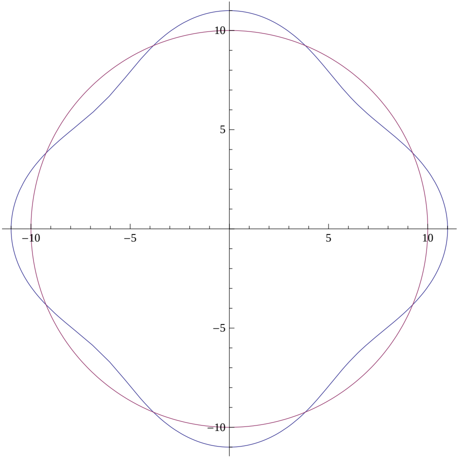


This causes elliptic flow. It is harder to destroy this than

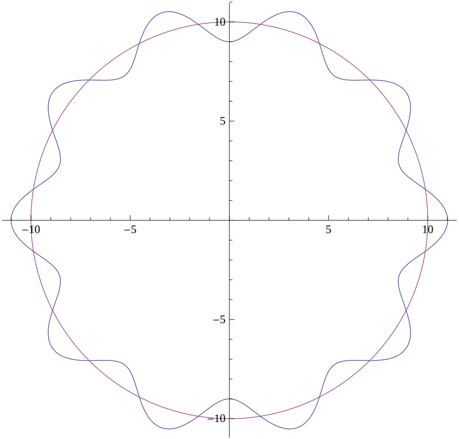


this (v_3) ...

ϵ_n



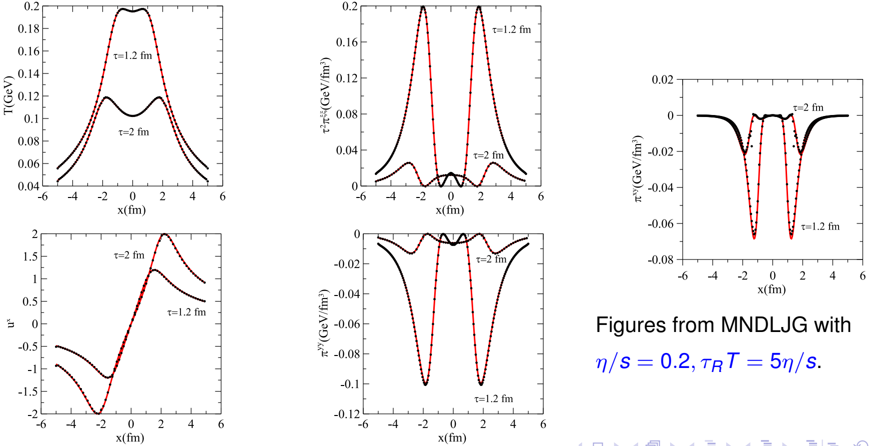
or this (v_4) ...



or this (v_{10}) ...

Confidence in viscous-hydro solutions

- Comparison with the viscous-Gubser flow and MUSIC
- Analytic ideal-hydro solution by [Gubser, Phys. Rev. D 82, 085027 (2010), Gubser and A. Yarom, Nucl. Phys. B 846, 469 (2011)]
- Semi-analytic Viscous-hydro solution by [Marrochio, Noronha, Denicol, Luzum, Jeon and Gale, arXiv:1307.6130].

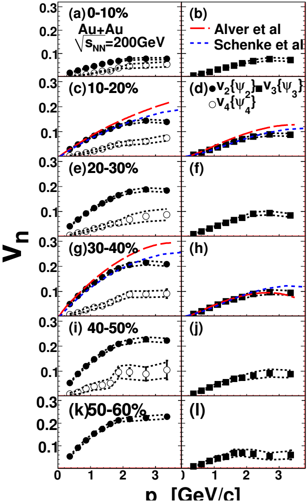


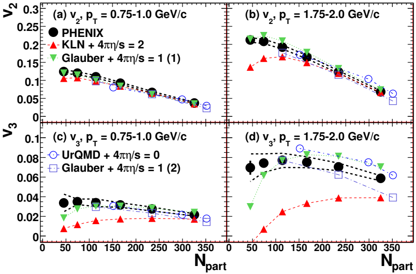
Figures from MNDLJG with

$\eta/s = 0.2, \tau_R T = 5\eta/s$.

E-by-E MUSIC vs RHIC Data

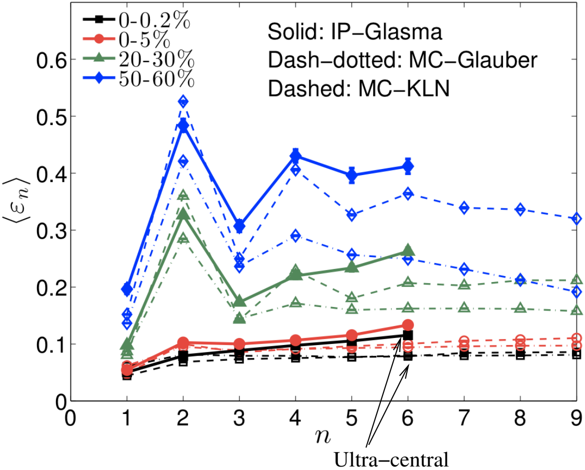
Phenix (arXiv:1105.3928)





v_3: Our predictions (Green Triangles)

Eccentricity distributions



In UC collisions: ϵ_n are almost purely fluctuation driven.

Figure from [Heinz and Snelling, Annu. Rev. Nucl. Part. Sci. 63 (2013) 123-151]

How Central is Ultra-Central?

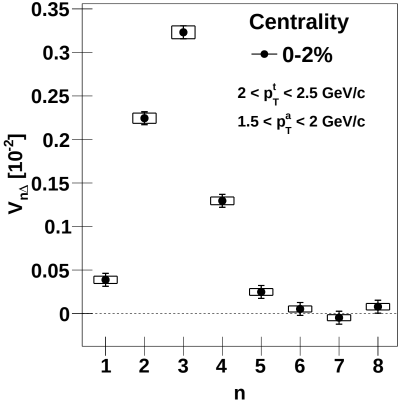
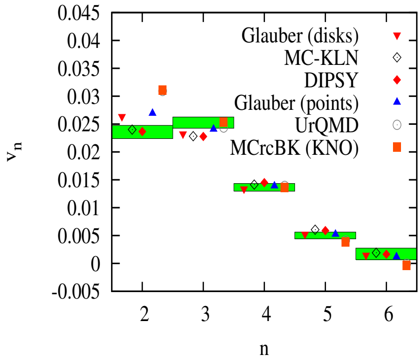


Figure from [ALICE, Phys.Lett. B708 (2012) 249-264]



[Green bars: $0 - 1\,\%$ ATLAS]. Figure from [Luzum and Ollitrault, Nuclear Physics A 904-905 (2013) pp. 377-380]

- As Centrality $\to 0$, $v_3 \to v_2$
- At $0 - 1\,\%$, $v_3 \approx v_2$