

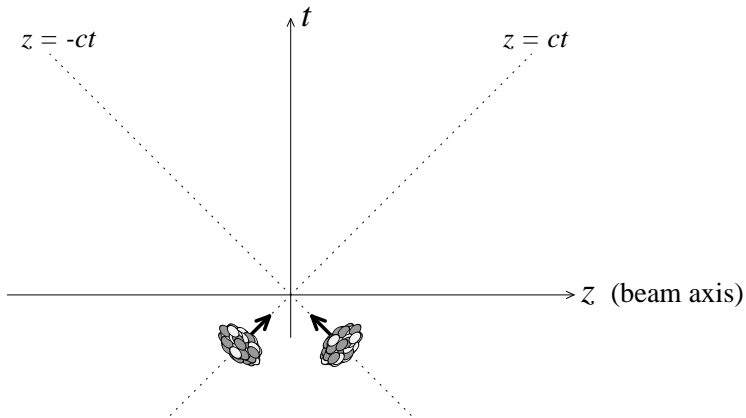
# *QCD in Heavy Ion Collisions: II*

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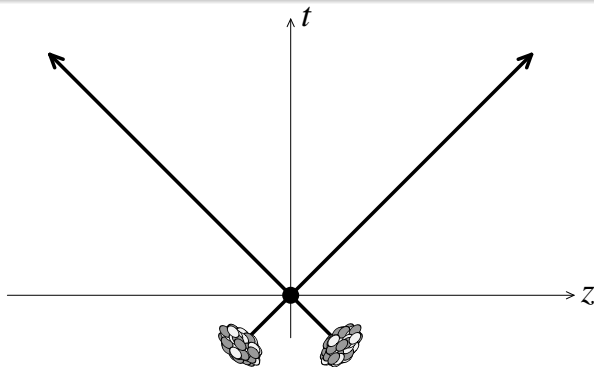


# Lecture I: Initial conditions



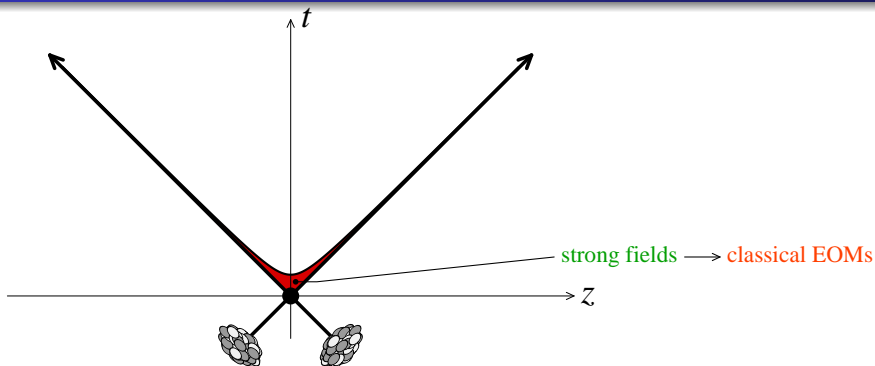
- $\tau < 0$  : hadronic wavefunctions prior to the collision
  - high-energy evolution & the Color Glass Condensate
  - it applies to any highly energetic hadron (proton or nucleus)

# Lecture I: Initial conditions



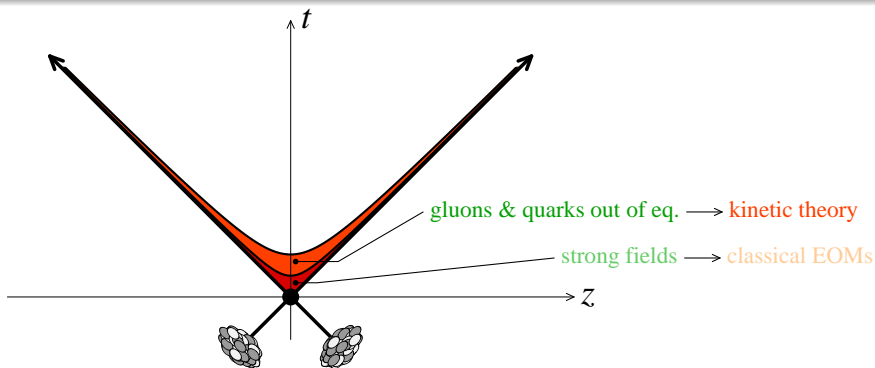
- $\tau < 0$  : hadronic wavefunctions prior to the collision
- $\tau \sim 0 \text{ fm}/c$  : the hard scattering
  - production of hard particles: jets, direct photons, heavy quarks
  - calculable within (standard) perturbative QCD ('leading twist')
  - 'hard probes' of the surrounding medium

# Lecture I: Initial conditions



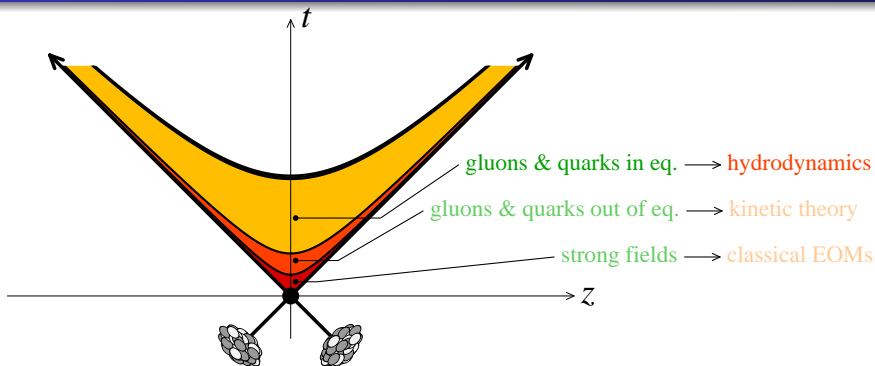
- $\tau < 0$  : hadronic wavefunctions prior to the collision
- $\tau \sim 0 \text{ fm}/c$  : the hard scattering
- $\tau \sim 0.2 \text{ fm}/c$  : strong color fields (or 'glasma')
  - semi-hard quanta ( $p_{\perp} \lesssim 2 \text{ GeV}$ ): gluons, light quarks
  - make up for most of the multiplicity
  - sensitive to the physics of saturation ('higher twist')

# Lecture II: Quark–Gluon Plasma



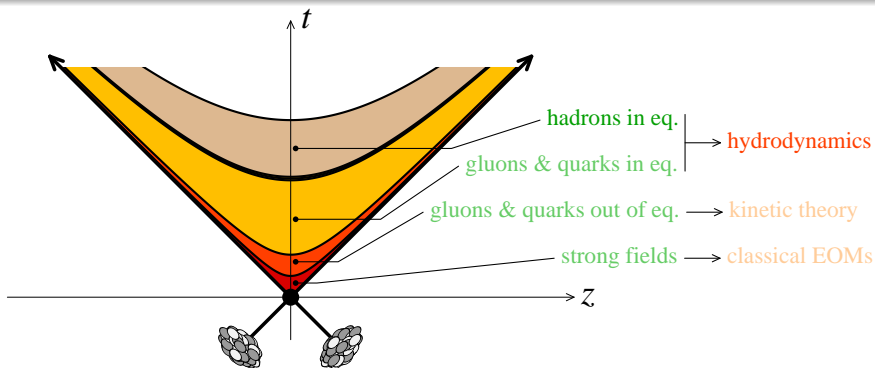
- $\tau \sim 1 \text{ fm}/c$  : thermalization
  - experiments suggest a fast thermalization
  - ...but this is not yet firmly understood within QCD
  - weak or strong coupling ?
  - kinetic theory, plasma instabilities, AdS/CFT

# Lecture II: Quark–Gluon Plasma



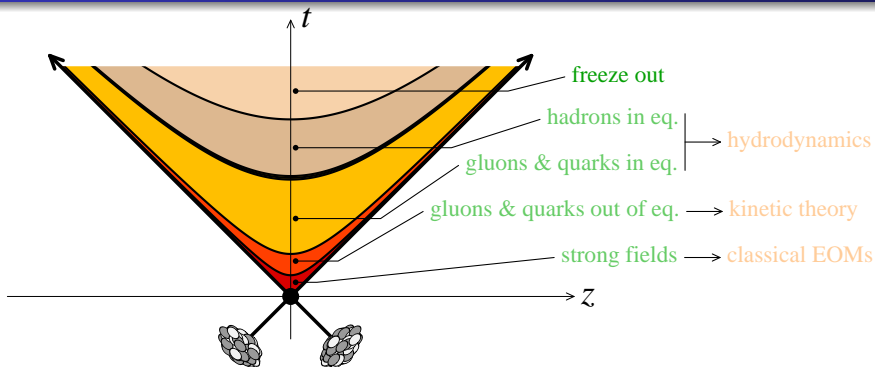
- $\tau \sim 1 \text{ fm}/c$  : thermalization
- $1 \lesssim \tau \lesssim 10 \text{ fm}/c$  : quark–gluon plasma
  - thermodynamics: lattice QCD vs. perturbative QCD
  - transport phenomena: kinetic theory, hard thermal loops
  - flow : hydrodynamics
  - jet quenching: medium–induced gluon radiation, AdS/CFT

# Lecture II: Quark–Gluon Plasma



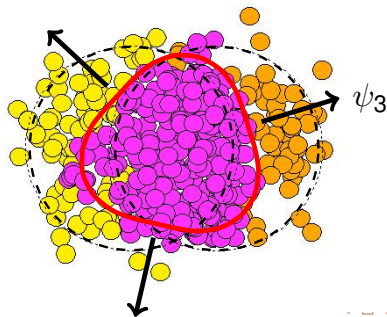
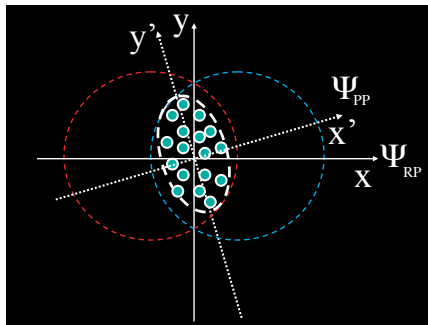
- $\tau \sim 1 \text{ fm}/c$  : thermalization
- $1 \lesssim \tau \lesssim 10 \text{ fm}/c$  : quark–gluon plasma
- $10 \lesssim \tau \lesssim 20 \text{ fm}/c$  : hot hadron gas
  - hadronisation: confinement
  - the hadron gas keeps expanding and cooling down

# Lecture II: Quark–Gluon Plasma



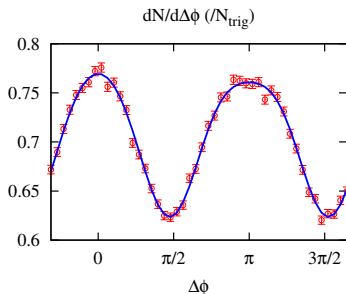
- $\tau \sim 1 \text{ fm}/c$  : thermalization
- $1 \lesssim \tau \lesssim 10 \text{ fm}/c$  : quark–gluon plasma
- $10 \lesssim \tau \lesssim 20 \text{ fm}/c$  : hot hadron gas
- $\tau > 20 \text{ fm}/c$  : freeze out
  - the density becomes too small to have interactions
  - the produced hadrons exhibit a thermal spectrum

# Flow and Thermalization

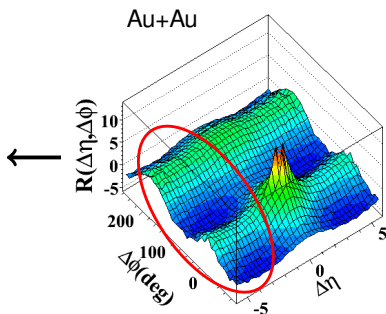


# From ridge to flow

- What is the origin of the double peak structure ( $\Delta\phi = 0$  and  $\Delta\phi = \pi$ ) seen in di-hadron correlations in Au+Au ?



(STAR, arXiv:1010.0690)

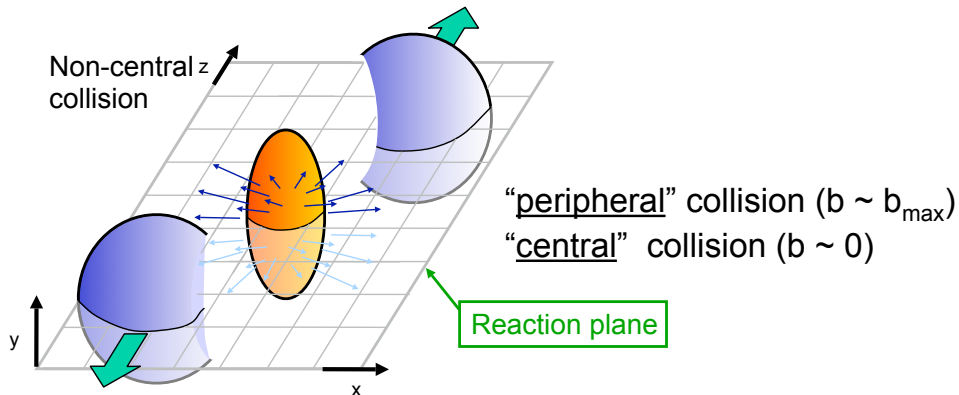


(PHOBOS, Phys.Rev. C81 (2010) 024904)

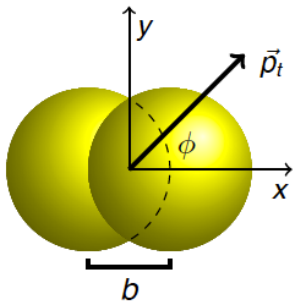
$$\mathcal{R} \equiv \frac{\langle N_1 N_2 \rangle - \langle N_1 \rangle \langle N_2 \rangle}{\langle N_1 \rangle \langle N_2 \rangle} \propto v_2^2 \cos(2\Delta\phi)$$

- This is **elliptic flow** !

# The geometry of a HIC



Number of participants ( $N_{\text{part}}$ ): number of incoming nucleons (participants) in the overlap region

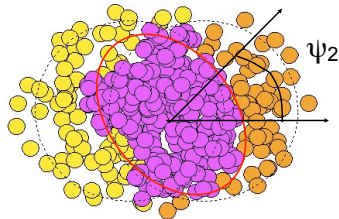
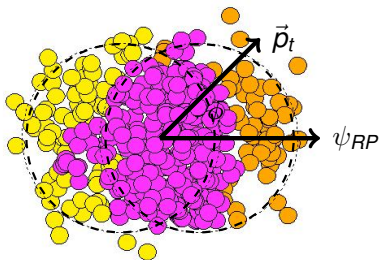


$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2\phi$$

$v_2$  : the 'coefficient of the elliptic flow'

- Non-central  $AA$  collision: **impact parameter**  $b_{\perp} > 0$
- The interaction region is (roughly) **elliptic**
- Pressure gradient is larger along the **smaller axis** ( $x$ )
- Fluid velocity is proportional to the **pressure gradient**
- Particle emerge predominantly **parallel to the fluid velocity**  
 $\implies$  **the particle distribution is not axially symmetric !**

# The role of fluctuations (1)

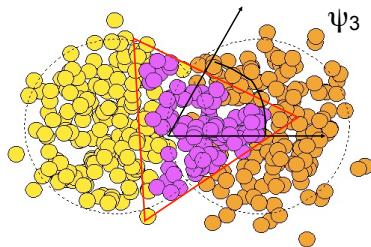
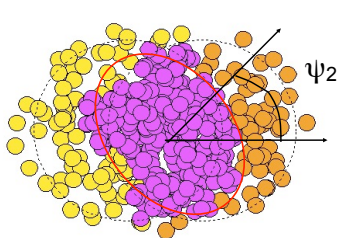


- Nucleons are **randomly distributed** inside a nucleus.
- The **participants** (nucleons which undergo at least one collision) do not make exactly an ellipse ...
- ... and the **minor axis** of that (approximate) ellipse needs not be exactly along the  $x$  axis !

$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2(\phi - \Psi_2)$$

- The **event plane** is not the same as the **reaction plane** !

# The role of fluctuations (2)

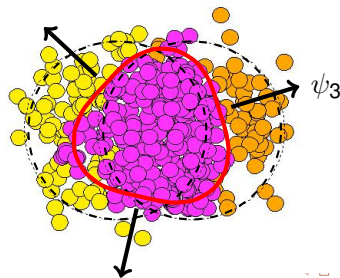
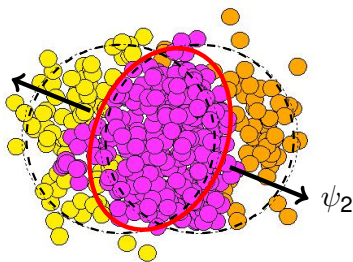


- In some events, the shape of the interaction can be quite different from an ellipse !
- Then one speaks about triangular flow ...

$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2(\phi - \Psi_2) + 2v_3 \cos 3(\phi - \Psi_3) + \dots$$

- ... or even higher harmonics

# The role of fluctuations (3)



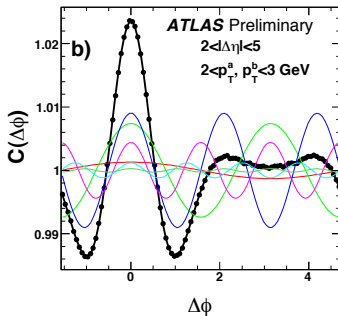
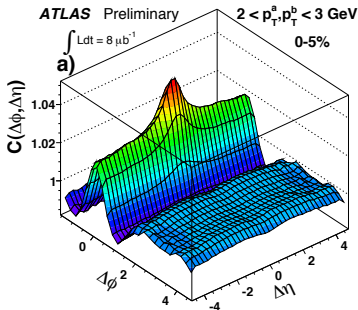
- And of course all these harmonics can coexistent (in different proportions) within a **same event** !

$$\frac{dN}{d\phi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos n(\phi - \Psi_n)$$

- This amounts to a **Fourier decomposition** of the azimuthal distribution of the participants !
- The most amazing: **all these  $v_n$ 's can actually be measured**

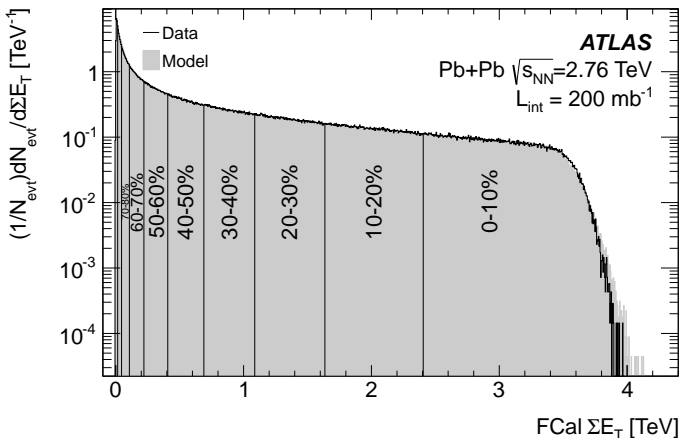
$$\left\langle \frac{dN_{pairs}}{d\Delta\phi} \right\rangle \propto 1 + 2 \sum_{n=1}^{\infty} \langle v_n^2 \rangle \cos n(\phi - \Psi_n)$$

- The reference phases  $\Psi_n$  drop out in the convolution !



- Integrate the data within slices of  $\Delta\eta$ , perform a Fourier transform per slice, then present  $v_n$  as functions of  $\Delta\eta$ ,  $p_{\perp}$  and in bins of centrality

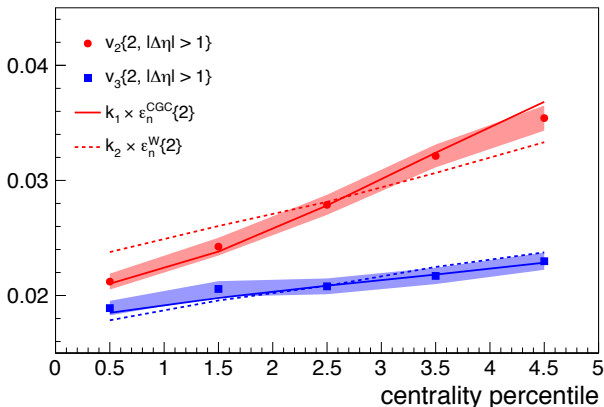
# Centrality bins in a HIC



- The **more central** an event is, the **higher the (transverse) energy** deposited in the forward calorimeter
- The 10% events with the highest energy deposit  $\equiv$  'the 10% most central events'

# Centrality dependence for $v_2$

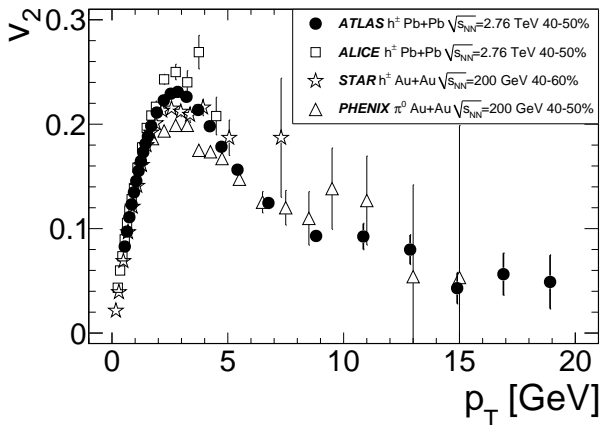
ALICE, arXiv:1105.3865



- The larger the centrality, the smaller  $v_2$  !

for central collisions, the interaction region has spherical symmetry  
 $\Rightarrow$  no flow !

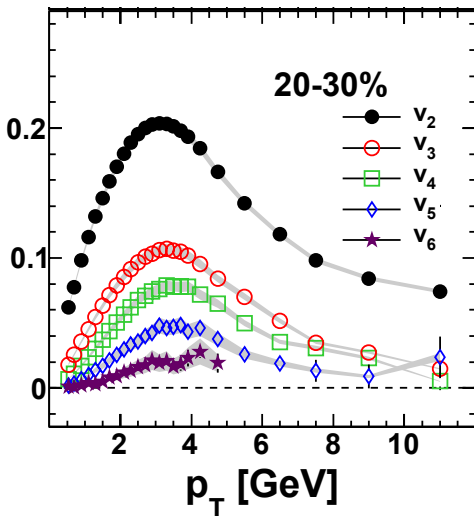
# Momentum dependence for $v_2$



- $v_2$  first rises up to  $3 \div 4$  GeV, then decreases again.
  - ▷ relatively hard/fast particles cannot be driven by the flow  
(*imagine a bullet flowing with the wind*)
- No significant increase in  $v_2$  from RHIC to LHC

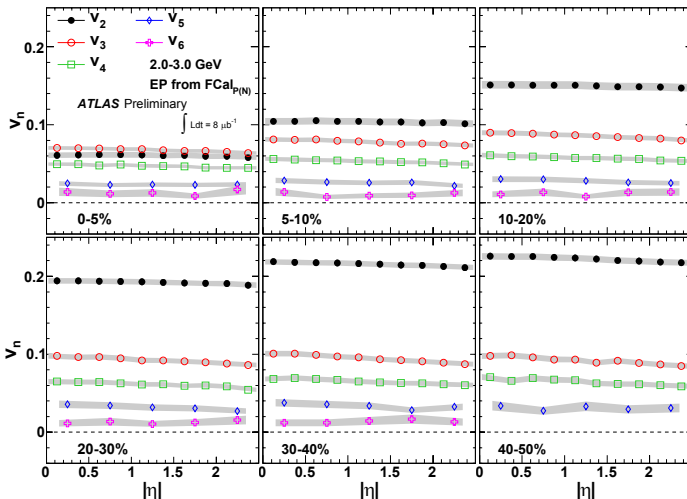
# $p_{\perp}$ dependence for $v_n$ , $n = 2 - 6$

(Talk by J. Jia for the ATLAS Collaboration at Quark Matter 2011)



- Similar  $p_{\perp}$  dependence for all  $n$ : rise up to 3-4 GeV, then fall

# Pseudorapidity dependence for $v_n$



- Weak  $\eta$  dependence for all  $v_n$ 's !
- Distributions which are **boost-invariant** (independent of  $\eta$ ) at early times **flow in the same way** and give rise to 'ridge' and 'hump'

# From flow to Hydro

- What can we **learn** out of the flow data (concerning QCD) ?
- We first learn that this matter is a **fluid** (it flows !)
  - 'this matter': hadrons until freeze-out
  - partonic matter in the intermediate stages
- Non-trivial ! It implies **relatively strong interactions** !
  - dust (no interactions) does not flow !
  - a liquid flows better than a gas (weak interactions)
- If it flows, one can use **hydrodynamics**
  - the effective theory for flow (see below)
- Hydro involves **initial conditions** and **transport coefficients**, which teach us about **the state of the system**
- Success of hydro **strongly suggests** (but not necessarily implies) **local thermal equilibrium**

# Hydrodynamics in a nut shell

- Standard thermodynamics: a system in **global thermal equilibrium**
  - pressure ( $P$ ), temperature ( $T$ ), chemical potential ( $\mu$ ) are independent of time ...
  - and uniform throughout the volume  $V$  of the system
- Hydrodynamics is about **(quasi) local thermal equilibrium**
  - $P$ ,  $T$  and  $\mu$  can vary with space and time ...
  - ... but they vary so slowly that one can still assume thermal equilibrium to hold locally, in the neighborhood of any point
  - the velocity  $\mathbf{v}$  can be different for different fluid elements
- Hydrodynamics : **effective theory of small gradients**
- It holds when the **mean free path** of the particles in the system is much smaller than any system size.
  - 'mean free path' : distance between two successive collisions

# Hydro equations = the conservation laws

$$\partial_\mu T^{\mu\nu} = 0$$

$$\partial_\mu J_B^\mu = 0$$

- $T^{\mu\nu}$  (energy–momentum tensor) and  $J_B^\mu$  (baryonic current) :
  - fluid velocity:  $u^\mu = \gamma(1, \mathbf{v})$ ,  $\gamma = 1/\sqrt{1-v^2}$
  - energy density  $\varepsilon = E/V$  & pressure  $P$
  - additional parameters ('viscosities') for a non-ideal fluid
- 'Ideal fluid'  $\equiv$  local thermal equilibrium

$$T_{(0)} = \begin{pmatrix} \epsilon & 0 & 0 & 0 \\ 0 & P & 0 & 0 \\ 0 & 0 & P & 0 \\ 0 & 0 & 0 & P \end{pmatrix} \quad \text{in the local rest frame : } u^\mu = (1, 0)$$

- After a boost to the laboratory frame, this becomes:

$$T^{\mu\nu} = (\varepsilon + P)u^\mu u^\nu - Pg^{\mu\nu}$$

# Viscous hydrodynamics

- Ideal hydro assumes that there is no dissipation (no friction)
- You may think this means the coupling is weak...but you'd be wrong !
  - ▷ it actually means that the coupling is infinite ! (see below)
- Real fluids have no infinite coupling, so they have dissipation.
- This is described by transport coefficients known as viscosities

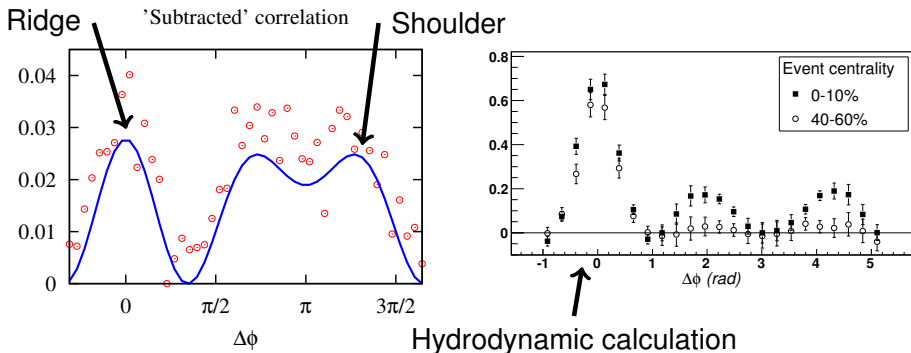
$$T^{\mu\nu} = (\varepsilon + P)u^\mu u^\nu - Pg^{\mu\nu} \oplus (\eta, \zeta) \otimes \partial u \oplus$$

N.B. Viscous effects enter  $T^{\mu\nu}$  as gradient corrections

- For the hydro problem to be well defined, one needs to specify:
  - the equation of state which relates  $\varepsilon$  to  $P$
  - the initial conditions (at  $\tau = \tau_0$ ) for  $\varepsilon$  and  $\mathbf{v}$
  - the viscosities  $\eta, \zeta$

# Hydro calculations ...

- ... do a good job in qualitatively explaining the 'ridge'...

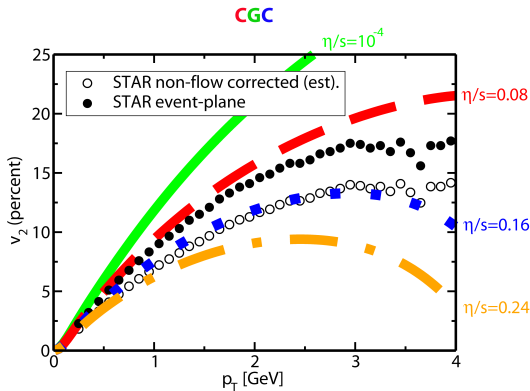


(STAR, arXiv:1010.0690)

(Takahashi, Tavares, Andrade, Grassi, Hama, Kodama, Xu, Phys.Rev.Lett.103, 242301 (2009))

# Hydro simulations for $v_2$

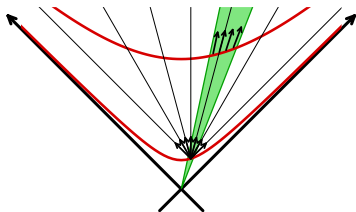
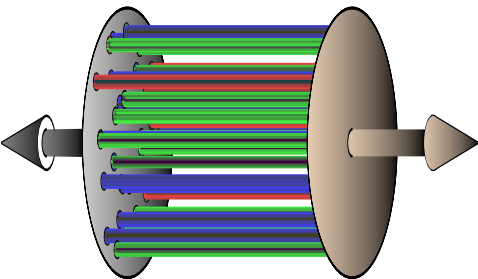
- ... and quantitatively reproducing the elliptic flow !  
(Luzum and Romatschke, 08)



- However, a good hydro description of the data requires :
  - a very short equilibration (isotropisation ?) time  $\tau_0 \lesssim 1 \text{ fm}/c$
  - a very small viscosity/entropy ratio  $\eta/s < 0.2$
- Both properties are puzzling ... at least at weak coupling !

# The thermalization puzzle

- The energy-momentum distribution right after the collision is **maximally anisotropic** : longitudinal expansion, glasma flux tubes



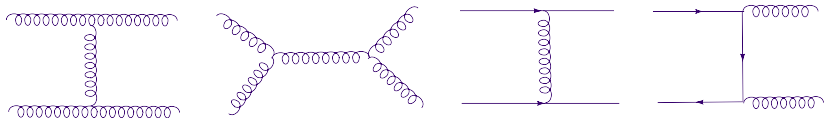
$$T_{\text{eq}} = \begin{pmatrix} \varepsilon & 0 & 0 & 0 \\ 0 & P & 0 & 0 \\ 0 & 0 & P & 0 \\ 0 & 0 & 0 & P \end{pmatrix}$$

$$T_{\text{initial}} = \begin{pmatrix} \epsilon & 0 & 0 & 0 \\ 0 & \varepsilon & 0 & 0 \\ 0 & 0 & \varepsilon & 0 \\ 0 & 0 & 0 & -\varepsilon \end{pmatrix}$$

- How can the system become isotropic over such a short time  
 $\tau_0 \lesssim 1 \text{ fm}/c$  ??

# Thermalization at weak coupling

- To evolve towards isotropy and thermal equilibrium, particles must exchange energy and momentum with each other.
- They can do that through **collisions**.
- **Weak coupling**: the dominant mechanism is  $2 \rightarrow 2$  elastic scattering



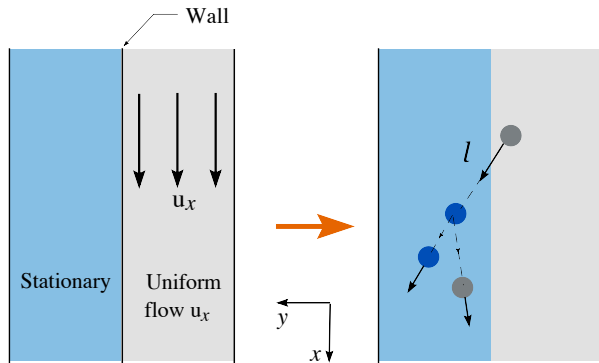
- Cross-section ( $\sigma$ ) scales like  $|\text{amplitude}|^2$ , hence like  $g^4 \sim \alpha_s^2$
- **Mean free path** ( $\ell$ ) = average distance between successive collisions

$$\ell \sim \frac{1}{\text{density} \times \sigma} \sim \frac{1}{\alpha_s^2}$$

- Typical equilibration time:  $\tau_{\text{eq}} \sim \ell/v \sim 1/\alpha_s^2$
- **Weakly coupled systems have large equilibration times !**

# Shear viscosity

- Weakly coupled systems also have large viscosity/entropy ratio !
- $\eta$  : a measure of a fluid ability to transfer  $p_x$  in the  $y$  direction



$$\frac{1}{A} \frac{dp_x}{dt} = -\eta \frac{du_x}{dy}$$

- Proportional to the mean free path  $\ell \propto 1/\sigma \sim 1/g^4$   
 $\Rightarrow$  larger at weak coupling ! (Maxwell, 1860)

# Viscosity over entropy density ratio

- $\eta \sim \ell \times \varepsilon$  ( $\ell$  : mean free path;  $\varepsilon$  : energy density). Thus,

$$\frac{\eta}{s} \sim \ell \frac{\varepsilon}{s} \sim \frac{\text{mean free path}}{\text{de Broglie wavelength}}$$

*(since  $\varepsilon/s \sim \text{energy per particle} \sim 1/\lambda_B$ )*

- Heisenberg's uncertainty principle forbids  $\ell/\lambda_B$  to be smaller than one  
*(actually smaller than  $\hbar$ , but we work in 'natural units' :  $\hbar = 1$ )*
- Hence,  $\frac{\eta}{s} \gtrsim \mathcal{O}(1)$
- Weakly interacting systems have  $\eta/s \gg 1$
- The matter produced in HIC has  $\eta/s \sim \mathcal{O}(1)$   
 $\implies$  'strongly-coupled quark-gluon plasma' (sQGP), or 'perfect liquid'

# RHIC serves us the perfect liquid !

## RHIC Scientists Serve Up "Perfect" Liquid

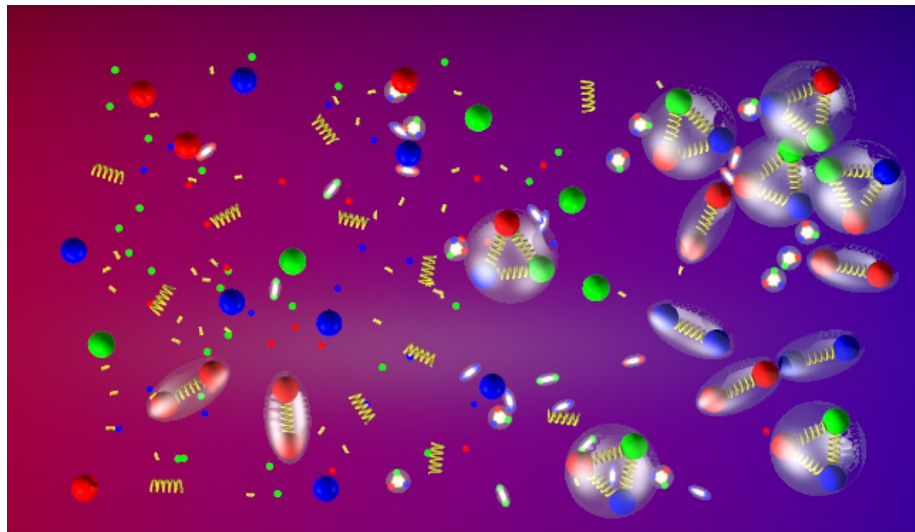
New state of matter more remarkable than predicted -- raising many new questions

Monday, April 18, 2005

TAMPA, FL -- The four detector groups conducting research at the [Relativistic Heavy Ion Collider](#) (RHIC) -- a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory -- say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In [peer-reviewed papers](#) summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a *liquid*.

- Still under debate ... more to come !

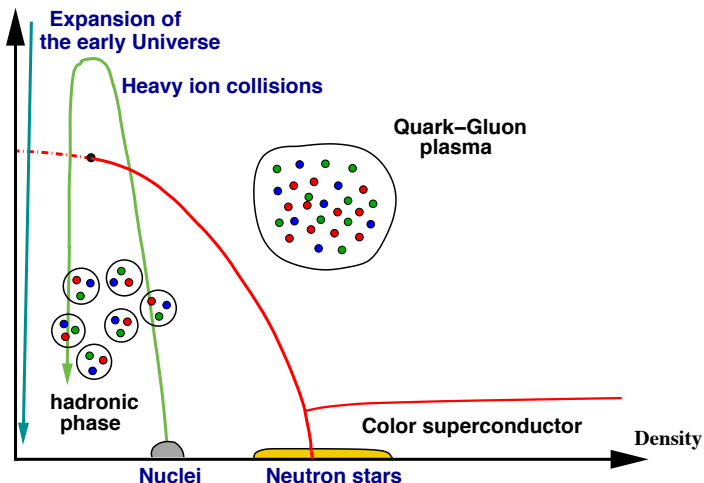
# Quark-Gluon Plasma



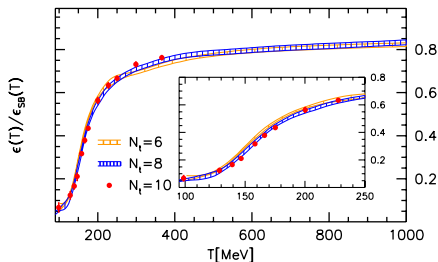
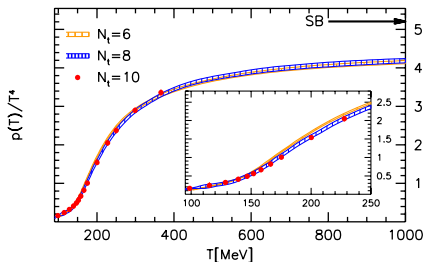
# Phase-diagram for QCD

- ... as explored by the expansion of the Early Universe ...

Temperature



- ... and in the ultrarelativistic heavy ion collisions.

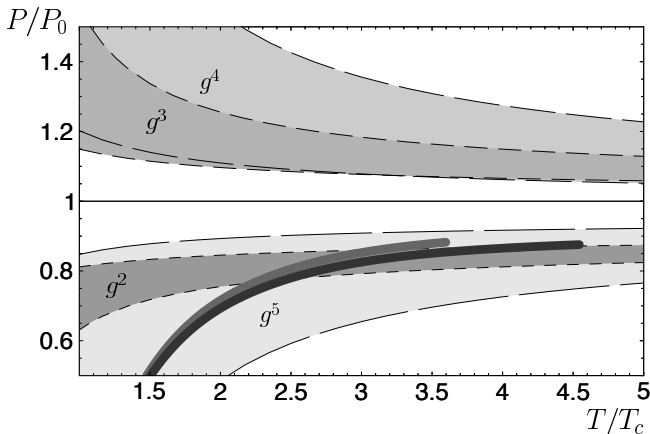


- With increasing temperature, the coupling  $g(T)$  decreases, so the exact result approaches towards the Stefan–Boltzmann limit

$$P_{SB} = \frac{\pi^2}{90} \left\{ 2(N_c^2 - 1) + \frac{21}{6} N_c N_f \right\}$$

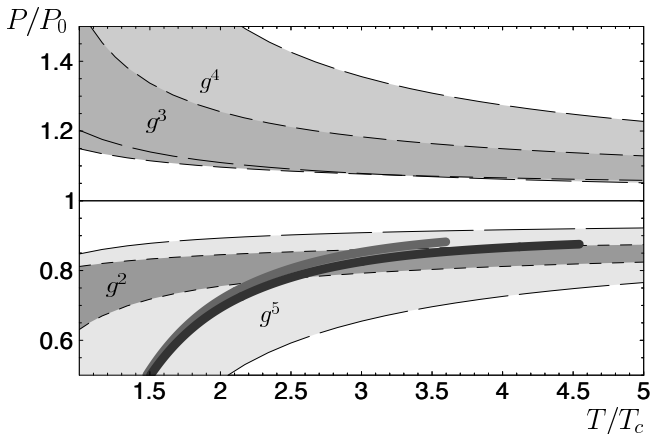
- Can one understand this approach in **perturbation theory** ?
- For  $T \gtrsim 2.5T_c$ ,  $\epsilon(T) - \epsilon_{SB}(T)$  is **about 20%**
- The first perturbative correction to  $\epsilon_{SB}(T)$ , of  $\mathcal{O}(g^2)$ , is numerically **about 20% as well !**

# QCD thermodynamics: perturbation theory



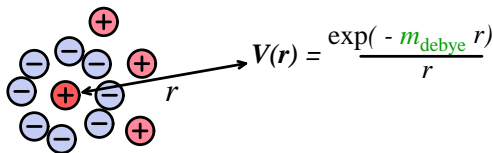
- By itself, the  $\mathcal{O}(g^2)$  seems to do a pretty good job. **However...**
- Successive perturbative approximations —  $\mathcal{O}(g^2)$ ,  $\mathcal{O}(g^3)$ ,  $\mathcal{O}(g^4)$ ,  $\mathcal{O}(g^5)$  — jump up and down, **without any sign of convergence**.

# QCD thermodynamics: perturbation theory

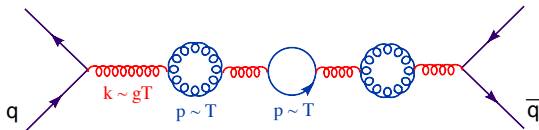


- This problem appears for **any field theory**, including weakly coupled QED, or scalar  $\phi^4$  theory !
- In QCD,  $\mathcal{O}(g^6)$  and higher cannot be computed in perturbation theory anymore (**infinitely many diagrams**)

# Recall : Debye screening



- Thermal effect associated with dressing the propagator:  $m_{\text{Debye}} \sim gT$



- The electric gluon acquires a mass which is 'non-perturbative' at 'soft' momenta  $k \sim gT$ :

$$G_{00}(k) = \underbrace{\frac{1}{k^2 + m_D^2}}_{\text{fine !}} = \underbrace{\frac{1}{k^2} \left[ 1 - \frac{m_D^2}{k^2} + \left( \frac{m_D^2}{k^2} \right)^2 \dots \right]}_{\text{not fine !}}$$

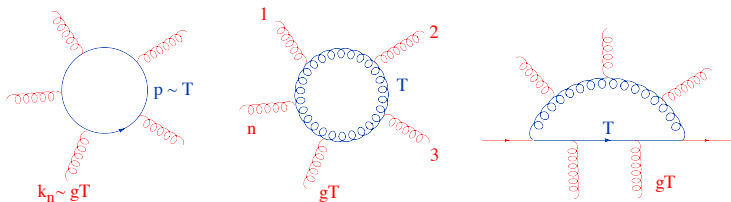
# Hard Thermal Loops

- In a field theory at finite  $T$ , **strict** perturbation theory makes no sense
- The plasma develops **collective phenomena** ...

*Debye screening, Landau damping, waves ('plasmons')...*

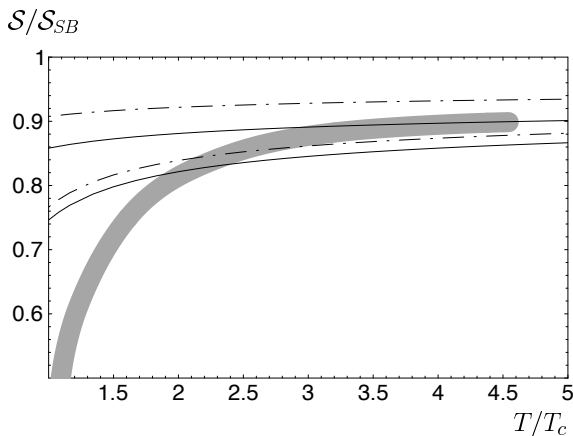
... which in general can be **computed in perturbation theory**, but whose effects are **non-perturbative**

$\Rightarrow$  they need to be resummed to all orders



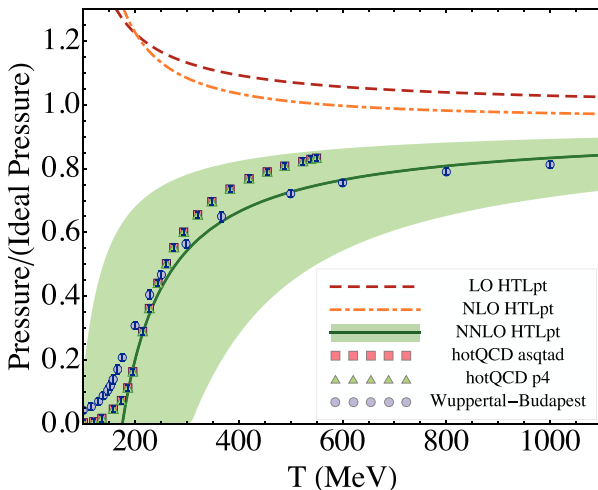
- **Hard Thermal Loops** : one loop diagrams with internal momenta  $p \sim \mathcal{O}(T)$  ('hard') and external momenta  $k_i \sim \mathcal{O}(gT)$  ('soft')
- This requires **reorganizations of the perturbative expansion**

# HTL-resummed entropy



- 'Two-particle-irreducible' resummation of the HTL self-energies  
(*J.-P. Blaizot, A. Rebhan, E. I., 2000*)
- Good agreement with the lattice data (Bielefeld) for  $T \gtrsim 2.5T_c$

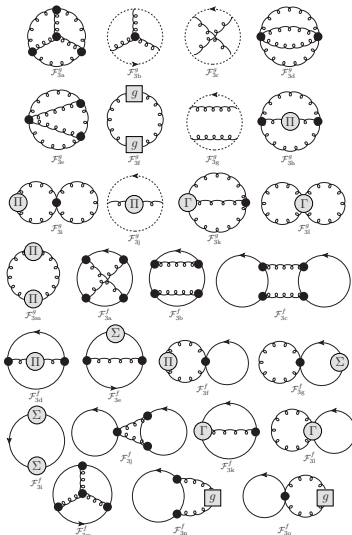
# HTL-resummed pressure



- 'Screened perturbation theory' up to 3 loop order.  
(Andersen, Leganger, Strickland, Nan Su, 2011)
- Good convergence & good agreement with lattice data at 3-loop level

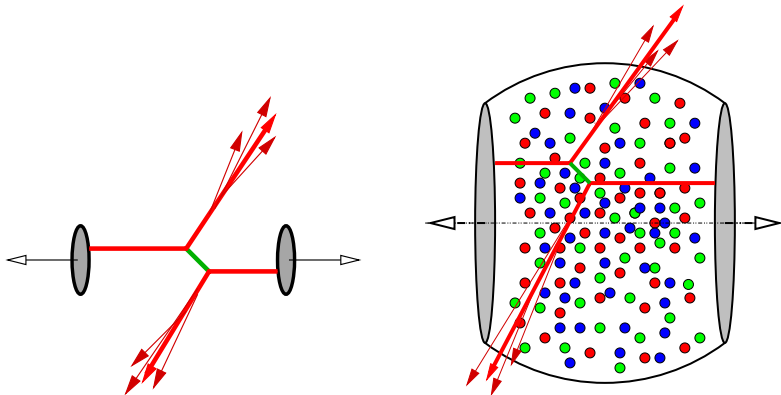
## HTL-resummed pressure at 3 loop order

- Not an easy job though ! 😊



# Jet quenching

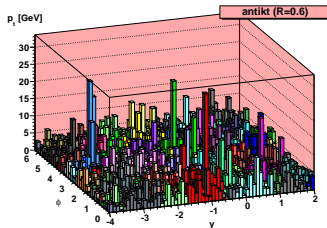
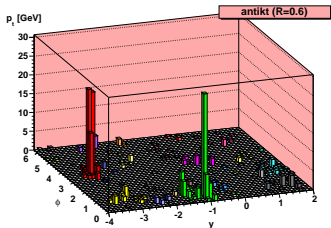
- How to probe the properties of the QGP in HIC ?



- Study the effects of the medium on the propagation of a 'hard probe', so like a jet

# 'Jets' vs. 'leading particles'

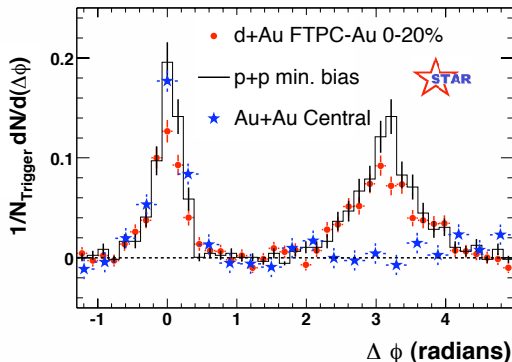
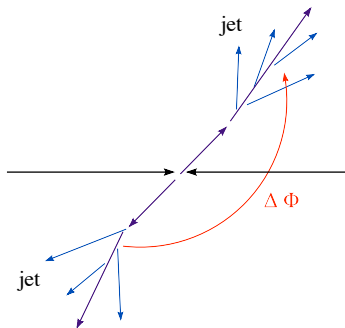
- A 'jet': the ensemble made by the 'leading particle' (a virtual parton which initiated the jet) and the products of its 'fragmentation'
- The definition of a 'jet' is also a matter of conventions ...
  - it depends upon the maximal rapidity ( $\Delta Y$ ) and azimuthal ( $\Delta\phi$ ) separation between the particles that we associate with a given 'jet'
  - ... and also upon the jet reconstruction algorithm
- Jet reconstruction is particularly delicate in the context of HIC...



- ... and of course it requires a good, specialized, detector !

# Jet quenching at RHIC

- Studies of jet quenching at RHIC have focused on 'leading particles'

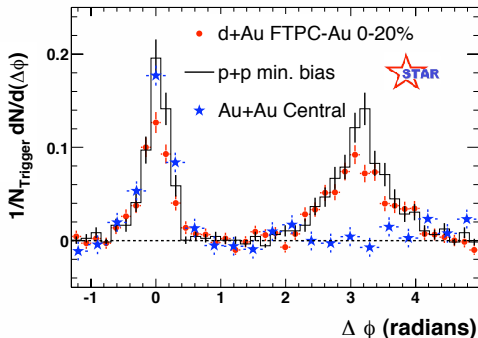
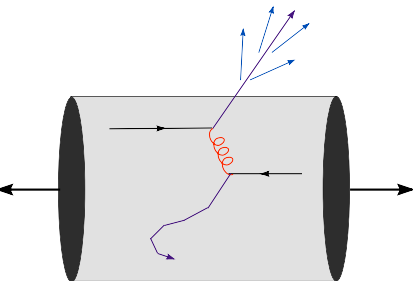


[Nucl.Phys.A783:249-260,2007]

- Azimuthal correlations between the produced jets:

p+p or d+Au : a peak at  $\Delta\Phi = 180^\circ$

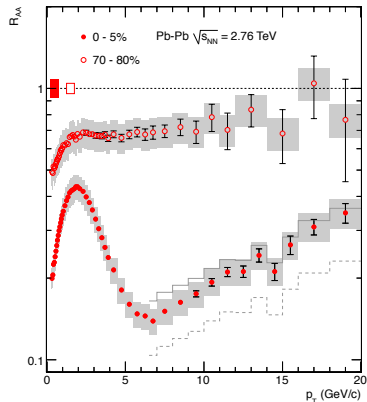
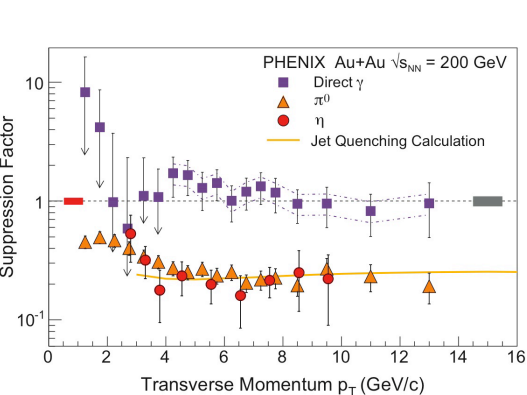
# Jet 'quenching' in nucleus–nucleus collisions



- The “away–side” jet has disappeared !  
absorption (or energy loss, or “jet quenching”) in the medium
- The matter produced in a heavy ion collision is **opaque**  
high density, or strong interactions, ... or both

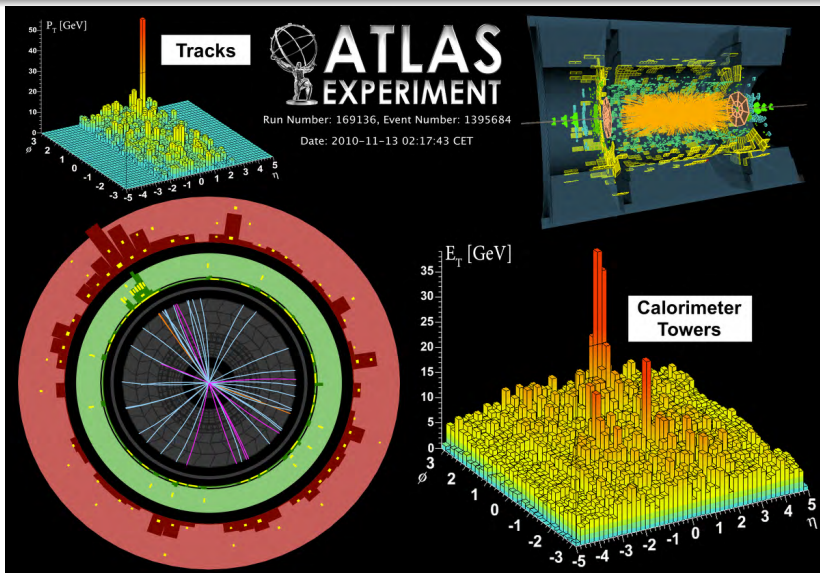
# Nuclear modification factor at RHIC & the LHC

$$R_{A+A} \equiv \frac{1}{A^2} \frac{dN_{A+A}/d^2p_{\perp}d\eta}{dN_{p+p}/d^2p_{\perp}d\eta}$$



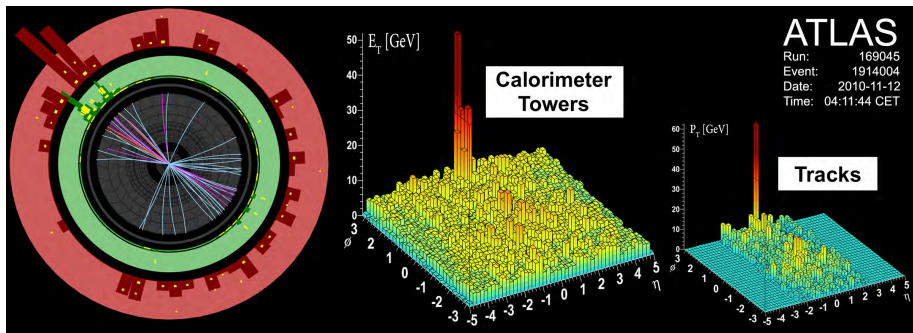
- Strong suppression ( $R_{AA} \lesssim 0.2$ ) in central collisions
- Large energy loss in the medium

# Jets in HIC at the LHC



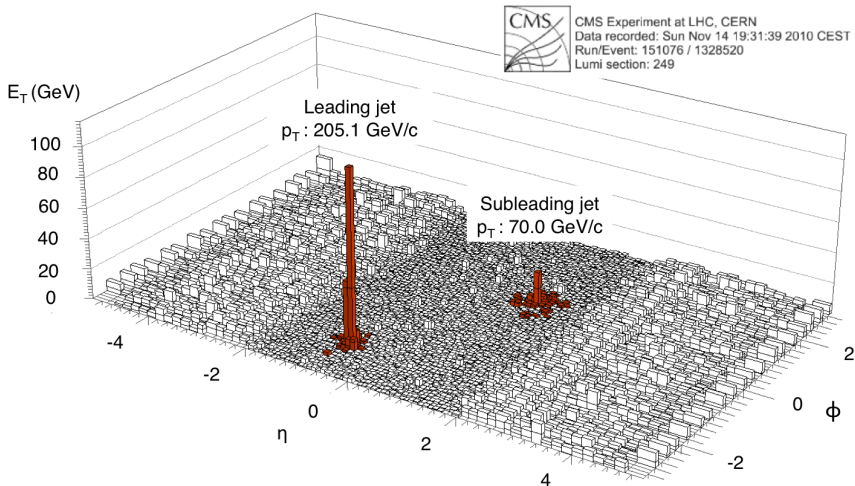
- Pb+Pb collision at  $\sqrt{s_{NN}} = 2.76$  TeV

# Di-jet asymmetry (*ATLAS*)



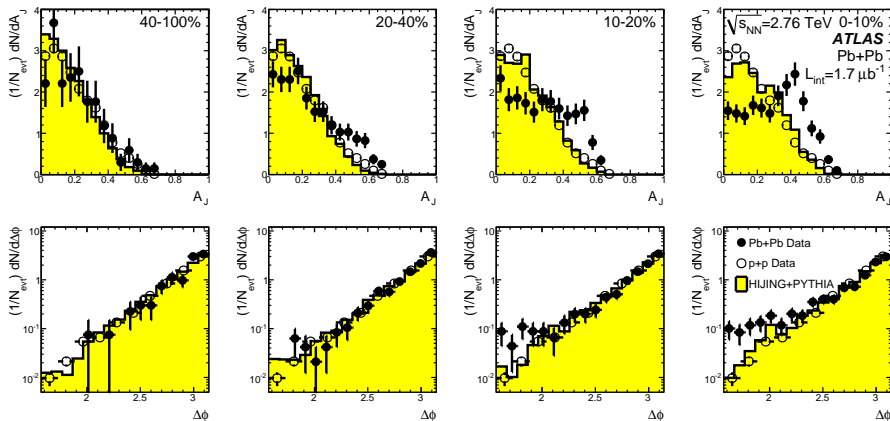
- Central Pb+Pb: mono-jet events
- The secondary jet cannot be distinguished from the background:  $E_{T1} \geq 100$  GeV,  $E_{T2} > 25$  GeV

# Di-jet asymmetry (CMS)



- Central Pb+Pb: the secondary jet is barely visible
- The jet energy has been redistributed in the transverse plane

# Di-jet asymmetry (*ATLAS*)

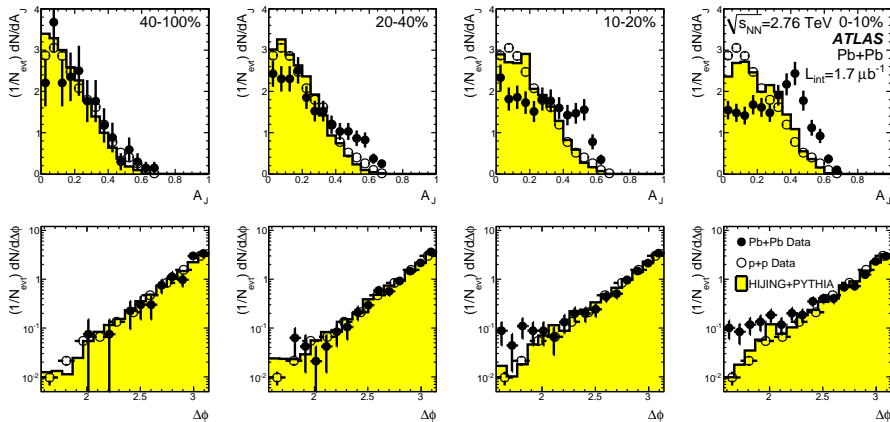


- Event fraction as a function of the di-jet energy imbalance

$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T1}}$$

- ...and of the azimuthal angle  $\Delta\phi$ , for different centralities.

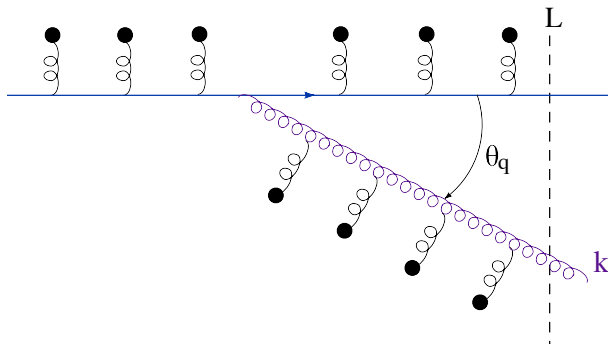
# Di-jet asymmetry (*ATLAS*)



- Additional energy loss of **20 to 30 GeV** due to **the medium**
- Typical event topology: still a pair of **back-to-back** jets
- The **secondary jet loses energy** without being deflected
- Medium-induced emissions of **soft** gluons at **large angles**

# Medium-induced gluon radiation (*BDMPS-Z*)

- Additional radiation triggered by interactions in the medium  
(*Baier, Dokshitzer, Mueller, Peigné, Schiff, Zakharov*  $\sim 1995$ )



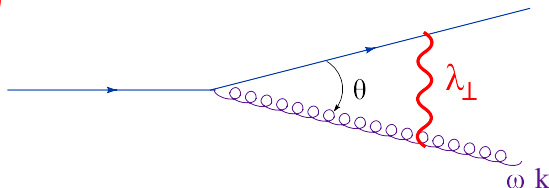
- A complicated problem: medium effects must be included to all orders
- Results (at least) qualitatively consistent with the LHC data !
- 2 fundamental concepts: formation time & momentum broadening

# The formation time

- By the uncertainty principle, it takes some time to emit a gluon !
  - ▷ the gluon must lose quantum coherence with respect to its source
- Gluon with energy  $\omega$  and transverse momentum  $k_{\perp}$  :
  - ▷ the quark–gluon transverse separation  $b_{\perp}$  at the emission time  $\tau_f$  must be larger than the gluon transverse wavelength  $\lambda_{\perp}$

$$b_{\perp} \simeq \theta \tau_f \gtrsim \lambda_{\perp} \simeq 1/k_{\perp}$$

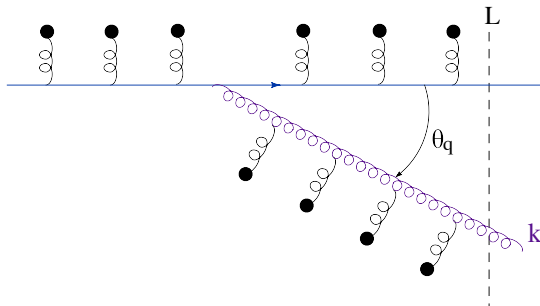
$$k_{\perp} \simeq \omega \theta$$



$$\tau_f \simeq \frac{\omega}{k_{\perp}^2} \simeq \frac{1}{\omega \theta^2}$$

# Transverse momentum broadening

- The gluon receives **random kicks** from the plasma constituents
- Parton mean free path  $\ell$  ( $\ell \sim 1/g^2T$  for a QGP)
- Average (momentum)<sup>2</sup> transfer per scattering  $m_D^2$  ( $m_D \sim gT$ )



$$\frac{d\langle k_{\perp}^2 \rangle}{dt} \simeq \frac{m_D^2}{\ell} \equiv \hat{q} \quad \text{'jet quenching parameter'}$$

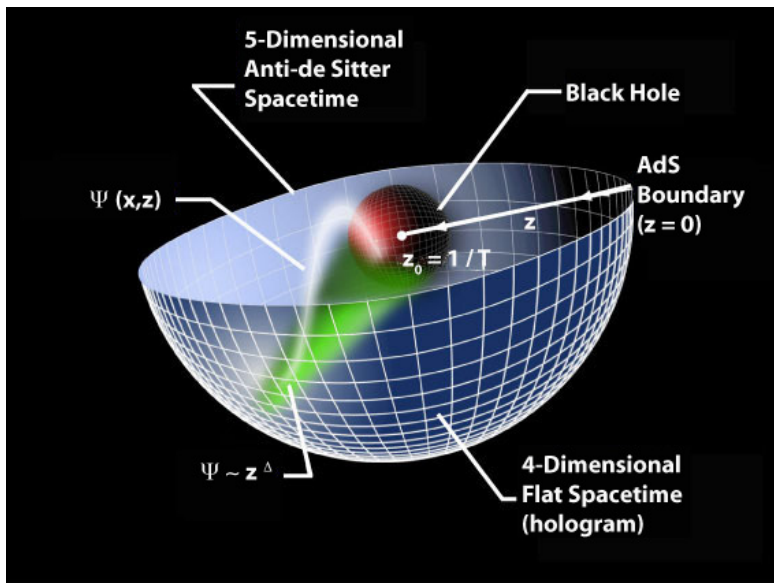
# In-medium formation time

- The gluon acquires a (momentum) $^2 \sim \hat{q}$  per unit time ...
- ... and hence a momentum  $k_f^2 \simeq \hat{q} \tau_f$  during its formation
- The formation time  $\tau_f$  is determined by the condition of quantum decoherence as  $\tau_f \simeq \omega/k_f^2$

$$\tau_f \simeq \sqrt{\frac{\omega}{\hat{q}}}, \quad \theta_f \equiv \frac{k_f}{\omega} \simeq \left( \frac{\hat{q}}{\omega^3} \right)^{1/4}$$

- The smaller the energy  $\omega$ , the shorter the formation time  $\tau_f$  and the larger the formation angle  $\theta_f$  !
- This has the right characteristics to explain the LHC data ! ✓

# The AdS/CFT correspondence



8-2007  
0505A14

# The evidence for strong coupling

- Three main experimental signatures:
  - small viscosity-over-entropy ( $\eta/s$ ) ratio ('perfect fluid')
  - early thermalization  $\tau_{\text{eq}} \lesssim 1 \text{ fm/c}$
  - strong 'jet quenching' (energy loss, momentum broadening)
- A rather **shaky paradigm** ...
  - a large elliptic flow  $v_2$  can also be explained by a larger initial eccentricity together with a larger value for  $\eta/s$
  - instead of early thermalization, it is enough to assume early expansion, like free streaming
  - so far, perturbative calculations were too crude to be convincing ... but progress is along the way !
- ... but a **fascinating one** !

# The AdS/CFT correspondance

- A 'duality' (equivalence) between two very different theories
  - a conformal field theory (CFT) at strong coupling;
  - a string theory in Anti-de-Sitter (AdS) space-time at weak coupling.

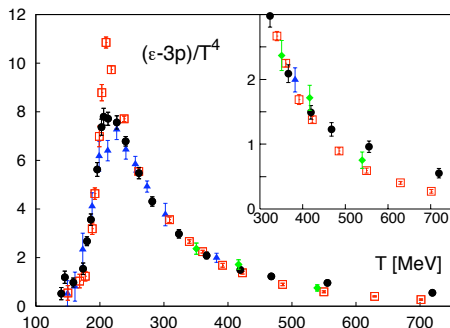
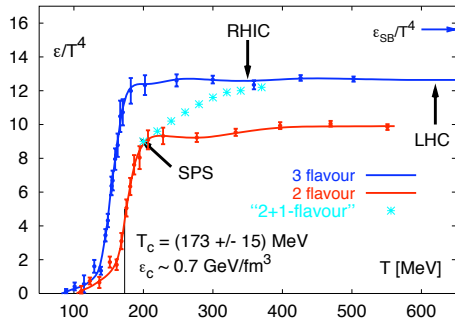
*(Maldacena, 97; Gubser, Klebanov, Polyakov, 98; Witten, 98)*

- The CFT :  $\mathcal{N} = 4$  Supersymmetric Yang-Mills
  - color gauge group  $SU(N_c)$
  - conformal invariance  $\implies$  fixed coupling  $g$
  - no confinement
  - strong 't Hooft coupling :  $\lambda \equiv g^2 N_c \gg 1$  &  $g^2 \ll 1$
- Is this a good model for QCD ??
- Perhaps better suited for studies of the quark-gluon plasma
  - deconfined, nearly conformal, relatively strong coupling

# 'Trace anomaly' in lattice QCD

- Remember:  $T^{\mu\nu} = \text{diag}(\varepsilon, P, P, P)$  :

▷ this would be traceless ( $\varepsilon = 3P$ ) in a CFT



$$\text{QCD : } \langle T_{\mu}^{\mu} \rangle \equiv \varepsilon - 3P \propto \beta(g)$$

- $(\varepsilon - 3P)/\varepsilon_0 \lesssim 10\%$  for any  $T \gtrsim 2T_c \simeq 400$  MeV
- $g \approx 1.5 \div 2 \implies \lambda \equiv g^2 N_c \simeq 6 \div 10$

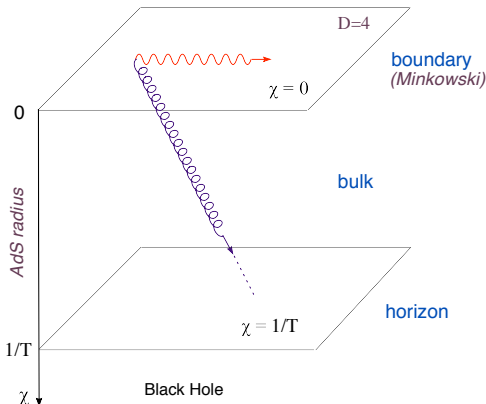
# The AdS/CFT correspondance (2)

- The String Theory : type IIB in the  $\text{AdS}_5 \times S^5$  space-time
- Finite- $T$  plasma in the CFT  $\leftrightarrow$  adding a Black Hole in  $\text{AdS}_5$ 
  - ▷ a Black Hole has entropy and thermal (Hawking) radiation
- The strong 't Hooft coupling regime of the gauge theory:
  - $\lambda \equiv g^2 N_c \gg 1$  &  $g^2 \ll 1$  (large  $N_c$ )
- ... corresponds to the 'supergravity' regime of the string theory:
  - weak coupling & weak curvature
  - classical equations of motion in a curved space-time
- Well defined rules for computing quantum correlations in the CFT at strong coupling via semi-classical calculations in the string theory

# AdS<sub>5</sub> Black Hole space–time

- AdS<sub>5</sub> : our Minkowski world  $\times$  a ‘radial’ dimension  $\chi$

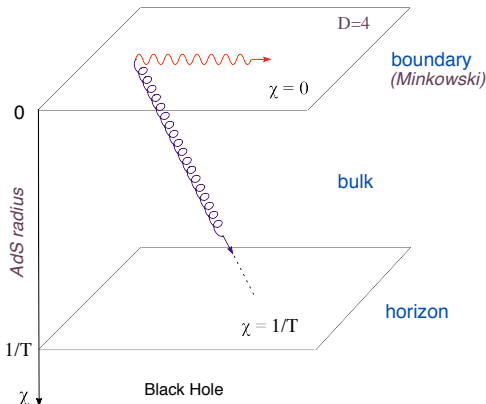
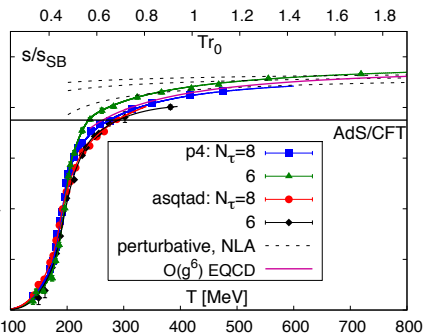
- ‘radial’, or ‘5th’, coordinate :  
 $0 \leq \chi < \infty$
- the gauge theory lives at the  
Minkowski boundary  $\chi = 0$
- finite temperature  $T$ :  
black hole horizon at  $\chi = 1/T$



$$S_{\text{BH}} = \frac{\text{Horizon area}}{4G_{10}} \Rightarrow s \equiv \frac{S_{\text{BH}}}{V_{3D}} = \frac{\pi^2}{2} N_c^2 T^3 = \frac{3}{4} s_0$$

# AdS<sub>5</sub> Black Hole space-time

- AdS<sub>5</sub> : our Minkowski world  $\times$  a 'radial' dimension  $\chi$



$$S_{BH} = \frac{\text{Horizon area}}{4G_{10}} \Rightarrow s \equiv \frac{S_{BH}}{V_{3D}} = \frac{\pi^2}{2} N_c^2 T^3 = \frac{3}{4} s_0$$

# Viscosity over entropy density ratio

(Policastro, Son, Starinets, 2001)

- Viscosity = the response of a fluid under shear forces ...
- ... hence, to a gravitational wave :

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

= the absorption cross section for a low-energy graviton

- Absorption cross section = area of horizon (known in GR)
- Entropy is also proportional to the area of the horizon

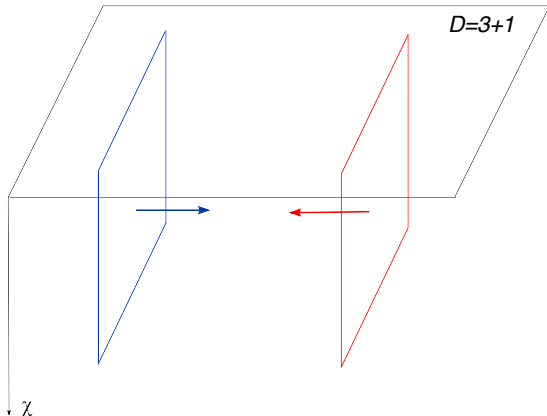
$$\frac{\eta}{s} \rightarrow \frac{\hbar}{4\pi} \quad \text{as} \quad \lambda \rightarrow \infty$$

- Universality follows from properties of black hole horizons

# Heavy Ion Collisions

- Ultrarelativistic Heavy Ion Collision in 4D  $\longleftrightarrow$

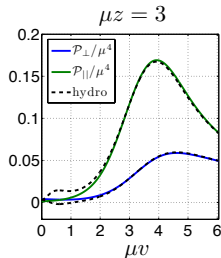
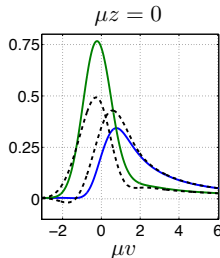
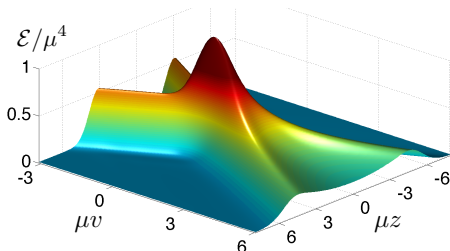
The scattering between two gravitational shock-waves in  $\text{AdS}_5$



- Thermalization  $\longleftrightarrow$  Formation of a BH horizon

# Thermalization from shock-wave scattering

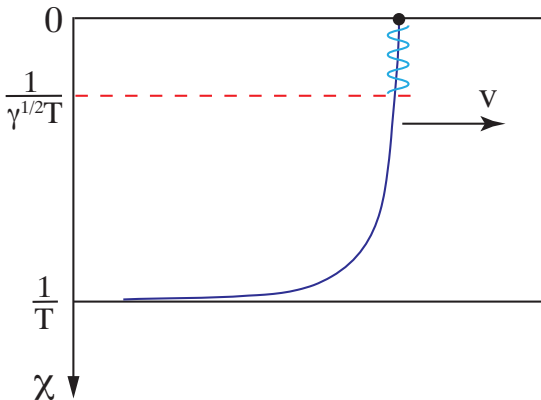
(Chesler and Yaffe, 2010)



- The remnants of the two shock waves move away from each other, but with velocities  $v < 1$ .
- The pressure shows isotropisation.

# Heavy Quark in a strongly-coupled plasma

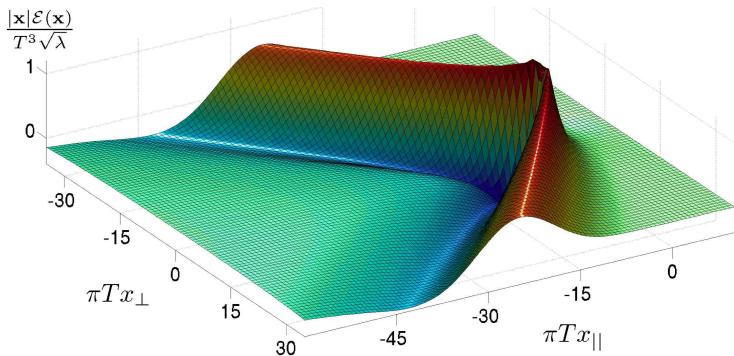
- Heavy quark in 4D  $\longleftrightarrow$  'Trailing string' in  $\text{AdS}_5$  BH
- Energy loss  $dE/dt$   $\longleftrightarrow$  Energy flux down the string



*Herzog, Karch, Kovtun, Kozcaz, and Yaffe; Gubser (2006)*

*Casalderrey-Solana, Teaney (2006); Giecold, E.I., Al Mueller (2009)*

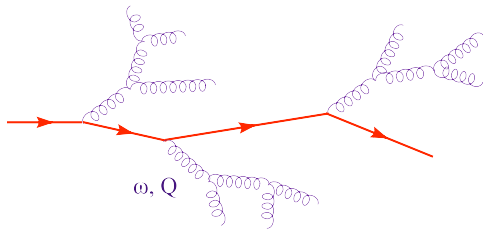
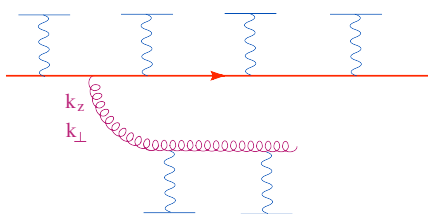
# Energy loss by the heavy quark



- If the quark velocity is larger than the speed of sound ( $c_s = 1/3$ )  
 $\Rightarrow$  Mach cone (*Chesler and Yaffe, 2007*)
- The experimental evidence at RHIC is still under debate

# Medium-induced radiation at strong coupling

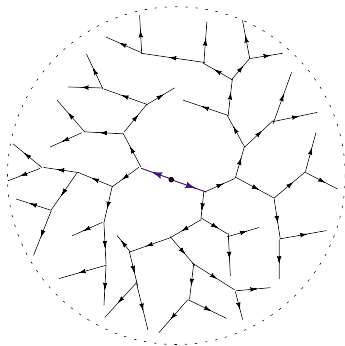
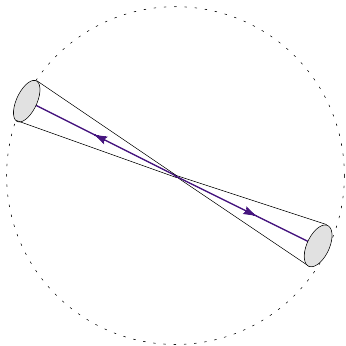
- Remember: Weak coupling: thermal rescattering



- Strong coupling: medium induced parton branching
- There are no plasma constituents to scatter off !
  - ▷ at strong coupling, the plasma looks like a jelly, without pointlike constituents !
- All the partons branch down to very small values of  $x$ :  
no 'valence quarks' (*Hatta, E.I., Mueller, 2008*)

# There are no jets at strong coupling !

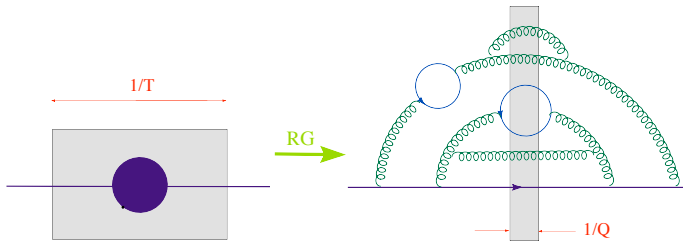
- $e^+e^-$  annihilation in COM frame:  $q^\mu = (\omega, 0, 0, 0)$
- Typical final state at **weak coupling** :  
a pair of back to back jets with high momenta  $k \simeq \omega/2$



- Typical final state at **strong coupling** :  
an isotropic distribution of many soft particles ( $k_i \sim \omega_i \sim \Lambda$ )  
(Hatta, Mueller & E.I, 08; Hofman and Maldacena, 2008)

# Instead of conclusions: Why gravity ?

- Why should **gravity** describe **gauge theory at strong coupling** ?
- OPE for DIS: **Partons**  $\longleftrightarrow$  'twist-2' operators
- The operators depend upon the **resolution scale**



- $\lambda \rightarrow \infty$  : rapid evolution  $\Rightarrow$  all operators are suppressed
- ... with one exception: **the energy momentum tensor  $T^{\mu\nu}$**   
 $\Rightarrow$  **the effective theory for scattering must be gravity !**