Testing Gauge-String Duality* with Nuclear Collision Data from RHIC

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2010 APS April Meeting
Thurgood Marshall East
Feb 13, 2010

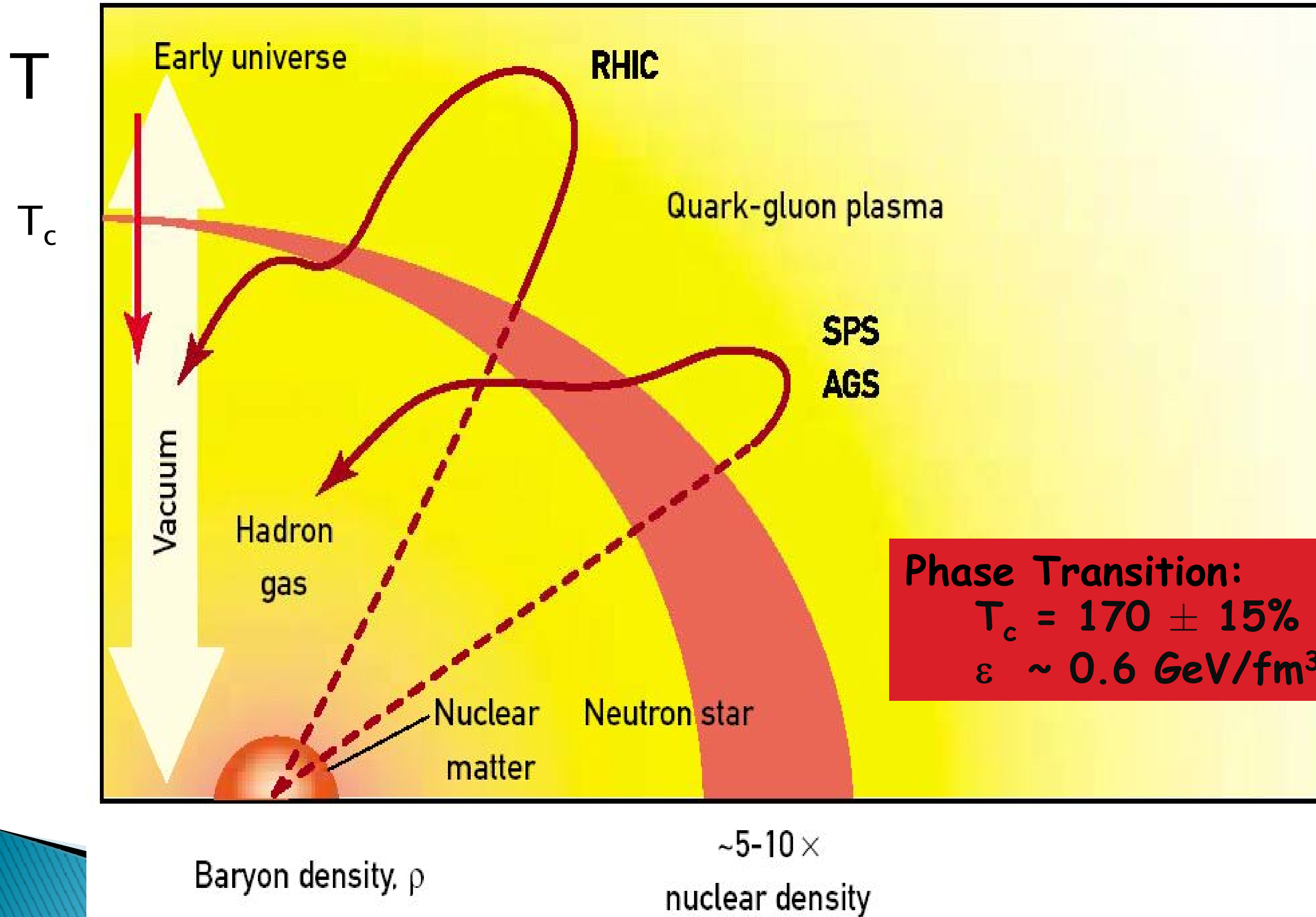
*aka AdS5/CFT

10:45 am

Outline

- Some thoughts about what we are looking for
- Introduction to heavy ions and RHIC
- Several Topics
  - Elliptic flow $\Rightarrow \eta/s$
  - Jet (quark) energy loss $\hat{q}$
  - Heavy quark diff coefficient
  - τ_0 (thermalization time) and T_{init}
  - Mention others
- Summarize (Scorecard) and conclude

Phases of Nuclear Matter



Phase Transition:
T_c = 170 ± 15% MeV
ε ~ 0.6 GeV/fm^3

BNL-RHIC Facility

Soon to Come – the LHC

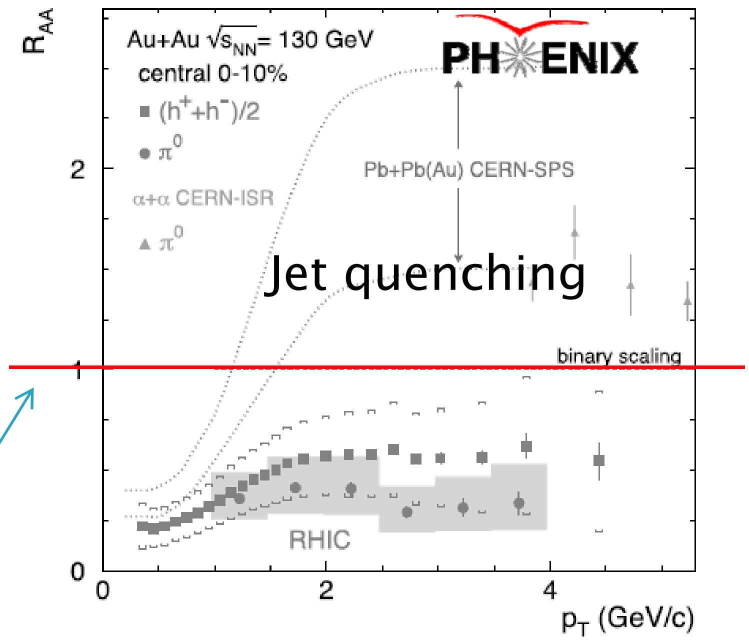
Collide Au + Au ions for maximum volume

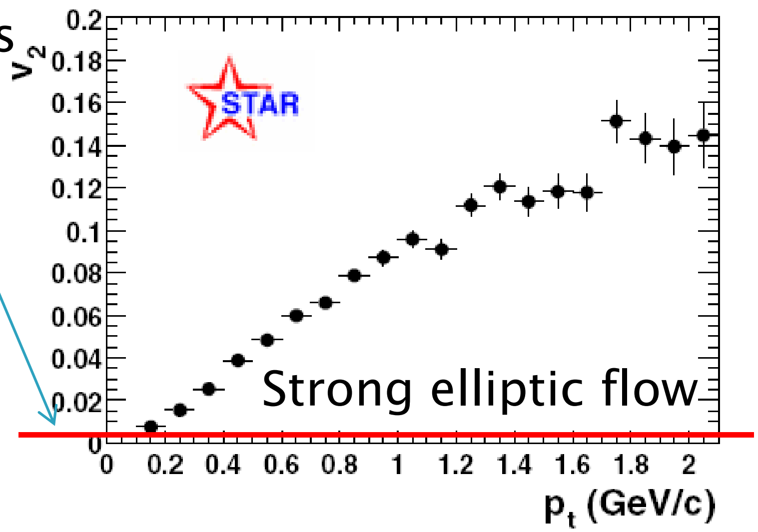
$\sqrt{s}$ = 200 GeV/nucleon pair, p+p and d+A to compare

A bit of history

- Old paradigm
  - RHIC – “weakly” interacting gas– Quark gluon plasma
    - Everything “easy” to calculate using pQCD and stat mech.
- What we found
  - Strongly interacting fluid– the sQGP

Naïve expectations





Everything “hard” to calculate

Gauge –String Duality

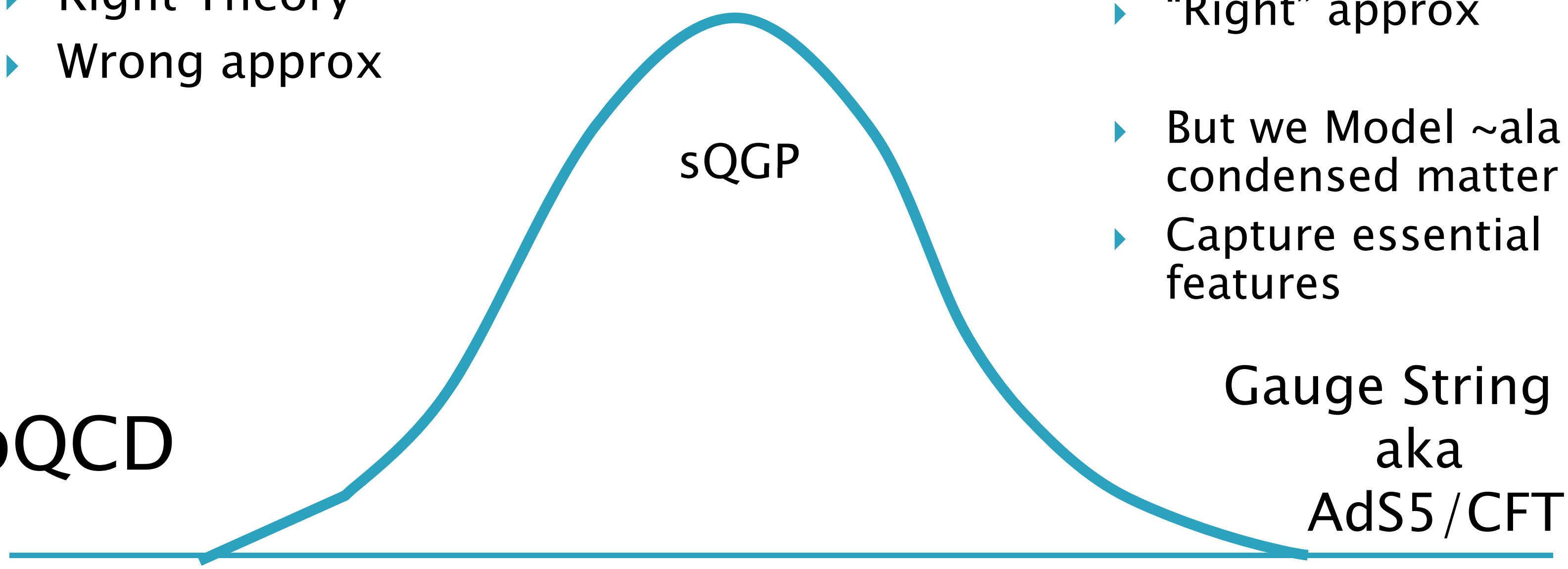
~~String Theory~~ to the rescue ?

- Right Theory
- Wrong approx

- Wrong Theory ($\mathcal{N}$=4 Supersymmetry)
- "Right" approx

- But we Model ~ala condensed matter
- Capture essential features

pQCD



Gauge String duality
aka
AdS5/CFT

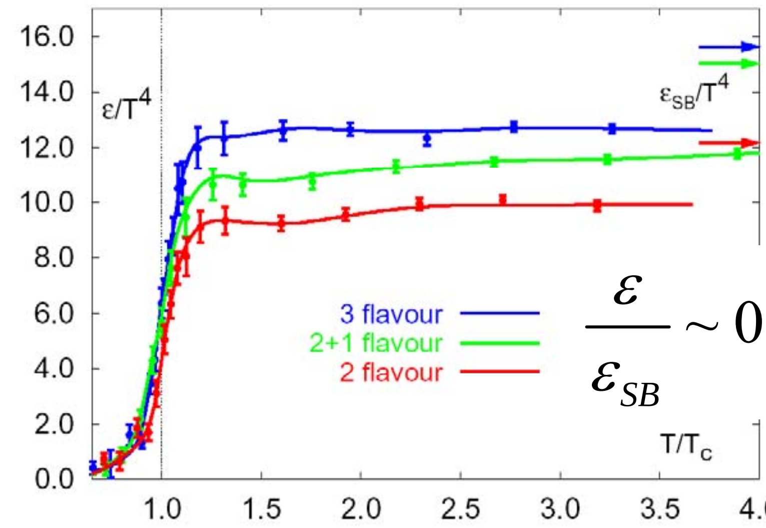
α_S

Weak coupling limit

$$\frac{\lambda^{t'Hooft}}{4\pi N_{colors}}$$

Strong coupling limit

Why do we think AdS/CFT will work?

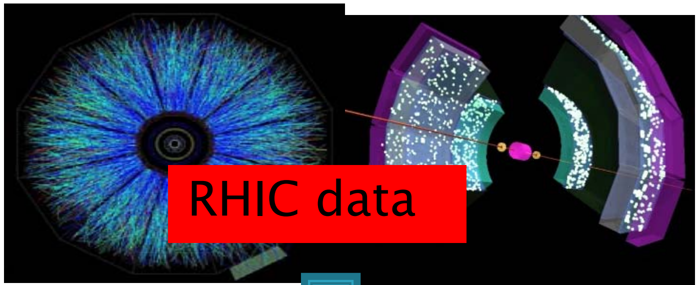


$$\frac{\varepsilon}{\varepsilon_{SB}} \sim 0.8$$

- Problems:
- conformal theory (no running coupling)
  - BUT!
  - RHIC in a region T>Tc where α_s is ~constant (T is only scale)
- What about the coupling size?
  - expansion on the strong coupling side is in $1/\lambda$
    - RHIC $\alpha_S \sim ½ \Rightarrow 1/\lambda \sim 1/20$ $\lambda = 4\pi N_{colors}\alpha_s$ (N_C=3~LARGE!)
- What about all those extra super-symmetric particles, the fact that there are no quarks…
  - Find universal features
  - Pick parameters insensitive to differences
  - Make modifications to the simplest theory ($\mathcal{N}=4$) to make it look more like QCD

➡ Ultimately find a dual to QCD

The Task



Fits to data
Hydro/QCD based model

Parameters

Gauge- String Duality aka AdS5/CFT

field theory e.g.
$\mathcal{N}=4$ Supersymmetry
a “model”

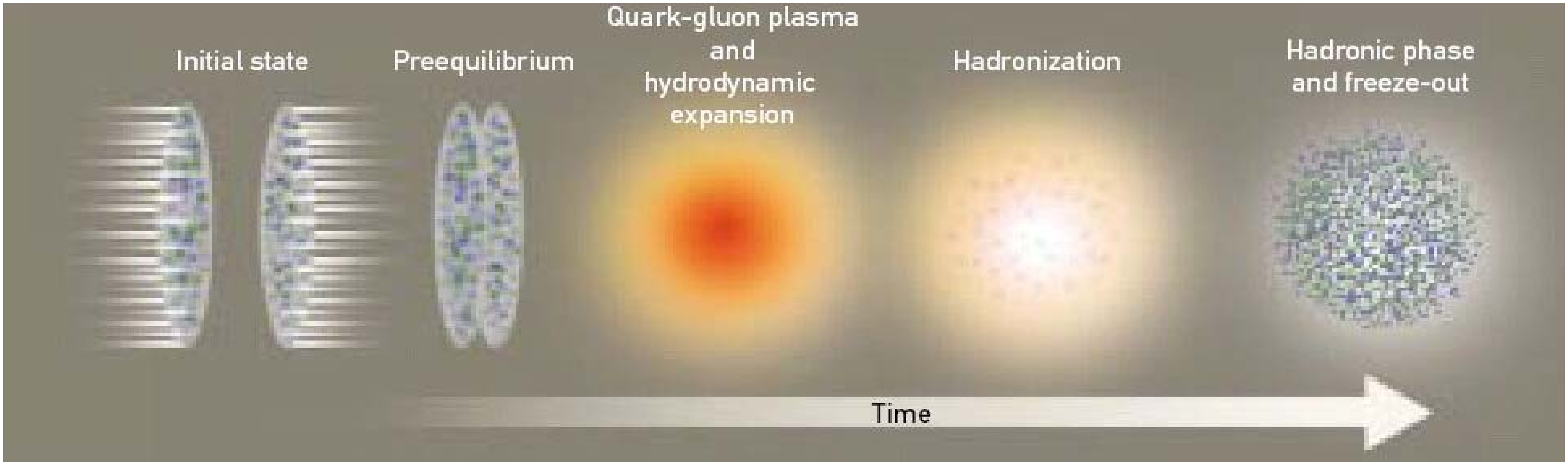
More modeling
rescaling

Parameters

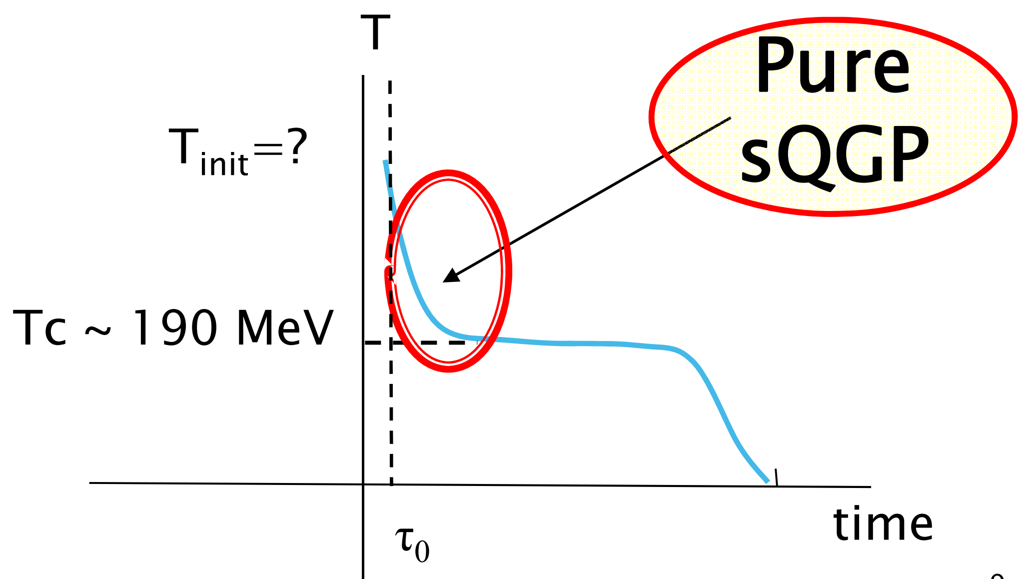
QCD

Compare
And learn

Stages of the Collision



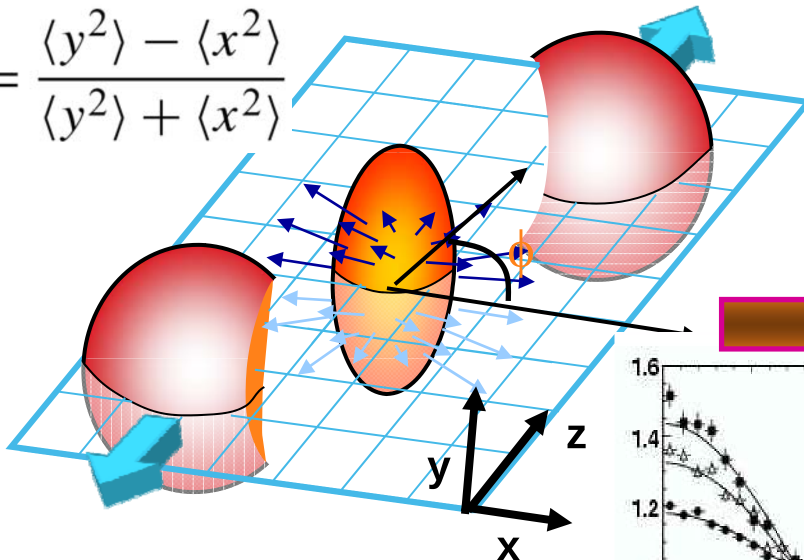
- Relativistic Heavy Ion Collisions
  - Lorenz contracted pancakes
  - Pre-equilibrium < $\tau \sim 1$ fm/c ??
  - QGP and hydrodynamic expansion $\tau \sim$ few fm/c ??



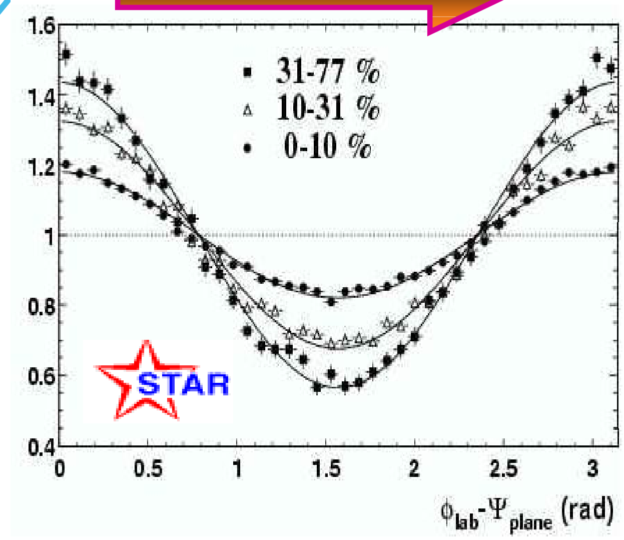
Flow: A collective effect

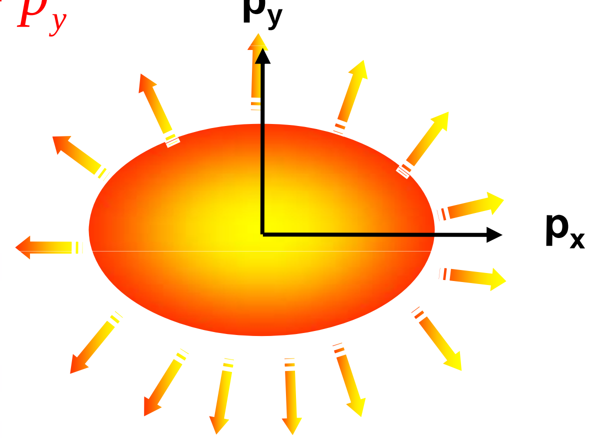
$$\varepsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$

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



Coordinate space: initial asymmetry





Momentum space: final asymmetry

$$dn/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\,\phi) + \ldots$$

Initial spatial anisotropy converted into momentum anisotropy.
Efficiency of conversion depends on the properties of the medium.

Hydrodynamics

a critical tool to extract information from data

Hydrodynamic Equations

$$\partial_\mu T^{\mu\nu} = 0,$$ Energy-momentum conservation

$$\partial_\mu n_i^\mu = 0$$ Charge conservations (baryon, strangeness, etc…)

For perfect fluids (neglecting viscosity!),

$$T^{\mu\nu} = (e + P)u^\mu u^\nu - P g^{\mu\nu}$$

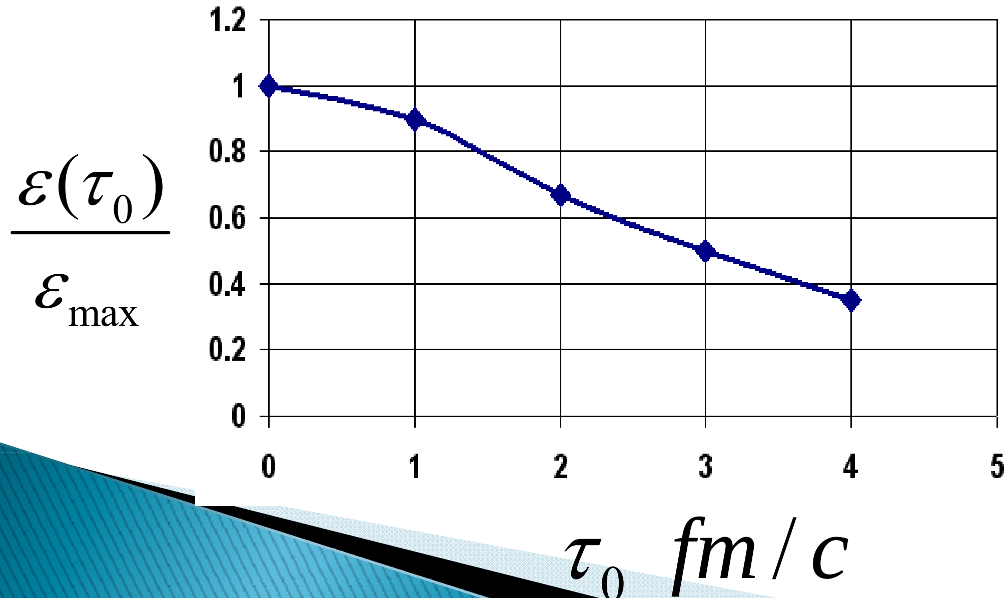
Energy density Pressure 4-velocity

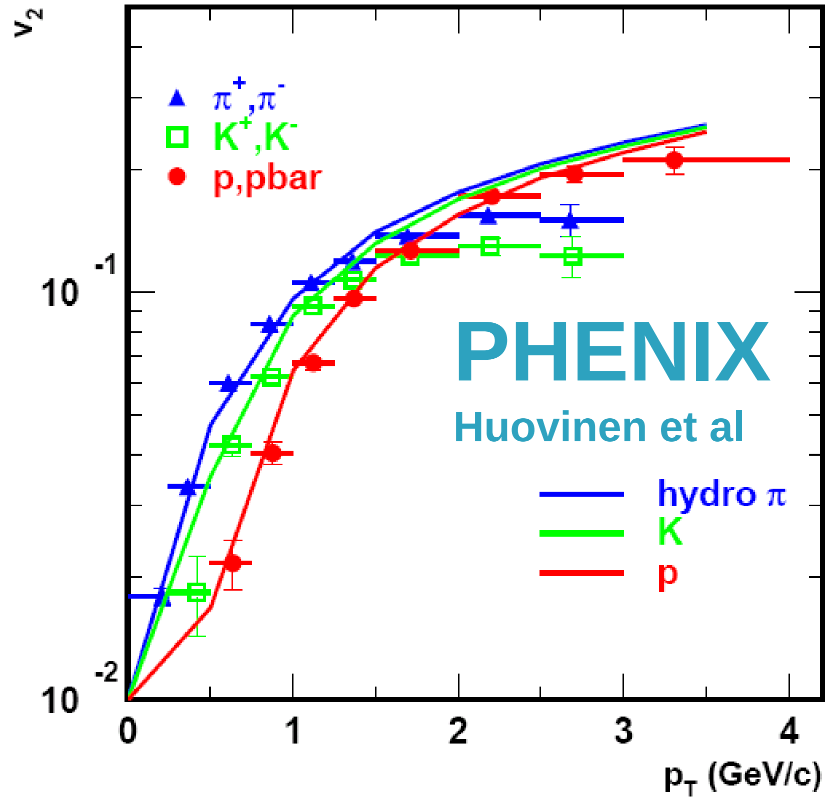
Within ideal hydrodynamics, pressure gradient *dP*/*dx* is the driving force of collective flow.

Strong flow Implies early thermalization

- If system free streams
  - spatial anisotropy is lost
  - v_2 is not developed

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





detailed hydro calculations (QGP+mixed+RG, zero viscosity

- τ_0 ~ 0.6 –1.0 fm/c
- ε~15–25GeV/fm^3
- (ref: cold matter 0.16 GeV/fm^3)

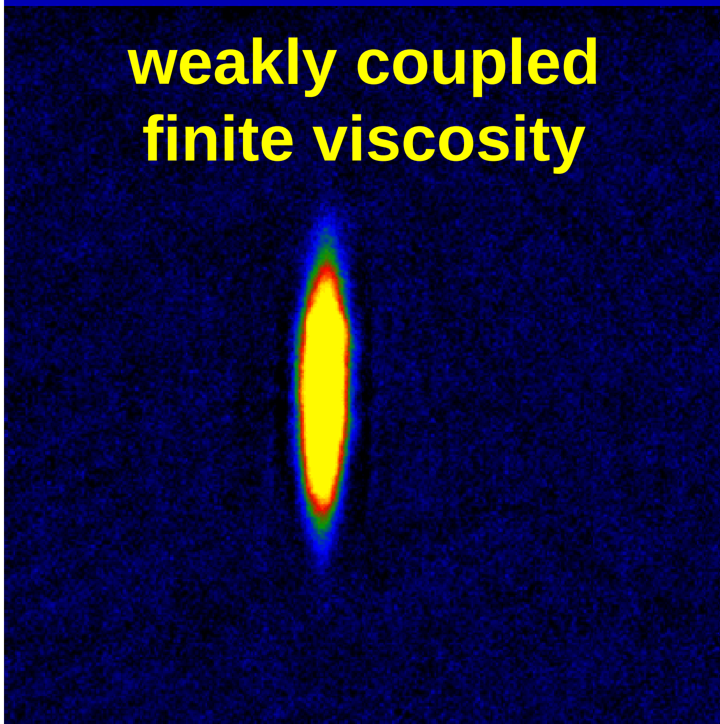
Viscosity

Strongly Coupled fluids have small viscosity!

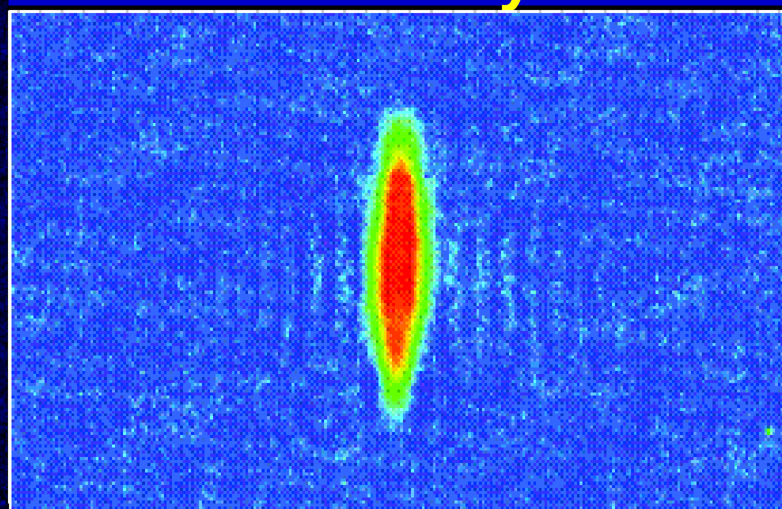
Anisotropic Flow

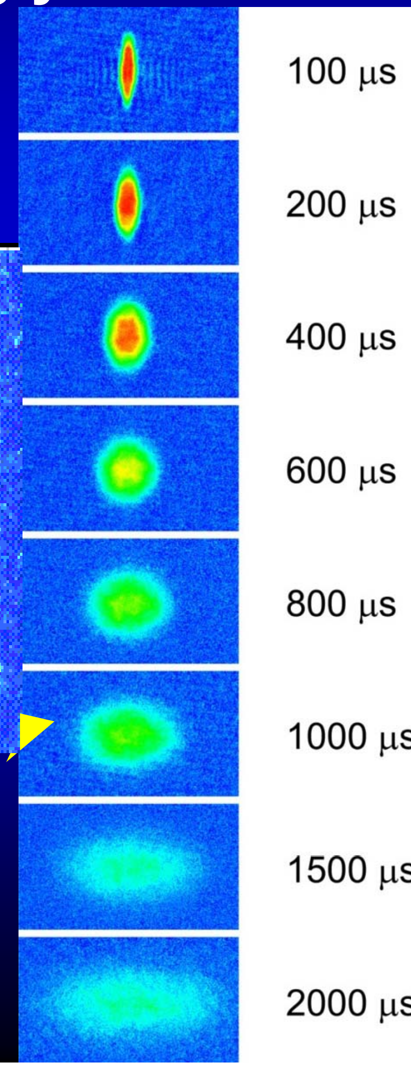
- **Conversion of spatial anisotropy to momentum anisotropy depends on viscosity**
- **Same phenomena observed in gases of strongly interacting atoms (Li6)**

M. Gehm, et al
Science 298 2179 (2002)



strongly coupled
viscosity=0

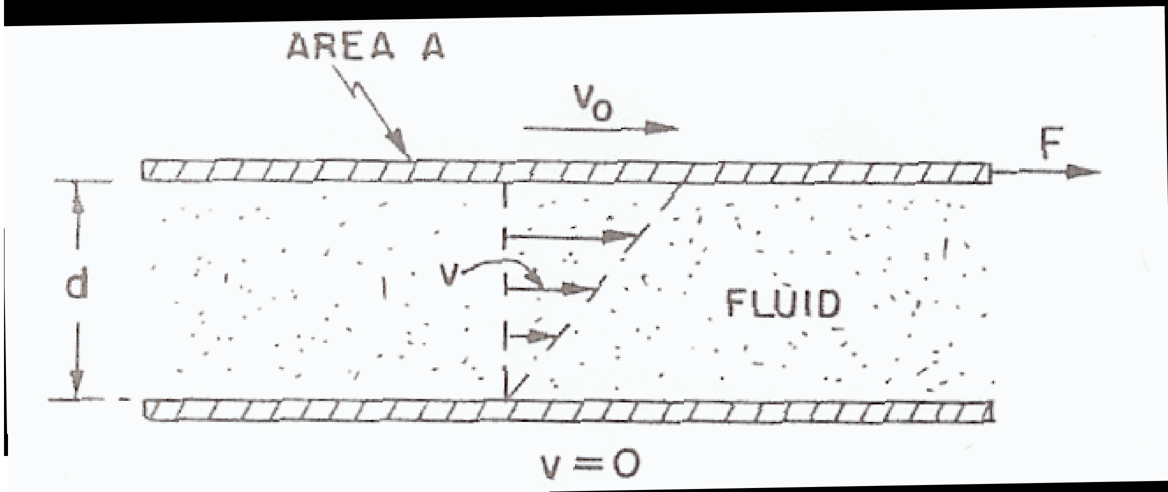




The RHIC fluid behaves like this,

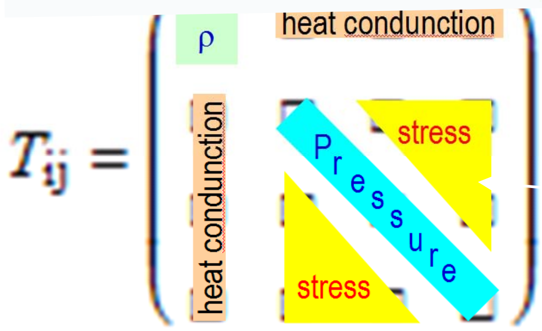
that is, viscocity~0

Calculating the viscosity



$$\frac{F}{A} = \eta \, \frac{v_0}{d} \, .$$

$$\frac{\Delta F}{\Delta A} = \eta \, \frac{\Delta v_x}{\Delta y} = \eta \, \frac{\partial v_x}{\partial y} \, .$$



energy momentum
stress tensor

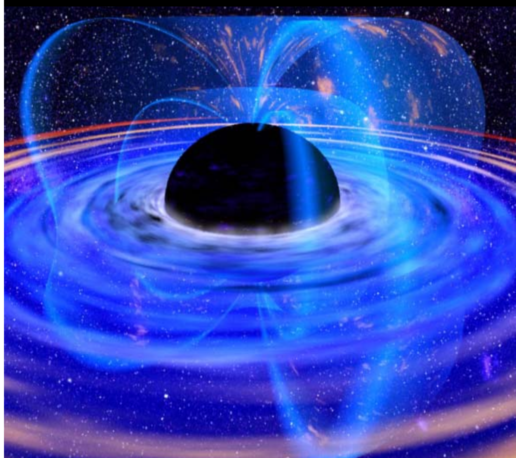
the low-brow sheer force(stress) is:

$$S_{xy} = \eta \left(\frac{\partial v_y}{\partial x} + \frac{\partial v_x}{\partial y} \right)$$

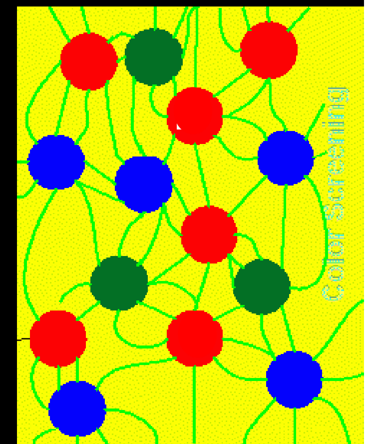
$$T_{ij} = \delta_{ij} p - \eta \left(\partial_i u_j + \partial_j u_i - \frac{2}{3} \delta_{ij} \partial_k u_k \right)$$

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

using gauge–string duality



Gravity ⟷ dual ⟷ $\mathcal{N}$=4 SYM "QCD" strong coupling



$$\sigma(\omega) = \frac{\kappa^2}{\omega}\int dt\, d\mathbf{x}\, e^{i\omega t}\langle[T_{xy}(t,\mathbf{x}), T_{xy}(0,0)]\rangle$$

Gravity — $\mathcal{N}$=4 Supersymmetry

$\kappa = \sqrt{8\pi G}$

Policastro, Son, Starinets hep-th 0104066

"The key observation… is that the right hand side of the Kubo formula is known to be proportional to the classical absorption cross section of gravitons by black three-branes."

$$\eta = \frac{1}{2\kappa^2}\sigma(0)$$

σ(0)=area of horizon

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

finishing it up

Entropy
black hole "branes ⇔ Entropy
$\mathcal{N}=4$ SYM
"QCD"

Entropy
black hole
Bekenstetein, Hawking
= Area of black hole horizon $=\sigma(0)$

$$s_{\mathrm{SYM}\ "QCD"} = \frac{\text{black hole area}}{4G}$$

$$\frac{\eta}{s} = \frac{\hbar}{4\pi k_B} = 6\times 10^{-13}\,Ks$$

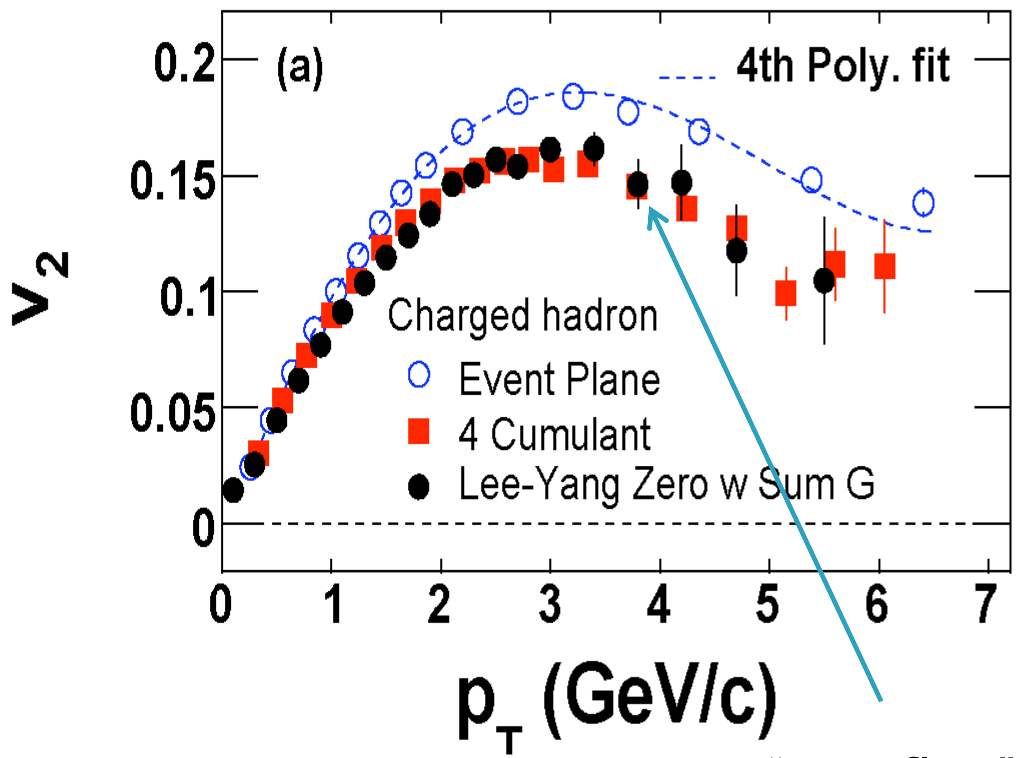
This is believed to be a universal lower bound for a wide class of Gauge theories with a gravity dual

k=8.6 E−5 eV/K

Son, Starinets hep-th 0405231

What does the data say?

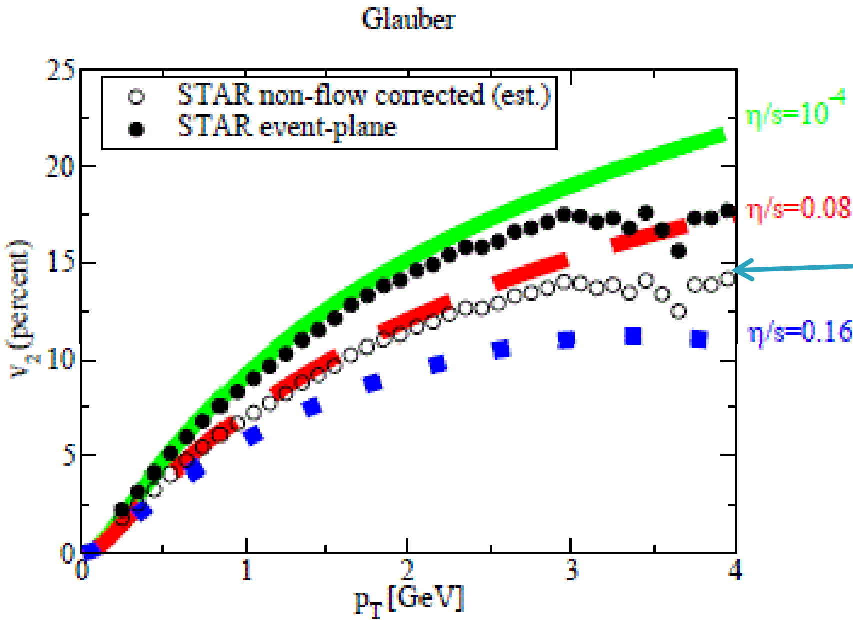
- Data from STAR
  - Note – "non-flow contribution subtraction (resonances, jets…)"
- Use Relativistic-Viscous hydrodynamics
- Fit data to extract η
  - Will depend on initial conditions



STAR "non-flow" subtracted data

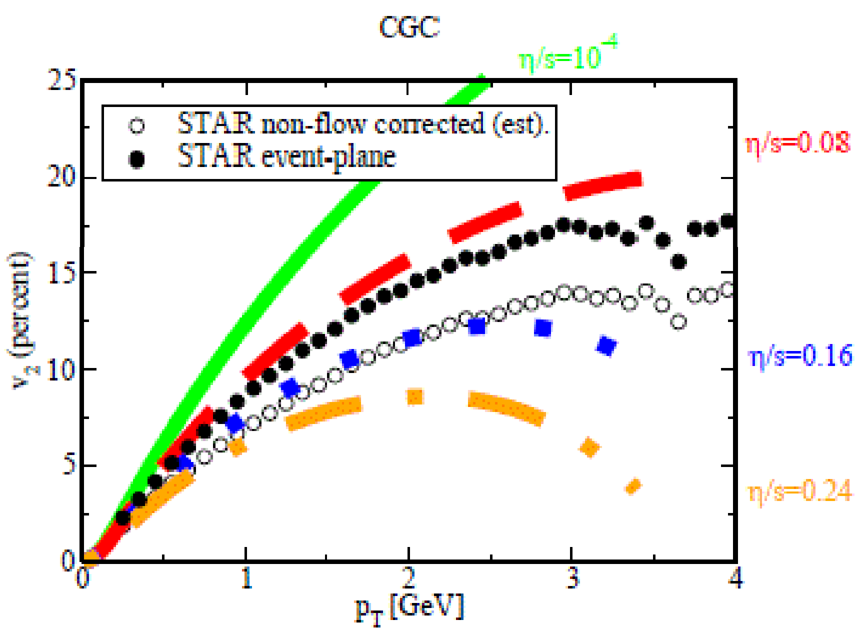
Task was completed recently by Paul Romatschke after non-flow Subtraction was done on the data

Extracting η/s



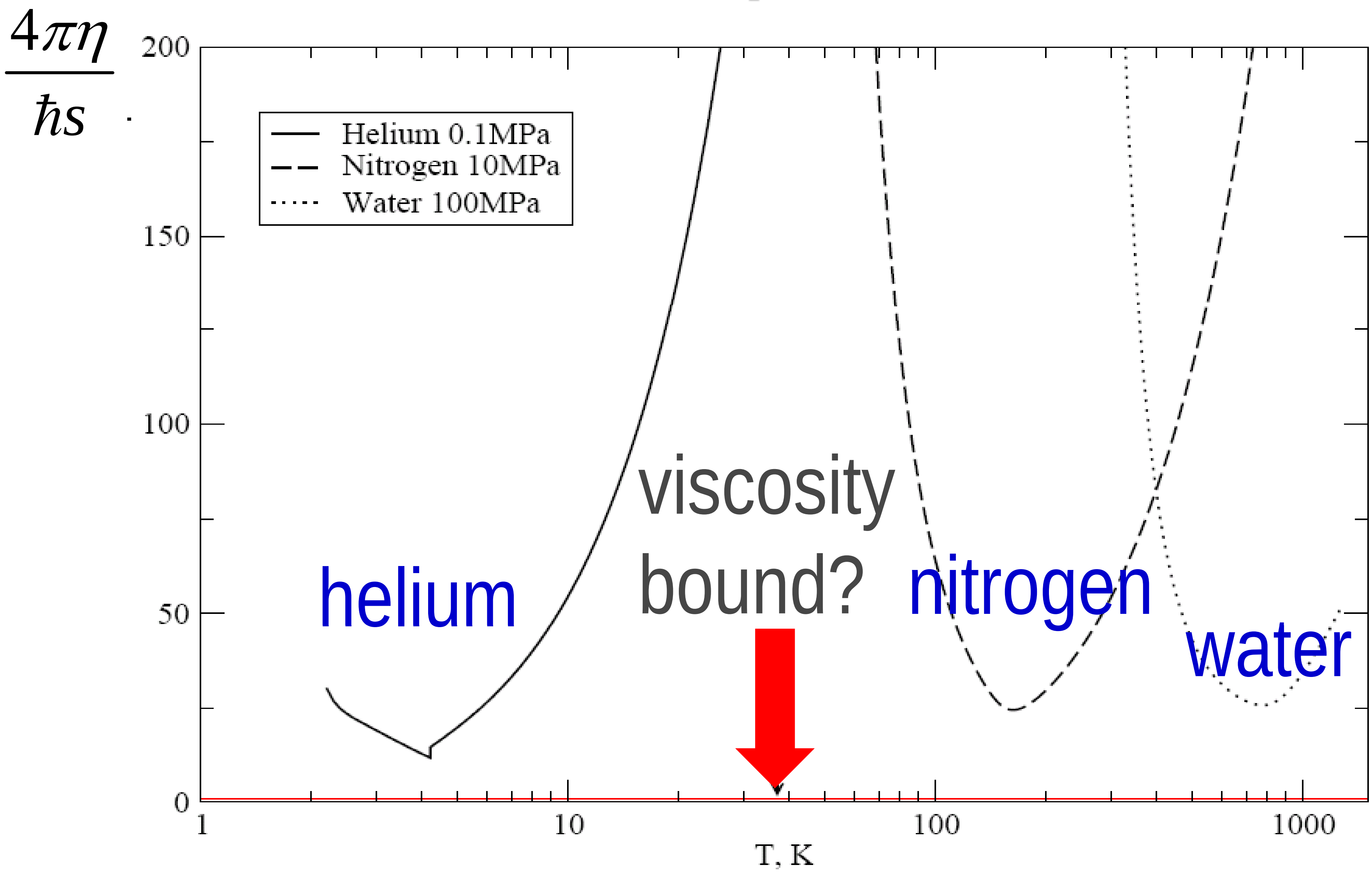
STAR "non-flow" subtracted

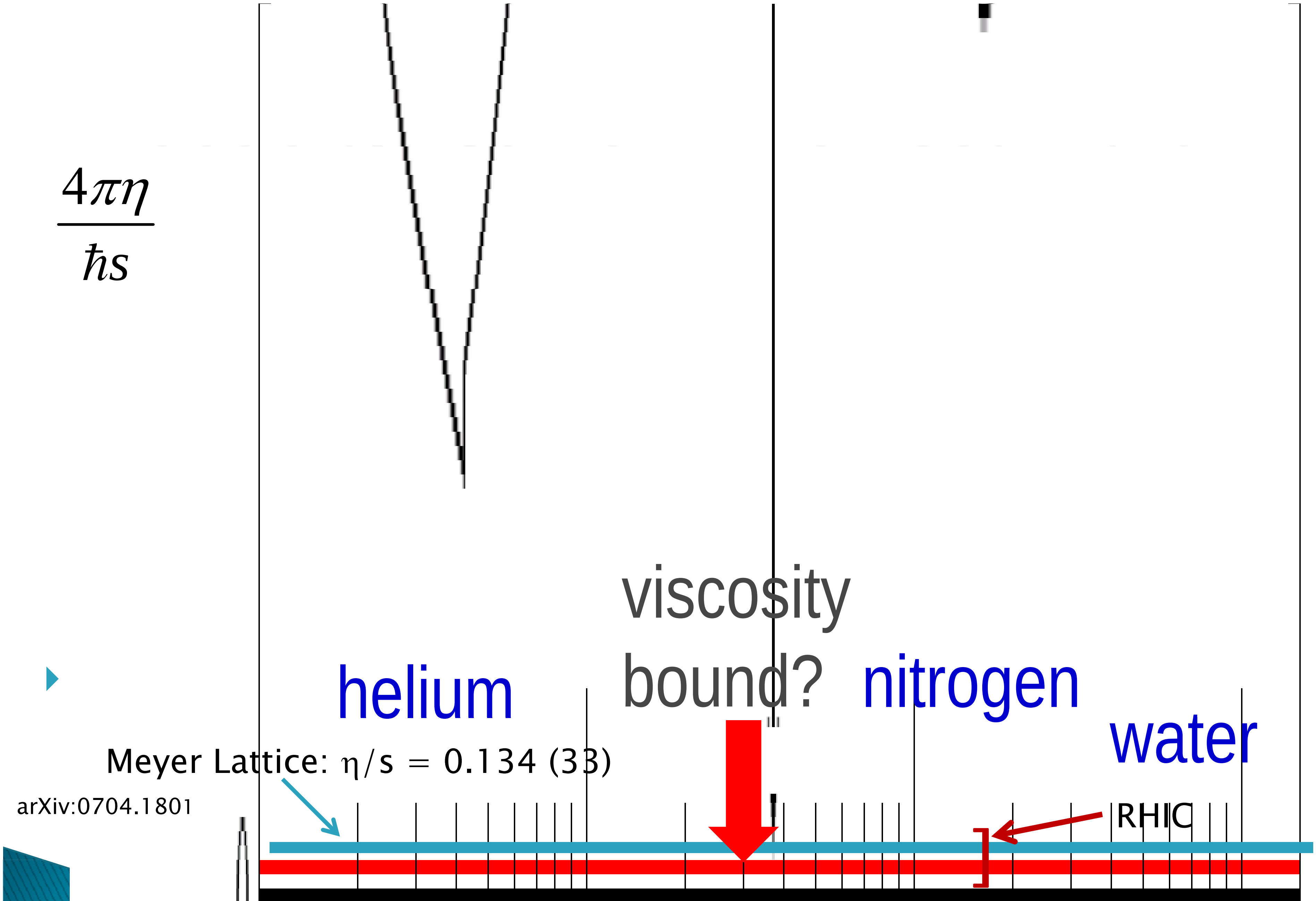
Phys.Rev.C78:034915 (2008)



- Best fit is to η/s ~0.08 = $1/4\pi$
  - With glauber initial conditions
- Using CGC (saturated gluon) initial conditions η/s ~0.16
- Note: Demir and Bass
  - hadronic stages of the collision do not change the fact that the origin of the low viscosity matter is in the partonic phase (arXiv:0812.22422)

sQGP – the most perfect fluid?



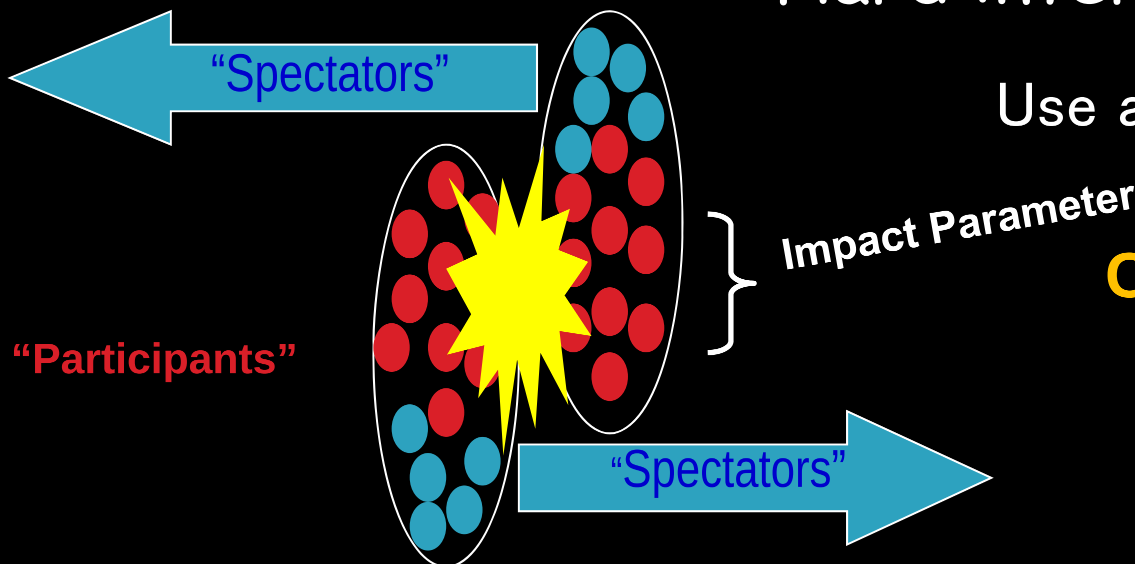

$\frac{4\pi\eta}{\hbar s}$
helium
viscosity
bound?
nitrogen
water
Meyer Lattice: η/s = 0.134 (33)
arXiv:0704.1801
RHIC

Jet quenching

Centrality and R_{AA} :the suppression factor

- Hard interactions ~ $N_{collisions}$

Use a Glauber model



Centrality def'n

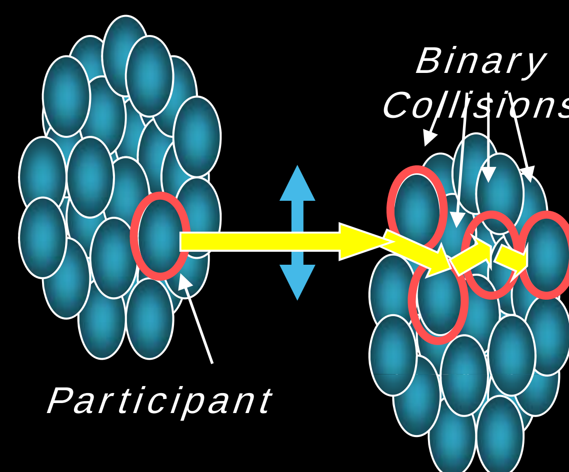
head on – central

glancing - peripheral

$$R_{AA} = \frac{\dfrac{AuAu\ yield}{N_{coll}^{AuAu}}}{\dfrac{pp\ yield}{N_{coll}^{pp}}}$$

$$N_{coll}^{AuAu} = 1000$$

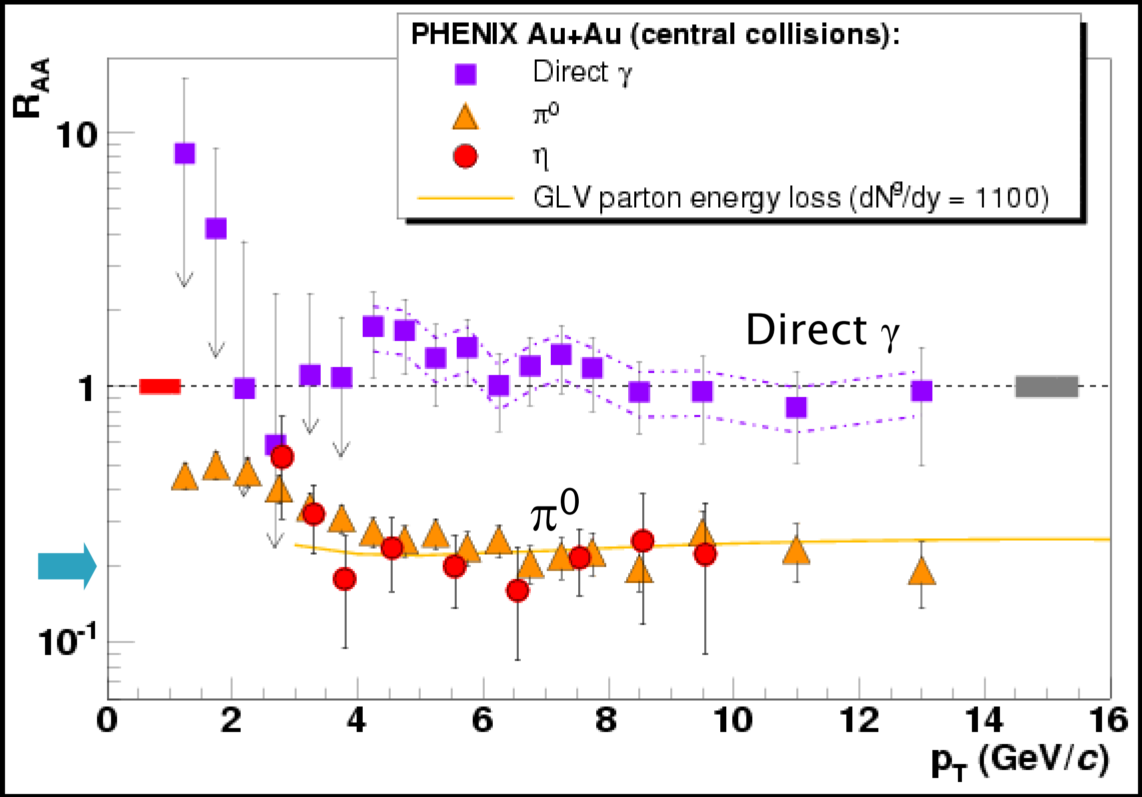
$$N_{coll}^{pp} = 1$$



What is the energy density? "Jet quenching"

AuAu 200 GeV

0.2



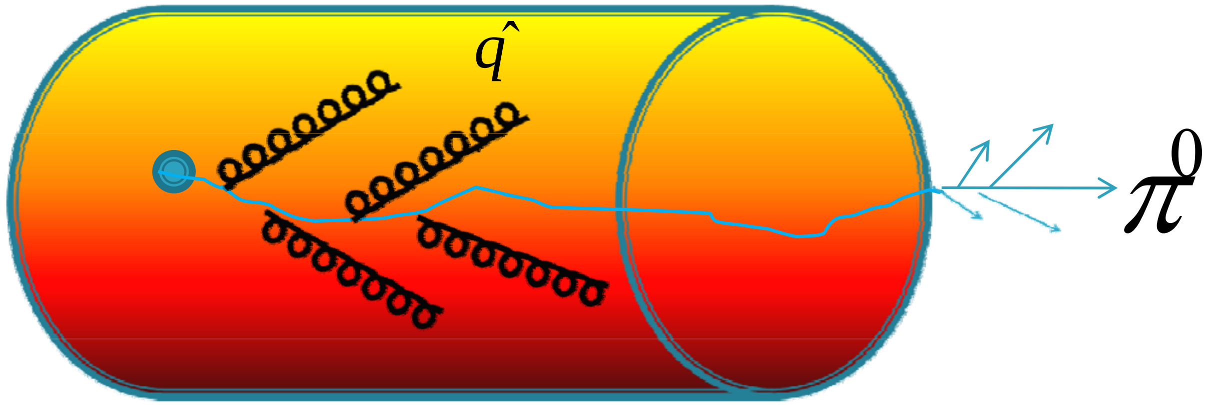
direct photons scale as N_{coll}

π^0 suppressed by 5!

$$R_{AA} = \frac{1}{\langle n_{coll}\rangle}\frac{d^2N_{AB}/dy\,dp_T}{d^2N_{pp}/dy\,dp_T}$$

Hard probes in QCD– the jet quenching parameter

- QCD – hard probes (jets)
- Assumption – Quark energy loss by radiation of gluons

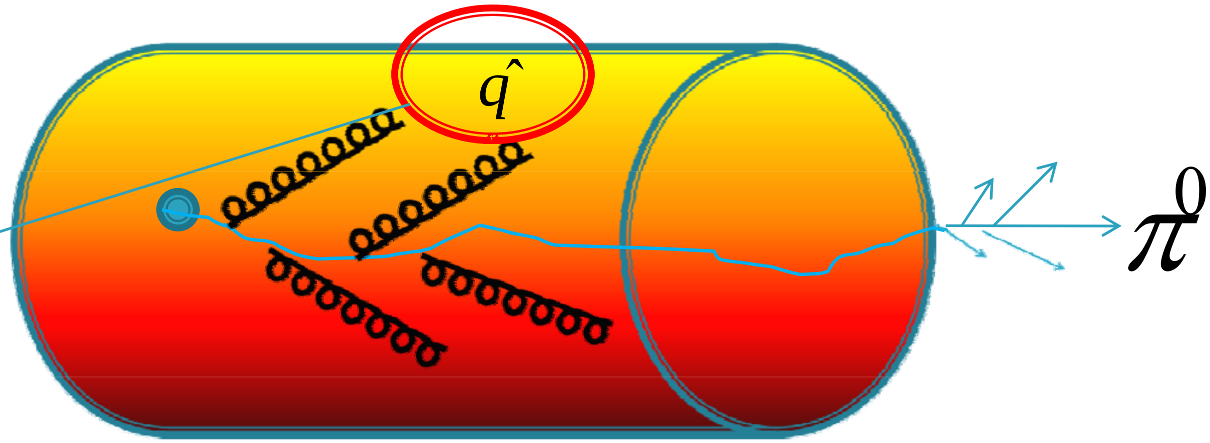


- $\mathcal{N}=4$ SYM– no running of coupling $\Rightarrow$ no hard probes (a quark would not form a jet– just a soft glow of gluons)
- Various schemes
  - Introduce heavy quark
  - Start with jet as an initial state
  - Formulate the problem in pQCD
    - Non perturbative coupling to medium is embodied in one constant $\hat{q}$ ($<p_T^2>$/length)
    - $\mathcal{N}=4$ SYM$\Rightarrow$ $\hat{q}$ (Liu, Rajagopal, Wiedemann)

Hard probes in QCD– the jet quenching parameter

Formulate in terms of
Wilson loop and calculate
In N=4 SYM using Ads/CFT

$$\hat{q}_{SYM} = \frac{\pi^{3/2}\Gamma\left(\frac{3}{4}\right)}{\Gamma\left(\frac{5}{4}\right)}\sqrt{\lambda}T^3$$



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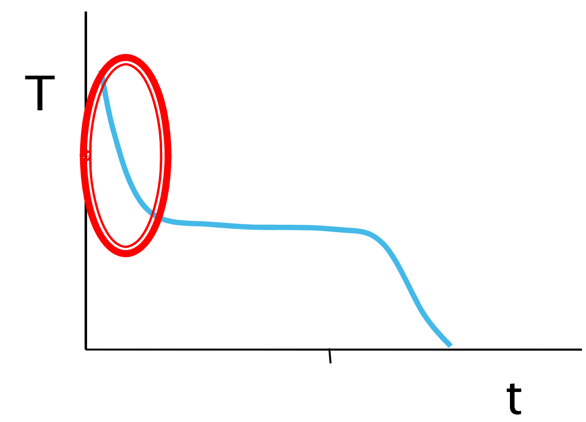
    - $\mathcal{N}$=4 SYM⇒ $\hat{q}$ (Liu, Rajagopal, Wiedemann)

hep-ph/0605178

Plugging in numbers

- solution was for static medium at temperature T

T	q
0.3 GeV	4.5 GeV^2/fm
0.4 GeV	10.6
0.5 GeV	20.7



- But the temperature is falling at RHIC as a function of time.

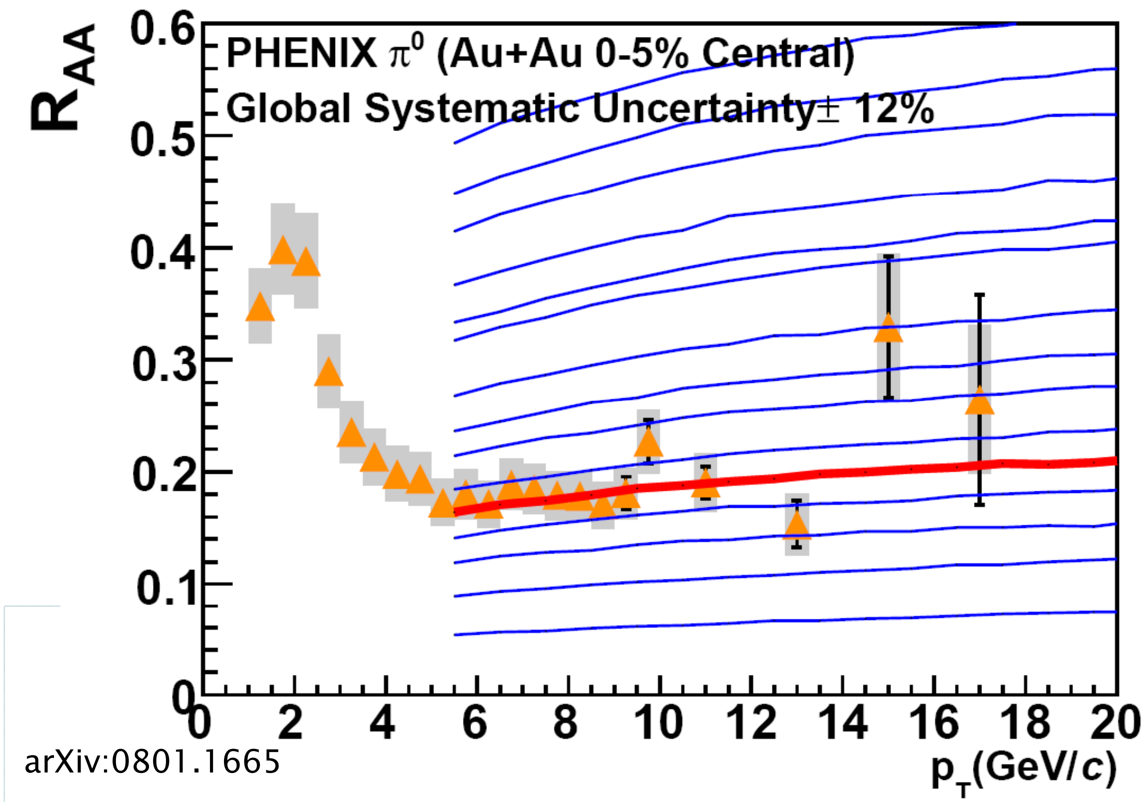
$$\bar{\hat{q}}(AdS) = 5 - 15 \quad GeV^2 / fm$$

What do the experiments get?

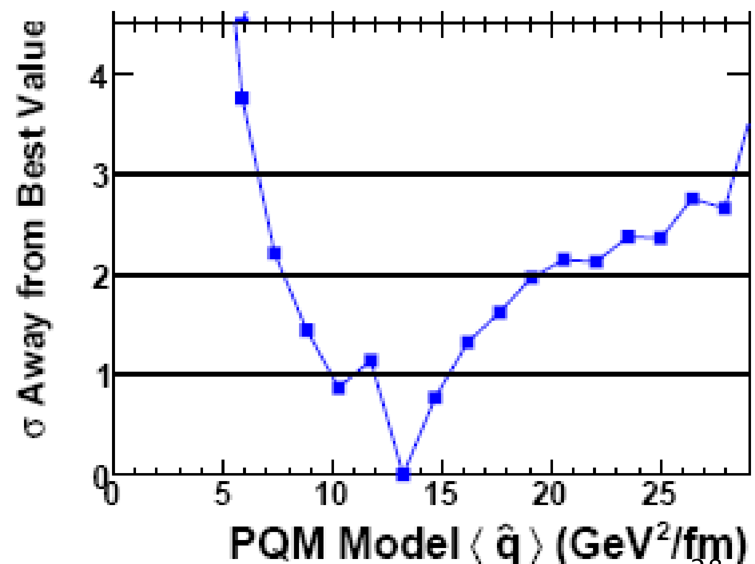
- Use PQM model (parton quenching model)
  - Realistic model of energy loss (BDMPS) $\hat{q}$
  - Realistic geometry

cf $\bar{\hat{q}} = 5 - 15 \quad GeV^2 / fm$

$$\hat{q} = 13.2^{+2.1}_{-3.1} \quad 2\sigma^{+6.3}_{-5.2}$$



arXiv:0801.1665



m_u~3 MeV
m_d~5 MeV
m_s~100 MeV
m_c~1,300 MeV
m_b~4,700 MeV

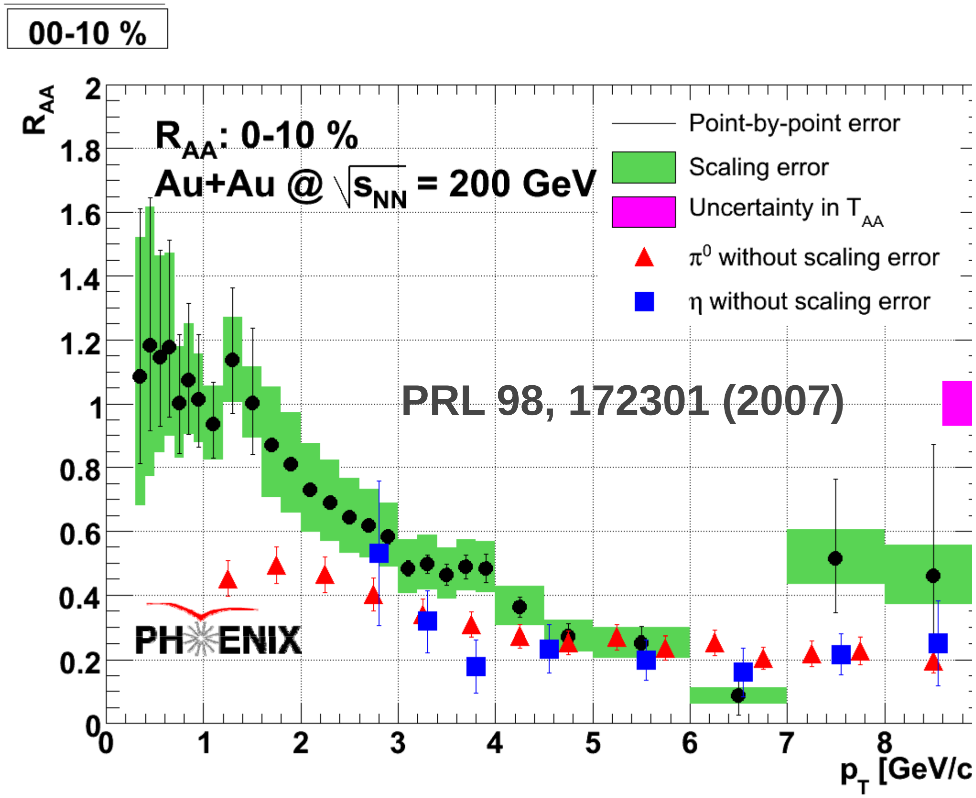
Λ_{QCD}~200 MeV

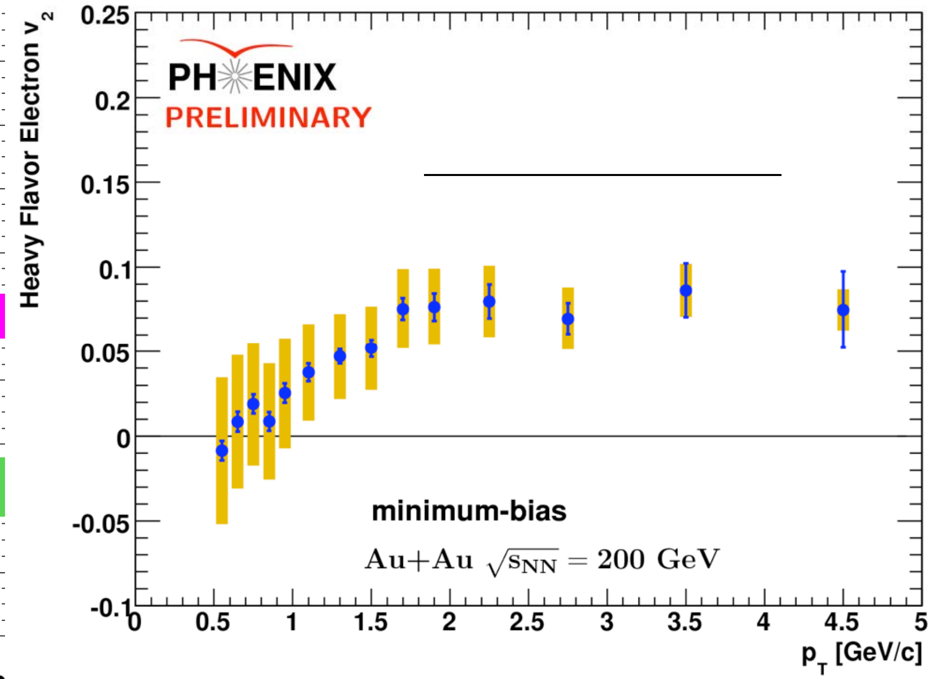
heavy quark diffusion

throw a pebble in the stream

see if it moves

Non photonic electrons (aka charm+bottom)





- high p_T non-photonic $e^{\pm}$ suppression increases with centrality
- similar to light hadron suppression at high p_T

- non-photonic $e^{\pm}$ Flow

➔charm suppressed and thermalizes

Can we describe this in the context of the sQGP?

AdS: D_{HQ} the diffusion coefficient

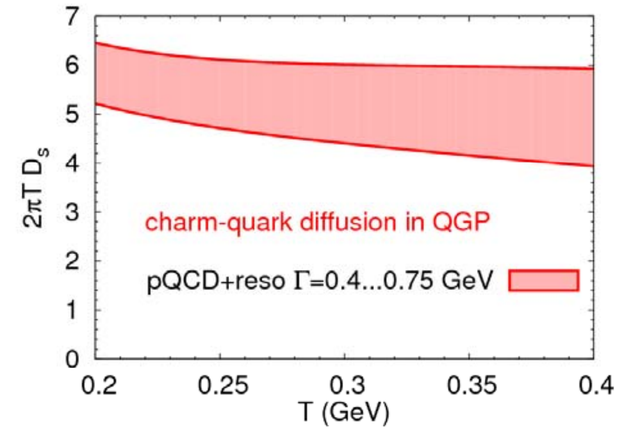
- Make modification to $\mathcal{N}=4$
  - Add heavy quark (adding a D7 Brane)
- Drag a heavy quark at a constant velocity and see how much force is needed – calculate a drag coefficient
  - $M\mu=f/v$ $D=T/\mu M$ $D=\frac{2}{\pi\sqrt{\lambda}T}=\frac{0.15}{T}$
- Rescale to QCD
  - Herzog: $\frac{D_{QCD,\alpha_s=0.5}}{D_{QCD,\alpha_s\to 0}}\sim\frac{D_{SYM,\lambda=19}}{D_{SYM,\lambda\to 0}}$ *Where* $\frac{D_{QCD,\alpha_s\to 0}}{D_{SYM,\lambda\to 0}}\sim 4$

Gubser: alternate set of parameters ($\lambda=5.5$, $3^{1/4}T_{SYM}=T_{QCD}$)

$D_{HQ}(AdS)=0.6/T$

hep-th/0605158, hep-th/0605191

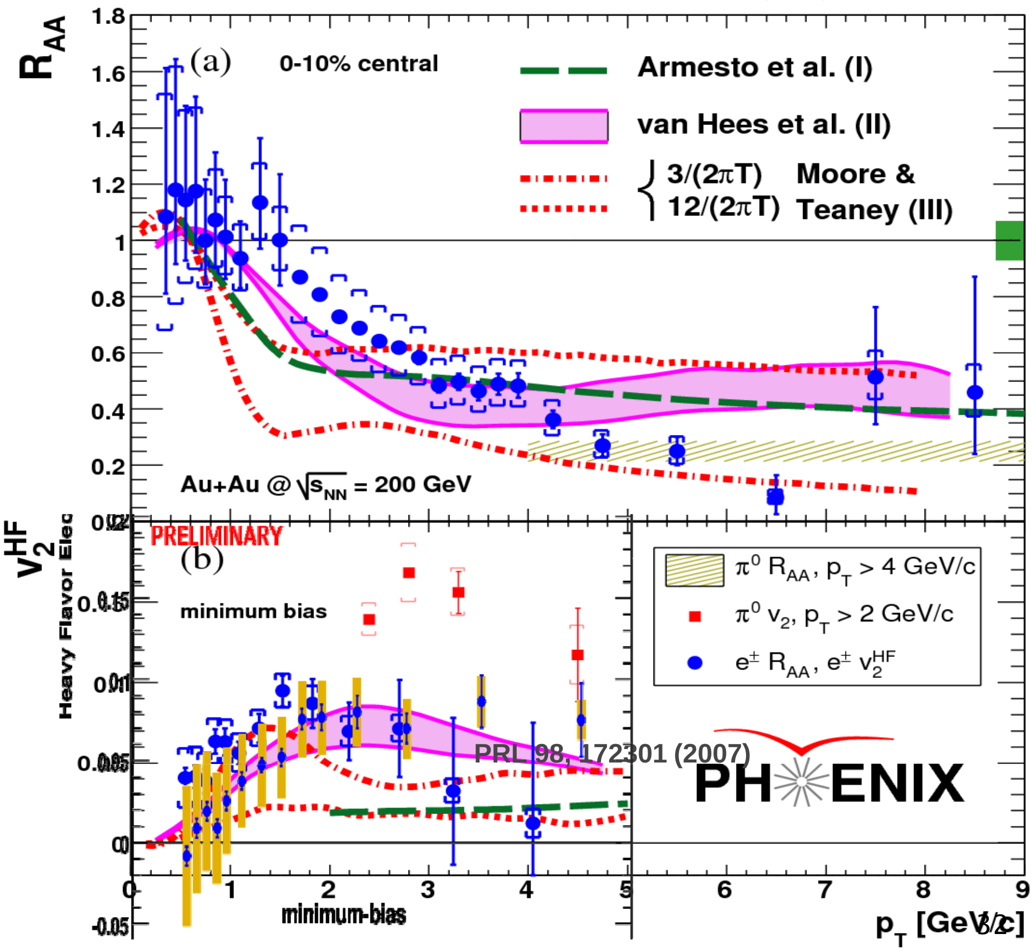
Getting D_{HQ} from data



- Rapp and vanHees
- model has "non-pertubative" features
  - resonant scattering
- fits flow and R_{AA}

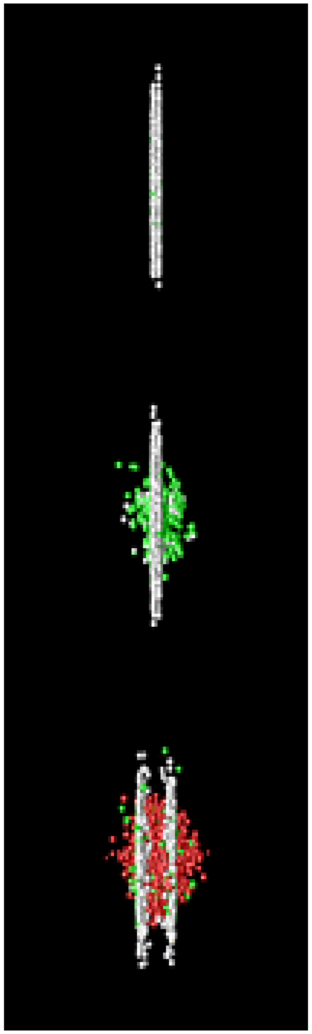
- $D_{HQ} = 4\text{-}6/2\pi T = 0.6\text{-}0.9/T$

Cf D(AdS)=0.6/T



Equilibration and temperature

Temperature and τ_0



- Equilibration time (τ_0) from AdS

model → Rapidly expanding Spherical plasma Ball ⟷ dual ⟷ Black hole in AdS5

Perturb it

~ hydro-like modes
~non hydro-like

Study rate of equilibration to hydrodynamical description

Find rate of decay Of non hydo-like modes

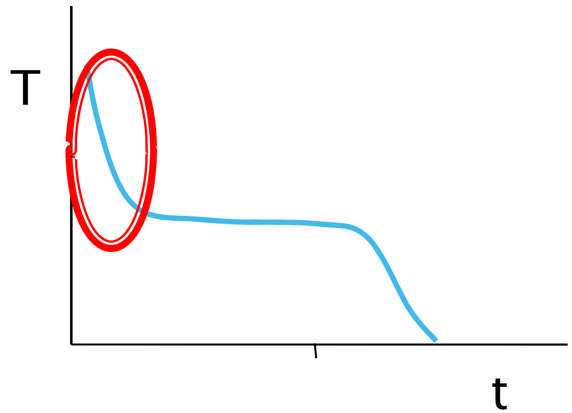
$$\tau_{\text{e-fold}} = 1/8.6T_{max}$$

$$\tau_0\,(\text{AdS}) = 4\ \tau_{\text{e-fold}}$$

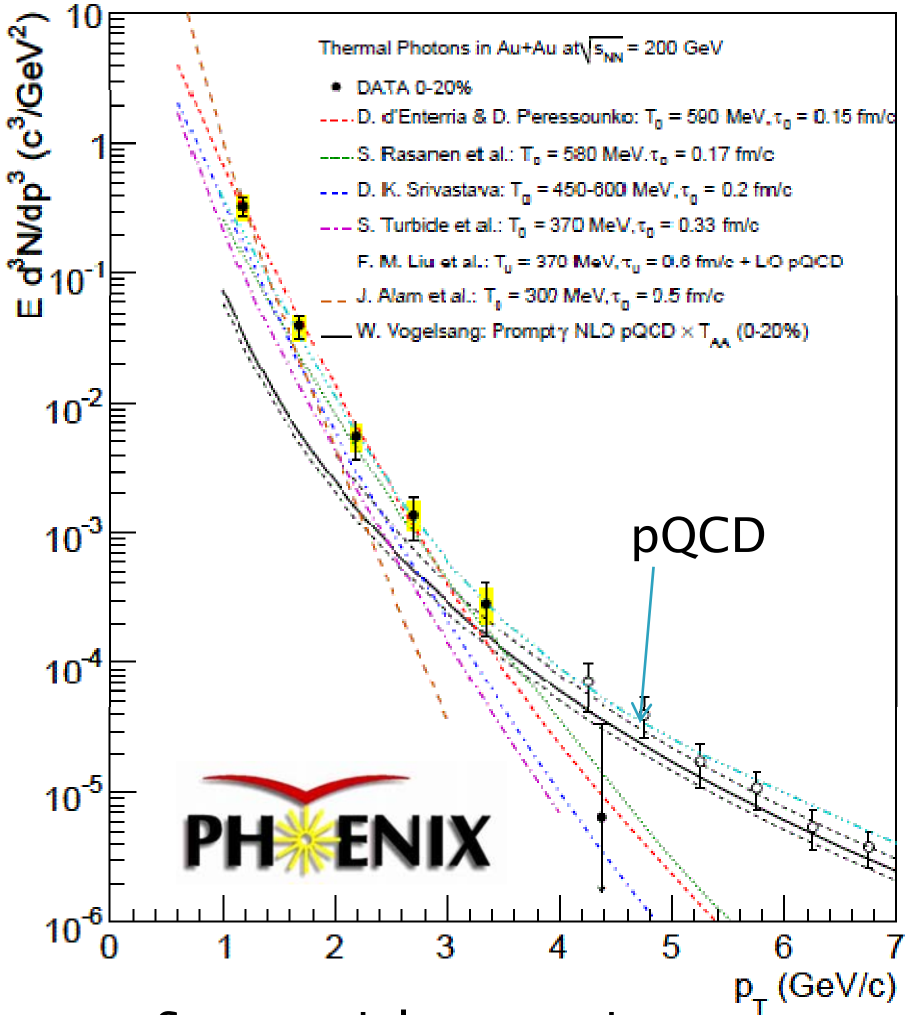
Xiv:hep-th/0611005

Thermal photons – Temperature from the data

- Make a measure of low p_T photons (black body radiation)

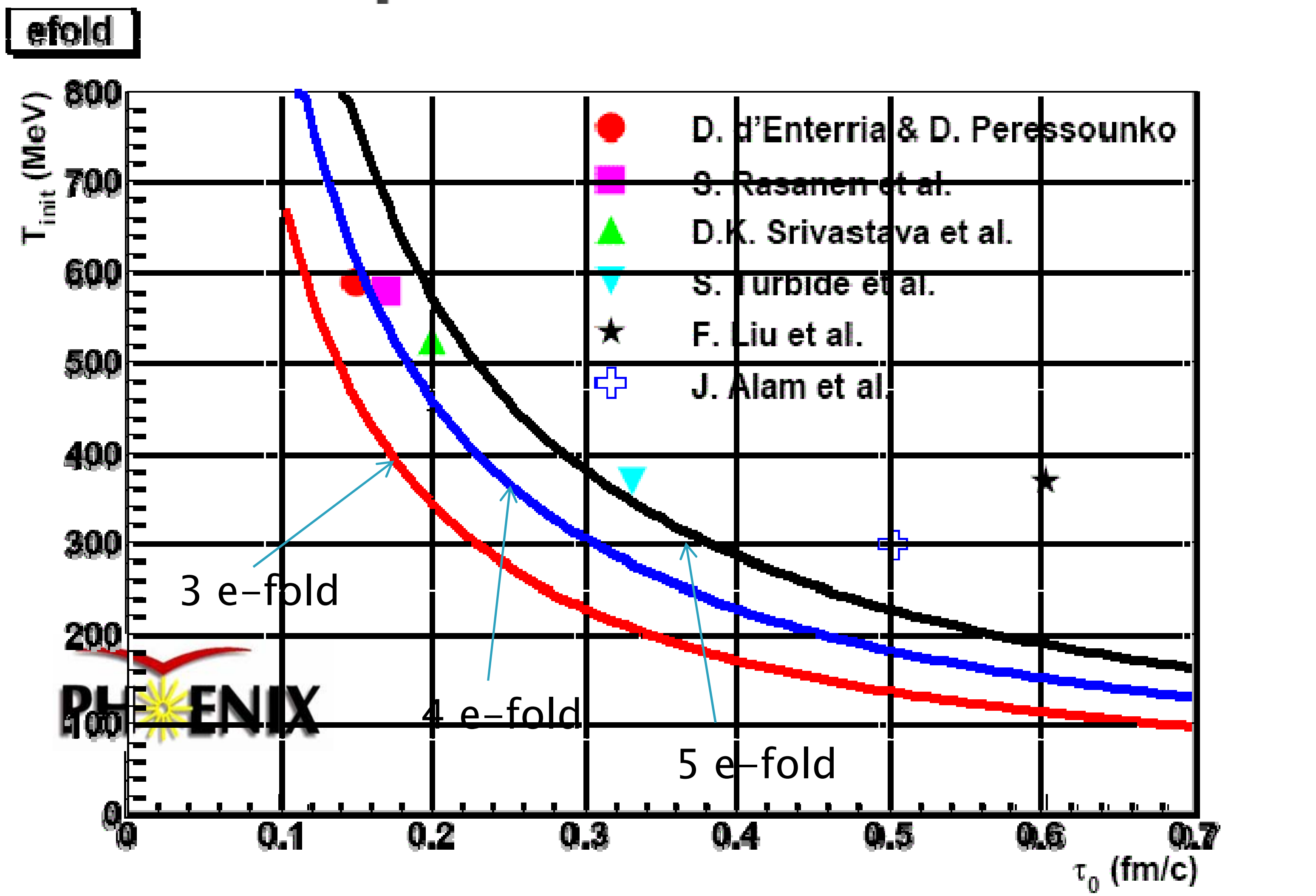


Use a model of time dependence and fit data



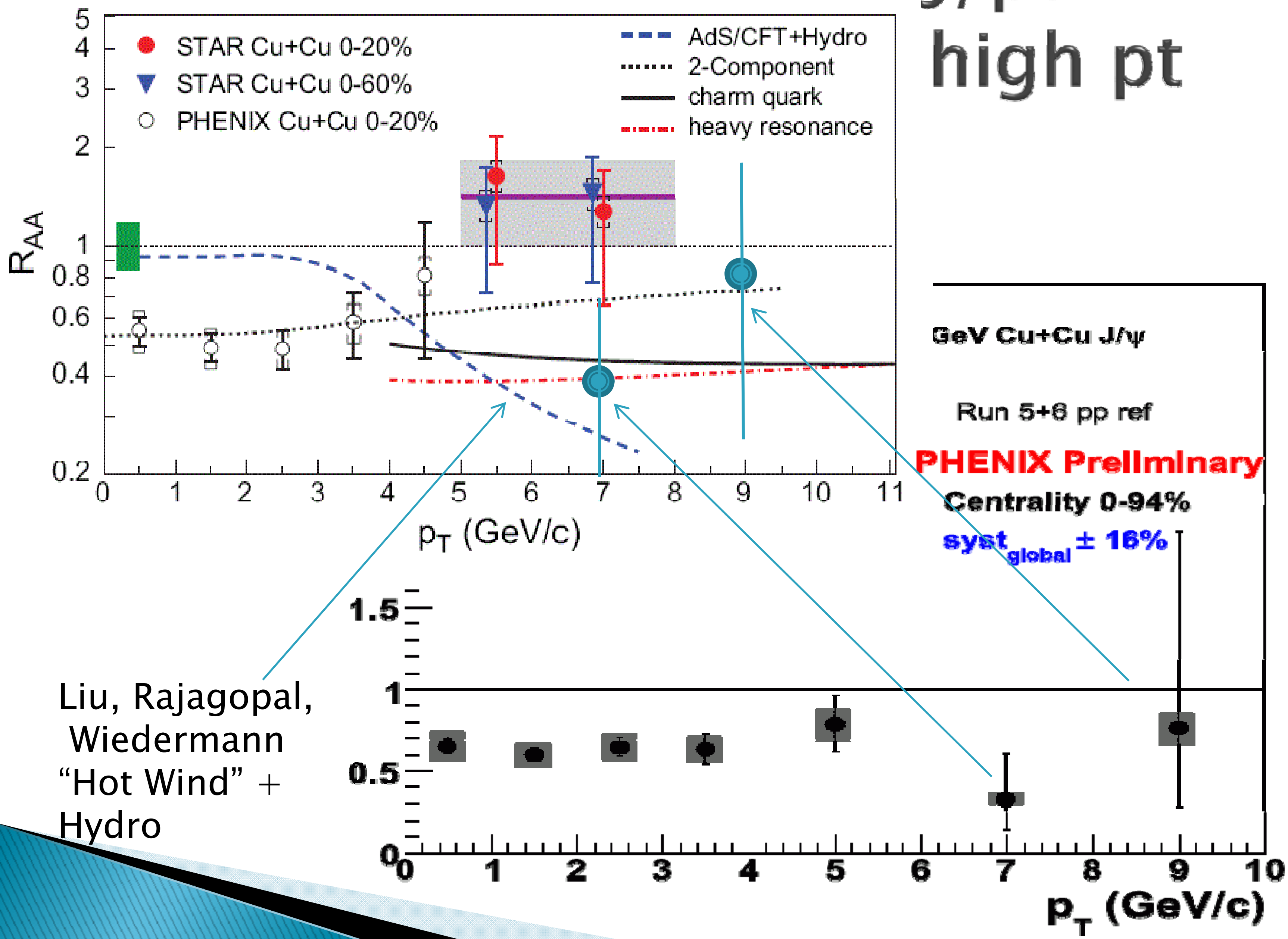
See special symposium

Thermal photons



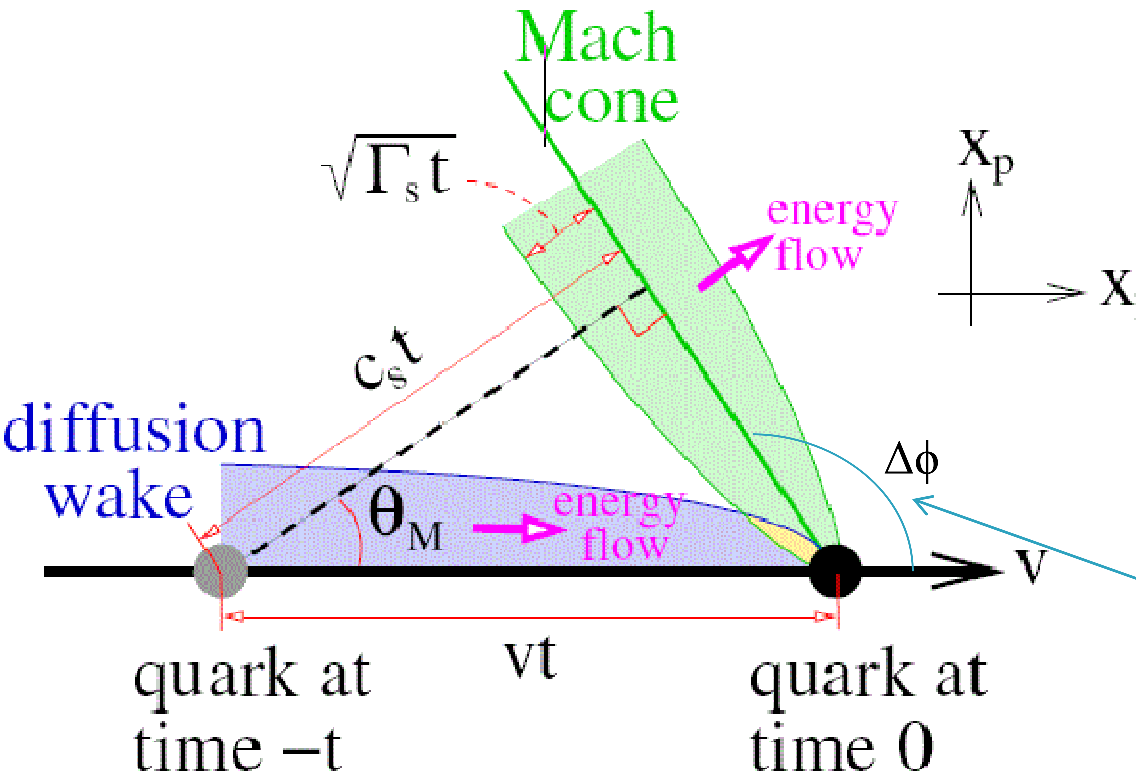
- Models follow same trend depend on τ_0

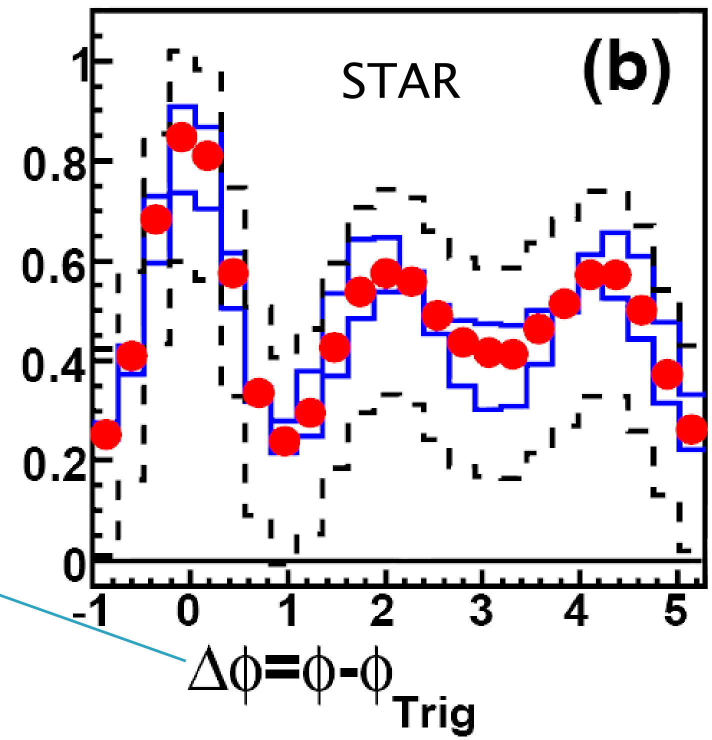
J/psi high pt

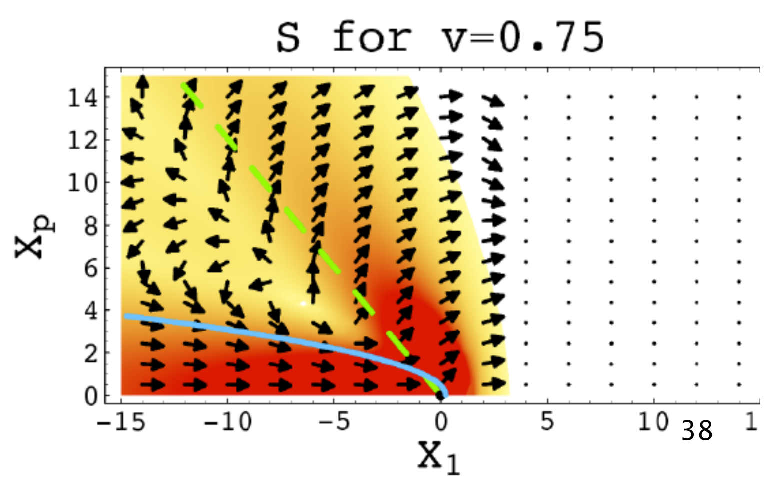


Liu, Rajagopal, Wiedermann "Hot Wind" + Hydro

Mach cones and diffusion wakes







SCORECARD

quantity	units	Theory	Experiment	data	method	Collab	comment
s/s_{SB} [1]		0.77	~0.8			Lattice	1st order correction
η/s [2]		0.1	~0.08	Charged flow	Viscous hydro[9]	STAR	Universal? 1st order
$\hat{q}$ [3]	GeV^2/fm	5-15	13	R_AA (pion)	Fit to PQM [10]	PHENIX	Average over time
$D_{HQ}(\tau_{HQ})$ @T=0.300 GeV [4]		0.6/T	0.6-0.9 /T	HQ decay e-	Fit to[11] Rapp, vanHees	PHENIX	Rescaled theory
$T(\tau_0=3fm)$ [5]	GeV	0.300 (4-efold)	0.380		Fit to[12] models	PHENIX	
τ_0 [6]	fm	0.3	0.6		Fit to flow [13]	STAR/ PHENIX	Init cond needed
J/ψ [7]	stronger suppression pt>5			Some inconsistency between experiments		wait for more data [14]	
Mach cones, [8] diffusion wakes		exists	Something is there			Need more studies [15]	

A word of caution

- There are complications and assumptions that I skipped over e.g.
  - for Hydro
    - need to use Israel-Stewart as not to violate causality
    - need EOS (from lattice – at the moment various ones are used for the fits)
  - The electrons from experiment are actually ~½ B mesons at high p_T. For the AdS side we (I) typically assumed m=1.4

    - And the list goes on

Conclusion

- The Gauge-String Duality (AdS/CFT) is a powerful new tool
- The various theoretical together are giving us a deeper understanding of the sQGP
  - Can work hand in hand to with the experimentalists
- pQCD, Gauge String Dualities, Lattice, Viscous Hydrodynamics, Cascade simulations, …
  - Bring different strengths and weakness
  - ALL are needed and must work together

References for scorecard

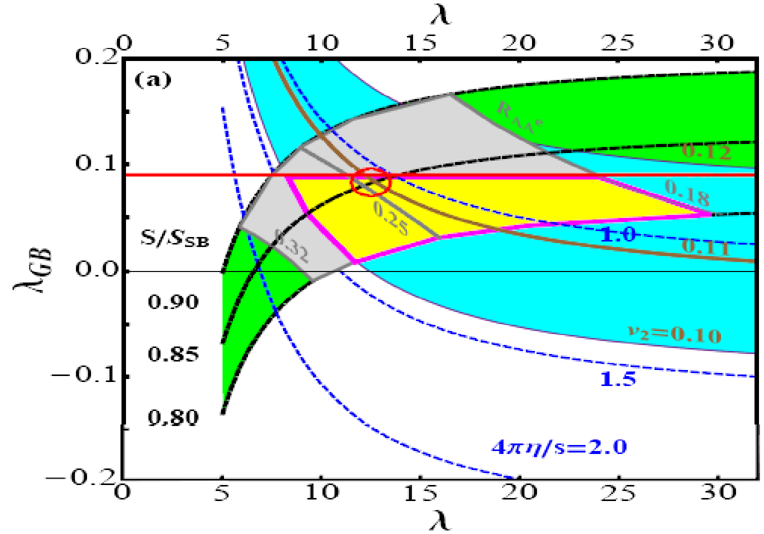
- [1]hep-th/9805156
- [2]hep-th 0405231
- [3]hep-ph/0605178
- [4]hep-th/0605158, hep-th/0605191
- [5]arXiv:hep-th/0611005
- [6]arXiv:0705.1234
- [7]hep-ph/0607062
- [8]arXiv:0706.4307
- [9]Phys.Rev.C78:034915 (2008)
- [10]arXiv:0801.1665
- [11]Phys. Rev. Lett. 98, 172301 (2007)
- [12]arXiv:0804.4168
- [13]nucl-th/0407067
- [14]Phys. Rev. C 80 (2009) 41902
- [15]arXiv:0805.0622

Plugging in numbers

$$\alpha_S^{sQGP} \sim 0.5 \quad (0.35)$$

$$\lambda^{Supersym} = 4\pi N_{colors} \alpha_S \sim 19\,(13)$$

$$\frac{1}{\lambda} = 0.05 \;\; (0.08)$$



$$\frac{\eta}{s} = \frac{1}{4\pi}\left(1 + 15\frac{\zeta(3)}{\lambda^{3/2}} + \ldots\right)$$

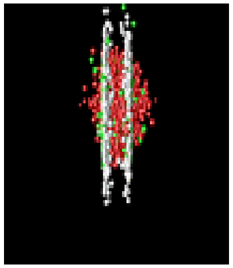
1st order correction 20%

$$\frac{S}{S_{SB}} = \frac{3}{4}\left(1 + \frac{15}{8}\frac{\zeta(3)}{\lambda^{3/2}} + \ldots\right)$$

1st order correction 3%

$\hat{q}$

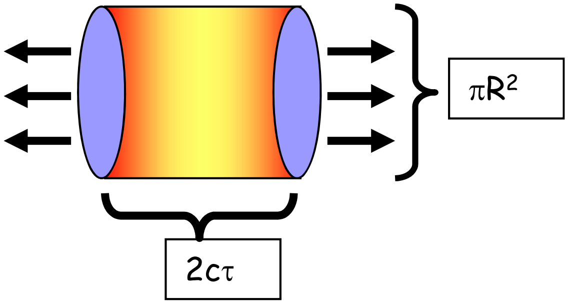
Energy Density

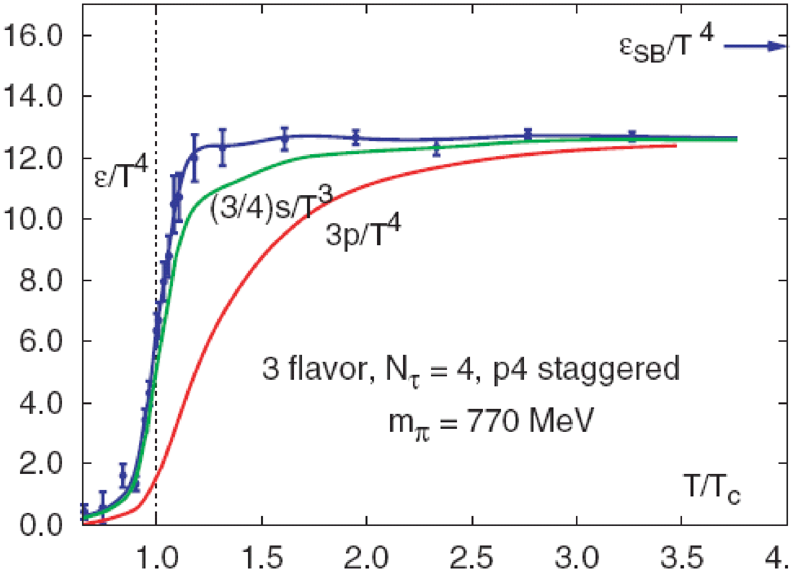


Energy density far above transition value predicted by lattice.

$$\varepsilon_{Bj} = \frac{1}{\pi R^2} \frac{1}{2c\tau} \left(2 \frac{dE_T}{dy} \right)$$

R~7fm





Lattice: T_C~190 MeV (ε_C ~ 1 GeV/fm^3)

PHENIX: Central Au-Au yields

Phase transition– fast cross over
to experimentalist: 1st order

$$\left\langle \frac{dE_T}{d\eta} \right\rangle_{\eta=0} = 503 \pm 2\,GeV$$

$$\varepsilon \sim 15 \frac{GeV}{fm^3} \ @\ \tau = 0.6\ fm/c\ (thermalization)$$