Selected results from hydrodynamics and applications of AdS/CFT at RHIC

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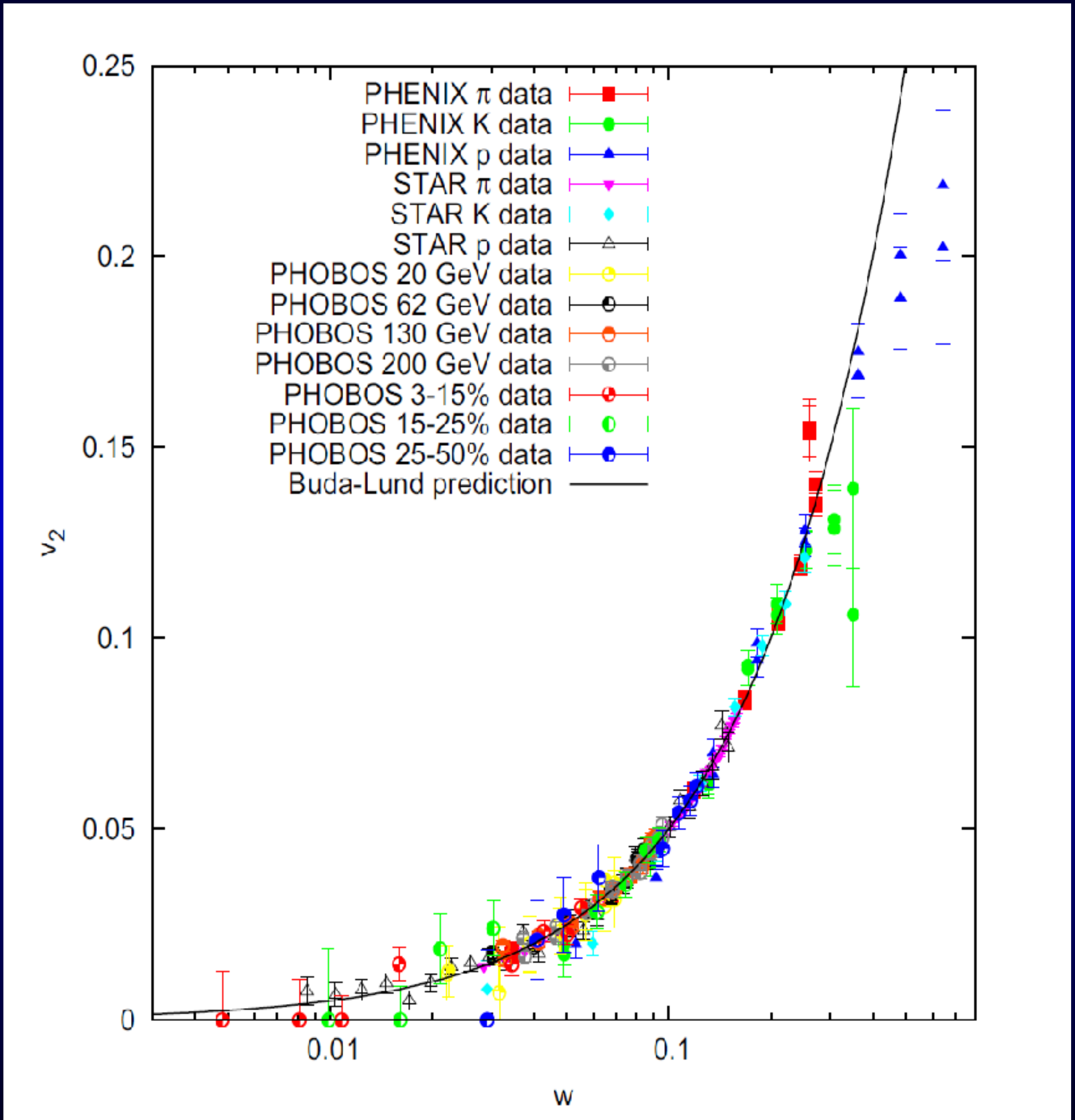
based on S. Gubser, arXiv:0907.4808 [hep-th]
and works of R. Baier, M. Csanád, M.I. Nagy, S. Gubser, R. Vértesi and A. Ster

How well fluid dynamics works at RHIC?



M. Csanád, T. Cs. et al, Eur. Phys.J.A38:363-368,2008

Scaling predictions for (viscous) fluid dynamics

$$T'_x = T_f + m\dot{X}_f^2 \,,$$
$$T'_y = T_f + m\dot{Y}_f^2 \,,$$
$$T'_z = T_f + m\dot{Z}_f^2 \,.$$

- Slope parameters increase linearly with mass
- Elliptic flow is a universal function its variable w is proportional to transverse kinetic energy and depends on slope differences.

$$v_2 = \frac{I_1(w)}{I_0(w)}$$

$$w = \frac{k_t^2}{4m}\left(\frac{1}{T'_y} - \frac{1}{T_x}\right),$$

$$w = \frac{E_K}{2T_*}\varepsilon$$

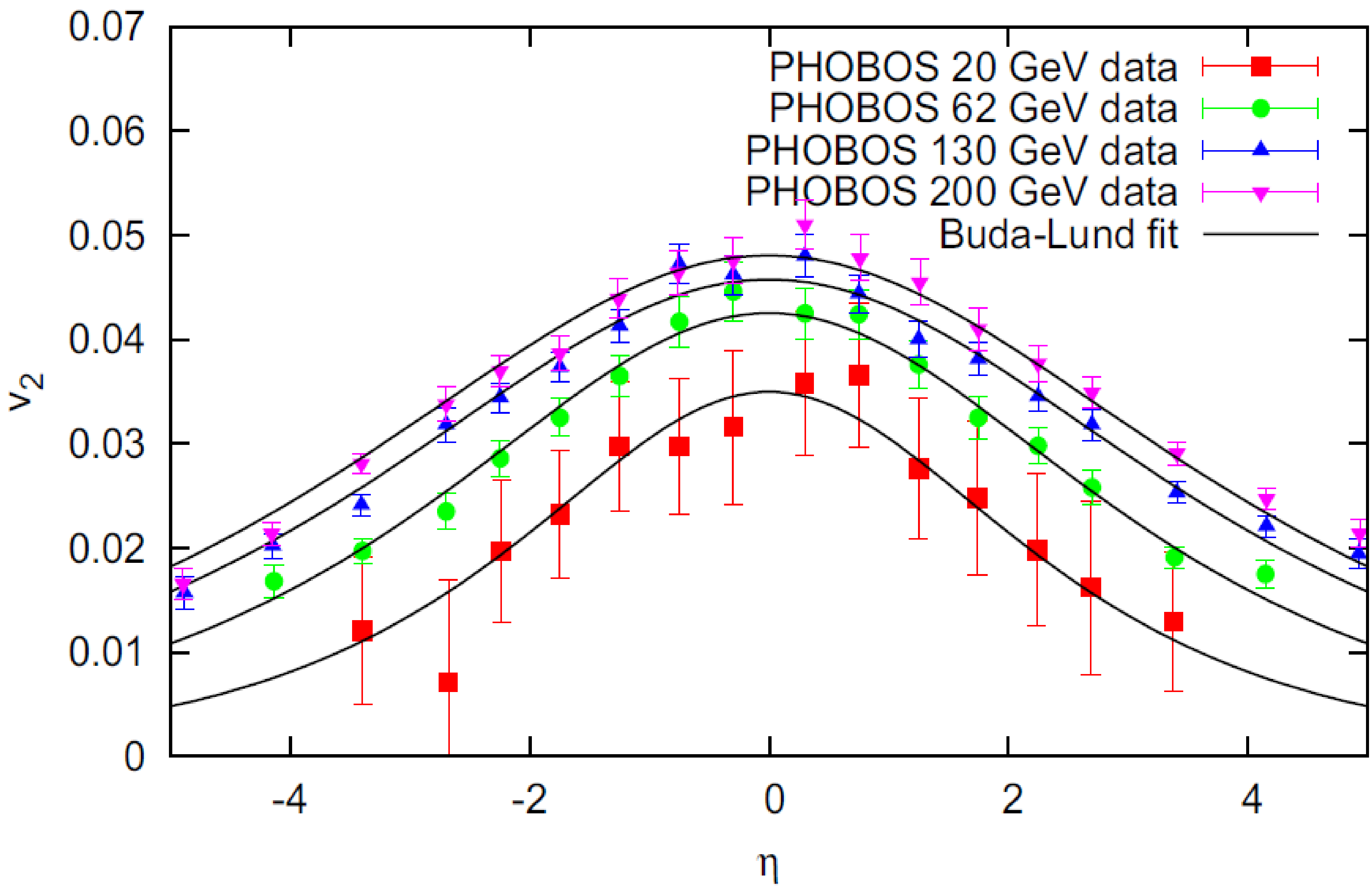
Inverse of the HBT radii increase linearly with mass analysis shows that they are asymptotically the same

Relativistic correction: m -> m_t

hep-ph/0108067, nucl-th/0206051, visc. in prep.

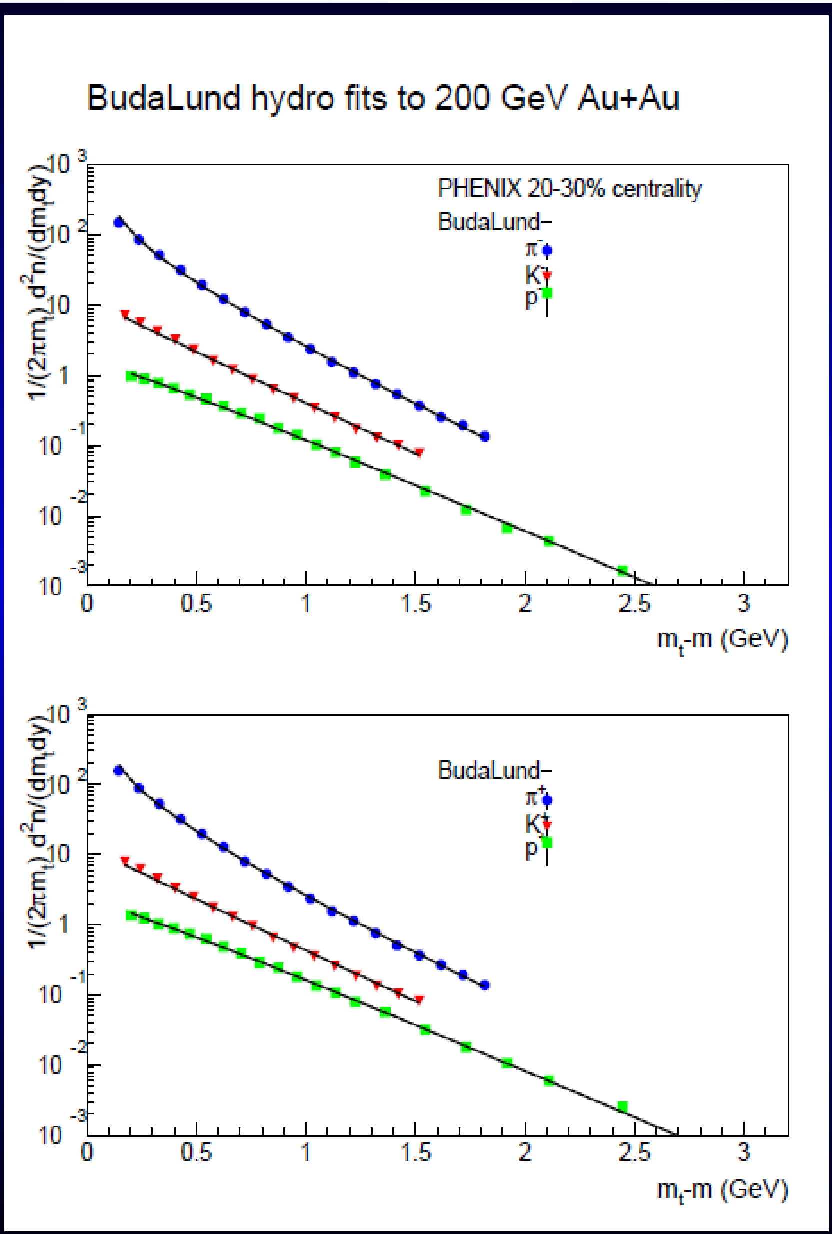
$$R'^{-2}_x = X_f^{-2}\left(1 + \frac{m}{T_f}\dot{X}_f^2\right),$$
$$R'^{-2}_y = Y_f^{-2}\left(1 + \frac{m}{T_f}\dot{Y}_f^2\right),$$
$$R'^{-2}_z = Z_f^{-2}\left(1 + \frac{m}{T_f}\dot{Z}_f^2\right).$$

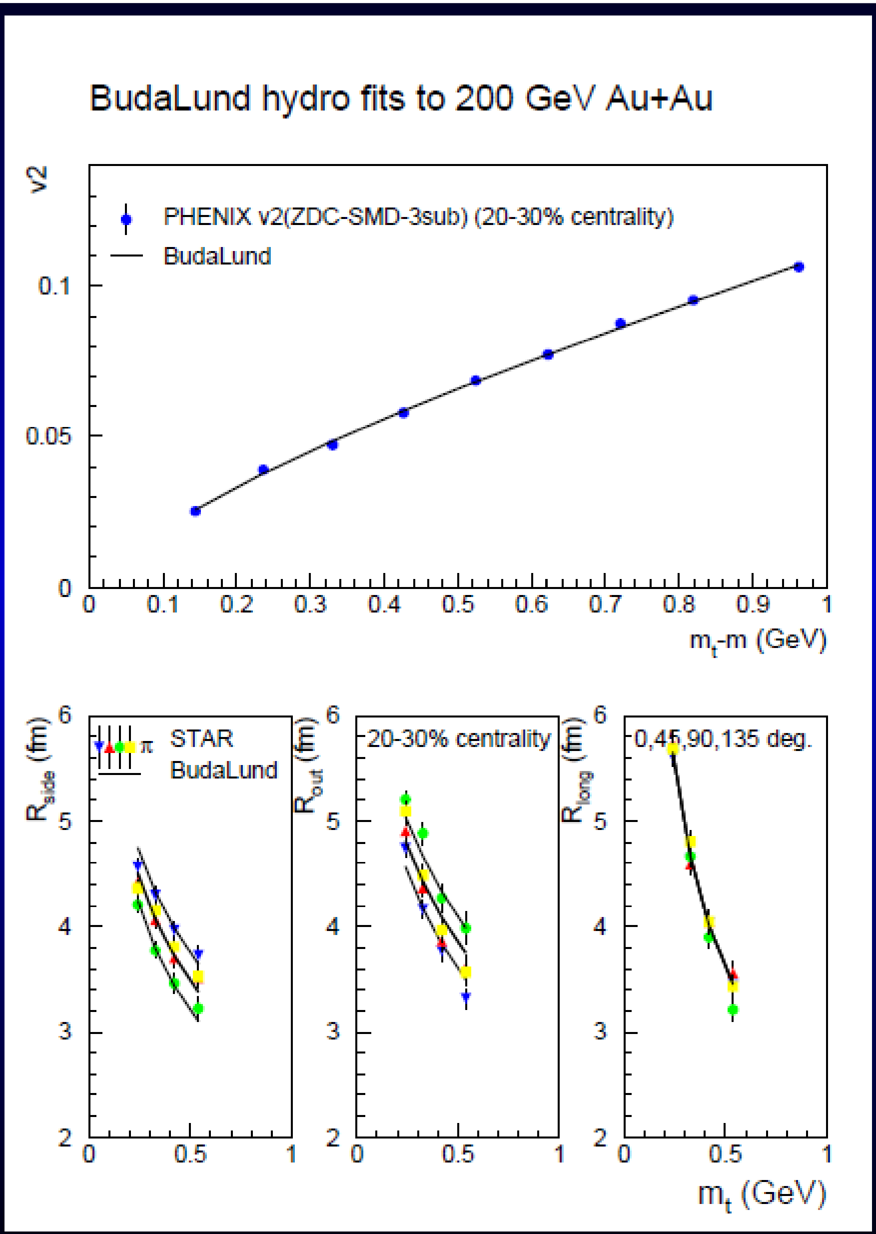
Results



PHOBOS 20 GeV data
PHOBOS 62 GeV data
PHOBOS 130 GeV data
PHOBOS 200 GeV data
Buda-Lund fit
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
-4
-2
0
2
4
v_2
η

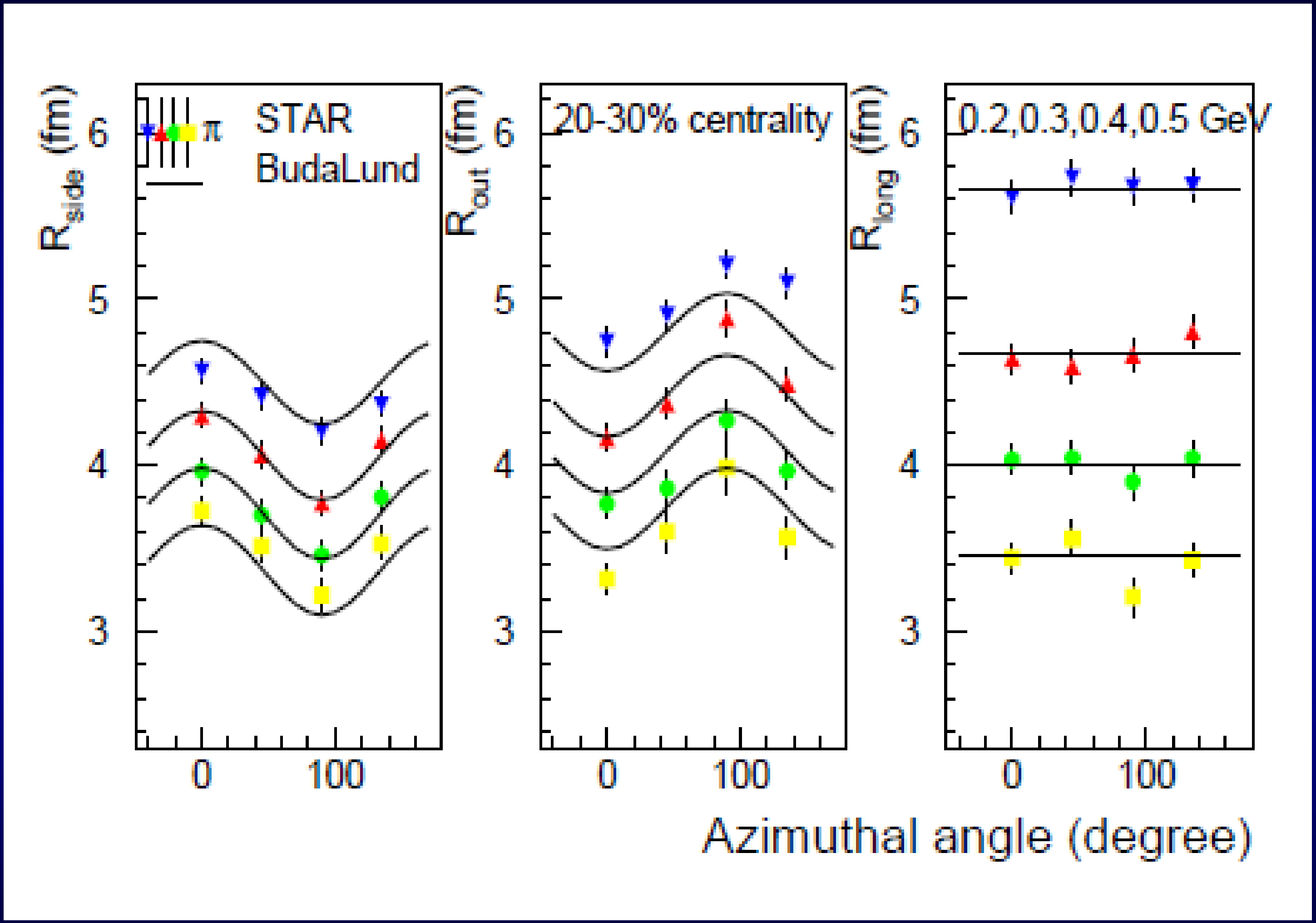
Simultaneous description of soft sector





including azymuthally sensitive HBT radii too

Simultaneous description of soft sector



Hydro works perfectly, utilizing scaling solutions, but ...

A. Ster, M. Csanád, T.Cs, B. Tomasik, in prep.

New, simple, exact solutions of rel. hydro

$$v = \tanh \lambda\eta,$$
$$p = p_0 \left(\frac{\tau_0}{\tau}\right)^{\lambda d \frac{\kappa+1}{\kappa}} \left(\cosh \frac{\eta}{2}\right)^{-(d-1)\phi_\lambda}$$

Possible cases (one row of the table is one solution):

Case	λ	d	κ	ϕ_λ
a.)	2	$\in \mathbb{R}$	d	0
b.)	$\frac{1}{2}$	$\in \mathbb{R}$	1	$\frac{\kappa+1}{\kappa}$
c.)	$\frac{3}{2}$	$\in \mathbb{R}$	$\frac{4d-1}{3}$	$\frac{\kappa+1}{\kappa}$
d.)	1	$\in \mathbb{R}$	$\in \mathbb{R}$	0
e.)	$\in \mathbb{R}$	1	1	0

Nagy, Cs.T., Csanád: nucl-th/0605070, arXiv:0709.3677v1, arXiv:0805.1562

→ New, accelerating, d dimension

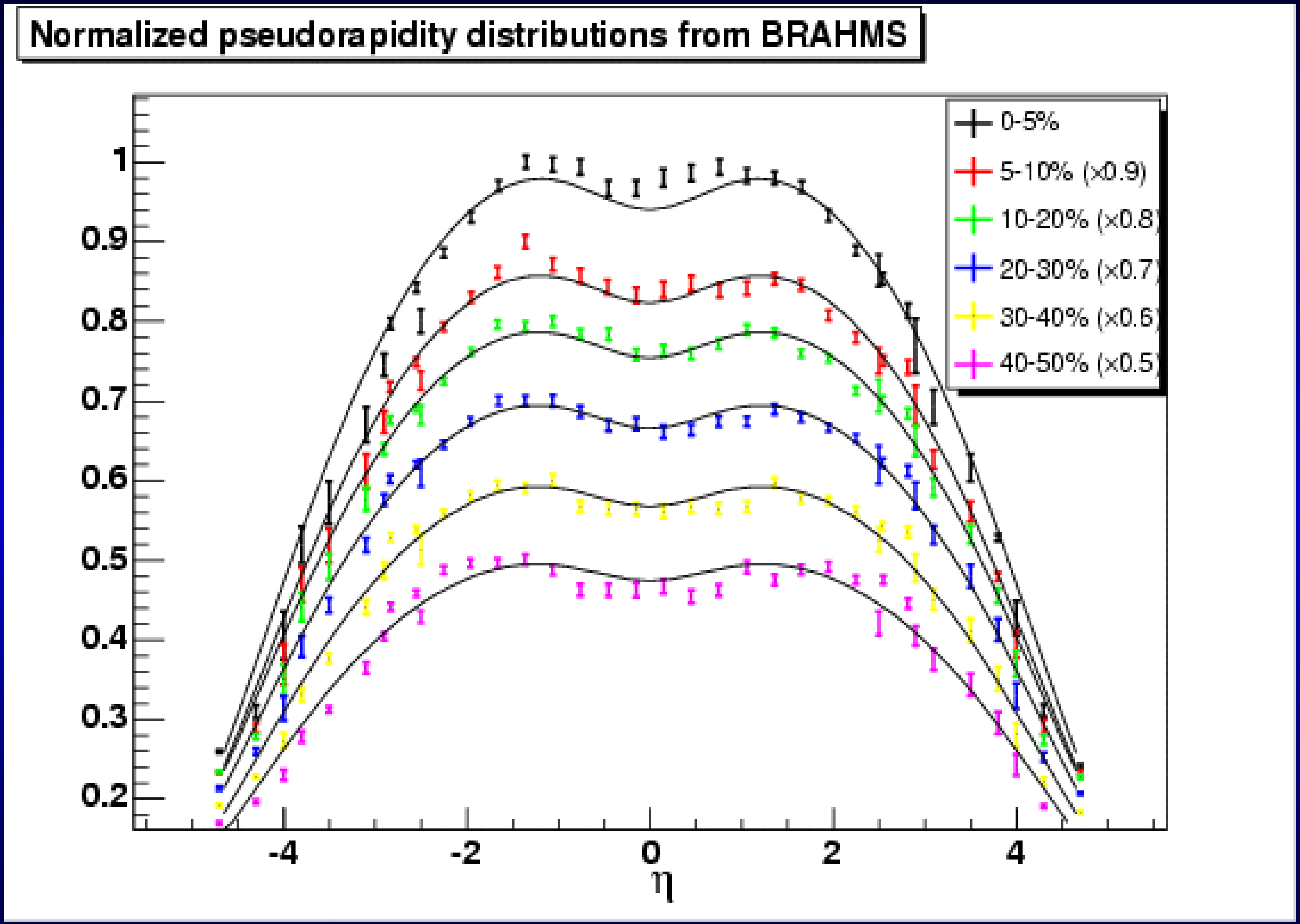
→ d dimensional with $p=p(\tau,\eta)$ (thanks T. S. Biró)

→ Hwa-Bjorken, Buda-Lund type

→ Special EoS, but general velocity

If $\kappa = d = 1$, general solution is obtained, for ARBITRARY initial conditions. It is STABLE !

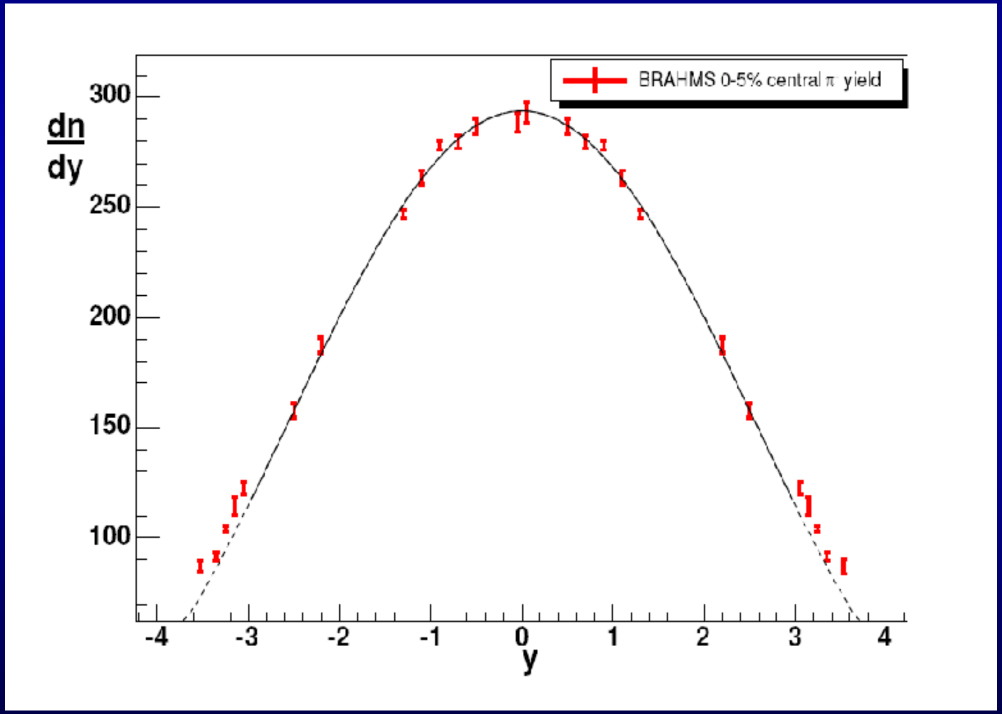
Pseudorapidity distributions



BRAHMS data fitted with the analytic formula of
Additionally: y→η transformation

BRAHMS rapidity distribution

$$\frac{dn}{dy} \approx \left.\frac{dn}{dy}\right|_{y=0} \cosh^{\pm\frac{\alpha}{2}-1}\left(\frac{y}{\alpha}\right) e^{-\frac{m}{T_f}\left[\cosh^{\alpha}\left(\frac{y}{\alpha}\right)-1\right]},$$



$$\lambda = \frac{\alpha - 1}{\alpha - 2}.$$

α	7.4 ± 0.13
$\left.\frac{dn}{dy}\right\|_{y=0}$	294 ± 1
χ^2/NDF	$30.6/14$
CL	0.6%
T_f (MeV)	200 (fixed)
m (MeV)	140 (fixed)
λ	1.18 ± 0.01 (derived)

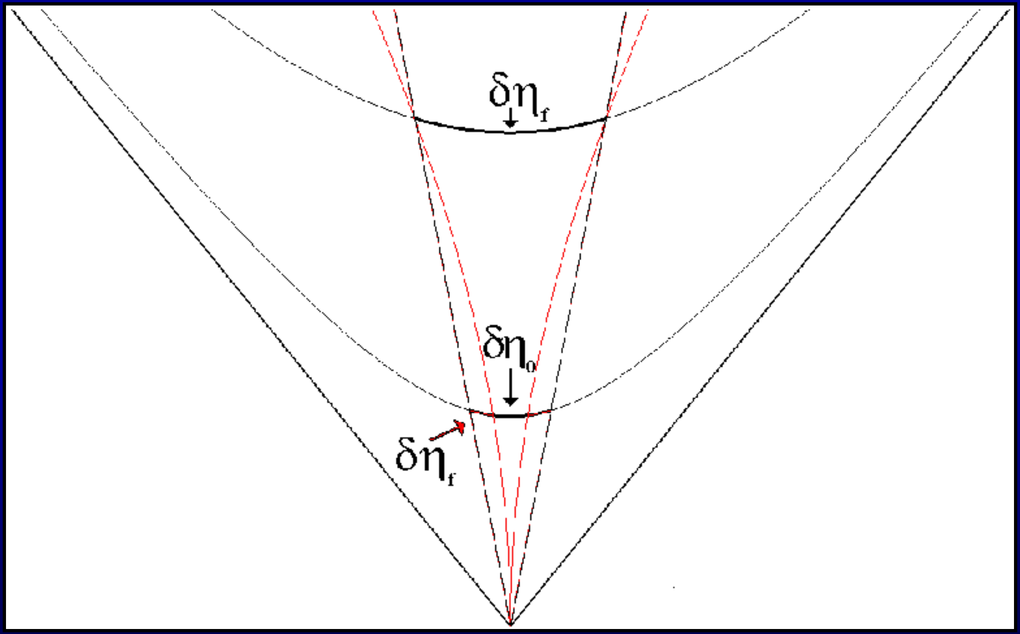
BRAHMS data fitted with the above analytic formula

Advanced energy density estimate

Fit result: $\lambda > 1$

Flows accelerate: ⟺ do work

⟺ initial energy density is higher than Bjorken's



$$\frac{\varepsilon_c}{\varepsilon_{Bj}} = (2\lambda - 1)\left(\frac{\tau_f}{\tau_0}\right)^{\lambda-1}$$

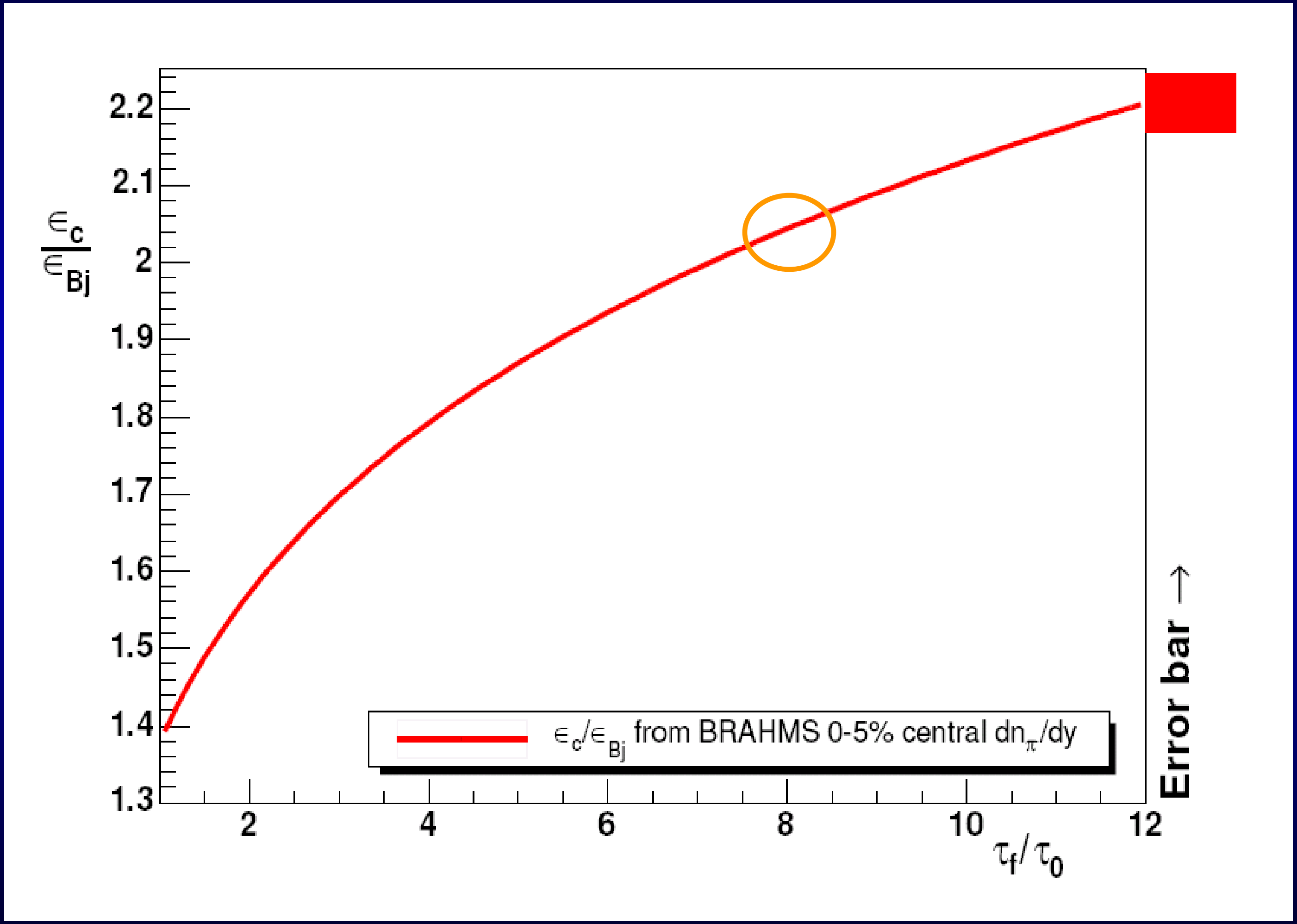
Corrections due to work and acceleration. Ref:

$$\varepsilon_{Bj} = \frac{\langle m_t \rangle}{(R^2\pi)\tau_0}\frac{dn}{dy}.$$

For $\lambda > 1$ (accelerating) flows, both factors > 1

Advanced energy density estimate

Correction depends on timescales, dependence is:



With a tipical τ_f/τ_0 of ~8-10, one gets a correction factor of 2!

Conjecture: EoS dependence of ε_0

Four constraints

1) ε_{Bj} is independent of EoS (λ = 1 case)

2) c_s^2= 1 case is solved for any λ > 0.5

$$\frac{\varepsilon_c}{\varepsilon_{Bj}} = (2\lambda - 1)\left(\frac{\tau_f}{\tau_0}\right)^{\lambda-1}$$

Corrections due to respect these limits.

3) c_s^2 dependence of $\varepsilon(\tau)$ is known

4) Numerical hydro results

Conjectured formula – given by the principle of Occam's razor:

$$\frac{\varepsilon_{c_s^2}}{\varepsilon_{Bj}} = (2\lambda - 1)\left(\frac{\tau_f}{\tau_0}\right)^{\lambda-1}\left(\frac{\tau_f}{\tau_0}\right)^{(\lambda-1)(1-c_s^2)}$$

Using λ = 1.18, c_s = 0.35, τ_f/τ_0 = 10, we get e_{cs}/e_{Bj} = 2.9

ε_0 = 14.5 GeV/fm^3 in 200 GeV, 0-5 % Au+Au at RHIC

Perfect hydro conclusion

New exact, accelerating relativistic hydrodynamic sols.

- Analytic (approximate) calculation of observables
- Realistic rapidity distributions; BRAHMS data well described

No go theorem: same final states, different initial states

New estimate of initial energy density:

- $\varepsilon_c/\varepsilon_{Bj}$ ~ 2 @ RHIC
- dependence on c_s estimated, $\varepsilon_c/\varepsilon_{Bj}$ ~ 3 for $c_s = 0.35$

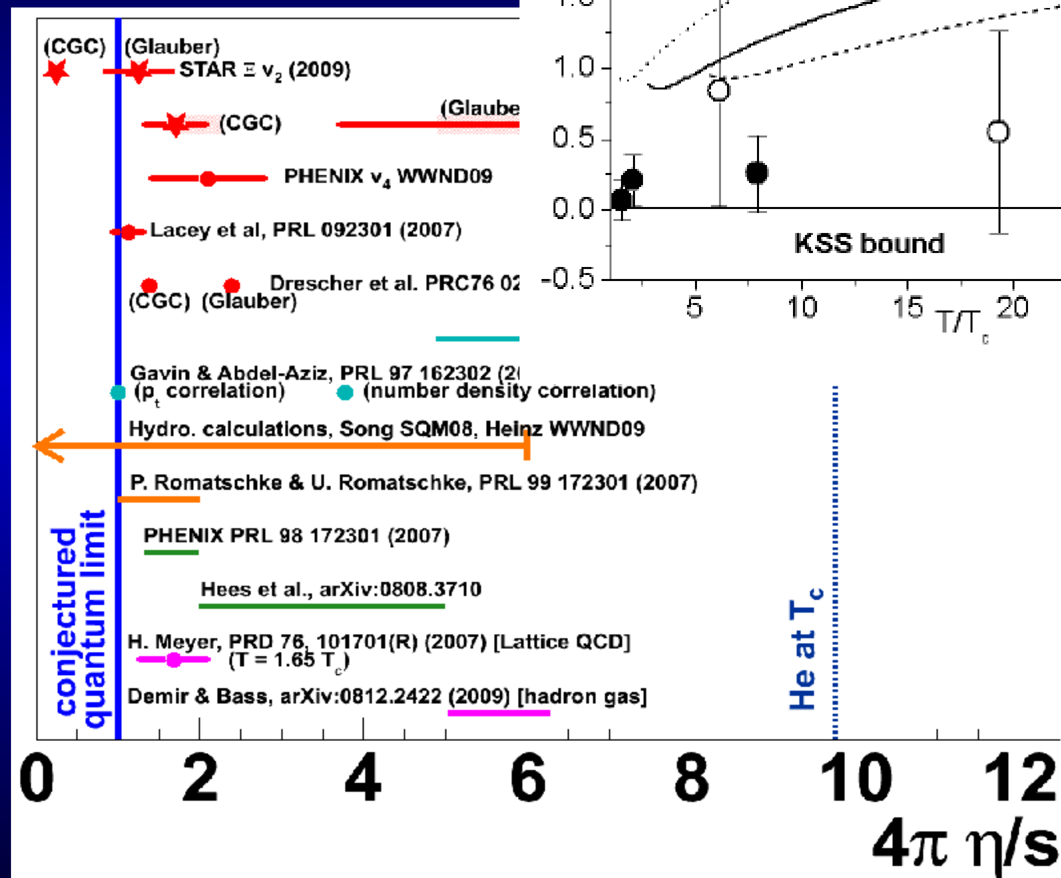
A lot to gain …

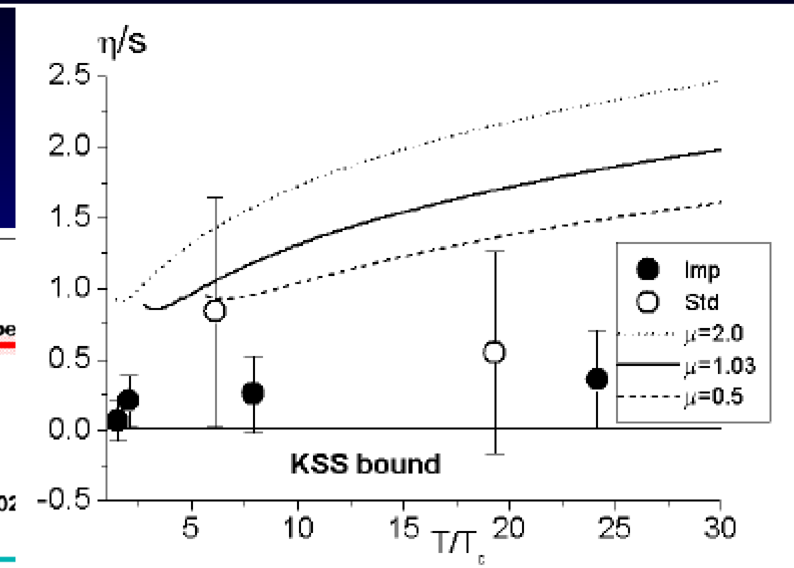
- advanced energy density estimate changes completely the $s_{NN}^{1/2}$ or the centrality, where $\varepsilon_{crit,lQCD}$ ~ 1 GeV/fm^3 is reached

But again, how perfect is Quark Fluid?

Status at QM 2009 (April 09)

Adopted from A. Tang:





It is very low!

small η/s

large σ

large α_s

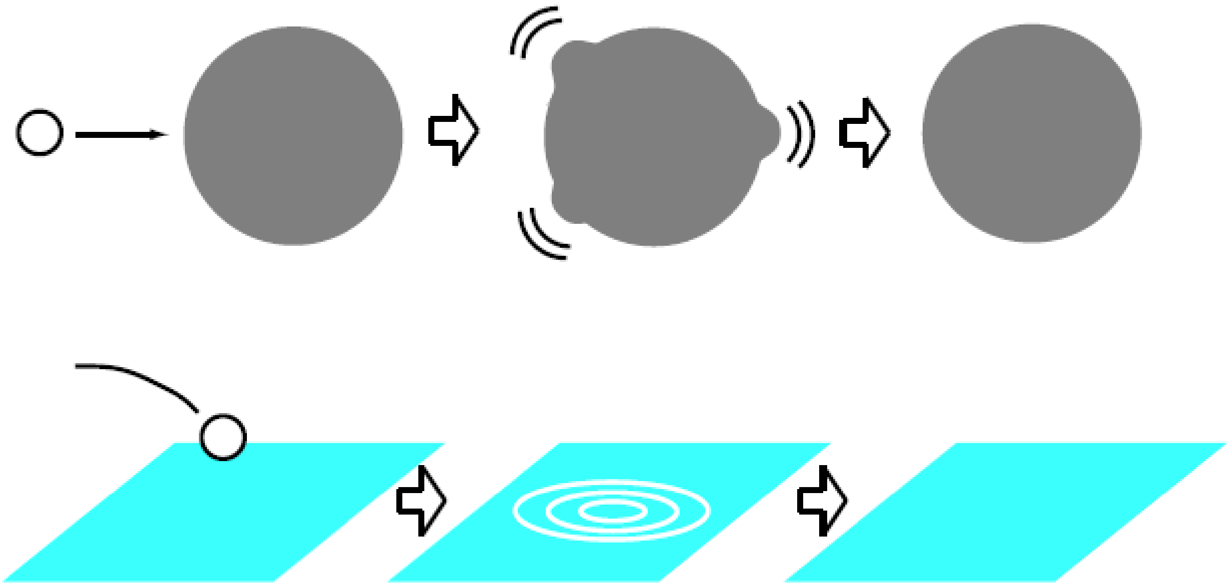
strong coupling limit of QCD

CFT/AdS/gravity correspondence:

black holes at RHIC?

Perfect Fluid- Gravity duality

Illustration:



[from M. Natsuume]

quasinormal modes:

gravitational perturbation to a black hole

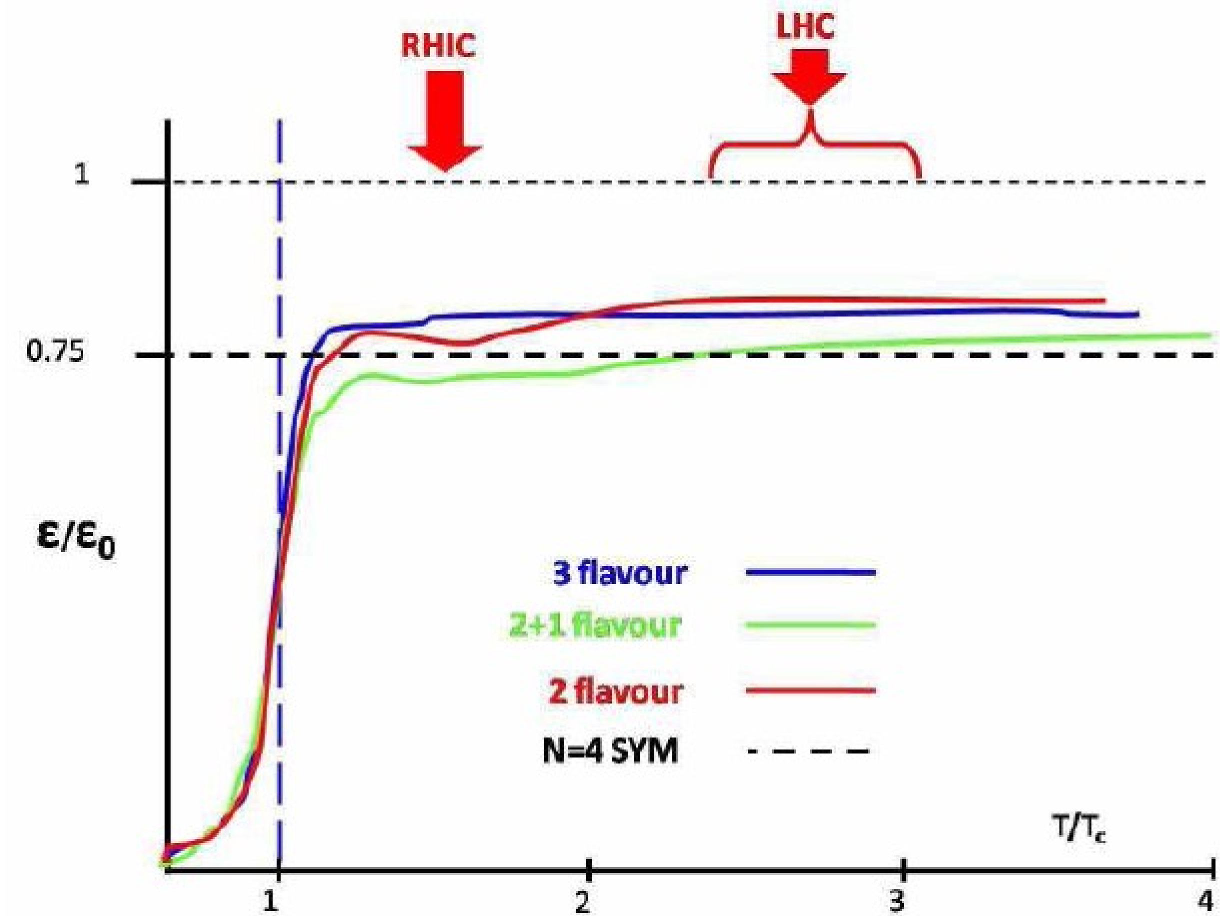
and to a hydrodynamic system

What about equation of state?

Equation of State from AdS/CFT:

25% less e than that of ideal gas of massless quanta

But perils!



energy density of QCD and SYM - via BH entropy

[from Myers and Vazquez 08]

What about shear viscosity?

near equilibrium: $\eta \simeq \epsilon \bar{v} \lambda_f, \quad entropy\ density \ \ s \simeq \epsilon/m \quad \rightarrow$

$$\frac{\eta}{s} \simeq m\bar{v}\lambda_f \simeq \hbar \, \frac{mean\ free\ path}{deBroglie\ wavelength}$$

- dilute system (QFT $->$ kinetic theory $->$ hydro):
  scale $\lambda_f \ \rightarrow \frac{\eta}{s} >> \hbar$, e.g. pQCD $(N_f = 0)$

$$\frac{\eta}{s} \simeq 3.8 \frac{1}{g^4 \ln(2.8/g)} \simeq O(1) \ \ for \ g = 2.5$$

BUT with $\ln(2.8/g) \simeq O(1) : \frac{\eta}{s} \simeq 0.1 \quad \rightarrow$ sensitive to constant under the log !

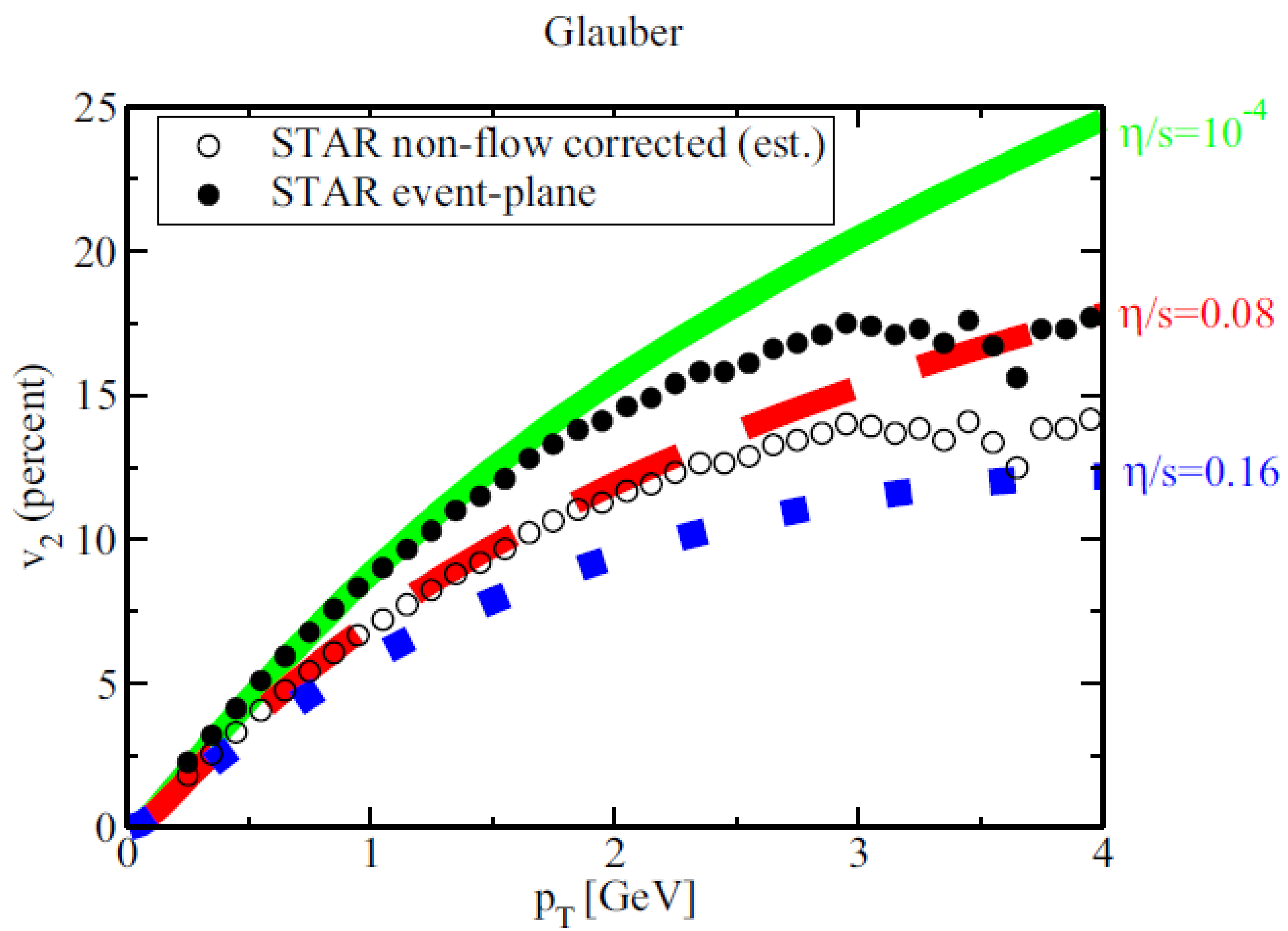
[Arnold, Moore and Yaffe 03]

- strongly coupled system (QFT $->$ hydro):
  scale $1/T \ \rightarrow \frac{\eta}{s} = \frac{\hbar}{4\pi} \simeq 0.08$

[Policastro, Son and Starinets 01]

But perils!

Conform hydro with shear viscosity 1

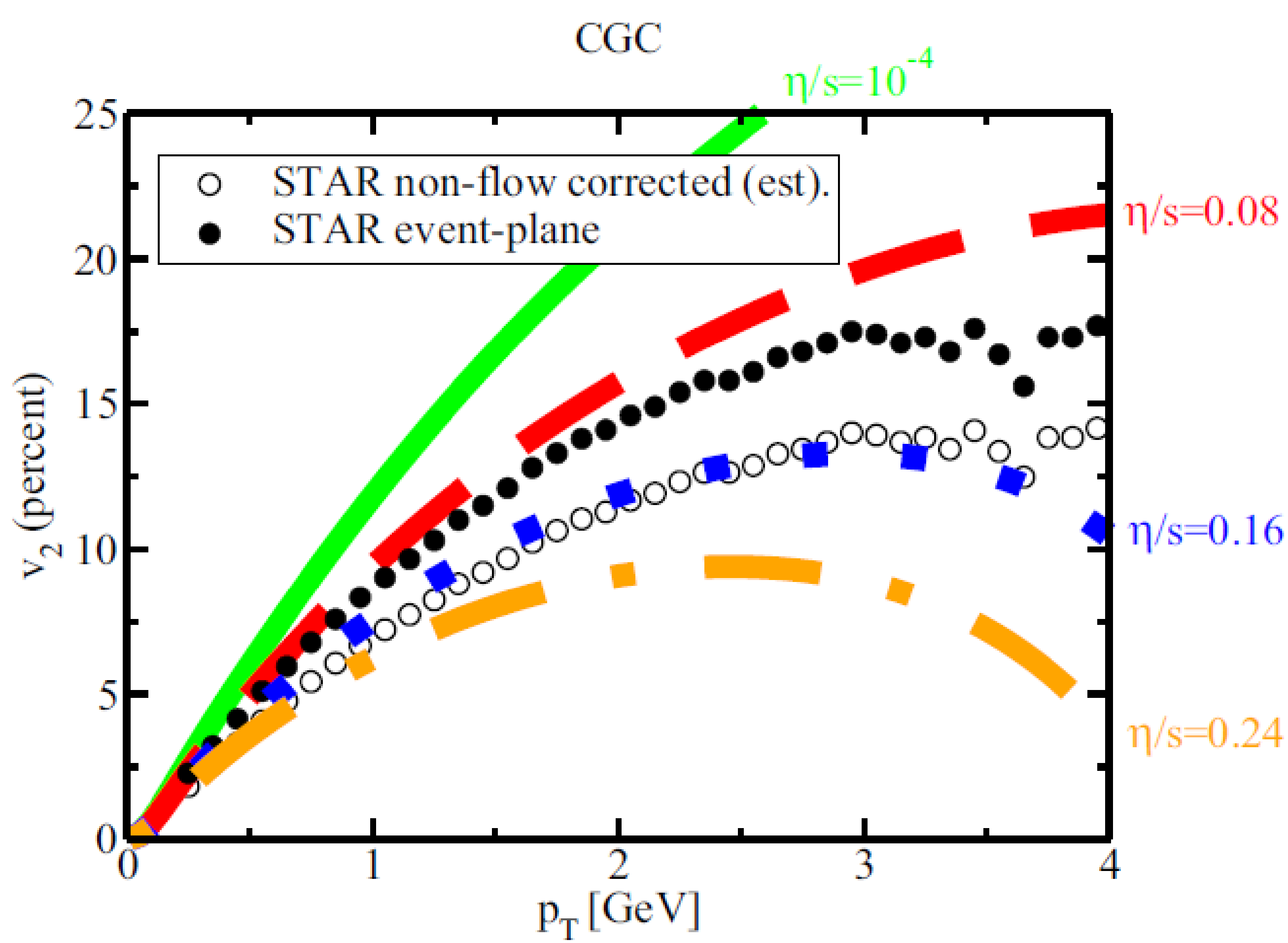


elliptic flow

But perils!

[Luzum and Romatschke 08]

Conform hydro with shear viscosity 2



elliptic flow

[Luzum and Romatschke 08]

But perils!

Comparision and some perils

	QCD	$\mathcal{N}$=4 SYM
T=0	$N_c=3=N_f$, confinement, discrete spectrum, scattering, ...	N_c large, N_f/N_c small, deconfined, conformal, supersymmetric, ...
	very different !!	
$T>T_c$	strongly-coupled plasma of gluons & fundamental matter deconfined, screening, finite corr. lengths, . . .	strongly-coupled plasma of gluons & adjoint and fundamental matter deconfined, screening, finite corr. lengths, . . .
	very similar !!	
$T>>T_c$	runs to weak coupling	remains strongly-coupled
	very different !!	

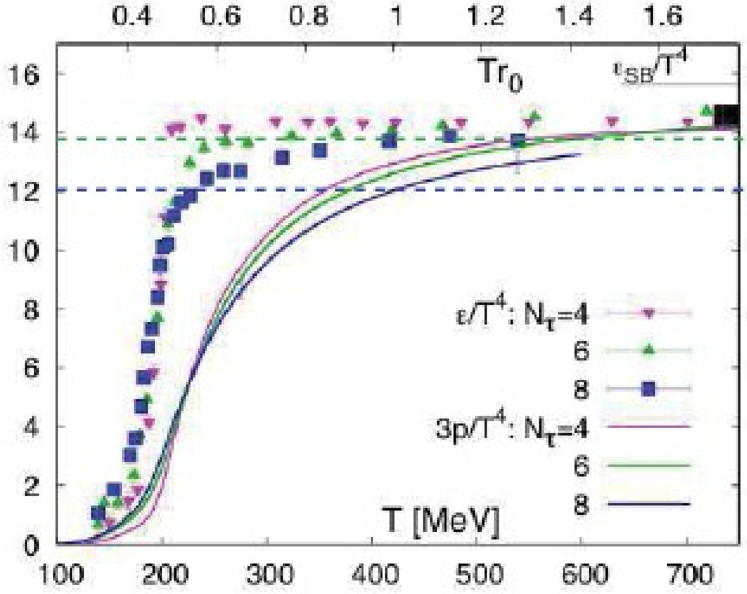
QCD and $\mathcal{N} = 4\ SYM$ as a function of temperature

[from Myers and Vazquez 08]

Some perils, following Gubser's talk

$\mathcal{N}=4$ SYM has considerably more degrees of freedom as QCD: for $SU(3)$,

$$\epsilon_{\text{free}}^{SYM} \approx 39T^4 \qquad \epsilon_{\text{free}}^{QCD} \approx 16T^4 \quad \text{(3 massless flavors)}$$



$\epsilon/\epsilon_{\text{free}} = 0.88 \leftrightarrow \lambda_{SYM} = 5.5$

$\epsilon/\epsilon_{\text{free}} = 0.77 \leftrightarrow \lambda_{SYM} = 6\pi$

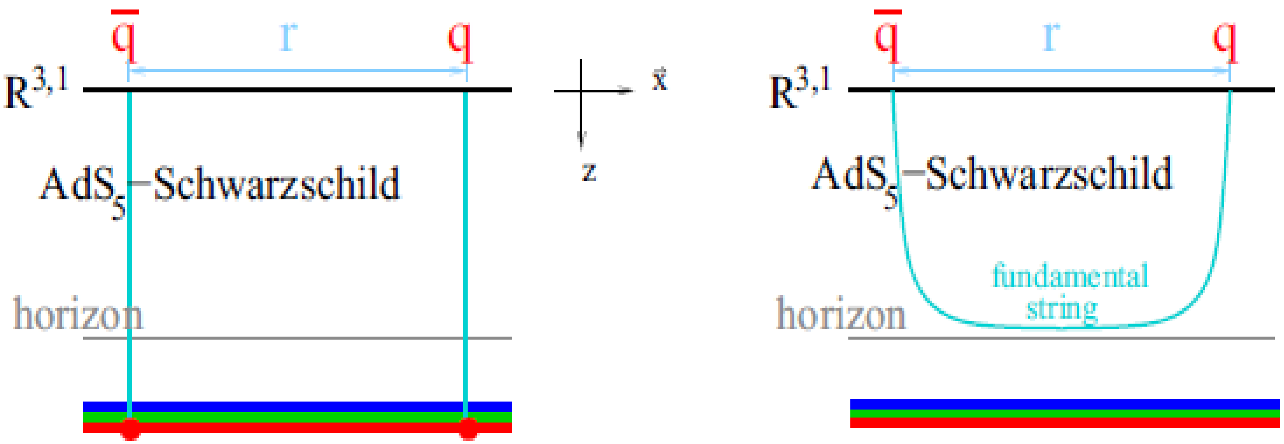
[Bazavov et al. 2009]

- Constant λ_{SYM} cannot match running λ_{QCD} except in a limited window. We're interested in $200\,\text{MeV} \lesssim T \lesssim 300\,\text{MeV}$.

QCD is significantly non-conformal in this window.

Static $q\underline{q}$ potential, following Gubser's

Static $q\bar{q}$ potential favors $\lambda \approx 5.5$.



- Fundamental charge arises because hanging string ends on a D3-brane.
- A color singlet pair charges can lower their energy by joining their hanging strings.

SYM: $$V_{q\bar{q}}(r) = -\frac{4\pi^2}{\Gamma(1/4)^4}\frac{\sqrt{\lambda}}{r} \times \left[1 - (\text{Debye screening})\right]$$

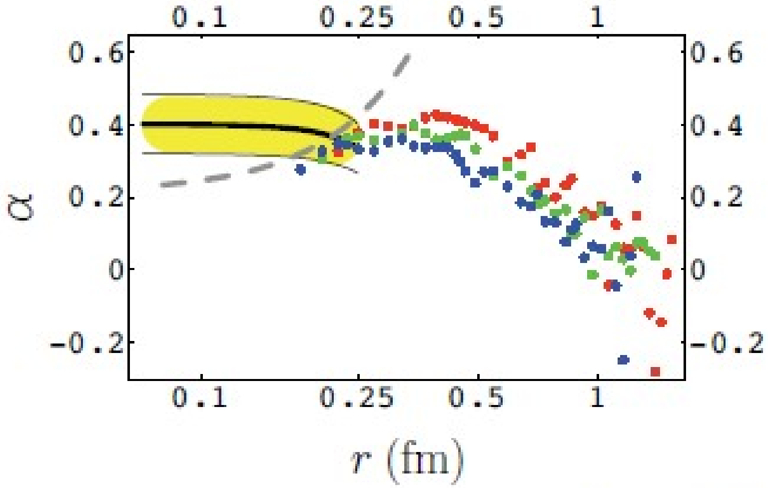
QCD: $$V_{q\bar{q}}(r) = \left(-\frac{4\alpha/3}{r} + \sigma r\right) \times \left[1 - (\text{Debye screening})\right]$$

Static $q\underline{q}$ potential redux

More precisely: $\alpha_{q\bar{q}}(r,T) = \frac{3}{4} r^2 \frac{\partial F_{q\bar{q}}}{\partial r}$ is the effective coupling.

$T_{SYM} = 190\,\text{MeV} \quad \leftrightarrow \quad T_{QCD} \approx 240\,\text{MeV}$

if we match $\boxed{\epsilon_{SYM} = \epsilon_{QCD}}$.



$T_{\text{lattice}} = 209,\ 233,\ 255\,\text{MeV}$
[Kaczmarek and Zantow 2005]

[Gubser 2006c]

- Curve shown corresponds to $\lambda = 5.5\,^{+2.5}_{-2}$ in SYM. Surprising because then $\alpha_{SYM} \approx 0.15$.

Match to string theory is conspicuously imperfect because SYM doesn't confine. And string theory curve isn't even understood for $r \gtrsim 0.25\,\text{fm}$; but see [Bak et al. 2007].

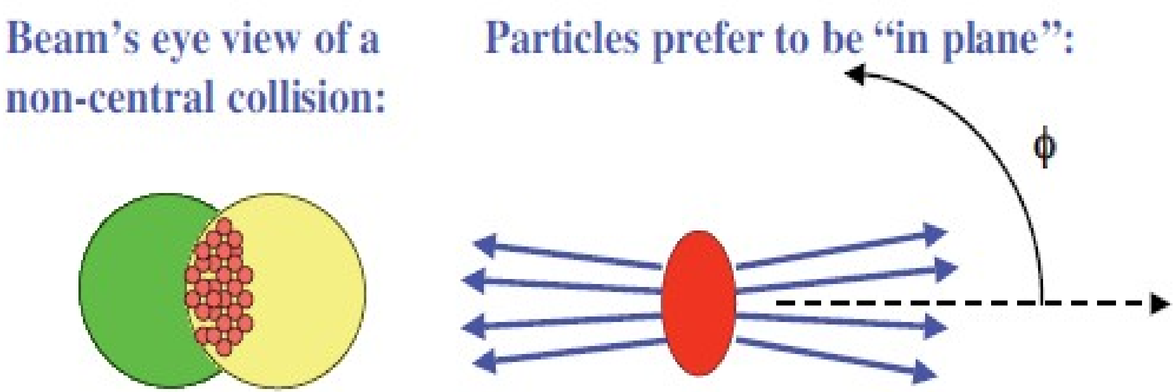
Static $q\underline{q}$ potential: fine with v2 data

$\lambda = 5.5$ significantly affects viscosity [Policastro et al. 2001; Buchel 2008]:

$$\frac{\eta}{s} = \frac{1}{4\pi}\left(1 + \frac{15\zeta(3)}{\lambda^{3/2}} + \ldots\right) \approx 0.2 \qquad \text{for } \lambda = 5.5.$$

⚠ higher order terms could be important.

$\eta/s \approx 0.2$ is not far from elliptic flow data, with CGC initial eccentricity and a soft EOS.



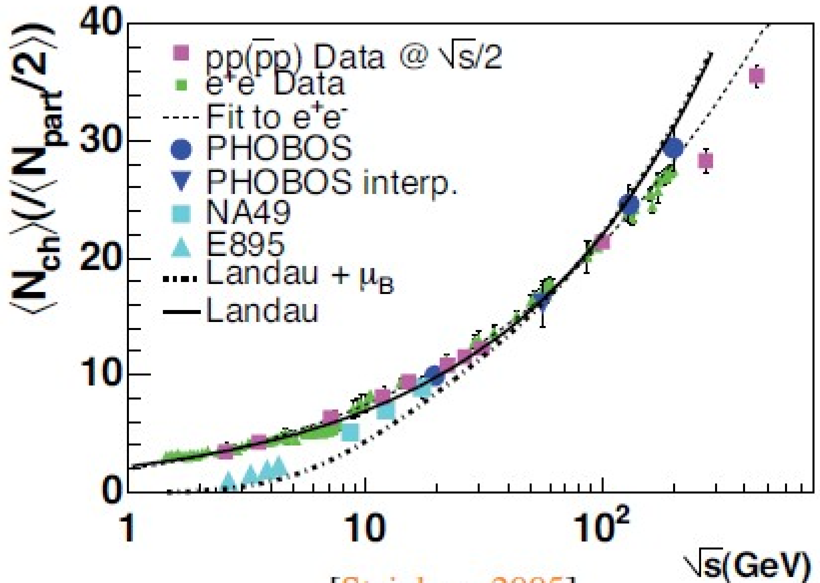
Anisotropic expansion is driven by pressure gradient, which is greater "in plane."

Progress and perils

Bulk/Soft physics:

- evaluation of bulk viscosity
  - dihadron correlations
  - Mach cone like, non-hydro structures
  - multiplicity distributions !!

$N_{\text{charged}} \sim E^{2/3}$ is faster than Landau ($E^{1/2}$) and *much* faster than CGC ($\sim E^{0.3}$)

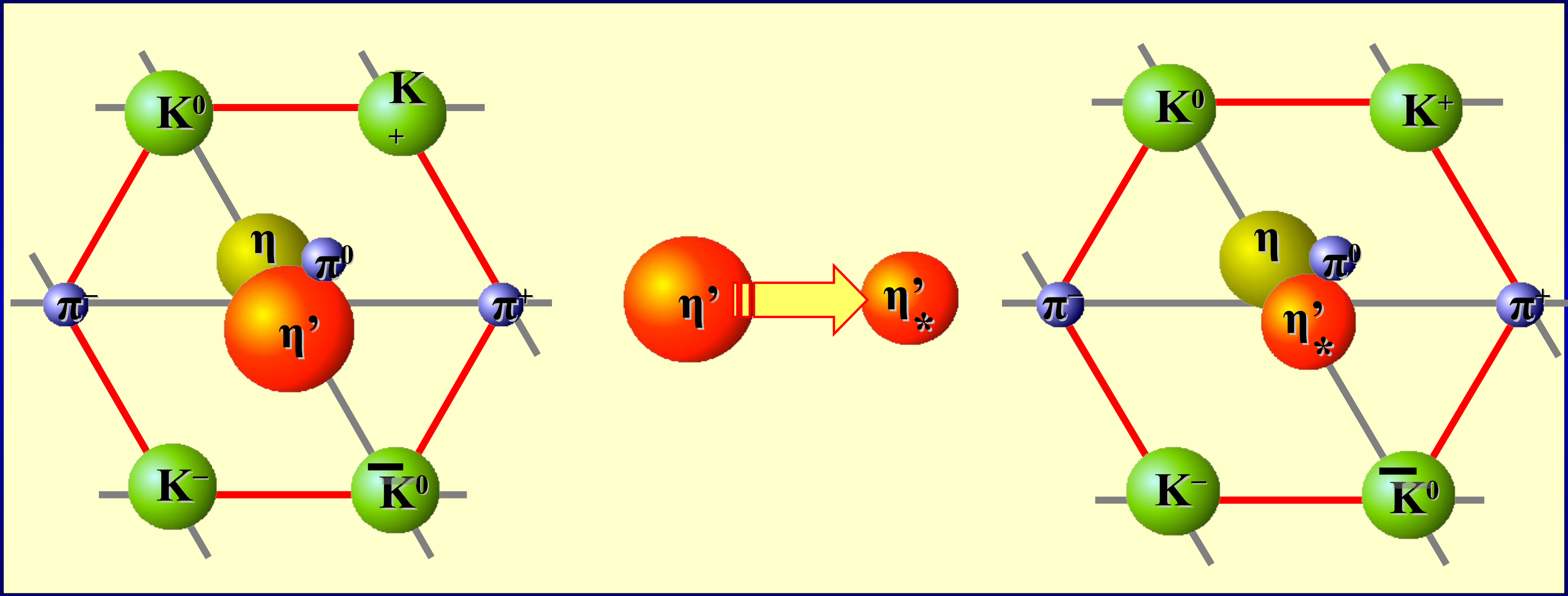


[Steinberg 2005]

Hard physics:

See the talk of G. Barnaföldi

Significant in-medium η′ mass reduction in $\sqrt{s_{nn}}$ = 200 GeV Au+Au collisions

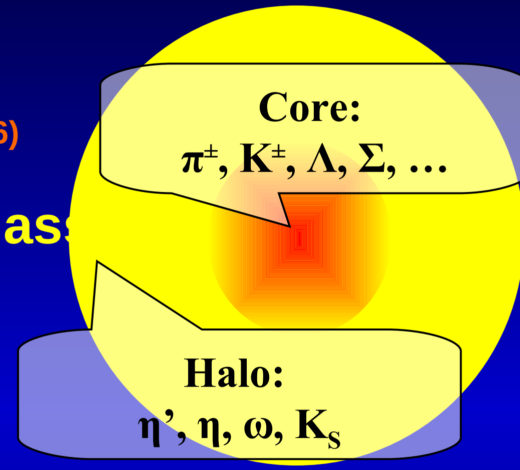


R. Vértesi, T. Cs, J. Sziklai, arXiv:0905.2803 [nucl-th]

Motivation

- **Approximate SU(3) symmetry**
  - Spontaneous symmetry breaking → 9 Goldstone bosons
  - $U_A(1)$-breaking terms → η' gains extra mass

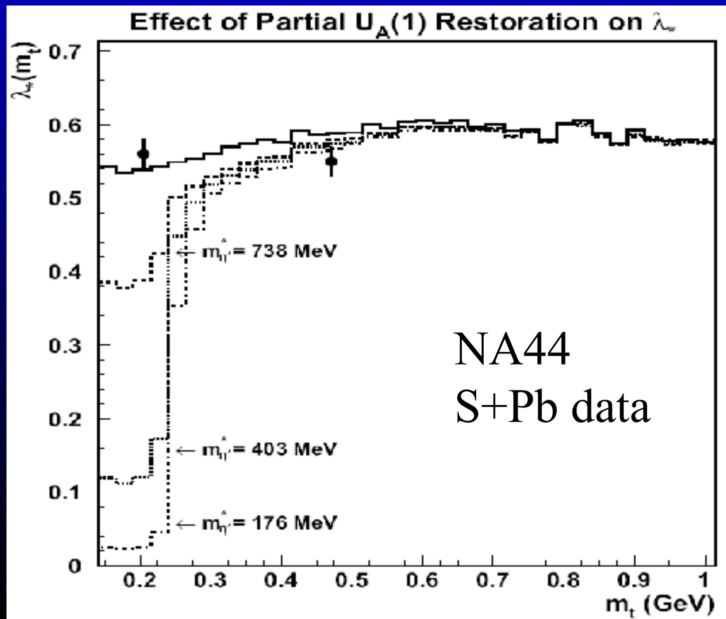
    Refs: T. Kunihiro, Phys.Rev.Lett. B218 363 (1989)
    J.Kapusta, D.Kharzeev, L.McLerran, Phys.Rev. D53 5028 (1996)
    Z.Huang, X.-N. Wang, Phys.Rev. D53 5034 (1996)
  - In hot medium, η' mass reduced to quark model mass
- **Signal: Enhanced η' production at low p_T**



$$\frac{N^*_{\eta'}}{N_{\eta'}} = \left(\frac{m^*_{\eta'}}{m_{\eta'}}\right)^{\alpha} e^{-\left(\frac{m^*_{\eta'}-m_{\eta'}}{T}\right)}$$

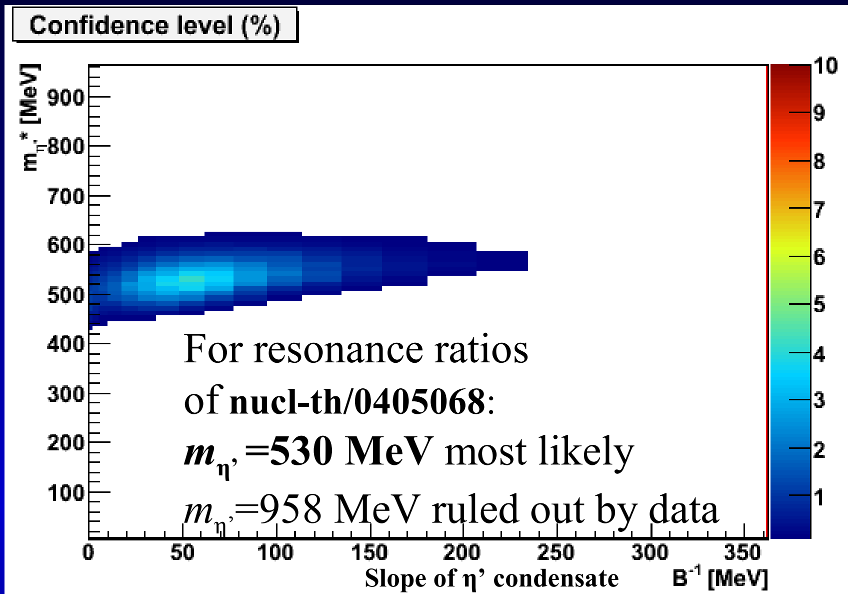
- **Observation channel: pion BEC**
  - η' has long lifetime, decays into pions
  - Core-halo picture: more η's enhance halo
  - Measurable through the parameter λ^*

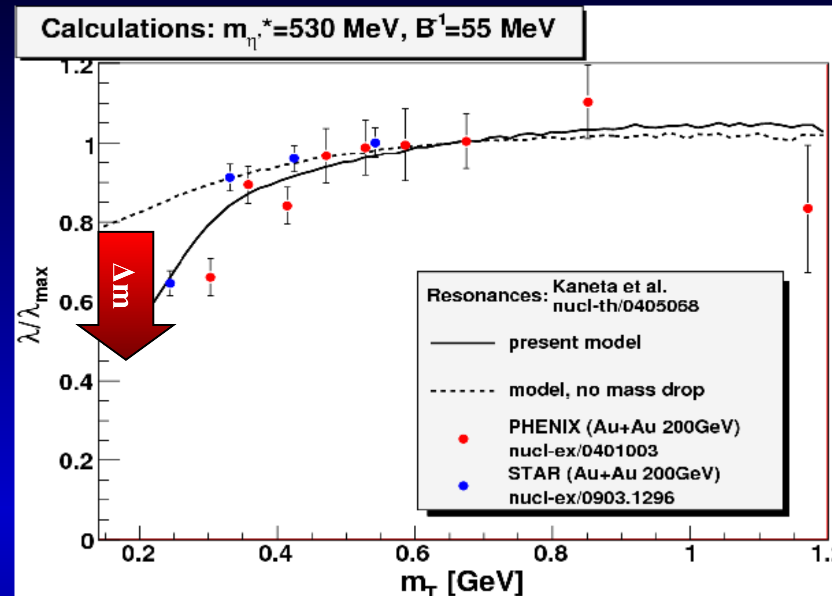
$$\lambda^* = \left(\frac{N^{\pi^+}_{\text{core}}}{N^{\pi^+}_{\text{halo}} + N^{\pi^+}_{\text{core}}}\right)^2$$

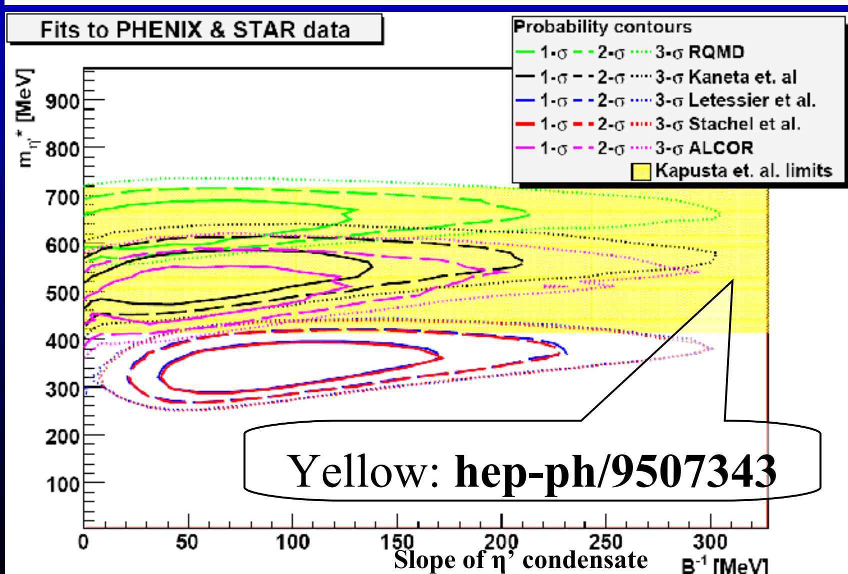


Vance, T. Cs, Kharzeev, Phys. Rev. Lett. 81 2205

Simulation and Results







6 models for the particle ratios

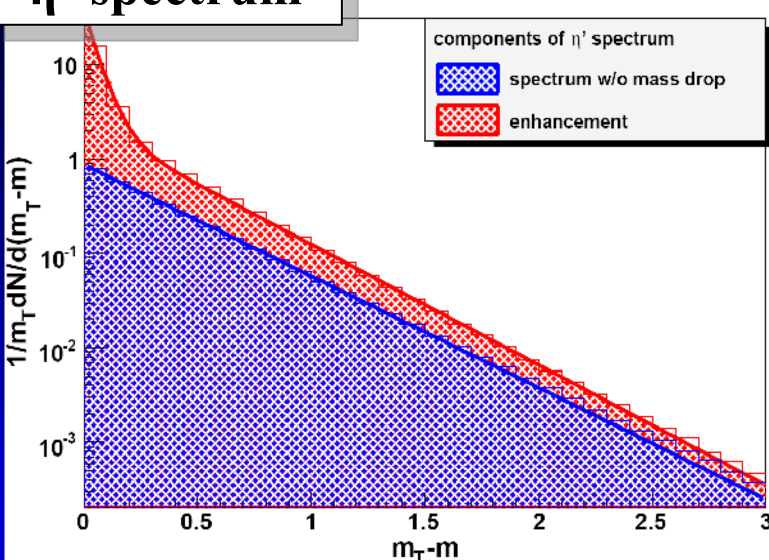
(ALCOR, FRITIOF, Letessier et.al., Kaneta et.al., RQMD, Stachel et.al.)

Resonance decays: JETSET

Systematic studies for freezeout parameters and prefactors

Cross-check plan: low p_T and dileptons

η' spectrum



- Resonance ratios: nucl-th/0405068
  - Enhancement factor ~24
  - Breaks m_T scaling for η'

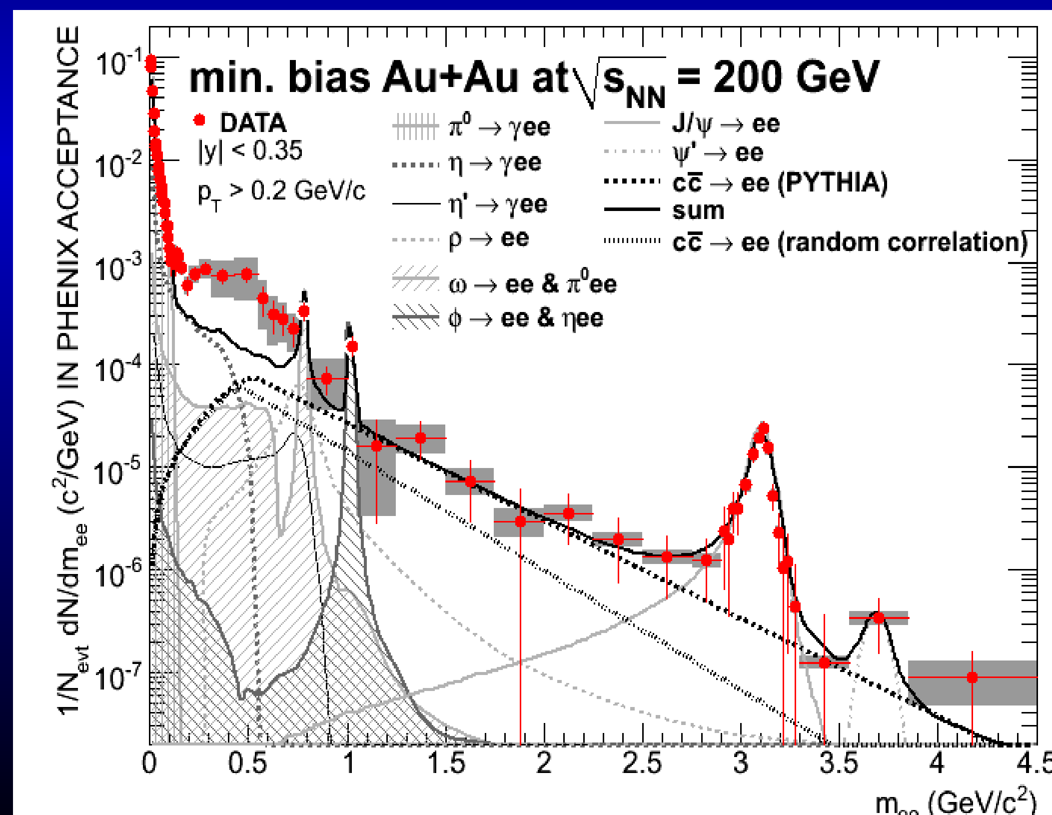
Excess at $m_{\ell\ell}$<1 GeV

Seen at SPS (CERES) and RHIC (PHENIX)

Only in A+B reactions

Absent in p+p

Possible explanation: η' enhancement

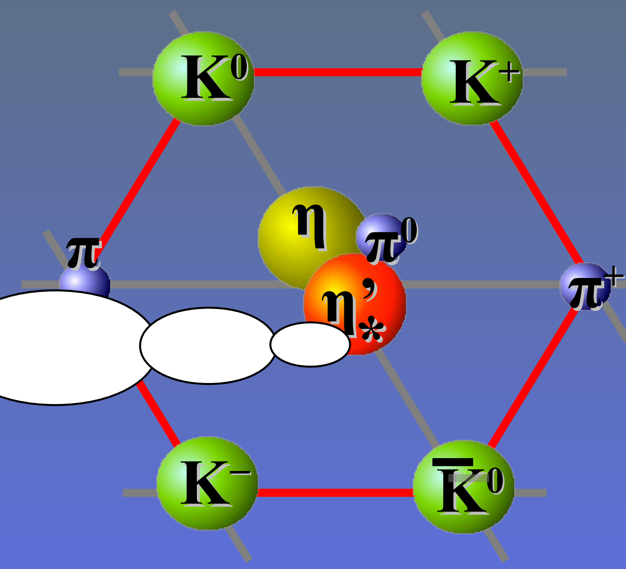


Conclusion

$$m^{*}_{\eta'} < m_{\eta'} - 200\ \mathrm{MeV}$$

at the 99.9% confidence level

from PHENIX+STAR $\pi^+\pi^+$
correlation data + 6 models



Cross-check with dilepton spectrum needed

More λ^* data at low p_T is needed to reduce systematics

-> Chiral restoration at lower T as deconfinement?

Revitalize interest in chiral symmetry restoration

Summary II

How well hydro works at RHIC?

in p_t < 1.5 GeV: it works perfectly
scaling laws for spectra, v2, HBT radii predicted
but: quark number scaling of v2 is exp. discovery

The hottest, most perfect and most opaque fluid - ever made

AdS/CFT correspondence: PRogress and PERILS

(1) Exact results in hydro: see Bajnok's talk.

(2) New scaling laws discovered

(3) QCD: Possibly chiral symmetry restored at lower T than confinement.

Backup slides

Correlations for VARIOUS Quark Matters

Transition to hadron gas may be:
- (strong) 1st order
- second order (Critical Point, CP)
- cross-over
- from a supercooled state (scQGP)

<u>Type of phase transition:</u> | <u>its correlation signature:</u>

Strong 1st order QCD phase transition:
(Pratt, Bertsch, Rischke, Gyulassy) — $R_{out} >> R_{side}$

Second order QCD phase transition:
(T. Cs, S. Hegyi, T. Novák, W.A. Zajc) — non-Gaussian shape
α(Lévy) decreases to 0.5

Cross-over quark matter-hadron gas transition:
(lattice QCD, Buda-Lund hydro fits) — hadrons appear from a region with $T > T_c$

Supercooled QGP (scQGP) -> hadrons:
(T. Cs, L.P. Csernai) — pion flash ($R_{out} \sim R_{side}$)
same freeze-out for all
strangeness enhancement
no mass-shift of ϕ