Quark Gluon plasma: The perfect liquid with heavy quark impurities

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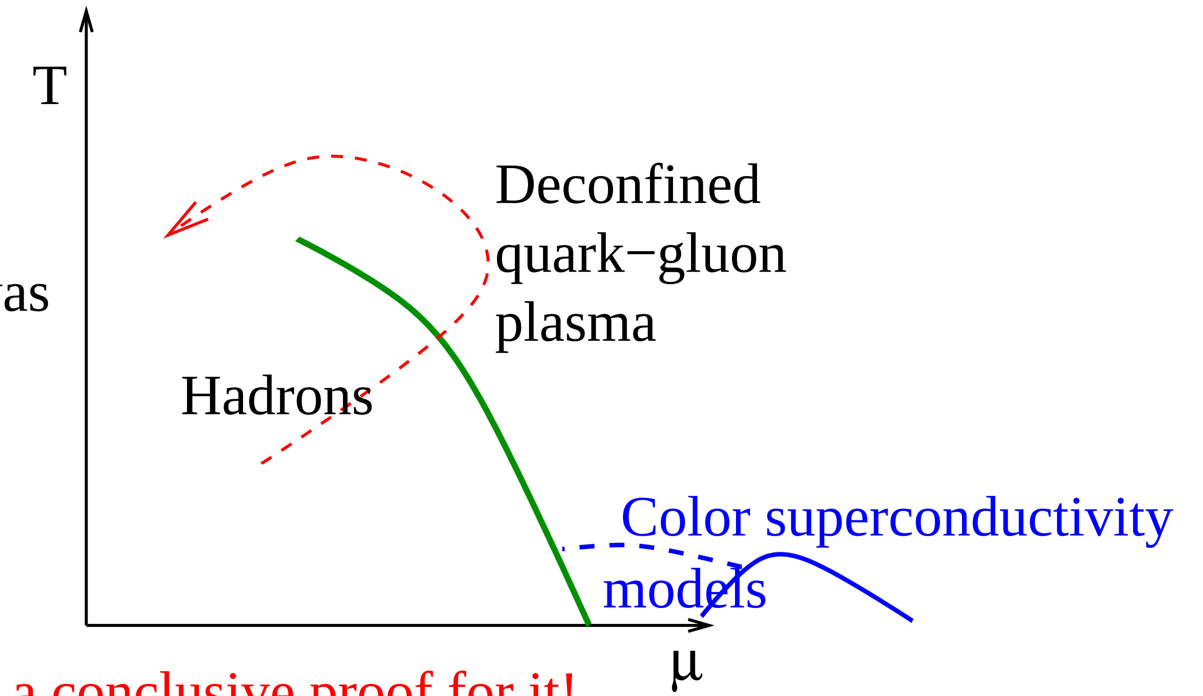
Synopsis

- Why we think the Quark-Gluon Plasma is a liquid
  RHIC white papers,nucl-th/0405013

- Why heavy quarks seem to confirm it

- Why heavy quarks can be use to link QGP hydrodynamics to QCD
  Based on GT,J.Noronha,1004.0237,in press,PLB

What RHIC was built for:

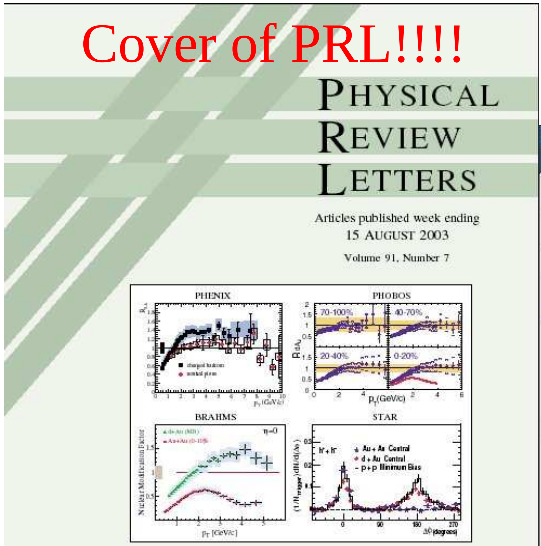


It did not find a conclusive proof for it!

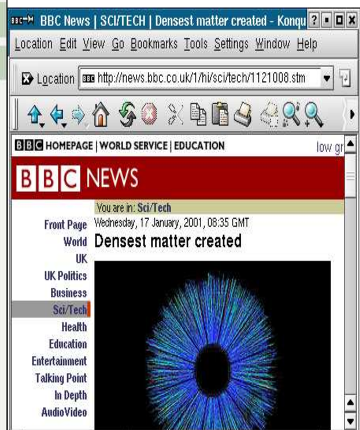
But it became famous...

WHY?!

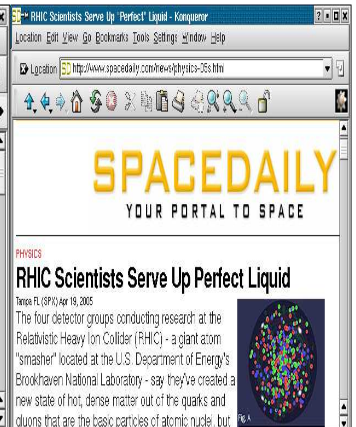
Cover of PRL!!!!



BBC!



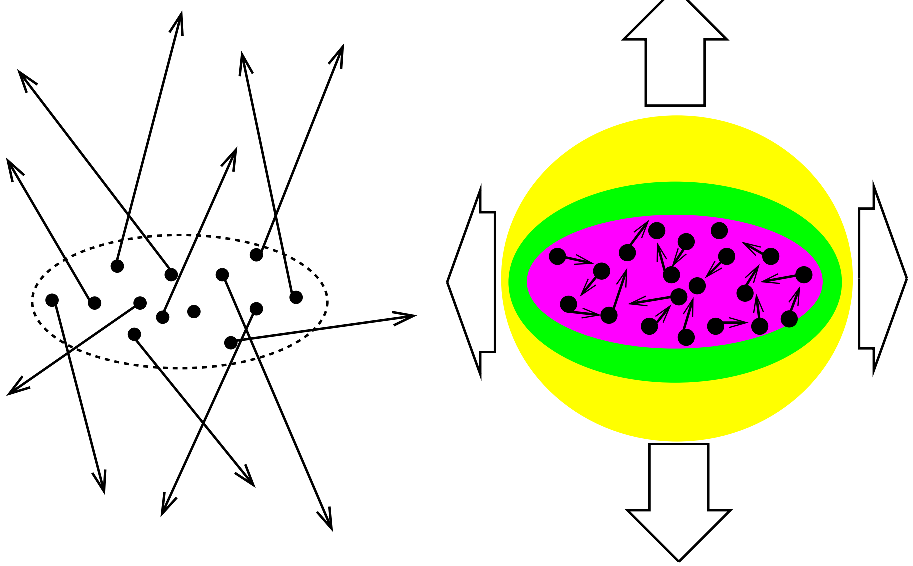
SPACE DAILY!



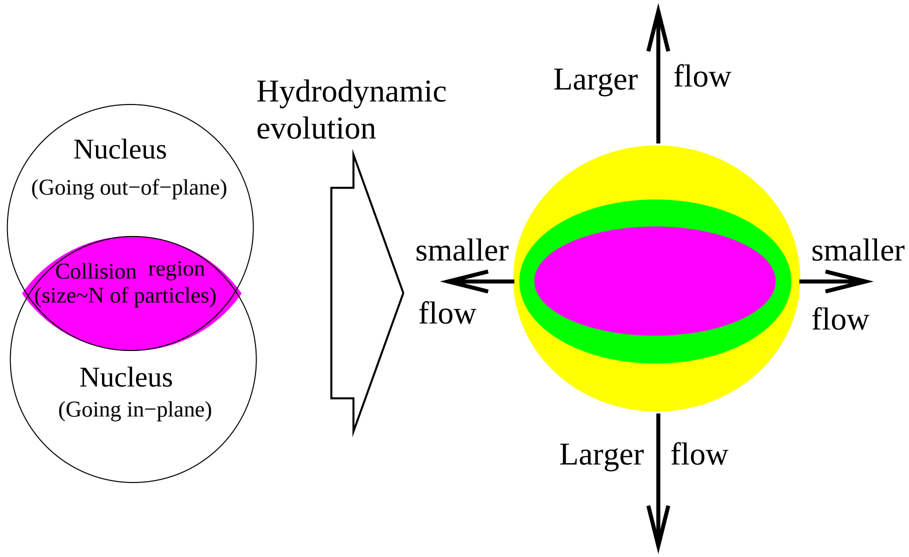
What kind of "medium" is created in nuclear collisions?

A "dust"
Particles ignore each other, their path is independent of initial shape

A "fluid"
Particles continuously interact. Expansion determined by density gradient (shape)



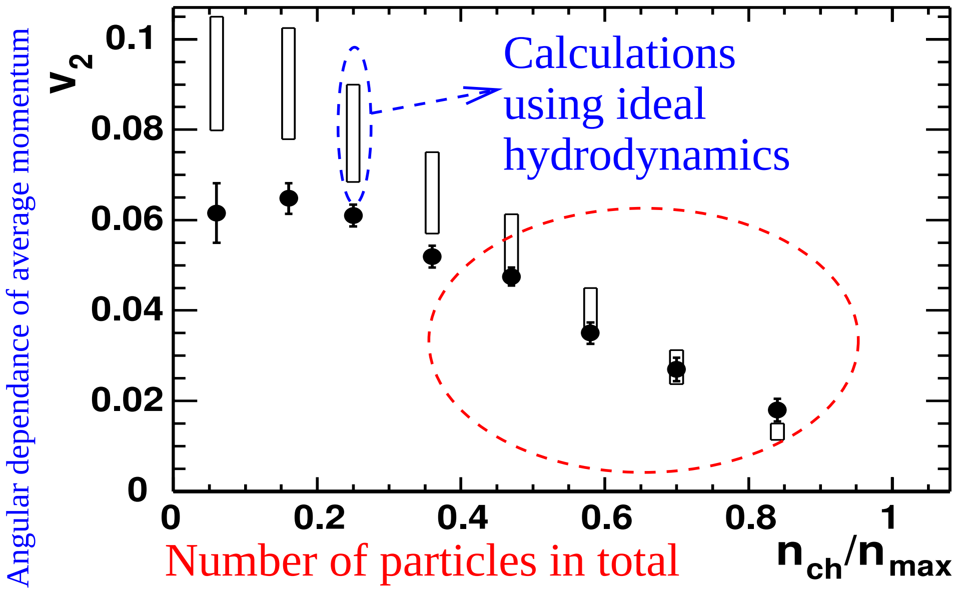
Quantitatively distinguished by mean free path, viscosity



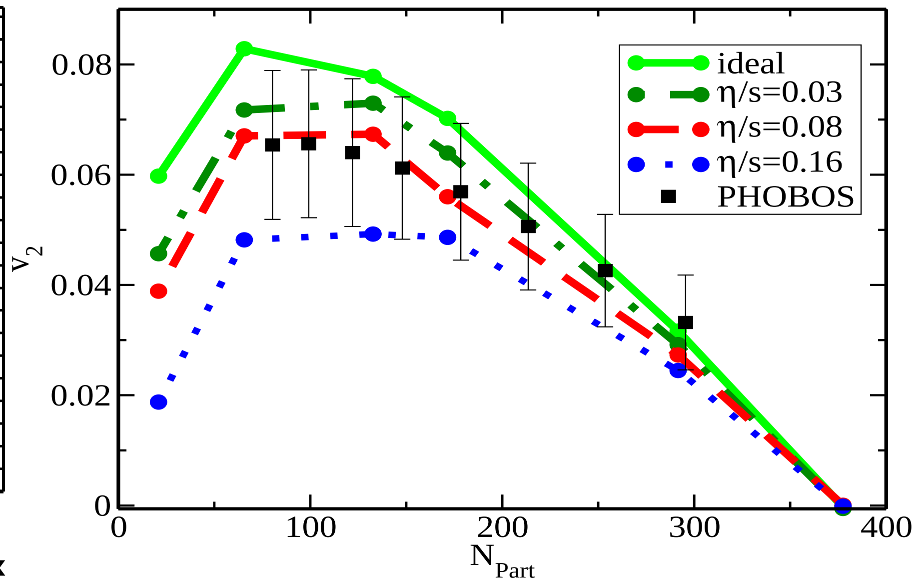
Hydrodynamics predicts flow eccentricity as a function of number of particles ($\sim$ area of overlap region). Parametrized by 2nd Fourier component, v_2

$$E\frac{dN}{d^3p} = \sum_n E\frac{dN}{dp_z p_T dp_T}\left(1 + 2v_n \cos(n\phi)\right)$$

P.Kolb and U.Heinz,Nucl.Phys.A702:269,2002.



P.Romatschke,PRL99:172301,2007



Data described by ideal hydrodynamics (mean free path between particle collisions is zero!

What should viscosity be?

Microscopic picture:"collective" effects implemented from perturbative dynamics via Boltzmann equation (neglecting quantum correction):

$$\left(\frac{1}{m}p^{\mu}\frac{\partial}{\partial x^{\mu}}+F^{\mu}\frac{\partial}{\partial p^{\mu}}\right)f(x,p)=C^{2body}[f]+C^{3body}[f]+...$$

$$C^{2body}=\int d^3[X,X',P,P']\sigma(P,P'\Leftrightarrow p,p')\left[f(X,P)f(X',P')-f(x,p)f(X',P')\right]$$

Ideal hydro: $C=0$ (Gain=Loss) $f=\Upsilon e^{-p_{\mu}u^{\mu}/T}$ always,(T,u_{μ} change)

Non-ideal: Expand $C[f]$ around $f-f_{eq}$,$\equiv$ Knudsen n.$K=l_{mfp}\partial_{\mu}u_{\nu}$

So the small parameter for hydro is the Knudsen Number $K = l_{mfp} \partial_\mu u_\nu$
Ideal hydro $O(K^0)$,Navier-Stokes $O(K^1)$,Israel-Stewart $O(K^2)$. Note K "really" a "tensor". (Grad expansion):

$$f = f_{eq}\left[\frac{u^\mu p_\mu}{T}\right]\left[1 + \underbrace{\epsilon}_{O(K^1)[\zeta]+higher} + \underbrace{\epsilon_\mu}_{O(K^1)[\eta]+higher} p^\mu + \underbrace{\epsilon_{\mu\nu}}_{O(K^2)+higher} p^\mu p^\nu + \ldots\right]$$

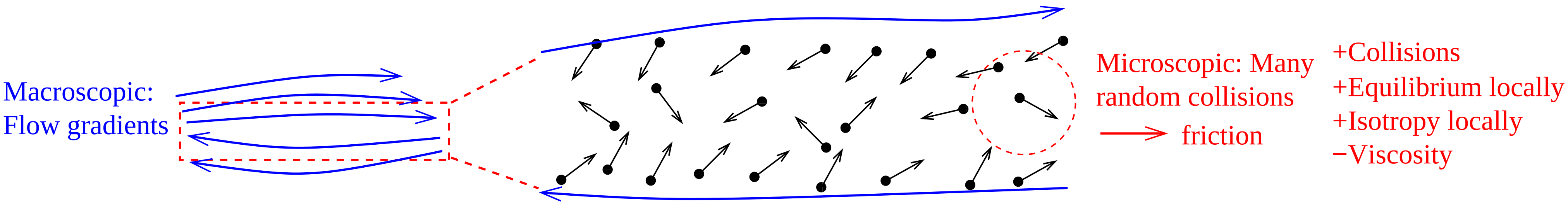
Plug into Boltzmann equation use H-theorem and obtain ϵ_μ in terms of $\eta \partial u$ etc.. For first order, we can show that

$$\eta = \frac{4}{5}\langle p \rangle n = \frac{1}{5}\langle p \rangle s l_{mfp} \quad , \quad \zeta = \left(c_s^2 - \frac{1}{3}\right)^2 \eta$$

Last relation relies on 1 reaction, broken if elastic and inelastic collisions equivalent to Kubo formulae in perturbative case!

$$So \qquad \eta \sim e l_{mfp} \sim sT l_{mfp}$$

Note: This means that η/s is a "pure" number in natural units (no scale)! It reflects the "readiness of thermalization" of the system, the speed at which the the degress of freedom$\sim s$ rethermalize when disturbed (by a flow gradient). (NB:Superfluid has low η but also low s .)



It might be counter-intuitive that a low l_{mfp} (ie, a lot of reinteractions) mean low η . But viscosity is a "diffusion" of momentum due to the finiteness of l_{mfp} . When l_{mfp} small, MANY collisions prevent diffusion

η and perturbation theory

Perturbation theory means,generally, weak coupling constant. Ie, a large mean free path and a large viscosity

$$\frac{\eta}{s} \sim e l_{mfp} \sim \frac{T}{\sigma_{crossection}} \sim \frac{1}{\alpha^2 \ln \alpha}\Big|_{perturbation\quad theory} \sim_{any\quad \underbrace{\geq 1}_{sensible}\quad \alpha}$$

$\eta/s < 1$ would require a α too large for calculation to work!

Attempts to lower this by many-body effects ($3 \leftrightarrow 2$ collisions, Plasma instabilities). But low experimental viscosity (see later!) encourages us to look beyond perturbation theory

In this regime can not use Boltzmann equation (No scattering approximation for each collision, no matrix elements but...

How low can the viscosity be? Lets forget we cant use the Boltzmann equation at strong coupling!A rough estimate: (Danielewicz and Gyulassy, 1987)

$$l_{mfp} \geq \langle \lambda_{debroglie} \rangle \sim 1/\langle p \rangle$$

If one plugs this into the Boltzmann equations and calculates viscosity the usual way, a lower limit is obtained

$$\eta/s \geq 1/12$$

but this procedure is less than rigurous:Remember, we cant use Boltzmann!

A way to make this (a bit!) more rigurous: Hydrodynamics (and viscosity) from AdS/CFT

The AdS-CFT correspondence: Every $\left\langle \hat{O}_{CFT} \right\rangle$ a 4D $N_{susy} = 4$ Gauge theory with N_c colors and T'hooft coupling λ , can be calculated by translating to a 10D string theory, with 5 Anti-DeSitter ($\Lambda < 0$) dimensions, 5 dimensions compactified on a sphere, and a string coupling constant of $g_s = \lambda/(4\pi N_c)$

- dictionary between $\hat{O}_{CFT}$ and $\hat{O}_{ADS}$ can be worked out
- Links strongly coupled CFT to weakly coupled perturbative string theory. Infinitely strongly coupled CFT $\Leftrightarrow$ classical supergravity.

Entropy density Can be extracted from the entropy of the Black hole: $s = \frac{3}{4} s_{SB}$

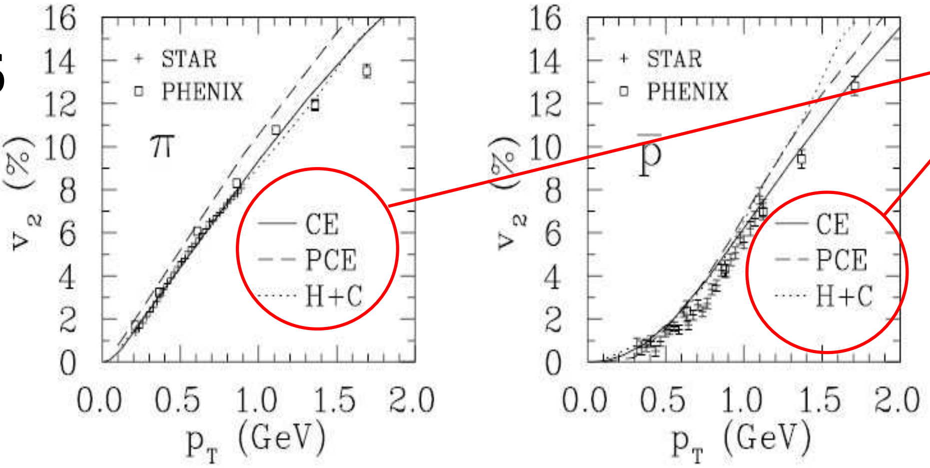
η Can be gotten with the Kubo formula, via the linearized theory of perturbations of a Black hole in AdS-space $\eta \sim \lim_{w \to 0} e^{iwx} \langle h_{\mu\nu}(0) h_{\mu\nu}(x) \rangle$. Plugging in the numbers we get the famous "limit"

$$\frac{\eta}{s} = \frac{1}{4\pi}$$

(Compare with Kinetic theory limit of $1/15\pi$).
NB: It <u>seems</u> the bound is violated for more complicated dual theories. <u>not clear</u> if η/s can go to 0.

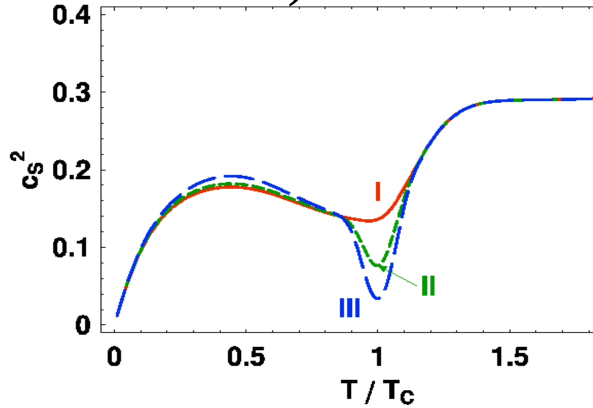
Hydrodynamics gives us an edge to probe QCD thermal physics. But...

P.Huovinen et al
ARNPS.56:163,2006
nucl−th/0605008



Different
EoSs

(And we know EOS
from lattice)



No one knows from first principles η/s in QCD (rather than $\mathcal{N}=4$ SYM), and v_2 insensitive to Equation of state (which we do know). Need additional "lever" on EoS to link calculable QCD and data! Such as heavy quarks

Hydrodynamics and heavy quarks

A "heavy" particle in a medium can be thought of as undergoing Brownian motion (hit infinitely many times by light medium particles, each collision exchanging a small amount of momentum). Langevan equation approach gives, for diffusion coefficient D

$$D \sim \mathcal{O}(1) \frac{\eta}{e+p}$$

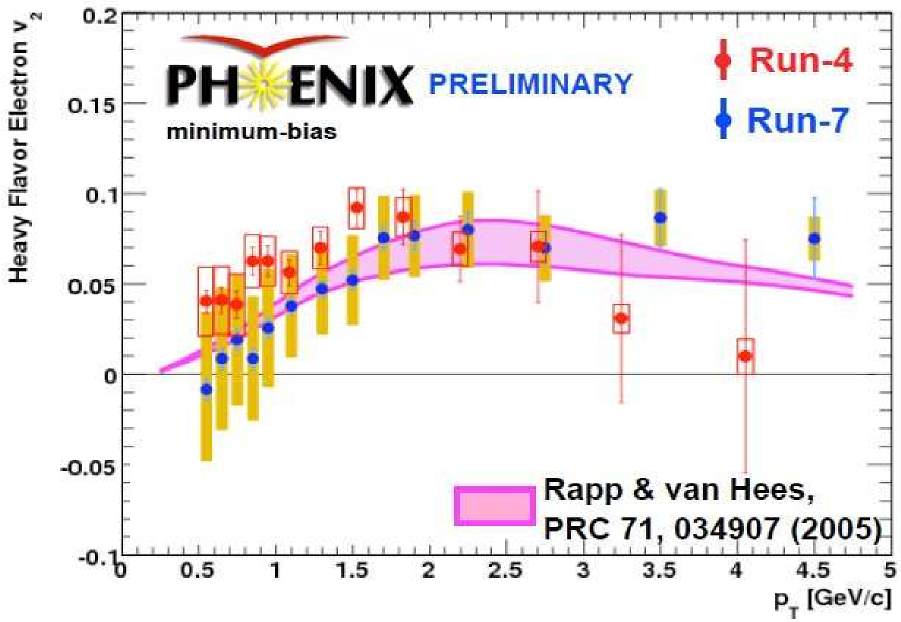
In other words,

$$\tau_{light} \sim \frac{\eta}{p+e} \quad , \quad \tau_{heavy} \sim \frac{M}{T} \tau_{light}$$

Thus Heavy quark thermalization $\Leftrightarrow$ Stricter limits on η
Problem: Experimentally, <u>not</u> "heavy quarks" but <u>non-photonic electrons</u>

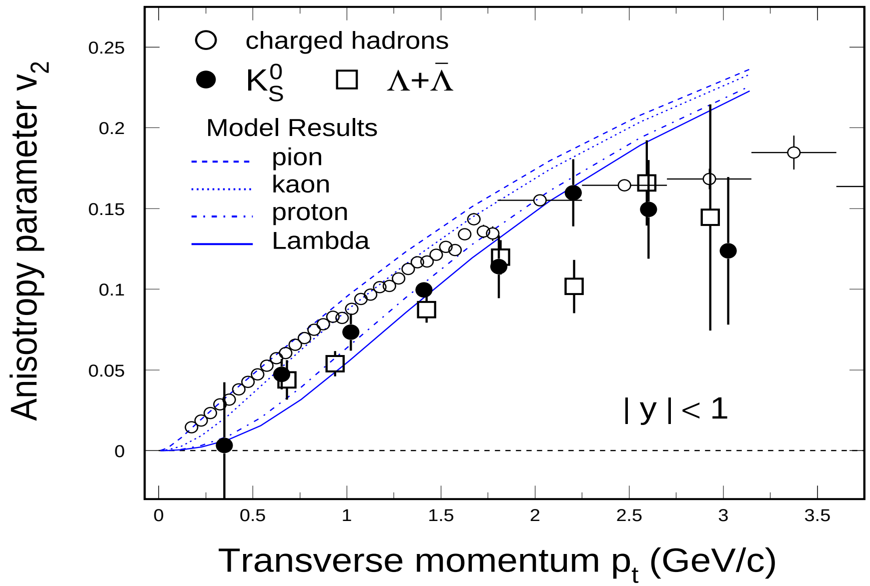
Heavy quarks (nonphotonic electrons)

PHENIX,PRL 98 172301 (2007)



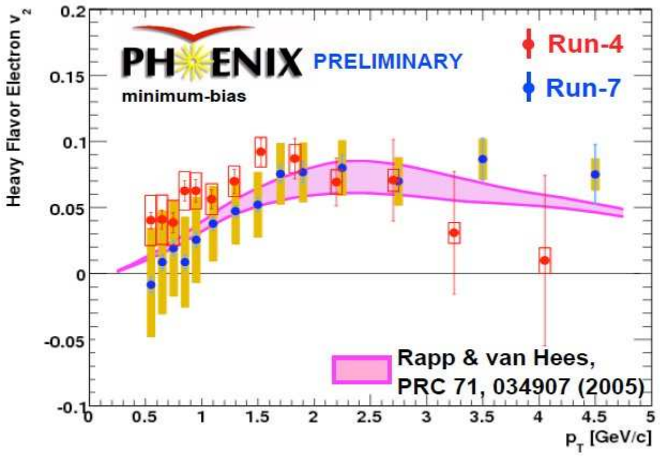
Light quarks

STAR,NPA 757, 102 (2005)

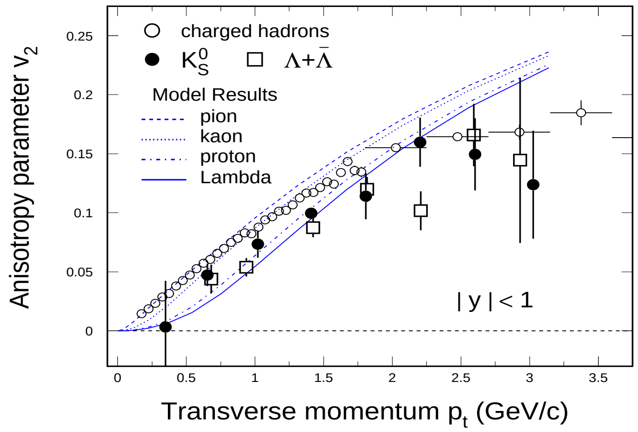


v_2 of heavy and light quarks same within error bar!!!!

Heavy quarks (nonphotonic electrons)
PHENIX,PRL 98 172301 (2007)



Light quarks
STAR,NPA 757, 102 (2005)



- Heavy quarks thermalized with the rest of the system (as light quarks)
- When Diffusion coefficient calculated, its compatible with a $\eta/s \leq 0.1$

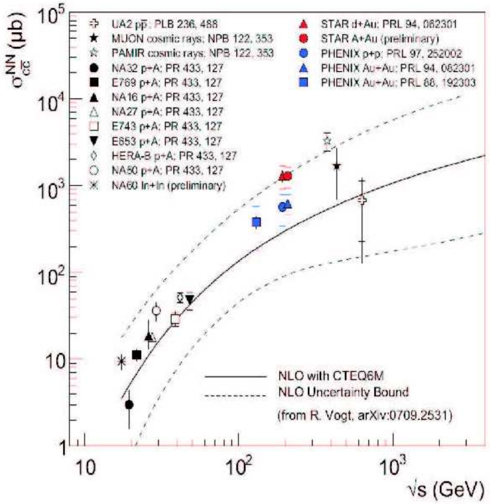
Heavy quark measurements uphold "perfect fluid" idea. HUGE uncertainity from inability to distinguish c/b, ignorance o resonance admixture,but...

Leads to interesting consequences (GT+Noronha, 1004.0237,in press,PLB)

Widsom from cooking: The thermal and transport properties of water change when you salt it! (Boiling point goes up, heat capacity goes down!)

Charm and beauty abundance, what you should remember

- Its mass is $\gg T$ for most (all?) of the evolution, even at the LHC
- It should be far $\sim 10^2$ above chemical equilibrium
- Its still very dilute ($f_c = N_c/N_{ch} \ll 1$)
(NB: Throghout this talk, by "charm" I mean "charm+beauty", as all the calculations apply to both. However this is a correction, as $N_b \ll N_c$)
- It fluctuates event by event in a Poissonian manner
- It should to a good approximation be conserved, as annihillation probability $\sim f_c^2$ (need quark and antiquark close)

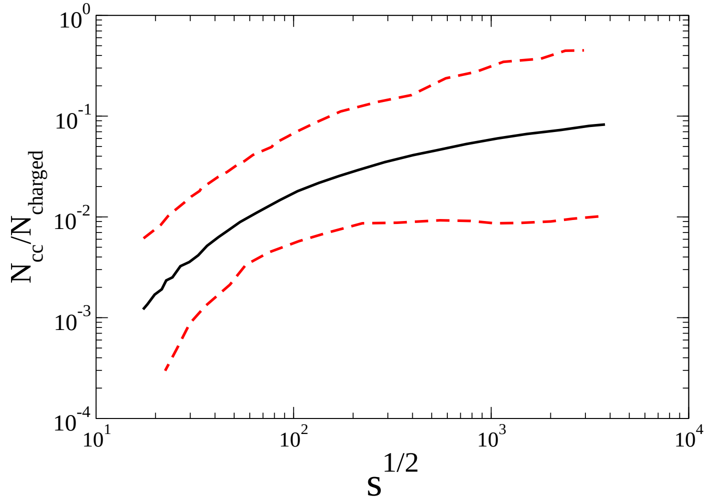


R.Vogt, 0709.253
pQCD estimate:

$N_{charm} \sim 10^{1-2}$ in Pb−Pb

HUGE uncertainities, NOT including rescattering, saturation

"higher end" favoured by data



Using $dN/dy \sim N_{part} \ln \sqrt{s}$ and $N_c \sim N_{coll} \frac{\Delta y}{4\pi\Lambda_{QCD}^{-2}} \sigma_{X\rightarrow c\bar{c}}$ we get $N_c/N_{ch} \sim 10^{-(3-2)}$ <u>on average</u>!

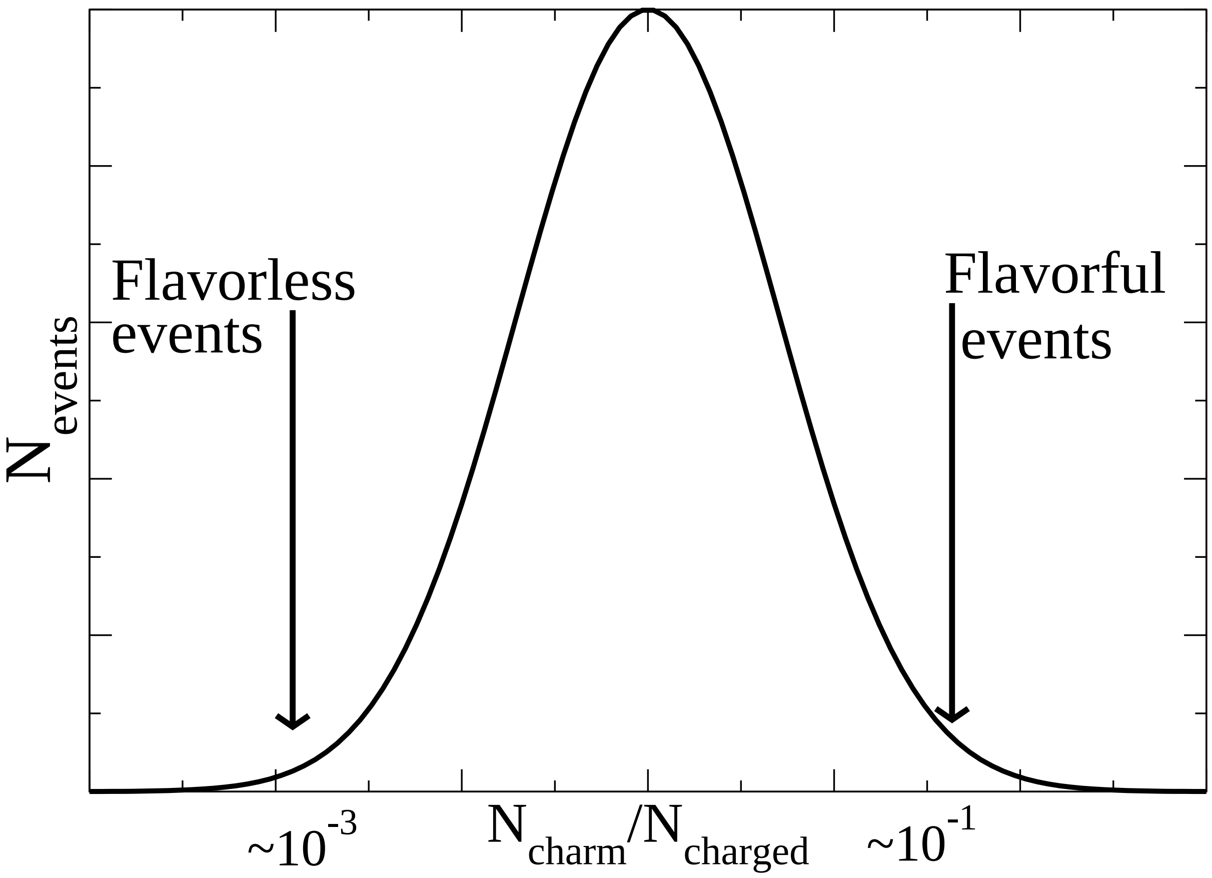
Of course N_c/N_{ch} fluctuates

- Charm fluctuates with a binomial distribution $\leftarrow$ Poissonian
- dN/dy fluctuations above poissonian (KNO? Glauber?)
- Charm produced by collisions ,dN/dy by wounded nucleons

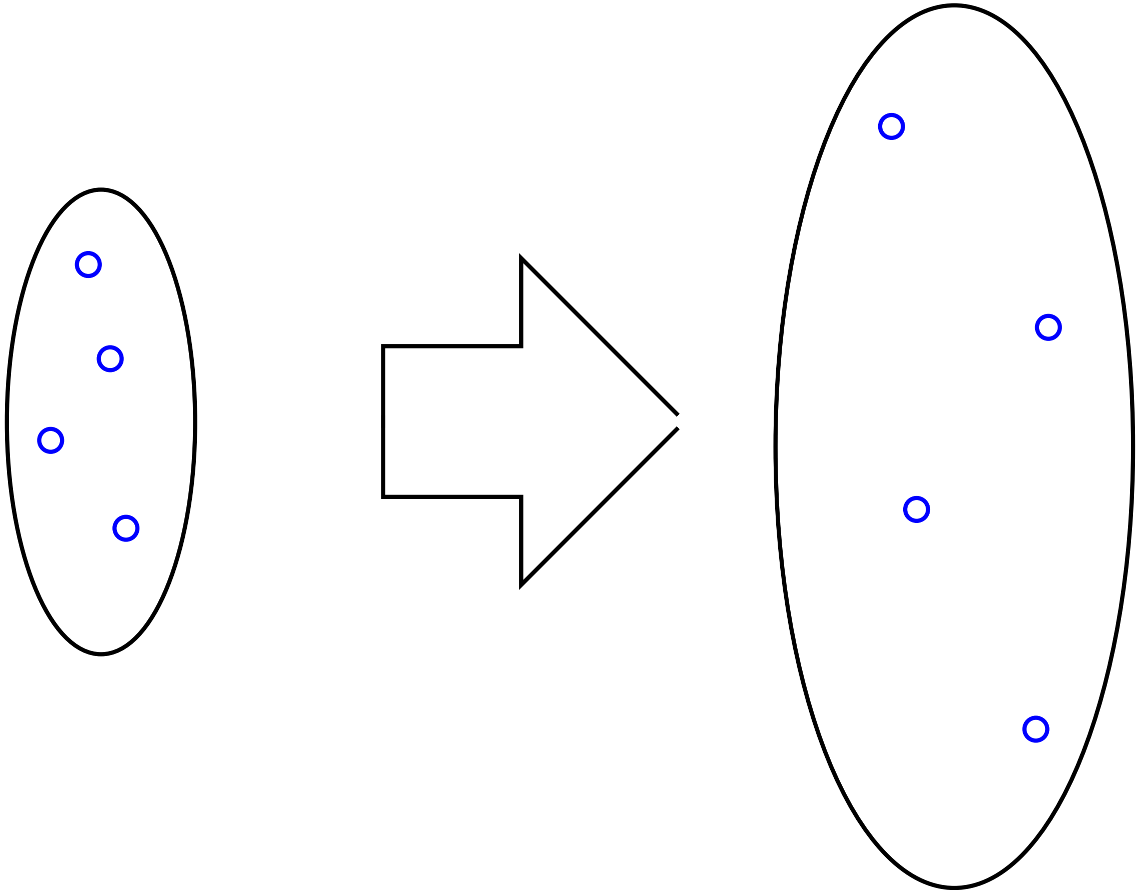
$$\sigma_{N_c/N_{ch}} = \underbrace{\frac{\left\langle (\Delta N_c)^2 \right\rangle}{\langle N_c \rangle^2}}_{\sim Poisson} + \underbrace{\frac{\left\langle (\Delta N_{ch})^2 \right\rangle}{\langle N_{ch} \rangle^2}}_{-ve \quad binomial} - 2 \underbrace{\frac{\langle \Delta N_{ch} \Delta N_c \rangle}{\langle N_{ch} \rangle \langle N_c \rangle}}_{\Delta N_{part} \Delta N_{coll}}$$

complicated,but both observable e-by-e!

So, with enough luminosity, can <u>bin</u> events according to N_c/N_{ch}



In an ideal homogeneus fluid $\tilde{\rho}$ locally conserved to a good approximation.



And we can do this quatitatively to a good approximation from lattice data!

If we add an "infinitely heavy quark" to the system, the renormalized free energy (excluding the quark mass) is given by the Polyakov loop expectation value

$$F_{total} = F_{plasma} - TN_c \ln \ell + \mathcal{O}\left(\frac{T \ln \ell}{m_c}\right)$$

The last correction is big at the LHC, but less then unity, and small until $T \simeq T_c$. Also no difference between quark and anti-quark non-perturbatively. Hence, in the dilute limit free energy density depends on $\tilde{\rho}$

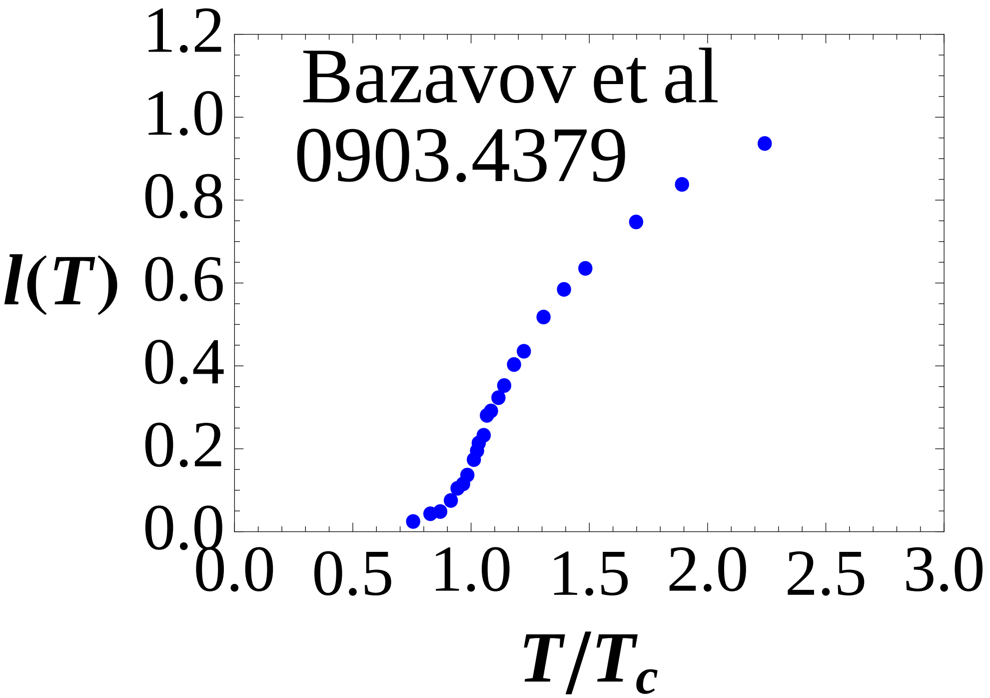
$$f = f_{plasma} - T\tilde{\rho}s \ln \ell$$

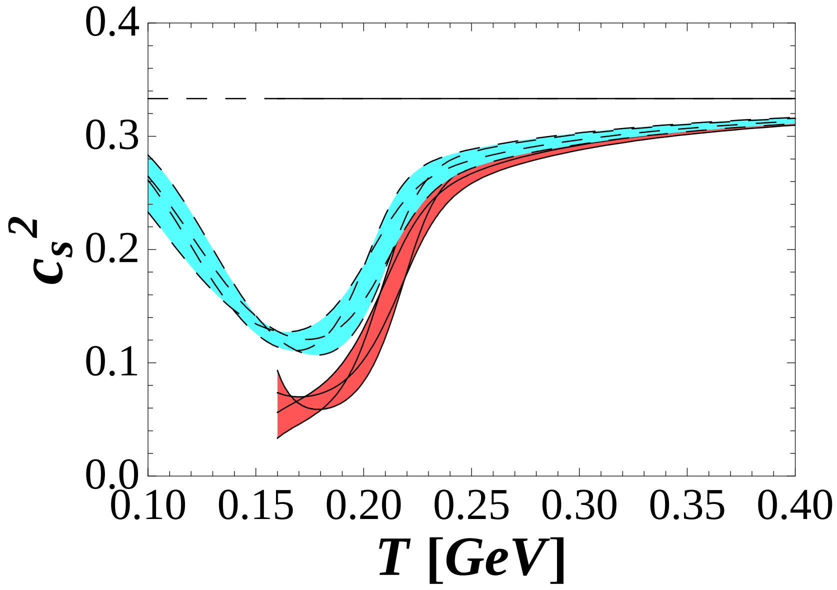
Note $\ln \ell \to -\infty$at confinement

And now we are set!

$$P = -f \qquad , \qquad e = -T^2 \frac{d}{dT}\frac{F}{T} \qquad , \qquad c_s^2 = \frac{dP}{de}$$

And the Polyakov loop expectation value is known from the lattice!





A consistent decrease of the speed of sound, directly proportional to the "flavorness" of the medium. Effect is greatest close to T_c (due to rapid variation in ℓ) but always present. Physically intuitively clear: Admixture of heavy particles slows systems response to pressure.

What happens when $T < T_c$?

Polyakov loop method can no longer be used as $\ell \rightarrow 0$, so

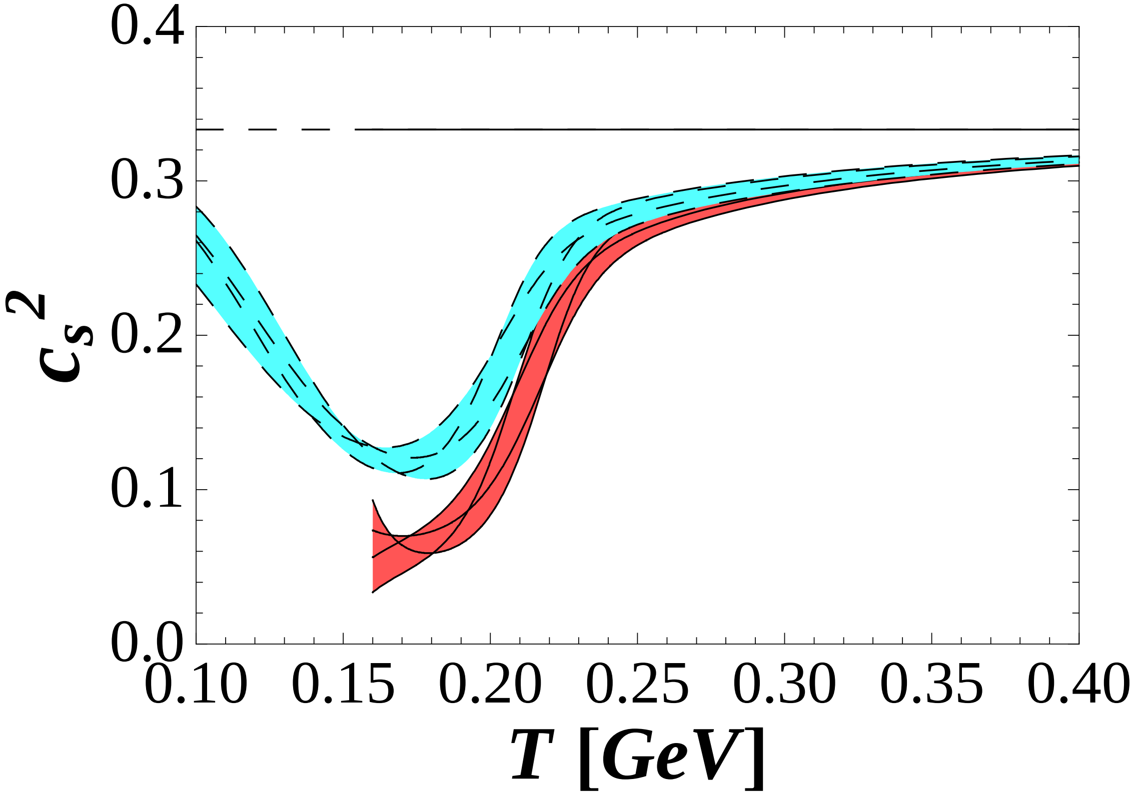
$$-T \ln \ell \rightarrow \infty \gg m_{quark}$$

In confined phase, strings can break, so Polyakov loop not anymore a measure of the free energy

The Hadron resonance gas model , if it also applies to heavy quarks, gives us a way to estimate the effect of salting by a mixture of dilute heavy mesons in a sea of pions. Using thextbook formulae for mixtures of ideal gases,

$$c_s^2 \sim c_{s\pi}^2 + \tilde{\rho} c_{sD}^2 \sim \frac{1}{3} + \tilde{\rho} \frac{5T}{3m}$$

Parametrically, this contains <u>two</u> small parameters, $\tilde{\rho}, T/m$, and hence its smaller than the Polyakov estimate which only has $\tilde{\rho}$.



So, "salting" response to the equation of state <u>only</u> arises in the deconfined regime, since dominating effect Polyakov-loop driven. Same argument shows salting response small $\mathcal{O}\left(\tilde{\rho}\frac{T}{M}\right)$ @ <u>weak</u> coupling! need sQGP

This qualitative behaviour is unique to asymptotically free confining theories.

An example: $\mathcal{N}=4$ SYM (Not confining nor asymptotically free). There, $\ln \ell \sim \sqrt{\lambda}$ so

$$F = \frac{3}{4}\left(F_{SB} - \tilde{\rho} T \sqrt{\lambda} s_{sb} \right)$$

Do the calculation, c_s independent of $\tilde{\rho}$! (Everything cancels out. Makes sense: Quark infinitely heavy, and conformal invariance exact!).

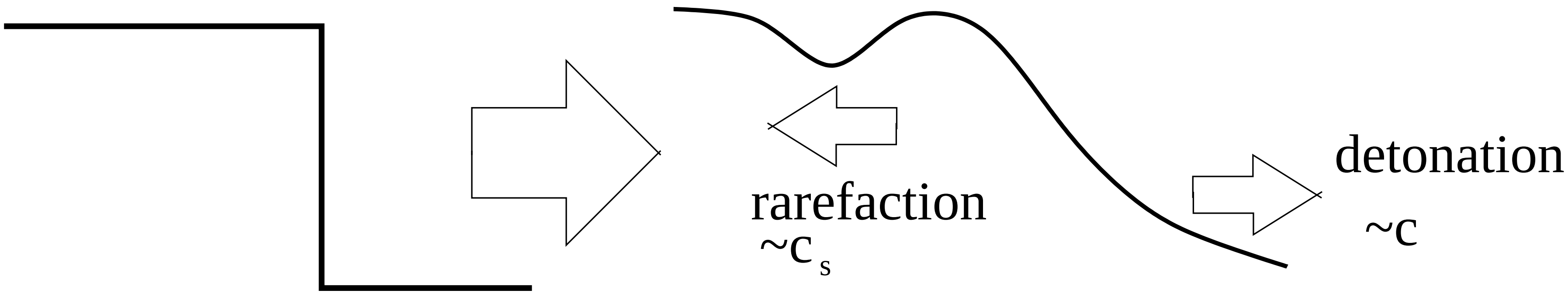
Relating c_s to physical observables...By Taylor-expanding around c_s ...

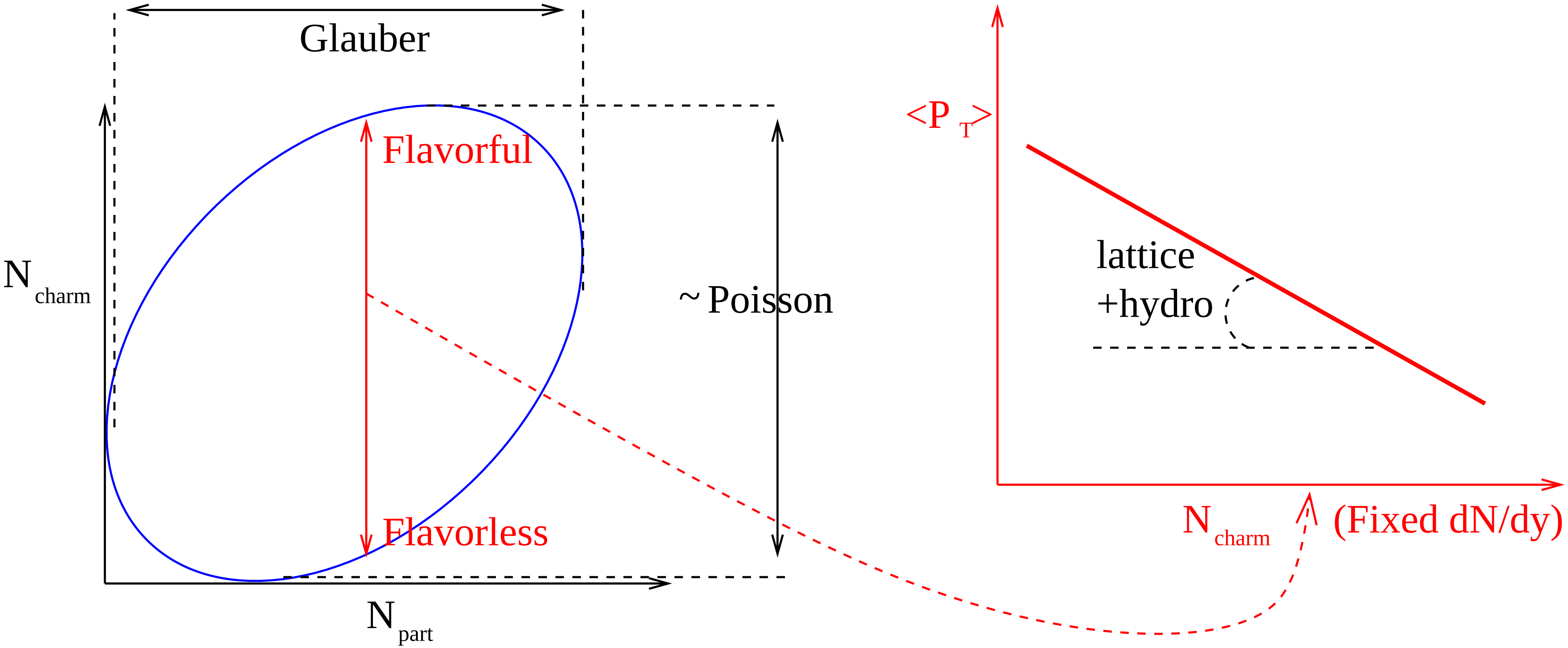
$$\langle p_T \rangle \sim T_f + m_\pi f(N_{part}, \sqrt{s}) \langle c_s \rangle_\tau^\alpha \quad , \quad (\alpha \simeq 2)$$

c_s comes as limiting speed of the rarefaction wave in a shock

Exact in a shallow shock (sound wave)

Approximate in a deep shock, as rarefaction wave, carrying bulk of p_T, moves with c_s in rest frame





So we expect to have a correlation between $\tilde{\rho}$ and $\langle p_T \rangle$ whose slope is rigorously calculable from lattice and hydro

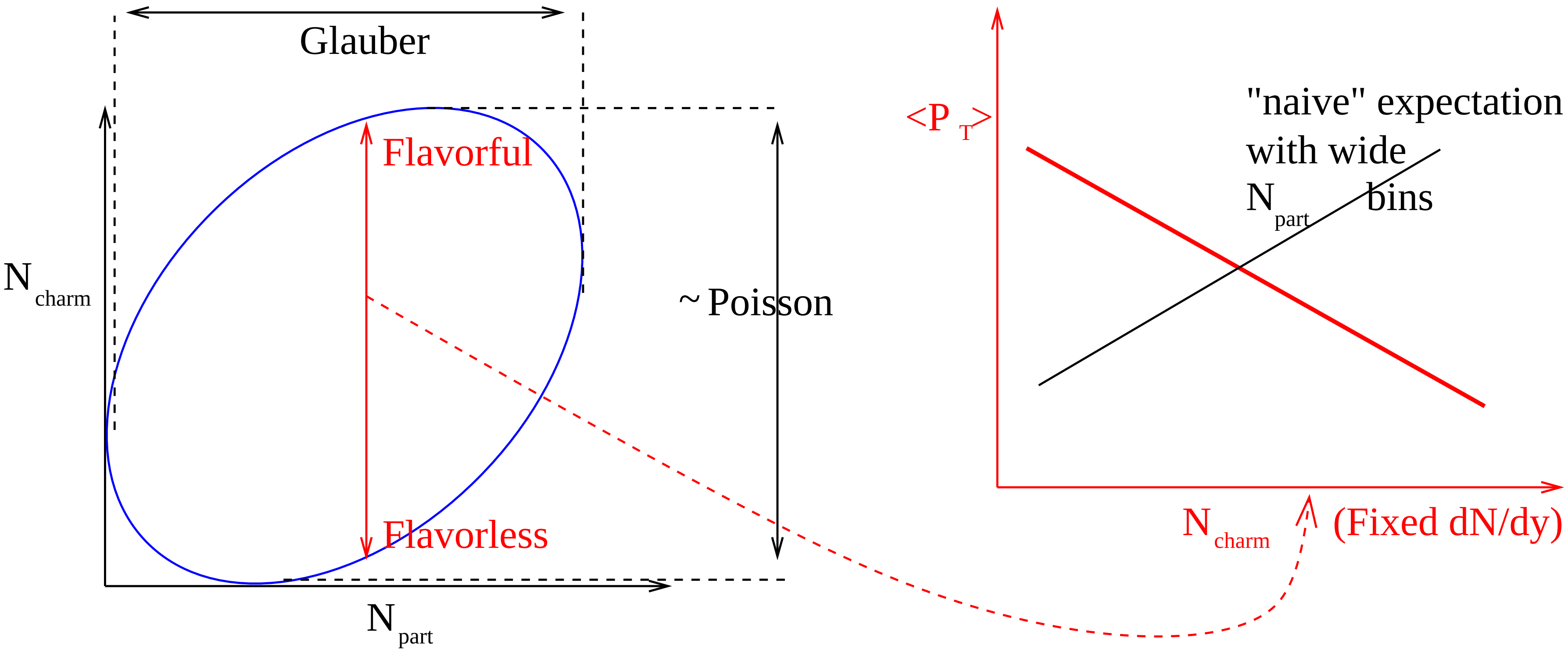
This is <u>not</u> conservation of energy (and is <u>not</u> contaminated by it)

dN/dy at mid-rapidity is controlled by soft ($x \ll 1$) partons

charm at mid-rapidity is controlled by harder ($x\sqrt{s} > \Lambda_{QCD}$) partons

So the energy to create charm at mid-rapidity is created at significant (> 1) forward or backward rapidity. If soft physics local in rapidity (Bjorken picture) conservation of energy will <u>not</u> lower $\langle p_T \rangle$ at mid-rapidity!

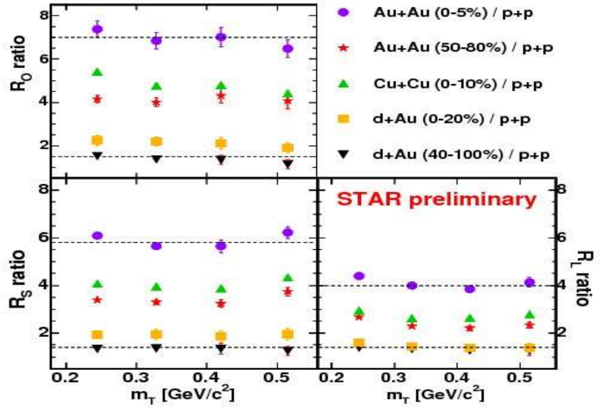
Effect anti-correlated with N_{part} fluctuations

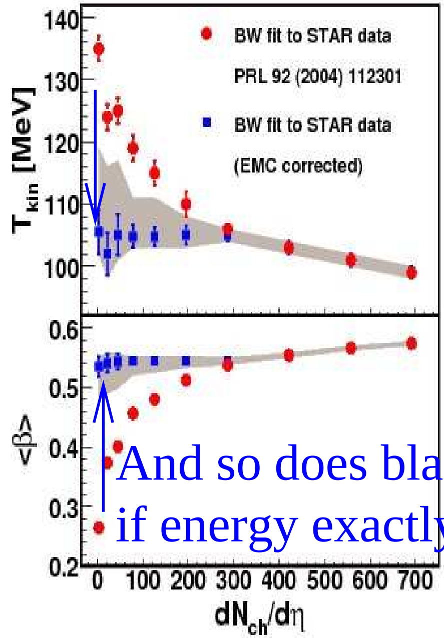


A hotter system than average has more flow and more charm.
Correlation not perfect, as $dN/dy \sim N_{part}, N_{cc} \sim N_{coll} \neq N_{part}$

Fluctuations larger in smaller systems, $\sigma_{\tilde{\rho}} \sim \left(\frac{dN}{dy}\right)^{-1}$

Star HBT results indicate
p−p flows ~ Au−Au





And so does blast wave fit
if energy exactly conserved

M.Lisa and Z.Chajecki
QM2005
QM2009
Data from STAR collab.

At RHIC, $p-p$ events with $dN/dy \sim 10$,$2c\bar{c}$ pairs have $\tilde{\rho} \sim 10\%$

People speculate weather p-p also flows at RHIC. This might be way to tell!

Conclusions

- RHIC seems to have produced a "perfect" fluid
- Viscosity much below naive perturbative expectations
- Likely window into non-perturbative physics
- Heavy quarks...
  - Validate the perfect liquid evidence via Langevin-analysis
  - Response of equation of state to "chemical" impurities Reliable link between data and non-perturbative QCD!

RHIC made the perfect soup. The LHC could make a soup which is not only perfect, but also flavorful!