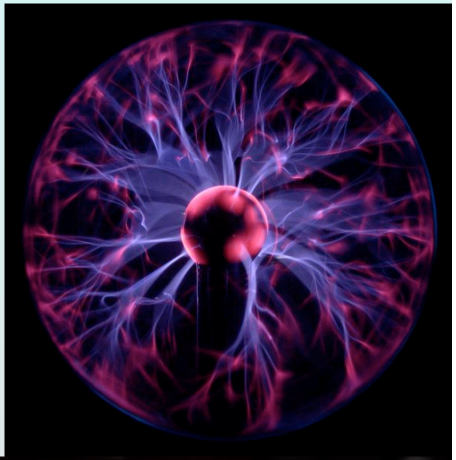
# Measuring Properties of the Shortest Lived Plasma in the World

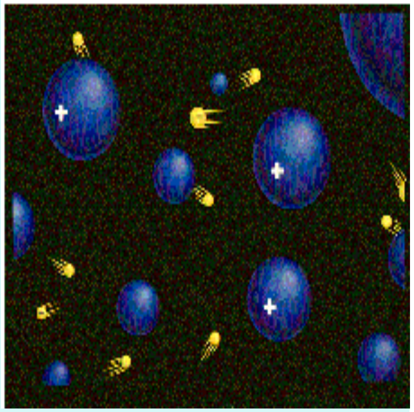
Barbara Jacak

Stony Brook

September 23, 2008



# what is a plasma?

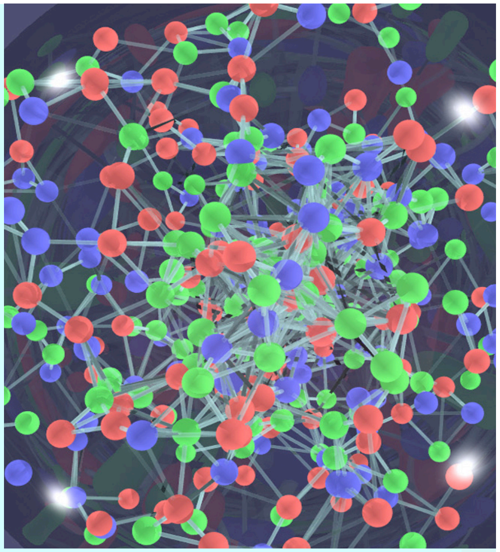


- 4th state of matter (after solid, liquid, gas)
- a plasma is:
  - ionized gas, macroscopically neutral
  - exhibits collective effects

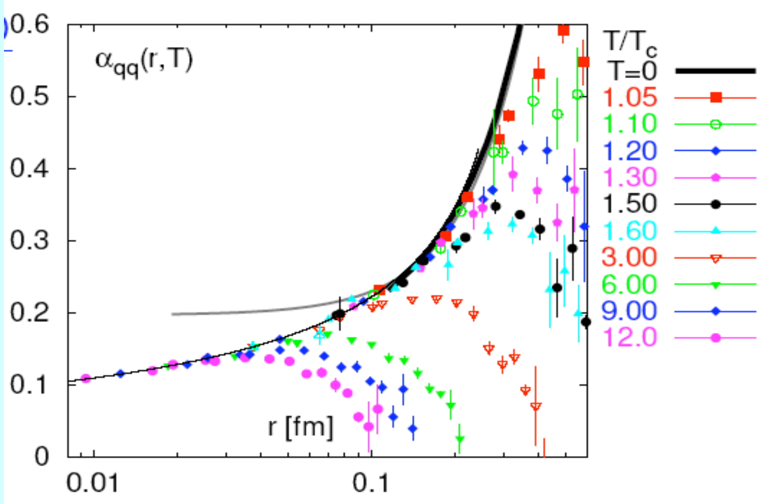
- interactions among charges of multiple particles
  - spreads charge into characteristic (Debye) length, $\lambda_D$
  - multiple particles inside this length
    - they screen each other
  - plasma size > $\lambda_D$

- "normal" plasmas are electromagnetic (e + ions)
  - quark-gluon plasma interacts via strong interaction

# quark gluon plasma



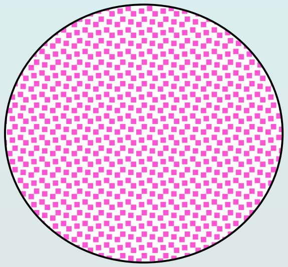
- color forces rather than EM
  exchanged particles: g instead of $\gamma$
  gluons self-interacting
  $\therefore$ theory is non-abelian
- "normal" plasmas
  can vary $\rho$, T independently
  strongly *or* weakly coupled
- QCD plasma
  T determines all properties
  limits analogy to EM plasma
  *(heavy q mass sets new scale)*
  intrinsically strongly coupled for accessible T
  $\alpha_s$ ~0.35; quarks & gluons NOT asymptotically free
  …not your mother's plasma



# Debye screening in plasma

- Debye length: distance over which the influence of an individual charged particle is felt by the other particles in the plasma
- charged particles arrange themselves so as to effectively shield any electrostatic fields within a distance of order $\lambda_D$
- $\lambda_D = \left( \frac{\varepsilon_0 kT}{n_e e^2} \right)^{1/2}$

$n_e$ = number density
e = charge

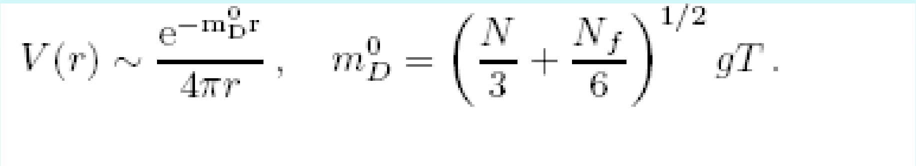


- Debye sphere = sphere with radius $\lambda_D$
- # of electrons inside Debye sphere is large

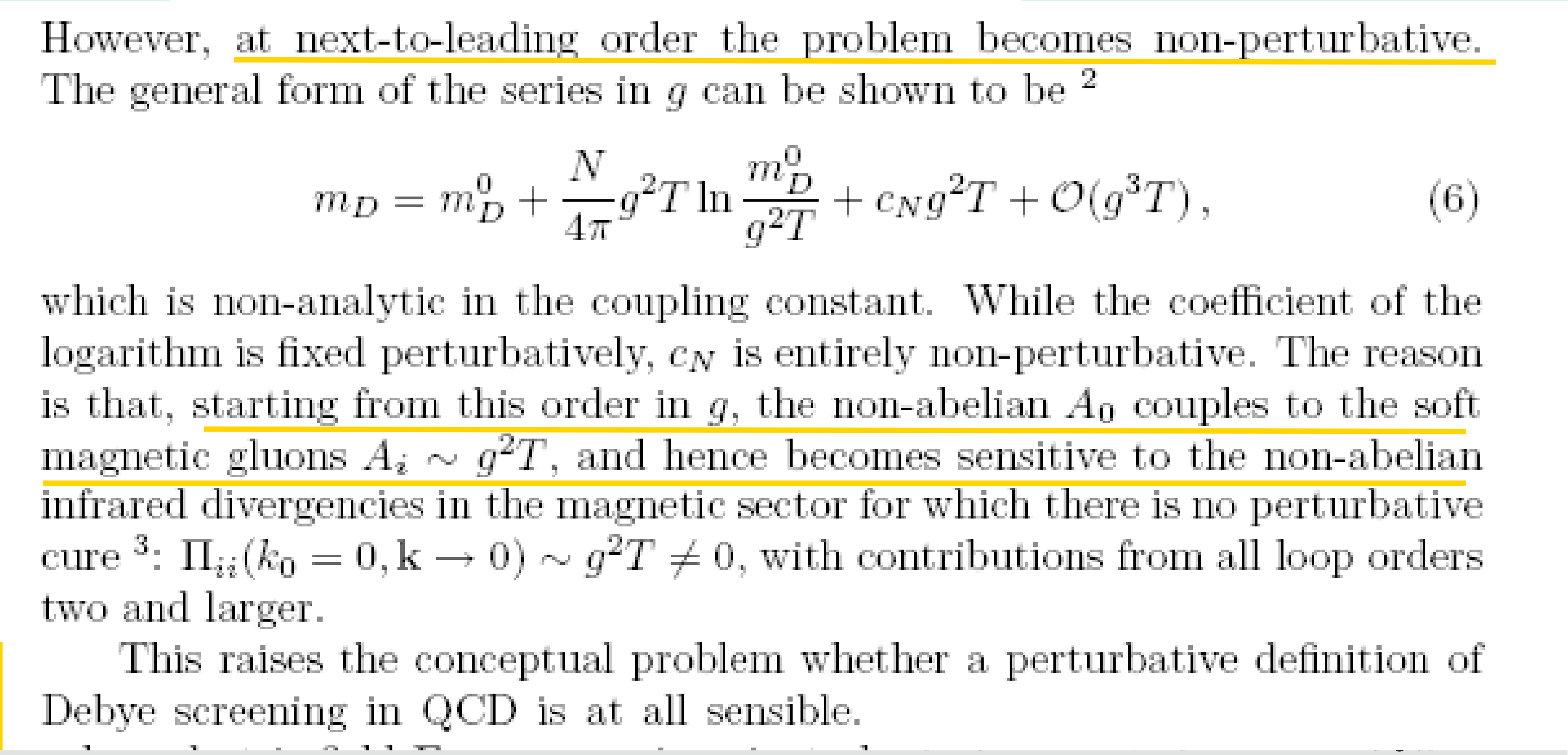
$N_D = N/V_D = \rho V_D \quad V_D = 4/3\, \pi\, \lambda_D^3$

# Debye screening in QCD: a tricky concept

- **in leading order QCD (O. Philipsen, hep-ph/0010327)**



$$V(r) \sim \frac{\mathrm{e}^{-m_D^0 r}}{4\pi r}, \quad m_D^0 = \left(\frac{N}{3} + \frac{N_f}{6}\right)^{1/2} gT\,.$$

- 

However, at next-to-leading order the problem becomes non-perturbative. The general form of the series in $g$ can be shown to be [2]

$$m_D = m_D^0 + \frac{N}{4\pi} g^2 T \ln \frac{m_D^0}{g^2 T} + c_N g^2 T + \mathcal{O}(g^3 T)\,, \qquad (6)$$

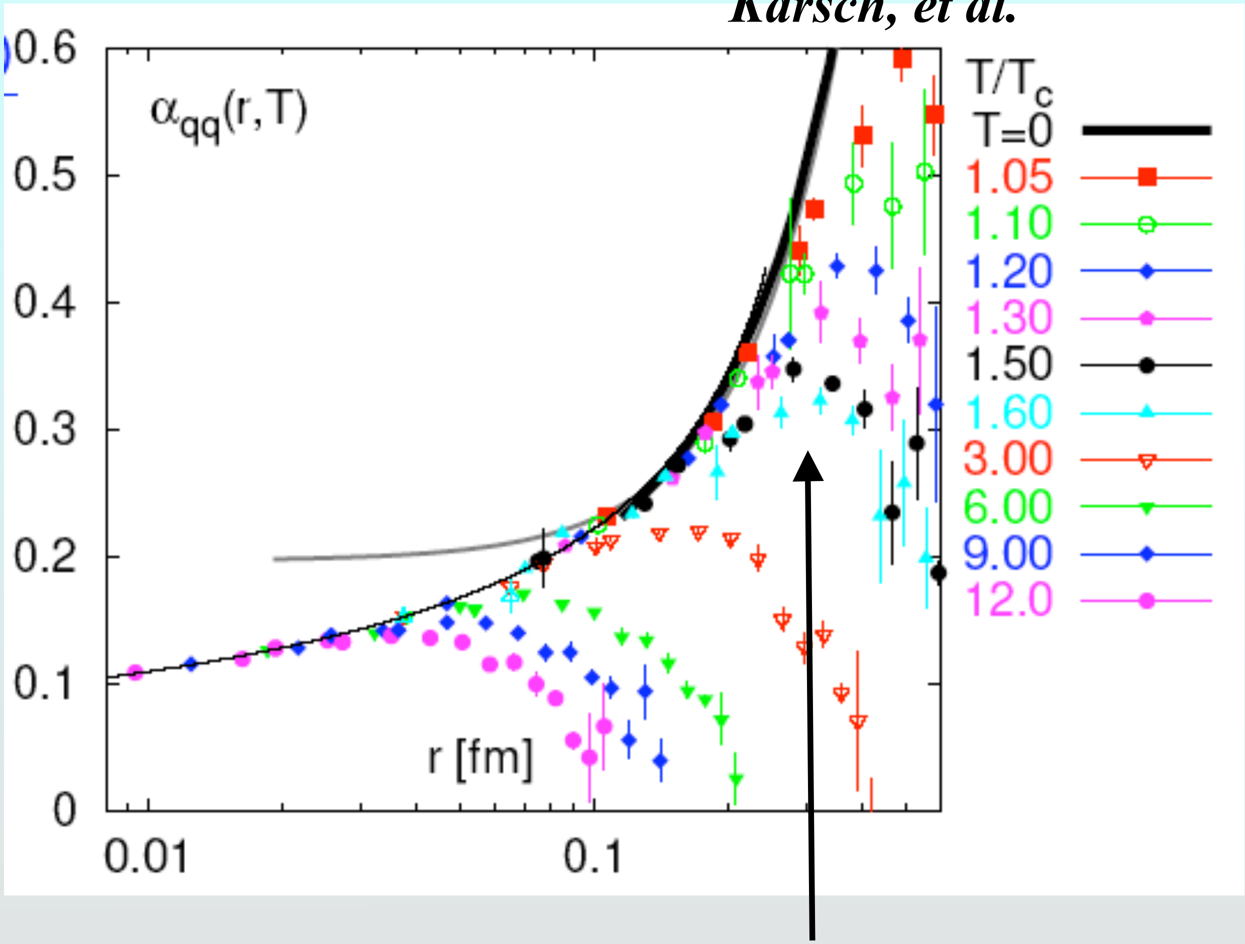
which is non-analytic in the coupling constant. While the coefficient of the logarithm is fixed perturbatively, $c_N$ is entirely non-perturbative. The reason is that, starting from this order in $g$, the non-abelian $A_0$ couples to the soft magnetic gluons $A_i \sim g^2 T$, and hence becomes sensitive to the non-abelian infrared divergencies in the magnetic sector for which there is no perturbative cure [3]: $\Pi_{ii}(k_0 = 0, \mathbf{k} \to 0) \sim g^2 T \neq 0$, with contributions from all loop orders two and larger.

This raises the conceptual problem whether a perturbative definition of Debye screening in QCD is at all sensible.

# don’t give up! ask lattice QCD

*Karsch, et al.*

**running coupling**



**coupling drops off for r > 0.3 fm**

# screening masses from gluon propagator

***Screening mass, $m_D$, defines inverse length scale***

***Inside this distance, an equilibrated plasma is sensitive to insertion of a static source***

***Outside it's not.***

**T dependence of electric & magnetic screening masses**

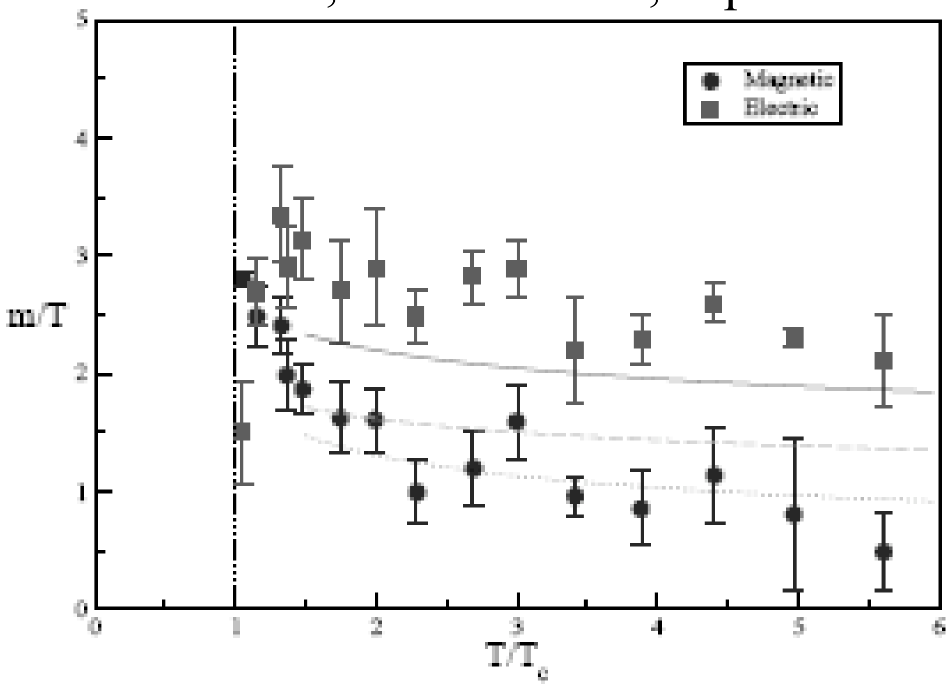
**Quenched lattice study of gluon propagator**

**figure shows:**

**$m_{D,m}$= 3Tc, $m_{D,e}$= 6Tc at 2Tc**

**∴ $\lambda_D \sim 0.4, 0.2$ fm**

Nakamura, Saito & Sakai, hep-lat/0311024



*magnetic screening mass is non-zero*

*not very gauge-dependent, but DOES grow w/ lattice size (long range is important)*

# Implications of $\lambda_D \sim 0.3$ fm?

- can use to estimate Coupling parameter, $\Gamma$
- $\Gamma = \langle PE\rangle / \langle KE\rangle$ but also given by $\Gamma = 1/N_D$

  for $\lambda_D = 0.3$fm and $\varepsilon = 15$ GeV/fm$^3$

  $V_D = 4/3\ \pi\ \lambda_D^3 = 0.113$ fm$^3$

  $E_D = 1.7$ GeV

  to convert to number of quasiparticles:

  use gT or $g^2T$ for $T \sim 2T_c$ and $g^2 = 4$

  get $N_D = 1.2 – 2.5 \quad \therefore \Gamma \sim 1$
- NB: for $\Gamma \sim 1$

  plasma is NOT fully screened – strongly coupled!

  affects interaction $\sigma$!

  *strongly coupled EM plasmas behave as liquids, can even make crystals for $\Gamma \geq 150$*

  *dusty plasmas, cold atoms+ions , warm dense matter*

# calculating transport in QGP

**weak coupling limit**

*perturbative QCD*

*kinetic theory, cascades*

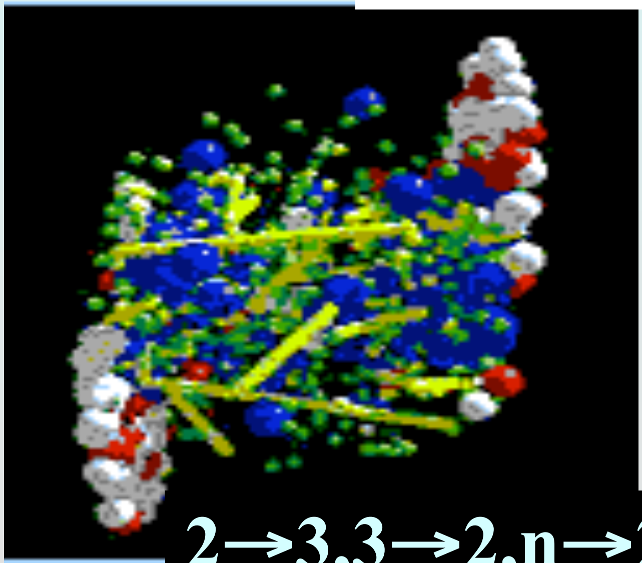
**strong coupling limit**

*not so easy!*

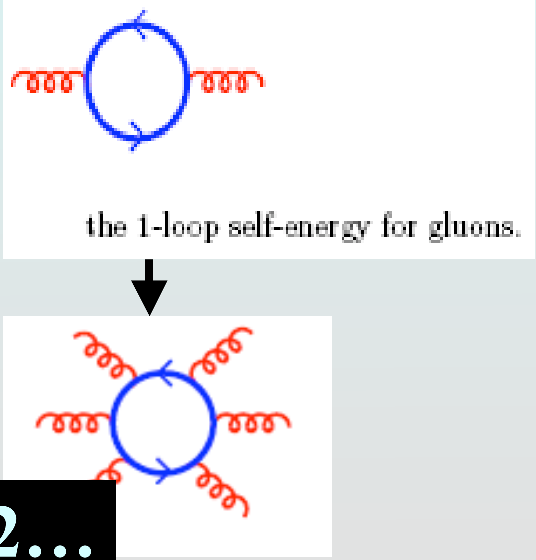
*gravity ↔ supersym 4-d*

*AdS/CFT: QCD-like theory*

*resummation of hard thermal loops*



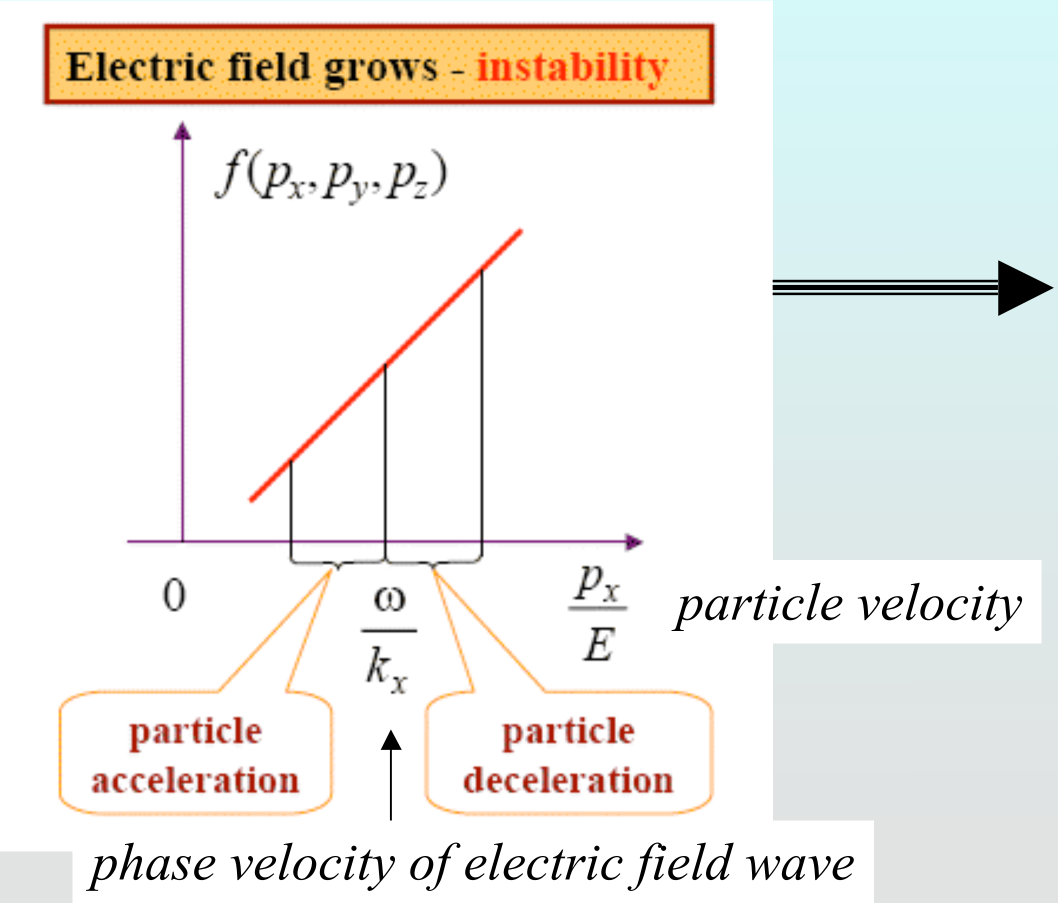
2→3,3→2,n→2…

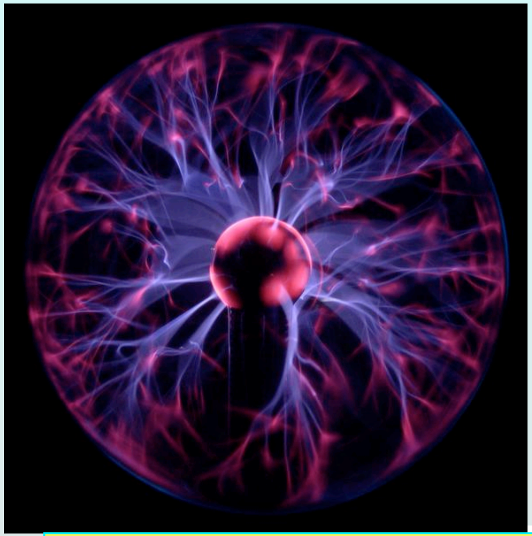


the 1-loop self-energy for gluons.

# Plasma instabilities

- a mode with growing amplitude
  transfer energy from the plasma particles to EM field
- e.g. Weibel instability - causes beam filamentation



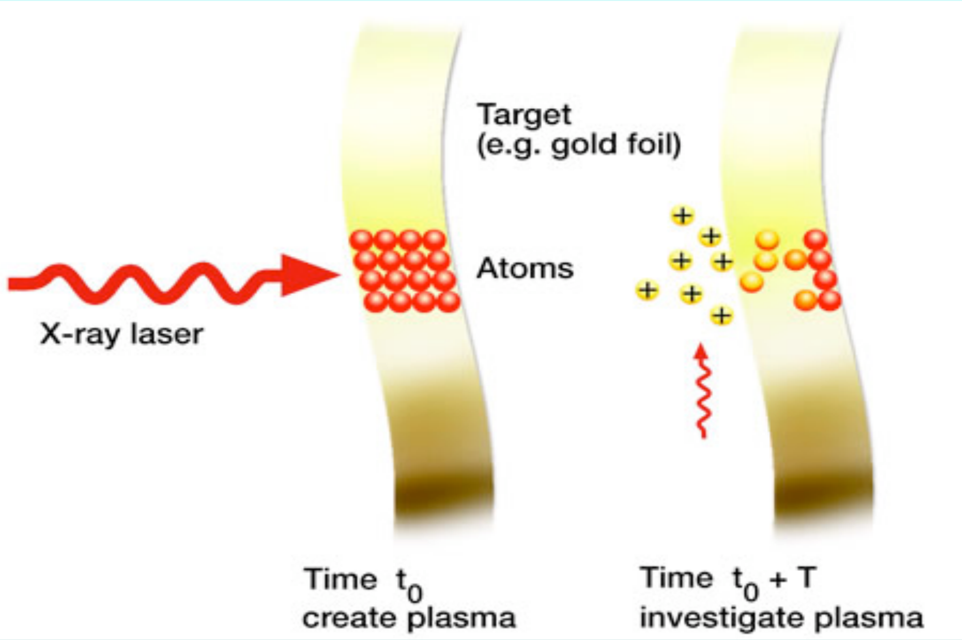


**Mechanism to *quickly* isotropize momentum of colliding heavy ions?**

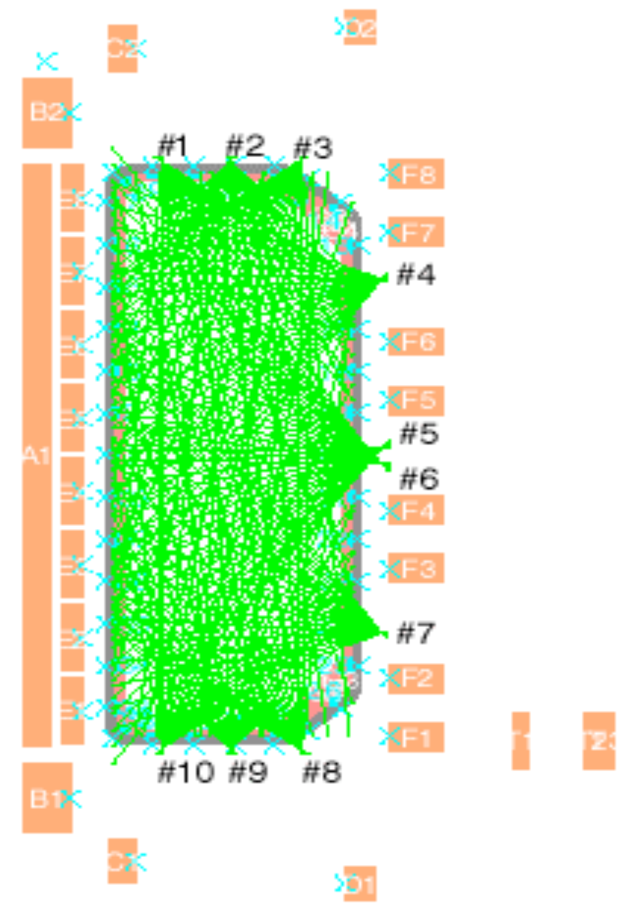
**Non-abelian plasma is self-limiting**

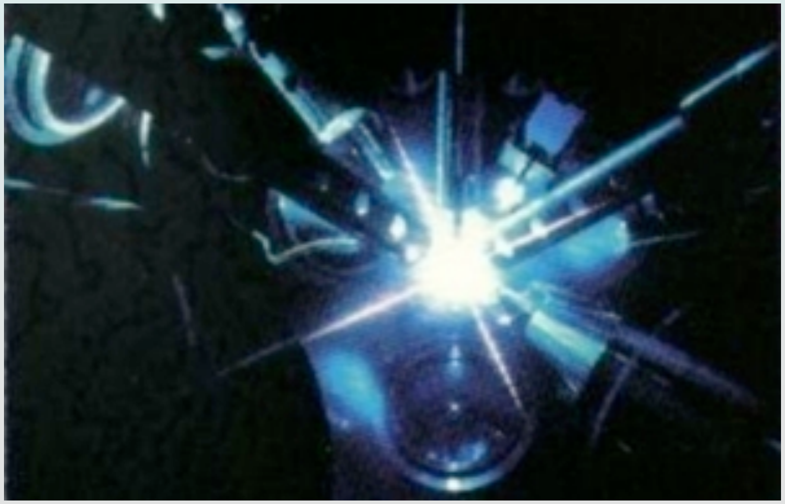
***Rebhan***

# Some typical plasma diagnostics



*X-ray tomography: to get temporal and spatial evolution of plasma mode activity, we use 10 soft X-ray cameras with 20 channels each, at 70 kHz max.*

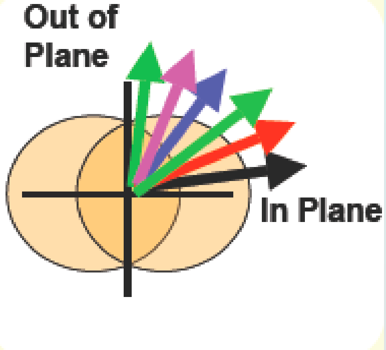


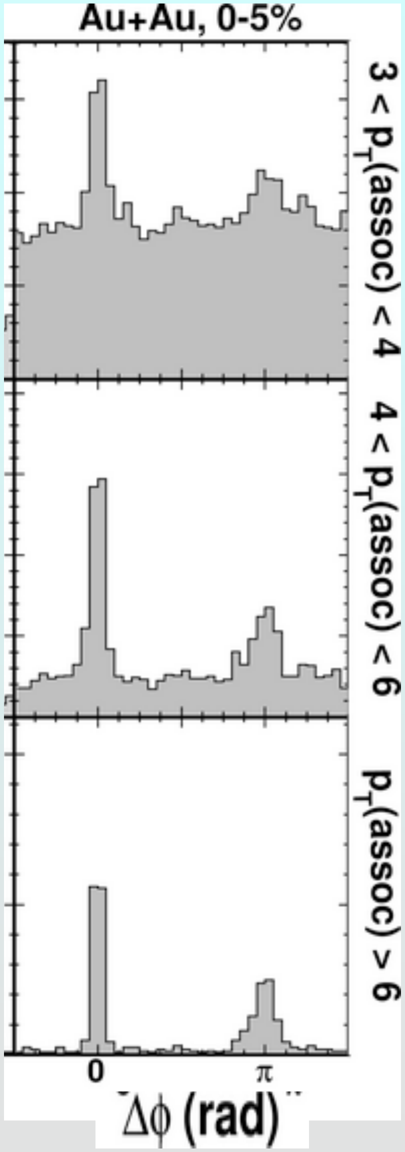


# Parton energy loss: similar probe

- Instead of an external x-ray beam
  use partons from initial hard scatterin
  "self-generated" probe → *density*

- $R_{AA}$ integrates over all directions
  Reaction plane dependent $R_{AA}$
  allows selecting a direction
  Back-to-back jets control
  path length in plasma
  di-hadrons work too





- Next step: "calibrate" the probe
  $\gamma_{direct}$ - jet or γ-h, reconstructed jets

# measure dynamic (transport) plasma properties

- measure dynamic properties - transport of:

  particle number, energy, momentum, charge
  *diffusion* *sound* *viscosity* *conductivity*

- emission from the bulk can reflect collective motion
- but other useful probes require

  auto-generation in the heavy ion collision
  large $Q^2$ processes to separate production & propagation
  large $E_{tot}$ (high $p_T$ or M) to set scale other than T(plasma)

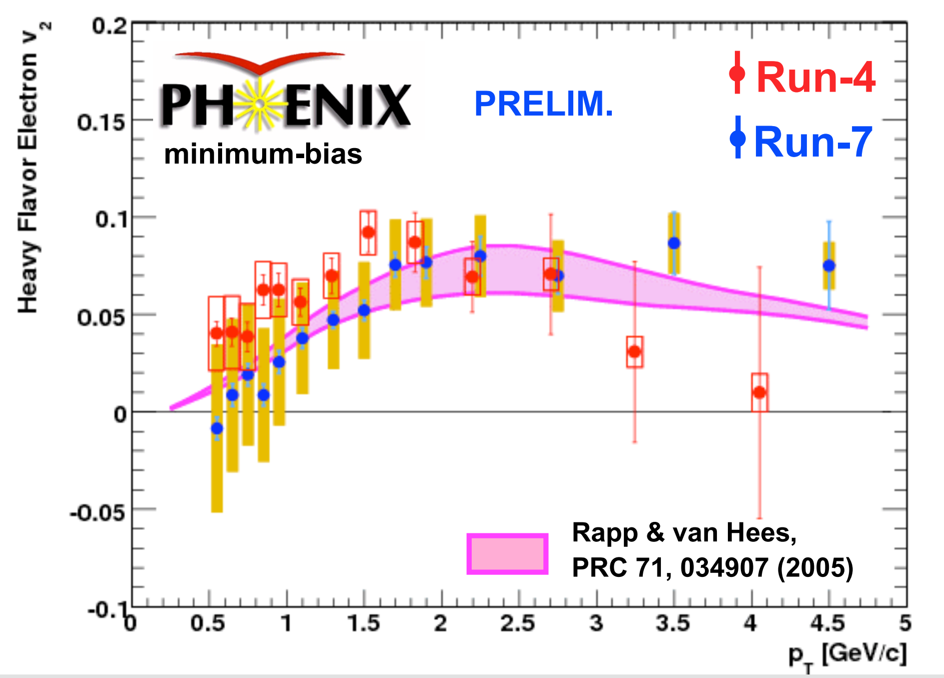
# How to get at these

| property | measurement |
|---|---|
| T | $\gamma, \gamma*$ as fn. of $\varepsilon, \mu$ |
| density | quark, gluon energy loss |
| equation of state | particle flows as fn. of $\varepsilon, \mu$<br>critical point location |
| screening length | onium spectroscopy |
| $\rho$ (x,v) | jet tomography |
| diffusion | open C, B spectra & flow |
| viscosity | light & charmed hadron flows used to constrain 3d hydro |
| energy transport i.e. sound | >2 particle correlations vs. T, $p_T$<br>Medium response to jet energy |

# Diffusion (& viscosity, redux)

***Consider heavy quark probes:***

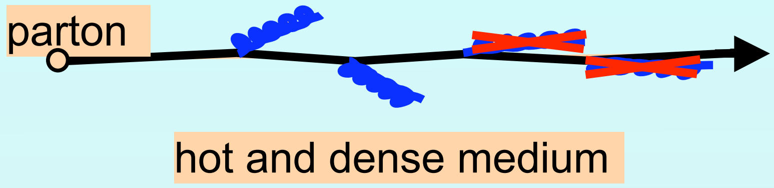
- **Hard probe - production in initial NN collisions (maybe *some* thermal production at LHC…)**
- **Large mass: different scale for probe than medium**



**Charm actually flows along with the bulk medium!**

**Consider how c quarks diffuse through the plasma**

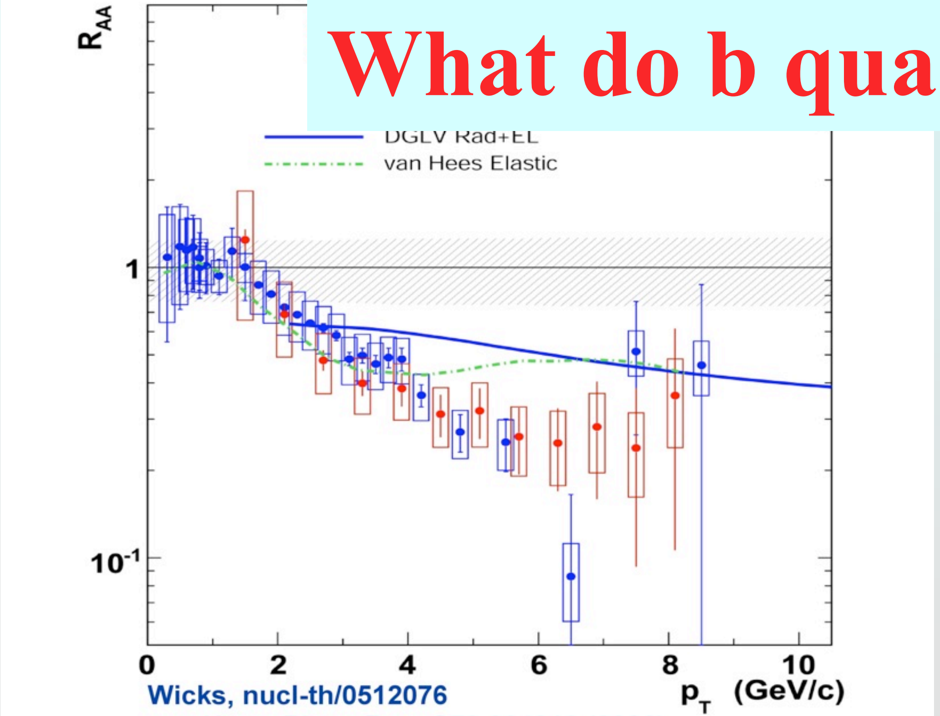
# Heavy quarks radiate AND collide


parton

hot and dense medium

STAR Phys. Rev. Lett. 98 (2007) 192301

PHENIX Phys.Rev.Lett.98 (2007) 172301



Wicks, nucl-th/0512076

van Hess, Phys. Rev. C73 034913 (2006)

* In strongly coupled medium: diffusion of charm quarks

D ∝ collision time, determines relaxation time

<v> λ

NB: η = 1/3 ρ <v> λ

∴ D = η/ρ ~ η/s

→ extract D get η/s!

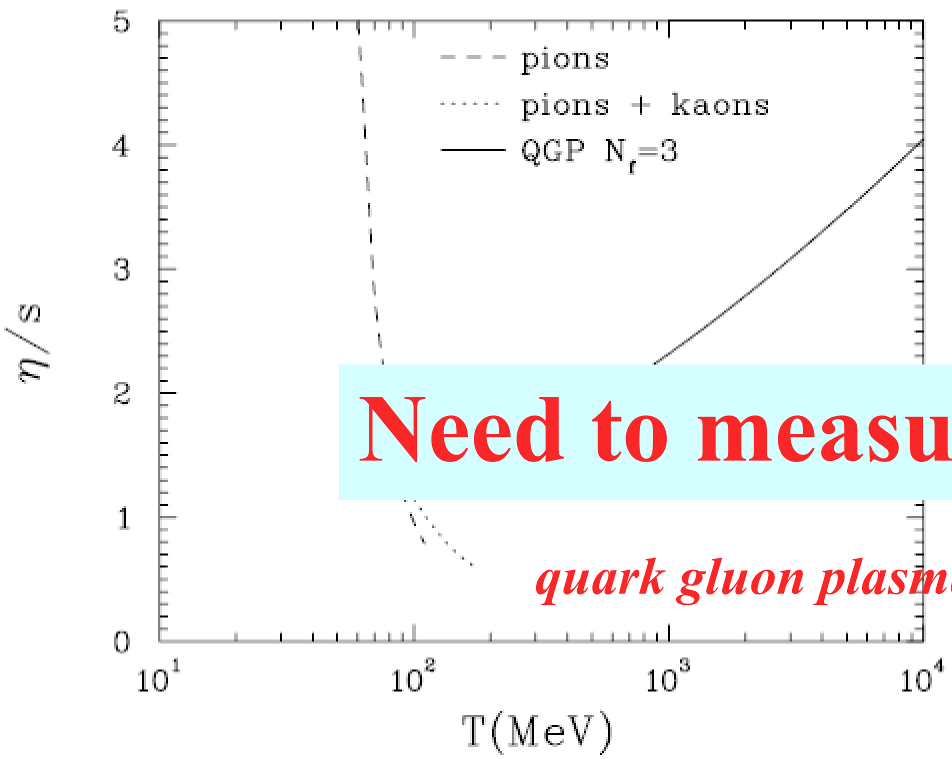
*D ~ 4-6/(2πT) for charm*

*η/s = (1.3 – 2.0)/ 4π*

*(model dependent, but not on hydro)*

**What do b quarks do?????????**

# minimum η/s at phase boundary?

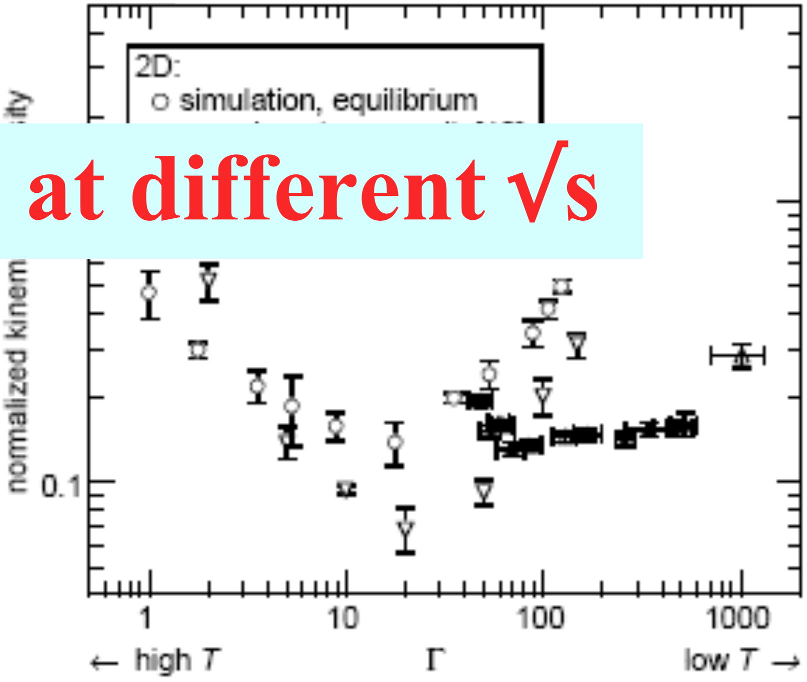


*quark gluon plasma*

Csernai, Kapusta & McLerran
PRL97, 152303 (2006)

*strongly coupled dusty plasma*

B. Liu and J. Goree,
cond-mat/0502009

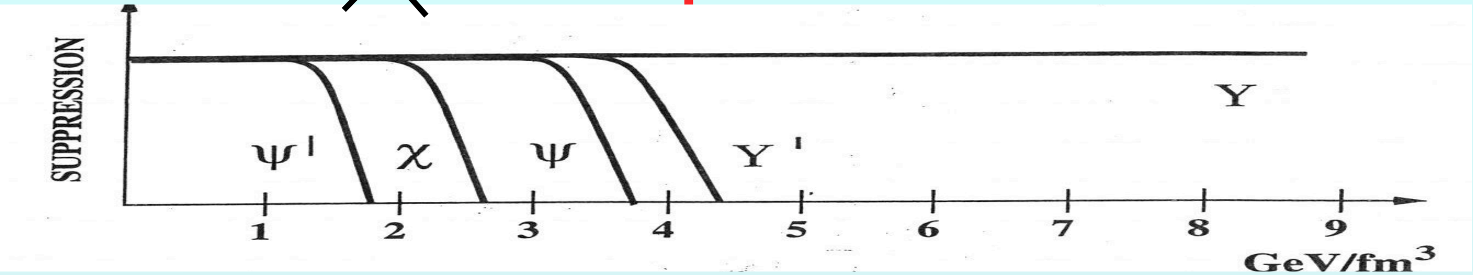


**Need to measure at different √s**

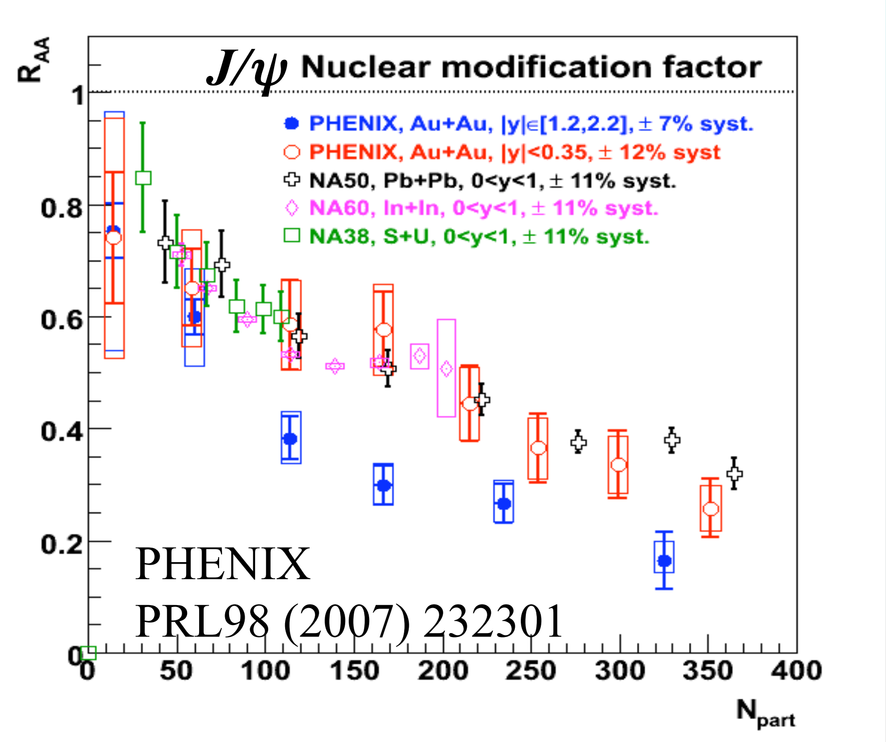
**minimum observed in other strongly coupled systems –**
**kinetic part of η decreases with Γ while potential part increases**

# Screening length

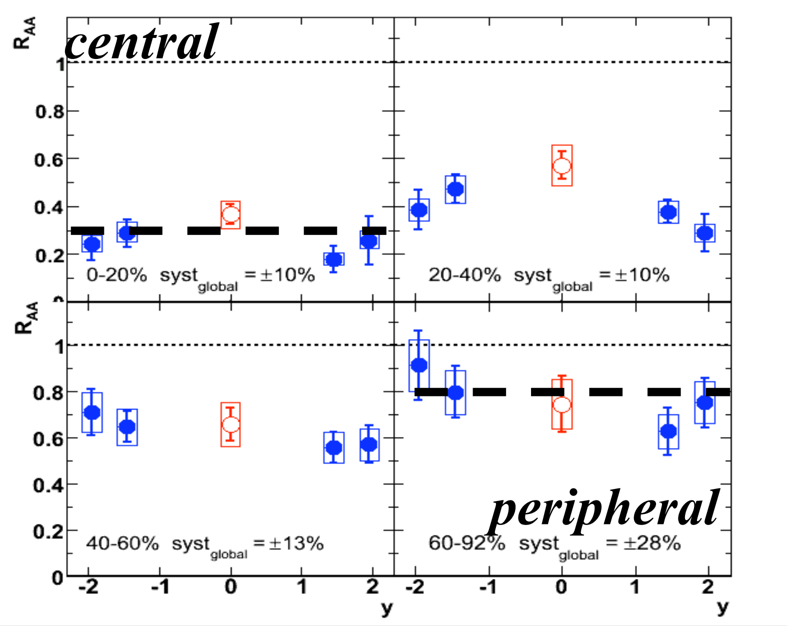
- The idea ~~is~~ was simple



- Nature is not



PHENIX
PRL98 (2007) 232301



*Disentangle final state coalescence & feeding from plasma screening!*

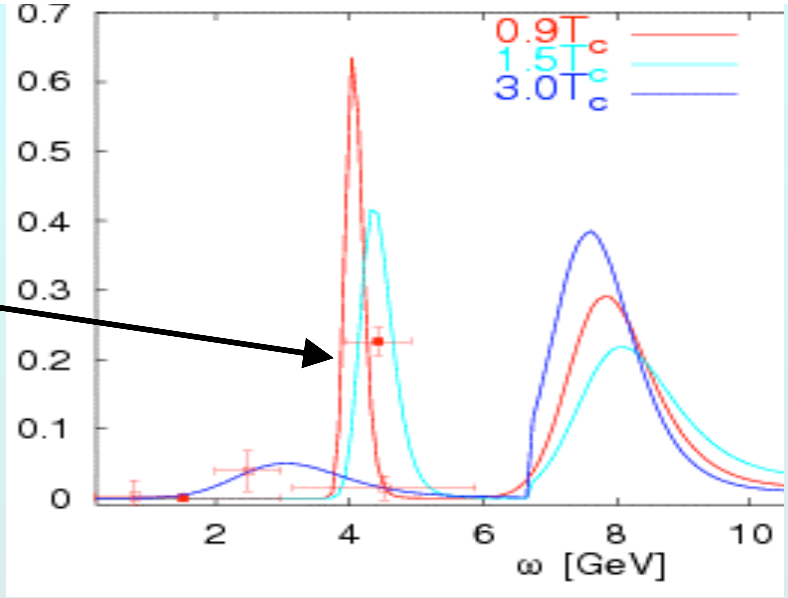
# Lattice: J/ψ fully dissolved?

**Lattice QCD shows $c\bar{c}$ correlations at $T > T_c$, implying that interactions are not zero**

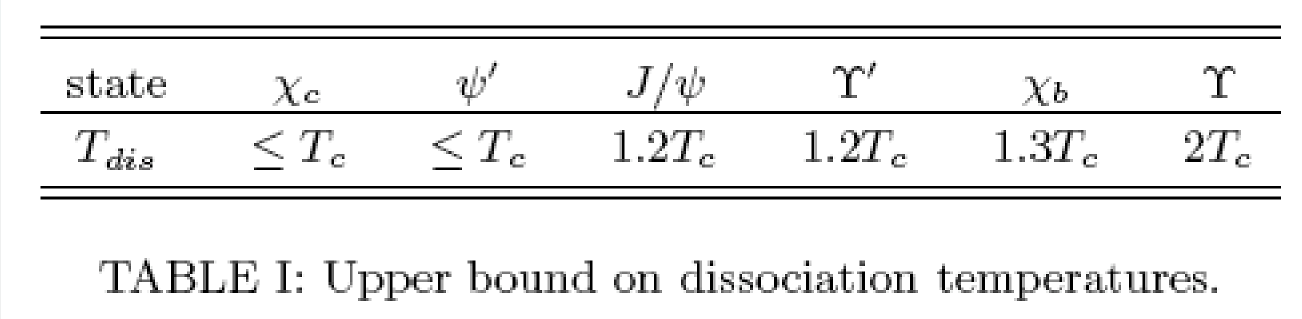
**Expect in strongly coupled plasma?**

**Big debate: J/ψ all gone?**
**resonant states?**
**leftover correlations?**

Asakawa & Hatsuda, PRL92, 012001 (2004)



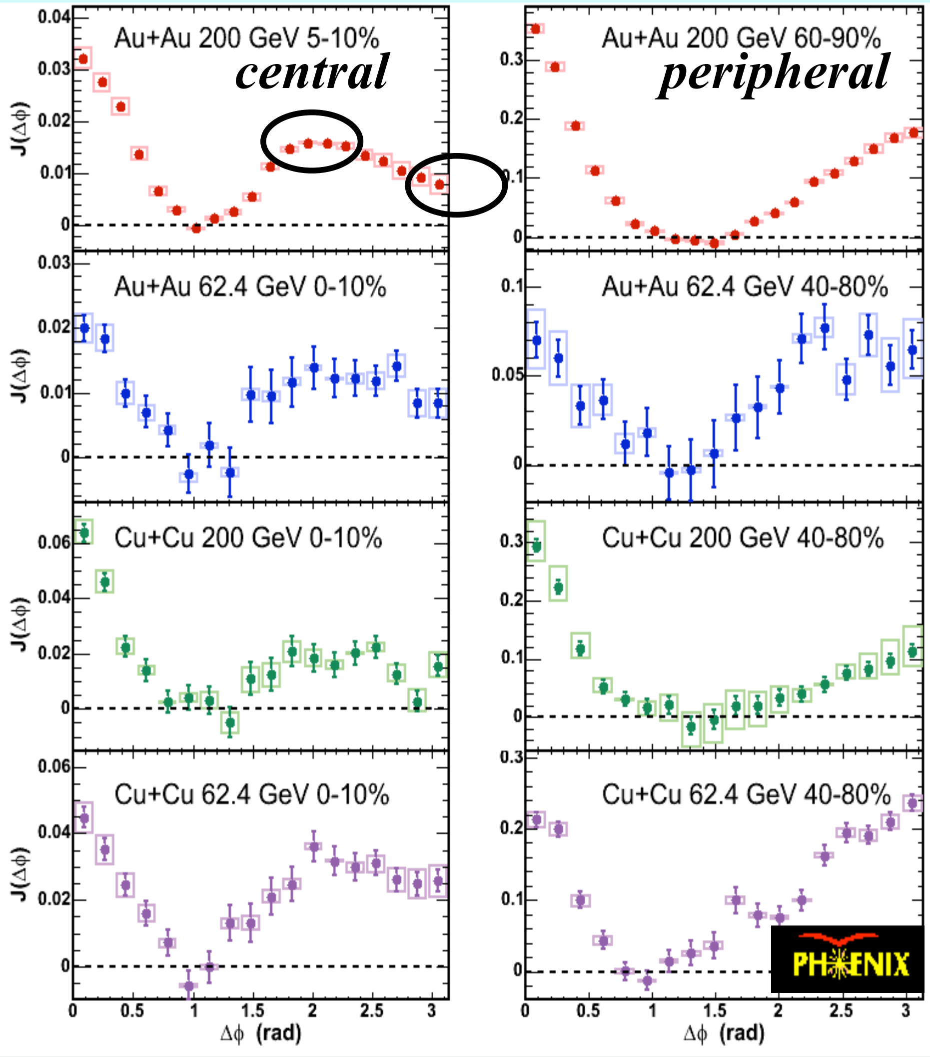
Mocsy & Petrecky, PRL99, 211602 (2007)

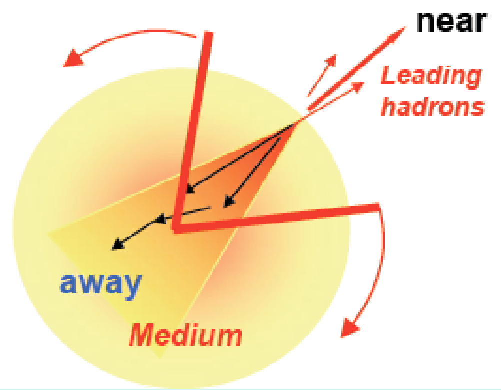


| state | $\chi_c$ | $\psi'$ | $J/\psi$ | $\Upsilon'$ | $\chi_b$ | $\Upsilon$ |
|---|---|---|---|---|---|---|
| $T_{dis}$ | $\leq T_c$ | $\leq T_c$ | $1.2T_c$ | $1.2T_c$ | $1.3T_c$ | $2T_c$ |

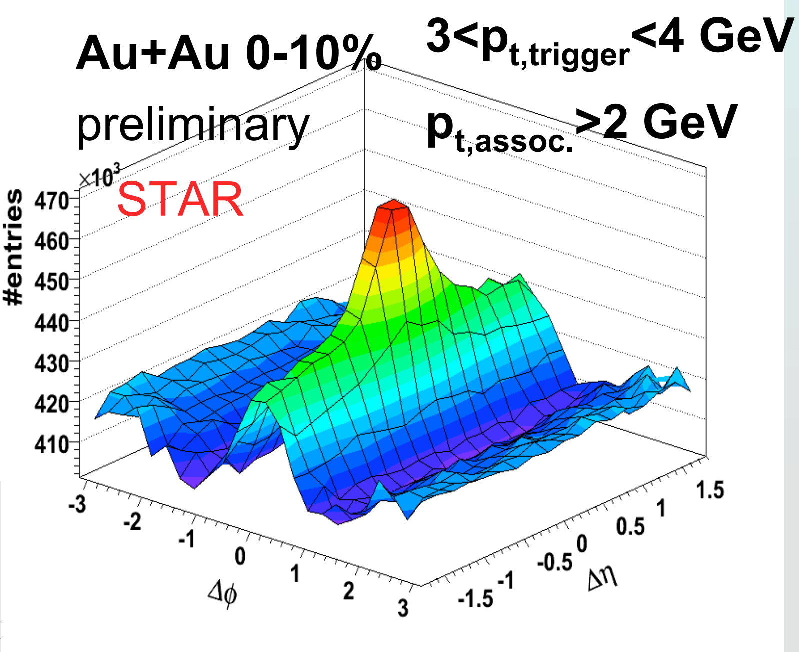
TABLE I: Upper bound on dissociation temperatures.

# Where does lost jet energy go?



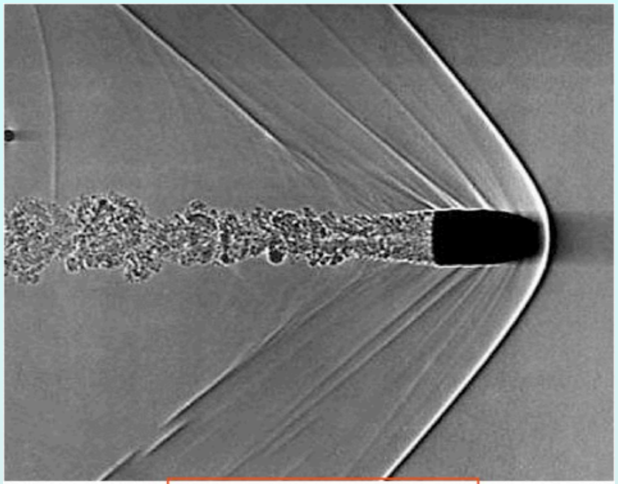


***low $p_T$ looks very modified medium response?***



**$1 < p_{T,a} < 2.5 < p_{T,t} < 4$ GeV/c**

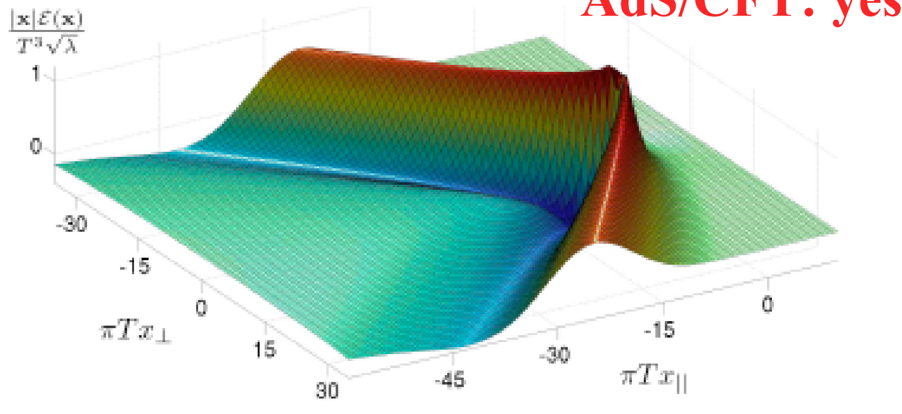
# excites a sound (density) wave?



$$\cos(\theta_M) = c_s$$

*Chesler & Yaffe, 0706.0368(hep-th)*

AdS/CFT: yes it does!

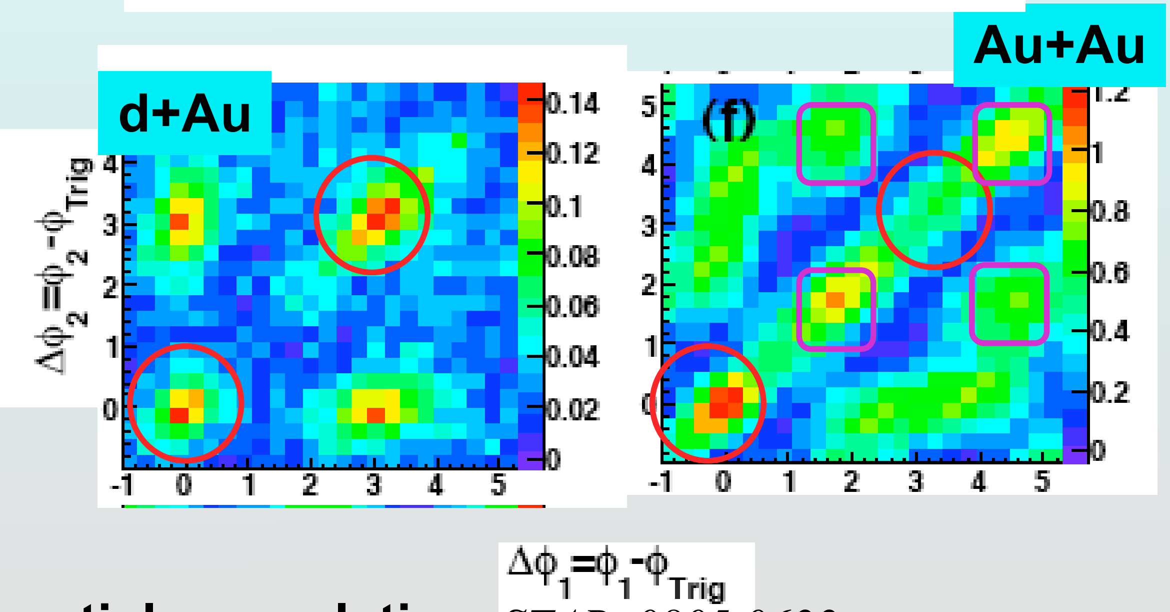


*Peak:* $\phi = \pi - (1.2\text{-}1.38)$

→ **speed of sound**

**$c_s$~0.2-0.4**

($c_s^2$=0.33 in QGP,
~0.19 in hadron gas)



**3 particle correlation** *STAR, 0805.0622*

# Compressional and shear wakes in a two-dimensional dusty plasma crystal

NOSENKO *et al.* PHYSICAL REVIEW E 68, 056409 (2003)

*Are shocks in strongly coupled EM plasma. QGP also shown to support shockwaves*

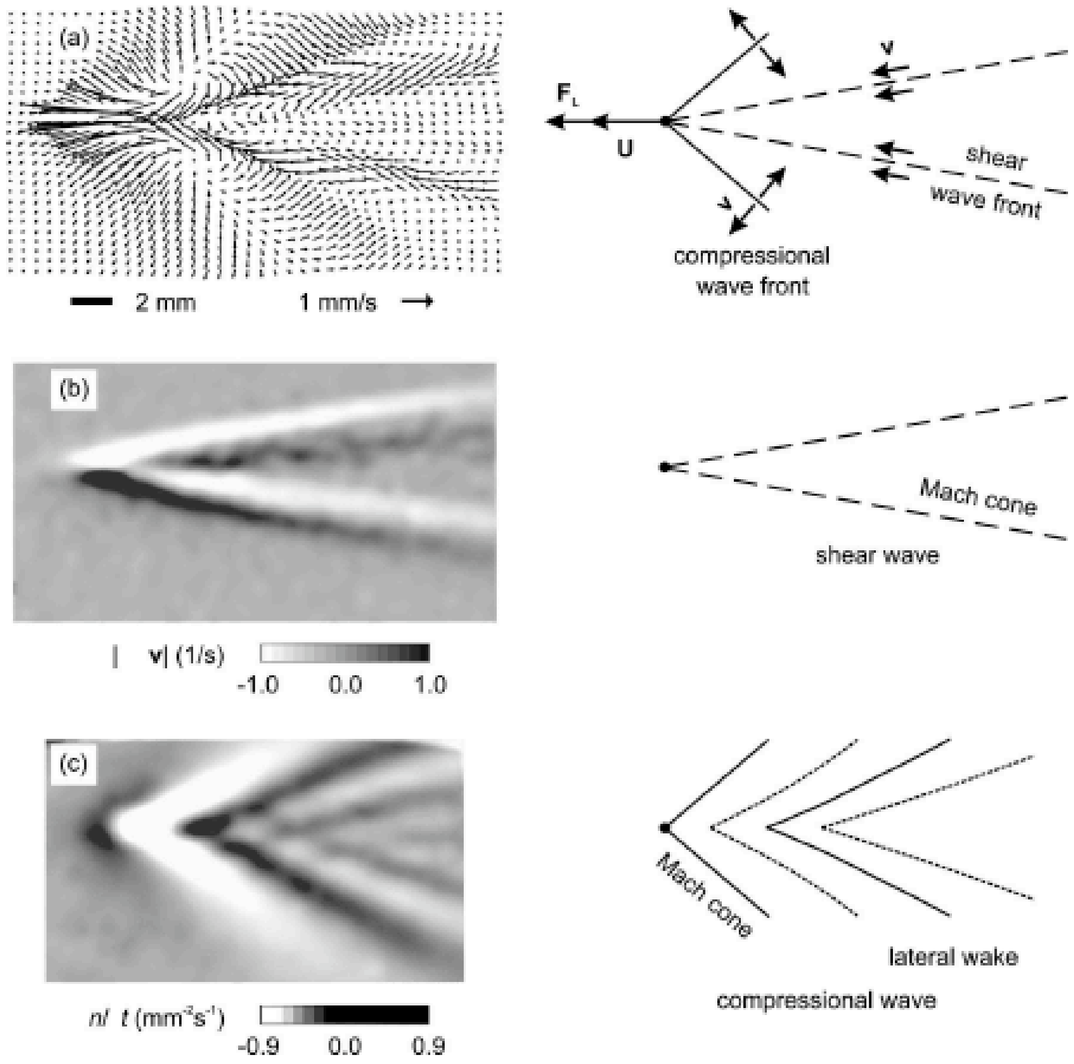
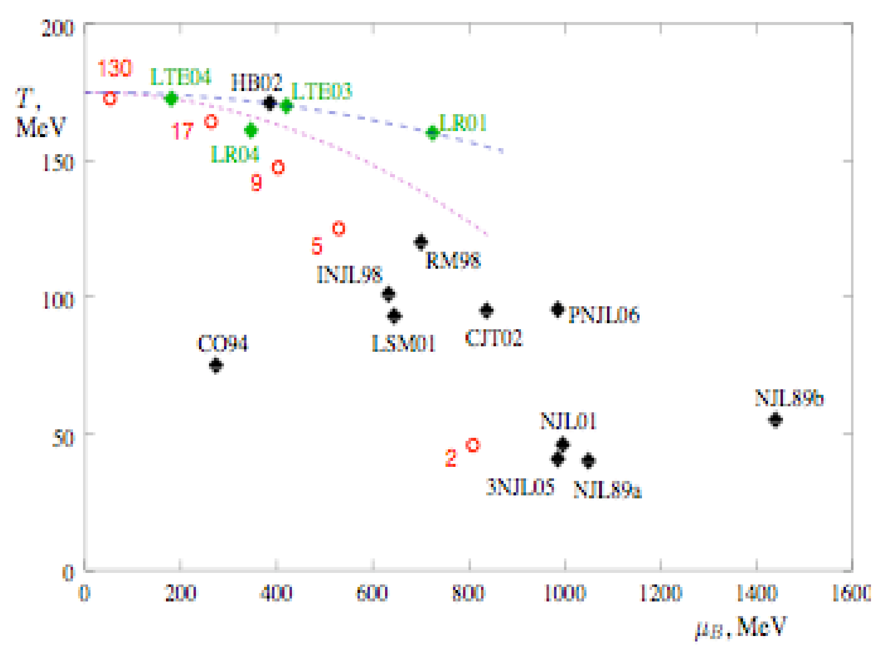


FIG. 4. The compressional- and shear-wave Mach cones, excited simultaneously. The scanning speed $U$ is higher than the sound speed for both the compressional and shear waves. Maps are shown for (a) particle velocity $\mathbf{v}$, (b) vorticity $|\nabla \times \mathbf{v}|$, and (c) $\partial n/\partial t$, where $n$ is the particle areal number density.

*(shear generally a phenomenon in crystals but not liquids)*

# Critical endpoint → EOS



- *Where is it?*
  - Start at SPS & RHIC
  - Precision & rarer probes at FAIR
- **Bulk variables**
  - Spectra, $<p_T>$, yield ratios
    - many ~known from SPS
  - Fluctuations
    - $2^{nd}$ order phase transition - long range correlations
    - lots of work to do here (experiment AND theory)
  - Bulk collective flow
    - $v_2$ scaling behavior near CEP? Need $\pi$,K,p $v_2$
  - HBT re-emerges as good probe of the space-time evolution as $\sqrt{s}$ decreases

# Rare CEP probes

- **Multi-particle correlations**

  In addition to fluctuations signatures*

- **Di-leptons and photons**

  Use √s dependence to help disentangle hadron gas and partonic radiation*

  Not only $T_{init}$, but also relative lifetimes change

  *Rate of partonic contribution increases with √s*

  *Hadron gas always starts at Tc, lifetime decreases with √s*

- **Charm approaching threshold**

  How much does this add without confusion?*

*** Need help from theory!**

# In closing:

- Nuclear physics with high energy heavy ion collisions connects to other branches of physics!
- **Particle physics - obviously**
- **Condensed matter**

  Strongly correlated systems

  Condensates, cold atoms (Hatsuda's talk)
- **Plasma physics**

  Theoretical ideas/tools in common

    also molecular dynamics

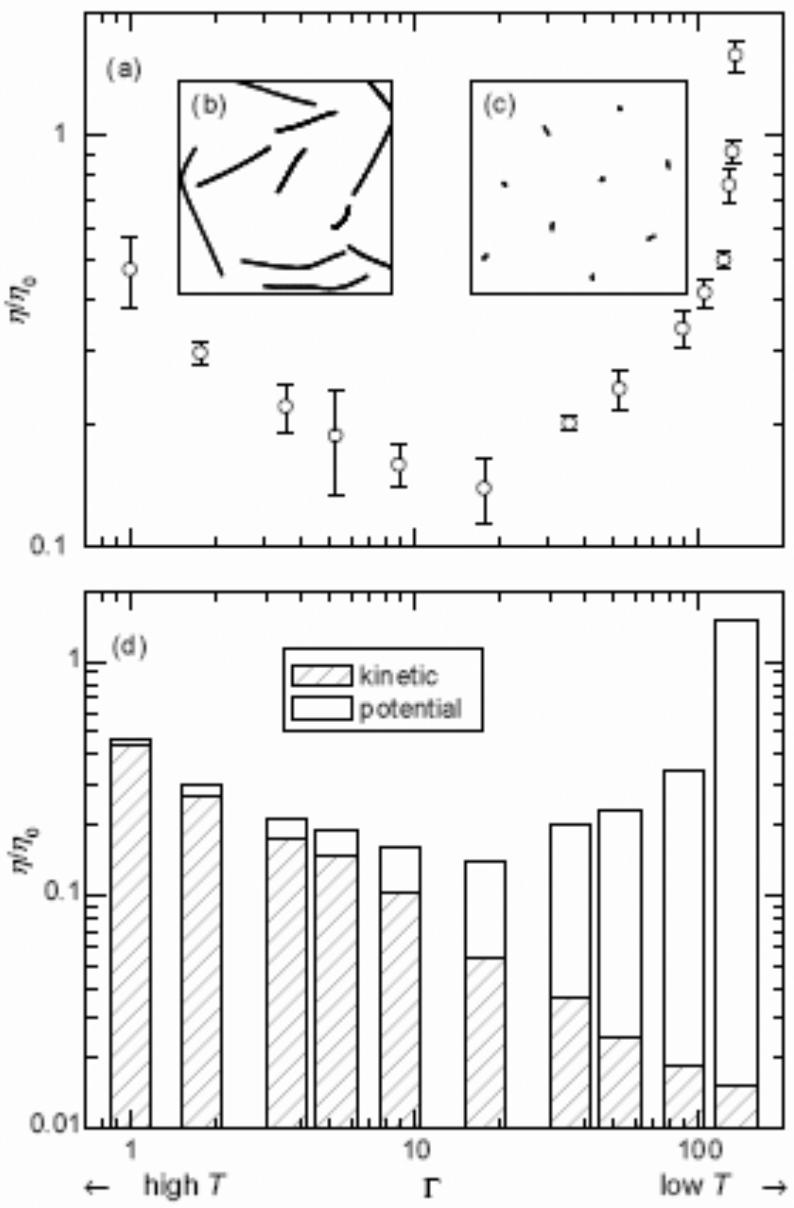
  Experimental approaches to learn matter properties
- **String theory**

  Tool via AdS/CFT for ∞ strongly coupled limit

  *This connection was a big surprise!*


i’m in ur fizx lab
testn ur string therry

# use this technique to measure viscosity



melt crystal with laser light
induce a shear flow (laminar)
image the dust to get velocity
study:
- spatial profiles $v_x(y)$
- moments, fluctuations → T(x,y)
- curvature of velocity profile
  - → drag forces
- viscous transport of drag in
  - ⊥ direction from laser

compare to viscous hydro.
- extract $\eta/\rho$
  - shear viscosity/mass density

PE vs. KE competition governs
- coupling & phase of matter

*Csernai,Kapusta,McLerran nucl-th/0604032*

# important differences

- Medium created by colliding beams doesn't last long

  lifetime ~ 10 fm/c ~ 3 x $10^{-23}$ sec (3 x $10^{-5}$ attosecond)

- Relevant energy scale given by T ~ 200 MeV

  wavelength of a photon with energy of 200 MeV:

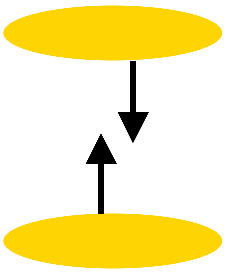
  ~ 6 fm = 6 x $10^{-6}$ nm

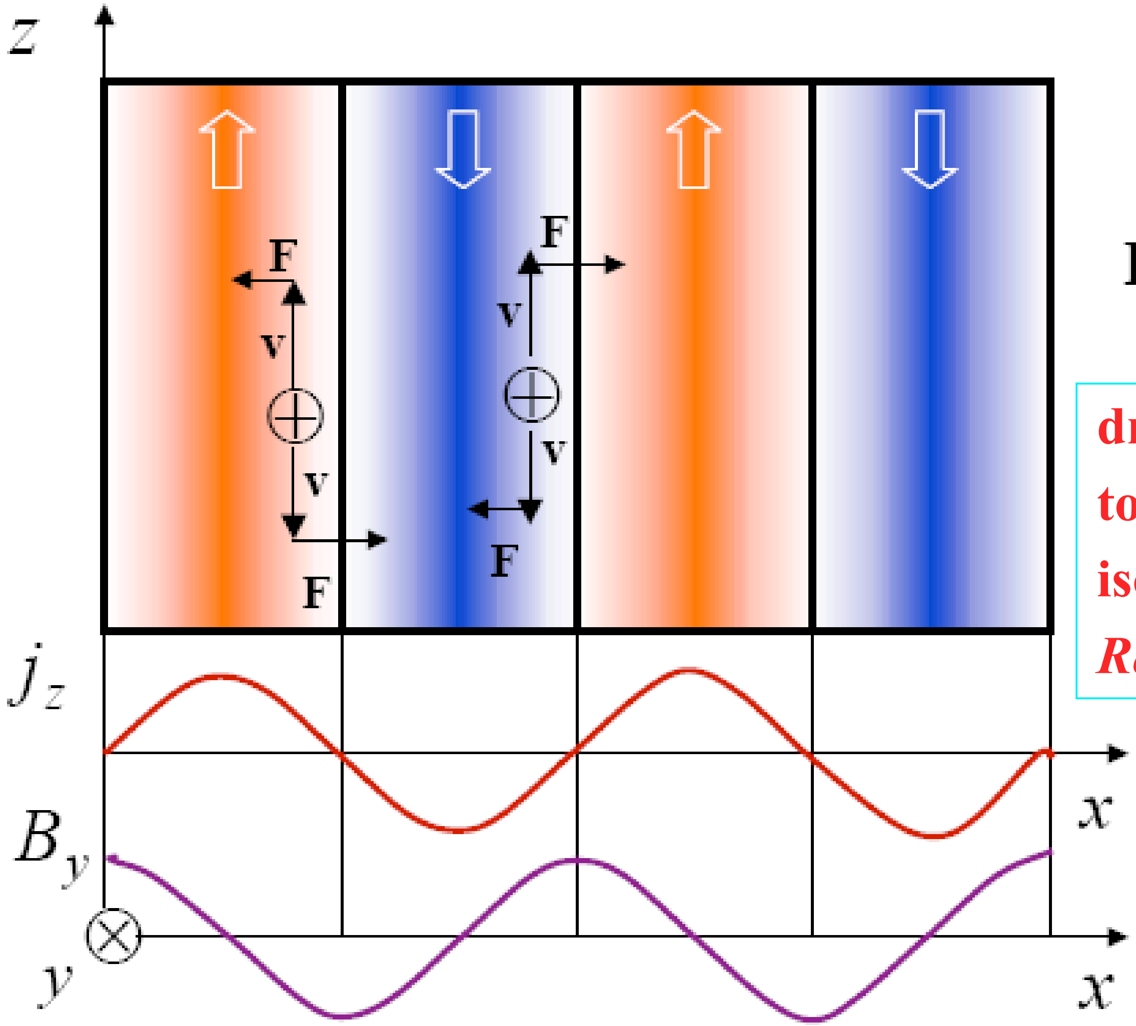
  1/1000th that of gamma rays!

*Not going to study this plasma with any laser known to man!*

*To study a plasma of gluons, want a probe sensitive to color not charge* *from S. Mrowczynski, QM05*

# Mechanism of filamentation





Lorentz force

$$\mathbf{F} = q\,\mathbf{v} \times \mathbf{B}$$

**drives system toward fast isotropization?**

***Rebhan***

Ampere's law

$$\nabla \times \mathbf{B} = \mathbf{j}$$

# QGP viscosity is lower than that of liquid He!

$\eta/s$ ~4 times smaller than of helium (but at $T \sim 10^{12}$ K)

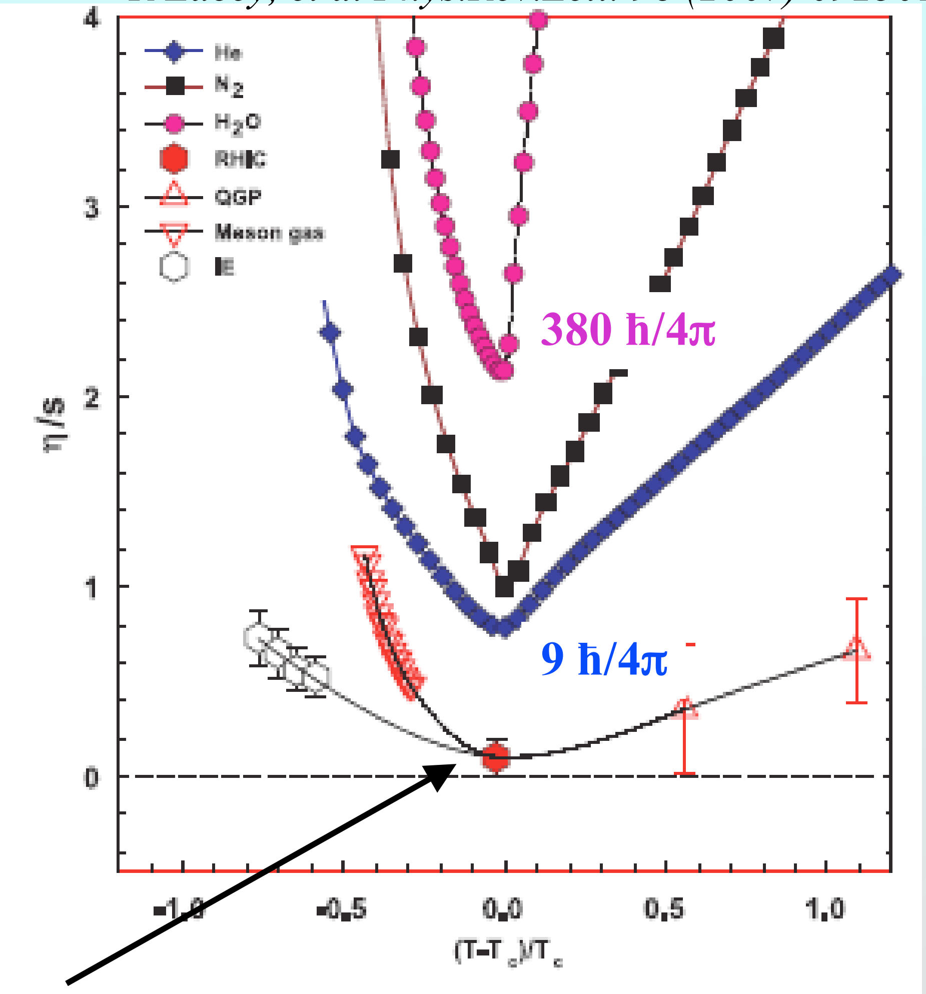
close to the conjectured limit $\eta/s = \hbar/4\pi$

P. Kovtun, D.T. Son, A.O. Starinets, Phys.Rev.Lett.94:111601, 2005

motivated by AdS/CFT (Anti-deSitter/Conformal Field Theory) correspondence

J. Maldacena: Adv. Theor. Math. Phys. 2, 231, 1998

*R Lacey, et al Phys.Rev.Lett. 98 (2007) 092301*



"near perfect" fluid at RHIC

# expect low viscosity in strongly coupled plasma

**Gelman, Shuryak, Zahed, nucl-th/0601029**

◊ **Shear viscosity** η **in (classical) quark gluon plasma**

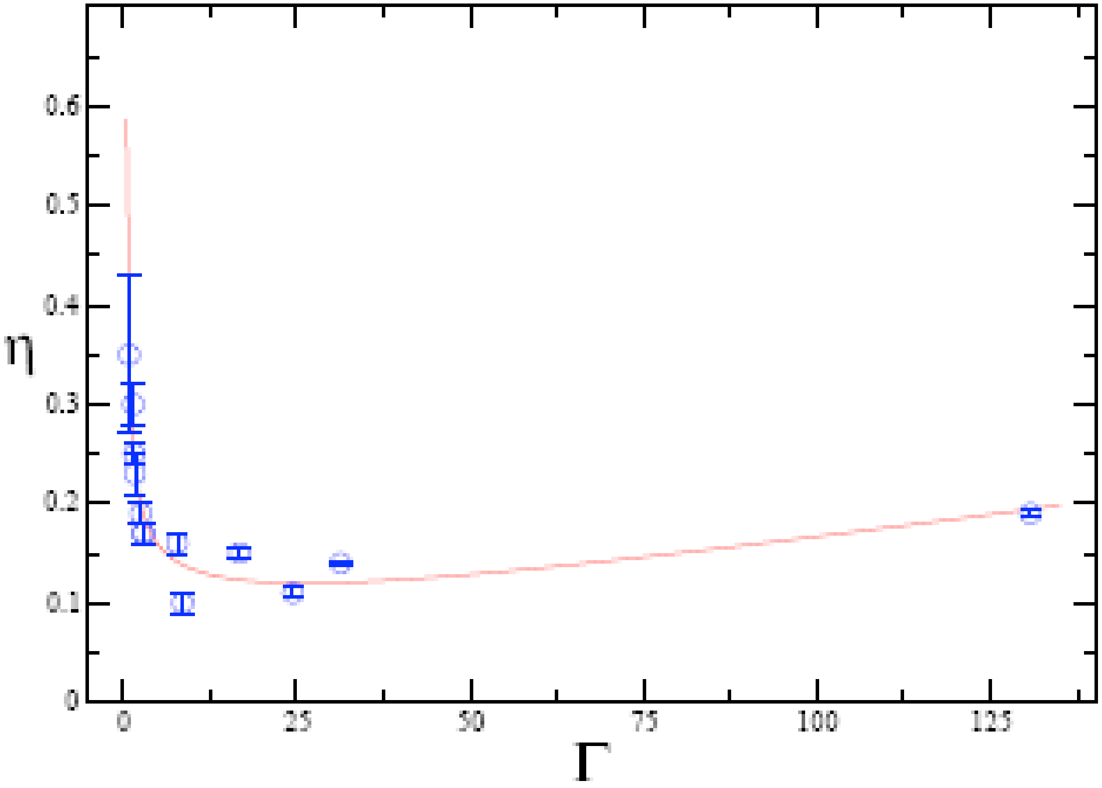


FIG. 5. Shear viscosity of one species cQGP as a function of the dimensionless coupling Γ. Blue points are the MD simulations; the red curve is the fit in eq. (32).