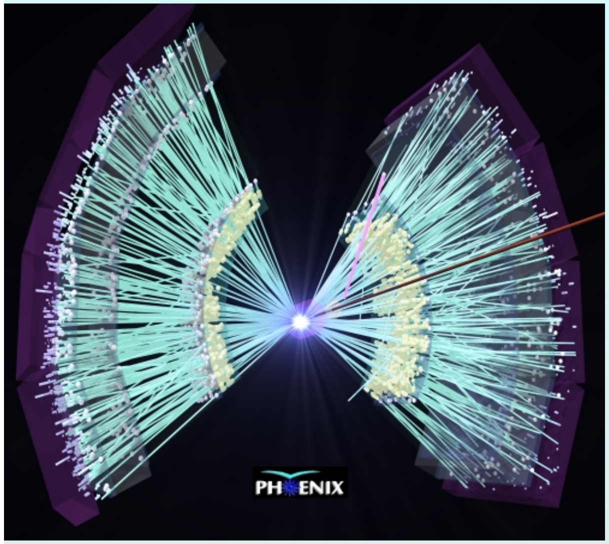
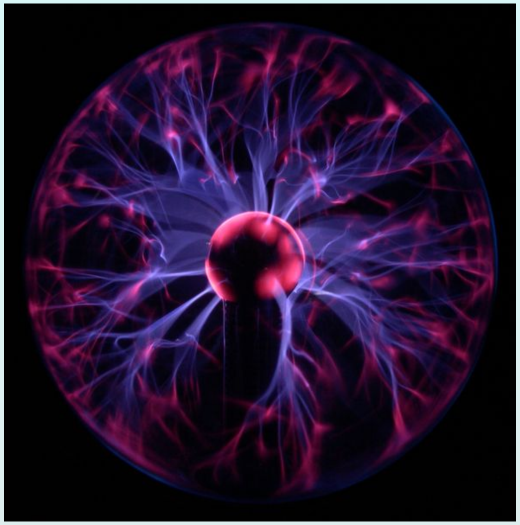
QCD at trillions of degrees



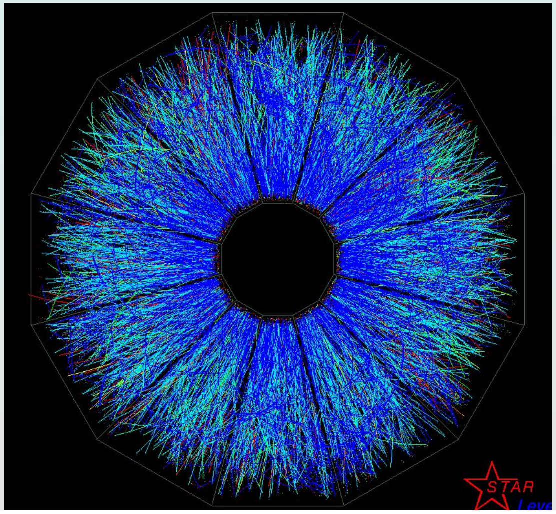
Barbara Jacak

Stony Brook



LPSC Colloquium

Sept. 24, 2013



Outline

- What's QCD matter & why does it matter?

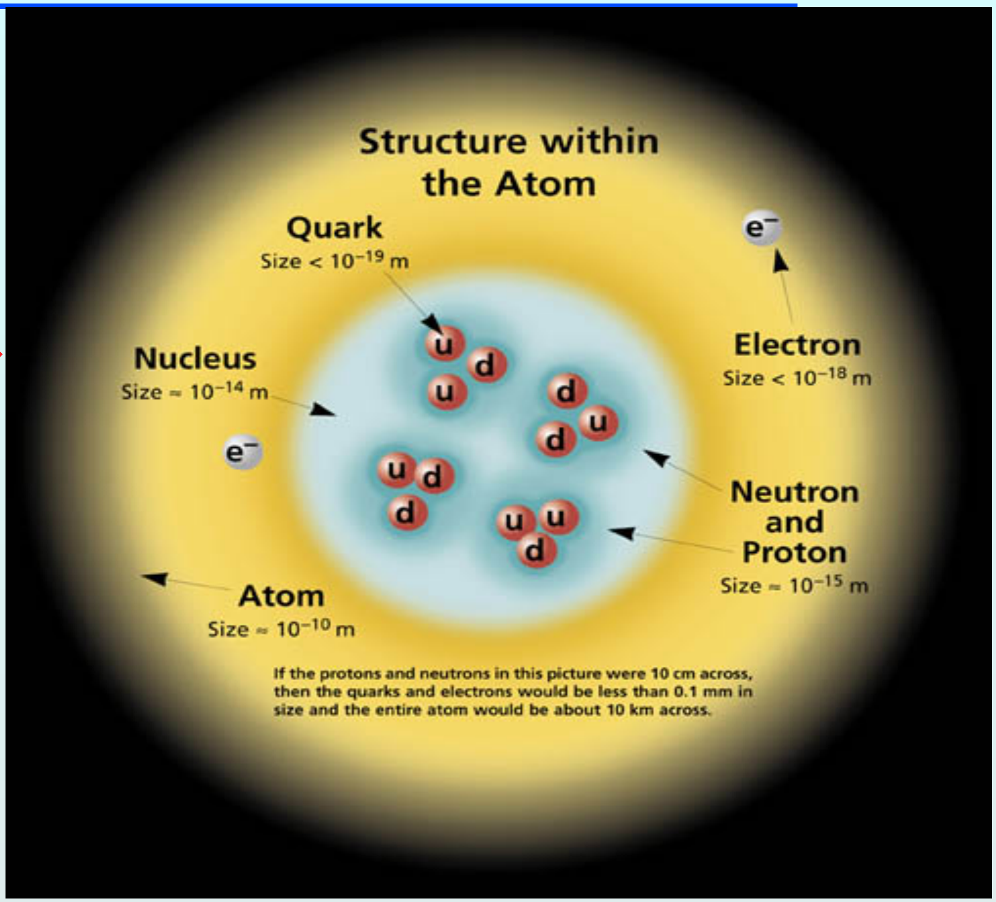
- How we know
  It's hot enough for quark gluon plasma
  That it is a liquid
  It's strongly coupled

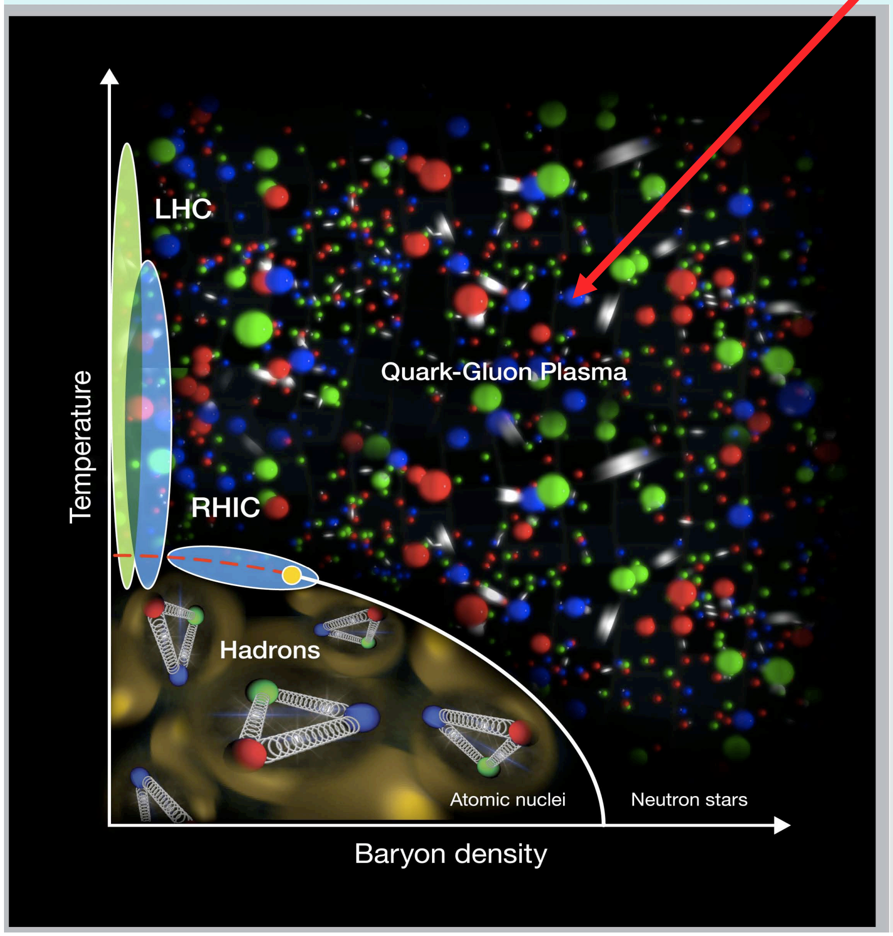
- Some things we don't know
  and how we'll answer them

Create the hottest matter on earth

Heat to T > 10^{12} K

last seen in nature a few μ second after the Big Bang!



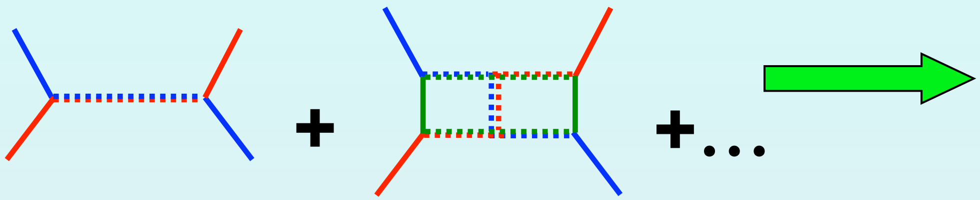


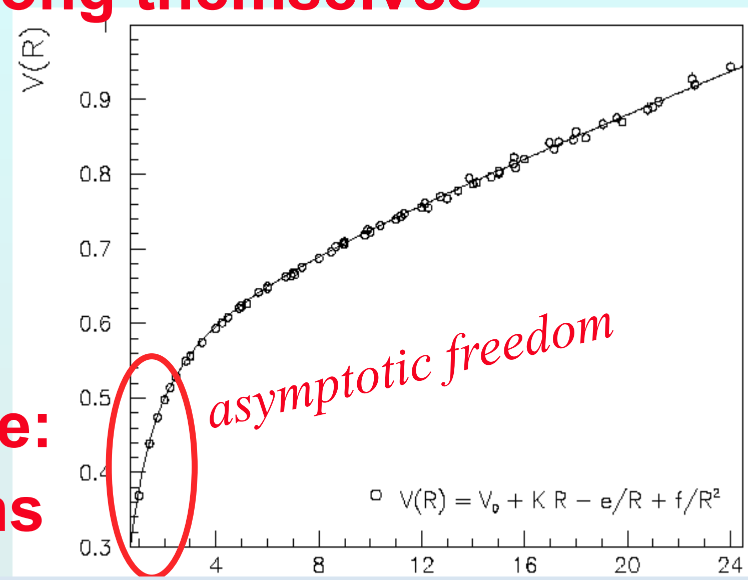
How does quark gluon plasma work?

QCD Matter

- Strong interaction = gluon exchange
- Gluons carry color → interact among themselves

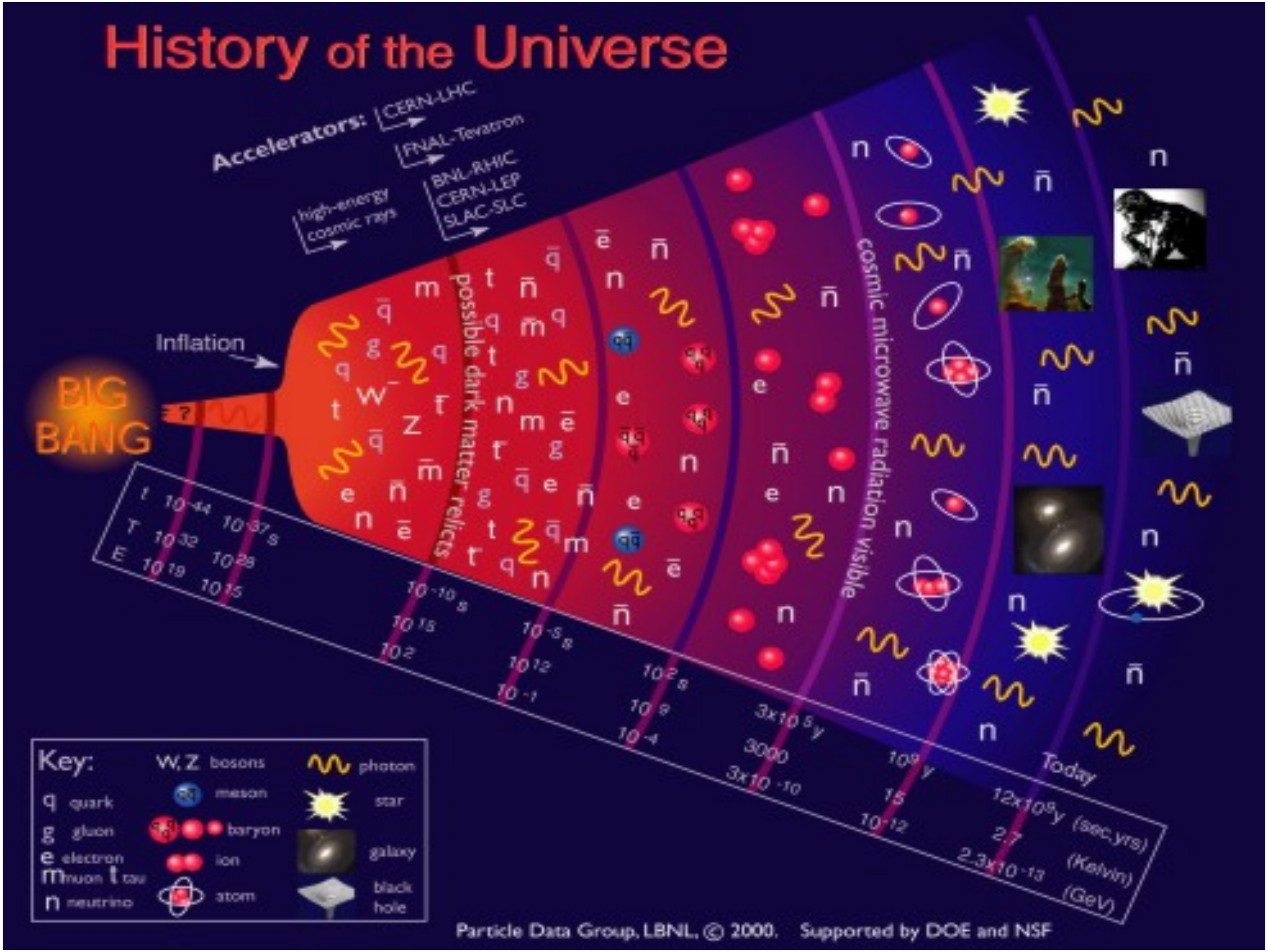
  theory is non-abelian





- Curious property at large distance:

  confinement of quarks in hadrons



History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10^-44 10^-37 s
T 10^32 10^28
E 10^19 10^15
10^-10 s
10^15
10^2
10^-5 s
10^12
10^-1
10^2 s
10^9
10^-4
3x10^5 y
3000
3x10^-10
10^9 y
15
10^-12
Today
12x10^9 y (sec,yrs)
2.7 (Kelvin)
2.3x10^-13 (GeV)
Key:
q quark
g gluon
e electron
m muon
t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

The heaters

Large Hadron Collider **Relativistic Heavy Ion Collider**

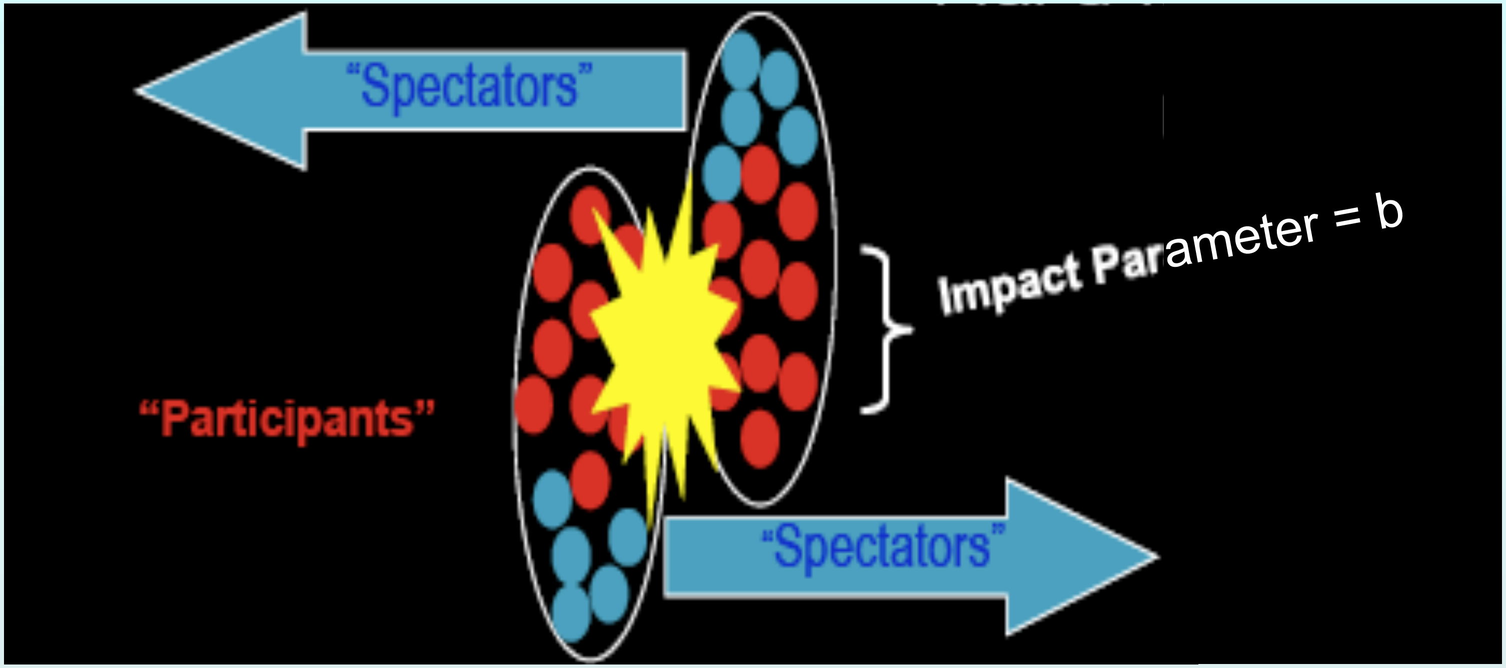
CERN in Geneve **Brookhaven in New York**

Pb+Pb @ 2.76 TeV/A **Au+Au @ 200 MeV/A**

Collide heavy ions for max temperature & volume

p+p and p/d+A for comparison

a bit of geometry, terminology

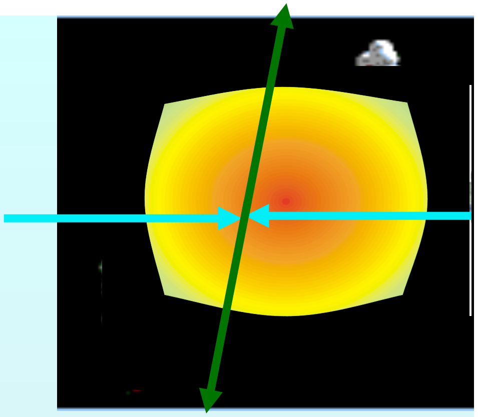


Peripheral collisions:
few participant nucleons
(small N_{part})
few NN collisions (N_{coll})

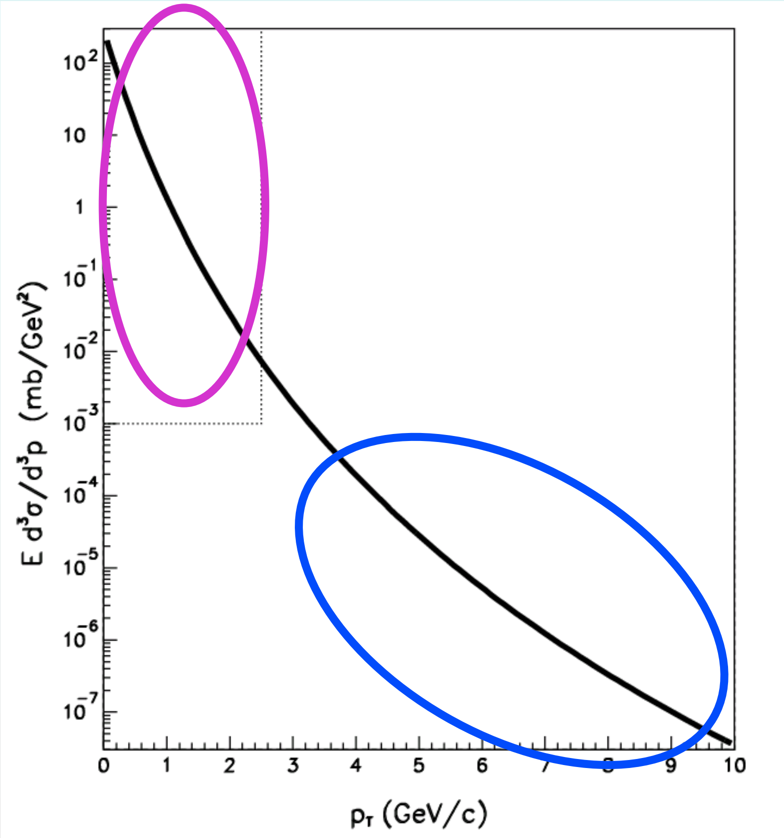
Central collisions:
large N_{part} & N_{coll}
Ncoll near 1000
in ~ head-on Au+Au

"centrality" = fraction of total A+A cross section
(0-5% = very central)

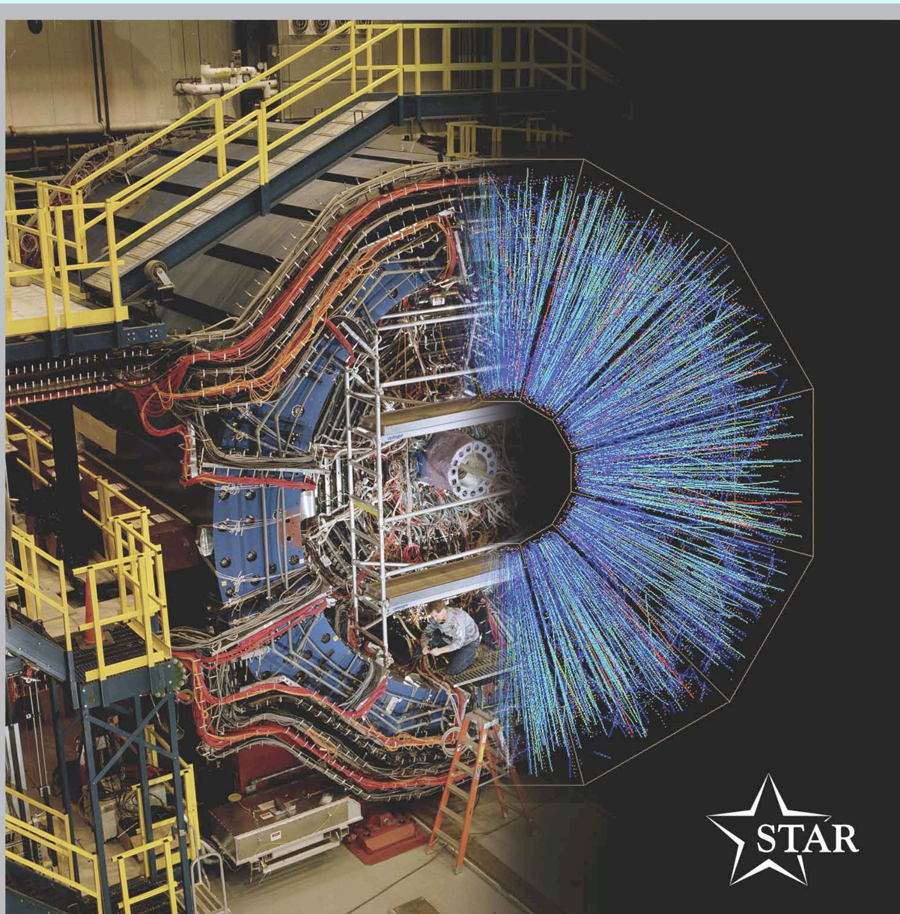
study plasma with radiated & "probe" particles

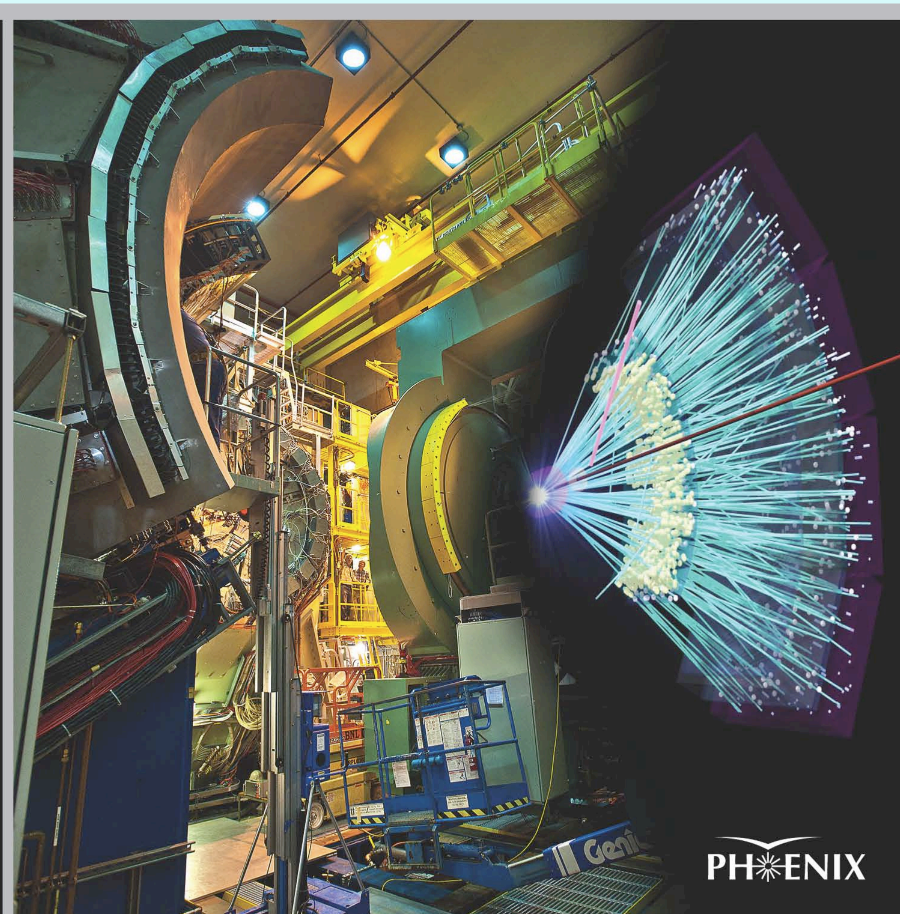


- as a function of transverse momentum
  90° is where the action is (max T, ρ)
  p_L between the two beams: midrapidity
- p_T < 1.5 GeV/c
  "thermal" particles
  radiated from bulk medium
  "internal" plasma probes
- p_T > 3 GeV/c
  large E_{tot} (high p_T or M)
  set scale other than T(plasma)
  autogenerated "external" probe
  describe by perturbative QCD
- control probe: photons
  EM, not strong interaction
  produced in Au+Au by QCD
  Compton scattering



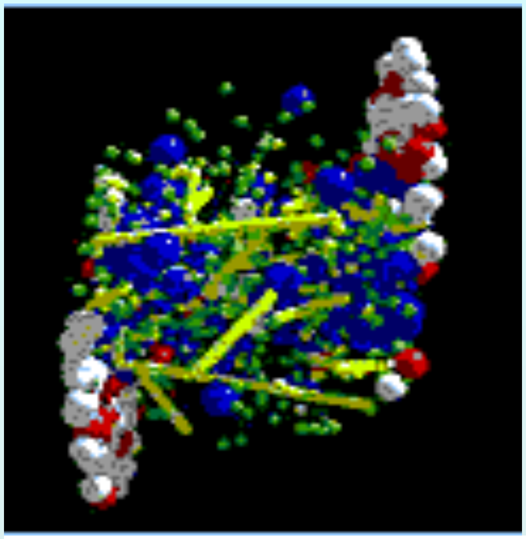
Experiments at RHIC





DISCOVERIES

Hottest Science Experiment on the Planet*

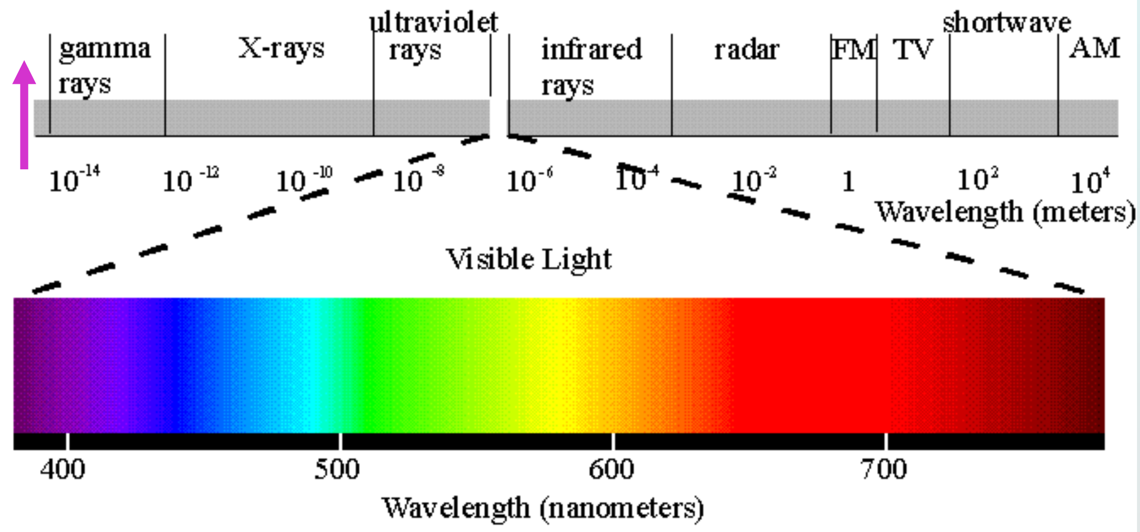


plasma lives for 3×10^{-23} s

droplet is 10^{-12} cm across

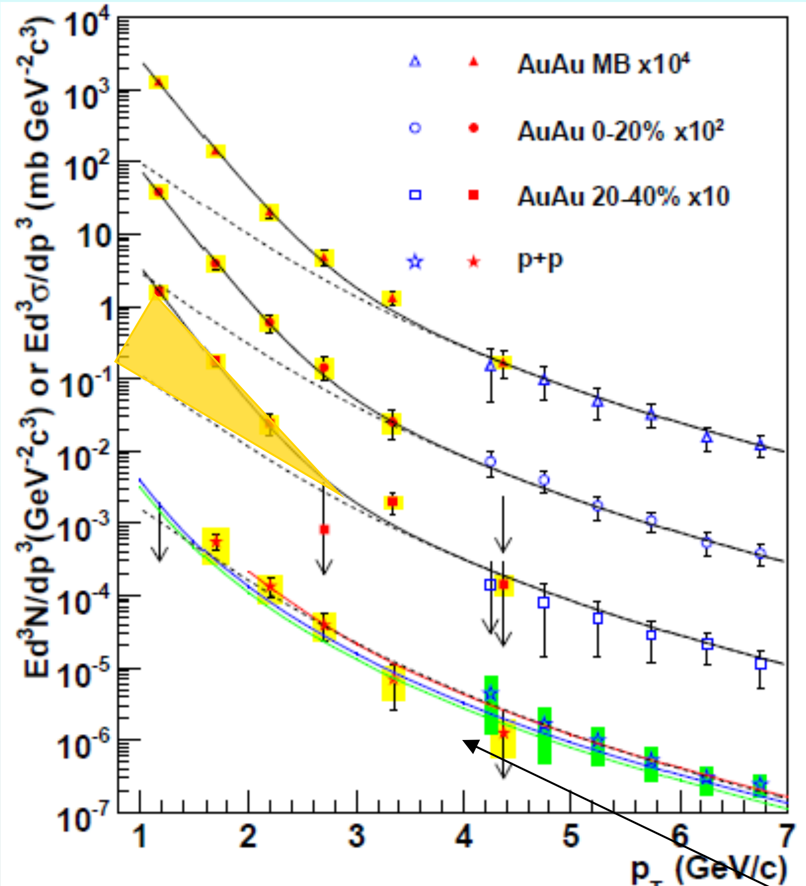
can't use a thermometer!

So we look at radiation

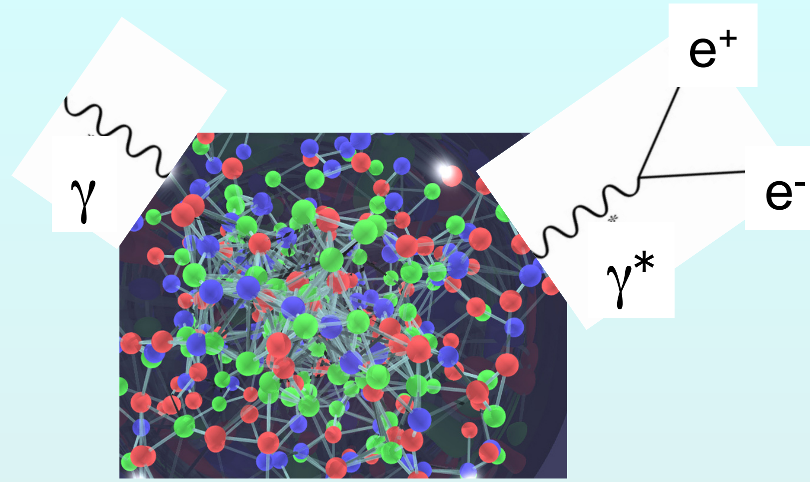


*** According to Discover Magazine**

Thermal radiation



PRL 104, 132301 (2010)

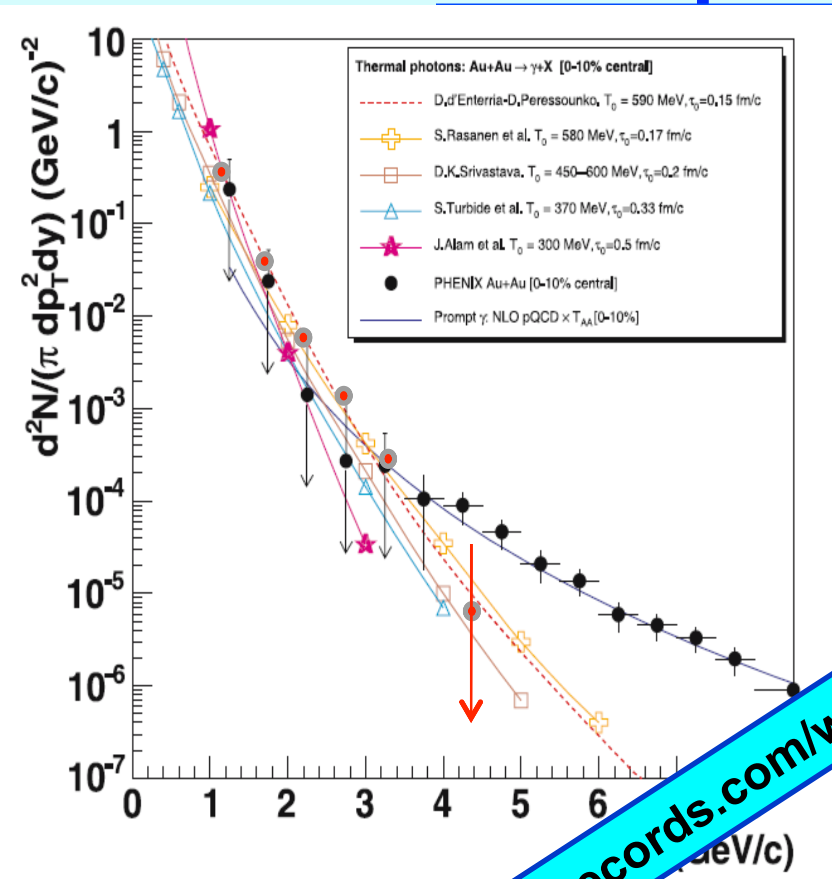


Low mass, high p_T e^+e^- → nearly real photons

Large enhancement above p+p in the thermal region

pQCD γ spectrum (Compton scattering @ NLO) agrees with p+p data

direct photons: $T_{init} > T_c$!

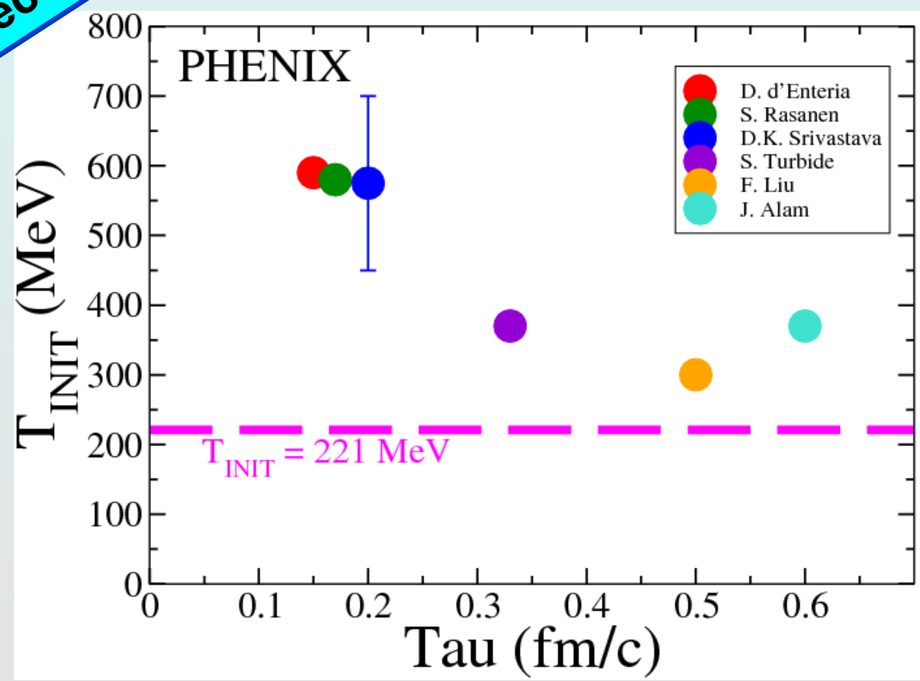


- **Exponential fit in p_T:**

T_{avg} = 221 ±23 ±18 MeV

- **Multiple hydrodynamics models reproduce data**

T_{init} ~ 300 MeV



NB: T_c ~ 150 MeV

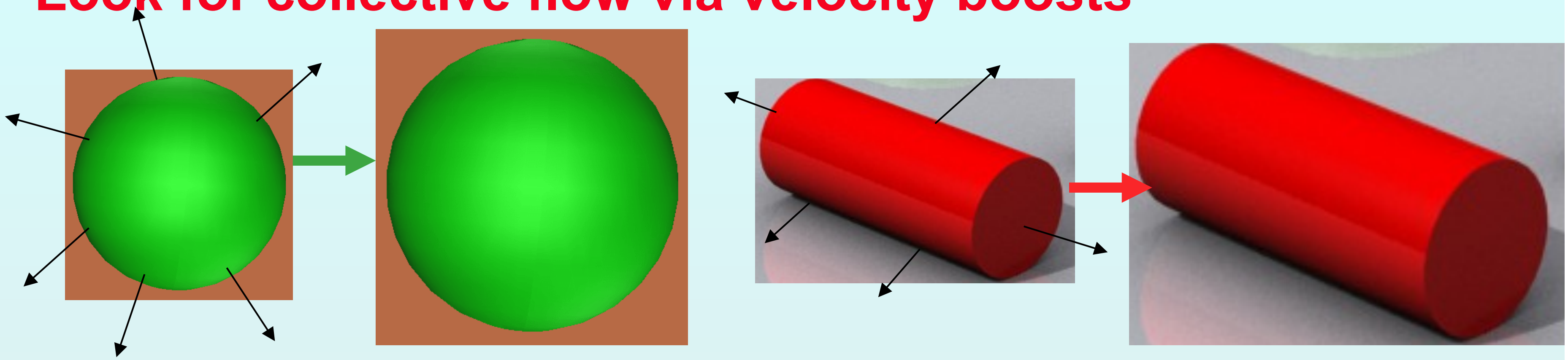
@ LHC T_{avg} = 304±51 MeV

hydrodynamic T_{init} ~ 30%

higher than at RHIC

Does hot QCD matter exhibit collectivity?

Look for collective flow via velocity boosts



Is the expansion hydrodynamical?

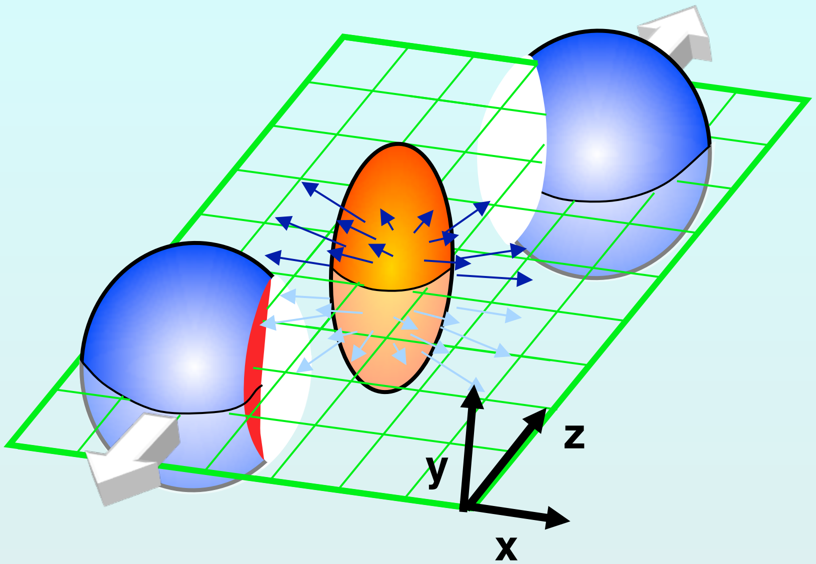
Model expansion of the system with fluid dynamics

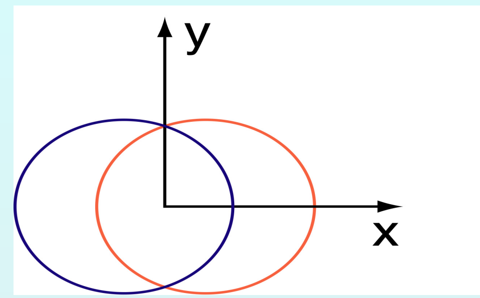
$$\partial_t \begin{pmatrix} \rho \\ \rho u \\ \rho v \\ e \end{pmatrix} + \partial_x \begin{pmatrix} \rho u \\ \rho u^2 + p \\ \rho u v \\ u(e+p) \end{pmatrix} + \partial_y \begin{pmatrix} \rho v \\ \rho u v \\ \rho v^2 + p \\ v(e+p) \end{pmatrix} -$$

$$\partial_x \begin{pmatrix} 0 \\ \tau_{11} \\ \tau_{12} \\ \tau_{11} u + \tau_{12} v + k \partial_x \Theta \end{pmatrix} - \partial_x \begin{pmatrix} 0 \\ \tau_{21} \\ \tau_{22} \\ \tau_{21} u + \tau_{22} v + k \partial_y \Theta \end{pmatrix} = 0\,,$$

where u and v are the components of the velocity, ρ the density, p the pressure, e total energy density, τ_{ij} the components of the viscous part of the stress tensor, Θ the absolute temperature and k is the heat conductivity.

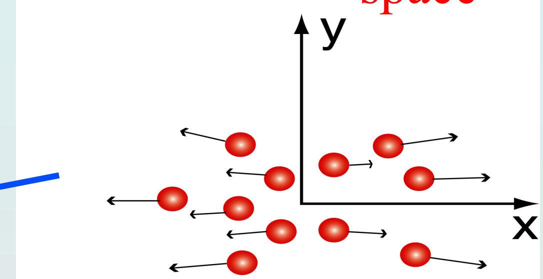
Watch QGP blow up → collective flow (v_2)

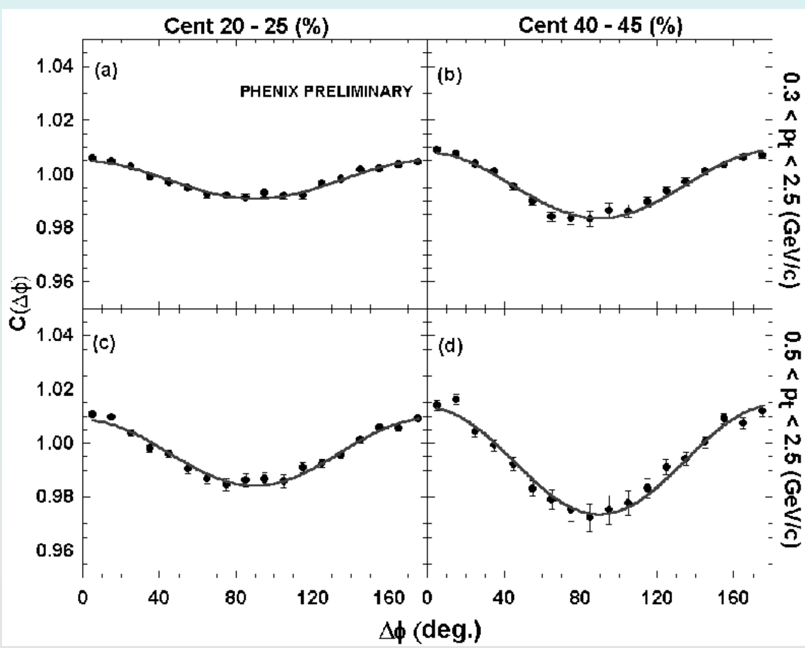




Almond shape overlap region in coordinate space

momentum space

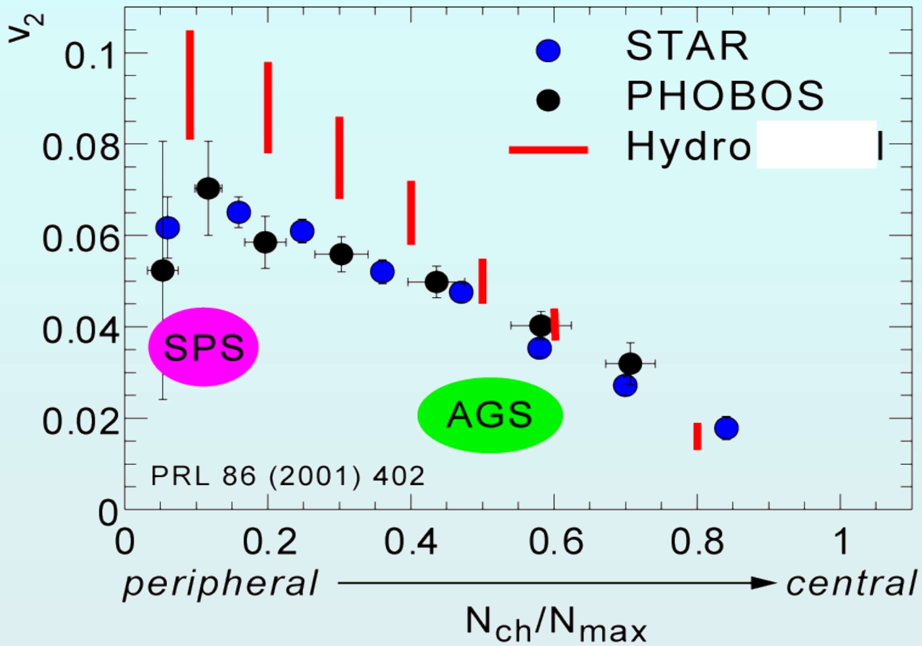




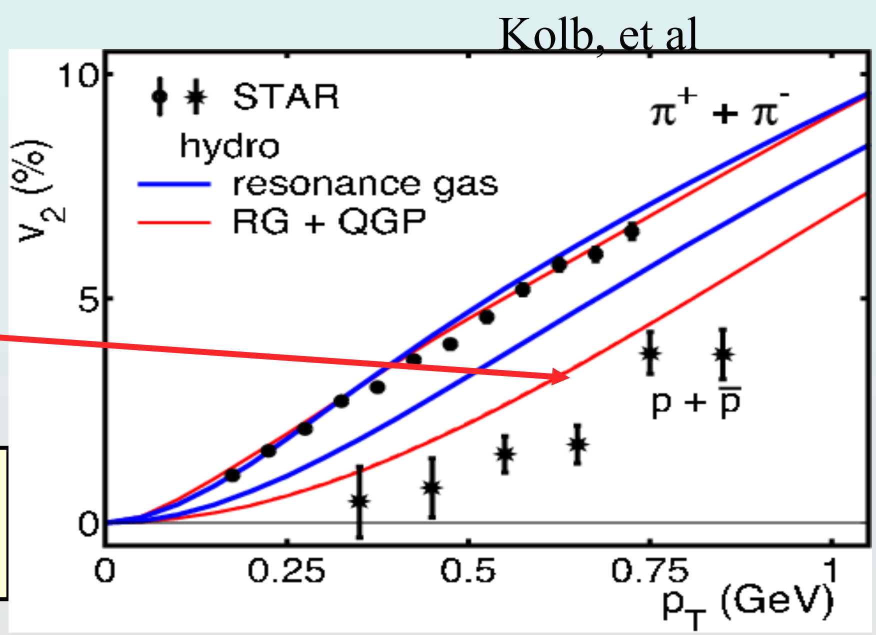
$$dN/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi) + \dots$$

"elliptic flow"

QCD matter flows like a liquid



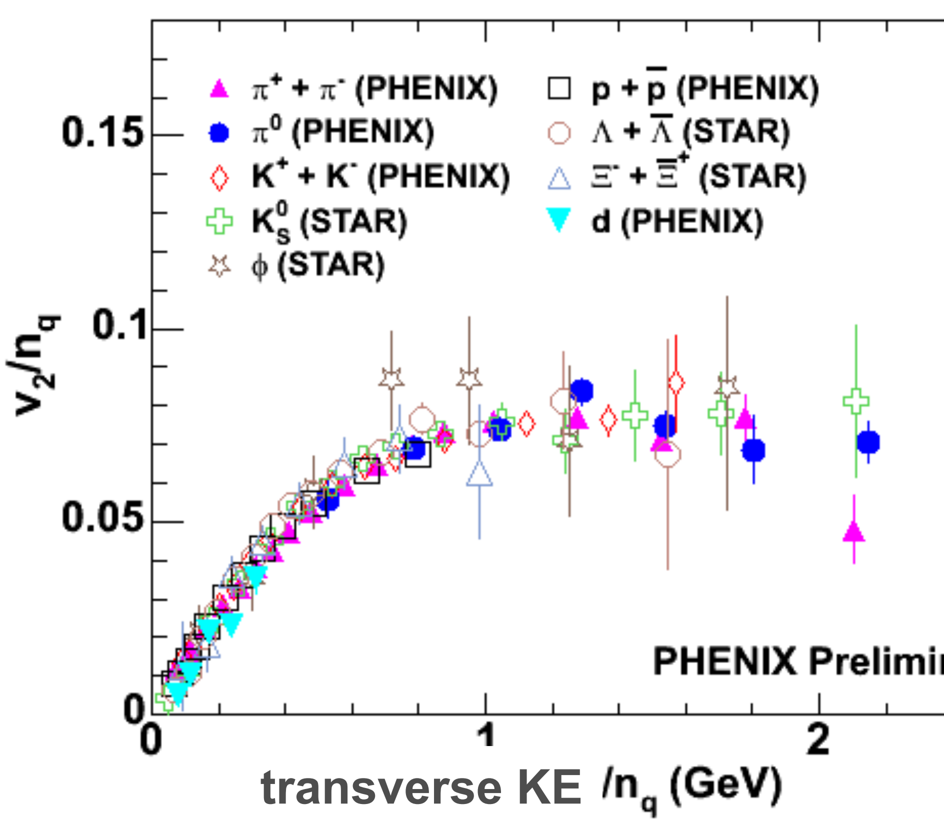
- **huge pressure buildup**
- **large anisotropy → it all happens fast**
- **efficient equilibration mechanism??**

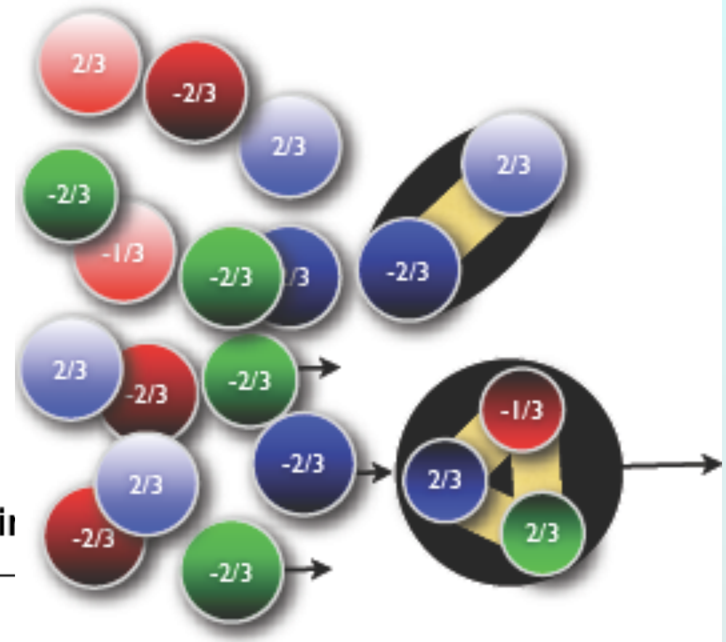


Hydrodynamics reproduces elliptic flow of q-$\bar{q}$ and 3q states
Mass dependence requires
QGP - NOT gas of hadrons

only works with viscosity/entropy ~ 0
"perfect" liquid (D. Teaney, PRC68, 2003)

Elliptic flow scales with number of quarks





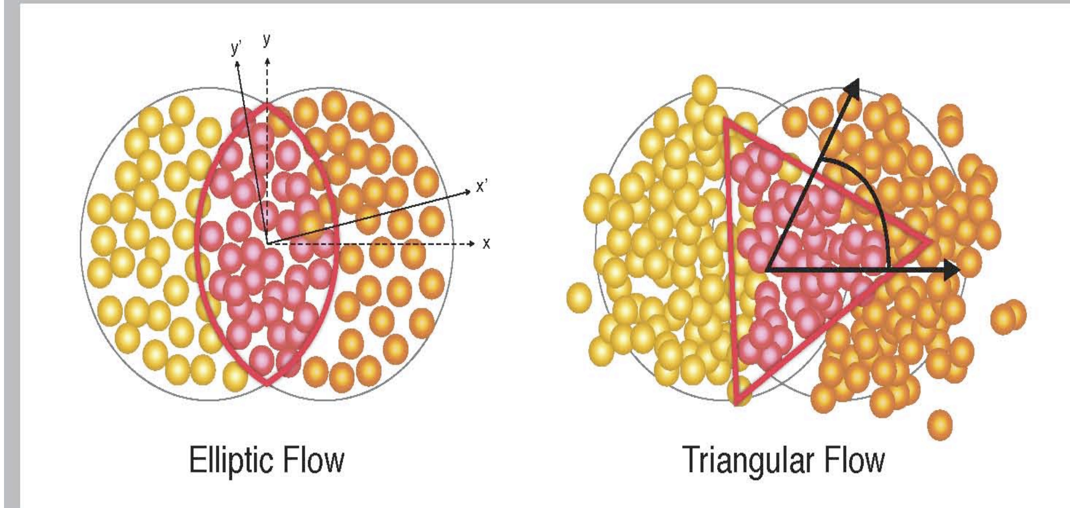
All particles flow as if frozen out from a flowing soup of constituent quarks

implication: valence quarks, not hadrons

pressure builds early, dressed quarks are

similar behavior seen at LHC

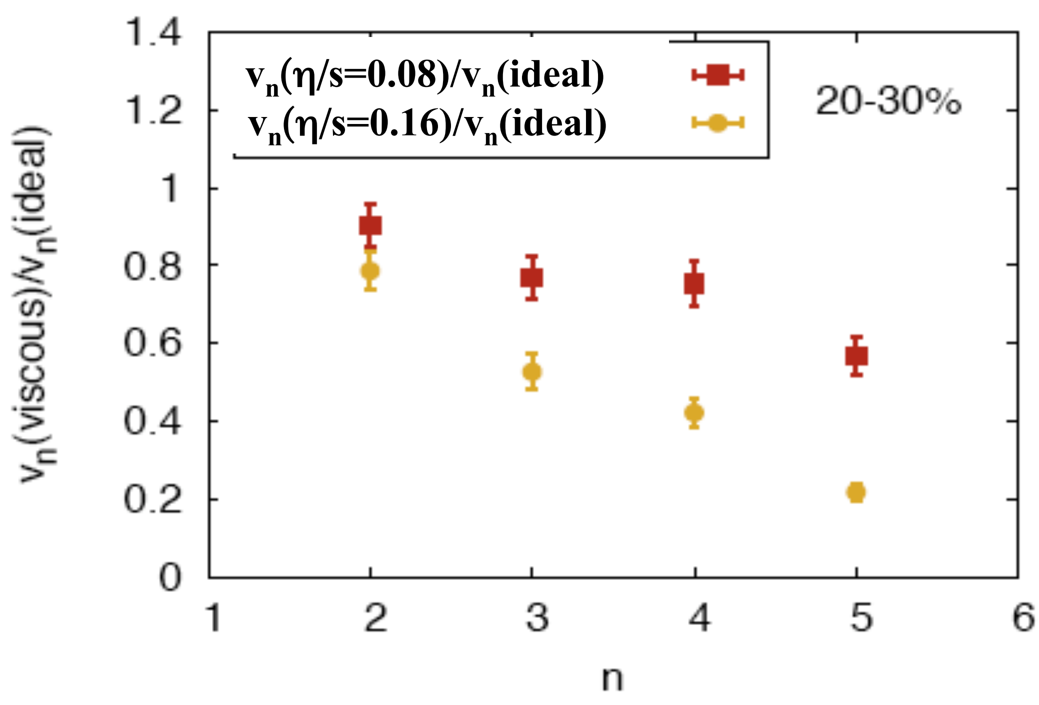
Higher harmonics exist & are useful!



Nucleons move around inside the nucleus

-> locations of NN scattering fluctuate

- Hydro gets it right if initial conditions are allowed to fluctuate
- Better sensitivity to the viscosity/entropy ratio (viscosity increases dissipation)
- η/s = 0.08 works better!



Surprise: viscosity/entropy is small

Viscosity: inability to transport momentum & sustain a wave

low viscosity → absorbs particles & transports disturbances

Viscosity/entropy near $1/4\pi$ limit from quantum mechanics!

∴ liquid at RHIC is "perfect"

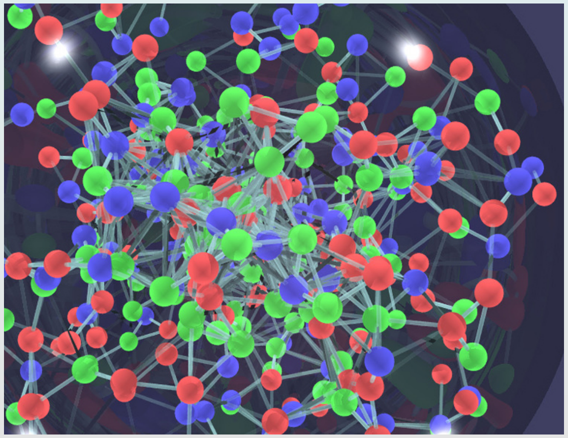
Example: milk. Liquids with higher viscosities will not splash as high when poured at the same velocity.

Good momentum transport: neighboring fluid elements "talk" to each other

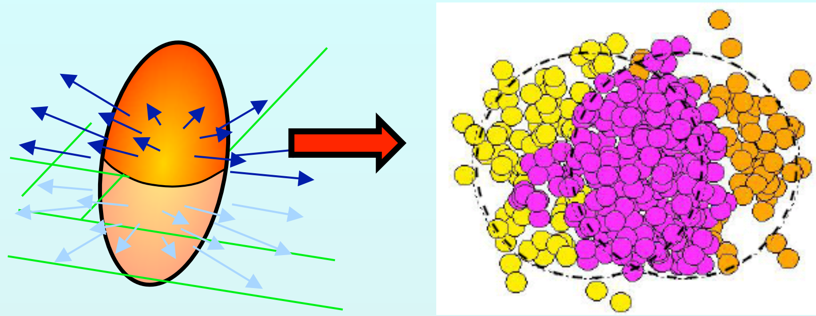
→ QGP is strongly coupled

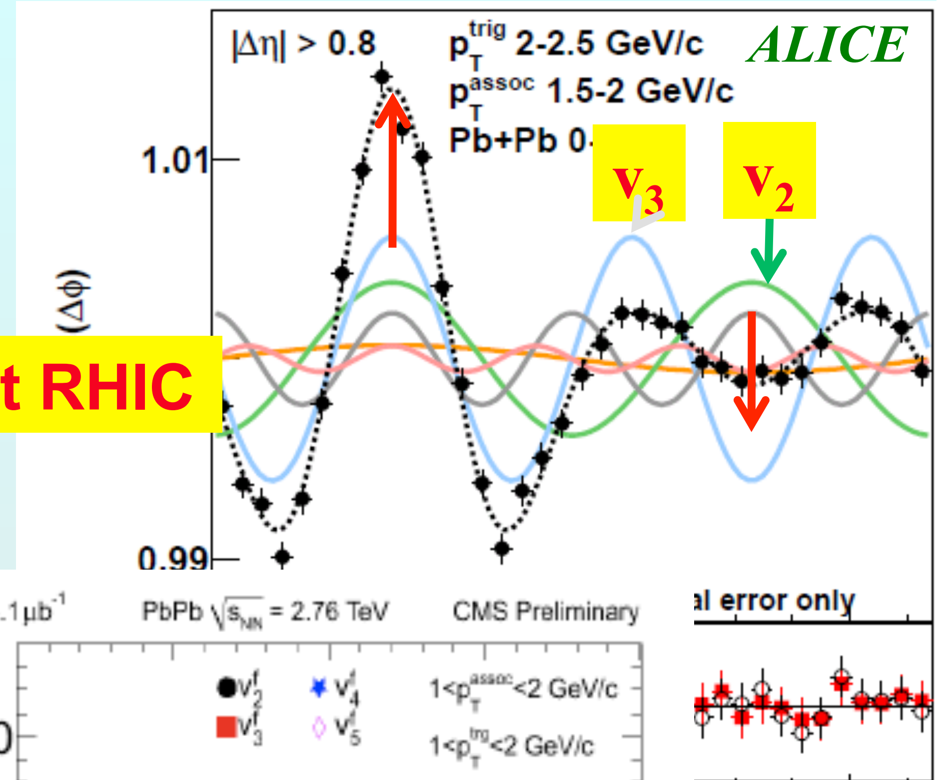
Should affect opacity :

e.g. q,g collide with "clumps" of gluons, not individuals

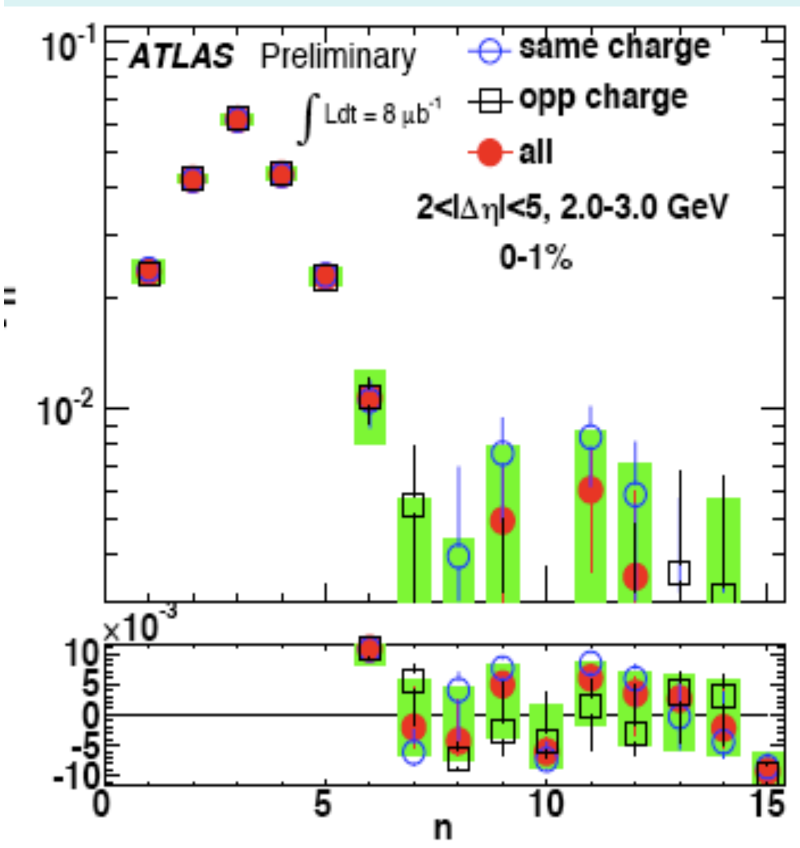


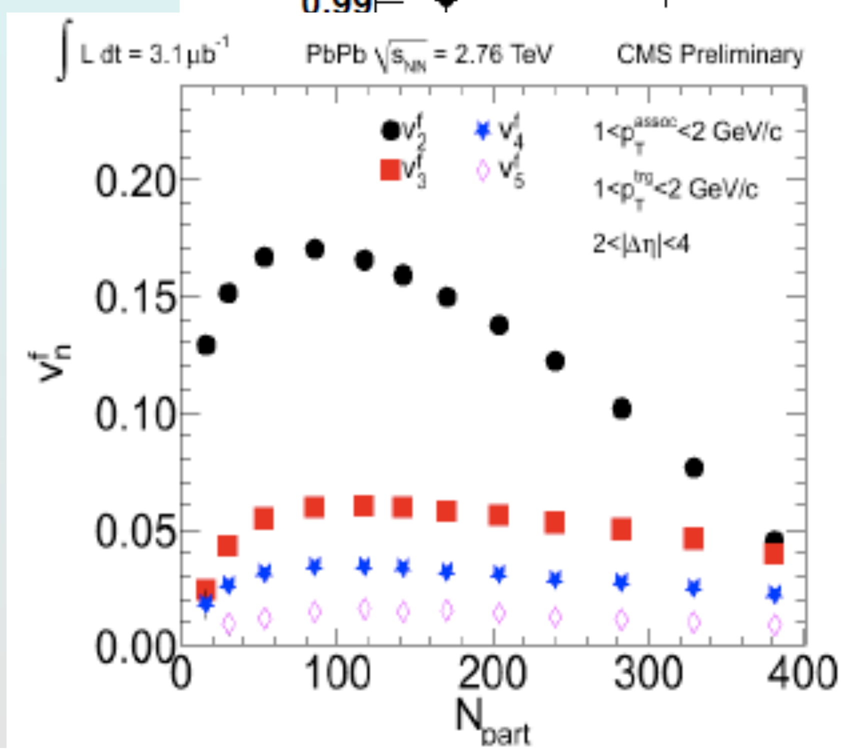
At the LHC



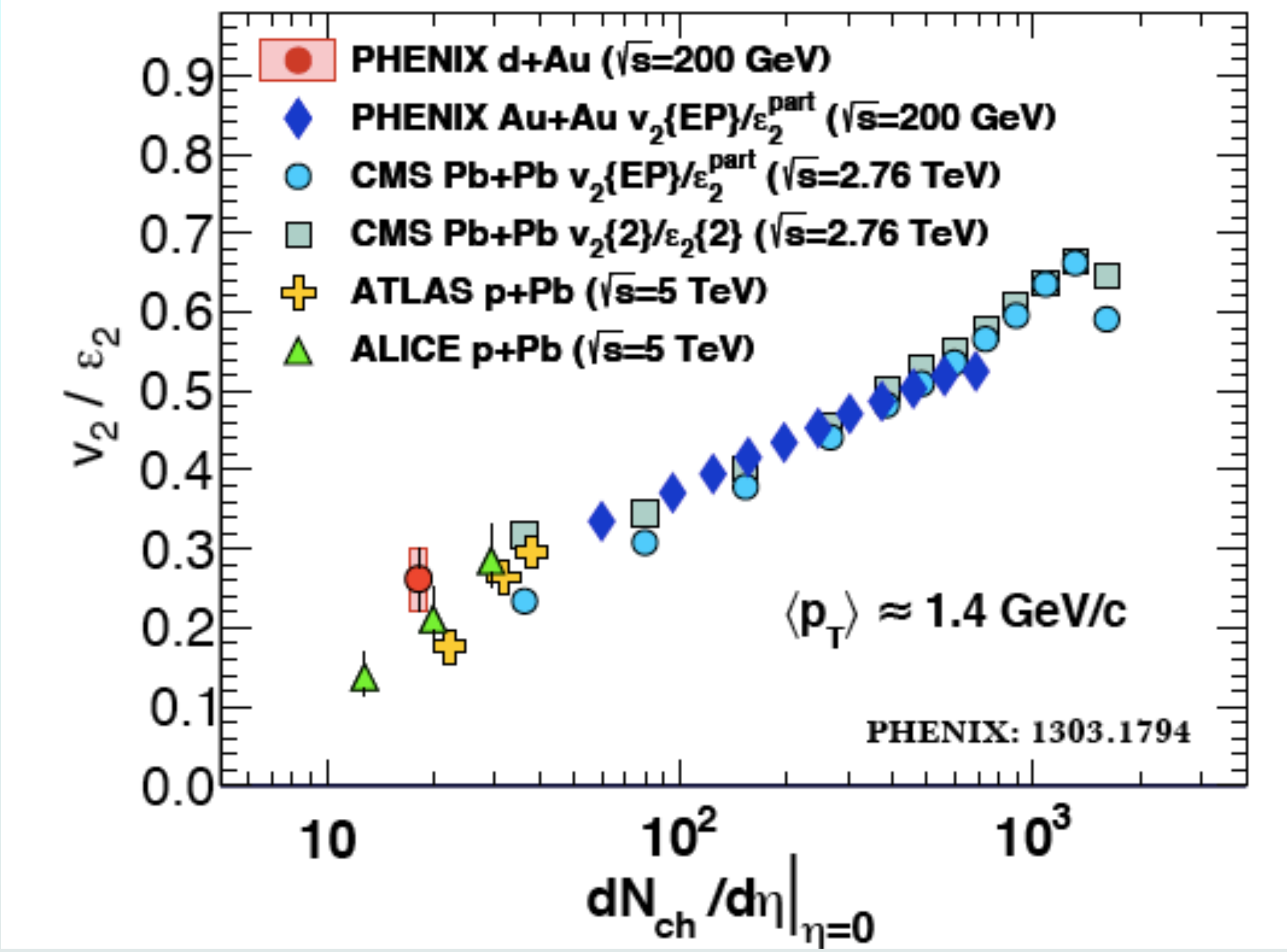


- **Hydro: T_{init} 30% higher than at RHIC**





A mystery: see flow in p/d + Au too!

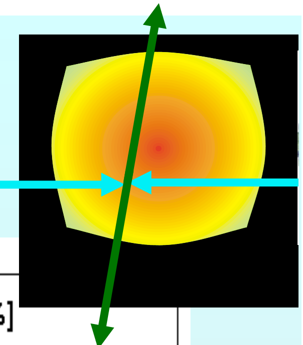


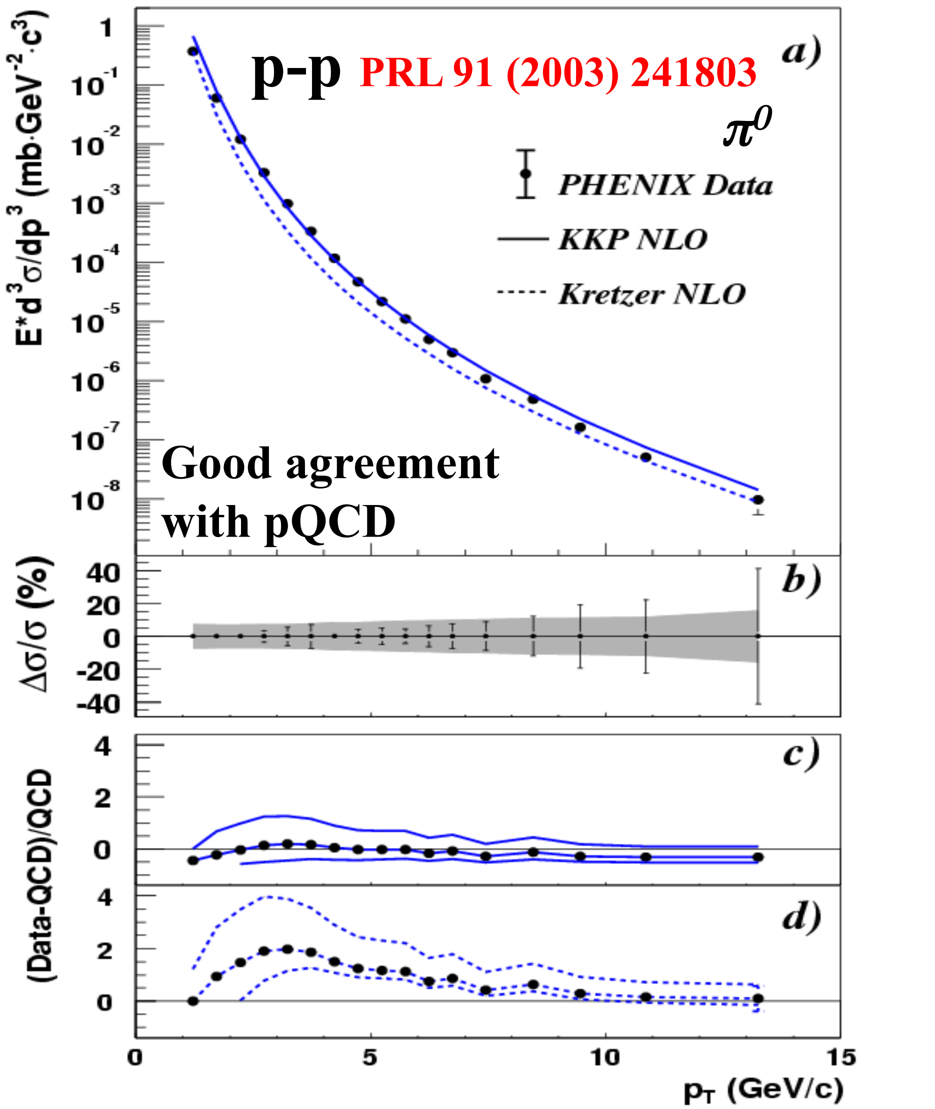
Maybe a small drop of QGP is made in p/d+Au too?!

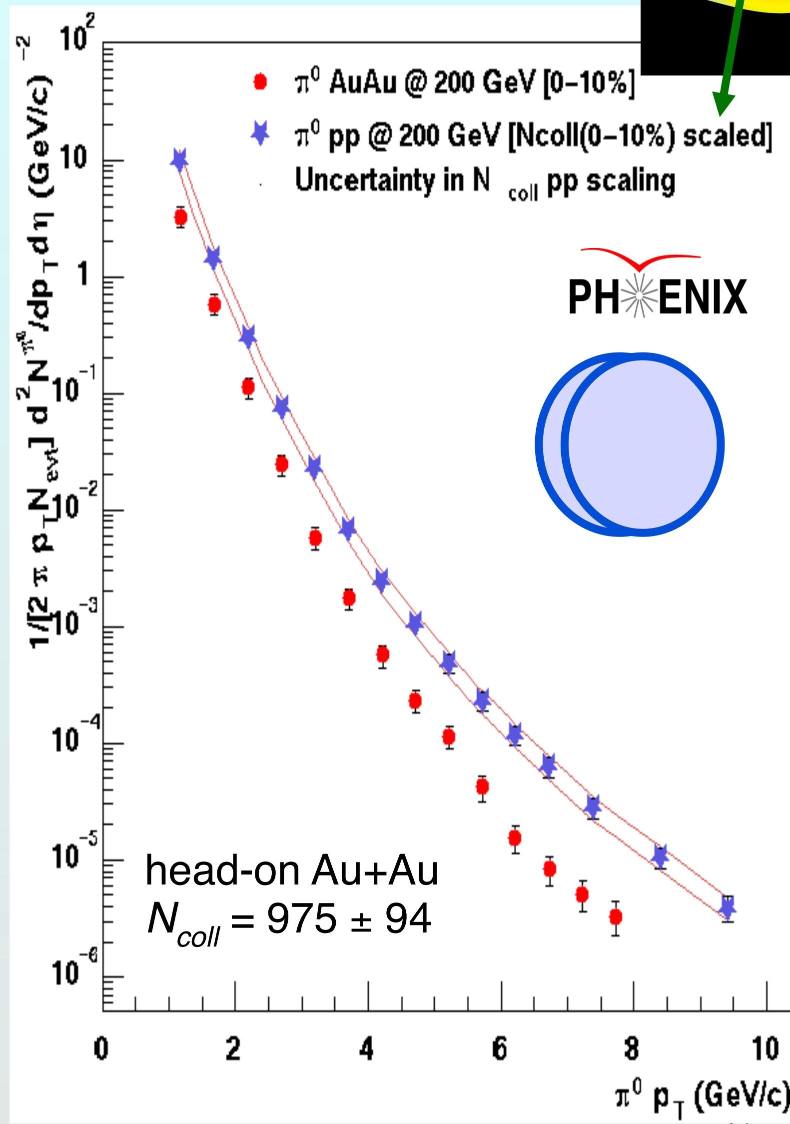
Deepens mystery: how can matter thermalize so fast?

Strong coupling should make the plasma opaque to colored probes

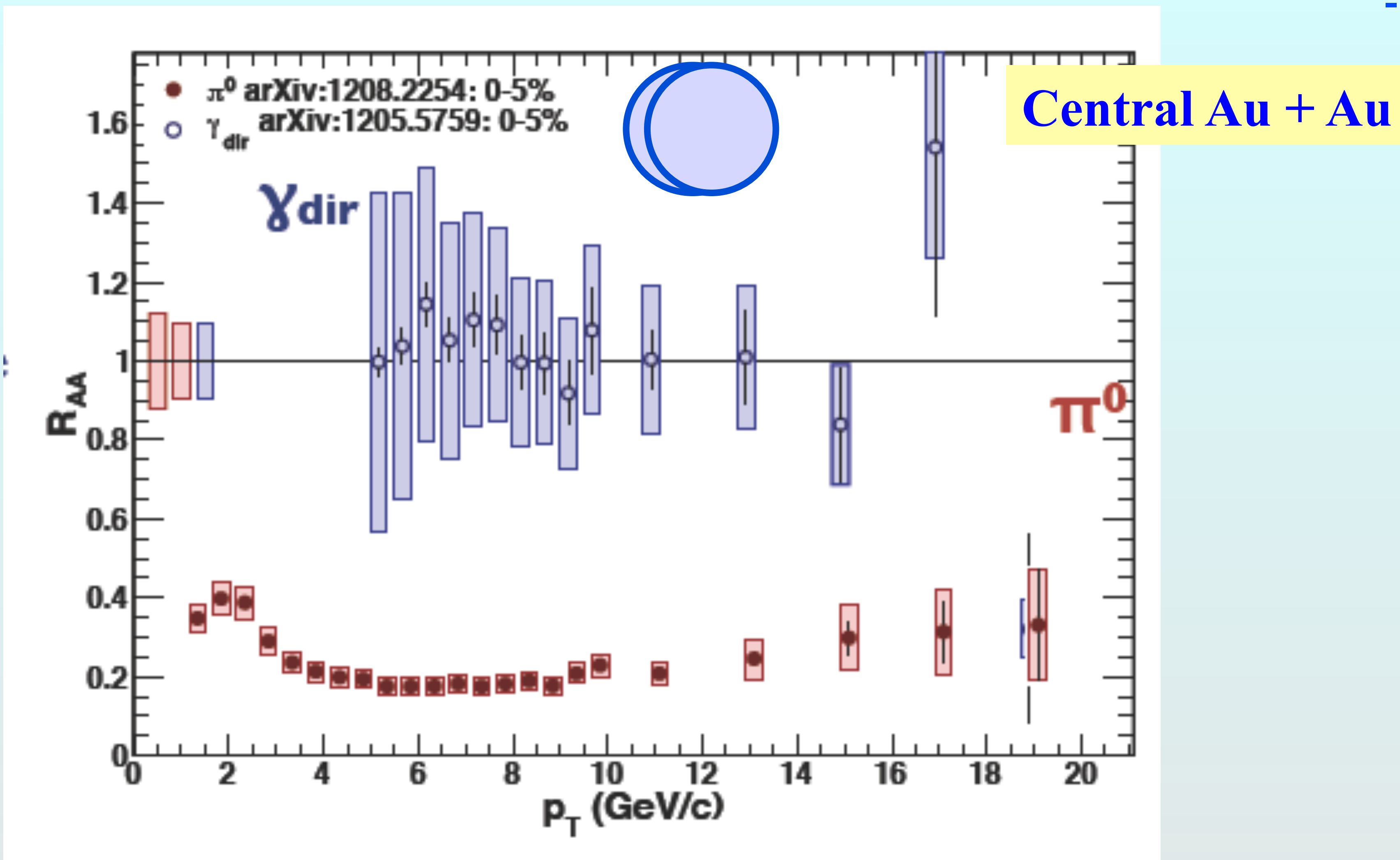
“External” probe of plasma opacity





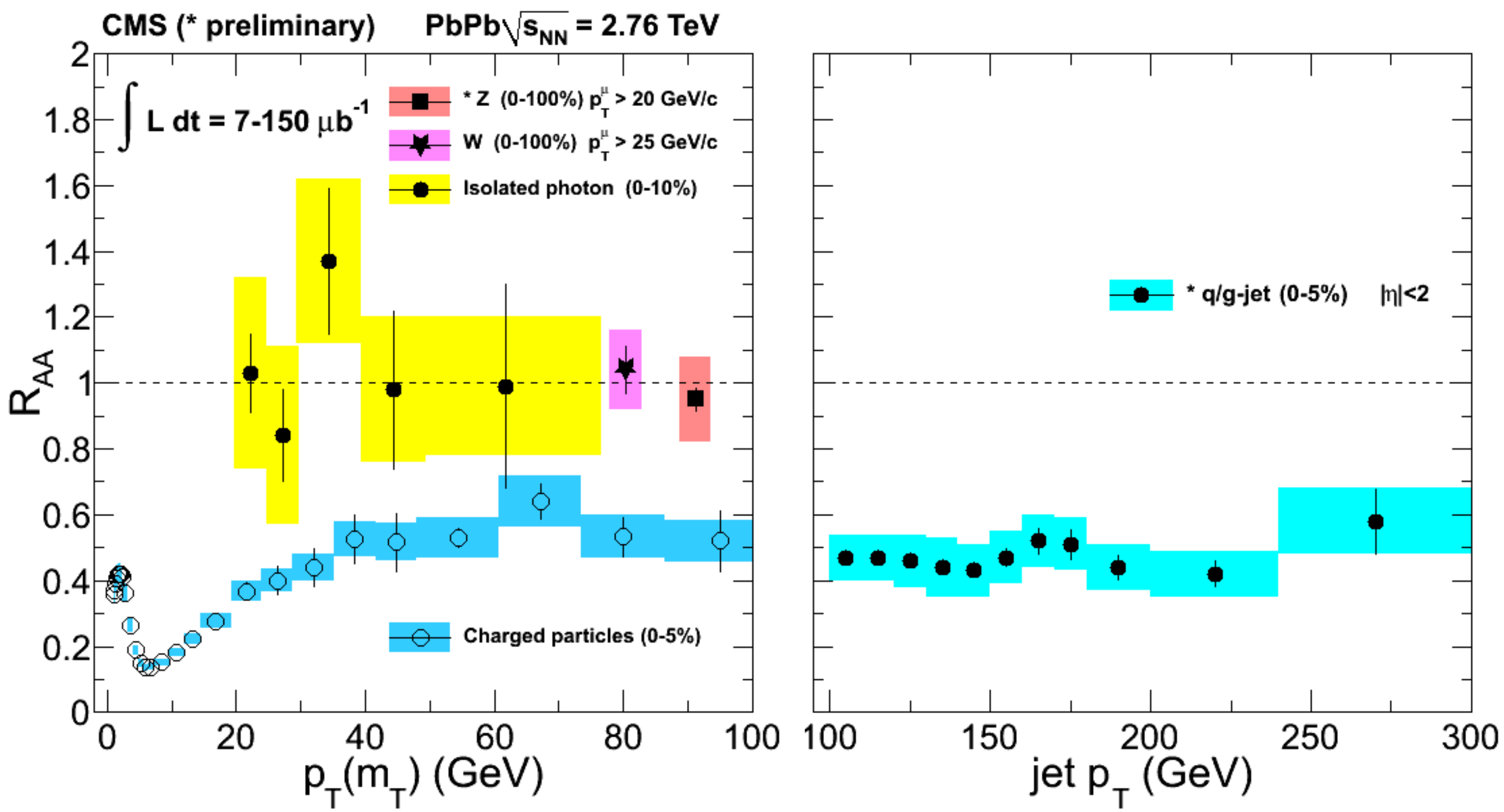


colored objects lose energy, photons don't



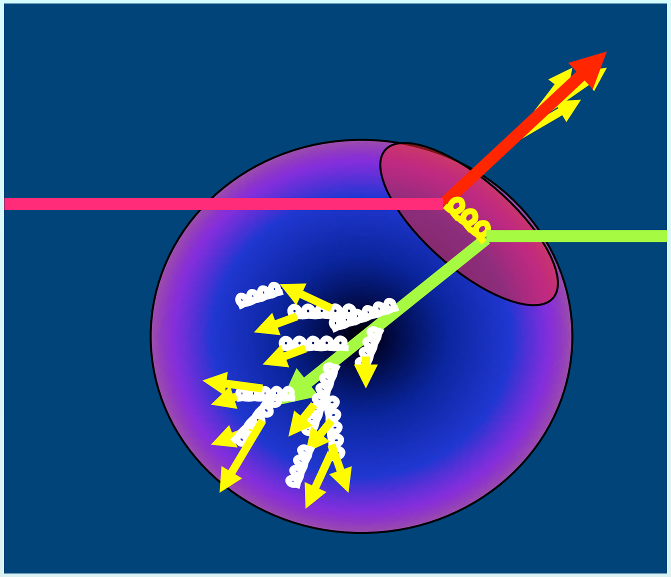
$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

Energy lost even by very energetic q & g

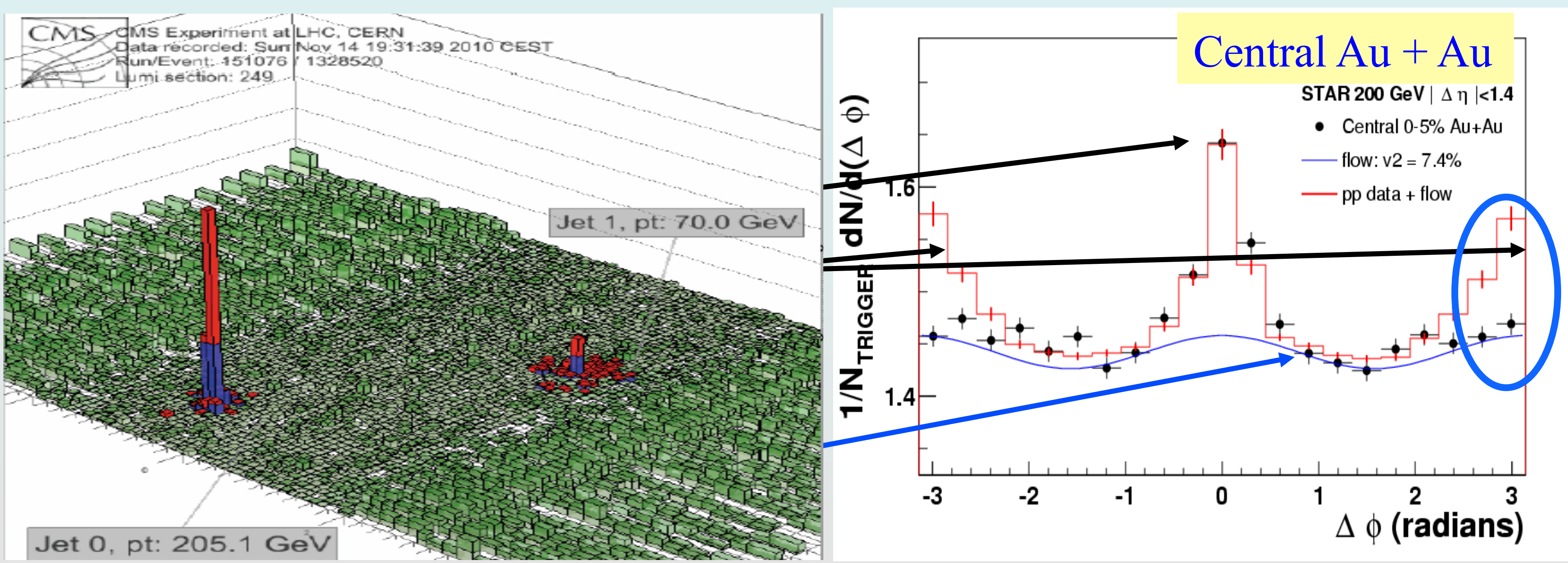


- LHC experiments reach to 300 GeV!

Just how opaque IS it?

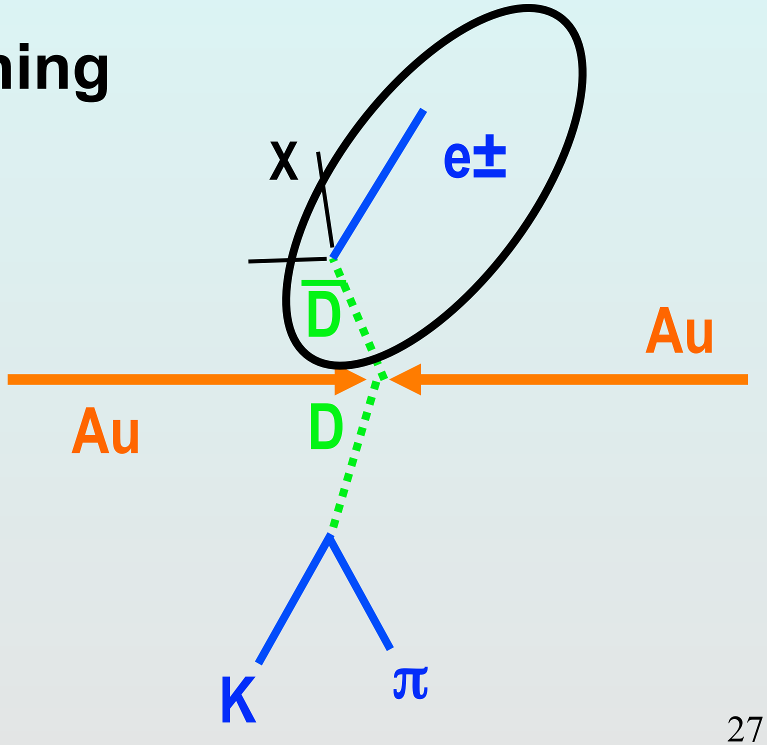


- Use jet *pairs*
- high p_T hadron tag hard scattering near surface
- second particle to probe the medium
- answer: VERY opaque!

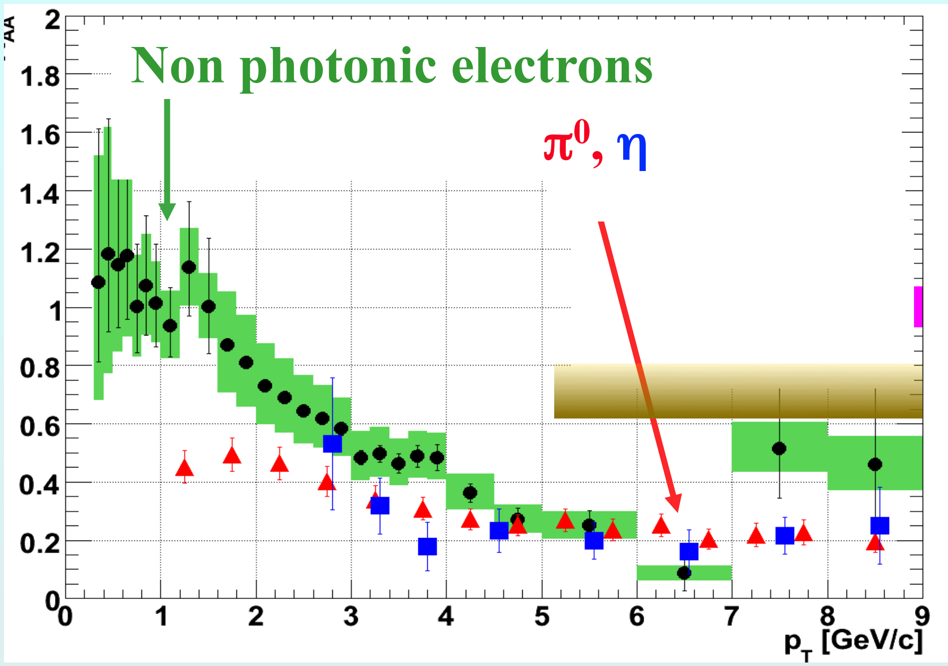


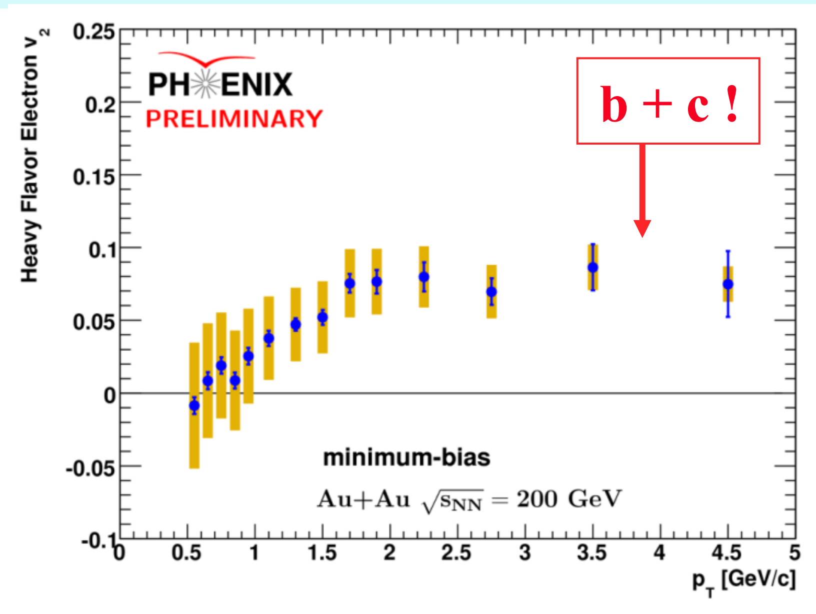
What happens to more massive probes?

- Diffusion of heavy quarks traversing QGP
  $M_c \sim 1.3$ GeV/c^2
- Prediction: less energy loss than light quarks
  large quark mass reduces phase space for radiated gluons
- Measure via semi-leptonic decays of mesons containing charm or bottom quarks



Surprise: large heavy quark energy loss!



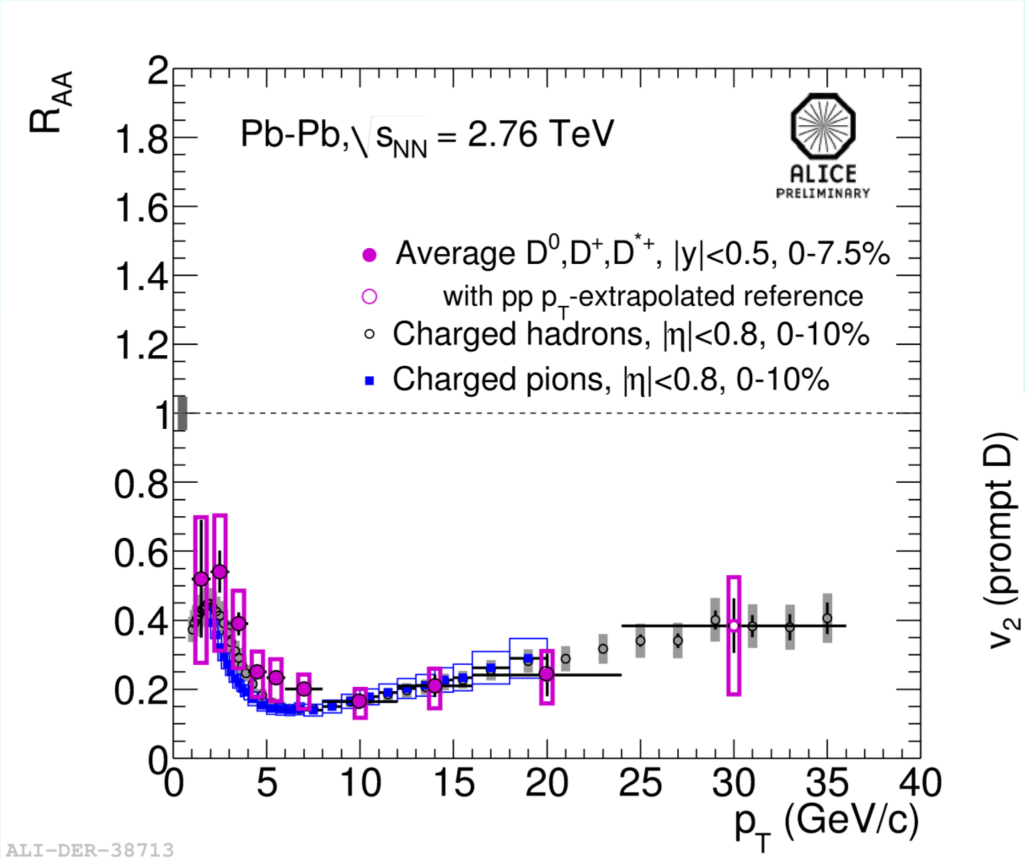


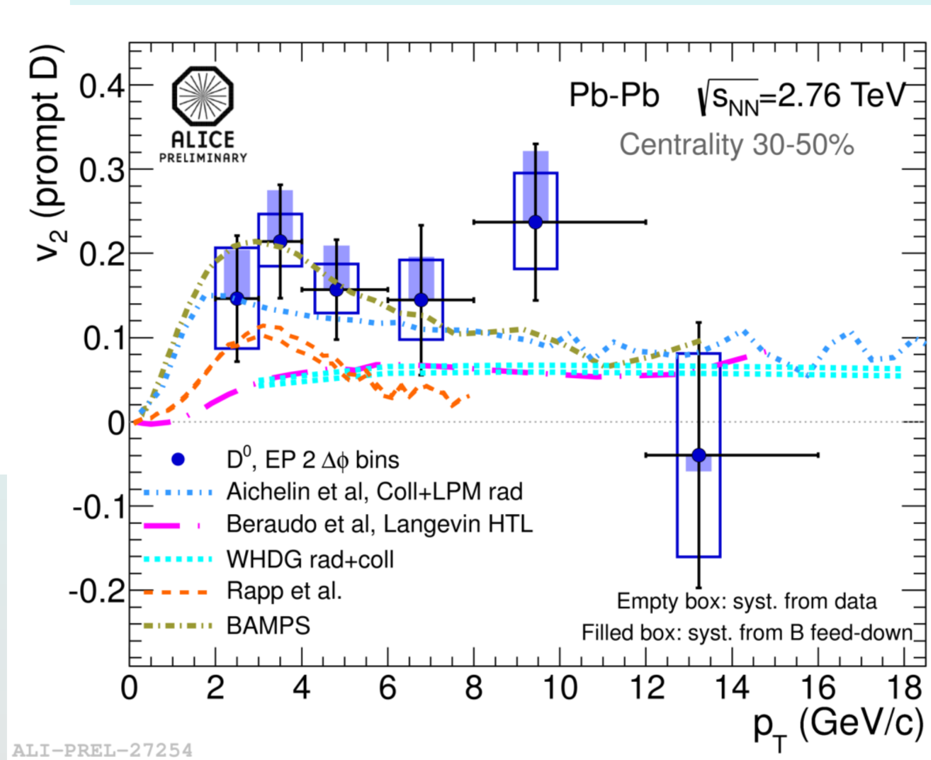
- ► **more energy loss than gluon radiation can explain!**
- ► **charm quarks flow along with the QGP liquid!!**

Who ordered that?

Mix of radiation + collisions (diffusion)
but collisions with what?
Drag force of strongly coupled plasma on moving quark?

Same behavior in QGP at LHC





- Can reproduce energy loss and flow at both energies
- Charm quarks diffusing thru strongly coupled QGP

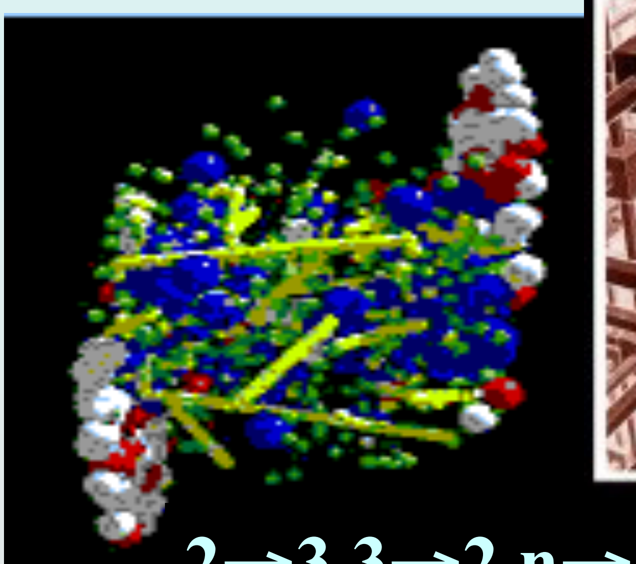
Calculating transport in QGP

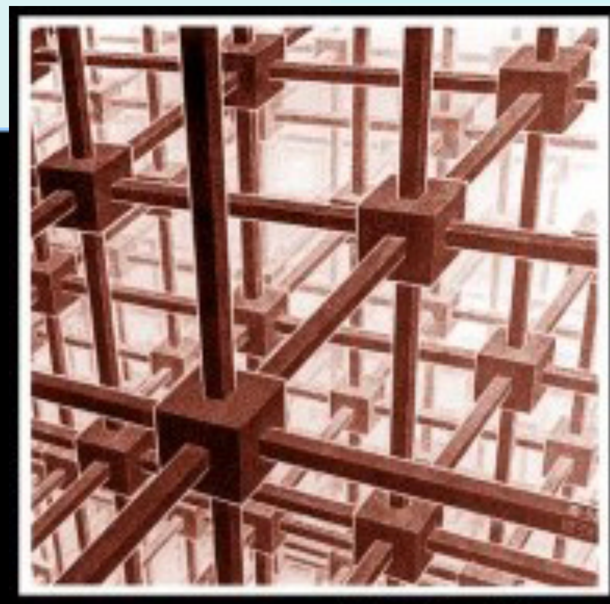
weak coupling limit

perturbative QCD

kinetic theory, cascades

interaction of particles



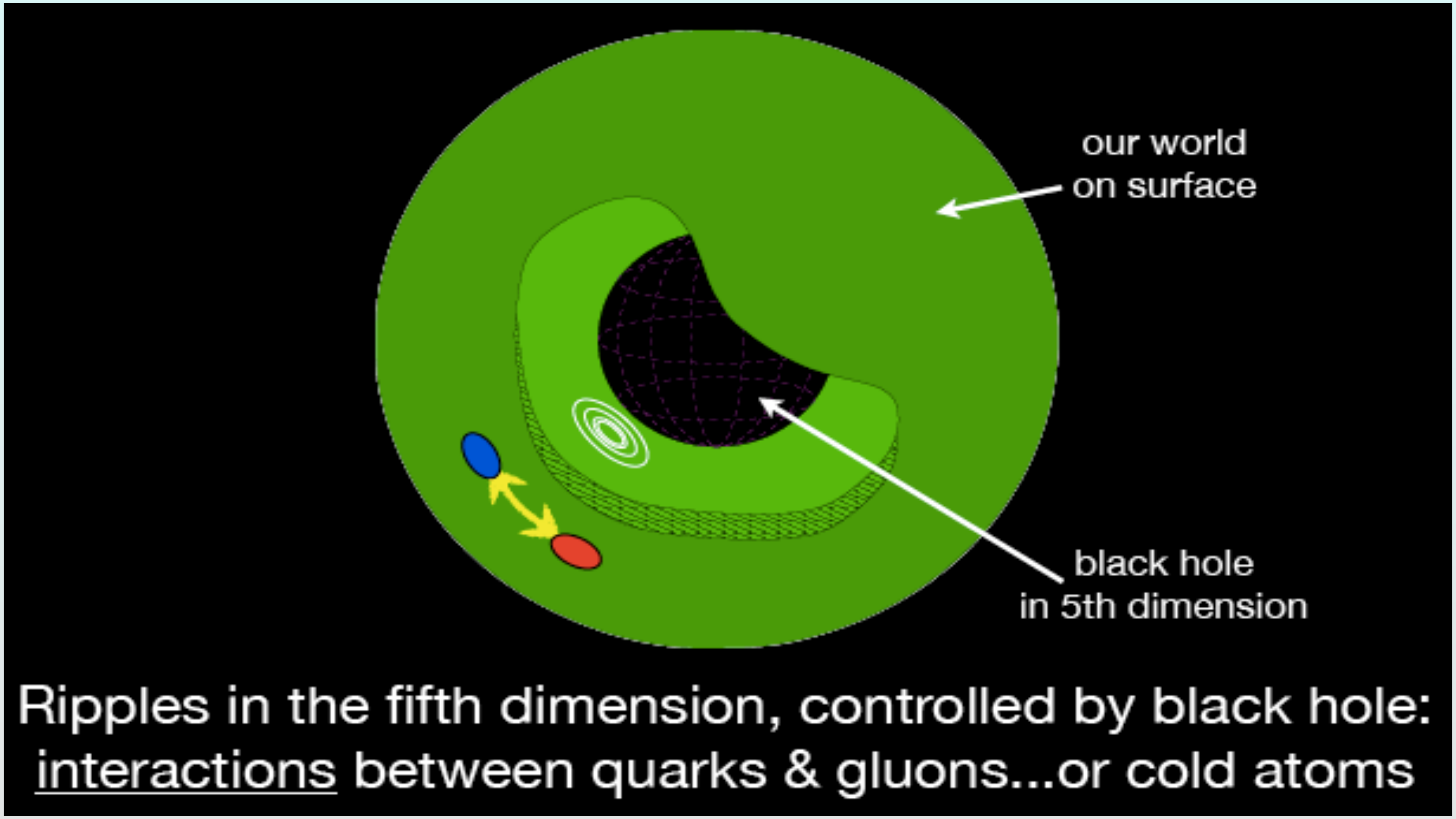


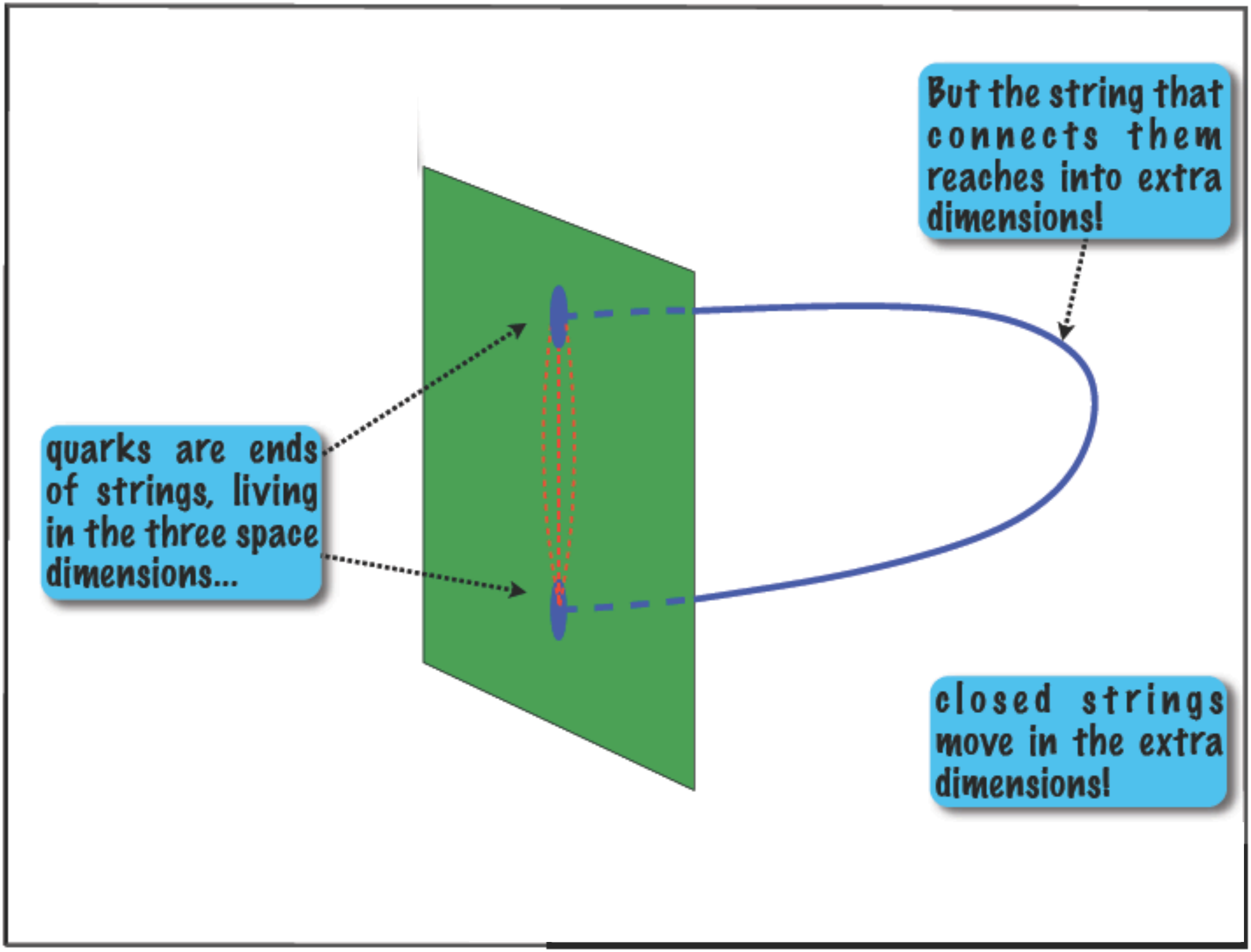
2→3,3→2,n→2…

Lattice QCD

Surprise: string theorists have something to say about this

- ***using methods from string theory and its duality with black holes***
- ***Black holes have infinite gravity at their event horizon***




But the string that connects them reaches into extra dimensions!
quarks are ends of strings, living in the three space dimensions...
closed strings move in the extra dimensions!

Using the duality

Anti de-Sitter/Conformal Field Theory Correspondence

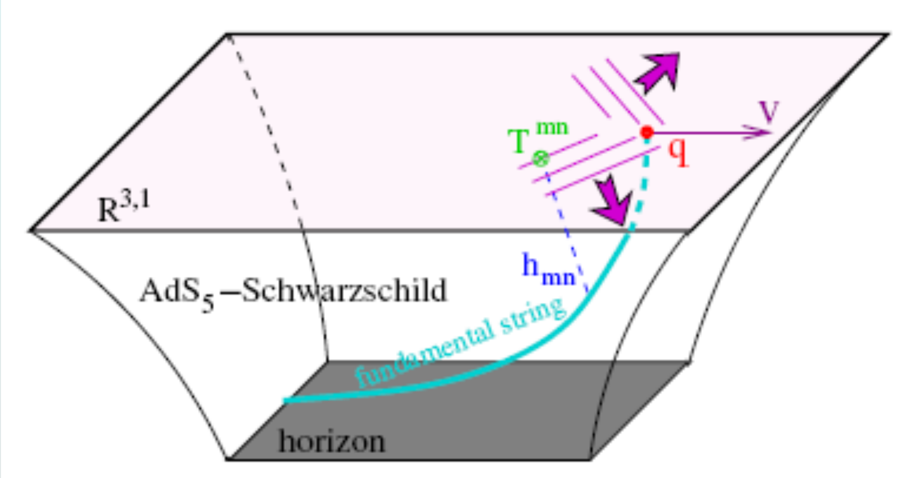
N=4 Supersymmetric Yang-Mills theory - a field theory similar to QCD

⟷ *Maldacena*

Weakly coupled type IIB on AdS_5xS^5 Dual to gravity near a black hole

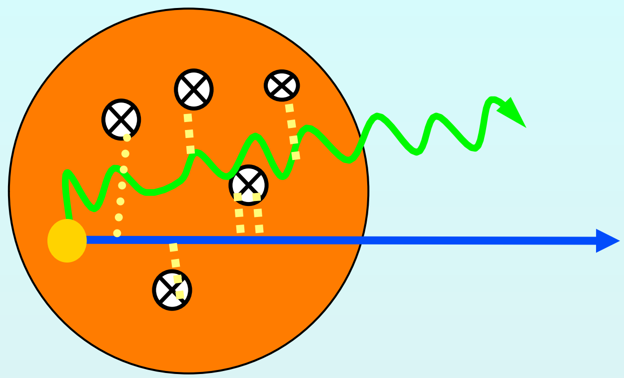
Predict properties of strongly coupled fluid ($\eta/s \geq 1/4\pi$) & non-equilibrium processes (large c quark energy loss)

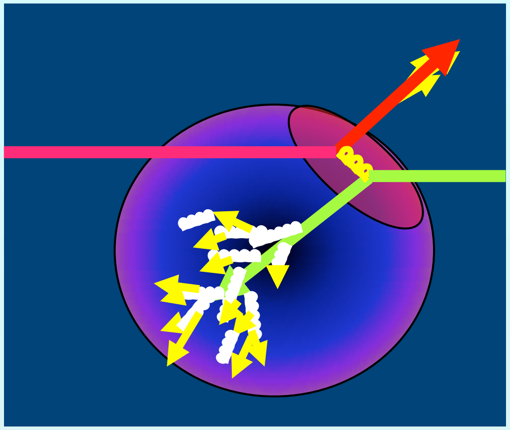
"easy" to calculate evolution of stress-energy tensor



Son, Policastro, Starinets; Gubser

How is energy lost & where does it go?





- Excite collective modes of the plasma?
- Collisions with plasma constituents

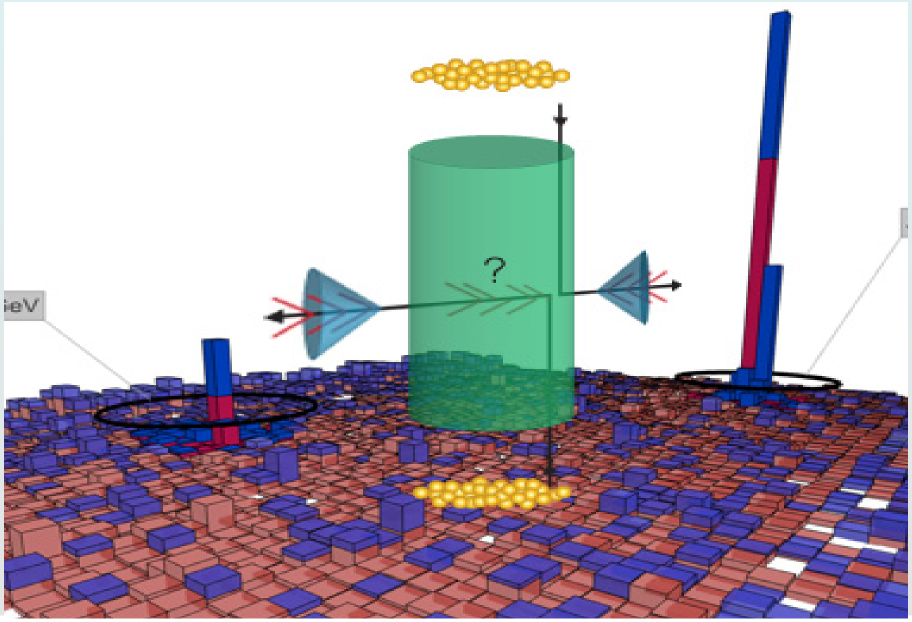
  Induce gluon radiation?

    pQCD says yes

    g_{rad} interact with g_{plasma}?

  Lose energy through

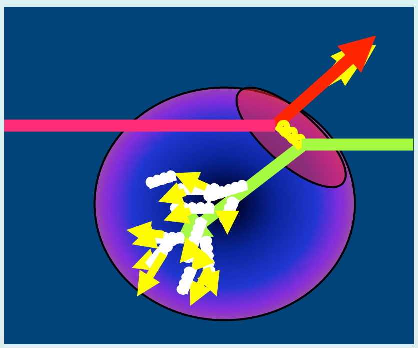
    elastic collisions?



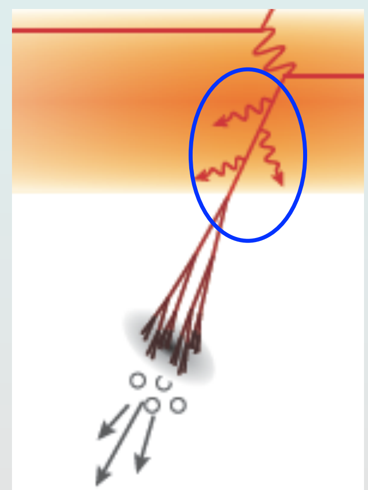
Search for the lost energy

- If AdS/CFT is right, don't produce gluons
- If medium enhances gluon radiation/splitting:

extra gluons at small angles (in/near jet cone)

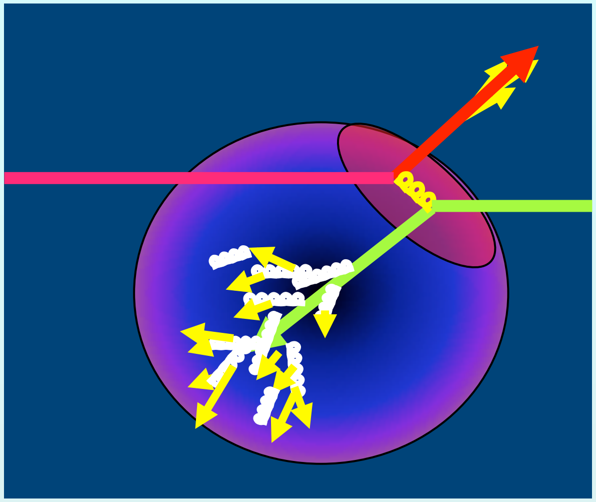


radiated gluons thermalize in medium (i.e. they're gone!)



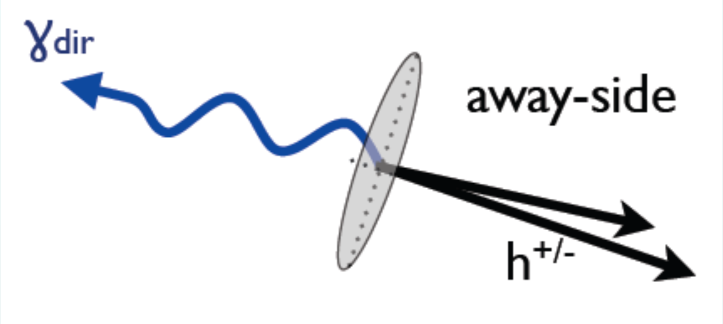
remain correlated with leading parton, but broaden/change jet

Jet Fragmentation function



$D(z) = 1/N_{jet}\, dN(z)/dz;\ z = p_{had}/p_{jet}$

Measure: count partners per trigger as fraction of trigger momentum



$z_T = p_{Ta}/p_{Tt} \sim z$ for γ trigger

$\xi = \ln(1/z_T)$

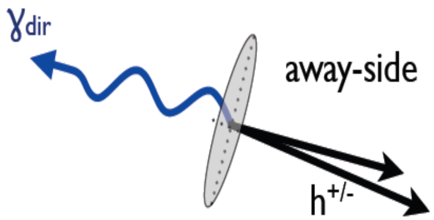
Modification factor similar to R_{AA}:

$$I_{AA} \equiv \frac{(1/N_{trig} dN/d\xi)_{AA}}{(1/N_{trig} dN/d\xi)_{pp}}$$

FFn experimental challenge:

measure the parton p

Use trigger γ or jet



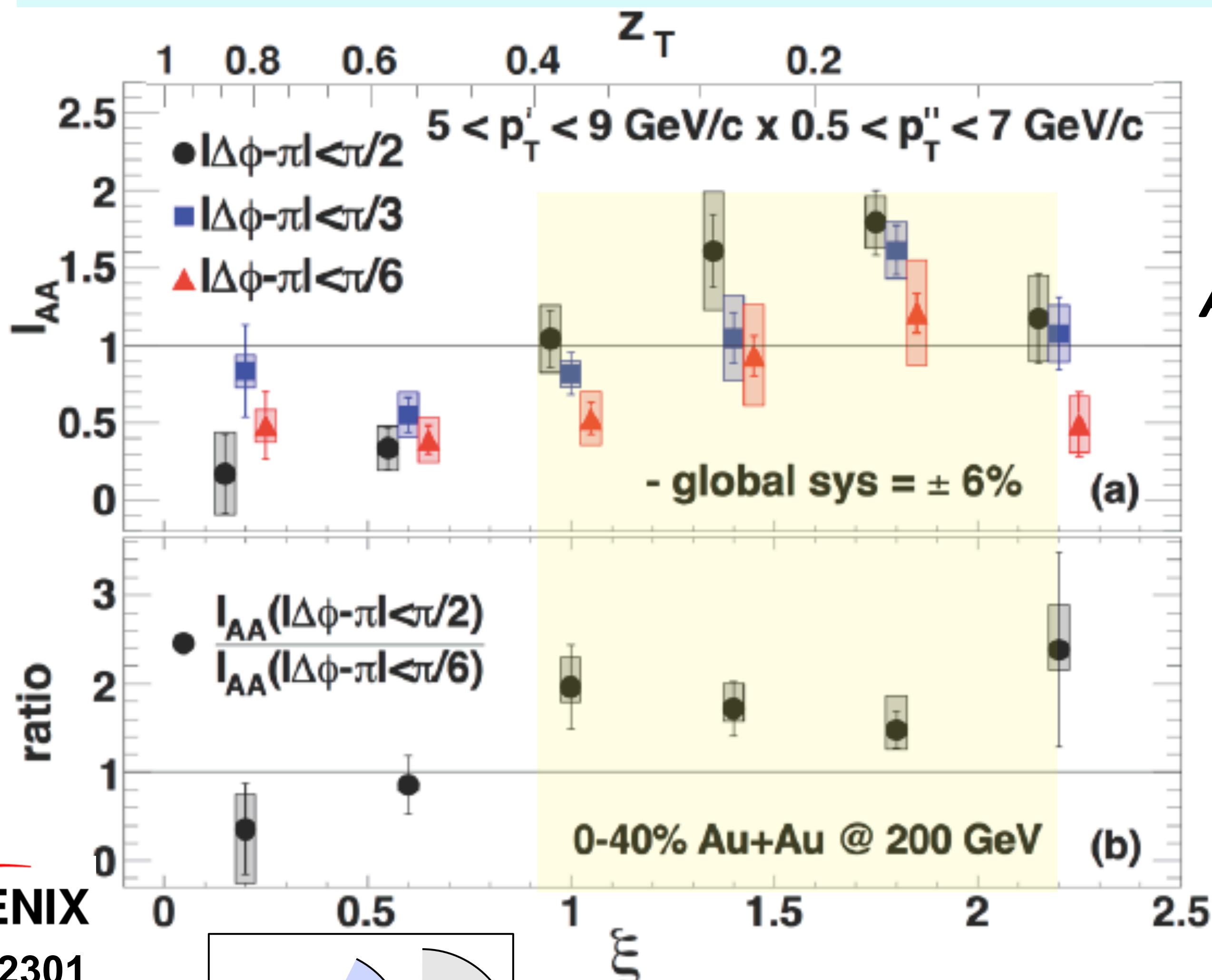
Frag. Function via γ-h correlation

γ: parton energy, h: fragmentation fn.

"Extra" soft particles at larger angles near the away side jet

Provide constraints on gluon splitting

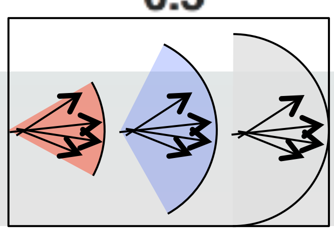
Is it perturbative?



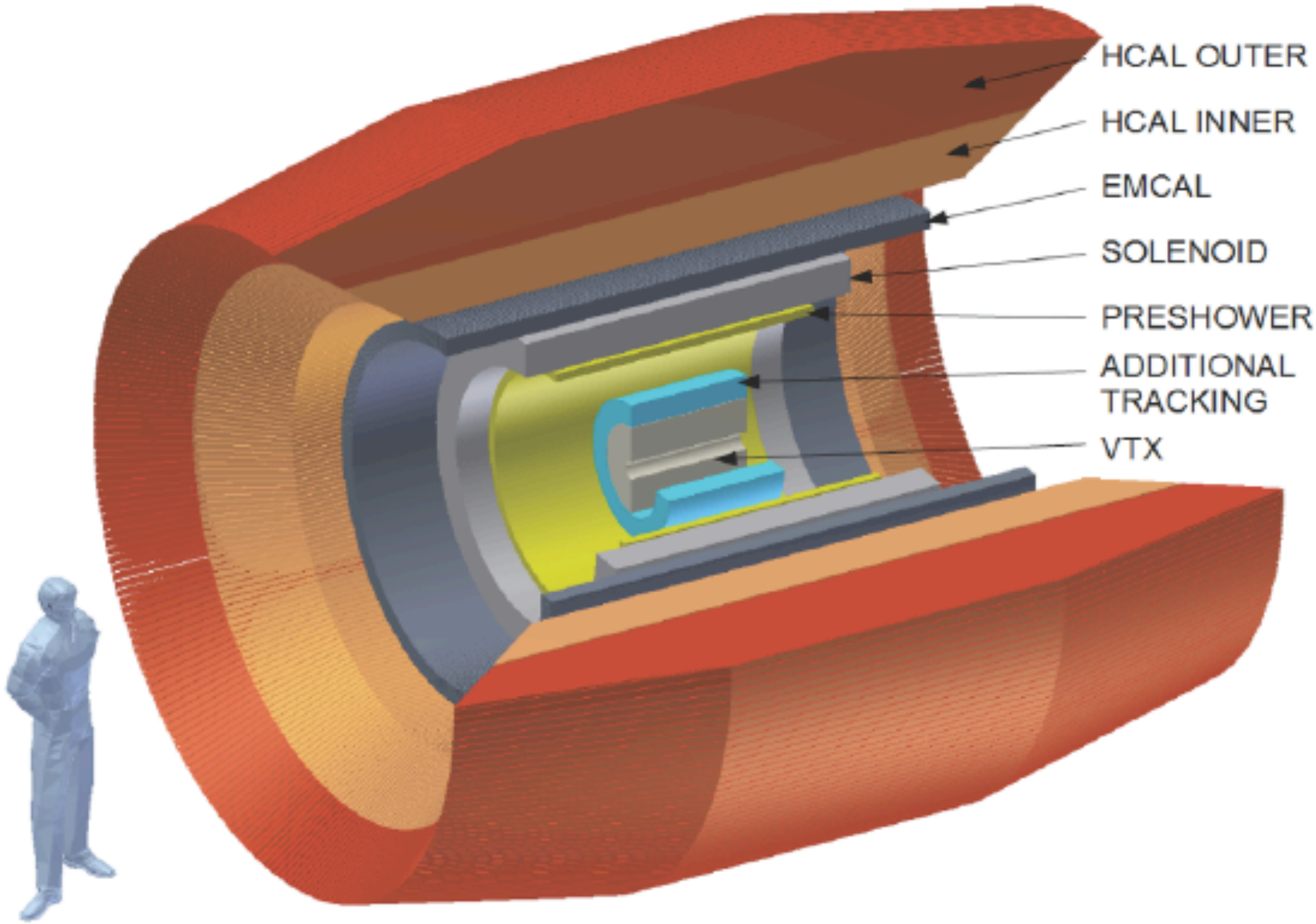
Au+Au/ p+p

PHENIX

PRL 111, 032301 (2013)



Upgrade PHENIX for jets at RHIC



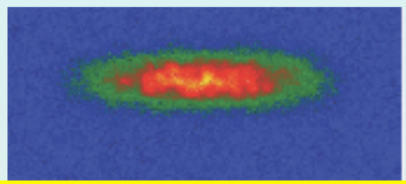
sPHENIX Proposal: arXiv:1207.6378

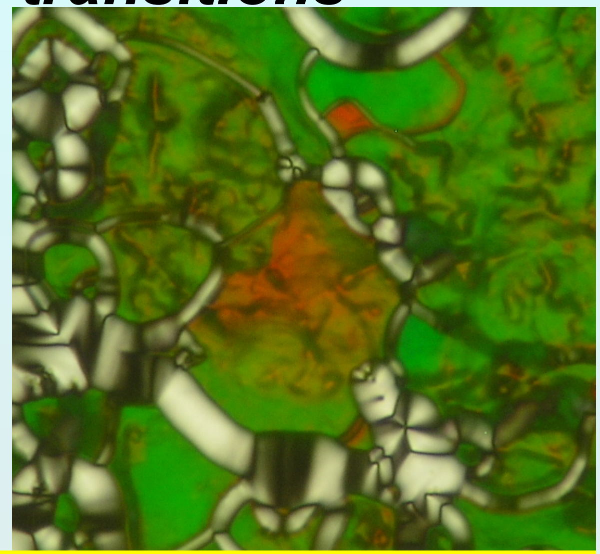
Compact, hermetic jet and quarkonium detector

Many types of strongly coupled matter

Quark gluon plasma is like other systems with strong coupling - all flow and exhibit phase transitions

Cold atoms: coldest & hottest matter on earth are alike!





Dusty plasmas &

In all these cases have a competition:

Attractive forces ⇔ repulsive force or kinetic energy

High T_c superconductors: magnetic vs. potential energy

Result: many-body interactions, not pairwise!

QCD is a great test lab: we *know* the Lagrangian!


i'm in ur fizx lab
testn ur string therry

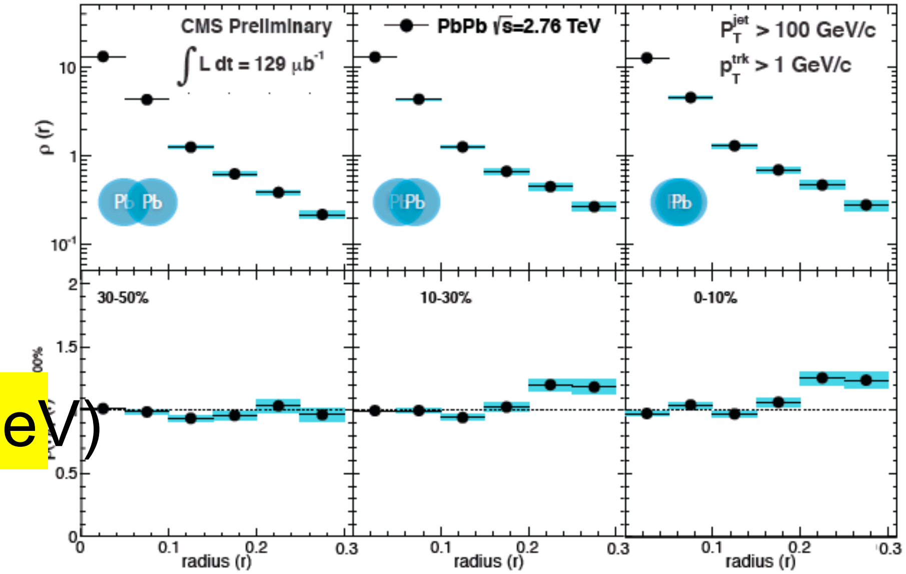
- **Backup**

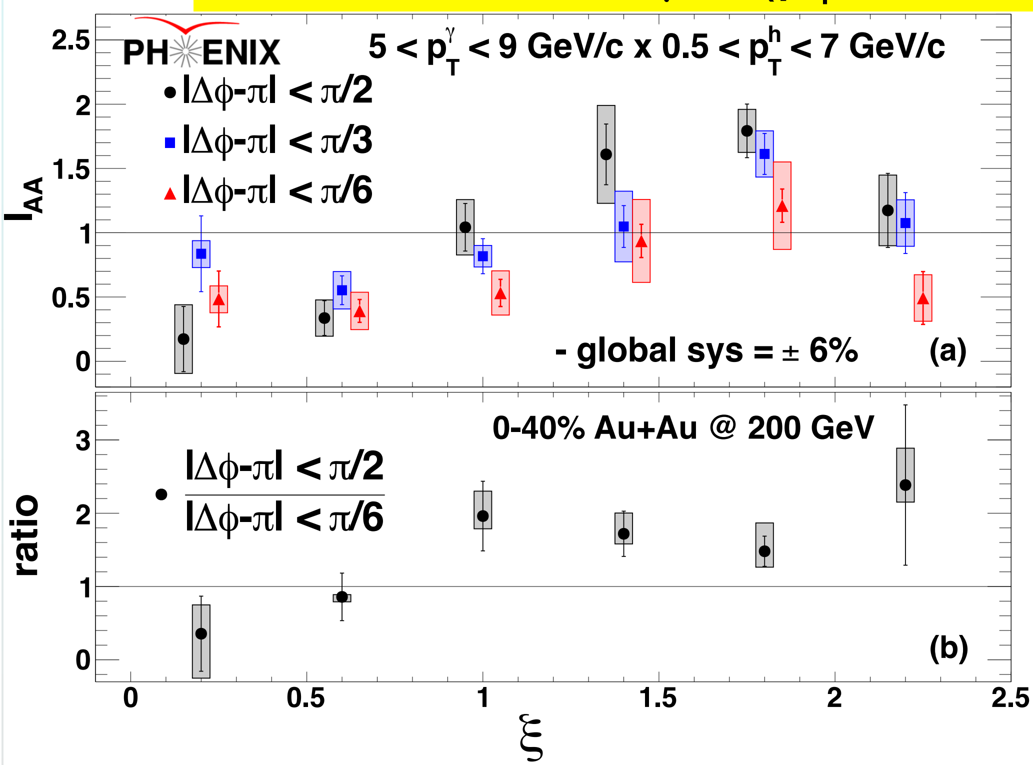
Comparison to similar LHC results

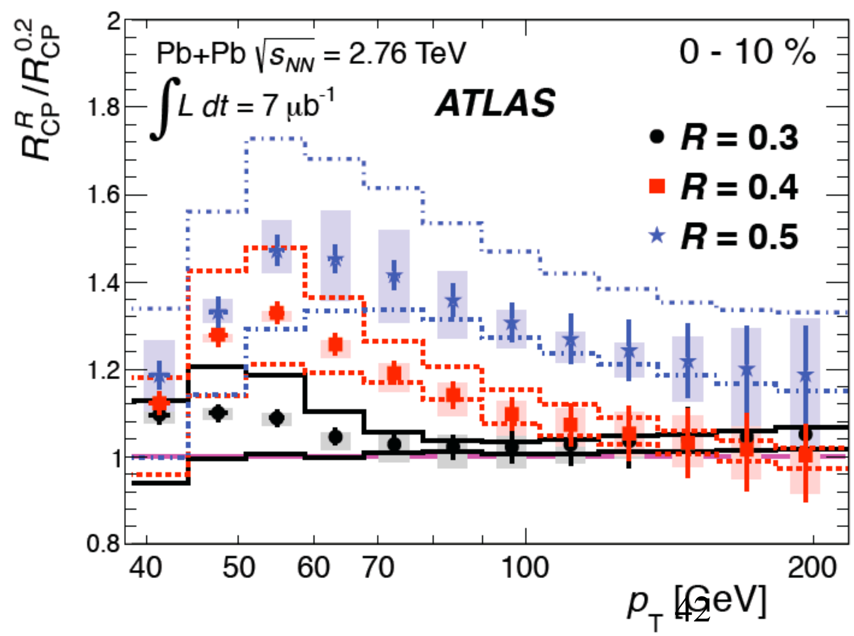
Similar story at LHC:

distribution of particles associated with jet is broadened relative to p+p/peripheral A+A

but not in CMS γ-h (p_T>60 GeV)







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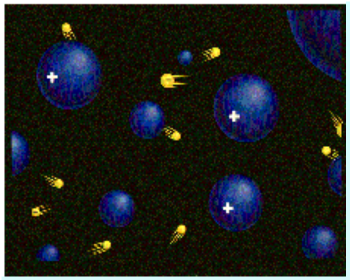
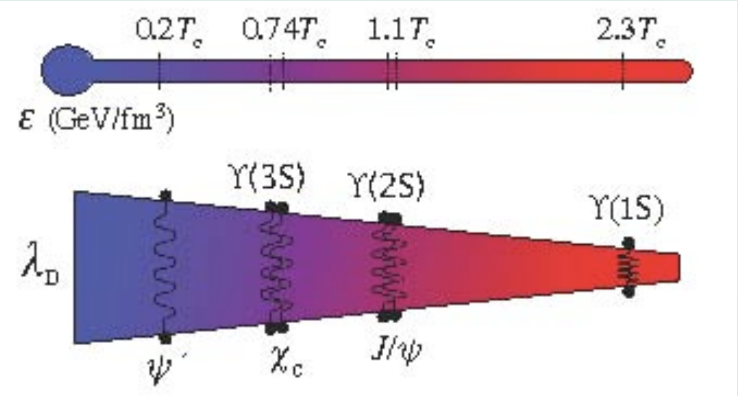
Some open questions and how we'll answer them



Is there a relevant color screening length?

- Plasma: interactions among charges of multiple particles spreads charge into characteristic (Debye) length, λ_D
  particles inside Debye sphere screen each other
- Strongly coupled = few (~1-2) particles in Debye sphere
  Partial screening -> liquid-like properties
- *Test* QGP *screening with heavy quark bound states*
  Do they survive?
  All? None? Some? Which size?

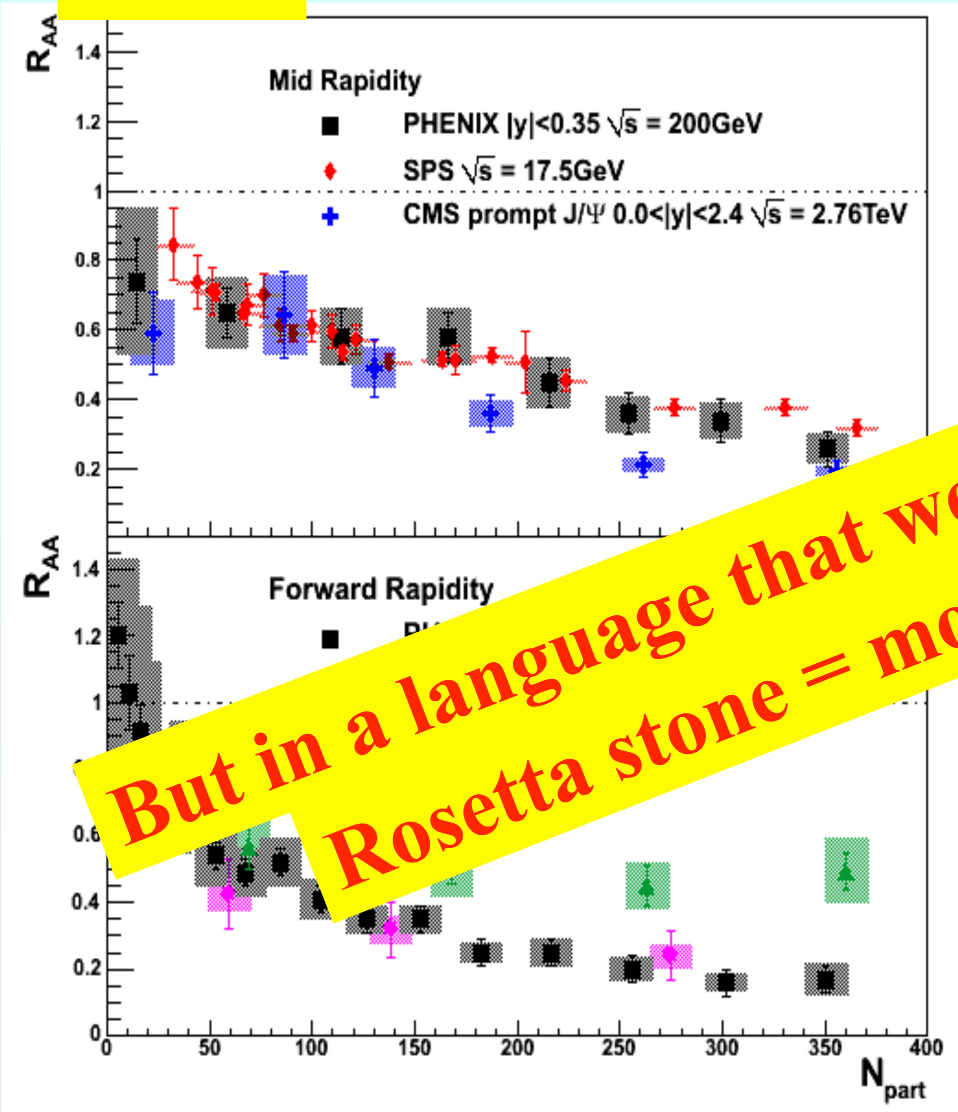


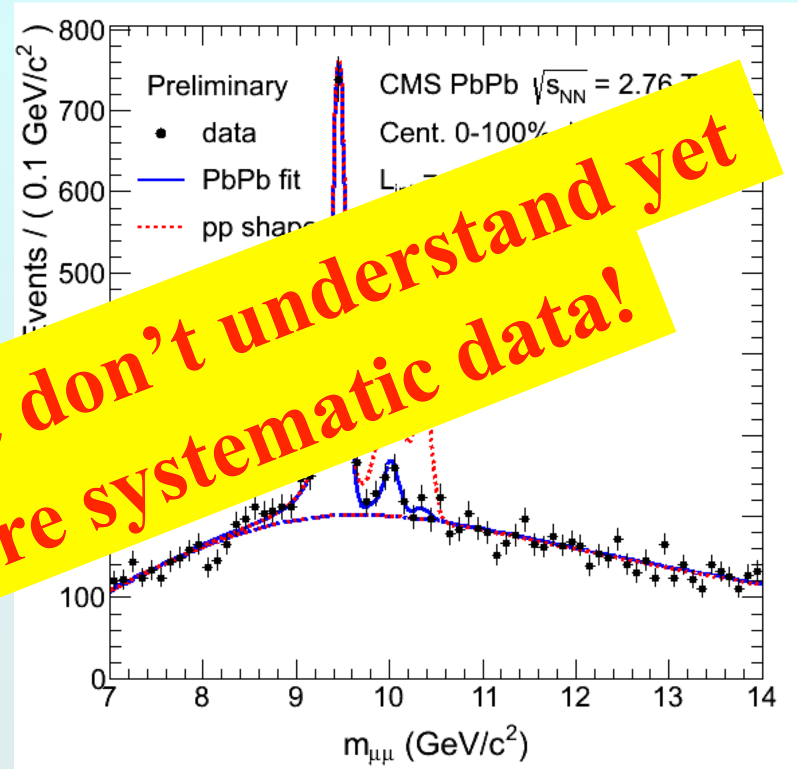
- Are residual correlations important?

The data speak

charm

bottom





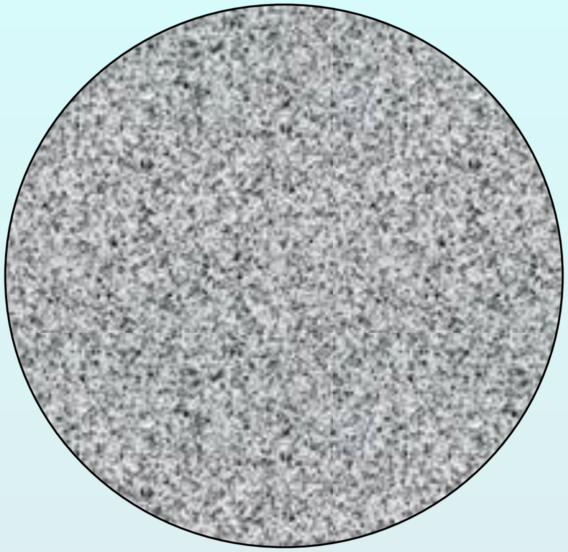
But in a language that we don't understand yet

Rosetta stone = more systematic data!

Sequential suppression of Υ family

J/ψ R_{AA} similar from 17.5-200 GeV! @ 2.76 TeV lower at mid-y, higher at forward y. Lose some & gain some…

Lose some and gain some

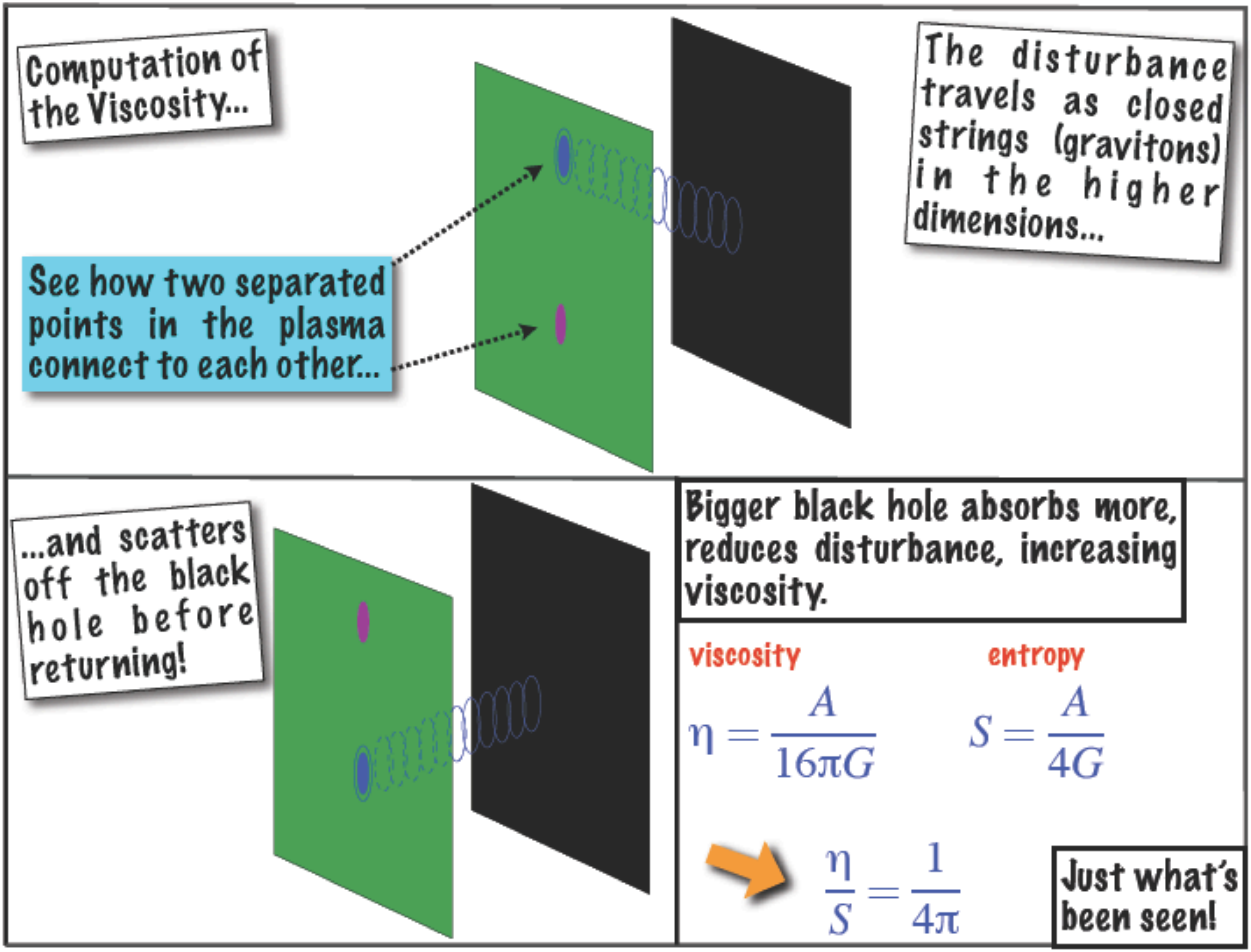


Drop of QGP filled with gluons + some quarks

- QGP screens primordial bound c-cbar and b-bbar bound states
  - They melt in the plasma!
  - depends on binding energy (i.e. size of the bound state)
- quarks find one another when the system falls below T~150 MeV – form the hadrons we observe
- Occasionally a c can find a cbar
  - Probability increases with the number of c-cbar pairs made
  - Increases with beam energy

Measure energy, quark mass dependence to sort out (b's are rare)

Initial state affects c&b – study p+A!



Computation of the Viscosity...
See how two separated points in the plasma connect to each other...
The disturbance travels as closed strings (gravitons) in the higher dimensions...
...and scatters off the black hole before returning!
Bigger black hole absorbs more, reduces disturbance, increasing viscosity.
viscosity
$\eta = \frac{A}{16\pi G}$
entropy
$S = \frac{A}{4G}$
$\frac{\eta}{S} = \frac{1}{4\pi}$
Just what's been seen!

Heavy quark probe answers this year!

- **Do even *b* quarks come to a screeching halt?**

  M_b ~ 4.2 GeV/c^2

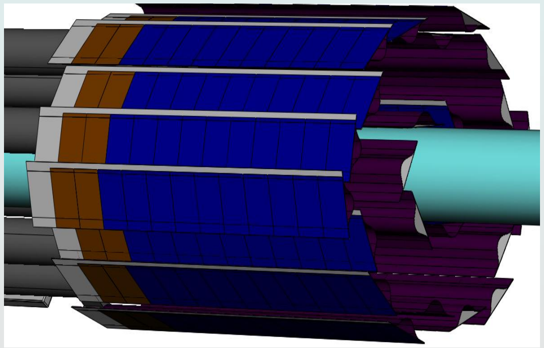
  What does *b* fate tell us about interactions inside?

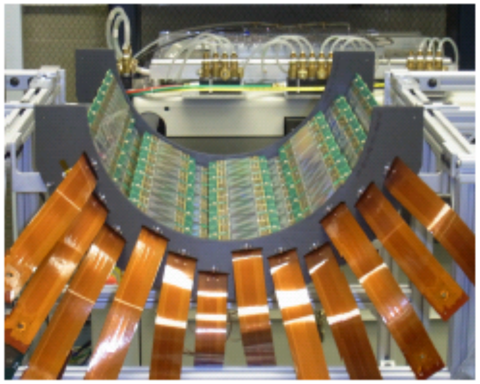
- **Add silicon detector arrays around beam pipe to both PHENIX and STAR; ALICE already has one**

  Tag displaced vertex

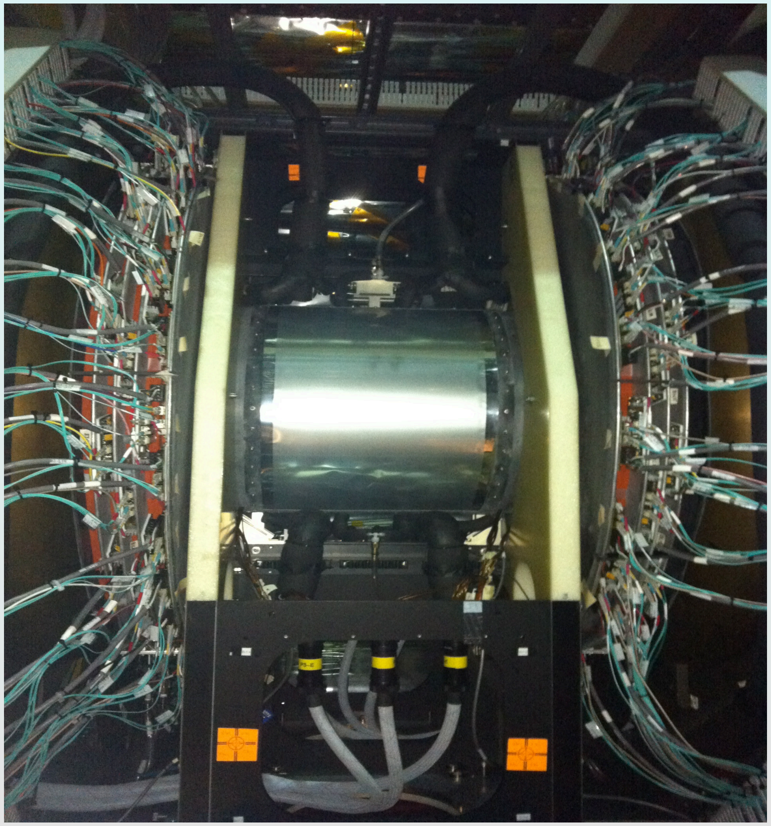
  to separate c,b

  Reconstruct D & B mesons

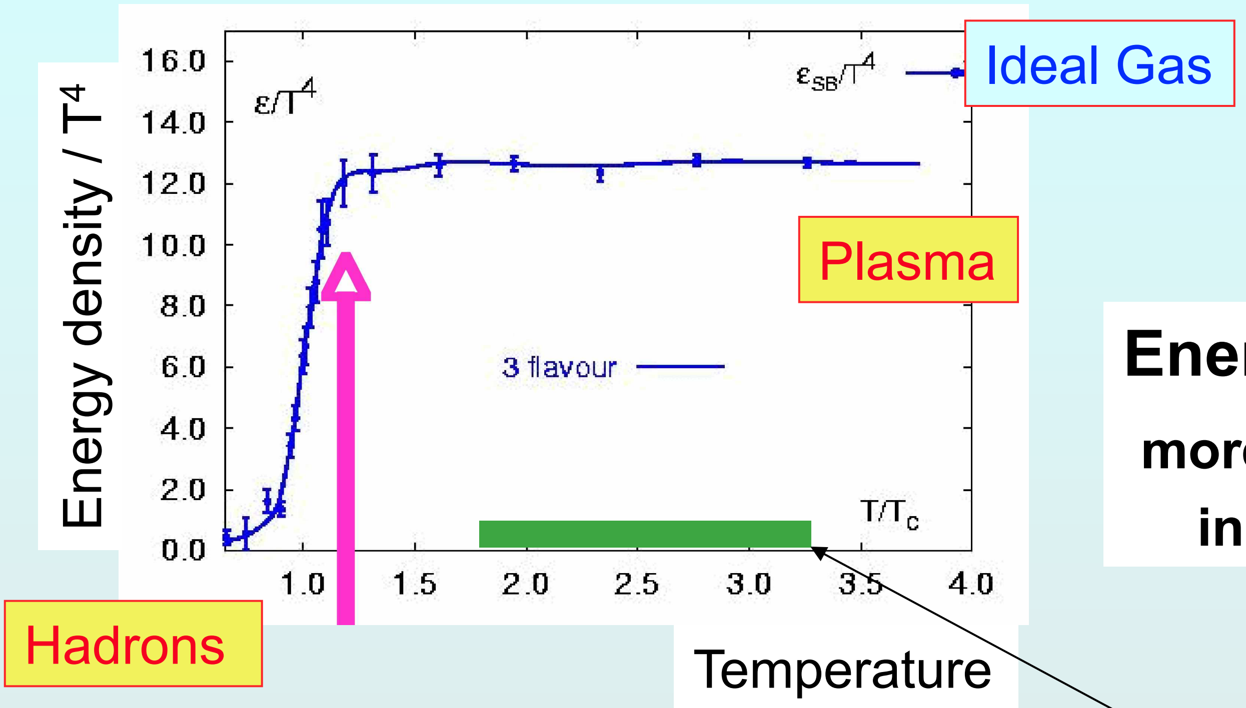




VTX Stripixel Layer 4



So, it must be quark gluon plasma



$$\varepsilon = g\frac{\pi^2}{30}T^4$$

Energy density ∝ T^4

more degrees of freedom in the plasma phase

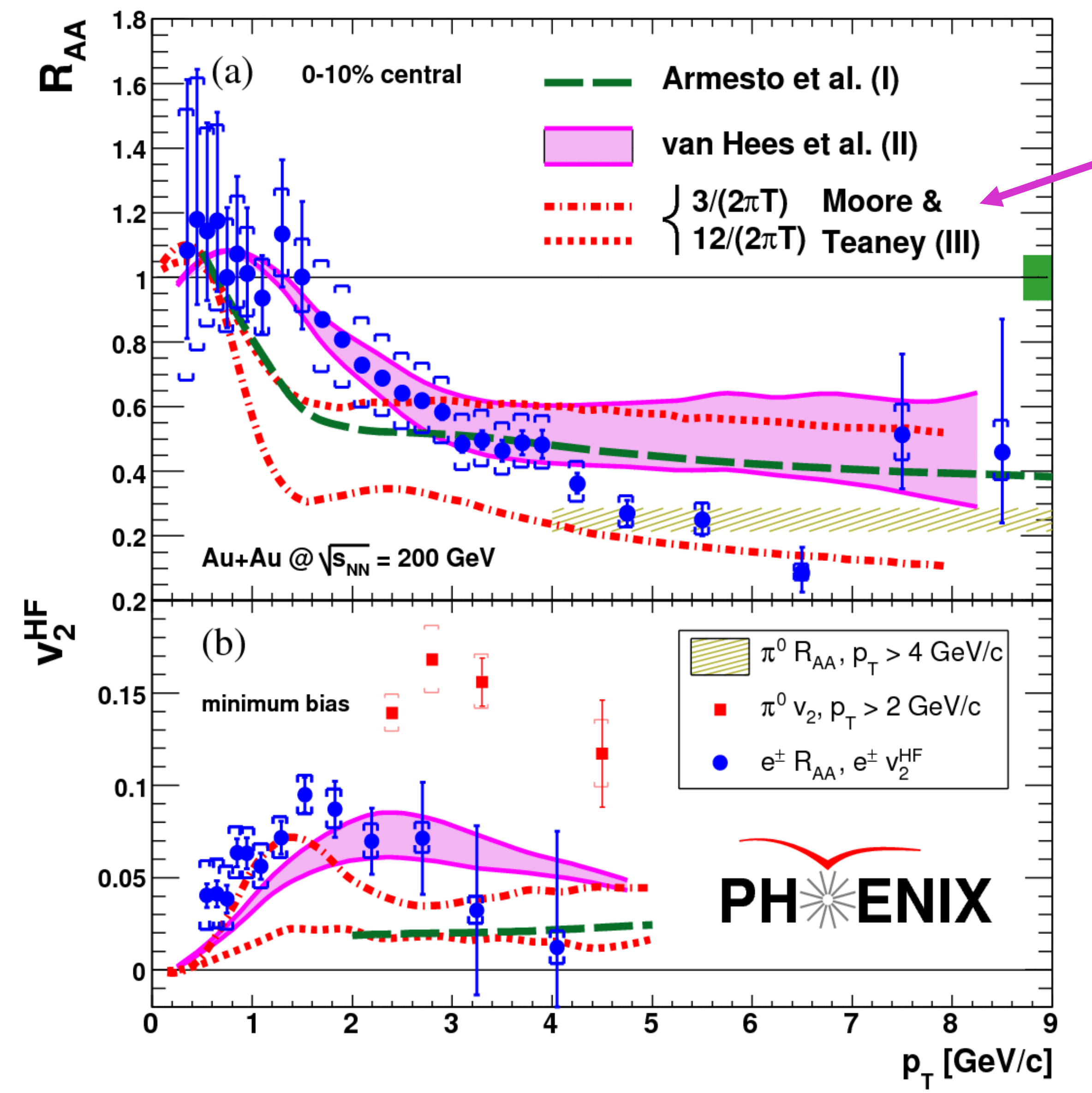
We are somewhere around here

T_c ~ 150 MeV

ε ~ 3 GeV/fm^3

an independent measure of viscosity

PRL98, 172301 (2007)



Heavy quark diffusion (Langevin equation)

drag force ↔ random force ↔ $<\Delta p_T^2>$/unit time ↔ D*

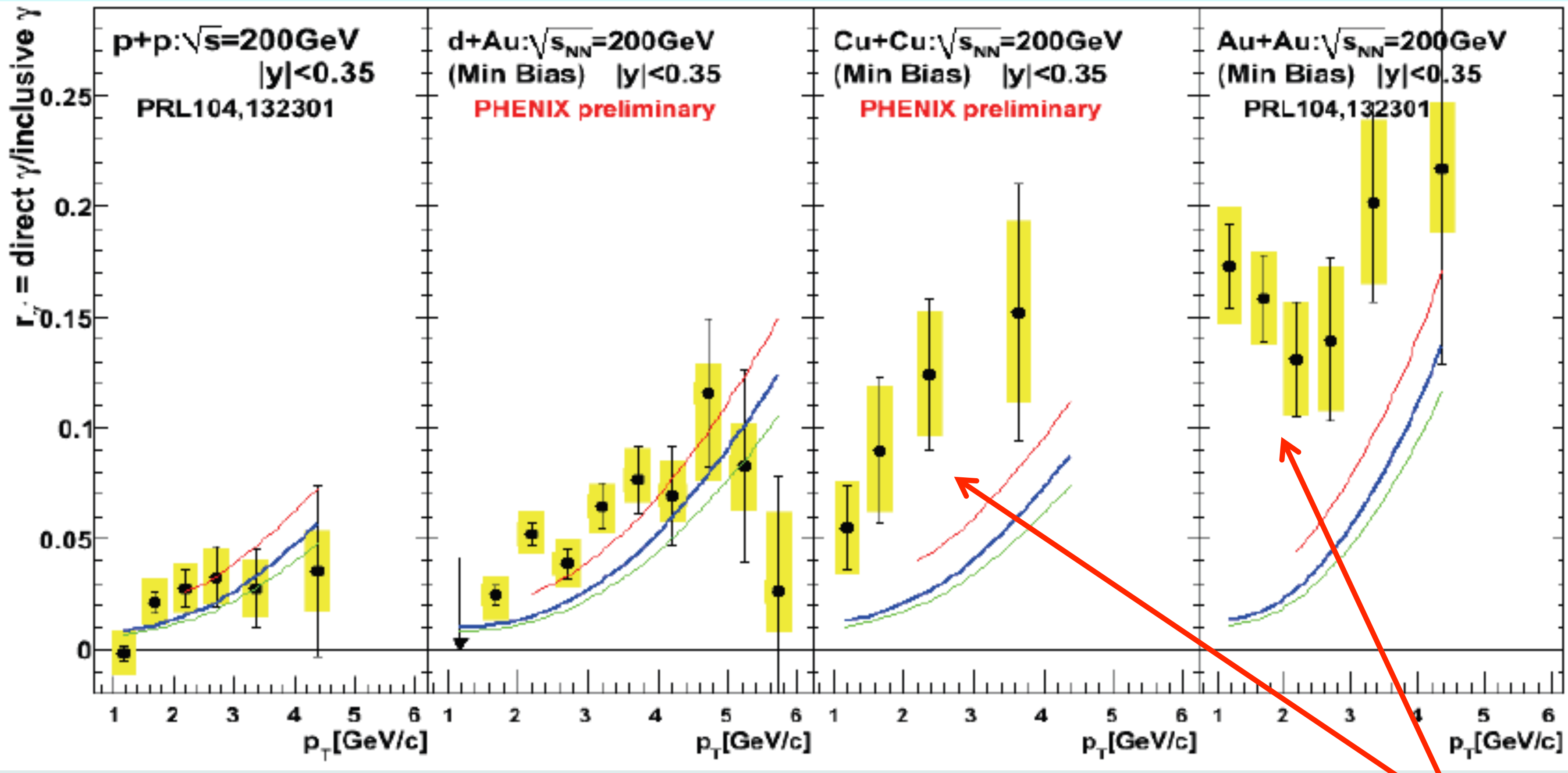
~ agrees with data
slow relaxation ruled out
Fast due to strong coupling

D ~ 4-6/(2πT)

$\eta = 1/3\ \rho <v> \lambda$
$D = <v>/\ 3\rho s$
$D = \eta/\rho \sim \eta/S$

→ η/S = (1.3 – 2.0)/ 4π

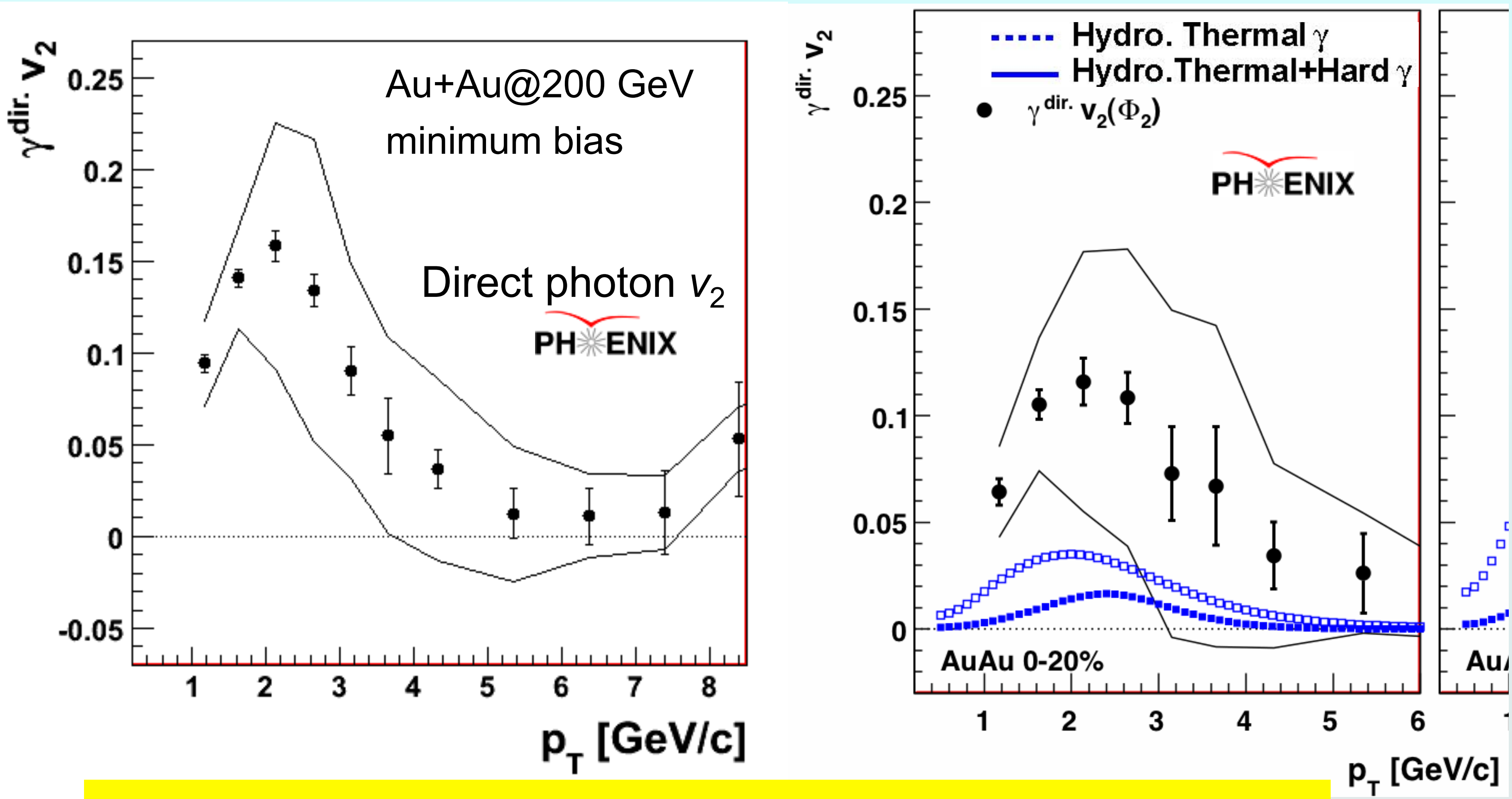
Thermal photon rates



Observe excess photons beyond pQCD in AA collisions.

Thermal photons also flow!

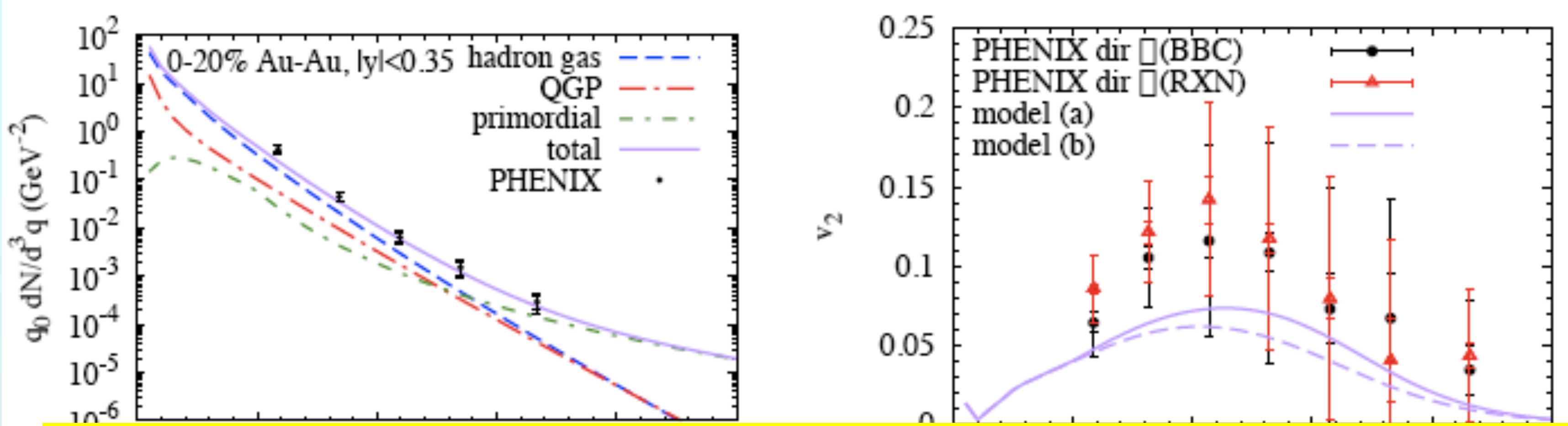
arXiv:1105.4126



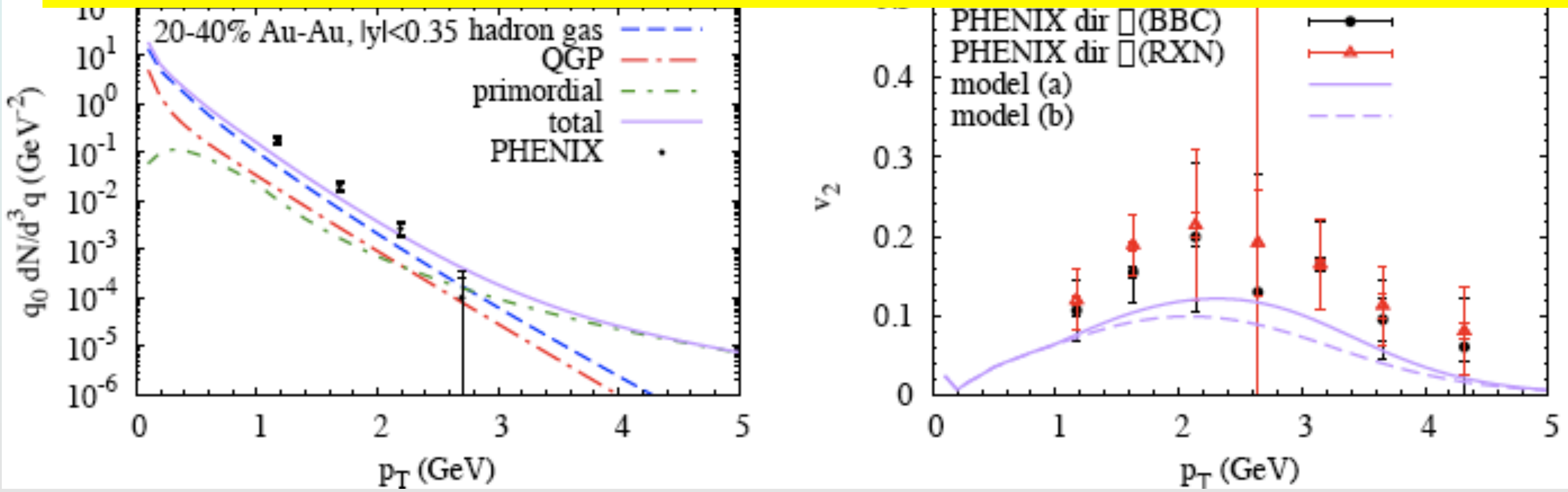
Flow magnitude is surprising. Can "extras" explain it?

+ photons from expanding hadron gas

vanHees, Gale & Rapp, arXiv:1108.2131



Answer = yes, if “extras” come from a very rapidly expanding hadron gas, that lives longer than initially expected



What are the properties of hot QCD matter?

- thermodynamic (equilibrium)

  T, P, ρ

  EOS (relation between T, P, V, energy density)

  v_{sound}, static screening length

- transport properties (non-equilibrium)*

  particle number, energy, momentum, charge

  diffusion sound viscosity conductivity

In plasma: interactions among charges of multiple particles

charge is spread, screened in characteristic (Debye) length, λ_D

NB: we deal with strong, not EM force: exchange g instead of γ

measuring these is new for nuclear/particle physics!

Nature is nasty to us: does a time integral…

Lepton pair emission ↔ EM correlator

e.g. Rapp, Wambach Adv.Nucl.Phys 25 (2000)

Emission rate of dileptons per volume

$$\frac{dR_{ll}}{d^4q} = -\frac{\alpha^2}{3\pi^3}\frac{L(M)}{M^2}\mathrm{Im}\Pi^{\mu}_{em,\mu}(M,q;T)f^B(q_0,T)$$

$$f^B(q_0,T) = 1/(e^{q_0/T}-1)$$

$$L(M) = \sqrt{1-\frac{4m_l^2}{M^2}}(1+\frac{2m_l^2}{M^2})$$

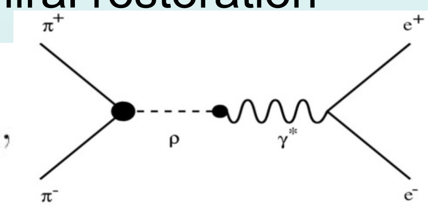
γ*→ee decay

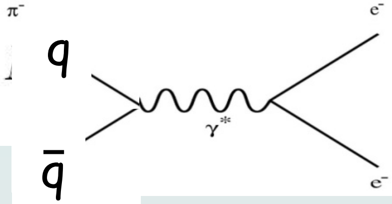
EM correlator
Medium property

Boltzmann factor
temperature

Hadronic contribution
Vector Meson Dominance → Medium modification of meson
Chiral restoration

$$\mathrm{Im}\Pi^{\mathrm{vac}}_{\mathrm{em}}(M) = \begin{cases} \sum_{V=\rho,\omega,\phi}\left(\frac{m_V^2}{g_V}\right)^2 \mathrm{Im}D_V(M) & , \\ -\frac{M^2}{12\pi}\left(1+\frac{\alpha_s(M)}{\pi}+\ldots\right)N_c\sum_{q=u,d,s}(e_q)^2 & , \end{cases}$$

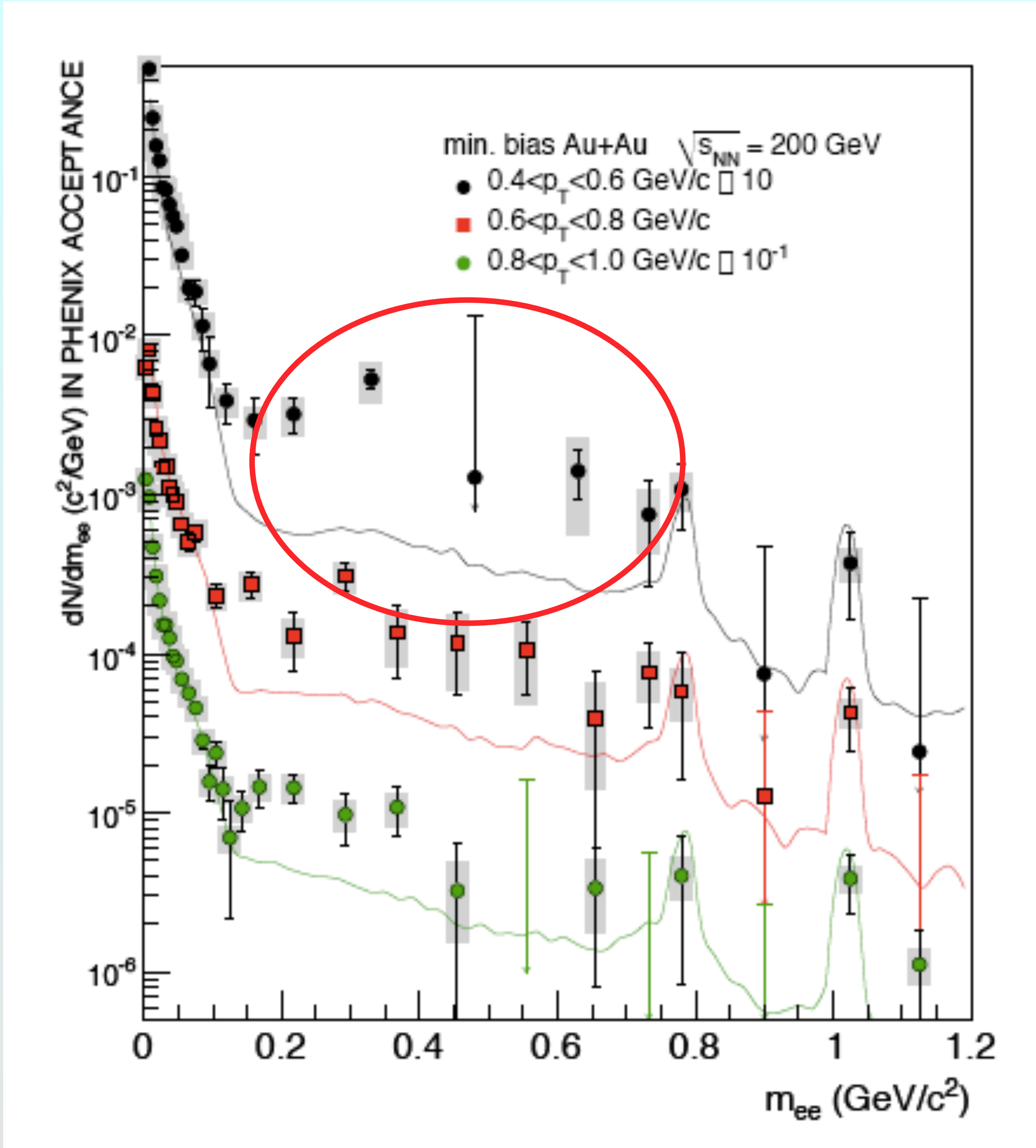




$q\bar{q}$ annihilation → Thermal radiation from partonic phase (QGP)

From emission rate of dileptons, the medium effect on the EM correlator as well as temperature of the medium can be decoded.

e^+e^- looks intriguing



2004 data

arXiv: 0912.0244

PRC, in press

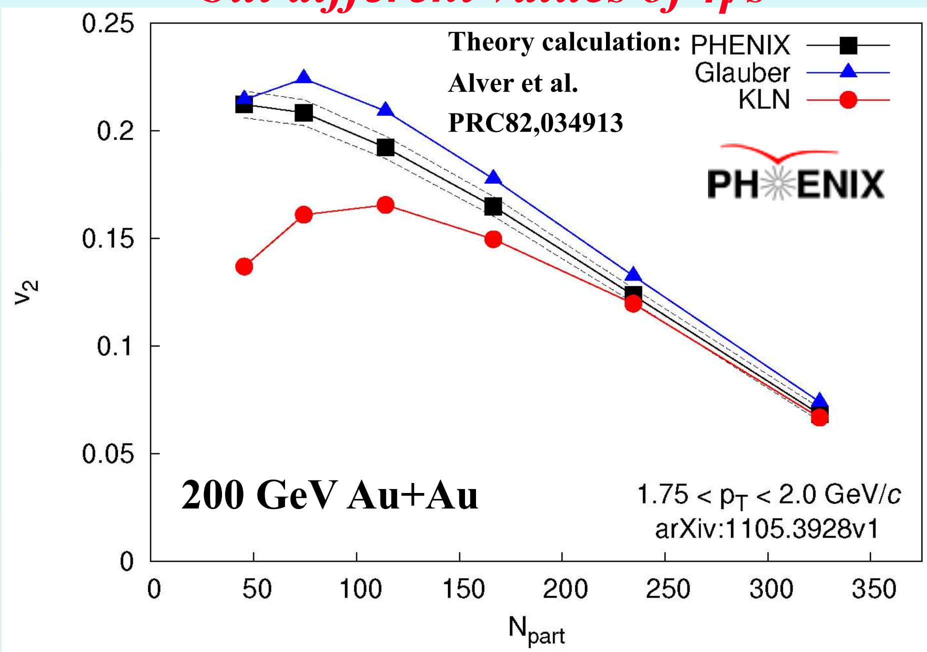
We're taking more, better data now

Fluctuations, flow and the quest for η/s

arXiv:1105.3928

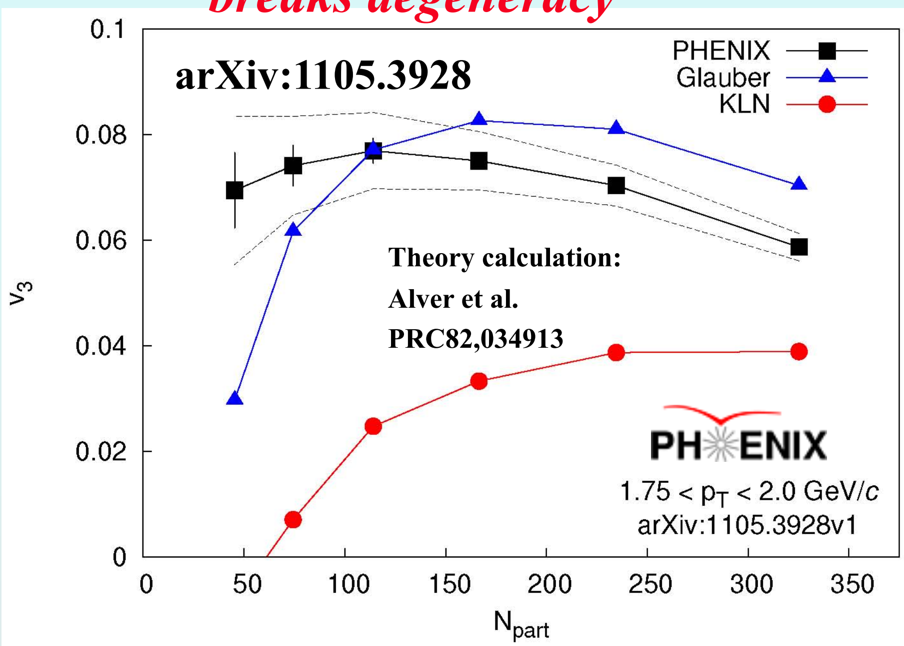
***v_2* described by both Glauber and CGC**

but different values of η/s



***v_3* described only by Glauber**

breaks degeneracy



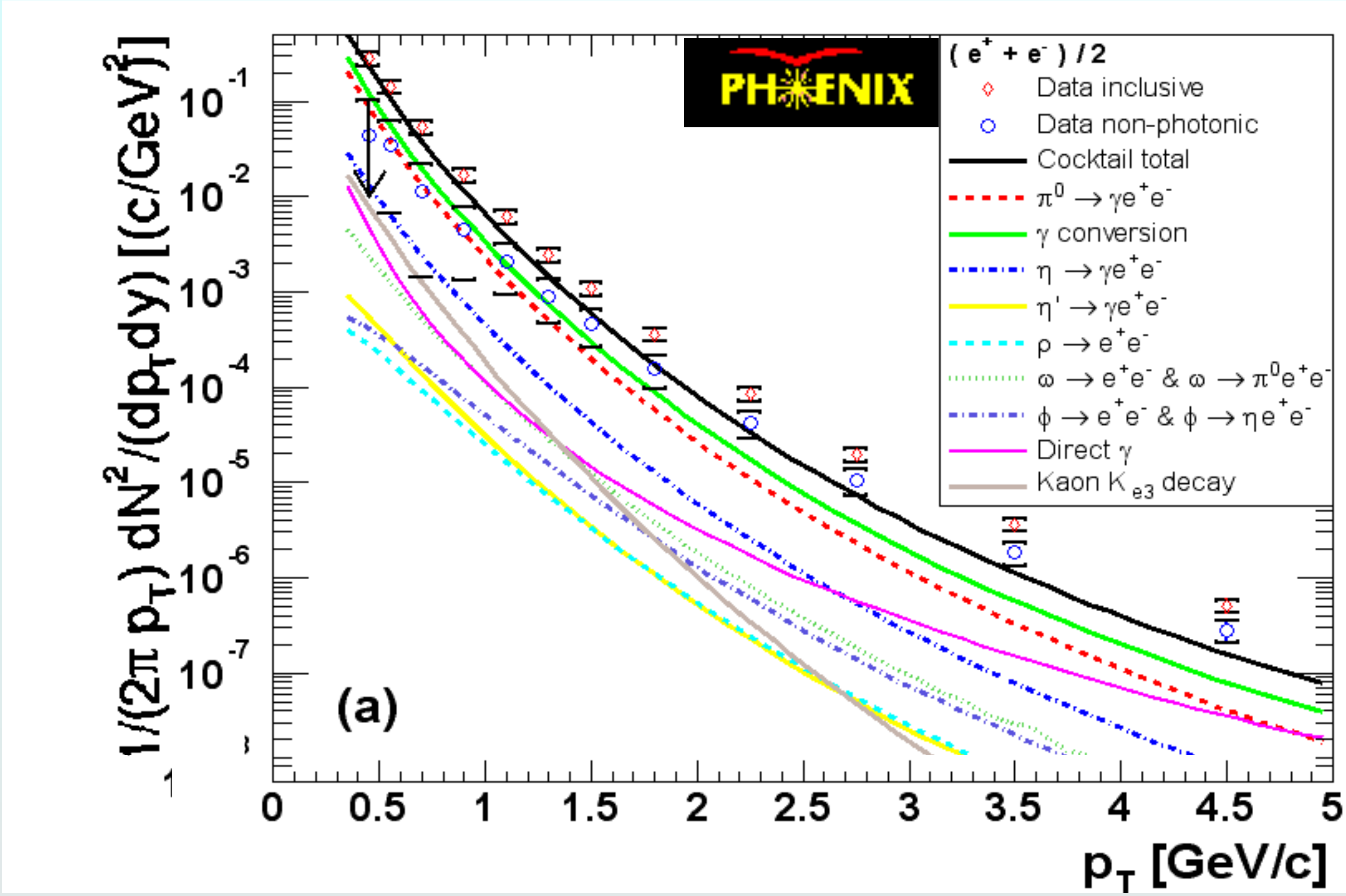
Lappi, Venugopalan, PRC74, 054905
Drescher, Nara, PRC76, 041903

- Glauber
  - Glauber initial state
  - $\eta/s = 1/4\pi$

2 models with
Different fluctuations,
Eccentricity, ρ distribution

- MC-KLN
  - CGC initial state
  - $\eta/s = 2/4\pi$

c,b decays via single electron spectrum



compare data to "cocktail" of (measured) hadronic decays

PRL 96, 032301 (2006)

High m_{eff} → large collisional energy loss

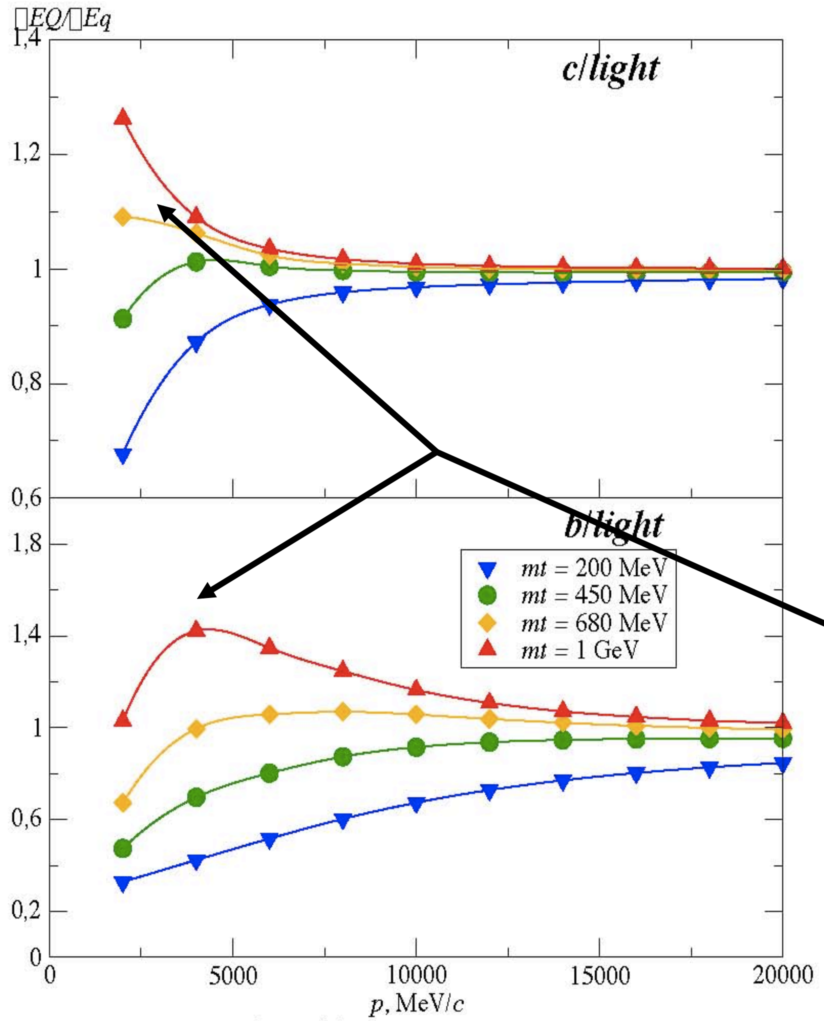


Fig. 3. The heavy-to-light ratio $\Delta E_Q/\Delta E_q$ of collisional energy loss for charm quarks (upper panel) and bottom quarks (lower panel), compared to that of light quarks (m_q = 200 MeV). The results for the numerator ΔE_Q and the denominator ΔE_q are the same as used for plotting Fig. 2.

R. Kolevatov &
U.A. Wiedemann
arXiV:0812.0270

- The "clumps"?
- b/c separation allows to test!

Quantum lower bound on viscosity/entropy

Kovtun, Son, Starinets, Phys.Rev.Lett.94:111601, 2005

$$\frac{\eta}{s} = \frac{\hbar}{4\pi k_B} \approx 6.08 \times 10^{-13} \text{ K s} .$$

Lower bound for class of thermal quantum field theories

$$S = \frac{A}{4G} ,$$

Entropy proportional to area of event horizon

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

Viscosity from correlation in stress energy tensor

$$\sigma_{\rm abs}(\omega) = -\frac{2\kappa^2}{\omega} \operatorname{Im} G^{\rm R}(\omega) = \frac{\kappa^2}{\omega} \int dt\, d\mathbf{x}\, e^{i\omega t} \langle [T_{xy}(t, \mathbf{x}), T_{xy}(0, 0)] \rangle ,$$

Dual to graviton absorption cross section

$$\eta = \frac{\sigma_{\rm abs}(0)}{2\kappa^2} = \frac{\sigma_{\rm abs}(0)}{16\pi G} .$$

The absorption cross section for the scalar is constrained by a theorem [17, 18], which states that in the low-frequency limit $\omega \to 0$ this cross section is equal to the area of the horizon, $\sigma_{\rm abs} = a$. Since $s = a/4G$, one immediately finds that

$$\frac{\eta}{s} = \frac{\hbar}{4\pi k_B} , \tag{14}$$

Timescales according to AdS/CFT

- Horizon of black hole in AdS at distance $1/\pi T$ from boundary
  - Sets light arrival time
  - Black holes form by gravity
  - Gravitons travel at c
- Timescale for black hole formation is $\tau = 1/\pi T$
  - For T=318 MeV, τ = hbar c /1 GeV = 0.2 fm
- Decay rate for non-hydro modes
  - $\tau_{e\text{-fold}} \sim 1/8.6T_{init}$ yielding $\tau \sim 0.3$ fm/c
- still need to separate τ and T_{init}

Gubser & Karch, Ann Rev. Nucl. Part. Sci. 59, 145 (2009)

Friess, Gubser, Michalogiorgakis, Pufu, JHEP 04, 80 (2008))

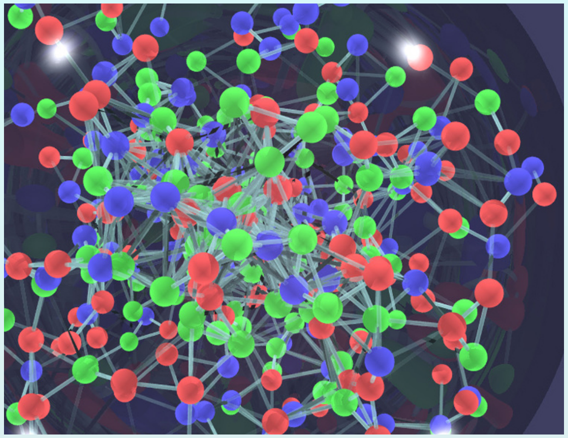
- Of course, the coupling is NOT ∞

Currently a raging debate

- Just *WHAT* is interacting in the hot dense plasma?

Individual gluons?

Pure fields?



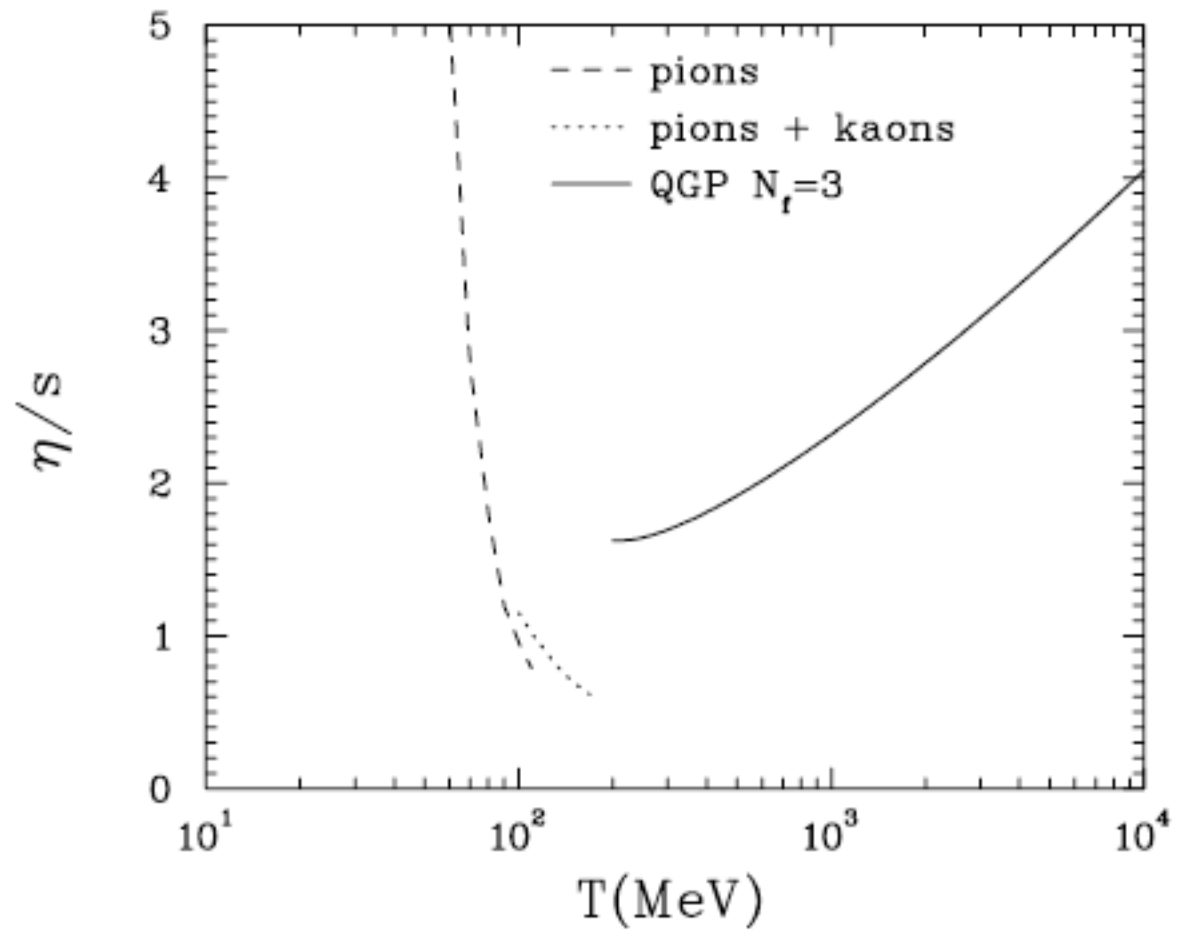
Multi-gluons that continuously split & re-form?

i.e. composite quasiparticles

(in classical liquids voids fill this role)

- Energy loss mechanism tests these ideas
- Quantify dynamical properties of this new material:
  Viscosity, speed of sound, diffusion
  i.e. transport of momentum, energy & particles

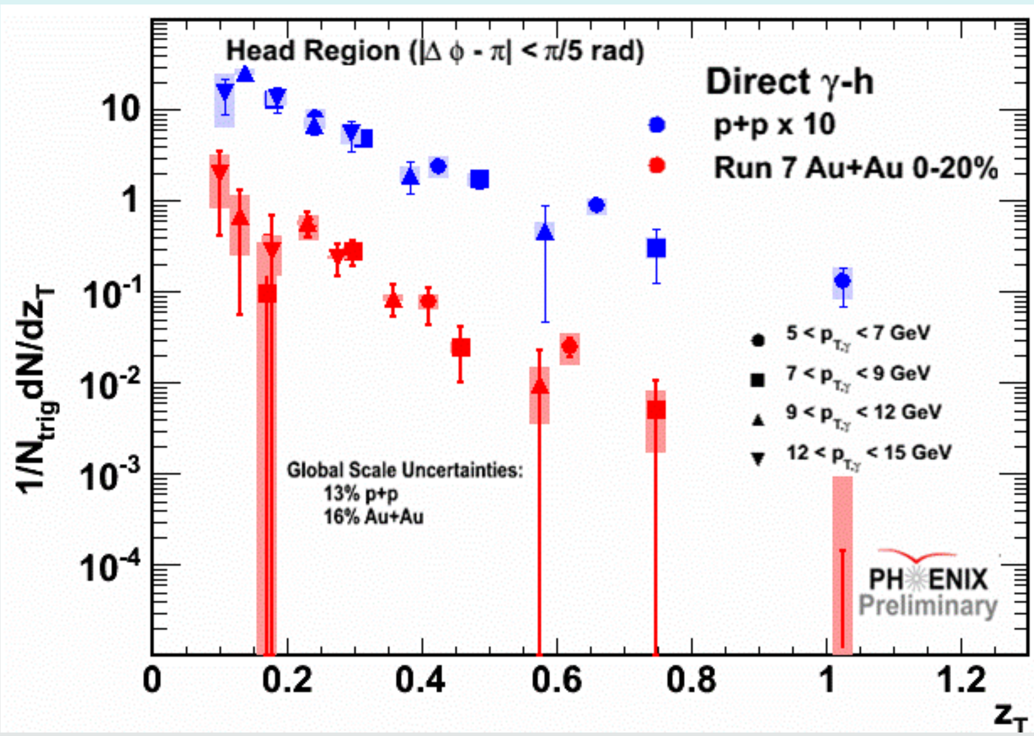
Viscosity *should* be low near phase transition



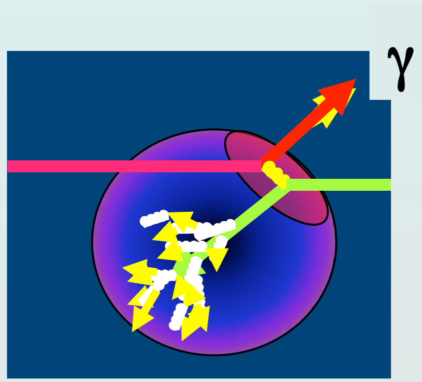
Csernai, Kapusta, McLerran

New questions, continued

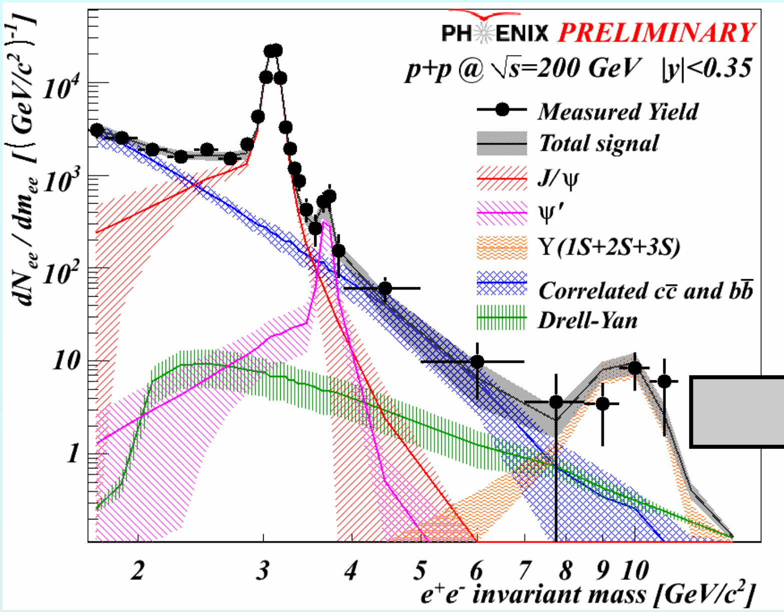
- Precision jet probes of energy transport in medium
  - Energy loss mechanism?
  - What are the degrees of freedom?
  - Is heavy quark fragmentation modified?

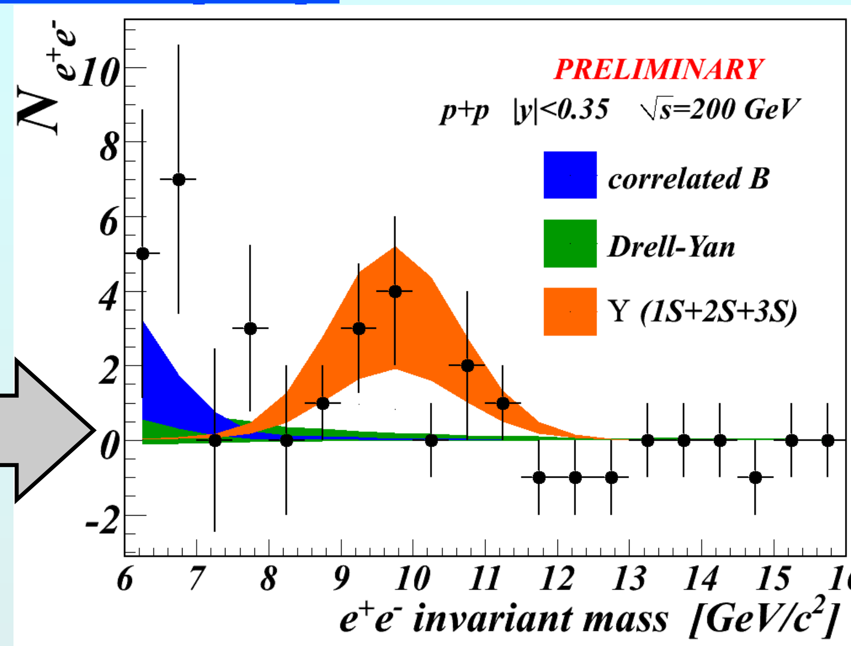


Calibrate the probe energy: use QCD Compton process



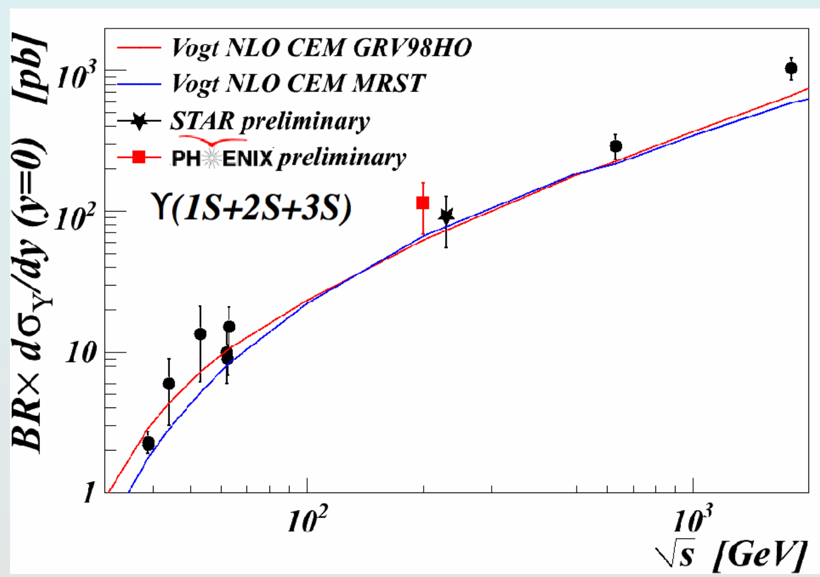
Upsilon in p+p



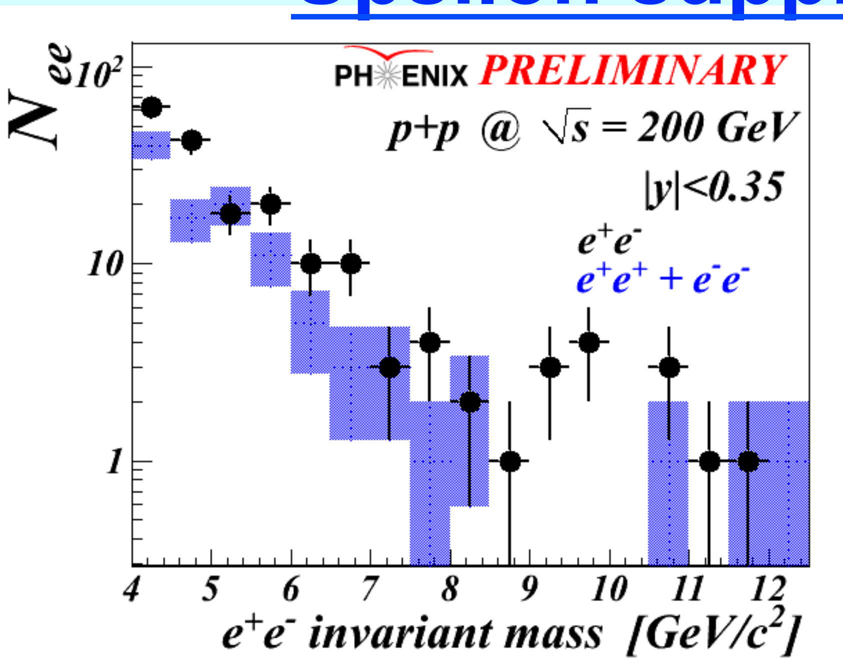


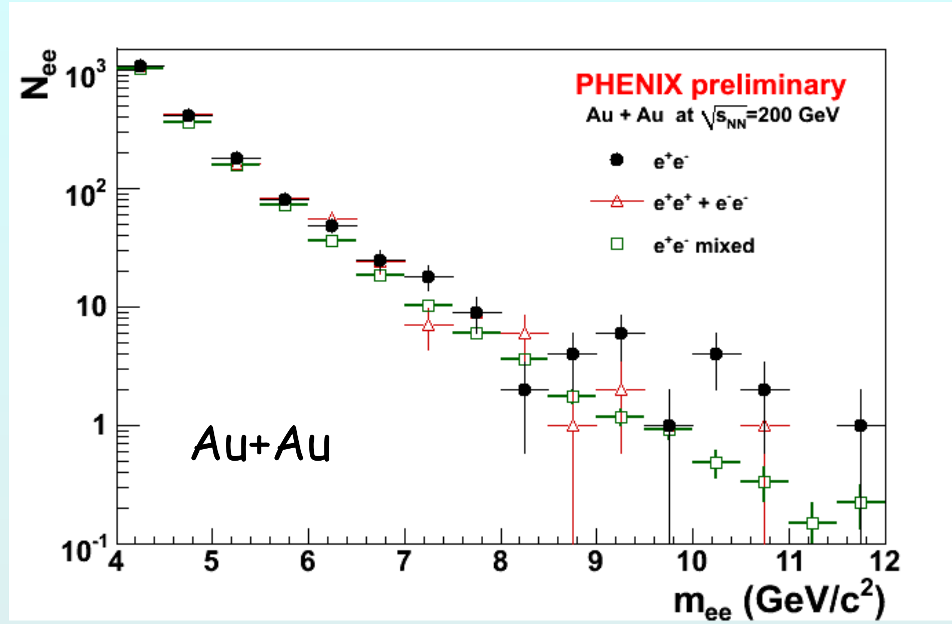
Cross section follows world trend

$$BR * \frac{d\sigma}{dy}\Big|_{|y|<0.35} = 114^{+46}_{-45}\, pb$$



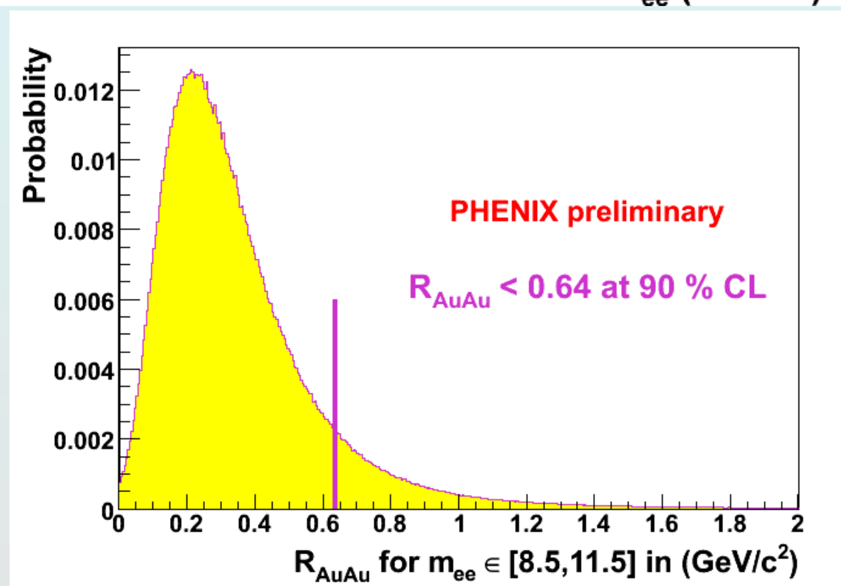
Upsilon suppressed in Au+Au!





	p+p	Au+Au
N[8.5,11.5]	10.5(+3.7/-3.6)	11.7(+4.7/-4.6)
$N_{J/\Psi}$	2653 ±70±345	4166 ±442(+187/-304)
$R_{AA}(J/\Psi)$	---	0.425 ±0.025±0.072

R_{AA} [8.5,11.5] < 0.64 at 90% C.L.



Should Υ's be suppressed?

Υ as onium melting baseline…

	$R_{AuAu}(y=0)$
J/Ψ	0.425 ± 0.025 ± 0.072
8.5<M<11.5 GeV	< 0.64 at 90% C.L.

- σ_{abs} of Υ ~1/2 of J/Ψ : E772 (*PRL 64, 2479 (1990)*)
  - E772 Υ nuclear dependence corresponds to R_{AuAu} = 0.81
- Lattice expectations in Au+Au - Υ_{2S+3S} suppressed: R_{AuAu} = 0.73
- **absorption x lattice ~ 0.73 x 0.81 ~ 0.60 ???**

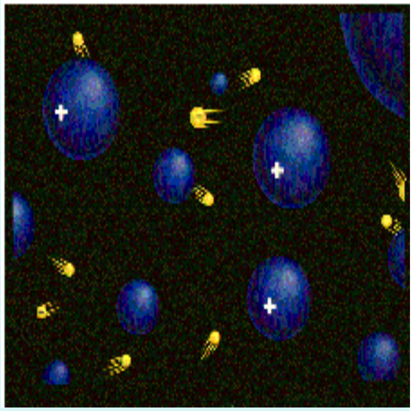
need serious theory estimate instead of this naïve speculation!

  - e.g. Grandchamp et al. hep-ph/0507314

ALSO:

- Υ in anti-shadowing region
- CDF: 50% of Υ from χ_b (p_T>8 GeV/c) & ~25%? at our p_T
  - *PRL84 (2000) 2094*

what is a plasma?



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

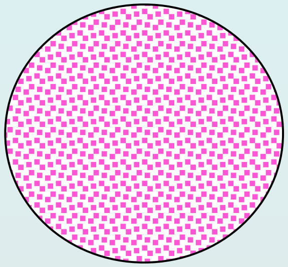
- interactions among charges of multiple particles
  spreads charge into characteristic (Debye) length, λ_D
  multiple particles inside this length
    they screen each other
  plasma size > λ_D

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

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 λ_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 λ_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)

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

- 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]

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

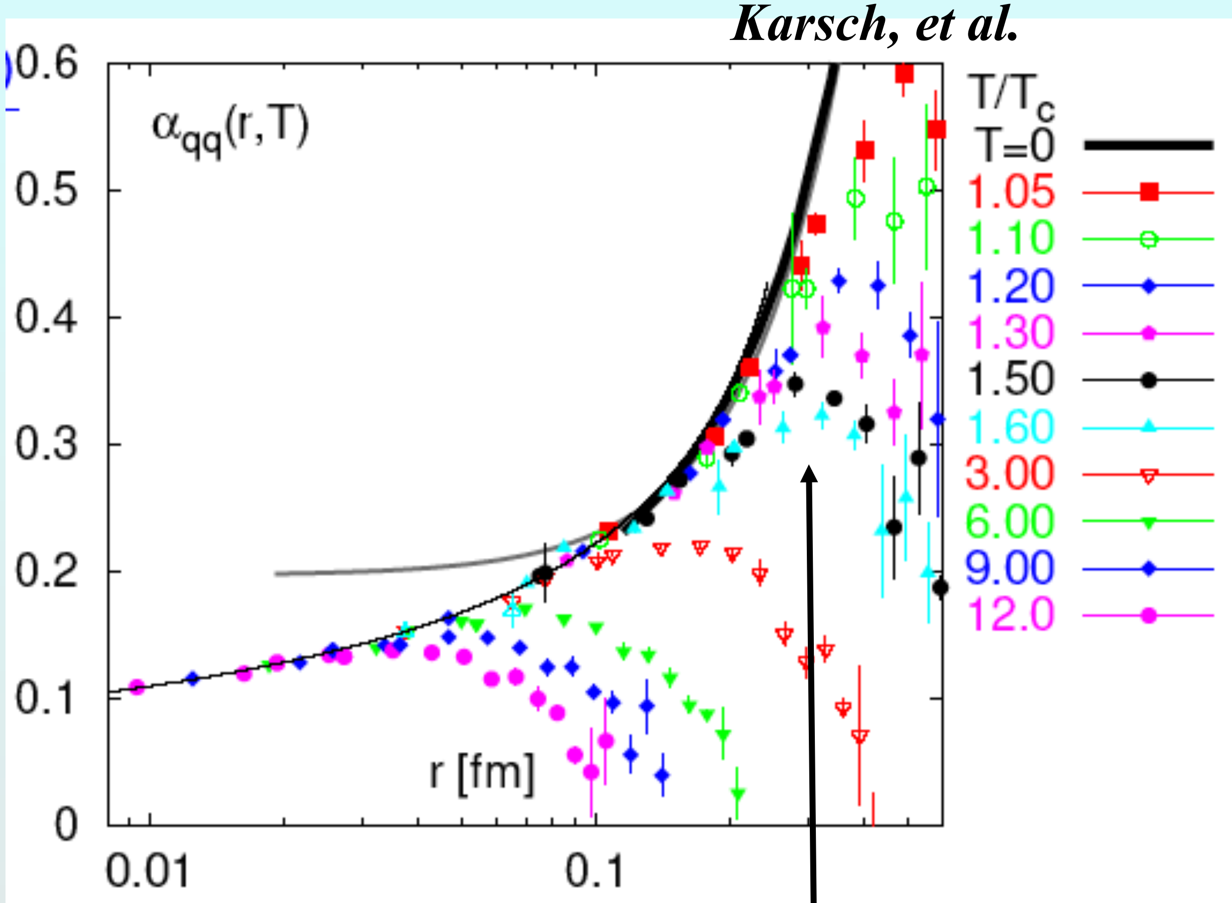
which is non-analytic in the coupling constant. While the coefficient of the logarithm is fixed perturbatively, c_N is entirely non-perturbative. The reason is that, starting from this order in g, the non-abelian A_0 couples to the soft magnetic gluons $A_i \sim g^2 T$, and hence becomes sensitive to 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.

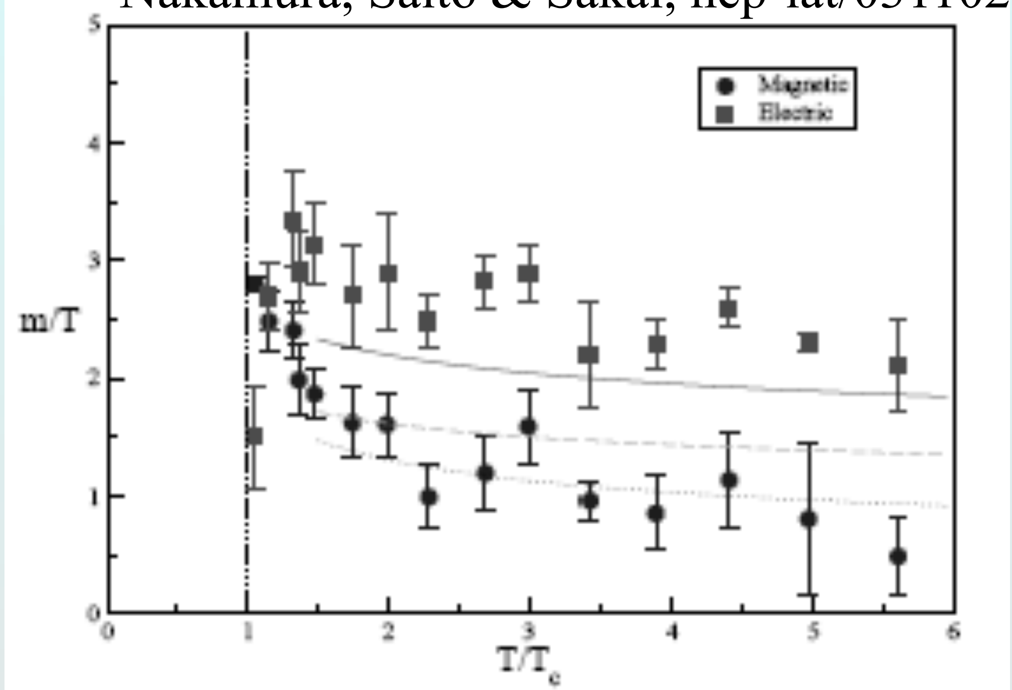
T dependence of electric & magnetic screening masses
Quenched lattice study of gluon propagator

figure shows:

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

$\therefore\ \lambda_D \sim 0.4,\ 0.2$ 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 λ_D ~ 0.3 fm?

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

  for λ_D = 0.3fm and ε = 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 ~ $2T_c$ and $g^2 = 4$

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

  plasma is NOT fully screened – strongly coupled!

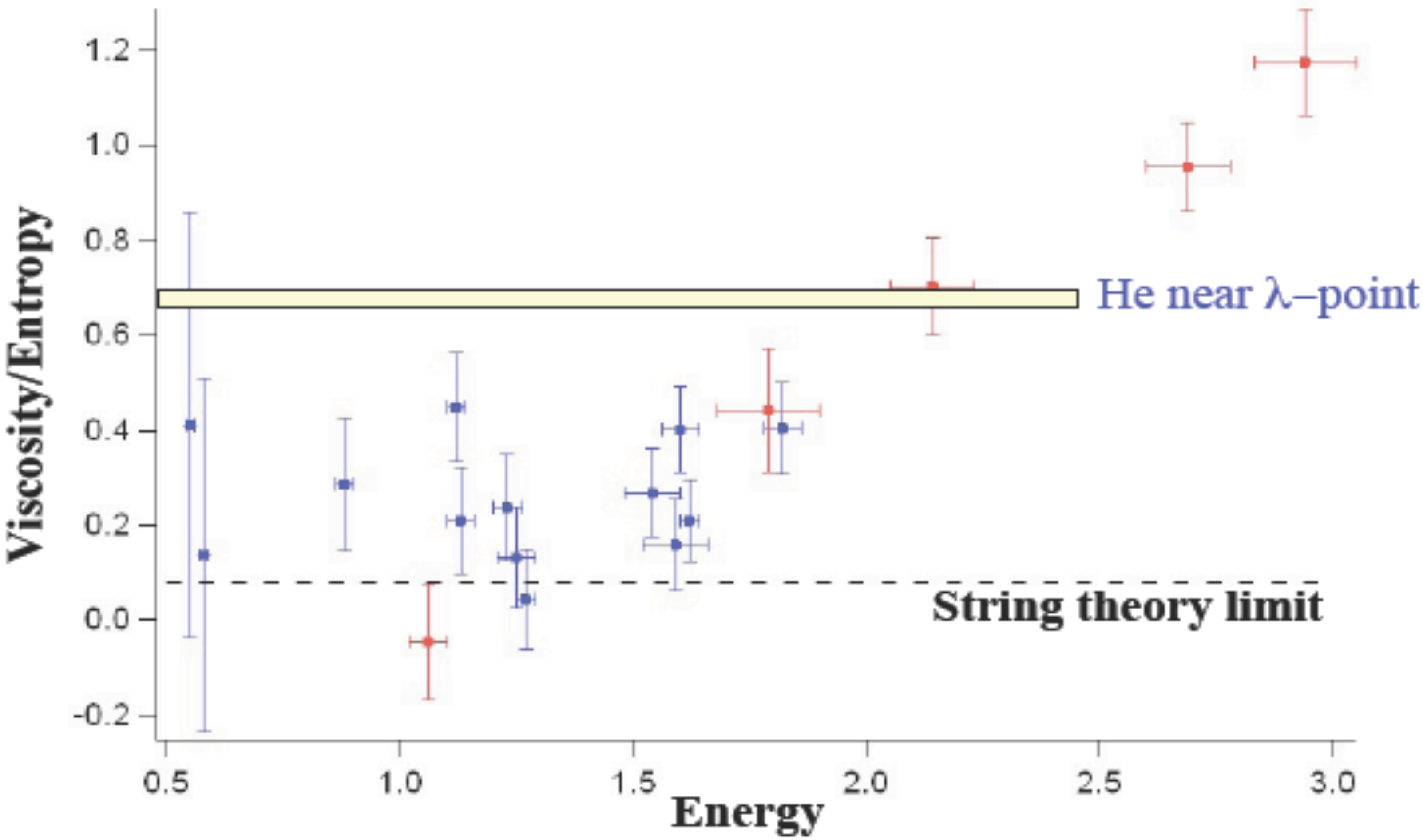
  affects interaction σ!

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

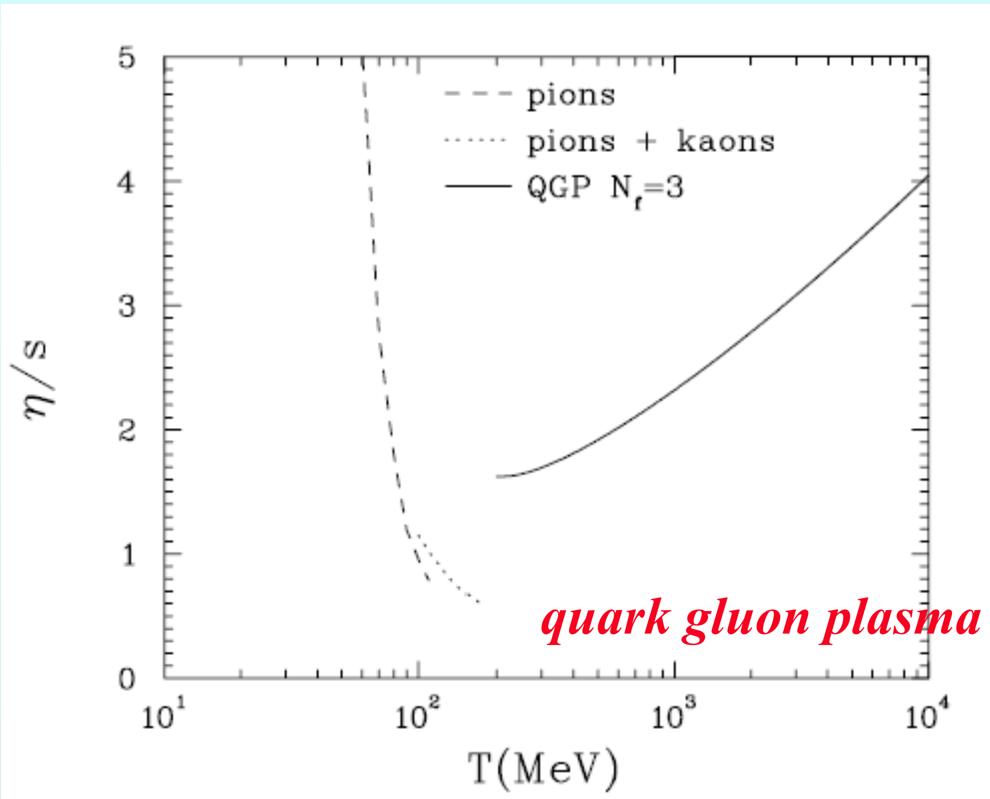
  dusty plasmas, cold atoms+ions , warm dense matter

Viscosity/Entropy (natural units)

Duke Physics
Atom Cooling and Trapping



minimum η at phase boundary?

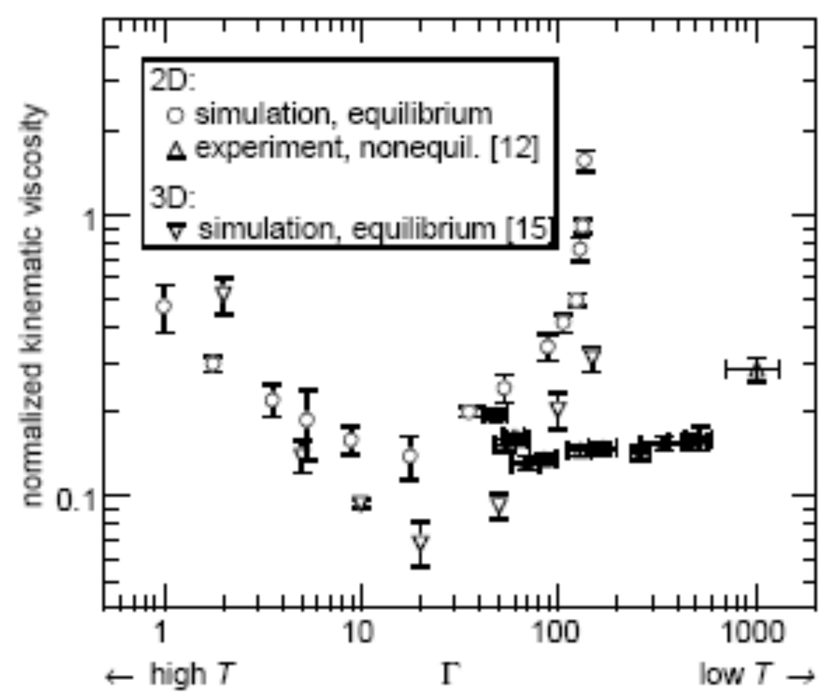


quark gluon plasma

Csernai, Kapusta & McLerran
PRL97, 152303 (2006)

strongly coupled dusty plasma

B. Liu and J. Goree,



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