Extreme Matter, Heavy Flavor Quarks, the Quark-Gluon Plasma (and some black holes mixed in)

- introductory remarks: physics in the strongly coupled limit
- the counter-intuitive world of viscosity
- how does gravity get into the game?
- the world of cold quantum gases
- hot and dense matter, quark-gluon plasma, RHIC and LHC

pbm
RQW 2010, Nantes, Oct. 2010

FIAS Frankfurt Institute for Advanced Studies

GSI

TECHNISCHE UNIVERSITÄT DARMSTADT

a new paradigm: strongly coupled systems

strongly coupled systems arise when the scattering cross section becomes very large

the viscosity/entropy density ratio η/s of such matter is then 'universal', i.e. independent of its detailed structure

from purely dimensional considerations

$$\frac{F}{A} = \eta \frac{v}{d} \quad \rightarrow \quad \eta \text{ has dimensions of kg/(m s)}$$

the entropy density s has dimension $1/m^3$ ($k_B = 1$)

$\rightarrow$ η/s has dimension kg m^2 s^{-1}, i.e. the dimension of $\hbar$

kinetic theory, viscosity, and the Heisenberg uncertainty relation

Estimate of viscosity from kinetic theory

$$\eta \sim \rho v \ell, \qquad s \sim n = \frac{\rho}{m}$$

$$\frac{\eta}{s} \sim m v \ell \sim \hbar \frac{\text{mean free path}}{\text{de Broglie wavelength}}$$

Quasiparticles: de Broglie wavelength $\lesssim$ mean free path

Therefore $\eta/s \gtrsim \hbar$

Danielewicz & Gyulassy 1985
Dam Son, QM2006

shear viscosity and cross section

$$\eta = 4/15 \cdot \rho v l = 4/15 \cdot m v n l = 4/15 \cdot \langle p \rangle n l \qquad (1)$$

with ρ the mass density, m the particle mass, n the particle density, and l the mean free path

(S.R. de Groot et al., Relativistic Kinetic Theory, North Holland, Amsterdam 1980)

then, with $l = 1/(n\sigma)$ where σ is the scattering cross section

$$\eta = 4/15 \cdot \langle p \rangle / \sigma \qquad (2)$$

note: the larger the cross section, the smaller the viscosity

also: viscosity is independent of density!

coefficient in front of $\hbar$

can be derived using AdS/CFT correspondence

Maldacena's conjecture:
some string theories in curved space time are
connected to conformal gauge theories in flat
(3+1) dimensional space

In the limit of very strong coupling the string theory
becomes identical to a version of Einstein's theory of general
relativity with negative cosmological constant

In technical terms:
4 dimensional N=4 Super Symmetric
SU(N_c) Yang-Mills theory ($N_c = \infty$) is dual to
Type II B Super String theory in an $AdSxS_5$

a new paradigm: strongly coupled systems

in strongly coupled systems, η/s is close to $\frac{\eta}{s} = \frac{\hbar}{4\pi}$
(Policastro, Son, Starinets, PRL 87 (2001) 081601)

in weakly coupled systems, η/s is large and diverges for a nearly ideal gas

in the dilute limit, $\frac{\eta}{s} \sim \epsilon\tau >> 1$

with ϵ : mean energy/particle
and τ : mean time between collisions

viscosity of pitch

experiment started in Queensland, Australia in 1927

only eight drops have fallen since then

determine shear viscosity of pitch to be 10^{11} times that of water

$\eta = 2.3\ 10^{8}$ Pa s

note: for QGP the shear viscosity

$\eta = 5\ 10^{11}$ Pa s

it is not the viscosity, but the η/s ratio which determines the properties of a fluid

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U Queensland

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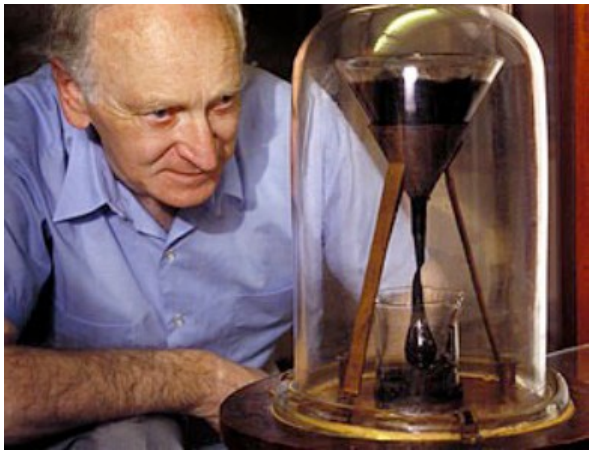


note: for QGP the shear viscosity

$\eta = 5\ 10^{11}$ Pa s

waiting for nr. 8

it is not the viscosity, but the η/s ratio which determines the properties of a fluid

viscosity and QCD

Strong interactions described by Quantum chromodynamics (QCD)

QCD is weakly coupled at high energy (high temperature, small distances), but strongly coupled at low energy ($\lesssim 1$ GeV): "asymptotic freedom"

In weakly coupled QCD:

Dam Son 2005

$$\eta = \frac{\#}{g^4 \ln(1/g)}$$

At experimentally achievable temperatures (few hundreds MeV) $g \gtrsim 1$.
Estimate of error: $> 100\%$

No strong-coupling technique to compute η

Lattice QCD: numerically solves QCD but in imagninary time, while we need real-time Green's functions.

Gauge/gravity duality (AdS/CFT correspondence) becomes a tool.

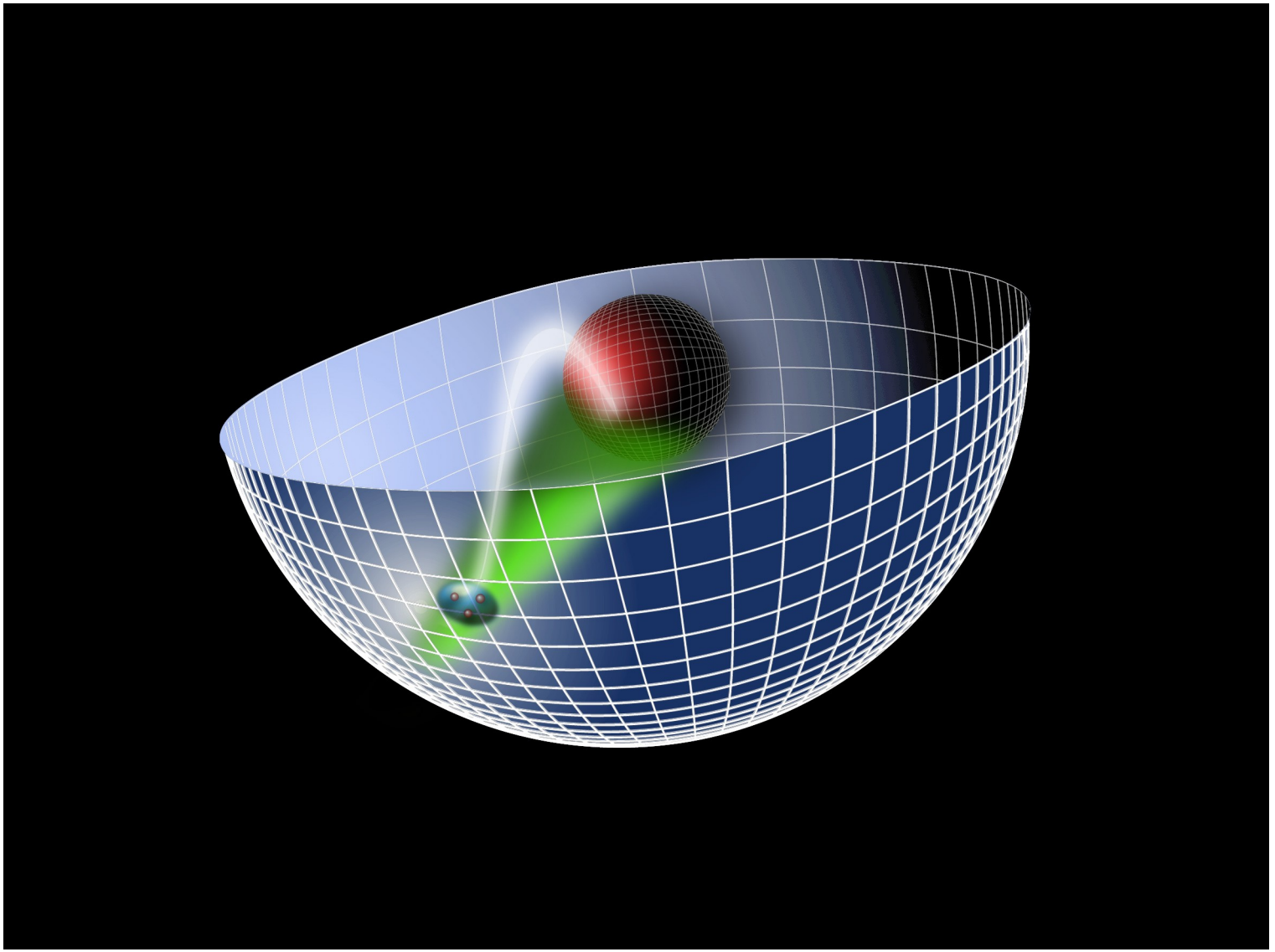
viscosity and entropy density in AdS/CFT

viscosity is obtained by computing the absorption cross section of low energy gravitons by the black hole

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

entropy is obtained via S = A/(4G) where A is the area of the black hole horizon and G is the gravitational constant

View of a proton in AdS/CFT a la Brodsky



2-2007
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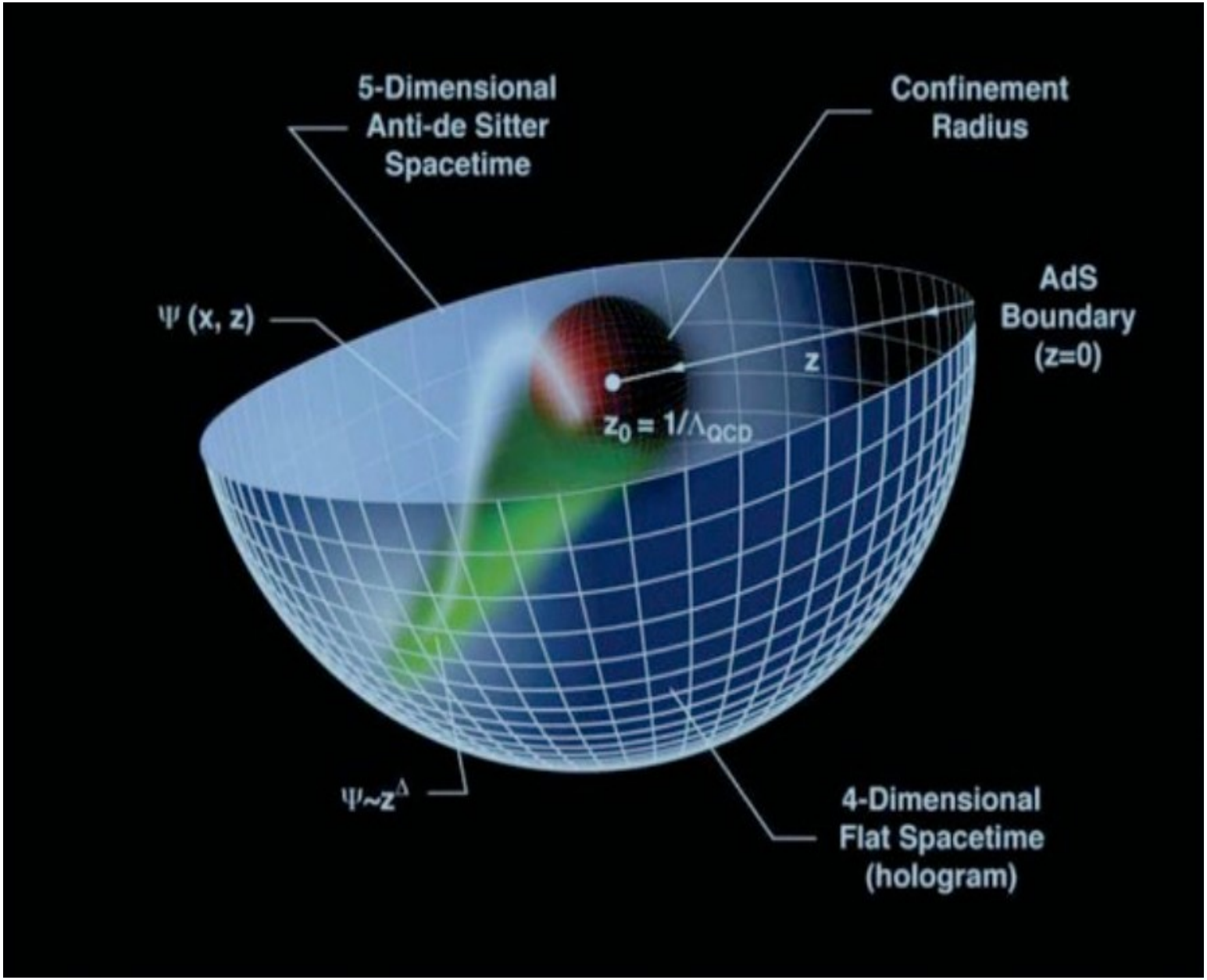
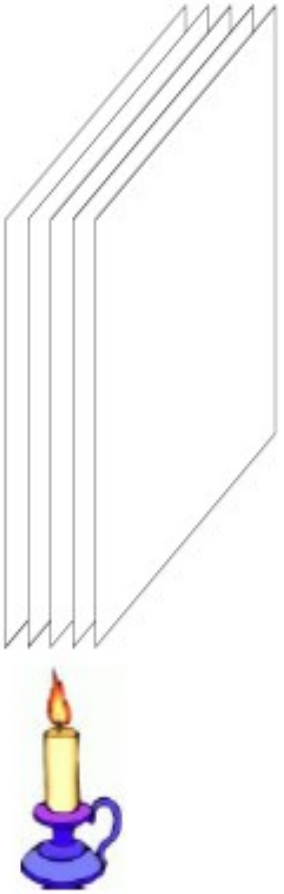

5-Dimensional
Anti-de Sitter
Spacetime
Confinement
Radius
AdS
Boundary
(z=0)
Ψ (x, z)
z
$z_0 = 1/\Lambda_{QCD}$
$\Psi \sim z^{\Delta}$
4-Dimensional
Flat Spacetime
(hologram)

Finite temperature AdS/CFT correspondence



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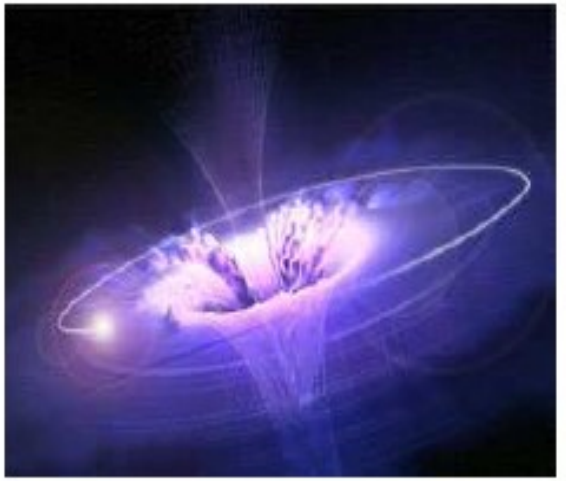


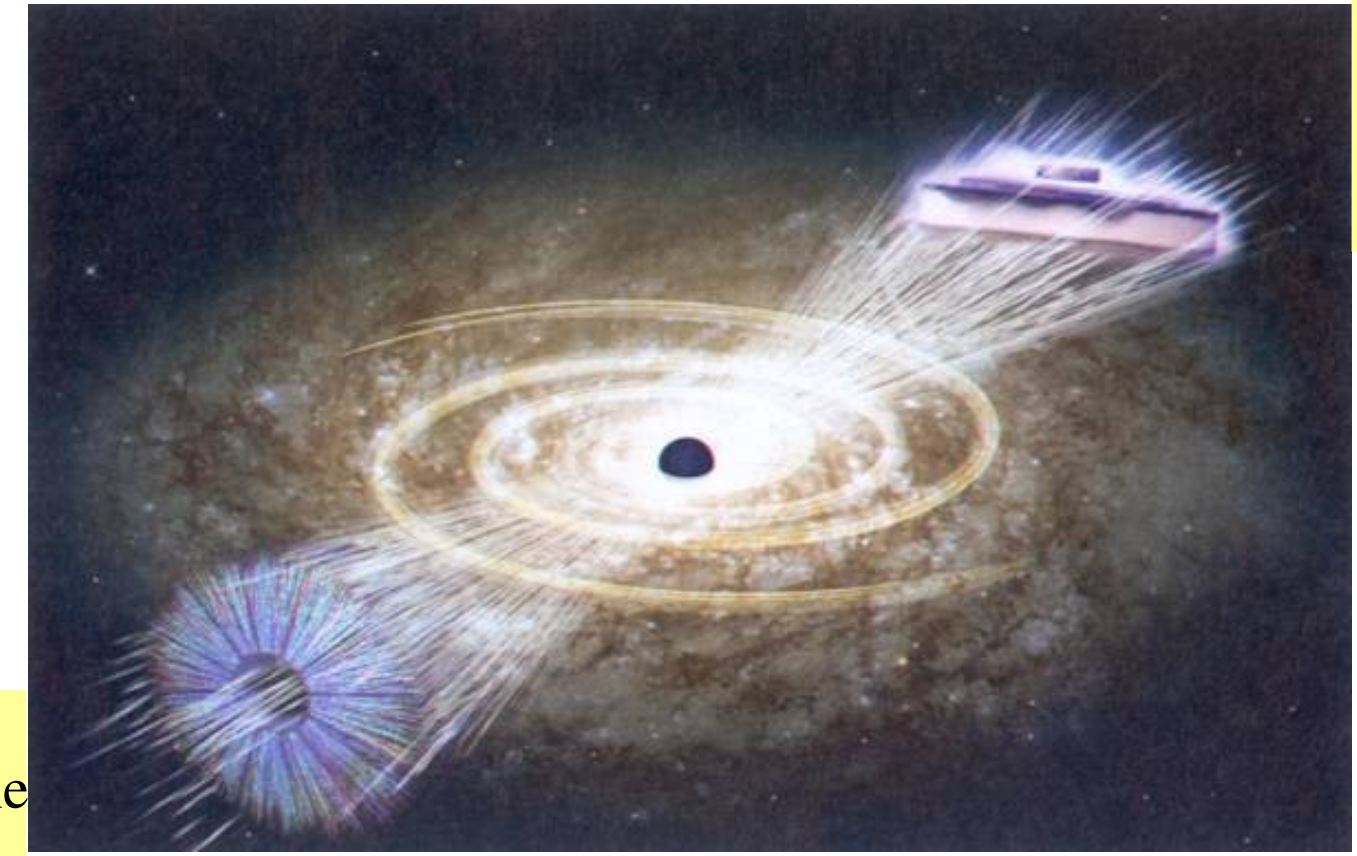
Thermal gauge theory = black hole in anti de-Sitter space

Dam Son, QM2006

Black holes, strings, QGP and high-T_c superconductors

Nature 448 Aug. 29 (2007) 1001

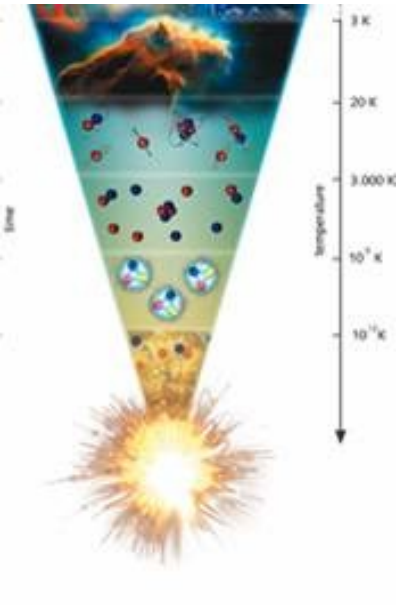
Nernst effect in 2-d cuprates high T_c super-conductivity

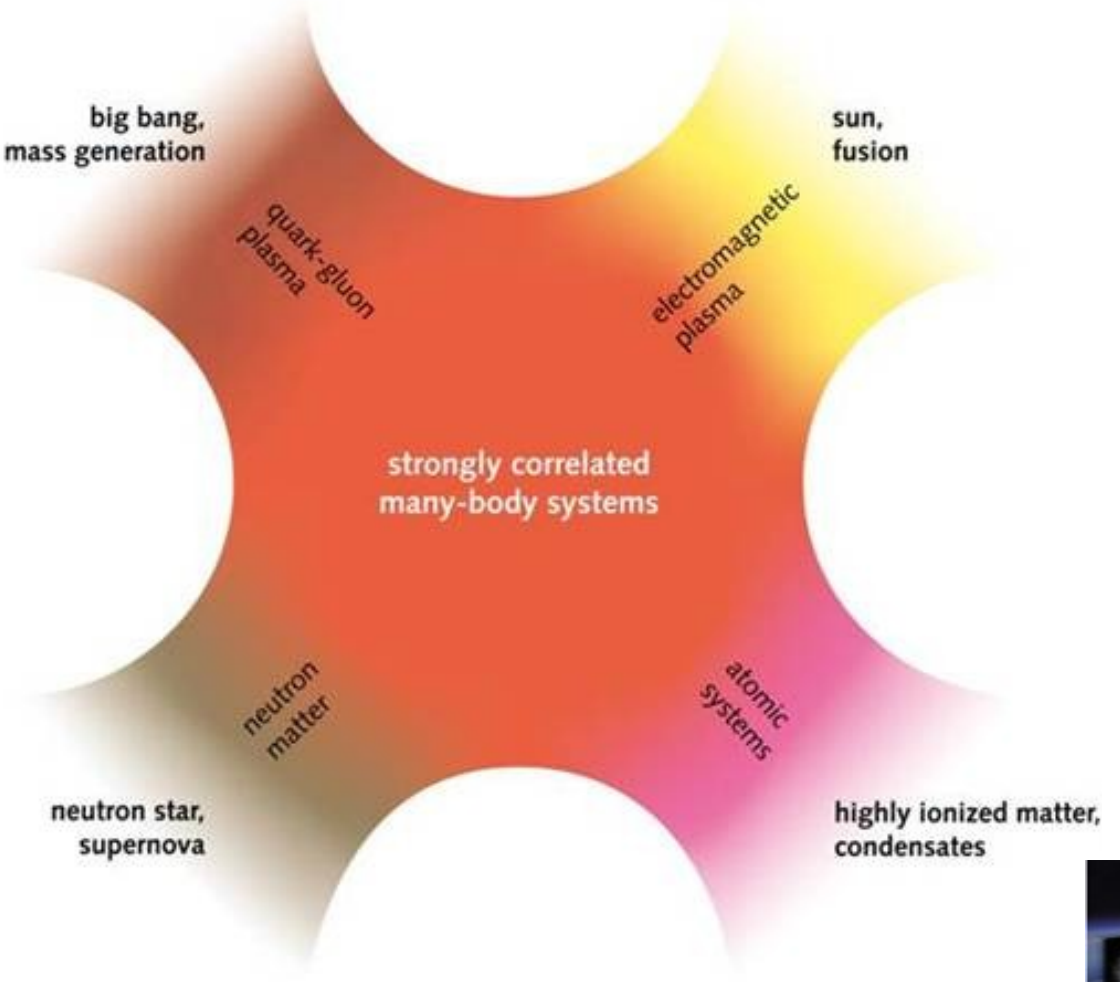


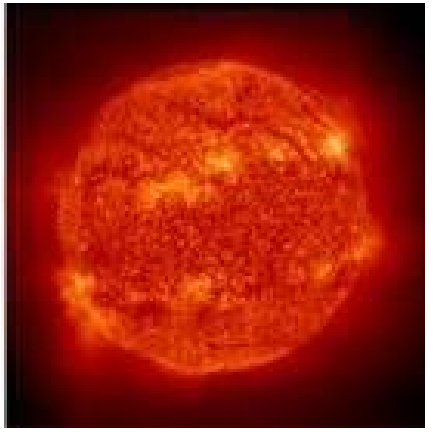
viscosity in the quark-gluon plasma (QGP)

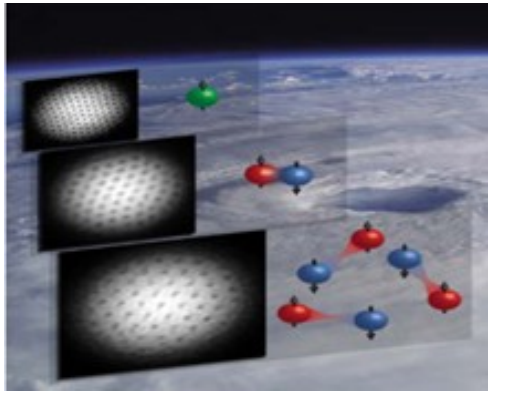
AdS/CFT correspondence

strongly coupled systems in nuclear physics and related areas

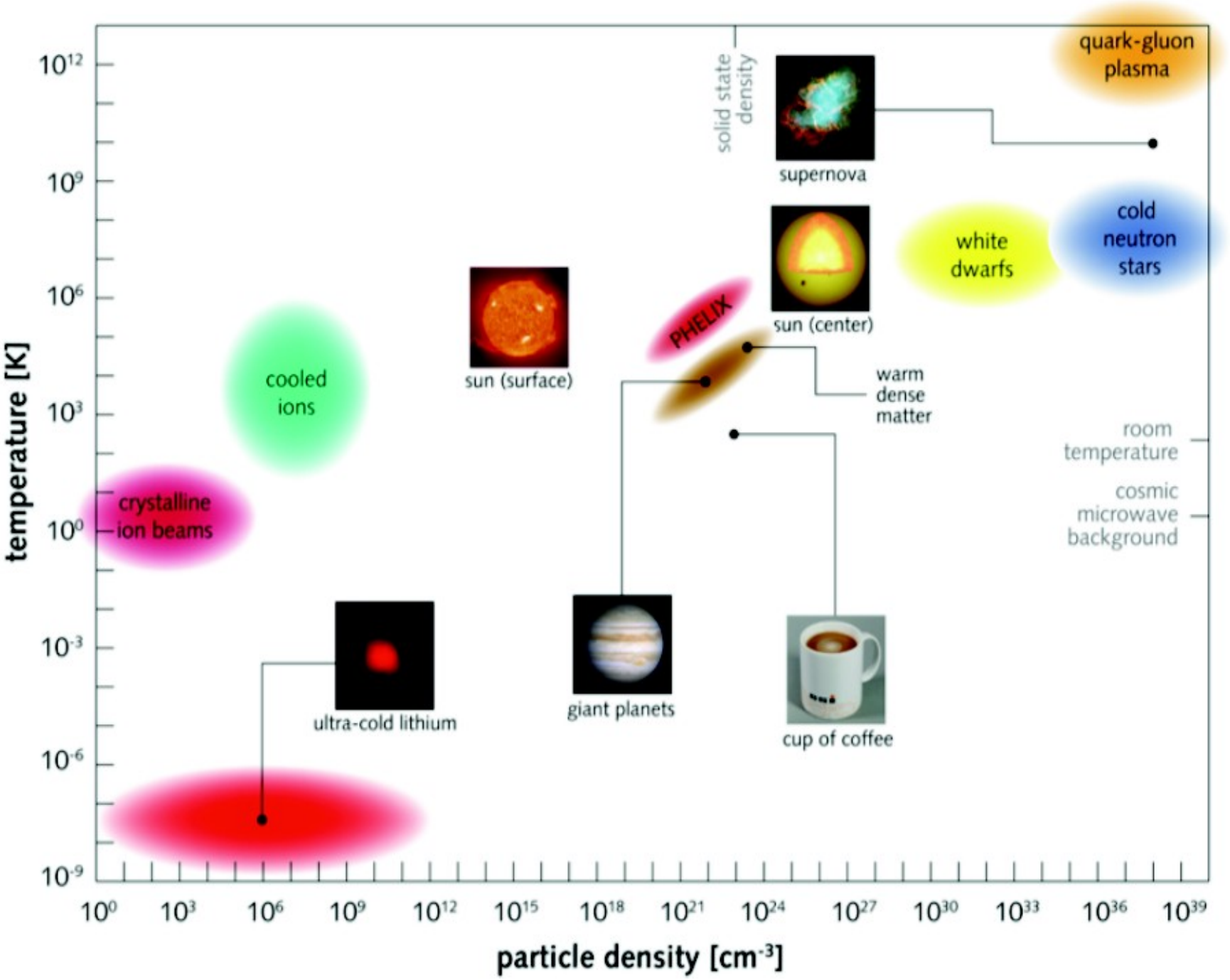








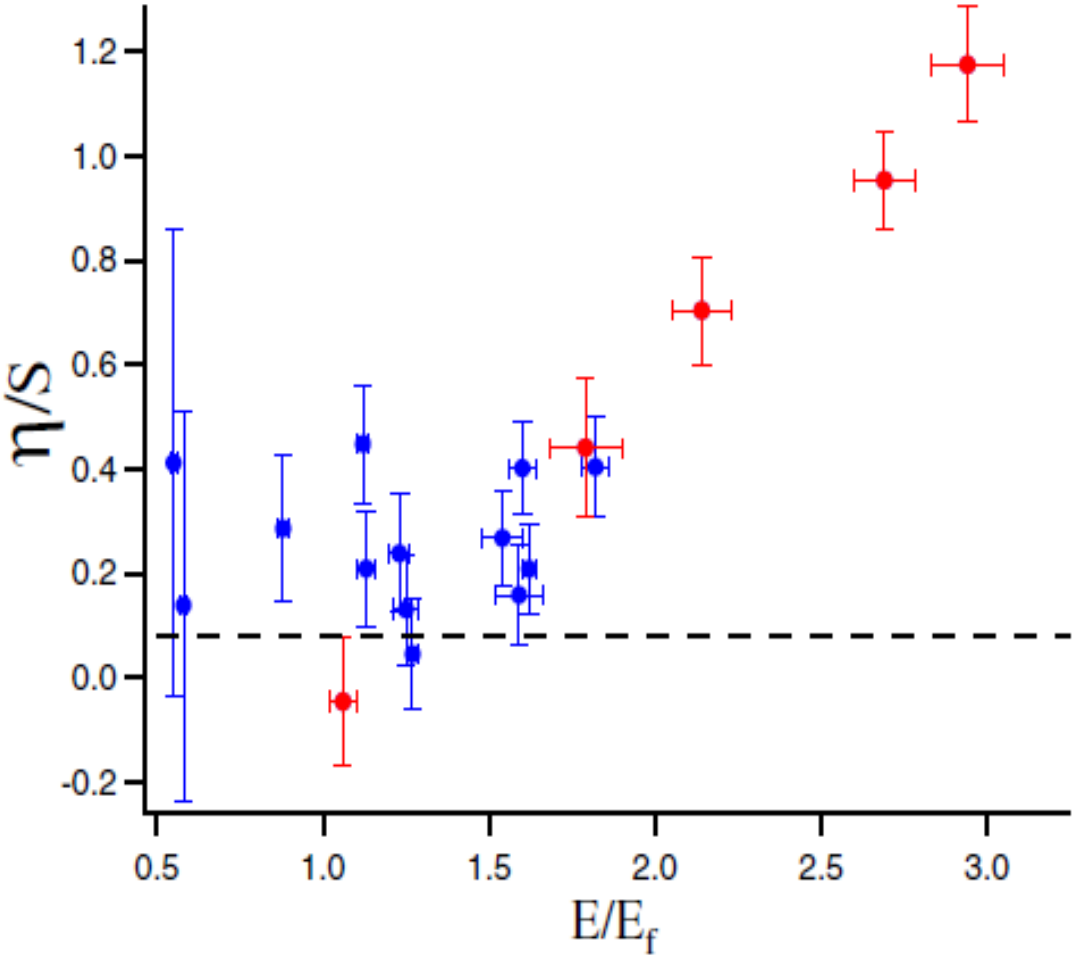
extreme matter



an ultracold interacting Fermi gas as a (nearly) perfect fluid

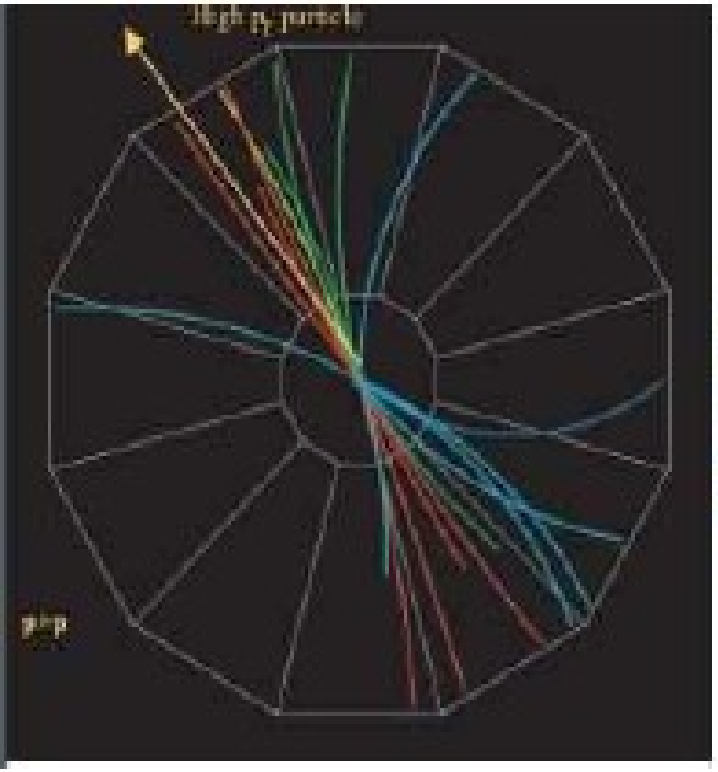
$T(^6Li) = 200$ nK

n.b.: it is not the superfluid phase which behaves as an ideal fluid!

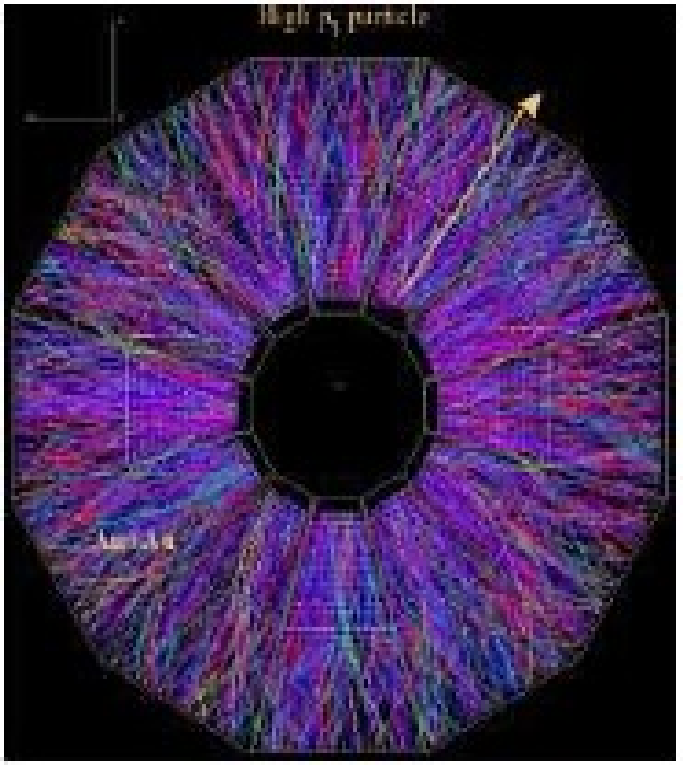


John E. Thomas, Nucl. Phys. A380 (2009) 665c
Physics Today, May 2010

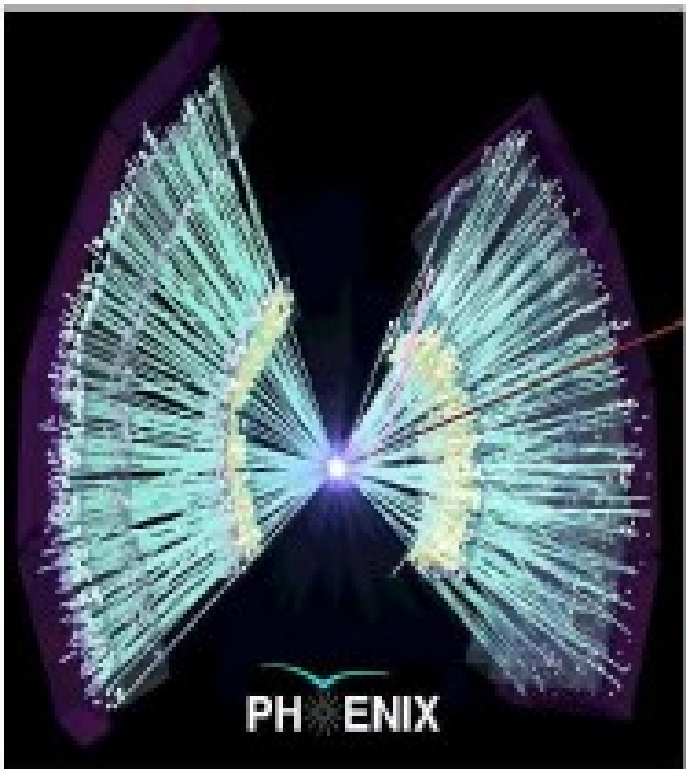
hot and dense matter



STAR pp

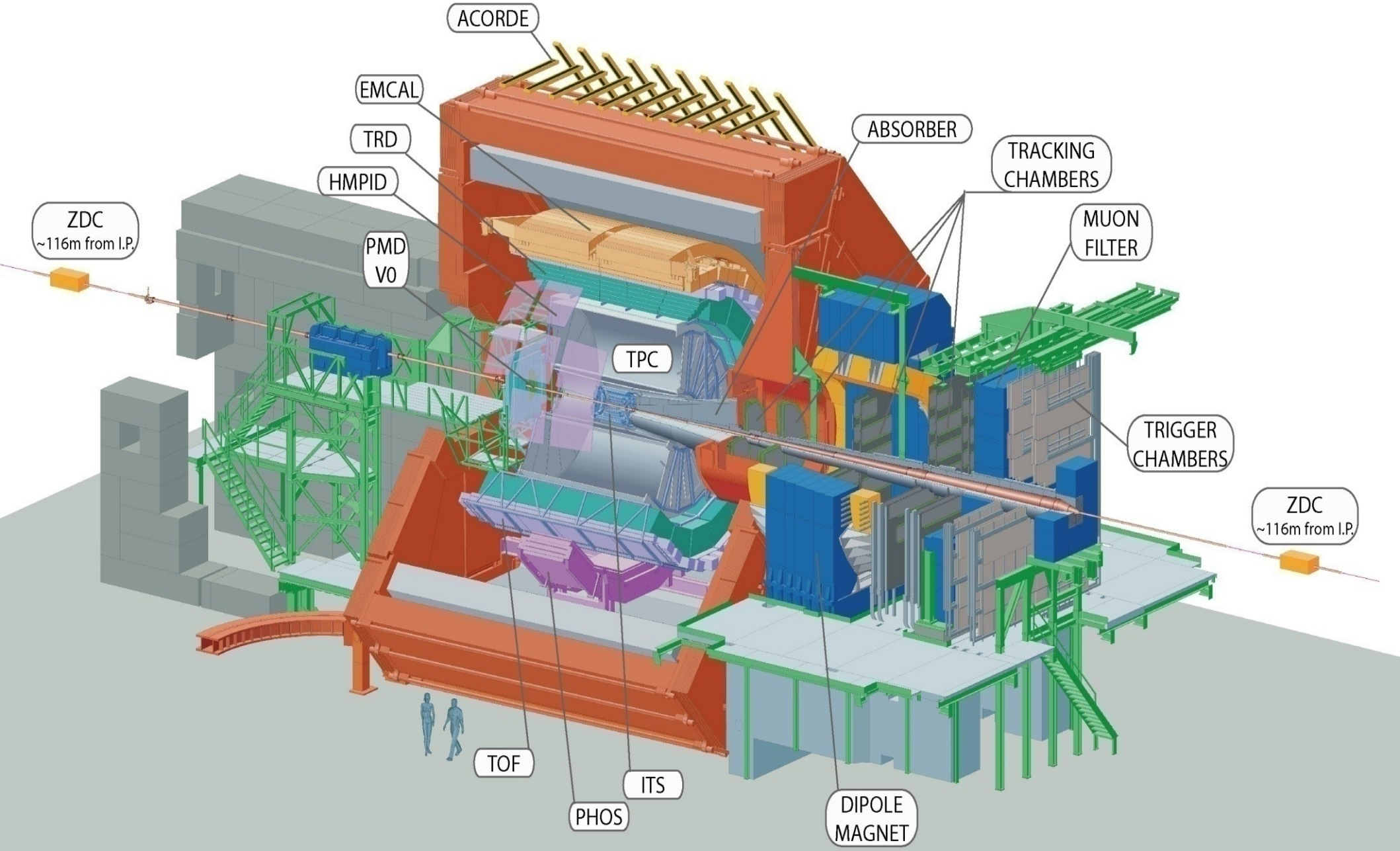


STAR AuAu

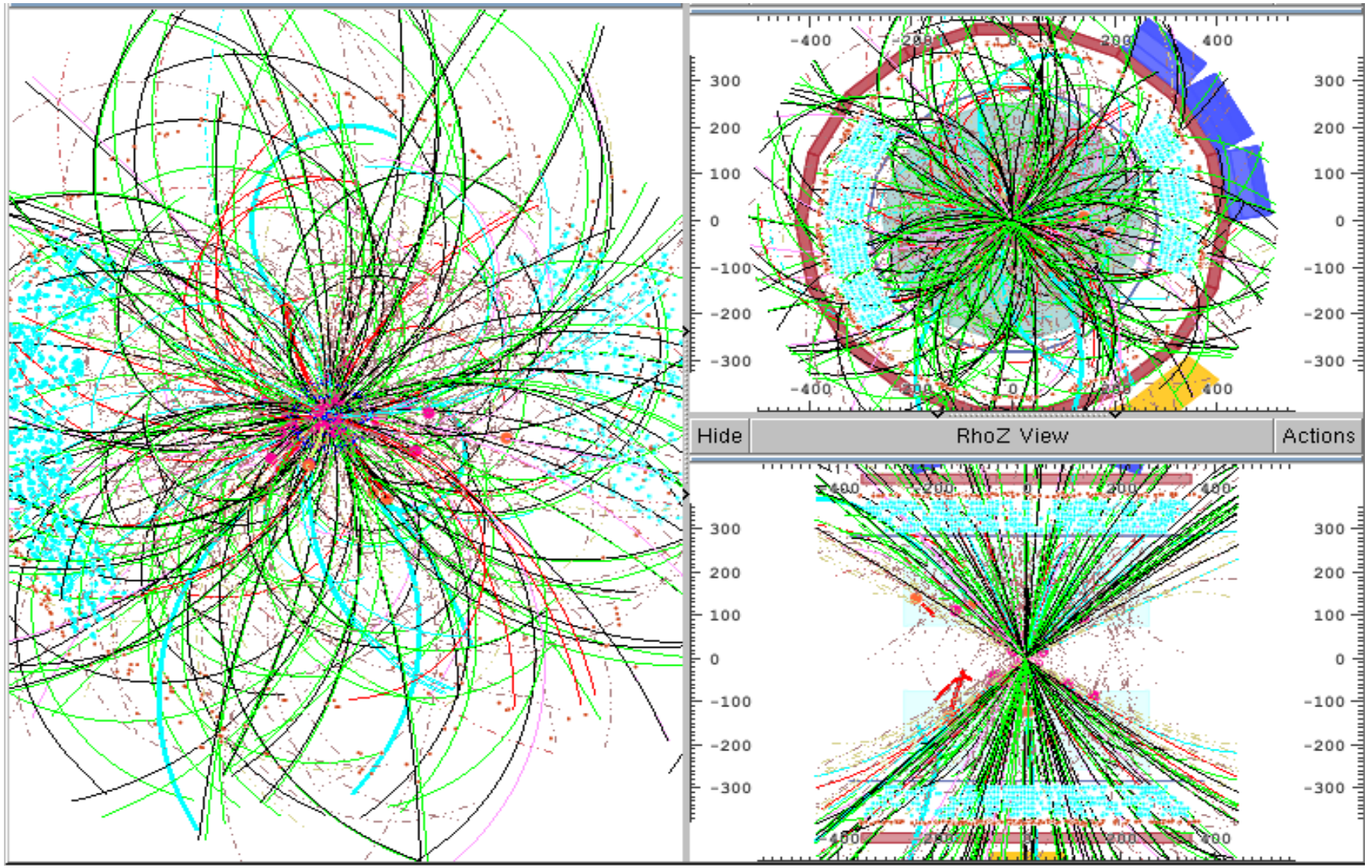


PHENIX AuAu

ALICE, the major nuclear physics experiment at LHC



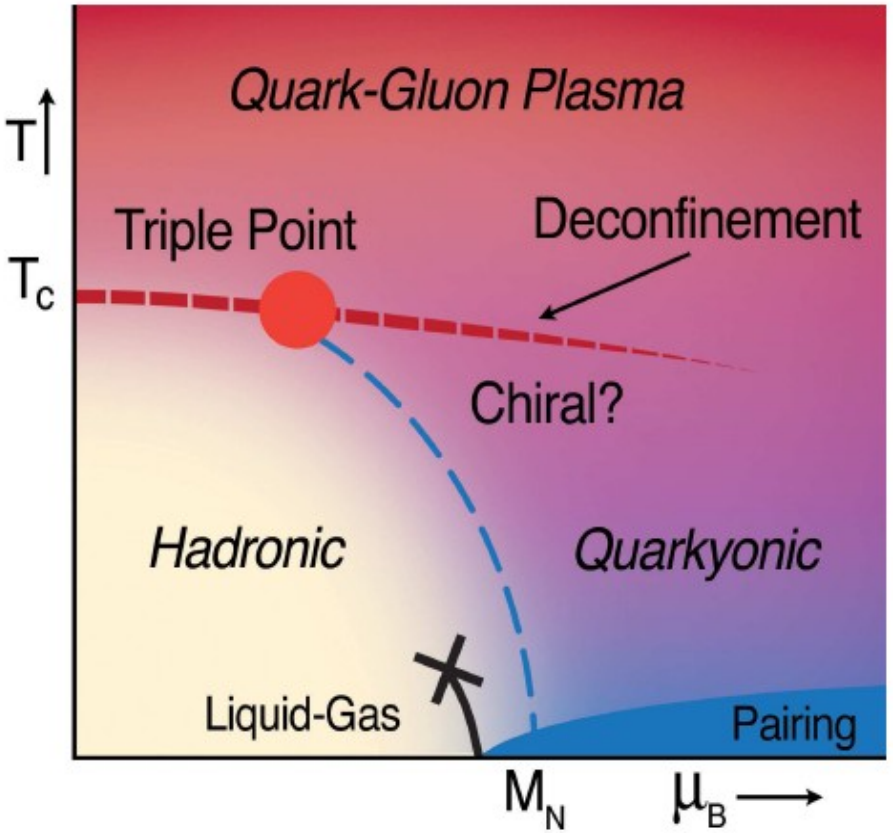
hot and dense matter?



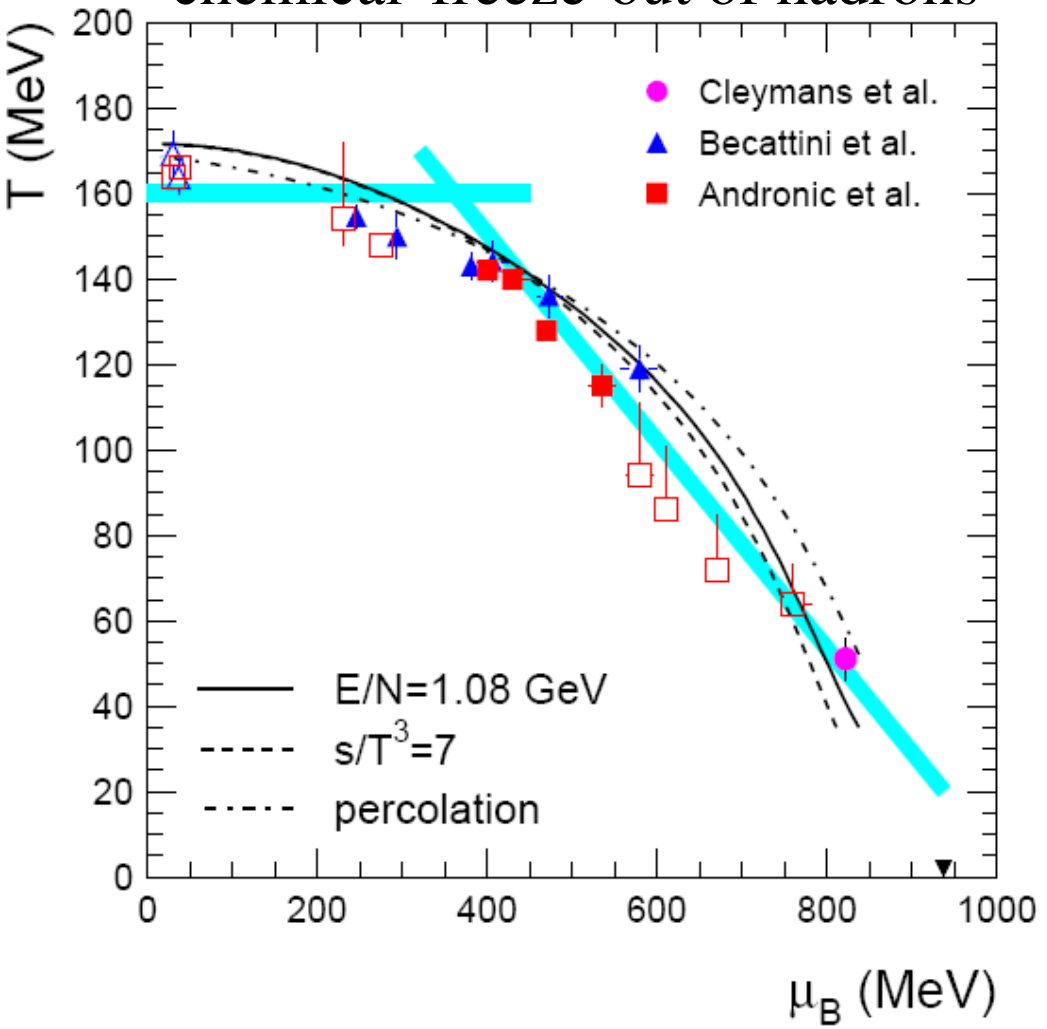
ALICE pp at 7 TeV, more than 120 charged tracks

the QCD phase diagram

Andronic et al.,, arXiv:0911.4806
Nucl. Phys. A837 (2010) 65



data points:
'chemical' freeze-out of hadrons



all lattice groups now agree: T_c(mu=0) is close to 170 MeV

Bazavov & Petreczky, arXiv:1005.1131 [hep-lat]

S. Borsanyi et al., arXiv:1005.3508 [hep-lat]

review: pbm, wambach
RMP 81 (2009) 1031

Is the QGP in the strongly coupled regime-- results from Lattice QCD

Deviation from ideal gas (pure gauge)

– suggests strong interactions –

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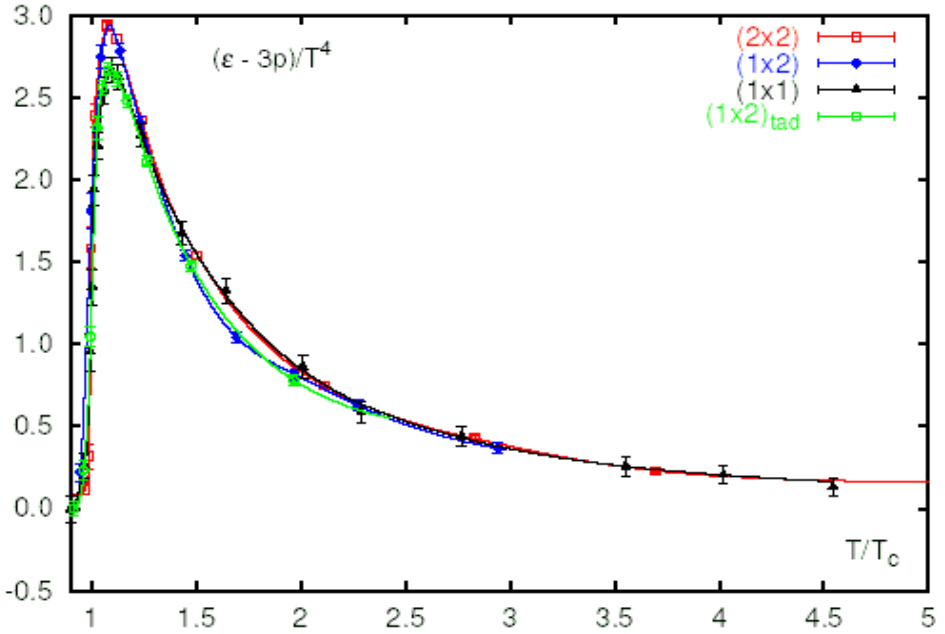
evidence for significant deviations from ideal gas behavior;
at least up to $T \simeq (2-3)\, T_c$; i.e. in the regime accessible to RHIC



colored bound states above T_c ??

significant interactions among constituents near Tc, what about LHC?

The QGP in the strongly coupled limit: observable consequences

- ideal fluid flow since η/s is close to AdS/CFT limit

- energy loss of heavy quarks via the trailing string picture

- momentum dependence of charmonium suppression (compared to pp collisions)

heavy ion collisions and hydrodynamics

for T > 200 MeV in 2-flavor QGP $n_{parton} > 4/fm^3$ and with typical perturbative cross sections $\lambda < 0.8$ fm
rescattering between particles formed in primary collisions may lead to local thermal equilibrium rapidly
treat system as particle fluid using language and tools of hydrodynamics

$\partial_\mu T^{\mu\nu} = 0$ $\partial_\mu j^\mu = 0$ with energy-mom tensor $T^{\mu\nu}$ and 4-current of cons. charge j^μ

for ideal fluid: $T^{\mu\nu} = (\varepsilon+p)u^\mu u^\nu - pg^{\mu\nu}$ and $j_i^\mu = n_i u^\mu$

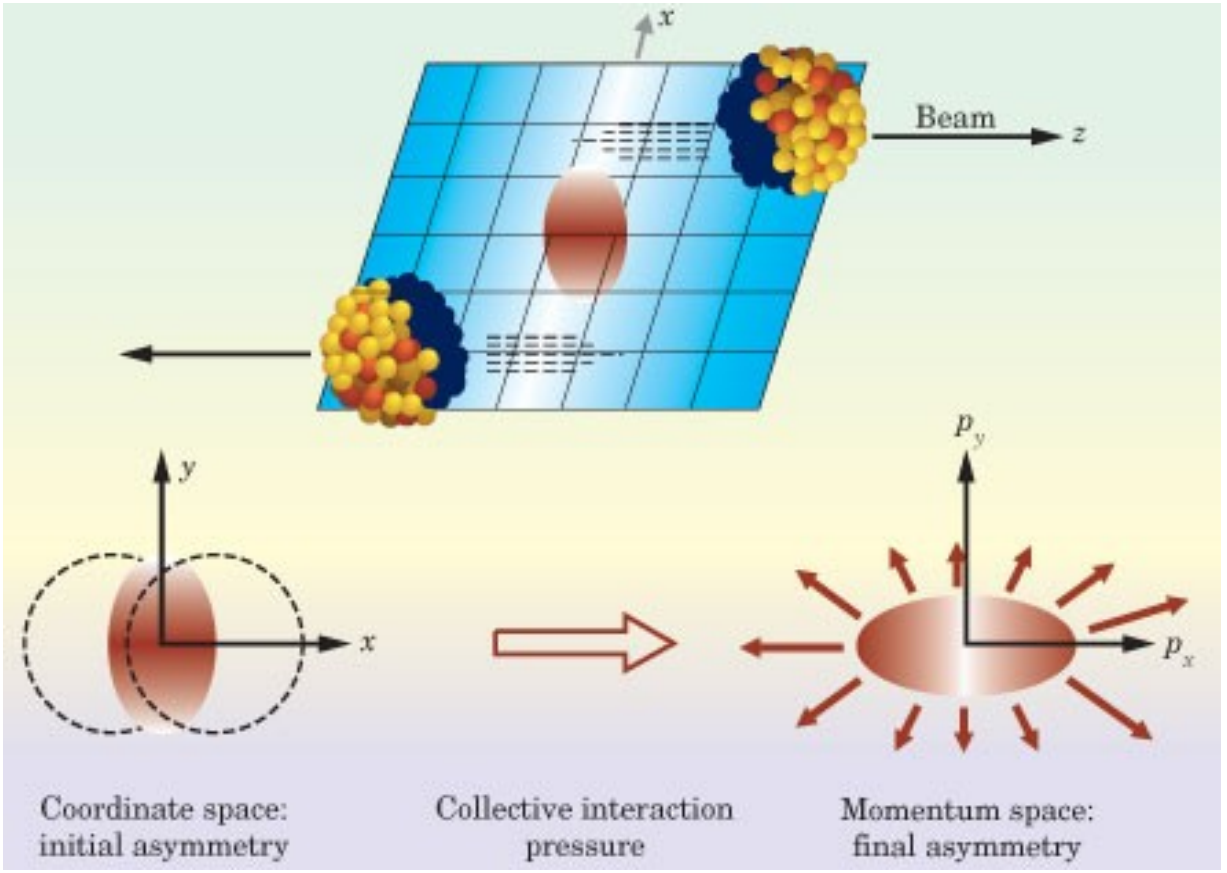
ε: energy density p: pressure u^μ: flow 4 velocity
generally all fields functions of x

generally only EoS and initial condition needed to calculate evolution

EoS: $p = p(\varepsilon, n_1, \ldots, n_n)$ connection pressure – densities

initial cond.: in ideal fluid expansion isentropic, final state multiplicity gives initial entropy, pick volume → system completely determined

Azimuthal Anisotropy Parameter v_2



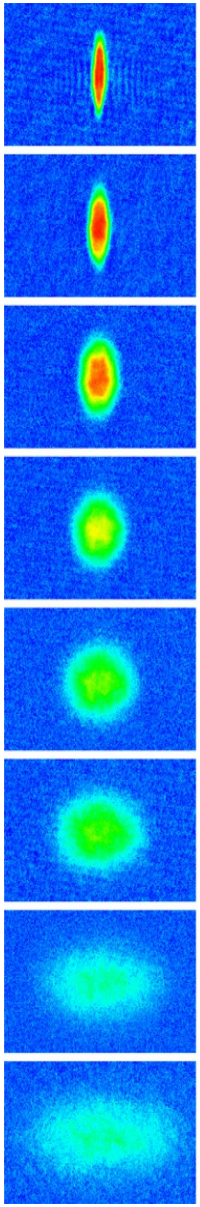
Fourier decomposition of momentum distributions rel to reaction plane:

$$\frac{dN}{dp_t\,dy\,d\phi} = N_0 \cdot \left[1 + \sum_{i=1} 2\,v_i\left(y, p_t\right)\cos\left(i\phi\right)\right]$$

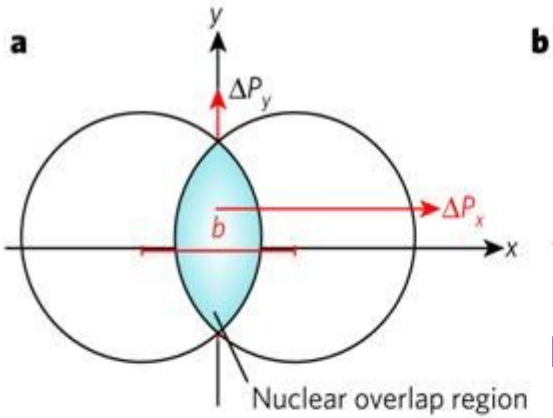
quadrupole component v_2

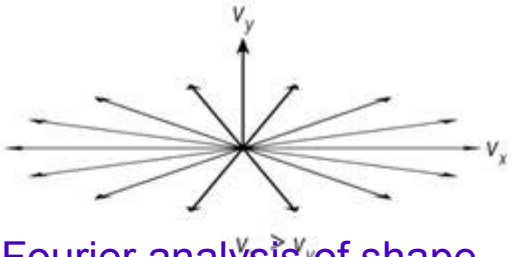
"elliptic flow"

QGP and ultra-cold quantum gases



ultra-cold ^{6}Li
< 100 nK
~10^{-12} eV

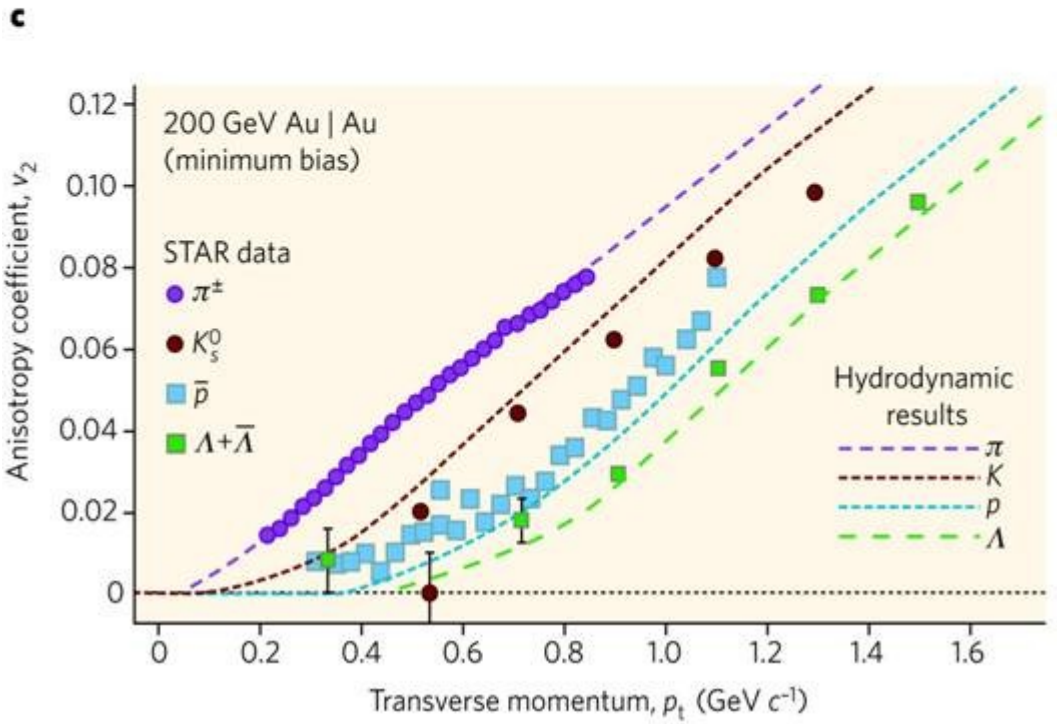




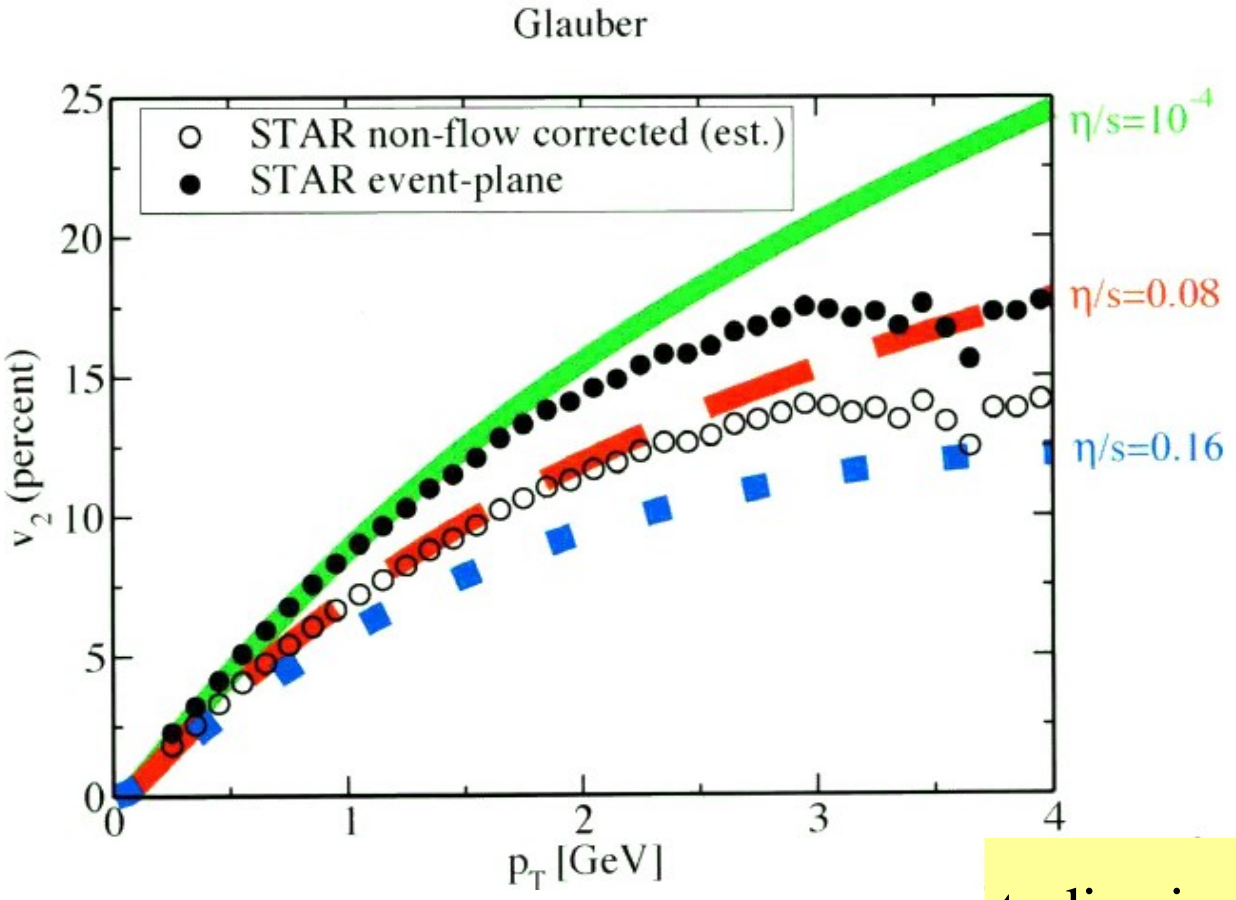
Fourier analysis of shape

QGP
2.1 TK
~10^8 eV

collective expansion at strong coupling



the QGP as a nearly perfect fluid



studies imply that

η/s < (3×AdS/CFT limit)

Luzum & Romatschke, PRC 78 (2008) 034915

Note: viscosity of QGP is 25 orders of magnitude larger than that of ultra-cold Li - it is η/s that counts!

quark number scaling in hydrodynamic flow

scaled flow coefficient for mesons and baryons coincide

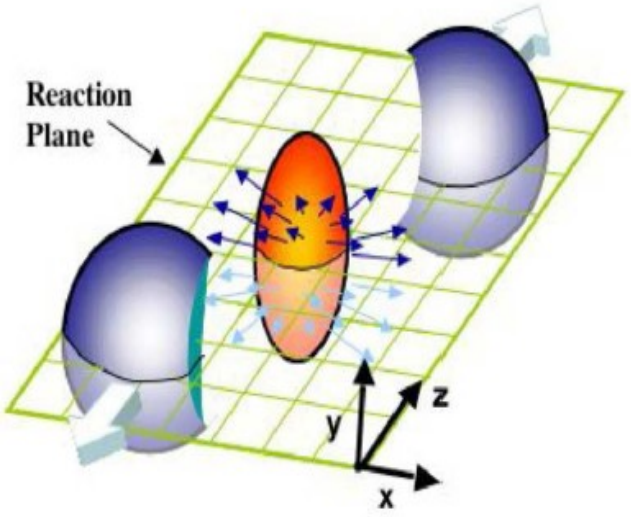
is flow determined in the partonic phase?

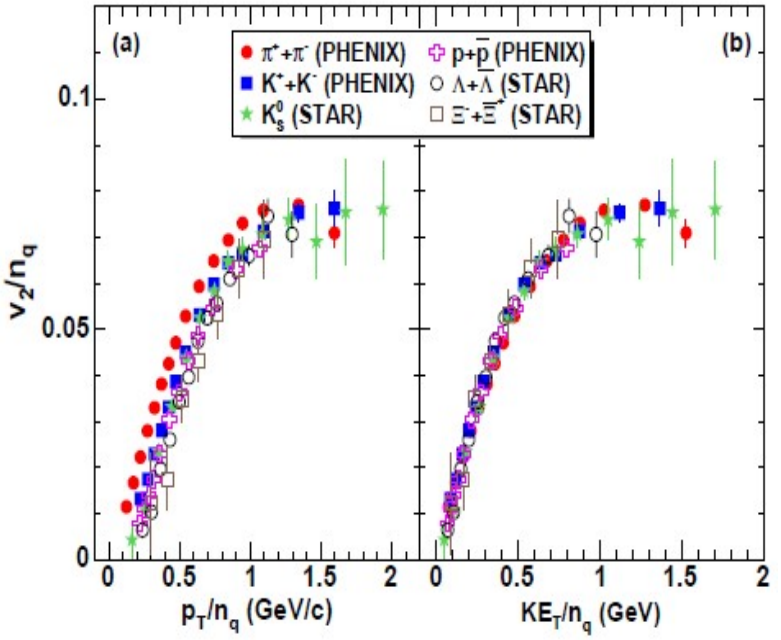
STAR:

*PRL**92**,* 052302(04)
*PRL**95**,* 122301(05)
*PRC**77**,* 54901(08)
*PRC**81**,* 44902(10)

PHENIX:

PRL 98, 162301 (07)



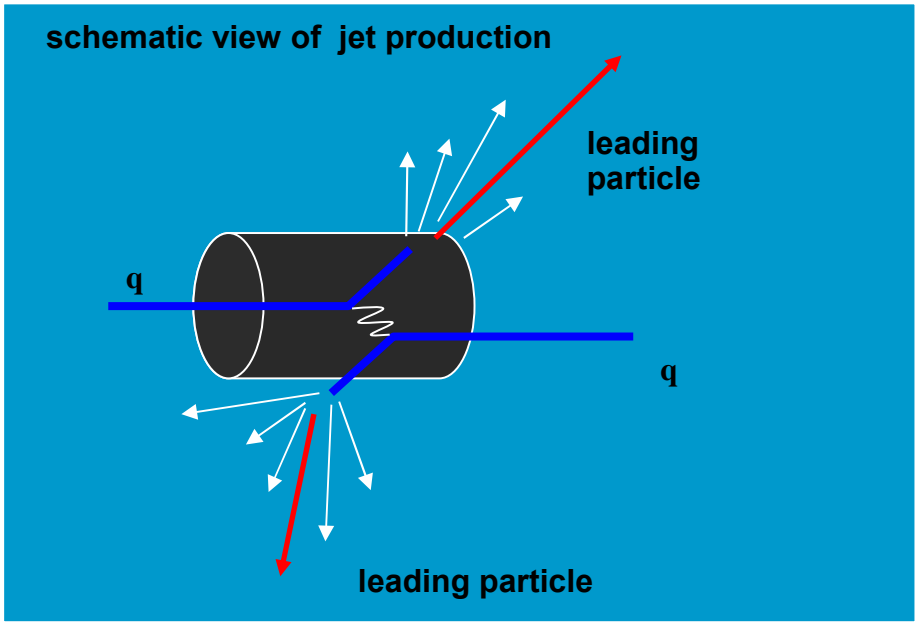


AdS/CFT and energy loss of heavy quarks

- summary of energy loss info in QGP
- energy loss and flow of heavy quarks
- String dragging: energy loss mechanism in AdS/CFT

Jet quenching

- Hard parton scattering observed via leading particles
- Expect strong $\Delta\phi=\pi$ azimuthal correlations



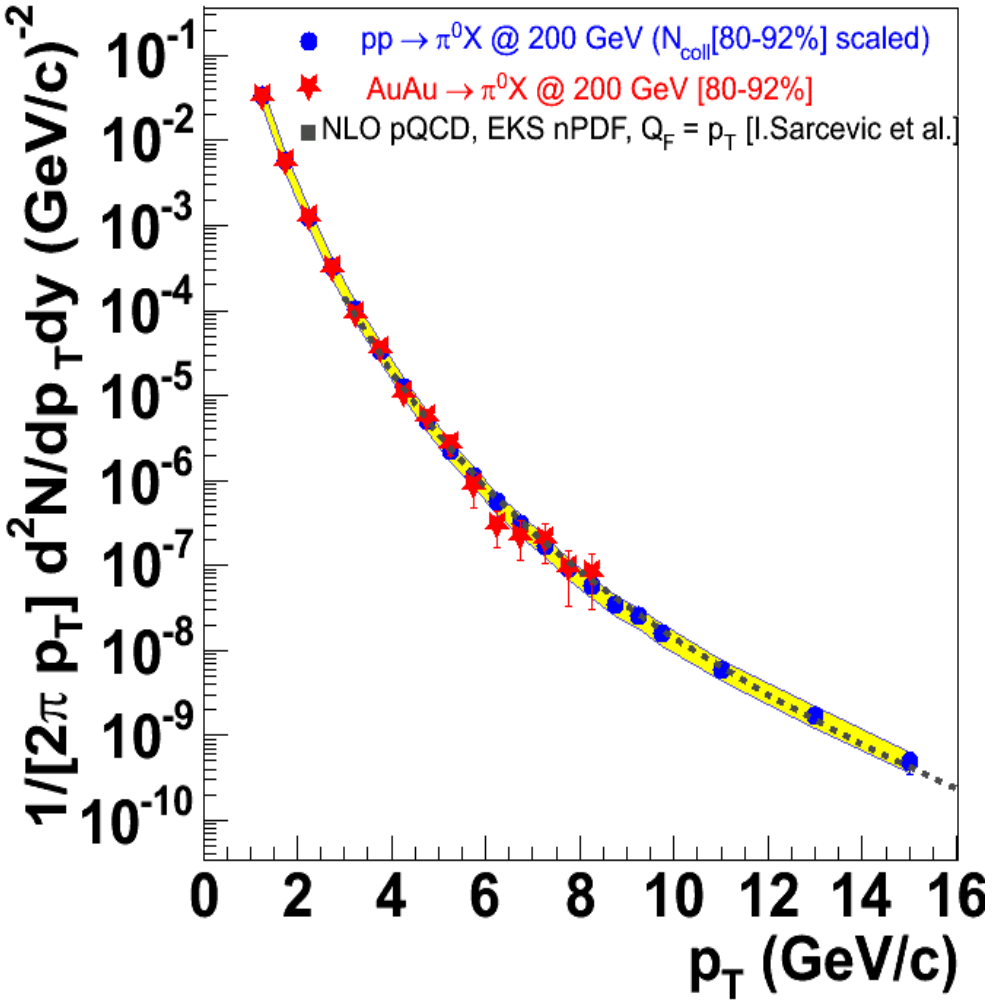
However, the scattered partons may lose energy (~ several GeV/fm) in the colored medium

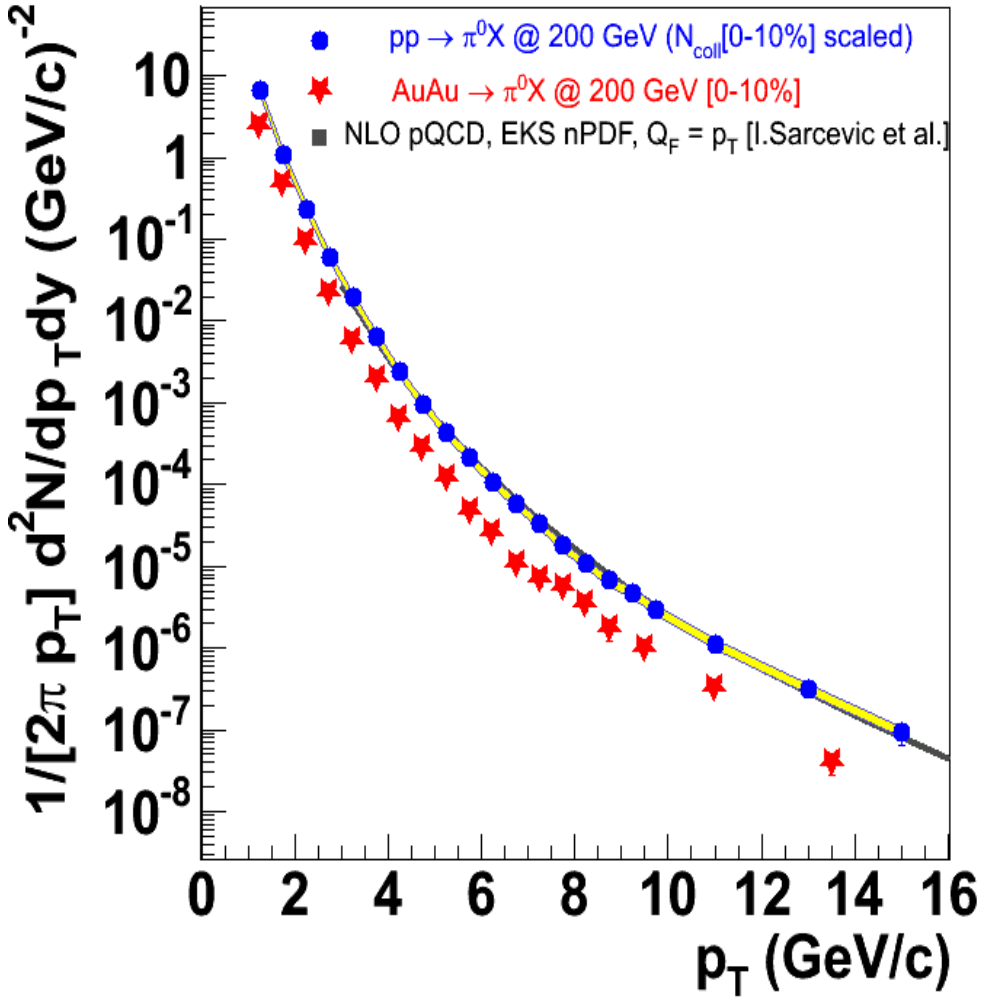
$\rightarrow$ momentum reduction (fewer high p_T particles in jet)

$\rightarrow$ no jet partner on other side

spectra suppressed at high p_t in AuAu relative to pp

proton data scaled to AuAu with appropriate number of binary collisions





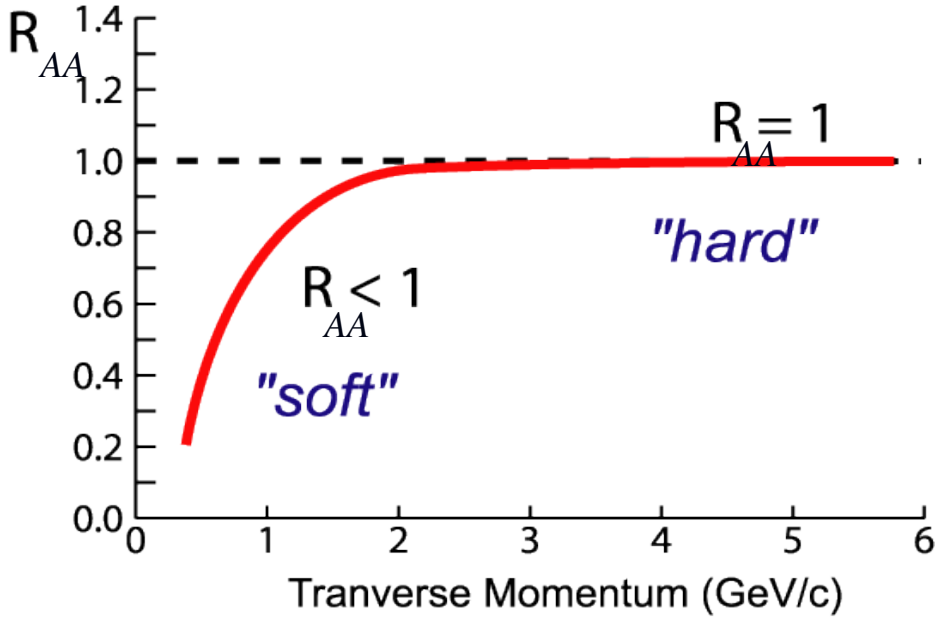
PHENIX PRL 91 (2003) 072305 and 241803

Definition of R_{AA}

R_{AA} = medium/vacuum

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

$\langle N_{binary} \rangle / \sigma_{inel}^{p+p}$



no medium effects:

$R_{AA} < 1$ in regime of soft physics

$R_{AA} = 1$ at high-p_T where hard scattering dominates

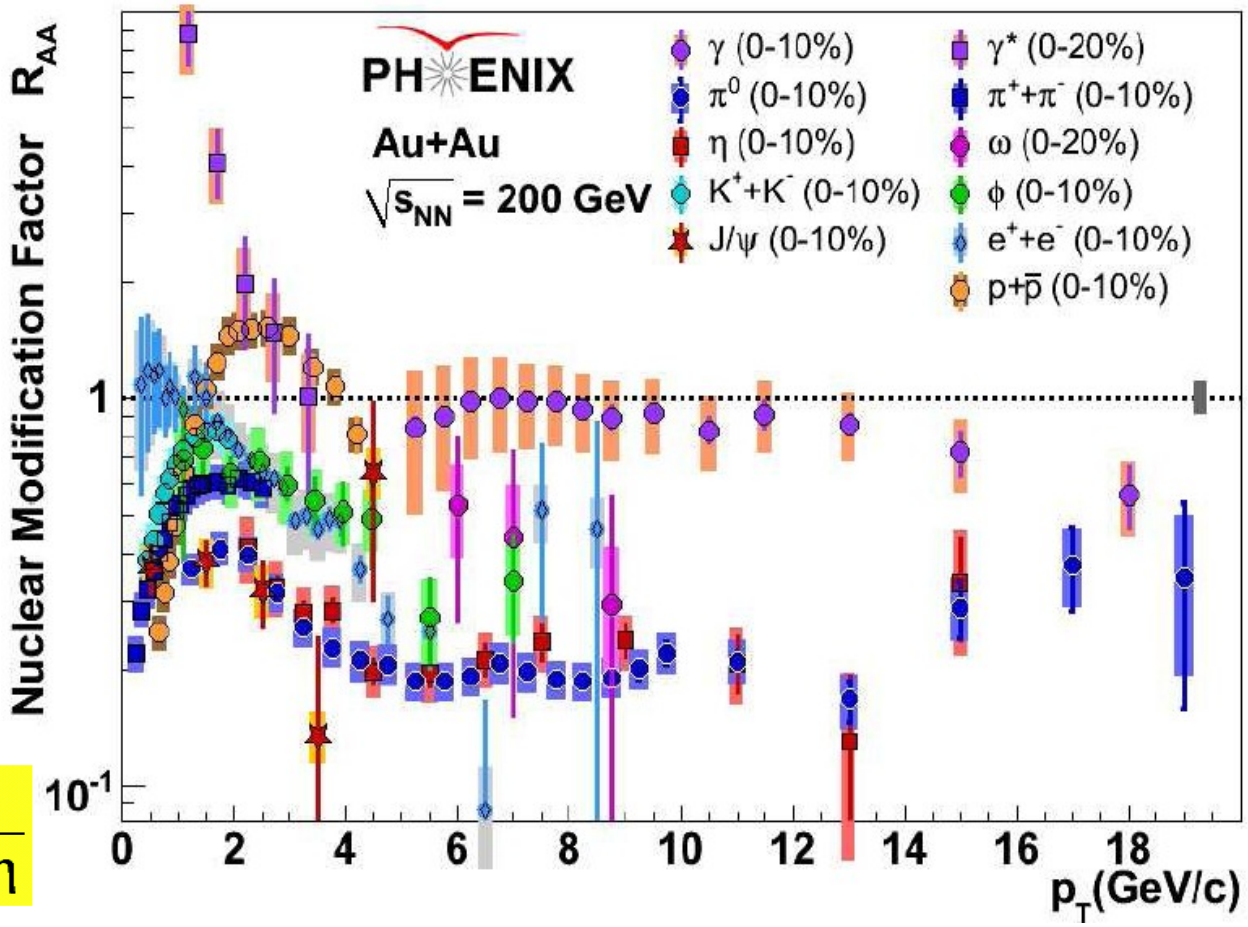
Suppression:

$R_{AA} << 1$ at high-p_T

nuclear suppression factor R_{AA}

high momentum hadron suppression - quenched jets
low momentum photon enhancement – direct radiation from QGP
high momentum photons unmodified - control measurement

Fig. from M.J. Tannenbaum, arXiv:1006.5701 [nucl-ex]



pQCD region ever reached at LHC energy?

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

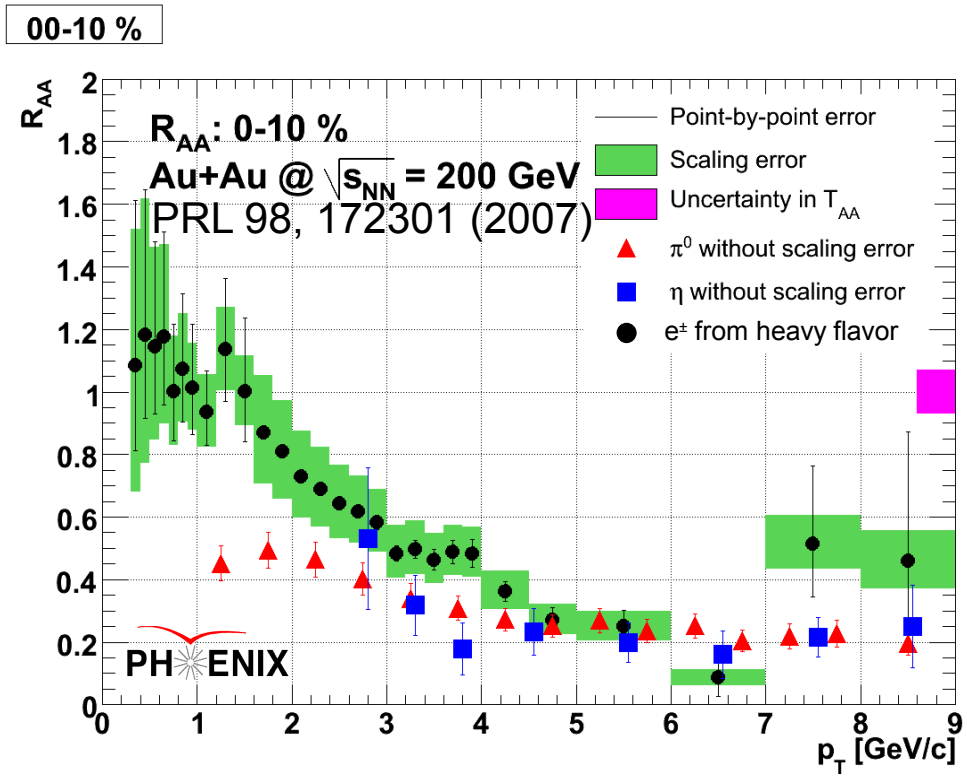
$<N_{binary}>/\sigma_{inel}^{p+p}$

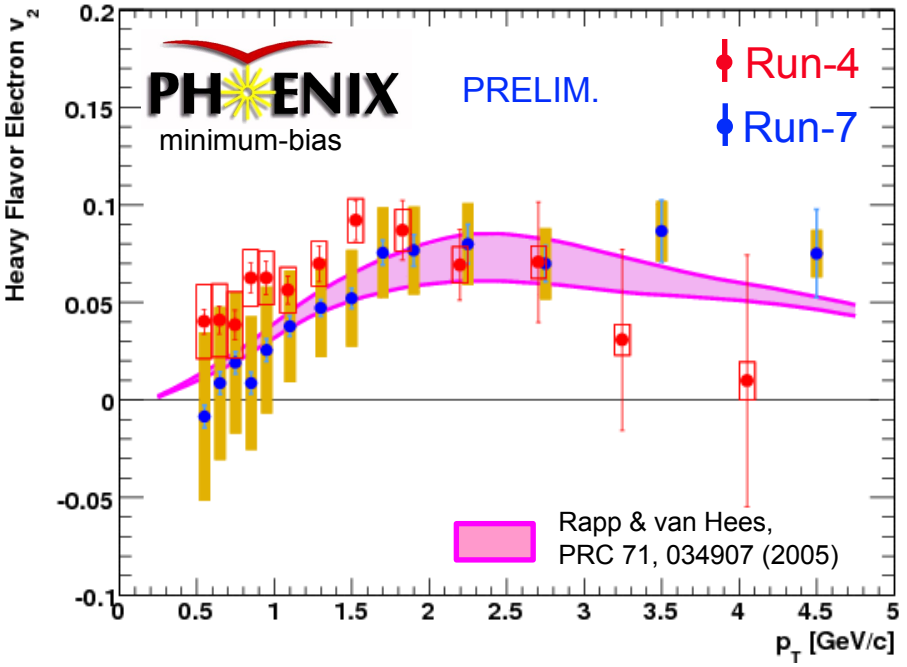
further big surprize at RHIC: strong energy loss of heavy quarks

electrons from heavy flavor mesons

strong energy loss

hydrodynamic flow

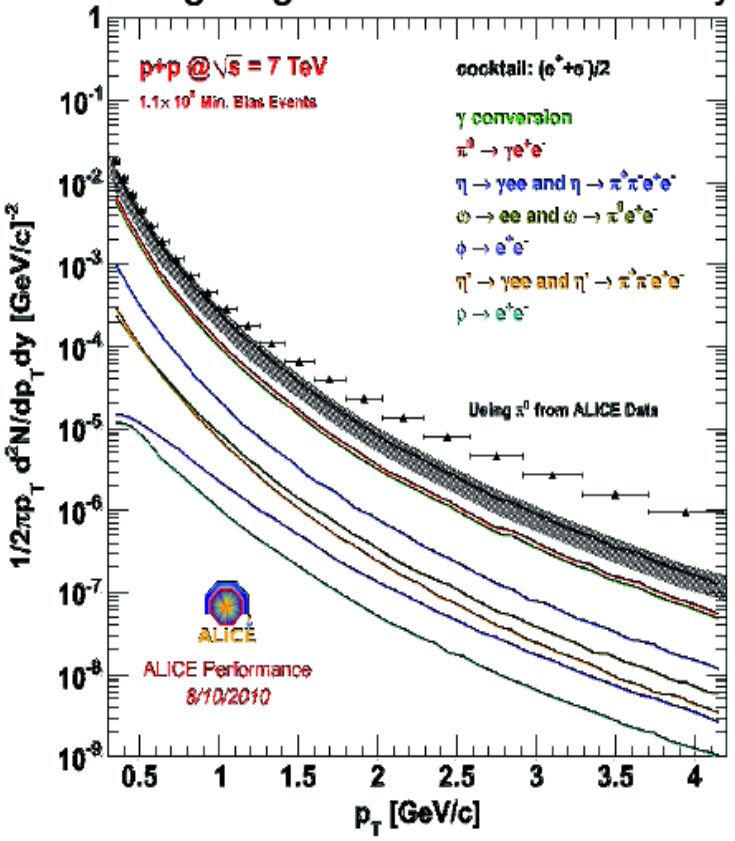


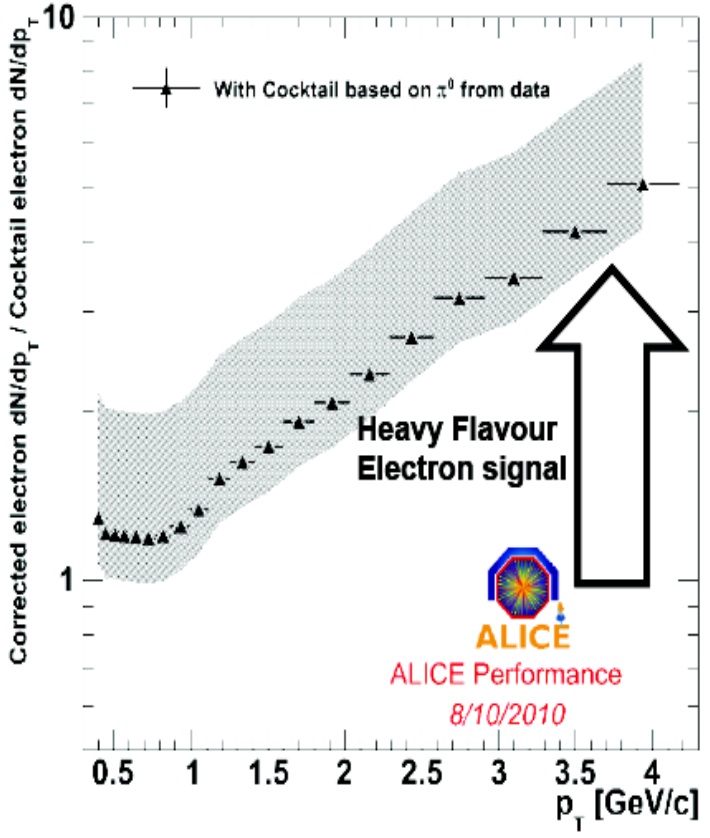


these data are not well explained, measure heavy quarks „directly“ at LHC

Excellent prospects: 1st heavy flavor signal in pp electrons at 7 TeV with ALICE

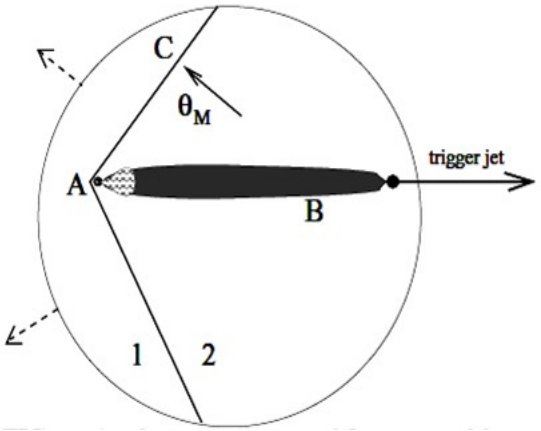
- Cocktail based in π^0 cross section measured from double conversion reconstruction
- Large signal from D and B decay electrons in ratio to cocktail





Energy loss of heavy quarks in AdS/CFT

Wake effect or "sonic boom"



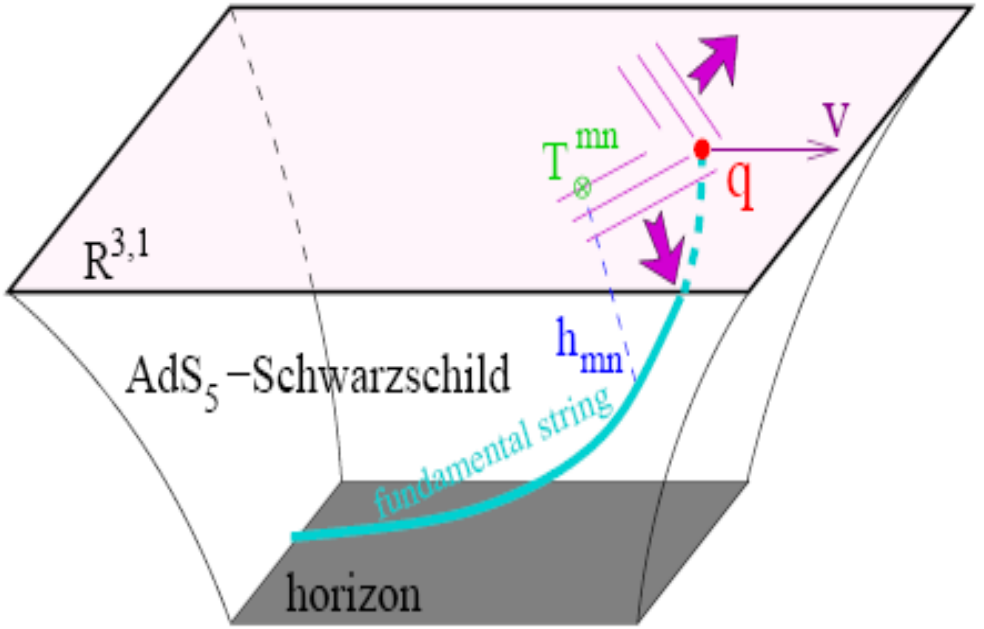
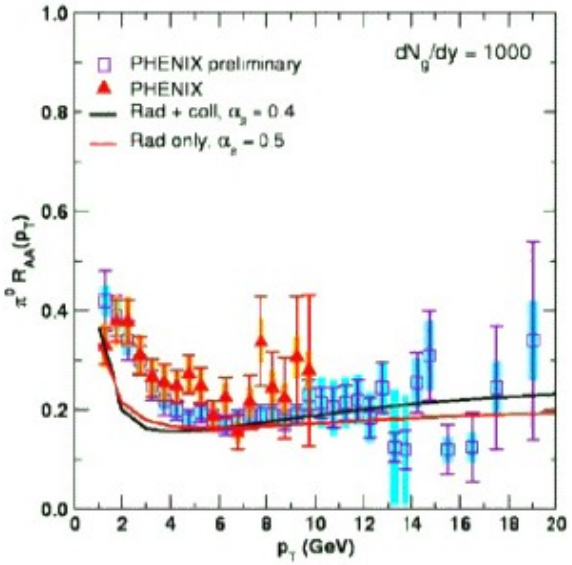
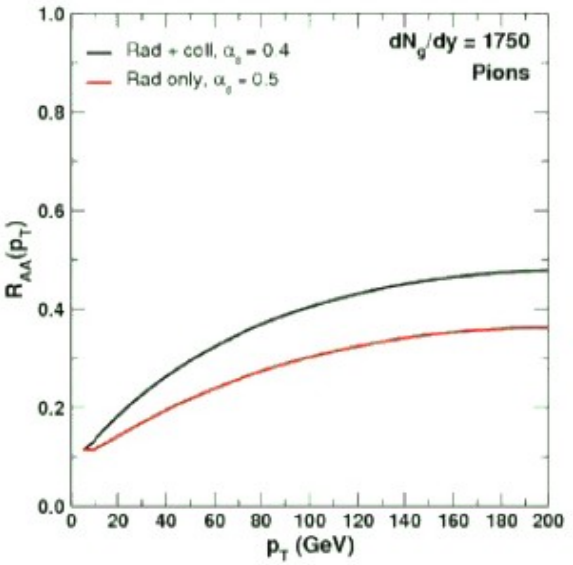


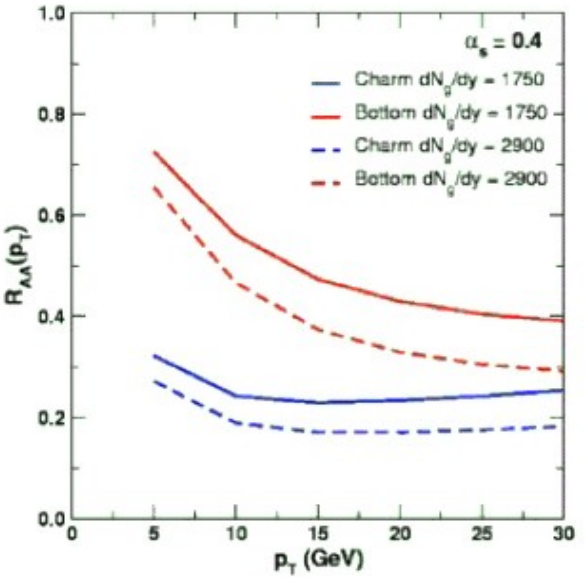
Figure 1: The AdS_5-Schwarzschild background is part of the near-extremal D3-brane, which encodes a thermal state of $\mathcal{N} = 4$ supersymmetric gauge theory [25]. The external quark trails a string into the five-dimensional bulk, representing color fields sourced by the quark's fundamental charge and interacting with the thermal medium.

Predictions for jet quenching at LHC

S. Wicks and M. Gyulassy







LHC data will be decisive

Charmonium as a probe for the properties of the QGP

the main idea: implant charmonia into the QGP and observe their modification, in terms of suppressed (or enhanced) production in nucleus-nucleus collisions with or without plasma formation

- is the medium deconfined?
- does AdS/CFT play a role

Charmonium suppression

original proposal: H. Satz and T. Matsui, Phys. Lett. B178 (1986) 416

assumptions:

- **all** charmonia are produced before QGP formation
- suppression takes place in QGP
- some charmonia might survive beyond T_c

→ sequential suppression pattern due to feeding

actually, in 1978, Edward Shuryak investigated gluonic destruction of charmonium,

$$gJ/\psi \rightarrow \bar{c}c$$

and concluded that it would not survive the gluon-rich plasma

E. V. Shuryak, Phys. Lett. B **78**, 150 (1978) [Sov. J. Nucl. Phys. **28**, 408.1978 YAFIA,28,796 (1978 YAFIA,28,796-808.1978)].

Charmonium (re)generation model

- statistical hadronization model

  original proposal: pbm, J. Stachel, Phys. Lett. B490 (2000) 196

  assumptions:

  - all charm quarks are produced in hard collisions, N_c const. in QGP
  - all charmonia are dissolved in QGP or not produced before QGP
  - charmonium production takes place at the phase boundary with statistical weights

    $\rightarrow$ yield ~ N_c^2 -- quarkonium enhancement at high energies

    -- no feeding from higher charmonia

sQGP and Charmonium Suppression

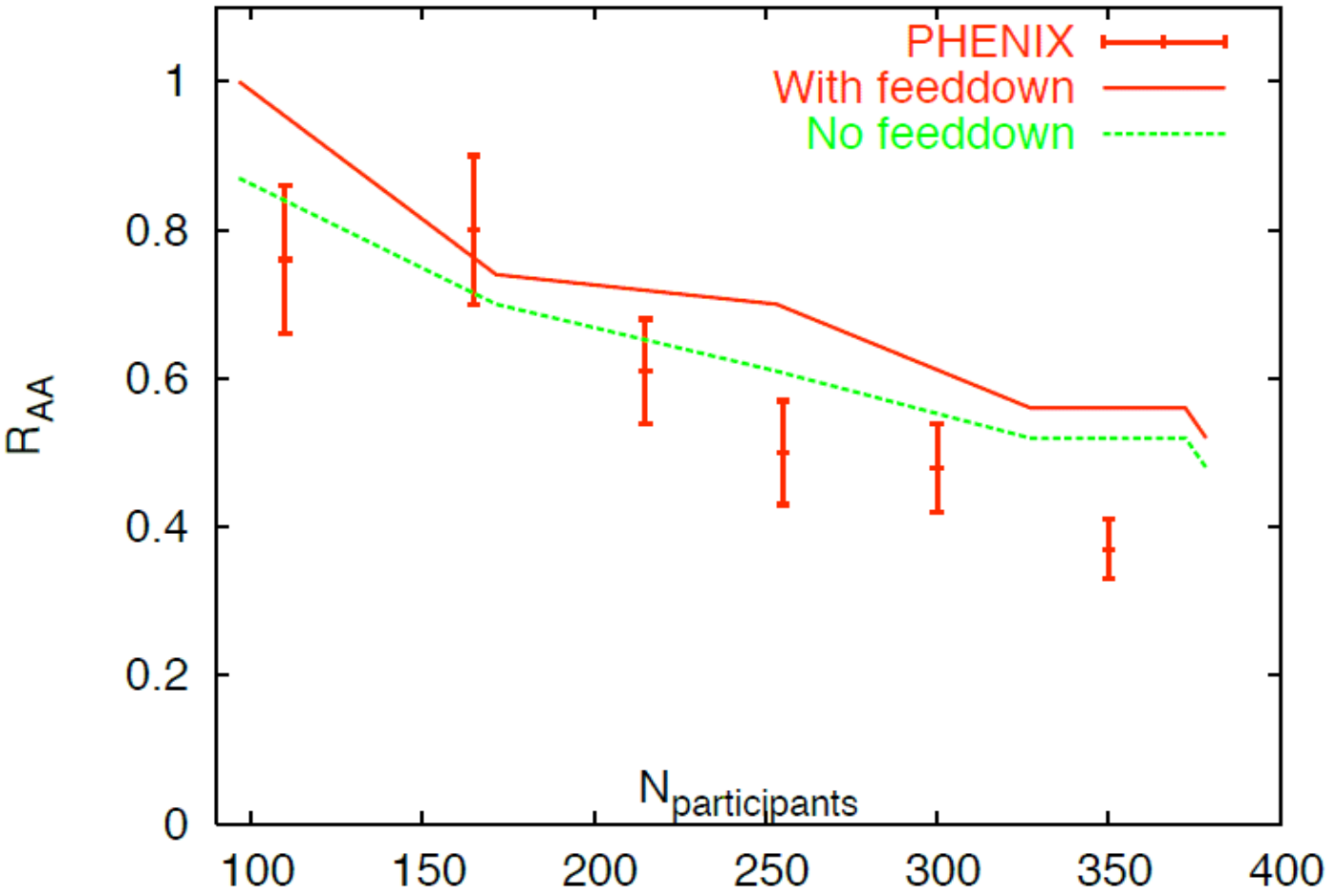
argument: spatial diffusion of charm quarks is slow in ideal fluid

$\Rightarrow$ recombination at the phase transition strongly favors 'diagonal' pairs

expect little enhancement in this scenario

C. Young and E. Shuryak, arXiv:0803.2866 [nucl-th]

sQGP and Charmonium Suppression



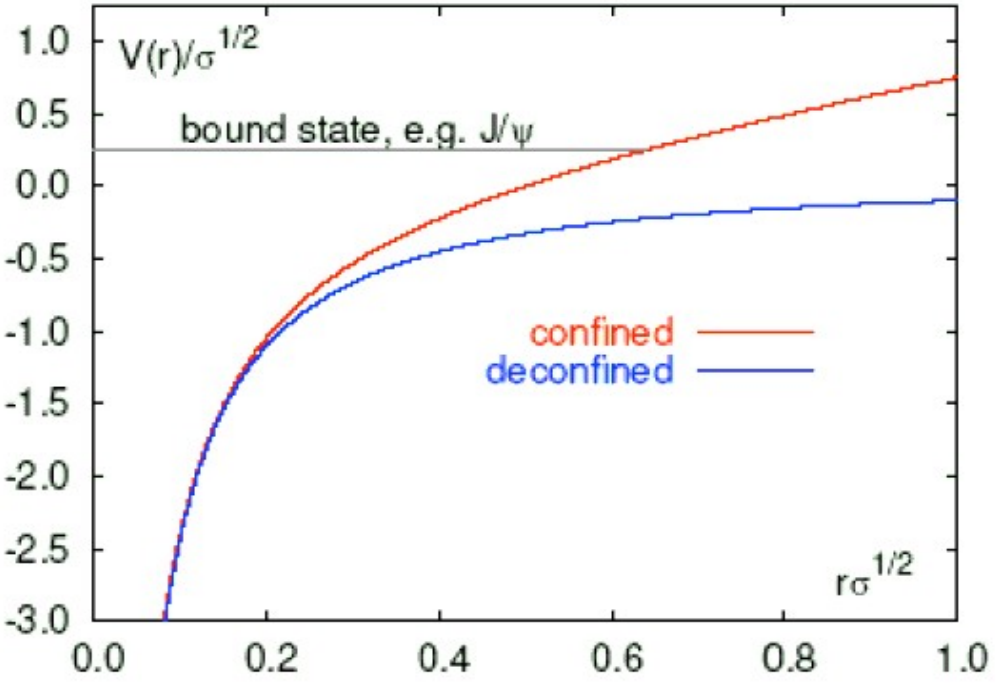
C. Young and E. Shuryak, arXiv:0803.2866 [nucl-th]

Debye screening

V(r,T large) no bound state

V(r,T small) bound state

σ = string tension = 1 GeV/fm
= 0.2 GeV^2



Debye Screening

screened potential for heavy quark-antiquark pair

$$V_{q\bar{q}}(r,T) = \frac{\sigma}{\mu}\left(1 - \mathrm{e}^{-\mu(T)r}\right) - \frac{\alpha}{r}\mathrm{e}^{-\mu(T)r}$$

Debye radius $r_{Debye} = 1/\mu(T) = L_s$ screening lenth

$$r_{Debye} \propto 1/n_g^{1/3} \propto 1/(g(T)\,T)$$

AdS/CFT hot wind scenario for charmonium

In AdS/CFT the screening length depends on the velocity v of the charmonium, and thereby on the relativistic γ factor via

$$L_s(v,T) \sim L_s(0,T)/\sqrt{\gamma}$$

screening length decreases with momentum of charmonium

if screening length falls below charmonium radius, → suppression

Liu, Rajagopal, Wiedemann, Phys. Rev. Lett. 98 (2007) 182301

assumption: charmonium survives to about 2 Tc in the QGP for v=0 but is screened at large v due to 'hot wind'

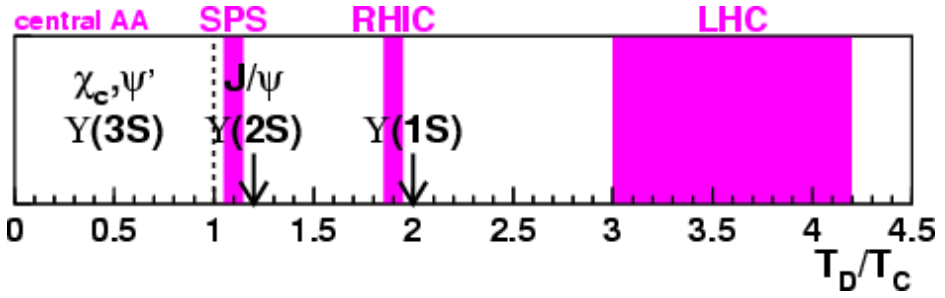
Survival of Quarkonia in the QGP

recent development:
J/ψ does not survive above T_c

predicted quarkonium dissociation temperatures

in the QGP

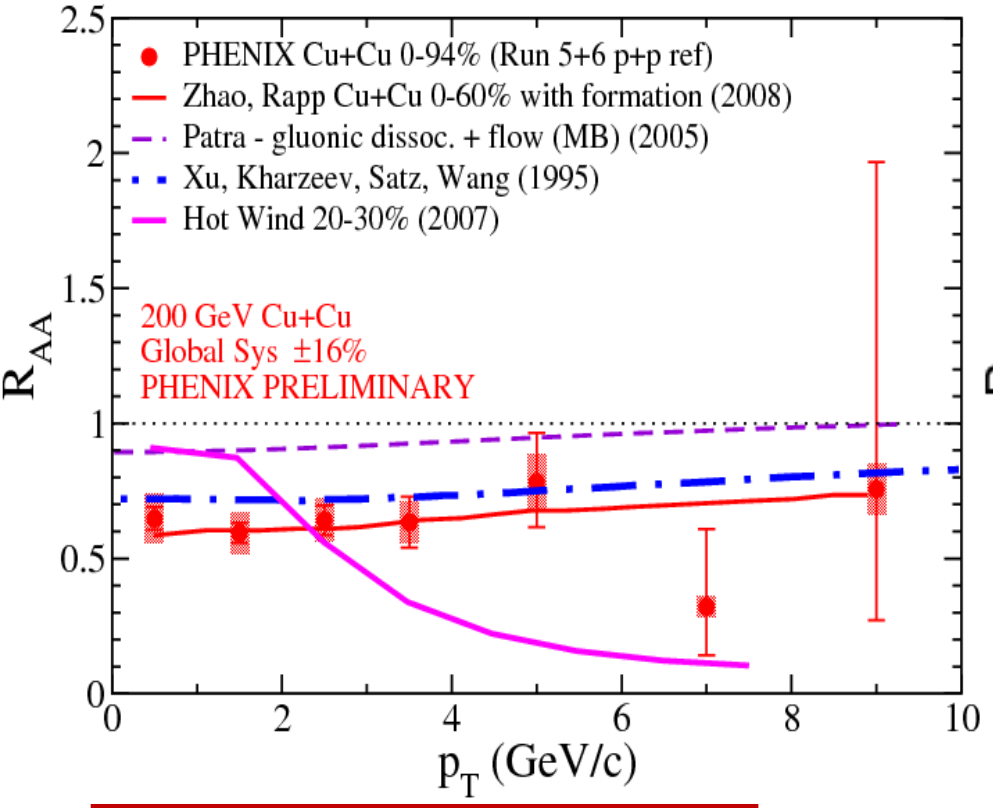
A. Mocsy & P. Petreczky, Phys. Rev. Lett. 99 (2007) 211602



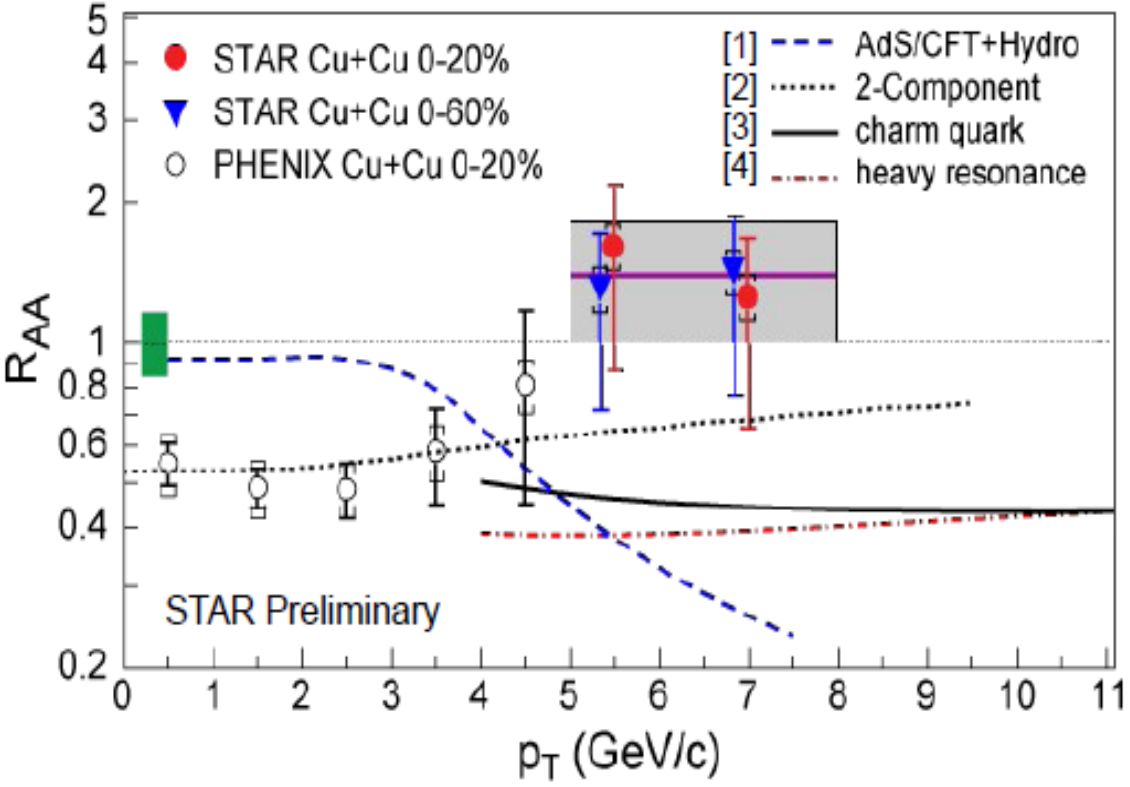
expect all charmonia to be destroyed
by QGP
but: regeneration at the phase boundary!

AdS/CFT predictions (hot wind) not? substantiated at RHIC

need LHC data



PHENIX Minimum Bias

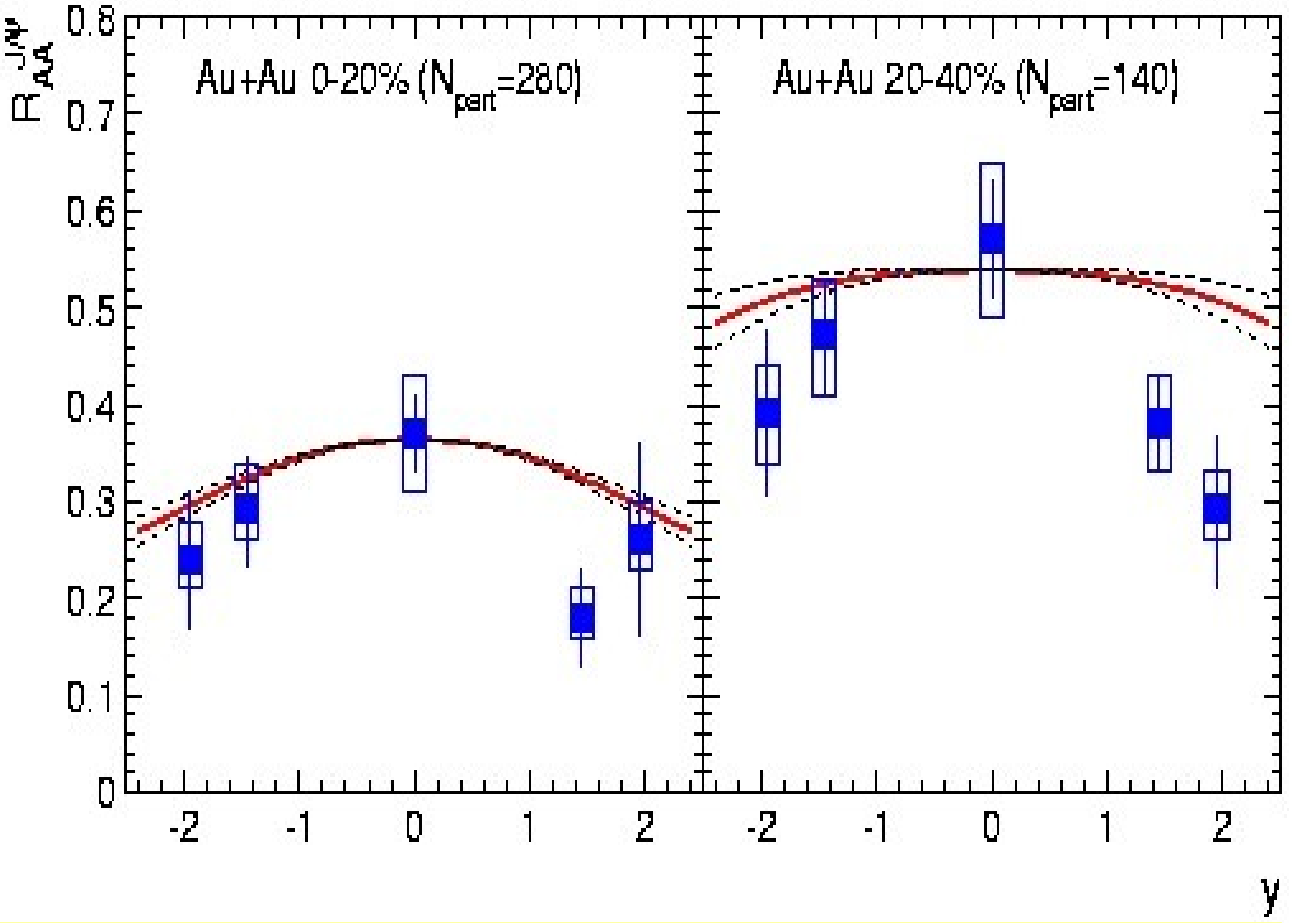


STAR + PHENIX Central collisions

charmonium production from PHENIX at RHIC

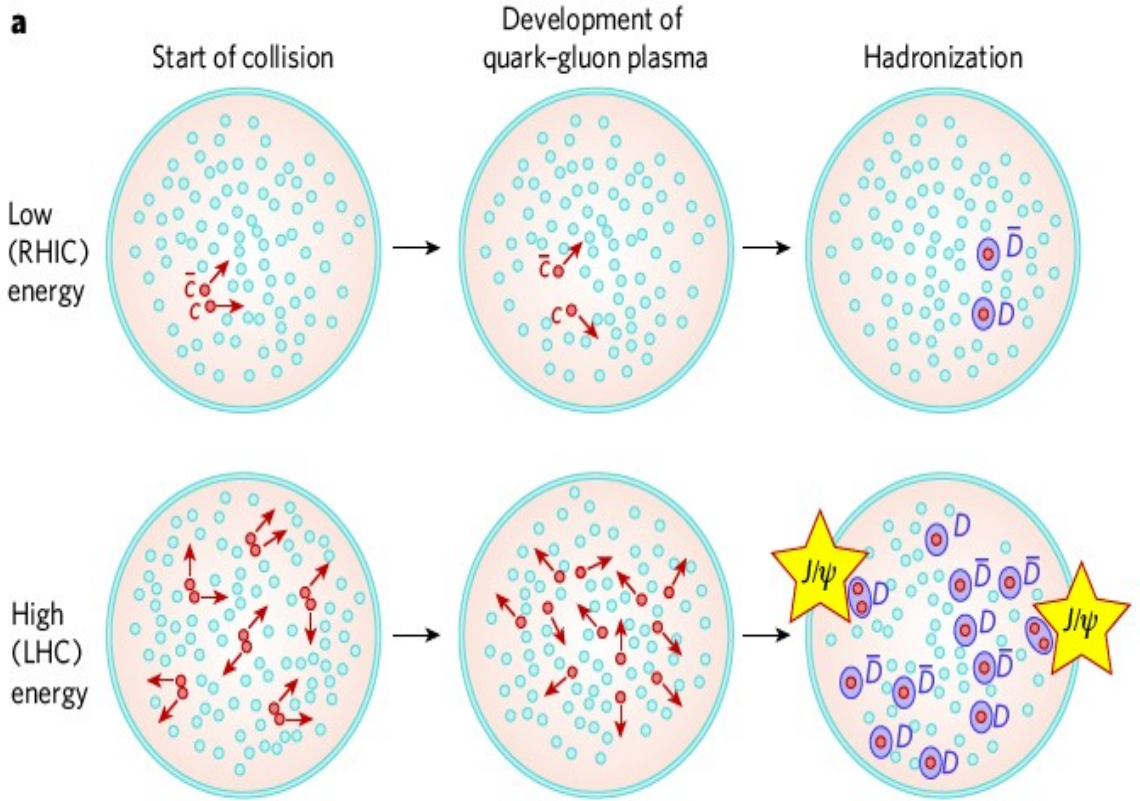
data: PHENIX coll. Phys.Rev.Lett.98:232301, 2007. nucl-ex/0611020

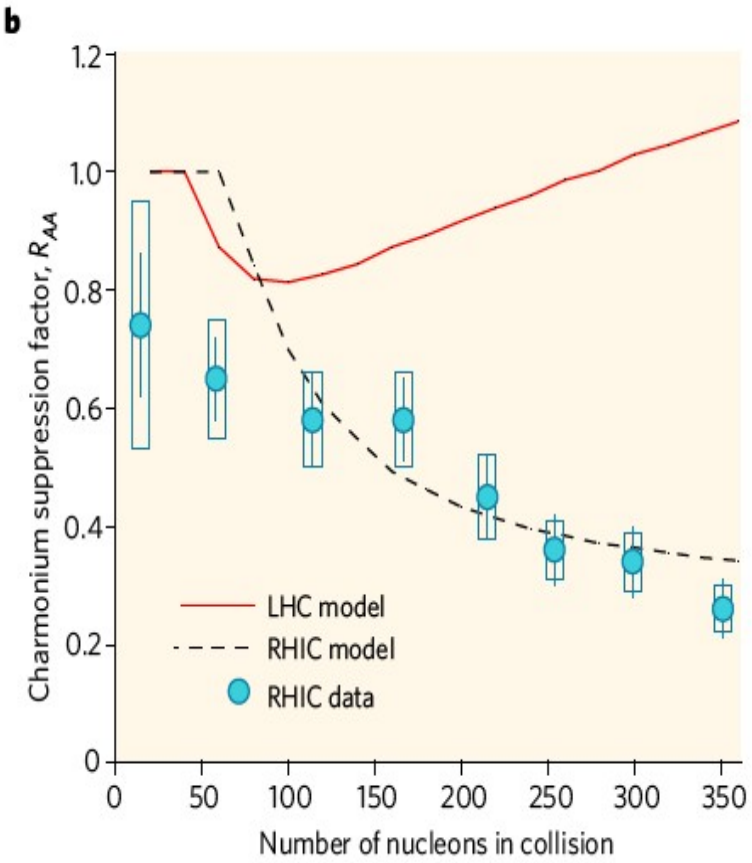
calc.: Andronic et al., Phys. Lett. B652 (2007) 659



suppression is smallest at mid-rapidity (90 deg. emission)
a clear indication for generation of J/psi at the phase boundary

quarkonium as a probe for deconfinement at the LHC





charmonium enhancement as fingerprint of deconfinement at LHC energy

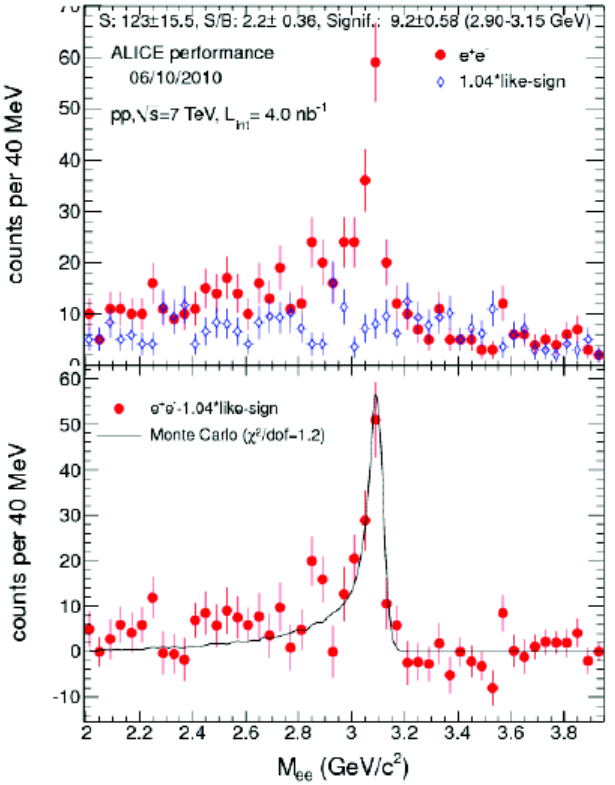
Andronic, pbm, Redlich, Stachel, Phys. Lett. B652 (2007) 659

Already first J/psi's observed with 7 TeV pp in ALICE

- High quality tracks in TPC and ITS
  - point in pixels to reduced γ conversions
- e PID from TPC dE/dx
  - to be extended with TOF, TRD
- Inclusive J/ψ
  - no B separation for now
- Data sample
  - 10^8 min. bias → L = 4.0 nb^{-1}
- Signal extraction
  - bin counting after like-sign bkg subtraction

$$N_{J/\psi} = 123 \pm 15$$

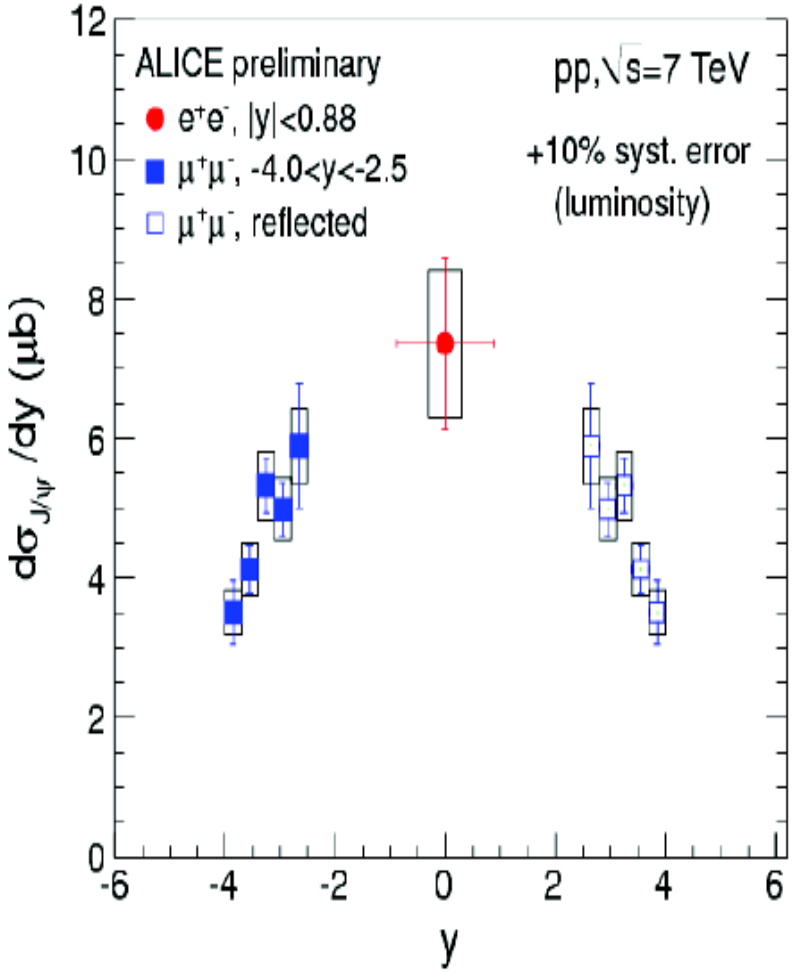
- Systematic errors:
  - 18% from efficiency corrections (tracking, PID)
  - 10% from normalization
  - -25%+10% from polarization



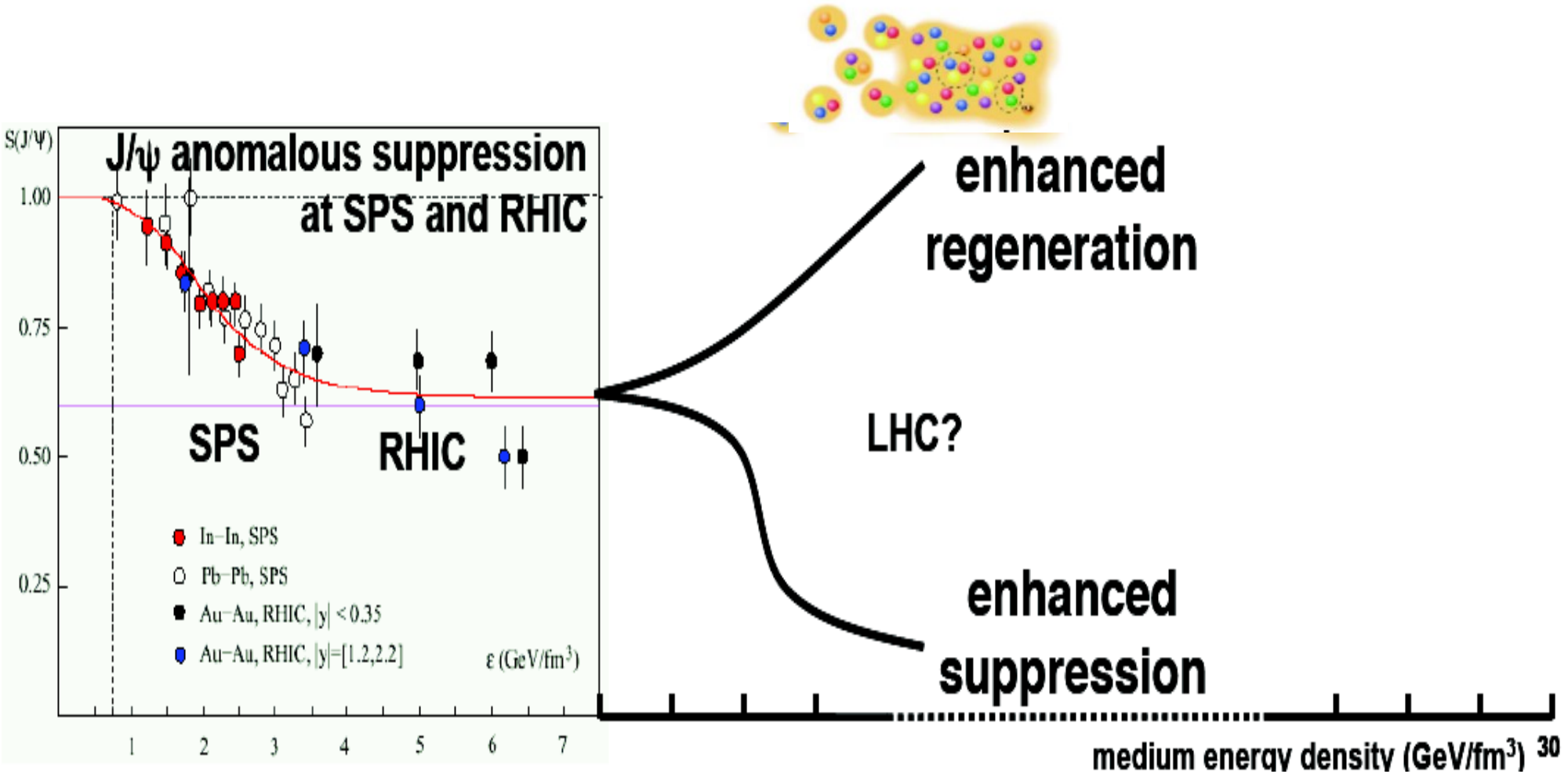
First J/psi inclusive rapidity distribution ever at a collider!

PbPb data to come soon

- Measurement of $d\sigma/dy$ in $-0.9<y<4$



- Next steps:
  - extend high p_t coverage
  - measure ψ' production in the forward region
  - measure polarization



data from the LHC will be decisive

first PbPb collisions in November 2010

summary

- strongly coupled systems with very small viscosity/entropy density ratio exist in many different areas of nature
- cold quantum gases, neutron matter and quark-gluon plasma are all examples in this regime
- for the first time, quantitative analysis of strongly coupled quark-gluon plasma is possible using the AdS/CFT correspondence
- from RHIC we have intriguing results supporting some but not all aspects of the 'strong coupling' scenario for the QGP
- **the LHC is the place to test these ideas**