Magnetic Component of Strongly Coupled Quark-Gluon Plasma

& QCD Phase Diagram from E-M Duality Perspective

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OUTLINE

- **E-M Duality for sQGP**
- **When Magnetic Scenario Meets Heavy Ion Data**
- **Pin Down the Parameters of Magnetic Component**
- **Discussions of QCD Phase Diagram**

E-M Duality in General

See:e.g. J. Harvey , hep-th/9603086

- ***What E-M duality says:***

  a) D+1 local field theory E, allowing D-dim. Topological Excitations M

  → convenient at E-coupling < 1 (M mass 1/E-coupling)

  b) an eff. local field theory based on M with E non-local

  → convenient at E-coupling > 1

  c) further more the **M-coupling ~ 1/ E-coupling** !!!

  working examples ? YES !

- 2-D Ising model: $Z[\beta,\sigma] = Z[\beta',\mu]$ $\quad sinh(2\beta') = \dfrac{1}{sinh(2\beta)}$

- 2-D sine-Gordon --- Thirring Model

$$\frac{\beta^2}{4\pi} = \frac{1}{1+g/\pi}$$

$$S_{SG} = \int d^2x \left(\tfrac{1}{2}\partial_\mu\phi\partial^\mu\phi + \frac{\alpha}{\beta^2}(\cos\beta\phi - 1) \right)$$

$$S_T = \int d^2x \left(\bar\psi i\gamma_\mu\partial^\mu\psi + m\bar\psi\psi - \frac{g}{2}\bar\psi\gamma^\mu\psi\bar\psi\gamma_\mu\psi \right)$$

- **More nontrivial: \cal N=2 SYM Seiberg-Witten:**

Minimal Lesson:

D.o.F. in per. Spectrum may NOT be the D.o.F. at strong coupling !

New Quest for D.o.F

hadrons: ***E-Composite***

interaction so strong → quarks/gluons confined !
however: hadrons are merely excitations of some more complicated stuff →

QCD vacuum: Magnetic

dual superconductor
monopole condensation
(`t Hooft -- Mandelstam)
(lattice: Giacomo/Suzuki/Greensite/....)

???

quarks, gluons: ***EQP***

dominating thermodynamics
pQCD calculable

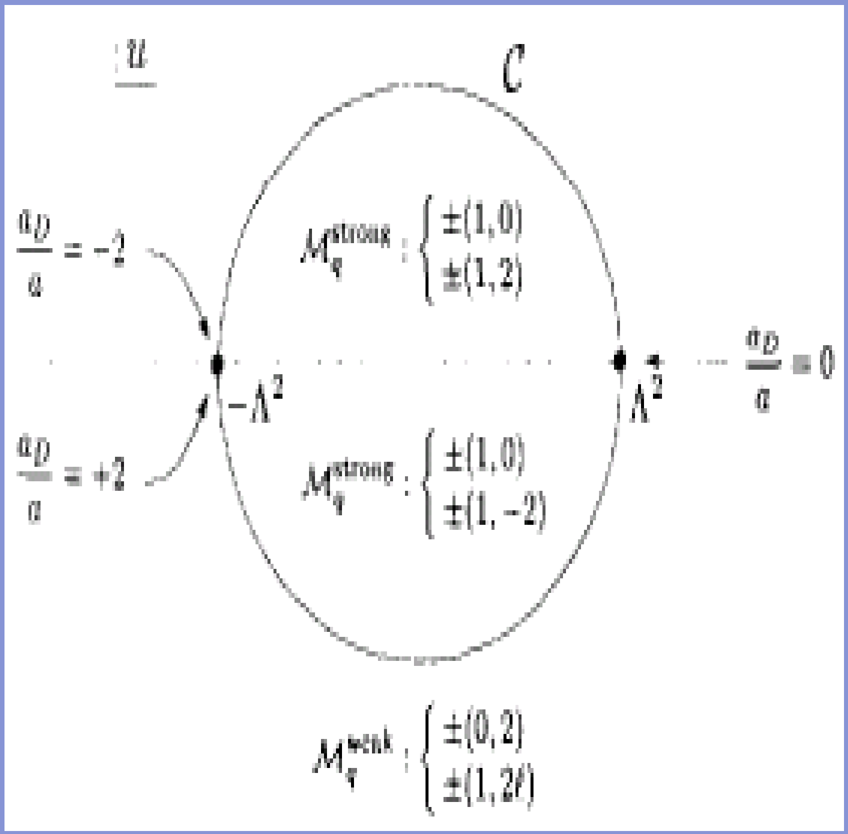
non-pert. scale: e^2 T
M-sector setting in

dim. reduction → MQCD
heavy, strongly correlated monopoles
(Kolthas-Altes, Meyer, …)

Tc ***~ 4 Tc*** ***Very High T***

Hadronic World **S-QGP** **wQGP**

Magnetic D.o.F: Lessons from S-W



From: Lerche, hep-th/9611190

Summarizing the ***E-component*** in sQGP

- quarks/gluons from high-T down to Tc become heavy and rare, gradually ceasing already about 1.5Tc
- hadrons from low-T do NOT necessarily melt right at Tc, instead they survive to about 1.5Tc and then dissolve into quarks and gluons at higher T

*Q: what about **M-component**?*

q/g/H all heavy, who are ruling the bulk?

- N=2 SYM: solved by Seiberg-Witten
- Deg. vacua: complex higgs U
  energy scale set by |U| (our analog: T)
- confining point: monopole becomes massless and forms condensate
- on way to that: gluons more and more heavy and strongly coupled
- monopoles the OPPOSITE !!

Magnetic Scenario for sQGP

JL & Shuryak, PRC75:054907,2007

hadrons:
E-Composite

1.5 Tc: e=g ?!

quarks, gluons: ***EQP***

E-S-C

$$\frac{eg}{4\pi\hbar c} = 1$$

E-W-C

$$\tilde{\beta}(\alpha)_E + \tilde{\beta}(\alpha)_M = 0$$

M-W-C

M-S-C

QCD vacuum:
Magnetic

dual superconductor, monopole ondensate

Magnetic Plasma
made of ***light and abundant***
magentic monopoles

non-pert. scale: e^2 T
M-sector setting in

heavy, strongly correlated monopoles

Tc | *~ 4 Tc* | *Very High T*

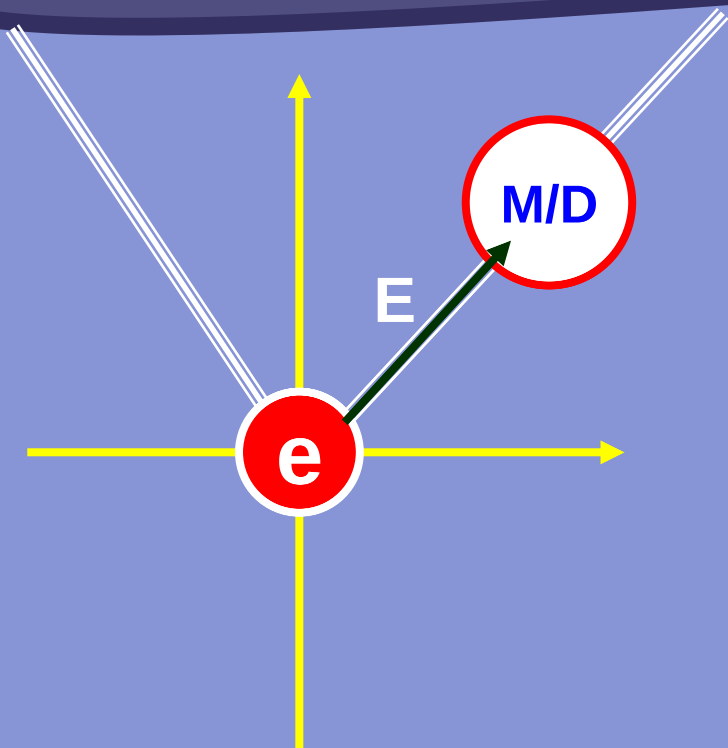
Hadronic World | **S-QGP** | **wQGP**

When Magnetic Scenario Meets Heavy Ion Data

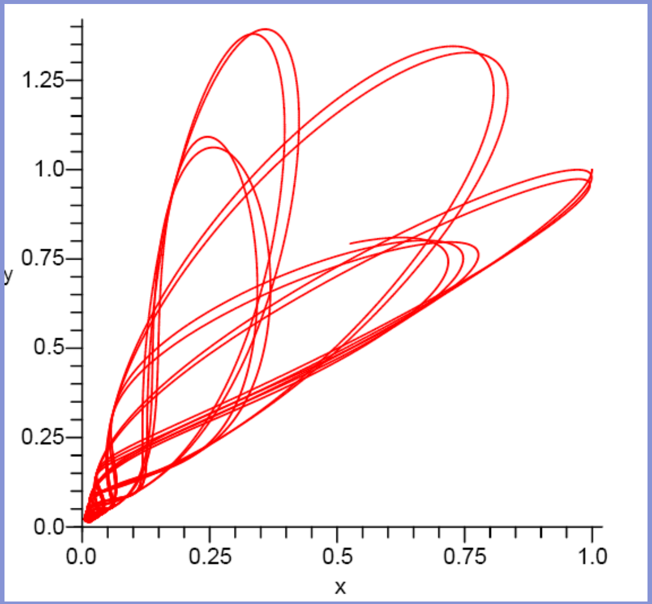
JL & Shuryak, PRC75:054907,2007
Also: JL & Shuryak, to appear

- sQGP: a strongly-coupled plasma with both Electric and Magnetic charges
- What would be the transport properties of such a mixture plasma, e.g. viscosity, diffusion,…
- Strong constraints from heavy ion data !
- Also, is the magnetic component important for jet quenching ?

Warmup: Single Monopole Motion I



$$\vec{F} = e(\vec{E} + \frac{\vec{v}}{c} \times \vec{B}) + g(\vec{B} - \frac{\vec{v}}{c} \times \vec{E})$$

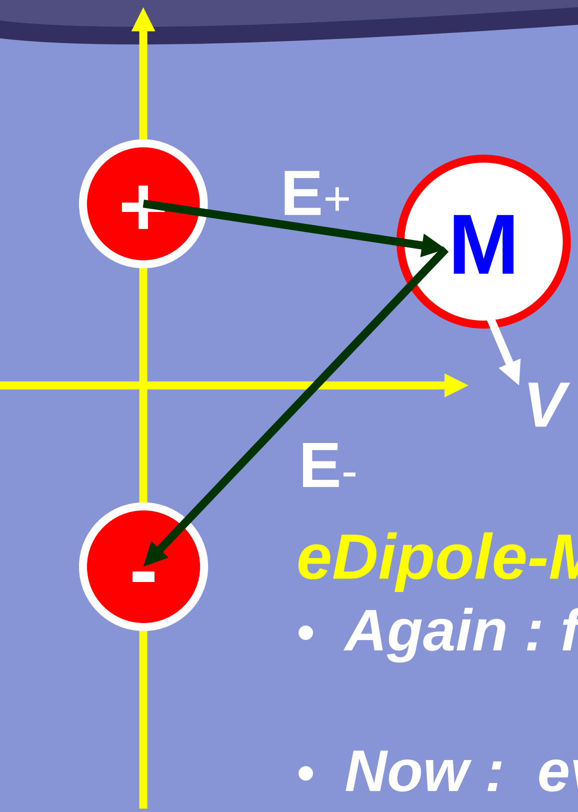


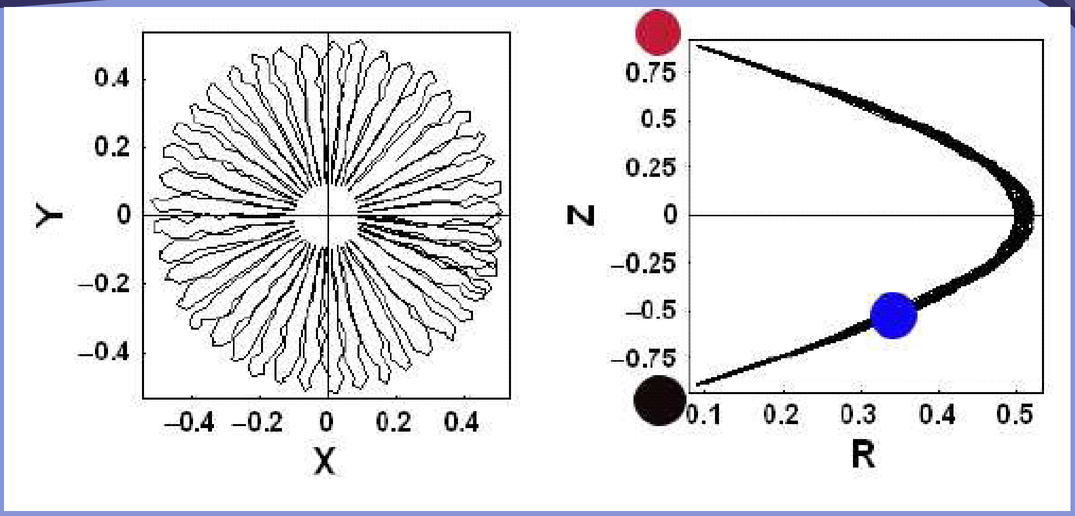
Charge-Monopole

- **studied in great details by many people, both classical and quantum**
- ***Poincare cone: focusing & bouncing***

A. S. Goldhaber, et al, Am. J. Phys. 58(1990)429
K. A. Milton, hep-ex/0002040

Warmup: Single Monopole Motion II

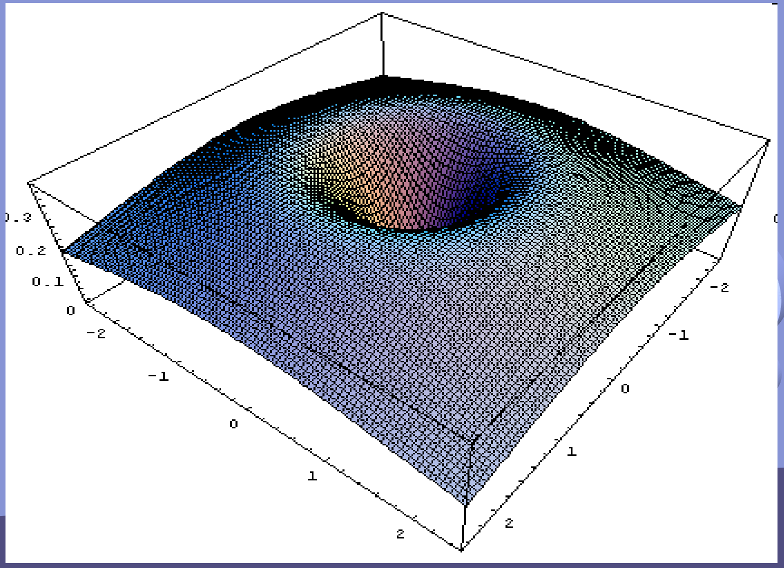




eDipole-Monopole

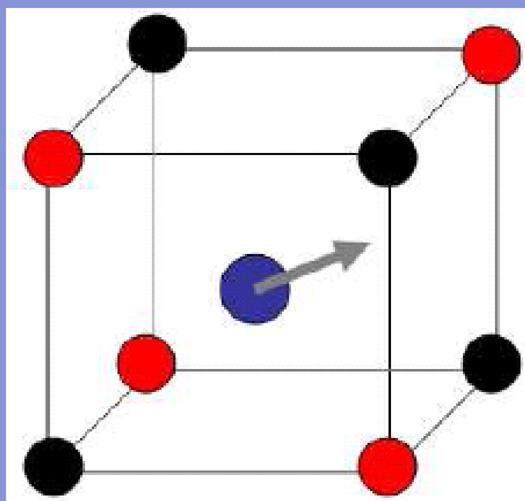
- *Again : focusing & bouncing*
- *Now : even trapping*
- *Important for transport !*

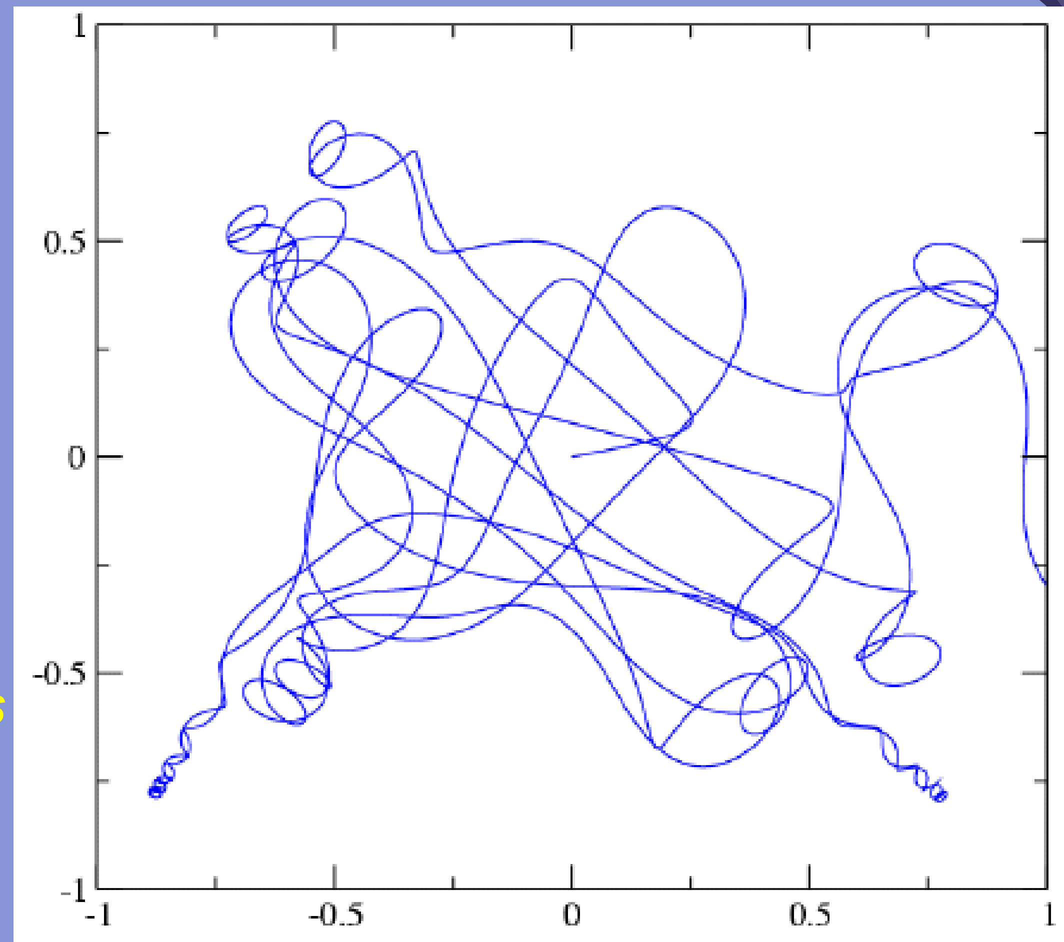
E-M PING-PONG



Warmup: Single Monopole Motion III

A grain of salt :

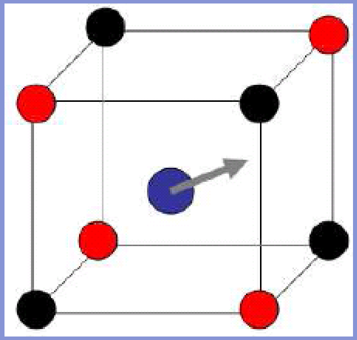




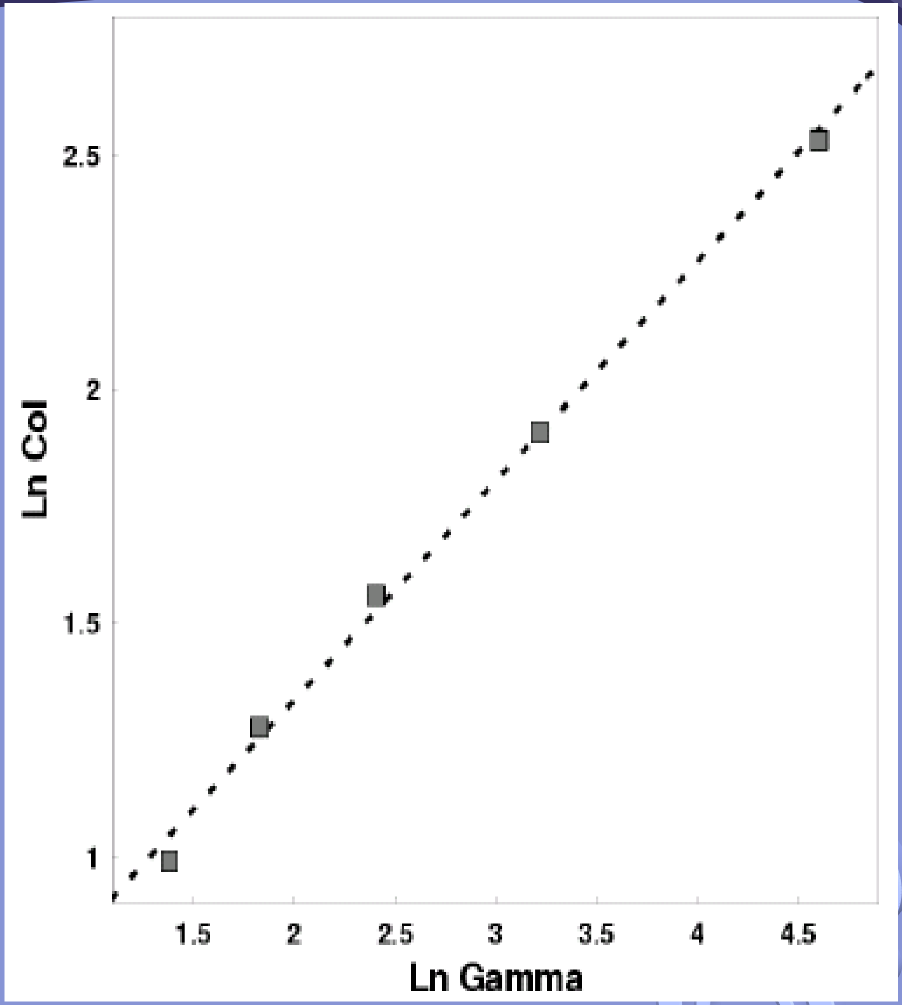
- *Very complicated trajectories*
- *Cone-like structure near the corners*
- *Multi-bouncing before eventually escaping*

Warmup: Single Monopole Motion III

A Cage for Monopole :



$$C = v\,\tau_{esc.}/L$$
$$\Gamma = PE/KE \sim 1/v^2$$
$$C \sim \Gamma^{0.47}$$
$$MFP \sim \frac{1}{C}$$
$$D \sim 1/\Gamma^{0.47}$$



Lorentz Trapping Effect

- *Enhance very much the collision rate*
- *Monopole can be trapped locally for a time scale much longer than micro. time scale*

Absent for E-charge in the same setting

MD for E-M Mixture Plasma

MD is a powerful tool :

- QED Coulomb plasma extensively studied
- Non-Abelian Coulomb plasma studied by *Gelman, Shuryak, and Zahed*
- Extremely useful for calculating transport properties

New Window -- 1st MD for E-M mixture

- Lorentz force betwne E-M
- ~1000 particles in a "cup"
- ***Varying E/M ratio: M00,M25,M50***
- ***Varying Gamma as well***
- Measure viscosity, diffusion
- Mapping to sQGP parameters

$$\Gamma = \left| \frac{<U>}{<E_k>} \right| \approx \frac{e^2/a}{k_B T}$$

$\Gamma < 1$ weakly-coupled (gas)

$\Gamma > 1$ strongly-coupled (liquid $\sim$ 1- few 10; solid $\sim$ 100)

For sQGP: $\Gamma \approx 3 - 10$

Transport properties are sensitive to Γ regime

$M \quad \sim 3T$

r_0 core size $\quad \sim 1/3T$

$\tau = \sqrt{m r_0^3 / e^2} \quad \sim 1/4.2T$

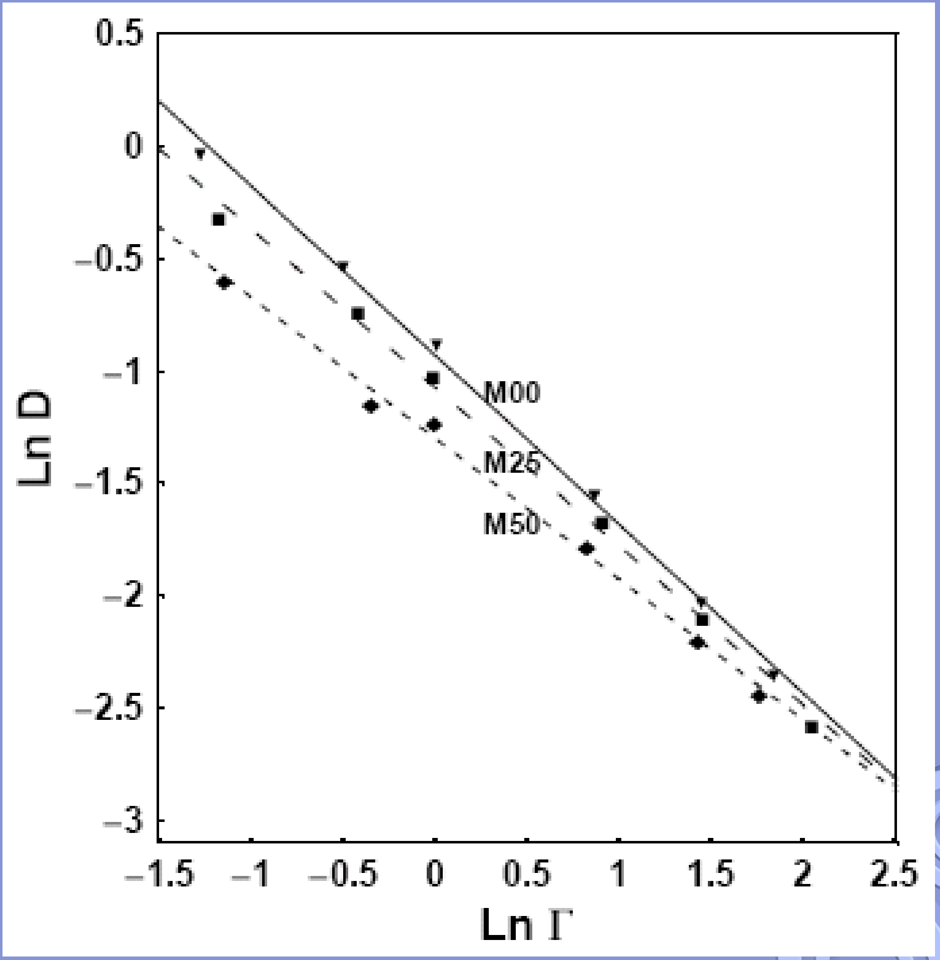
$$\to Observable(\Gamma)[UNIT] = \#_{MD}(\Gamma) \times UNIT_{QGP}$$

Transport: Diffusion

$$D(\tau) = \frac{1}{3N} < \sum_{i=1}^{N} v_i(\tau) \cdot v_i(0) >$$

$$D = \int_0^\infty D(\tau)\, d\tau$$

$$M00 \quad : \quad D = 0.396 / \Gamma^{0.752}$$
$$M25 \quad : \quad D = 0.342 / \Gamma^{0.707}$$
$$M50 \quad : \quad D = 0.273 / \Gamma^{0.626}$$



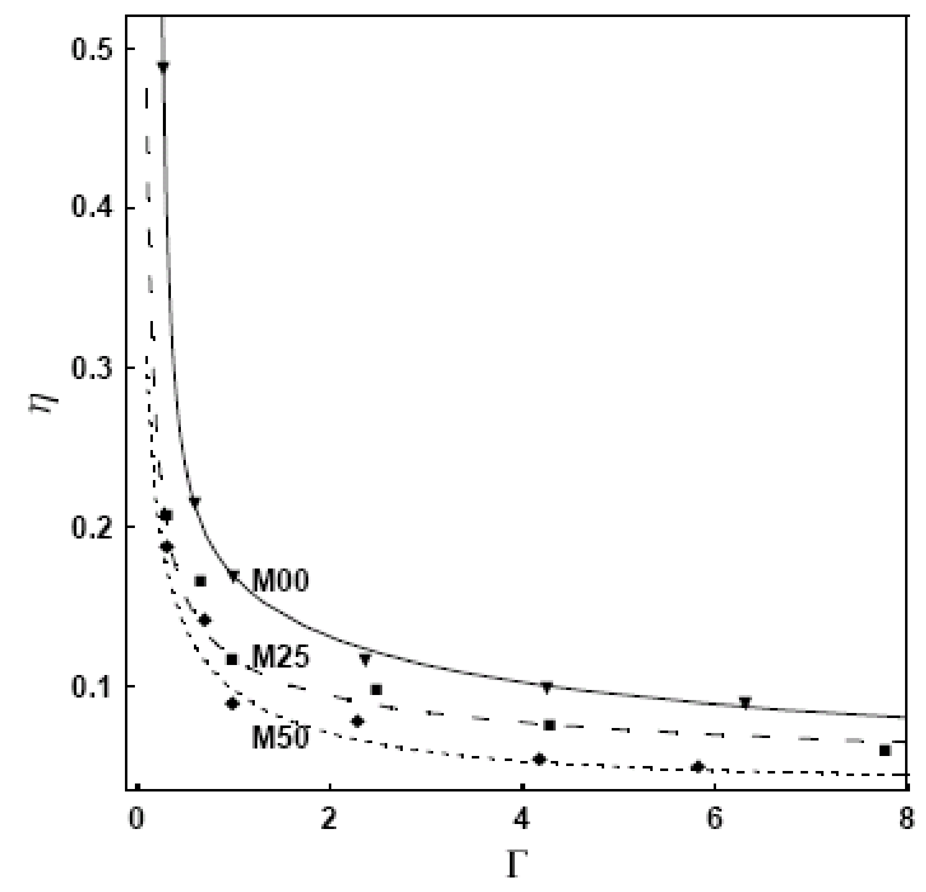
- *More mixing → less diffusion*
- power law
- the power is close to 0.47 (cube-analysis) and the 0.5 (AdS/CFT)

Transport: Viscosity

$$\eta(\tau) = \frac{1}{3VT} < \sum_{l<k}^{1,2,3} T_{lk}(\tau) T_{lk}(0) >$$

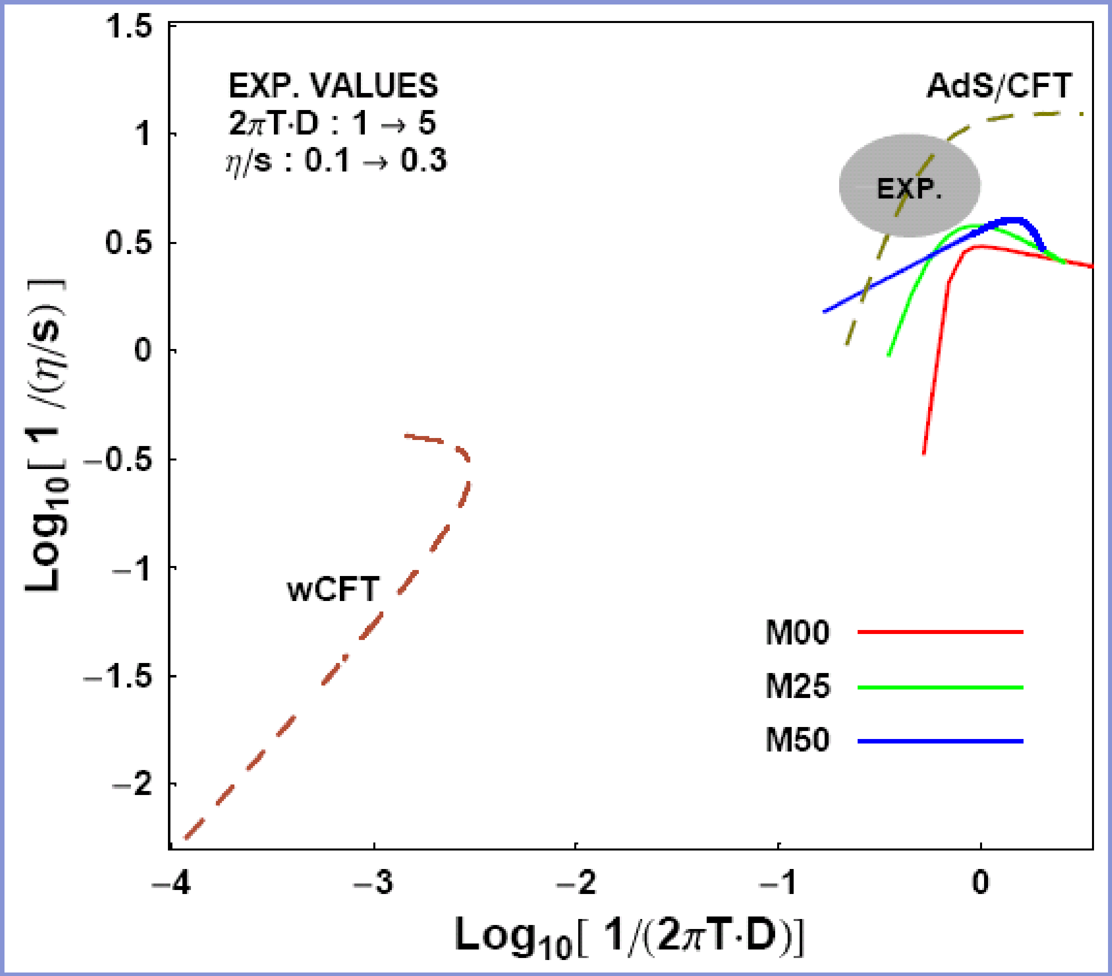
$$\eta = \int_0^\infty \eta(\tau) d\tau$$

$$\begin{aligned} T_{lk} &= \sum_{i=1}^{N} m(\boldsymbol{v}_i)_l(\boldsymbol{v}_i)_k + \frac{1}{2}\sum_{i\neq j}(\boldsymbol{r}_{ij})_l(\boldsymbol{F}_{ij})_k \\ &= \sum_{i=1}^{N} m(\boldsymbol{v}_i)_l(\boldsymbol{v}_i)_k + \sum_{i=1}^{N} m(\boldsymbol{r}_i)_l(\boldsymbol{a}_i)_k \end{aligned}$$



- *More mixing → less visicosity*
- **rapid rising for Gamma < 1**
- **tendency to rise again for Gamma~10**

Transport Summary



RHIC Results:
viscous hydro → \eta/s
heavy flaovr → diffusion

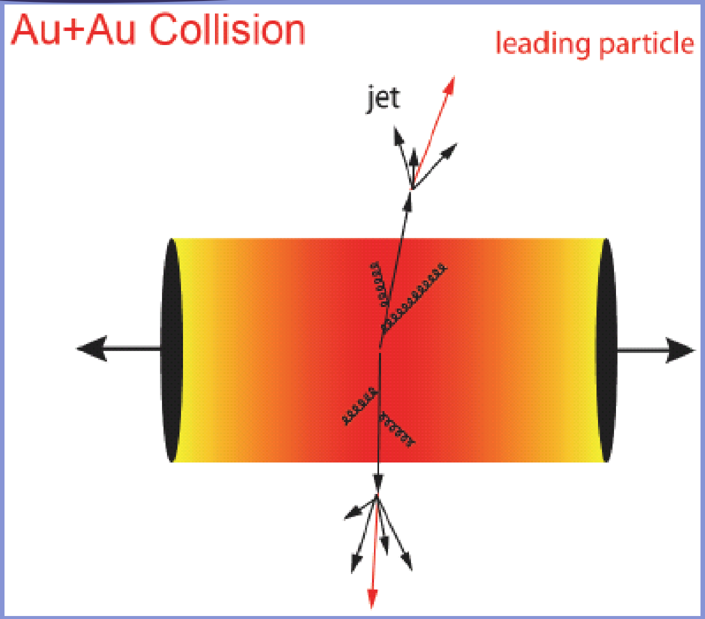
Weakly coupled limit:
both proportional to M.F.P.

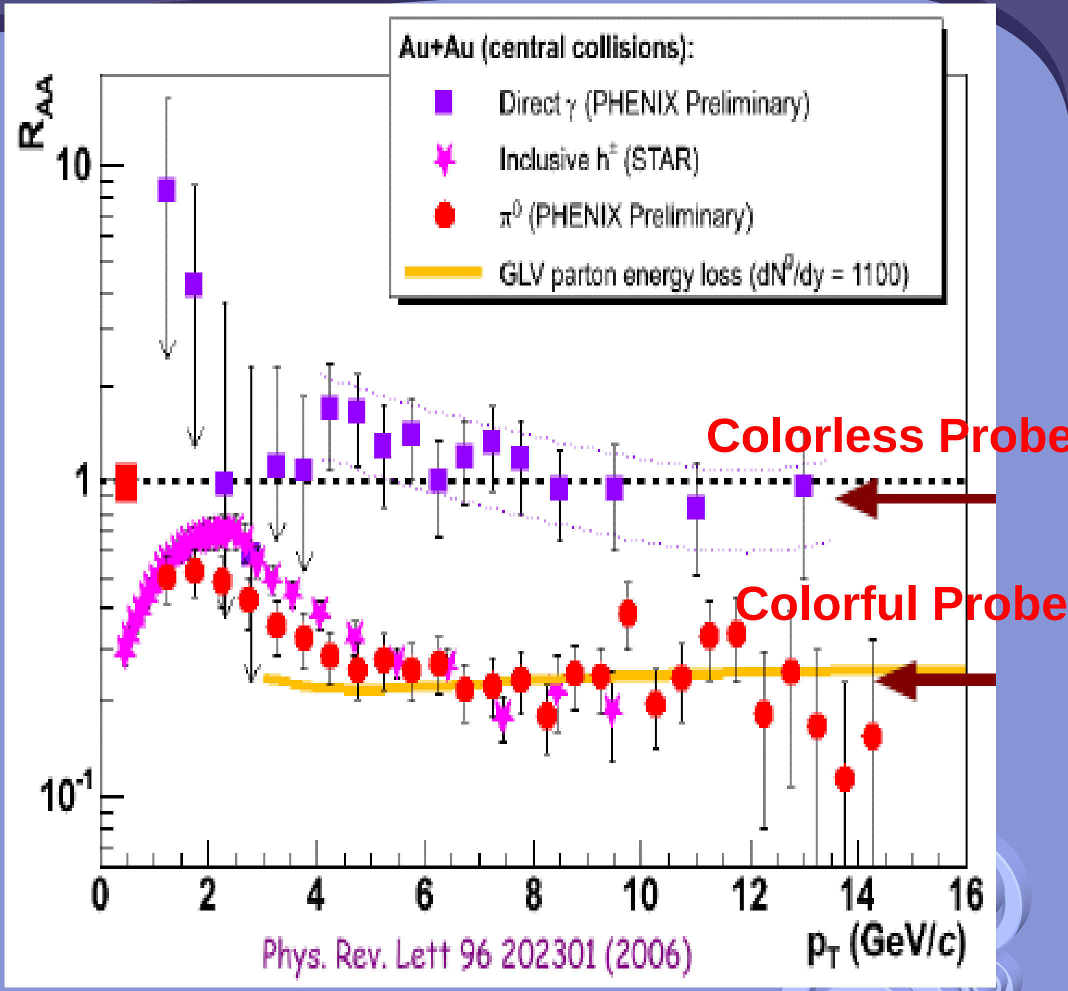
AdS/CFT predictions:
(Kovtun,Son,Strainet; Casselderrey & Teaney)

$$\frac{\eta}{s} = \frac{1}{4\pi}\left(1 + \frac{135\zeta(3)2^{-9/2}}{\lambda^{3/2}} + \ldots\right)$$

$$D(2\pi T) = \frac{4}{\sqrt{\lambda}}$$

Jet Quenching at RHIC





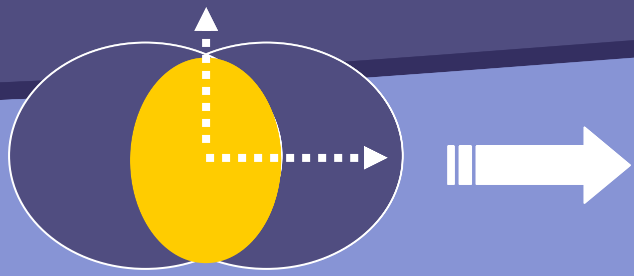
Nuclear Modification Factor:

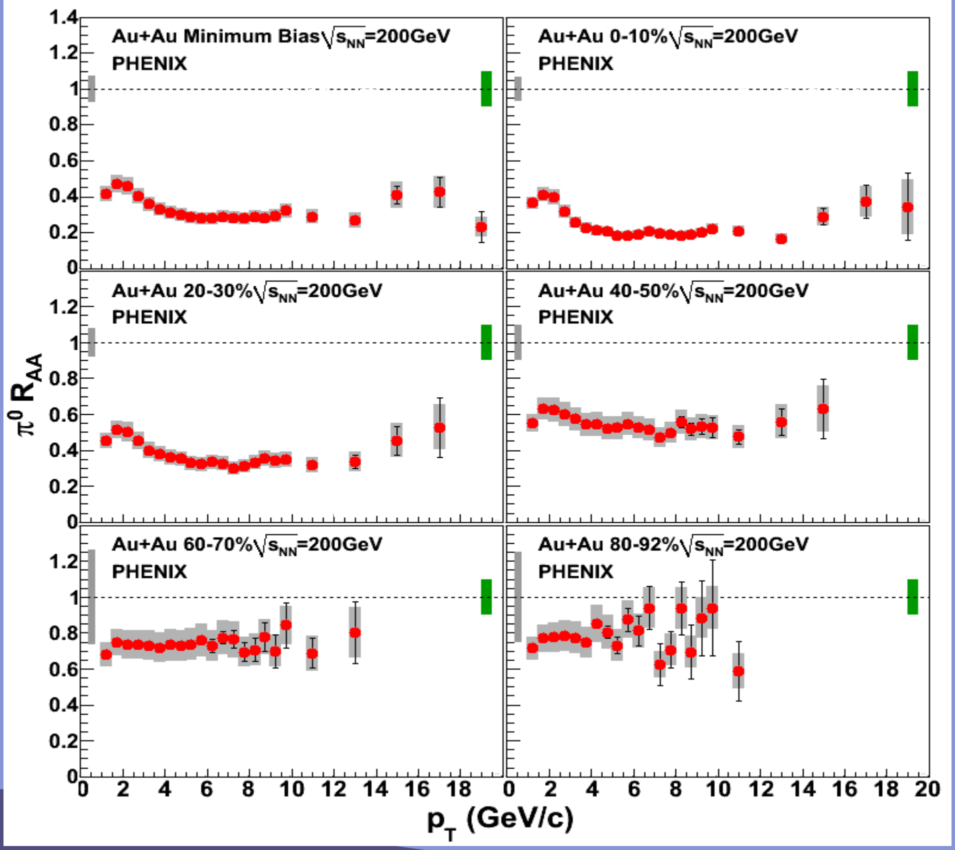
$$R_{AA}(p_T) = \frac{(1/N_{AA}^{evt})\, d^2N_{AA}^{\pi^0}/dp_T\,dy}{\langle T_{AA}\rangle \times d^2\sigma_{pp}^{\pi^0}/dp_T\,dy},$$

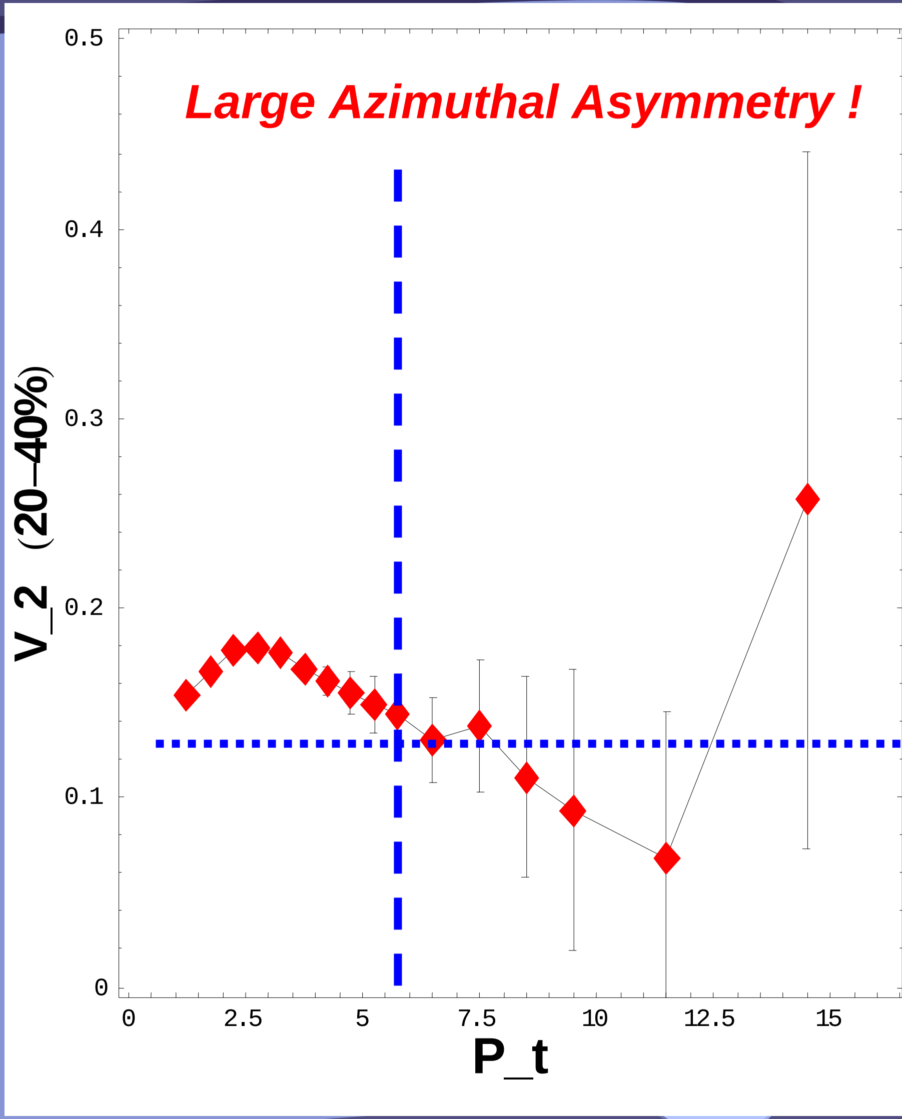
R_aa = 1 : NO medium effect, just bunch of pp

Raa & V2 from Phenix

PHENIX,
PRC76:034904,2007
arXiv:0801.4020







Jet Energy Loss

$$\frac{dE}{dx} = \mathcal{F}[\,J \,|\, M \,|\, M + J\,] \rightarrow \Delta E = \int_i^f \mathcal{F} \cdot dx$$

Probe dependence:

$$\mathcal{F} \rightarrow < \mathcal{F} > |_{species} \propto E \rightarrow E_f = E_i \times e^{-\int_i^f \tilde{\mathcal{F}} \cdot dx}$$

Medium dependence:

$$\tilde{\mathcal{F}} \propto \kappa[s(x)] \cdot s(x)$$

Entangled dependence:

$$\tilde{\mathcal{F}}\; dx \rightarrow \tilde{\mathcal{F}}\; x\, dx$$

All together :

$$E_f = E_i \times e^{-\int_i^f \kappa[s(x)] \cdot s(x) \cdot x \cdot dx}$$

Note:
mid rapidity
high Pt > 5GeV
→ E ~ Pt

Raa AND V2 of High Pt Hadron

PHENIX,
PRC76:034904,2007
arXiv:0801.4020

Raa : well described by most models

$$E_f = E_i \times f \qquad f = e^{-\int_i^f \kappa[s(x)]\cdot s(x)\cdot x\cdot dx}$$

$$R_{AA}(P_T) = f^{(n-2)} \qquad n \approx 8.10$$

V2 in non-central collisions : surprisingly large !
no satisfactory model ; what's thegeometric limit ?

$$R^{\mathrm{raw}}(\Delta\phi, p_T) \approx R_0\left[1 + 2v_2^{\mathrm{raw}}\cos(2\Delta\phi)\right],$$

Shuryak, PRC66:027902,2002

• hard sphere nuclei with sharp edges
• constant \kappa
→ even black limit can NOT produce enough v_2

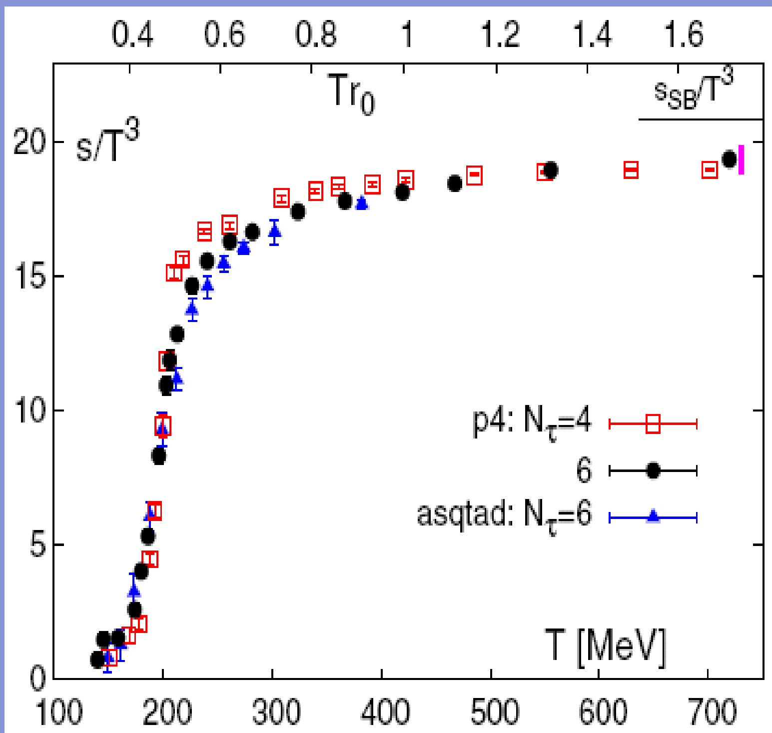
Drees & Feng & Jia, PRC71:034909,2005

• Woods-Saxon + medium dilution + quadratic length
• constant \kappa
→ only bring down the v_2 (except cylindrical geo. up ~10%)

Possible improvement : CGC like initial → 10% increase of the final v_2 !

Rethinking about the \kappa

From: PRD77:014511,2008.

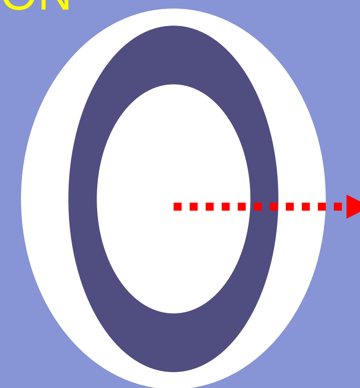


Pantuev, JETP Lett.85:104-108,2007

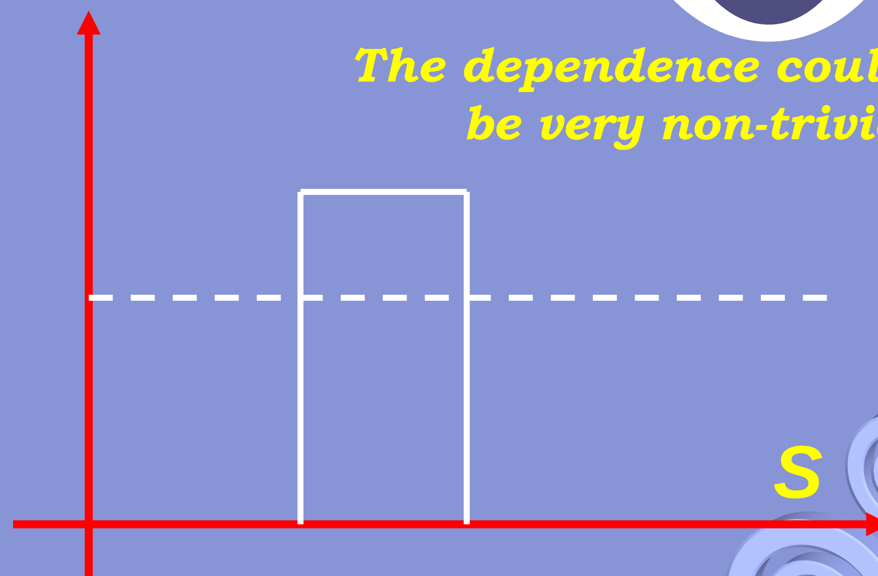
Jet absorption retarded by
a “latent time” of about 2-3fm

From “almond” to “ONION”

$$\kappa[s(x)]$$



The dependence could be very non-trivial !



Scanning the RHIC Fireball with Jet

Key idea of our geometric model:

$$\kappa[s] = \kappa_c \times \theta[s - s_{min}] \times \theta[s_{max} - s] \quad \rightarrow \quad f = e^{-\kappa_c \int_{s=s_{min}}^{s=s_{max}} s(x)\cdot x \cdot dx}$$

Varying s_min & s_max to scan layer by layer : really a kind of jet tomography !

The jet :

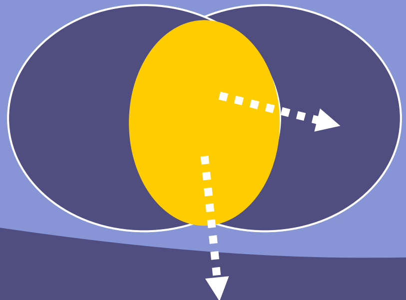
ignited in x-y plane according to density of binary collision

randomly escaping near \phi=0,\pi/2,\pi,3\pi/2 directions

The medium :

initial profile → Woods-Saxon with impact b & Npart. scaling

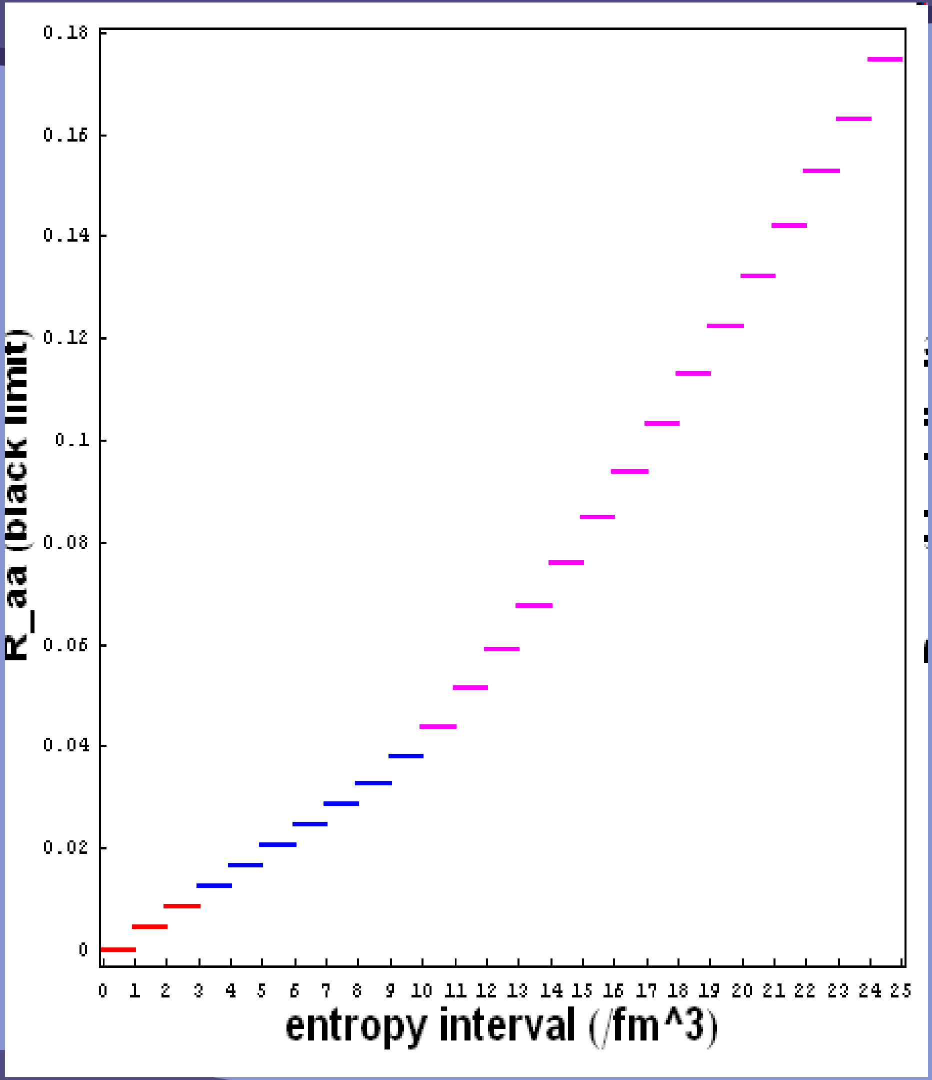
evolution → Bjorken dilution ~ 1/ \tau

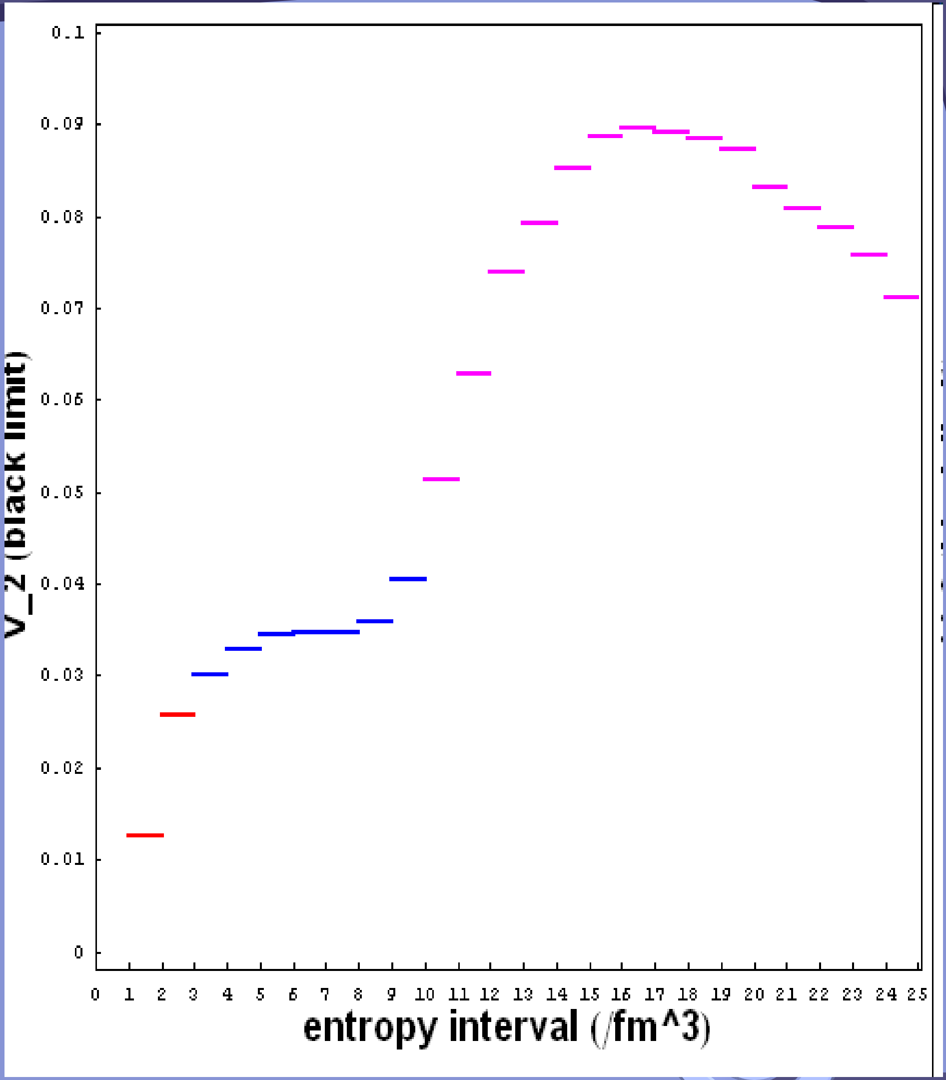


$$\bar{R}_{AA}(P_T) = \frac{R_{AA}(P_T, \phi = 0) + R_{AA}(P_T, \phi = 90)}{2}$$

$$v_2(P_T) = \frac{[R_{AA}(P_T, \phi = 0) - R_{AA}(P_T, \phi = 90)]/2}{R_{AA}(P_T, \phi = 0) + R_{AA}(P_T, \phi = 90)}$$

Black Limit Raa & V2





b=7 , N_part ~ 260 , \tau_0 = 1 fm

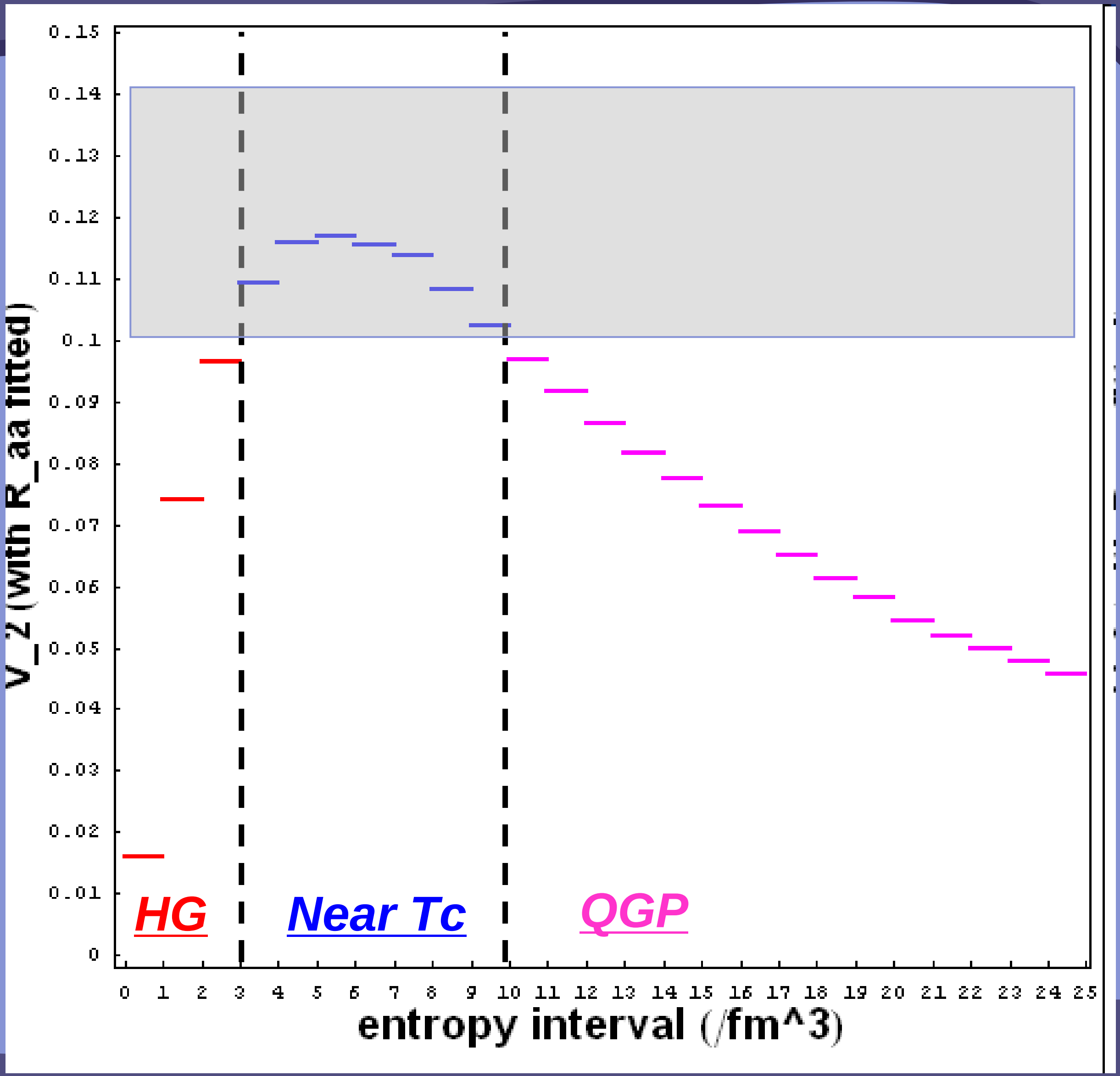
V2 with constrained Raa

R_aa is constrained by measurements :
b=7fm → R_aa ~ 0.33 (PHENIX 20-30%)

For each layer scan:
→
first adjust \kappa to fit the R_aa
→
then calculate the V_2

PHENIX V2 20-40%
5-15 GeV: ~ 0.10-0.14

b=7 , N_part ~ 260 , \tau_0 = 1 fm

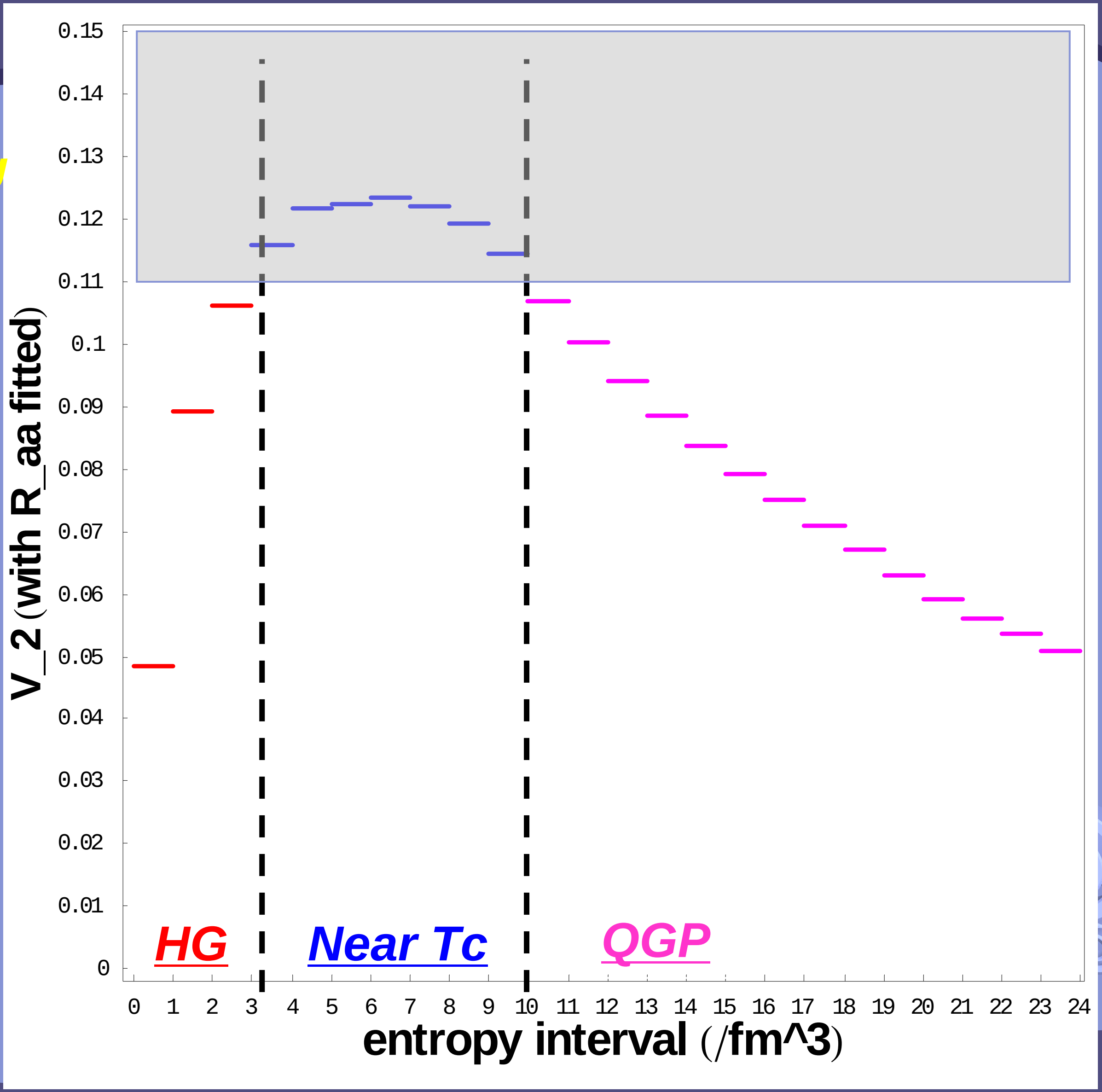


V2 with constrained Raa @ another centrality

R_aa is constrained by measurements :
b=10fm → R_aa ~ 0.52 (PHENIX 40-50%)

For each layer scan:
→
first adjust \kappa to fit the R_aa
→
then calculate the V_2

PHENIX V2 40-60%
5-15 GeV: ~ 0.11-0.15

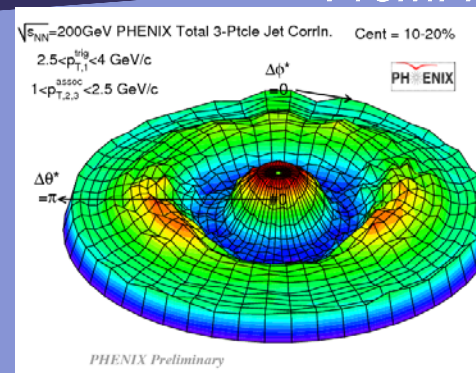


b=10 , N_part ~ 120 , \tau_0 = 1 fm

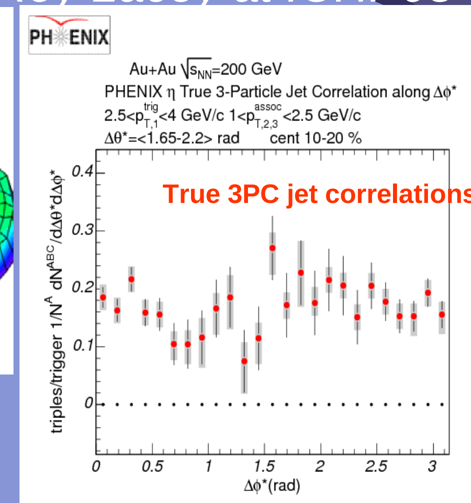
The Near Tc Region

From: Roy Lacey at ICHP08

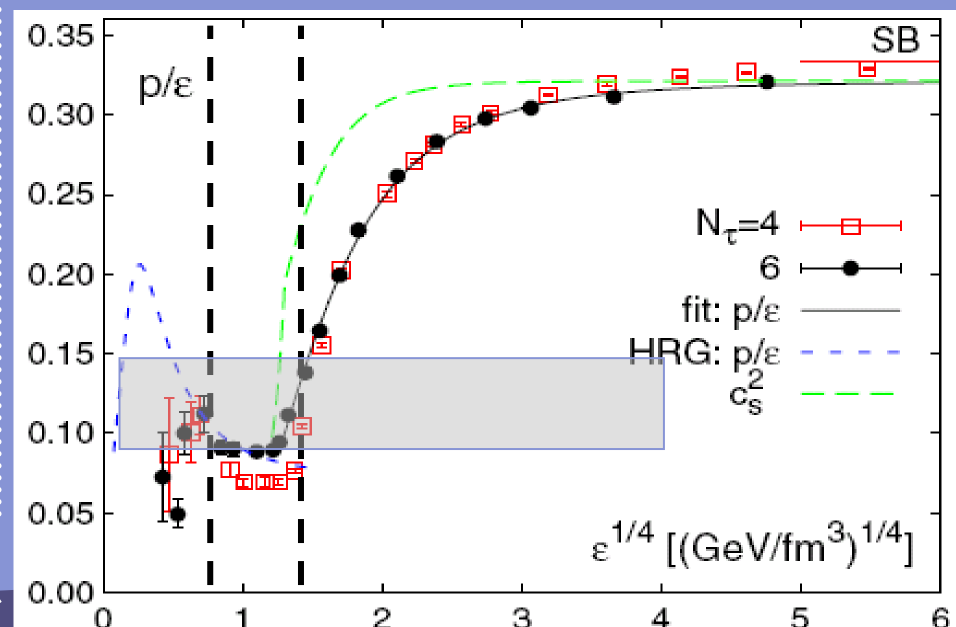
No wonder the Near Tc Region shall be special on general ground.
However:
Our study of azimuthal asymmetry in high Pt hadron yield suggest in Particular that ------
Jet quenching happens mostly in this Near Tc Region !



$$\langle c_s \rangle \sim 0.35, \qquad \frac{\eta}{s} \sim 2\times\left(\frac{1}{4\pi}\right)$$



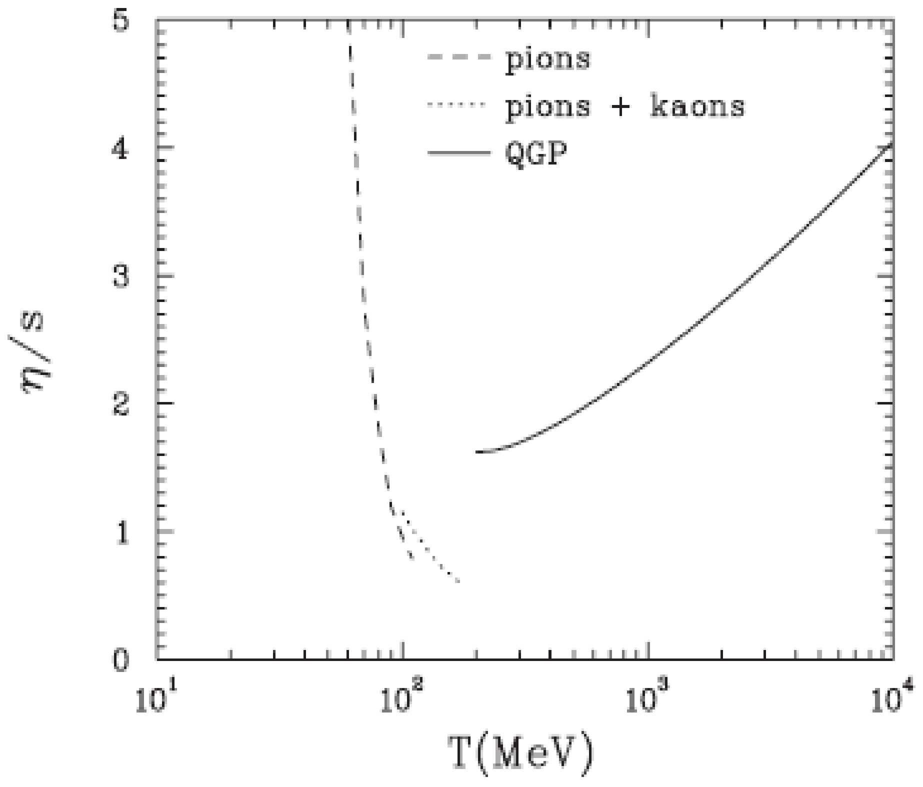
Is there any independent evidence for such a conclustion ?
Yes → the conical flow created from interaction of away-side jet with the medium



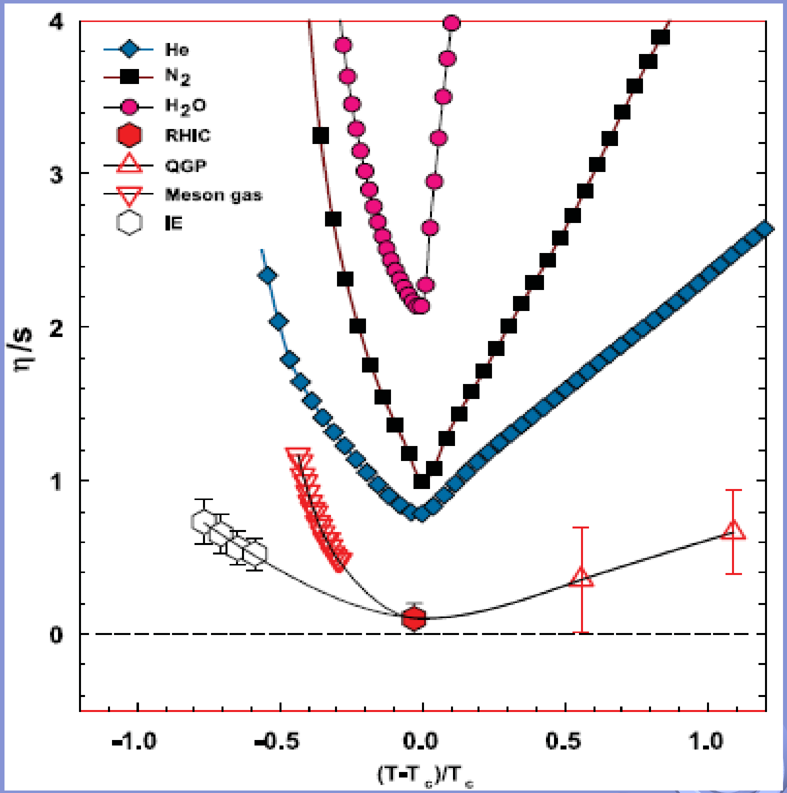
From: PRD77:014511,2008. →

In light of \eta / s

From: Csernai, Kapusta, McLerran



From: Lacey & Collaborators



Minimal viscosity around Tc
→ Strong dissipation/relaxation concentrated locally

Thanks to Larry for pointing out this to me .

Magnetic Quenching of Electric Jet

Why more quenching in the Magnetic Plasma near Tc rather than in the QGP at higher T ?

- ***Time argument :***

$$\int \frac{d\tau}{\tau} \to Ln[\frac{\tau_f}{\tau_i}] \to \; Ln[2]_{MP} \; : \; Ln[5]_{QGP} \approx 0.4:1$$

$$\int \frac{\tau d\tau}{\tau} \to 1:1$$

- ***Mass argument :*** $\frac{\alpha_e \cdot \alpha_m \cdot v_m^2 \cdot \Delta t^2}{M_m} / \frac{\alpha_e^2 \cdot \Delta t^2}{M_e} \sim M_e \; : \; M_m \approx 3:1$

- ***Density argument :***

$$n_m \; : \; n_e > 1$$

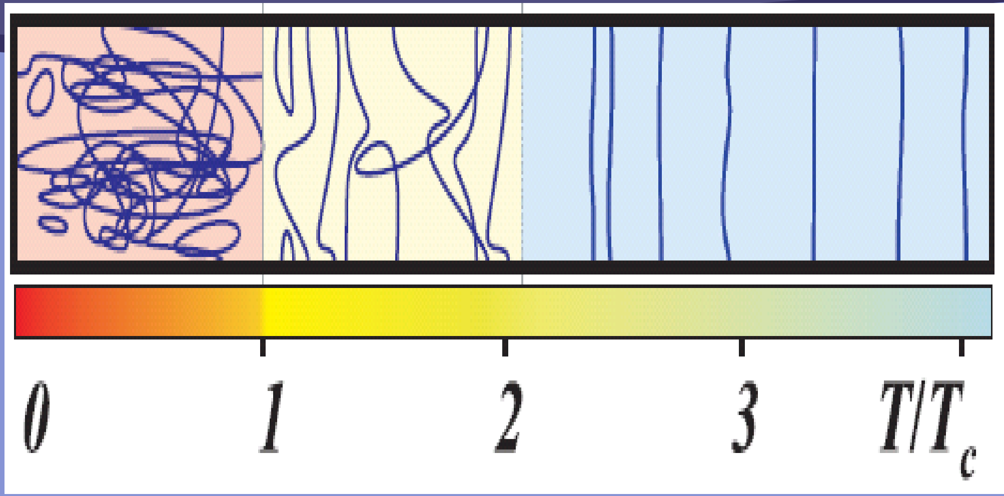
- ***Transport cross-section argument :*** $\sigma_m : \sigma_e[\theta \to \pi] \sim 2$

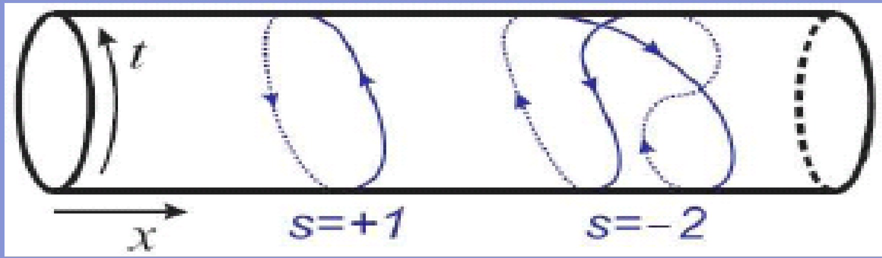
Pin Down the Parameters of Magnetic Component

JL & Shuryak, arXiv: 0804.0255

- Lattice Gauge Theory (LGT) is another important way of studying sQGP
- LGT provides important support for the dual superconductivity scenario of color confinement
- Are there evidence for the magnetic component of sQGP from LGT?
- Further: can the parameters of magnetic component be measured or inferred ?

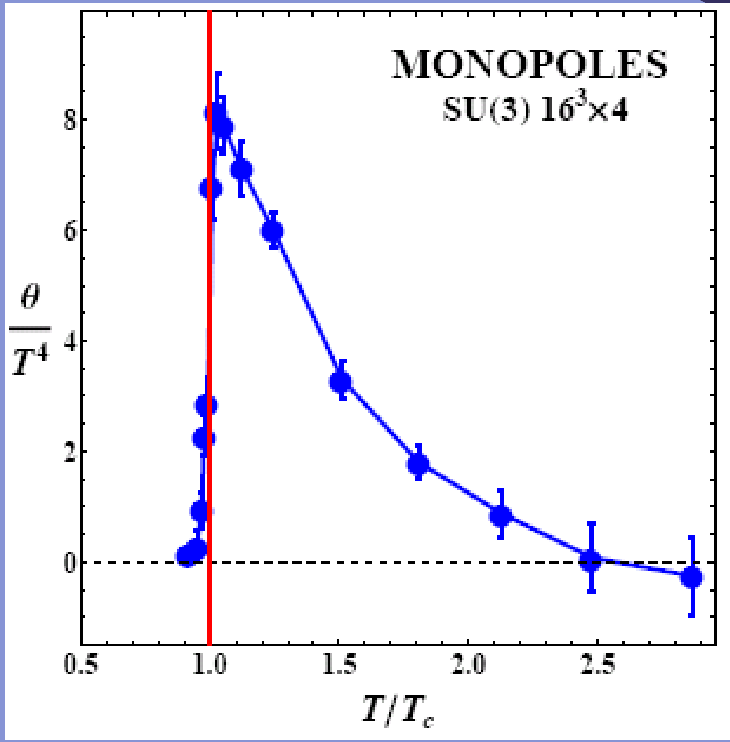
Magnetic Monopoles on the Lattice





$$\rho(T) \approx T_c^3 \qquad (T_c < T < 2T_c)\,.$$

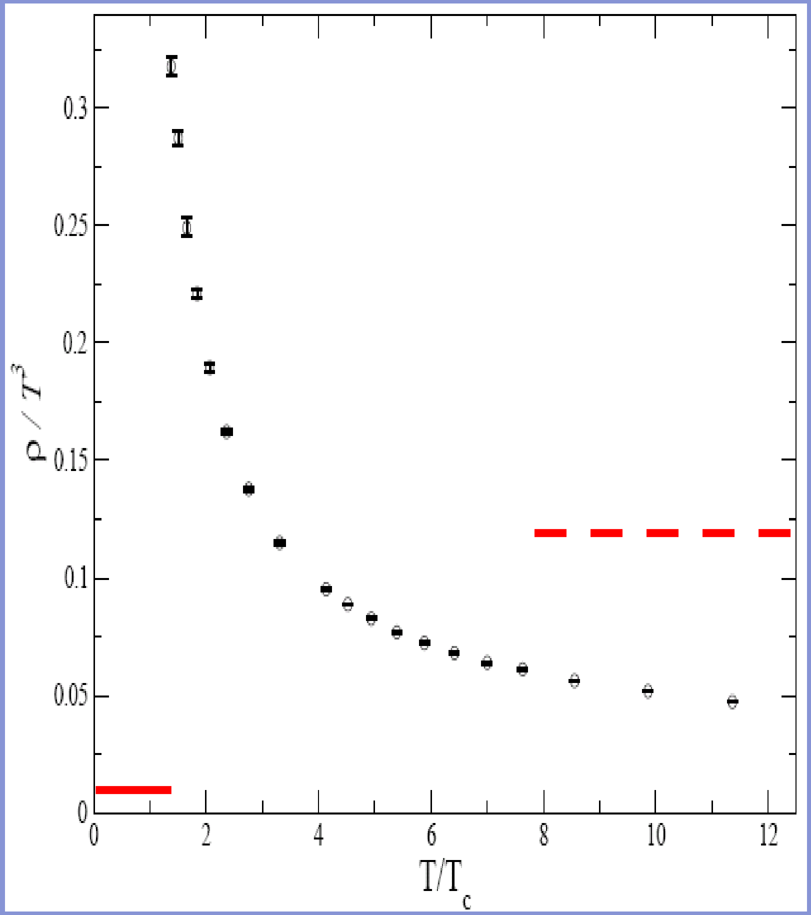
$$\zeta(3)/\pi^2 \approx 0.12.$$



$$\frac{\theta(T)}{T^4} = 6N_t^4\left(\frac{\partial\beta(a)}{\partial\log a}\right)\cdot\left(\langle S_P\rangle_T - \langle S_P\rangle_0\right)$$

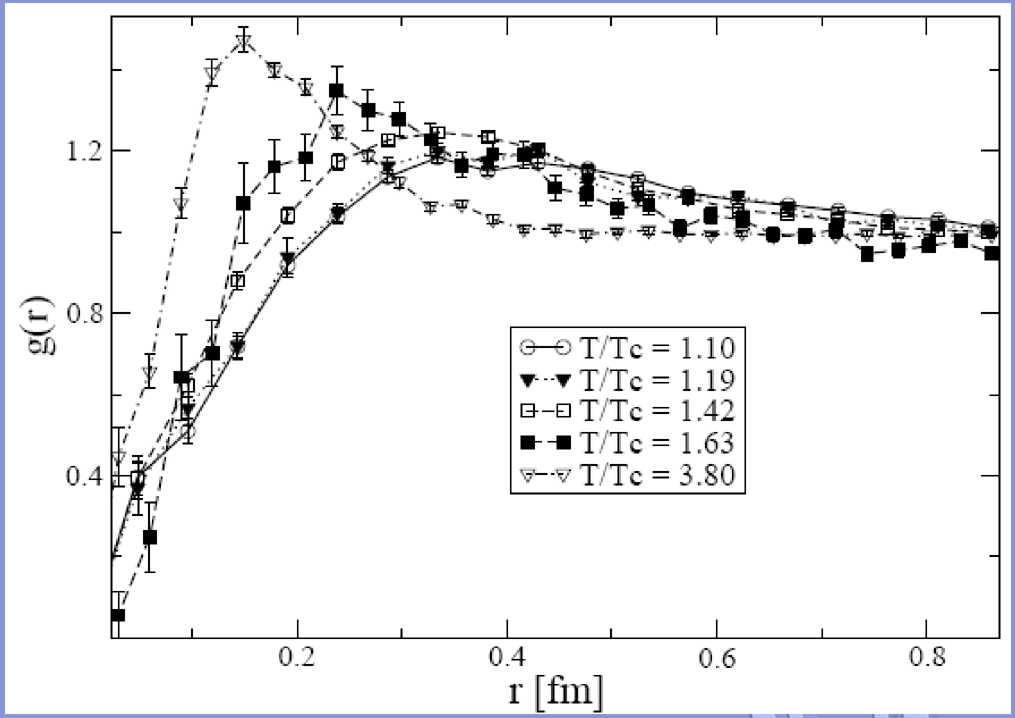
Chernodub & Zakharov , arXiv:0611228,0806.2874; Chernodub, et al, arXiv: 0710.2547

Monopole Density & Correlation



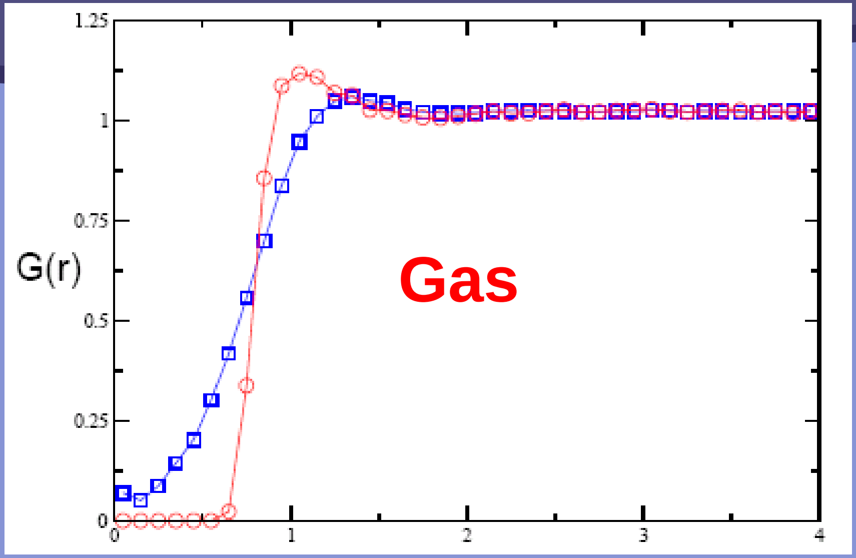
M-anti-M , M-M equal-time spatial orrelation functions

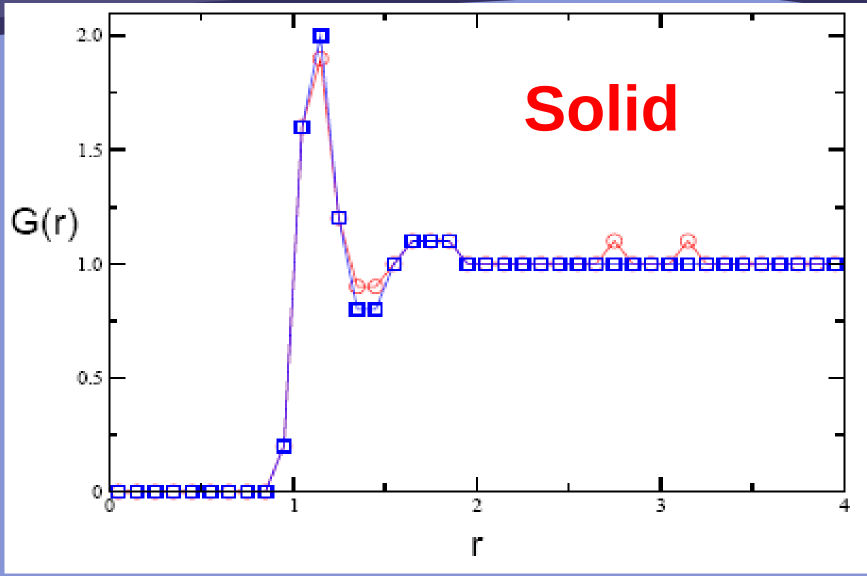
$$G_{ab}(r) \equiv \frac{< \sum_{i=1,N_a} \sum_{j=1,N_b} \delta(|r_i^a - r_j^b| - r) >}{N_a N_b 4\pi r^2 / V}$$

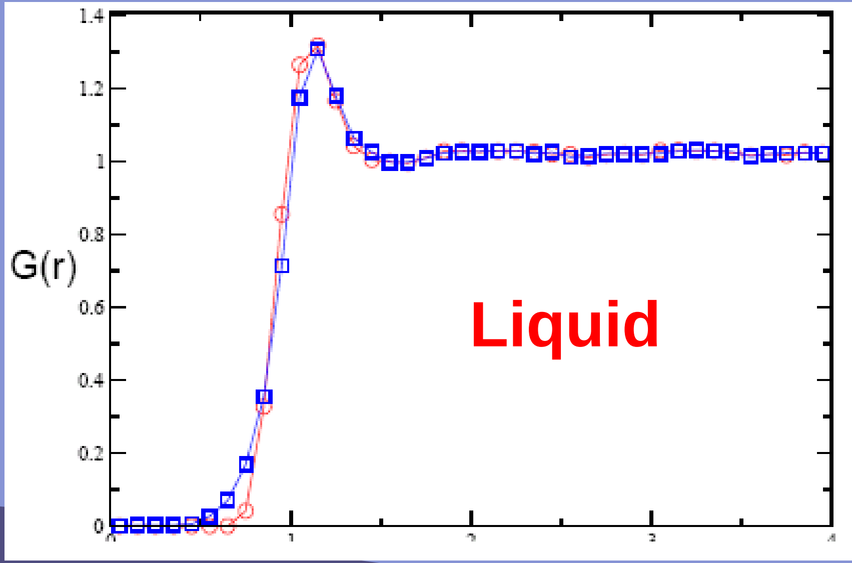


D'Alessandro & D'Elia , arXiv:0711.1266

The Correlation Teaches us sth.





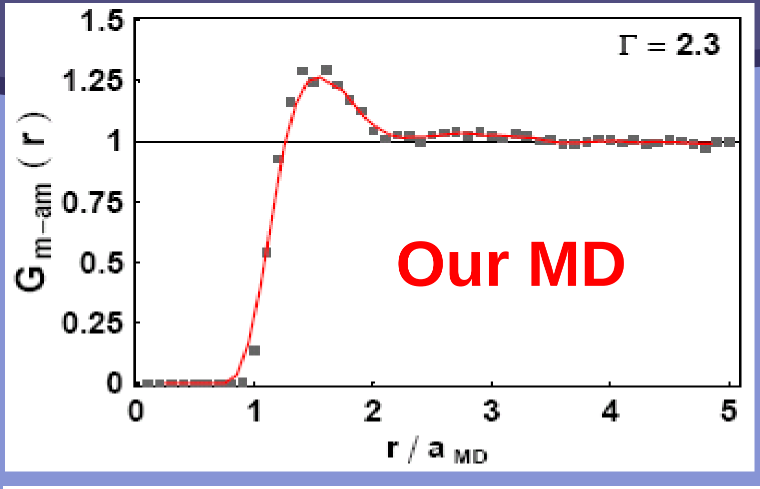


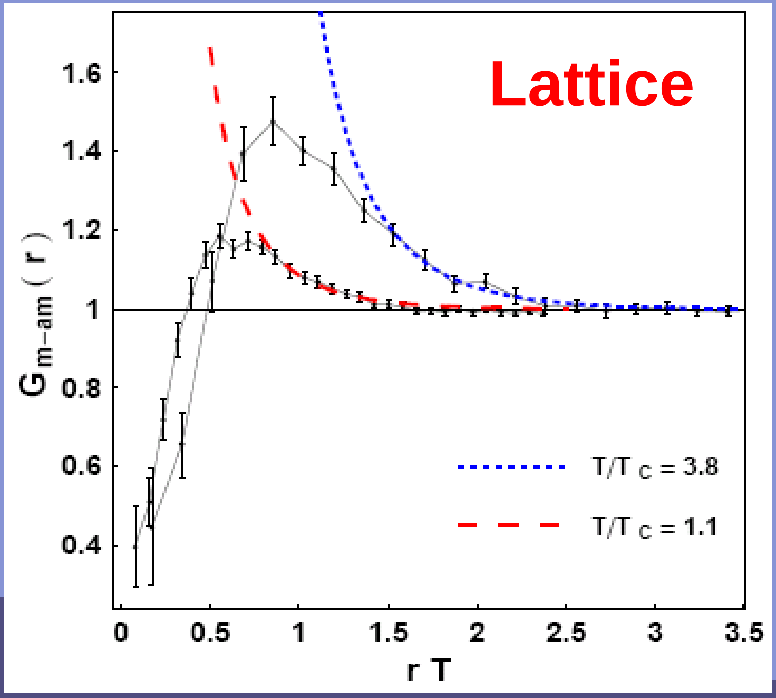
$$f(\vec{r}_i^a, \vec{r}_j^b) \approx f(\vec{r}_i^a) \cdot f(\vec{r}_j^b) \cdot [1 + \hat{O}(g^{ab} - 1)]$$

$$g(r) \simeq \exp(-V(r)/T)$$

From: Gelman, Shuryak, & Zahed, nucl-th/0601029

From Correlation to M-Coupling

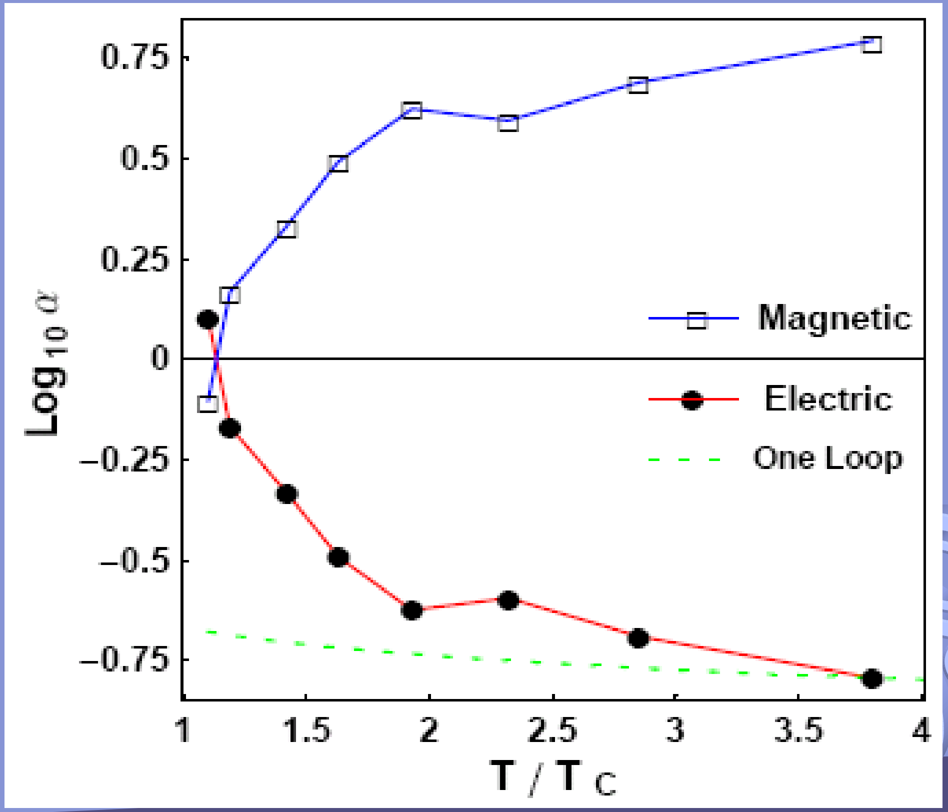




JL & Shuryak, arXiv: 0804.0255

$$G_{M\bar{M}}(r) \sim exp\left[\frac{\alpha_M e^{-r/R_d}}{rT}\right]$$

M-coupling runs to be large at high T !



Magnetic Component is a Good Liquid

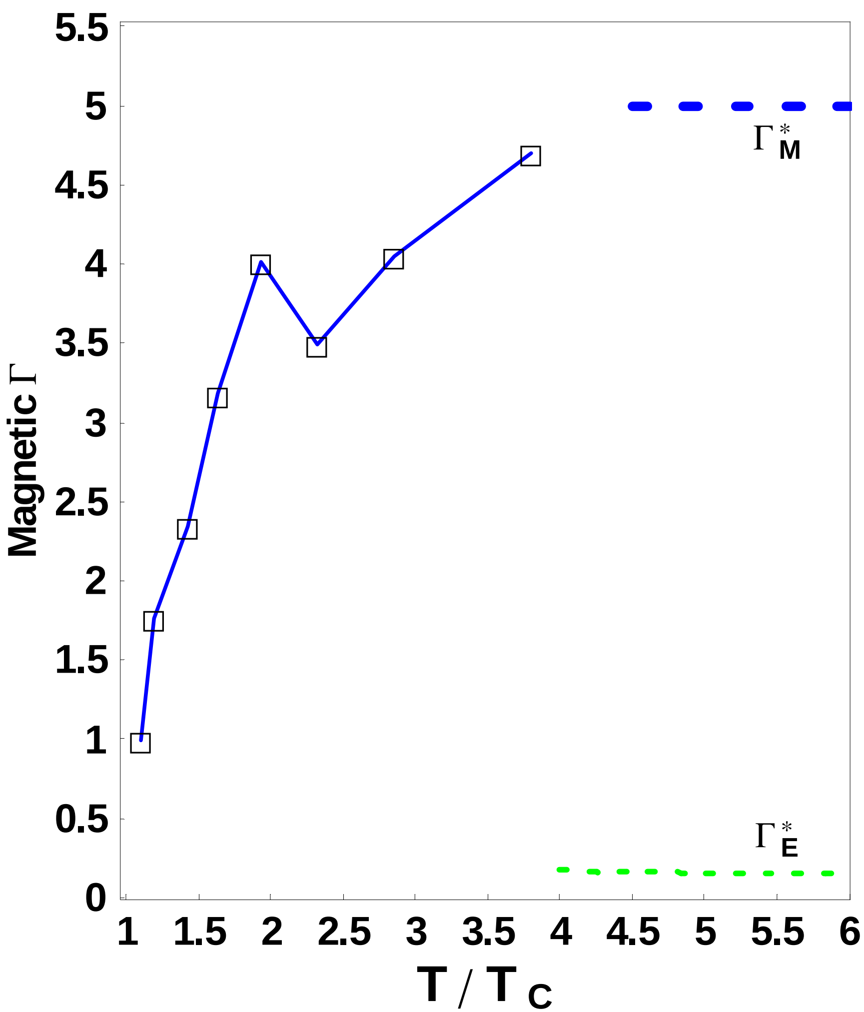
JL & Shuryak, arXiv: 0804.0255

Plasma coupling of M-component: $\Gamma \equiv \frac{\alpha_C / (\frac{3}{4\pi n})^{1/3}}{T}$

High T end :

$$\Gamma_M \sim \frac{\alpha_M n_M^{1/3}}{T} \sim \frac{\alpha_M (\alpha_E^3 T^3)^{1/3}}{T}$$

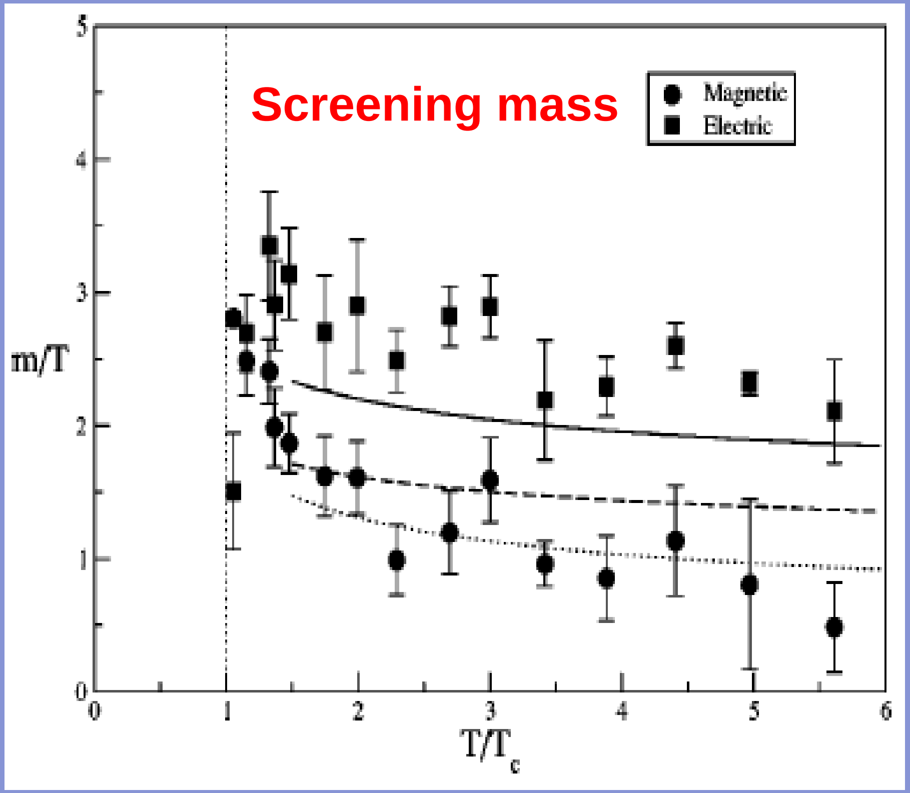
$$\Gamma_E \sim \alpha_E << 1$$



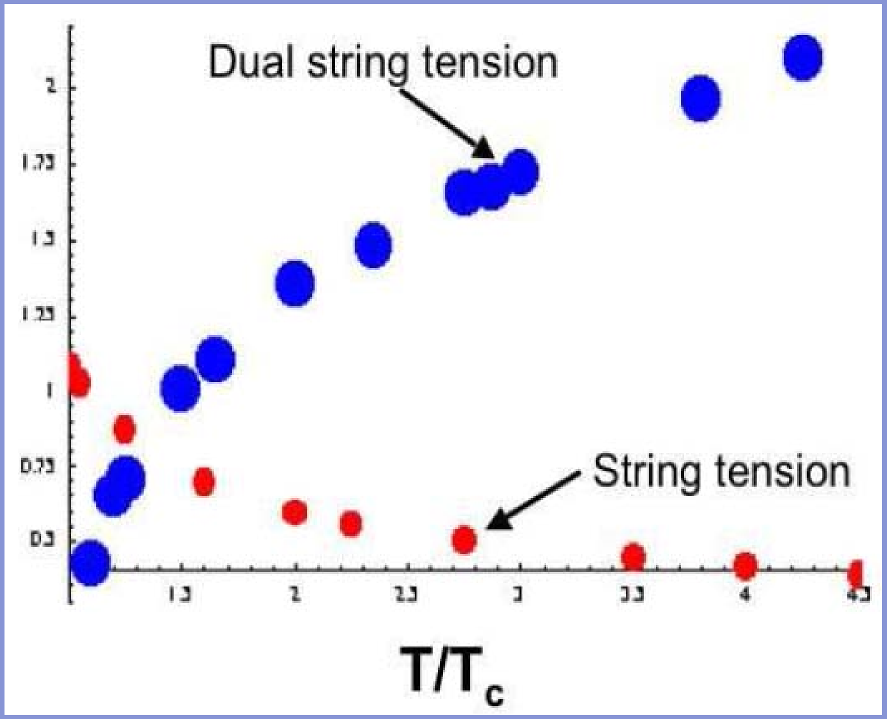
- *a magnetic component of sQGP made of dense monopoles;*
- *the magnetic coupling runs oppositely to the electric, crossing around 1.5Tc;*
- *the magnetic component should be a good liquid:*

all these are supported by the lattice calculations→ need more

More E-M Crossing



A. Nakamura, et al, PRD69(2004)014506



M. Baker, PRD78(2008)014009

Dual QCD : vacuum
& finite T<3T

Summary

Electric component of sQGP 1-2Tc

- Susceptibilities →→ quarks/gluons: heavy below 1.5Tc
- Potential model Q.M. →→ hadrons: survive above 1.5Tc

They are NOT the only players, nor the dominant !

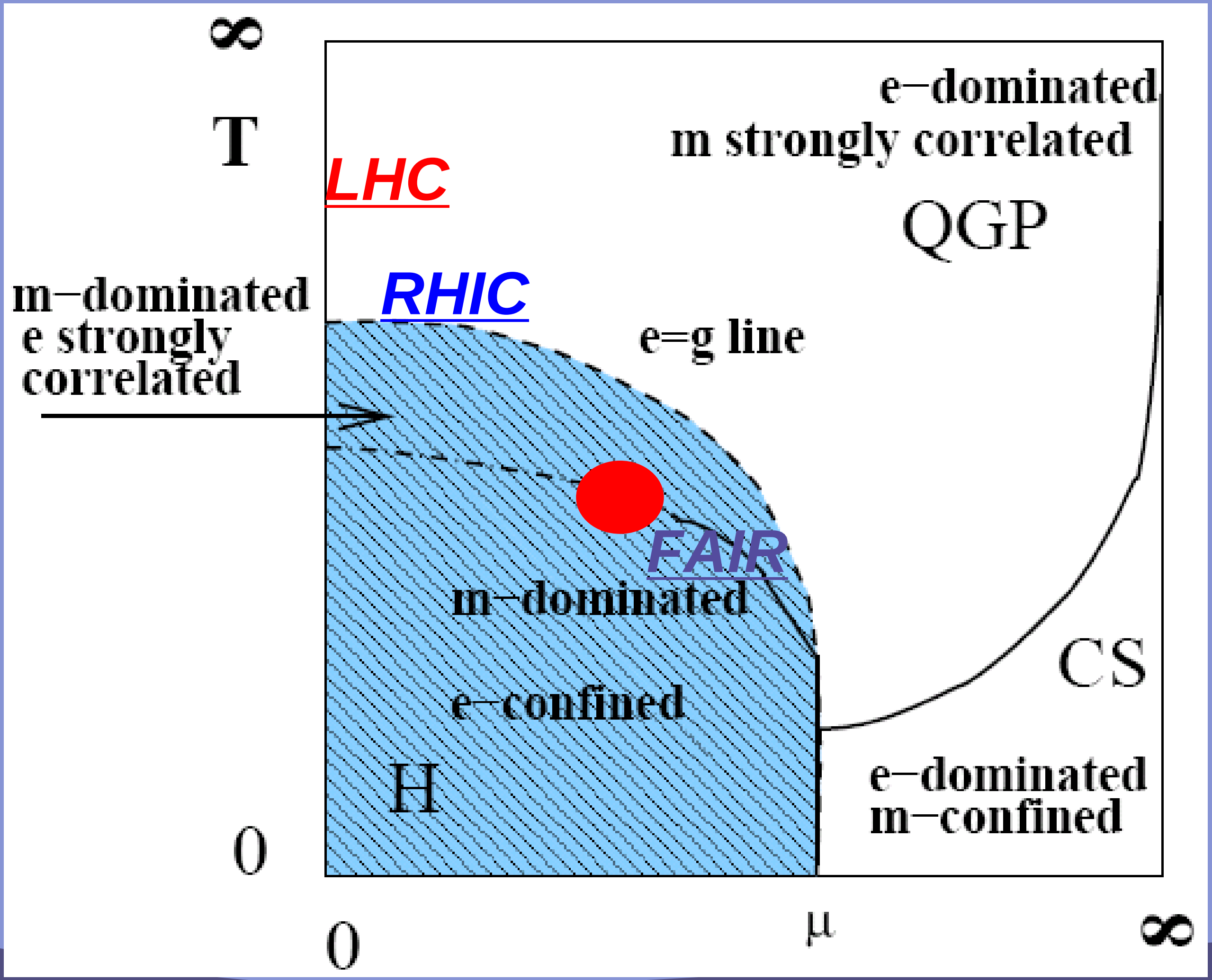
E-M duality →→

Magnetic component of sQGP 1-2Tc

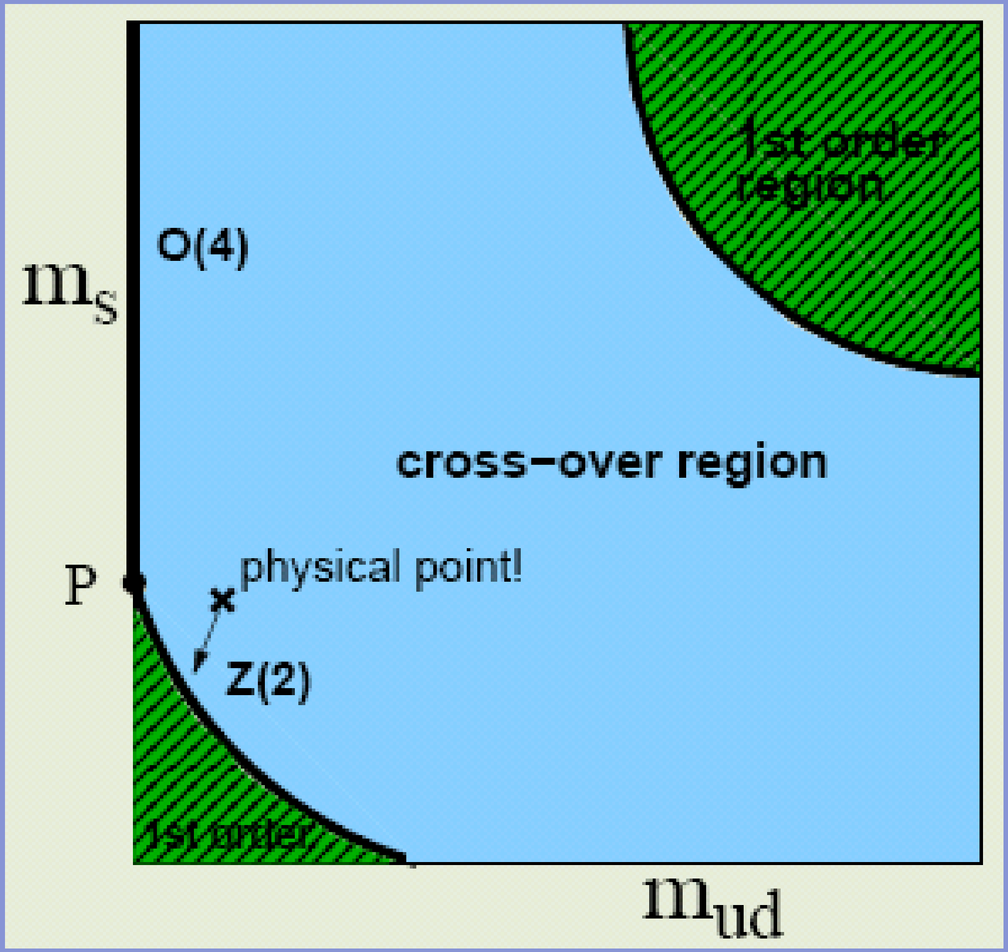
- A good liquid made of dense monopoles
- Condense at lower T while become dilute and stronger coupled at higher T, oppositely to the electric
- Using MD we showed a mixture plasma explains the transport properties of the RHIC measurements
- It helps us understand the geometry & physics of jet quenching

Magnetic Scenario (with time)
→→ a deeper theoretical understanding of sQGP

New Phase Diagram from E-M Duality



The Order of Transition ?



The Order-Disorder Transition ?

$$L(\vec{x}) = Tr[Pe^{i\int_0^{\frac{1}{T}} A_0(\vec{x},t)dt}]$$

CROSSOVER !! ??
[real QCD vacuum
is confining, for sure.]

Is dual superconductivity the correct picture for QCD confinement ?

Symmetric Phase ---- deconfined
< Magnetic U(1) > = 0

NO CROSSOVER

Asymmetric Phase ---- confined
< Magnetic U(1) > NOT 0

Pisa group (Di Giacomo and collaborators) *arXiv:0710.1174 & refs therein*

$$\mu(\vec{y},t) = \exp\left[i\frac{1}{e}\int d^3x\ \vec{E}(\vec{x},t)\vec{b}(\vec{x}-\vec{y})\right]$$

$$\vec{b}(\vec{x}-\vec{y}) = \frac{q}{2}\frac{\vec{r}\wedge\vec{n}_3}{r(r-\vec{r}\cdot\vec{n}_3)}.$$

$$N_f = 2\ \mathrm{QCD}$$

$$C_V - C_0 = L_s^{\frac{\alpha}{\nu}}\Phi_c(\tau L_s^{\frac{1}{\nu}}, mL_s^{y_h})$$

$$\chi - \chi_0 = L_s^{\frac{1}{\nu}}\Phi_\chi(\tau L_s^{\frac{1}{\nu}}, mL_s^{y_h})$$

1st ORDER ??

DISCLAIMER: I am not to be blamed for the results ☺